MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Line-intensity mapping: challenges and opportunities

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Introduction

- Precision cosmology: CMB, clustering & BAO, lensing, SNeIa, GWs, …

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- Standard cosmological model: ΛCDM
- Excellent reproduction of the observations, but…
  - Persistent discrepancies between different cosmological probes (high-z vs low-z?): H_0, $\sigma_8\Omega_M^{0.5}$
  - Phenomenological model: nature of DM and DE? Primordial Universe?

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- Excellent reproduction of the observations, but…
- First stars, reionization, galaxy formation and evolution, …
- Improvement of observations, new models, **new probes/observables**, …

Outline

- What is LIM?
- Potential and oportunities
- Optimizing information return
- Observational challenges
- Novel science cases

*If interested, check Bernal & Kovetz 2022, LIM Theory Review

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

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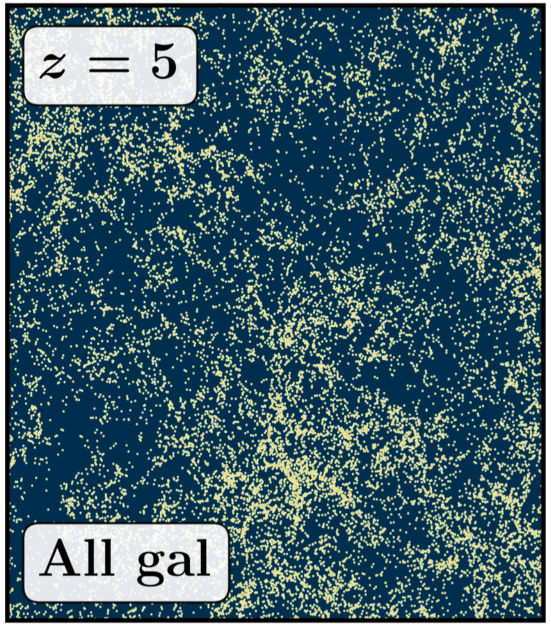
Bernal & Kovetz (2022)



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

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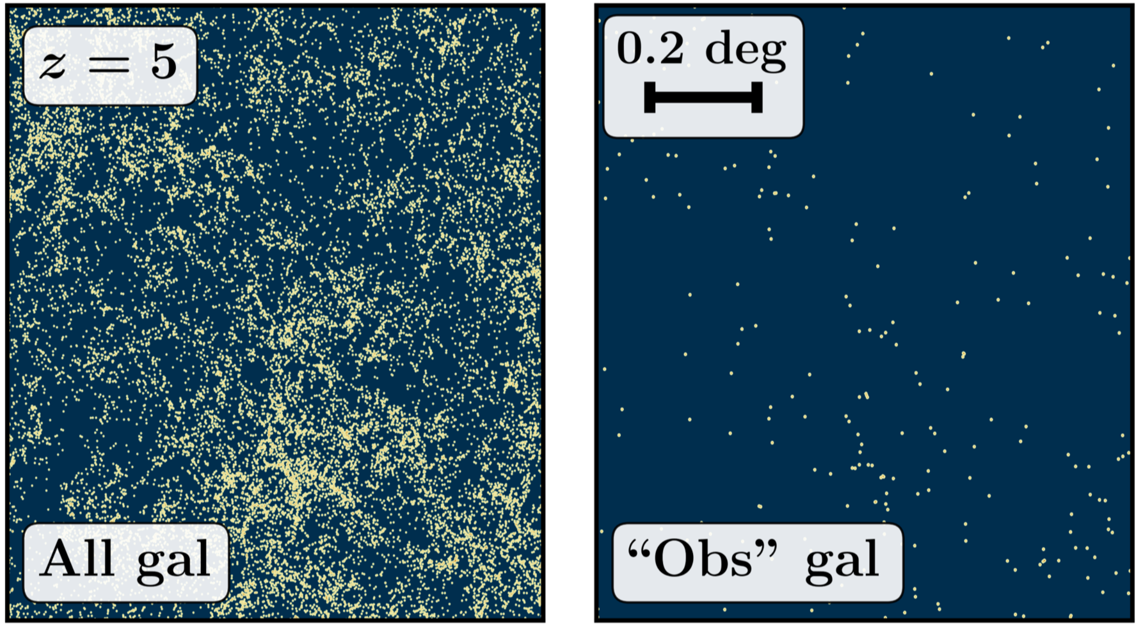

Bernal & Kovetz (2022)

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- All haloes

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

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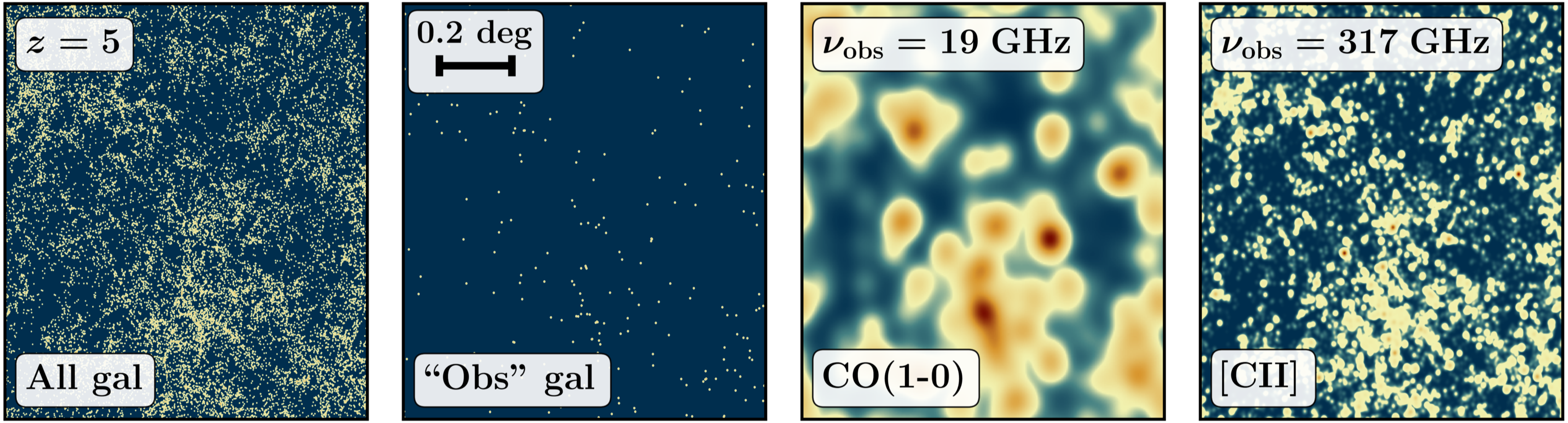
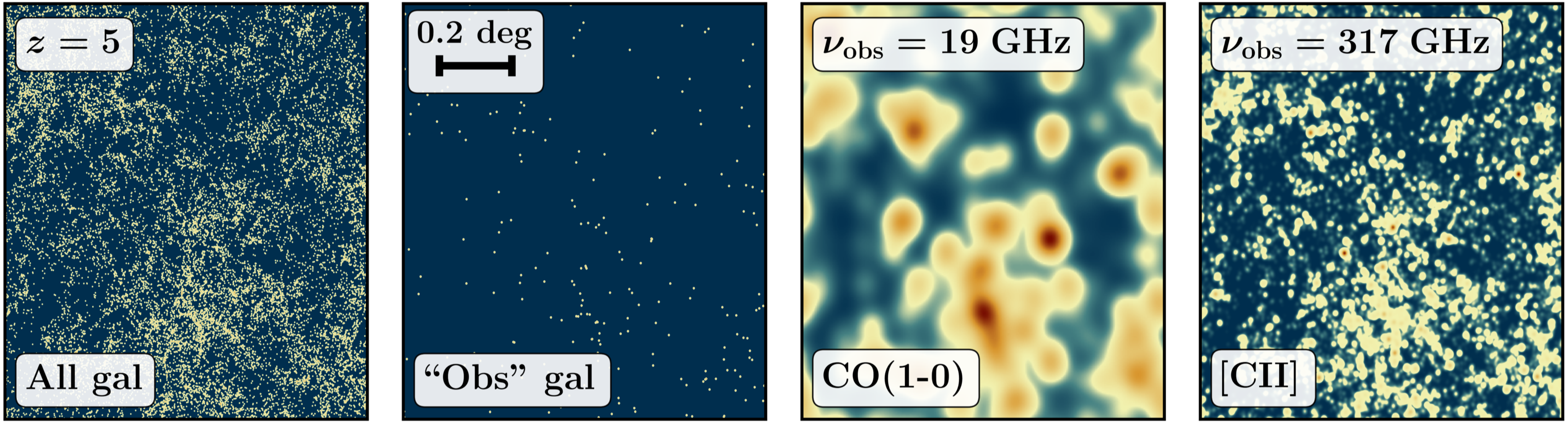


Bernal & Kovetz (2022)

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



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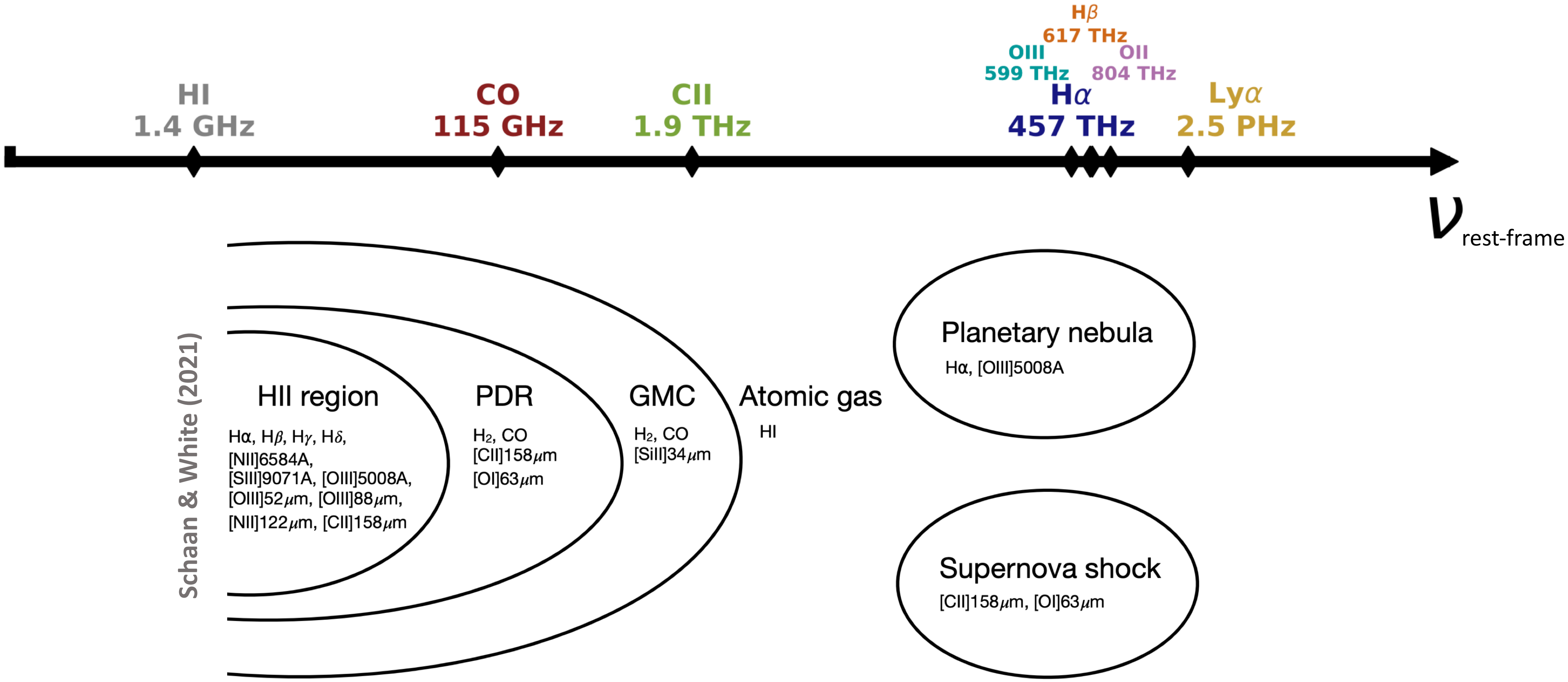
Three main features that make LIM unique:

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

Intrinsically multitracer



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

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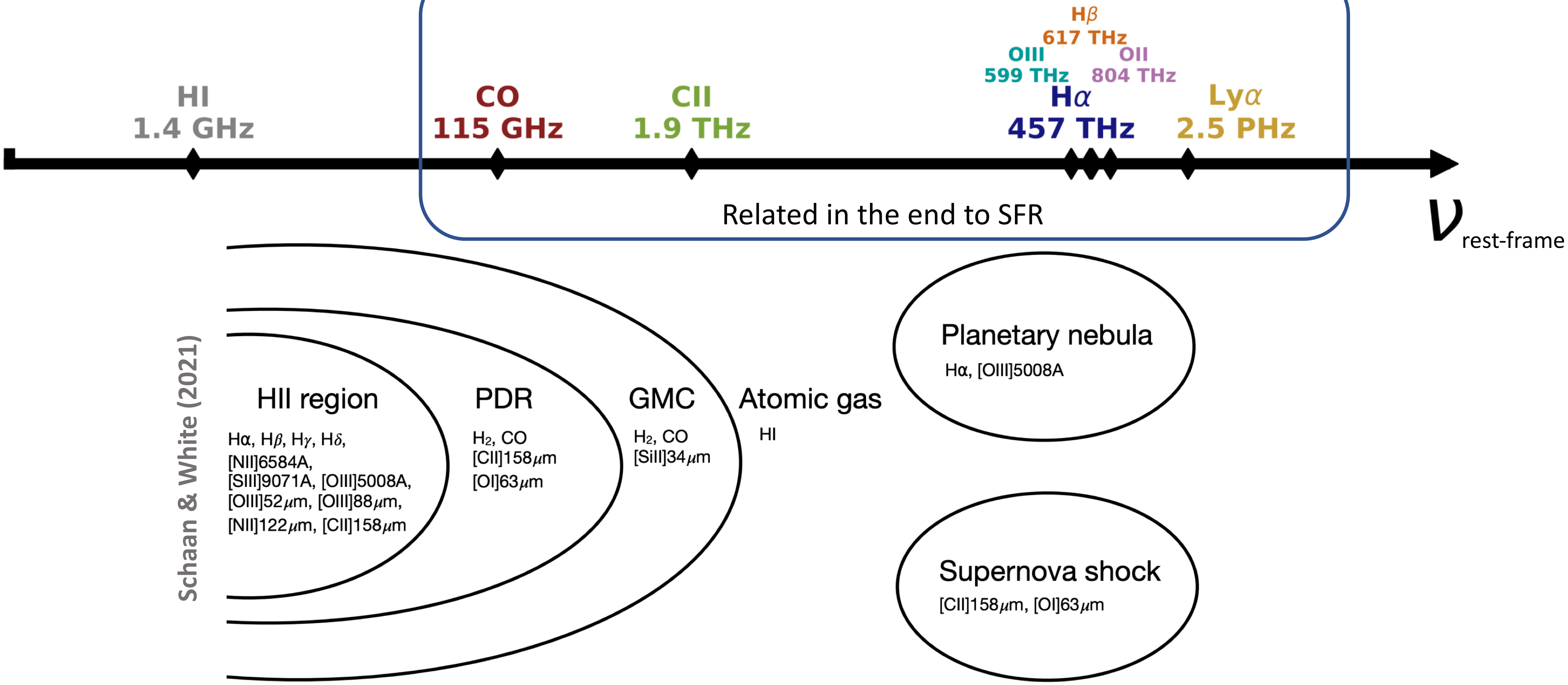
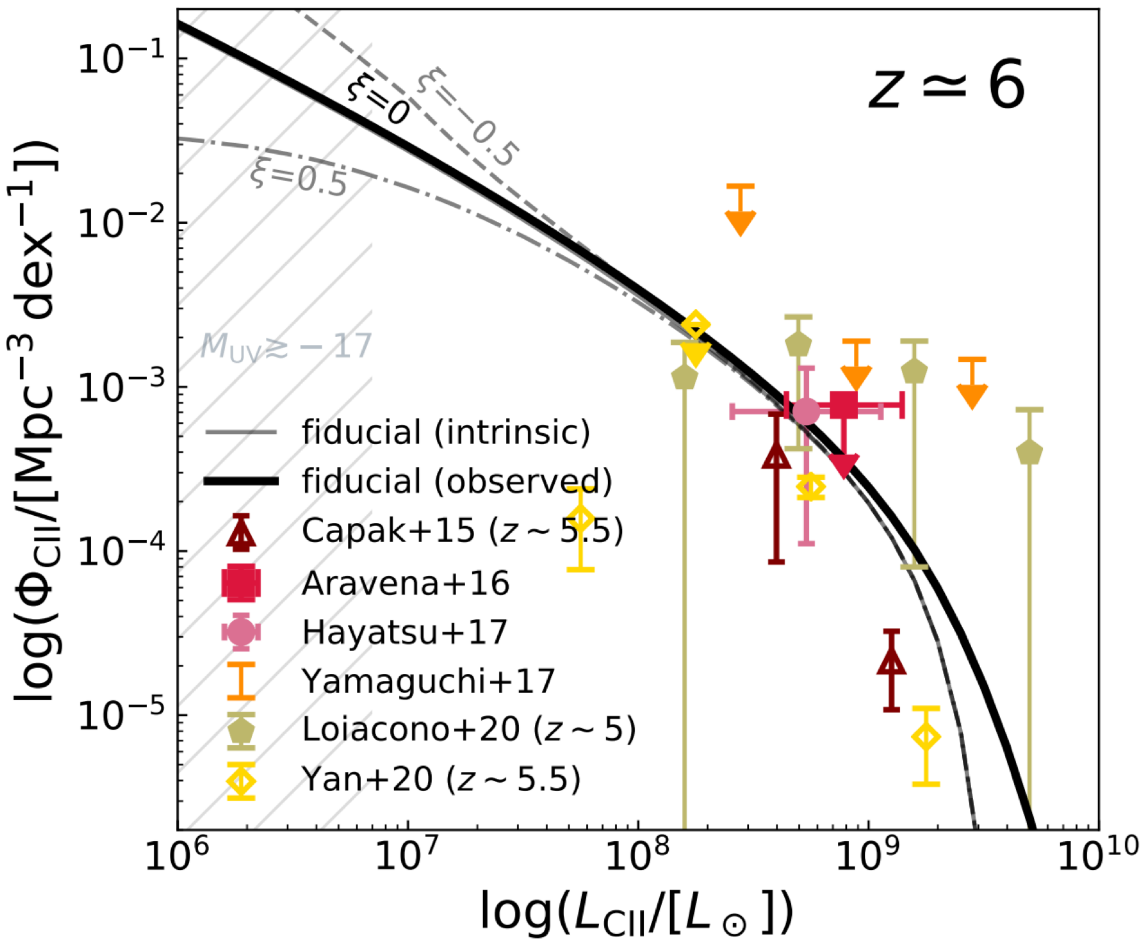
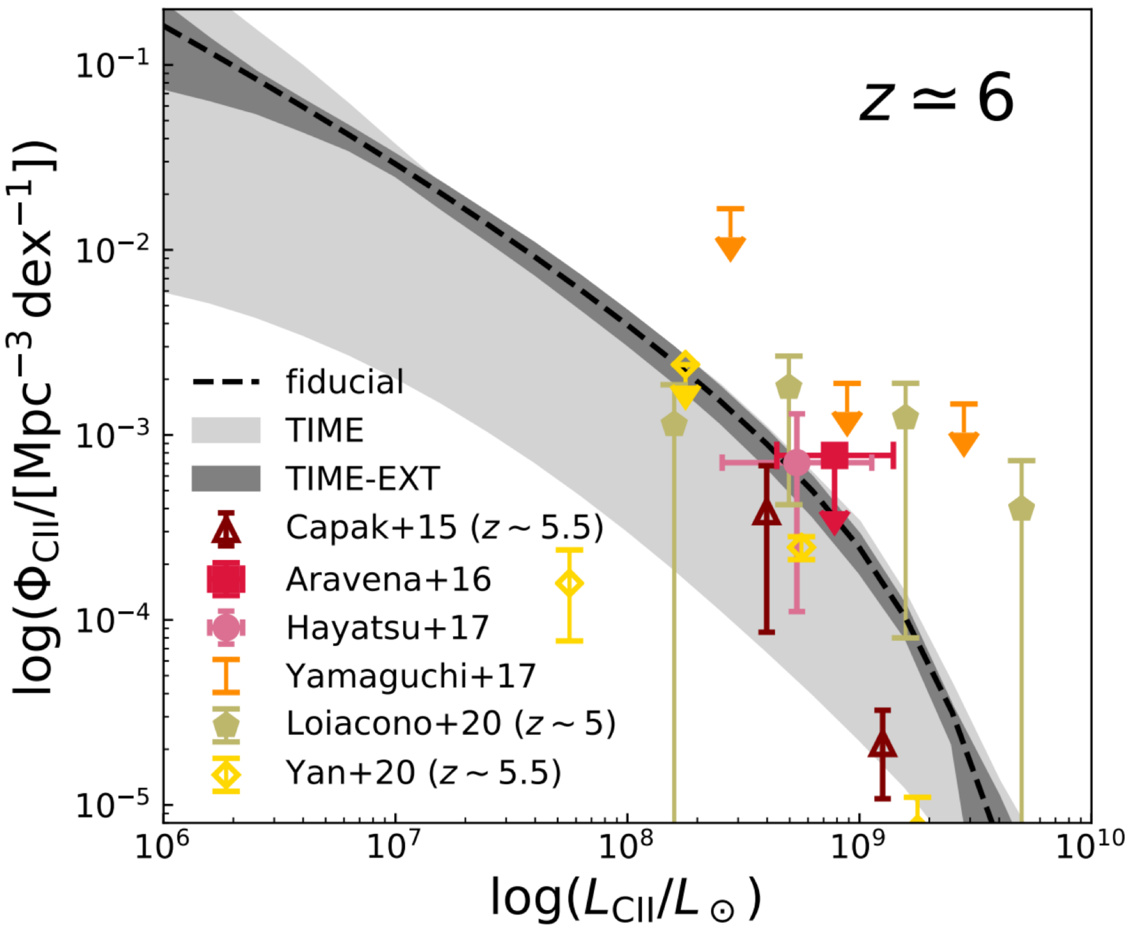


$\Phi(L_1, L_2, \dots)$: combine with continuum, and statistically probe all the SED

Leaving no photon behind

Probes the faint end of the LF (equiv. light end of the HMF)

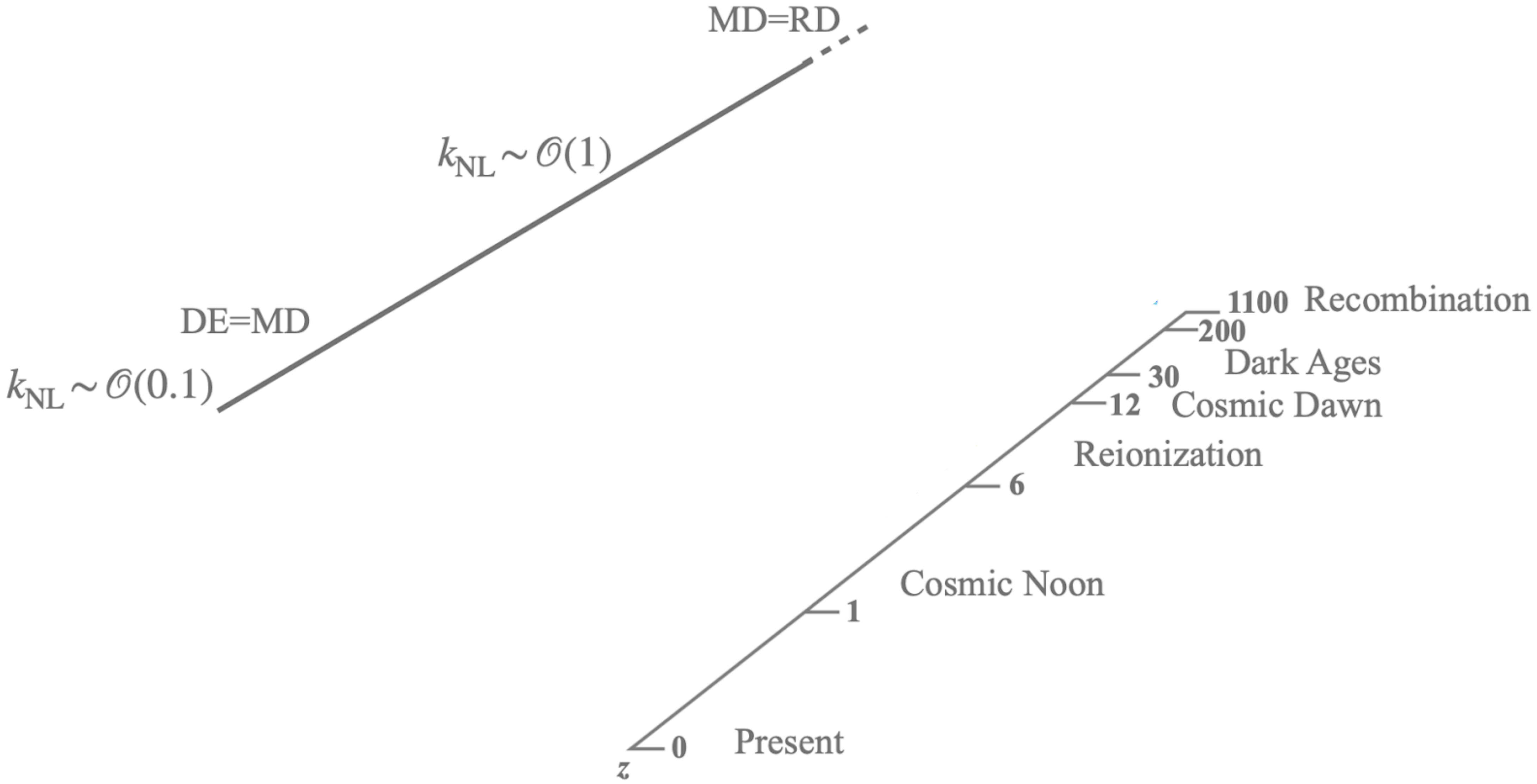




Sun+(2021)

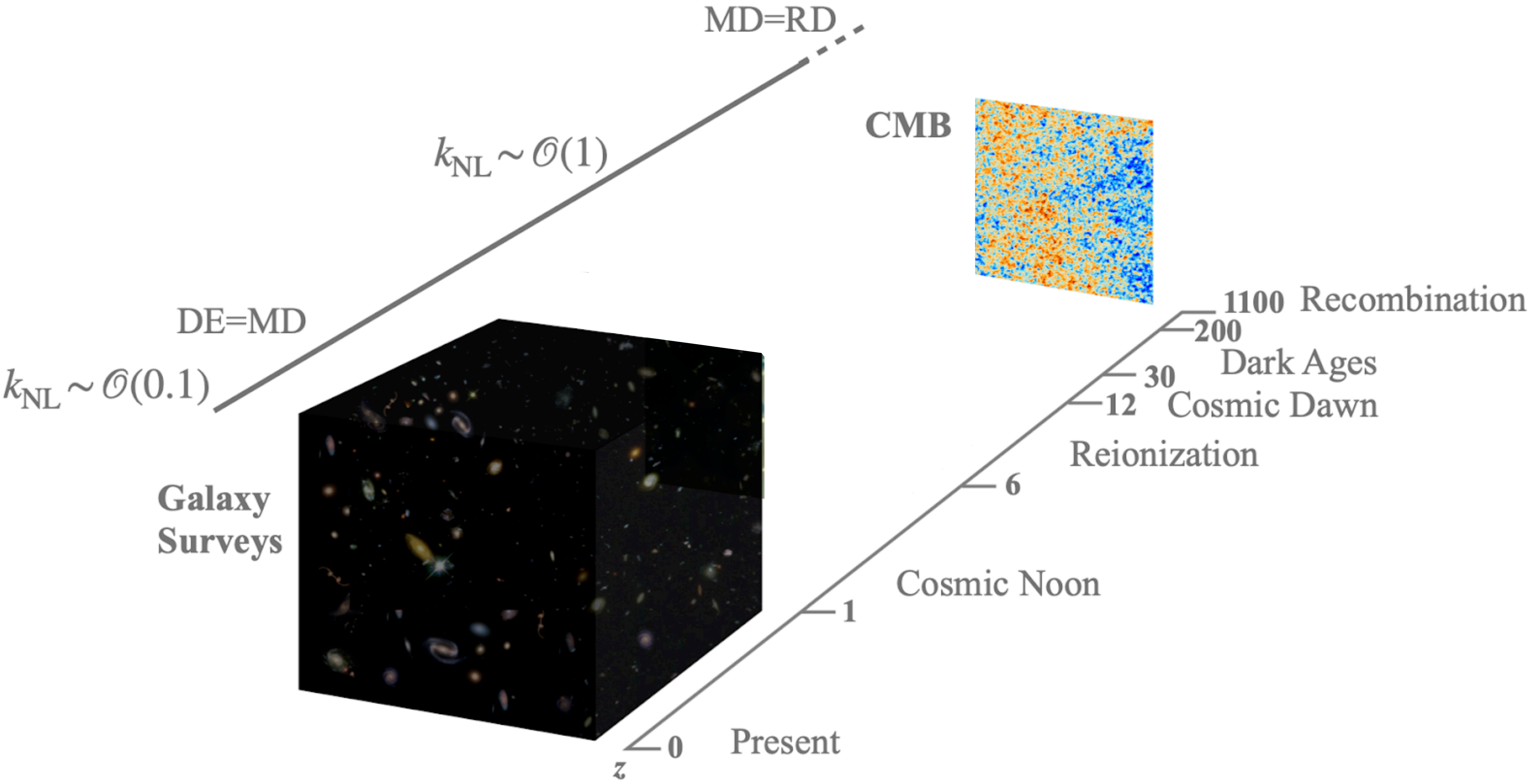
TIME-EXT: More time, less noise, (~ x12 total)

Filling the gaps in cosmic history



Bernal & Kovetz (2022)

Filling the gaps in cosmic history



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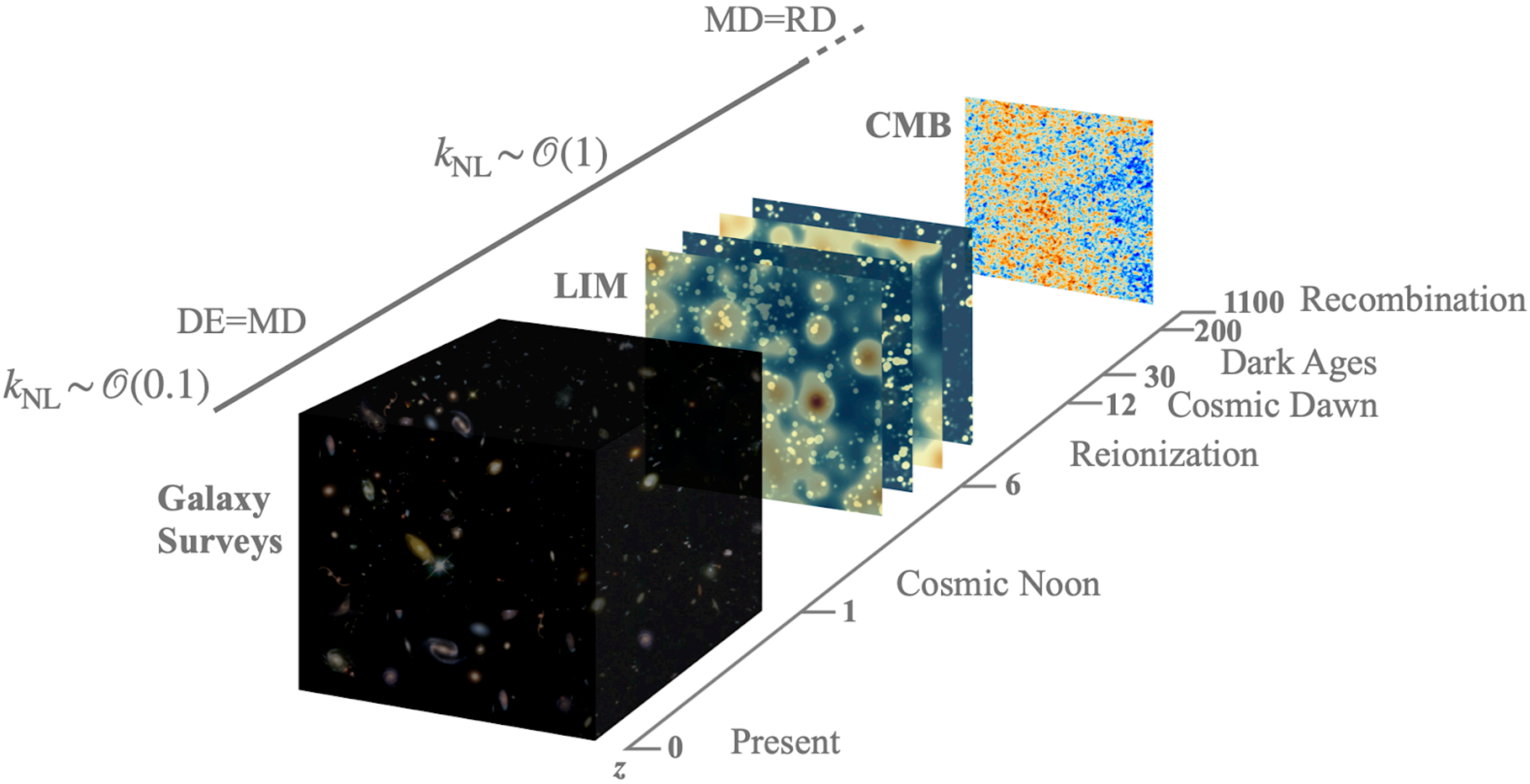

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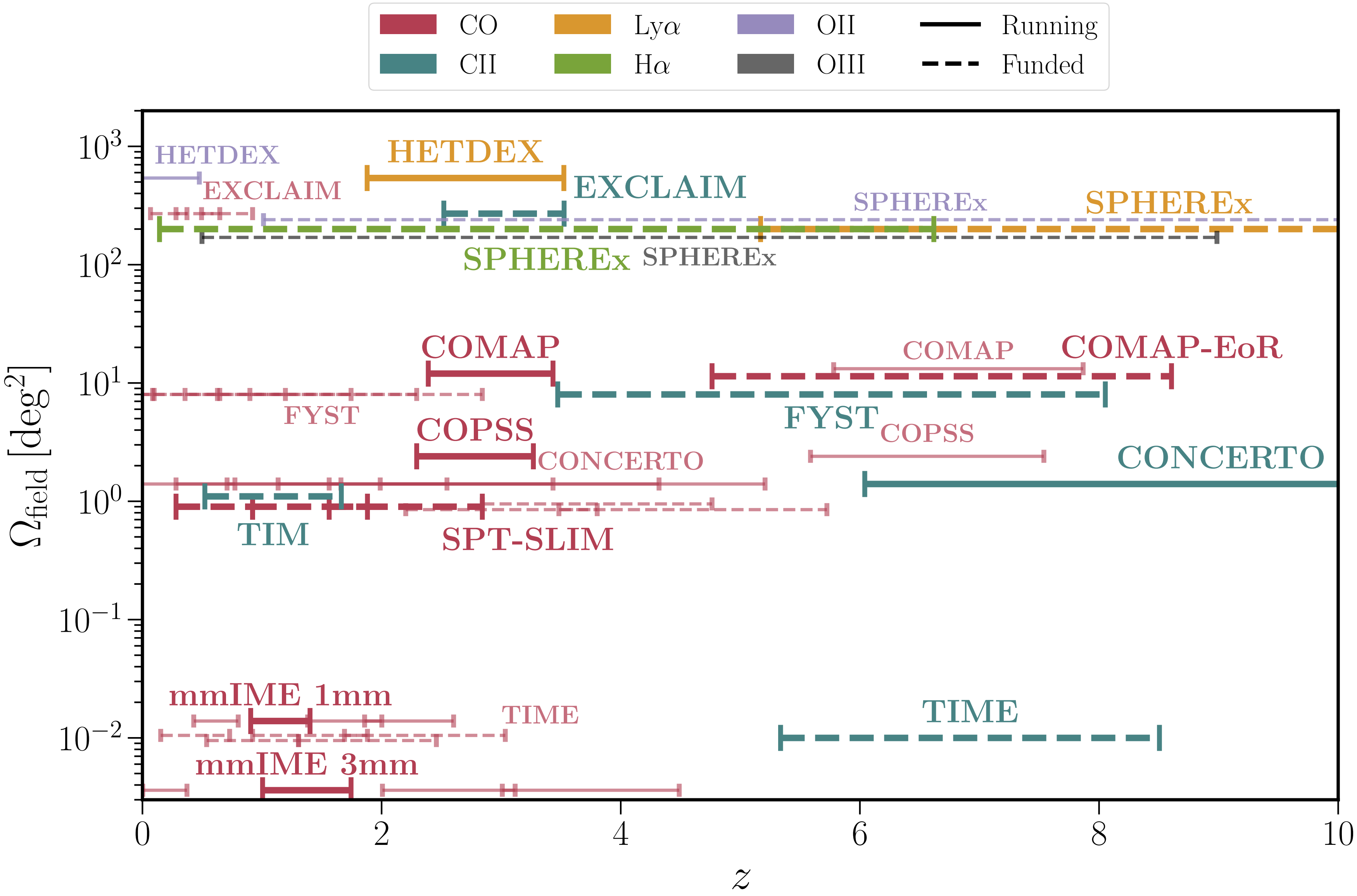

Bernal & Kovetz (2022)

Using LIM for cosmology

- Intensity traces density: cosmological information degenerate with astrophysics

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

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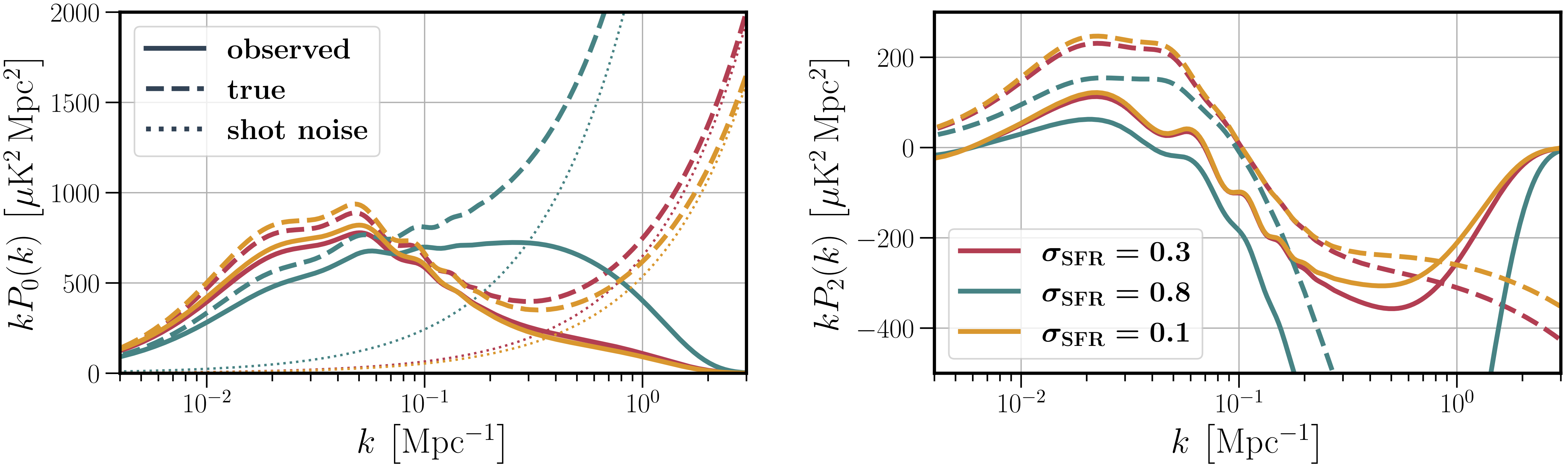

Bernal & Kovetz (2022)

COMAP-like but for 200 deg^2

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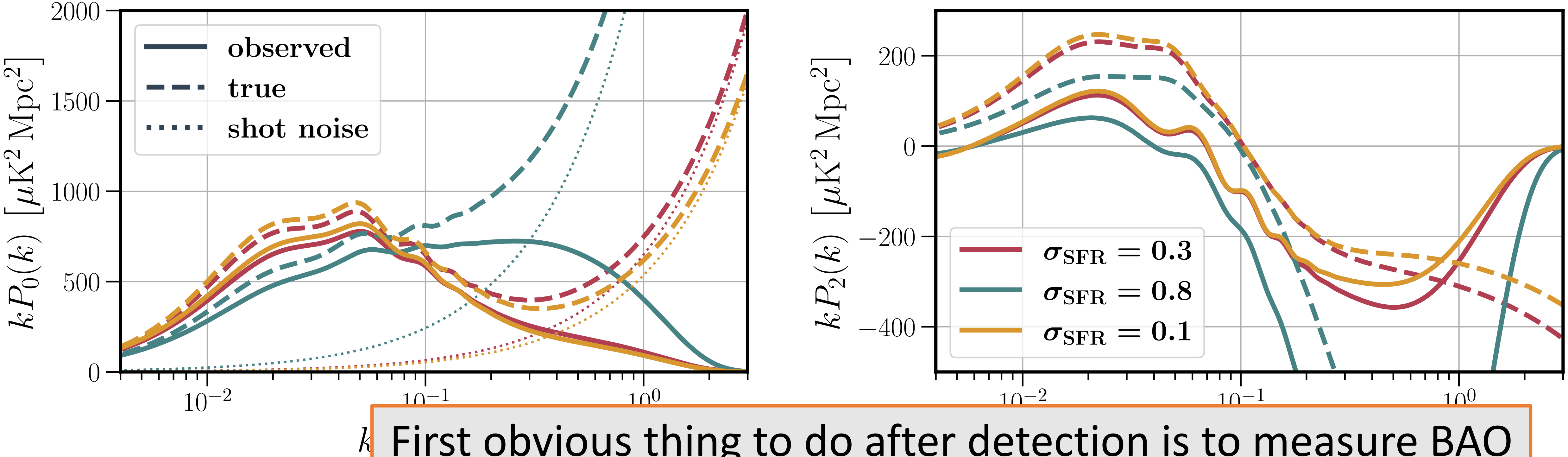
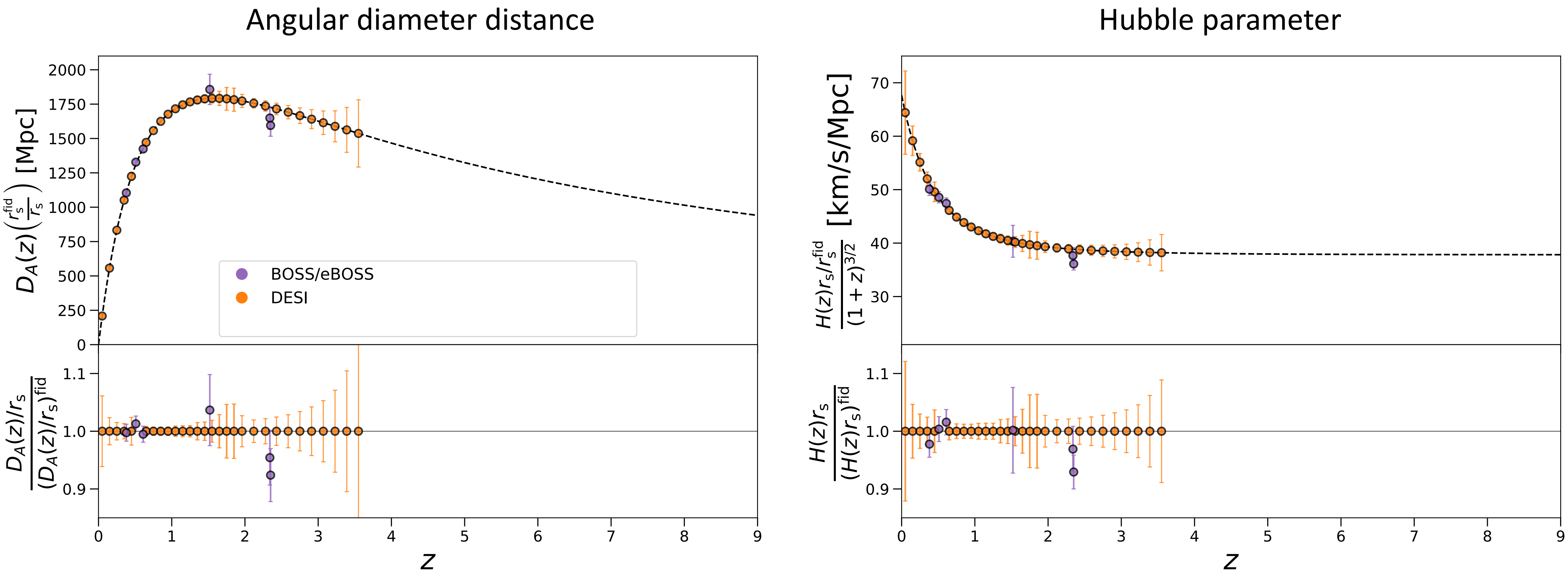


First obvious thing to do after detection is to measure BAO (uncalibrated standard ruler $\propto r_d H_0$)

Bernal & Kovetz (2022)

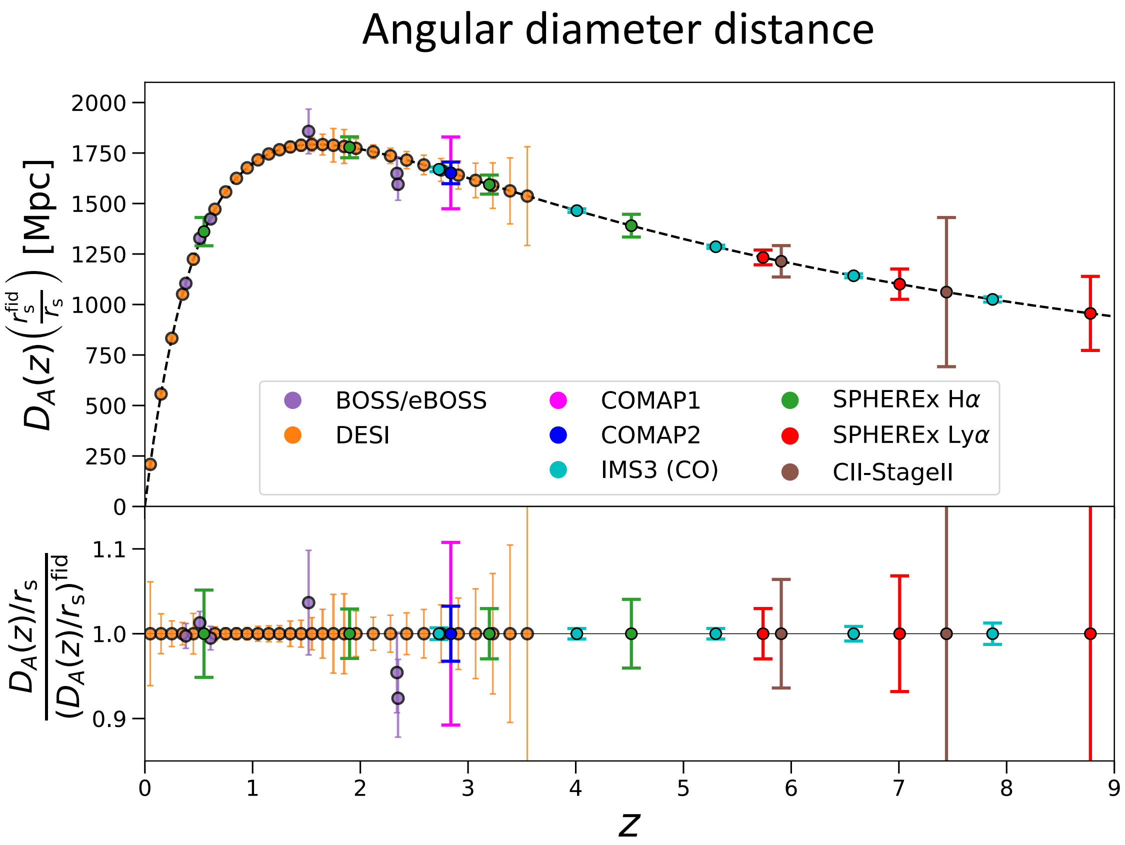
LIM BAO

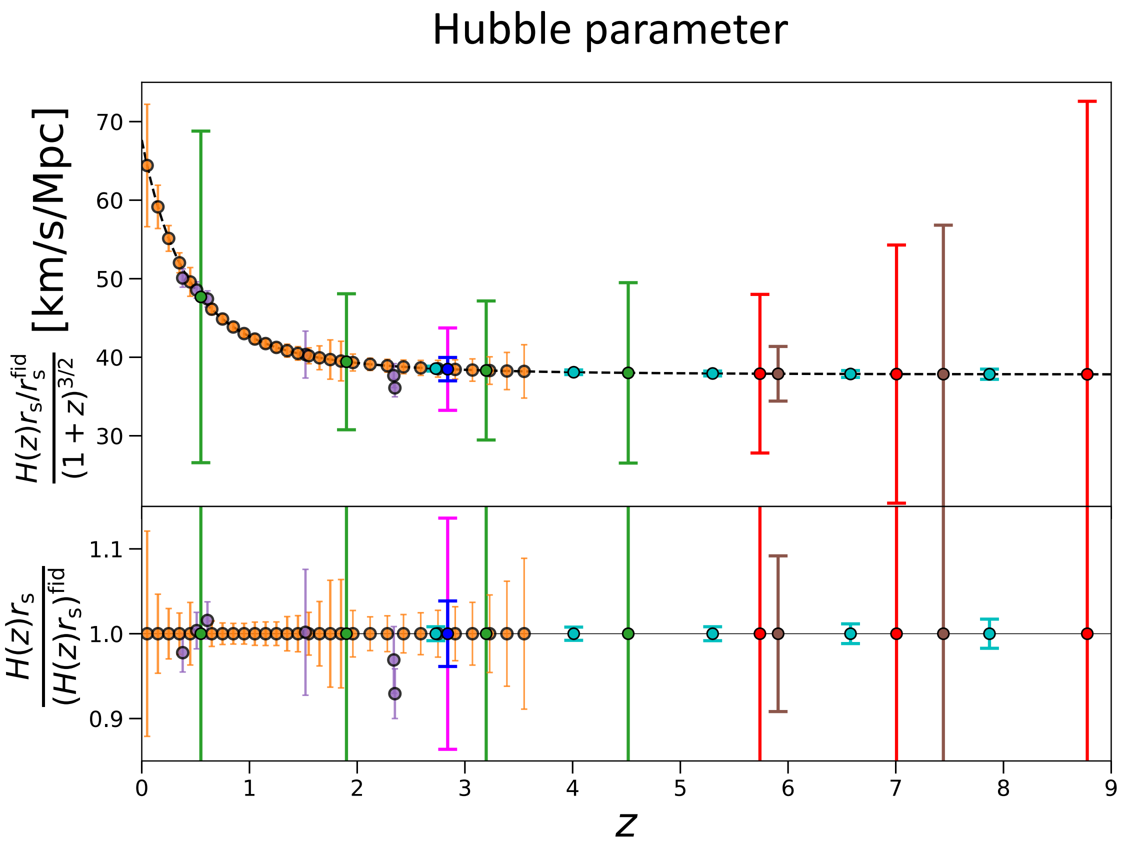


Current and coming constraints using galaxy surveys

Bernal +(2019)

LIM BAO





Current and coming constraints using galaxy surveys

+ Star-Formation-related LIM BAO

Bernal +(2019)

Probing large volumes

$$A_\perp = D_M^2 \Omega_{field} \qquad L_\parallel = \frac{c\Delta\nu(1+z)}{H\nu_{obs}}$$

- At z = 3, $D_M \sim 6.5$ Gpc, $H \sim 300$ km/s/Mpc
- $\frac{V}{\Omega_{field}\Delta\nu/\nu_{obs}} = 40\ \mathrm{Gpc}^3$/sr
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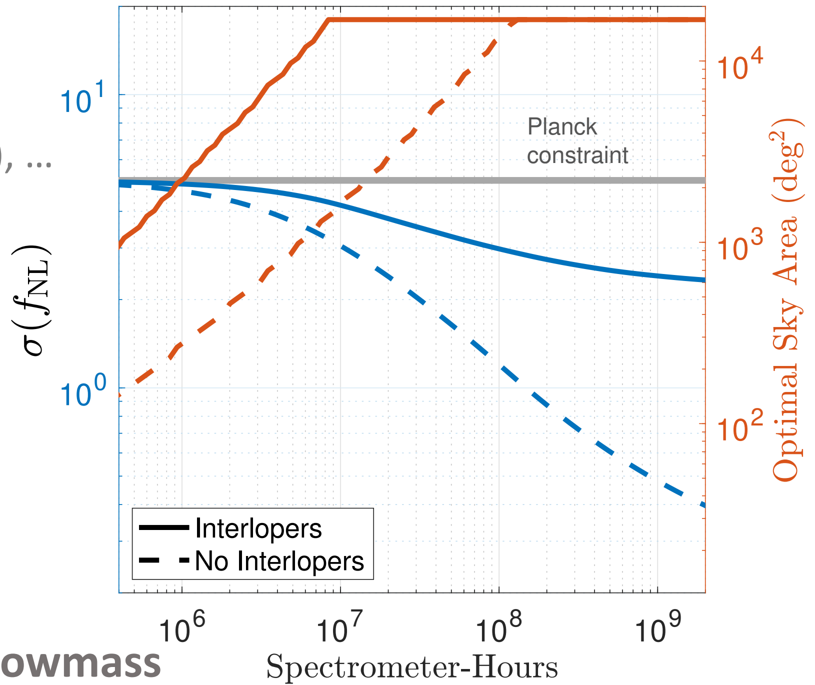
- Measure f_{NL}, through k^{-2} dependence on the P(k)

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



- Very limited by systematics and foregrounds,

  cross correlations help

Karkare+ (2022) Snowmass

Information return from line-intensity maps

- Intensity traces density: cosmological information degenerate with astrophysics

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

- Limitations:
    - Intensity maps are highly non-Gaussian: lots of information beyond P(k)
    - P(k) only depends on 1st and 2nd moments of the luminosity functions
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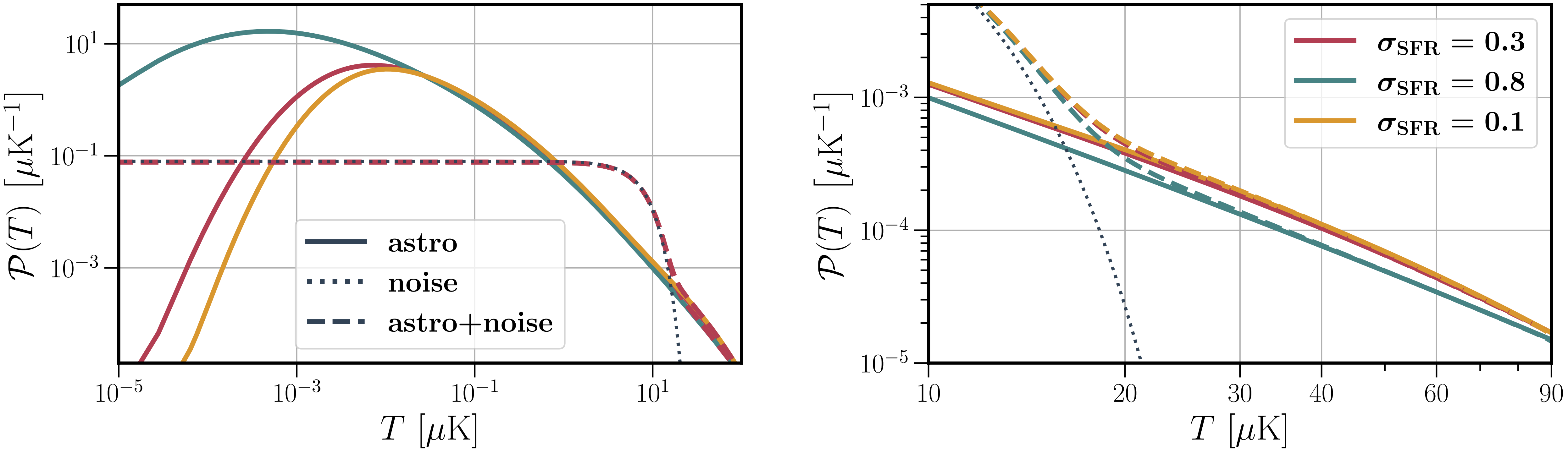

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COMAP-like but for 200 deg^2

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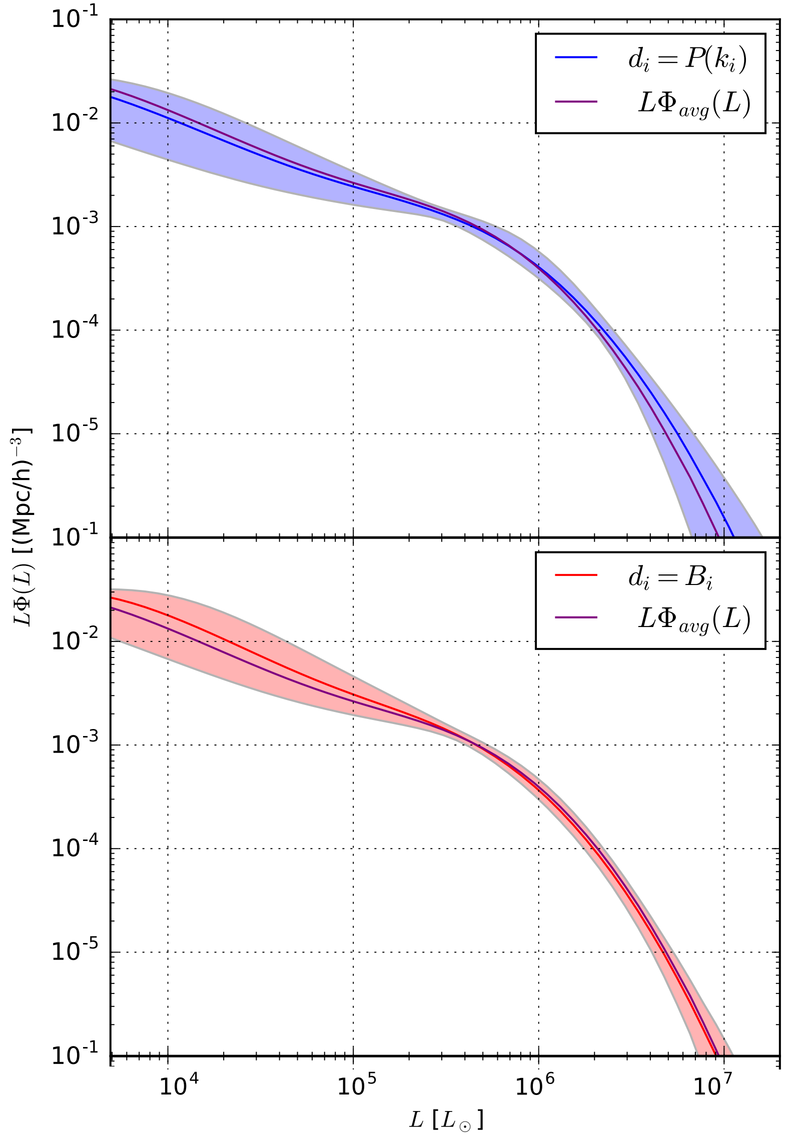
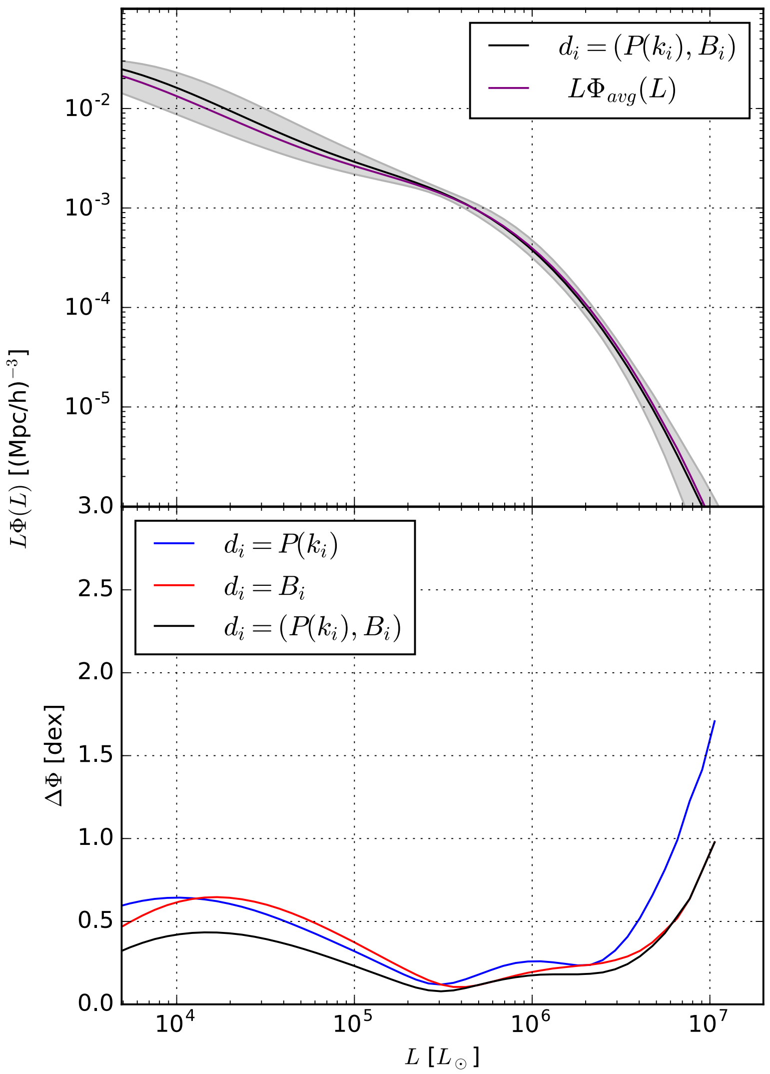
P(k): best for cosmo, integrals of luminosity functions

VID: best for astro, integrals of clustering

Combining VID and P(k)





Ihle+(2019)

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:

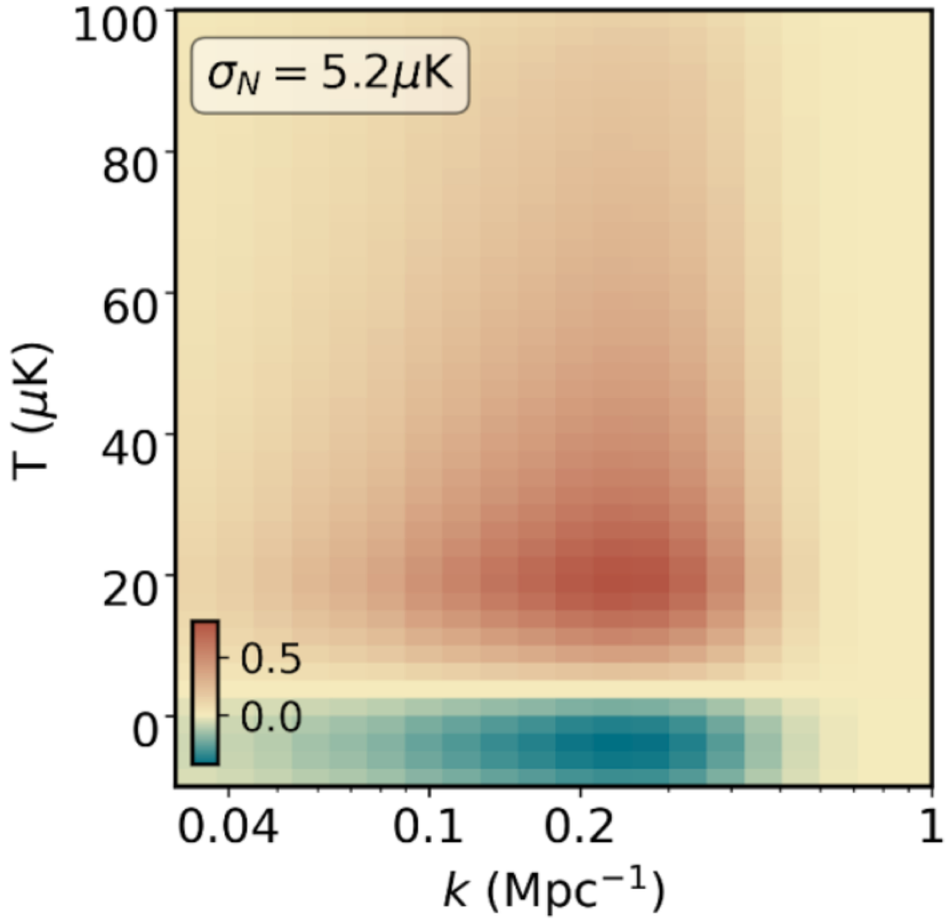
  $$\mathcal{P}(I) \rightarrow \mathcal{P}(I, \delta(\boldsymbol{x}))$$

- Proportional to collapsed bispectrum

- Example for COMAP Y5: CO(1-0), z ~ 2.4-3.4

- Definitely important to take into account

  very soon



Sato-Polito & Bernal (2022)

Contamination of intensity maps

- Continuous foregrounds:
  - Uncorrelated (galactic, not that bad for higher freq)
  - Correlated (CIB, blurring of radial info, loss of long line-of-sight modes)
    - Combine with galaxy surveys Switzer+(2015), Switzer (2017), Switzer+(2018)
    - Neural networks Pfeffer+(2019), Moriwaki+(2021)

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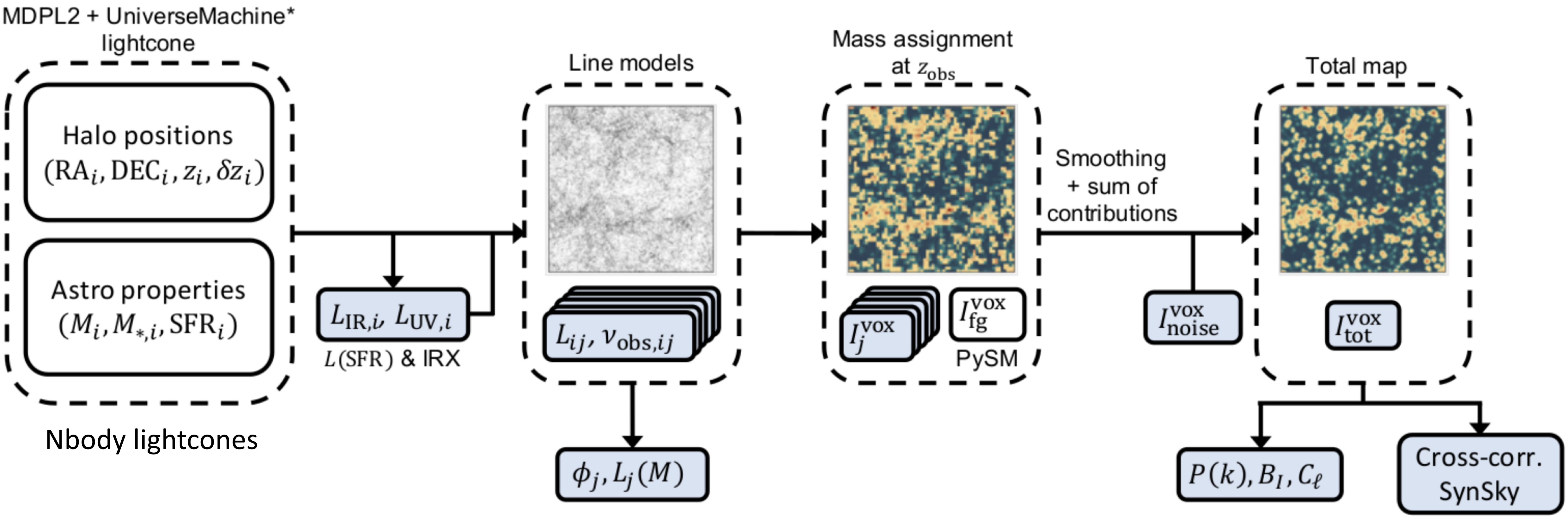
- Line interlopers: Main problem for higher freq. LIM surveys
  - $\nu_{obs} = \nu/(1+z) = \nu'/(1+z')$ → other lines redshifted to same ν_{obs}
  - Two approaches:
    - Masking: targeted (external data) and blind (contaminated voxels are expected to be brighter)

      Breysse+(2015), Sun+(2018)

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

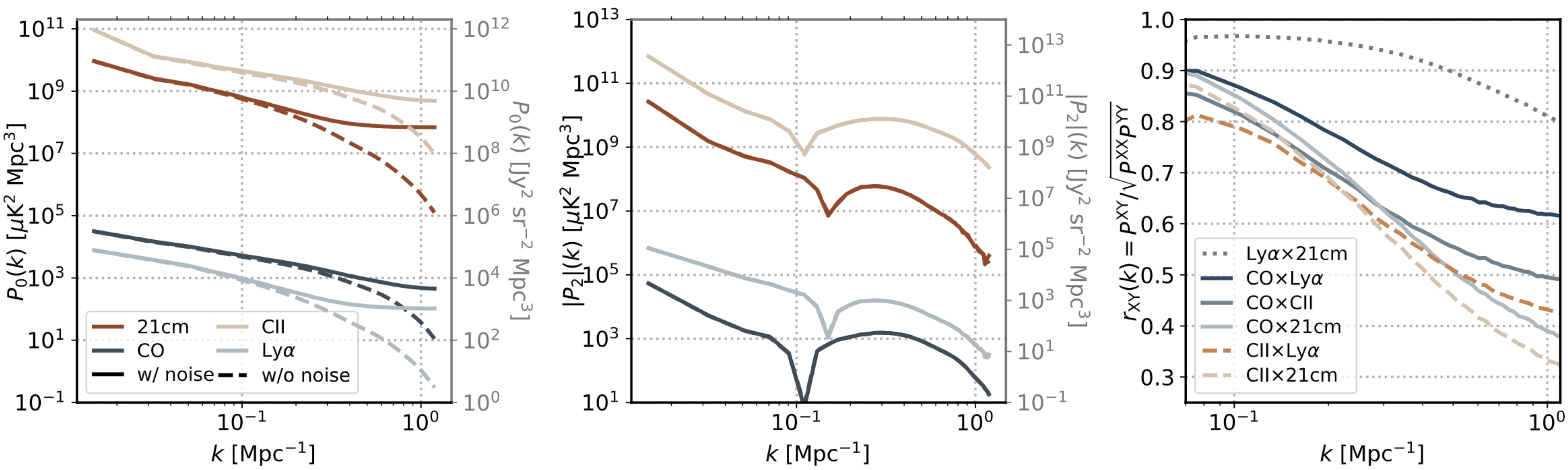
      Lidz & Taylor (2016), Sun+(2018), Gong+(2020), Cheng+(2020)

Skyline code structure



Adapted from a slide by G. Sato-Polito

Power spectra and correlation coefficients

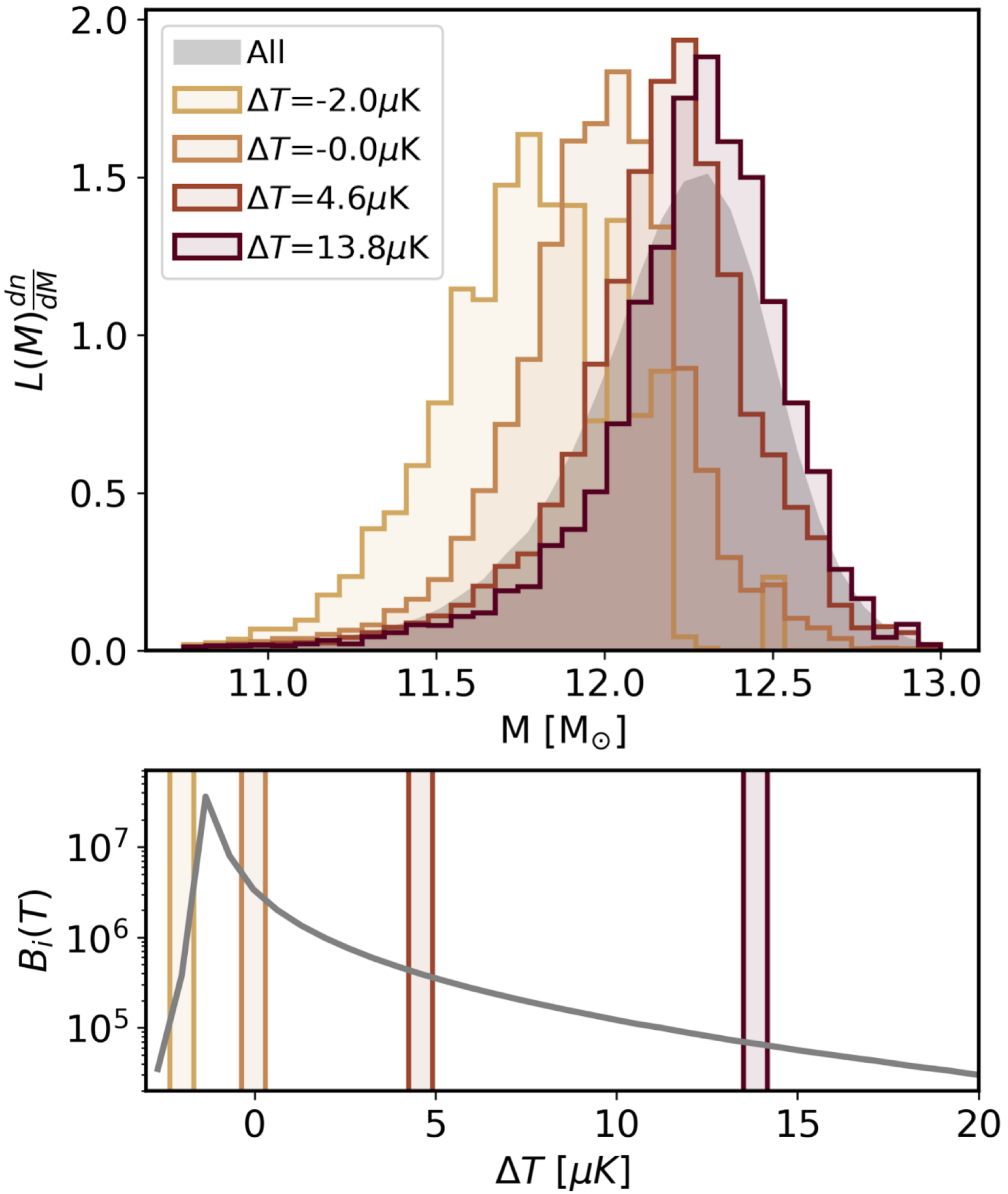


- No specific survey, trying to get uniform comparison (S/N = 5 at k = 0.1, 2' resolution, R=700, z = 3)
- Crosscorrelation coefficient < 1 because of shot noise and non linear biases
- Check loss of information due to non linearities

Sato-Polito, Kokron, Bernal (in prep)

Which halos does LIM measure?

- Check if LIM actually is sensitive to the faint emitters
- CO(1-0), z ~ 3



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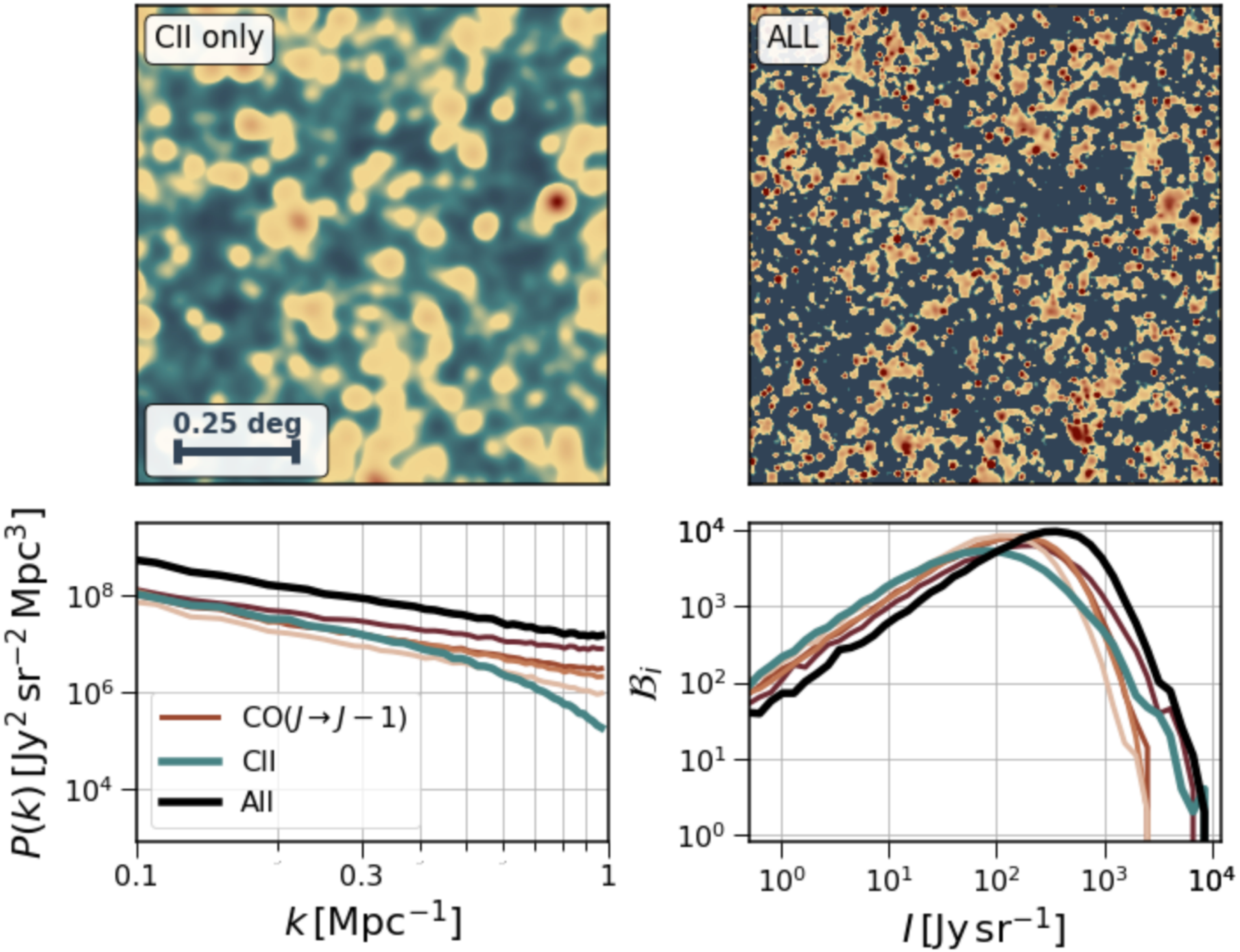
Line interlopers

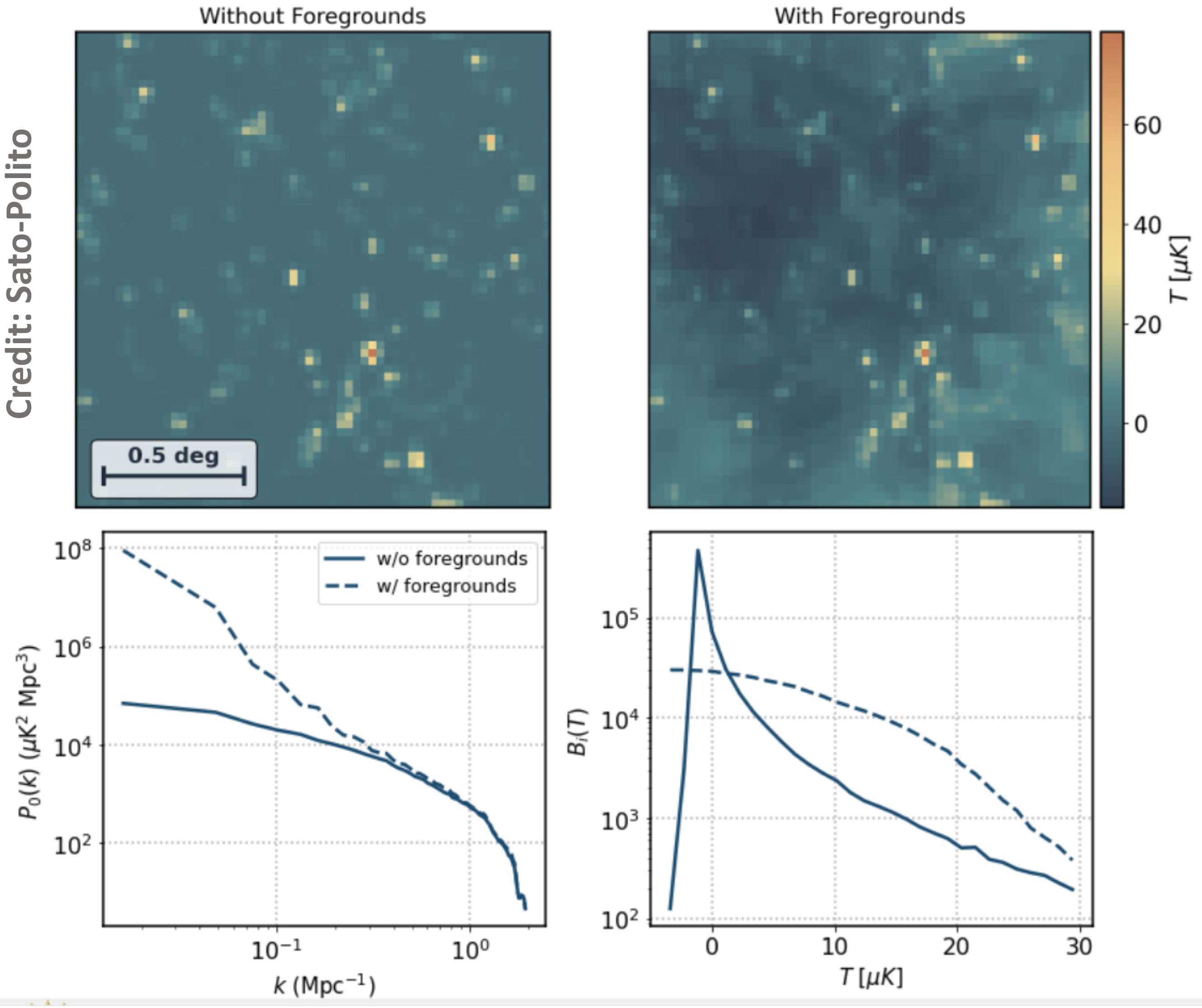


- Targeting CII at z = 5
- CO lines:
  - J = 4 at z = 0.46
  - J = 5 at z = 0.82
  - J = 6 at z = 1.18
  - J = 7 at z = 1.55
- Brighter red, higher J

Sato-Polito, Kokron, Bernal (in prep)

Galactic foregrounds

Credit: Sato-Polito



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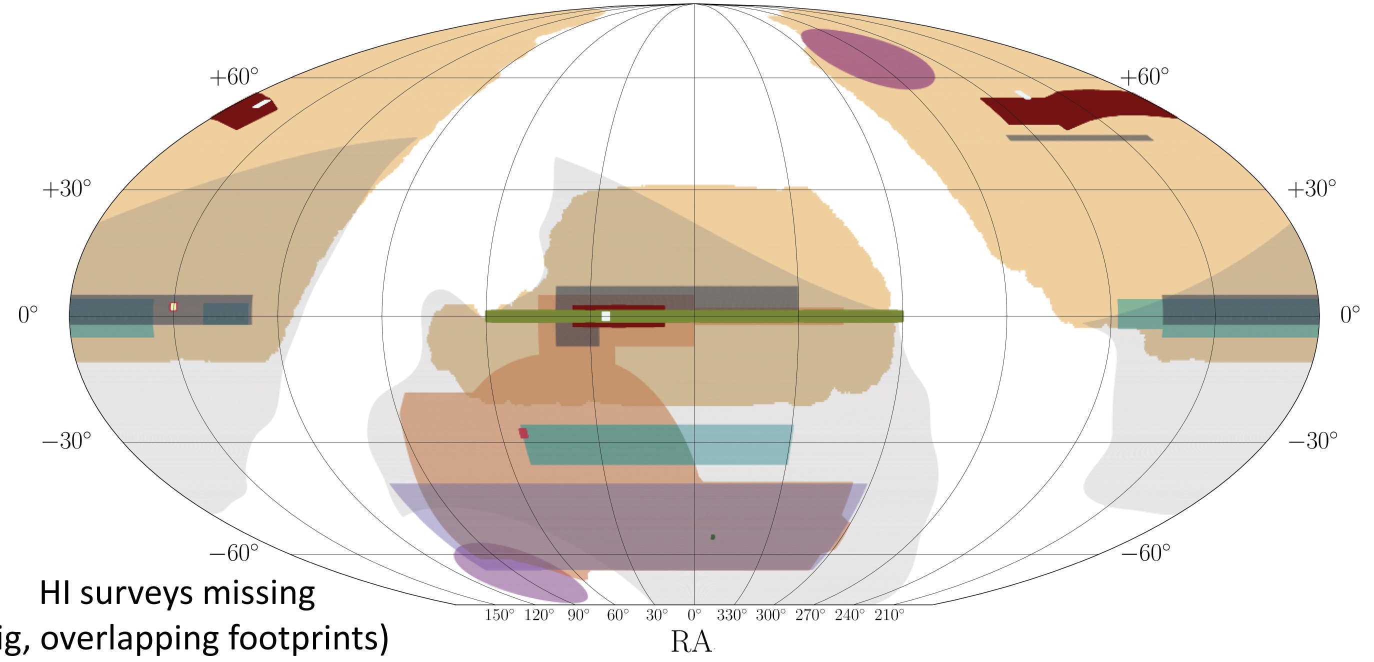
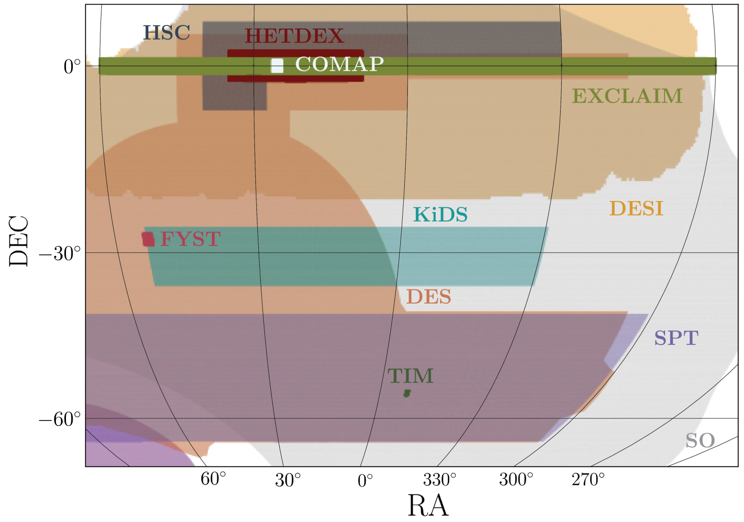
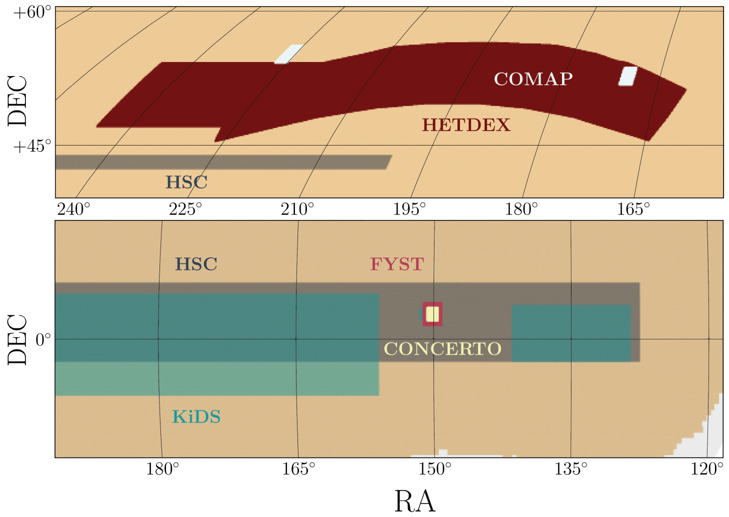
Cross-correlating to clean and extract info



HI surveys missing
(big, overlapping footprints)





- Currently small experiments and pathfinders (except HI)
- Multi-tracer by definition
- Great overlap with galaxy surveys and CMB
- Cross correlations leave foregrounds and interlopers out (contribute to the noise!)

- Great future: joint analyses, bigger z range, wider surveys, etc.

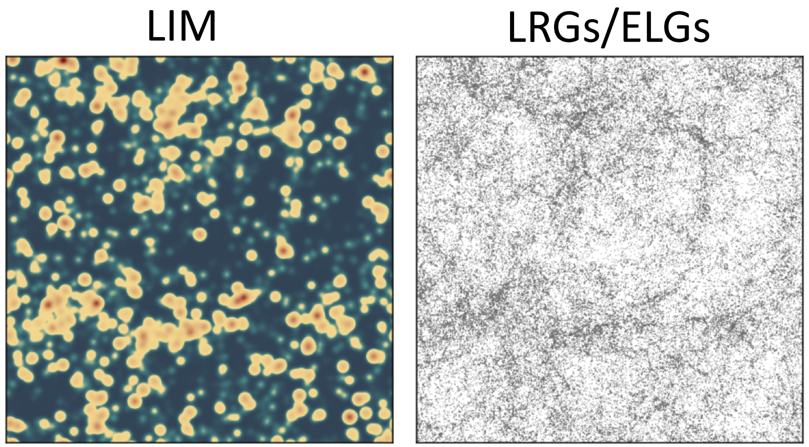
Bernal & Kovetz (2022)

Sato-Polito, Kokron, Bernal (in prep)

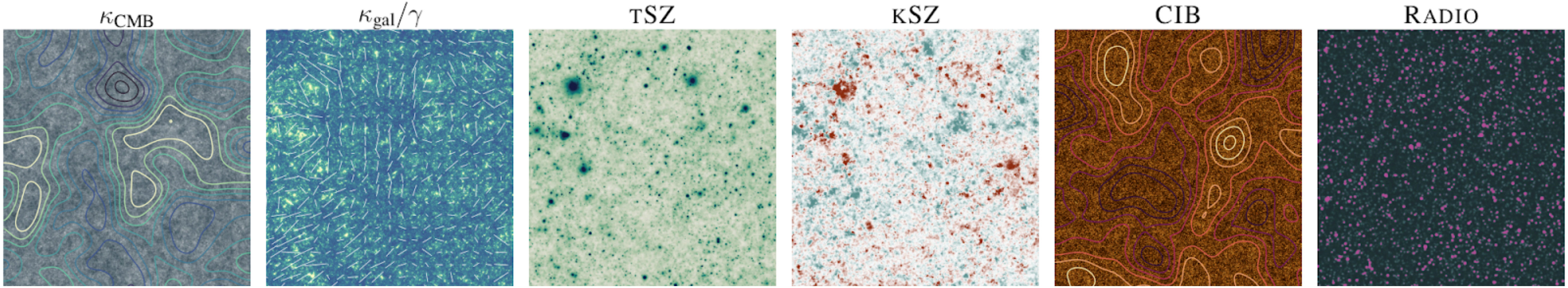
SkyLine and cross correlations

- 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



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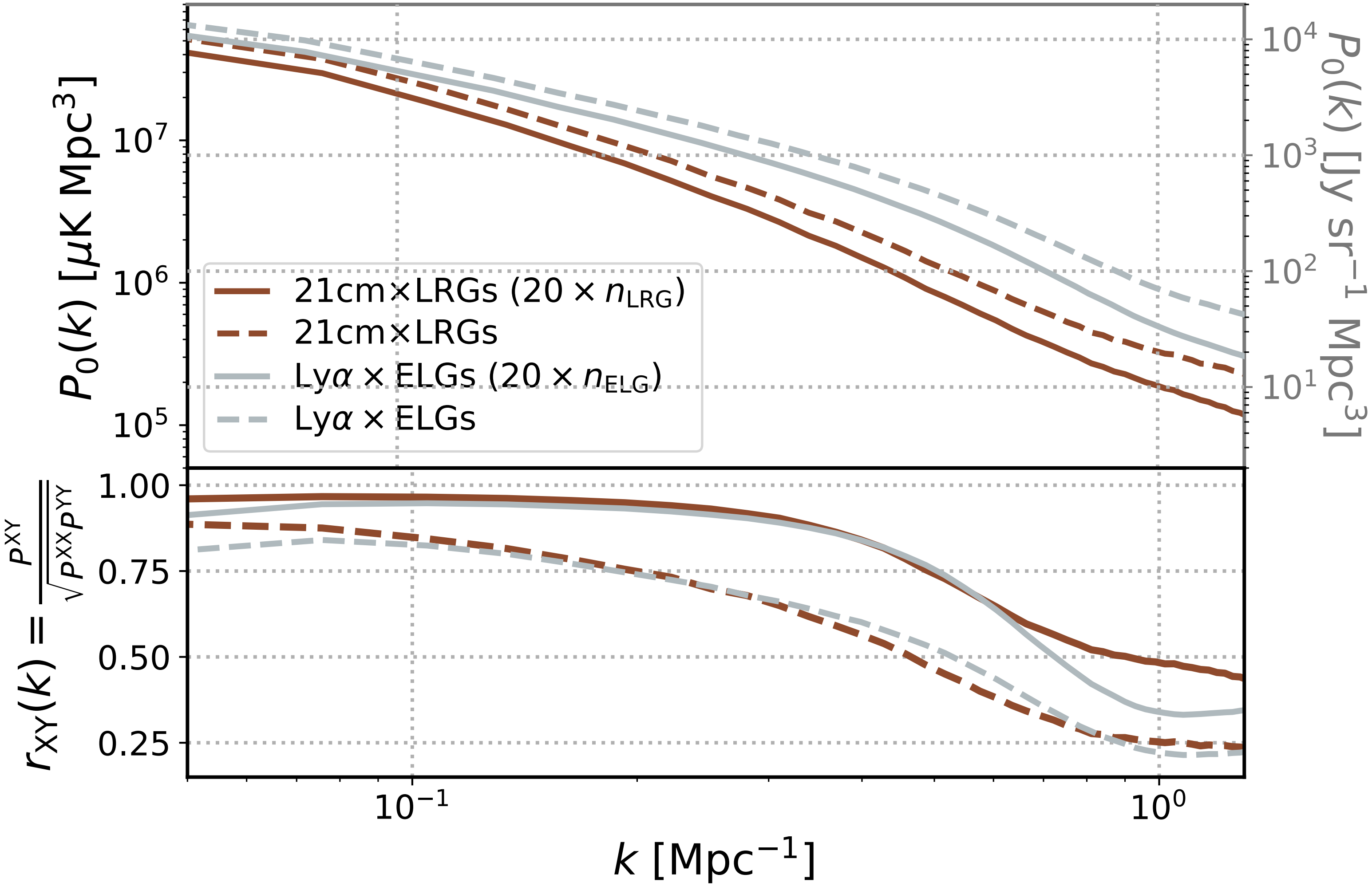

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- 21cm x LRGs ; z = [0.4,1.4]
- Lya x ELGs ; z = [2.2,3.2]
- 400 deg2

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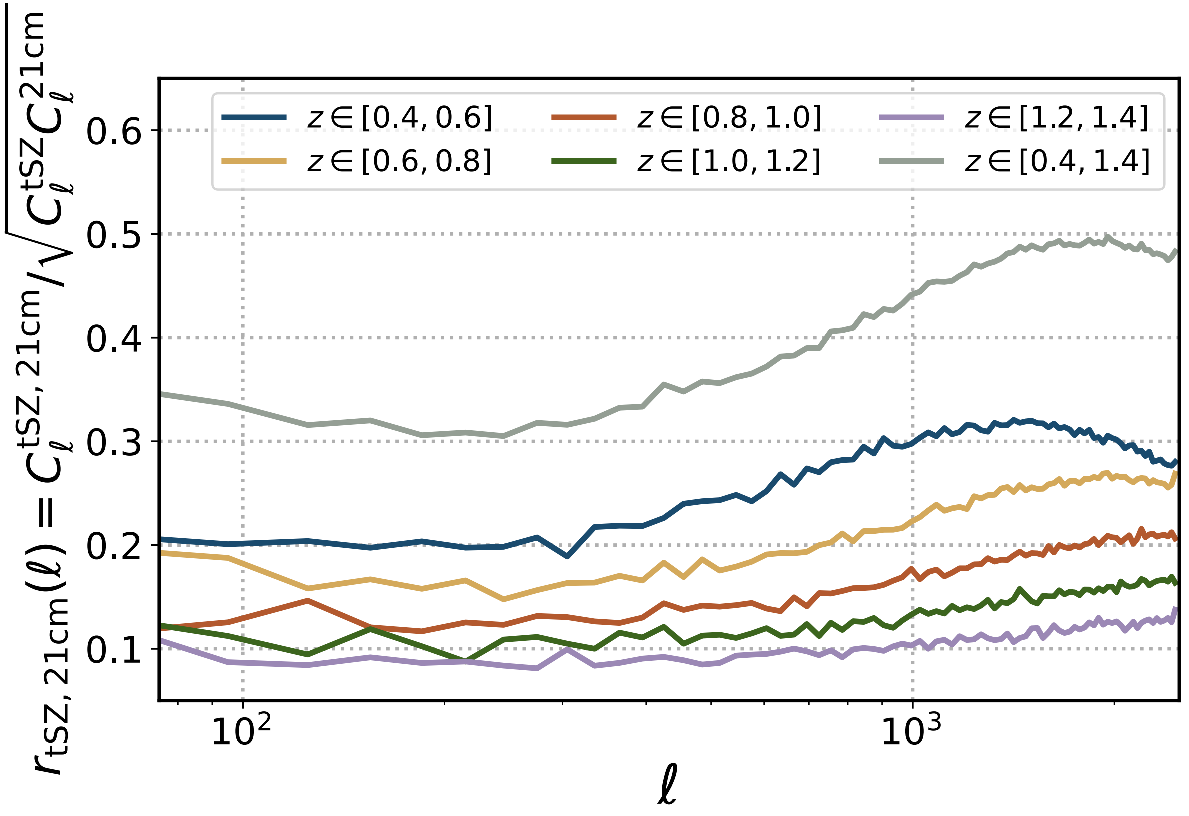
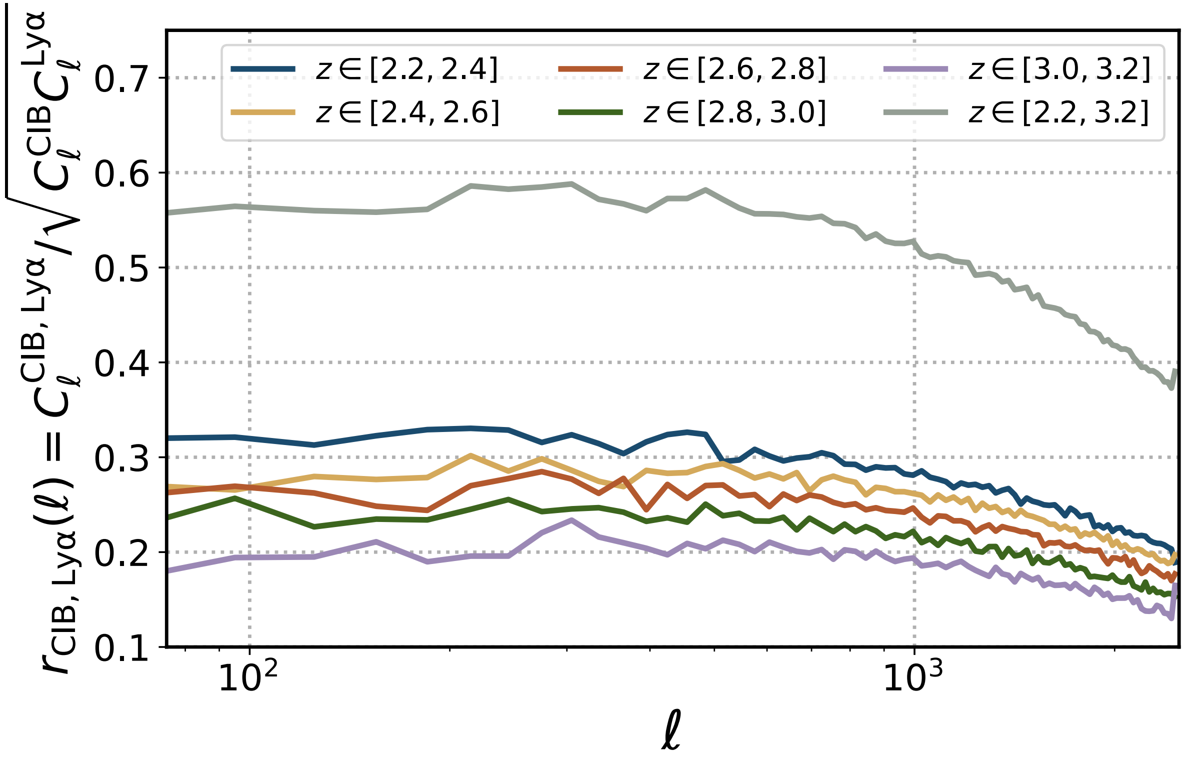




Full sky maps

Contamination of intensity maps

- Continuous foregrounds: problem for HI surveys, less severe at higher frequencies

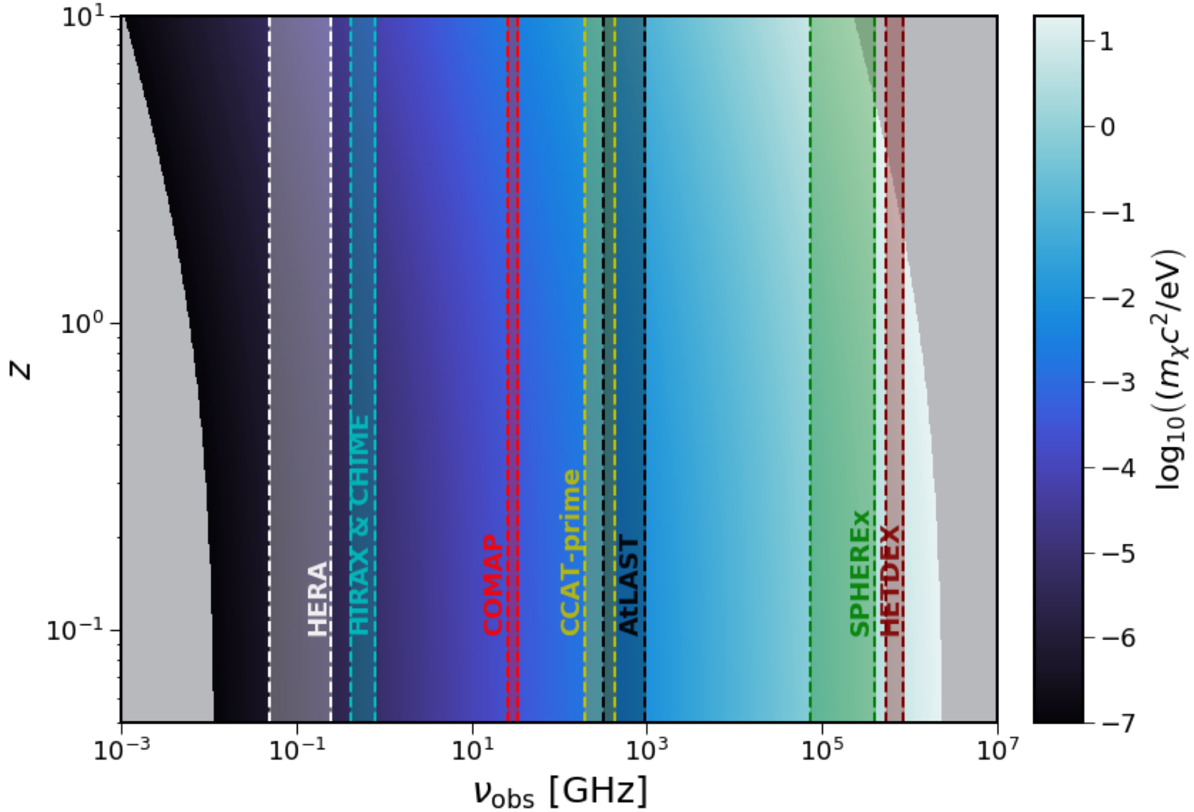
- **Line interlopers**: Main problem for higher freq. LIM surveys
  - $\nu_{obs} = \nu/(1+z) = \nu'/(1+z')$ → other lines redshifted to same ν_{obs}
  - Two approaches:
    - Masking: targeted (external data) and blind (contaminated voxels are expected to be brighter)
    - Model the effect of known interlopers in the likelihood and analyses

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

Creque-Sarbinowski & Kamionkowski (2022)

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

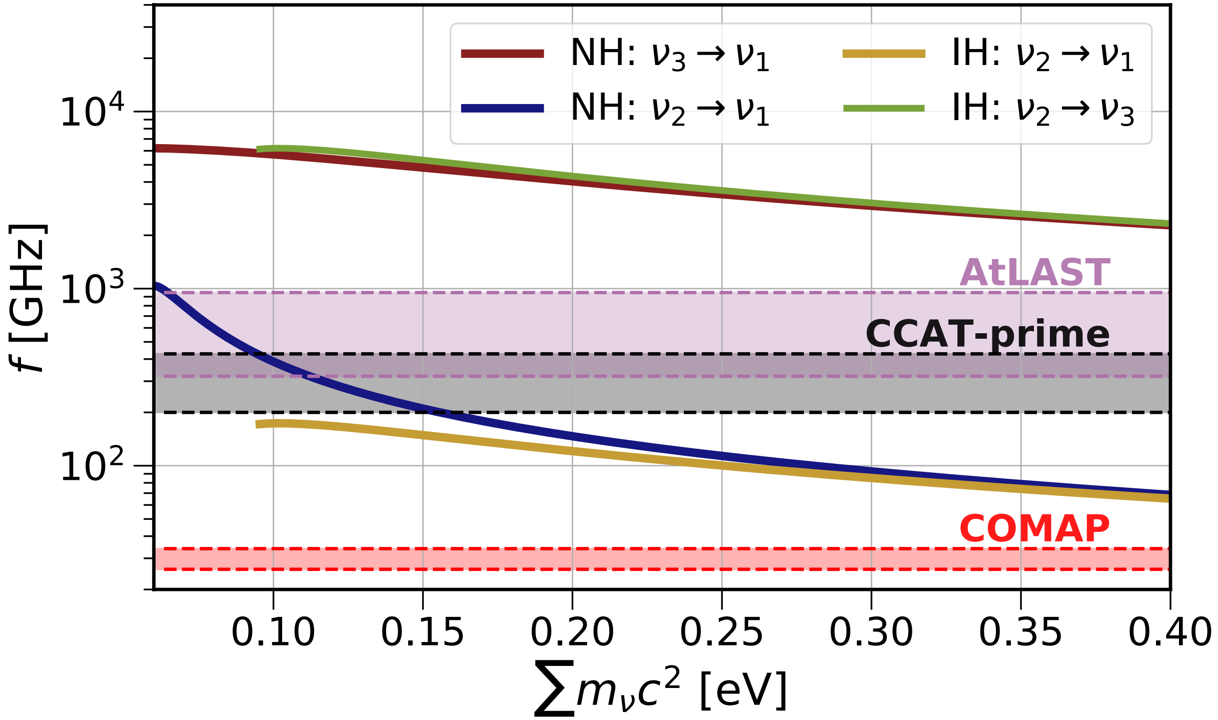


$$\chi \to \gamma + \gamma$$

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

DM & Neutrinos

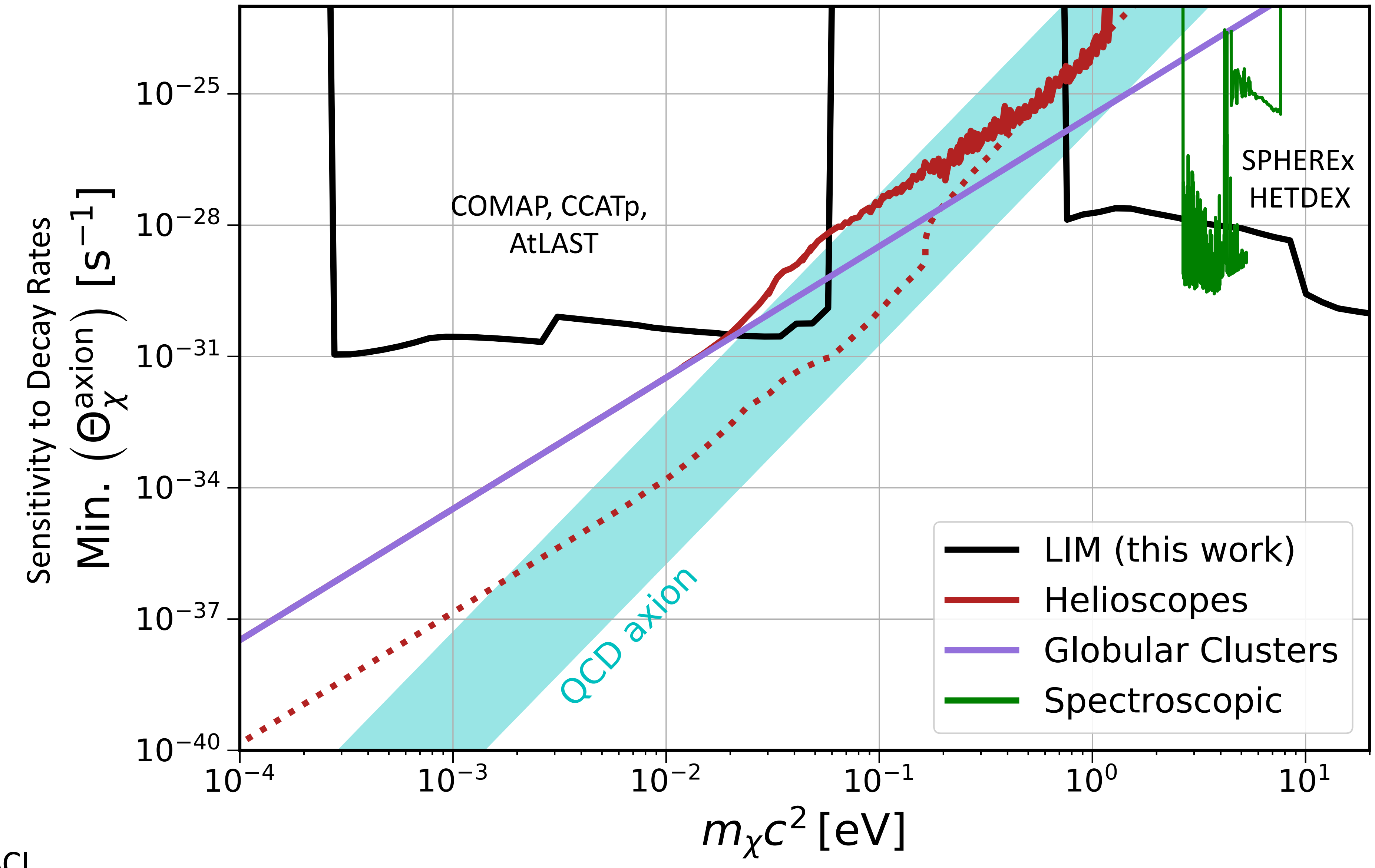
- Neutrinos:
  - Controlled by the electromagnetic transition moments
  - SM prediction of neutrino lifetime: $\tau_\nu \sim 10^{40-50}$ s ($\gg t_U$)
  - BSM physics may enhance transition moments: detection → BSM physics!
  - Traces directly the cosmic neutrino density field



$$\nu_i \rightarrow \nu_j + \gamma$$

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

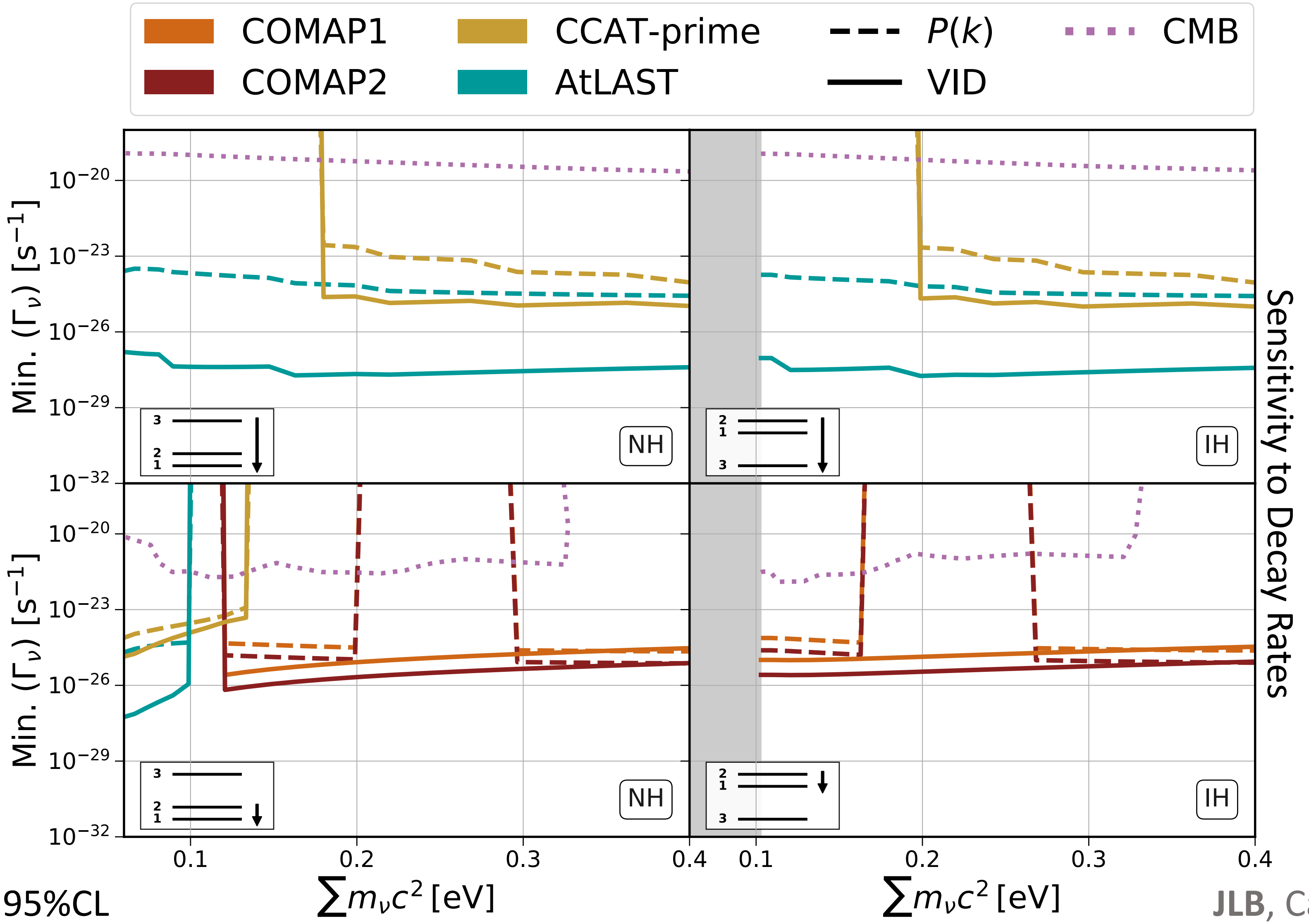
Sensitivity in axion context



95%CL

JLB, Caputo, Kamionkowski (2021)

Sensitivities to neutrino decay



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

↓ 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: $< 4.5\times10^{-12}\mu_B$

95%CL

JLB, Caputo, Villaescua-Navarro, Kamionkowski (2021)

Challenges & improvements

- Challenges:
  - Astrophysical uncertainties: marginalization, break degeneracies
  - Other contaminants: loss of information, potential biases
  - Line broadening (currently testing BAO robustness against this)
- Reasons to be optimistic:
  - Many pathfinders and experiments in the pipeline (and theory efforts too!)
  - Other summary statistics
  - BAO: clean measurement
  - Exotic decays:
    - Extensible to other interloper-treatement, summary statistics, etc
    - Multiprobe with galaxy clustering and weak lensing
  - New info and checks through cross correlations

Conclusions

- LIM has the potential to become a key pillar for cosmology and astrophysics
  1. Capture faint and diffuse sources
  2. Access beyond the reach of galaxy surveys
  3. Quickly map large three-dimensional volumes

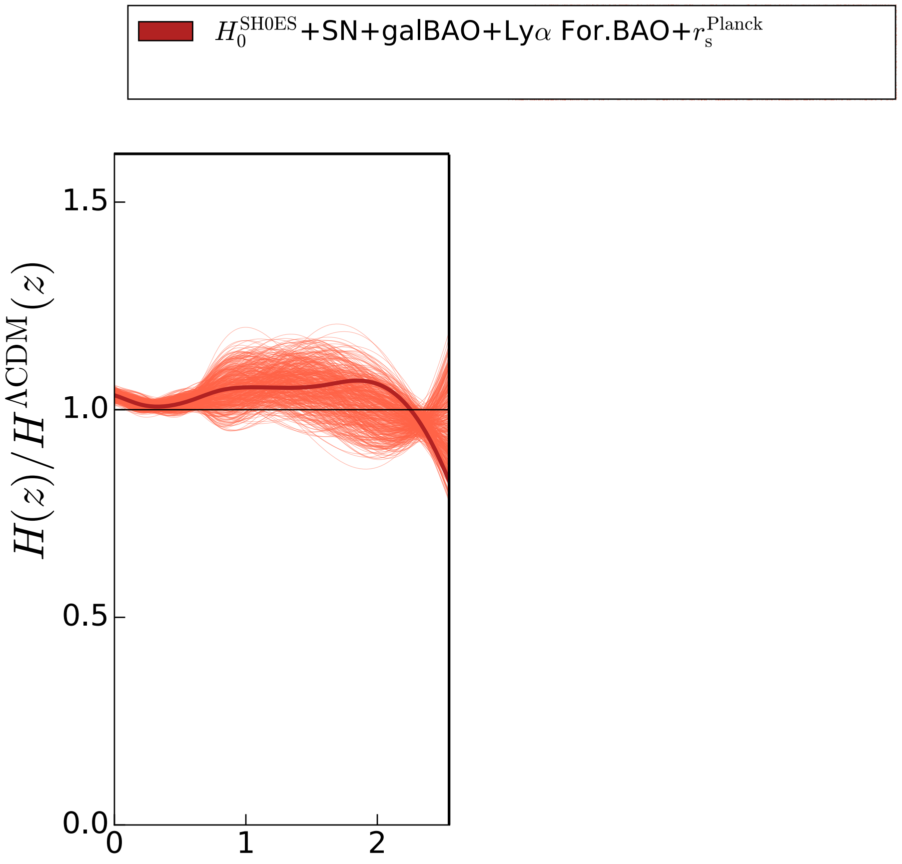
- Very non Gaussian maps: P(k) + VID (+ …); use of simulations also required
  - SkyLine: playground to test methods and understand and maximize LIM's potential

- Intrinsic multi-tracer nature + lots of overlap and synergies with other observables

- Window to new regimes, new observational methods: new avenue for probing new physics
- Lots to do! come talk to me if you're curious about new science cases and beyond LCDM searches!

Back up slides

Constraining the expansion history



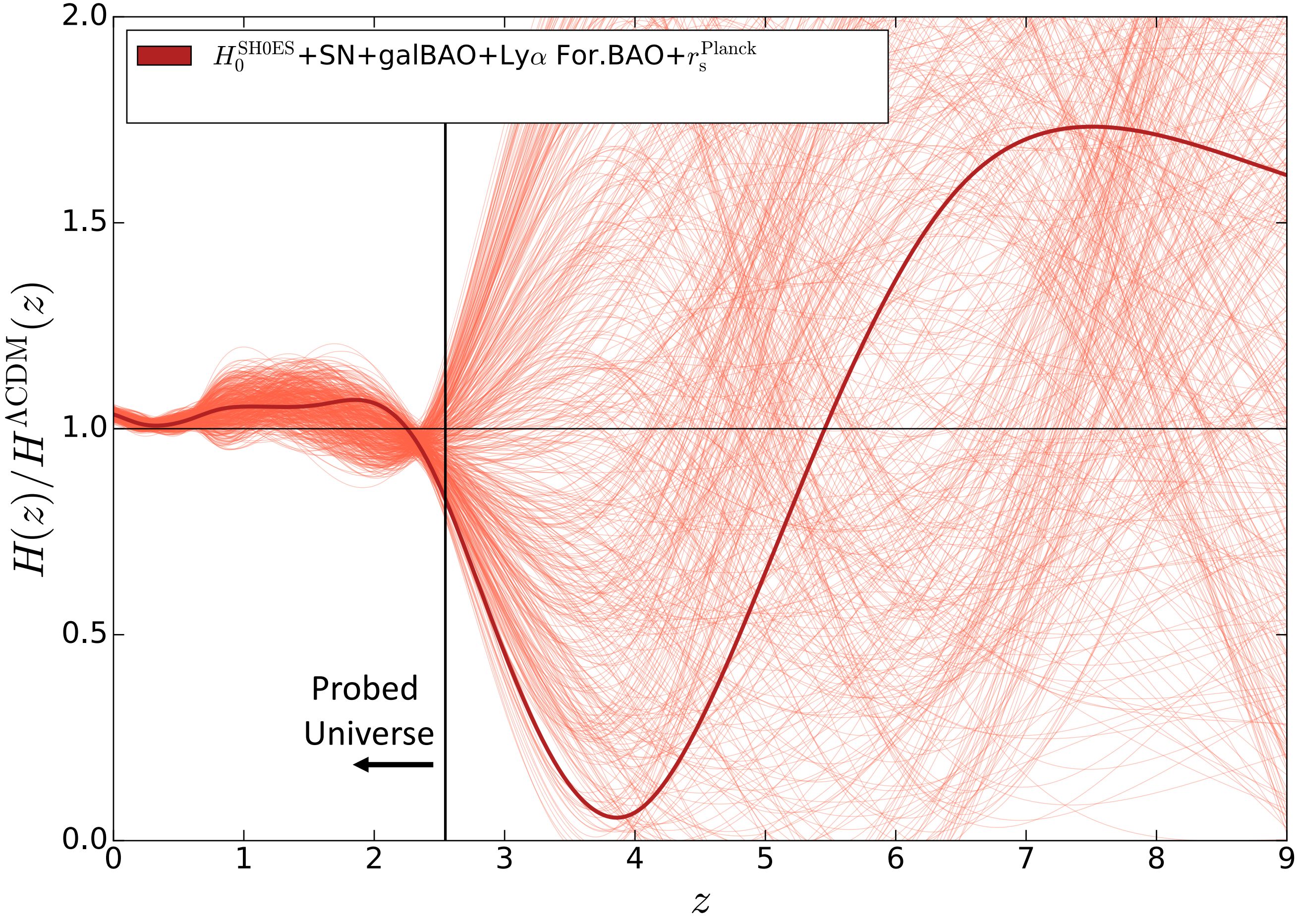
Model independent $H(z)$ reconstructed with cubic splines

Current constraints using galaxy surveys (and H_0 and r_s)

Bernal +(2019)

Constraining the expansion history

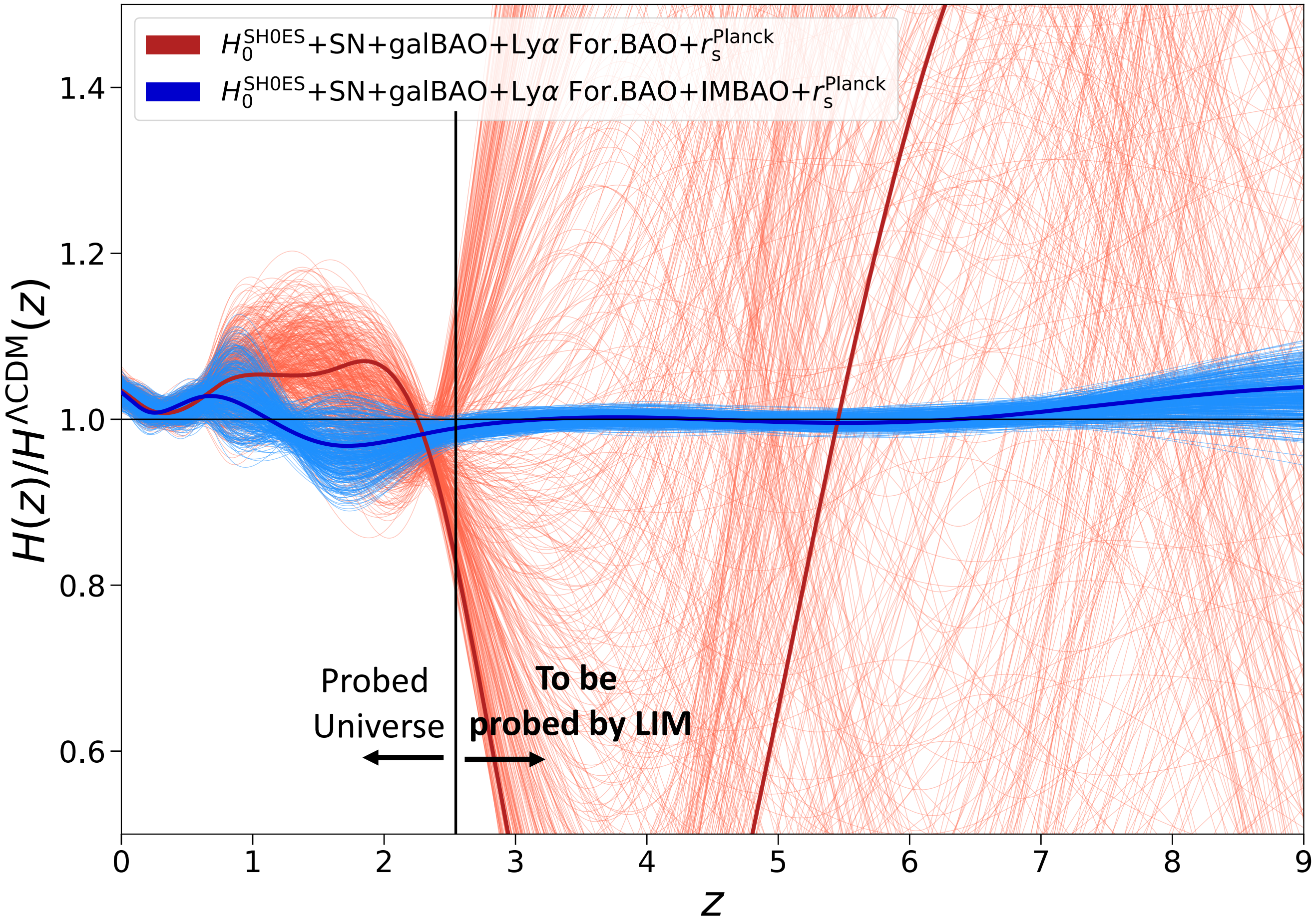
Model independent $H(z)$ reconstructed with cubic splines



Current constraints using galaxy surveys (and H_0 and r_s)

$H(z)$ beyond the reach of galaxy surveys

Model independent $H(z)$ reconstructed with cubic splines



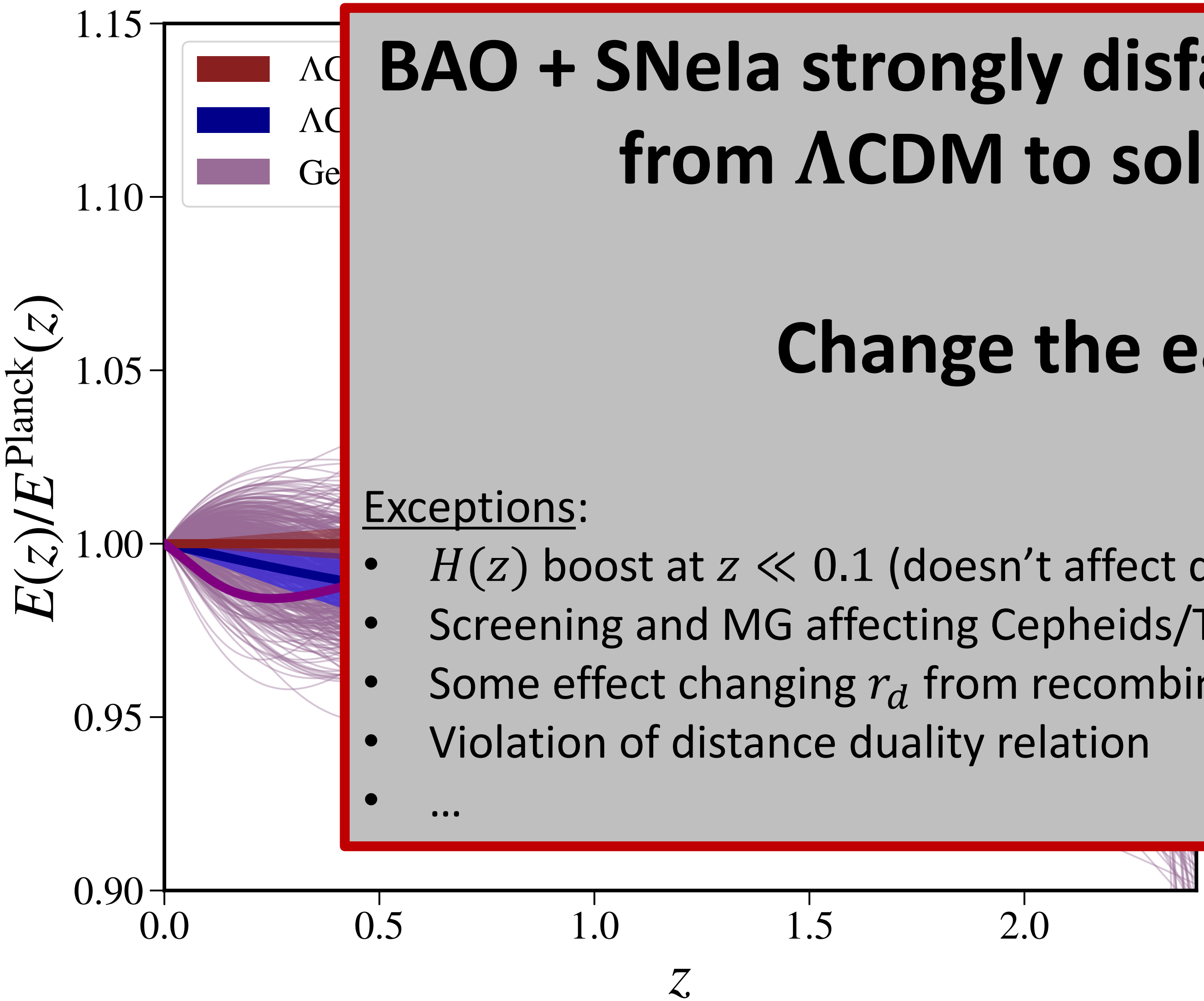
Bridge early and late Universe to probe post-recombination solutions

Current constraints using galaxy surveys (and H_0 and r_s) and **ADDING LIM BAO**

Bernal +(2019)

High-z vs low-z

Done using MABEL



BAO + SNeIa strongly disfavors any low z deviation from ΛCDM to solve the H_0 tension

Change the early Universe

Exceptions:

- $H(z)$ boost at $z \ll 0.1$ (doesn't affect distances): Raveri 2019, Benevento+2020
- Screening and MG affecting Cepheids/TRGB calibration (Desmond+2019,2020)
- Some effect changing r_d from recombination to BAO measurements (?)
- Violation of distance duality relation
- …

Using LIM for cosmology

- Focus on the anisotropic power spectrum:

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

$$\langle T(z)\rangle \propto \int L \frac{dn}{dL} dL \qquad P_{shot} \propto \int L^2 \frac{dn}{dL} dL$$

- Amplitude determined by LF and bias

- Signal limited by resolution at small scales and by size of volume probed at large scales (modeled with window functions)

- Use Legendre multipoles to explore anisotropy!

BAO Cosmology

User's guide:JLB+2019a

Using LIM for cosmology

- Focus on the anisotropic power spectrum:

- Alcock-Paczynski effect: $k_\parallel^{meas} = k_\parallel^{true}\alpha_\parallel$; $k_\perp^{meas} = k_\perp^{true}\alpha_\perp$

$$\alpha_\parallel = \frac{(H(z)r_s)^{fid}}{H(z)r_s}$$

$$\alpha_\perp = \frac{D_A(z)/r_s}{(D_A(z)/r_s)^{fid}}$$

BAO feature helps to measure the AP effect

User's guide:JLB+2019a

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: $P(k,\mu,z) = \left(\frac{\langle T\rangle b\sigma_8 + \langle T\rangle f\sigma_8\mu^2}{1+0.5(k\mu\sigma_{FoG})^2}\right)^2 \frac{P_m(k)}{\sigma_8^2} + P_{shot}(z)$

User's guide:JLB+2019a

Using LIM for cosmology

- Focus on the anisotropic power spectrum:
- Alcock-Paczynski effect: $k_\parallel^{meas} = k_\parallel^{true}\alpha_\parallel$; $k_\perp^{meas} = k_\perp^{true}\alpha_\perp$
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- Include experimental window function: $\tilde{P}(k,\mu,z) = W(k,\mu,z)P(k,\mu,z)$

User's guide:JLB+2019a

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 local PNG: P(k)

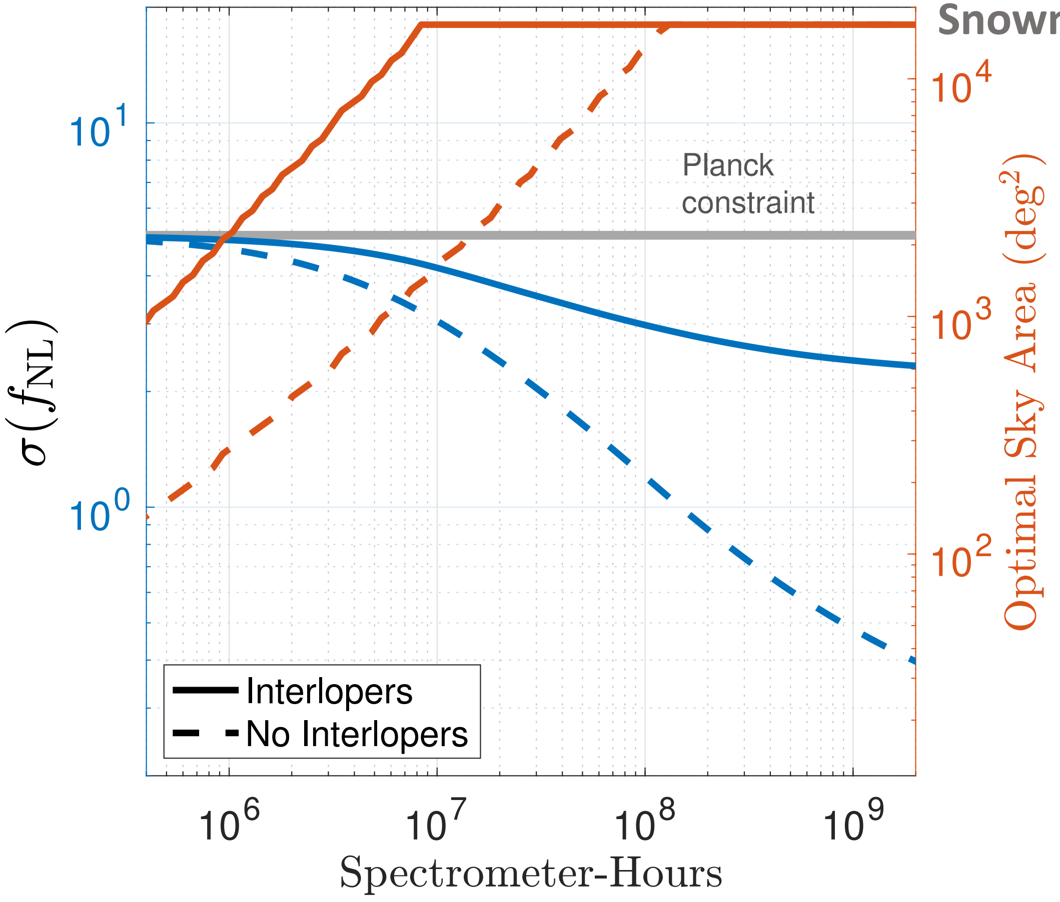
- Intensity traces density: cosmological information degenerate with astrophysics

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

- 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

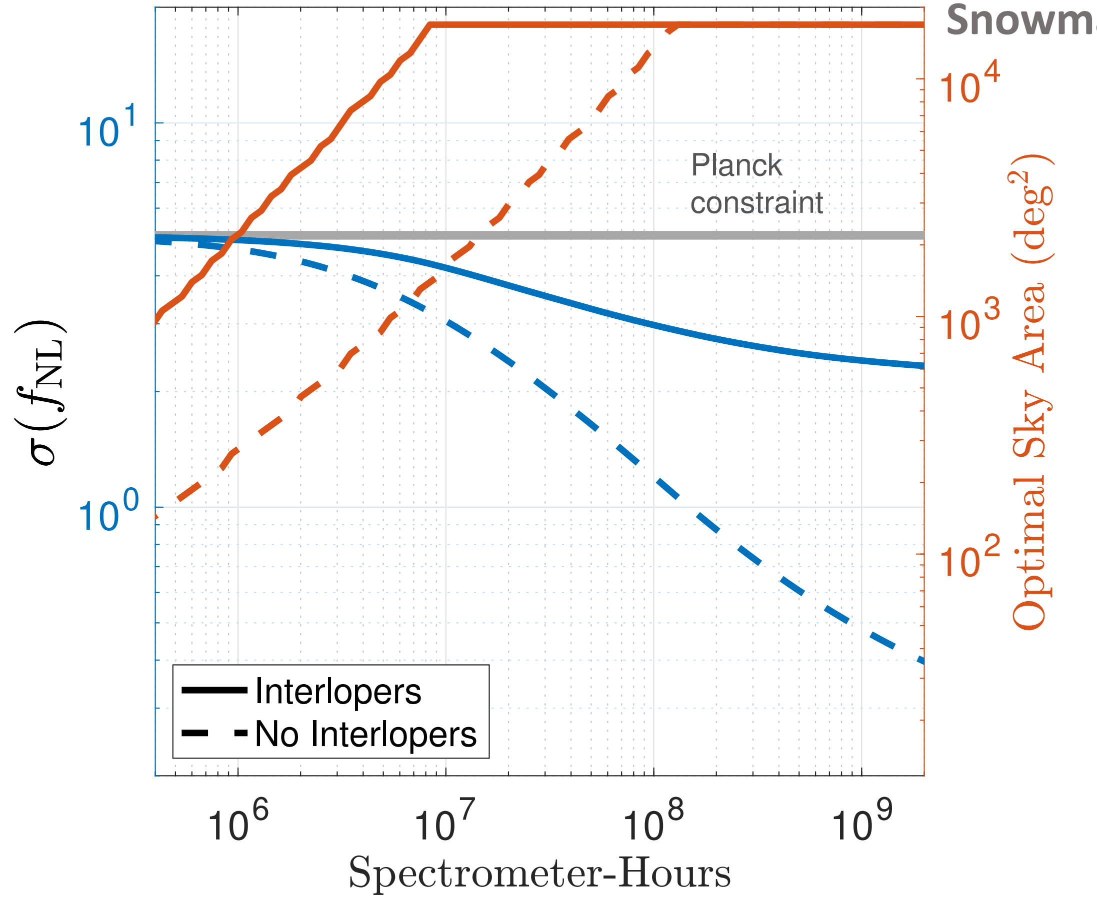
Using LIM for local PNG: P(k)

- 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

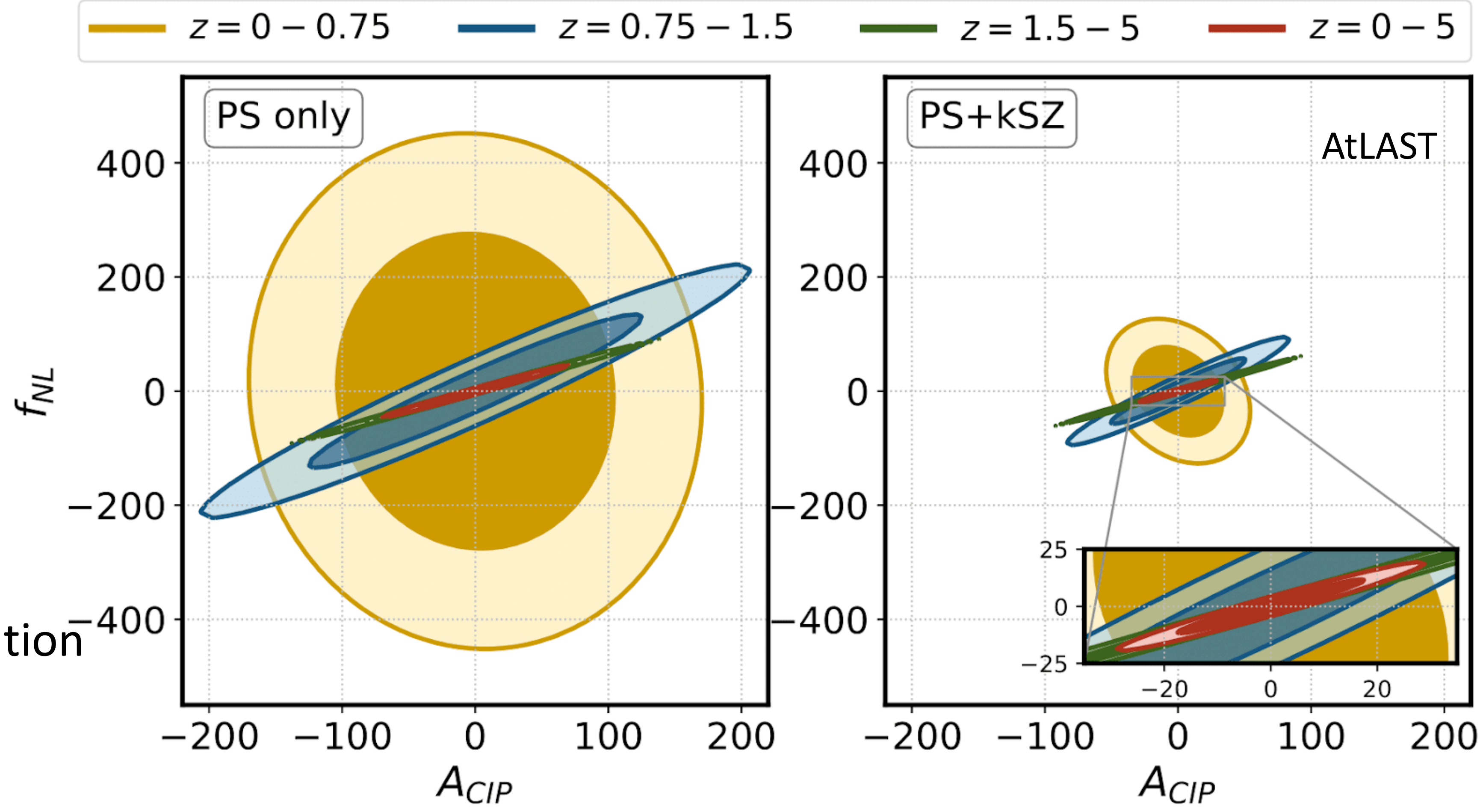


Assuming known b_ϕ, see Alex's talk

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



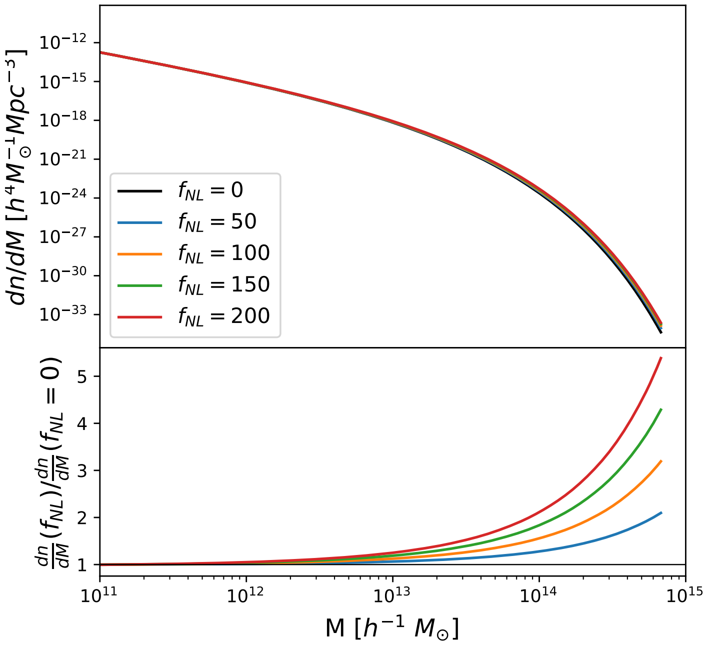
Sato-Polito, Bernal+ (2021)

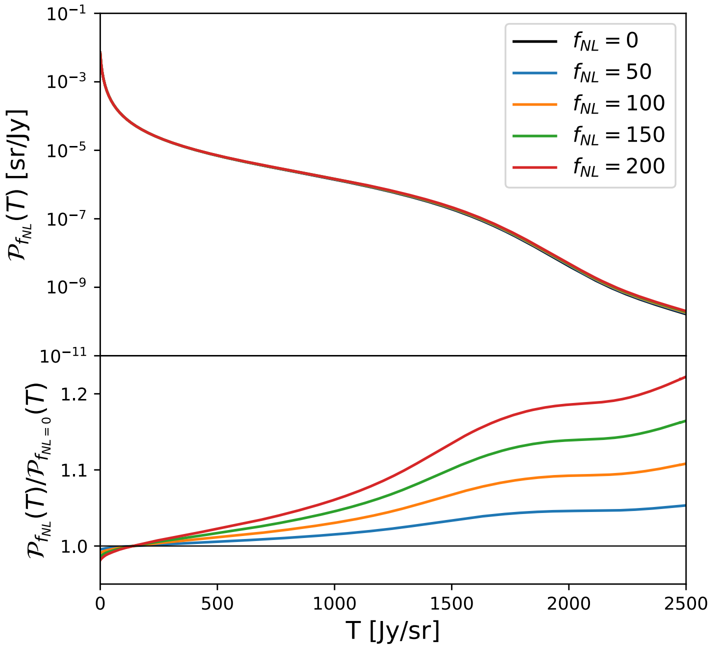
See Neha's talk for more in kSZ bispectrum and velocity reconstruction

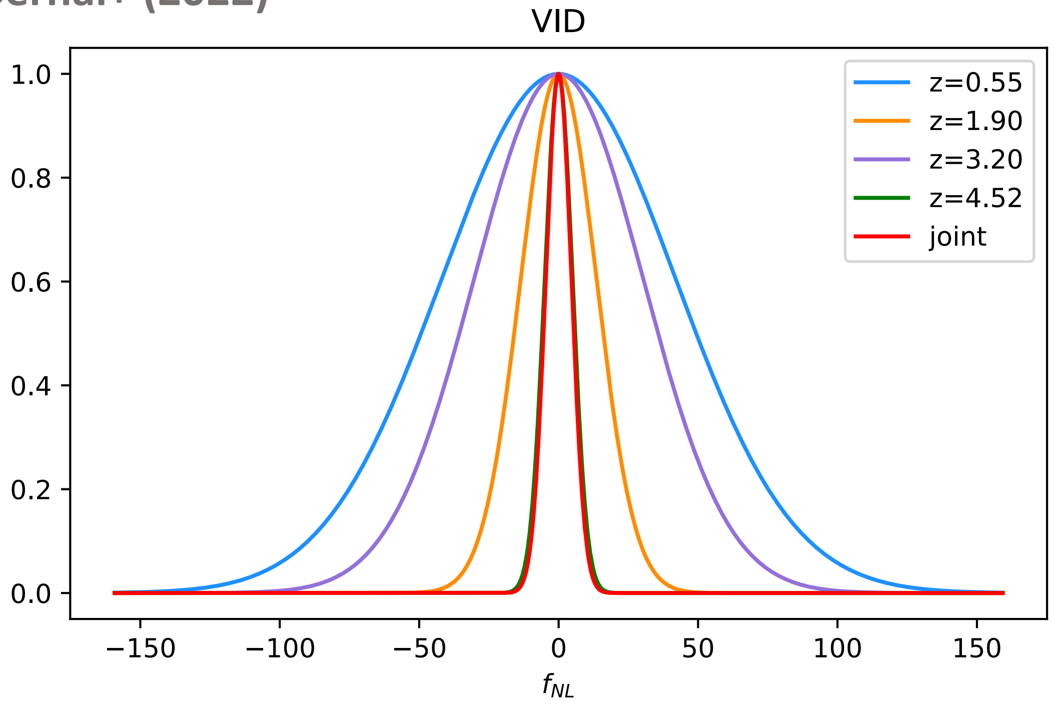
Sabla, Sato-Polito, Bernal+ (in prep)

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)**





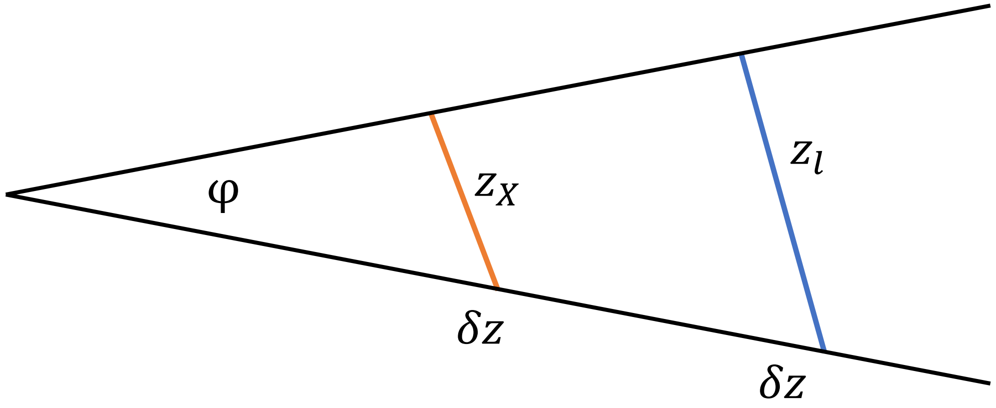


SPHEREx, Hα, $z = 3.2$

PRELIMINARY

Effect in power spectrum

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



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

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

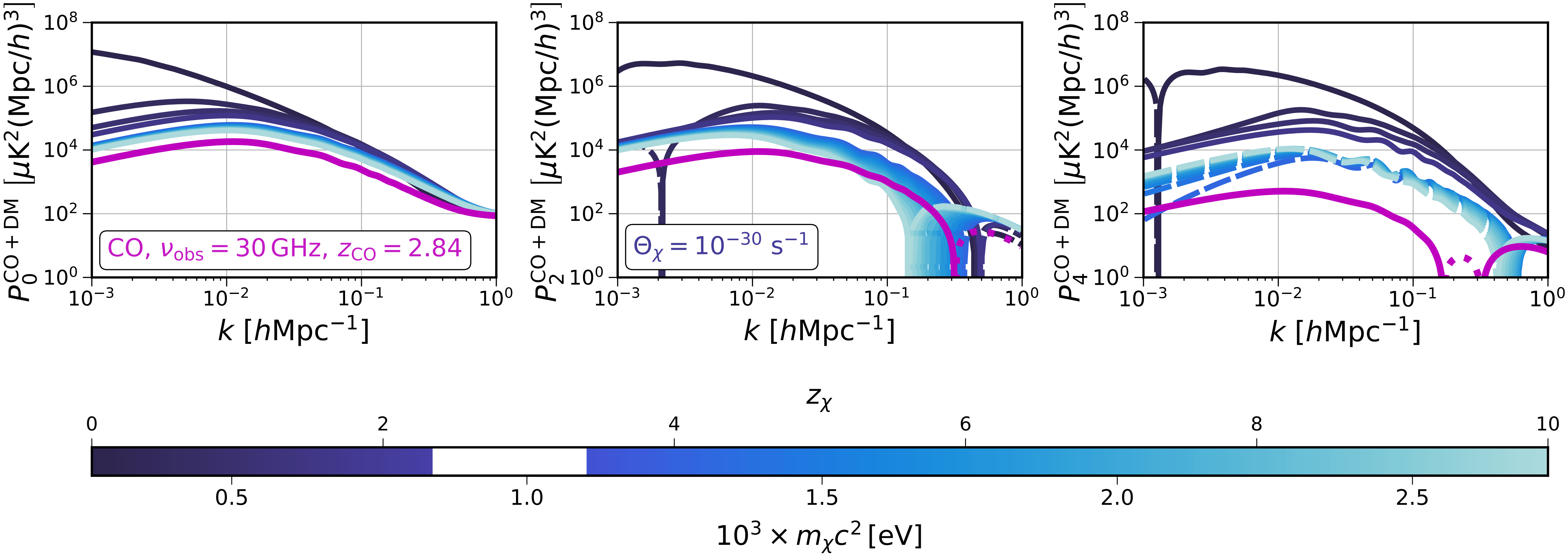
- Model it similar to AP effect: $k_i^{true} \equiv k_i^{infer}/q_i$

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

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

Effect in power spectrum

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



Effect in VID

- Each voxel receives contributions from both emissions:

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

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

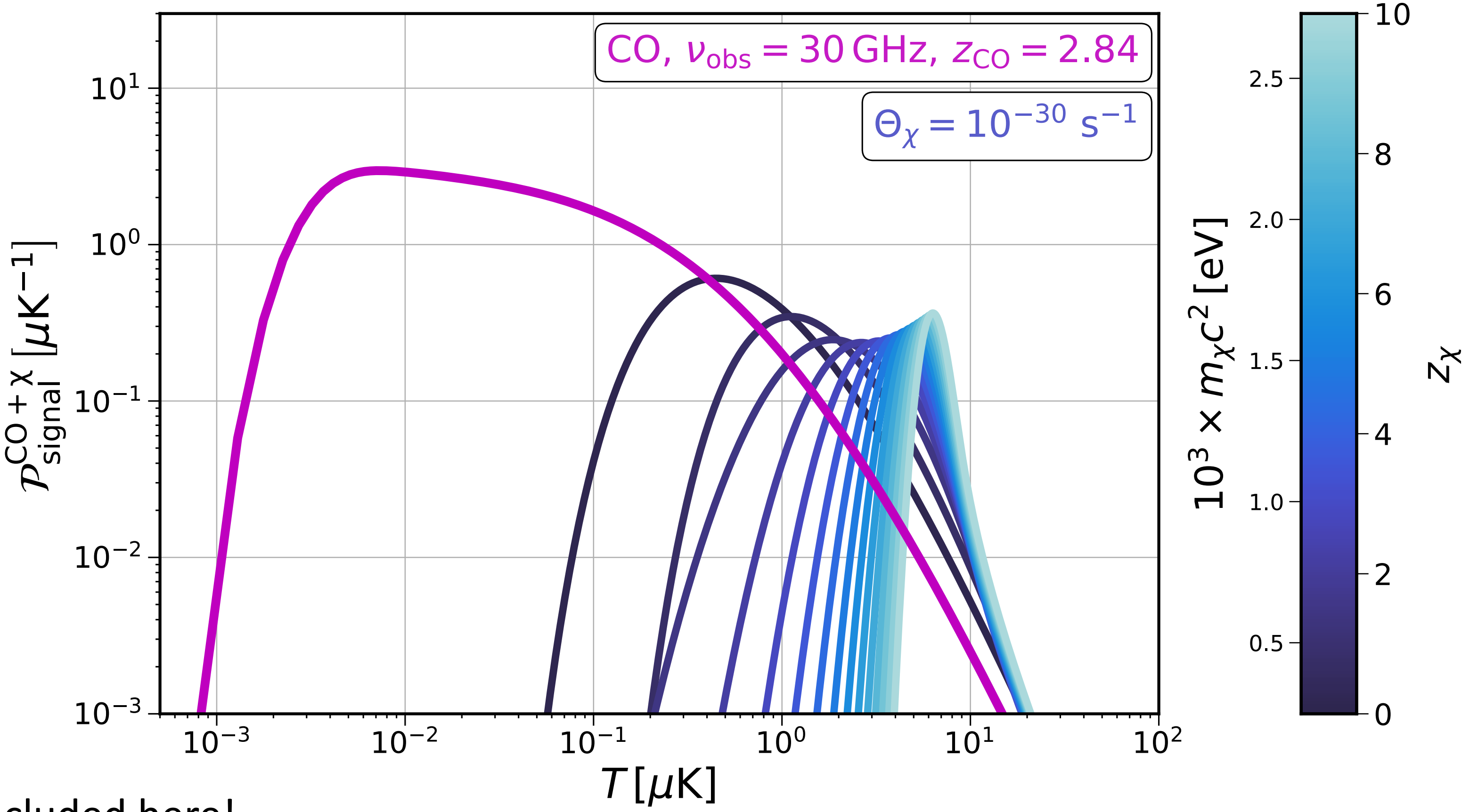
- $\mathcal{P}_{\tilde{\rho}}$: PDF of normalized densities. Obtained from simulations

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

Effect in VID

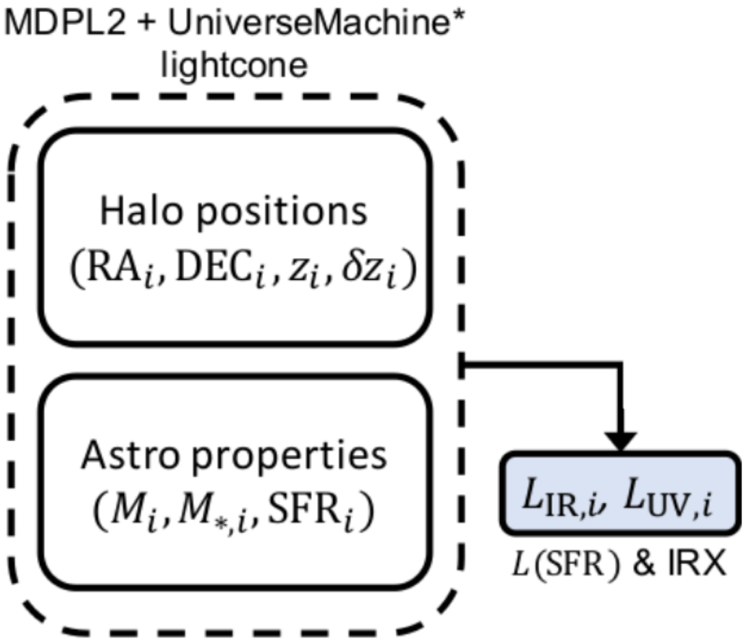
- Each voxel receives contributions from both emissions:

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



No noise contribution included here!

Skyline code structure



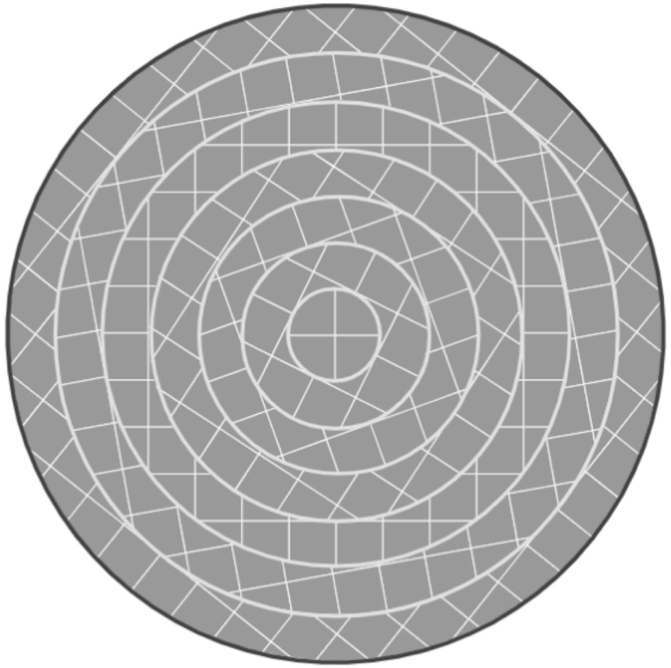


Figure 1. The scheme of box rotation used in generating lightcones from the MDPL2 simulation box. Each individual grid represents a 1 h^{-1}Gpc box.

Omori in prep.