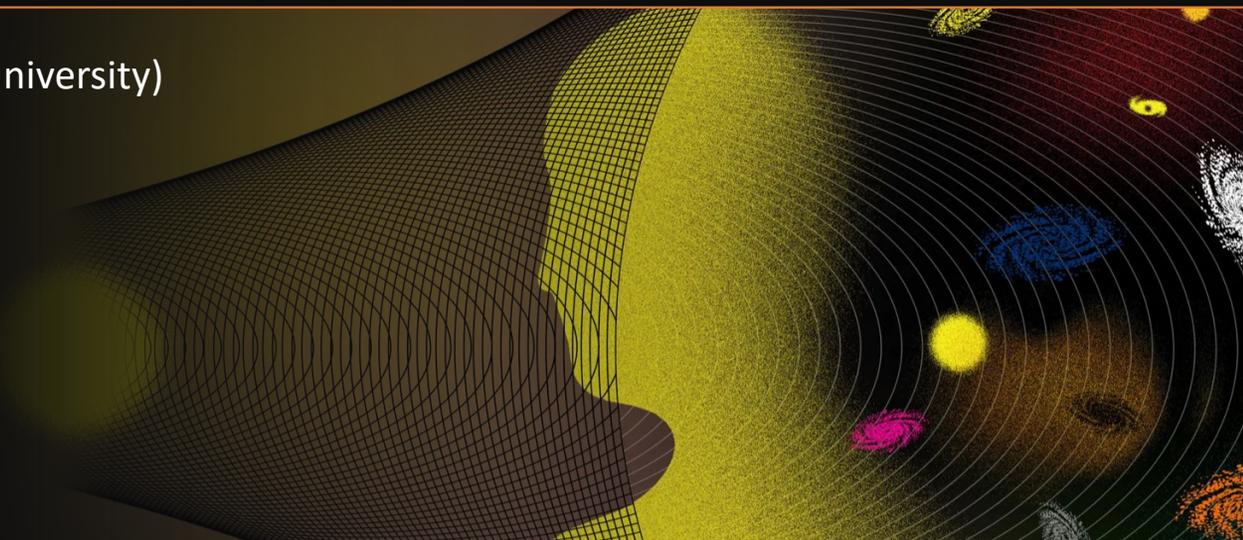


# New Cosmic Frontiers

Marc Kamionkowski (Johns Hopkins University)

3 June 2022

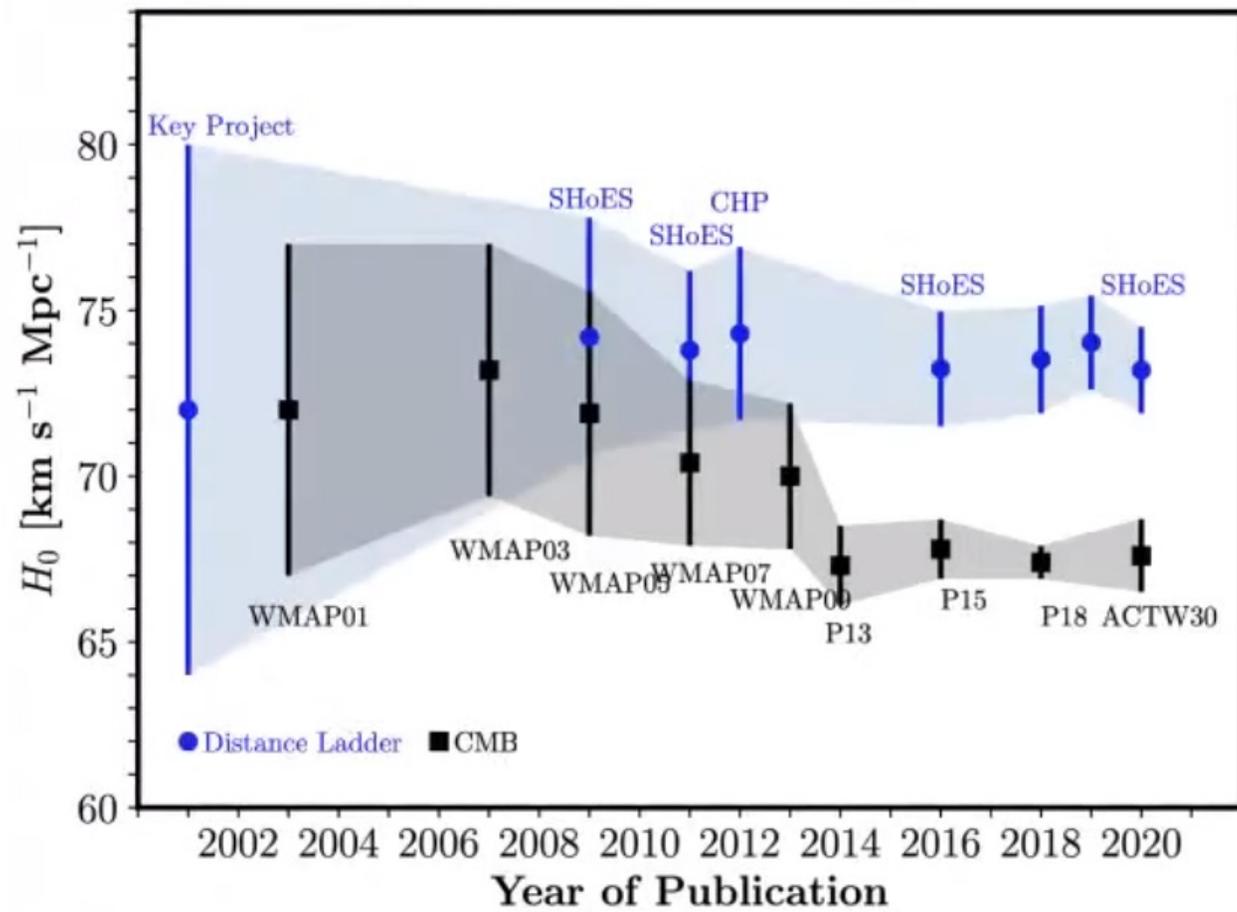




# Outline

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- The Hubble tension and early dark energy
- Line-intensity mapping and the dark Universe
- kSZ tomography
- New cosmological-perturbation numerics

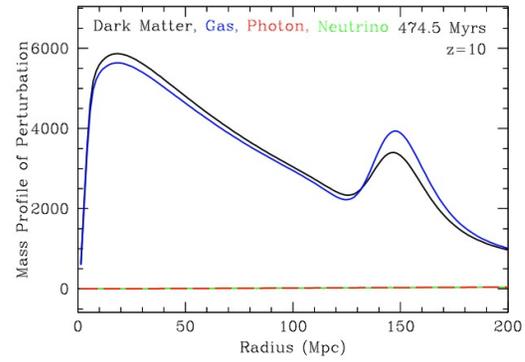
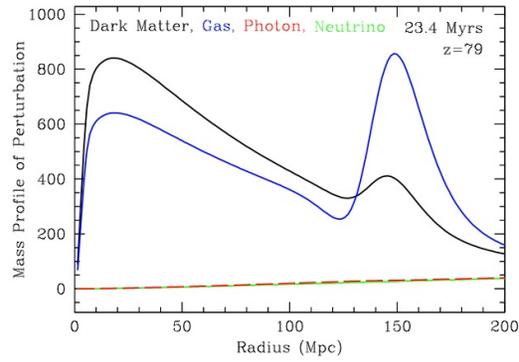
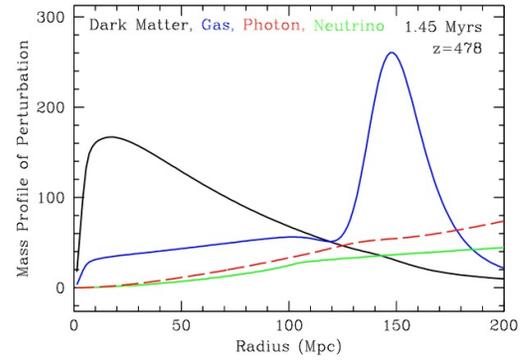
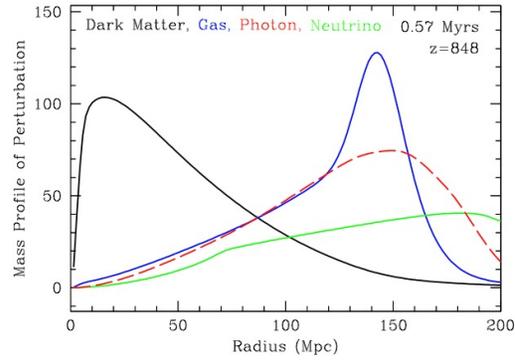
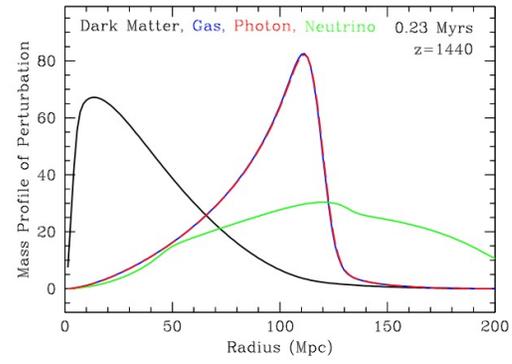
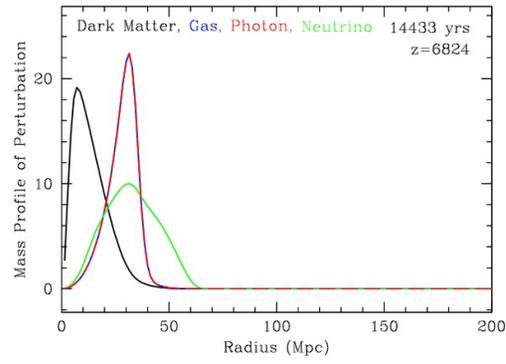


The Hubble “tension”: Why does the expansion rate inferred from the CMB differ from that observed locally?

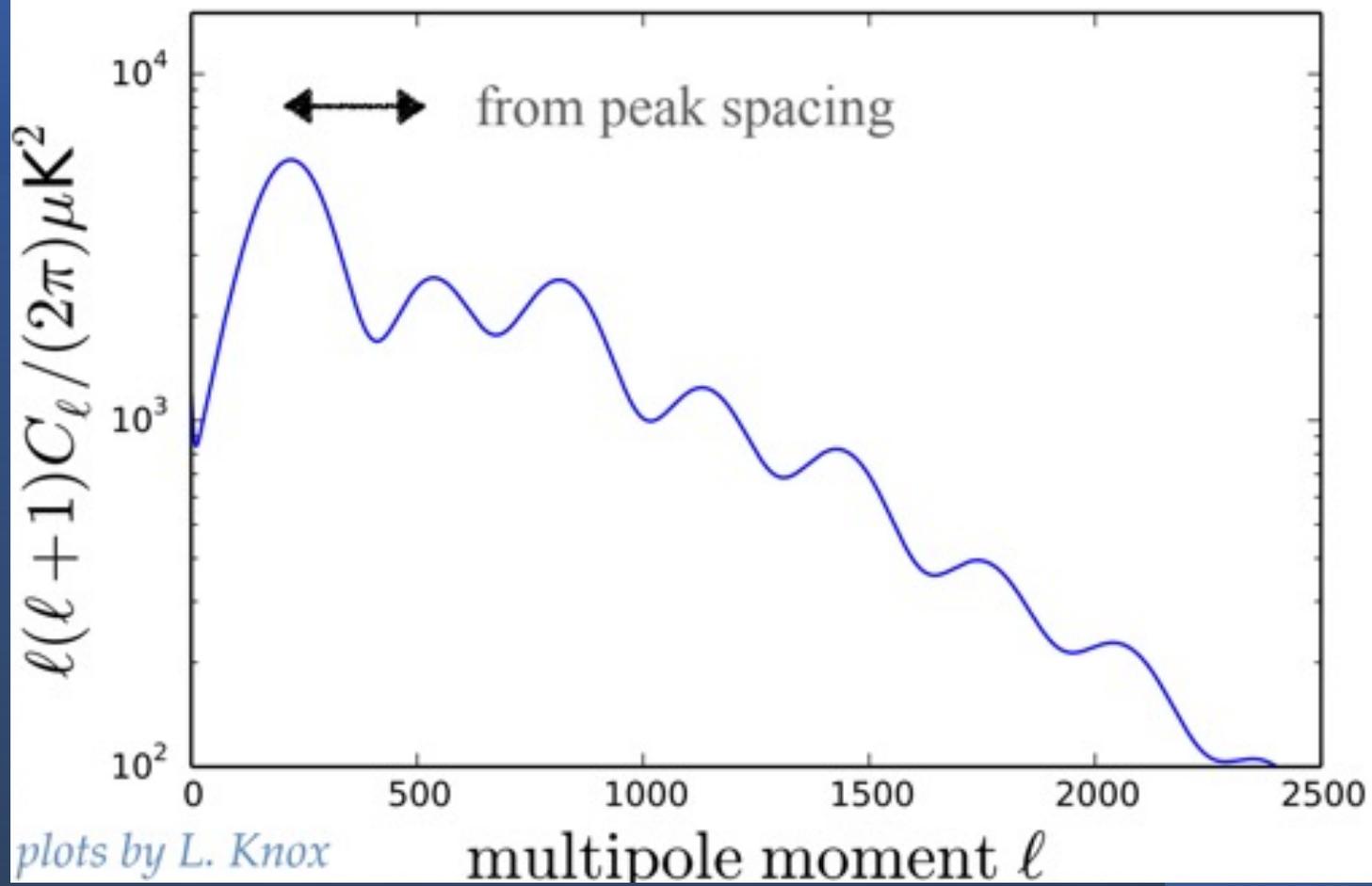
- Problem with local measurements?
- Problem with CMB measurements?
- Problems with both?
- New physics?

The Hubble “tension”: Why does the expansion rate inferred from the CMB differ from that observed locally?

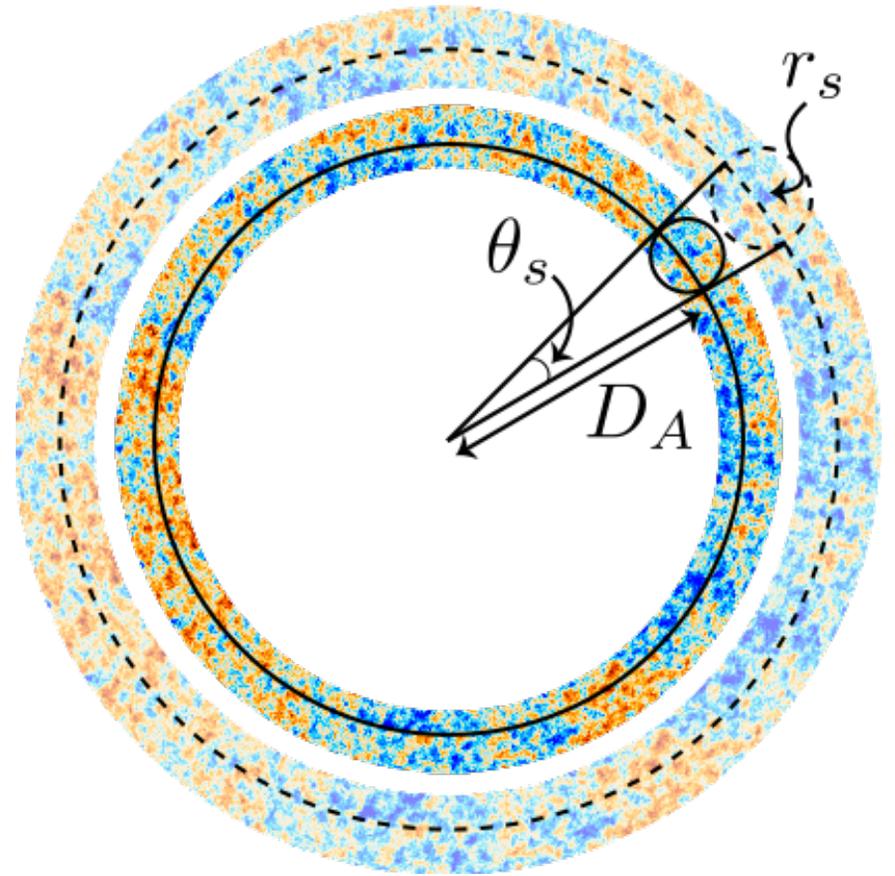
- Problem with local measurements?
- Problem with CMB measurements?
- Problems with both?
- New physics?



Bassett & Hlozek 2009



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



$$D_A = \frac{c}{H_0} \int_{t_{\text{rec}}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}$$

$$r_s = \frac{1}{H_{\text{rec}}} \int_0^{t_{\text{rec}}} \frac{c_s(t) dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}$$

$$H_0 = H_{\text{rec}} \frac{\int_{t_{\text{rec}}}^{t_0} \frac{c dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\text{rec}}} \frac{c_s(t) dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}}$$

To increase  $H_0$ , can

- Decrease matter density at late times
- Decrease sound speed in early Universe
- Increase matter density at early times

$$H_0 = H_{\text{rec}} \frac{\int_{t_{\text{rec}}}^{t_0} \frac{c dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\text{rec}}} \frac{c_s(t) dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}}$$

To increase  $H_0$ , can

- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe
- Increase matter density at early times

# Late-time solutions

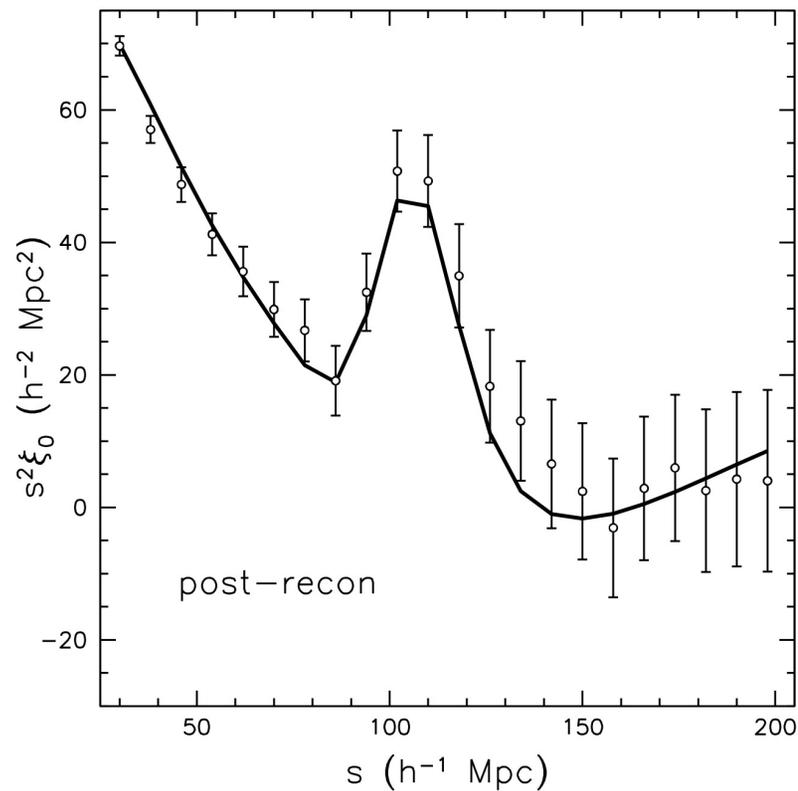
---

- Modify late expansion history to increase  $D_A$   
e.g., exotic dark energy; phantom energy; exotic dark matter;
- Requires energy density *smaller* than in standard model: negative-density matter?!?! Violation of null energy condition?!?!

# Late-time solutions: disfavored by BAO in galaxy distribution

Sound horizon imprinted on galaxy distribution measured in “redshift space”

Provides standard ruler to infer  $H_0$  --> lower  $H_0$

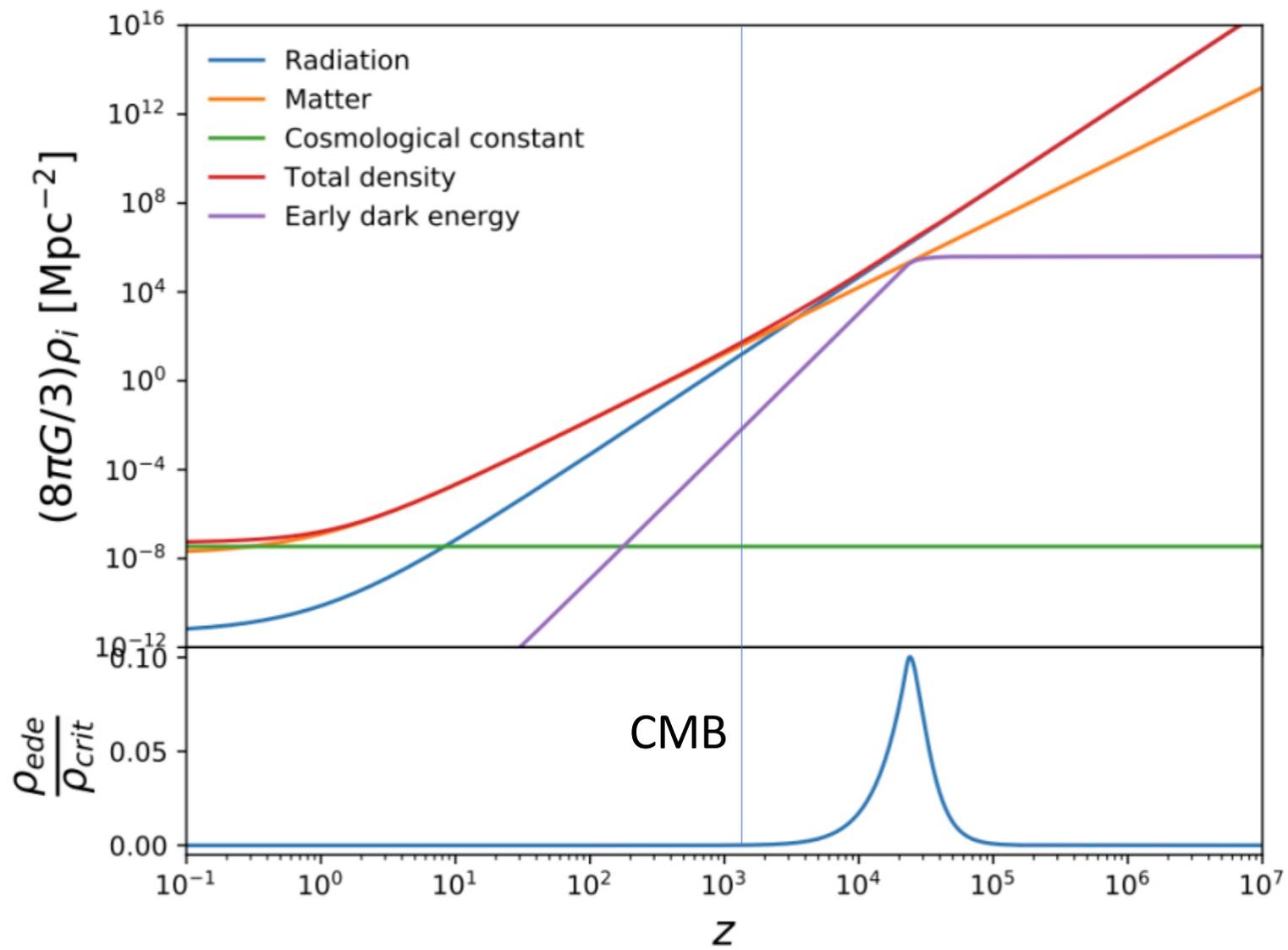


SDSS-BOSS Collaboration  
Anderson et al. 2013

$$H_0 = H_{\text{rec}} \frac{\int_{t_{\text{rec}}}^{t_0} \frac{c dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\text{rec}}} \frac{c_s(t) dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}}$$

To increase  $H_0$ , can

- Decrease matter density at late times (**late-time solutions**)
- Decrease sound speed in early Universe
- Increase matter density at early times (*early dark energy*)



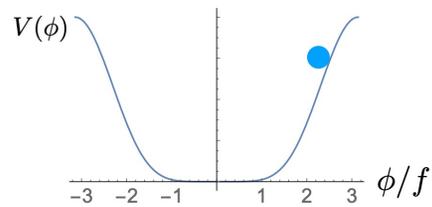
# Some possible physics of EDE

(Karwal & MK 2016)

- Behaves like cosmological constant at early times; decays as

$$(\text{scale factor})^{(2n-2)/(2n+2)}$$

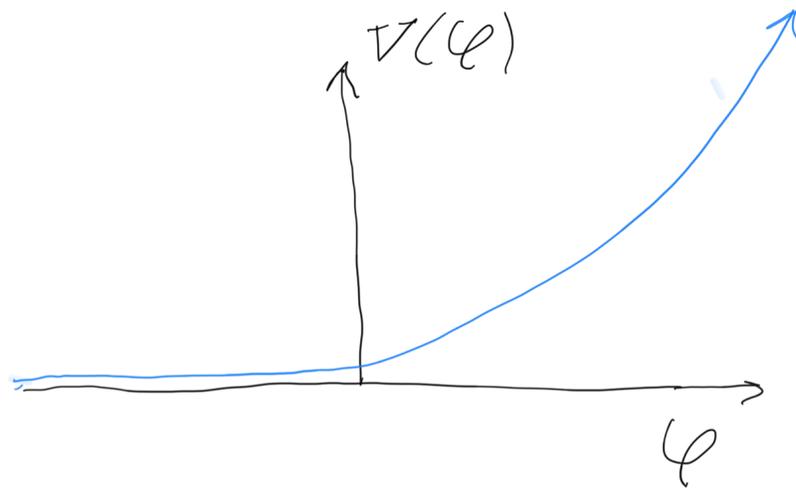
at late times (MK, Pradler & Walker, 2014)



$$V(\phi) \propto \left[ 1 - \cos\left(\frac{\phi}{f}\right) \right]^n$$

Or

(Karwal & MK 2016)



# Since then....tons of EDE models

## Early Dark Energy(s) & Modified Gravity

**Early dark energy, the Hubble-parameter tension, and the string axiverse**

Tanvi Karwal and Marc Kamionkowski  
Department of Physics and Astronomy, Johns Hopkins University,  
3400 N. Charles St., Baltimore, MD 21218  
(Dated: November 8, 2016)

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**Rock 'n' Roll Solutions to the Hubble Tension**

Prateek Agrawal<sup>1</sup>, Francis-Yan Cyr-Racine<sup>2,3</sup>, David Pinner<sup>1,3</sup>, and Lisa Randall<sup>1</sup>

<sup>1</sup>Department of Physics, Harvard University, 77 Oxford St., Cambridge, MA 02138, USA  
<sup>2</sup>Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Blvd NE, Albuquerque, NM 87131, USA  
<sup>3</sup>Department of Physics, Brown University, 183 Hope St., Providence, RI 02912, USA

**Not all have the same success...**

**Early Dark Energy Can Resolve The Hubble Tension**

Vivian Poulin<sup>1</sup>, Tristan L. Smith<sup>2</sup>, Tanvi Karwal<sup>1</sup>, and Marc Kamionkowski<sup>1</sup>

<sup>1</sup>Department of Physics and Astronomy, Johns Hopkins University,  
3400 N. Charles St., Baltimore, MD 21218, United States and  
<sup>2</sup>Department of Physics and Astronomy, Swarthmore College,  
500 College Ave., Swarthmore, PA 19081, United States

**Early dark energy from massive neutrinos — a natural resolution of the Hubble tension**

Jeremy Sakstein\* and Mark Trodden<sup>1</sup>  
Center for Particle Cosmology, Department of Physics and Astronomy,  
University of Pennsylvania 209 S. 33rd St., Philadelphia, PA 19104, USA

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**Dark Energy,  $H_0$  and Weak Gravity Conjecture**

Nemanja Kaloper<sup>a,1</sup>

<sup>a</sup>Department of Physics, University of California, Davis, CA 95616, USA

**Acoustic Dark Energy: Potential Conversion of the Hubble Tension**

Meng-Xiang Lin<sup>1</sup>, Giampaolo Benevento<sup>2,3,1</sup>, Wayne Hu<sup>1</sup> and Marco Raveri<sup>1</sup>

<sup>1</sup>Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics,  
Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA  
<sup>2</sup>Dipartimento di Fisica e Astronomia "G. Galilei",  
Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy  
<sup>3</sup>INFN, Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy

**Early dark energy from massive neutrinos — a natural resolution of the Hubble tension**

Jeremy Sakstein\* and Mark Trodden<sup>1</sup>  
Center for Particle Cosmology, Department of Physics and Astronomy,  
University of Pennsylvania 209 S. 33rd St., Philadelphia, PA 19104, USA

**Is the Hubble tension a hint of AdS around recombination?**

Gen Ye<sup>1,\*</sup> and Yun-Song Piao<sup>1,2†</sup>

<sup>1</sup>School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China and  
Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, Ch

**Early dark energy from massive neutrinos — a natural resolution of the Hubble tension**

Jeremy Sakstein\* and Mark Trodden<sup>1</sup>  
Center for Particle Cosmology, Department of Physics and Astronomy,  
University of Pennsylvania 209 S. 33rd St., Philadelphia, PA 19104, USA

**Thermal Friction as a Solution to the Hubble Tension**

Kim V. Berghaus<sup>1</sup> and Tanvi Karwal<sup>1,2</sup>

<sup>1</sup>Department of Physics and Astronomy, Johns Hopkins University,  
3400 N. Charles St., Baltimore, MD 21218, United States and  
<sup>2</sup>Center for Particle Cosmology, Department of Physics and Astronomy,  
University of Pennsylvania, 209 S. 33rd St., Philadelphia, PA 19104, United States  
(Dated: November 15, 2019)

**Scalar-tensor theories of gravity, neutrino physics, and the  $H_0$  tension**

Mario Ballardini,<sup>a,b,c,d,1</sup> Matteo Braglia,<sup>a,b,c</sup> Fabio Finelli,<sup>b,c</sup> Daniela Paoletti,<sup>b,c</sup> Alexei A. Starobinsky,<sup>c,2</sup> Caterina Umiltà<sup>3</sup>

**New Early Dark Energy**

Florian Niedermann<sup>1,\*</sup> and Martin S. Sloth<sup>1,†</sup>

<sup>CP<sup>3</sup>-Origins, Center for Cosmology and Particle Physics Phenomenology</sup>

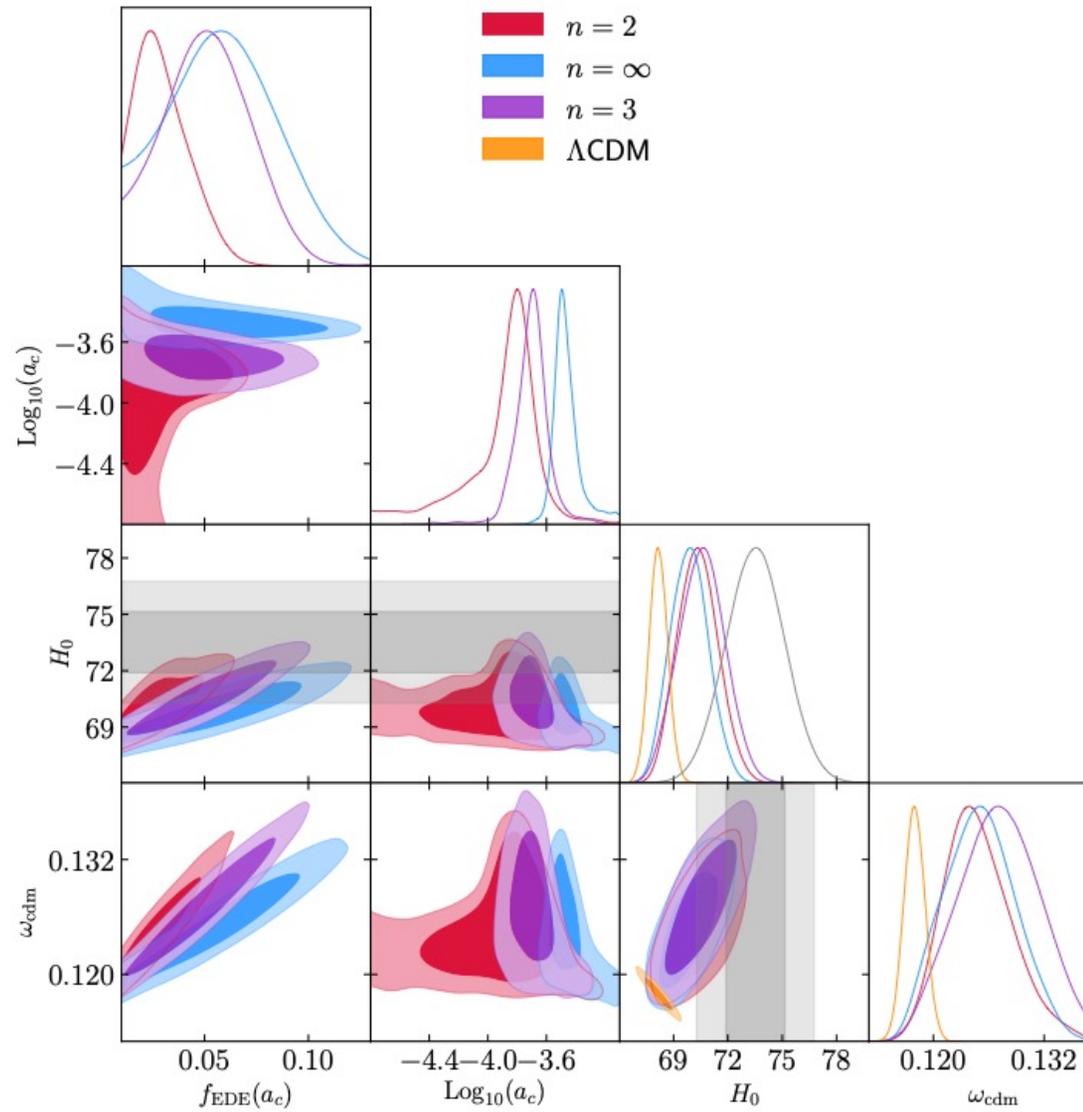
**Gravity in the Era of Equality: Towards solutions to the Hubble problem without fine-tuned initial conditions**

Miguel Zumalacárregui<sup>1,2,3,\*</sup>

<sup>1</sup>Max Planck Institute for Gravitational Physics (Albert Einstein Institute)  
Am Mühlenberg 1, D-14478 Potsdam-Golm, Germany  
<sup>2</sup>Berkeley Center for Cosmological Physics, LBNL and University of California at Berkeley,  
Berkeley, California 94720, USA  
<sup>3</sup>Institut de Physique Théorique, Université Paris Saclay CEA, CNRS, 91191 Gif-sur-Yvette, France  
(Dated: June 11, 2020)

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# Results of late-2018 data analysis



Poulin et al. 2018

New tests of scenario:

Measurements of fine-grain  
features of CMB polarization by  
ACTPol/SPT3G/Simons/CMB-  
S4/etc

# The Atacama Cosmology Telescope: Constraints on Pre-Recombination Early Dark Energy

J. Colin Hill<sup>1,2</sup> Erminia Calabrese<sup>3</sup> Simone Aiola<sup>2</sup> Nicholas Battaglia,<sup>4</sup> Boris Bolliet,<sup>1</sup> Steve K. Choi<sup>5,4</sup> Mark J. Devlin<sup>6</sup> Adriaan J. Duivenvoorden<sup>7</sup> Jo Dunkley<sup>8,7</sup> Simone Ferraro<sup>9,10</sup> Patricio A. Gallardo<sup>11</sup> Vera Gluscevic,<sup>12</sup> Matthew Hasselfield<sup>2</sup> Matt Hilton,<sup>13,14</sup> Adam D. Hincks<sup>15</sup> Renée Hložek<sup>15,16</sup> Brian J. Koopman<sup>17</sup> Arthur Kosowsky<sup>18</sup> Adrien La Posta,<sup>19</sup> Thibaut Louis,<sup>19</sup> Mathew S. Madhavacheril<sup>20,12</sup> Jeff McMahon,<sup>21,11,22,23</sup> Kavilan Moodley,<sup>13,14</sup> Sigurd Naess<sup>2</sup> Umberto Natale,<sup>3</sup> Federico Nati<sup>24</sup> Laura Newburgh,<sup>17</sup> Michael D. Niemack<sup>5,4,25</sup> Bruce Partridge,<sup>26</sup> Frank J. Qu,<sup>27</sup> Maria Salatino,<sup>28,29</sup> Alessandro Schillaci,<sup>30</sup> Neelima Sehgal<sup>31</sup> Blake D. Sherwin,<sup>27,32</sup> Cristóbal Sifón<sup>33</sup> David N. Spergel,<sup>2,8</sup> Suzanne T. Staggs<sup>7</sup> Emilie R. Storer,<sup>7</sup> Alexander van Engelen,<sup>34</sup> Eve M. Vavagiakis,<sup>5</sup> Edward J. Wollack<sup>35</sup> and Zhilei Xu<sup>36</sup>

<sup>1</sup>*Department of Physics, Columbia University, New York, NY 10027, USA*

<sup>2</sup>*Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*

<sup>3</sup>*School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, Wales CF24 3AA, UK*

<sup>4</sup>*Department of Astronomy, Cornell University, Ithaca, NY 14853, USA*

<sup>5</sup>*Department of Physics, Cornell University, Ithaca, NY 14853, USA*

<sup>6</sup>*Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA 19104, USA*

<sup>7</sup>*Department of Physics, Jadwin Hall, Princeton University, Princeton, NJ 08544, USA*

9 Sep 2021

Recent developments.....

EDE is not preferred by *Planck* CMB power spectrum data alone, which yield a 95% confidence level (CL) upper limit  $f_{\text{EDE}} < 0.087$  on the maximal fractional contribution of the EDE field to the cosmic energy budget. ~~In this paper, we fit the EDE model to CMB data from the Atacama Cosmology Telescope (ACT) Data Release 4. We find that a combination of ACT, large-scale *Planck* TT (similar to *WMAP*), *Planck* CMB lensing, and BAO data prefers the existence of EDE at > 99.7% CL:  $f_{\text{EDE}} = 0.091^{+0.020}_{-0.036}$ , with  $H_0 = 70.9^{+1.0}_{-2.0}$  km/s/Mpc (both 68% CL). From a model-selection standpoint, we find that EDE is favored over  $\Lambda$ CDM by these data at roughly  $3\sigma$  significance. In contrast, a joint analysis of the full *Planck* and ACT data yields no evidence for EDE, as previously found for *Planck* alone. We show that the preference for EDE in ACT alone is driven by its TE and EE power spectrum data. The tight constraint on EDE from *Planck* alone is driven by its high- $\ell$  TT power spectrum data. Understanding whether these differing constraints are physical in nature, due to systematics, or simply a rare statistical fluctuation is of high priority. The best-fit EDE models to ACT and *Planck* exhibit coherent differences across a wide range of multipoles in TE and EE, indicating that a powerful test of this scenario is anticipated with near-future data from ACT and other ground-based experiments.~~

Recent developments.....



## Needs:

More small-scale CMB polarization data

Independent local measurements

GWs

lensing time delays

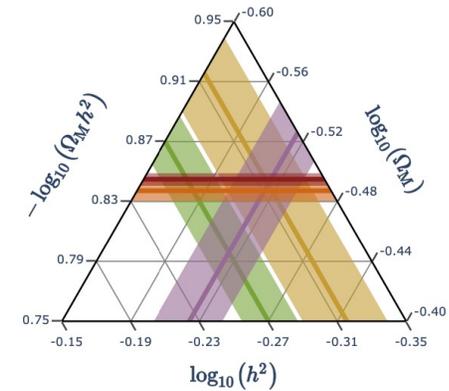
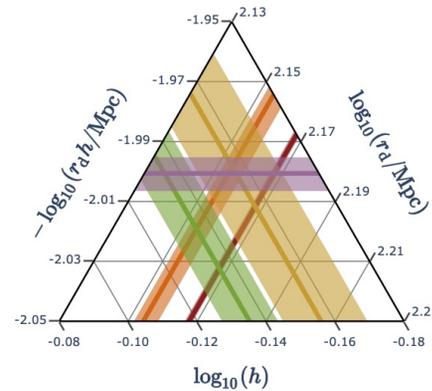
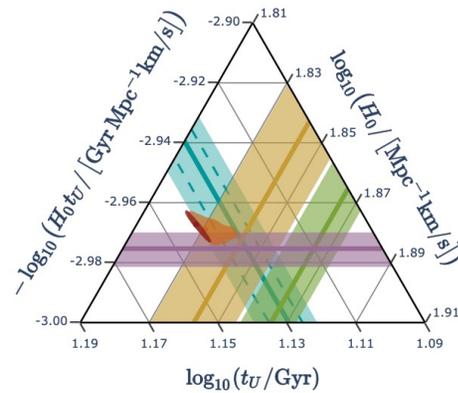
TRGB

stellar ages

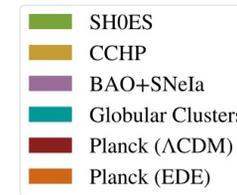
.....

# Cosmic chronometers (Globular-cluster ages)

Loeb & Jimenez 2002;  
Stern et al. 2009;  
Moresco et al. 2012



Cosmic triangles  
(Bernal et al. 2021)



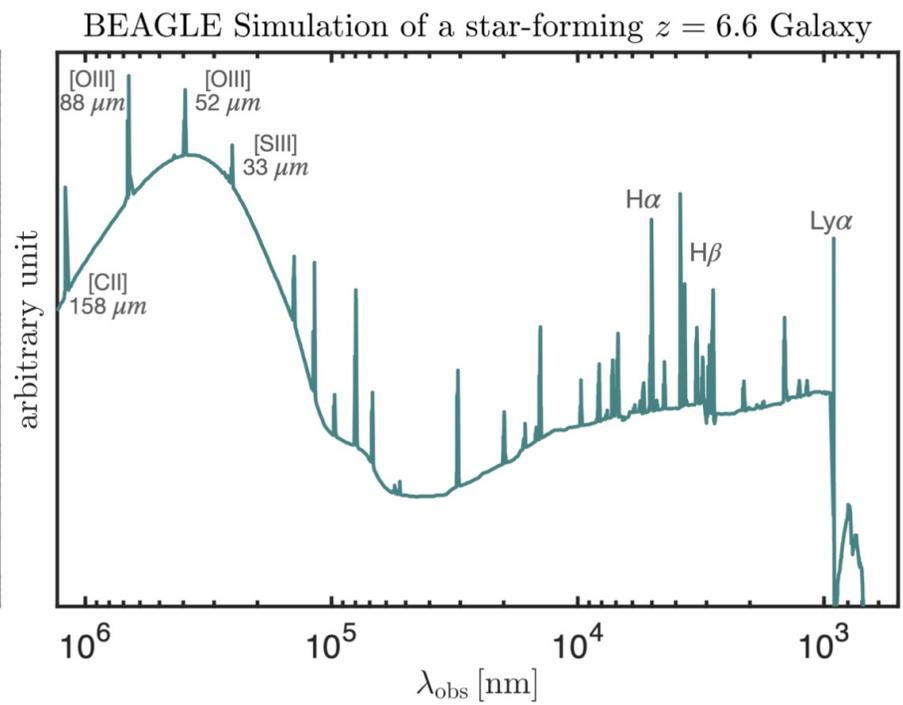
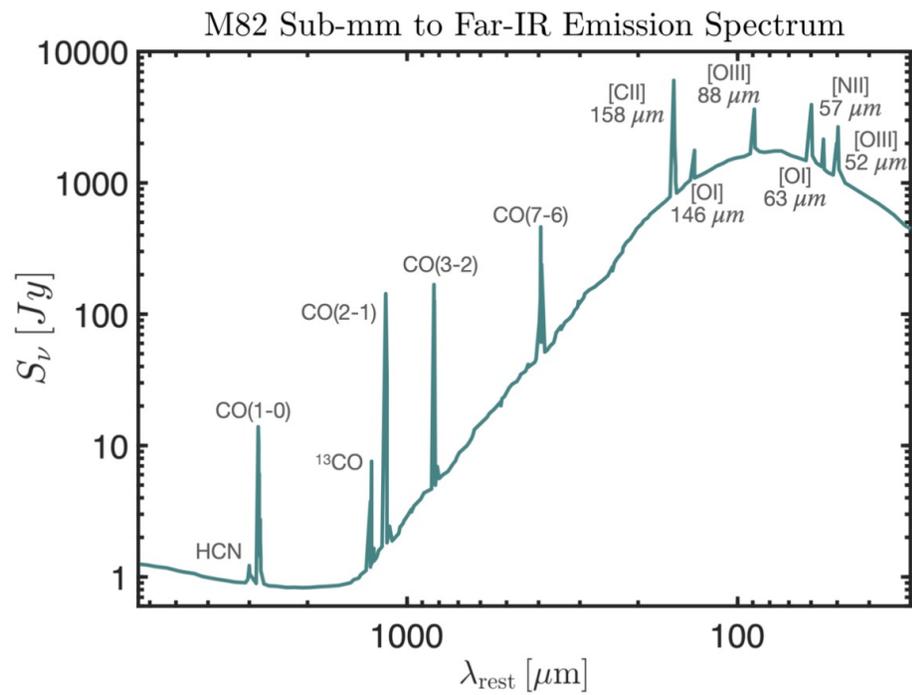
$$t(z) = \frac{1}{H_0} \int_z^\infty \frac{dz}{(1+z) \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)}}$$

## 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

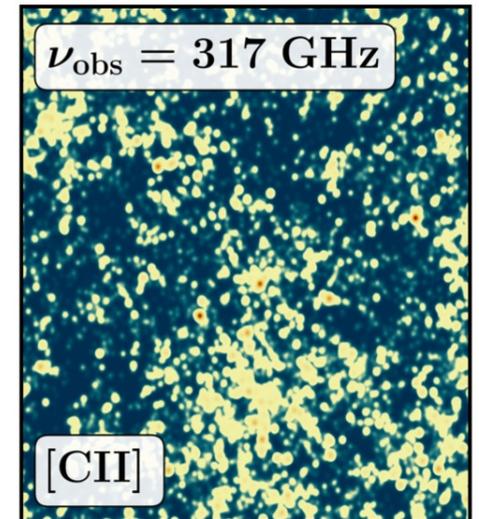
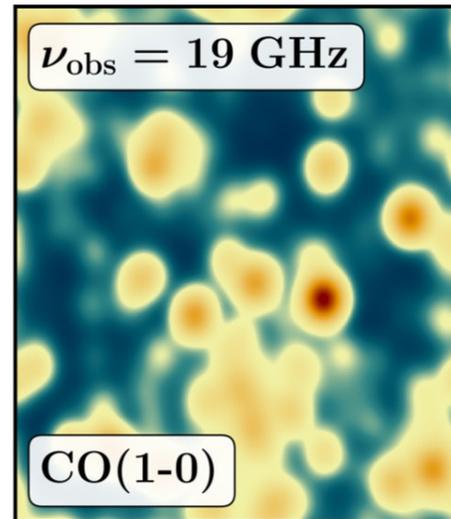
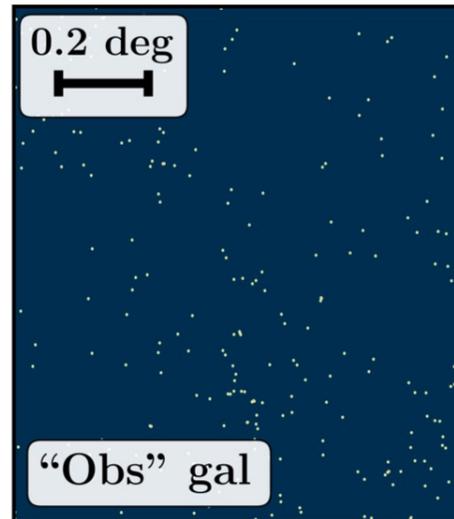
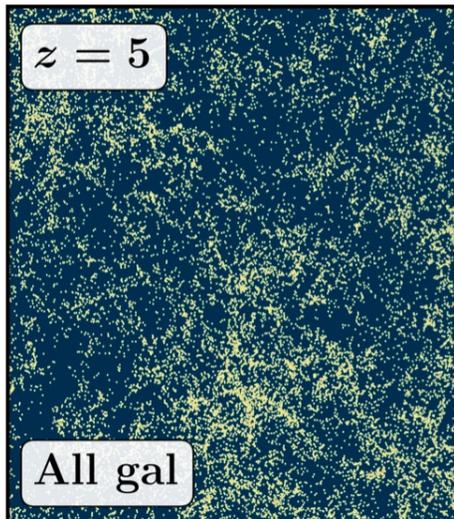
Reviews/refs: Kovetz et al., 1709.09066; Bernal, Breysse, Gil-Marín, Kovetz, arXiv:1907.10067; *Bernal & Kovetz, in preparation*

# Emission lines

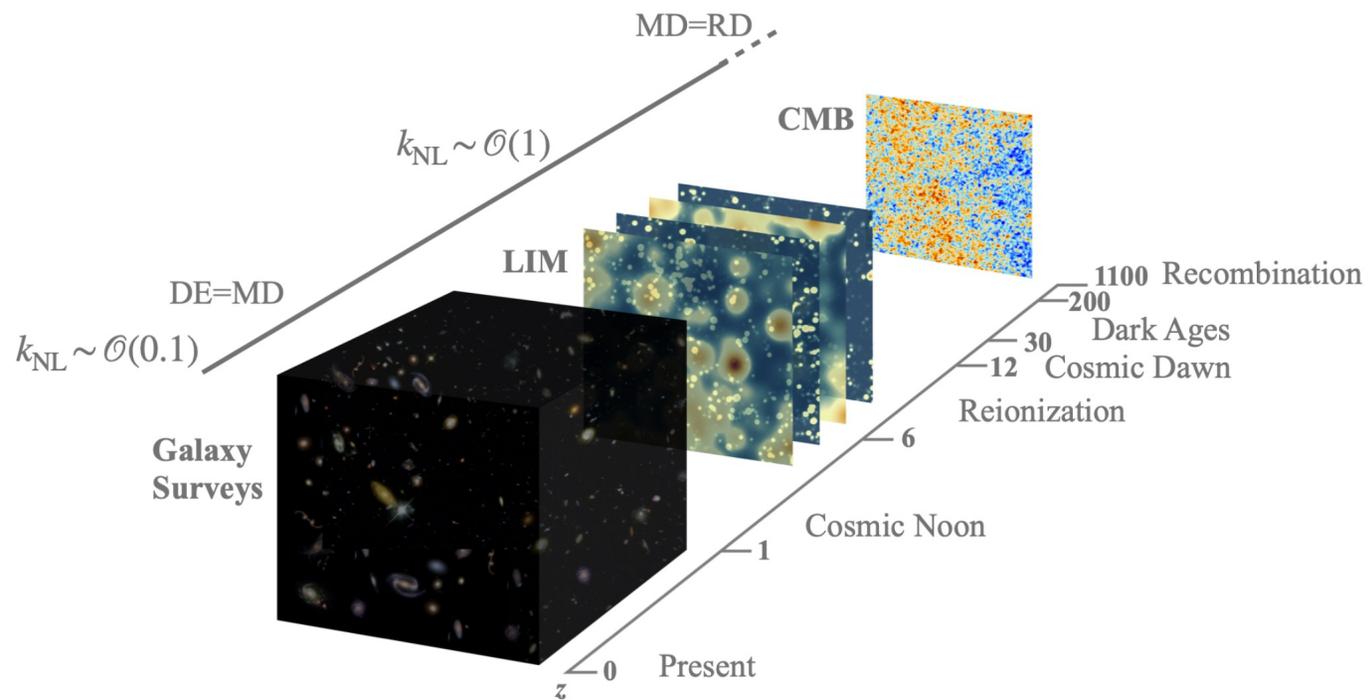


Galaxy surveys: detailed distribution of brightest galaxies

Intensity maps: noisy distribution of all galaxies and IGM

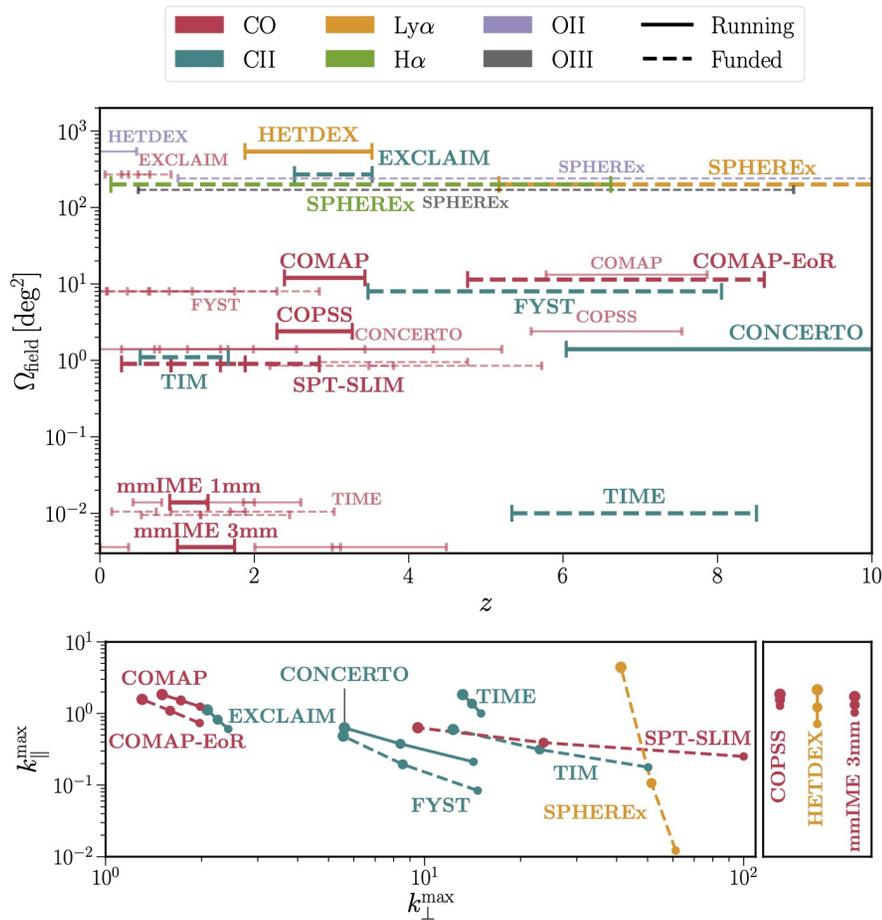


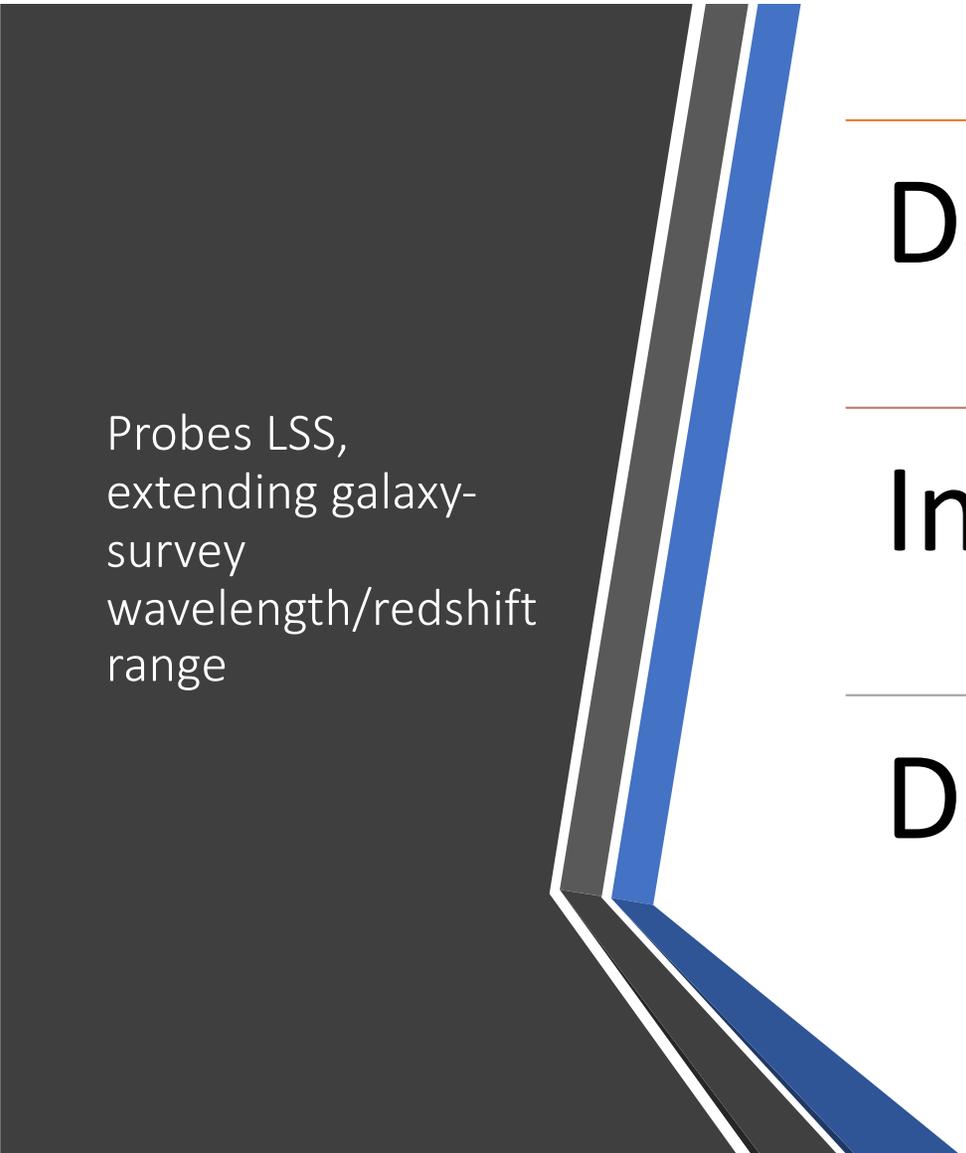
# Probing the Universe



# Probing the Universe with LIM

- Exciting experimental landscape!





Probes LSS,  
extending galaxy-  
survey  
wavelength/redshift  
range

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Dark energy

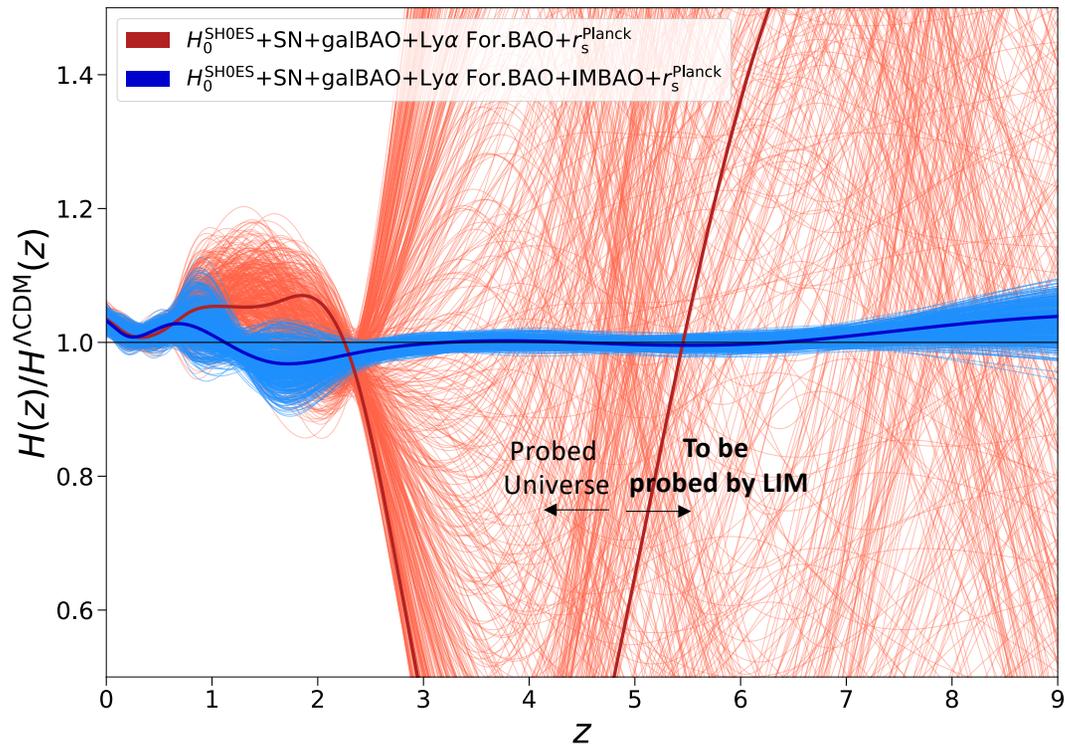
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Inflation

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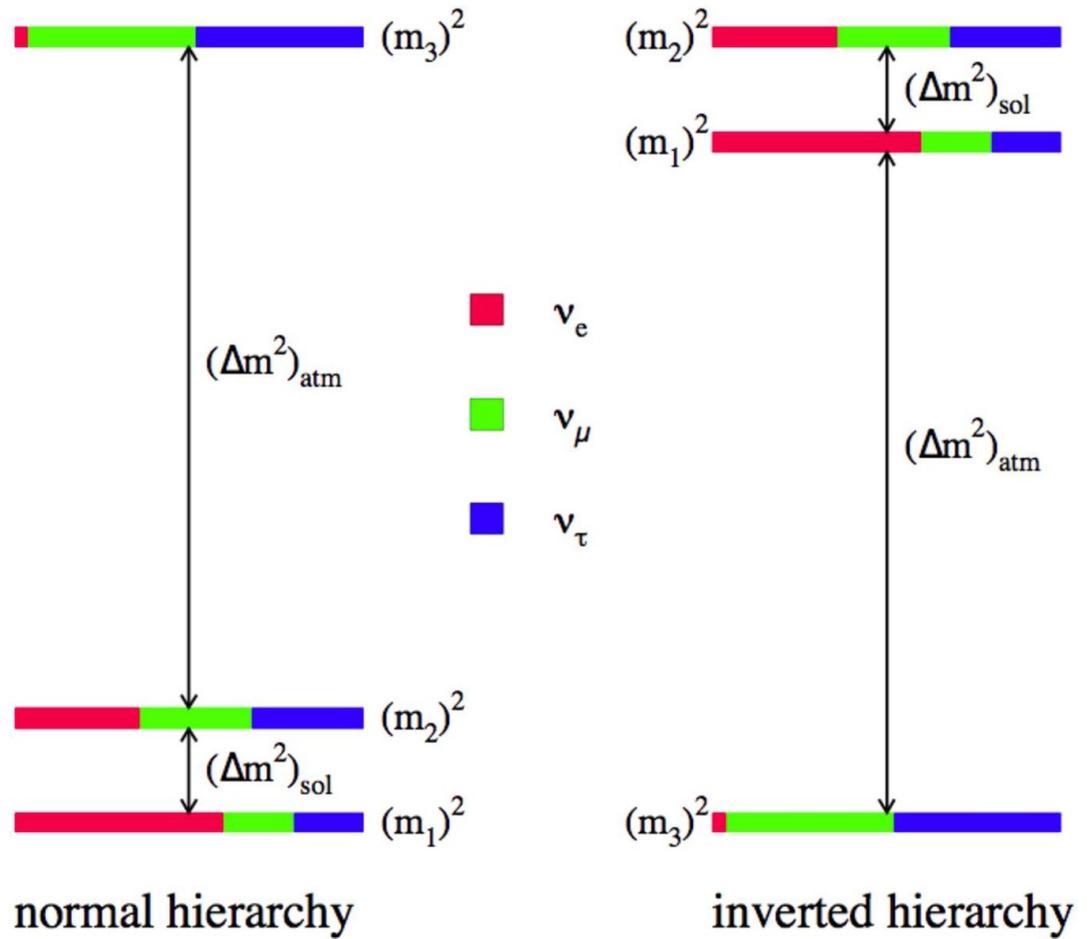
Dark-matter physics

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



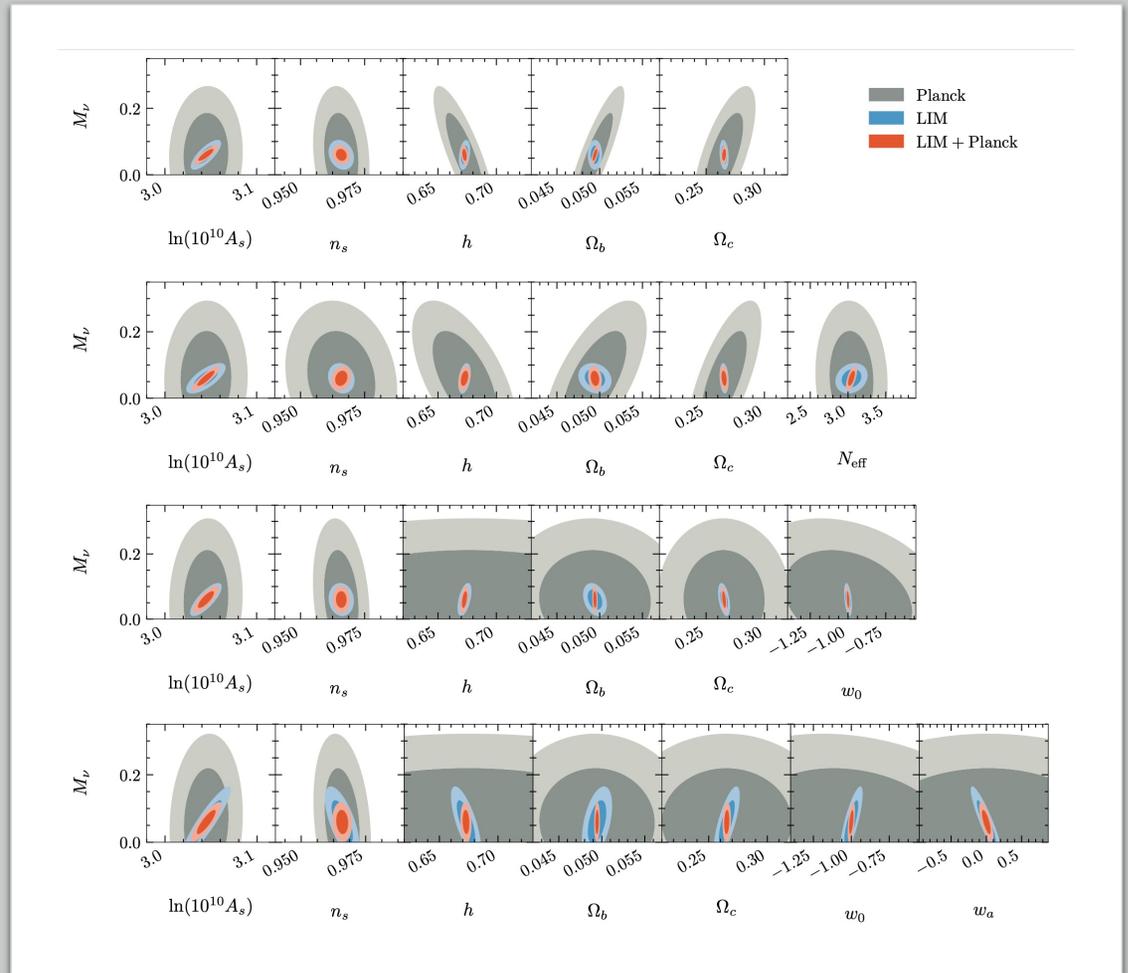
Bernal, Breyse, Kovetz 2019

# Neutrino masses



# Neutrino masses:

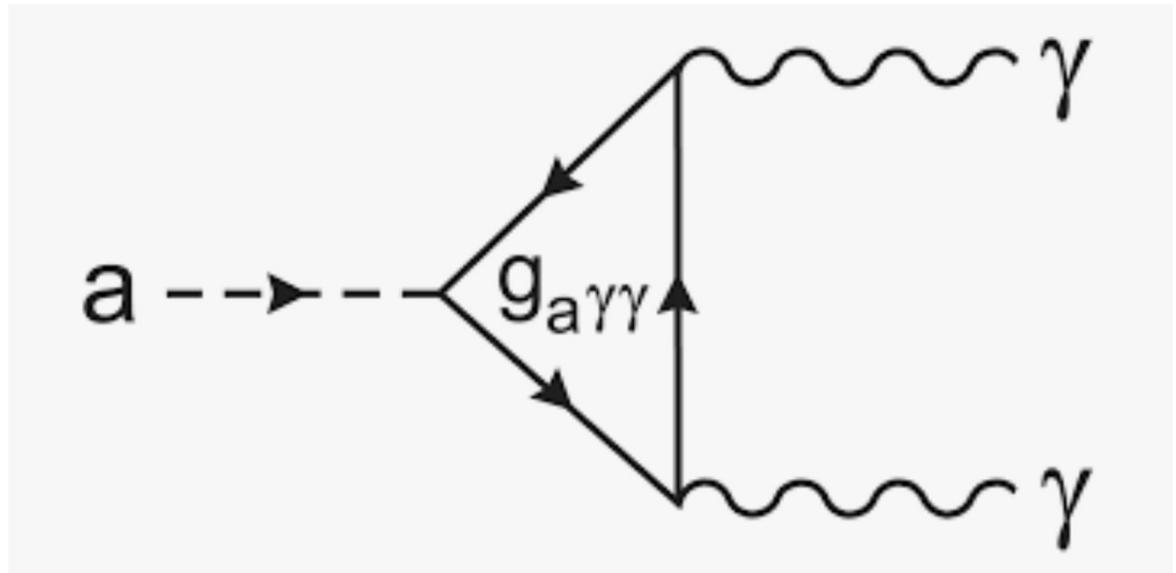
- Dizgah et al.,  
arXiv:2110.00014



Can also seek photon lines from  
radiative dark-matter/neutrino  
decay/annihilation

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

Dark-matter  
and  
neutrino  
decay (and  
annihilation)  
lines from  
IM

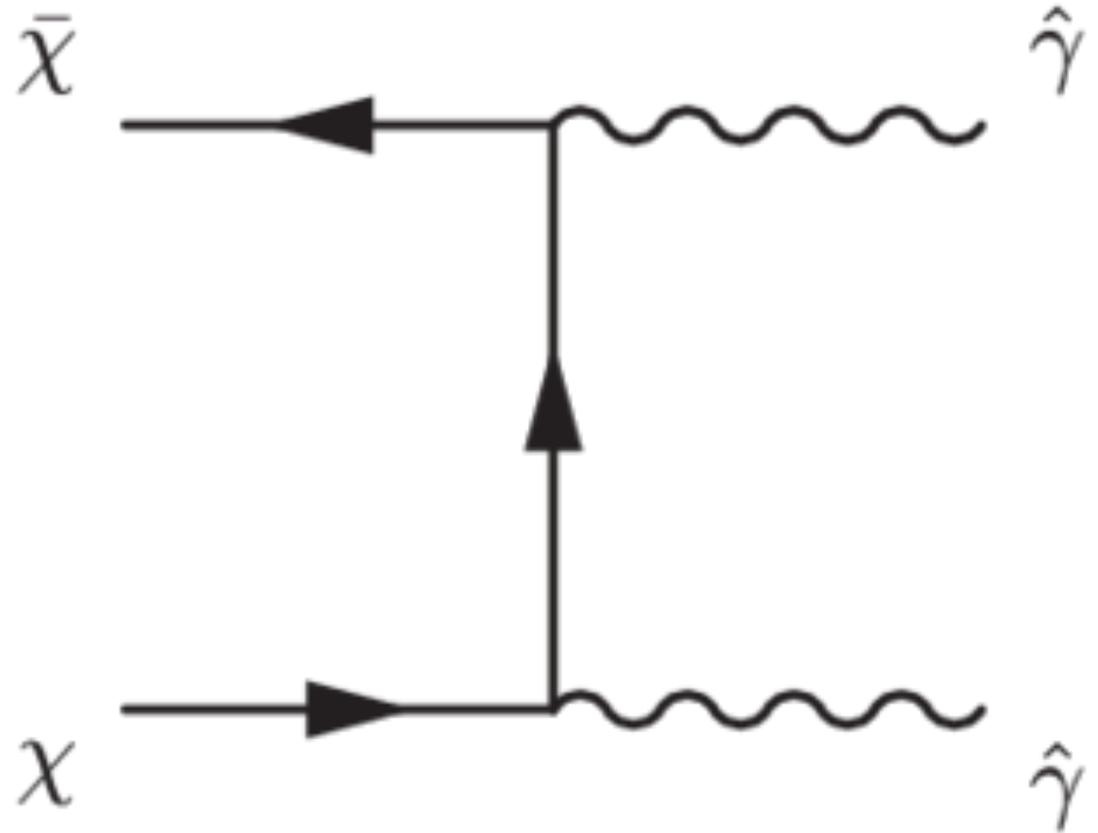


- Axion decay

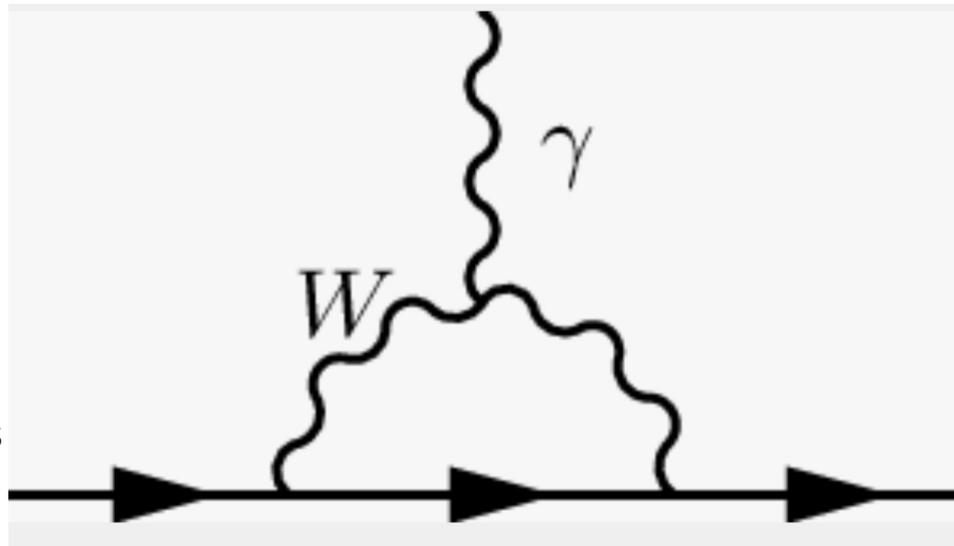
Dark-matter and  
neutrino decay (and  
annihilation) lines from  
IM

---

- Dark matter annihilation



# Neutrino decay



Parameterized by (transition) magnetic moment

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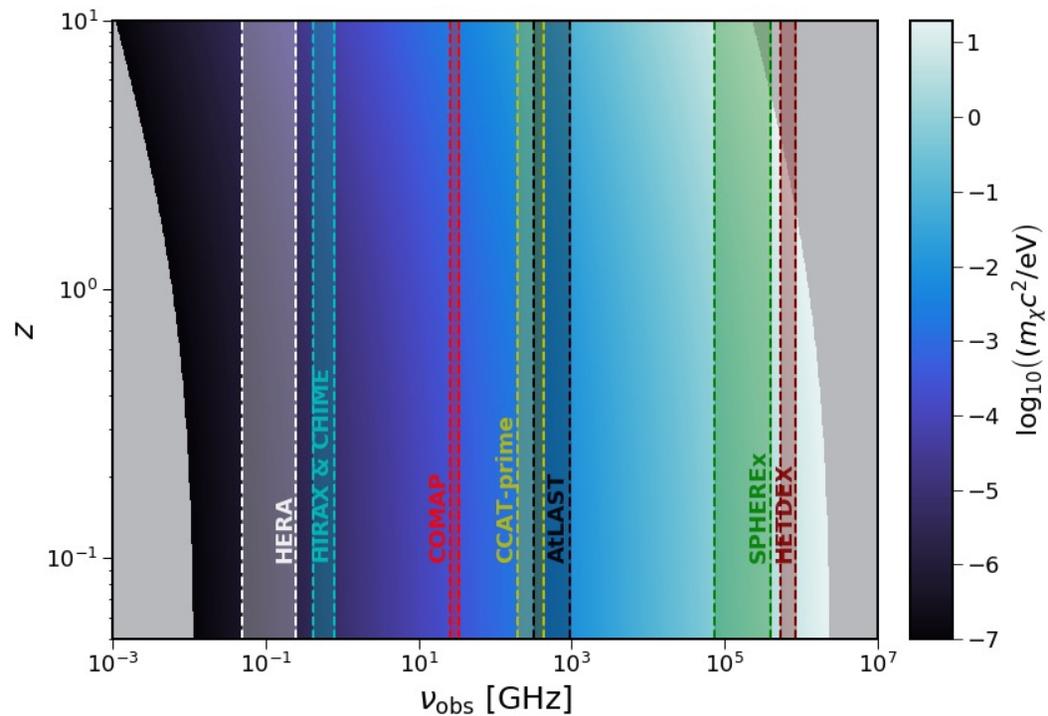
Decay/annihilation  
line is  
unbiased/biased  
tracer of dark-  
matter distribution  
→ should cross-  
correlate with LSS



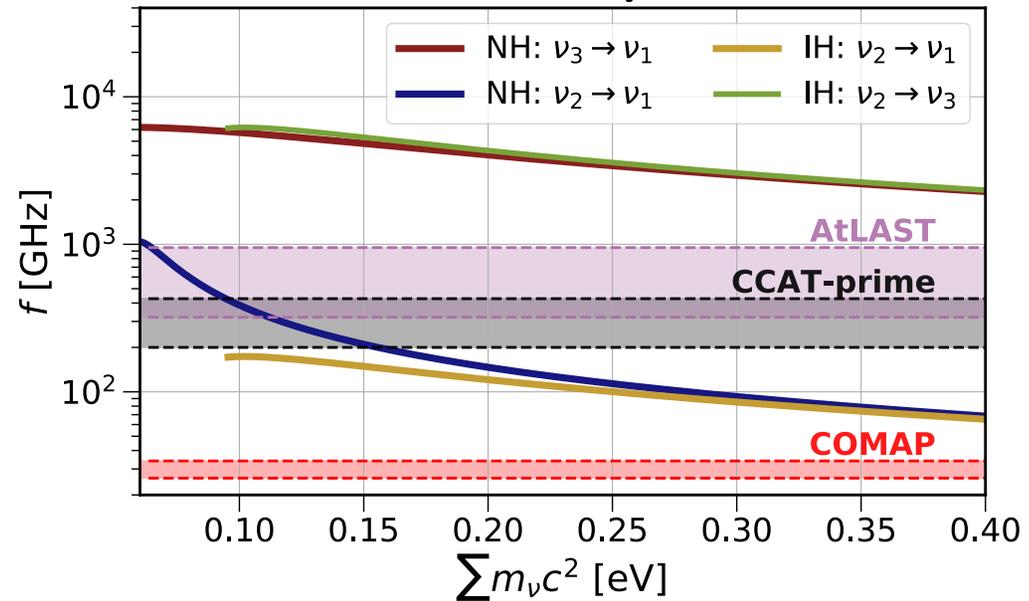
# Exotic radiative decays

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

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



# Exotic radiative decays



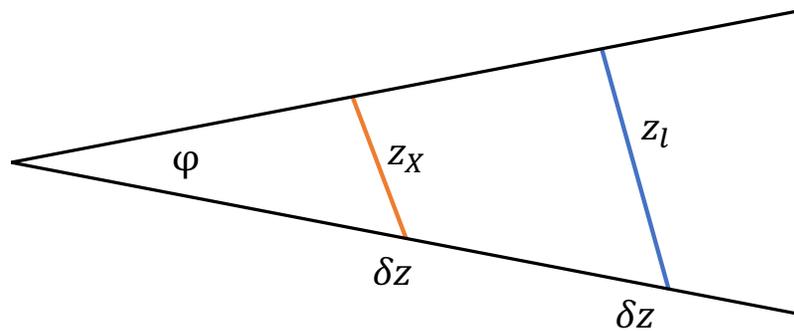
- Neutrino decay:  $\nu_i \rightarrow \nu_j + \gamma$

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

- Traces directly the cosmic neutrino density field

# How to distinguish from astrophysical line

- Clustering anisotropy



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

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

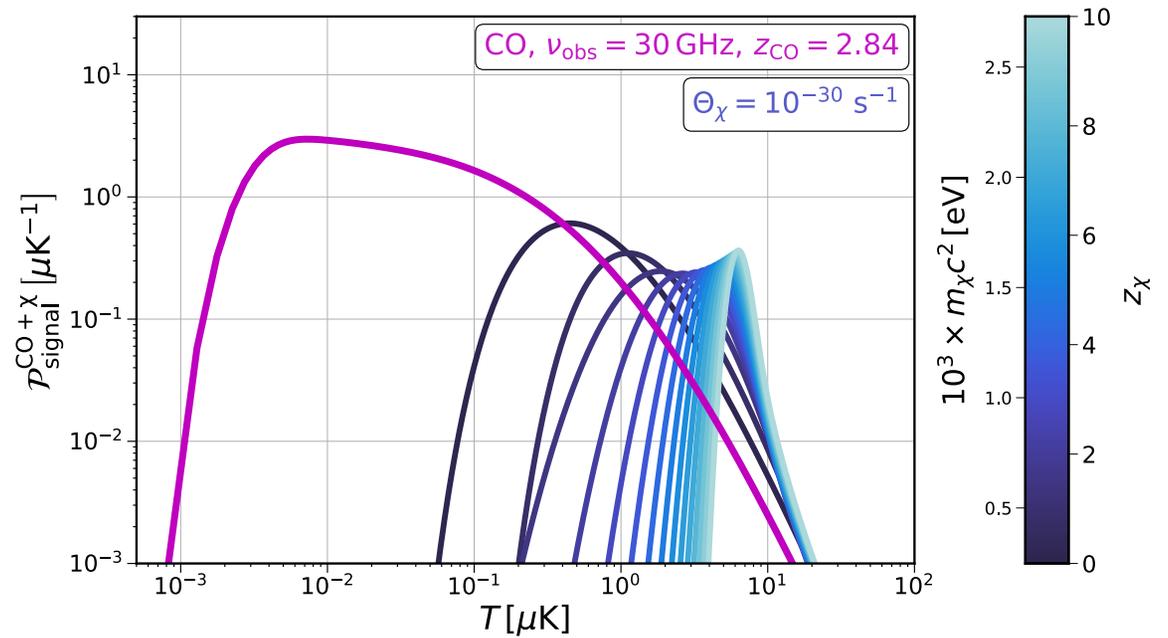
# Voxel intensity distribution

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- PDF of normalized densities. Obtained from simulations
- We provide the first analytic fit to  $\mathcal{P}_{\tilde{\rho}_v}$ , using Quijote simulations and symbolic regression

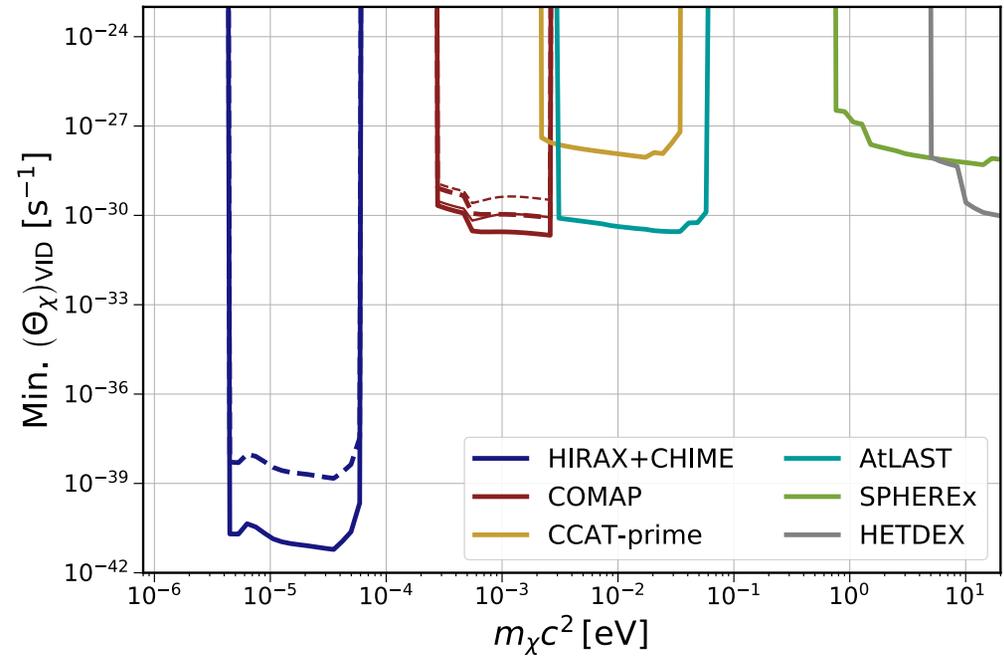
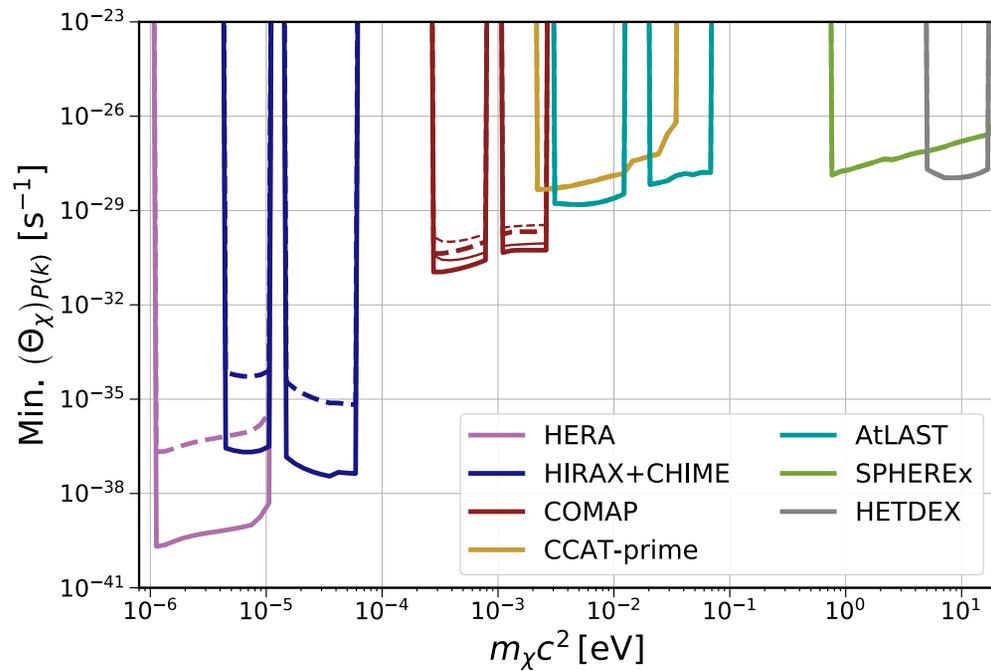
# Effect in VID

- Each voxel receives contributions from both emissions:



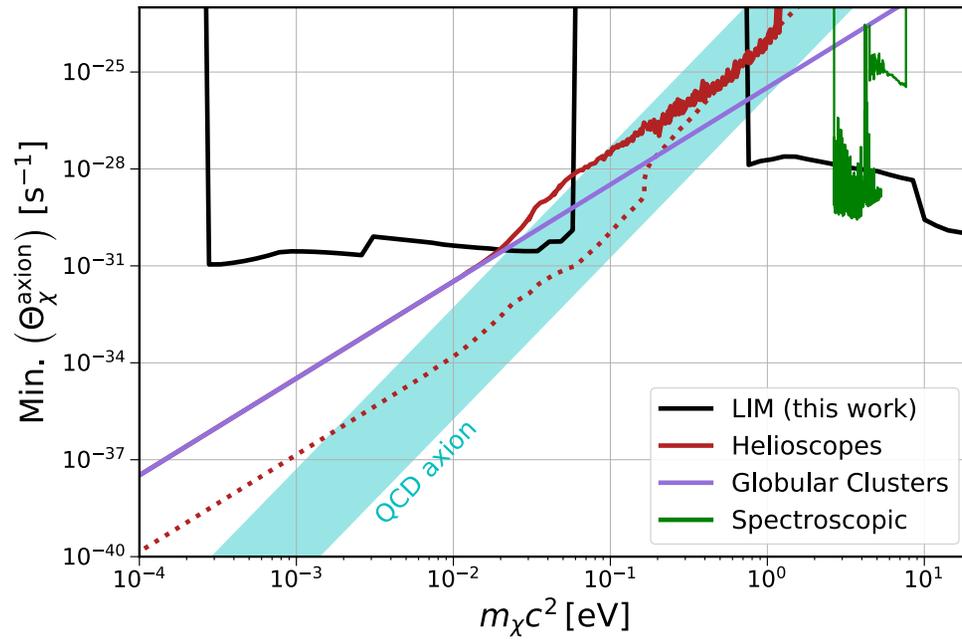
# Sensitivity to DM decays

- After marginalizing over astrophysical uncertainties of the target emission line

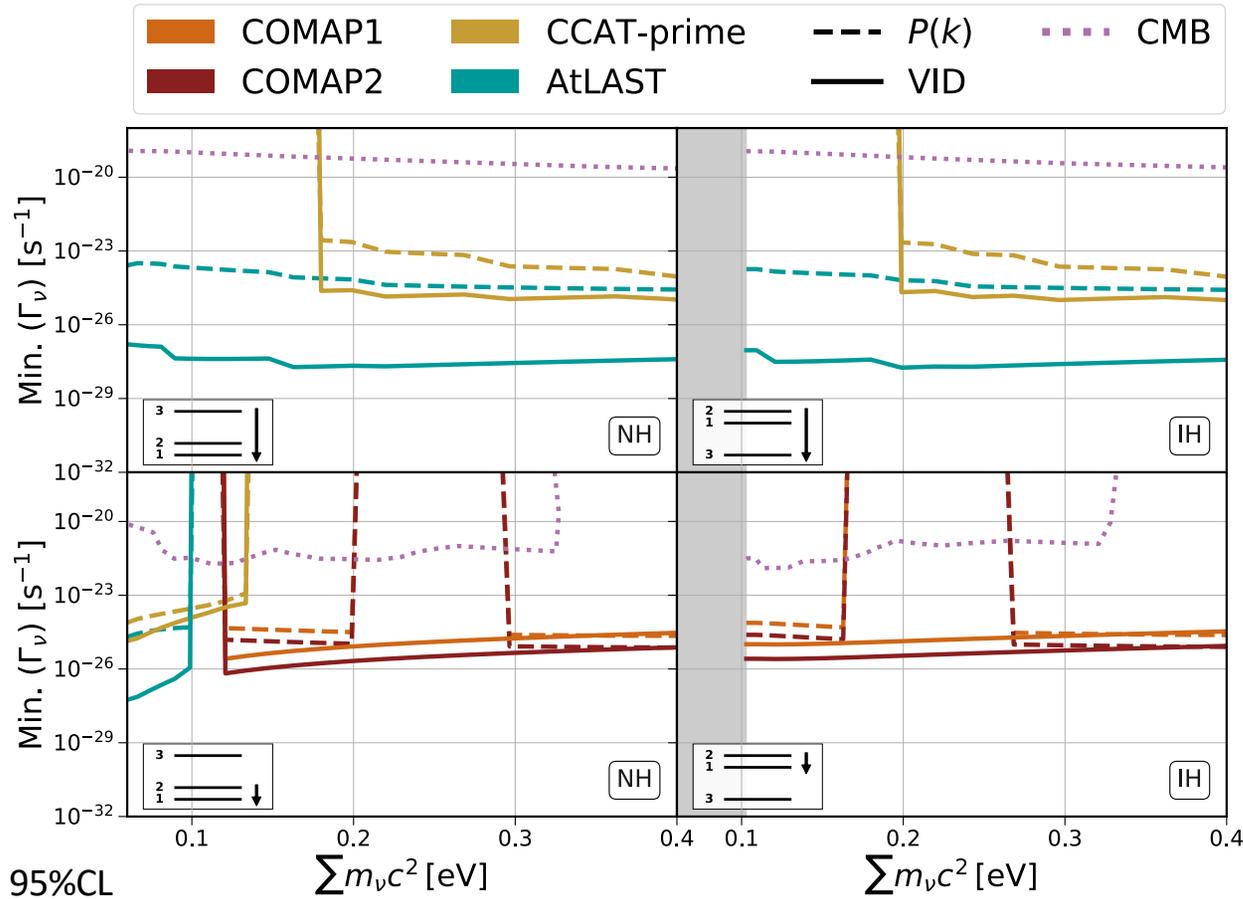


95%CL

# Sensitivity to axions



# Sensitivities to neutrino decay

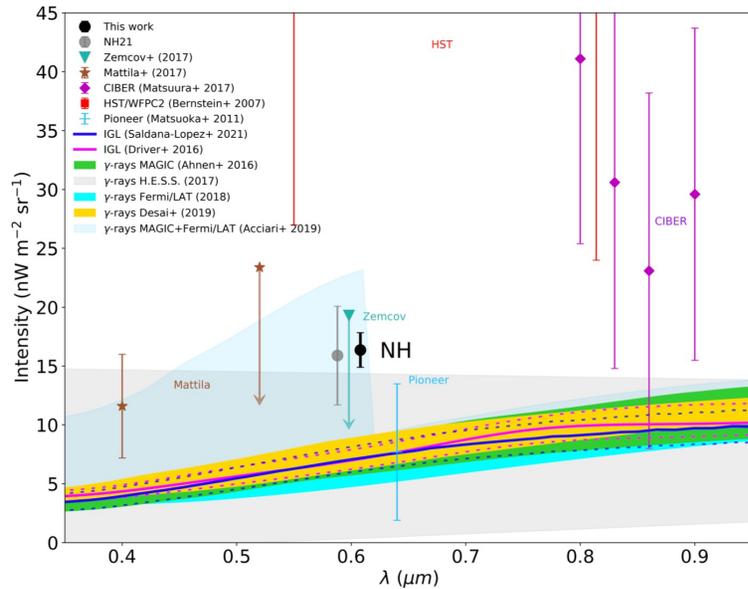


$$\Gamma_{ij} \sim 10^{-28} - 10^{-25} s^{-1}$$

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

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

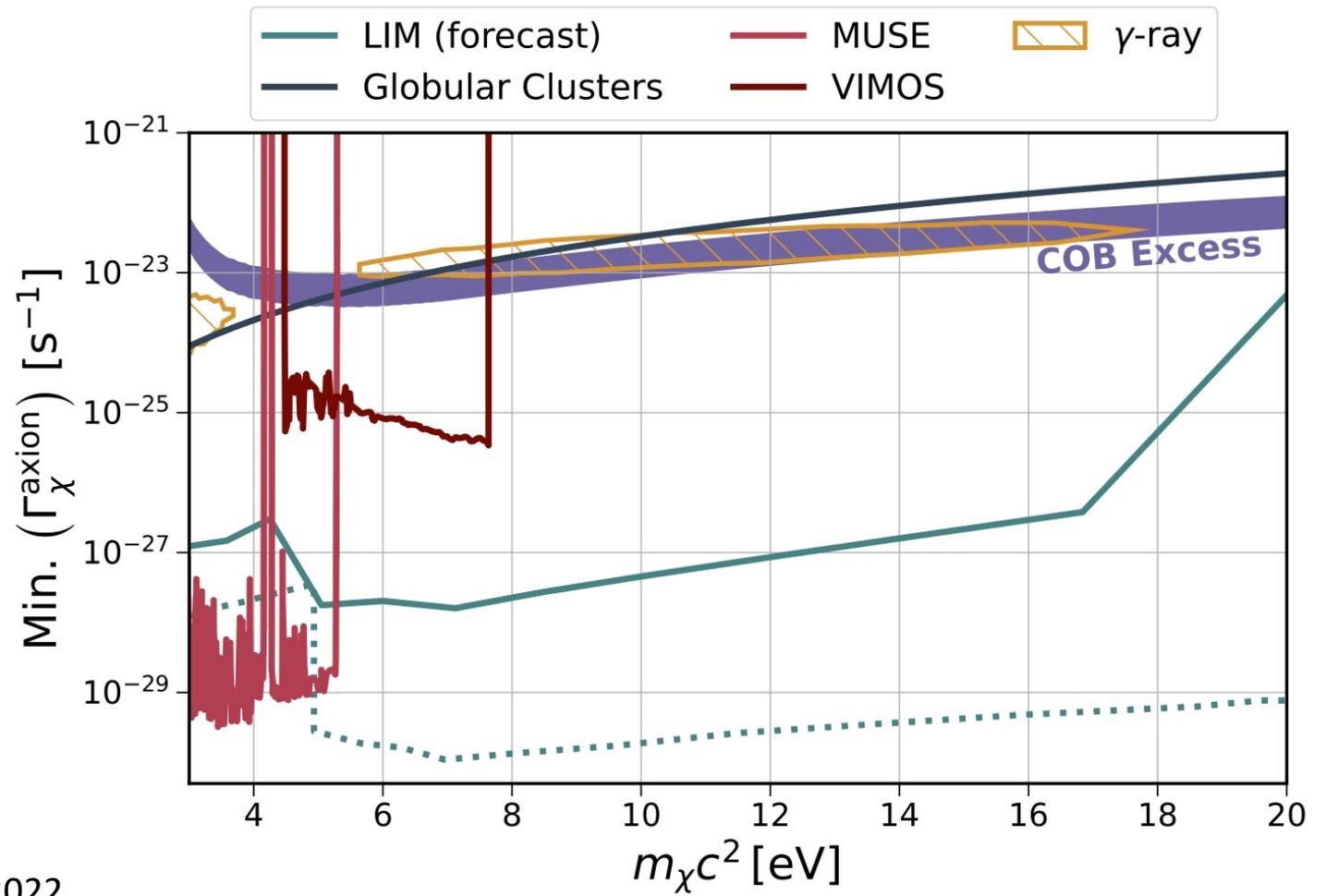
# Recent development.....



DRAFT VERSION FEBRUARY 10, 2022  
Typeset using L<sup>A</sup>T<sub>E</sub>X twocolumn style in AASTeX63

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

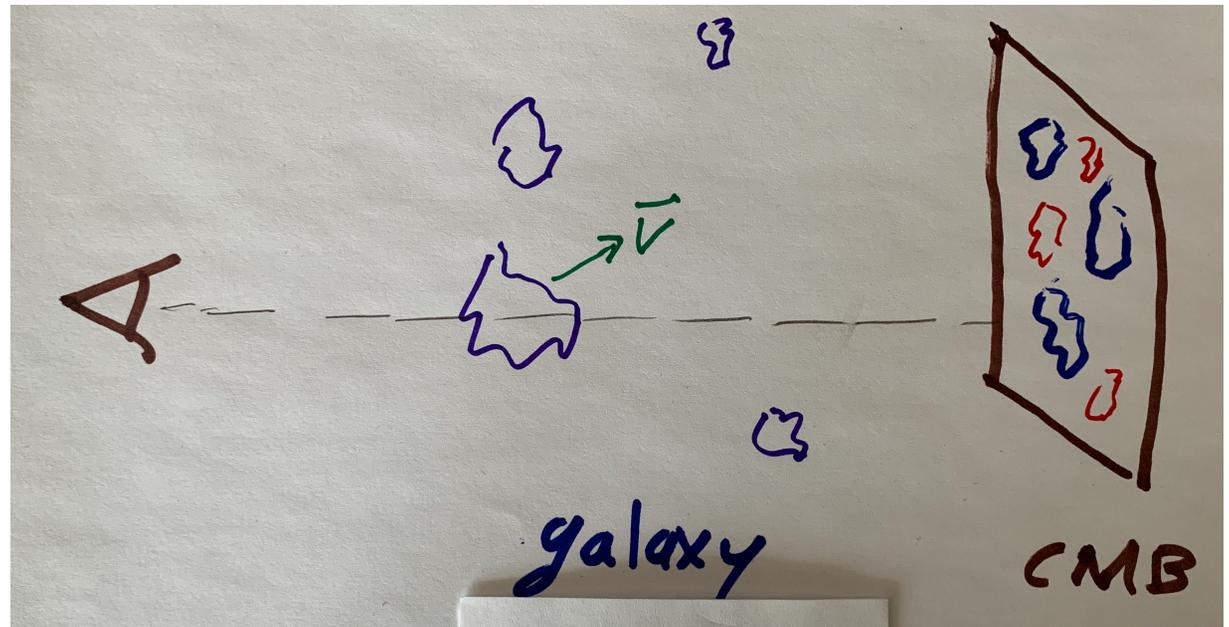
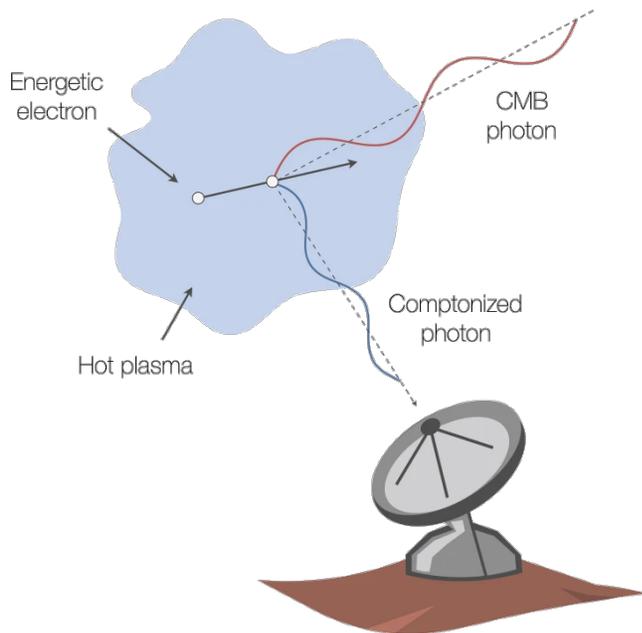
TOD R. LAUER,<sup>1</sup> MARC POSTMAN,<sup>2</sup> JOHN R. SPENCER,<sup>3</sup> HAROLD A. WEAVER,<sup>4</sup> S. ALAN STERN,<sup>5</sup>  
G. RANDALL GLADSTONE,<sup>6,7</sup> RICHARD P. BINZEL,<sup>8</sup> DANIEL T. BRITT,<sup>9</sup> MARC W. BUIE,<sup>3</sup> BONNIE J. BURATTI,<sup>10</sup>  
ANDREW F. CHENG,<sup>4</sup> W.M. GRUNDY,<sup>11</sup> MIHALY HORÁNYI,<sup>12</sup> J.J. KAVELAARS,<sup>13</sup> IVAN R. LINSOTT,<sup>14</sup> CAREY M. LISSE,<sup>4</sup>  
WILLIAM B. MCKINNON,<sup>15</sup> RALPH L. MCNUTT,<sup>4</sup> JEFFREY M. MOORE,<sup>16</sup> JORGE I. NÚÑEZ,<sup>4</sup> CATHERINE B. OLKIN,<sup>3</sup>  
JOEL W. PARKER,<sup>3</sup> SIMON B. PORTER,<sup>3</sup> DENNIS C. REUTER,<sup>17</sup> STUART J. ROBBINS,<sup>3</sup> PAUL M. SCHENK,<sup>18</sup>  
MARK R. SHOWALTER,<sup>19</sup> KELSI N. SINGER,<sup>3</sup> ANNE. J. VERBISER,<sup>20</sup> AND LESLIE A. YOUNG<sup>3</sup>

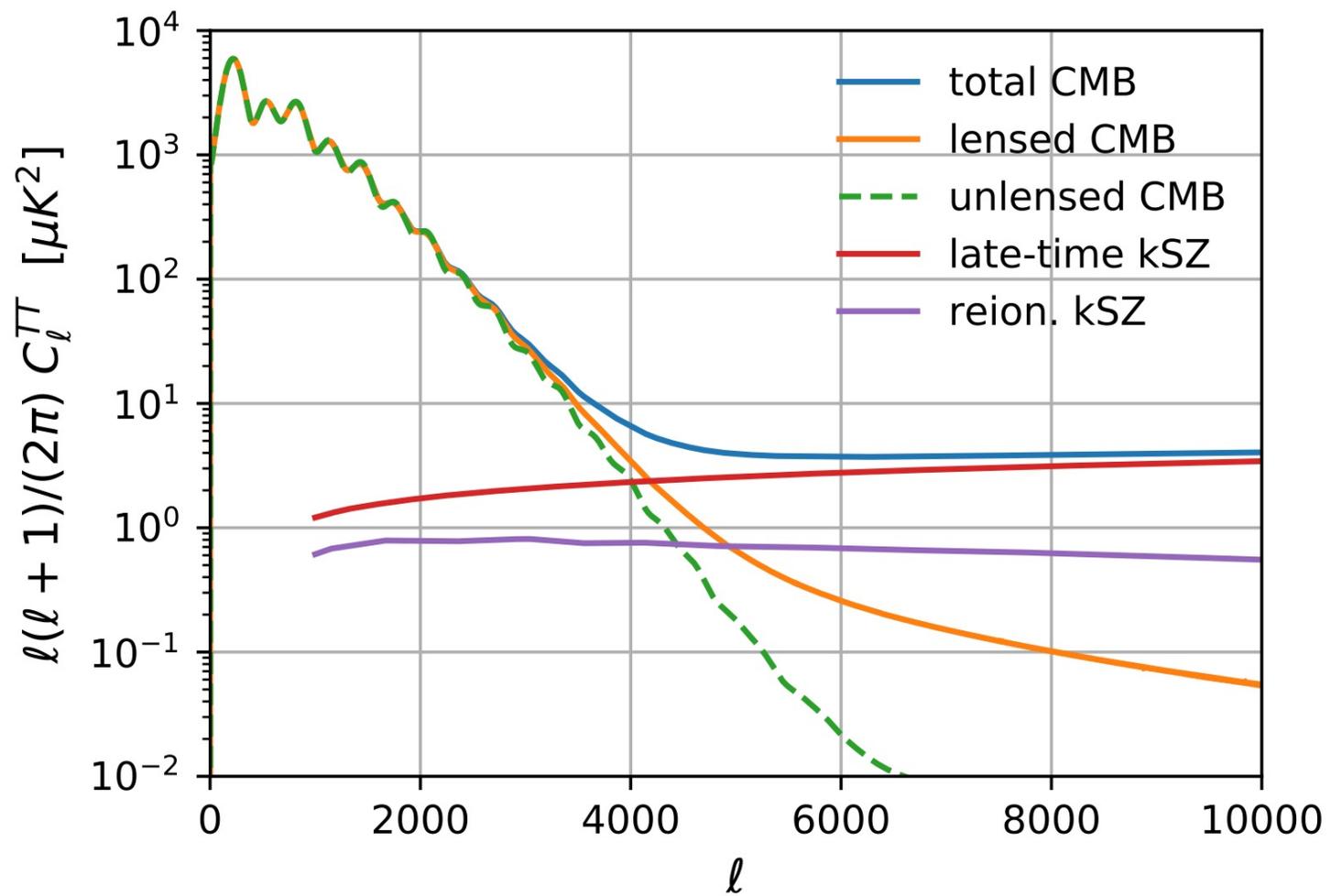


Bernal, Sato-Polito, MK, 2022

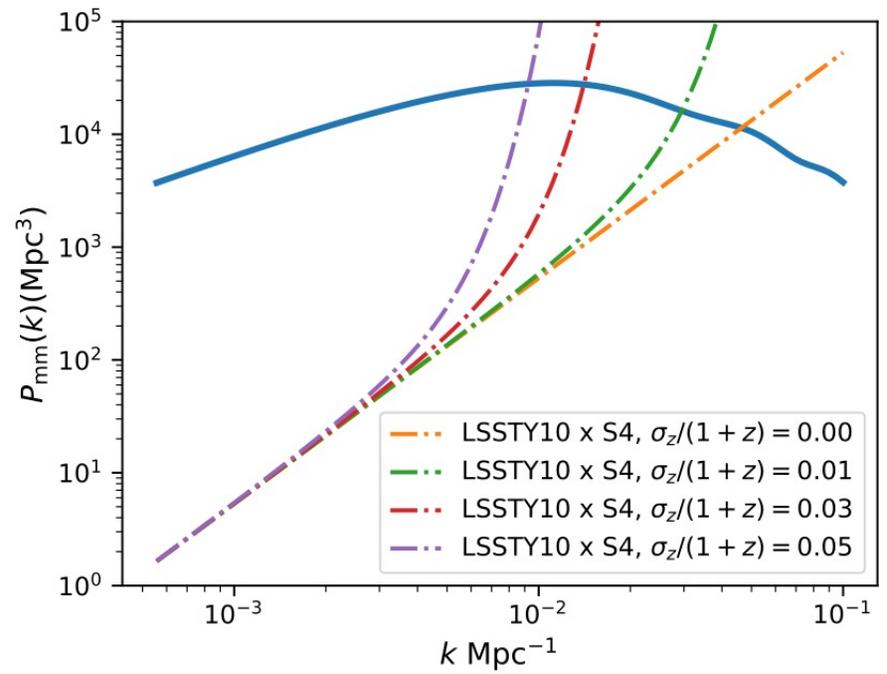
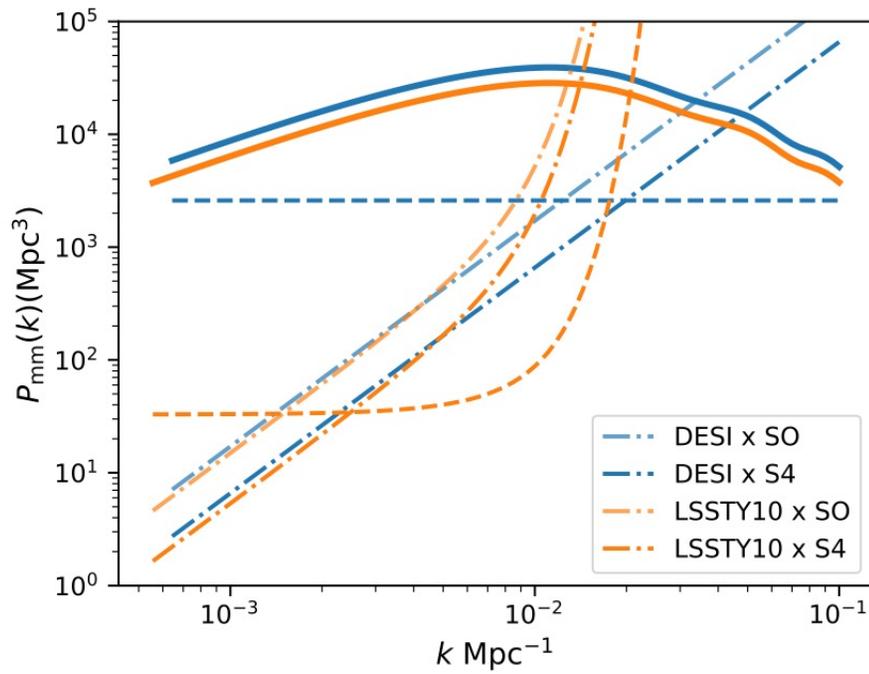
### III. Kinetic-Sunyaev-Zeldovich tomography: new probe of 3d *mass* distribution

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



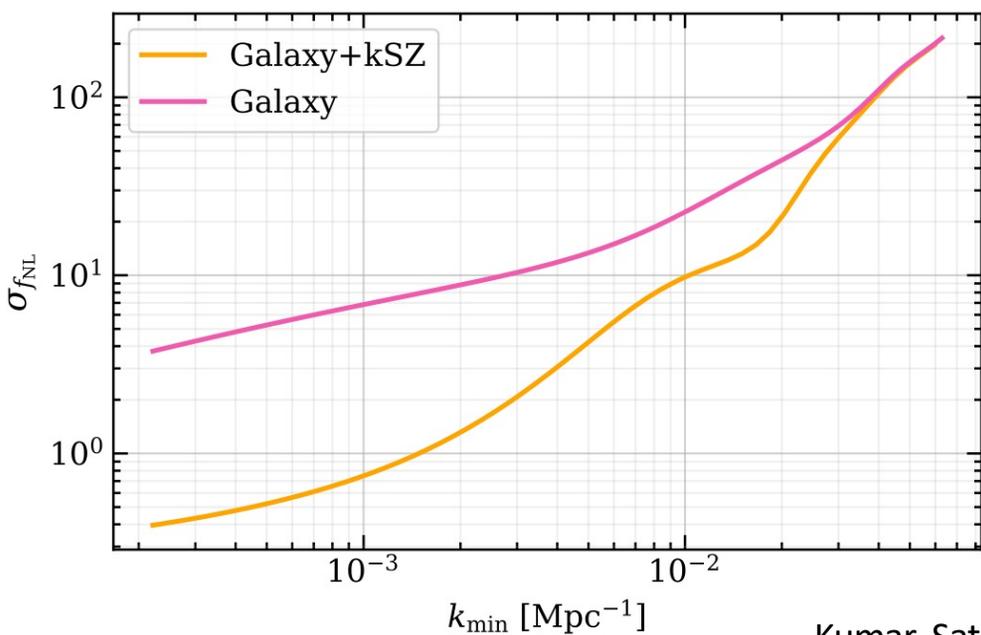


# matter power spectrum (Smith et al. arXiv:1810.13423)

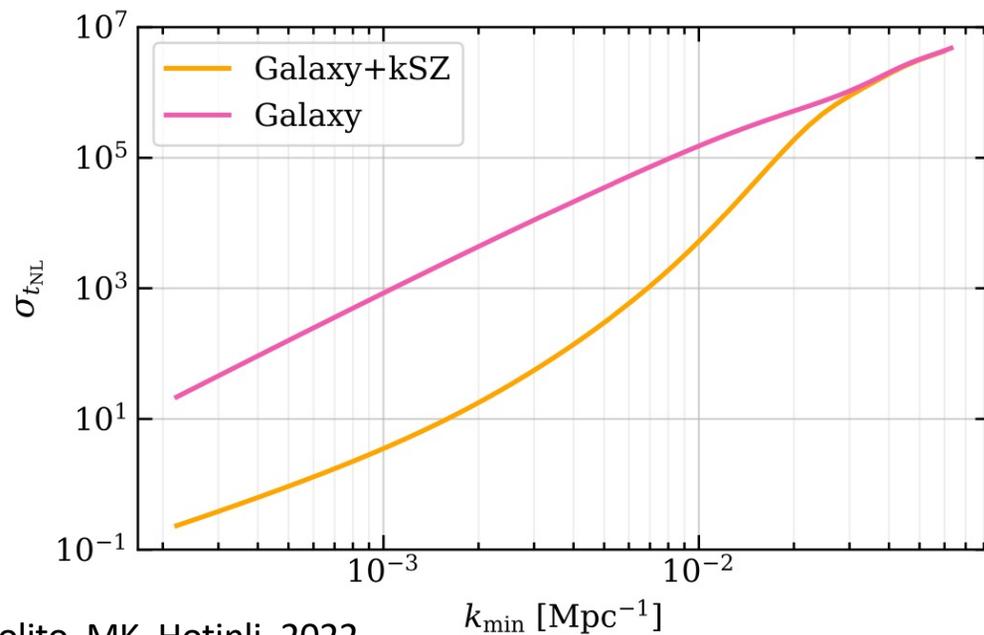


# Can compare matter and galaxy distributions *independently*

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

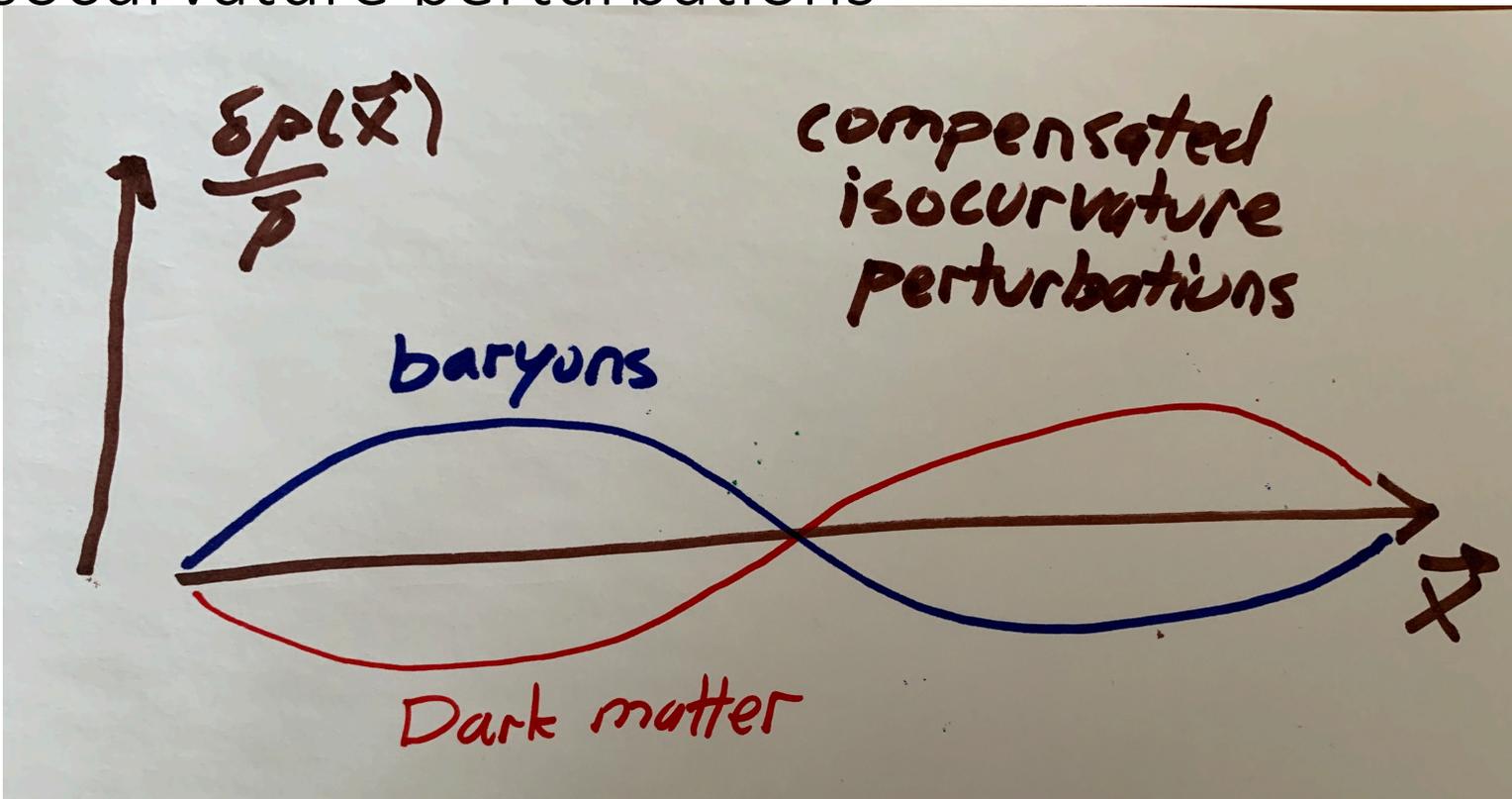


Kumar, Sato-Polito, MK, Hotinli, 2022

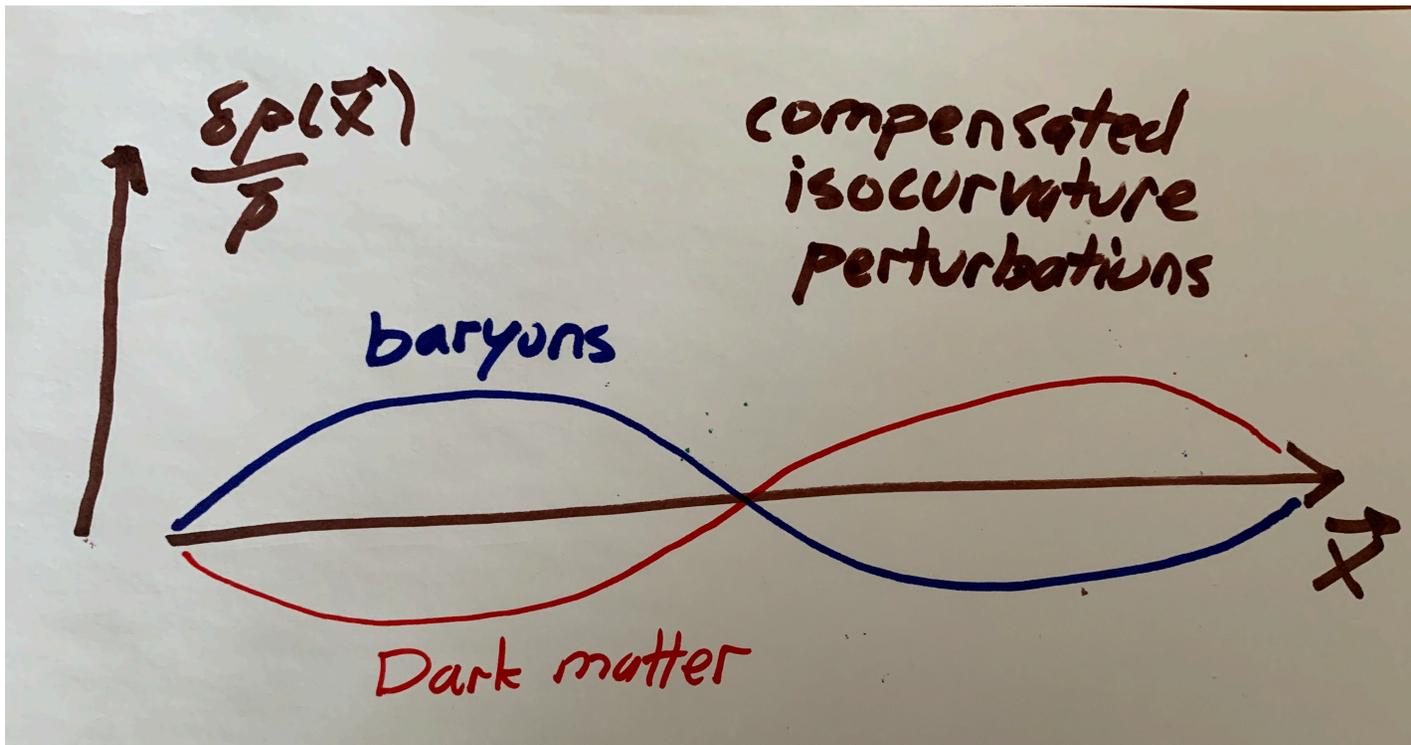


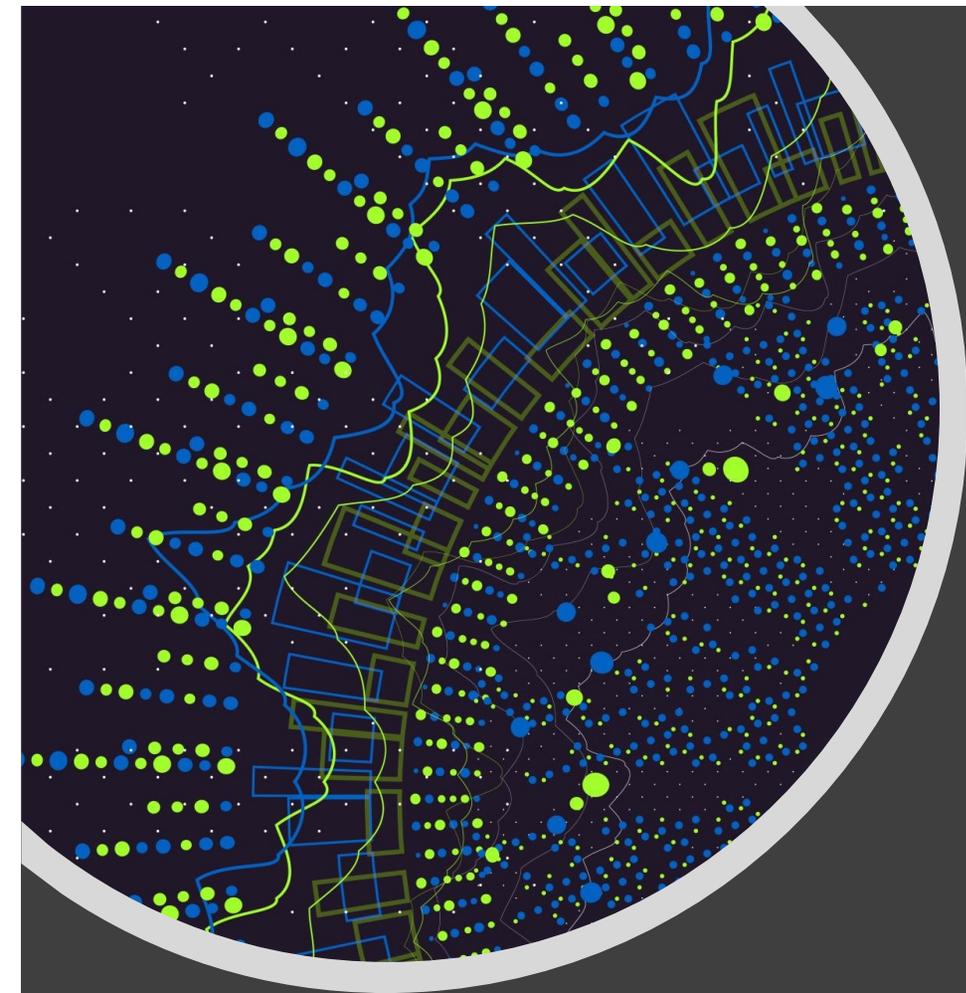
$k_{\text{min}}$  [ $\text{Mpc}^{-1}$ ]

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



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





## Some cosmic frontiers in 2022

- Hubble tensión
- Line-intensity mapping
- kSZ tomography