Multi-tracing the Large Scale Structure of the Universe

Forecasts for radio-optical synergies and the state of the art of radio surveys

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INFN

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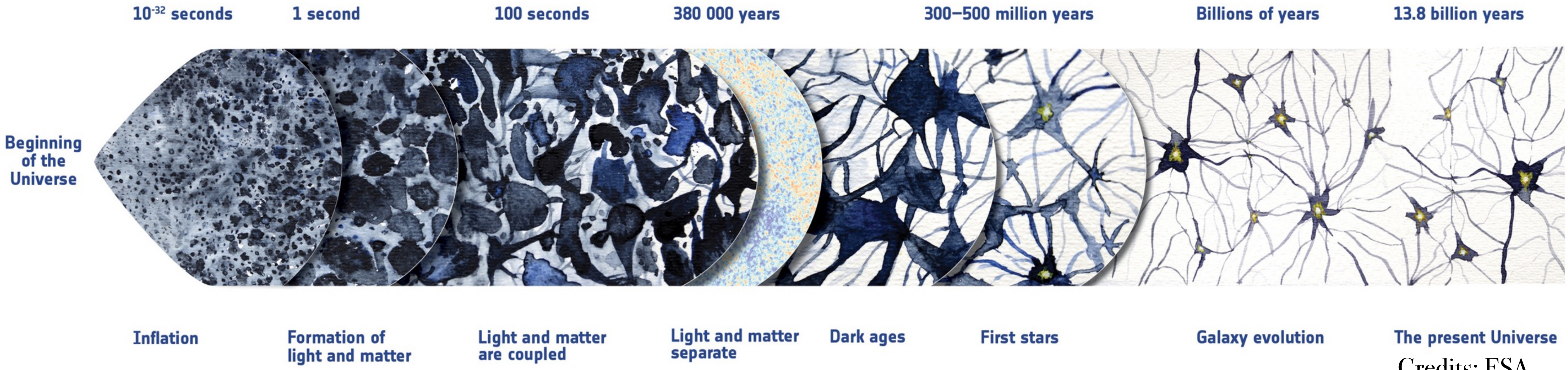
euclid consortium

SKAO

ΛCDM

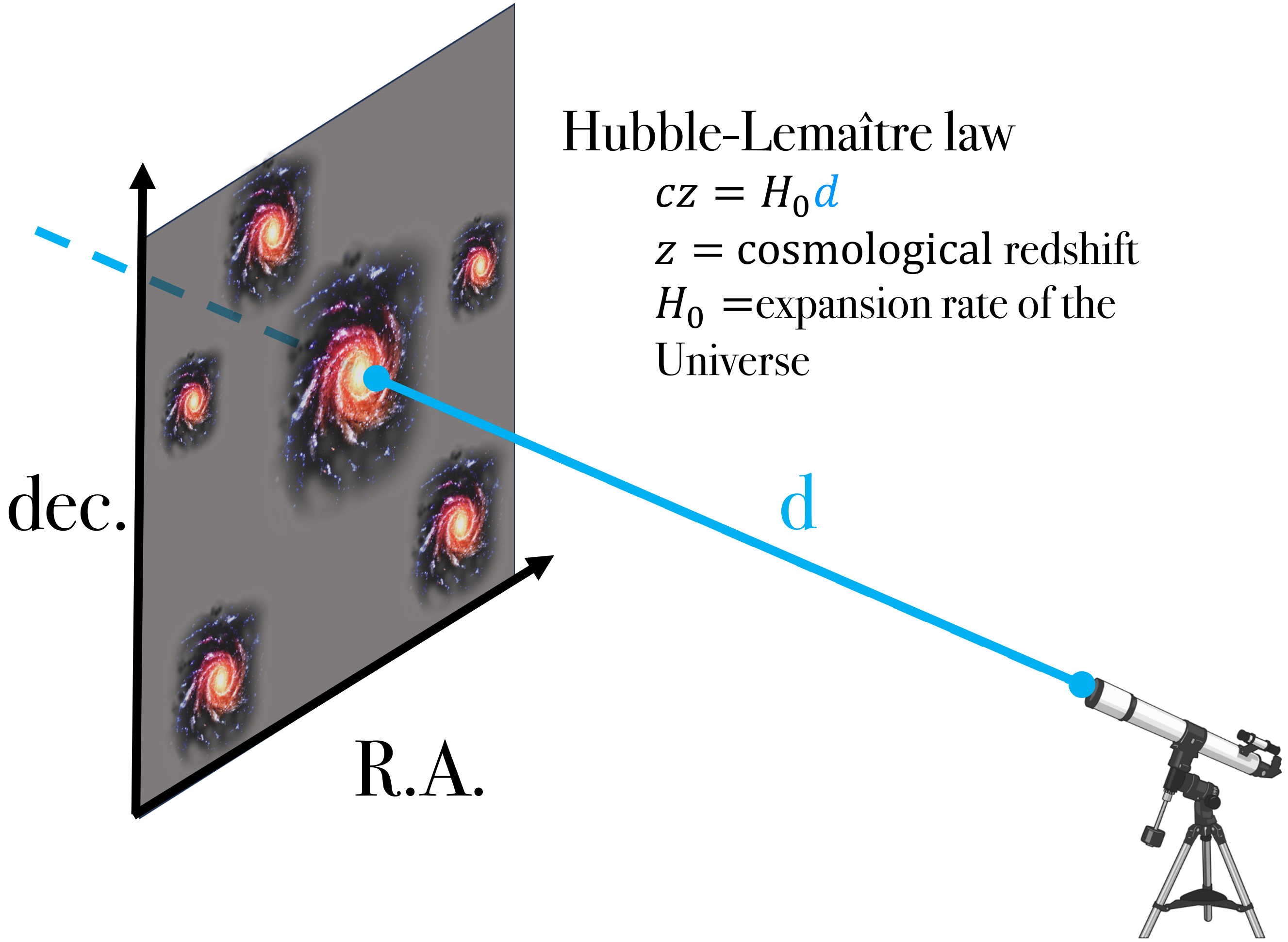
- Evolution of the Universe from primordial fluctuations up to the cosmic web
  - Λ: cosmological constant / dark energy
  - CDM: cold dark matter
  - Inflation



Credits: ESA

The large scale structure

- Matter spatial distribution determined by the cosmological parameters
- Statistical properties of dark matter tracers to constrain the cosmological parameters
  - Cosmological surveys of the three dimensional distribution of dark matter tracers



Hubble-Lemaître law

$cz = H_0 d$

z = cosmological redshift

H_0 =expansion rate of the Universe

Power spectrum

- From dark matter…
  - Density contrast

$$\delta_{\mathrm{m}}(\boldsymbol{x}, z) = \frac{\rho(\boldsymbol{x}, z) - \bar{\rho}(z)}{\bar{\rho}(z)} \rightarrow \tilde{\delta}_{\mathrm{m}}(\boldsymbol{k}, z)$$

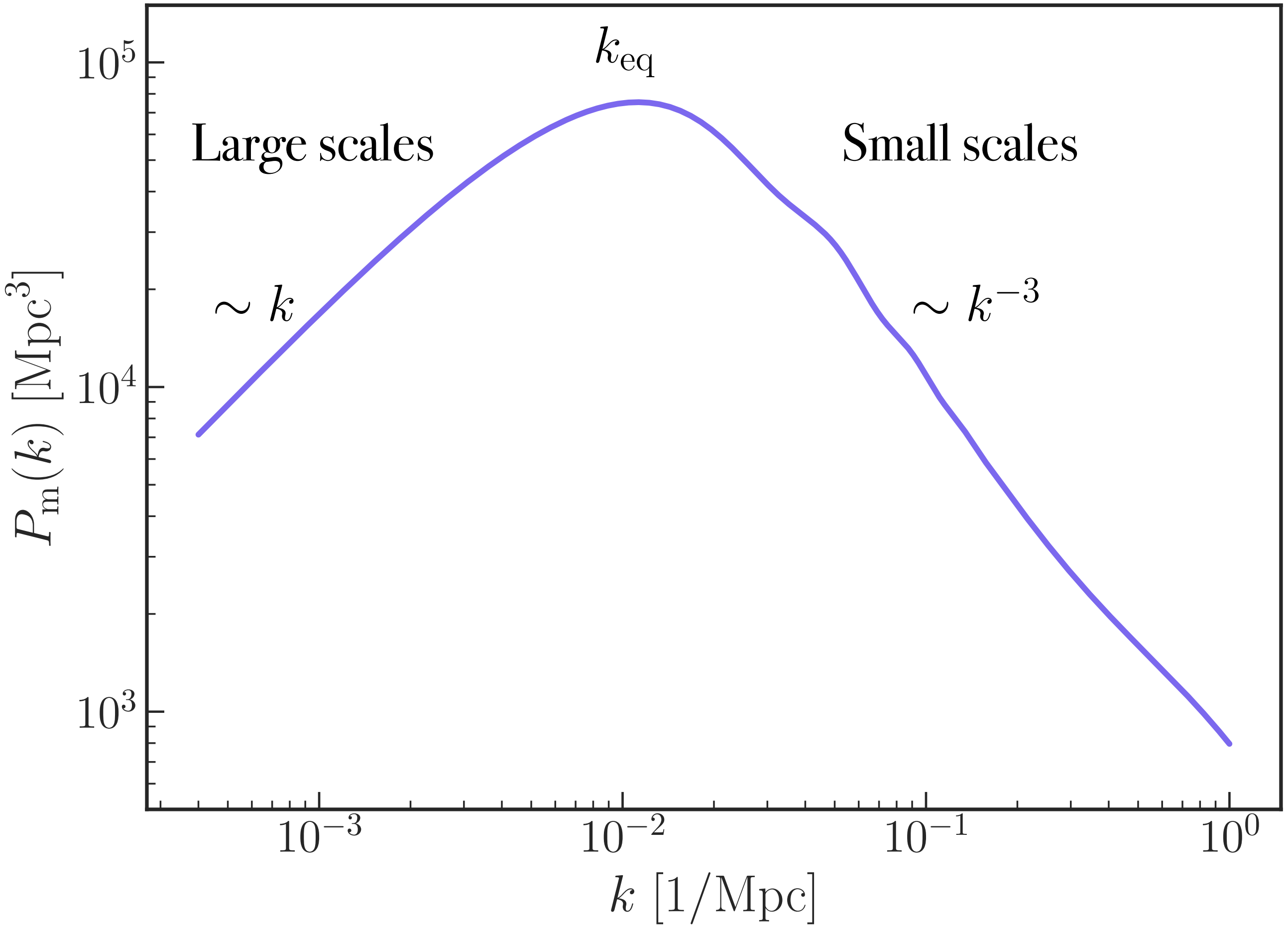
  - Power spectrum

$$P_{\mathrm{m}}(k, z) = \langle \tilde{\delta}_{\mathrm{m}}(k, z) \tilde{\delta}^{*}_{\mathrm{m}}(k, z) \rangle$$

- … to its tracers

$$\delta_t(\boldsymbol{x}, z) = b_t(z) \delta_{\mathrm{m}}(\boldsymbol{x}, z)$$

$$P_t(k, z, \mu) = [b_t(z) + f(z)\mu^2]^2 \, P_{\mathrm{m}}(k, z)$$



Matter tracers

Galaxies

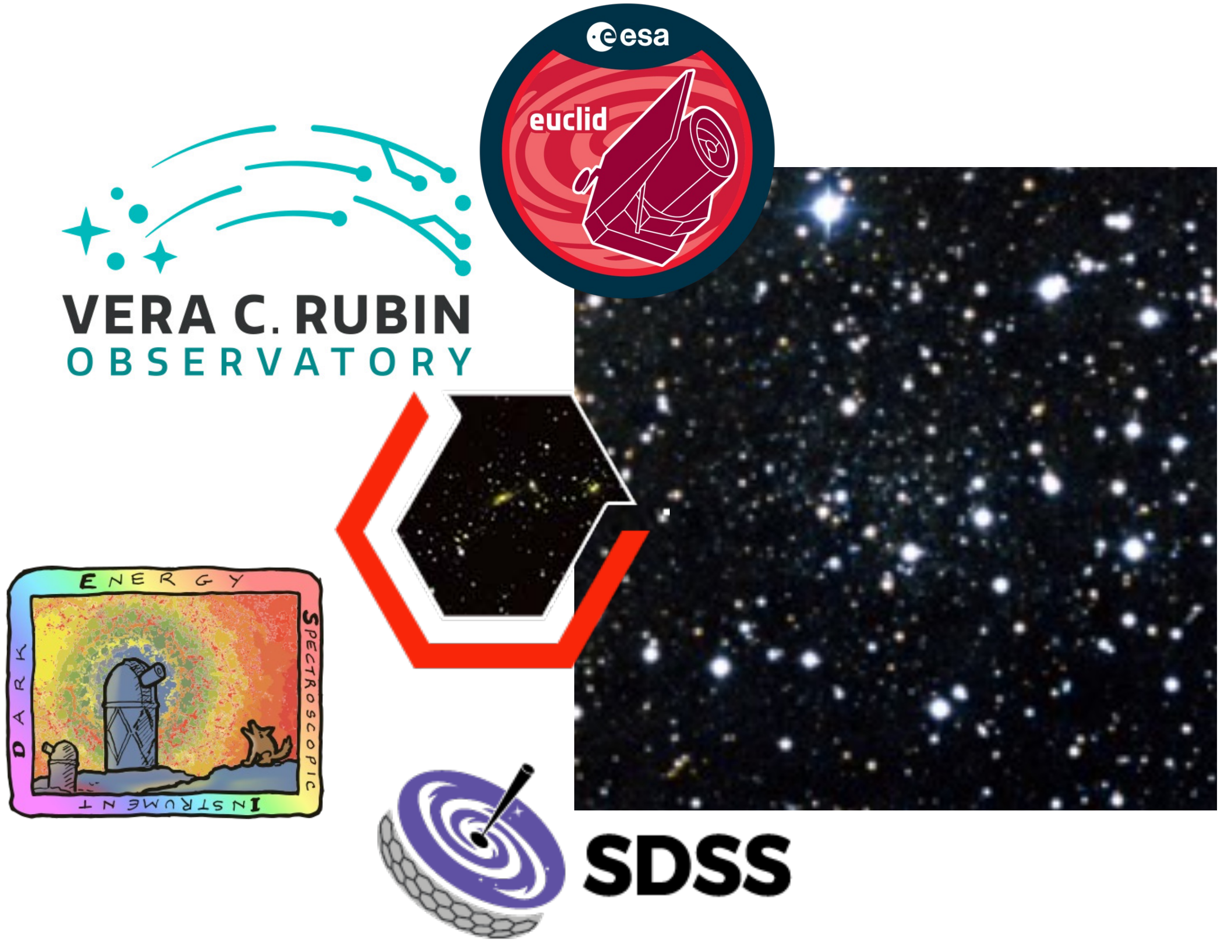
- Emission in caracteristic spectral lines
- Spectroscopic/photometric surveys (optical and NIR bands): single sources resolved

Matter tracers

Galaxies

Matter tracers

Galaxies



Neutral Hydrogen (HI)

- Emission at 21cm from the hyperfine spin-flip transition of neutral hydrogen (HI)
- Intensity mapping (IM) in the radio band: low angular of the total flux from unresolved sources

Matter tracers

Galaxies

esa
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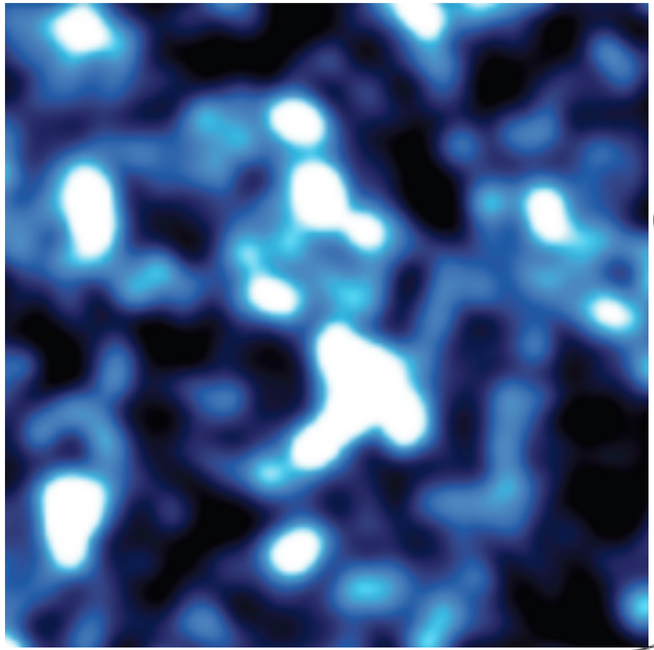
VERA C. RUBIN OBSERVATORY
DARK ENERGY SPECTROSCOPIC INSTRUMENT
SDSS

Neutral Hydrogen (HI)

SKAO
Hydrogen Epoch of Reionization Array
HERA
The Search for COSMIC DAWN
HIRAX
GREEN BANK OBSERVATORY
chime



Multi-tracer technique

- Large scales: cosmic variance limited
- Multi-tracer technique: combination of independent tracers of the same underlying matter distribution to overcome cosmic variance [Seljak (2008)]

- Data vector

$$\boldsymbol{P} = \{P_{\mathrm{gg}}, P_{\mathrm{gH\,I}}, P_{\mathrm{H\,IH\,I}}\}$$

- Full covariance matrix [Karagiannis et al.(2023)]

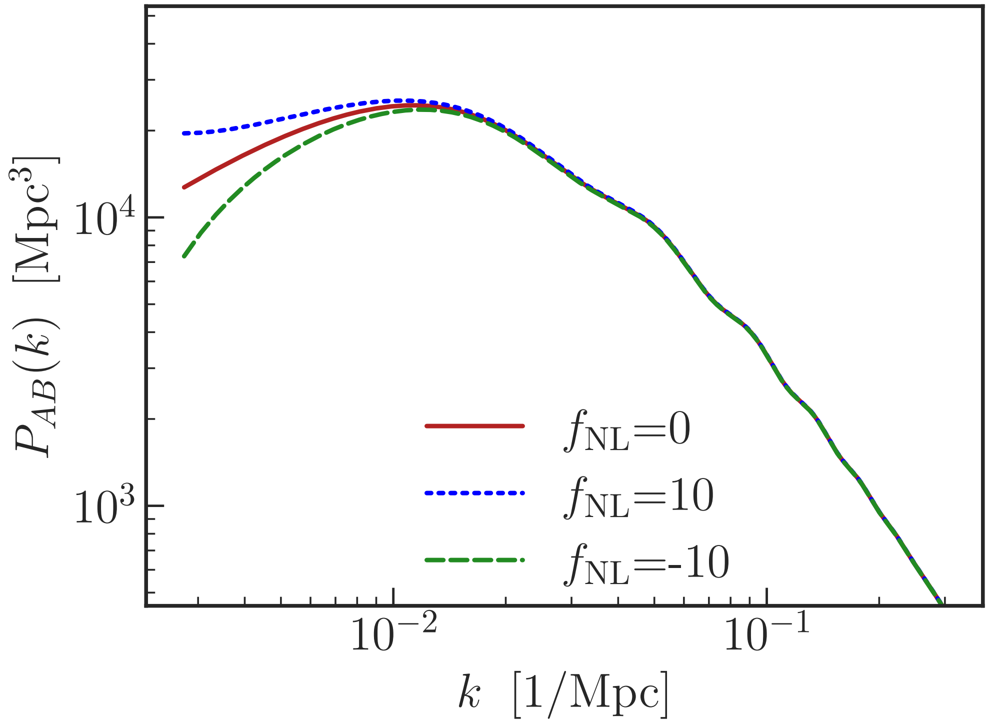
$$\mathrm{Cov}(\boldsymbol{P}) = \frac{2}{N_{\mathrm{m}}} \begin{bmatrix} \tilde{P}_{\mathrm{gg}}^2 & \tilde{P}_{\mathrm{gg}}\tilde{P}_{\mathrm{gH\,I}} & \tilde{P}_{\mathrm{gH\,I}}^2 \\ \tilde{P}_{\mathrm{gg}}\tilde{P}_{\mathrm{gH\,I}} & \frac{1}{2}\left(\tilde{P}_{\mathrm{gg}}\tilde{P}_{\mathrm{H\,IH\,I}} + \tilde{P}_{\mathrm{gH\,I}}^2\right) & \tilde{P}_{\mathrm{H\,IH\,I}}\tilde{P}_{\mathrm{gH\,I}} \\ \tilde{P}_{\mathrm{gH\,I}}^2 & \tilde{P}_{\mathrm{H\,IH\,I}}\tilde{P}_{\mathrm{gH\,I}} & \tilde{P}_{\mathrm{H\,IH\,I}}^2 \end{bmatrix}$$

$$\tilde{P}_{AB} = P_{AB} + P_{AB}^{\mathrm{noise}}\delta_{AB}$$

Primordial non-Gaussianity

- Predicted by inflationary models
  - Direct proof of inflation
  - Information on the dynamics of Early Universe
- Primordial non-Gaussianity of local-type: $f_{\mathrm{NL}} \neq 0$
- Current constraints from CMB [Planck Collaboration: (2018)]
  - $|f_{\mathrm{NL}}| < 5$
  - $\sigma(f_{\mathrm{NL}}) \sim 5$
- Primordial non-Gaussianity and the Large Scale Structure
  - $b_A(z) \rightarrow b_A(z) + \Delta b_A(k,z) f_{\mathrm{NL}}$

$$\Delta b_A(k,z) = 3\,[b_A(z) - 1]\,\frac{\delta_c \Omega_{\mathrm{m},0} H_0^2}{c^2 k^2 T(k) D(z)}$$



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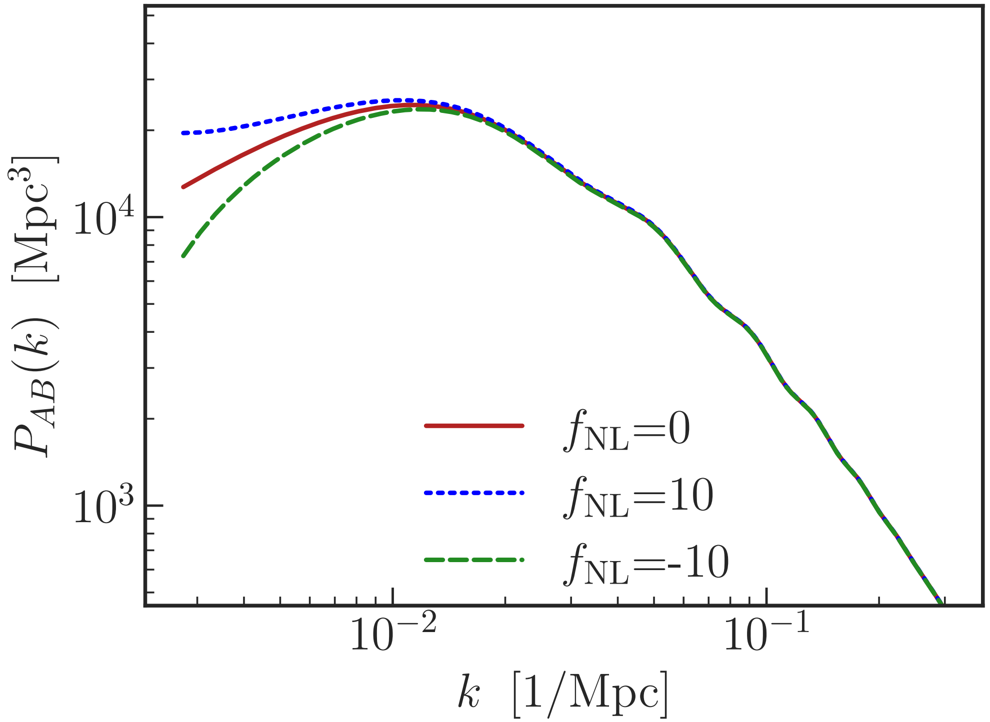


Analysis

- HI and galaxy synthetic data vectors (auto and cross correlations)
  - Stage IV surveys
  - Including systematics

} synthetic multi-tracer data vector

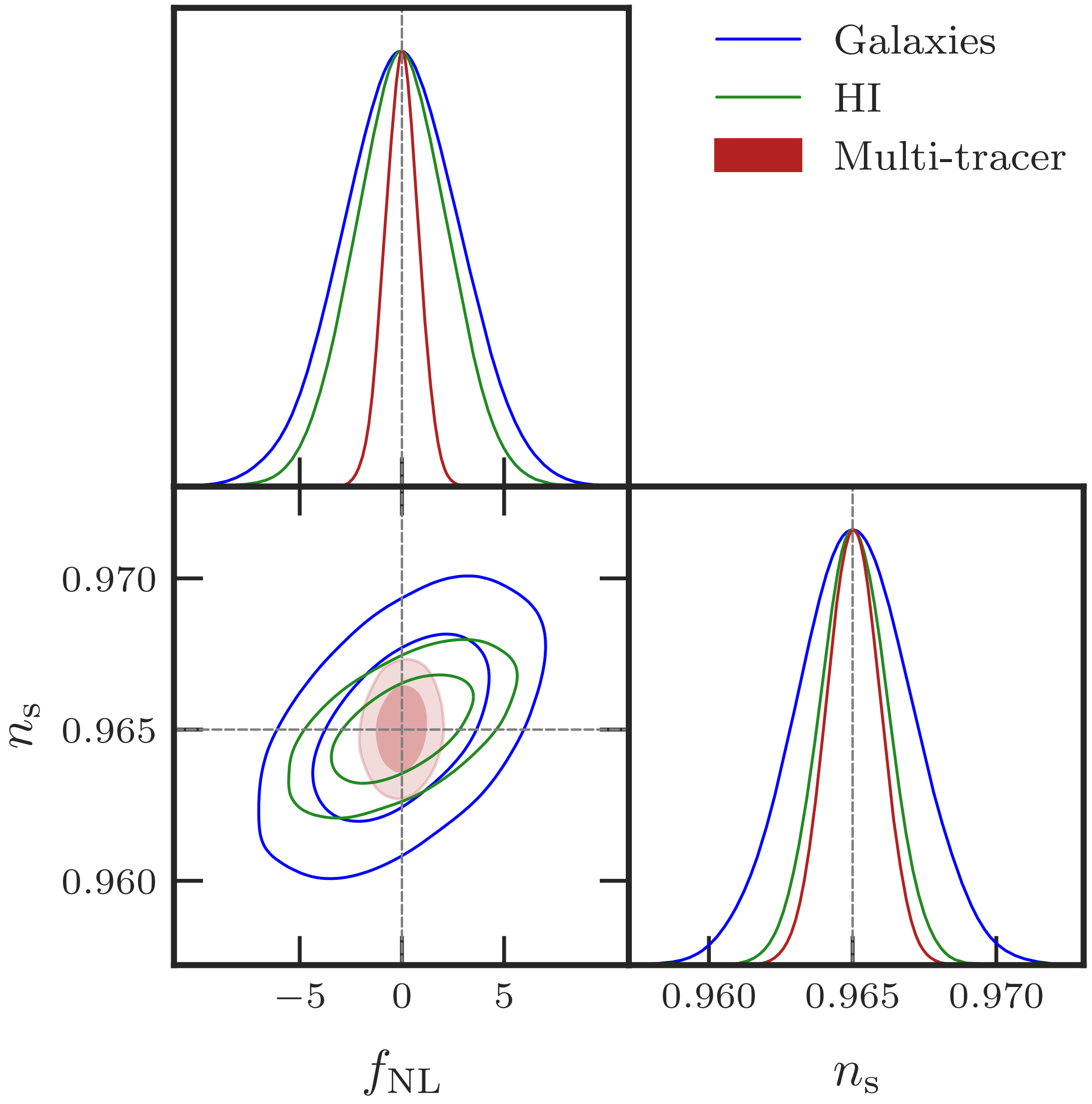
- Multivariate analysis: maximization of the likelihood with MCMC method

$$\ln \mathcal{L}\,(\boldsymbol{\theta}; \boldsymbol{d}) \propto [\boldsymbol{d} - \boldsymbol{P}(\boldsymbol{\theta})]^{\mathrm{T}} \mathrm{Cov}^{-1}\, [\boldsymbol{d} - \boldsymbol{P}(\boldsymbol{\theta})]$$

  - $\boldsymbol{P}(\boldsymbol{\theta}) =$ theoretical multi-tracer data vector
  - $\boldsymbol{\theta} = \{f_{\mathrm{NL}}, n_{\mathrm{s}}, b_{\mathrm{g}}(z), b_{\mathrm{HI}}(z)\}$
- Analysis of the constraints, focusing on f_{NL}

Results

- All fiducial parameters recovered and constrained
- Marginalized uncertainty on f_{NL}:
  - Galaxies auto-correlation: $f_{NL} = 0.0 \pm 2.8$
  - HI auto-correlation: $f_{NL} = 0.0 \pm 2.3$
  - Multi-tracer techique: $f_{NL} = 0.0 \pm 0.76$
- Multi-tracer technique: tightest constraints



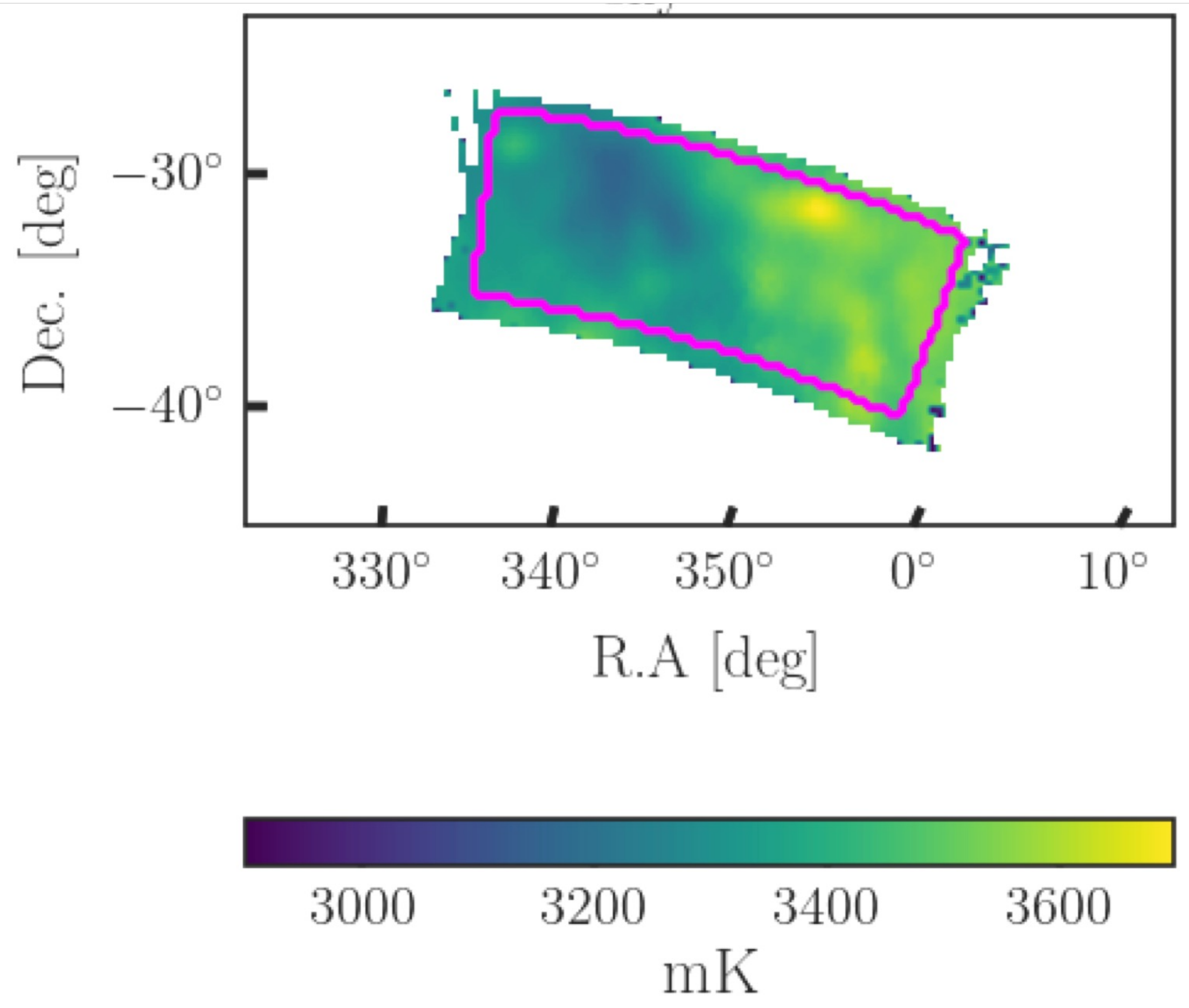
[**MBS**, Camera, Maartens (2023)]

HI IM WITH MEERKAT

- SKAO precursor
- Sud Africa, Karoo
- 64 antennas (diameter:13,5m)
- Frequency bands:
  - L-band: $580 < \nu < 1015$ MHz
  - UHF band: $900 < \nu < 1970$ MHz

- MeerKAT Large Area Synoptic Survey (MeerKLASS) [Santos et al. (2016)]
- 2019 pilot survey (L-band):
  - Validation of the calibration pipeline [Wang et al. (2021), Li et al. (2021)]
  - First detection in cross-correlation with galaxies [Cunnington et al. (2023)]
- 2021 survey (L-band):
  - Re-detection of the cross-correlation [Cunnington, **MBS** et al. (2023)]
  - Auto-power spectrum being extracted [**MBS** et al. (TBS)]
- 2023-2028 (UHF-band): new observing season

HI IM WITH MEERKAT



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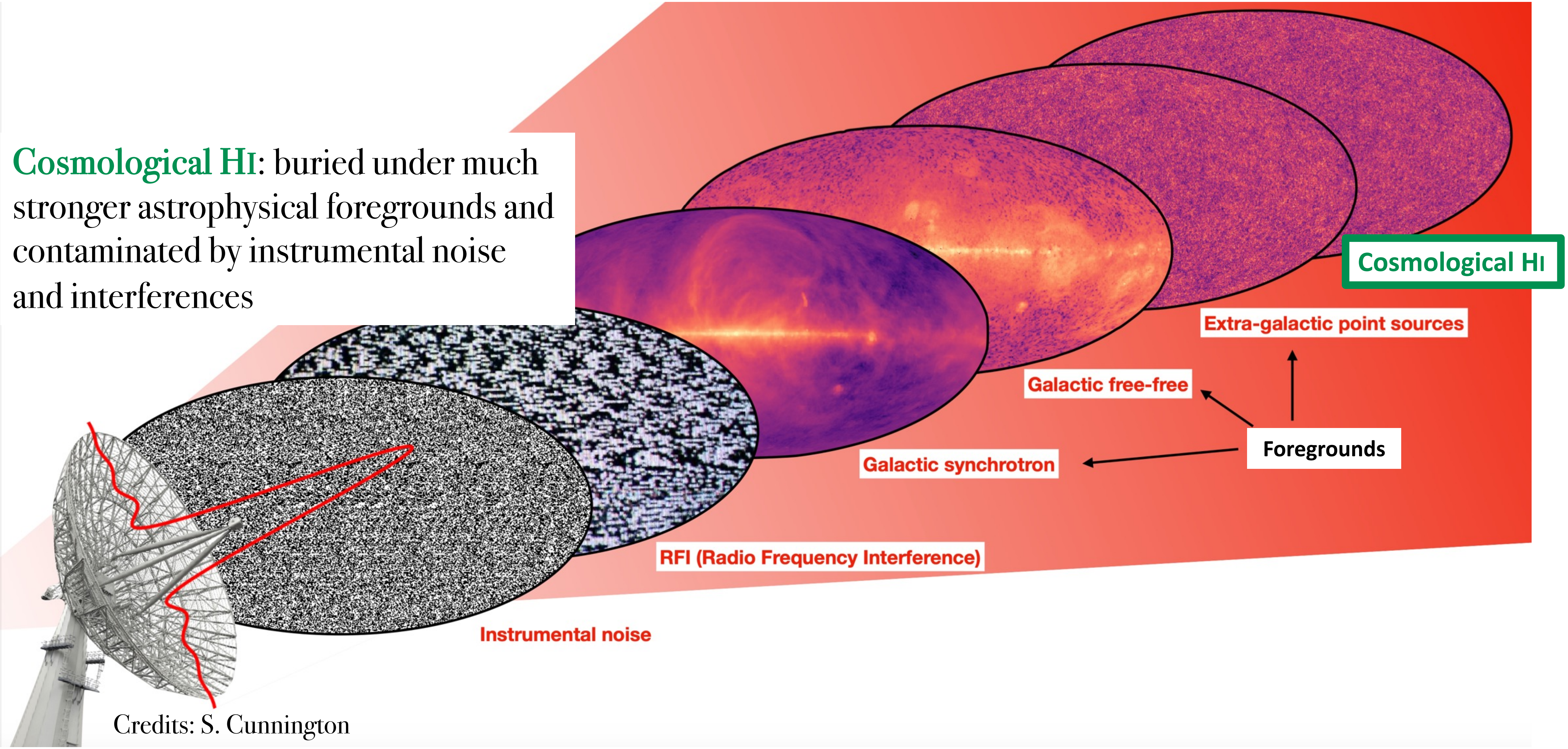
Why is HI intensity mapping hard?

Cosmological HI: buried under much stronger astrophysical foregrounds and contaminated by instrumental noise and interferences

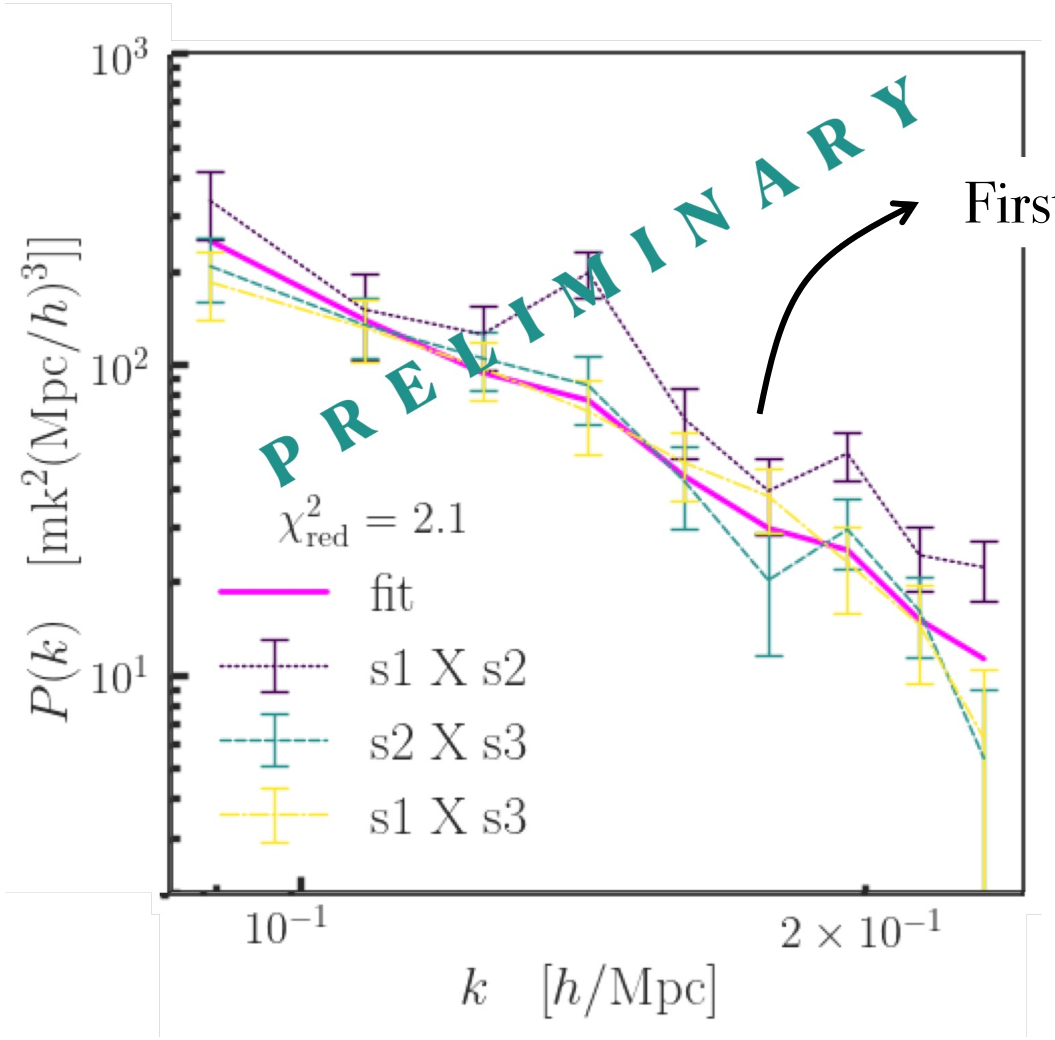


Credits: S. Cunnington

THE HI AUTO POWER SPECTRUM

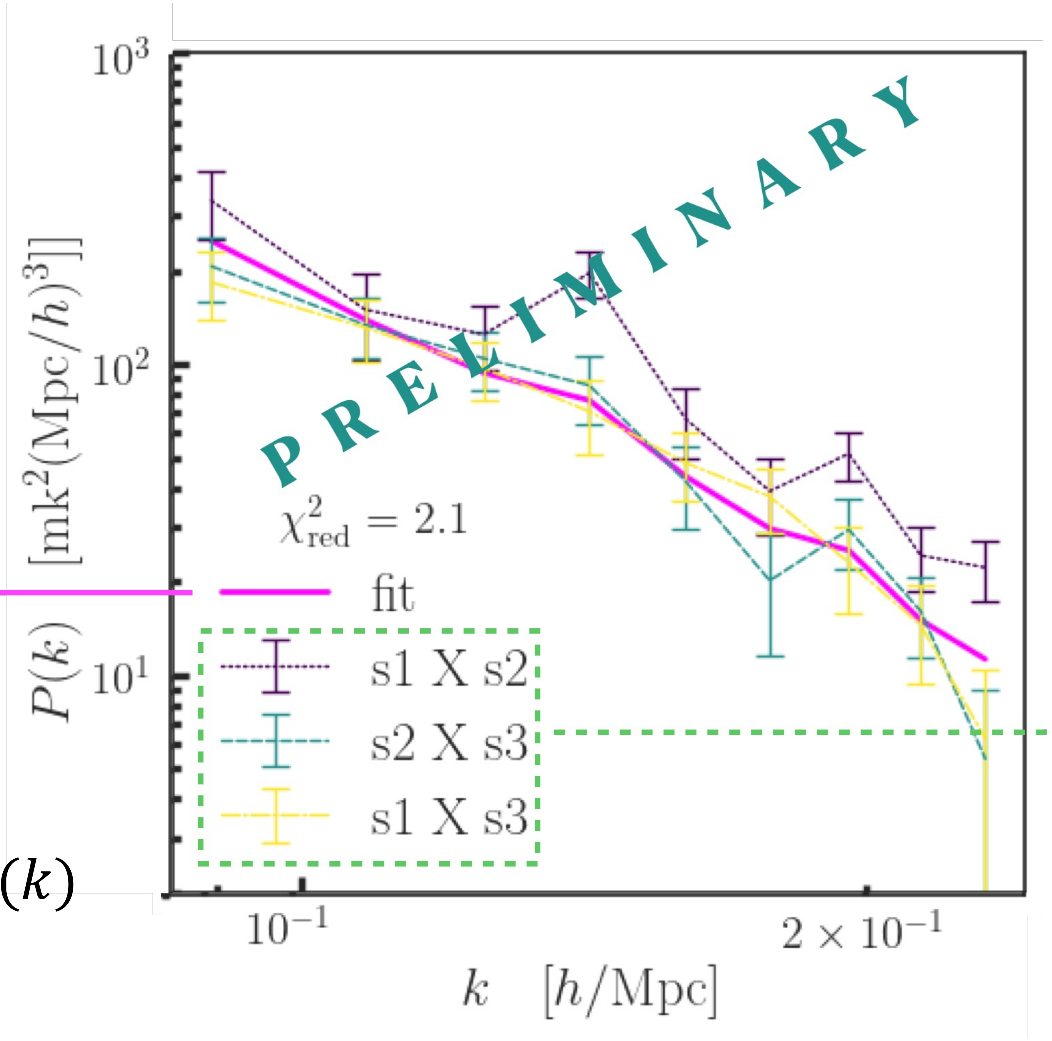
- Internal cross-correlations: building independent subsets from the same survey [Wolz et al. (2021)]
  - The HI cosmological signal is the only correlated part
  - Contaminants not correlated between subsets
  - Noise free cross-subset power spectra

Some preliminary results



First ever HI auto-power spectra

Some preliminary results



One only common fit-curve

Stripe division: three cross-$P(k)$ measured

$$P_{i\times j} \propto \boldsymbol{T^2_{\rm HI} b^2_{\rm HI}} (1 + f\mu^2)^2 P_{\rm m}(k)$$

Conclusions

- The MeerKLASS 2021 survey in the L-band, being the deepest single-dish survey, carry a relaevant amout of information
- Internal cross-correlations:
  - Help in mitigating systematics that affect HI intensity mapping observation
  - Possibility to detect the power spectrum without the need of a cross-correlation with a spectroscopic galaxy survey
- Open road for synergies between surveys, exploiting the complementarities of different tracers

Back-up slides

Power spectrum: Tracers

$$P_{AB}(k,z,\mu) = [b_A(z) + f(z)\mu^2][b_B(z) + f(z)\mu^2]P_{\mathrm{m}}(k,z)$$

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Tracers

$A = B \rightarrow$ auto-correlation

$A \neq B \rightarrow$ cross-correlation

Power spectrum: Tracers

$$P_{AB}(k,z,\mu) = [b_A(z) + f(z)\mu^2][b_B(z) + f(z)\mu^2]P_{\rm m}(k,z)$$

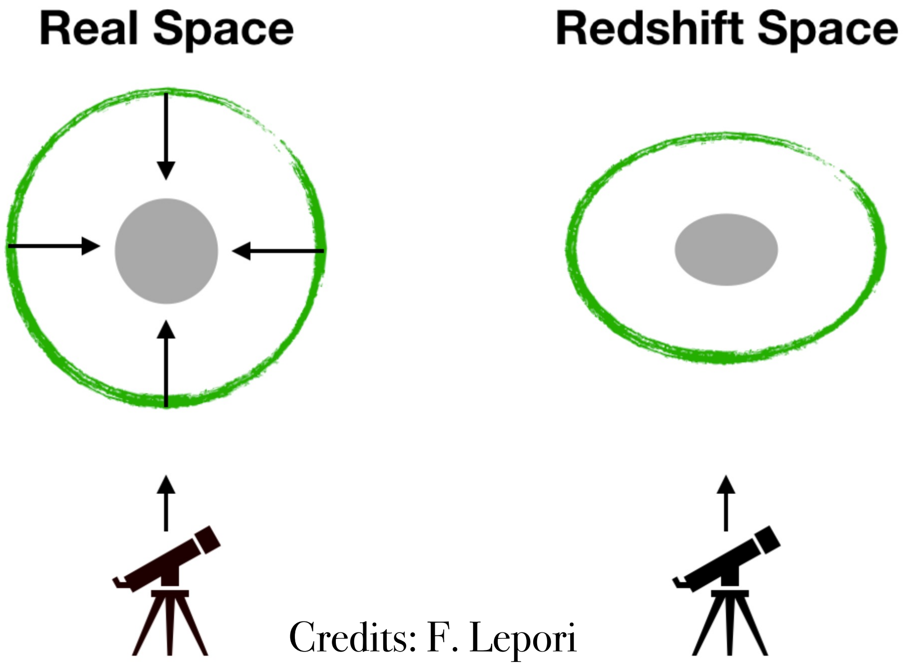
Linear bias

$$\delta_{A,B}(\boldsymbol{x},z) = b_{A,B}(z)\delta_{\rm m}(\boldsymbol{x},z)$$

Power spectrum: Tracers

$$P_{AB}(k,z,\mu) = [b_A(z) + f(z)\mu^2][b_B(z) + f(z)\mu^2]P_\mathrm{m}(k,z)$$

Redshift Space Distortions



Credits: F. Lepori

General setup

HI IM survey

- SKAO-like survey
- Sky coverage: $f_{\text{sky}} = 0.48$
- Thermal noise
- Beam damping
- Foreground avoidance

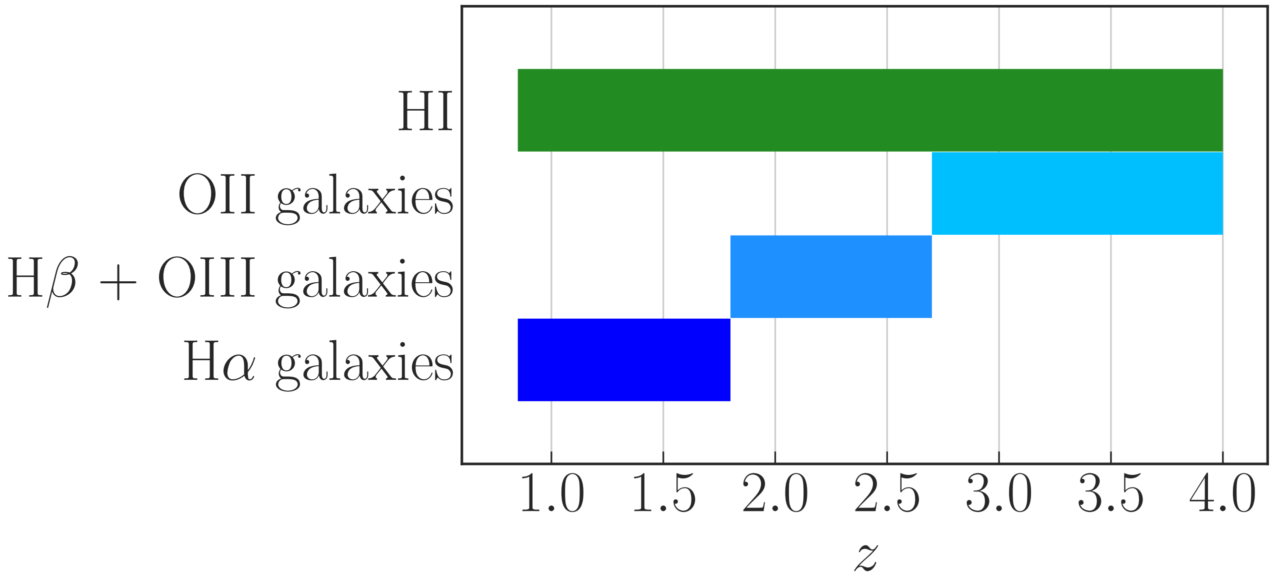
Galaxy survey

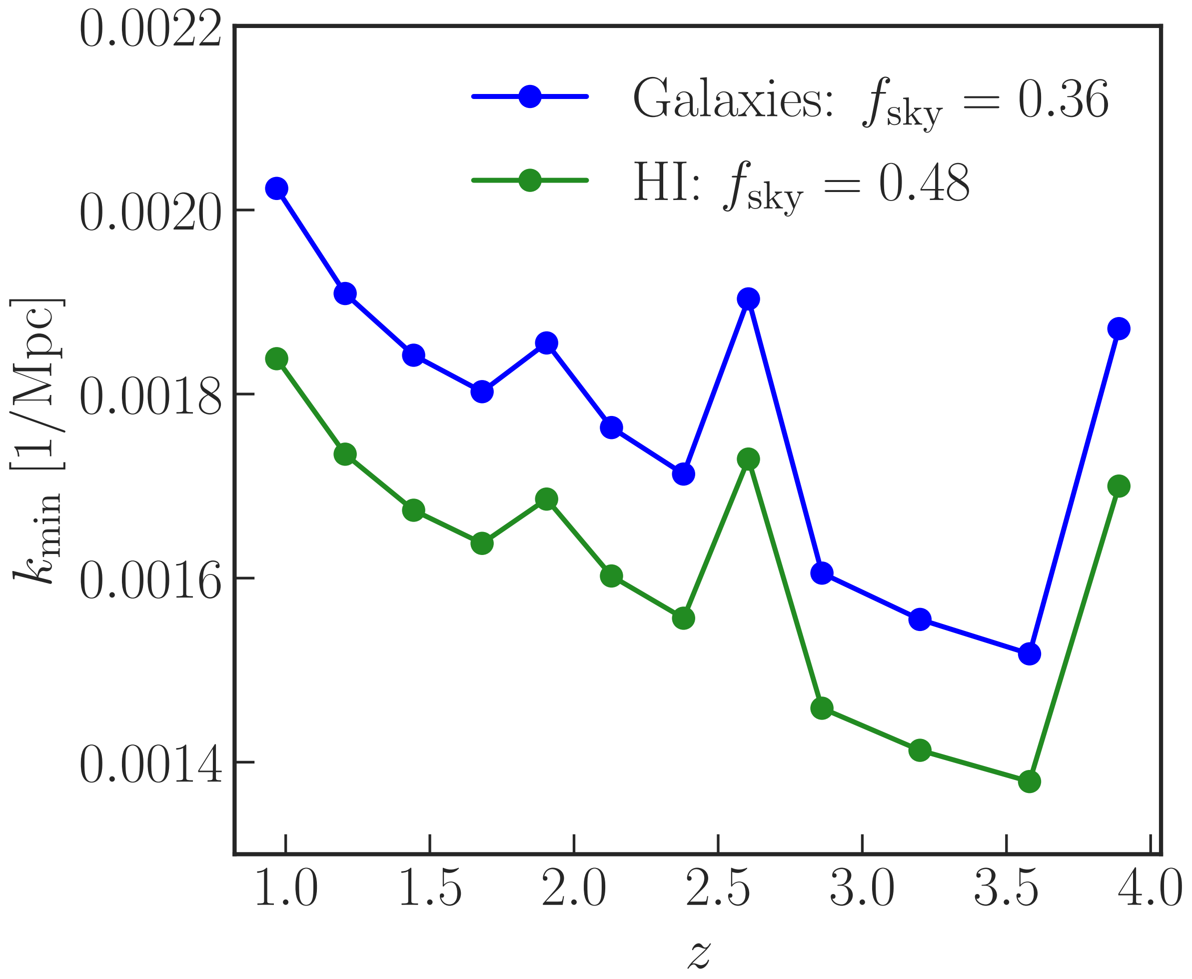
- Stage-IV spectroscopic survey
- Redshift range covered with different ELG types [Fonseca, Camera (2020)]
- Flux limit: $F_{\text{c}} = 2 \cdot 10^{-16} \text{erg s}^{-1}\ \text{cm}^{-2}$
- Sky coverage: $f_{\text{sky}} = 0.36$
- Shot noise

- 12 redshift bins for $z \in [0.85, 4]$

- 10 bins for $k \in [k_{\text{min}}(z), k_{\text{max}}(z)]$
  - $k_{\text{min}}(z) = \frac{2\pi}{V^{1/3}(z)}$
  - $k_{\text{max}}(z) = 0.08(1+z)^{2/(2+n_{\text{s}})} h\text{Mpc}^{-1}$

General setup





HI systematics

- HI auto-power spectrum: $P_{\mathrm{HIHI}}(k,z,\mu) \longrightarrow \mathcal{D}_{\mathrm{b}}{}^2(k,z,\mu)\mathcal{D}_{\mathrm{fg}}(k,z,\mu)P_{\mathrm{HIHI}}(k,z,\mu)$
- Galaxy-HI cross-power spectrum: $P_{\mathrm{gHI}}(k,z,\mu) \longrightarrow \mathcal{D}_{\mathrm{b}}(k,z,\mu)\mathcal{D}_{\mathrm{fg}}(k,z,\mu)P_{\mathrm{gHI}}(k,z,\mu)$
  - Beam damping

    $\mathcal{D}_{\mathrm{b}}(k,z,\mu) = \exp\left[-\frac{(1-\mu^2)k^2\chi^2(z)\theta_{\mathrm{b}}^2(z)}{16\ln 2}\right]$ with θ_{b} the beam of the dish
  - Foreground contamination

    $\mathcal{D}_{\mathrm{fg}}(k,z,\mu) = 1 - \exp\left[-\left(\frac{\mu k}{k_{\parallel\mathrm{fg}}}\right)^2\right]$ with $k_{\parallel\mathrm{fg}} = 0.01h\mathrm{Mpc}^{-1}$

Analysis

- Maximization of the likelihood with MCMC method

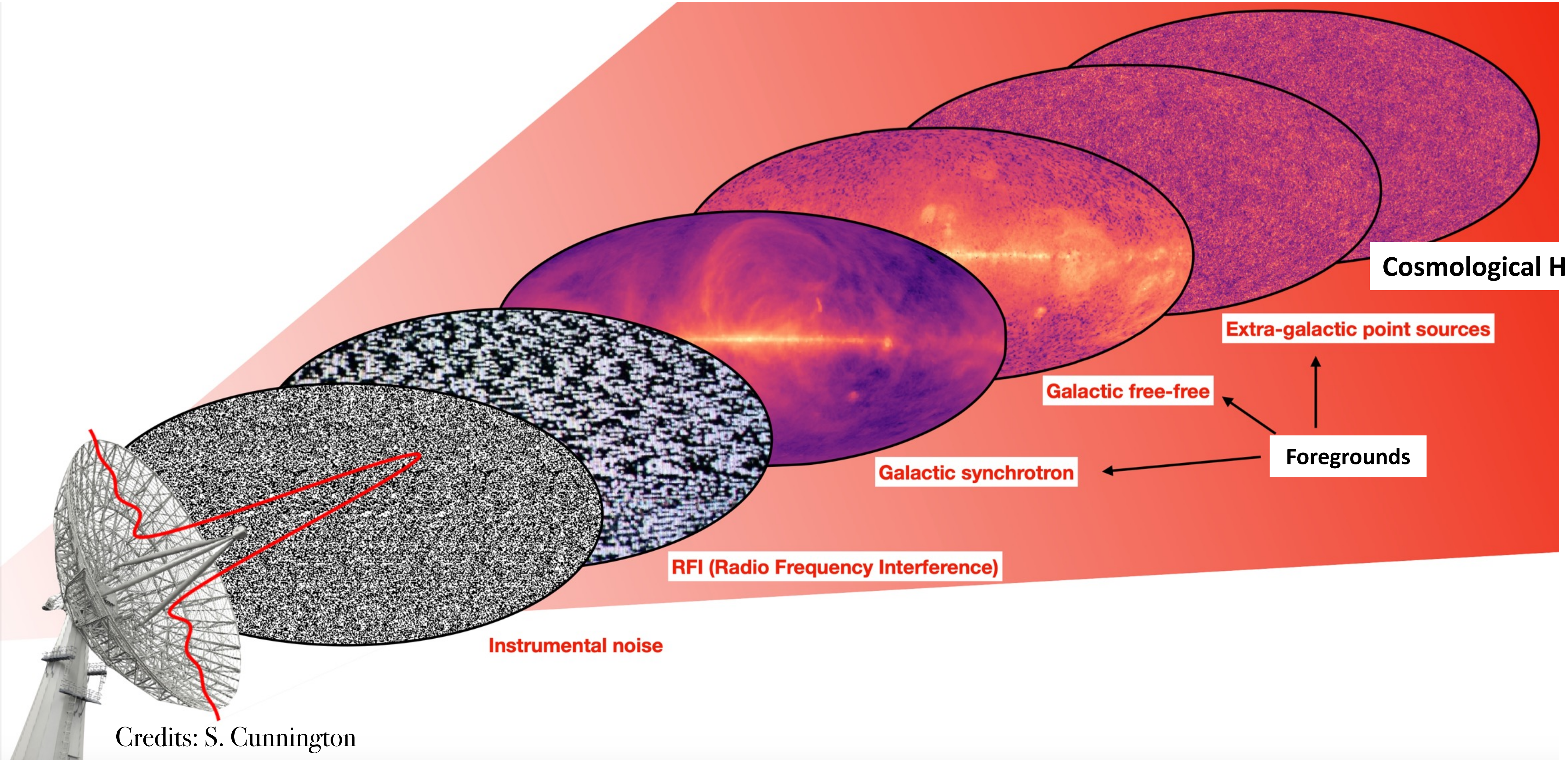
  $$\ln \mathcal{L}\,(\boldsymbol{\theta}; \boldsymbol{d}) \propto [\boldsymbol{d} - \boldsymbol{P}(\boldsymbol{\theta})]^{\mathrm{T}} \mathrm{Cov}^{-1}\,[\boldsymbol{d} - \boldsymbol{P}(\boldsymbol{\theta})]$$

  - $\boldsymbol{P}(\boldsymbol{\theta}) =$ theoretical data vector
  - $\boldsymbol{\theta} = \{f_{\mathrm{NL}}, n_{\mathrm{s}}, b_{\mathrm{g}}(z), b_{\mathrm{HI}}(z)\}$
- Full multi-tracer likelihood [Viljoen et al. (2020)]

  $$\ln \mathcal{L}_{\mathrm{MT}}^{\mathrm{tot}} = \ln \mathcal{L}_{\mathrm{MT}}^{\mathrm{overlap}} + \ln \mathcal{L}_{\mathrm{gg}}^{\mathrm{non-overlap}} + \ln \mathcal{L}_{\mathrm{HIHI}}^{\mathrm{non-overlap}}$$

- Analysis of the constraints:
  - All the redshift bins
  - With respect to the redshift (2 redshift bins at a time)
  - With respect to the ELG type of the galaxy surveys (4 redshift bins at a time)

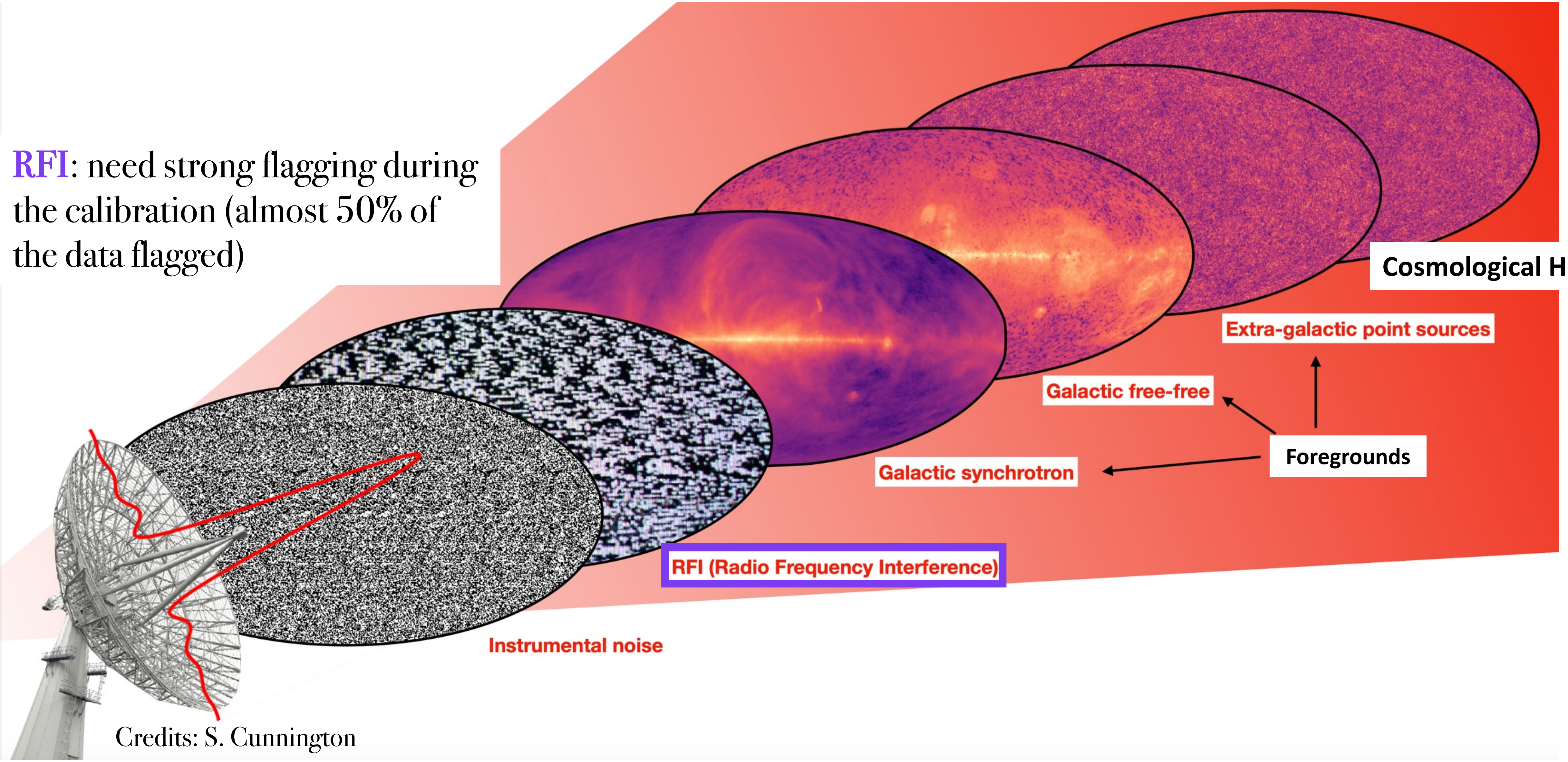
Why is Hi intensity mapping hard?



Credits: S. Cunnington

Why is HI intensity mapping hard?

RFI: need strong flagging during the calibration (almost 50% of the data flagged)



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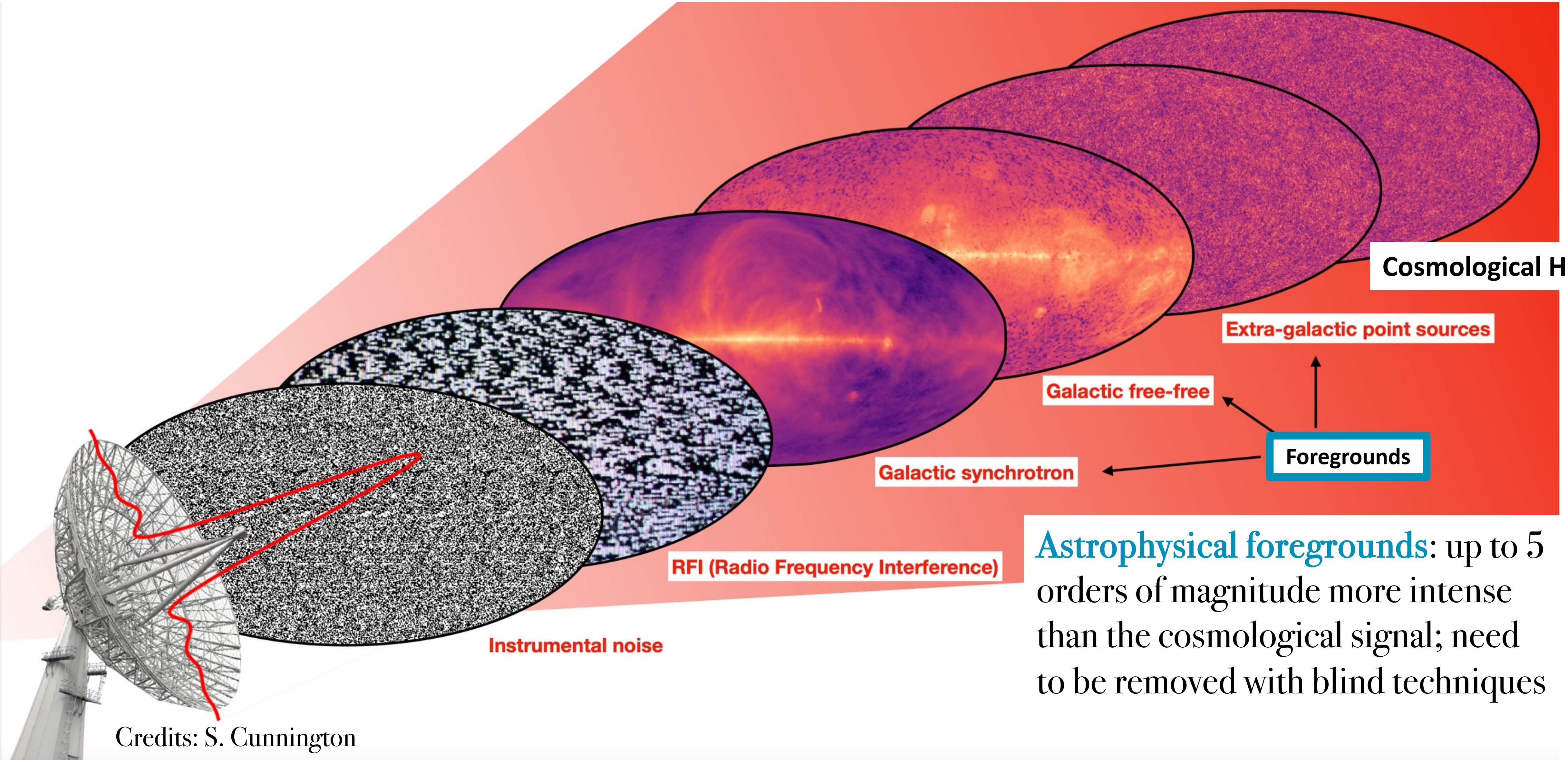
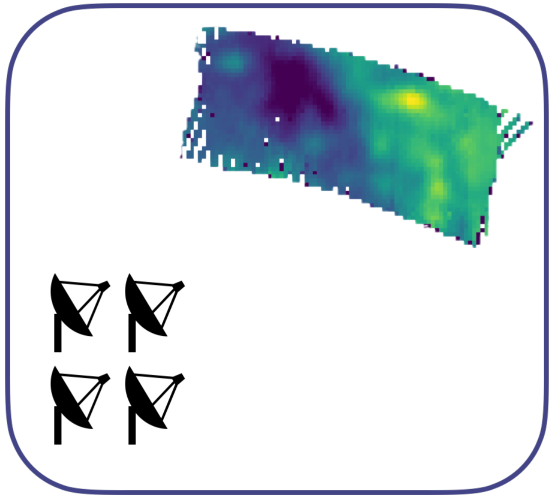


Credits: S. Cunnington

Astrophysical foregrounds: up to 5 orders of magnitude more intense than the cosmological signal; need to be removed with blind techniques

Single dish technique

- All the antennas of the array observe the same region at the same
- Low angular-resolution survey of the total 21cm flux from unresolved sources
- High signal-to-noise ratio
- Large cosmic volumes covered



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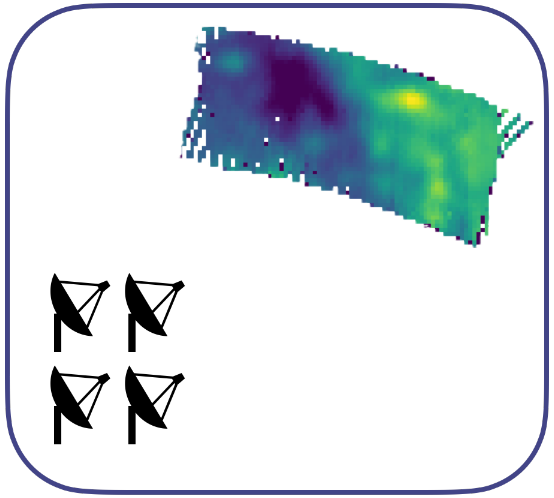
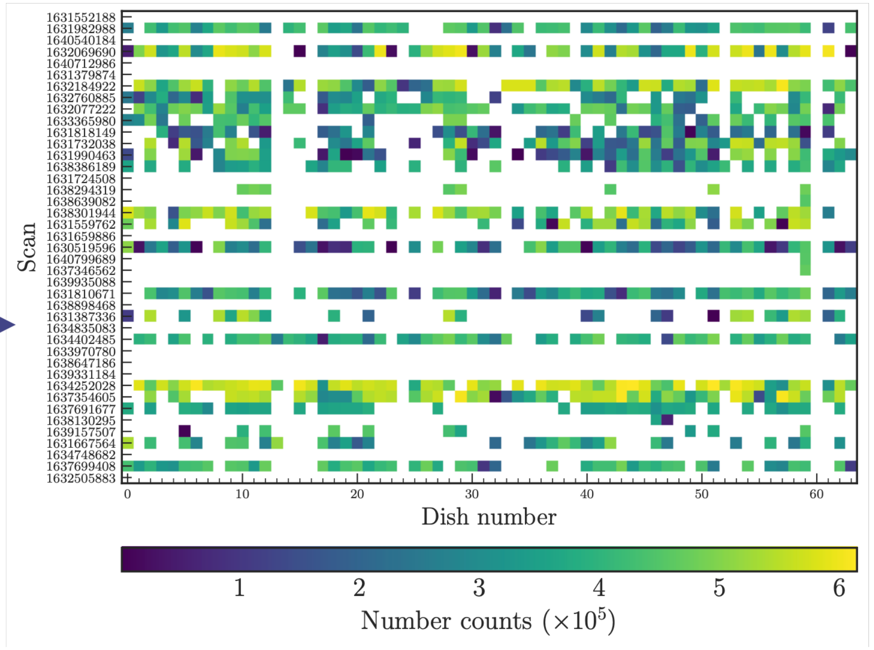


x *n* times



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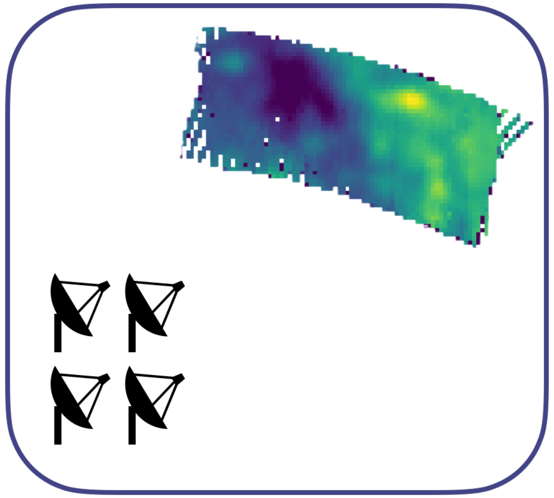
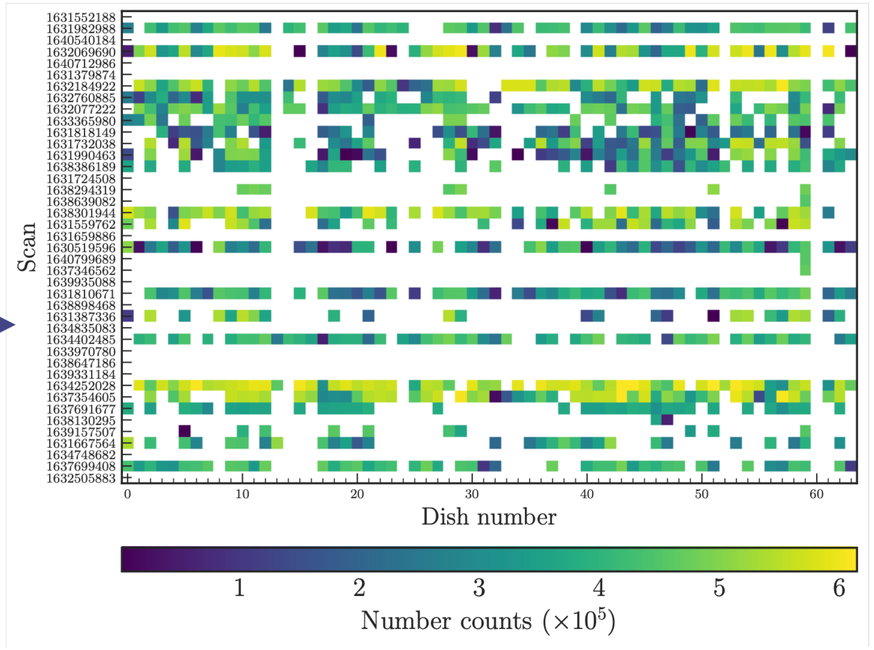


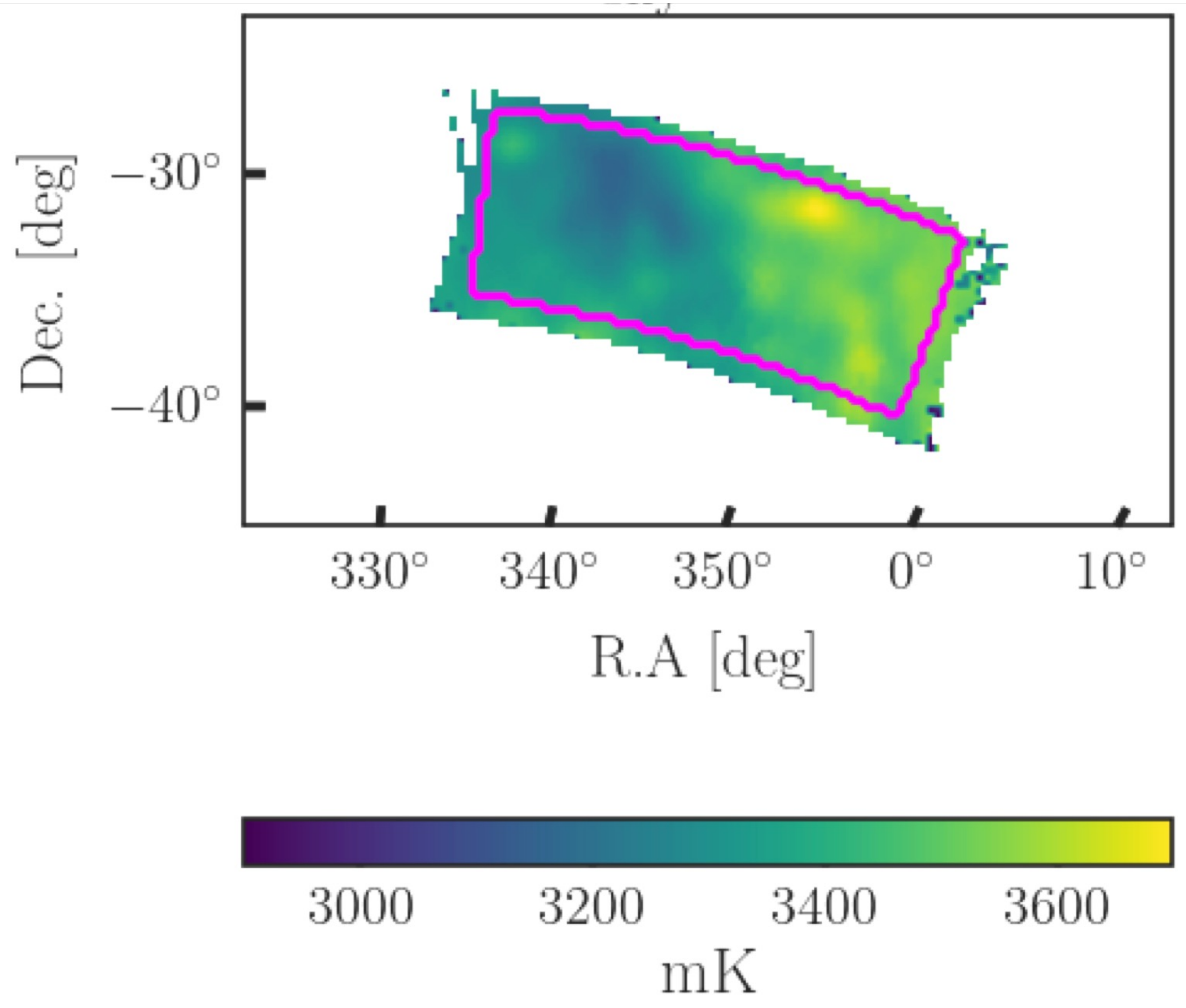
x *n* times →



→ Combined calibrated map

The 2021 data set

- The deepest HI survey
  - 62 hours of observation
  - 236 deg^2 patch
- Suitable to tackle the challenge of pursuing the measurements of the HI power spectrum in auto-correlation



The HI auto power spectrum

Full data set auto-correlation

- HI cosmological signal
- Noise
- Residuals foregrounds
- Contaminants

Internal cross-correlations

- Building independent subsets from the same survey [Wolz et al. (2021)]
- The HI cosmological signal is the only correlated part
- Contaminants not correlated between subsets
- Noise free cross-subset power spectra

MeerKLASS multi-subset fits

- Multi-tracer formalism translated to a multi-scan formalism (with cross power spectra only)

$$\boldsymbol{P} = \{P_{12}, P_{23}, P_{13}\}$$

$$\mathrm{Cov}(\boldsymbol{P},\boldsymbol{P}) \propto \begin{vmatrix} \frac{1}{2}\left(P_{11}P_{22}+P_{12}P_{12}\right) & \frac{1}{2}\left(P_{13}P_{22}+P_{12}P_{23}\right) & \frac{1}{2}\left(P_{11}P_{23}+P_{12}P_{13}\right) \\ & \frac{1}{2}\left(P_{22}P_{33}+P_{23}P_{23}\right) & \frac{1}{2}\left(P_{12}P_{33}+P_{13}P_{23}\right) \\ & & \frac{1}{2}\left(P_{11}P_{33}+P_{13}P_{13}\right) \end{vmatrix}$$