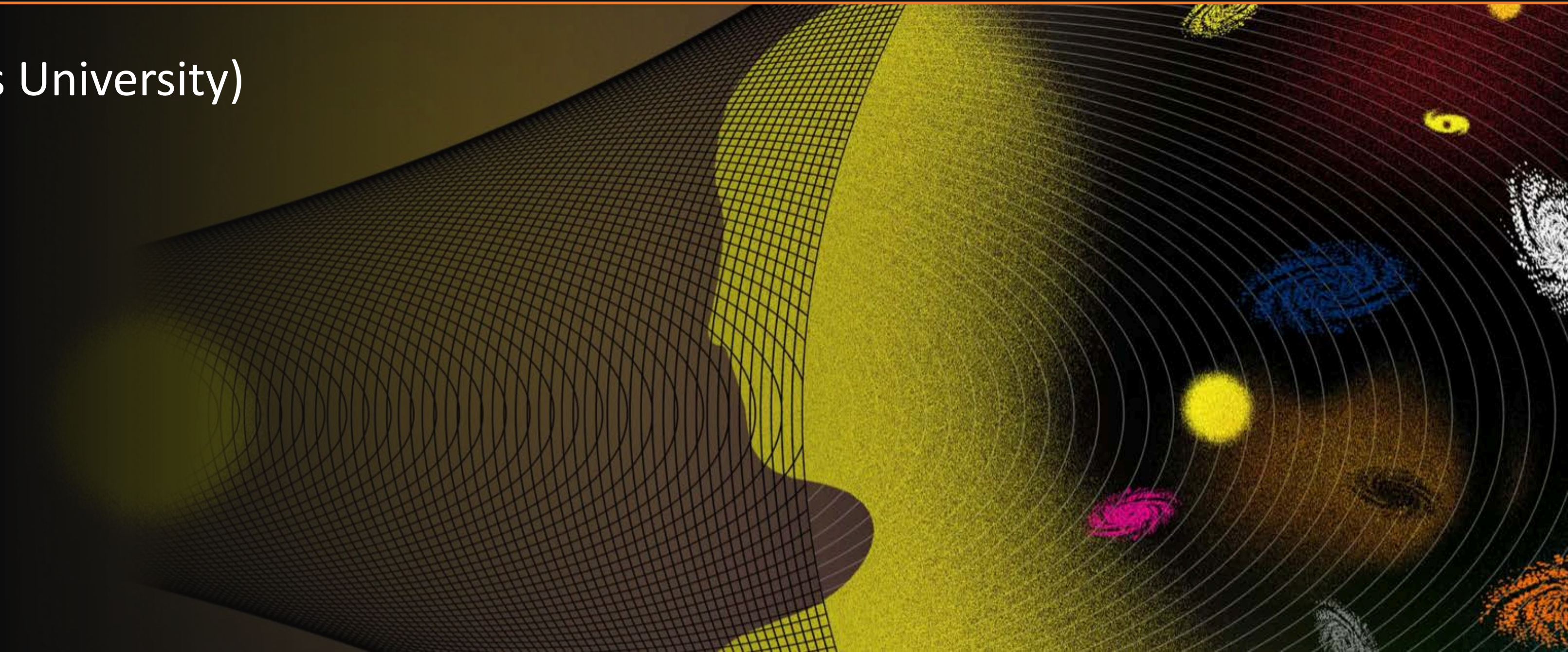
Hubble trouble and early dark energy AND the cosmic optical background excess

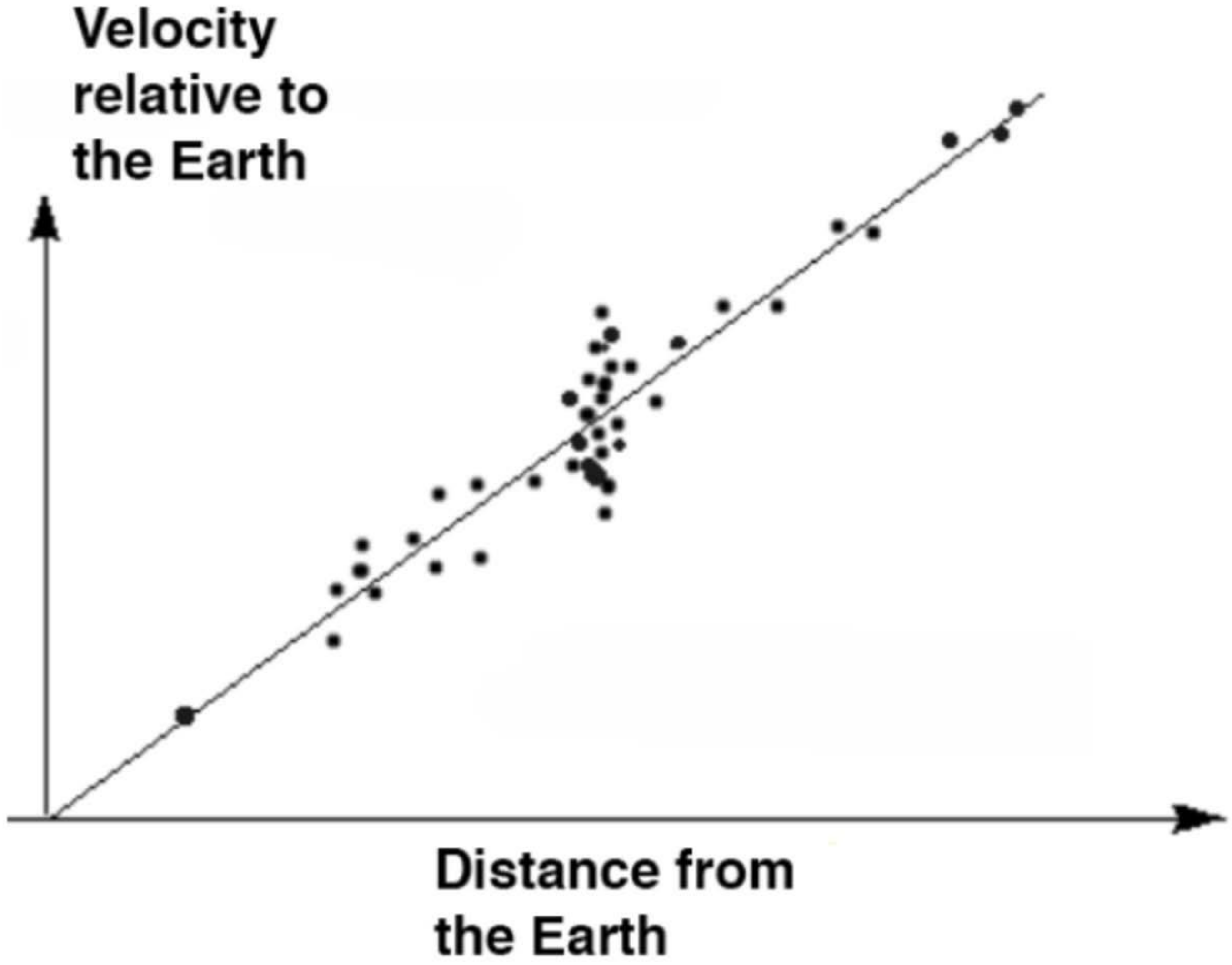


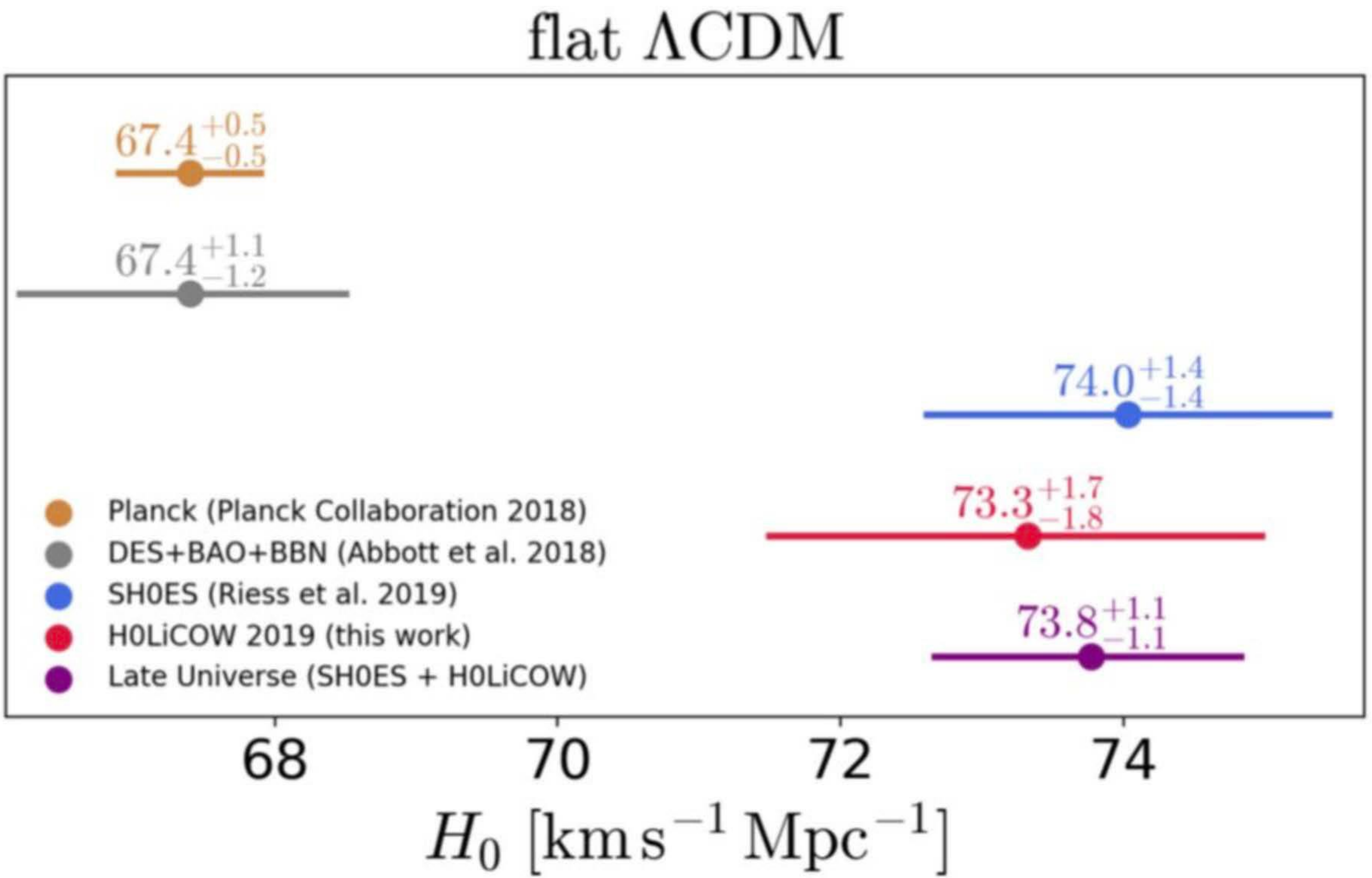
Marc Kamionkowski (Johns Hopkins University)

N3AS 25 October 2022

Hubble law

$$v = H_0 D$$




flat ΛCDM
$67.4^{+0.5}_{-0.5}$
$67.4^{+1.1}_{-1.2}$
$74.0^{+1.4}_{-1.4}$
$73.3^{+1.7}_{-1.8}$
$73.8^{+1.1}_{-1.1}$
Planck (Planck Collaboration 2018)
DES+BAO+BBN (Abbott et al. 2018)
SH0ES (Riess et al. 2019)
H0LiCOW 2019 (this work)
Late Universe (SH0ES + H0LiCOW)
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]

The Hubble “tension”: Why does the expansion rate inferred from the CMB differ from that observed locally?

- Problem with local measurements?
- Problem with CMB measurements?
- Problems with both?
- New physics?

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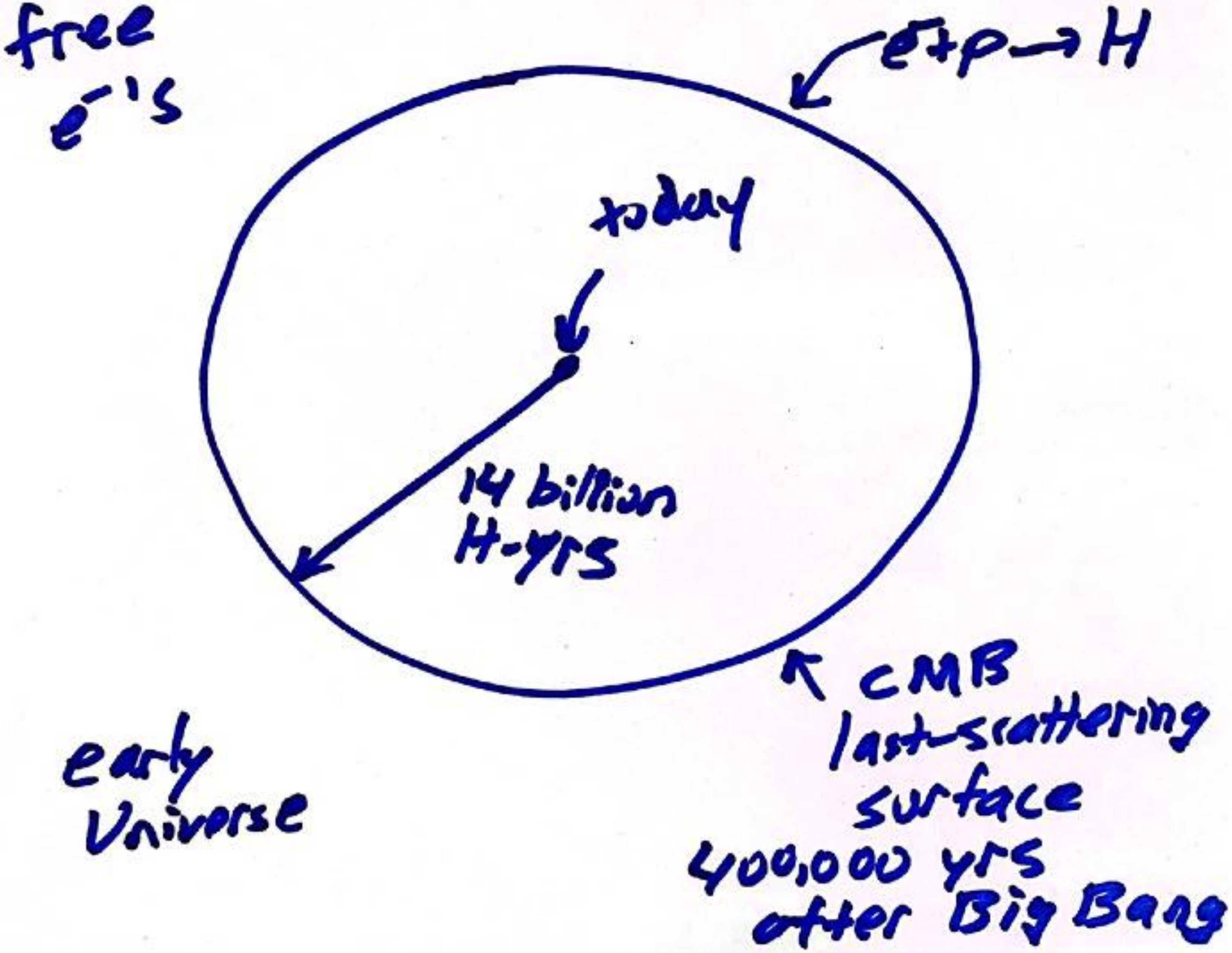
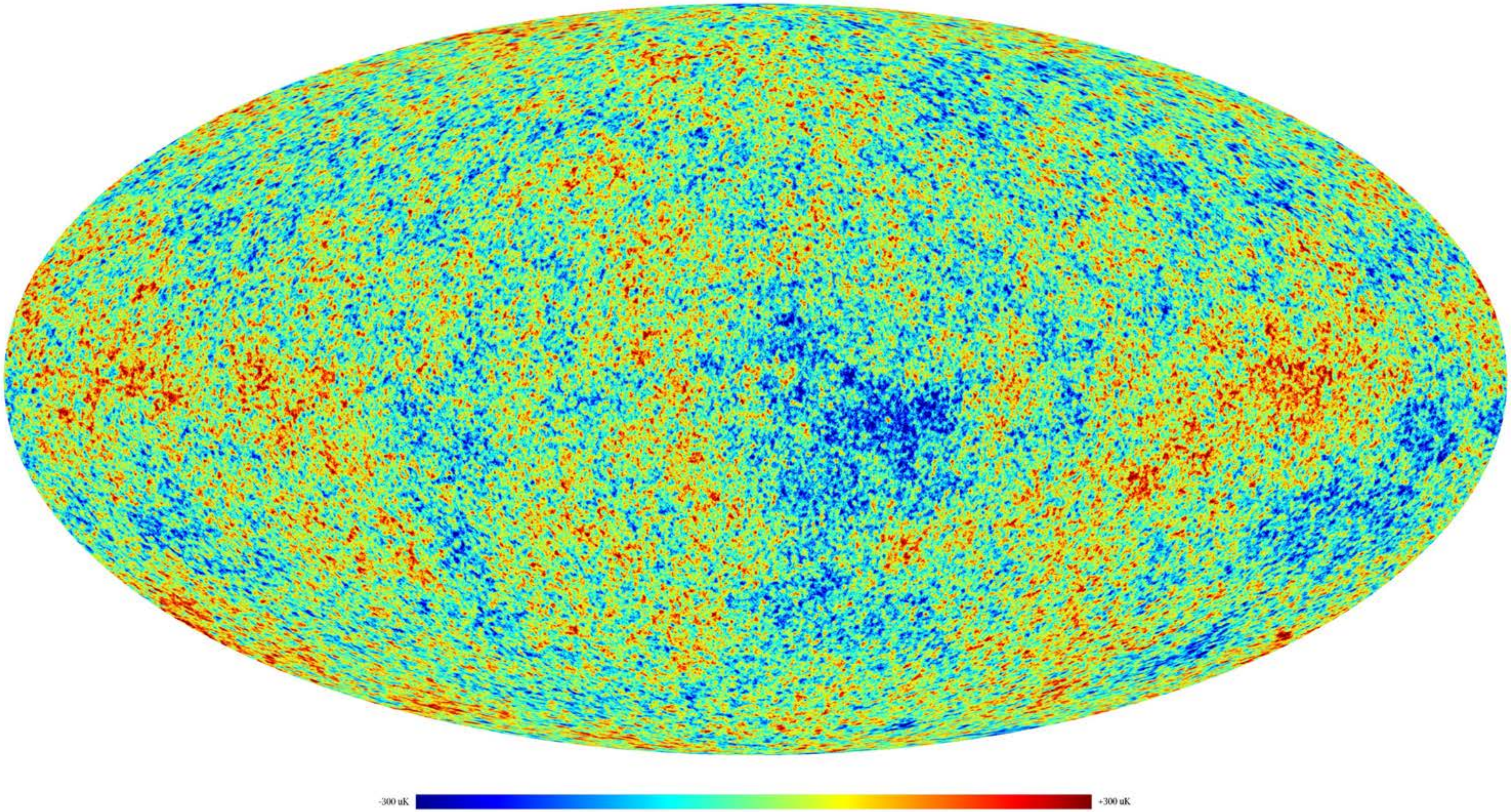
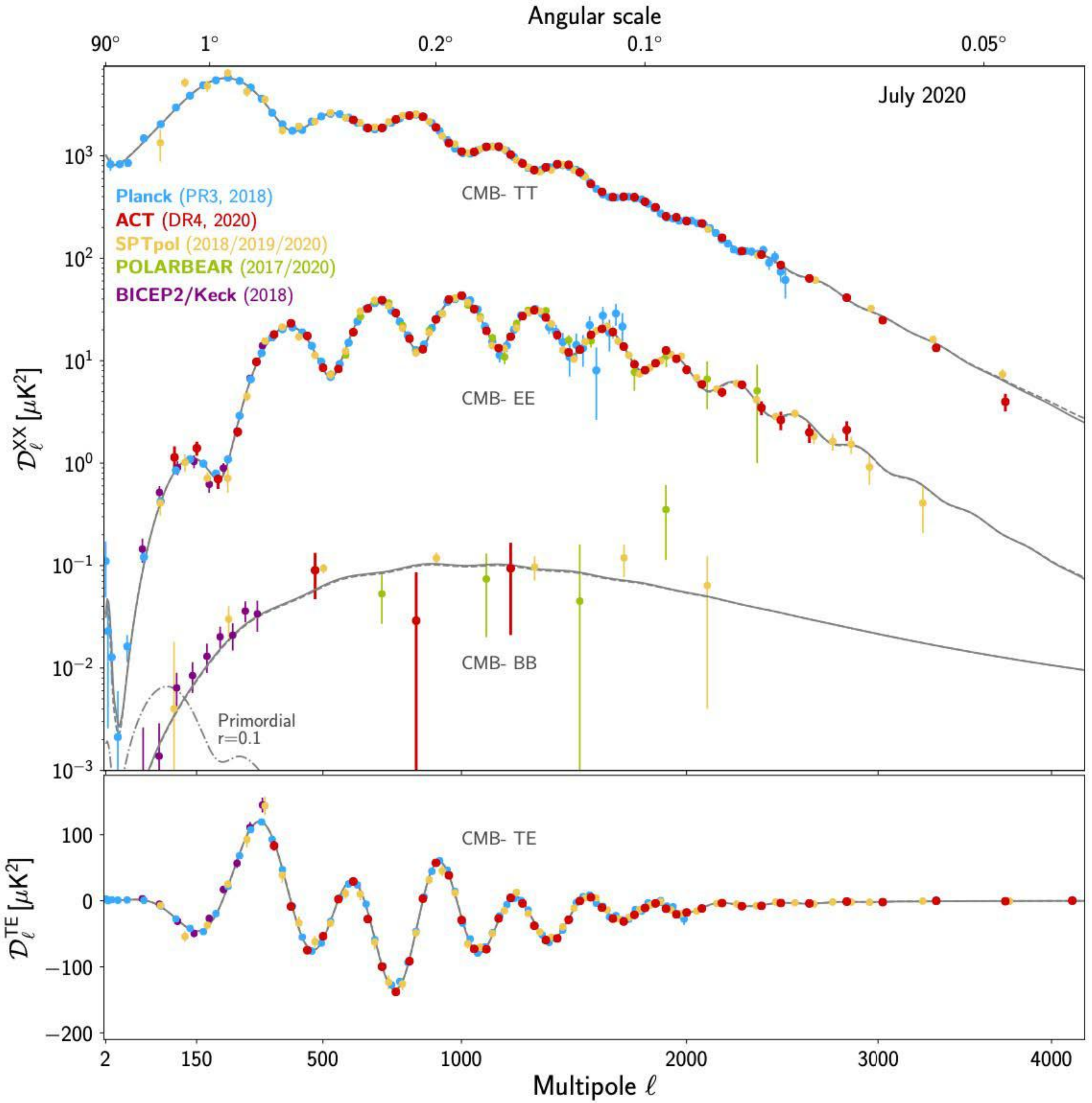


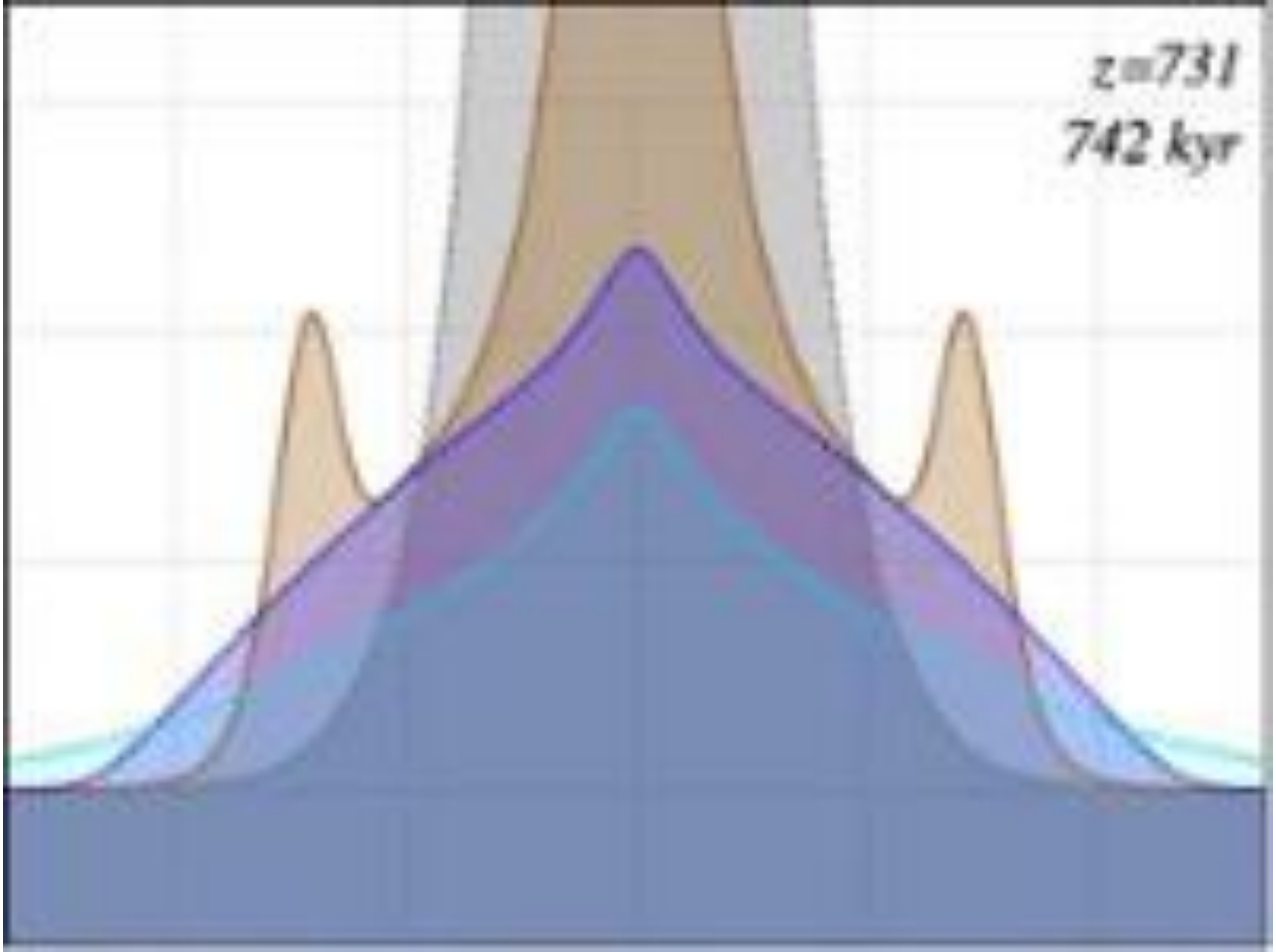
free
e^-'s
$e^+p \to H$
today
14 billion
H-yrs
early
Universe
CMB
last-scattering
surface
400,000 yrs
after Big Bang


-300 uK
+300 uK

CMB power spectrum:

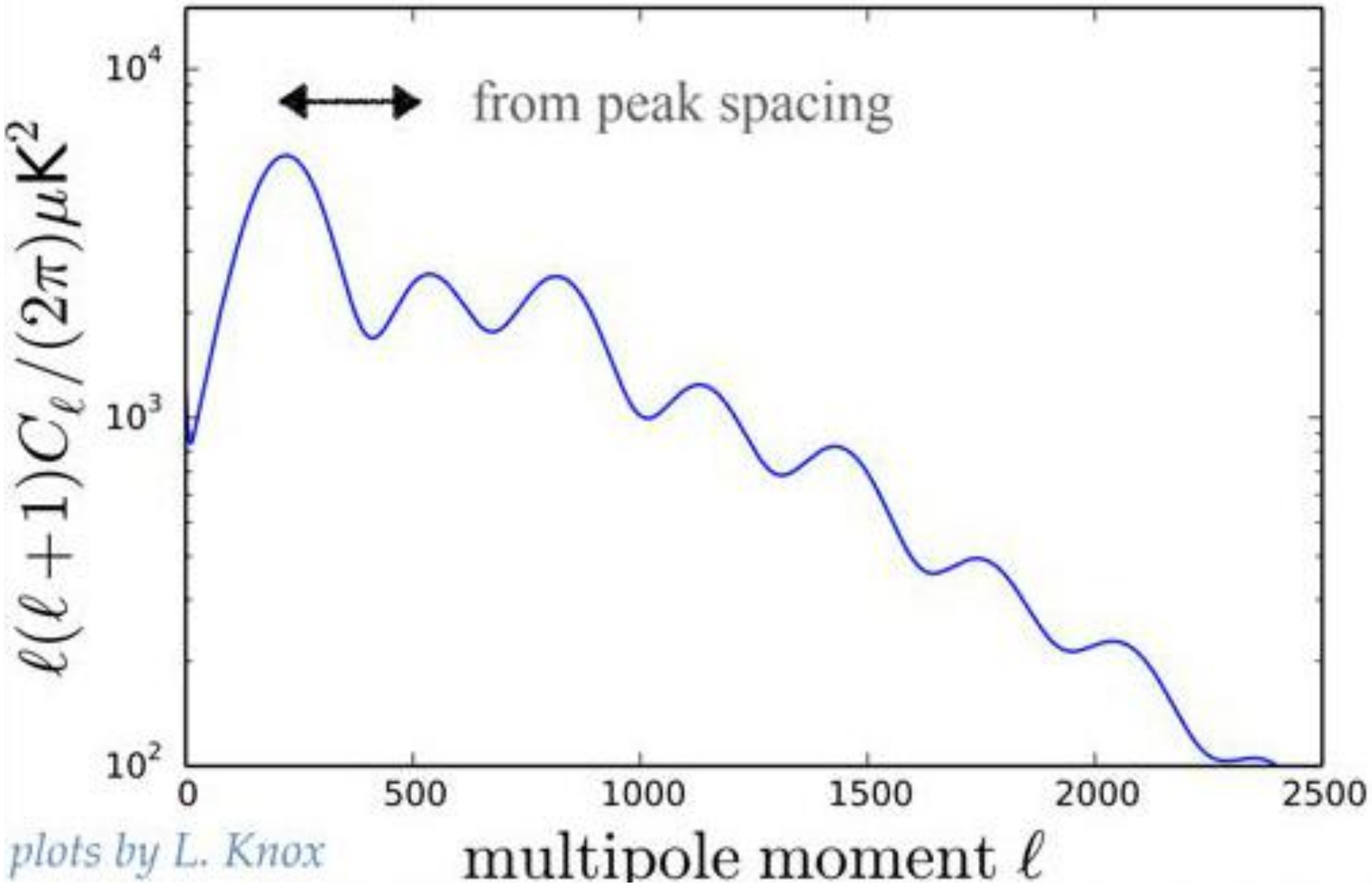
~ |Fourier transform|^2




z=731
742 kyr

Acoustic peaks come from Fourier-space ”ringing” of these spherical shells

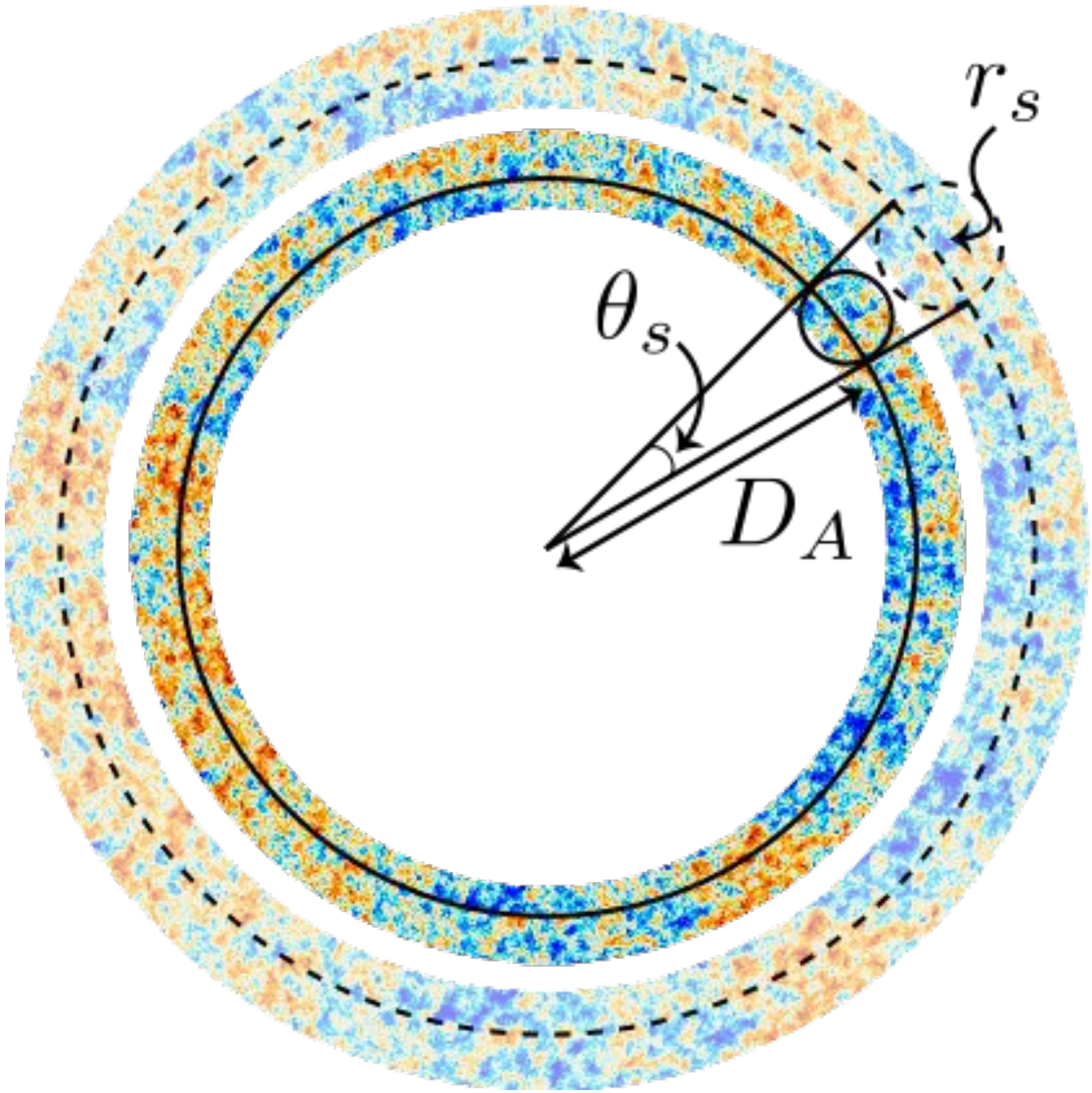
Wavenumber (l) $\propto$ (sound horizon)$^{-1}$



from peak spacing
$\ell(\ell+1)C_\ell/(2\pi)\mu K^2$
10^4
10^3
10^2
0
500
1000
1500
2000
2500
plots by L. Knox
multipole moment ℓ

- Baryon and DM densities from (Silk) damping at higher l and from relatives heights of even/odd peaks

$$\theta_s = \frac{r_s}{D_A}$$



$$D_A = \frac{c}{H_0} \int_{t_{rec}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}$$

$$r_s = \frac{1}{H_{\rm rec}} \int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}$$

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\,dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\,dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

- Decrease matter density at late times
- Decrease sound speed in early Universe
- Increase matter density at early times

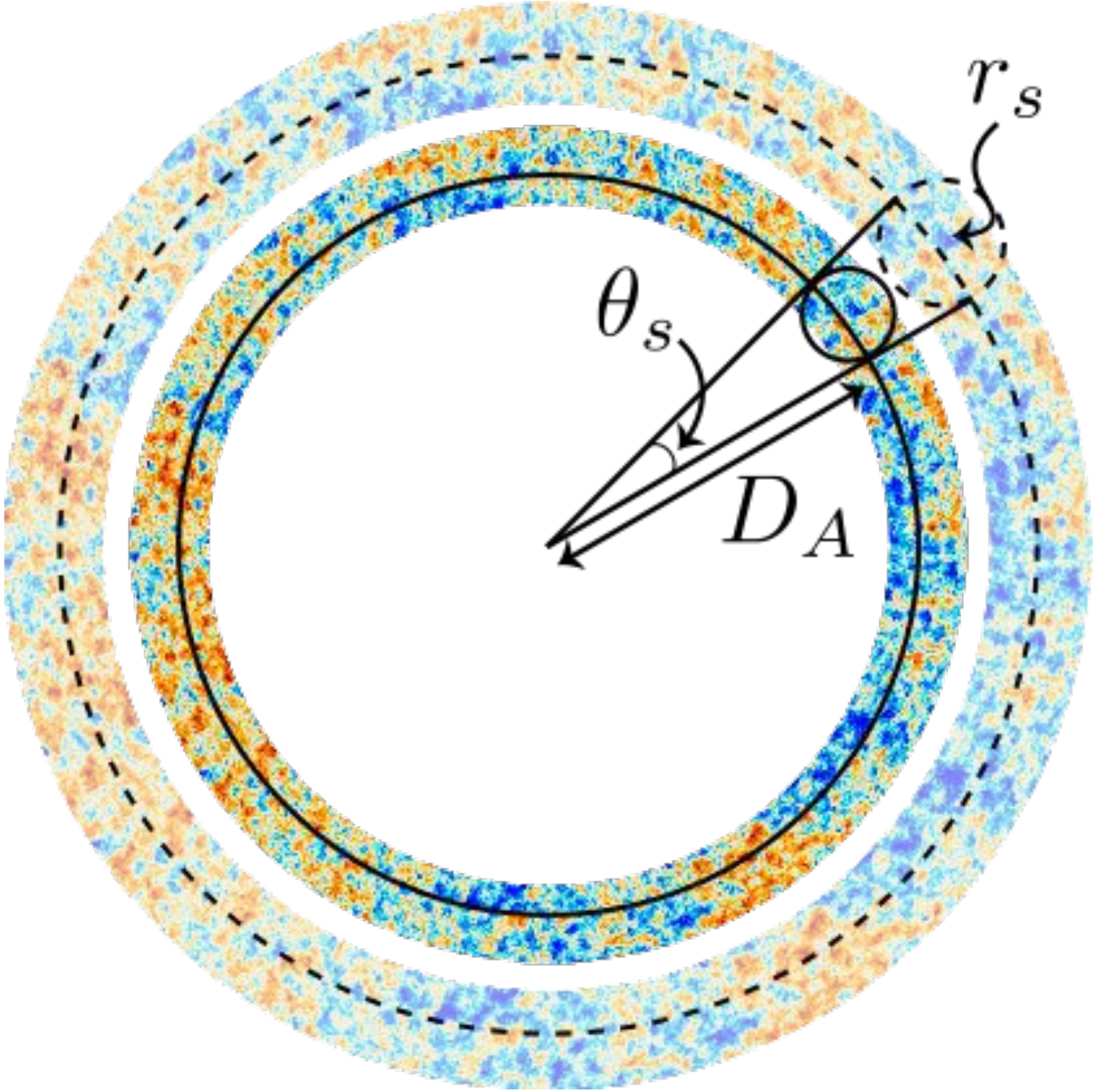
$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe
- Increase matter density at early times

$$H_{\rm cmb} \propto \frac{1}{D_A} \propto \frac{\theta_s}{r_s}$$

$$\theta_s = \frac{r_s}{D_A}$$



Late-time solutions

Modify late expansion history to increase D_A

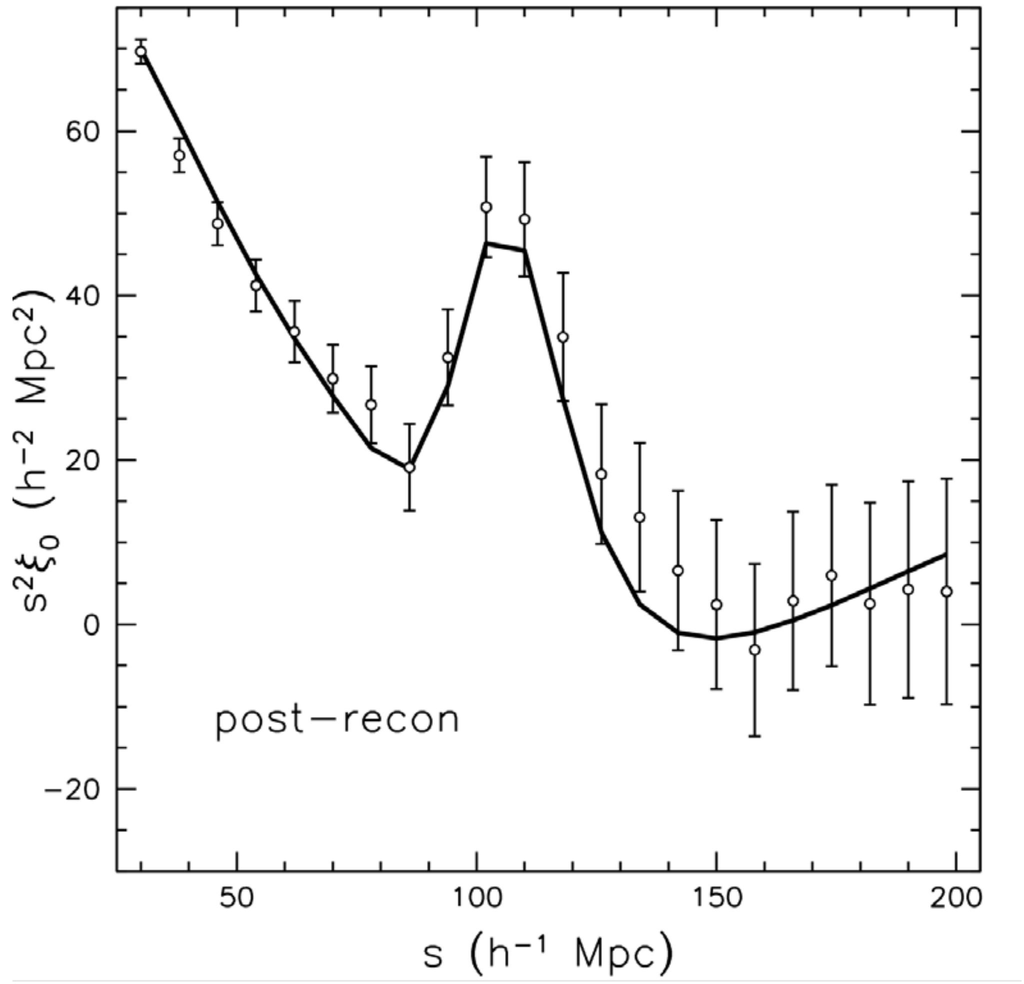
e.g., exotic dark energy; phantom energy; exotic dark matter;

Requires energy density *smaller* than in standard model: negative-density matter?!?! Violation of null energy condition?!?!

Late-time solutions: Empirically disfavored by BAO in galaxy distribution

Sound horizon imprinted on galaxy distribution measured in “redshift space”

Provides standard ruler to infer H_0 --> lower H_0



SDSS-BOSS Collaboration
Anderson et al. 2013

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

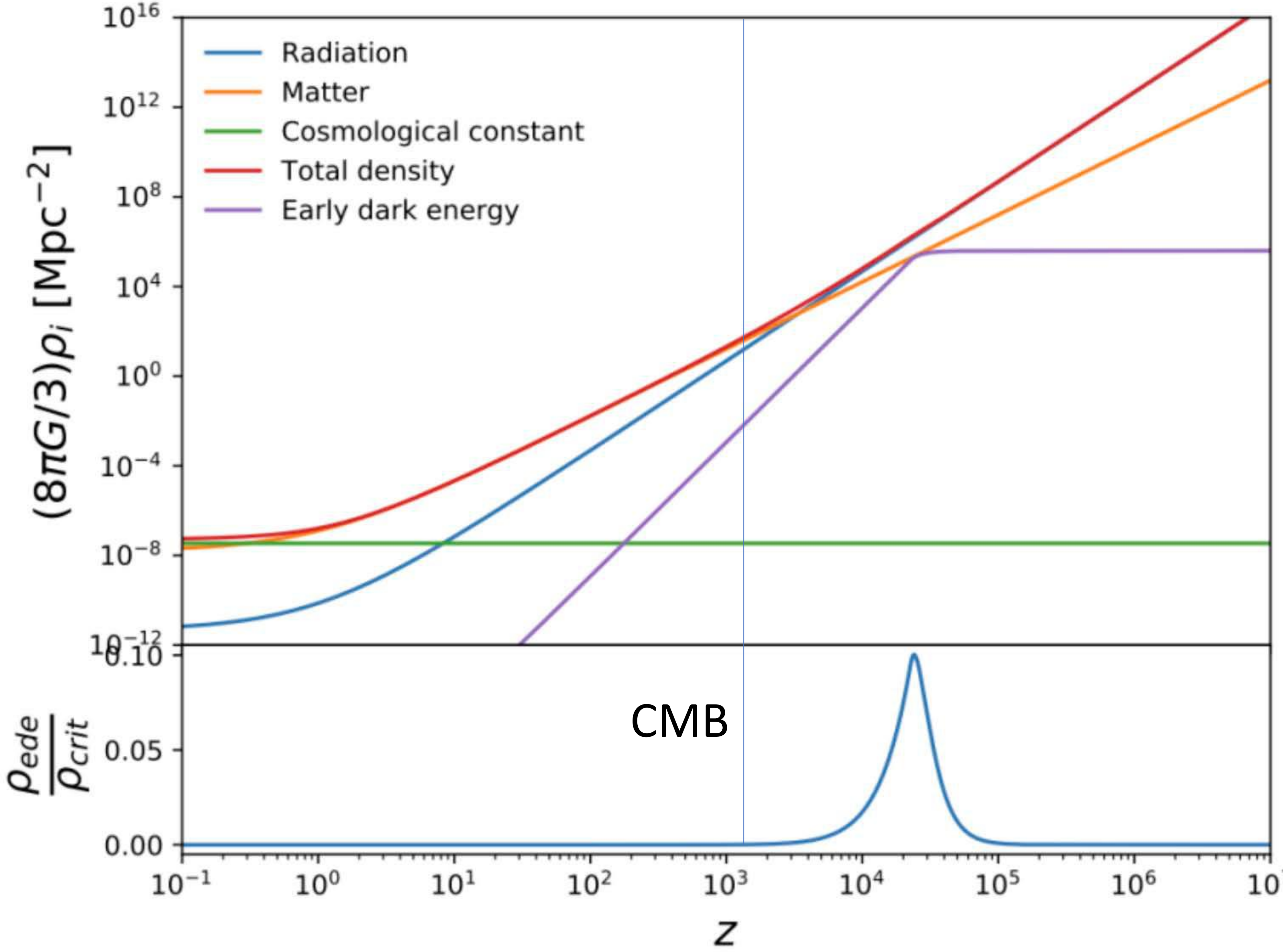
To increase *H_0*, can

- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe
- Increase matter density at early times *(early dark energy)*

Possible solution: Early dark energy

(Karwal,MK, 2016)

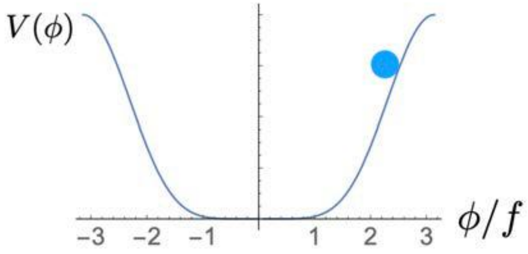
- Suppose early Universe expands faster
- Then less time for sound waves to propagate
- Smaller sound horizon
- Larger H_0 inferred from CMB



Radiation
Matter
Cosmological constant
Total density
Early dark energy
$(8\pi G/3)\rho_i$ [Mpc^{-2}]
10^{16}
10^{12}
10^{8}
10^{4}
10^{0}
10^{-4}
10^{-8}
10^{-12}
$\frac{\rho_{ede}}{\rho_{crit}}$
0.10
0.05
0.00
CMB
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
z

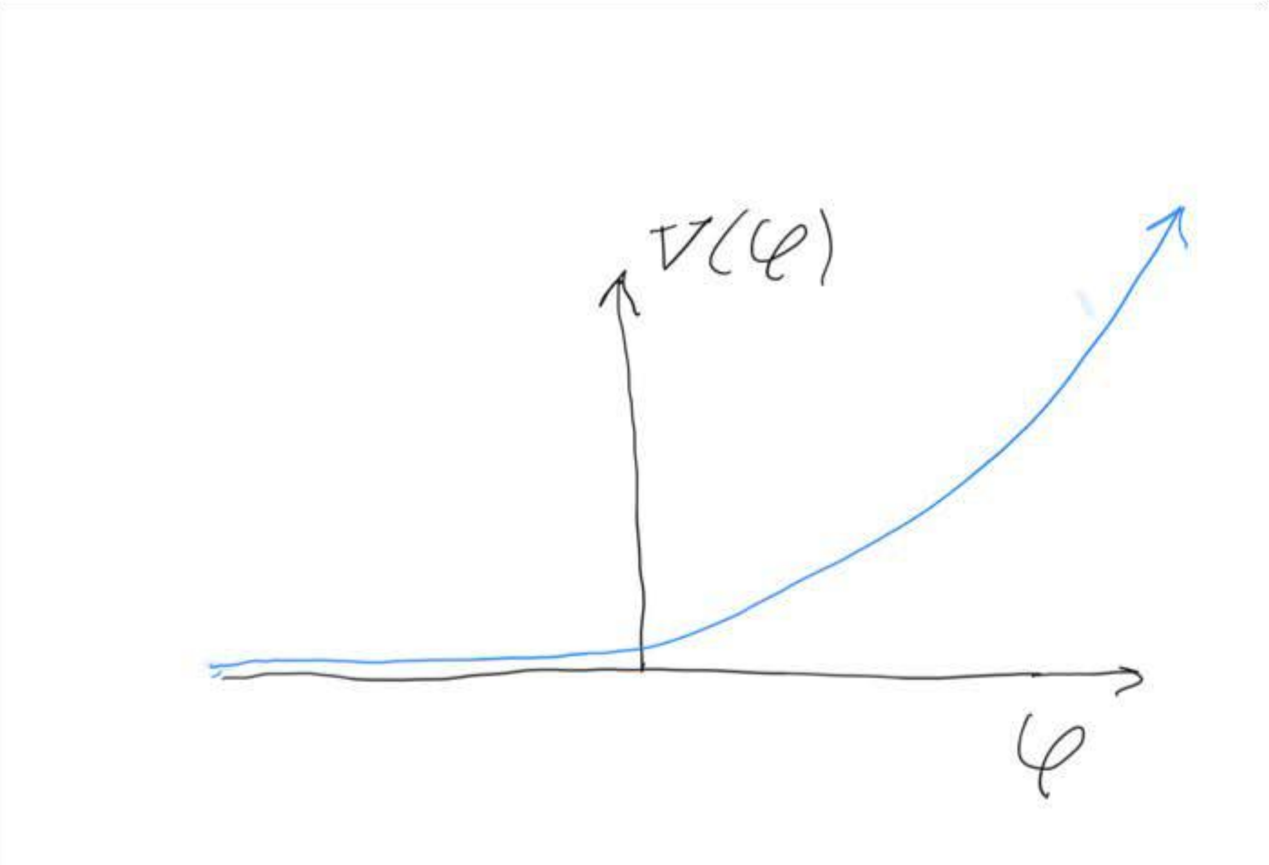
The (postulated) physics of DE

$$(\text{scale factor})^{(2n-2)/(2n+2)}$$



$$V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$

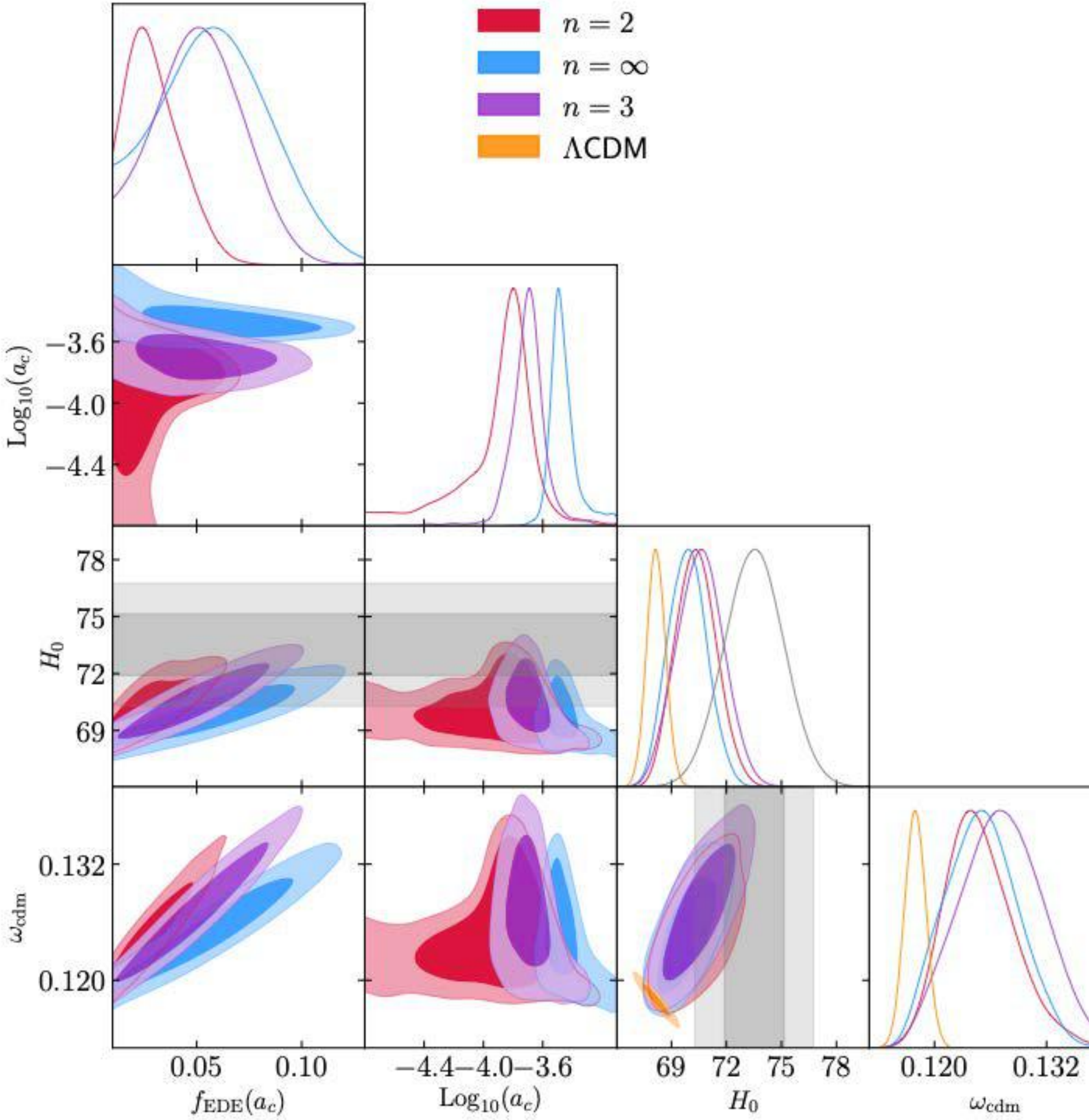
or



Devil is in the details:

Need detailed calculations to show that model predictions are consistent with CMB measurements (Poulin, Karwal, Smith, MK, 2018)

Results



Poulin et al. 2018

New tests of scenario:

Measurements of fine-grain features of CMB polarization by ACTPol/SPT3G/Simons/CMB-S4/etc

The Atacama Cosmology Telescope: Constraints on Pre-Recombination Early Dark Energy

J. Colin Hill,[1,2] Erminia Calabrese,[3] Simone Aiola,[2] Nicholas Battaglia,[4] Boris Bolliet,[1] Steve K. Choi,[5,4] Mark J. Devlin,[6] Adriaan J. Duivenvoorden,[7] Jo Dunkley,[8,7] Simone Ferraro,[9,10] Patricio A. Gallardo,[11] Vera Gluscevic,[12] Matthew Hasselfield,[2] Matt Hilton,[13,14] Adam D. Hincks,[15] Renée Hložek,[15,16] Brian J. Koopman,[17] Arthur Kosowsky,[18] Adrien La Posta,[19] Thibaut Louis,[19] Mathew S. Madhavacheril,[20,12] Jeff McMahon,[21,11,22,23] Kavilan Moodley,[13,14] Sigurd Naess,[2] Umberto Natale,[3] Federico Nati,[24] Laura Newburgh,[17] Michael D. Niemack,[5,4,25] Bruce Partridge,[26] Frank J. Qu,[27] Maria Salatino,[28,29] Alessandro Schillaci,[30] Neelima Sehgal,[31] Blake D. Sherwin,[27,32] Cristóbal Sifón,[33] David N. Spergel,[2,8] Suzanne T. Staggs,[7] Emilie R. Storer,[7] Alexander van Engelen,[34] Eve M. Vavagiakis,[5] Edward J. Wollack,[35] and Zhilei Xu[36]

[1] *Department of Physics, Columbia University, New York, NY 10027, USA*

[2] *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*

[3] *School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, Wales CF24 3AA, UK*

[4] *Department of Astronomy, Cornell University, Ithaca, NY 14853, USA*

[5] *Department of Physics, Cornell University, Ithaca, NY 14853, USA*

[6] *Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA 19104, USA*

[7] *Department of Physics, Jadwin Hall, Princeton University, Princeton, NJ 08544, USA*

(Dated: September 10, 2021)

The early dark energy (EDE) scenario aims to increase the value of the Hubble constant (H_0) inferred from cosmic microwave background (CMB) data over that found in the standard cosmological model (ΛCDM), via the introduction of a new form of energy density in the early universe. The EDE component briefly accelerates cosmic expansion just prior to recombination, which reduces the physical size of the sound horizon imprinted in the CMB. Previous work has found that non-zero

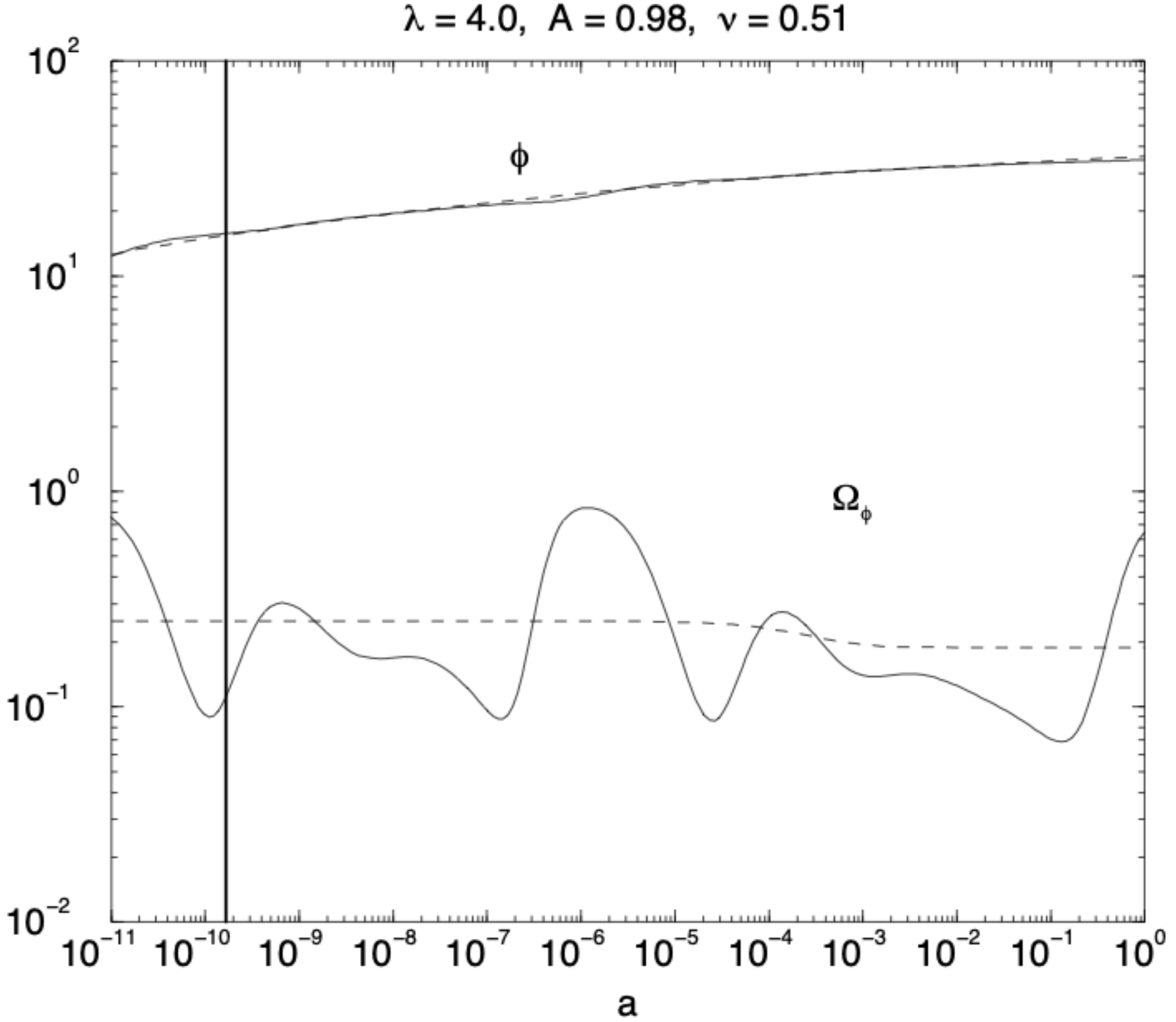
EDE is not preferred by *Planck* CMB power spectrum data alone, which yield a 95% confidence level (CL) upper limit $f_{\mathrm{EDE}} < 0.087$ on the maximal fractional contribution of the EDE field to the cosmic energy budget. In this paper, we fit the EDE model to CMB data from the Atacama Cosmology Telescope (ACT) Data Release 4. We find that a combination of ACT, large-scale *Planck* TT (similar to *WMAP*), *Planck* CMB lensing, and BAO data prefers the existence of EDE at $> 99.7\%$ CL: $f_{\mathrm{EDE}} = 0.091^{+0.020}_{-0.036}$, with $H_0 = 70.9^{+1.0}_{-2.0}$ km/s/Mpc (both 68% CL). From a model-selection standpoint, we find that EDE is favored over ΛCDM by these data at roughly 3σ significance. In contrast, a joint analysis of the full *Planck* and ACT data yields no evidence for EDE, as previously found for *Planck* alone. We show that the preference for EDE in ACT alone is driven by its TE and EE power spectrum data. The tight constraint on EDE from *Planck* alone is driven by its high-ℓ TT power spectrum data. Understanding whether these differing constraints are physical in nature, due to systematics, or simply a rare statistical fluctuation is of high priority. The best-fit EDE models to ACT and *Planck* exhibit coherent differences across a wide range of multipoles in TE and EE, indicating that a powerful test of this scenario is anticipated with near-future data from ACT and other ground-based experiments.

Recurrent dark energy?

- $\Lambda \neq 0$ today
- Inflation → $\Lambda \neq 0$ in the early Universe
- EDE (if this is what's going on) → $\Lambda \neq 0$ at z ~ 10,000

- Recurring periods of "Λ-like" behavior throughout cosmic history?

E.g. tracking oscillating energy (Dodelson, Kaplinghat, Stewart, astro-ph/0002360; Griest, astro-ph/0202052)



String Axiverse? (MK, Pradler, Walker, 2014; based on Arvanitaki et al., 2009; Svrcek & Witten, 2006)

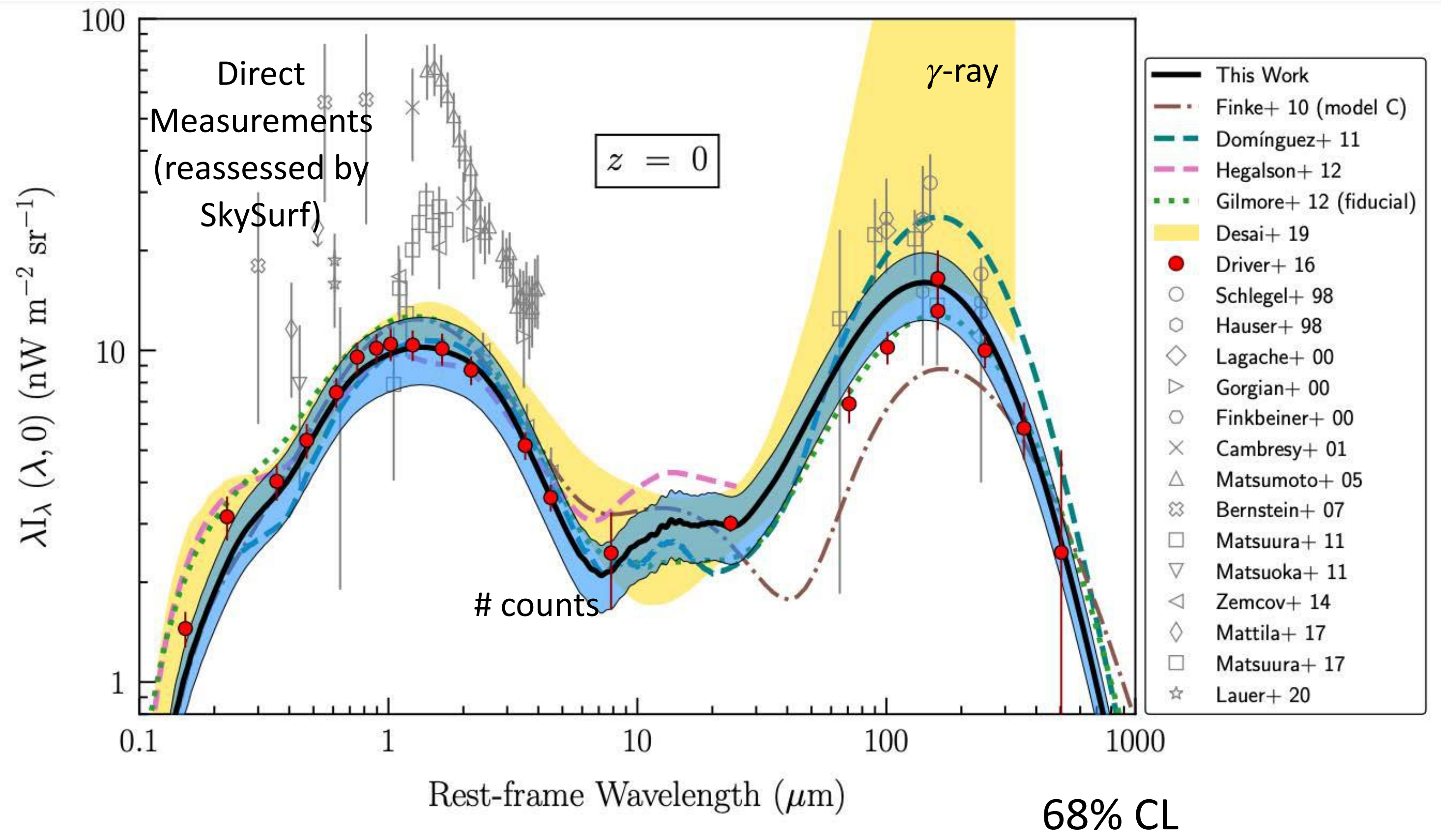
- ~100 axion fields
  - masses distributed logarithmically

- At each Log(Hubble time) , chance that axion field may act like dark energy

- Resemblance to "assisted quintessence" (e.g., Sabla&Caldwell 2021)

Summary

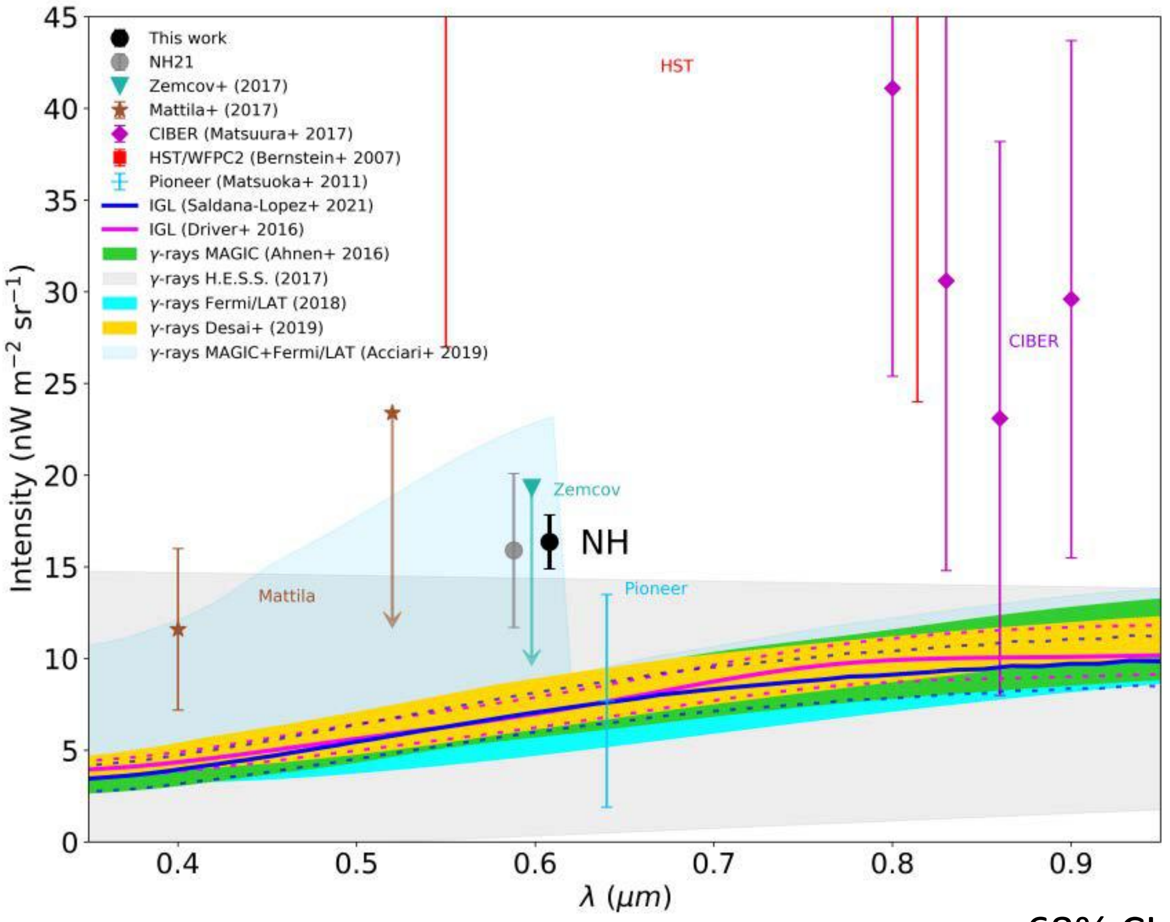
Extragalactic Background Light



- Aggregate of *all* emitted radiation

Saldana-Lopez+(2021)

COB excess



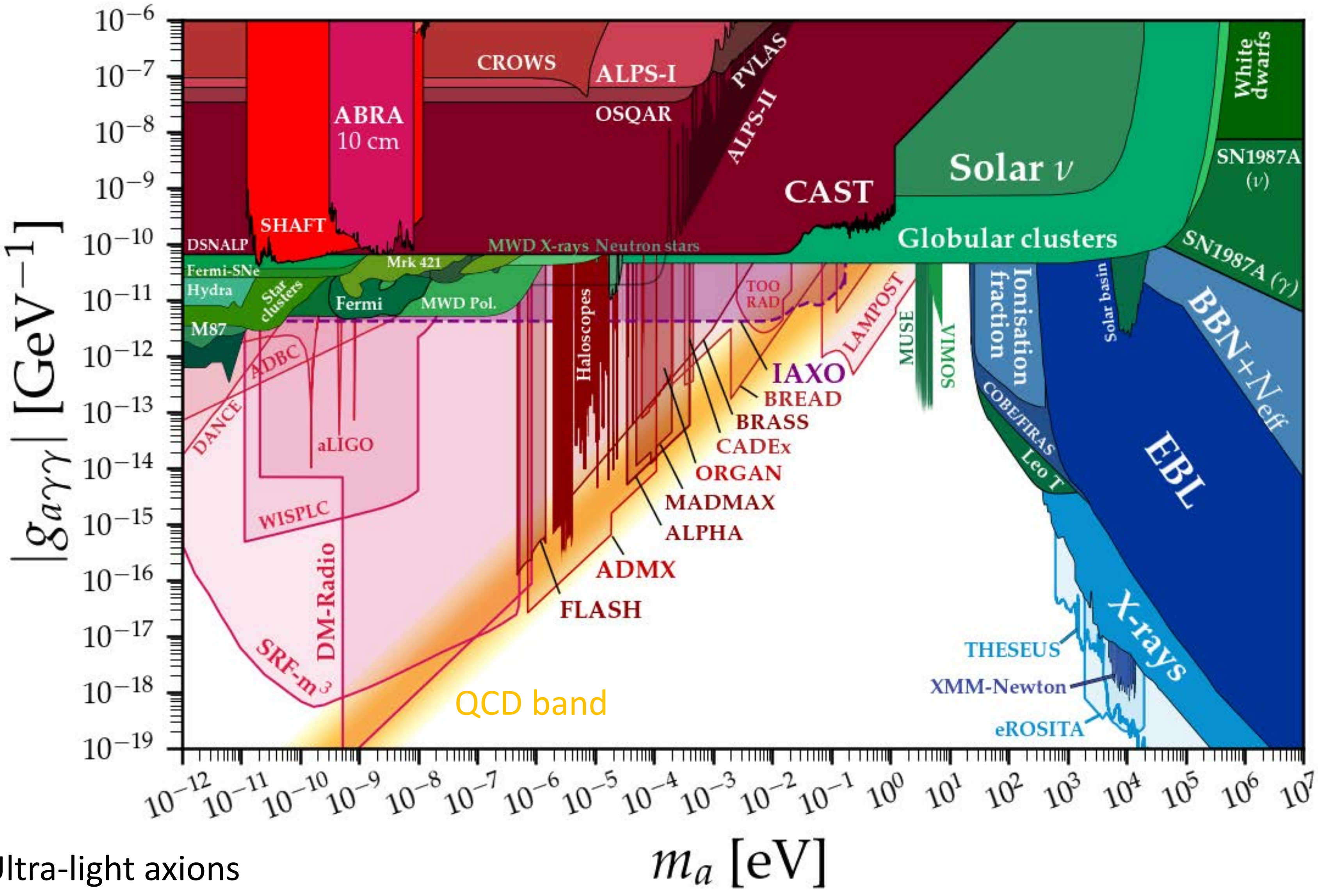
68% CL

- New direct observations from New Horizons (> 50 AU) at 0.61 microns
- 1st high significance detection ($> 8\sigma$)
- $> 4\sigma$ excess wrt estimation from IGL

Lauer+(2022)

Axion and ALPs

Coupling with photons assuming all DM

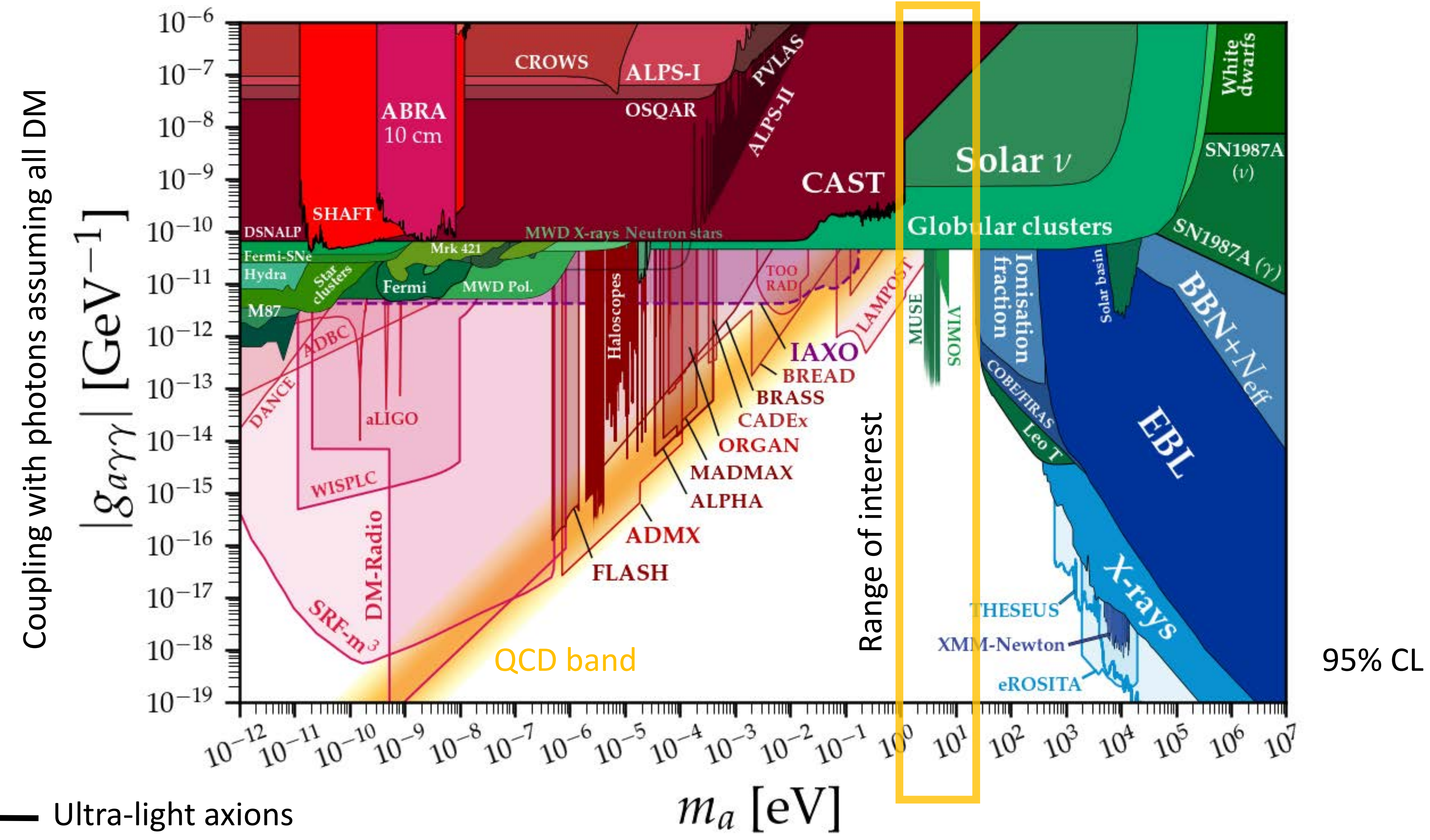


95% CL

← Ultra-light axions

Adams+(2022); Snowmass

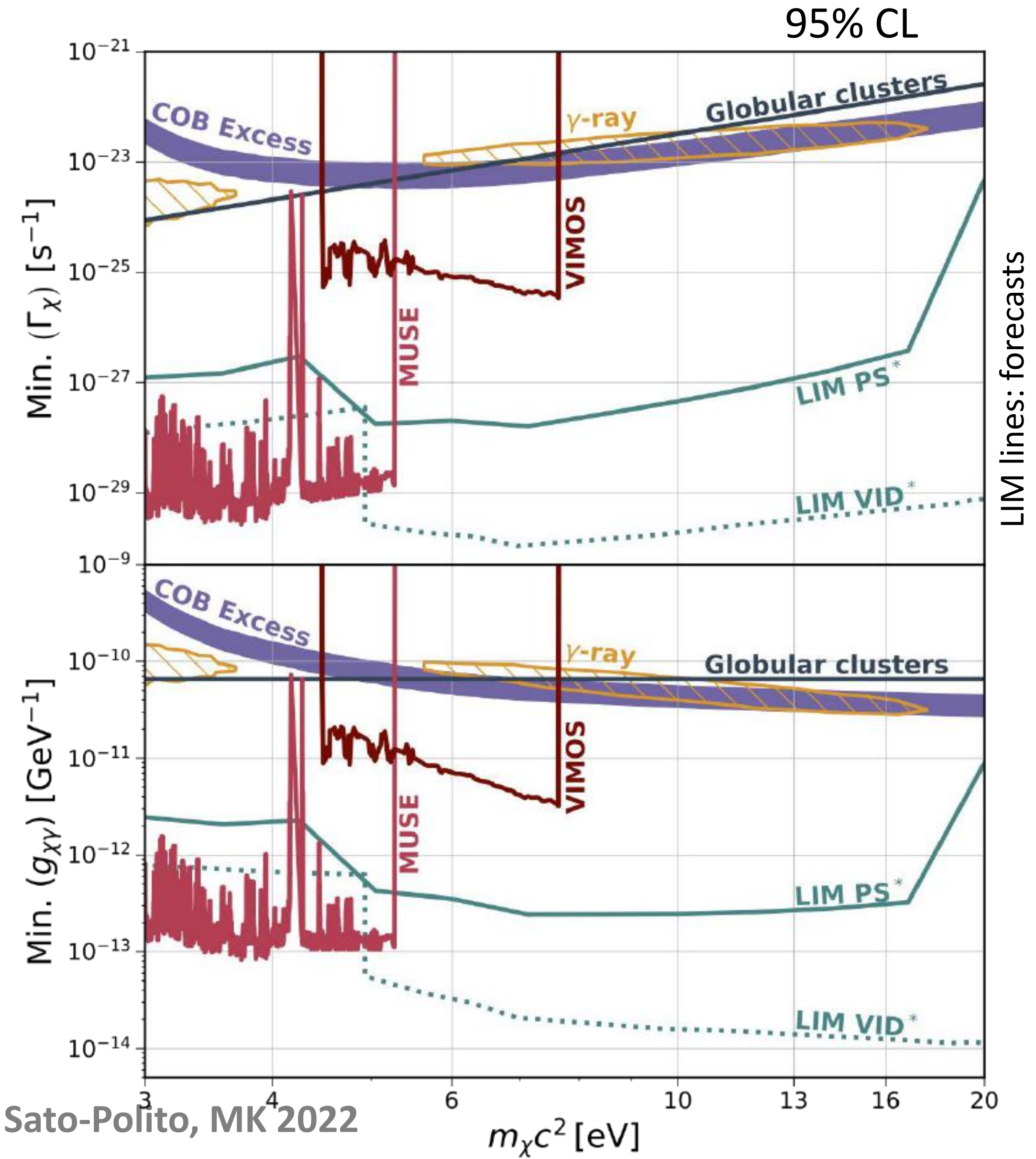
Axion and ALPs



Ultra-light axions

Adams+(2022); Snowmass

ALPs contributing to COB excess



Bernal, Sato-Polito, MK 2022

$$I_\lambda \propto \frac{\Gamma_a}{\lambda_{obs}\left(1+z_*\right)H(z_*)}$$

$z_* \equiv z$ of axion decay
$\Gamma_a \propto m_a^3 g_{a\gamma}^2$

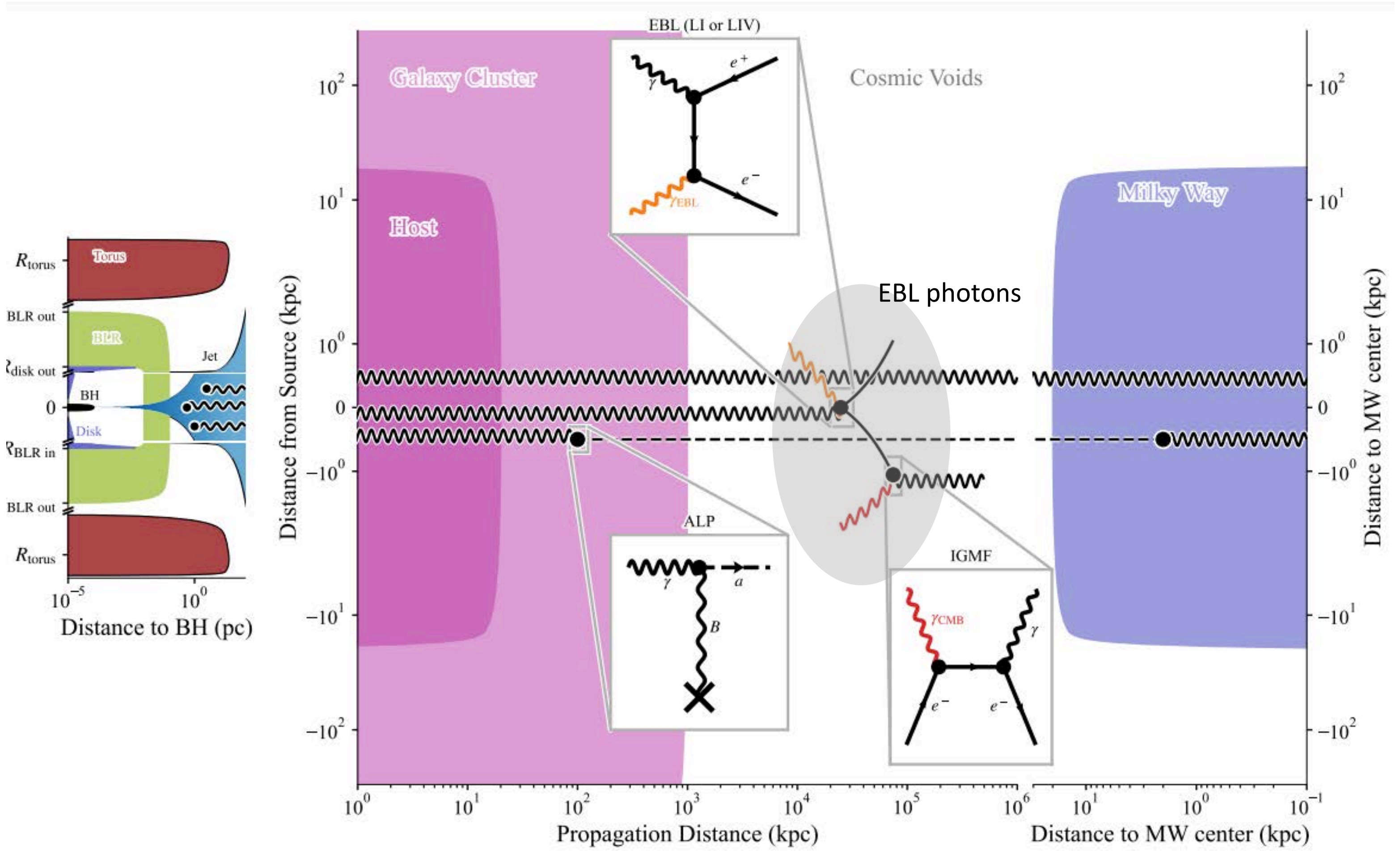
- Parameter region allowed by current observations
- Overlaps with hint from γ-ray extinction Korochkin+(2019)
- Will be probed by LIM (strongest sensitivity in this range, SPHEREx + HETDEX) Bernal+(2021)

γ-ray attenuation

- Flux of high-energy γ-rays attenuated by IR-NUV EBL photons: $\gamma + \gamma \rightarrow e^- + e^+$

- $$\epsilon_{\min} = \frac{2m_e^2c^4}{E_\gamma(1+z)(1-\mu)}$$

- $\sigma_{\gamma\gamma}$ peaks at $\sim \epsilon_{\min}$



Biteau & Meyer (2022)

γ-ray attenuation

- Flux of high-energy γ-rays attenuated by IR-NUV EBL photons: $\gamma + \gamma \rightarrow e^- + e^+$

- Energy threshold: $\epsilon_{\min} = \dfrac{2m_e^2c^4}{E_\gamma(1+z)(1-\mu)}$

- Integrated effect: measurements of $\tau(E_\gamma, z_s)$ as tomographic and chromatic EBL probe*

$$\tau\left(E_\gamma, z_s\right) = c \int_0^{z_s} \frac{dz}{H(z)(1+z)} \underbrace{\int_{\epsilon_{\min}}^{\infty} \frac{dn}{d\epsilon} \int_{-1}^{1} d\mu \sigma_{\gamma\gamma}(E_\gamma, \epsilon, z, \mu)}_{\text{1/Mean free path}}$$

*Assuming no secondary γ-ray production, Essey+(2010)

- ~800 blazars (Fermi-LAT+Cherenkov telescopes)

Budget the EBL

- Measured binned $\tau(E_\gamma, z_s)$ from Fermi-LAT and Cherenkov telescopes
- Standard contributions to the EBL:
  - galaxies at $z < 6$: Observational, from HST/CANDELS (most dominant part) Saldana-Lopez+(2021)
  - galaxies at $z > 6$: Theoretical (ARES), calibrated to UVLF, + PopIII stars Mirocha(2014), Mirocha+(2017), Mirocha+(2018)
  - IHL: Theoretical, calibrated to NIR-optical background fluctuations Cooray+(2012), Mitchell-Wynne+(2015)
- Objective: Is there something else beyond standard?
  - Compute τ_i from each contribution to the EBL
  - Consider extreme cases to account for uncertainties
  - Add uncertainties in quadrature
  - Work with $\tau_{\rm res}$ as the residual after subtraction from standard sources

$$\tau_{\rm res} = \tau_{\rm meas} - \sum \tau_i \, ; \qquad \sigma^2\left(\tau_{\rm res}\right) = \sigma^2\left(\tau_{\rm meas}\right) + \sum \sigma^2(\tau_i)$$

Budget the EBL

- $\tau_{\rm res} > 0$: additional EBL required to explain the optical depth slightly higher than inferred
- Axion decays? Misestimation of standard sources?
- Science case: Explore axion parameter space ($\mathrm{m}_a,\ \Gamma_a$) (assuming all DM)
- Null cases:

A) frequency-independent re-scaling $F_{\rm eEBL}$ of the EBL from galaxies at $z < 6$:

EBL γ # density:

$$\left(\frac{dn}{d\epsilon}\right)^{\rm new}_{\rm gal,\ z<6} = (1 + F_{\rm eEBL})\left(\frac{dn}{d\epsilon}\right)^{\rm old}_{\rm gal,\ z<6}$$

B) Boost errors for EBL from galaxies at $z < 6$ until $\tau_{\rm res}$ consistent with 0 and fit for ($\mathrm{m}_a,\ \Gamma_a$)

$$\Delta\chi^2_{a-\mathrm{eEBL}} = 0.7$$

Signif. over null

$$\mathrm{ALPs} = 2.1\sigma$$

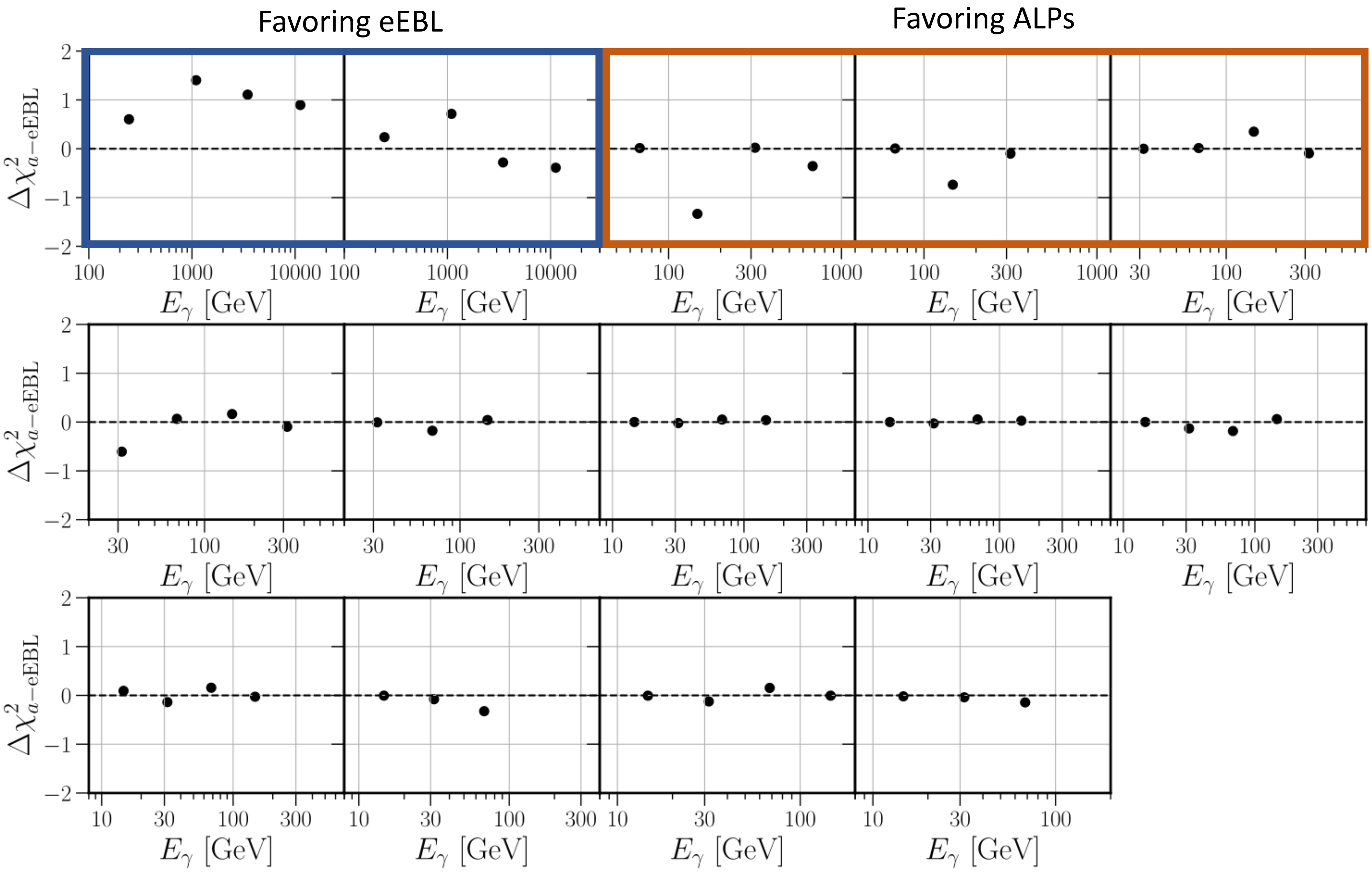
$$F_{\mathrm{eEBL}} = 2.7\ \sigma$$

Best fit

$$\Gamma_a = 2.5 \times 10^{-24}\ \mathrm{s}^{-1}$$

$$m_a = 9.1\ \mathrm{eV}/c^2$$

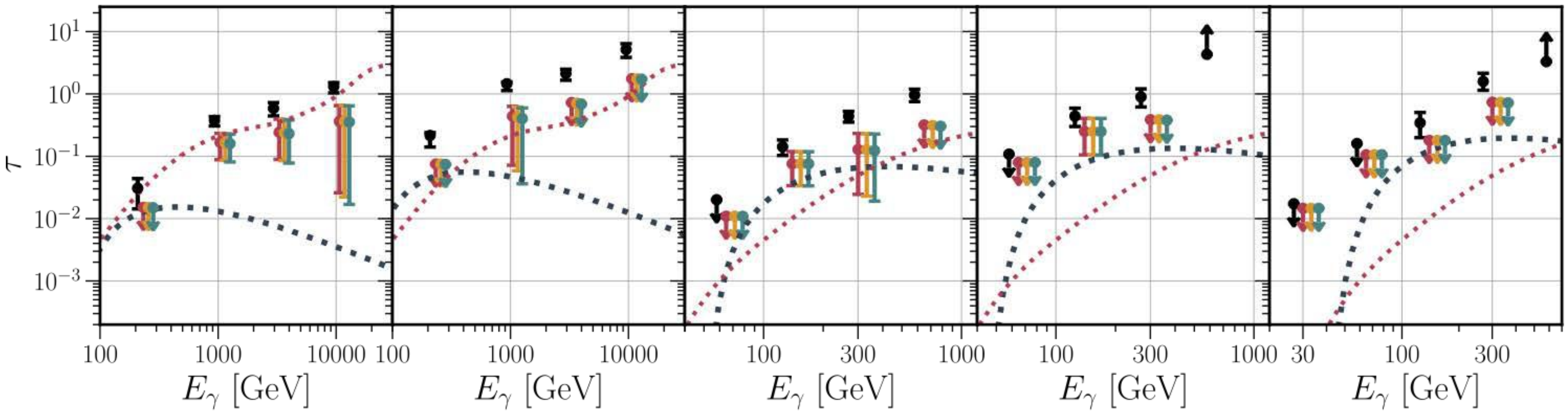
$$F_{\mathrm{eEBL}} = 0.22 \pm 0.08$$

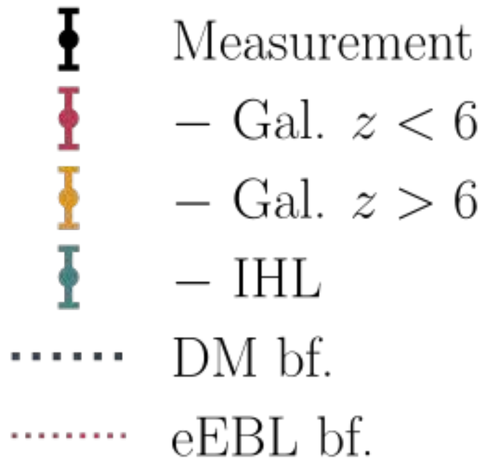


Bernal, Caputo, Mirocha, Sato-Polito, MK 2022b

Caution: log-log plot

68% CL





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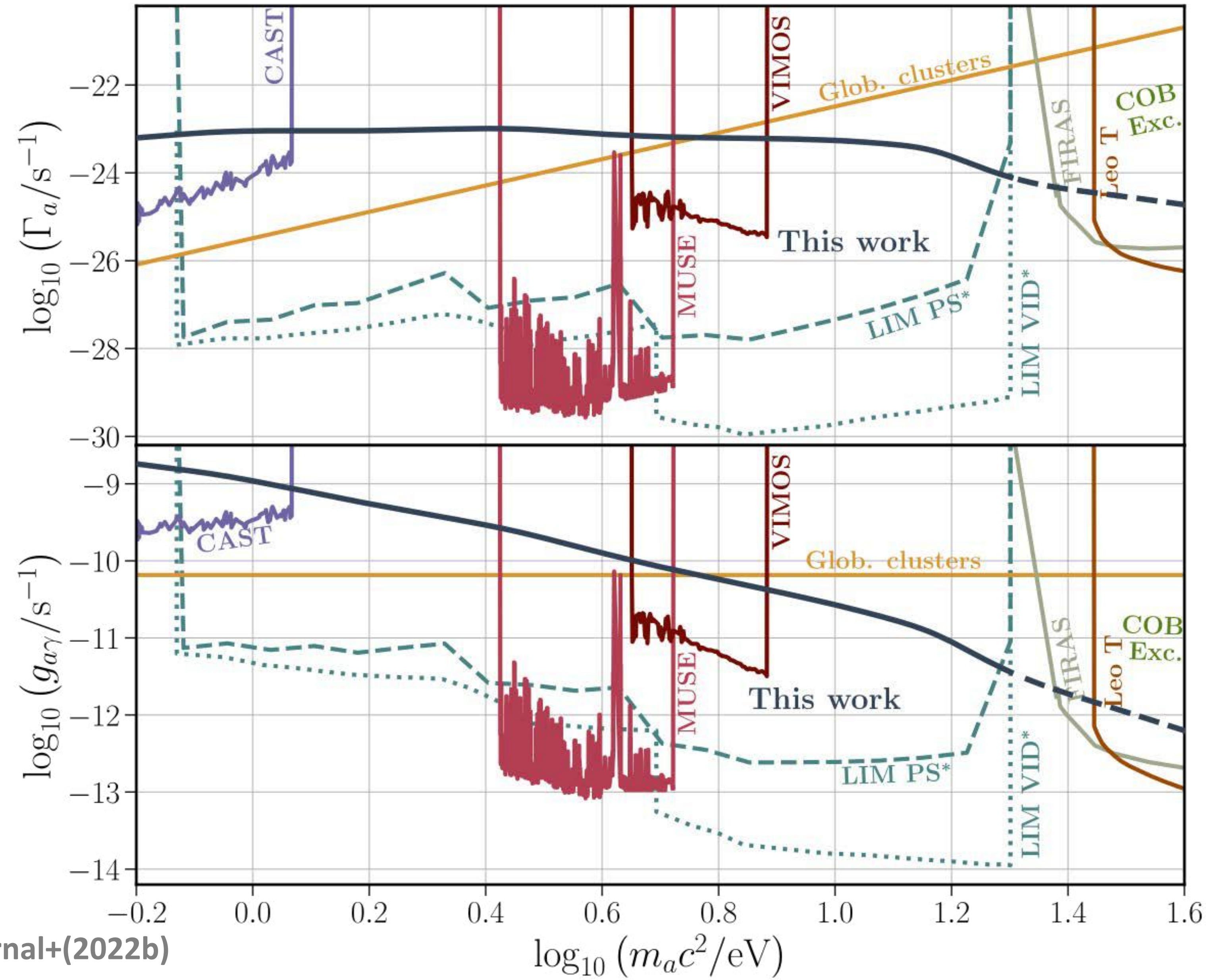
Bernal+(2022b)

Understanding the axion hint



Bernal+(2022b)

- Unconstrained best-fit
- 2σ significance
- Overlap with explanation for COB excess
- **Strongest constraints at 3σ for** $m_ac^2 \in [8,\ 25]$ eV

- Bimodal distribution
- Poor fit to local blazars
- Also preference for F_{eEBL}

$\Gamma_a = 2.5 \times 10^{-24}\,\mathrm{s}^{-1}$

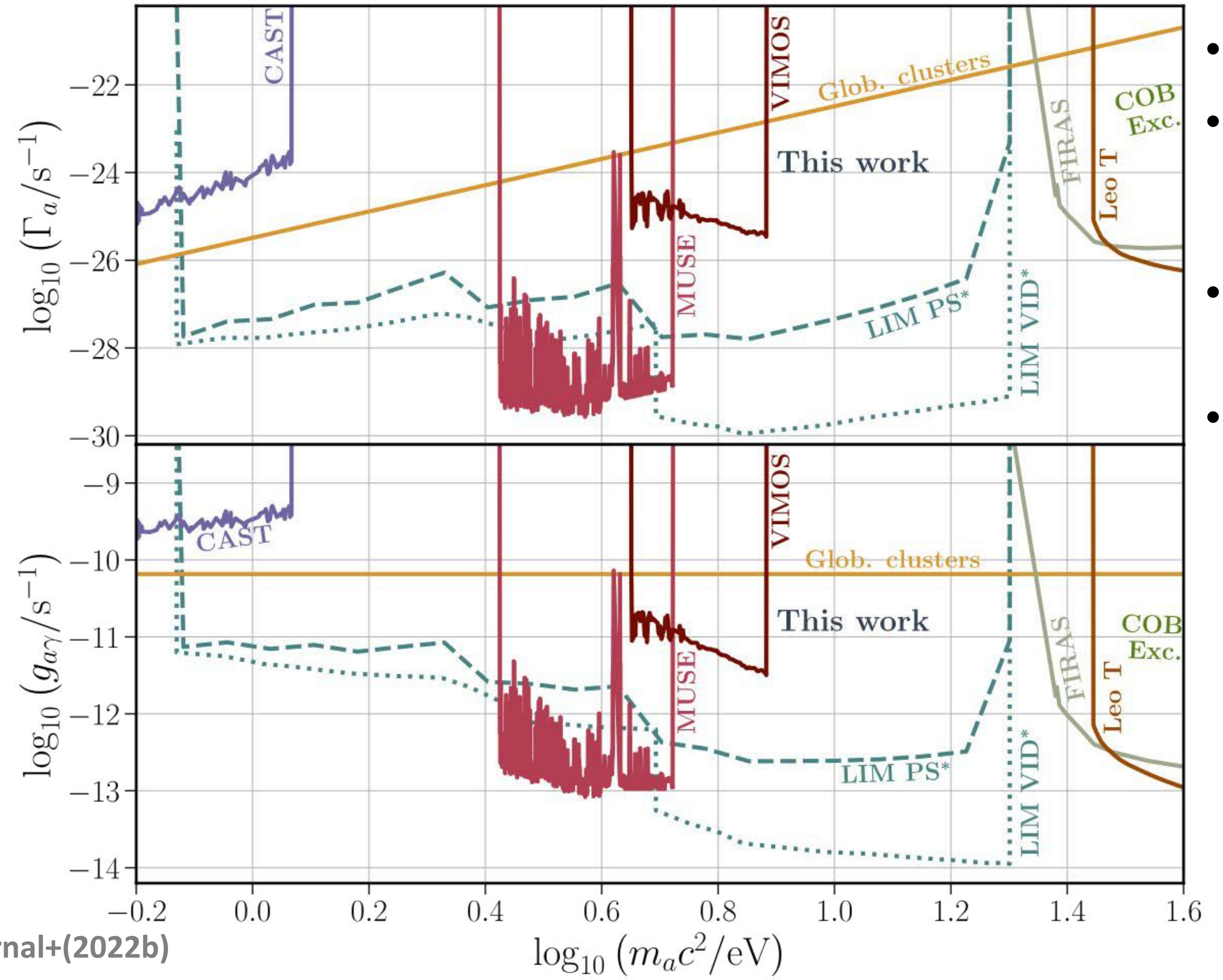
2.1σ

$m_a = 9.1\,\mathrm{eV}/c^2$

$\Gamma_a \propto m_a^3 g_{a\gamma}^2$

95% CL

Understanding the axion hint



Bernal+(2022b)

- Removing 1st redshift bin
- $\Delta\chi^2_{a-\mathrm{eEBL}} = -3.2$
- Much stronger evidence, but ruled out
- F_{eEBL} similar significance

4.0σ

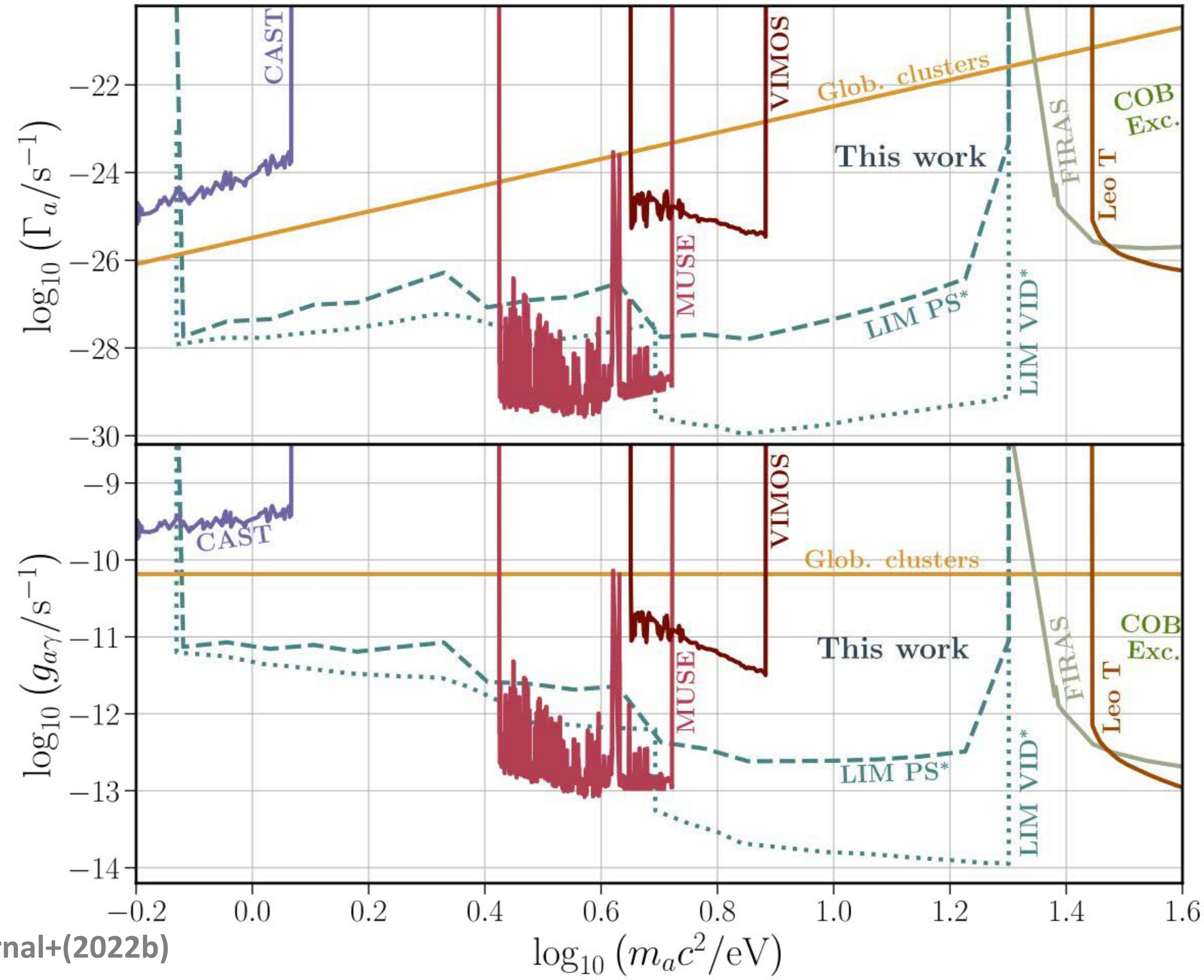
$\Gamma_{a,\,\mathrm{bf}} = 1.0 \times 10^{-23}\ \mathrm{s}^{-1}$

$m_{a,\,\mathrm{bf}} = 5.7\ \mathrm{eV}/c^2$

$\Gamma_a \propto m_a^3 g_{a\gamma}^2$

95% CL

Null case B



Bernal+(2022b)

- 3σ limits after boosting uncertainties until all $\tau_{\rm res}$ are upper limits
- Still the strongest limits

95% CL

$\Gamma_a \propto m_a^3 g_{a\gamma}^2$

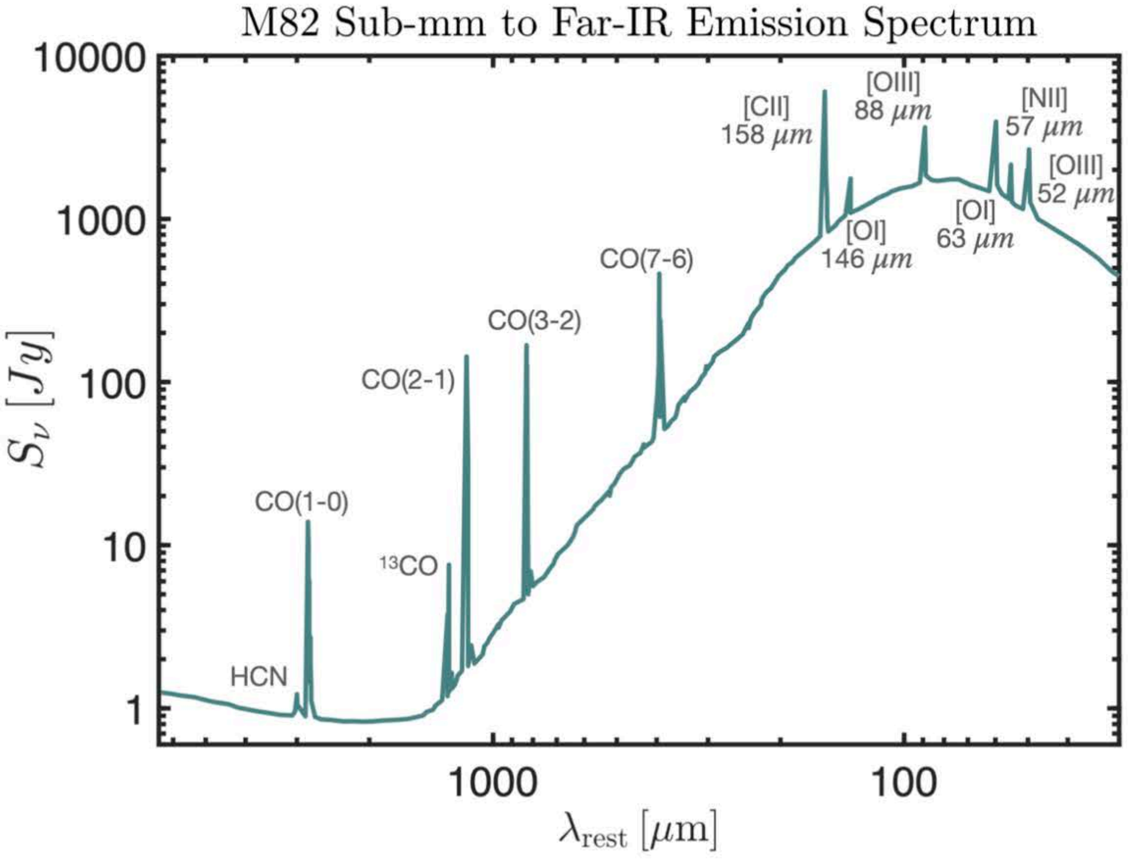
Conclusions

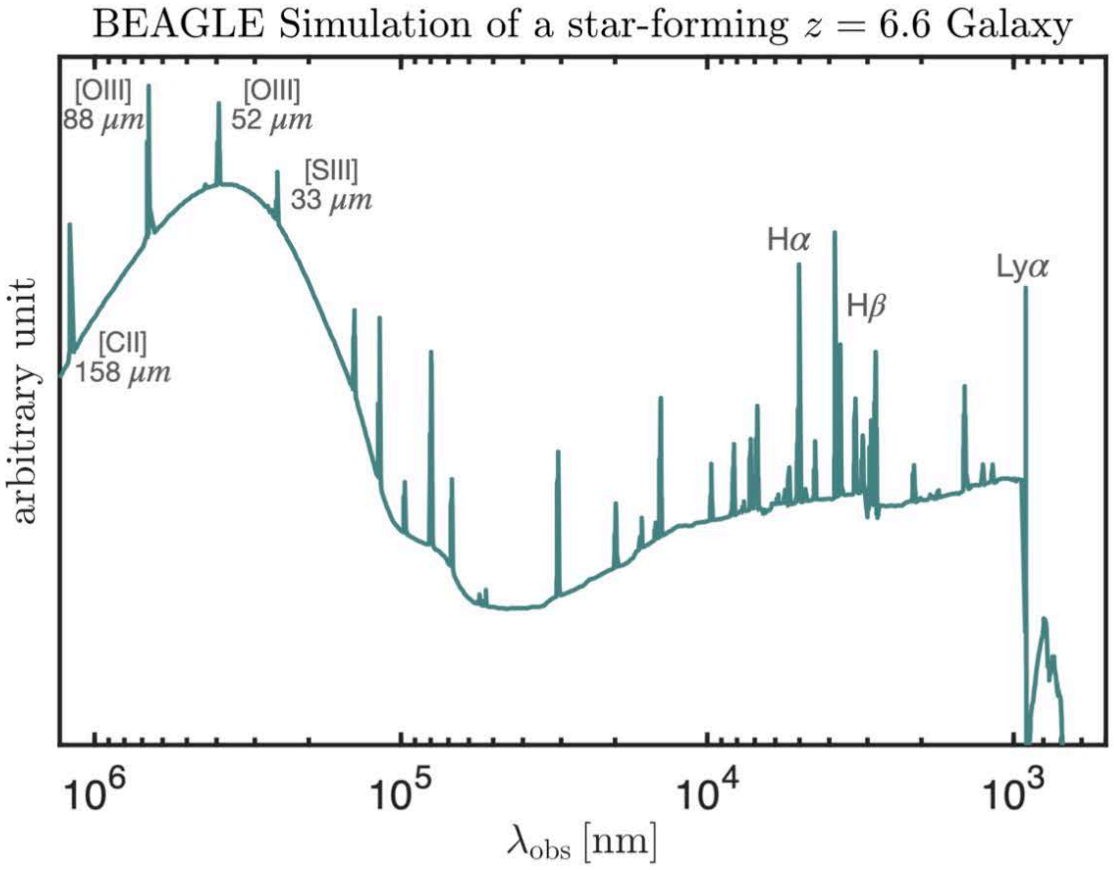
- Multi-electronvolt ALP decays may contribute to the COB excess
- γ-ray absorption needs more EBL than observed/inferred from standard astro sources
- Can be explained with a frequency independent increase of 14-30% in the contribution from galaxies at $z < 6$ (with 2.7σ significance)
- Multielectronvolt-scale axion dark matter may also work (with 2.1σ significance)
- **Strongest constraints to date on axion-photon coupling for masses between 8-25 eV**
- Promising future, with more observations by existing and forthcoming γ-ray and Cherenkov telescopes, as well as improved EBL determinations with experiments like SPHEREx and JWST
- LIM prospects: huge improvement in sensitivity

- New way to study large-scale structure
- LIM: use integrated light in given pixel on sky
- Information from all galaxies and IGM along LoS
- Use redshift of identifiable spectral line $\rightarrow$ 3D

Reviews/refs: Kovetz et al., 1709.09066; Bernal, Breysse, Gil-Marin, Kovetz, arXiv:1907.10067; *Bernal & Kovetz, in preparation*

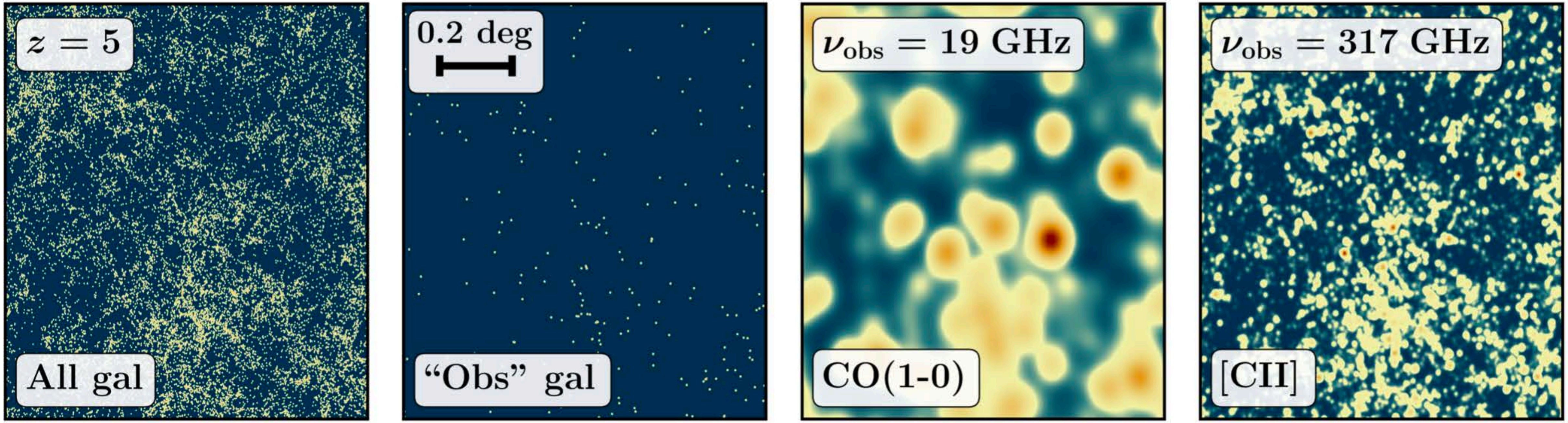
Emission lines



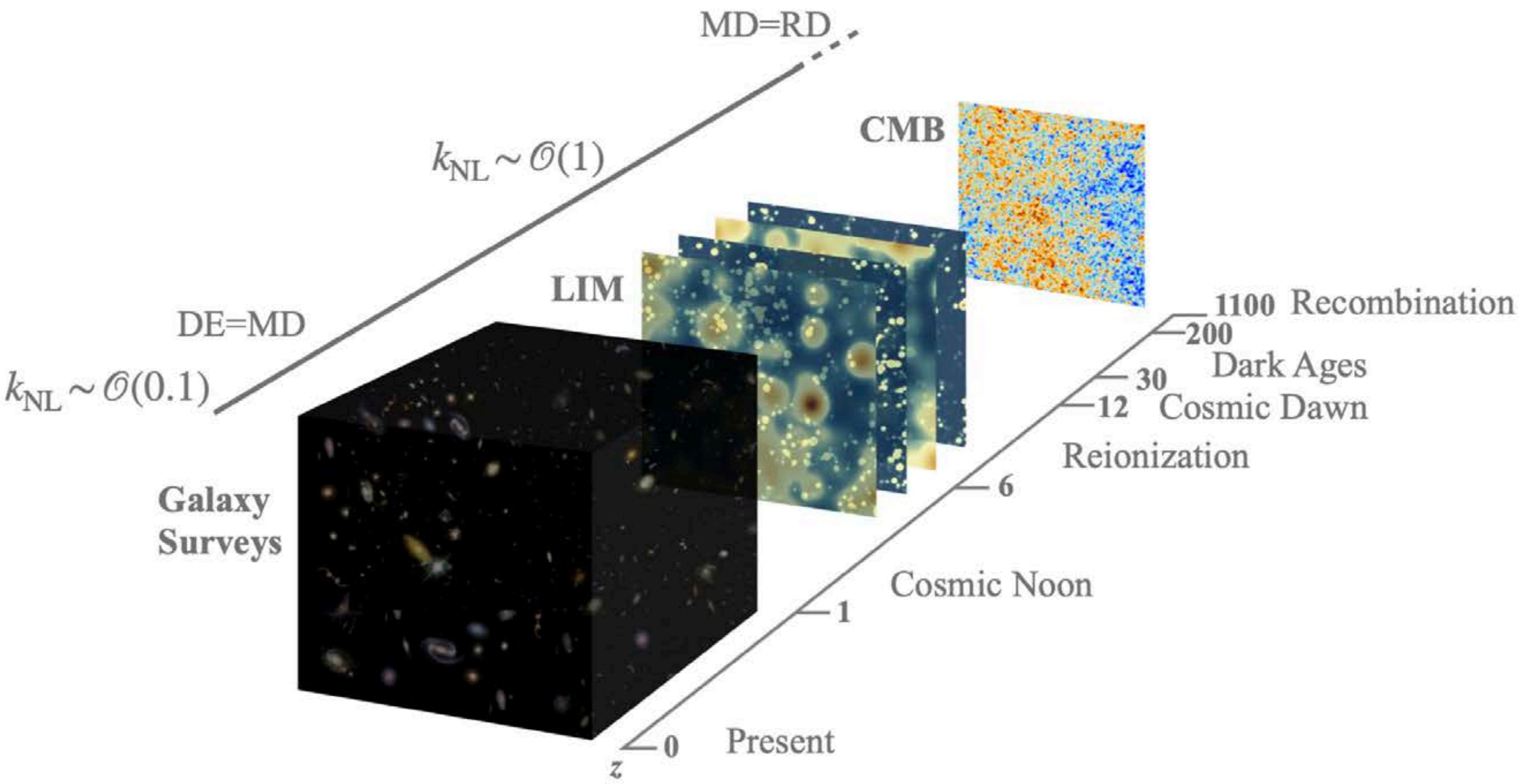


Galaxy surveys: detailed distribution of brightest galaxies

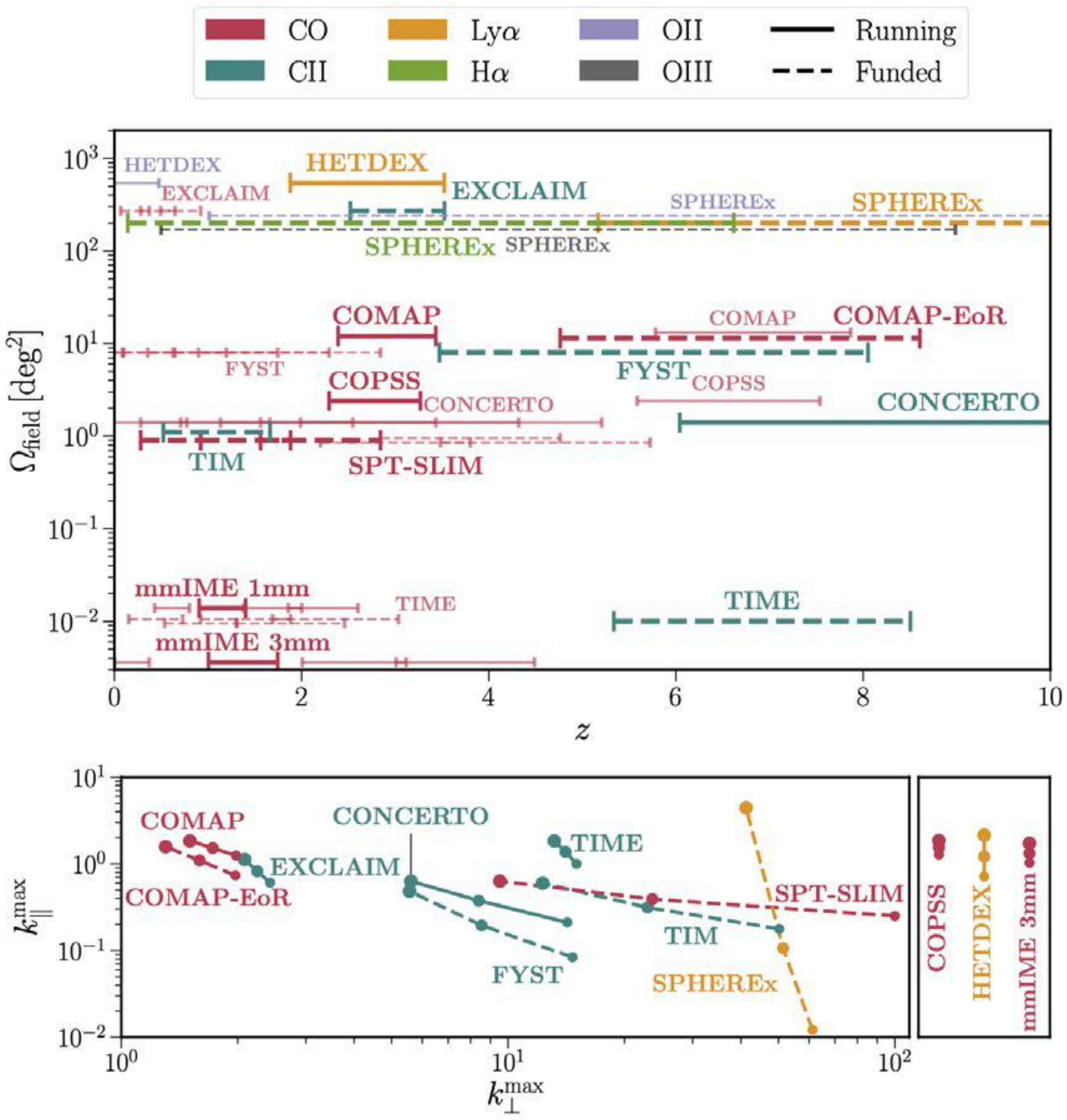
Intensity maps: noisy distribution of all galaxies and IGM



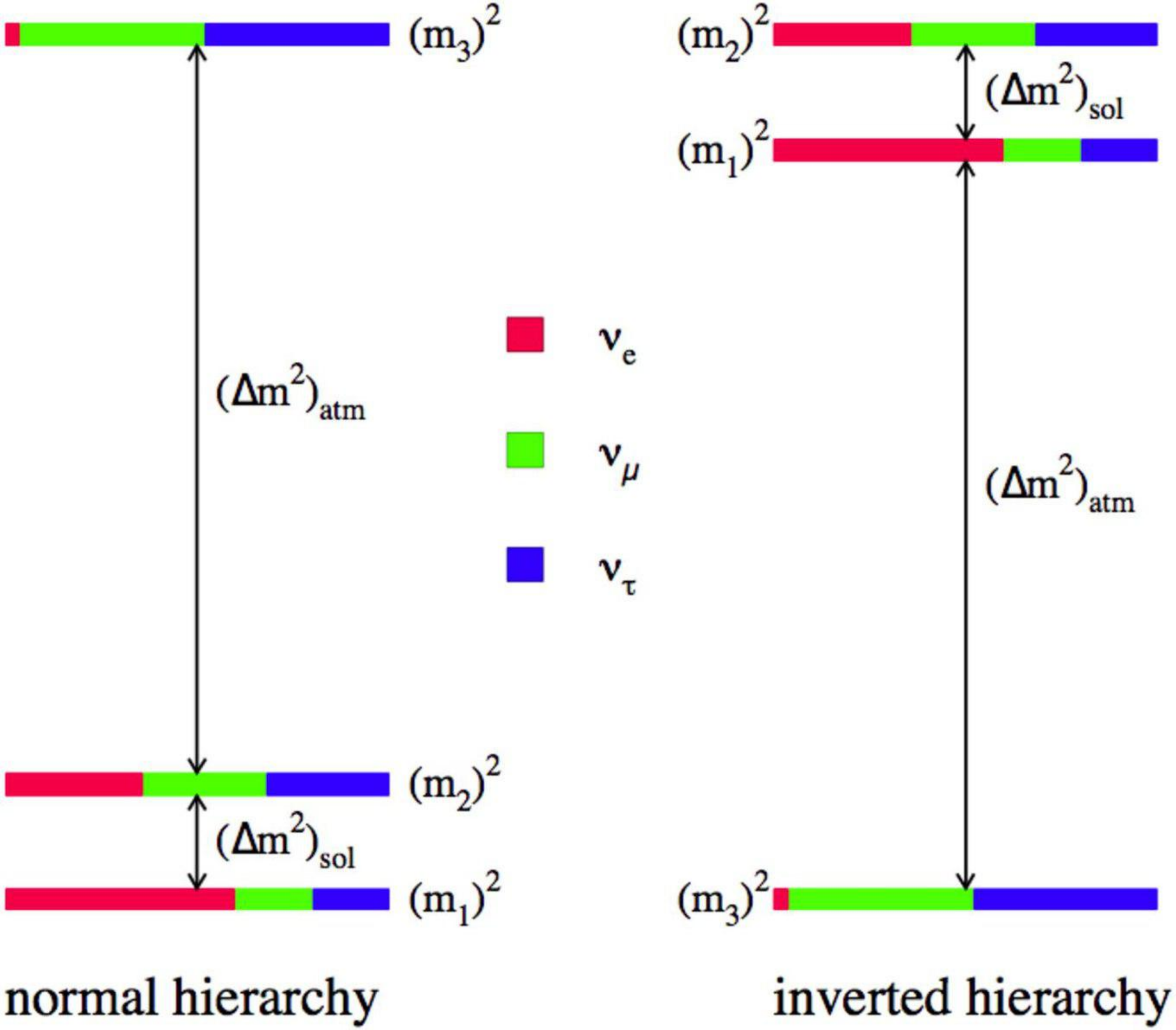
Probing the Universe



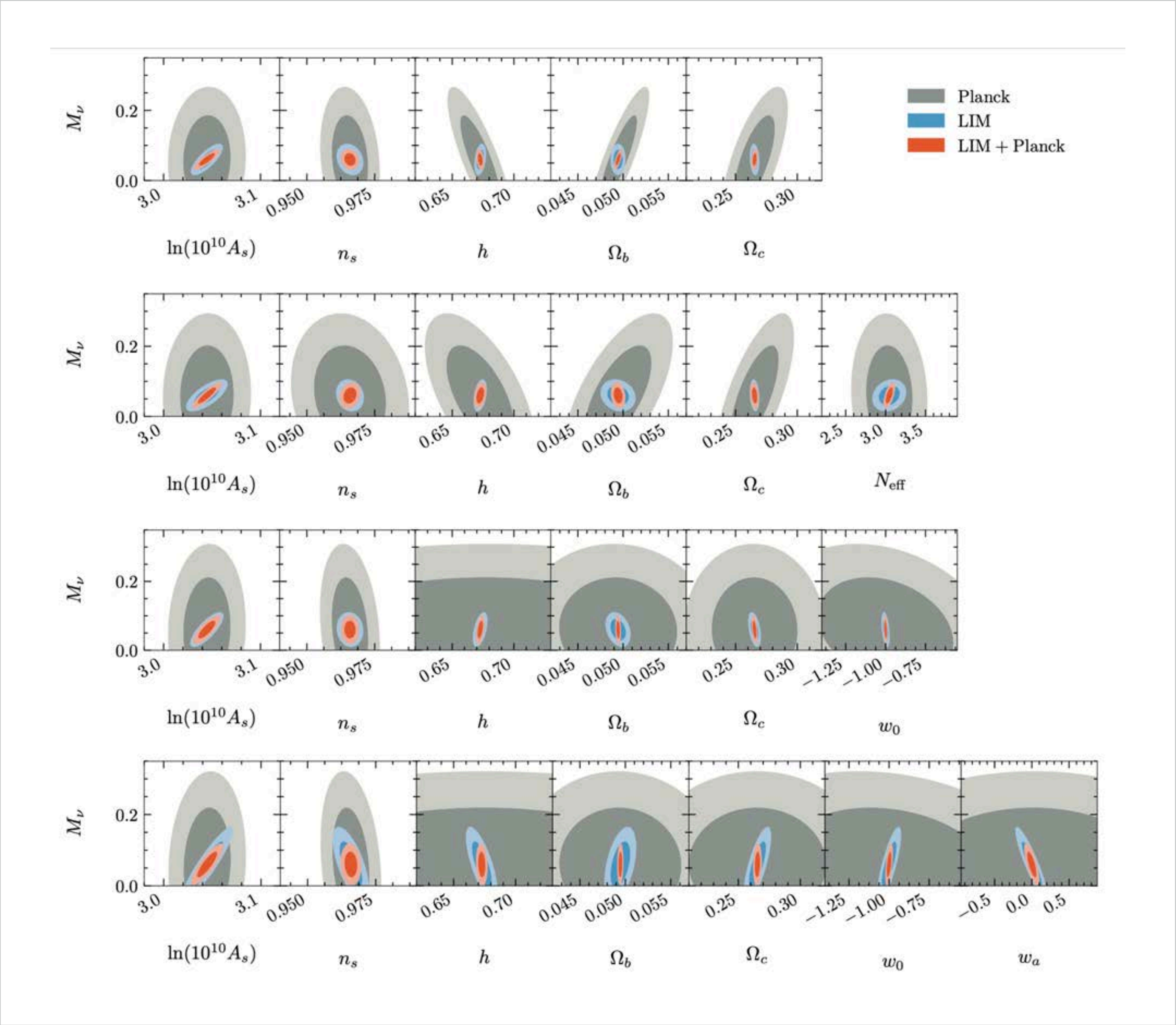
Probing the Universe with LIM



Neutrino masses

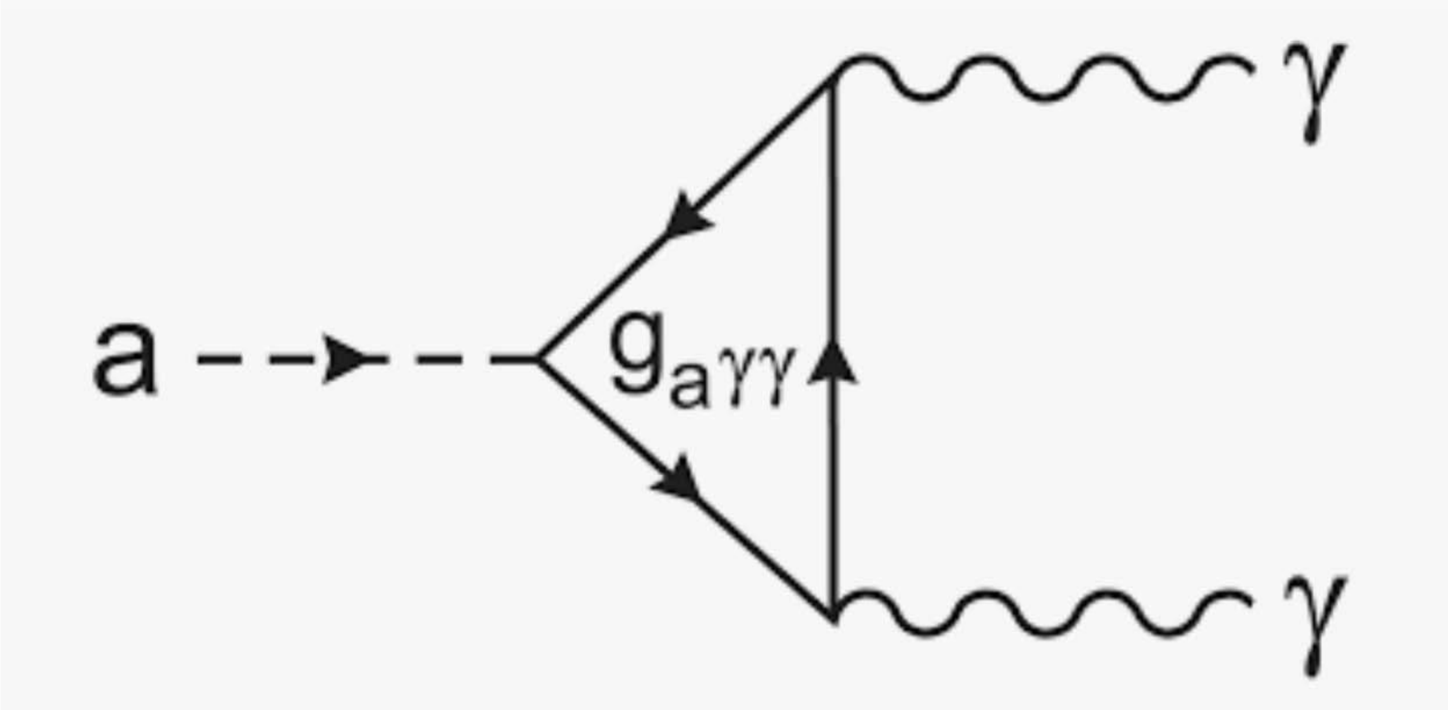


Neutrino masses:



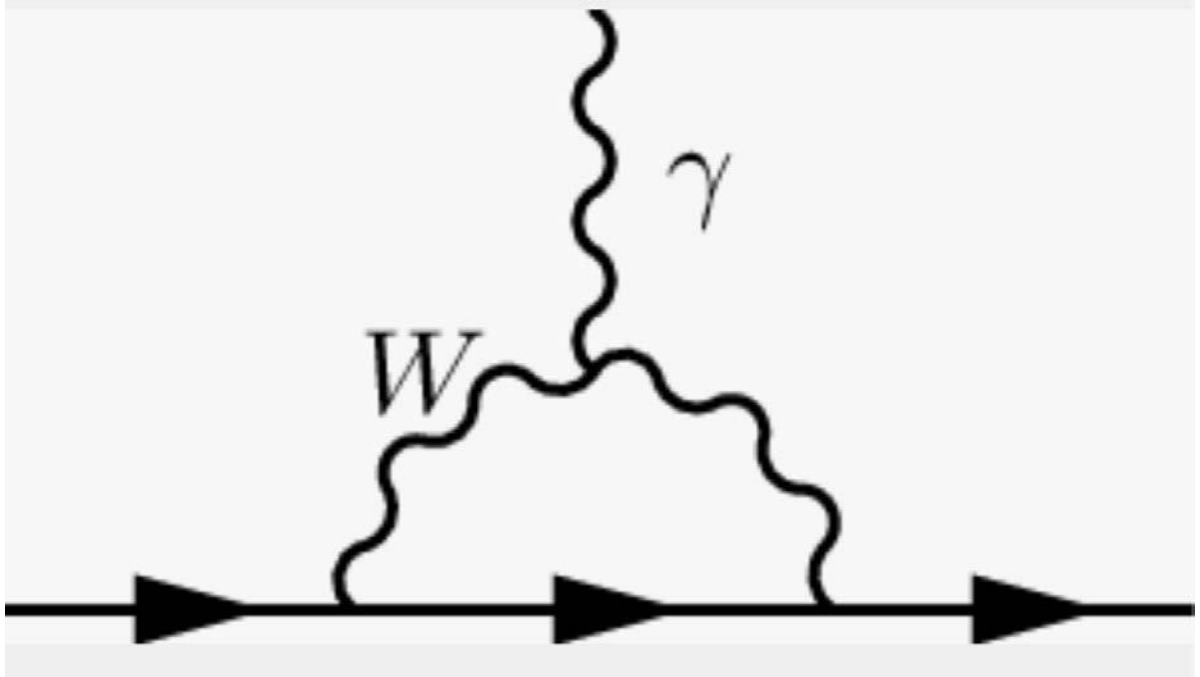
photon lines from radiative dark-matter/neutrino decay/annihilation

(Creque-Sarbinowski, MK 2018; Bernal, Caputo, MK 2021; Bernal, Caputo, Villaescusa-Navarro, MK 2021)


a
$g_{a\gamma\gamma}$
γ
γ

Neutrino decay

Heavier neutrino mass eigenstate



Lighter neutrino mass eigenstate

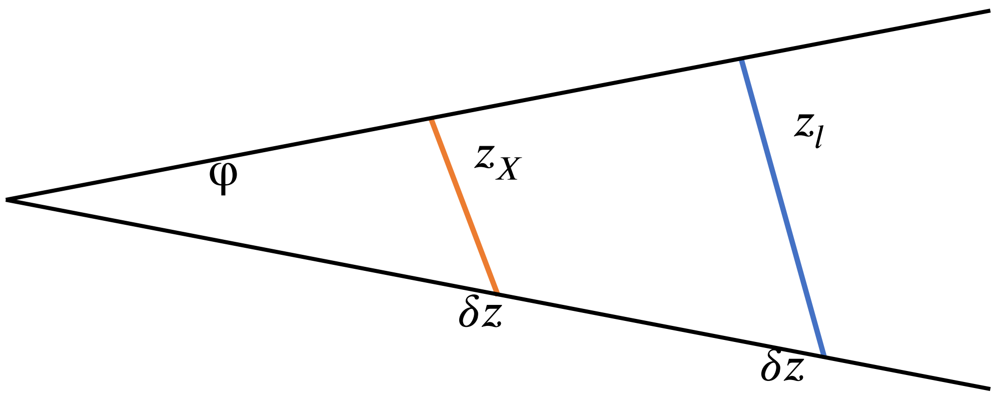
Parameterized by (transition) magnetic moment

Decay/annihilation line is unbiased/ biased tracer of dark-matter distribution

→should cross-correlate with LSS

How to distinguish from astrophysical line

- Clustering anisotropy



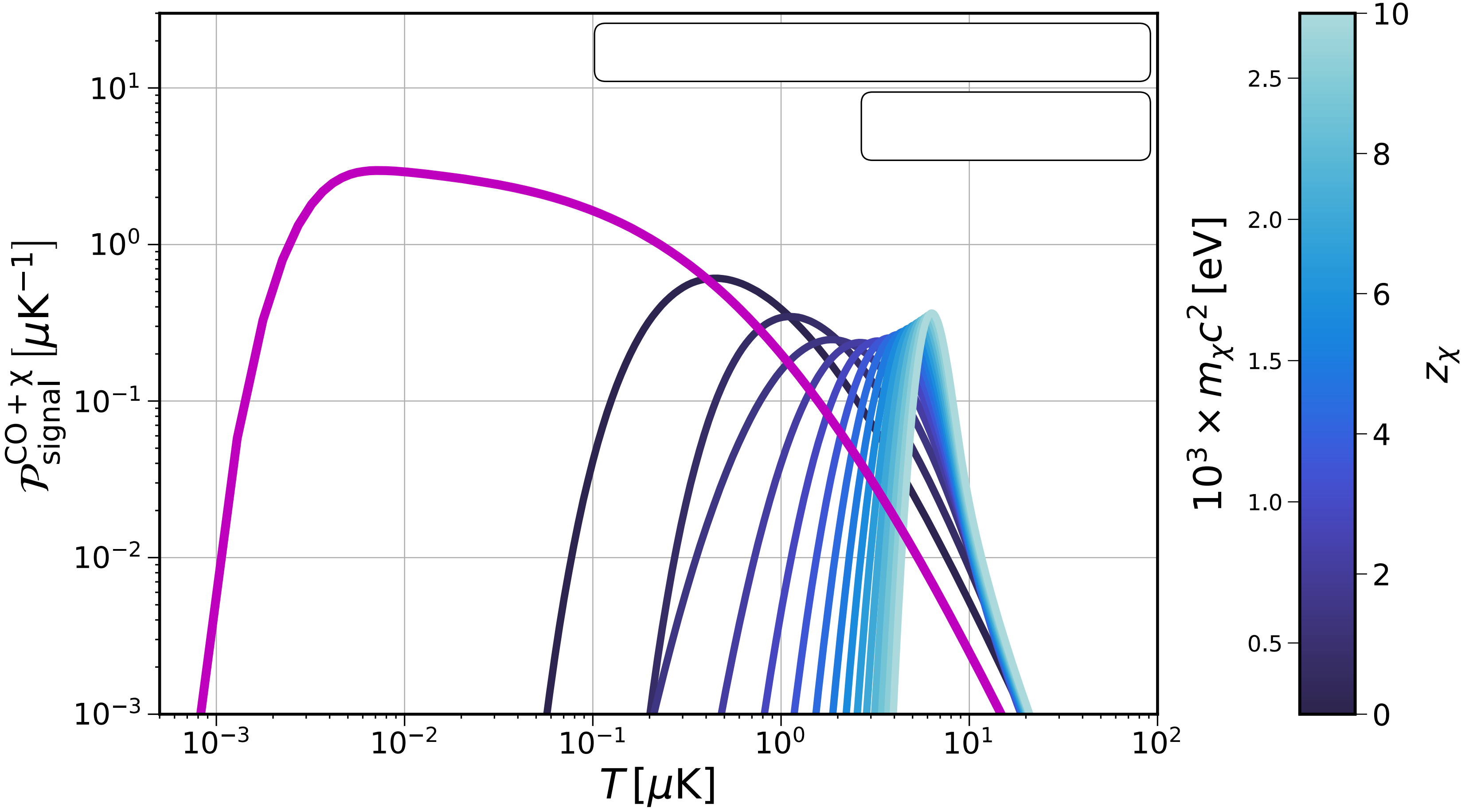
$$x_\perp = D_M(z)\theta$$

$$x_\parallel = \frac{c\delta z}{H(z)}$$

Voxel intensity distribution (VID)

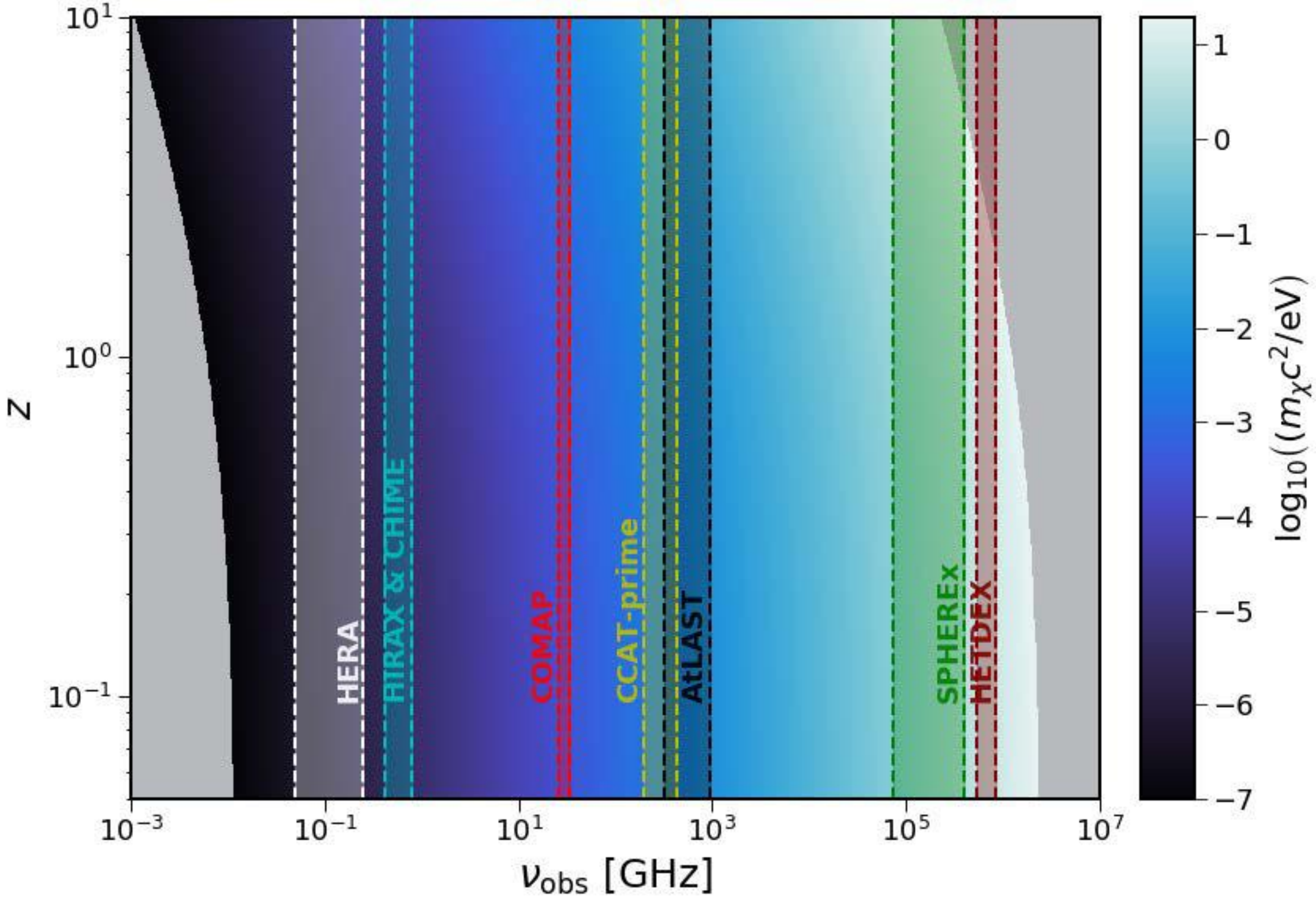
- PDF of luminosity density in each pixel

Effect in VID



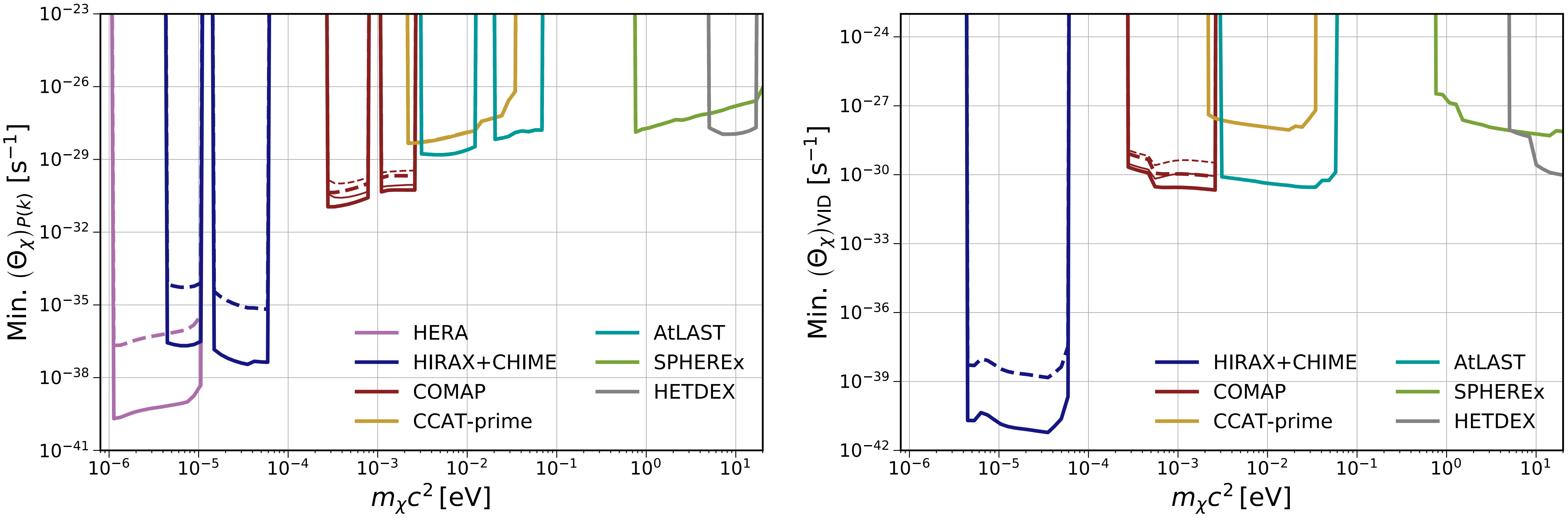
Exotic radiative decays

- Decaying dark matter: $\chi \to \gamma + \gamma$ $\quad\quad \nu_\gamma = m_\chi c^2 / 2h_P$

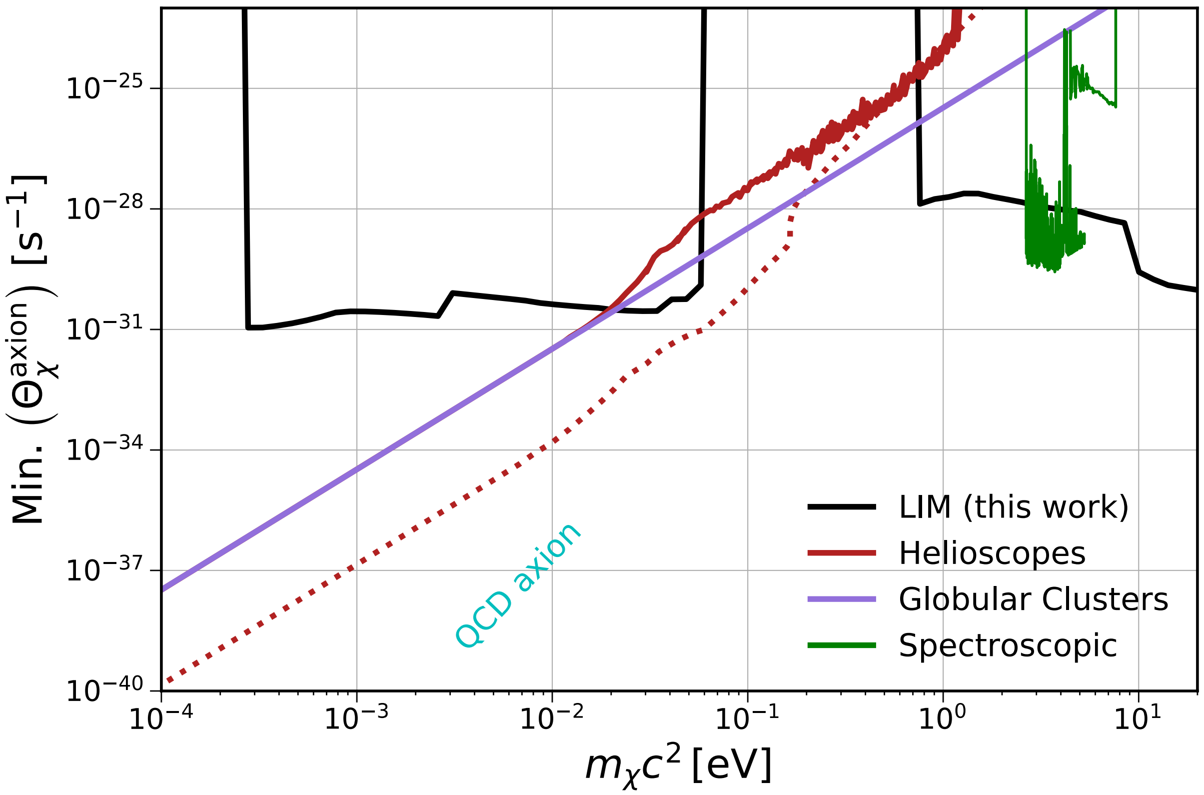


Sensitivity to DM decays

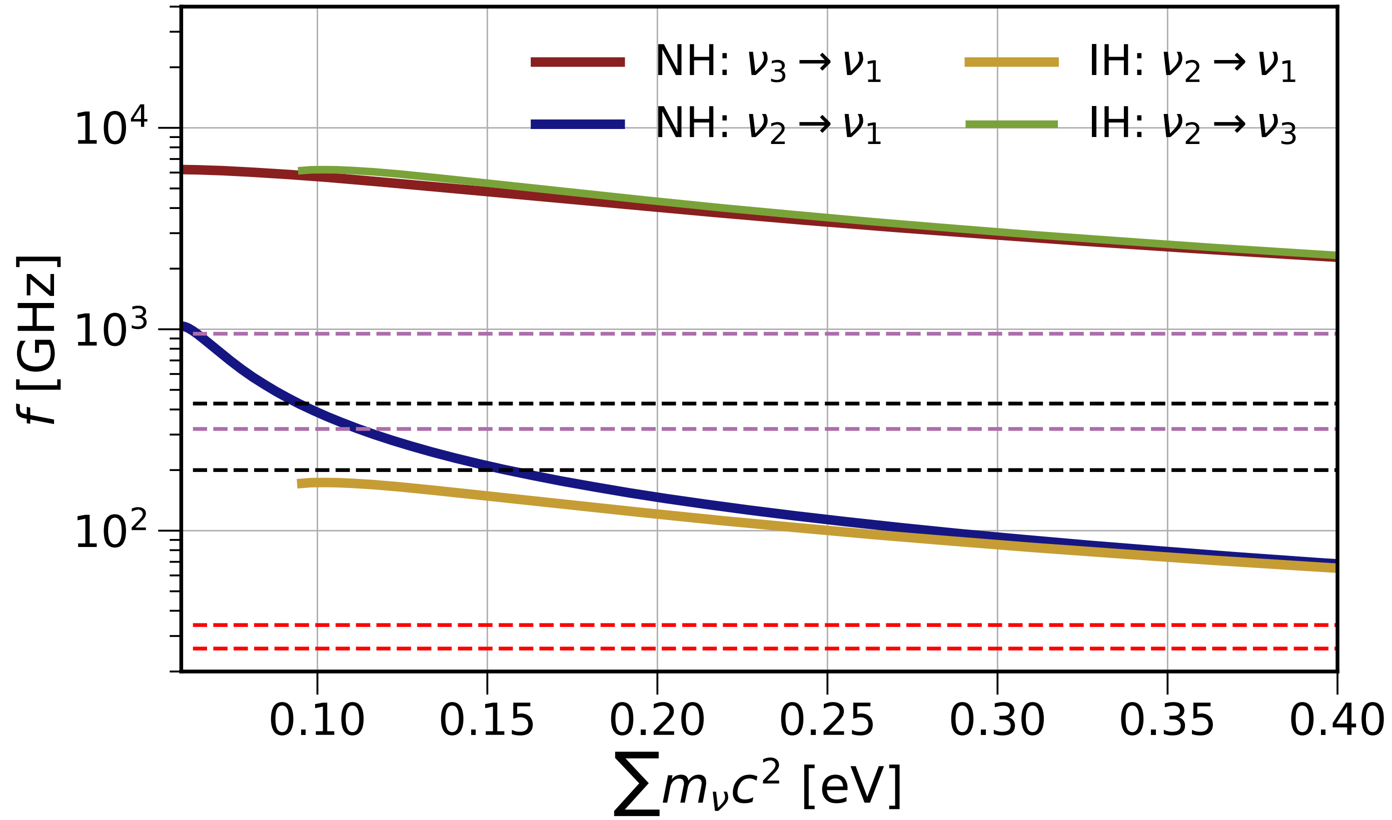
- After marginalizing over astrophysical uncertainties of the target emission line



Sensitivity to axions



Exotic radiative decays

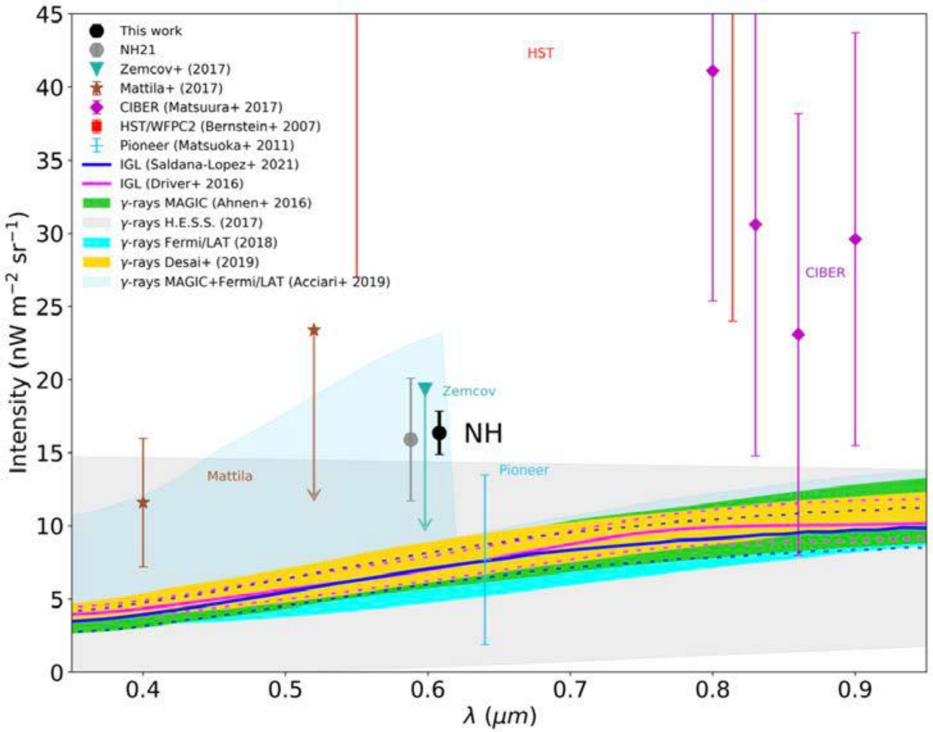


- Neutrino decay: $\nu_i \rightarrow \nu_j + \gamma$

$$f_{ij} = (m_i^2 - m_j^2)c^2/2h_P m_i$$

- Traces directly the cosmic neutrino density field

Recent development.....



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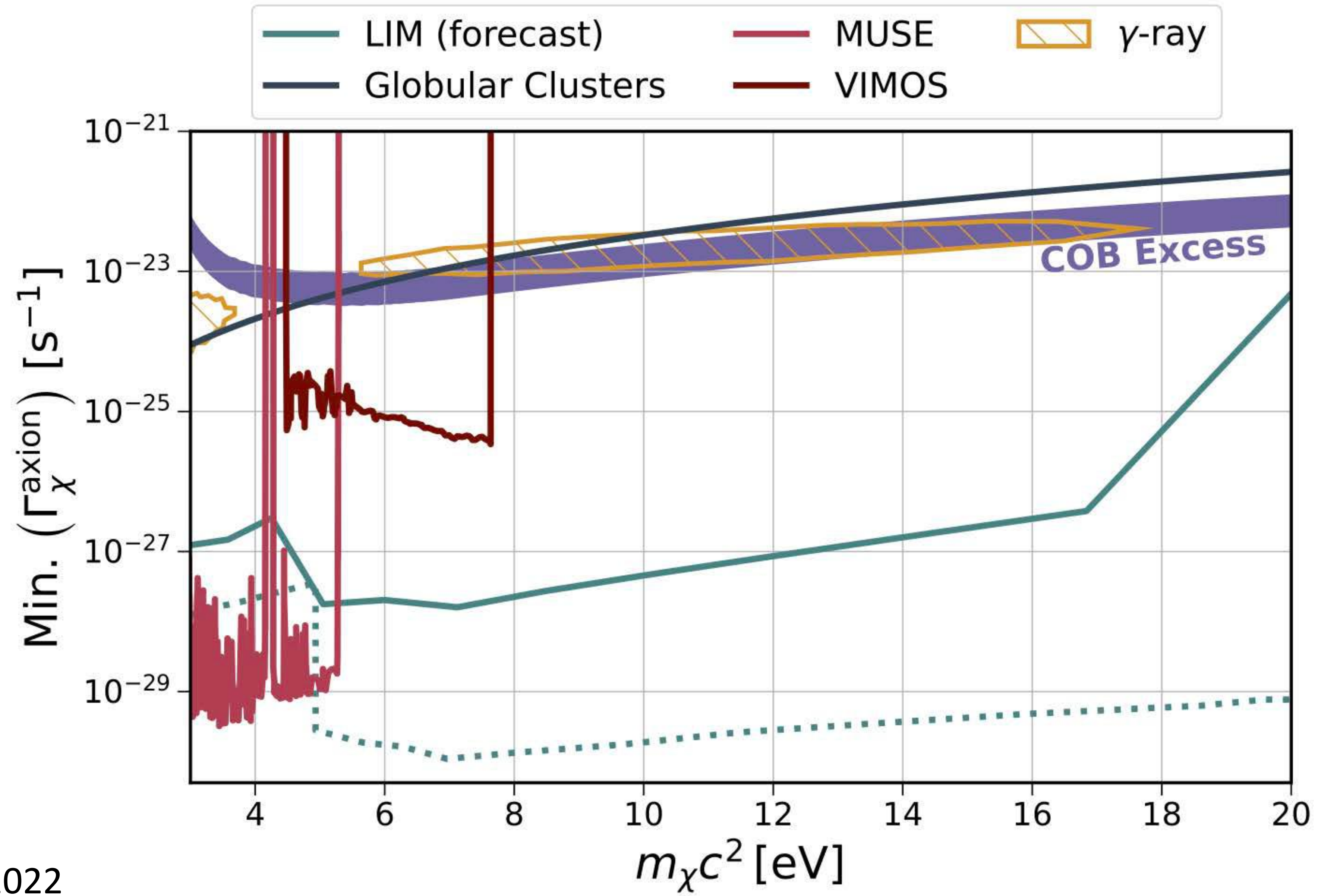
Anomalous Flux in the Cosmic Optical Background Detected With New Horizons Observations

TOD R. LAUER,[1] MARC POSTMAN,[2] JOHN R. SPENCER,[3] HAROLD A. WEAVER,[4] S. ALAN STERN,[5] G. RANDALL GLADSTONE,[6,7] RICHARD P. BINZEL,[8] DANIEL T. BRITT,[9] MARC W. BUIE,[3] BONNIE J. BURATTI,[10] ANDREW F. CHENG,[4] W.M. GRUNDY,[11] MIHALY HORÁNYI,[12] J.J. KAVELAARS,[13] IVAN R. LINSCOTT,[14] CAREY M. LISSE,[4] WILLIAM B. MCKINNON,[15] RALPH L. MCNUTT,[4] JEFFREY M. MOORE,[16] JORGE I. NÚÑEZ,[4] CATHERINE B. OLKIN,[3] JOEL W. PARKER,[3] SIMON B. PORTER,[3] DENNIS C. REUTER,[17] STUART J. ROBBINS,[3] PAUL M. SCHENK,[18] MARK R. SHOWALTER,[19] KELSI N. SINGER,[3] ANNE. J. VERBISCER,[20] AND LESLIE A. YOUNG[3]



Bernal, Sato-Polito, MK, 2022