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



COMAP





COMAP is funded by the NSF (AST 1910999, 1518282, 1517598, 1517288, 1517108, 2206834). We are also grateful to the Keck Institute for Space Studies (KISS) for funding "The First Billion Years: A Technical Development Program for Spectral Line Observations".



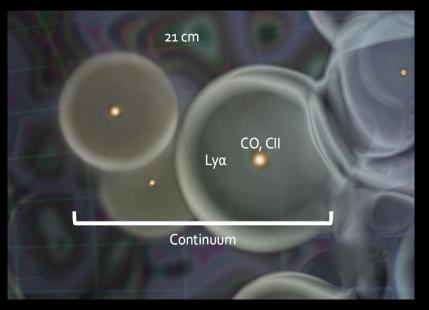
Why do CO Line Intensity Mapping?

CO is an excellent probe of galaxy formation

 CO probes dense, molecular
 hydrogen regions—the regions which are about to collapse into stars

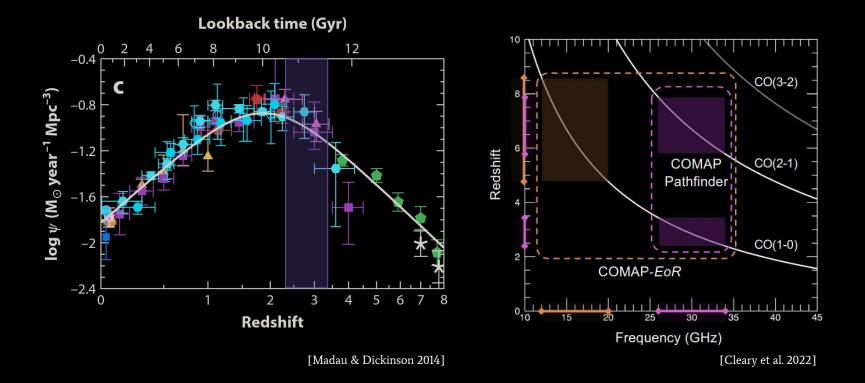
COMAP

- 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]

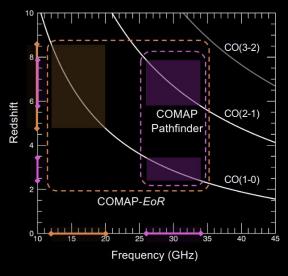
CO is particularly interesting around star formation peaks

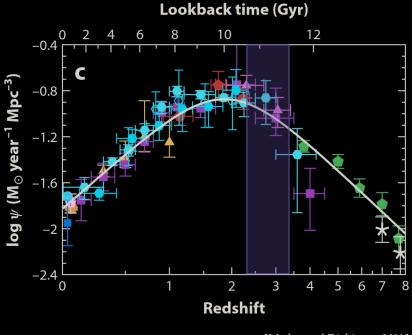


What is COMAP?

Quick Facts about the COMAP Instrument

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





[Madau and Dickinson 2014]

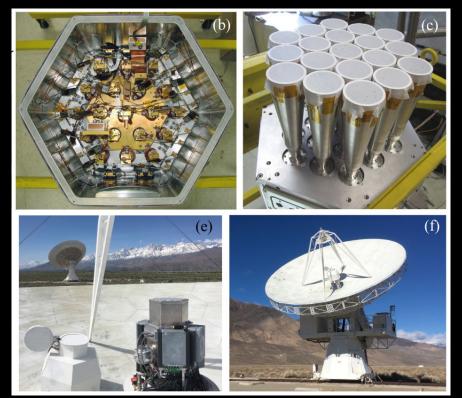
[Cleary et al. 2022]

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COMAP

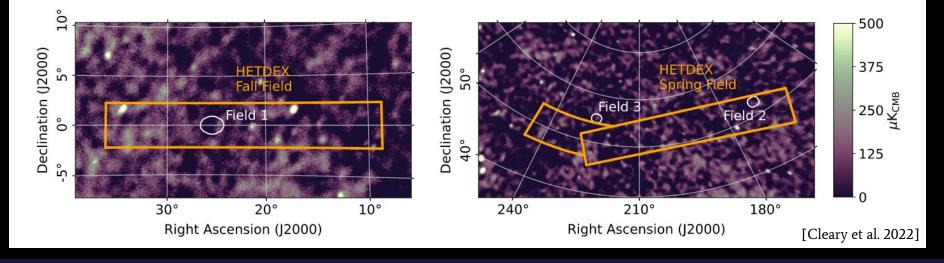
• 10.4 m Pathfinder instrument with 19-feed focal plane array



Quick facts about the COMAP instrument

- Targeting the CO(J=1-0) rovibrational transition at redshifts 2.4-3.4
 - \circ 26-34 GHz, R ~ 1000
- 10.4 m Pathfinder instrument with 19-feed focal plane array

- COMAP covers 12 deg² over 3 fields
 - \circ Cosmological volume of 60 million Mpc³



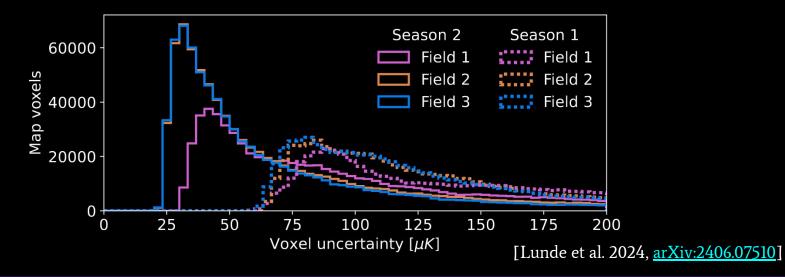
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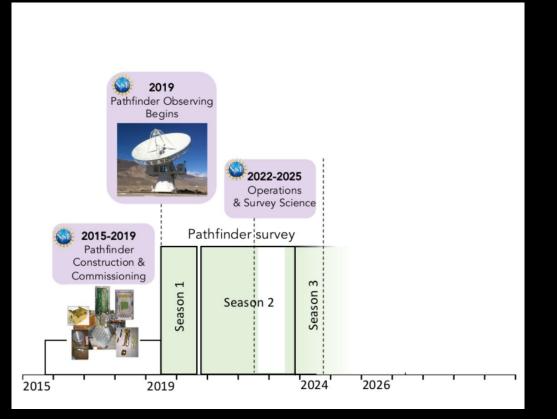
COMAP

• 10.4 m Pathfinder instrument with 19-feed focal plane array

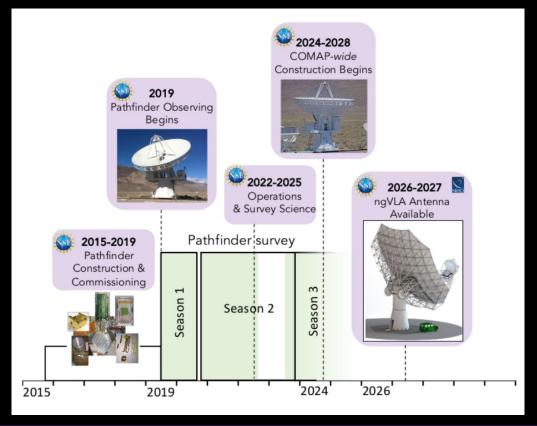
- COMAP covers 12 deg² over 3 fields
 - Cosmological volume of 60 million Mpc³
- Season 2: 25 50µK uncertainty



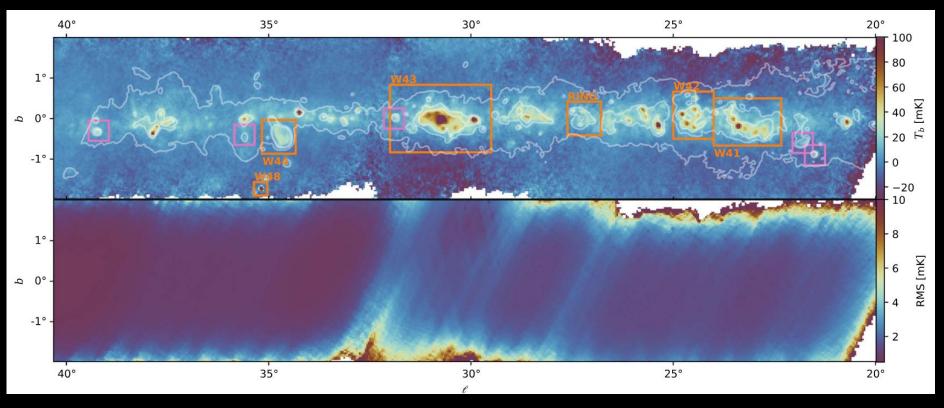
COMAP is currently partway through its planned Pathfinder survey



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



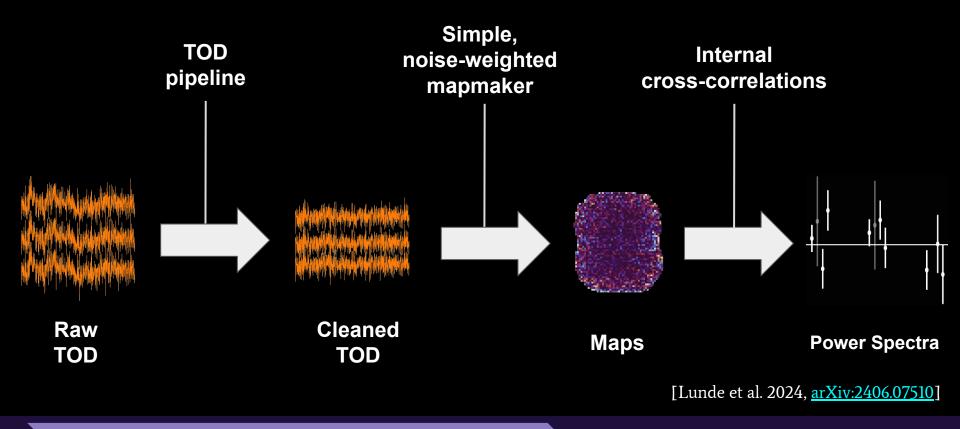
COMAP is also performing a mK-sensitivity Galactic Plane Survey



[Rennie et al. 2022, <u>arXiv: 2111.05932</u>]

Power Spectra

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



COMAP has the tightest upper limits on the CO power spectrum at $z \sim 3$

\$0°

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

$$+ P_{shot}$$

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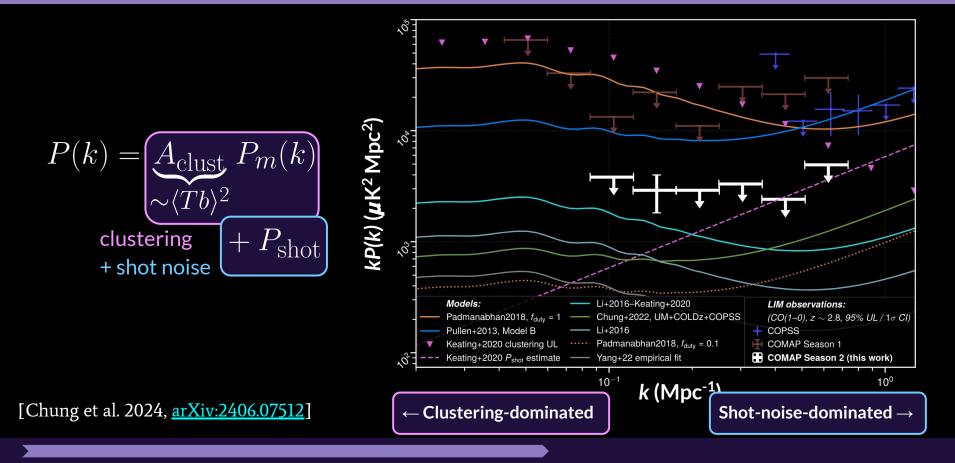
$$P(k) = \underbrace{A_{clust}}_{\sim \langle Tb \rangle^2} P_m(k)$$

$$P_{shot}$$

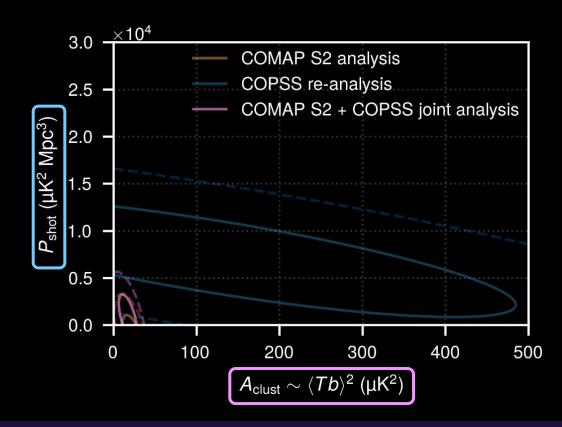
COMAP

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



Our limits constrain the properties of the CO power spectrum



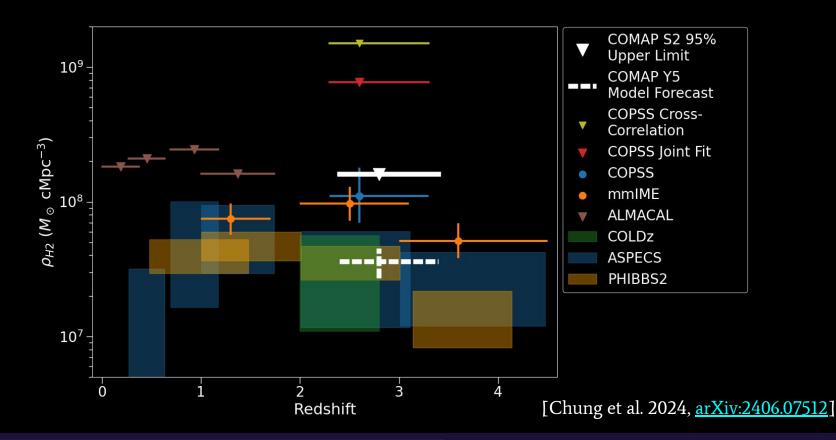
$$P(k) = \underbrace{A_{\text{clust}}}_{\sim \langle Tb \rangle^2} P_m(k)$$

clustering
+ shot noise + P_{shot}

[Chung et al. 2024, arXiv:2406.07512]

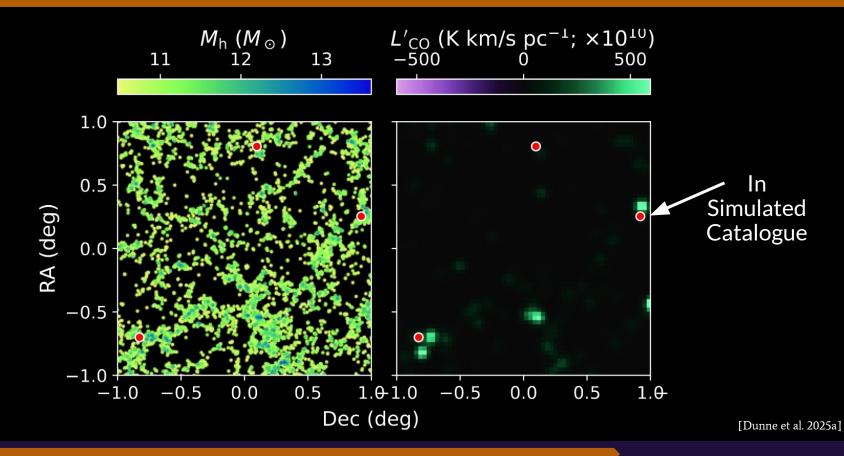
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These lead to constraints on the cosmic molecular gas density



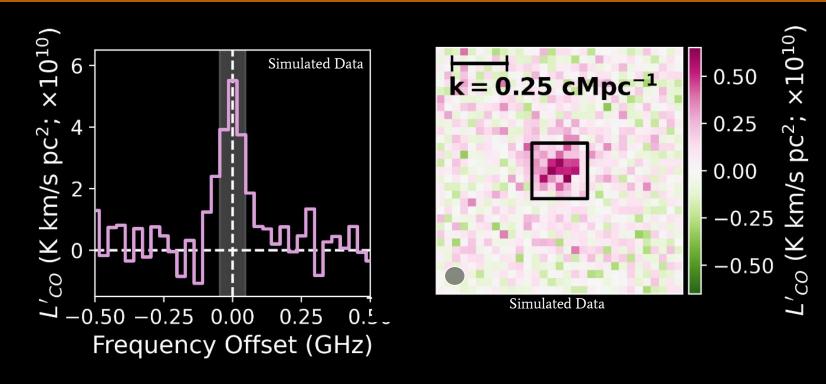
COMAP x Galaxy Catalogues

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



COMAP

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



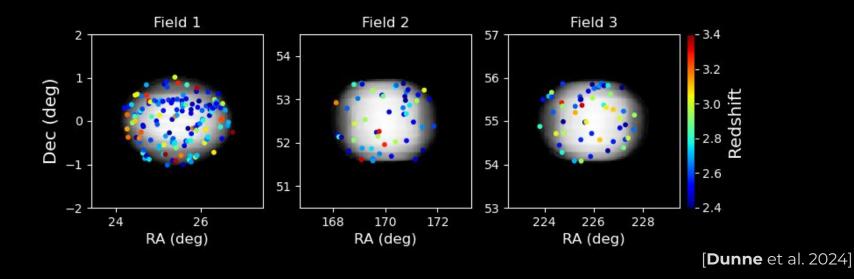
 $\sqrt{N_{obj}}$ improvement in sensitivity

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

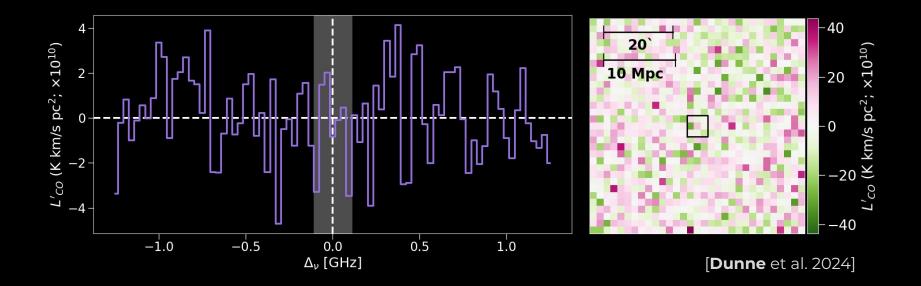
We performed an initial stack analysis on eBOSS

The extended Baryon Oscillation Spectroscopic Survey (eBOSS):

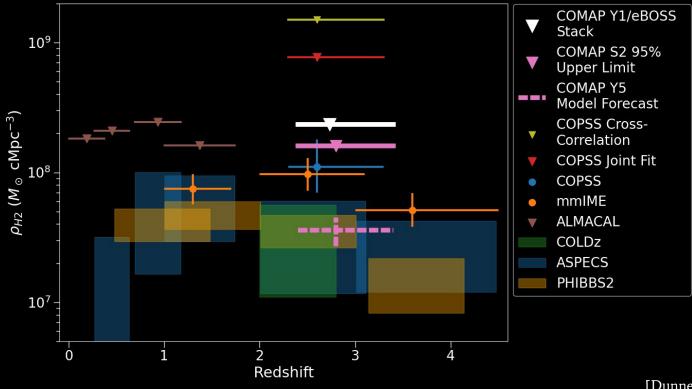
- Quasi-Stellar Object (**QSO**, or Quasar) catalogue
- More than 750 000 objects total, **243** of which are in the COMAP footprint



The COMAP-eBOSS S1 stack did not detect any signal

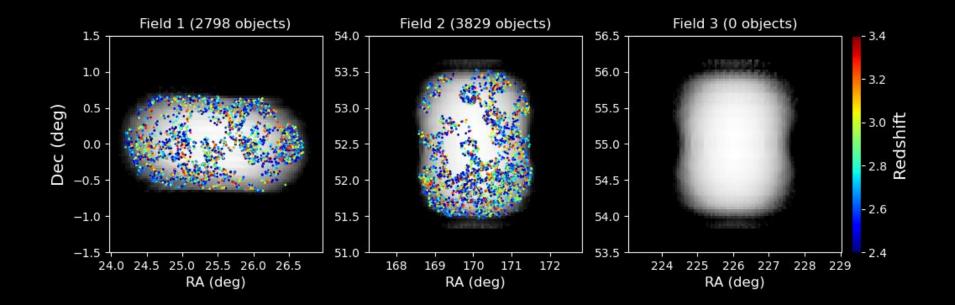


... but did lead to a tight constraint on molecular gas density



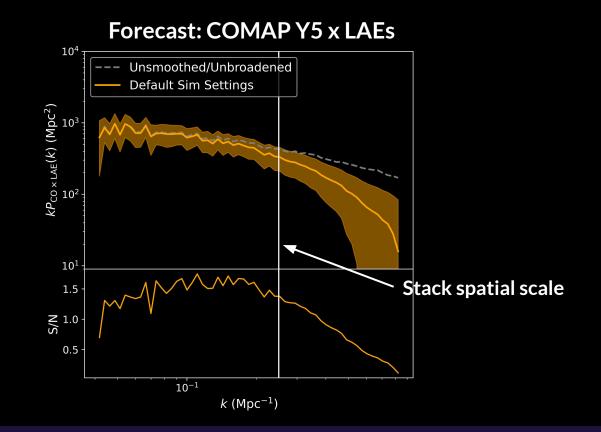
[Dunne et al. 2024]

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



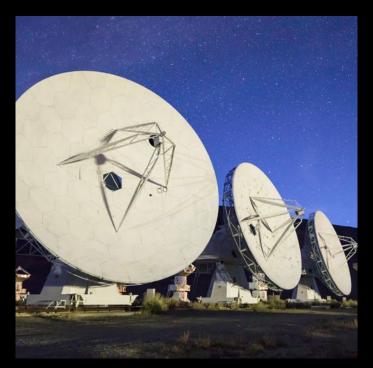
Total S/N ~ 10

EoR Science with COMAP

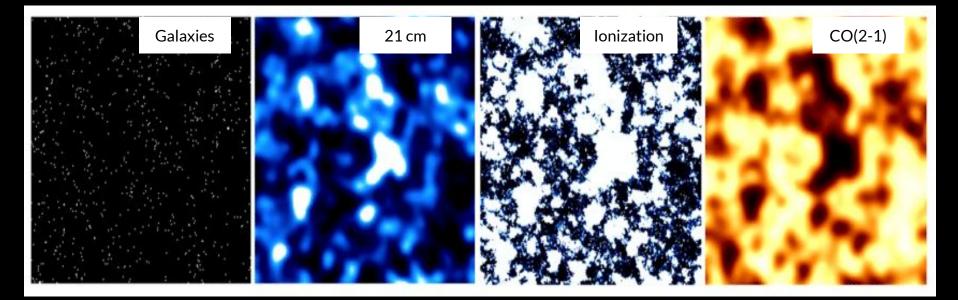
COMAP-wide is an experiment under construction to study the EoR

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 deg²
- Science Targets: Cross-Correlations
 - CO x 21 cm at z~7
 - CO x Spectroscopic Galaxies at z~3

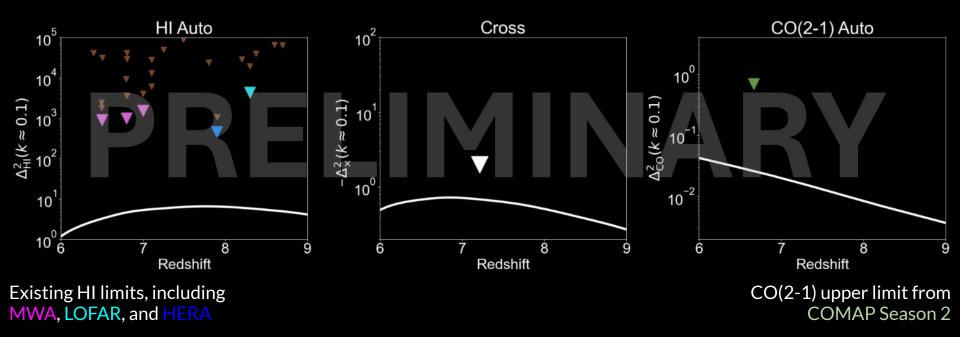


CO and 21 cm emission are anticorrelated during reionization

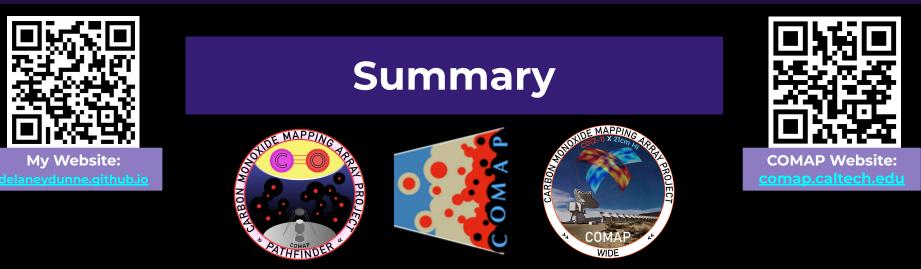


(Credit: Adam Lidz)

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



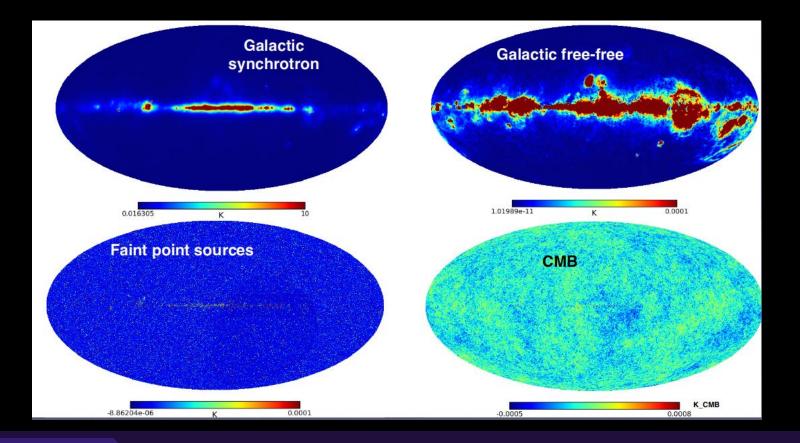
[Credit: Patrick Breysse and Hannah Fronenberg]



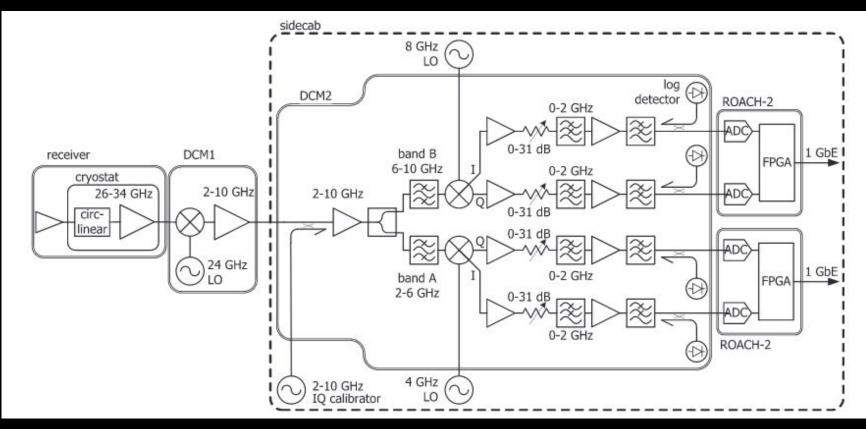
- COMAP is an active LIM experiment targeting cosmic CO emission z~3
- We have the tightest constraints available on the z~3 power spectrum
- Joint analysis techniques with galaxy catalogues could constrain cosmic CO further
- Upcoming COMAP stages will expand into the EoR

EXTRA SLIDES

CO foregrounds are comparatively minor

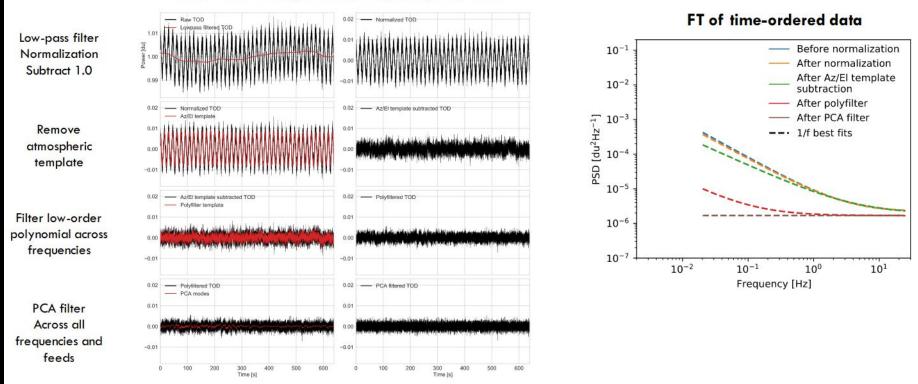


COMAP Instrument – signal path



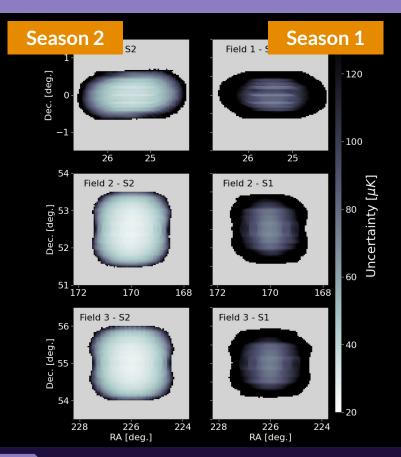
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Time-series: single feed, frequency and scan



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

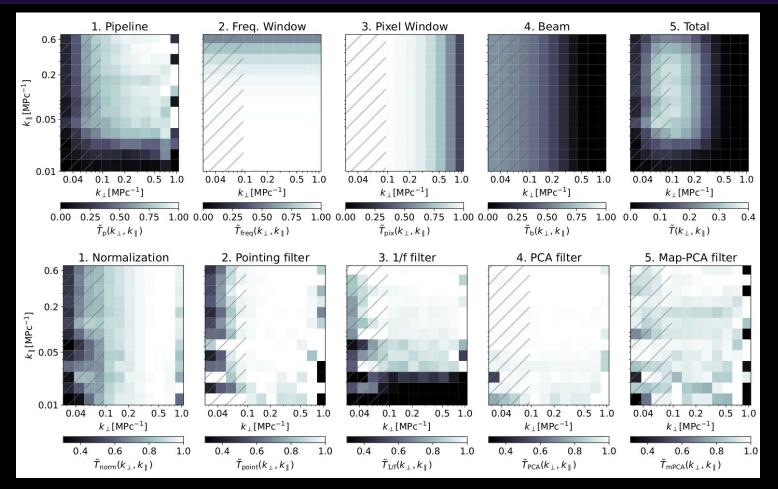
25 – 50μK uncertainty over a cosmological volume of 60 million Mpc³.



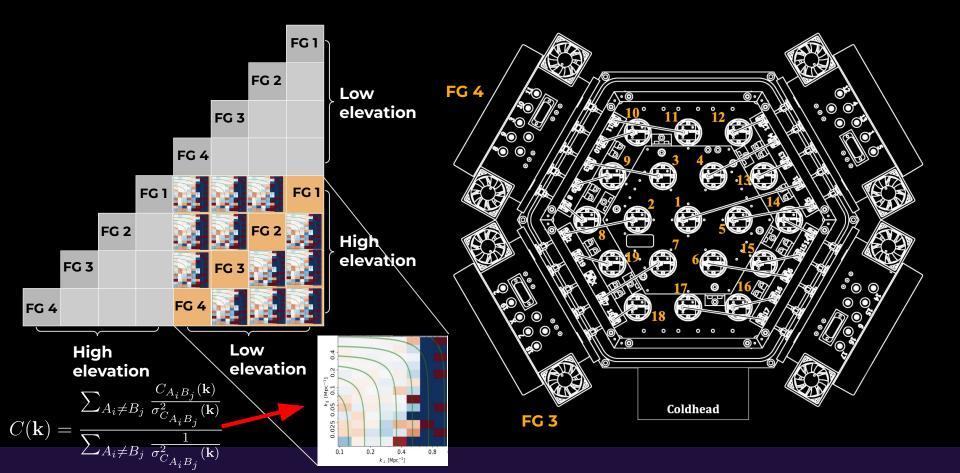
[Lunde et al. 2024, <u>arXiv:2406.07510</u>]

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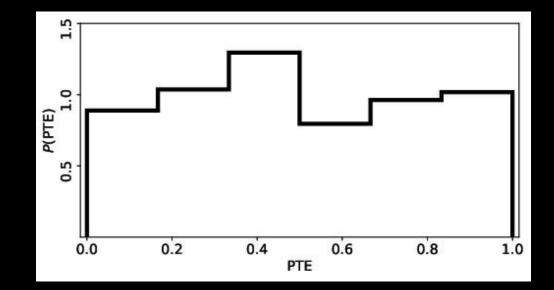
Feed(-Group) Pseudo Cross-Power Spectrum (FPXS/FGPXS)



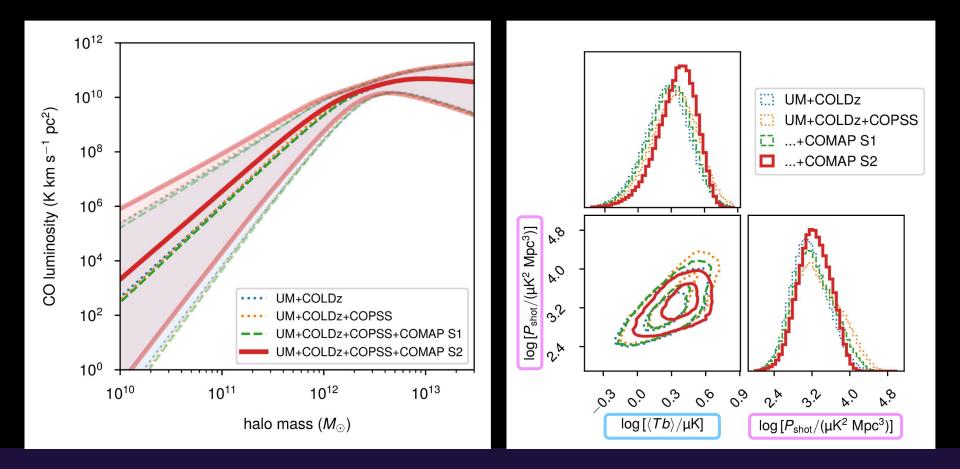
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Results — Null Test Framework

(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)					
	Fie	ld 1	Fie	eld 2	Fi	ield 3	Fie	ld 1	Fie	eld 2	Fi	eld 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



COMAP S2: data release and power spectrum results

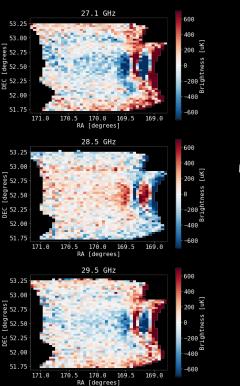
Data reduction and mapmaking: <u>arXiv:2406.07510</u>

Power spectrum constraints: arXiv:2406.07511

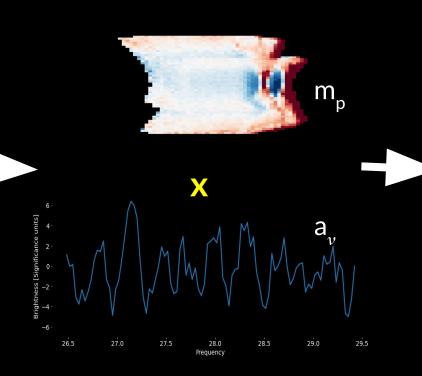
Implications for cosmic CO: <u>arXiv:2406.07512</u>

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<footnote><text><footnote><footnote><footnote></footnote></footnote></footnote></text></footnote>	<footnote><text><footnote><footnote><footnote></footnote></footnote></footnote></text></footnote>	side, more effective data cleaning in both the time- and map-domain has allowed us to elimin	¹¹ Kawli Institute for Particle Astrophysics and Cosmology and Physics Department, Stan	
<text><footnote><footnote><text></text></footnote></footnote></text>	<text><footnote><footnote><text></text></footnote></footnote></text>	increased sensitivity, two new pointing-correlated systematic errors have emerged, and we intre	¹⁰ Department of Physics, Othersity of Maryland, College Park, MD 20742	USA ⁵ Department of Physics, Southern Methodist University, Dollas, TX 75275, USA
<text><text><footnote><text><text><text><text></text></text></text></text></footnote></text></text>	<text><text><footnote><text><text><text><text></text></text></text></text></footnote></text></text>	67% on large angular scales, and after applying this filter, the maps appear consistent with inst	Received MM DD, YYYY; accepted MM DD, YYYY	⁶ California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA ⁷ Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway
 A constraint opposite biological data data data data data data data da	 A constraint opposite biological data data data data data data data da	analysis. Combining this with the increase in row observational hours, the effective amount of da	ABSTRACT	
 - null (a. b. langer phone in many phone in obtaining phone in the state of the sta	 - null (a. b. langer phone in many phone in obtaining phone in the state of the sta	constraints on cosmological CO line emission published to date.	We present updated constraints on the cosmological 3D power spectrum of carbon monox	¹⁰ David A. Danlap Department of Astronomy, University of Toronto, 50 St. George Street, Toronto, ON, MSS 3H4, Canada ¹¹ Kavli Institute for Particle Astrophysics and Cosmology & Physics Department, Stanford University, Stanford, CA 94305, USA
 * numl (p. 1. home for the stand production and fact or the stand production and fact	 * numl (p. 1. home for the stand production and fact or the stand production and fact	Key words. galaxies: high-redshift - radio lines: galaxies - diffuse radiation - methods: data a	2.4–3.4. The constraints are derived from the two first seasons of Carbon monOside Mappu intensity mapping observations aiming to trace star-formation during the Epoch of Galaxy J	¹⁰ Department of Physics, University of Miami, 1320 Carpto Sano Avenue, Cond Gables, FL 33146, USA
 * real [_a t.] addition to all on proper prop	 * real [_a t.] addition to all on proper prop			¹⁴ Jodrell Bank Centre for Astrophysics, Department of Physics & Astronomy, The University of Manchester, Oxford Road, March ester, M13 991, UK
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************************************	************************************		maa seaccion methodology. The updated spherically- and field-averaged PGPXS, C(4), a exceed of around 34%, with an excess of 2.7 σ in the most sensitive bia. Our power spectri	Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yaseong-gu, Daejeo 34141, Republic of Korea
the number of the first sector with the intermetation with the inter	the number of the first sector with the intermetation with the inter	* e-muil: j.g.s.lundelastro.uio.no	(FPX5) of COMAP ES. Each of these bins individually constrains the CO power spectra	¹⁰ Brookhaven National Laboratory, Upton, NY 11973-5000 ¹⁰ Department of Physics and Astronomy, University of British Columbia, Vancouver, BC Canada V6T 121, Canada
For words, patrixe, hydroxidit radio large patrixe, a dditar r	For words, patrixe, hydroxidit radio large patrixe, a dditar r		tests and find that these are consistent with the instrumental noise reediction. In sum, the	Received DD MMM YYYY; accepted DD MMM YYYY
1. Introduction 1. Introduction by officing the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos philos of the control website problem (2014) Philds are expres	1. Introduction 1. Introduction by officing the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos of the control website problem (2014) Philds are expressioned and the philos philos of the control website problem (2014) Philds are expres			ABSTRACT
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b) existing the carbon dependent in a critical part of the control	b) existing the carbon dependent in a critical part of the control			spectrum analysis is based on observations through the end of Season 2, covering the first three years of Pathinder operation
hight and faits. The intensity mapping (LLD) aims to map the pappond, arrange * ensult has strateributers, using and * ensult has strateributers with and * ensult has s	hight and faits. The intensity mapping (LLD) aims to map the pappond, arrange * ensult has strateributers, using and * ensult has strateributers with and * ensult has s		By collecting the combined redshift-dependent line emission & Wyithe 2008 Ko	we use our access constraints on the COCL-to intermemoly power spectrum at 2 ~ 3 to update corresponding constraints on the cosmological clustering of CO line emission and flux the cosmic molecular gas content at a key epoch of galaxy assembly. We fir
***** Chief and the second	***** Chief and the second		bright and faint, line intensity mapping (LIM) aims to map the proposed, among th	CO fluctuations and the bias of CO emission as a tracer of the underlying dark matter distribution. The COMAP Season 2 result
OMMOP End y Secret, including our data-drive provide monitoring a model of the halo - O connection and how quinter hand a comparison of the halo and	OMMOP End y Secret, including our data-drive provide monitoring a model of the halo - O connection and how quinter hand a comparison of the halo and		* e-mail: n.o. stutzer#astro.uio.no carbon ([C u]). Lyu	
With outined observations and attaching involvements in analysis, the COMAP Padfinder remains on track for a detection o cosmolygical closerup (of CO maioine)	With outined observations and attaching involvements in analysis, the COMAP Padfinder remains on track for a detection o cosmolygical closerup (of CO maioine)			
				With continued observations and matching improvements in analysis, the COMAP Pathfinder remains on track for a detection of
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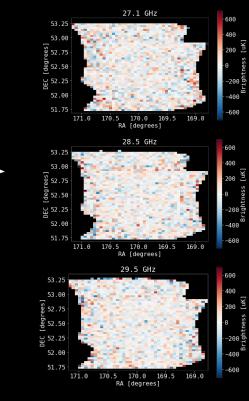
Unfiltered maps

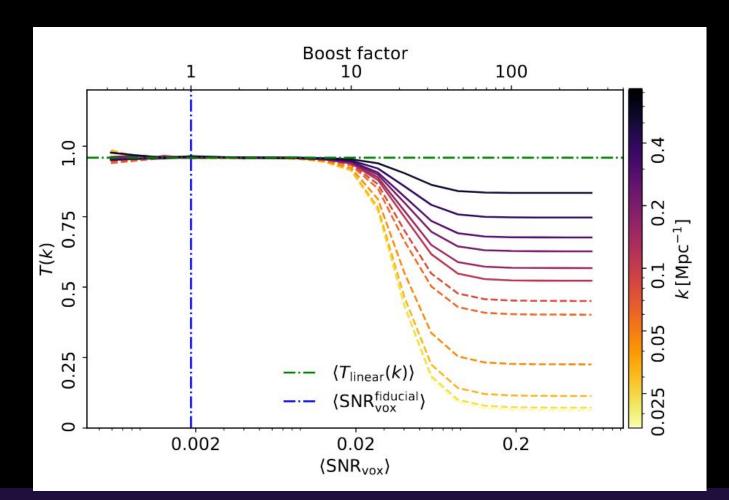


PCA Template

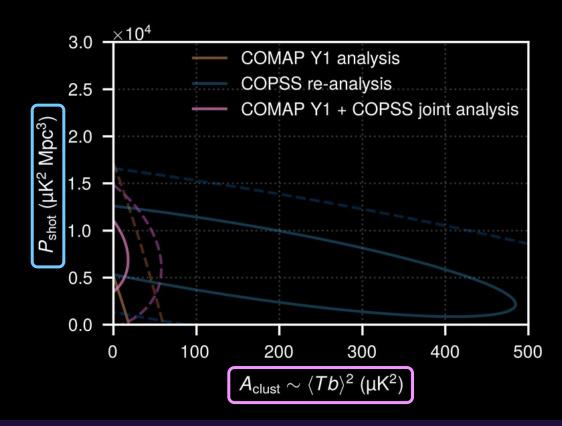


Filtered maps





Our limits constrain the properties of the CO power spectrum



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

clustering
+ shot noise + P_{shot}

[Chung et al. 2024, arXiv:2406.07512]

COMAP

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

