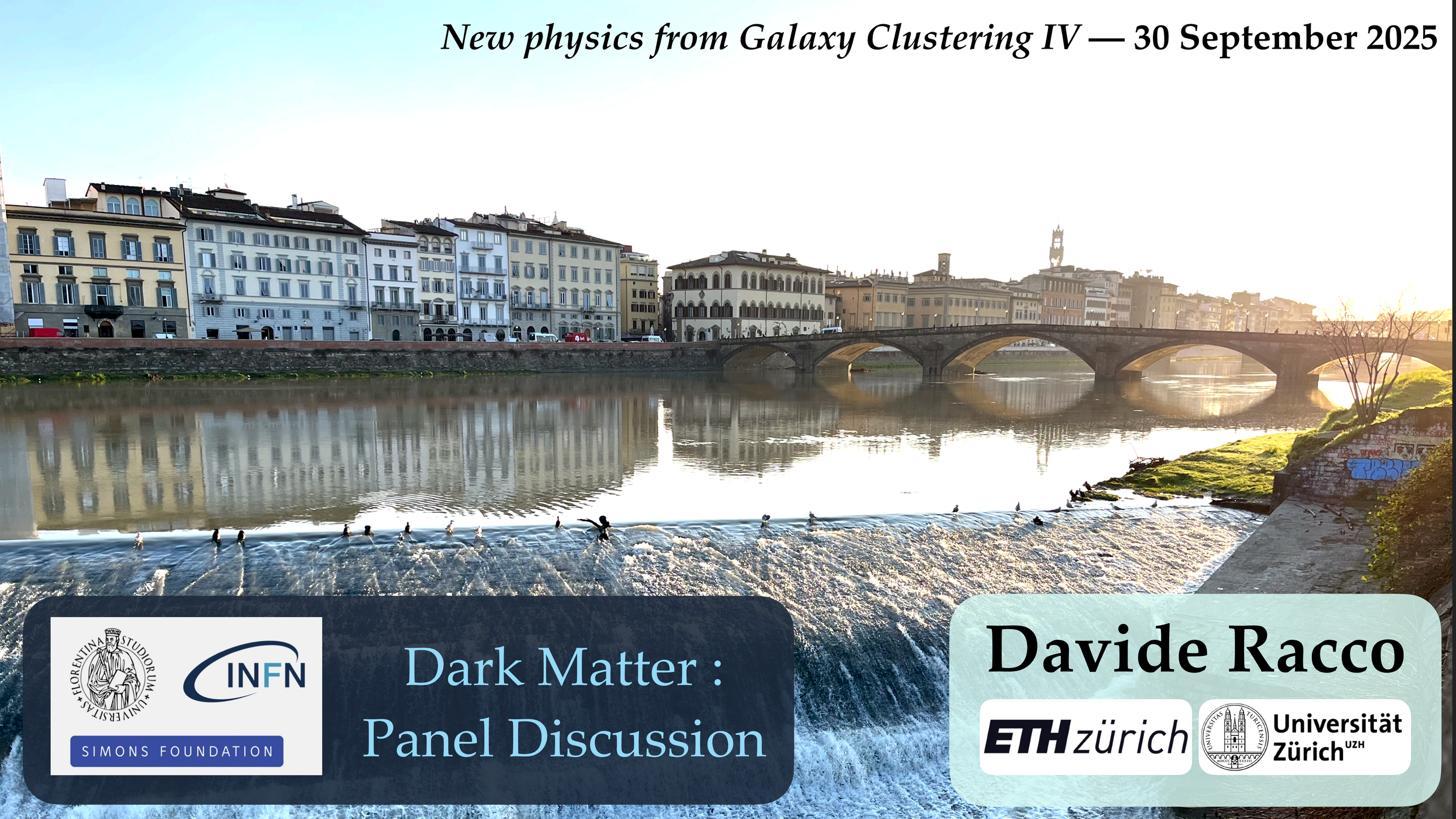
New physics from Galaxy Clustering IV — **30 September 2025**



Dark Matter : Panel Discussion

Davide Racco

ETH zürich

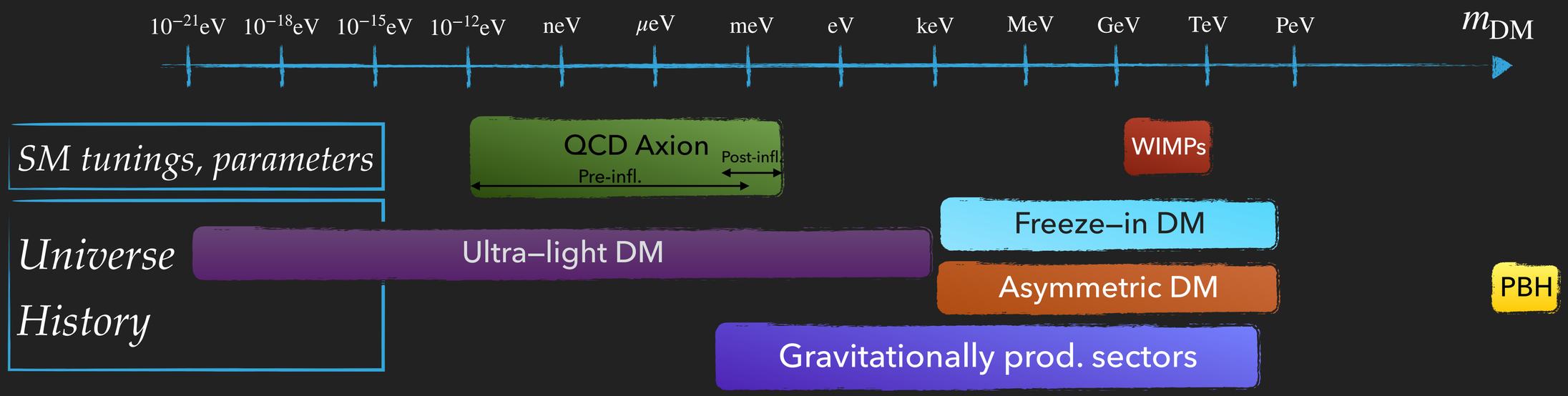
Universität Zürich[UZH]

EVERYTHING (?) WE ALWAYS WANTED TO KNOW ABOUT DARK MATTER

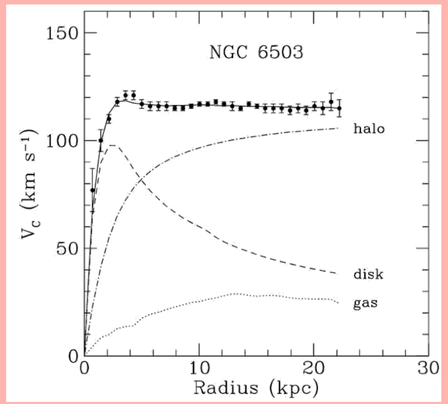
You will be suprised to see how much there is to say about something we know nothing about. Tomer Volansky @ GGI '14

- Mass — Fuzzy — sub-GeV — WIMP — … — "Wimpzilla" — PBH
  - Elementary / composite
  - Production
  - Probes
  - …
- Spin — Scalar — vector — Fermion
  - Particle / classical field
  - Gravitational production
- g_{DM} — Real — Complex
  - (Production)
- Gravitational interaction
  - Gravitational production
- Dark interactions — Long-range: super kpc — sub kpc — Short range
  - LSS probes
  - Galaxy or cluster dynamics
  - Production
- DM-SM interactions
  - Direct / Collider detection
  - Indirect detection
  - Production

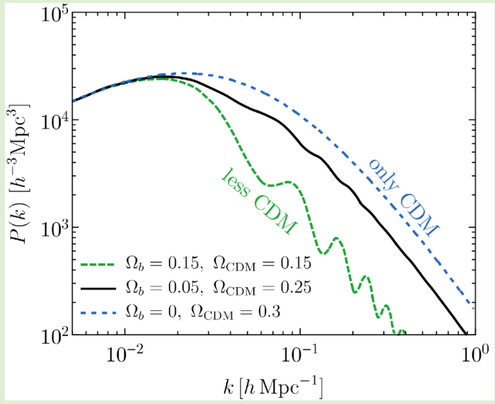
MOTIVATIONS FOR DARK MATTER CANDIDATES



Astrophysics (+ DM searches)



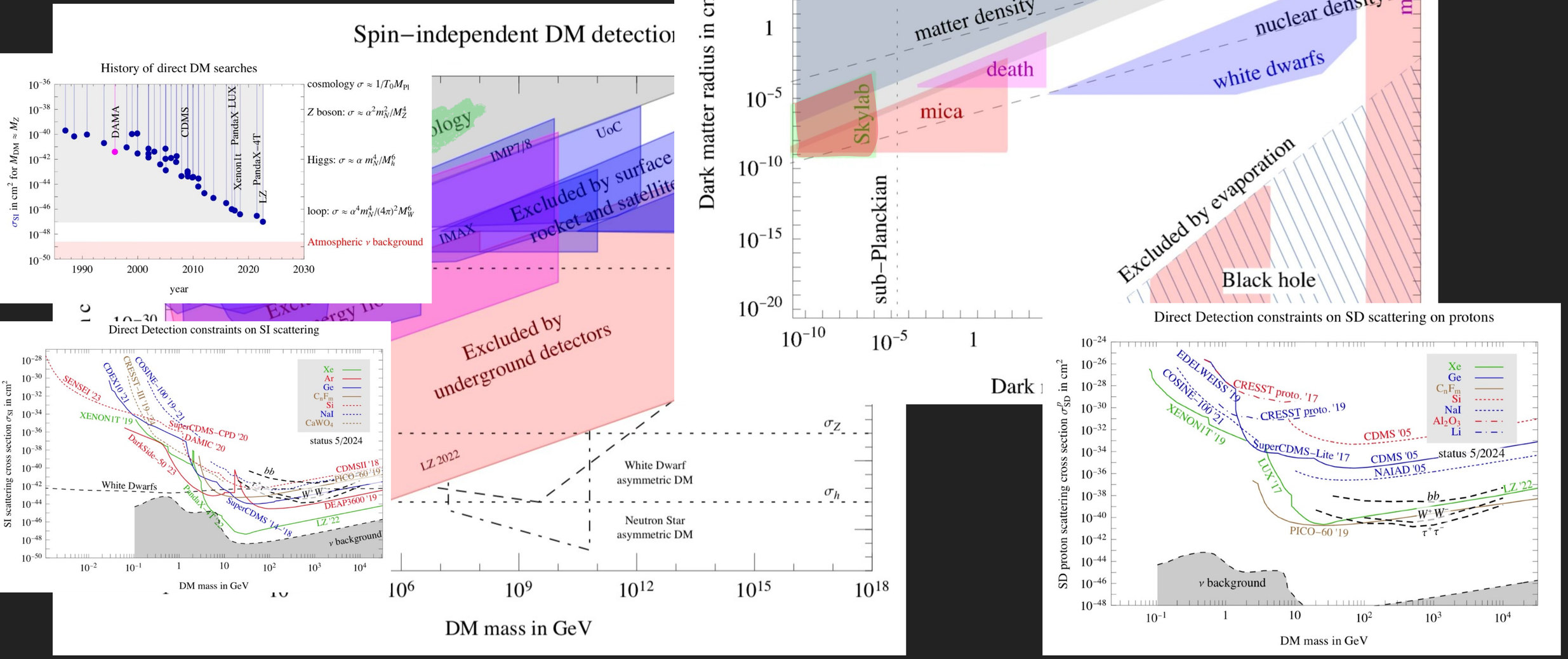
Cosmology



(IN)DIRECT SEARCHES

DIRECT SEARCHES

[‘24 Cirelli, Strumia, Zupan]



INTERPLAY OF EXP SEARCHES IN DM MODELS

- Avoid direct searches with SD couplings ⇒ gauge anomalies

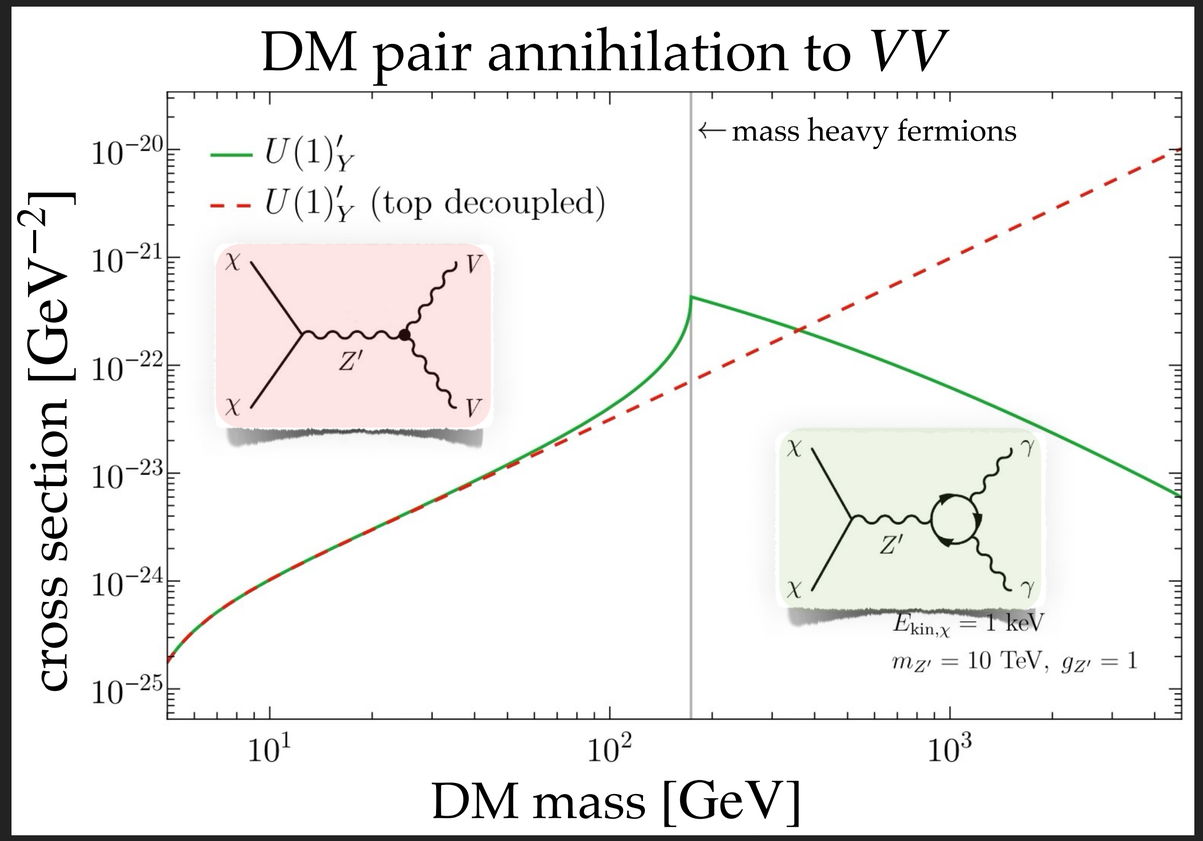
['17 Ismail, Katz, **DR**]

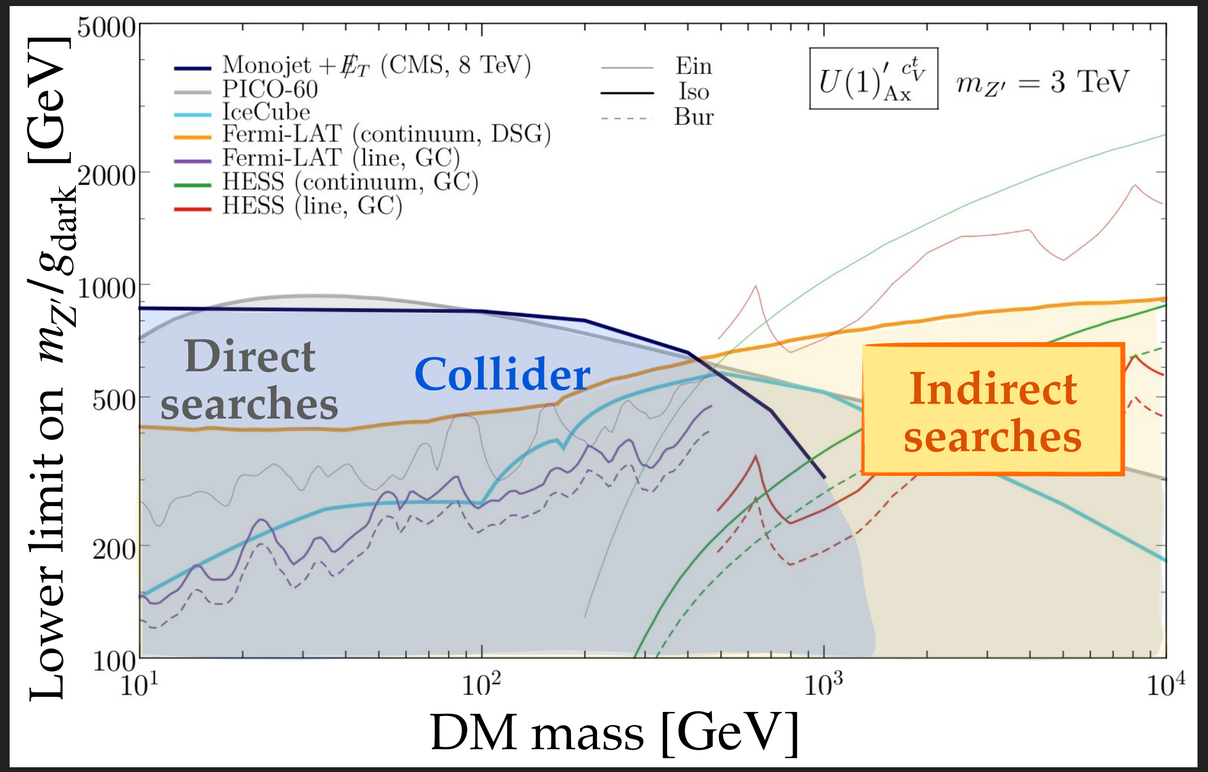
Gauge anomaly @ low scales ↔ Enhance reach indirect searches

- Coupling with SM vectors $\sim Z'_\mu V_\nu \partial^\mu V^\nu$

['84 D'Hoker, Farhi; '91 Preskill; ...; '17 Dror, Lasenby, Pospelov]

- $\bar{\chi}\chi \to \gamma\gamma, WW, ZZ$ grows with energy
- Enhanced sensitivity of DM indirect searches!

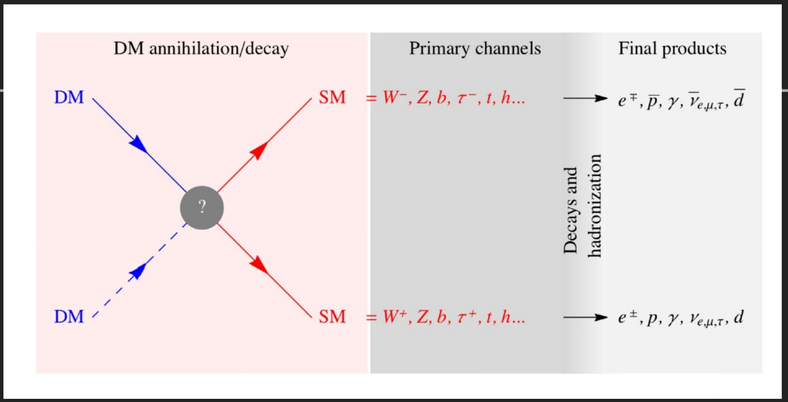


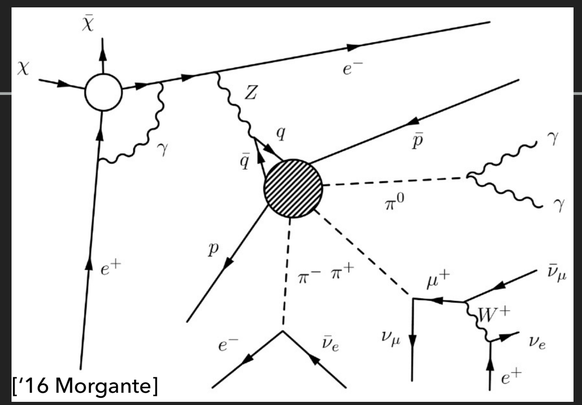


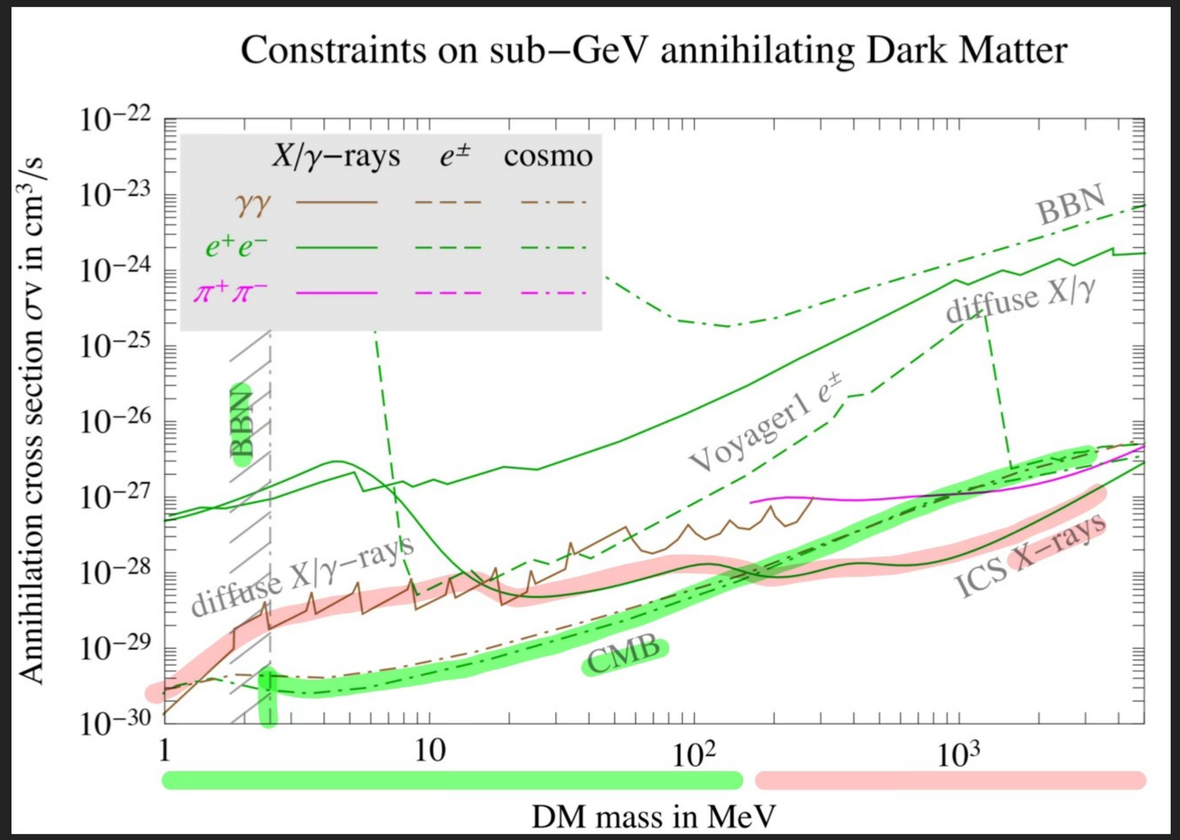
INDIRECT SEARCHES

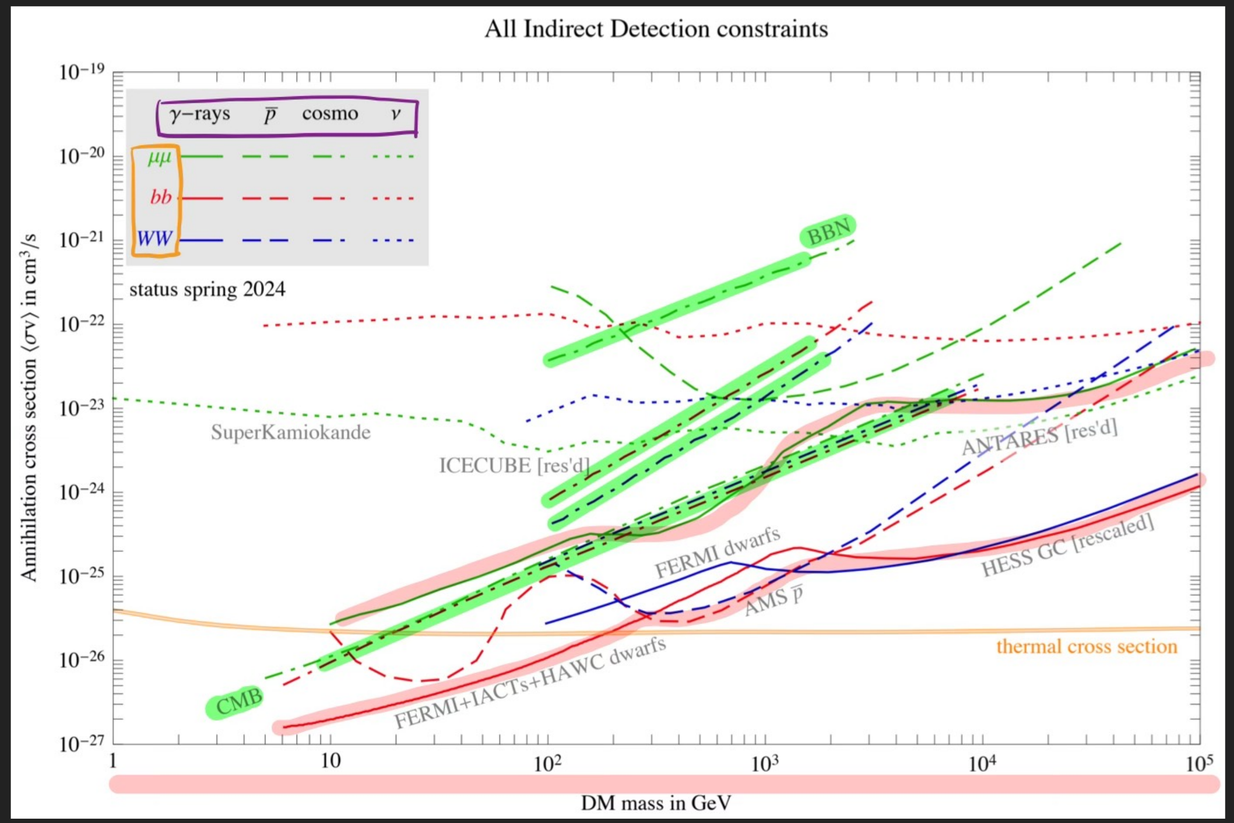
- X-rays, γ-rays, ν telescopes, cosmic rays
- CMB, BBN

[‘24 Cirelli, Strumia, Zupan]





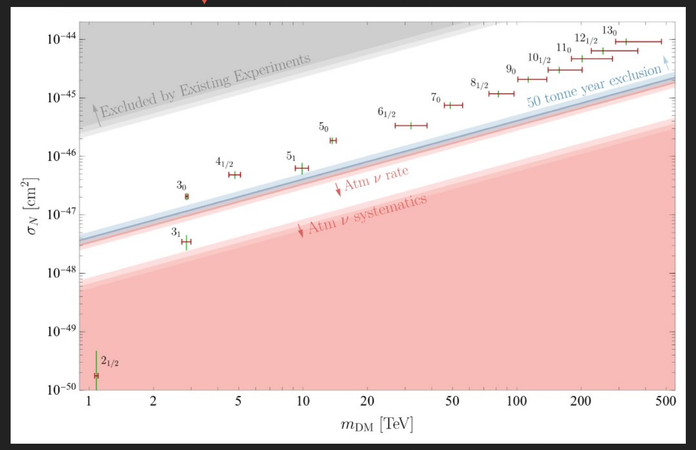




WHAT ABOUT WIMPS?

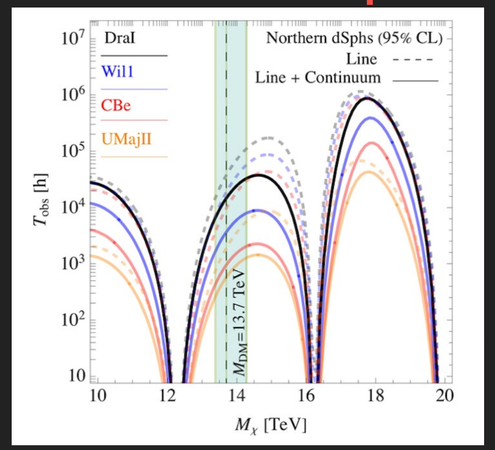
- Is the WIMP "dead"?
- No, Minimal Dark Matter might be around the corner

↓ direct detection



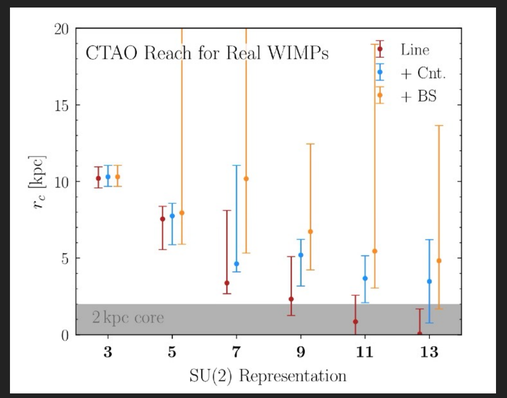
['25 Bloch, Bottaro, Redigolo, Vittorio]

indirect: CTA dSph



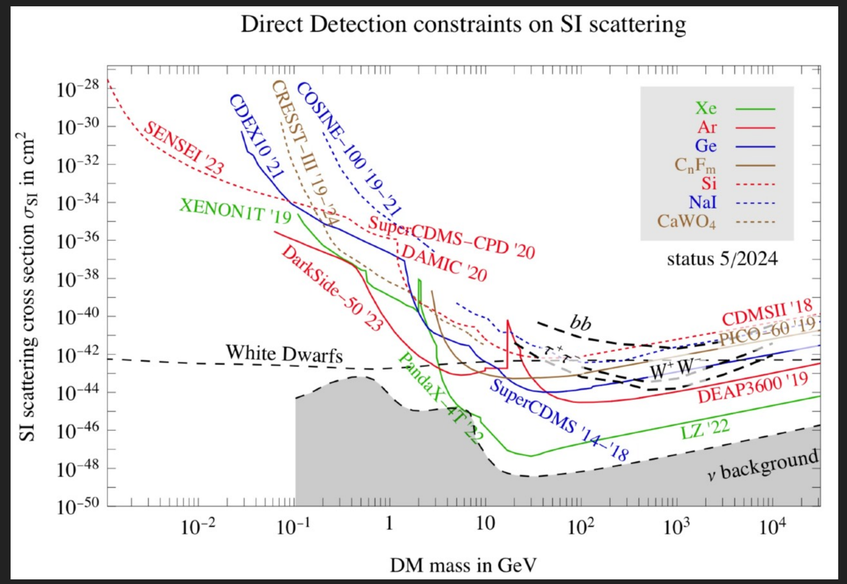
['25 Aghaie, Dondarini, Marino, Panci]

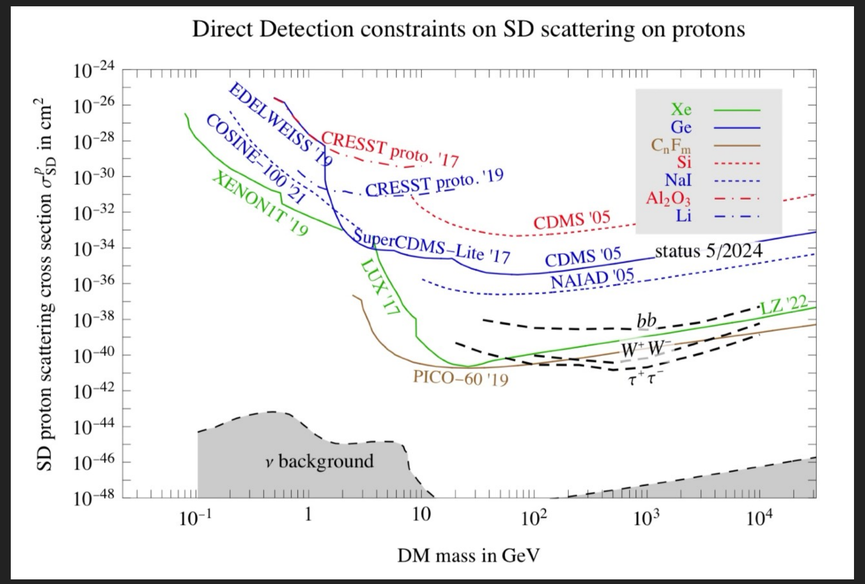
indirect: CTA Gal. Centre



['25 Baumgart, Bottaro, Redigolo, Rodd, Slatyer]

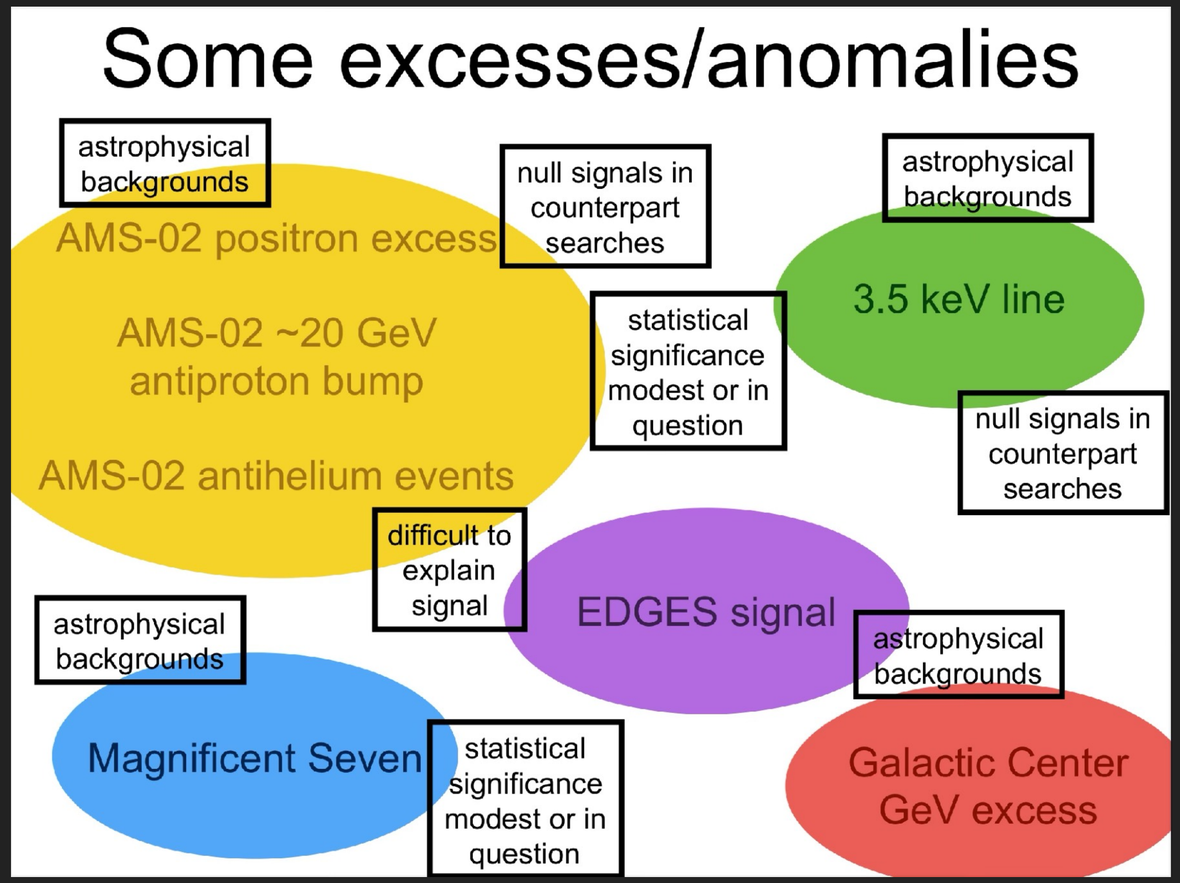
- SI bounds weakened by
  - spin-dependence
  - Velocity suppression





CONVINCING HINTS FROM INDIRECT SEARCHES?

Will we ever be convinced about some hint from indirect searches? A skeptical cosmologist



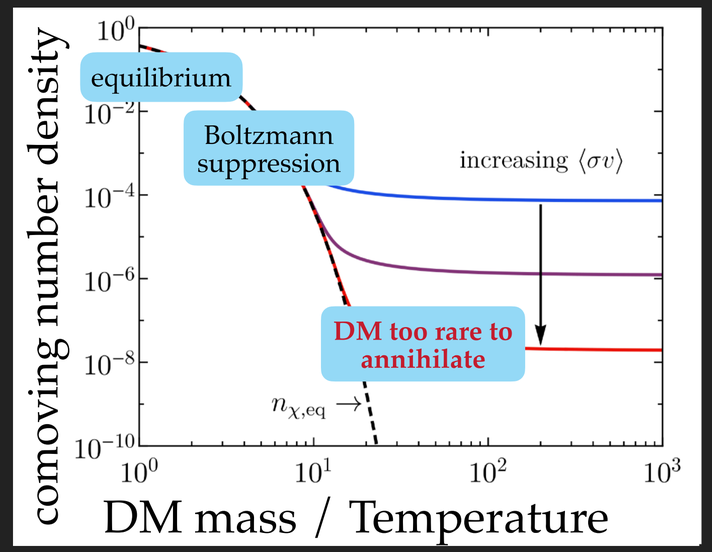
Some excesses/anomalies

- Annihilation/decay?
  - PAMELA/AMS-02 positron excess (needs O(TeV) DM with large cross section / short lifetime) [Aguilar et al (AMS-02) '13; see also Hooper et al '17]
  - AMS-02 ~10-20 GeV antiproton bump (needs O(10-100) GeV DM with thermal relic cross section) [Cui et al '17, Cuoco et al '17; see also Boudaud et al '19, Cuoco et al '19]
  - AMS-02 antihelium events (?? maybe annihilation?) [AMS Days at La Palma, La Palma, Canary Islands, Spain '18; see also Poulin et al '19, Winkler & Linden '21]
  - 3.5 keV X-ray line detected in a range of systems (needs 7 keV decaying DM, e.g. sterile neutrino) [Bulbul et al '14, Boyarsky et al '14; see also Abazajian et al '17, Dessert et al '20]
  - Galactic Center excess (GCE) seen in Fermi gamma-rays (to be discussed further…)
- Scattering? EDGES claimed observation of primordial 21cm signal with deep absorption trough (could potentially be explained by colder-than-expected early universe) [Bowman et al '18; see also Hills et al '18, Bradley et al '19].
- Oscillation? Hard non-thermal X-ray emission seen from 2/7 among nearby "Magnificent Seven" isolated neutron stars (could potentially be explained by light axions produced in stellar core which escape and convert to photons) [Buschmann et al '20].

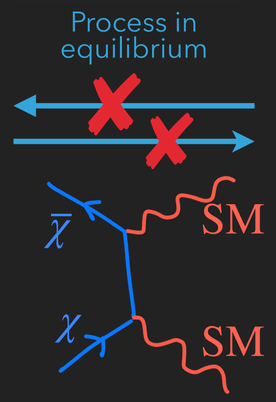
['20 Slatyer]

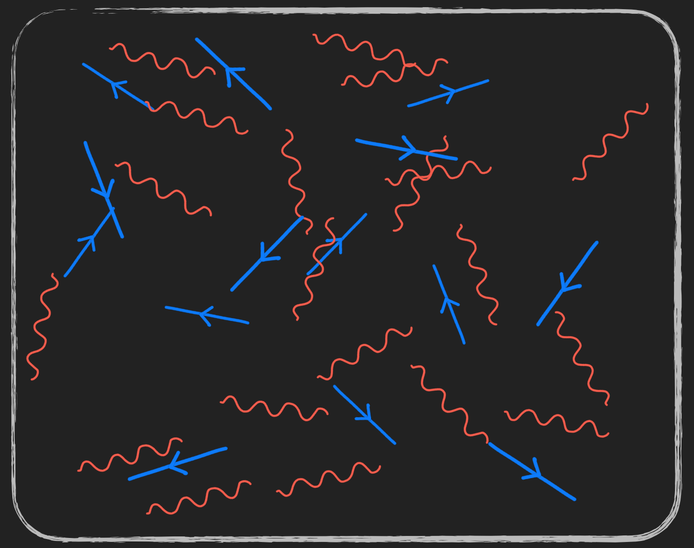
COSMOLOGICAL PRODUCTION MECHANISMS

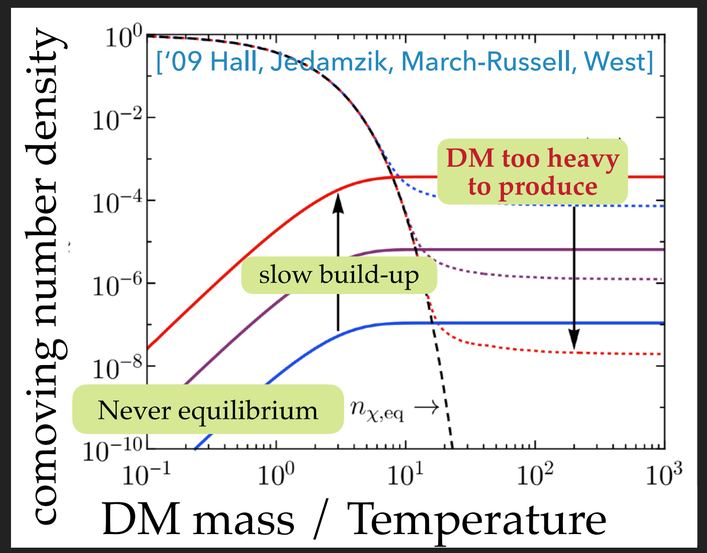
DARK MATTER PRODUCTION MECHANISMS: TARGET FOR SEARCHES



Freeze-Out

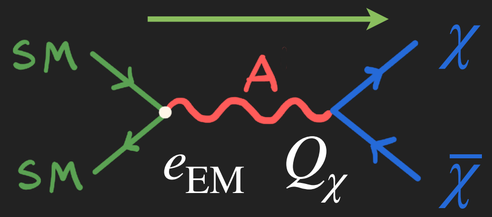


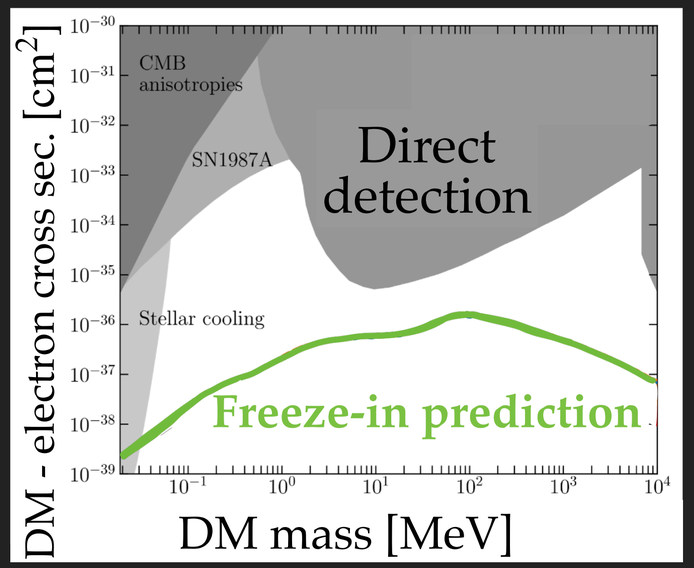




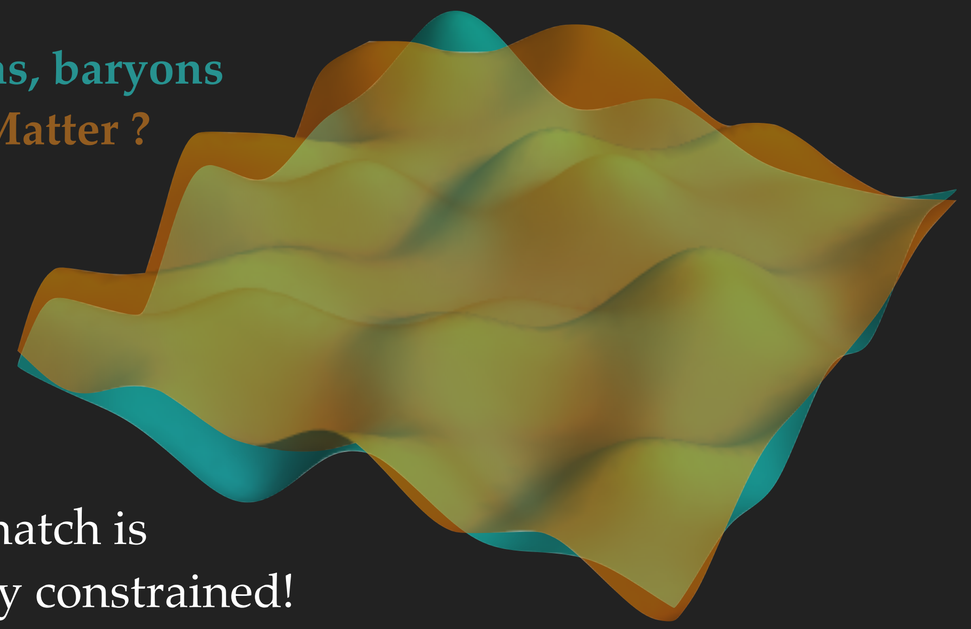
Freeze-In

- Particle with small coupling





- DM and SM never in equilibrium. Do they share same perturbations? ['22 Bellomo, Berghaus, Boddy]



A mismatch is strongly constrained!

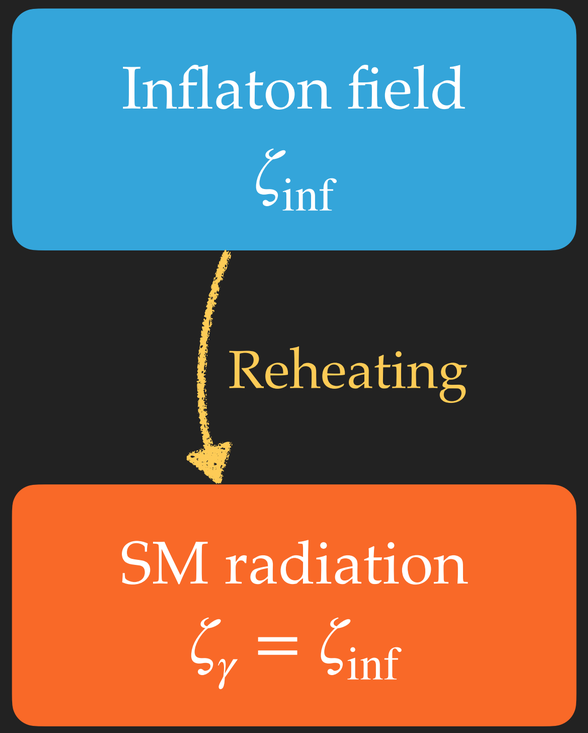
$$\frac{\text{perturbation}}{\text{average}} \to \frac{\delta\rho(t,\mathbf{x})}{\rho(t)}$$

- Single-clock argument: ['04 Weinberg]
  all spatial perturbations $\longleftrightarrow T_{\rm SM}(t,\mathbf{x})$

['22 **DR**, Riotto]

- DM energy density $\rho_{\rm DM}(t,\mathbf{x}) \leftrightarrow T_{\rm SM}(t,\mathbf{x})$
  — regardless of thermalisation!
- DM and SM share origin of perturbations
  $\Rightarrow$ cannot differ later

- Thermal bath: $\zeta_\gamma(t, \mathbf{x}) \leftrightarrow \delta T(t, \mathbf{x})$
- **Adiabatic** perturbations: any fluid component following these pert.



Different source of ζ?

$$\zeta_\alpha = -\psi - H\frac{\delta\rho_\alpha(t, \mathbf{x})}{\dot\rho_\alpha(t)}$$

$$\mathcal{S}_{\alpha,\beta} = 3(\zeta_\alpha - \zeta_\beta)$$

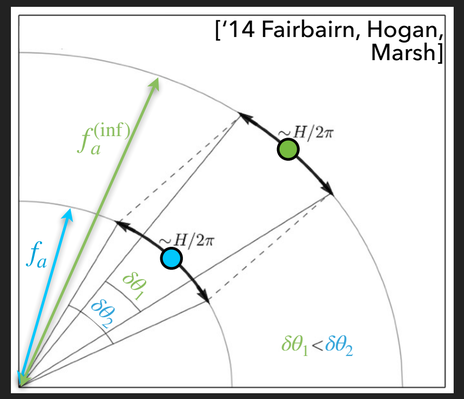
- **Isocurvature** perturbations: a fluid component with $\neq$ curv. pert.

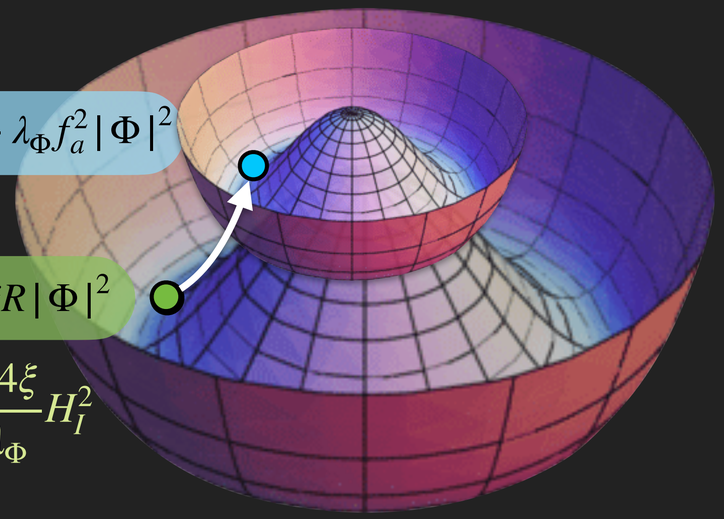
ISOCURVATURE BOUND FOR THE QCD AXION

- Large $H_{\text{inflation}} \Rightarrow$ fluctuations in $\theta_{\text{misalignment}} \Rightarrow$ constrained by isocurvature. How general is this?
- $\sigma_\theta = \dfrac{H_{\text{inf}}}{2\pi} \dfrac{1}{f_a^{(\text{inf})}}$

Isocurvature, B-modes $\leftrightarrow$ Axion parameters

['91 Linde;
'13 Folkerts, Germani, Redondo;
'14 Fairbairn, Hogan, Marsh;
'16 Kearney, Orlofsky, Pierce; ...]



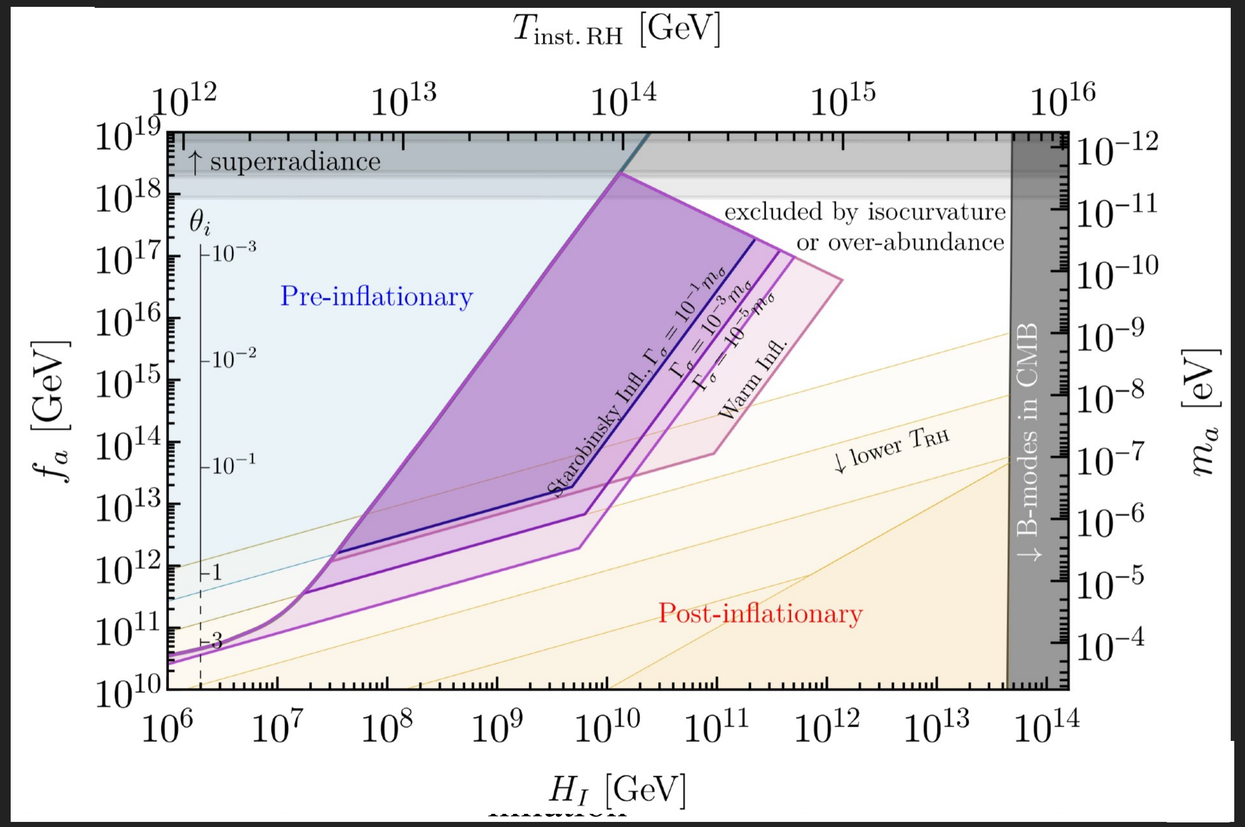


$V_\Phi = \lambda_\Phi |\Phi|^4 - \lambda_\Phi f_a^2 |\Phi|^2$

$-2\xi R |\Phi|^2$

During inflation

$$\left(f_a^{(\text{inf})}\right)^2 = f_a^2 + 2\frac{\xi}{\lambda_\Phi} R \approx \frac{24\xi}{\lambda_\Phi} H_I^2$$



['25, Graham, **DR**]

GRAVITATIONAL PRODUCTION OF DARK MATTER

Oscillator with $\omega(t)$ → level crossing

time-dependent $\omega_k(t)$ in expanding Universe → from initial vacuum to non-vacuum later

Gravitational production

neV | μeV | meV | eV | keV | MeV | GeV | TeV | 10^6 GeV | 10^9 GeV | 10^{12} GeV | 10^{15} GeV → $m_{\rm DM}$

Single Species

Massive vector A'

['15 Graham, Mardon, Rajendran]

Fermion ψ

['99 Kuzmin, Tkachev]

['11 Chung, Everett, Yoo, Zhou]

Dark Sector

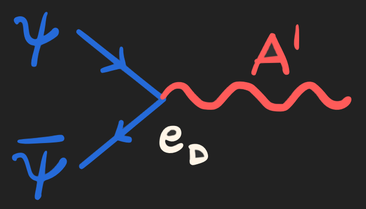
['21 Arvanitaki, Dimopoulos, Galanis, **DR**, Simon, Thompson]

Massive Dark QED

ψ dark matter

A' grav. prod.

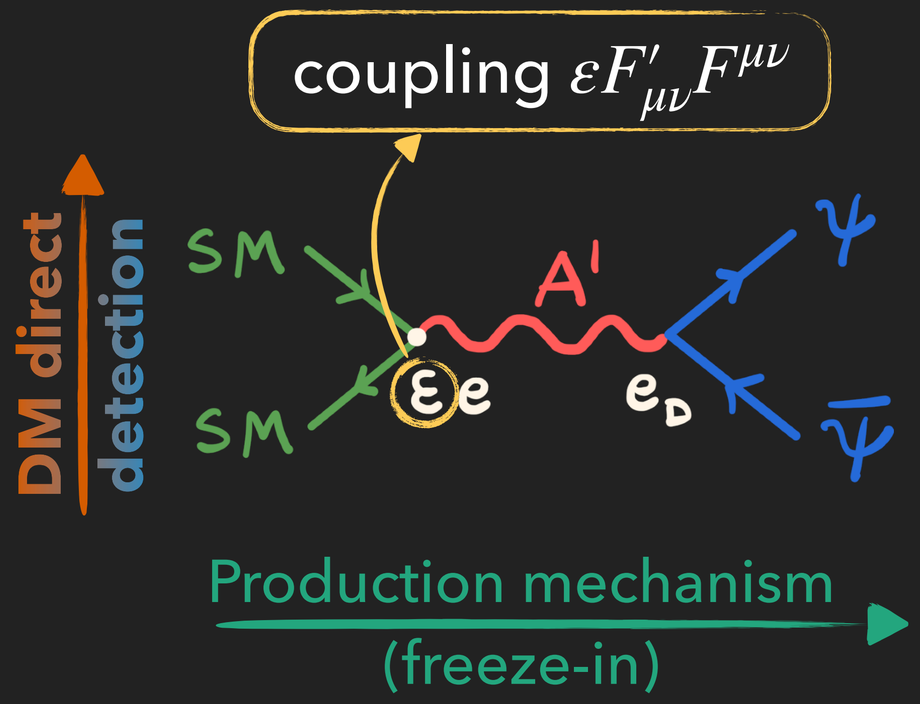
Dynamics in particle sector ↔ Motivated DM targets

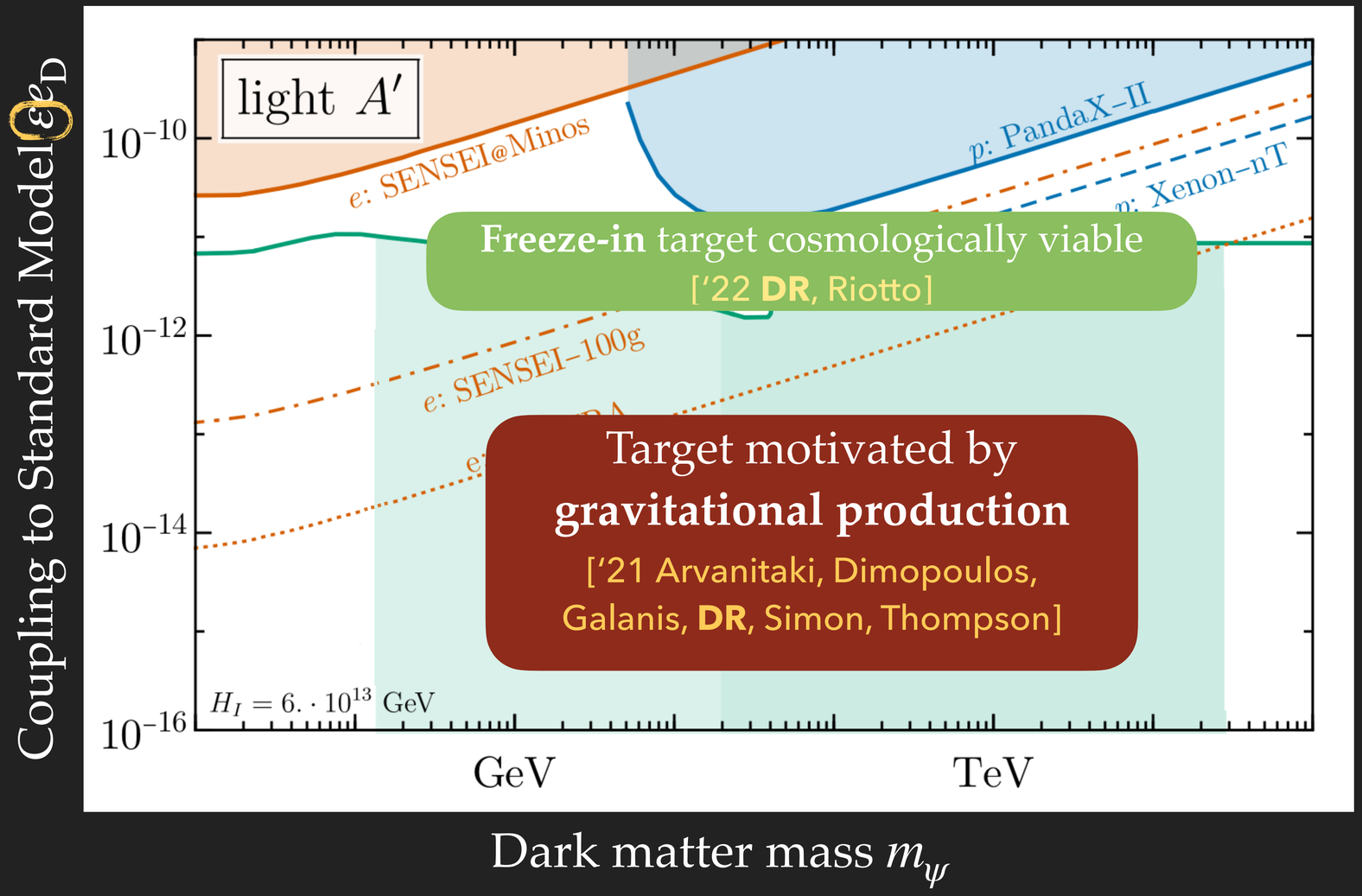


[see also: '19 Long, Wang; '20, '22, '24 Redi, Tesi +; '22 East, Huang; '23, '24 Bastero-Gil, Ferraz, Ubaldi, Vega-Morales; '20 Gross, Karamitsos, Landini, Strumia]

TARGETS FOR MILLICHARGED PARTICLES

DM production mechanism ↔ Exp. target below m_{WIMP}





Freeze-in target cosmologically viable
['22 **DR**, Riotto]

Target motivated by
gravitational production
['21 Arvanitaki, Dimopoulos, Galanis, **DR**, Simon, Thompson]

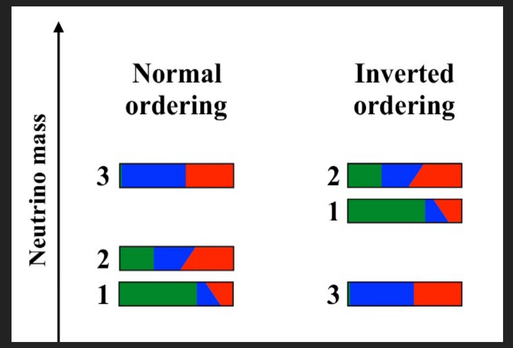
DARK MATTER AND LARGE-SCALE STRUCTURES

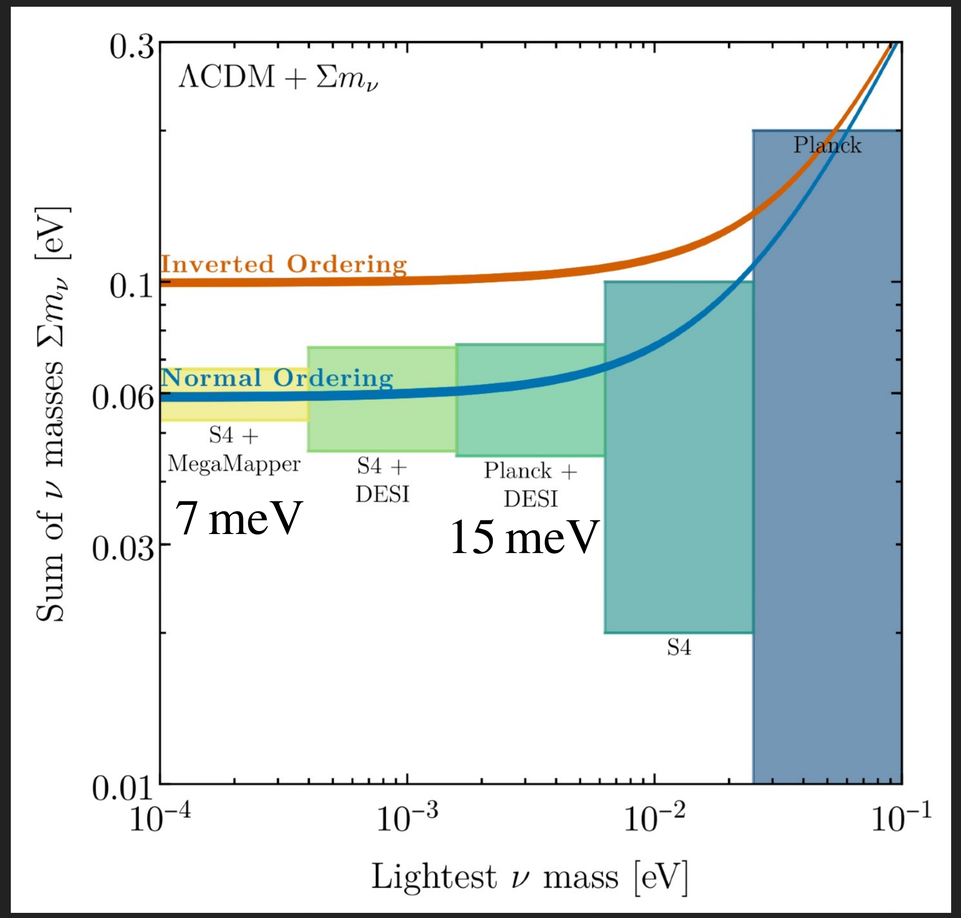
NEUTRINO MASSES FROM COSMOLOGY

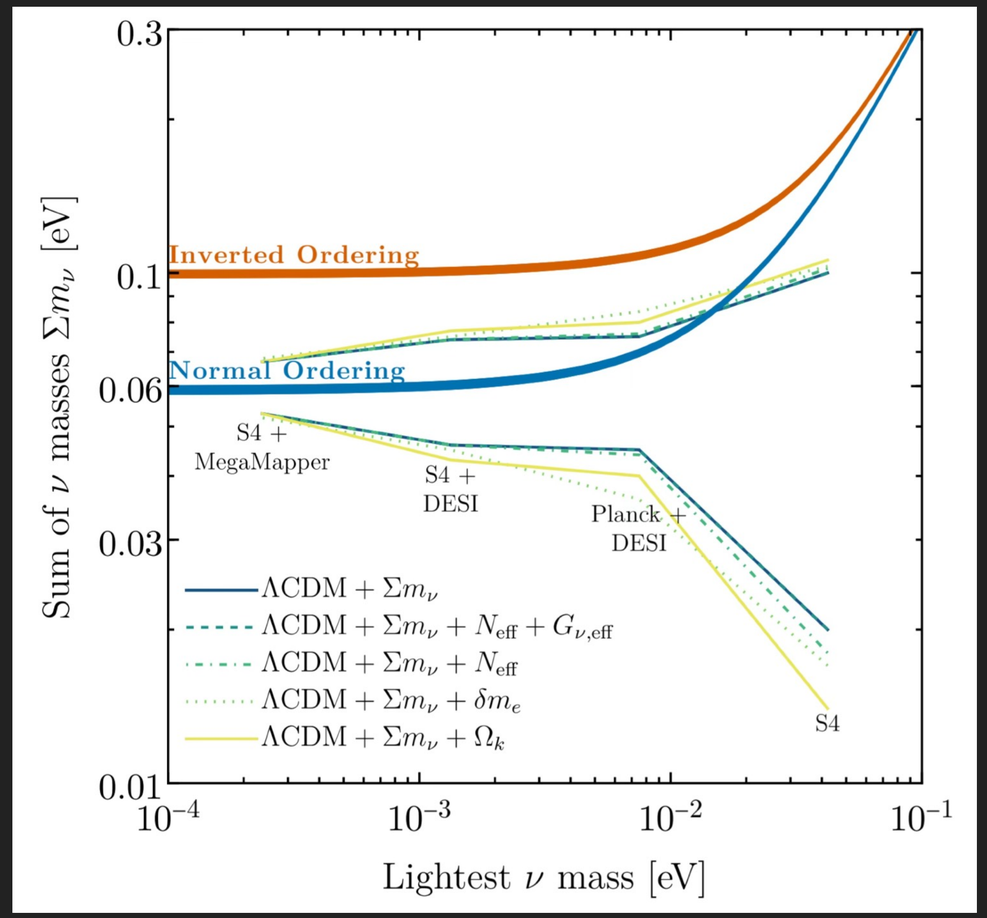
['24 **DR**, Zhang, Zheng]

- Large-scale structures → impact of light species
- Σm_ν from cosmo (and ordering from lab. exps)

- Forecast of σ on Σm_ν with EFT of LSS
- Future CMB and LSS ($P + B_{1-\text{loop}}$)
- Small impact of new physics on $\sigma_{\Sigma m_\nu}$



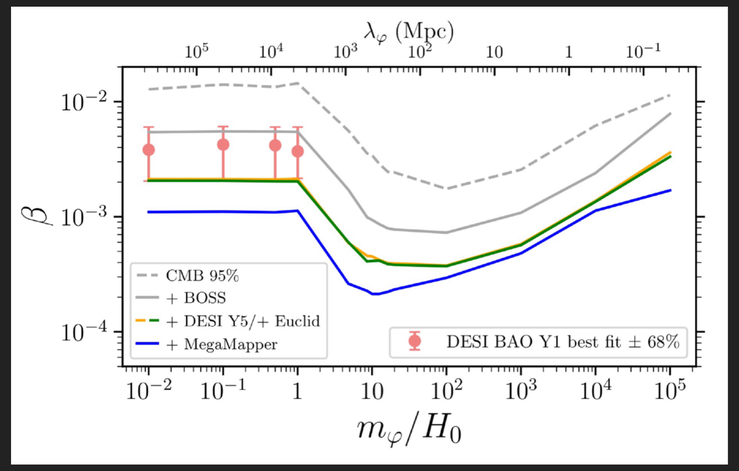




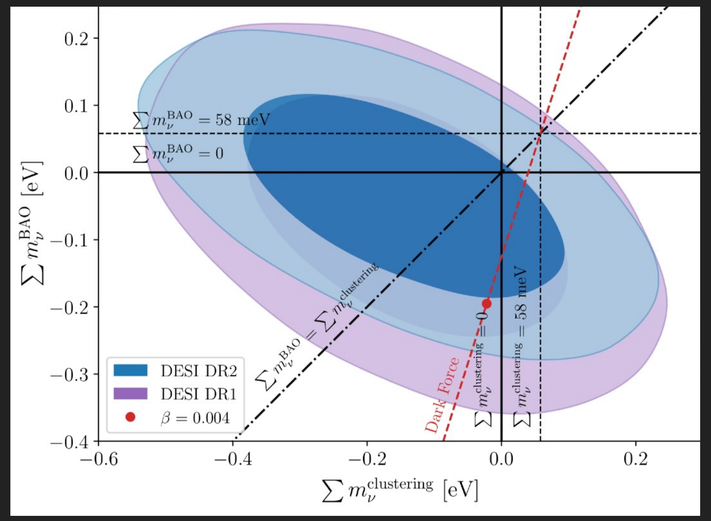
[see also: '18 Brinckmann, Hooper, Archidiacono, Lesgourgues, Sprenger; '19 Chudaykin, Ivanov; '24 Archidiacono+ (EUCLID); '25 Verdiani, Bellini, Moretti, Sefusatti, Carbone, Viel]

DARK SECTORS AND BAO "TENSION"

- Central value? Σm_ν $''<0''$ i.e. enhanced fluctuations

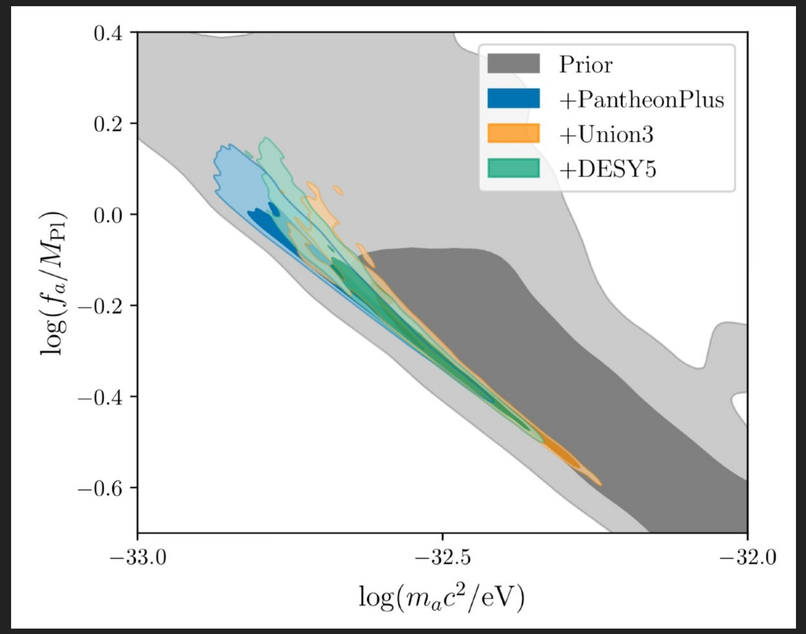


['24 Bottaro, Castorina, Costa, Redigolo, Salvioni]



['25 Graham, Green, Meyers]

- Evolving DE from rolling scalar: generically, tuning of initial conditions



[2503.20178 DESI]

- Impact on background vs perturbations: must track both

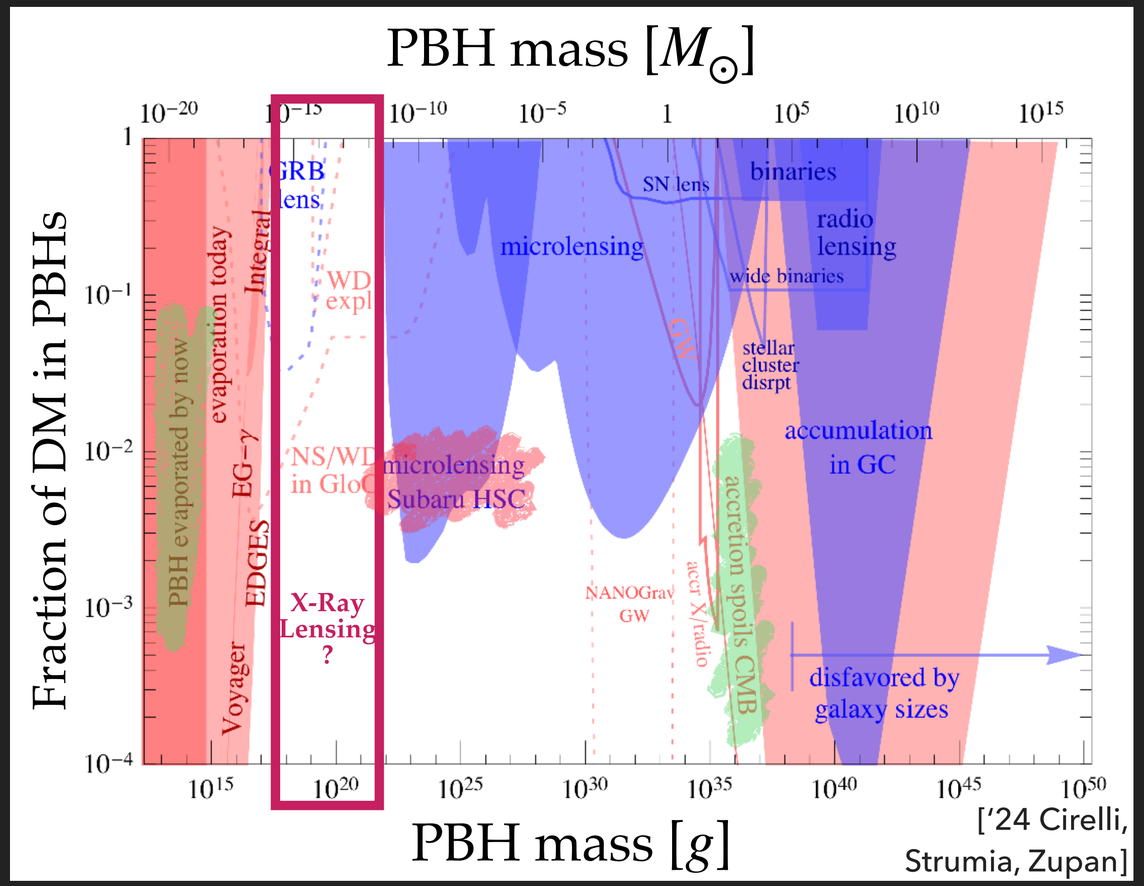
[e.g. '24, '25 Baryakhtar, Simon, Weiner]

DETECT ENHANCED FLUCTUATIONS FROM GRAVITATIONAL WAVES

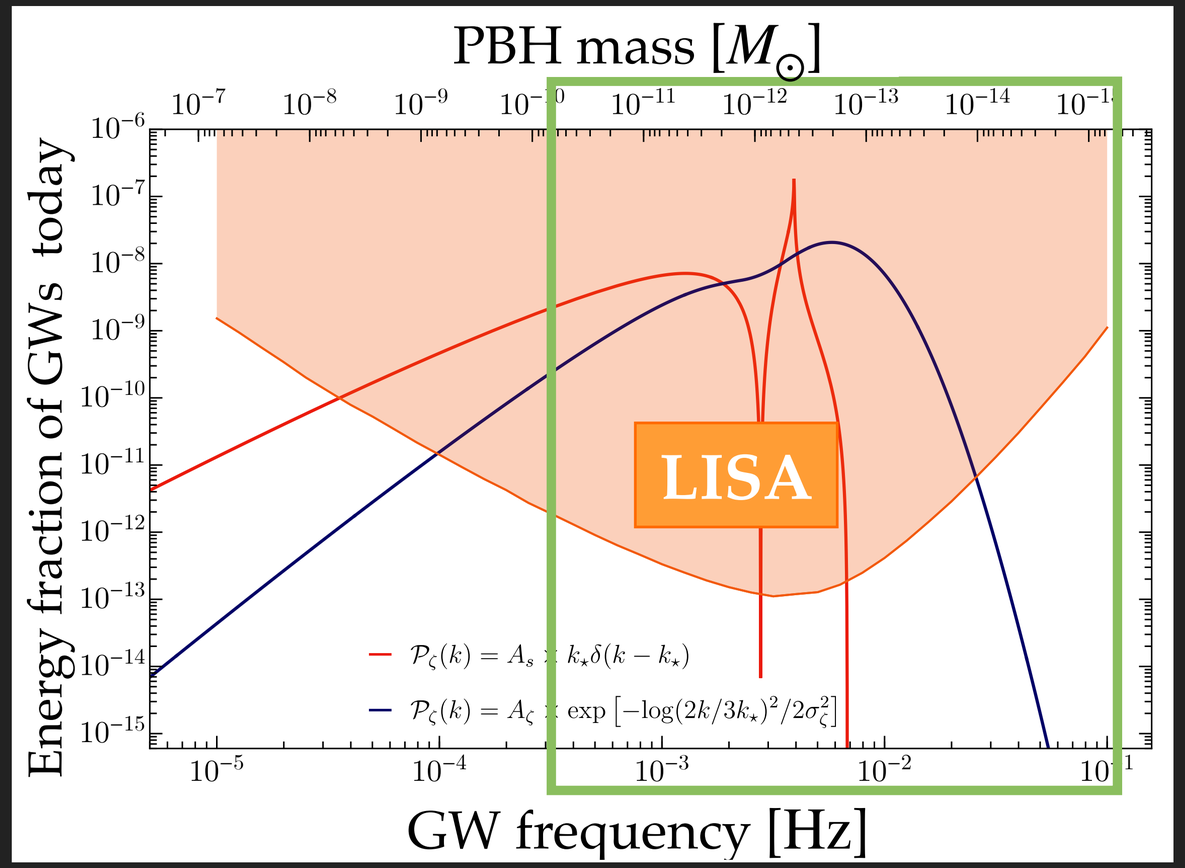
- Remaining window for PBHs → all Dark Matter :

['18 Bartolo, De Luca, Franciolini, Peloso, **DR**, Riotto]

GW background ↔ DM explained by PBH



['24 Cirelli, Strumia, Zupan]



- Sourced by anisotropic peaks of matter power spectrum ['25 Iovino, Perna, Perrone, **DR**, Riotto]
- *With LISA Cosmo Working Group*: from GW background to primordial perturbations ['25 **DR** et al.]

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Thank you for your attention!