Dark matter and neutrino decays with line-intensity mapping

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Fermilab CPC
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Johns Hopkins
Krieger School of Arts & Sciences

Introduction

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

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- Standard cosmological model: ΛCDM
- Excellent reproduction of the observations, but…
  - Persistent discrepancies between different cosmological probes (high-z vs low-z?): H_0, $\sigma_8\Omega_M^{0.5}$
  - Phenomenological model: nature of DM and DE? Primordial Universe?

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Strategies to explore DM and neutrino physics with LIM

Introduction

- Dark Matter:
  - Vast variety of candidates with rich phenomenology
  - Weak coupling with baryons: decaying dark matter (axion, sterile neutrinos, …)

- Neutrinos:
  - Controlled by the electromagnetic transition moments
  - SM prediction of neutrino lifetime: $\tau_\nu \sim 10^{40-50}$ s ($\gg t_U$)
  - BSM physics may enhance transition moments: detection → BSM physics!

Strategies to explore DM and neutrino physics with LIM

Phenomenological approach

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 $\rightarrow$ know redshift $\rightarrow$ 3D maps

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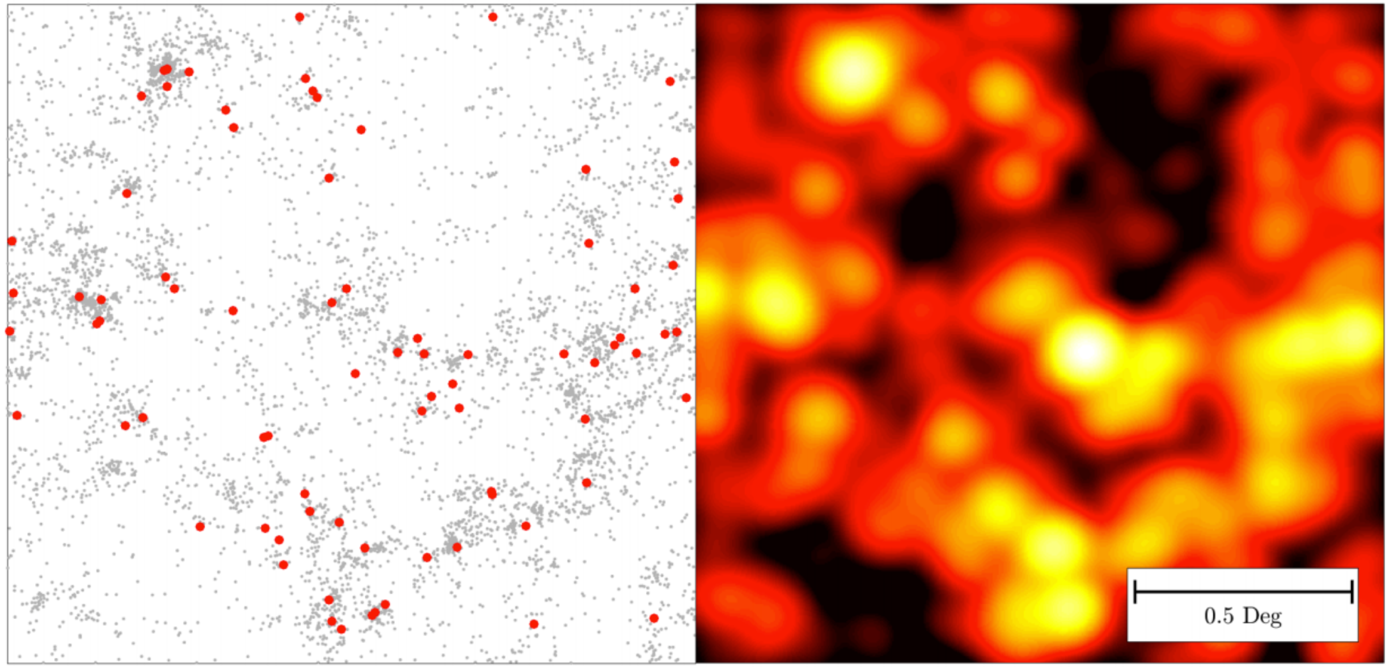
$\sim$ 4.5k hours of VLA can detect $\sim$ 1% of CO-emitting galaxies



$\sim$ 1.5k hours of COMAP mapping CO intensity fluctuations

P. Breysse

What is Line-Intensity Mapping?

- LIM: use the integrated signal without requiring a detection threshold
- Infor LoS
- Targ

Galaxy surveys: detailed distribution of brightest galaxies

Intensity maps: noisy distribution of all galaxies and IGM

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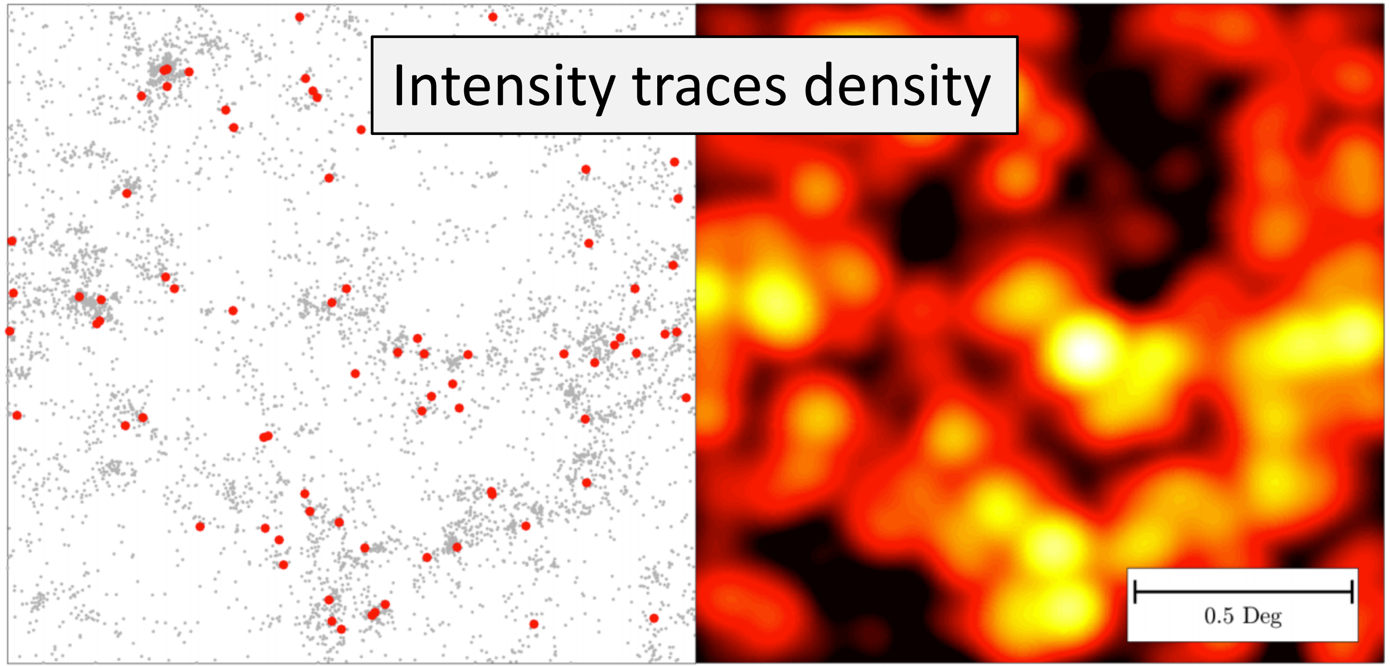

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Targeted lines

- We have multiple lines to exploit over more than 6 orders of magnitude in frequency
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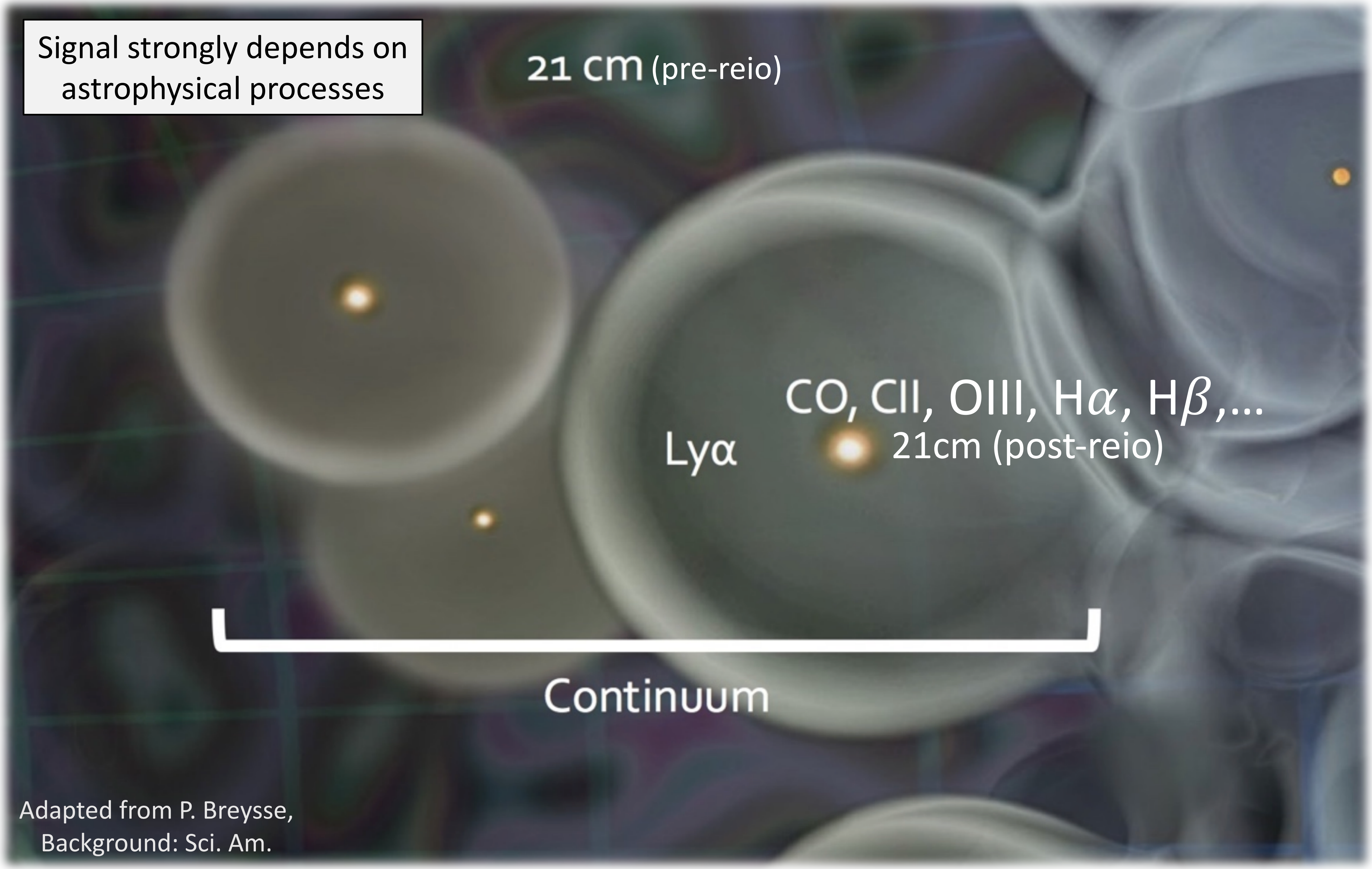
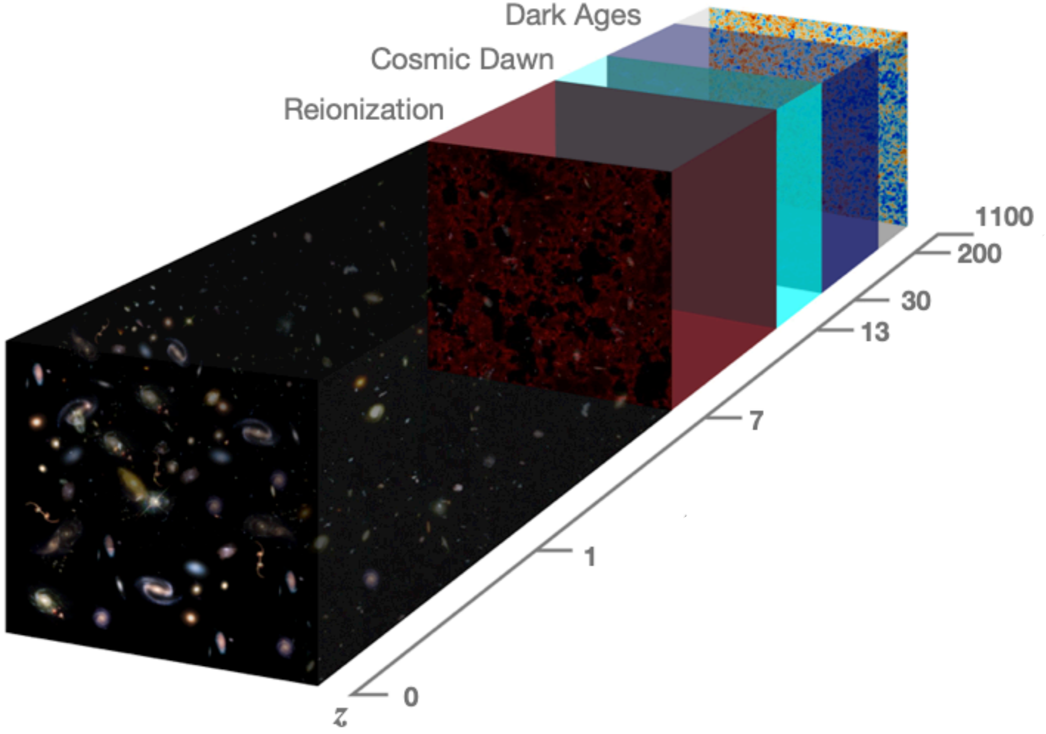
Any non-standard line?

Creque-Sarbinowski & Kamionkowski 2018


Signal strongly depends on astrophysical processes
21 cm (pre-reio)
CO, CII, OIII, Hα, Hβ,...
Lyα
21cm (post-reio)
Continuum
Adapted from P. Breysse,
Background: Sci. Am.

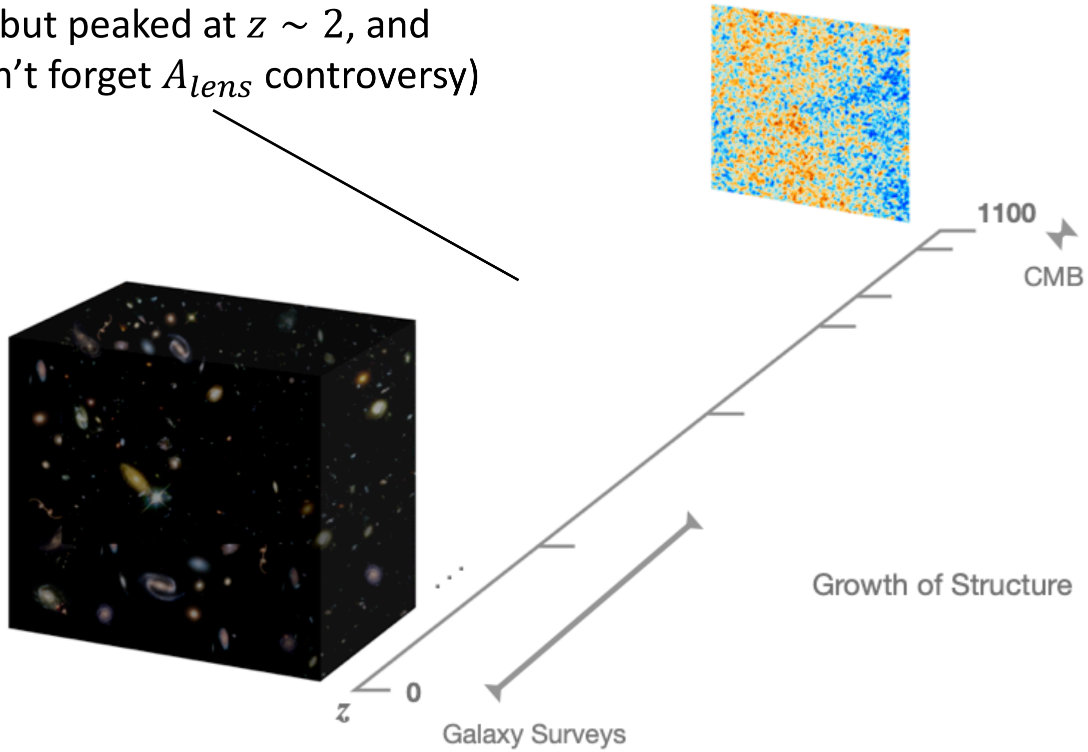
Probing the Universe

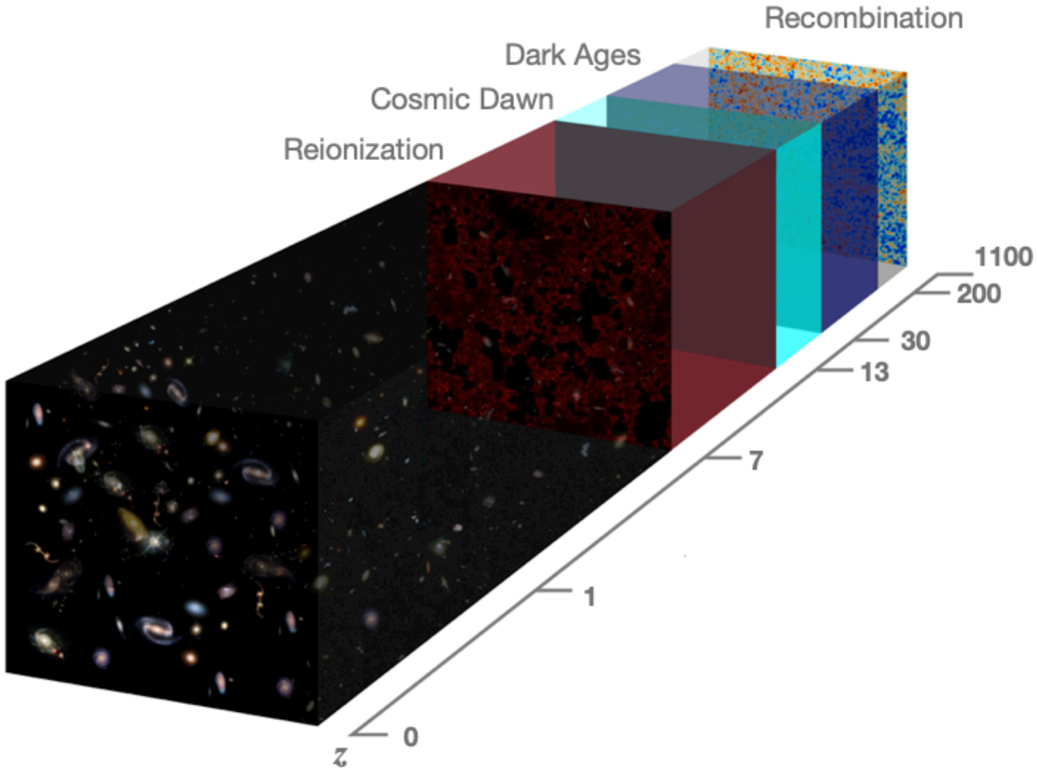


E. D. Kovetz

Probing the Universe

Indirect measurements with CMB lensing
(but peaked at $z \sim 2$, and
don't forget A_{lens} controversy)





E. D. Kovetz

Probed Universe

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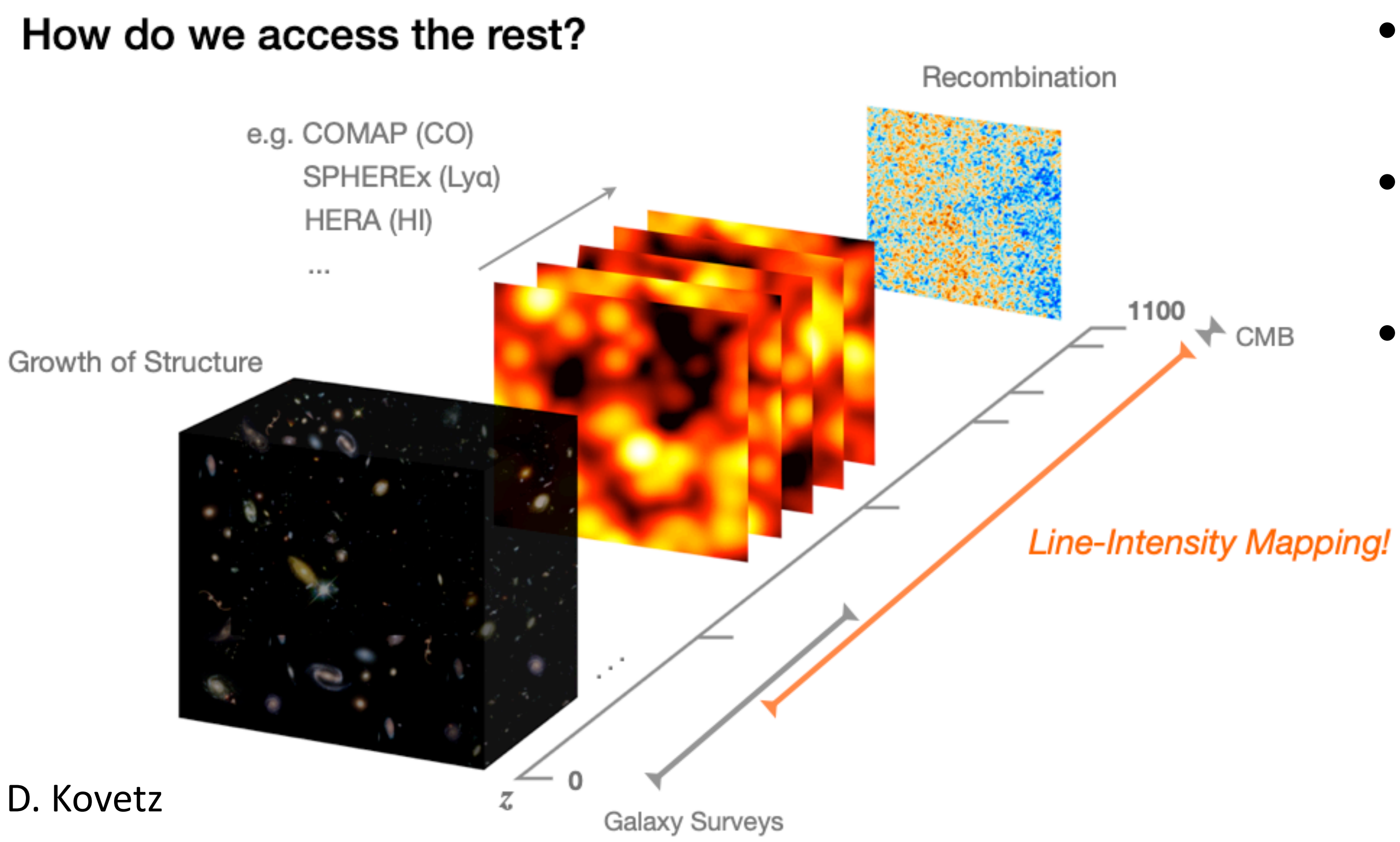


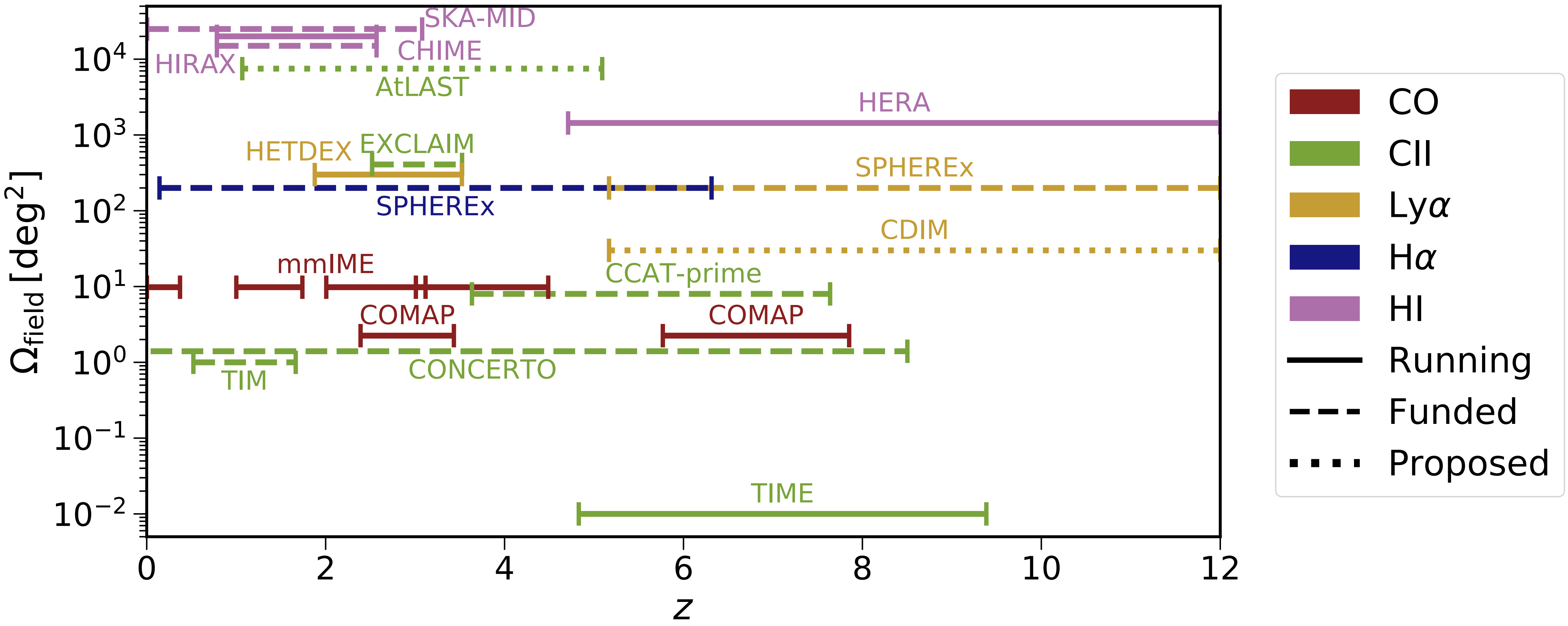
E. D. Kovetz

- Different stages of evolution across time
- But we have only exploited a small part
- LIM: fills the gap!

Probing the Universe with LIM

- Exciting experimental landscape!

Sensitivity is also key!



Using LIM for cosmology

- Focus on the anisotropic power spectrum:

$$P(k,\mu,z) = \langle T(z)\rangle^2 b^2(z) F_{RSD}^2(k,\mu,z) P_m(k,z) + P_{shot}(z)$$

$$\langle T(z)\rangle \propto \int L \frac{dn}{dL} dL \qquad P_{shot} \propto \int L^2 \frac{dn}{dL} dL$$

User's guide:JLB+2019a

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- Amplitude determined by LF and bias

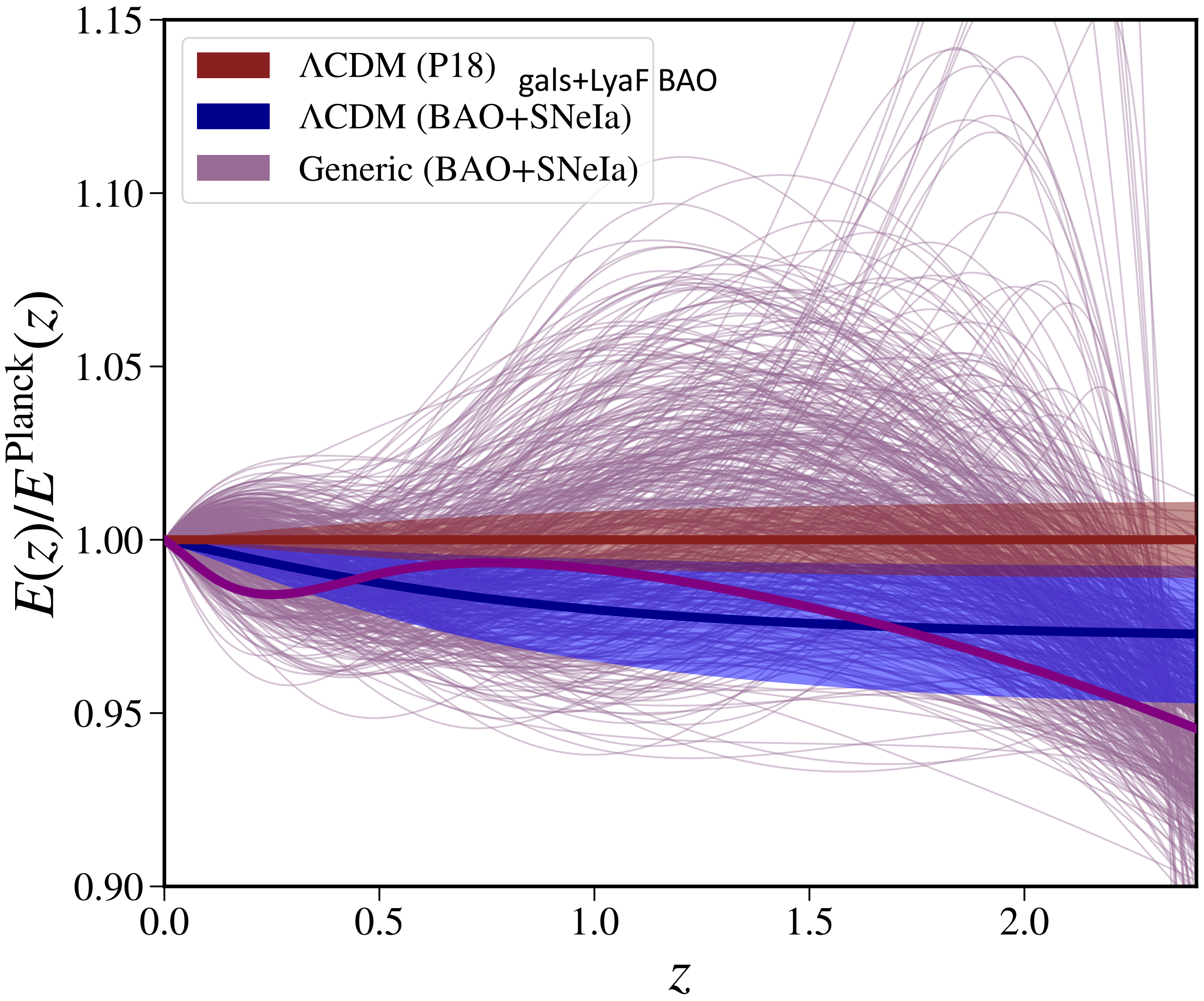
- Signal limited by resolution at small scales and by size of volume probed at large scales (modeled with window functions)

- Use Legendre multipoles to explore anisotropy!

User's guide:JLB+2019a

High-z vs low-z

Done using MABEL



- Planck 18 (ΛCDM):
  - $r_d h = 99.1 \pm 0.9$ Mpc
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- BAO + SNeIa (flexknot):
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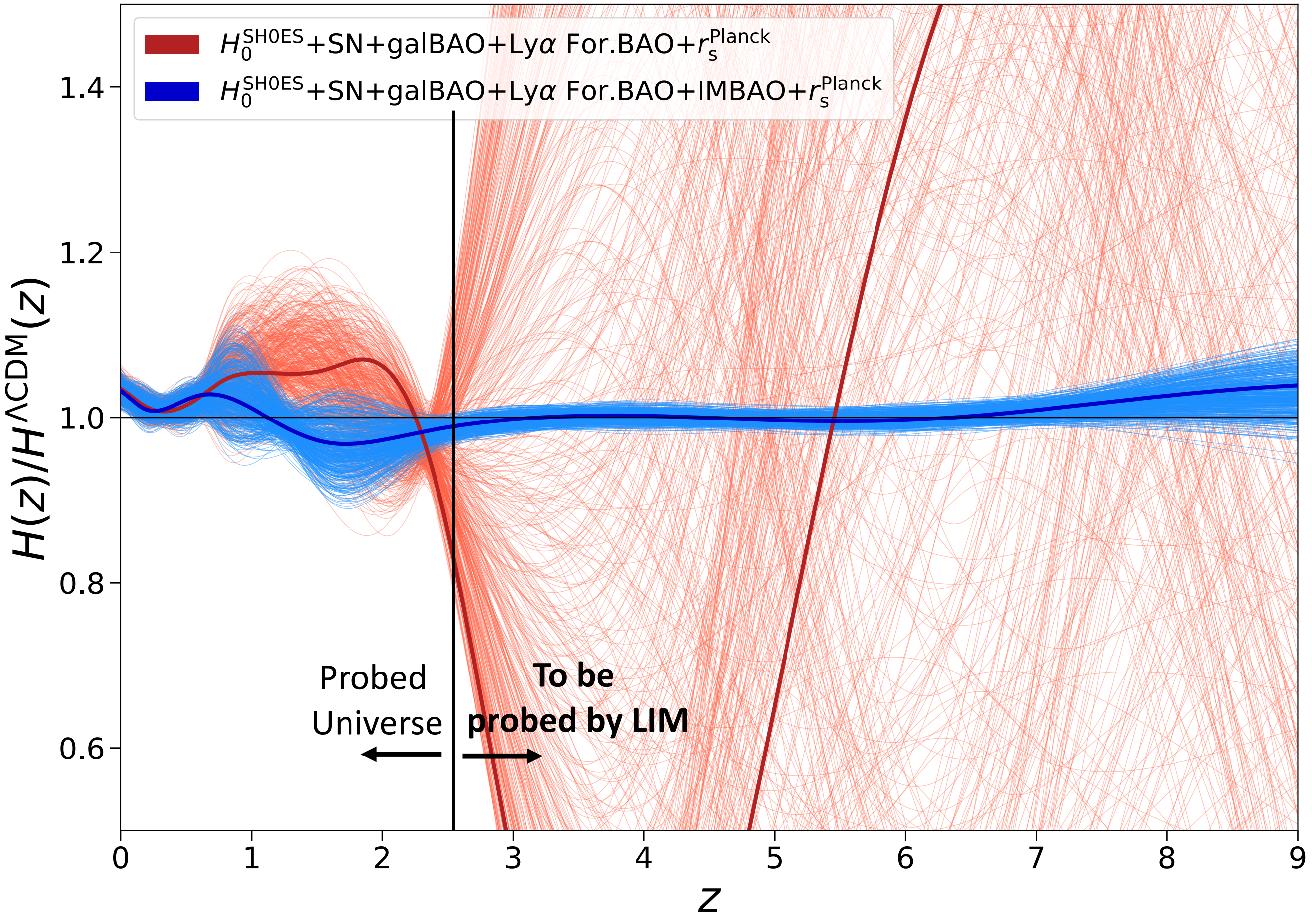
r_d needs to be smaller to match a larger H_0

JLB+2016
JLB+2021

$H(z)$ beyond the reach of galaxy surveys

Model independent $H(z)$ reconstructed with cubic splines



Bridge early and late Universe to probe post-recombination solutions

Current constraints using galaxy surveys (and H_0 and r_s) and **ADDING LIM BAO**

JLB+2019b

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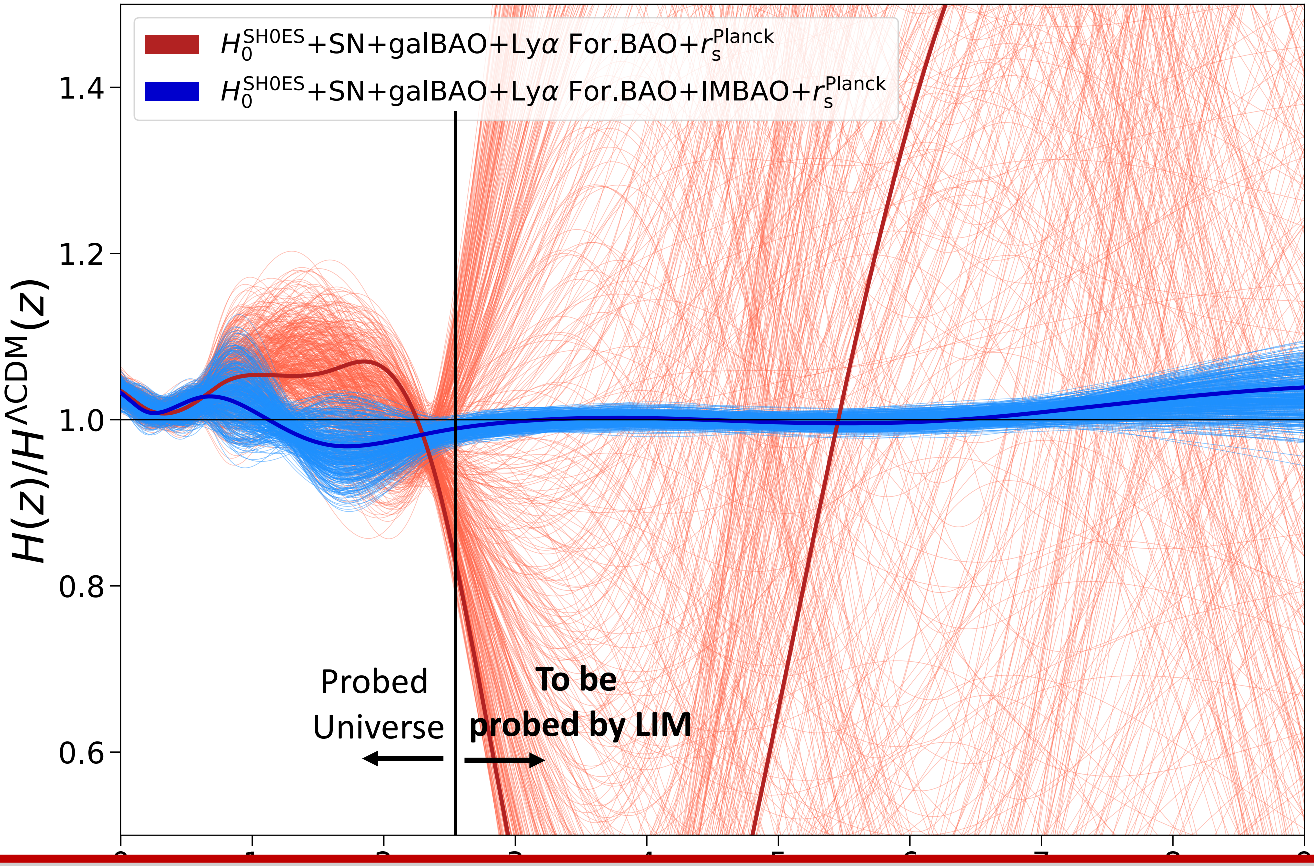

Bridge early and late Universe to probe post-recombination solutions

Also a constraint on $H_0 \times t_U \propto \int_0^z \frac{dz'}{(1+z')E(z')}$,

To be compared with t_U measurements from GCs

JLB+2021
Valcin,JLB+ 2020
Valcin+ 2021

Limitation of LIM P(k)

- Intensity maps are highly non-Gaussian: lots of information beyond P(k)
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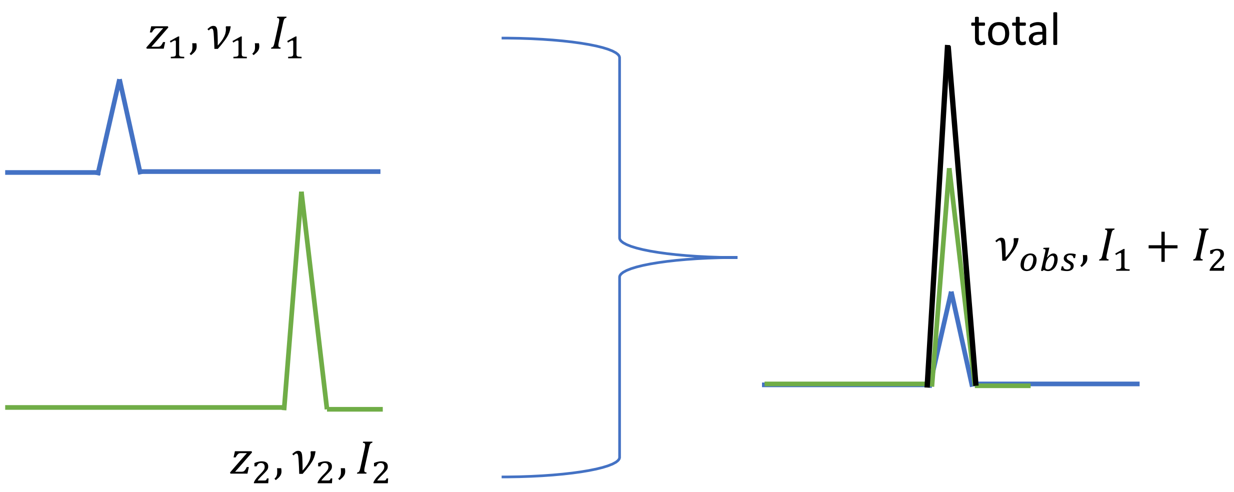
P(k): best for cosmo, integrals of luminosity functions

VID: best for astro, integrals of clustering

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

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

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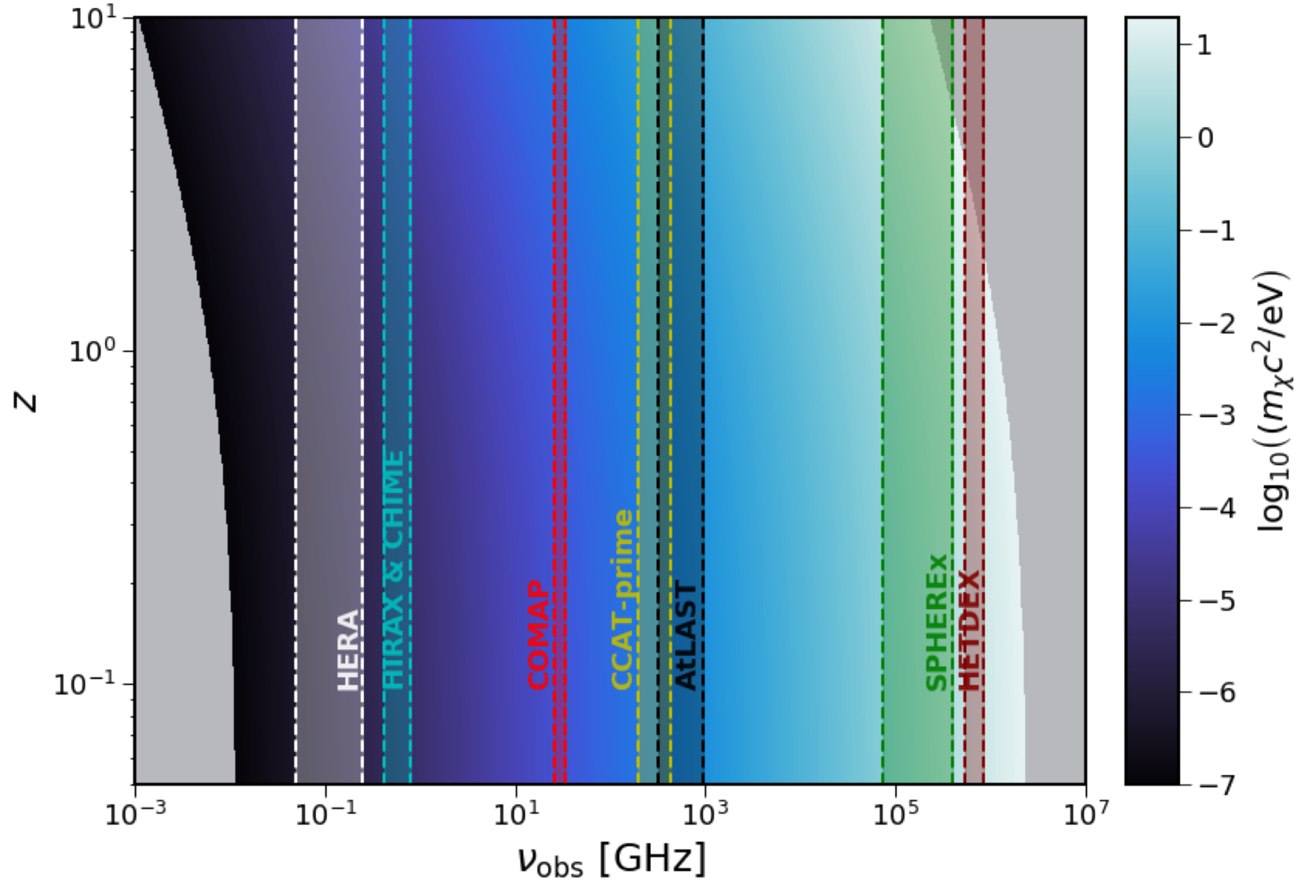
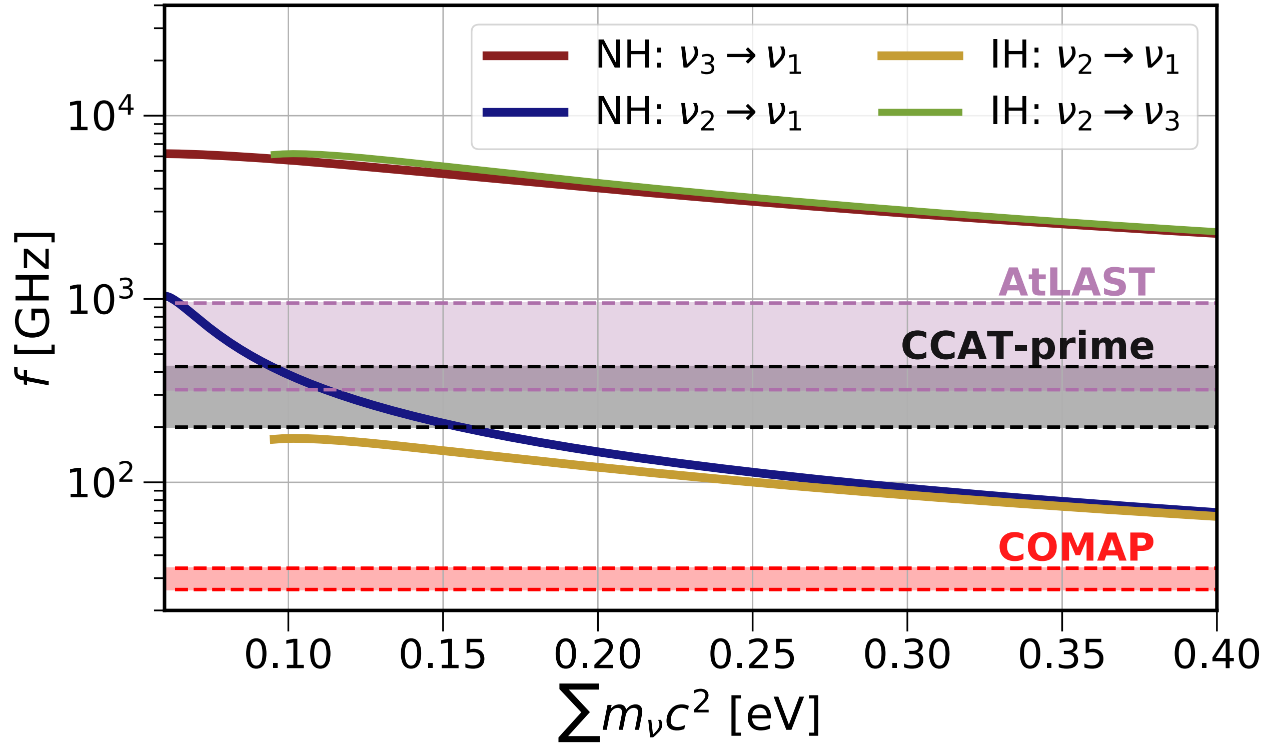


Exotic radiative decays



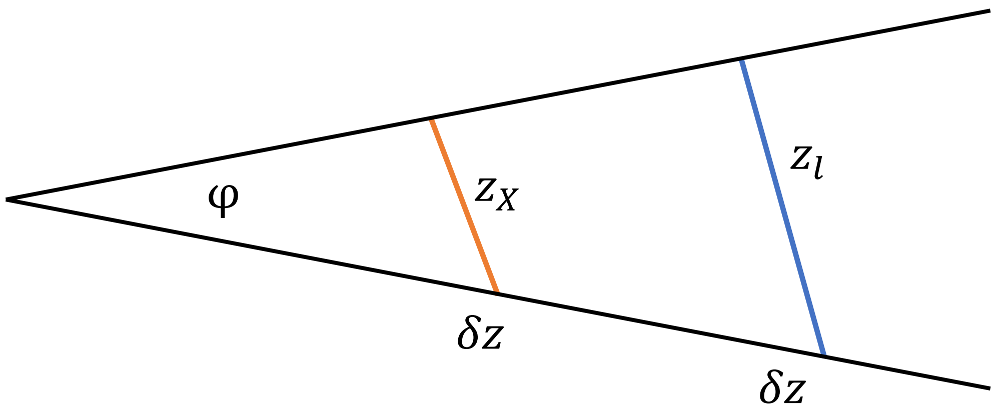
- Neutrino decay: $\nu_i \to \nu_j + \gamma$

$$f_{ij} = (m_i^2 - m_j^2)c^2/2h_P m_i \qquad \rho_L^{ij}(\boldsymbol{x}, z) = \frac{1}{6}\rho_\nu(\boldsymbol{x}, z)c^2\Gamma_{ij}\left(1 - \frac{m_j^2}{m_i^2}\right)$$

- Traces directly the cosmic neutrino density field

Effect in power spectrum

- Confusion in redshift

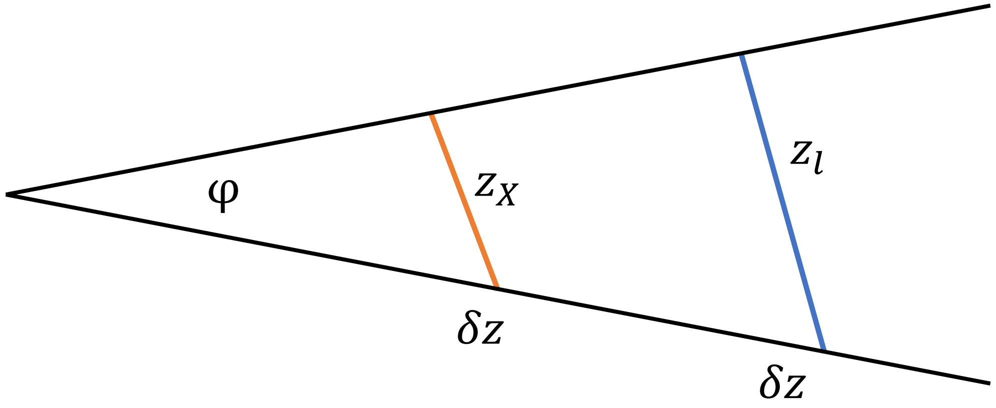


$$x_\perp = D_M(z)\theta$$

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

Effect in power spectrum

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



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

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

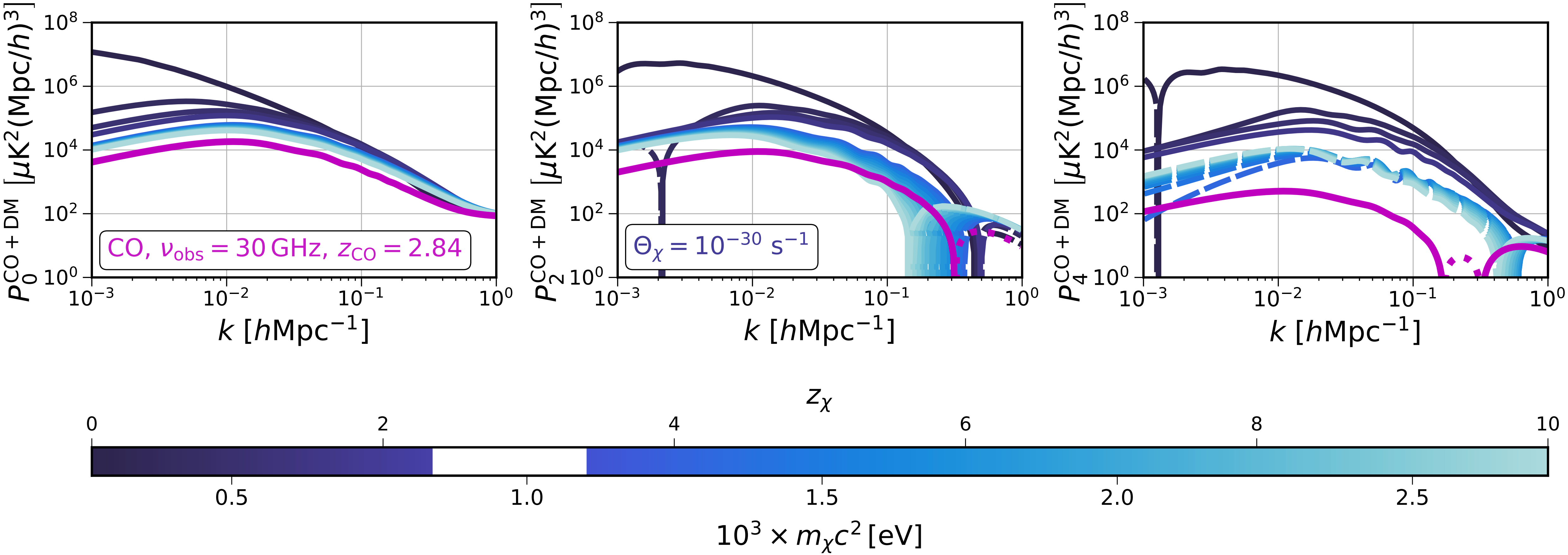
- Model it similar to AP effect: $k_i^{true} \equiv k_i^{infer}/q_i$

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

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

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:

$$T_{tot} = T_l + T_{noise}$$

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

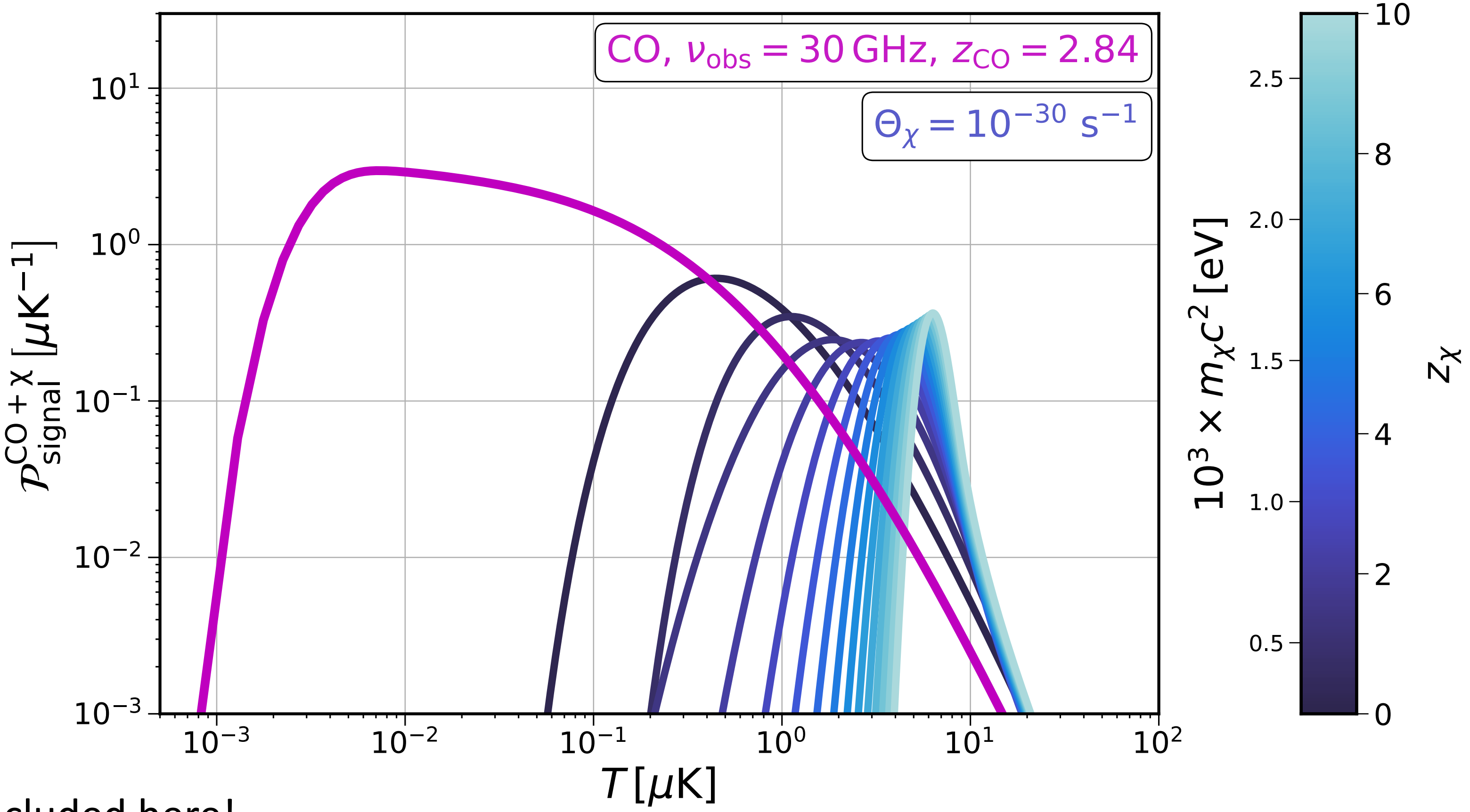
- $\mathcal{P}_{\tilde{\rho}}$: PDF of normalized densities. Obtained from simulations

- We provide the first analytic fit to $\mathcal{P}_{\tilde{\rho}_\nu}$, using Quijote simulations and symbolic regression

Effect in VID

- Each voxel receives contributions from both emissions:

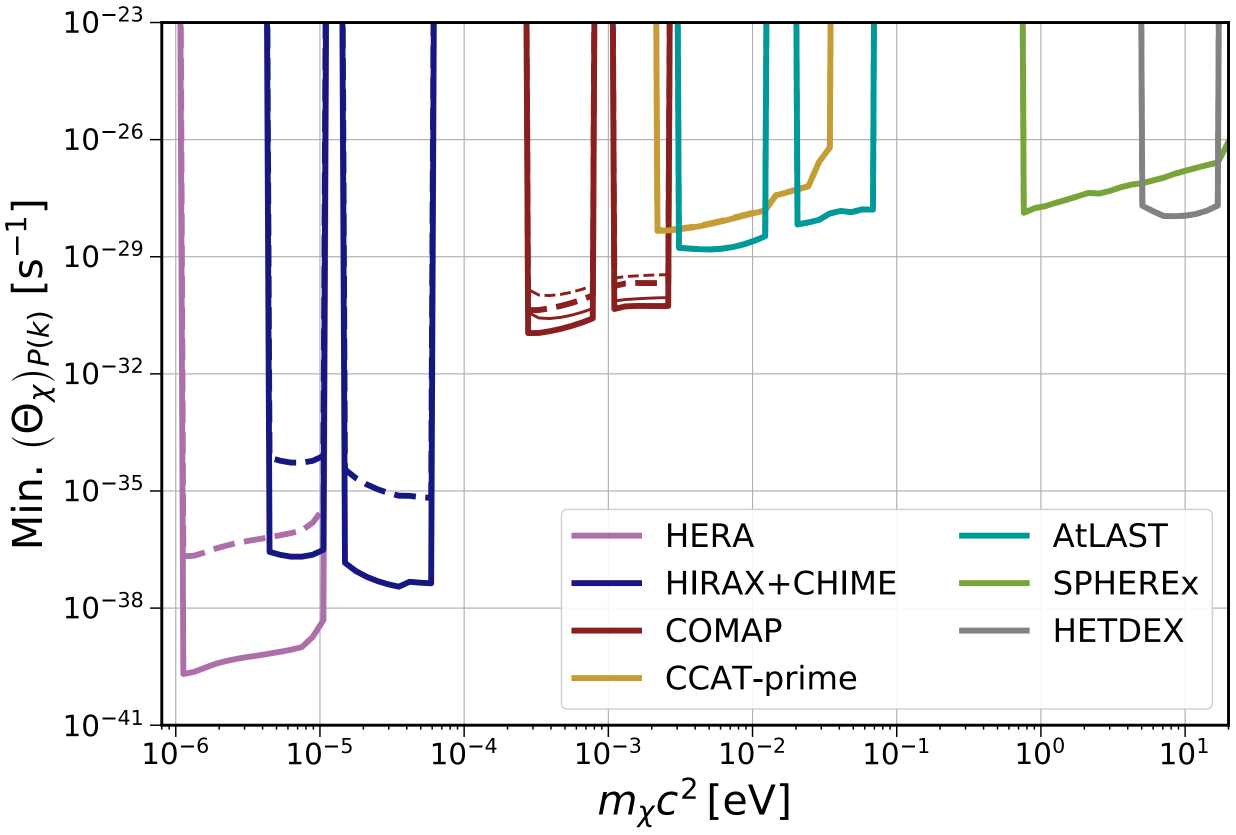
$$\mathcal{P}_{tot+\chi}(T) = \left(\left(\mathcal{P}_l * \mathcal{P}_\chi\right) * \mathcal{P}_{noise}\right)(T); \qquad \mathcal{P}_\chi = \mathcal{P}_{\tilde{\rho}}/\langle T_\chi \rangle$$

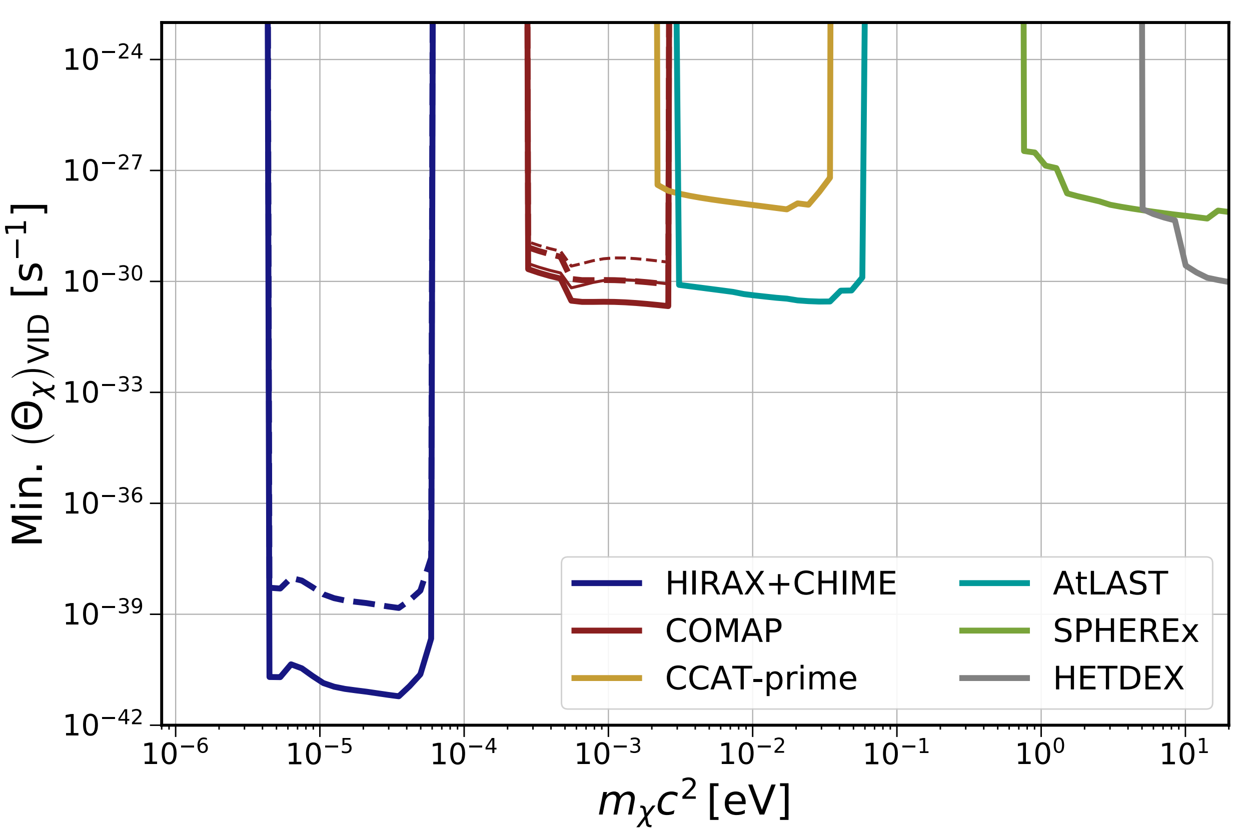


No noise contribution included here!

Sensitivity to DM decays

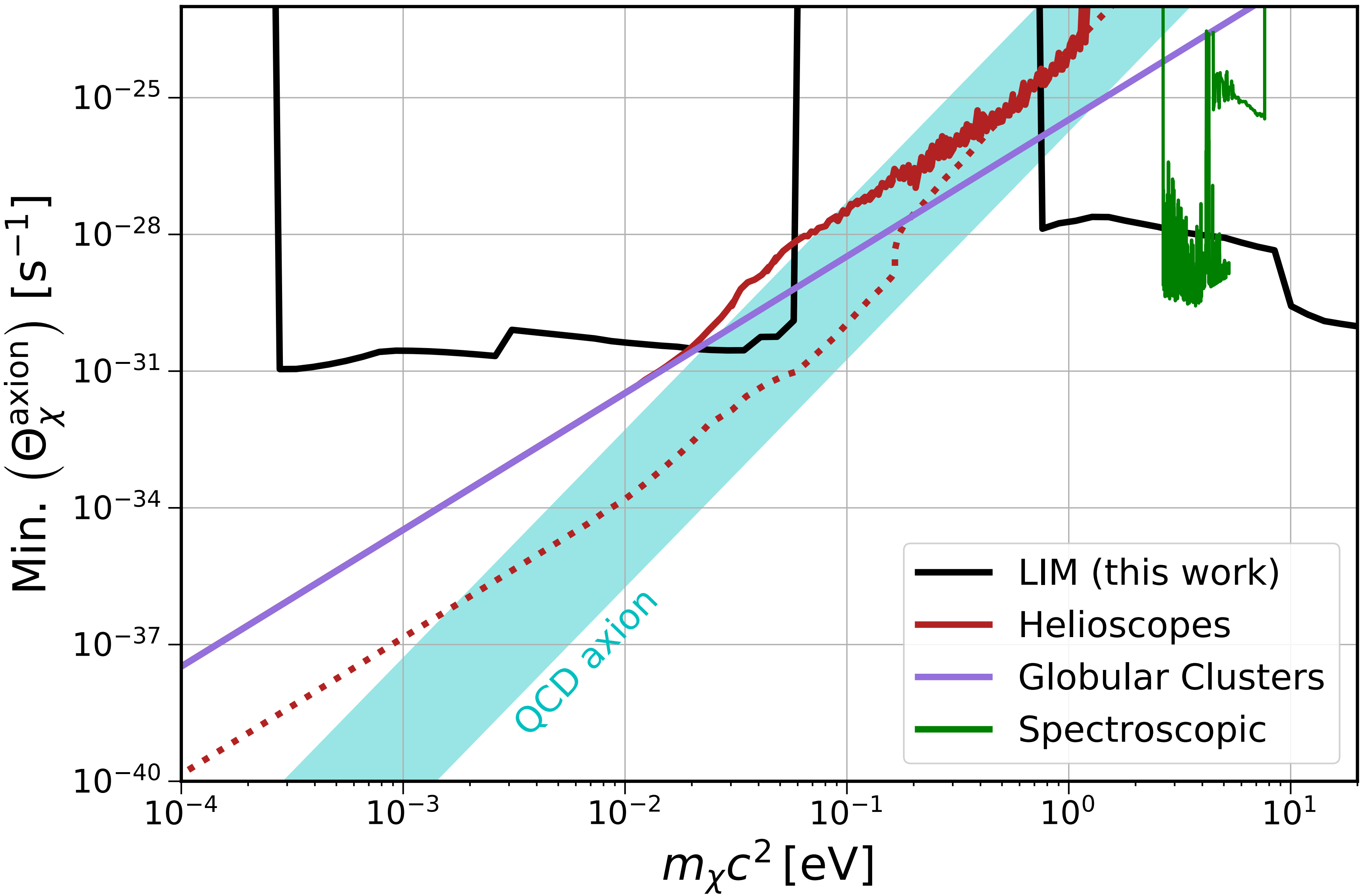
- After marginalizing over astrophysical uncertainties of the target emission line





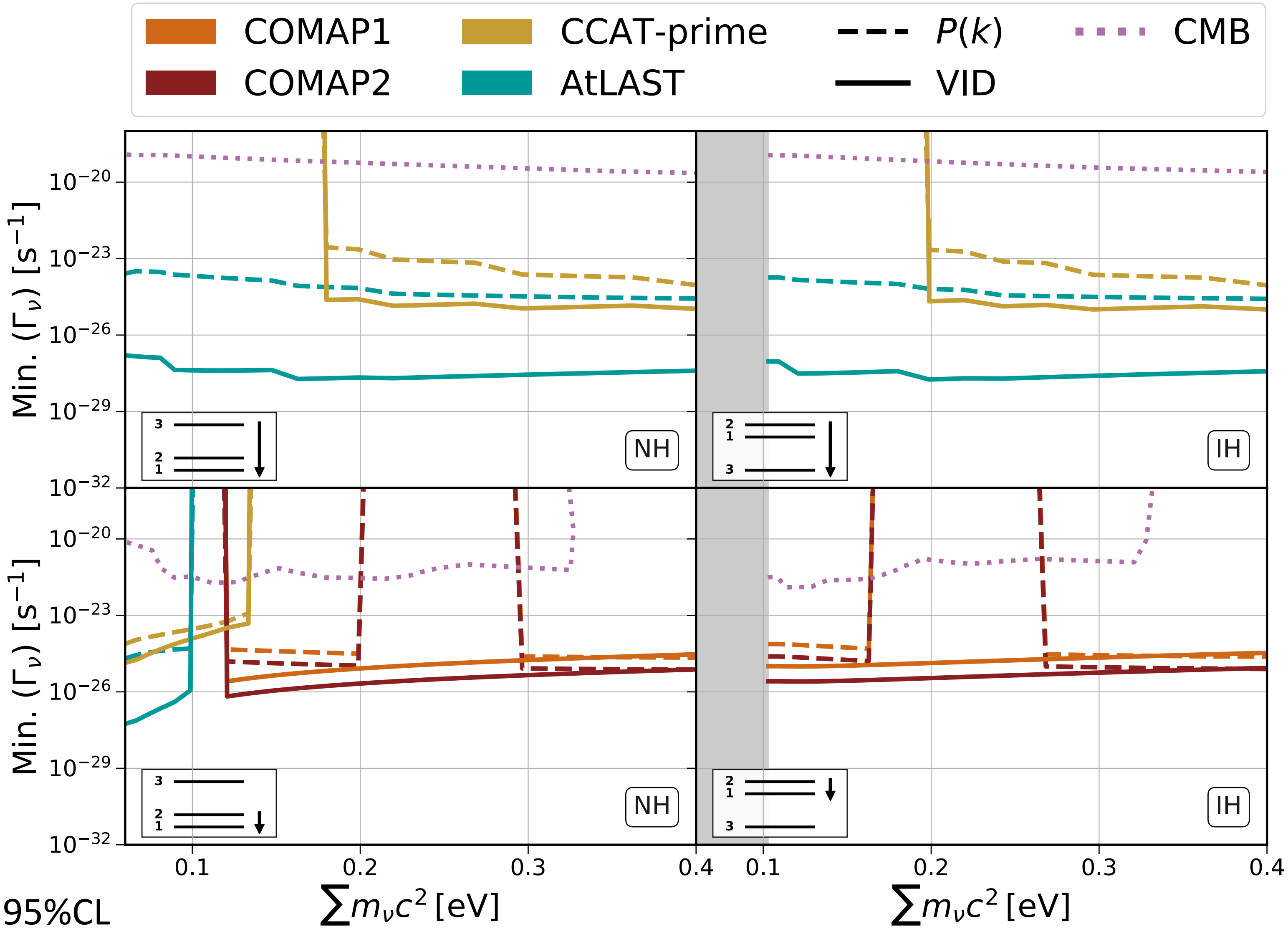
95%CL

Sensitivity in axion context



95%CL

Sensitivities to neutrino decay



95%CL

$$\Gamma_{ij} \sim 10^{-28} - 10^{-25} \mathrm{s}^{-1}$$

$$\downarrow$$

$$\mu_{ij}^{eff} \sim 10^{-12} - 10^{-8} \left(\frac{m_i c^2}{0.1\mathrm{eV}} \right)^{1.5} \mu_B$$

- CMB forescast: $3{\times}10^{-11} - 10^{-8}\mu_B$
- Borexino: $< 2.8{\times}10^{-11}\mu_B$
- TRGB: $< 4.5{\times}10^{-12}\mu_B$

Challenges & improvements

- Challenges:
  - Astrophysical uncertainties: marginalized over them
  - Other contaminants: modeled loss information
  - Line broadening

- Reasons to be optimistic:
  - Extensible to other summary statistics
  - Combination with cross-correlations with galaxy clustering and weak lensing
  - Confusion between DM and neutrino decays: characteristic differences when combining summary statistics and probes
  - Targeted masking to increase relative exotic contributions

Conclusions

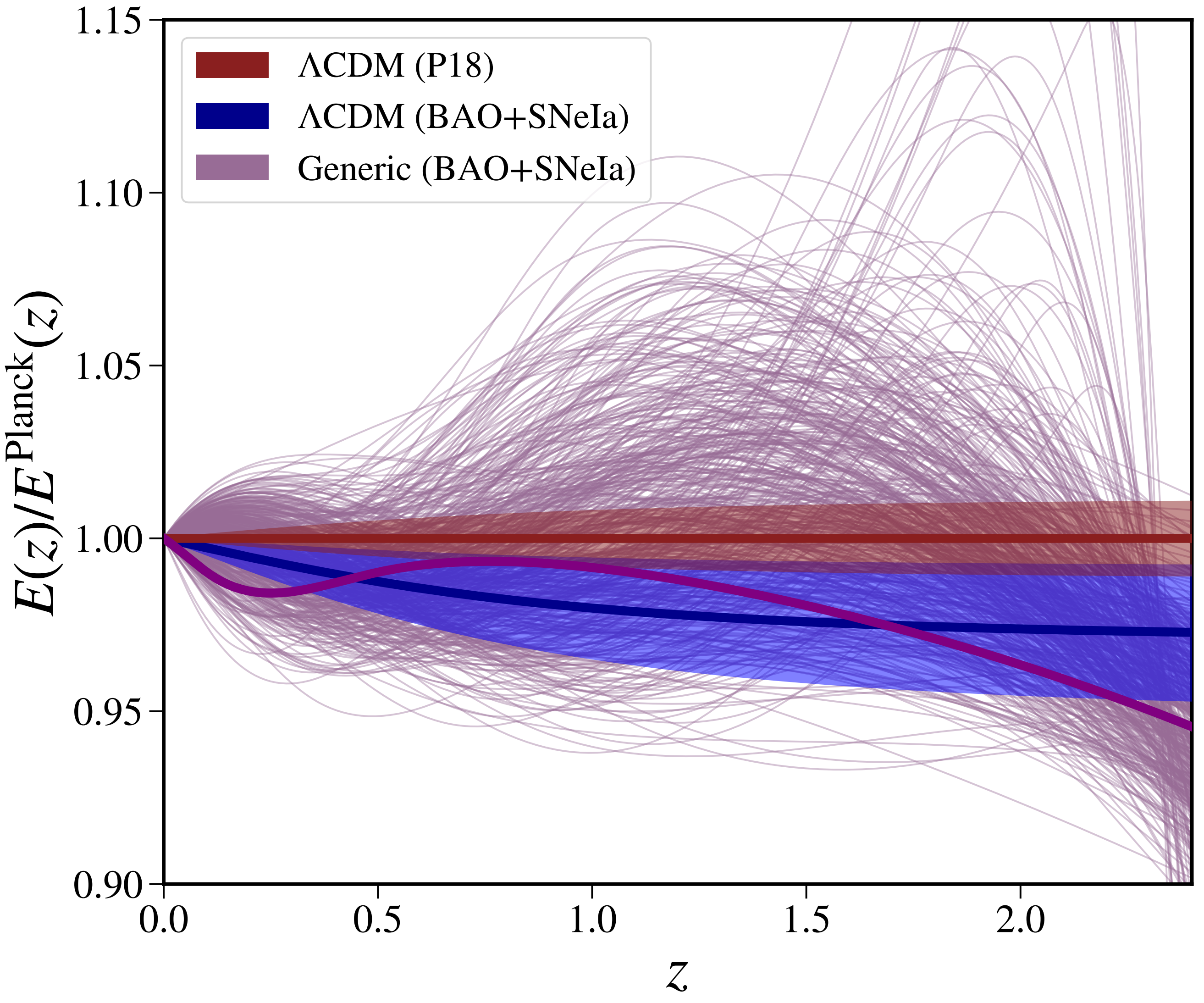
- LIM holds a great protential to unadvertedly detect exotic radiative decays as line-interlopers.
- Adapting techniques to identify and model interlopers is a cheap and powerful strategy.
- General treatment, for phenomenological DM and neutrino decays that can be translated later to specific models
- Sensitivity extremely competitive:
  - DM: HETDEX & SPHEREx will improve current constraints (1-10 eV) and AtLAST will be similar to IAXO (0.01-0.1 eV)
  - Neutrinos: Improve CMB forecasts and competitive with best constraints

Back up slides

JLB+ 2021

High-z vs low-z

Done using MABEL



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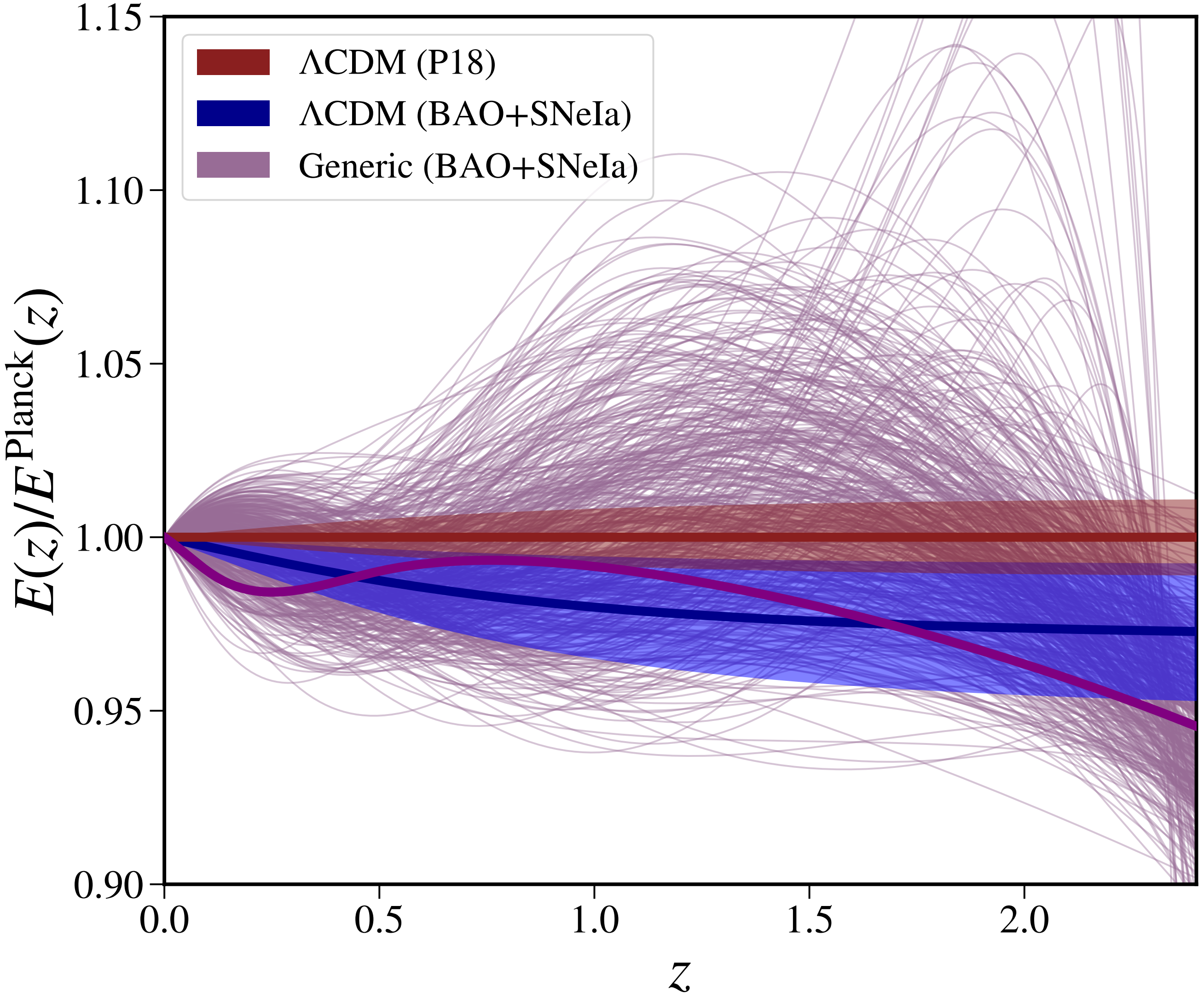

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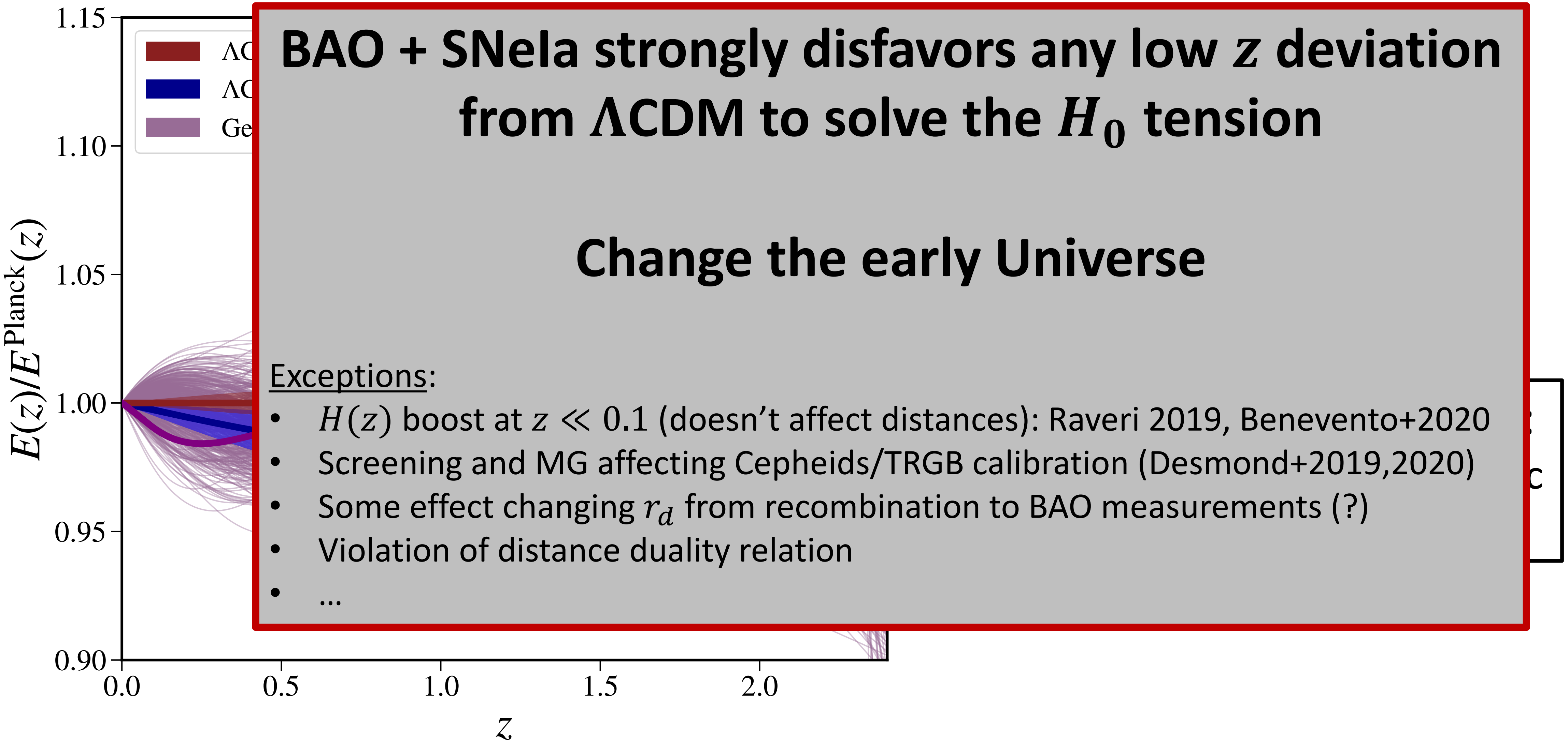


BAO + SNeIa strongly disfavors any low z deviation from ΛCDM to solve the H_0 tension

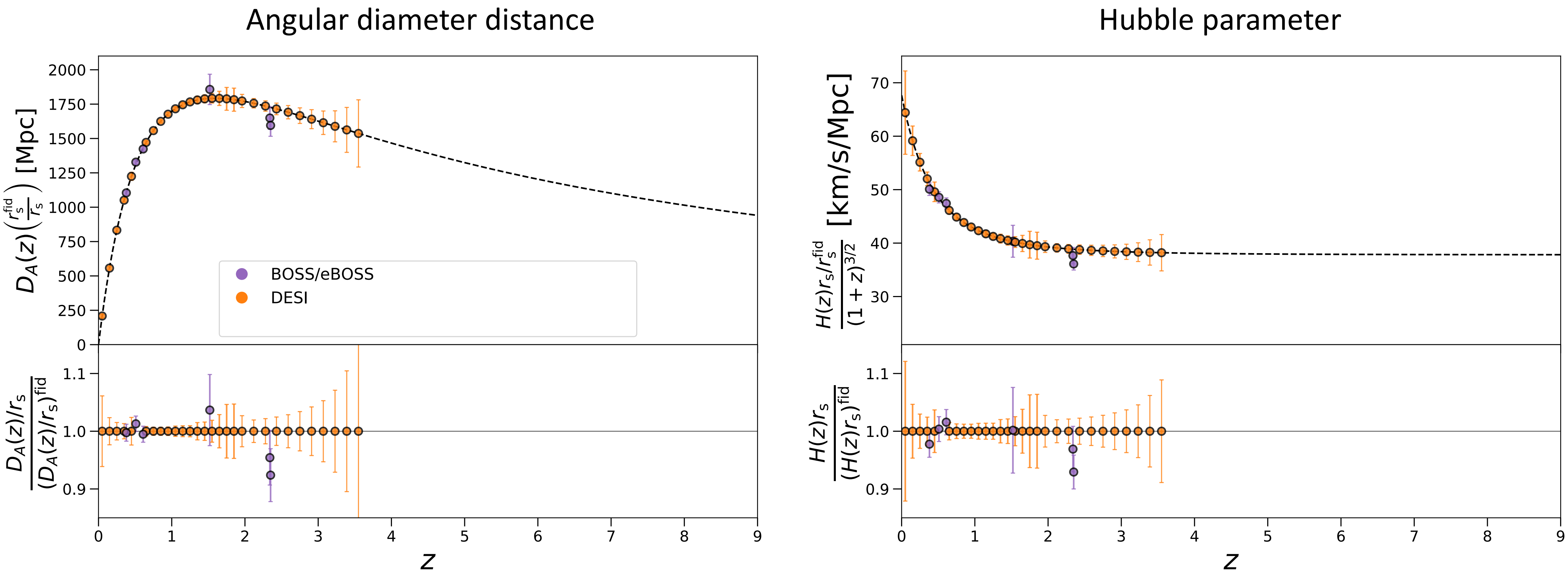
Change the early Universe

Exceptions:

- $H(z)$ boost at $z \ll 0.1$ (doesn't affect distances): Raveri 2019, Benevento+2020
- Screening and MG affecting Cepheids/TRGB calibration (Desmond+2019,2020)
- Some effect changing r_d from recombination to BAO measurements (?)
- Violation of distance duality relation
- …

JLB+2019b

LIM BAO

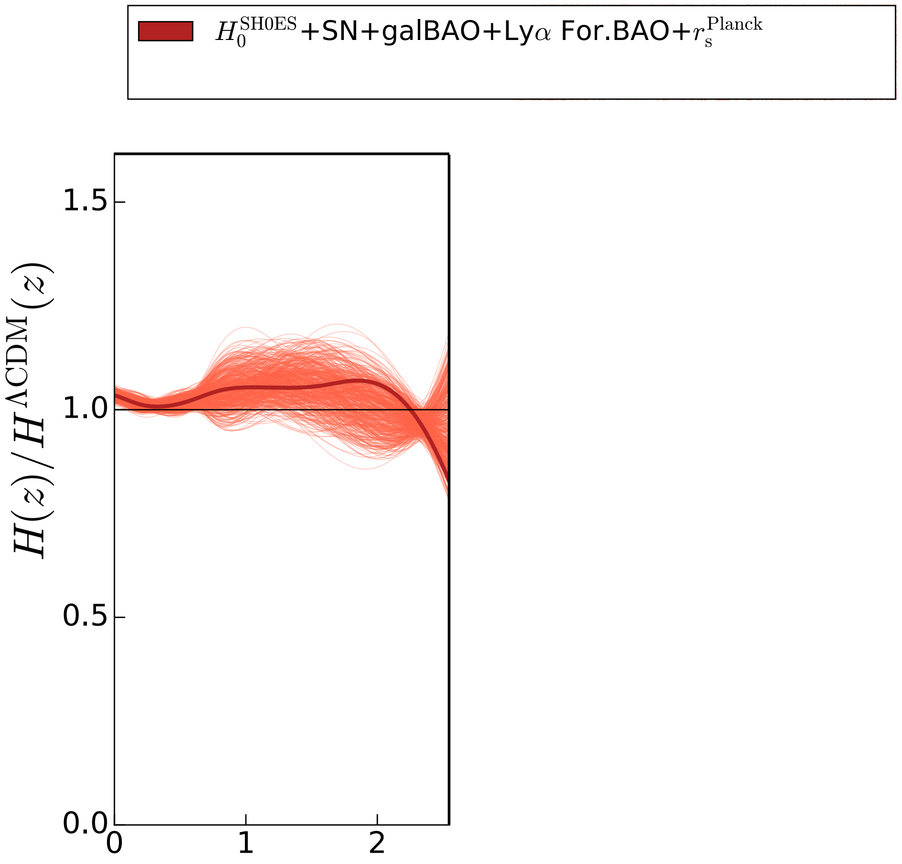


Current and coming constraints using galaxy surveys

Constraining the expansion history

JLB+2019b

Model independent $H(z)$ reconstructed with cubic splines



Current constraints using galaxy surveys (and H_0 and r_s)

JLB+2019b

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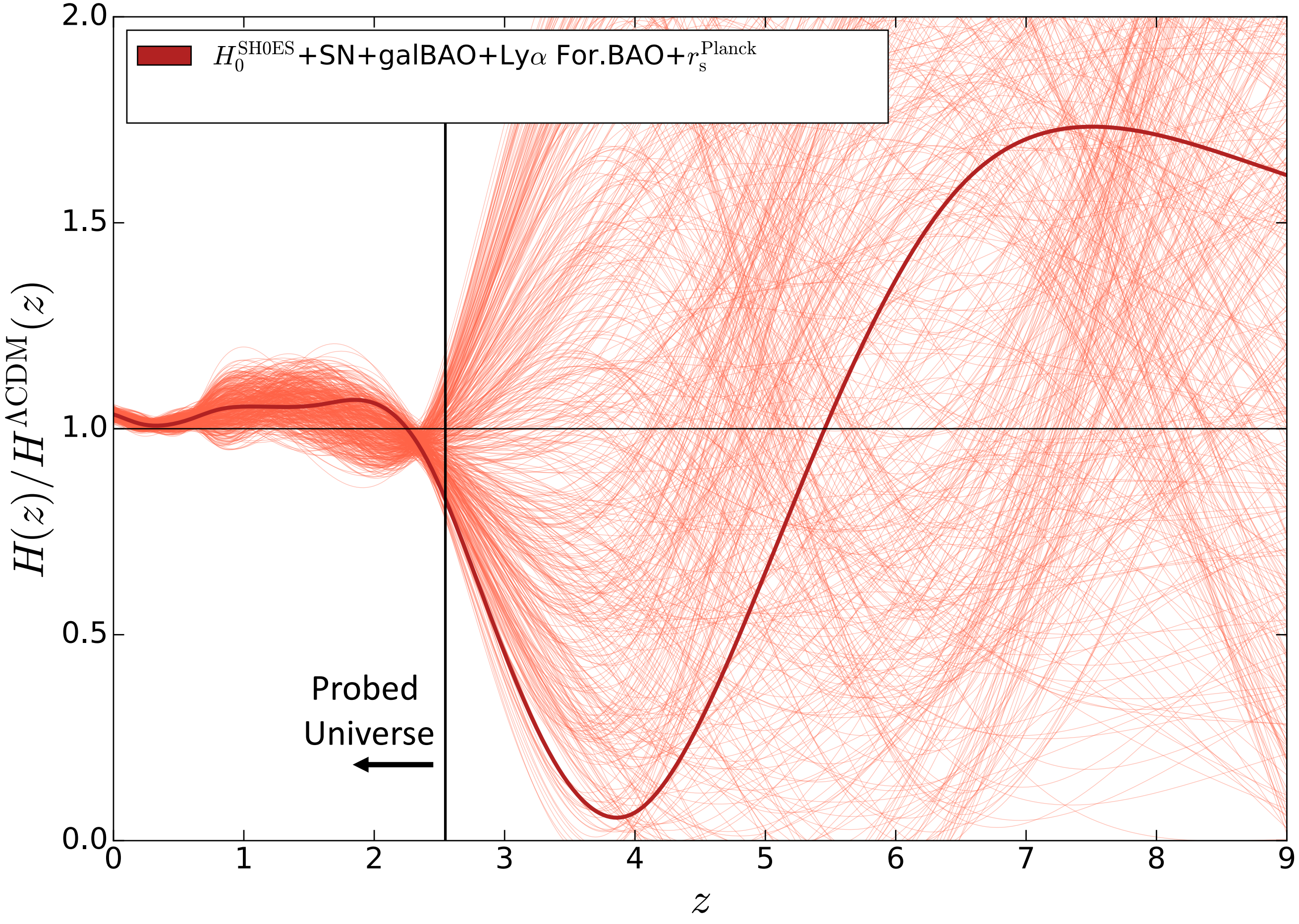

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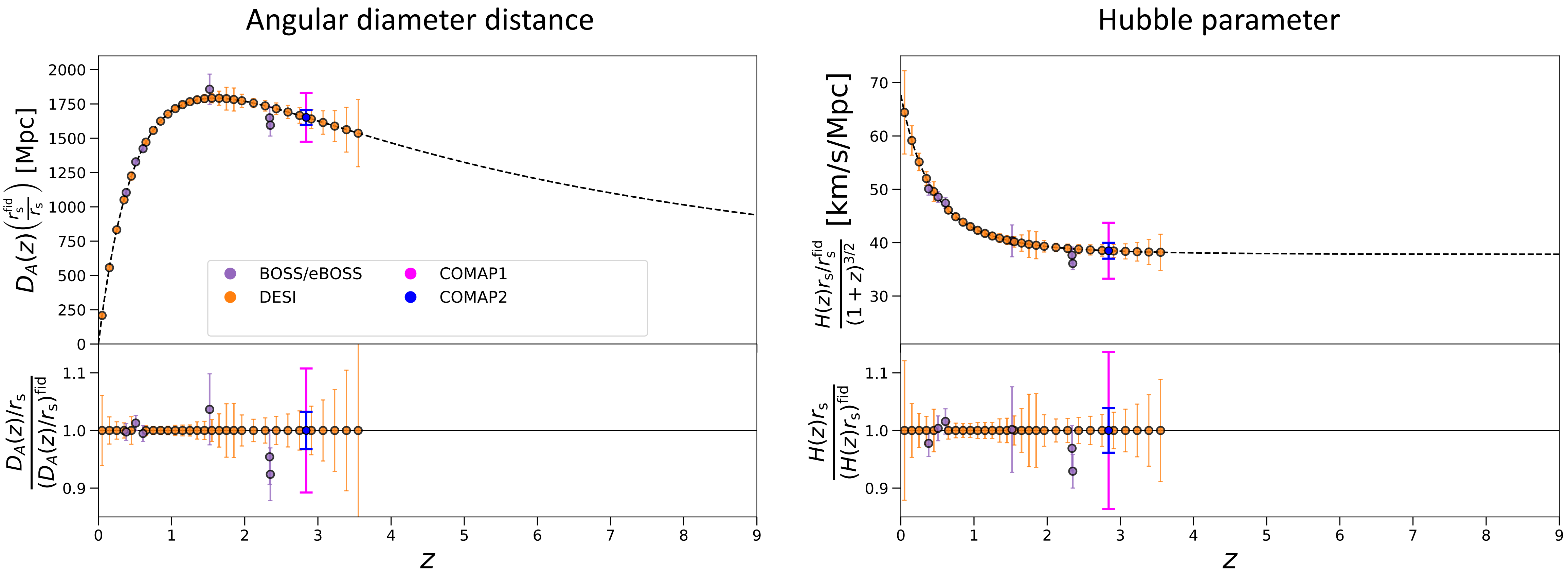


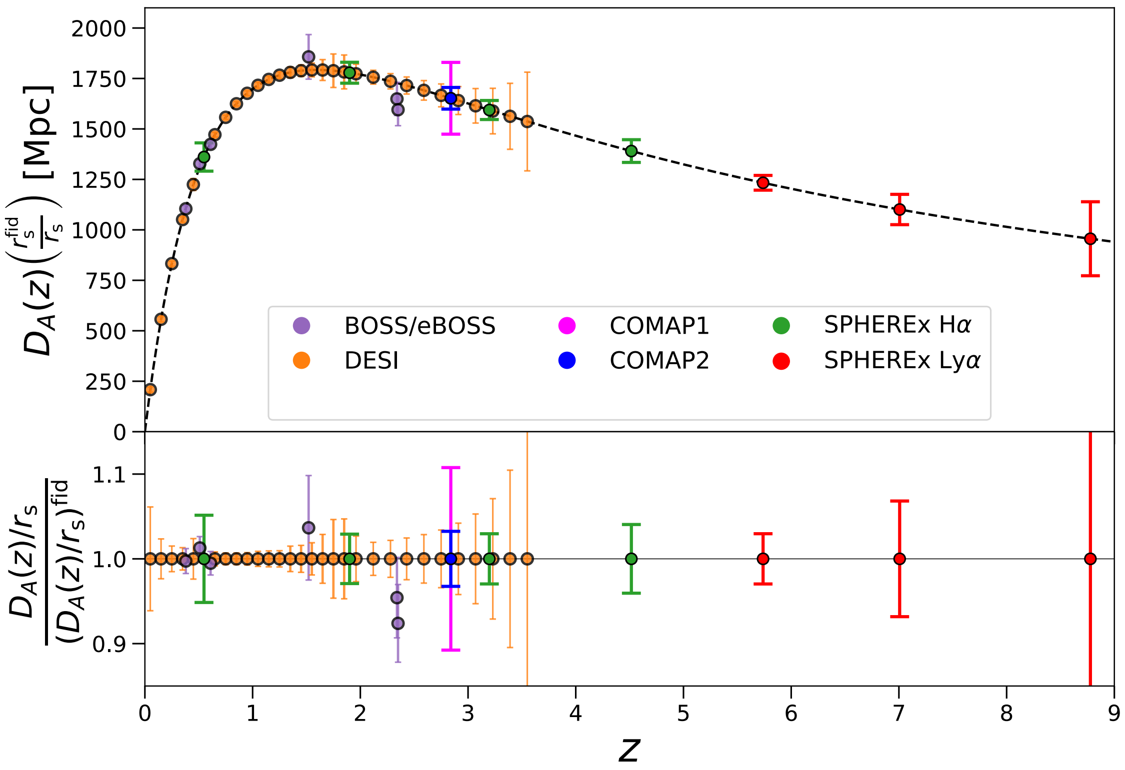
Current and coming constraints using galaxy surveys

+ Star-Formation-related LIM BAO

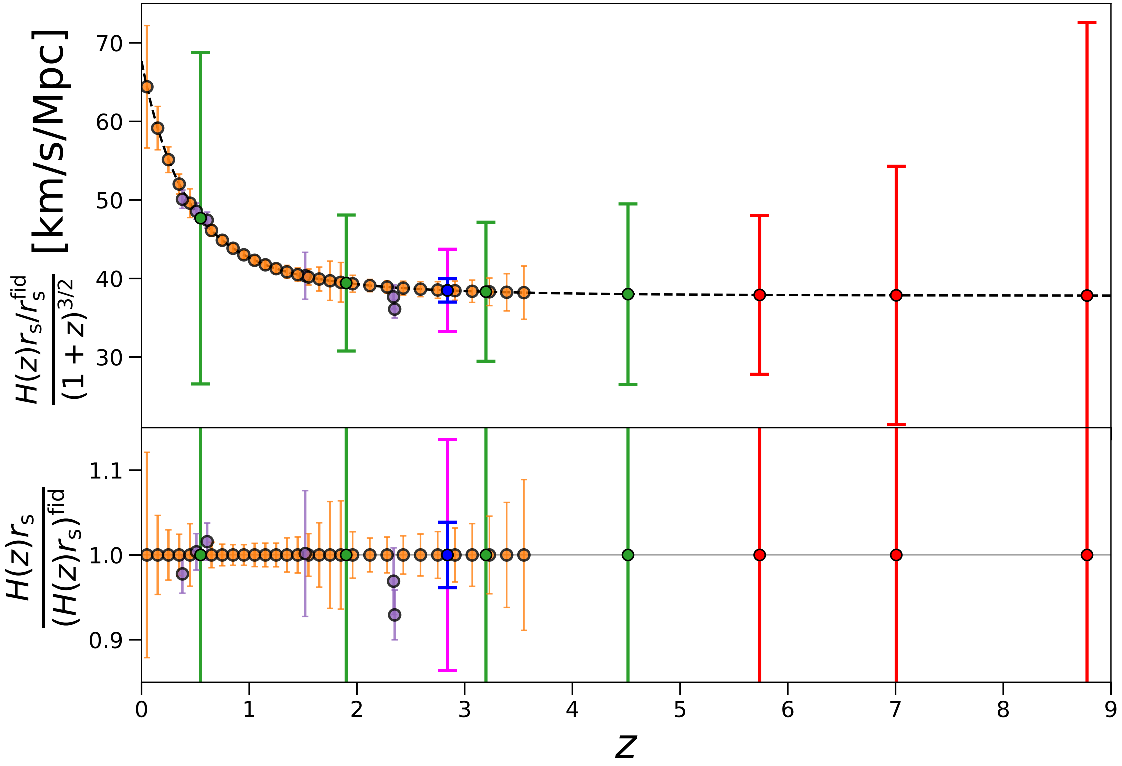
JLB+2019b

LIM BAO

Angular diameter distance



Hubble parameter



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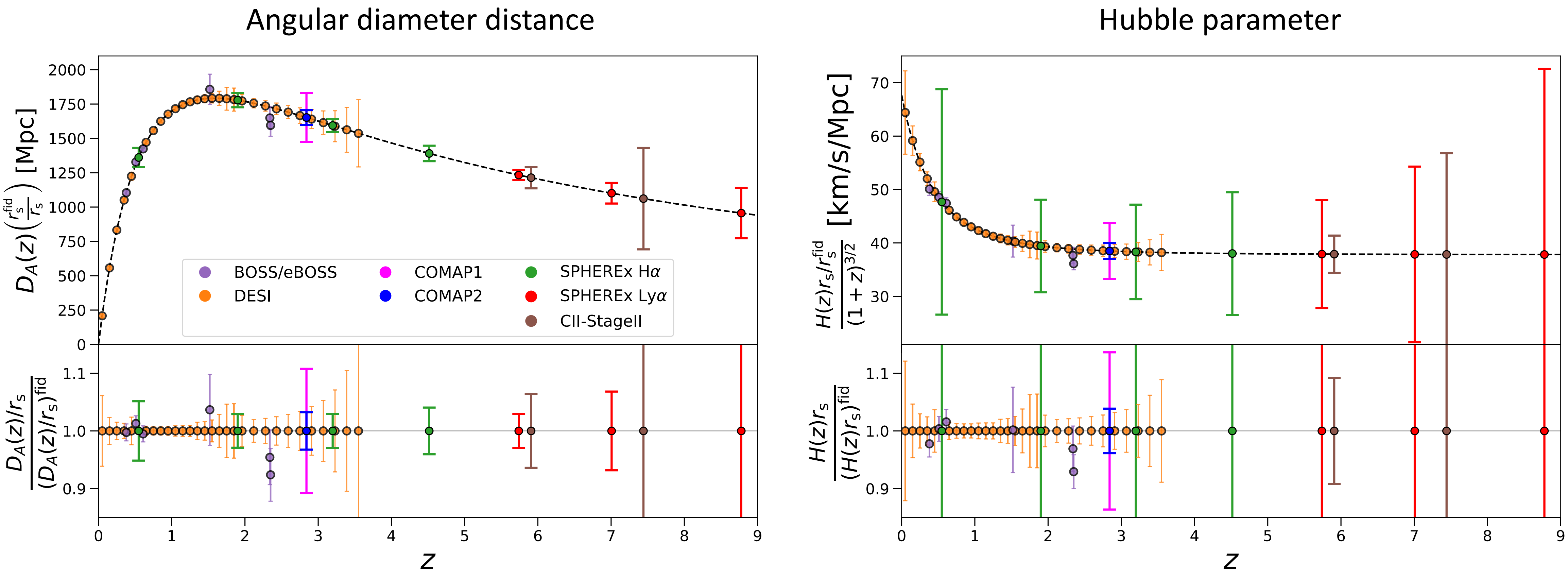
JLB+2019b



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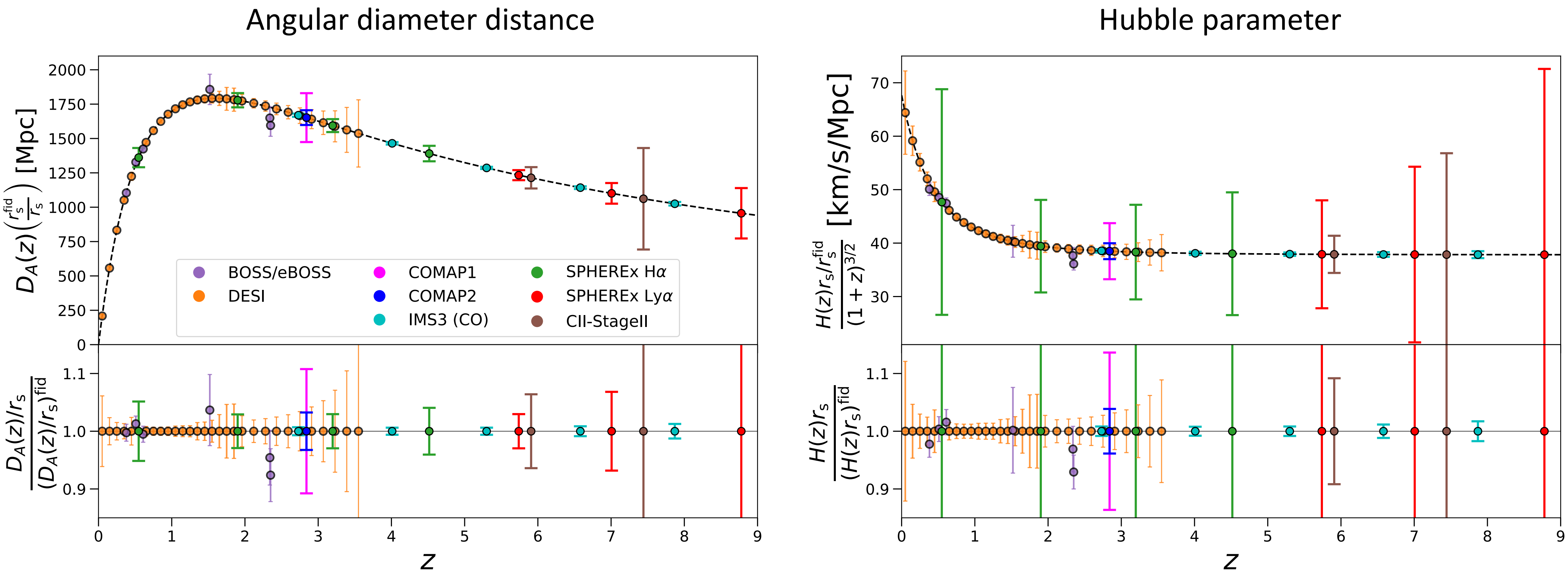

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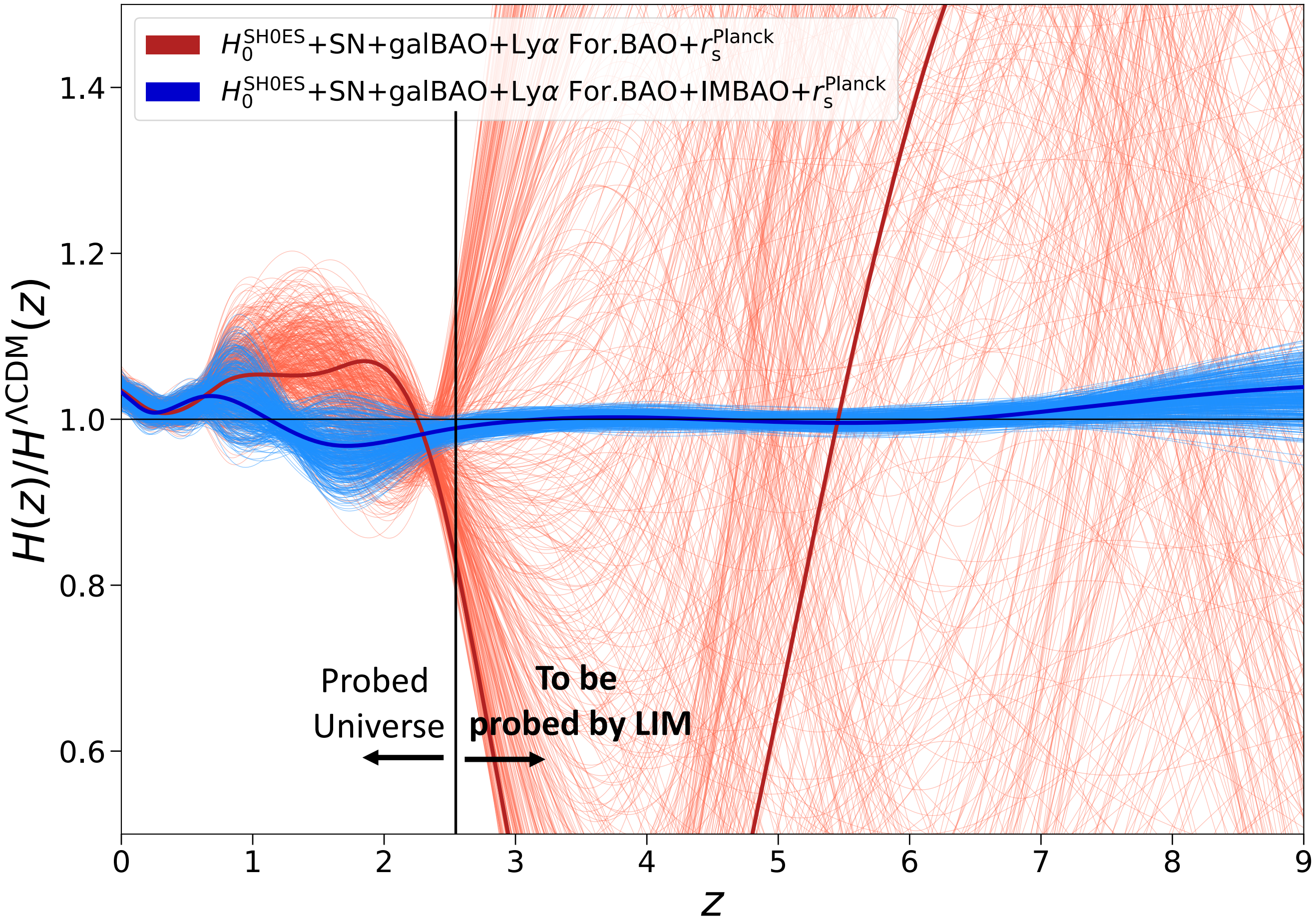

Bridge early and late Universe to probe post-recombination solutions

Current constraints using galaxy surveys (and H_0 and r_s) and **ADDING LIM BAO**

JLB+2019a
JLB+2019b