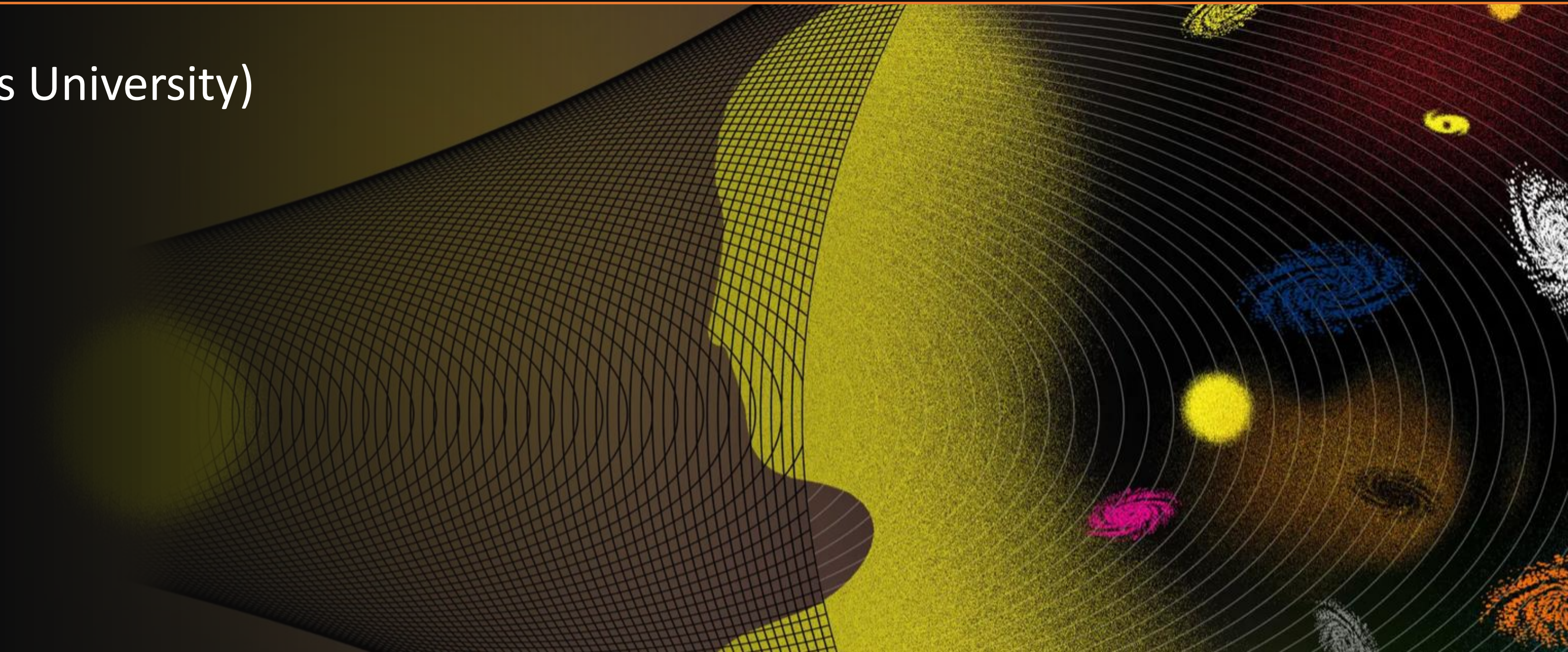
Line-Intensity Mapping (and kSZ tomography) and dark matter

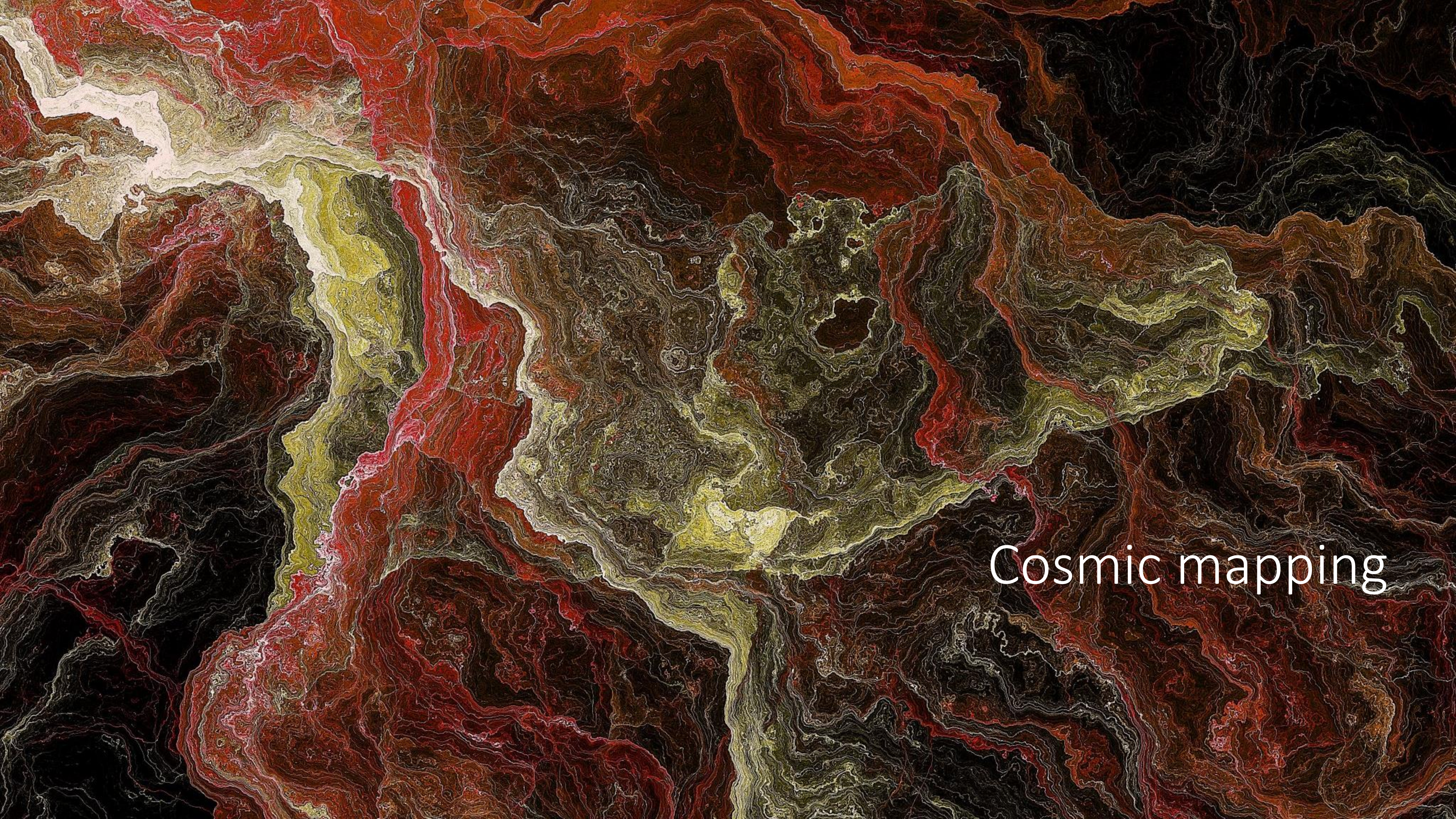
Marc Kamionkowski (Johns Hopkins University)

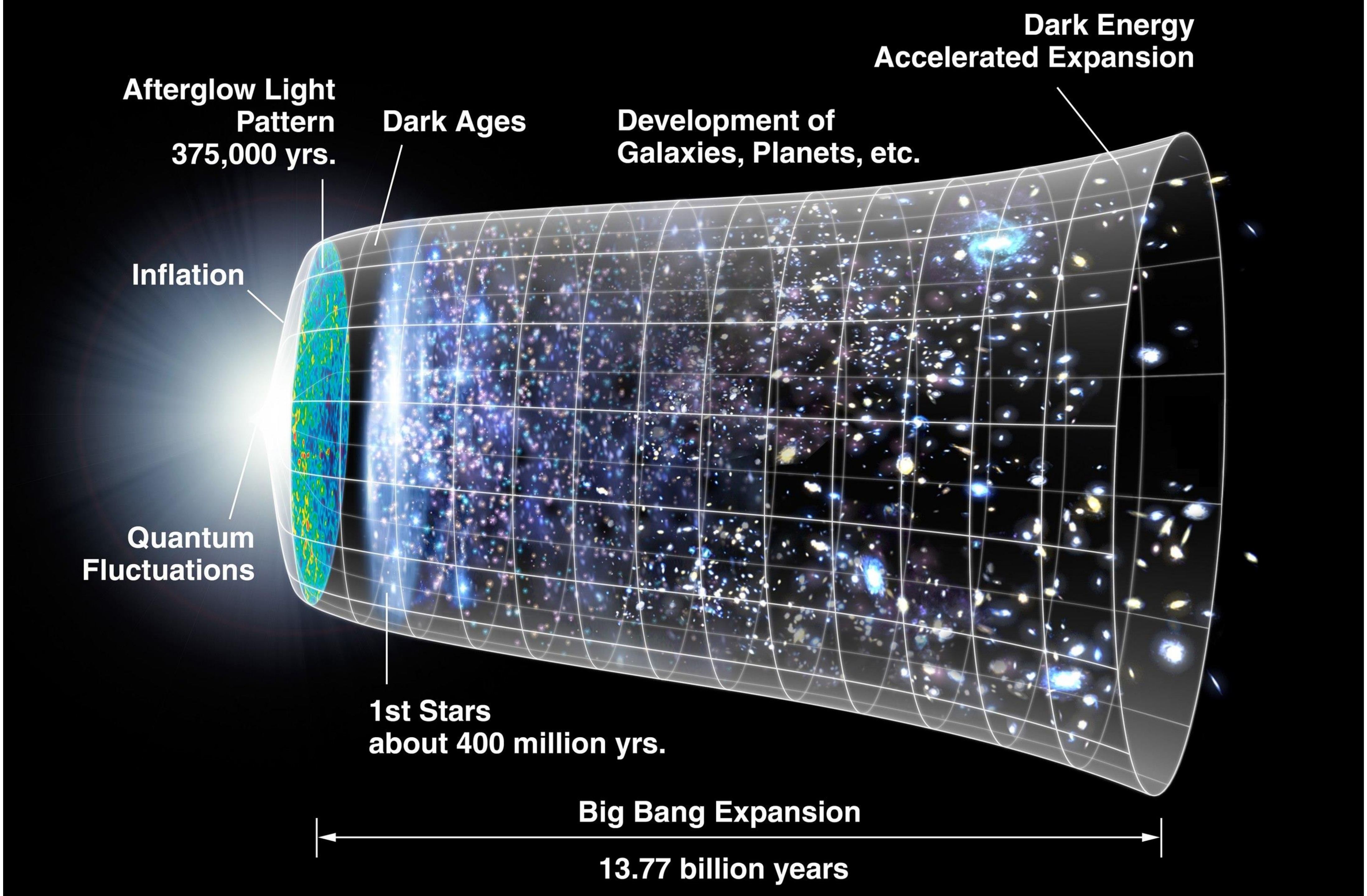
7 June 2022



Outline

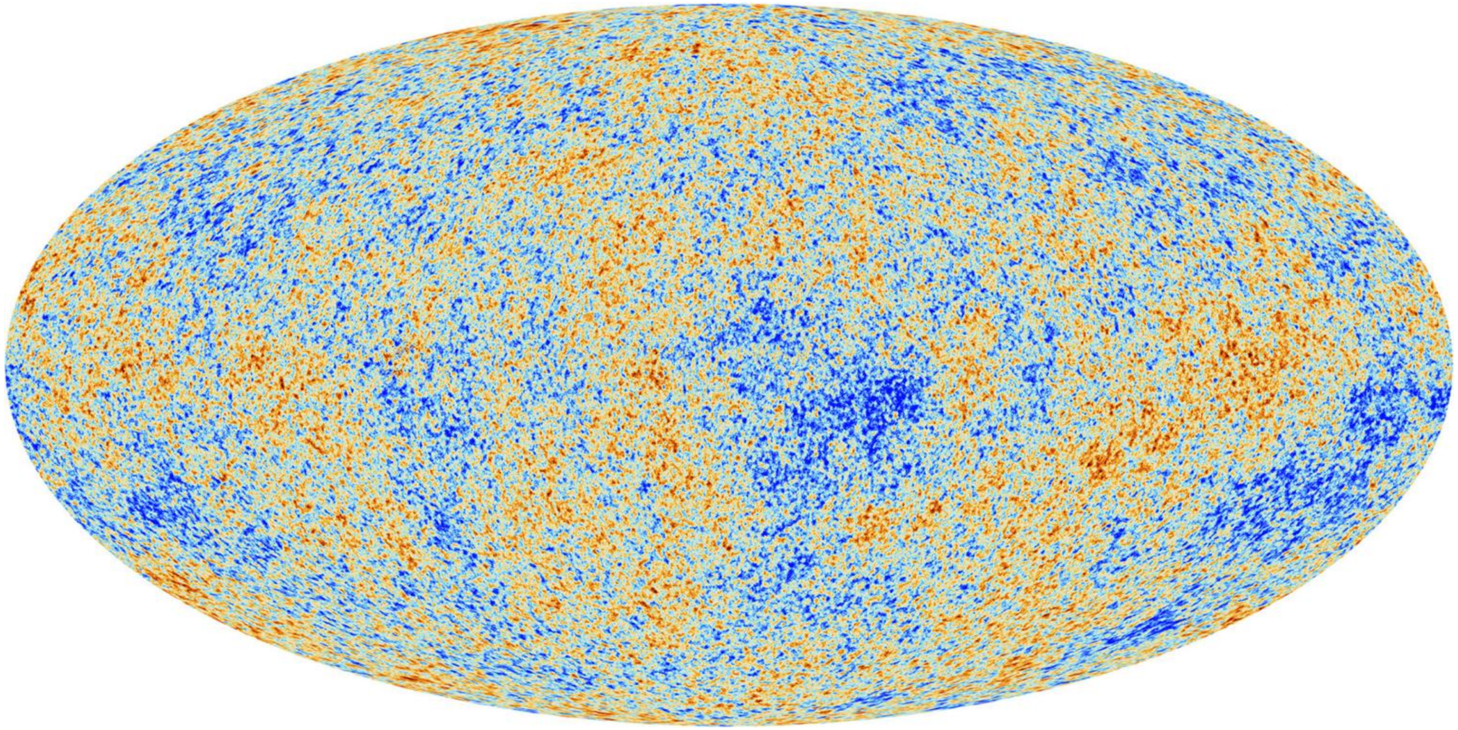
- CMB, galaxy surveys, and cosmology
- Line-intensity mapping
- kSZ (kinematic Sunyaev-Zeldovich) tomography


Cosmic mapping

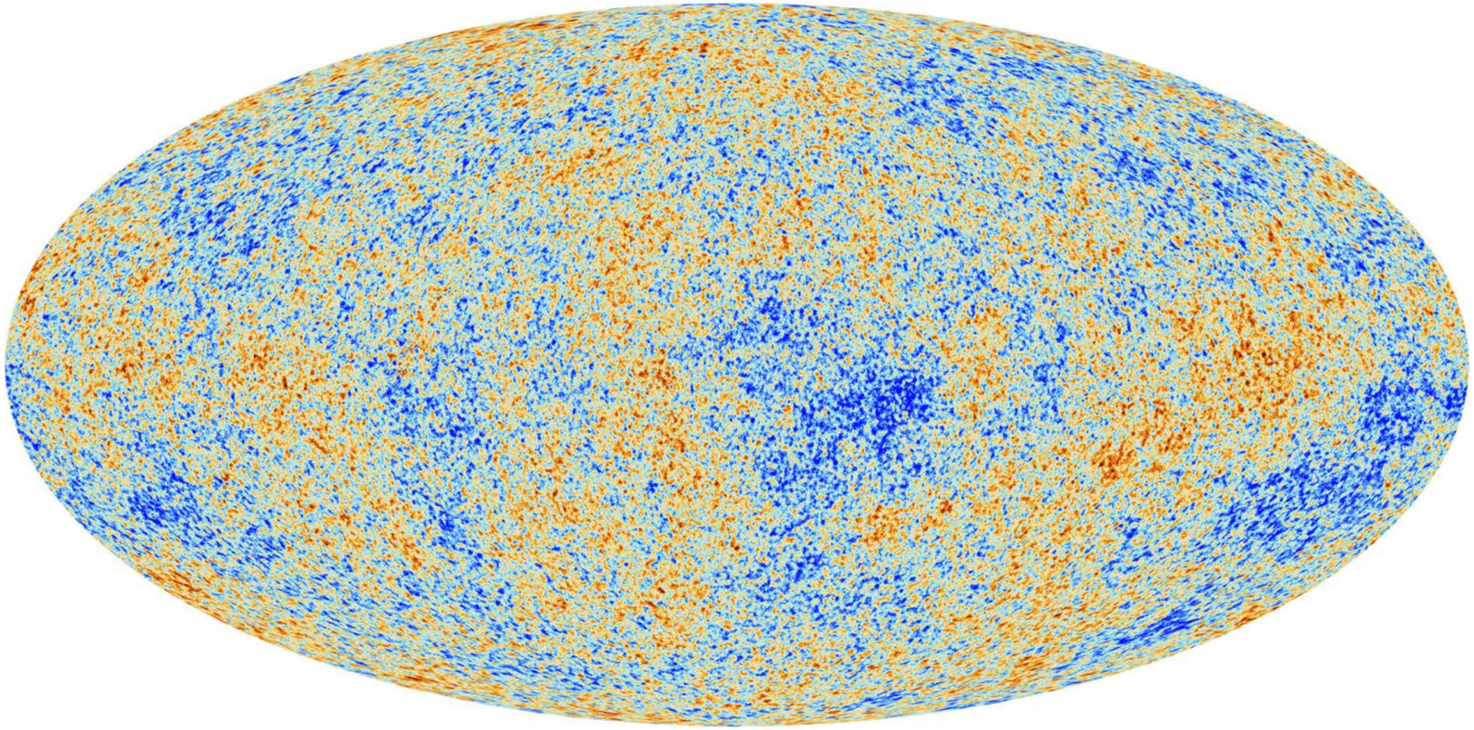

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

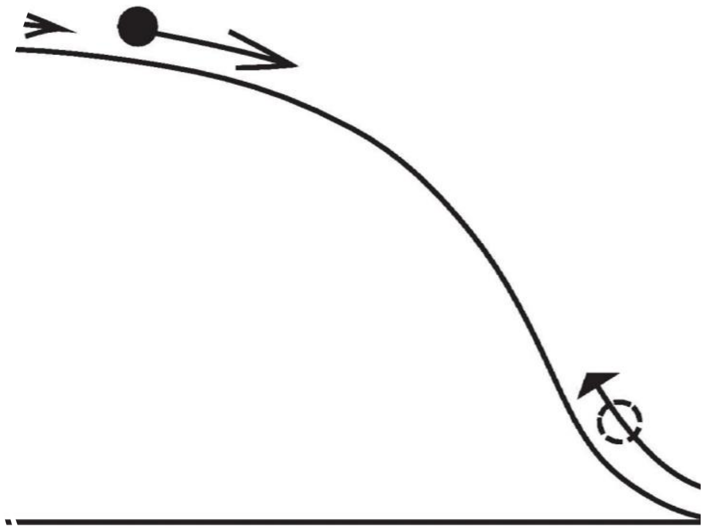
Cosmic microwave background (CMB)

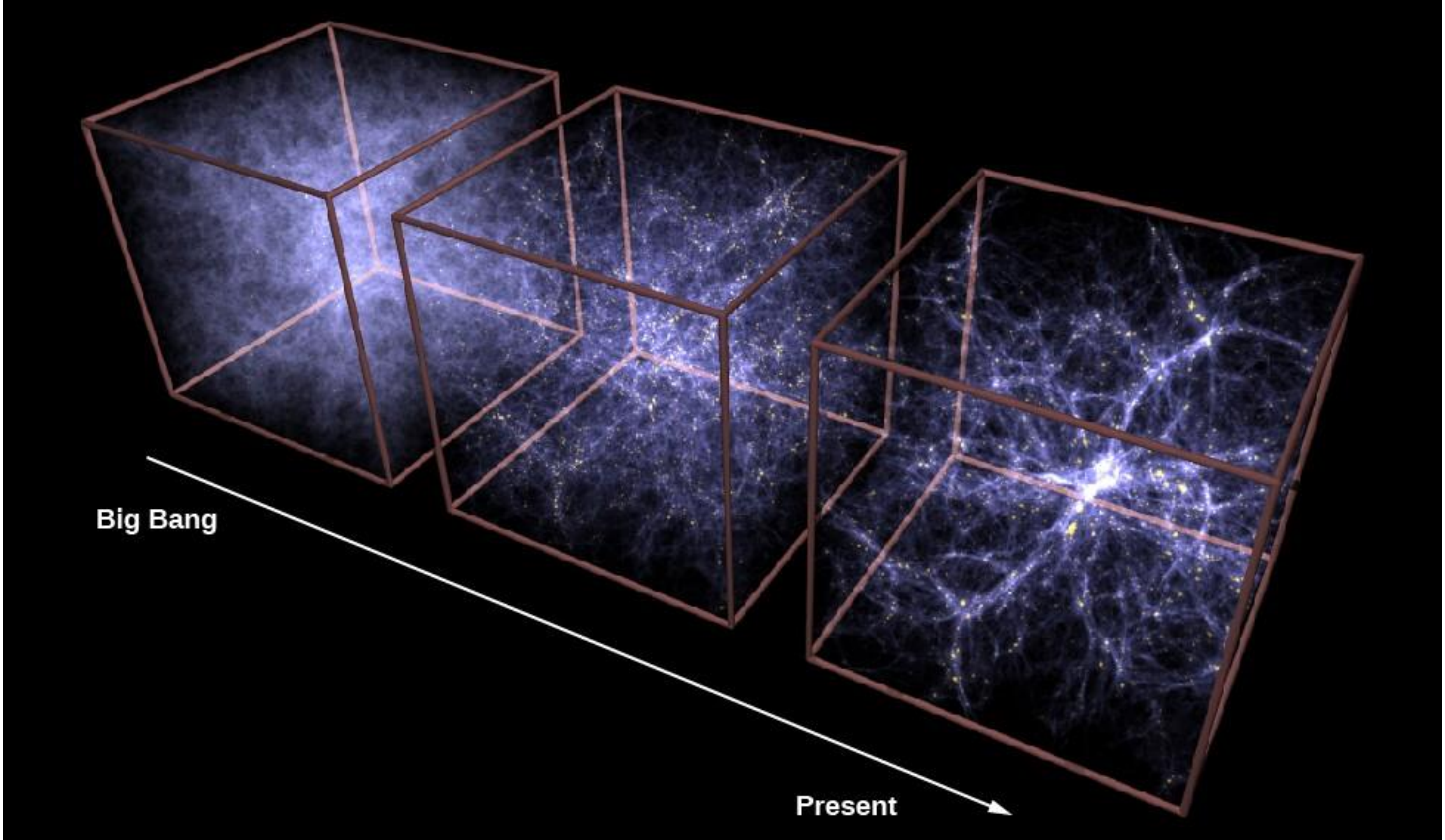
- Provides primordial perturbations
- Backlight for later Universe
    - Weak gravitational lensing
    - Sunyaev-Zeldovich (SZ) effect



Inflation






Big Bang
Present

Evolution of perturbations

- "Linear-theory growth factor": *D(z)*
  - dark energy
- Small-scale perturbations
  - Neutrino masses
  - ULAs (ultra-light axions)
- Baryon acoustic oscillations (BAOs) and redshift-space distortions (RSDs)
  - Anisotropy in clustering along/transverse to line of sight
    → dark energy, Hubble parameter, modified gravity

Cosmology and new physics

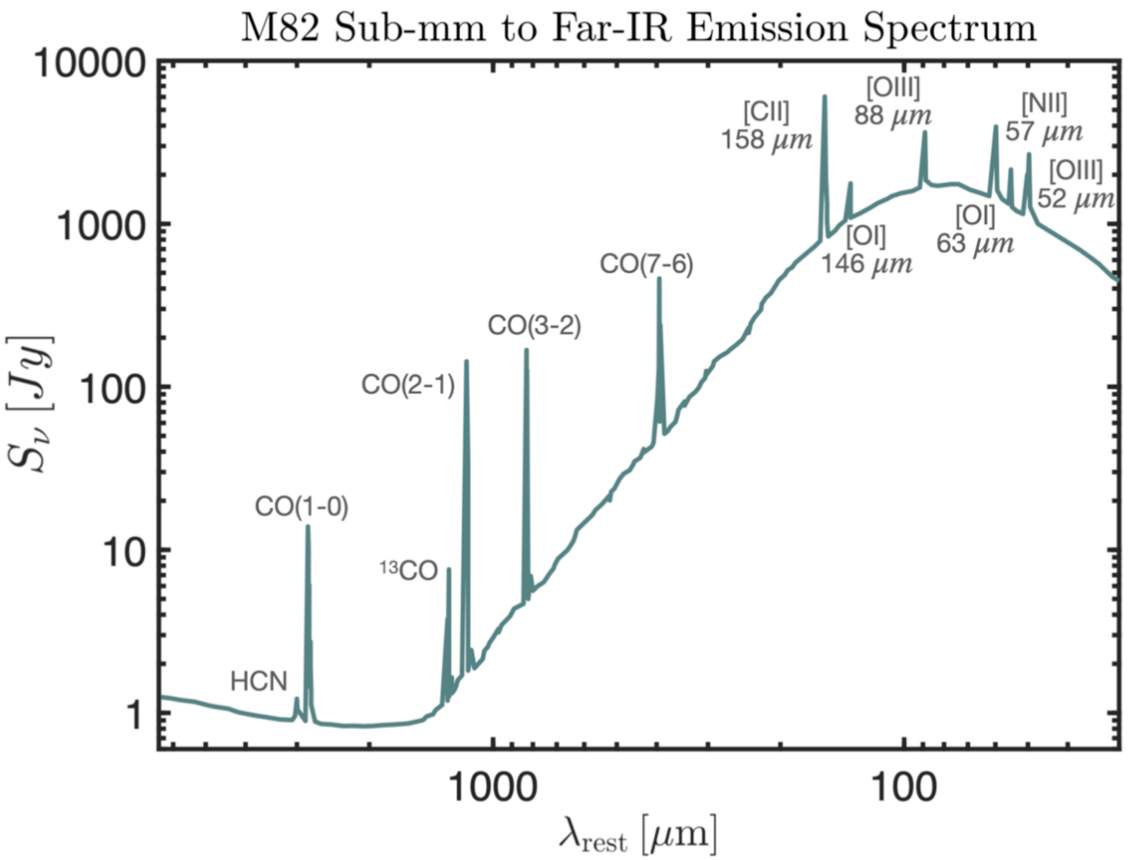
- Dark matter
- Dark energy
- Hubble tension and early dark energy
- inflation
- Neutrinos
- baryogenesis

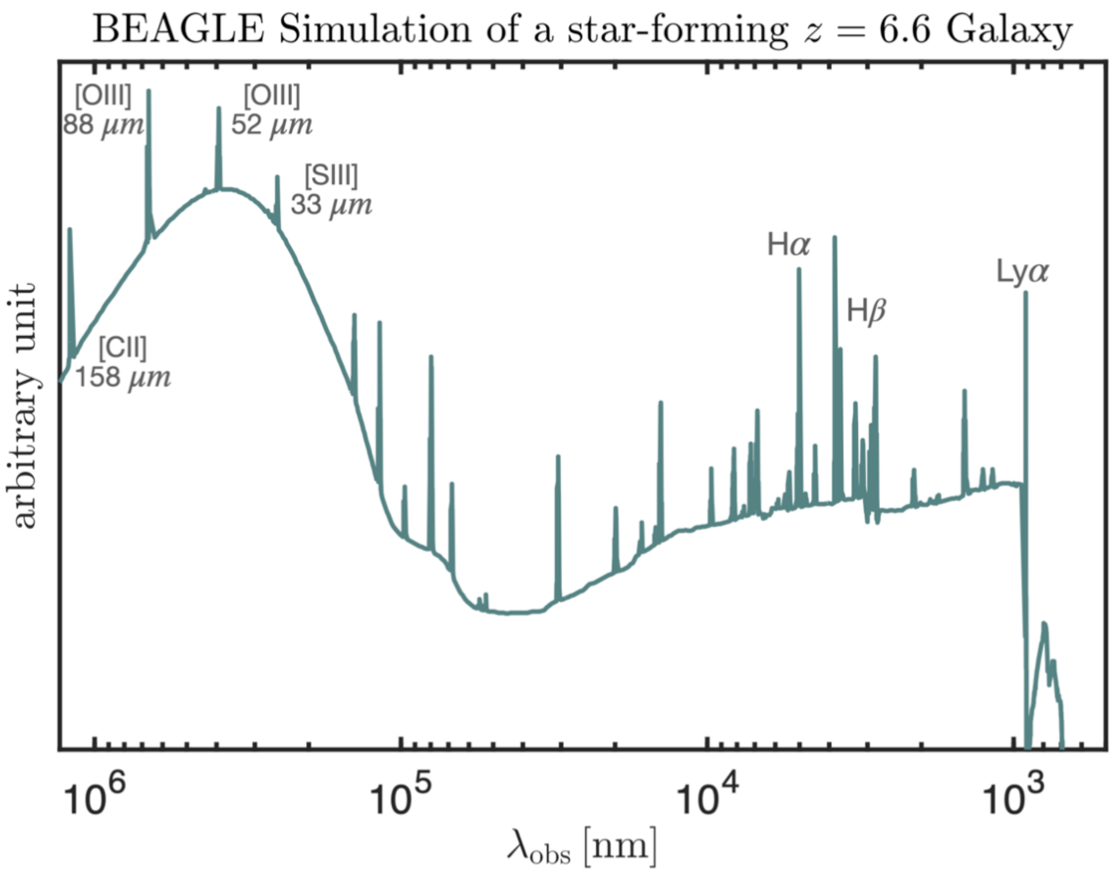
II. Line-Intensity Mapping

- New way to study large-scale structure
- LIM: use integrated light in given pixel on sky
- Information from all galaxies and IGM along LoS
- Use redshift of identifiable spectral line → 3D

Reviews/refs: Kovetz et al., 1709.09066; Bernal, Breysse, Gil-Marin, Kovetz, arXiv:1907.10067; *Bernal & Kovetz, in preparation*

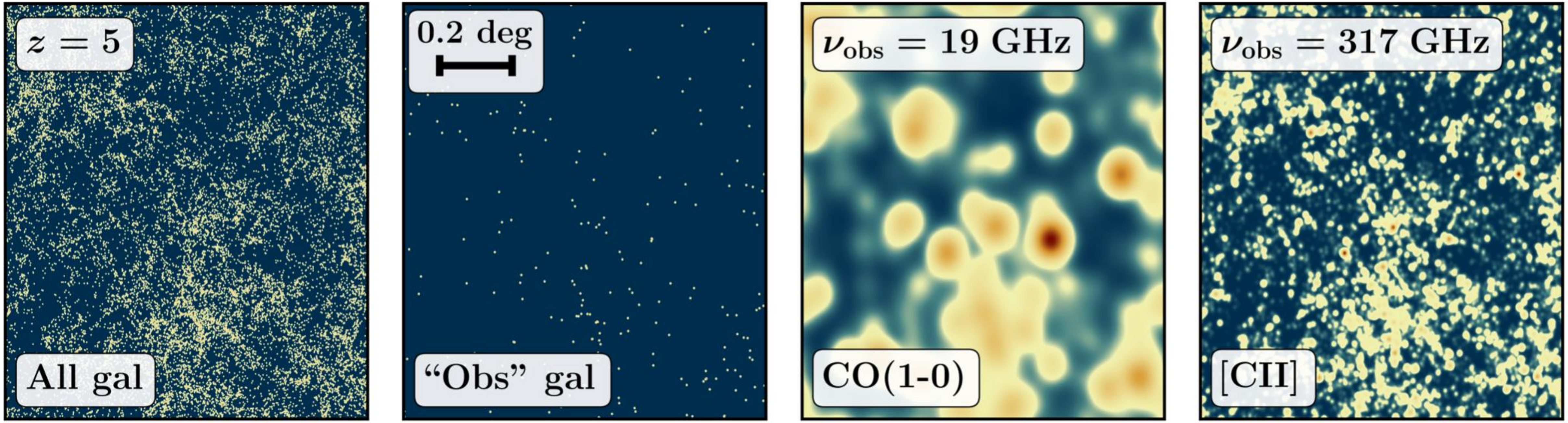
Emission lines



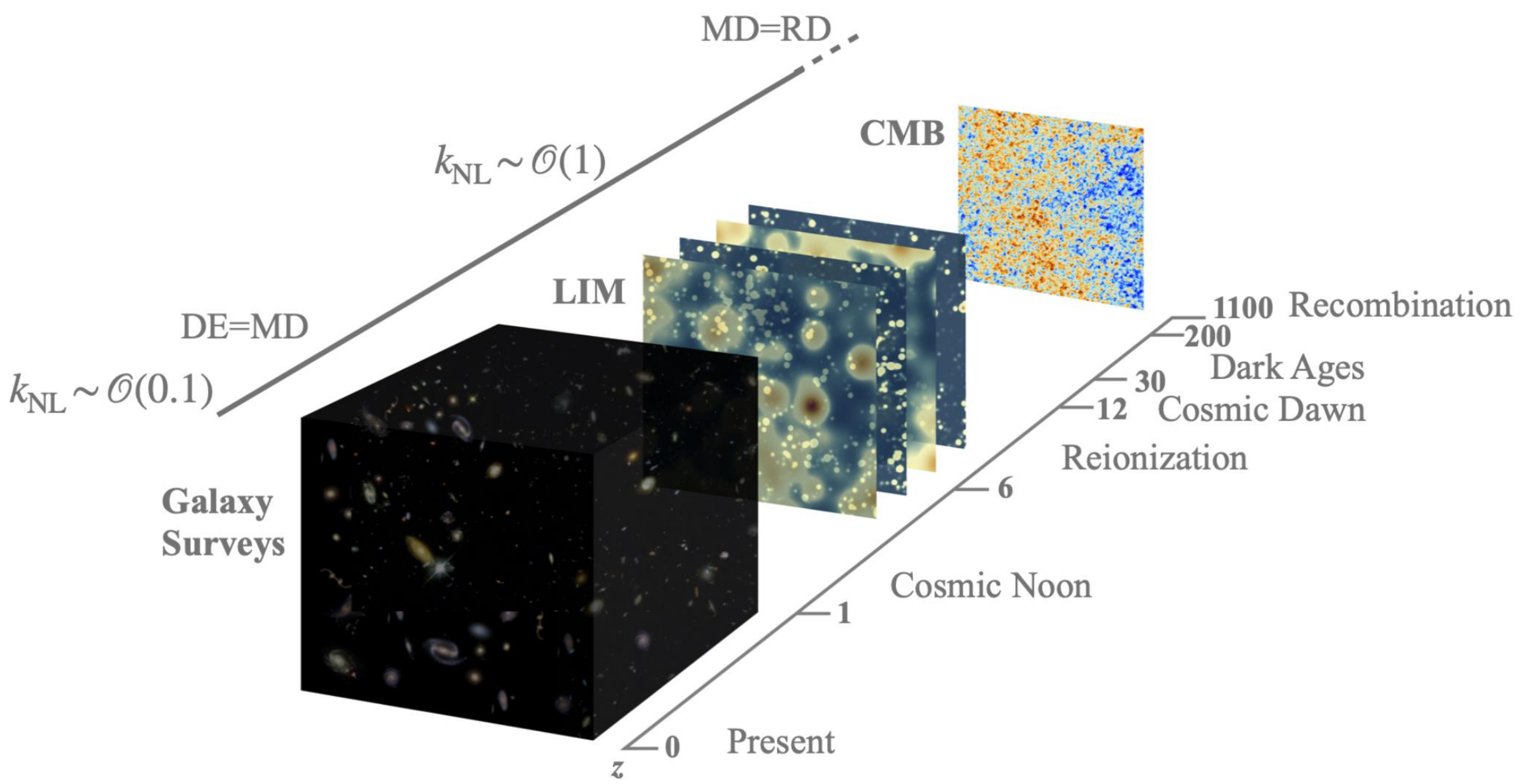


Galaxy surveys: detailed distribution of brightest galaxies

Intensity maps: noisy distribution of all galaxies and IGM

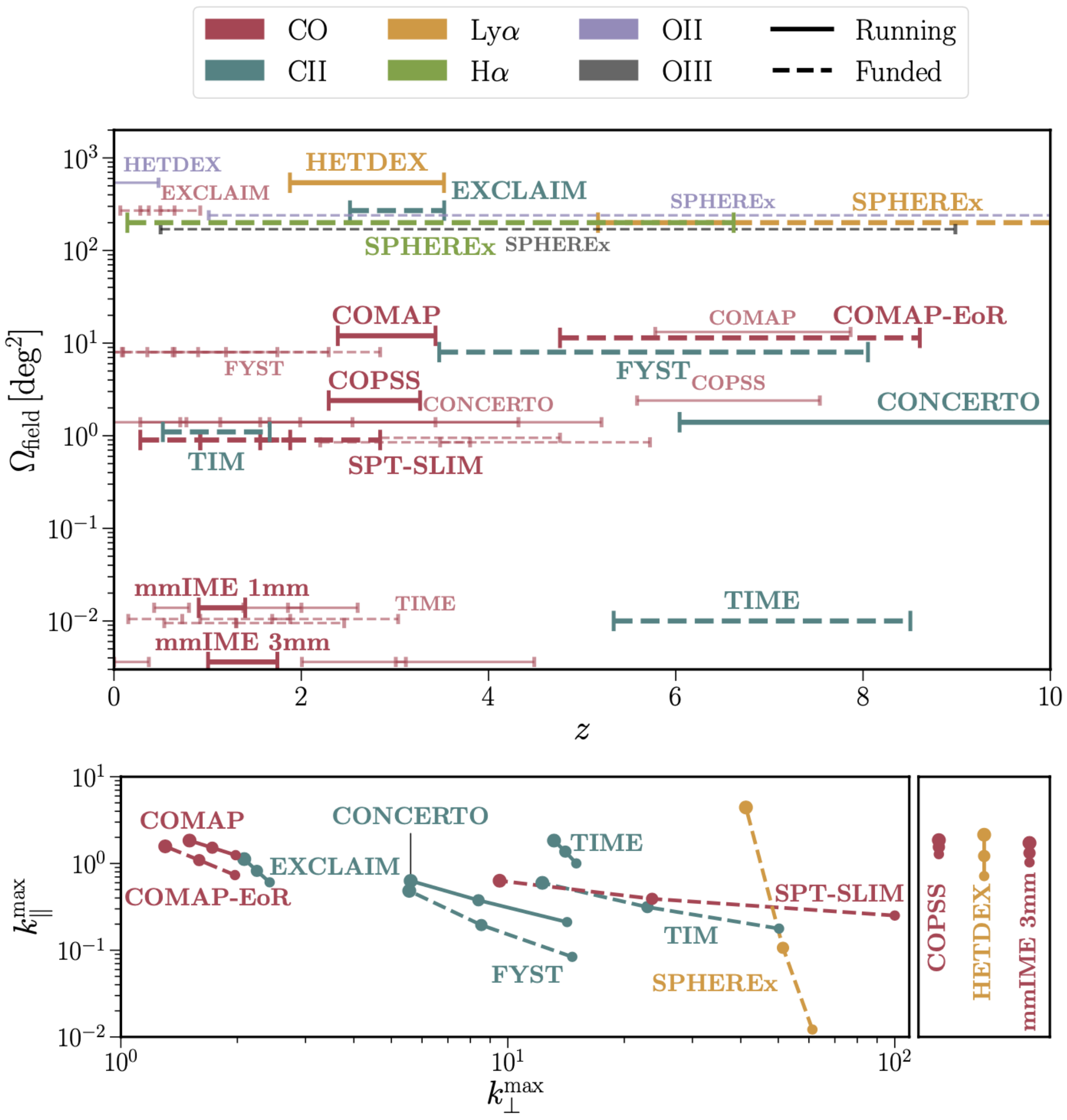


Probing the Universe



Probing the Universe with LIM

- Exciting experimental landscape!



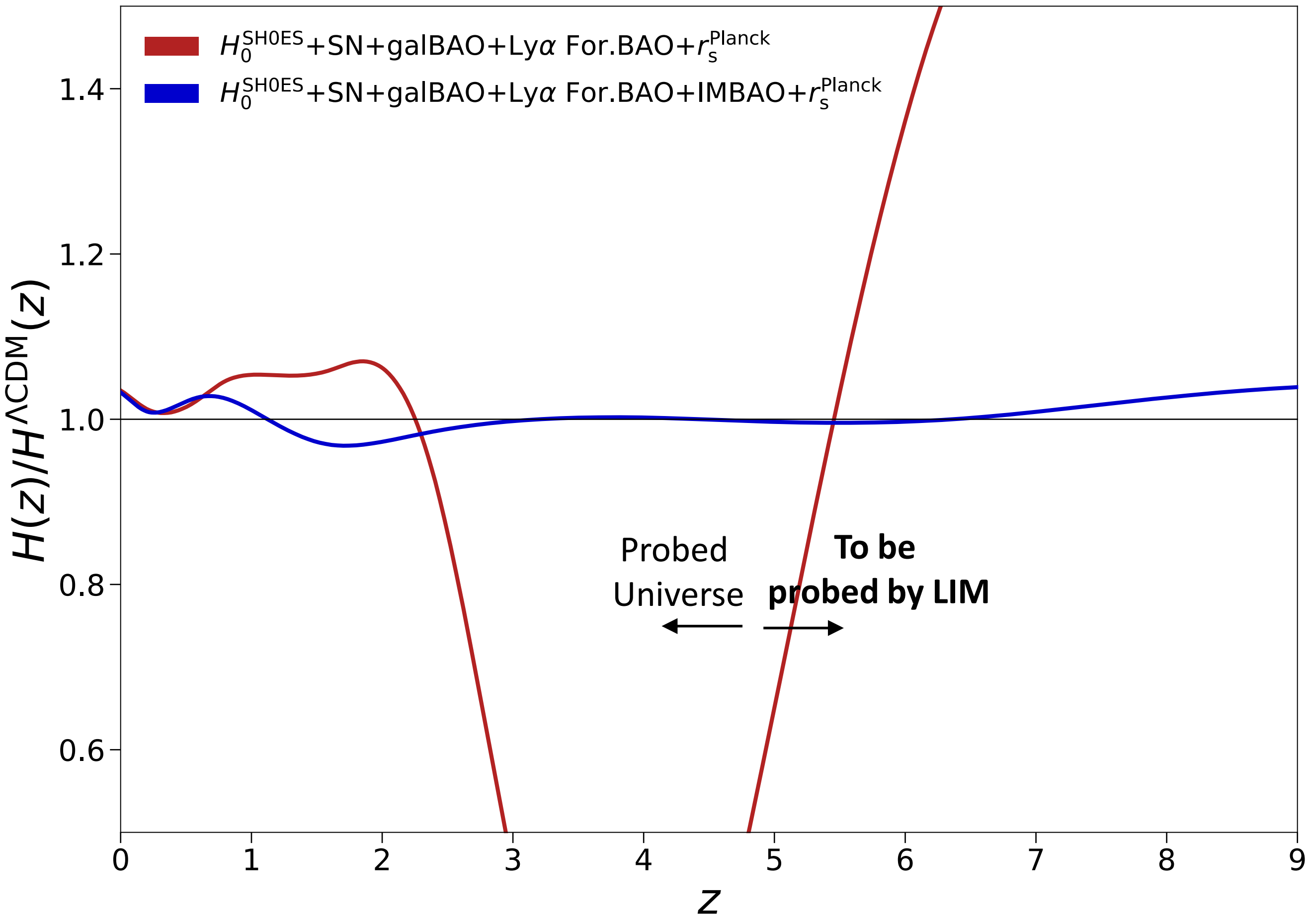
Probes LSS, extending galaxy-survey wavelength/redshift range

Dark energy

Inflation

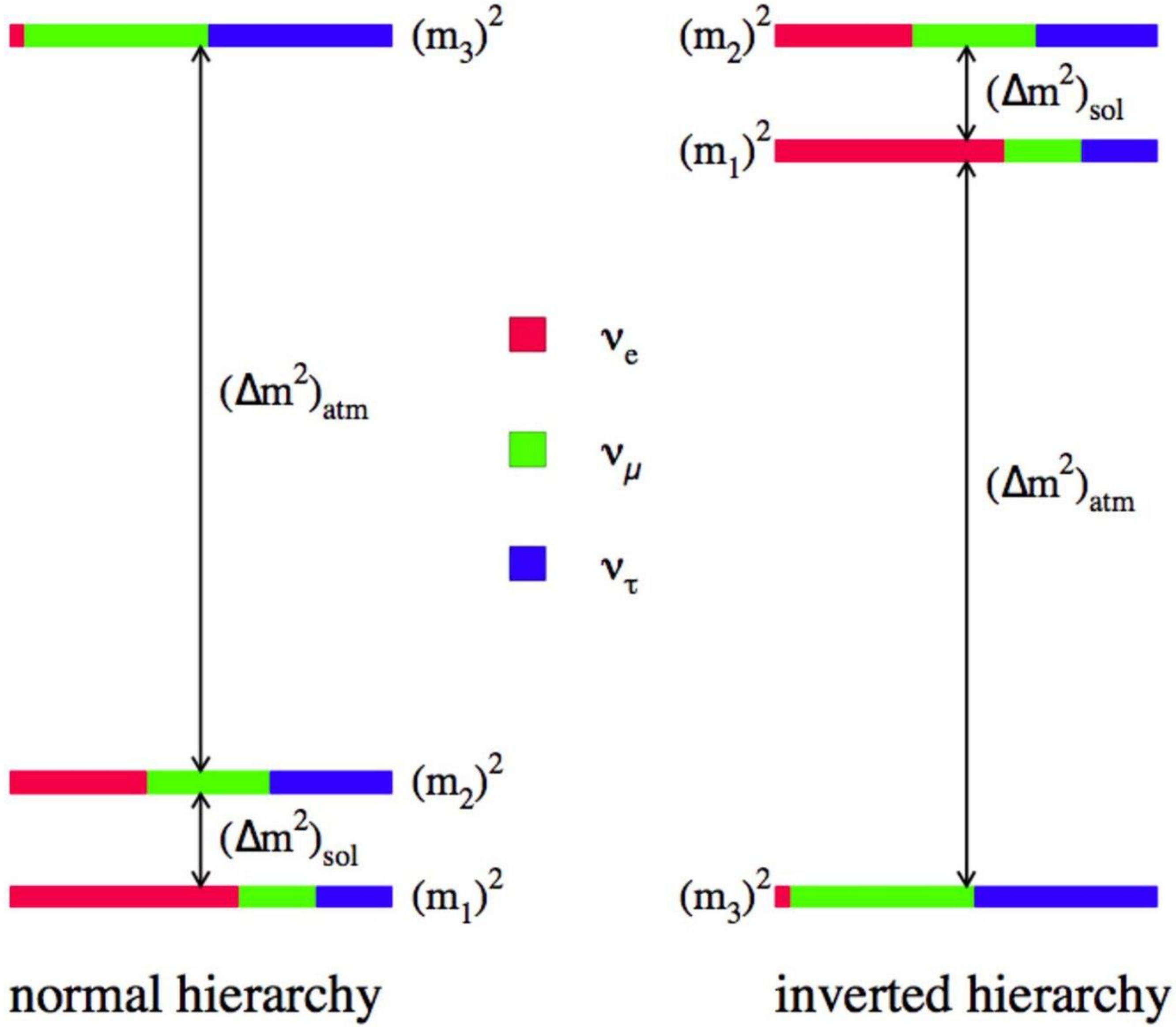
Dark-matter physics

Hubble tension: $H(z)$ beyond the reach of galaxy surveys



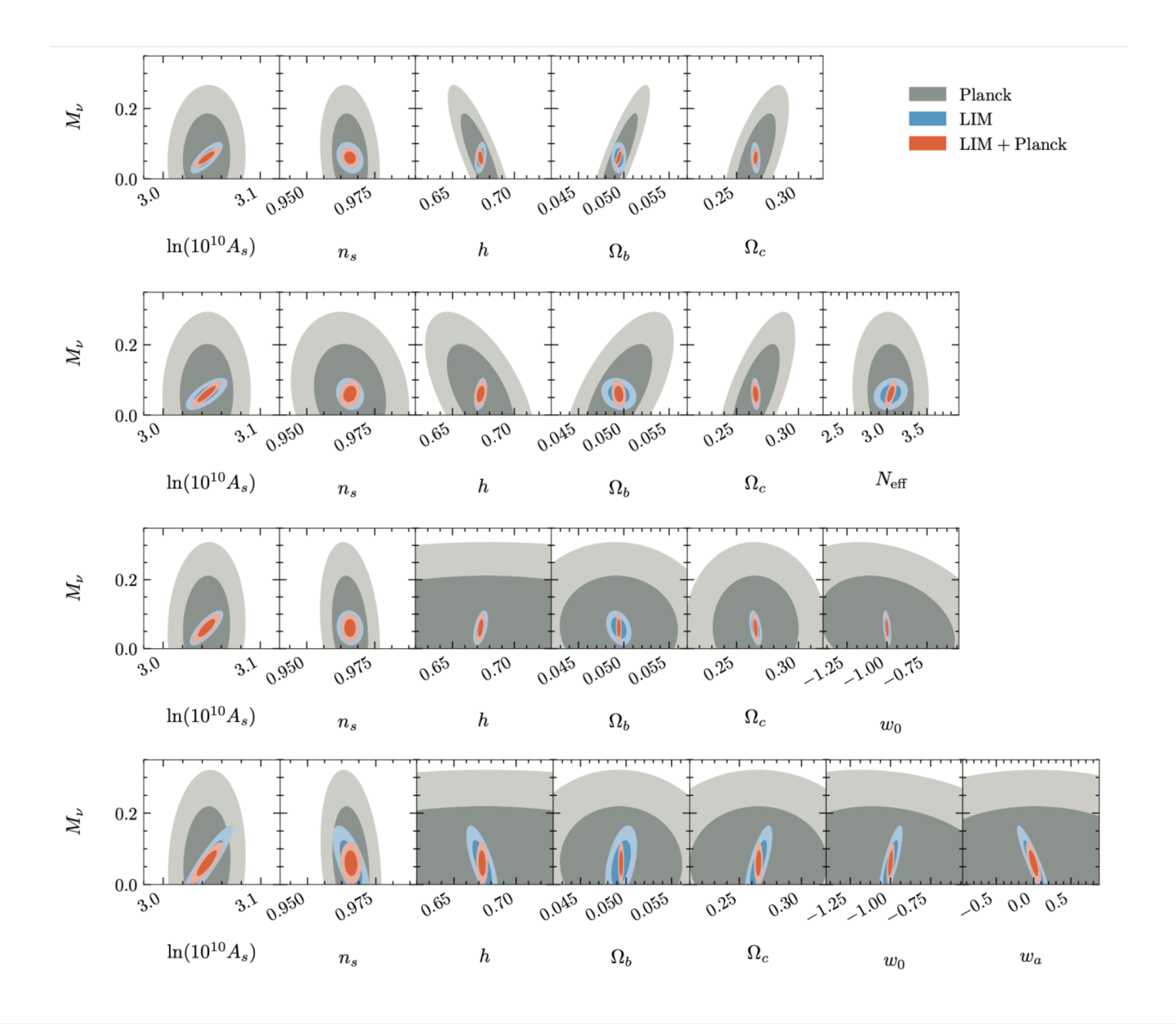
Bernal, Breysse, Kovetz 2019

Neutrino masses



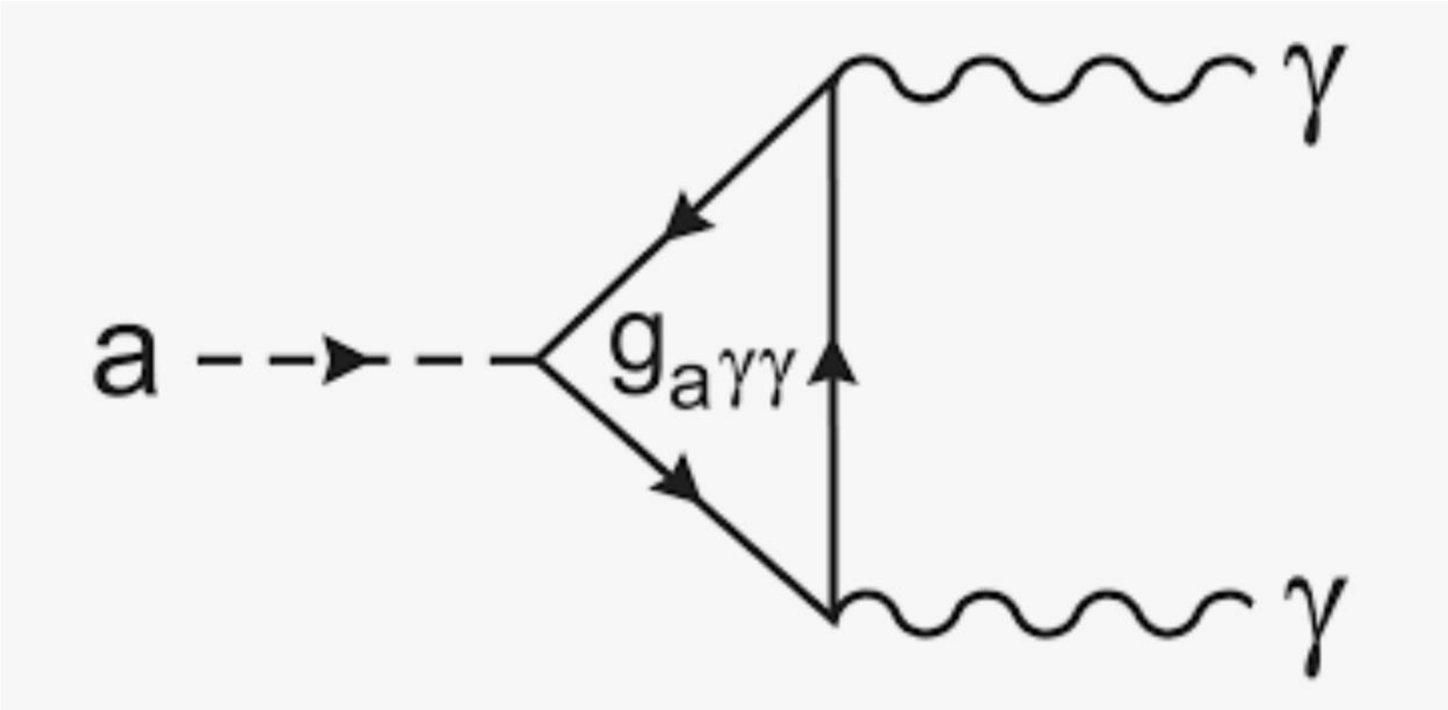
Neutrino masses:

- Dizgah et al., arXiv:2110.00014



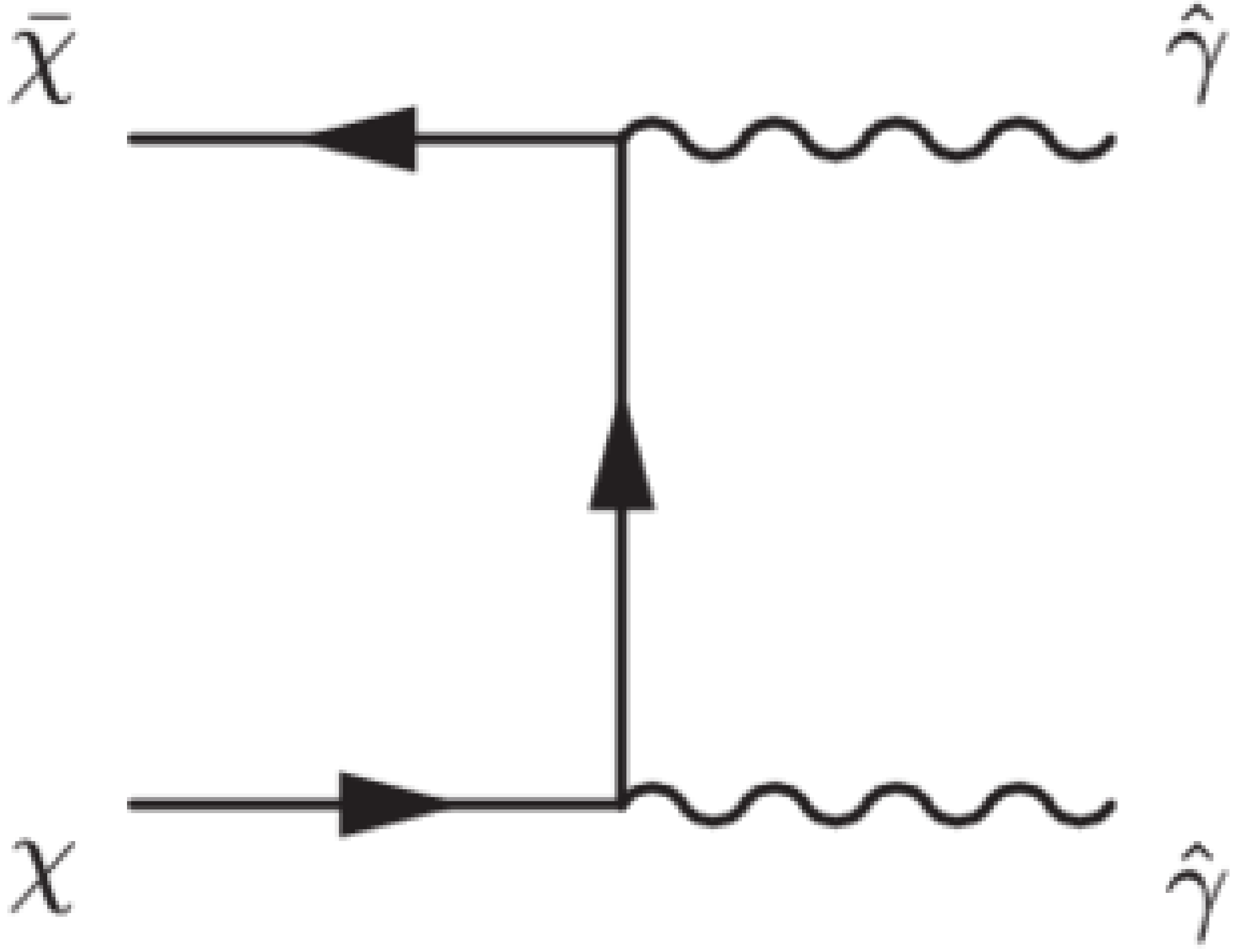
photon lines from radiative dark-matter/neutrino decay/annihilation

(Creque-Sarbinowski, MK 2018; Bernal, Caputo, MK 2021; Bernal, Caputo, Villaescusa-Navarro, MK 2021)



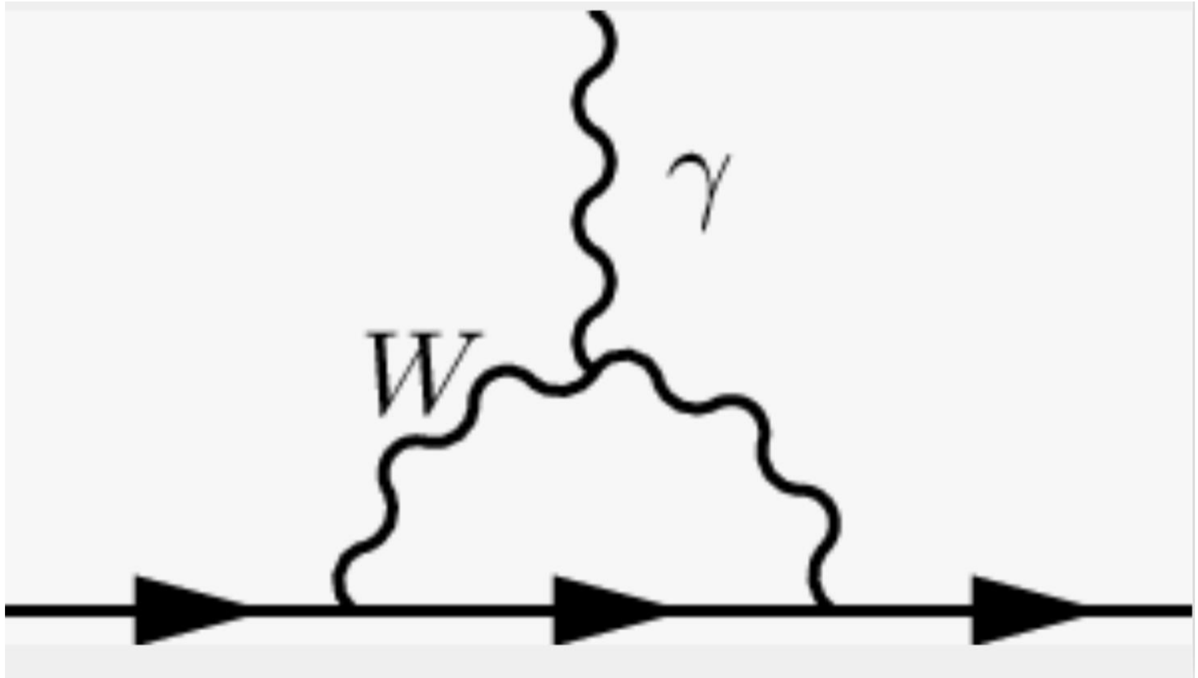
- Axion decay

• Dark matter annihilation



Neutrino decay

Heavier neutrino mass eigenstate



Lighter neutrino mass eigenstate

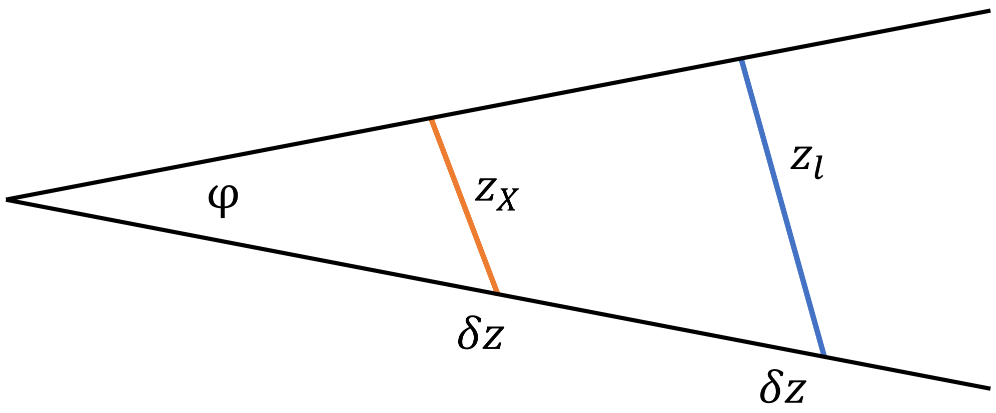
Parameterized by (transition) magnetic moment

Decay/annihilation line is unbiased/biased tracer of dark-matter distribution

→should cross-correlate with LSS

How to distinguish from astrophysical line

- Clustering anisotropy



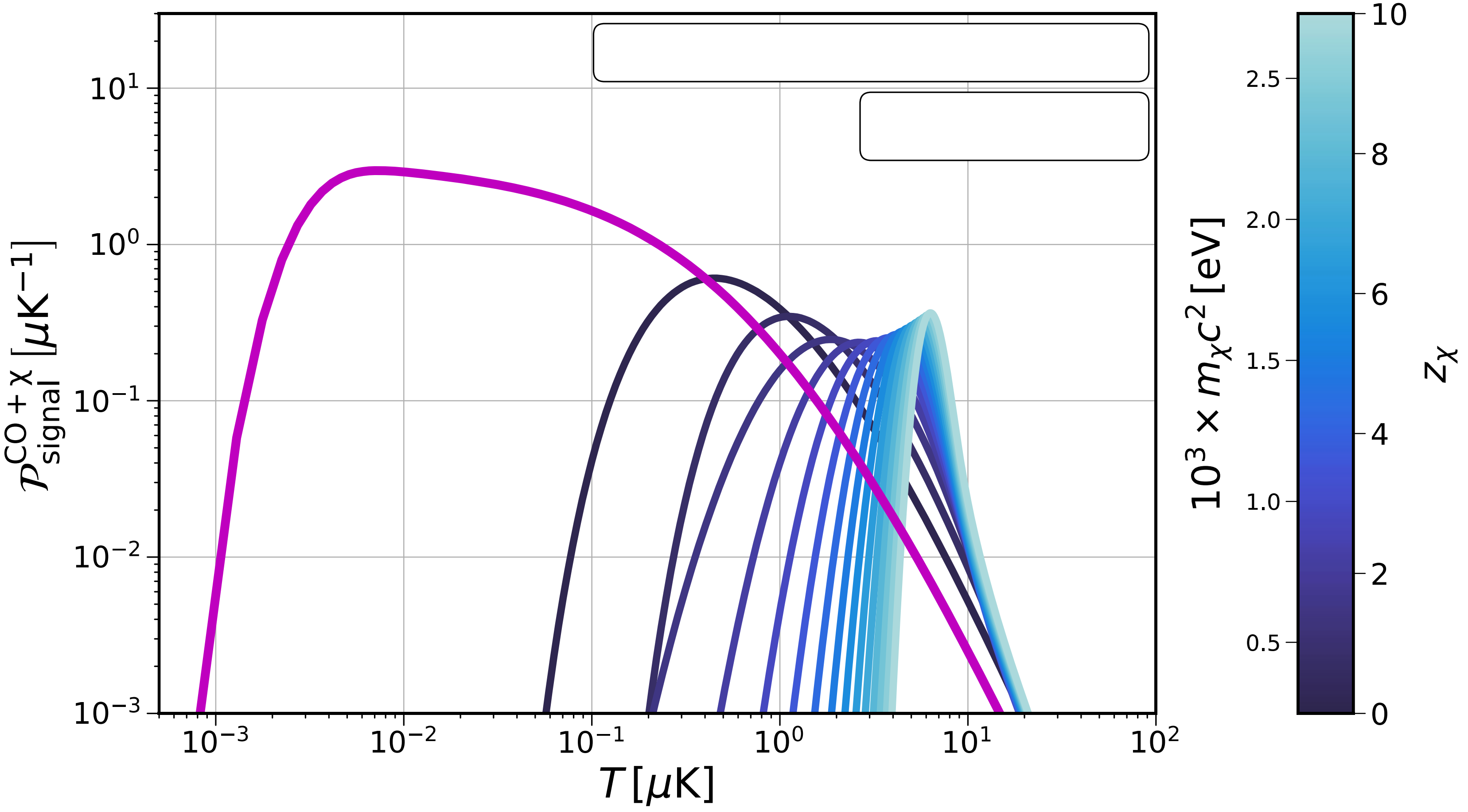
$$x_\perp = D_M(z)\theta$$

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

Voxel intensity distribution (VID)

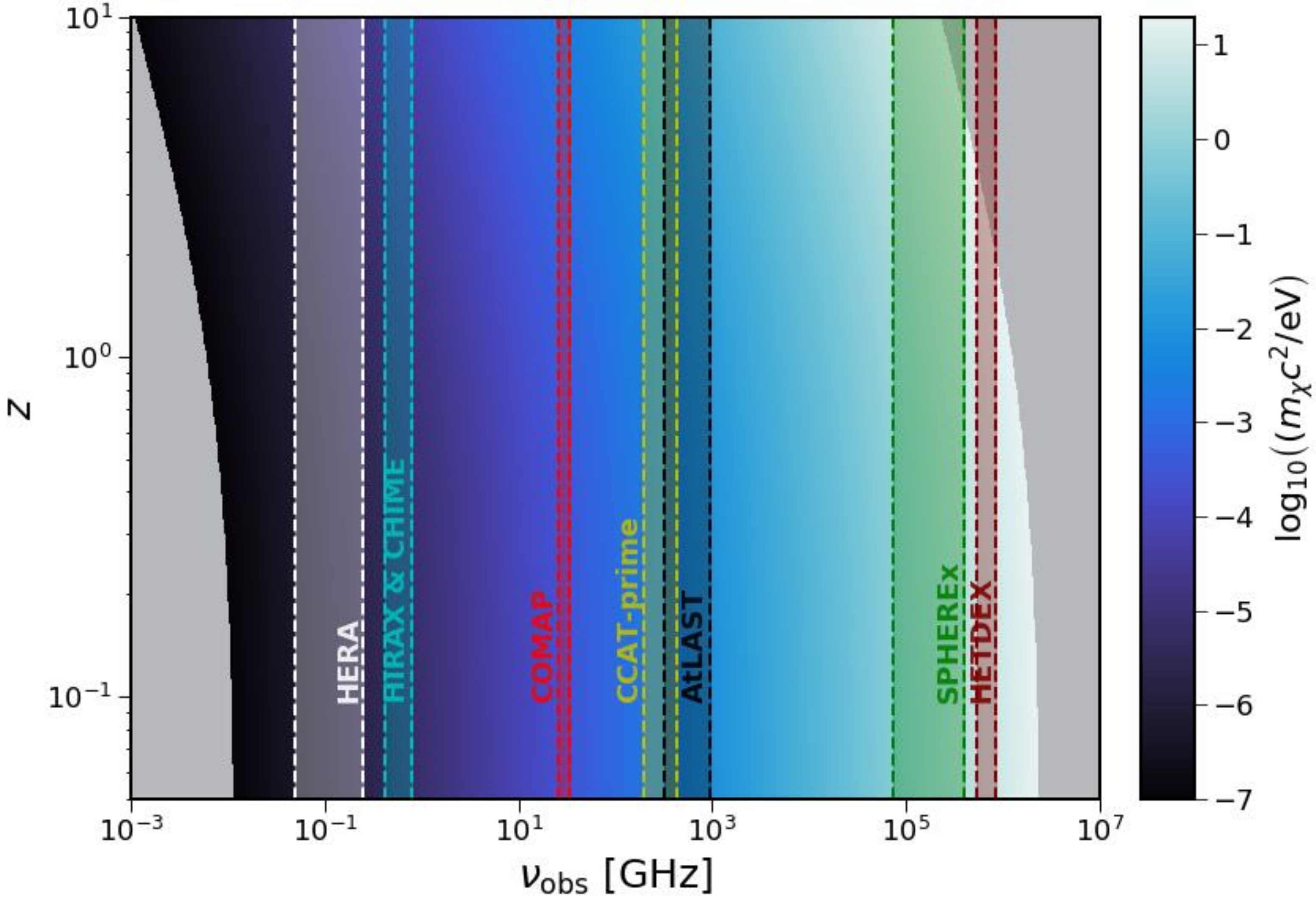
- PDF of luminosity density in each pixel

Effect in VID



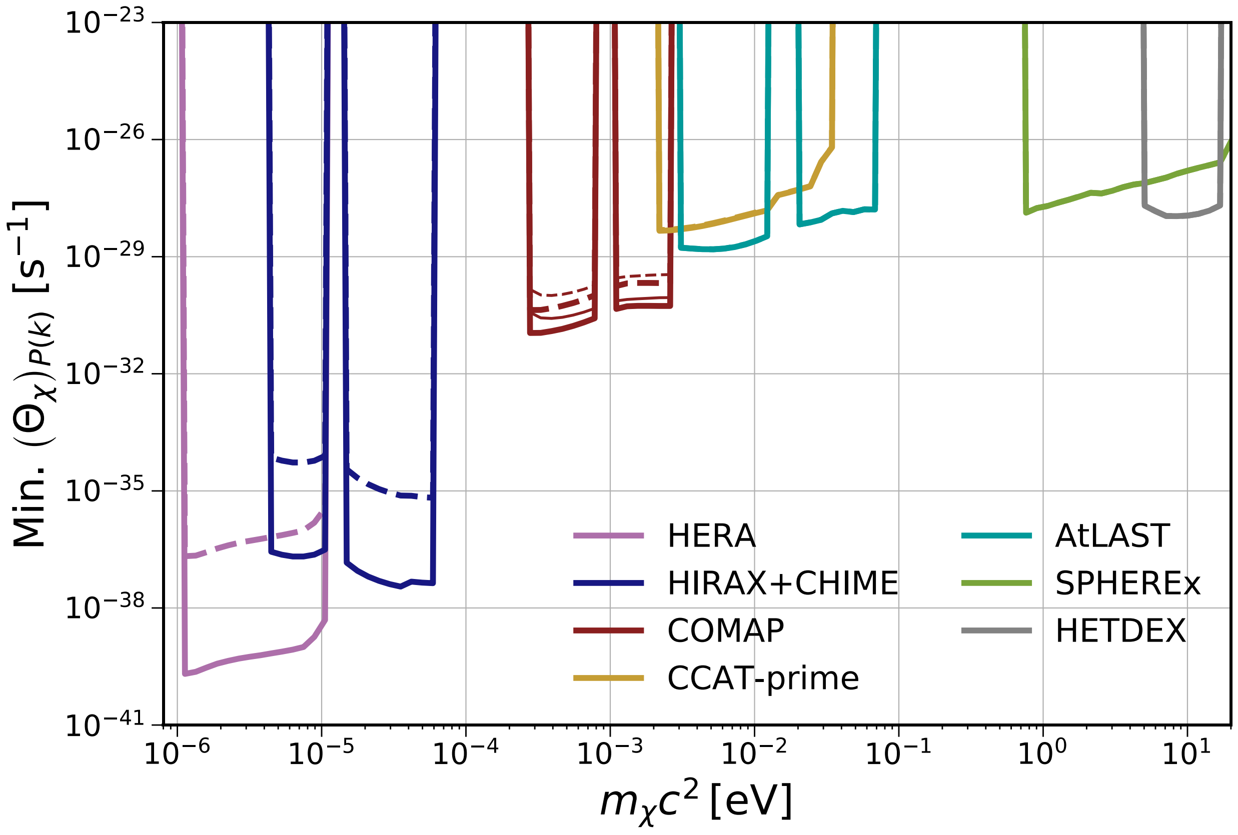
Exotic radiative decays

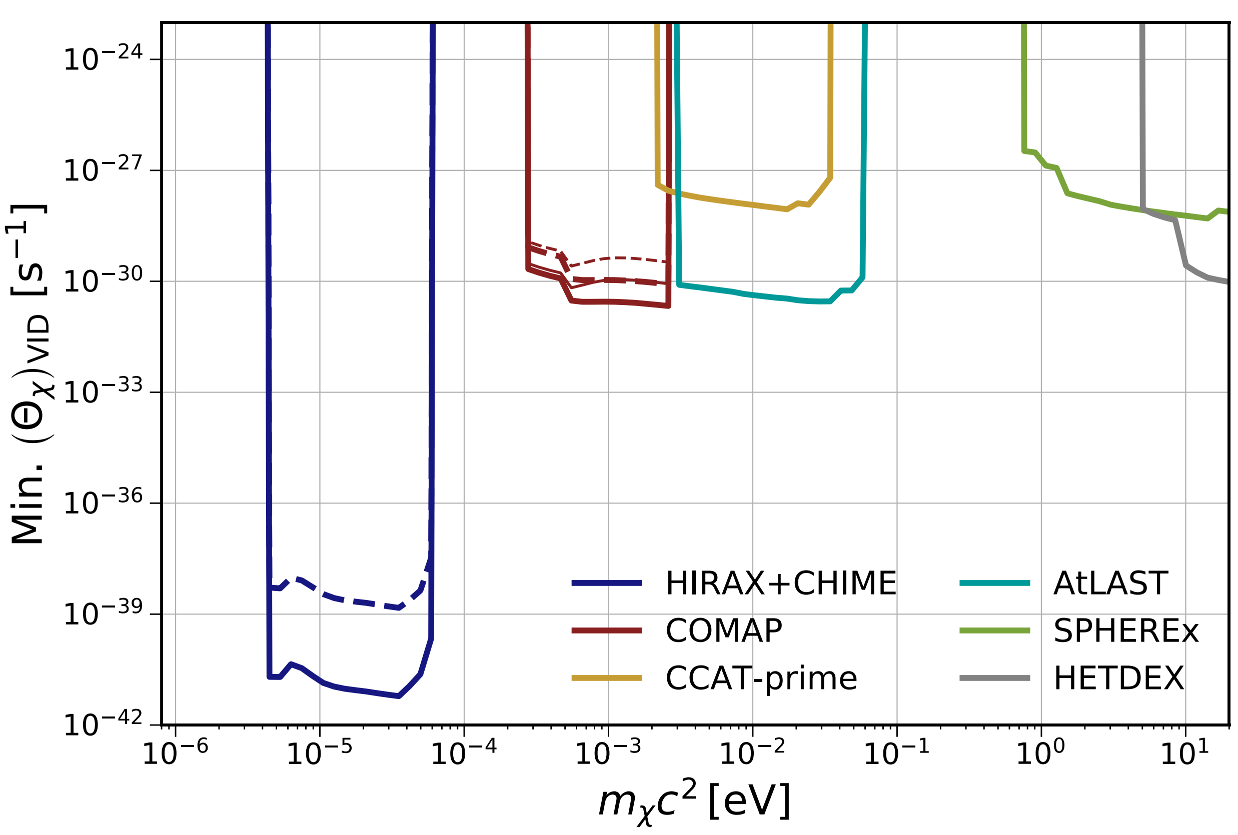
- Decaying dark matter: $\chi \rightarrow \gamma + \gamma$ $\nu_\gamma = m_\chi c^2 / 2h_P$



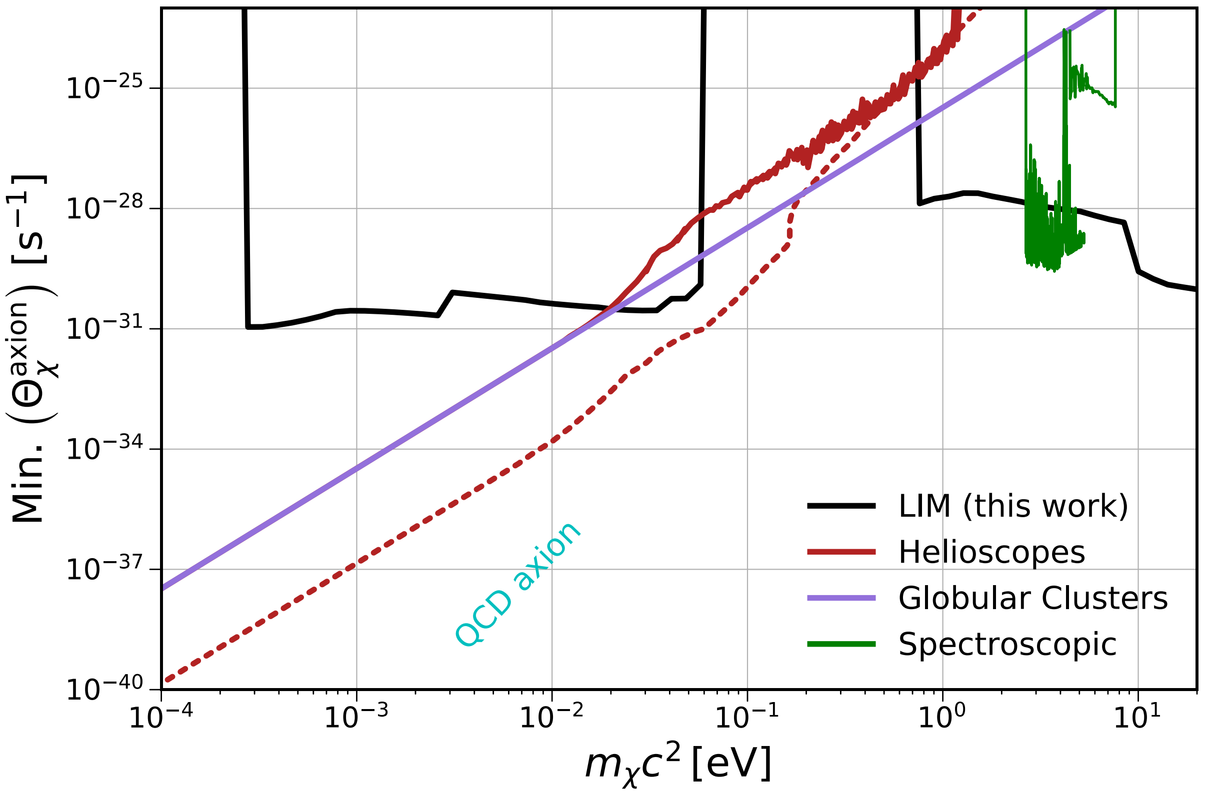
Sensitivity to DM decays

- After marginalizing over astrophysical uncertainties of the target emission line

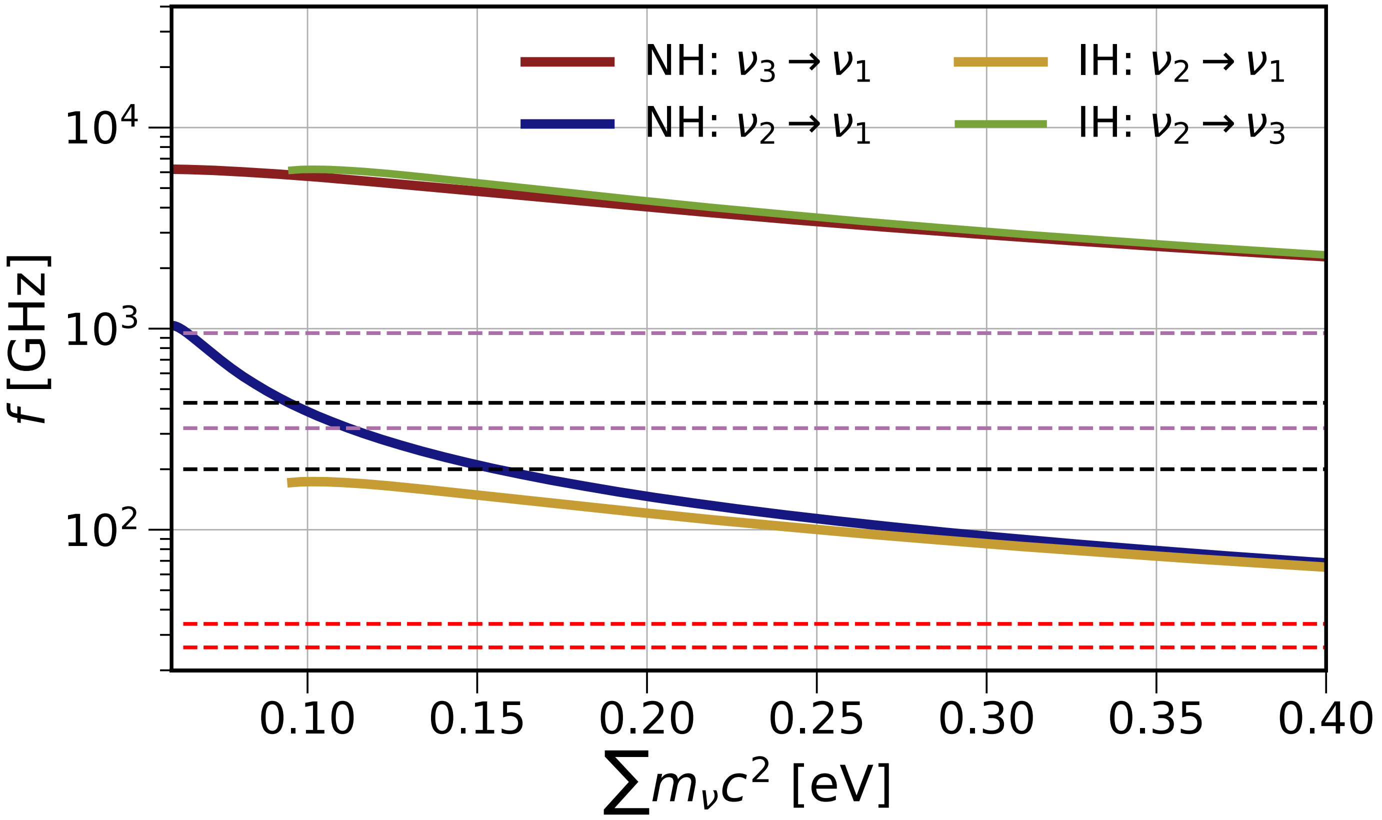




Sensitivity to axions



Exotic radiative decays

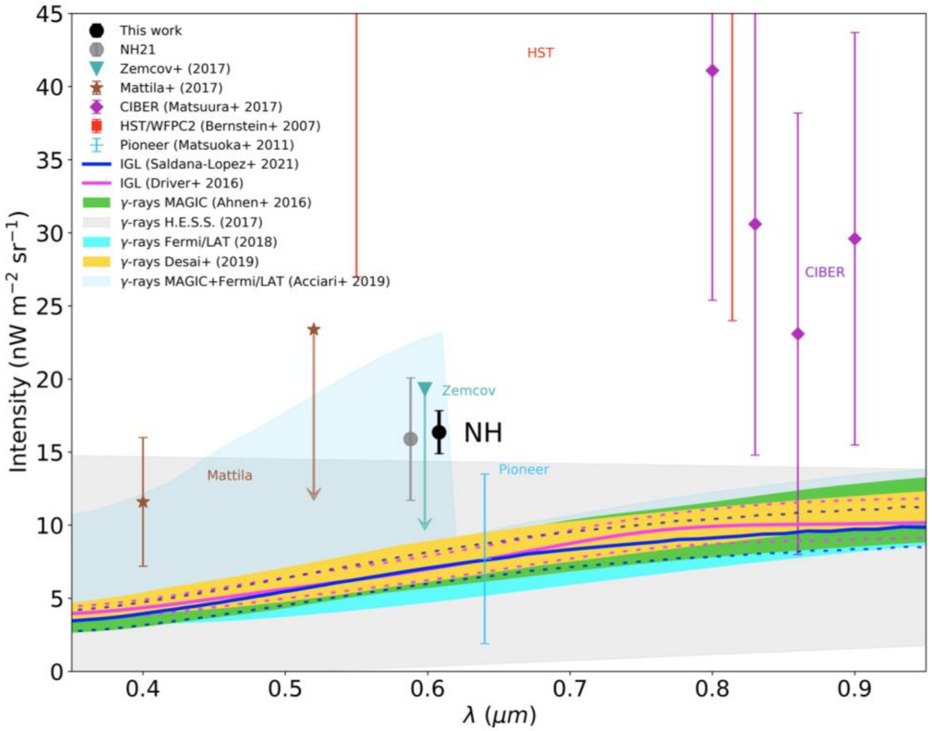


- Neutrino decay: $\nu_i \rightarrow \nu_j + \gamma$

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

- Traces directly the cosmic neutrino density field

Recent development…..



DRAFT VERSION FEBRUARY 10, 2022
Typeset using LaTeX **twocolumn** style in AASTeX63

Anomalous Flux in the Cosmic Optical Background Detected With New Horizons Observations

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ANDREW F. CHENG,[4] W.M. GRUNDY,[11] MIHALY HORÁNYI,[12] J.J. KAVELAARS,[13] IVAN R. LINSCOTT,[14] CAREY M. LISSE,[4]
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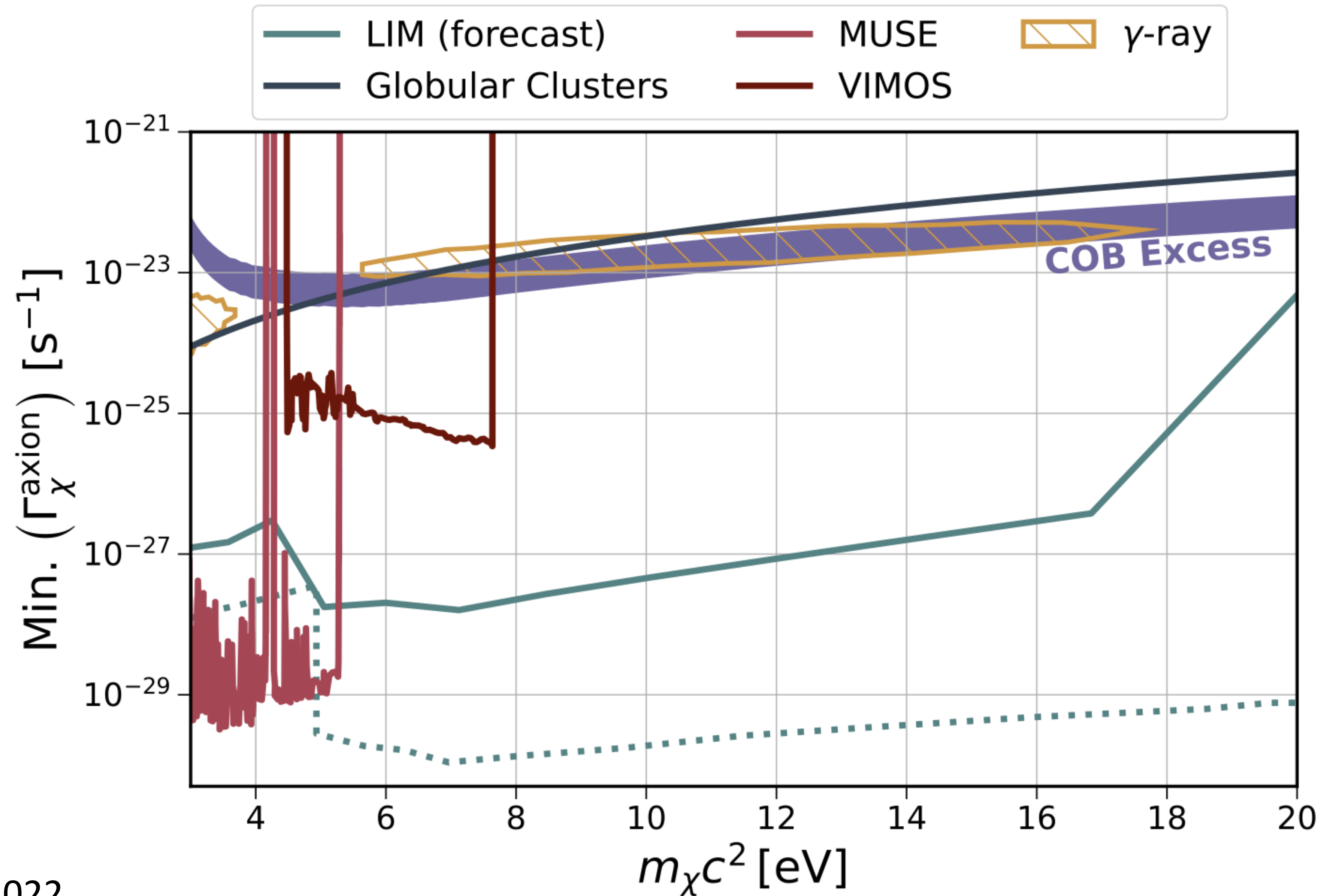
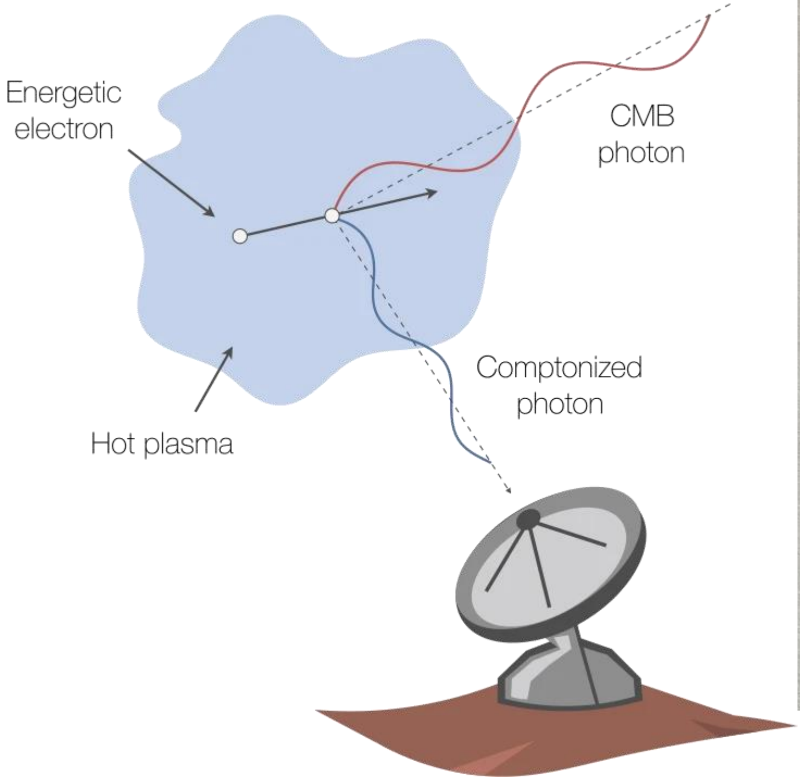
MARK R. SHOWALTER,[19] KELSI N. SINGER,[3] ANNE. J. VERBISCER,[20] AND LESLIE A. YOUNG[3]

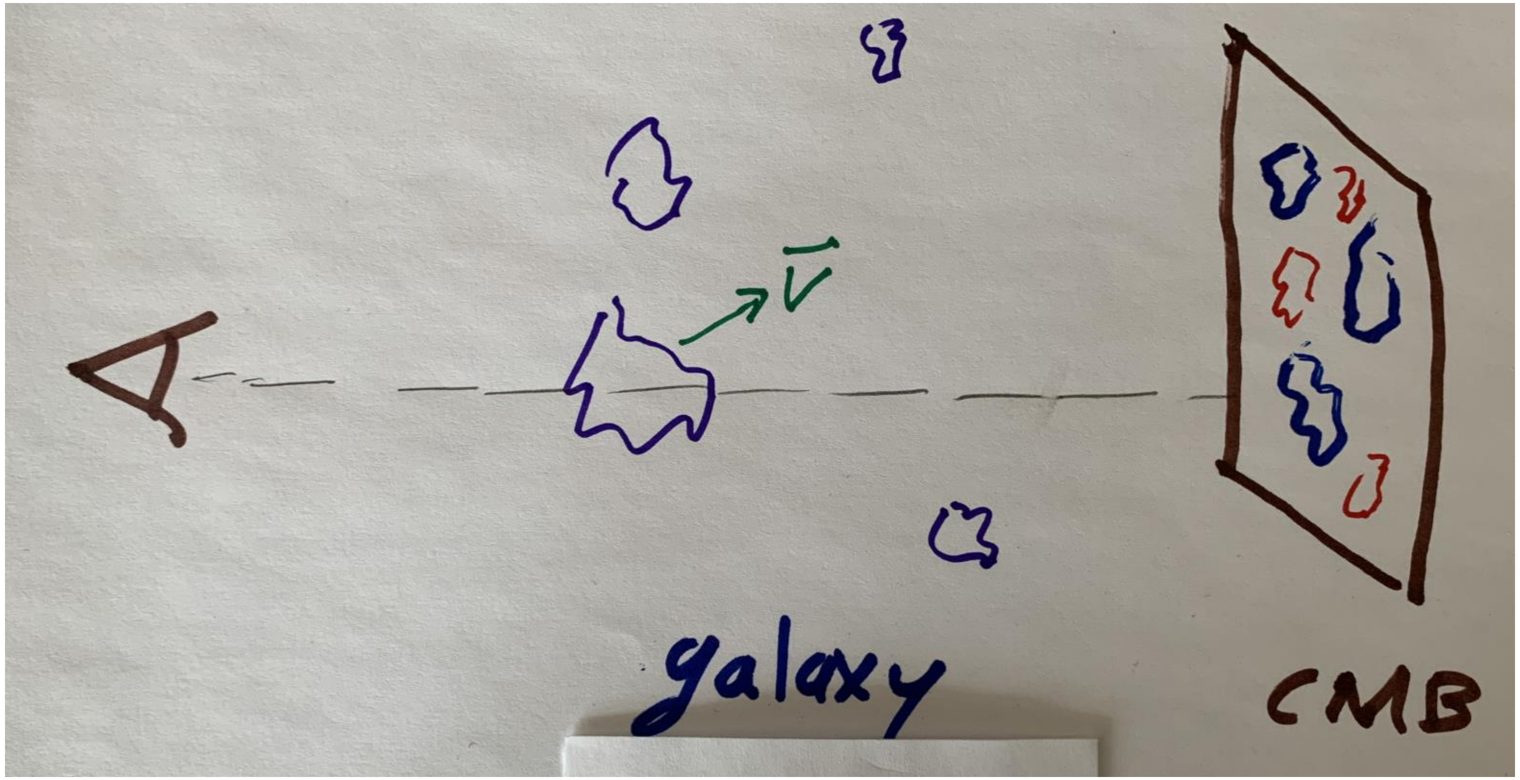


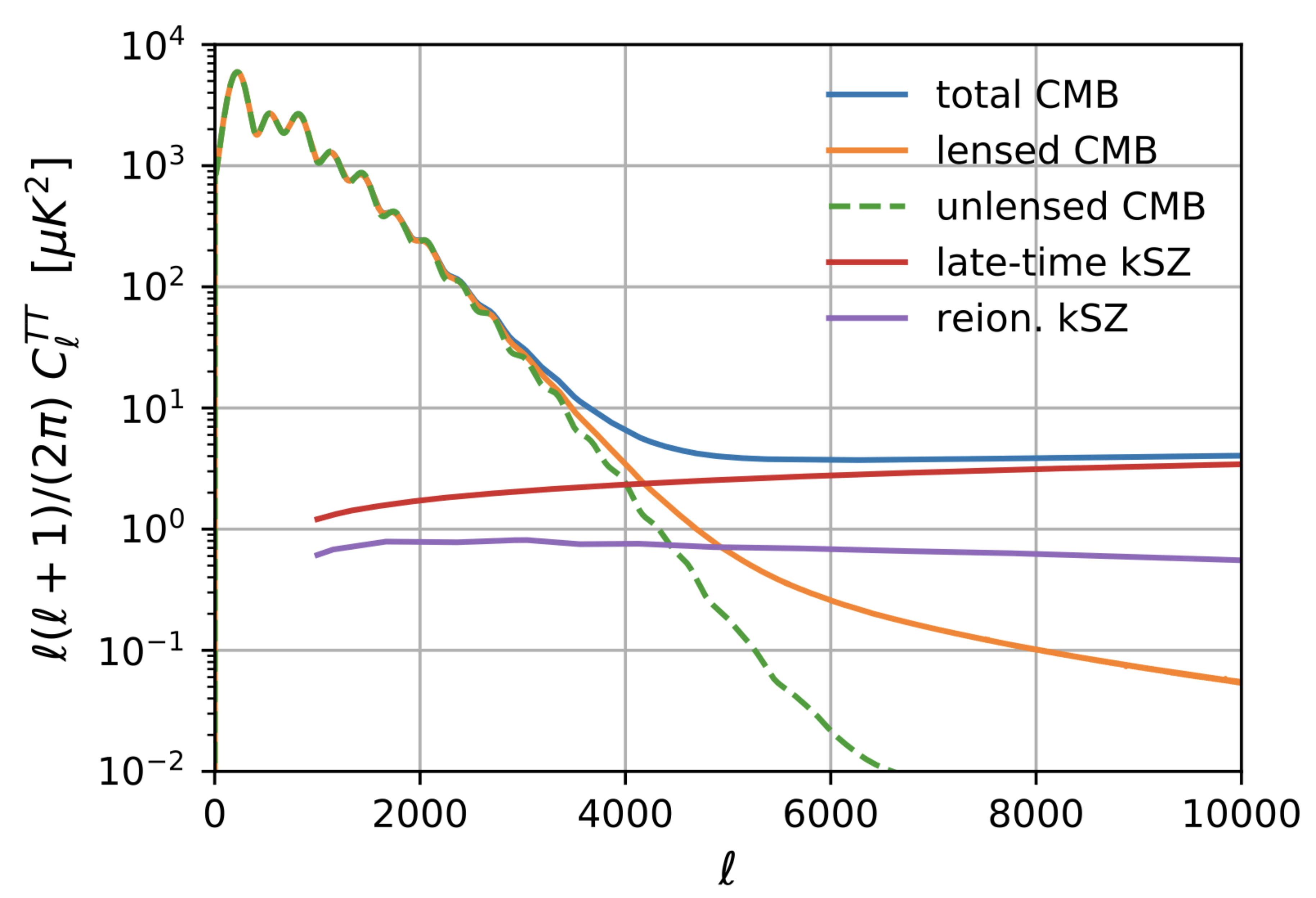
Bernal, Sato-Polito, MK, 2022

III. Kinetic-Sunyaev-Zeldovich tomography: new probe of 3d *mass* distribution

- Cross-correlate CMB and galaxy distribution to get cosmic velocity field

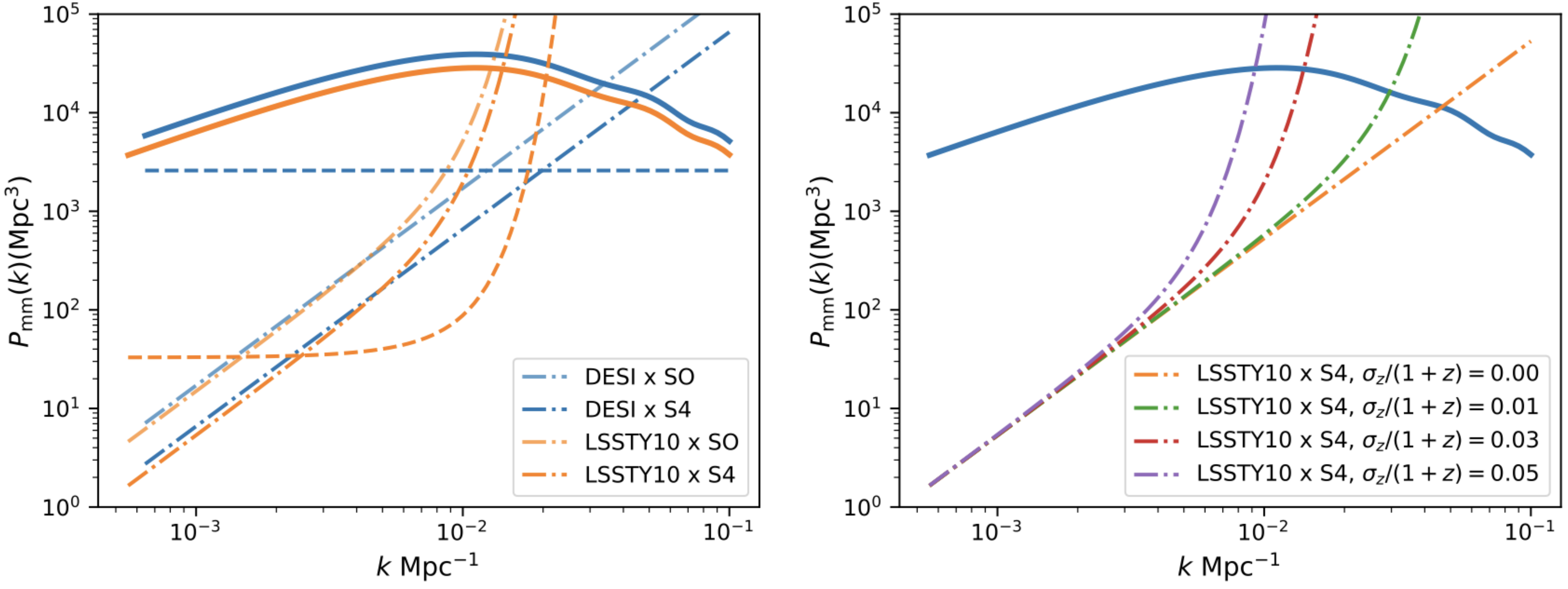






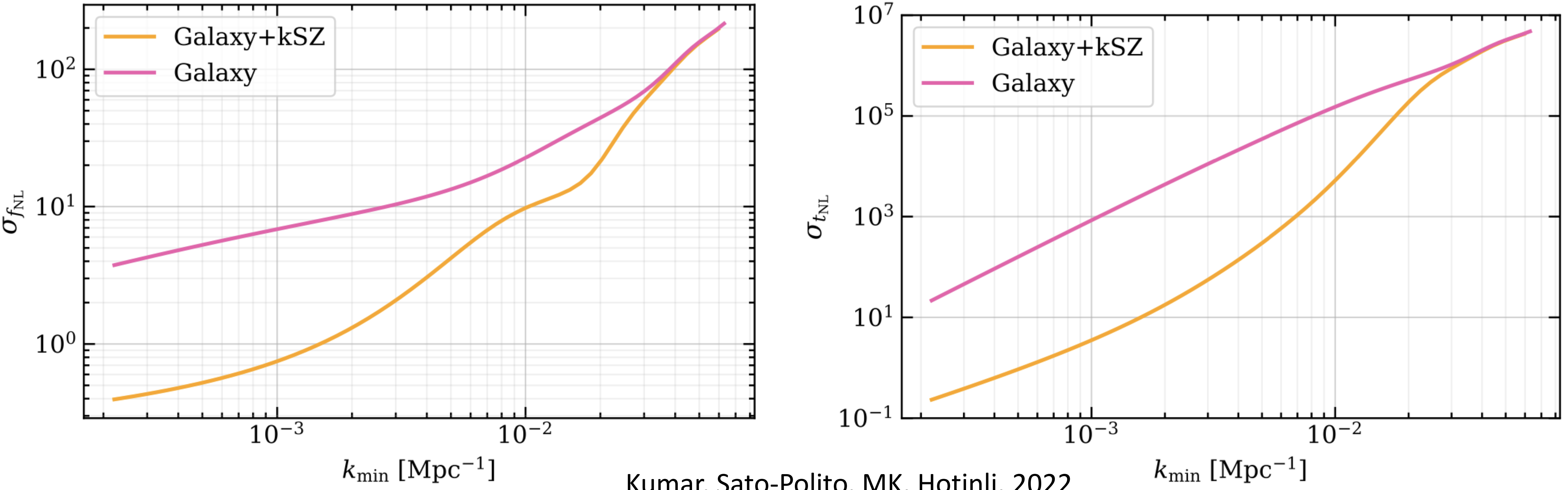
Smith et al. arXiv:1810.13423

matter power spectrum (Smith et al. arXiv:1810.13423)



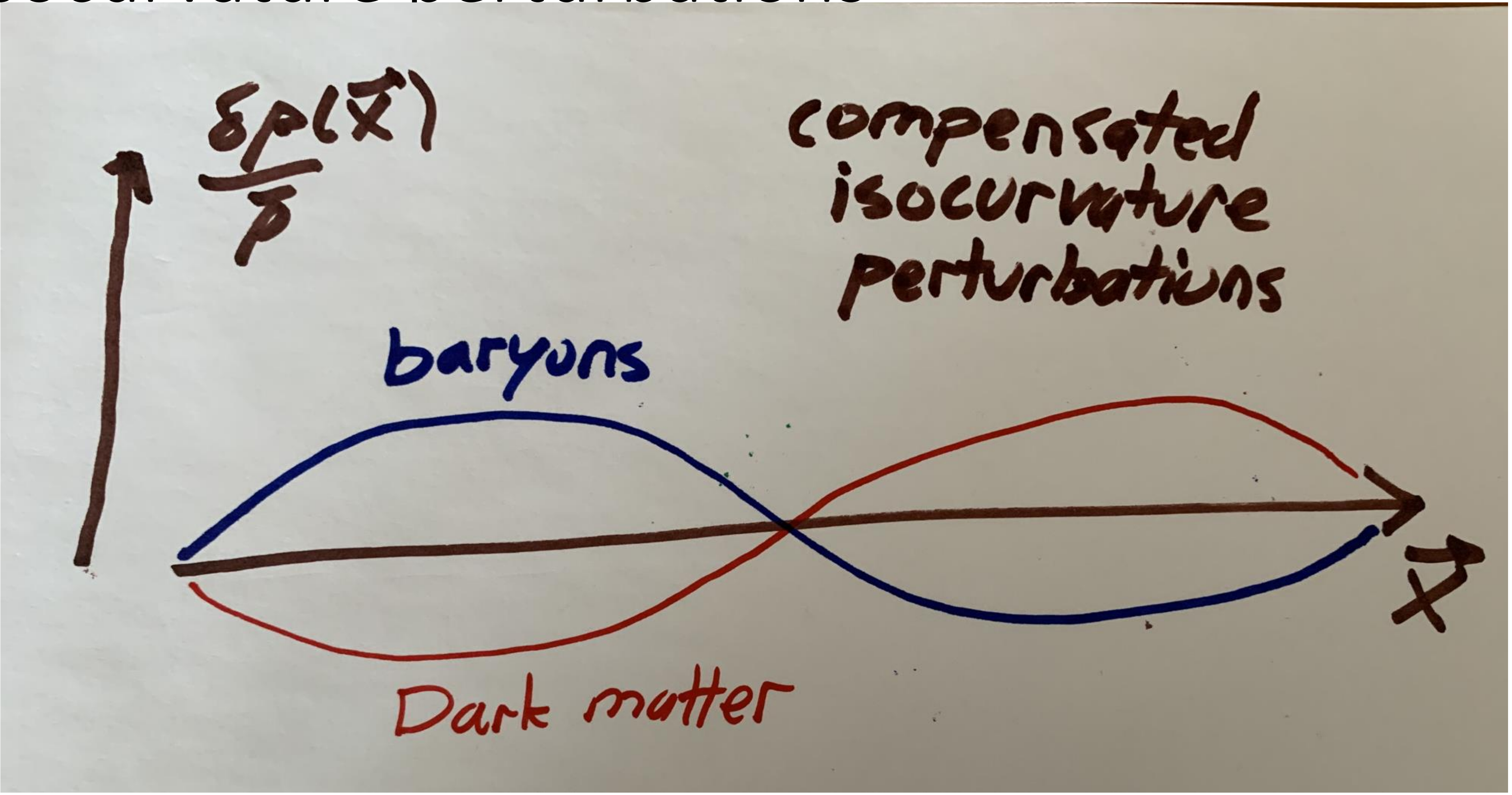
Can compare matter and galaxy distributions *independently*

- E.g., scale-dependent bias from local-model non-Gaussianity; not cosmic-variance limited (Munchmeyer et al. 1810.13424)



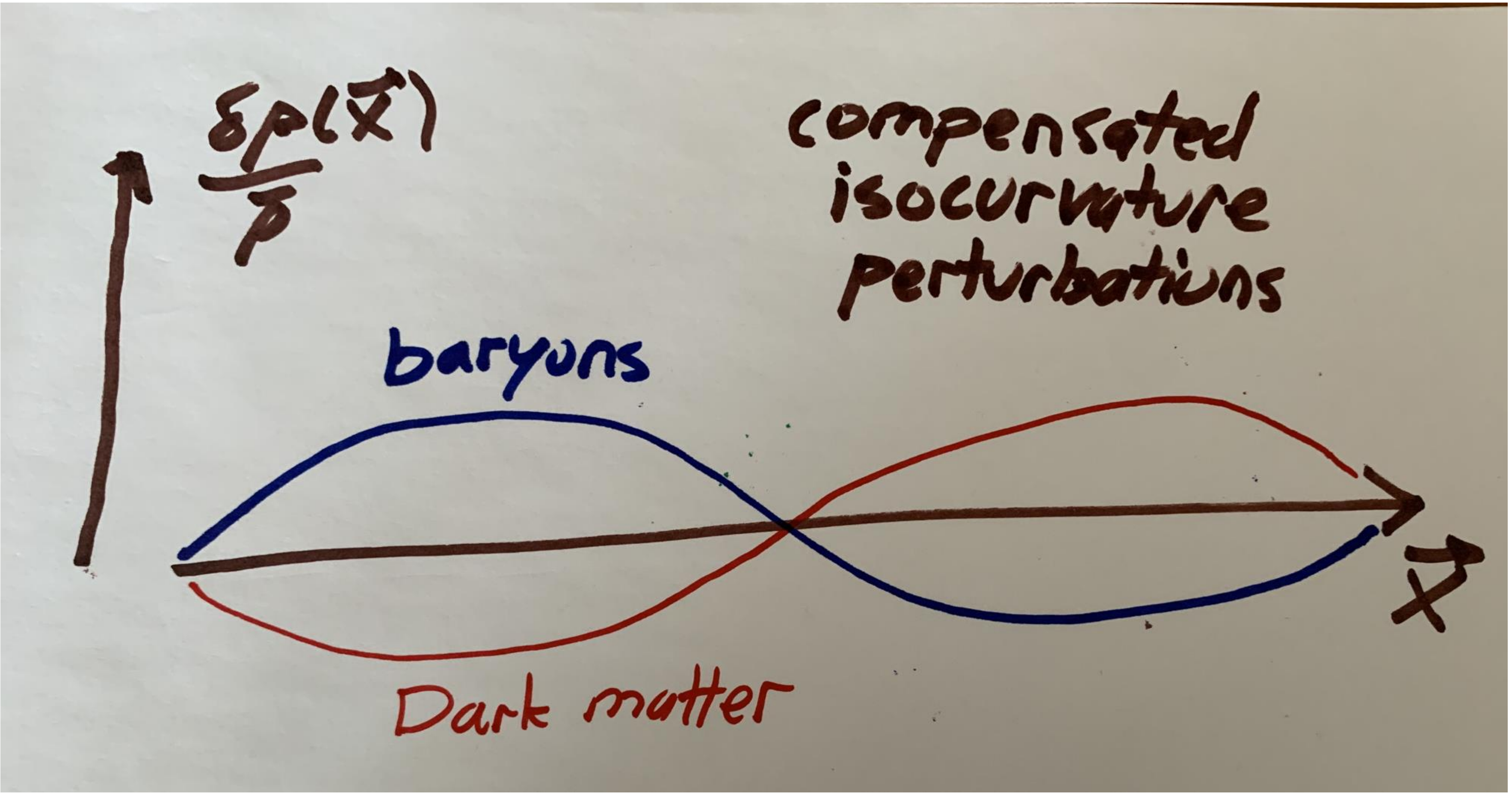
Kumar, Sato-Polito, MK, Hotinli, 2022

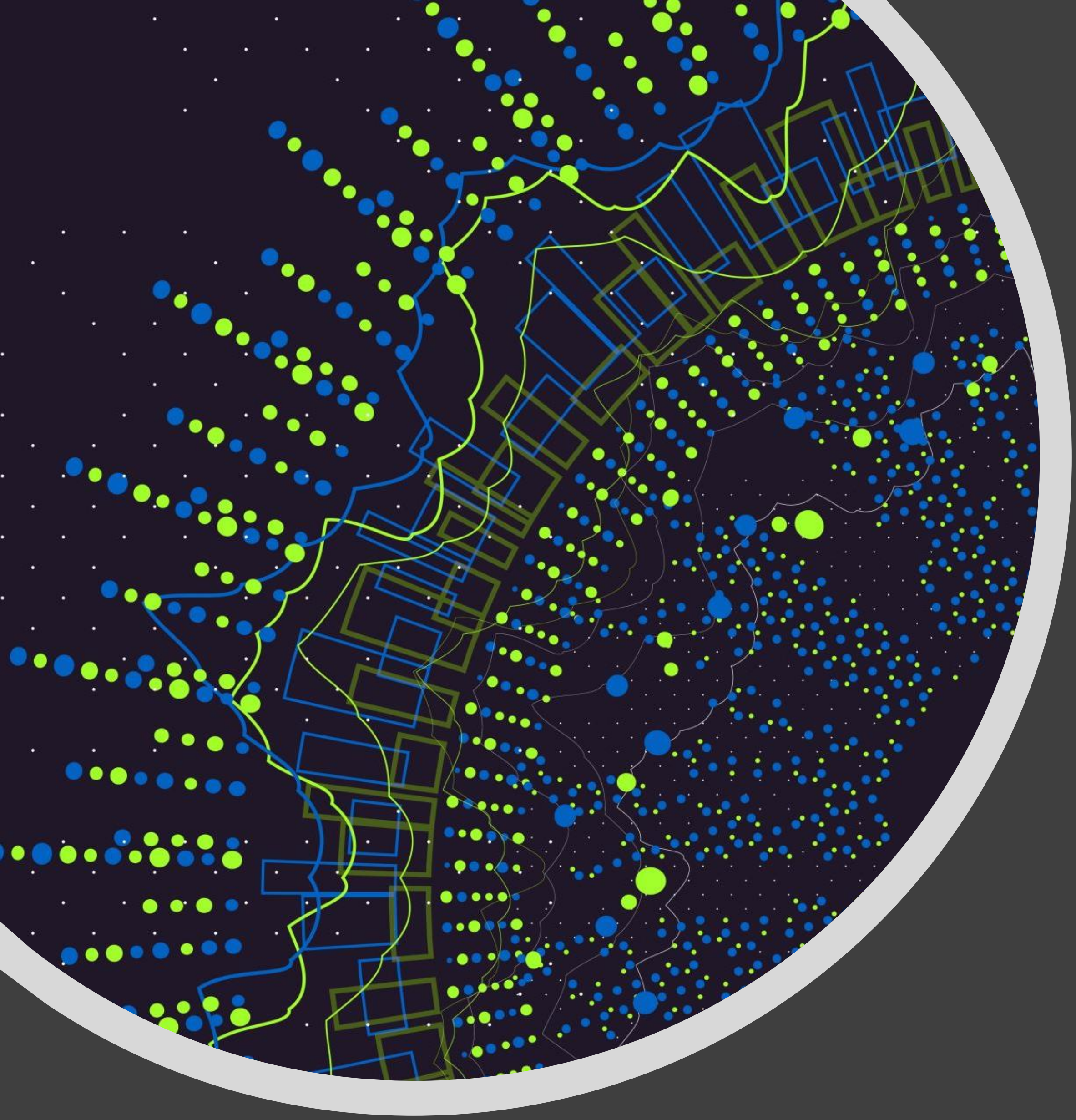
Useful if primordial baryon and dark-matter distributions differ; e.g., compensated isocurvature perturbations



Hotinli, Mertens, Johnson, MK 2019; N. Kumar et al., in prep

IM can provide foreground density field at high redshifts and large angular scales (Sato-Polito, Bernal, Boddy, MK 2021)





Conclusions

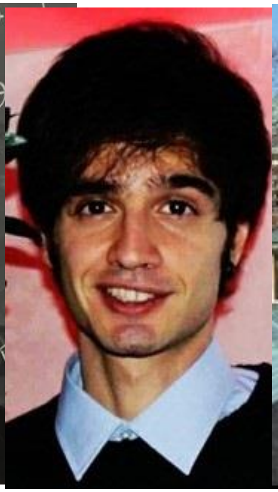
- New tools (LIM and kSZ tomography) in physical cosmology can be re-purposed to learn about the dark sector and other new physics

Neha Kumar

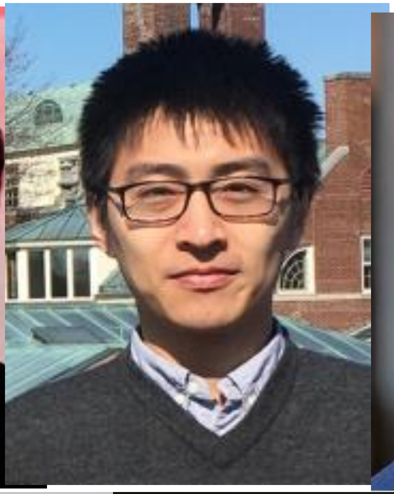
Cyril Creque-Sarbinowski

Kim Boddy

Andrea Caputo

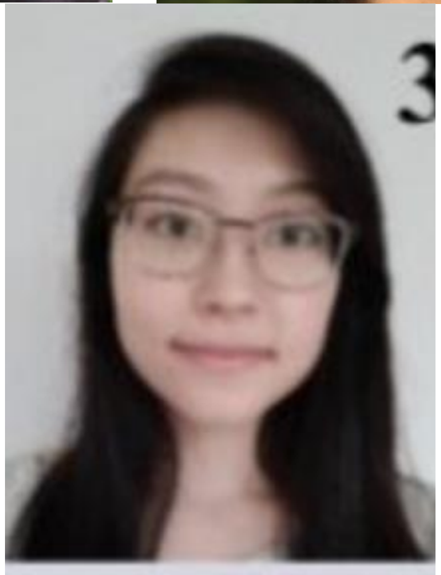


Liang Dai



Franciso Villaescusa-Navarro

Selim Hotinli



Gabriela Sato-Polito

Jose Luis Bernal

Ely Kovetz

Patrick Breysse

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

Recurrent dark energy?

- $\Lambda \neq 0$ today
- Inflation → $\Lambda \neq 0$ in the early Universe
- EDE (if this is what's going on) → $\Lambda \neq 0$ at z ~ 10,000

- Recurring periods of "Λ-like" behavior throughout cosmic history?

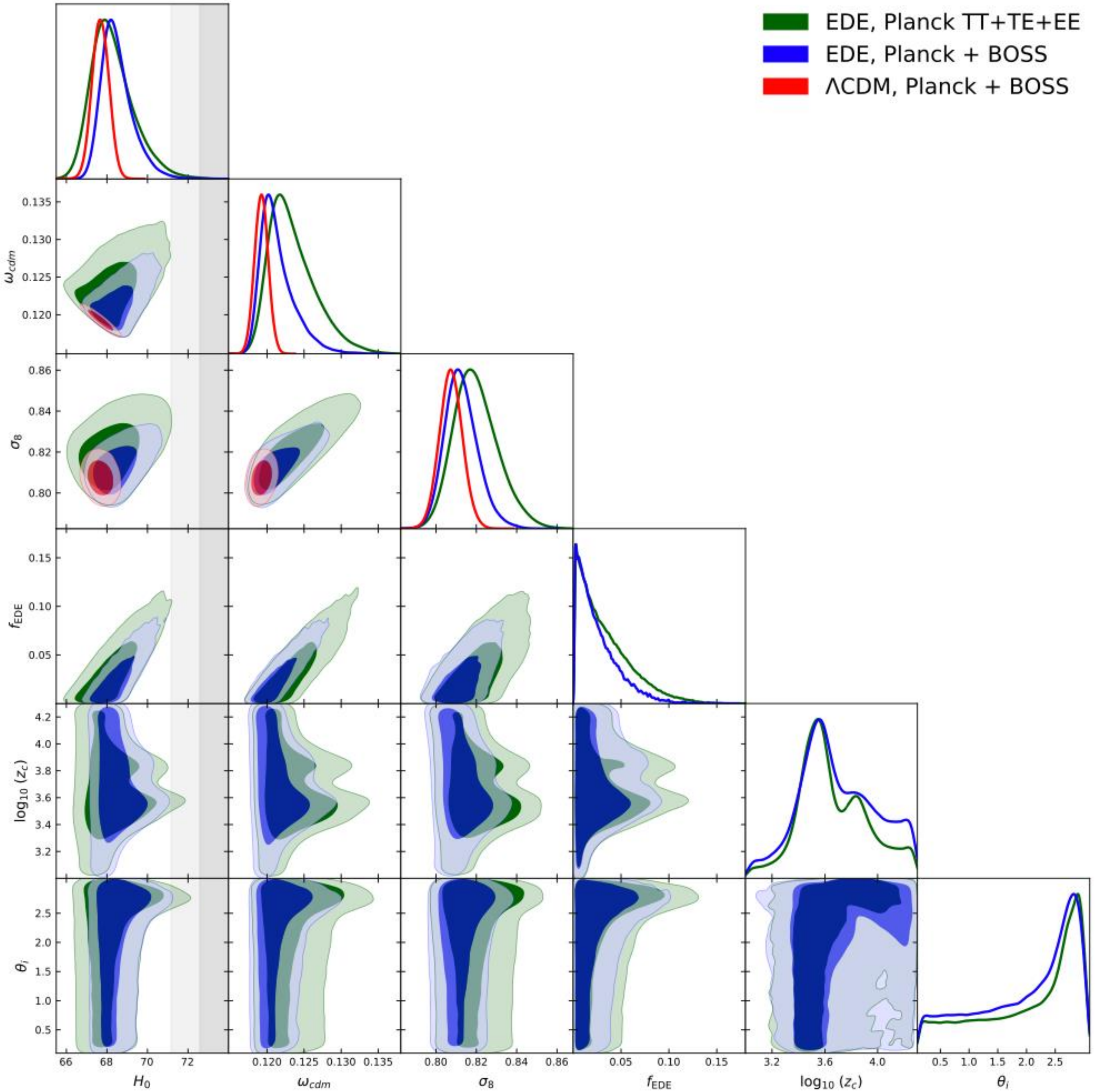
e.g., oscillating tracker field (Dodelson, Kaplinghat, Stewart, astro-ph/0002360; Griest, astro-ph/0202052)

string axiverse (Pradler, Walker, MK 2014)

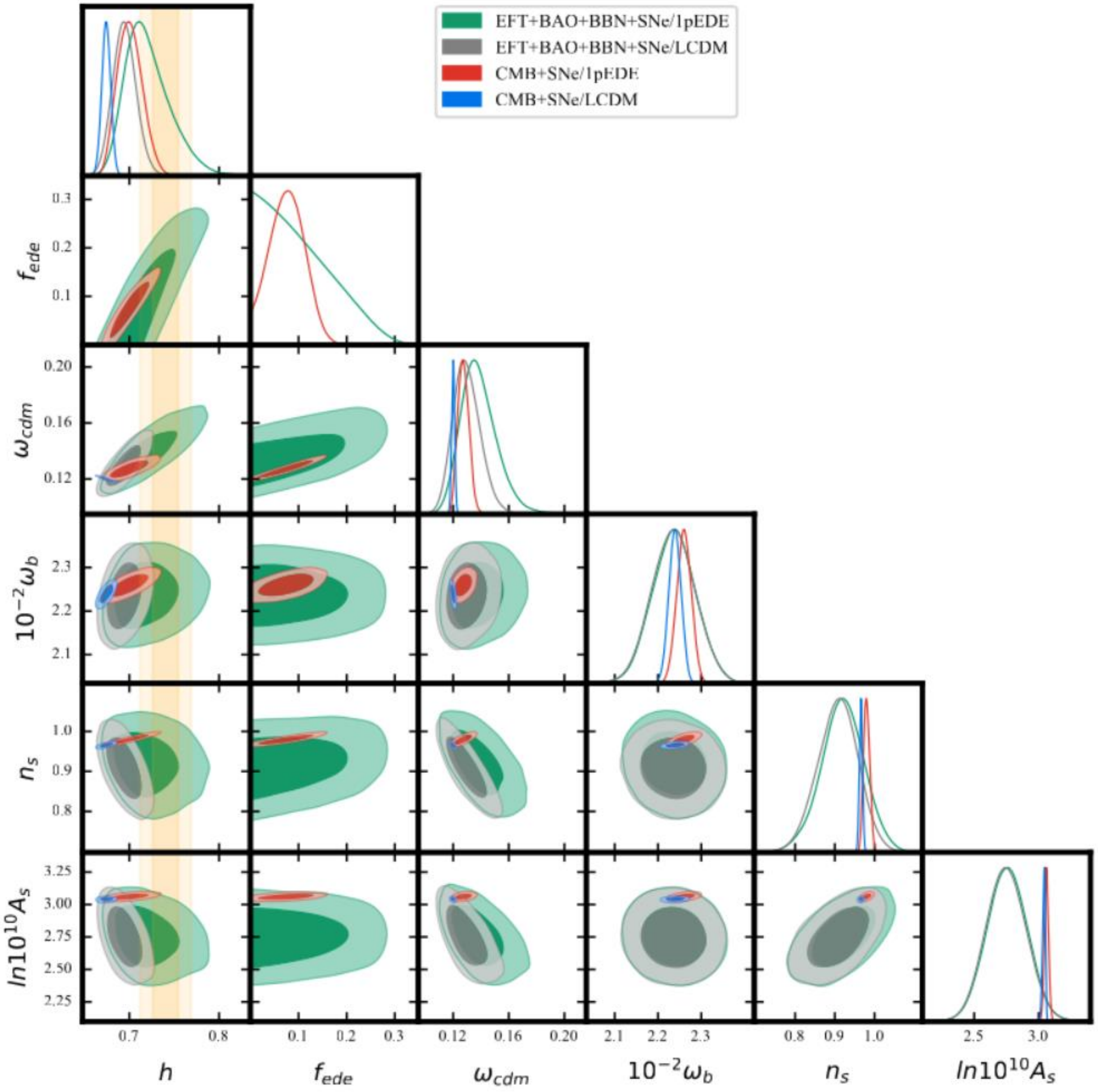
We disagree:

Conclusions follow from their choice of measure on the EDE parameter space.

Best-fit EDE model provides as good a fit to data as LambdaCDM
(Smith et al., in prep)



Power-spectra amplitudes inferred from CMB and LSS in tension, even in LambdaCDM



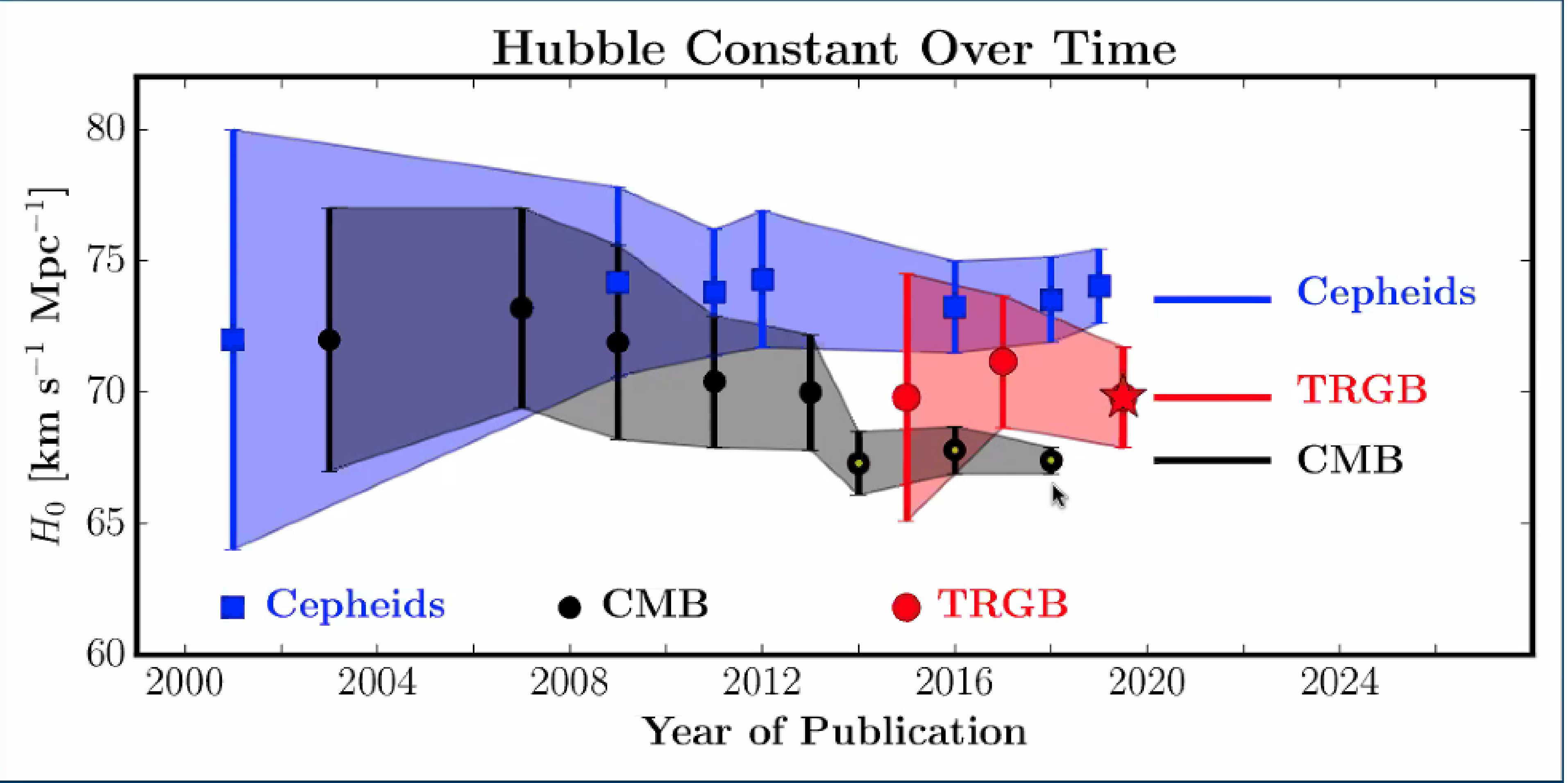
Smith et al., in prep

Have Dark Forces Been Messing With the Cosmos?

Axions? Phantom energy? Astrophysicists scramble to patch a hole in the universe, rewriting cosmic history in the process.

!!THEORY TALK!!

H_0 Values With Time

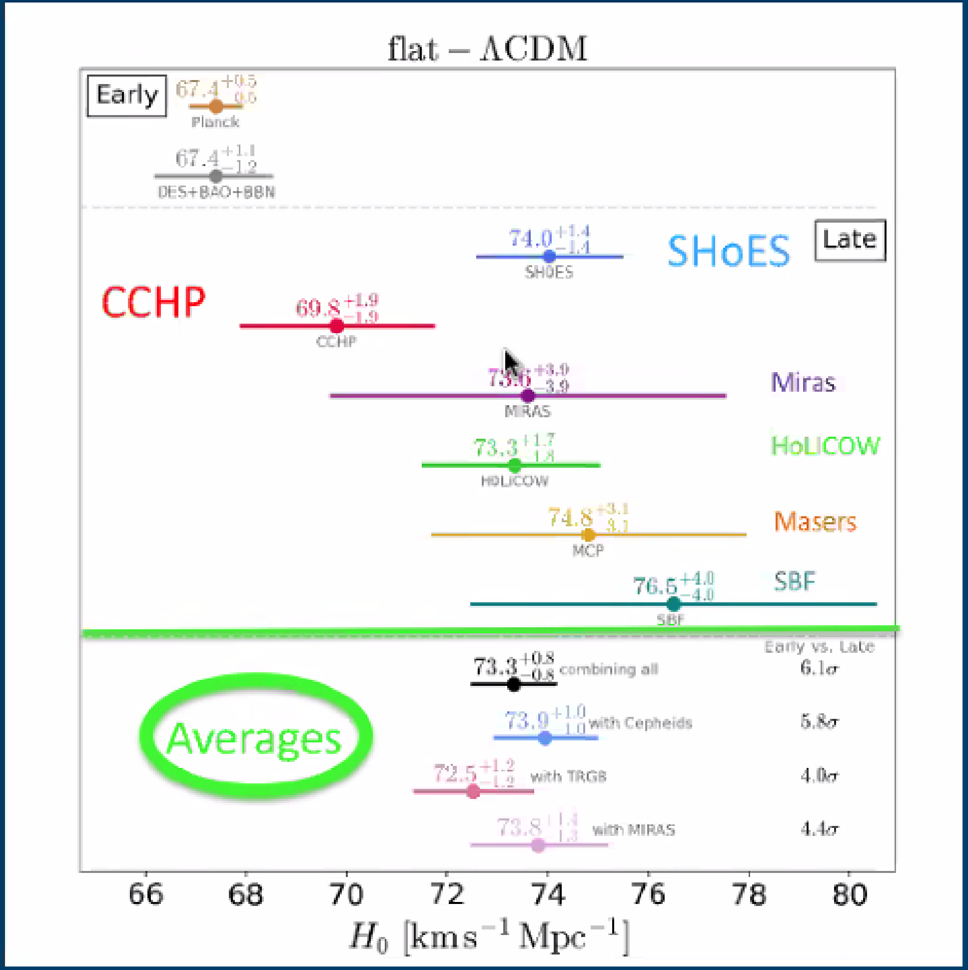


WLF et al. (2019, ApJ)

H_o "Consensus"

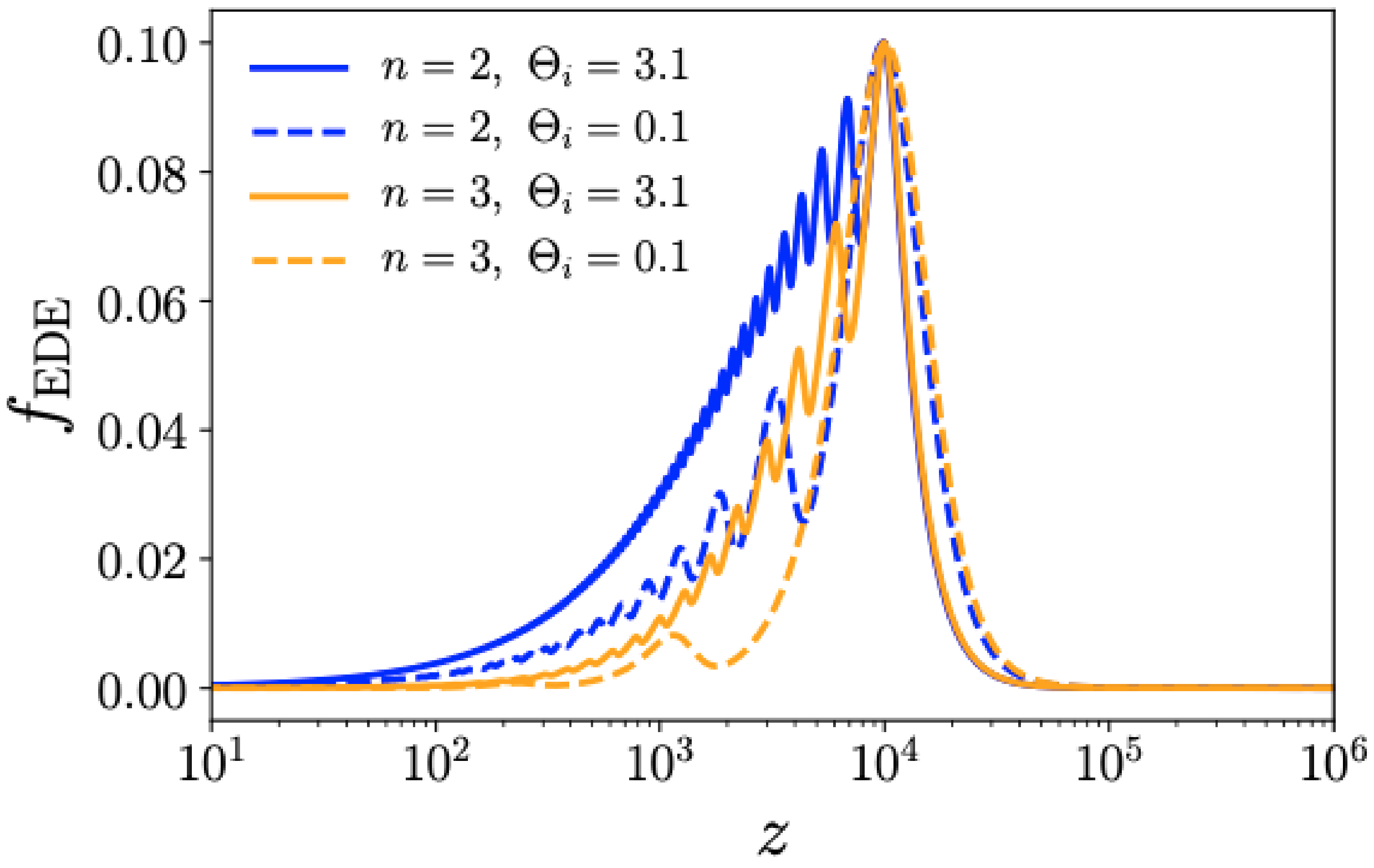
Kavli Meeting Santa Barbara, July 2019

Coordinators: Adam Riess, Tommaso Treu and Licia Verde

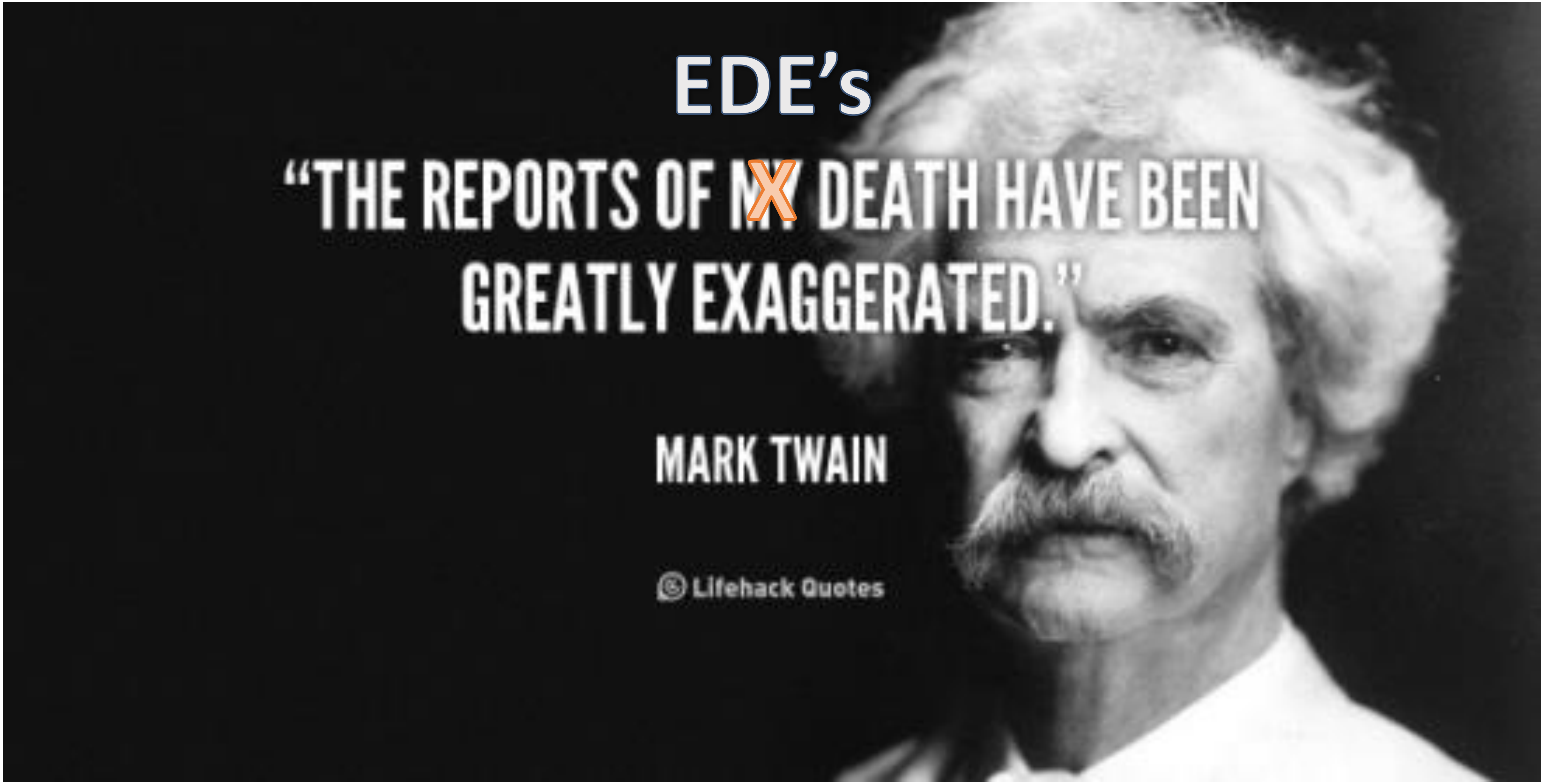


5-sigma Crisis

Verde, Treu & Riess (2019)

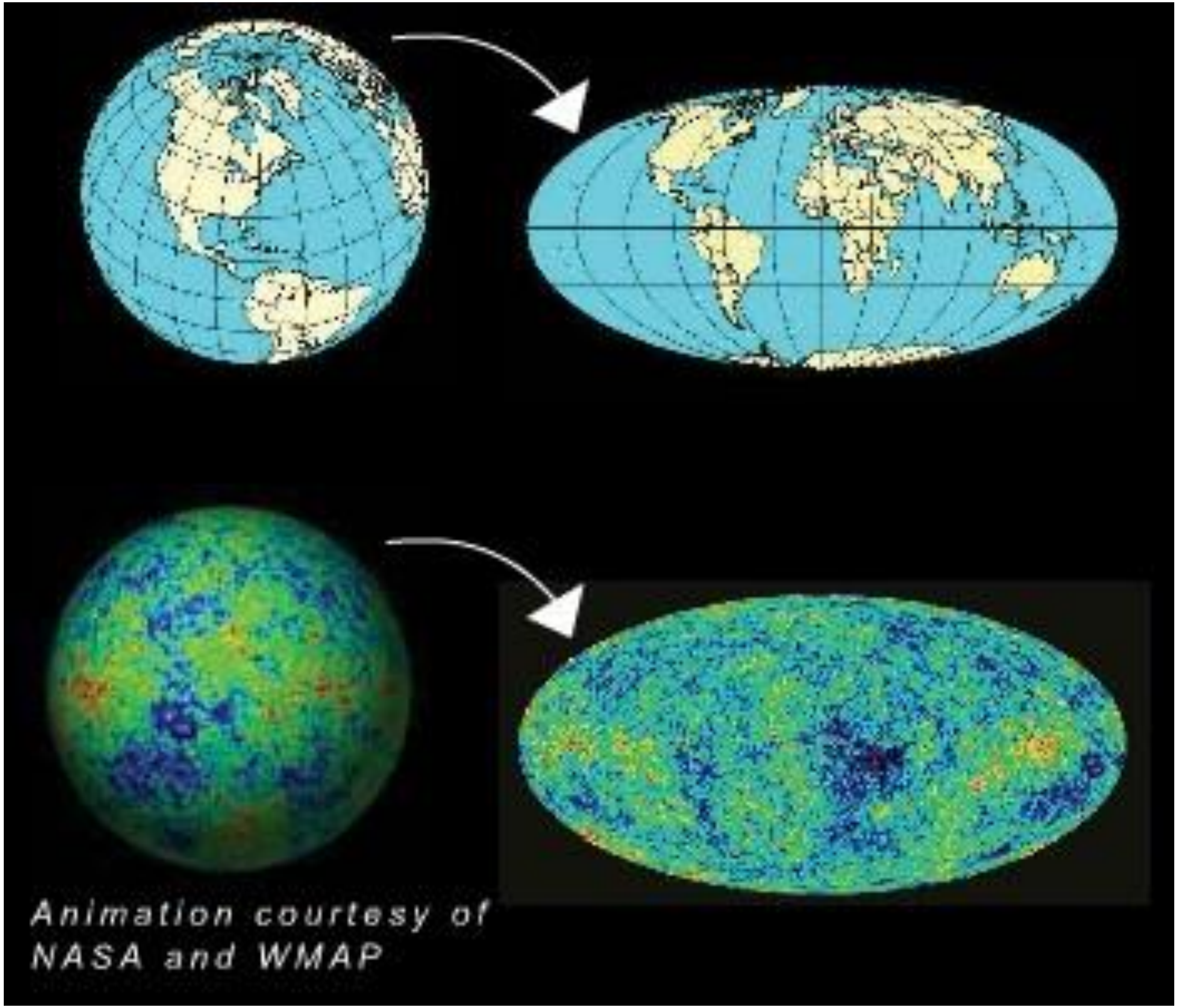


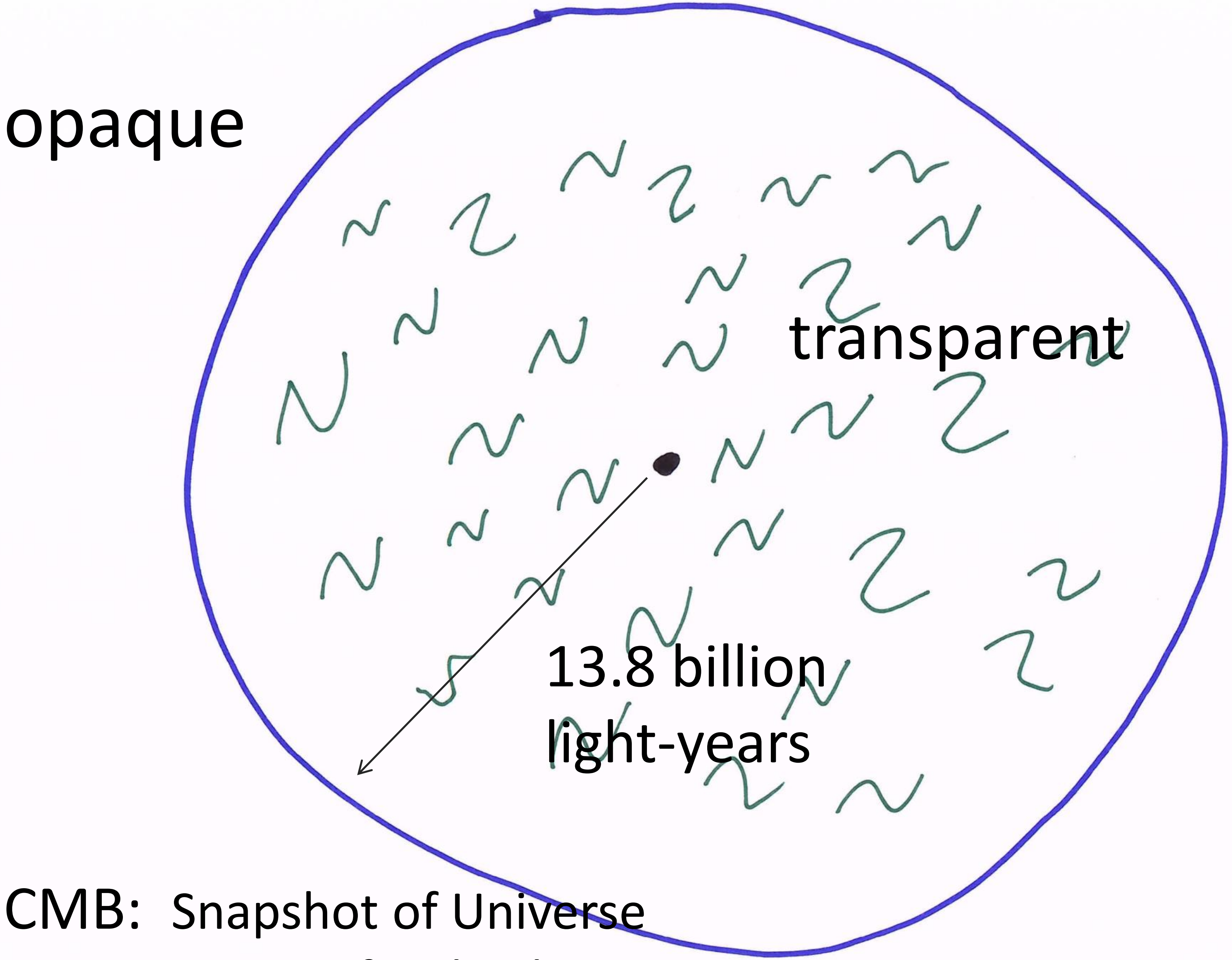
From Smith, Poulin, & Amin, 2019


EDE's
"THE REPORTS OF MY DEATH HAVE BEEN GREATLY EXAGGERATED."
MARK TWAIN
© Lifehack Quotes

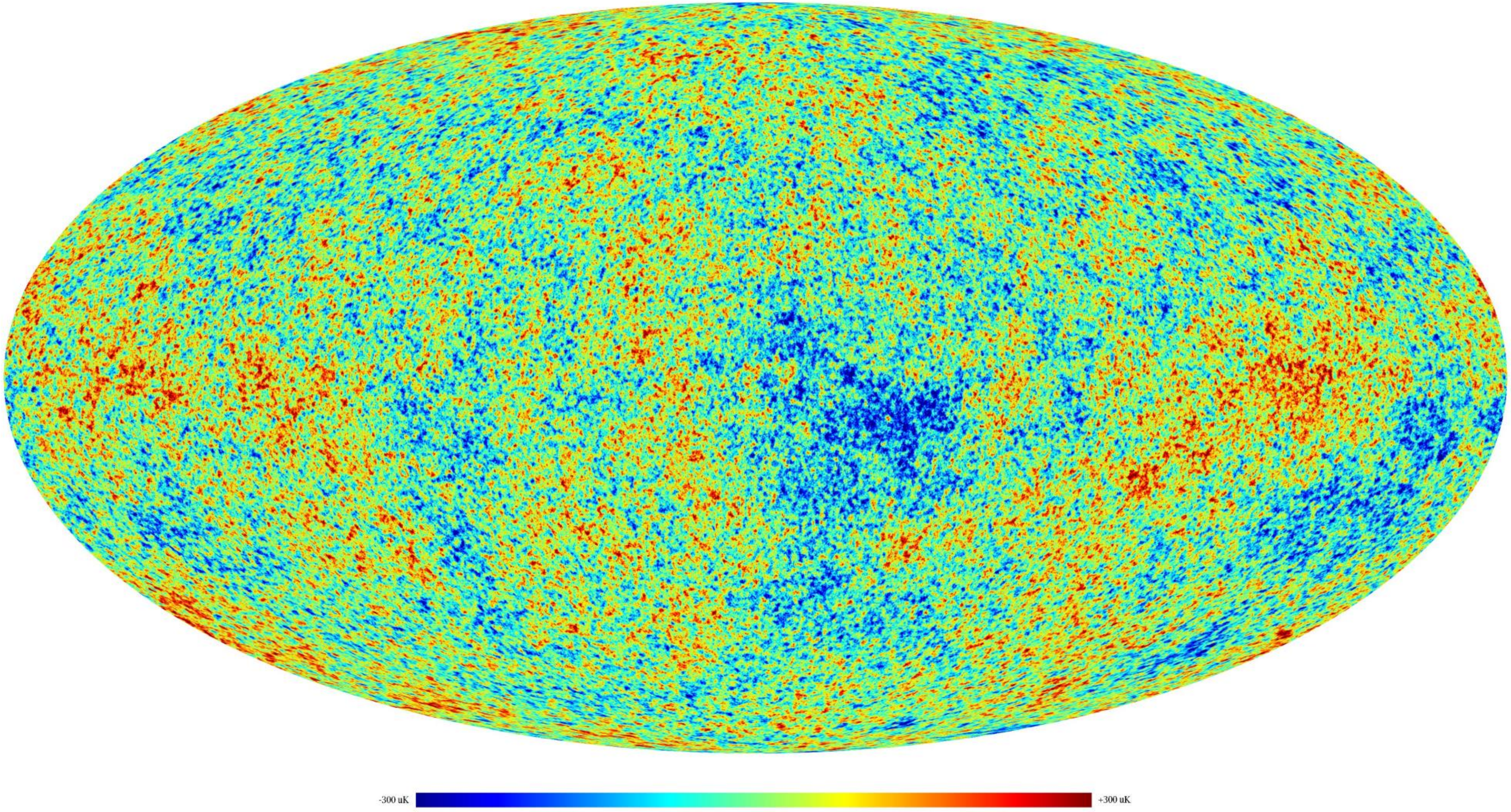
A problem with local measurements?

"I keep reminiscing how similar and different this is to 1998—I find the measurement side probably stronger than then…."
(Adam Riess, email, 31 July 2020)


Animation courtesy of
NASA and WMAP

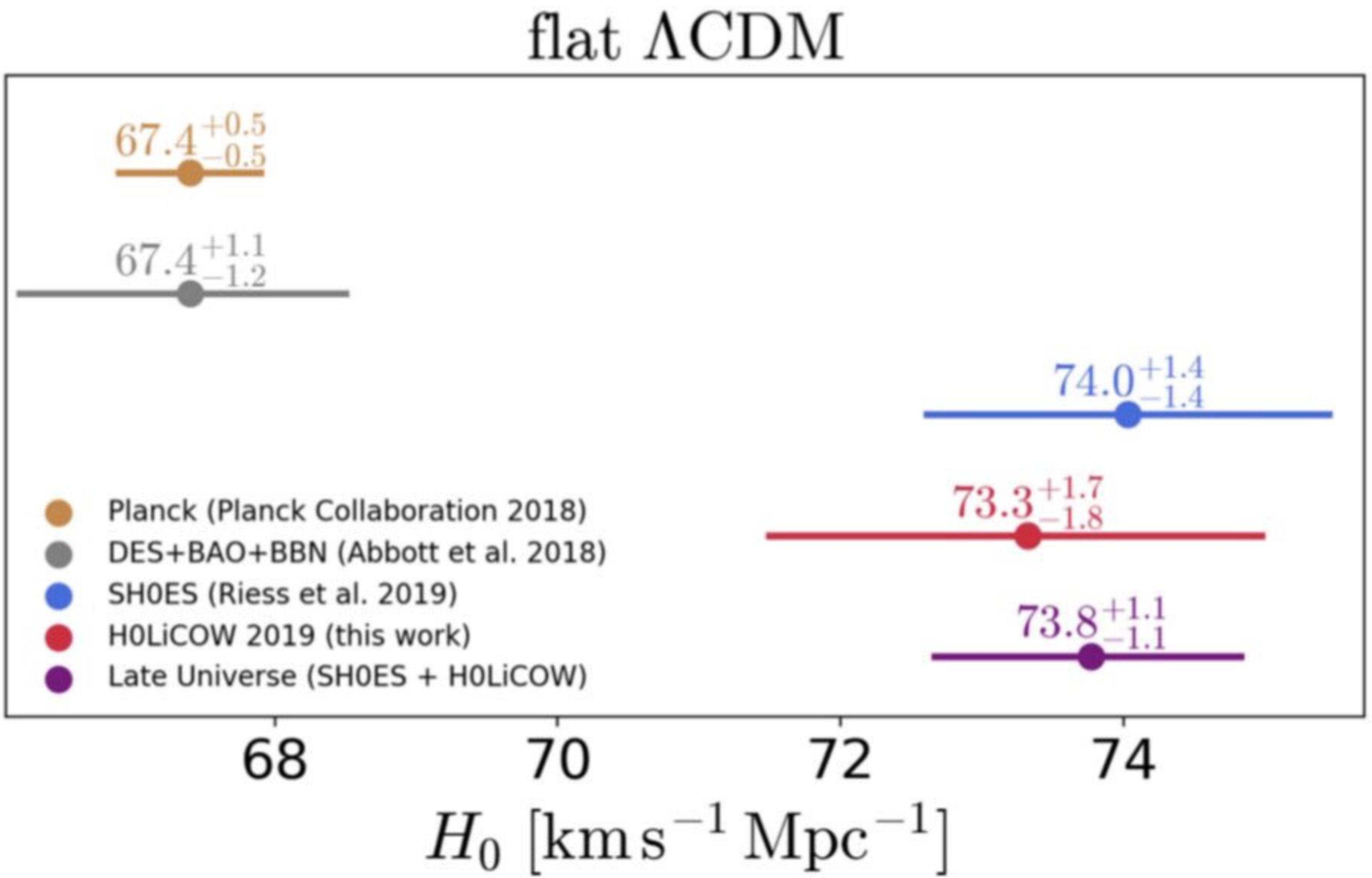


CMB: Snapshot of Universe
380,000 years after big bang

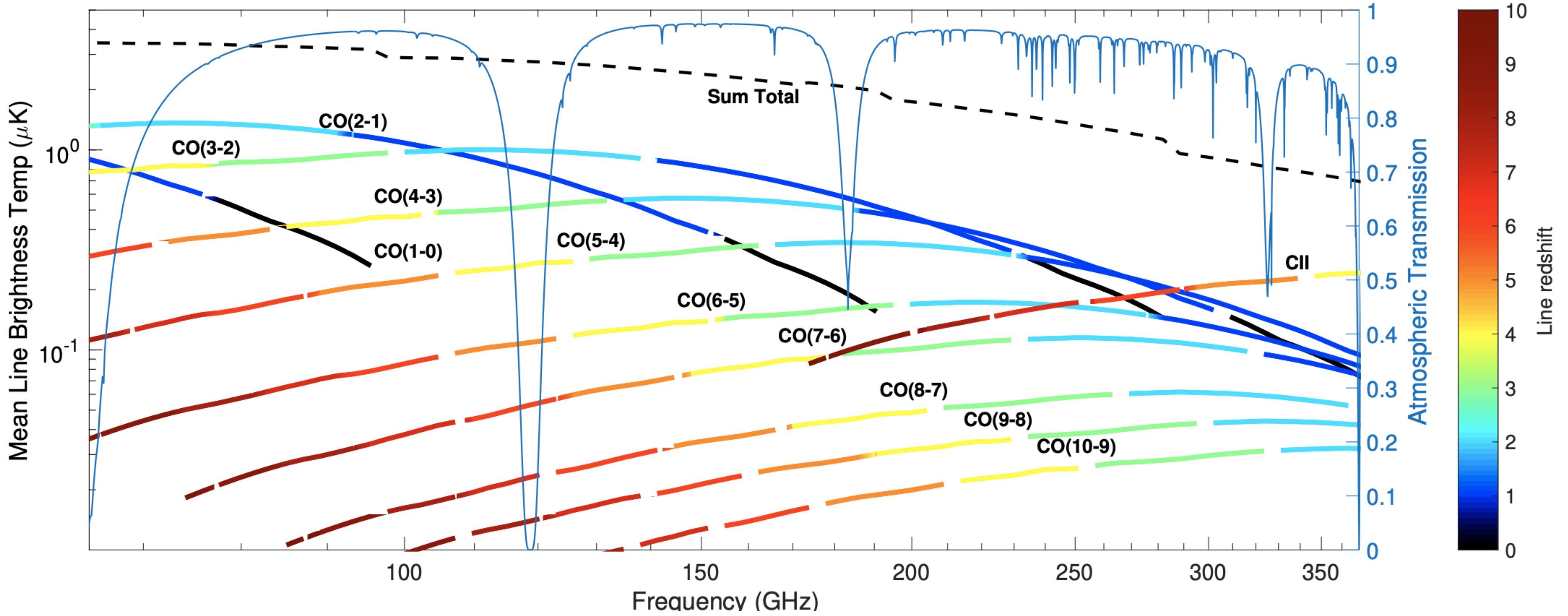


-300 uK
+300 uK


Dark Matter
Baryons



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}]



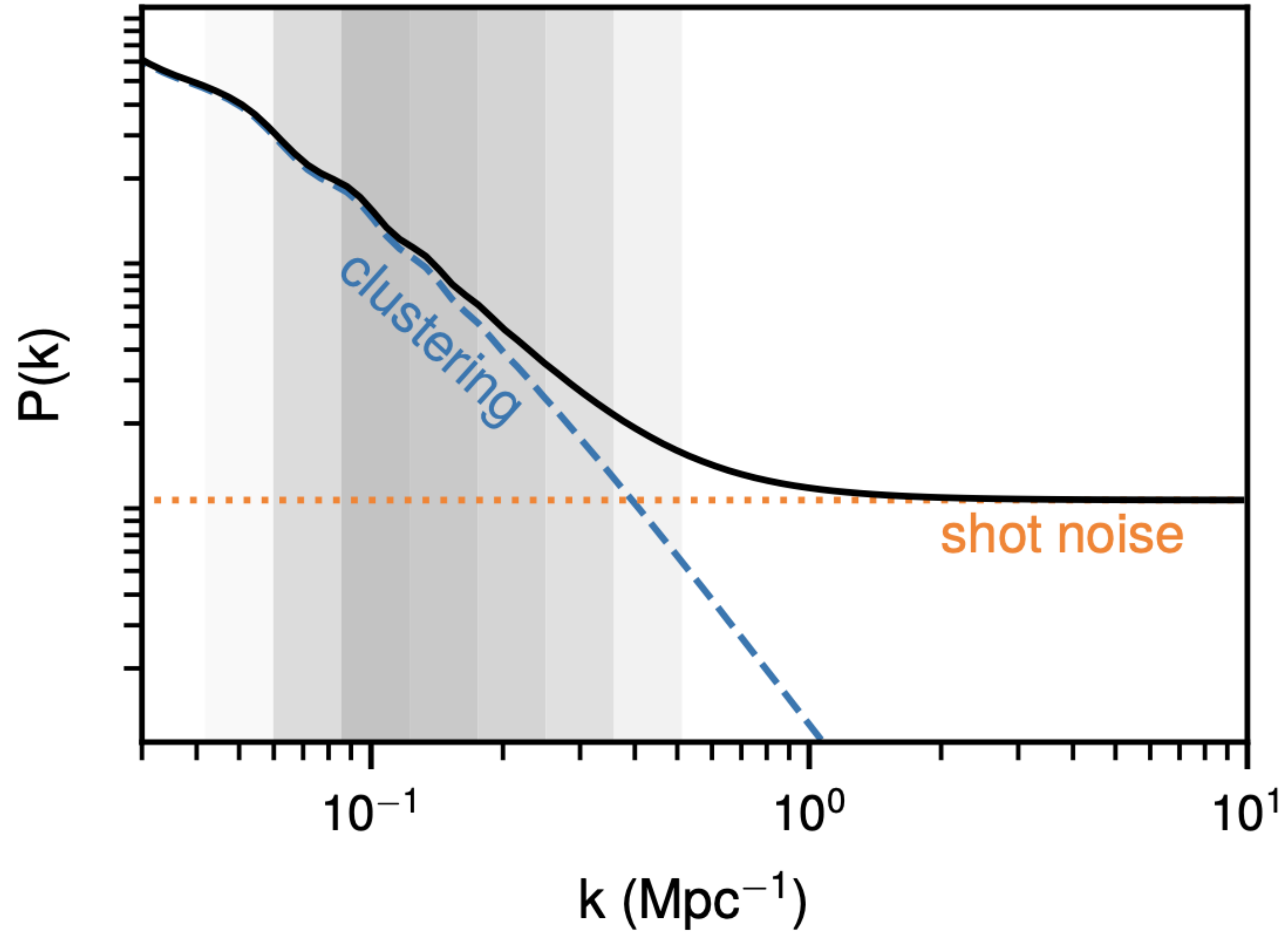
Dizgah et al. 2110.00014

Observables

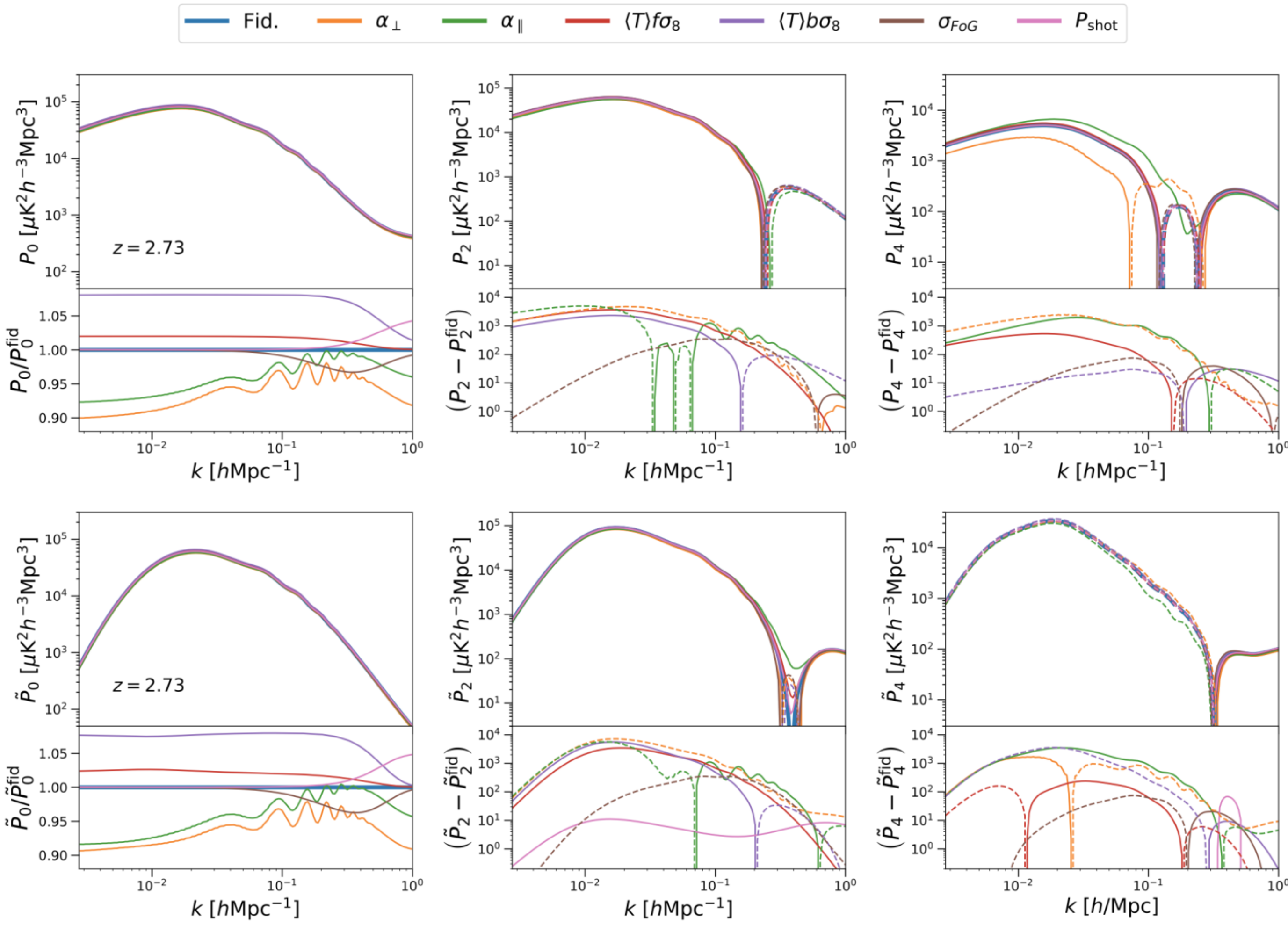
Power Spectrum (2-pt corr fn in Fourier space):

$$P(k, \mu) \qquad \mu = \cos(\hat{k} \cdot \hat{n})$$

Direction dependence from “redshift-space distortions” (from correction to Hubble-law–inferred distance from “peculiar” velocities with respect to Hubble flow)



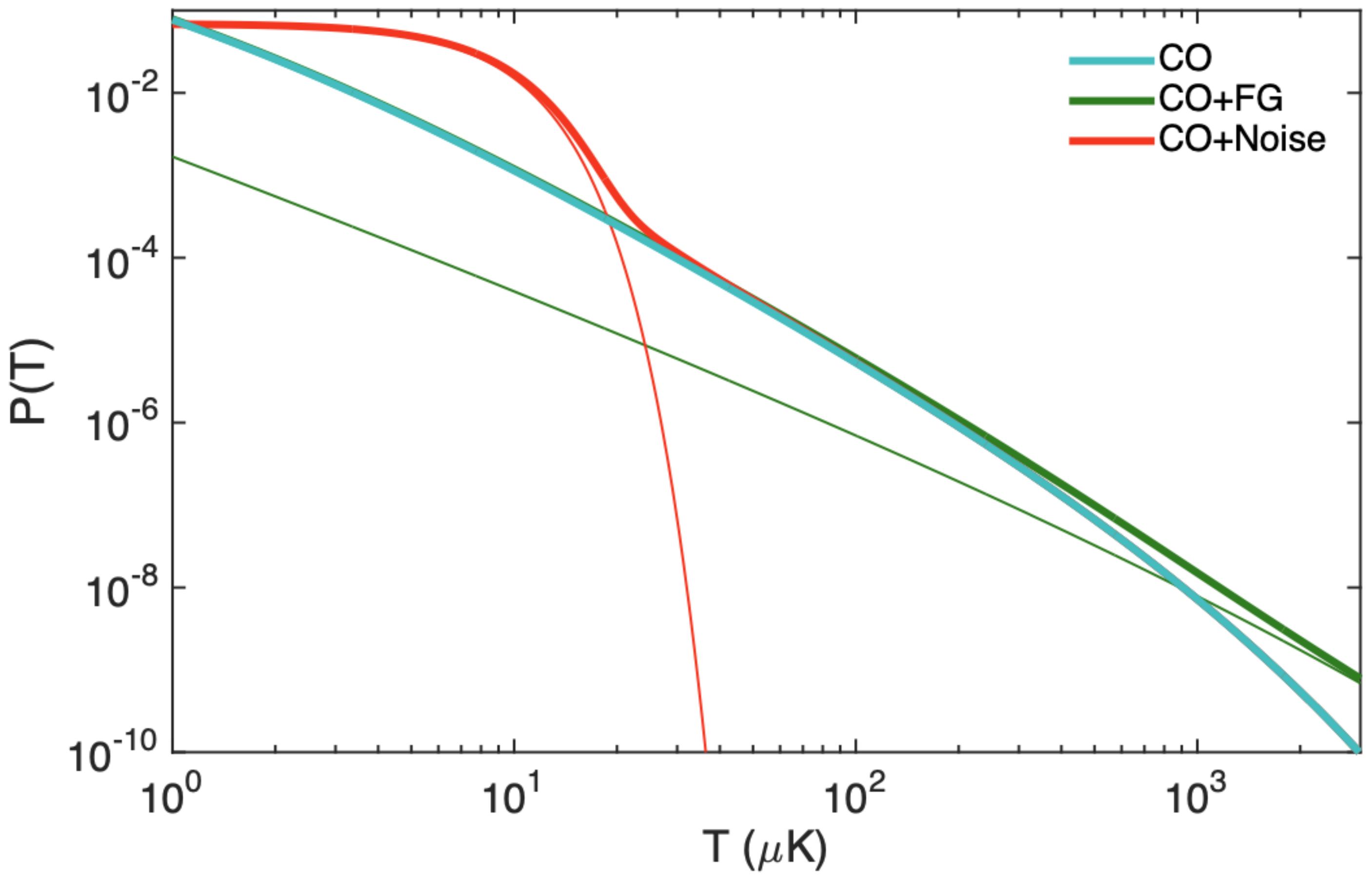
P(k)
clustering
shot noise
10^{-1}
10^{0}
10^{1}
k (Mpc^{-1})



Fid.
$\alpha_\perp$
$\alpha_\parallel$
$\langle T\rangle f\sigma_8$
$\langle T\rangle b\sigma_8$
σ_{FoG}
$P_{\rm shot}$
$z = 2.73$
P_0 [μK$^2 h^{-3}$Mpc^3]
$P_0/P_0^{\rm fid}$
P_2 [μK$^2 h^{-3}$Mpc^3]
$(P_2 - P_2^{\rm fid})$
P_4 [μK$^2 h^{-3}$Mpc^3]
$(P_4 - P_4^{\rm fid})$
$\tilde{P}_0$ [μK$^2 h^{-3}$Mpc^3]
$\tilde{P}_0/\tilde{P}_0^{\rm fid}$
$\tilde{P}_2$ [μK$^2 h^{-3}$Mpc^3]
$(\tilde{P}_2 - \tilde{P}_2^{\rm fid})$
$\tilde{P}_4$ [μK$^2 h^{-3}$Mpc^3]
$(\tilde{P}_4 - \tilde{P}_4^{\rm fid})$
k [hMpc^{-1}]
k [h/Mpc]

Observables

Voxel-intensity distribution (VID)



COMAP Early Science: I. Overview

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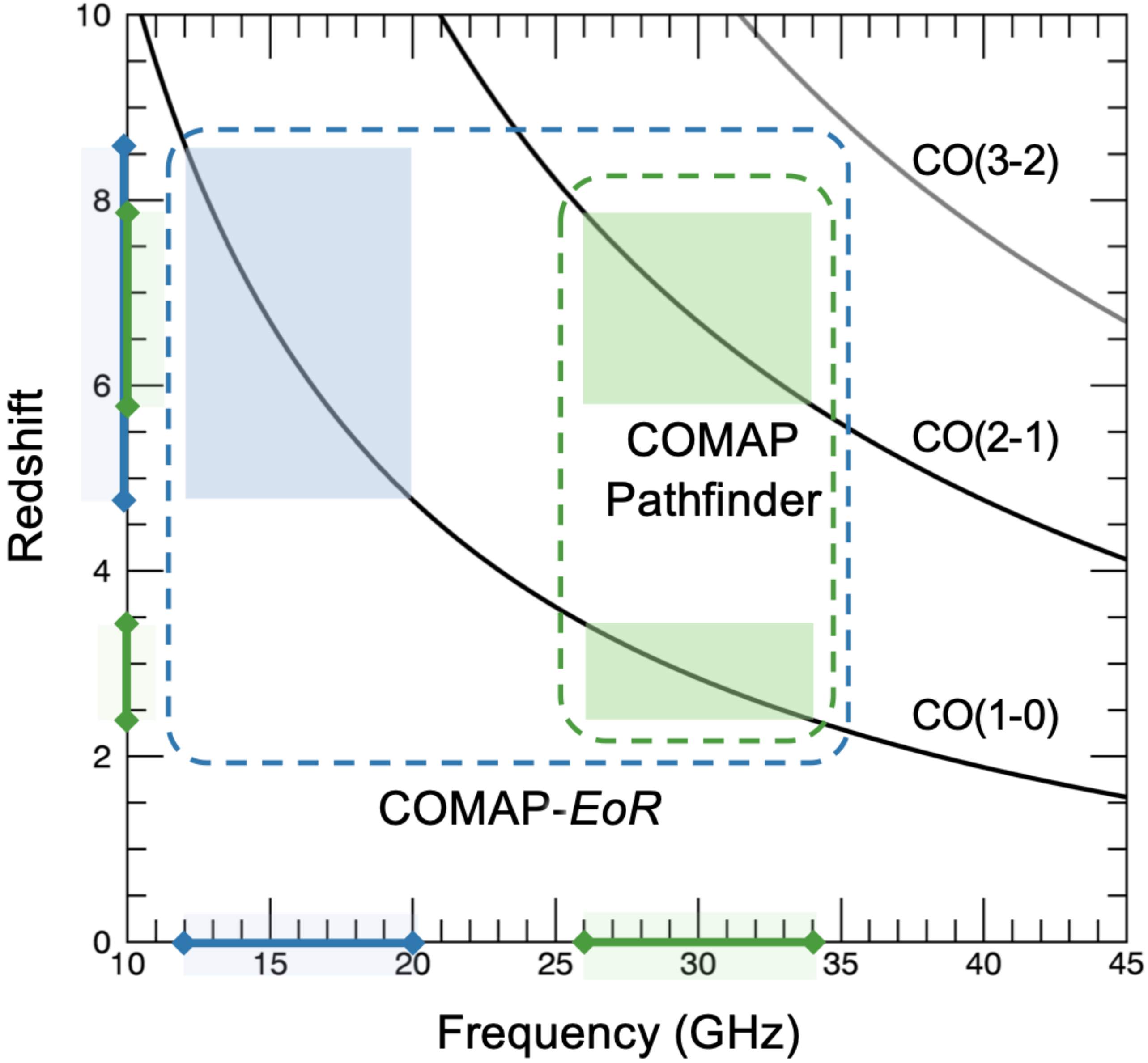
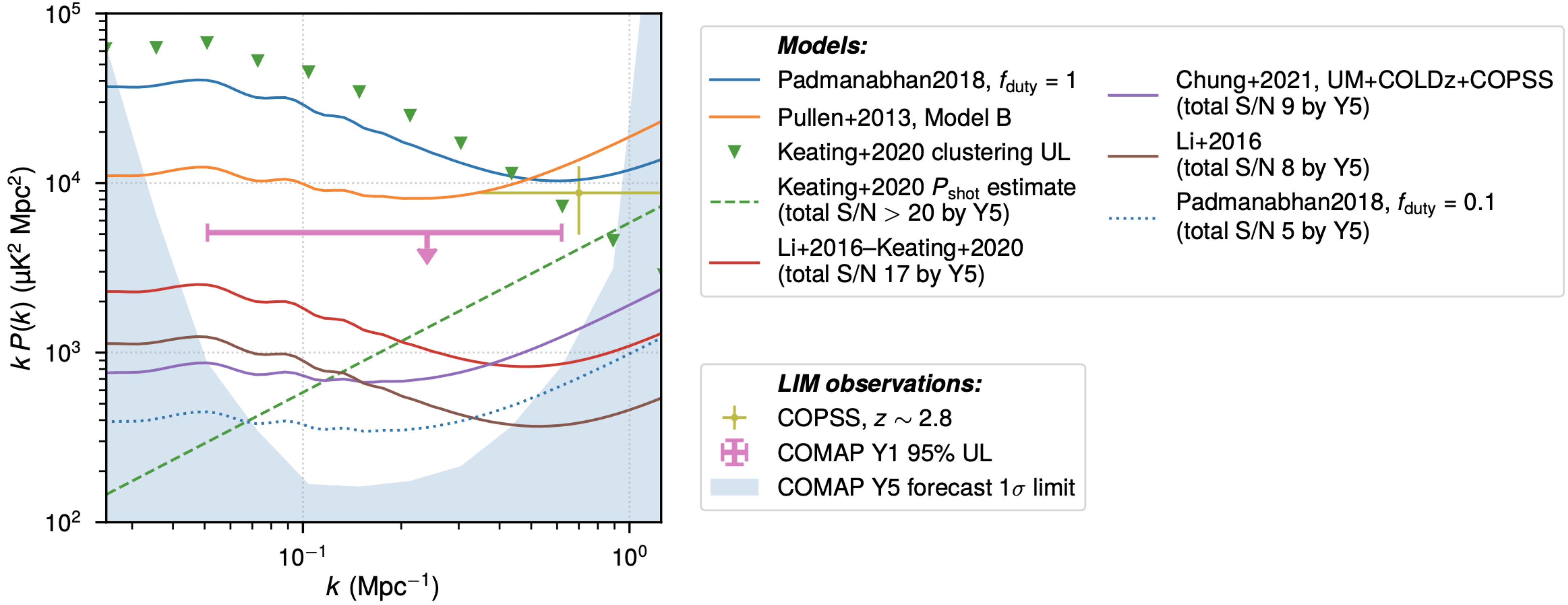
(COMAP Collaboration)

ABSTRACT

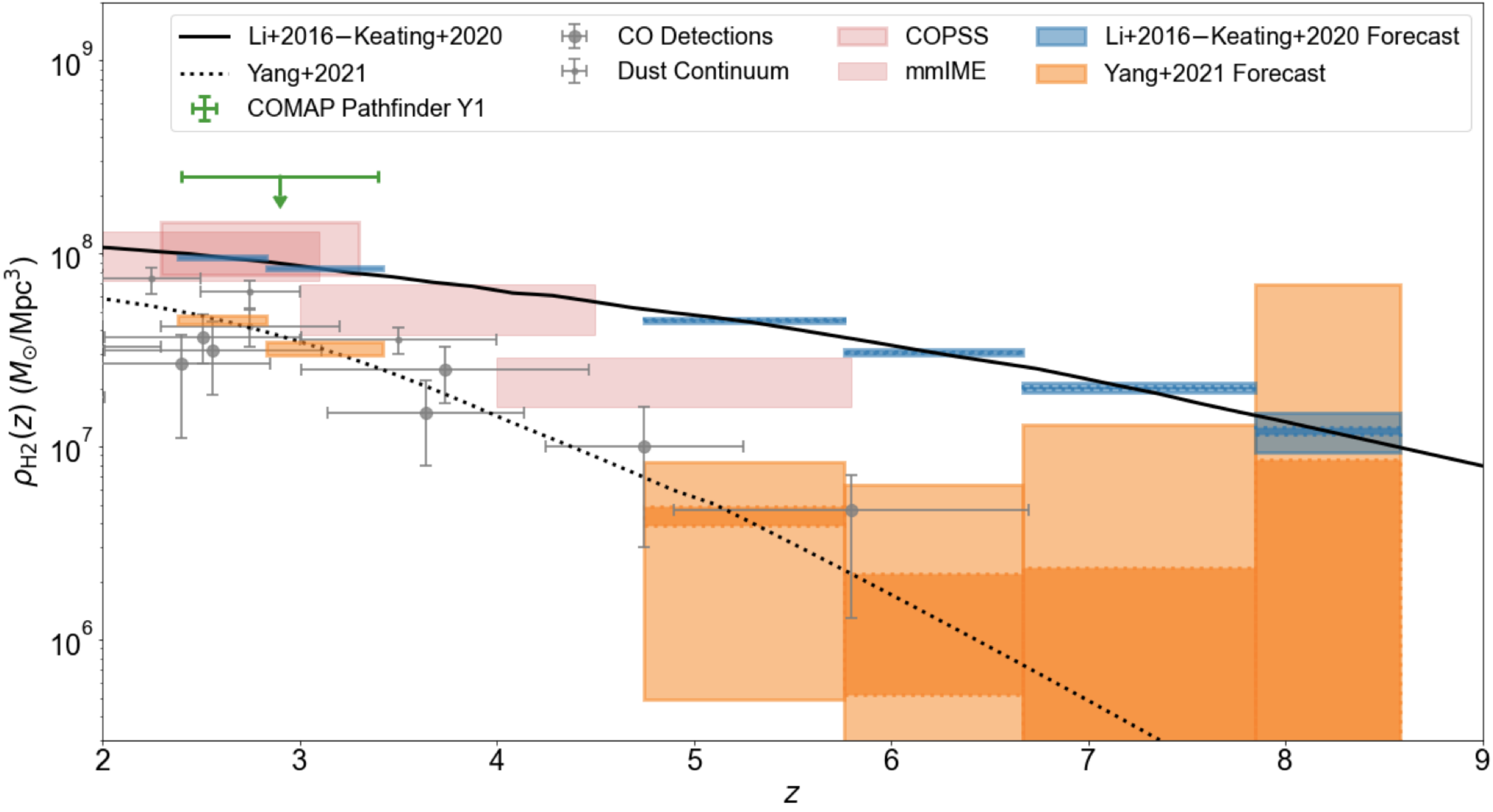
The CO Mapping Array Project (COMAP) aims to use line intensity mapping of carbon monoxide (CO) to trace the distribution and global properties of galaxies over cosmic time, back to the Epoch of Reionization (EoR). To validate the technologies and techniques needed for this goal, a Pathfinder instrument has been constructed and fielded. Sensitive to CO(1–0) emission from $z = 2.4$–3.4 and a fainter contribution from CO(2–1) at $z = 6$–8, the Pathfinder is surveying $12\,\mathrm{deg}^2$ in a 5-year observing campaign to detect the CO signal from $z \sim 3$. Using data from the first 13 months of observing, we estimate $P_{\mathrm{CO}}(k) = -2.7 \pm 1.7 \times 10^4 \mu\mathrm{K}^2\,\mathrm{Mpc}^3$ on scales $k = 0.051 - 0.62\,\mathrm{Mpc}^{-1}$ — the first direct 3D constraint on the clustering component of the CO(1–0) power spectrum. Based on these observations alone, we obtain a constraint on the amplitude of the clustering component (the squared mean CO line temperature–bias product) of $\langle Tb \rangle^2 < 49\,\mu\mathrm{K}^2$ — nearly an order-of-magnitude improvement on the previous best measurement. These constraints allow us to rule out two models from the literature. We forecast a detection of the power spectrum after 5 years with signal-to-noise ratio (S/N) 9–17. Cross-correlation with an overlapping galaxy survey will yield a detection of the CO–galaxy power spectrum with S/N of 19. We are also conducting a 30 GHz survey of the Galactic plane and present a preliminary map. Looking to the future of COMAP, we examine the prospects for future phases of the experiment to detect and characterize the CO signal from the EoR.



CO(3-2)
CO(2-1)
CO(1-0)
COMAP
Pathfinder
COMAP-*EoR*
Redshift
Frequency (GHz)
10
8
6
4
2
0
10
15
20
25
30
35
40
45



10^5
10^4
10^3
10^2
$k\,P(k)$ (μK^2 Mpc^2)
10^{-1}
10^0
k (Mpc^{-1})
Models:
Padmanabhan2018, $f_{\rm duty}$ = 1
Pullen+2013, Model B
Keating+2020 clustering UL
Keating+2020 $P_{\rm shot}$ estimate (total S/N > 20 by Y5)
Li+2016–Keating+2020 (total S/N 17 by Y5)
Chung+2021, UM+COLDz+COPSS (total S/N 9 by Y5)
Li+2016 (total S/N 8 by Y5)
Padmanabhan2018, $f_{\rm duty}$ = 0.1 (total S/N 5 by Y5)
LIM observations:
COPSS, $z \sim 2.8$
COMAP Y1 95% UL
COMAP Y5 forecast 1σ limit



Li+2016−Keating+2020
Yang+2021
COMAP Pathfinder Y1
CO Detections
Dust Continuum
COPSS
mmIME
Li+2016−Keating+2020 Forecast
Yang+2021 Forecast
10^9
10^8
10^7
10^6
$\rho_{\mathrm{H2}}(z)$ $(M_\odot/\mathrm{Mpc}^3)$
2
3
4
5
6
7
8
9
z