

Looking for multi-electronvolt ALP dark matter on the sky

José Luis Bernal
Johns Hopkins University
with

Andrea Caputo, Gabriela Sato-Polito, Marc Kamionkowski, and Jordan Mirocha
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 - Phenomenological model: nature of DM and DE? Primordial Universe?

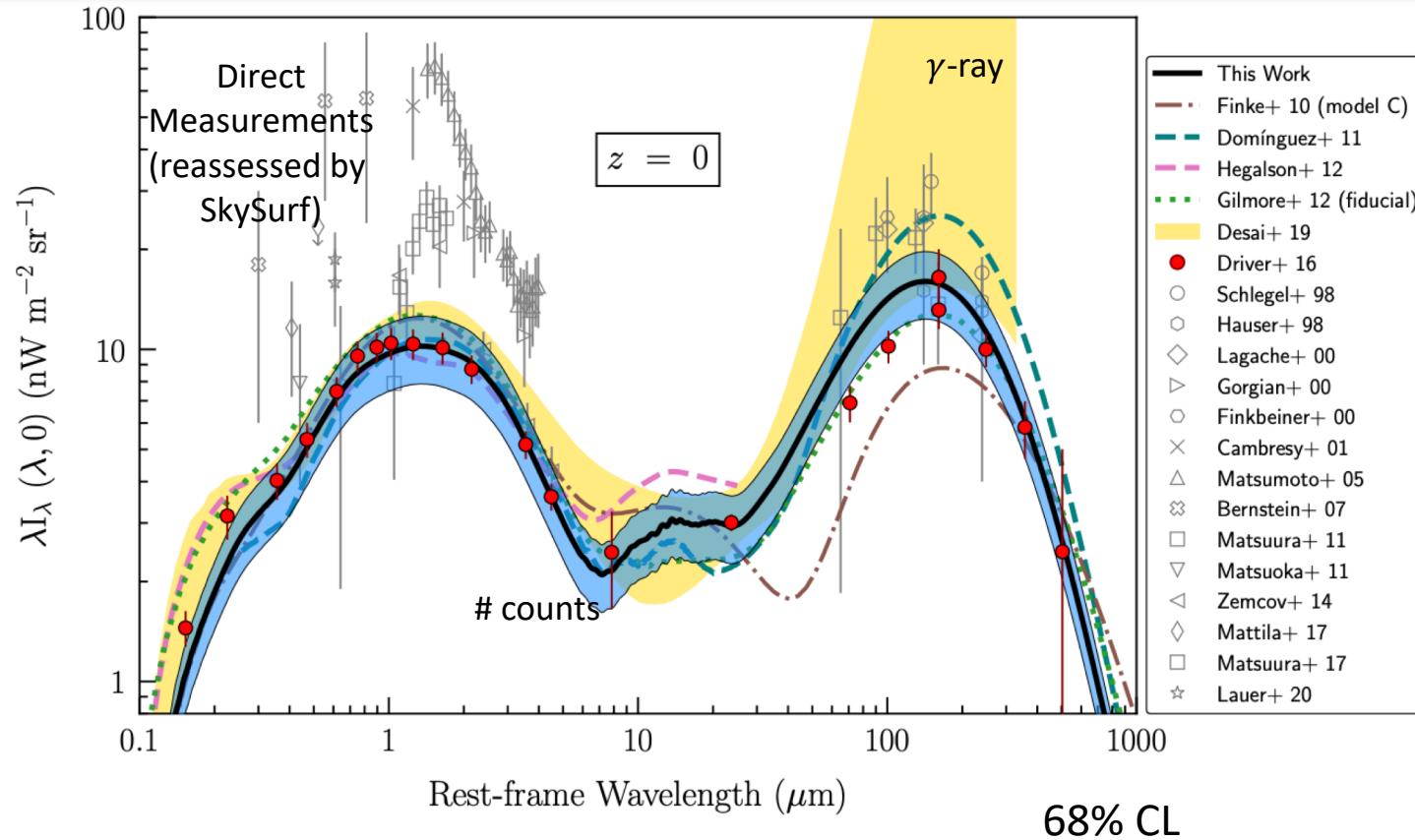
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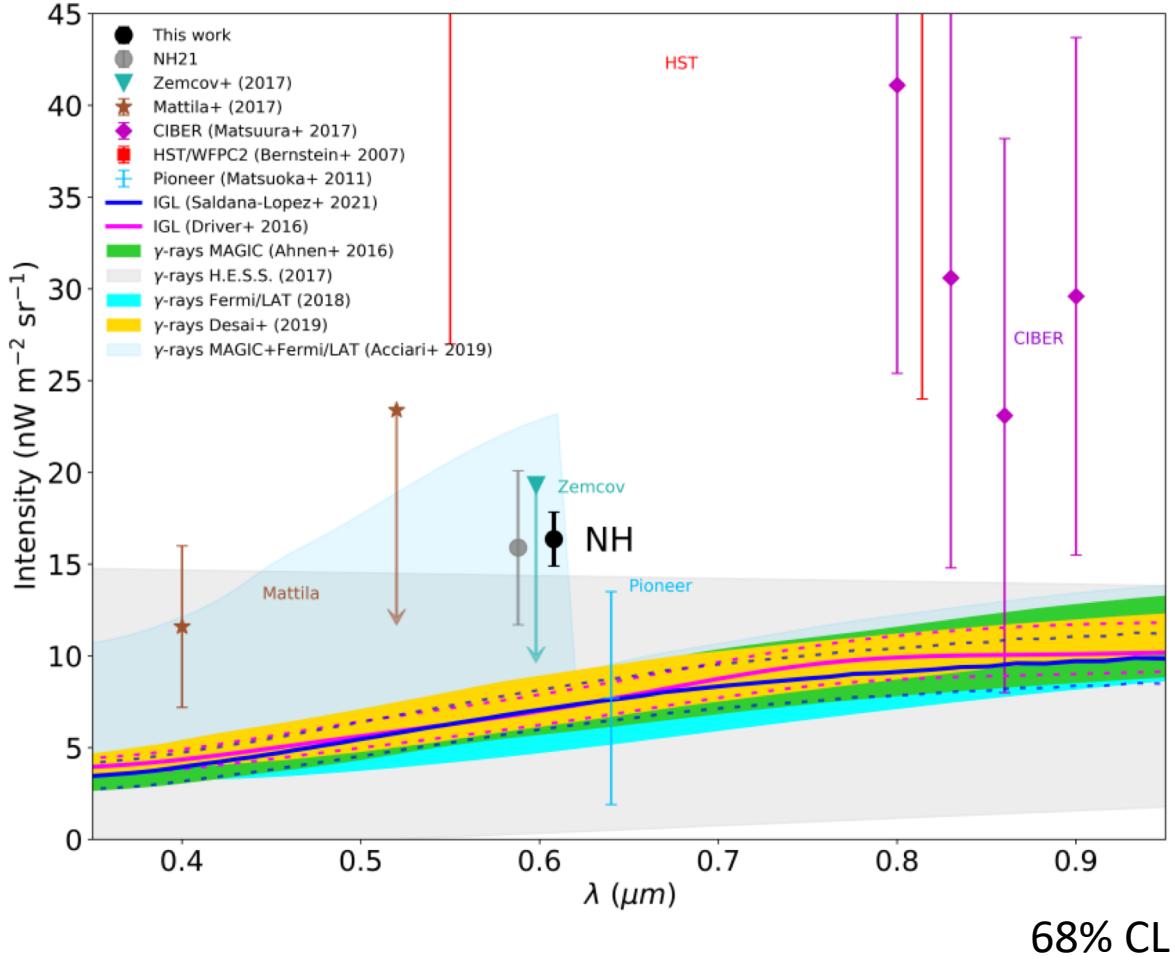
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Extragalactic Background Light



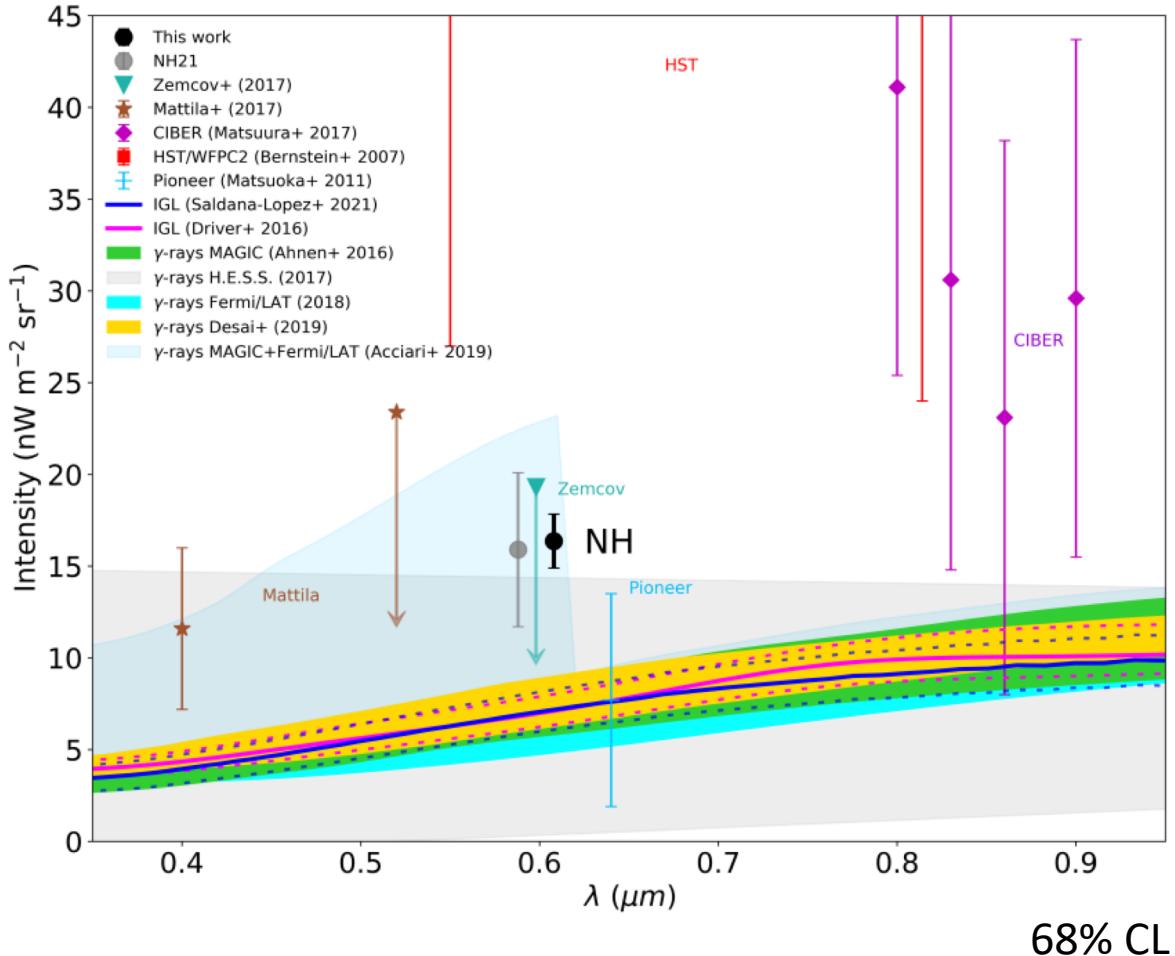
- Aggregate of *all* emitted radiation
- Census of all emitters
- Hard to measure directly – Zodiacal light
- Other approaches (blazars, inference from galaxy counts, theoretical estimates, ...)

COB excess



- 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
- Explanations?
 - Lots of faint galaxies Conselice+(2016)
 - IHL Cooray+(2012), Zemcov+(2014), Matsumoto+(2019)
 - Direct collapse black holes Yue+(2013)

COB excess

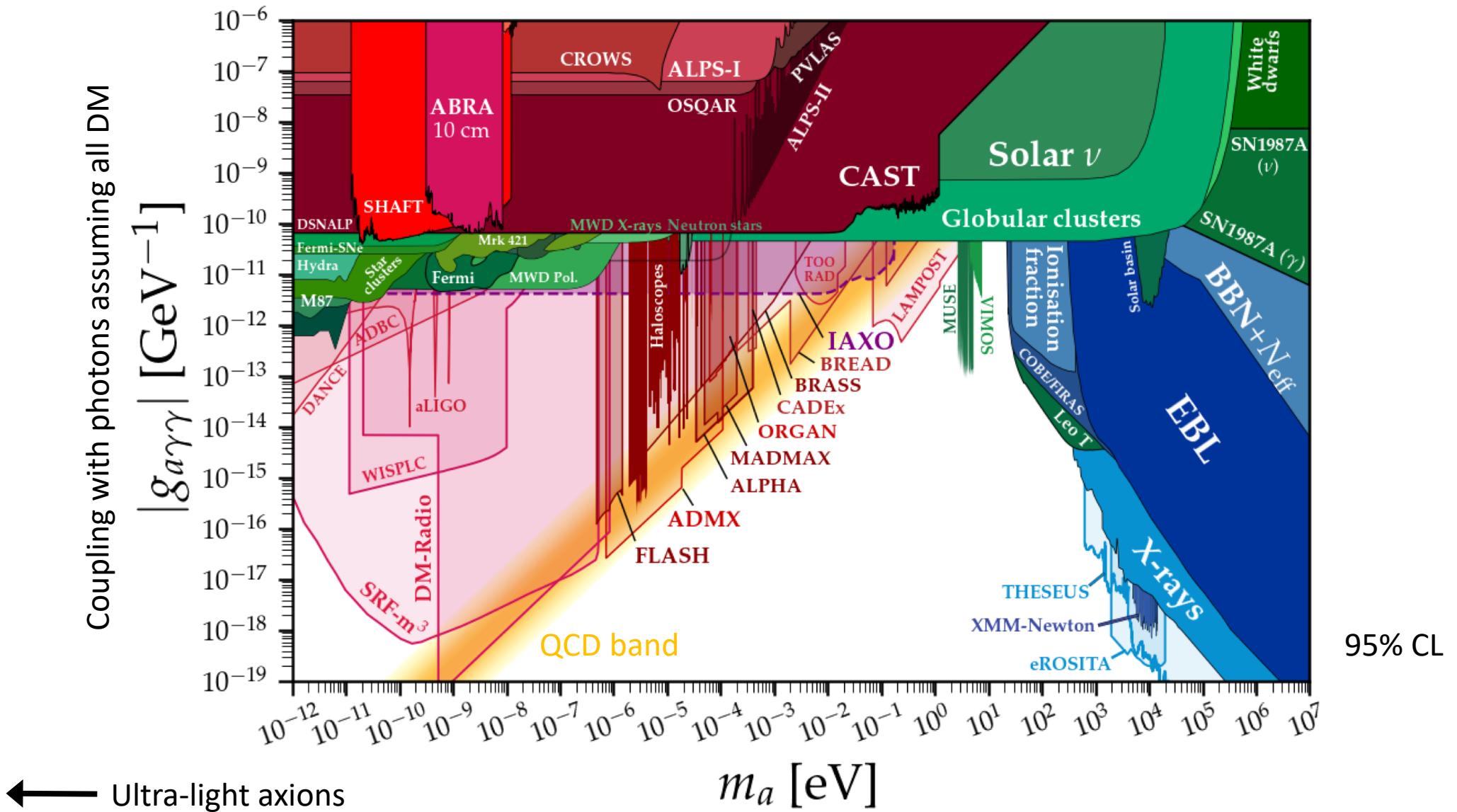


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 - ALP decays? Bernal+(2022a)

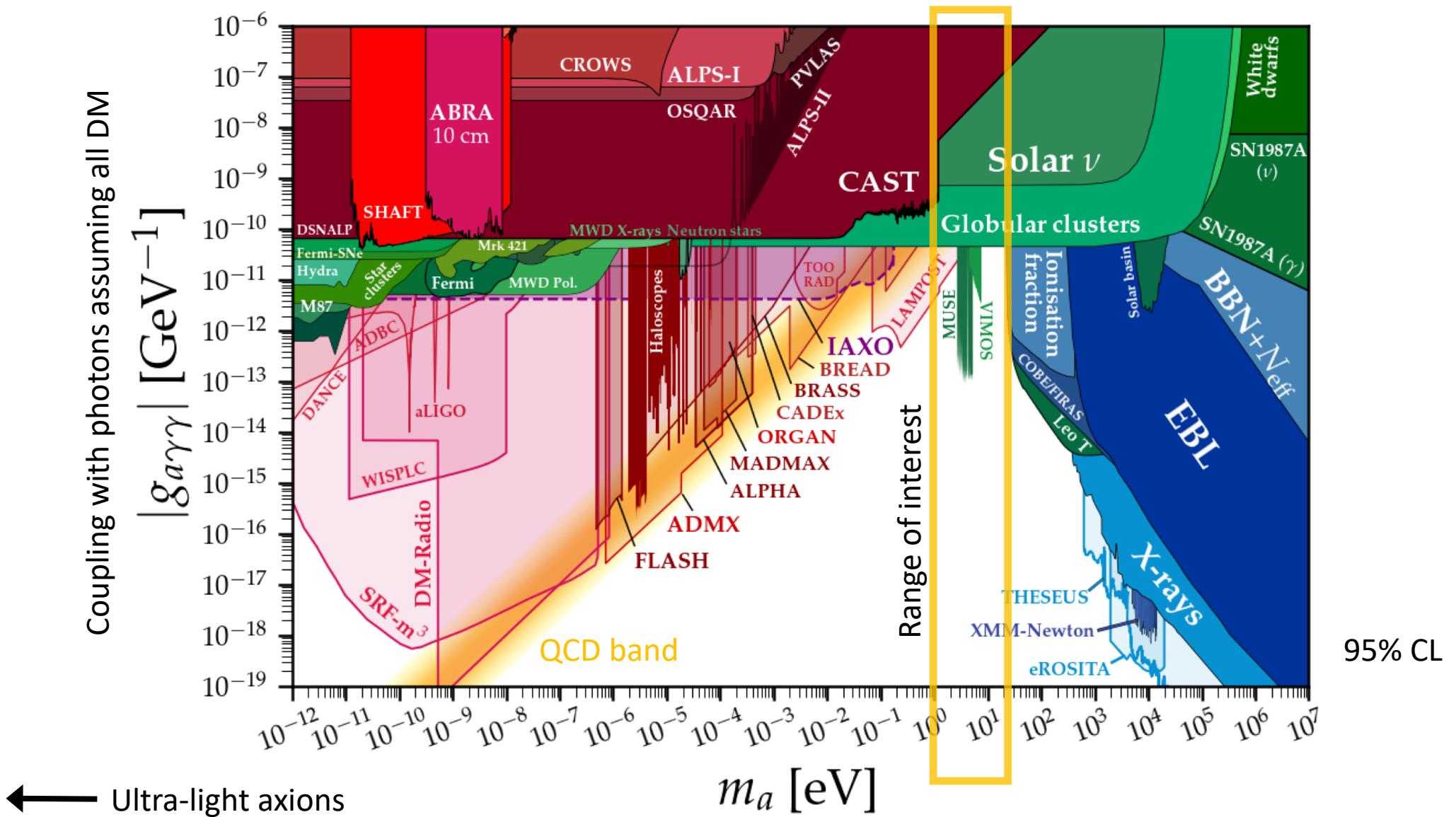
Axion and ALPs

- Axion: Pseudo-Nambu-Goldstone boson initially proposed to solve strong CP-problem.
- Coupling with photons: photon-axion oscillation, radiative decays ($\Gamma_a \propto m_a^3 g_{a\gamma}^2$)
 $a \rightarrow \gamma + \gamma$; emission line
- Wave DM / Fuzzy DM: effective self-interactions, suppression of clustering at small scales
- Beyond the coupling required to solve the QCD axion: ALPs

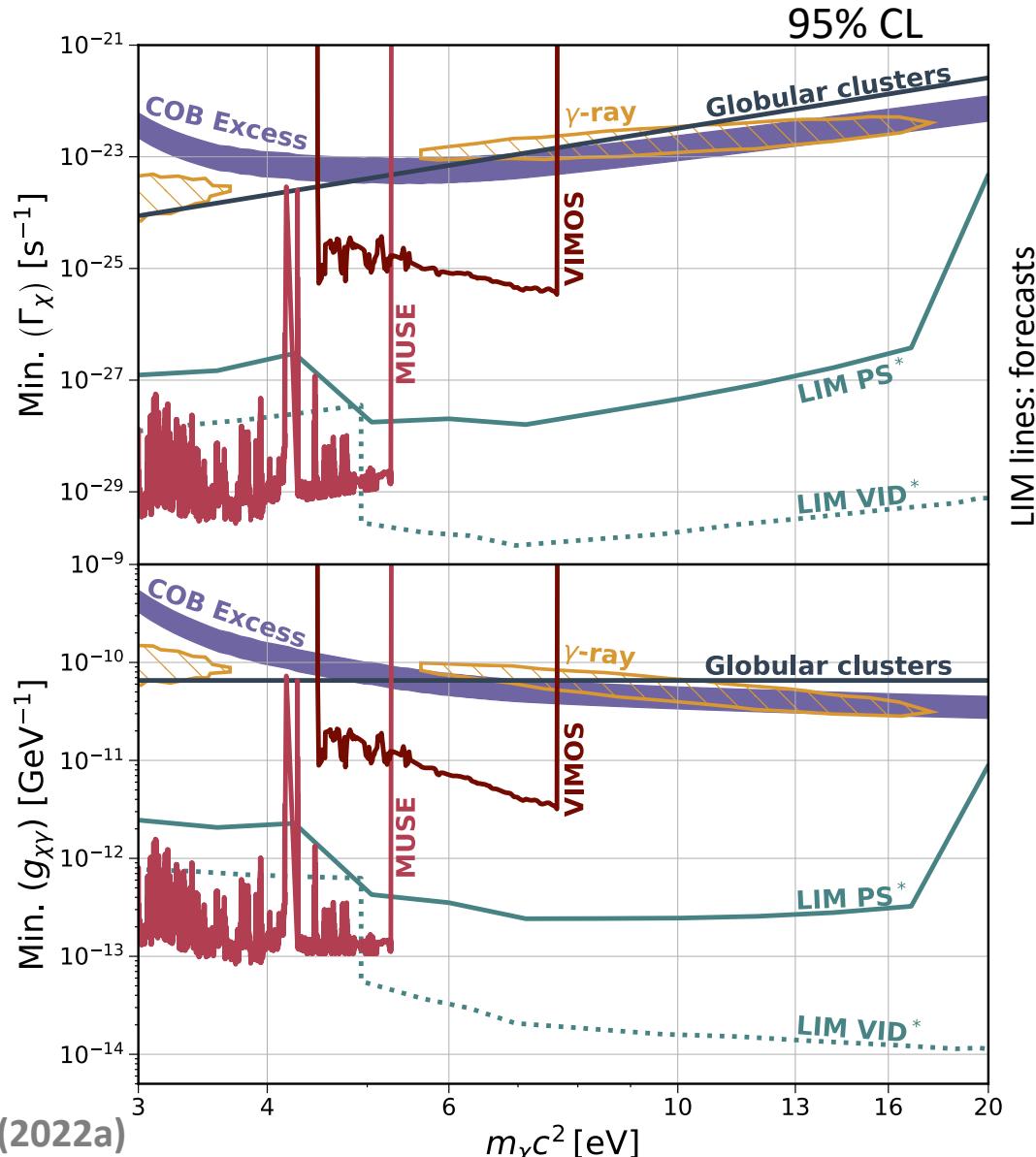
Axion and ALPs



Axion and ALPs



ALPs contributing to COB excess



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

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

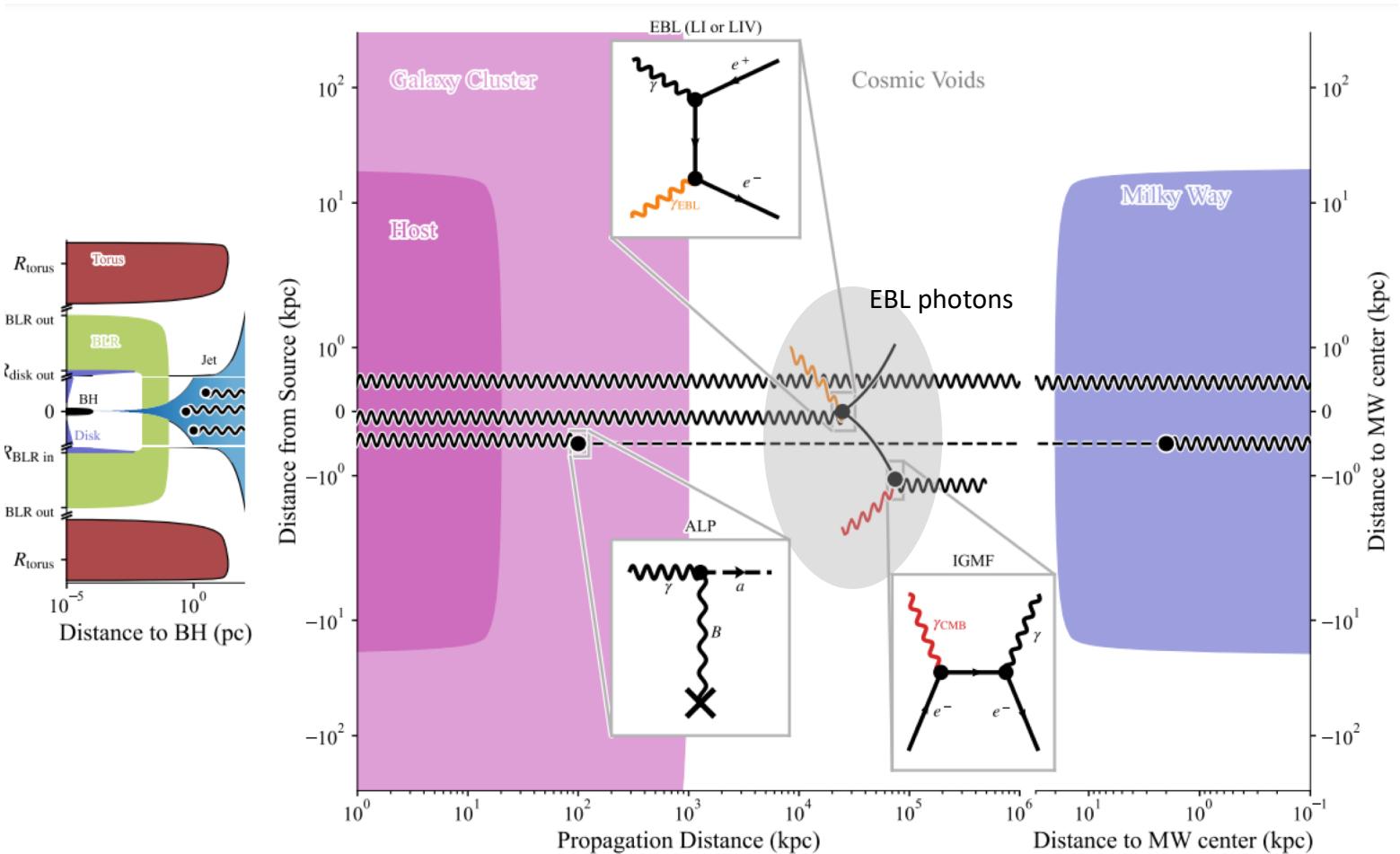
- Parameter region allowed by current observations
- Overlaps with hint from γ -ray extinction
Korochkin+(2019)
- Will be probed by LIM (strongest sensitivity in this range, SPHEREx + HETDEX) Bernal+(2021)

γ -ray attenuation

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

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

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



γ -ray attenuation

- Flux of high-energy γ -rays attenuated by IR-NUV EBL photons: $\gamma + \gamma \rightarrow e^- + e^+$
 - Energy threshold: $\epsilon_{\min} = \frac{2m_e^2 c^4}{E_\gamma(1+z)(1-\mu)}$
 - Integrated effect: measurements of $\tau(E_\gamma, z_s)$ as tomographic and chromatic EBL probe*
$$\tau(E_\gamma, z_s) = c \int_0^{z_s} \frac{dz}{H(z)(1+z)} \int_{\epsilon_{\min}}^{\infty} \frac{dn}{d\epsilon} \int_{-1}^1 d\mu \sigma_{\gamma\gamma}(E_\gamma, \epsilon, z, \mu)$$

*Assuming no secondary γ -ray production, Essey+(2010)
 - ~800 blazars (Fermi-LAT+Cherenkov telescopes)
 - Science cases:
 - EBL probe Finke & Razzaque(2009), Abdollahi+(2018), Acciari+(2019), Desai+(2019)
 - Expansion rate of the Universe Dominguez+(2019)
 - Axion-photon oscillations Hooper & Serpico (2007), Mirizzi+(2007), Hochmuth & Sigl (2007), de Angelis+(2007); Abramowski+(2013) Ajello+(2016), Li+(2021), Jacobsen+(2022)
 - Pop III stars Gilmore (2012)
 - Axion decays Kalashev+(2018), Korochkin+(2020 a, b)
- Assuming EBL

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 τ_{res} as the residual after subtraction from standard sources

$$\tau_{\text{res}} = \tau_{\text{meas}} - \sum \tau_i ; \quad \sigma^2(\tau_{\text{res}}) = \sigma^2(\tau_{\text{meas}}) + \sum \sigma^2(\tau_i)$$

Budget the EBL

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

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

$$\text{EBL } \gamma \# \text{ density: } \left(\frac{dn}{d\epsilon} \right)_{\text{gal}, z < 6}^{\text{new}} = (1 + F_{\text{eEBL}}) \left(\frac{dn}{d\epsilon} \right)_{\text{gal}, z < 6}^{\text{old}}$$

B) Boost errors for EBL from galaxies at $z < 6$ until τ_{res} consistent with 0 and fit for (m_a, Γ_a)

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

Signif. over null

ALPs = 2.1σ

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

Best fit

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

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

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

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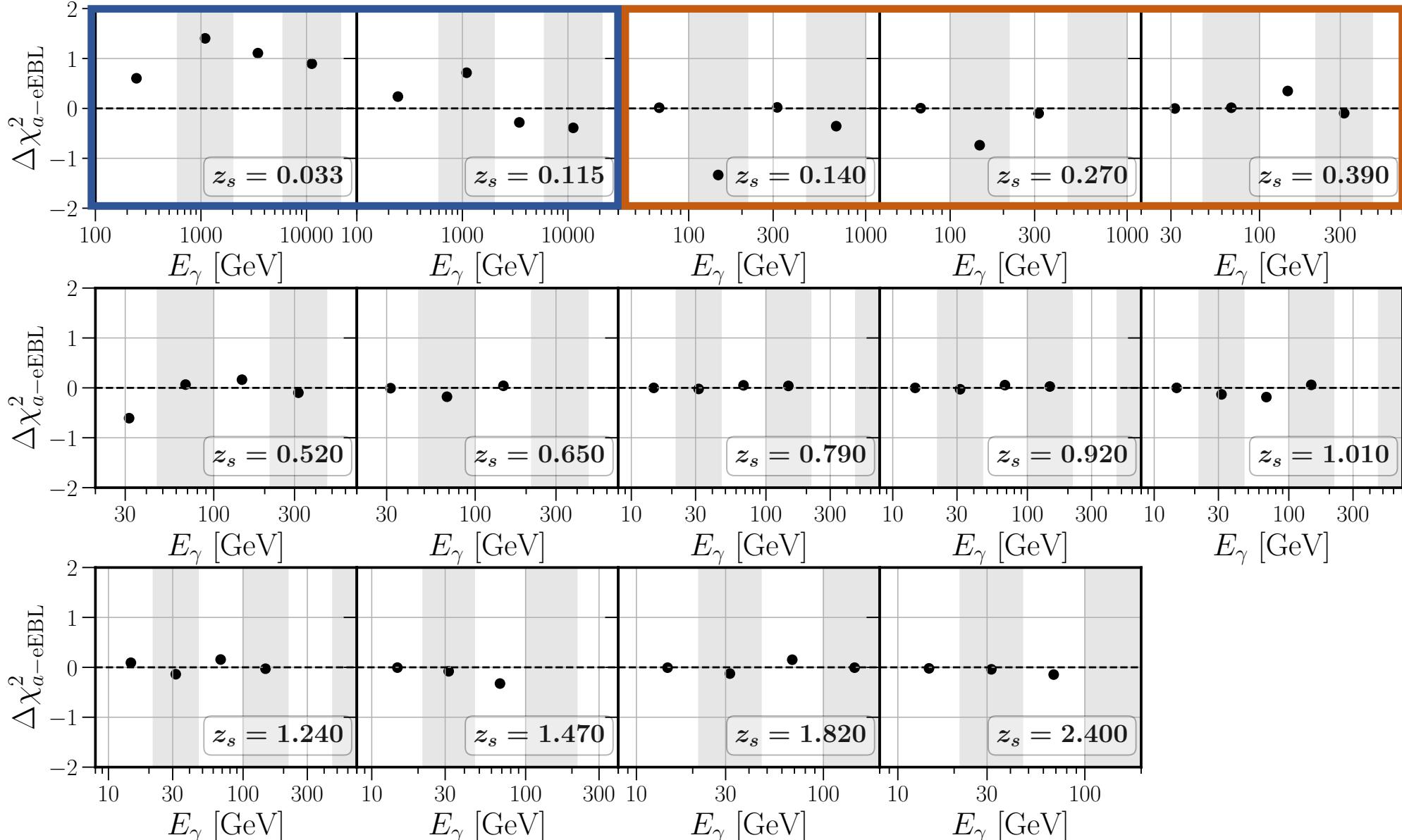
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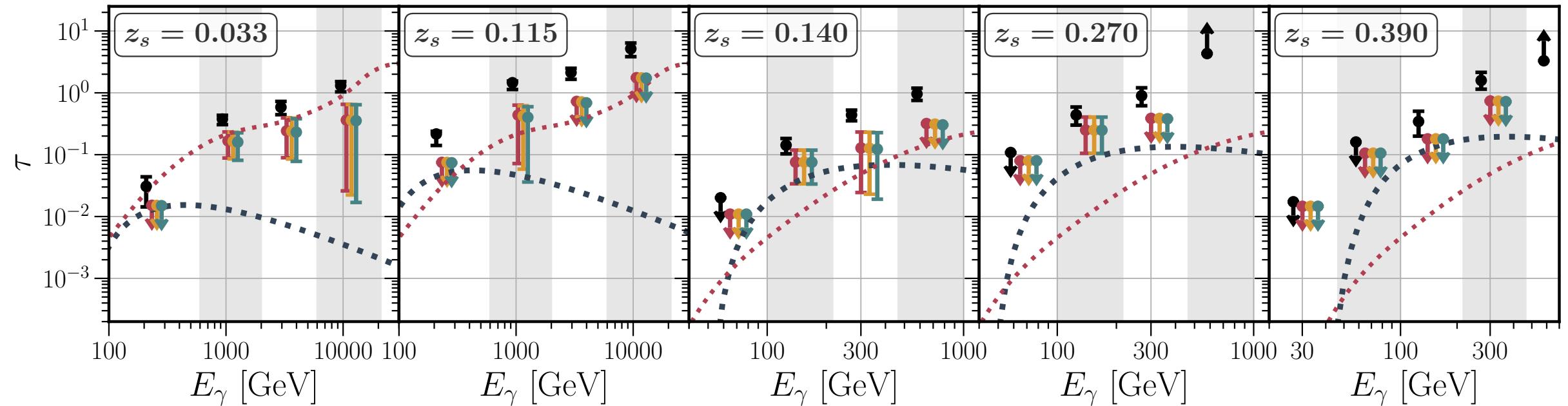
Favoring eEBL

Favoring ALPs



Caution: log-log plot

68% CL



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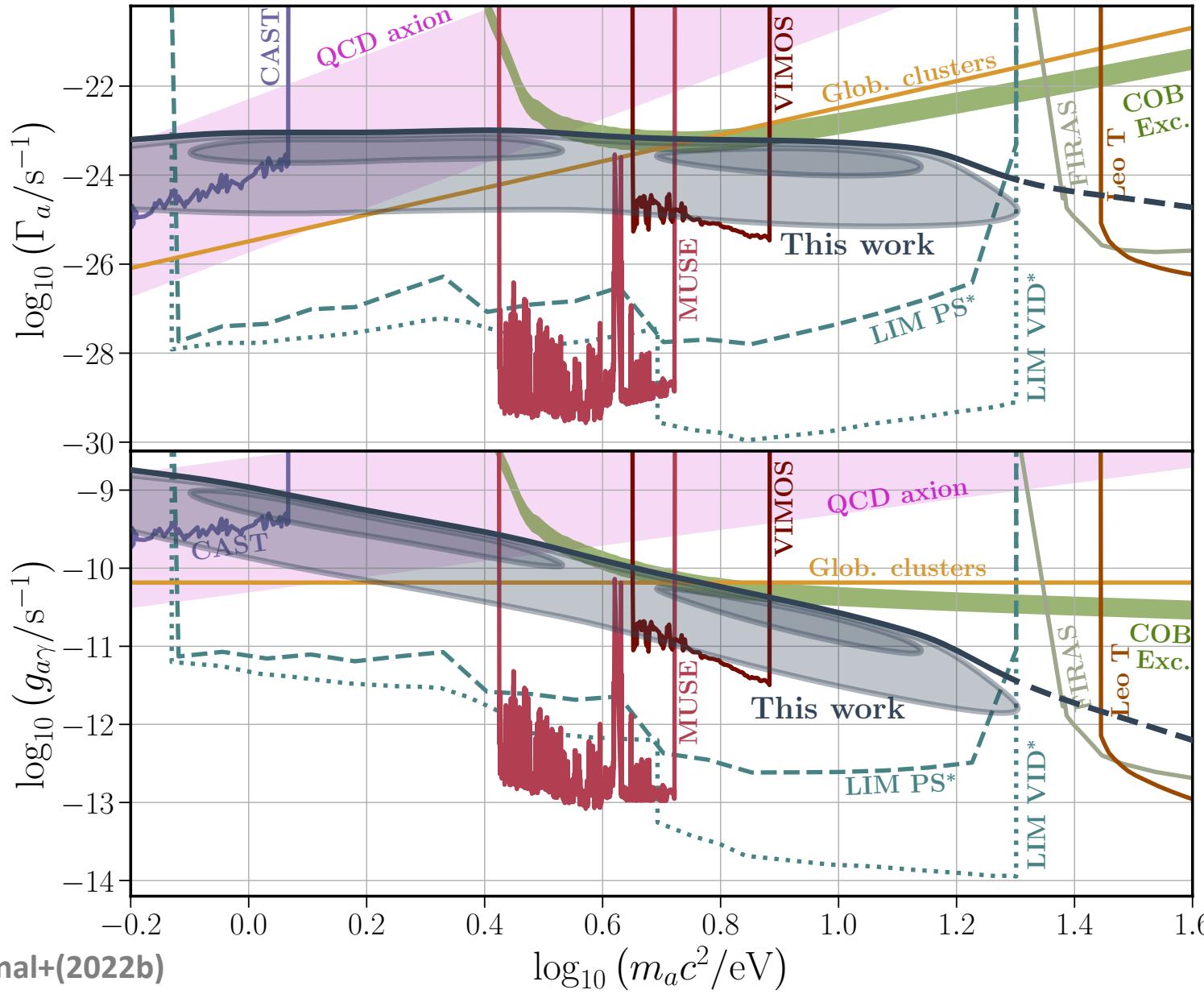
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- Measurement
- Gal. $z < 6$
- Gal. $z > 6$
- IHL
- DM bf.
- eEBL bf.

Understanding the axion hint



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

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

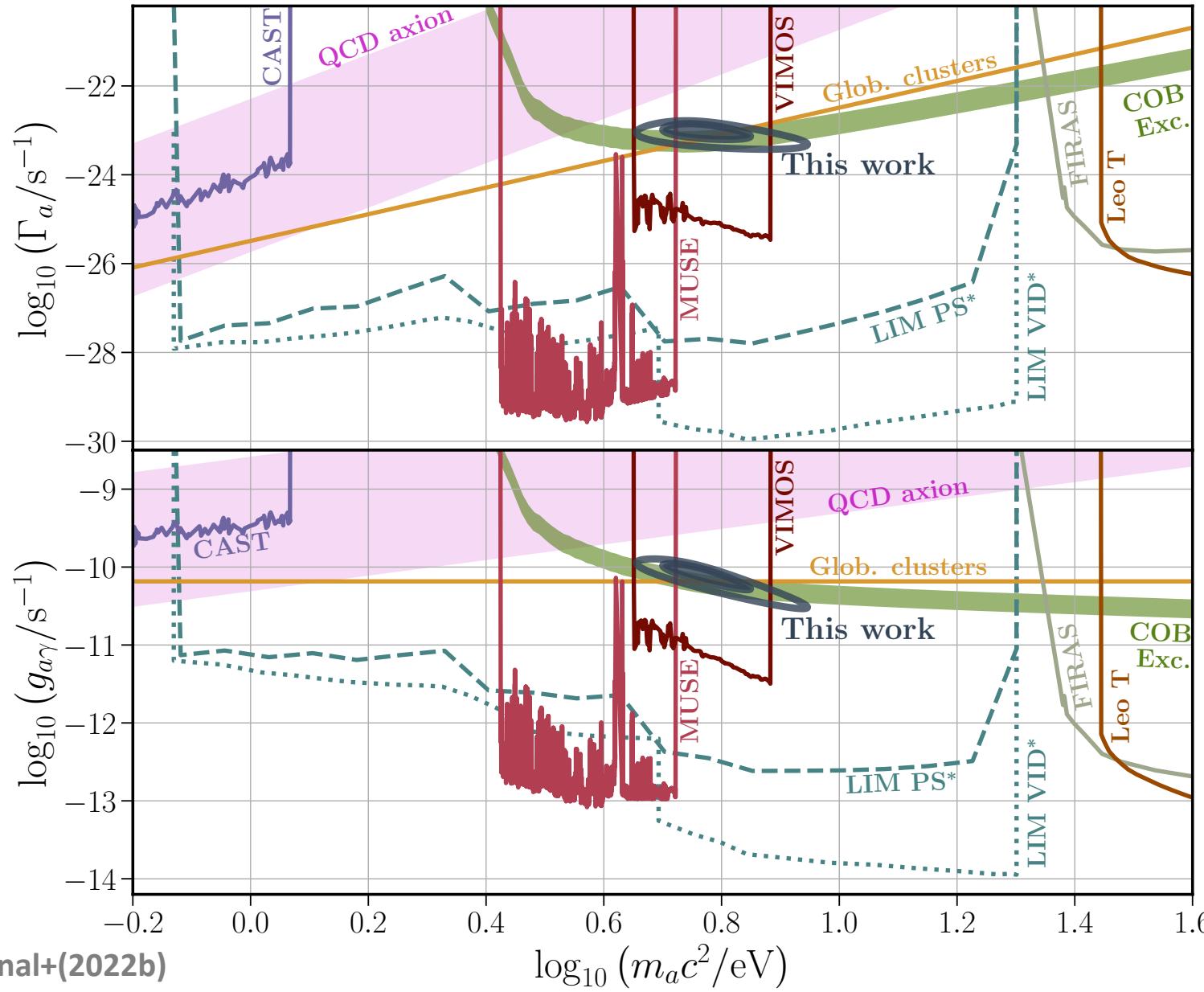
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95% CL

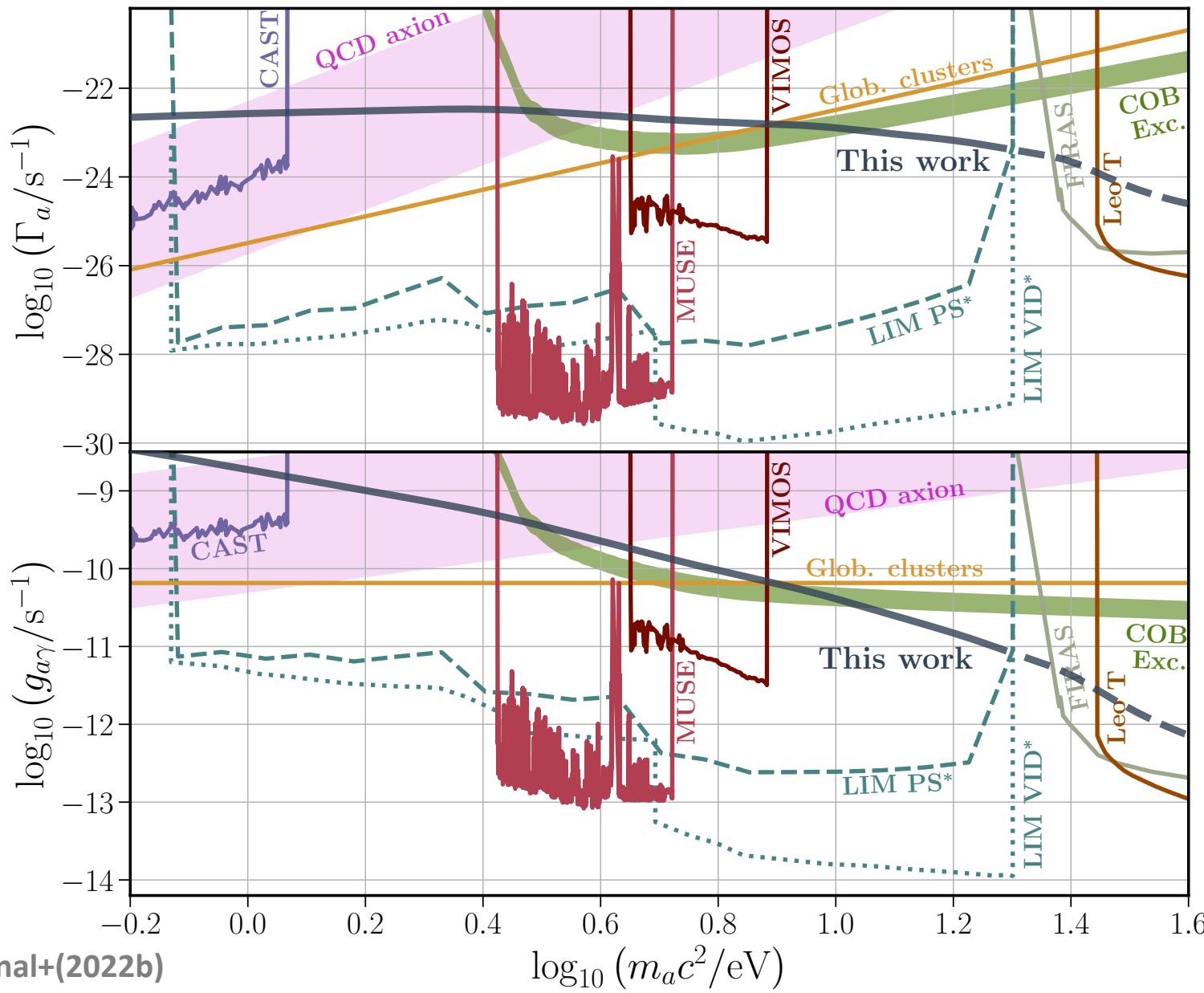
$$\Gamma_a \propto m_a^3 g_{a\gamma}^2$$

Understanding the axion hint



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

Null case B



- 3σ limits after boosting uncertainties until all τ_{res} are upper limits
- Still the strongest limits

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

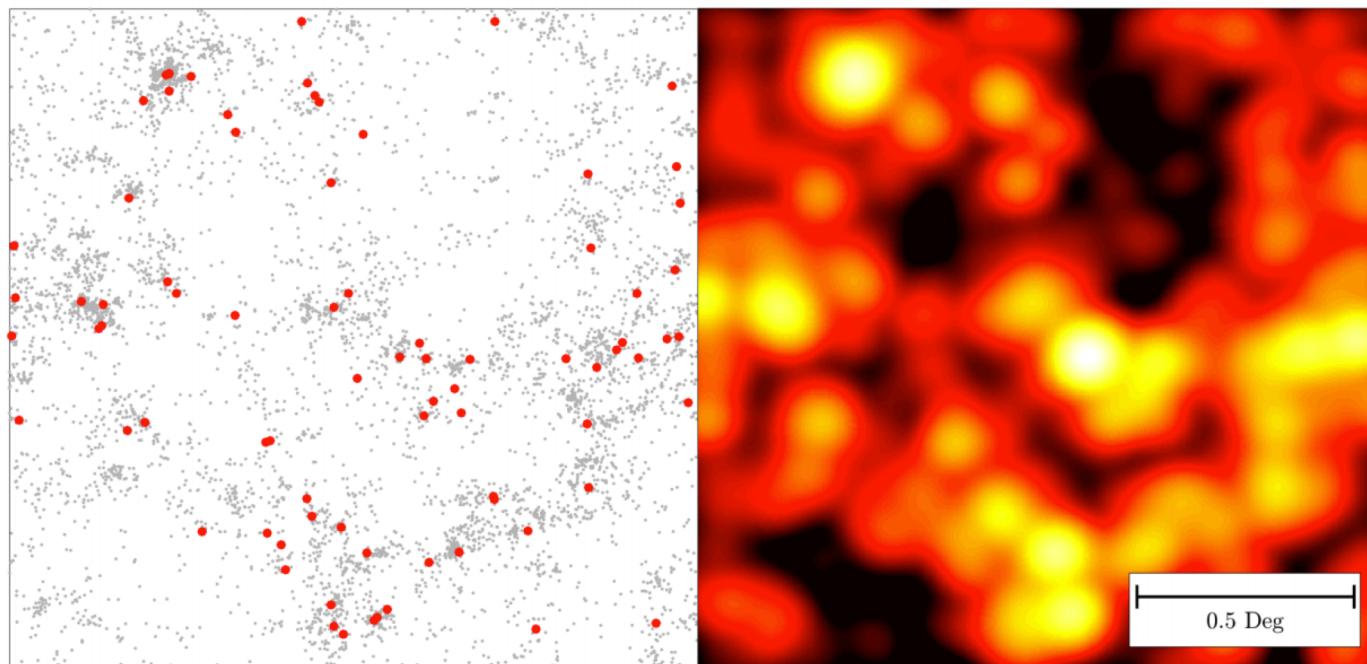
What is Line-Intensity Mapping?

- LIM: use the integrated signal without requiring a detection threshold
- Information from all incoming photons, from all galaxies and IGM along the LoS
- Target a identifiable spectral line → know redshift → 3D maps

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can detect ~ 1% of
CO-emitting galaxies

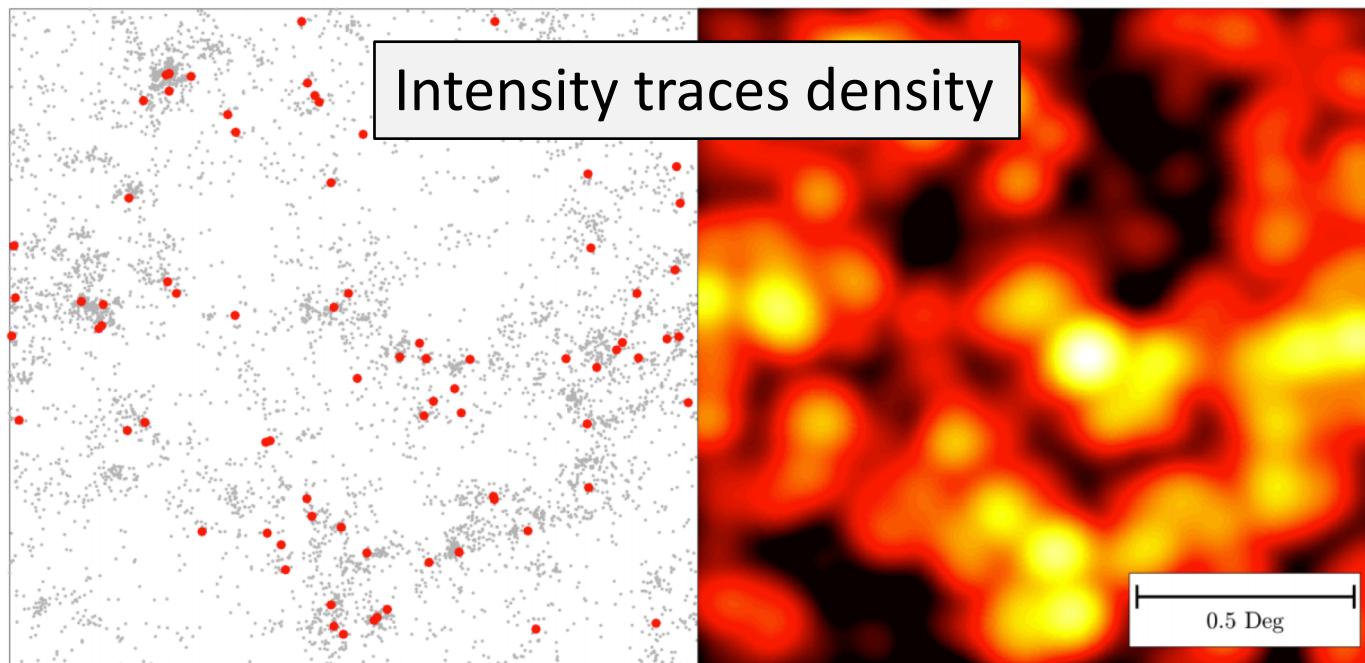


~ 1.5k hours of COMAP
mapping CO intensity
fluctuations

What is Line-Intensity Mapping?

- LIM: use the integrated signal without requiring a detection threshold
- Inform Galaxy surveys: detailed distribution of brightest galaxies LoS
- Target Intensity maps: noisy distribution of all galaxies and IGM

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Using LIM for cosmology

- Intensity traces density: cosmological information degenerate with astrophysics

$$\delta T \sim \langle T \rangle b \delta_m \Rightarrow P_{TT} \sim \langle T \rangle^2 b^2 P_m + \langle T^2 \rangle$$

- Limitations:
 - Intensity maps are highly non-Gaussian: lots of information beyond $P(k)$
 - $P(k)$ only depends on 1st and 2nd moments of the luminosity functions
 - $P(k)$ mostly relevant for cosmology, but degenerate with some astro

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P(k): best for cosmo, integrals of luminosity functions

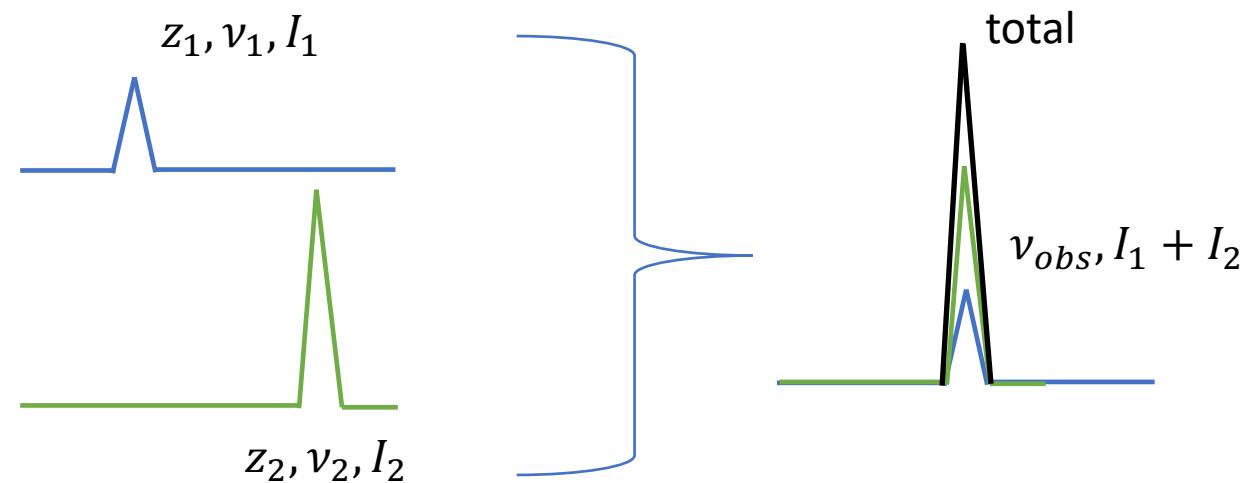
Working on their combination & covariance

VID: best for astro, integrals of clustering

Sato-Polito & JLB (2022)

Contamination of intensity maps

- Continuous foregrounds: problem for HI surveys, less severe at higher frequencies
- **Line interlopers:** Main problem for higher freq. LIM surveys
 - $\nu_{obs} = \nu/(1+z) = \nu'/(1+z') \rightarrow$ other lines redshifted to same ν_{obs}



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- **Line interlopers:** Main problem for higher freq. LIM surveys
 - $\nu_{obs} = \nu/(1+z) = \nu'/(1+z') \rightarrow$ other lines redshifted to same ν_{obs}
 - Two approaches:
 - Masking: targeted (external data) and blind (contaminated voxels are expected to be brighter)
 - Model the effect of known interlopers in the likelihood and analyses

Breysse, Kovetz, Kamionkowski (2015)

Sun, Moncelsi, Viero, Silva (2018)

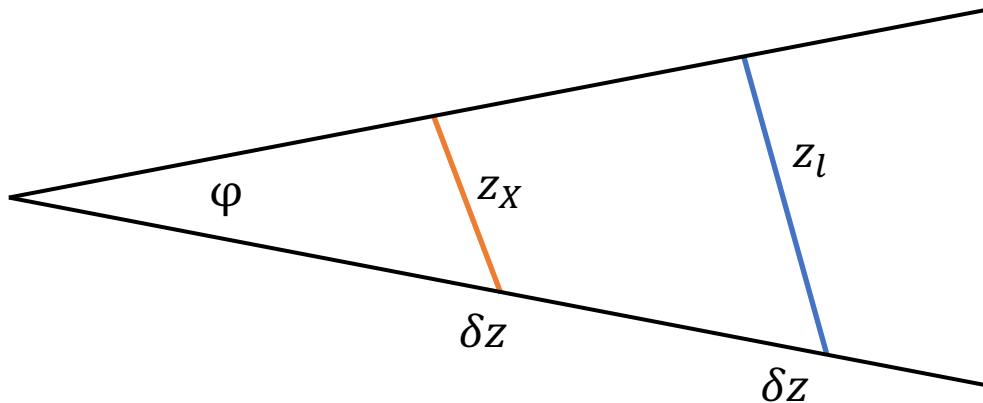
Lidz & Taylor (2016) Sun, Moncelsi, Viero, Silva (2018)

Gong, Chen, Cooray (2020) Cheng, Chang, Bock (2020)

Exotic radiative decays would be inadvertently detected as a line interloper!!

Effect in power spectrum

- Confusion in redshift → projection effects → **extra anisotropy**



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

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

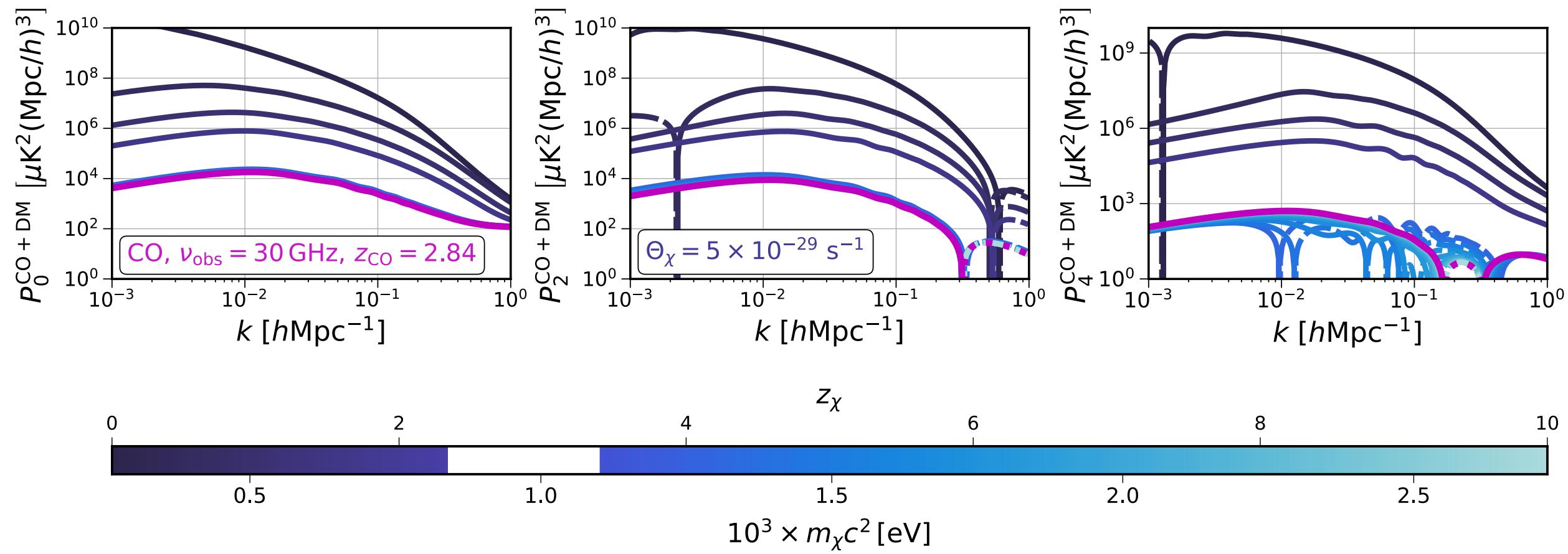
- Model it similar to AP effect: $k_i^{true} \equiv k_i^{infer}/q_i$

$$q_{\parallel} = \frac{(1+z_X)/H(z_X)}{(1+z_l)/H(z_l)}$$

$$q_{\perp} = \frac{D_M(z_X)}{D_M(z_l)}$$

Effect in power spectrum

- $P_{tot} = P_l + P_X$; $k_i^{true} \equiv k_i^{infer} / q_i$

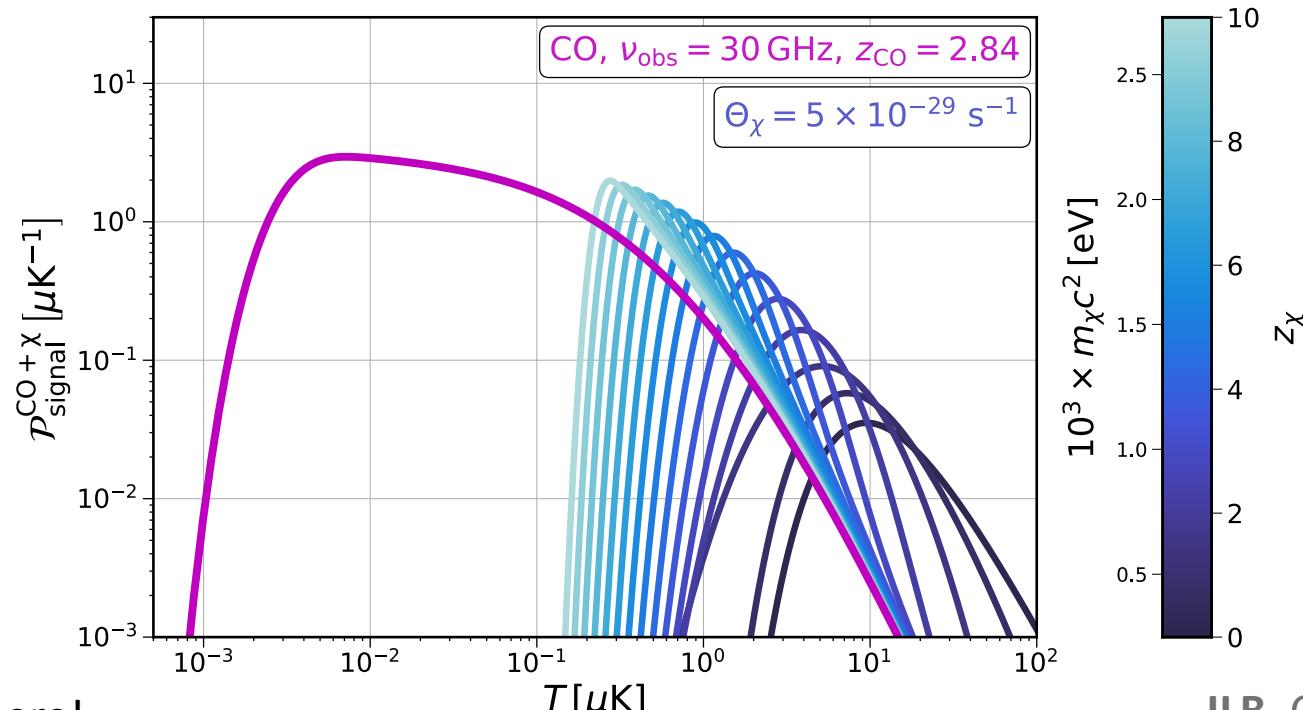


Effect in VID

- Each voxel receives contributions from both emissions:

$$T_{tot} = T_l + T_{noise} \quad \mathcal{P}_{tot+X}(T) = ((\mathcal{P}_l * \mathcal{P}_X) * \mathcal{P}_{noise})(T); \quad \mathcal{P}_X = \mathcal{P}_{\tilde{\rho}}/\langle T_X \rangle$$

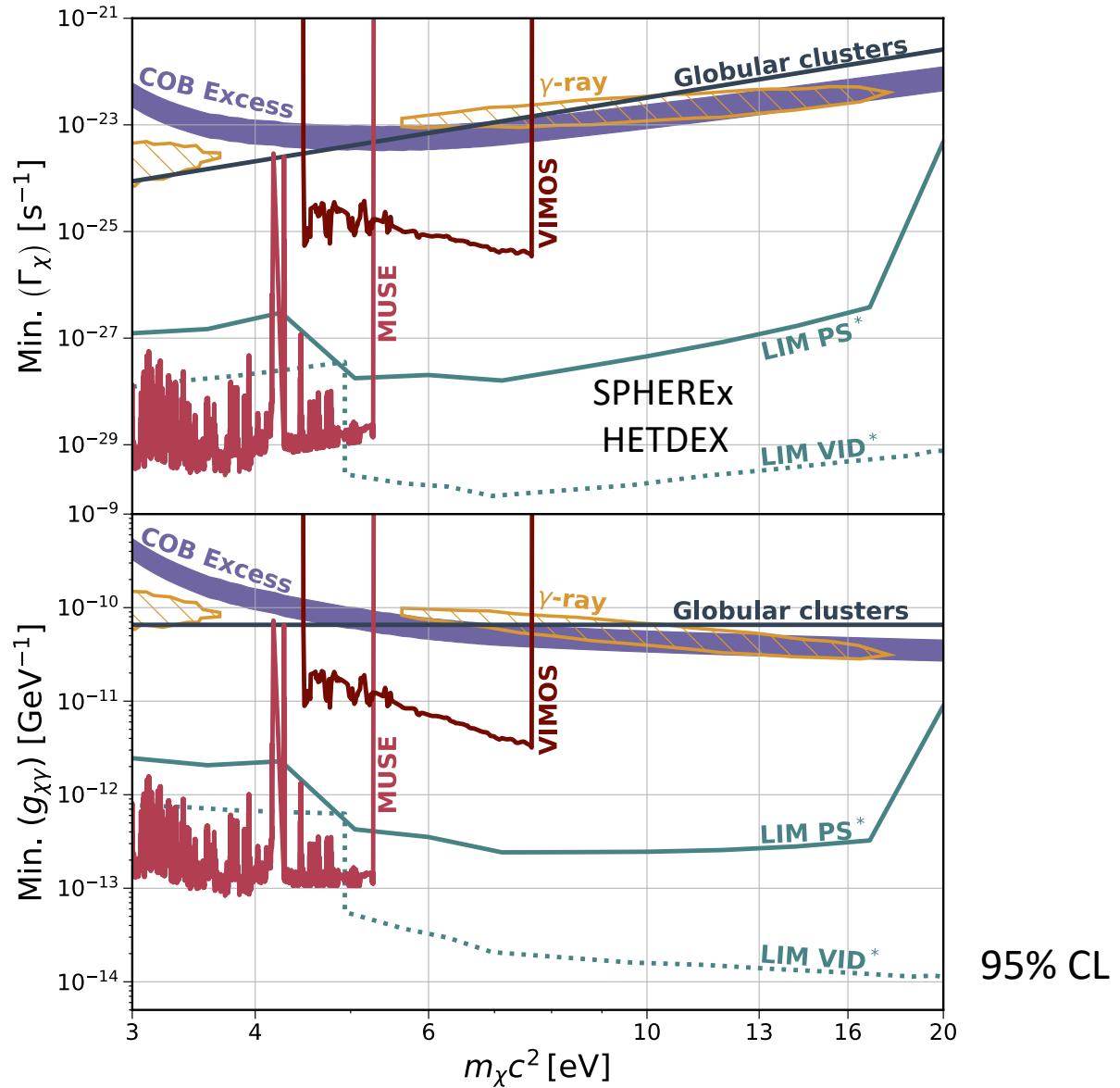
- $\mathcal{P}_{\tilde{\rho}}$: PDF of normalized densities. Obtained from simulations



No noise contribution included here!

JLB, Caputo, Kamionkowski (2021)

Sensitivity in axion context



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

Back up slides

Explanations for the excess?

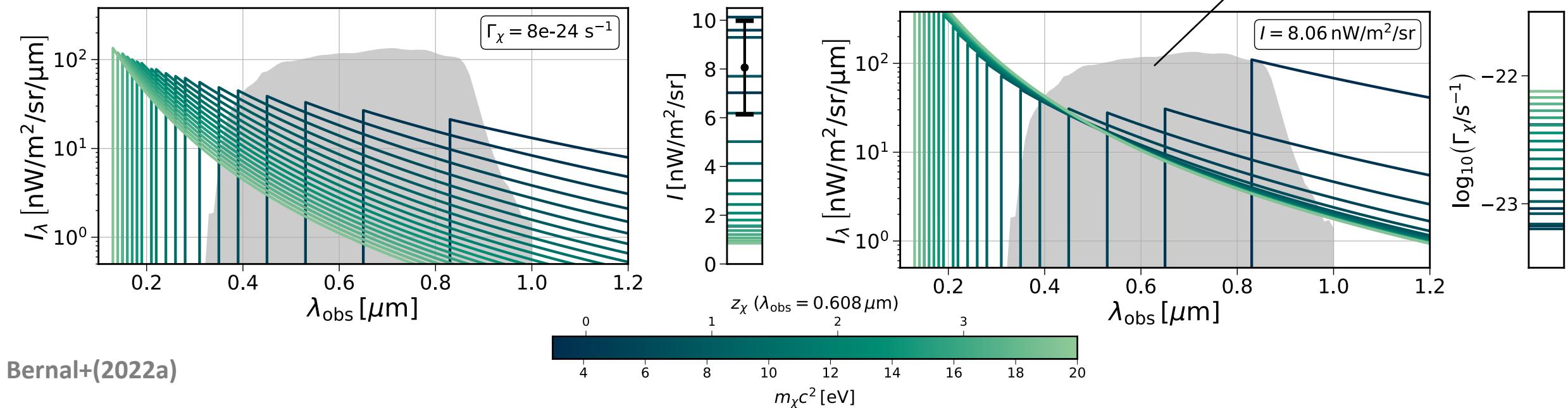
- Misestimation of the abundance of faint galaxies (extrapolated to estimate IGL) Conselice+(2016)
- Intra halo light Cooray+(2012), Zemcov+(2014), Matsumoto+(2019)
- Radiation from very bright early emitters, like direct-collapse black holes Yue+(2013)
- ALP decays

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

$z_* \equiv z$ of axion decay

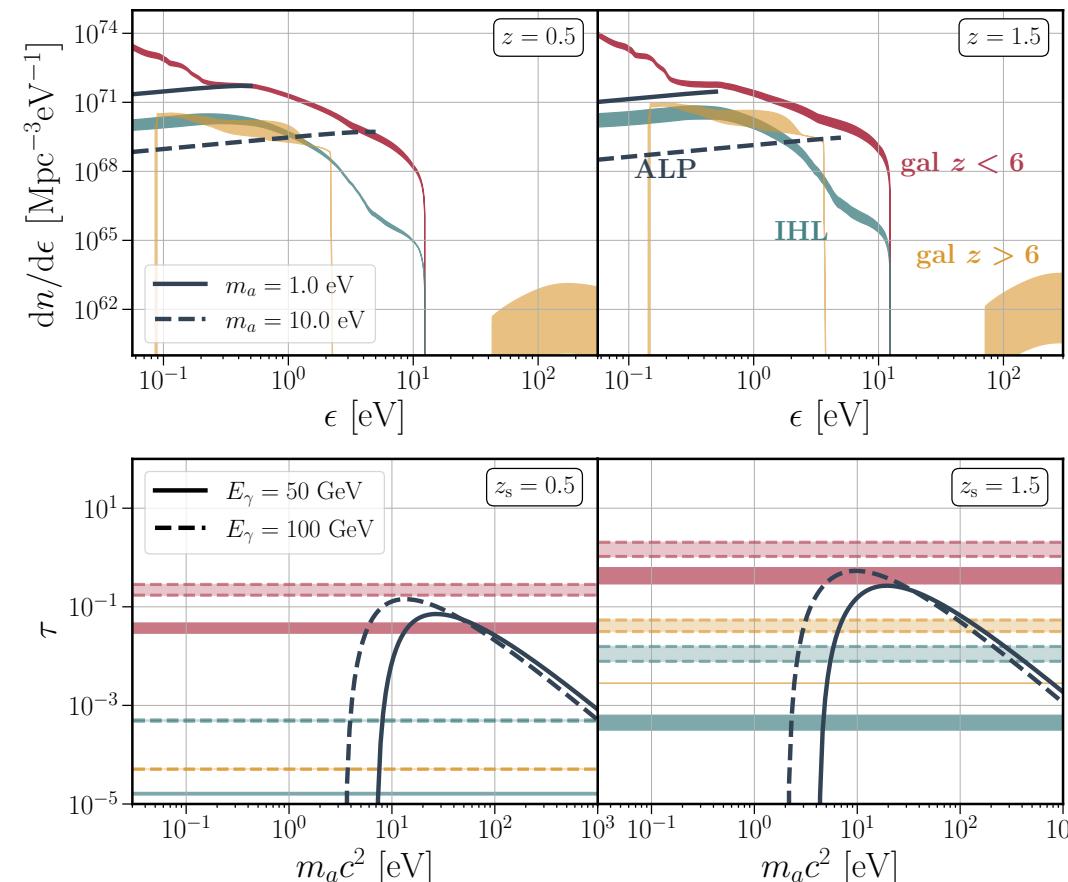
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LORRI responsivity



Budget the EBL

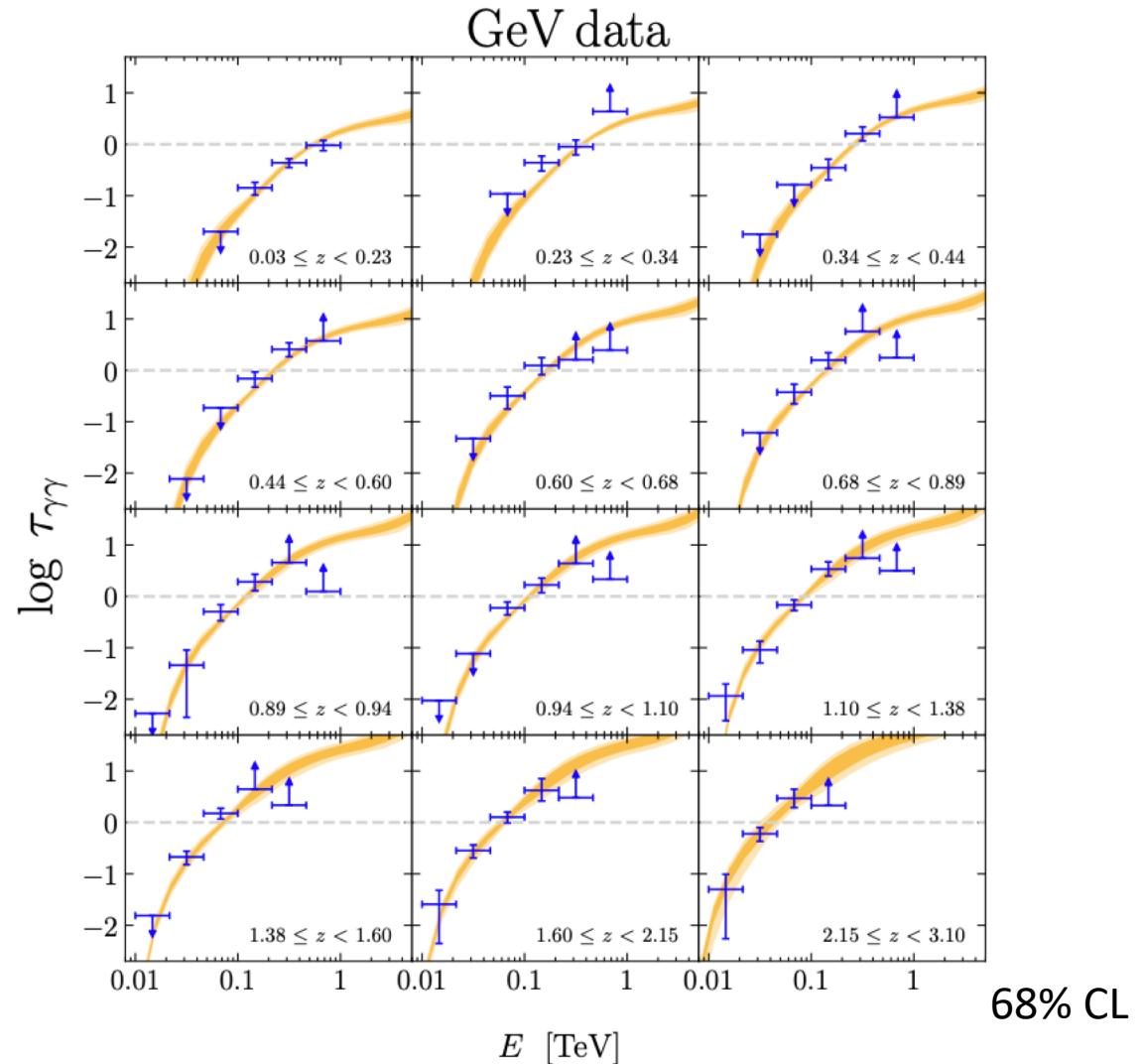
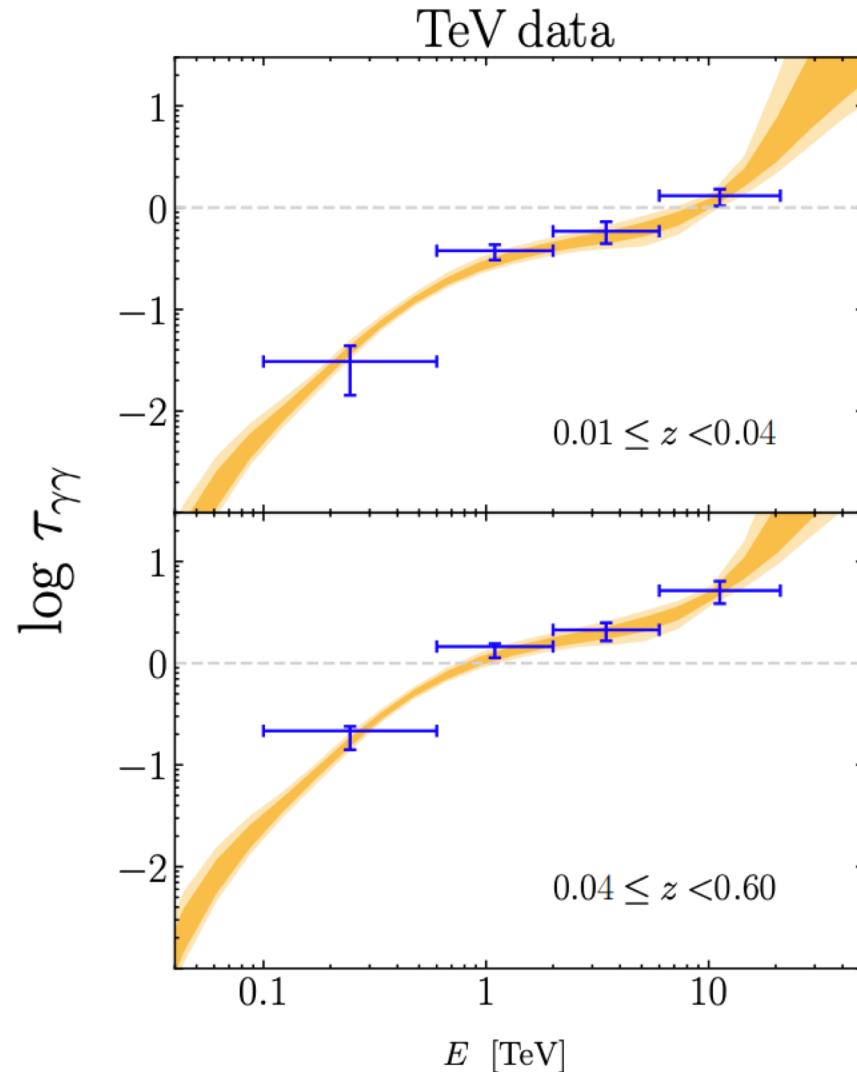
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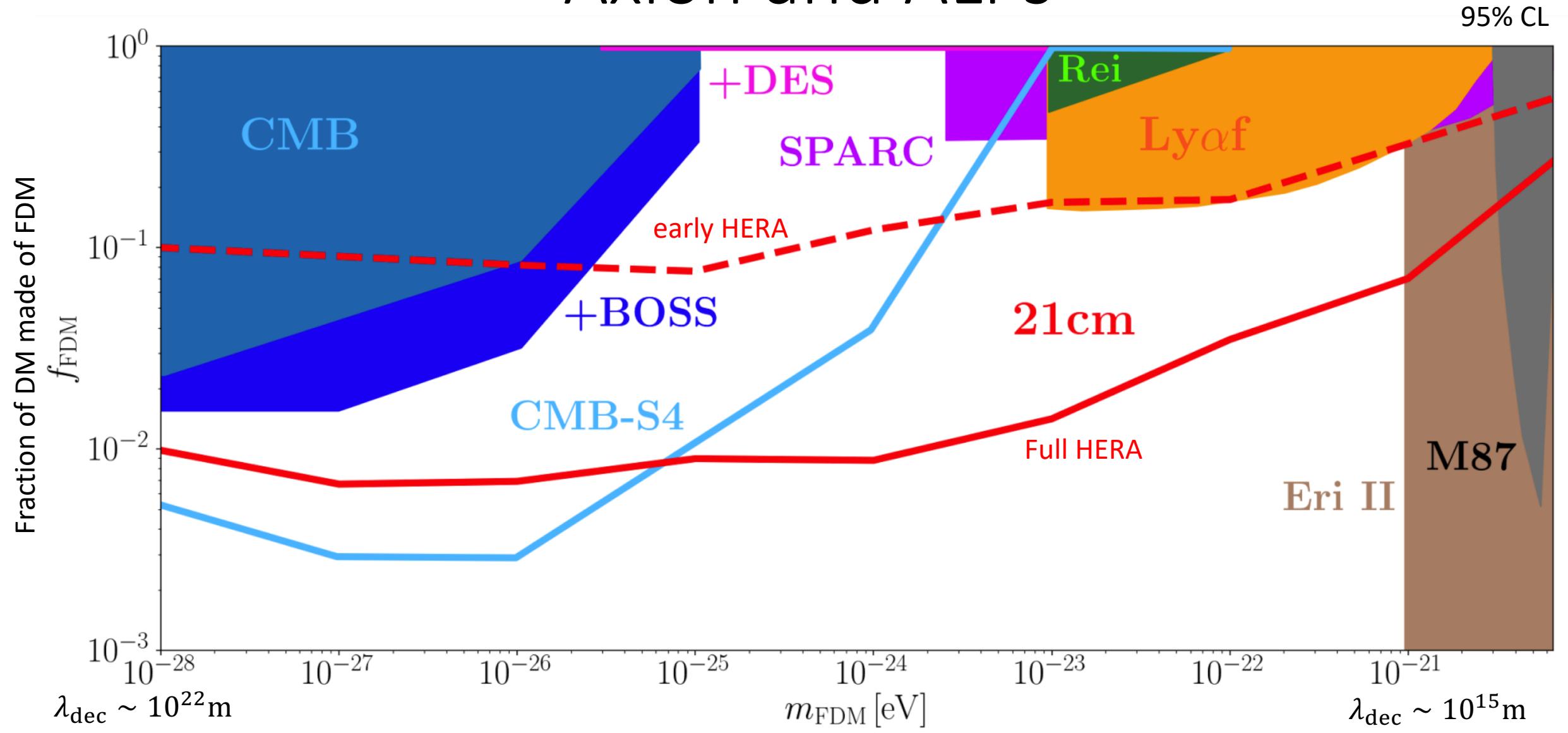
$$\Gamma_a = 3 \times 10^{-24} \text{ s}^{-1}$$

$$\Gamma_a \propto m_a^3 g_{ay}^2$$

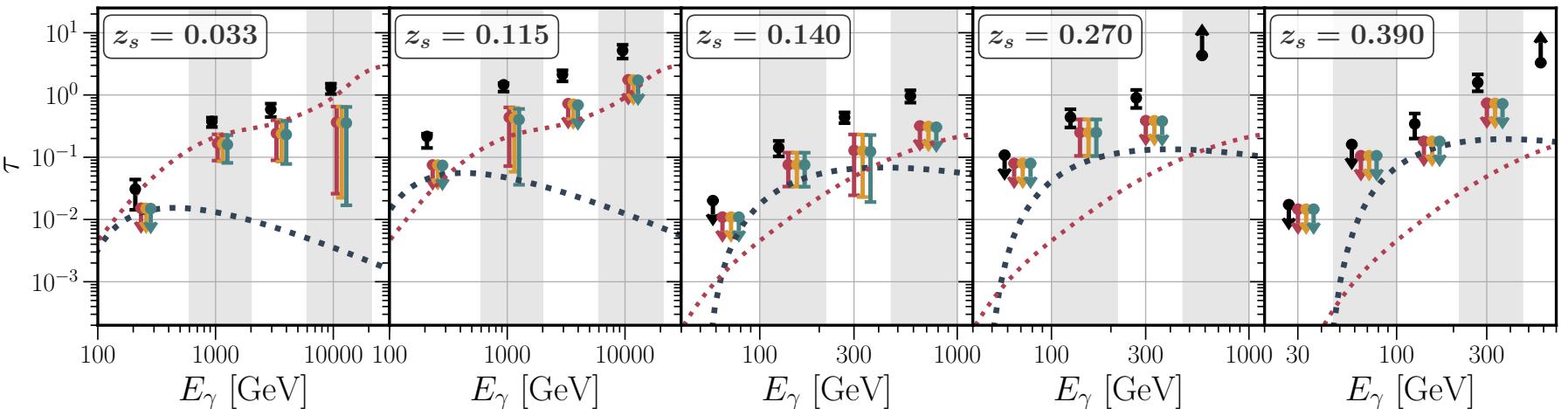
$$\tau(E_\gamma, z_s) = c \int_0^{z_s} \frac{dz}{H(z)(1+z)} \int_{\epsilon_{\min}}^{\infty} \frac{dn}{d\epsilon} \int_{-1}^1 d\mu \sigma_{\gamma\gamma}(E_\gamma, \epsilon, z, \mu)$$



Axion and ALPs



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Signif. over null

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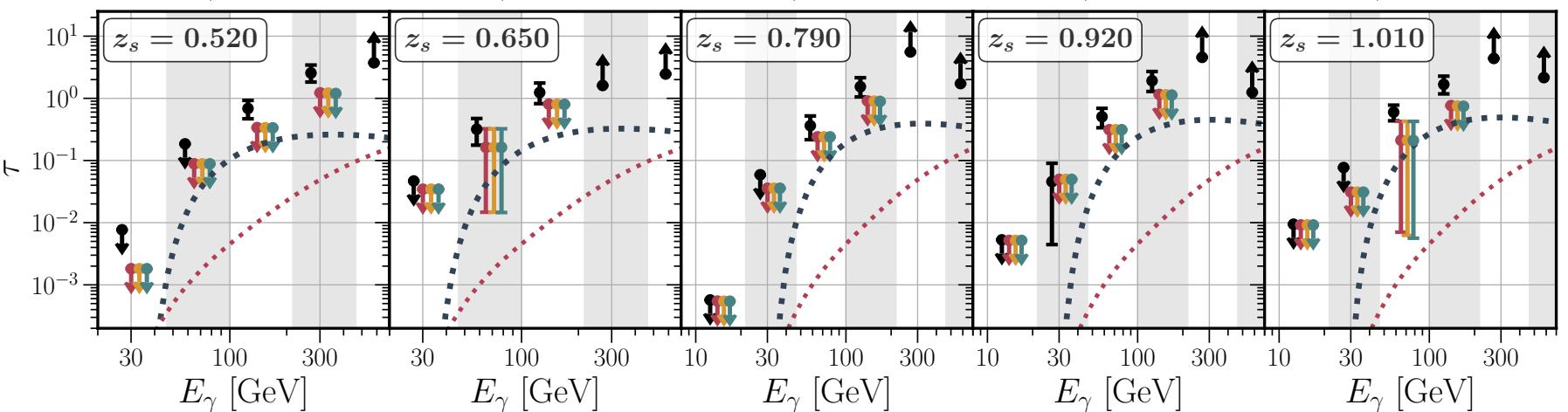
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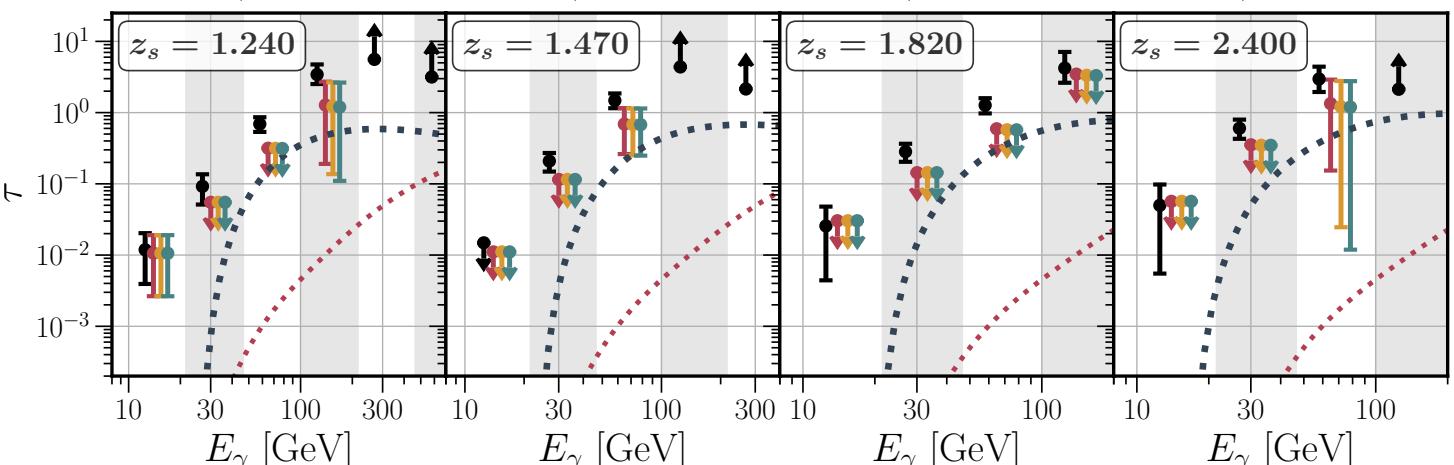
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- Measurement
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- DM bf.
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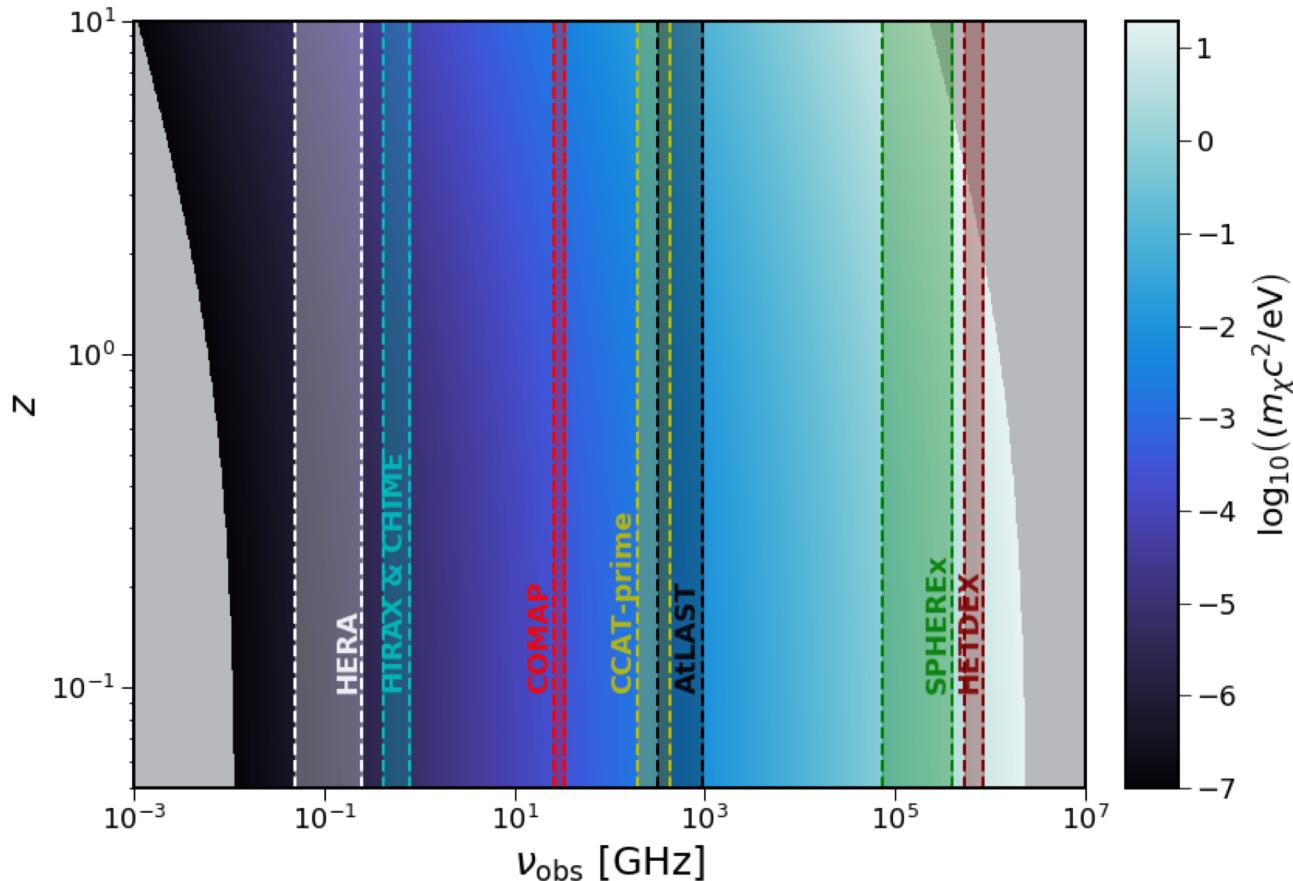
Careful: log-log

Exotic radiative decays

- Decaying dark matter: $\chi \rightarrow \gamma + \gamma$

$$\nu_\gamma = m_\chi c^2 / 2 h_P$$

$$\rho_L^\chi(x, z) = \rho_\chi(x, z) c^2 \Theta_\chi \boxed{\Gamma_\chi f_\chi f_{\gamma\gamma} f_{esc}} (1 + 2\mathcal{F}_\gamma)$$



Traces directly the DM density field

Challenges & improvements (LIM)

- Challenges:
 - Astrophysical uncertainties: marginalization, break degeneracies
 - Other contaminants: loss of information, potential biases
 - Line broadening (currently testing BAO robustness against this)
- Reasons to be optimistic:
 - Many pathfinders and experiments in the pipeline (and theory efforts too!)
 - Other summary statistics
 - Exotic decays:
 - Extensible to other interloper-treatment, summary statistics, etc
 - Multiprobe with galaxy clustering and weak lensing
 - New info and checks through cross correlations, new strategies