Exploring the Universe with Line-Intensity mapping

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JOHNS HOPKINS
KRIEGER SCHOOL of ARTS & SCIENCES

Introduction

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

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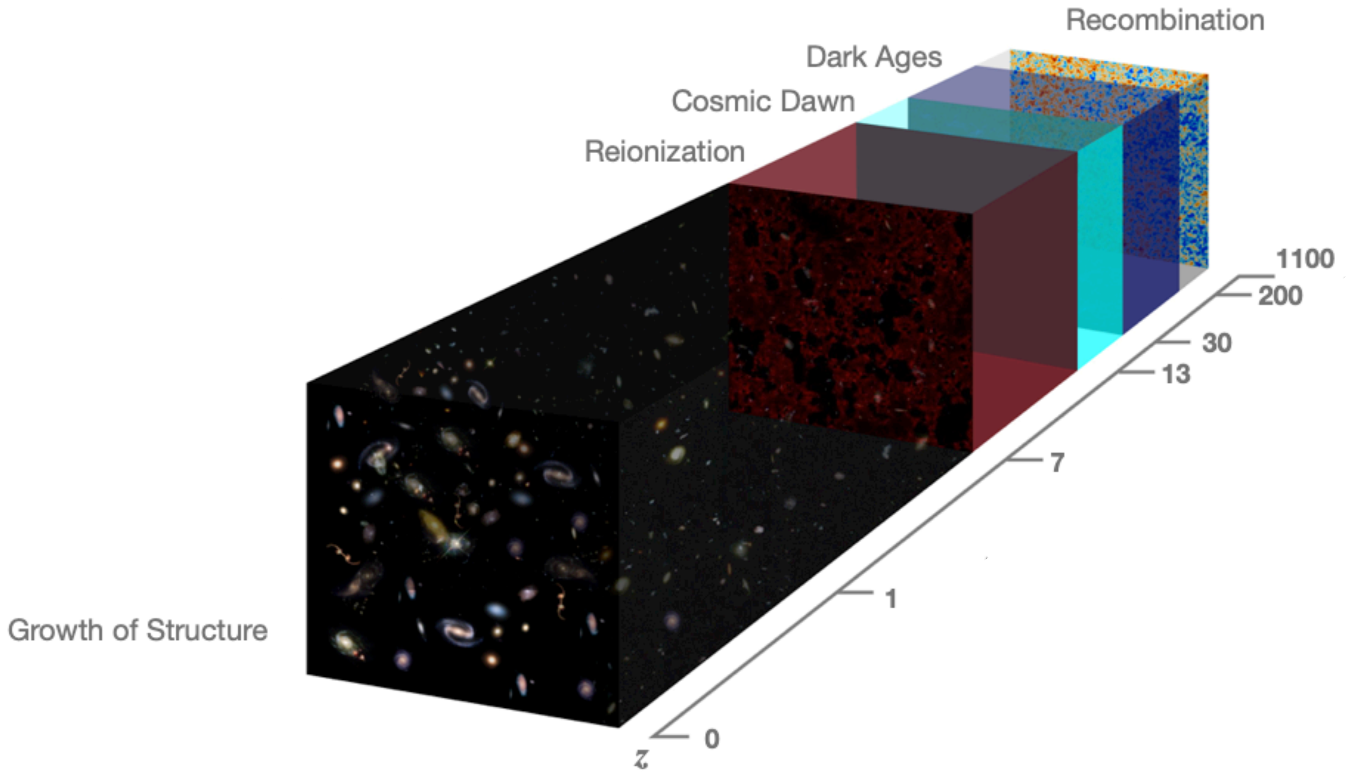
- Standard cosmological model: ΛCDM
- Excellent reproduction of the observations, but…
  - Persistent discrepancies between different cosmological probes (high-z vs low-z?): H_0, $\sigma_8\Omega_M^{0.5}$
  - Phenomenological model: nature of DM and DE? Primordial Universe?

Introduction

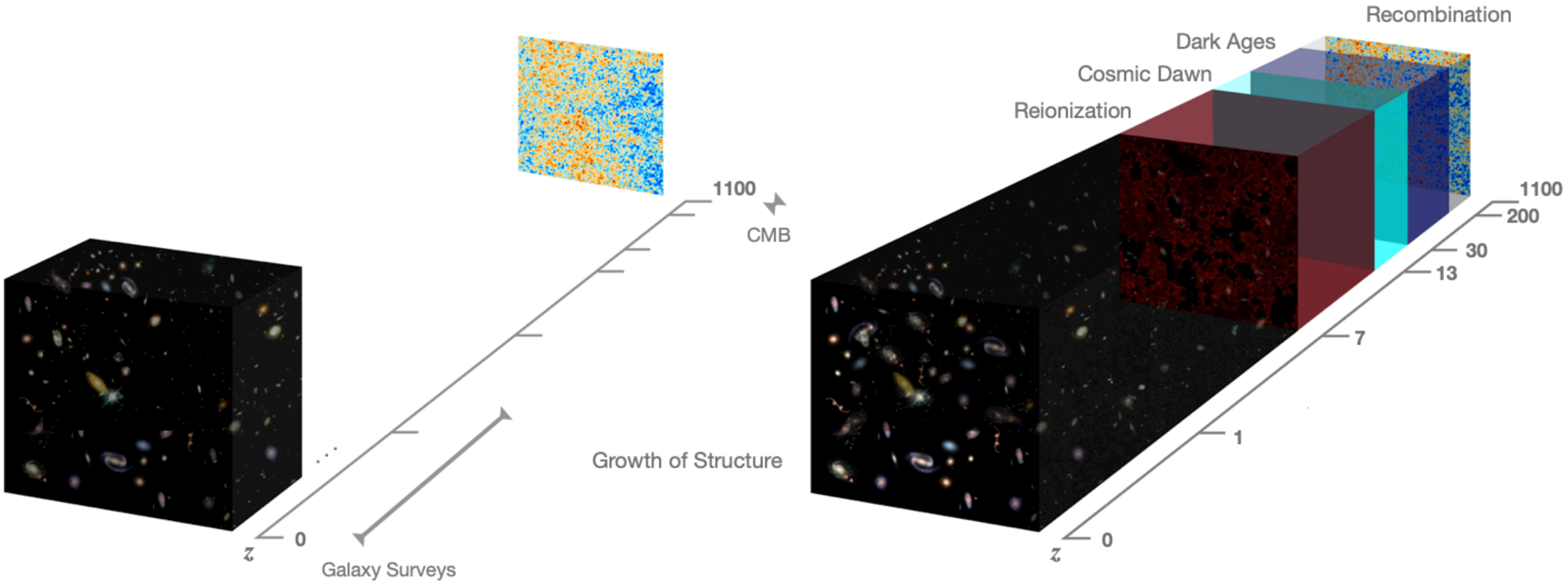
- Precision cosmology: CMB, clustering & BAO, lensing, SNeIa, GWs, …
- Standard cosmological model: ΛCDM
- Excellent reproduction of the observations, but…
- Improvement of observations, new models, **new cosmological probes**, …

Probing the Universe



E. D. Kovetz

Probing the Universe



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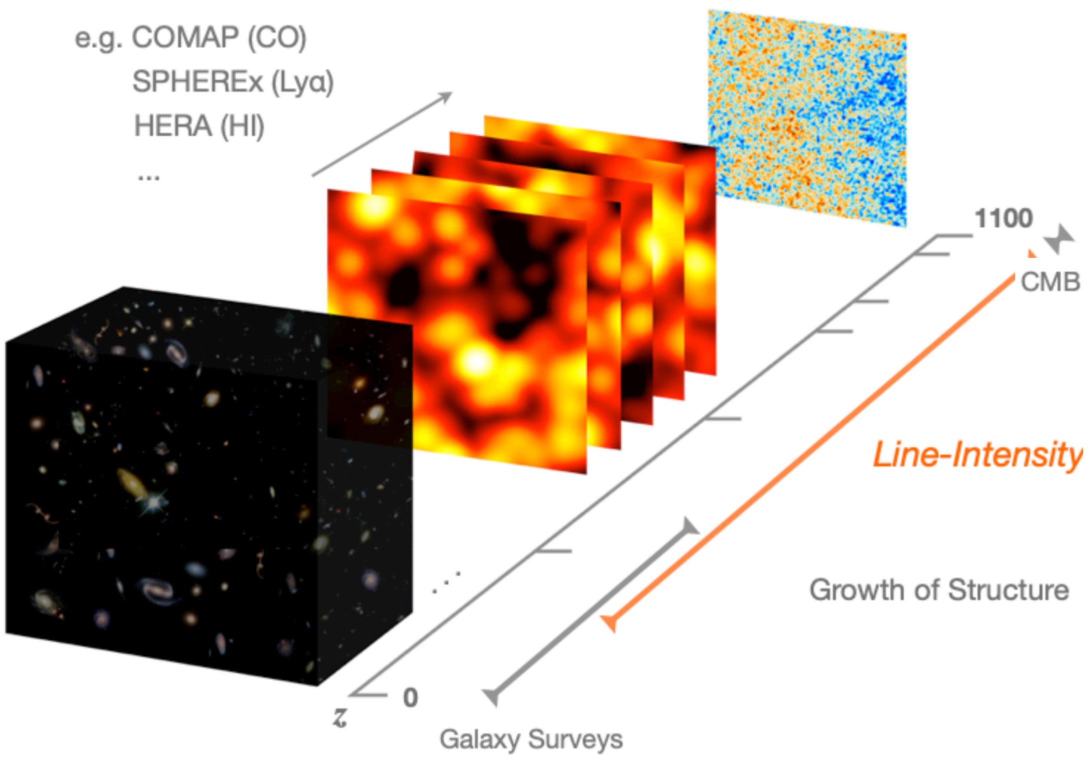

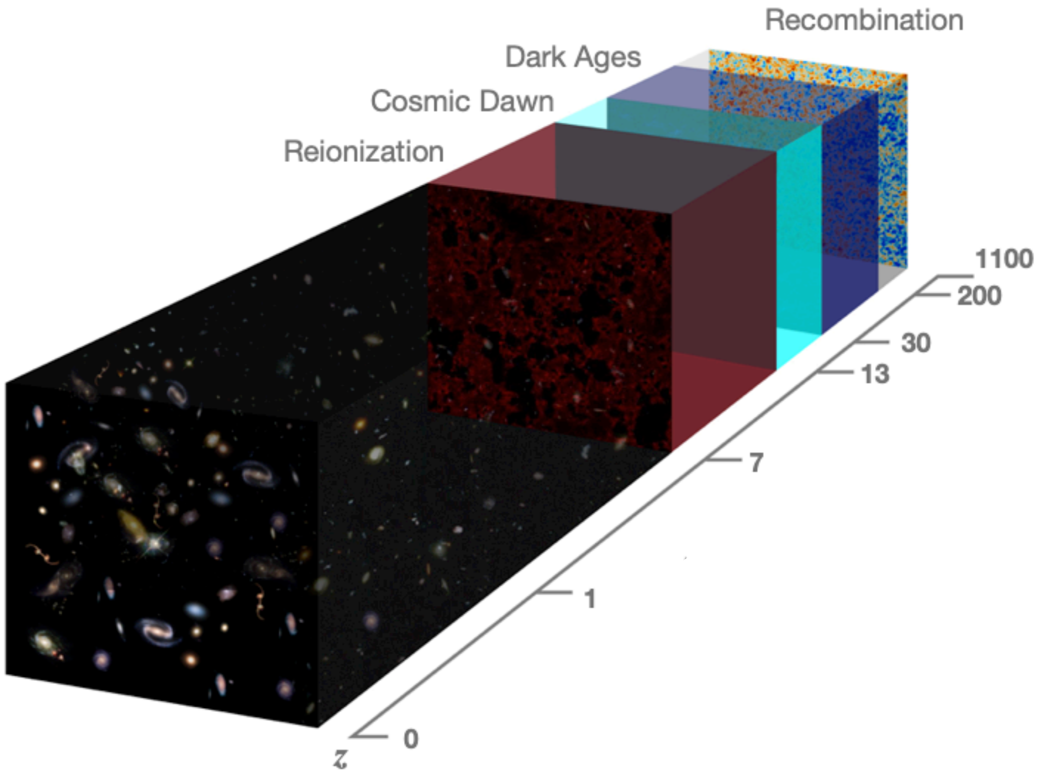

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Probed Universe

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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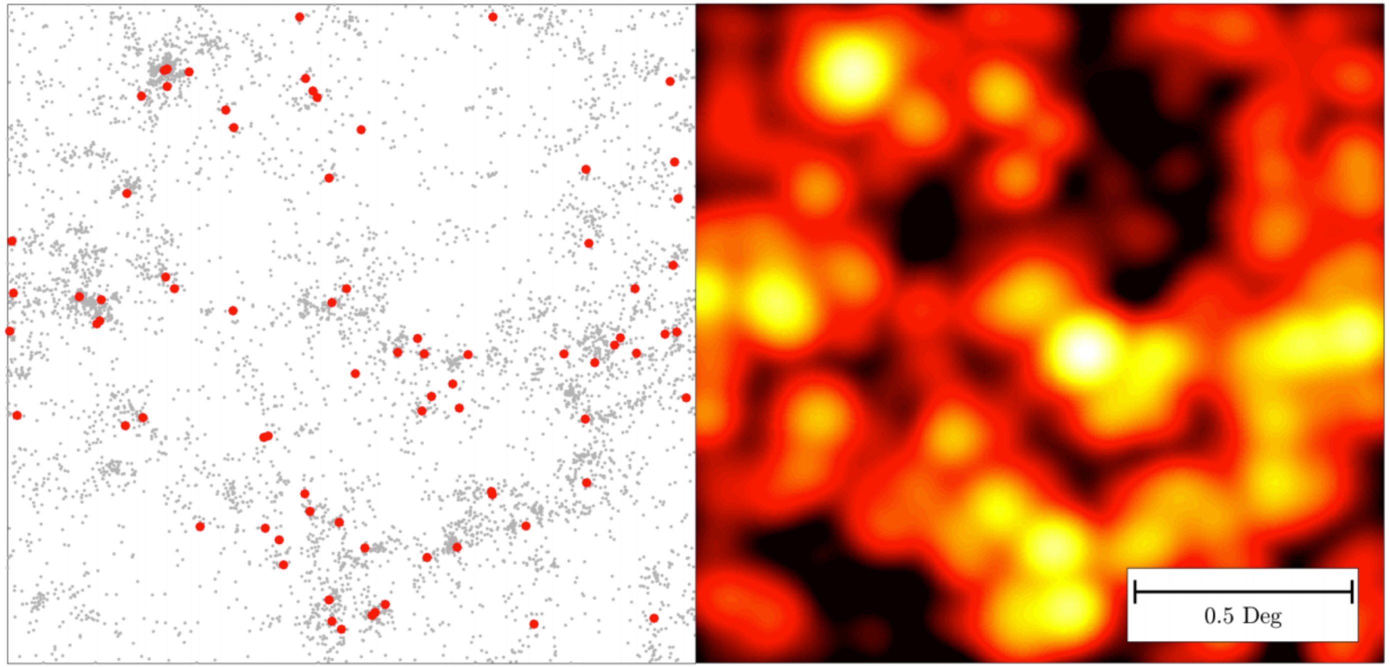


$\sim$ 1.5k hours of COMAP mapping CO intensity fluctuations

P. Breysse

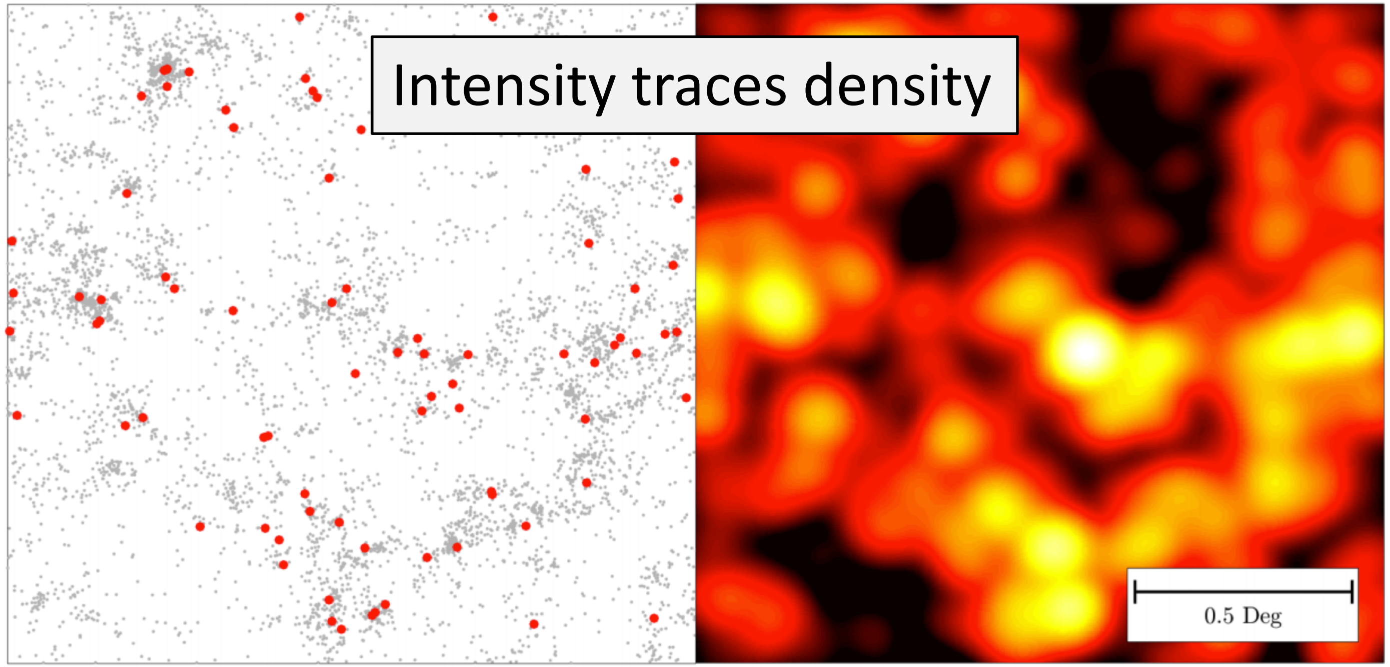
What is Line-Intensity Mapping?

- 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

~ 4.5k hours of VLA can detect ~ 1% of CO-emitting galaxies



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Targeted lines

- We have multiple lines to exploit over more than 6 orders of magnitude in frequency
- $\nu_{obs} = \nu_0/(1+z)$

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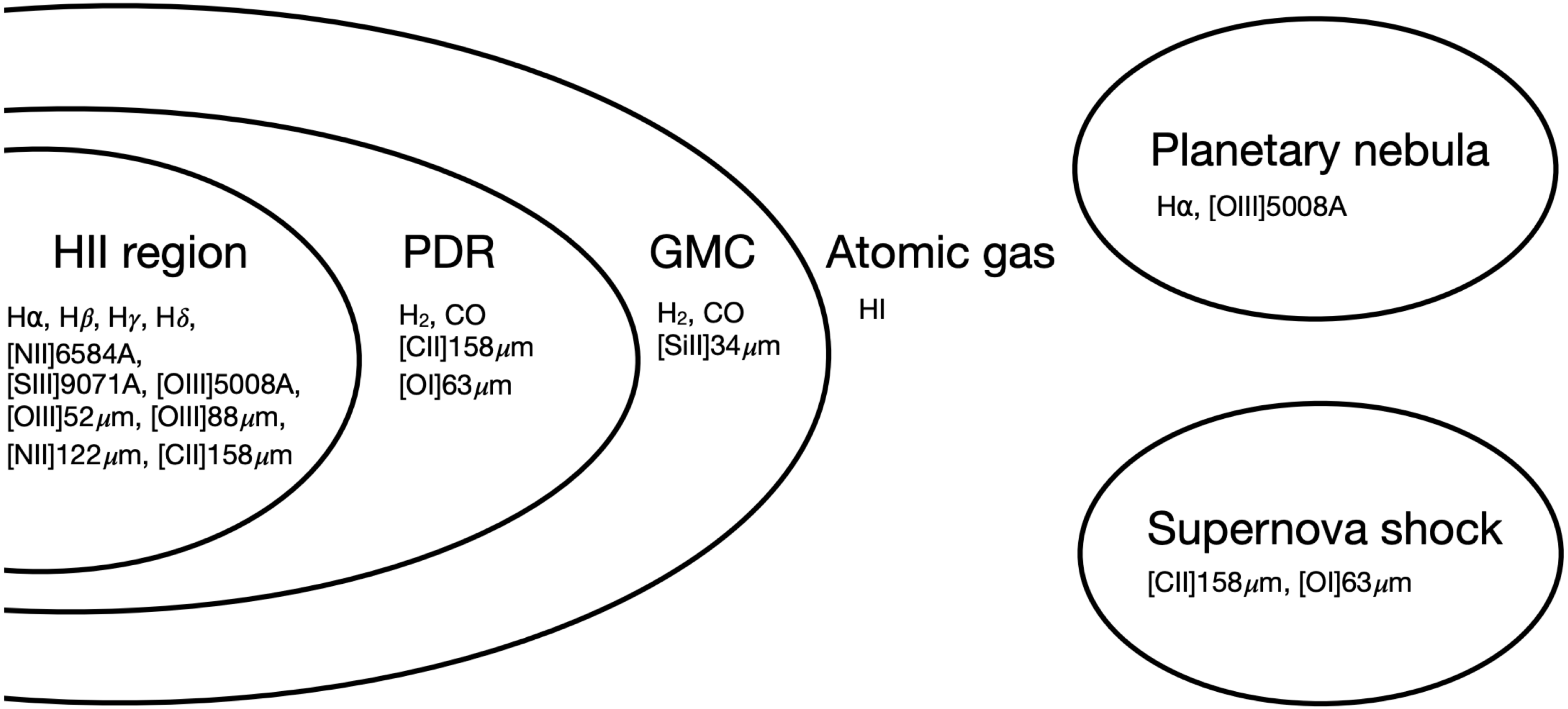
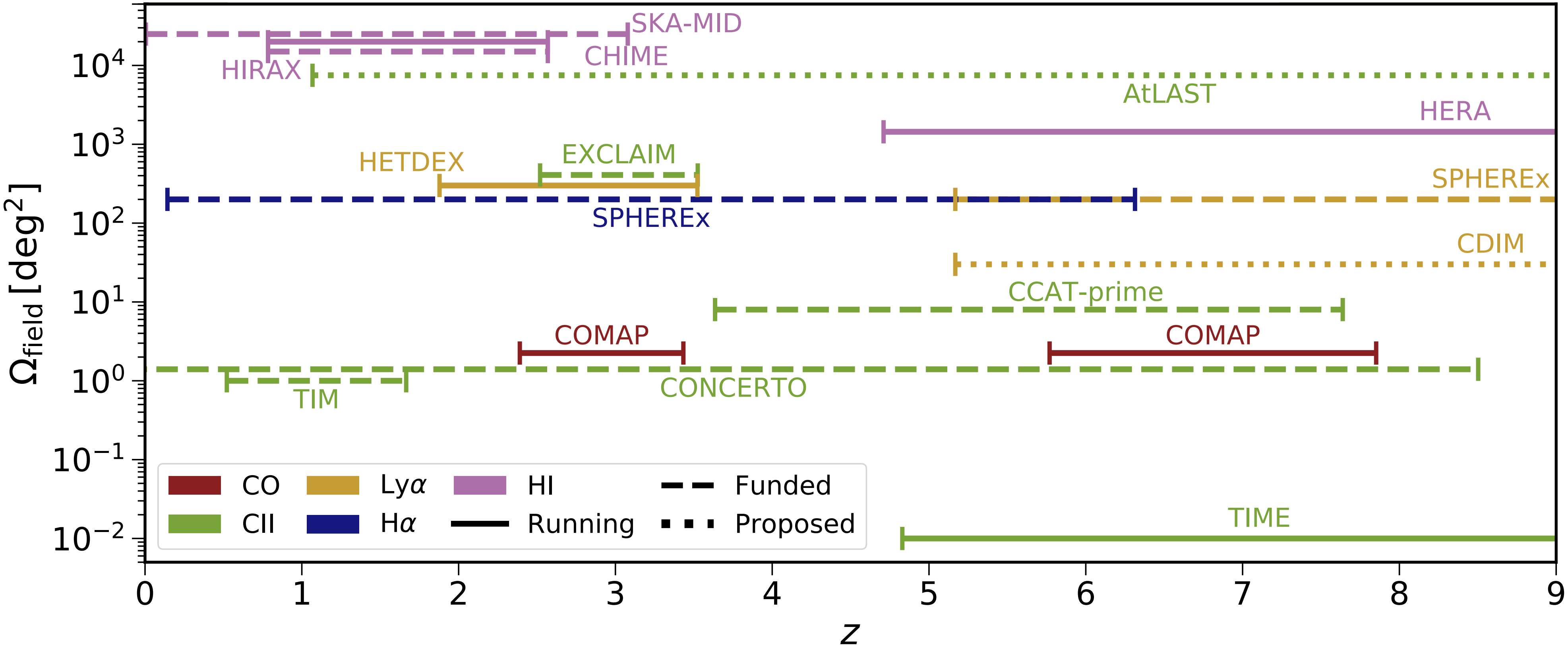


Schaan & White (2021)

Probing the Universe with LIM

- Exciting experimental landscape!



over more than 6 orders of magnitude in frequency

Using LIM for cosmology

- Intensity traces density: cosmological information degenerate with astrophysics

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

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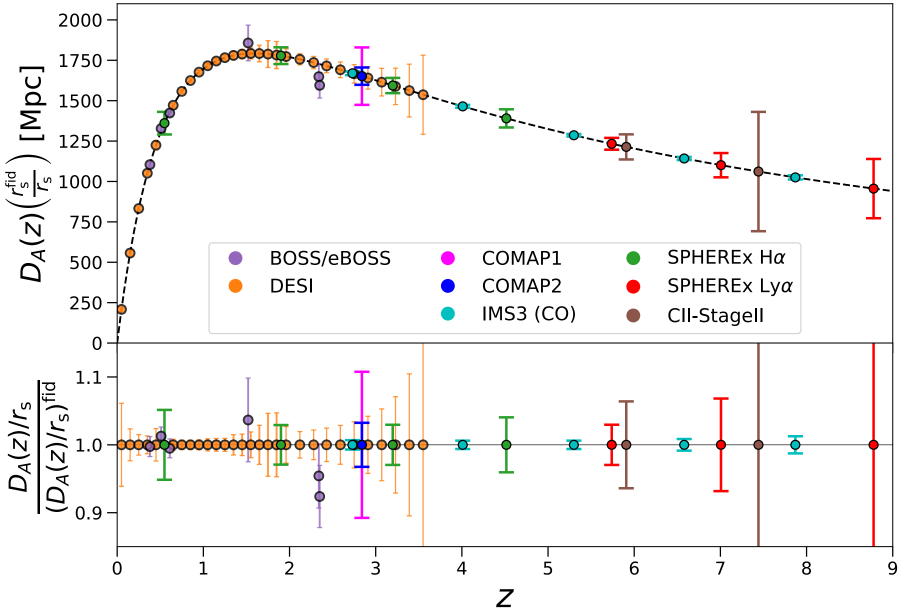

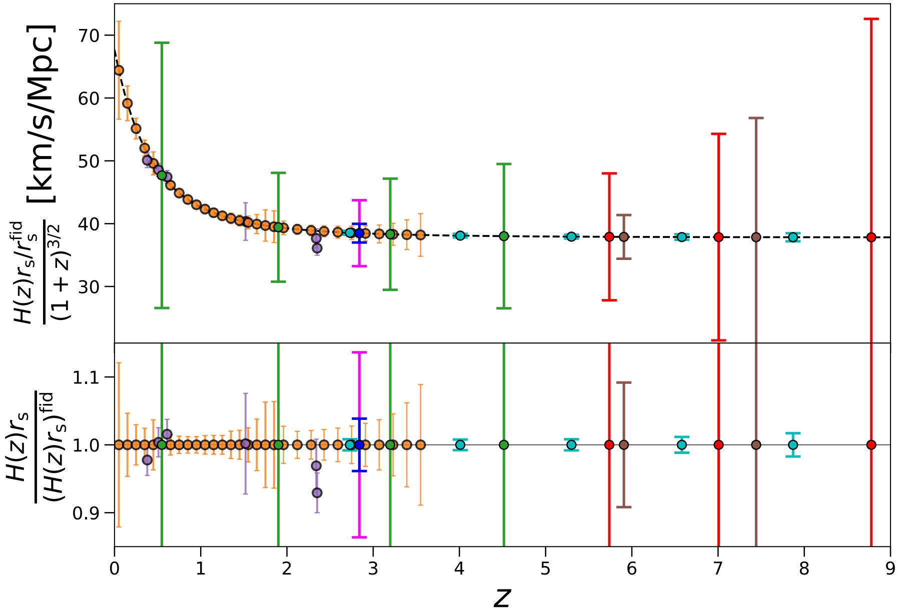

JLB, Breysse, Kovetz (2019)
JLB, Breysse,Gil-Marin, Kovetz (2019)

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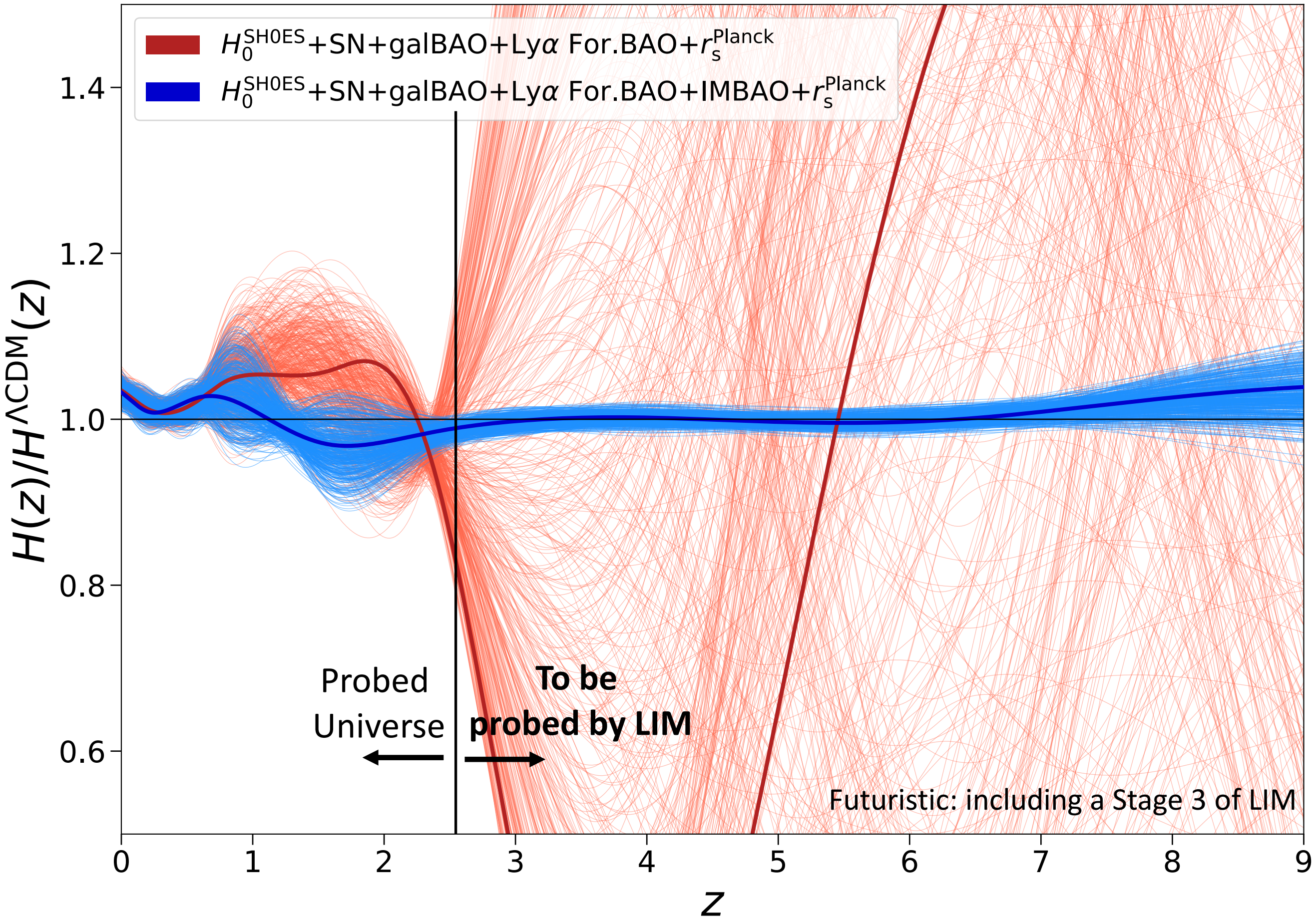
- Extending cosmic distance ladder to z > 3
- H_0 tension
- Dark energy
- $H_0 \times t_U \propto \int_0^z \frac{dz'}{(1+z')E(z')}$ constraints

$H(z)$ 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, Breysse, Kovetz (2019)
Muñoz (2019)
Karkare & Bird (2018)

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- 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

VID: best for astro, integrals of clustering

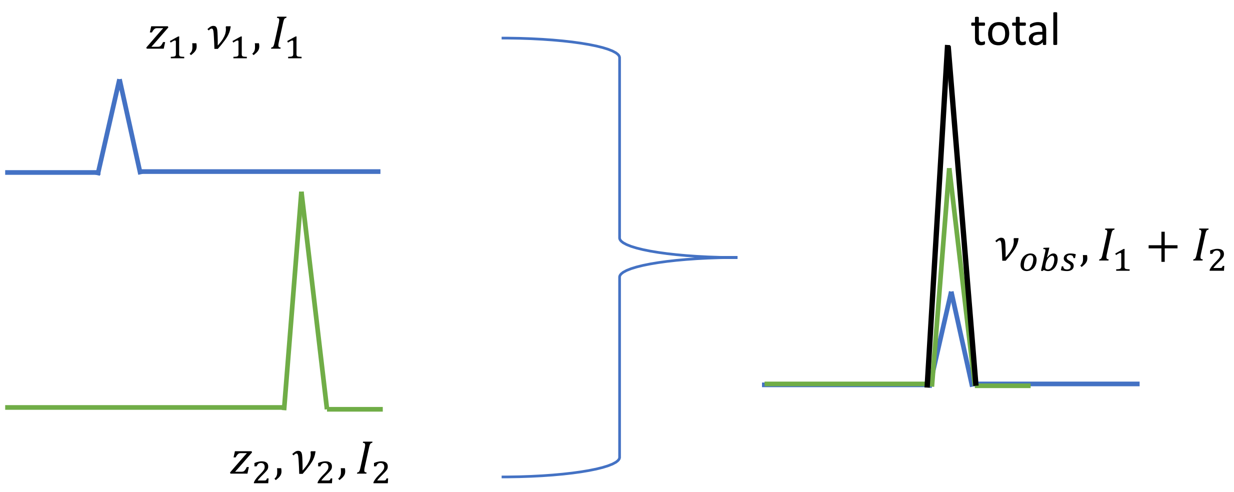
Working on their combination & covariance

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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  - 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)

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

Creque-Sarbinowski & Kamionkowski (2022)

DM & Neutrinos

- 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!

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

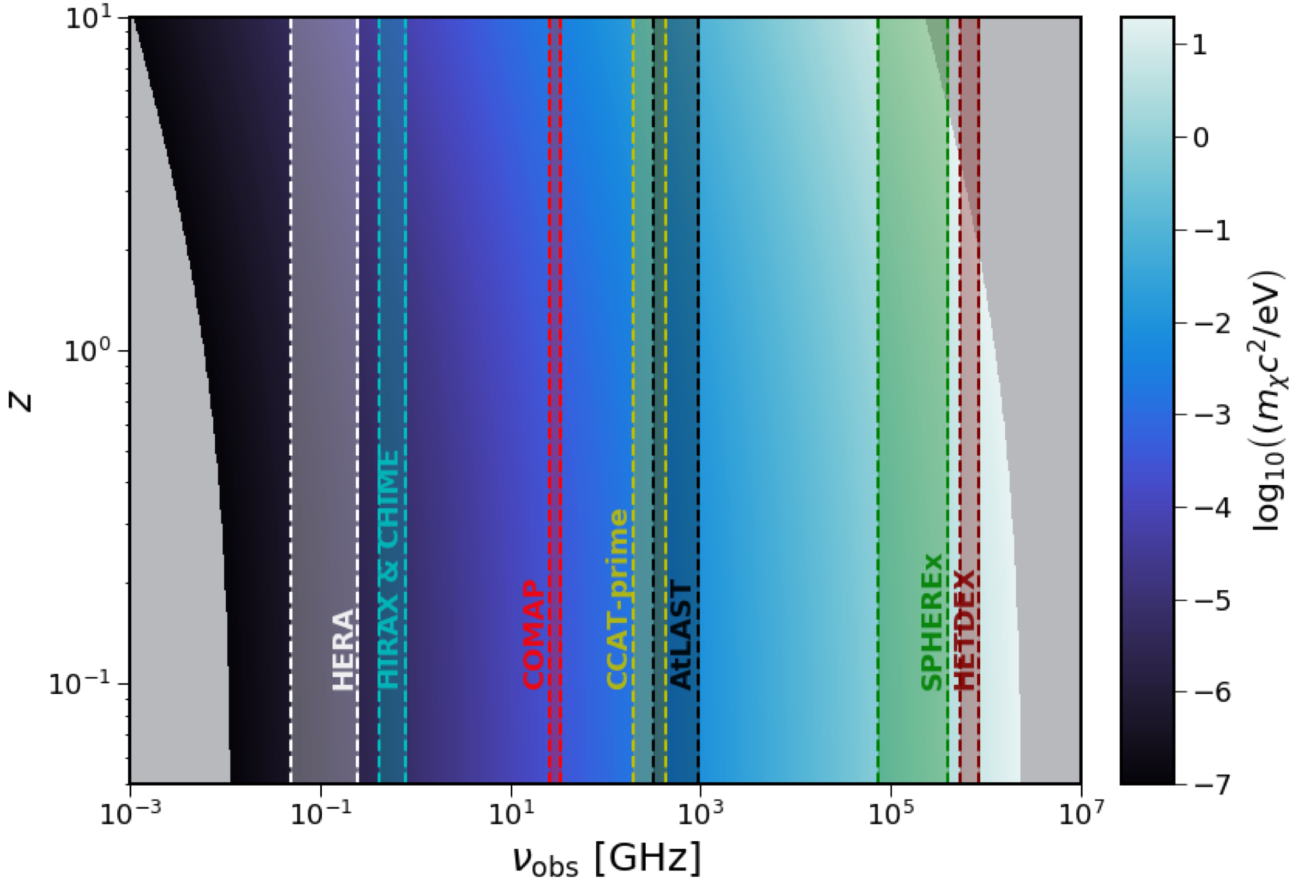
Phenomenological approach

Exotic radiative decays

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

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

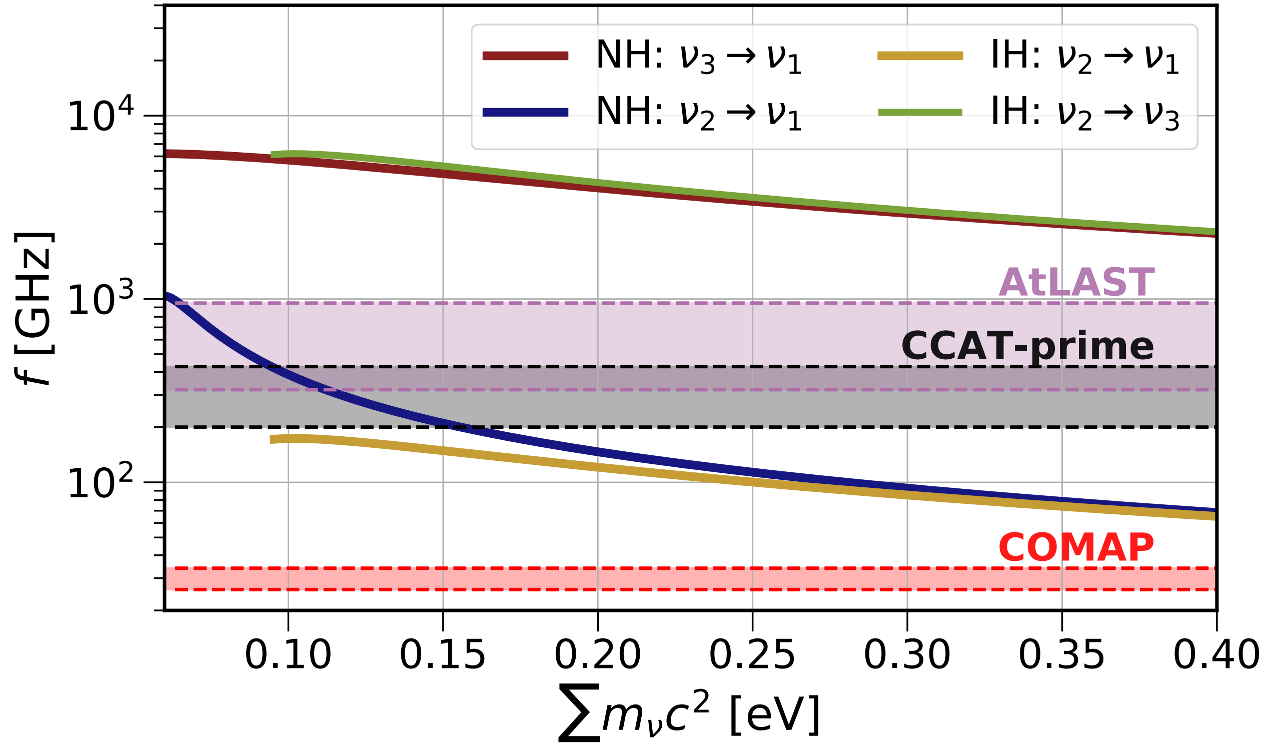
$$\rho_L^\chi(\boldsymbol{x}, z) = \rho_\chi(\boldsymbol{x}, z)c^2 \overbrace{\boxed{\Gamma_\chi f_\chi f_{\gamma\gamma} f_{esc}}}^{\Theta_\chi}(1 + 2\mathcal{F}_\gamma)$$



Traces directly the DM density field

JLB, Caputo, Kamionkowski (2021)

Exotic radiative decays



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

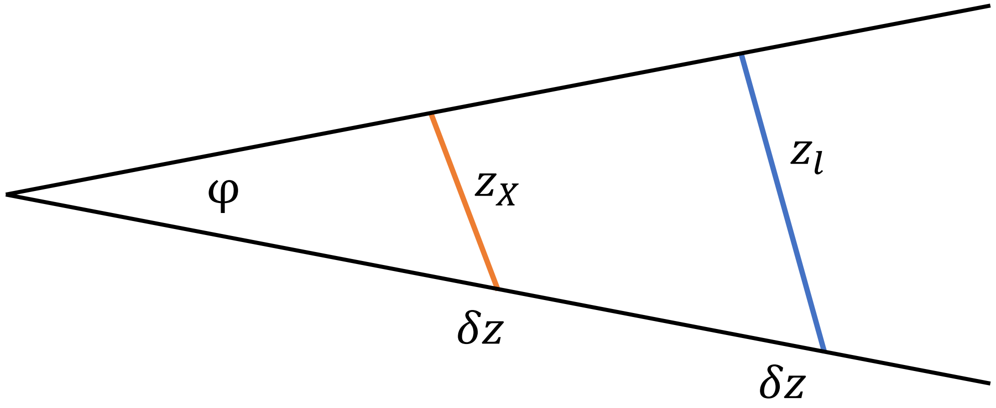
$$f_{ij} = (m_i^2 - m_j^2)c^2/2h_P m_i \qquad \rho_L^{ij}(\boldsymbol{x}, z) = \frac{1}{6}\rho_\nu(\boldsymbol{x}, z)c^2\Gamma_{ij}\left(1 - \frac{m_j^2}{m_i^2}\right)$$

  - Traces directly the cosmic neutrino density field

JLB, Caputo, Villaescusa-Navarro, Kamionkowski (2021)

Effect in power spectrum

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



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

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

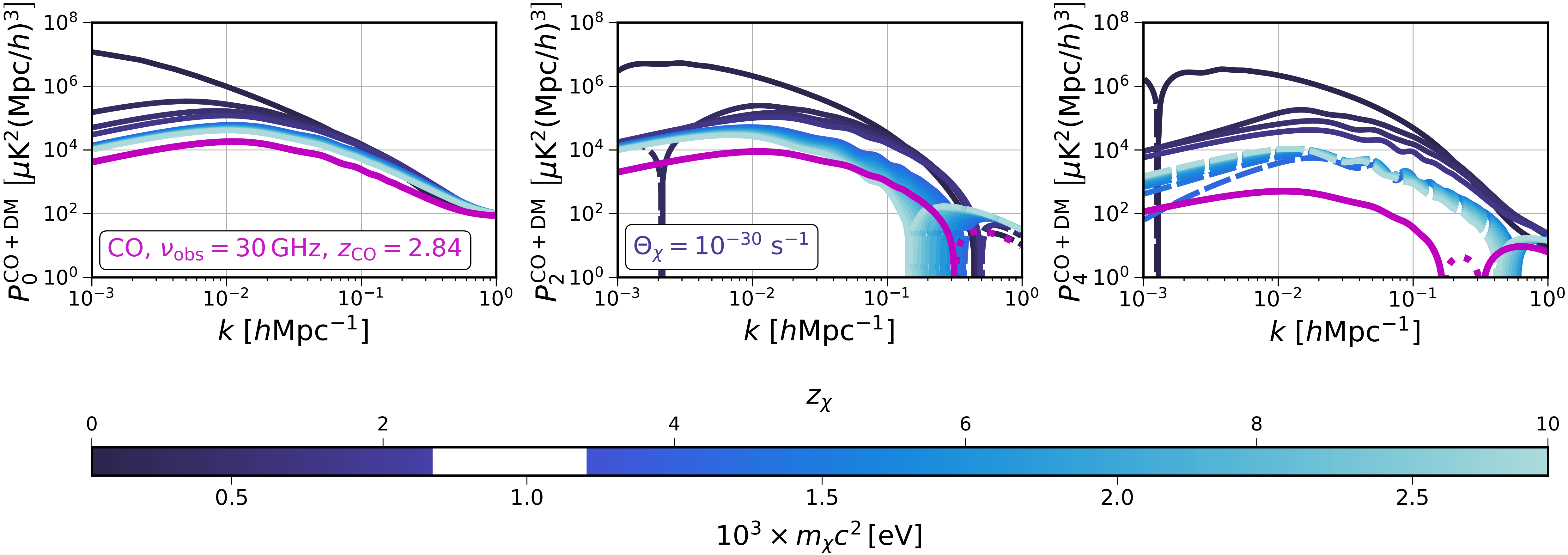
- Model it similar to AP effect: $k_i^{true} \equiv k_i^{infer}/q_i$

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

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

Effect in power spectrum

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



JLB, Caputo, Kamionkowski (2021)

Effect in VID

- Each voxel receives contributions from both emissions:

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

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

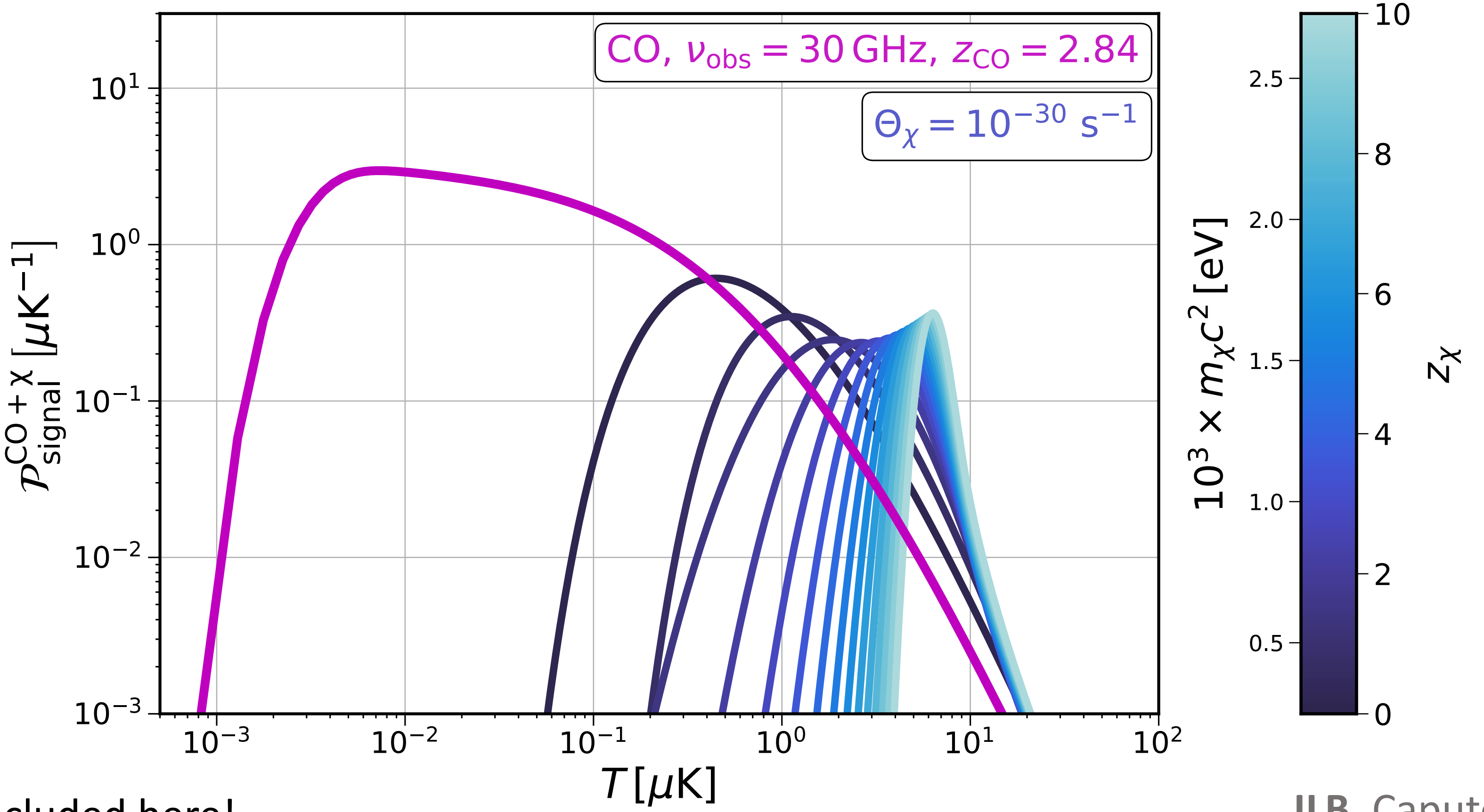
- $\mathcal{P}_{\tilde{\rho}}$: PDF of normalized densities. Obtained from simulations

- 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:

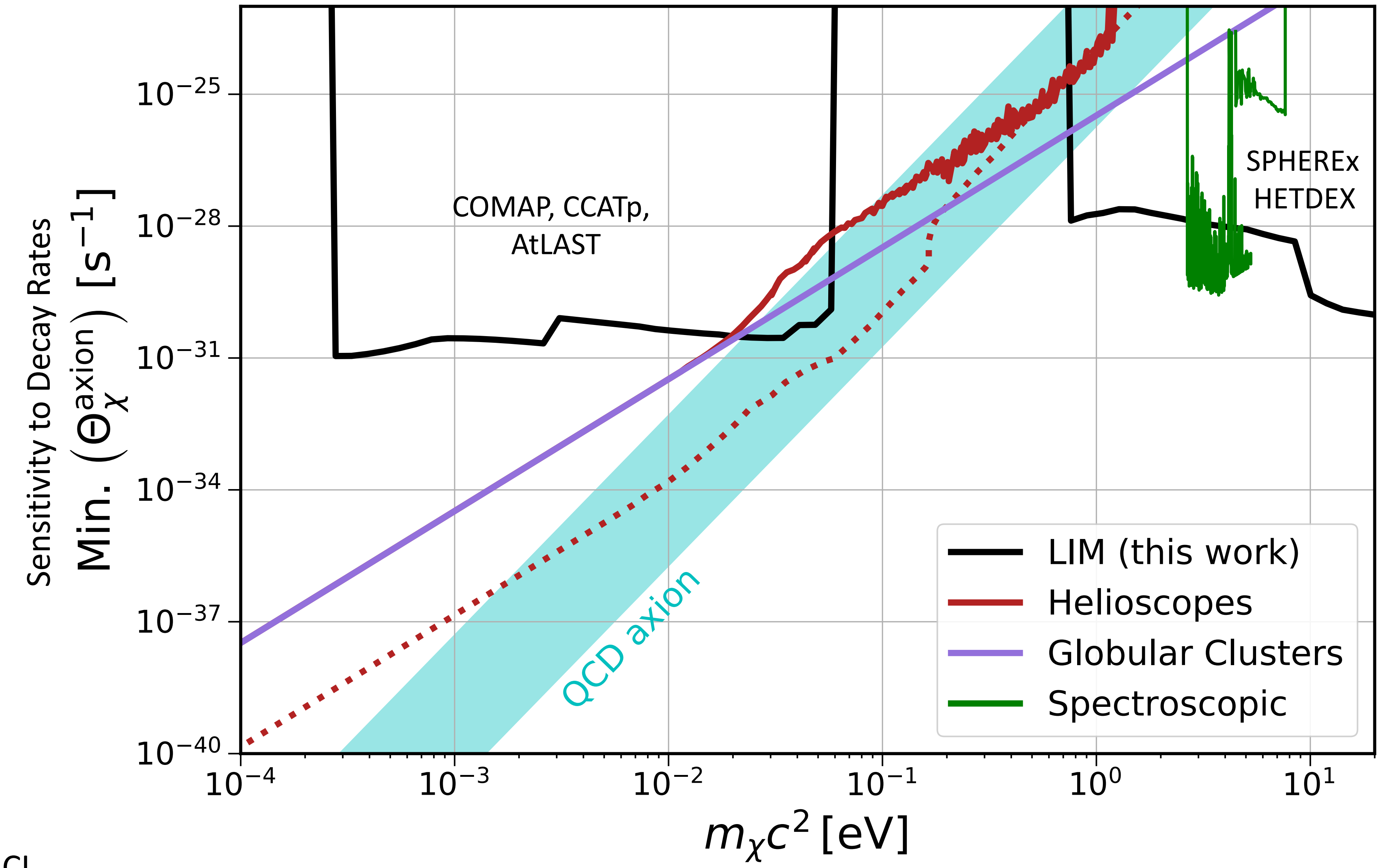
$$\mathcal{P}_{tot+\chi}(T) = \left(\left(\mathcal{P}_l * \mathcal{P}_\chi\right) * \mathcal{P}_{noise}\right)(T); \qquad \mathcal{P}_\chi = \mathcal{P}_{\tilde{\rho}}/\langle T_\chi \rangle$$



No noise contribution included here!

JLB, Caputo, Kamionkowski (2021)

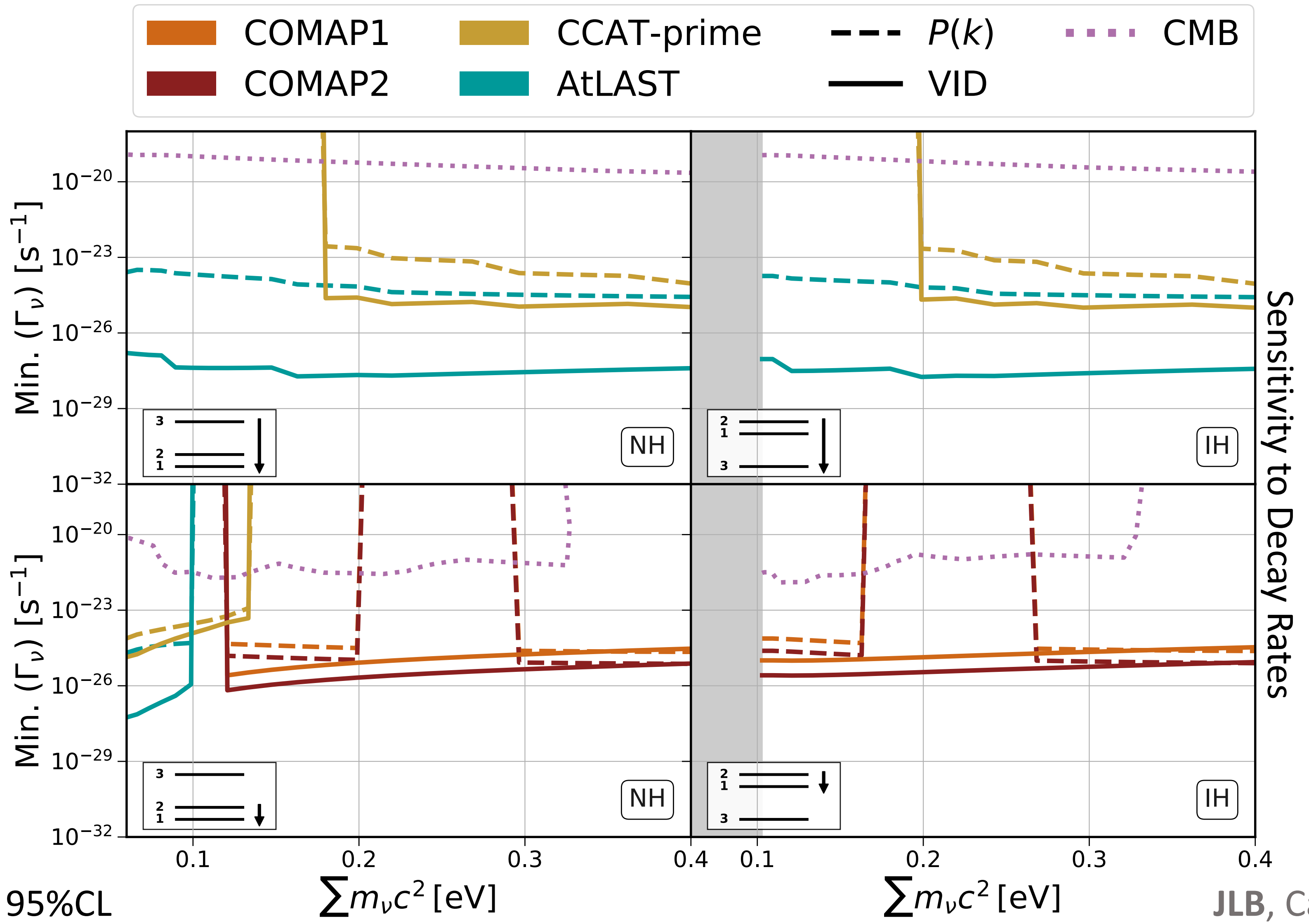
Sensitivity in axion context



95%CL

JLB, Caputo, Kamionkowski (2021)

Sensitivities to neutrino decay



95%CL

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

↓ Effective transition moment

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

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

JLB, Caputo, Villaescua-Navarro, Kamionkowski (2021)

Challenges & improvements

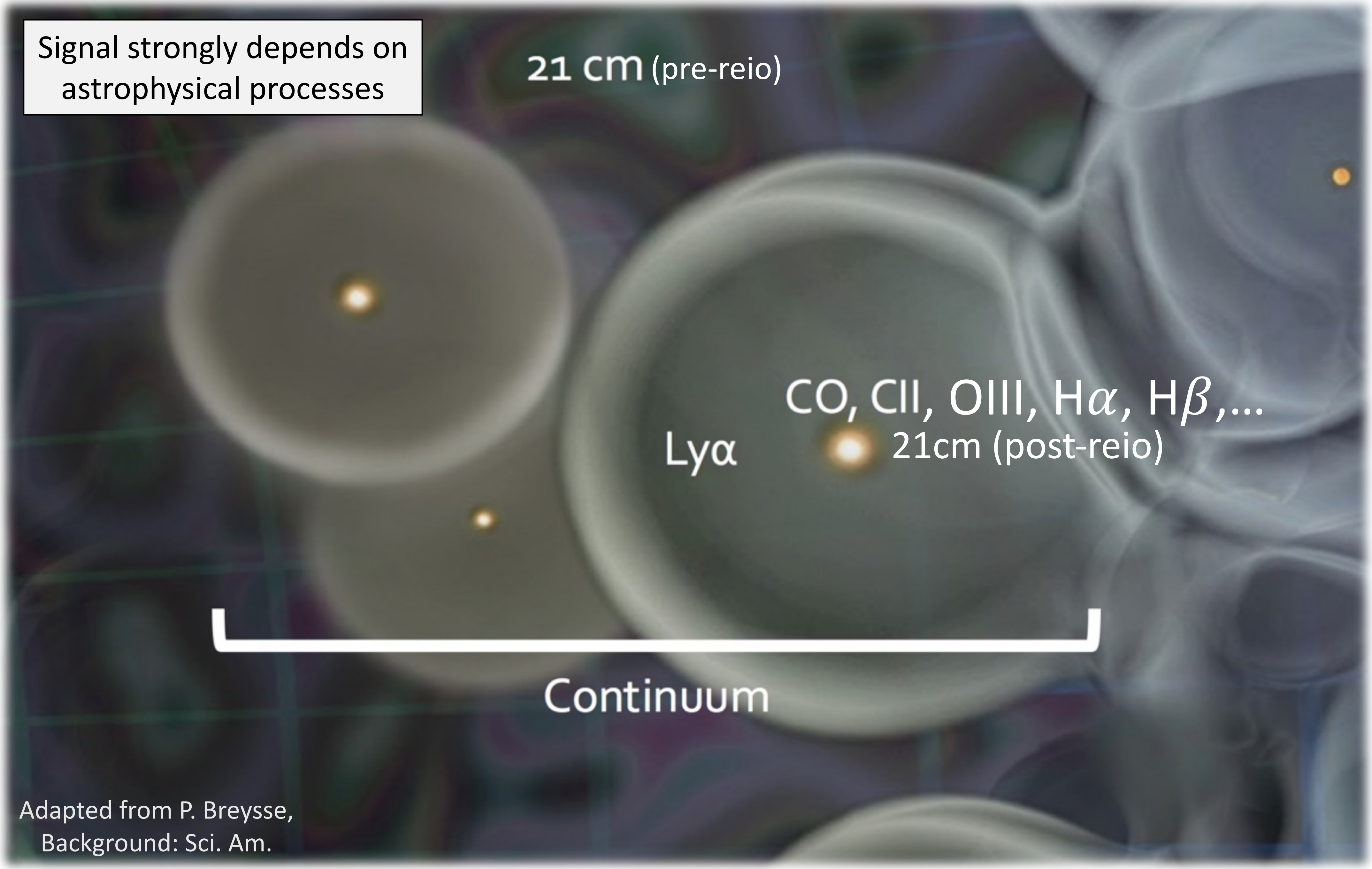
- Challenges:
  - Astrophysical uncertainties: marginalization, break degeneracies
  - Other contaminants: loss of information, potential biases
  - Line broadening (currently testing BAO robustness against this)
- Reasons to be optimistic:
  - Many pathfinders and experiments in the pipeline (and theory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

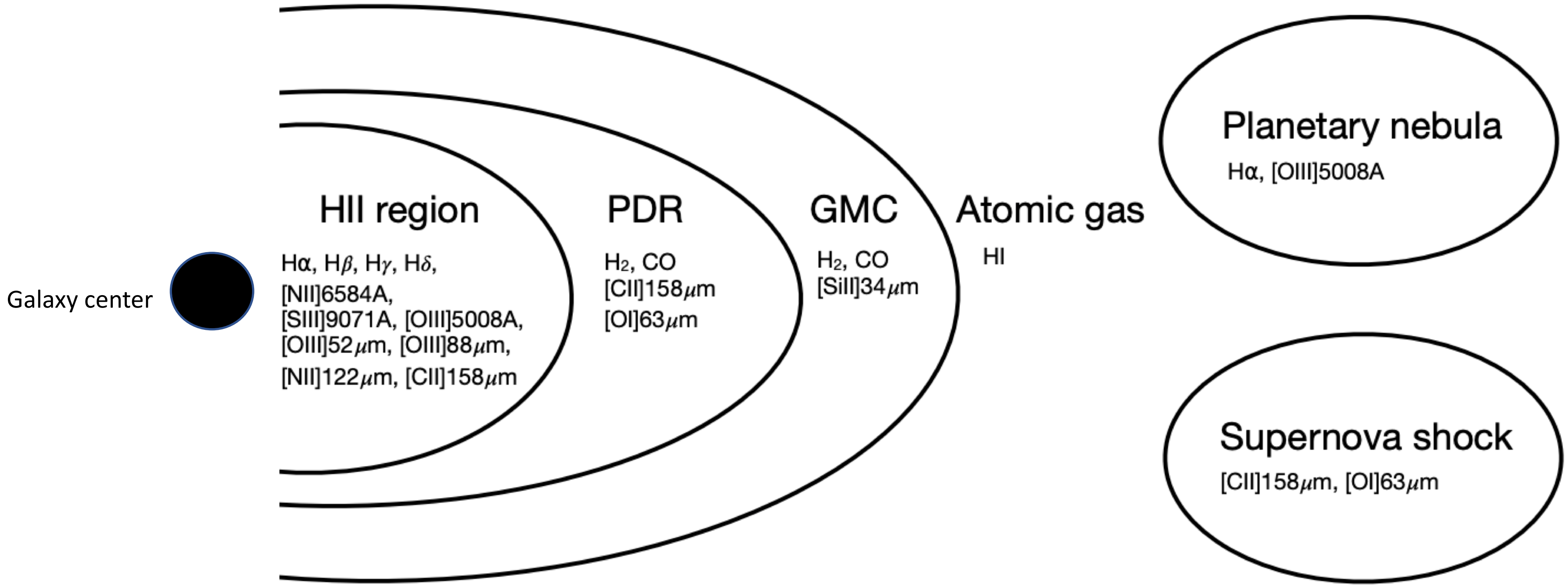
Conclusions

- LIM holds a great protential for cosmology:
  - DM nature through small scales clustering (cosmic dawn)
  - Early Universe: Primordial non-Gaussianity, CIPs, …
  - Neutrino cosmology

- LIM BAO will constrain dark energy at z<10
- Exotic decays: adapting techniques to identify and model interlopers is a cheap and powerful strategy.
  - 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

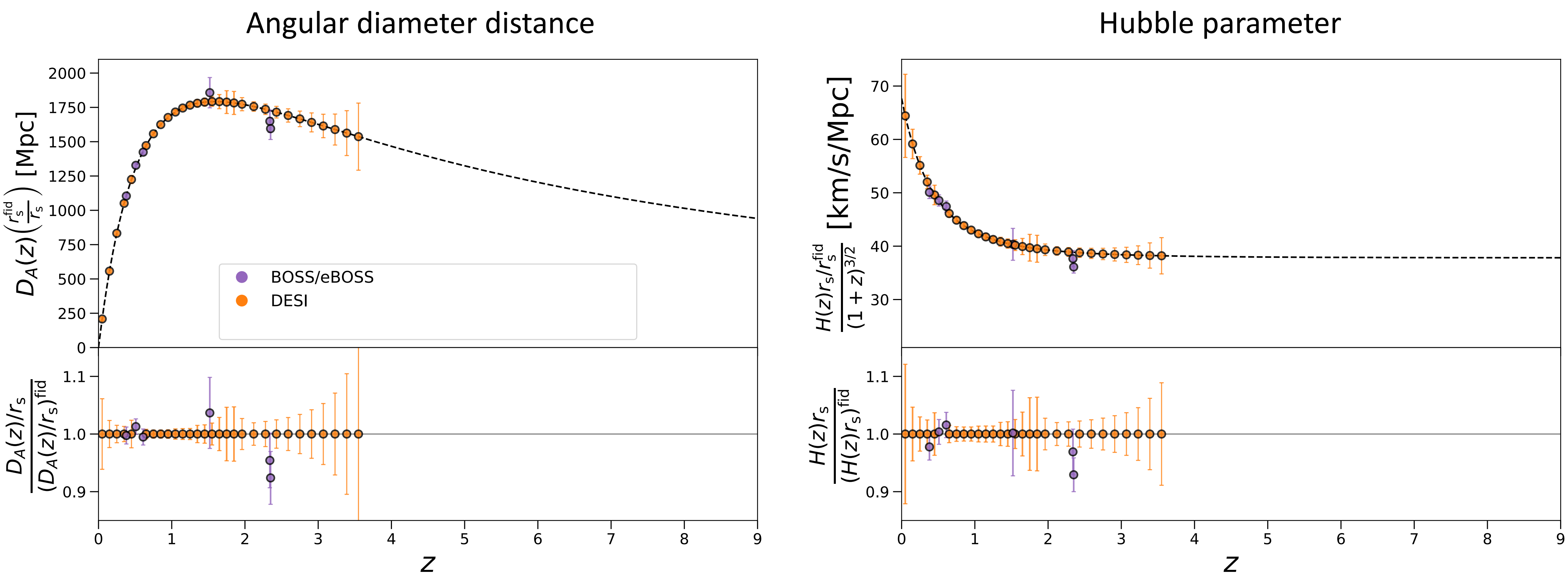

Signal strongly depends on astrophysical processes
21 cm (pre-reio)
CO, CII, OIII, Hα, Hβ,...
Lyα
21cm (post-reio)
Continuum
Adapted from P. Breysse,
Background: Sci. Am.



Adapted from Schaan & White 2021

JLB+2019b

LIM BAO

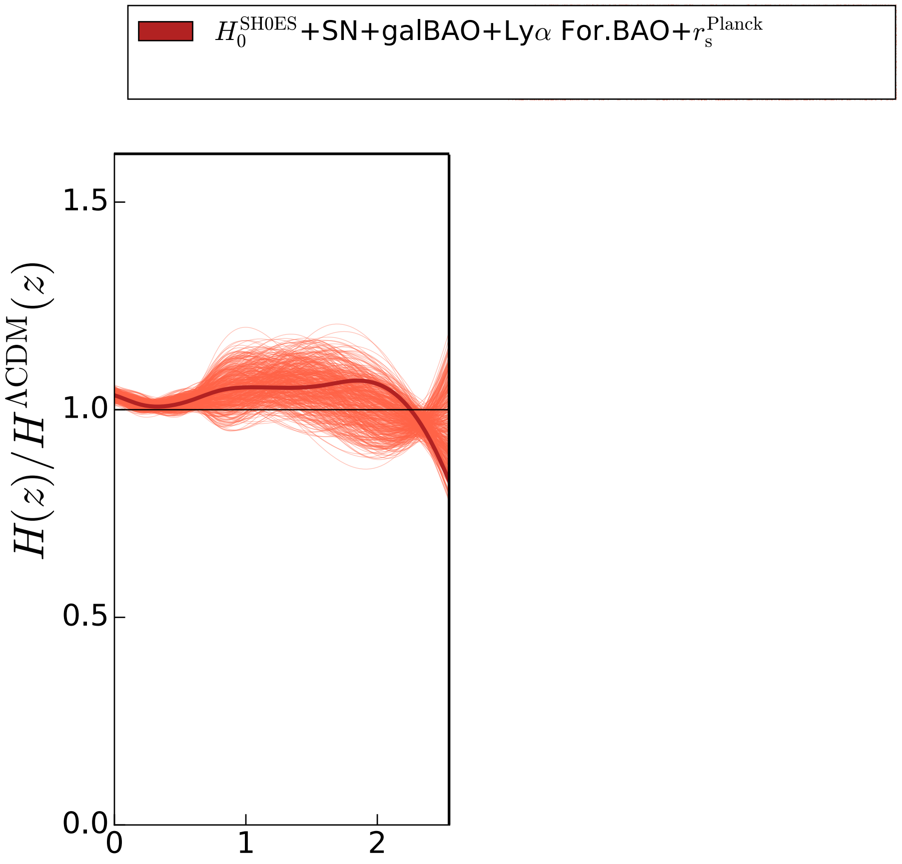


Current and coming constraints using galaxy surveys

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)

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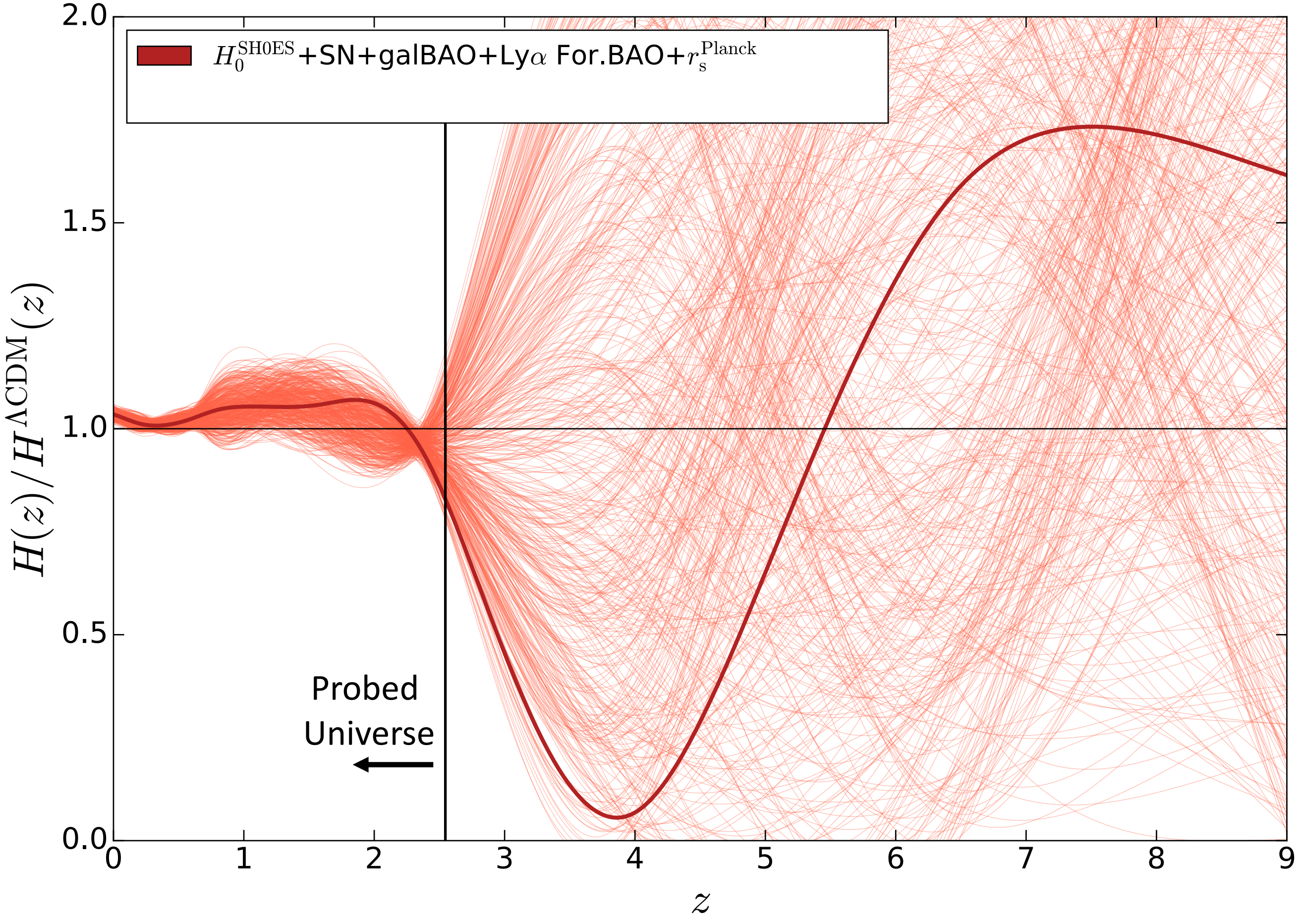

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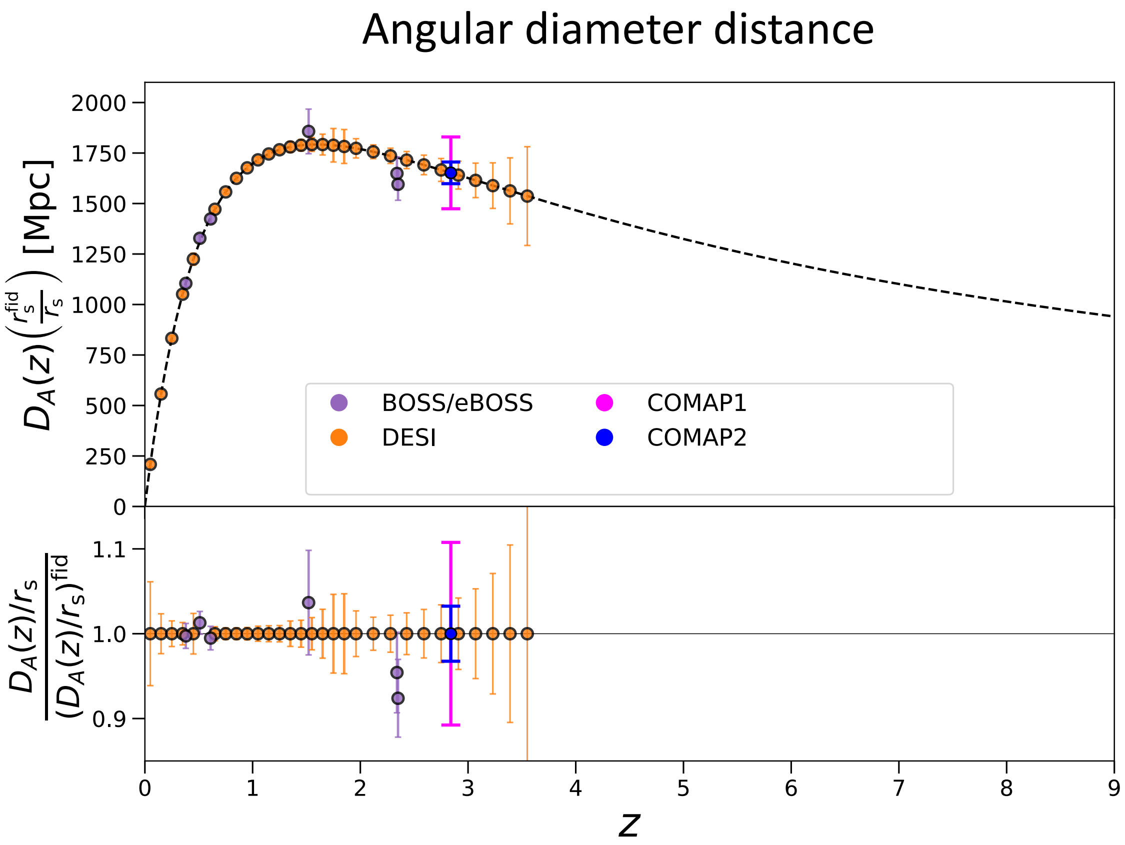
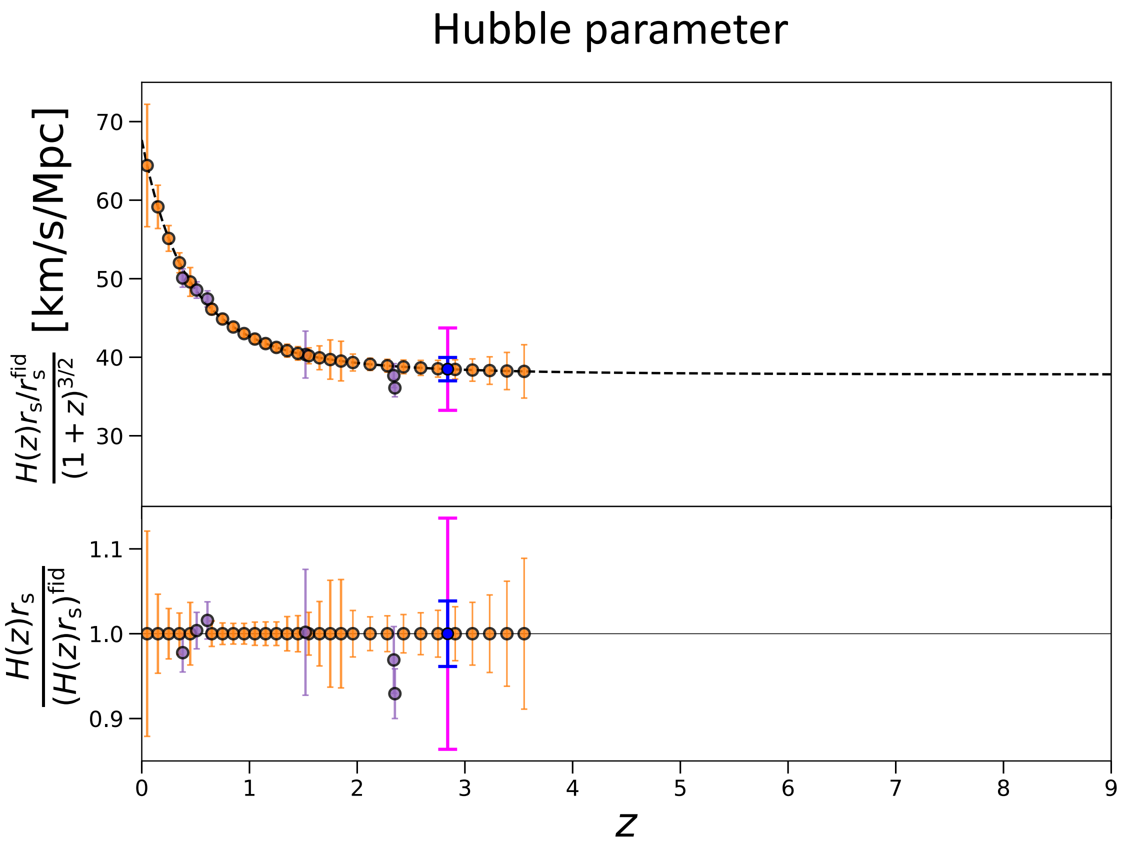




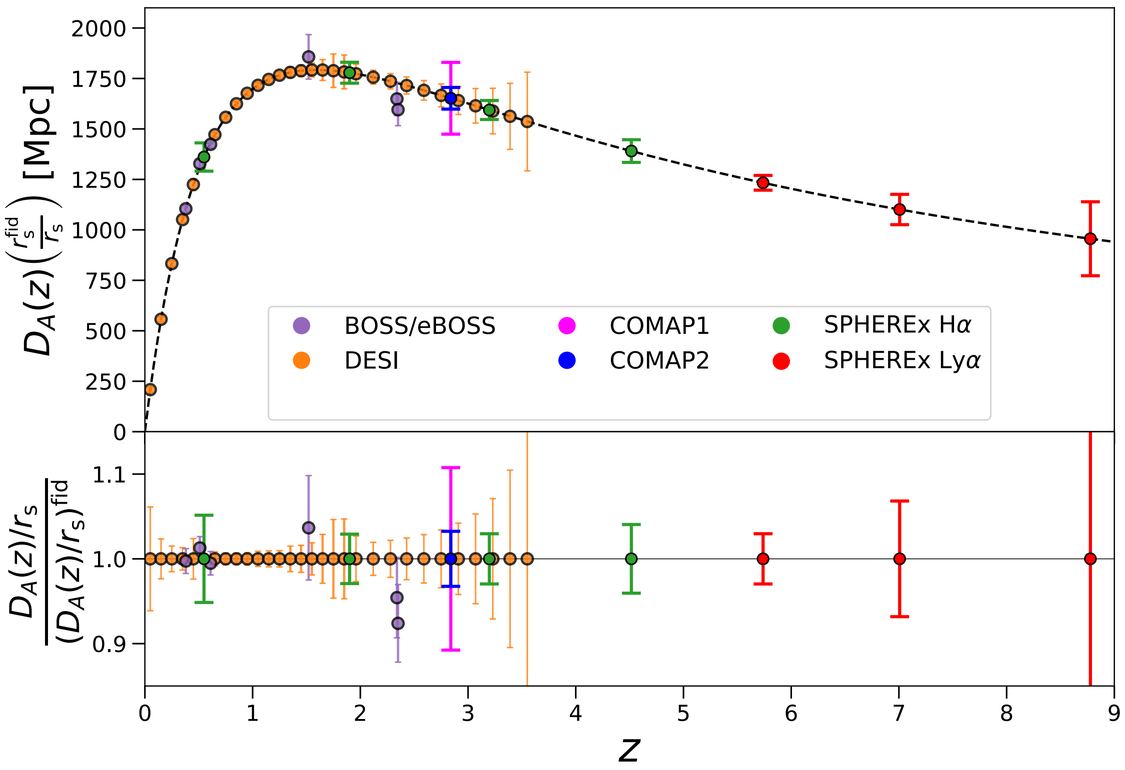
Current and coming constraints using galaxy surveys

+ Star-Formation-related LIM BAO

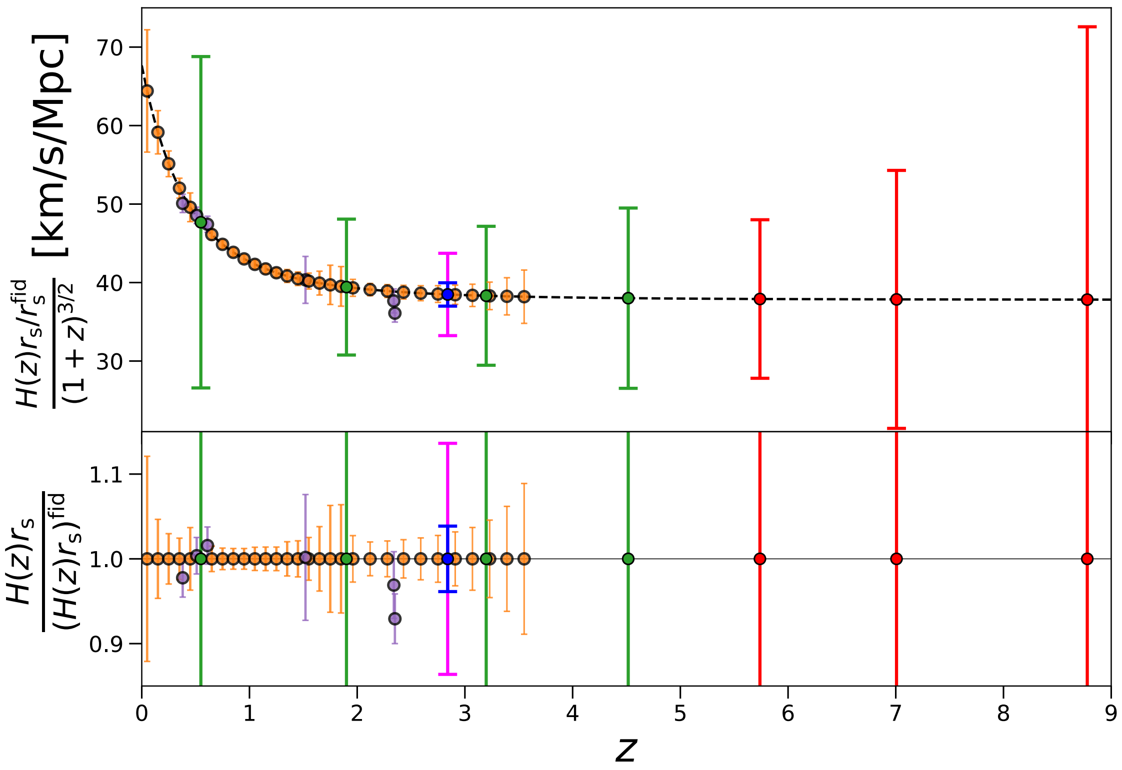
JLB+2019b

LIM BAO

Angular diameter distance



Hubble parameter



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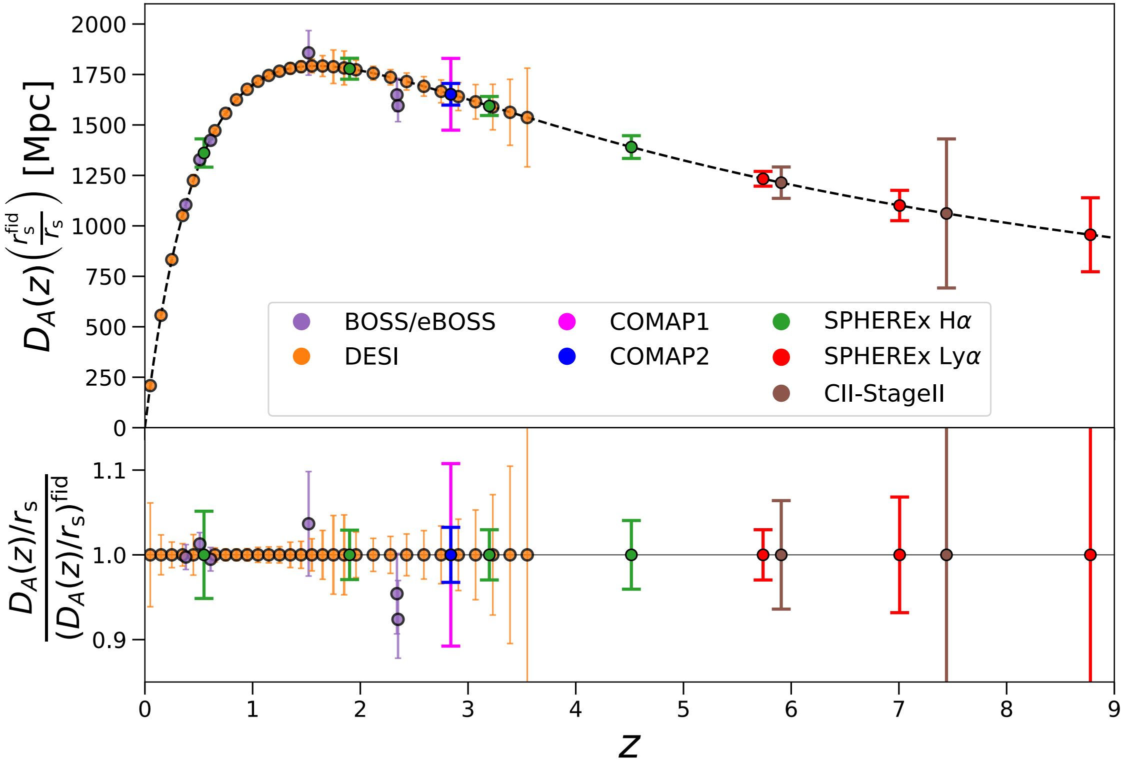

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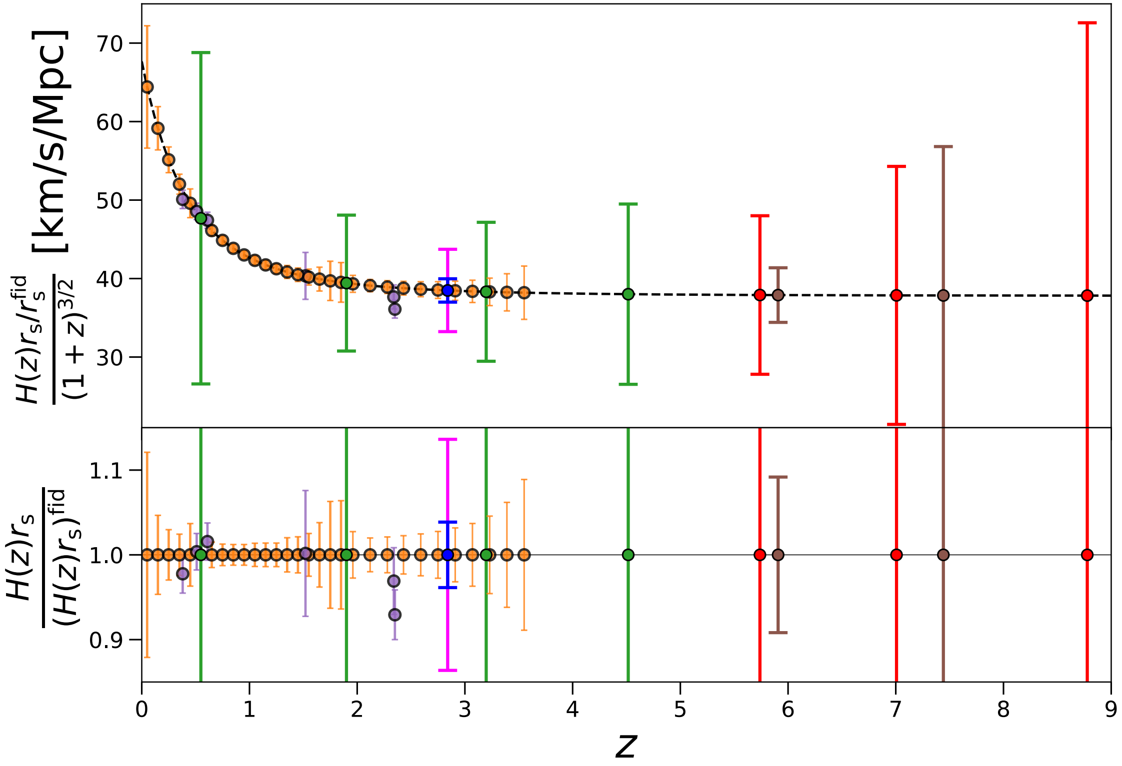

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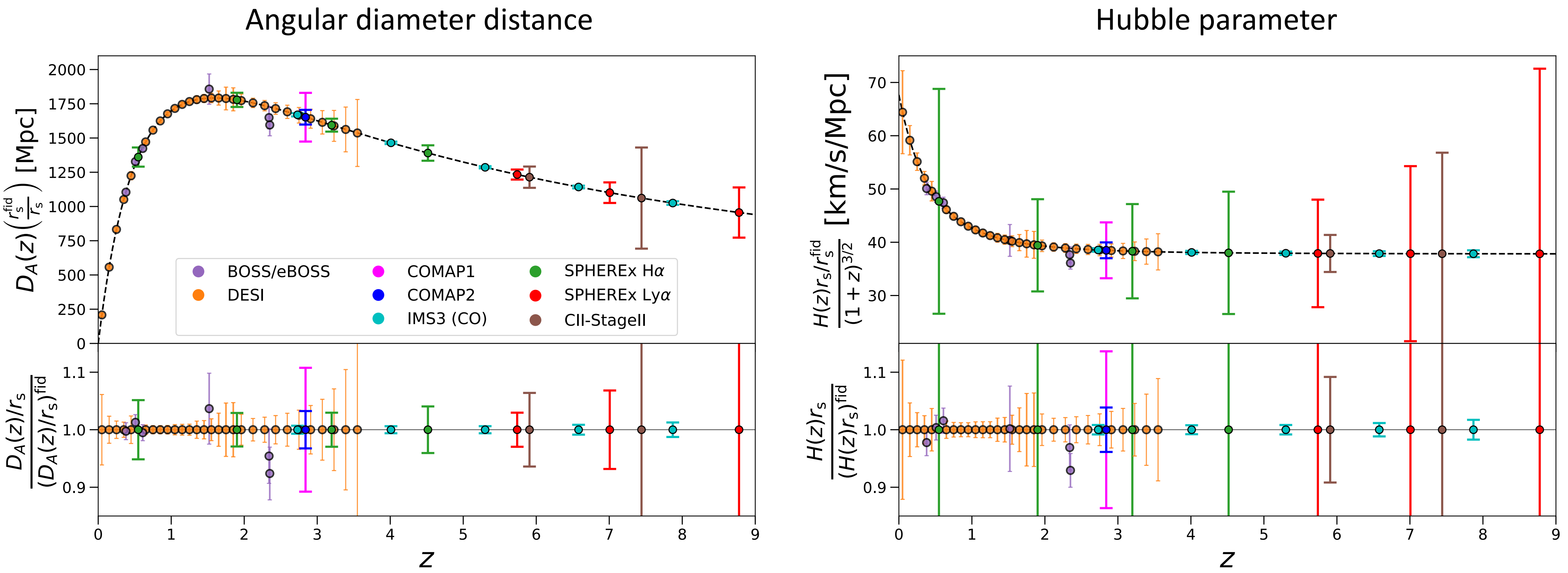

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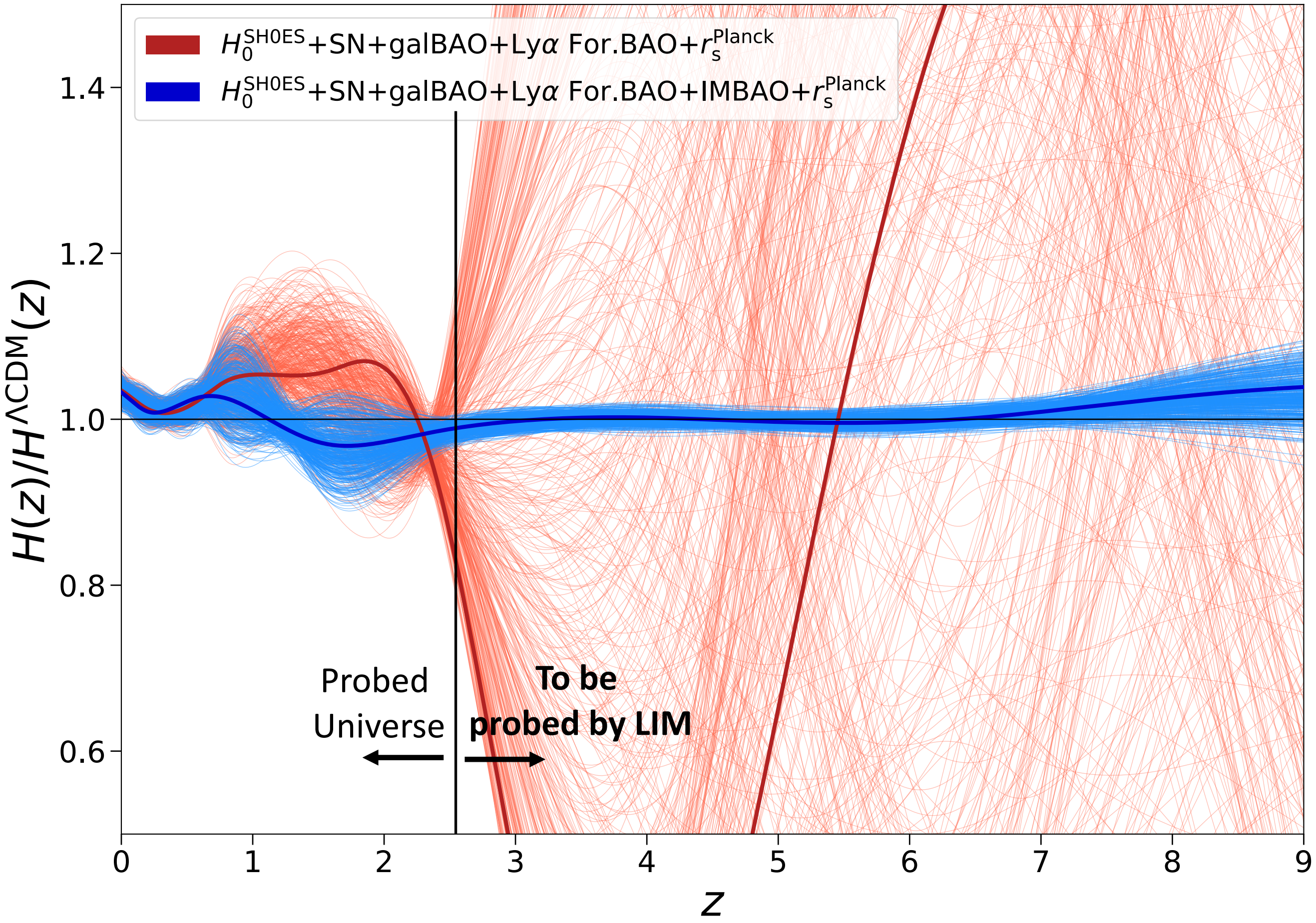

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Current constraints using galaxy surveys (and H_0 and r_s) and **ADDING LIM BAO**

JLB+2019a
JLB+2019b