# Primordial non-Gaussianity with Line-Intensity Mapping

(high-freq lines – see Steve Cunnington's talk on Wednesday)

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with
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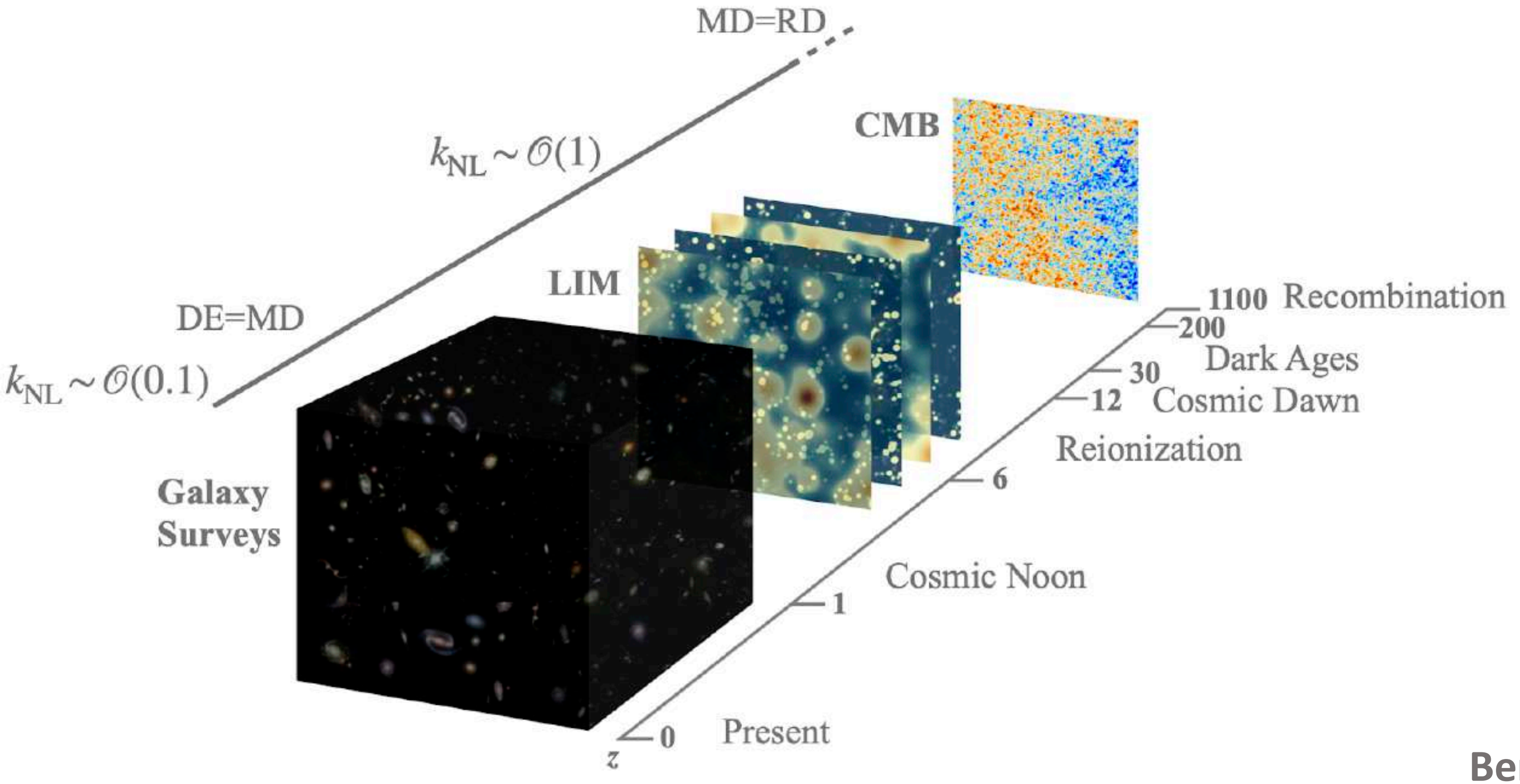
JOHNS HOPKINS
KRIEGER SCHOOL of ARTS & SCIENCES

# 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 → know redshift → 3D maps




Bernal & Kovetz (2022)

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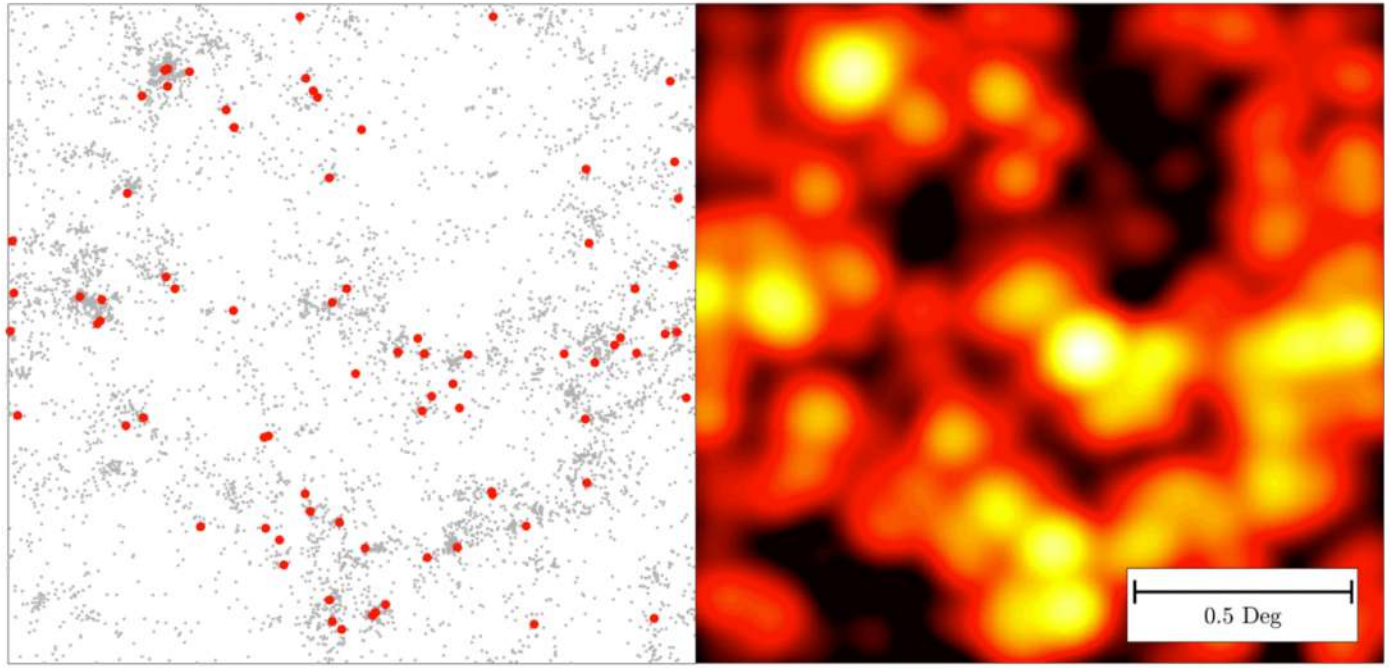
$\sim$ 4.5k hours of VLA can detect $\sim$ 1% of CO-emitting galaxies




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

P. C. Breysse

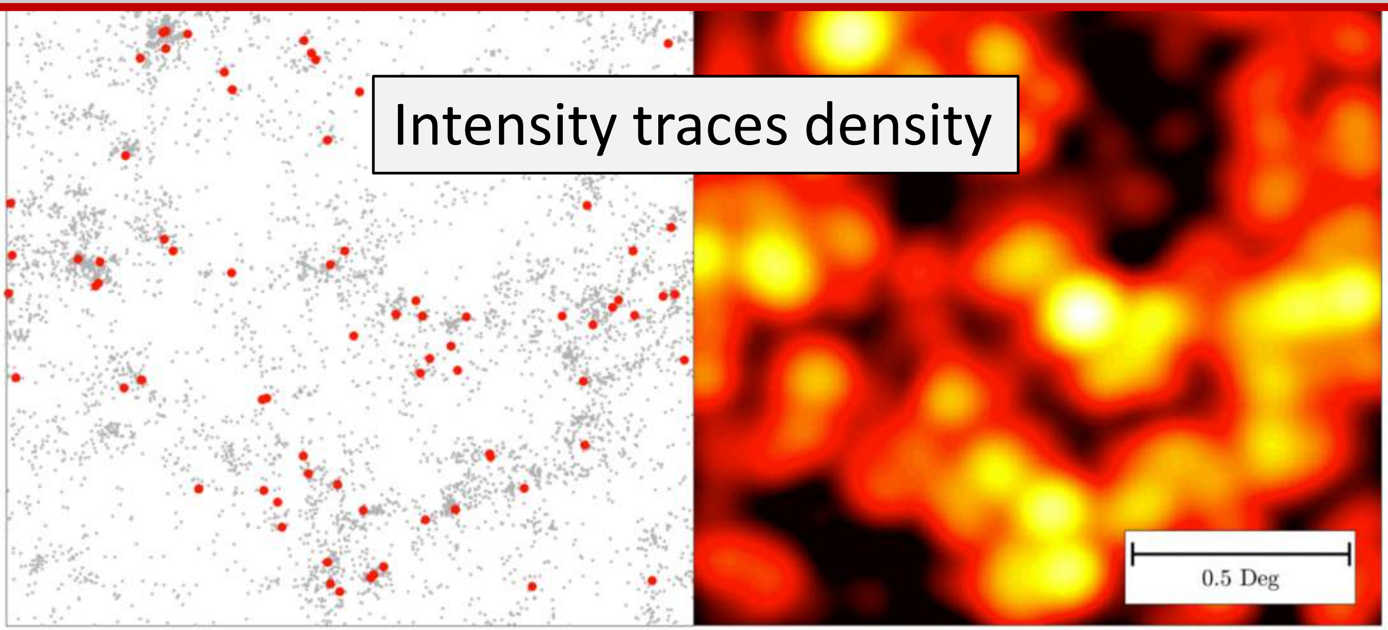
# What is Line-Intensity Mapping?

- LIM: use the integrated signal without requiring a detection threshold
- Information from all incoming photons, from all galaxies and IGM along the LoS
- 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




~ 1.5k hours of COMAP mapping CO intensity fluctuations

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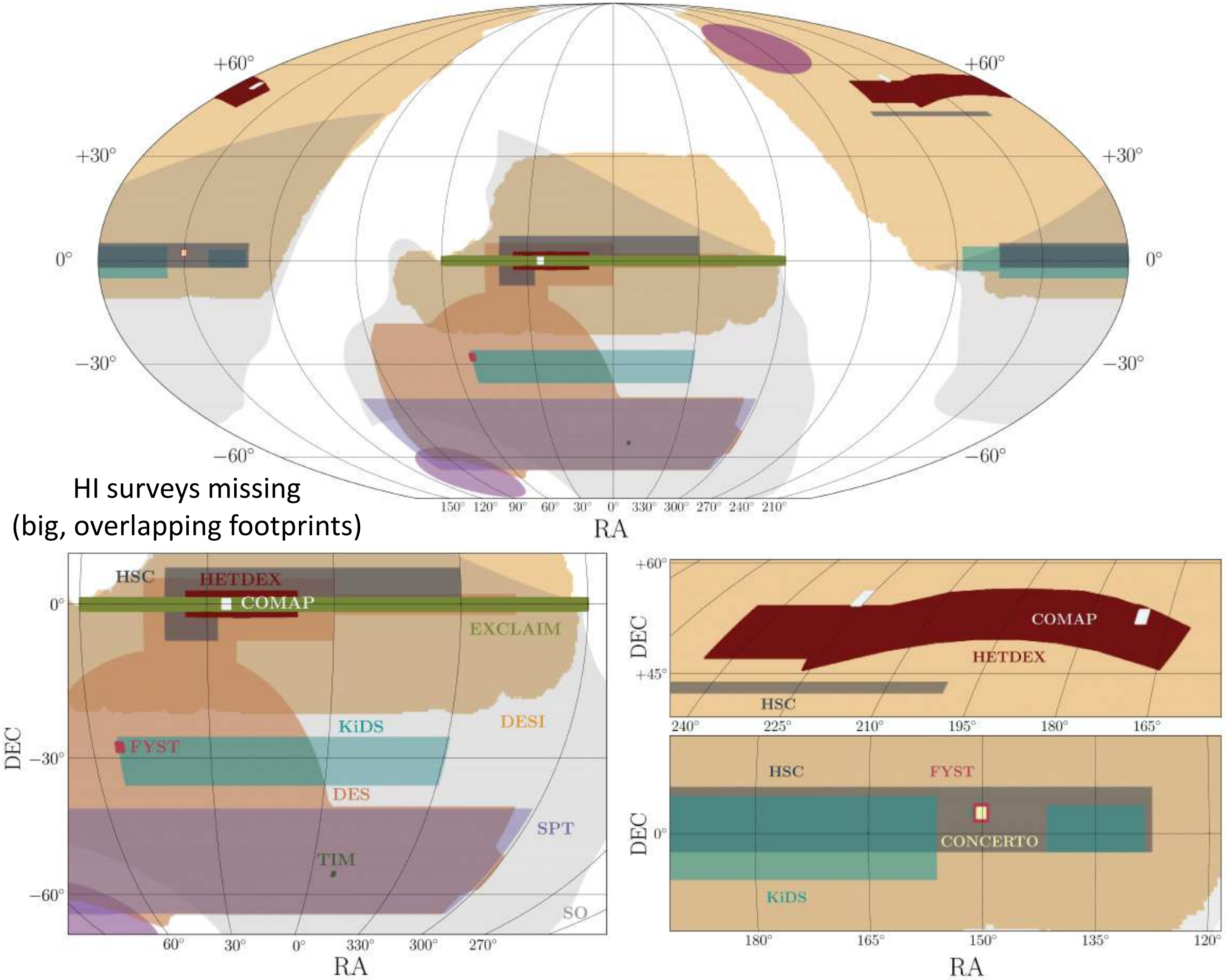
# What is Line-Intensity Mapping?




HI surveys missing
(big, overlapping footprints)

- Currently small experiments and pathfinders (except HI)
- Multi-tracer by definition
- Great overlap with galaxy surveys and CMB
- Great future: joint analyses, bigger z range, wider surveys, etc.

Bernal & Kovetz (2022)

# Using LIM for local PNG: P(k)

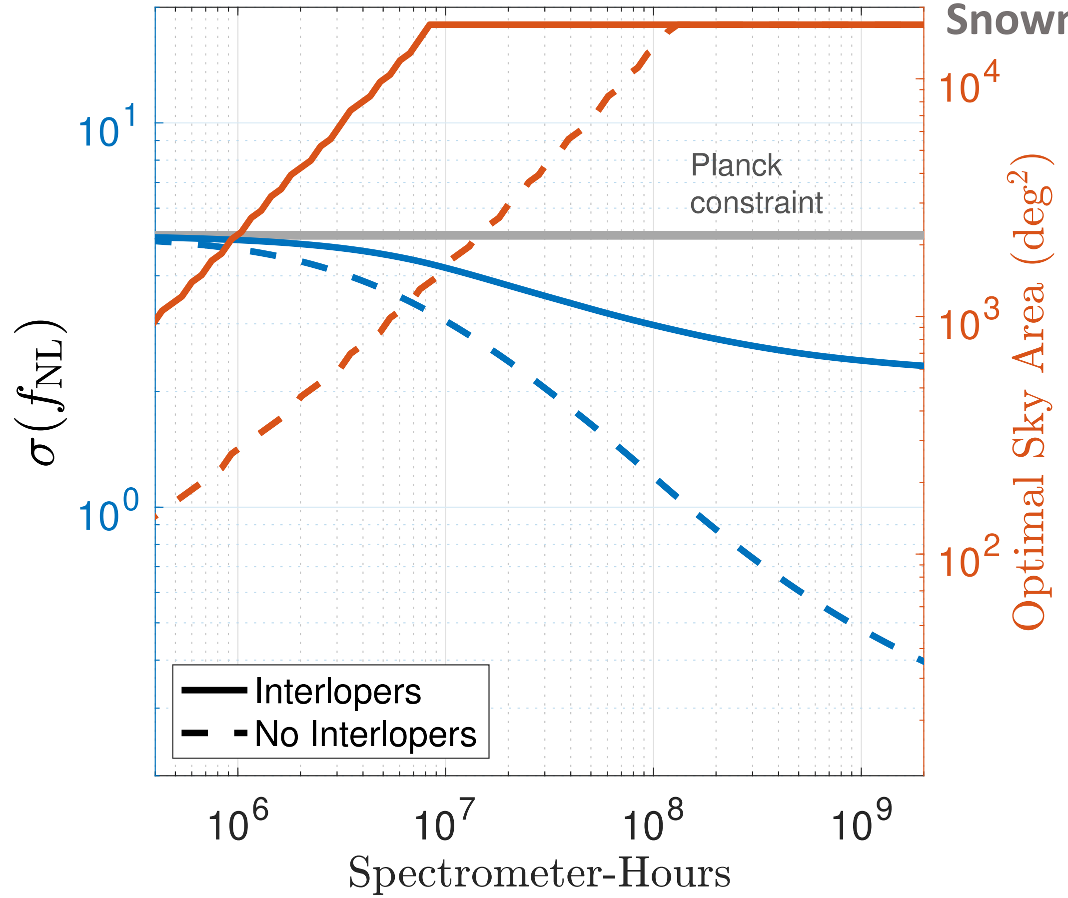
- Intensity traces density: cosmological information degenerate with astrophysics

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

- 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 $b_\phi$, see Alex's talk

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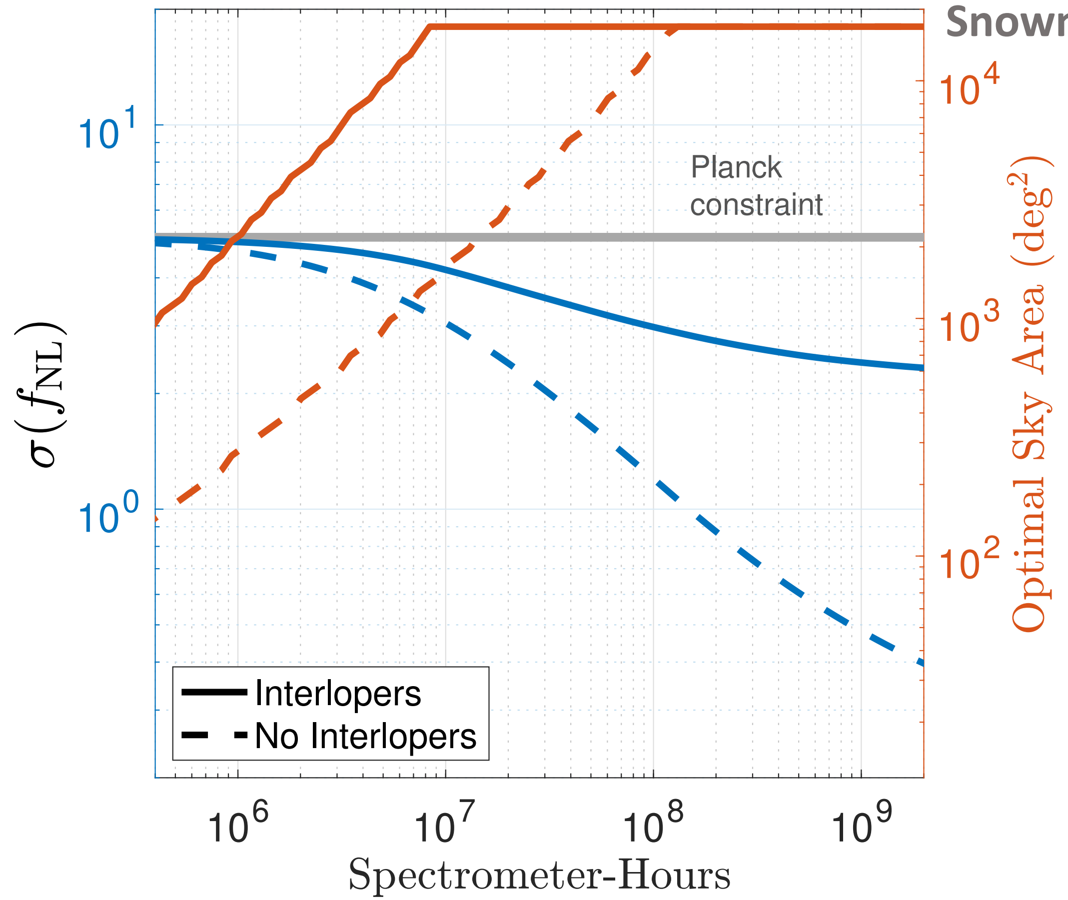
- Limitations:
  - Intensity maps are highly non-Gaussian: lots of information beyond P(k)
  - More challenges for PNG from B(k)
  - P(k) only depends on 1st and 2nd moments of the luminosity functions
  - P(k) mostly relevant for cosmology, but degenerate with some astro

Karkare+ (2022). Snowmass

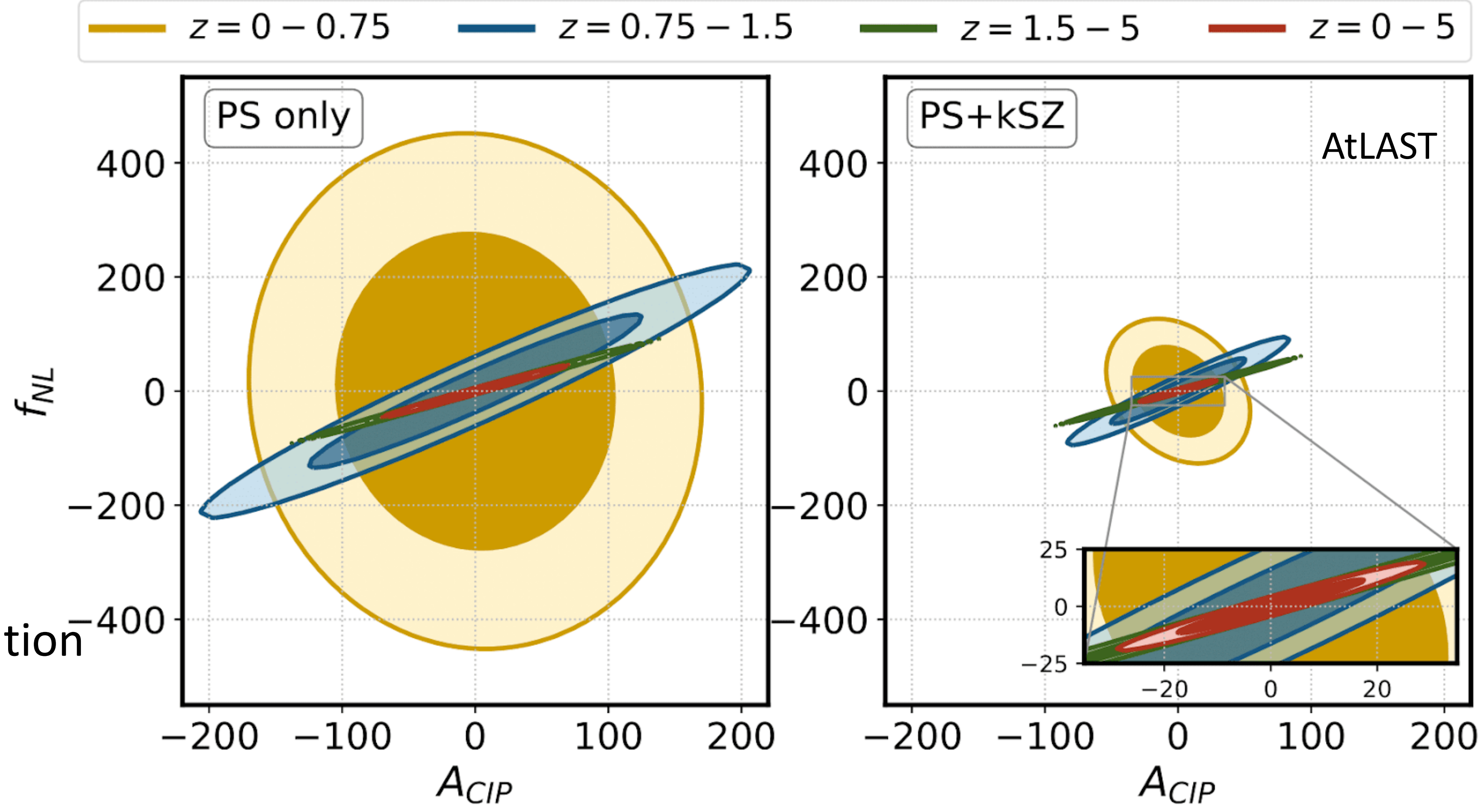



Assuming known $b_\phi$, see Alex's talk

# 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

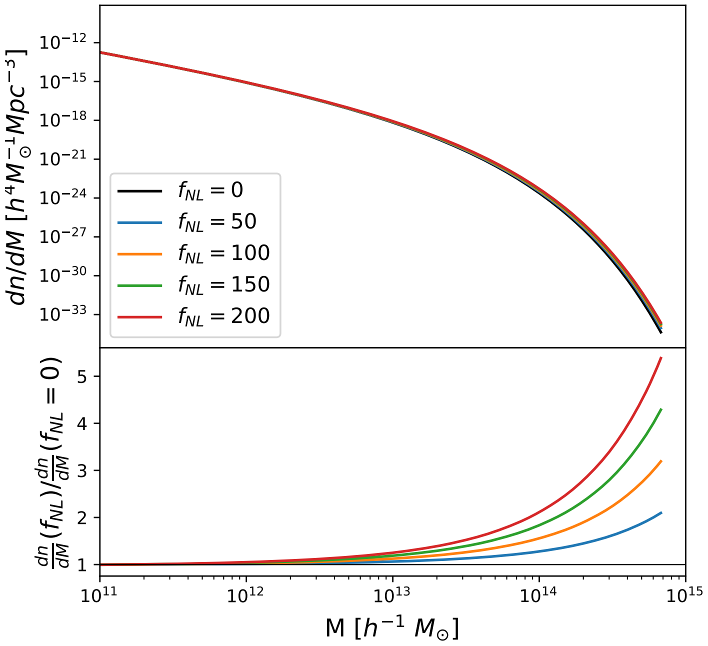


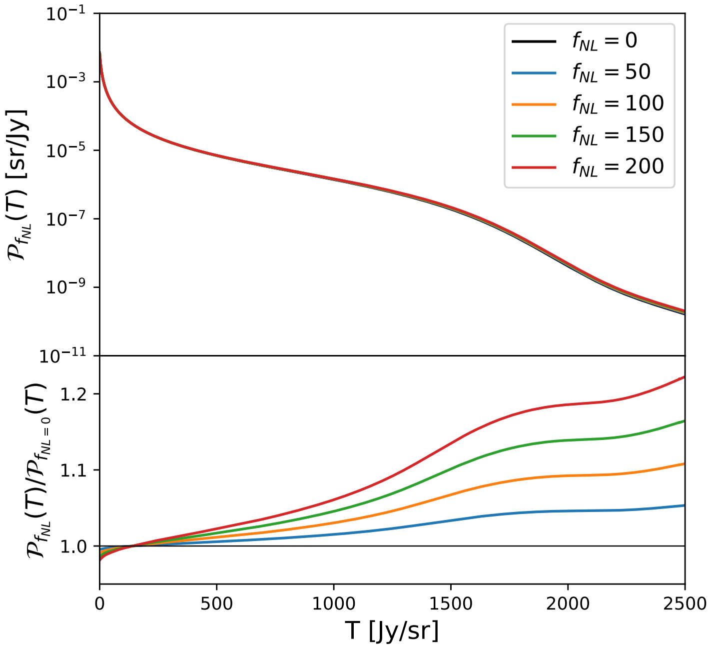

Sato-Polito, Bernal+ (2021)

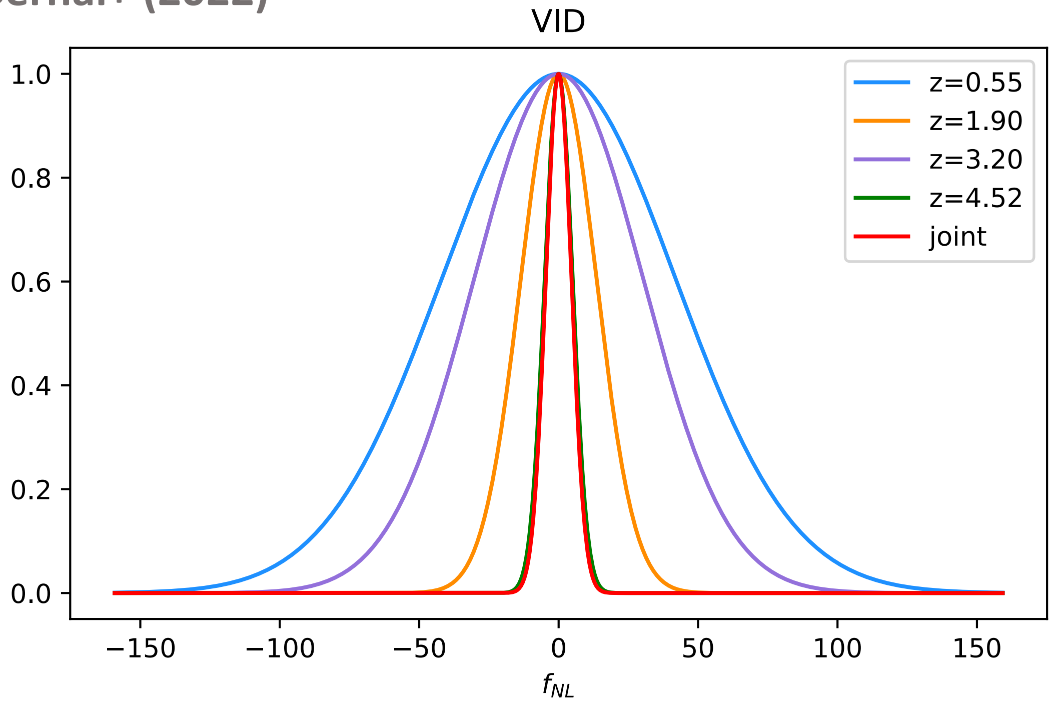
See Neha's talk for more in kSZ bispectrum and velocity reconstruction

# Using LIM for local PNG: VID

- Histogram: estimator for PDF -> given an astro model $L(M_h)$, sensitive to $\mathcal{P}(N) \rightarrow$ HMF
- HMF sensitive to PNG: $\left(\frac{dn}{dM}\right)_{NG} = \left(\frac{dn}{dM}\right)_{G} (1 + \Delta_{HMF}(\kappa_3, \nu))$
- Analytic covariance to combine with P(k) **Sato-Polito & Bernal+ (2022)**




SPHEREx, H$\alpha$, $z = 3.2$

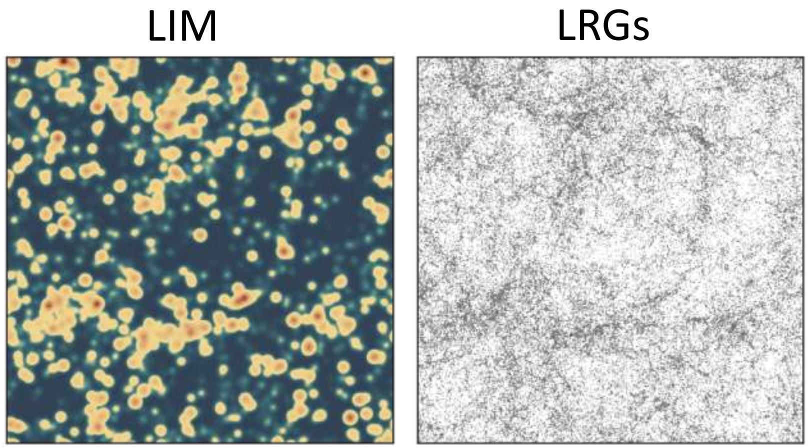
**PRELIMINARY**

Sato-Polito, Kokron, Bernal (in prep)

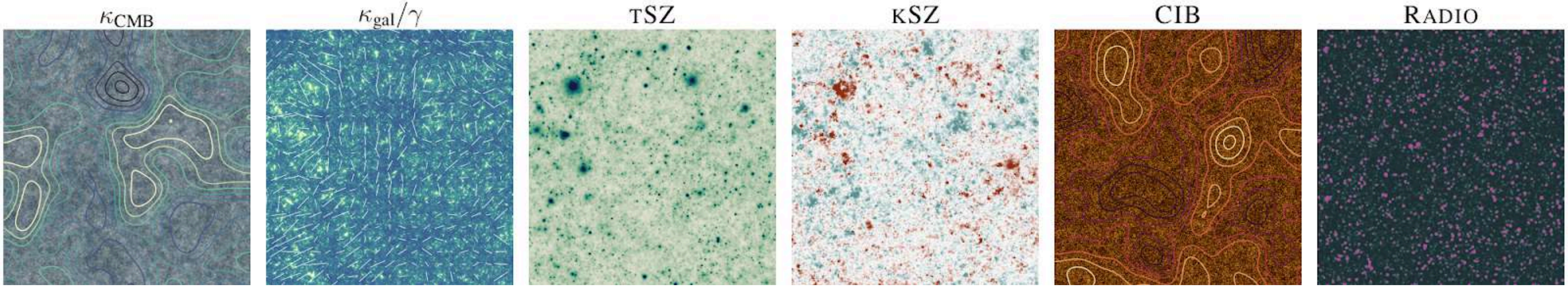
# Using LIM for local PNG: SkyLine

- SkyLine: Mock LIM lightcones (almost any line, contaminants, etc), including also LRGs + ELGs
- Coherent with MDPL2 Synthetic Skies: CMB secondaries and galaxy lensing

Omori (in prep)



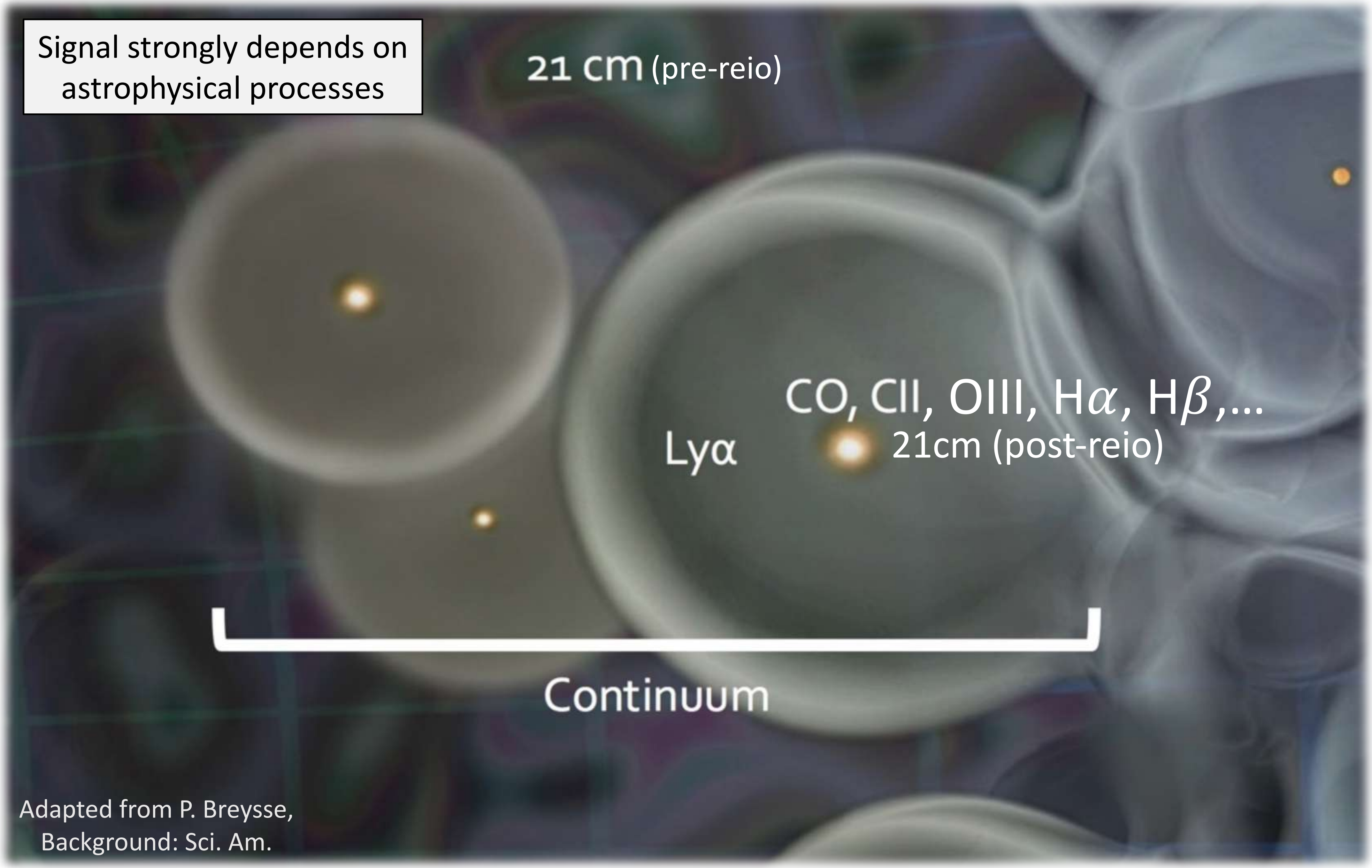

- First mocks that self-consistently models line-intensity, galaxies and CMB secondaries
- Can be used to test PNG if initial halo catalog simulated with PNGs



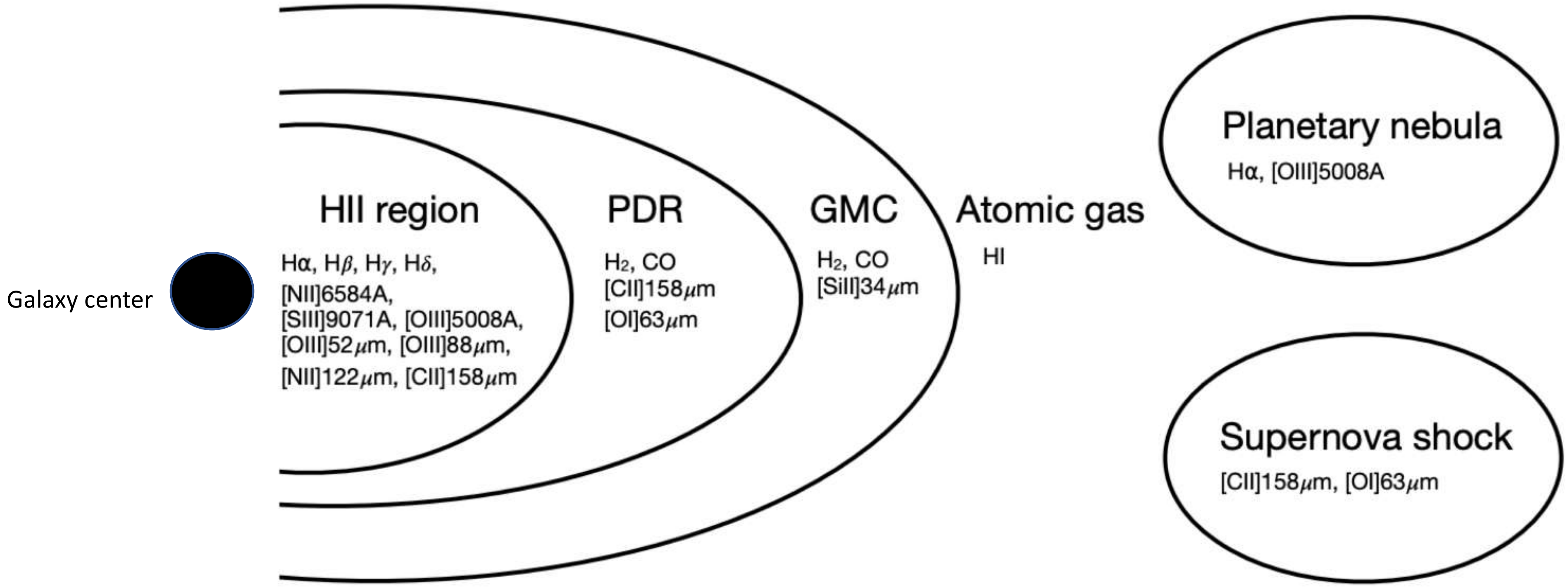
# Conclusions

- LIM holds a great protential for cosmology (and astrophysics)
- Reach for higher redshift and bigger volumes at lower cost
- Intrinsic multi-tracer nature + lots of overlap and synergies with other observables
- P(k), kSZ tomography, VID, … many different paths to probe local PNG, and distinguish from similar k-dependent biases as CIPs
- Lots to do (challenges, new science cases): come talk to me if you’re curious!

# Back up slides




Adapted from P. Breysse,
Background: Sci. Am.




Adapted from Schaan & White 2021

# Experimental details

## LIM

- CCAT-prime: The Epoch of Reionization Spectrometer (EoR-Spec), designed to probe CII emissions at z = 3.5-8.1, over 8 deg² of the sky, with 4000h of observing time, and resolution $R=\delta\nu/\nu=100$
- AtLAST: next-generation 50m single dish telescope with the goal of probing large-scale structure. Map 7500 deg² from redshifts z=1-5 for the CII line

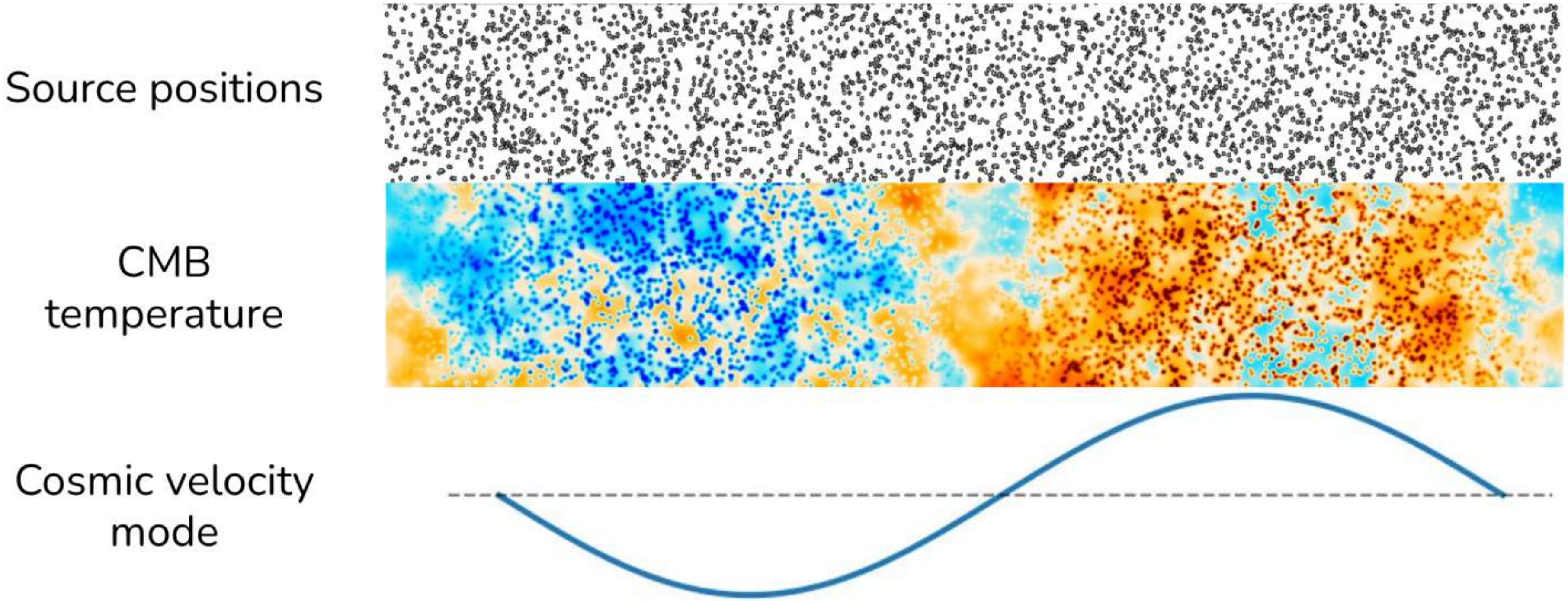
## CMB

- Simons Observatory (SO): early 2020s CMB experiment with a wide field-of-view, covering ~40% of the sky, with 1.4 arcmin resolution and a white noise level of 6 μK-arcmin
- CMB-S4: designed to test inflation, neutrino mass, and search for new light particles. Design still unspecified, but we assume 1 arcmin resolution and a white noise level of 1 μK-arcmin

Slide by G. Sato-Polito

# Velocity field

Reconstruct large-scale peculiar velocity field from CMB temperature and large-scale structure survey



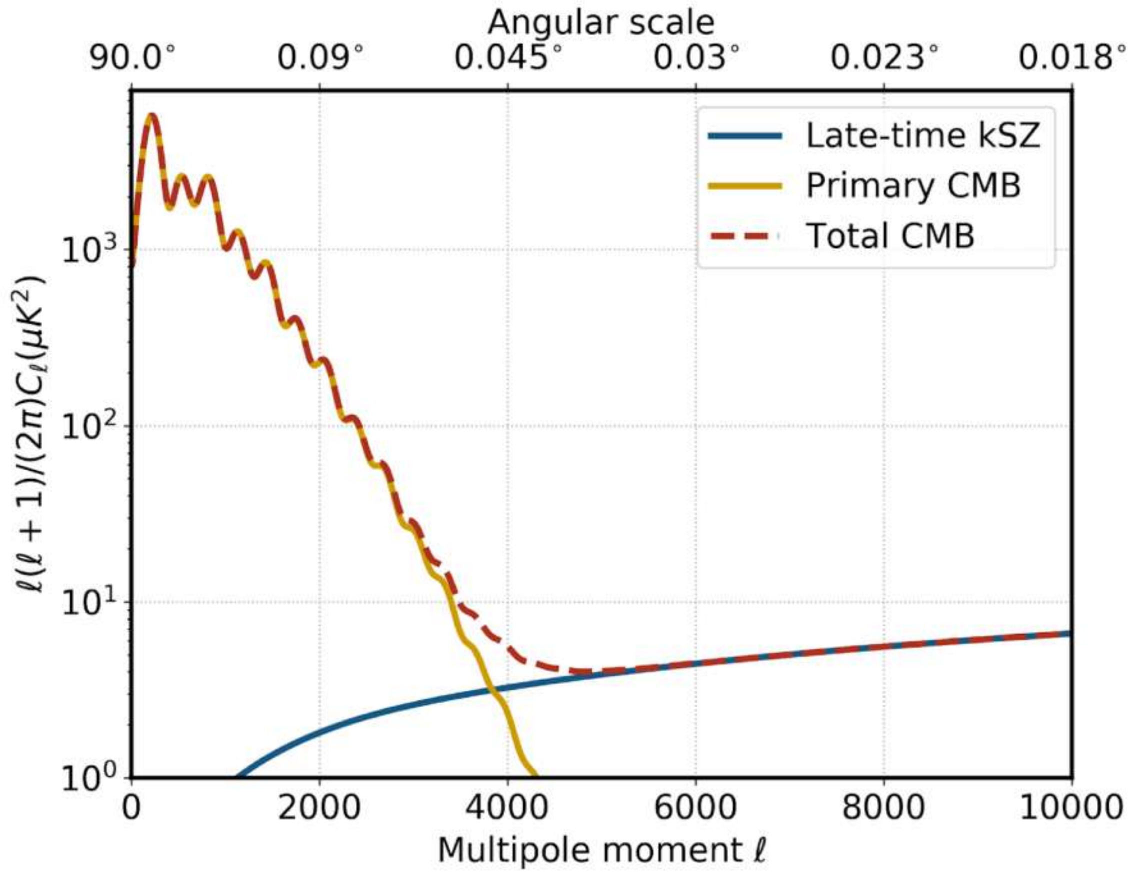

$$\hat{v} \propto \langle T\delta \rangle$$

Figure by Mathew Madhavacheril

Slide by G. Sato-Polito

# kSZ effect

Integrated effect is imprinted on the CMB




Slide by G. Sato-Polito

# kSZ bispectrum framework

Underlying signal in many different statistical approaches is captured by the 3-point function $\langle T\delta\delta\rangle$ (Smith et al 2018)

In particular, this framework includes **radial velocity reconstruction**:

$$\hat{v}_r(\boldsymbol{k}_L) \propto \langle T\delta\rangle_{\boldsymbol{k}_S}$$

Estimate large-wavelength velocity modes by averaging over short-wavelength modes in the CMB map and matter tracer

Slide by G. Sato-Polito

# kSZ detectability with LIM

For future CMB and intensity mapping of the CII fine structure transition

| Experiments | Detection significance | Redshift |
|---|---|---|
| CCAT-prime + SO | $<1\sigma$ | 3.7 |
| CCAT-prime "Phase II" + SO | $\sim3\sigma$ | 3.7 |
| AtLAST + CMB-S4 | $O(10^2 - 10^3)\sigma$ | 1-5 |

Slide by G. Sato-Polito

# Case study: theories of the early universe

## Primordial non-Gaussianity

- One of the key predictions is the probability distribution function of the primordial fluctuations
- Deviations from Gaussianity are parametrized as

$$\Phi(\mathbf{x}) = \Phi_{\mathrm{G}} + f_{\mathrm{NL}}\left[\Phi_{\mathrm{G}}^2(\mathbf{x}) - \langle\Phi_{\mathrm{G}}^2(\mathbf{x})\rangle\right]$$

## Compensated Isocurvature Perturbations

- Consider baryon fluctuations that are compensated by dark matter fluctuations
- Amplitude is parametrized as

$$A_{\mathrm{CIP}} = \frac{\text{isocurvature}}{\text{adiabatic}}$$

Slide by G. Sato-Polito

# Voxel Intensity Distribution (VID)

- Probability P(T) that a voxel has a temperature T
- Estimator = histogram
- Given by the probability that a voxel contains N emitters, and that these N emitters produce a total temperature T

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N)$$

$$\downarrow$$

$$\propto \left(\underbrace{\Phi * \Phi * \ldots * \Phi}_{N}\right)(T)$$

Breysse et al. (2016, 2017)

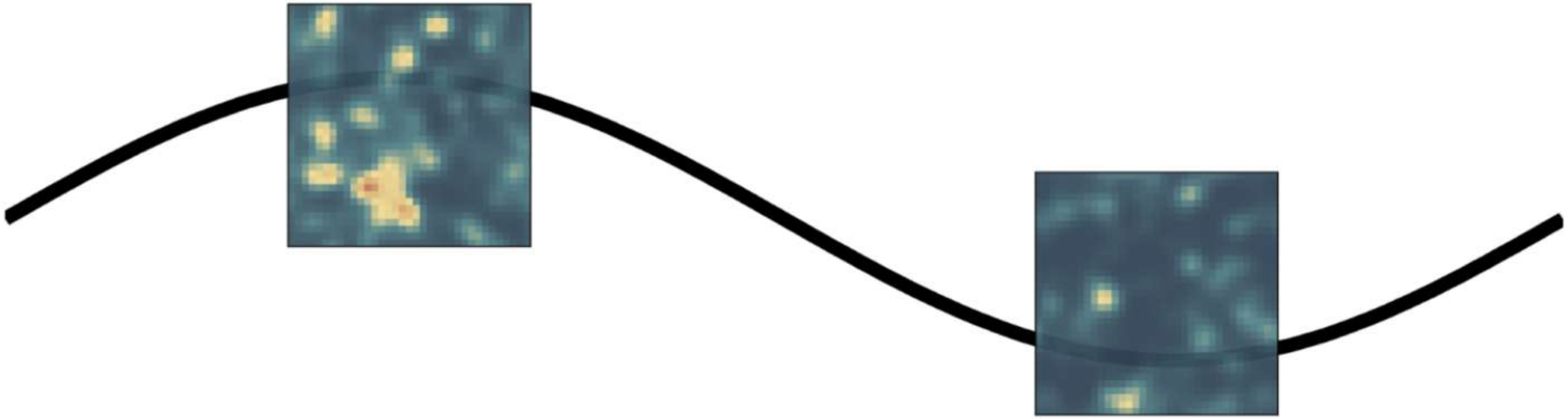
Slide by G. Sato-Polito

# Combining observables (PS+VID)

$$\propto \left(\underbrace{\Phi * \Phi * \ldots * \Phi}_{N}\right)(T)$$

$$P(k,z) = \langle T(z)\rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}$$

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N)$$



How can we understand the covariance between the power spectrum and the VID? GSP, José Luis Bernal, arXiv:2202.02330

Slide by G. Sato-Polito

# PS+VID

Extended VID formalism by considering position-dependent PDFs

- Promote the probability that a voxel contains N halos to a position/density dependent quantity

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N) \longrightarrow \mathcal{P}(T|\delta(\boldsymbol{x})) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N|\delta(\boldsymbol{x}))$$

- P(N) is now a Poisson distribution where the mean is determined by the matter density in a voxel

$$\mathcal{B}_i = \frac{N_{\rm vox}}{V_{\rm field}} \int_{\Delta T_i} {\rm d}T \int_{V_{\rm field}} {\rm d}^3\boldsymbol{x} \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}_{\rm Poiss}(N, \bar{N}_h) \left[1 + \delta_h^{\rm v}(\boldsymbol{x})(N - \bar{N}_h)\right]$$

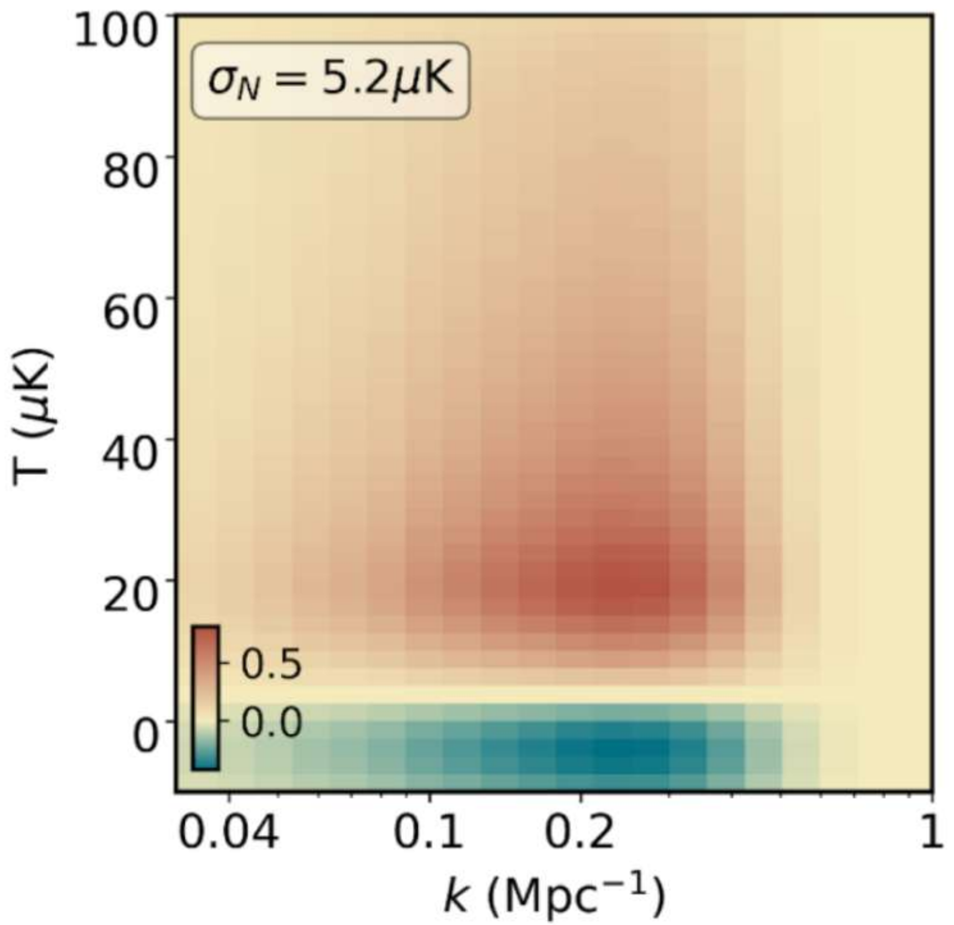
Slide by G. Sato-Polito

# PS+VID for COMAP

- CO Mapping Array Pathfinder (COMAP) test case
- Consider the CO J=1→0 line at z = 2.4-3.4 for the Y5 sensitivity

Correlation coefficient

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




Slide by G. Sato-Polito

# Conclusions

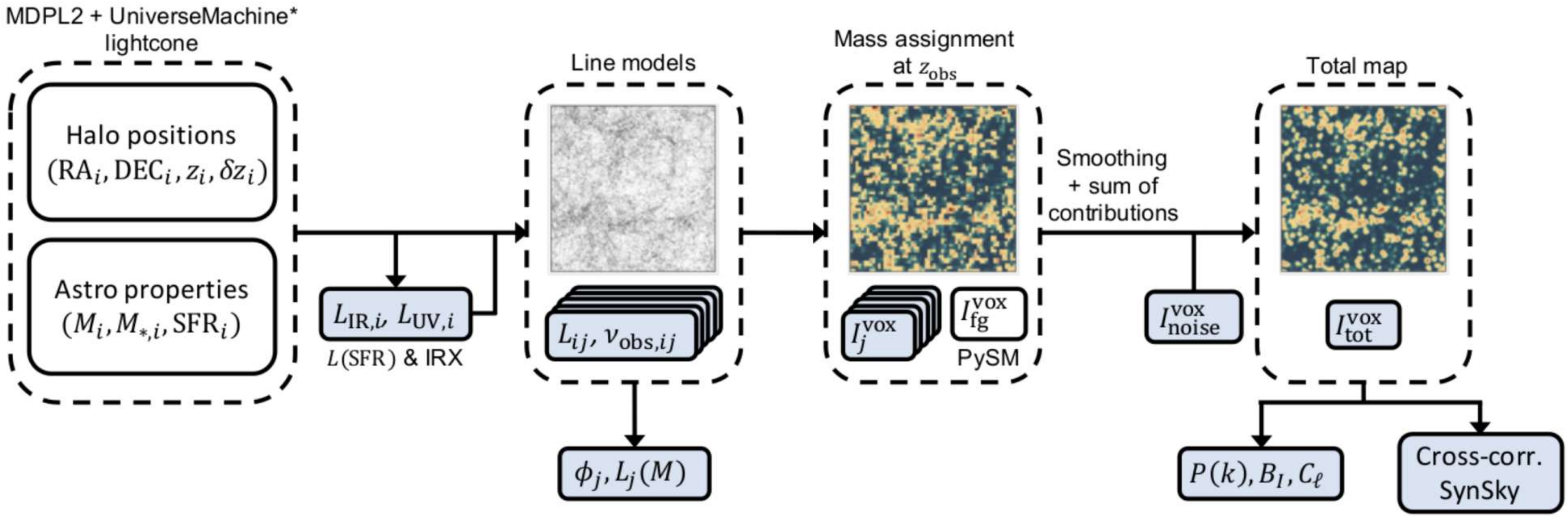
- Provided a general framework for understanding the joint information in 1- and 2-point statistics for temperature maps
- Agreement between analytical and numerical covariances
- Can be applied to any spectral line, epoch of the Universe, N-point statistic, etc.
- Combining the VID and the power spectrum can help break degeneracies between astrophysics and cosmology
- Ongoing experiments already have non-negligible cross-covariance!

Next...

- Forecasting constraints on astro and cosmo parameters with a proper covariance (with Vivian Sabla, José Luis Bernal, and Marc Kamionkowski)

Slide by G. Sato-Polito

# Skyline code structure




Slide by G. Sato-Polito