COB, blazars and LIM
view for
multi-eV ALP dark matter

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- Precision cosmology: CMB, clustering & BAO, lensing, SNeIa, GWs, …

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  - Phenomenological model: nature of DM and DE? Primordial Universe?

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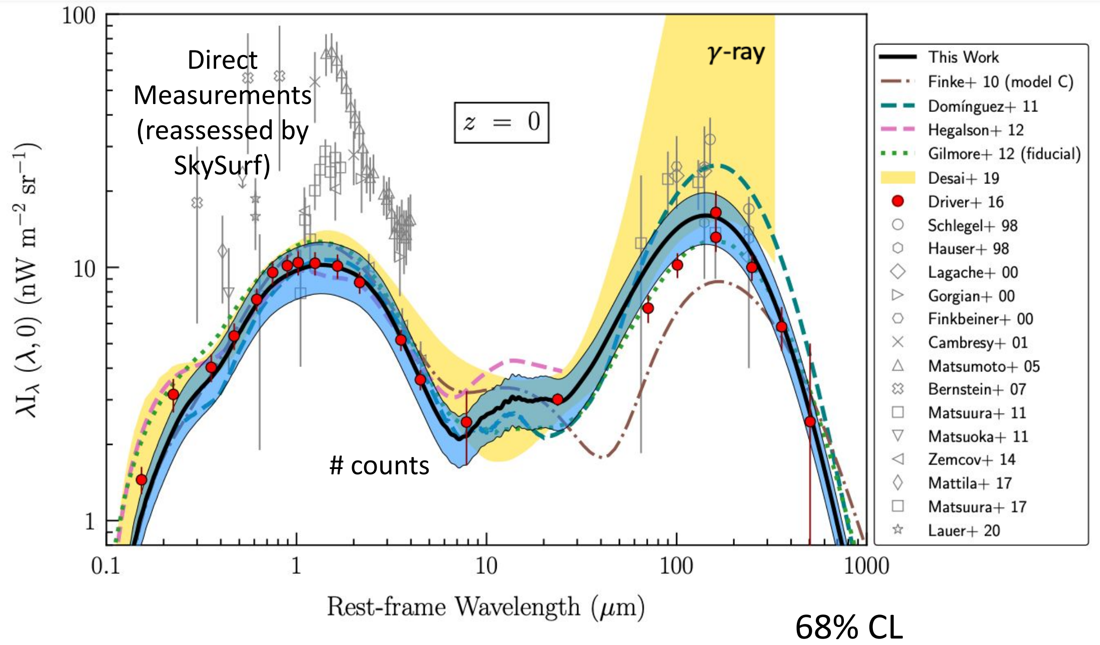
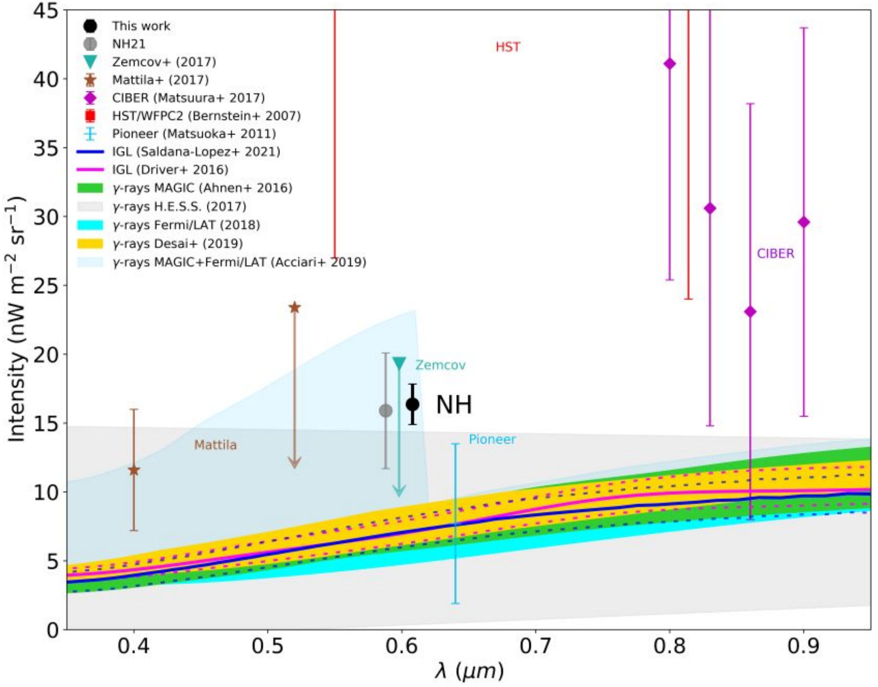
Extragalactic Background Light



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

Saldana-Lopez+(2021)

COB excess



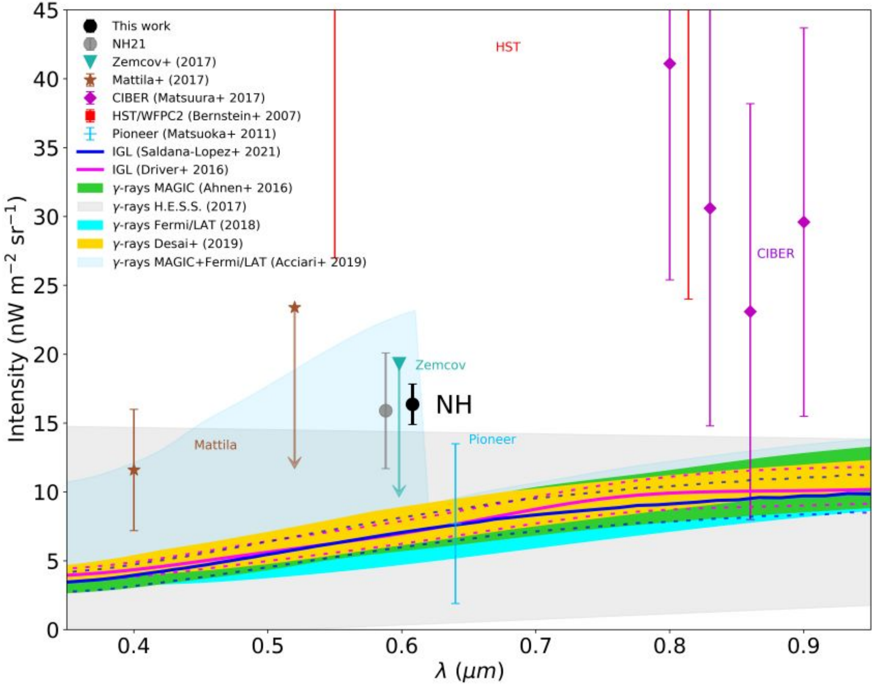
68% CL

- New direct observations from New Horizons (> 50 AU) at 0.61 microns
- 1[st] 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)

Confirmed by other teams/reanalyses!

Lauer+(2022)

COB excess



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  - ALP decays? Bernal+(2022a)

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Axion and ALPs

- Axion: Pseudo-Nambu-Goldstone boson initially proposed to solve strong CP-problem.

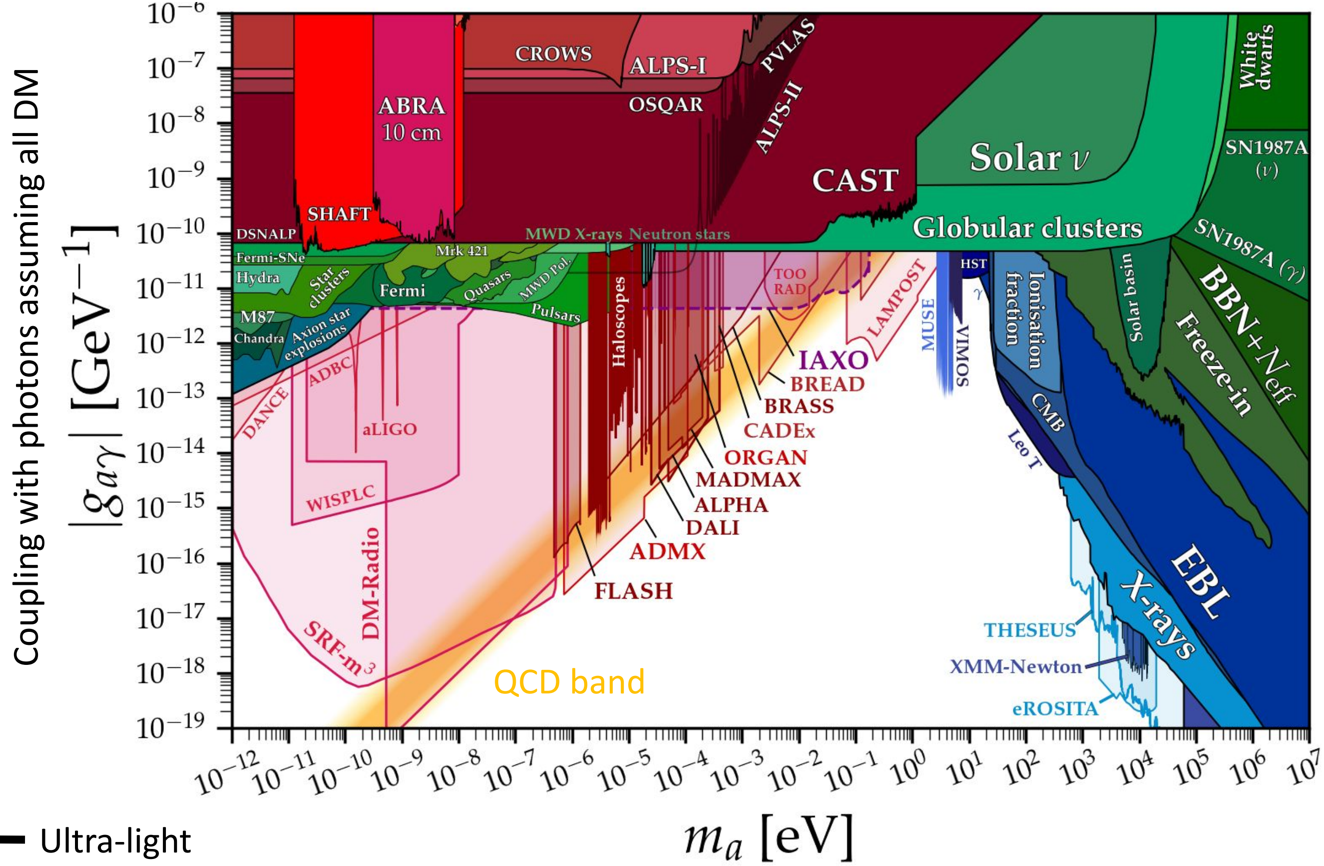
- Coupling with photons: photon-axion oscillation, radiative decays ($\Gamma_a \propto m_a^3 g_{a\gamma}^2$)

  $a \to \gamma + \gamma$; 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

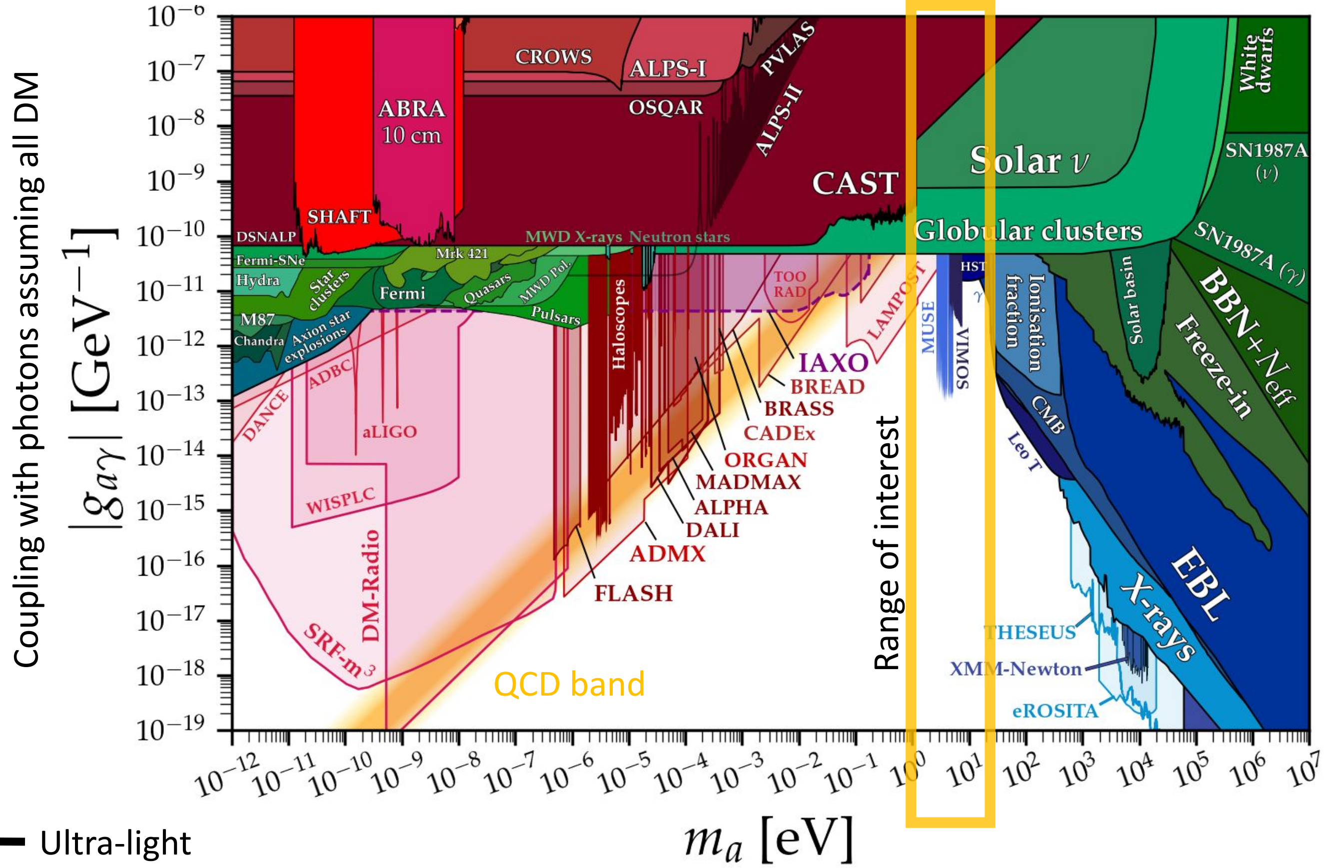


95% CL

← Ultra-light axions

Adams+(2022); Snowmass

Axion and ALPs



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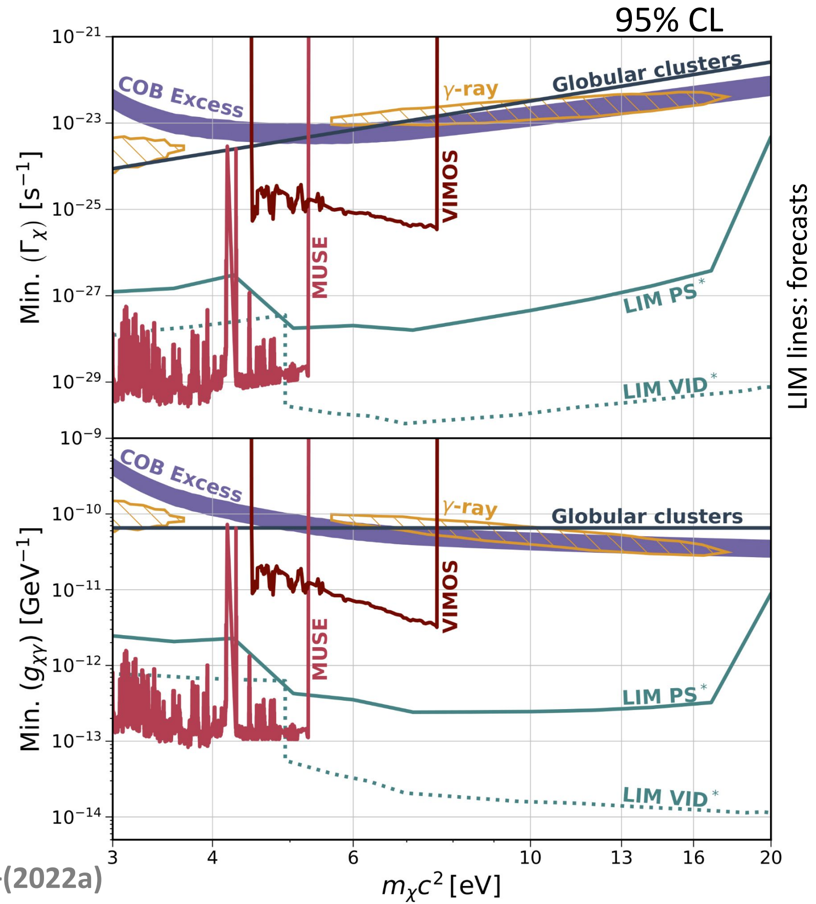
ALPs contributing to COB excess



Bernal+(2022a)

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

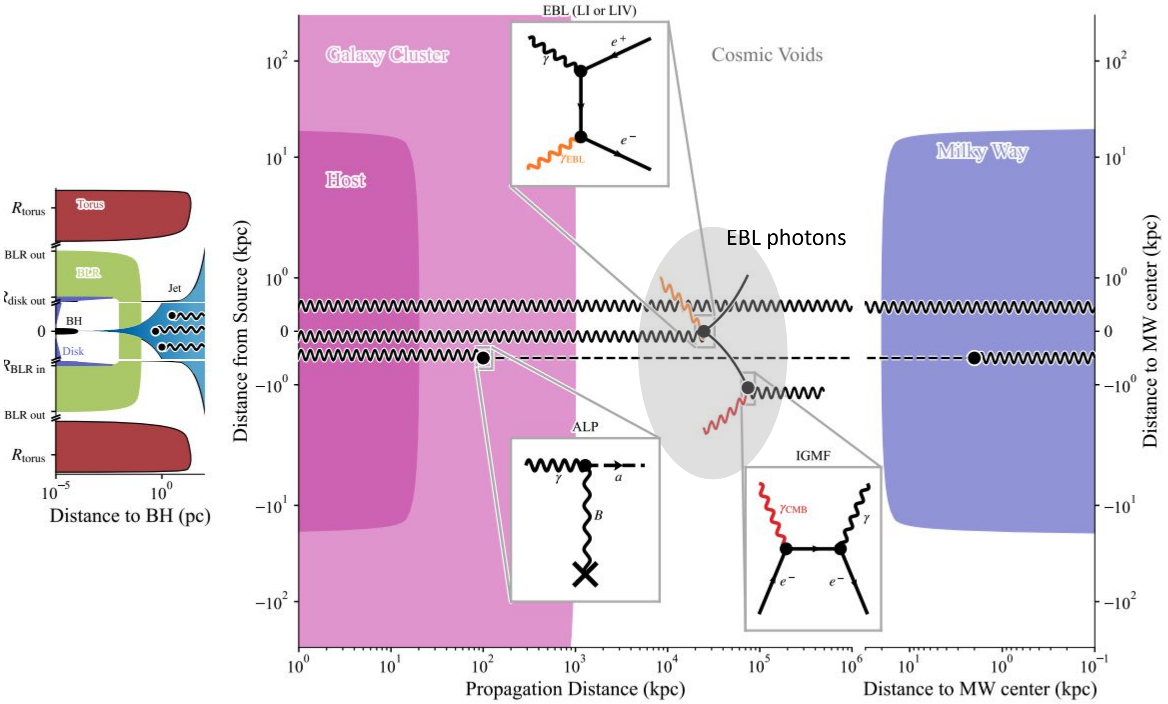
$z_* \equiv z$ of axion decay

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

- 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)

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

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

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

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

- $\sim$800 blazars (Fermi-LAT+Cherenkov telescopes)

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- ~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 (applies to: Expansion rate of the Universe, Axion-photon oscillations, Pop III stars, Axion decays)

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

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

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 (m_a, Γ_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 (m_a, Γ_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+(2022b)

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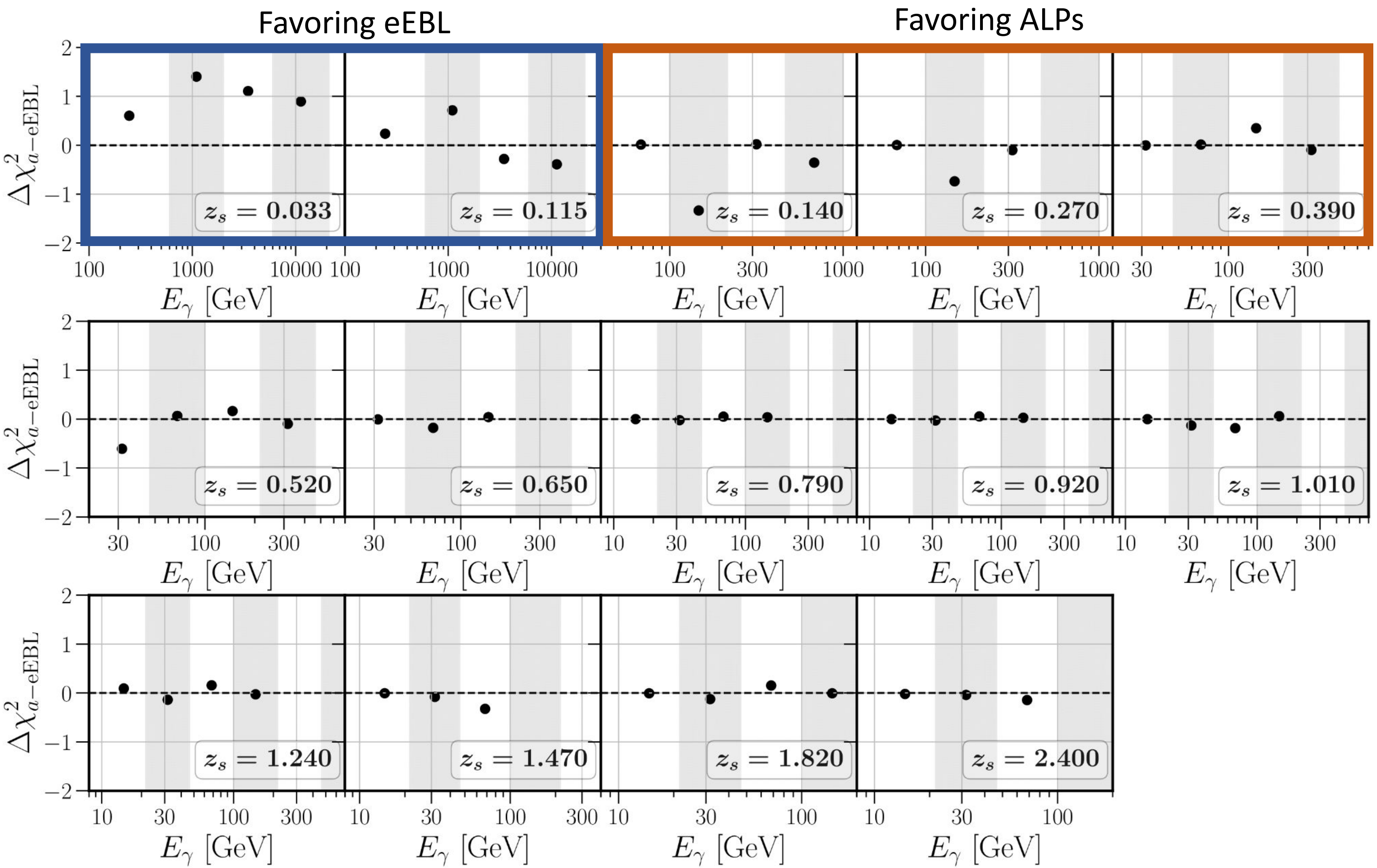

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Bernal+(2022b)

Caution: log-log plot

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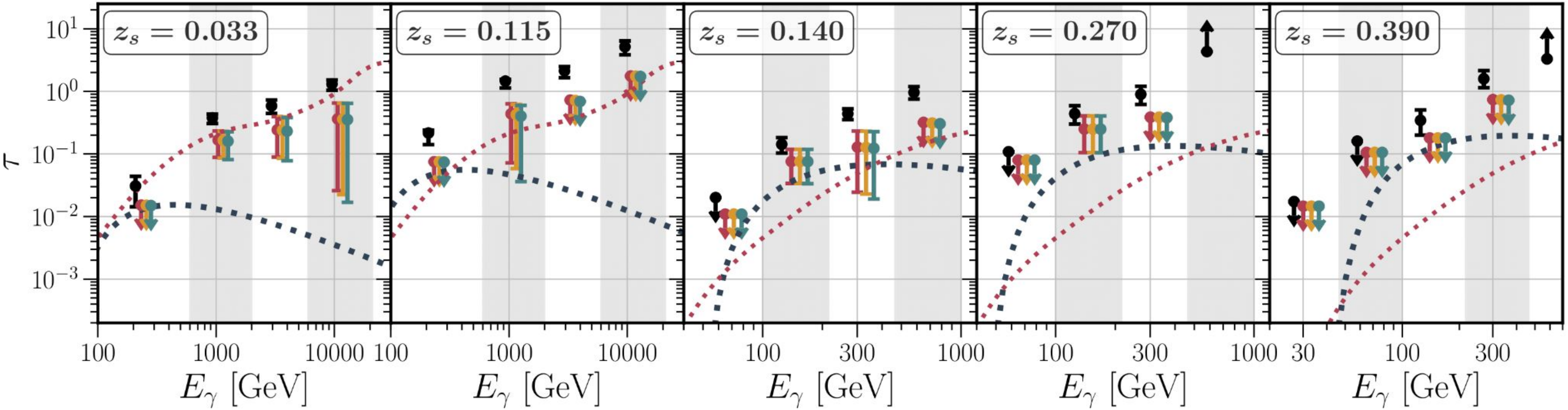

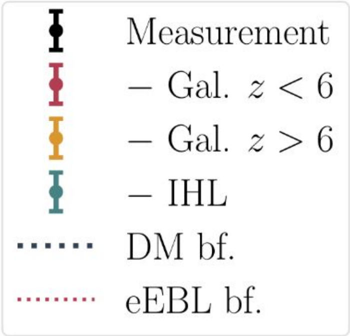

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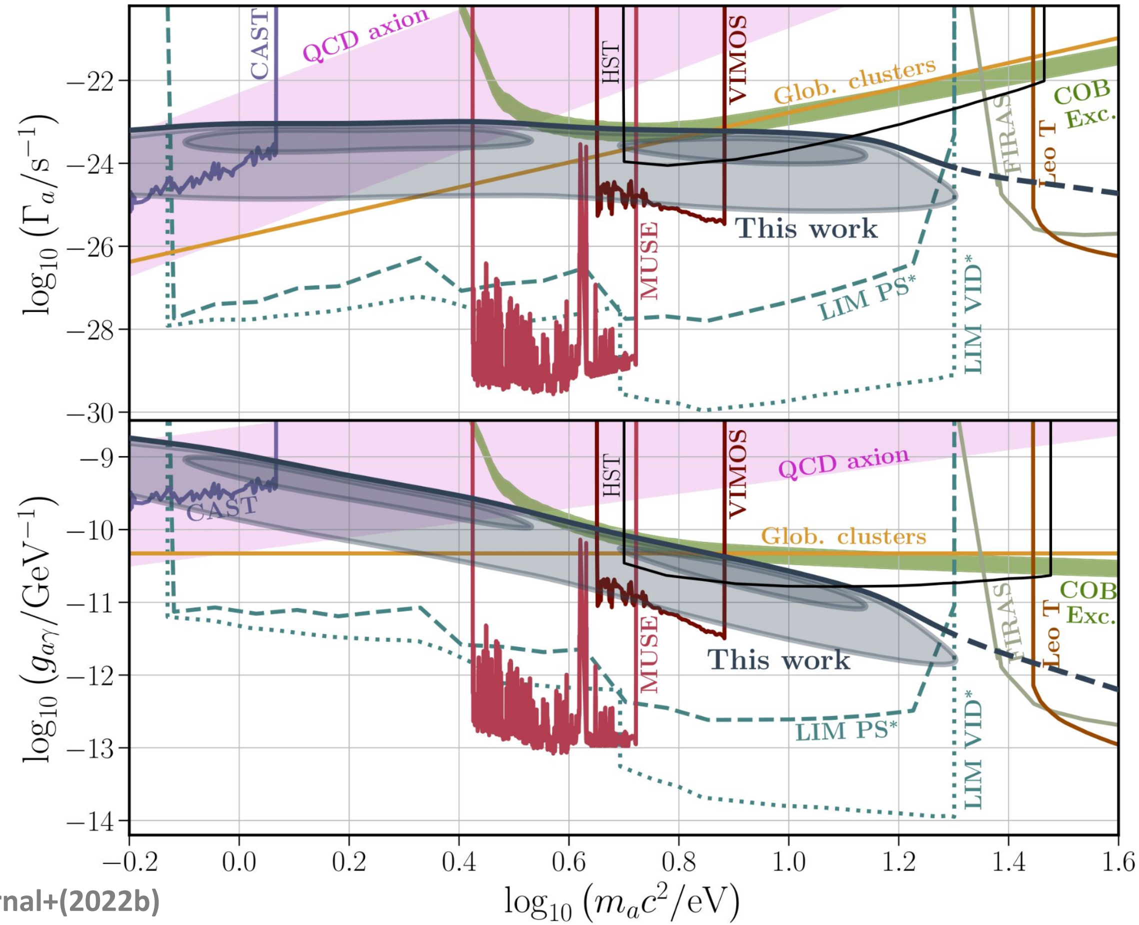
Bernal+(2022b)

Understanding the axion hint



Bernal+(2022b)

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

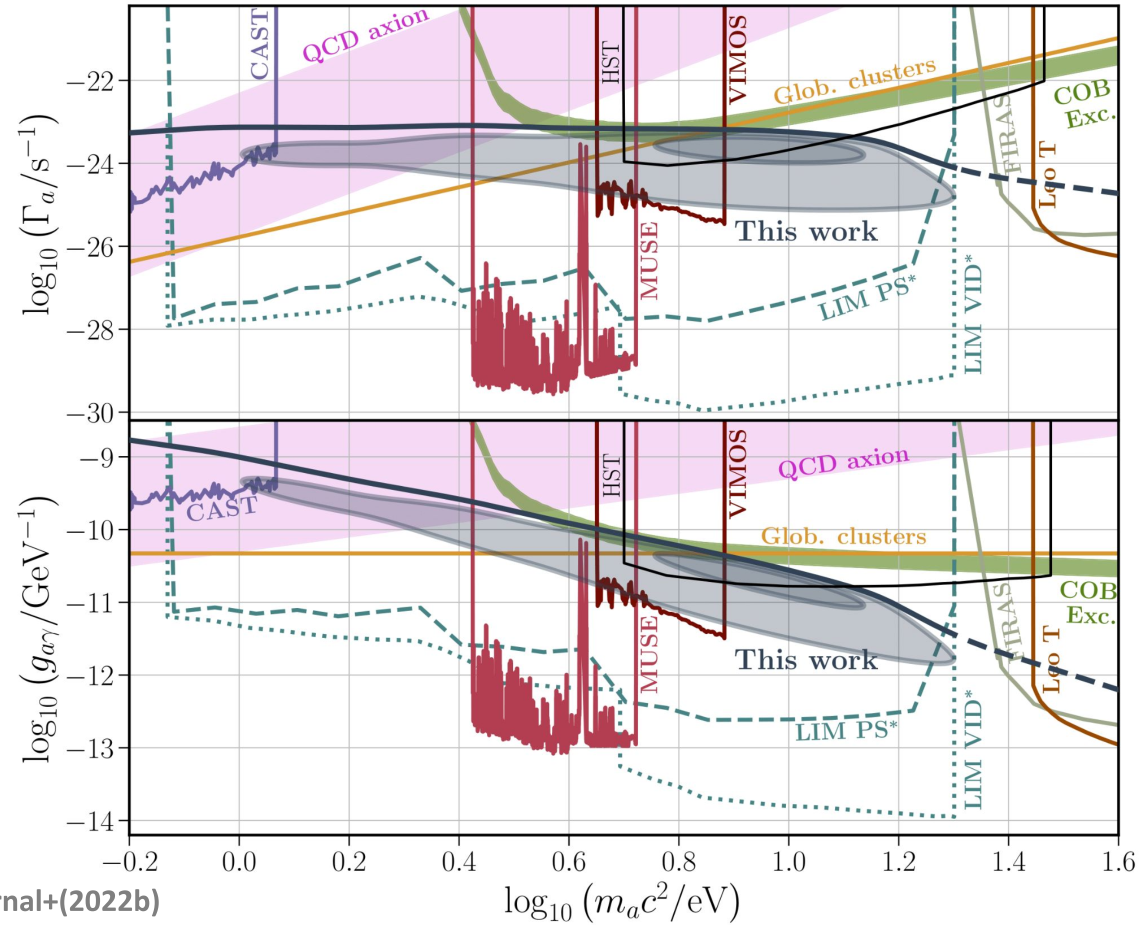
- Bimodal distribution
- Poor fit to local blazars
- Also preference for F_{eEBL}

2.1σ $\quad \Gamma_a = 2.5 \times 10^{-24}\ \mathrm{s}^{-1}$, $\quad m_a = 9.1\ \mathrm{eV}/c^2$

95% CL

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

Understanding the axion hint



Bernal+(2022b)

- Removing 1st redshift bin
- $\Delta\chi^2_{a-\mathrm{eEBL}} = -2.9$

1.9 σ $F_{\mathrm{eEBL}} = 0.17 \pm 0.09$

2.1σ $\Gamma_a = 2.5 \times 10^{-24}\ \mathrm{s}^{-1}$

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95% CL

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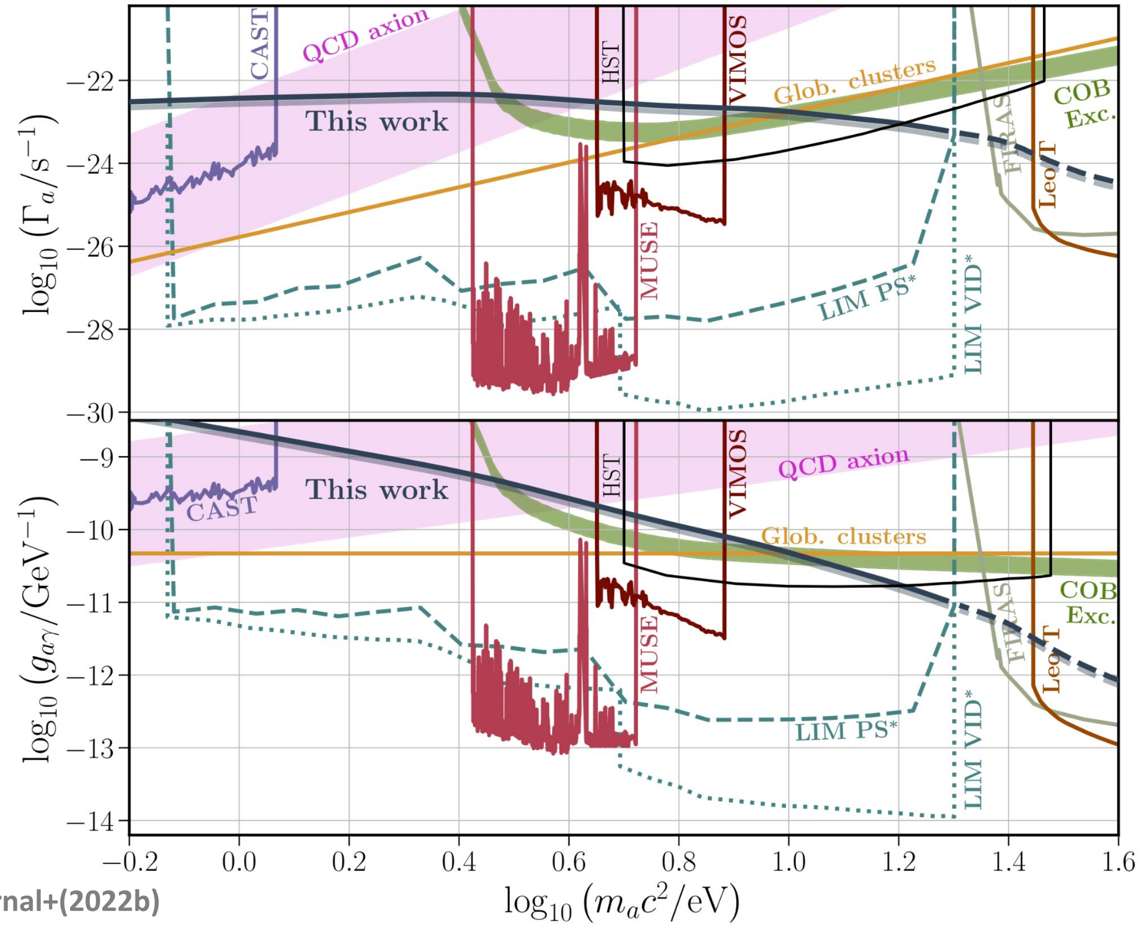
Null case B



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

Bernal+(2022b)

95% CL

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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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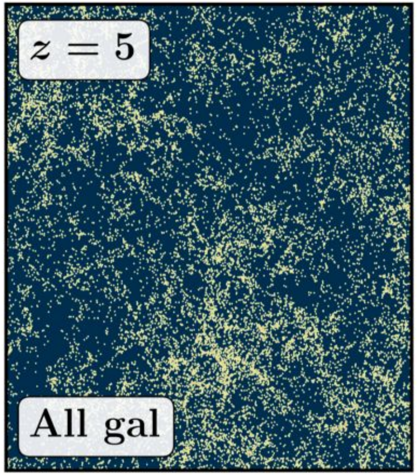
Bernal & Kovetz (2022)



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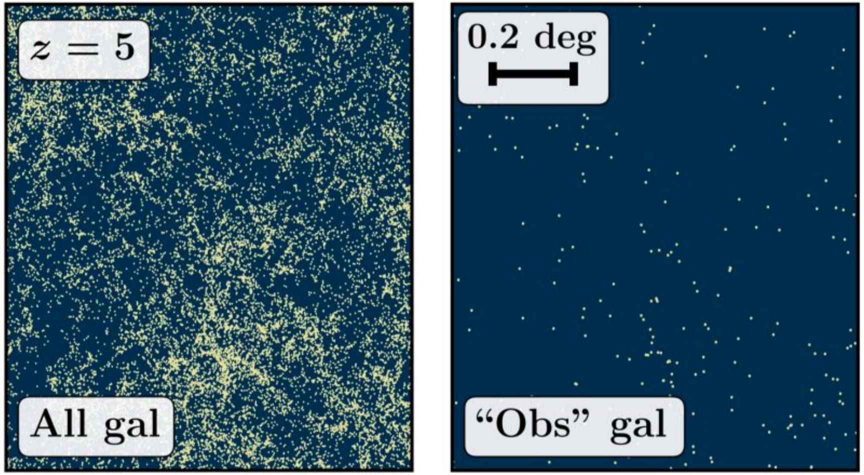
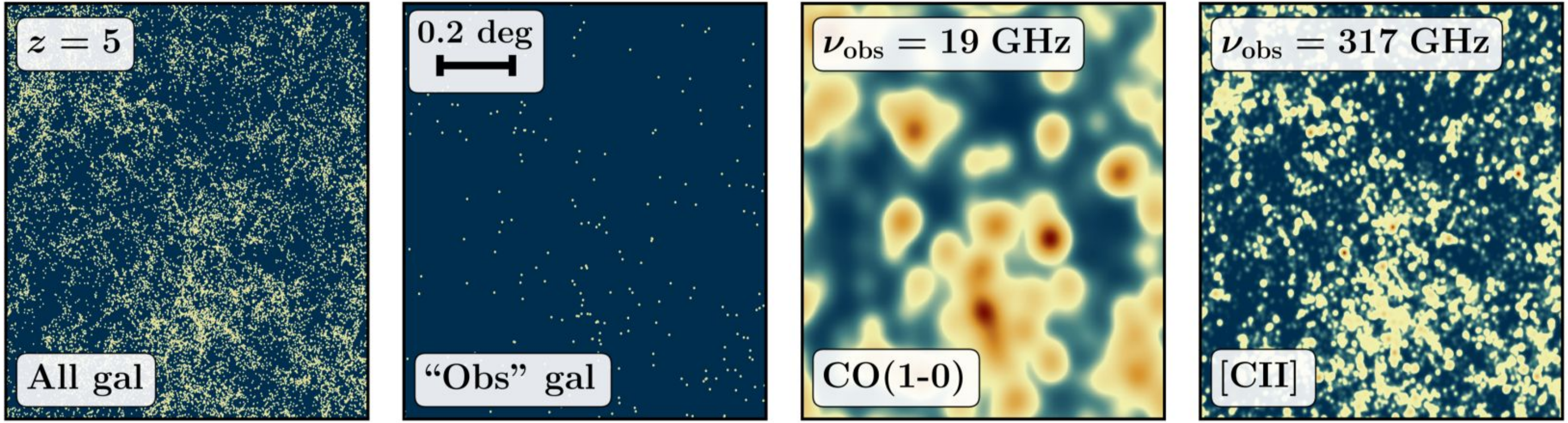


- 1 deg^2 at $z = 5, \Delta z = 0.2$
- All haloes
- Only $M_* > 10^{9.5}\, M_\odot$

What is Line-Intensity Mapping?

- Intensity fluctuations:
  - trace matter density fluctuations
  - Depend on line luminosity -> extragalactic astrophysics

- For cosmology: Noisy map of *all* galaxies and IGM (vs detailed map of brightest)
- For astrophysics: Aggregate of *all* emitters and diffuse emission



Bernal & Kovetz (2022)

Using LIM for cosmology

- Intensity traces density: cosmological information degenerate with astrophysics

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

- Limitations:
  - Intensity maps are highly non-Gaussian: lots of information beyond P(k)
  - P(k) only depends on 1^{st} and 2^{nd} 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

VID: best for astro, integrals of clustering

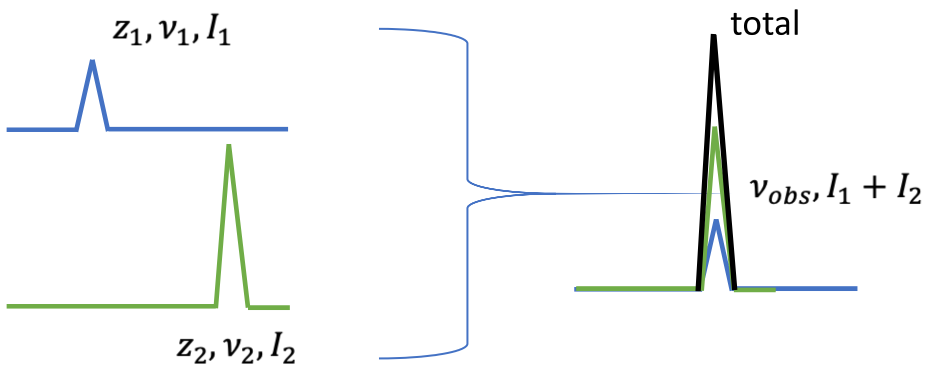
Working on their combination & covariance

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)

      Breysse, Kovetz, Kamionkowski (2015)
      Sun, Moncelsi, Viero, Silva (2018)
    - Model the effect of known interlopers in the likelihood and analyses

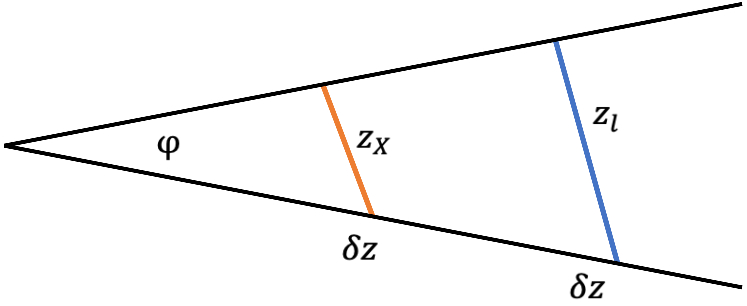
      Lidz & Taylor (2016) Sun, Moncelsi, Viero, Silva (2018)
      Gong, Chen, Cooray (2020) Cheng, Chang, Bock (2020)

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

Creque-Sarbinowski & Kamionkowski (2020)

Effect in power spectrum

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



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

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

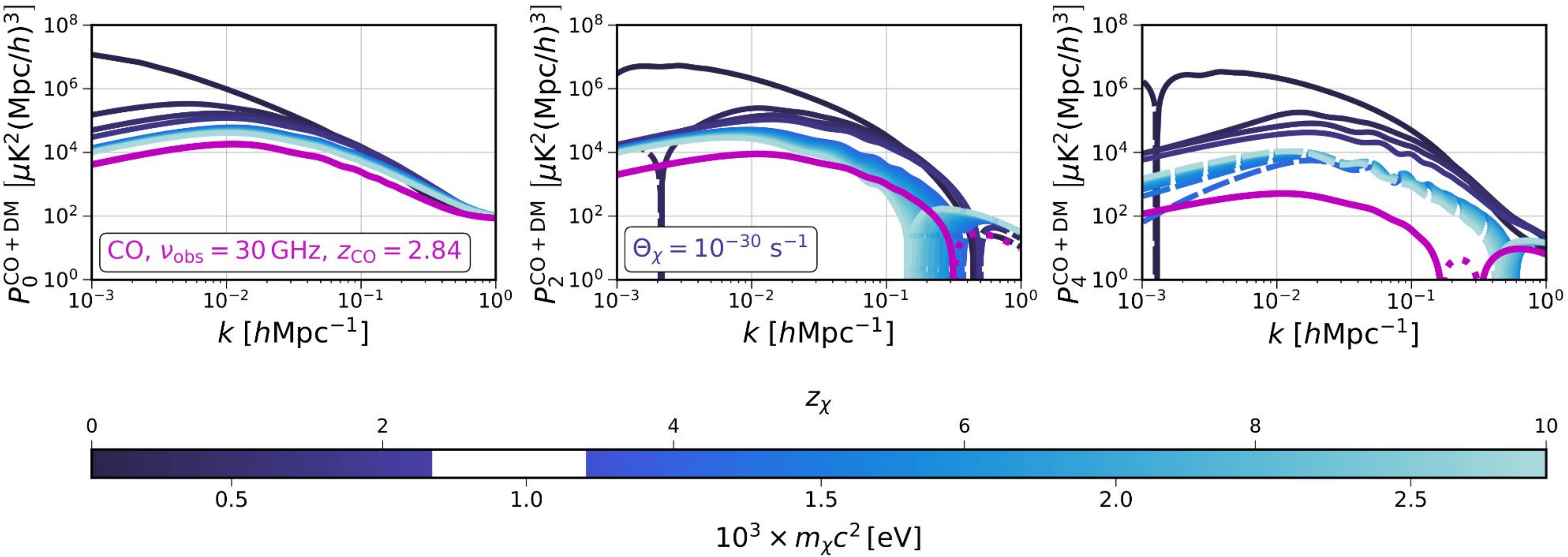
- Model it similar to AP effect: $k_i^{true} \equiv k_i^{infer}/q_i$

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

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

Effect in power spectrum

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



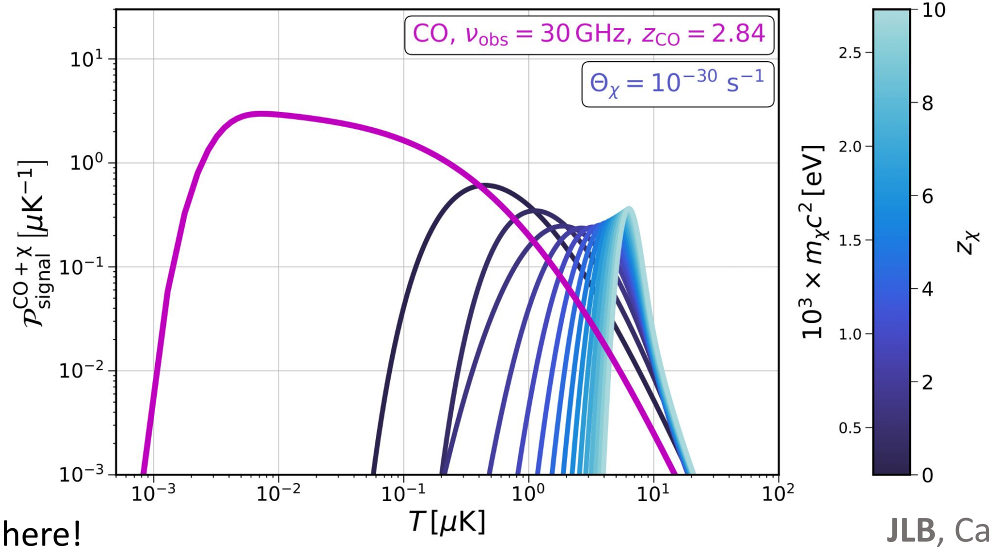
JLB, Caputo, Kamionkowski (2021)

Effect in VID

- Each voxel receives contributions from both emissions:

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

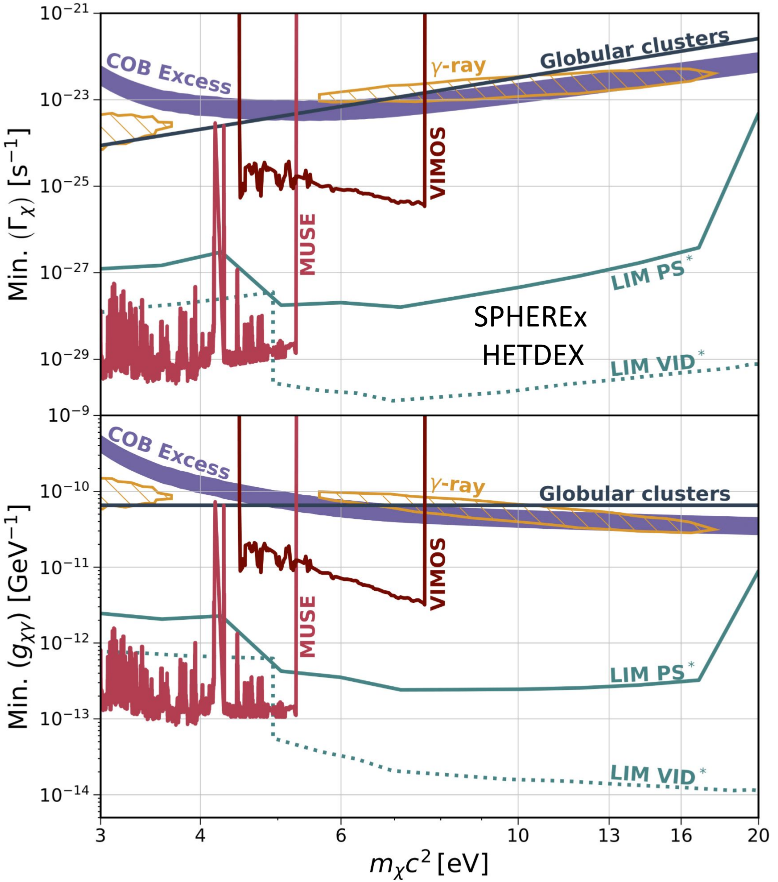
- $\mathcal{P}_{\tilde{\rho}}$: PDF of normalized densities. Obtained from simulations



No noise contribution included here!

JLB, Caputo, Kamionkowski (2021)

Sensitivity in axion context



95% CL

Bernal+ (2022a)

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?

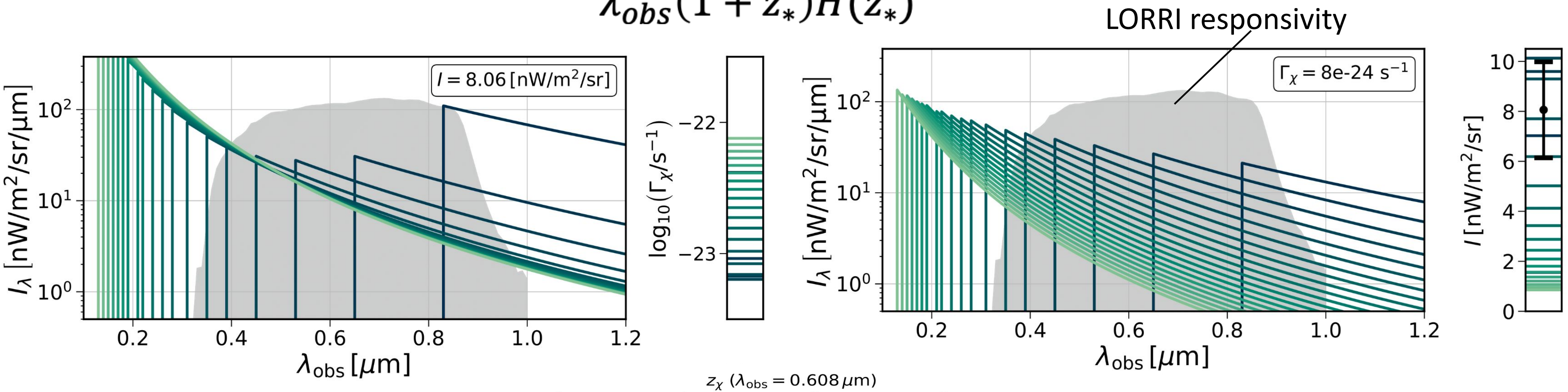
- Misestimation of the abundance of faint galaxies (extrapolated to estimate IGL) **Conselice+(2016)**
- Intra halo light **Cooray+(2012), Zemcov+(2014), Matsumoto+(2019)**
- Radiation from very bright early emitters, like direct-collapse black holes **Yue+(2013)**

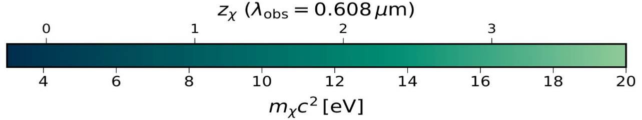
- ALP decays

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

$\boldsymbol{z_* \equiv z}$ **of axion decay**

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

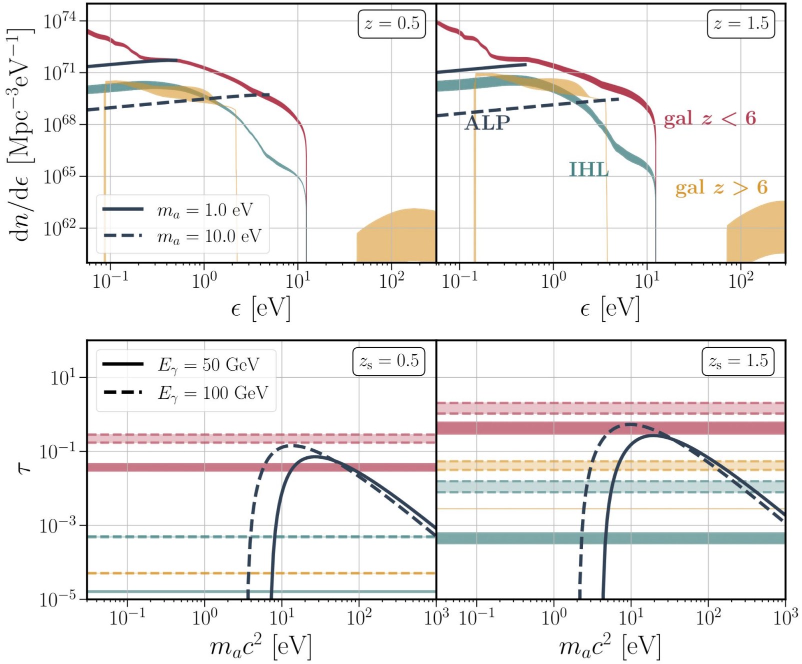




Bernal+(2022a)

Budget the EBL

- $\tau_{\mathrm{res}} > 0$: additional EBL required to explain the optical depth slightly higher than inferred
- Axion decays? Misestimation of standard sources?

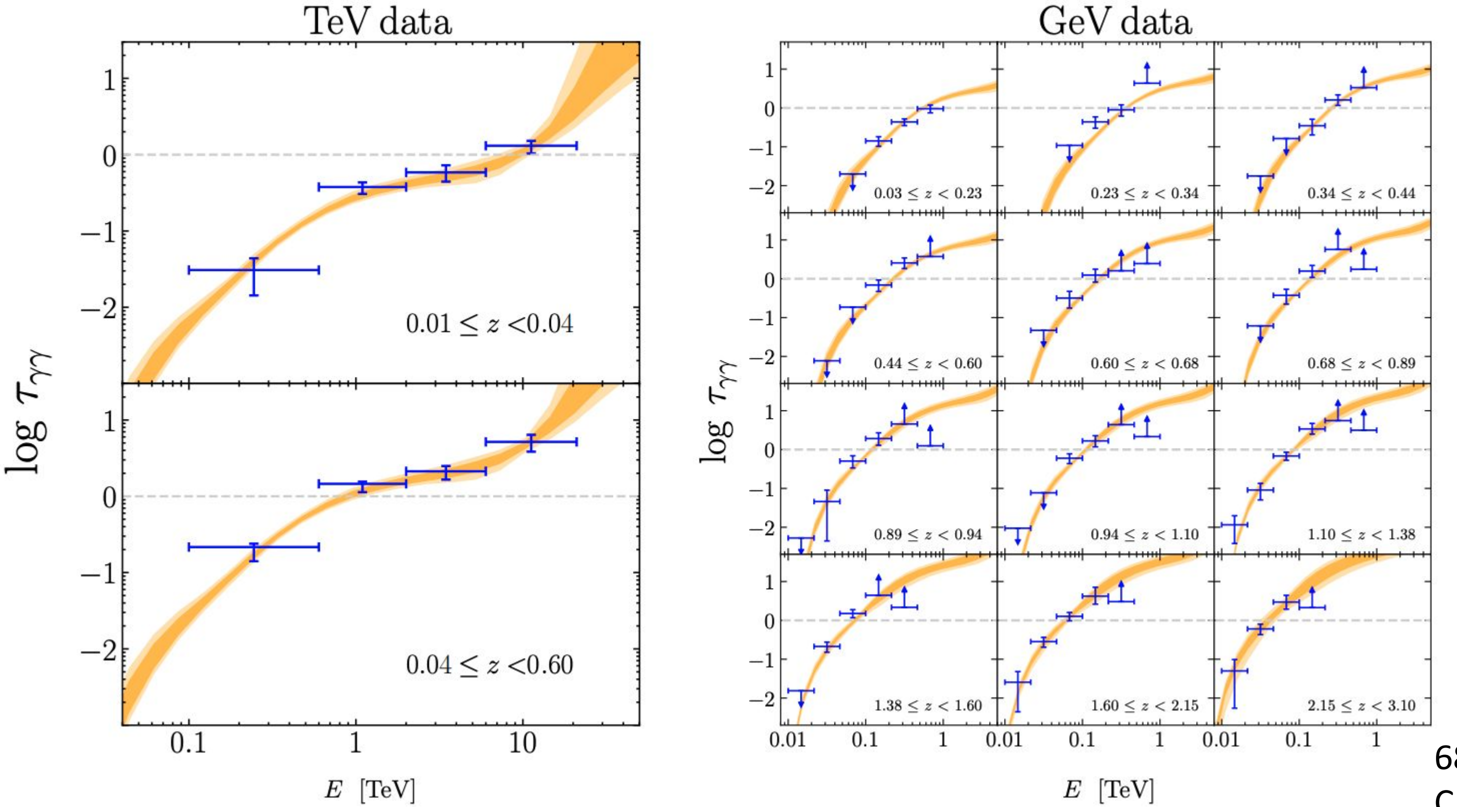


$\Gamma_a = 3{\times}10^{-24}\ \mathrm{s}^{-1}$

Bernal+(2022b)

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

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



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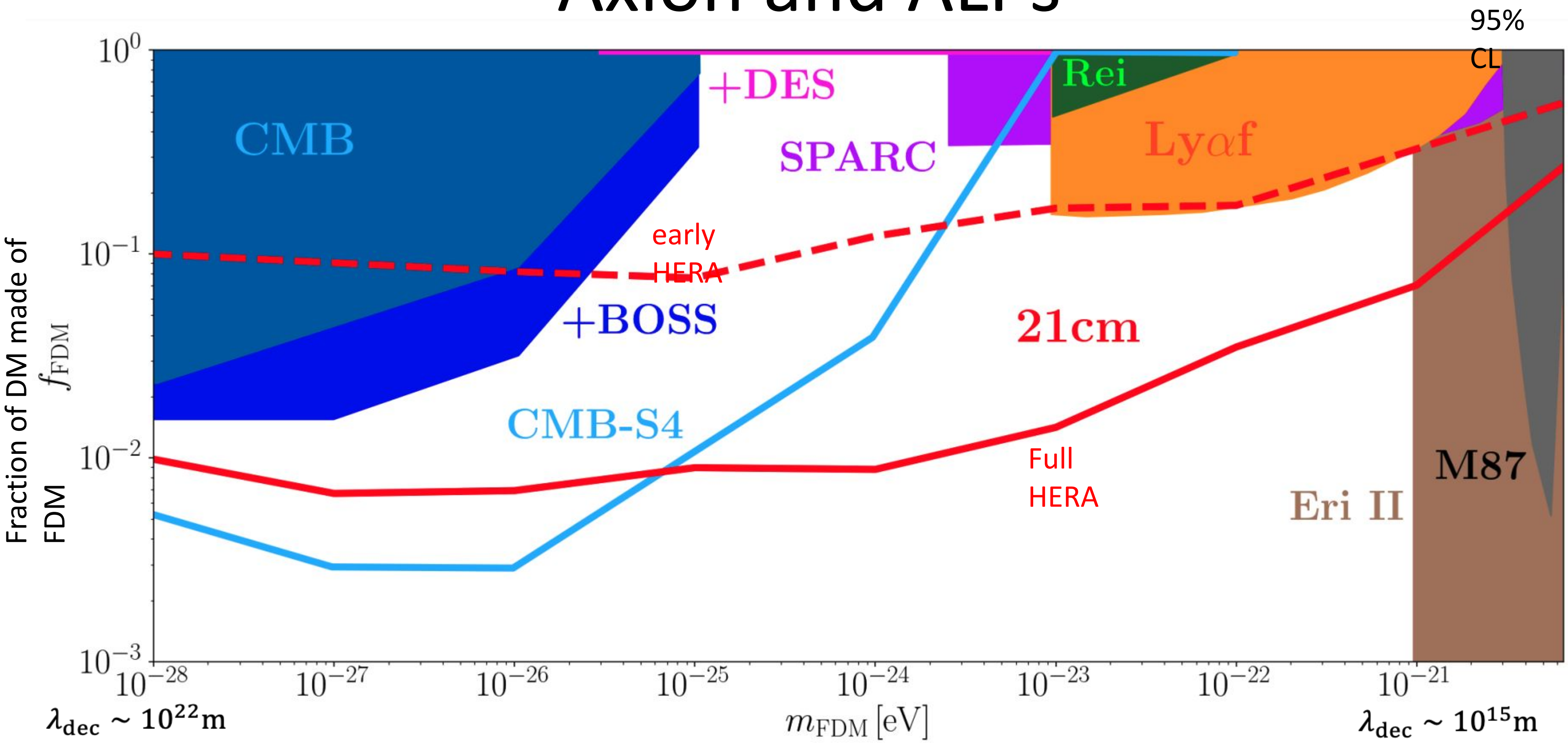
Desai+ (2019); Fermi-LAT (Ajello+, 2018)

Axion and ALPs



Flitter+(2022)

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

Signif. over null

$\mathbf{ALPs} = 2.1\sigma$

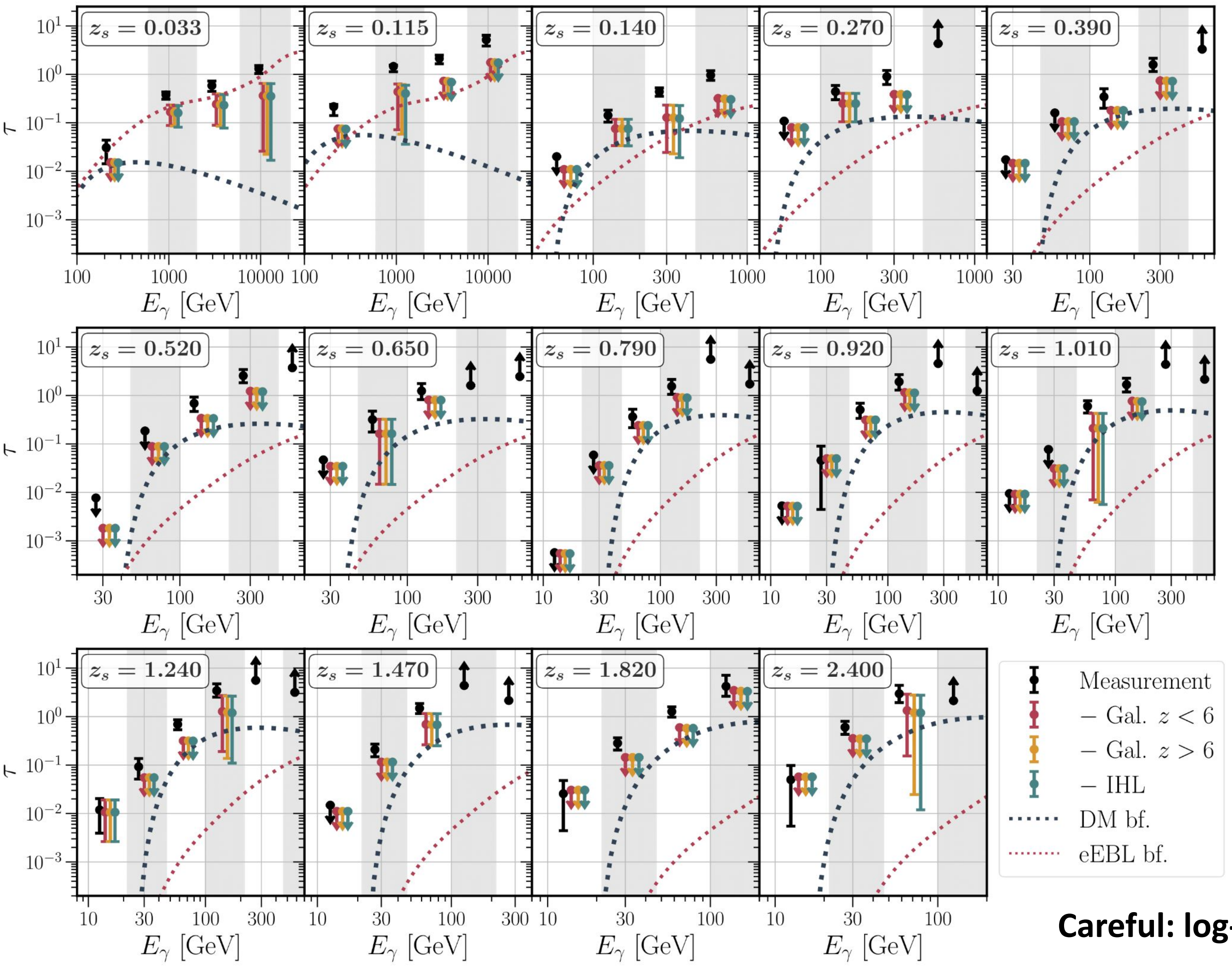
$F_{\mathrm{eEBL}} = 2.7\ \sigma$

Best fit

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

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

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



68% CL

Careful: log-log

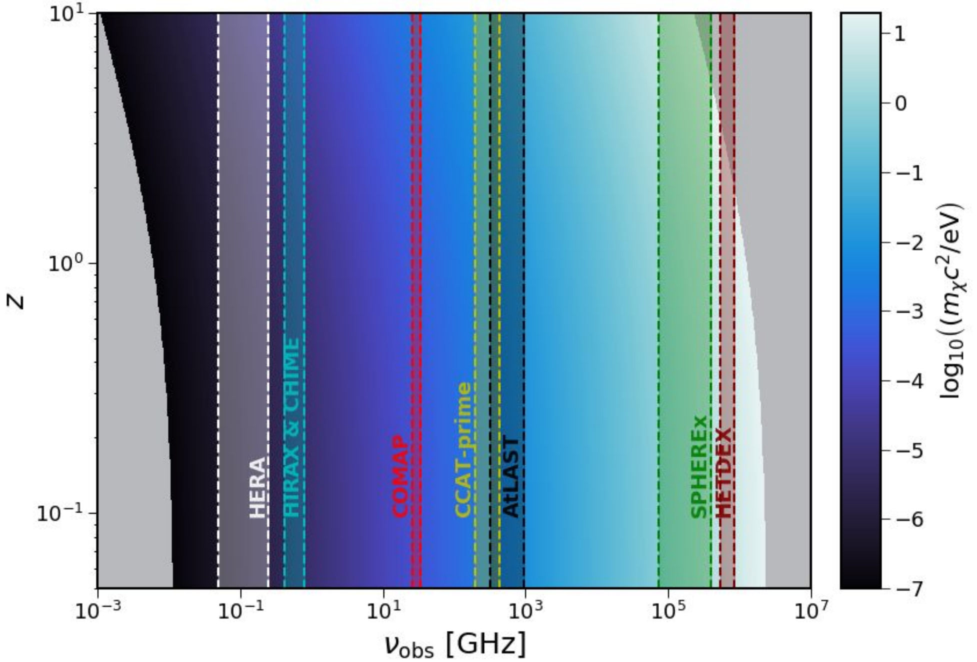
Bernal+(2022b)

Exotic radiative decays

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

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

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



Traces directly the DM density field

JLB, Caputo, Kamionkowski (2021)

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-treatement, summary statistics, etc
    - Multiprobe with galaxy clustering and weak lensing
  - New info and checks through cross correlations, new strategies