Line-Intensity Mapping for new physics

José Luis Bernal
Instituto de Física de Cantabria

Eucapt 2024

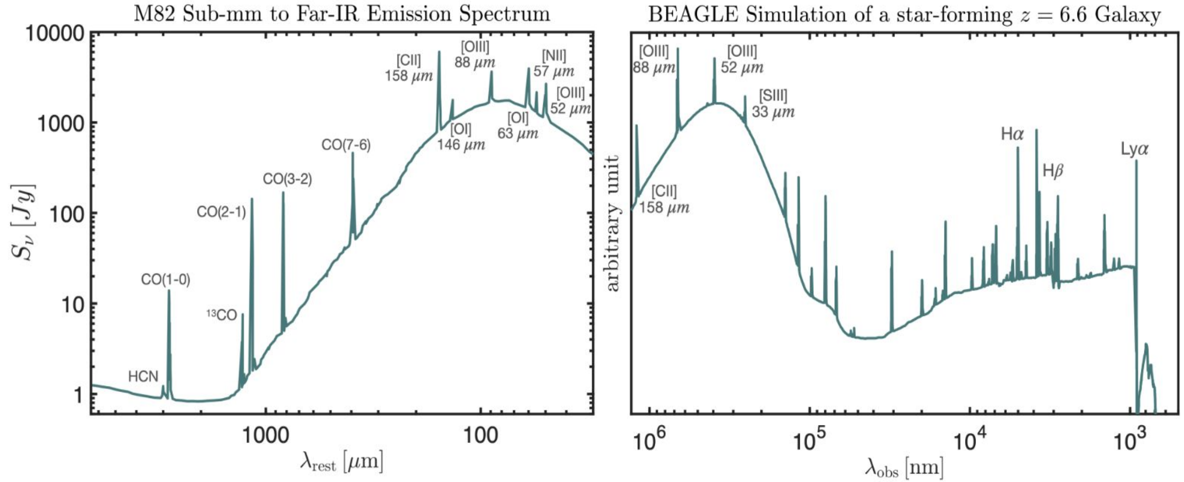
15/05/2024

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

- LIM: Target a identifiable spectral line → know redshift → 3D maps

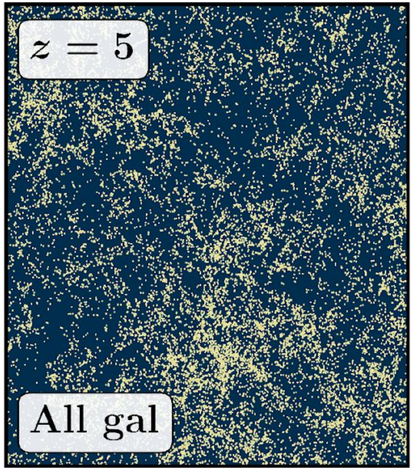


Bernal & Kovetz (2022)

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
- LIM: Target a identifiable spectral line → know redshift → 3D maps

Bernal & Kovetz (2022)



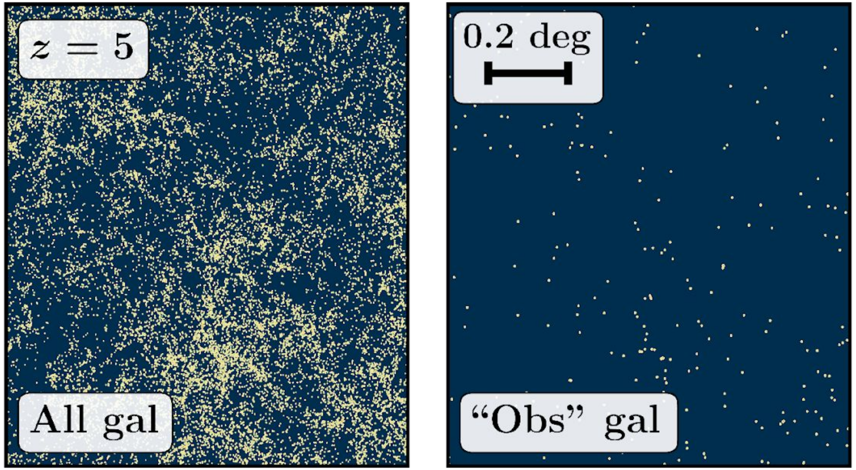
- 1 deg^2 at $z = 5, \Delta z = 0.2$
- All haloes

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

- LIM: Target a identifiable spectral line → know redshift → 3D maps



Bernal & Kovetz (2022)

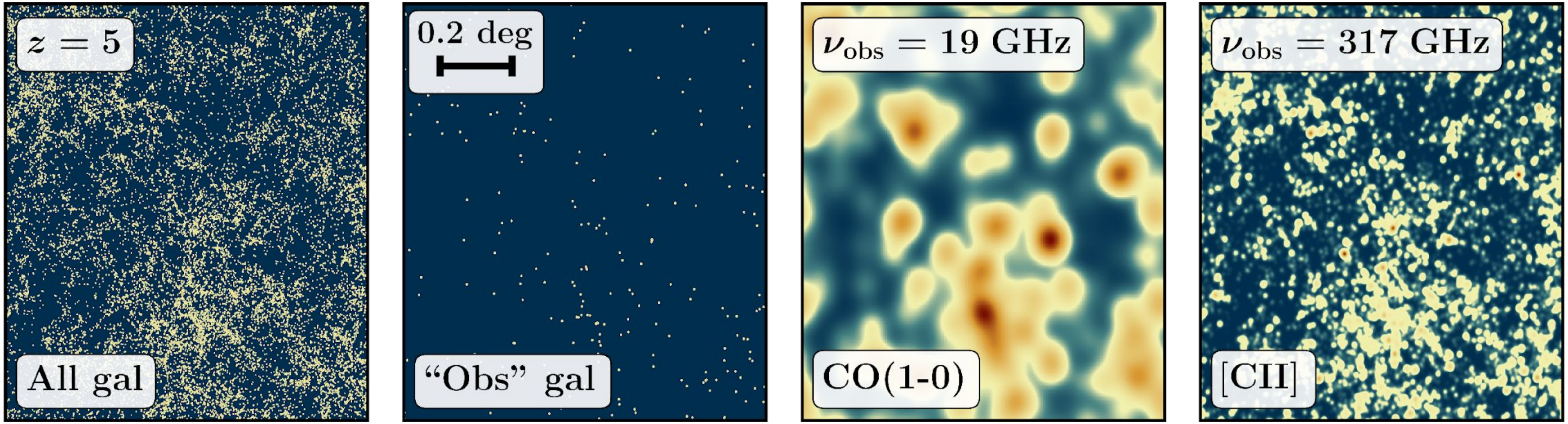
- 1 deg^2 at $z = 5, \Delta z = 0.2$

- All haloes

- Only $M_* > 10^{9.5}\ M_\odot$

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
- LIM: Target a identifiable spectral line → know redshift → 3D maps



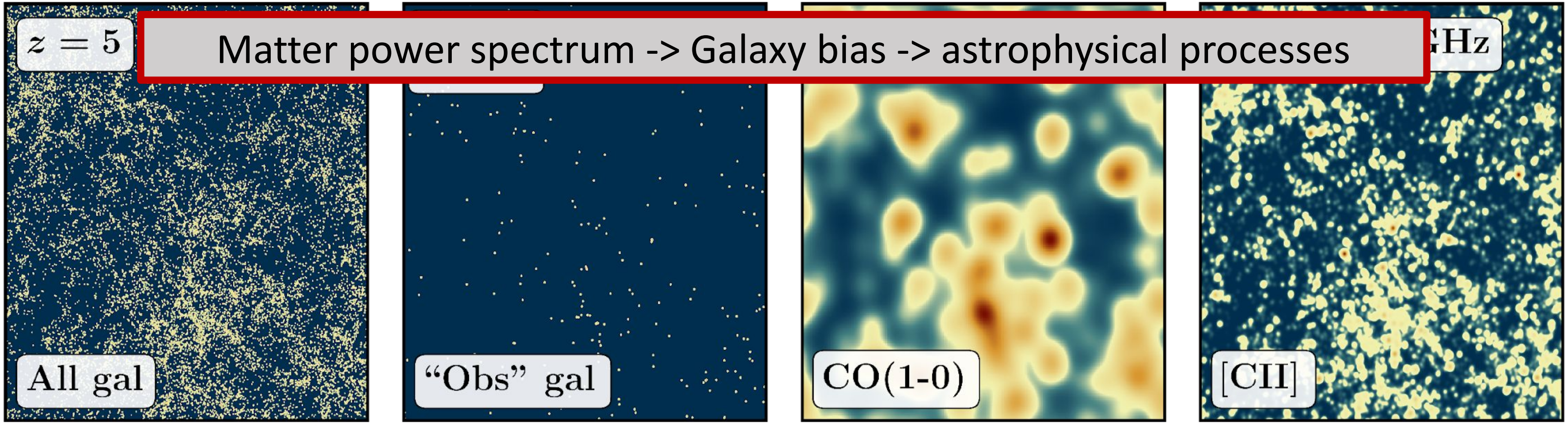
Bernal & Kovetz (2022)

What is Line-Intensity Mapping?

- Intensity fluctuations:
  - trace matter density fluctuations
  - Depend on line luminosity -> extragalactic astrophysics

- For cosmology: Noisy map of *all* galaxies and IGM (vs detailed map of brightest)
- For astrophysics: Aggregate of *all* emitters and diffuse emission

Matter power spectrum -> Galaxy bias -> astrophysical processes



Bernal & Kovetz (2022)

What is Line-Intensity Mapping?

- Intensity fluctuations:
  - trace matter density fluctuations
  - Depend on line luminosity -> extragalactic astrophysics

- For cosmology: Noisy map of *all* galaxies and IGM (vs detailed map of brightest)
- For astrophysics: Aggregate of *all* emitters and diffuse emission

Matter power spectrum -> Galaxy bias -> astrophysical processes

Three main features that make LIM unique:

1. Capture faint and diffuse sources
2. Access beyond the reach of galaxy surveys
3. Quickly map large three-dimensional volumes

New physics from:
changing P(k),
dn/dL [dndM+affecting astro],
new signals, ultra-large scales

***21cm from Cosmic Dawn + Reionization**

Information return from line-intensity maps

- LIM fluctuations trace matter: cosmology, but degenerate with astrophysics $T_i \propto L(M_i, \mathbf{\Theta}_i)$

$$\delta T \sim \langle Tb \rangle \delta_m \implies P_{TT} = \langle \delta T \delta T^* \rangle \sim \langle Tb \rangle^2 P_m + X_{LT}(z)^2 \int \mathrm{dL} \frac{\mathrm{d}n}{\mathrm{d}L} L^2$$

- Limitations:
  - Intensity maps are *highly* non-Gaussian: lots of information beyond P(k)
  - P(k) only depends on the 1st and 2nd [sic] moments of the luminosity function
  - P(k) mostly relevant for cosmology, degenerate with astro, but incapable to constrain it

- VID: 1pt distribution of intensities, proxy for the full luminosity function

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N) \propto \left(\underbrace{\Phi * \Phi * \ldots * \Phi} \right)(T)$$

Breysse+(2016, 2017)

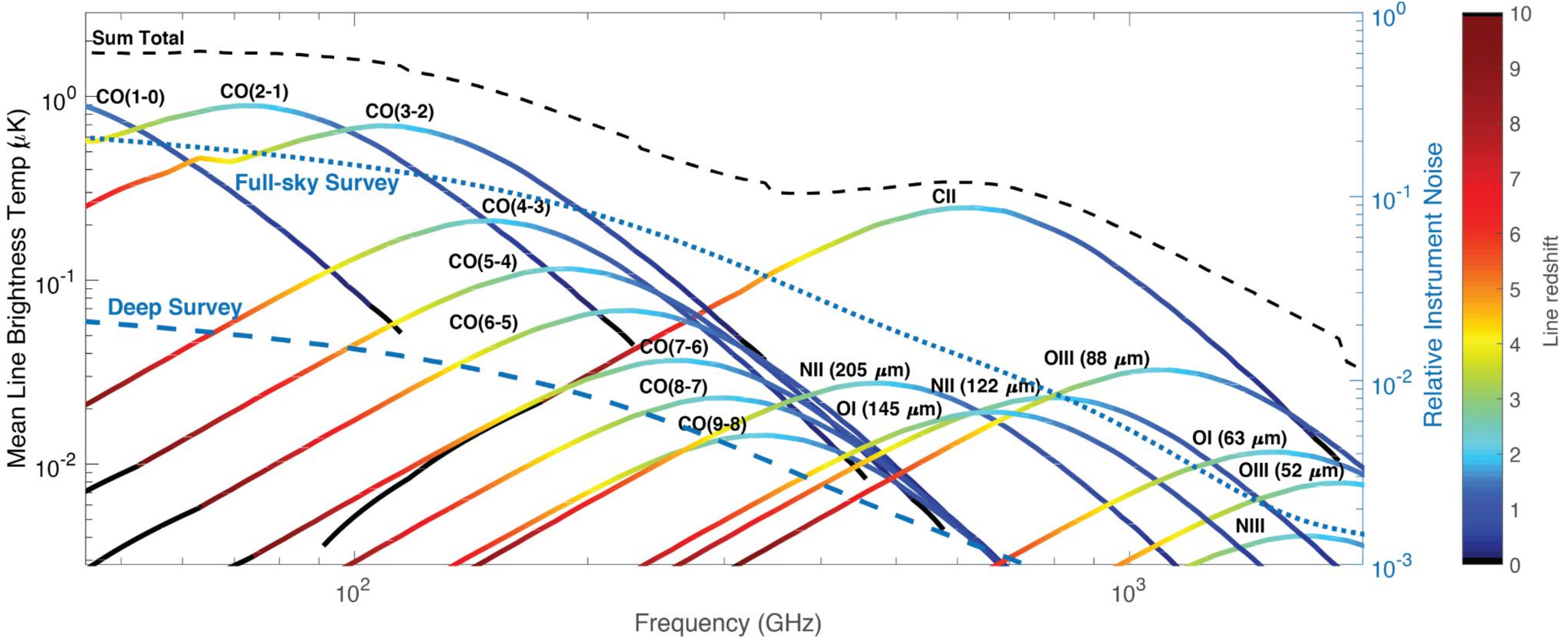
P(k): best for cosmo, integrals of luminosity functions

VID: best for astro, integrals of clustering

Contamination of intensity maps

- Continuous foregrounds (loss of long line-of-sight modes):
  - Uncorrelated: Galactic or CIB
    - Component separation Cunnington+ (2023), Carucci+ (2023), van Cuyk+ (2023)
    - Foreground wedge Pober (2014)
  - Correlated: CIB
    - Combine with galaxy surveys Switzer+ (2015), Switzer (2017), Switzer+ (2018)
    - Neural networks Pfeffer+ (2019), Moriwaki+ (2021)

Line interlopers



Silva + (2021)

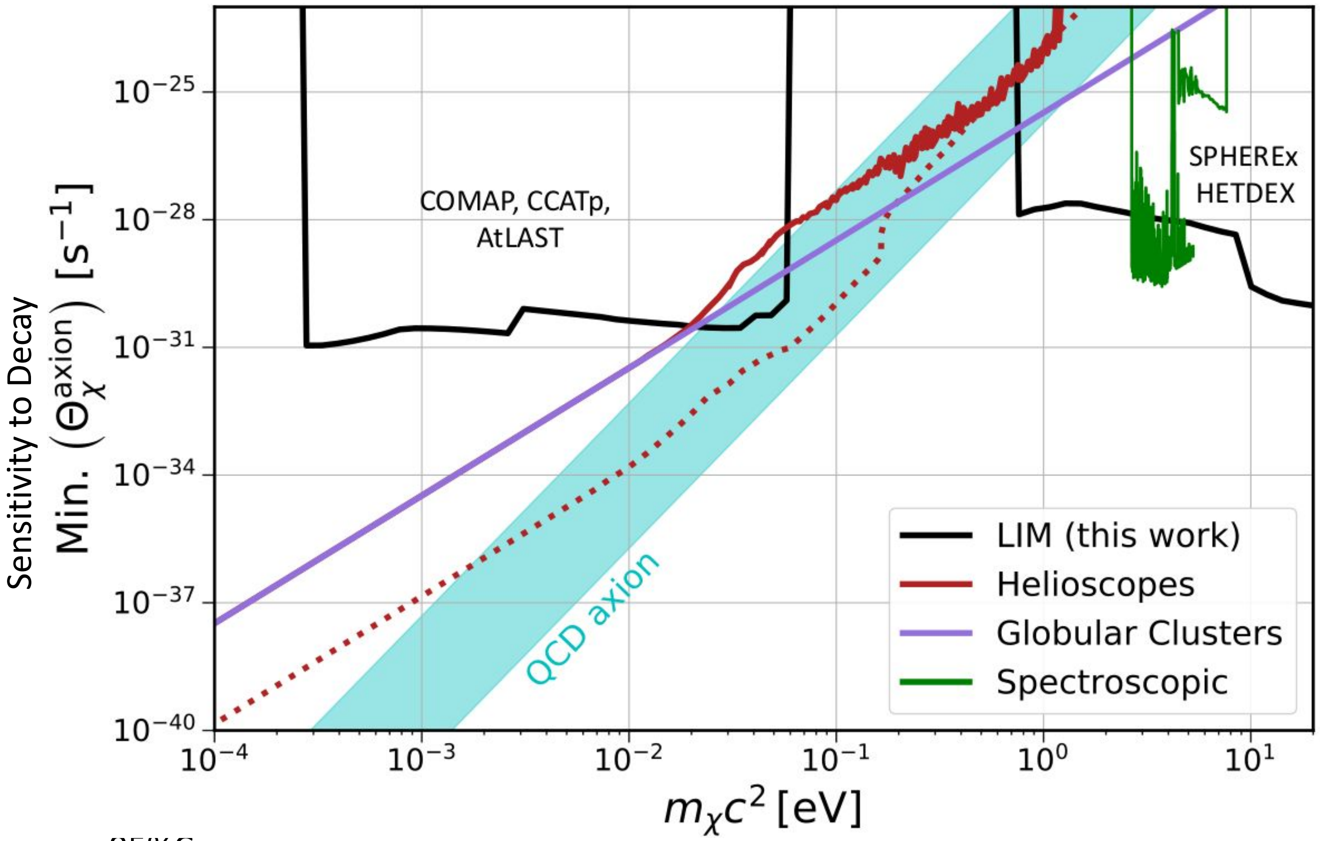
Contamination of intensity maps

- Continuous foregrounds (loss of long line-of-sight modes):
  - Uncorrelated: Galactic or CIB
    - Component separation **Cunnington+ (2023), Carucci+ (2023), van Cuyk+(2023)**
    - Foreground wedge **Pober (2014)**
  - Correlated: CIB
    - Combine with galaxy surveys **Switzer+ (2015), Switzer (2017), Switzer+ (2018)**
    - Neural networks **Pfeffer+ (2019), Moriwaki+ (2021)**

- Line interlopers (redshift and signal confusion):
    - Masking: targeted or blind **Breysse+ (2015), Sun+ (2018), van Cuyk+ (2023)**
    - Model them:projection effects **Lidz & Taylor (2016), Sun+ (2018), Gong+ (2020)**
    - Spectral templates: de-project at pixel level **Cheng+(2020)**
    - Nulling interlopers: similar to CMB lensing nulling **Bernal & Baleato-Lizancos (in prep)**
  - Exotic unknown signals!! DM and/or neutrino decay

Creque-Sarbinowski & Kamionkowski (2018), Bernal+ (2021), Nishikawa (2021), Bernal+ (2022)

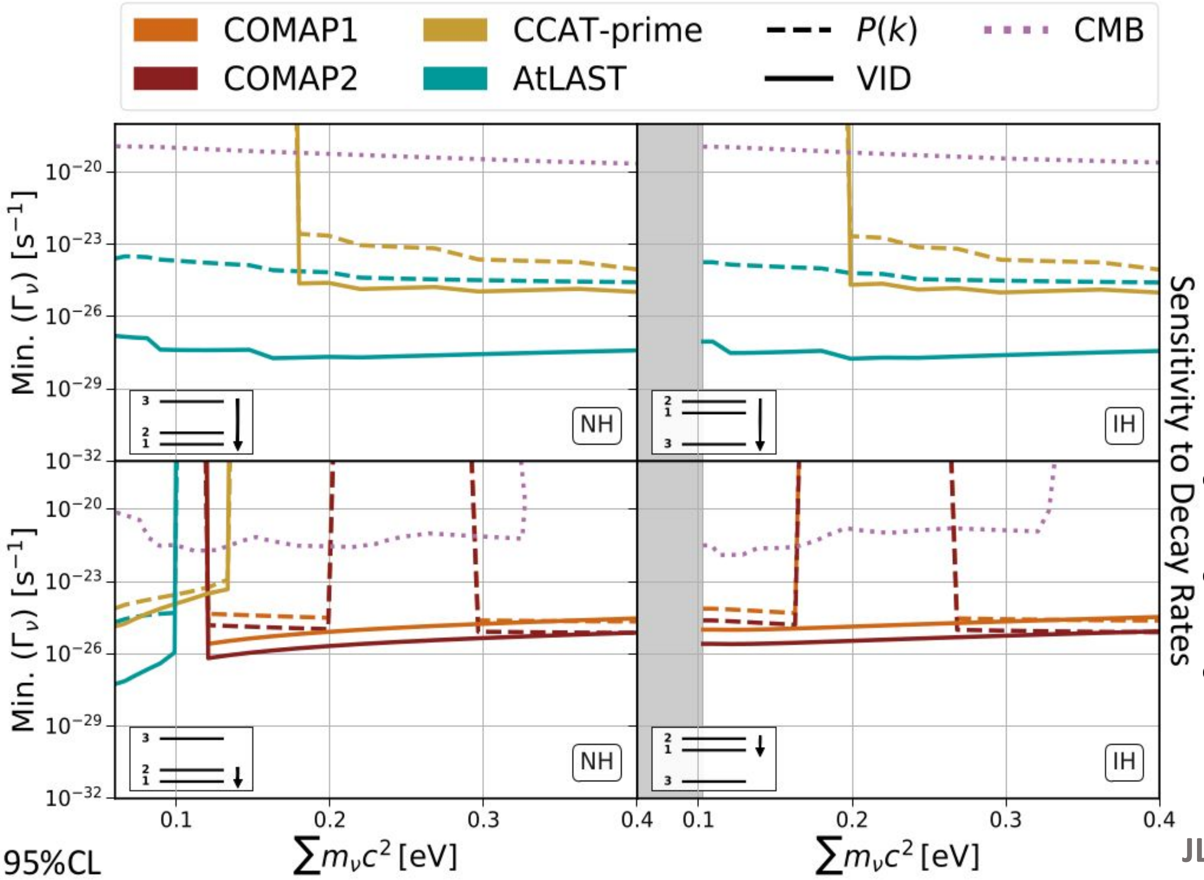
Sensitivity in axion context



95%C
L

JLB, Caputo, Kamionkowski

Sensitivities to neutrino decay



95%CL

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

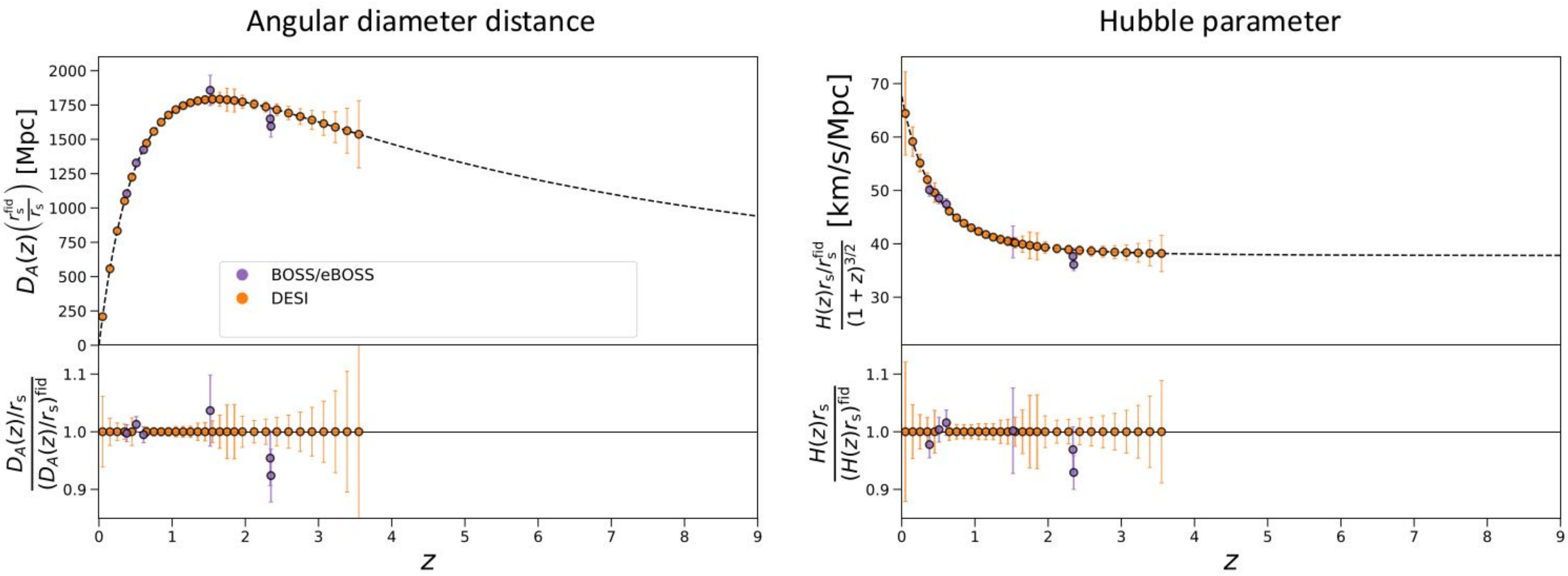
↓ Effective transition moment

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

- CMB forescast: $3\times10^{-11} - 10^{-8}\mu_B$
- Borexino: $< 2.8\times10^{-11}\mu_B$
- TRGB: $< 4.5\times10^{-12}\mu_B$

JLB, Caputo, Villaescua-Navarro, Kamionkowski

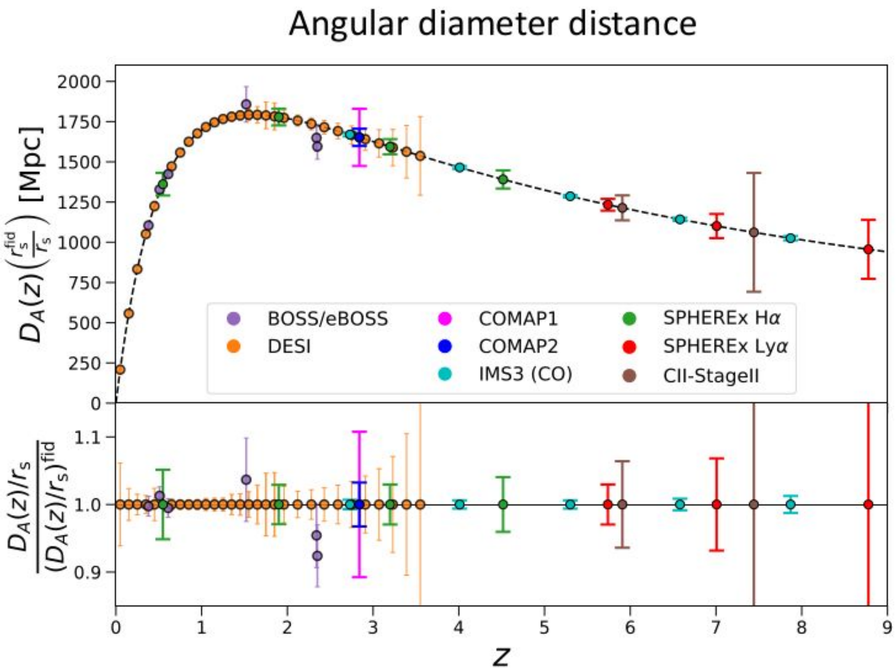
LIM BAO

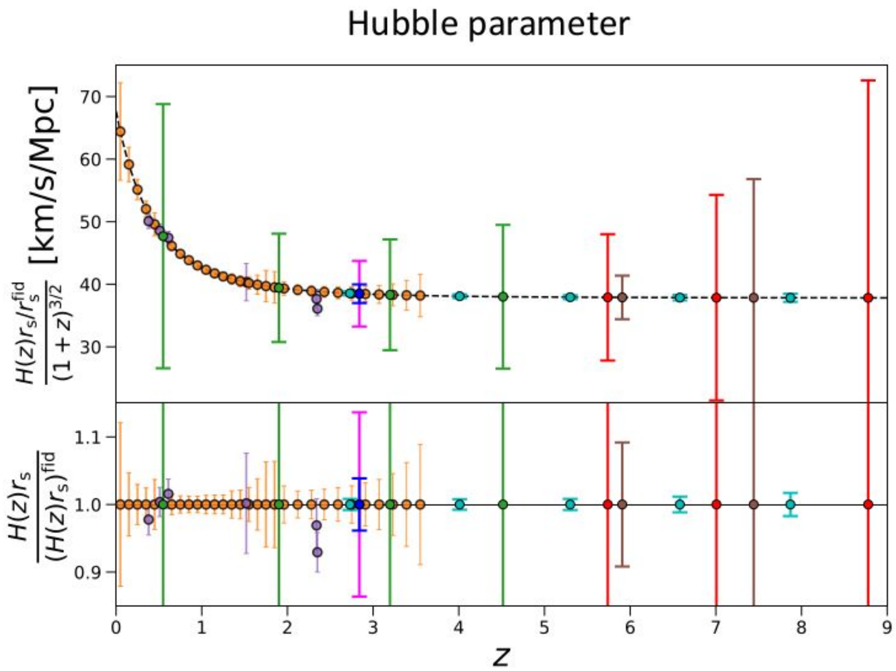


Current and coming constraints using galaxy surveys

Bernal +(2019b)

LIM BAO





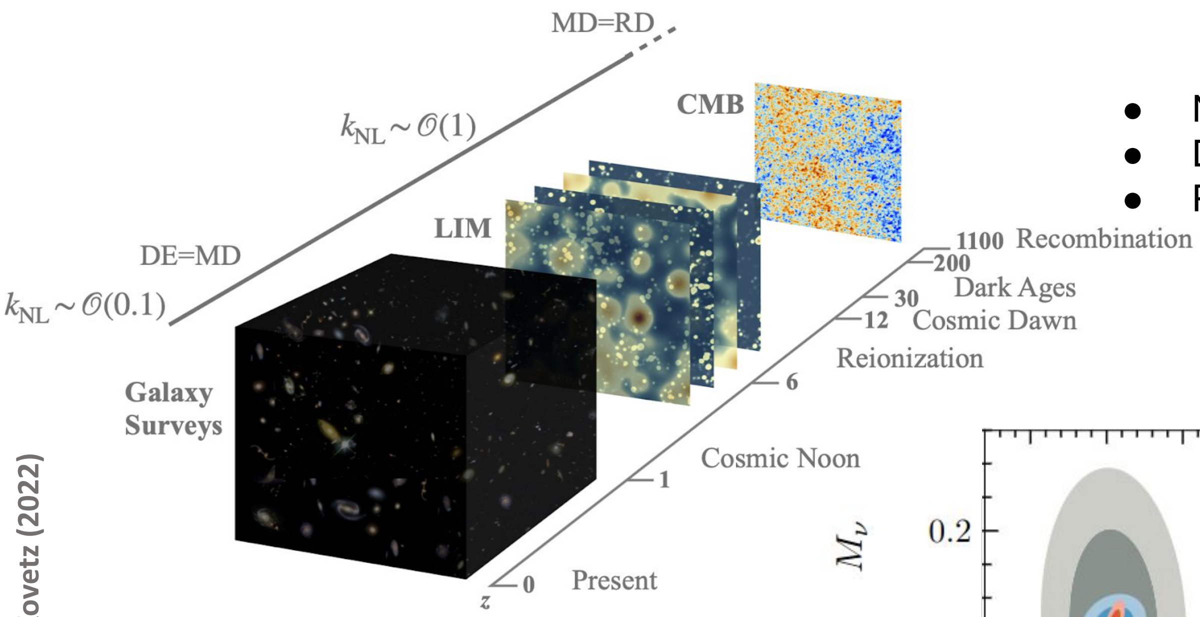
Add VAO at higher redshift
(Muñoz, 2019)

Current and coming constraints using galaxy surveys
+ Star-Formation-related LIM BAO

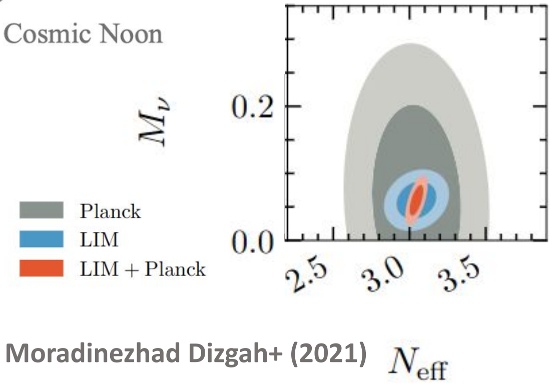
Bernal +(2019b)

Tomographic P(k) and big volumes

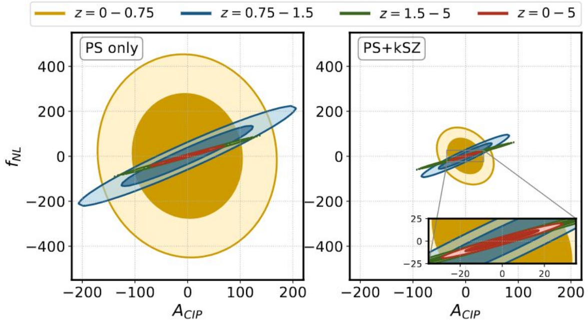
- Neutrino physics — Moradinezhad Dizgah+ (2021)
- DE & MG — Moradinezhad Dizgah+ (2023)
- PNG — Sato-Polito, Bernal+ (2021), Karkare+ (2022)



Bernal & Kovetz (2022)



Moradinezhad Dizgah+ (2021)



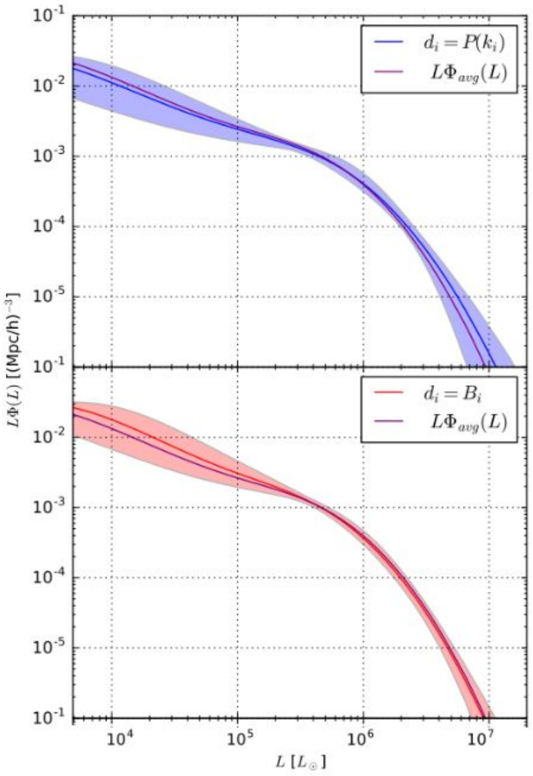
Sato-Polito, Bernal+ (2021)

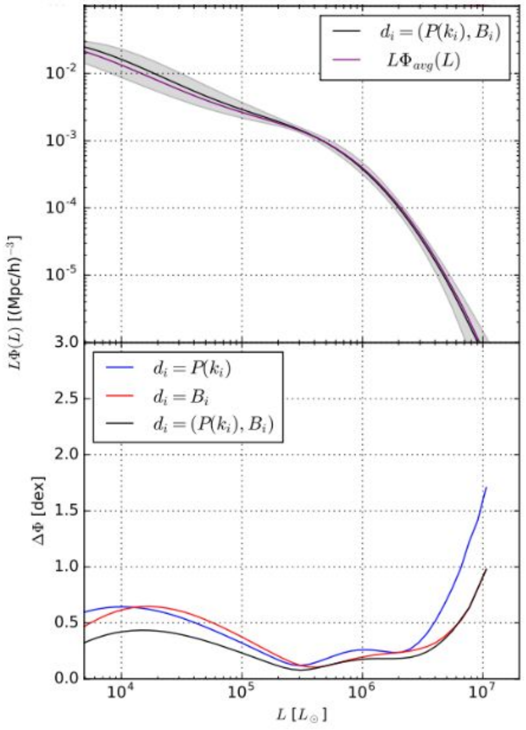
Combining VID and P(k)

Combination significantly improves constraints on the luminosity function
(Ihle+2019)

P(k) - VID covariance proportional to integrated bispectrum
(Sato-Polito & Bernal 2022)

Breaks degeneracies between astro & cosmo: improves beyond-LCDM sensitivity
(Sabla, Bernal+ 2024)





Combining VID and P(k)

Combination significantly improves constraints on the luminosity function
(Ihle+2019)

P(k) - VID covariance proportional to integrated bispectrum
(Sato-Polito & Bernal 2022)

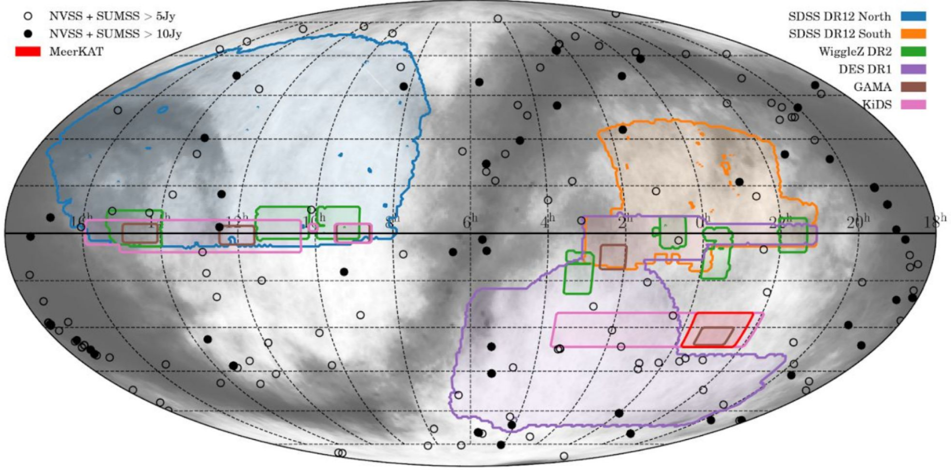
Breaks degeneracies between astro & cosmo: improves beyond-LCDM sensitivity
(Sabla, Bernal+ 2024)

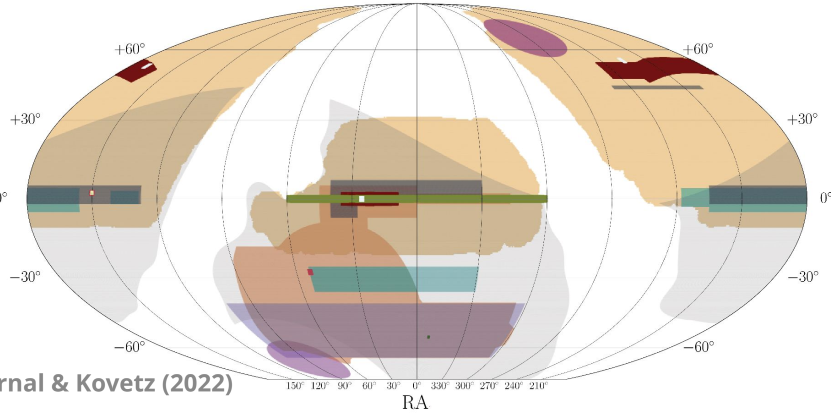
<u>Beyond-LCDM with VID+P(k):</u>
best for models that affect HMF -> dn/dL
(e.g., nCDM, fNL, …)
(Bauer+2020)

		COMAP-Y5			COMAP-XL		
Parameter	Fiducial	P_0	B_i	P_0+B_i	P_0	B_i	P_0+B_i
$k_{\rm cut}$ [Mpc^{-1}]	0.5	±8.74	±41.93	±2.42	±11.56	±1.48	±1.24
n	0.1	±15.95	±12.16	±0.24	±25.75	±0.15	±0.11
Ω_a/Ω_d ($m_a = 10^{-32}$ eV)	0.04	±0.76	±0.52	±0.04	±0.17	±0.31	±0.02
Ω_a/Ω_d ($m_a = 10^{-27}$ eV)	0.04	±0.19	±0.18	±0.02	±0.09	±0.07	±0.01
Ω_a/Ω_d ($m_a = 10^{-24}$ eV)	0.04	±78.2	±0.14	±0.06	±20.4	±0.06	±0.02
$f_{\rm NL}$	0	±3140	±71	±3.2	±220	±14.2	±0.38

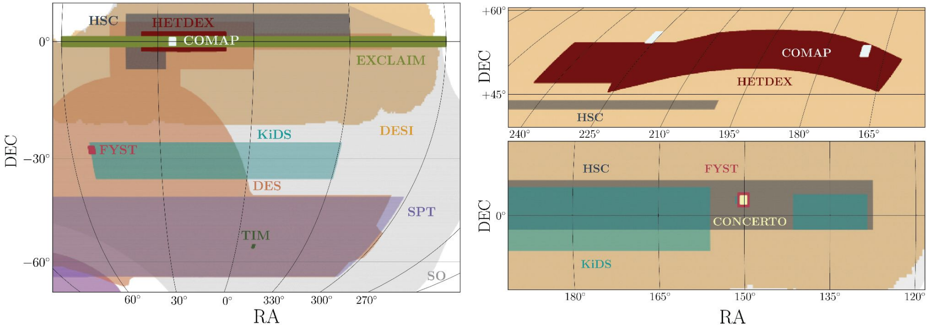
(Sabla, Bernal+ 2024)

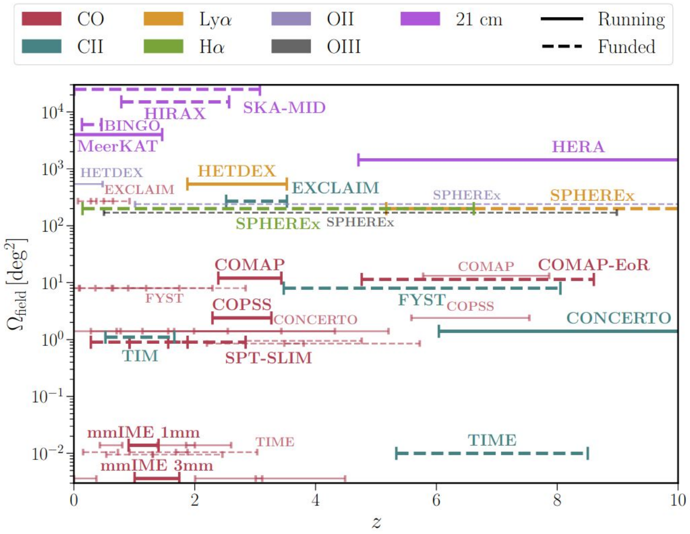
Many opportunities





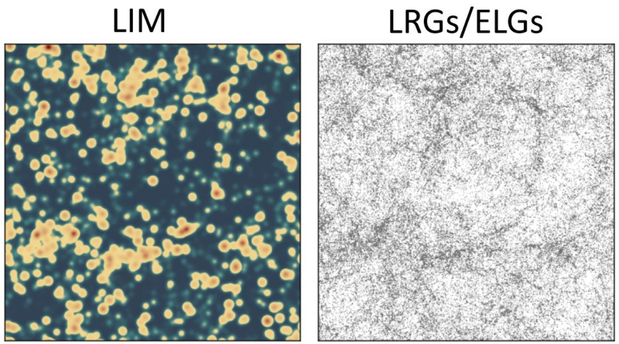
Bernal & Kovetz (2022)





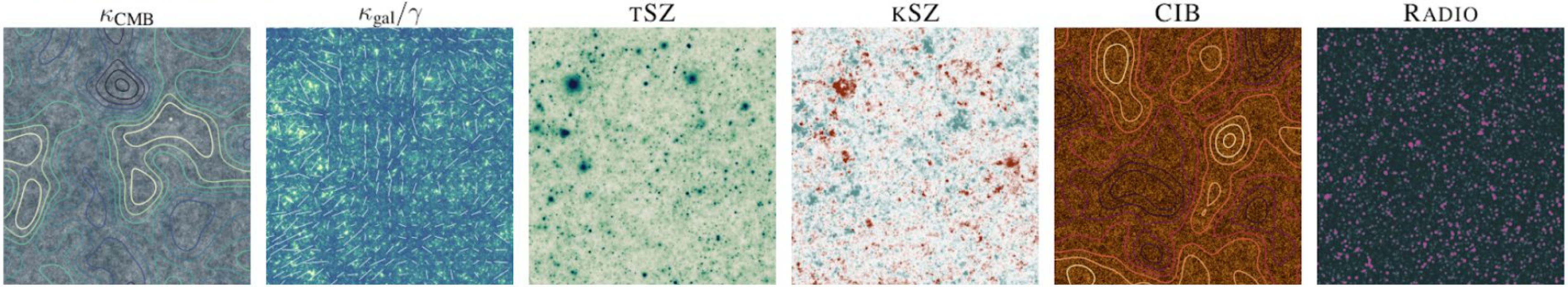
All probes, all cross-correlations

- SkyLine: Mock line observations (almost any line, contaminants, etc), LRGs and ELGs, …
- Agora: CMB secondaries and galaxy lensing
- Coherent when MDPL2 (and UniverseMachine) used for SkyLine!



- Opportunities to model and prepare for cross correlations with any probe
- Especially interesting for LIM x LIM, useful for correlations with lensing (project already proposed)

Sato-Polito, Kokron, Bernal (2022)
Omori (2022)



Conclusions

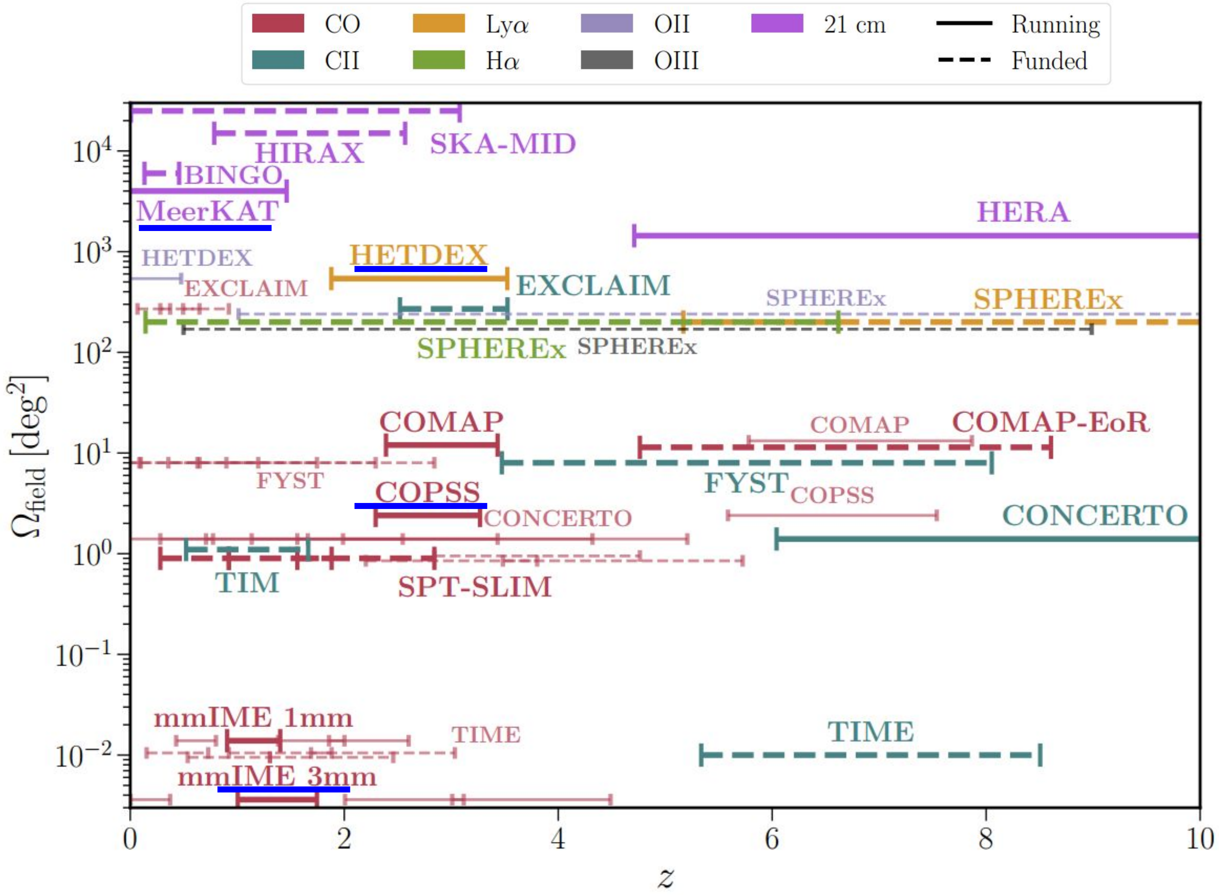
- LIM has the potential to become a key pillar for observational cosmology
  - Capture faint and diffuse sources
  - Access beyond reach of galaxy surveys
  - Quickly map huge volumes

- Challenges
  - Degeneracies with astrophysics (and other observational effects like line broadening)
  - Non linear bias and other non-trivial modeling
  - Foregrounds and contaminants

- Reasons to be optimistic
  - Many pathfinders and experiments observing and funded (and many theory efforts too!)
  - Many (very complementary) summary statistics
  - New information, and checks, through cross correlations
  - Excellent probe for new physics (HMF, energy injection, P(k), new signals, …)

Back up slides

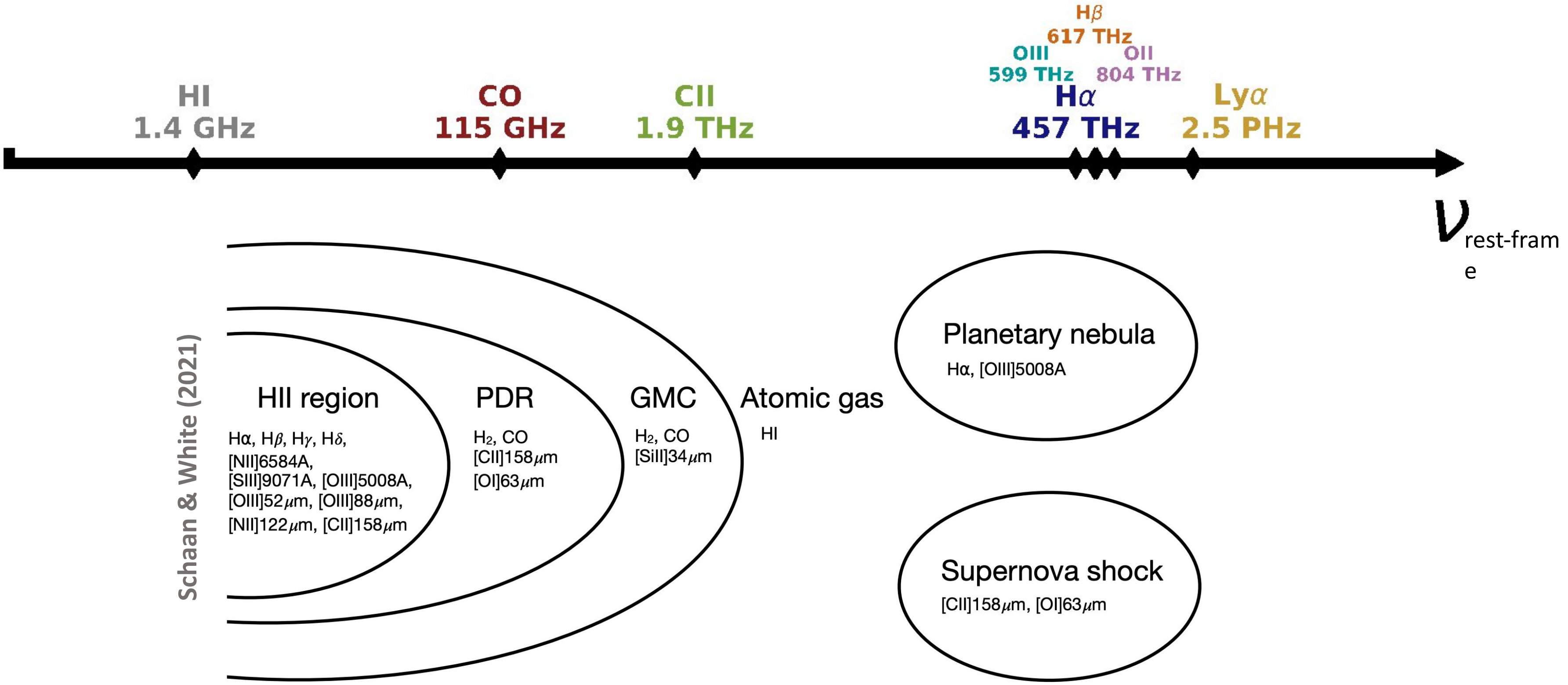
Filling the gaps in cosmic history



(adapted from)
Bernal & Kovetz (2022)

- Pathfinder stage
- Intrinsically multitracer
- All kind of astrophysics
- Huge range of freq (syst.)
- Planck x QSOs ([CII]), GBT, …

Intrinsically multitracer



$\Phi(L_1, L_2, \ldots)$: combine with continuum, and statistically probe all the SED

Using LIM for cosmology

- Focus on the anisotropic power spectrum:
- Alcock-Paczynski effect: $k_\parallel^{meas} = k_\parallel^{true}\alpha_\parallel$; $k_\perp^{meas} = k_\perp^{true}\alpha_\perp$
- Breaking degeneracies: $P(k,\mu,z) = \left(\frac{\langle T\rangle b\sigma_8 + \langle T\rangle f\sigma_8\mu^2}{1+0.5(k\mu\sigma_{FoG})^2}\right)^2 \frac{P_m(k)}{\sigma_8^2} + P_{shot}(z)$
- Include experimental window function: $\tilde{P}(k,\mu,z) = W(k,\mu,z)P(k,\mu,z)$
- Legendre multipoles: up to the hexadecapole! $\alpha_\parallel, \alpha_\perp, \langle T\rangle f\sigma_8$

BAO cosmology!

$$\tilde{P}_\ell(k^{meas},z) = \frac{H(z)}{H^{fid}(z)}\left(\frac{D_A^{fid}(z)}{D_A(z)}\right)^2 \frac{2\ell+1}{2}\int_{-1}^{1} d\mu^{meas}\,\tilde{P}(k^{true},\mu^{true},z)\mathcal{L}_\ell(\mu^{meas})$$

User's guide:JLB+2019a

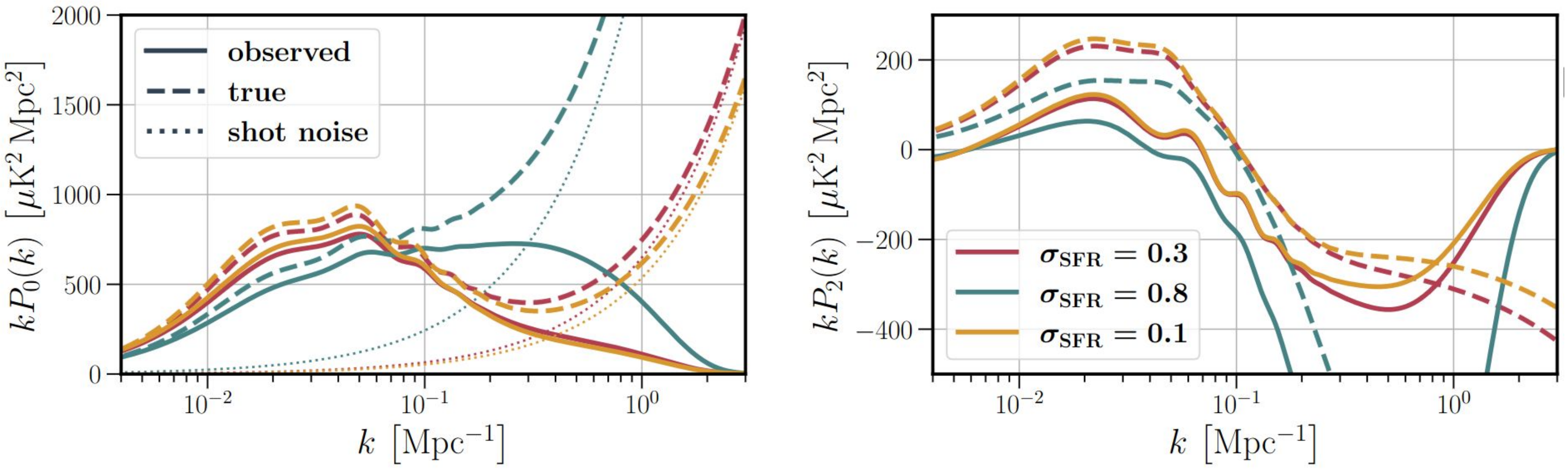
Using LIM for cosmology

Bernal+ (2019a)

- LIM fluctuations trace matter: cosmology, but degenerate with astrophysics $T_i \propto L(M_i, \mathbf{\Theta}_i)$

$$\delta T \sim \langle Tb \rangle \delta_m \Longrightarrow P_{TT} = \langle \delta T \delta T^* \rangle \sim \langle Tb \rangle^2 P_m + X_{LT}(z)^2 \int \mathrm{dL} \frac{\mathrm{d}n}{\mathrm{d}L} L^2$$

- Careful with interpretation of shot noise!!

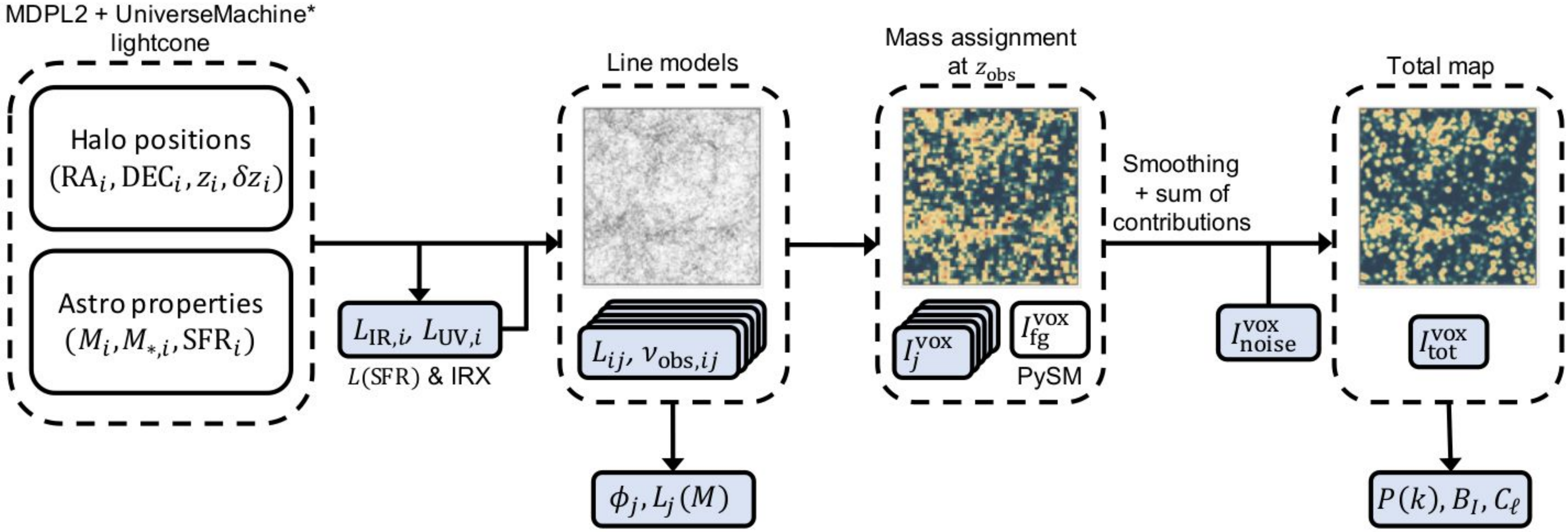


Bernal & Kovetz (2022)

COMAP-like but for 200 deg^2

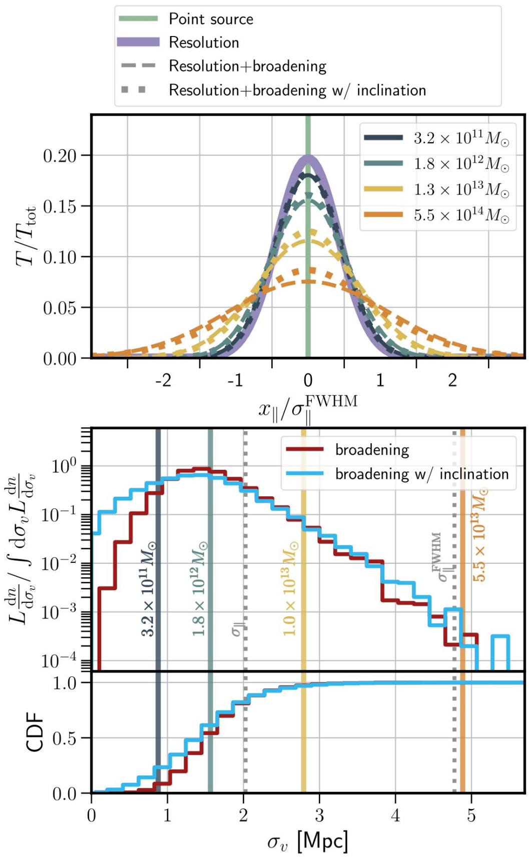
SkyLine

- Coherent multi-line, multi-probe simulated sky
- Mock map for a given experiment with *all* contributions, coherent with other probe



Sato-Polito, Kokron, Bernal (2022)

VID: extended contribution



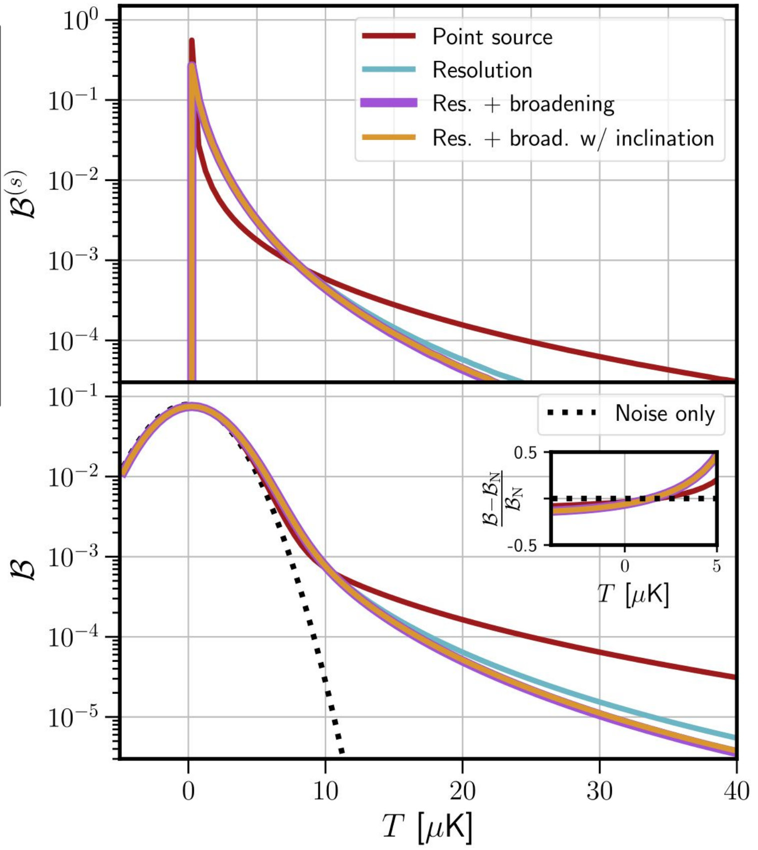
Experimental resolution + line broadening:
a emitter contributes to more than 1 voxel

$$T(\boldsymbol{x}) \propto \sum_s \frac{dL_s}{d\boldsymbol{x}}(\boldsymbol{x}|\boldsymbol{\vartheta}_s)$$

$\mathcal{P}_1 \sim$ Ergodic hypothesis

Big case-dependent effect: critical for VID but also for any 1-point statistic (CVID, DDE, etc)

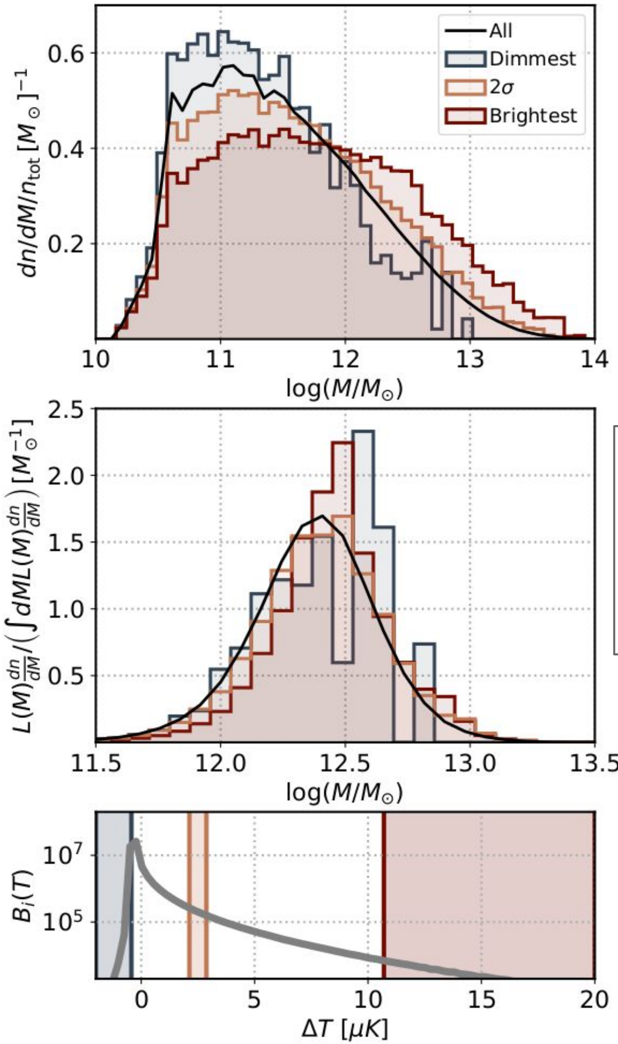
Effect agrees with simulations



Bernal (2023)

Which halos probed by LIM?

- We can use the maps to study if LIM is actually sensitive to faint emitters (which halos dominate the temperature of each voxel?)
- Many faint halos or few bright ones?
- Dimmest voxels dominated by light halos, more massive halos more common in brightest voxels
- Luminosity weighted distribution is *very* similar



CO(1→0), z~3

Sato-Polito, Kokron, Bernal (2022)

Using LIM for local PNG: P(k)

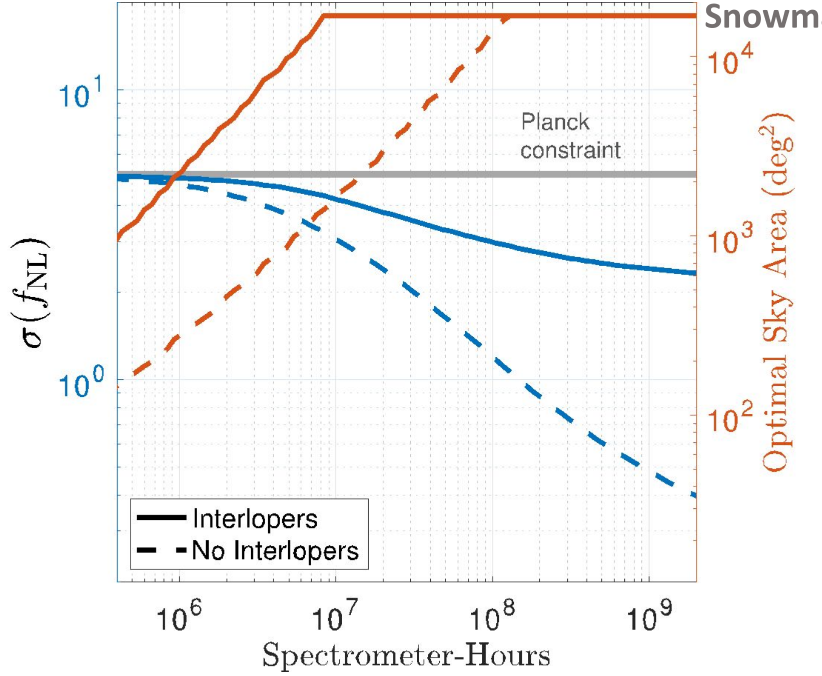
- Intensity traces density: cosmological information degenerate with astrophysics

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

- Assumes:
  - Observations in 80-310 GHz
  - R =300
  - Noise from interlopers
  - Excellent observing sites (only instrument noise)
  - Autopower spectrum: get to improve with x-corr.
  - Optimal sky coverage

- See also Bernal+(2019), Moradinezhad Dizgah+(2018, 2019), Liu & Breysse (2021), Chen & Pullen (2022), …

Karkare+ (2022). Snowmass



Assuming known b_ϕ, see Alex's talk

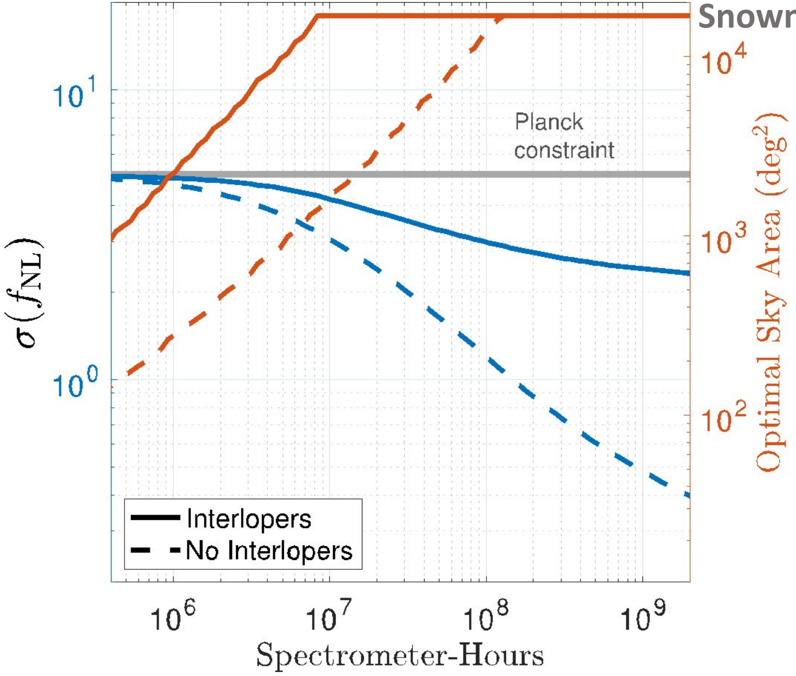
Using LIM for local PNG: P(k)

- Intensity traces density: cosmological information degenerate with astrophysics

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

- Limitations:
  - Intensity maps are highly non-Gaussian: lots of information beyond P(k)
  - More challenges for PNG from B(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

Karkare+ (2022). Snowmass

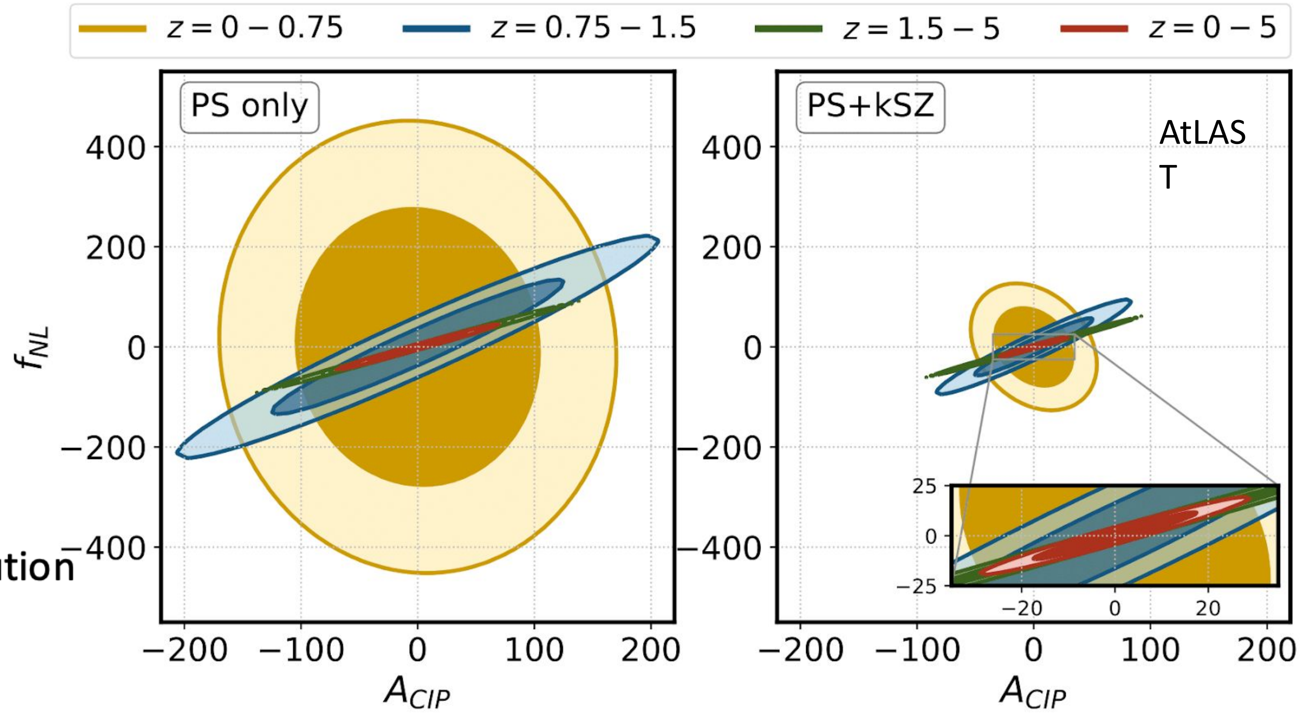


Assuming known b_ϕ, see Alex's talk

Using LIM for local PNG: kSZ tomography

- $\langle T\delta\delta \rangle$: LIM as tracer of LSS
- v_r reconstruction
- multitracer LIM x velocity
- Higher z (bigger volume)

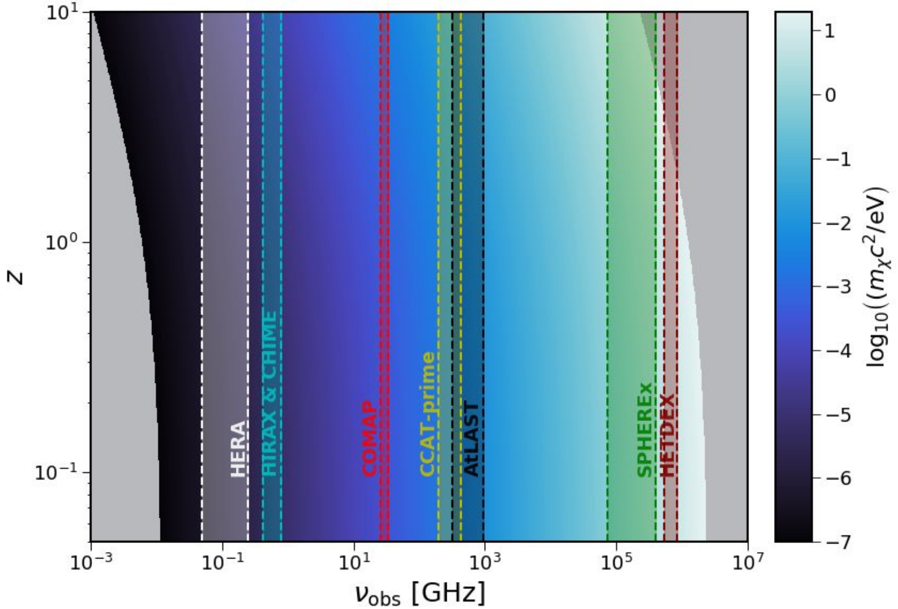
- Degeneracy with CIPs broken due to different z-evolution



Sato-Polito, Bernal+ (2021)

DM & Neutrinos

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

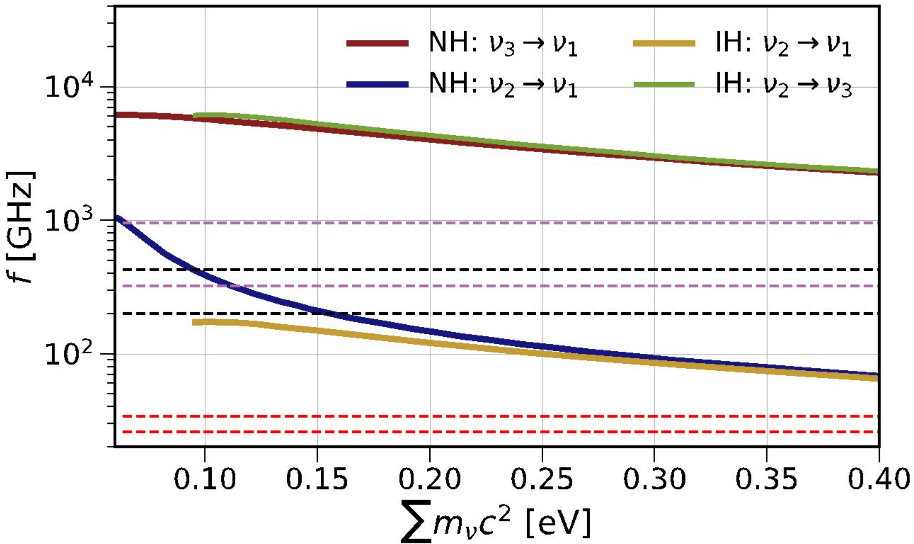


$$\chi \rightarrow \gamma + \gamma$$

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

DM & 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!
  - Traces directly the cosmic neutrino density field

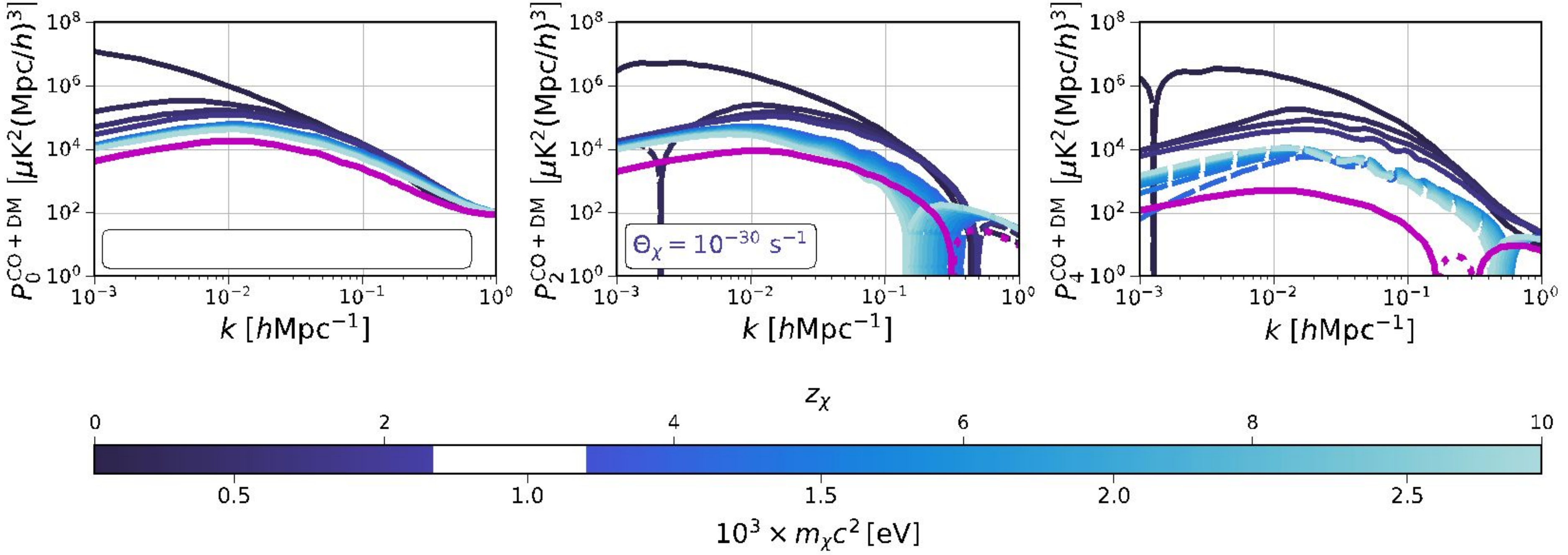


$$\nu_i \to \nu_j + \gamma$$

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

Effect in power spectrum

- $P_{tot} = P_l + P_X$; $\quad k_i^{true} \equiv k_i^{infer}/q_i \quad q_\parallel = \frac{(1+z_X)/H(z_X)}{(1+z_l)/H(z_l)} \quad q_\perp = \frac{D_M(z_X)}{D_M(z_l)}$



Effect in VID

- Each voxel receives contributions from both emissions:

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

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

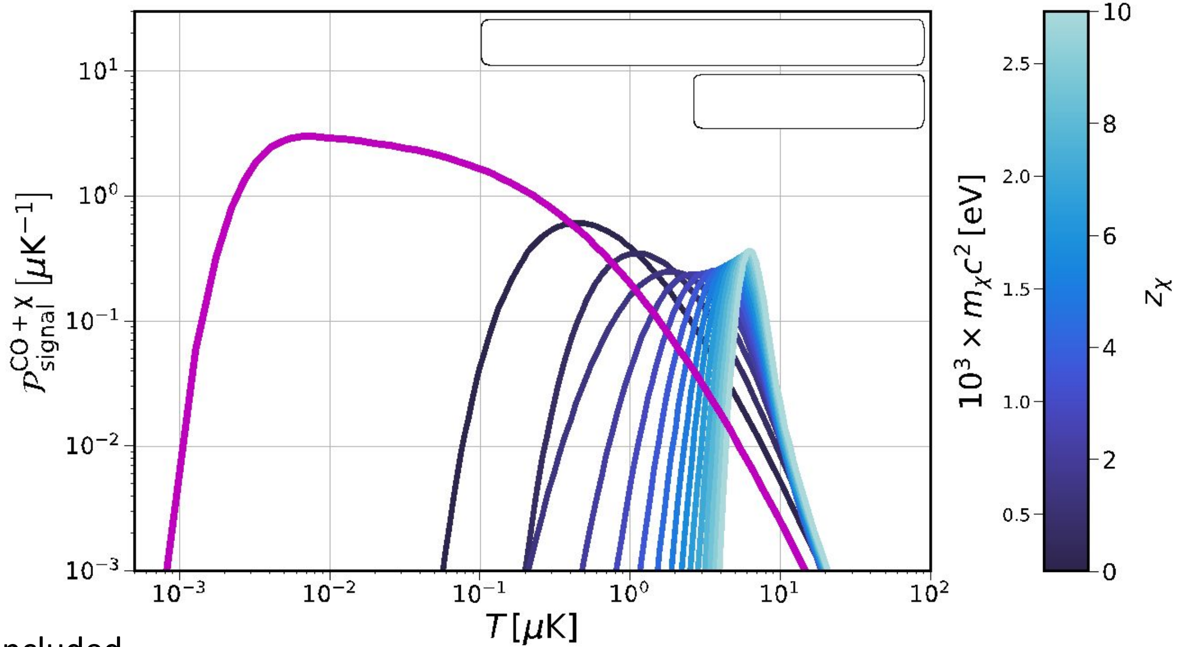
- $\mathcal{P}_{\tilde{\rho}}$: PDF of normalized densities. Obtained from simulations

- 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

Combining VID and P(k)

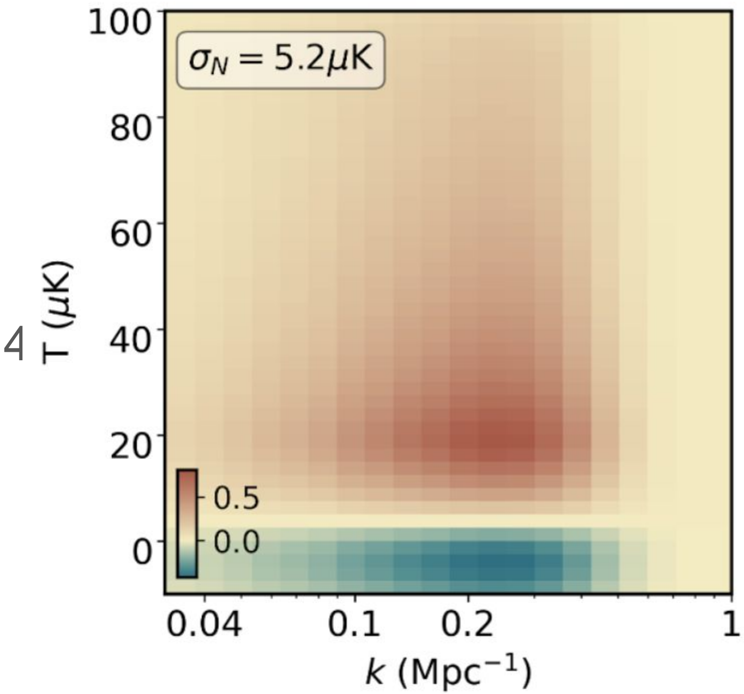
Correlation coefficient

$$c_{ij} = \frac{\mathrm{Cov}[\mathcal{B}_i, P(k_j)]}{\sigma_{\mathcal{B}_i}\sigma_{P(k_j)}}$$

- Analytic covariance computed using:

$$\mathcal{P}(I) \rightarrow \mathcal{P}(I, \delta(\boldsymbol{x}))$$

- Proportional to collapsed bispectrum
- Example for COMAP Y5: CO(1-0), z ~ 2.4
- Definitely important to take into account very soon



Sato-Polito & Bernal (2022)