Line-Intensity Mapping: progress and lessons learned

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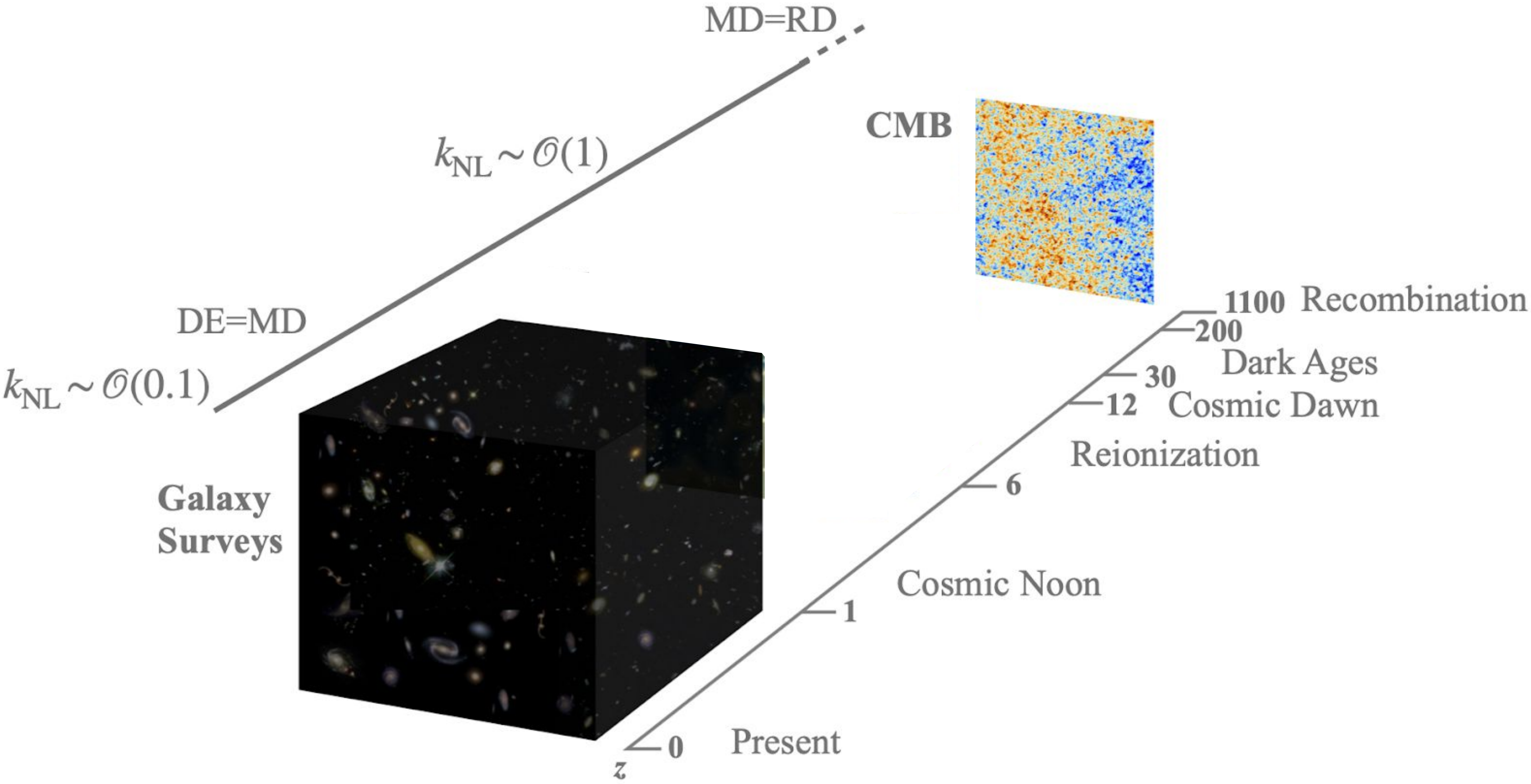
Outline / topics

- Introduction to LIM
- Real life: the problem of foregrounds
- Measuring LIM power spectra!
    - MeerKLASS
    - HETDEX
- Conclusions

Filling the gaps in cosmic history



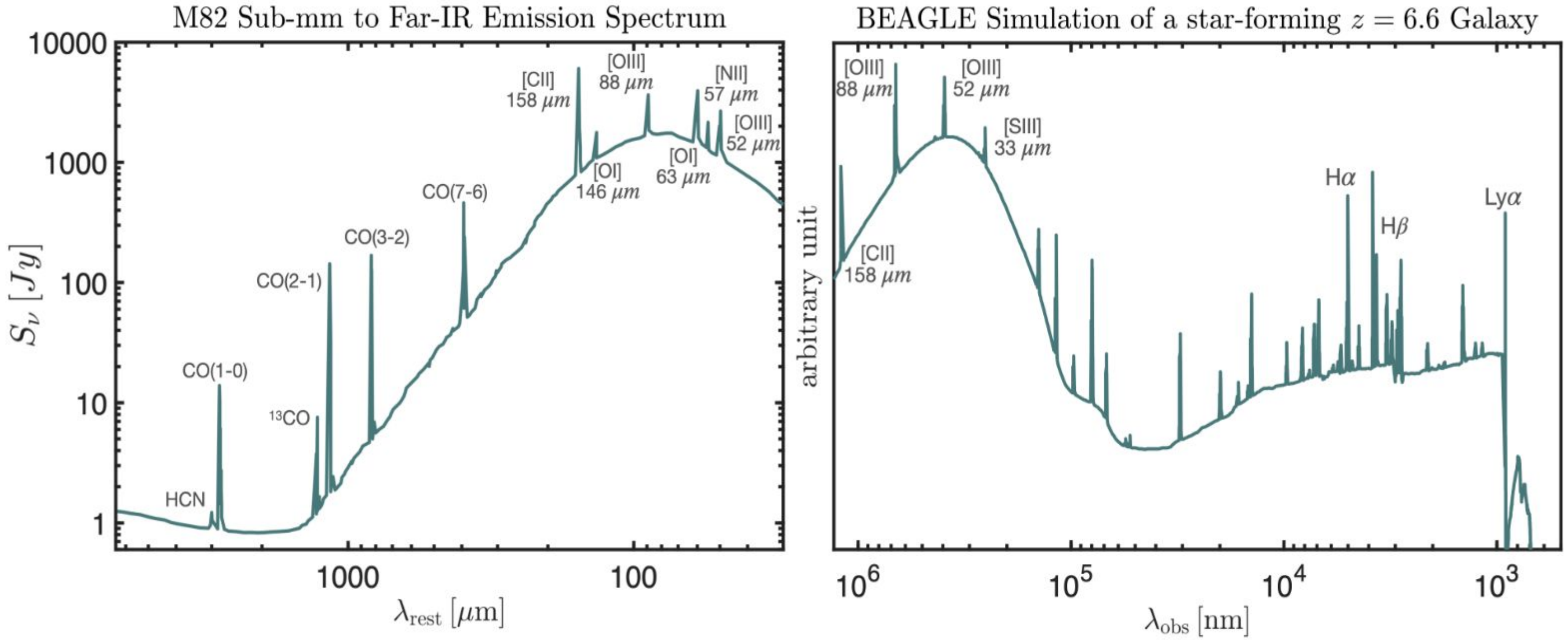
Bernal & Kovetz (2022)

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



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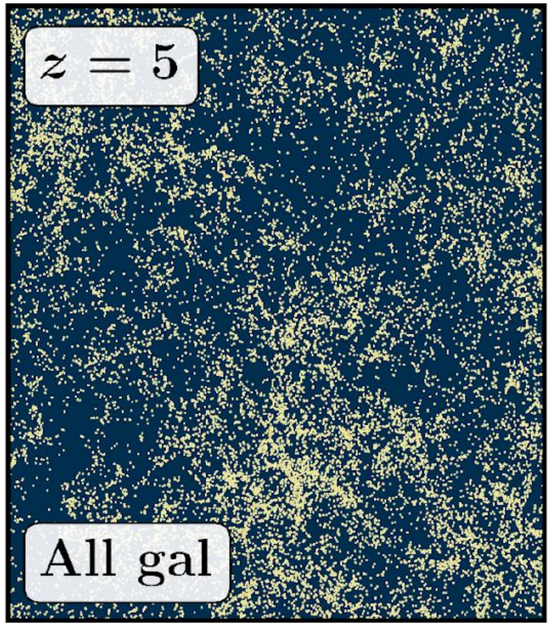

- 1 deg^2 at $z = 5, \Delta z = 0.2$
- All haloes

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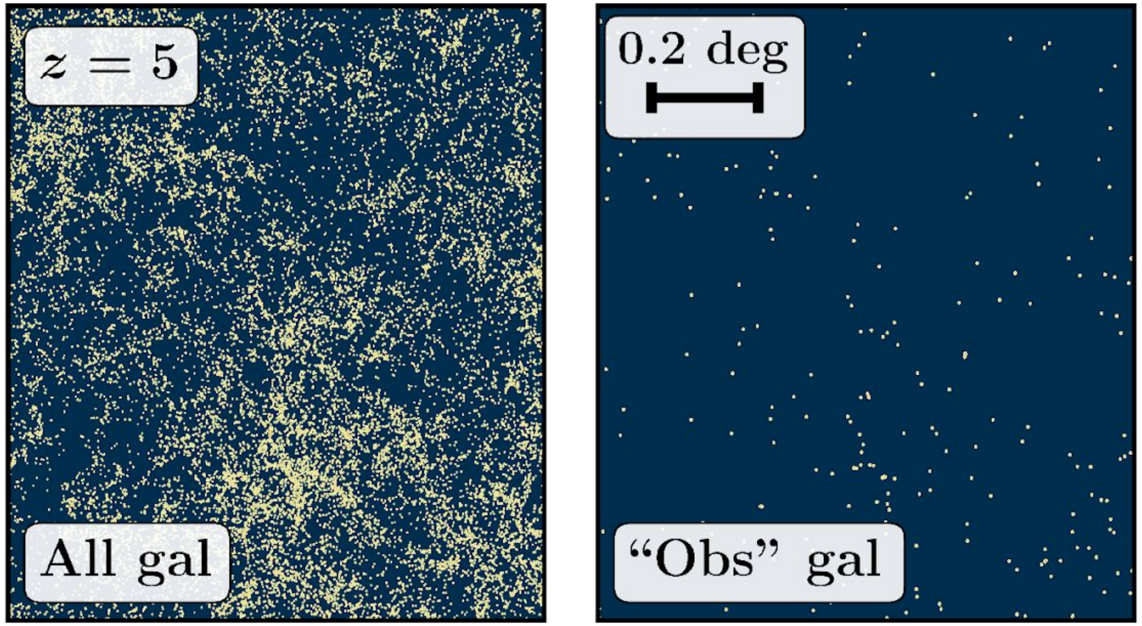

- 1 deg^2 at $z = 5, \Delta z = 0.2$

- All haloes

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

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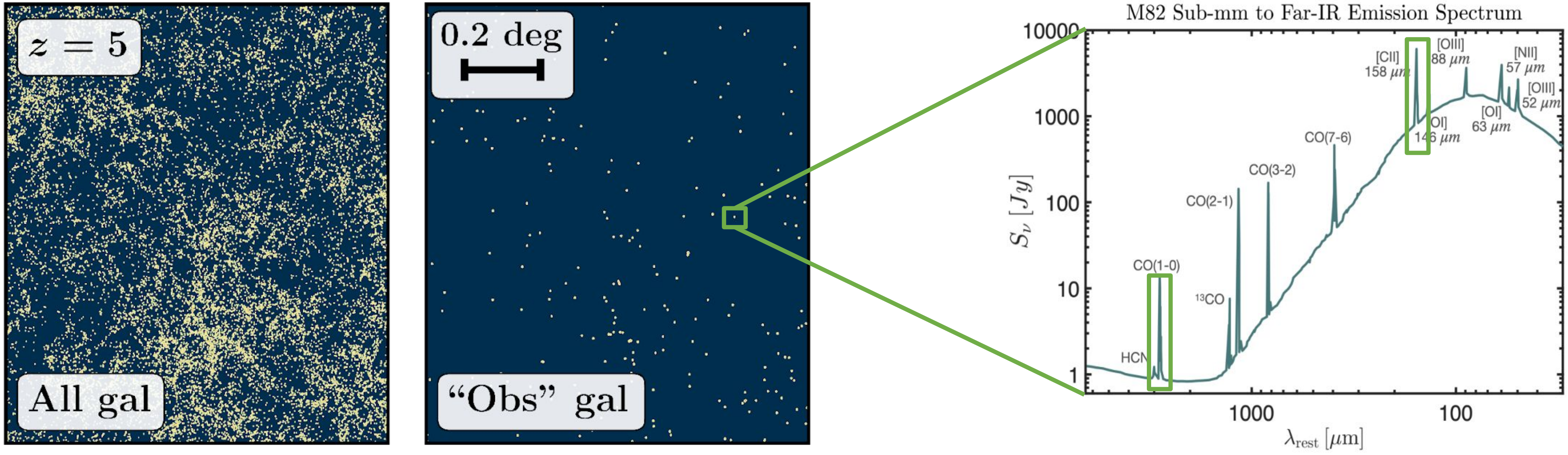

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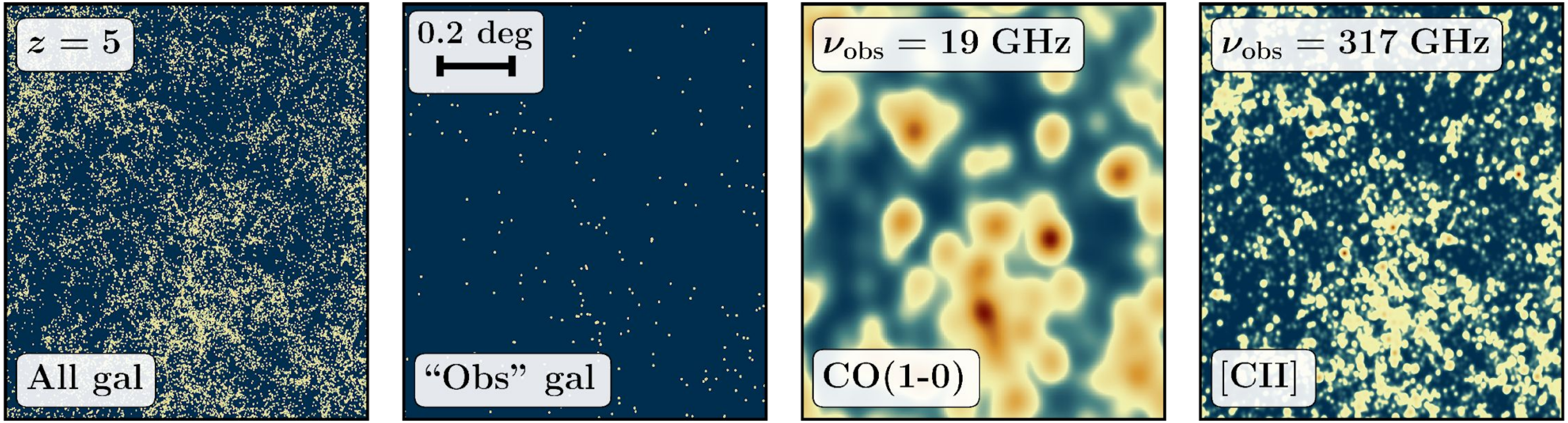
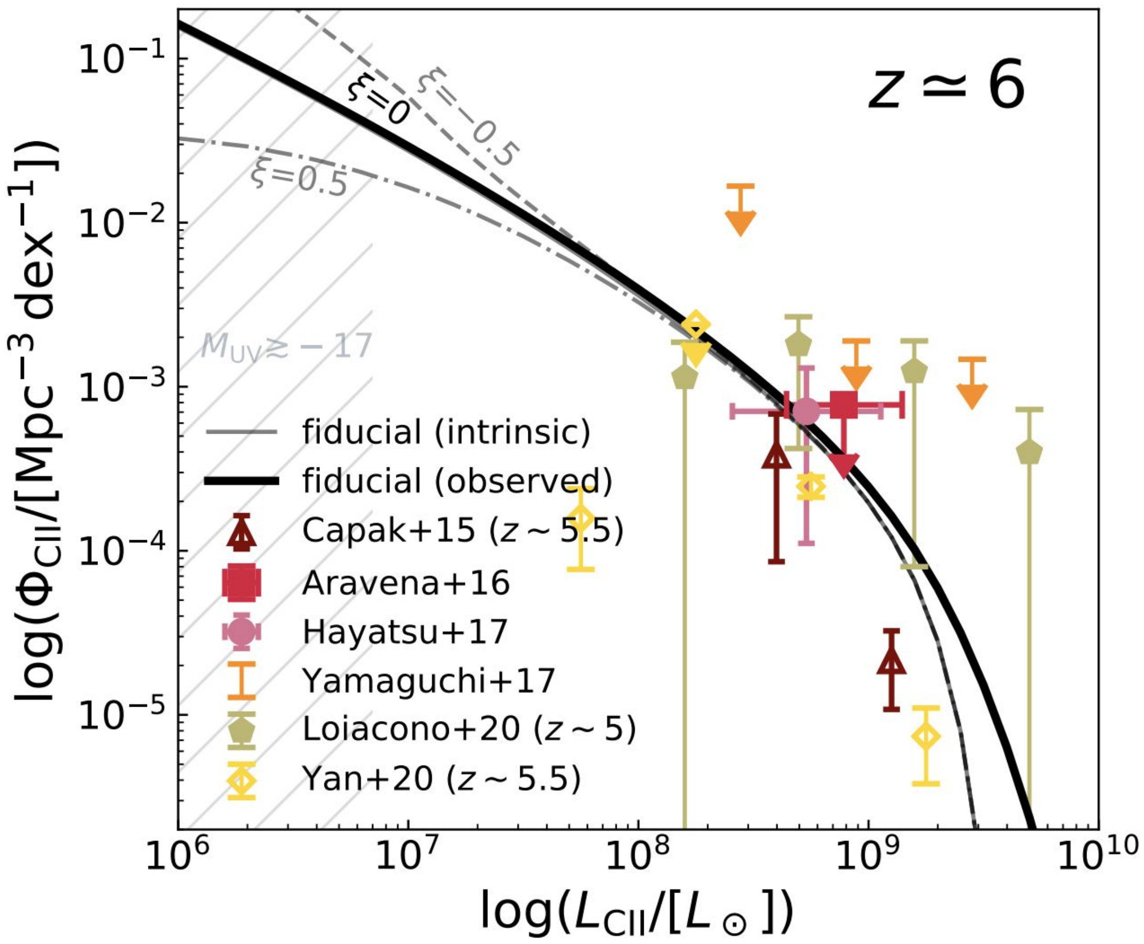
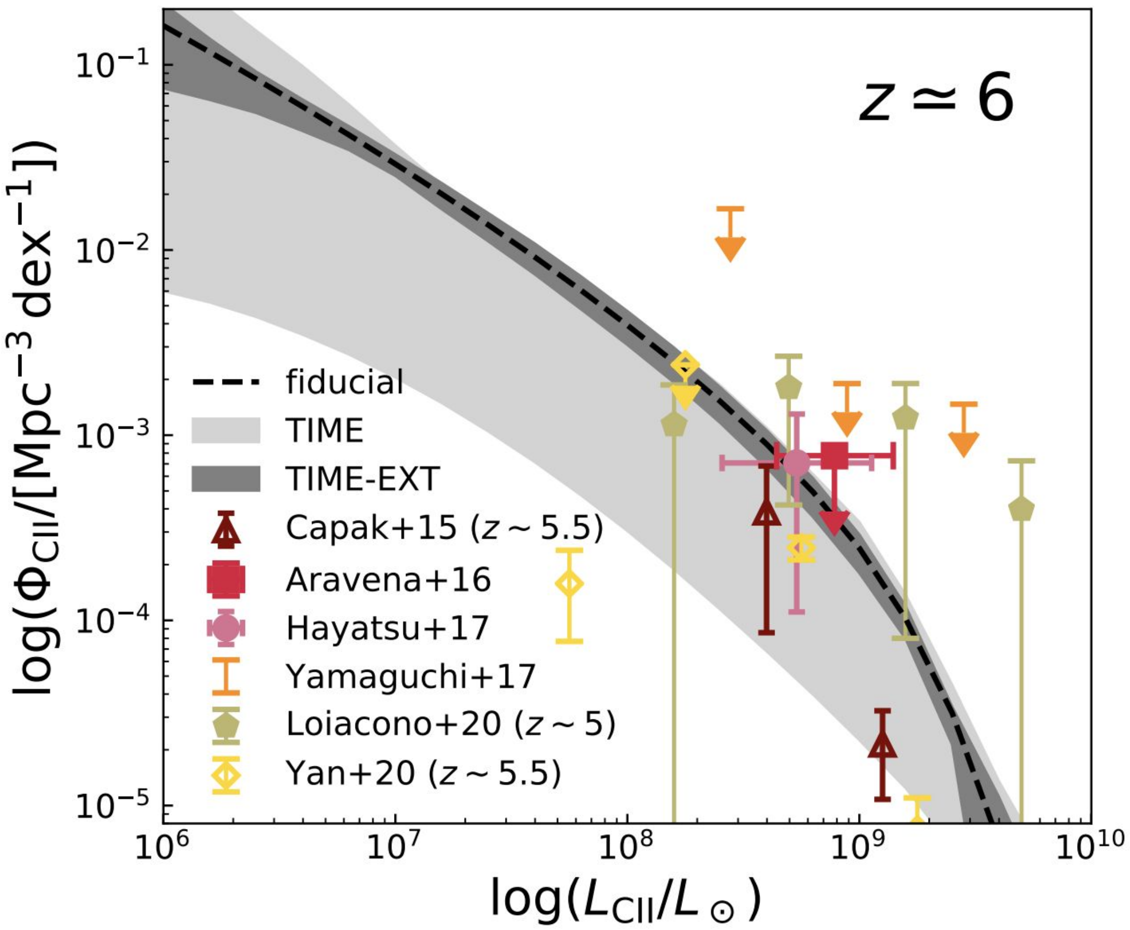


Bernal & Kovetz (2022)

Leaving no photon behind

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



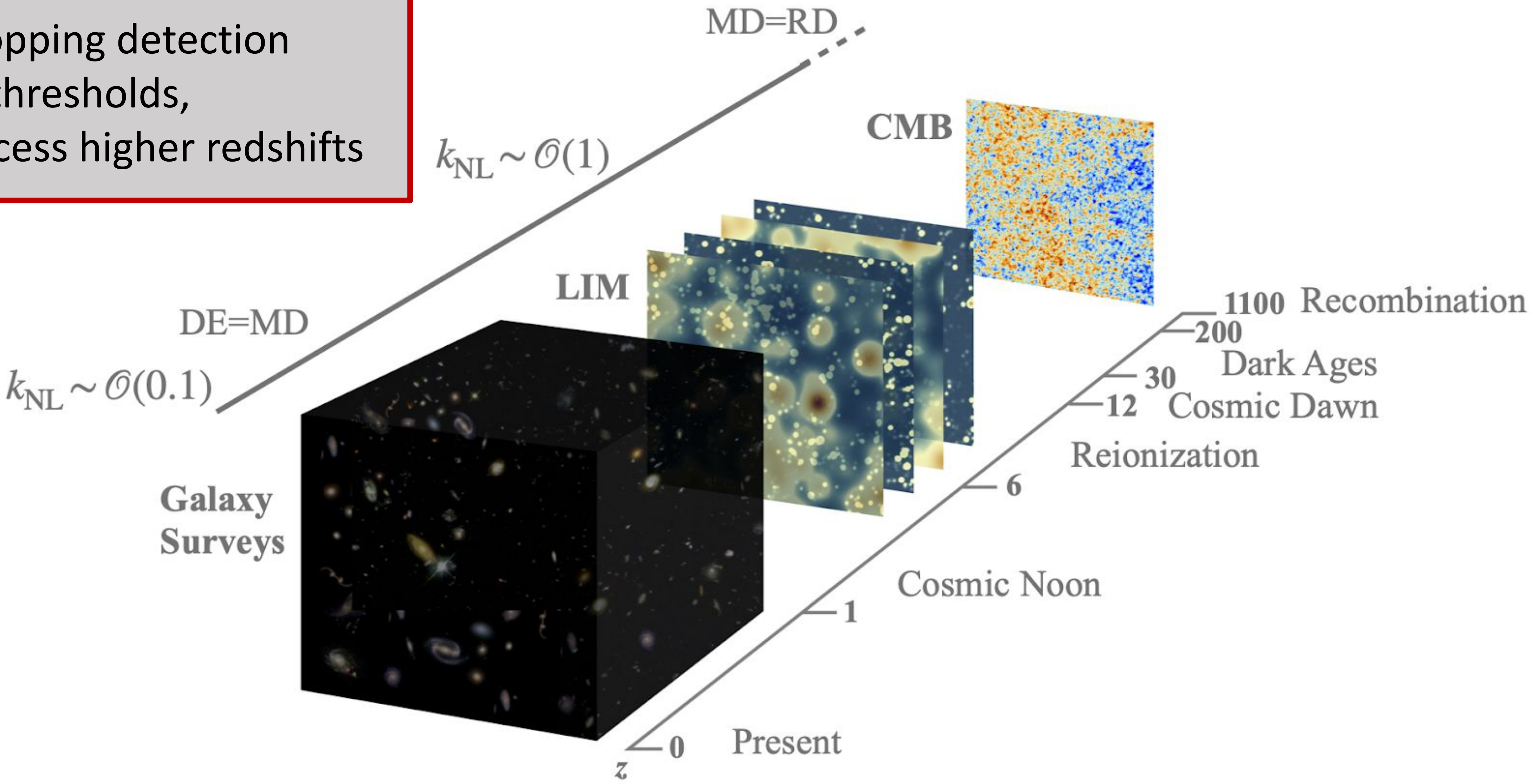


Sun+(2021)

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

Filling the gaps in cosmic history

By dropping detection thresholds,
we can access higher redshifts



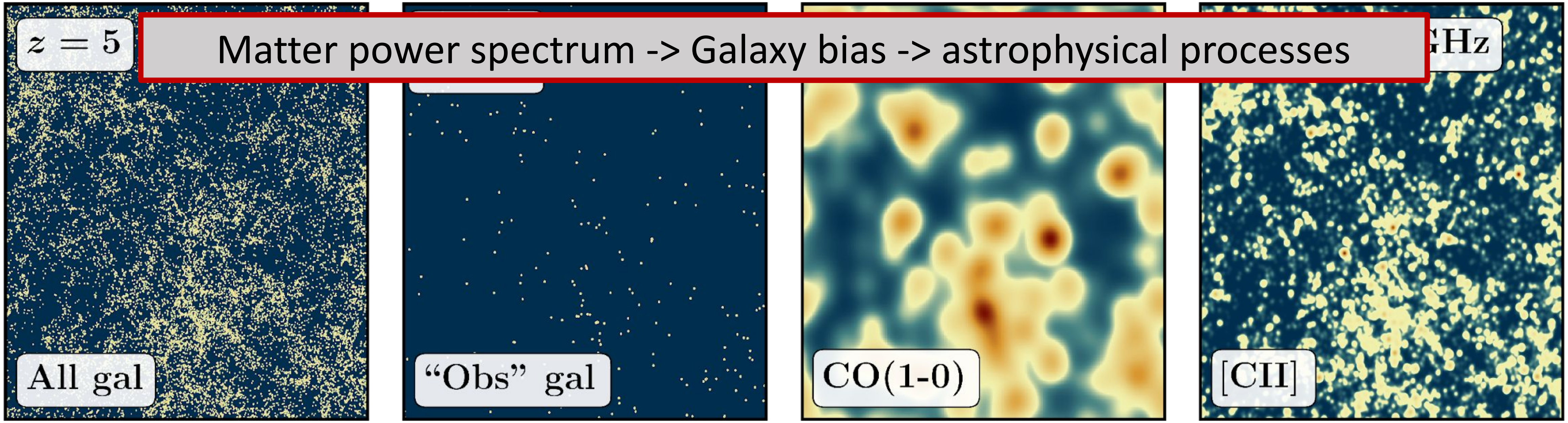
Bernal & Kovetz (2022)

What is Line-Intensity Mapping?

- Intensity fluctuations:
    - trace matter density fluctuations
    - Depends 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?

Map the faint & high-z Universe

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- For cosmology: Noisy map of *all* galaxies and IGM (vs detailed map of brightest)
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Matter power spectrum -> Galaxy bias -> astrophysical processes

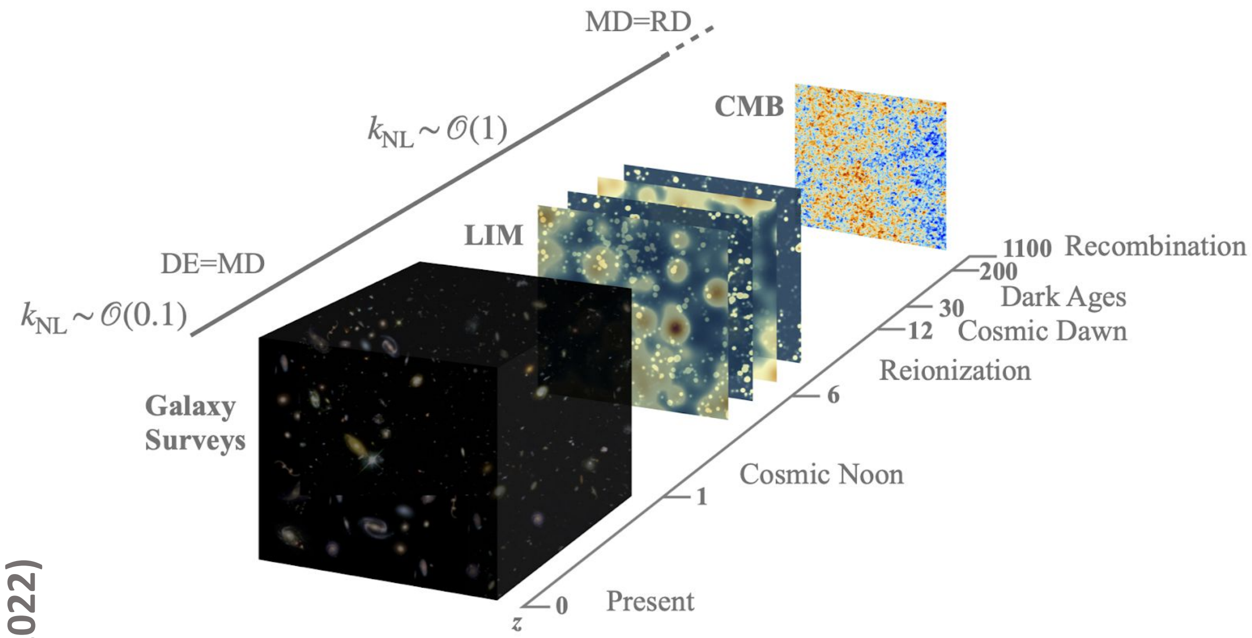
Three main features that make LIM unique:

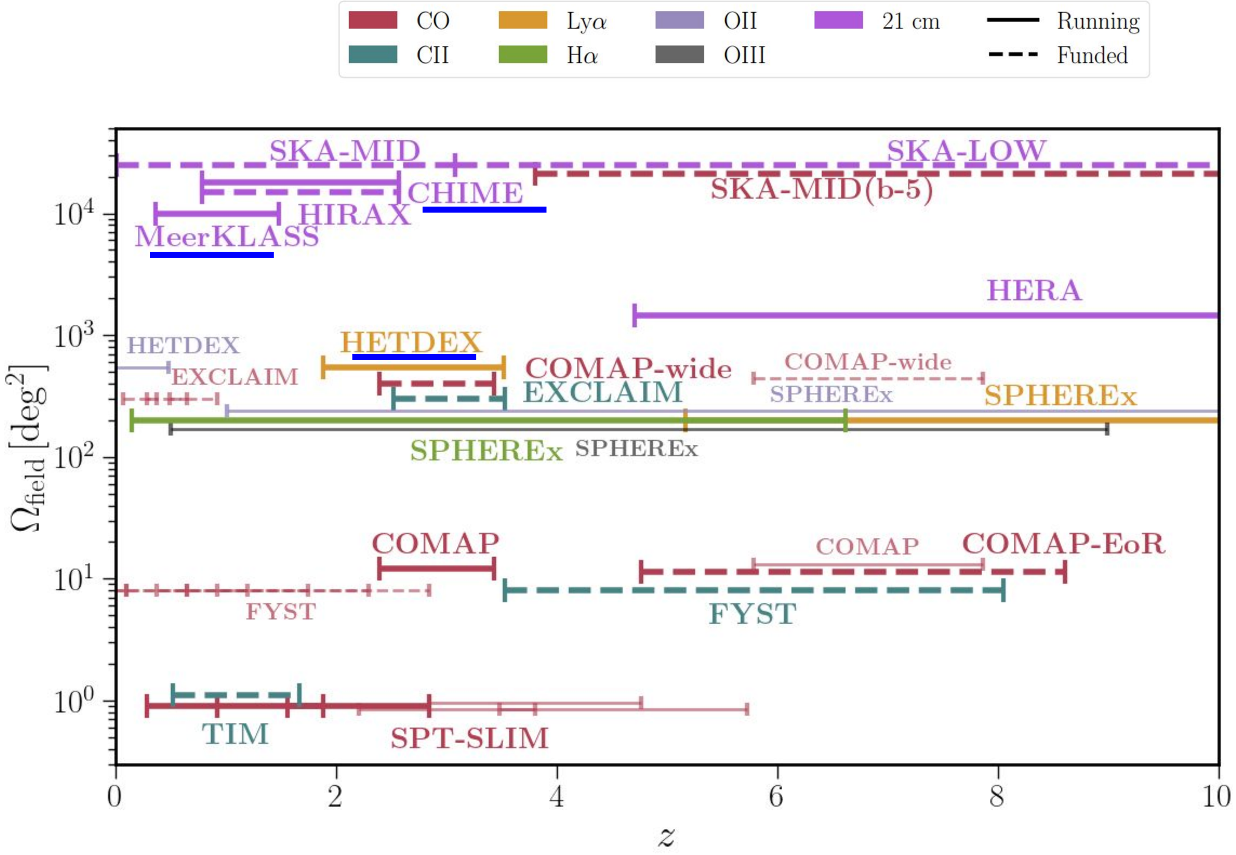
1. Capture faint and diffuse sources
2. Access beyond the reach of galaxy surveys
3. Quickly map large three-dimensional volumes

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

*Things are different for 21cm from Cosmic Dawn + Reionization

Filling the gaps in cosmic history





Bernal & Kovetz (2022)

- Pathfinder stage
- Intrinsically multitracer
- All kind of astrophysics

- Huge range of freq
- COPSS, mmIME, Planck x QSOs/gals ([CII], CO(3-2)), GBT, Planck + Herschel + IRAS (CBR), …

Information return from line-intensity maps

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

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

**Careful with interpretation of shot noise!!

- 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

- There are plenty of other summary statistics to explore too!

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- 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

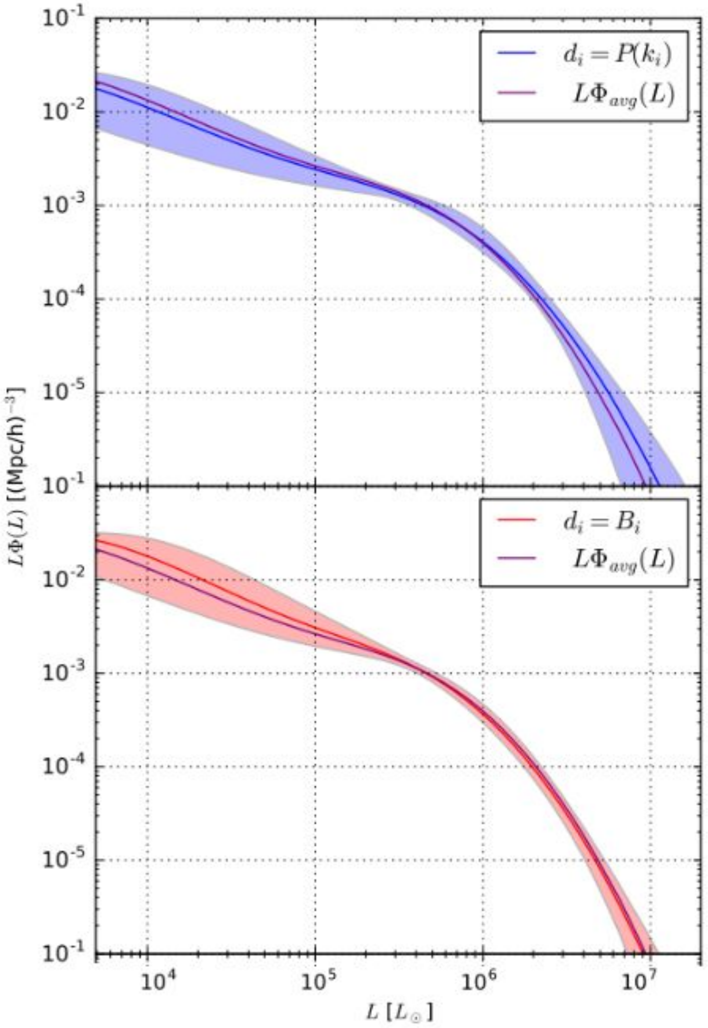
VID: best for astro, integrals of clustering

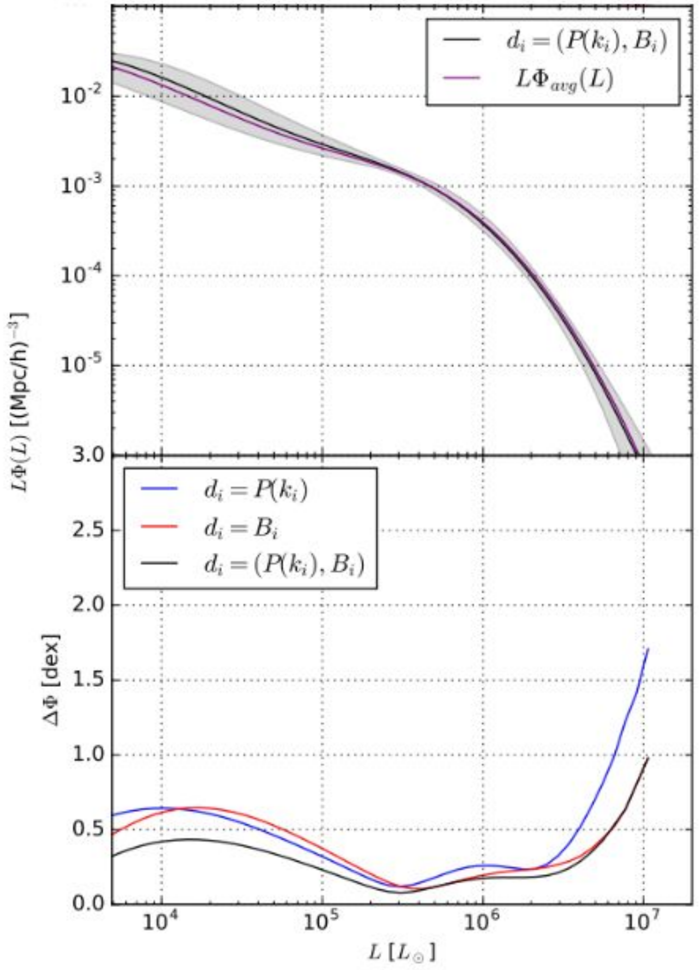
Combining VID and P(k)

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 (ULAs, PNG, …)
(Sabla, Bernal+ 2024)



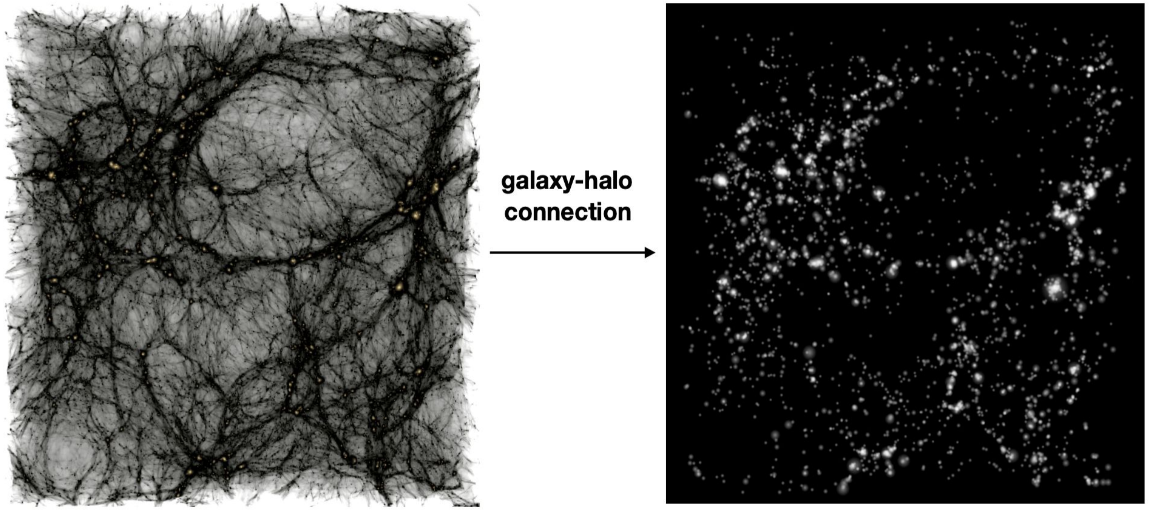


Accounting for resolution effects and line broadening is critical! (Bernal, 2023)

Ihle+(2019)

How do we go beyond?

DM Sims
(e.g., Nbody)



Connect astro prop.
with line intensity

Approaches to modeling the galaxy-halo connection

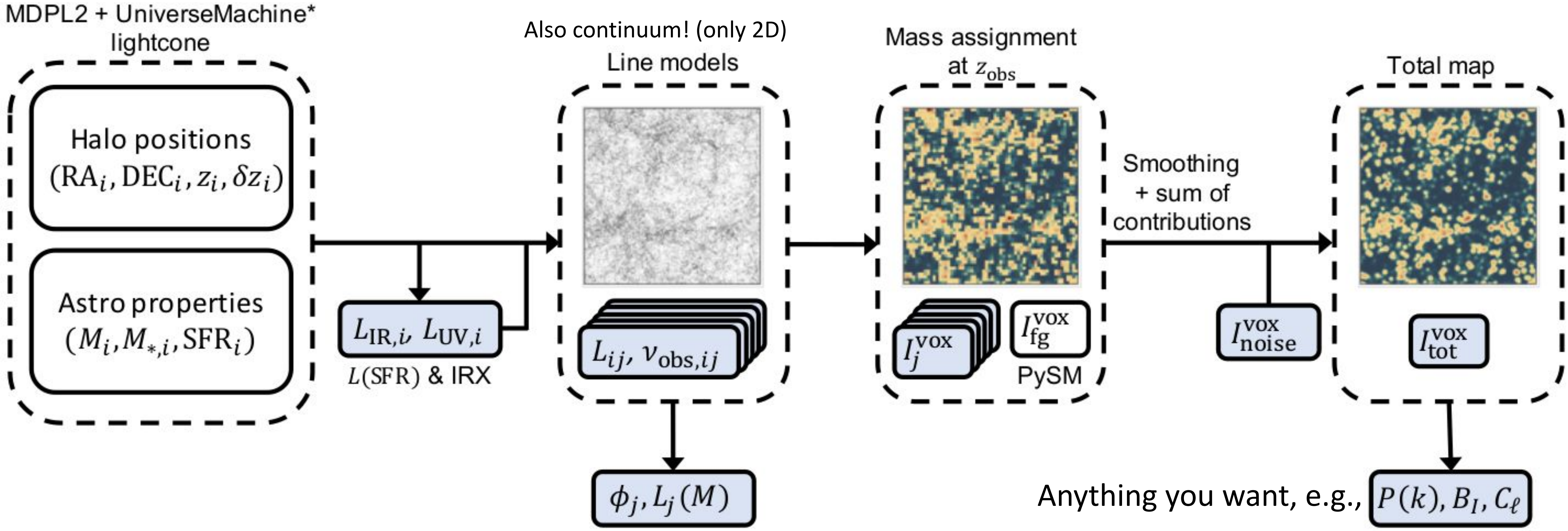
← physical models | empirical models →

Hydrodynamical Simulations	Semi-analytic Models	Empirical Forward Modeling	Subhalo Abundance Modeling	Halo Occupation Models
Simulate halos & gas; Star formation & feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos & subhalos) plus assumptions about galaxy—(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

"A (sub)-halo's star formation rate is tightly correlated with its potential well depth, redshift, and assembly history"

LIM in simulated lightcone skies

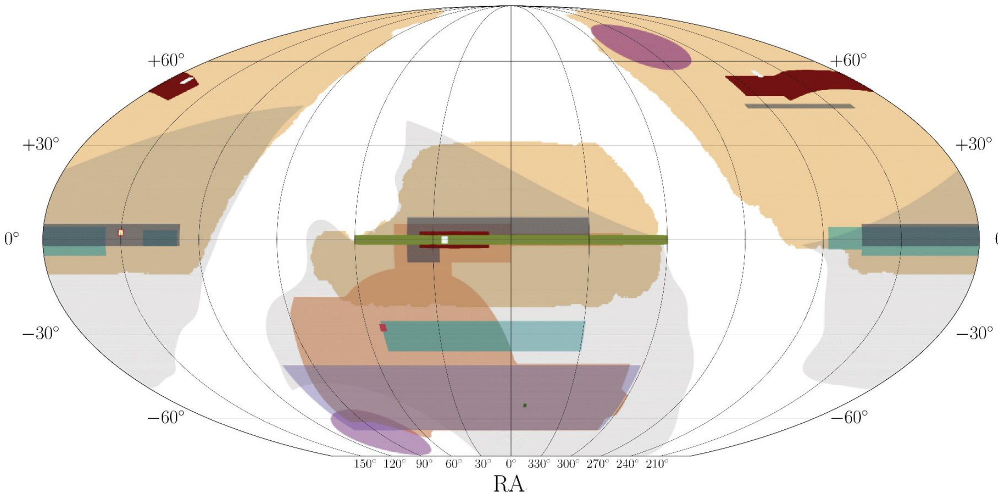
- Coherent multi-line, multi-probe simulated sky
- Mock map for a given experiment with *all* contributions, coherent with other probe



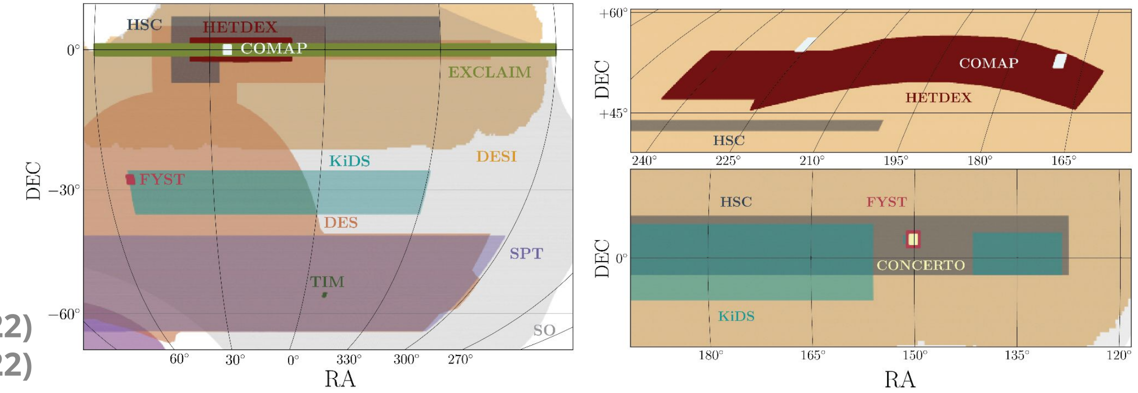
Sato-Polito, Kokron, Bernal (2022)

All probes in one sky

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

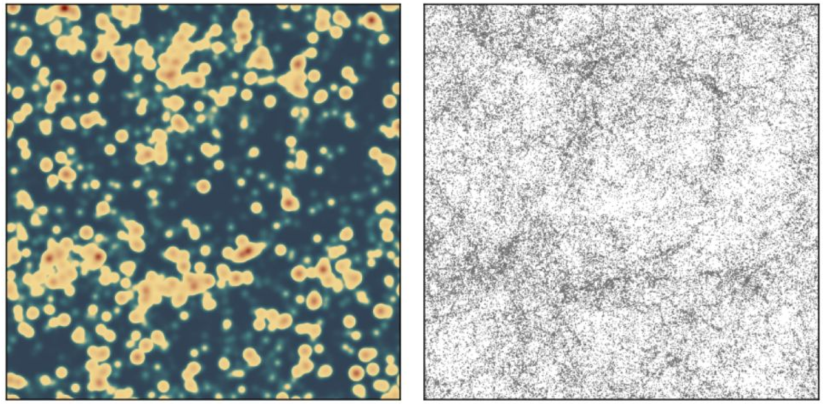


Bernal & Kovetz (2022)



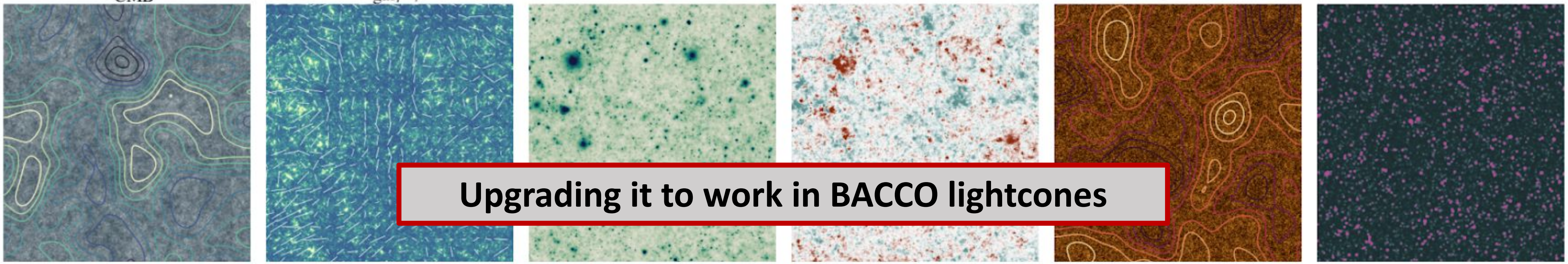
LIM

LRGs/ELGs



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

$\kappa_{\rm CMB}$ | $\kappa_{\rm gal}/\gamma$ | TSZ | KSZ | CIB | RADIO



Upgrading it to work in BACCO lightcones

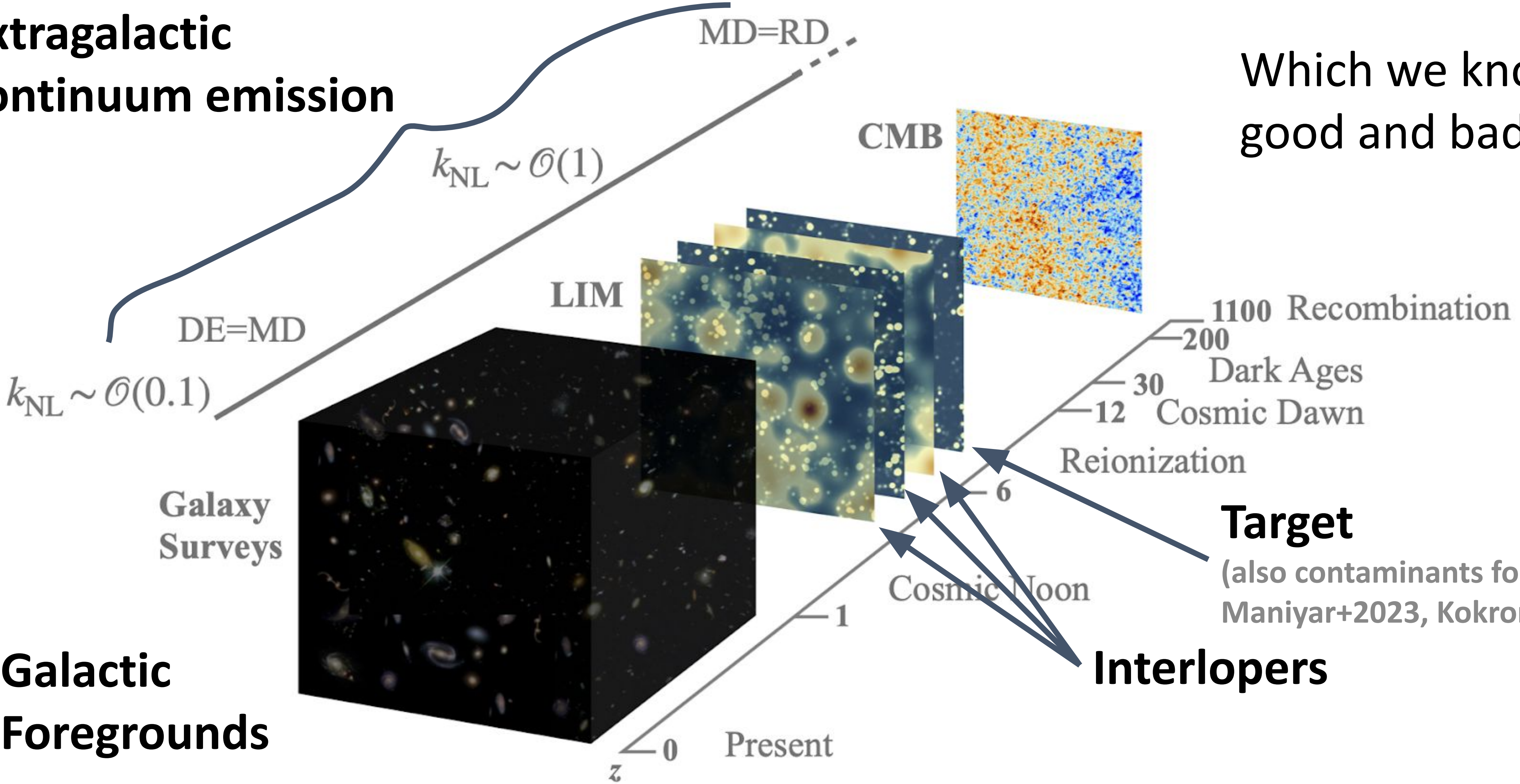
Real life:

dealing with foregrounds
(but progressing fast!!)

LIM reaches further, and collects all…

Extragalactic continuum emission

Which we know is good and bad



Target

(also contaminants for CMB!)
Maniyar+2023, Kokron+ 2024

Interlopers

Galactic Foregrounds

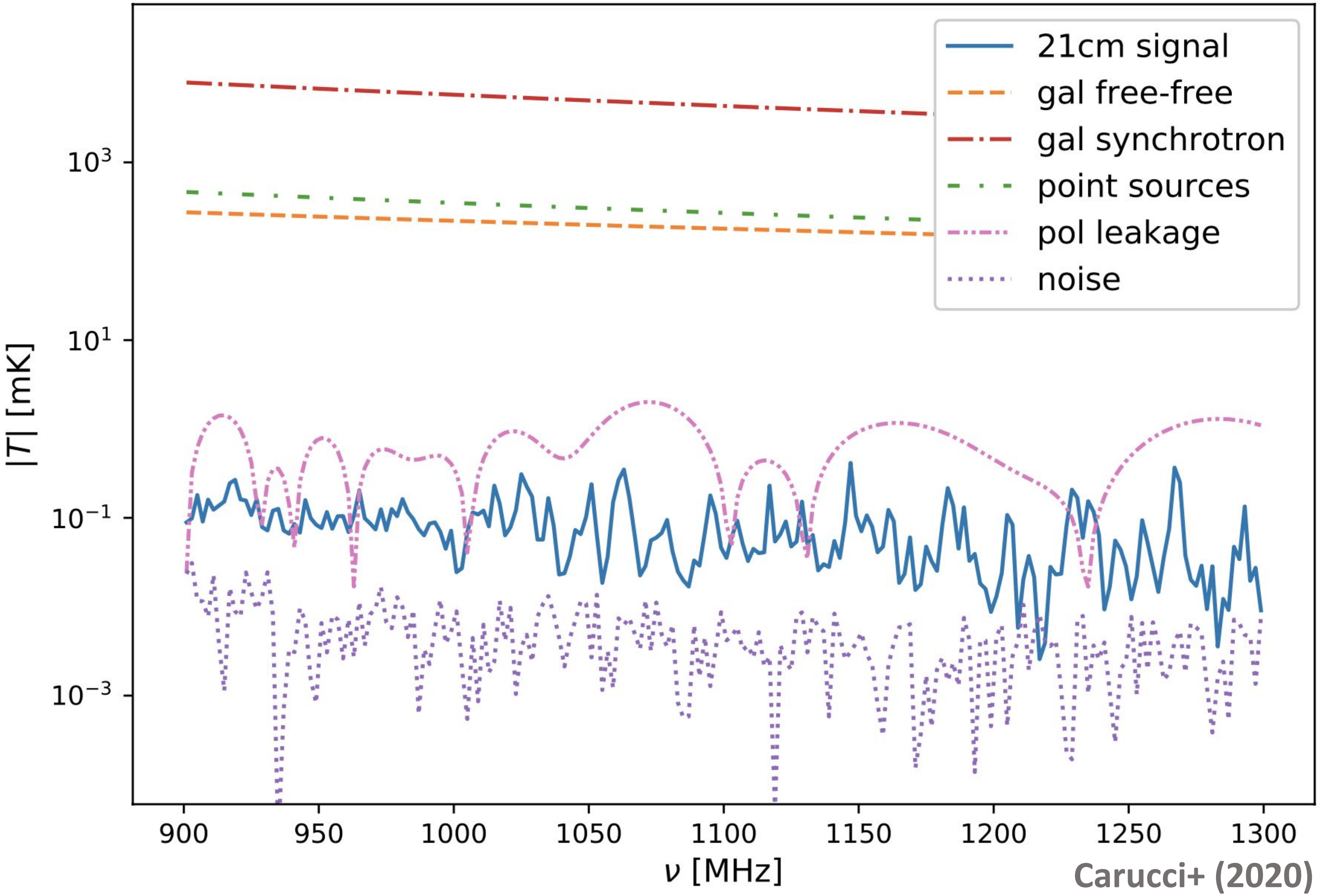
Bernal & Kovetz (2022)

Galactic foregrounds (the HI case)

- Clean foregrounds (and systematics) to very (**very**) good accuracy

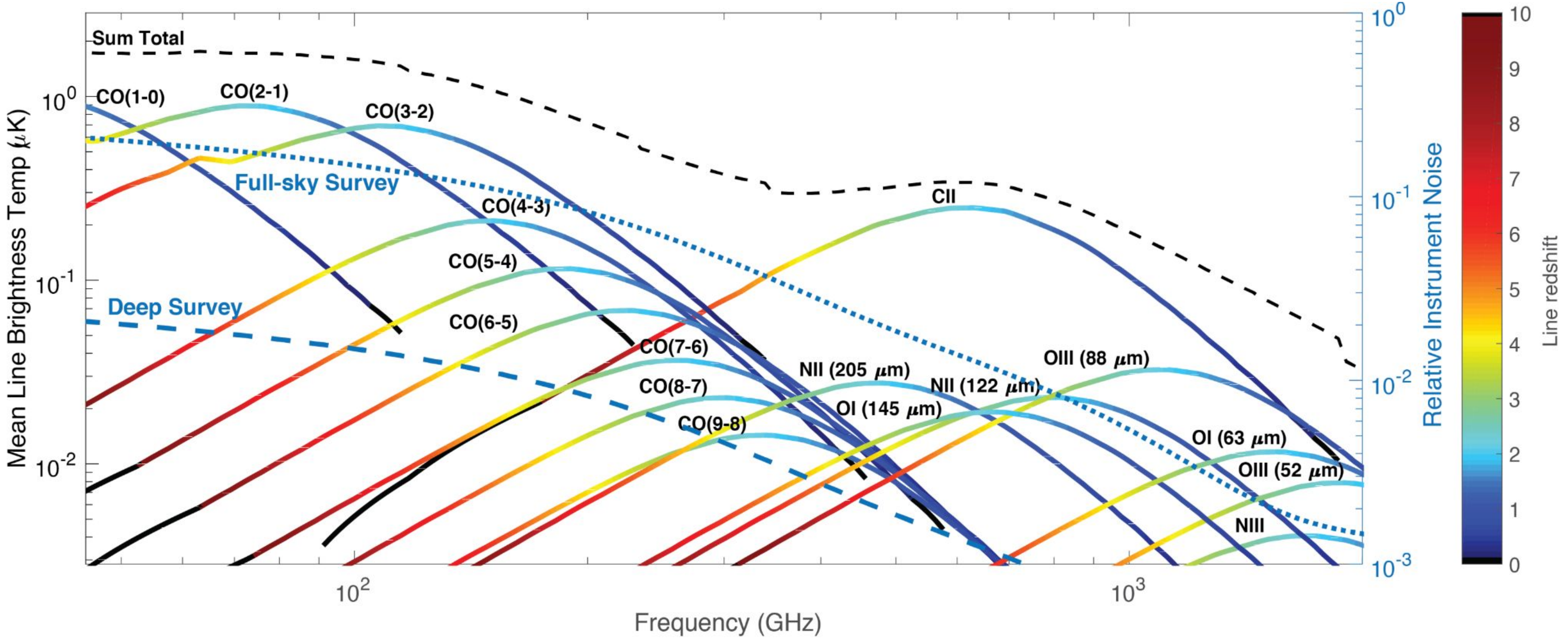
- Very hard to model: blind methods -> PCA
  - Signal loss?
  - Transfer function!

- Very different angular structure -> Use it to improve component separation
  - Multiscale PCA



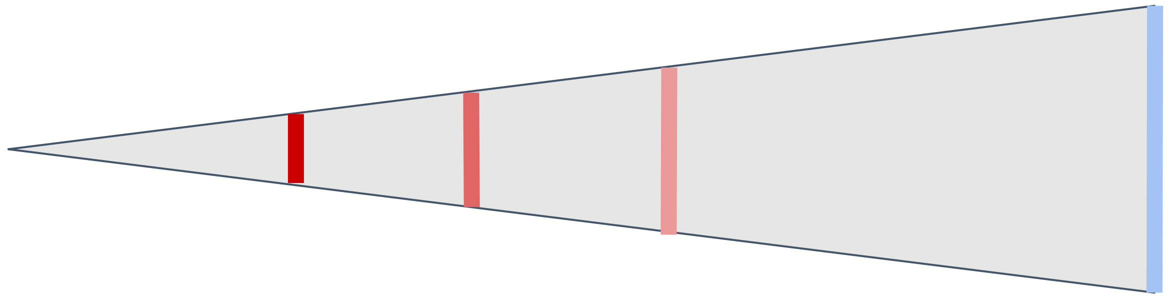
Carucci+ (2020)

Line interlopers



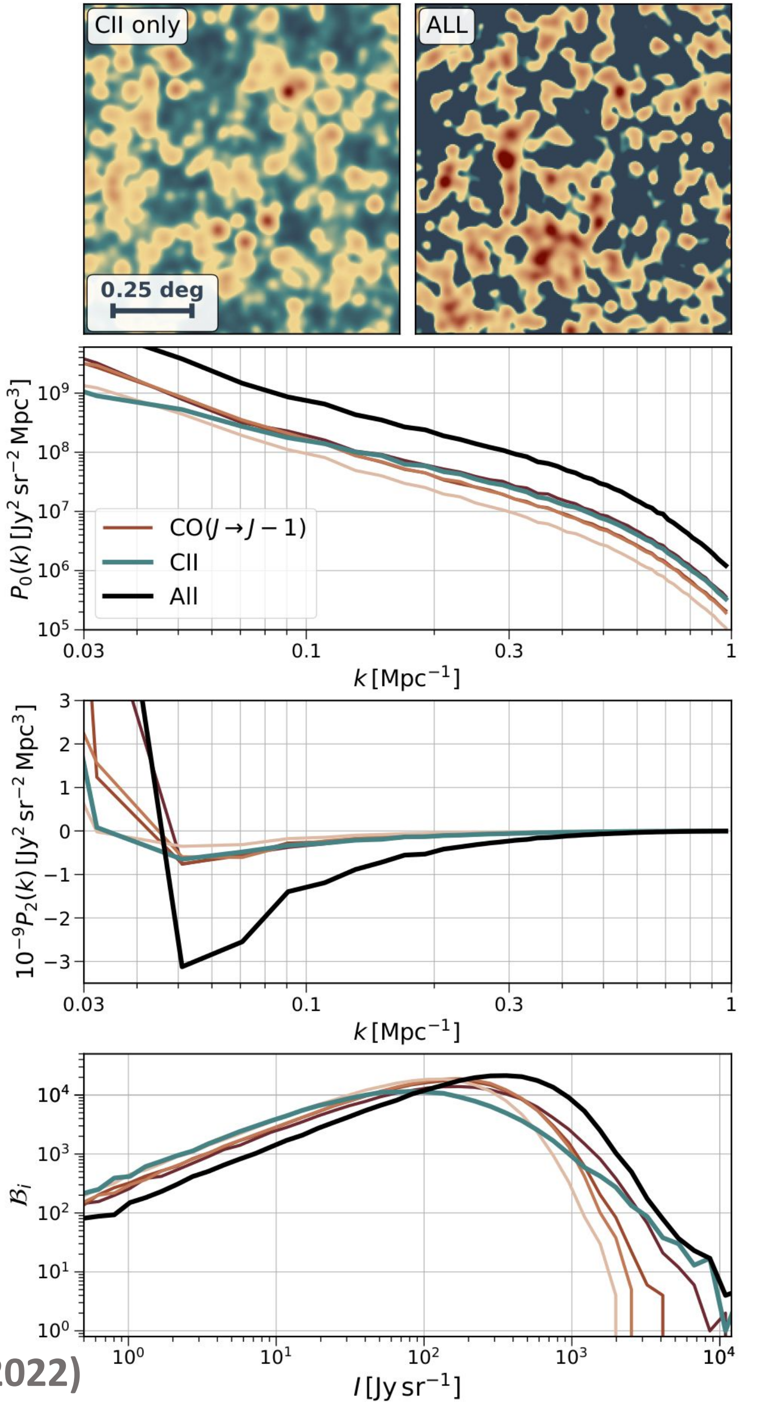
Line-interloper contamination

- Line interlopers (redshift and signal confusion):



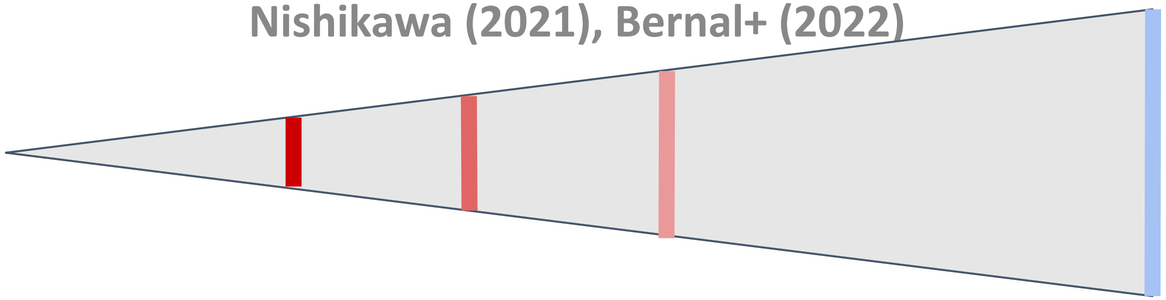
- Targeting CII at z = 5
- CO lines:
  - J = 4 at z = 0.46
  - J = 5 at z = 0.82
  - J = 6 at z = 1.18
  - J = 7 at z = 1.55
- Brighter red, higher J

Sato-Polito, Kokron, Bernal (2022)



Line-interloper contamination

- 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)**
  - Multi-LIM (X-freq. Cls) **Cheng+(2024)**
  - Nulling techniques **Bernal & Baleato Lizancos(2024)**
  - Exotic unknown signals!! DM and/or neutrino decay **Creque-Sarbinowski & Kamionkowski (2018), Bernal+ (2021a), Bernal+ (2022), Nishikawa (2021), Bernal+ (2022)**



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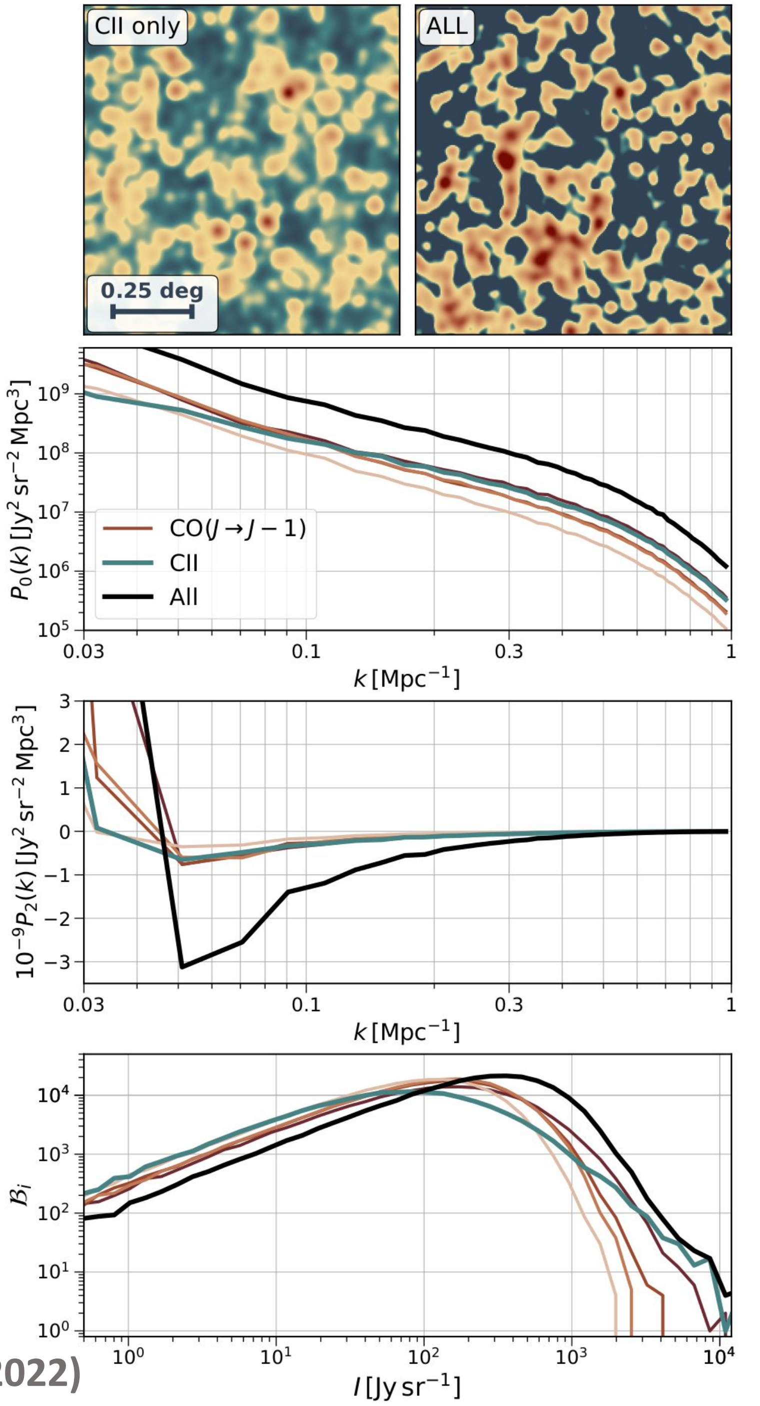


Sato-Polito, Kokron, Bernal (2022)

Real life:

We are measuring power spectra!

LIM surveys with MeerKAT

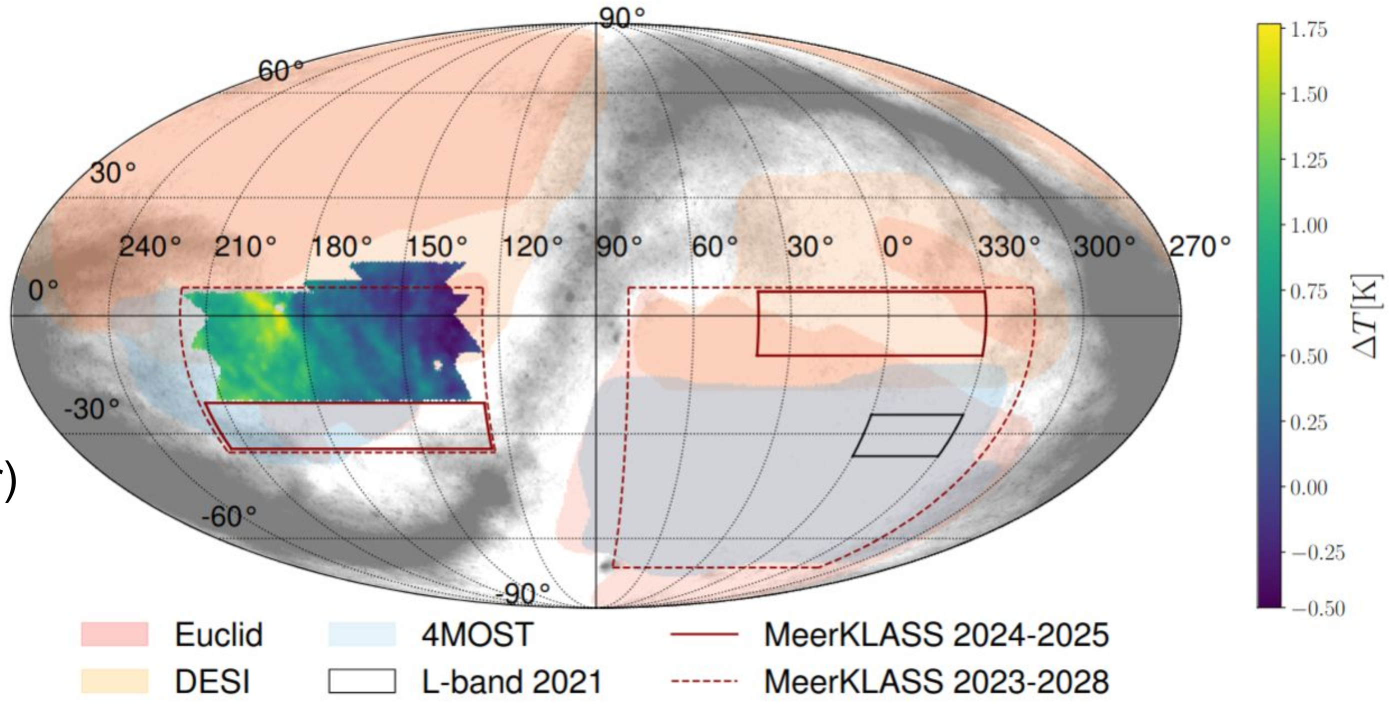
- **MeerKLASS:** MeerKAT Large Area Synoptic Survey (SKAO pathfinder)
- Aim: Cosmology (21cm LIM) but commensal with lots of other science (OTF continuum survey)
- Single dish: access to large scales, loss of small scales (64 13.5m-diameter dishes)
- Prioritize patches with overlapping galaxy surveys for cross-correlation

L-band:

- 900-1670 MHz (z<0.58)
- ~ 100 hours observed

UHF band:

- 580 MHz-1015 MHz (0.40 < z < 1.45)
- ~ 1400 hours, 5600 deg² observed (end of year)
- Project “approved”: 2,500 hours over 10,000 deg2 (continuum: 25 uJy rms, 13’’)

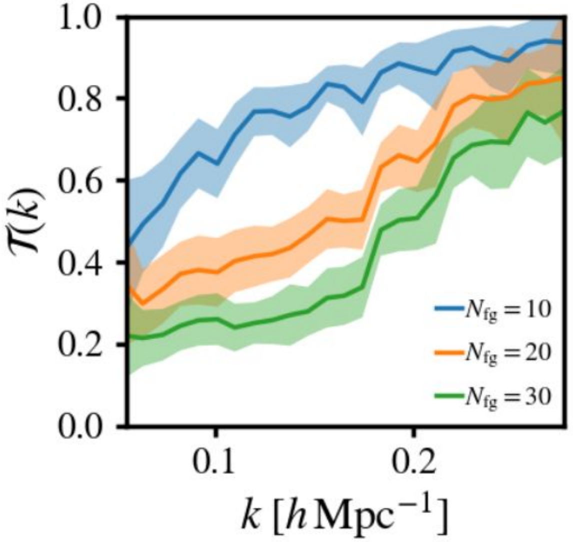


Measurements x galaxies

S.Cunnington, YC.Li+23 [arXiv:2206.01579]

- Clean foregrounds (and syst) to very (very) good accuracy
- Very hard to model: blind methods
  - Signal loss?
  - Transfer function!

- 1st MK L-band x WiggleZ (30 modes)



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$$\mathcal{T}(k) = \left\langle \frac{\mathcal{P}(\mathbf{M}_{\mathrm{c}}\,,\,\mathbf{M}_{\mathrm{g}})}{\mathcal{P}(\mathbf{M}_{\mathrm{HI}}\,,\,\mathbf{M}_{\mathrm{g}})} \right\rangle$$

10.5 h observation

Correlation with WiggleZ gals

$0.4 < z < 0.46$, 100 deg^2

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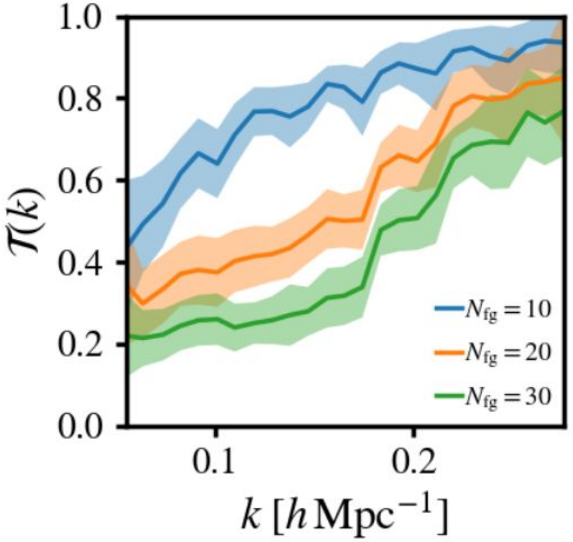

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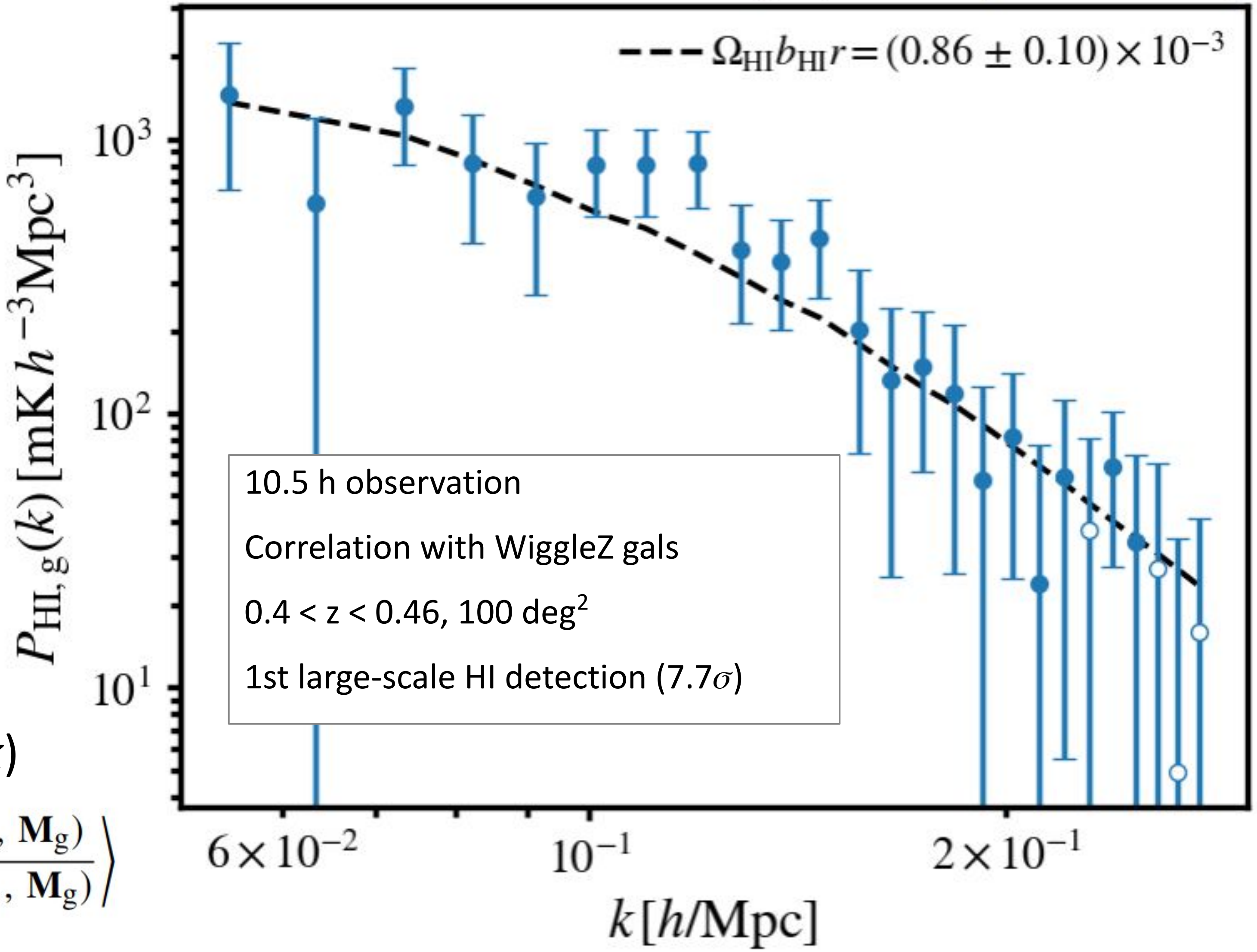
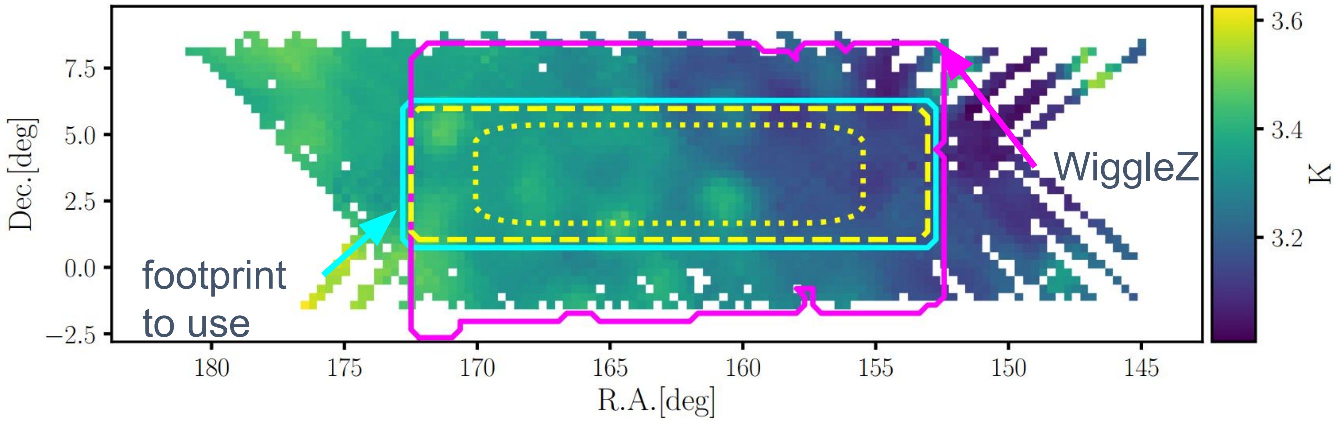
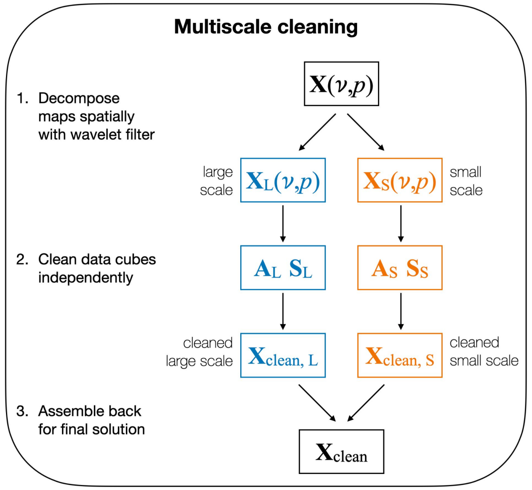


Cleaning radio foregrounds

- Standard: PCA -> We can do better
  - More uniform footprint
    - Remove bad pixels
    - Keep all channels
  - PCA deals poorly with outliers



- multiscale PCA: Add angular information to reduce component leakage
  - 2019 L-band: remove 4 large-scale and 8 small-scale modes (vs 30)



MK, Carucci+ (2025)

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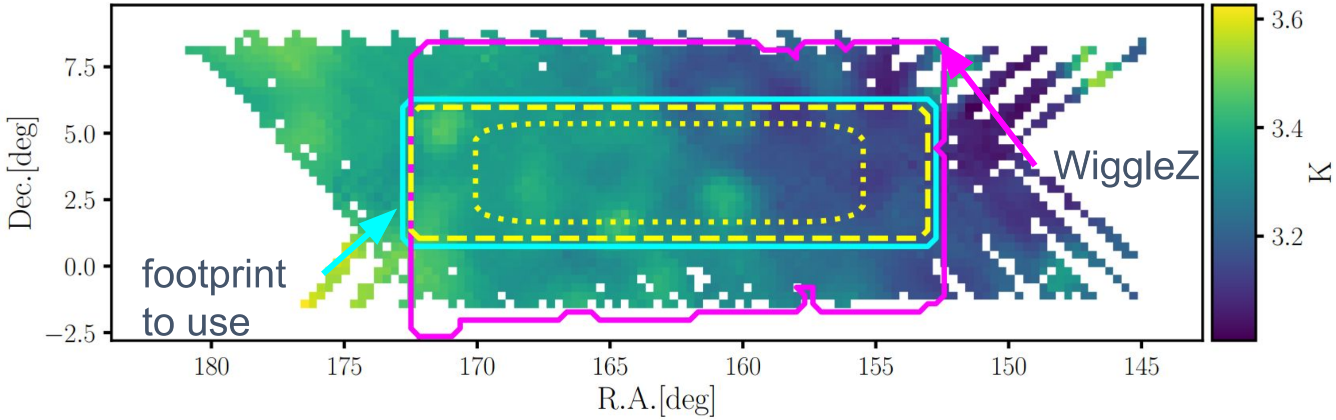

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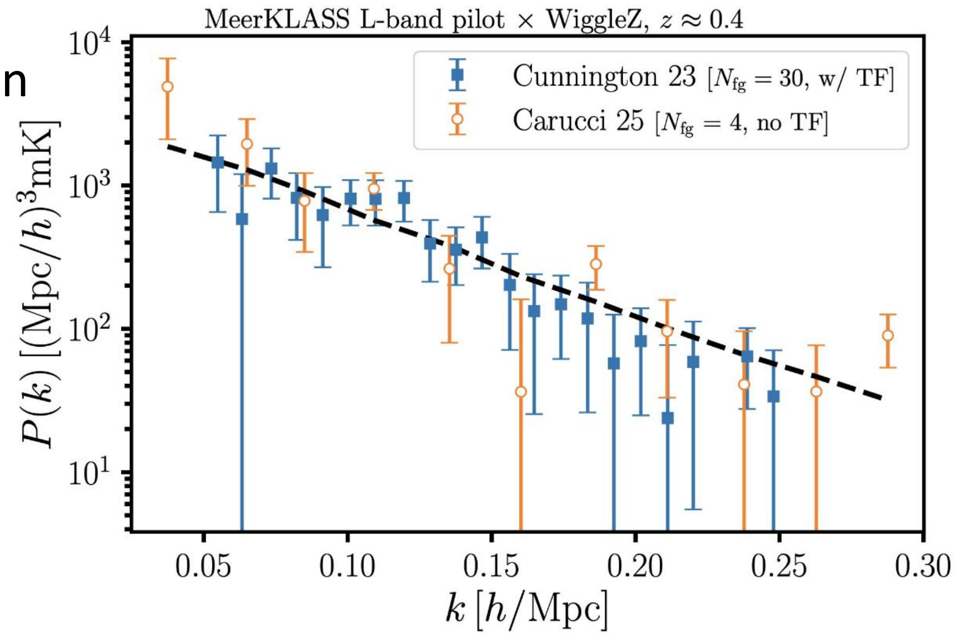
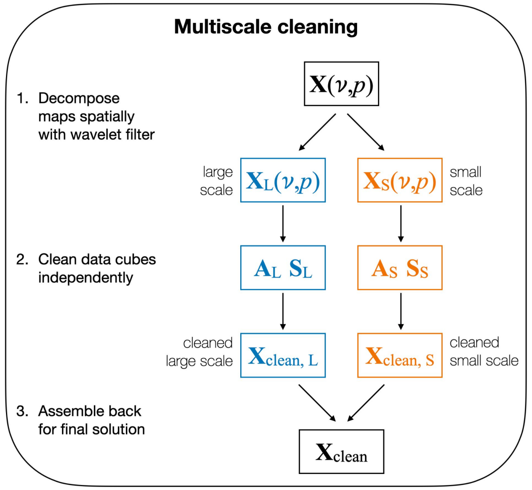




  - P(k) fit stable against k-cuts **without** transfer function (consistent!)
- Amplitude parameter significance:
  - 5.8σ vs 4.8σ (2023 analysis)

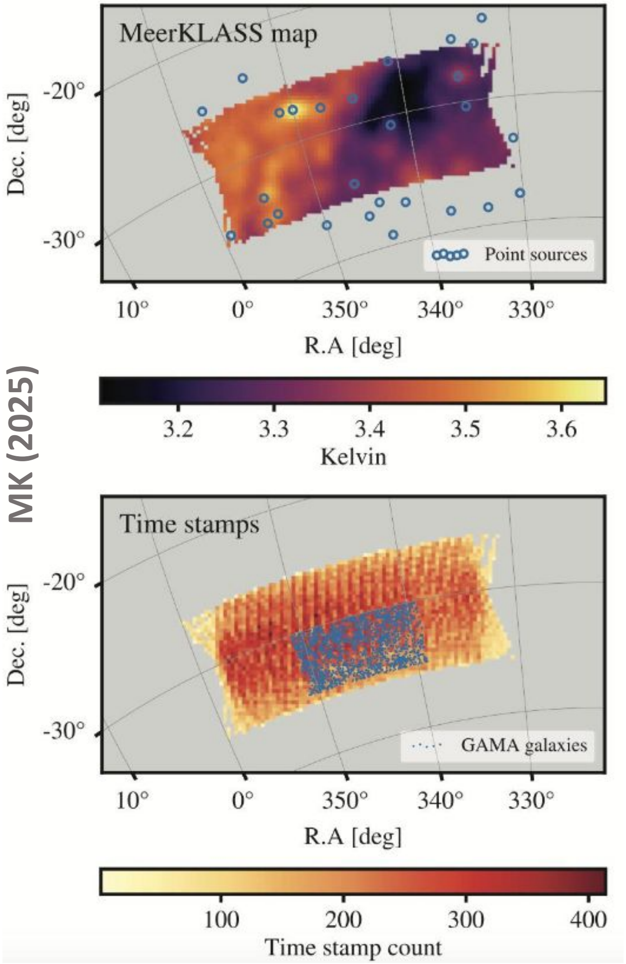
10.5 h observation

Correlation with WiggleZ gals

$0.4 < z < 0.46$, 100 deg^2

MK, Carucci+ (2025)

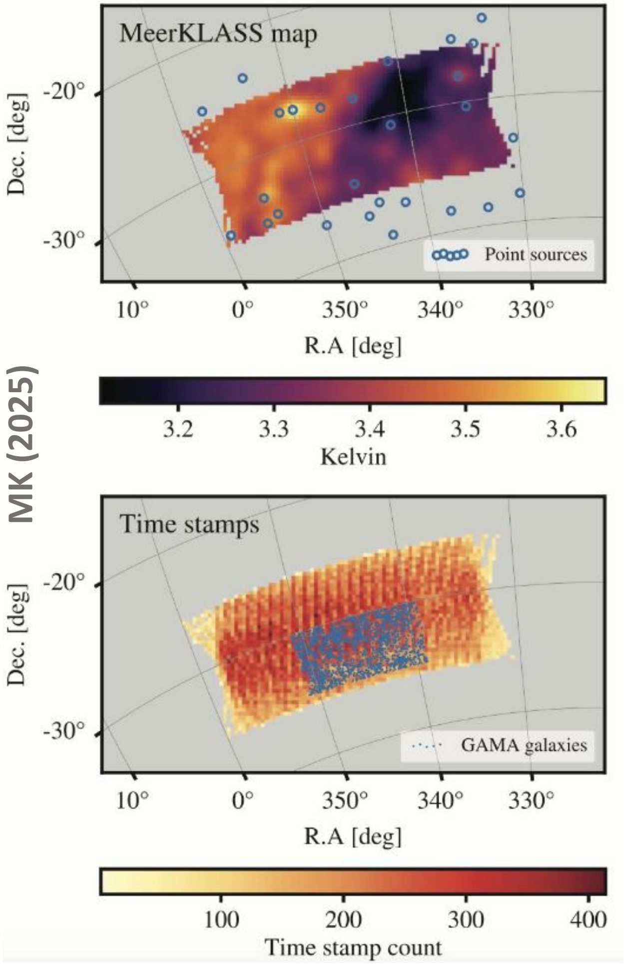
L-band deep survey



- 236 deg², 62 h (~40h after RFI)
- 0.39 < z < 0.46
- 10 modes removed (PCA+TF)
- MK x GAMA: >4σ , consistent
- Also in stacking Chen+ (2025)

L-band deep survey

MK (2025)



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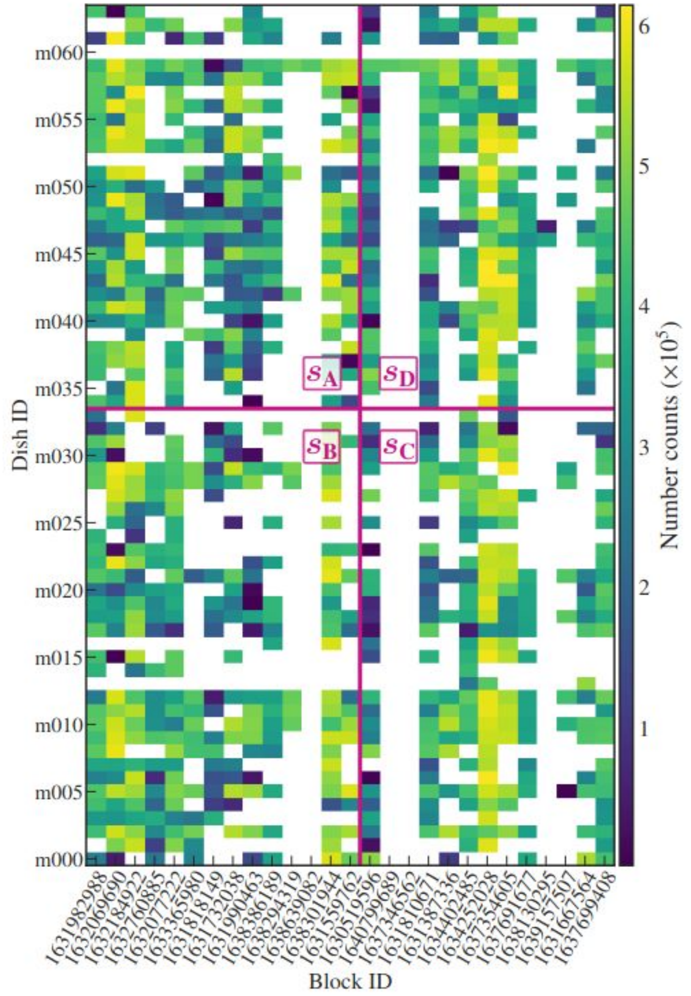
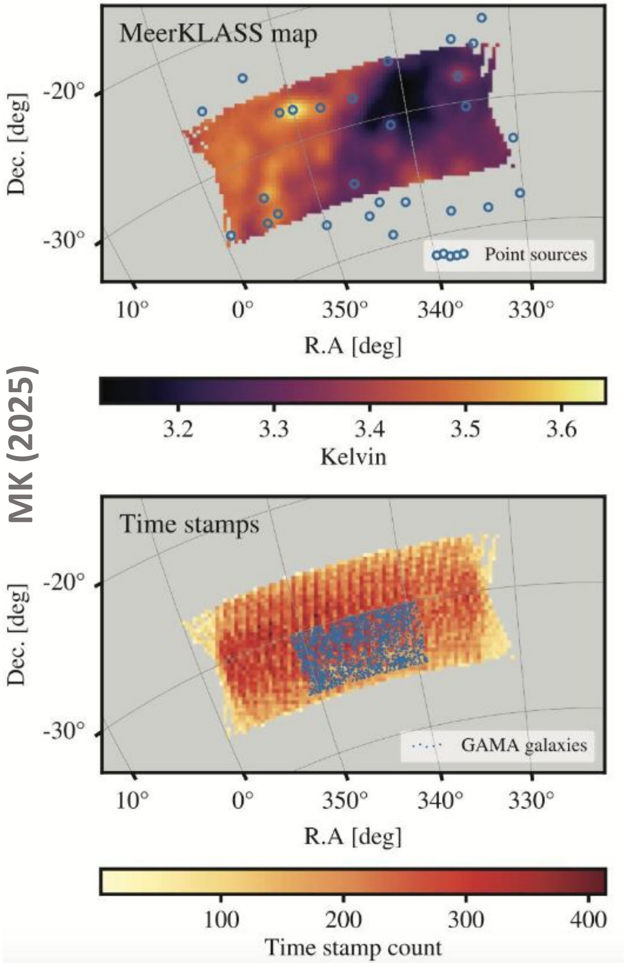
- <u>Aiming for auto-power spectrum!</u>
  - Internal splitting **super-cross** (split dish and time block)
    - Remove noise and uncorrelated systematics (dish- and time-like)
    - Different kinds of internal cross.
      - Block shuffling
      - Antenna informed
      - Super cross: AxC, BxD
      - $\{P_{AC}, P_{BD}\}$



MK (Submitted)

L-band deep survey



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- 0.39 < z < 0.46
- 10 modes removed (PCA+TF)
- MK x GAMA: >4σ , consistent
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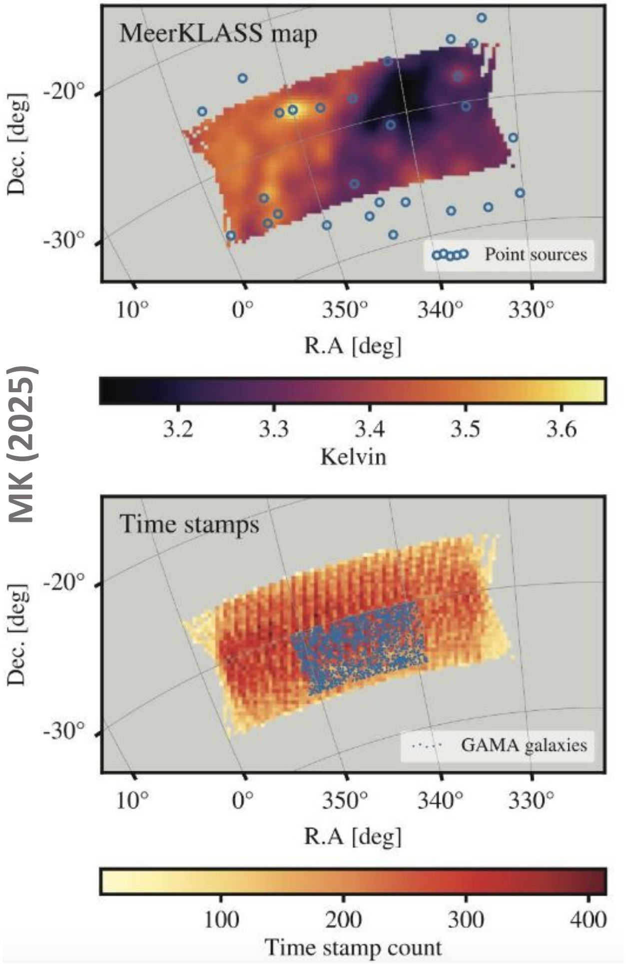
L-band deep survey



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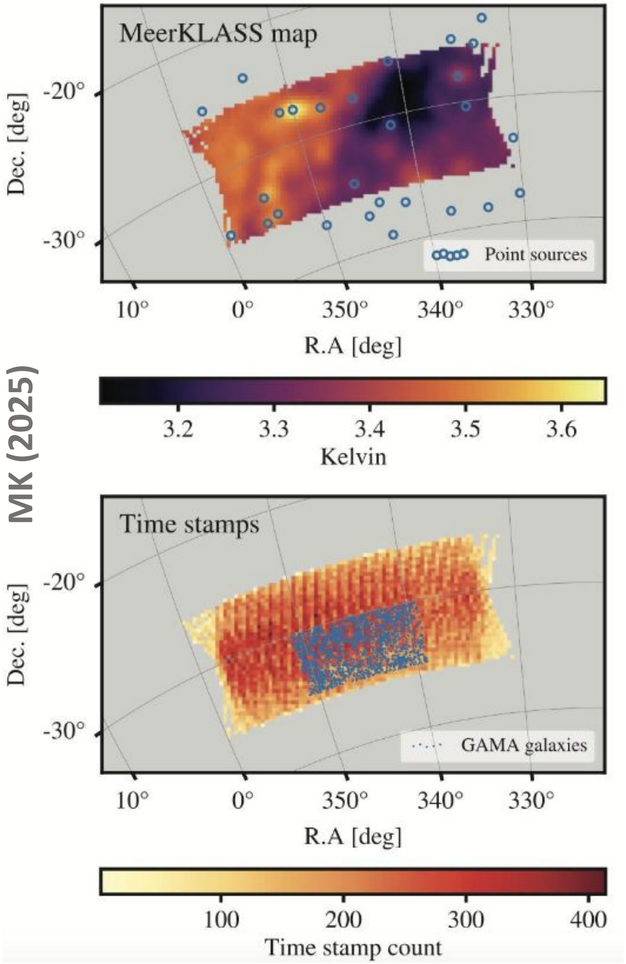

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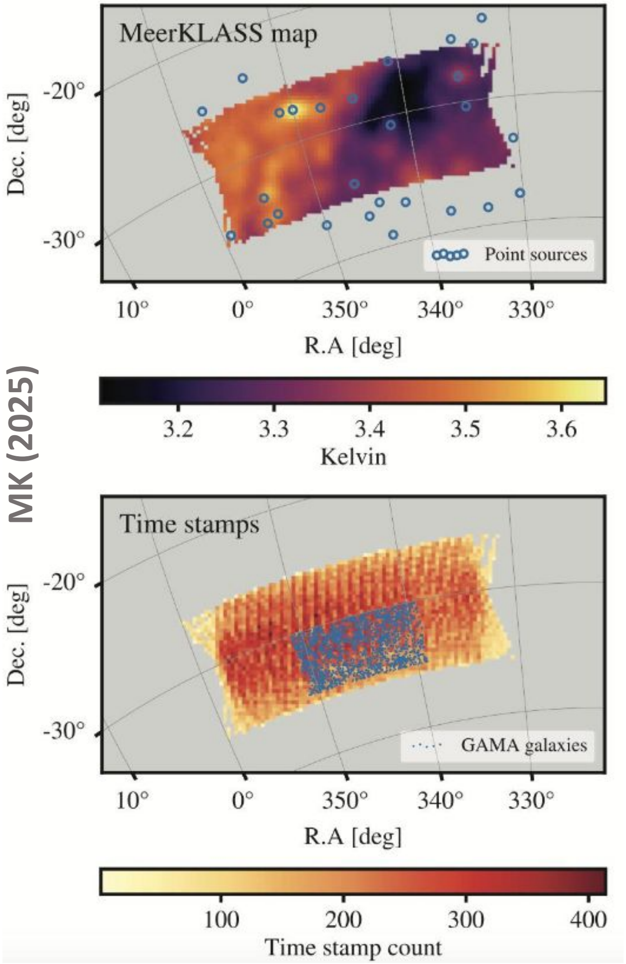

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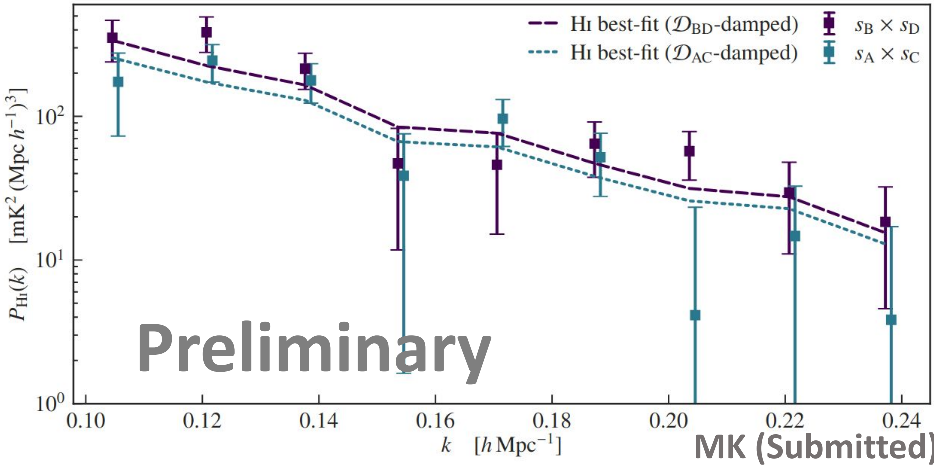
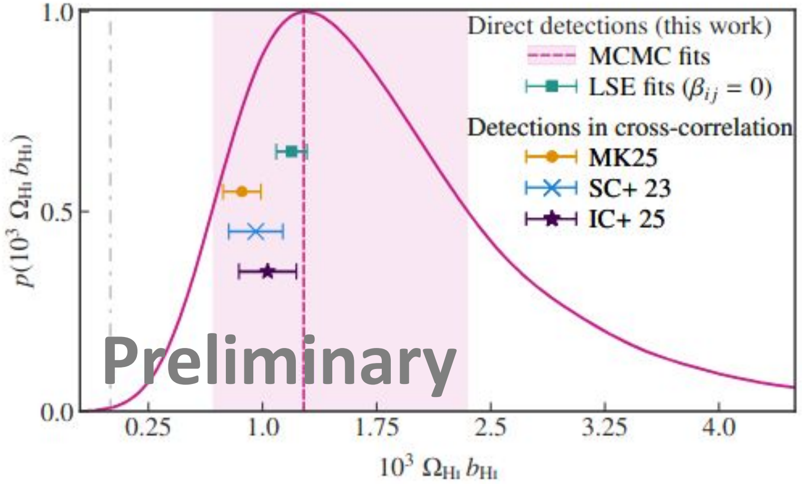
  - Jackknife covariance matrix
  - **Measurement! SNR = 7.3** (passing several tests)
    - Supersample covariance missing! **(Pamuk+ in prep)**





HETDEX

Gebhardt+2021

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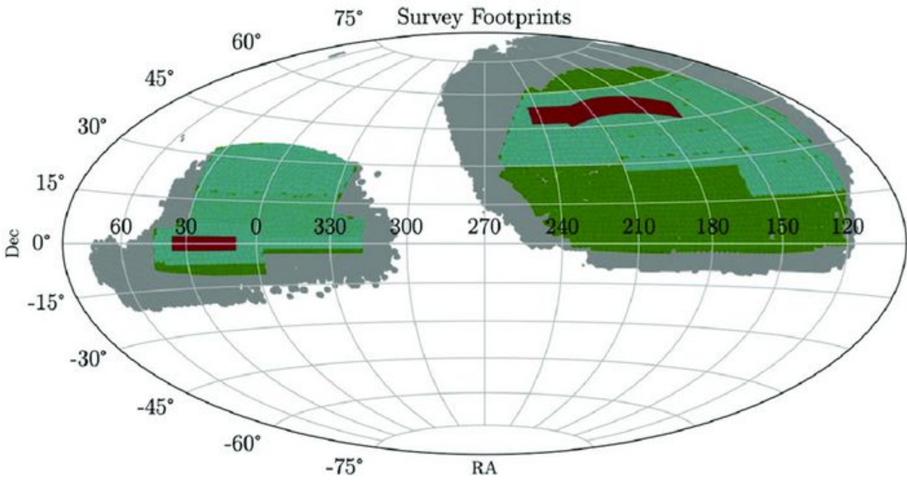

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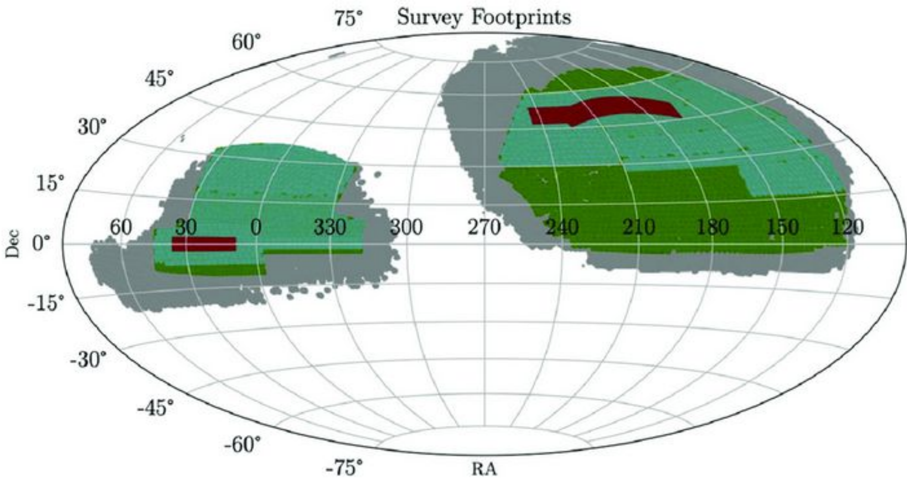
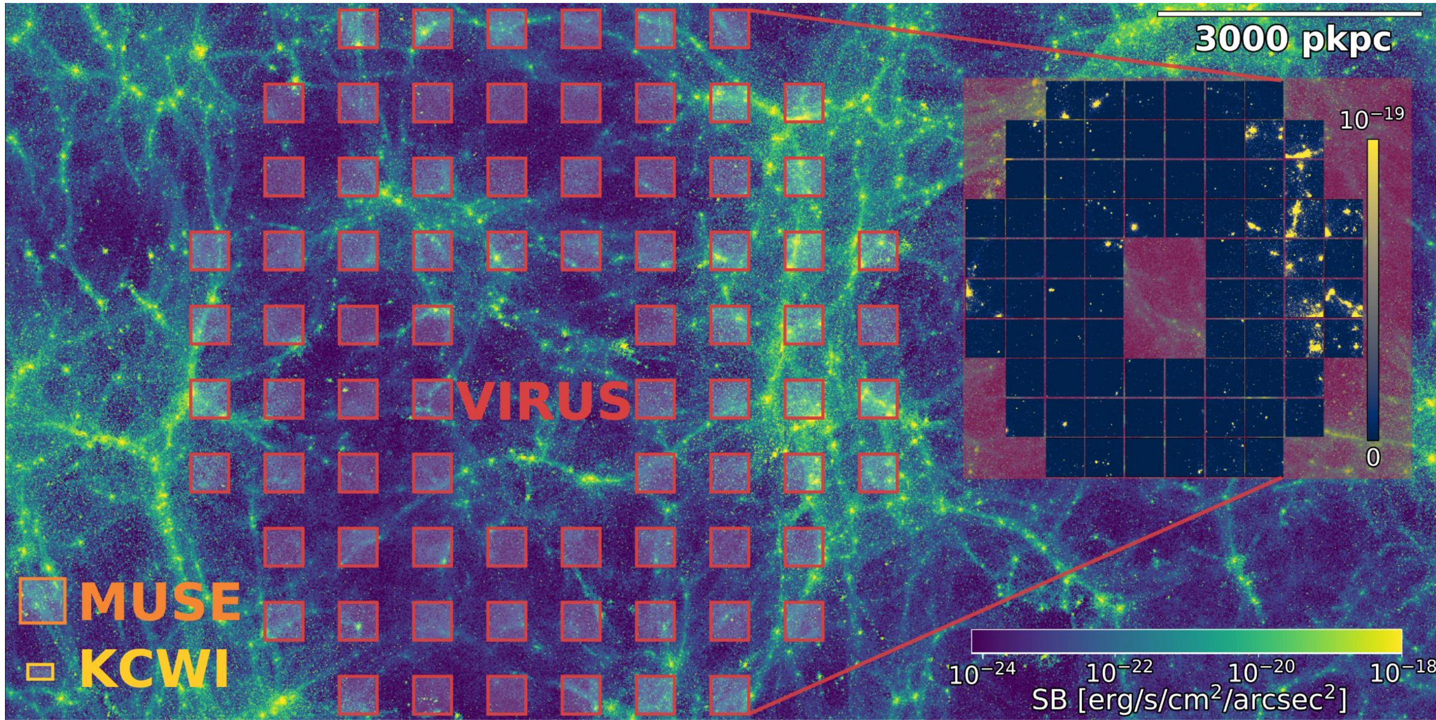


Credit: Chris Byrohl



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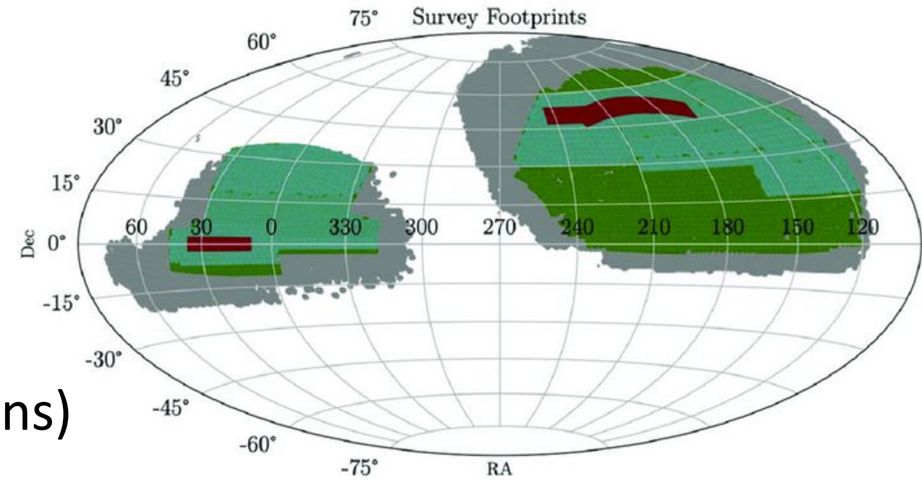

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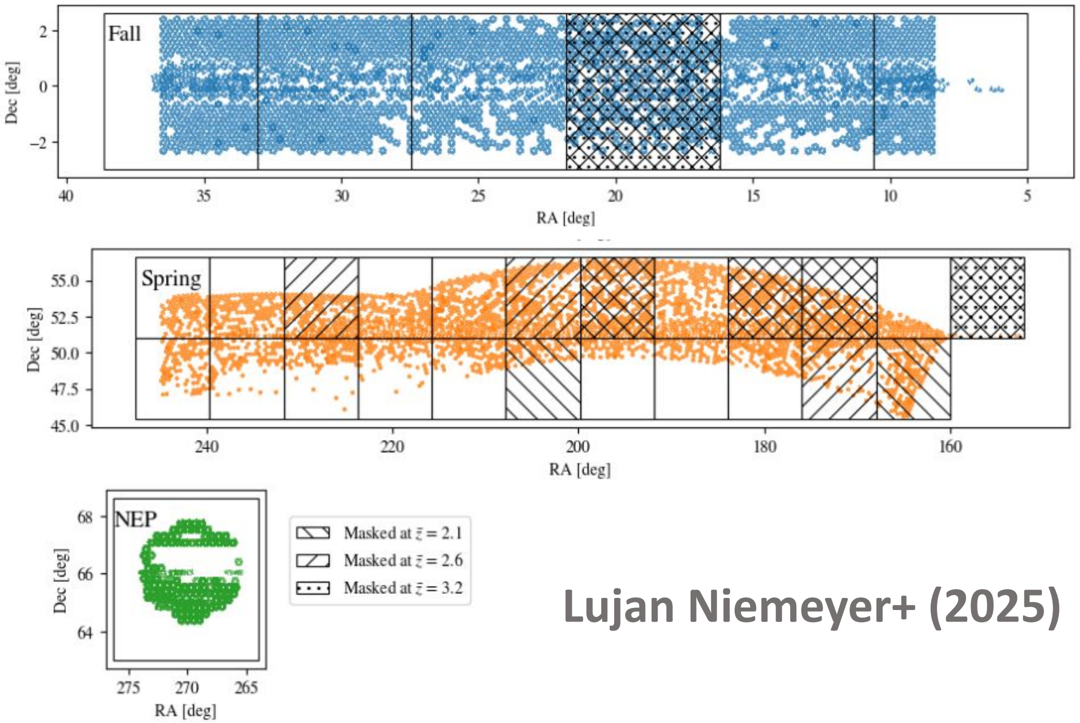
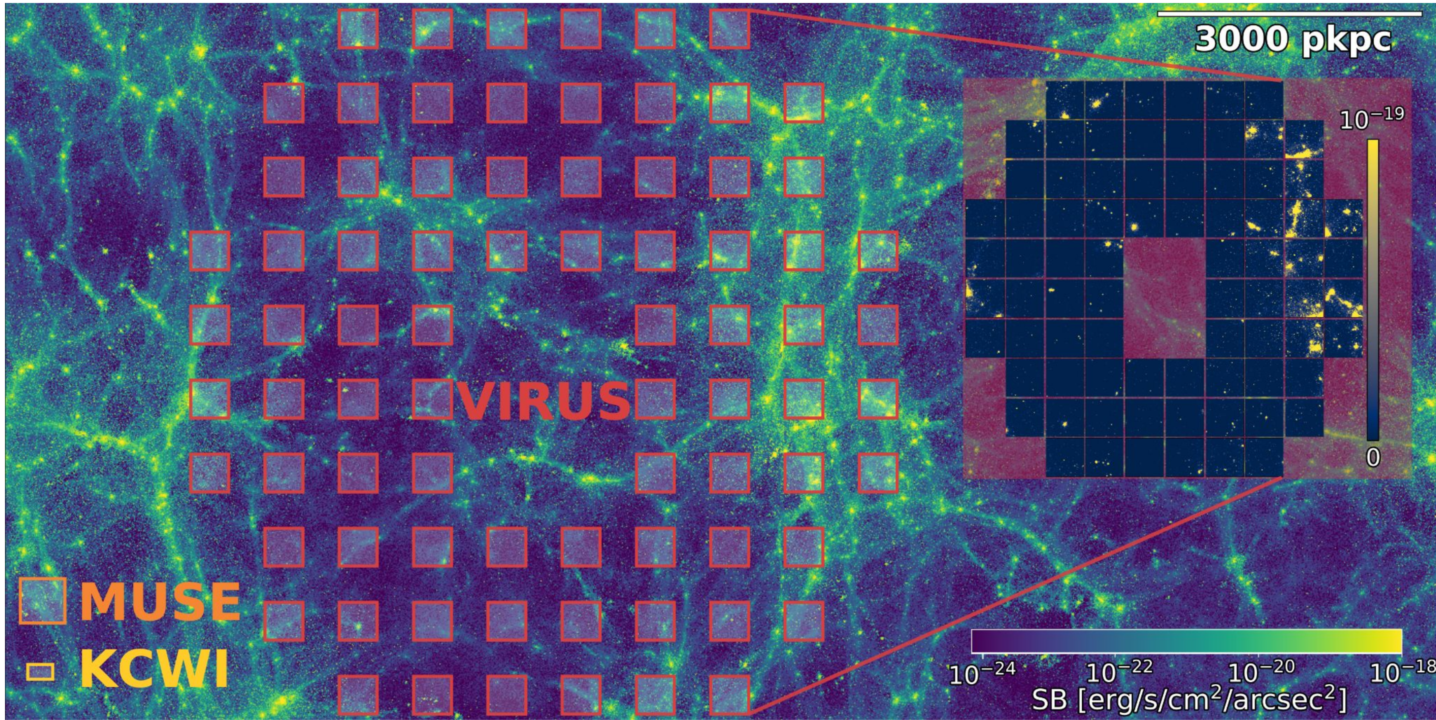


Lujan Niemeyer+ (2025)



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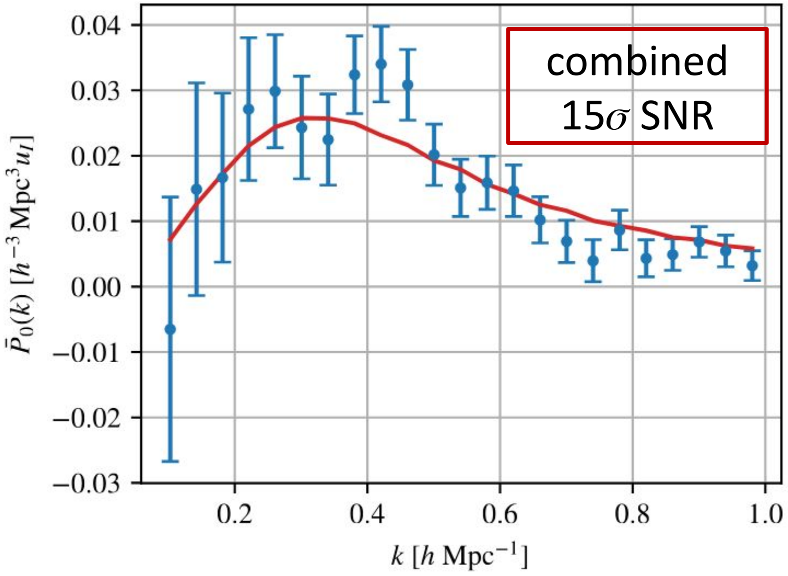
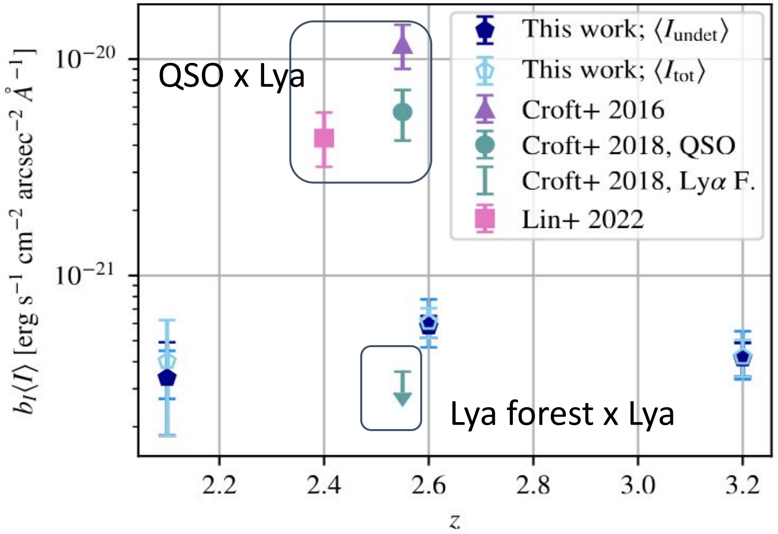
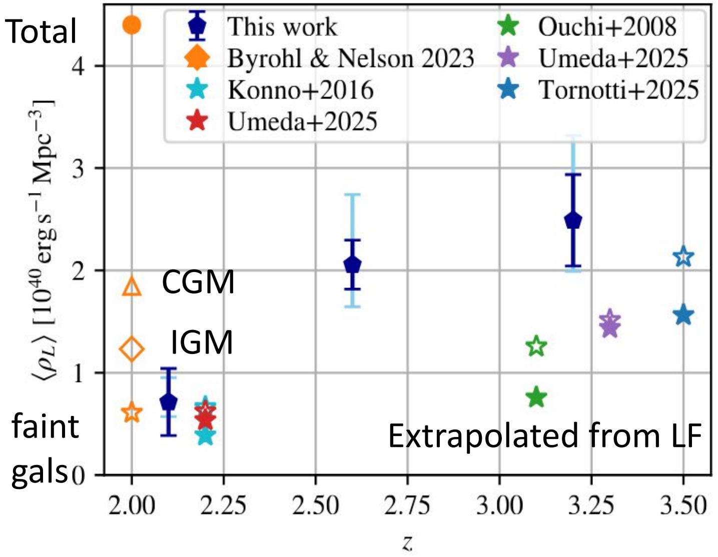




Mean luminosity density of undetected sources



Lujan Niemeyer+ (2025)

Conclusions

- LIM has the raw potential to explore the high-z Universe: a pillar for cosmology & astrophysics
    - Capture faint and diffuse sources
    - Access beyond the reach of galaxy surveys
    - Quickly map large three-dimensional volumes
- Very non Gaussian maps:
    - P(k) + VID (+ …): break degeneracies with astro => much better constraints

- Foregrounds are a challenge:
    - Interlopers: complementary strategies (masking, multi-channel, nulling)
    - Continuum: multiscale PCA is working well, adding more angular and frequency information
        - Can we reach non-blind approaches to minimize signal loss?

- Important milestones: Highest SNR LIM detection & first measurement in auto at cosmological scales
    - CHIME: 12.5-sigma detection in auto at small scales! ($1.01 < z < 1.34$) → Upgrade to CHORD
    - Clear future roadmap: MeerKLASS wide survey (LIM BAO?)
    - HETDEX: ready to inform models and expected improvement (more data, better pipeline: quadrupole? BAO?)
- Next generation LIM experiments? multiline IM, wider surveys, cosmological analyses