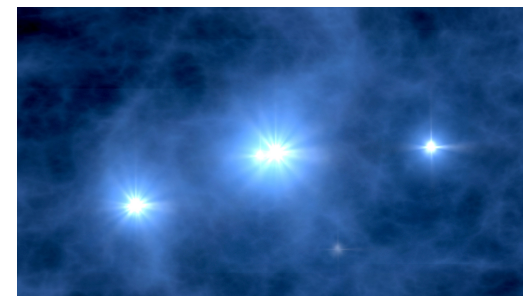
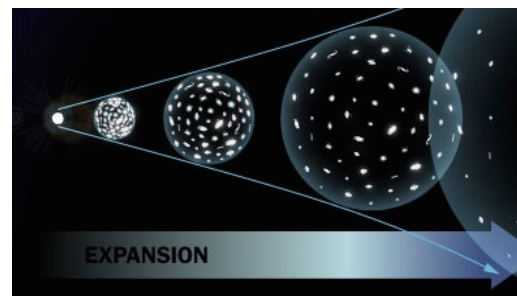
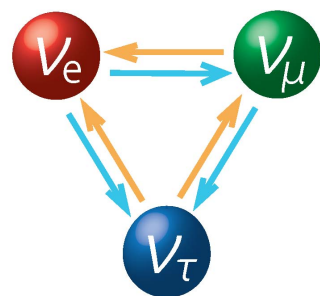
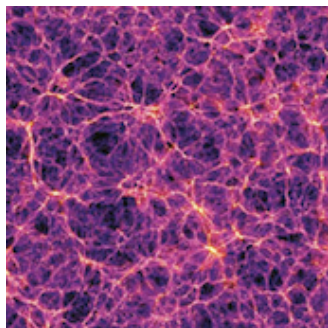
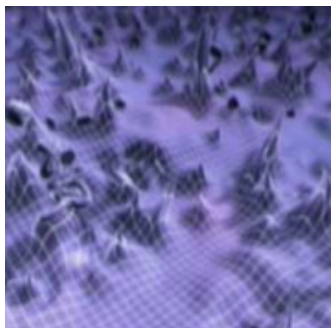
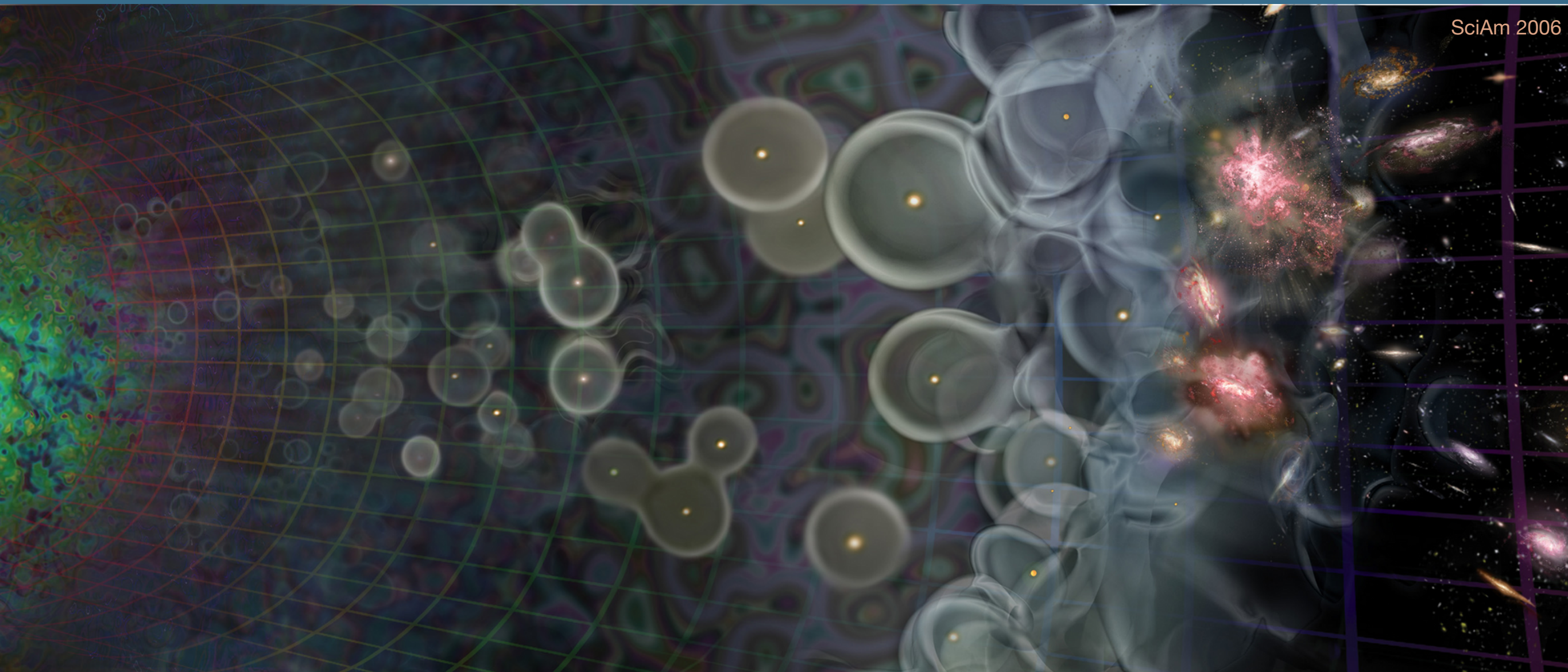


The Dawn of Cosmic Dawn Cosmology

Ely Kovetz

Ben-Gurion University

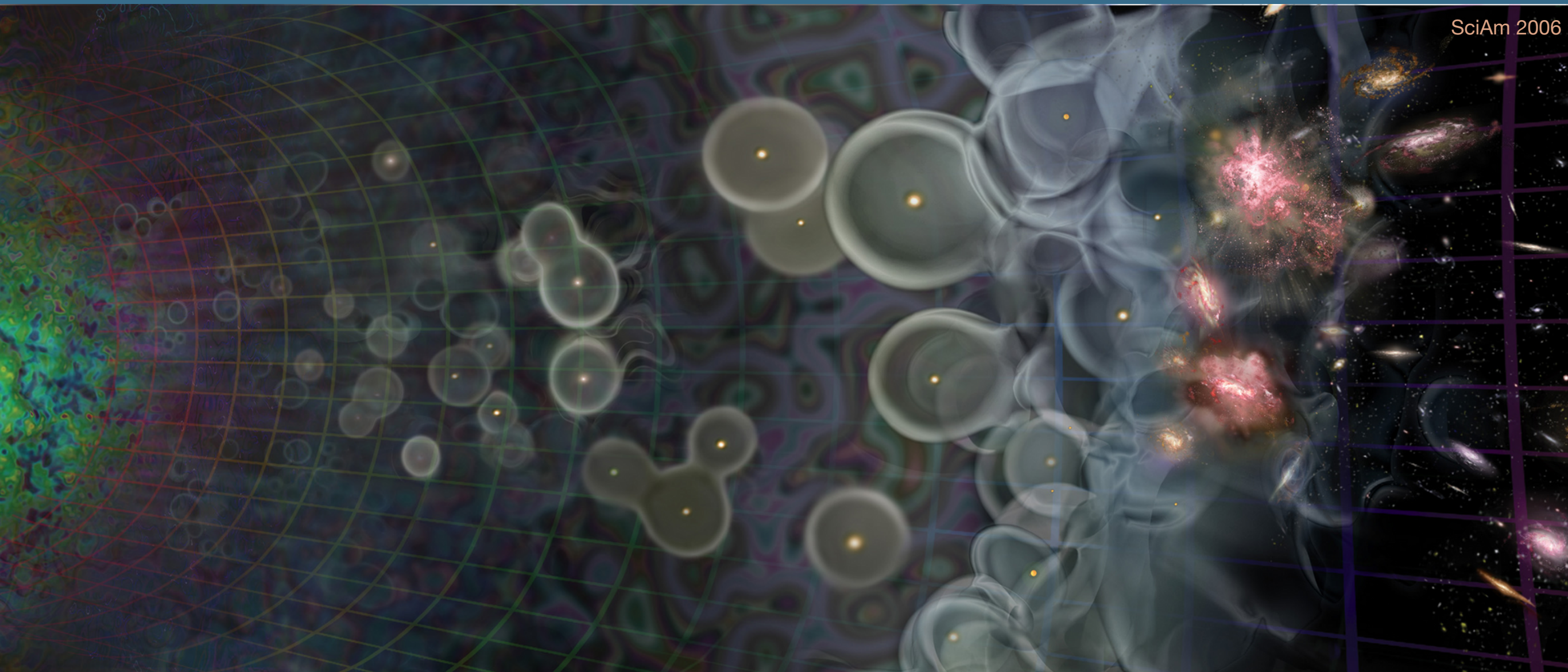


GGI Symposium September 2025

The Dawn of Cosmic Dawn Cosmology

Ely Kovetz

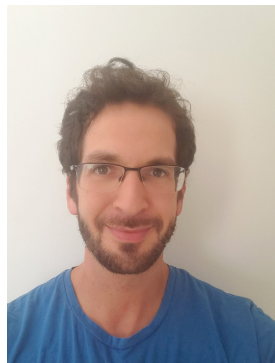
Ben-Gurion University



Sarah Libanore



Hovav Lazare



Jordan Flitter



Tal Adi



Debanjan Sarkar



Tal Kadosh

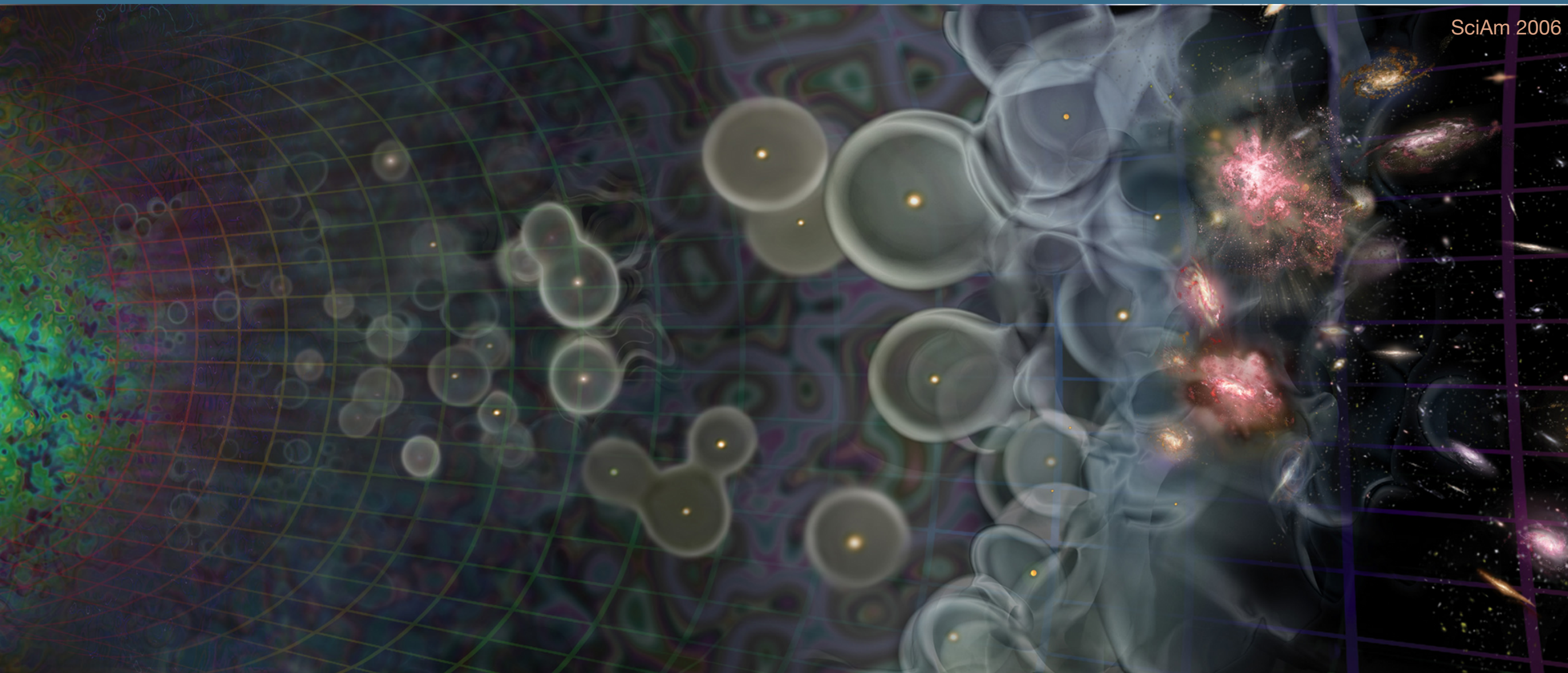


Julian Muñoz

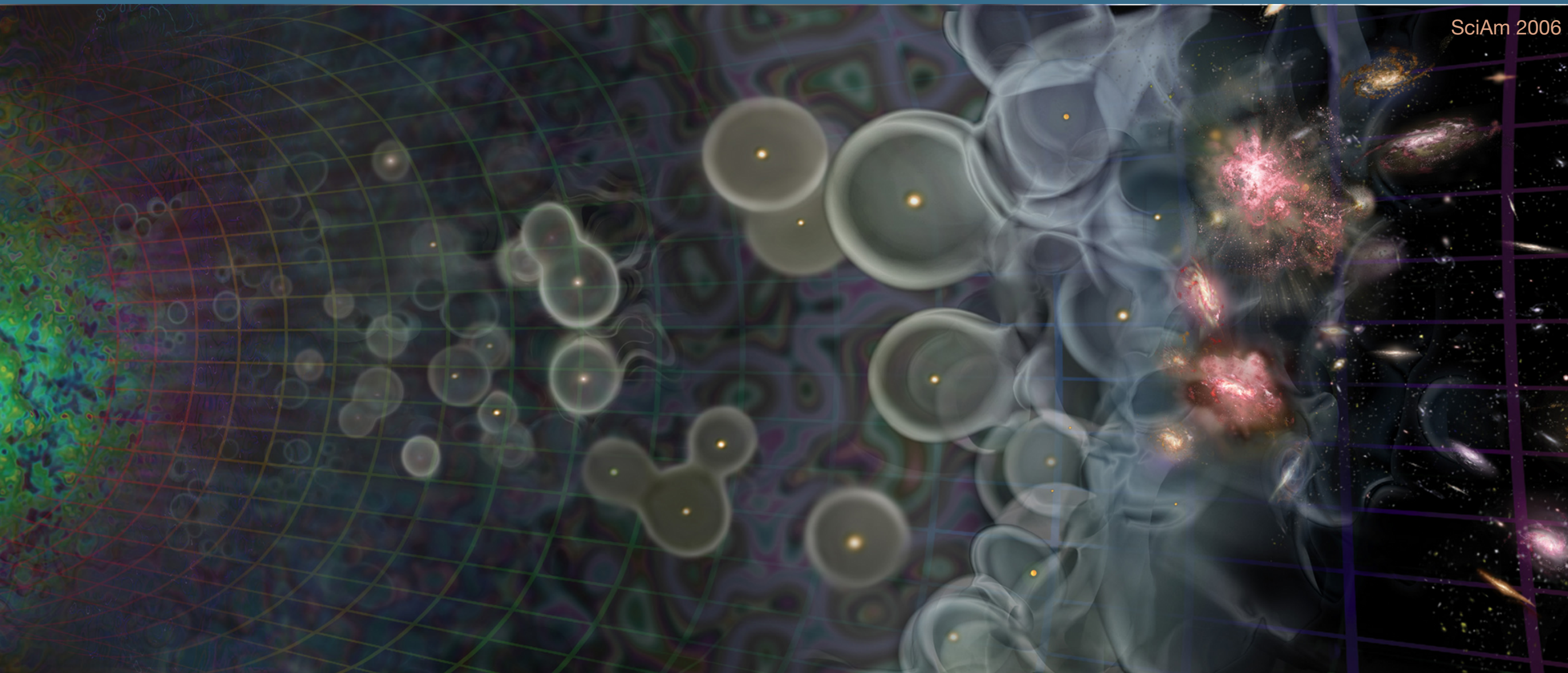


Kim Boddy

Teaser 1: cosmic dawn - no longer just forecasts!

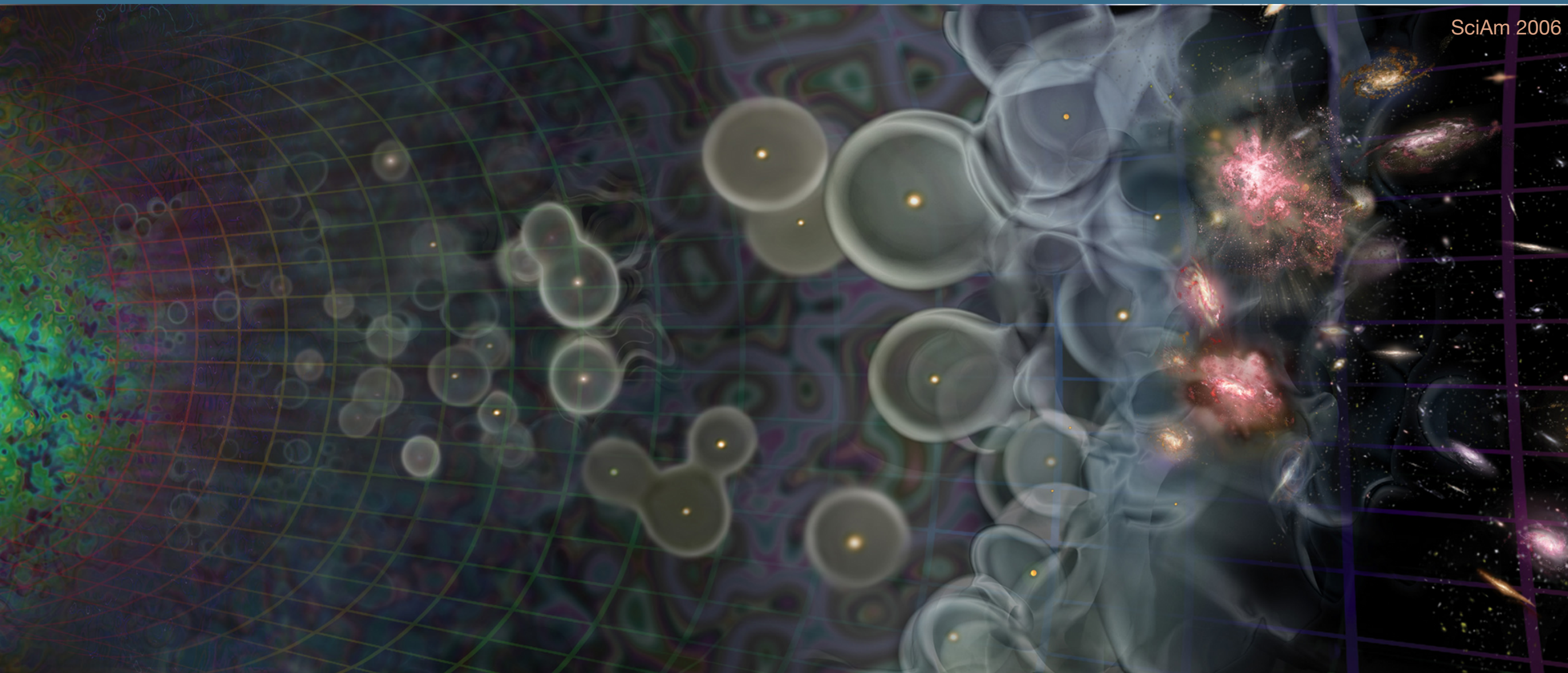


Teaser 1: cosmic dawn - no longer just forecasts!



We're already counting $\mathcal{O}(10^3)$ galaxies at cosmic dawn with HST and JWST.

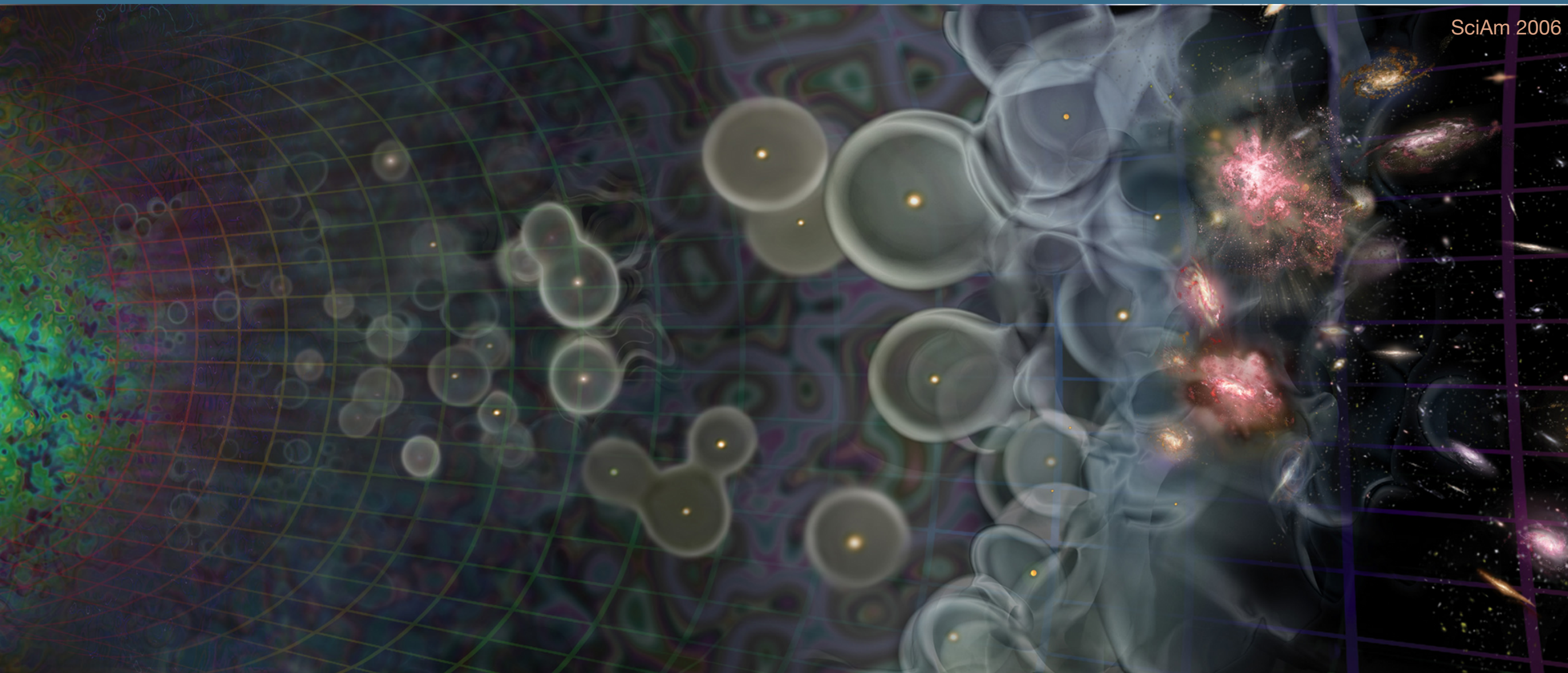
Teaser 1: cosmic dawn - no longer just forecasts!



We're already counting $\mathcal{O}(10^3)$ galaxies at cosmic dawn with HST and JWST.

→ Tightest constraints on dark matter with small scale phenomenology

Teaser 1: cosmic dawn - no longer just forecasts!

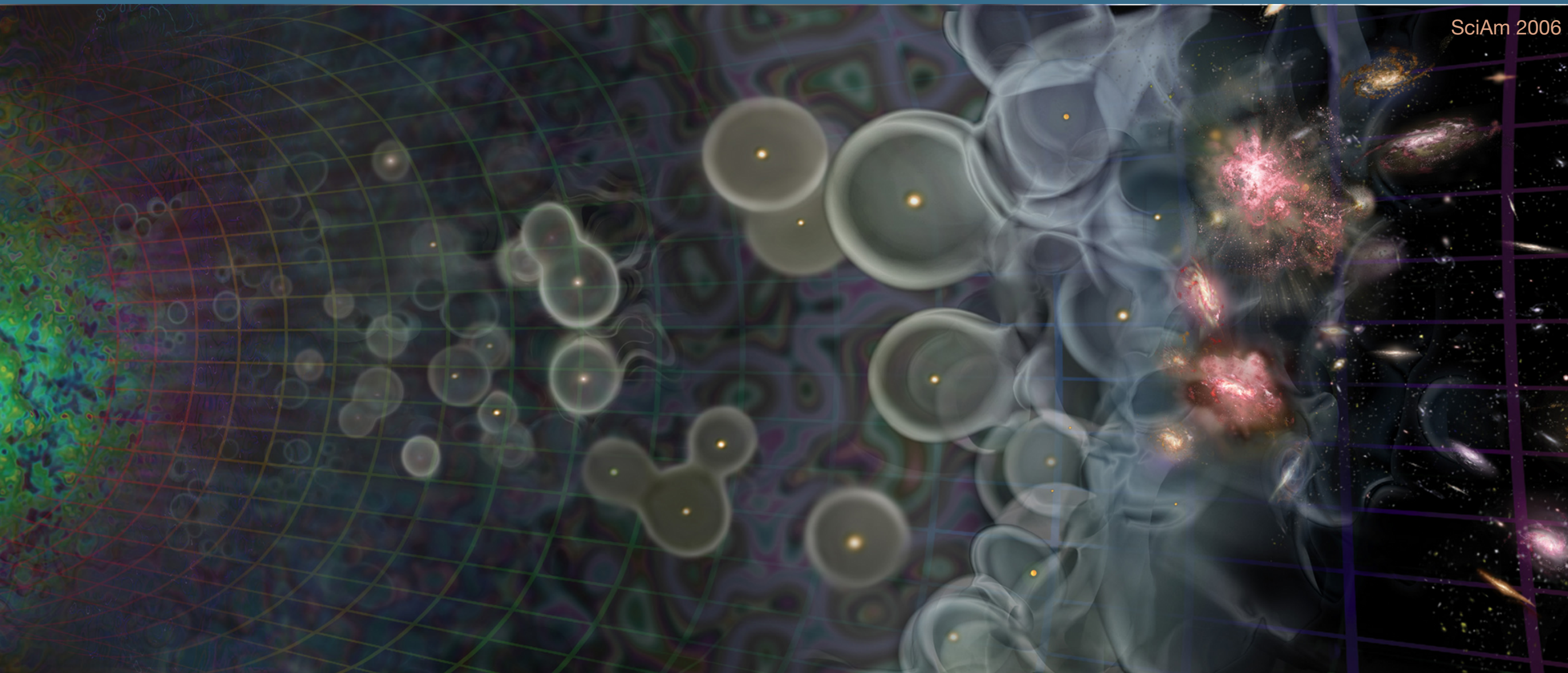


We're already counting $\mathcal{O}(10^3)$ galaxies at cosmic dawn with HST and JWST.

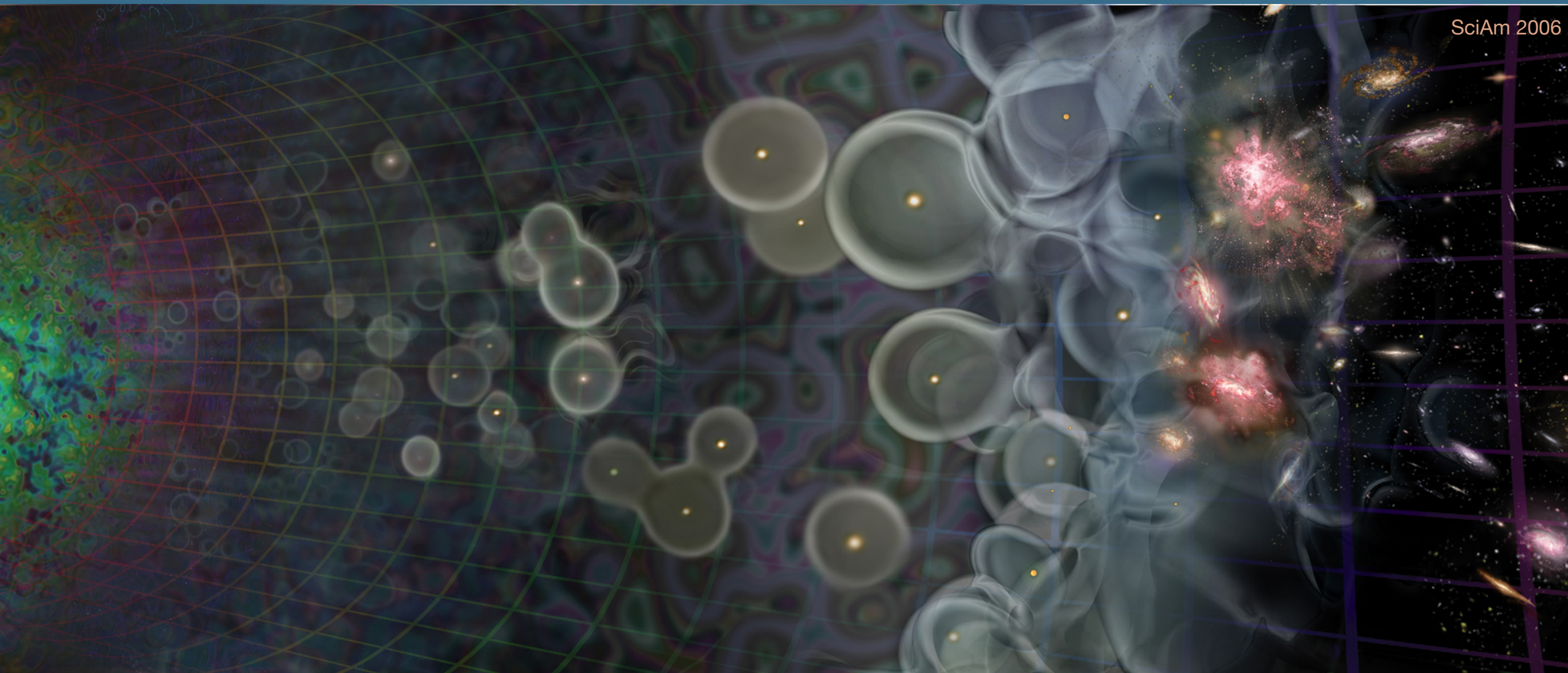
→ Tightest constraints on dark matter with small scale phenomenology

wait ~15 min.

Teaser 2: can we time the onset of reionization?

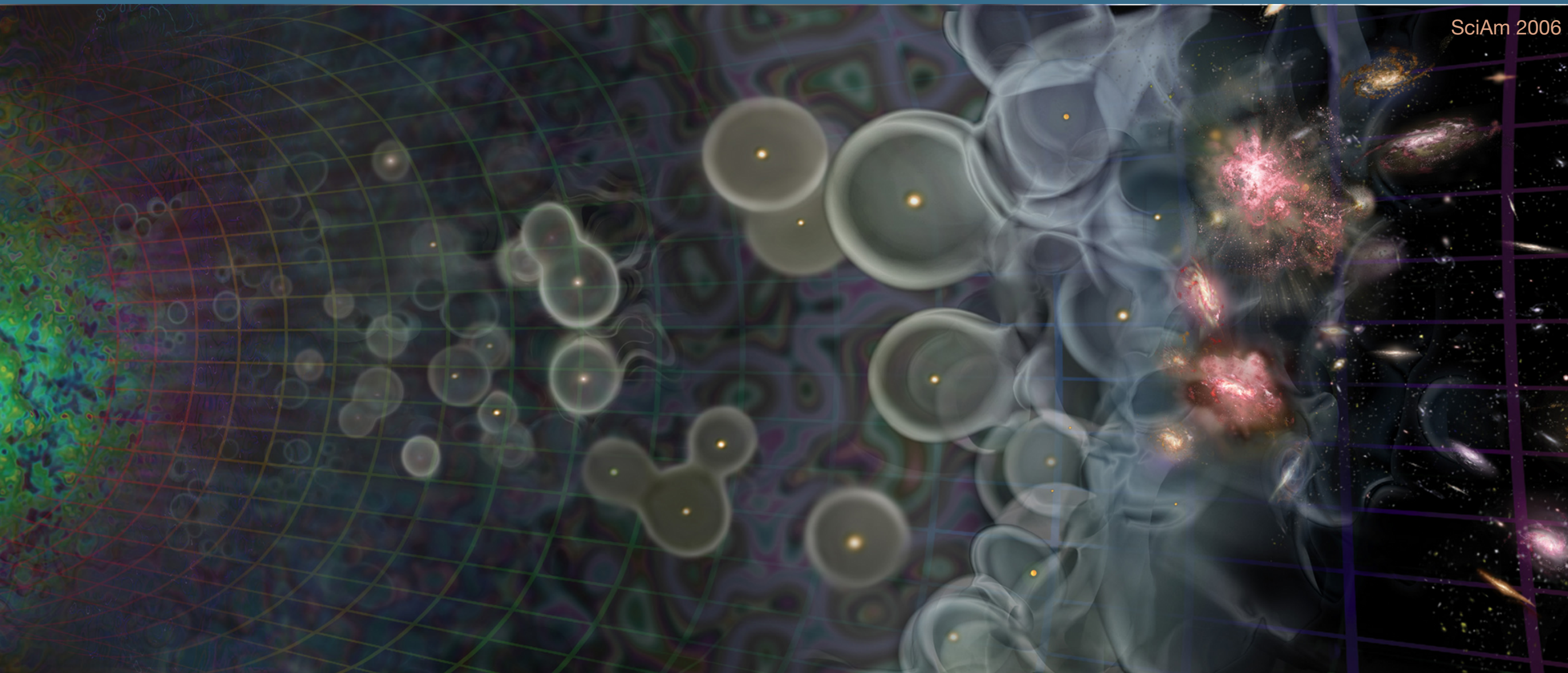


Teaser 2: can we time the onset of reionization?



CMB ←————→

Teaser 2: can we time the onset of reionization?



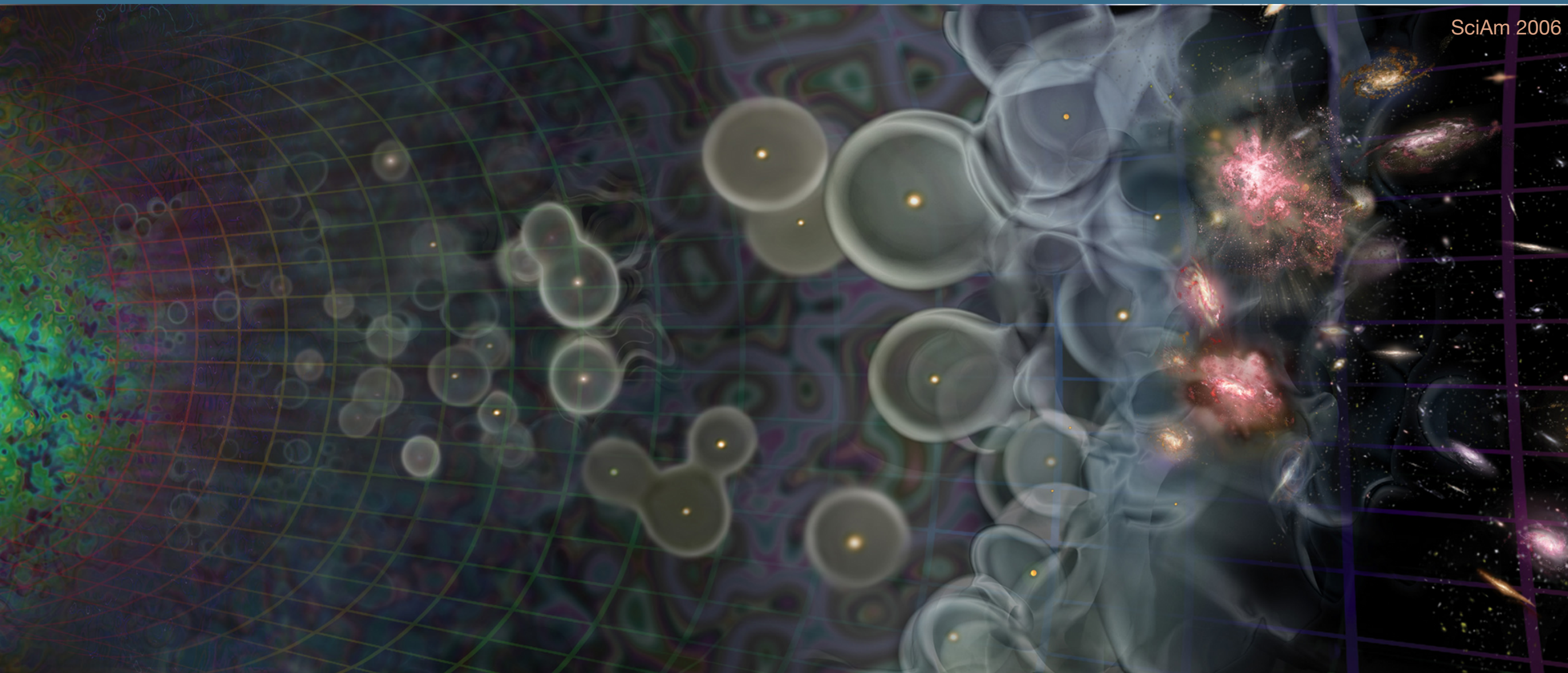
SciAm 2006

CMB ←————→



$\text{Ly}\alpha$ forest, GP trough, 21 cm

Teaser 2: can we time the onset of reionization?



CMB ←————→

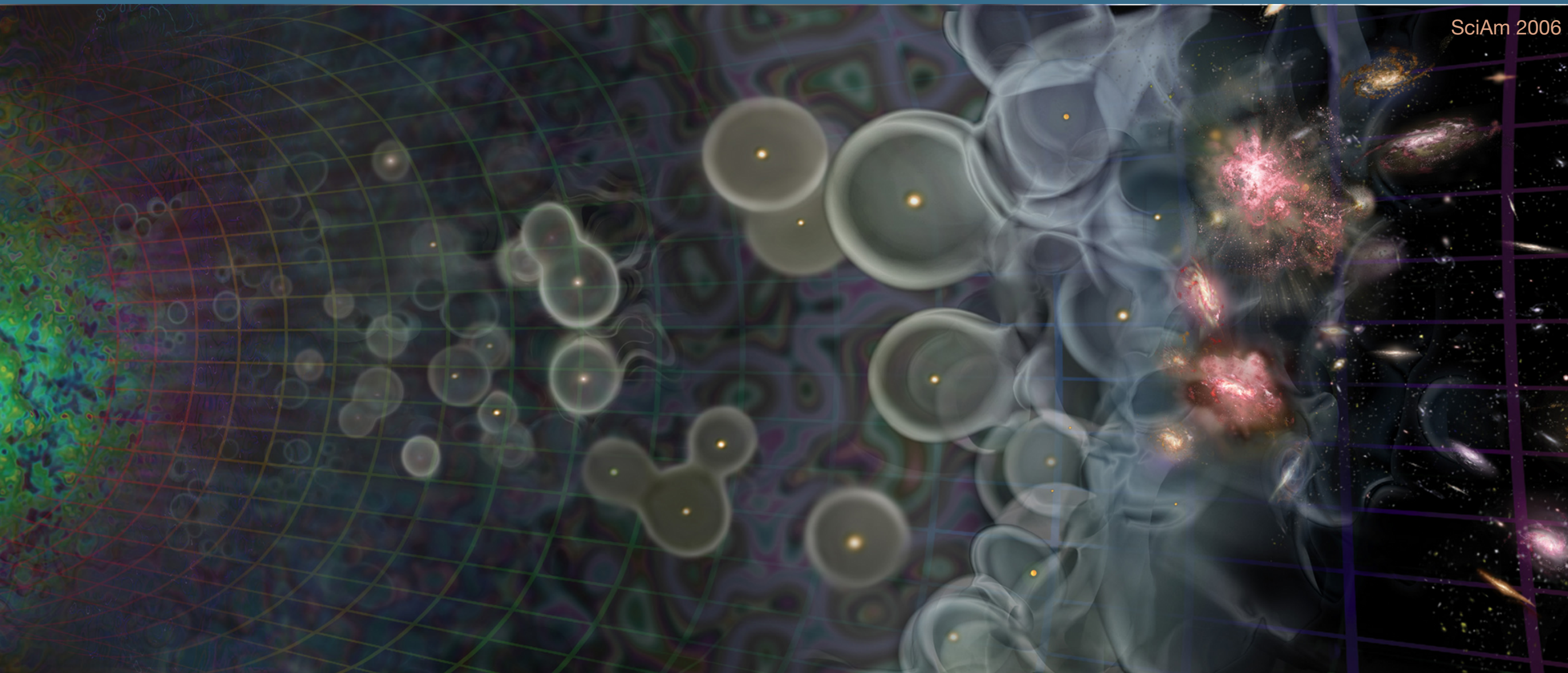
————→
 $x_{\text{HI}} \in \{1\%, 10\%\}$

??

————→

Ly α forest, GP trough, 21cm

Teaser 2: can we time the onset of reionization?



CMB ←————→

————→
 $x_{\text{HI}} \in \{1\%, 10\%\}$

?? wait ~30 min.

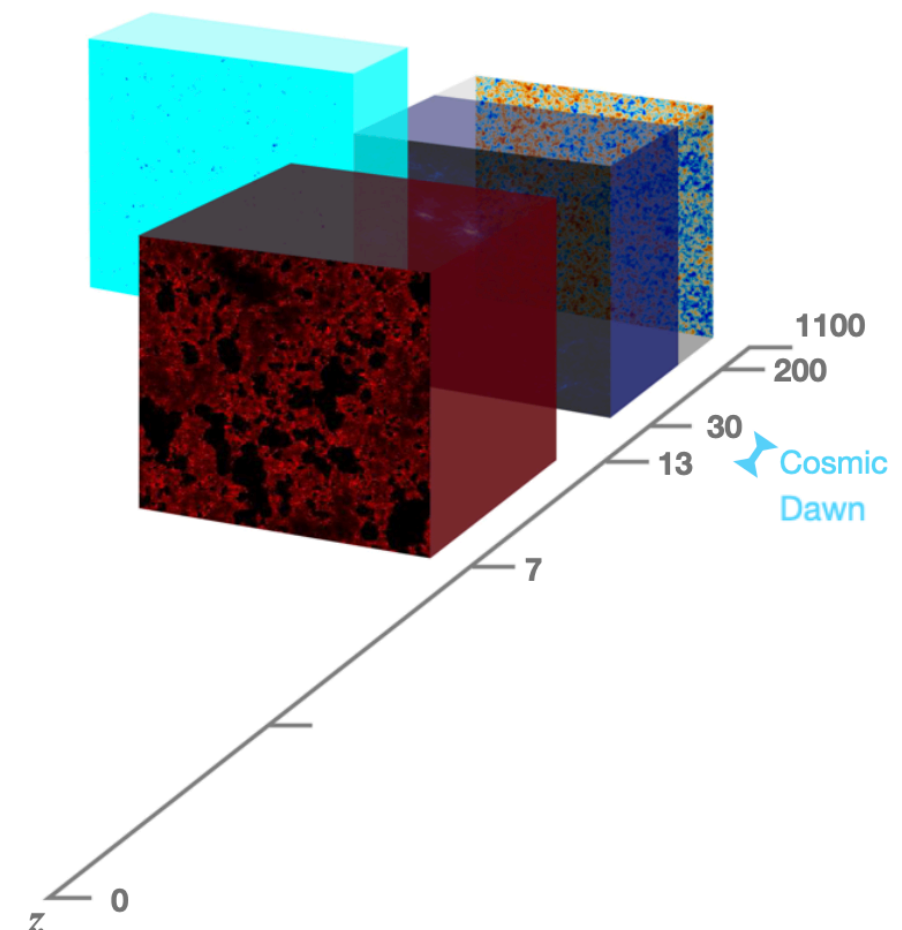
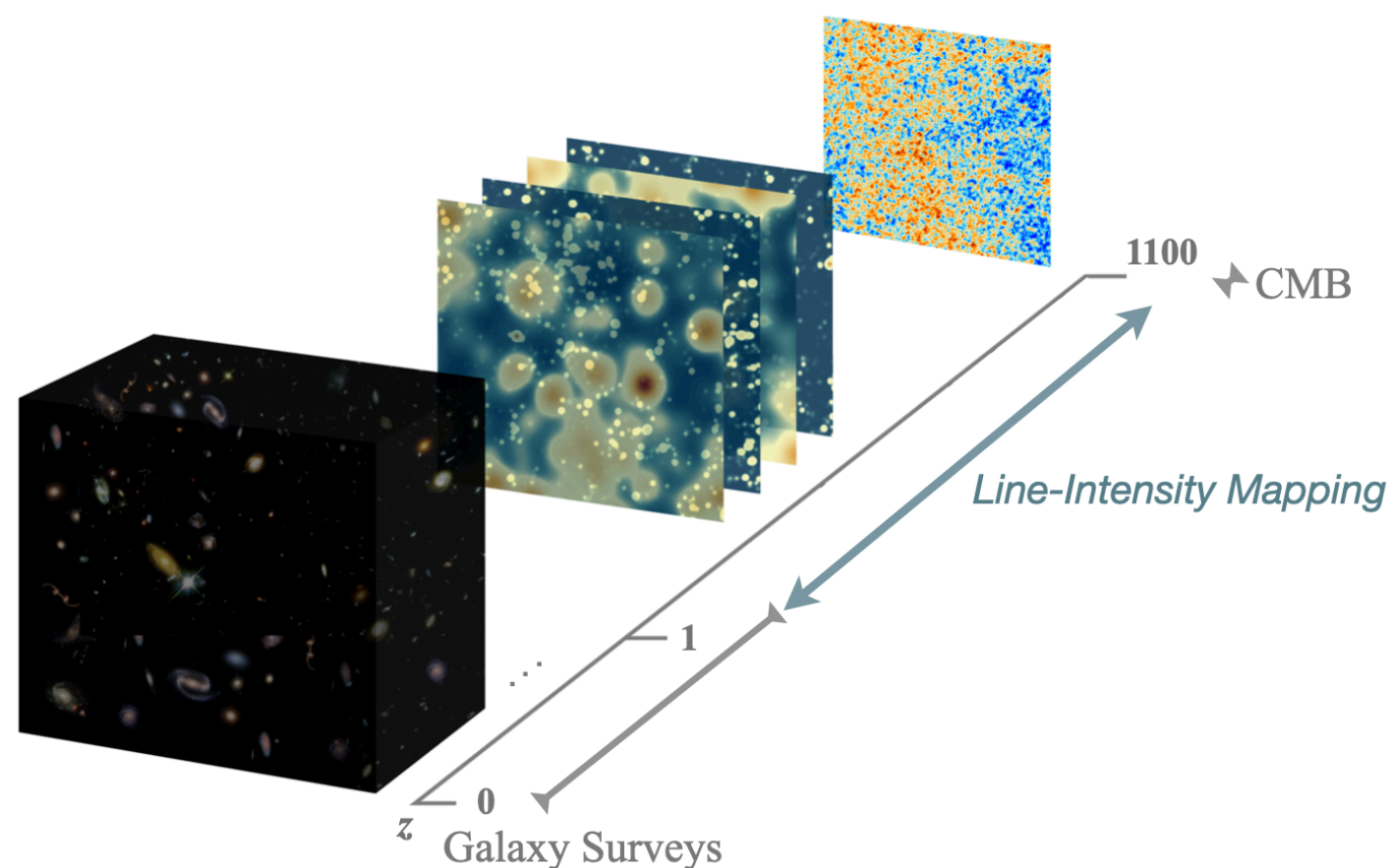
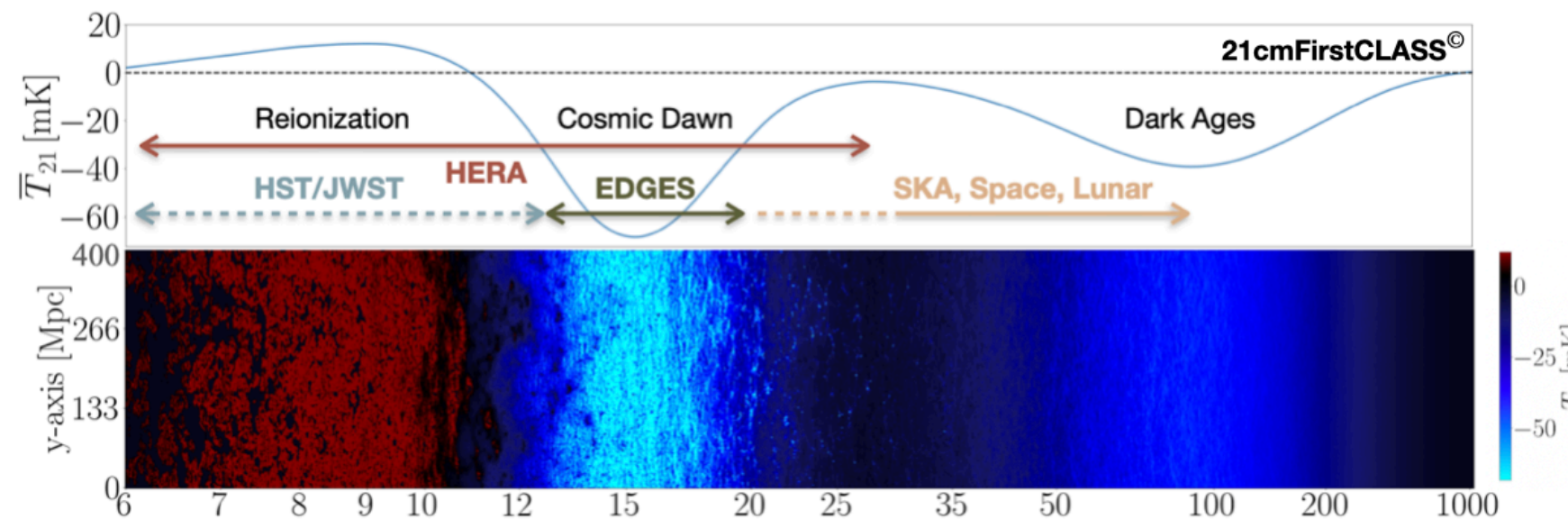
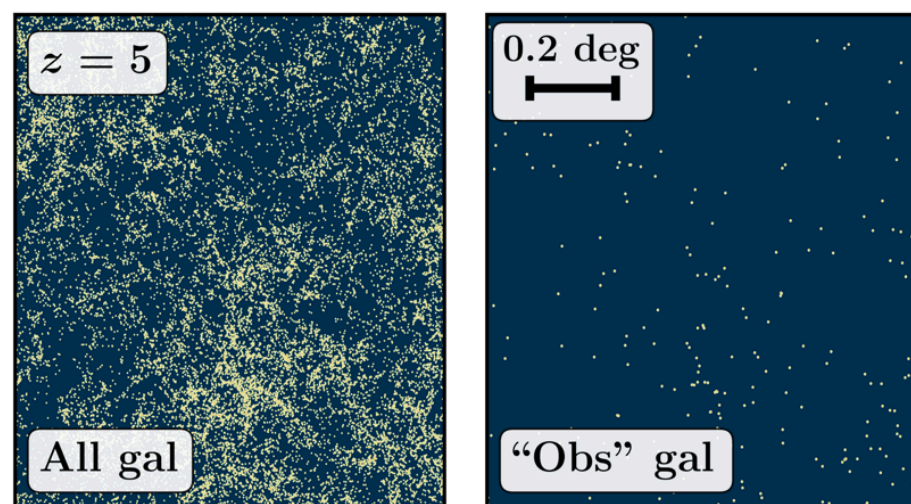
————→

Ly α forest, GP trough, 21 cm

Line-Intensity Mapping: Review and Outlook

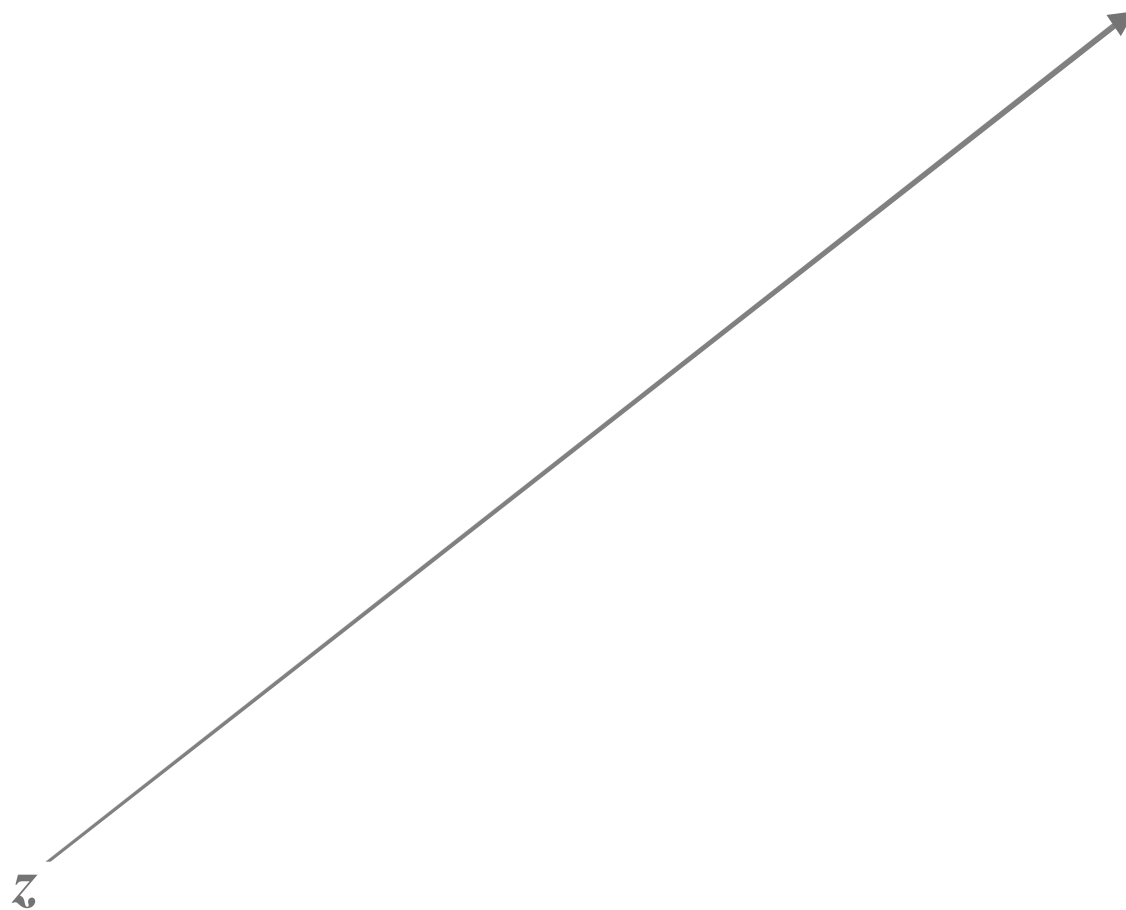
Ely Kovetz

Ben-Gurion University



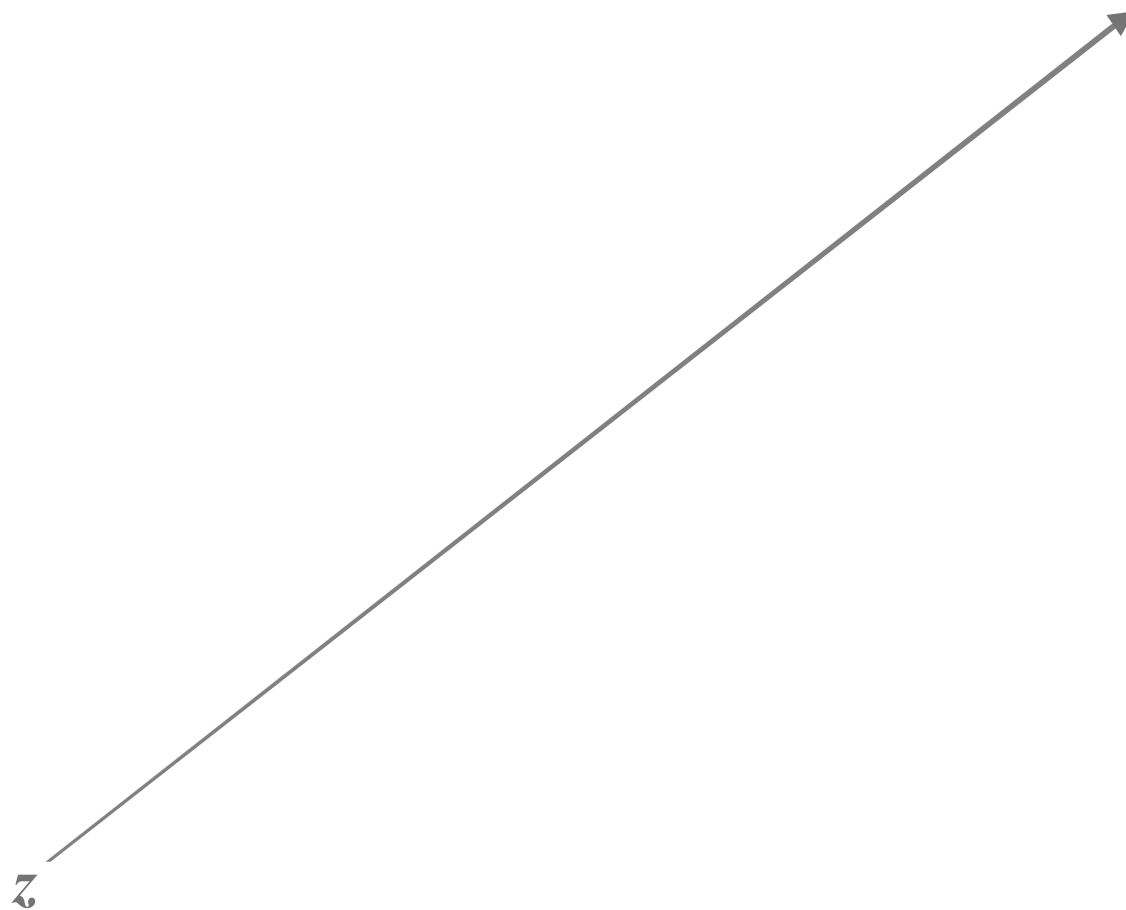
Line-Intensity Mapping: Introduction

Line-Intensity Mapping: Introduction

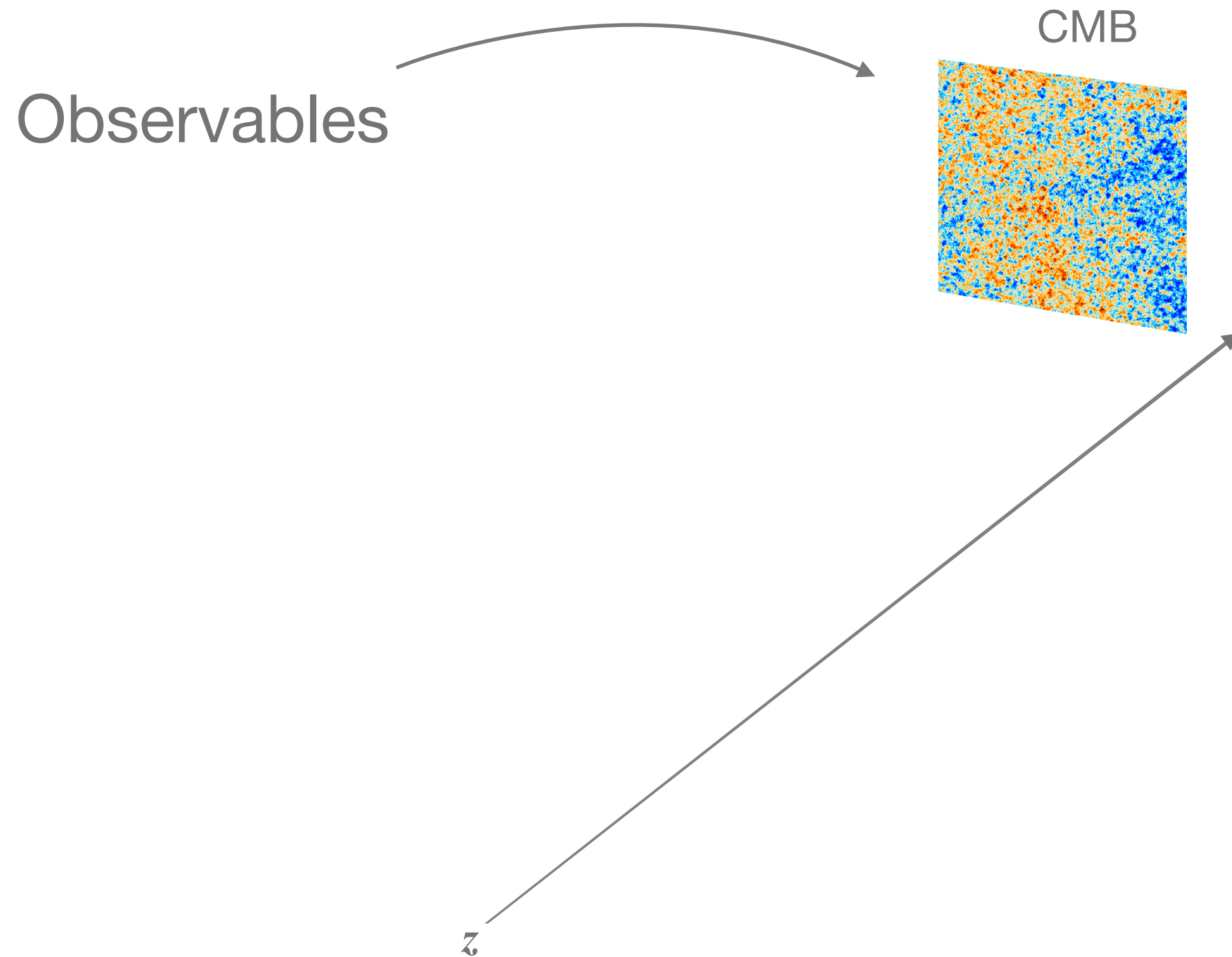


Line-Intensity Mapping: Introduction

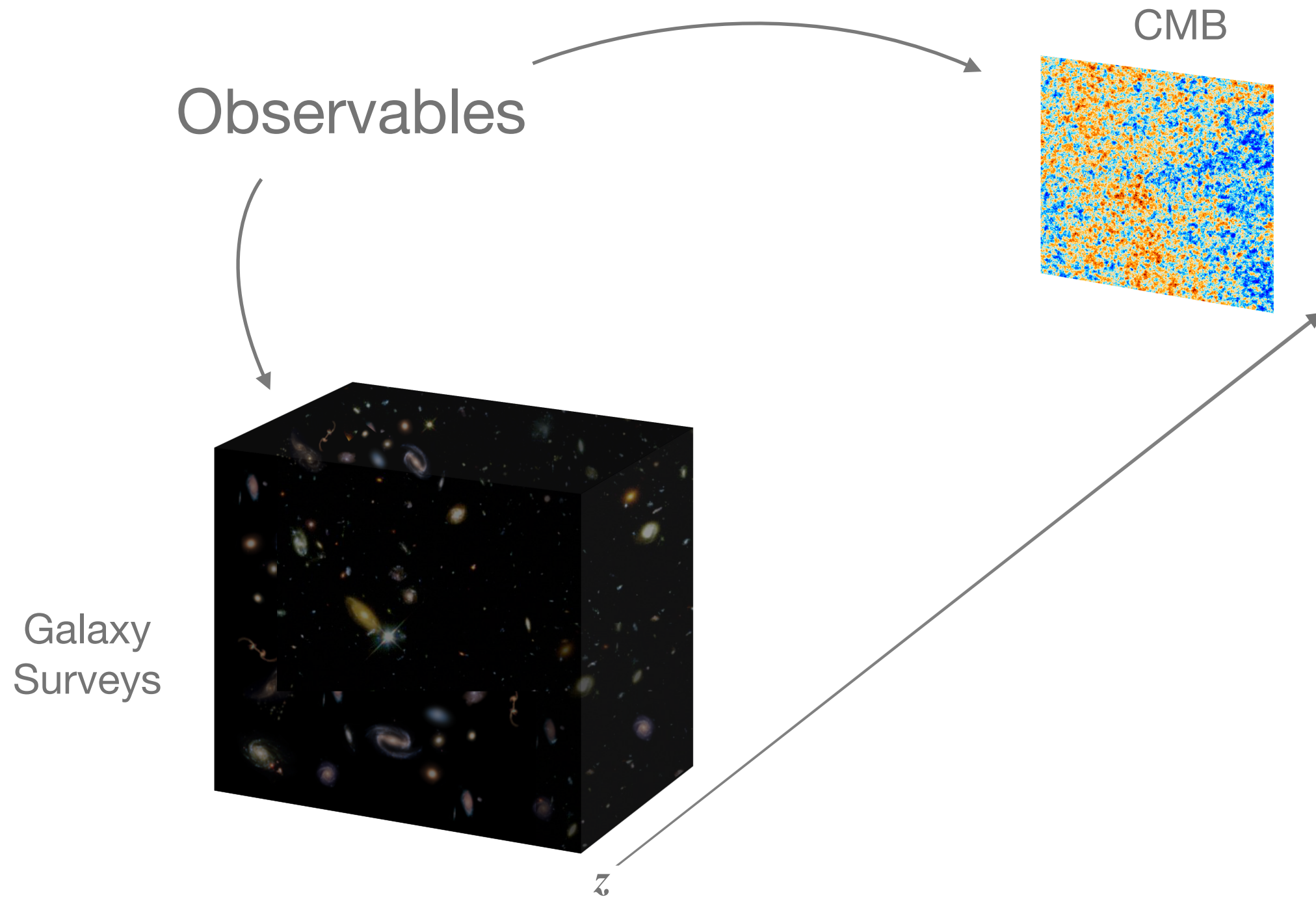
Observables



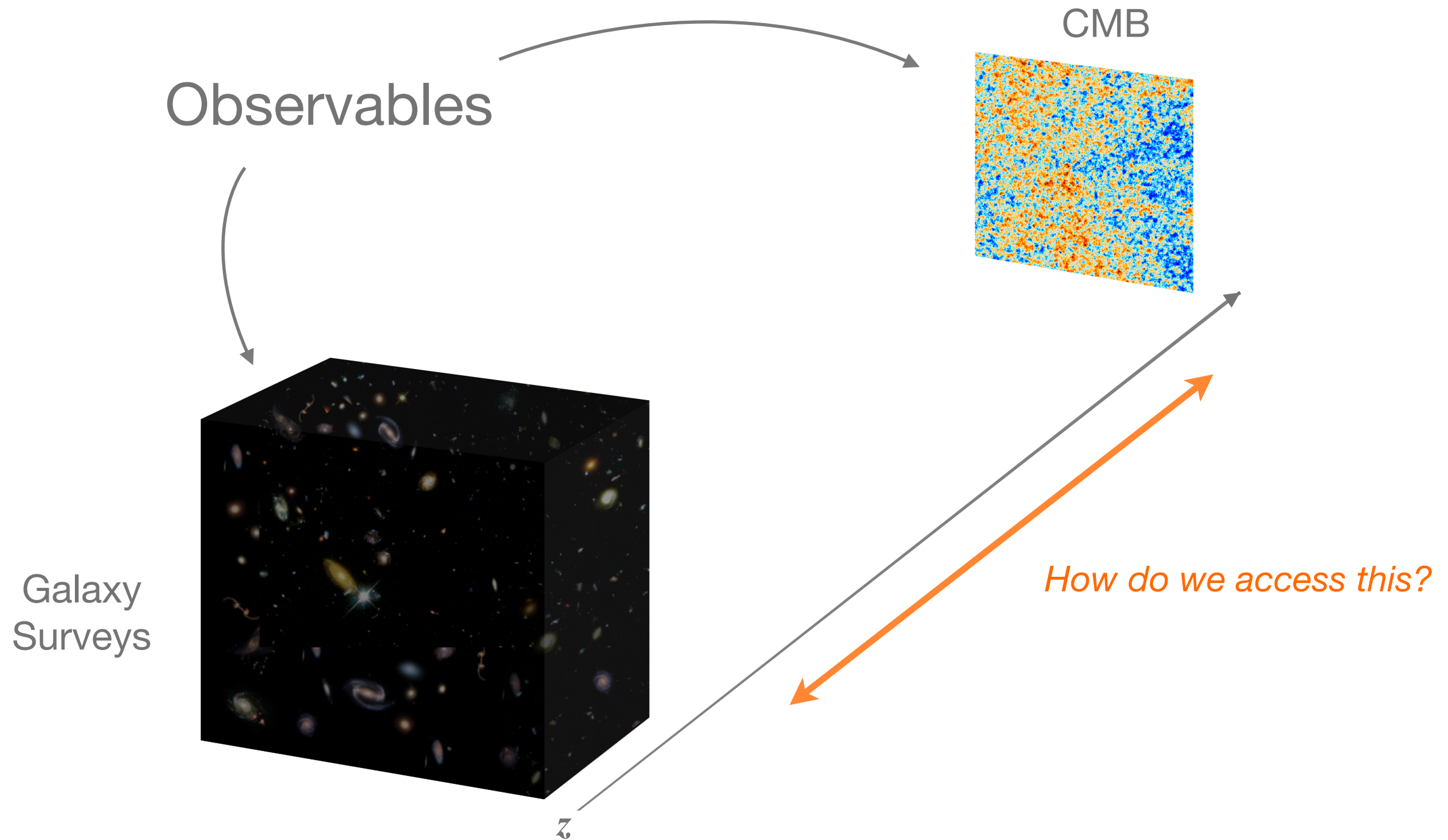
Line-Intensity Mapping: Introduction



Line-Intensity Mapping: Introduction



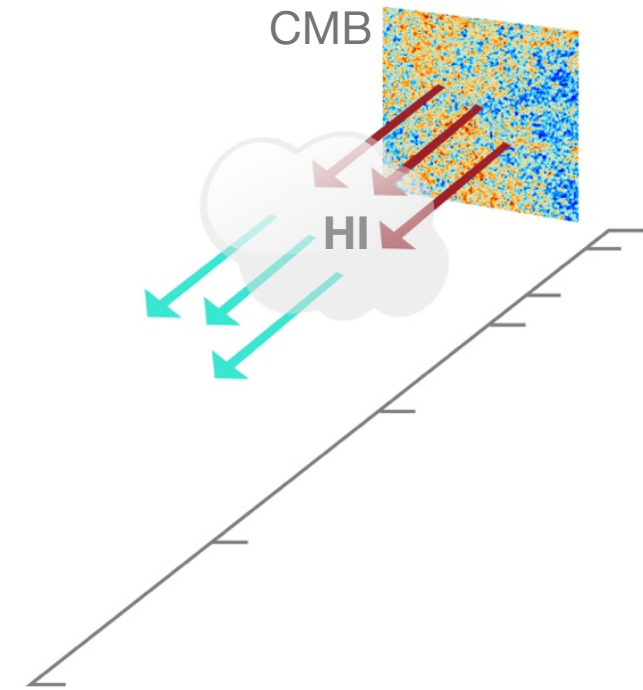
Line-Intensity Mapping: Introduction



Line-Intensity Mapping: Introduction

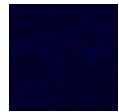
Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI

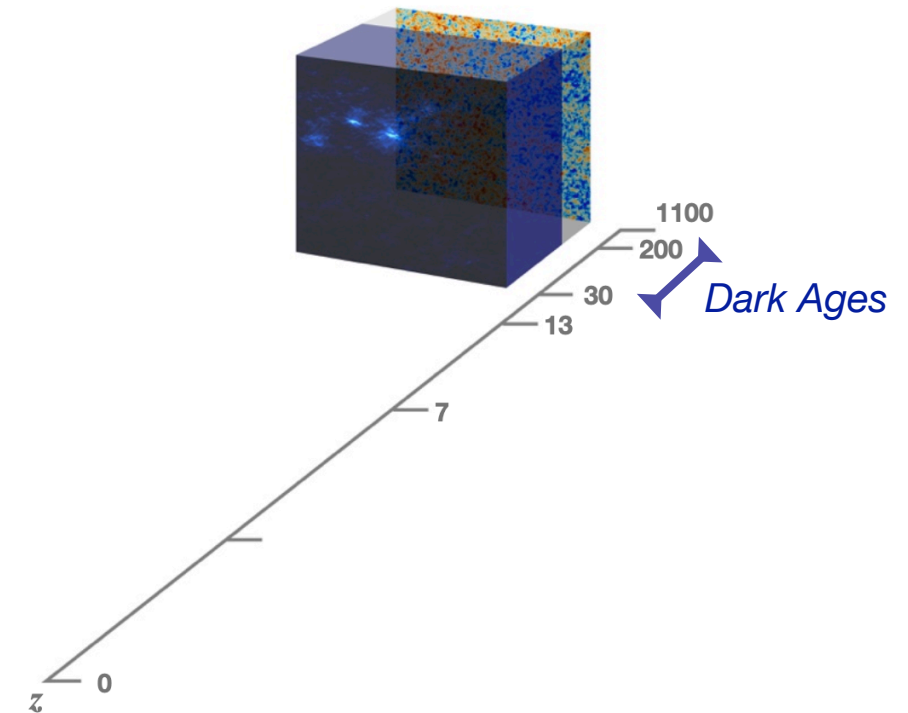


Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI

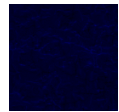


Dark Ages: adiabatic gas cooling; no stars

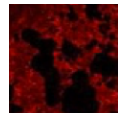


Line-Intensity Mapping: Introduction

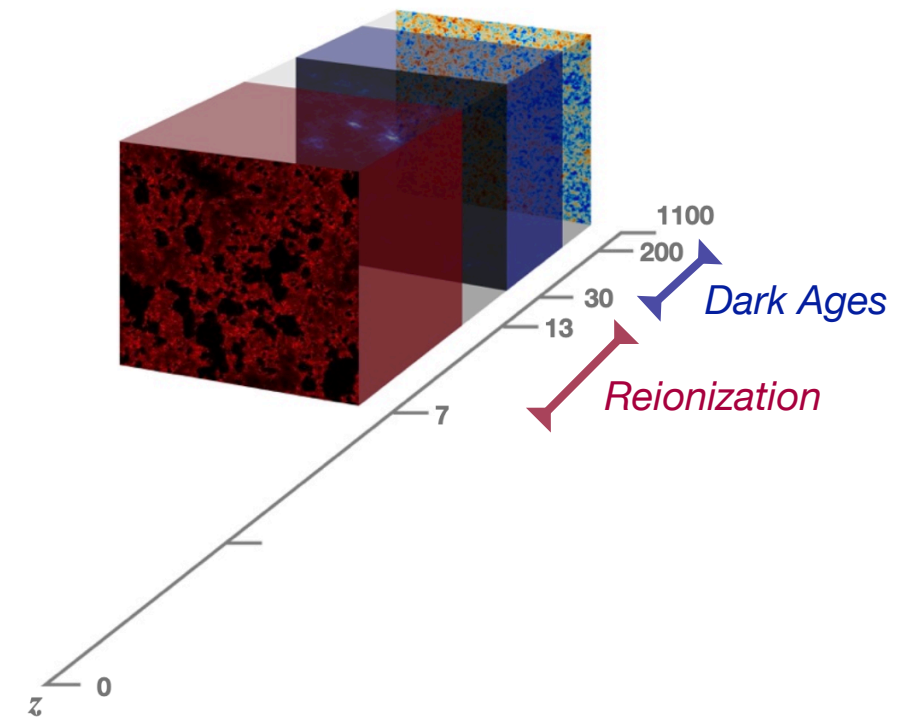
Earliest LIM signal: CMB interaction with HI



Dark Ages: adiabatic gas cooling; no stars

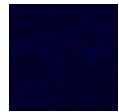


Reionization: emission against the CMB



Line-Intensity Mapping: Introduction

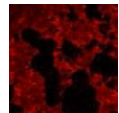
Earliest LIM signal: CMB interaction with HI



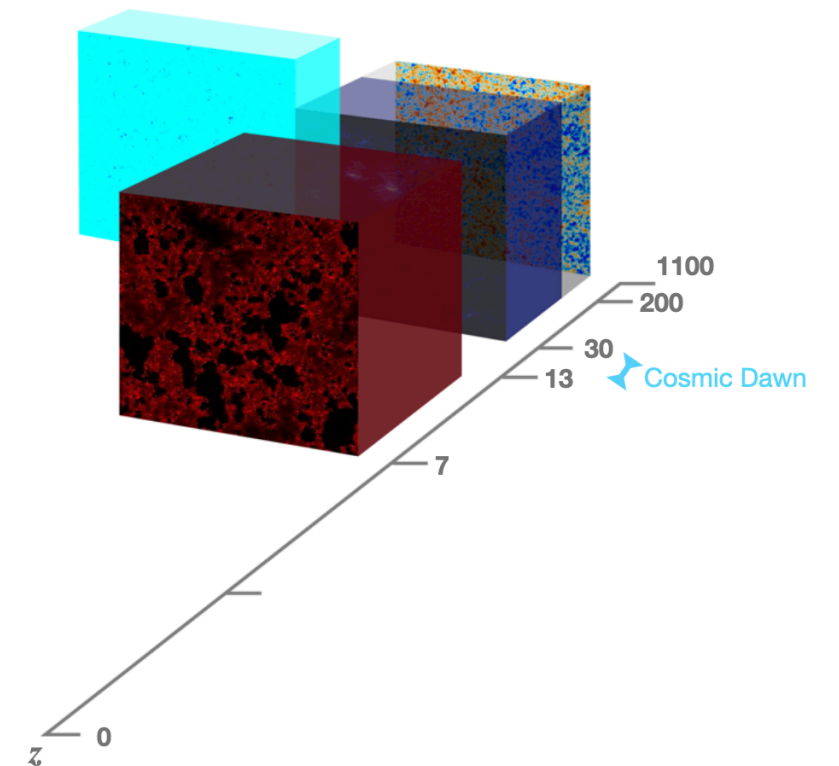
Dark Ages: adiabatic gas cooling; no stars



Cosmic dawn: turns on via Ly α from first stars

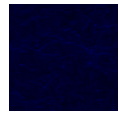


Reionization: emission against the CMB



Line-Intensity Mapping: Introduction

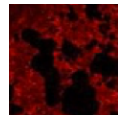
Earliest LIM signal: CMB interaction with HI



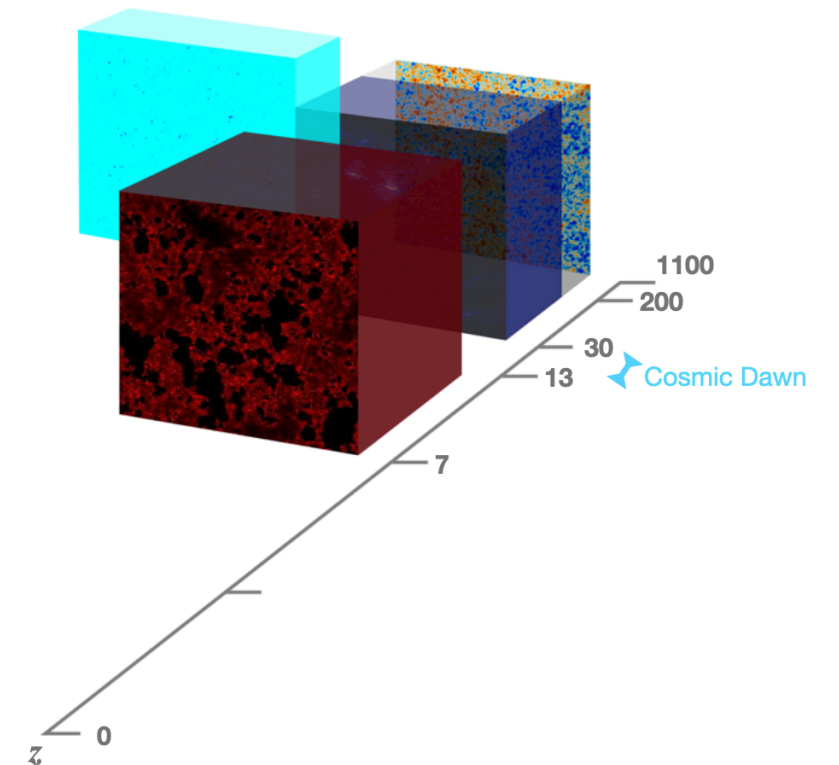
Dark Ages: adiabatic gas cooling; no stars



Cosmic dawn: turns on via Ly α from first stars

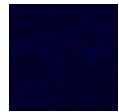


Reionization: emission against the CMB



Line-Intensity Mapping: Introduction

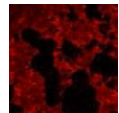
Earliest LIM signal: CMB interaction with HI



Dark Ages: adiabatic gas cooling; no stars

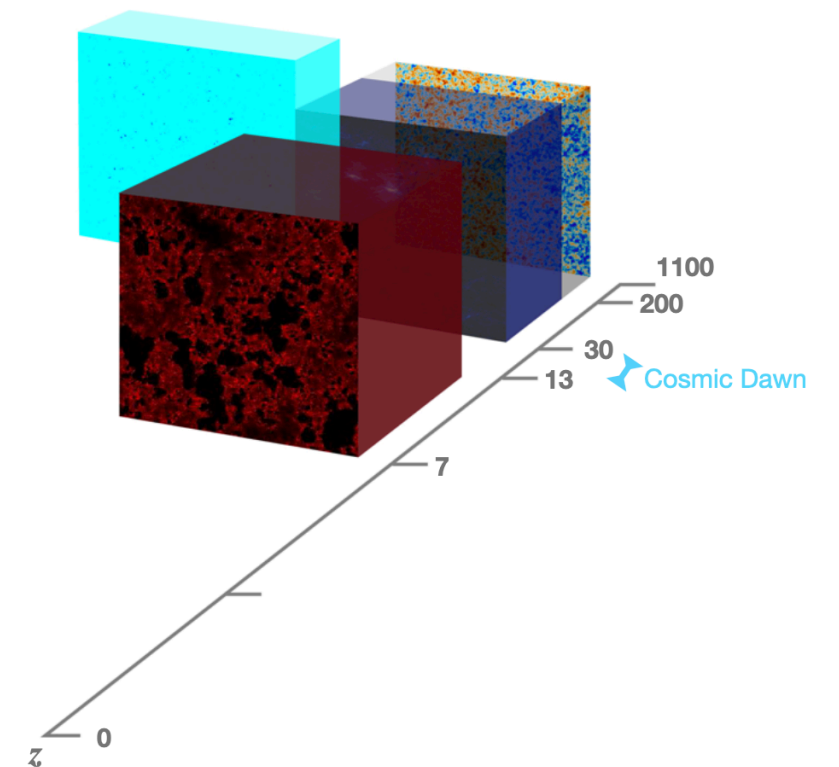


Cosmic dawn: turns on via Ly α from first stars



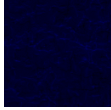
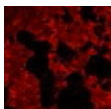
Reionization: emission against the CMB

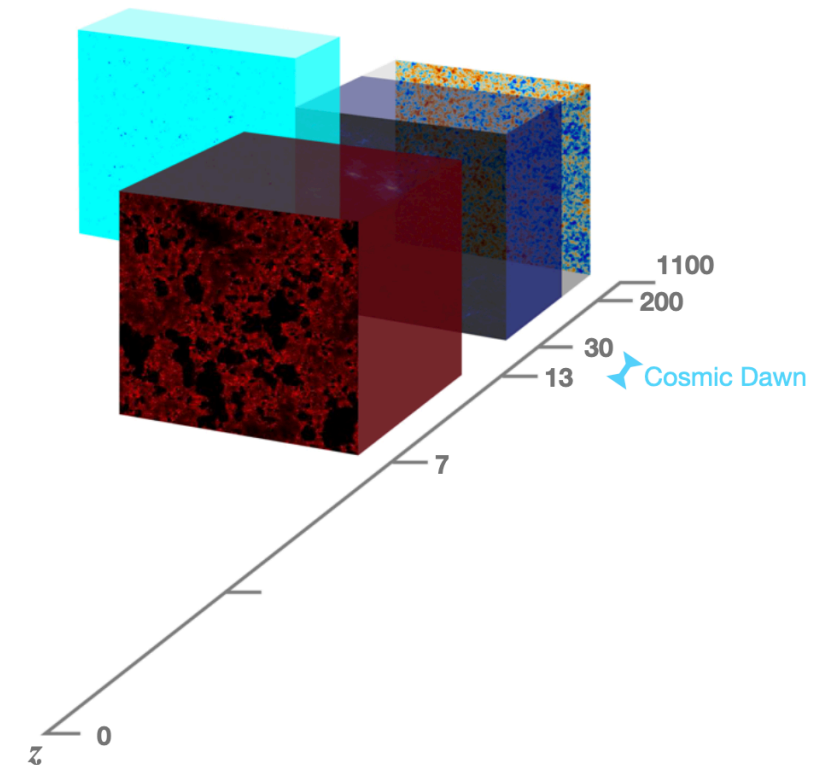
The 21cm brightness temperature contrast:



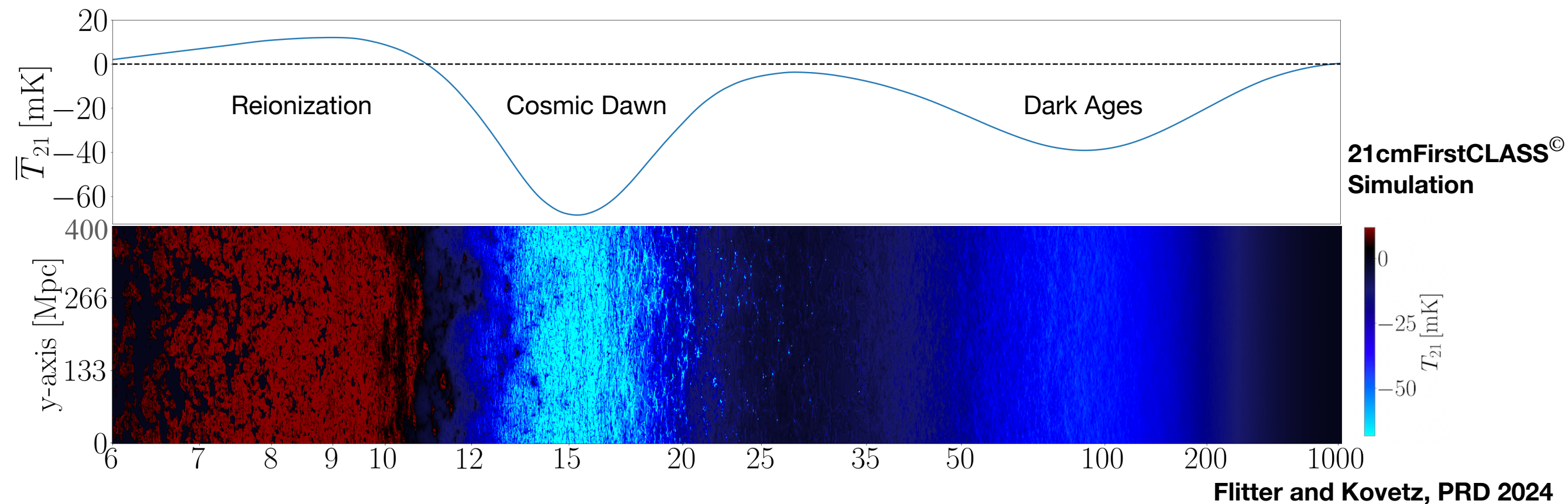
Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI

-  Dark Ages: adiabatic gas cooling; no stars
-  Cosmic dawn: turns on via Ly α from first stars
-  Reionization: emission against the CMB

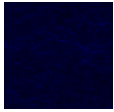
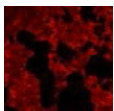


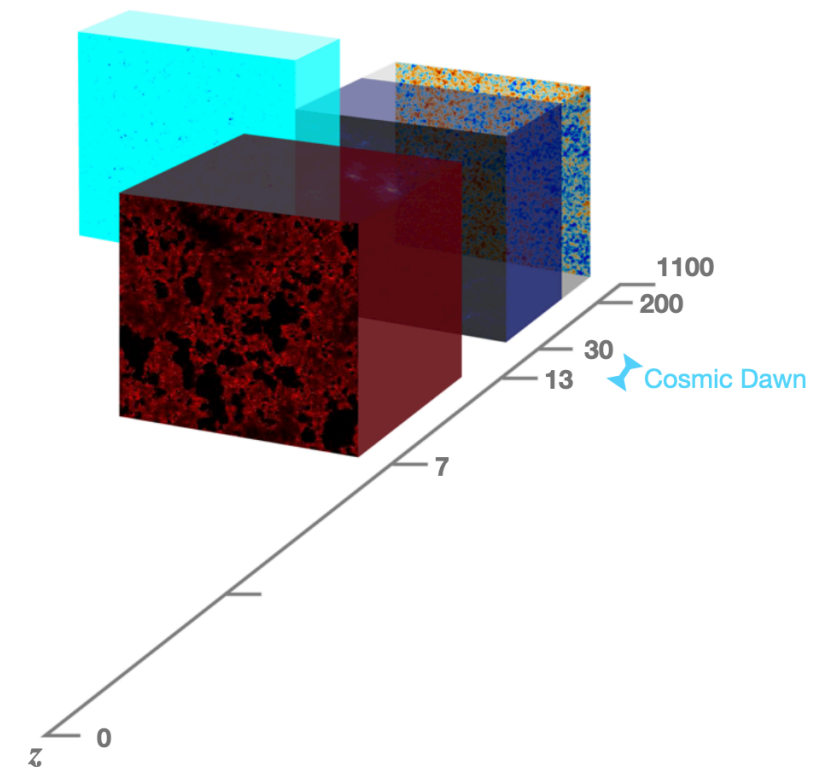
The 21cm brightness temperature contrast:



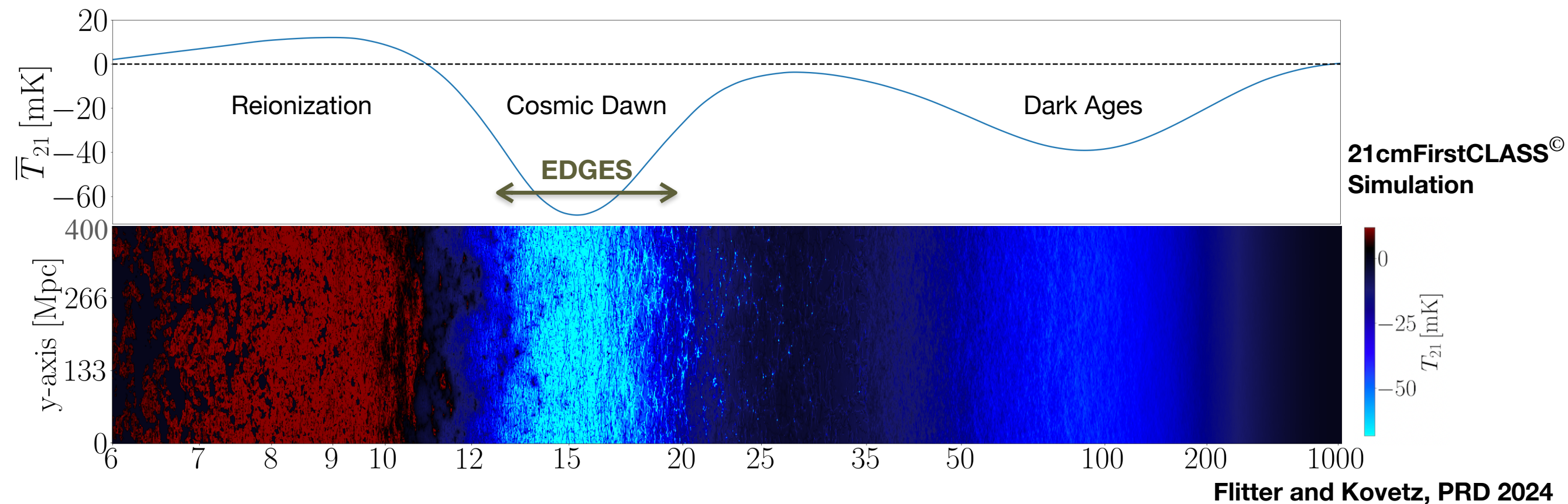
Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI

-  Dark Ages: adiabatic gas cooling; no stars
-  Cosmic dawn: turns on via Ly α from first stars
-  Reionization: emission against the CMB

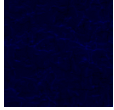
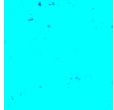
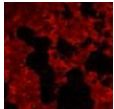


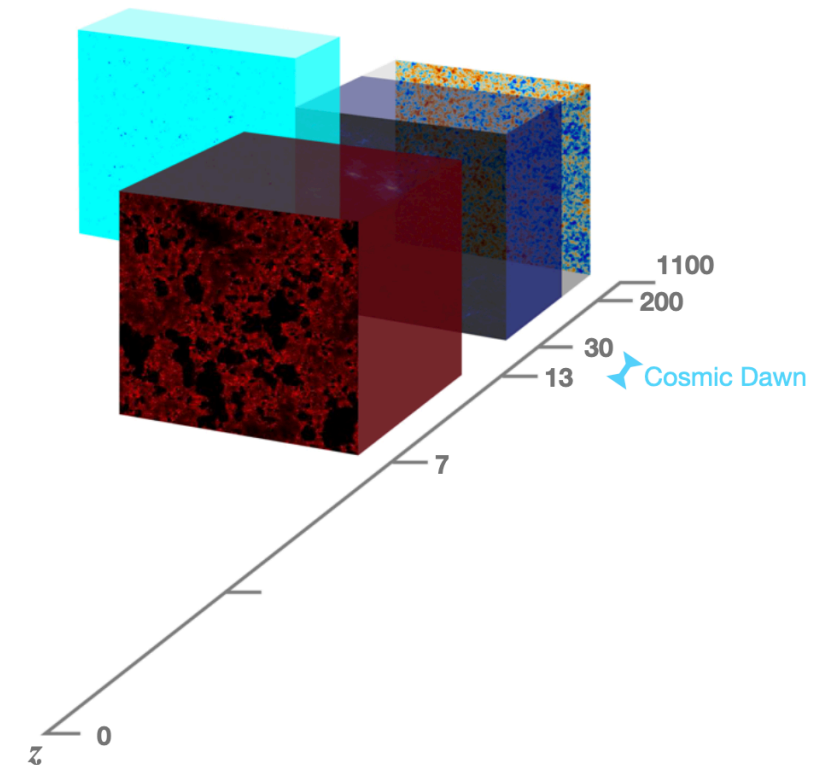
The 21cm brightness temperature contrast:



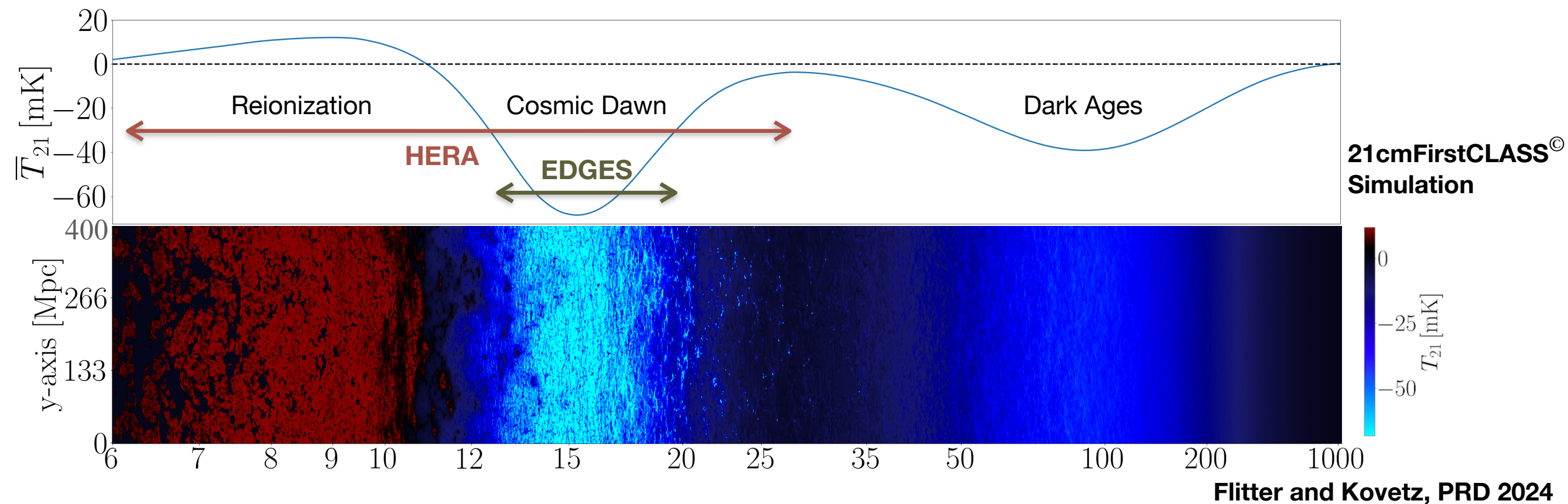
Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI

-  Dark Ages: adiabatic gas cooling; no stars
-  Cosmic dawn: turns on via Ly α from first stars
-  Reionization: emission against the CMB

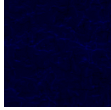
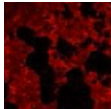


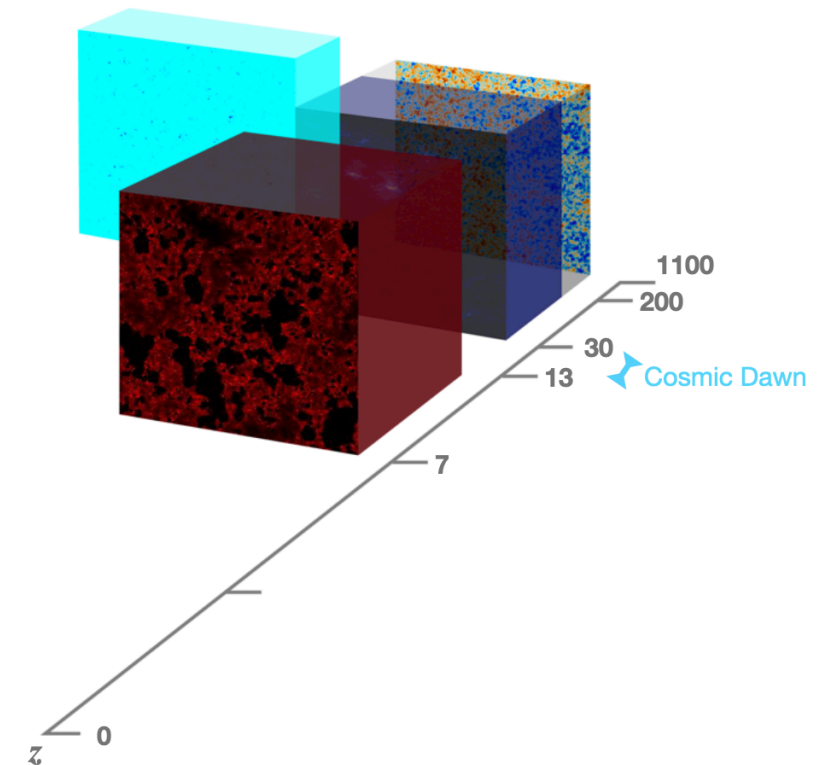
The 21cm brightness temperature contrast:



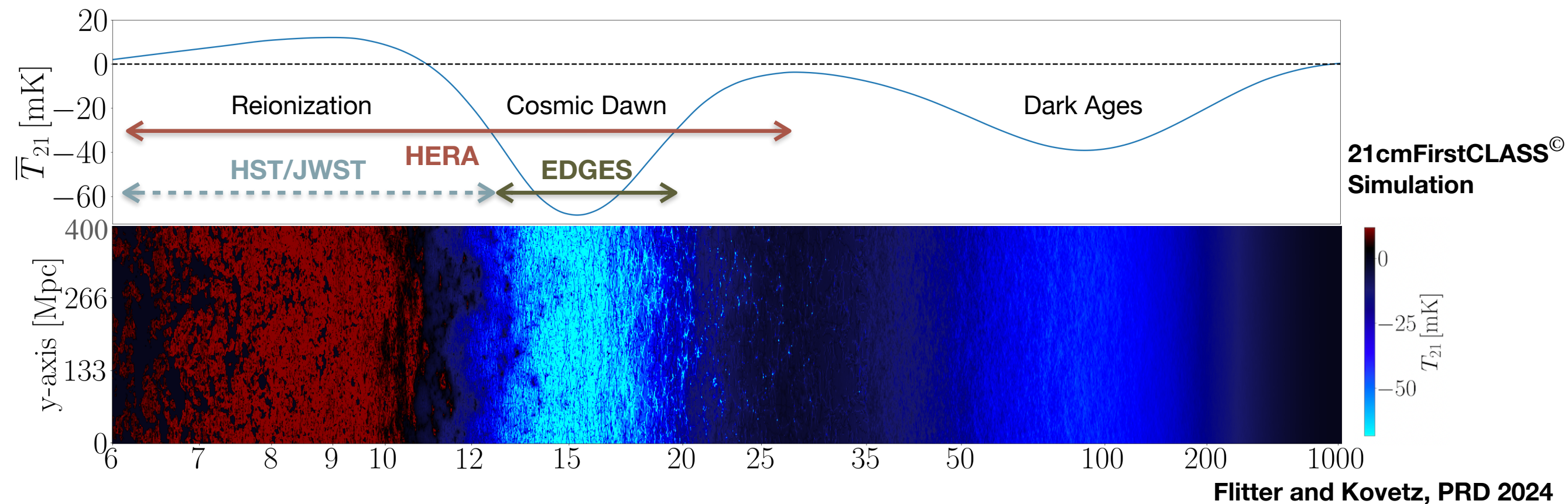
Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI

-  Dark Ages: adiabatic gas cooling; no stars
-  Cosmic dawn: turns on via Ly α from first stars
-  Reionization: emission against the CMB

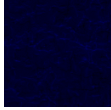
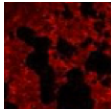


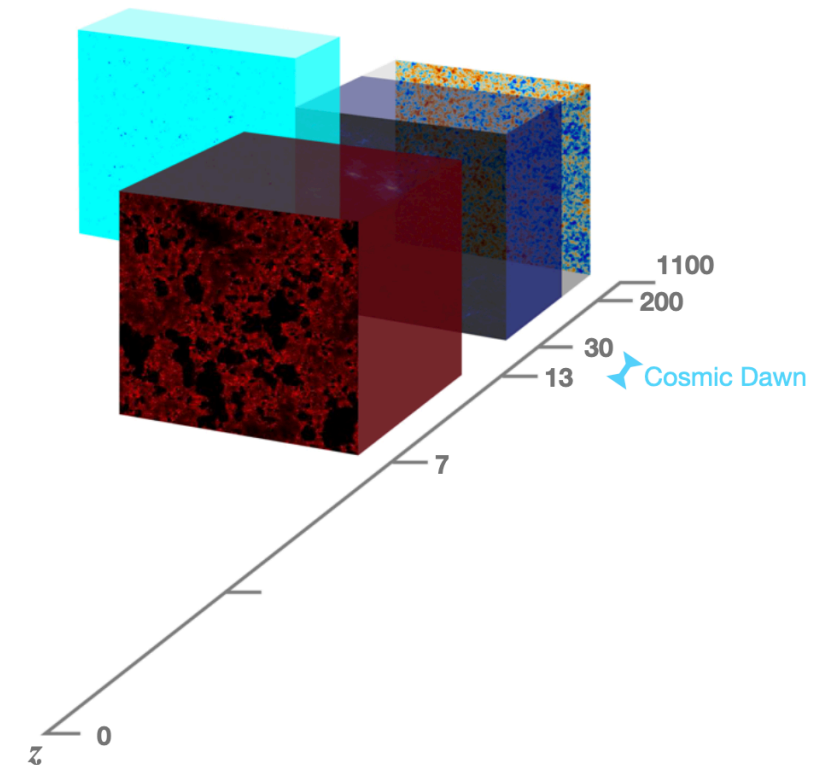
The 21cm brightness temperature contrast:



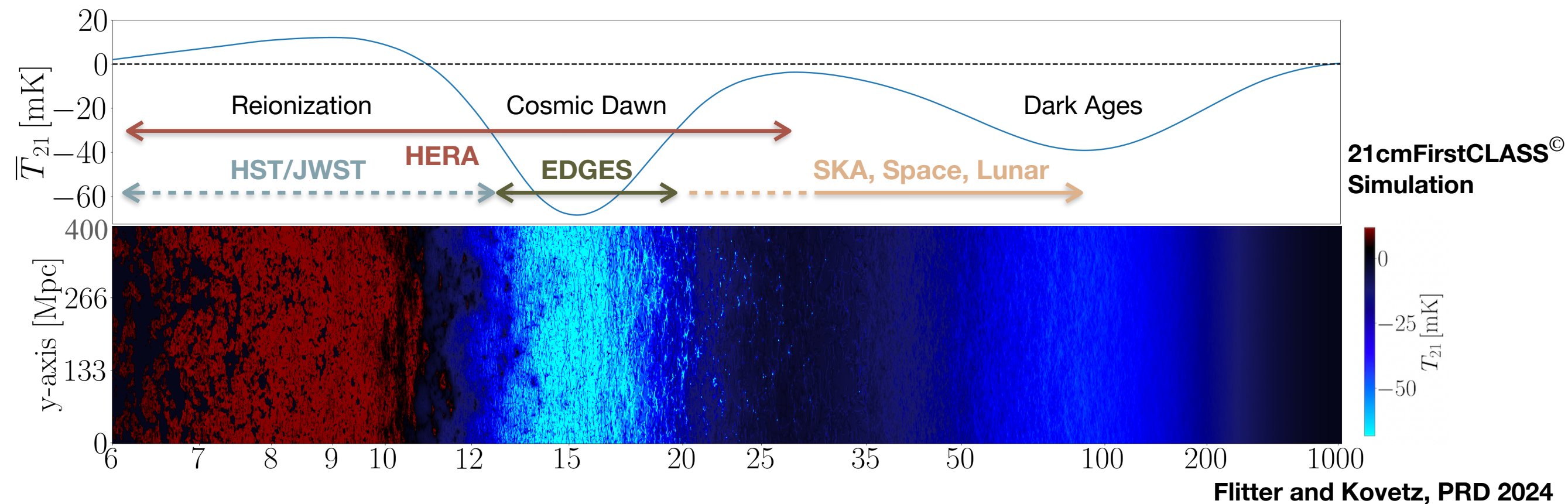
Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI

-  Dark Ages: adiabatic gas cooling; no stars
-  Cosmic dawn: turns on via Ly α from first stars
-  Reionization: emission against the CMB



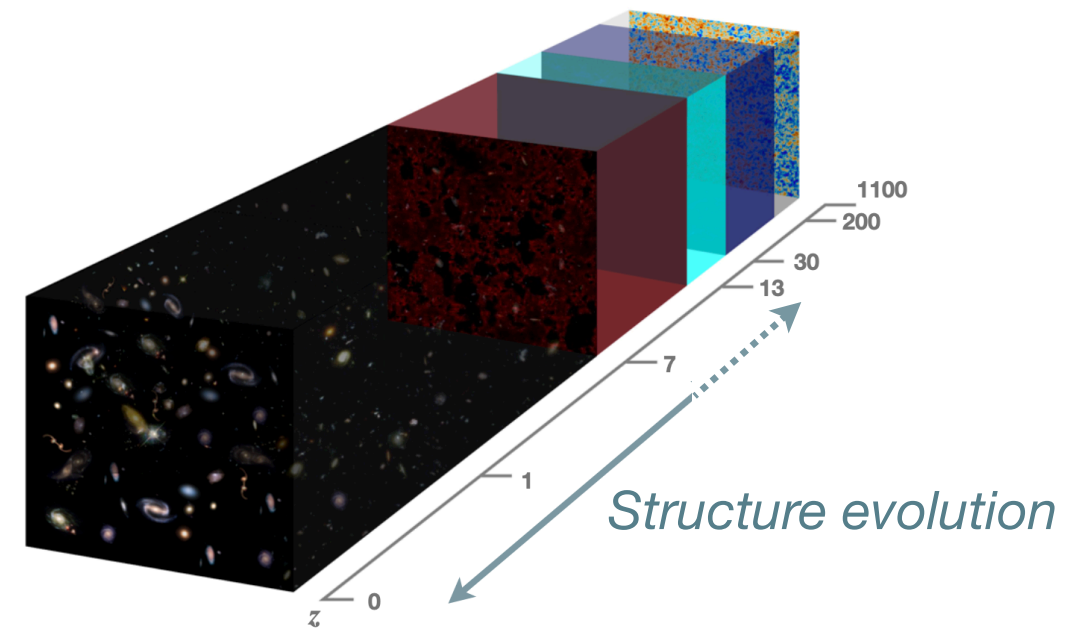
The 21cm brightness temperature contrast:



Line-Intensity Mapping: Introduction

Line-Intensity Mapping: Introduction

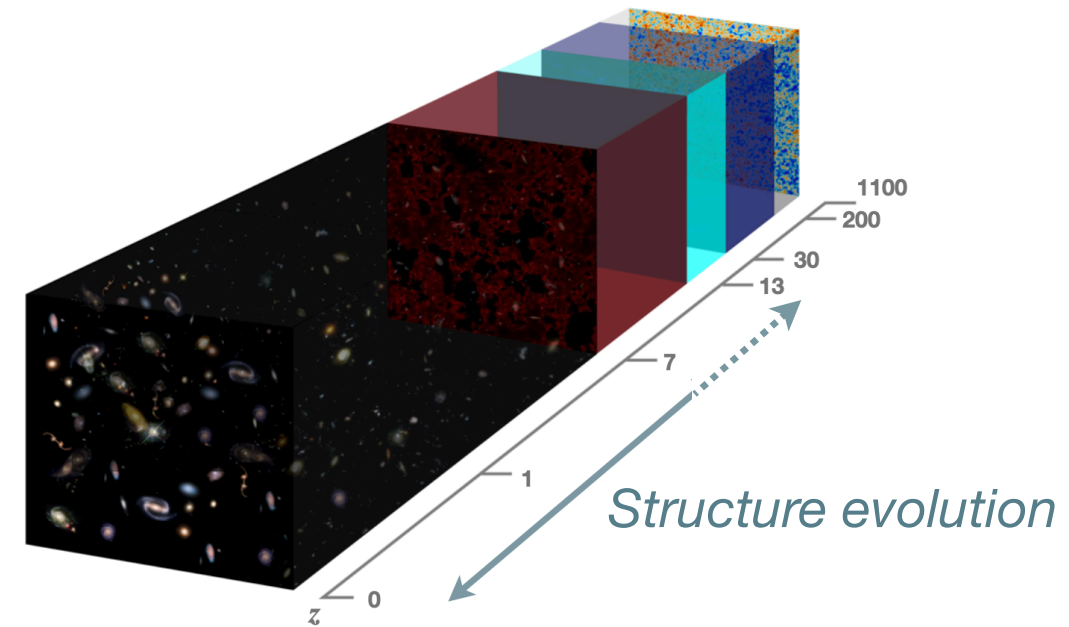
Growth of Structure:



Line-Intensity Mapping: Introduction

Growth of Structure:

In galaxies: host of atomic and molecular transitions

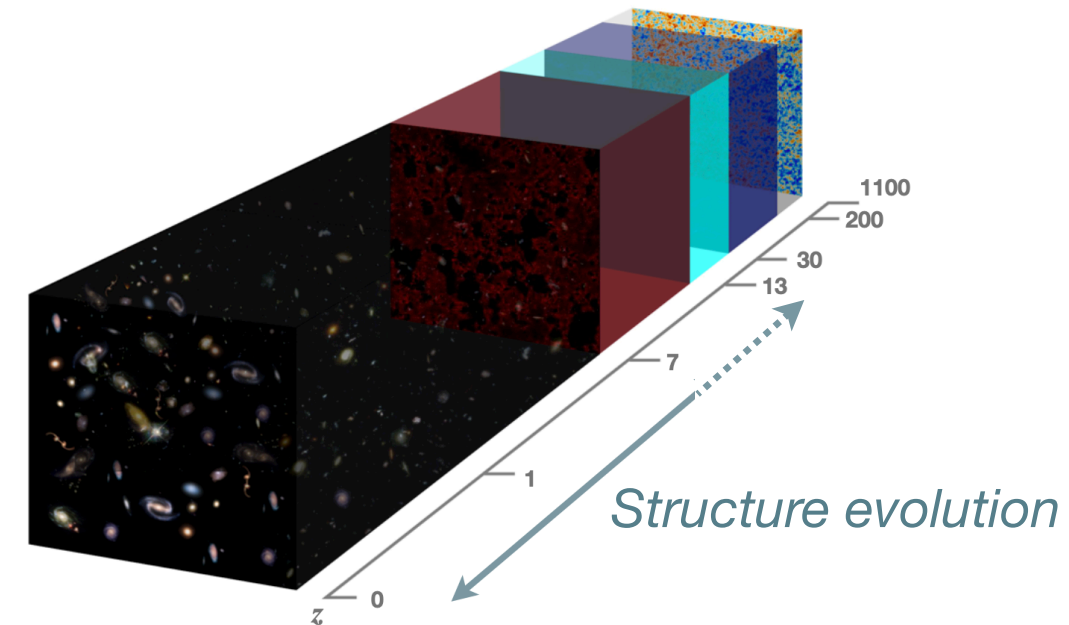


Line-Intensity Mapping: Introduction

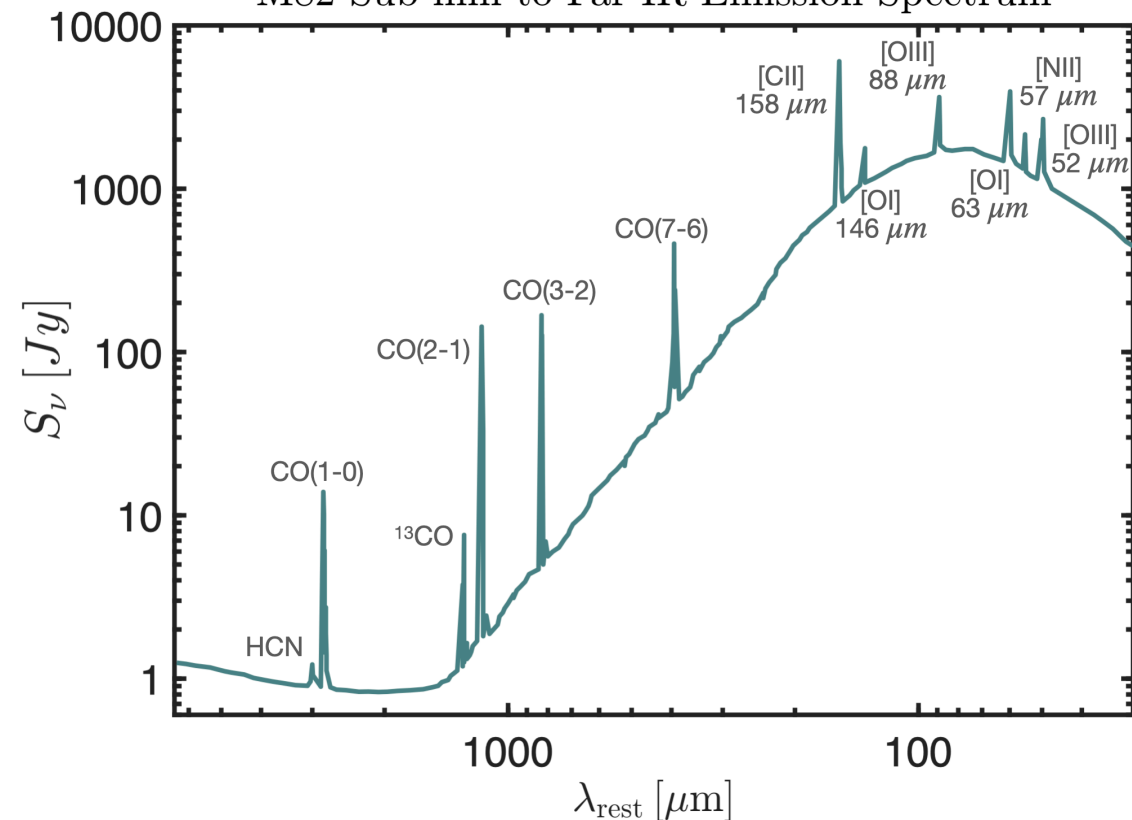
Growth of Structure:

In galaxies: host of atomic and molecular transitions

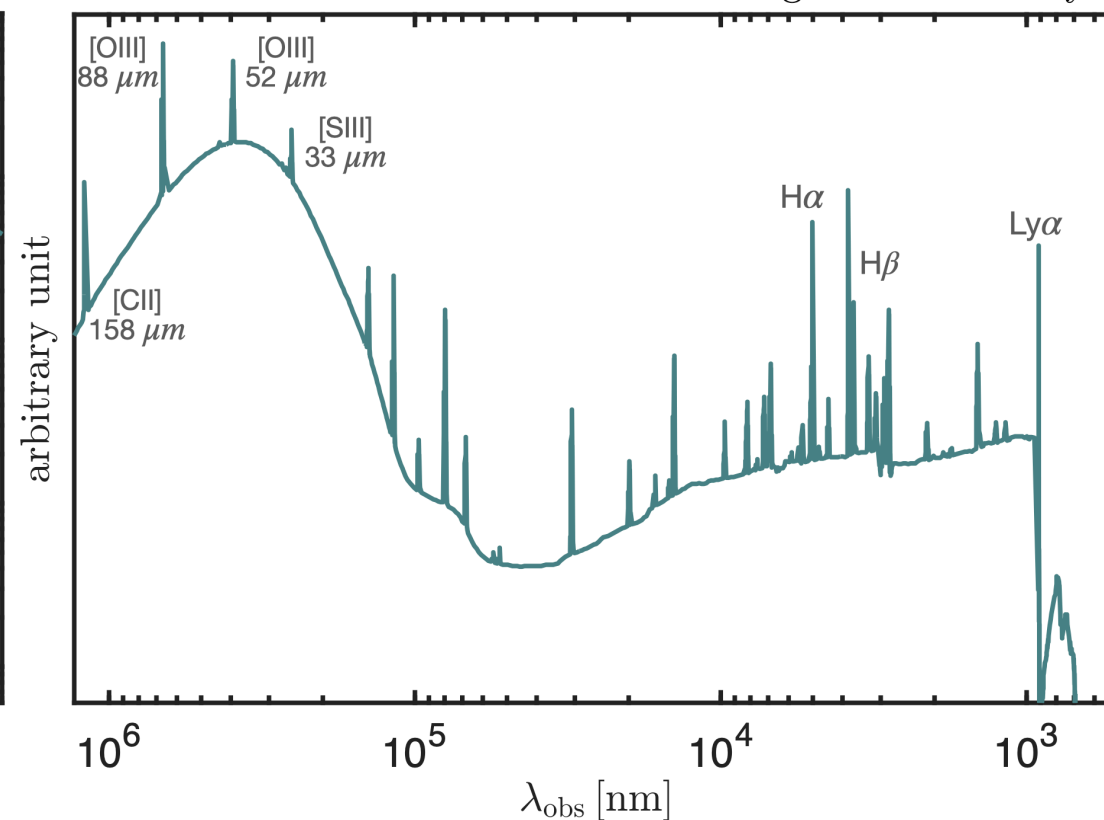
Spectrum of a typical galaxy:



M82 Sub-mm to Far-IR Emission Spectrum

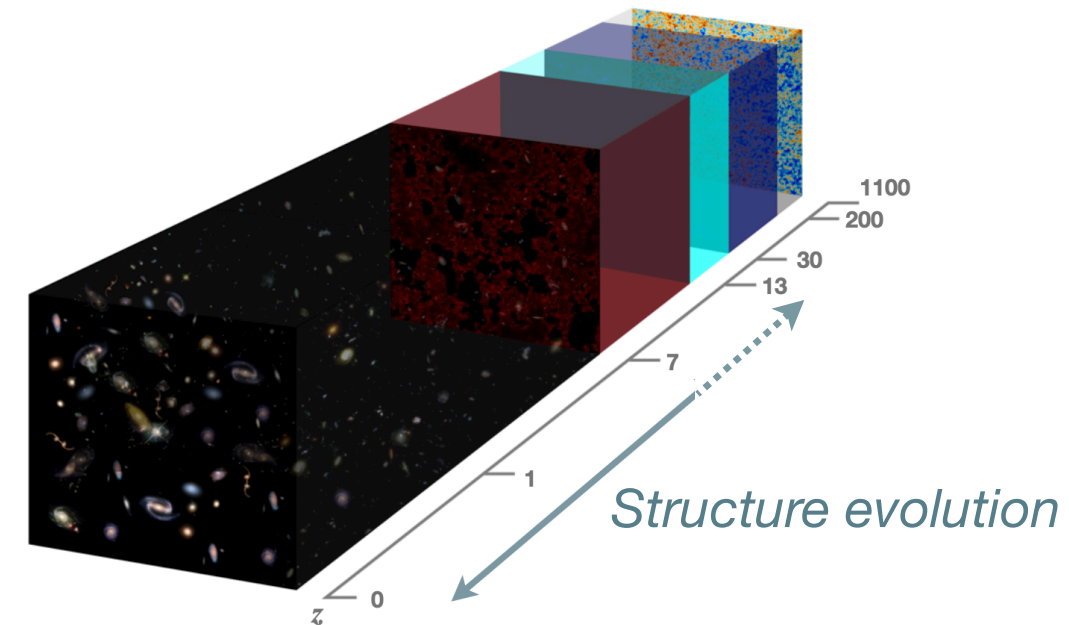
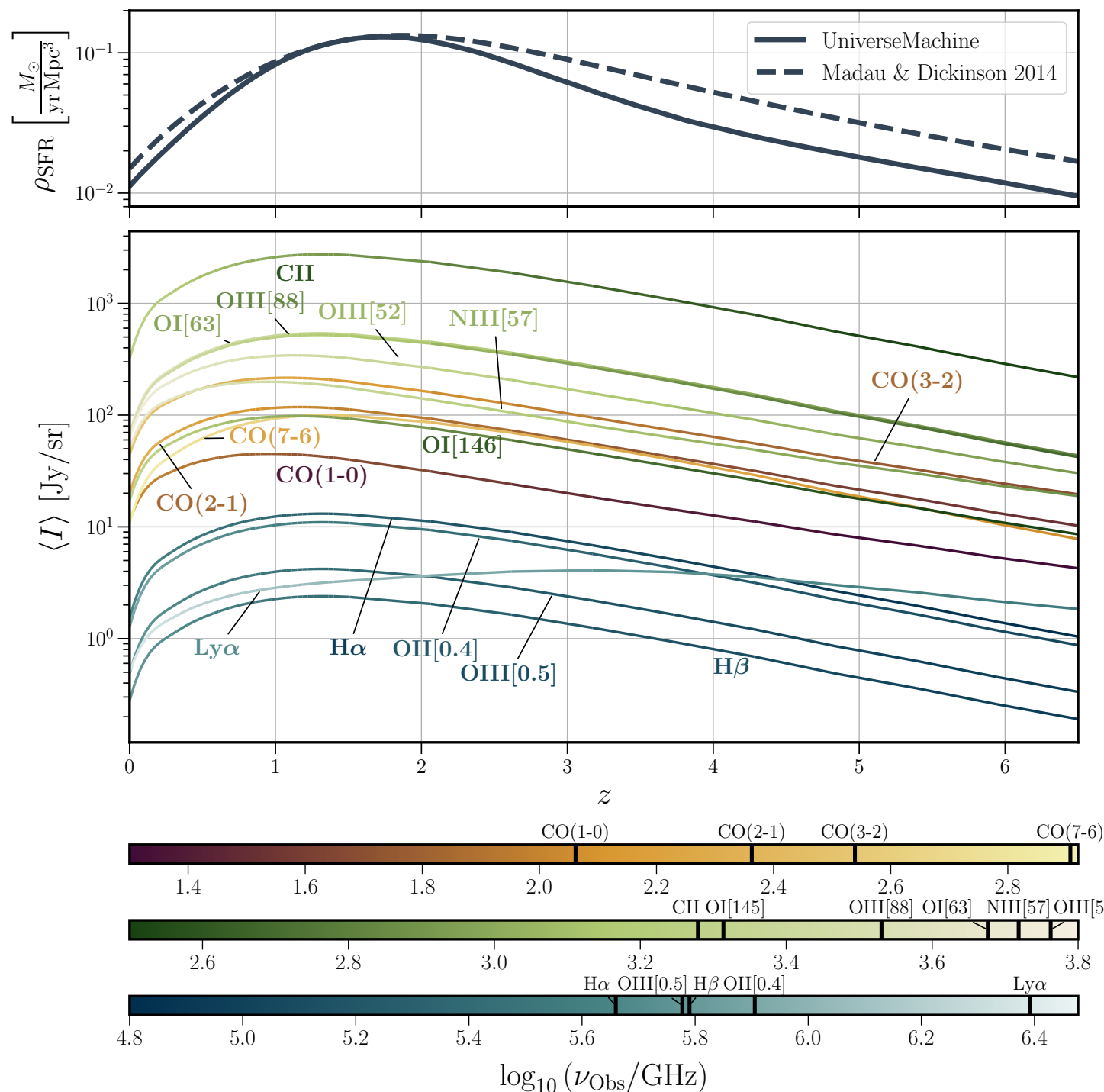


BEAGLE Simulation of a star-forming $z = 6.6$ Galaxy



Line-Intensity Mapping: Introduction

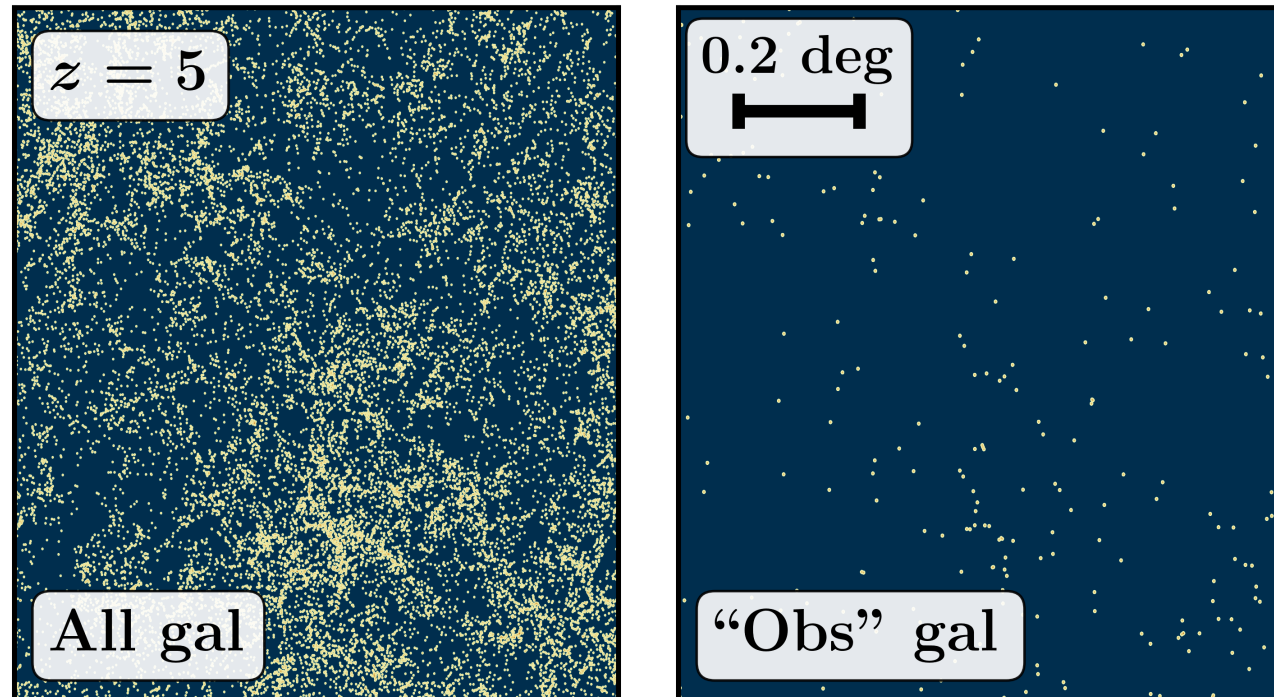
Growth of Structure: Star-formation lines



Line-Intensity Mapping: Introduction

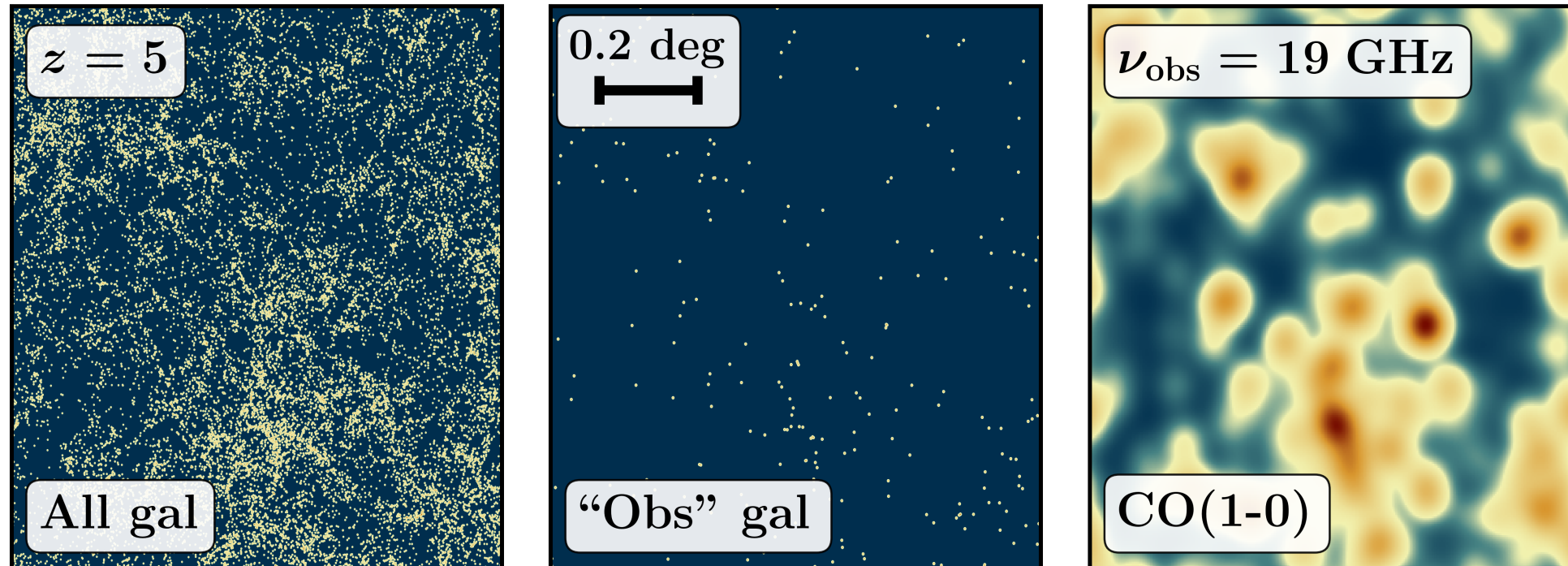
Line-Intensity Mapping: Introduction

Mapping galactic line-emission:



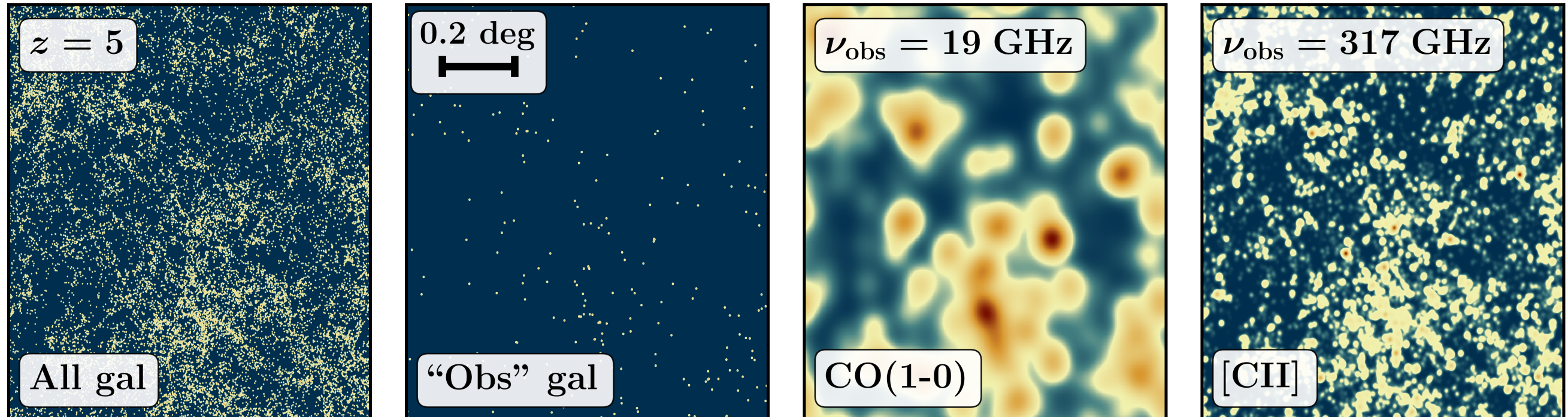
Line-Intensity Mapping: Introduction

Mapping galactic line-emission:

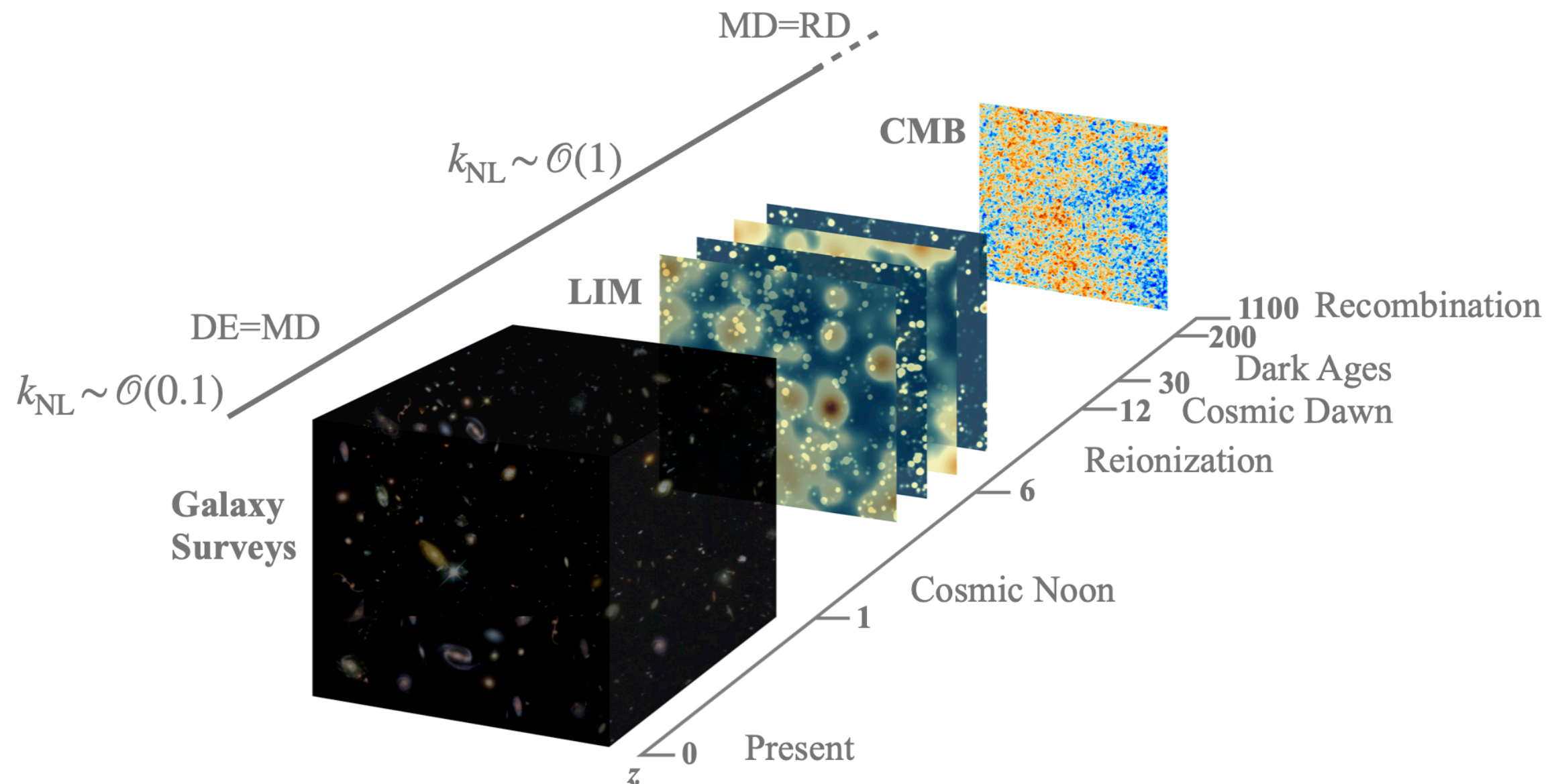


Line-Intensity Mapping: Introduction

Mapping galactic line-emission:



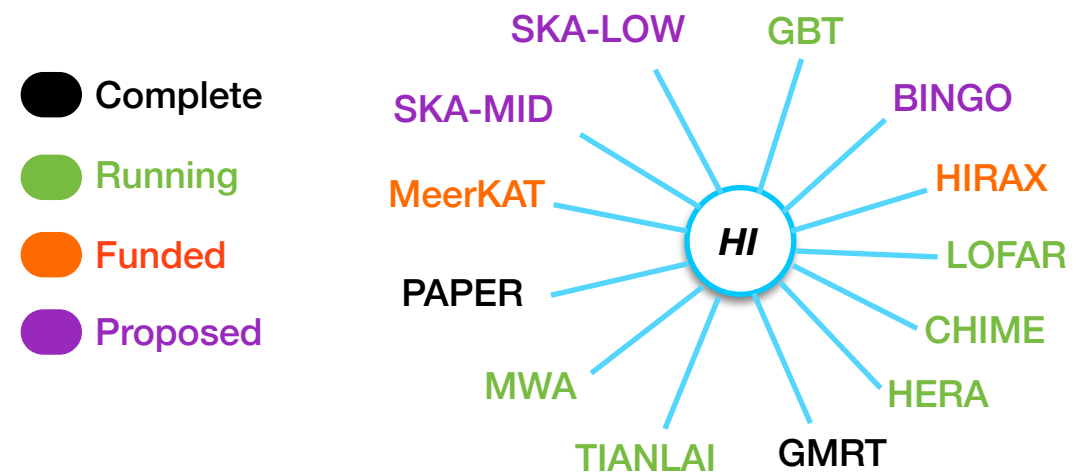
Line-Intensity Mapping: Introduction



Line-Intensity Mapping: Experimental Landscape

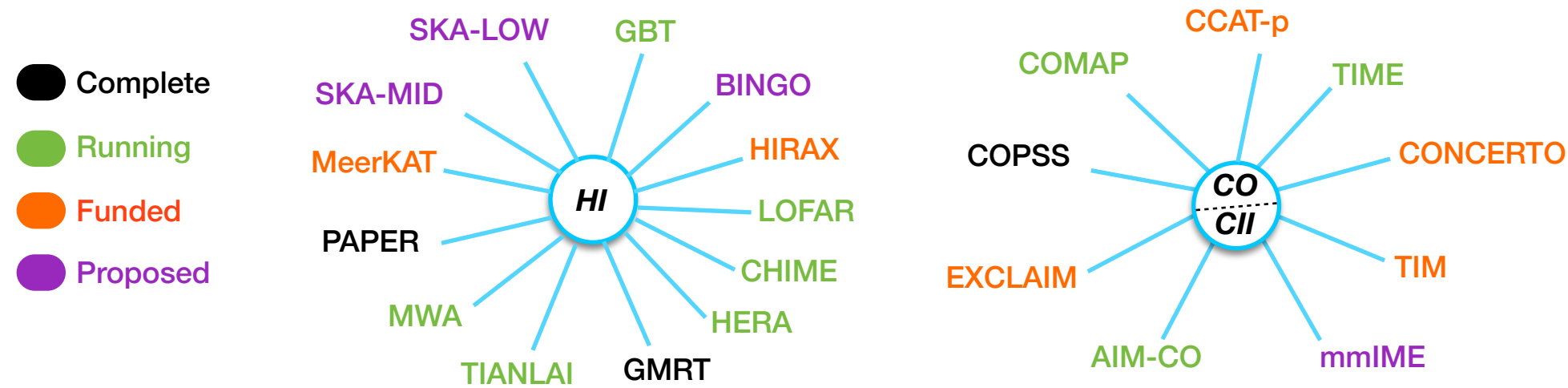


Line-Intensity Mapping: Experimental Landscape



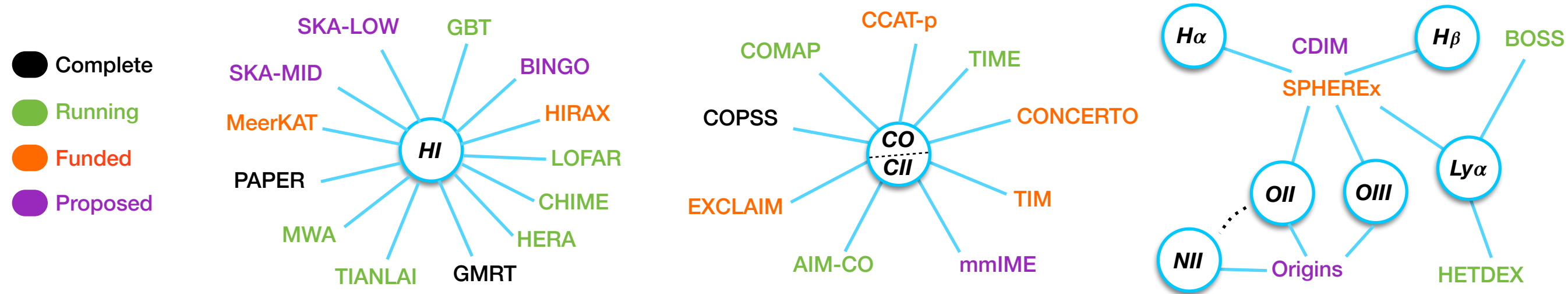
Astro2020: Kovetz et al. [arXiv:1903.04496]

Line-Intensity Mapping: Experimental Landscape



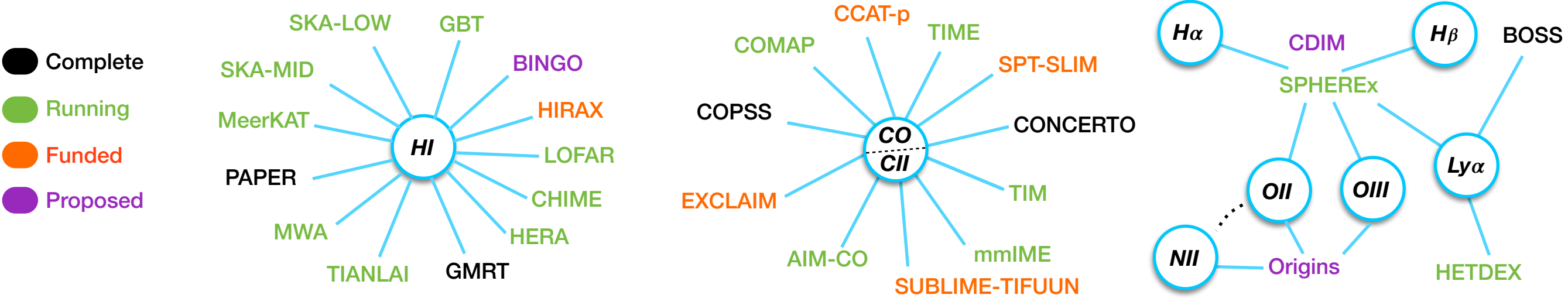
Astro2020: Kovetz et al. [arXiv:1903.04496]

Line-Intensity Mapping: Experimental Landscape



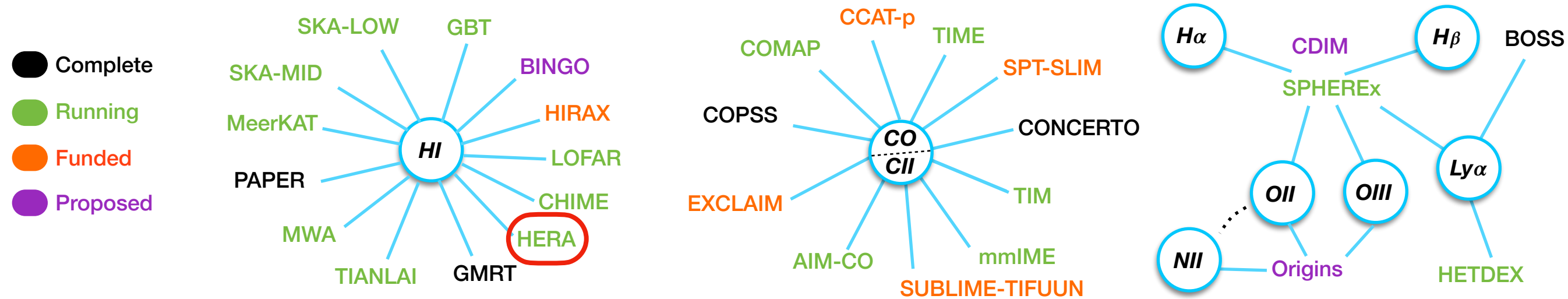
Astro2020: Kovetz et al. [arXiv:1903.04496]

Line-Intensity Mapping: Experimental Landscape



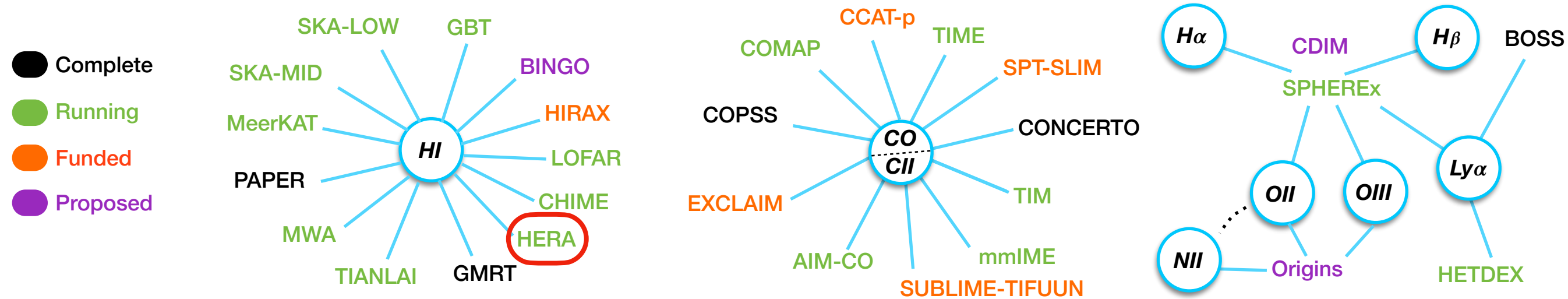
Astro2020: Kovetz et al. [arXiv:1903.04496]

Line-Intensity Mapping: Experimental Landscape

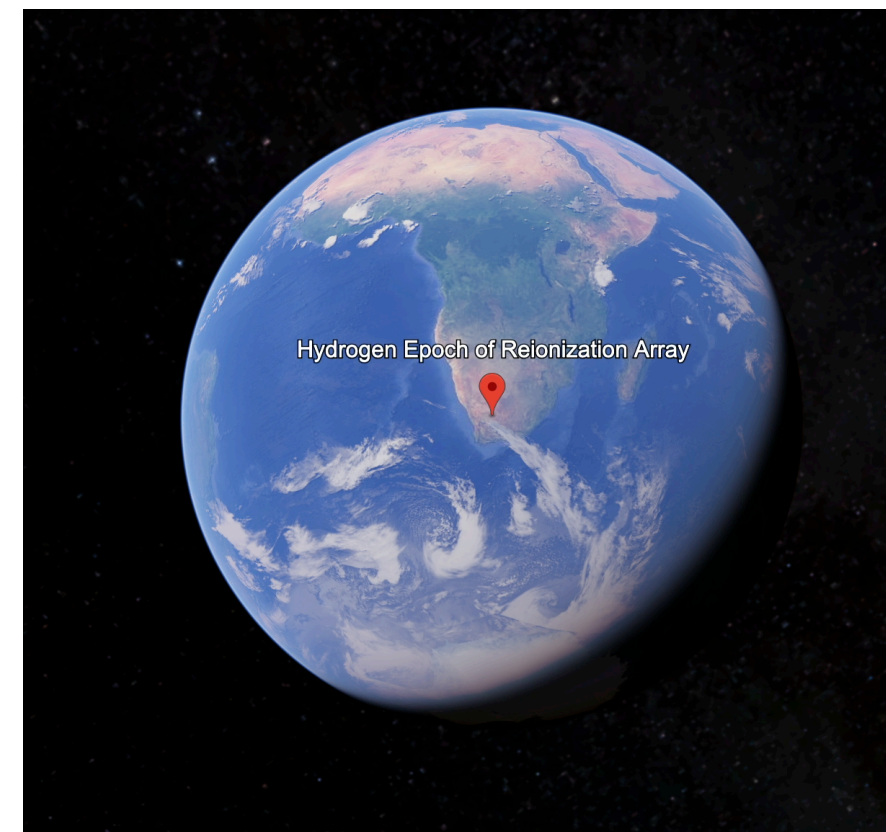


Astro2020: Kovetz et al. [arXiv:1903.04496]

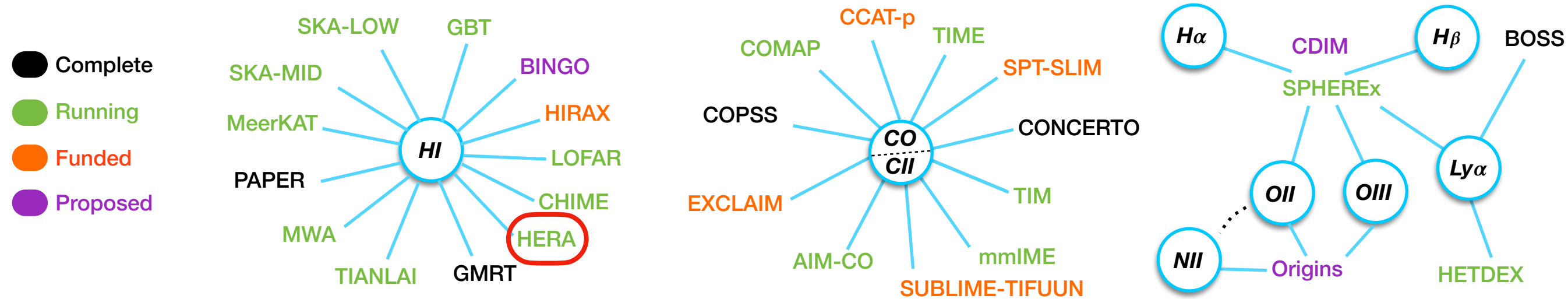
Line-Intensity Mapping: Experimental Landscape



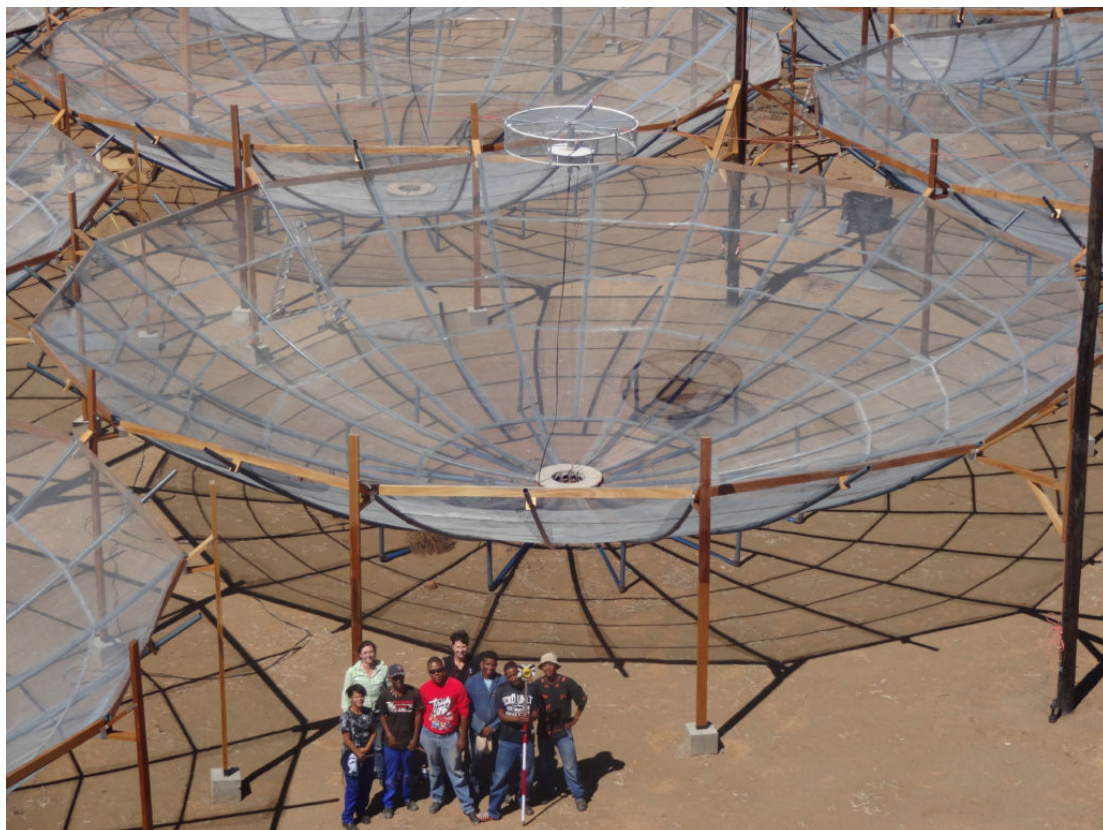
Astro2020: Kovetz et al. [arXiv:1903.04496]



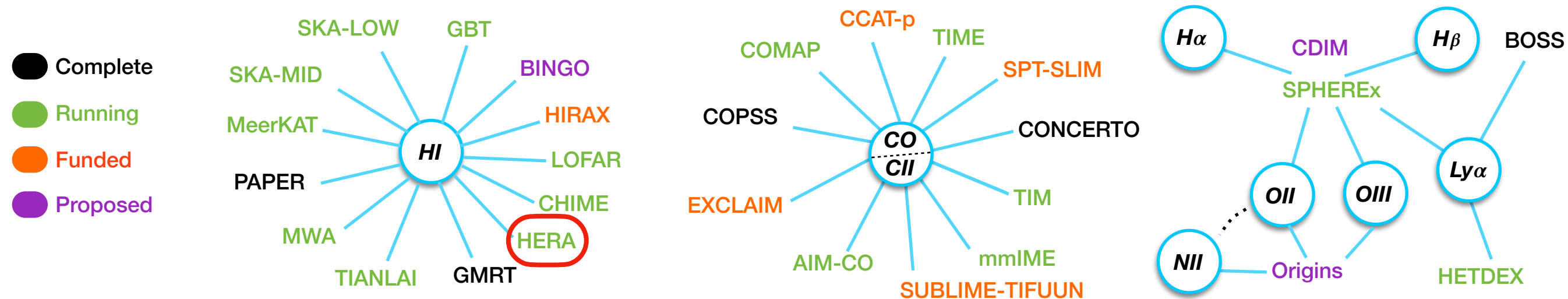
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]

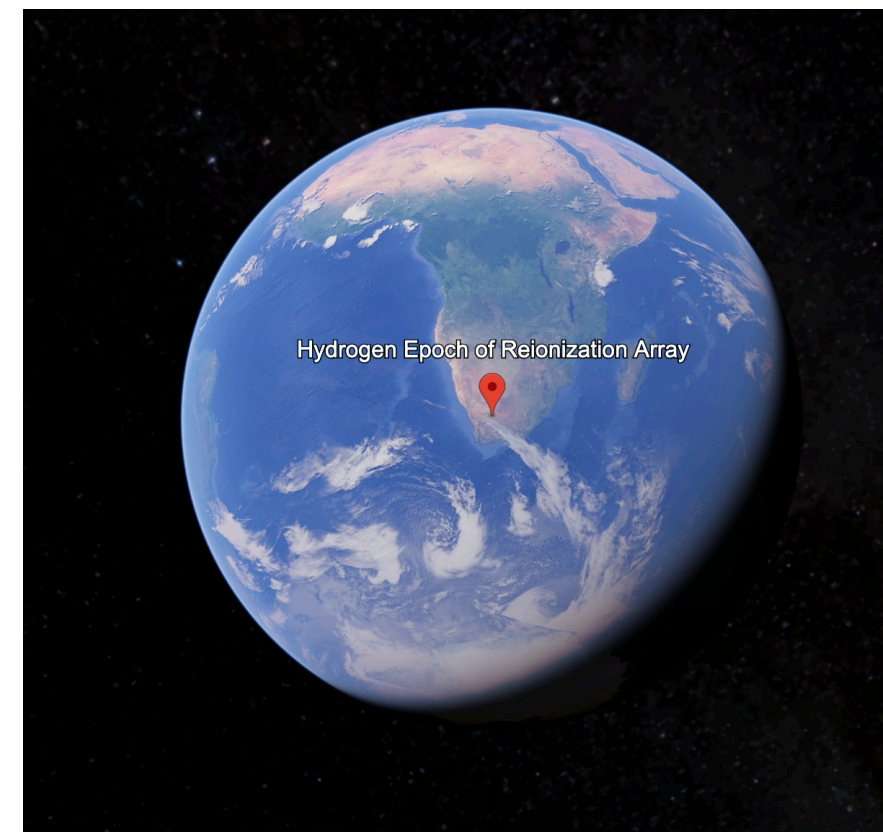
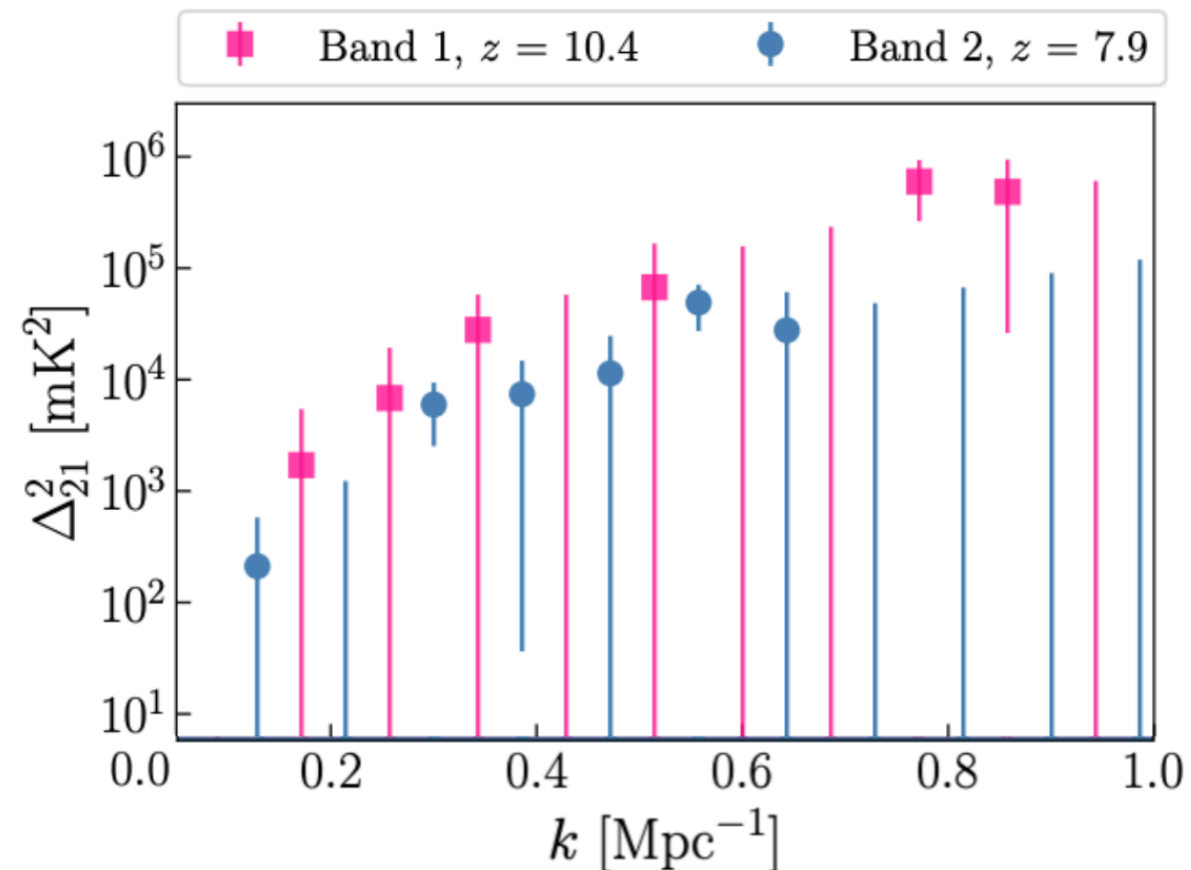


Line-Intensity Mapping: Experimental Landscape

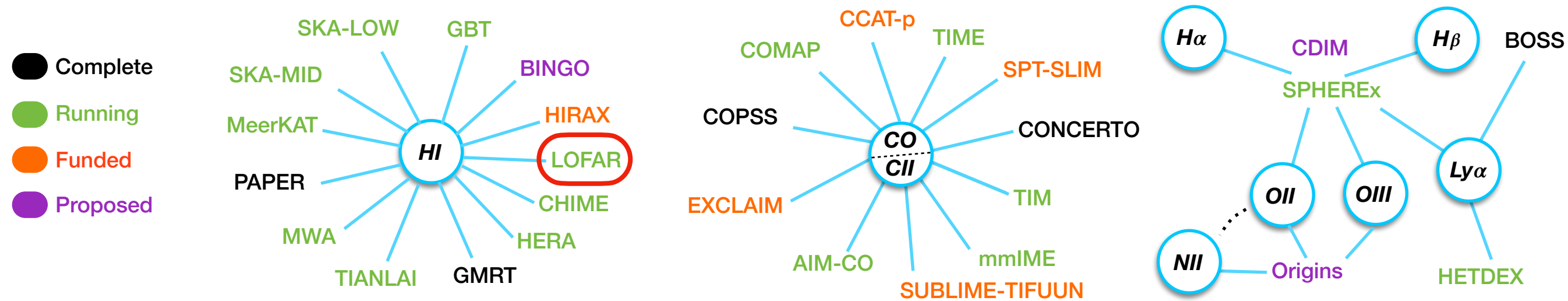


Astro2020: Kovetz et al. [arXiv:1903.04496]

HERA Phase I Results [arXiv:2108.07282]

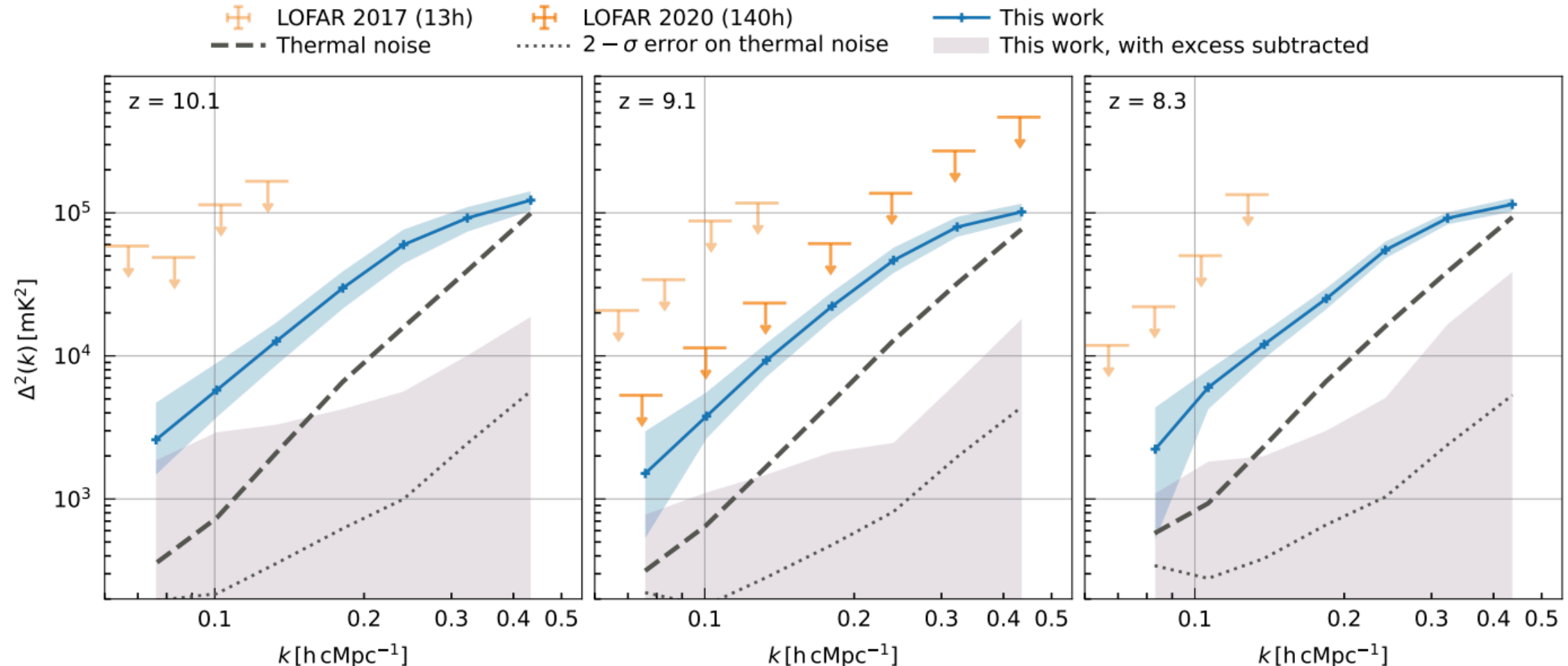


Line-Intensity Mapping: Experimental Landscape

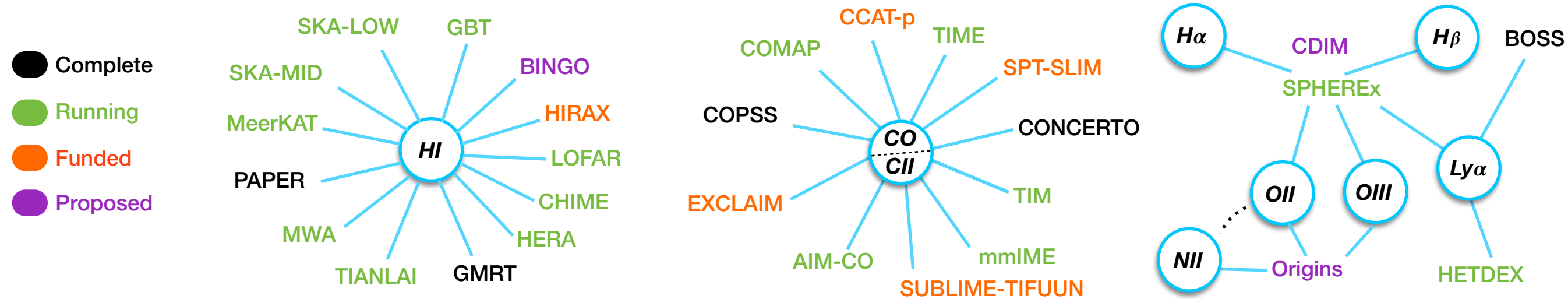


Astro2020: Kovetz et al. [arXiv:1903.04496]

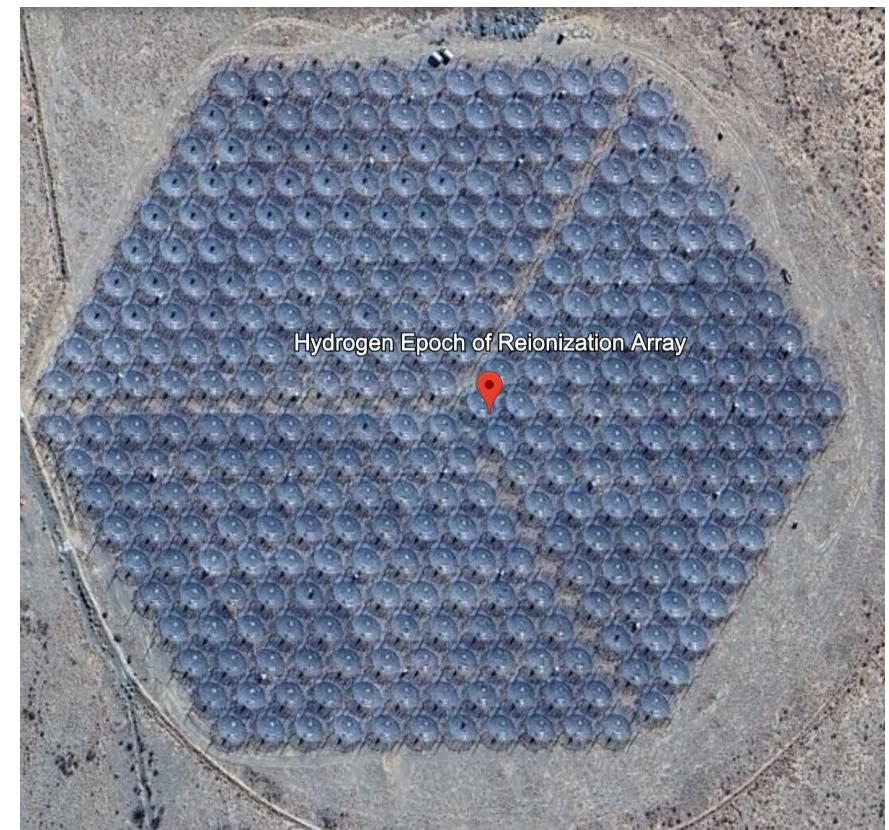
LOFAR Deepest Limits [arXiv:2503.05576]



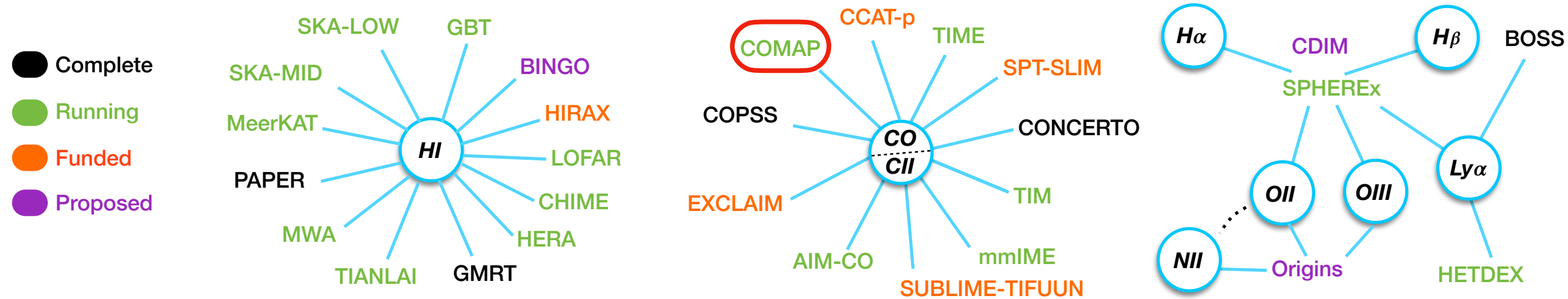
Line-Intensity Mapping: Experimental Landscape



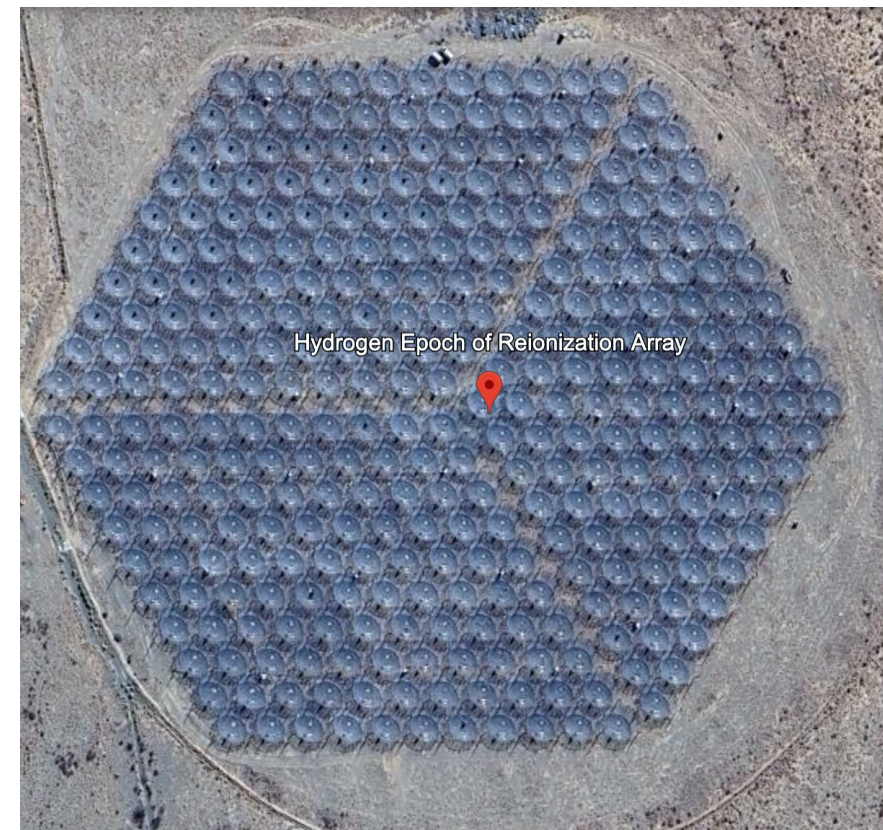
Astro2020: Kovetz et al. [arXiv:1903.04496]



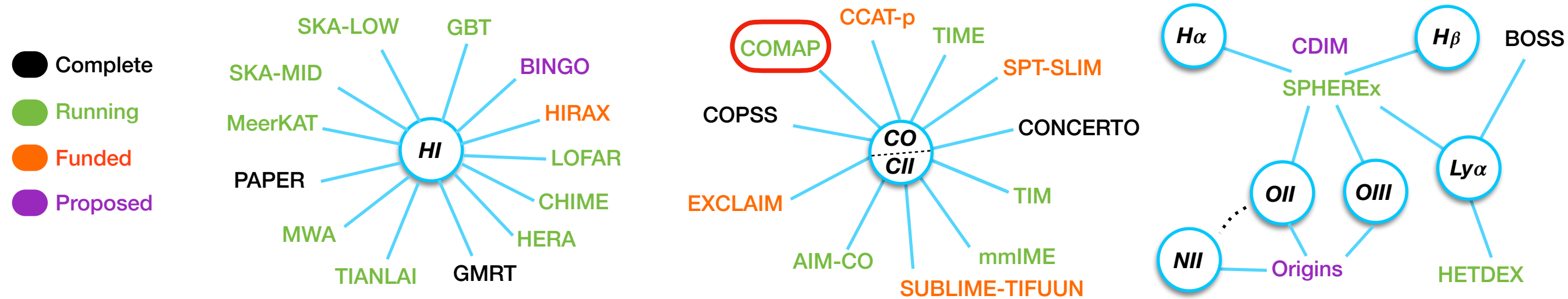
Line-Intensity Mapping: Experimental Landscape



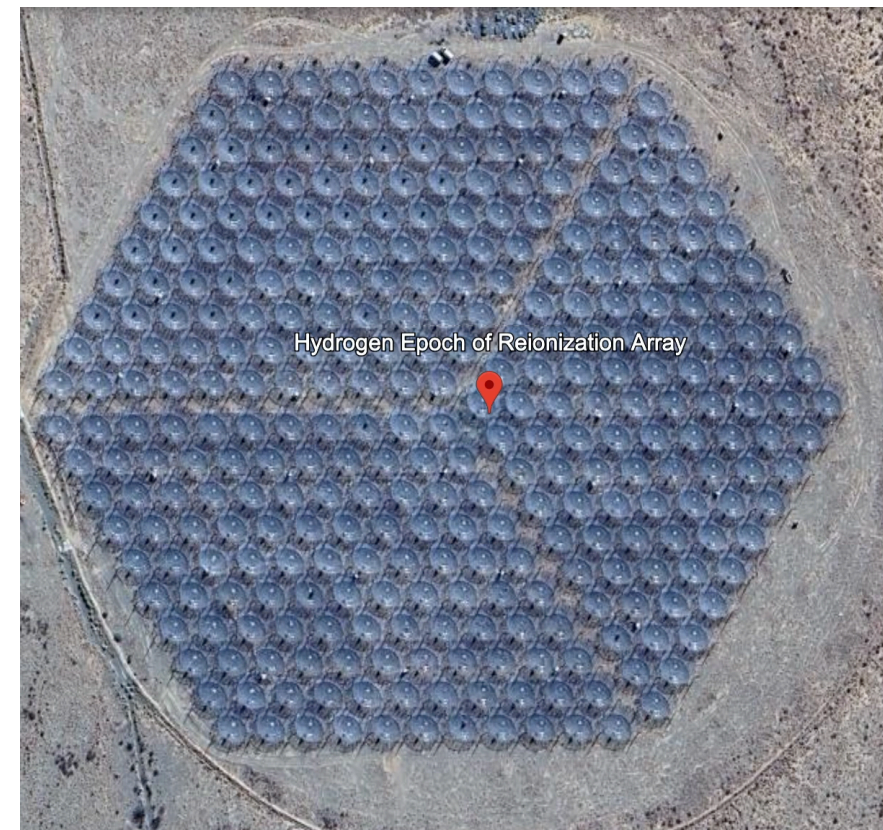
Astro2020: Kovetz et al. [arXiv:1903.04496]



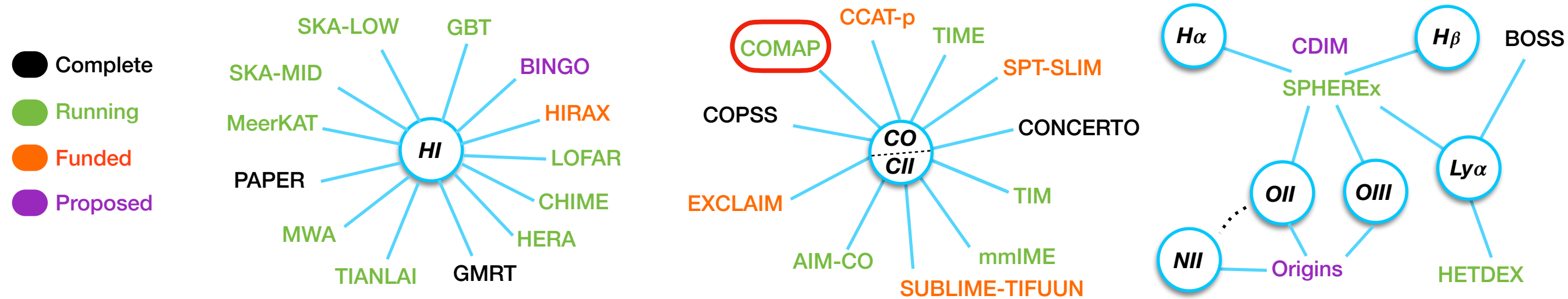
Line-Intensity Mapping: Experimental Landscape



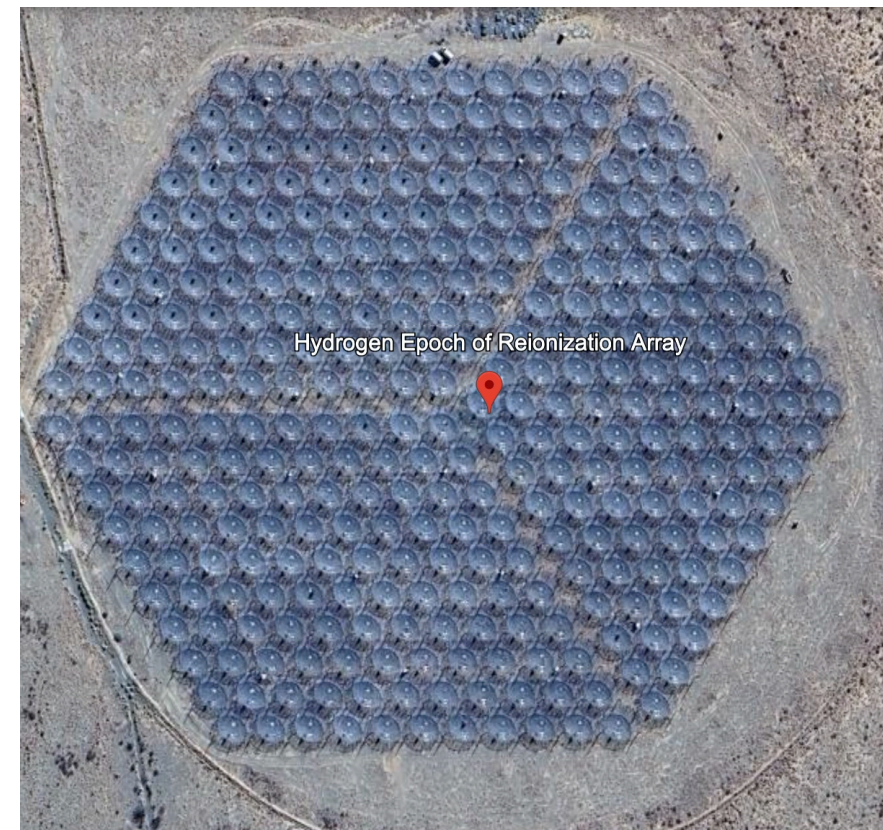
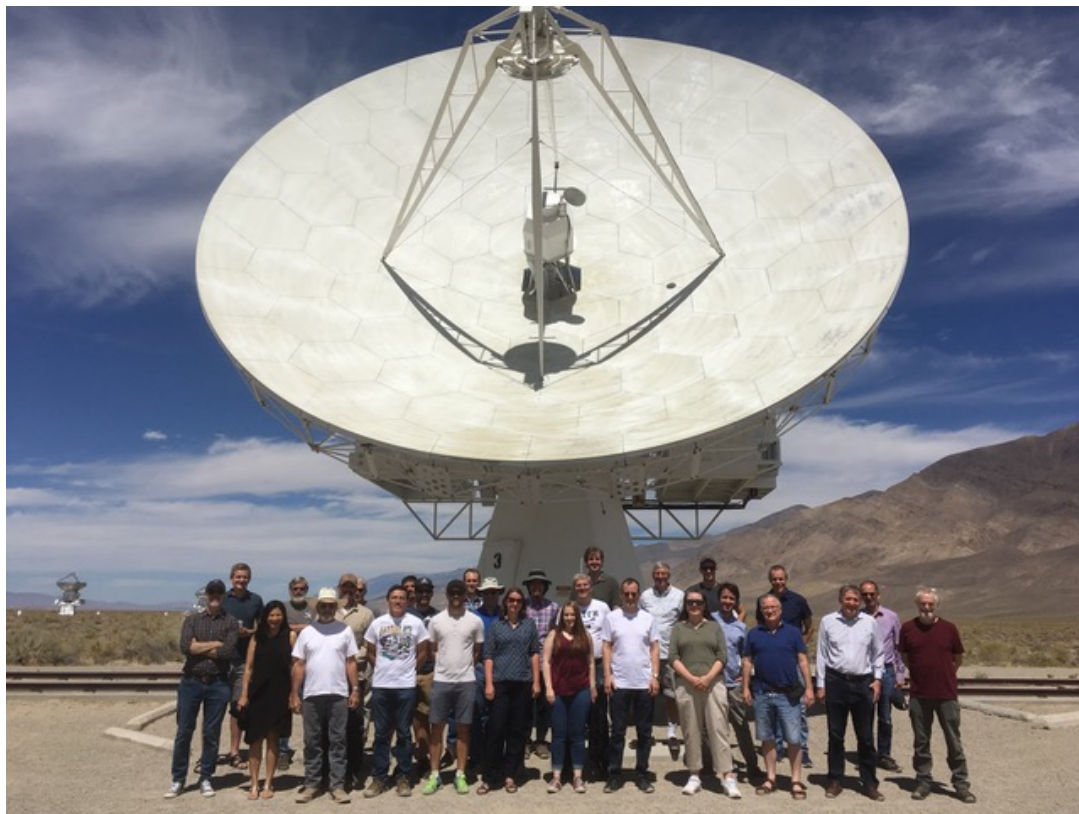
Astro2020: Kovetz et al. [arXiv:1903.04496]



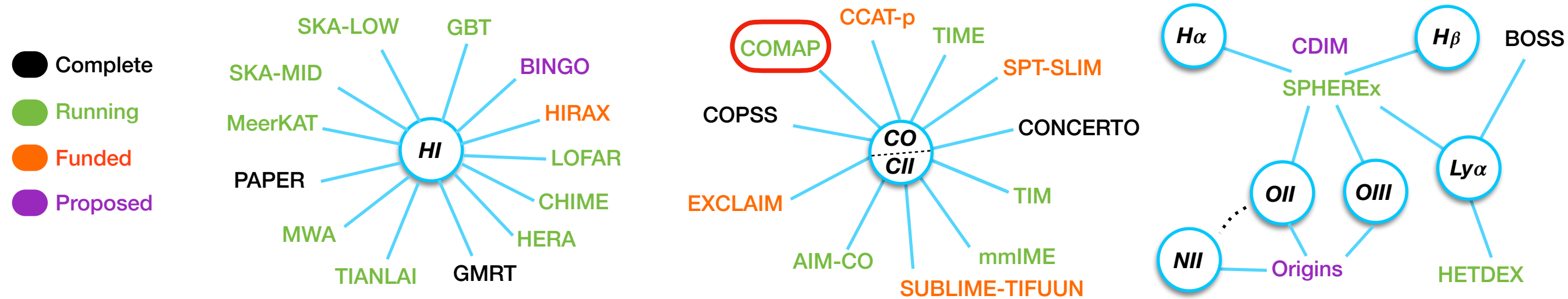
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]

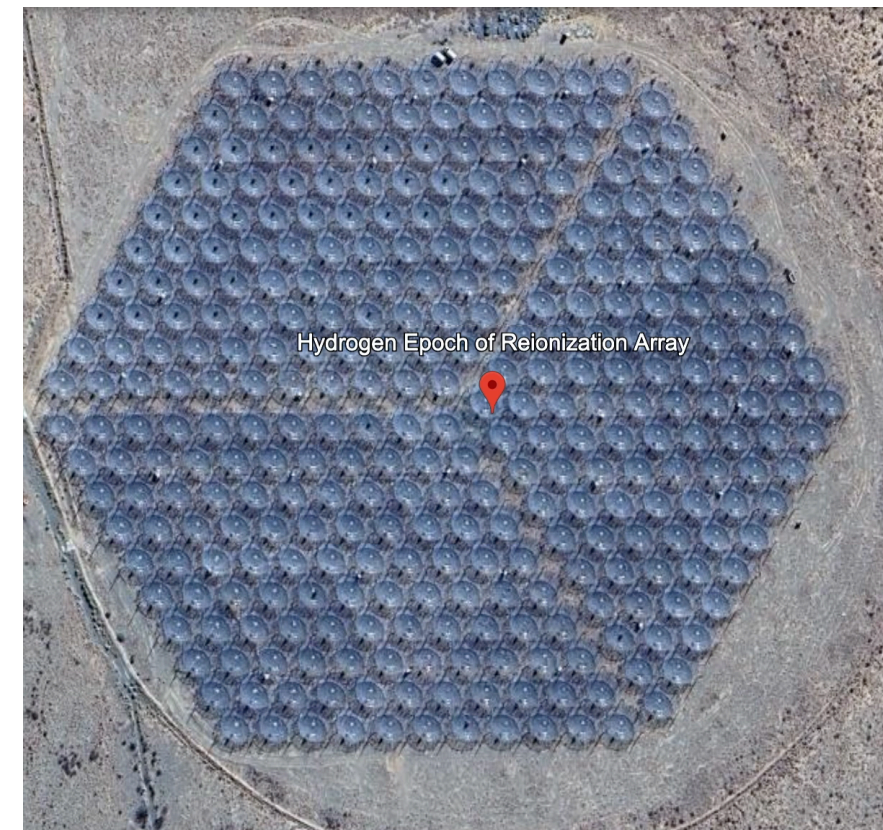
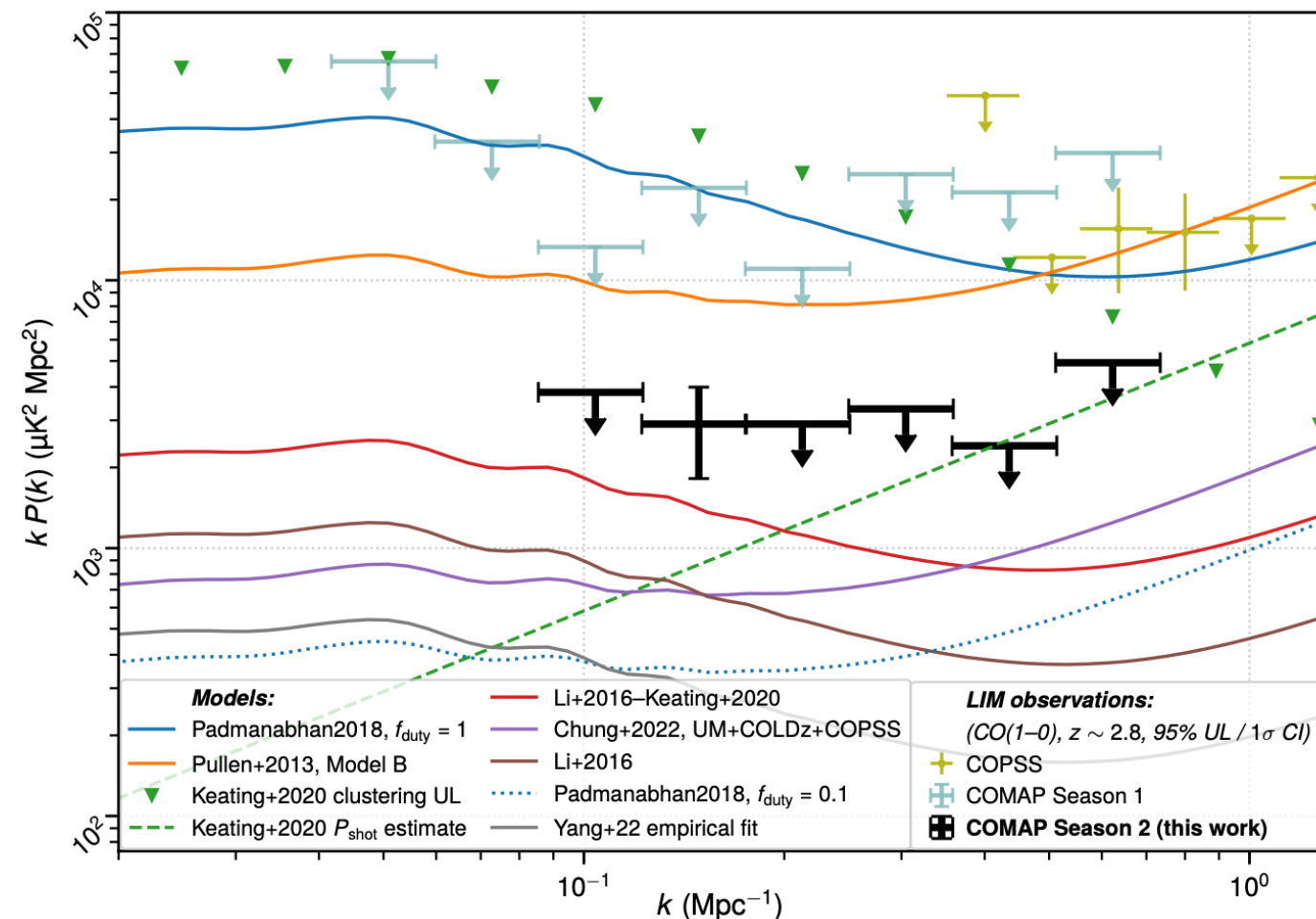


Line-Intensity Mapping: Experimental Landscape

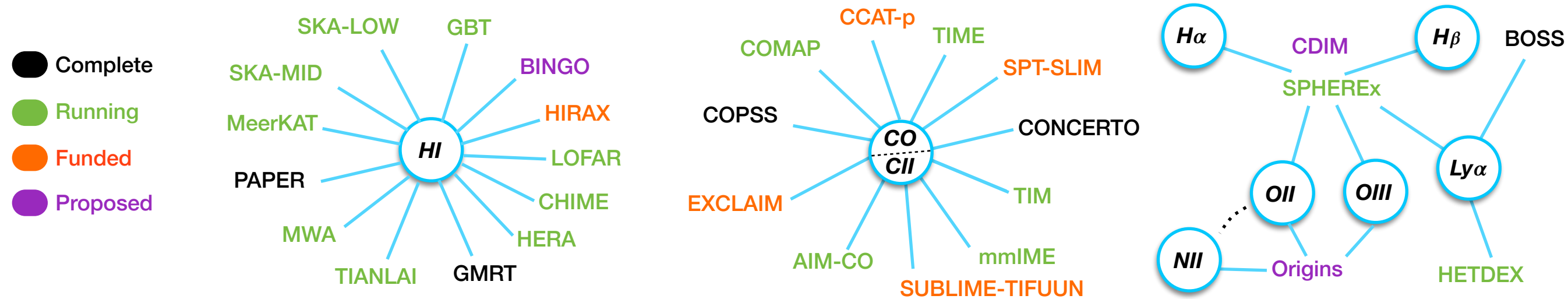


Astro2020: Kovetz et al. [arXiv:1903.04496]

COMAP Season 2 [arXiv:2406.07512]



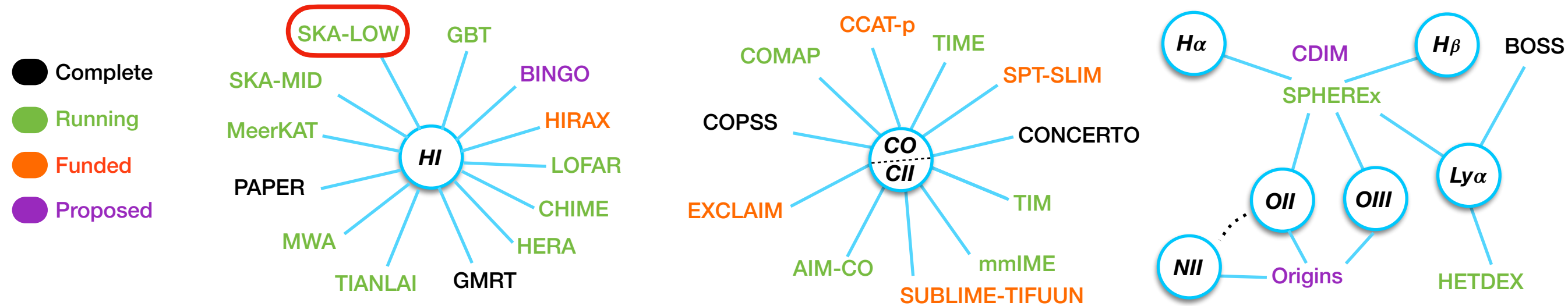
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]



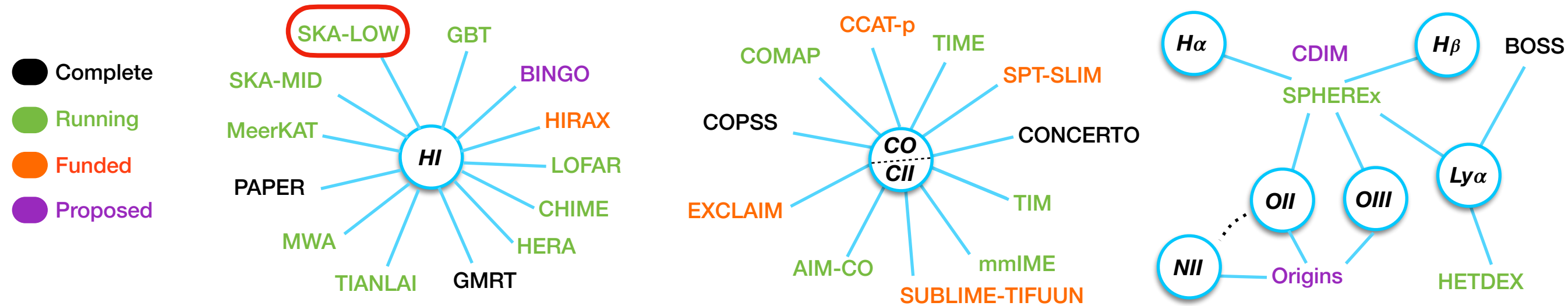
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]



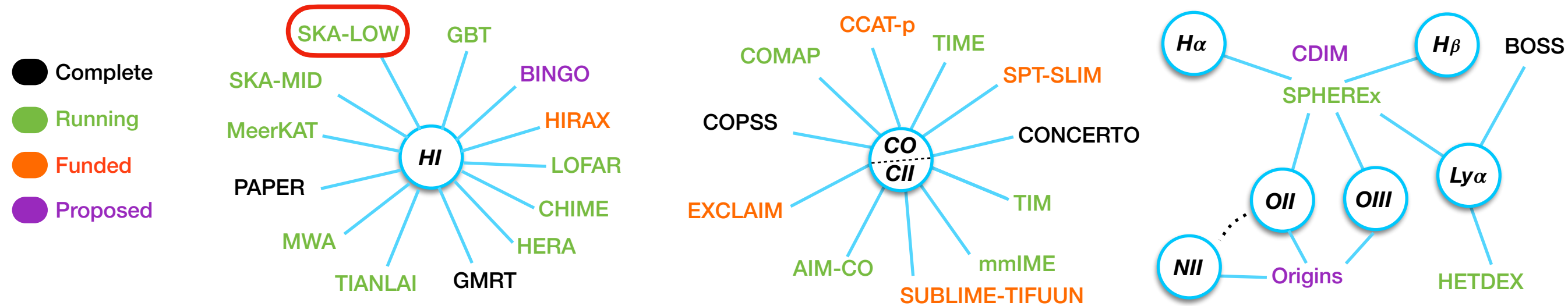
Line-Intensity Mapping: Experimental Landscape



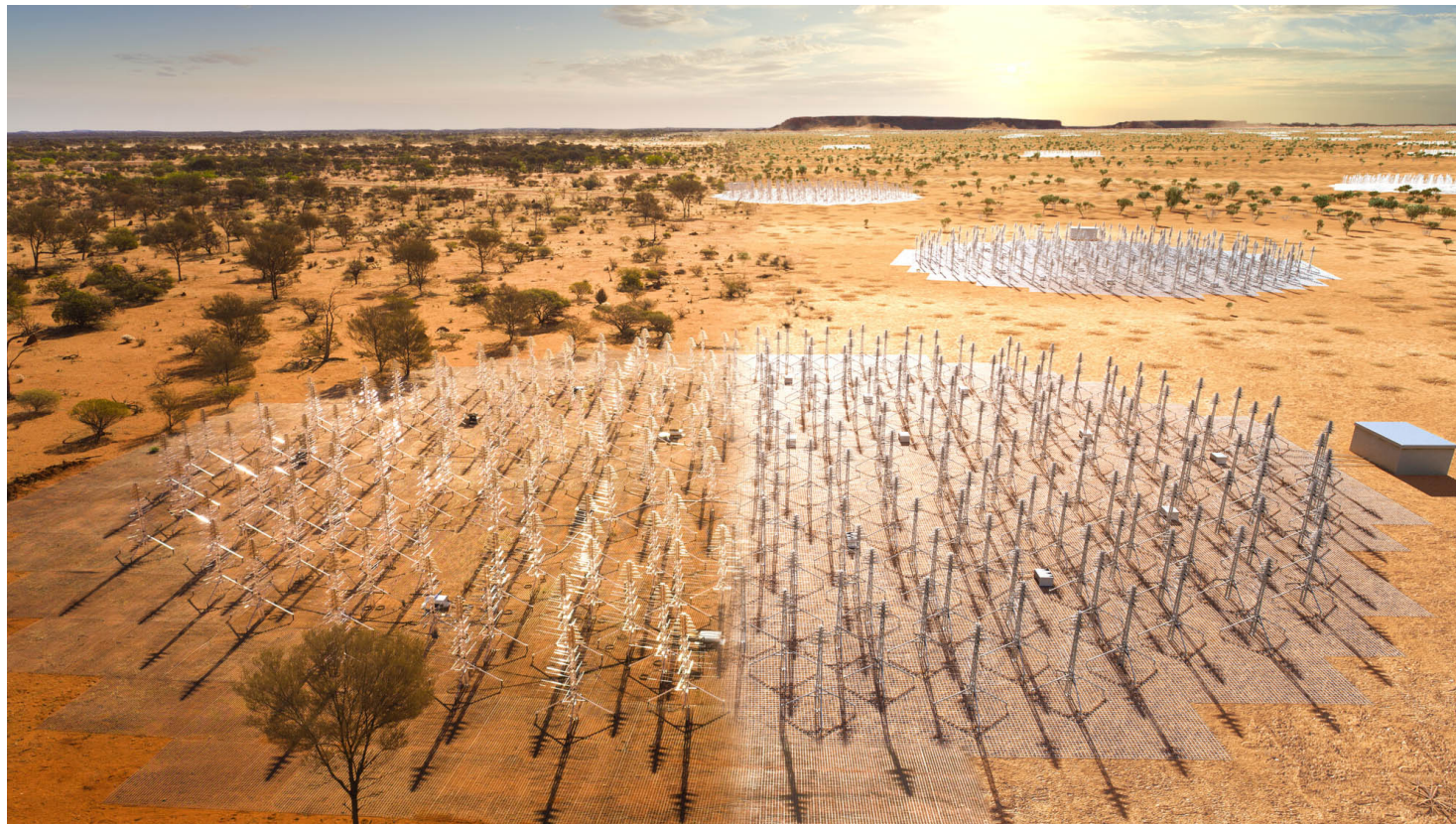
Astro2020: Kovetz et al. [arXiv:1903.04496]



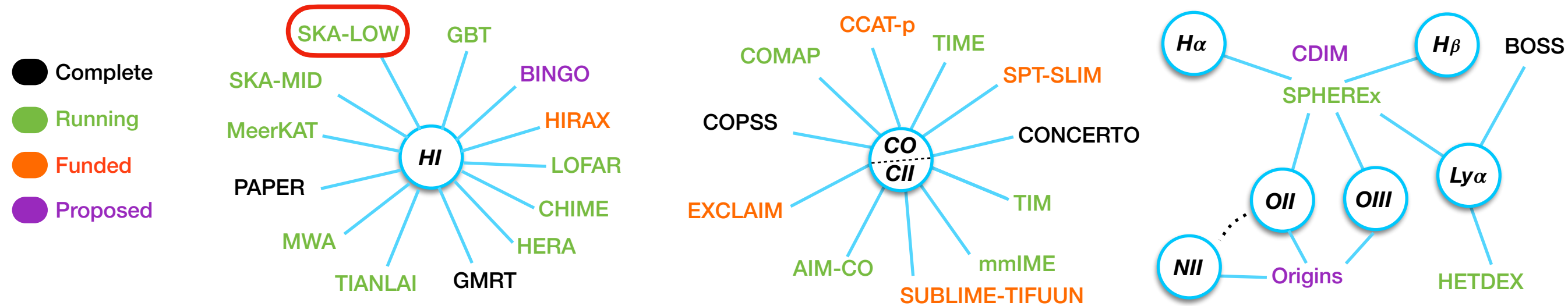
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]

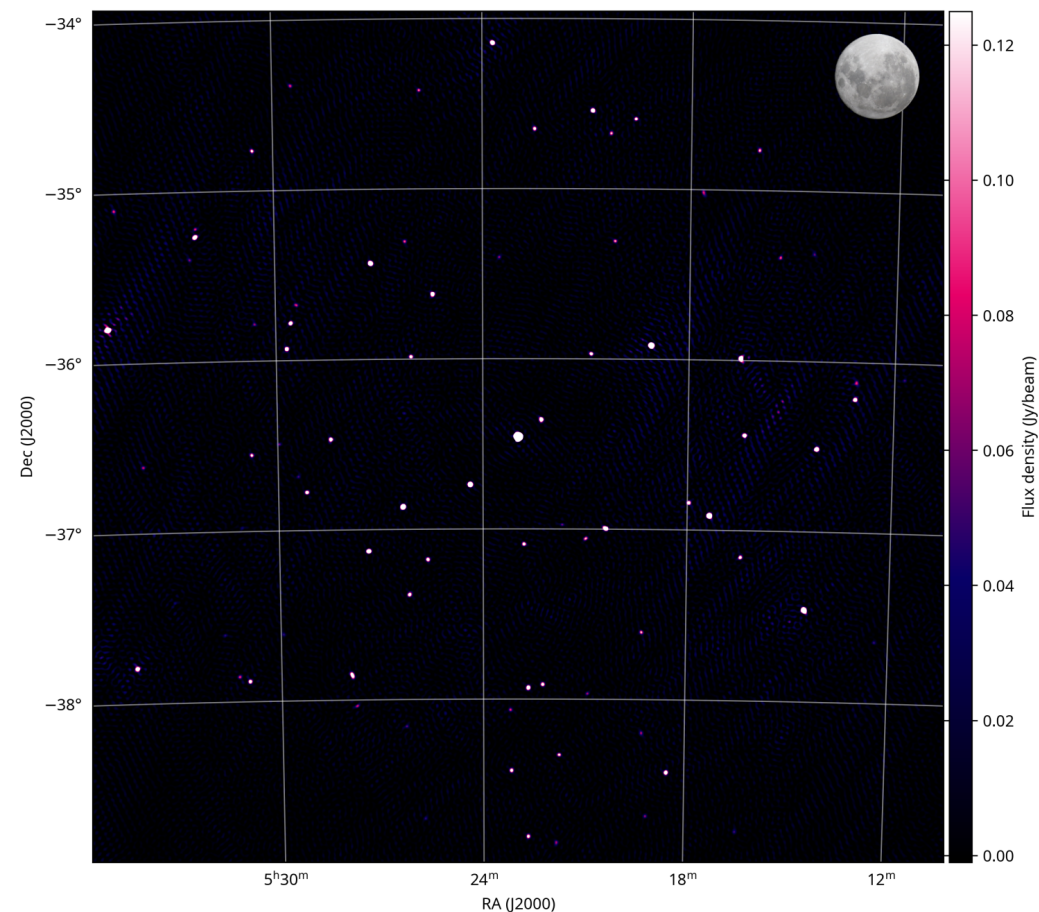


Line-Intensity Mapping: Experimental Landscape

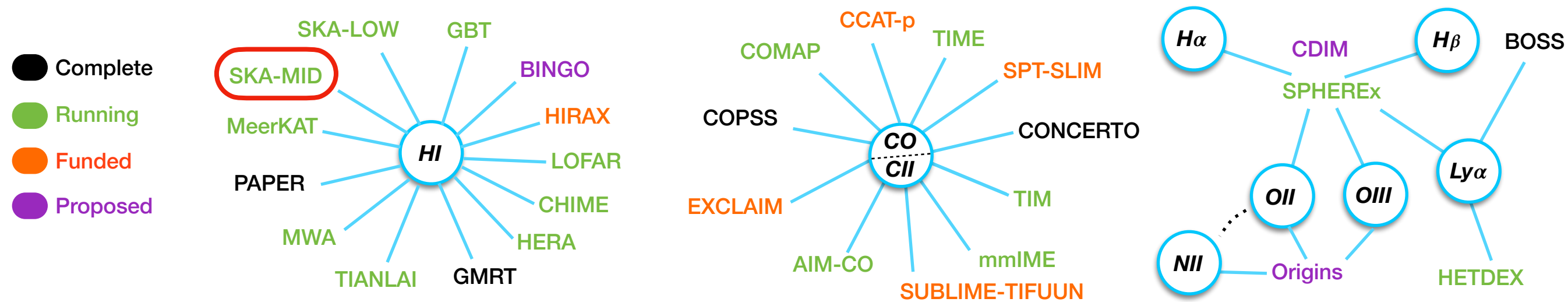


Astro2020: Kovetz et al. [arXiv:1903.04496]

First Light for SKA-LOW (Australia)!

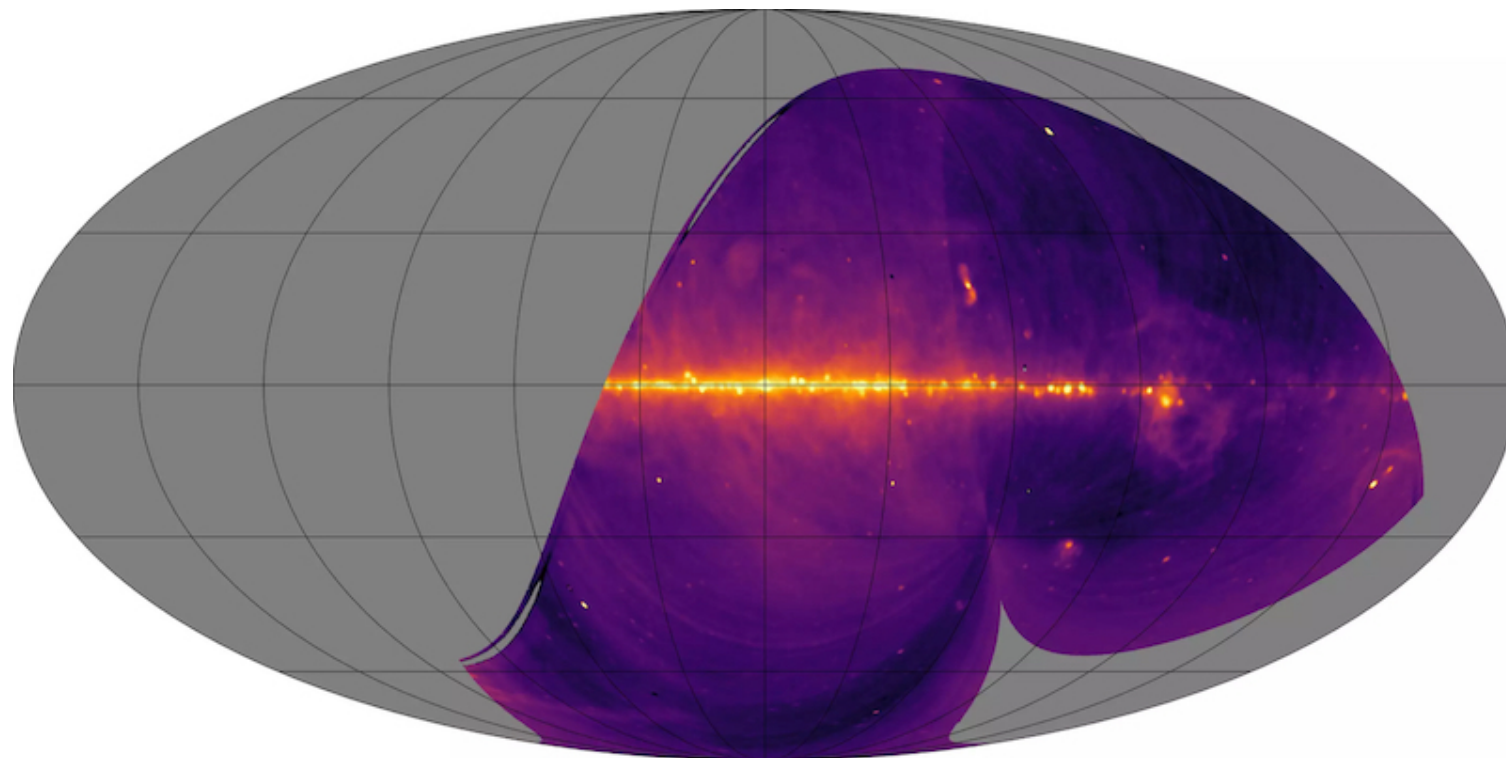


Line-Intensity Mapping: Experimental Landscape

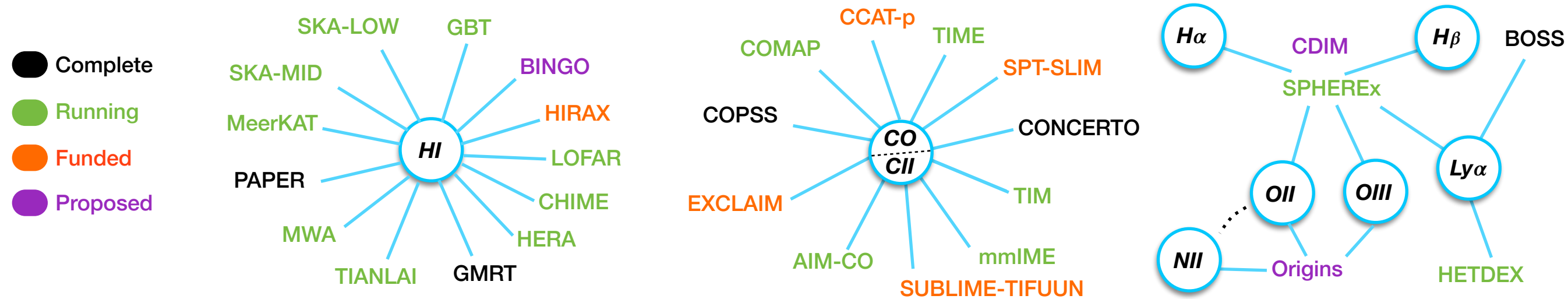


Astro2020: Kovetz et al. [arXiv:1903.04496]

First Light for SKAMPI (South Africa)!



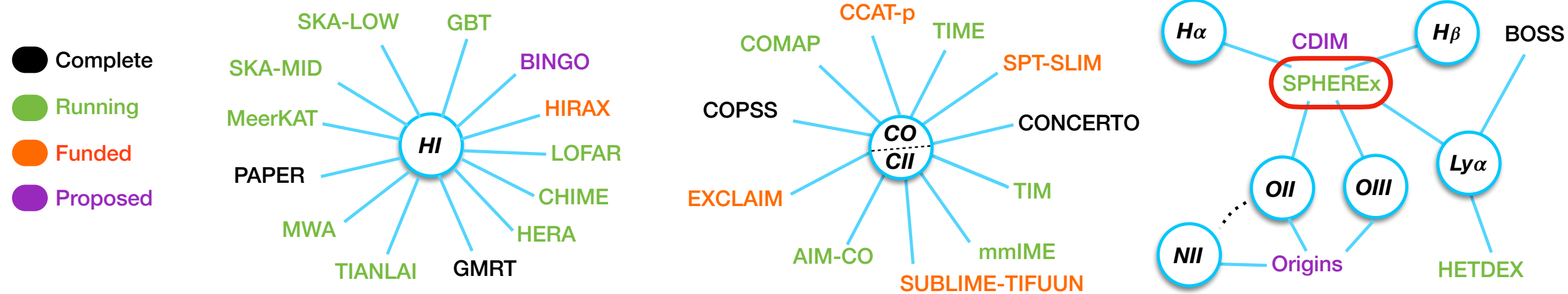
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]



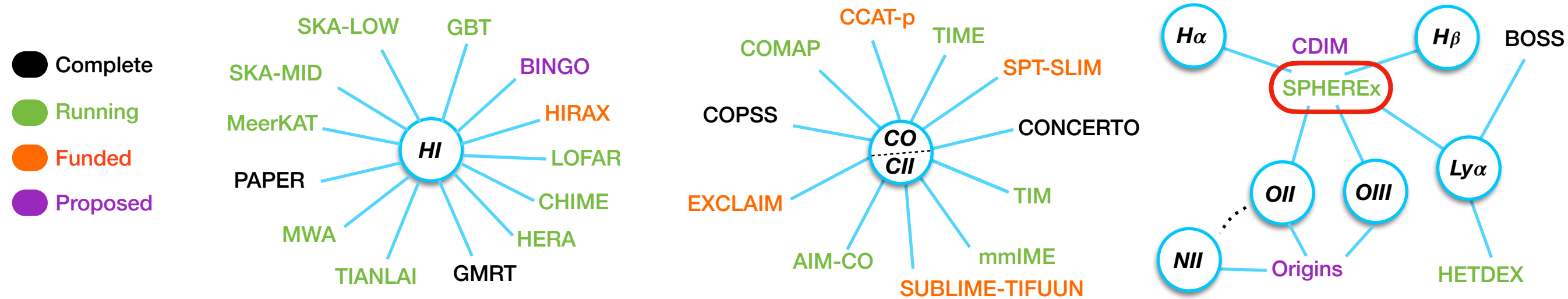
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]



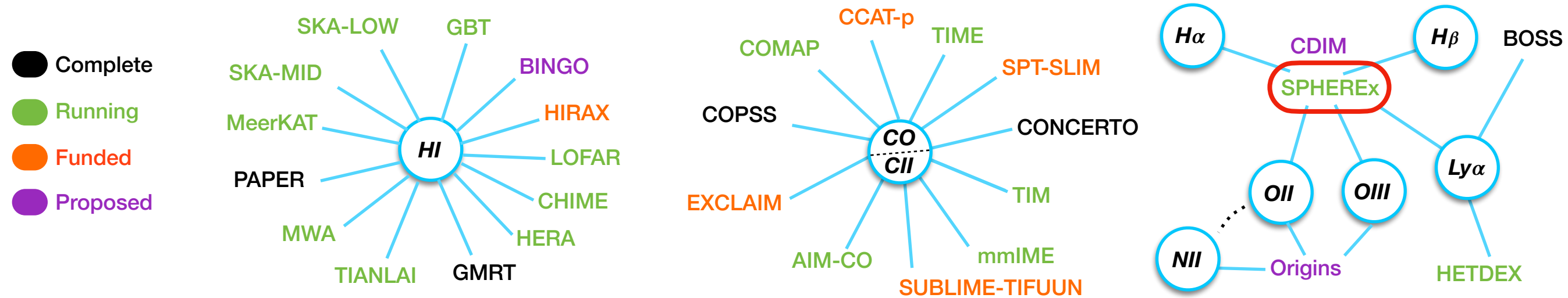
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]



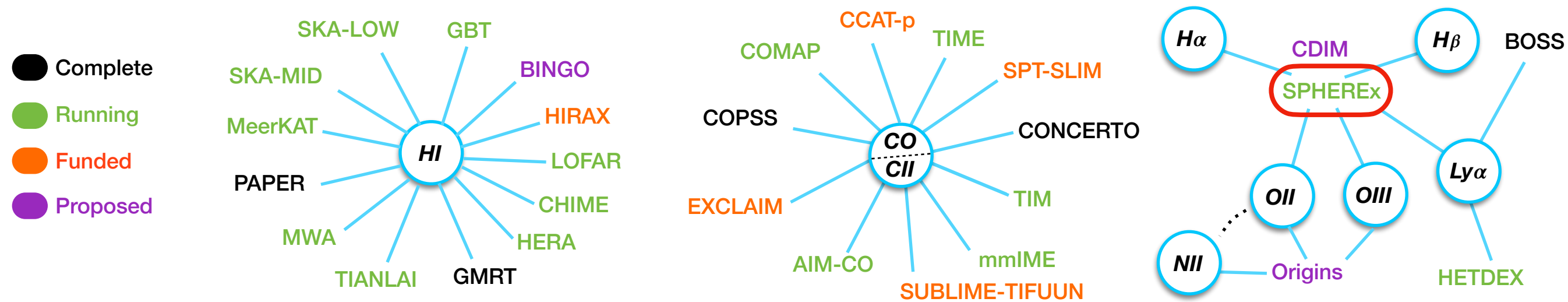
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]



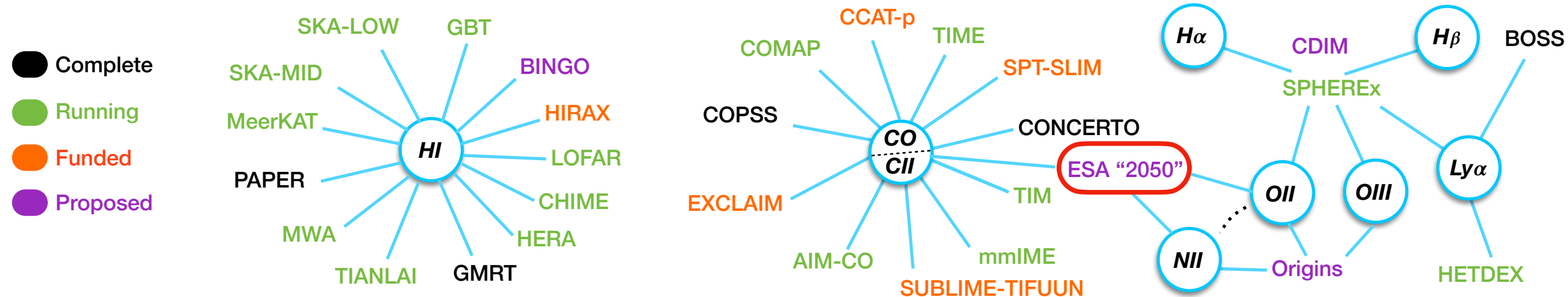
Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]



Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]

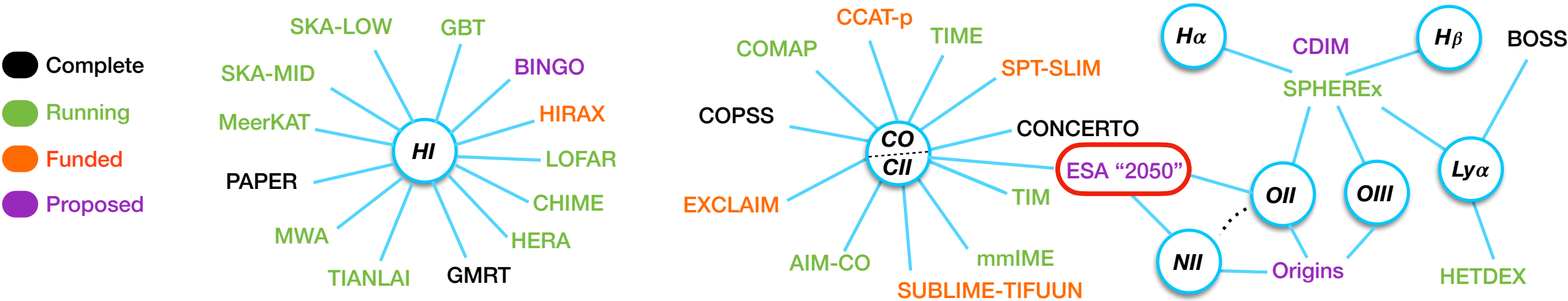


**Voyage 2050 sets sail:
ESA chooses future
science mission t...**

11/06/2021 12852 VIEWS 131 LIKES

ESA2050 proposal: Silva, Kovetz et al. [arXiv:1908.07533]

Line-Intensity Mapping: Experimental Landscape

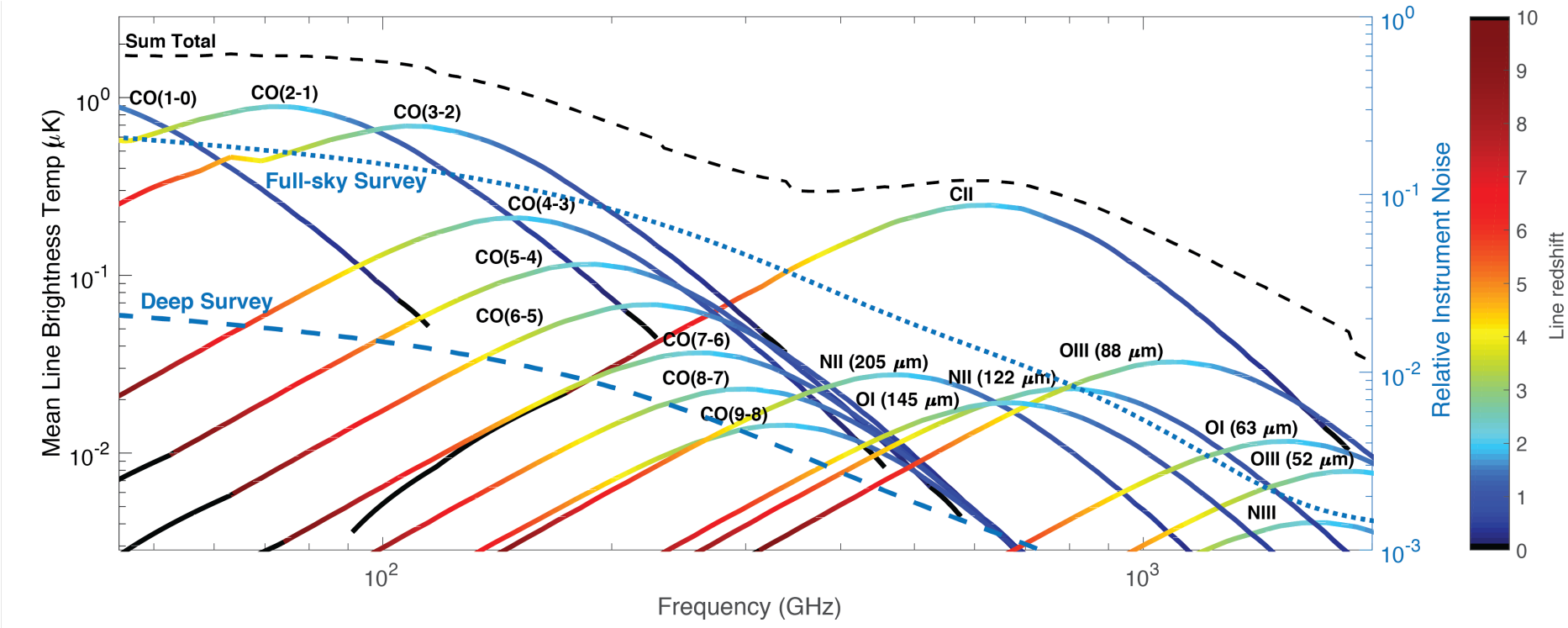


Astro2020: Kovetz et al. [arXiv:1903.04496]



Voyage 2050 sets sail:
ESA chooses future
science mission t...

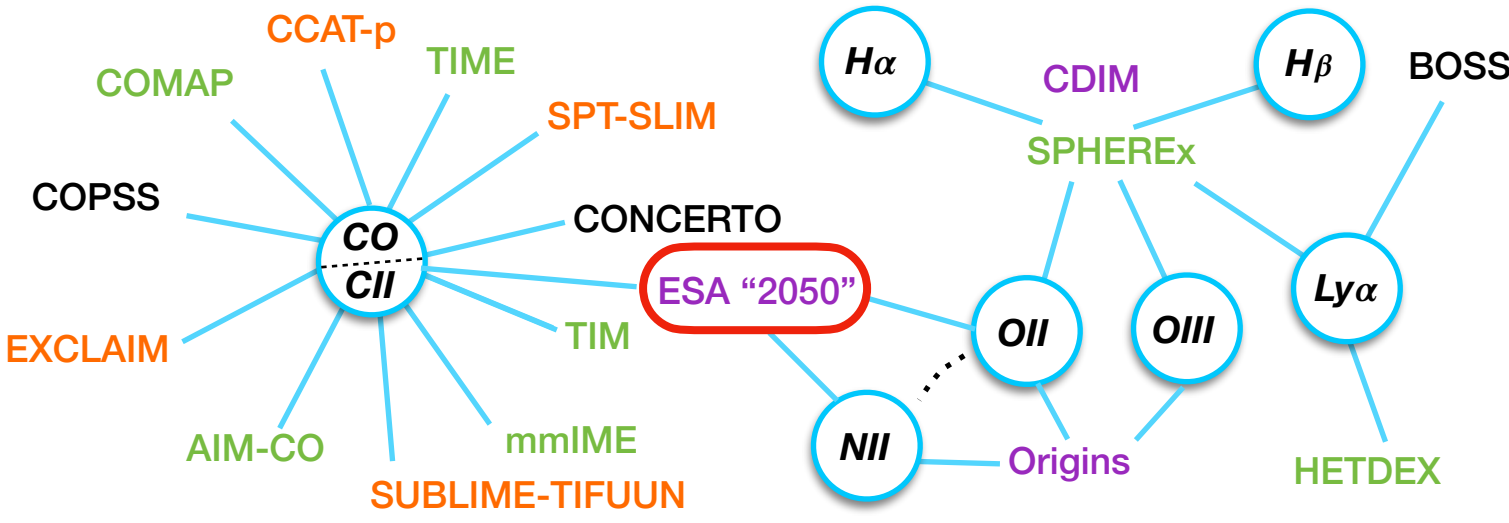
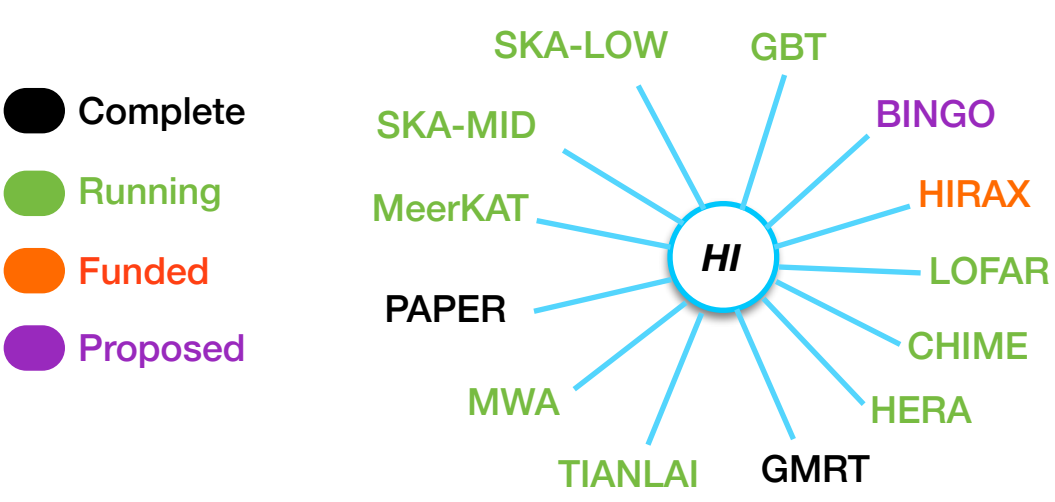
11/06/2021 12852 VIEWS 131 LIKES



(Courtesy of K. Keating)

ESA2050 proposal: Silva, Kovetz et al. [arXiv:1908.07533]

Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]

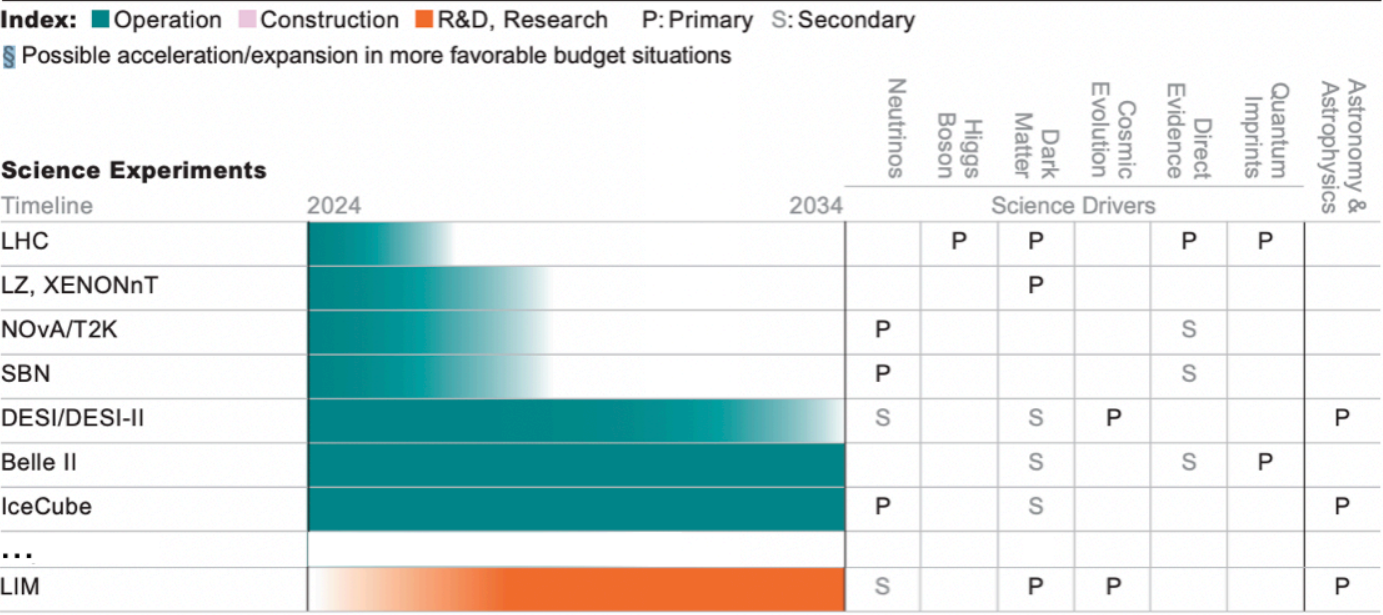


Voyage 2050 sets sail:
ESA chooses future
science mission t...

11/06/2021 12852 VIEWS 131 LIKES

ESA2050 proposal: Silva, Kovetz et al. [arXiv:1908.07533]

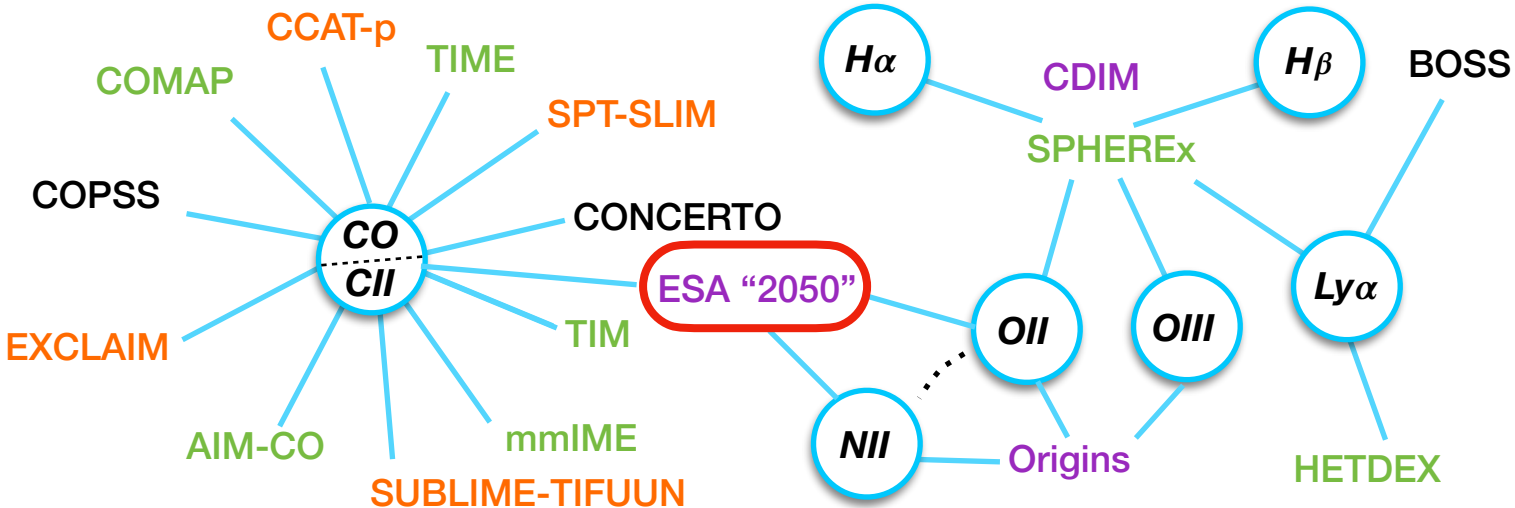
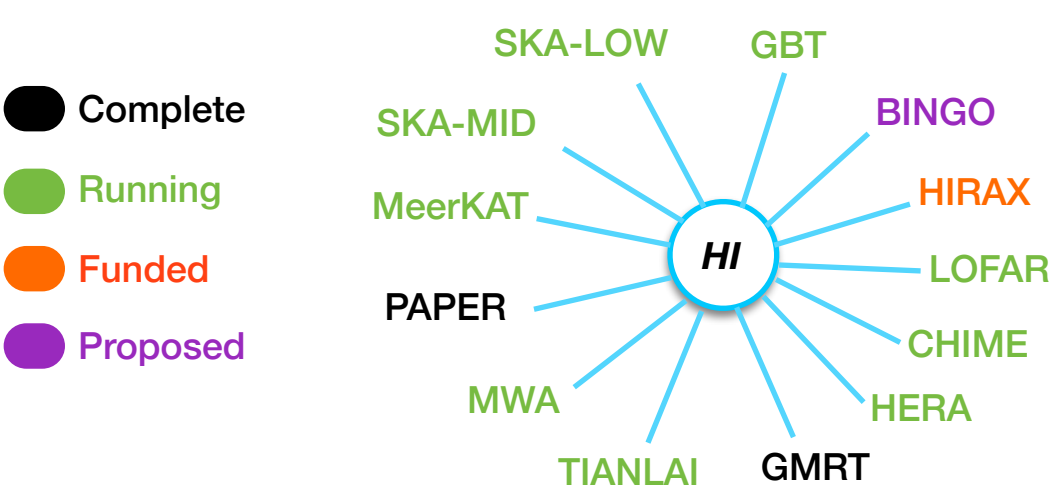
Figure 1 – Program and Timeline in Baseline Scenario



Particle Physics Project Prioritization Panel (P5) Recommendation

Snowmass White Paper: Karkare et al. [arXiv:2203.07258]

Line-Intensity Mapping: Experimental Landscape



Astro2020: Kovetz et al. [arXiv:1903.04496]

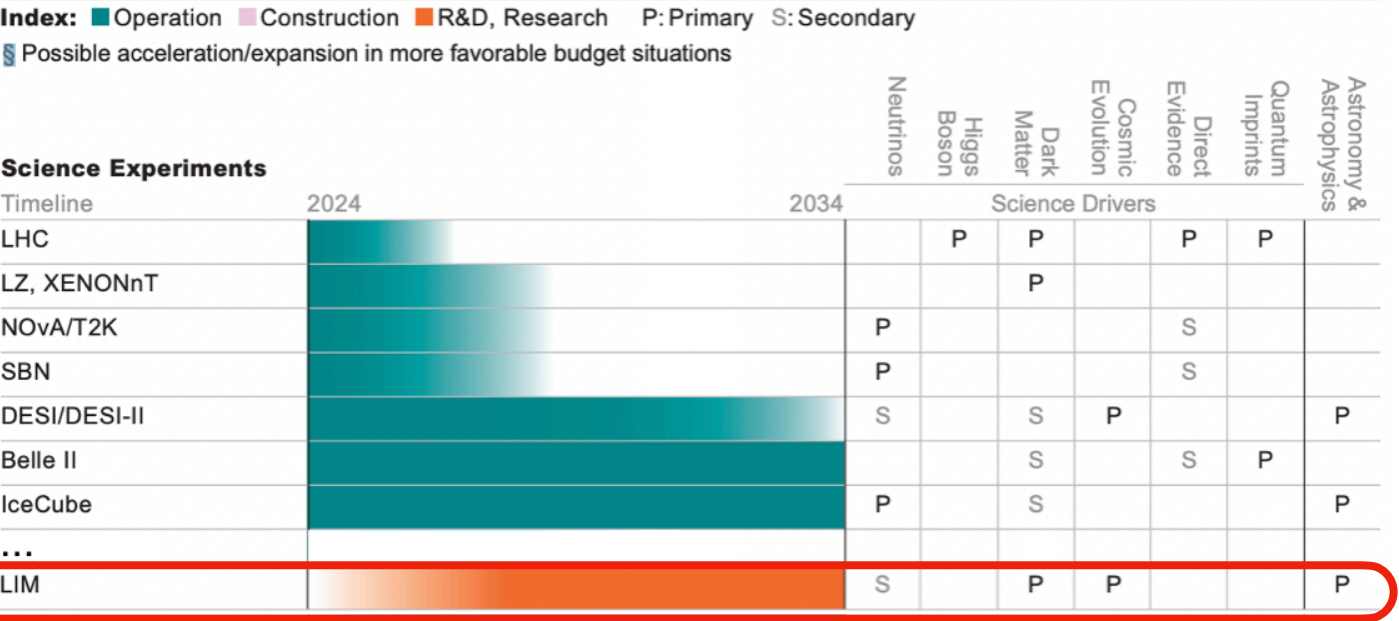


Voyage 2050 sets sail:
ESA chooses future
science mission t...

11/06/2021 12852 VIEWS 131 LIKES

ESA2050 proposal: Silva, Kovetz et al. [arXiv:1908.07533]

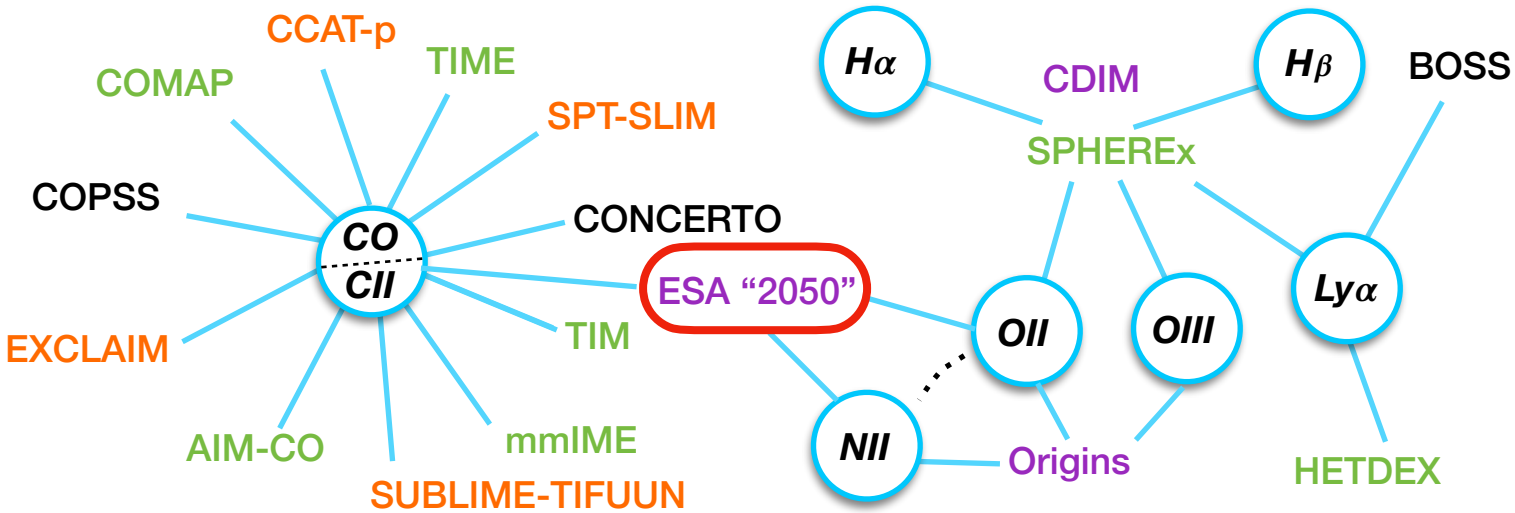
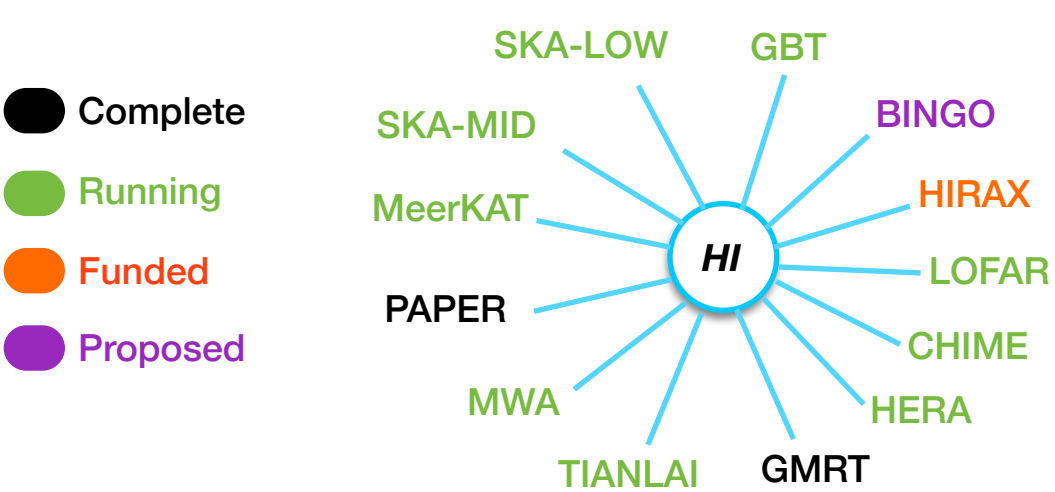
Figure 1 – Program and Timeline in Baseline Scenario



Particle Physics Project Prioritization Panel (P5) Recommendation

Snowmass White Paper: Karkare et al. [arXiv:2203.07258]

Takeaway: Line-Intensity Mapping is Coming!



Astro2020: Kovetz et al. [arXiv:1903.04496]



Voyage 2050 sets sail:
ESA chooses future
science mission t...

11/06/2021 12852 VIEWS 131 LIKES

ESA2050 proposal: Silva, Kovetz et al. [arXiv:1908.07533]

Figure 1 – Program and Timeline in Baseline Scenario

Index:
■ Operation
■ Construction
■ R&D, Research
P: Primary
S: Secondary

■ Possible acceleration/expansion in more favorable budget situations

Science Experiments		Science Drivers										Astronomy & Astrophysics
Timeline	2024	2034	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints				
LHC				P	P		P	P				
LZ, XENONnT					P							
NOvA/T2K			P				S					
SBN			P				S					
DESI/DESI-II			S		S	P					P	
Belle II					S		S	P				
IceCube			P		S							
...												
LIM			S		P	P					P	

Particle Physics Project Prioritization Panel (P5) Recommendation

Snowmass White Paper: Karkare et al. [arXiv:2203.07258]

Line-Intensity Mapping: What Can it Probe?

Line-Intensity Mapping: What Can it Probe?

Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

Line-Intensity Mapping: What Can it Probe?



Astrophysics

Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

Line-Intensity Mapping: What Can it Probe?

Astrophysics

Cosmology

Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

Line-Intensity Mapping: What Can it Probe?

Astrophysics

Cosmology

One's signal is another's foreground

Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

Line-Intensity Mapping: What Can it Probe?

Astrophysics

Cosmology

One's signal is another's foreground

Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

Teaser 1: cosmic dawn - no longer just forecasts!

Astrophysics

Cosmology

One's signal is another's foreground

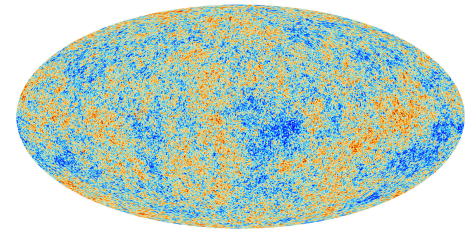
Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

Starting Point: Combining CMB and 21cm-LIM

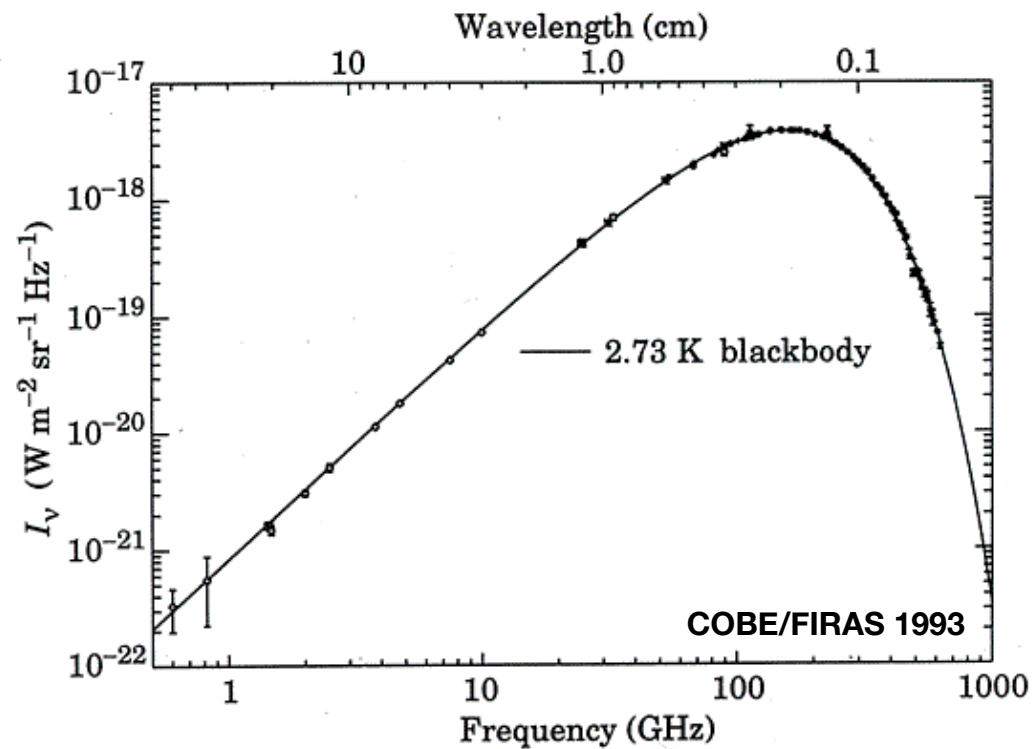
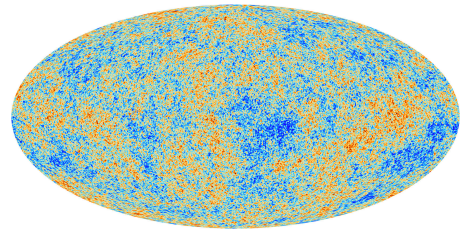
Starting Point: Combining CMB and 21cm-LIM

CMB



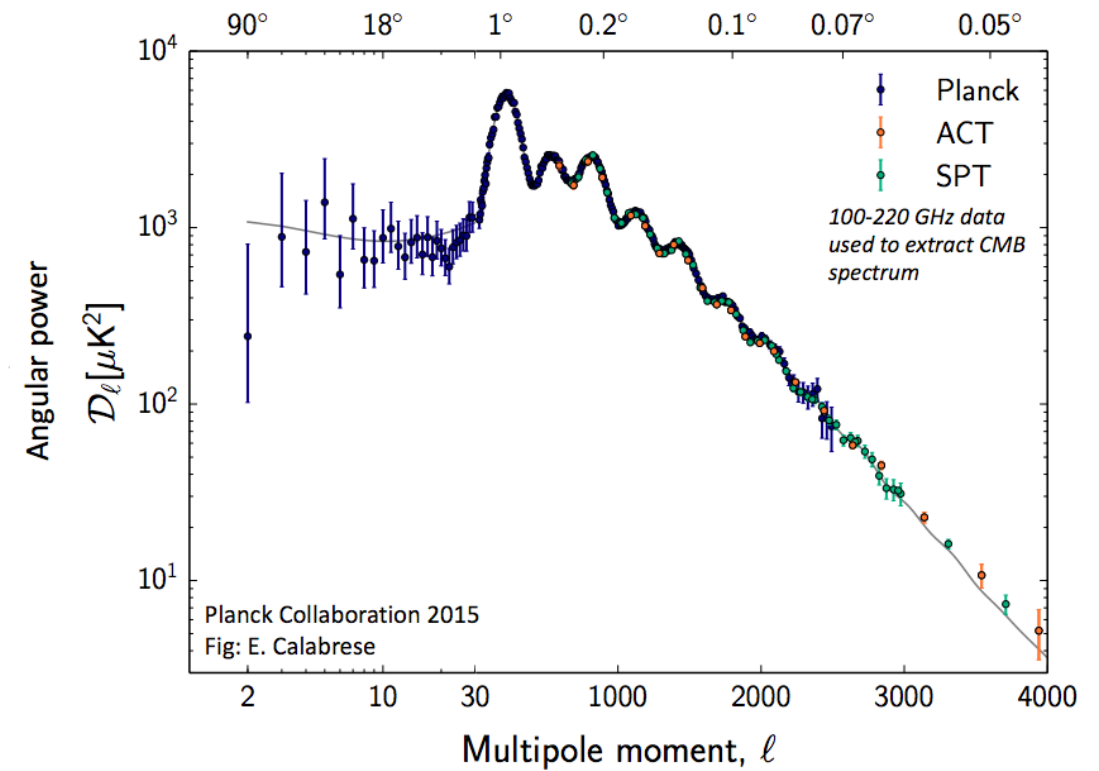
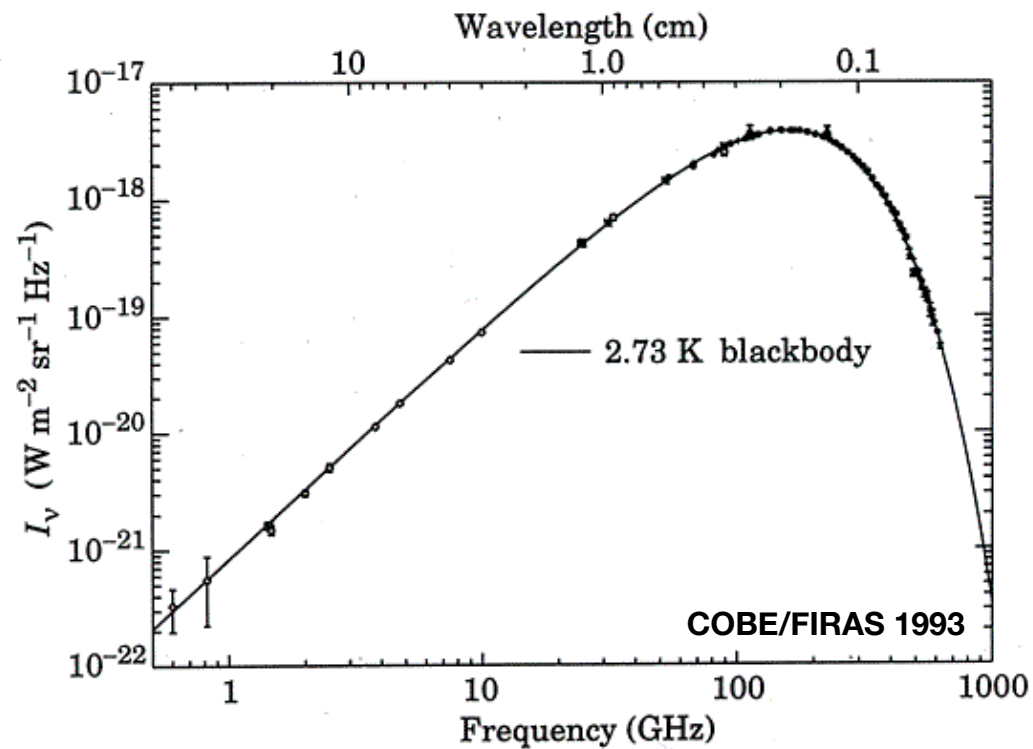
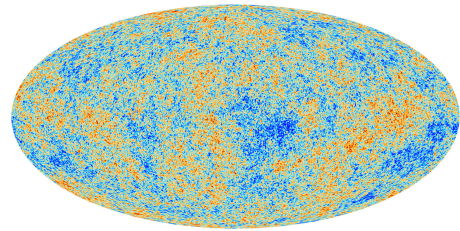
Starting Point: Combining CMB and 21cm-LIM

CMB



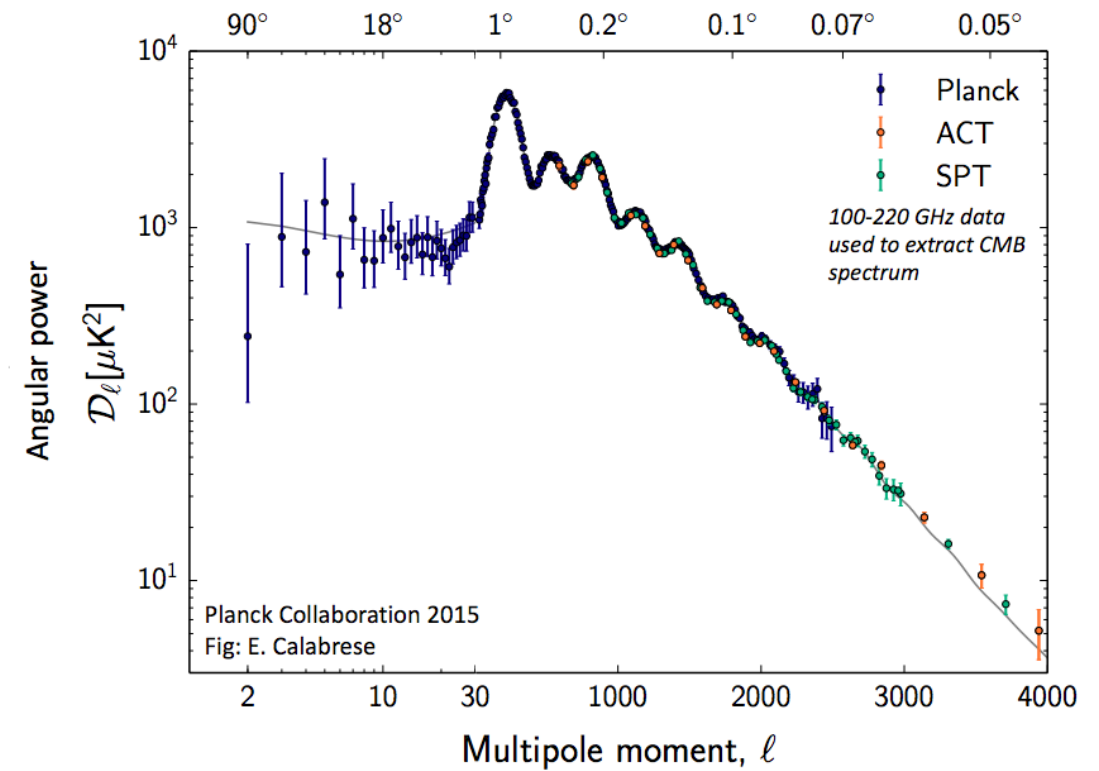
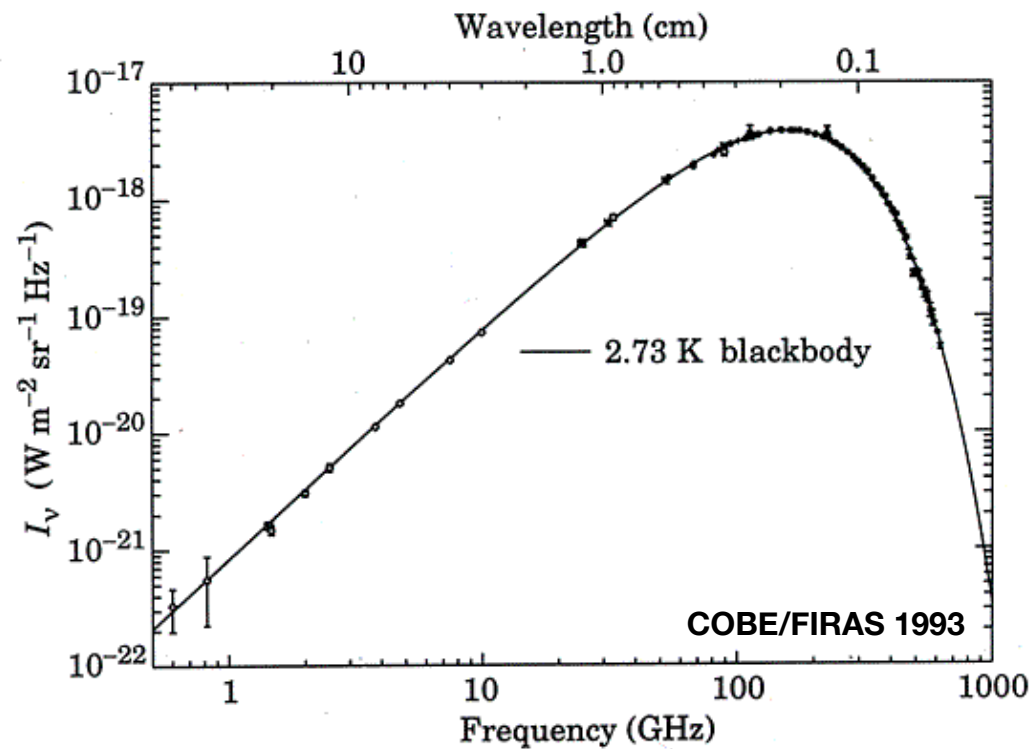
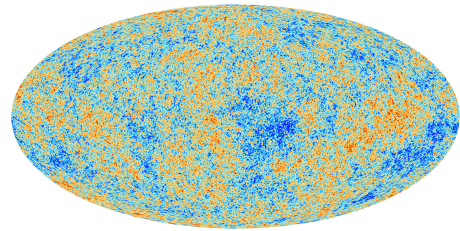
Starting Point: Combining CMB and 21cm-LIM

CMB

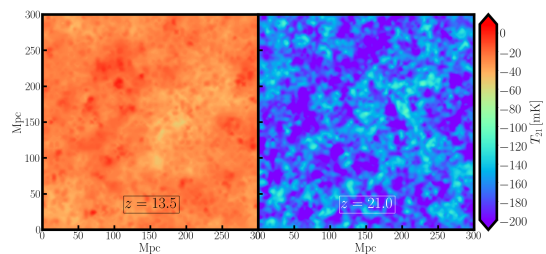


Starting Point: Combining CMB and 21cm-LIM

CMB

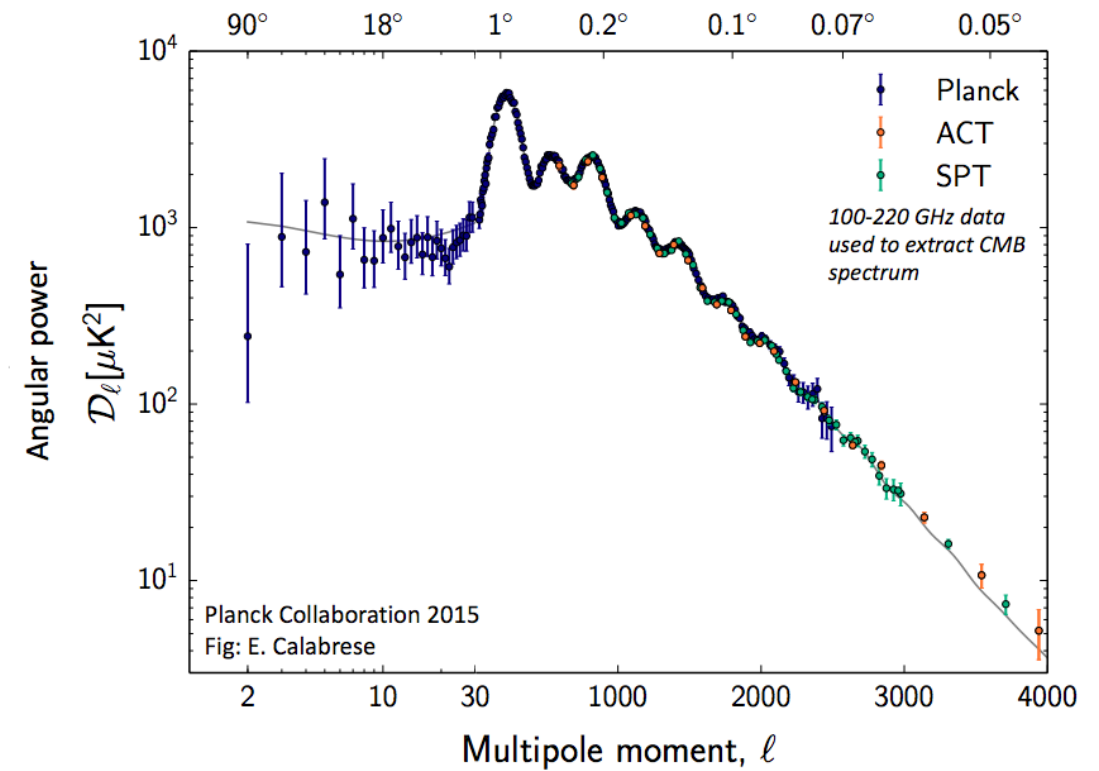
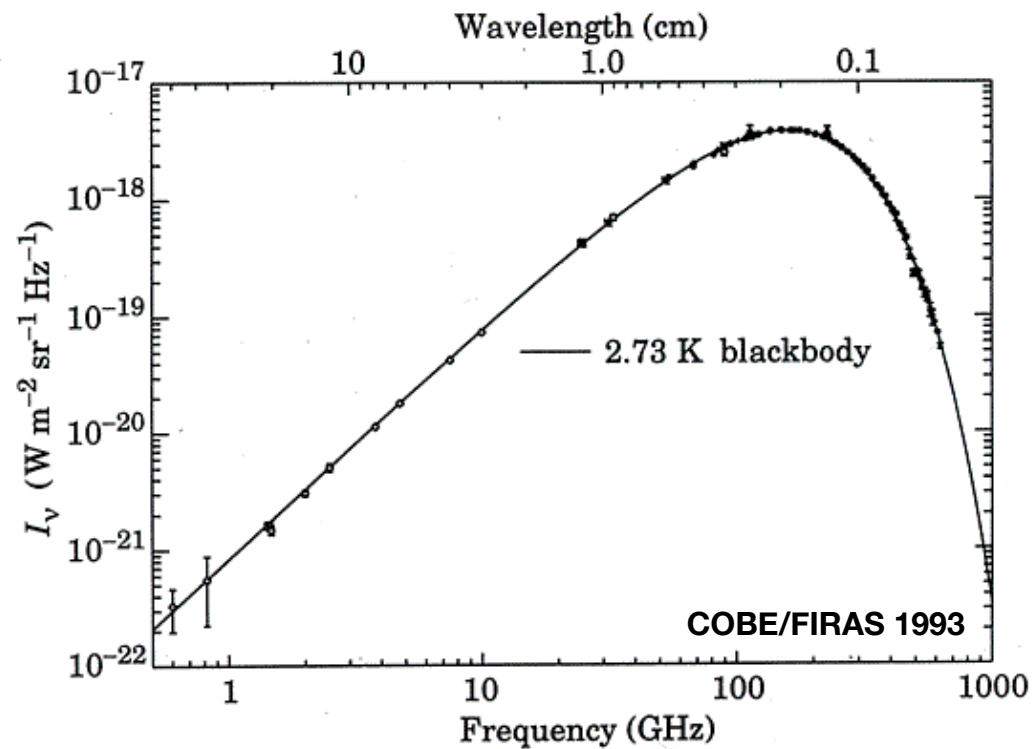
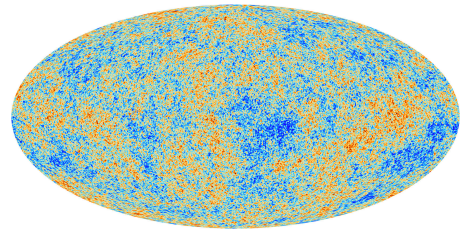


21cm

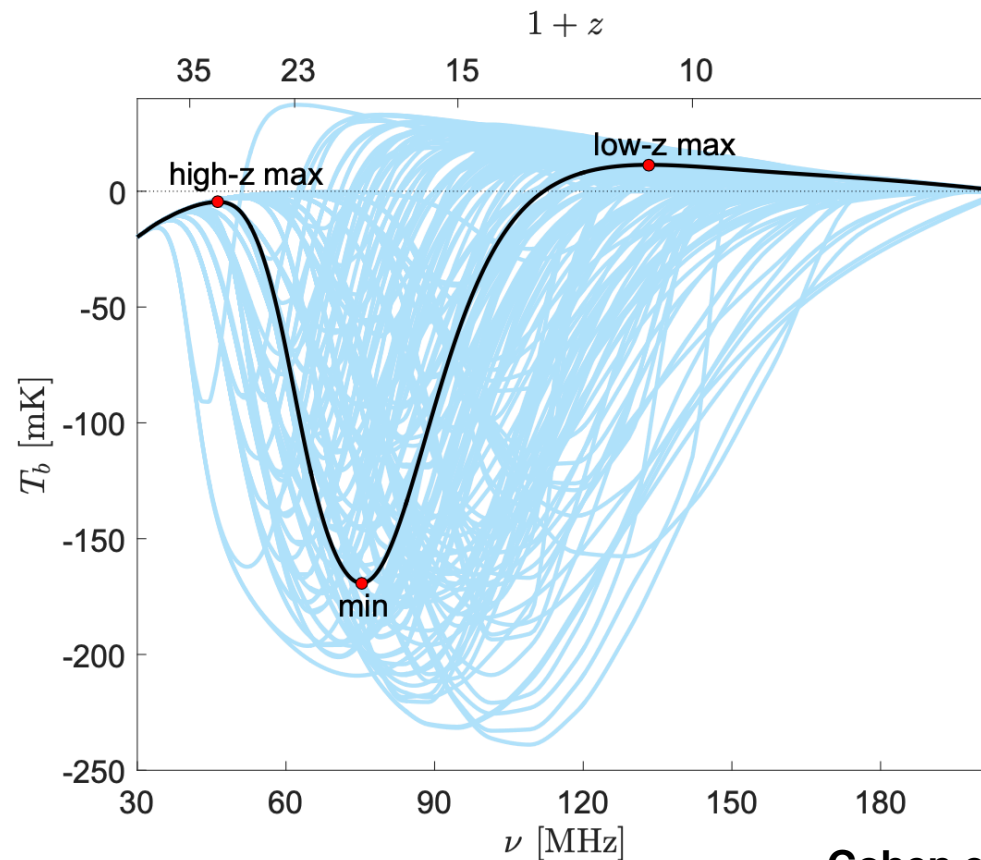
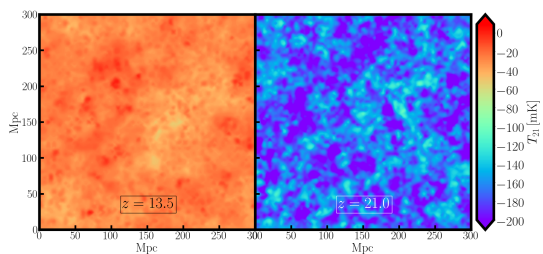


Starting Point: Combining CMB and 21cm-LIM

CMB

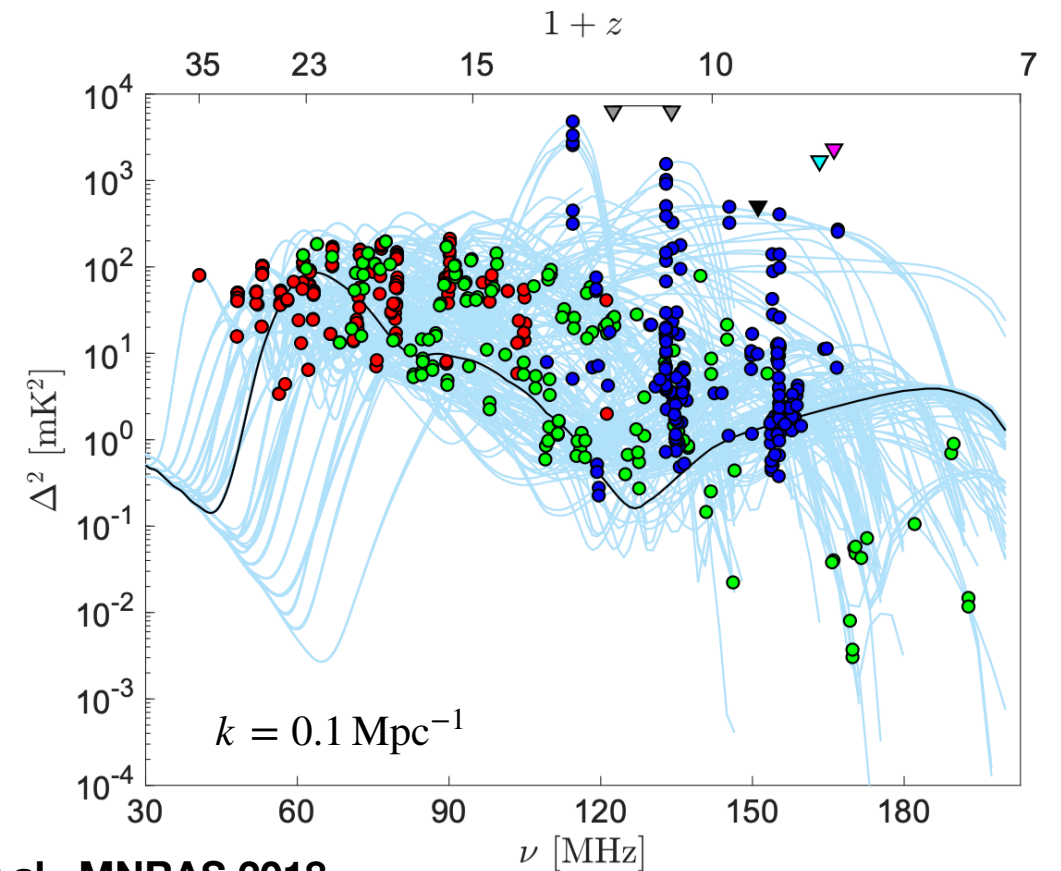
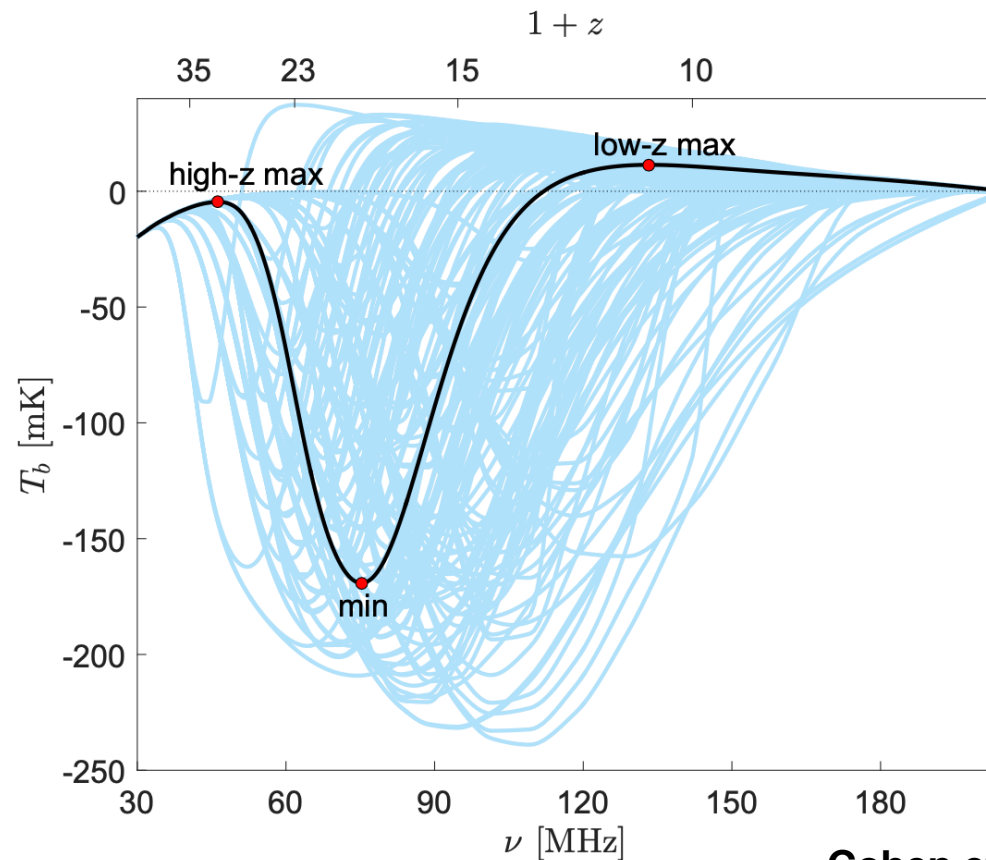
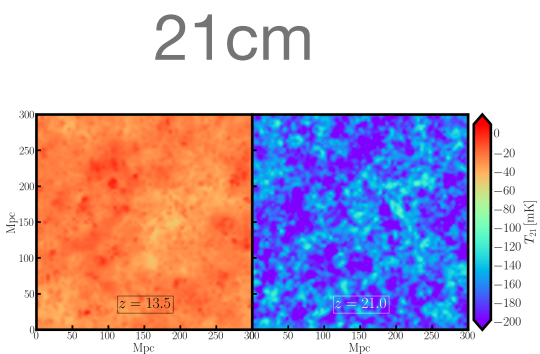
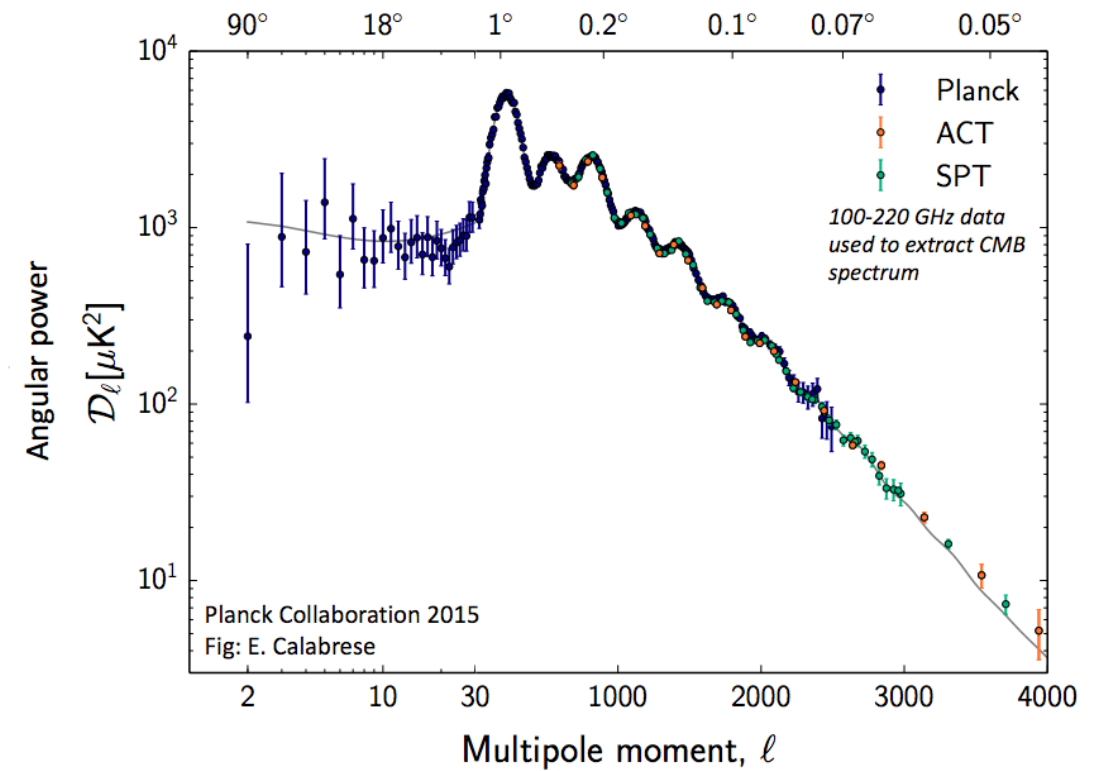
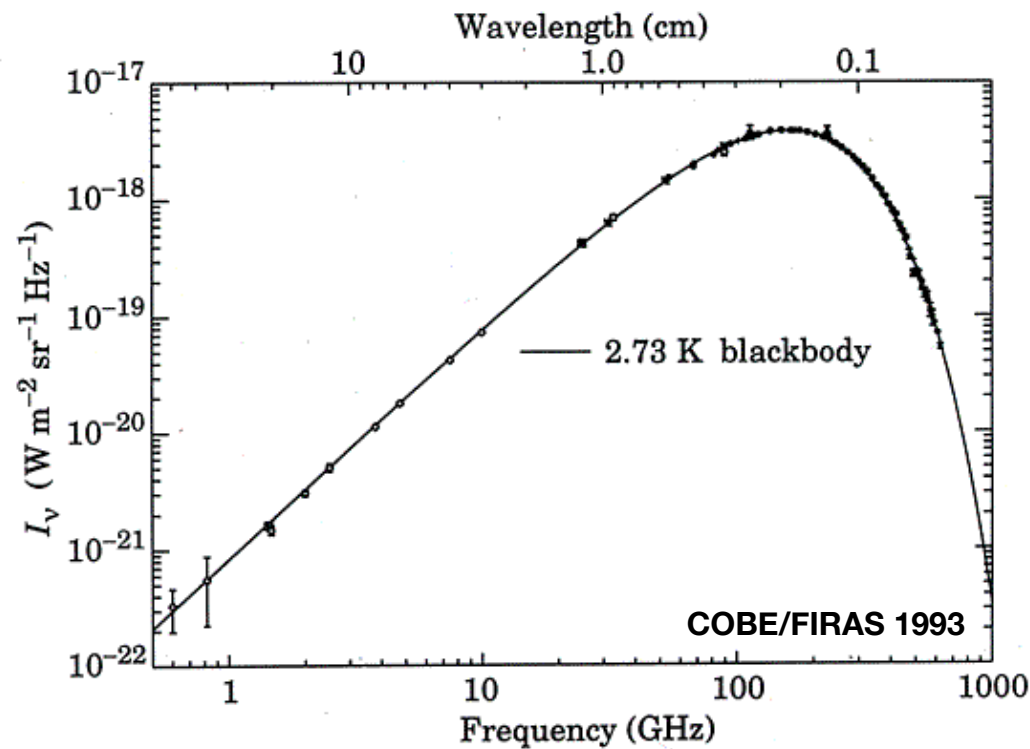
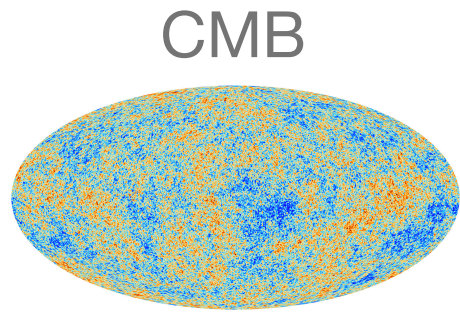


21cm



Cohen et al., MNRAS 2018

Starting Point: Combining CMB and 21cm-LIM



Cohen et al., MNRAS 2018

21 cm Line-Intensity Mapping: Public Codes

Full radiative-transfer hydrodynamical simulation (extremely computationally expensive):

CoDa (Ocvirk et al., MNRAS 2016) 21SSD (Semelin, MNRAS 2017) THESAN (Kannan et al., MNRAS 2011)

Ray-tracing algorithms (applied to N-body simulations; also very expensive):

C^2 – Ray (Mellema et al., New Astron. 2006) CRASH (Maselli et al., MNRAS 2003)

One-dimensional radiative transfer (much faster, approximated):

BEARS (Thomas et al., MNRAS 2009) GRIZZLY (Ghara et al., MNRAS 2018) BEORN (Schaeffer et al., arXiv:2305.15466)

Purely analytic codes (fastest):

CAMB (Lewis and Challinor, PRD 2007) Zeus21 (Munoz, arXiv:2302.08506) X21 (Katz et al., arXiv:2309.XXXXX)

Semi-numerical codes (excursion-set formalism):

SimFAST21 (Santos et. al, MNRAS 2010) 21cmFAST (Mesinger et al., MNRAS 2011)

21 cm Line-Intensity Mapping: Public Codes

Full radiative-transfer hydrodynamical simulation (extremely computationally expensive):

CoDa (Ocvirk et al., MNRAS 2016) 21SSD (Semelin, MNRAS 2017) THESAN (Kannan et al., MNRAS 2011)

Ray-tracing algorithms (applied to N-body simulations; also very expensive):

C^2 – Ray (Mellema et al., New Astron. 2006) CRASH (Maselli et al., MNRAS 2003)

One-dimensional radiative transfer (much faster, approximated):

BEARS (Thomas et al., MNRAS 2009) GRIZZLY (Ghara et al., MNRAS 2018) BEORN (Schaeffer et al., arXiv:2305.15466)

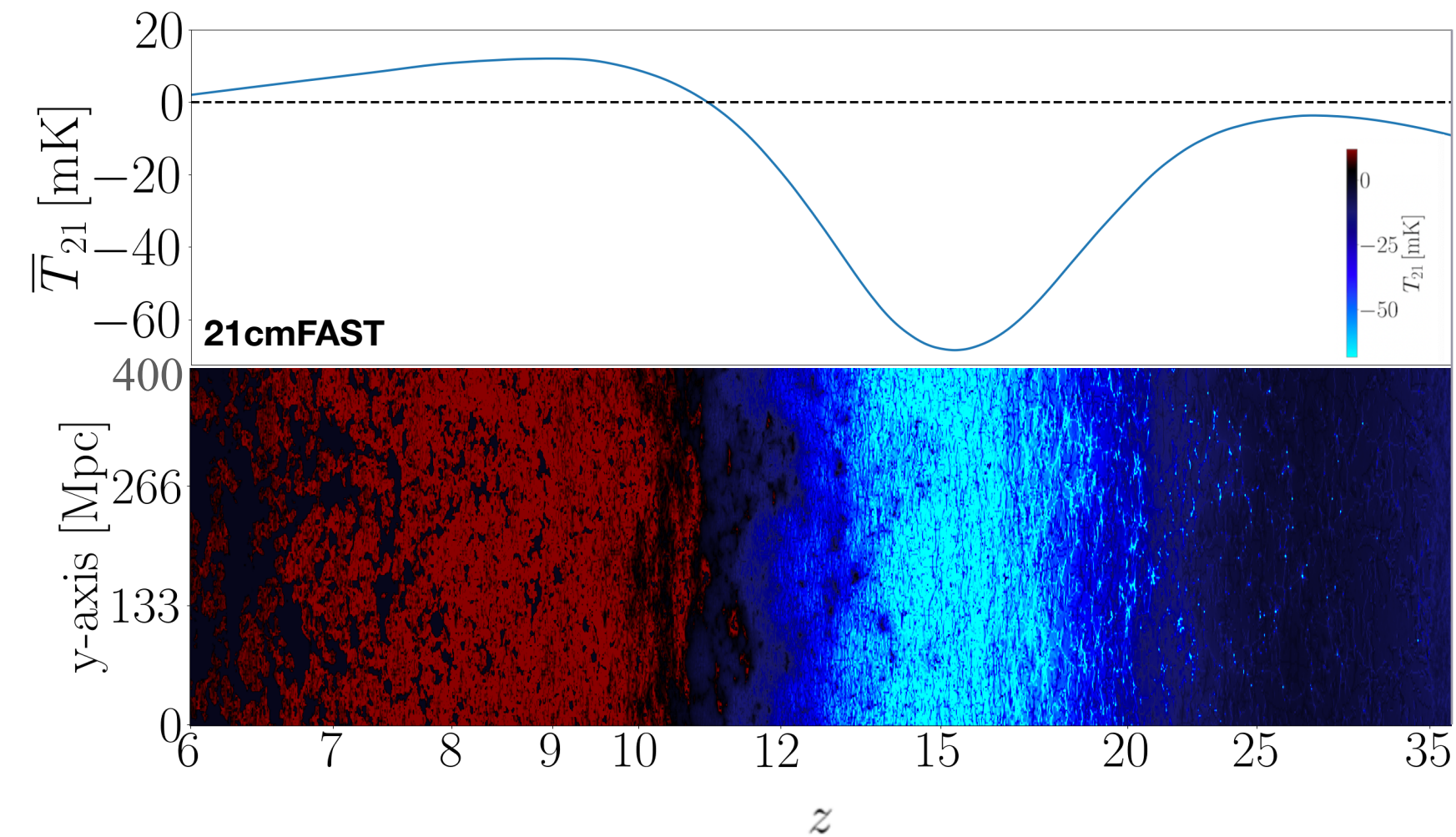
Purely analytic codes (fastest):

CAMB (Lewis and Challinor, PRD 2007) Zeus21 (Munoz, arXiv:2302.08506) X21 (Katz et al., arXiv:2309.XXXXXX)

Semi-numerical codes (excursion-set formalism):

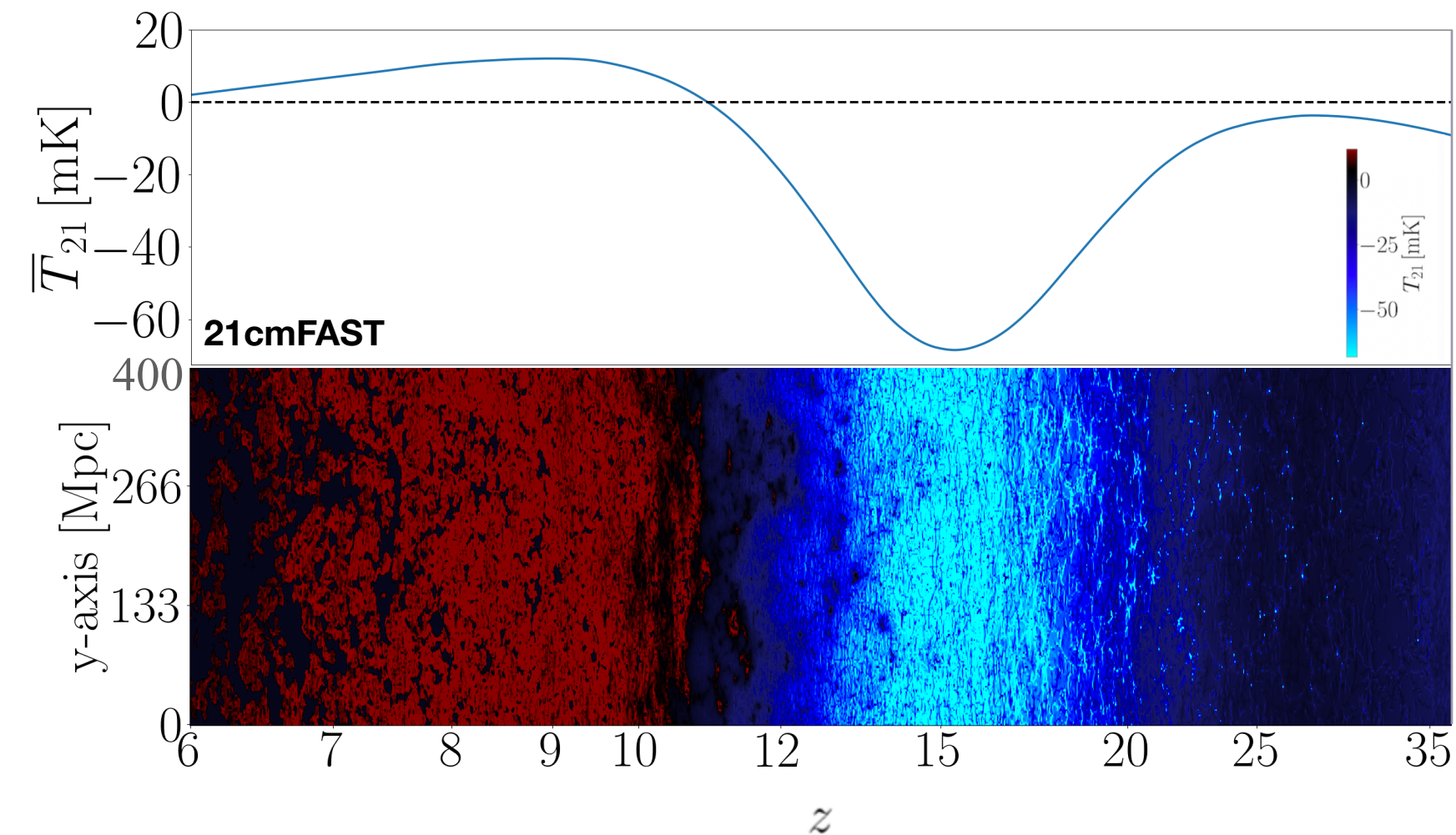
SimFAST21 (Santos et. al, MNRAS 2010) 21cmFAST (Mesinger et al., MNRAS 2011)

A First-CLASS Code for Cosmology with 21cm

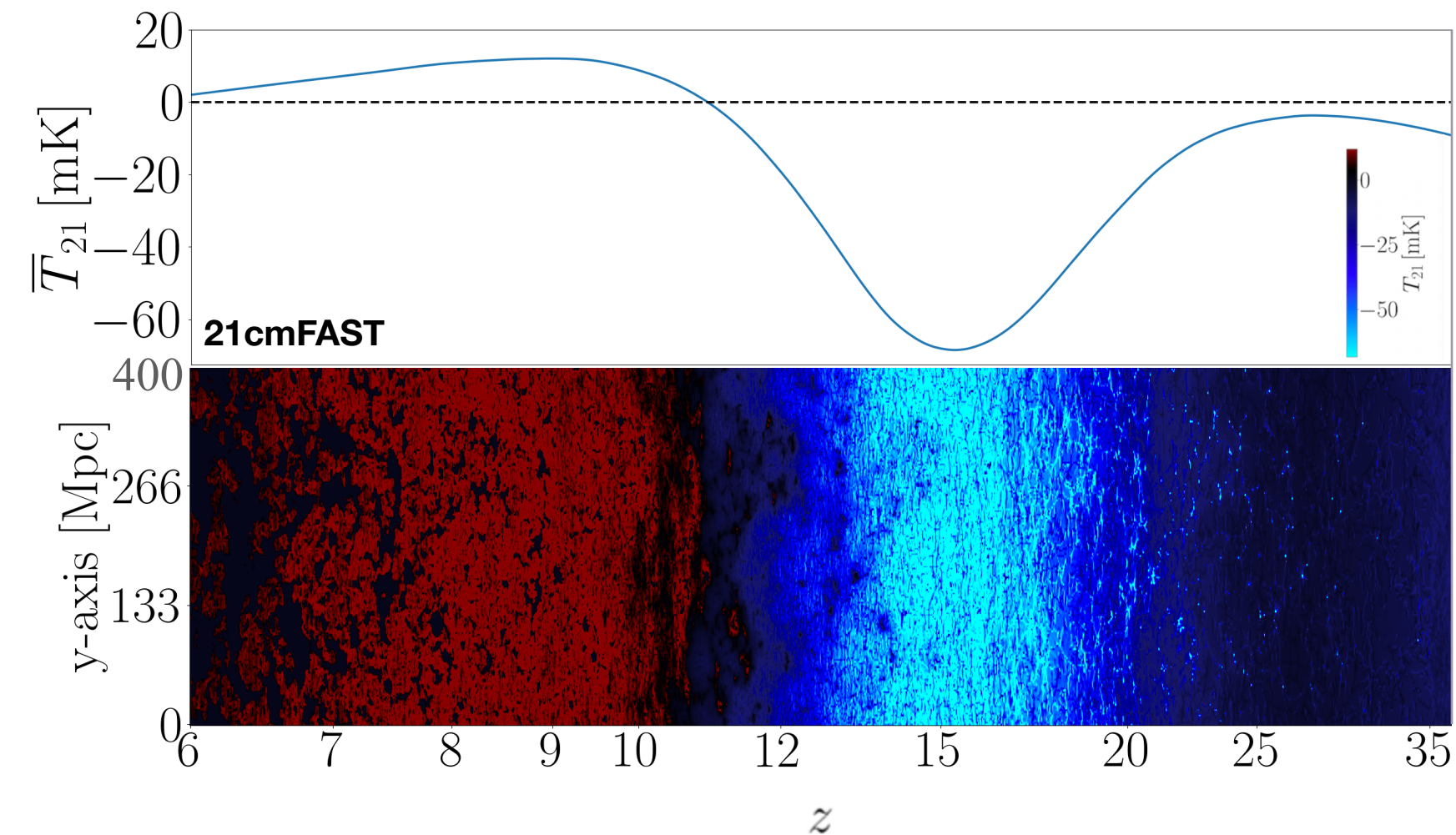


A First-CLASS Code for Cosmology with 21cm

Limitations for new physics:



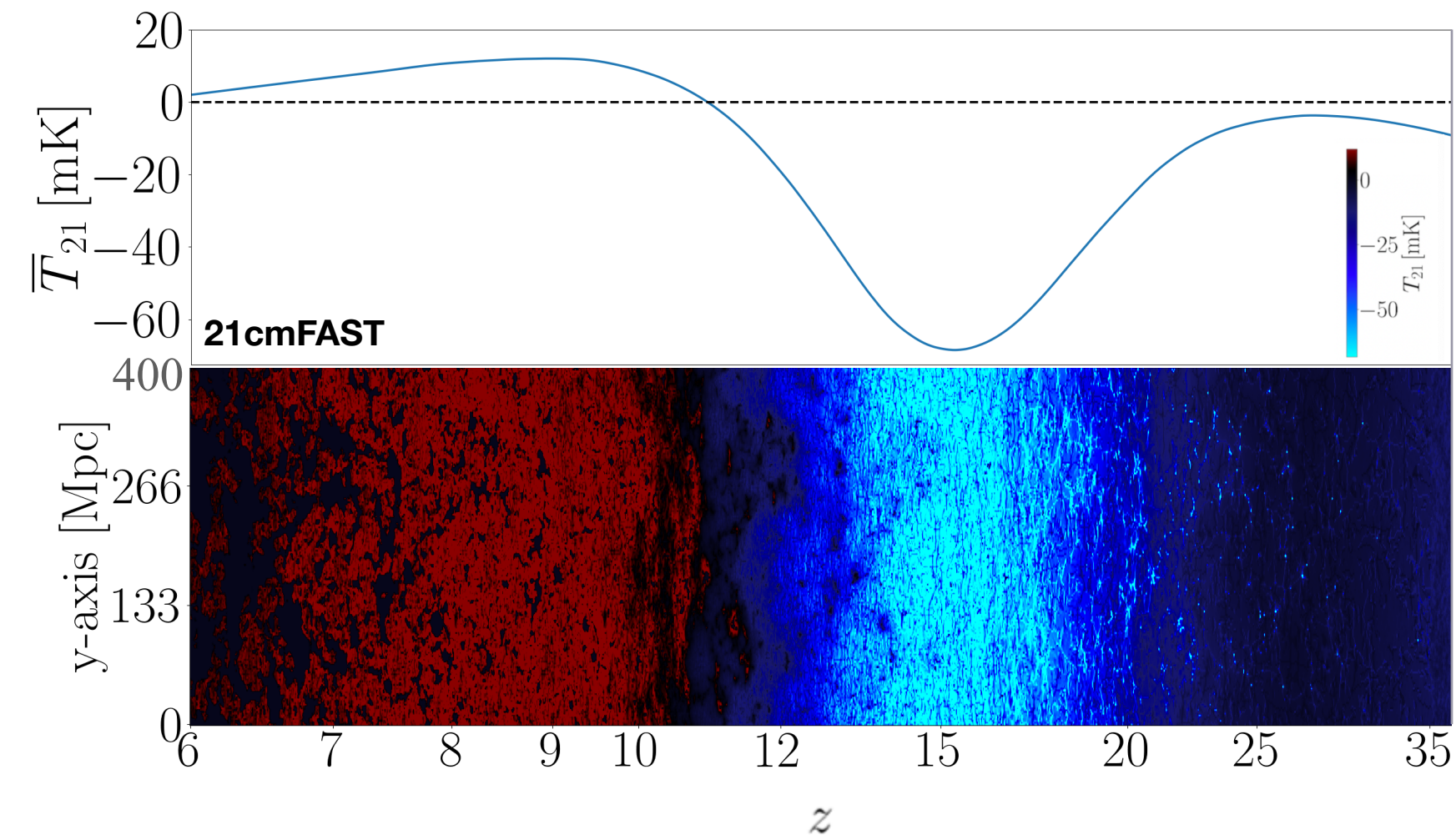
A First-CLASS Code for Cosmology with 21cm



Limitations for new physics:

- Initialized at $z = 35$

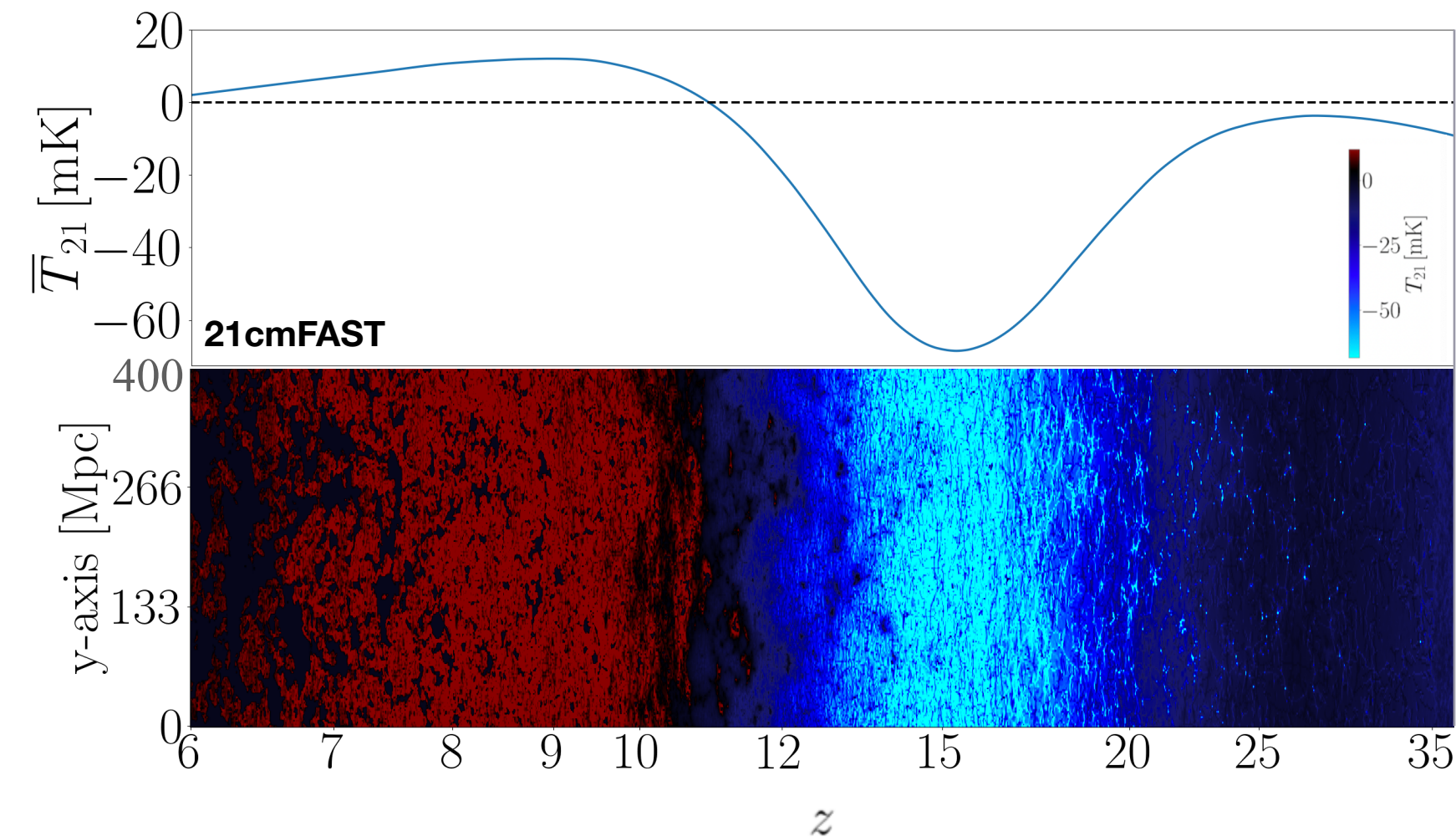
A First-CLASS Code for Cosmology with 21cm



Limitations for new physics:

- Initialized at $z = 35$
- Homogeneous initial boxes

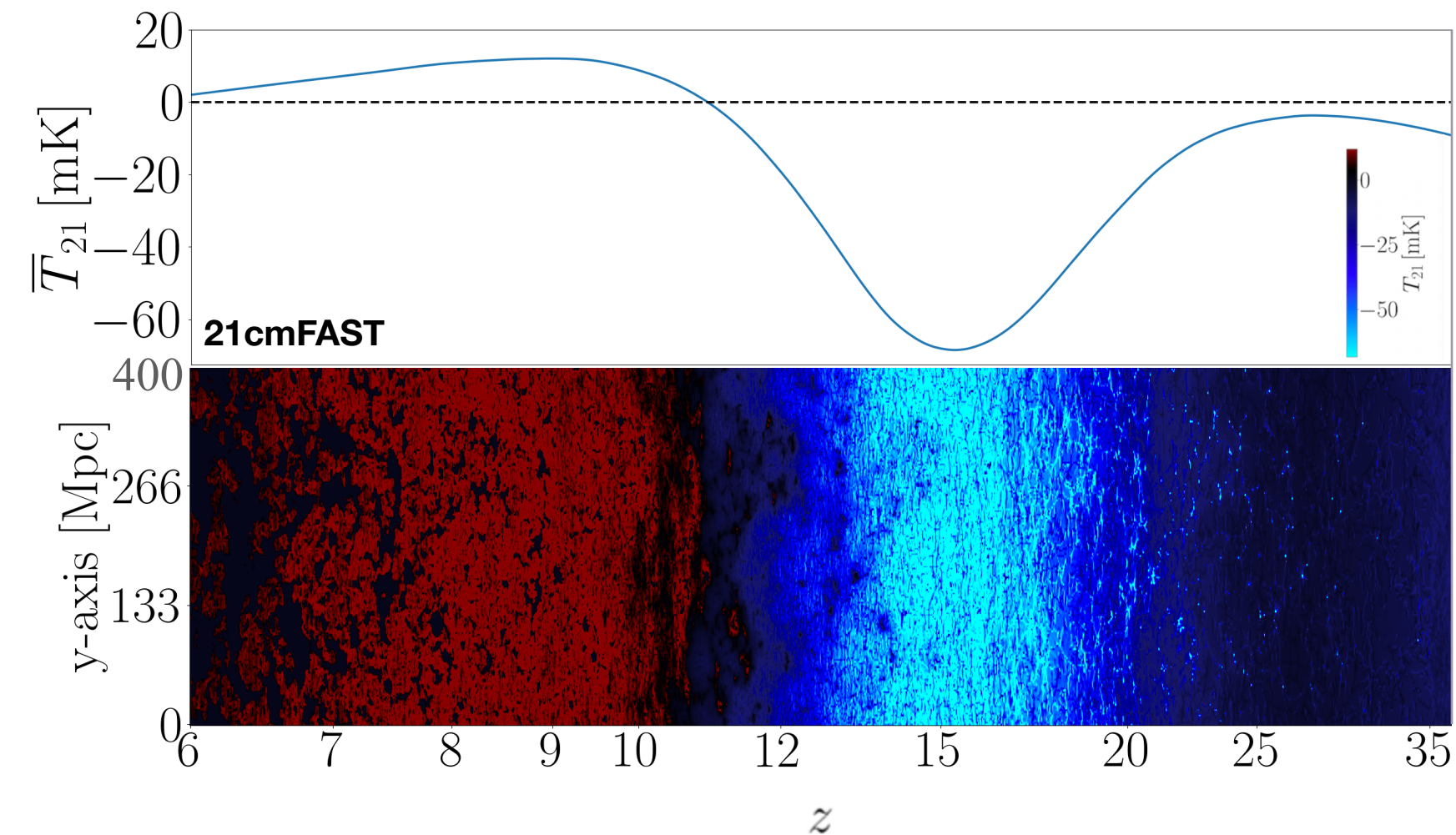
A First-CLASS Code for Cosmology with 21cm



Limitations for new physics:

- Initialized at $z = 35$
- Homogeneous initial boxes
- Assumes $\delta_b = \delta_m$

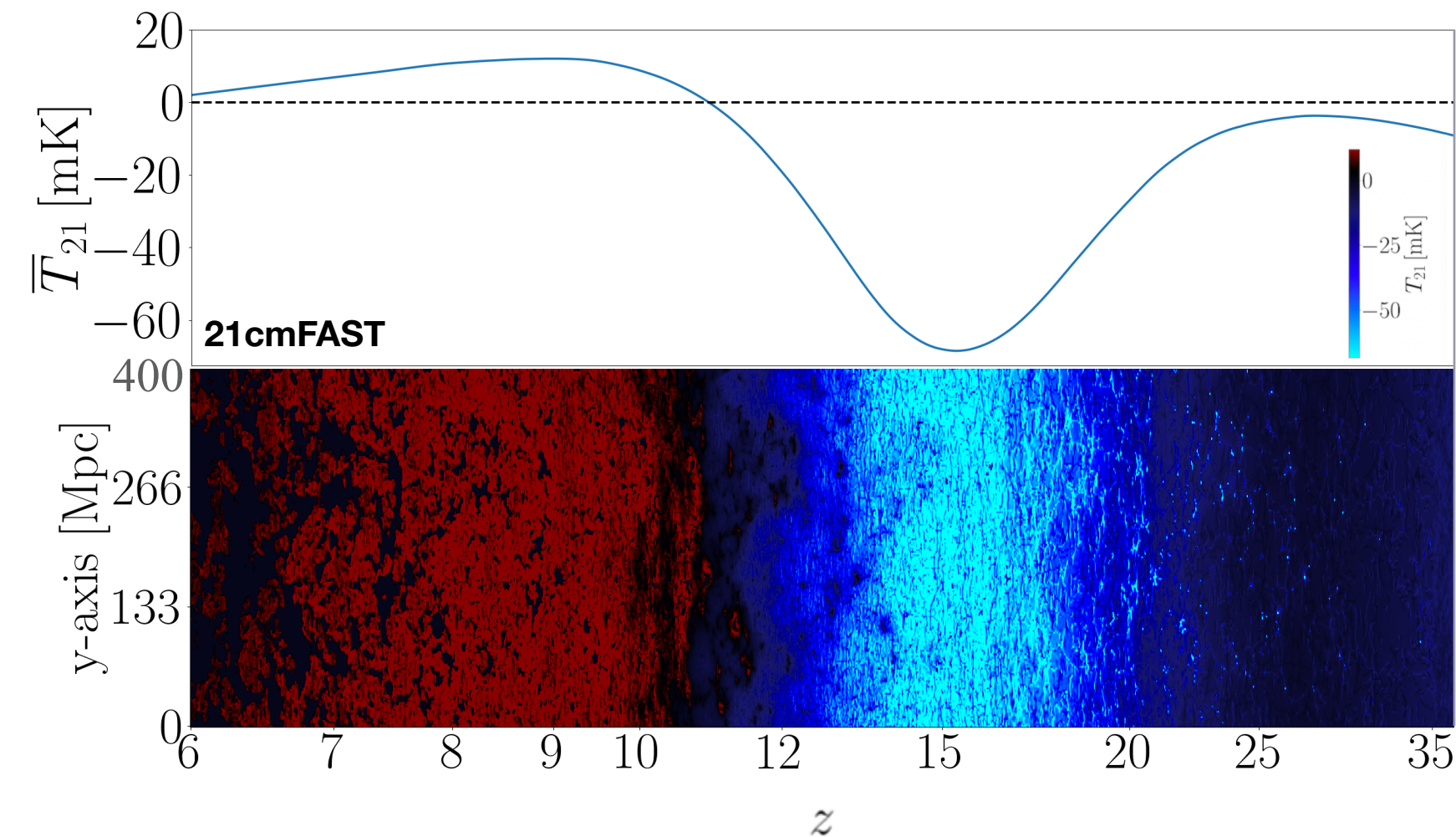
A First-CLASS Code for Cosmology with 21cm



Limitations for new physics:

- Initialized at $z = 35$
- Homogeneous initial boxes
- Assumes $\delta_b = \delta_m$
- Astro-cosmo degeneracy

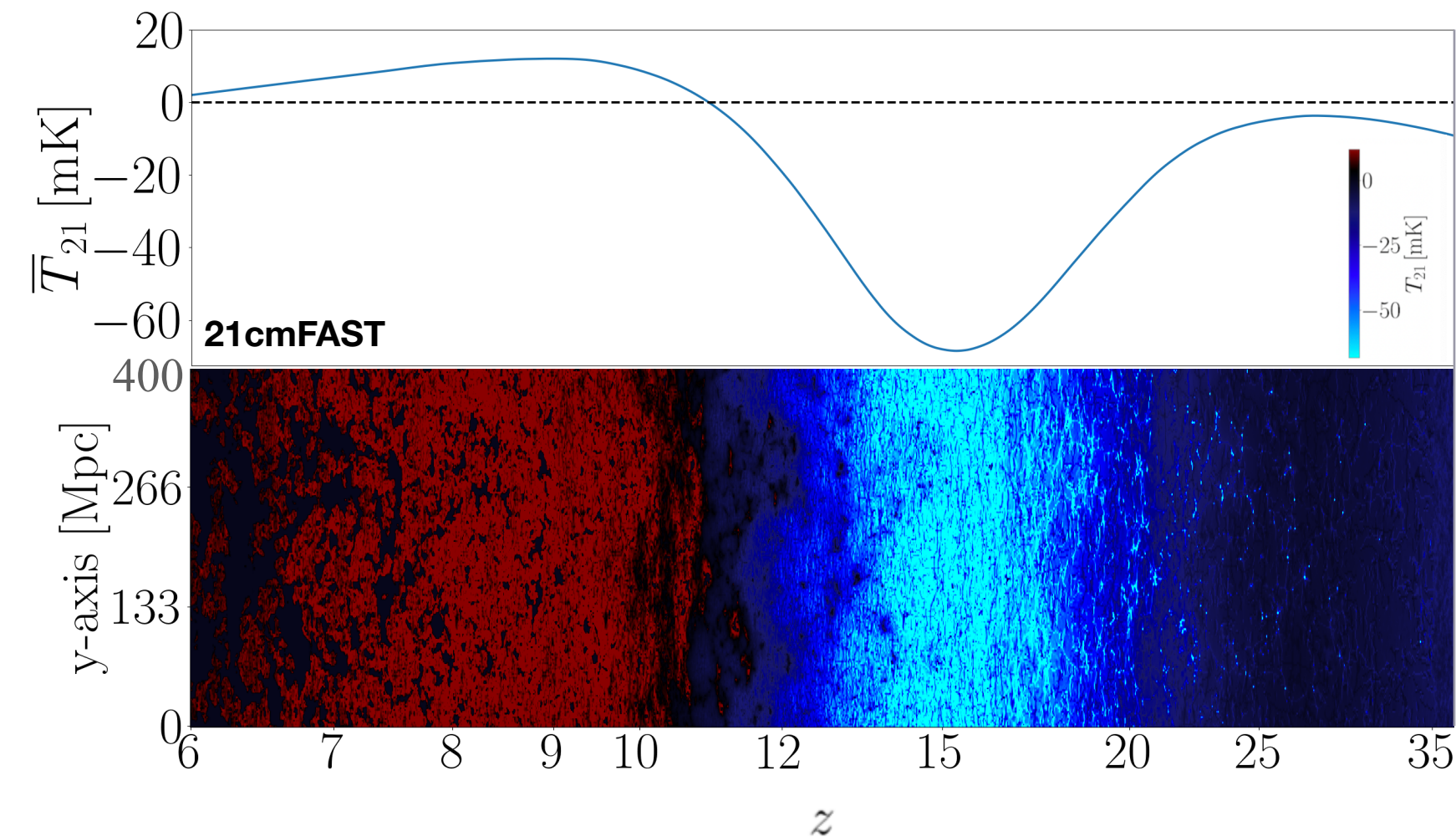
A First-CLASS Code for Cosmology with 21cm



Limitations for new physics:

- Initialized at $z = 35$
- Homogeneous initial boxes
- Assumes $\delta_b = \delta_m$
- Astro-cosmo degeneracy
- Slow in tight coupling regime

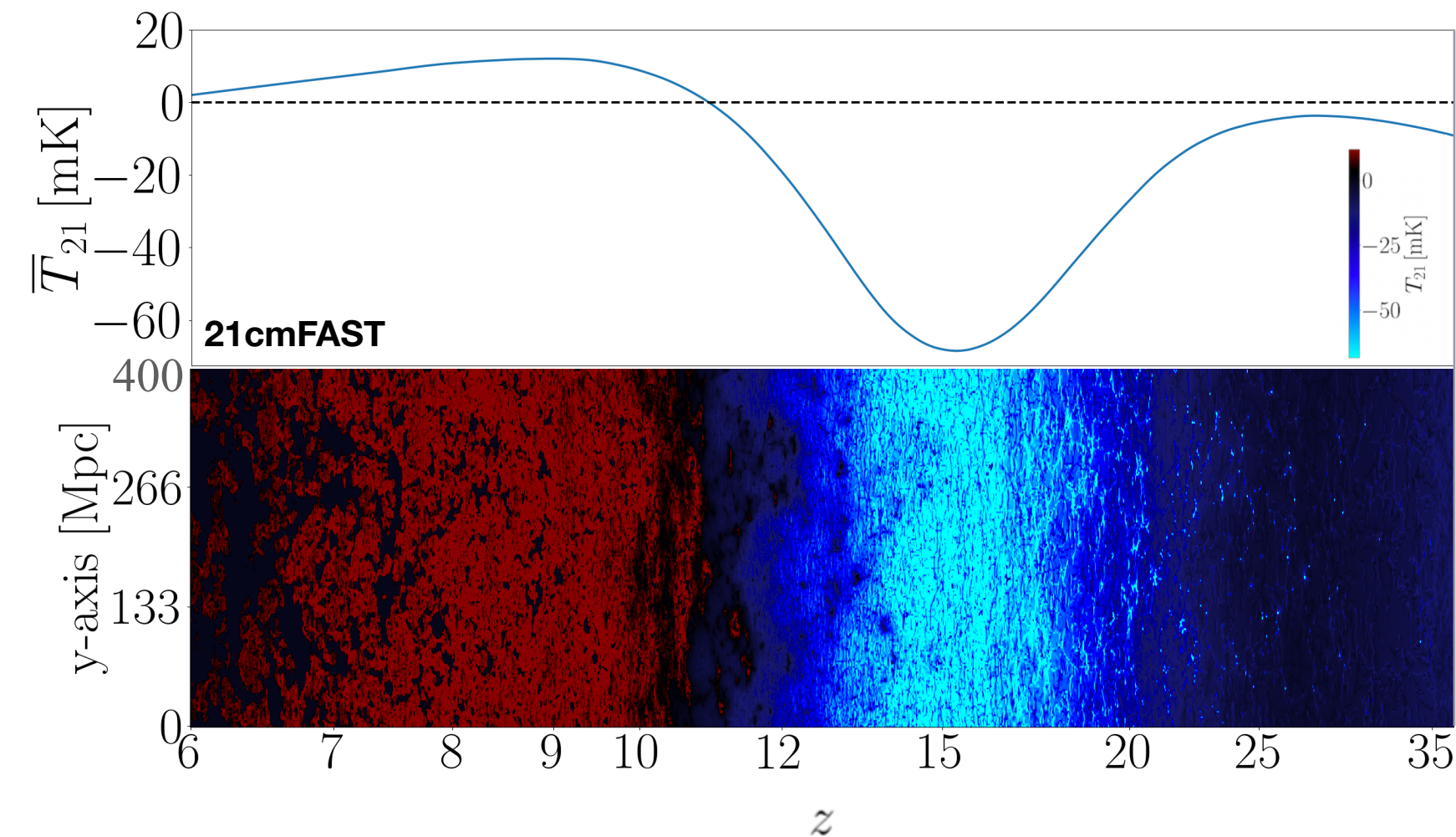
A First-CLASS Code for Cosmology with 21cm



Limitations for new physics:

- Initialized at $z = 35$
- Homogeneous initial boxes
- Assumes $\delta_b = \delta_m$
- Astro-cosmo degeneracy
- Slow in tight coupling regime
e.g. at high redshift:

A First-CLASS Code for Cosmology with 21cm

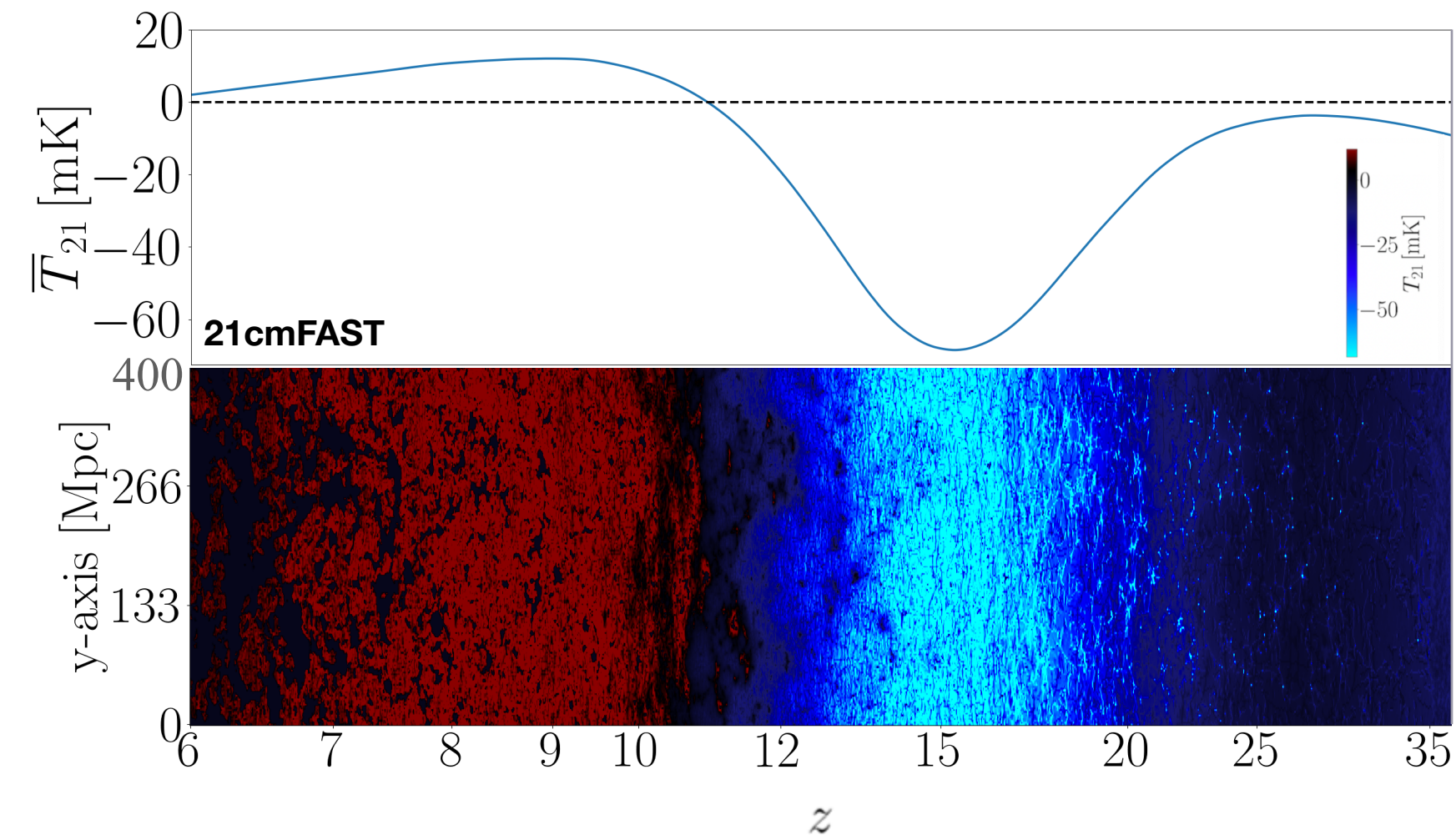


Limitations for new physics:

- Initialized at $z = 35$
- Homogeneous initial boxes
- Assumes $\delta_b = \delta_m$
- Astro-cosmo degeneracy
- Slow in tight coupling regime
e.g. at high redshift:

$$dT_k/dz \propto (\Gamma_C/H) (T_\gamma - T_k)$$

A First-CLASS Code for Cosmology with 21cm

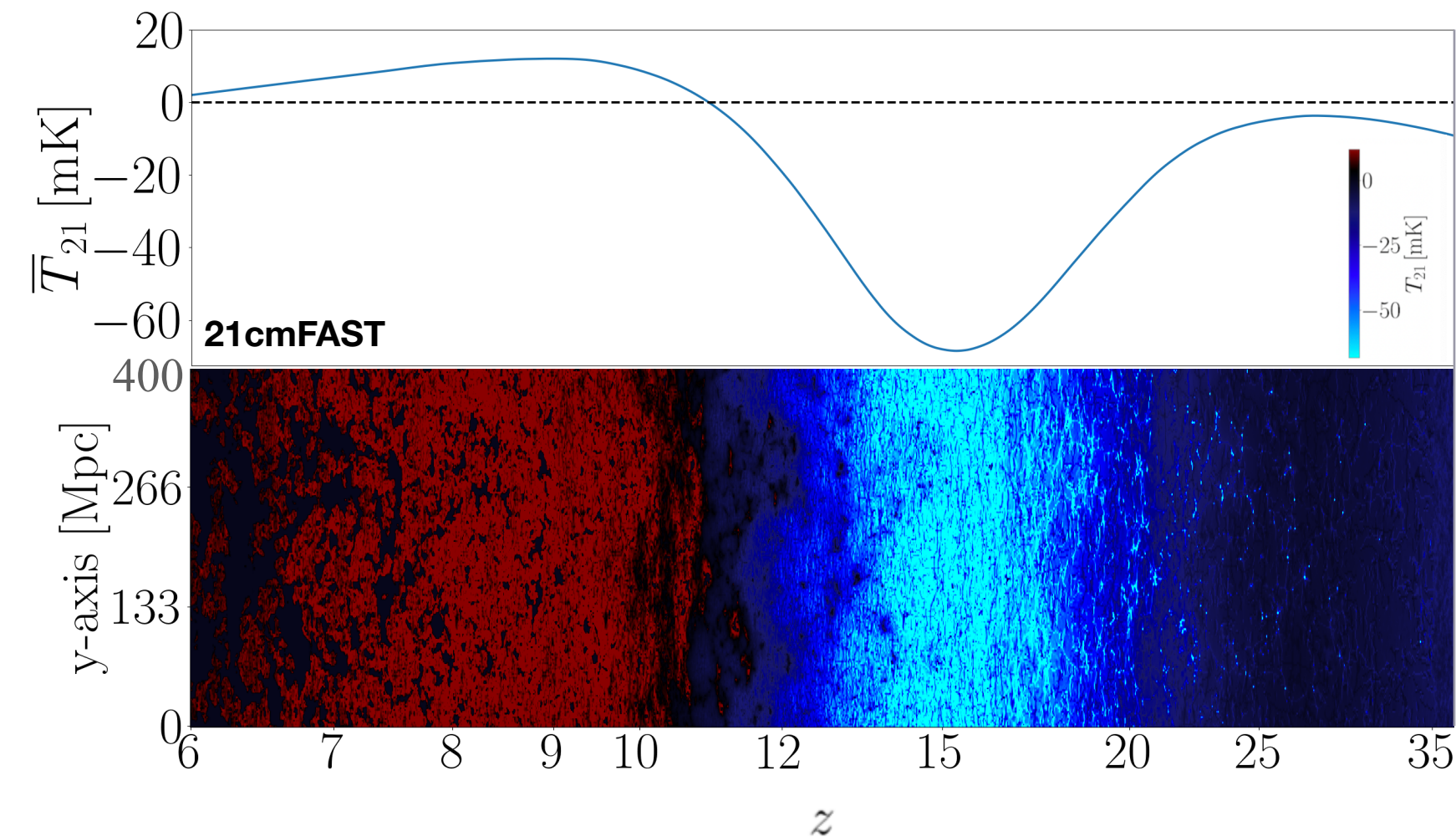


Limitations for new physics:

- Initialized at $z = 35$
- Homogeneous initial boxes
- Assumes $\delta_b = \delta_m$
- Astro-cosmo degeneracy
- Slow in tight coupling regime
e.g. at high redshift:

$$dT_k/dz \propto (\Gamma_C/H) \begin{pmatrix} T_\gamma - T_k \\ \gg 1 & \ll 1 \end{pmatrix}$$

A First-CLASS Code for Cosmology with 21cm



Limitations for new physics:

- Initialized at $z = 35$
- Homogeneous initial boxes
- Assumes $\delta_b = \delta_m$
- Astro-cosmo degeneracy
- Slow in tight coupling regime
e.g. at high redshift:

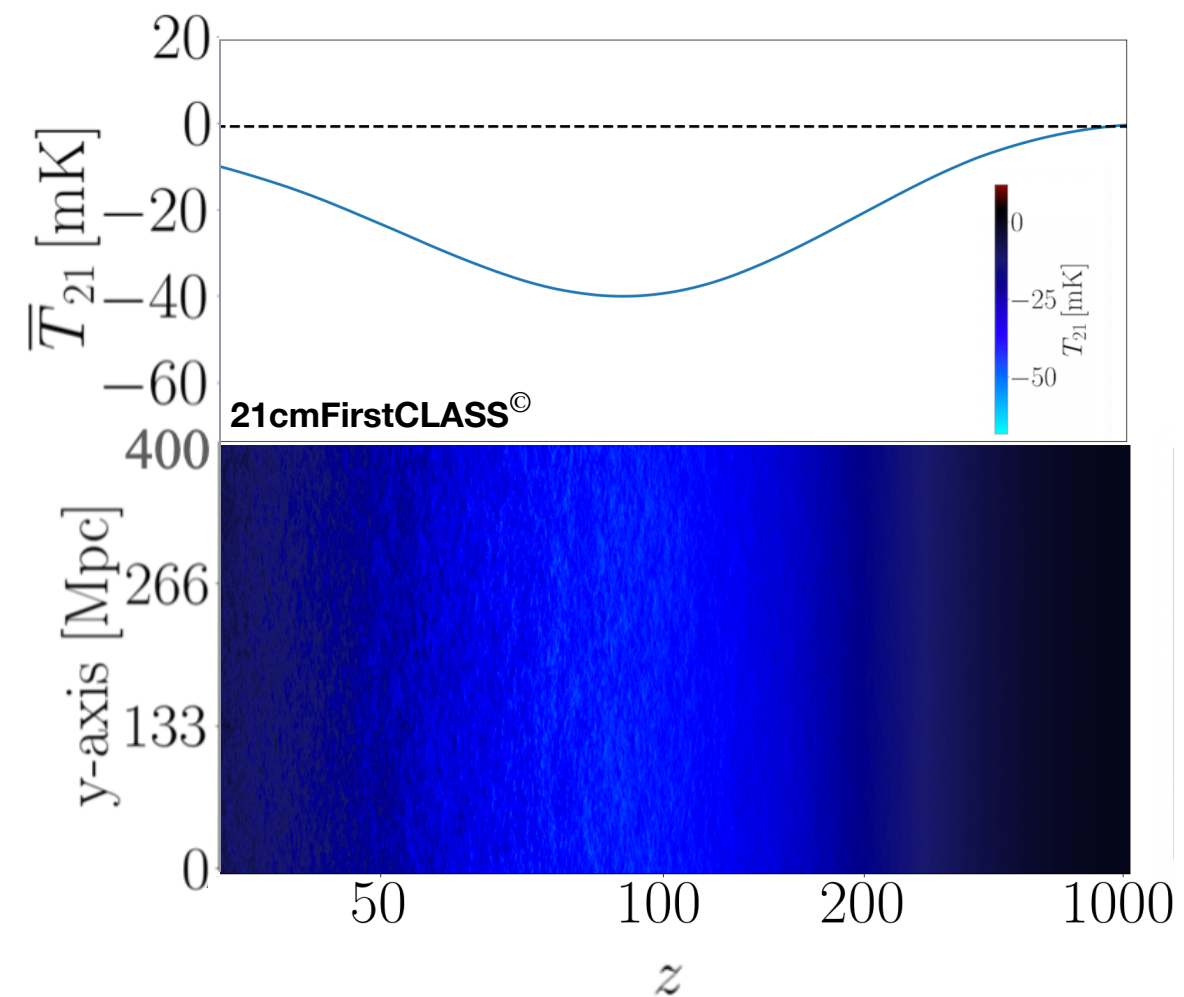
$$dT_k/dz \propto (\Gamma_C/H) \begin{pmatrix} T_\gamma - T_k \\ \gg 1 & \ll 1 \end{pmatrix}$$

→ requires $\Delta z \ll 1$ to solve

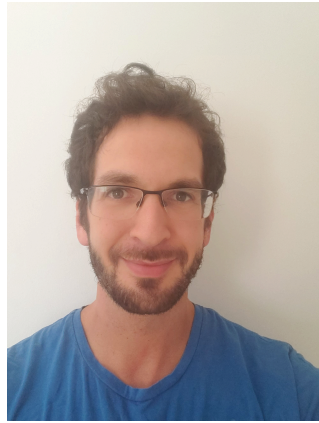
A First-CLASS Code for Cosmology with 21cm

Solution:

- Use initial conditions from a Boltzmann solver
 - Initialize with CLASS at $z = 1100$
- Calculate accurate recombination history
 - Incorporate Hyrec into the code
- Consistently track $\delta_b, \delta_m, \nu_{cb}, T_{\{i\}}$ evolution
 - Inhomogeneous boxes at $z = 35$
- Fold-in cosmic microwave background
 - Combined CMB+21cm constraints
- Astrophysical vs. cosmological effects
 - Explore parameter degeneracies
- Slow? (need $\Delta z \ll 1$ at Compton tight coupling)
 - Perturb in $\epsilon_{\gamma b} = H/\Gamma_C$, and solve for $\epsilon_{\gamma b}, \Delta T_{\gamma b}, \bar{T}_{\gamma b}$



A First-CLASS Code for Cosmology with 21cm



J. Flitter

21cmFirstCLASS I. Cosmological tool for Λ CDM and beyond

Jordan Flitter^{1,*} and Ely D. Kovetz¹

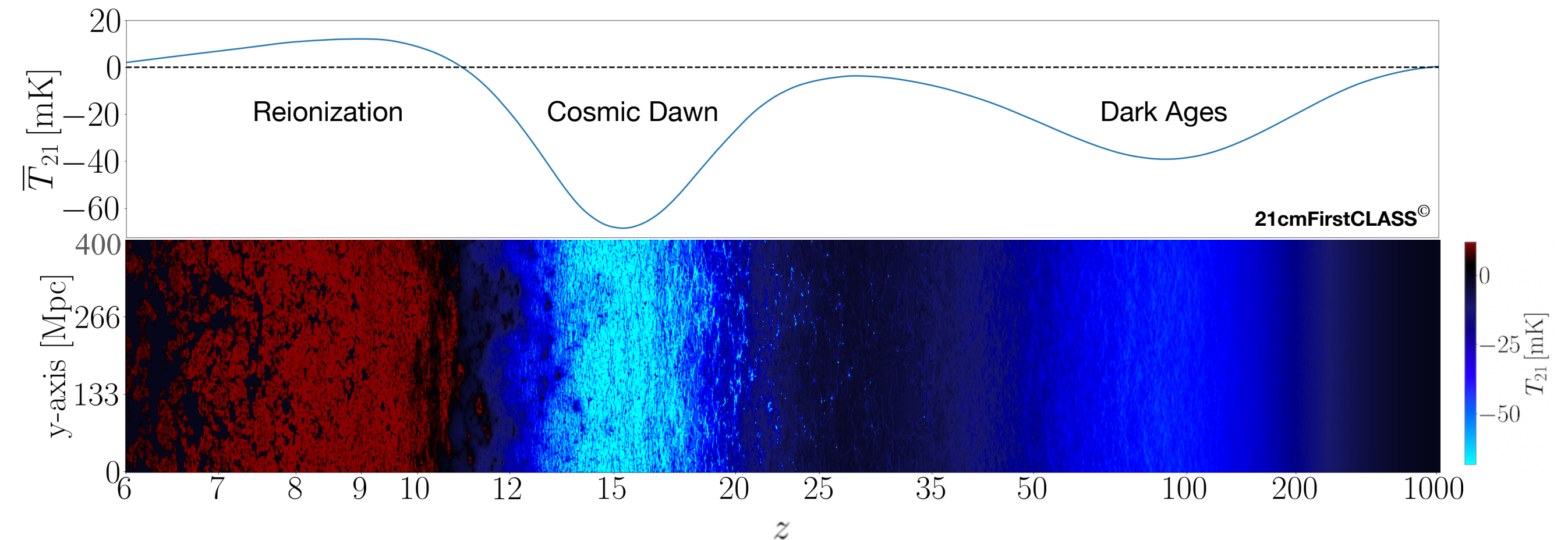
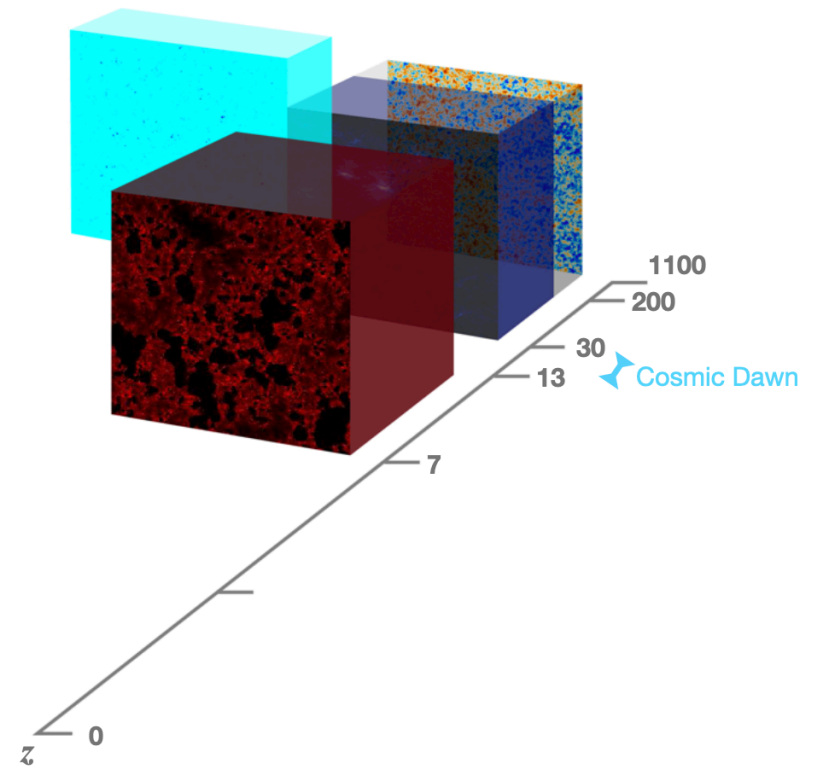
¹*Physics Department, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel*

21cmFirstCLASS II. Early linear fluctuations of the 21cm signal

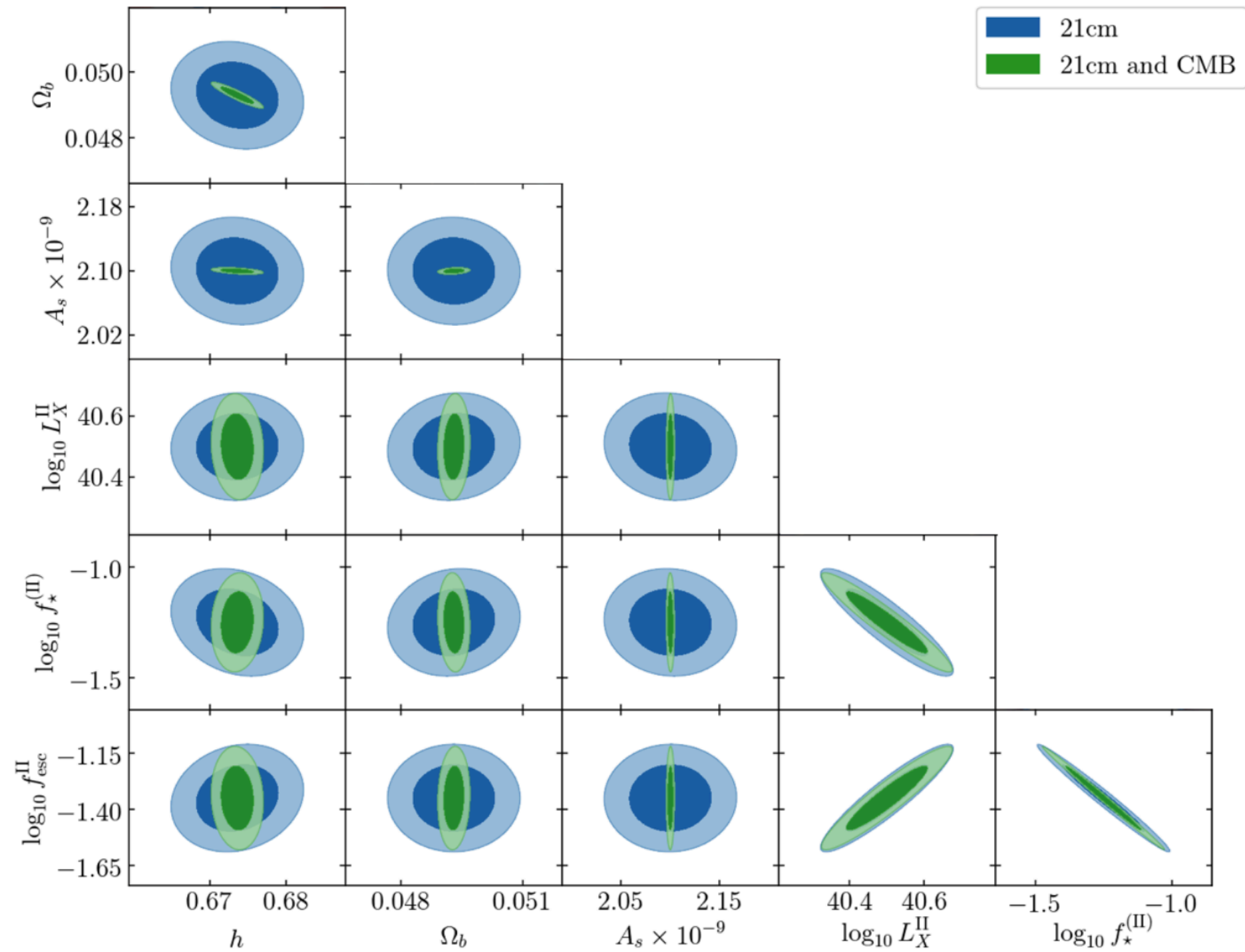
Jordan Flitter^{1,*} and Ely D. Kovetz¹

¹*Physics Department, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel*

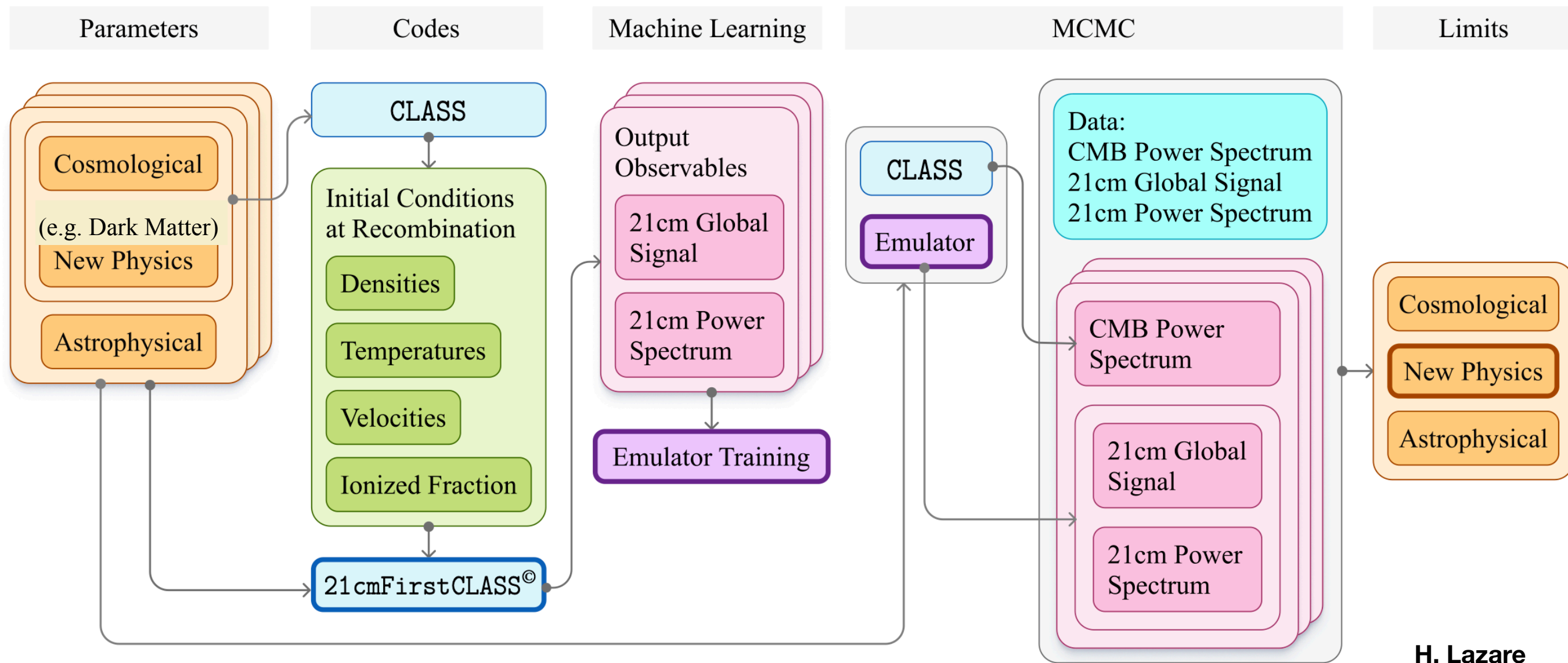
Find it on Github: <https://github.com/jordanflitter/21cmFirstCLASS>



A First-CLASS Code for Cosmology with 21cm



An End-to-End ML Pipeline for 21cm Analysis

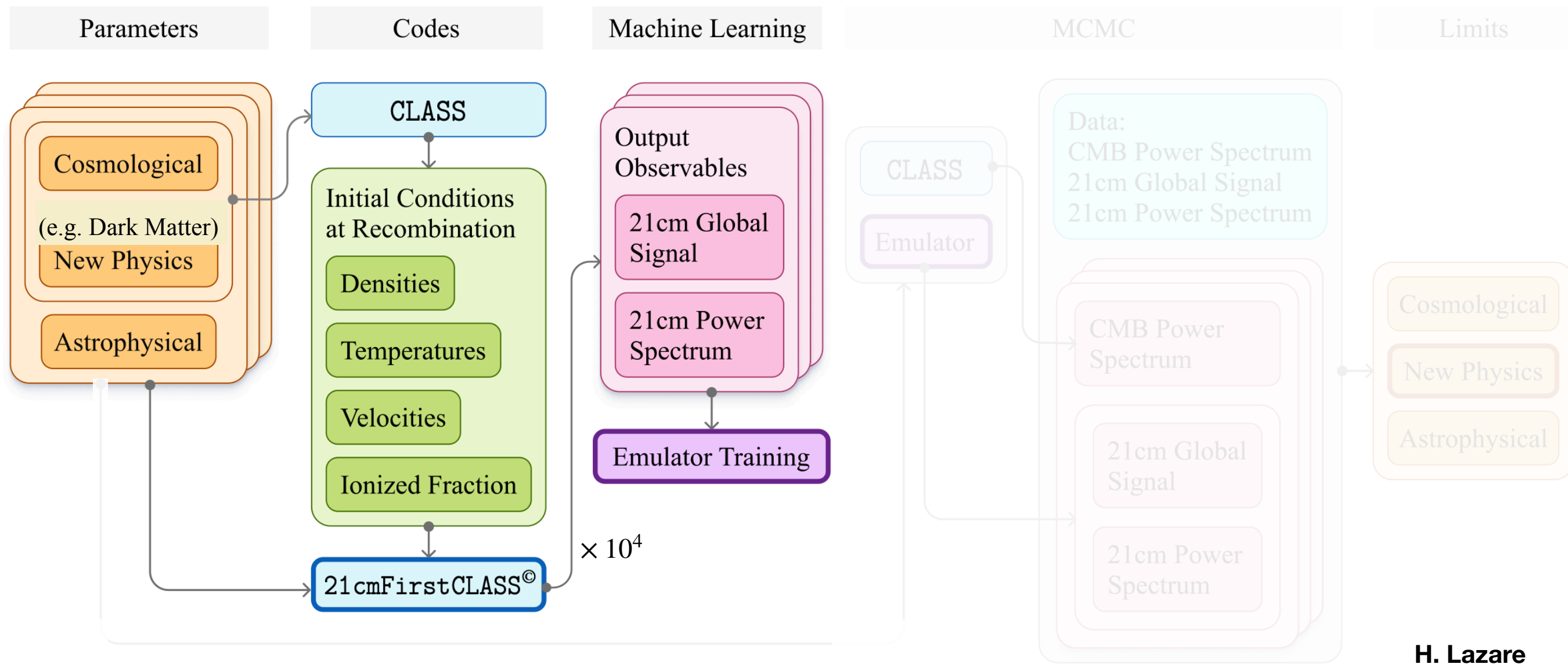


Lazare, Sarkar and Kovetz, PRD 2023; Lazare, Flitter and Kovetz, PRD 2024

H. Lazare



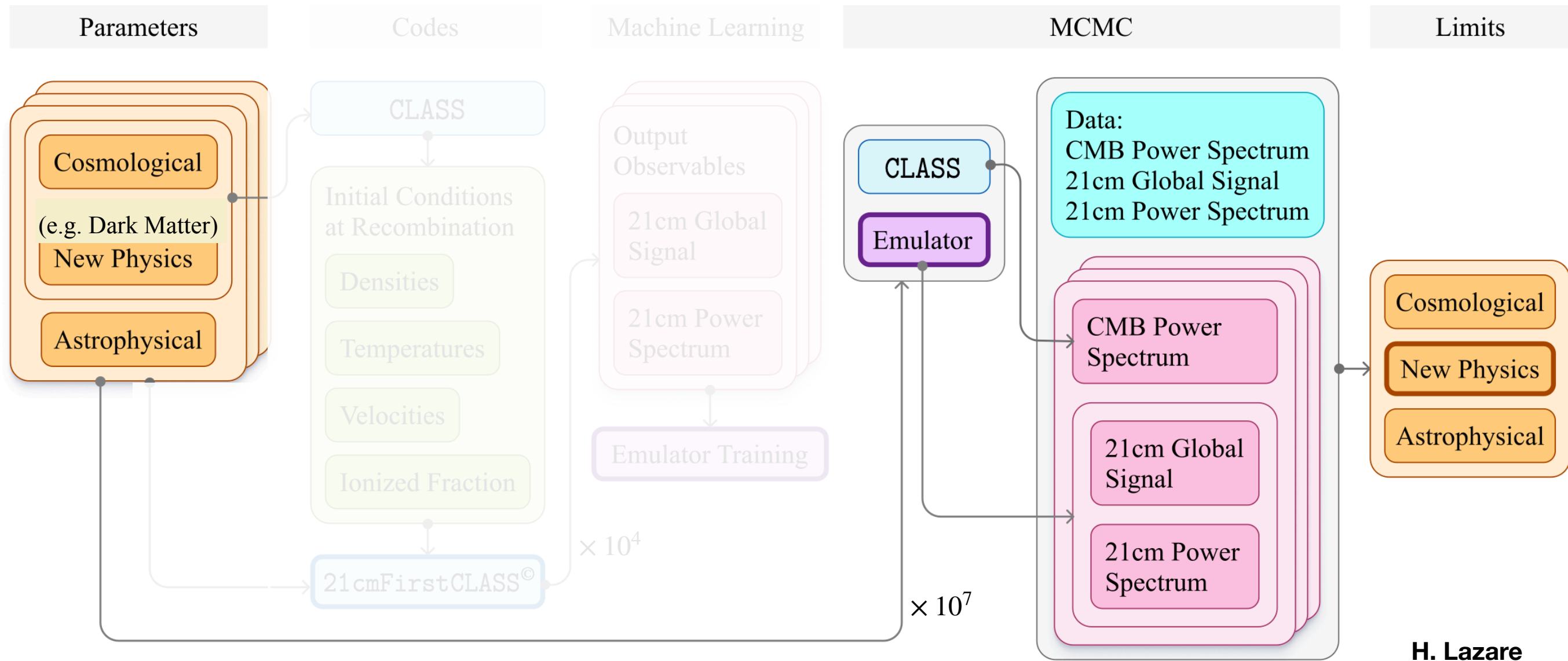
An End-to-End ML Pipeline for 21cm Analysis



H. Lazare



An End-to-End ML Pipeline for 21cm Analysis



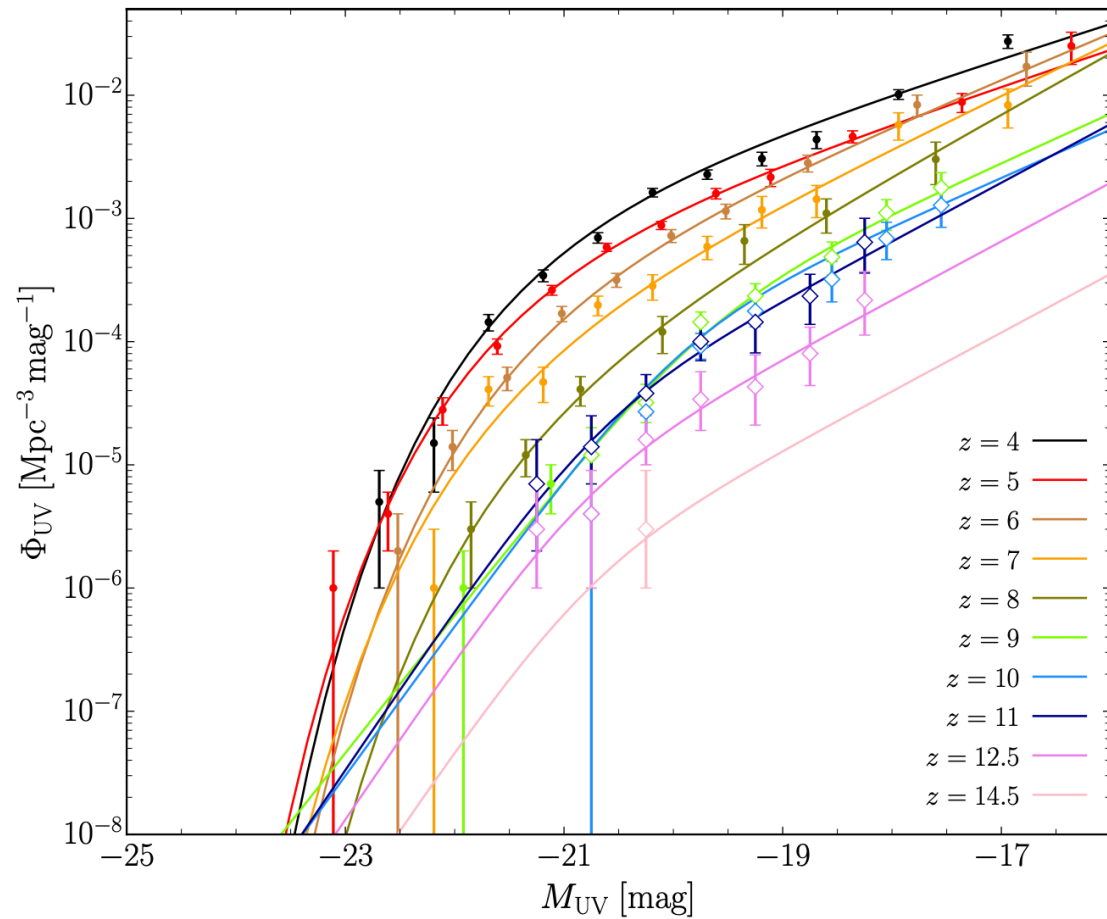
Lazare, Sarkar and Kovetz, PRD 2023; Lazare, Flitter and Kovetz, PRD 2024

H. Lazare



New: 21cm+CMB+UVLFs+EoR

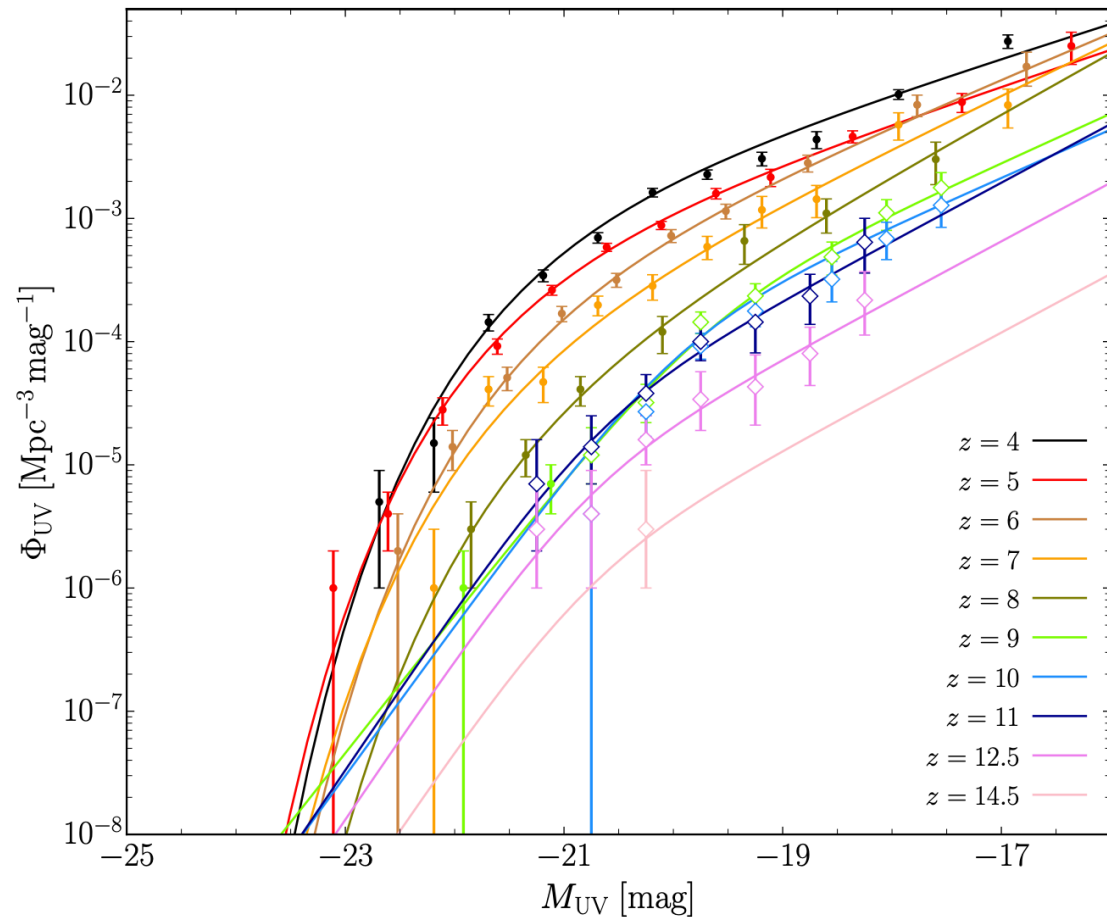
UVLFs from HST and JWST



Liu et al., ApJ 2024

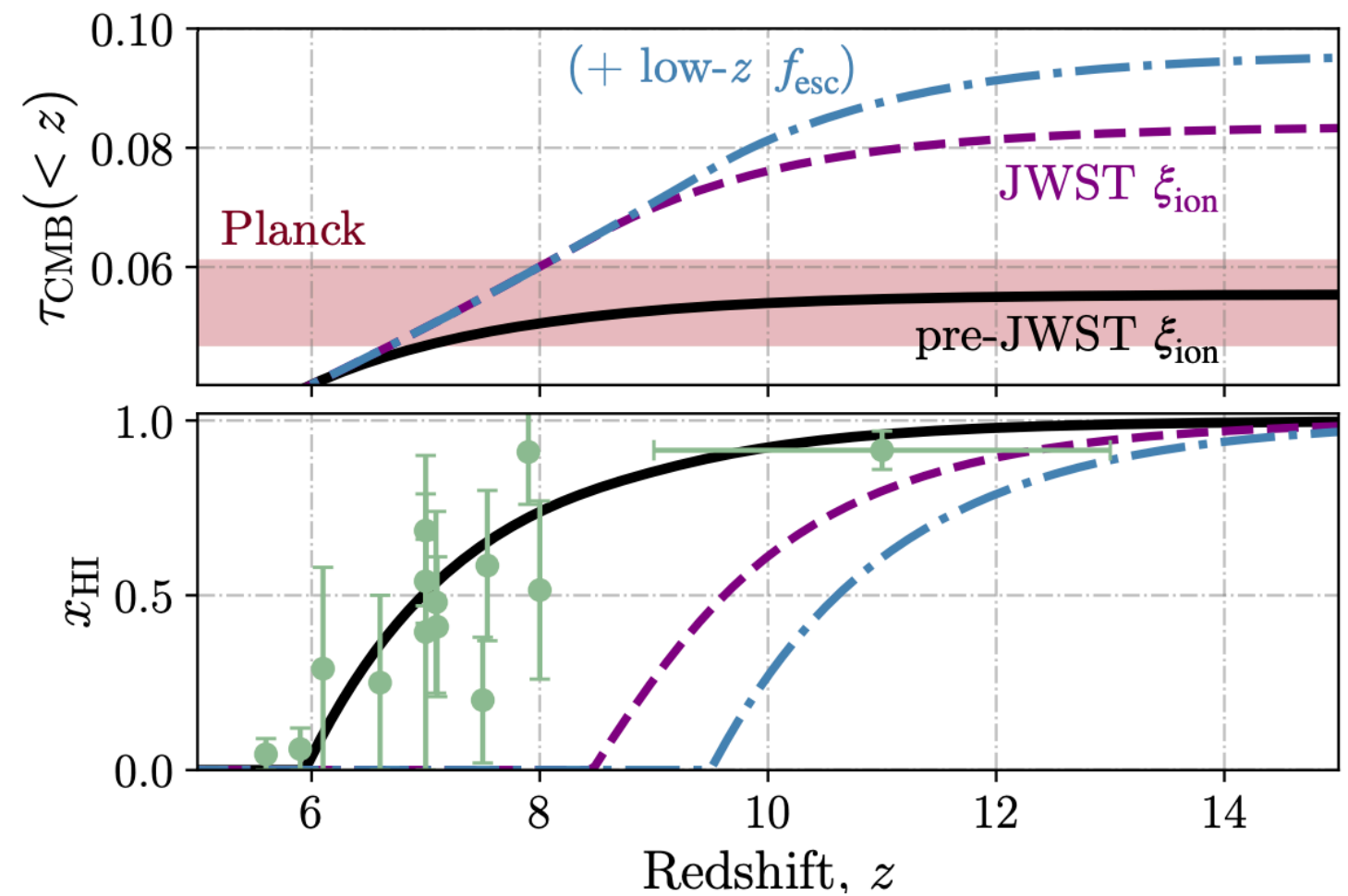
New: 21cm+CMB+UVLFs+EoR

UVLFs from HST and JWST



Liu et al., ApJ 2024

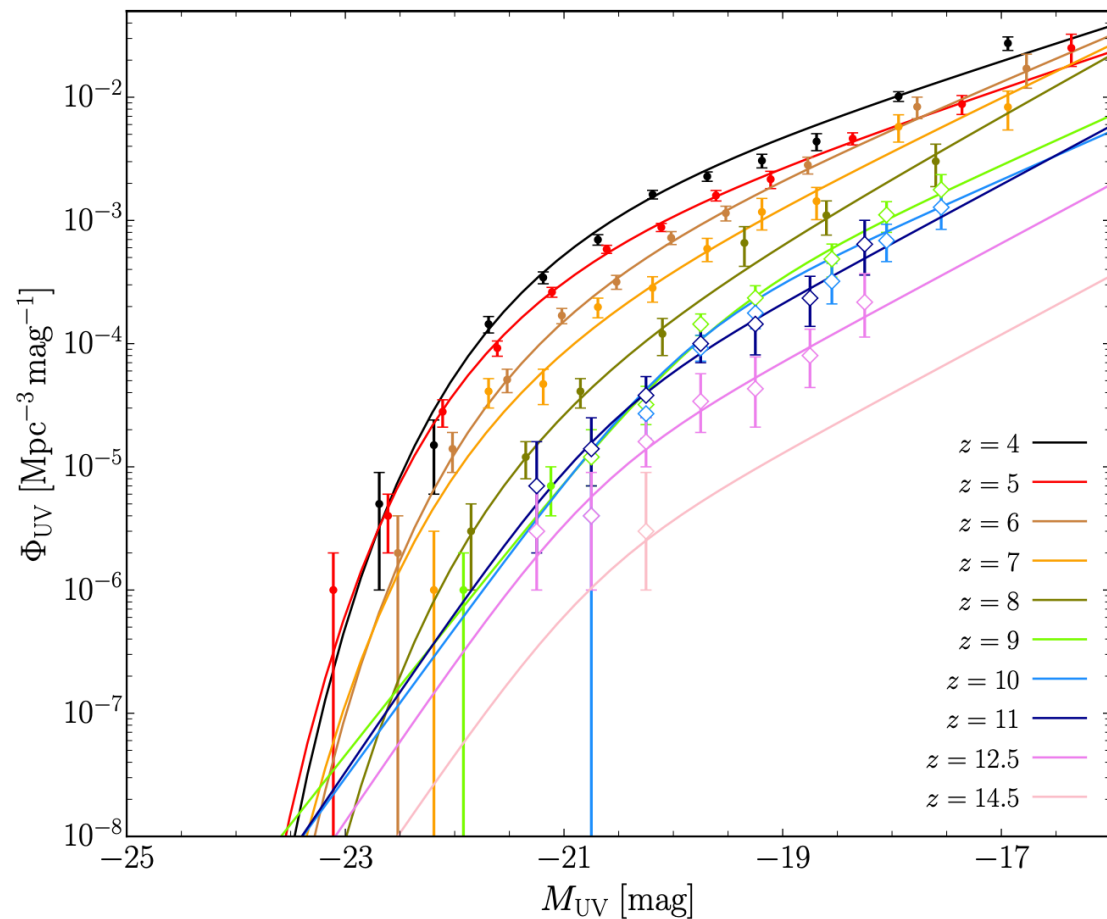
Optical depth and neutral fraction



Munoz et al., MNRAS 2024

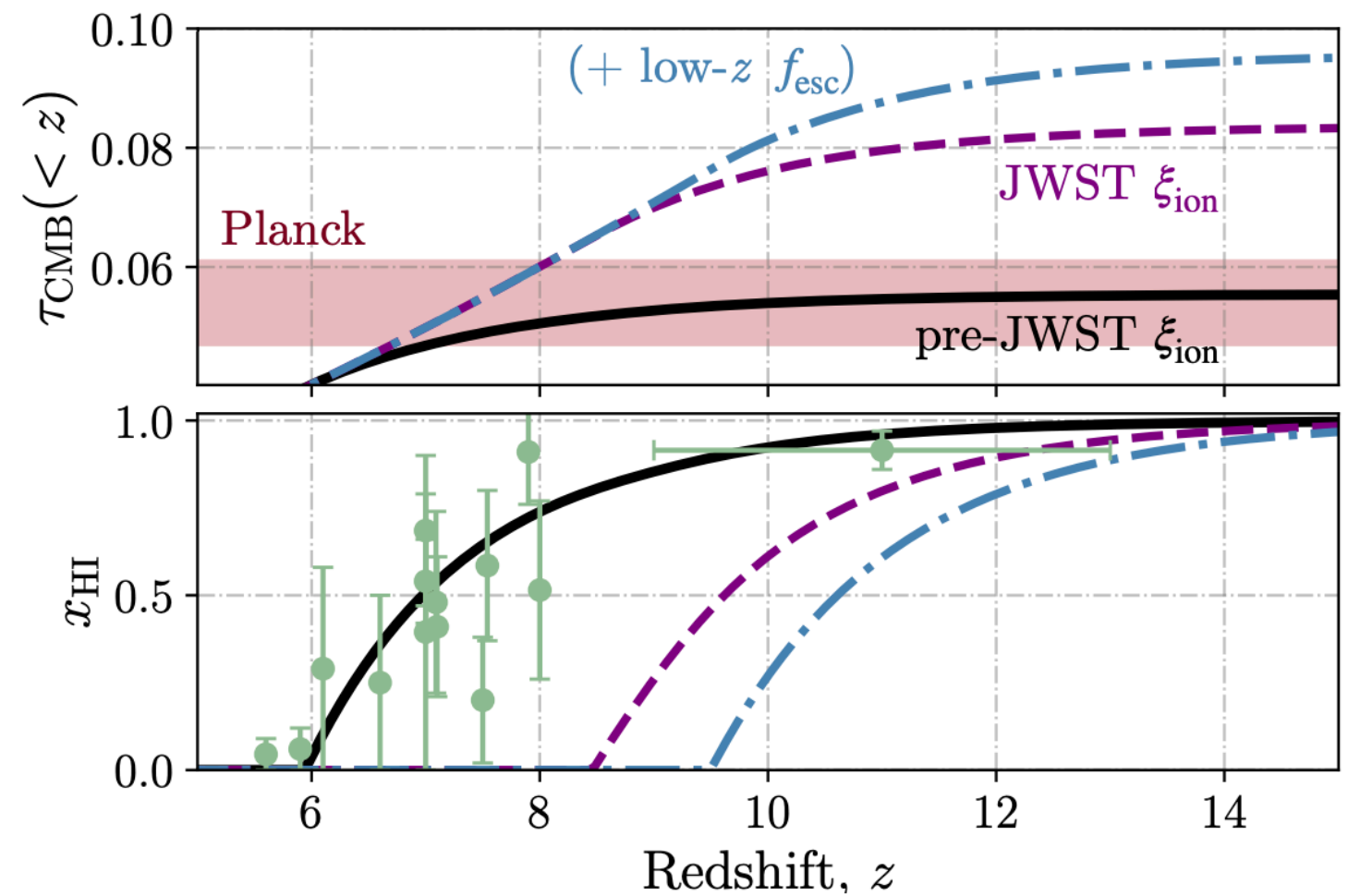
New: 21cm+CMB+UVLFs+EoR

UVLFs from HST and JWST



Liu et al., ApJ 2024

Optical depth and neutral fraction



Munoz et al., MNRAS 2024

21cmFirstCLASS can consistently simulate all these observables!

New: 21cm+CMB+UVLFs+EoR

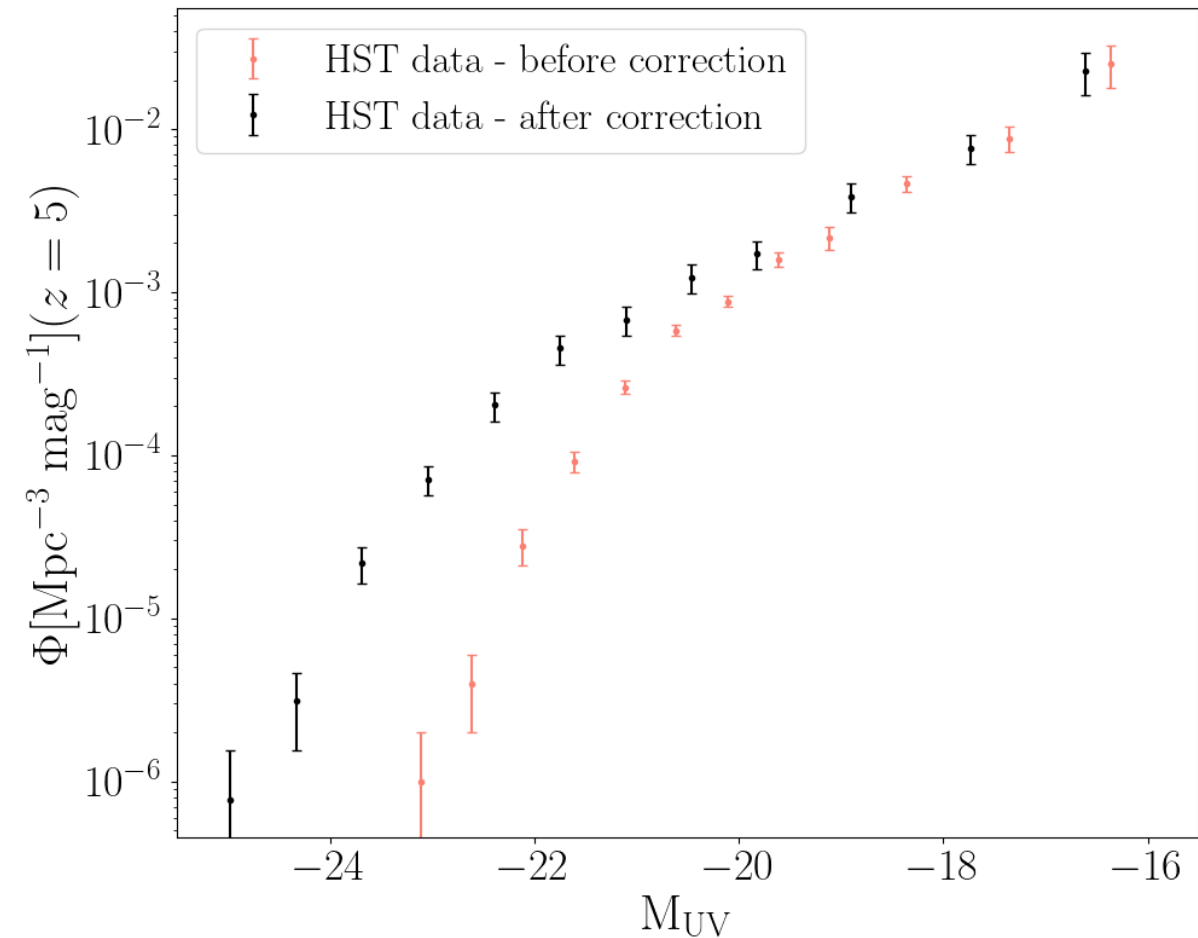
- UVLF data reevaluated to account for:

(a la GALLUMI, by Sabti et al., PRD 2022)

1. Cosmic variance (20% error added)

2. Dust attenuation

3. Alcock-Paczynski effect (observed volume corrected)



H. Lazare



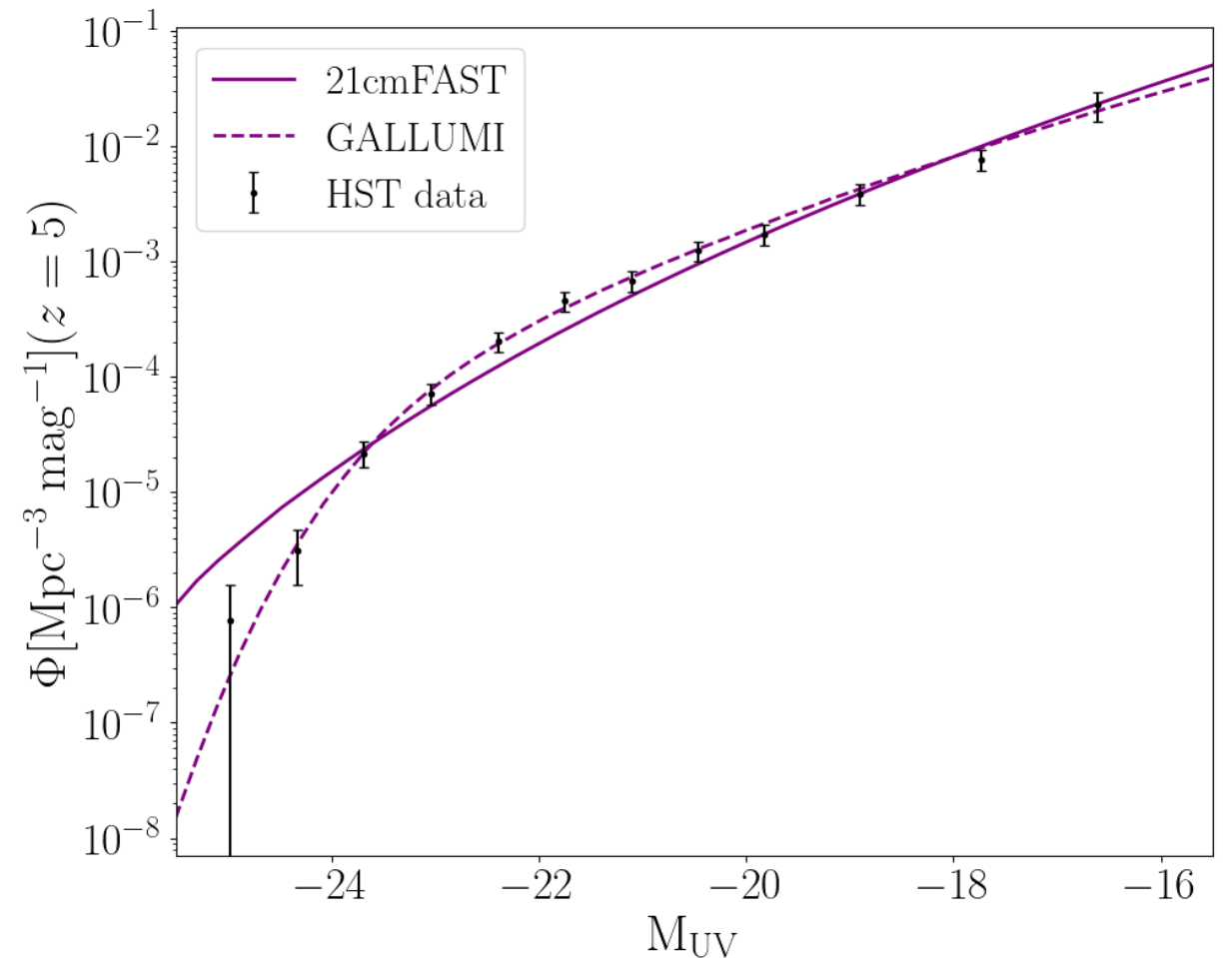
New: 21cm+CMB+UVLFs+EoR

- Stellar-to-halo mass relation updated to capture high luminosity UVLFs

$$\frac{M_*}{M_h} = f_{*,10} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_*} \left(\frac{\Omega_b}{\Omega_m} \right)$$



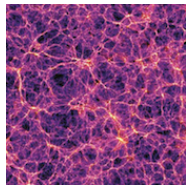
$$\frac{M_*}{M_h} = \frac{\epsilon_*}{\left(\frac{M_h}{M_p} \right)^{\alpha_*} + \left(\frac{M_h}{M_p} \right)^{\beta_*}}$$



$$\log_{10} \epsilon_*(z) = \epsilon_*^i + \epsilon_*^s \times \log_{10} \left(\frac{1+z}{1+6} \right) \quad \log_{10} \frac{M_p(z)}{M_\odot} = M_p^i + M_p^s \times \log_{10} \left(\frac{1+z}{1+6} \right)$$

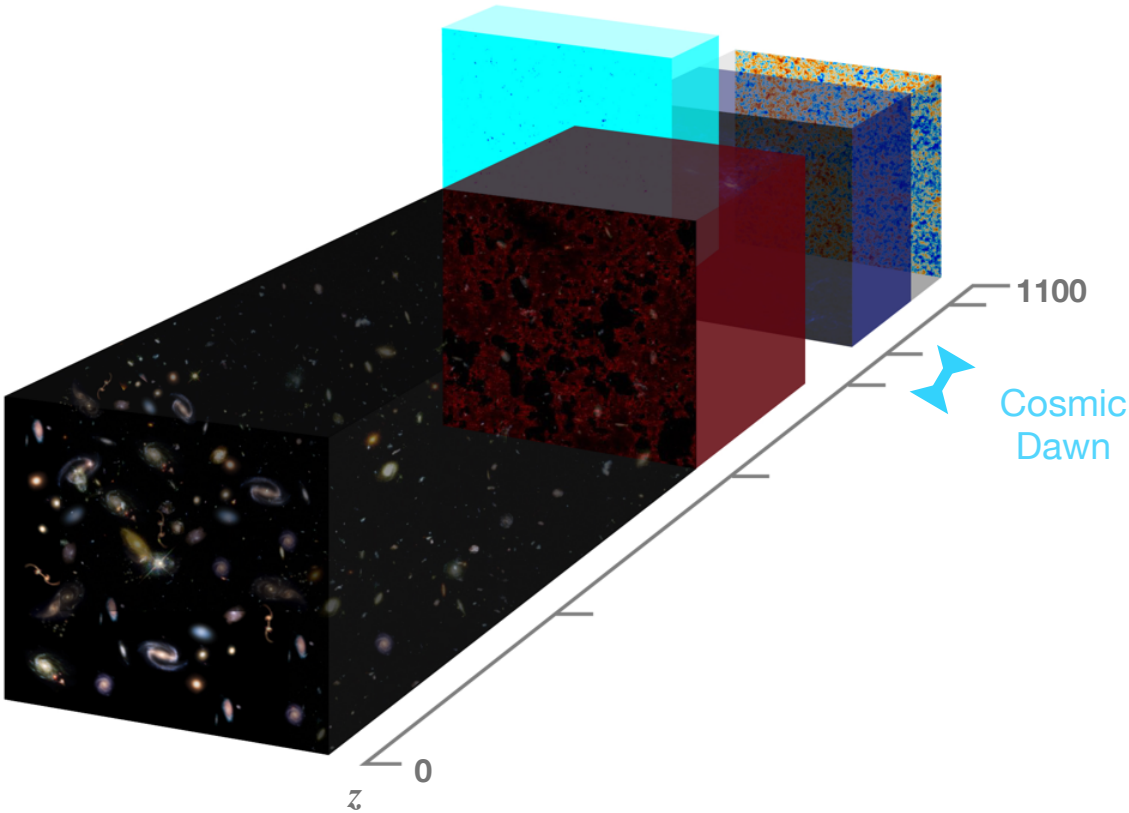
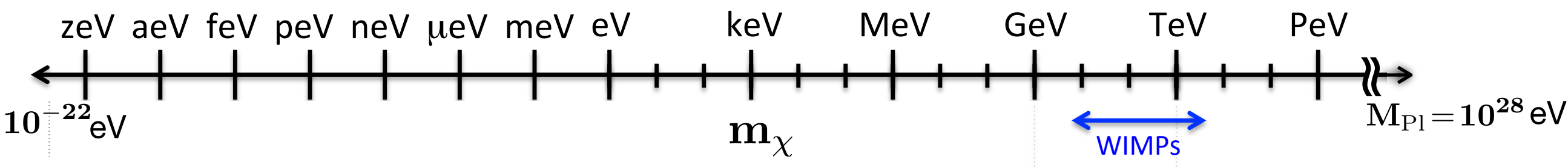
H. Lazare

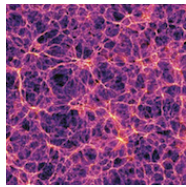




Cosmic Dawn Cosmology: Fuzzy Dark Matter

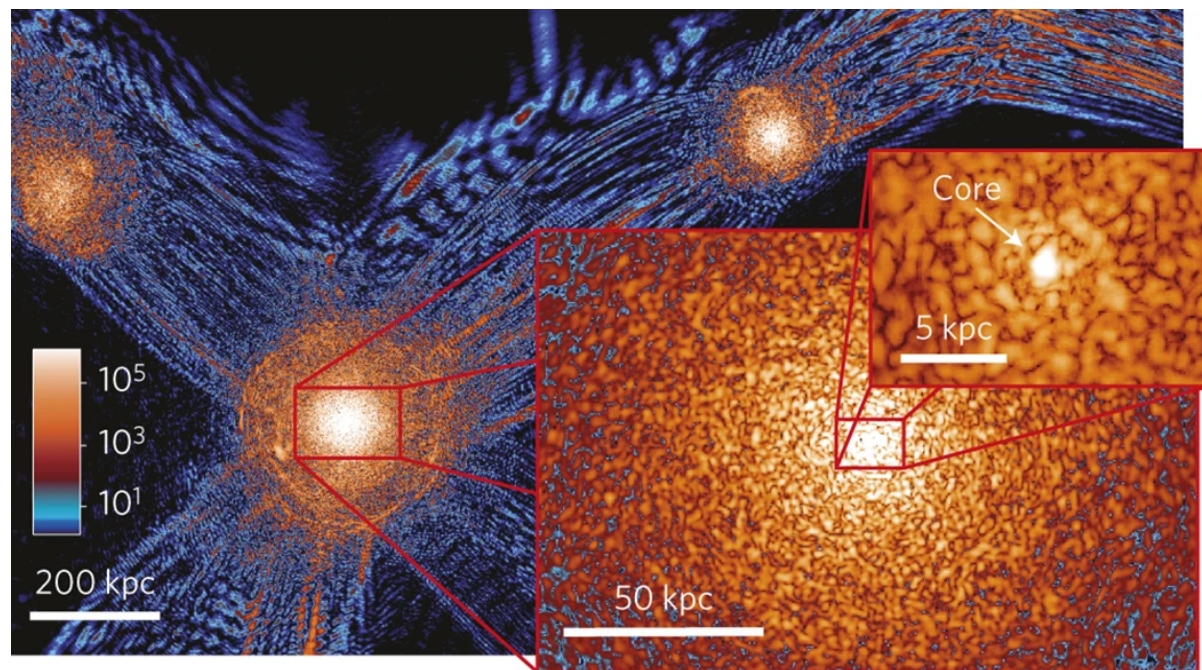
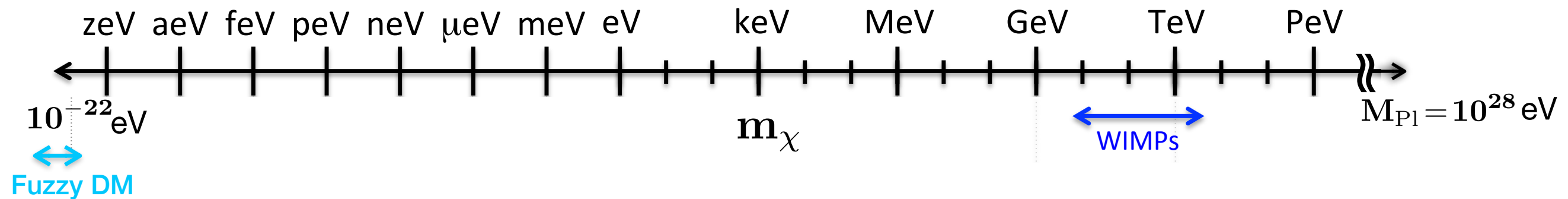
(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)



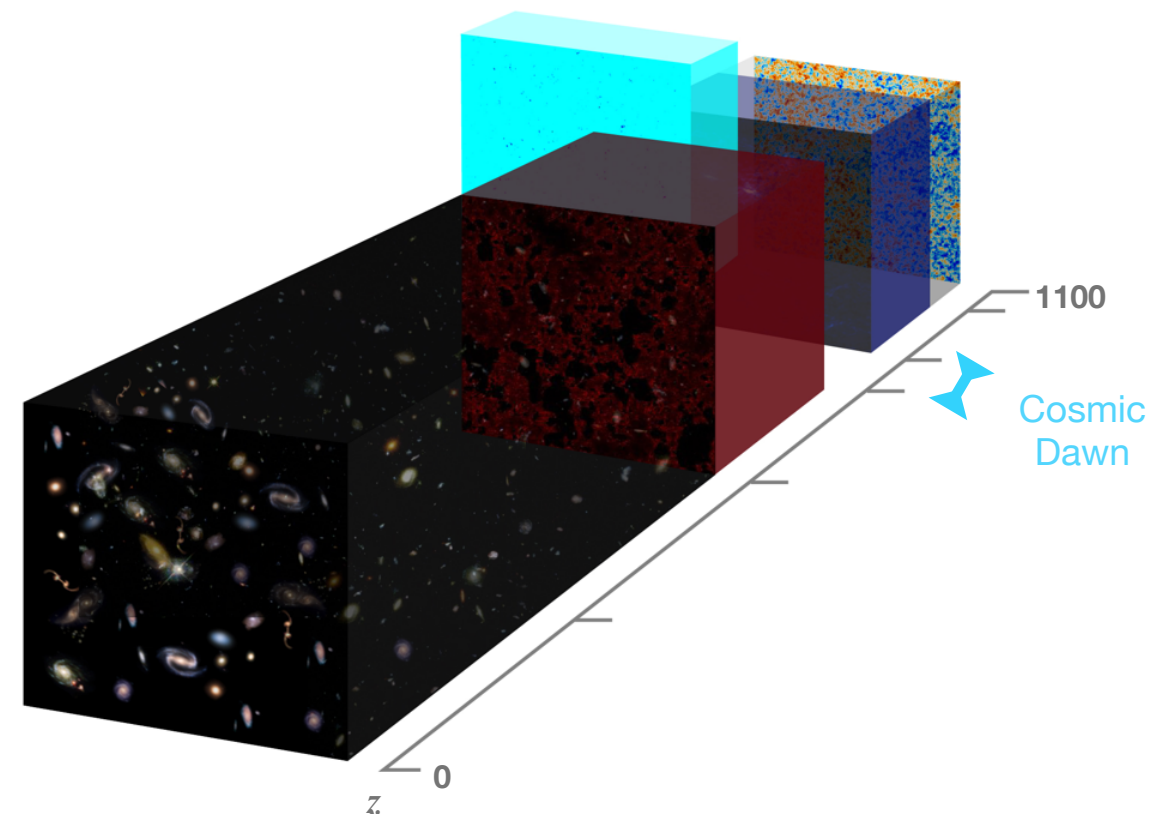


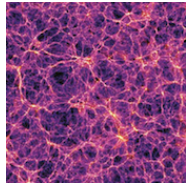
Cosmic Dawn Cosmology: Fuzzy Dark Matter

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)



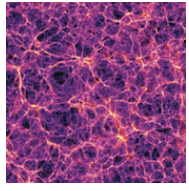
Schive et al, Nature 2014





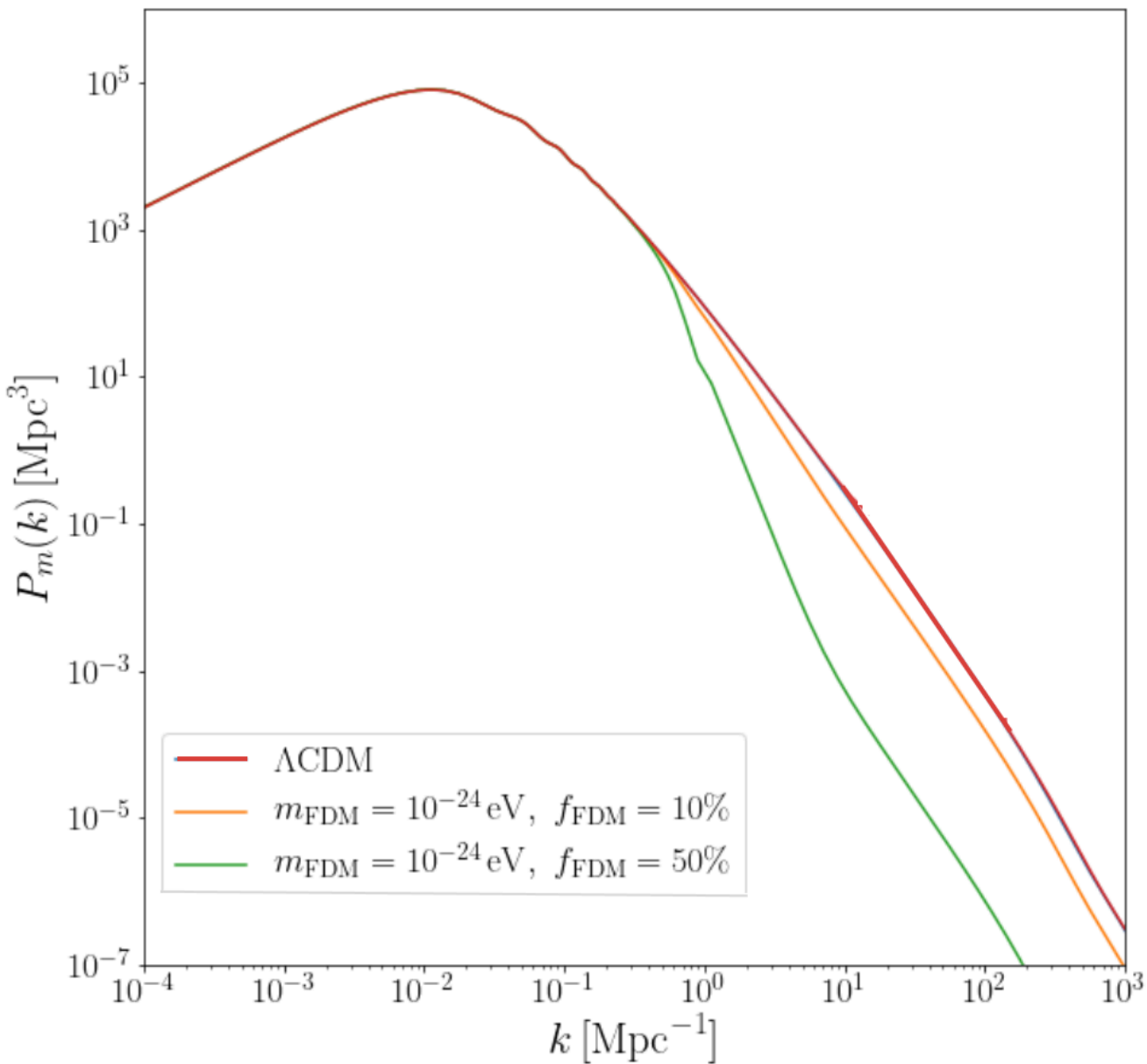
Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ delays the 21cm signal

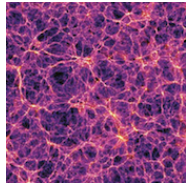


Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ delays the 21cm signal

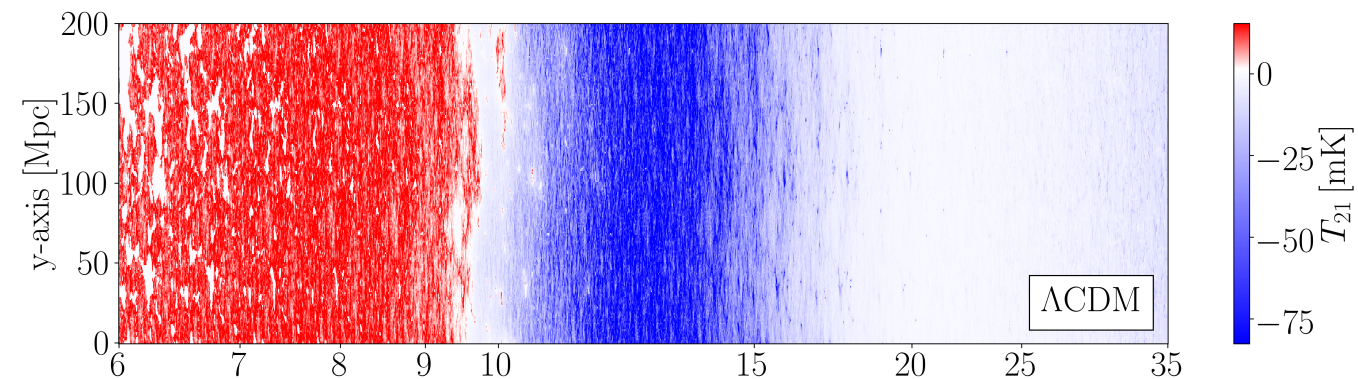
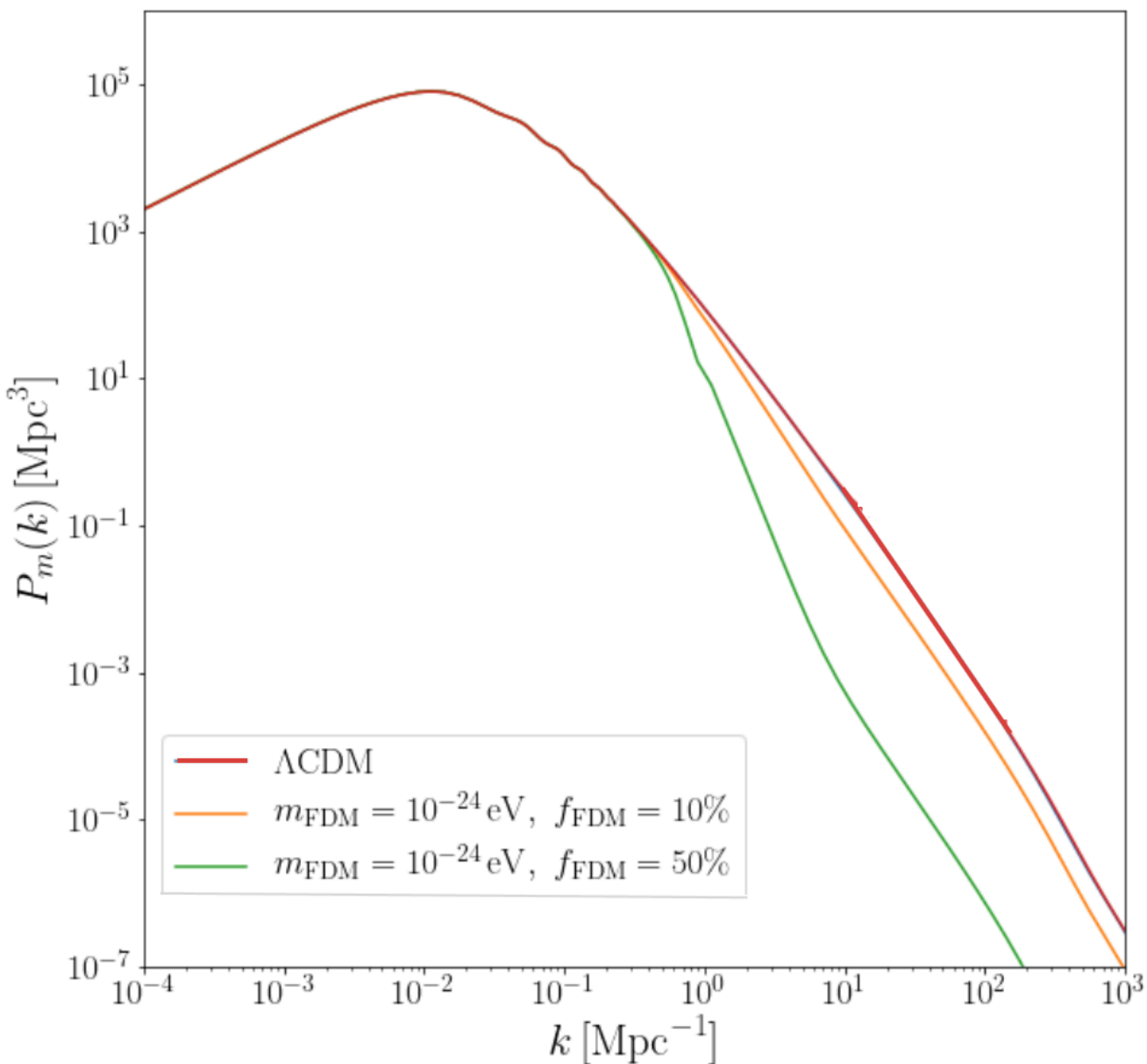


Flitter and Kovetz, PRD 2022

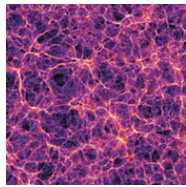


Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ delays the 21cm signal

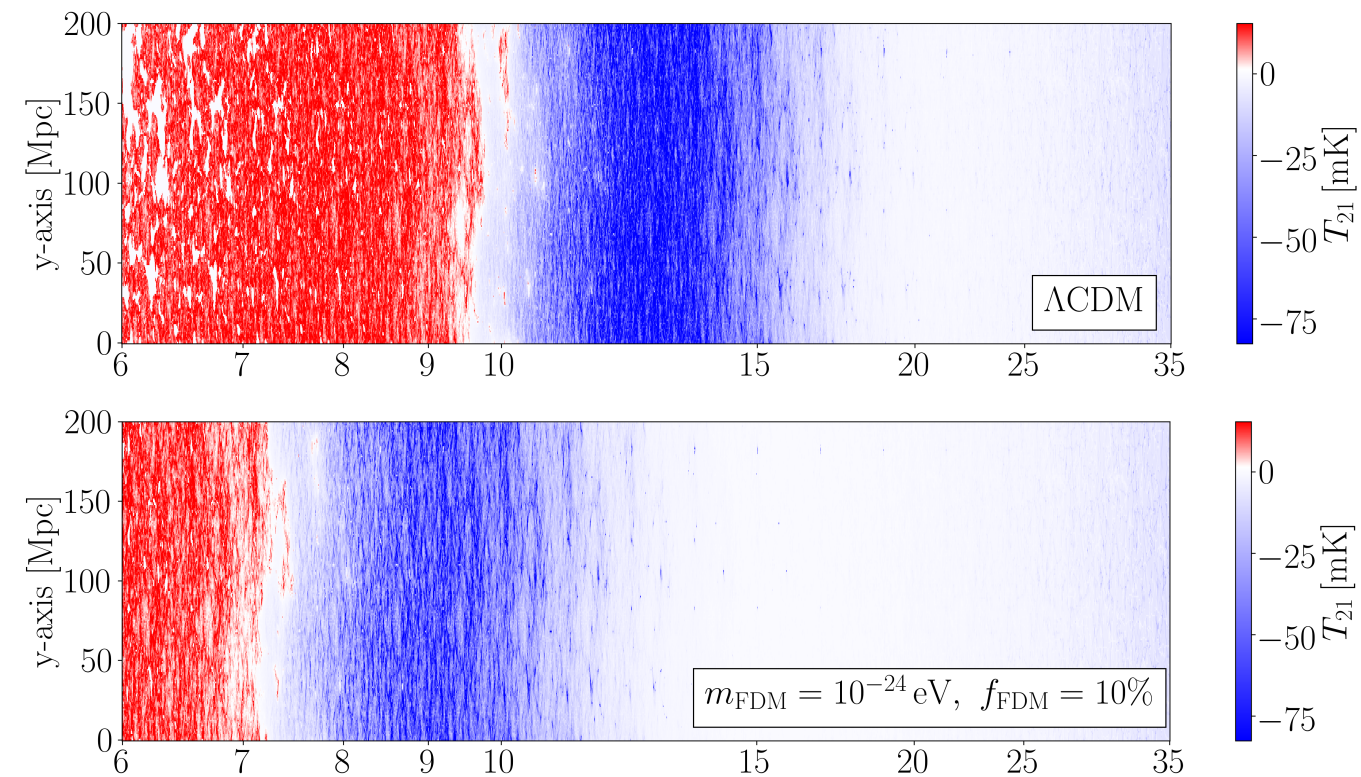
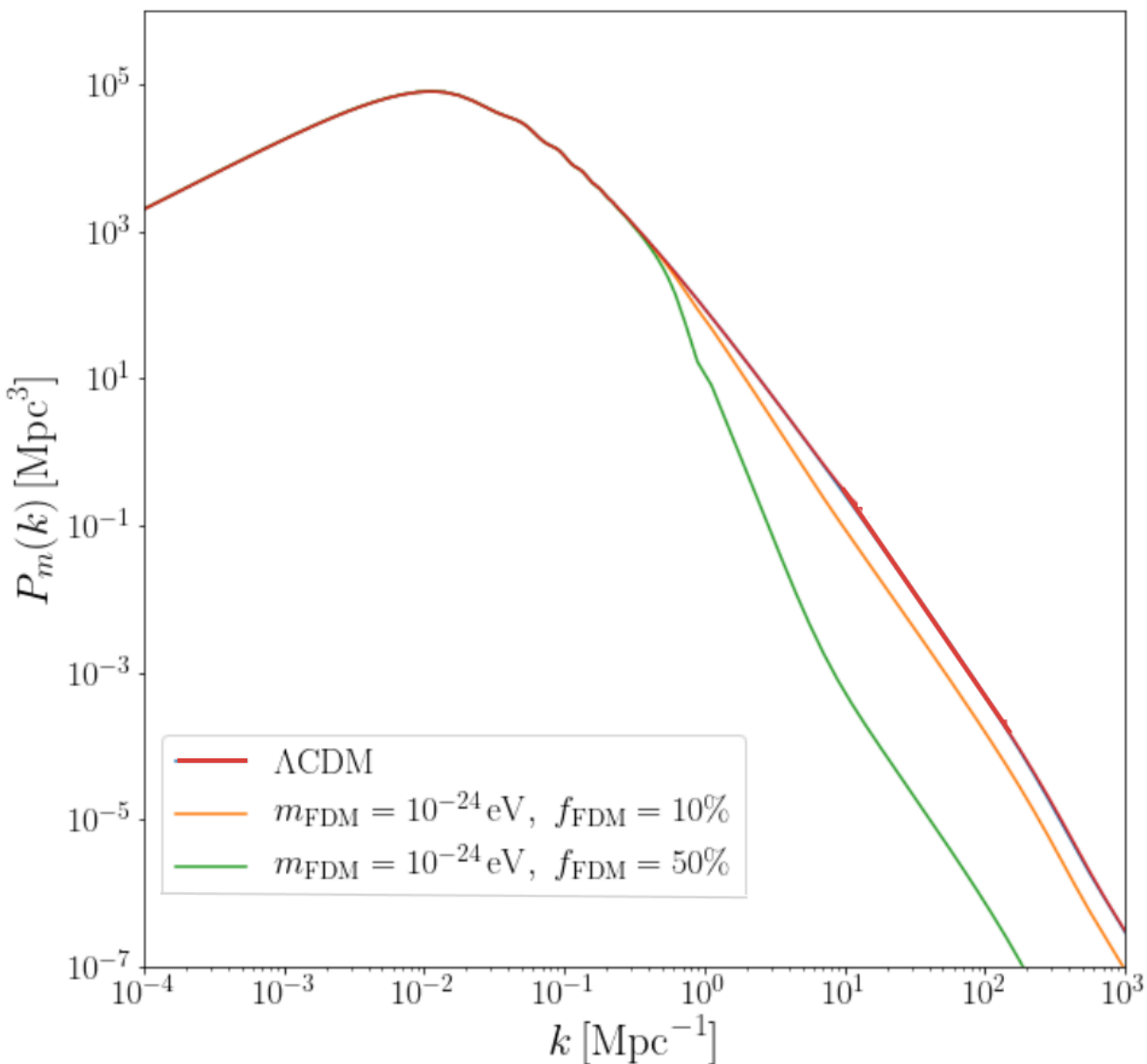


Flitter and Kovetz, PRD 2022

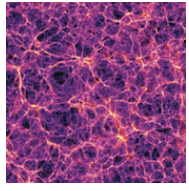


Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ delays the 21cm signal

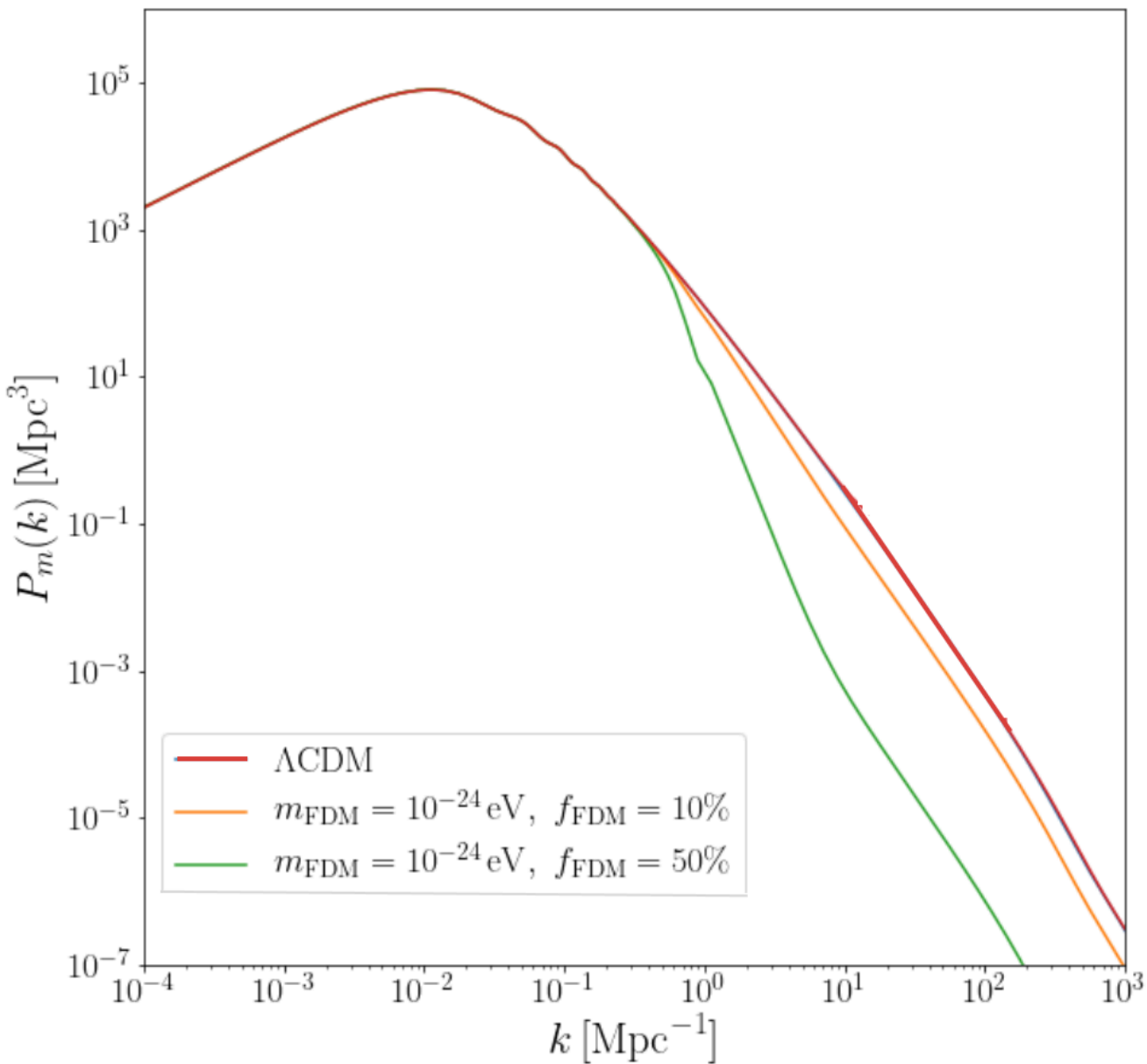


Flitter and Kovetz, PRD 2022

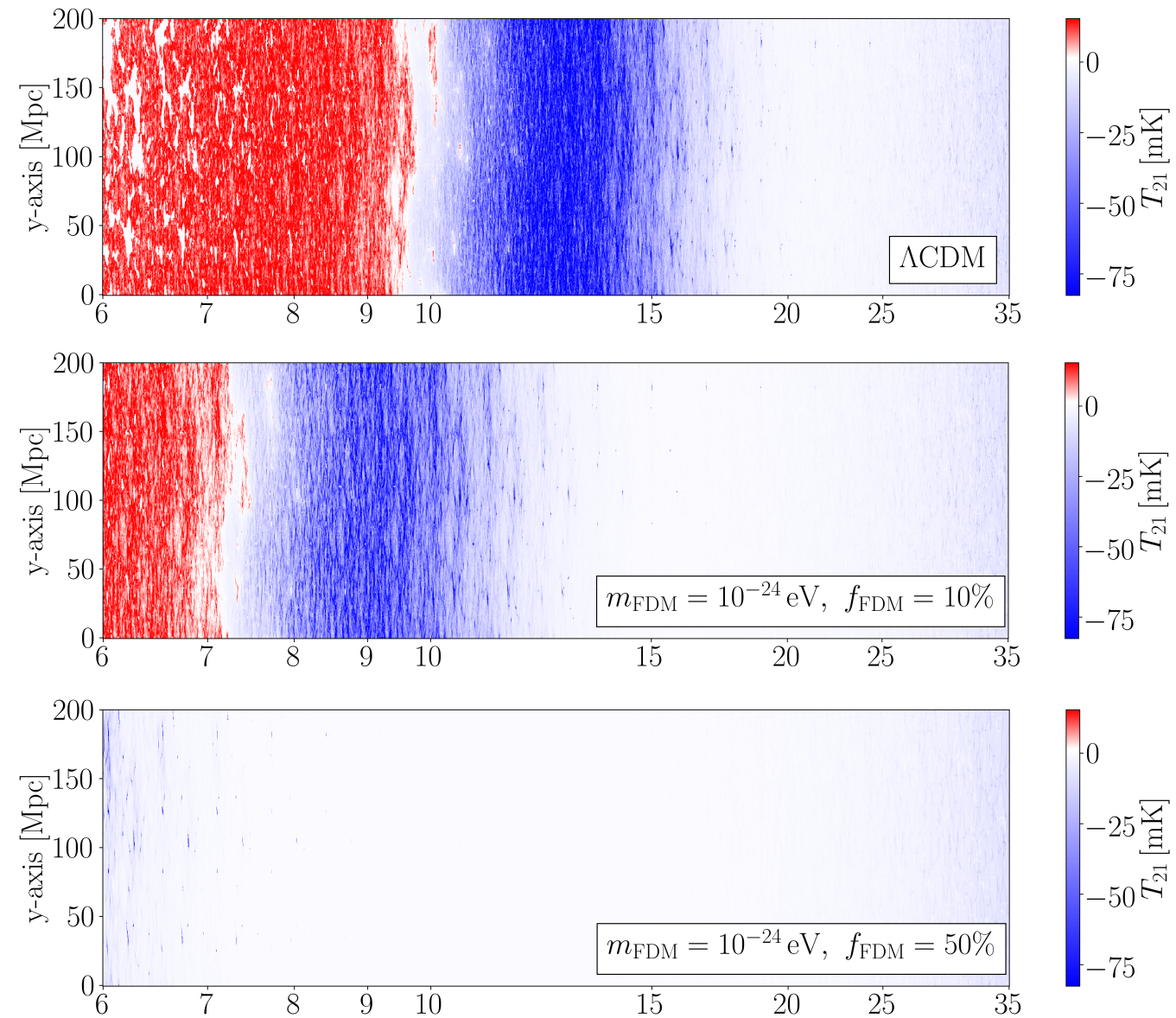


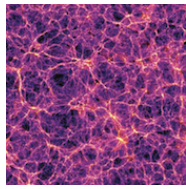
Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ delays the 21cm signal



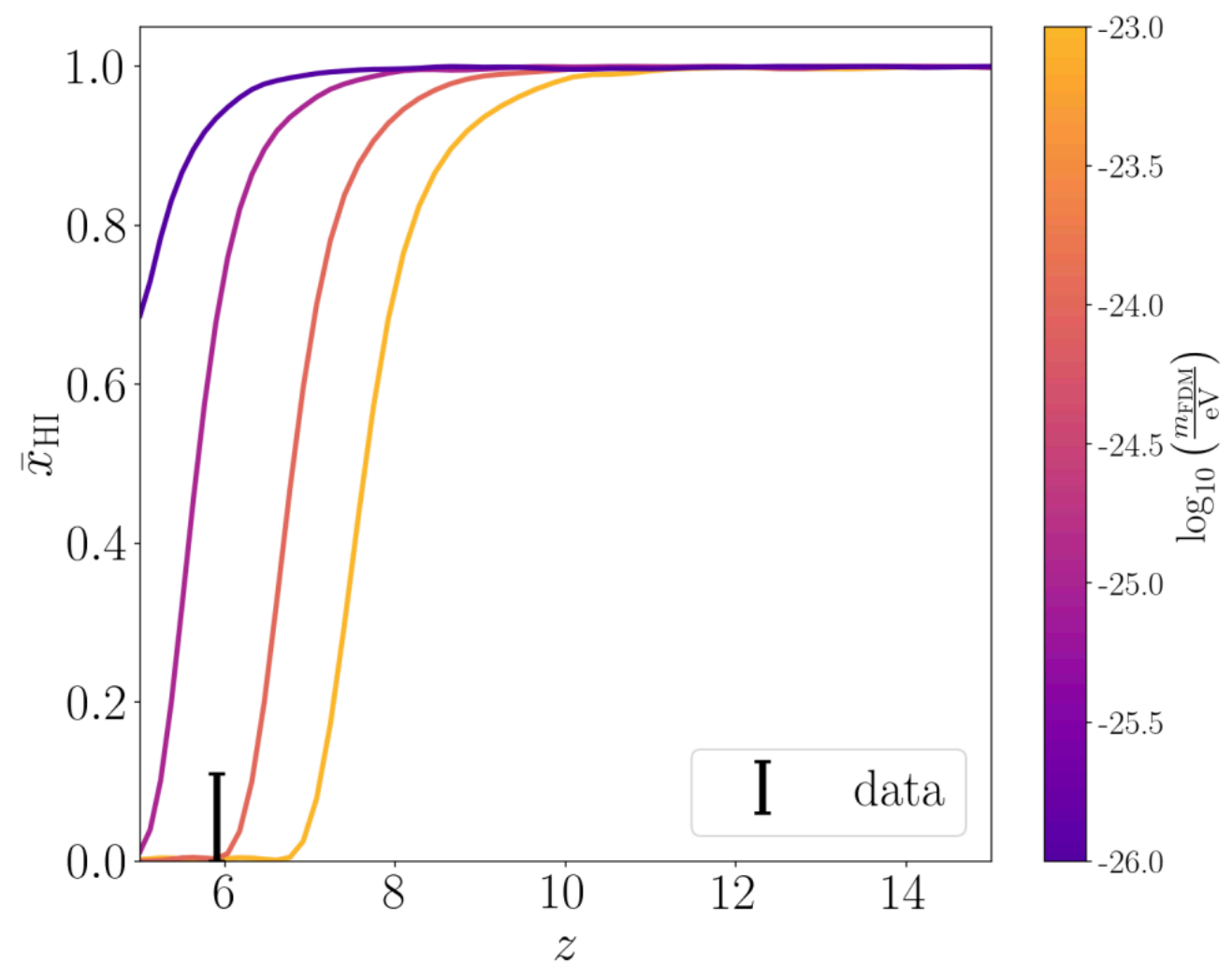
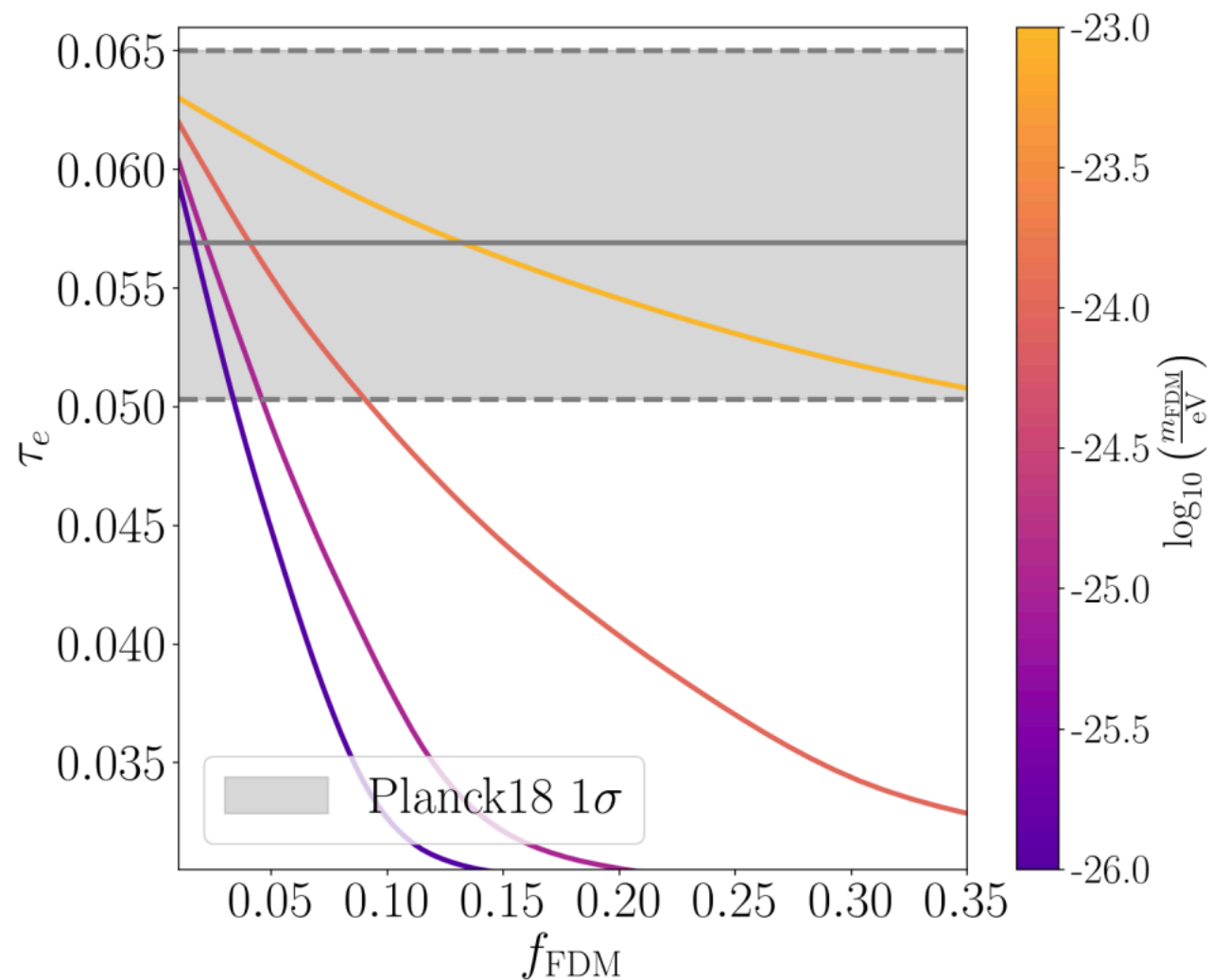
Flitter and Kovetz, PRD 2022

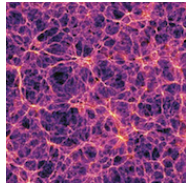




Cosmic Dawn Cosmology: Fuzzy Dark Matter

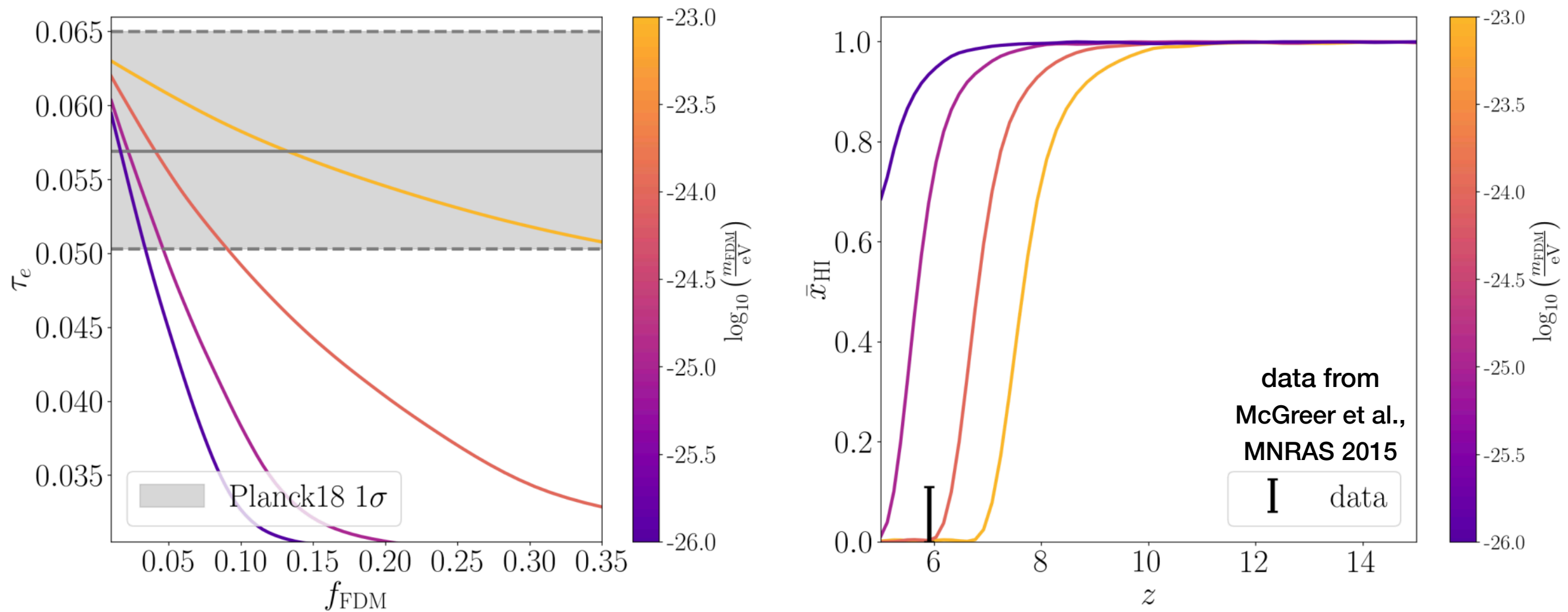
Fuzzy DM suppresses small scale clustering $\rightarrow$ affects reionization observables



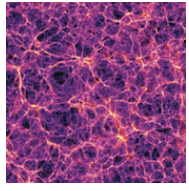


Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ affects reionization observables

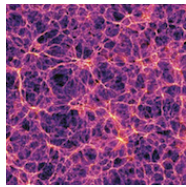


Lazare, Flitter and Kovetz, PRD 2024



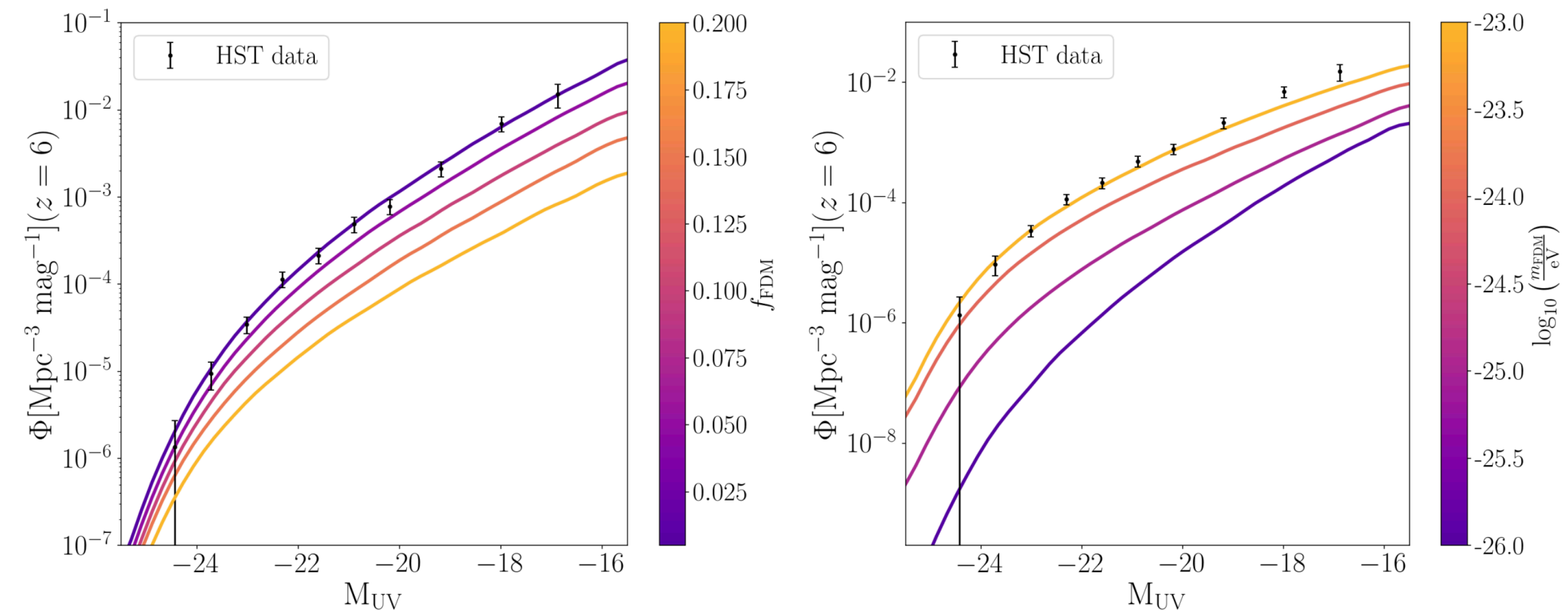
Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ suppresses high- z UVLF

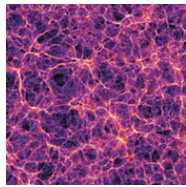


Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ suppresses high- z UVLF

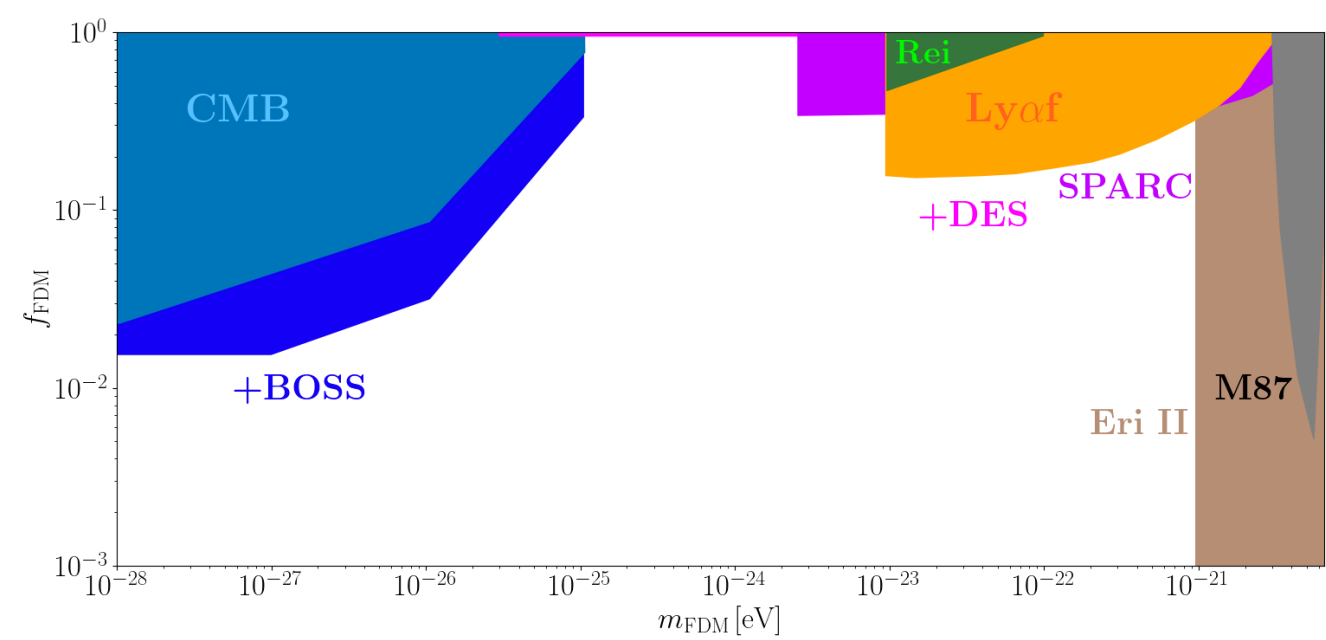
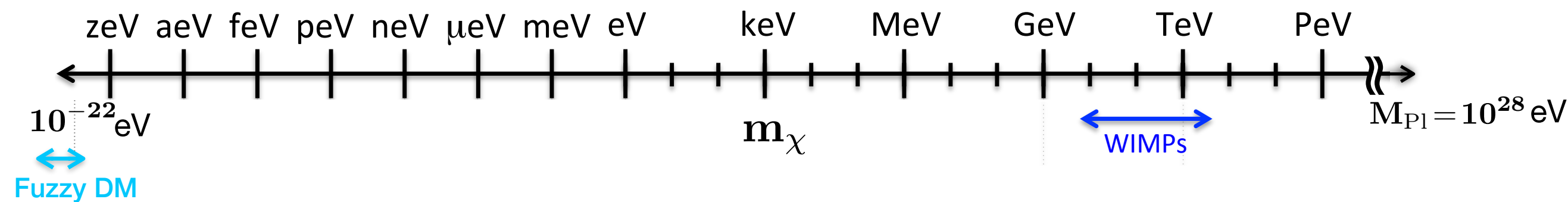


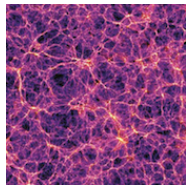
Lazare, Flitter and Kovetz, PRD 2024



Cosmic Dawn Cosmology: Fuzzy Dark Matter

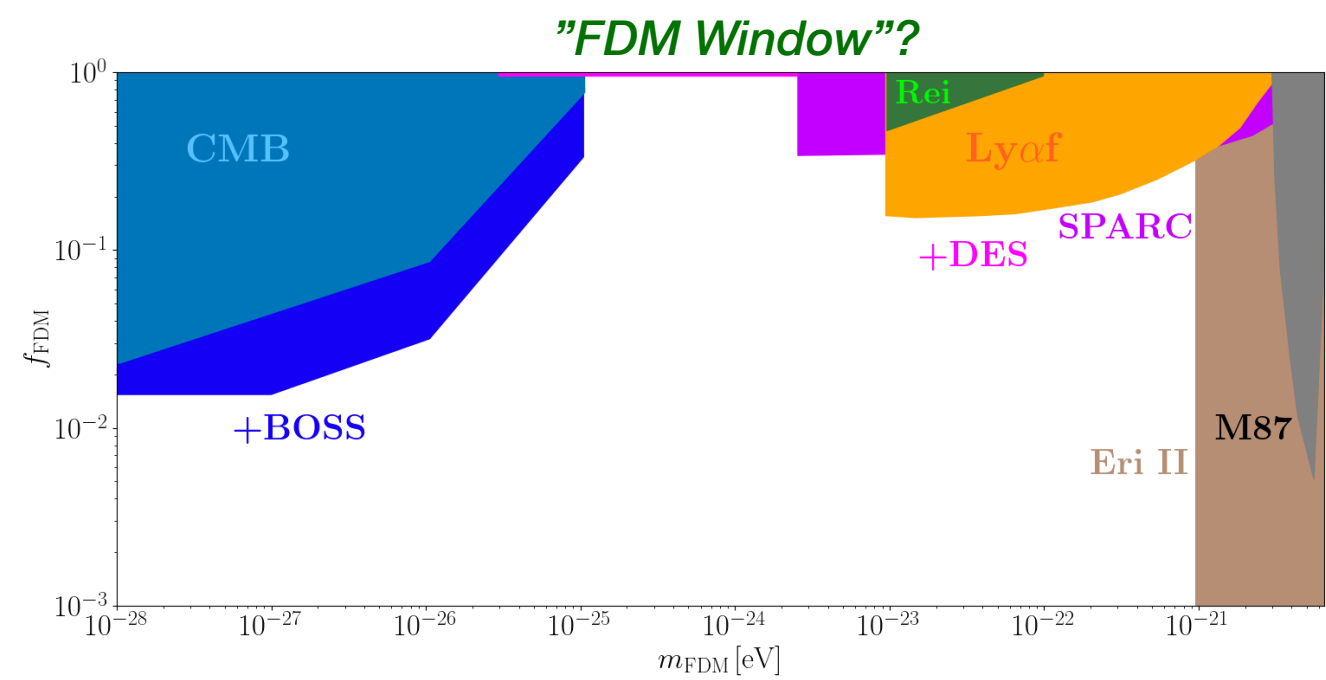
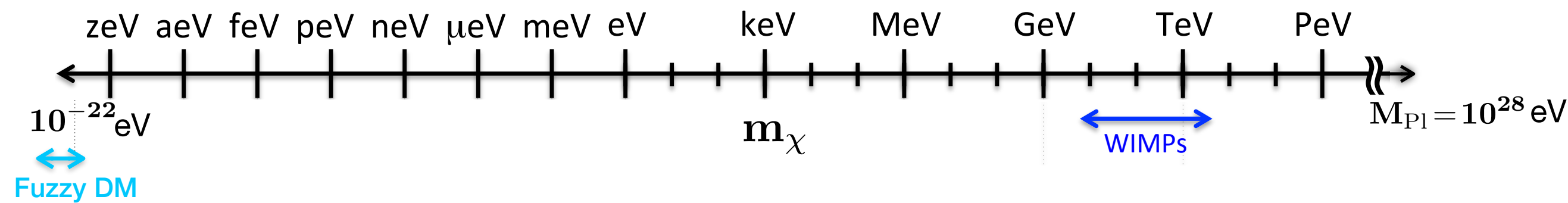
(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)

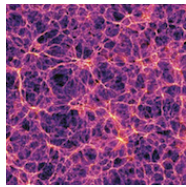




Cosmic Dawn Cosmology: Fuzzy Dark Matter

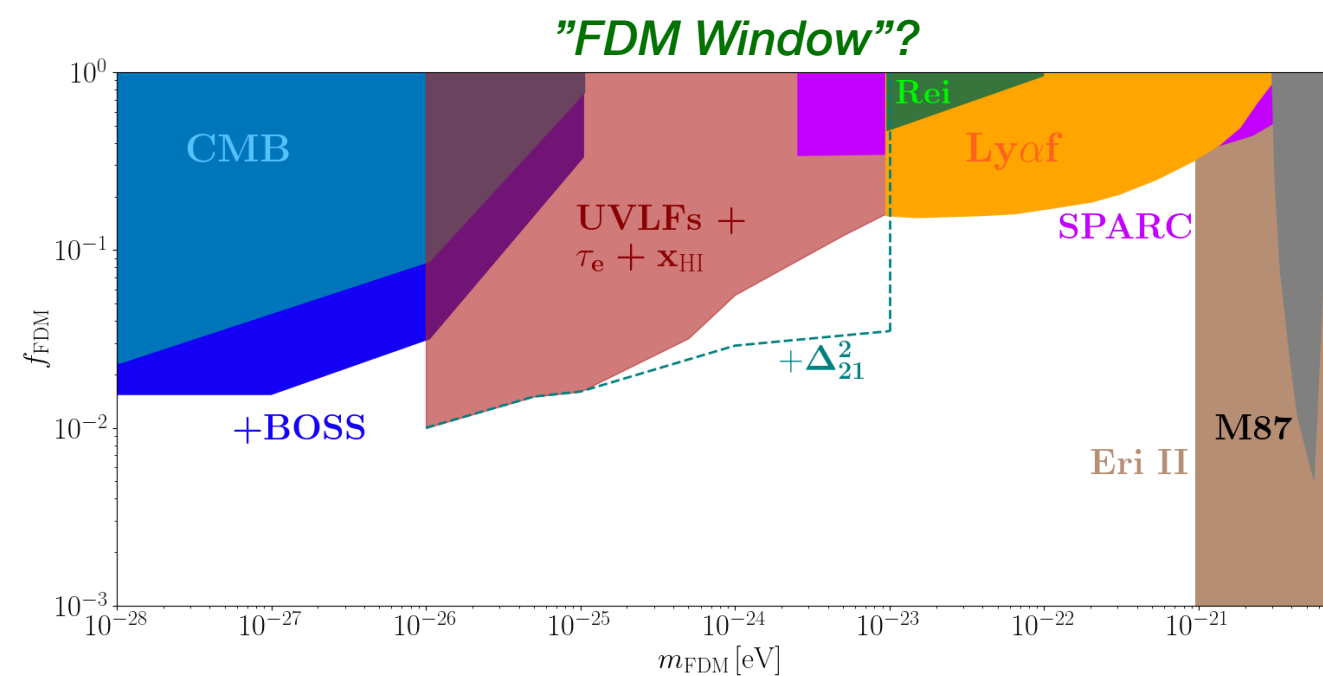
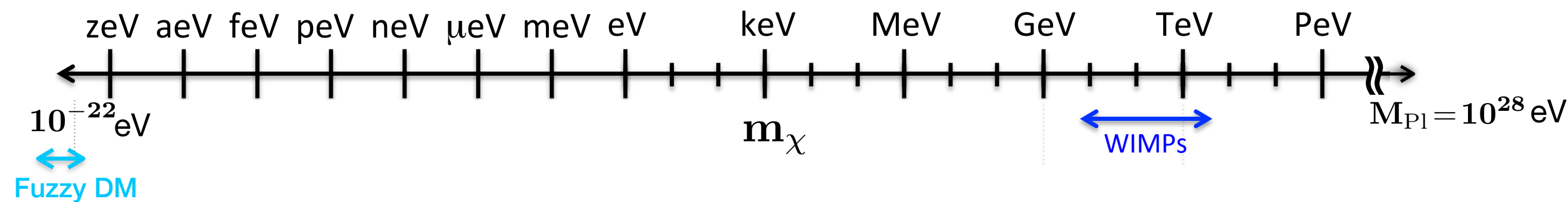
(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)



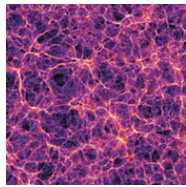


Cosmic Dawn Cosmology: Fuzzy Dark Matter

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)

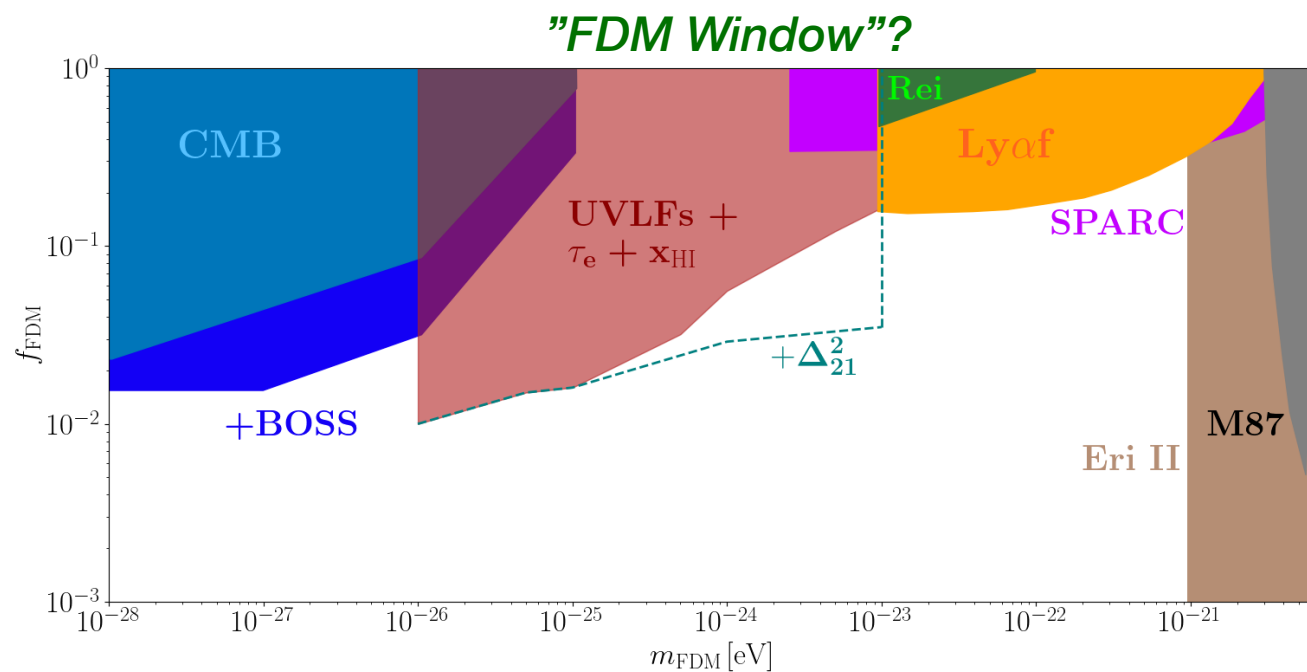
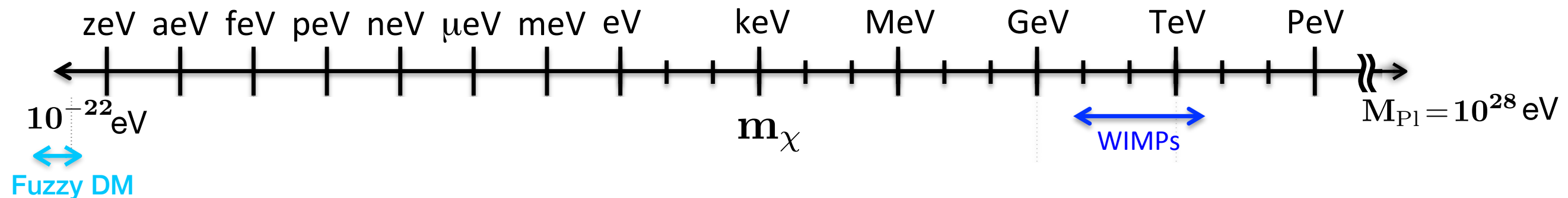


Lazare, Flitter and Kovetz, PRD 2024
(See also: Winch et al., ApJ 2024)

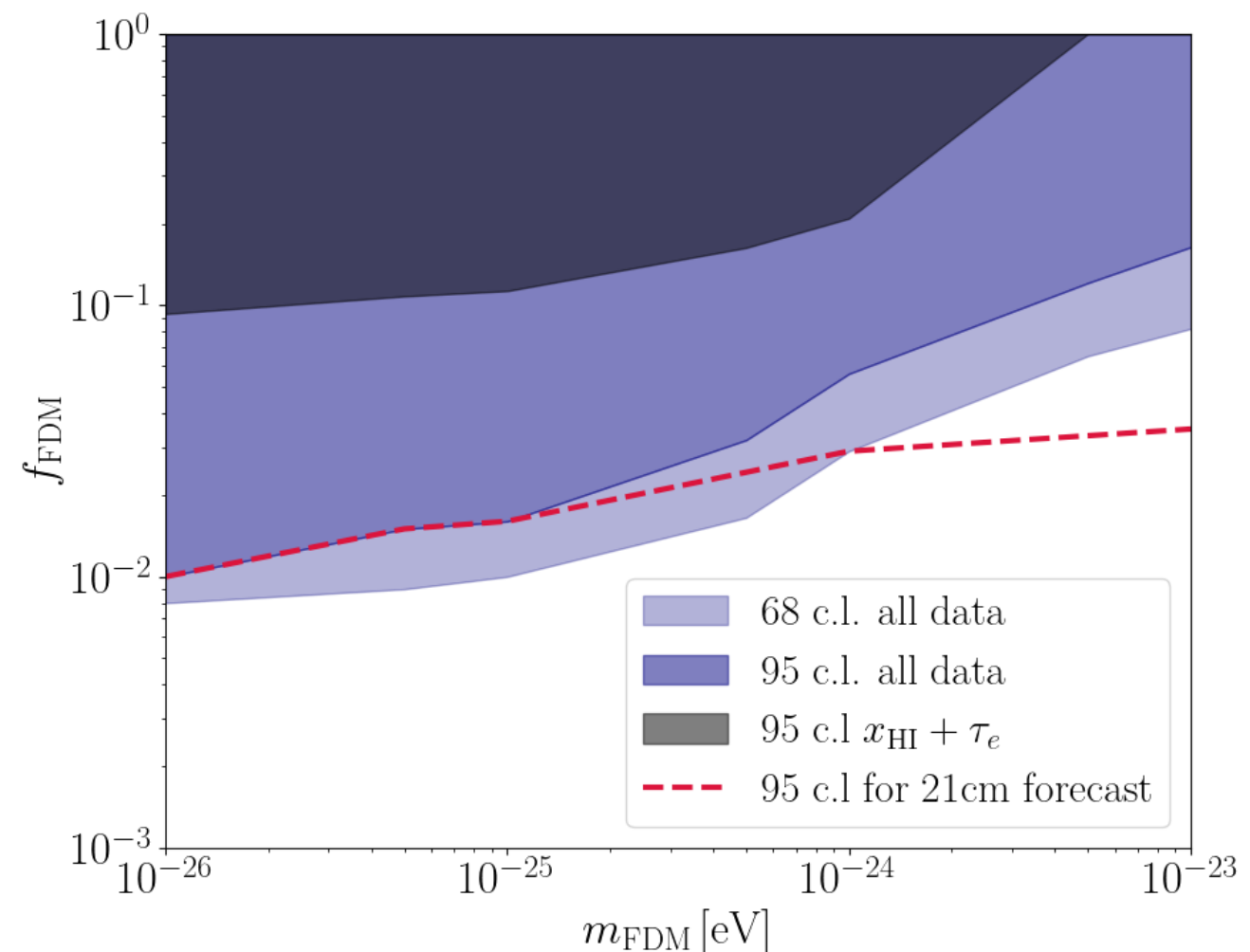


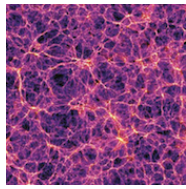
Cosmic Dawn Cosmology: Fuzzy Dark Matter

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)



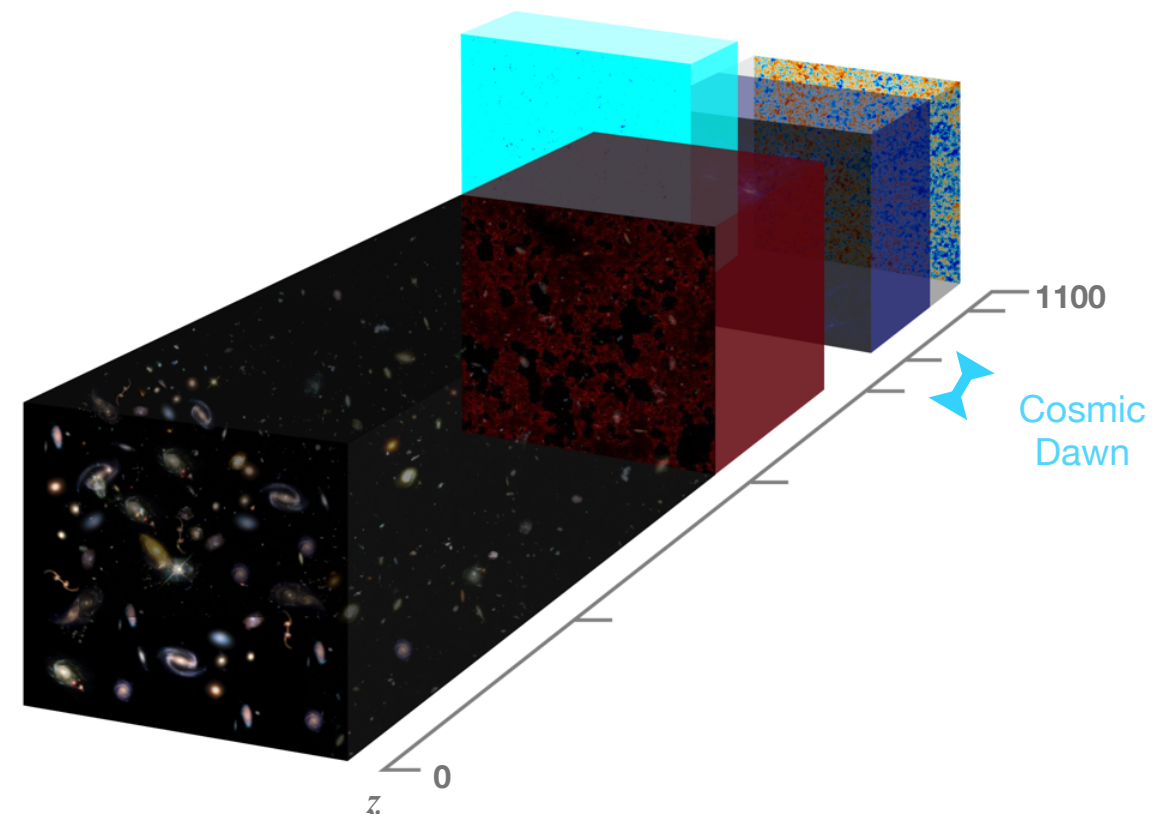
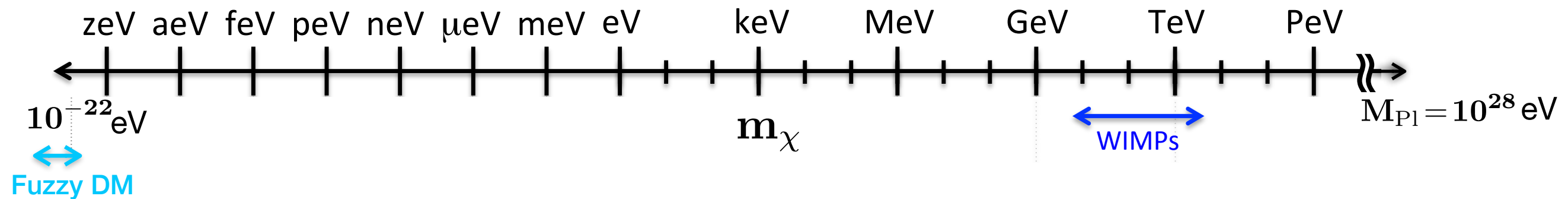
Lazare, Flitter and Kovetz, PRD 2024
(See also: Winch et al., ApJ 2024)



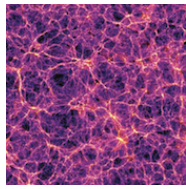


Cosmic Dawn Cosmology: Scattering DM

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)

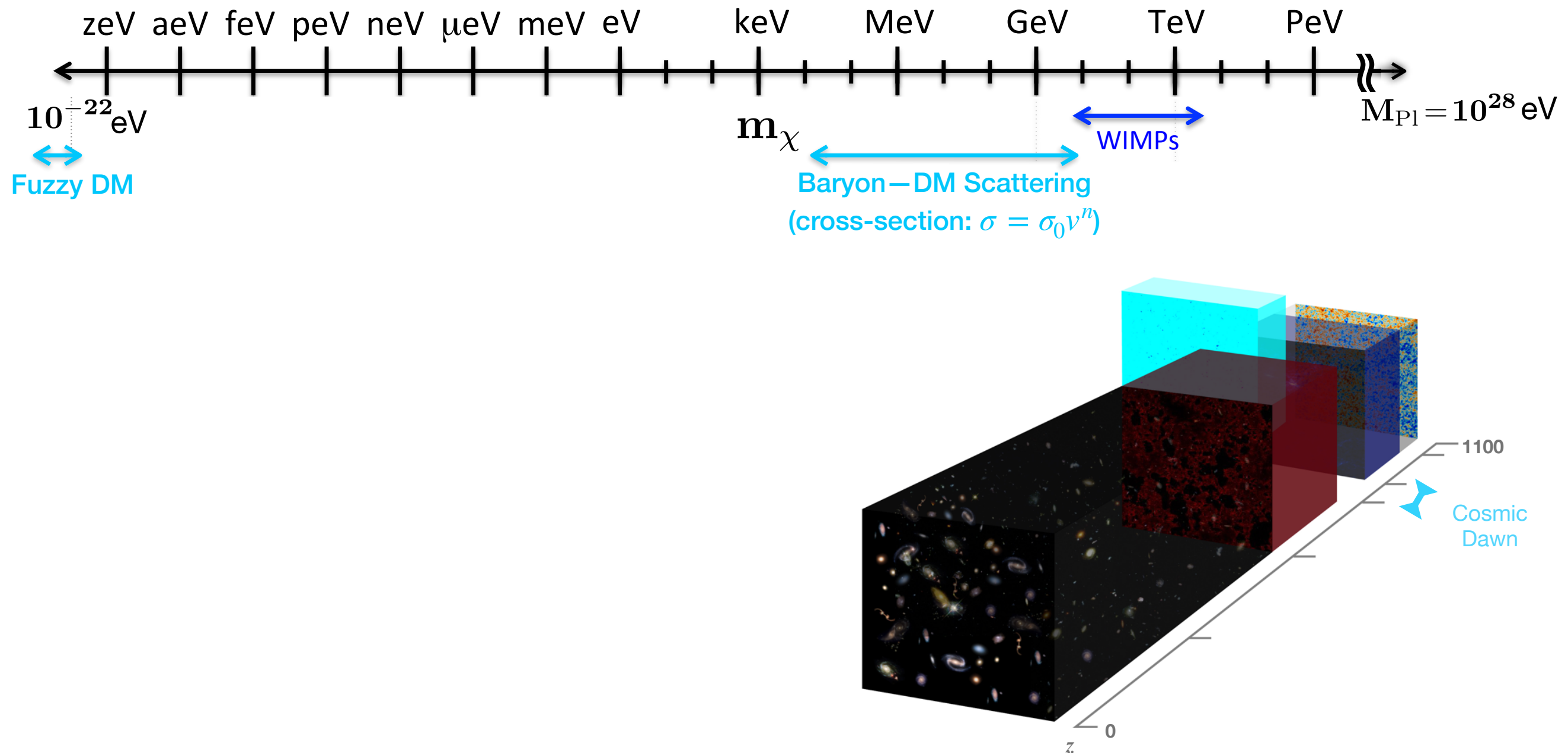


Lazare, Kovetz, Boddy and Munoz, to appear

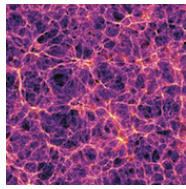


Cosmic Dawn Cosmology: Scattering DM

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)

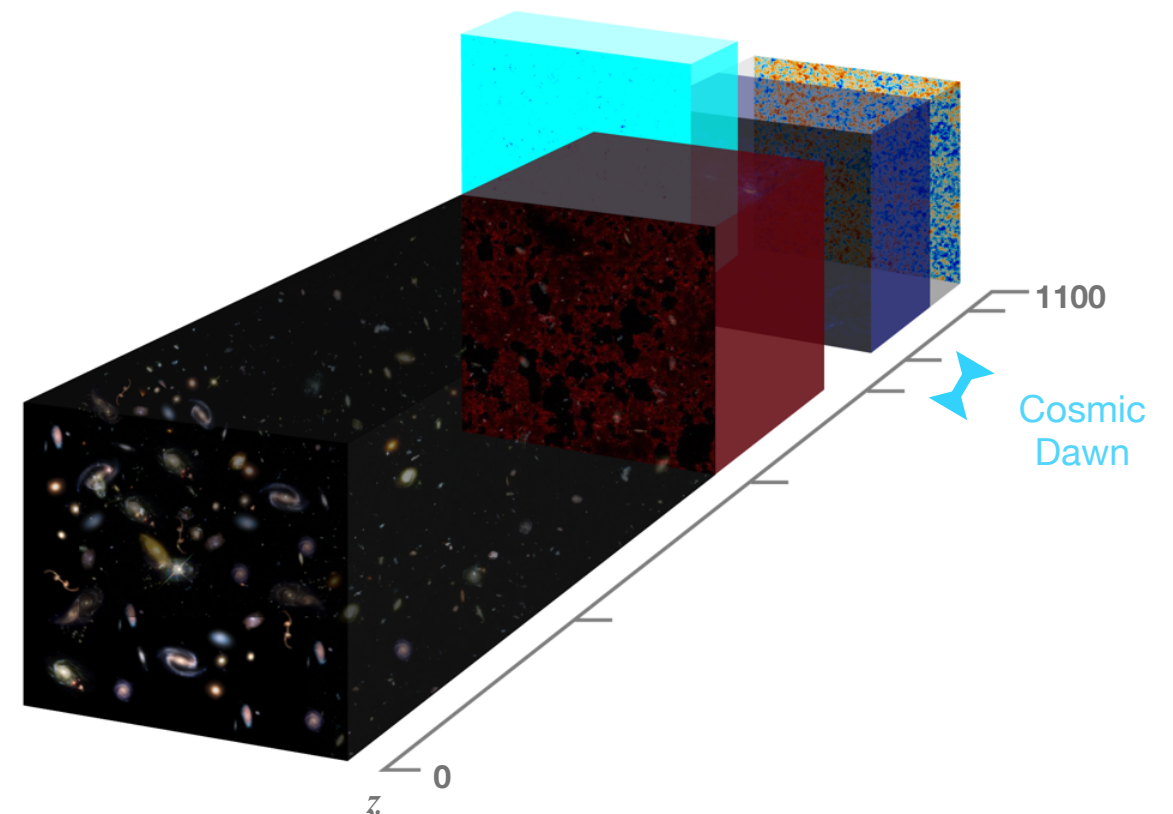
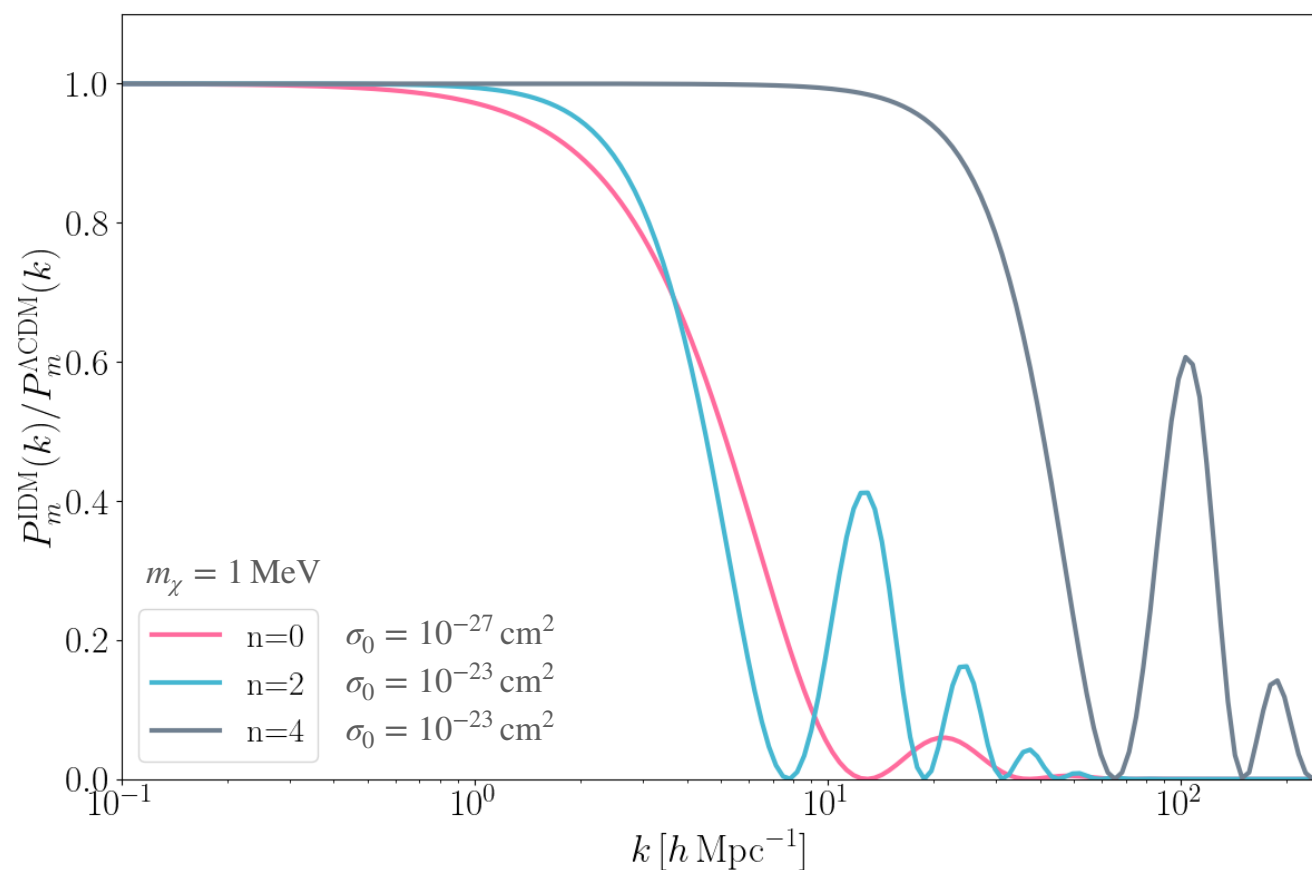
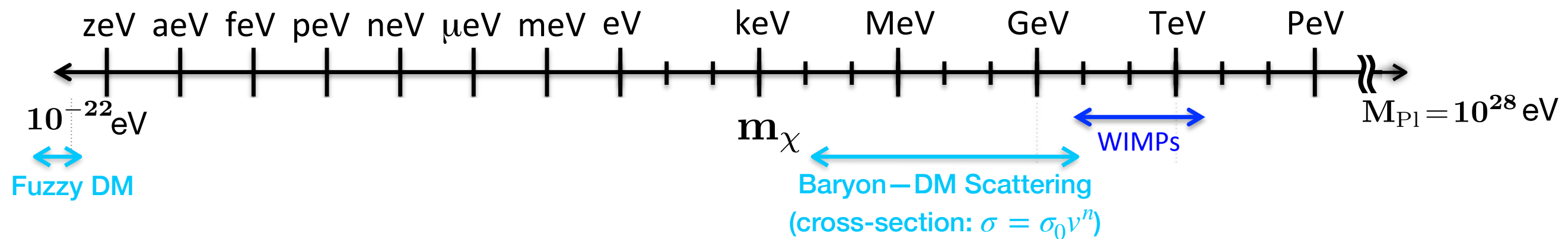


Lazare, Kovetz, Boddy and Munoz, to appear

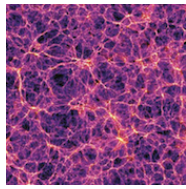


Cosmic Dawn Cosmology: Scattering DM

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)

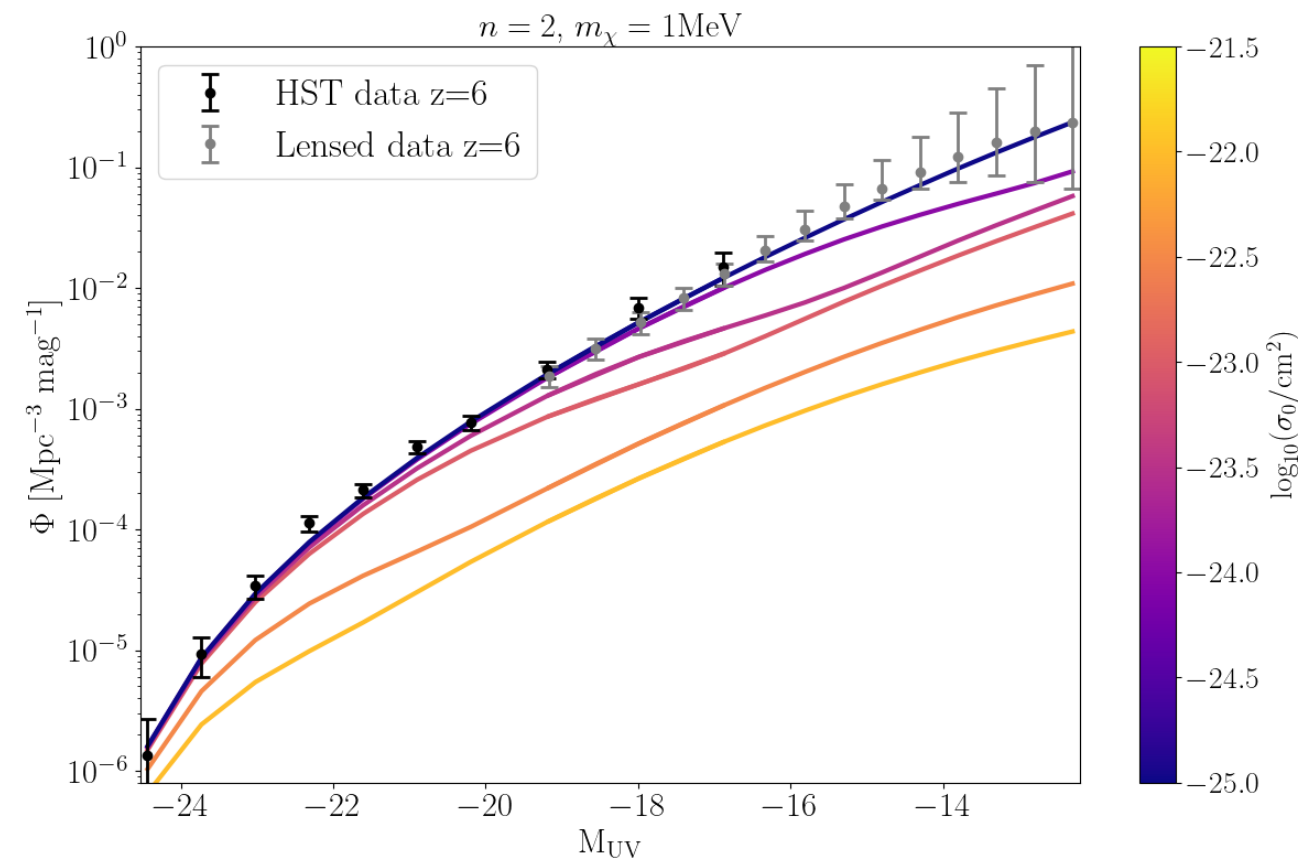
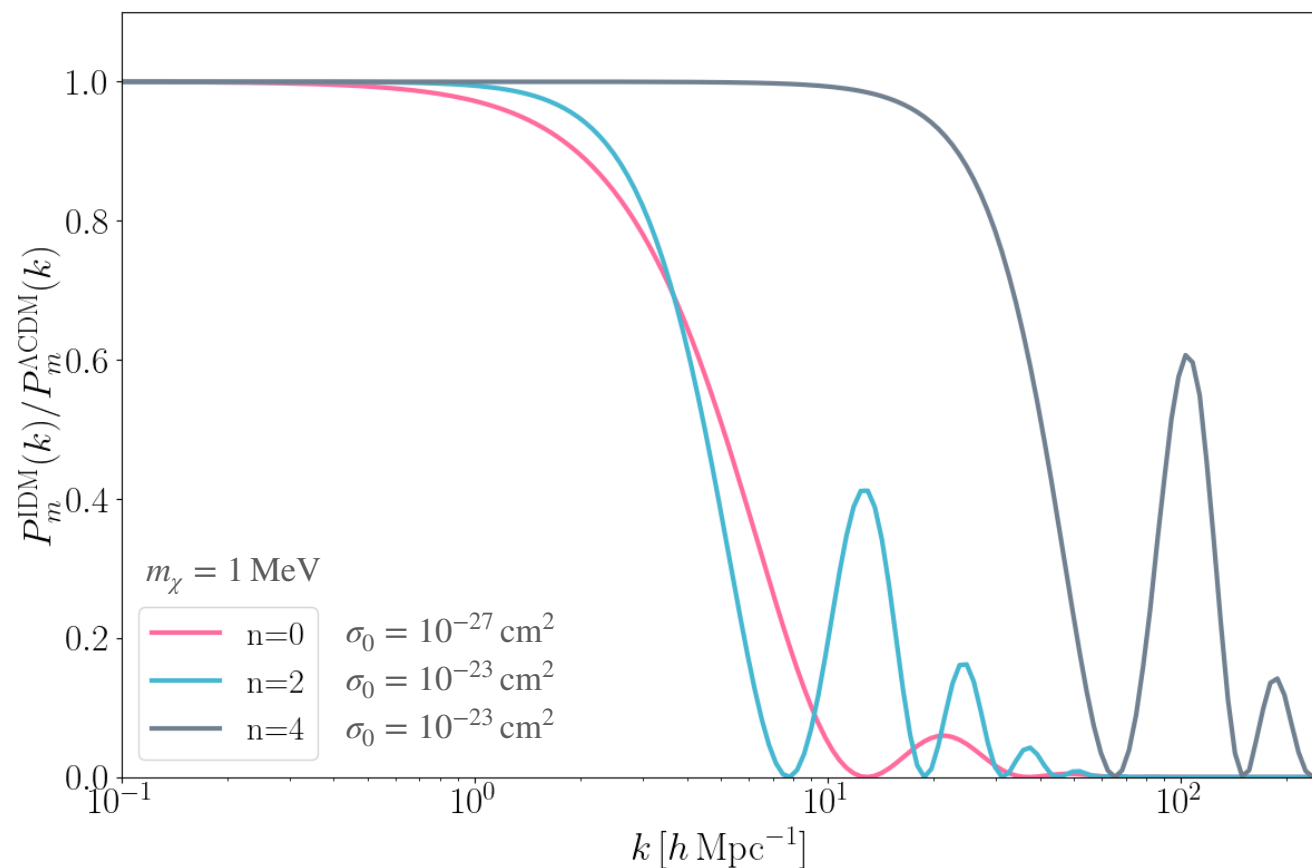
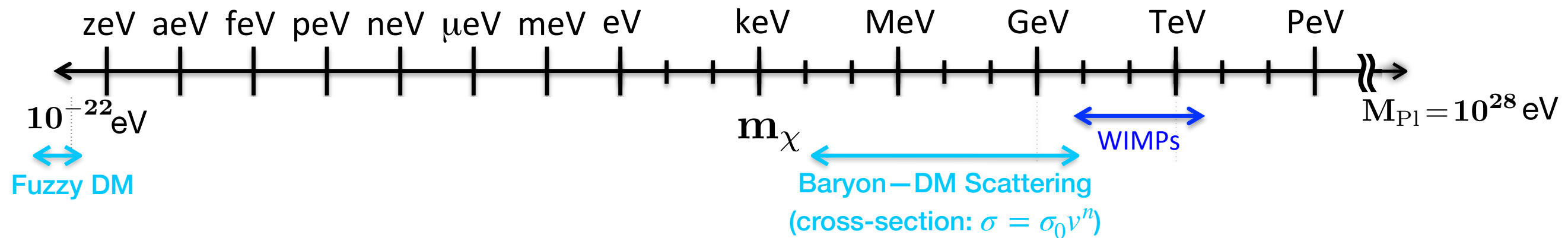


Lazare, Kovetz, Boddy and Munoz, to appear

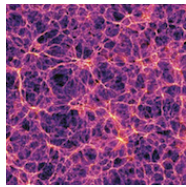


Cosmic Dawn Cosmology: Scattering DM

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)

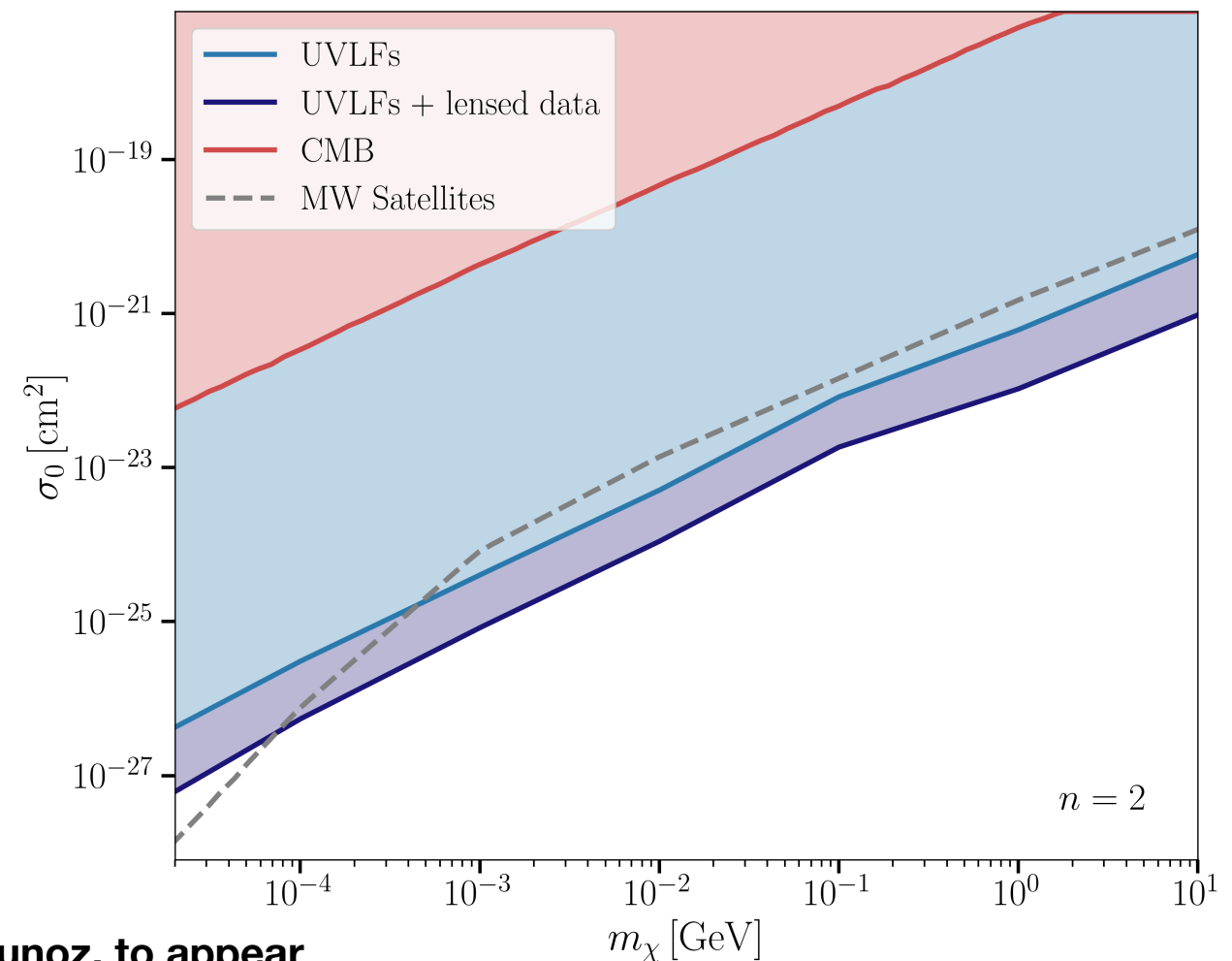
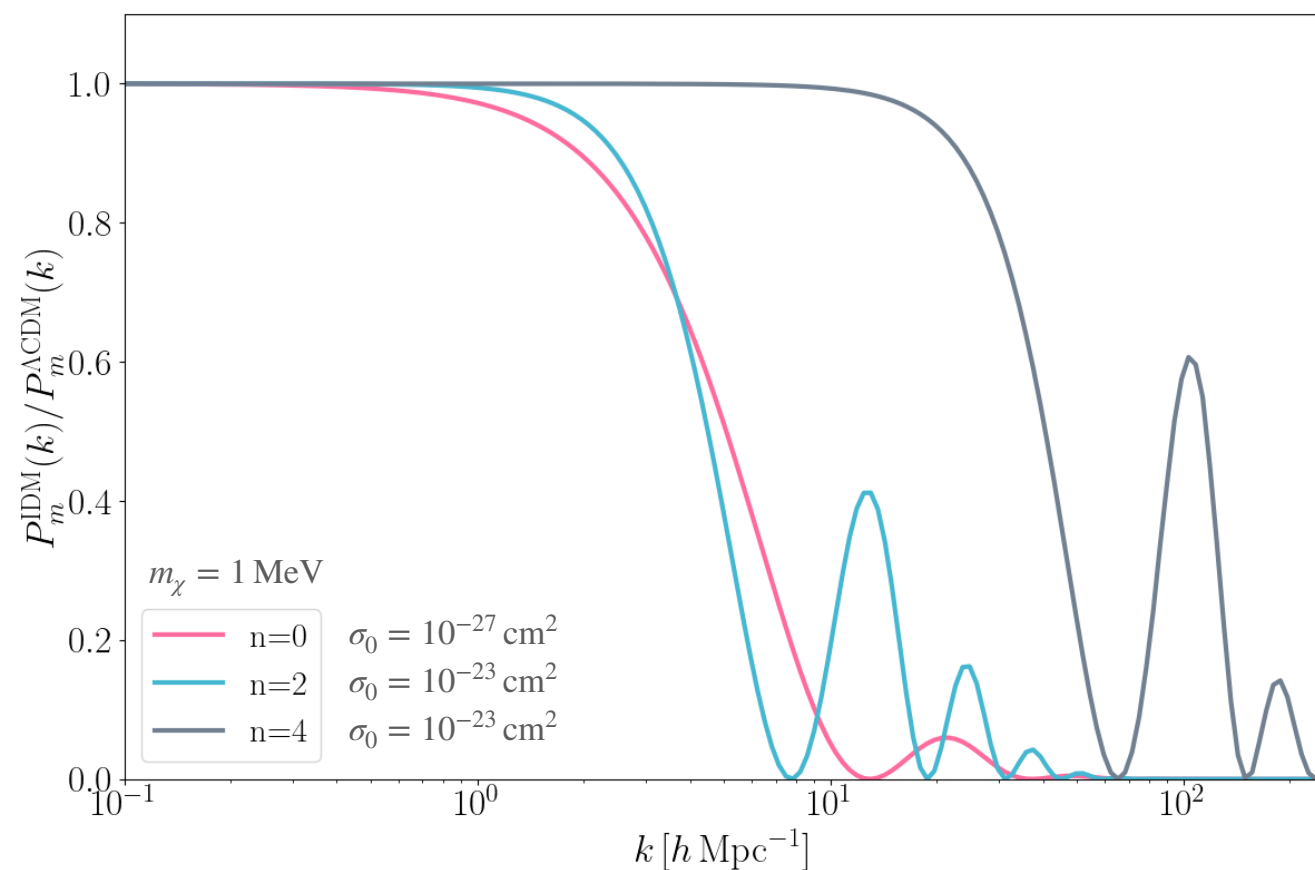
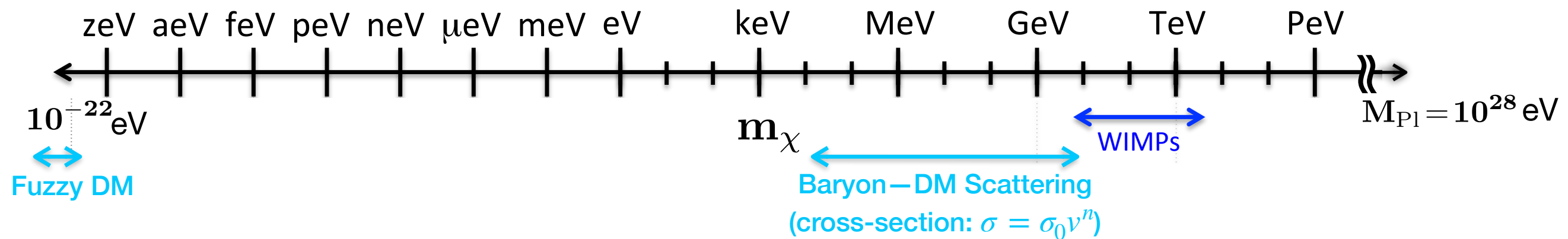


Lazare, Kovetz, Boddy and Munoz, to appear

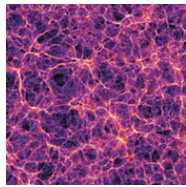


Cosmic Dawn Cosmology: Scattering DM

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)

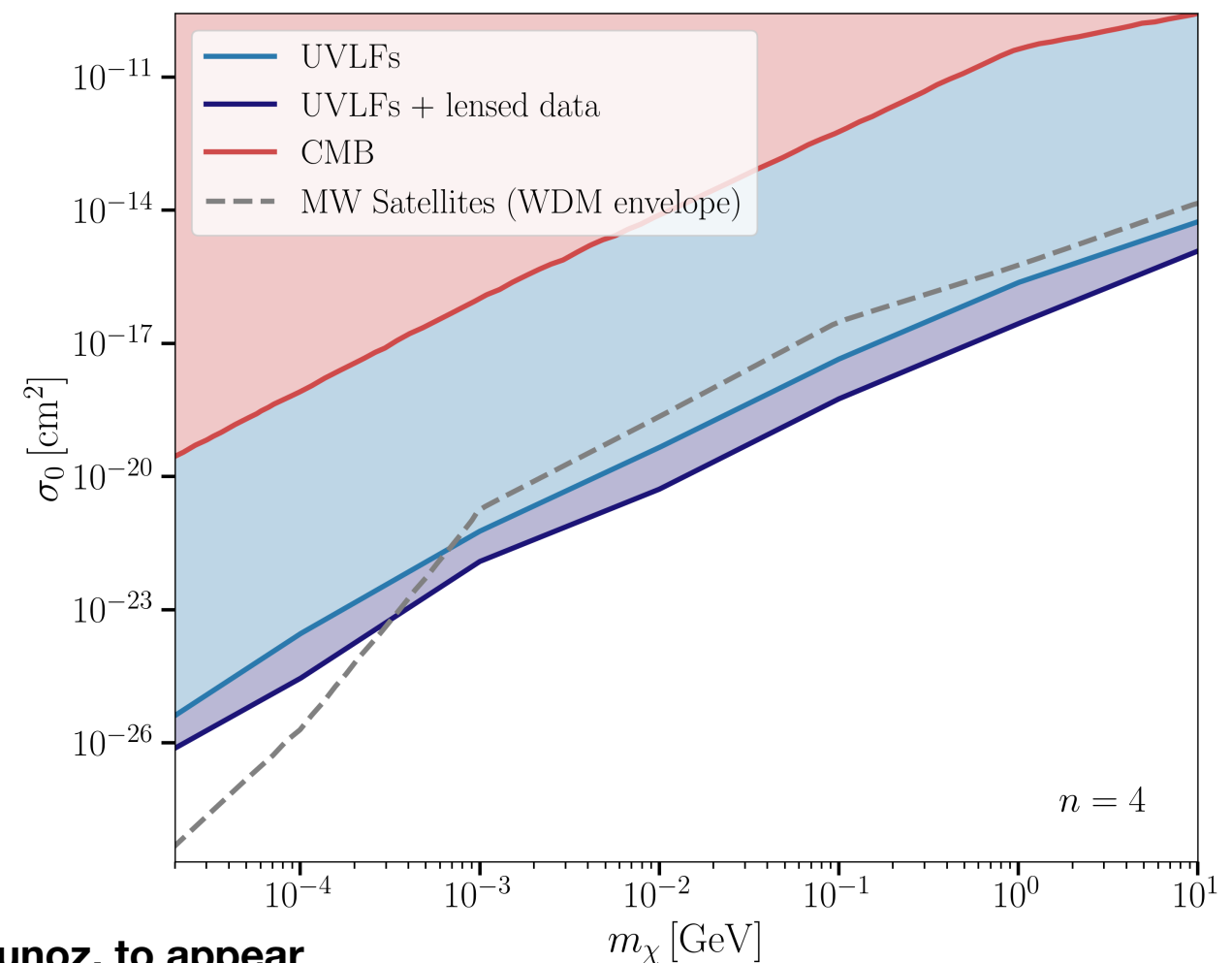
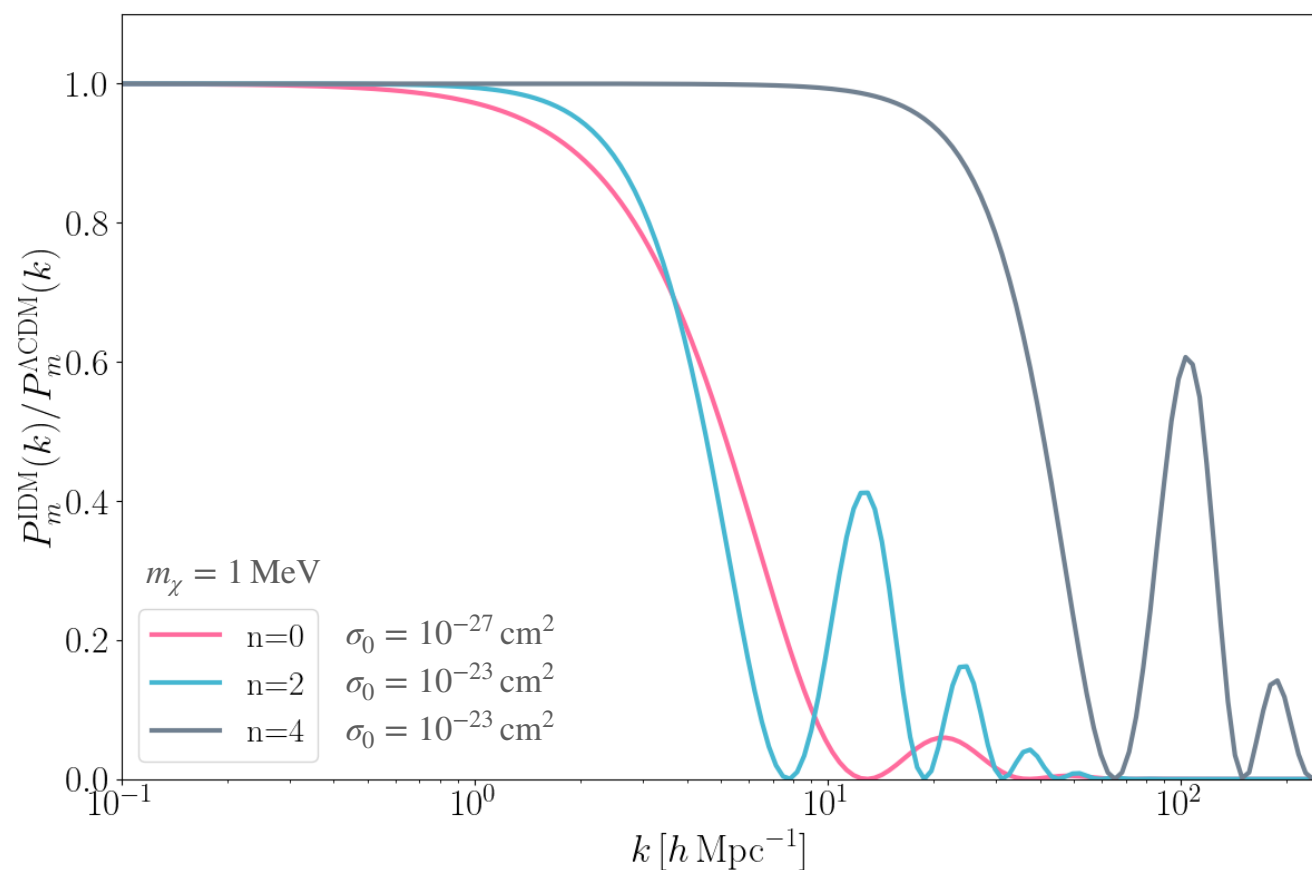
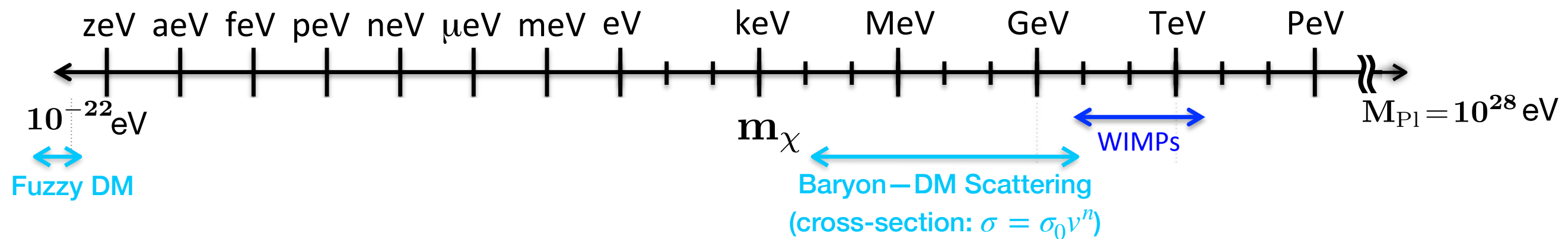


Lazare, Kovetz, Boddy and Munoz, to appear



Cosmic Dawn Cosmology: Scattering DM

(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)

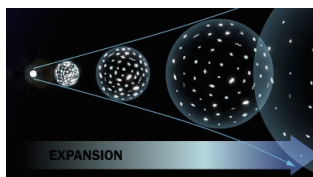
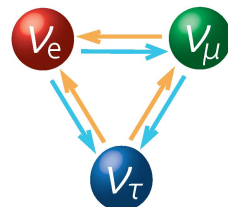
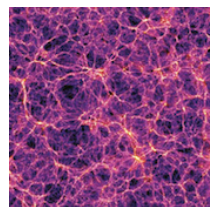
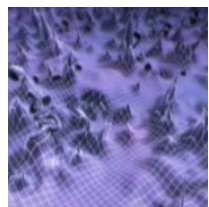
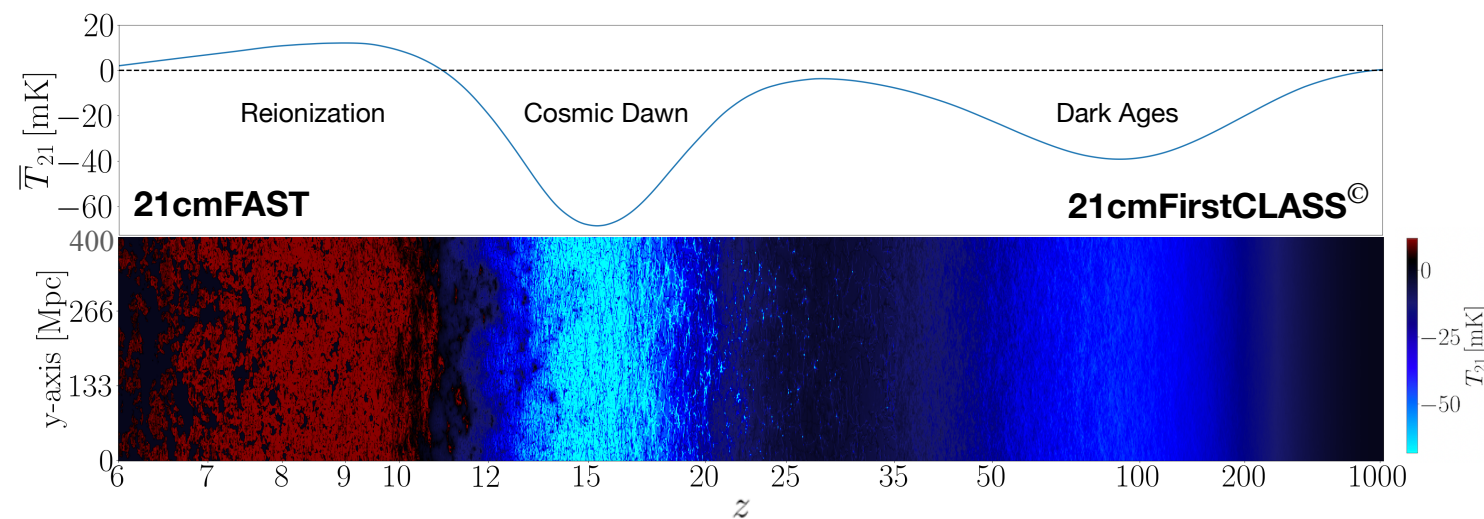
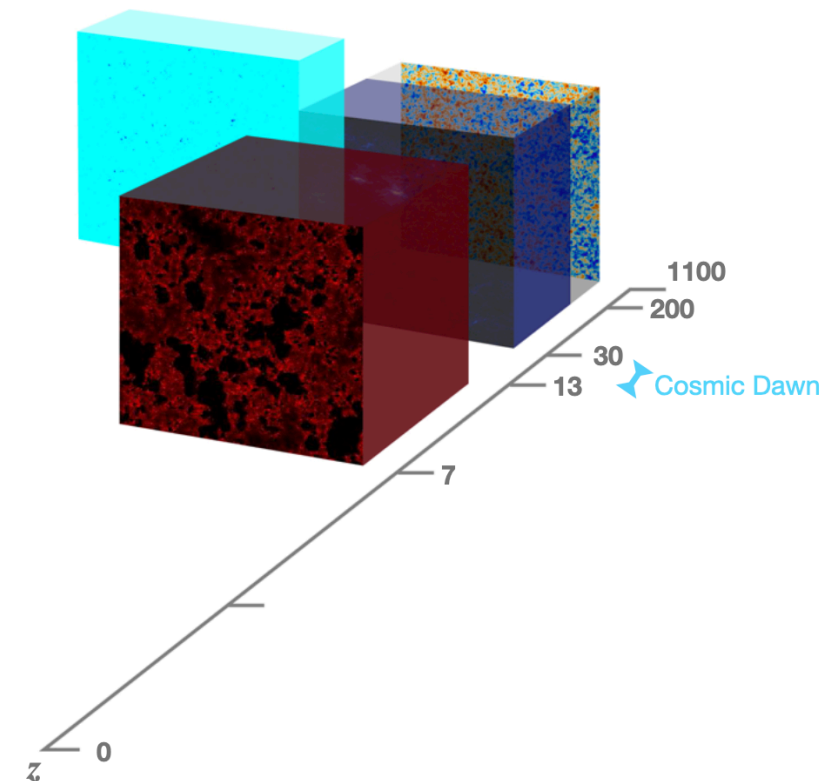


Lazare, Kovetz, Boddy and Munoz, to appear

The Dawn of Cosmic Dawn Cosmology - Part 1

Some conclusions:

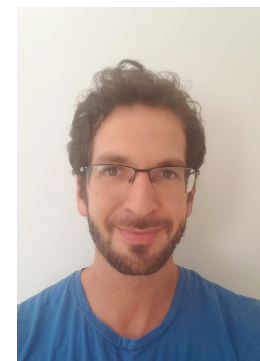
- We need robust, consistent and fast simulations.
- LIM is *unique* in many cases.
- At small scales, cosmic dawn can constrain:
 - Ultralight (fuzzy) dark matter
 - Interacting dark matter
 - Primordial magnetic fields
 - Early dark energy
 - Self-interacting neutrinos
 - Neutrino masses
 - ...



Sarah Libanore



Hovav Lazare



Jordan Flitter



Tal Adi



Debanjan Sarkar

Line-Intensity Mapping: What Can it Probe?

Astrophysics

Cosmology

One's signal is another's foreground

Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

Teaser 2: can we time the onset of reionization?

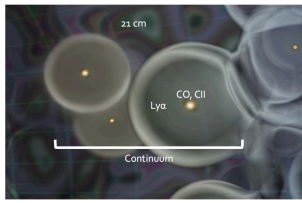
Astrophysics

Cosmology

One's signal is another's foreground

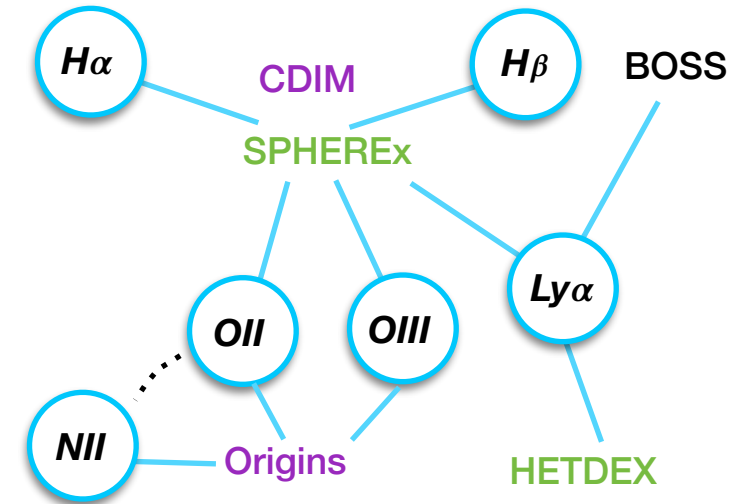
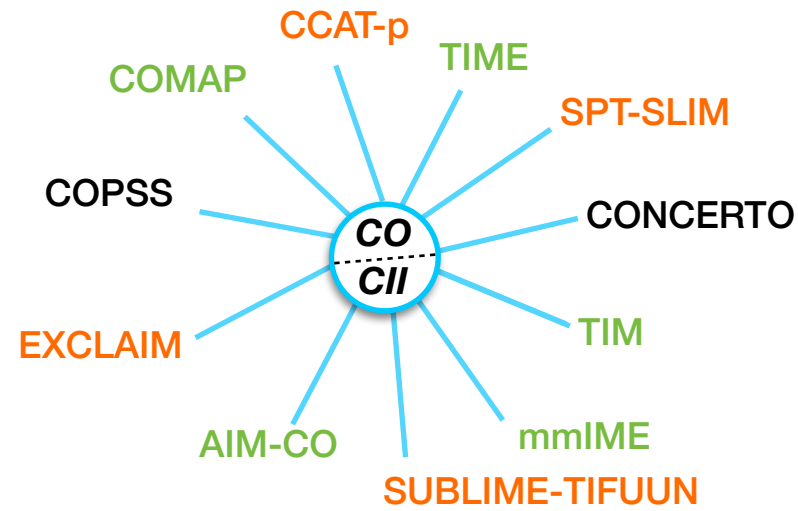
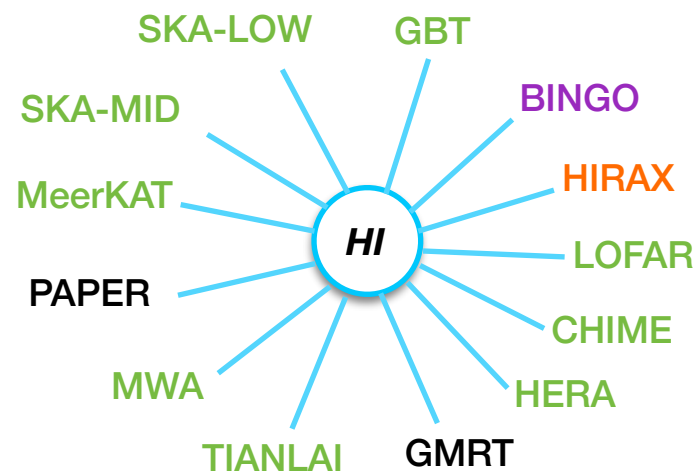
Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

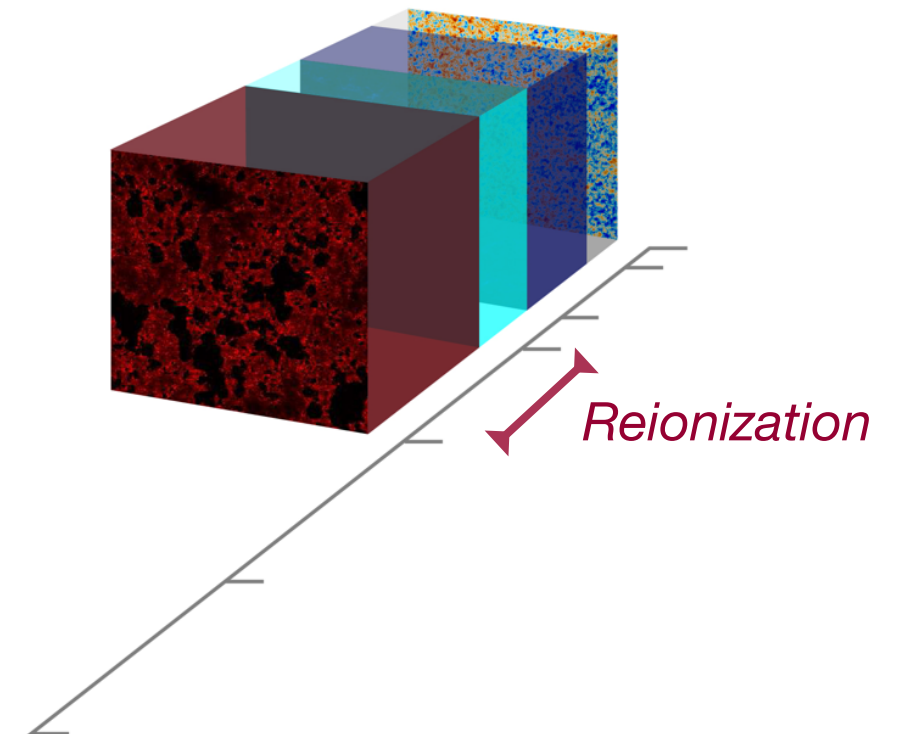


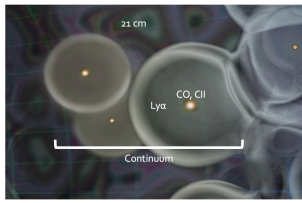
LIM Astrophysics: Epoch of Reionization

- Complete
- Running
- Funded
- Proposed

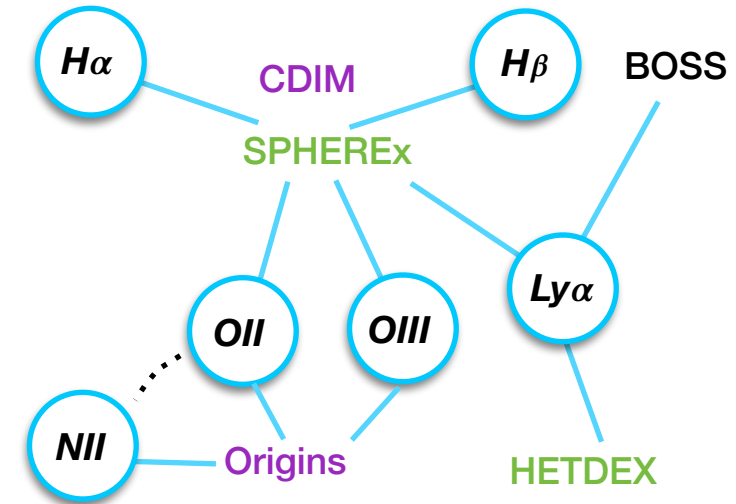
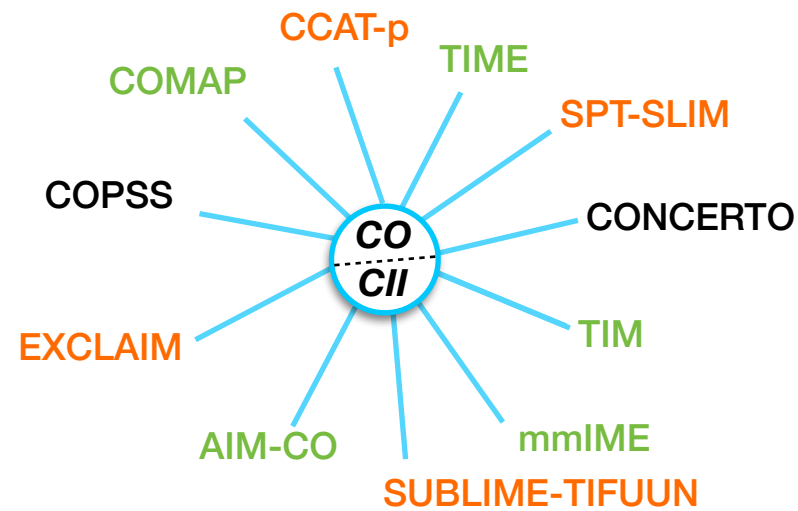
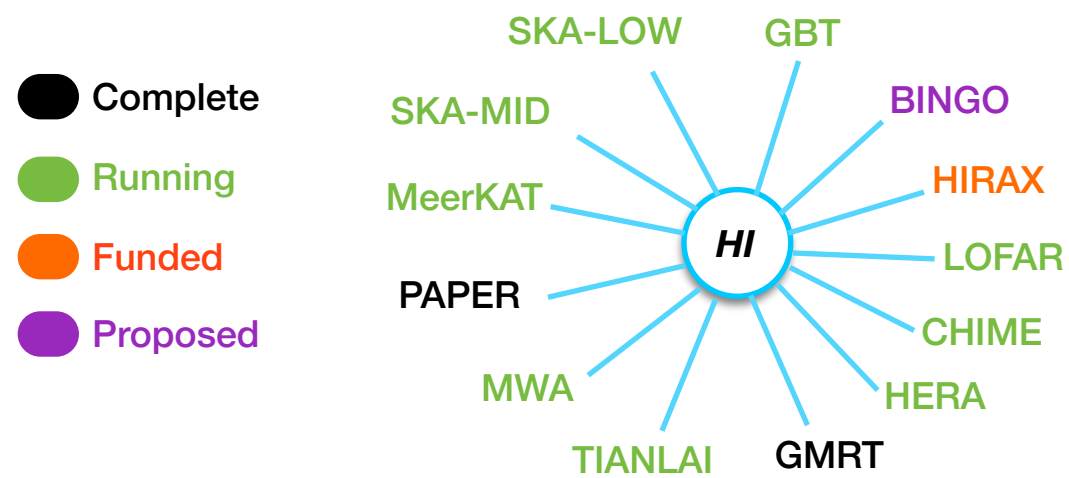


Astro2020: Kovetz et al. [arXiv:1903.04496]

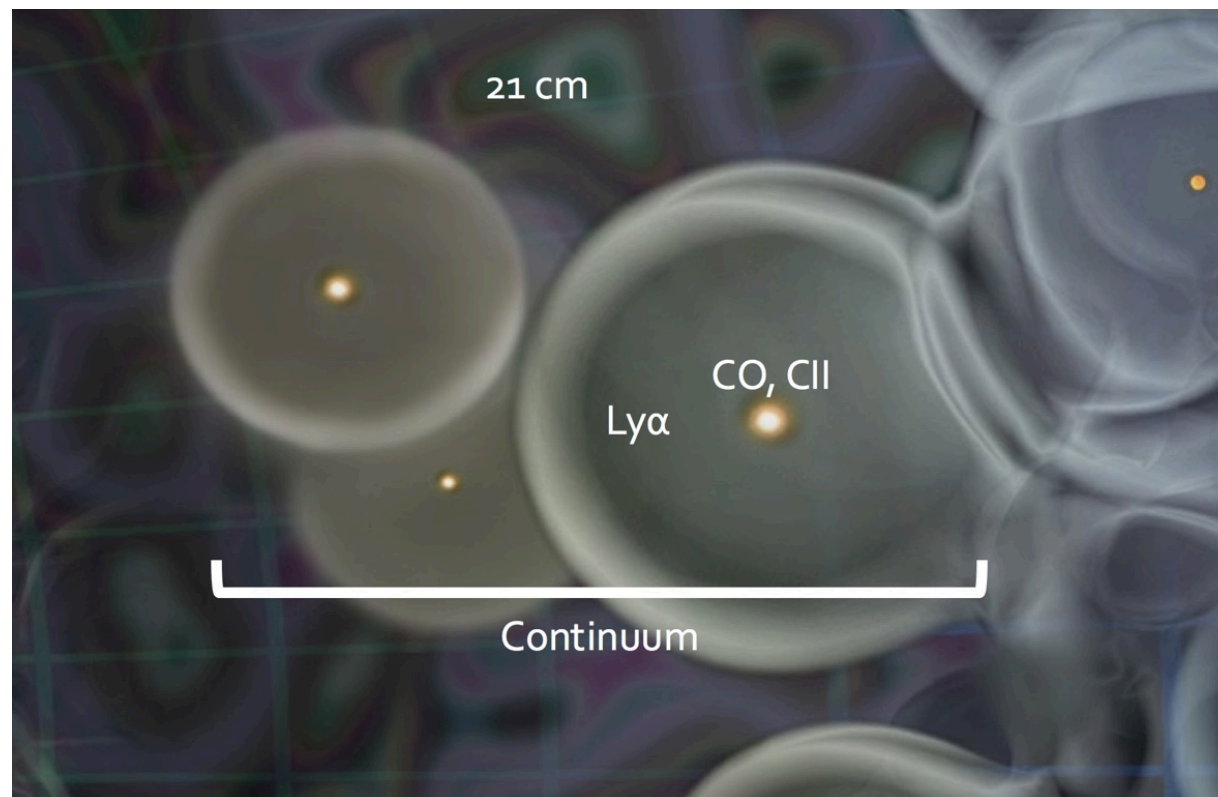




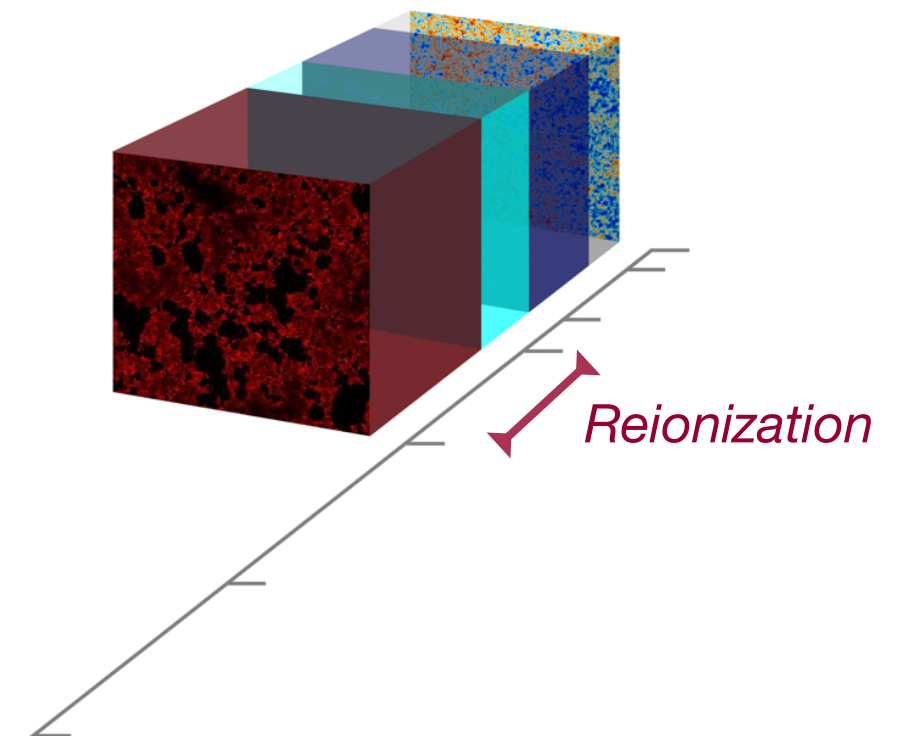
LIM Astrophysics: Epoch of Reionization

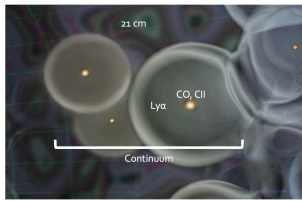


Astro2020: Kovetz et al. [arXiv:1903.04496]



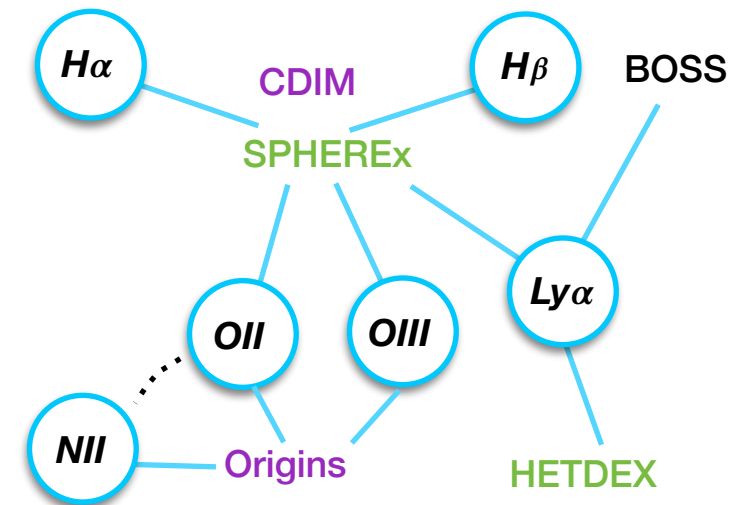
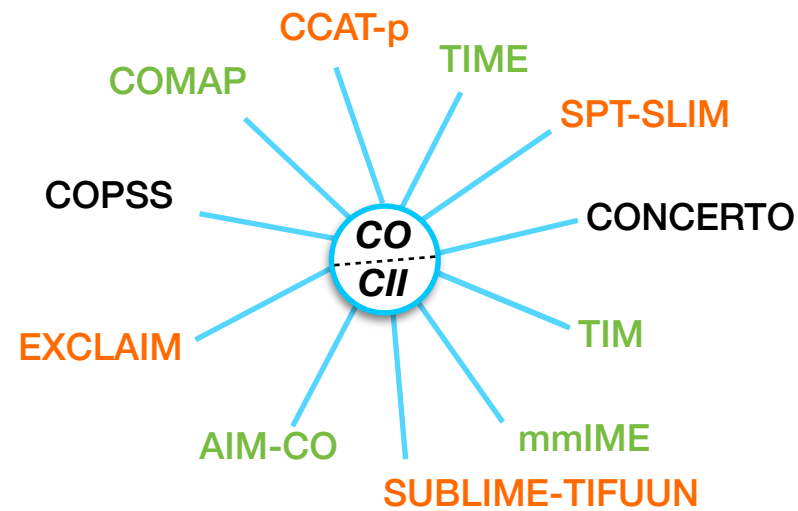
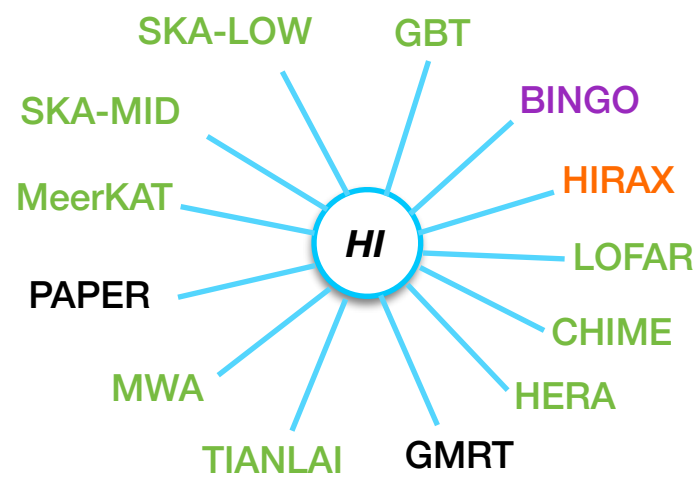
Kovetz et al., LIM Status Report [arXiv:1709.09066]





LIM Astrophysics: Epoch of Reionization

- Complete
- Running
- Funded
- Proposed



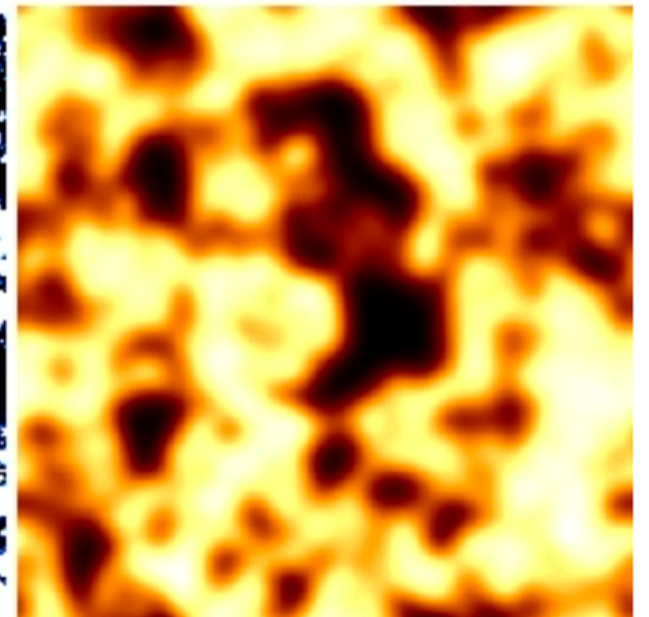
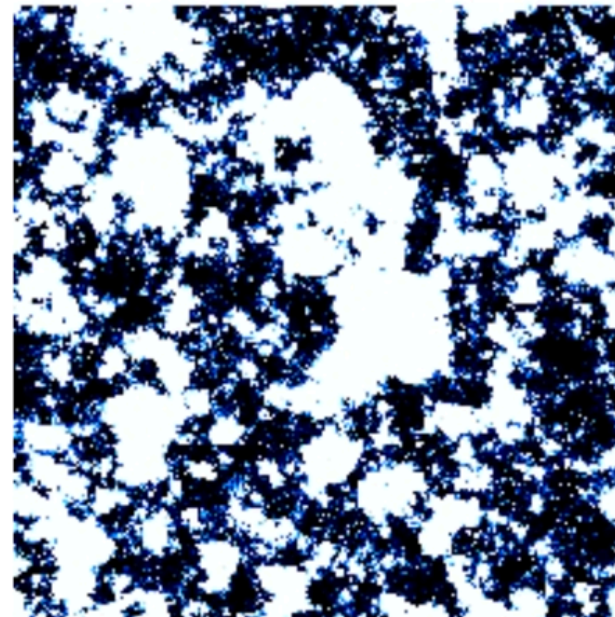
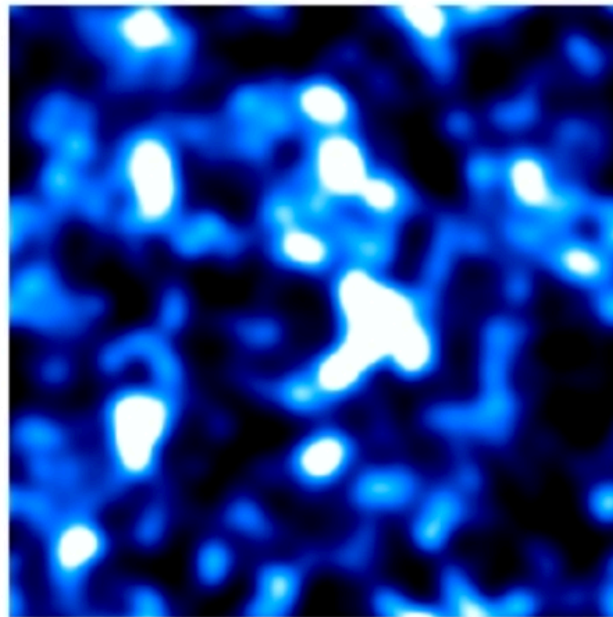
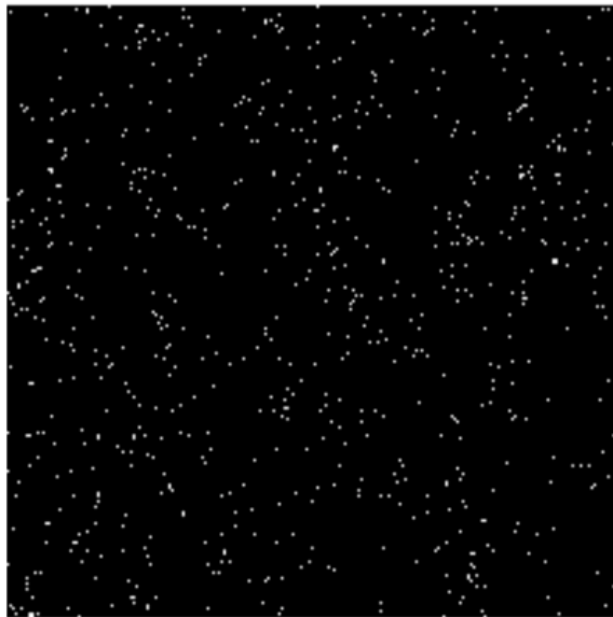
Astro2020: Kovetz et al. [arXiv:1903.04496]

EoR Galaxies

CO(2-1) LIM

Ionization field

Redshifted 21cm



(Courtesy of A. Lidz)

Starting Point: Combining 21cm and other lines

Full radiative-transfer hydrodynamical simulation (extremely computationally expensive):

CoDa (Ocvirk et al., MNRAS 2016) 21SSD (Semelin, MNRAS 2017) THESAN (Kannan et al., MNRAS 2011)

Ray-tracing algorithms (applied to N-body simulations; also very expensive):

$C^2 - Ray$ (Mellema et al., New Astron. 2006) CRASH (Maselli et al., MNRAS 2003)

One-dimensional radiative transfer (much faster, approximated):

BEARS (Thomas et al., MNRAS 2009) GRIZZLY (Ghara et al., MNRAS 2018) BEORN (Schaeffer et al., arXiv:2305.15466)

Purely analytic codes (fastest):

CAMB (Lewis and Challinor, PRD 2007) Zeus21 (Munoz, MNRAS 2023) X21 (Katz et al., arXiv:2309.XXXXXX)

Semi-numerical codes (excursion-set formalism):

SimFAST21 (Santos et. al, MNRAS 2010) 21cmFAST (Mesinger et al., MNRAS 2011)

Starting Point: Combining 21cm and other lines

Full radiative-transfer hydrodynamical simulation (extremely computationally expensive):

CoDa (Ocvirk et al., MNRAS 2016) 21SSD (Semelin, MNRAS 2017) THESAN (Kannan et al., MNRAS 2011)

Ray-tracing algorithms (applied to N-body simulations; also very expensive):

$C^2 - Ray$ (Mellema et al., New Astron. 2006) CRASH (Maselli et al., MNRAS 2003)

One-dimensional radiative transfer (much faster, approximated):

BEARS (Thomas et al., MNRAS 2009) GRIZZLY (Ghara et al., MNRAS 2018) BEORN (Schaeffer et al., arXiv:2305.15466)

Purely analytic codes (fastest):

CAMB (Lewis and Challinor, PRD 2007) Zeus21 (Munoz, MNRAS 2023) X21 (Katz et al., arXiv:2309.XXXXXX)

Semi-numerical codes (excursion-set formalism):

SimFAST21 (Santos et. al, MNRAS 2010) 21cmFAST (Mesinger et al., MNRAS 2011)

Starting Point: Combining 21cm and other lines

Approximation: the SFRD traces the underlying density field as an exponential.

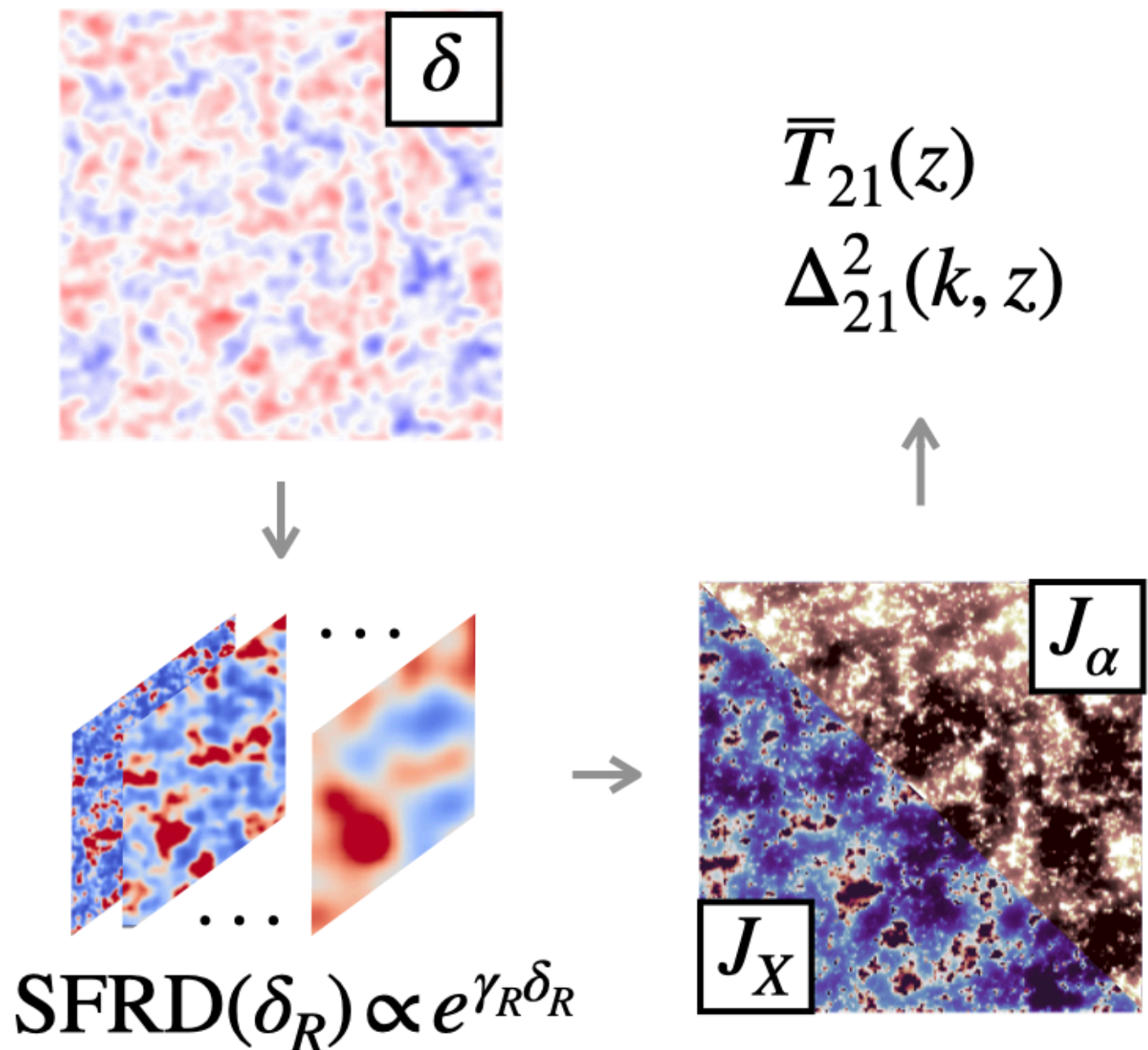
————→ The correlation function of the lognormal SFRD can be computed analytically.



Munoz, MNRAS 2023



Julian Muñoz



Starting Point: Combining 21cm and other lines

New: oLIMpus: An Effective Model for Line Intensity Mapping Auto- and Cross-Power Spectra in Cosmic Dawn and Reionization

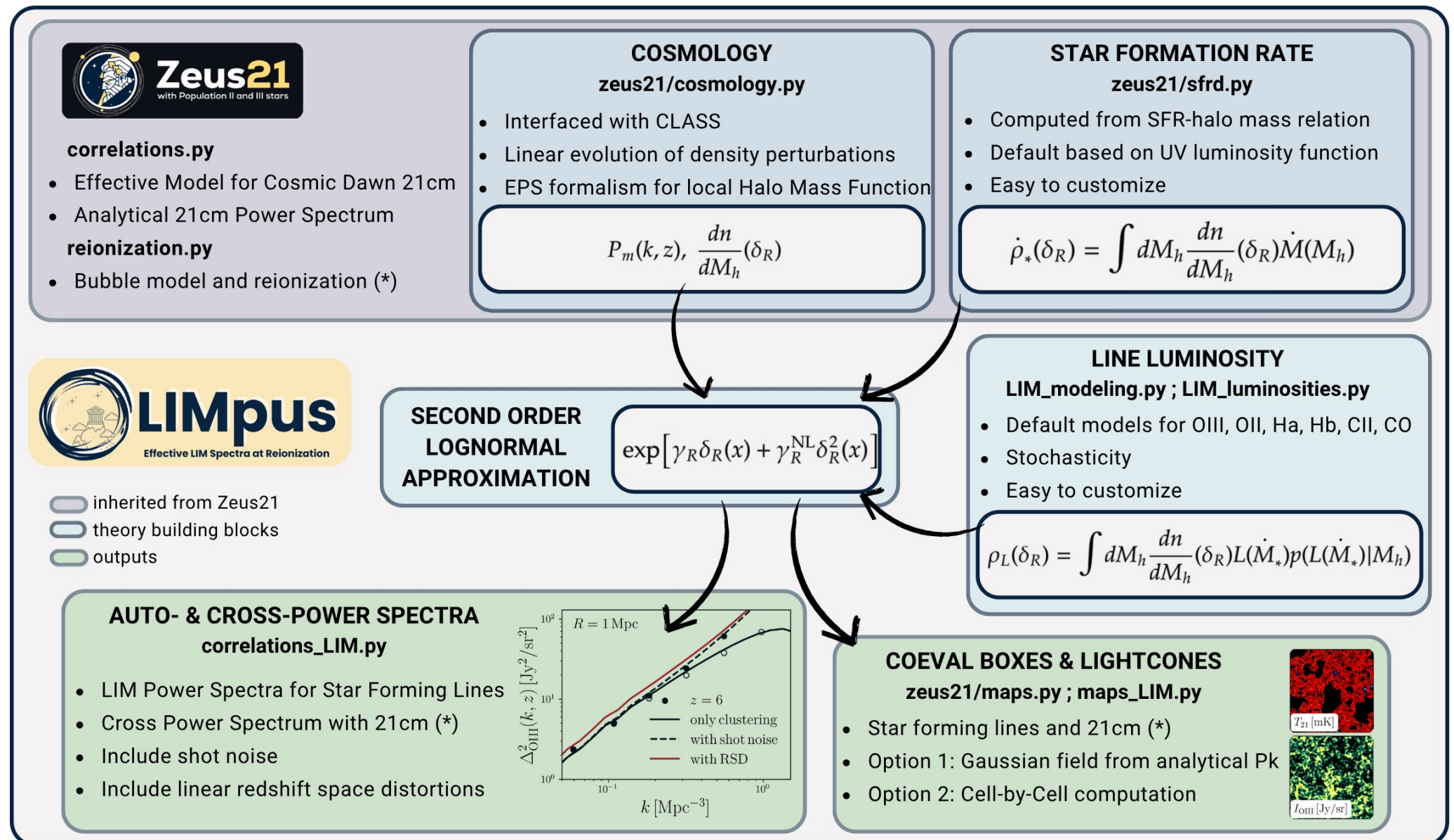
Sarah Libanore,^{1,*} Julian B. Muñoz,² and Ely D. Kovetz^{1,3}



Sarah Libanore



Julian Muñoz



Starting Point: Combining 21cm and other lines

New: oLIMpus: An Effective Model for Line Intensity Mapping Auto- and Cross-Power Spectra in Cosmic Dawn and Reionization

Sarah Libanore,^{1,*} Julian B. Muñoz,² and Ely D. Kovetz^{1,3}



correlations.py

- Effective Model for Cosmic Dawn 21cm
- Analytical 21cm Power Spectrum
- reionization.py**
- Bubble model and reionization (*)

COSMOLOGY

zeus21/cosmology.py

- Interfaced with CLASS
- Linear evolution of density perturbations
- EPS formalism for local Halo Mass Function

$$P_m(k, z), \frac{dn}{dM_h}(\delta_R)$$

STAR FORMATION RATE

zeus21/sfrd.py

- Computed from SFR-halo mass relation
- Default based on UV luminosity function
- Easy to customize

$$\dot{\rho}_*(\delta_R) = \int dM_h \frac{dn}{dM_h}(\delta_R) \dot{M}(M_h)$$



- inherited from Zeus21
- theory building blocks
- outputs

SECOND ORDER LOGNORMAL APPROXIMATION

$$\exp[\gamma_R \delta_R(x) + \gamma_R^{NL} \delta_R^2(x)]$$

LINE LUMINOSITY

LIM_modeling.py ; LIM_luminosities.py

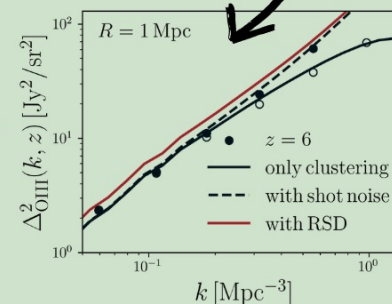
- Default models for OIII, OII, Ha, Hb, CII, CO
- Stochasticity
- Easy to customize

$$\rho_L(\delta_R) = \int dM_h \frac{dn}{dM_h}(\delta_R) L(\dot{M}_*) p(L(\dot{M}_*) | M_h)$$

AUTO- & CROSS-POWER SPECTRA

correlations_LIM.py

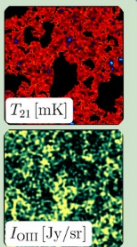
- LIM Power Spectra for Star Forming Lines
- Cross Power Spectrum with 21cm (*)
- Include shot noise
- Include linear redshift space distortions



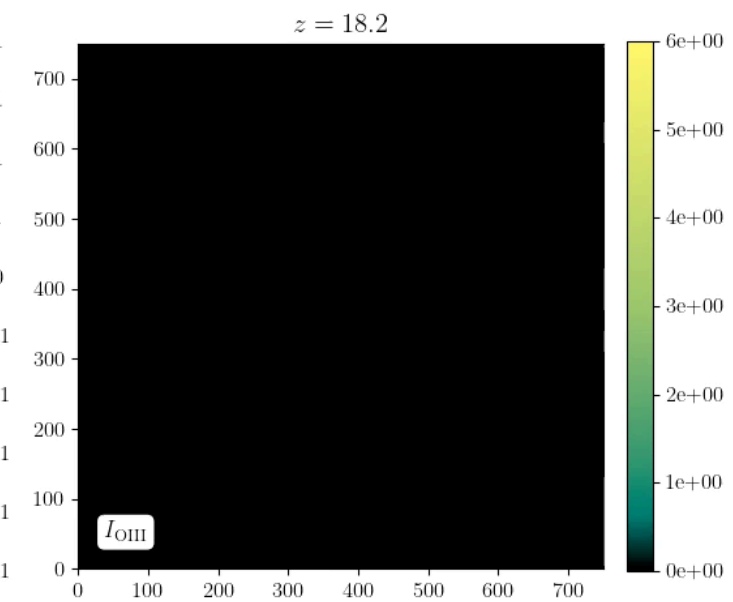
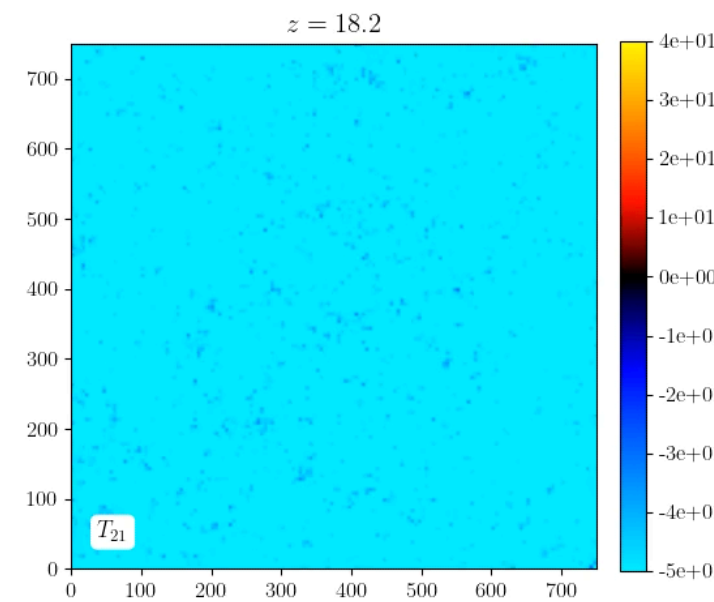
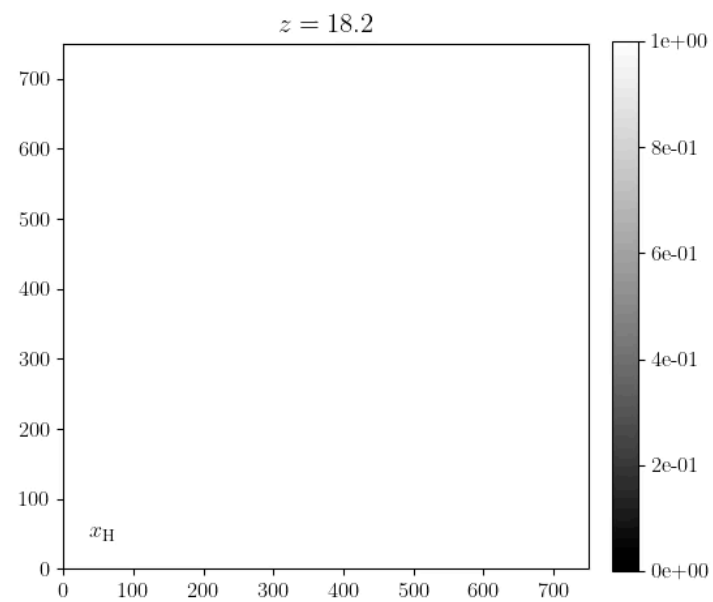
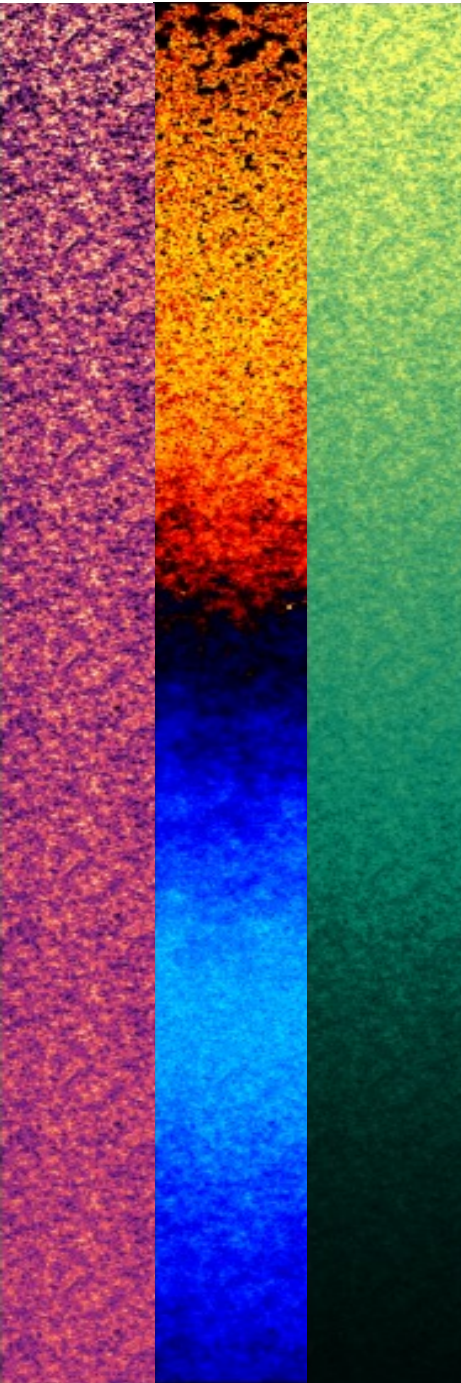
COEVAL BOXES & LIGHTCONES

zeus21/maps.py ; maps_LIM.py

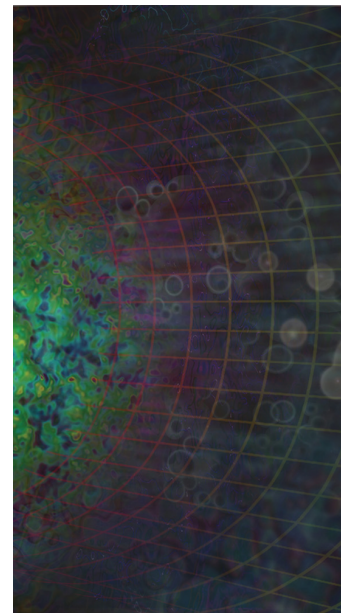
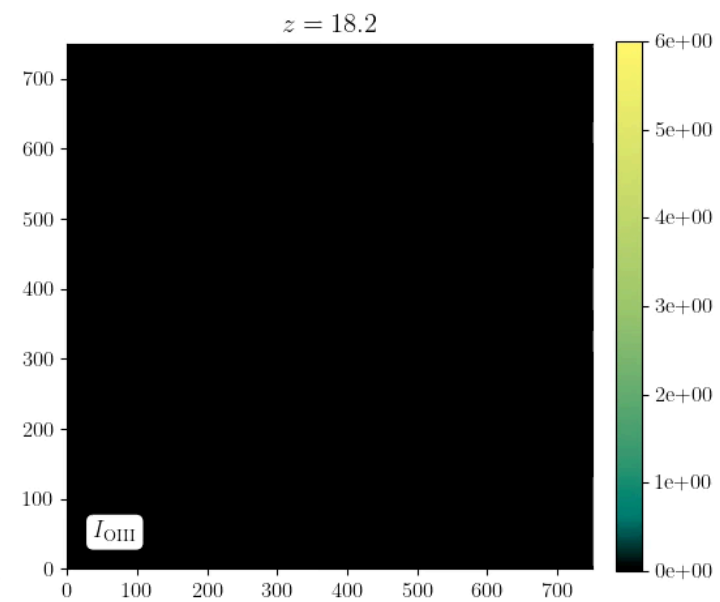
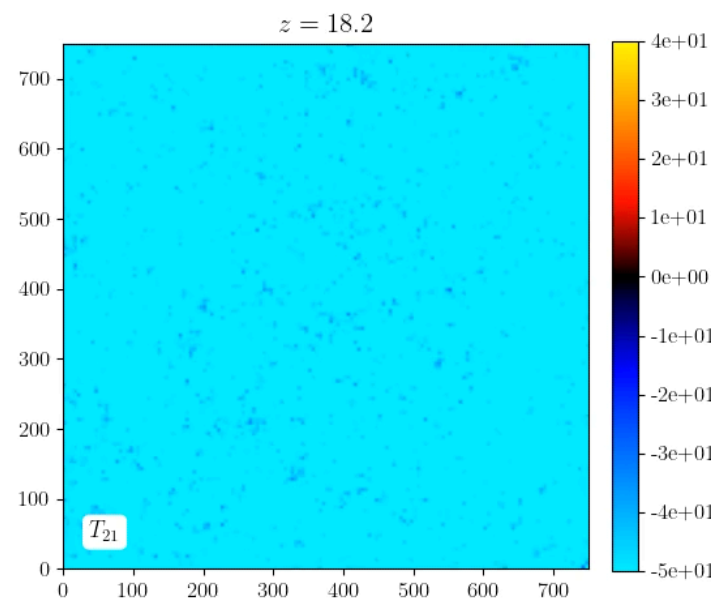
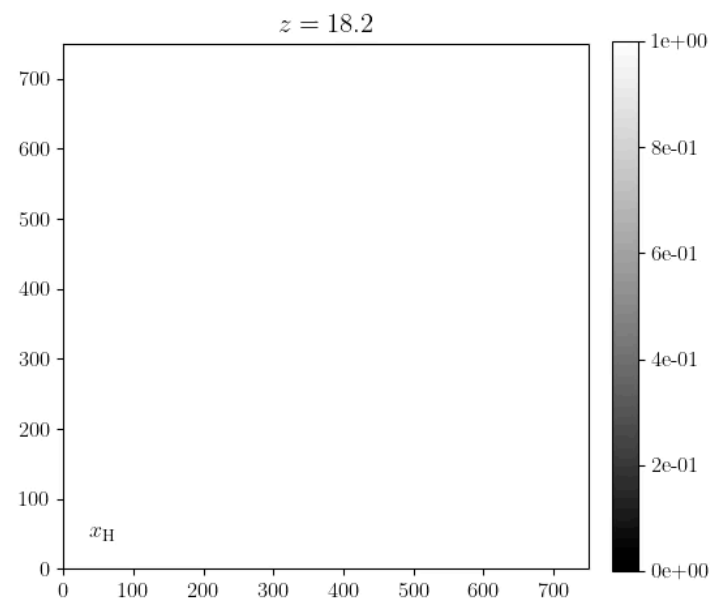
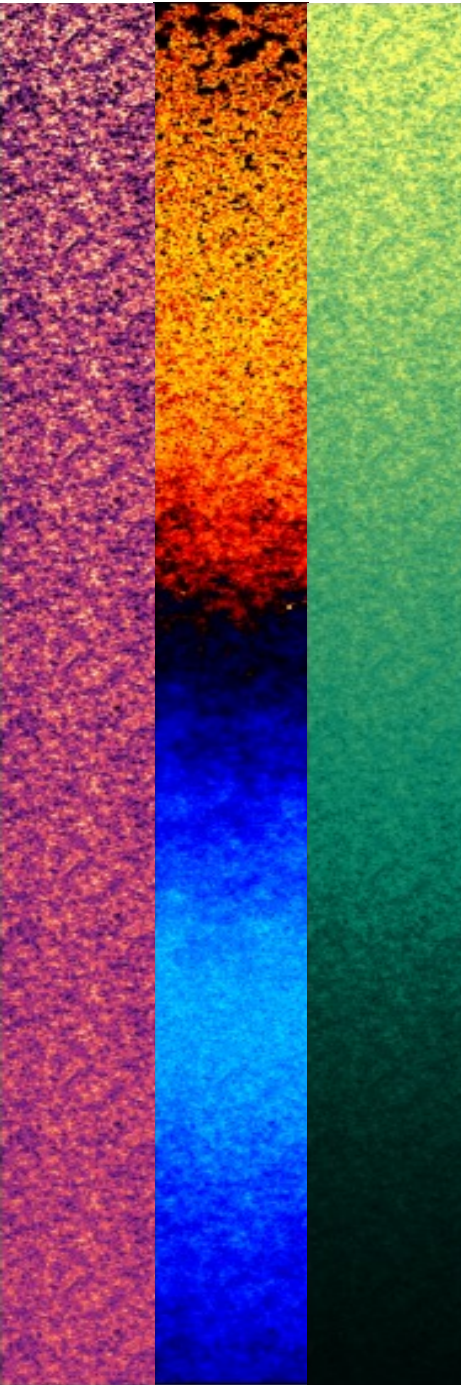
- Star forming lines and 21cm (*)
- Option 1: Gaussian field from analytical Pk
- Option 2: Cell-by-Cell computation



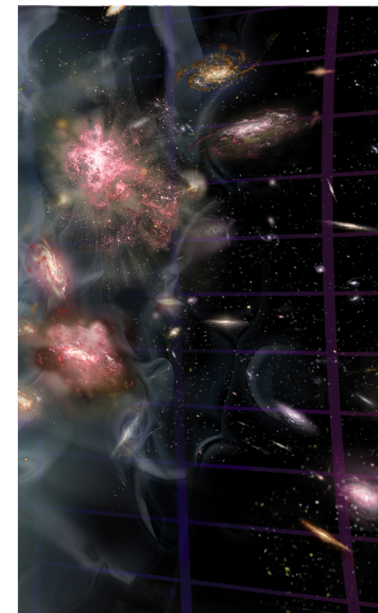
Starting Point: Combining 21cm and other lines

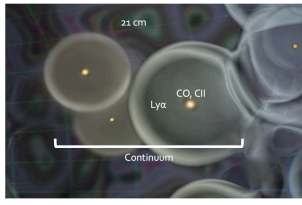


Starting Point: Combining 21cm and other lines



Can we
detect this?

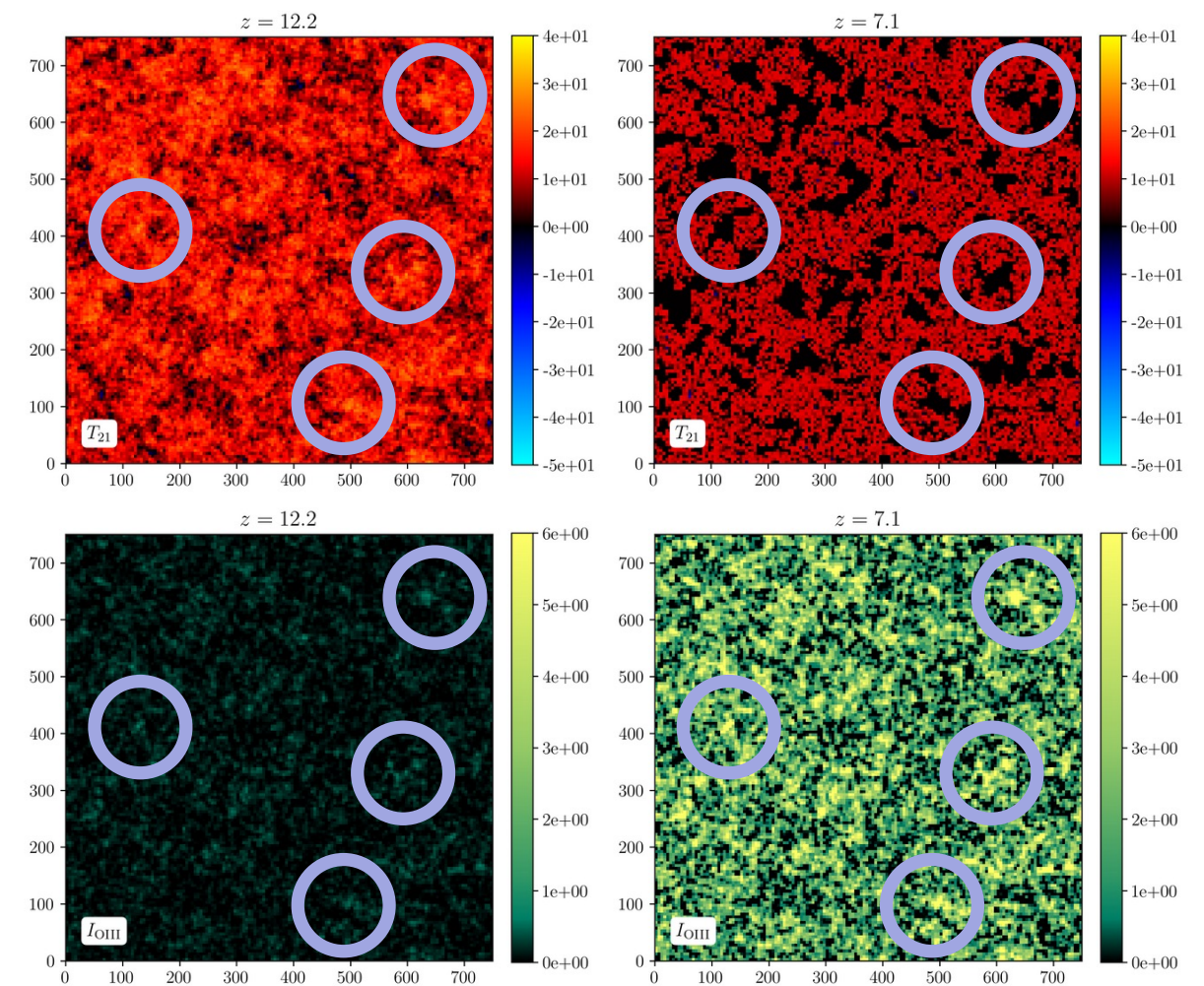


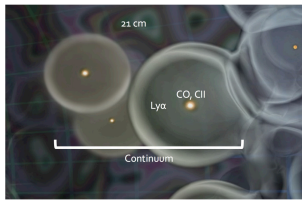


Can we determine when reionization began?

At high-density peaks:

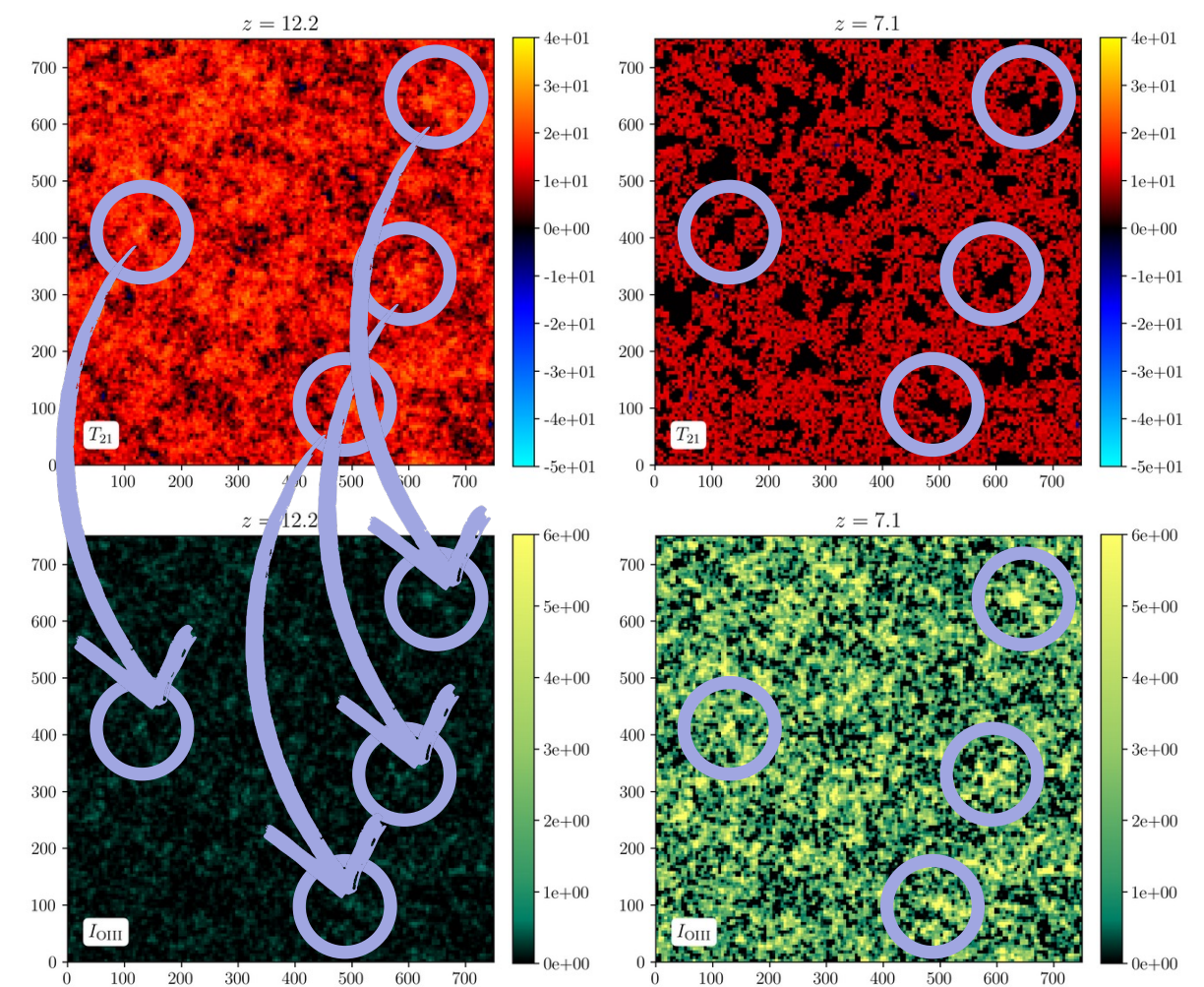
- Stars form faster
- IGM heats faster
- IGM ionizes faster
- Other lines emitted faster

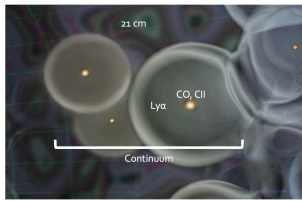




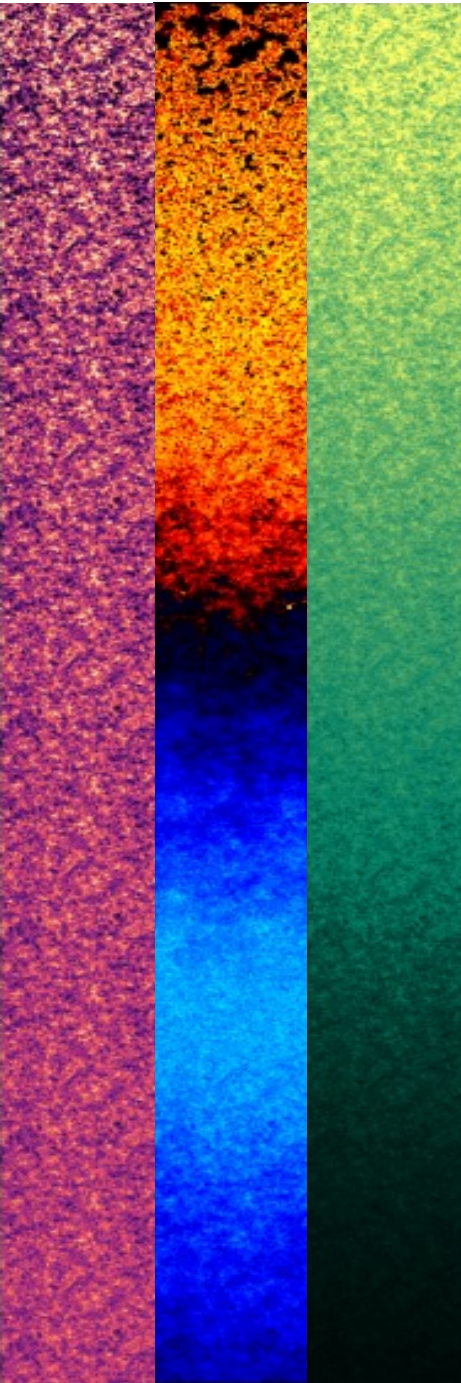
Can we determine when reionization began?

Cross correlate!





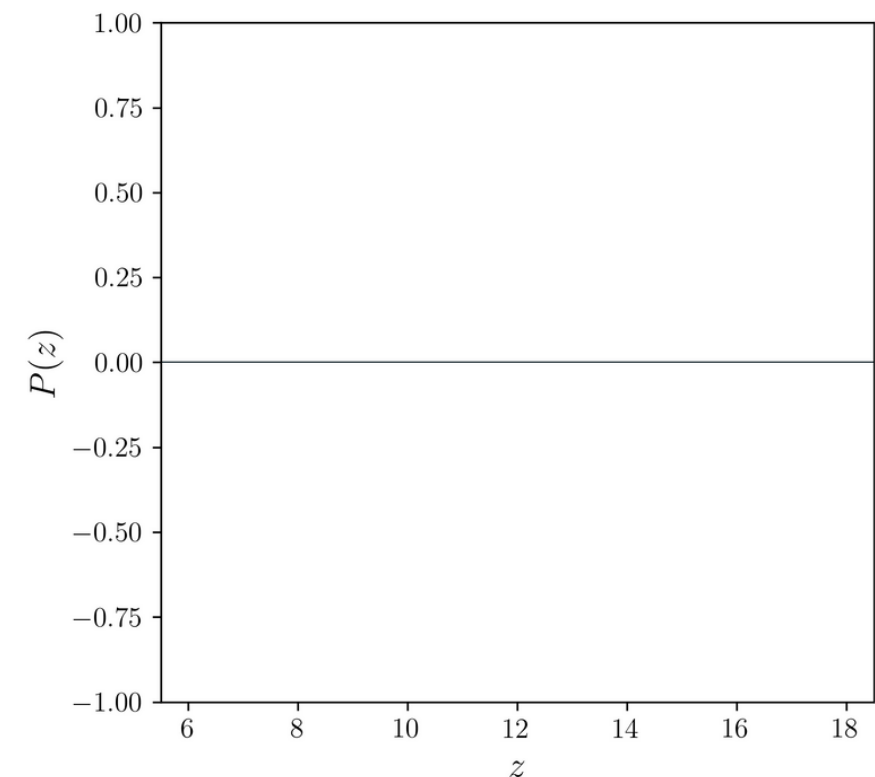
Can we determine when reionization began?

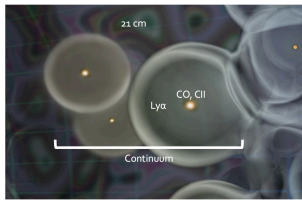


Cross correlate!

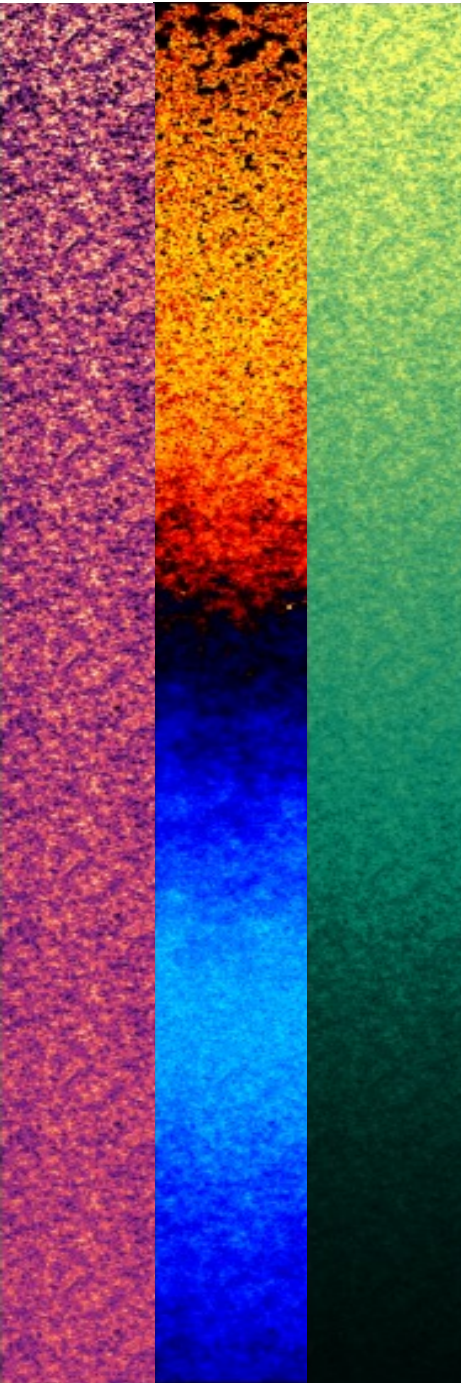
One-point Pearson coefficient:

$$P = \frac{\sum_{ij} (T_{21}^{ij} - \bar{T}_{21}) (T_{\text{OIII}}^{ij} - \bar{T}_{\text{OIII}})}{\sqrt{\sum_{ij} (T_{21}^{ij} - \bar{T}_{21})^2 (T_{\text{OIII}}^{ij} - \bar{T}_{\text{OIII}})^2}}$$





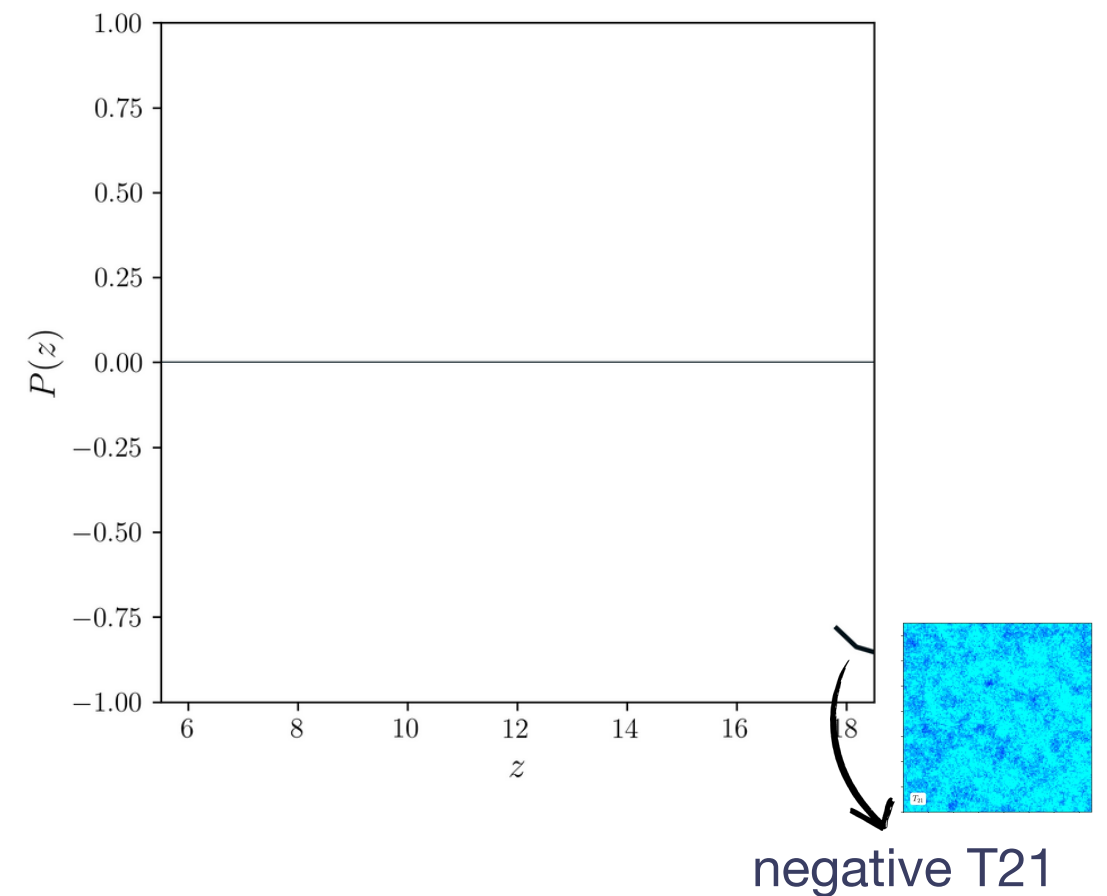
Can we determine when reionization began?

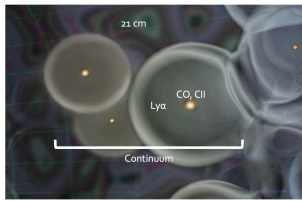


Cross correlate!

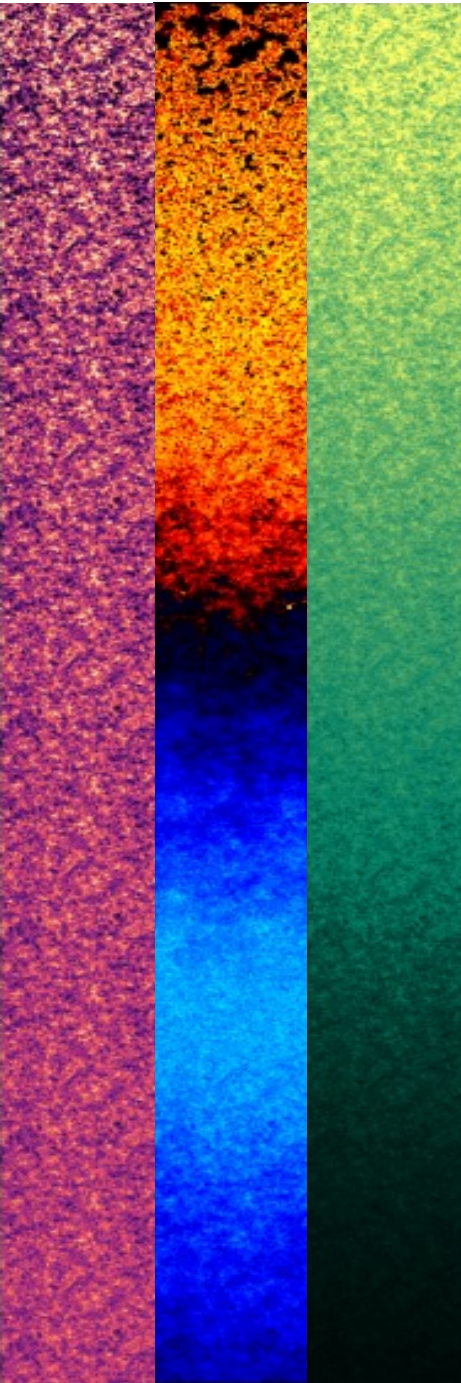
One-point Pearson coefficient:

$$P = \frac{\sum_{ij} (T_{21}^{ij} - \bar{T}_{21}) (T_{\text{OIII}}^{ij} - \bar{T}_{\text{OIII}})}{\sqrt{\sum_{ij} (T_{21}^{ij} - \bar{T}_{21})^2 (T_{\text{OIII}}^{ij} - \bar{T}_{\text{OIII}})^2}}$$





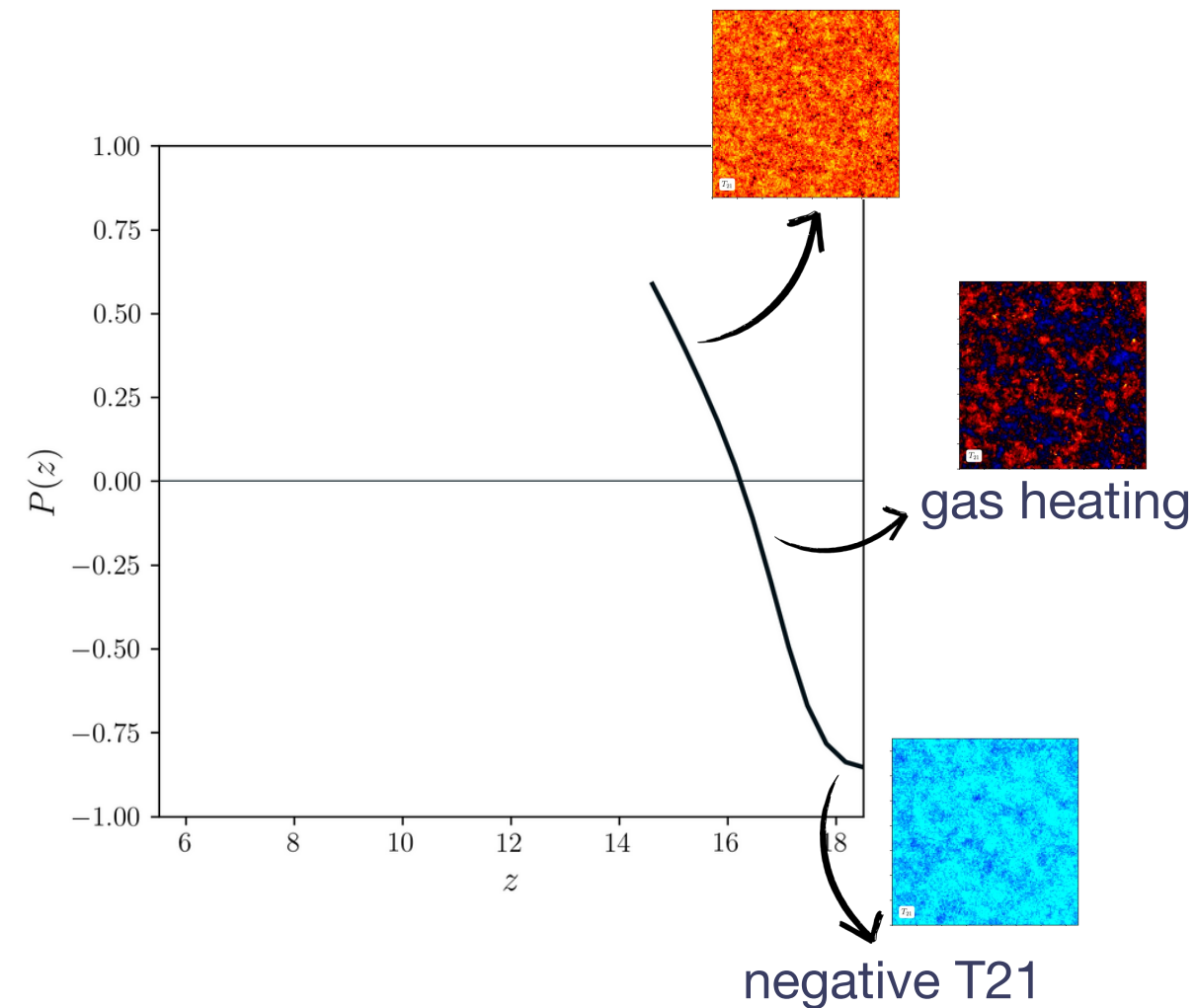
Can we determine when reionization began?

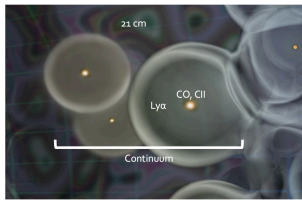


Cross correlate!

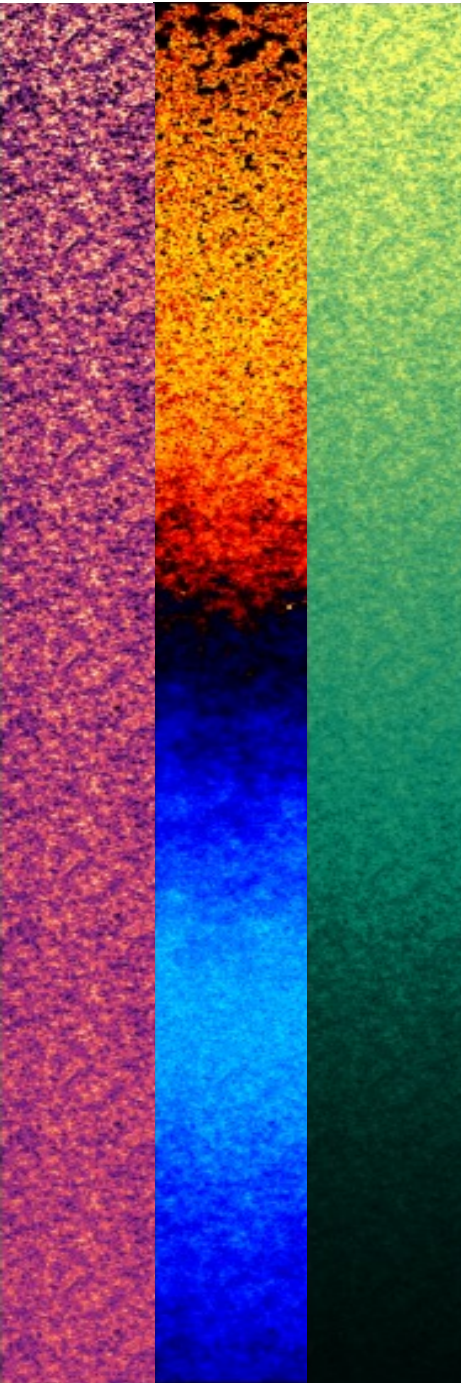
One-point Pearson coefficient:

$$P = \frac{\sum_{ij} (T_{21}^{ij} - \bar{T}_{21}) (T_{\text{OIII}}^{ij} - \bar{T}_{\text{OIII}})}{\sqrt{\sum_{ij} (T_{21}^{ij} - \bar{T}_{21})^2 (T_{\text{OIII}}^{ij} - \bar{T}_{\text{OIII}})^2}}$$

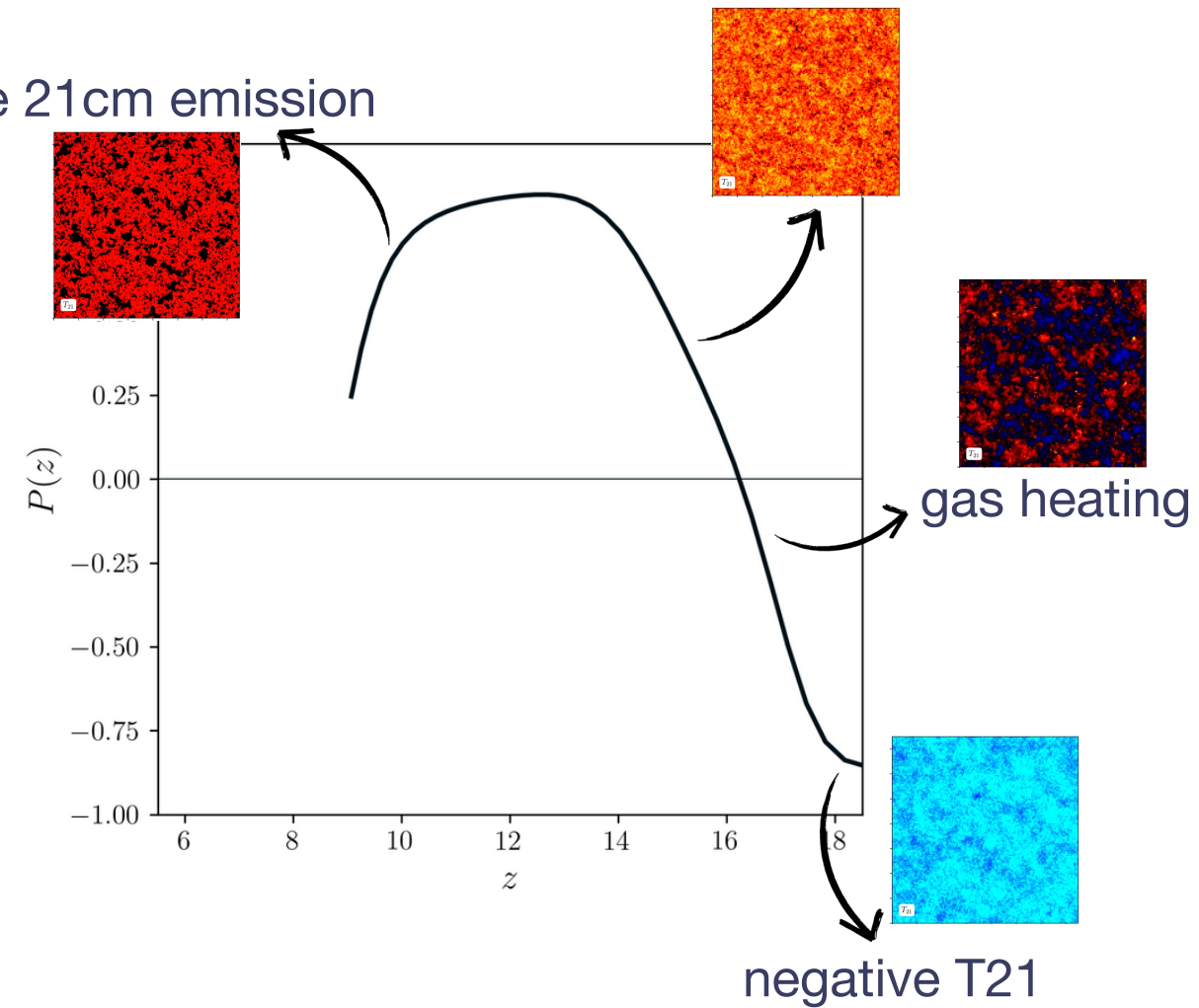


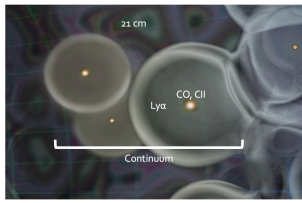


Can we determine when reionization began?

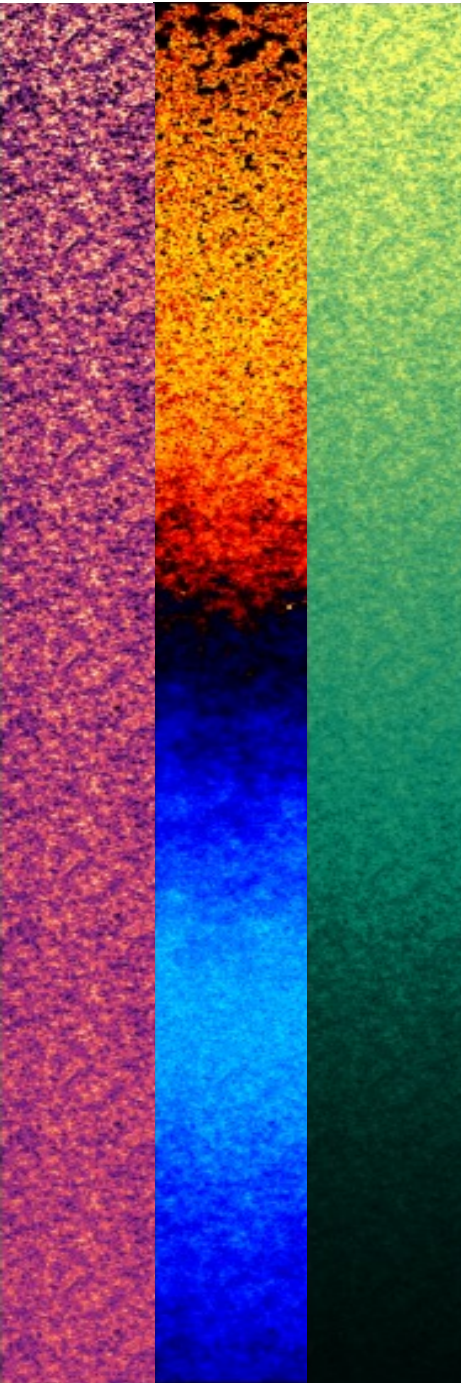


reionization suppresses the 21cm emission

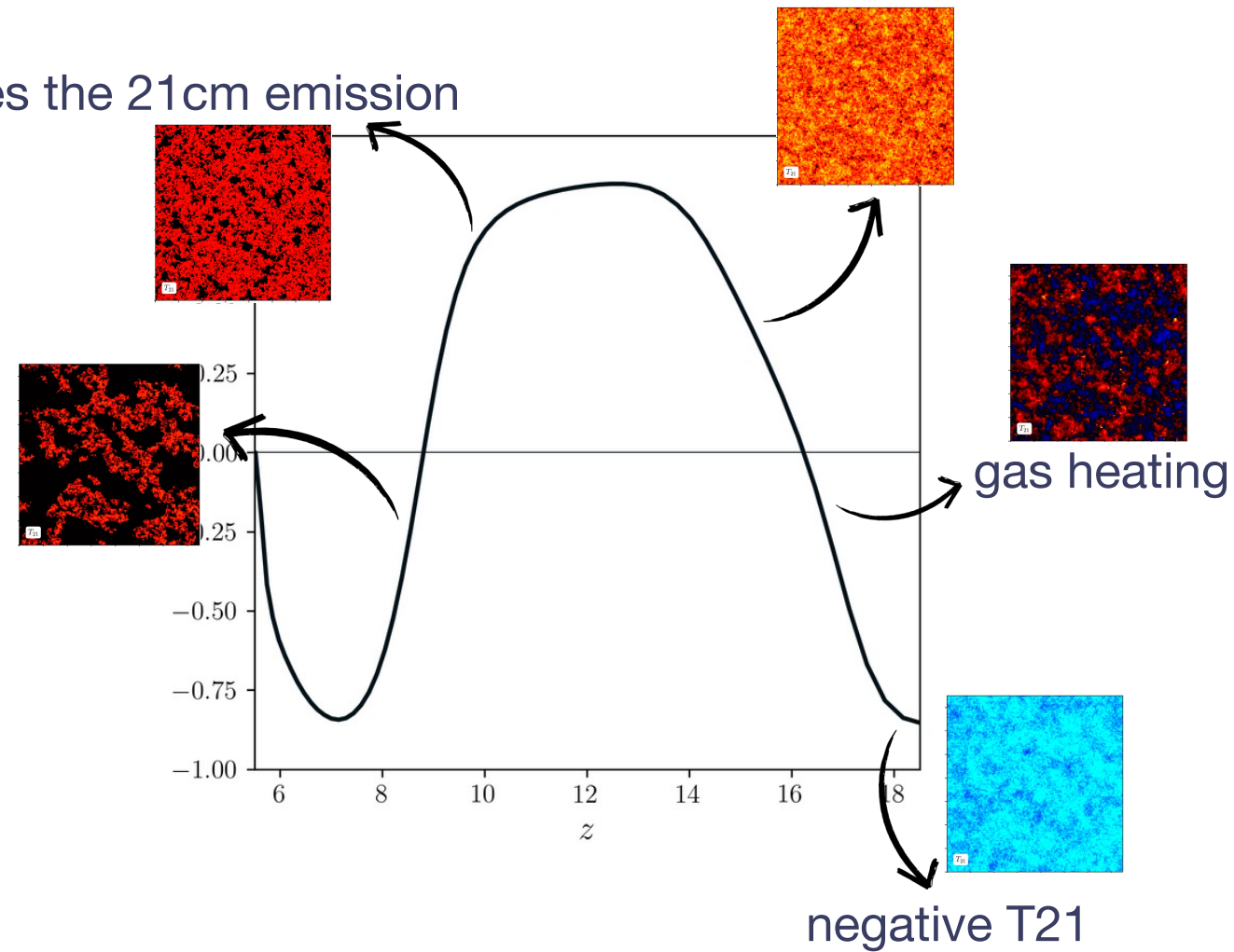


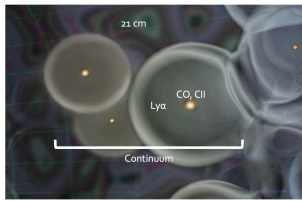


Can we determine when reionization began?

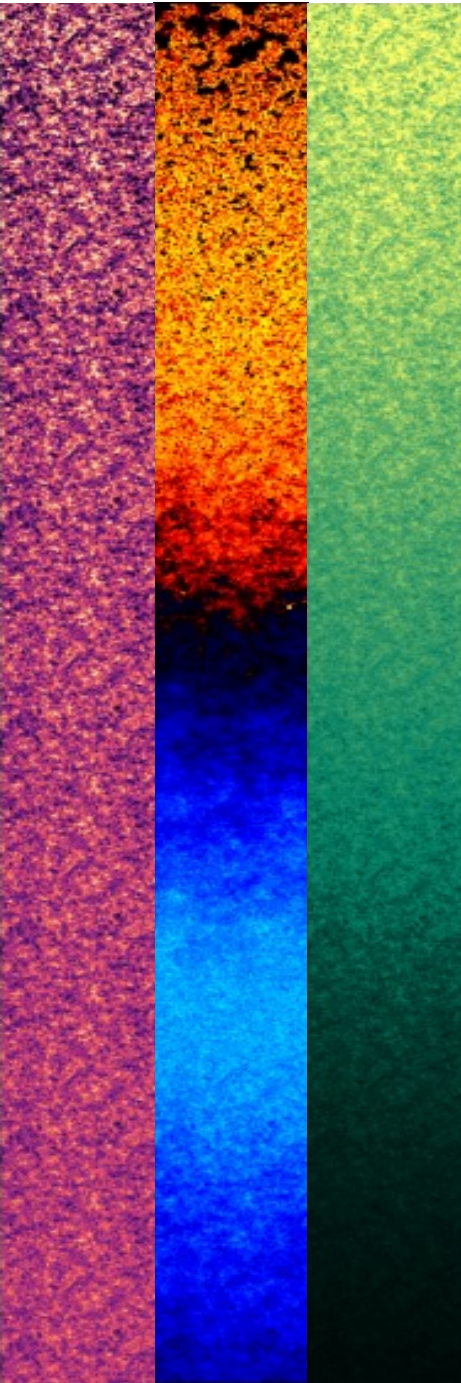


reionization suppresses the 21cm emission

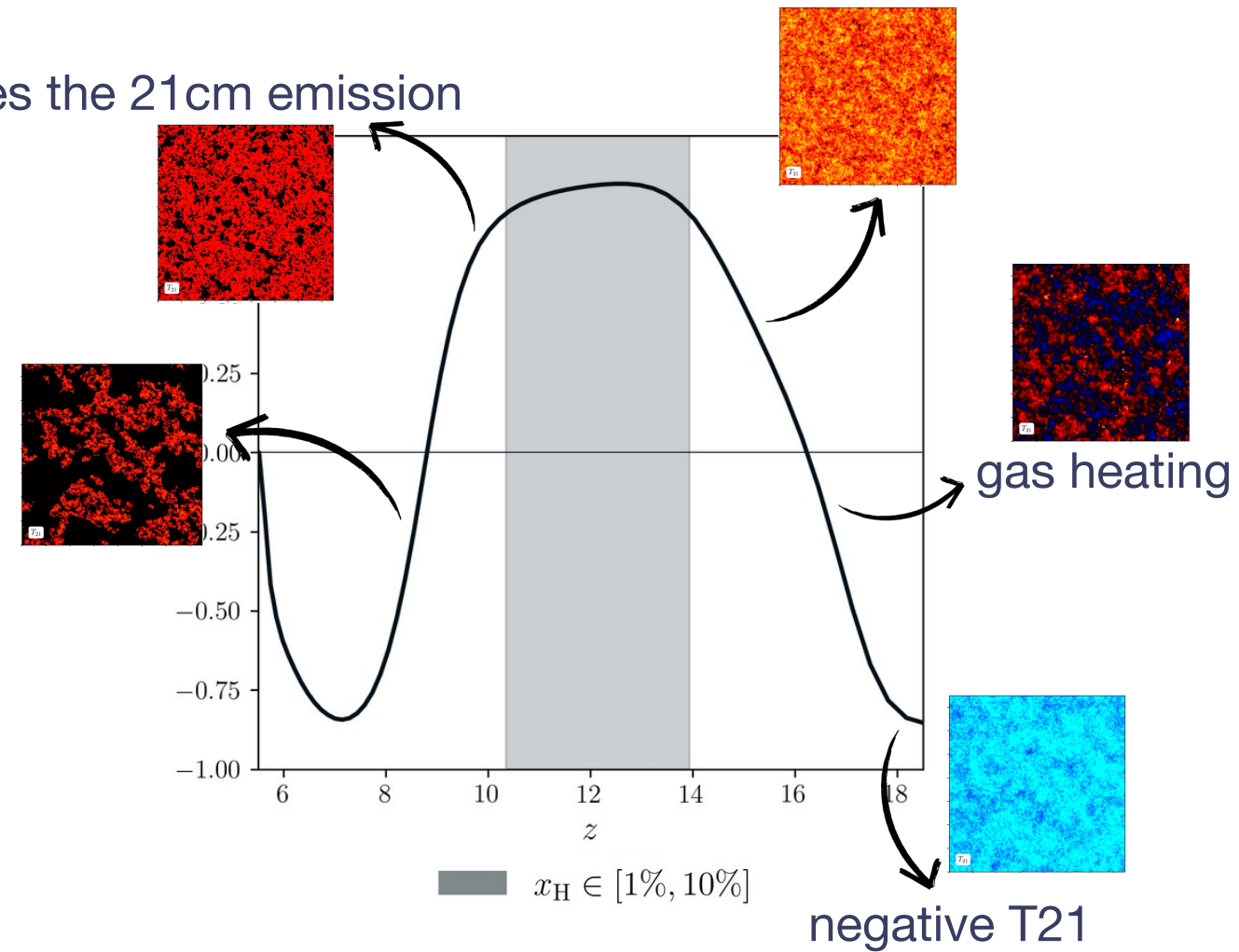


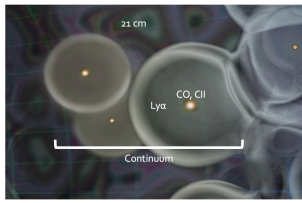


Can we determine when reionization began?



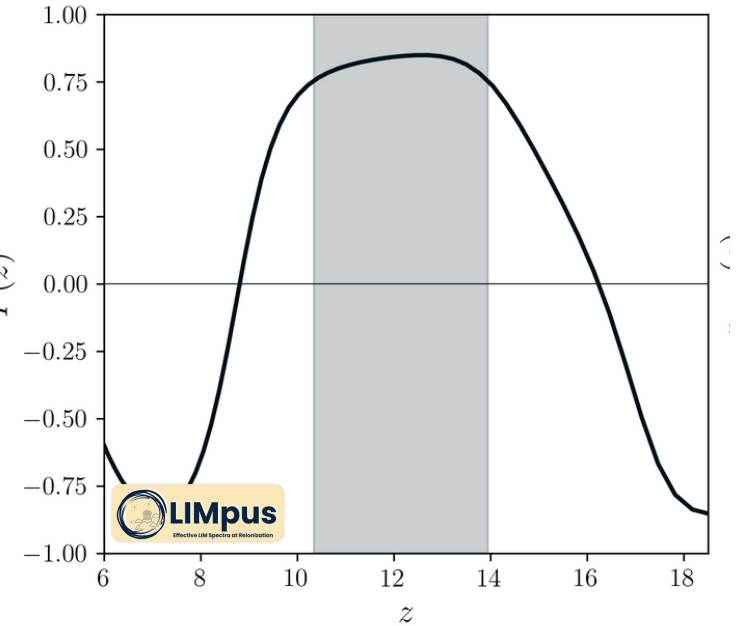
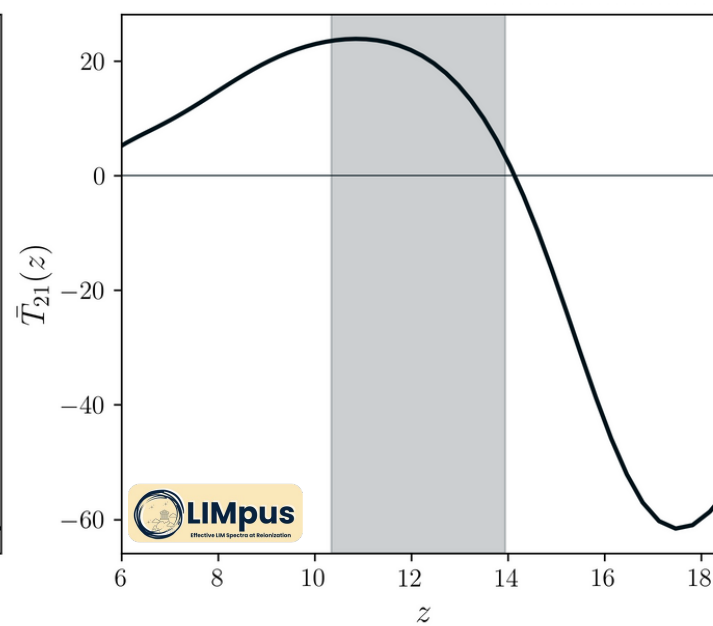
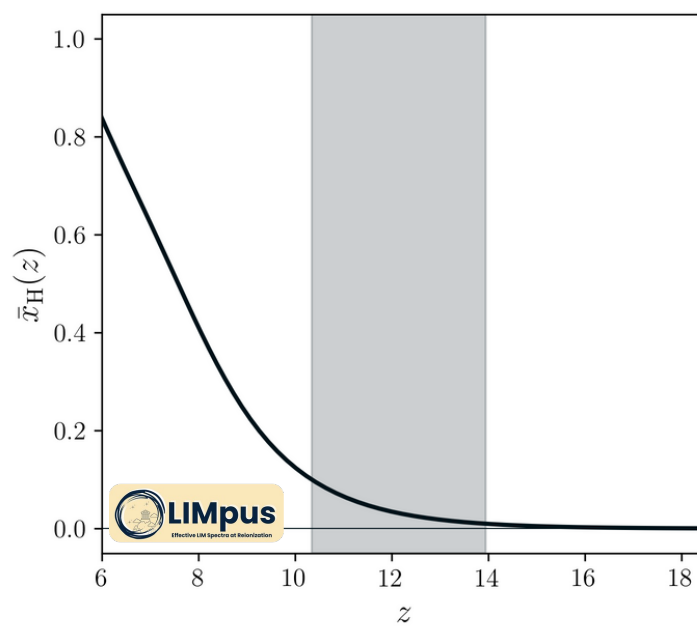
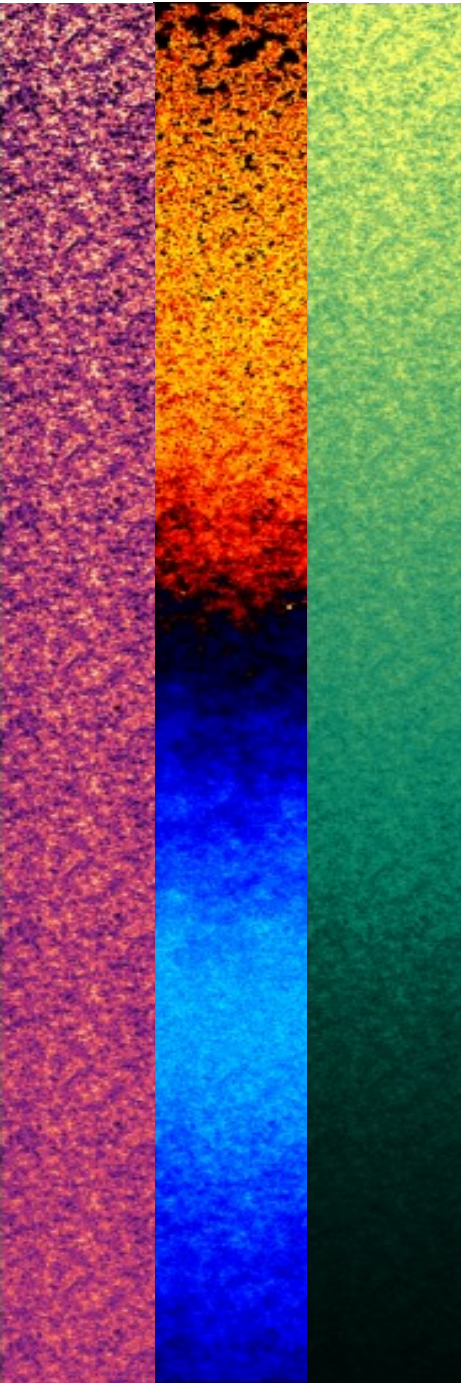
reionization suppresses the 21cm emission

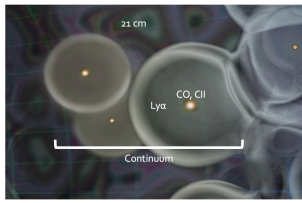




A New Boundary Condition on Reionization

Robust?





A New Boundary Condition on Reionization

Robust?

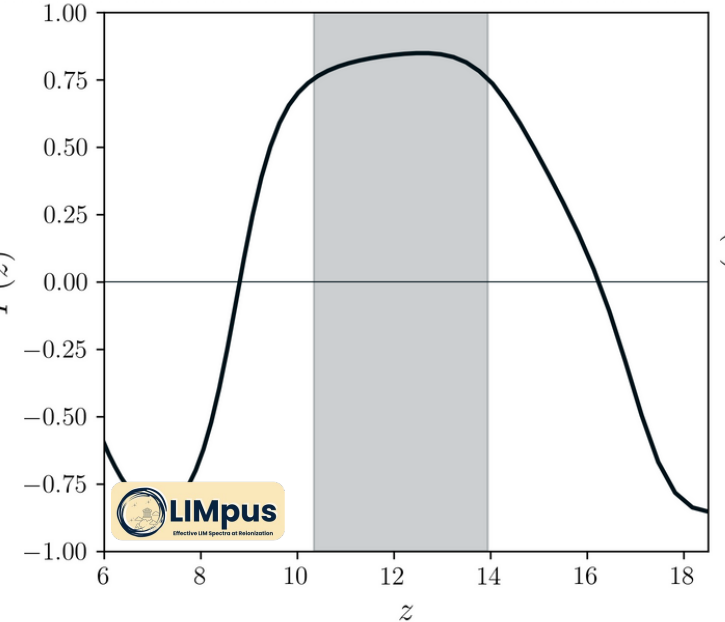
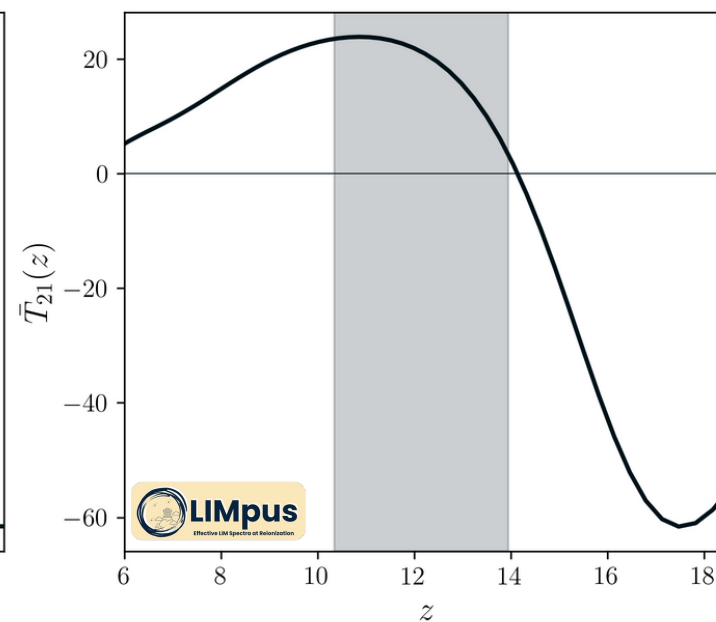
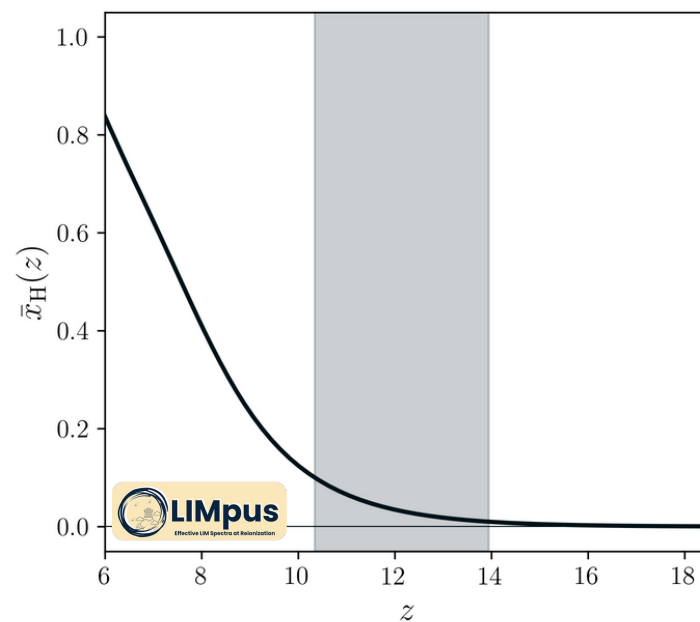
If I consider the correlation between 21cm temperature and OIII intensity mapping, what will its shape be as a function of redshift during cosmic dawn and reionization?

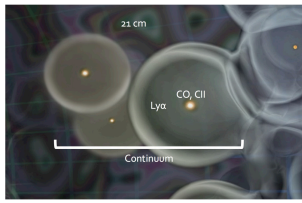
Grok

Visualizing the Shape

The shape of $\rho(z)$ resembles a curve that:

- Starts negative at high redshift ($z \sim 20-30$).
- Rises, crosses zero, and briefly becomes positive around $z \sim 12-15$.
- Dips to a negative peak during mid-reionization ($z \sim 7-9$).
- Returns to zero as reionization completes ($z \sim 6$).





A New Boundary Condition on Reionization

Robust?

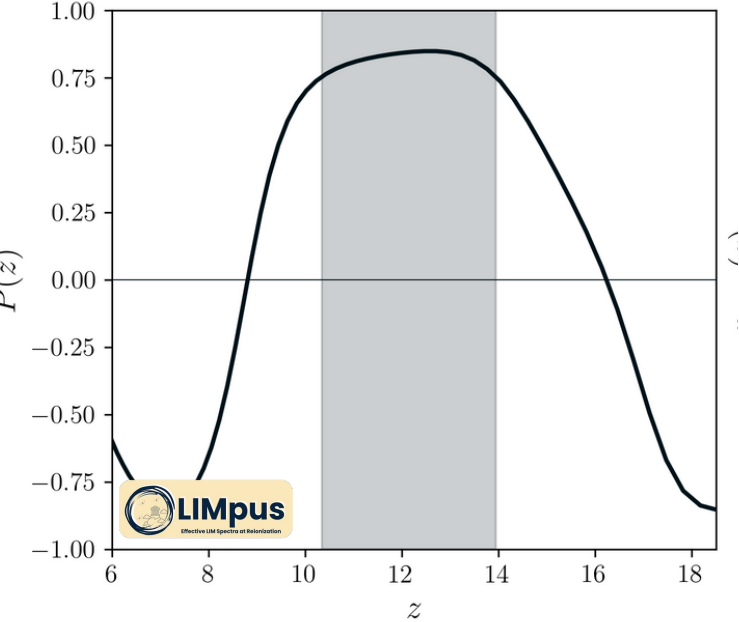
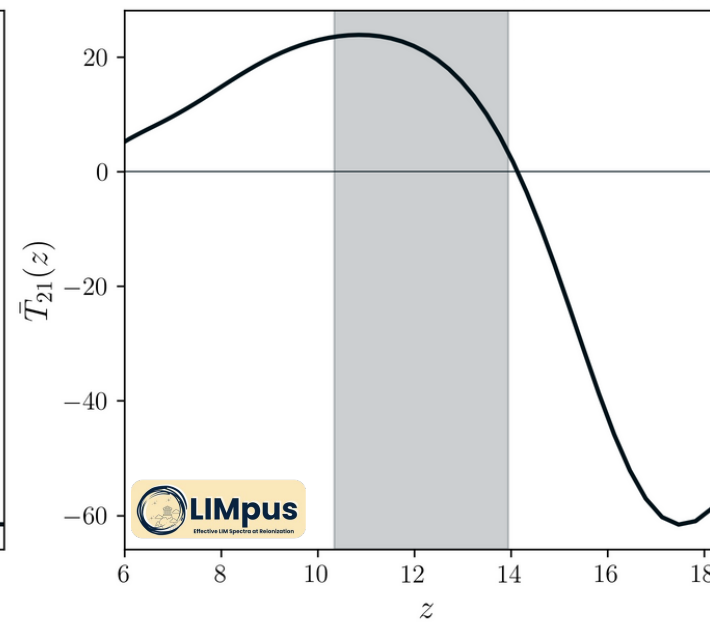
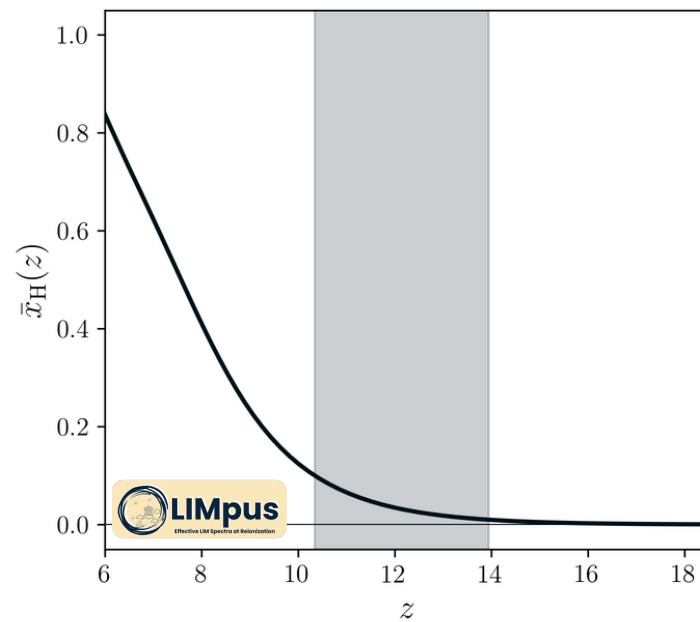
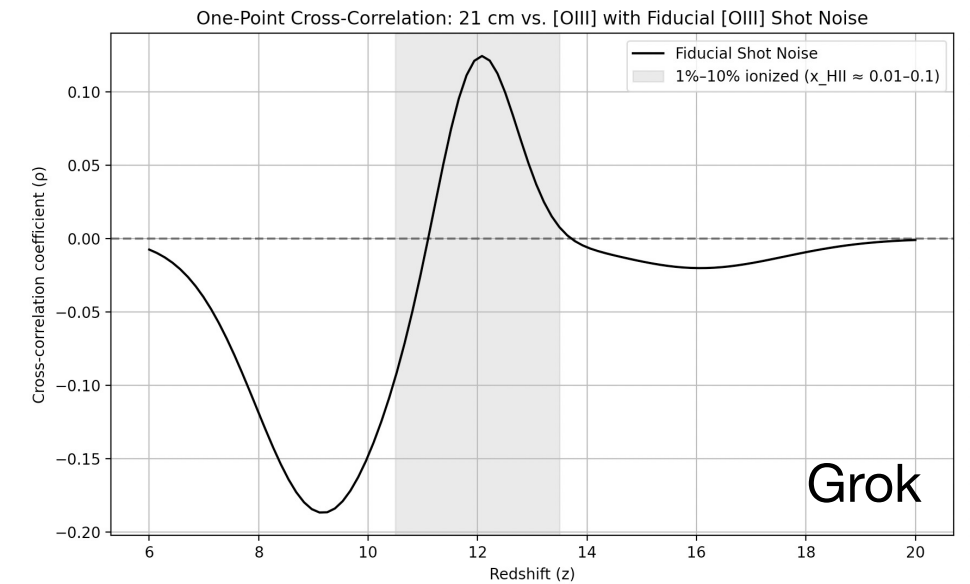
If I consider the correlation between 21cm temperature and OIII intensity mapping, what will its shape be as a function of redshift during cosmic dawn and reionization?

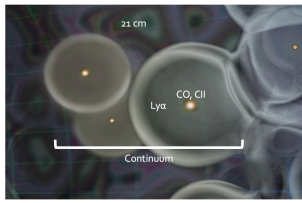
Grok

Visualizing the Shape

The shape of $\rho(z)$ resembles a curve that:

- Starts negative at high redshift ($z \sim 20-30$).
- Rises, crosses zero, and briefly becomes positive around $z \sim 12-15$.
- Dips to a negative peak during mid-reionization ($z \sim 7-9$).
- Returns to zero as reionization completes ($z \sim 6$).



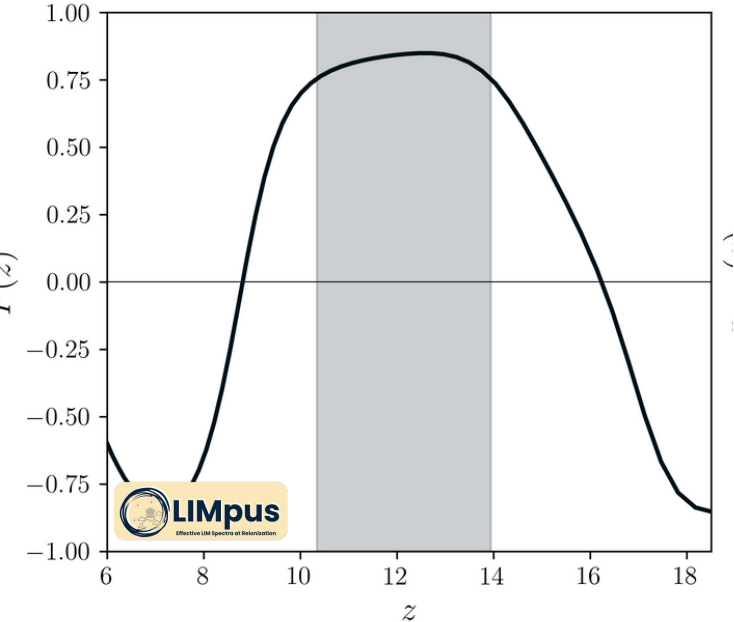
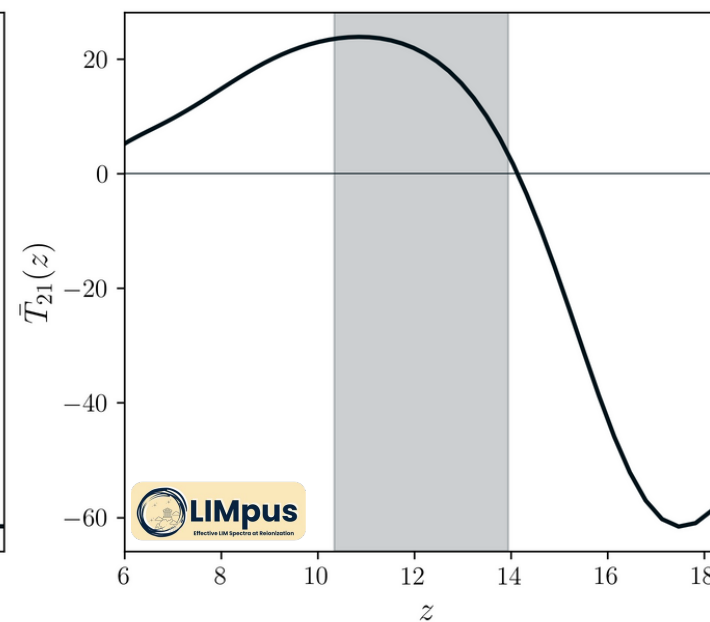
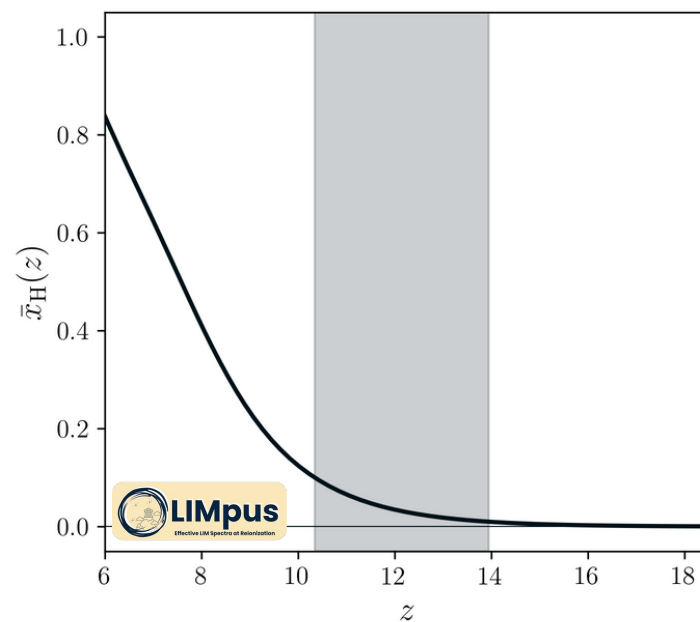
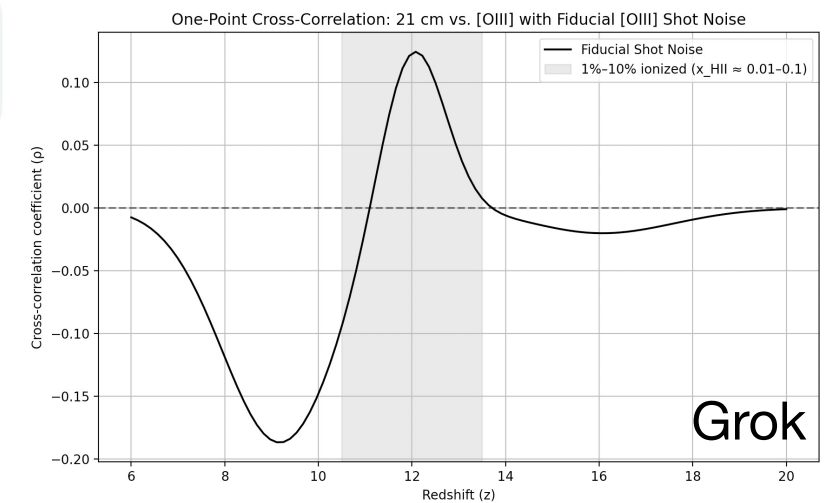


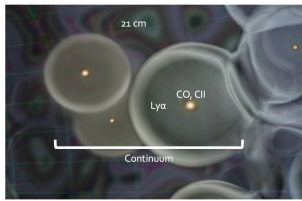
A New Boundary Condition on Reionization

Robust?

so, it measuring the maximum of this cross-correlation signal a way to probe the very early stages of reionization? is there any other way to do that?

Yes, measuring the **maximum** of the one-point cross-correlation coefficient (ρ) between the 21 cm brightness temperature (T_{21}) and [OIII] intensity ($I_{[\text{OIII}]}$) can indeed probe the **very early stages of reionization** (e.g., $z \sim 12-15$, when the ionized fraction $x_{\text{HII}} \approx 0.01-0.1$). This is because the cross-correlation is sensitive to the interplay between neutral hydrogen (traced by 21 cm) and ionized regions in early star-forming galaxies (traced by [OIII]). The maximum positive correlation, occurring around $z \sim 12-14$ in our phenomenological model, corresponds to the transition of the 21 cm signal from absorption to emission due to X-ray heating, just as reionization begins with the formation of the first ionized bubbles.





A New Boundary Condition on Reionization

Robust?

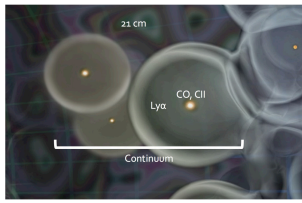
Robust Detection of Early Reionization Onset Through Multi-Messenger Tomography: A Parameter-Agnostic Approach with Joint 21cm and [OIII] Data
DENARIO¹
¹ Anthropic, Gemini & OpenAI servers. Planet Earth.

Probing Earliest Reionization Heating: A 21-cm Stacking Analysis Reveals Onset at $z=12.5$, Highlighting Limitations of [OIII] Tracers in Current Simulations
DENARIO¹
¹ Anthropic, Gemini & OpenAI servers. Planet Earth.

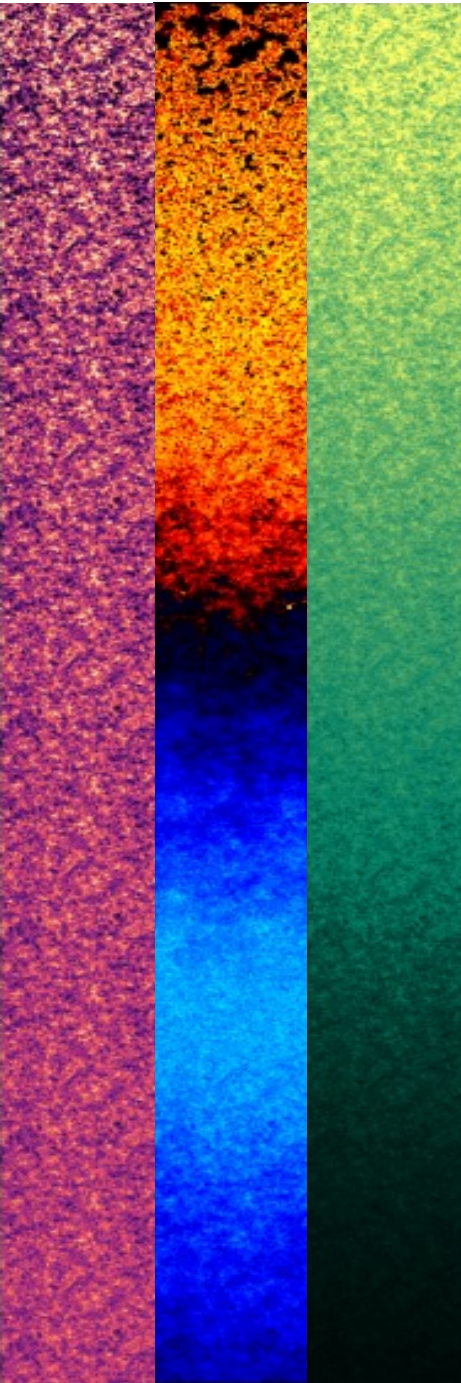
Pinpointing the Cosmic Dawn: Earlier Reionization Onset Detection with Interpretable Deep Learning on Synergistic 21cm and [OIII] Maps
DENARIO¹
¹ Anthropic, Gemini & OpenAI servers. Planet Earth.

A Deep Spatio-Temporal Learning Framework for Pinpointing the Onset of Cosmic Reionization using Joint 21-cm and [OIII] Maps
DENARIO¹
¹ Anthropic, Gemini & OpenAI servers. Planet Earth.

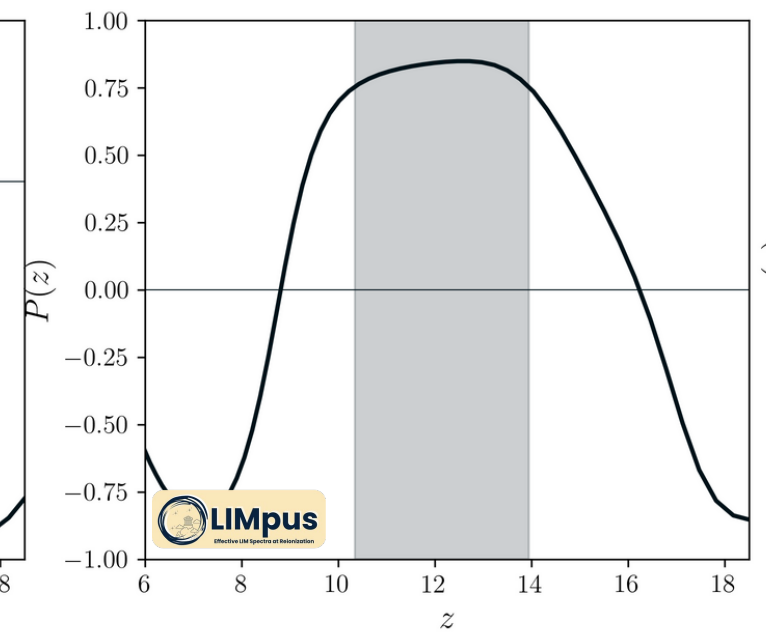
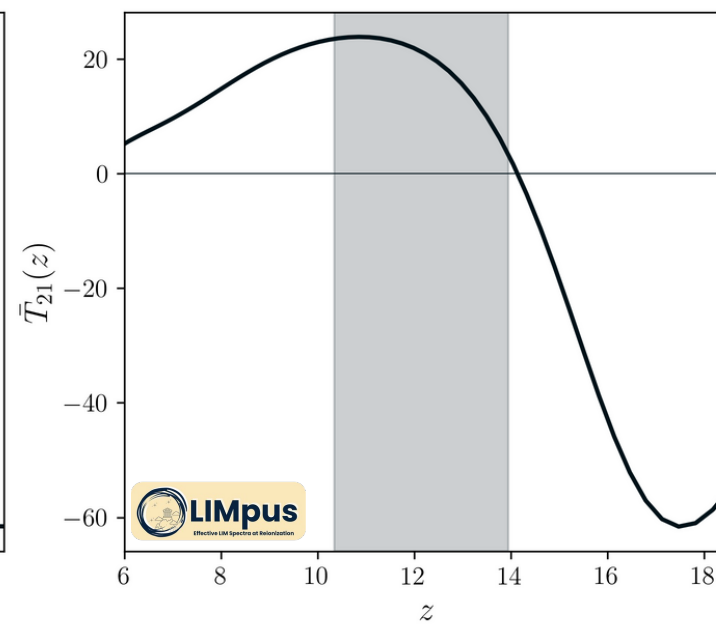
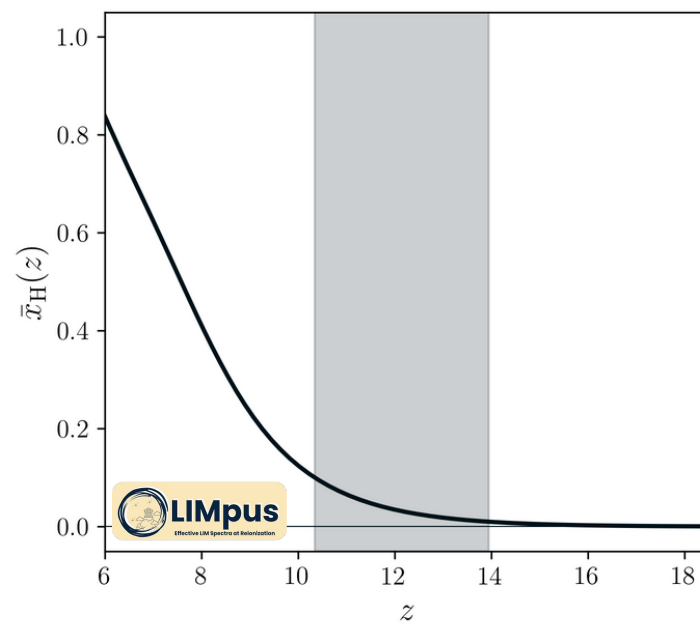
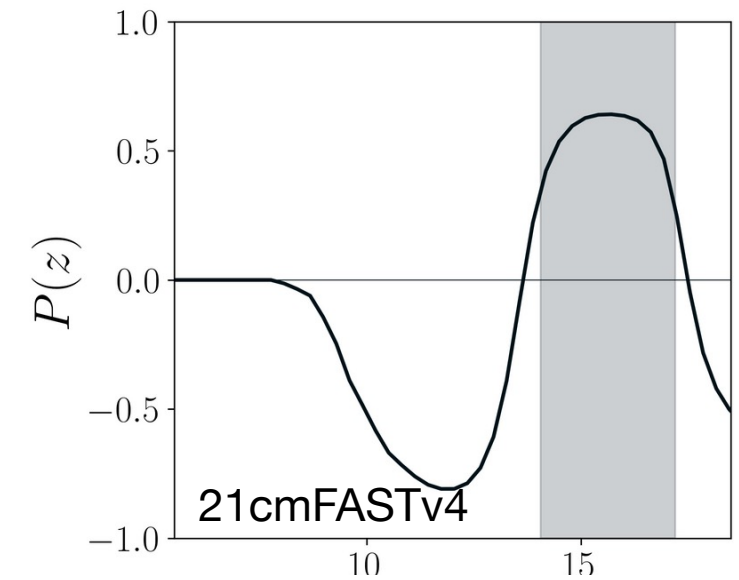
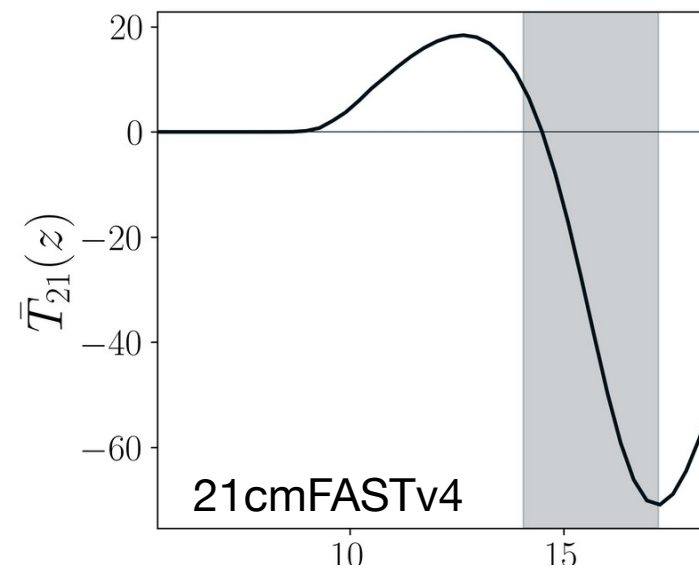
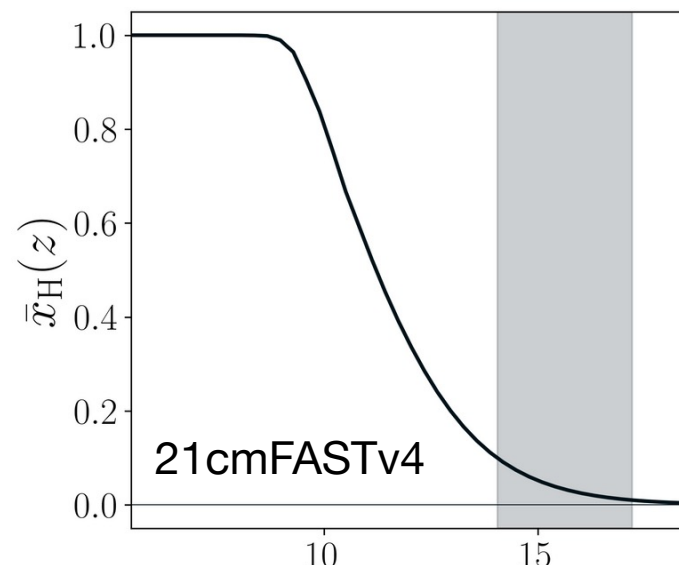


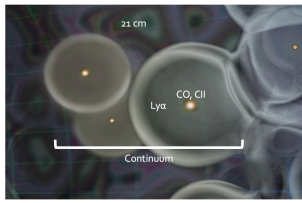


A New Boundary Condition on Reionization



Robust?



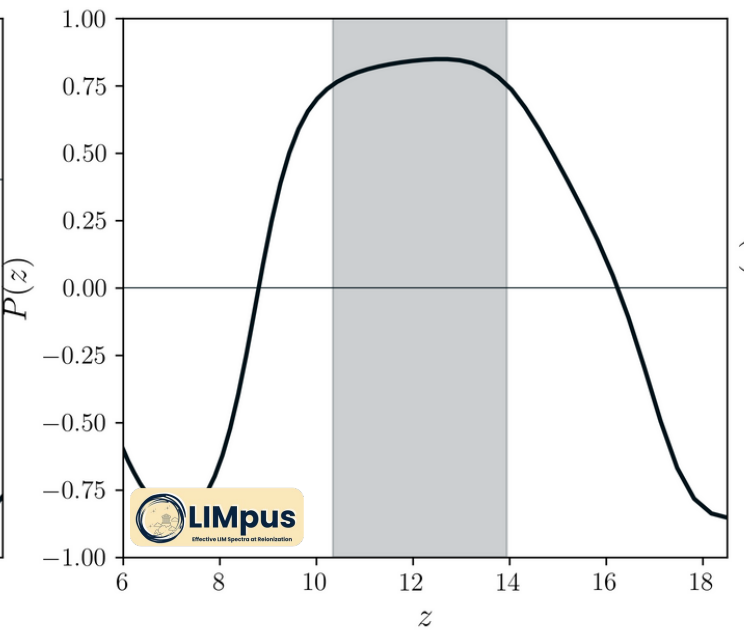
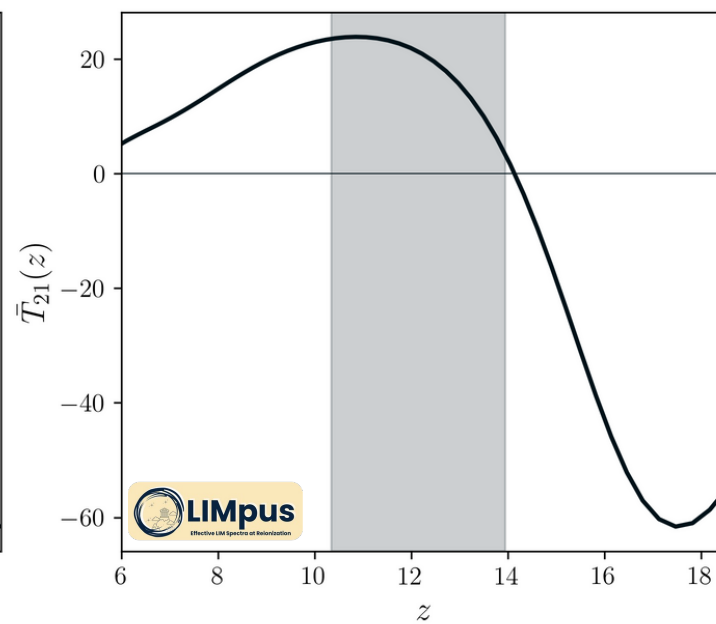
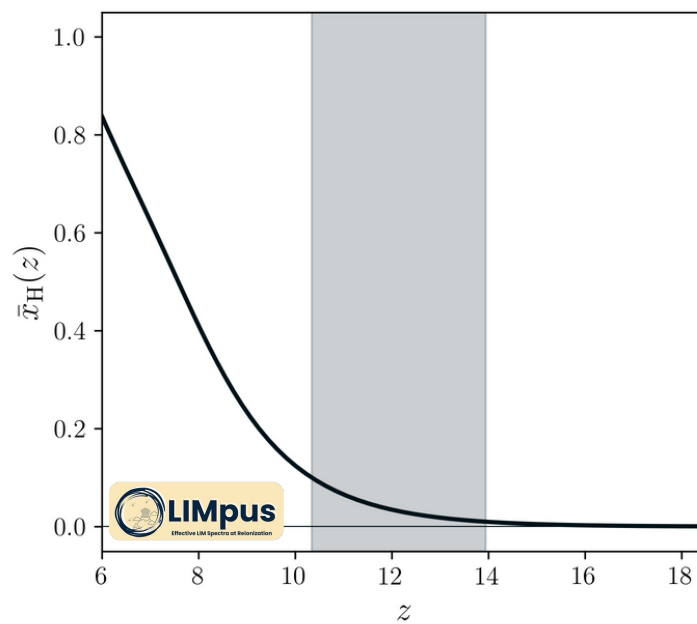
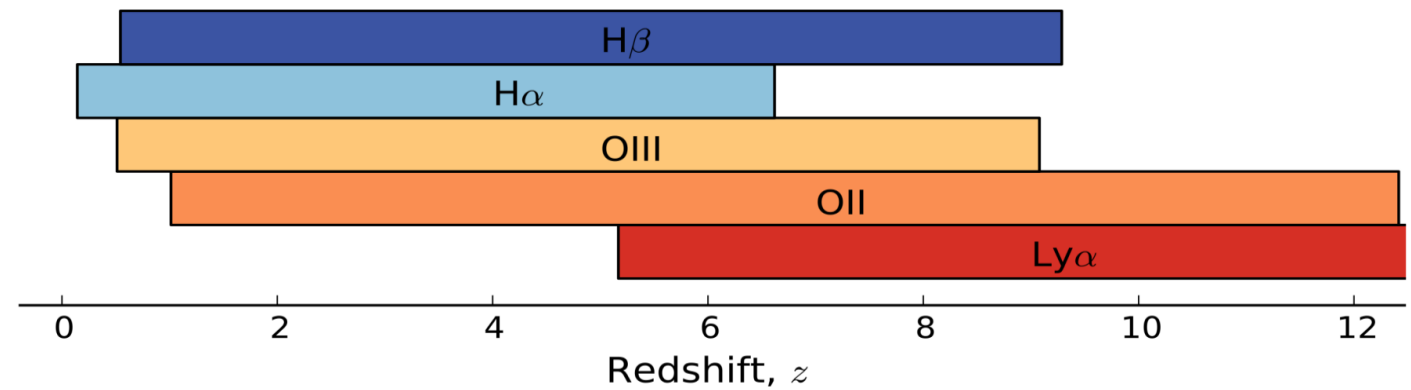


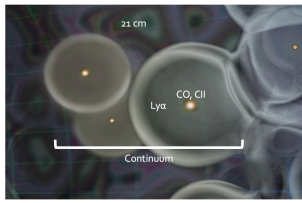
A New Boundary Condition on Reionization

Detectable?



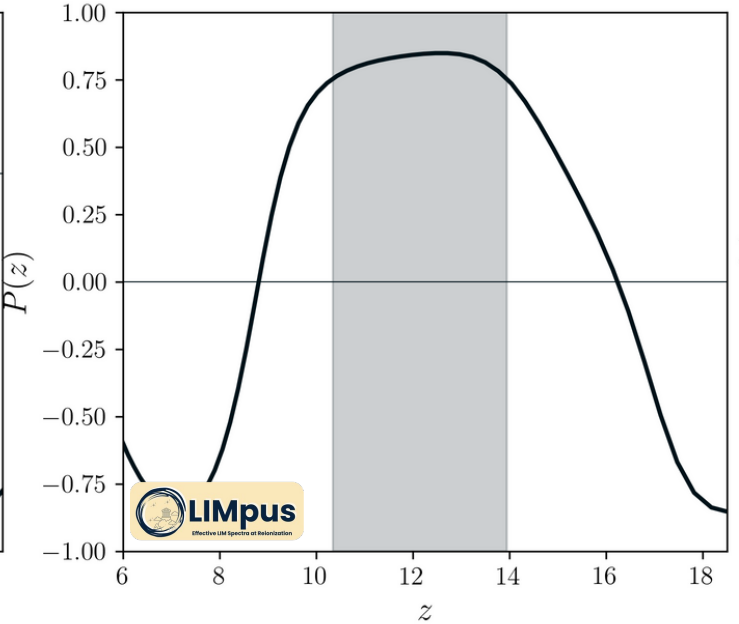
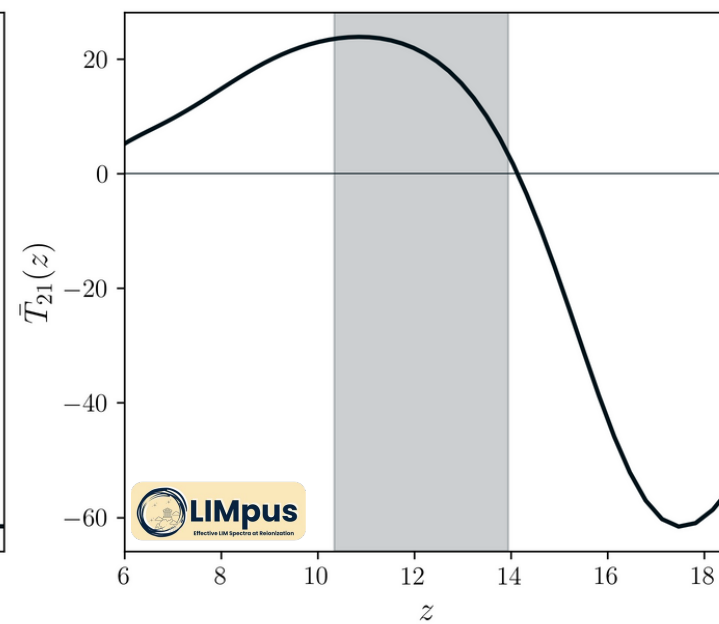
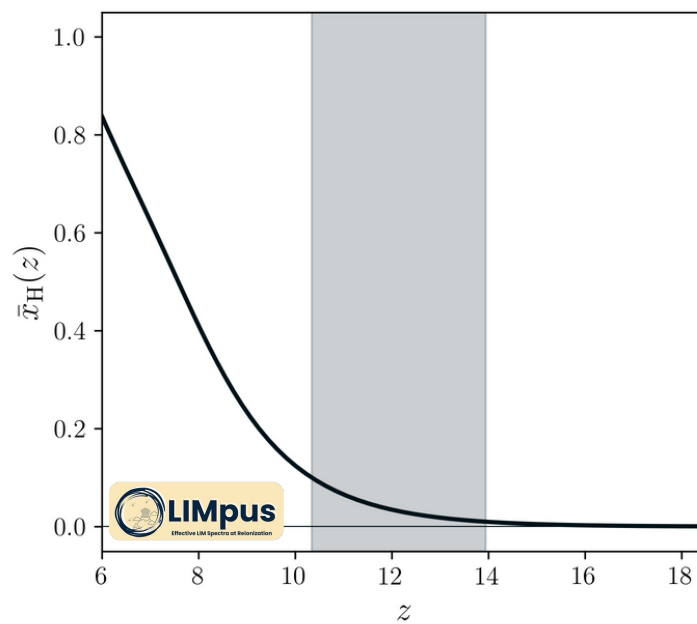
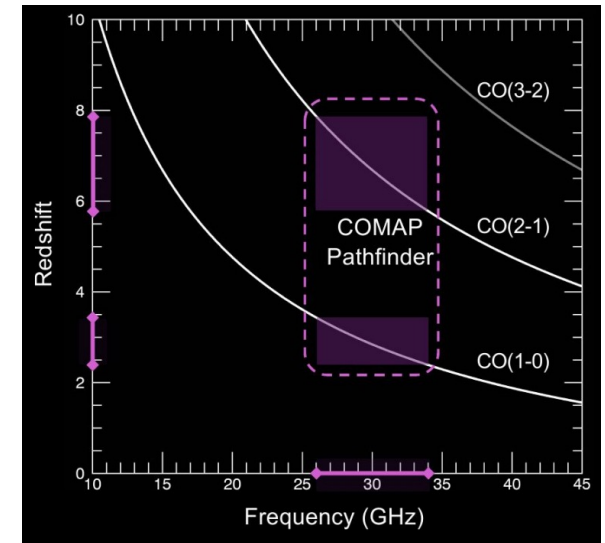
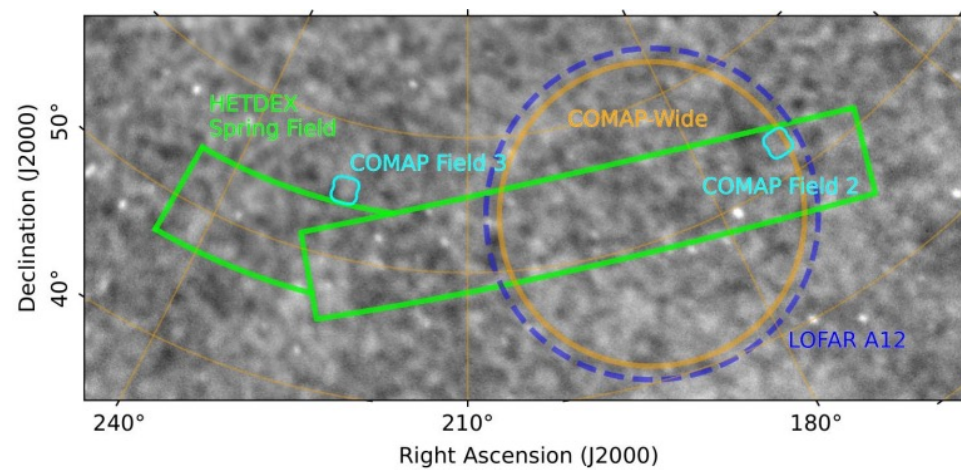
Redshift coverage of SPHEREx measured emission lines:





A New Boundary Condition on Reionization

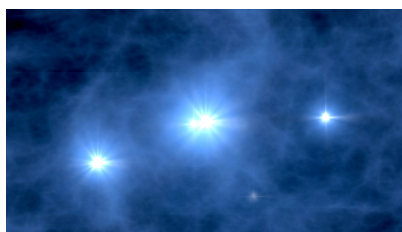
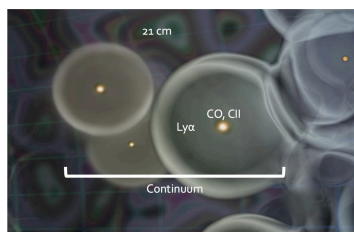
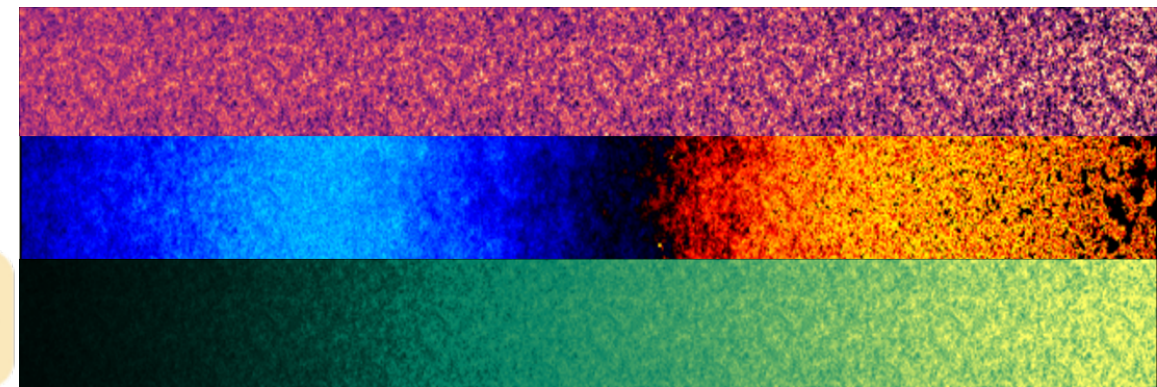
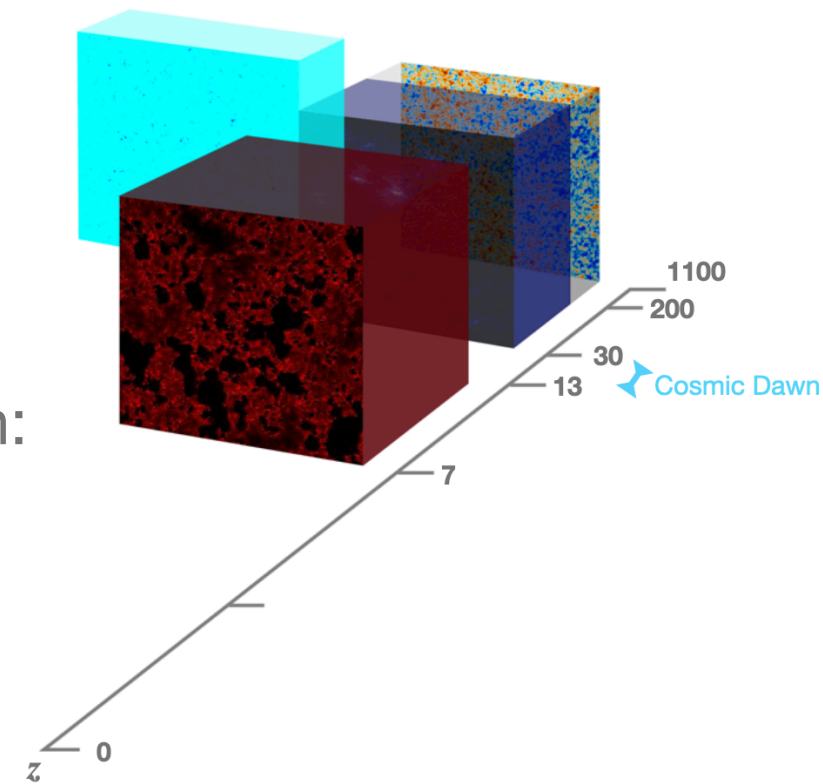
Detectable?



The Dawn of Cosmic Dawn Cosmology - Part 2

Some conclusions:

- We need robust, consistent and fast simulations.
- LIM is *unique* in many cases.
- Using multi-line intensity mapping, cosmic dawn can constrain:
 - Onset of reionization
 - EoR bubble morphology
 - Full star formation history
 - PopIII galaxy abundance
 - Feedback-free starbursts
 - Gastrophysics galore
 - ...



Sarah Libanore



Hovav Lazare

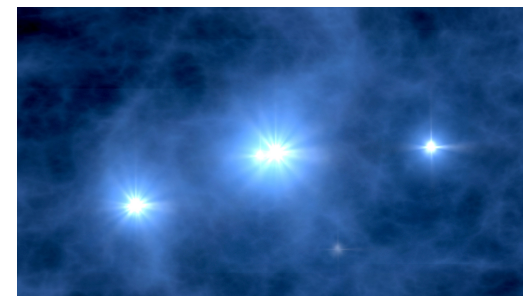
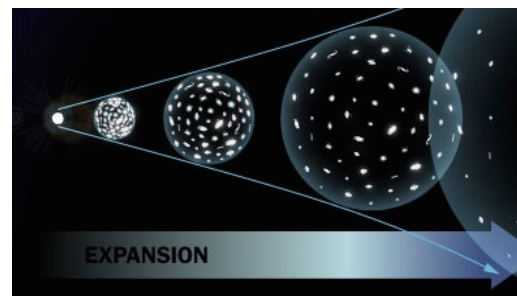
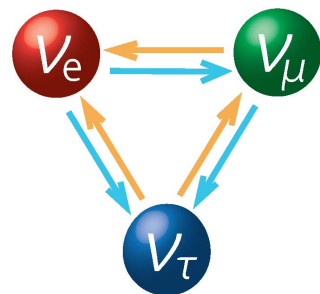
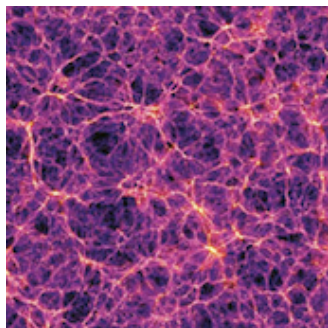
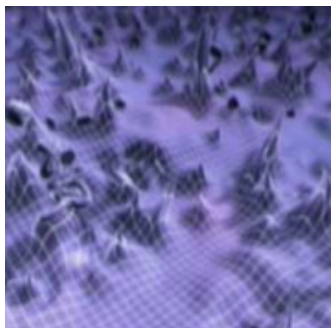
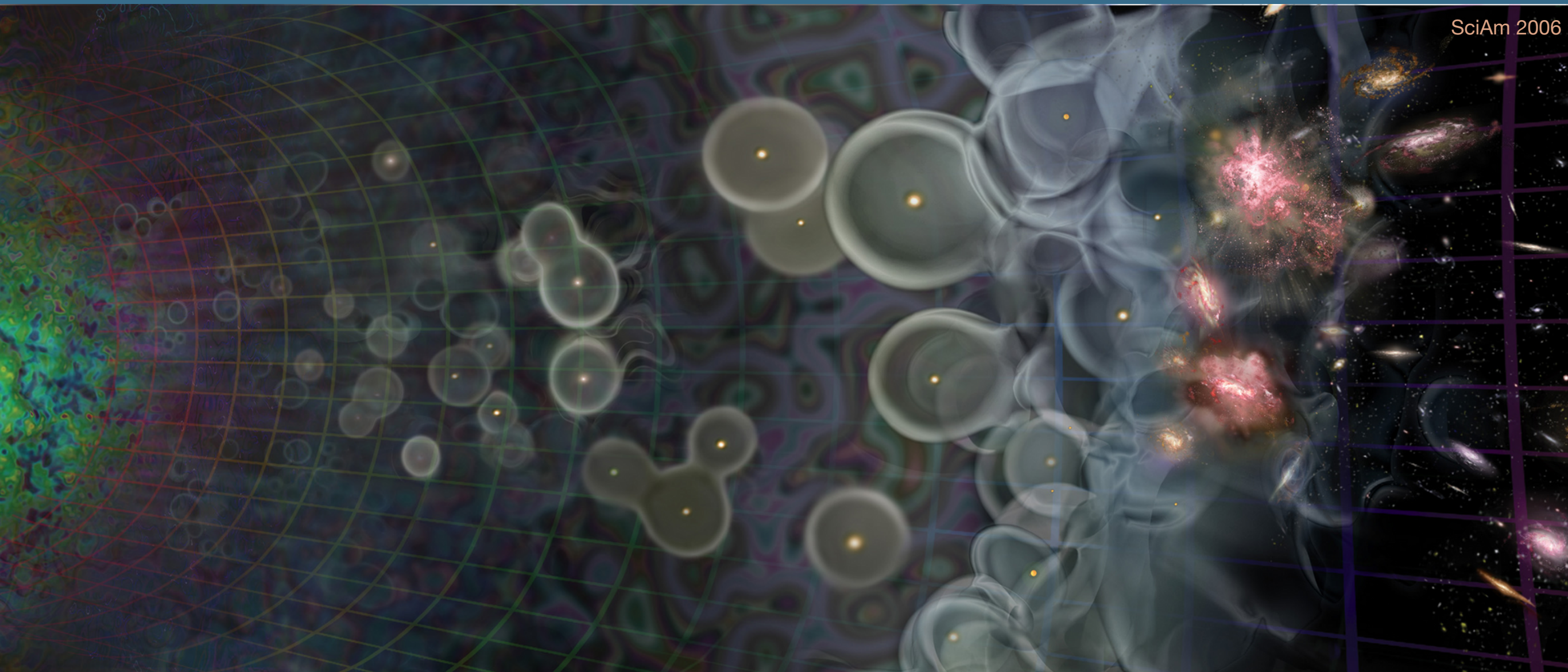


Tal Kadosh

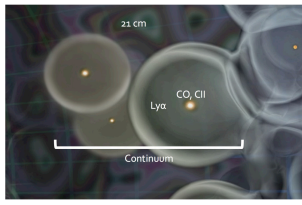
The Dawn of Cosmic Dawn Cosmology

Ely Kovetz

Ben-Gurion University



GGI Symposium September 2025



A New Boundary Condition on Reionization

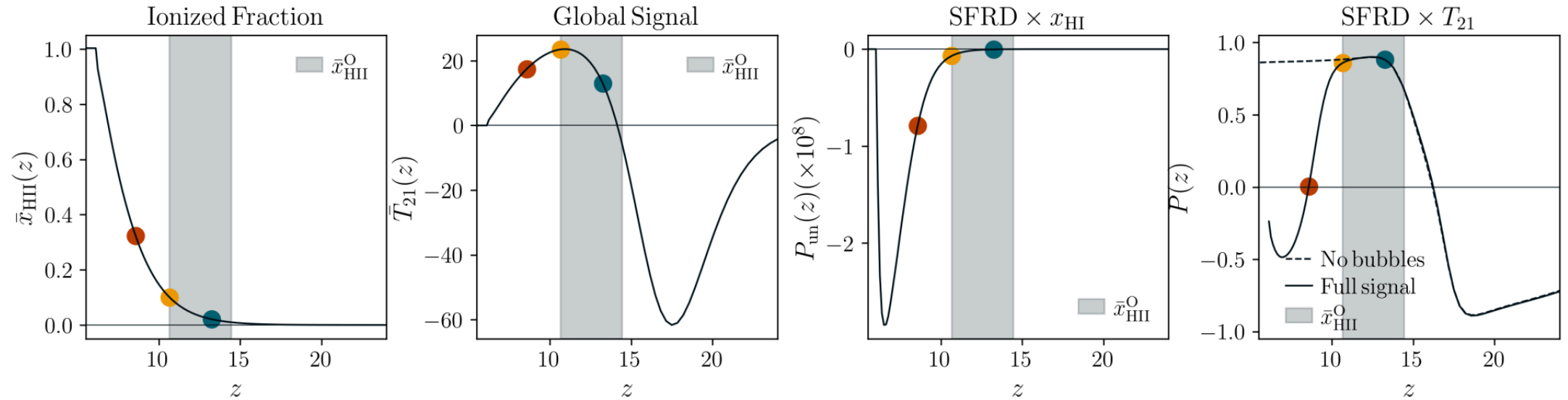
A New Boundary Condition on Reionization

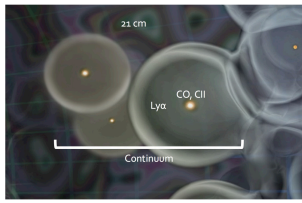
Sarah Libanore,^{1, *} Ely D. Kovetz,¹ Julian B. Muñoz,^{2, 3} Yonatan Sklansky,^{2, 3} and Emilie Th  lie^{2, 3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

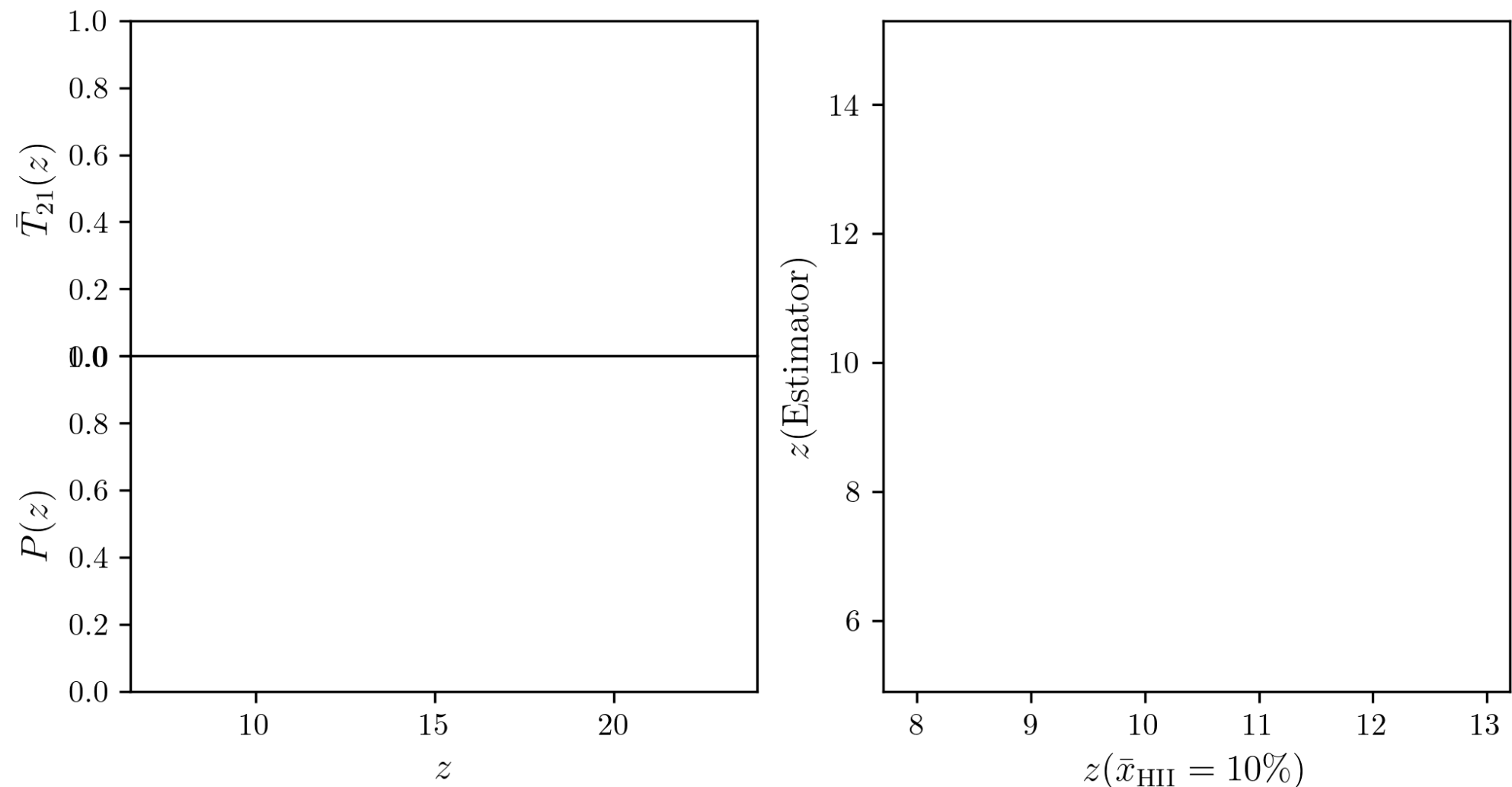
A New Boundary Condition on Reionization

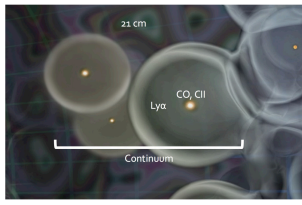
Sarah Libanore,^{1, *} Ely D. Kovetz,¹ Julian B. Muñoz,^{2, 3} Yonatan Sklansky,^{2, 3} and Emilie Thélie^{2, 3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

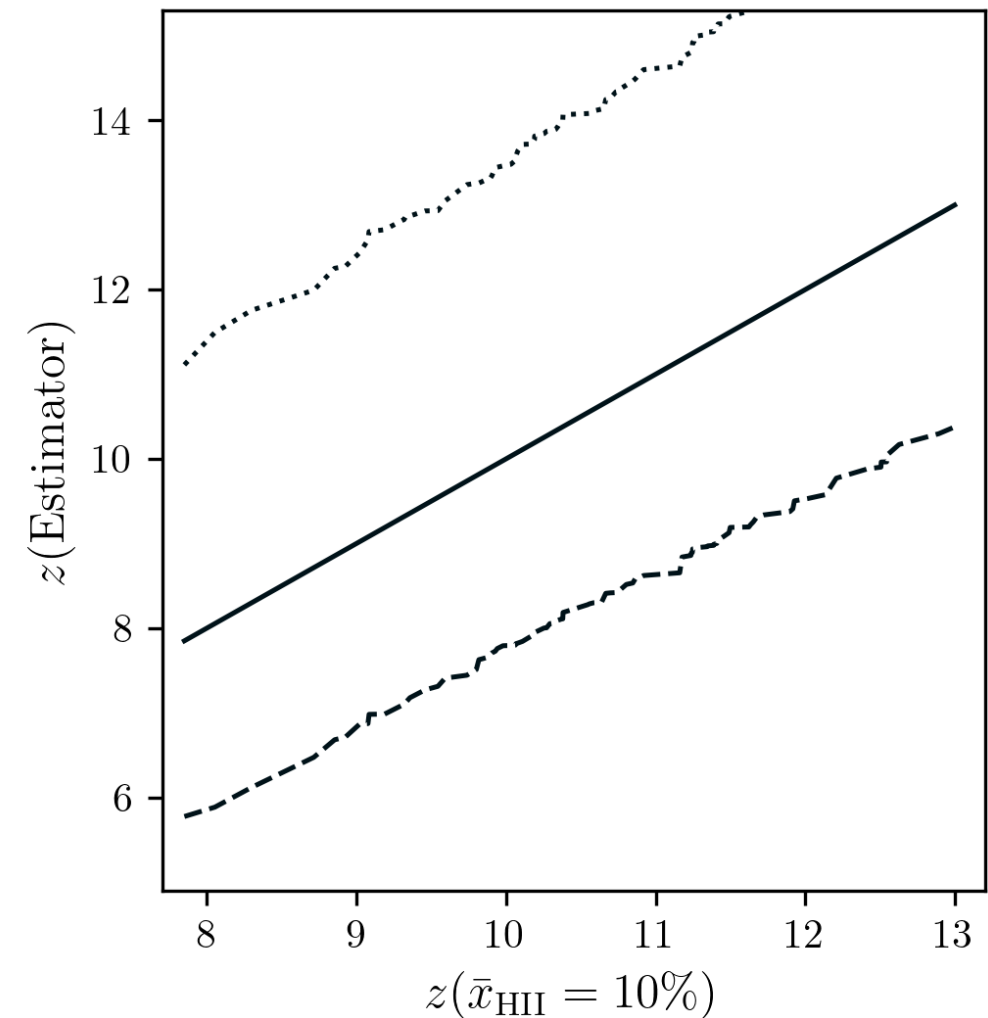
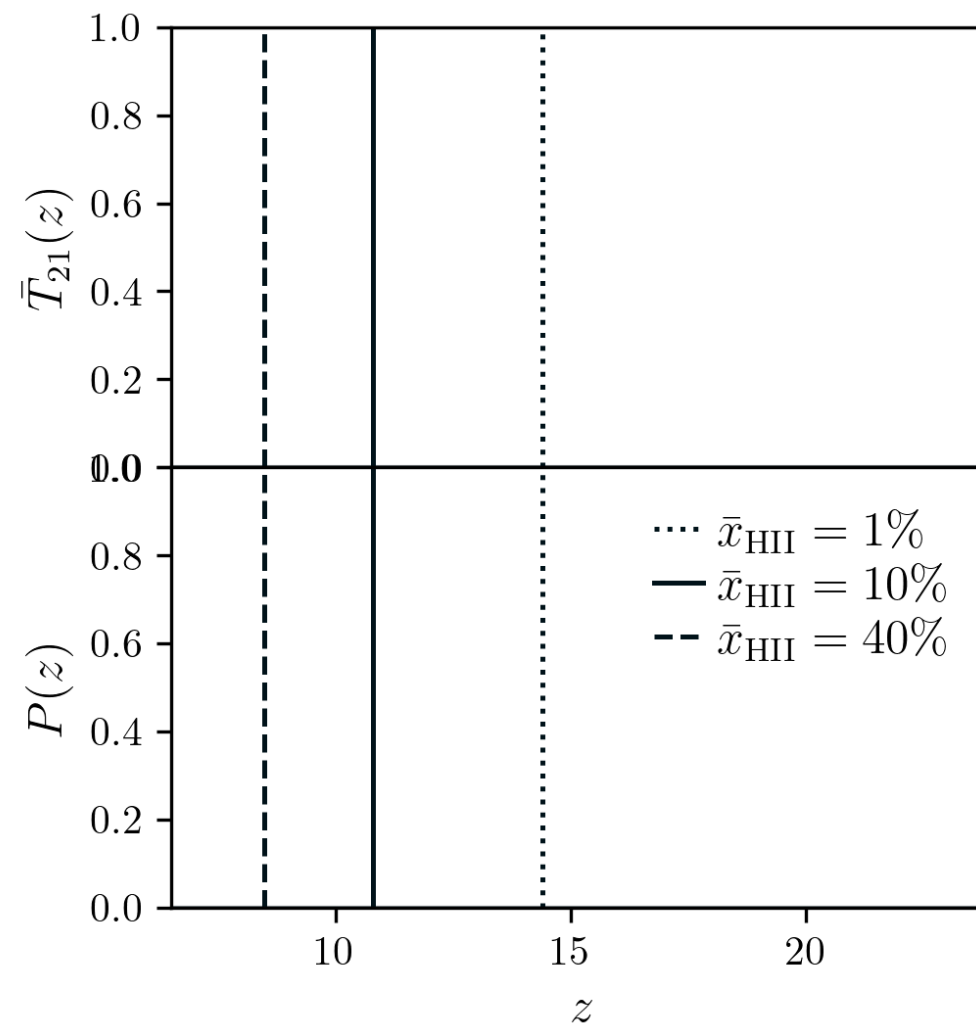
A New Boundary Condition on Reionization

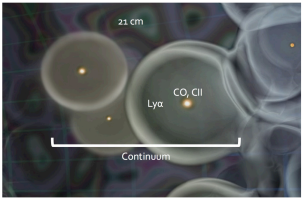
Sarah Libanore,^{1,*} Ely D. Kovetz,¹ Julian B. Muñoz,^{2,3} Yonatan Sklansky,^{2,3} and Emilie Thélie^{2,3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

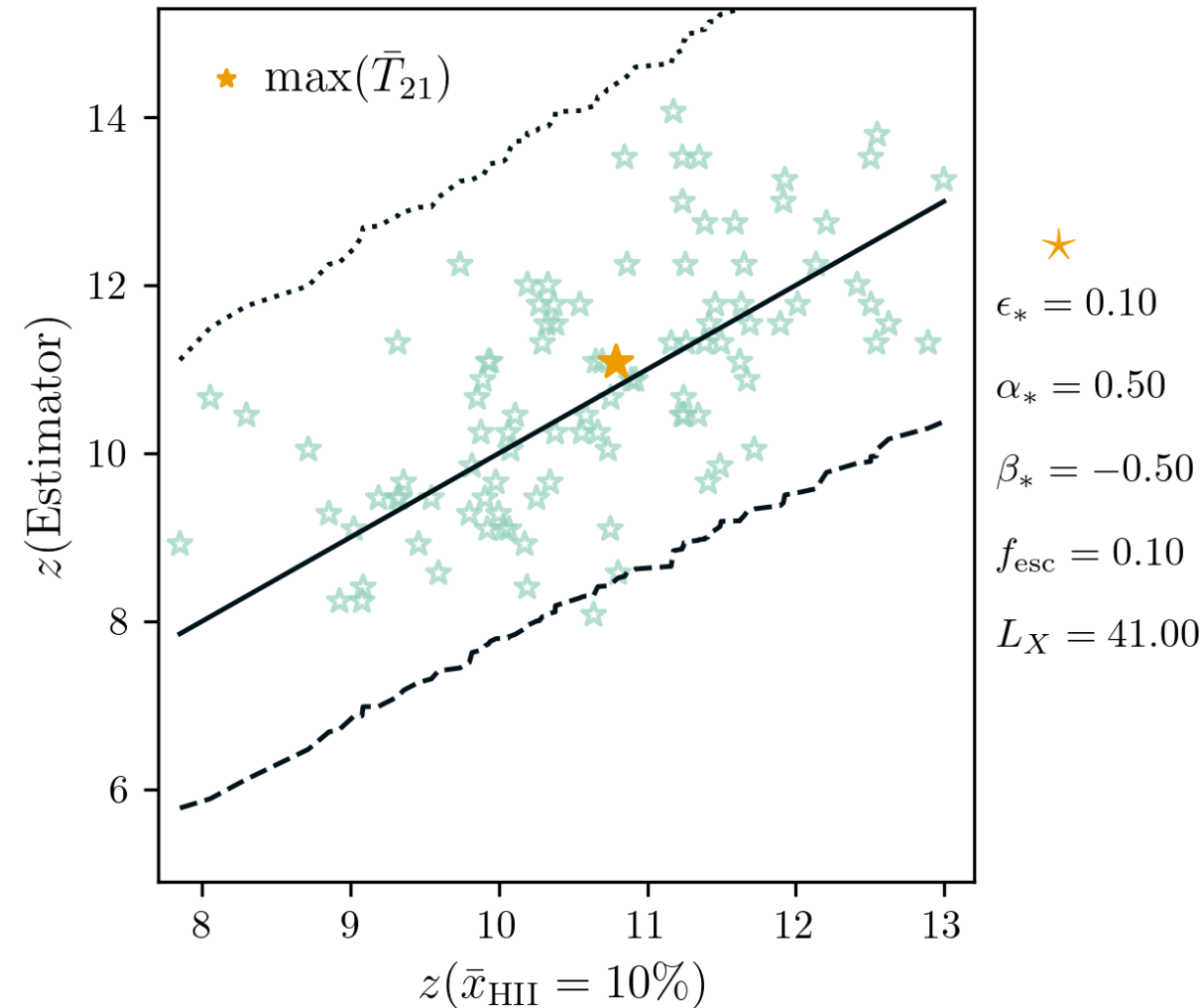
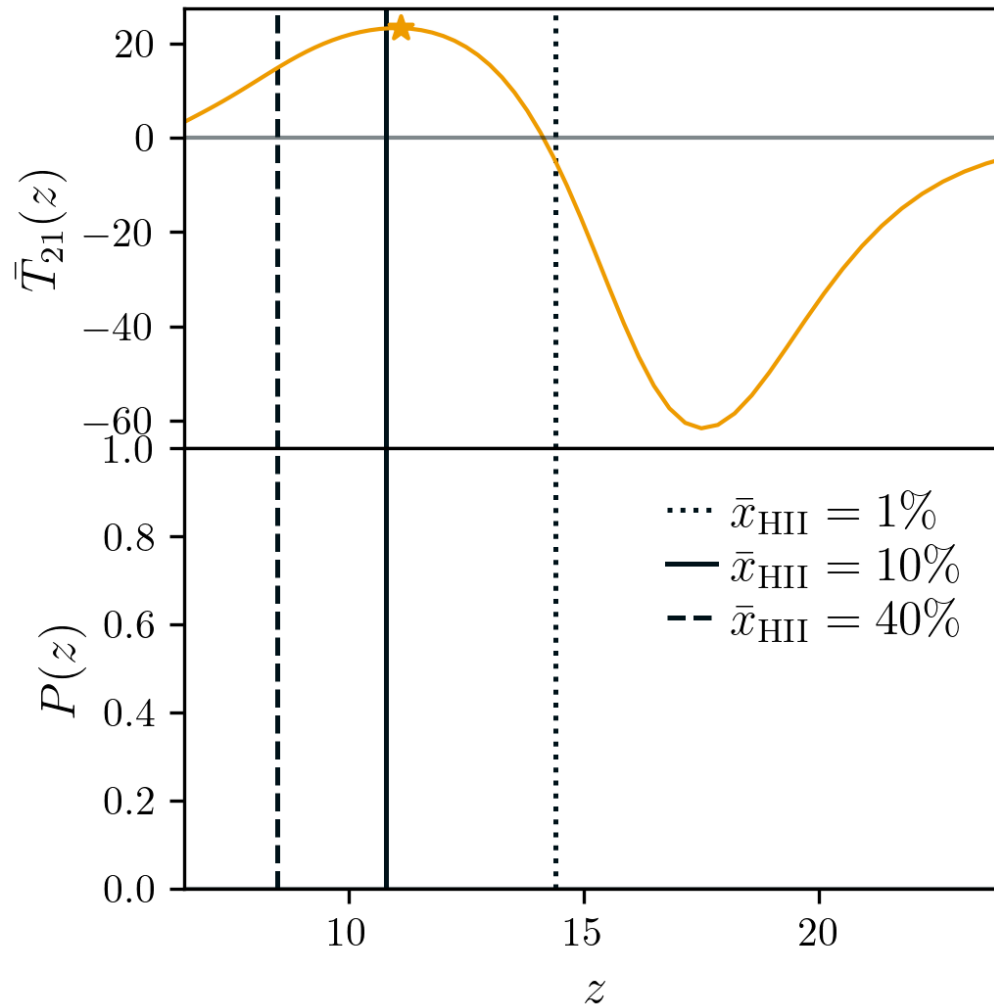
A New Boundary Condition on Reionization

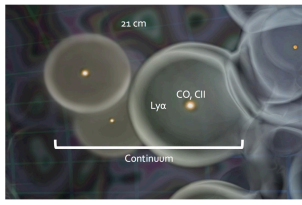
Sarah Libanore,^{1,*} Ely D. Kovetz,¹ Julian B. Muñoz,^{2,3} Yonatan Sklansky,^{2,3} and Emilie Th  lie^{2,3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

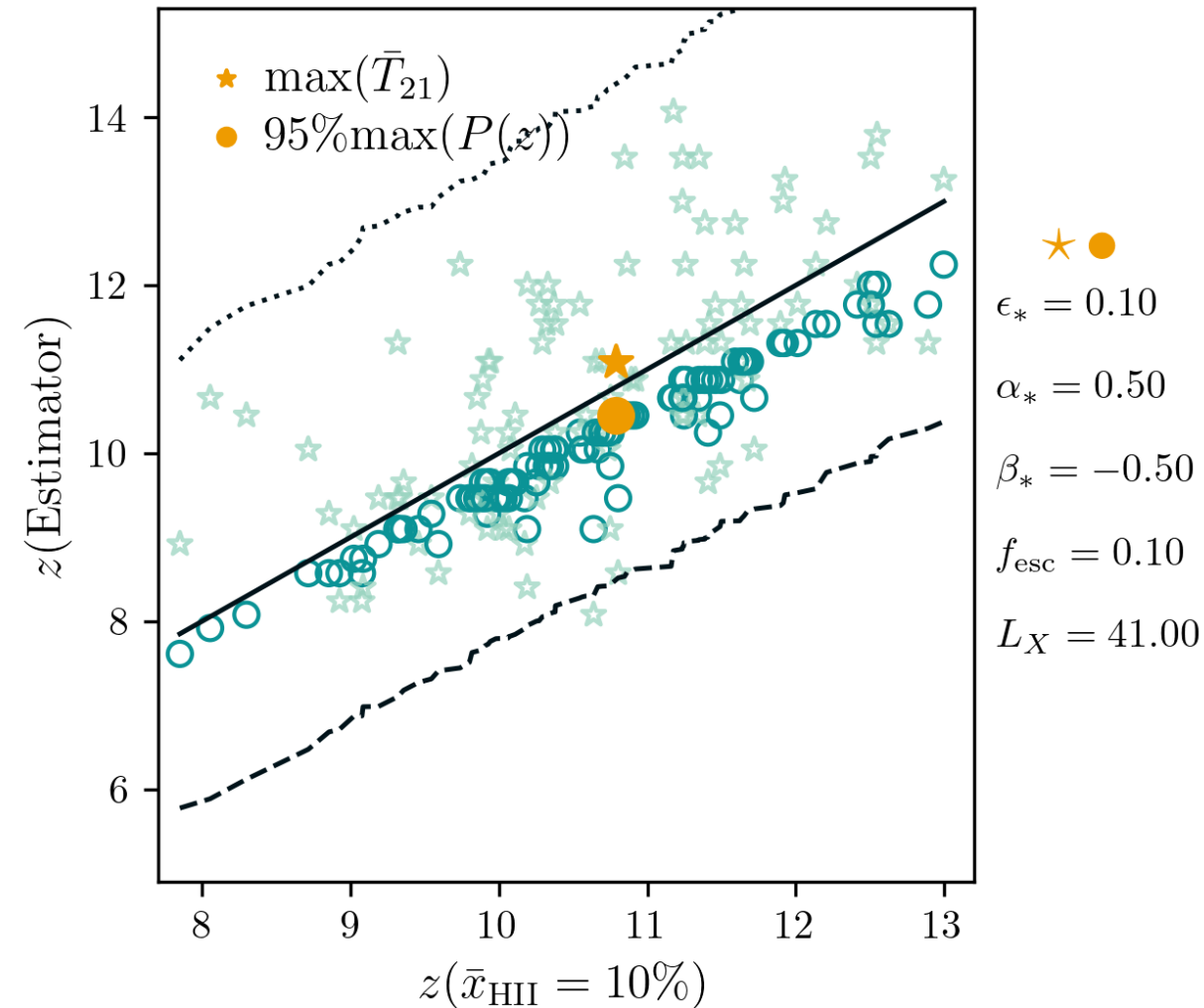
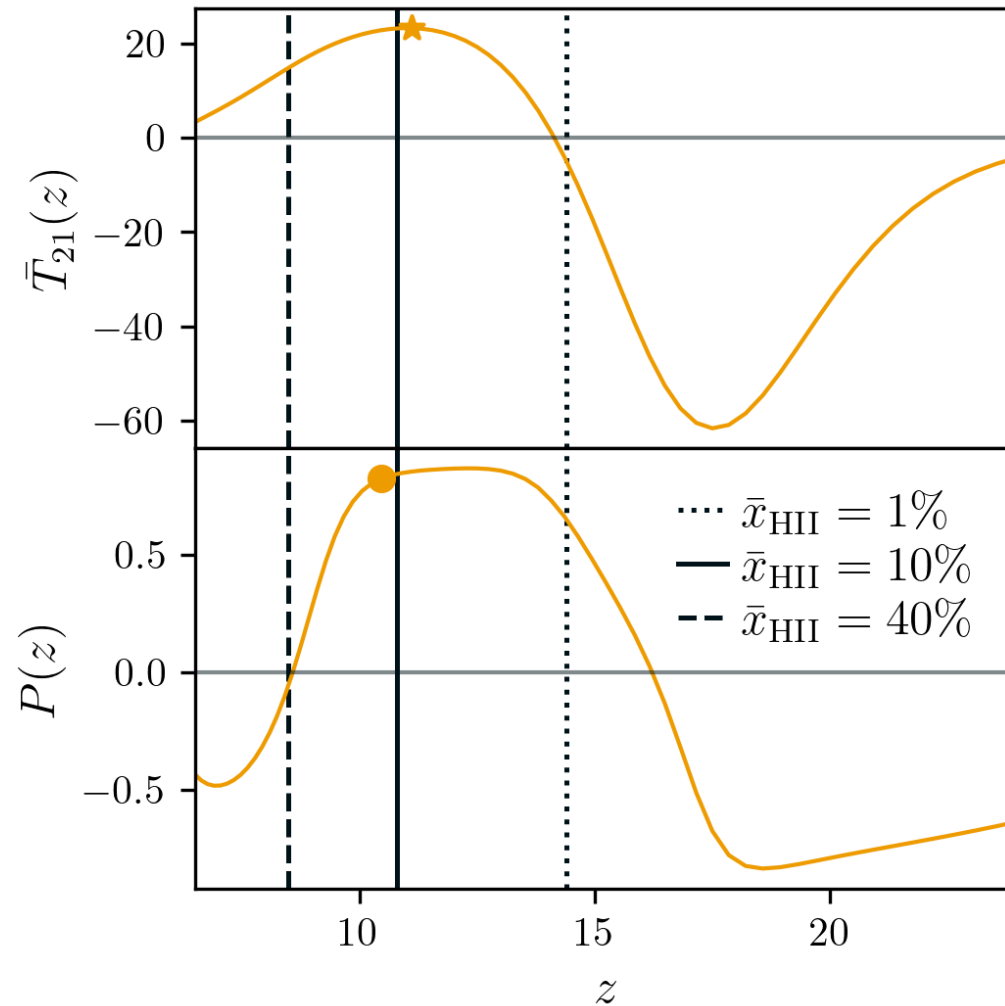
A New Boundary Condition on Reionization

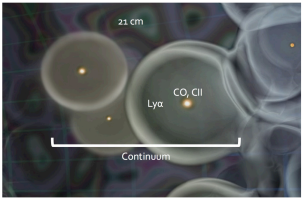
Sarah Libanore,^{1, *} Ely D. Kovetz,¹ Julian B. Muñoz,^{2, 3} Yonatan Sklansky,^{2, 3} and Emilie Thélie^{2, 3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

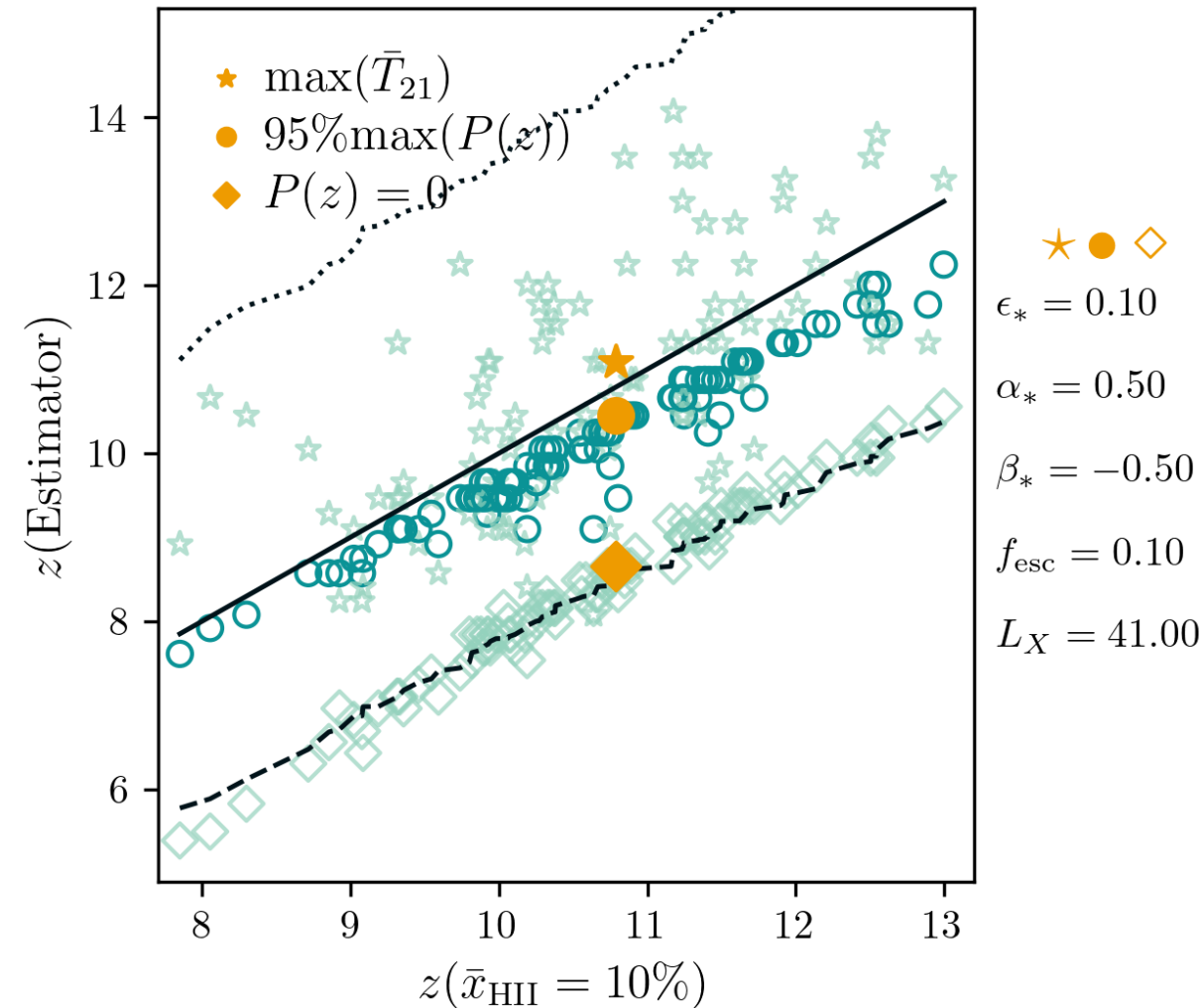
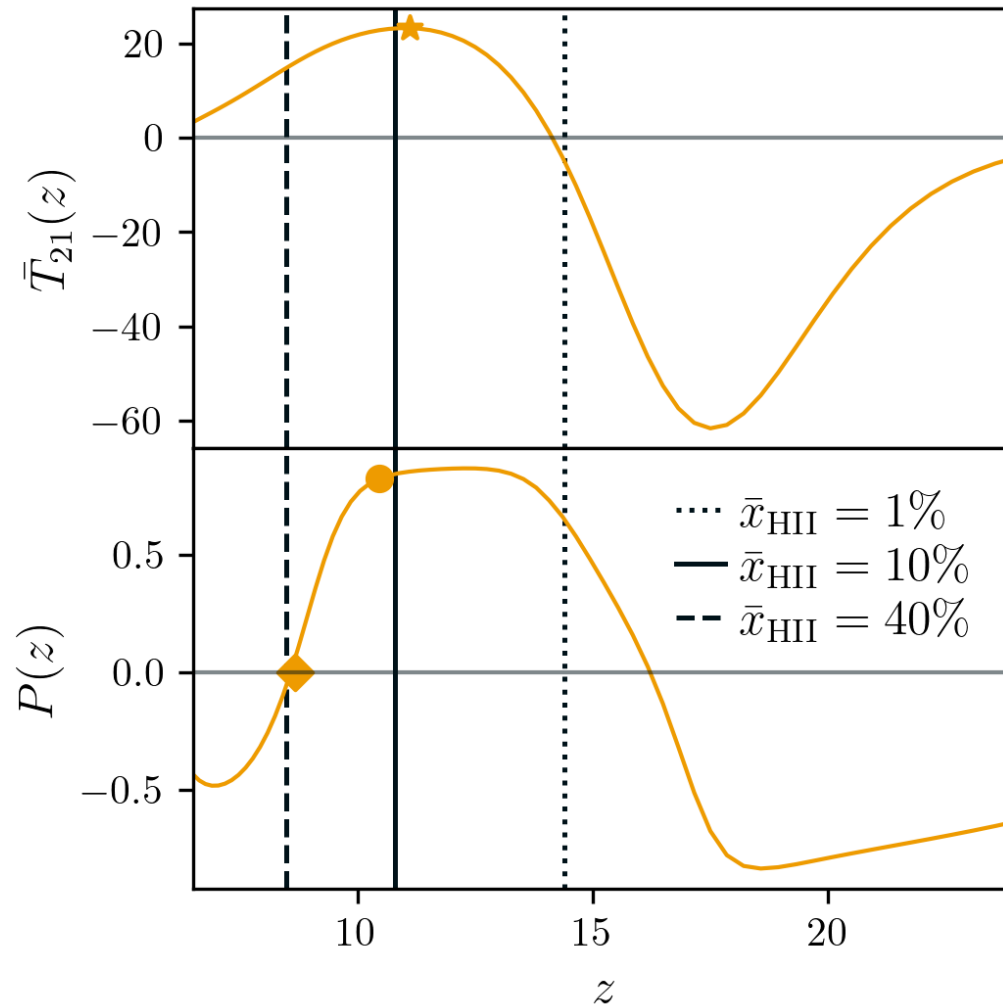
A New Boundary Condition on Reionization

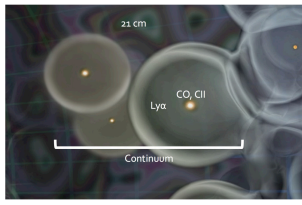
Sarah Libanore,^{1,*} Ely D. Kovetz,¹ Julian B. Muñoz,^{2,3} Yonatan Sklansky,^{2,3} and Emilie Thélie^{2,3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

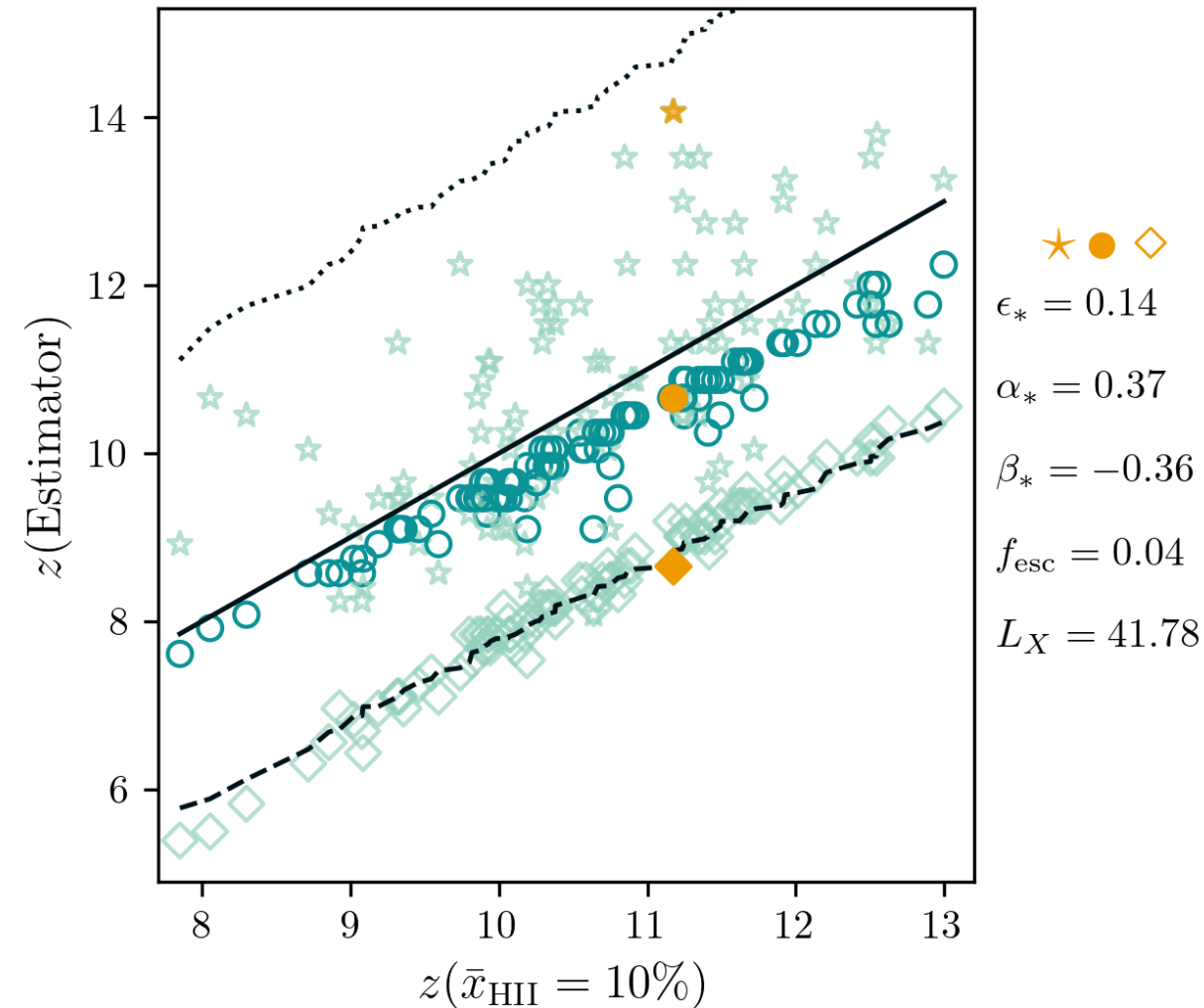
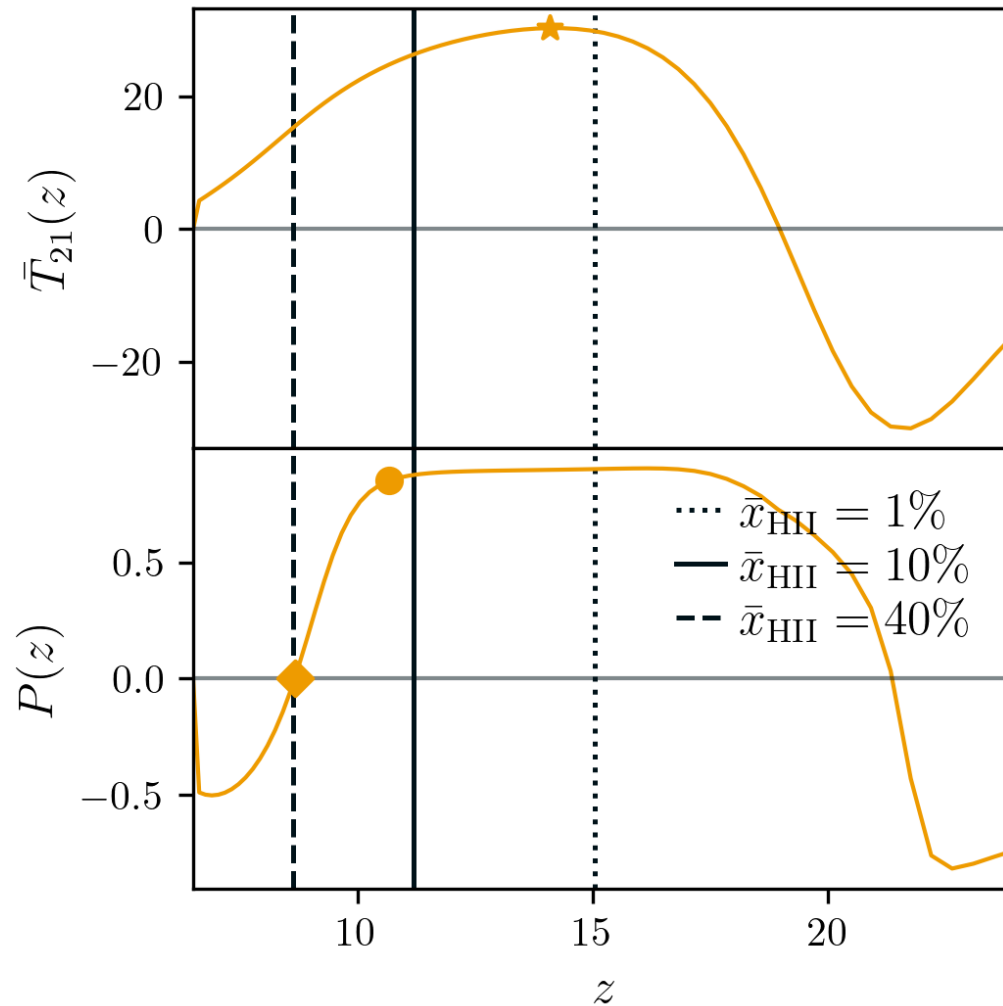
A New Boundary Condition on Reionization

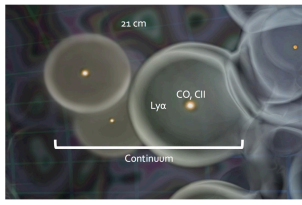
Sarah Libanore,^{1,*} Ely D. Kovetz,¹ Julian B. Muñoz,^{2,3} Yonatan Sklansky,^{2,3} and Emilie Thélie^{2,3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

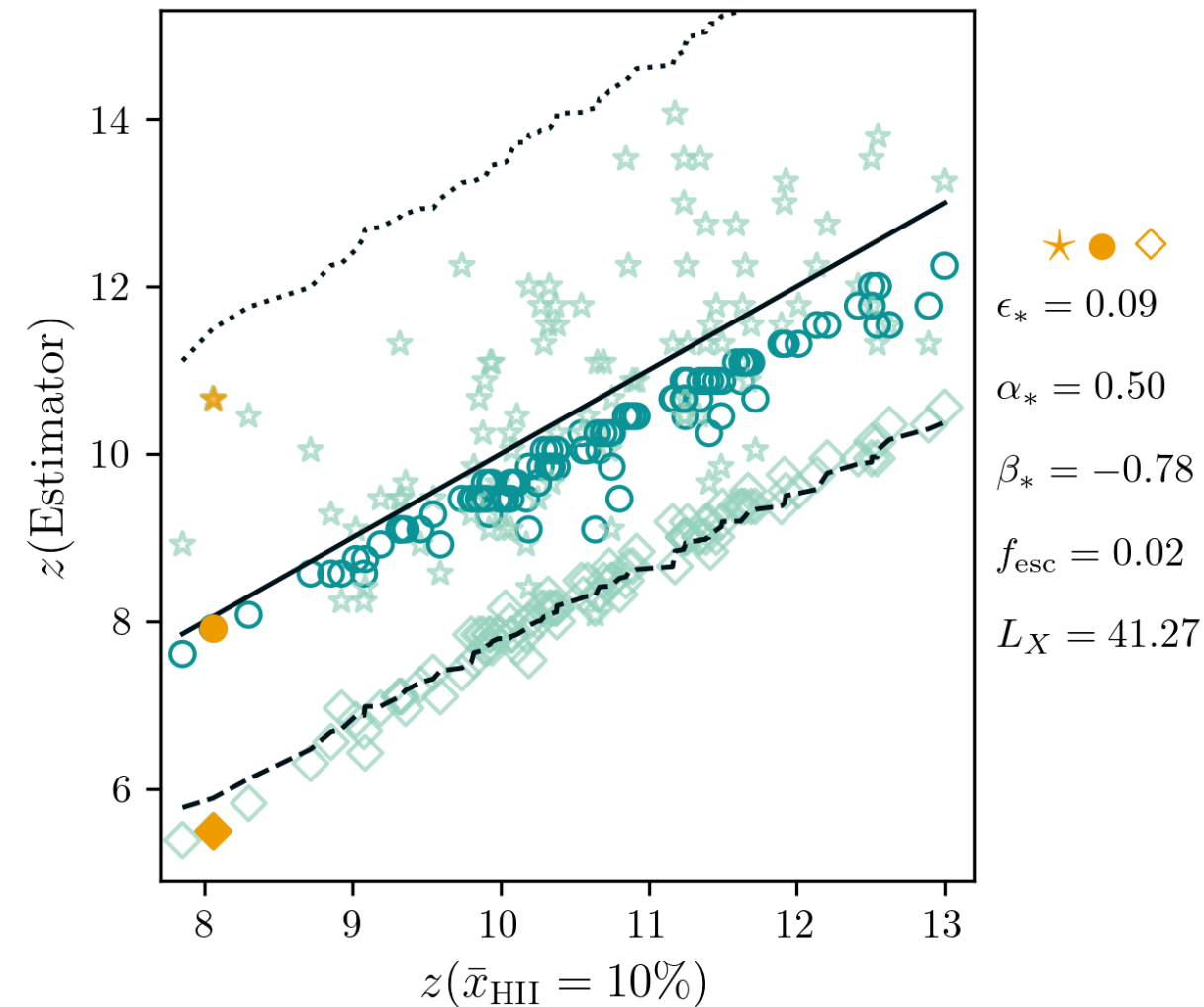
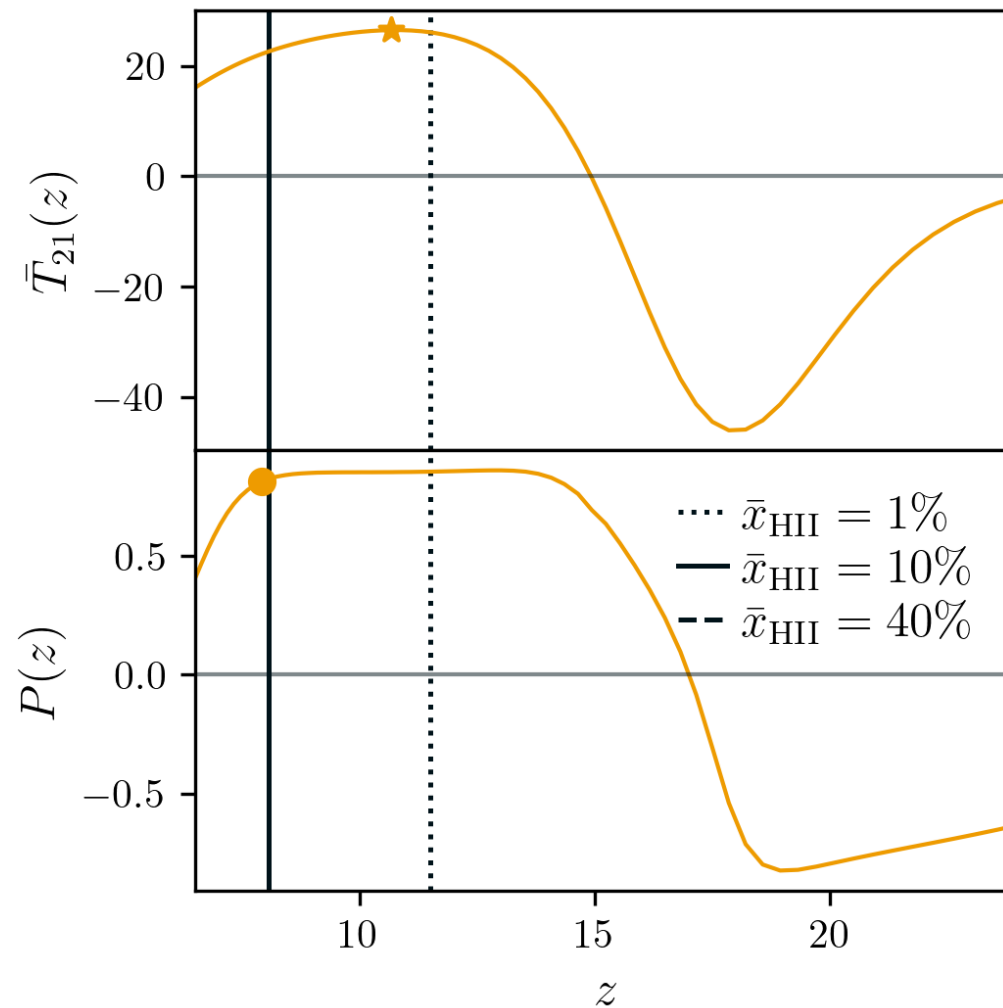
A New Boundary Condition on Reionization

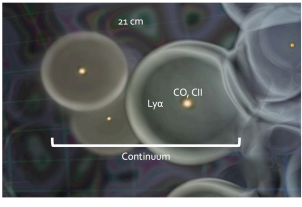
Sarah Libanore,^{1,*} Ely D. Kovetz,¹ Julian B. Muñoz,^{2,3} Yonatan Sklansky,^{2,3} and Emilie Thélie^{2,3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

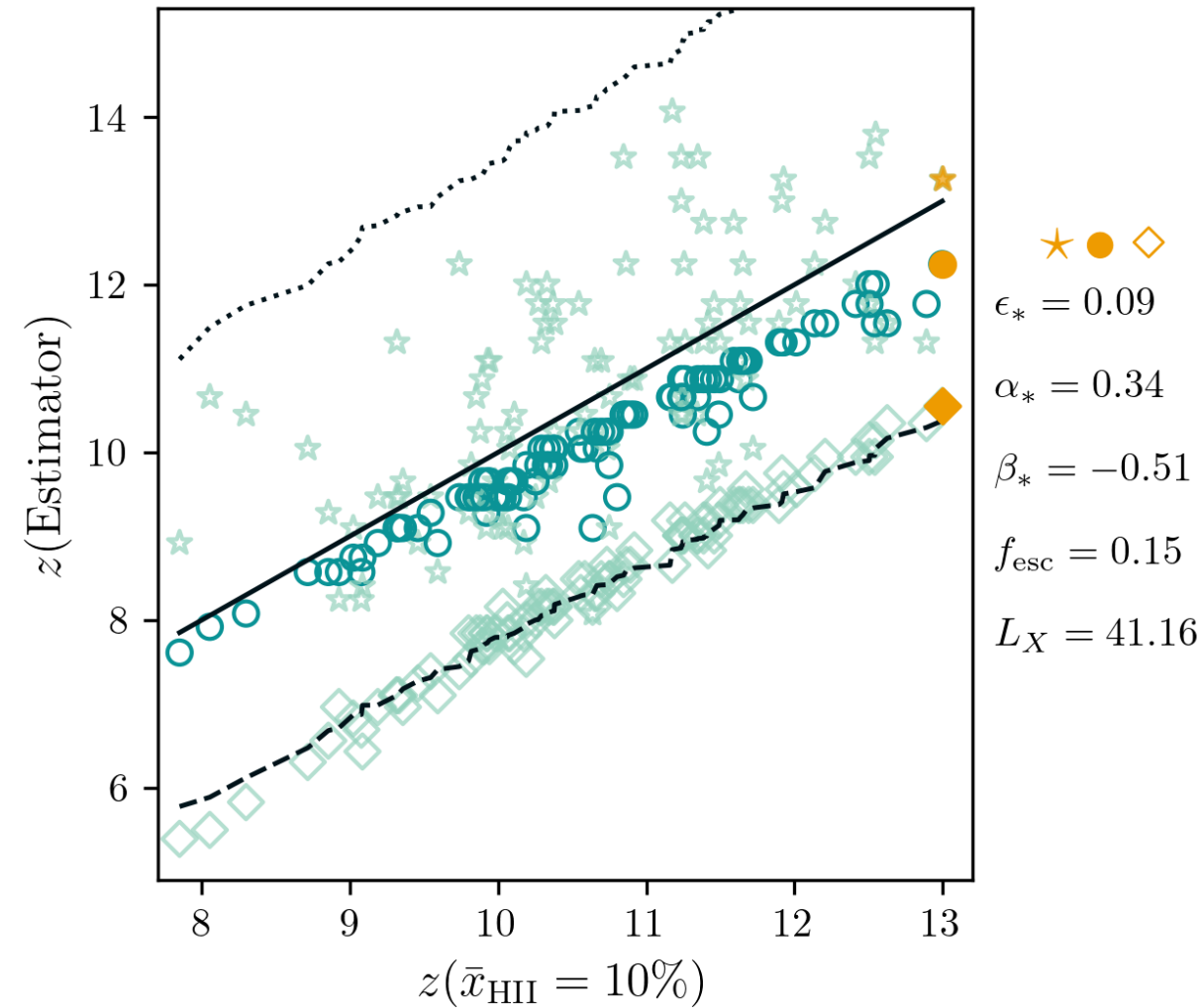
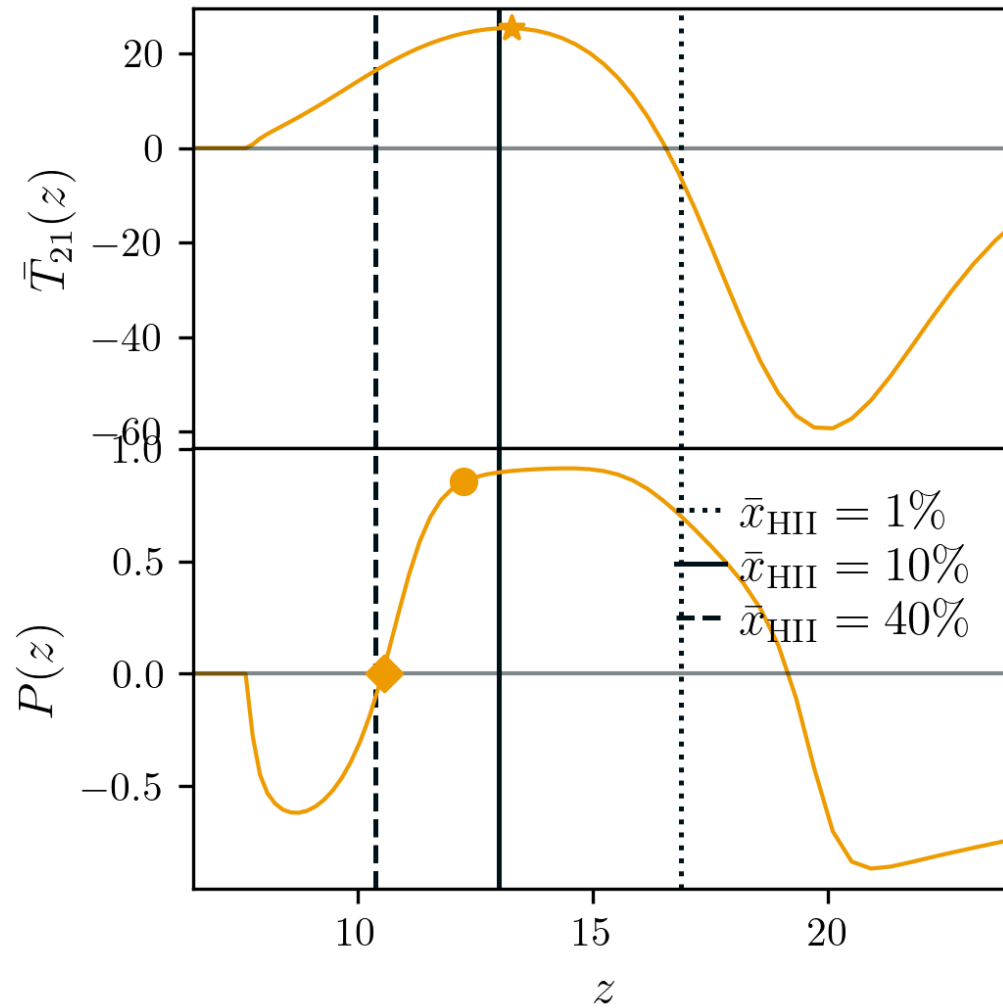
A New Boundary Condition on Reionization

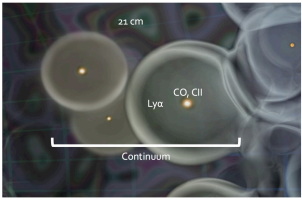
Sarah Libanore,^{1,*} Ely D. Kovetz,¹ Julian B. Muñoz,^{2,3} Yonatan Sklansky,^{2,3} and Emilie Th  lie^{2,3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*





A New Boundary Condition on Reionization

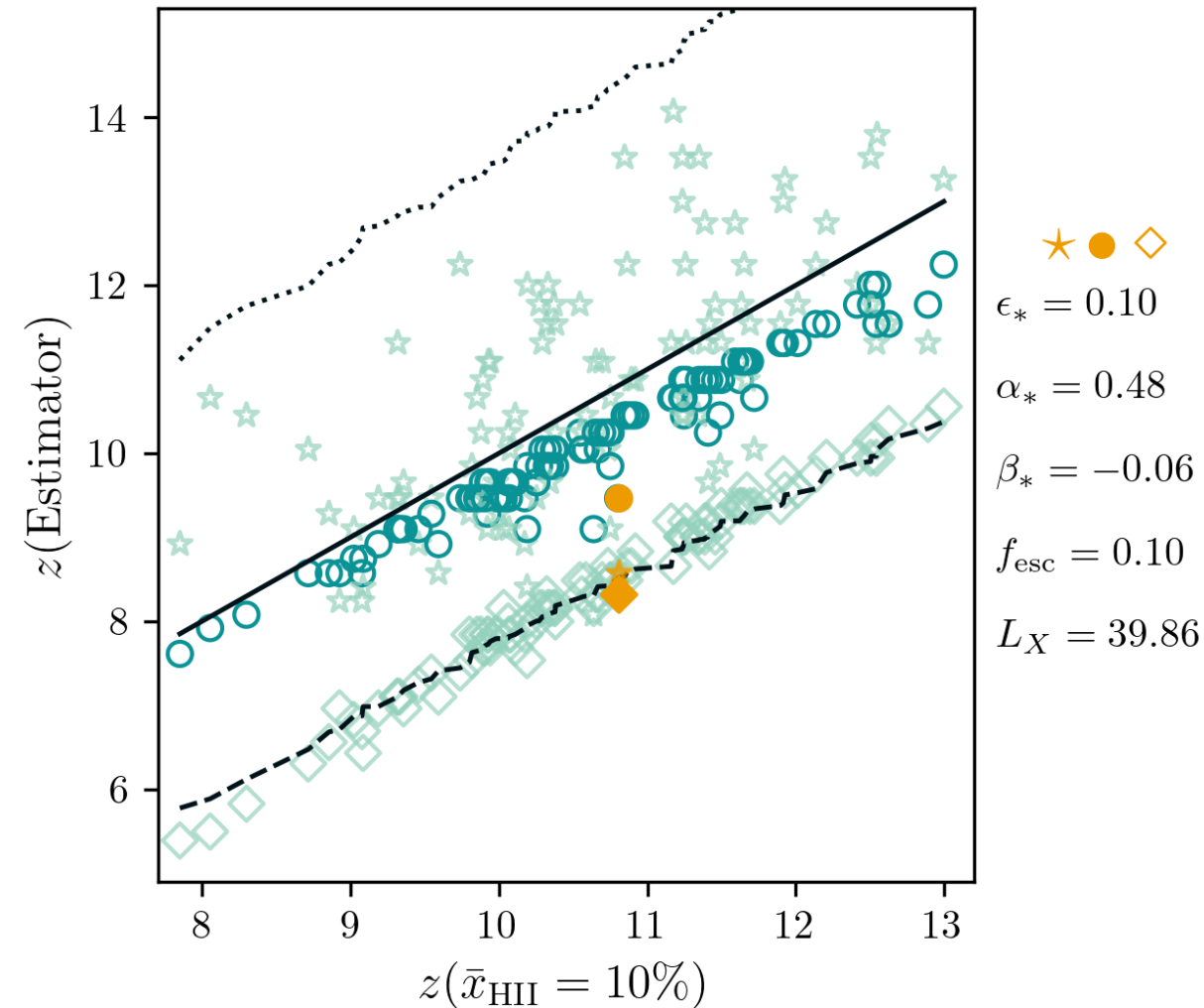
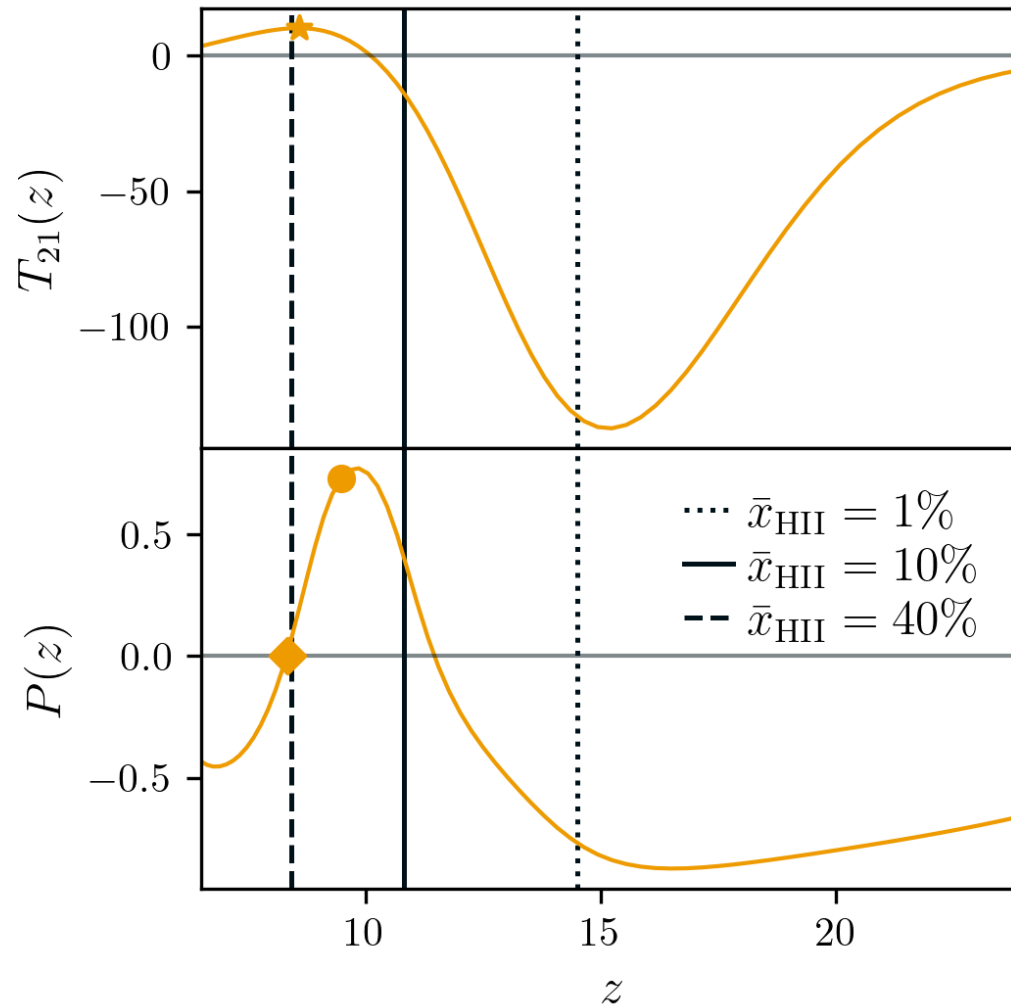
A New Boundary Condition on Reionization

Sarah Libanore,^{1,*} Ely D. Kovetz,¹ Julian B. Muñoz,^{2,3} Yonatan Sklansky,^{2,3} and Emilie Th  lie^{2,3}

¹*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

²*Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, Texas 78712, USA*

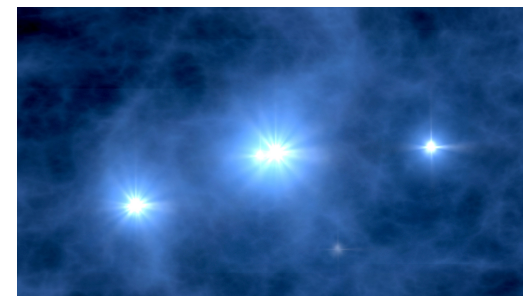
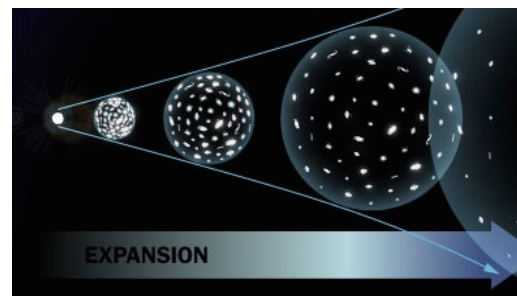
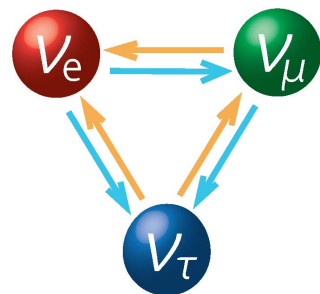
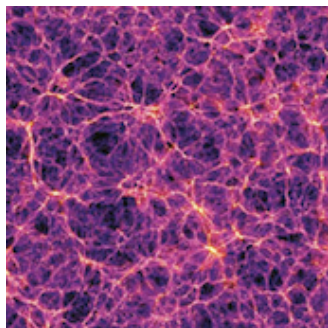
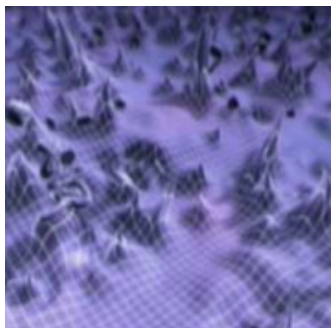
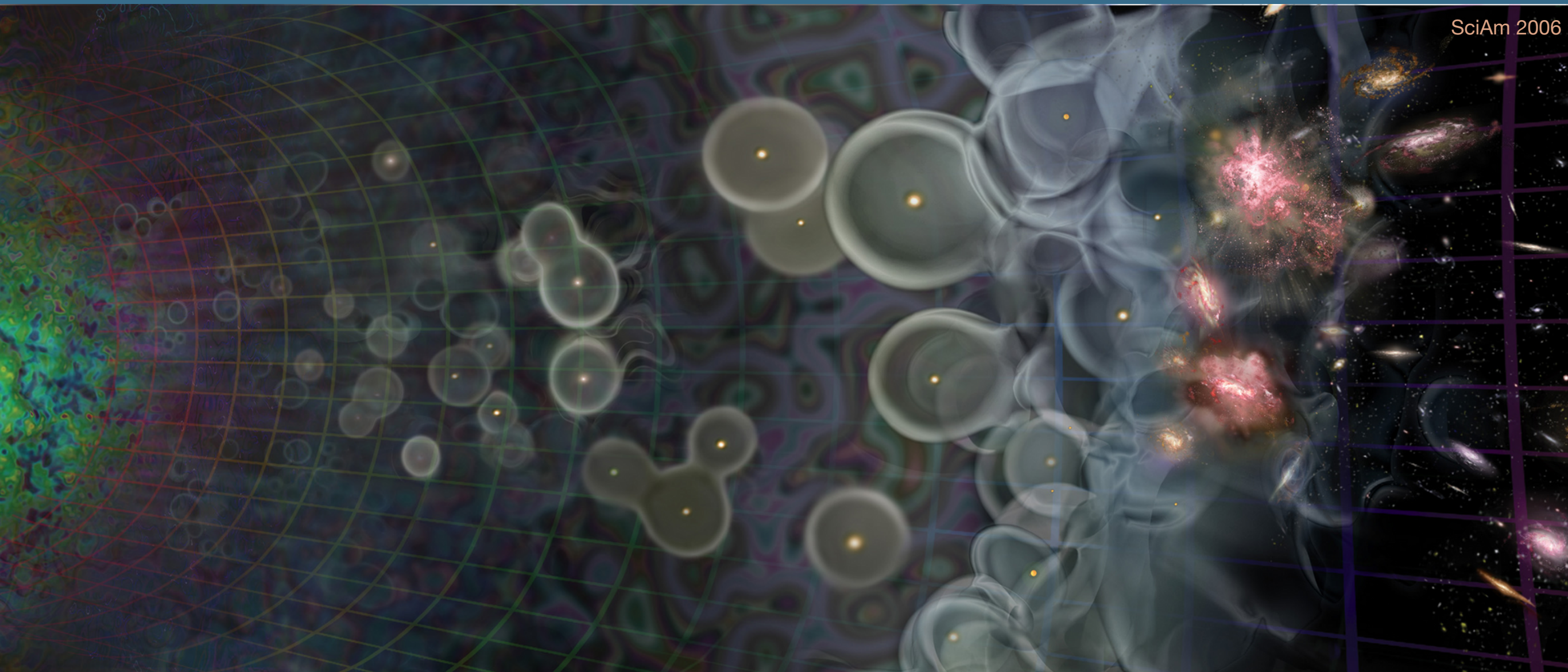
³*Cosmic Frontier Center, The University of Texas at Austin, Austin, TX 78712*



The Dawn of Cosmic Dawn Cosmology

Ely Kovetz

Ben-Gurion University



GGI Symposium September 2025