Dark matter and line-intensity mapping

Marc Kamionkowski
Johns Hopkins University

with José Luis Bernal, Andrea Caputo, Cyril Creque-Sarbinowski, and Francisco Villaescusa-Navarro

Who did the work

- Dark matter:
  - Creque-Sarbinowski & MK, 1806.11119
  - Bernal, Caputo, & MK, 2012.00771
- Neutrinos:
  - Bernal, Caputo, Villaescusa-Navarro, & MK, 2103.12099

- Other LIM collaborators:
  - E. Kovetz, P. Breysse, G. Sato-Polito, K. Boddy

- General background:
  - "Line-Intensity Mapping: 2017 Status Report," Kovetz et al., 1709.09066 [astro-ph.CO]
  - "User's guide to extracting cosmological information from line-intensity maps," Bernal, Breysse, Gil-Marín, & Kovetz, 1907.10067.

Line-Intensity Mapping

- LIM: use integrated light in given pixel on sky
- Information from all galaxies and IGM along LoS
- Use redshift of identifiable spectral line → 3D maps

Line Intensity Mapping (LIM)

July 7-9, 2021 •

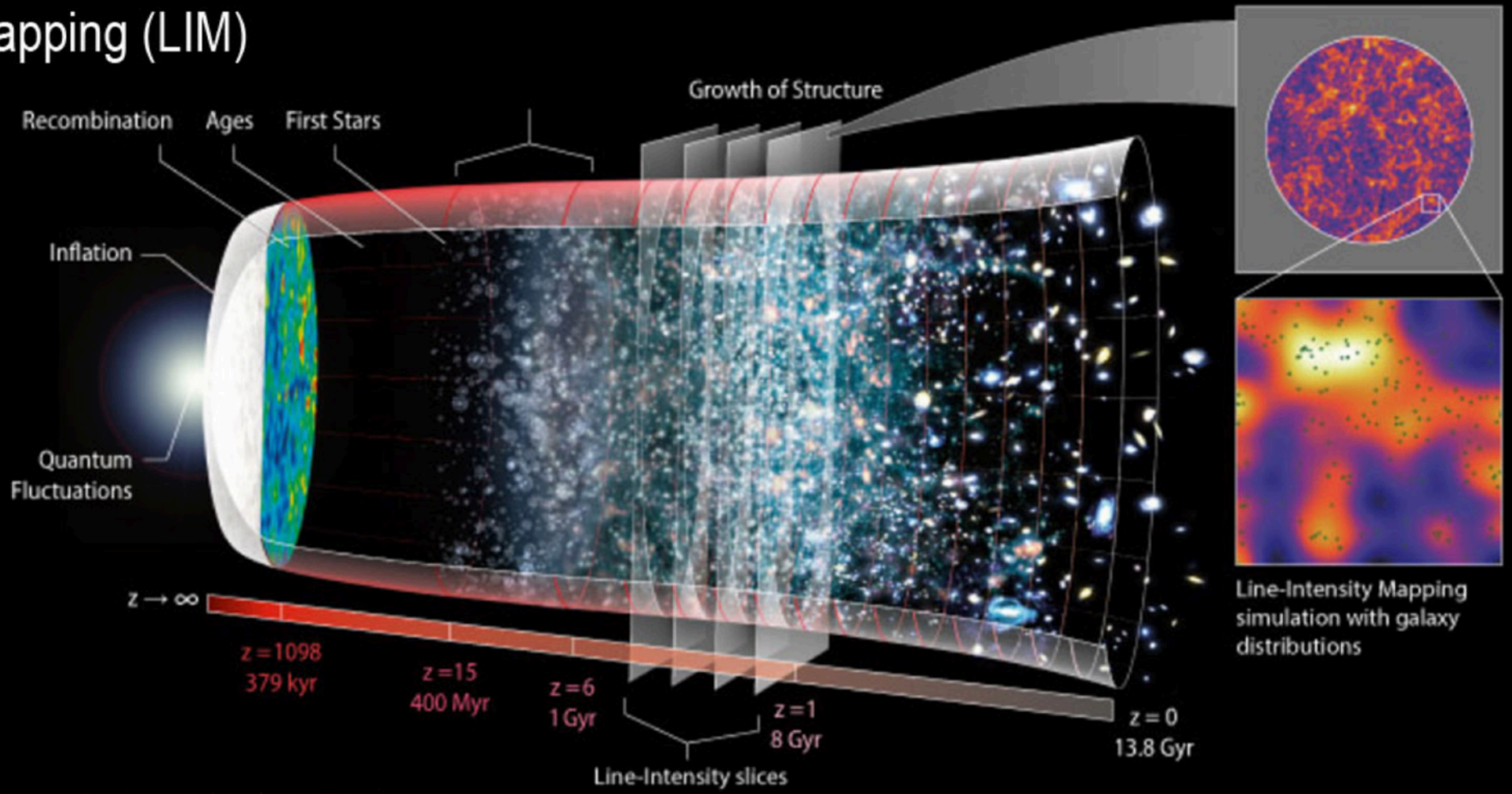


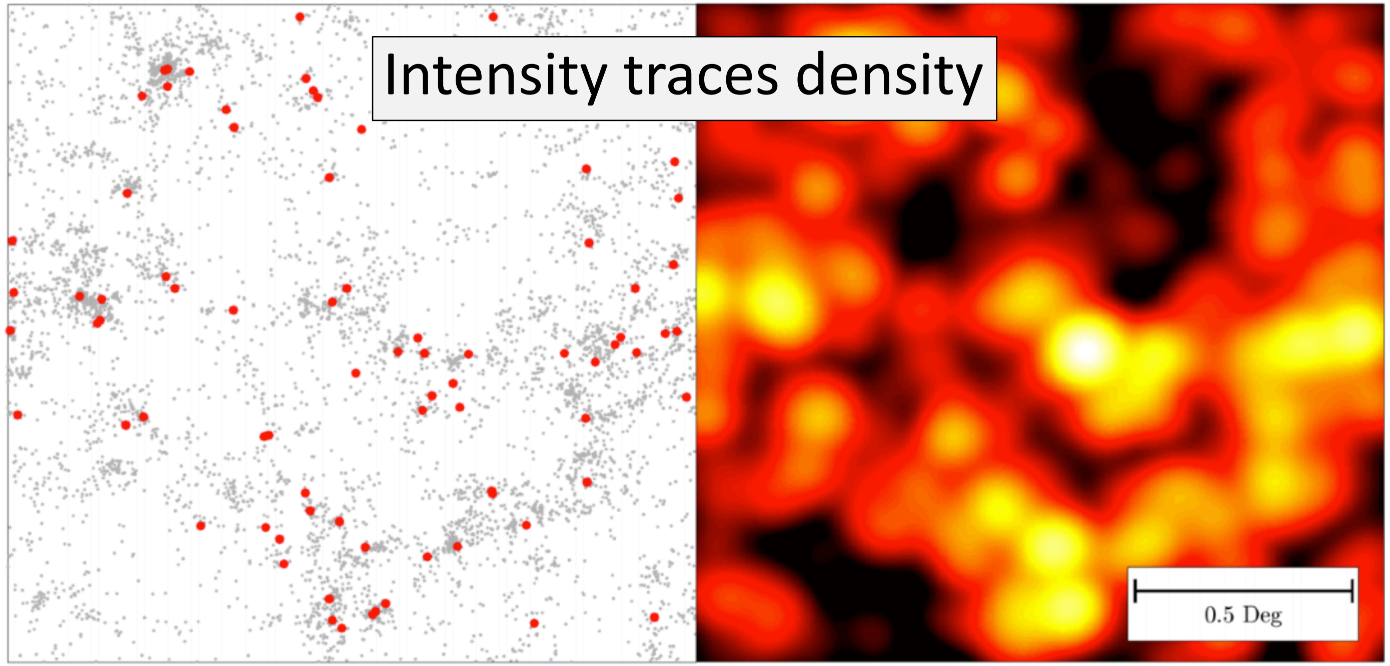
Image Credit: NASA / LAMBDA Archive Team

KICP workshop • 2021

Galaxy surveys: detailed distribution of brightest galaxies

Intensity maps: noisy distribution of all galaxies and IGM

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

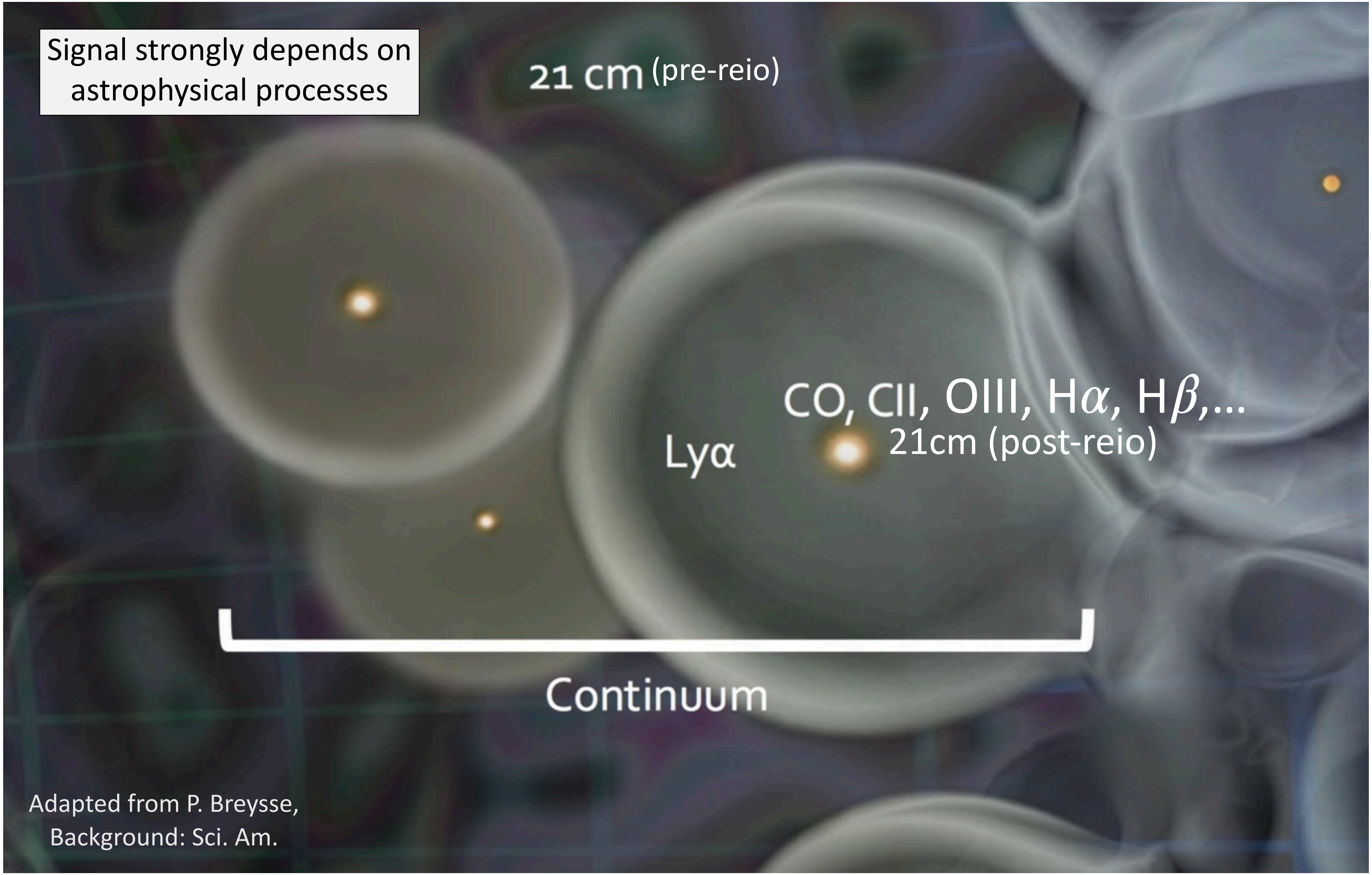


$\sim$ 1.5k hours of COMAP mapping CO intensity fluctuations

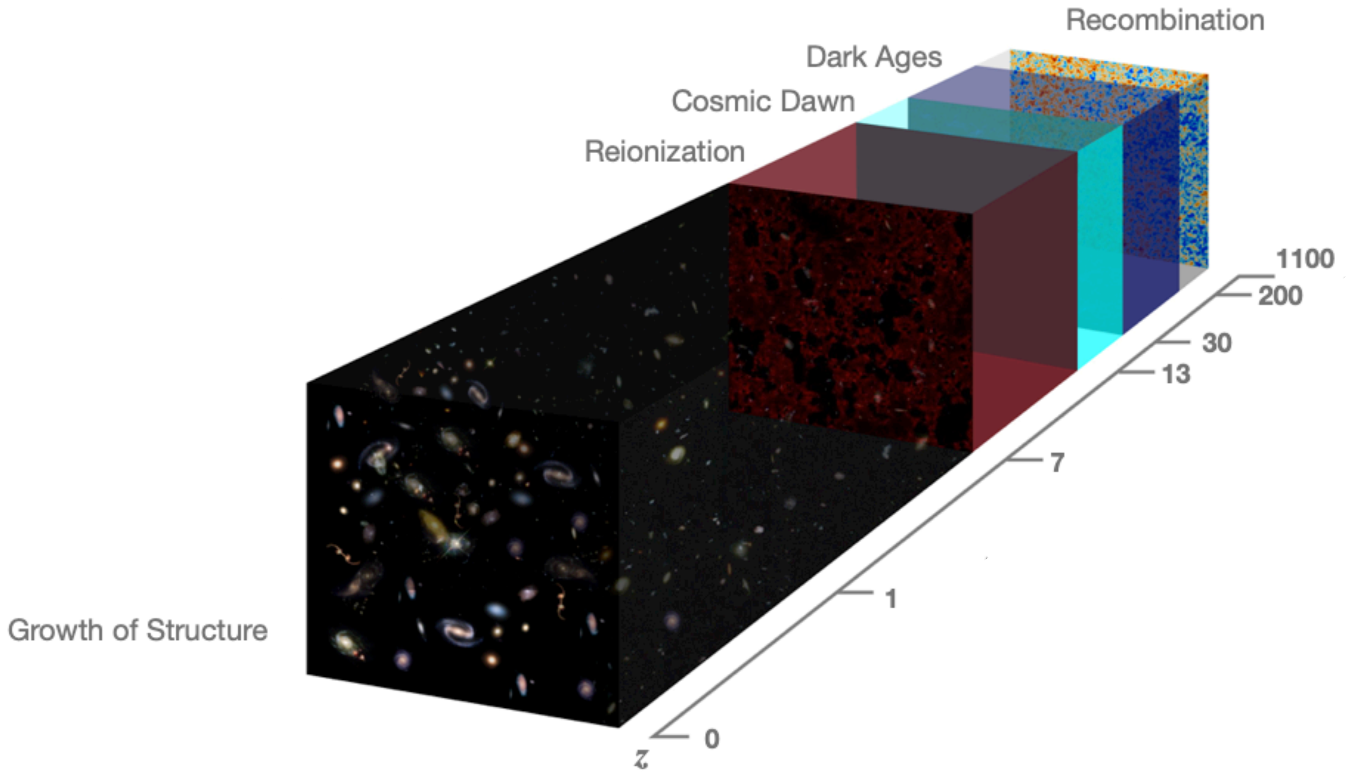
P. Breysse

Targeted lines

- $\nu_{obs} = \nu_0/(1+z)$


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

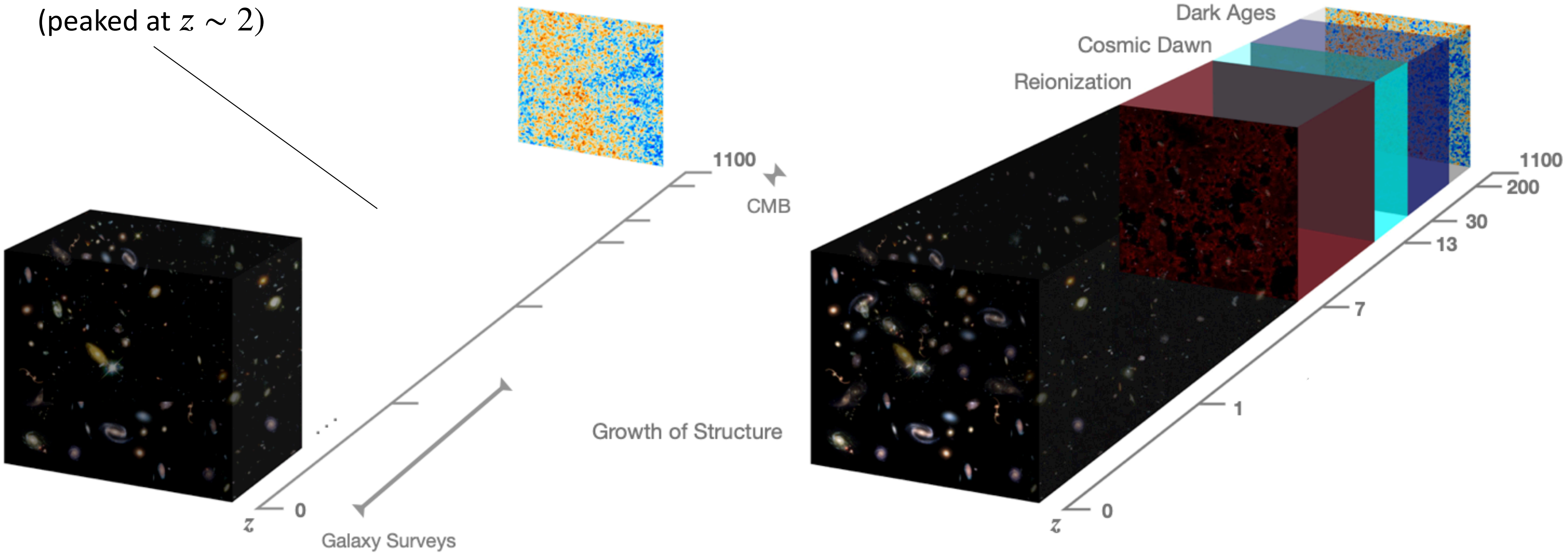
Probing the Universe



E. D. Kovetz

Probing the Universe

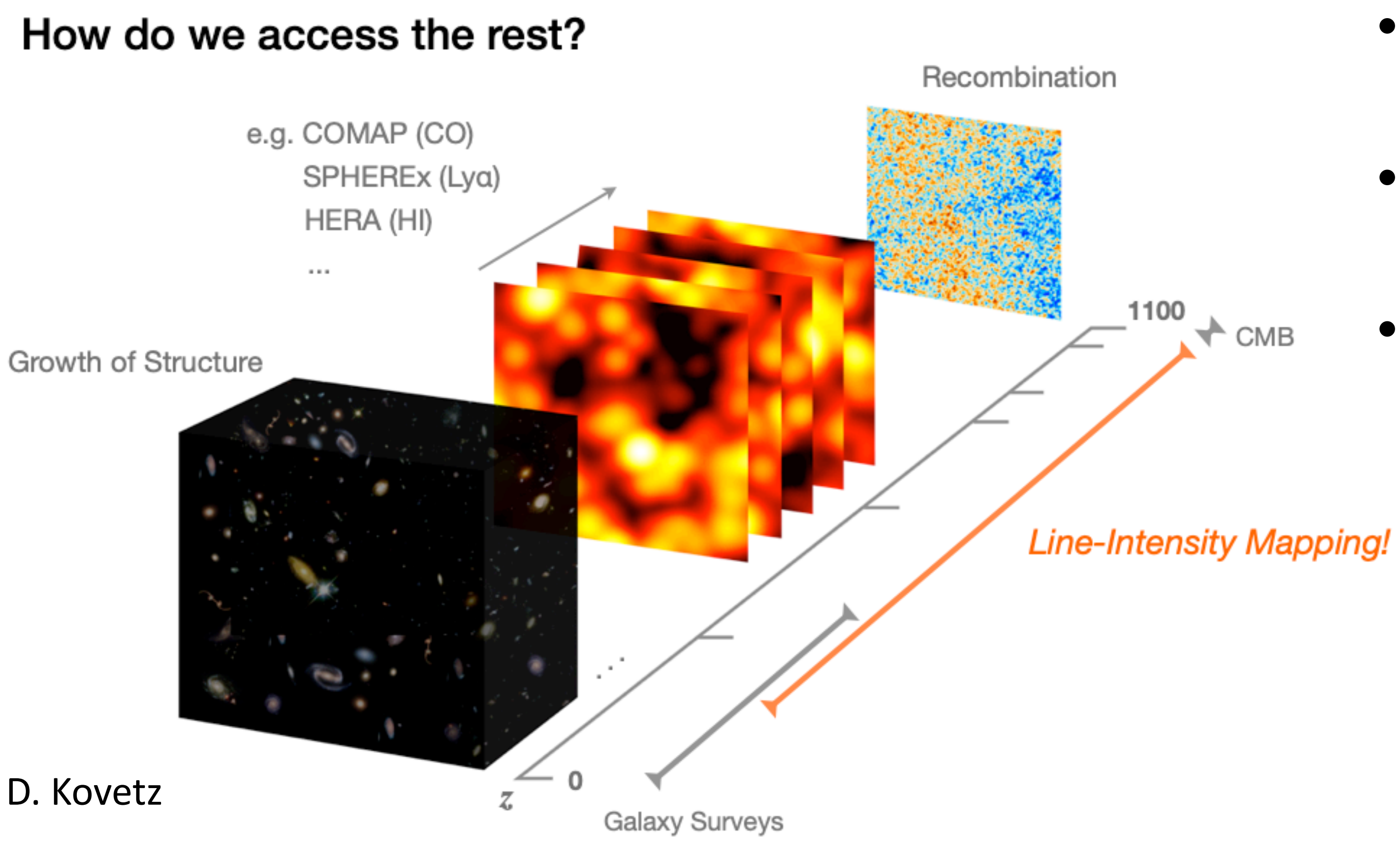
Indirect measurements with CMB lensing
(peaked at $z \sim 2$)



E. D. Kovetz

Probed Universe

Probing the Universe

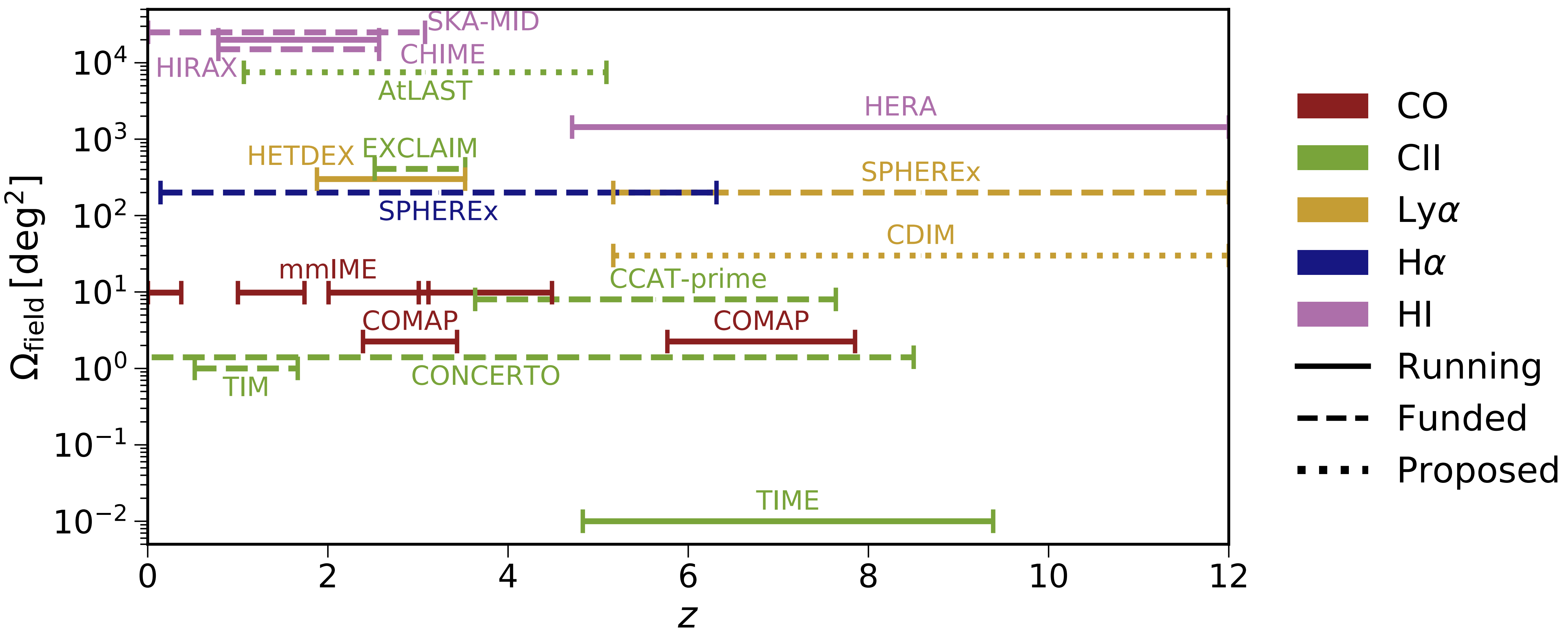


E. D. Kovetz

- 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!



Context: Spectacular Progress

First LIM community meeting, KIPAC, Stanford 2016

Second LIM community meeting, Johns Hopkins 2017

Third: Aspen Winter Conference, February 2018

2018 WINTER CONFERENCE
COSMOLOGICAL SIGNALS FROM COSMIC DAWN TO THE PRESENT

Fourth: CCA Flatiron Workshop, February 2019

FLATIRON INSTITUTE Center for Computational Astrophysics

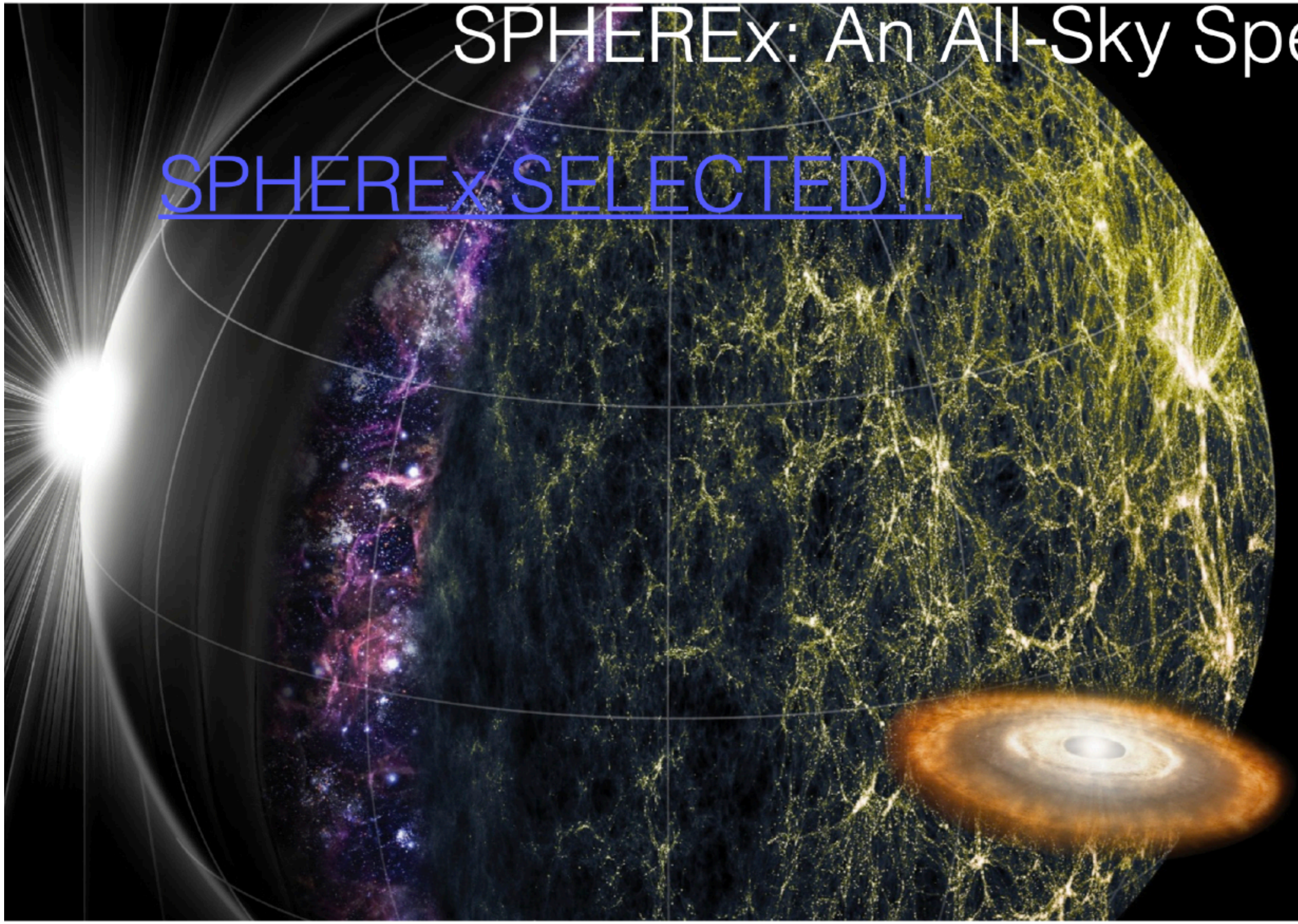
Fifth: Marseille L2S2 Conference, July 2019

8-12 July 2019
Marseille (France)
L2S2 : Lines in the Large Scale Structure
The 13th Edition of the
Marseille Cosmology Conference Series

Sixth: UChicago Workshop, July 2021

- Our field is maturing.

SPHEREx: An All-Sky Spectral Survey



SPHEREx SELECTED!!

Designed to Explore

The Origin of the Universe

The Origin and History of Galaxies

The Origin of Water in Planetary Systems

The First All-Sky Spectral Survey

A Rich Legacy Archive for the Astronomy Community with 100's of Millions of Stars and Galaxies

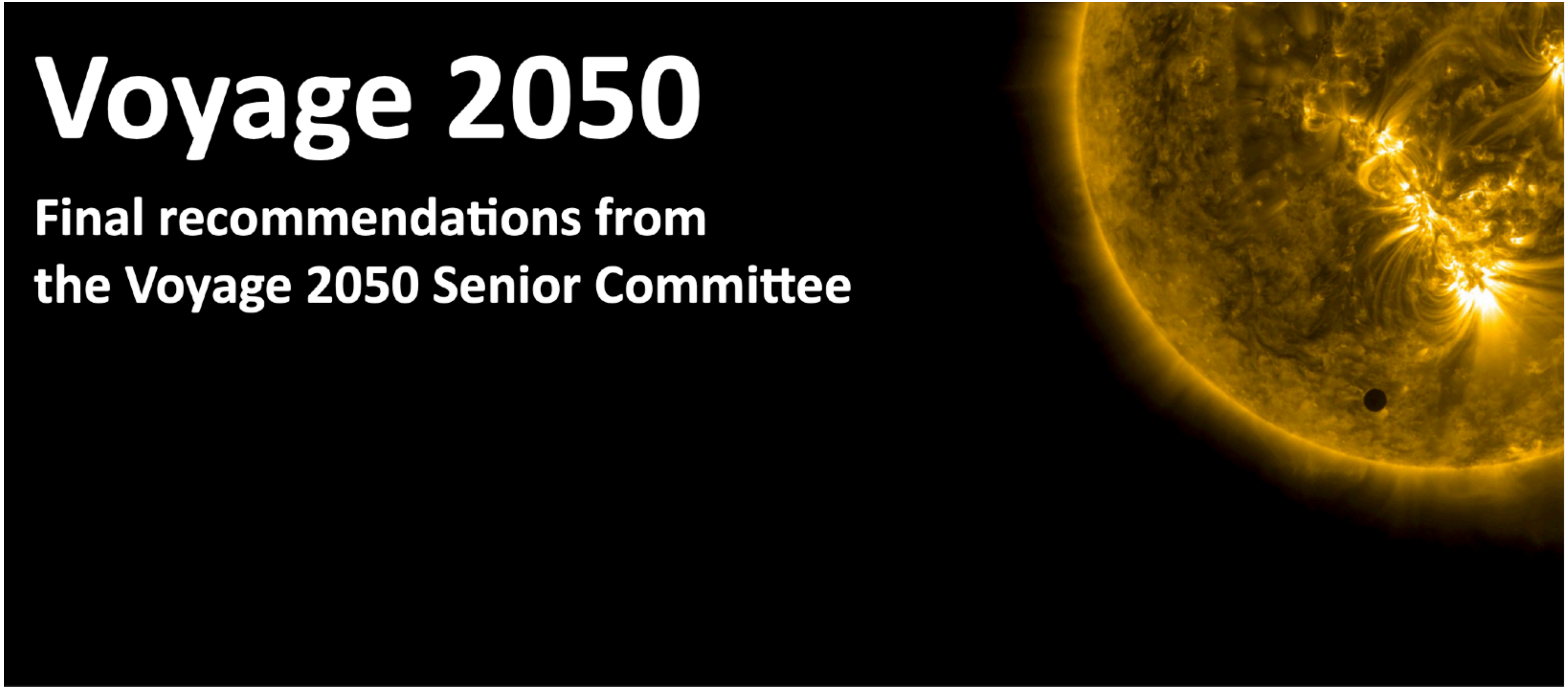
Low-Risk Implementation

No Moving Parts

Single Observing Mode

Large Technical & Scientific Margins

Follows successful CIT/JPL mgt. model of NuSTAR



3.1.12 Mapping the Cosmic Structure in Dark Matter, Missing Baryons, and Atomic and Molecular Lines

Some Science Goals

Cosmology:

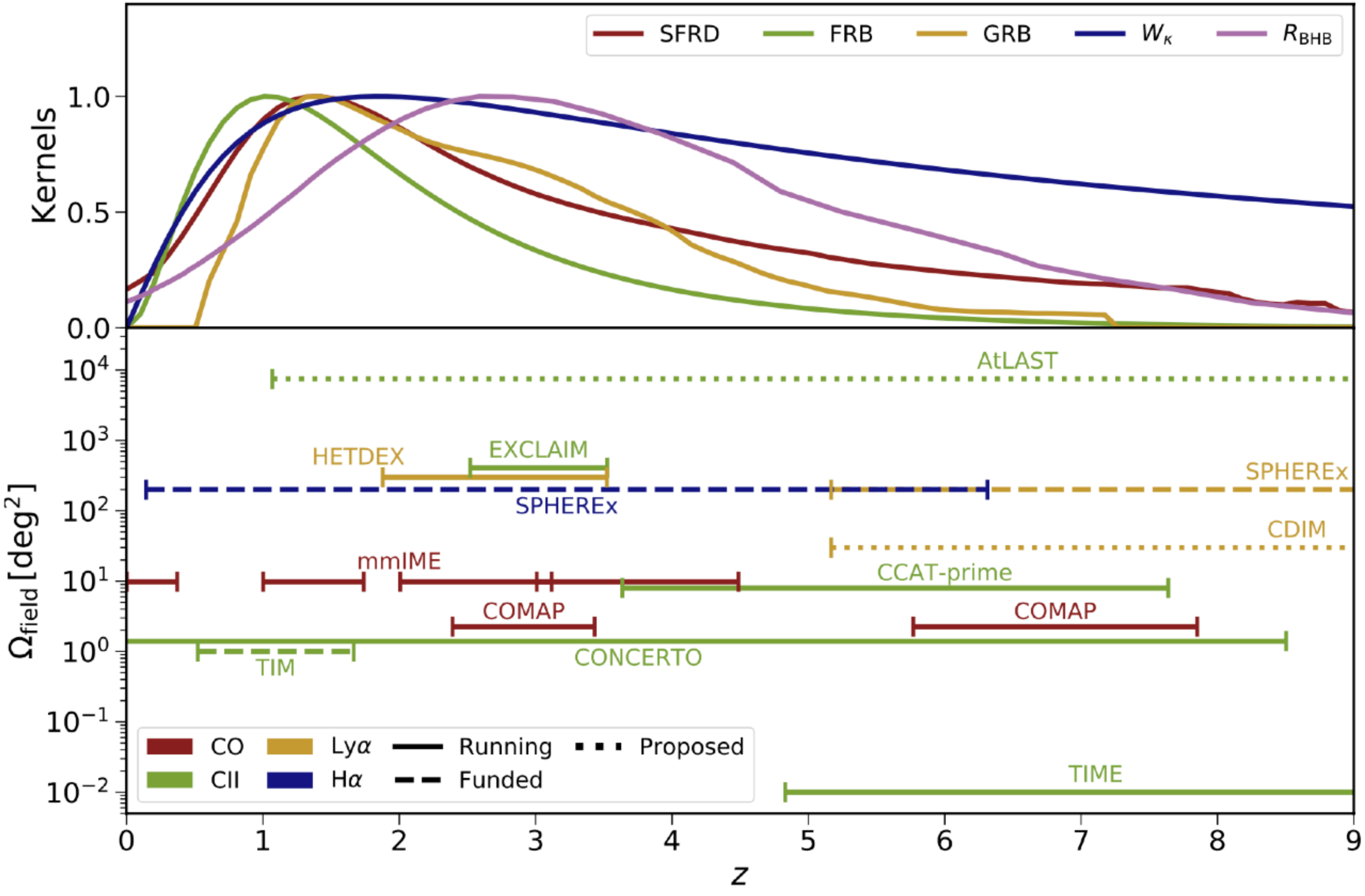
- Expansion rate history: BAO
- Neutrinos: sum of masses, decay
- Inflation (running, non-gaussianity, oscillations, CIP, etc.)
- Dark energy (wa/w0, etc.)
- Dark matter (decaying, annihilating, interacting)
- Modified gravity
- Optical depth to Reionization
- …
- …
- …

Astrophysics

- Reionization: bubble sizes, ionized fraction, duration
- Star formation rate (history, peak rise/fall, Pop III stars)
- Metallicity history
- AGN feedback
- Molecular gas density
- IGM density, evolution, clustering
- Faint end of luminosity function
- …
- …
- …

Unique Advantages of LIM: Overlap

Credit: José L. Bernal



Observables

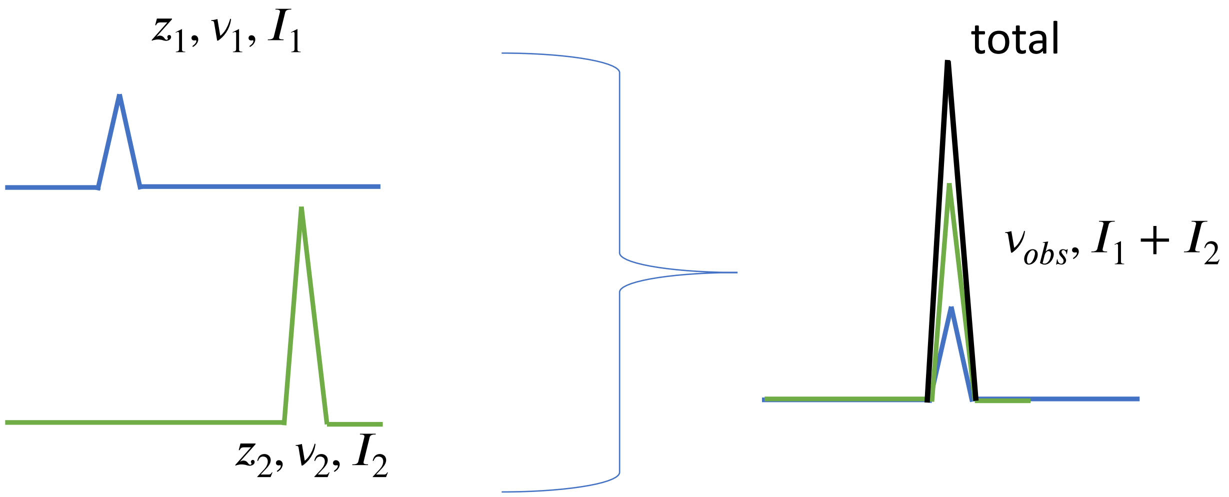
- Clustering anisotropy parametrized by monopole, dipole, quadrupole, hexadecapole in angle wrt LOS
    - Clustering along line of sight
    - Angular clustering

- Voxel-intensity distribution (VID) (one-point PDF)

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)

    - Model the effect of known interlopers in the likelihood and analyses

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  - Two approaches:
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    - Model the effect of known interlopers in the likelihood and analyses

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

Exotic radiative decays

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

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

$$\Theta_\chi$$

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

  - Traces directly the DM density field

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Θ_χ

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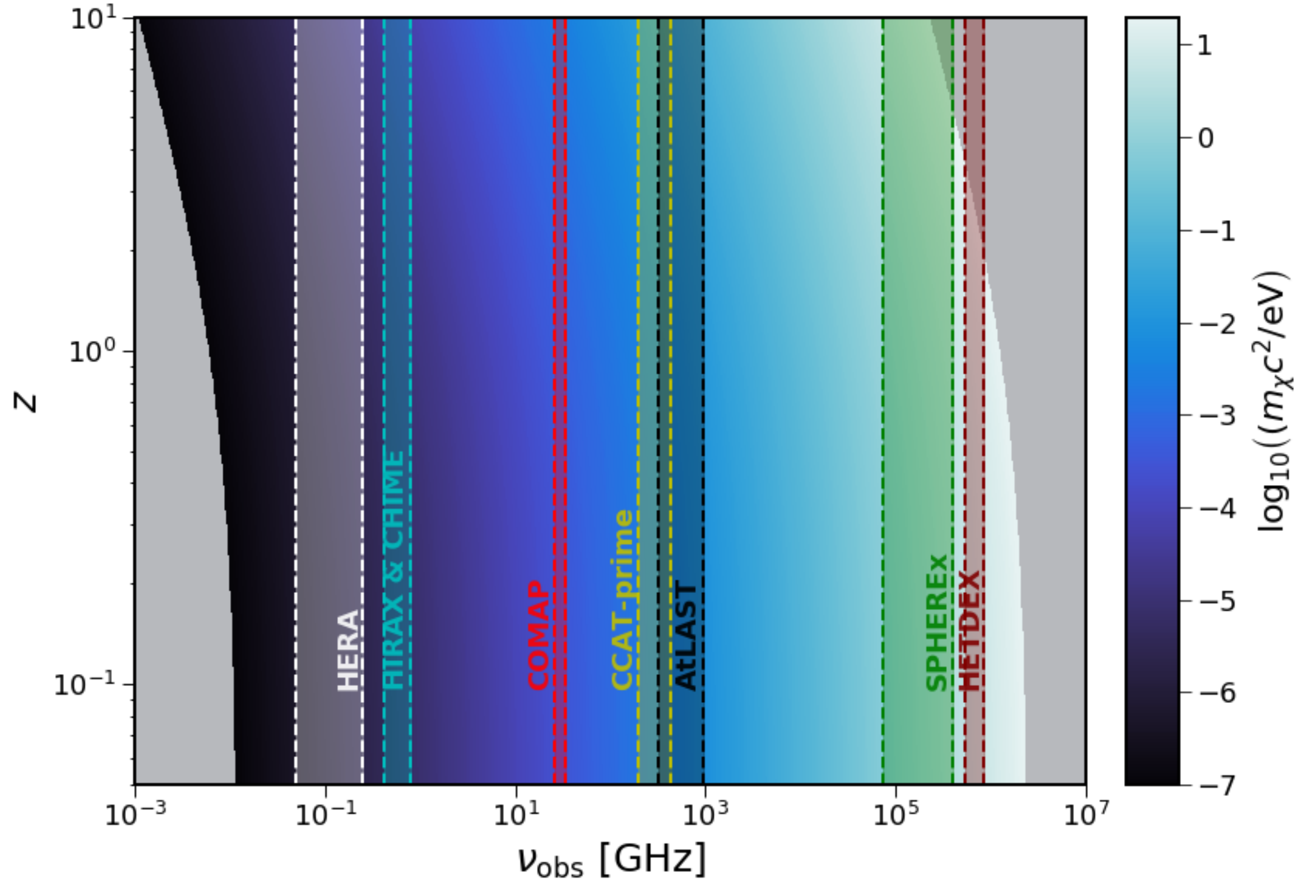
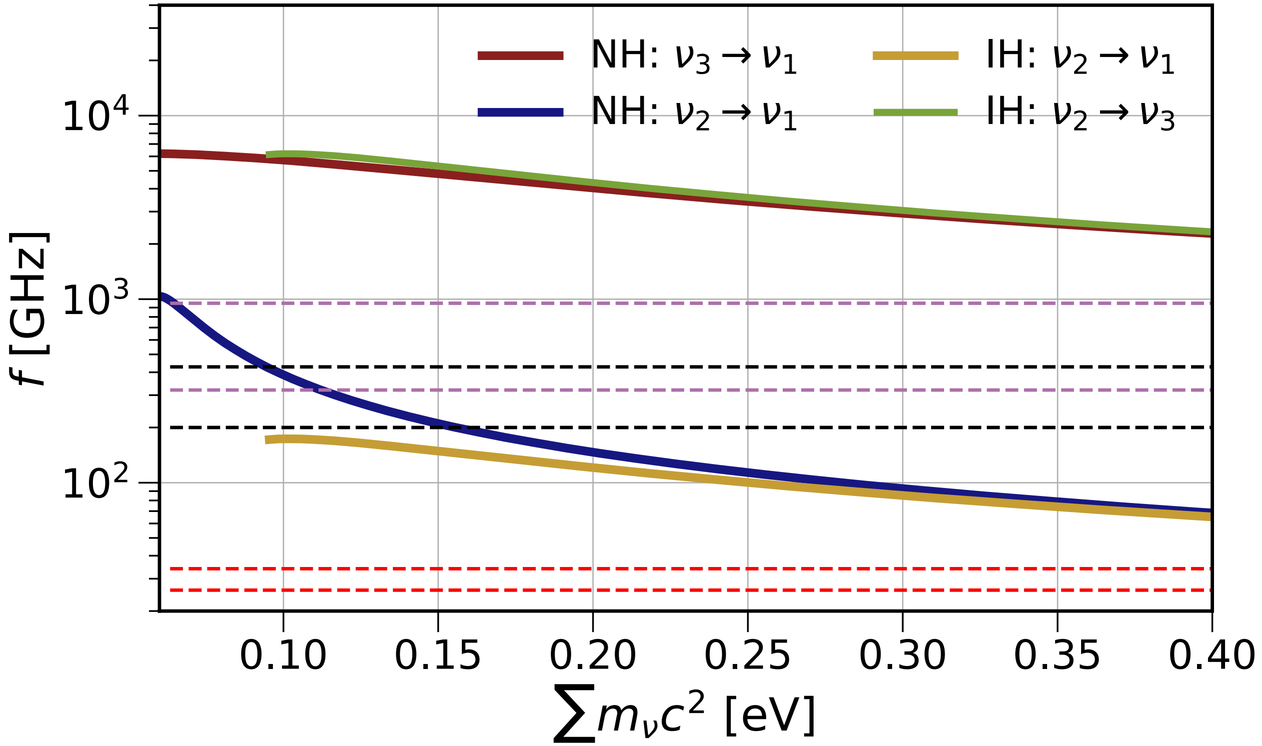


Exotic radiative decays



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

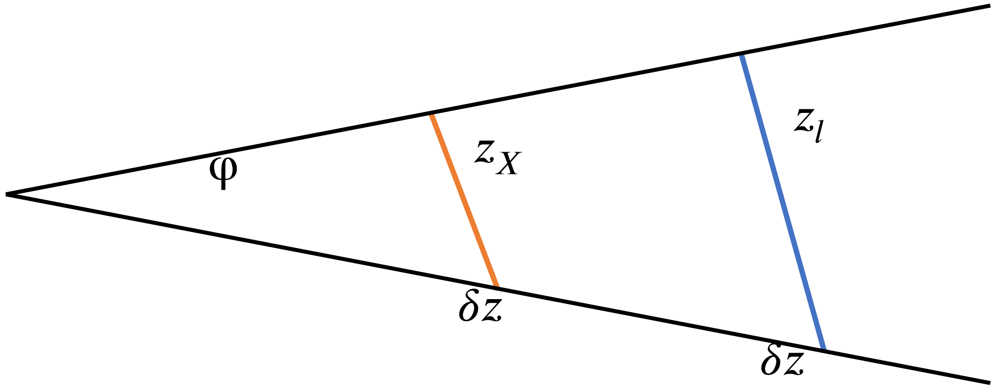
$$f_{ij} = (m_i^2 - m_j^2)c^2/2h_P m_i$$

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

- Traces directly the cosmic neutrino density field

Effect in power spectrum

- Confusion in redshift

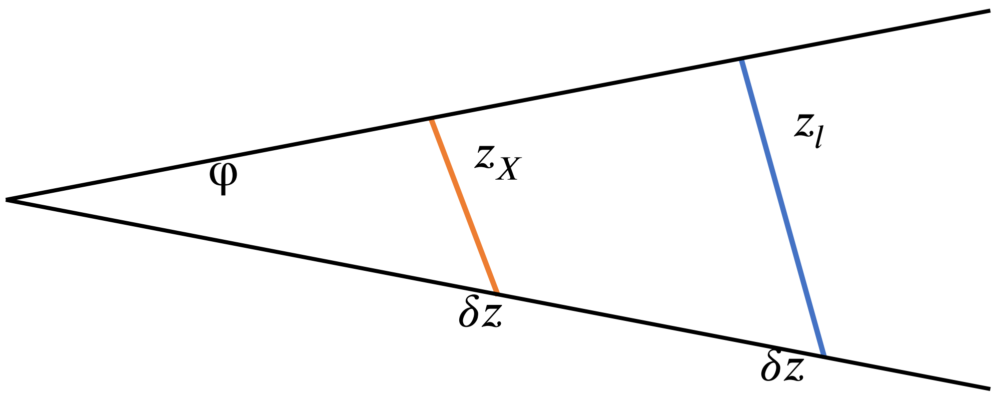


$$x_\perp = D_M(z)\theta$$

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

Effect in power spectrum

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



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

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

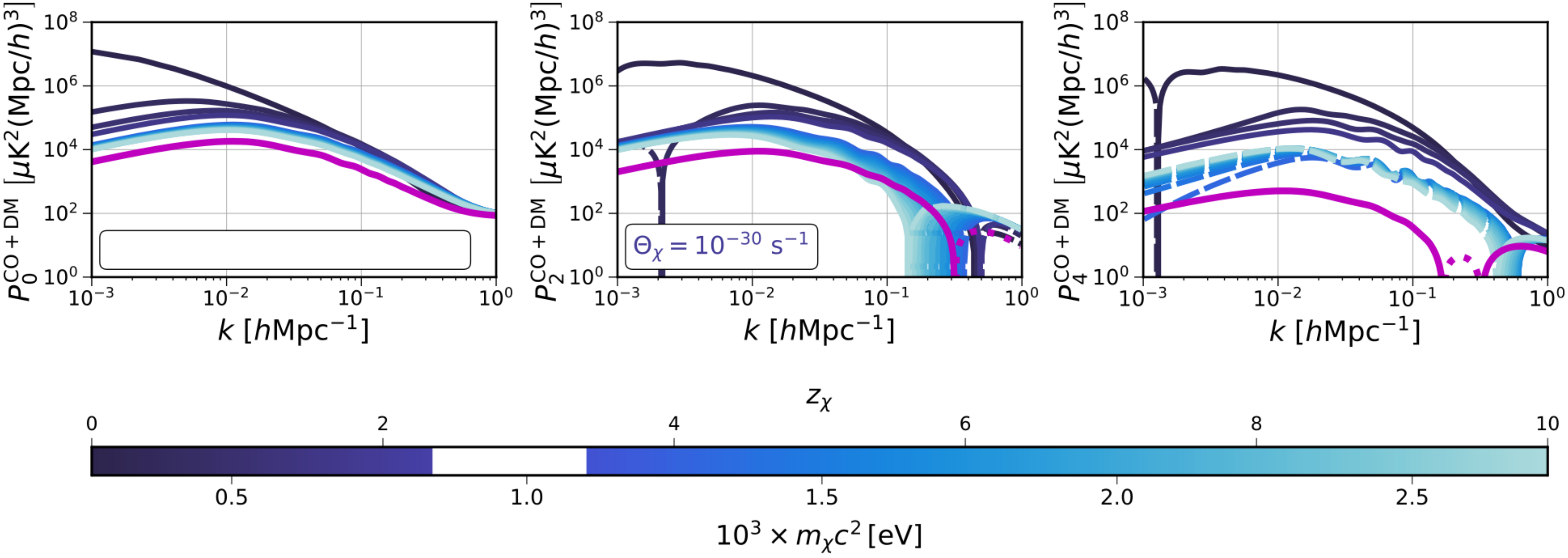
- Model it similar to Alcock-Paczynski effect: $k_i^{true} \equiv k_i^{infer}/q_i$

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

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

Effect in power spectrum

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



Effect in VID

- Each voxel receives contributions from both emissions:

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

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

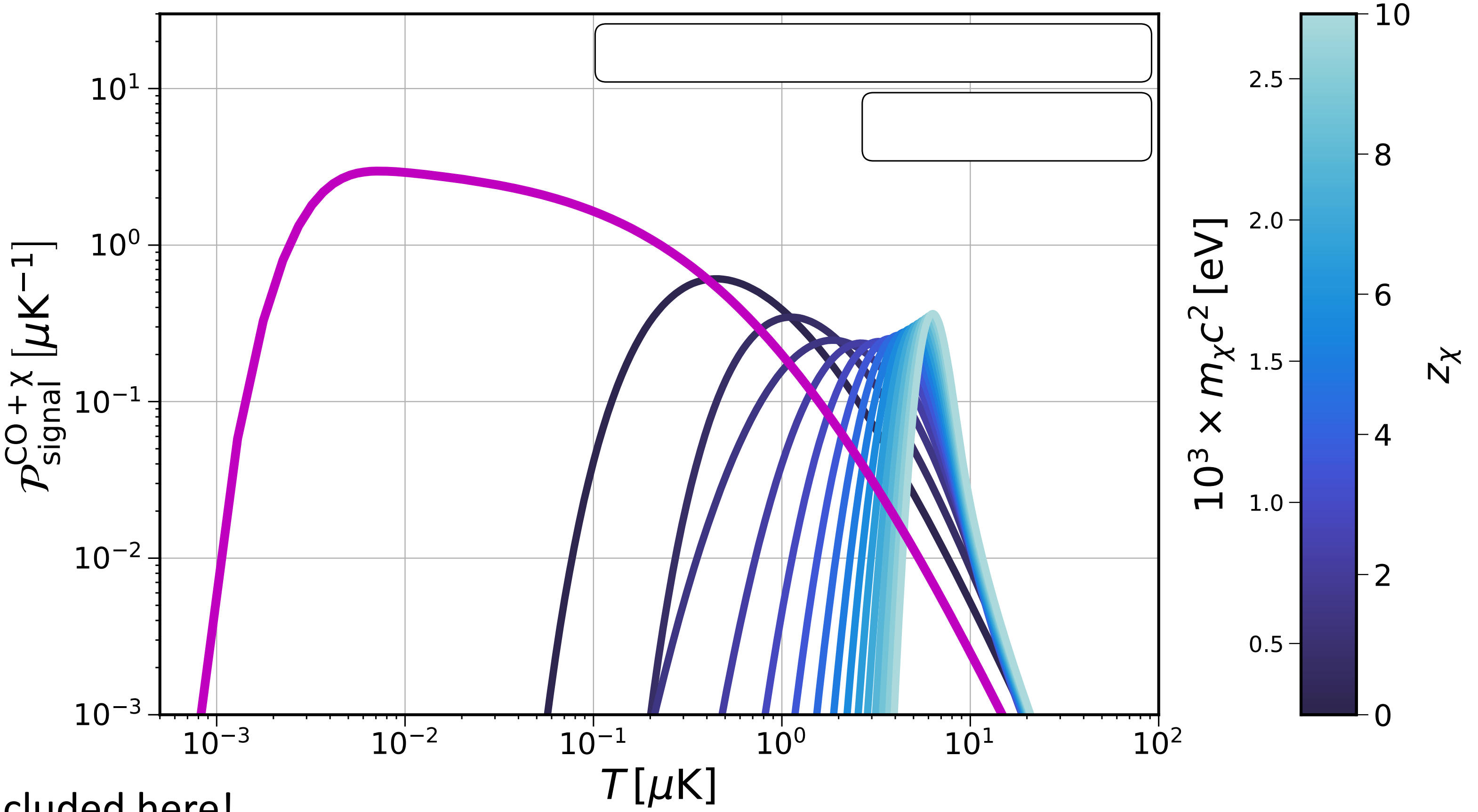
- $\mathscr{P}_{\tilde{\rho}}$: PDF of normalized densities. Obtained from simulations

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

Effect in VID

- Each voxel receives contributions from both emissions:

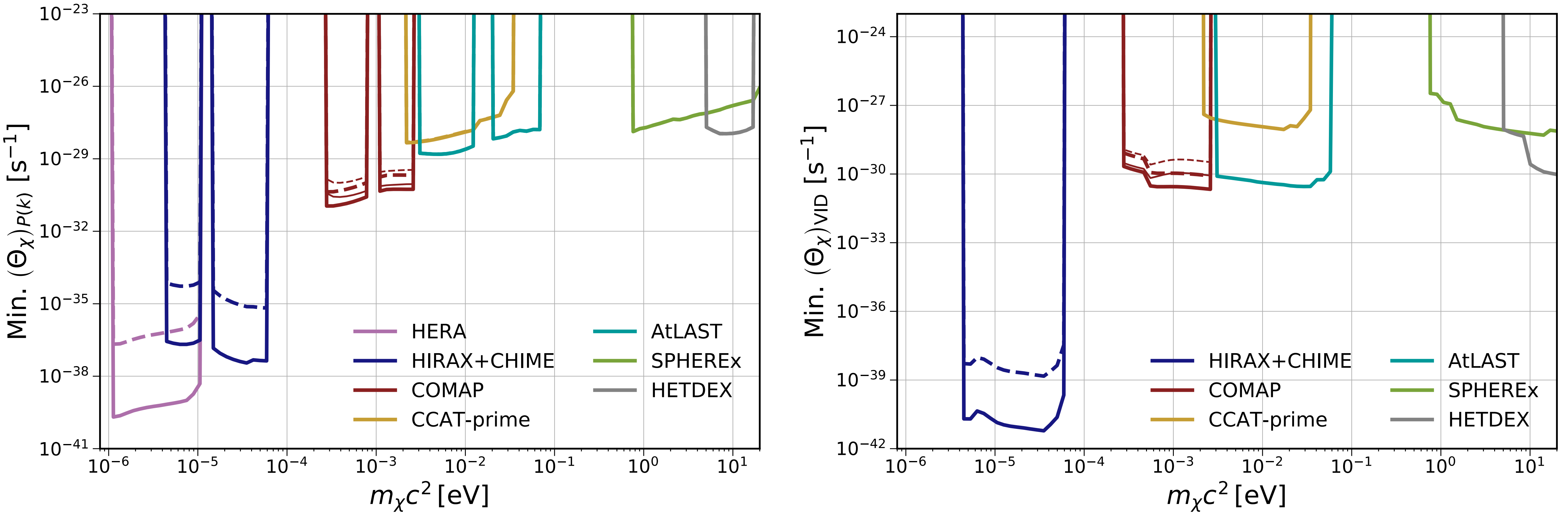
$$\mathcal{P}_{tot+\chi}(T) = \left(\left(\mathcal{P}_l * \mathcal{P}_\chi\right) * \mathcal{P}_{noise}\right)(T); \qquad \mathcal{P}_\chi = \mathcal{P}_{\tilde{\rho}} / \left\langle T_\chi \right\rangle$$



No noise contribution included here!

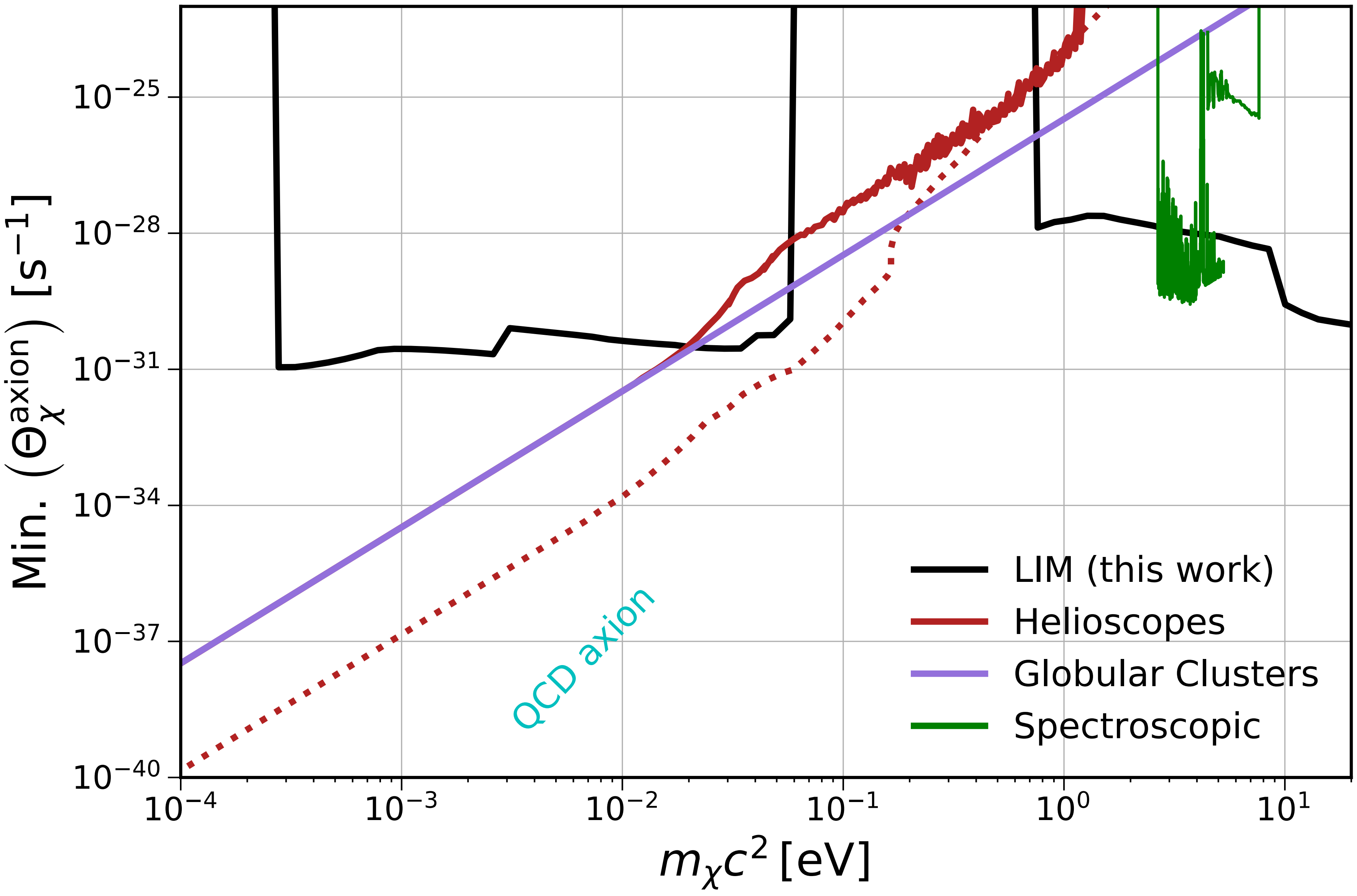
Sensitivity to DM decays

- After marginalizing over astrophysical uncertainties of the target emission line



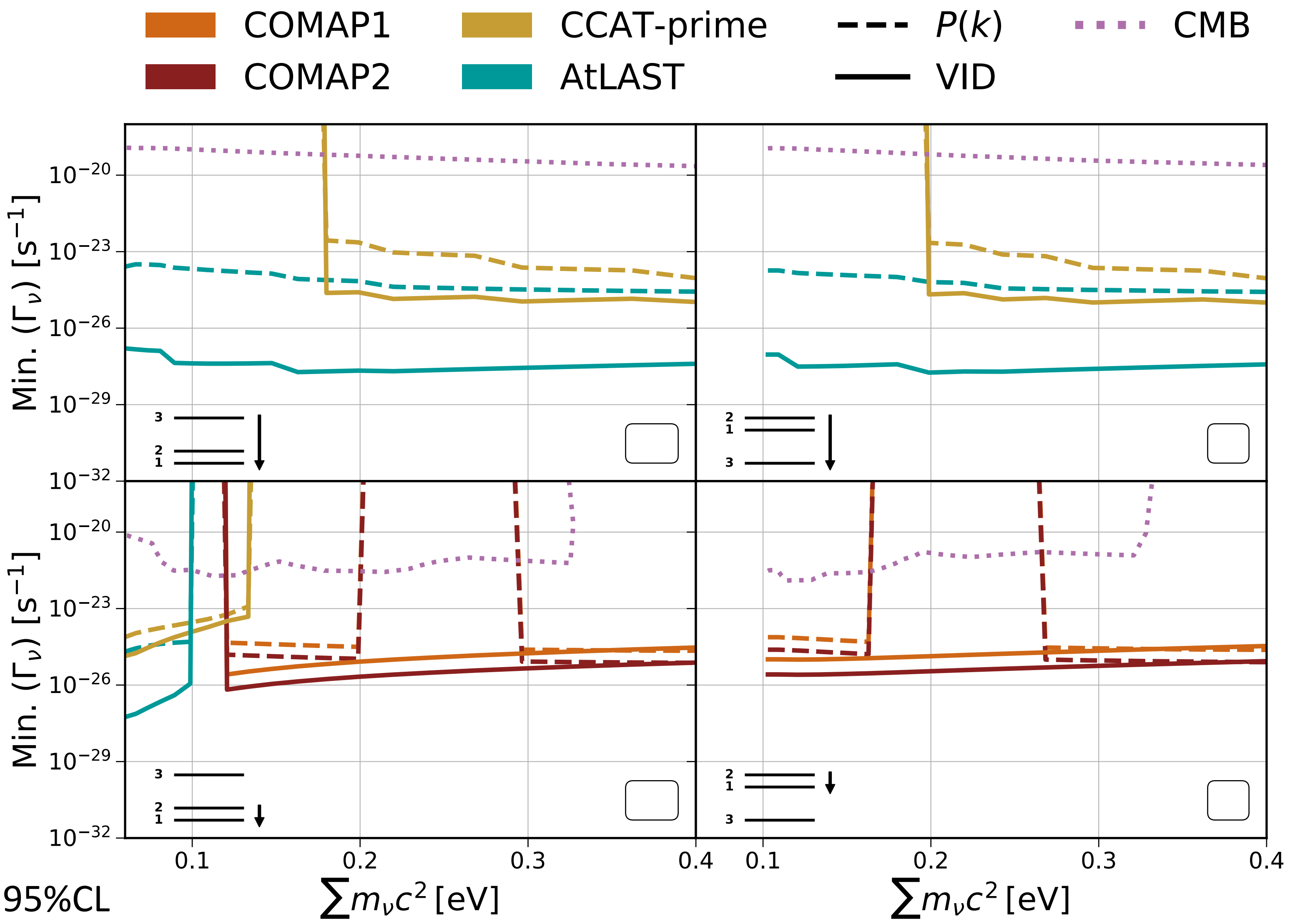
95%CL

Sensitivity to axions



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: $< 4.5 \times 10^{-12}\mu_B$

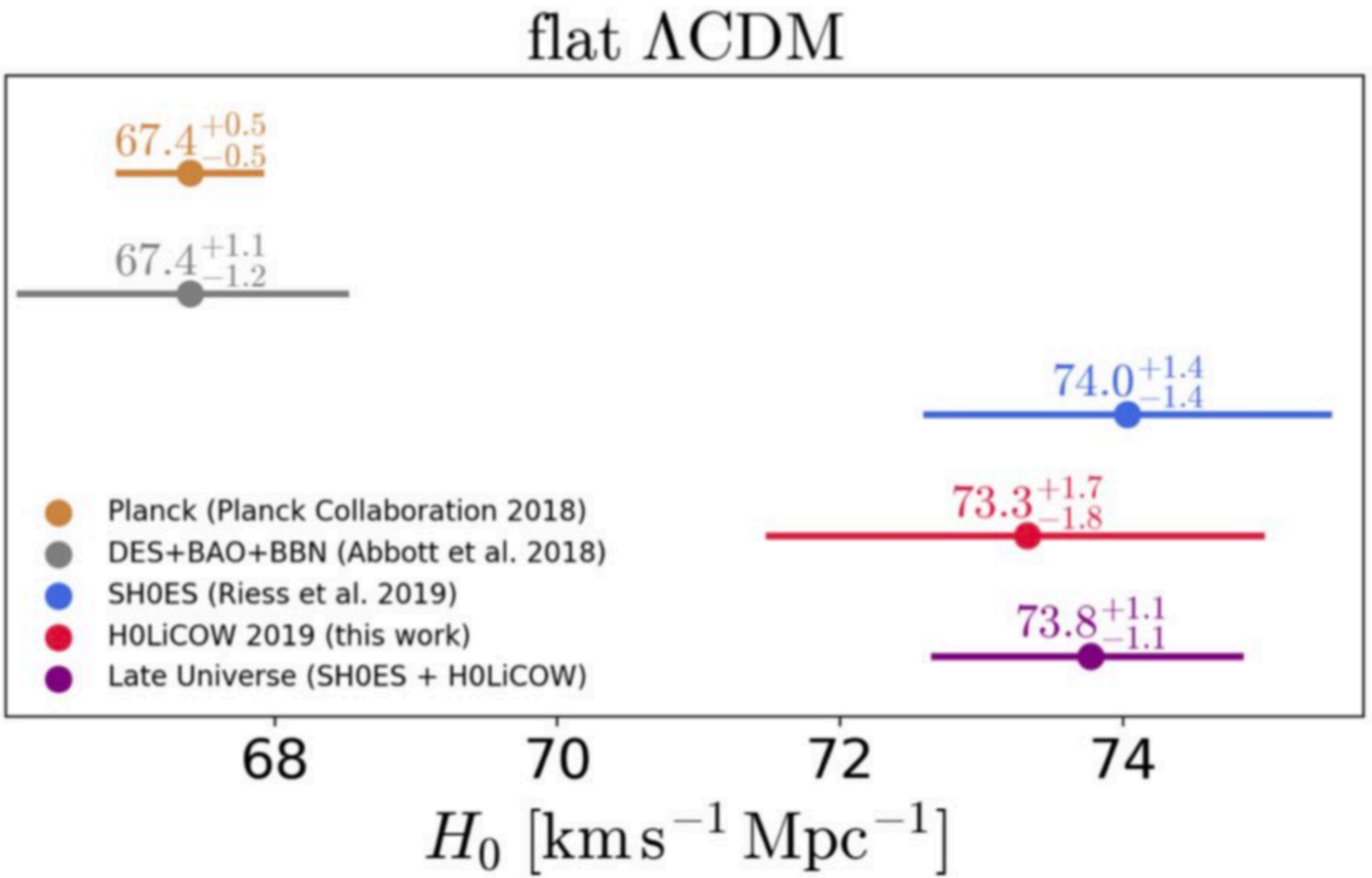
Challenges & improvements

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

- Reasons to be optimistic:
  - Extendable to other 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

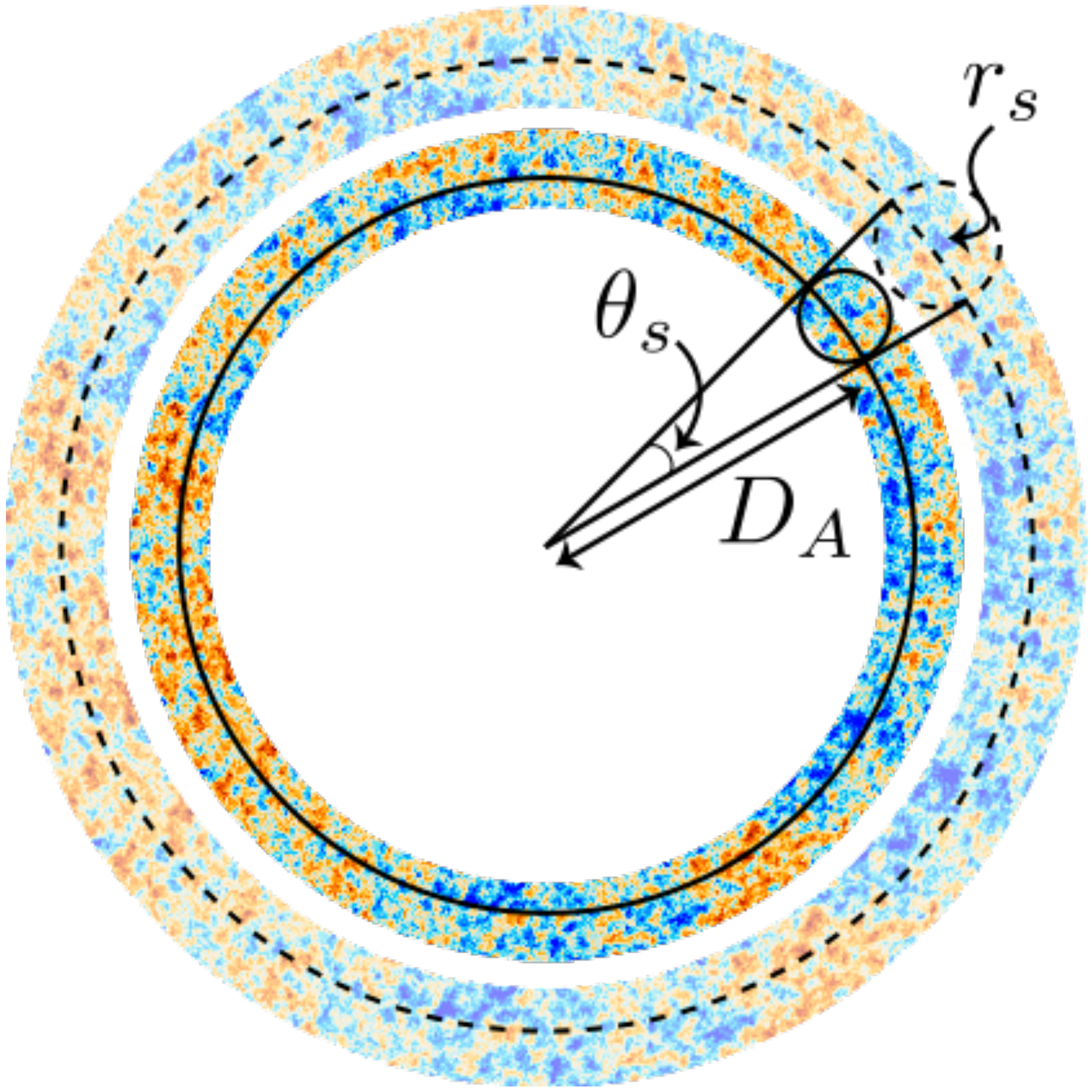
The Cosmic Expansion History from Line-Intensity Mapping

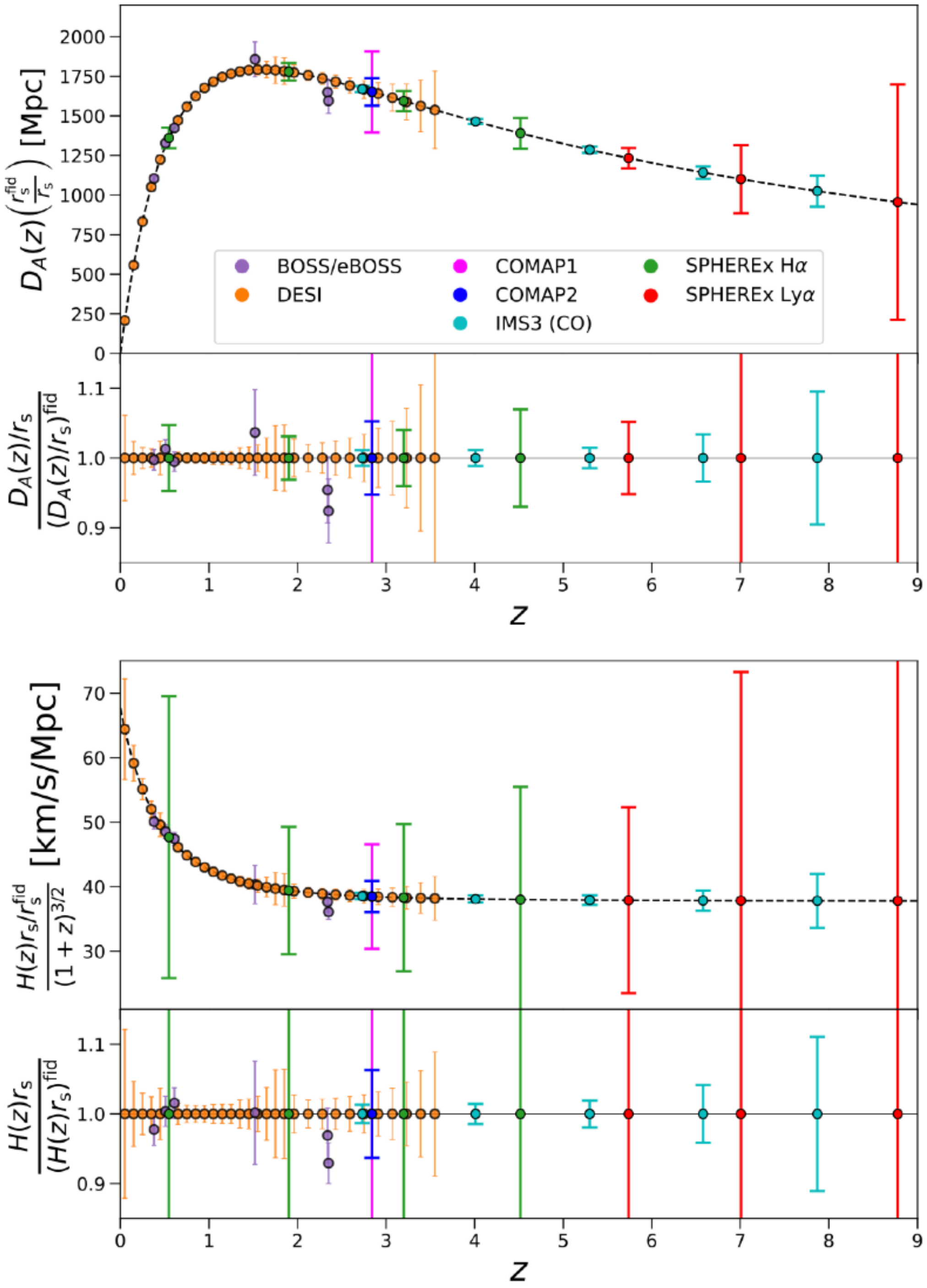
José Luis Bernal,[1, 2, 3] Patrick C. Breysse,[4] and Ely D. Kovetz[5]



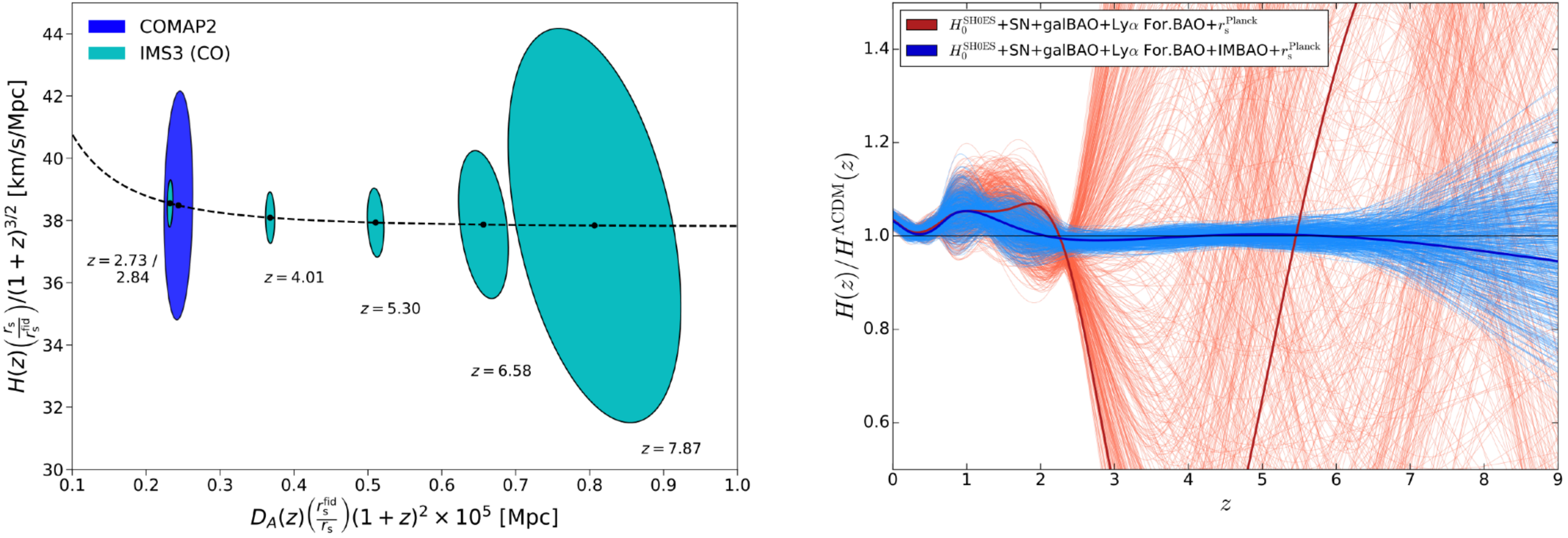
flat ΛCDM
$67.4^{+0.5}_{-0.5}$
$67.4^{+1.1}_{-1.2}$
$74.0^{+1.4}_{-1.4}$
$73.3^{+1.7}_{-1.8}$
$73.8^{+1.1}_{-1.1}$
Planck (Planck Collaboration 2018)
DES+BAO+BBN (Abbott et al. 2018)
SH0ES (Riess et al. 2019)
H0LiCOW 2019 (this work)
Late Universe (SH0ES + H0LiCOW)
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]

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





BOSS/eBOSS
DESI
COMAP1
COMAP2
IMS3 (CO)
SPHEREx Hα
SPHEREx Lyα
$D_A(z)\left(\frac{r_s^{fid}}{r_s}\right)$ [Mpc]
$\frac{D_A(z)/r_s}{(D_A(z)/r_s)^{fid}}$
$\frac{H(z)r_s/r_s^{fid}}{(1+z)^{3/2}}$ [km/s/Mpc]
$\frac{H(z)r_s}{(H(z)r_s)^{fid}}$
z
z



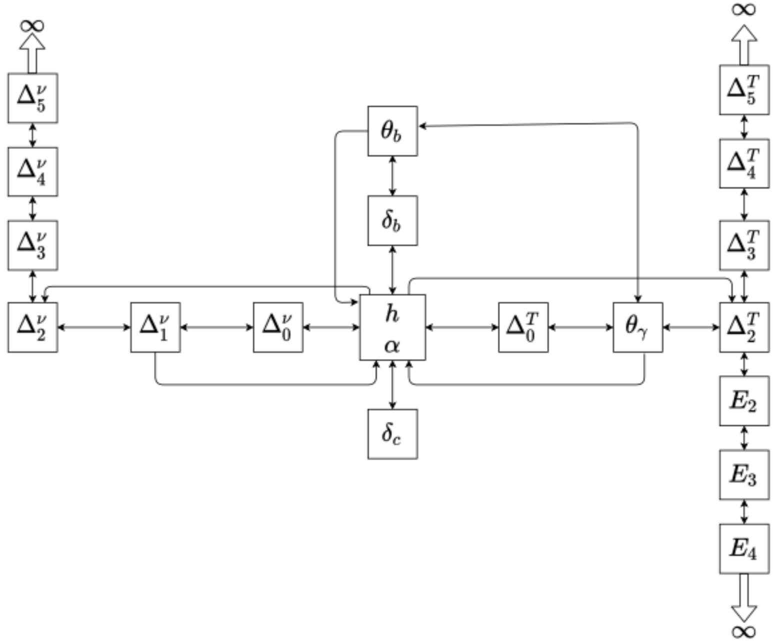
COMAP2
IMS3 (CO)
$z = 2.73$ / 2.84
$z = 4.01$
$z = 5.30$
$z = 6.58$
$z = 7.87$
$H(z)\left(\frac{r_s}{r_s^{fid}}\right)/(1+z)^{3/2}$ [km/s/Mpc]
$D_A(z)\left(\frac{r_s^{fid}}{r_s}\right)(1+z)^2 \times 10^5$ [Mpc]
H_0^{SH0ES}+SN+galBAO+Lyα For.BAO+r_s^{Planck}
H_0^{SH0ES}+SN+galBAO+Lyα For.BAO+IMBAO+r_s^{Planck}
$H(z)/H^{\Lambda CDM}(z)$
z

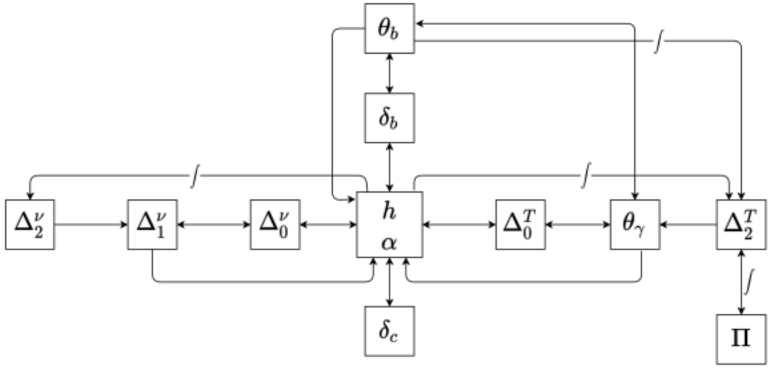
As an aside:

Cosmological perturbations without the Boltzmann hierarchy

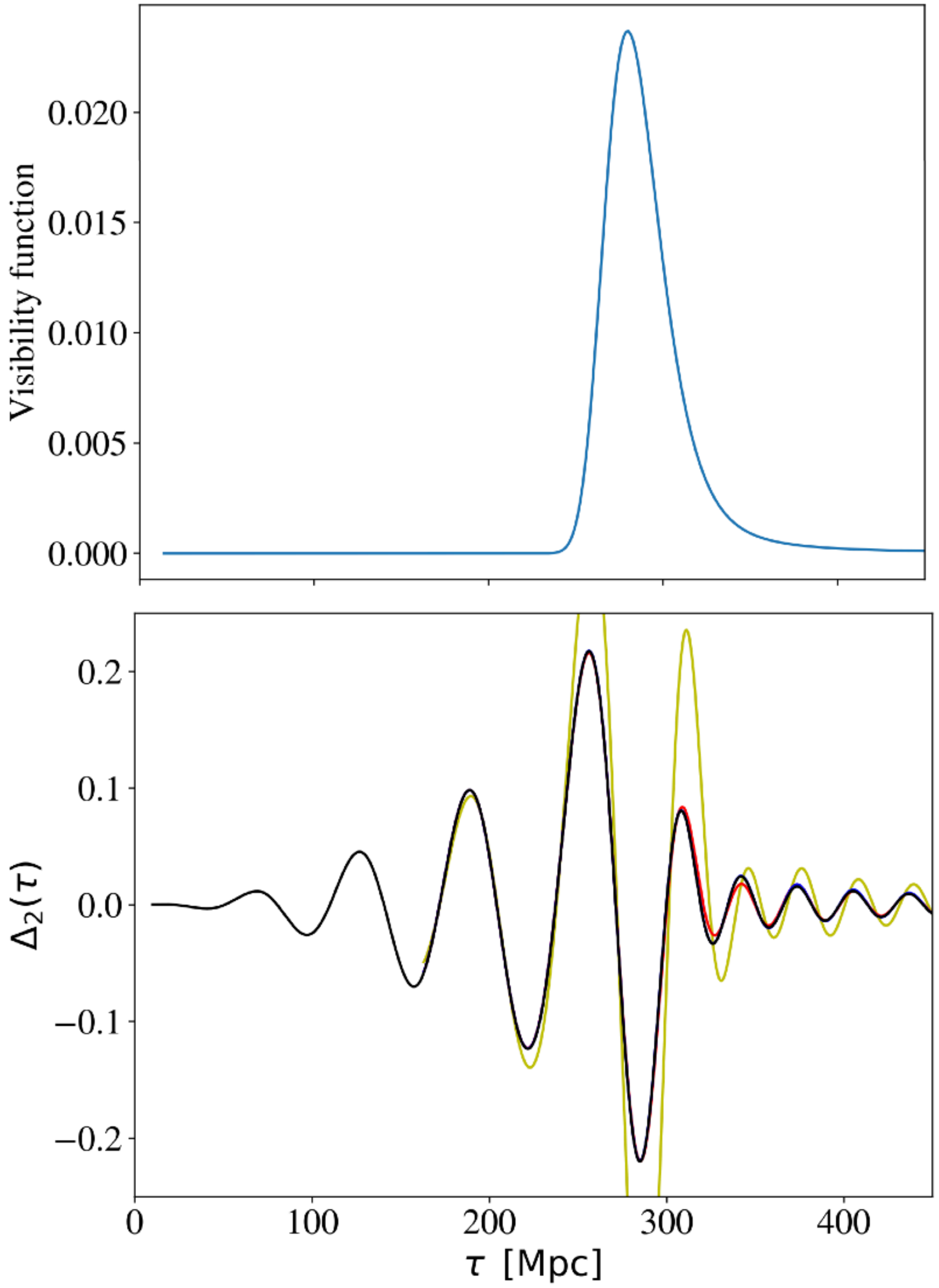
Marc Kamionkowski
Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218
(Dated: May 10, 2021)

arXiv:2105.02887





and work in progress with J. Bernal, L. Yi, and B. Zhou



Visibility function
0.020
0.015
0.010
0.005
0.000
$\Delta_2(\tau)$
0.2
0.1
0.0
−0.1
−0.2
0
100
200
300
400
τ [Mpc]

Conclusions

- LIM holds a great protential to probe exotic radiative decays
- Adapting techniques to identify and model interlopers is cheap and powerful
- 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