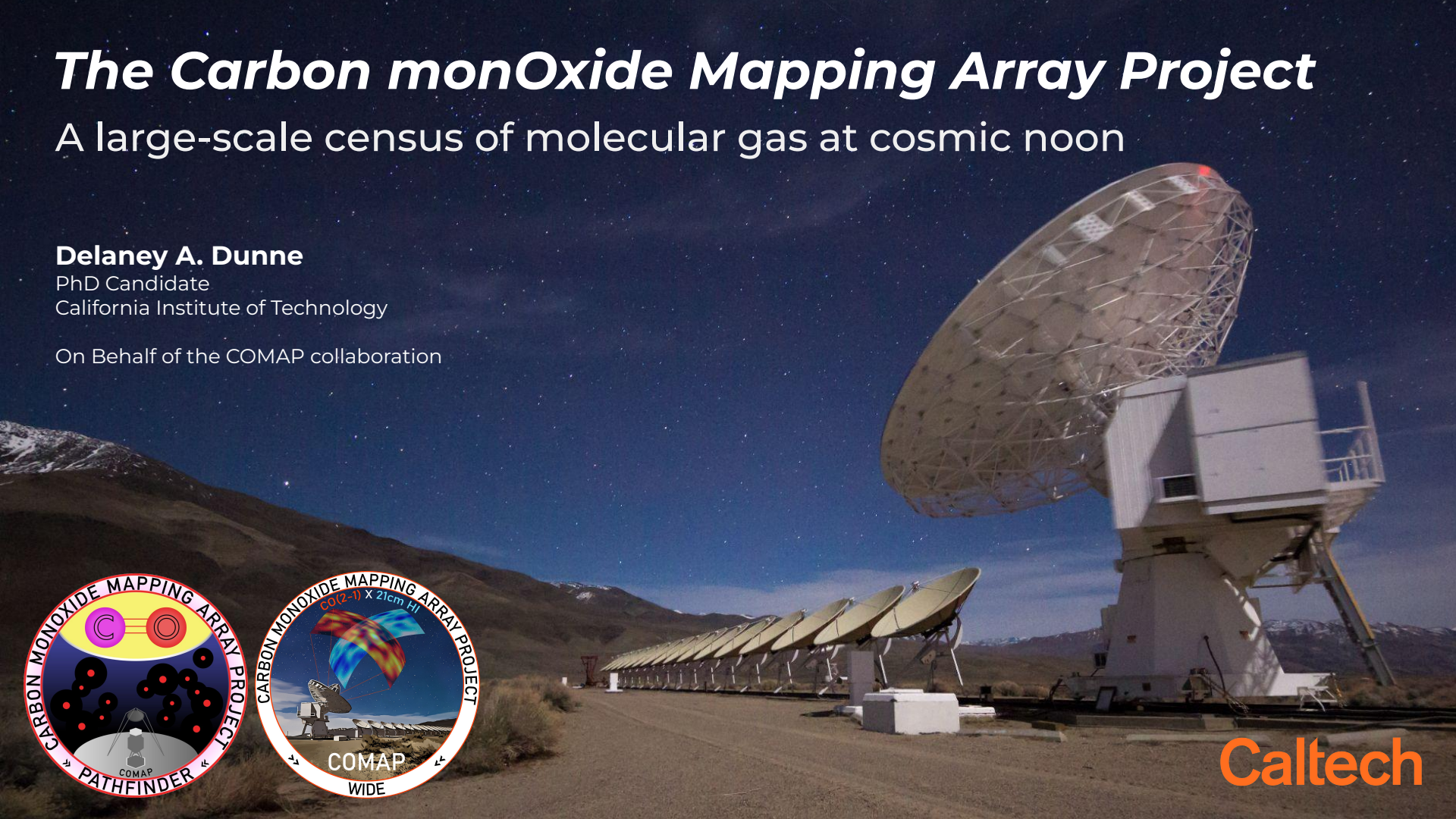
The Carbon monOxide Mapping Array Project

A large-scale census of molecular gas at cosmic noon

Delaney A. Dunne
PhD Candidate
California Institute of Technology

On Behalf of the COMAP collaboration



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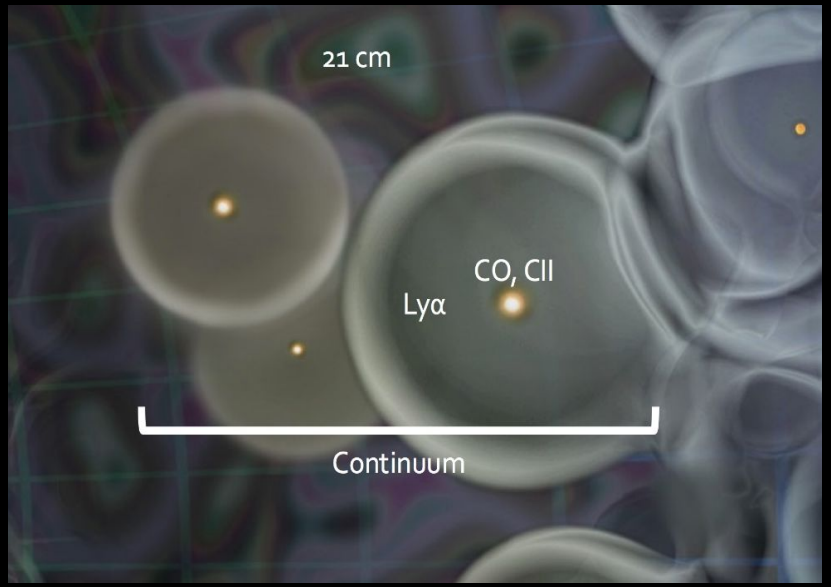
Keck Institute for Space Studies

Why do CO Line Intensity Mapping?

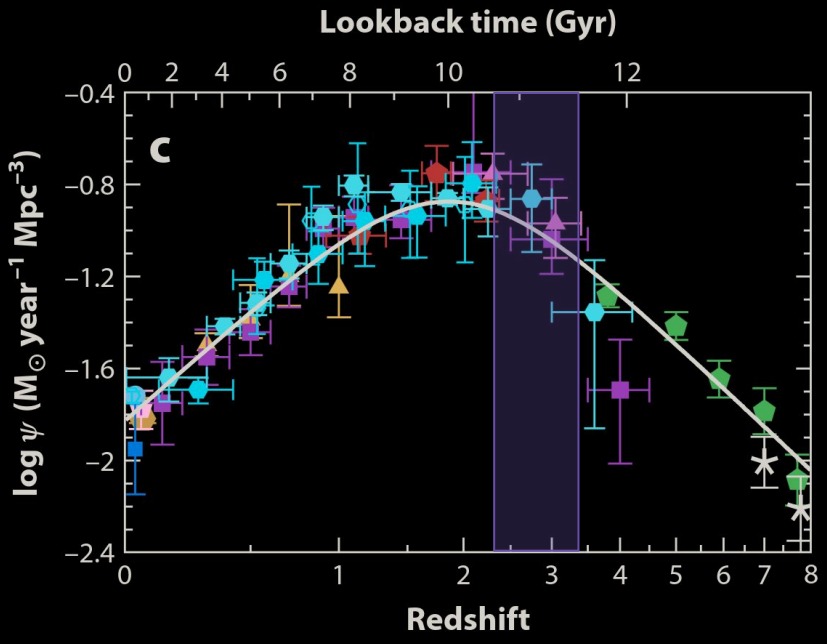
CO is an excellent probe of galaxy formation

- CO probes **dense, molecular hydrogen regions**—the regions which are about to collapse into stars
  - Correlates tightly with a **galaxy's star formation rate**
  - Extremely sensitive probe of **feedback** processes
- Scientifically, it's a great **complement** to other LIM tracers

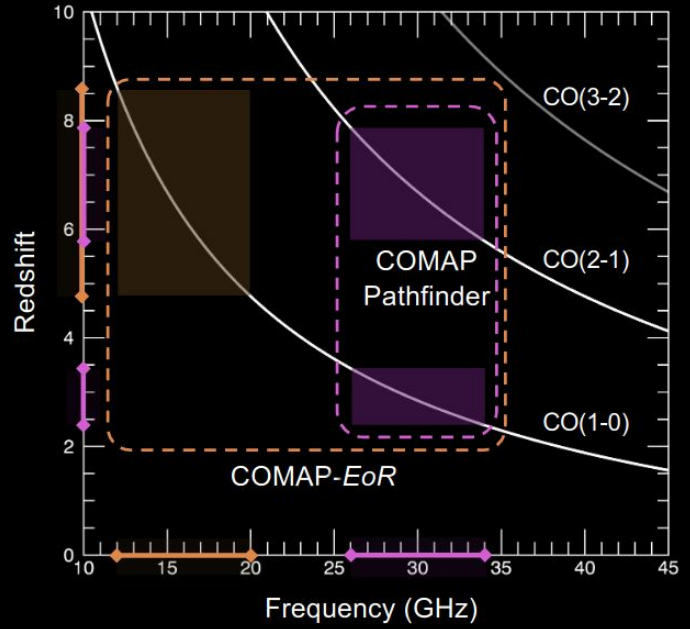


[Kovetz et al. 2017 via Breysse, Scientific American]

CO is particularly interesting around star formation peaks



[Madau & Dickinson 2014]

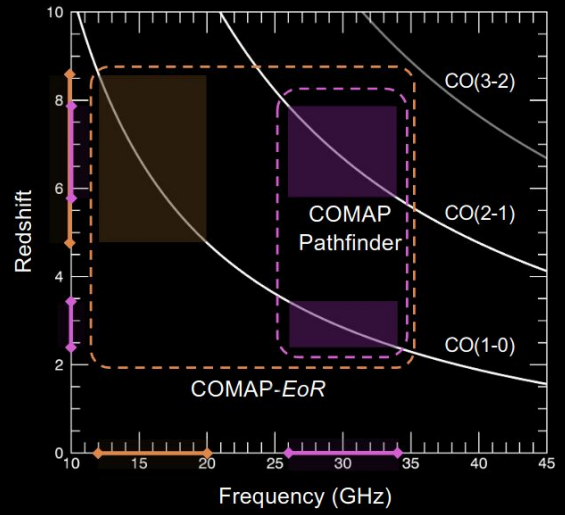


[Cleary et al. 2022]

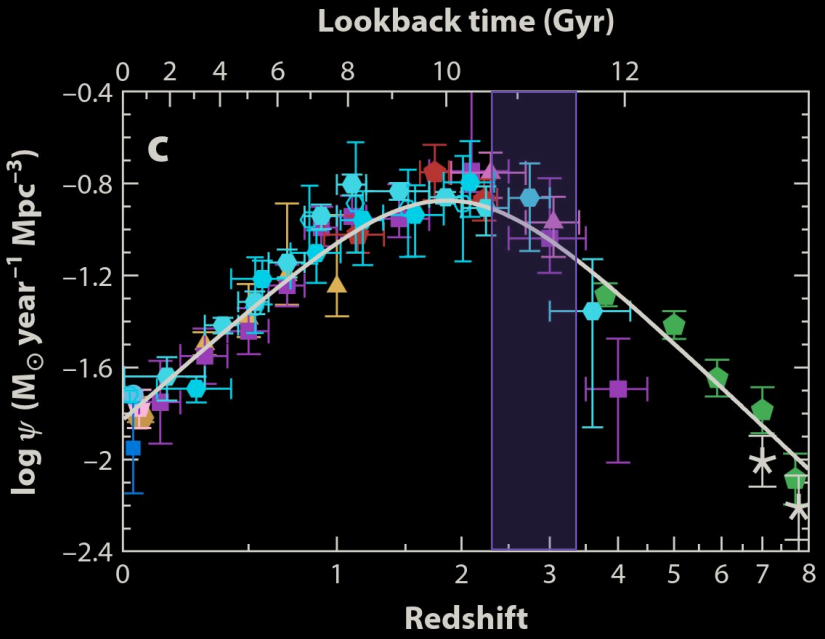
What is COMAP?

Quick Facts about the COMAP Instrument

- Targeting the CO(J=1-0) rovibrational transition at redshifts 2.4-3.4
  - 26-34 GHz, $R \sim 1000$



[Cleary et al. 2022]



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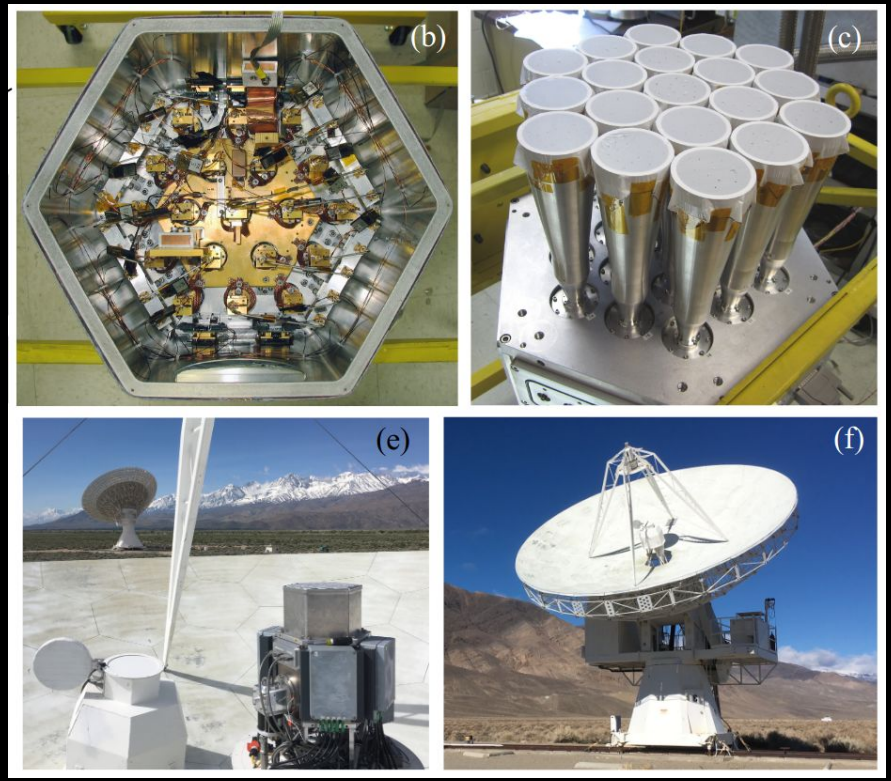

[Cleary et al. 2022]

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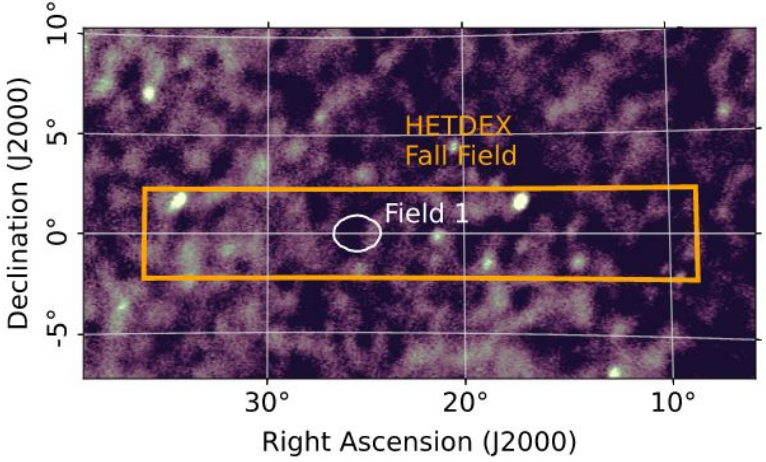
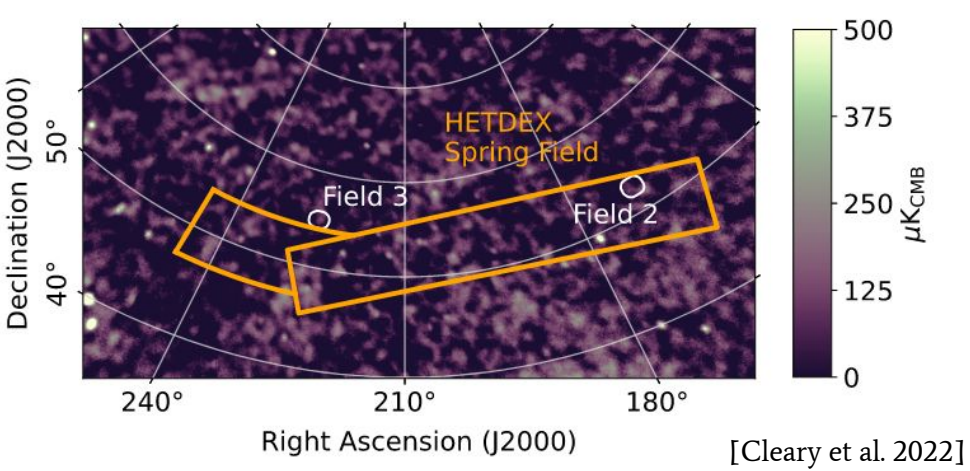
- COMAP covers 12 deg^2 over 3 fields
  - Cosmological volume of 60 million Mpc^3





[Cleary et al. 2022]

Quick facts about the COMAP instrument

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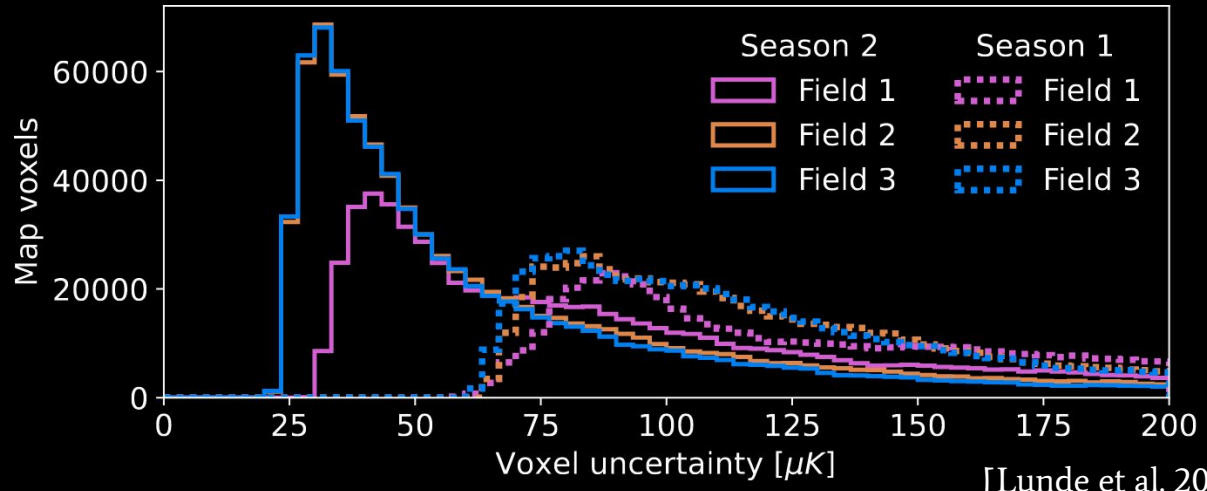
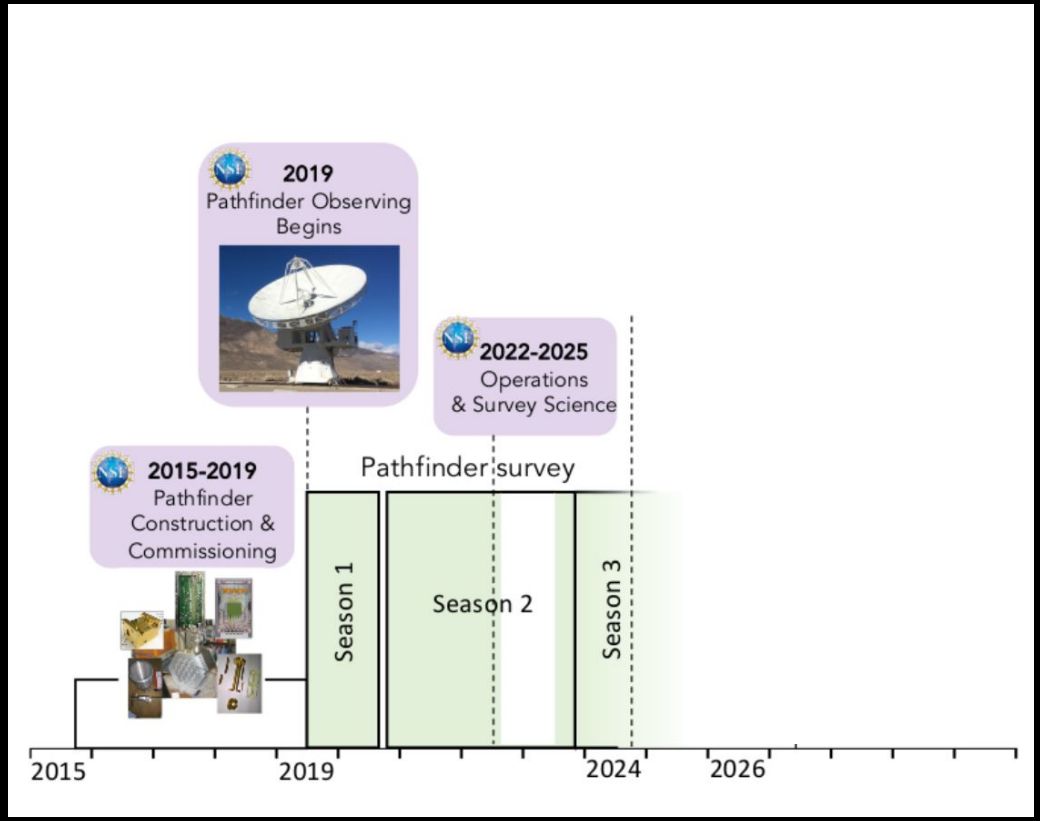
- COMAP covers 12 deg^2 over 3 fields
  - Cosmological volume of 60 million Mpc^3
- Season 2: 25 – 50μK uncertainty

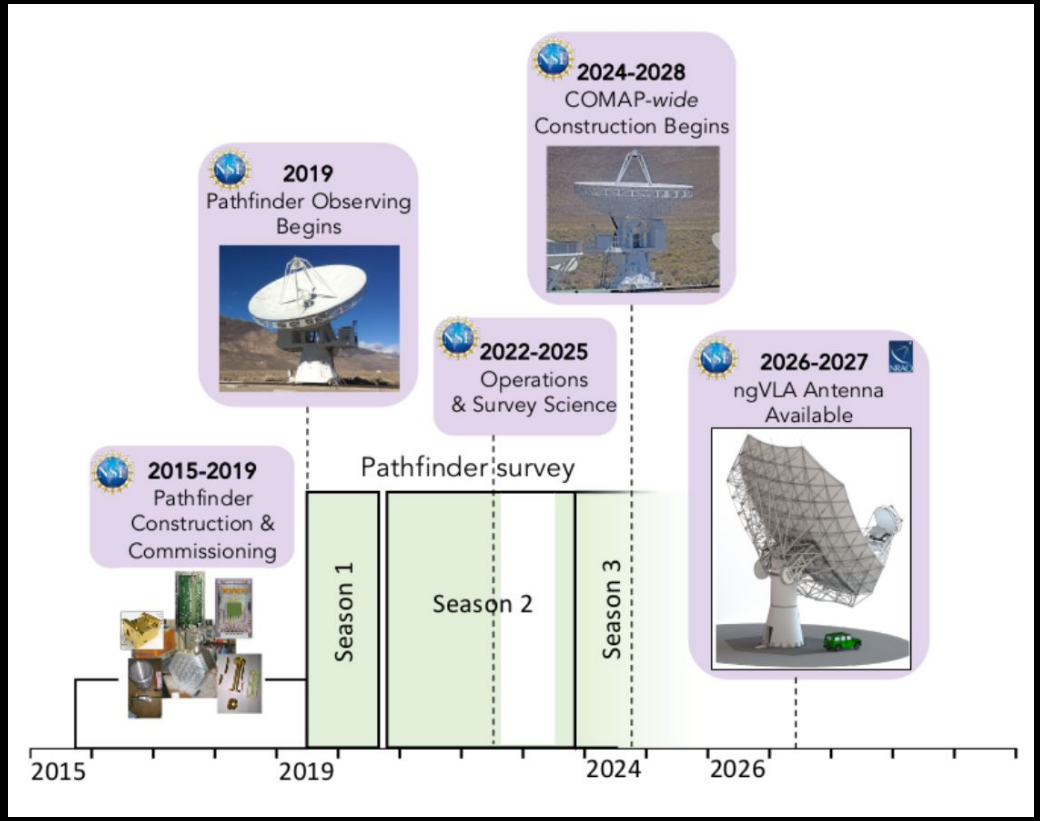


[Lunde et al. 2024, arXiv:2406.07510]

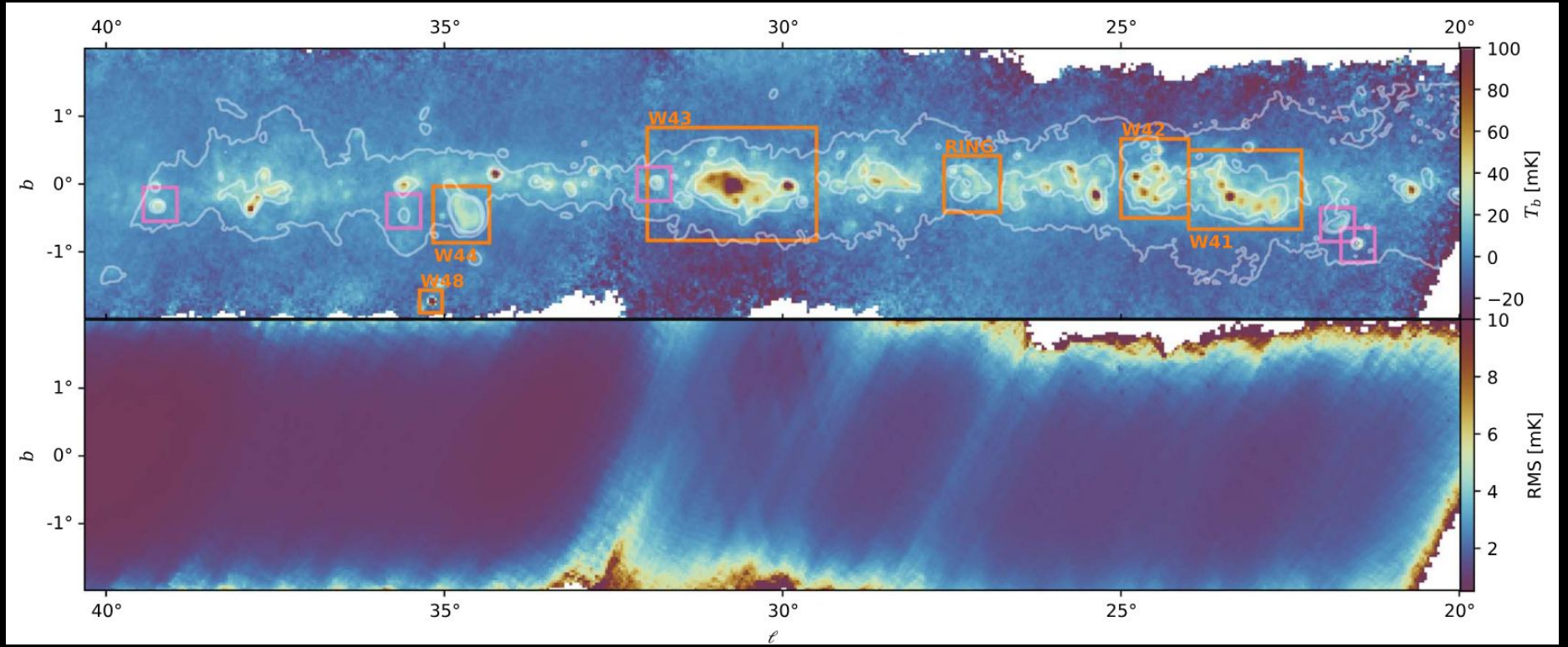
COMAP is currently partway through its planned Pathfinder survey



Several future stages of COMAP are planned (and funded!)



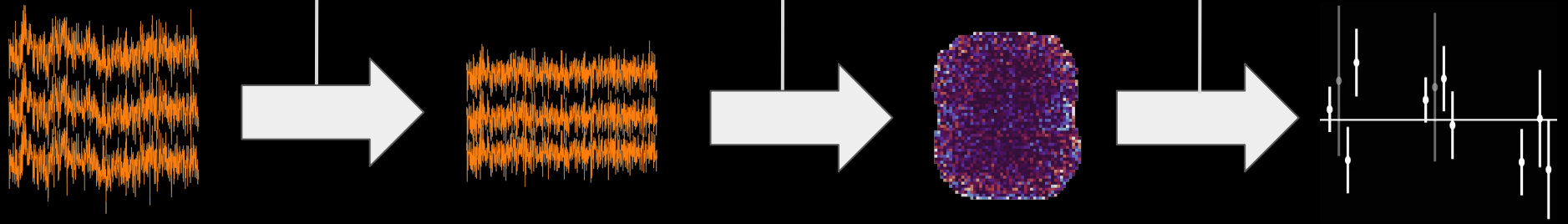
COMAP is also performing a mK-sensitivity Galactic Plane Survey



[Rennie et al. 2022, arXiv: 2111.05932]

Power Spectra

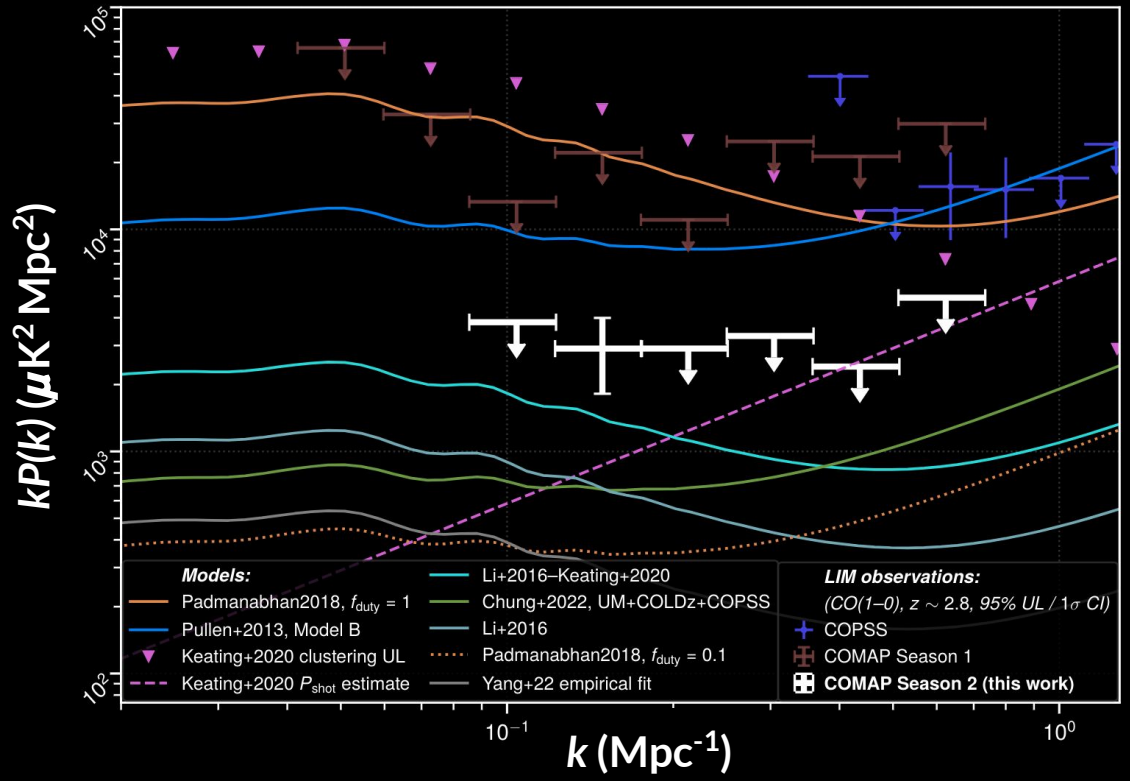
COMAP uses a filter-and-bin mapmaker to process time-ordered data



[Lunde et al. 2024, arXiv:2406.07510]

COMAP has the tightest upper limits on the CO power spectrum at z ~ 3

$$P(k) = \underbrace{A_{\rm clust}}_{\sim\langle Tb\rangle^2} P_m(k) + P_{\rm shot}$$



[Chung et al. 2024, arXiv:2406.07512]

COMAP has the tightest upper limits on the CO power spectrum at z ~ 3

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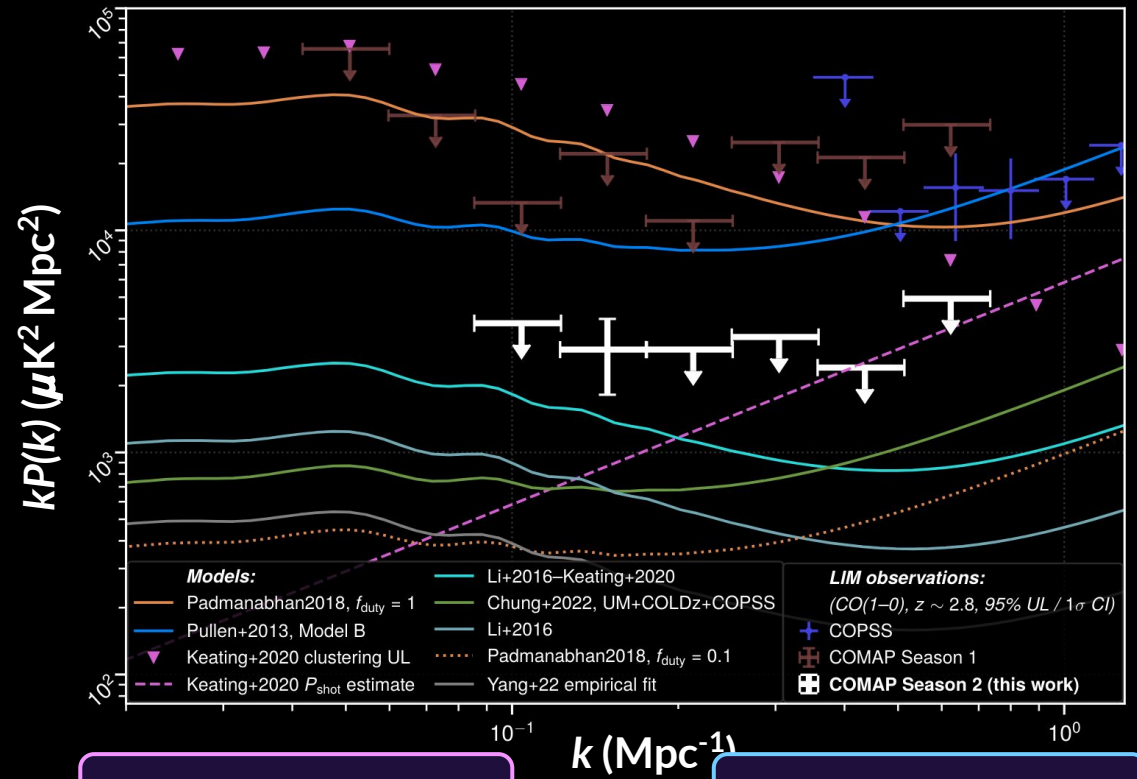
clustering
+ shot noise

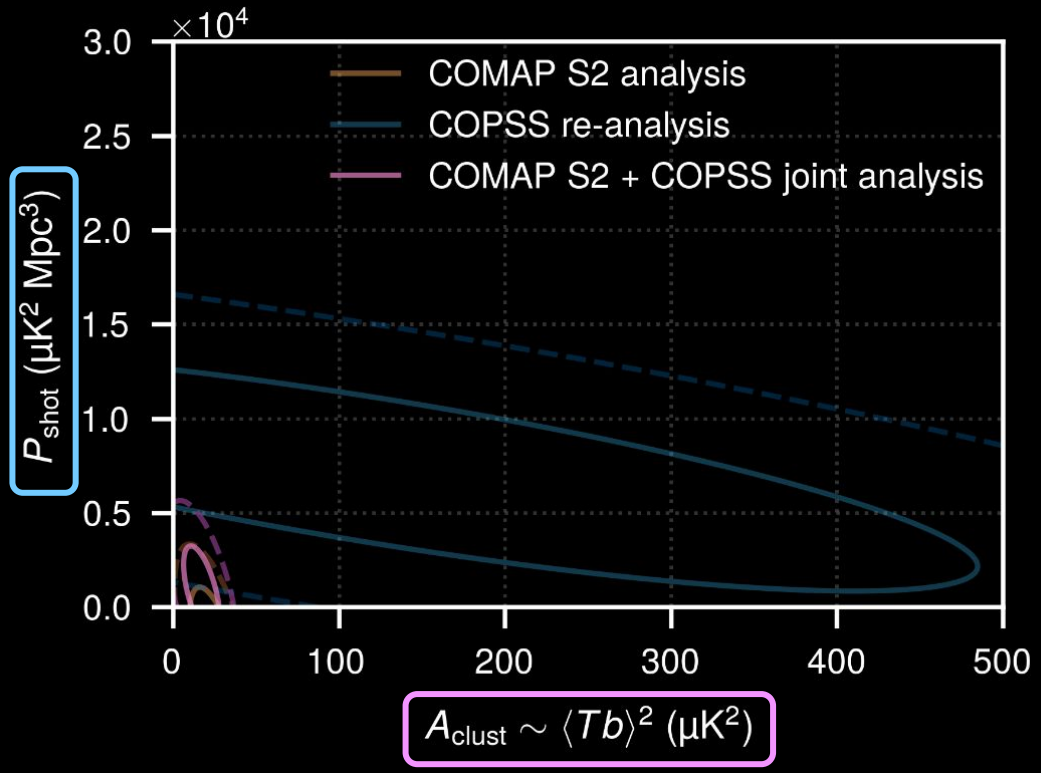


← Clustering-dominated

Shot-noise-dominated →

[Chung et al. 2024, arXiv:2406.07512]

Our limits constrain the properties of the CO power spectrum

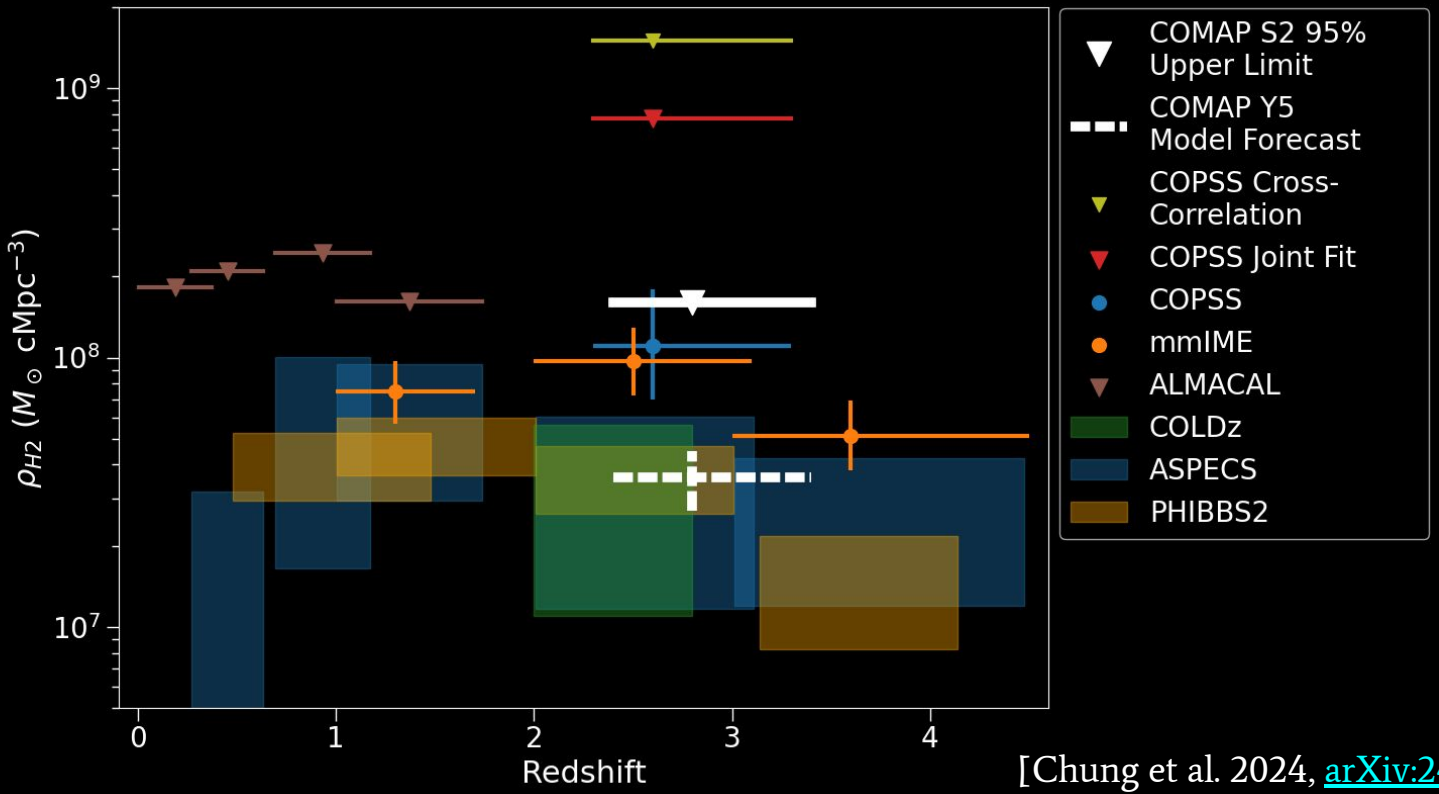


$$P(k) = \underbrace{A_{\rm clust}}_{\sim\langle Tb\rangle^2} P_m(k) + P_{\rm shot}$$

clustering + shot noise

[Chung et al. 2024, arXiv:2406.07512]

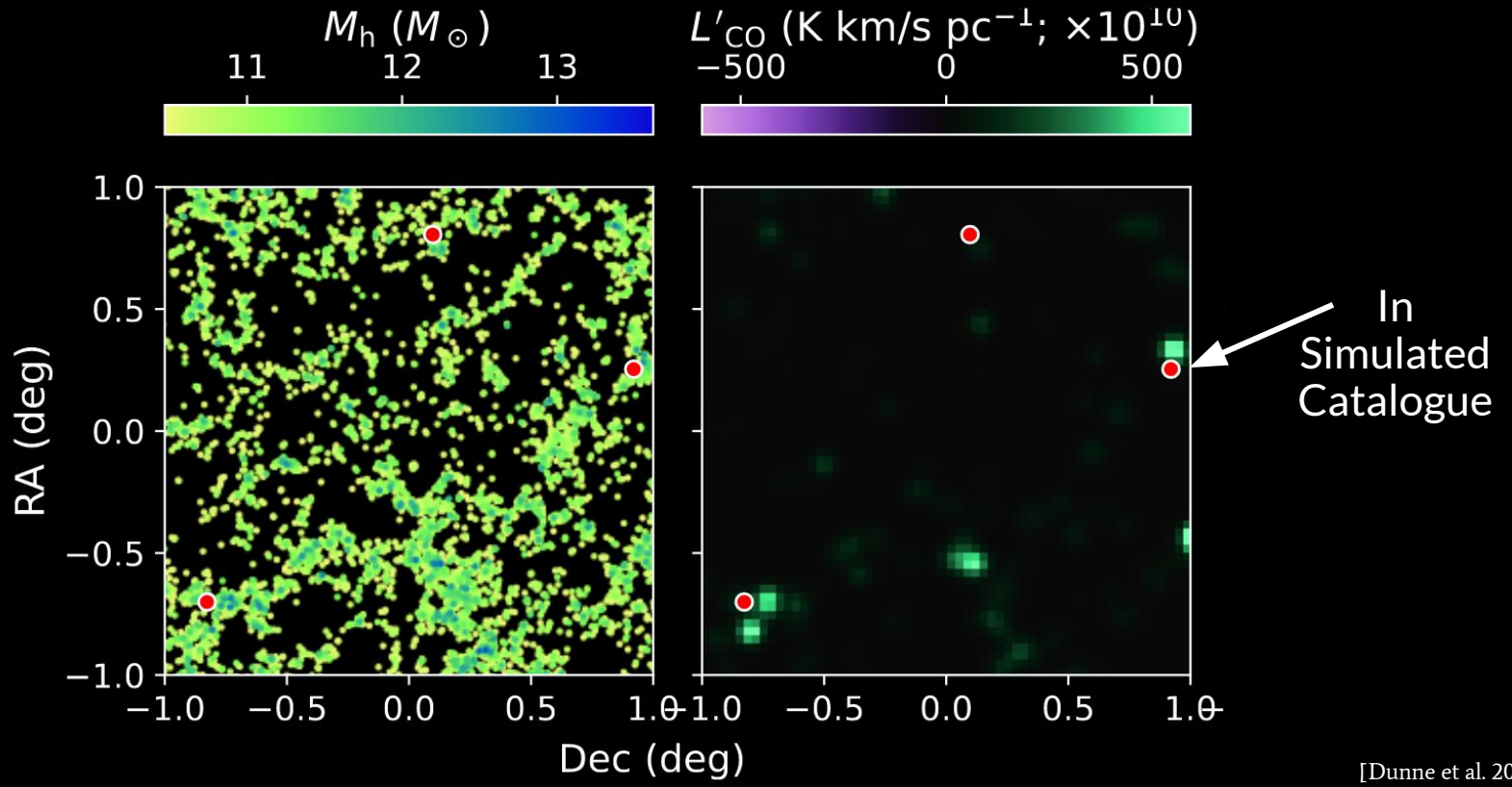
These lead to constraints on the cosmic molecular gas density



[Chung et al. 2024, arXiv:2406.07512]

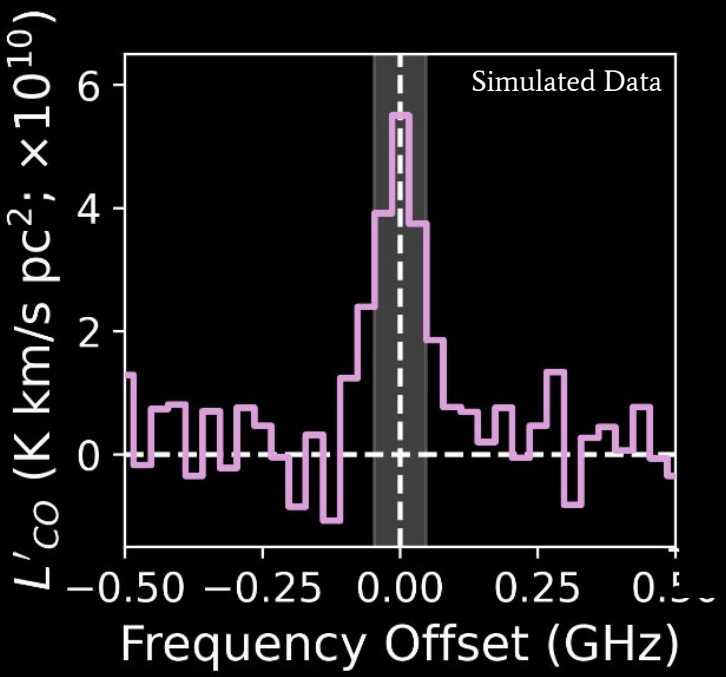
COMAP x Galaxy Catalogues

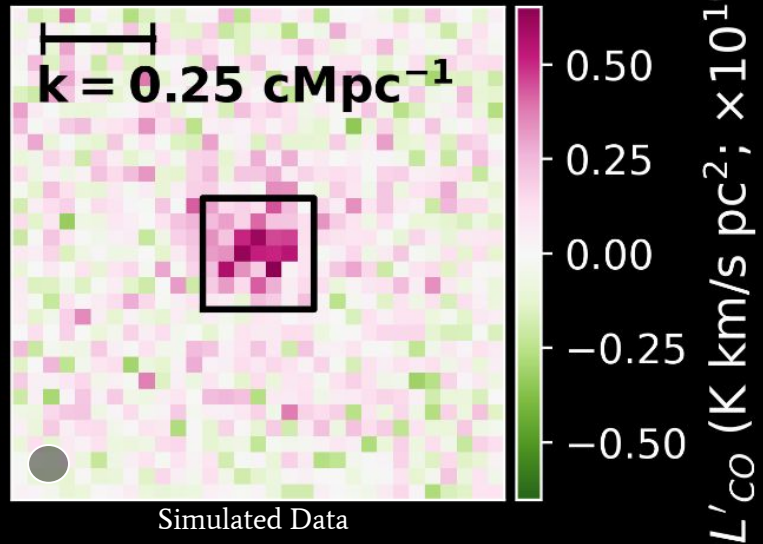
Resolved catalogues probe the same regions of the sky as LIM cubes



[Dunne et al. 2025a]

Stacking gives the average CO luminosity over regions selected by the catalogue





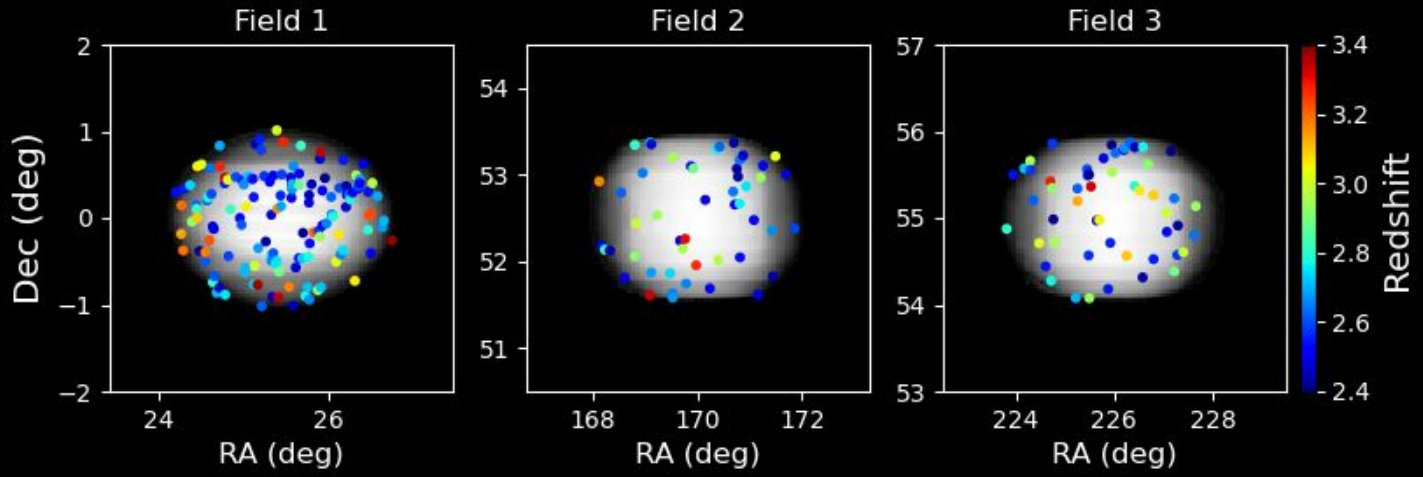
$\sqrt{N_{obj}}$ improvement in sensitivity

[**Dunne** et al. 2025a]

We performed an initial stack analysis on eBOSS

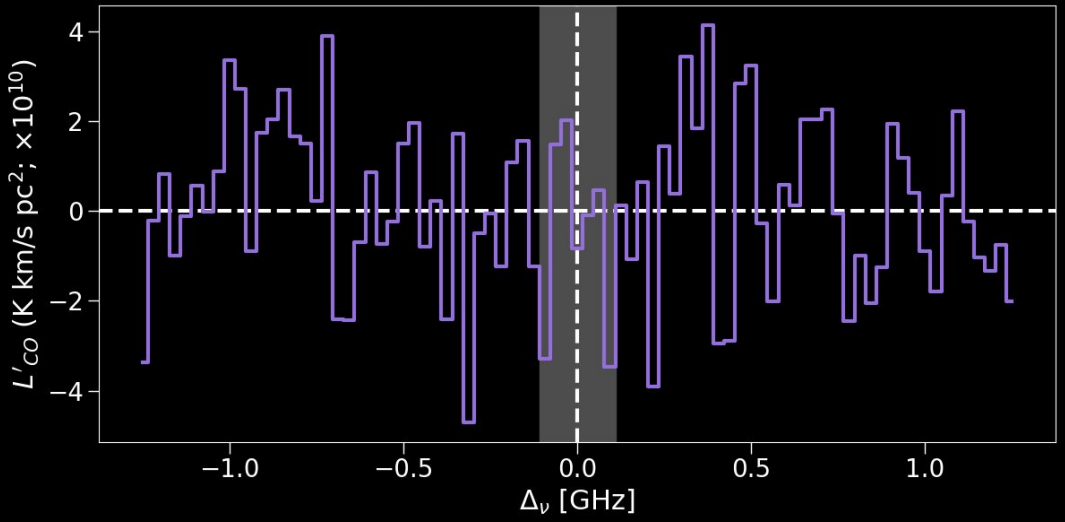
The **extended Baryon Oscillation Spectroscopic Survey (eBOSS)**:

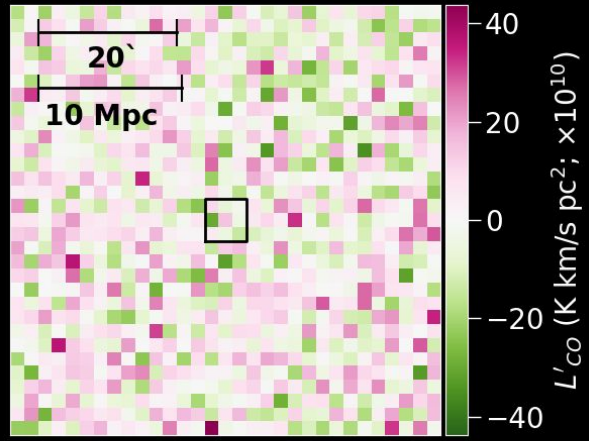
- Quasi-Stellar Object (**QSO**, or Quasar) catalogue
- More than 750 000 objects total, **243** of which are in the COMAP footprint



[**Dunne** et al. 2024]

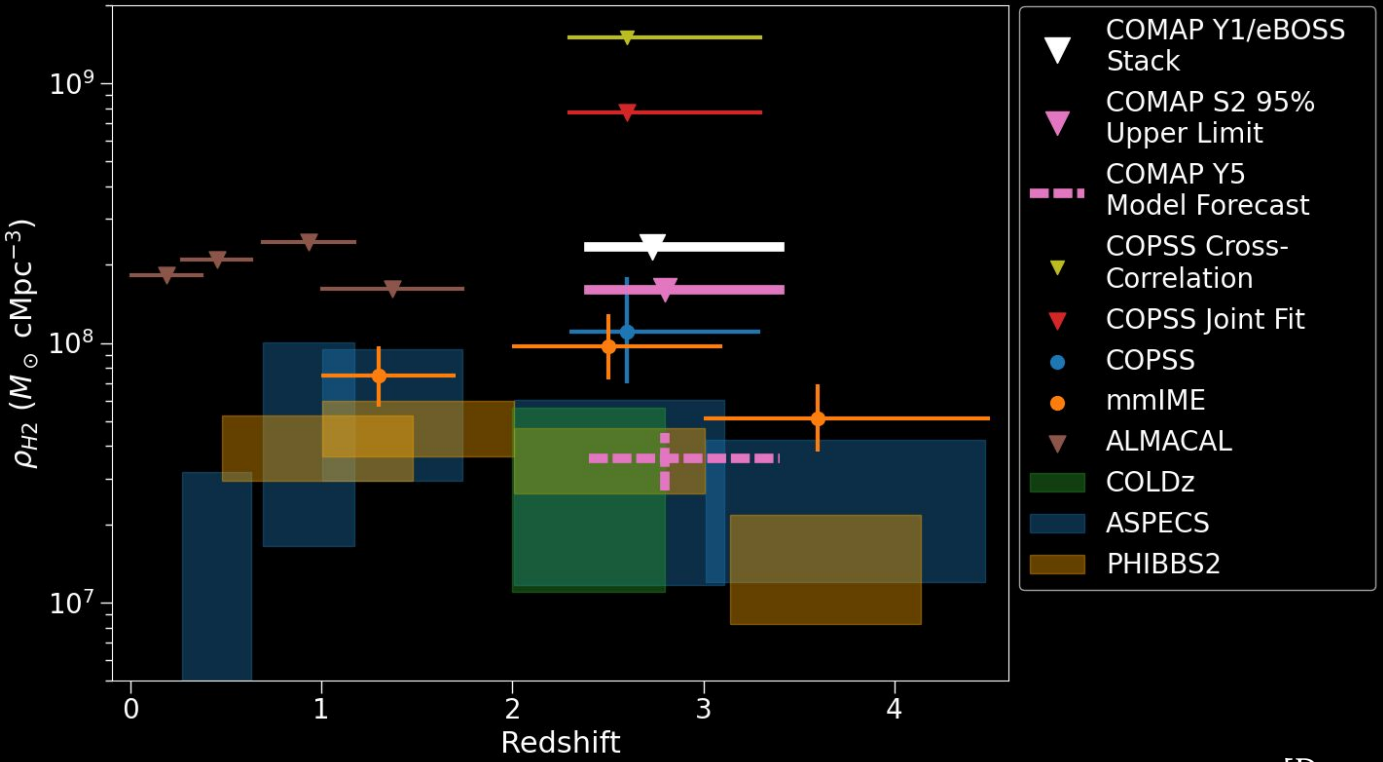
The COMAP-eBOSS S1 stack did not detect any signal





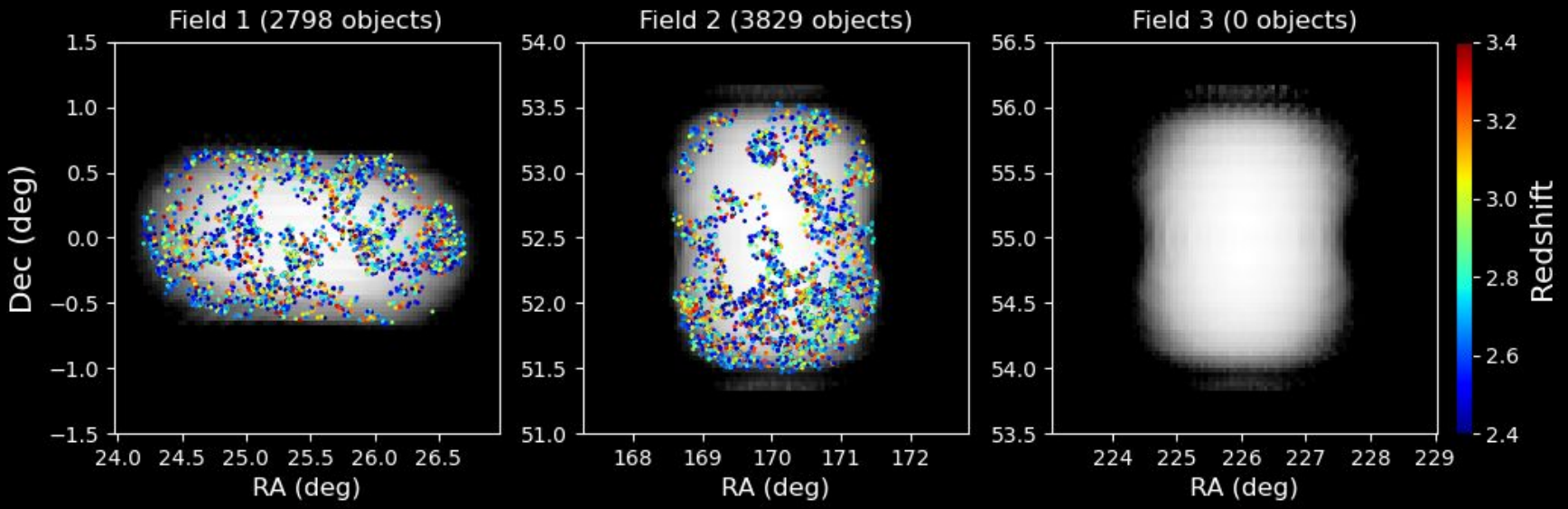
[**Dunne** et al. 2024]

… but did lead to a tight constraint on molecular gas density



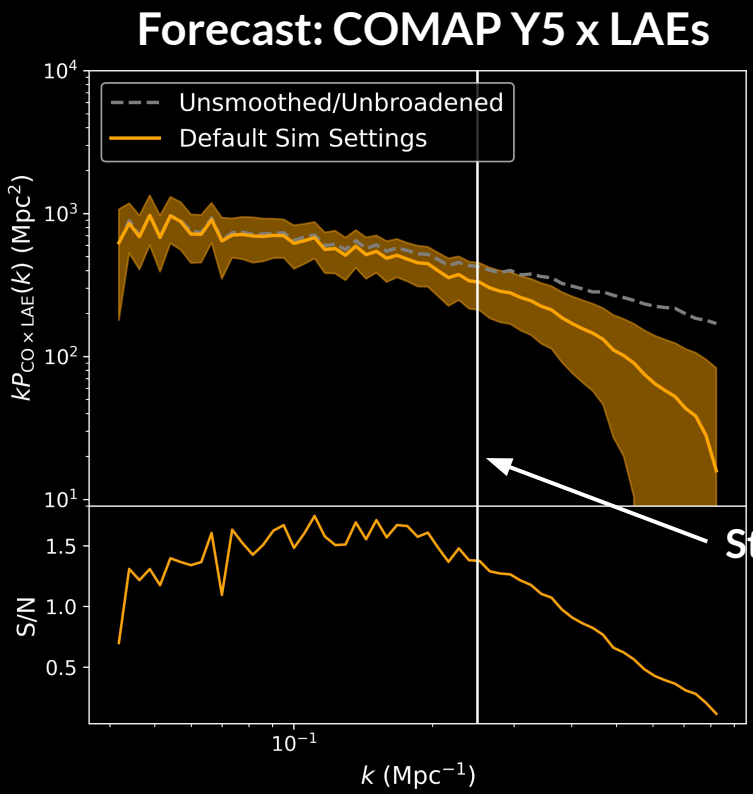
[Dunne et al. 2024]

A stack on HETDEX will lead to much higher stack sensitivity



[Dunne et al. 2025b *(in prep.)*]

Full cross-correlation analyses will measure other scales



Stack spatial scale

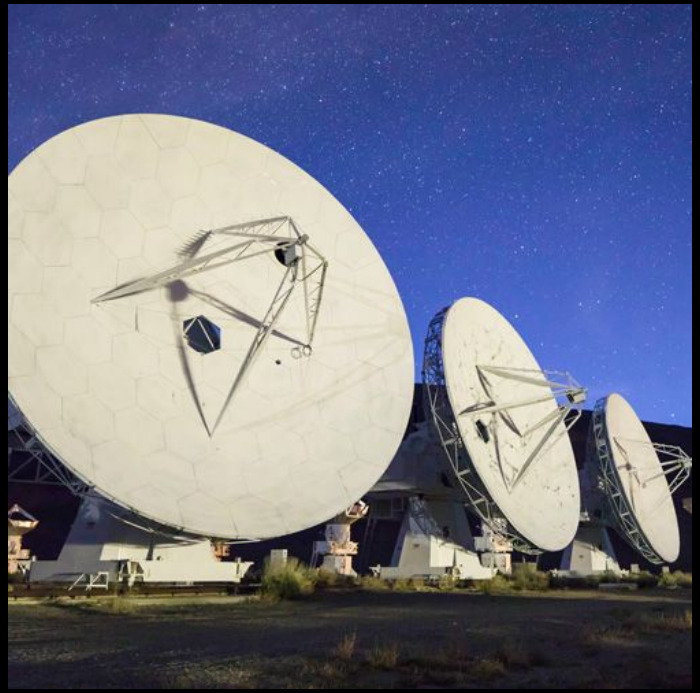
Total S/N ~ 10

EoR Science with COMAP

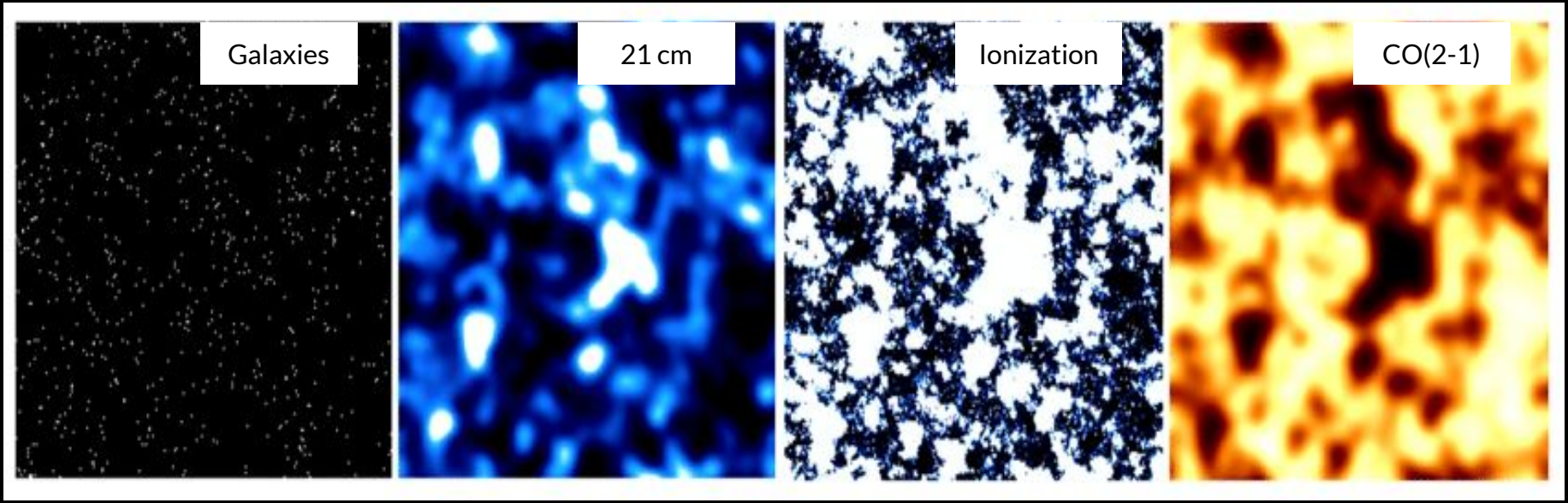
COMAP-*wide* is an experiment under construction to study the EoR

Duplicate* COMAP Pathfinder for wide-field intensity mapping

- 10.4 m antenna at Owens Valley Radio Observatory
- 19 feeds covering 26-34 GHz
- 2 year observing campaign on ~400 deg^2
- Science Targets: Cross-Correlations
  - CO x 21 cm at z~7
  - CO x Spectroscopic Galaxies at z~3

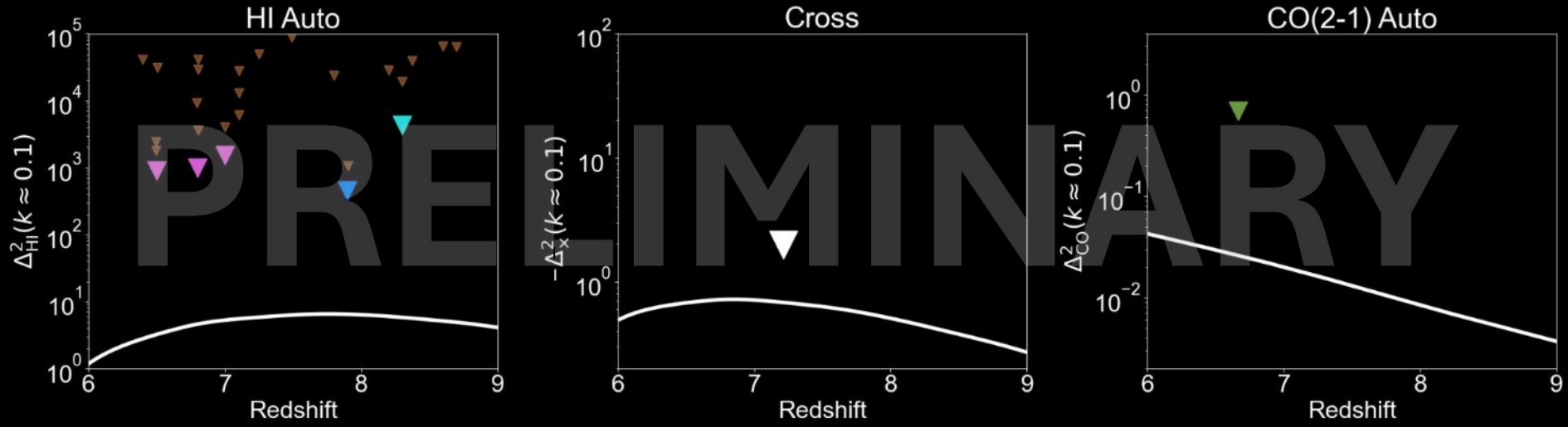


CO and 21 cm emission are *anticorrelated* during reionization



(Credit: Adam Lidz)

COMAP-*wide* x LOFAR will be the first limit of its kind



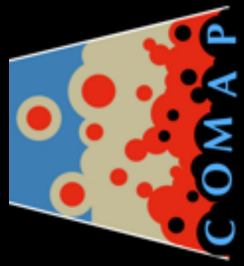
Existing HI limits, including MWA, LOFAR, and HERA

CO(2-1) upper limit from COMAP Season 2

[Credit: Patrick Breysse and Hannah Fronenberg]

My Website:
delaneydunne.github.io

Summary

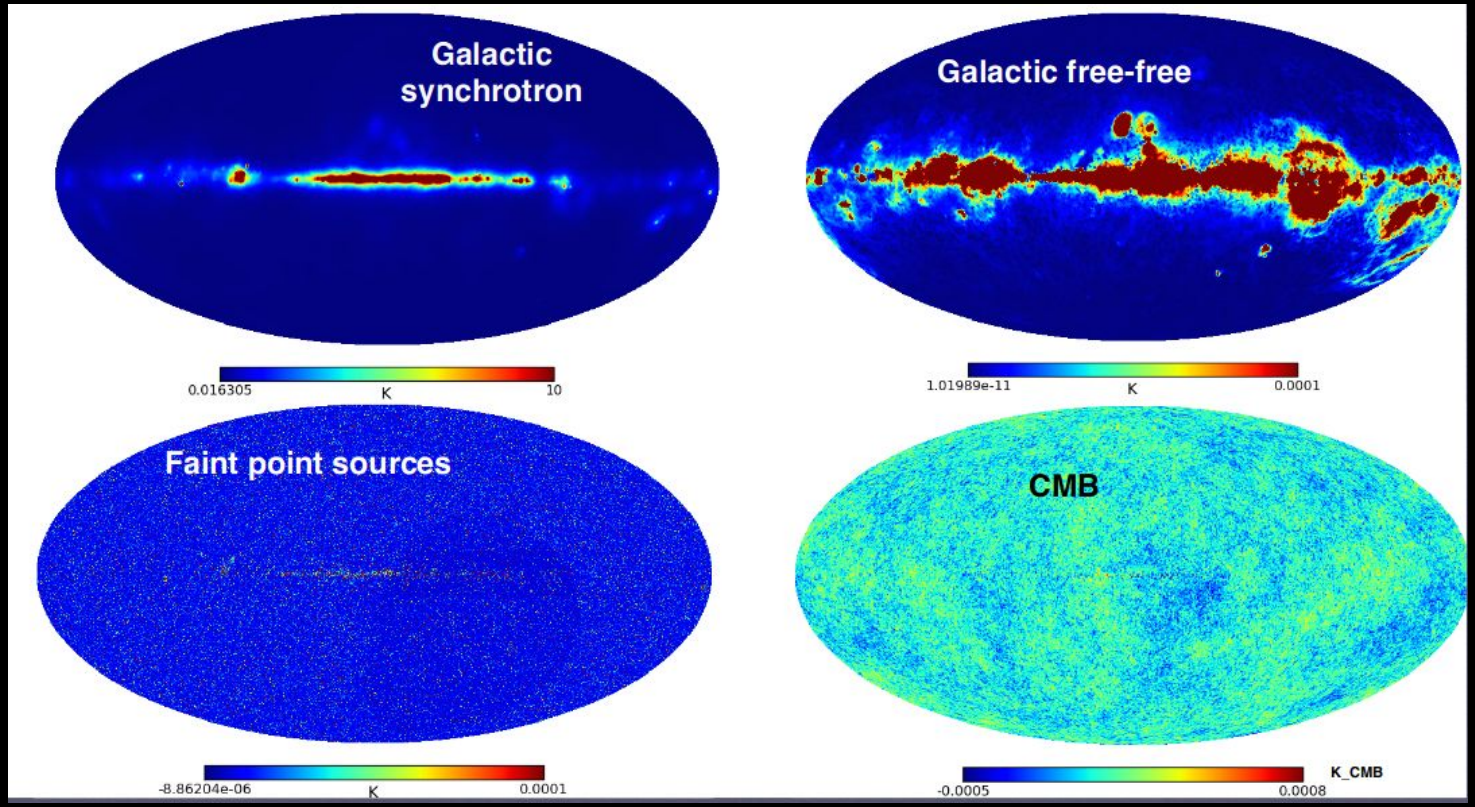


COMAP Website:
comap.caltech.edu

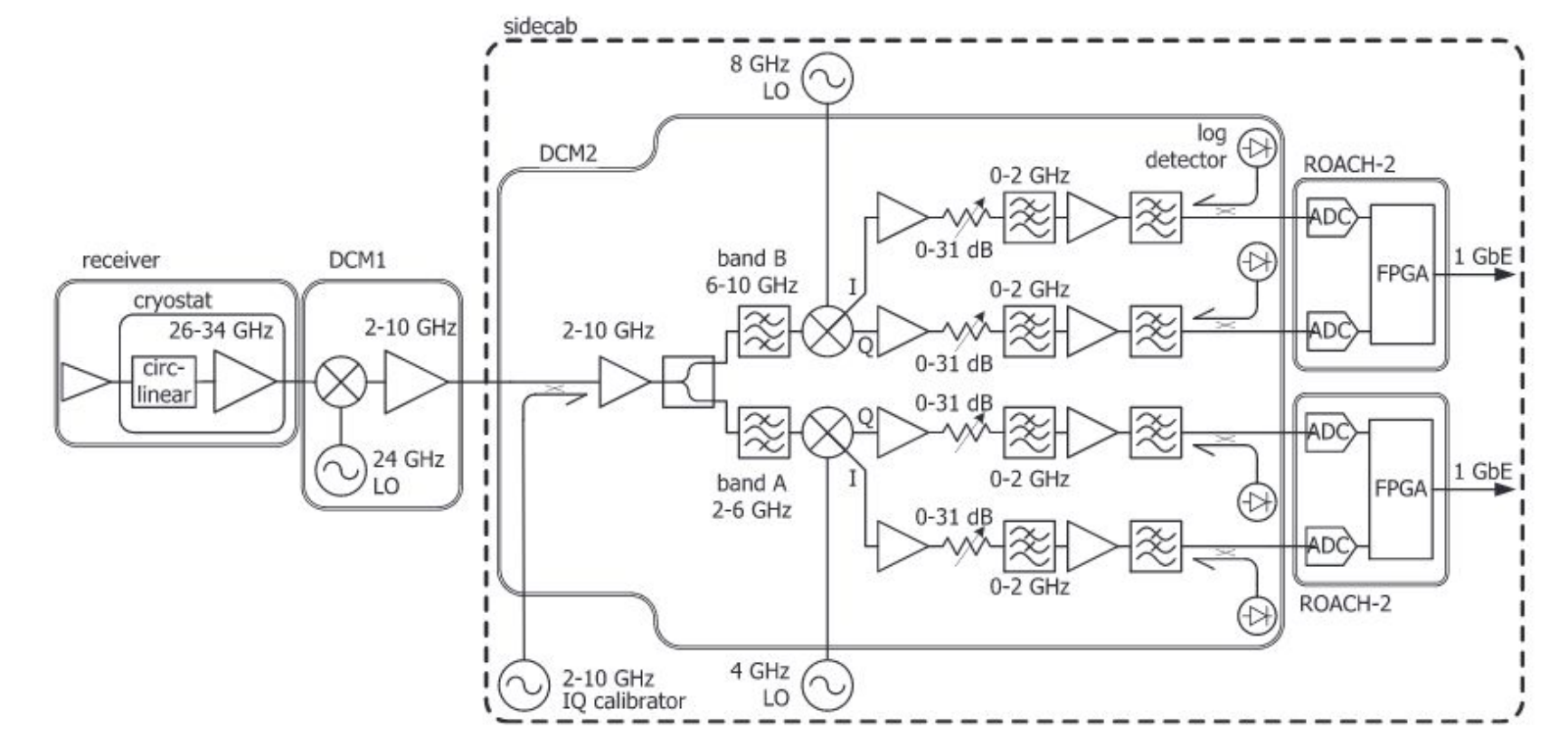
- COMAP is an active LIM experiment targeting cosmic CO emission z~3
- We have the tightest constraints available on the z~3 power spectrum
- Joint analysis techniques with galaxy catalogues could constrain cosmic CO further
- Upcoming COMAP stages will expand into the EoR

EXTRA SLIDES

CO foregrounds are comparatively minor



COMAP Instrument – signal path



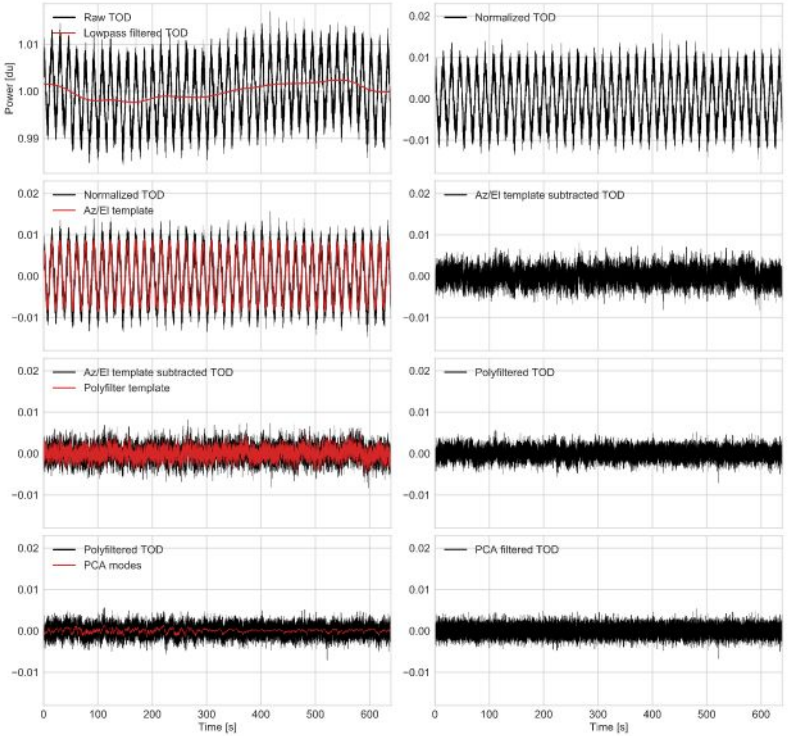
Time-series: single feed, frequency and scan

Low-pass filter
Normalization
Subtract 1.0

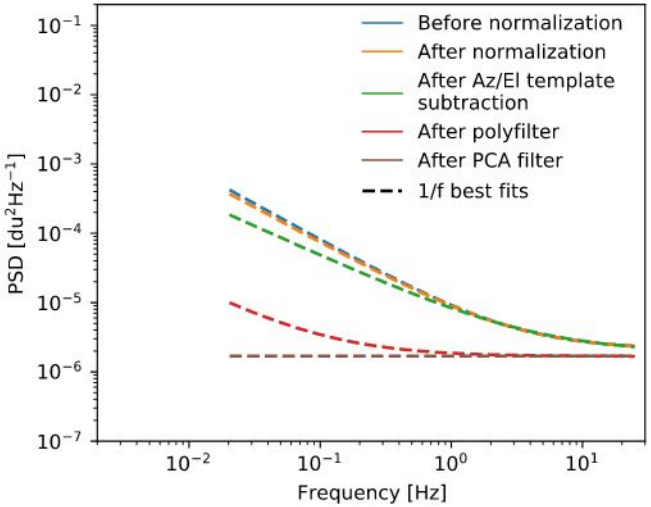
Remove atmospheric template

Filter low-order polynomial across frequencies

PCA filter
Across all frequencies and feeds



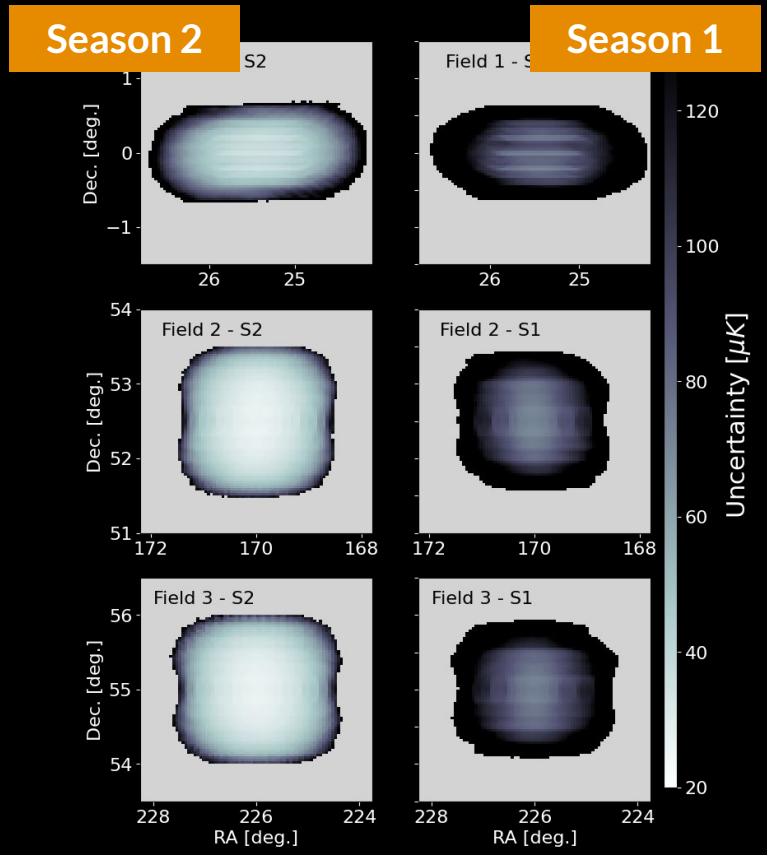
FT of time-ordered data



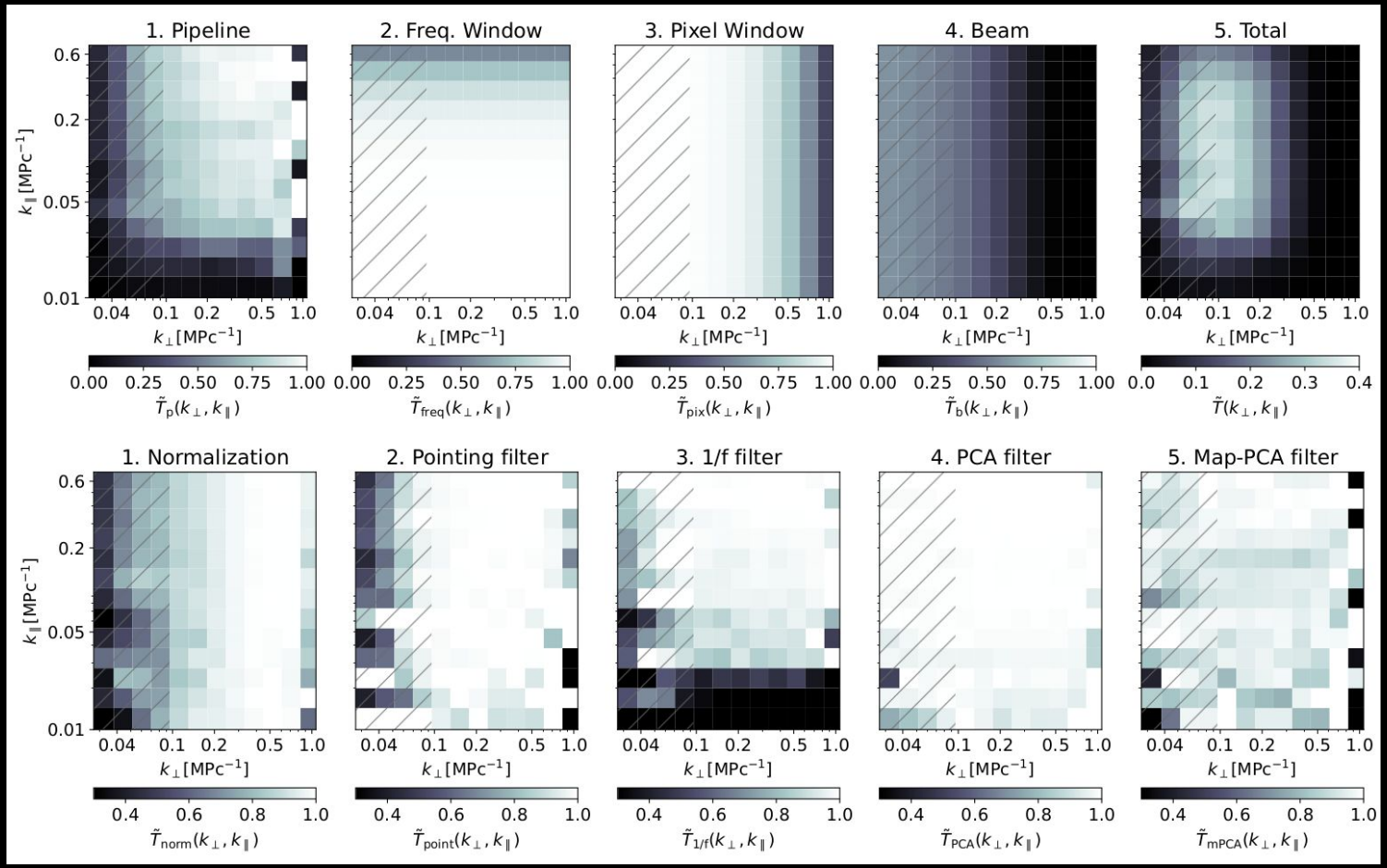
[Lunde et al. 2024 (incl. **Dunne**)]

Our current science results use ~17 500 hours of on-sky time

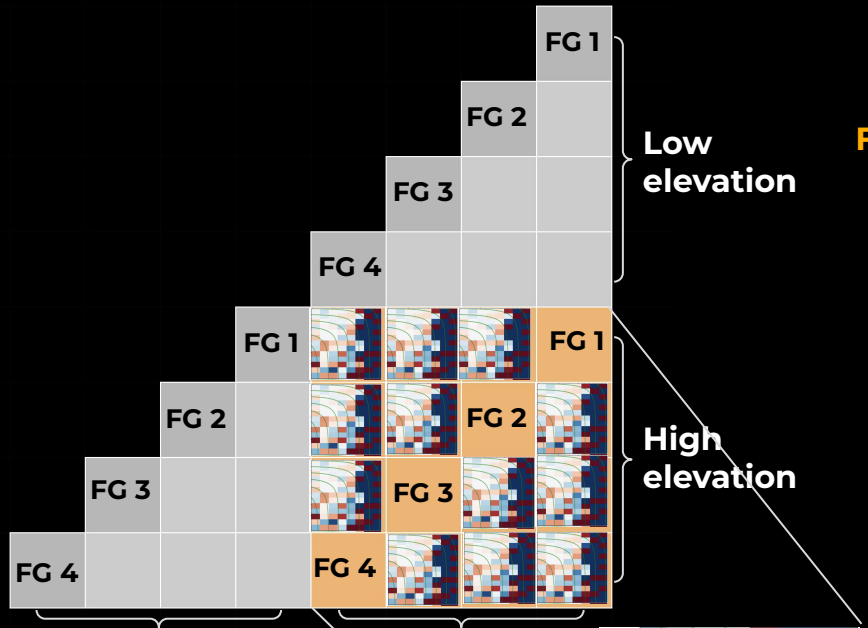
25 – 50μK uncertainty over a cosmological volume of 60 million Mpc^3.



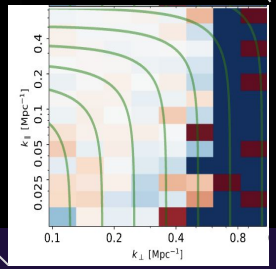
[Lunde et al. 2024, arXiv:2406.07510]

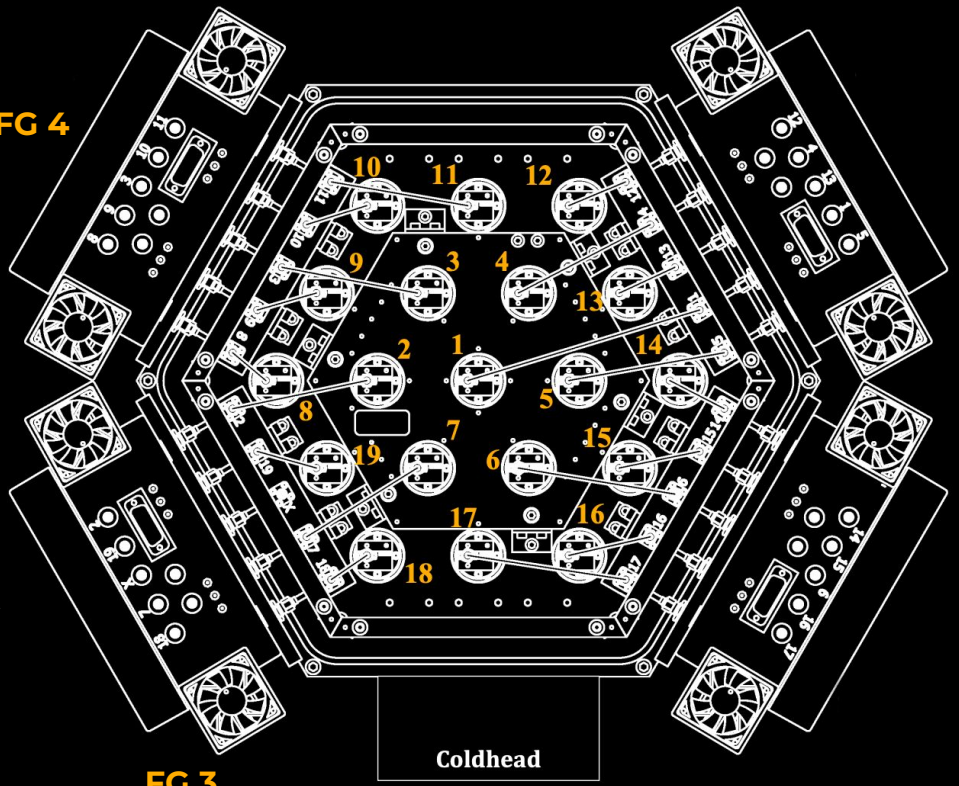

1. Pipeline
2. Freq. Window
3. Pixel Window
4. Beam
5. Total
1. Normalization
2. Pointing filter
3. 1/f filter
4. PCA filter
5. Map-PCA filter
$k_\parallel$ [MPc^{-1}]
$k_\perp$ [MPc^{-1}]
$\tilde{T}_{\rm p}(k_\perp, k_\parallel)$
$\tilde{T}_{\rm freq}(k_\perp, k_\parallel)$
$\tilde{T}_{\rm pix}(k_\perp, k_\parallel)$
$\tilde{T}_{\rm b}(k_\perp, k_\parallel)$
$\tilde{T}(k_\perp, k_\parallel)$
$\tilde{T}_{\rm norm}(k_\perp, k_\parallel)$
$\tilde{T}_{\rm point}(k_\perp, k_\parallel)$
$\tilde{T}_{\rm 1/f}(k_\perp, k_\parallel)$
$\tilde{T}_{\rm PCA}(k_\perp, k_\parallel)$
$\tilde{T}_{\rm mPCA}(k_\perp, k_\parallel)$

Feed(-Group) Pseudo Cross-Power Spectrum (FPXS/FGPXS)



$$C(\mathbf{k}) = \frac{\sum_{A_i \neq B_j} \frac{C_{A_i B_j}(\mathbf{k})}{\sigma^2_{C_{A_i B_j}}(\mathbf{k})}}{\sum_{A_i \neq B_j} \frac{1}{\sigma^2_{C_{A_i B_j}}(\mathbf{k})}}$$

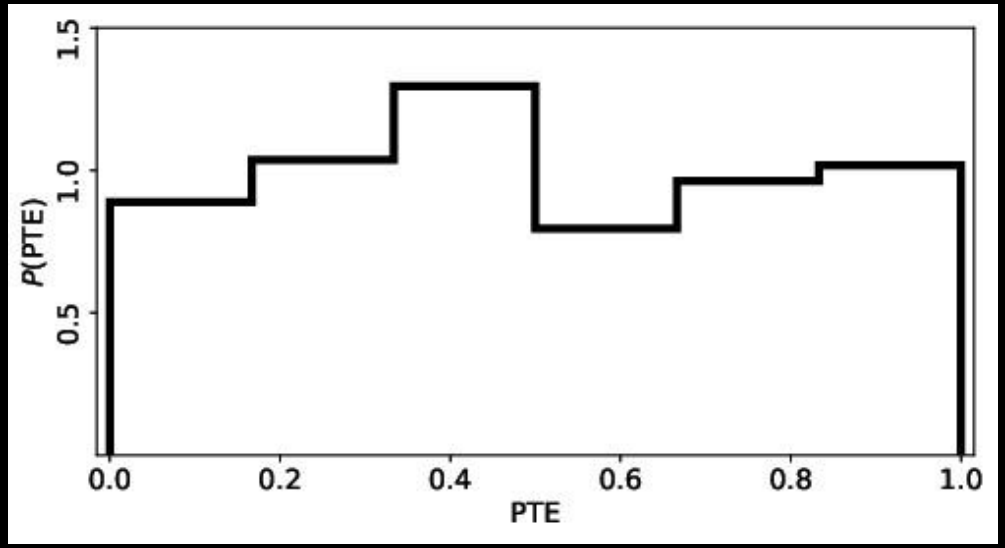




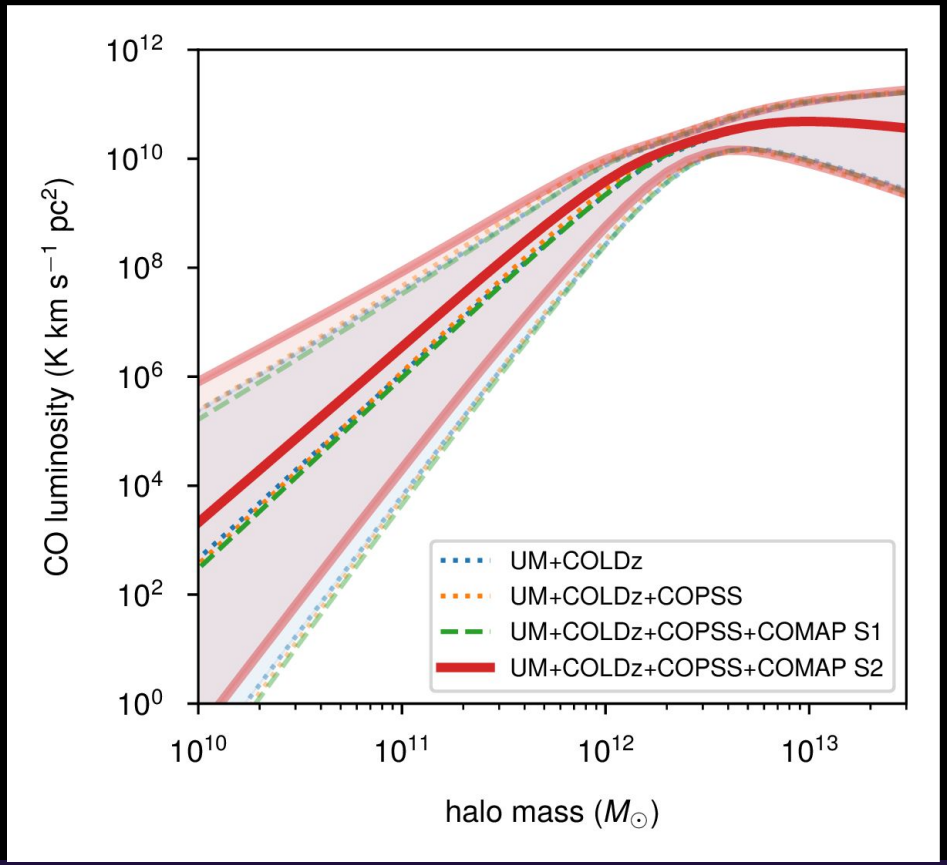
Results — Null Test Framework

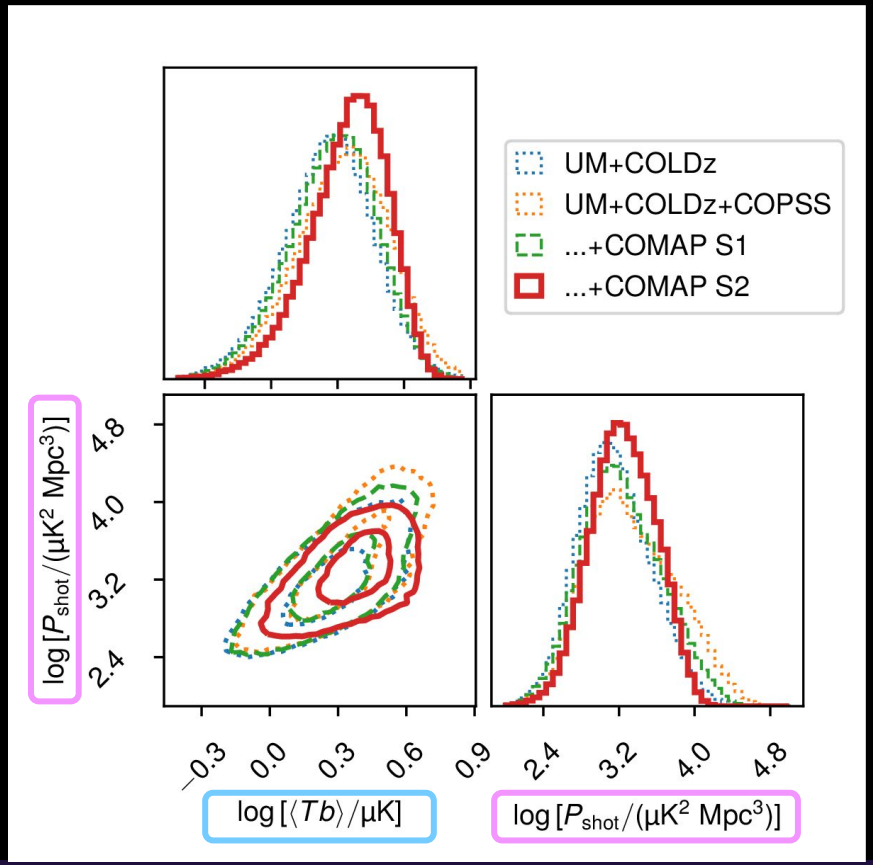
Difference map null tests
= 312 = 26 (null variables)
x 3 (fields)
x 2 (fast and slow scans)
x 2 (1D and 2D avg. FGPXS)

(For the interested: **A list of all 312 PTEs are in the paper**)



Kolmogorov-Smirnov probabilities-to-exceed (KS PTEs) [%]												
	Spherically-averaged (1D)						Cylindrically-averaged (2D)					
	Field 1		Field 2		Field 3		Field 1		Field 2		Field 3	
Combined	Fast	Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast	Slow
58.7	5.5	9.7	16.9	24.1	41.8	48.9	32.1	8.4	61.9	78.7	70.9	72.0


CO luminosity (K km s^{-1} pc^2)
halo mass ($M_\odot$)
UM+COLDz
UM+COLDz+COPSS
UM+COLDz+COPSS+COMAP S1
UM+COLDz+COPSS+COMAP S2


UM+COLDz
UM+COLDz+COPSS
...+COMAP S1
...+COMAP S2
log [P_{shot}/(μK^2 Mpc^3)]
log [⟨Tb⟩/μK]
log [P_{shot}/(μK^2 Mpc^3)]

COMAP S2: data release and power spectrum results

Data reduction and mapmaking:

arXiv:2406.07510

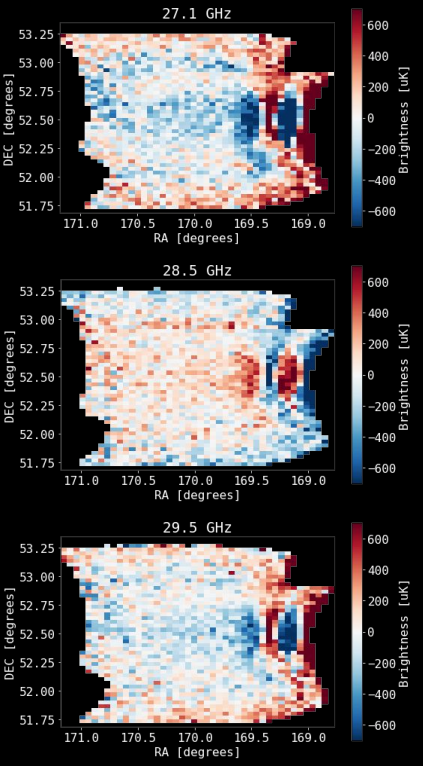
Power spectrum constraints:

arXiv:2406.07511

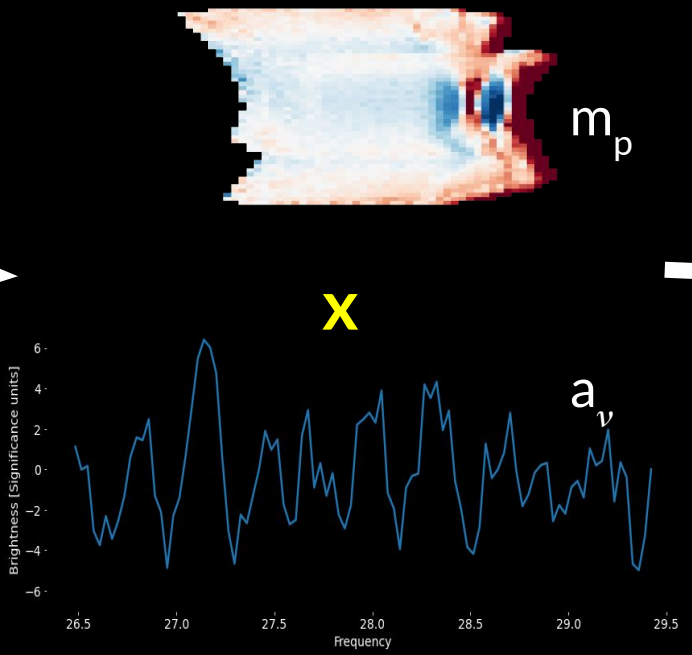
Implications for cosmic CO:

arXiv:2406.07512

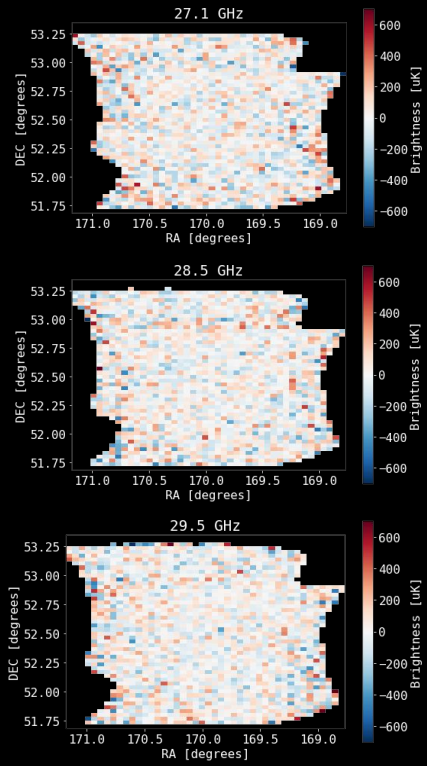
Unfiltered maps

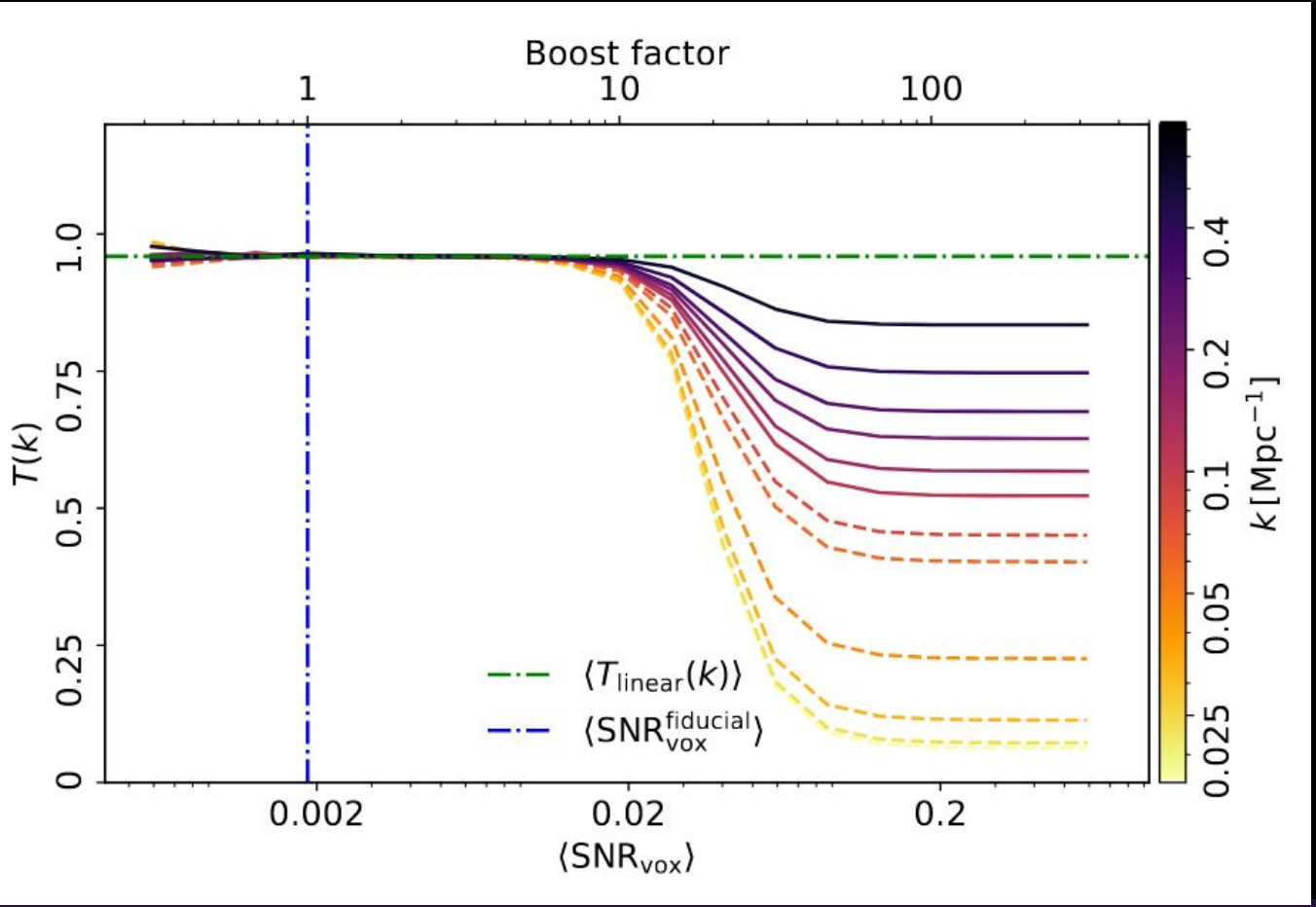


PCA Template

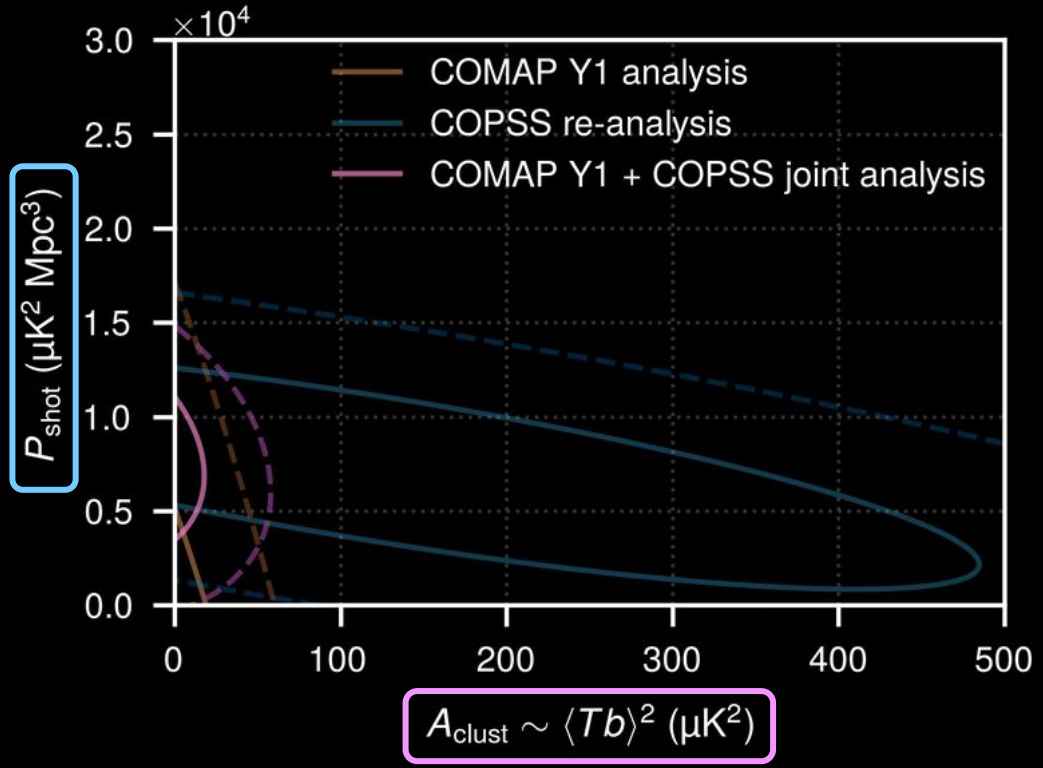


Filtered maps




Boost factor
1
10
100
1.0
0.75
0.5
0.25
0
$T(k)$
$\langle T_{\rm linear}(k)\rangle$
$\langle {\rm SNR}_{\rm vox}^{\rm fiducial}\rangle$
0.002
0.02
0.2
$\langle {\rm SNR}_{\rm vox}\rangle$
0.4
0.2
0.1
0.05
0.025
$k\,[{\rm Mpc}^{-1}]$

Our limits constrain the properties of the CO power spectrum



$$P(k) = \underbrace{A_{\rm clust}}_{\sim\langle Tb\rangle^2} P_m(k) + P_{\rm shot}$$

clustering + shot noise

[Chung et al. 2024, arXiv:2406.07512]

COMAP-*wide* will cross-correlate with LOFAR

OVRO is in the northern hemisphere, so LOFAR provides the best HI accessibility

COMAP-*wide*, LOFAR are well-matched in terms of mode coverage