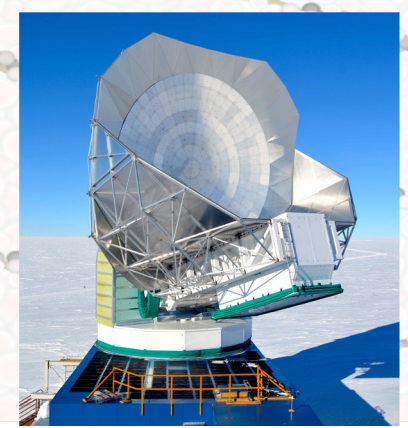


Line Intensity Mapping with Carbon Monoxide and COMAP

Kieran Cleary

Caltech

LIM25, June 3, 2025

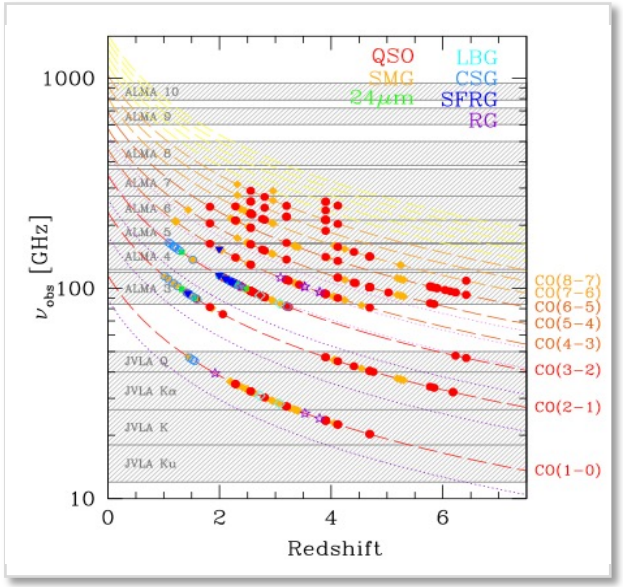

Why CO?

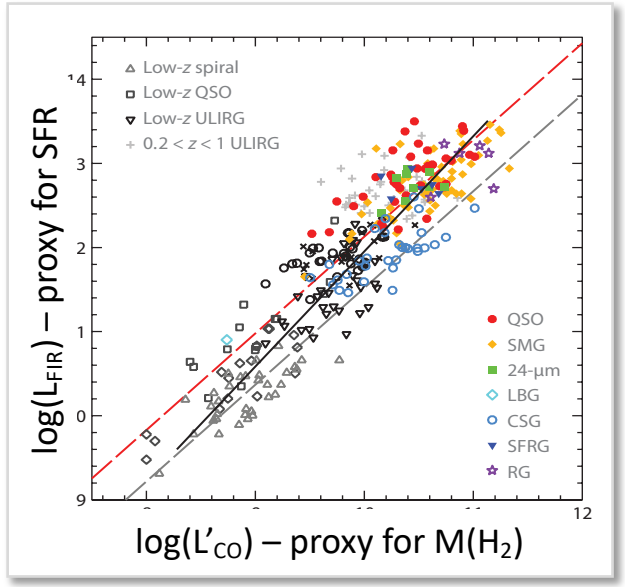
- Traces dense gas, ‘fuel’ for star-formation
- Bright, even at high z

THE ASTROPHYSICAL JOURNAL, 161:L43–L44, July 1970

CARBON MONOXIDE IN THE ORION NEBULA

R. W. WILSON, K. B. JEFFERTS, AND A. A. PENZIAS
Bell Telephone Laboratories, Inc., Holmdel, New Jersey, and
Crawford Hill Laboratory, Murray Hill, New Jersey
Received 1970 June 5





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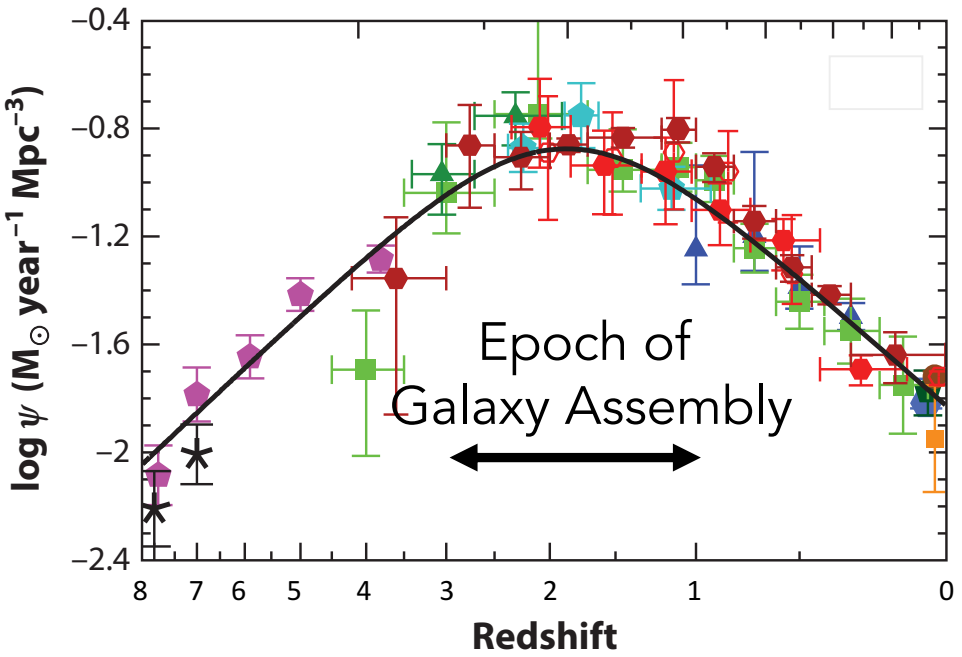
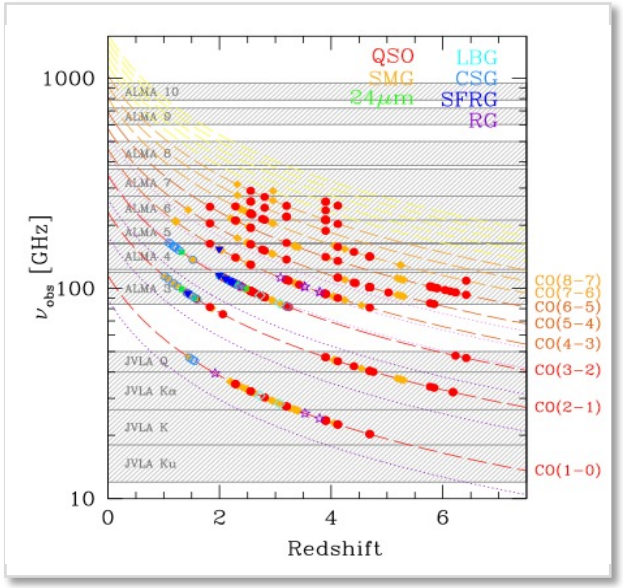
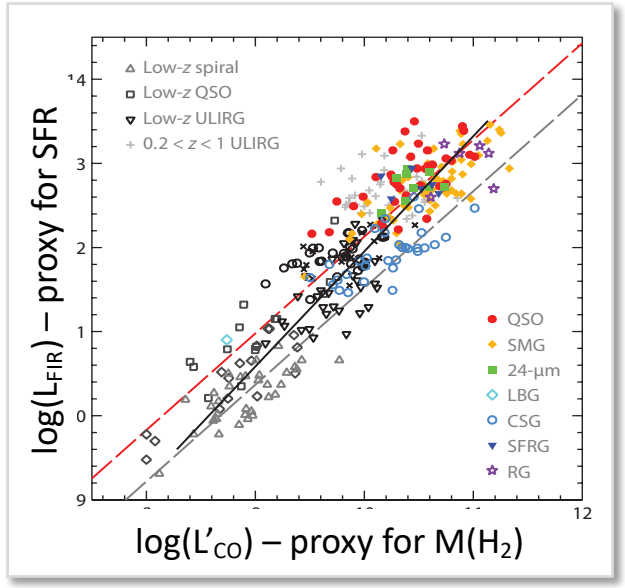
Adapted from Madau & Dickinson 2014

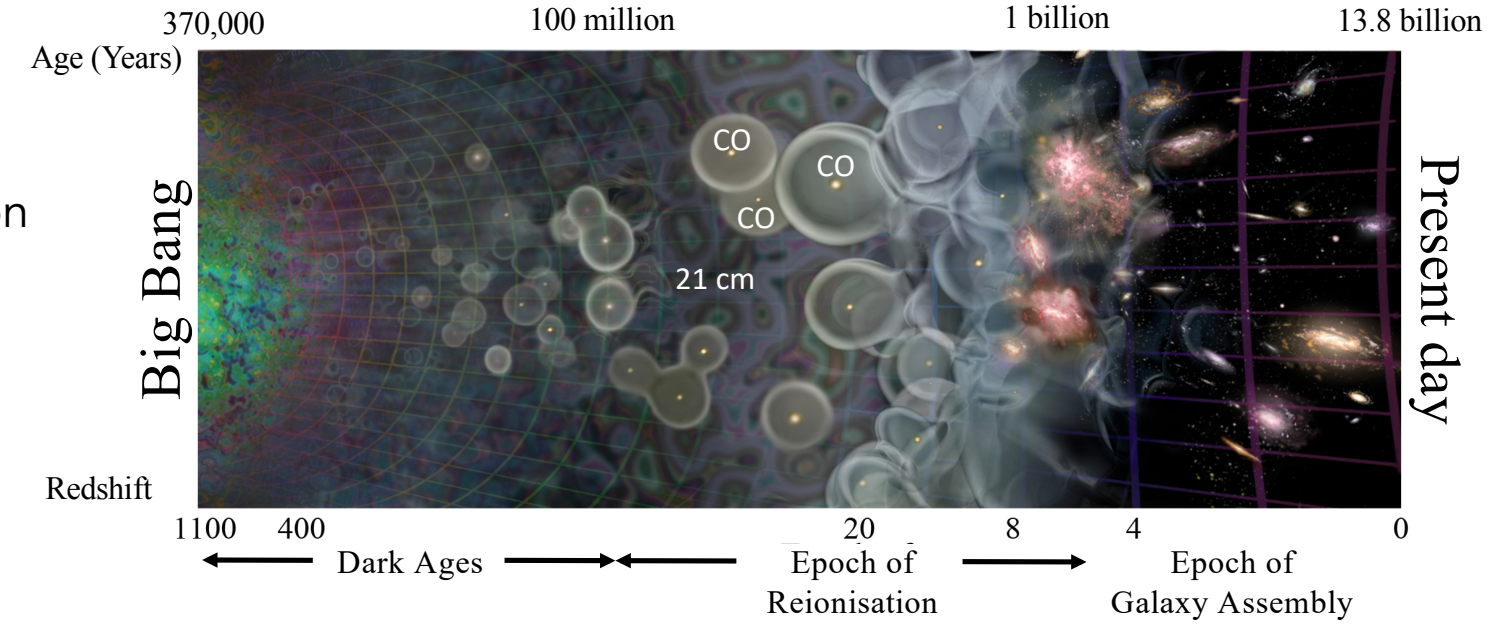


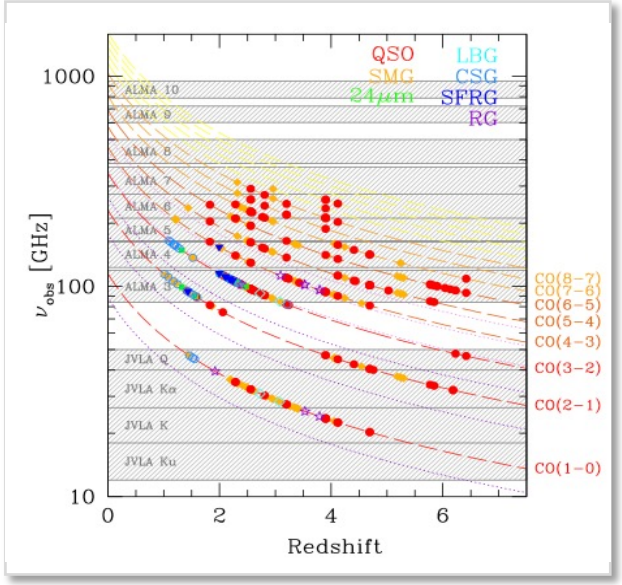


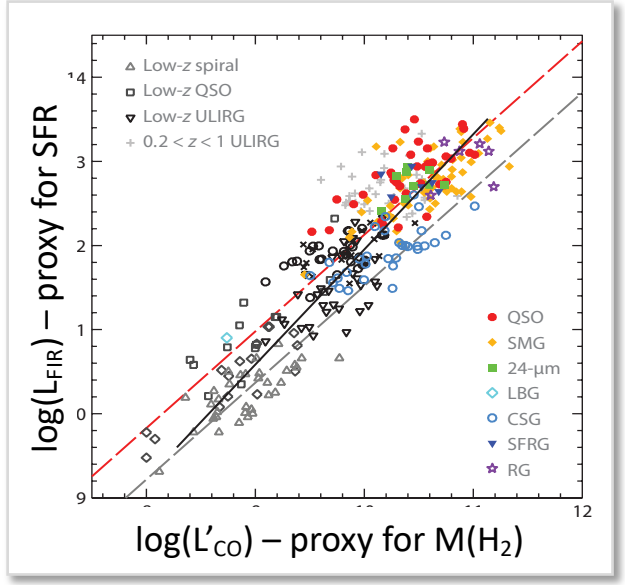


Why CO?

- Traces dense gas, 'fuel' for star-formation
- Bright, even at high z
- Complementary to HI at EoR

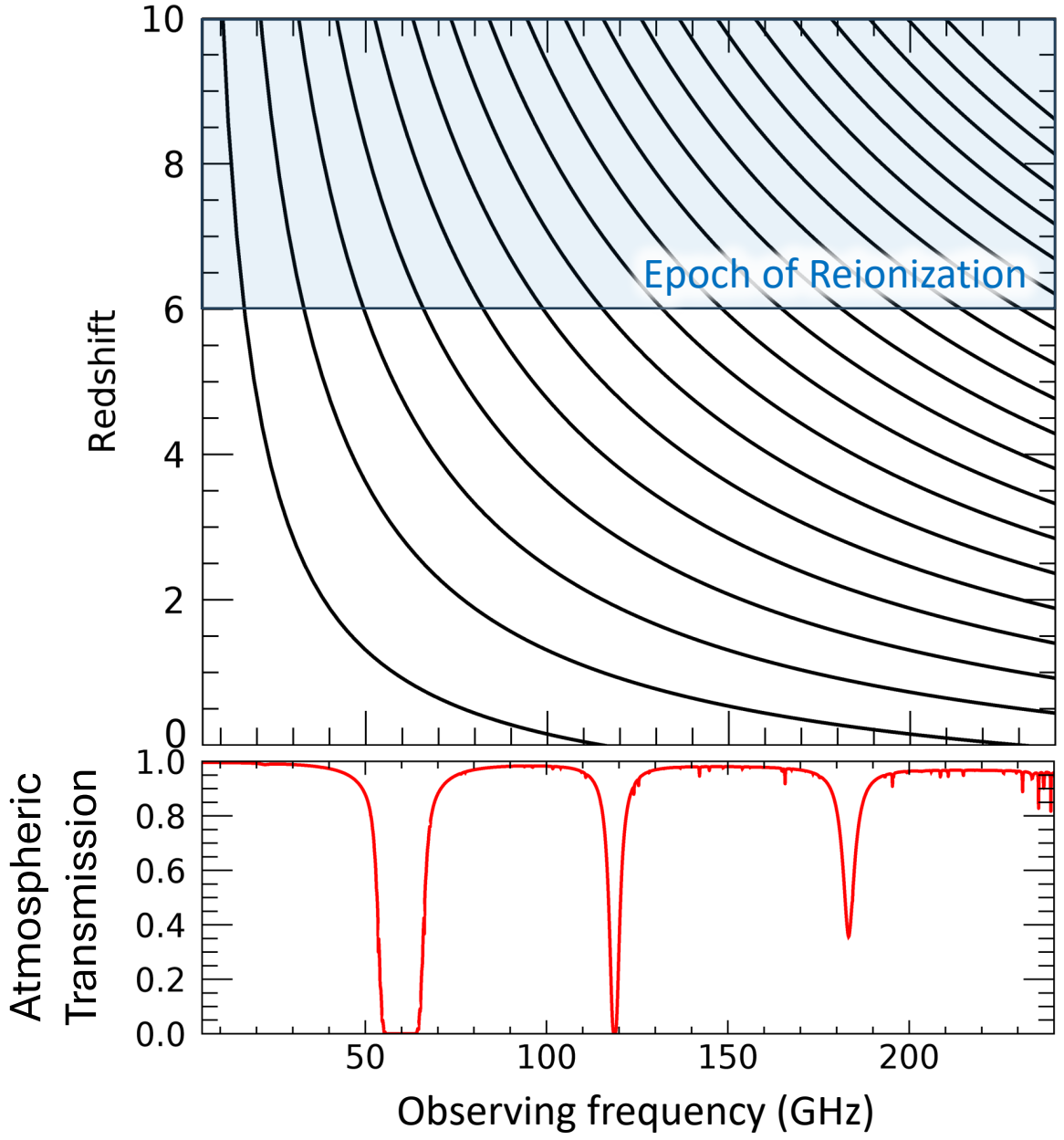






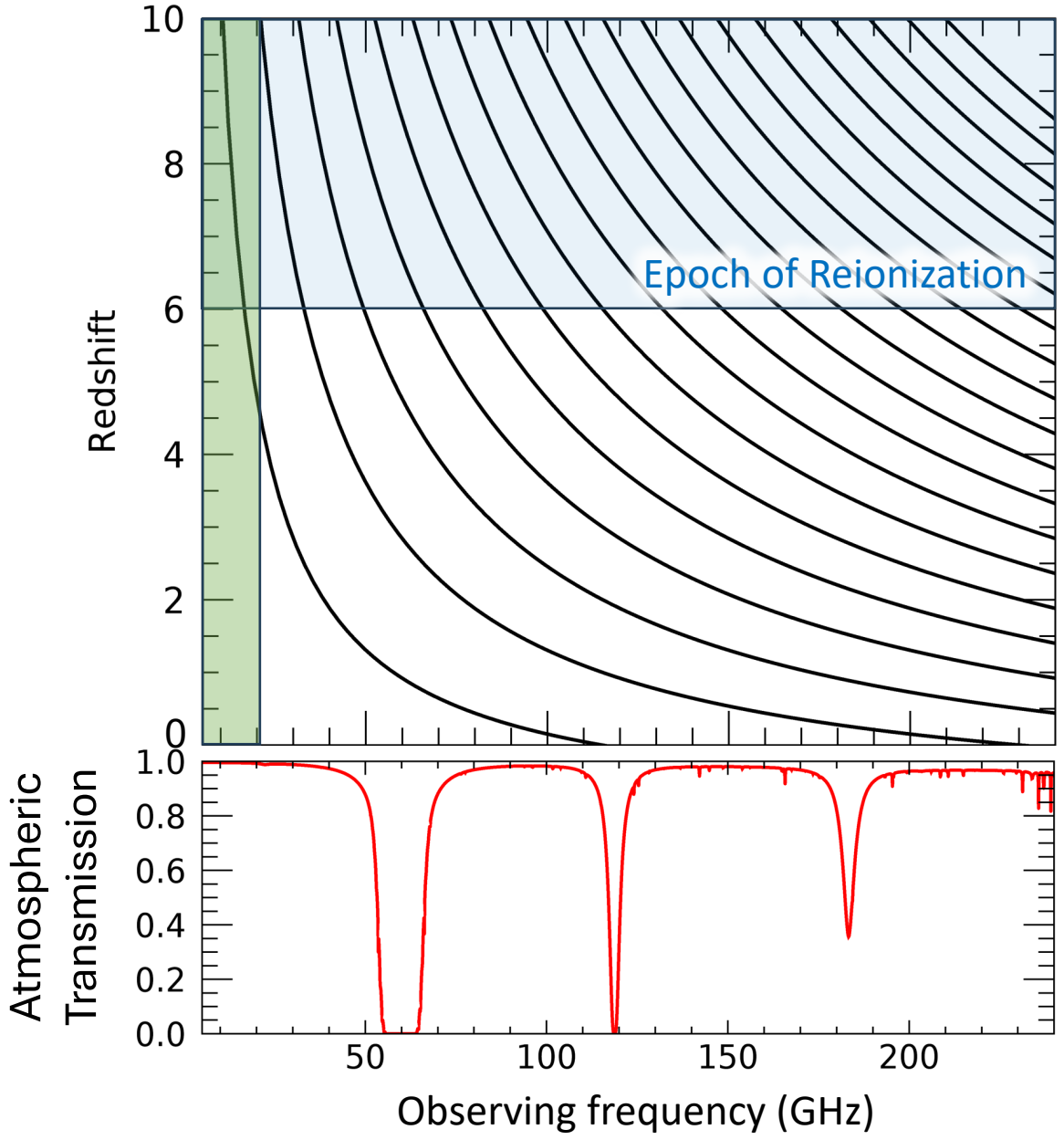
Why CO?

- Traces dense gas, ‘fuel’ for star-formation
- Bright, even at high z
- Complementary to HI at EoR
- Emits in line ‘ladder’
  - cross-correlate
- cm to mm-wave observations
  - accessible from ground
- Low RFI
- Low continuum foregrounds
- Low non-CO interlopers



Why CO?

- Traces dense gas, ‘fuel’ for star-formation
- Bright, even at high z
- Complementary to HI at EoR
- Emits in line ‘ladder’
- cm to mm-wave observations
- Low continuum foregrounds
- Low non-CO interlopers
- Access z=4-10 without any line interlopers



CO LIM Origins (Caltech Perspective)

Theory

Gong et al. (2011)

Carilli (2011)

Lidz et al. (2011)

Workshop

Keck Institute for Space Studies

First Billion Years

First Workshop Caltech August 2010

Workshop

Keck Institute for Space Studies

First Billion Years

Second Workshop Caltech August 2011

Judd Bowman
Dayton Jones
Tony Readhead
Mike Sieffert

Funding

Keck Institute for Space Studies

Technology Development (CO LIM, Caltech)

Funding

NSF

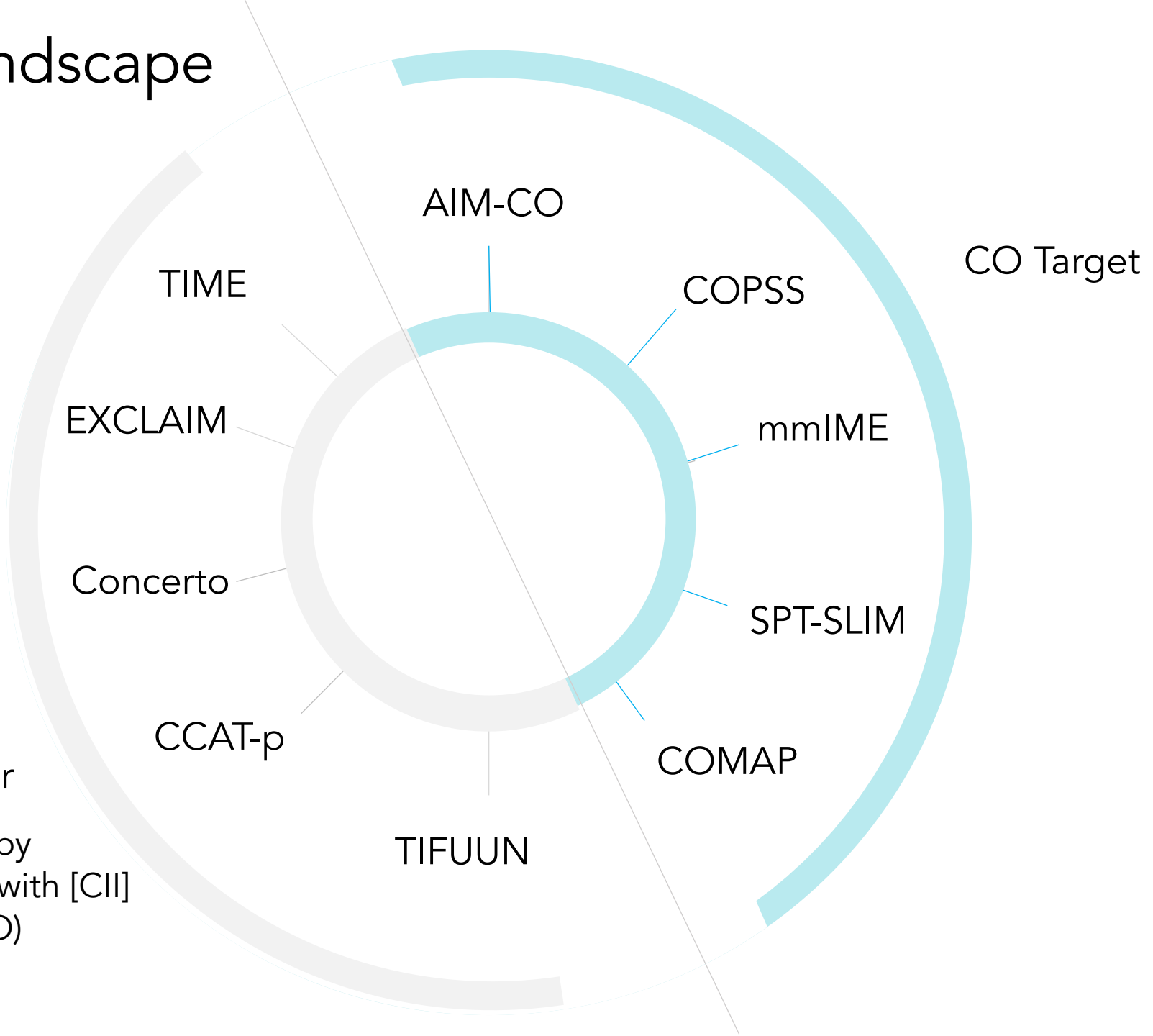
COMAP Pathfinder

Theory

Righi et al. (2008)

2008 2009 2010 2011 2012 2013 2014 2015

CO Experimental Landscape



C^+ Target
CO Interloper

(Covered in talk by
Guilaine Lagache: LIM with [CII]
and CONCERTO)

AIM-CO

Ground-based (Mauna Loa)
Interferometer (Yuan-Tseh Lee Array)
86-102 GHz

Line	Redshift
CO(3-2)	2.4-3.0
CO(2-1)	1.2-1.7

Observations started 2017

Experiment decommissioned in 2021

Potential for upper limits from data

COPSS

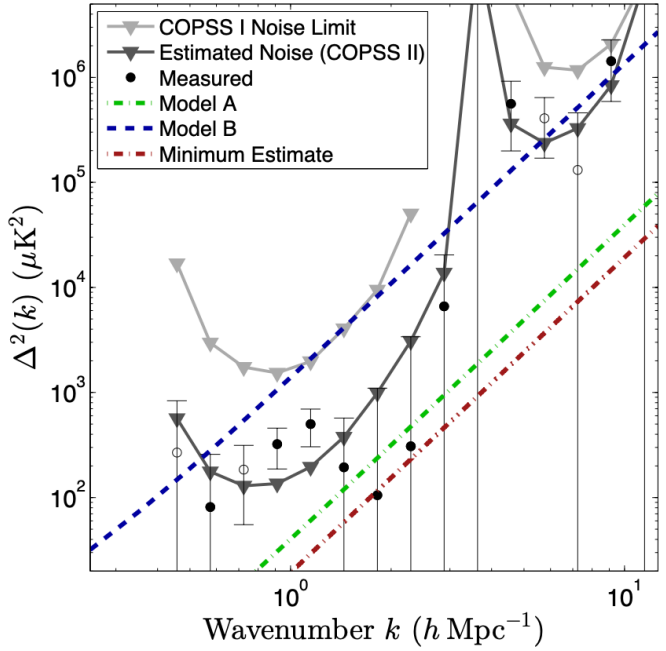
Ground-based (Cedar Flat)
Interferometer (SZA/CARMA)
27-35 GHz

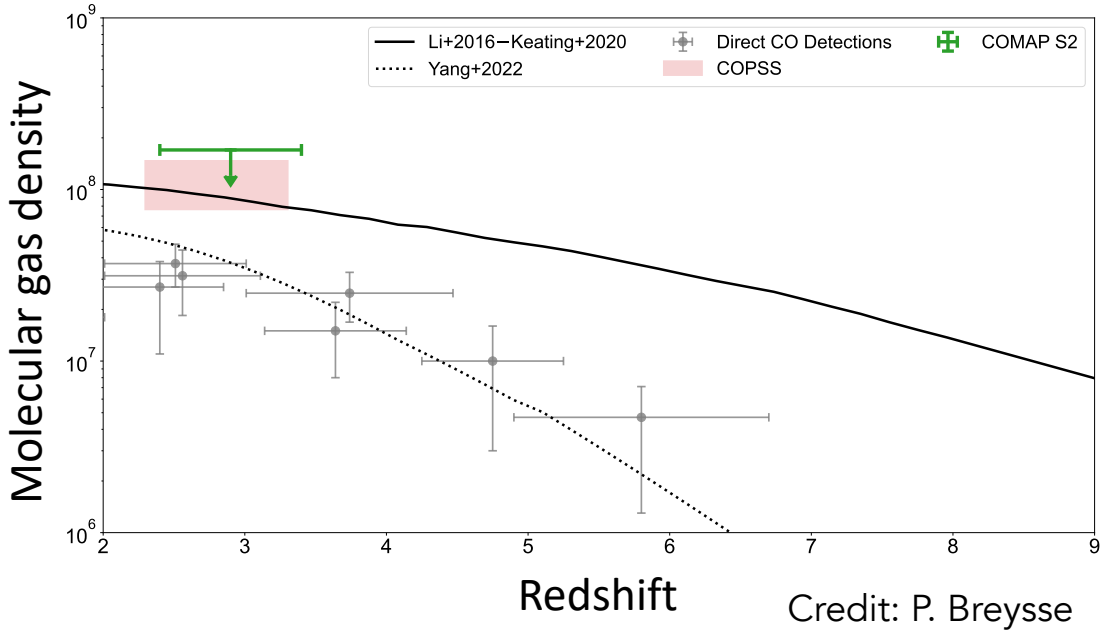
Phase	Line	Redshift	Area (sq. deg.)	K range (h Mpc^{-1})
COPSS I	CO(1-0)	2.3-3.3	1.7	0.5-2.0
COPSS II	CO(1-0)	2.3-3.3	0.7	0.5-10

First constraints on CO(1-0) power spectrum at z~3
Inferred constraint on the molecular gas density

More molecular gas in galaxies seen by LIM compared with traditional galaxy surveys?

Keating at al. (2016)

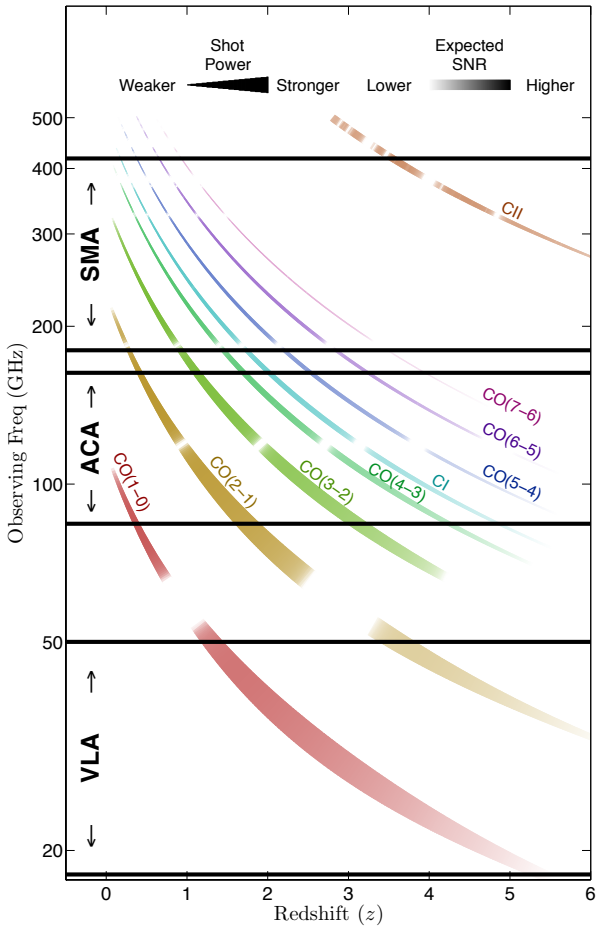




Credit: P. Breysse

mmIME

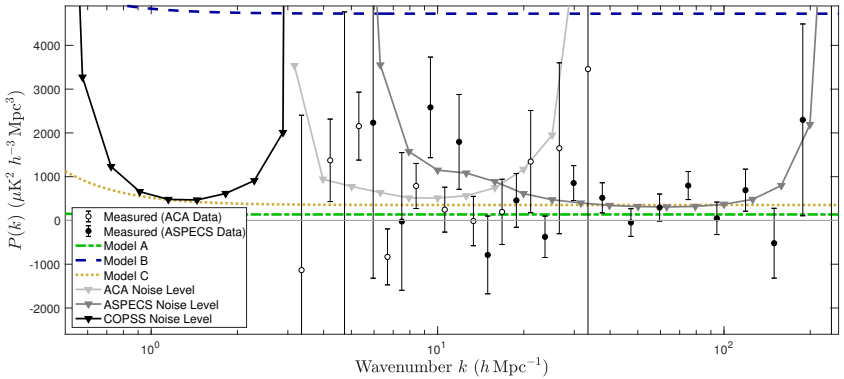
The Millimeter Intensity Mapping Experiment (mmIME)

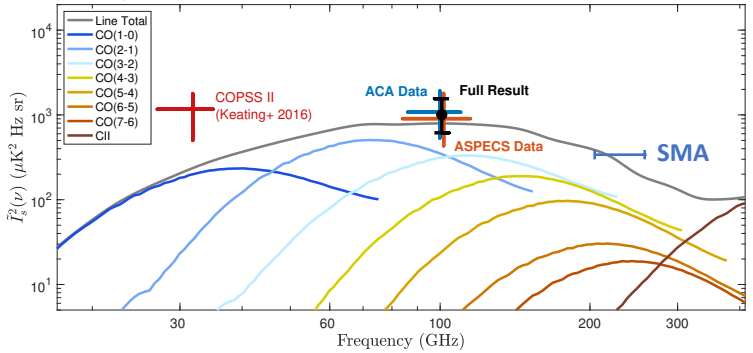


"It only looks like there's nothing there"

Garrett K. Keating (PI; CfA/SAO)

VLA (1cm) **ACA/ALMA (3mm)** **SMA (1mm)**

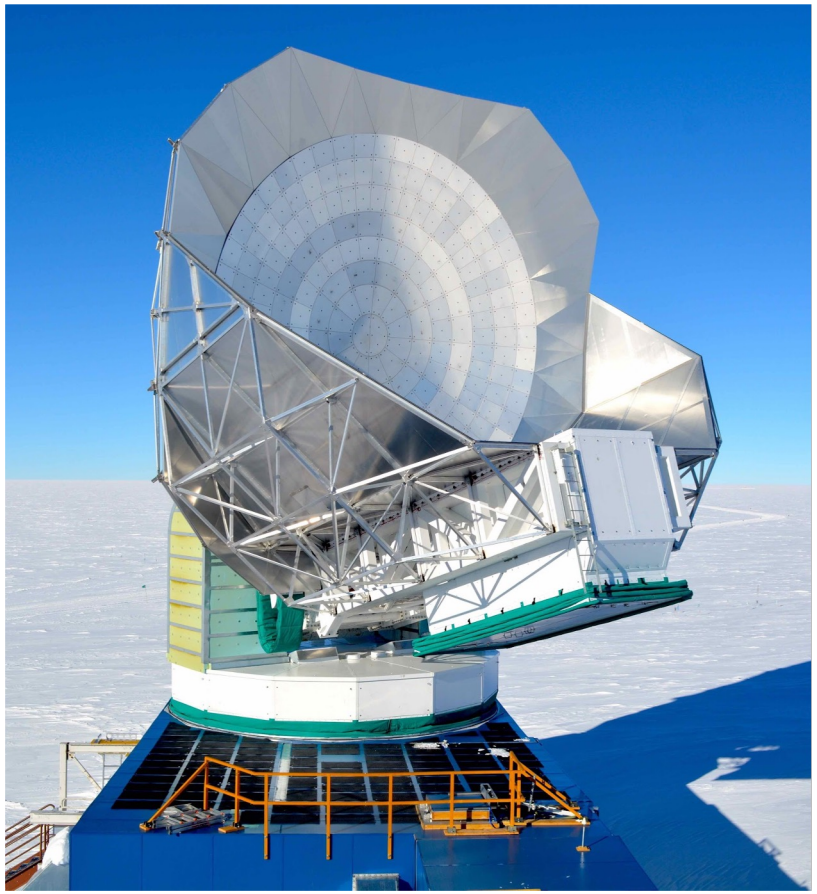




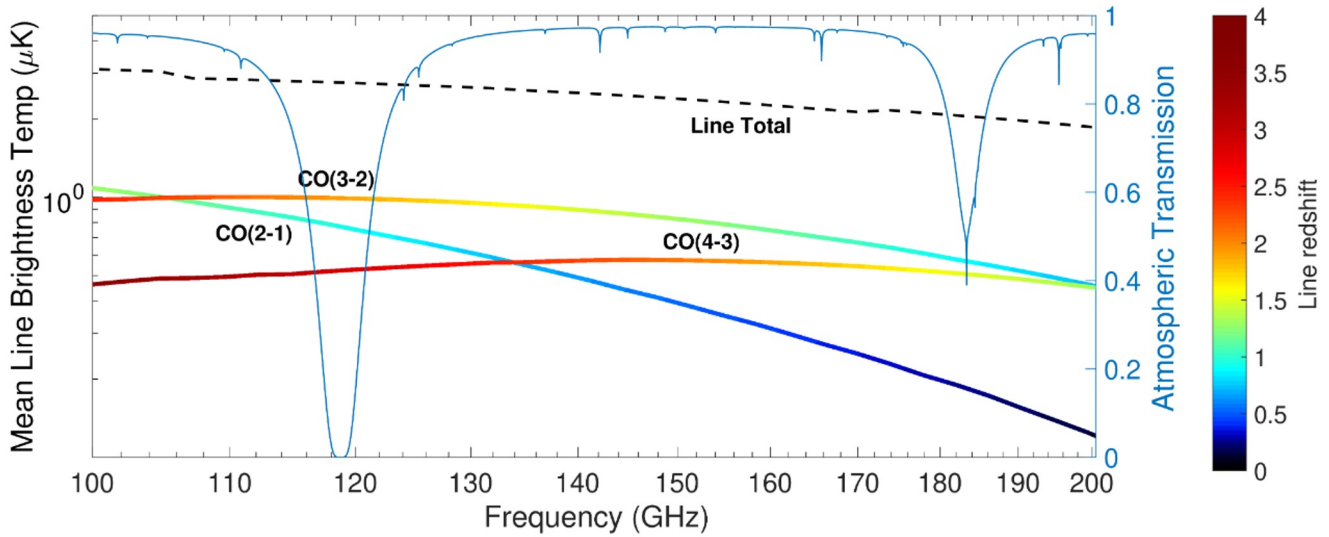
- Successful detection of aggregate CO @ 3mm with ALMA + ACA data
- Large-scale SMA program complete, analysis moving toward completion
- Looking at other archival datasets with VLA/ALMA

SPT-SLIM

The South Pole Telescope Shirokoff Line Intensity Mapper



A pathfinder to demonstrate the use of **on-chip millimeter-wave spectrometers** for LIM measurements.



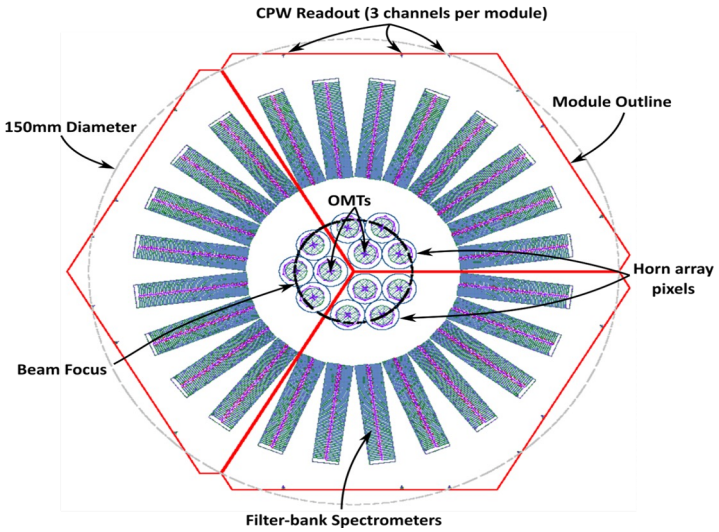
Targeting multiple CO lines from $0.5 < z < 2.5$:
12x spatial dual-pol pixels, each feeding two R=200 spectrometers from 120–180 GHz.

THE UNIVERSITY OF CHICAGO 1890 · Fermilab · SLAC · CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD · CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

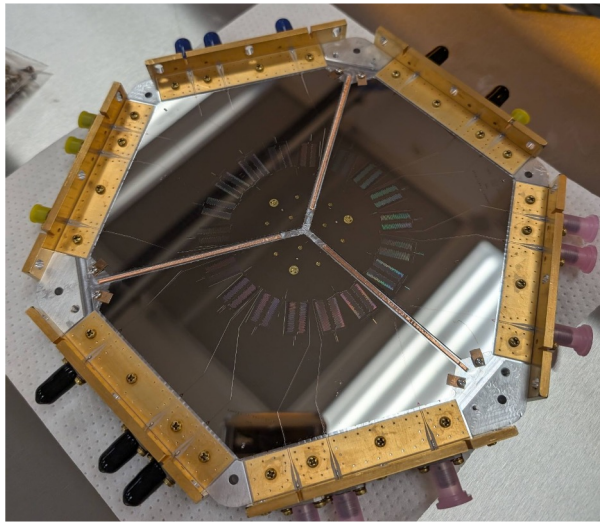
Argonne NATIONAL LABORATORY · McGill

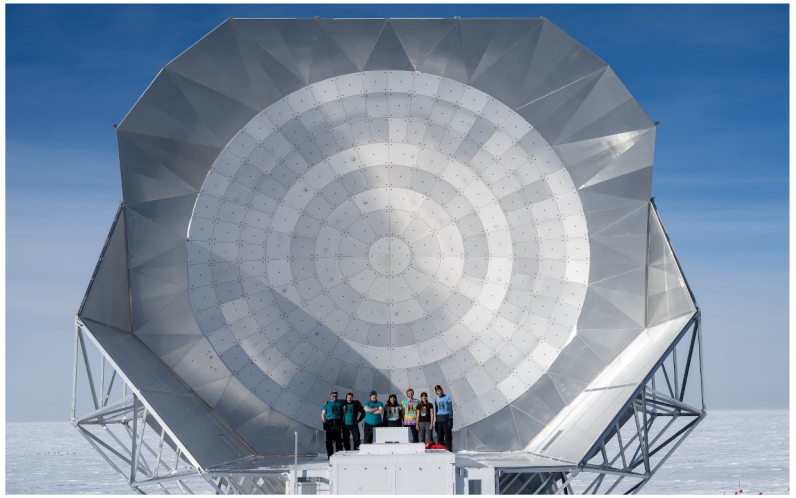
SPT-SLIM

The South Pole Telescope Shirokoff Line Intensity Mapper

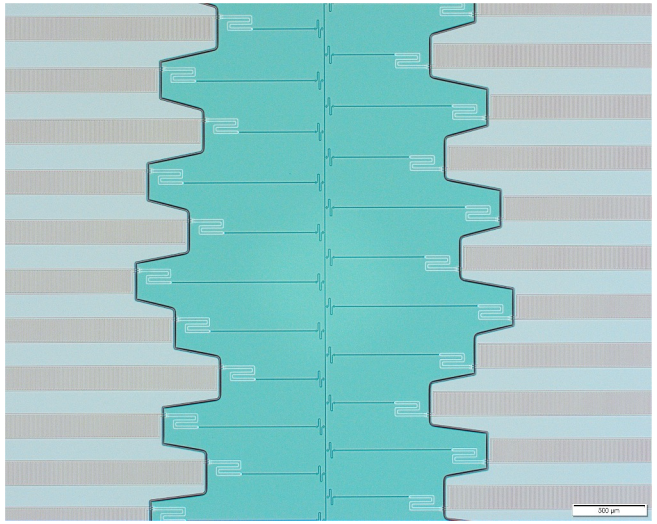


Deployed to the South Pole in **Jan. 2025,** planning for a second season.

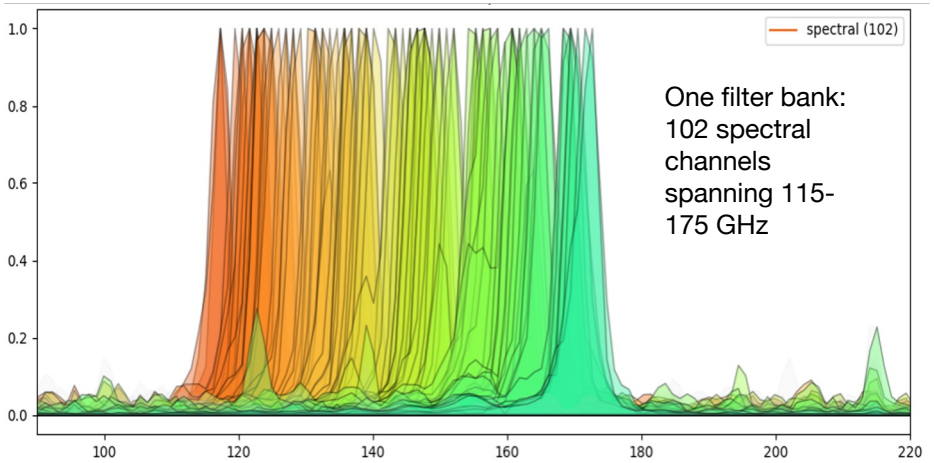


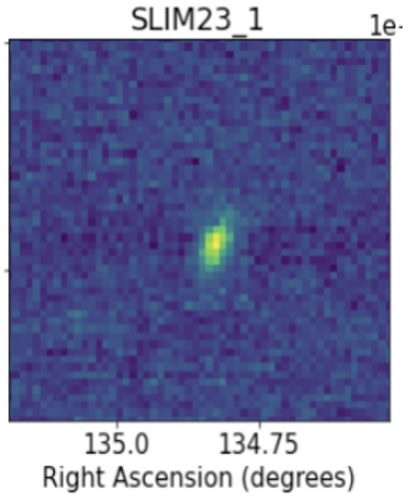


Analysis ongoing - see **Jessica Zebrowski**'s talk for more details!



Filter-bank spectrometer





C O M A P Pathfinder

Pathfinder frequency coverage: **26-34 GHz**

Sensitive to:

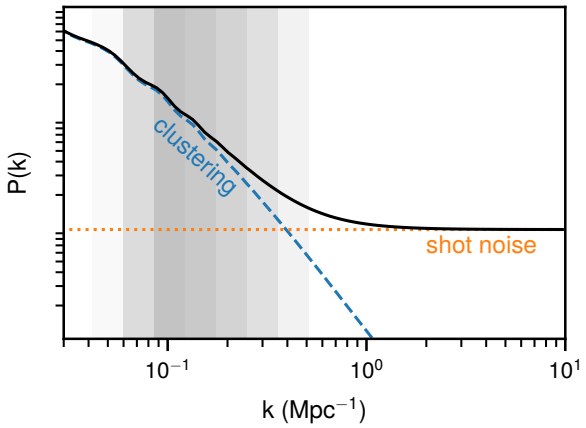
CO(1-0) at z = 2.4 – 3.4

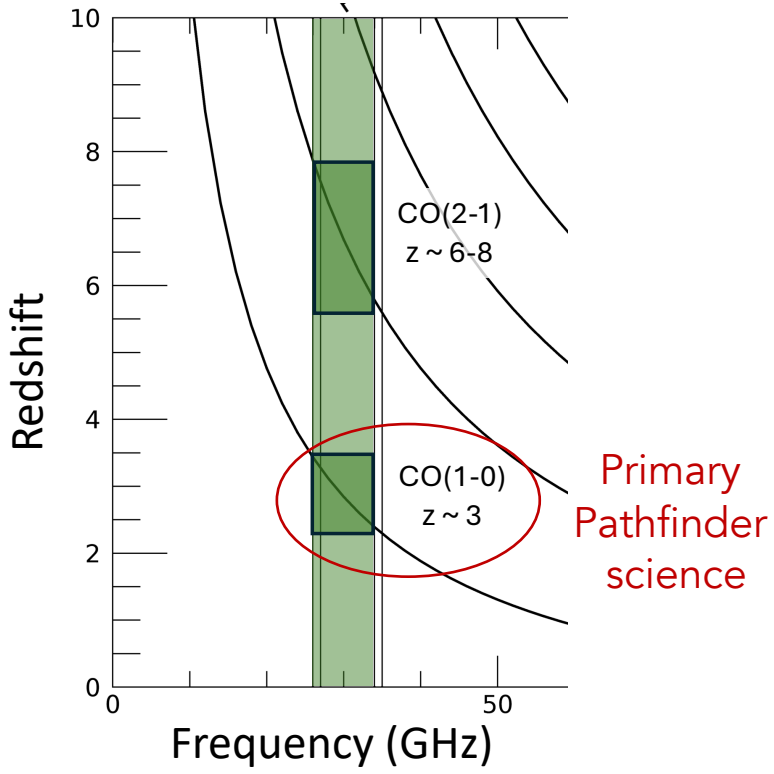
CO(2-1) at z = 6 - 8 (<10% of signal)

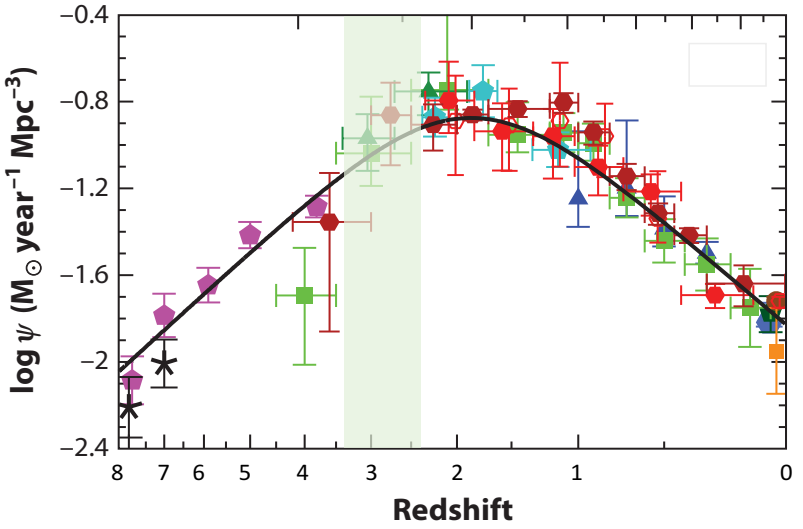
Primary goal: Detect CO power spectrum at z ~ 3

Sensitive to bright and faint galaxies

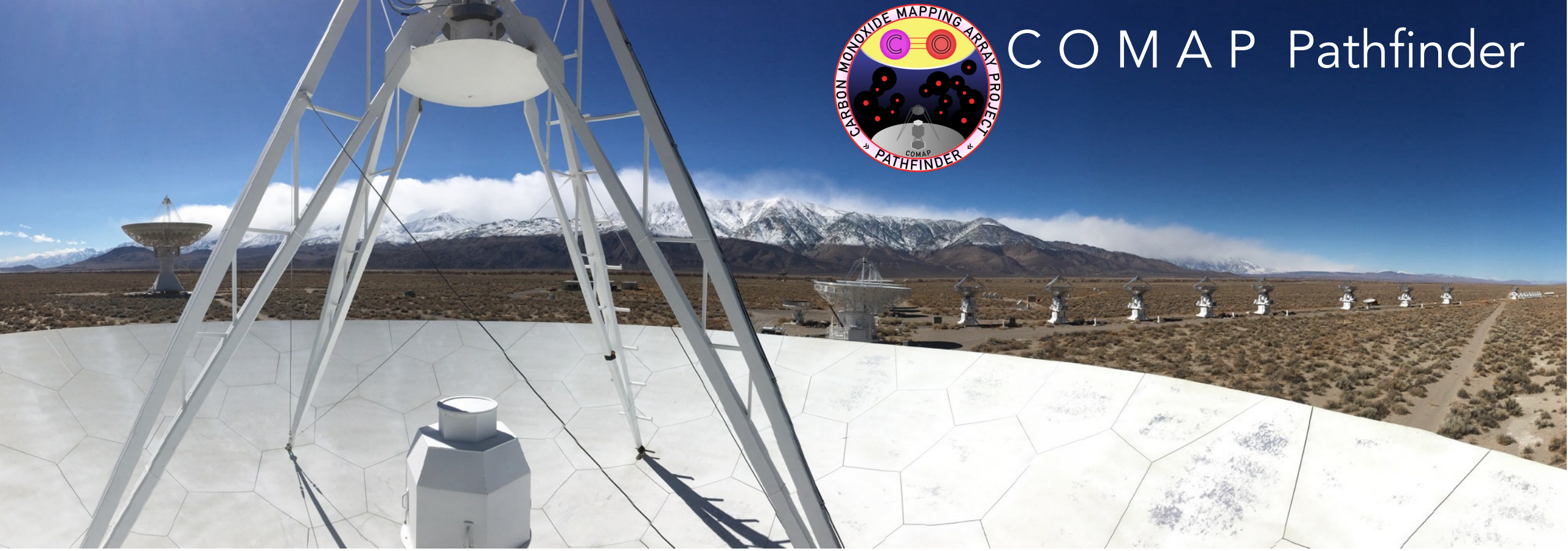
No assumptions about dust obscuration

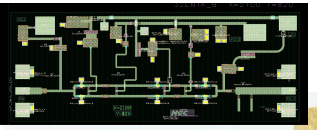


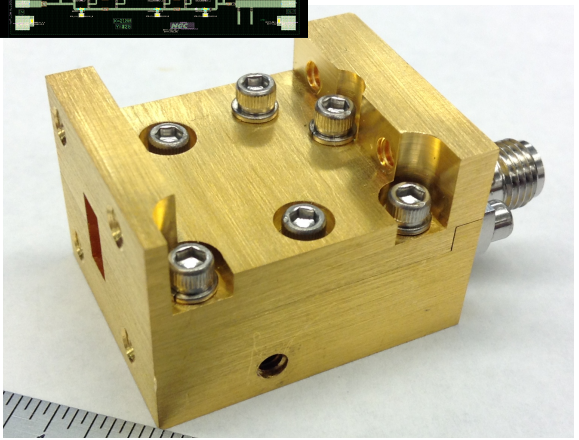


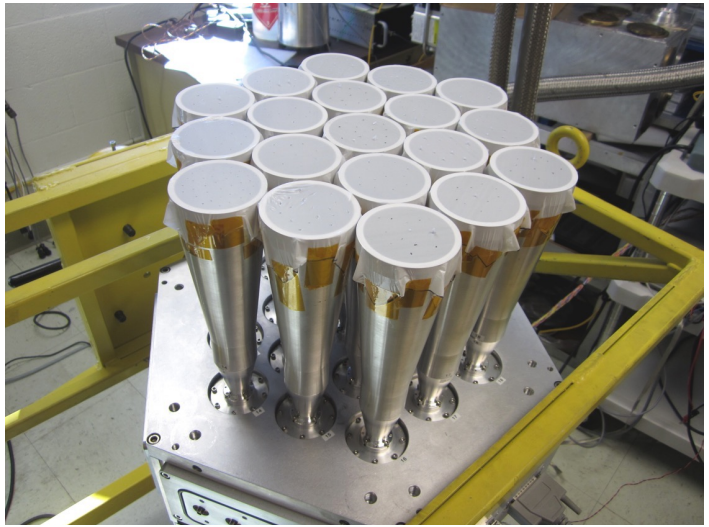


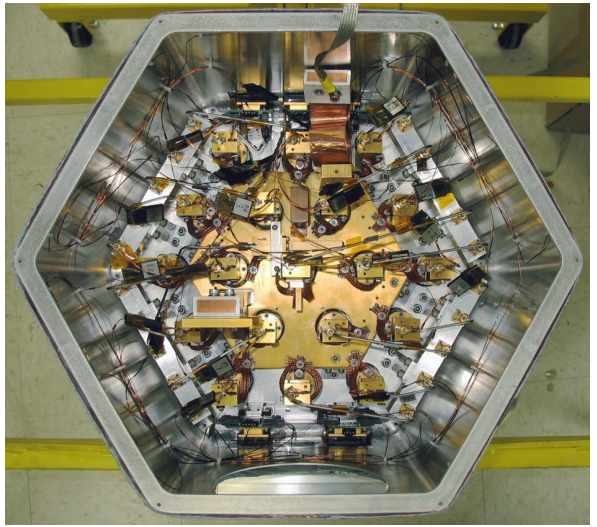
COMAP Pathfinder



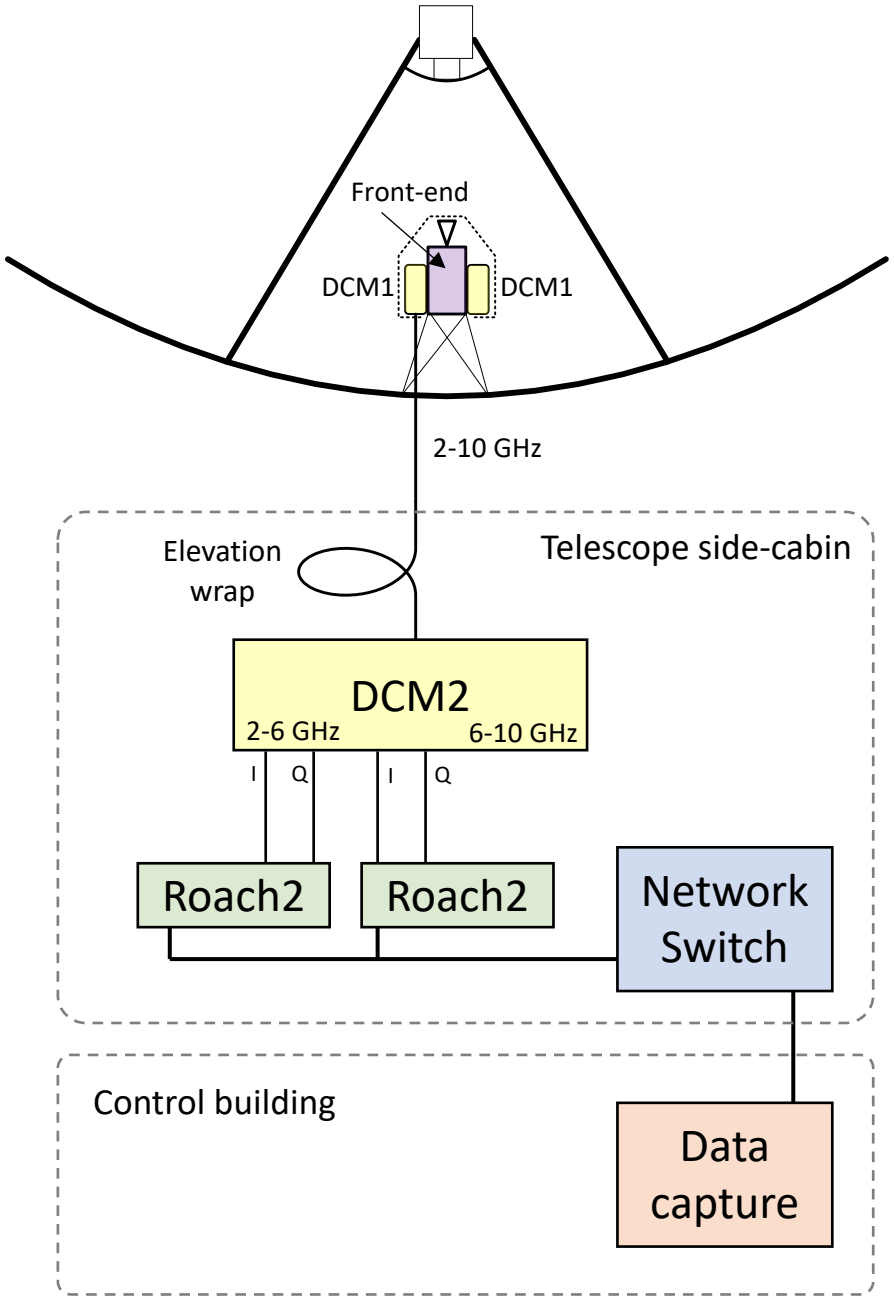




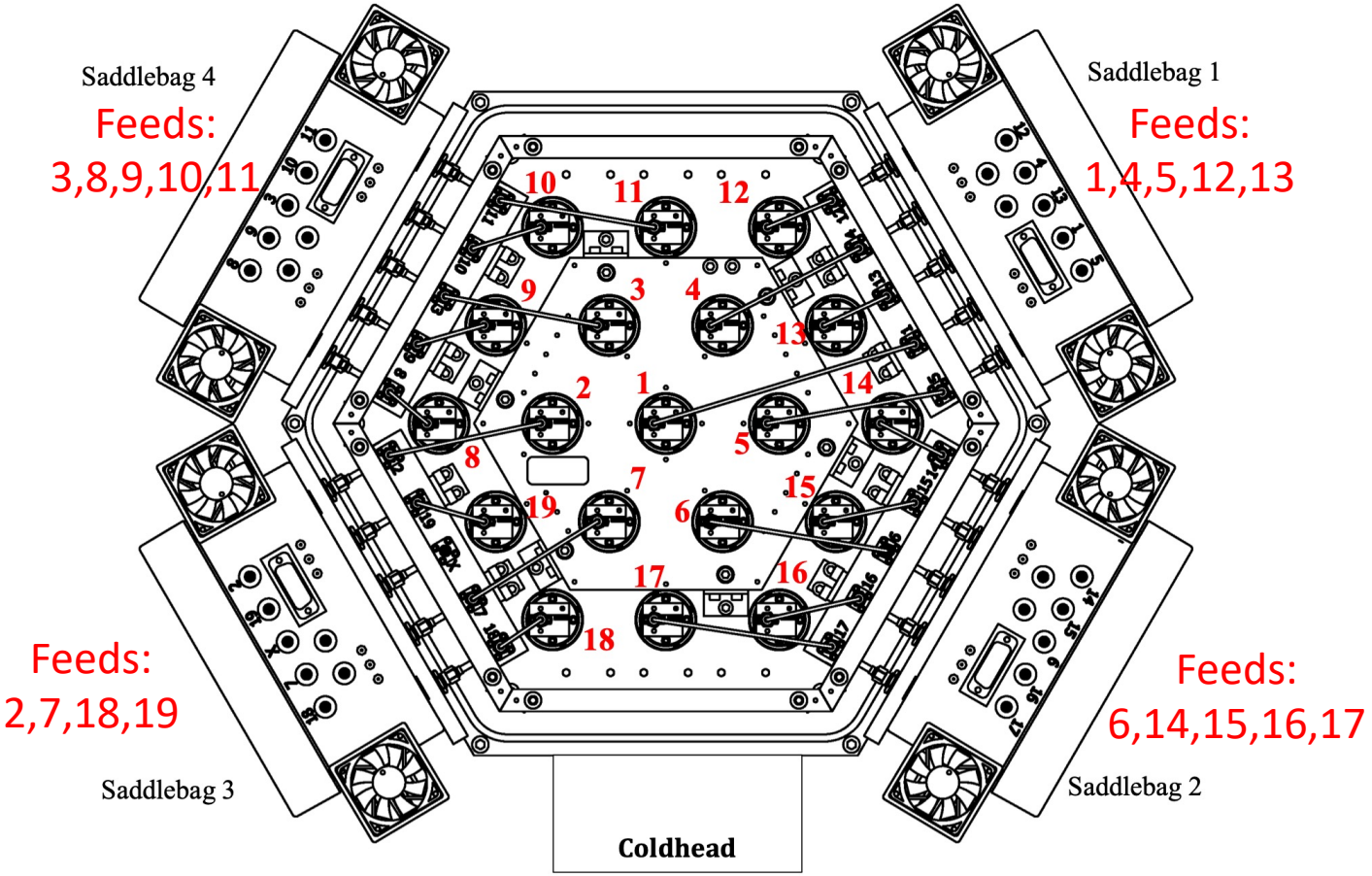




COMAP Pathfinder



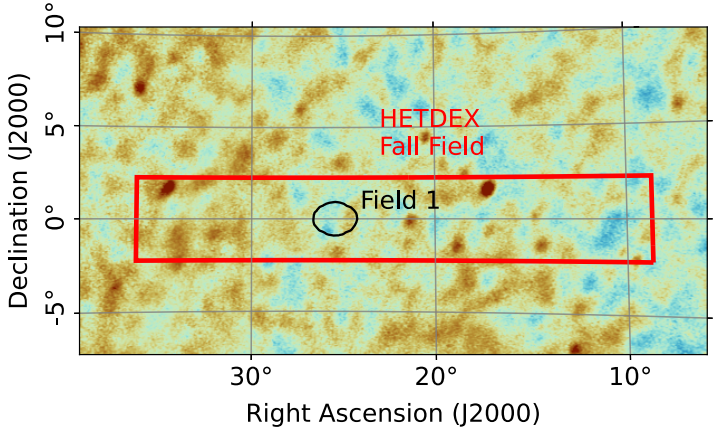
Receiver chain for each feed is independent, except for shared LO within each "saddlebag" (DCM1)

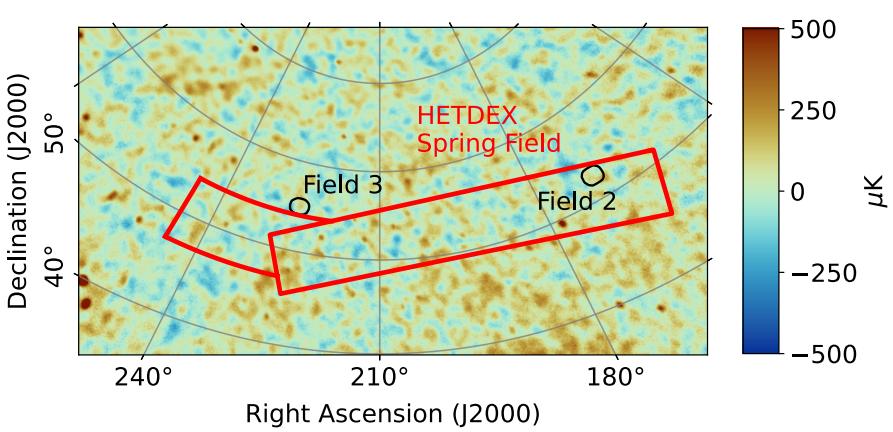


COMAP Pathfinder

Pathfinder Survey fields

Foss+2021





Pathfinder Survey:

Multi-year observing campaign

Three fields: each ~4 sq. deg.

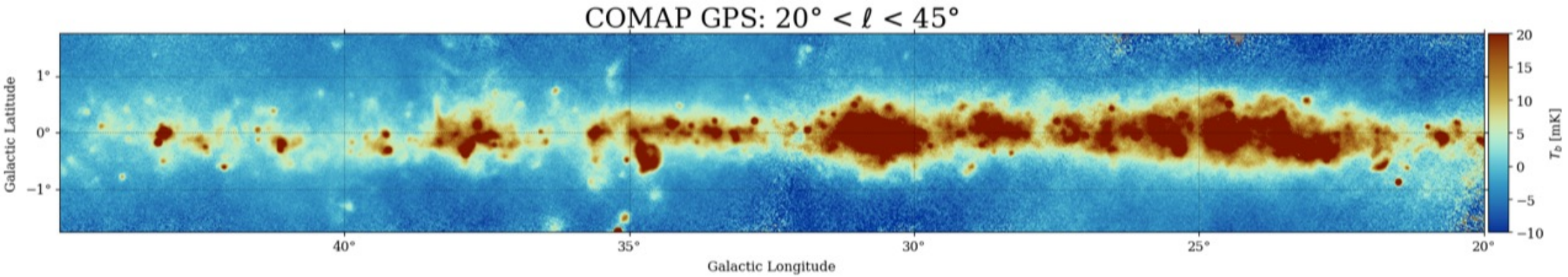
-Maximize observing efficiency

-Overlap with HETDEX

Observed between 35-65 deg. elevation

Remainder on point sources & Galactic fields

Fields overlap with HETDEX LAE survey z = 1-3

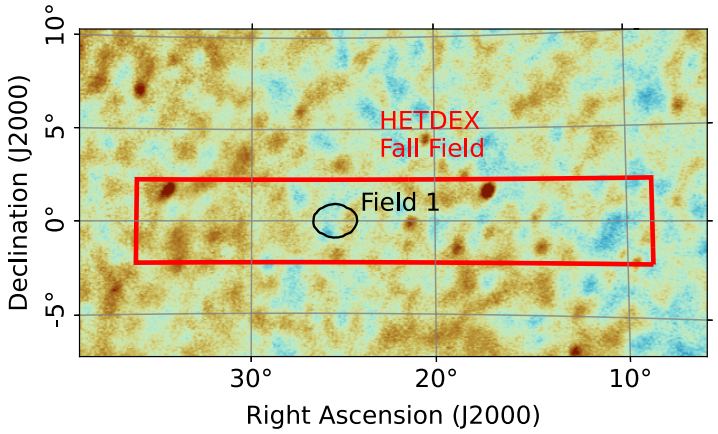


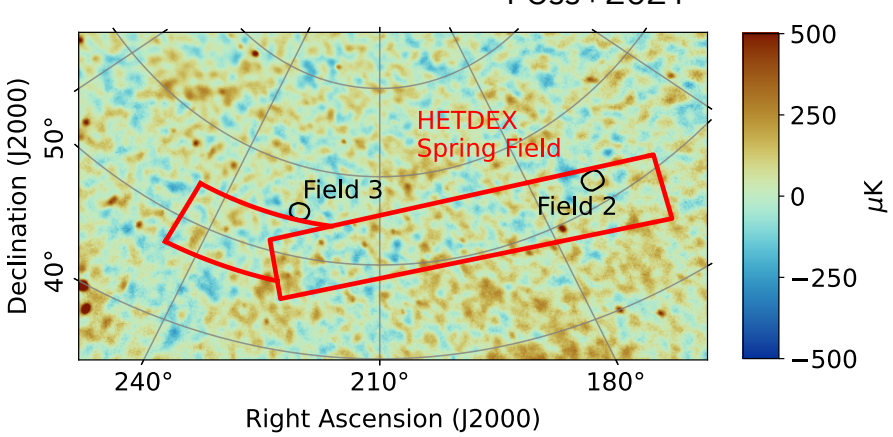
Credit: Stuart Harper, U. Manchester

COMAP Pathfinder

Pathfinder Survey fields

Foss+2021





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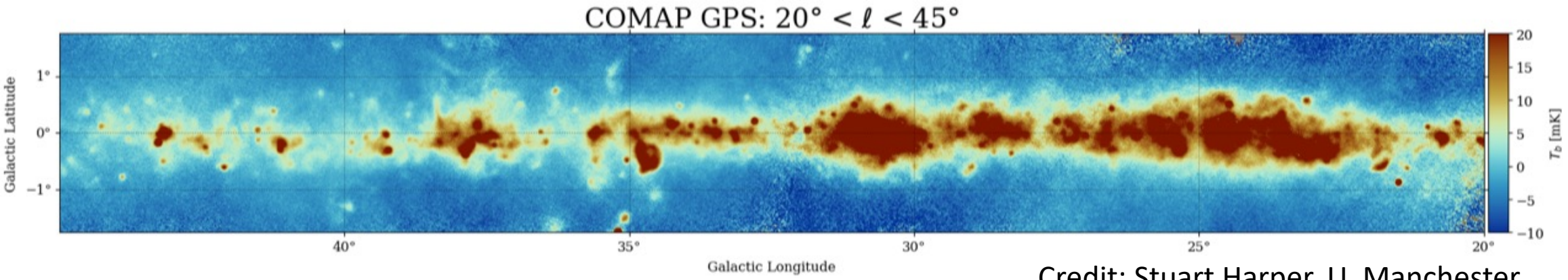
Remainder on point sources & Galactic fields

Delaney Dunne, Caltech

Three-Dimensional Stacking as a LIM Statistic

Wednesday, 16:00



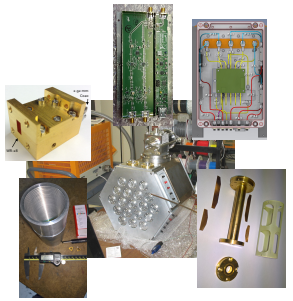
Credit: Stuart Harper, U. Manchester

COMAP Pathfinder

2019-2022
Pathfinder Observing Begins

2022-2025
Operations & Survey Science

2015-2019
Pathfinder Construction & Commissioning



COMAP S1 + S2 results out!

Pathfinder survey

Season 1

Season 2

Season 3

2015

2019

2024

2027

COMAP Pathfinder

Observed CO Power spectrum = (Clustering amplitude x Underlying matter power spectrum) + Shot noise

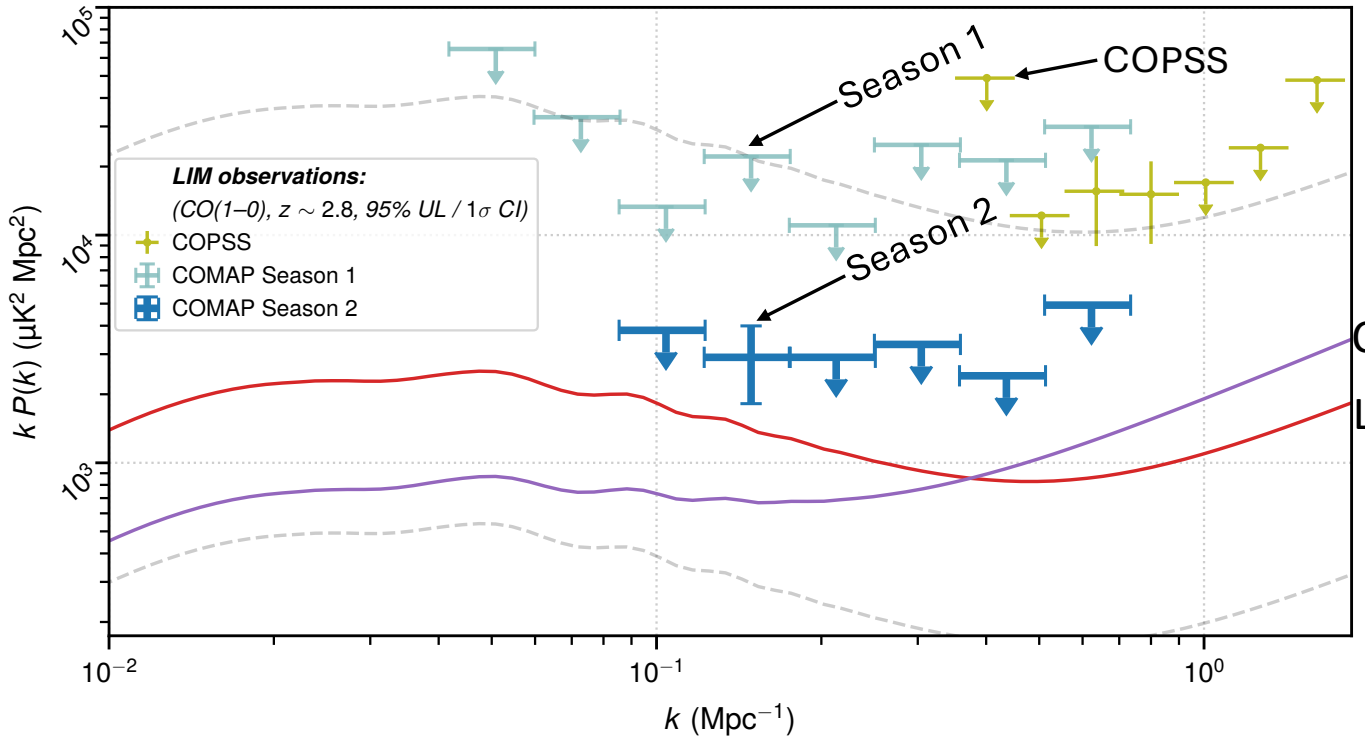
$$P_{\rm CO}(k) = A_{\rm clust} P_m + P_{\rm shot}$$

COMAP Pathfinder

Observed CO Power spectrum = (Clustering amplitude × Underlying matter power spectrum) + Shot noise

$$P_{\rm CO}(k) = A_{\rm clust} P_m + P_{\rm shot}$$

CO(1-0) Power Spectrum at z~3



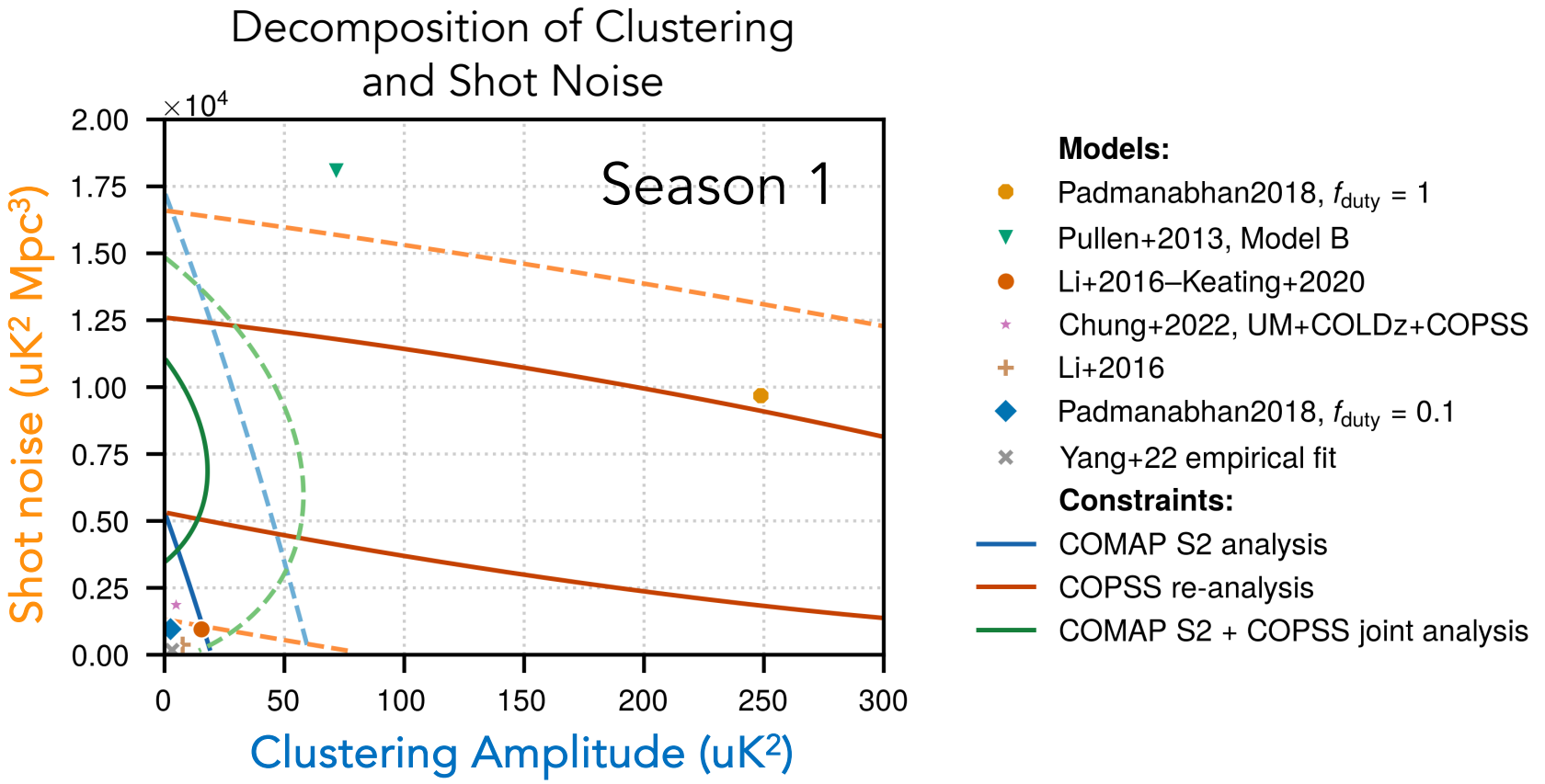
Chung+2022

Li+2016-Keating+2020

COMAP Pathfinder

Observed CO Power spectrum = (Clustering amplitude × Underlying matter power spectrum) + Shot noise

$$P_{\rm CO}(k) = A_{\rm clust} P_m + P_{\rm shot}$$



COMAP Pathfinder

Observed CO Power spectrum = (Clustering amplitude × Underlying matter power spectrum) + Shot noise

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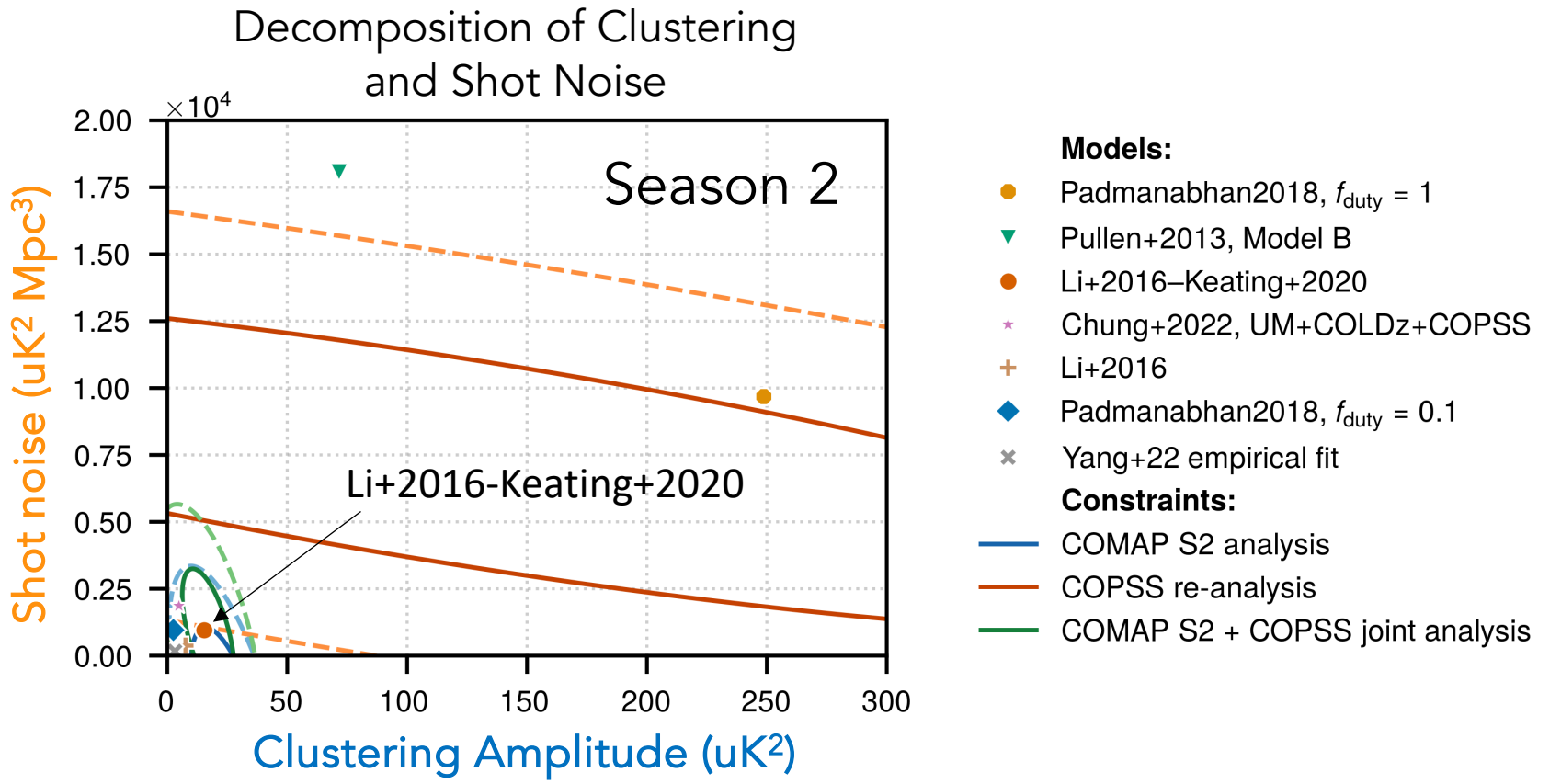
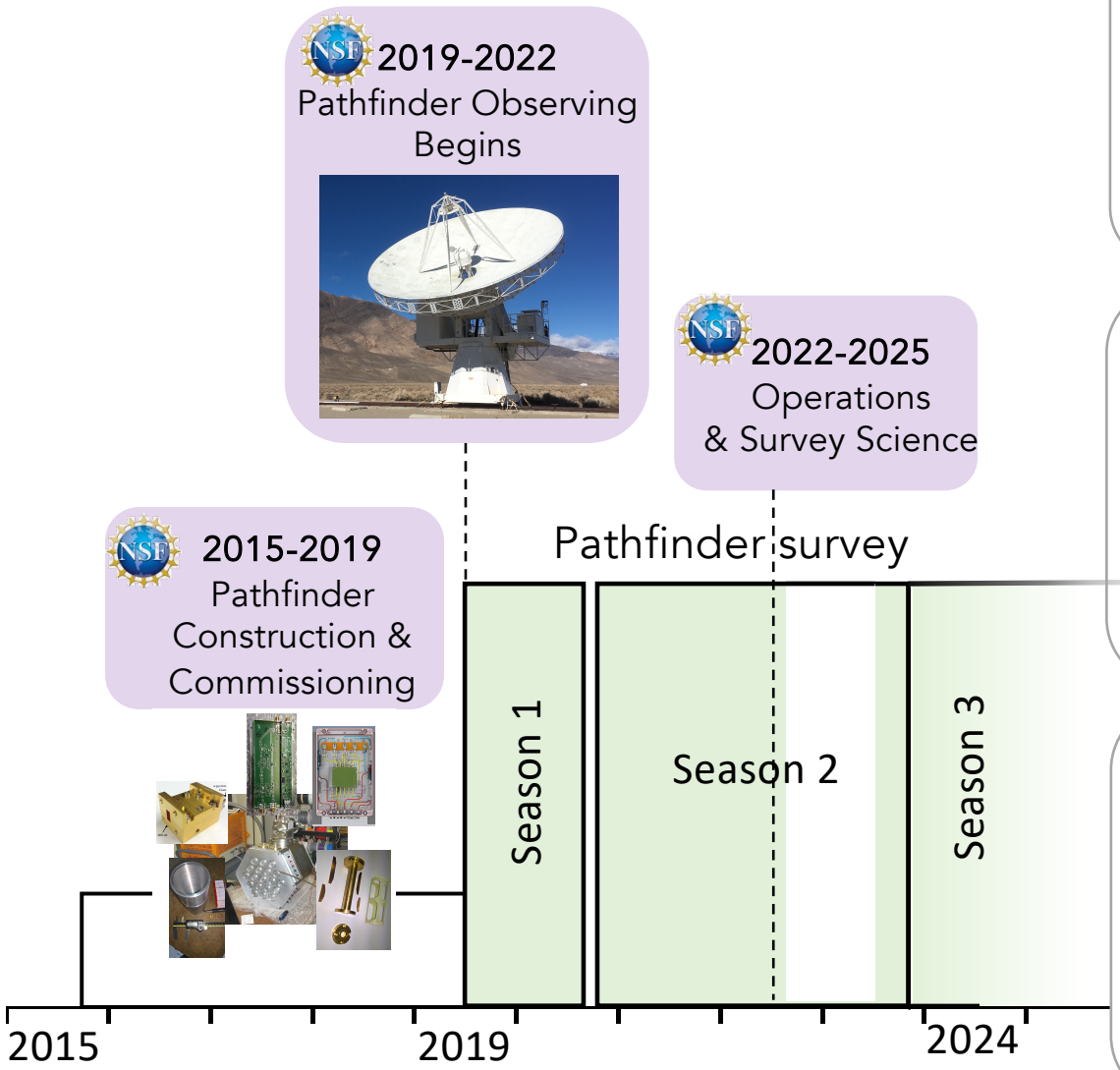


COMAP S1 + S2 results papers



Jonas Lunde, University of Oslo
COMAP Pathfinder – Season 2 results
I. *Improved data selection and processing*

arXiv: 2406.07510

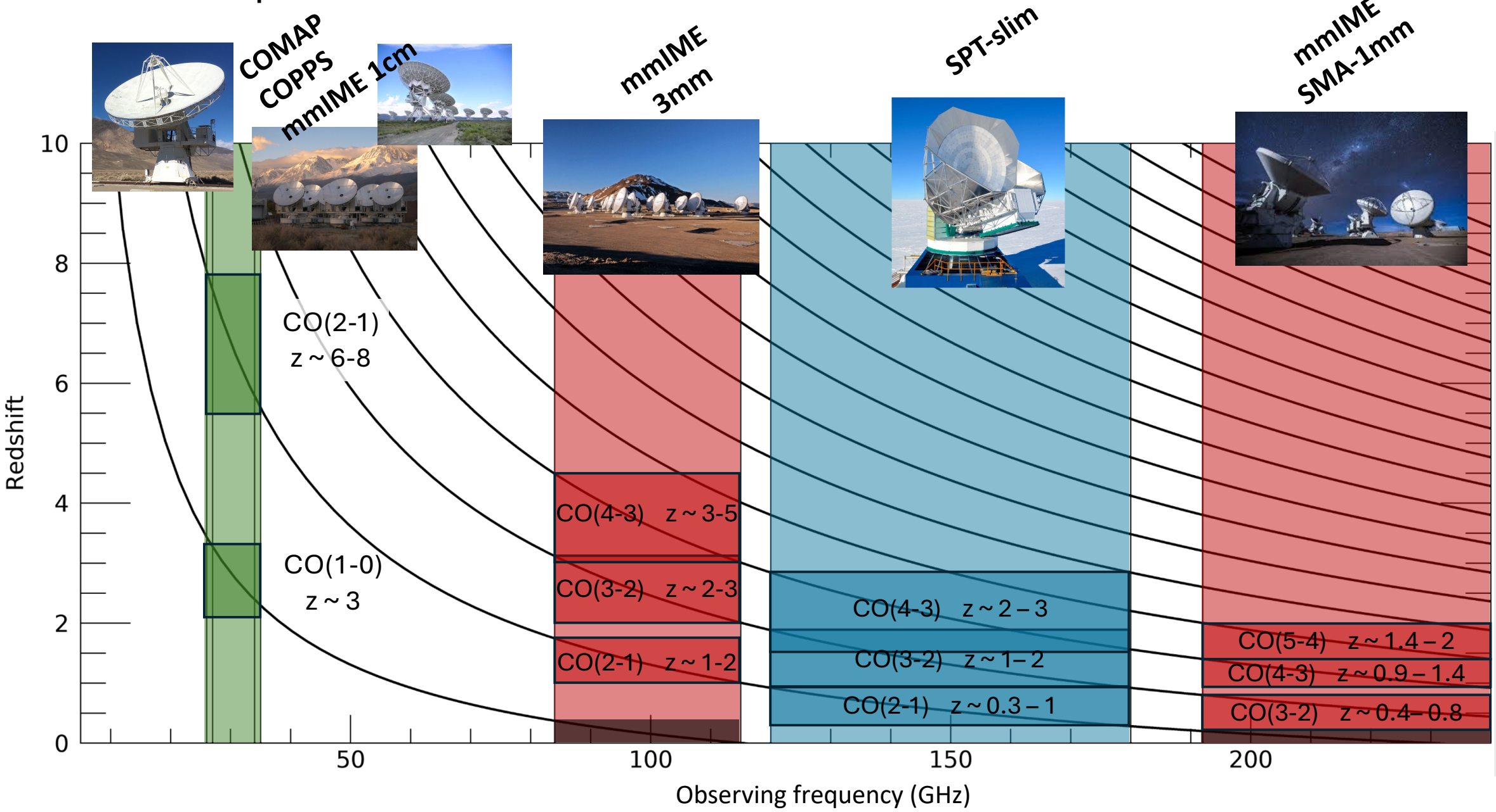
Nils-Ole Stutzer, University of Oslo
COMAP Pathfinder – Season 2 results
II. *Updated constraints on the CO(1-0) power spectrum*

arXiv: 2406.07511

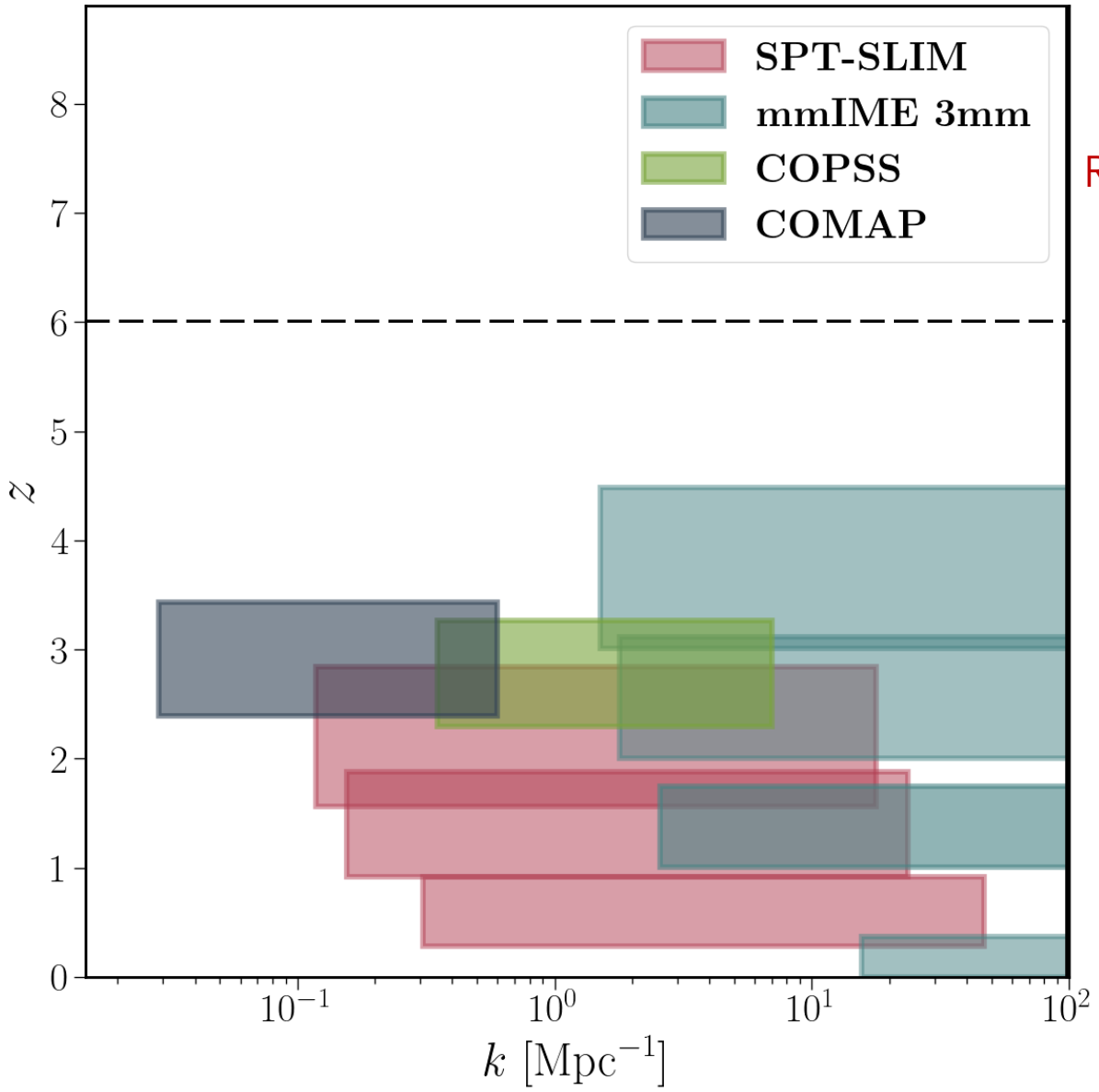
Dongwoo Chung, Cornell University
COMAP Pathfinder – Season 2 results
III. *Implications for cosmic molecular gas content at 'Cosmic Half-past Eleven'*

arXiv: 2406.07512

CO LIM Experiments



CO LIM Experiments



Epoch of Reionization

Epoch of Galaxy Assembly

Credit: Delaney Dunne & José Luis Bernal

The Future of CO LIM

<u>Short term:</u>

Independent observing strategies

Detections of CO LIM signal

- auto-correlation
- cross-correlation with
    - galaxy surveys

Science outputs: Constraints on:

$\langle T_{CO} b \rangle^2$	Mean CO temperature
P_{shot}	Shot noise power
$L_{CO}(M_h)$	CO luminosity/Halo mass relation
Φ_{CO}	CO luminosity function
ρ_{H_2}	Molecular gas density

The Future of CO LIM

Medium term:

Characterization of galaxy populations

Evolution across redshift

Extension to z>3 and into EoR

Cross-correlation

-multi-transition CO LIM

-other LIM tracers

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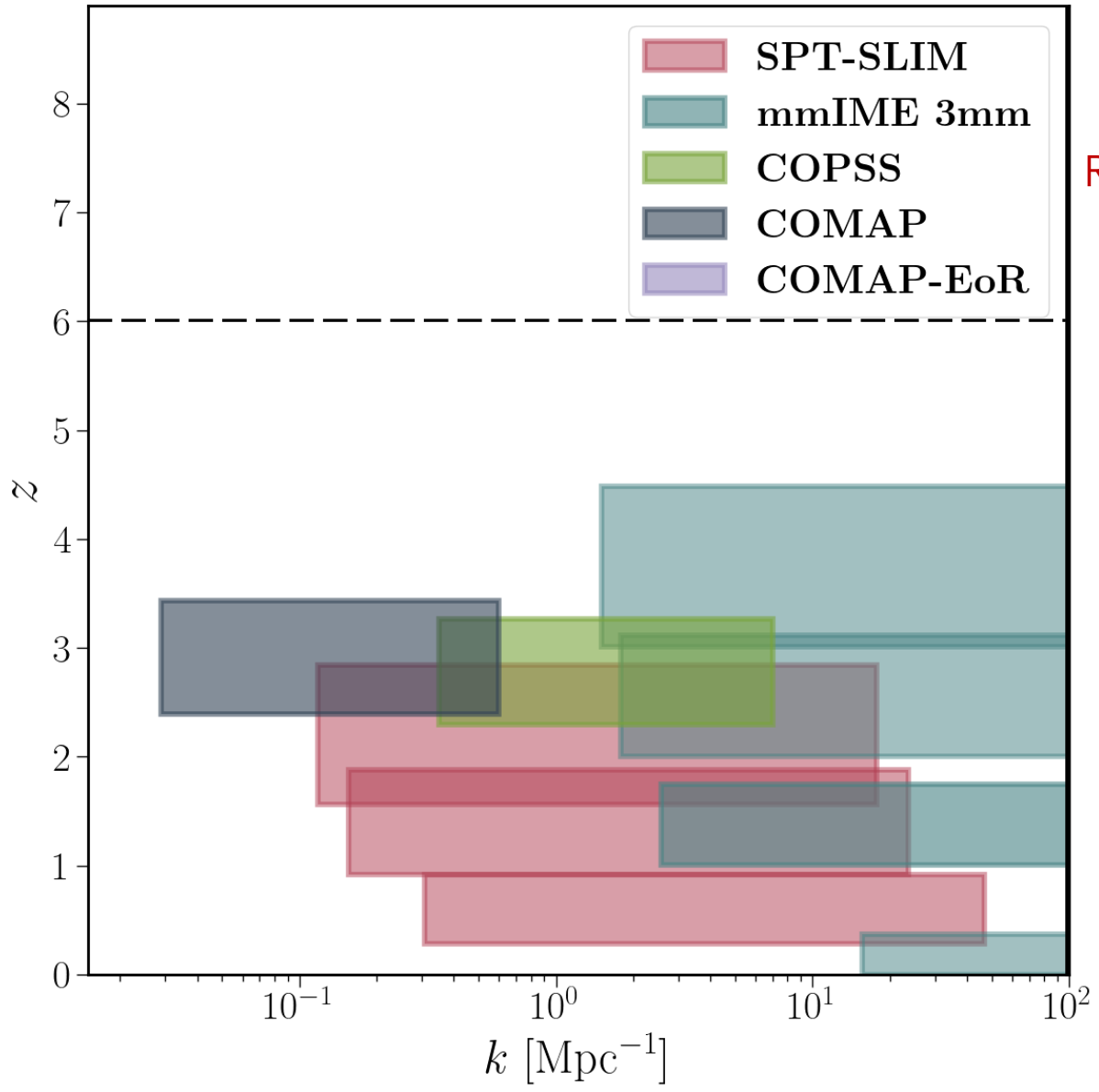

Epoch of Reionization

Epoch of Galaxy Assembly

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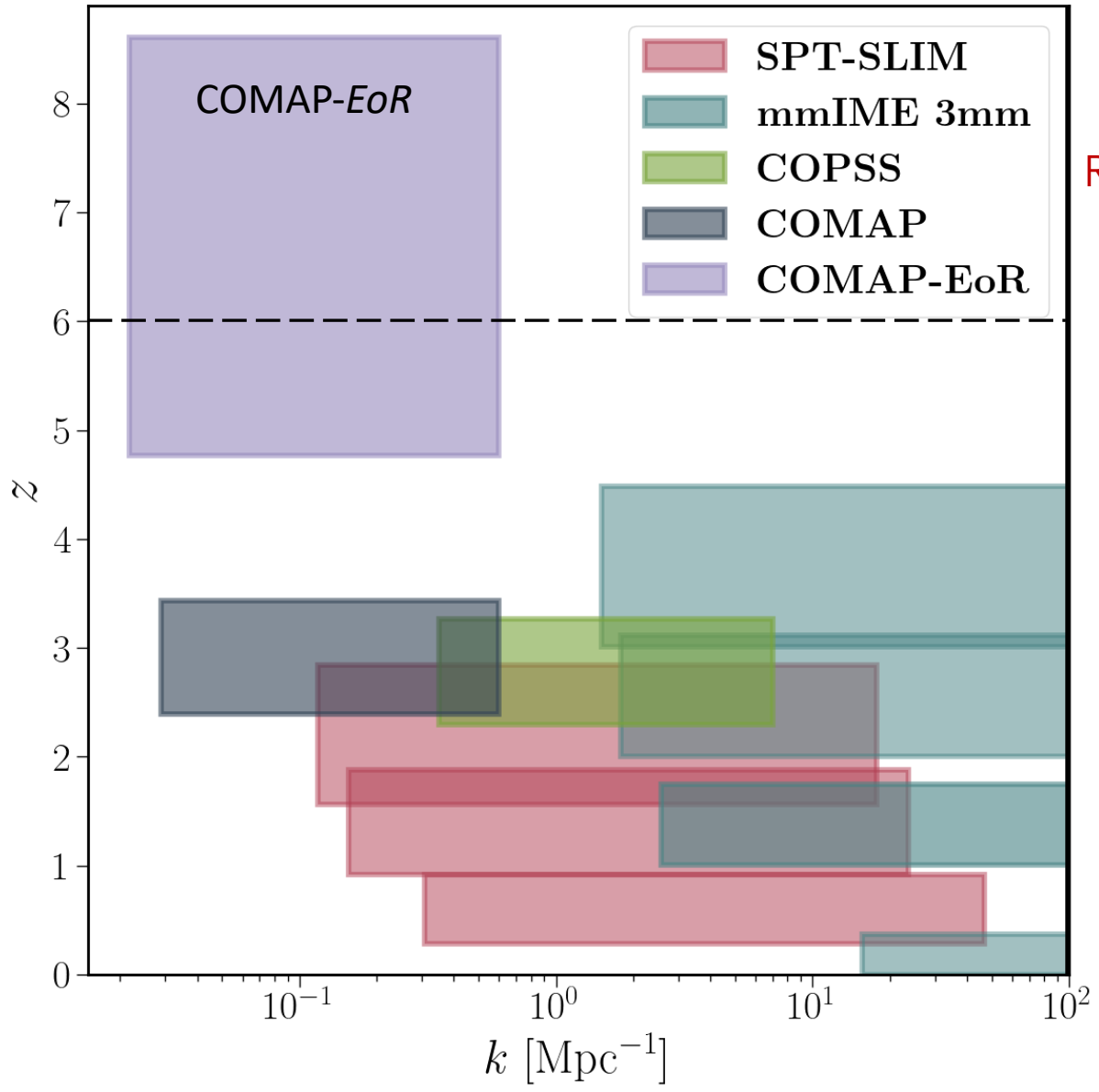
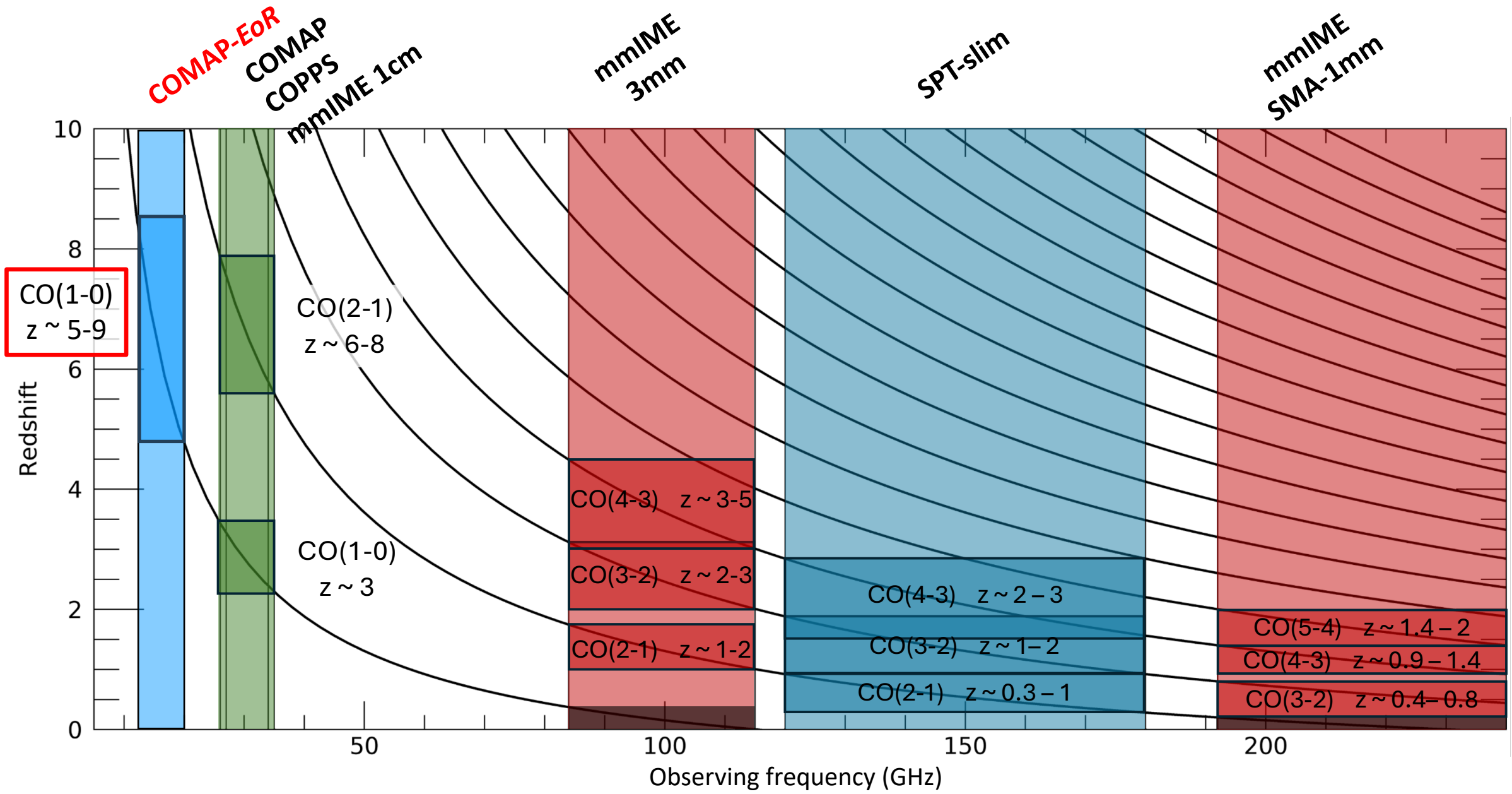


Credit: Delaney Dunne & José Luis Bernal

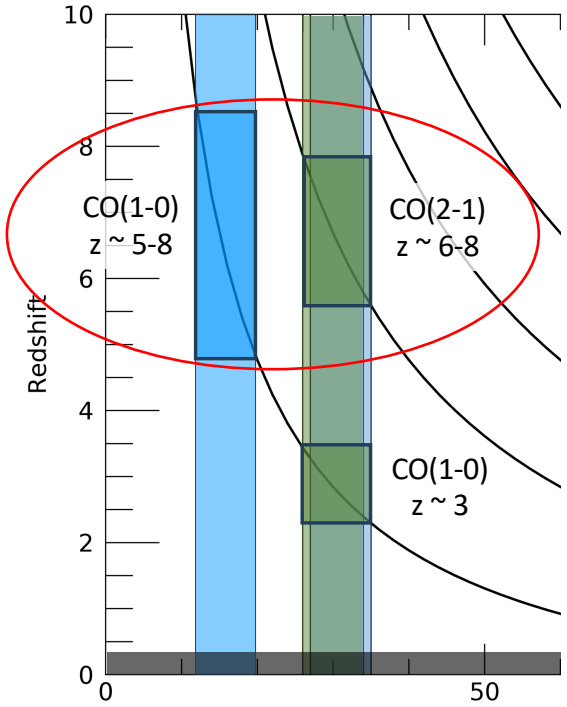
CO LIM Experiments

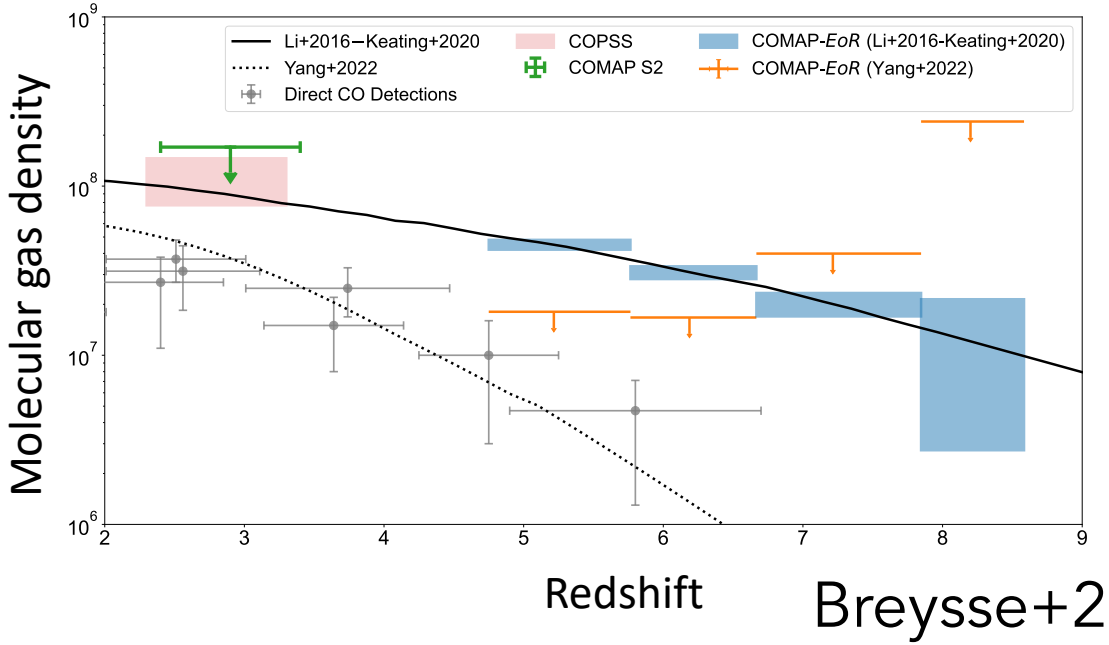


COMAP - *EoR*

CO(1-0)
auto-correlation
at z = 5 – 9

CO(1-0) x CO(2-1)
cross-correlation
at z = 6 - 8





Breysse+22

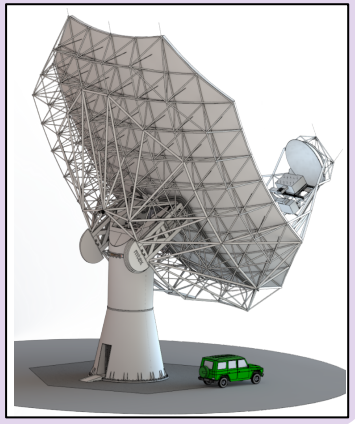
COMAP-*EoR*

2015-2019
Pathfinder Construction & Commissioning

2019-2022
Pathfinder Observing Begins

2022-2025
Operations & Survey Science

2027-2028
ngVLA Antenna Available



Pathfinder survey

Season 1

Season 2

Season 3

2015

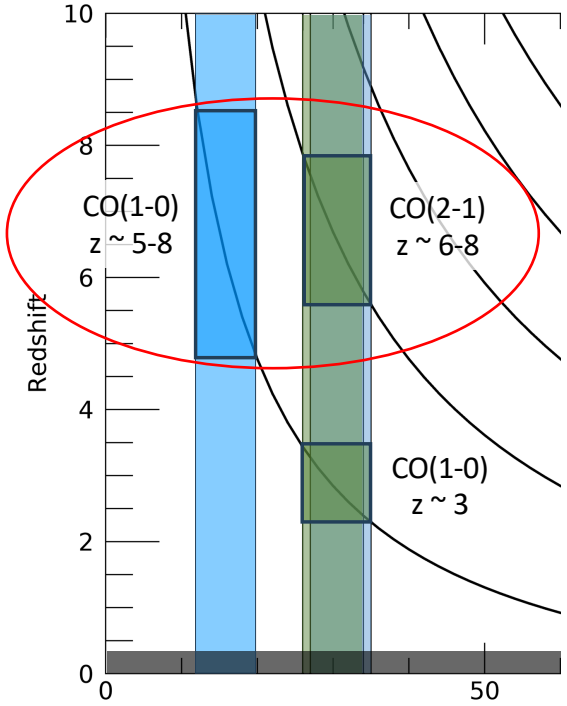
2019

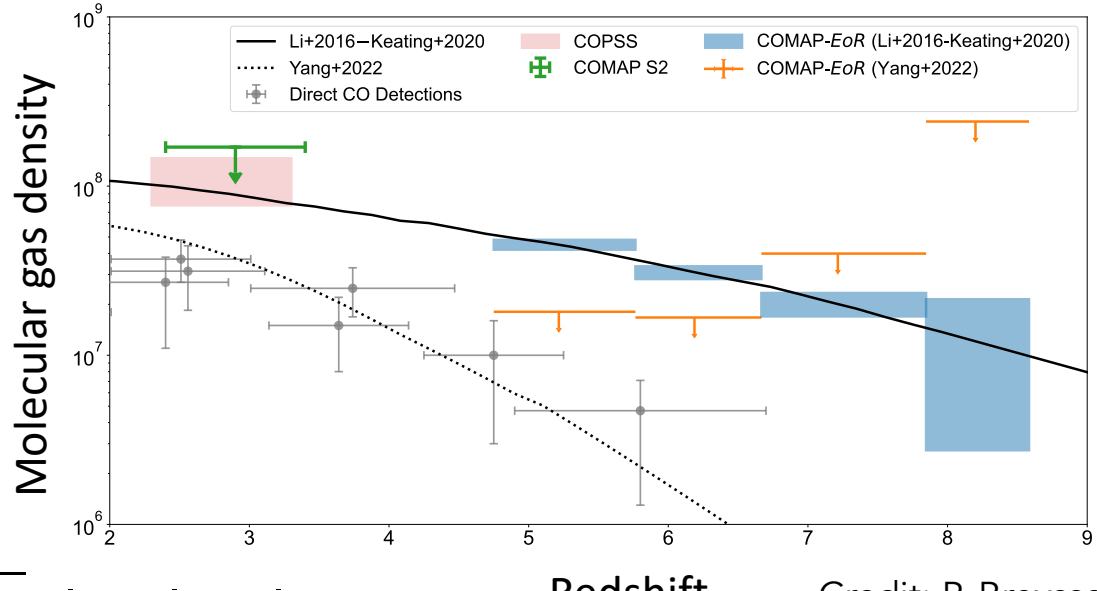
2024

2027

CO(1-0) auto-correlation at z = 5 – 9

CO(1-0) x CO(2-1) cross-correlation at z = 6 - 8





Credit: P. Breysse

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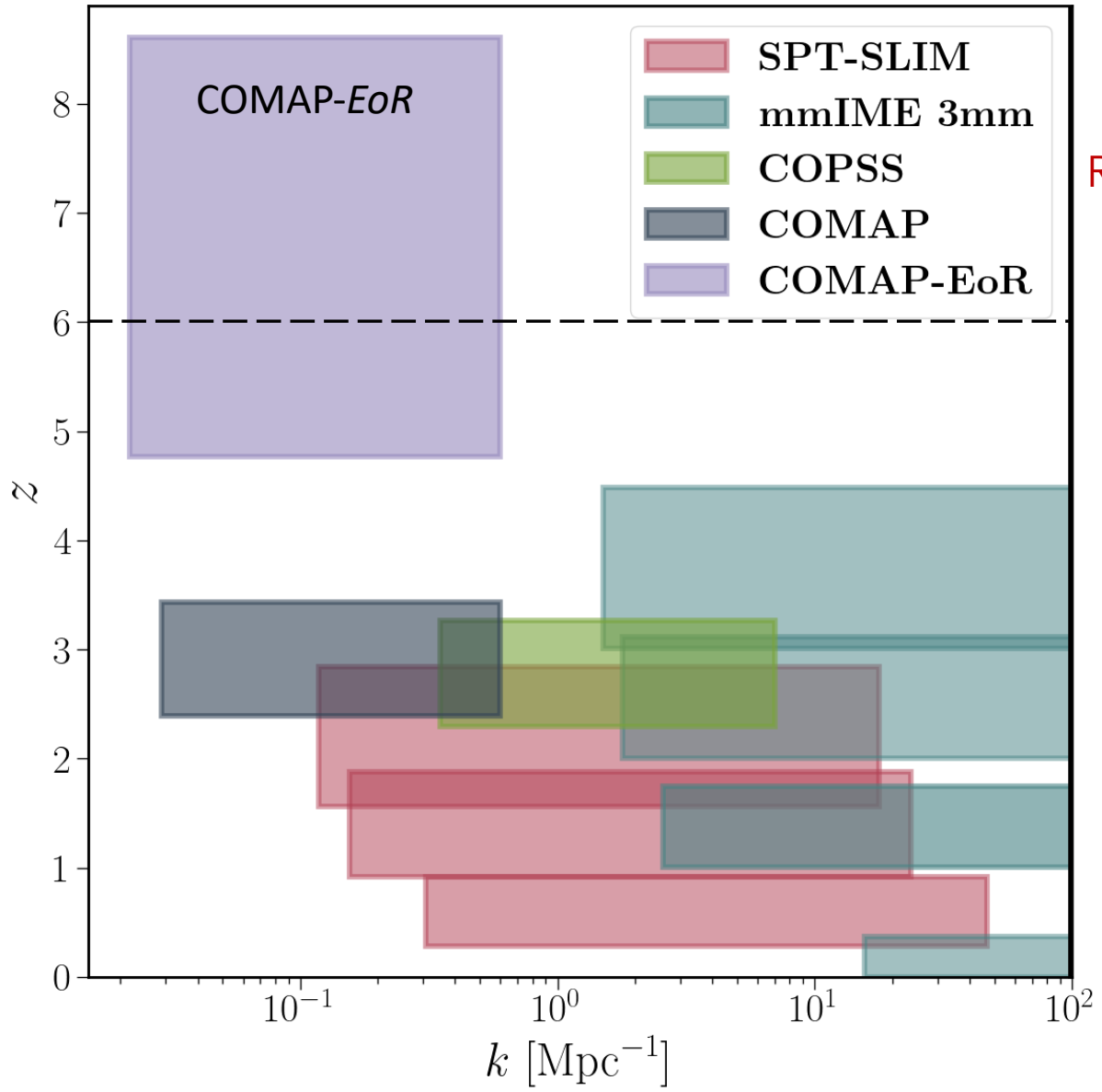
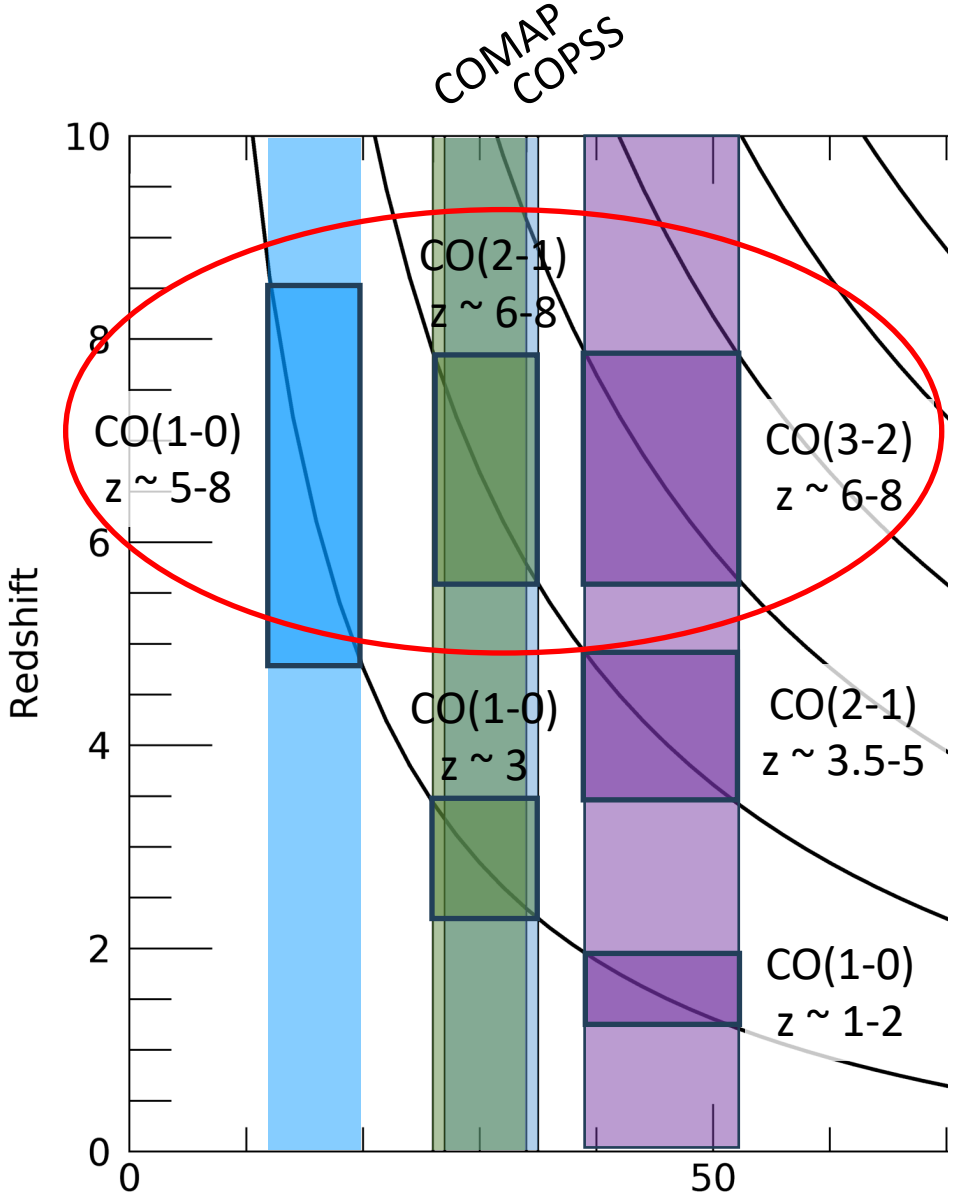


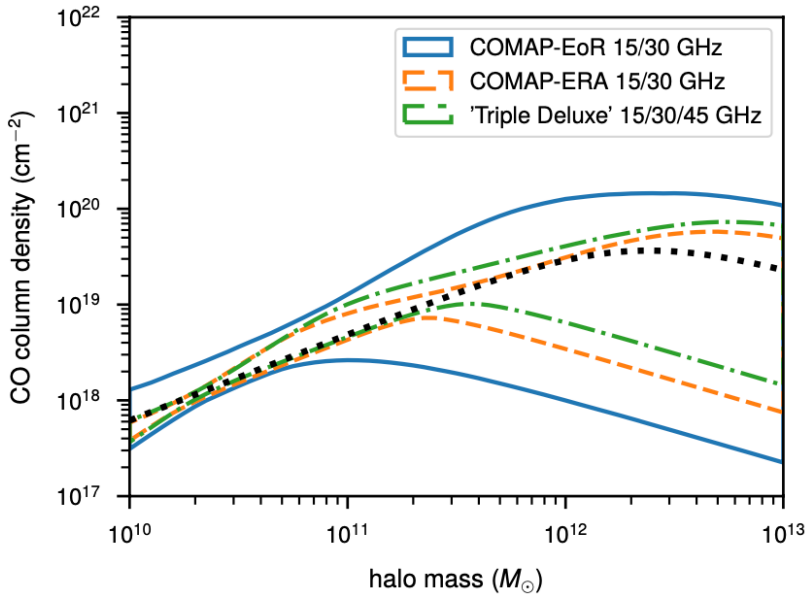
Epoch of Reionization

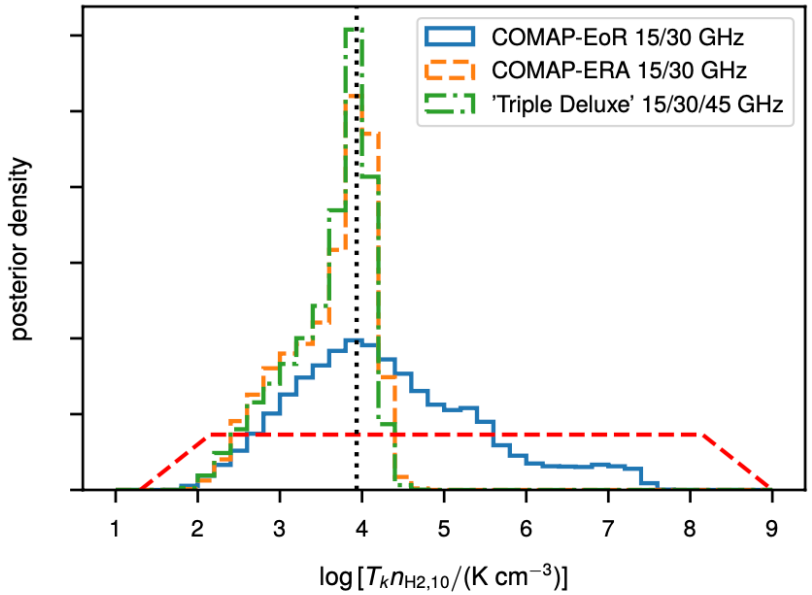
Epoch of Galaxy Assembly

Credit: Delaney Dunne & José Luis Bernal



"Triple-deluxe"
CO(1-0) x CO(2-1) x CO(3-2)





Chung 2023

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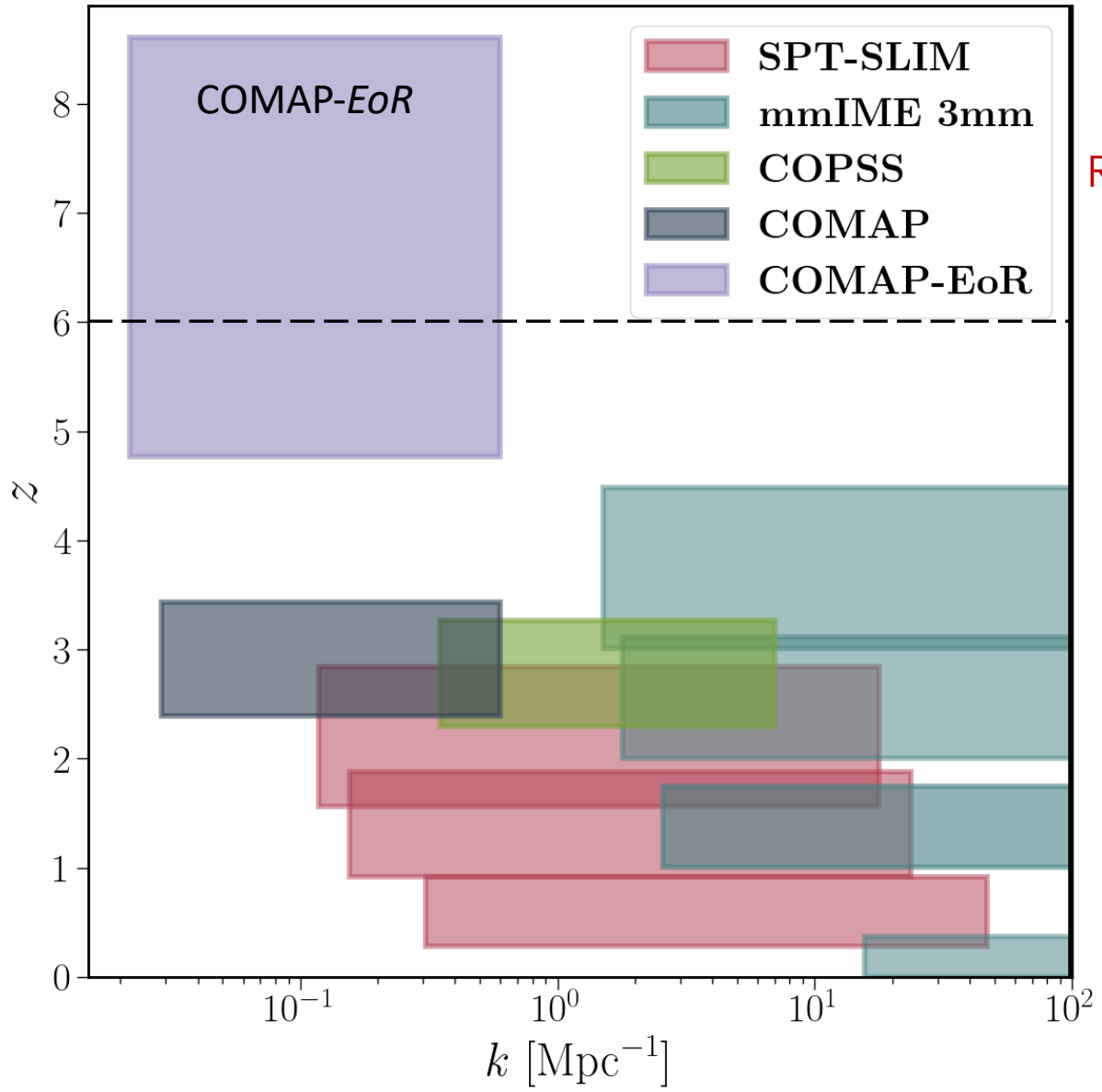

Epoch of Reionization

Epoch of Galaxy Assembly

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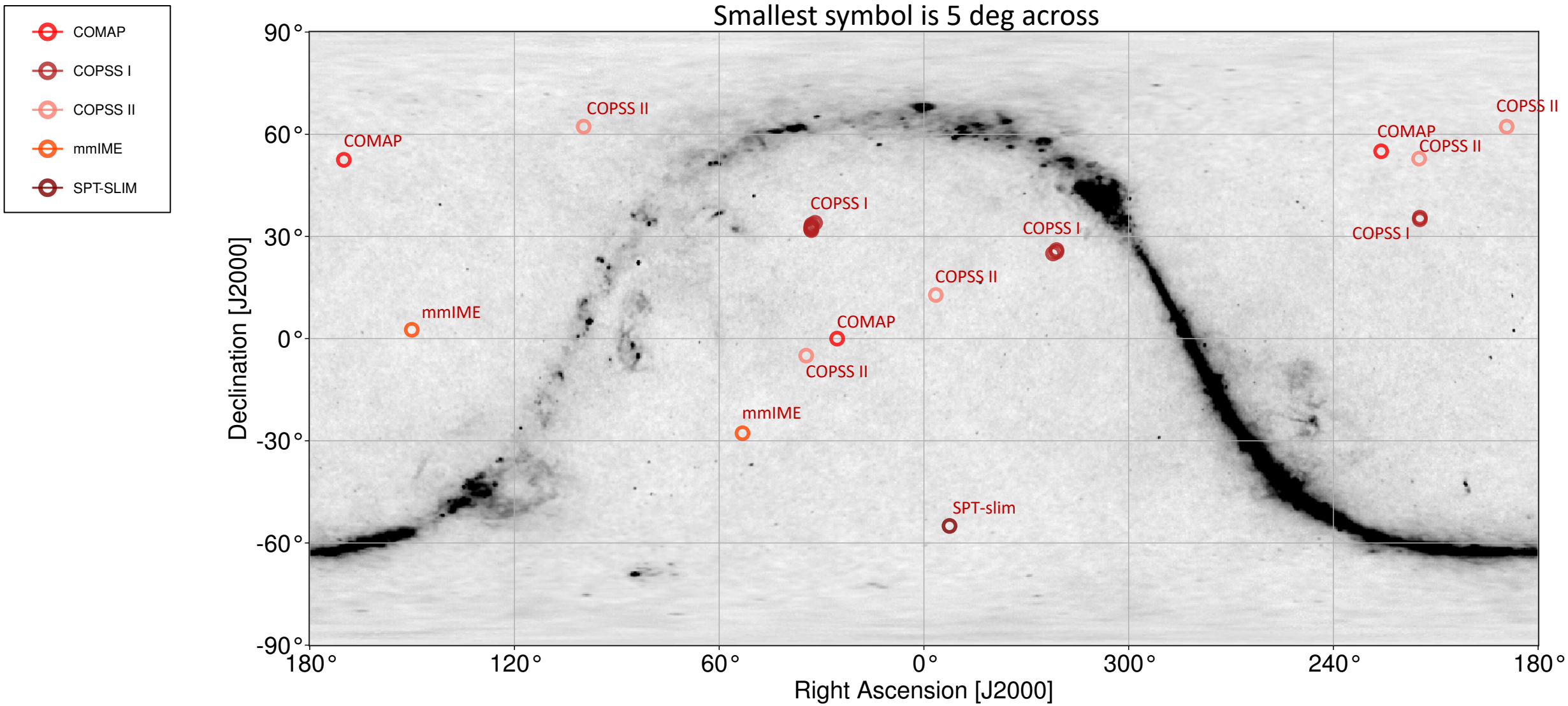
The Future of CO LIM: cross correlation of different LIM tracers



Credit: Nils-Ole Stutzer

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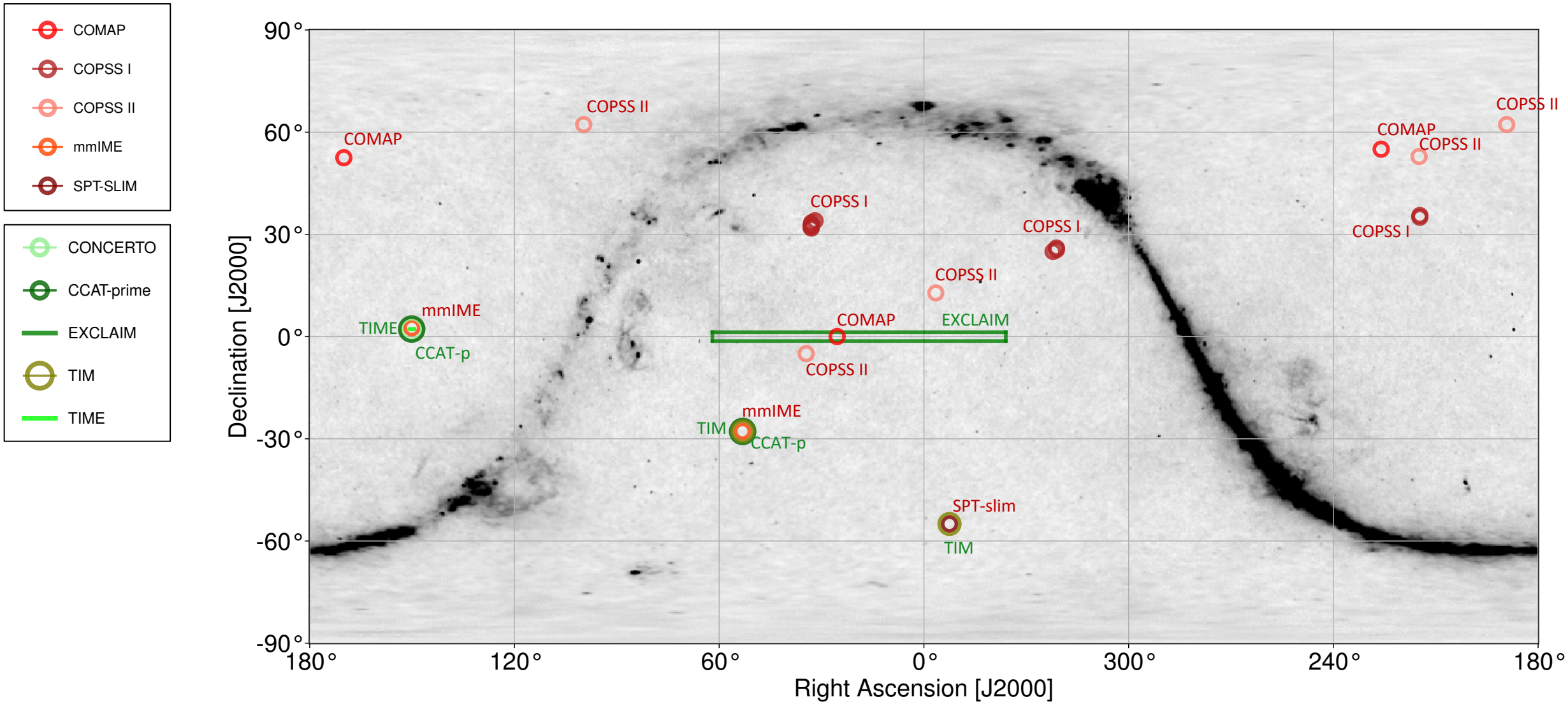

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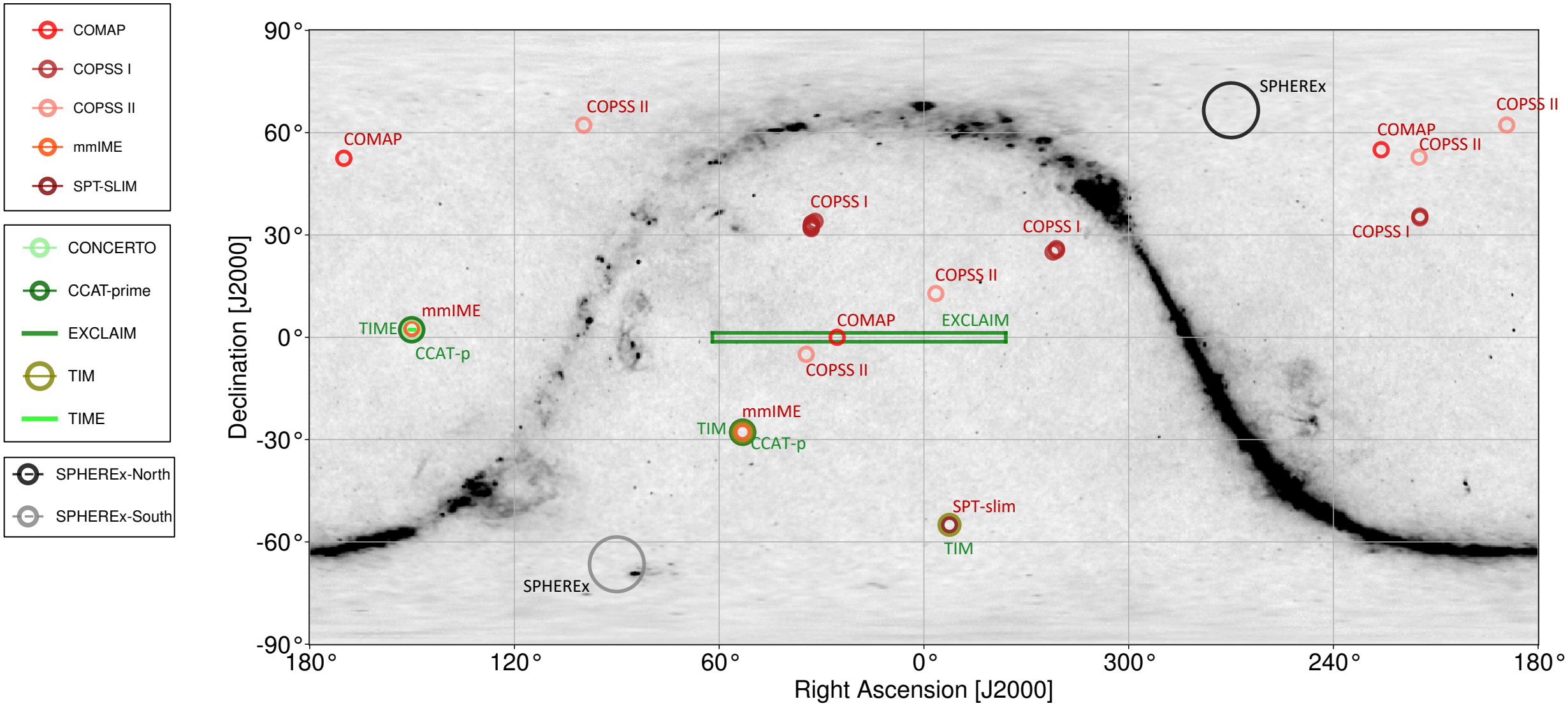

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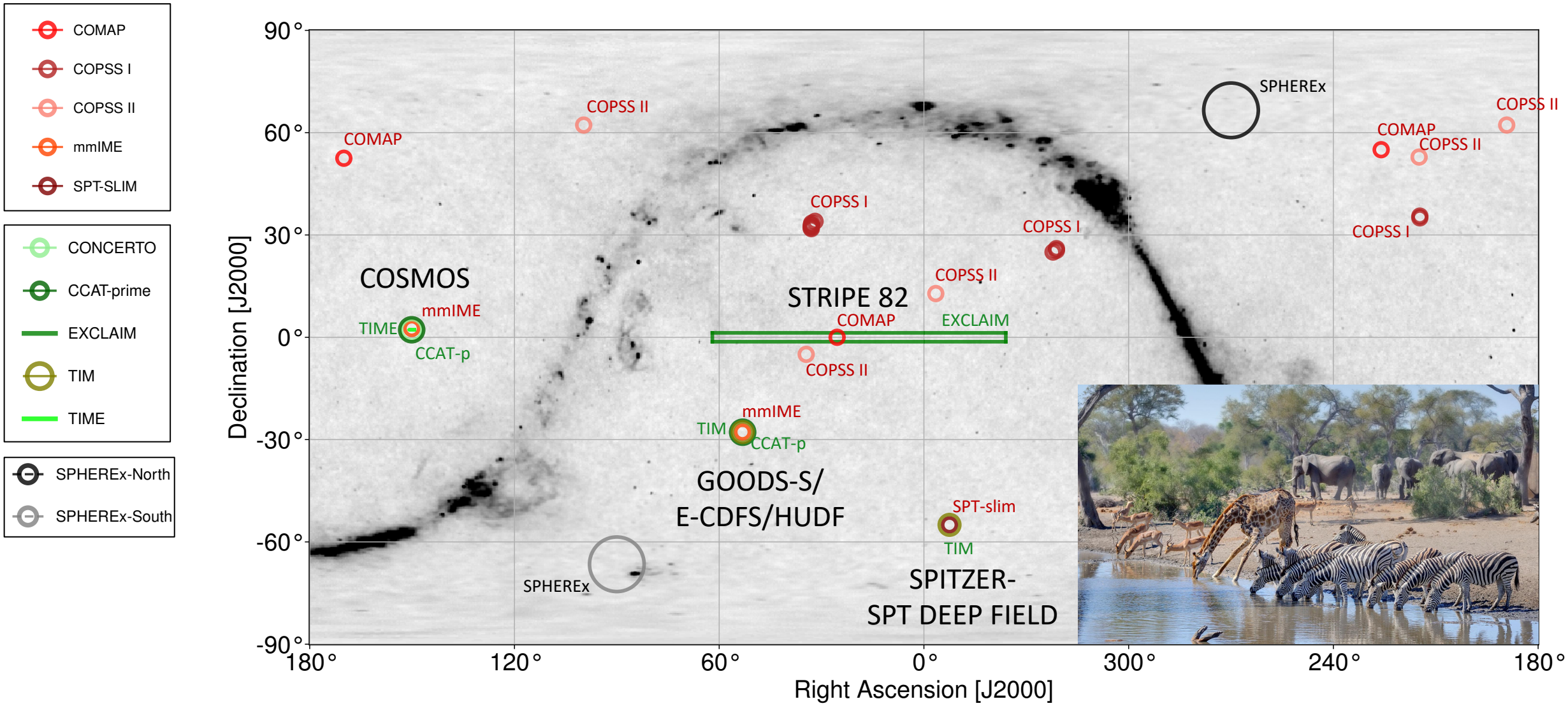
The Future of CO LIM: cross correlation of different LIM tracers



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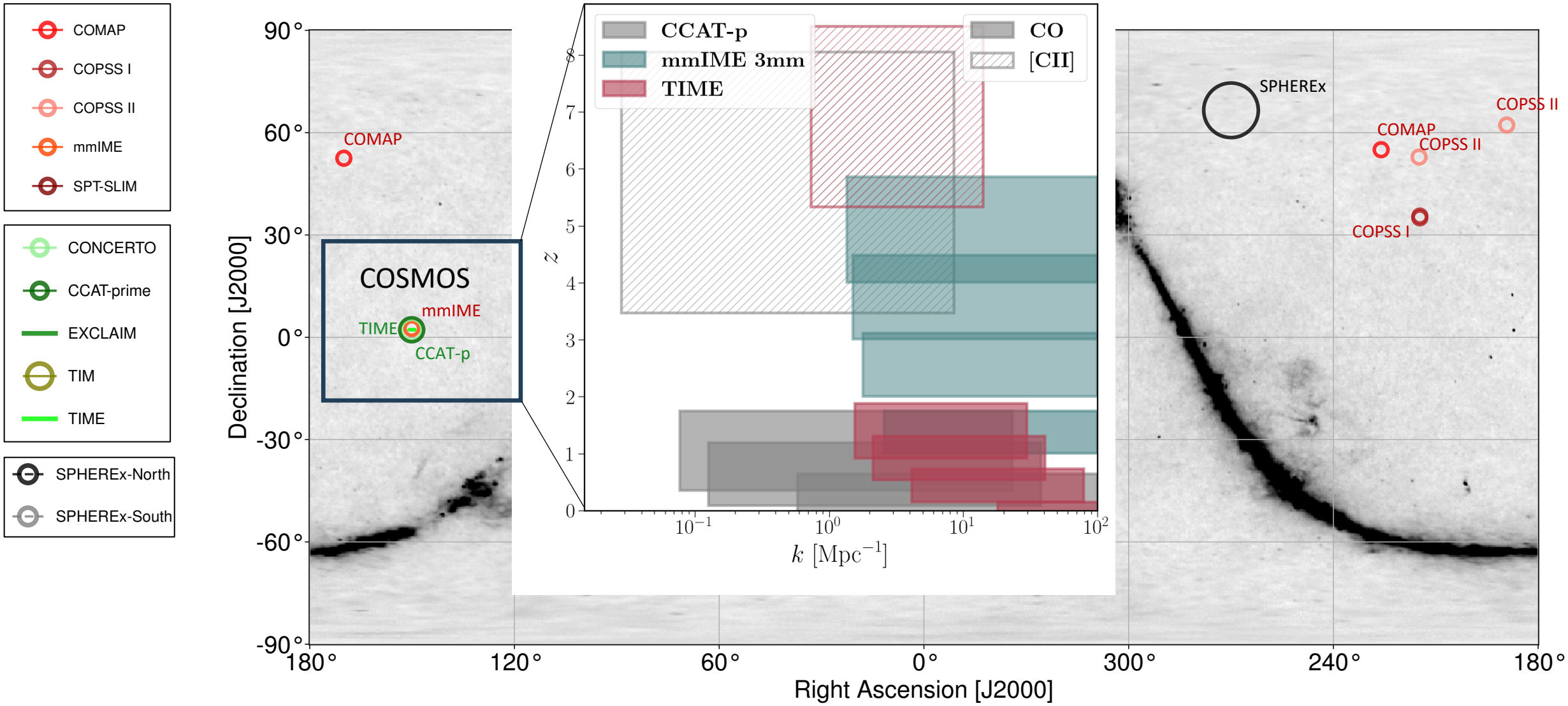
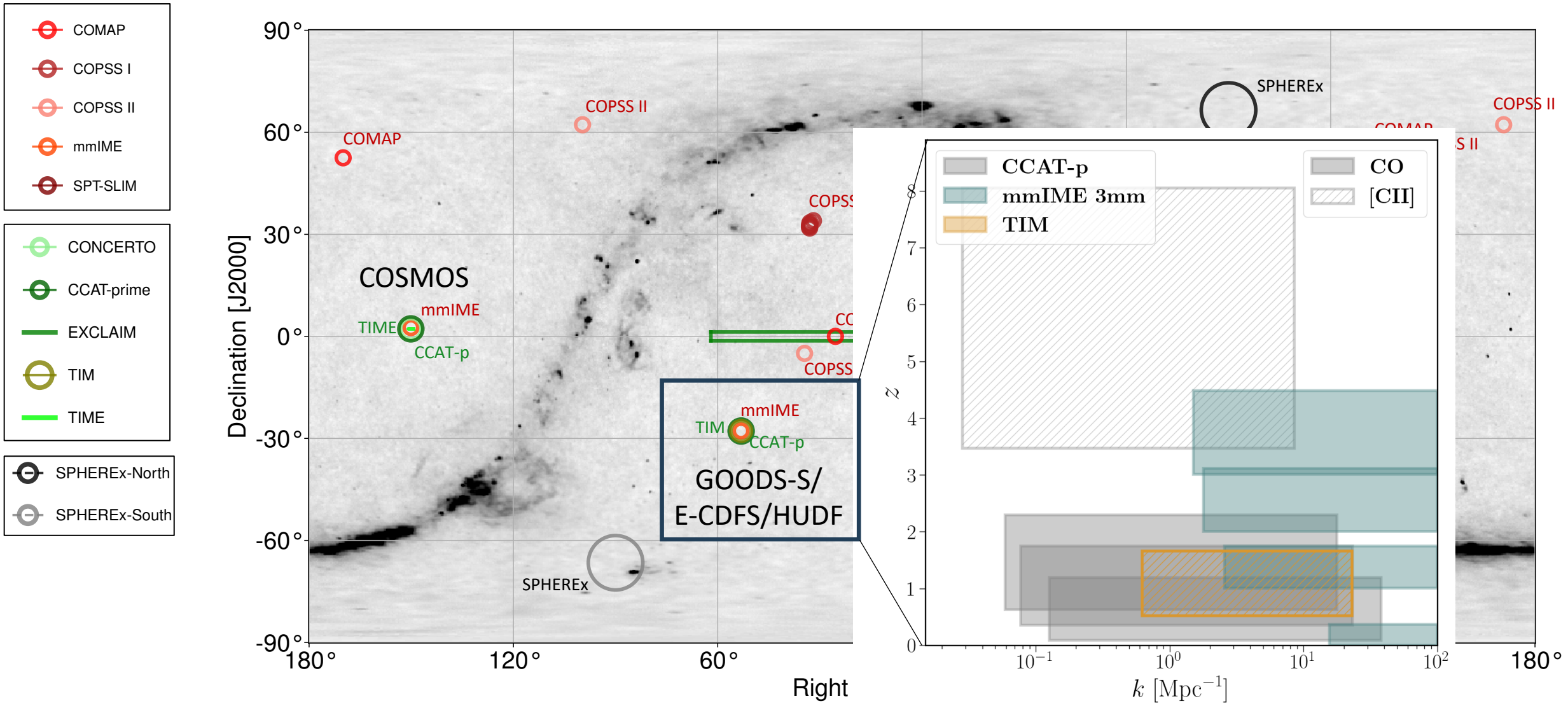


Credit: Nils-Ole Stutzer

The Future of CO LIM: cross correlation of different LIM tracers



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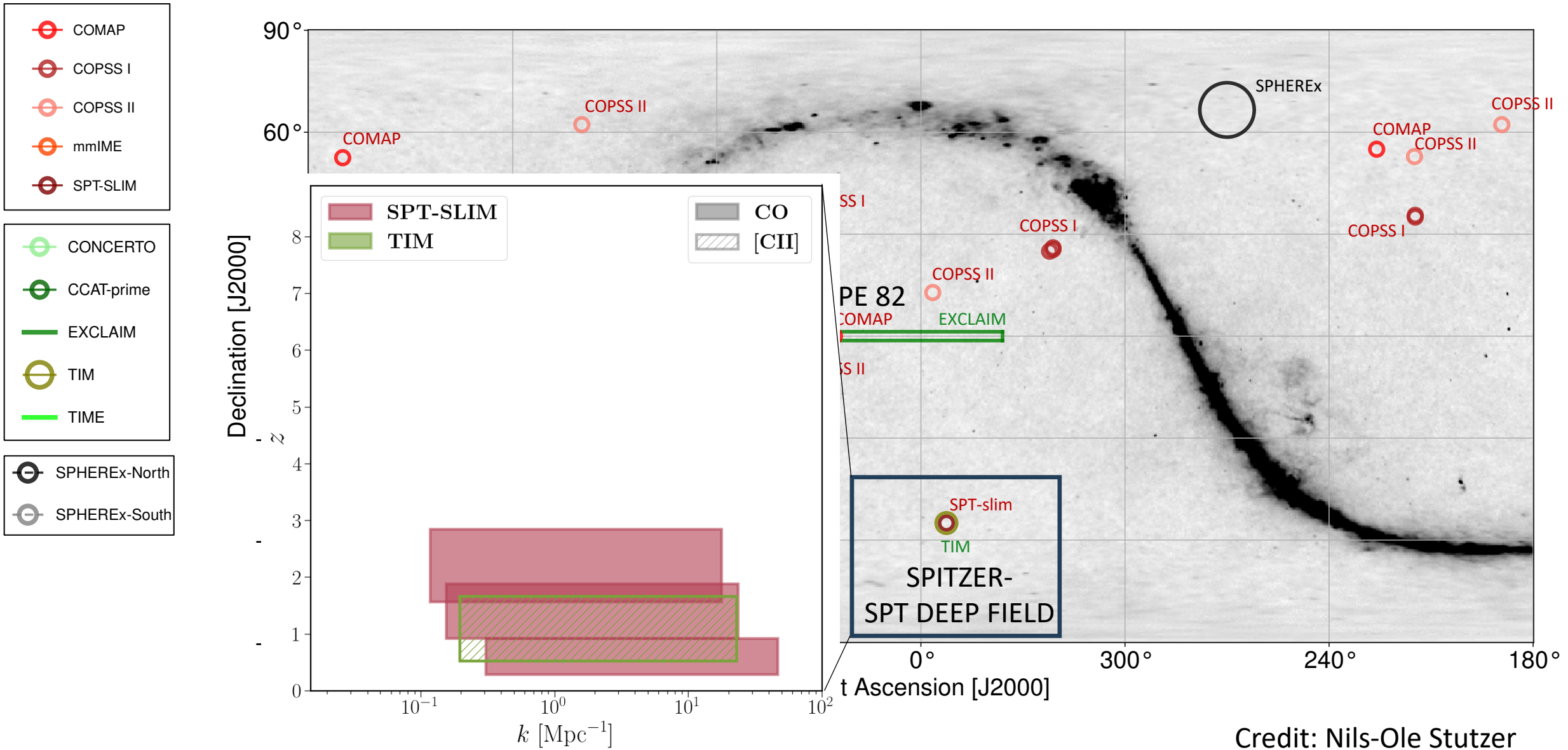
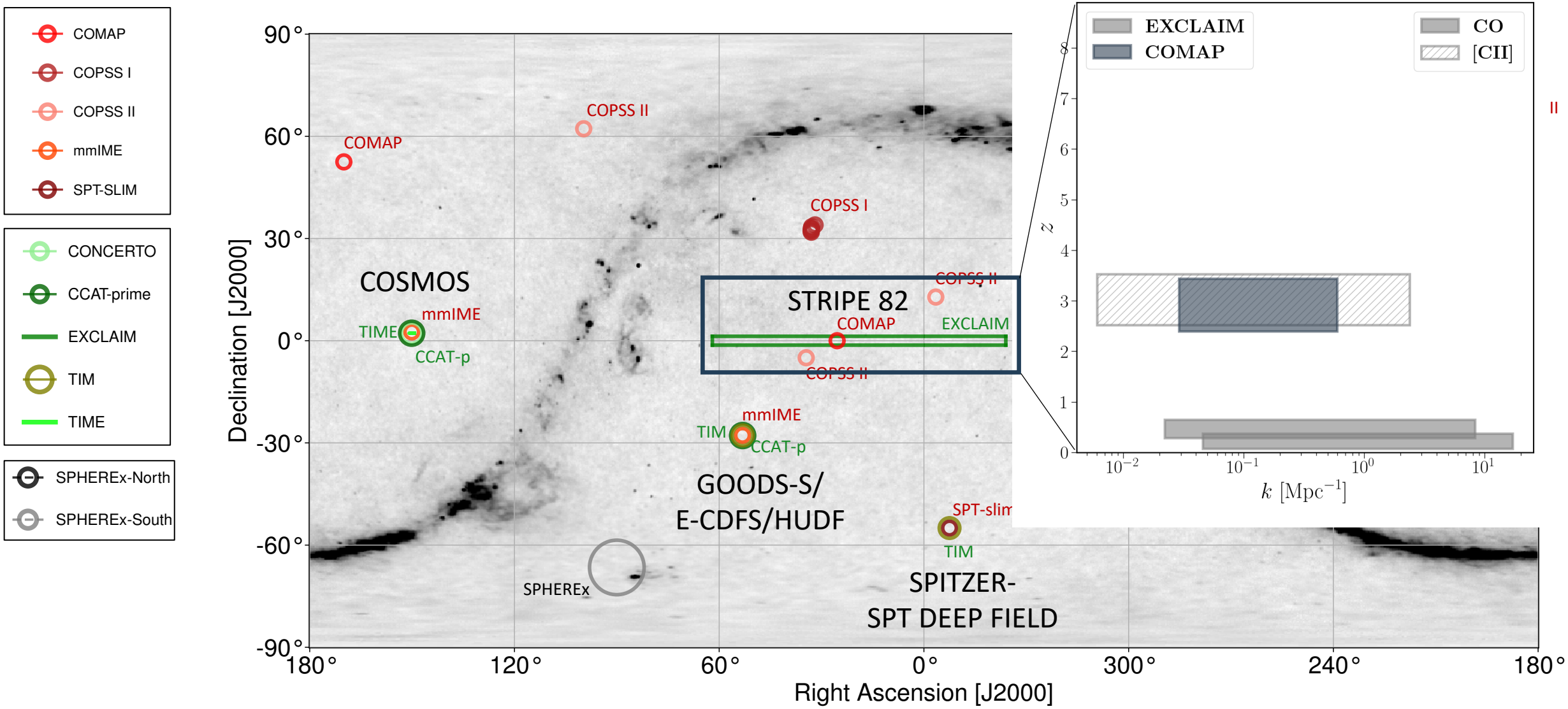


Credit: Nils-Ole Stutzer

The Future of CO LIM: cross correlation of different LIM tracers



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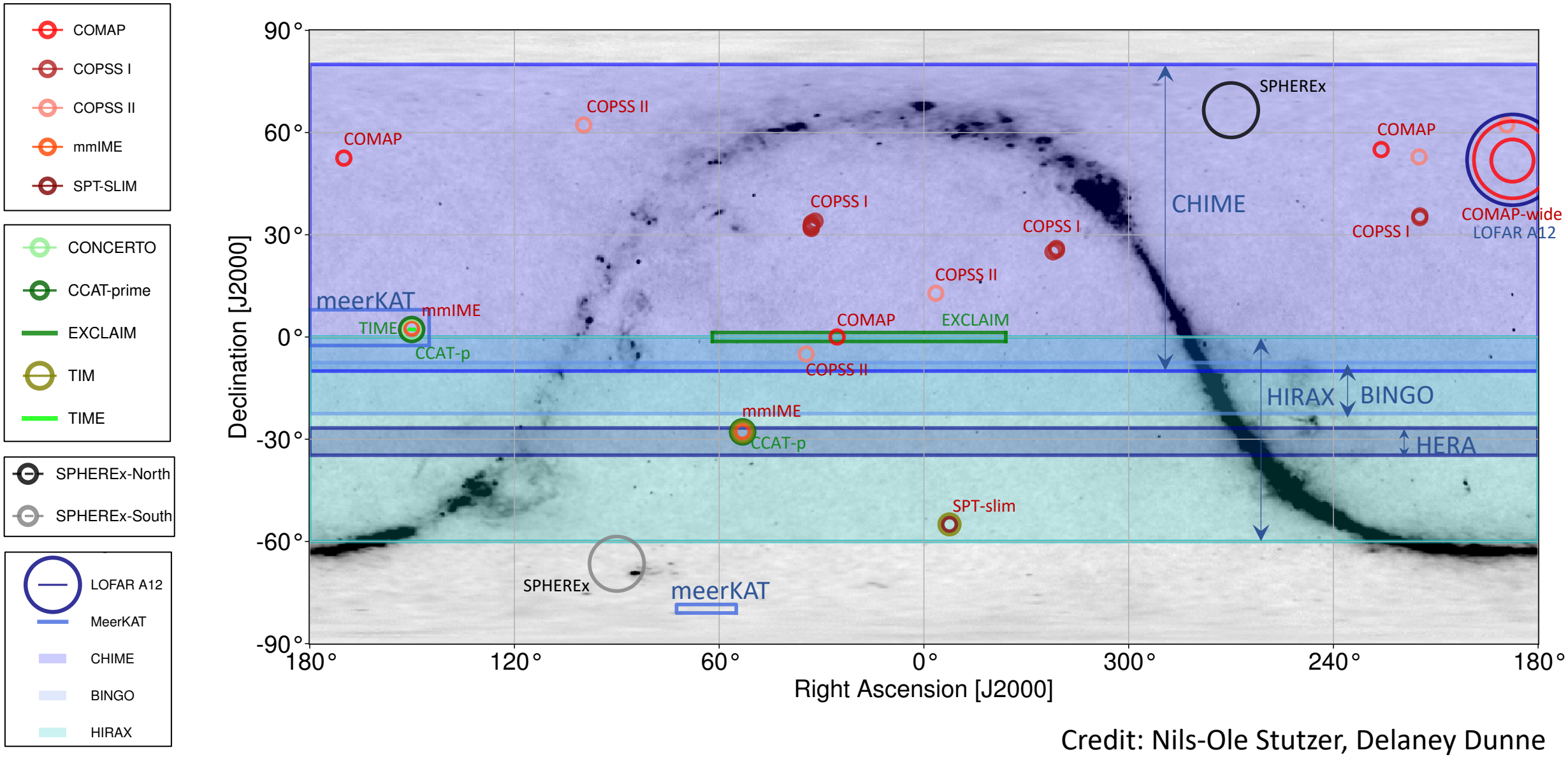

Credit: Nils-Ole Stutzer, Delaney Dunne

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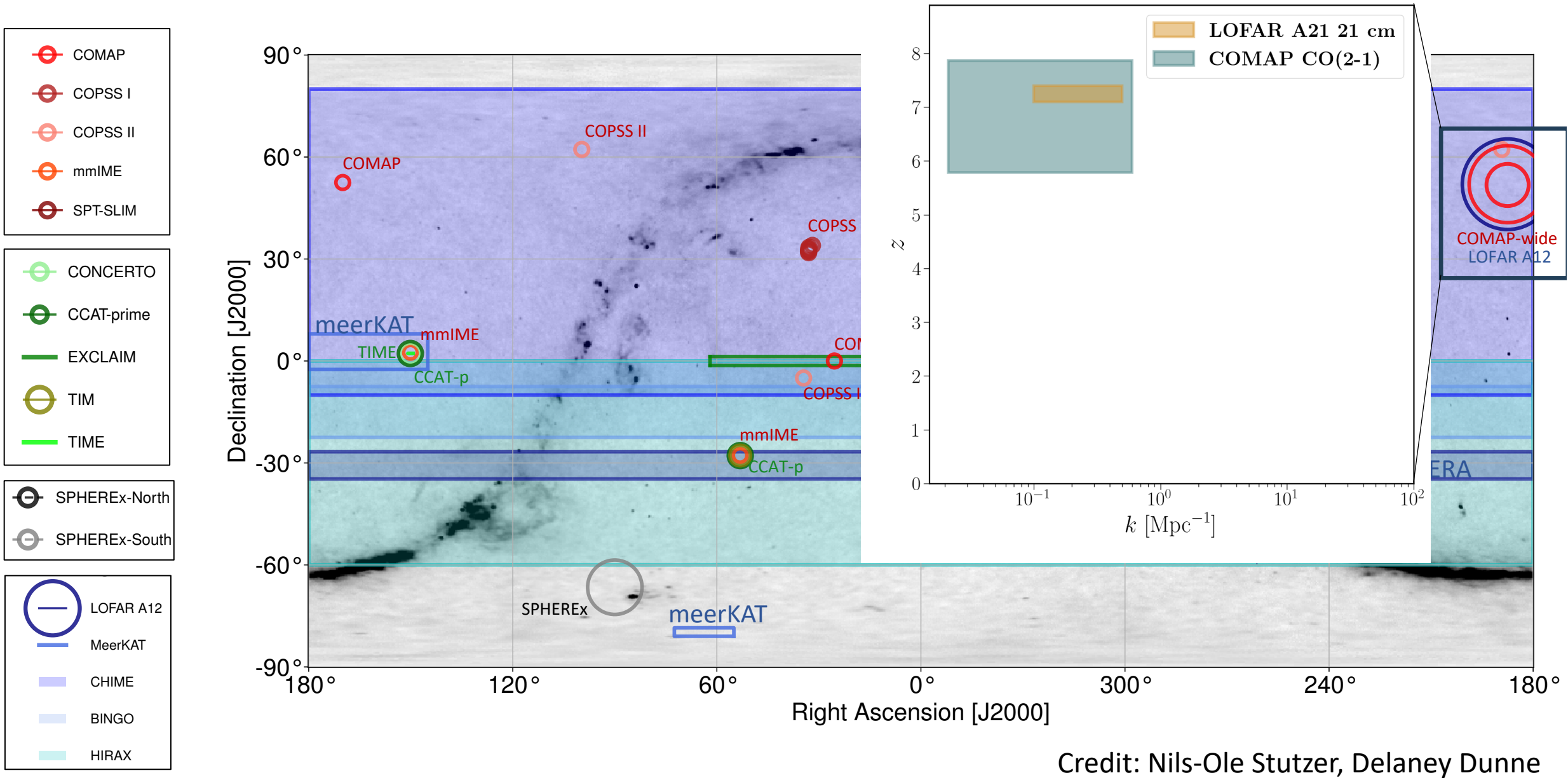
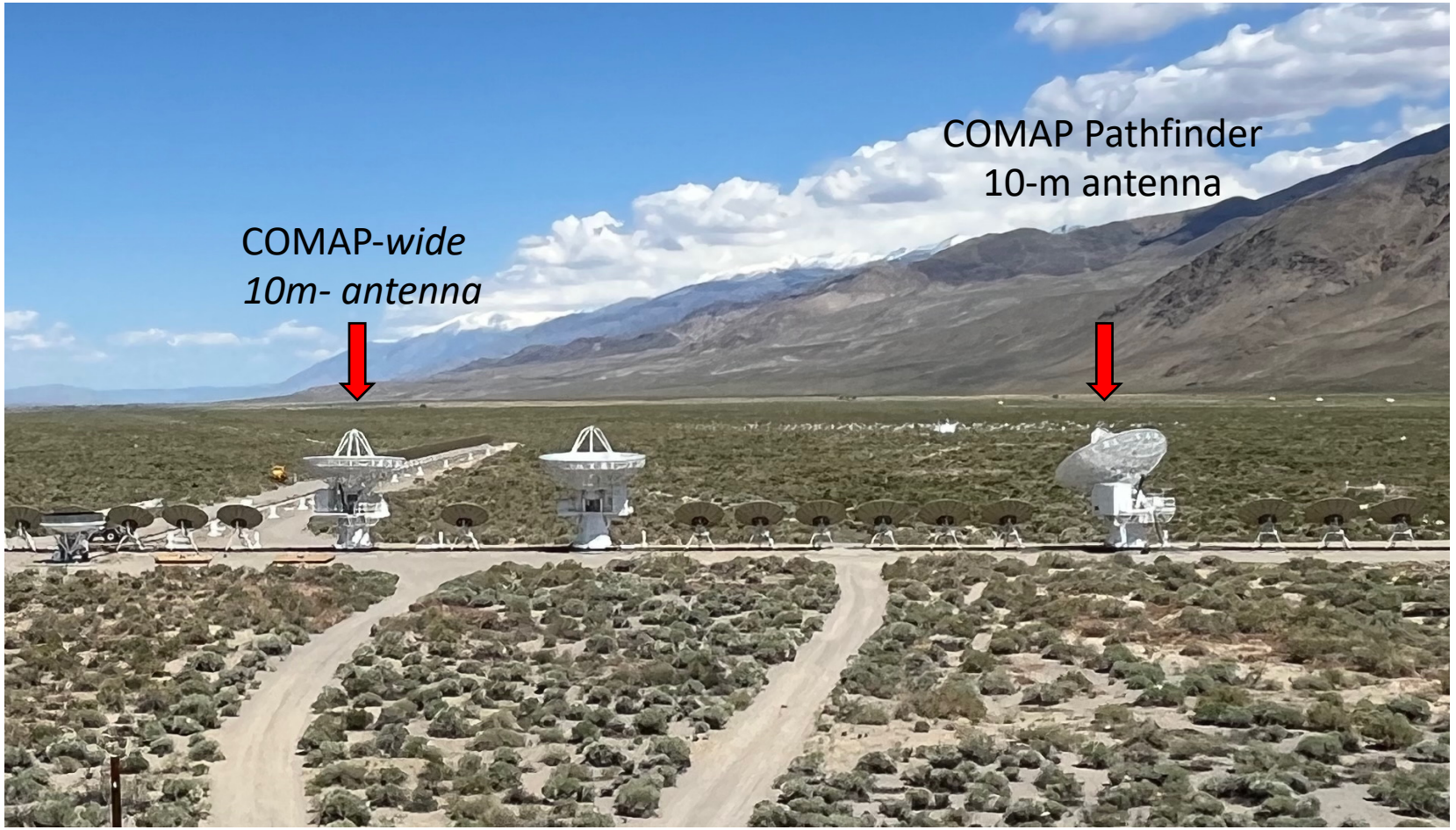
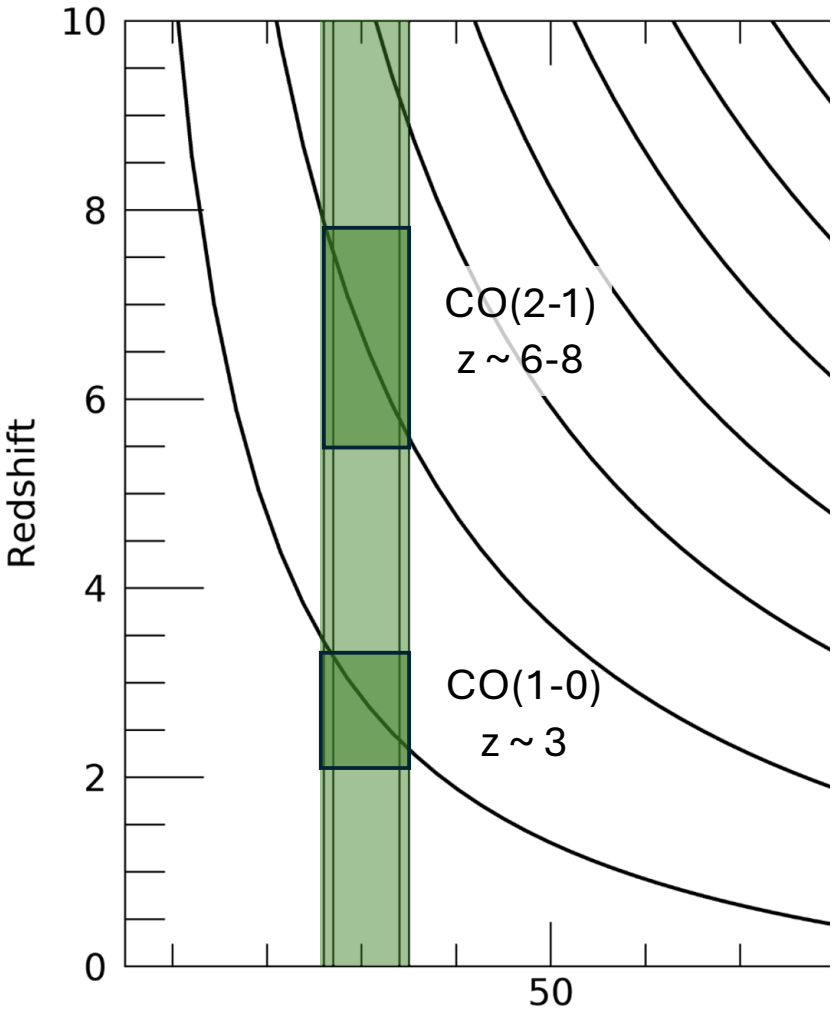


Credit: Nils-Ole Stutzer, Delaney Dunne

C O M A P - *wide*

- Duplicate* 19-feed 26-34 GHz receiver
- Field on second 10-m antenna at OVRO

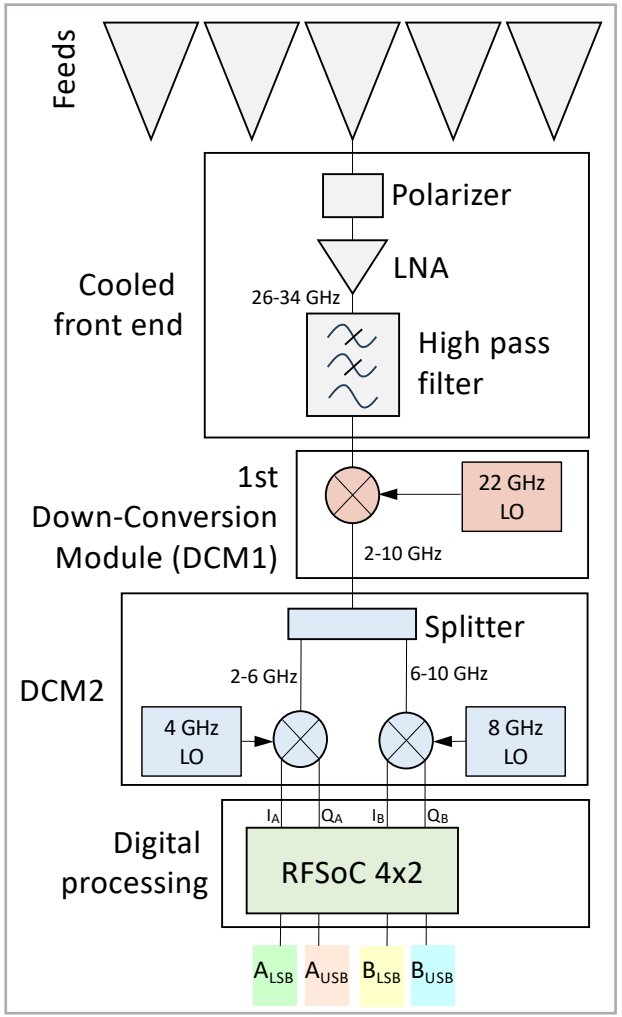




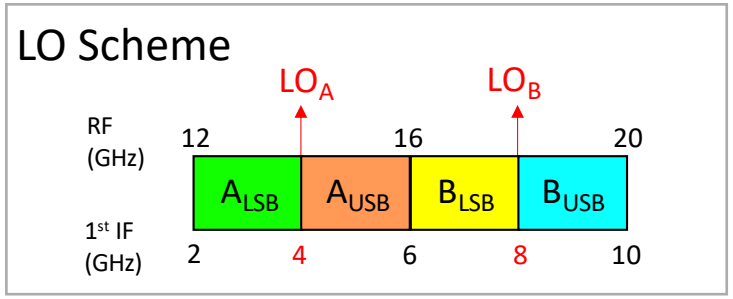
C O M A P - *wide*

*More sensitive LNAs

*RFSoC 4x2s instead of obsolete Roach2s

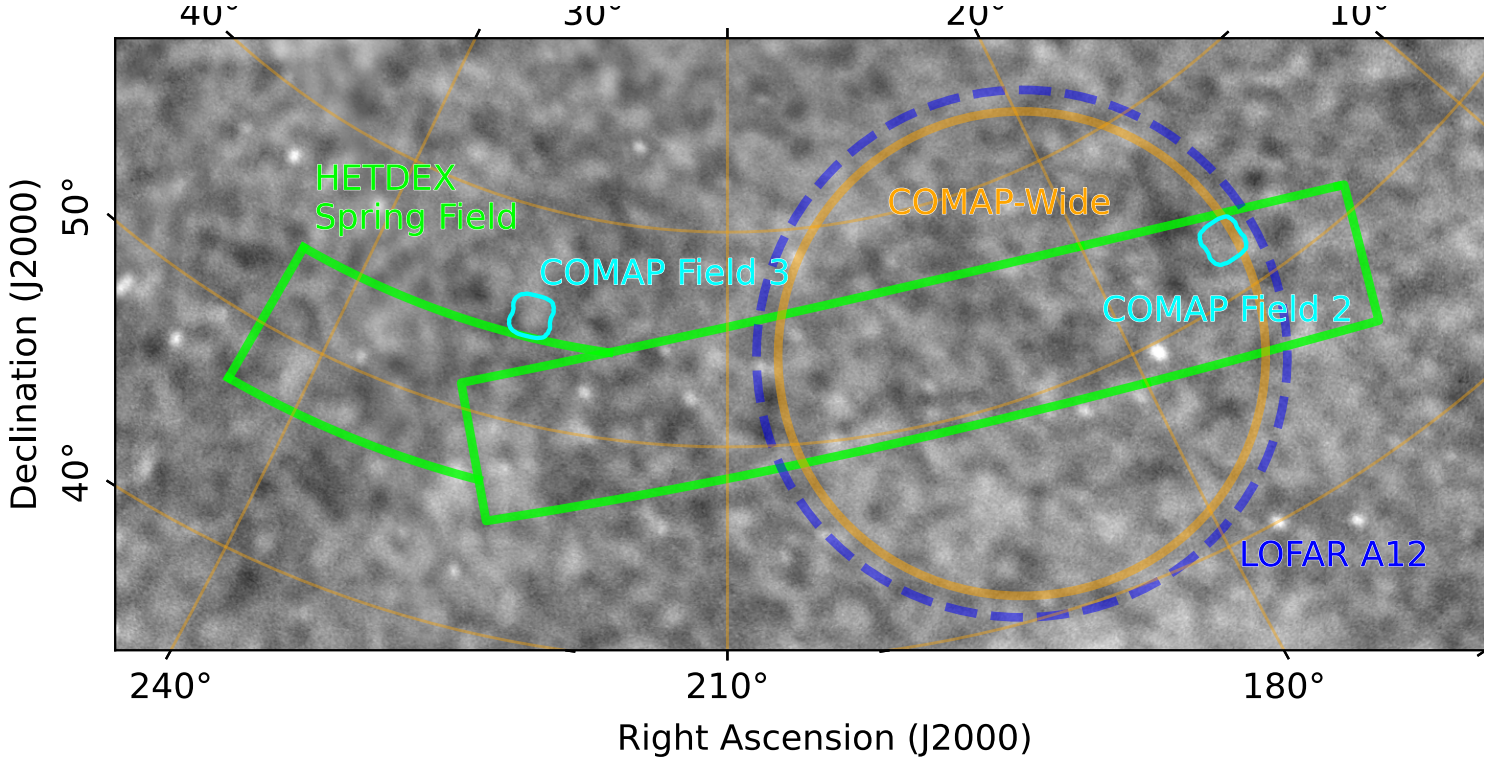


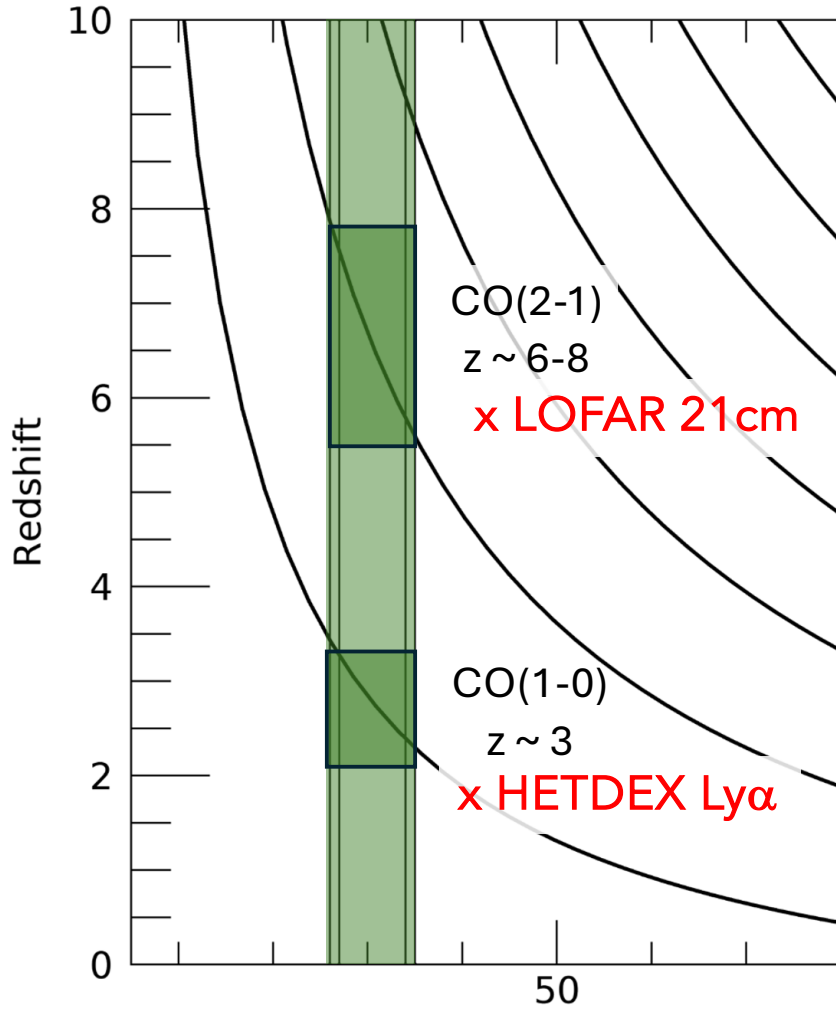
Largely a duplicate of Pathfinder receiver
Lower noise LNAs
- Tsys improved by 33%
RFSoC 4x2 not Roach2



C O M A P - *wide*

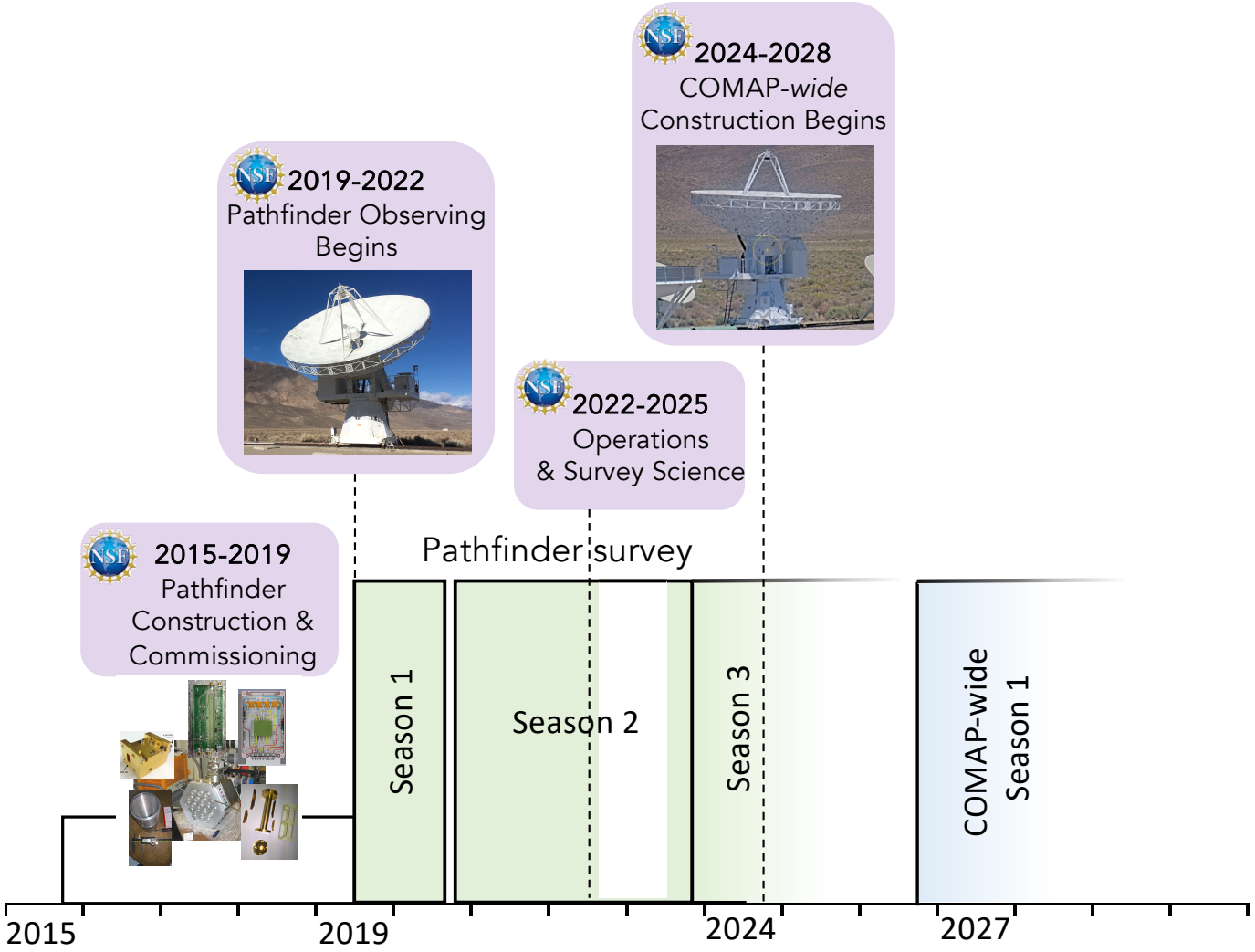
- Duplicate 26-34 receiver
- On second 10-m antenna at OVRO
- Perform 400 sq. deg. survey
- x-correlate with LOFAR A12 (21cm) at z~7 and HETDEX (Lyα) at z~3





C O M A P - *wide*

- COMAP-*wide* now funded by NSF
  - Started September 2024
- Observing expected to start by September 2026



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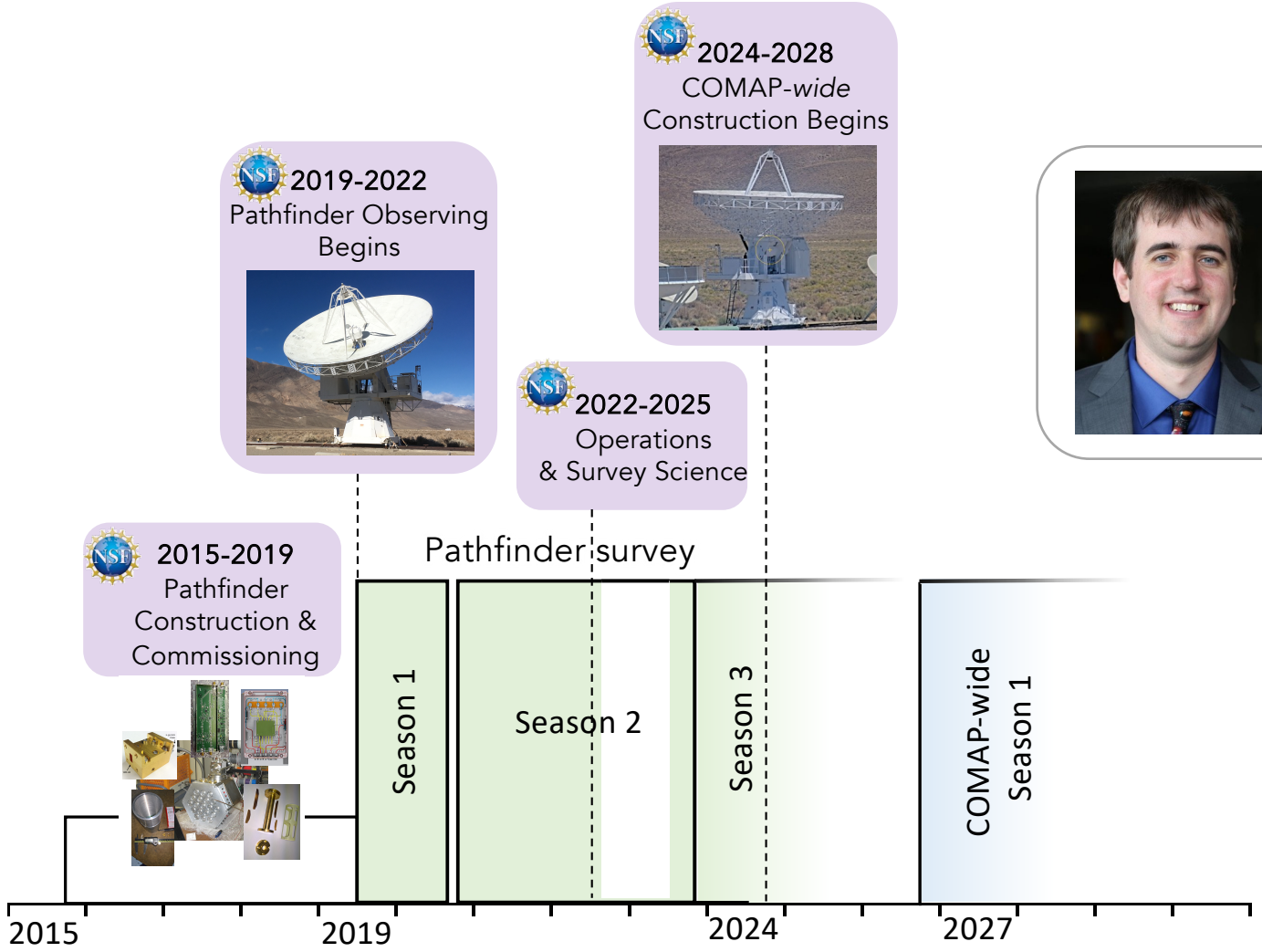
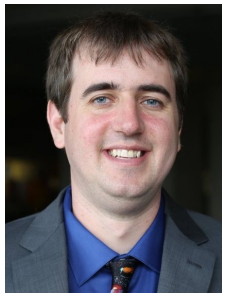


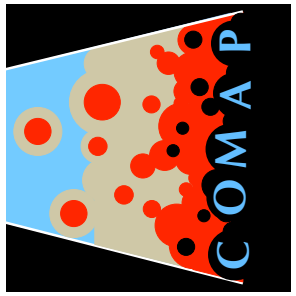


Patrick Breysse, Southern Methodist University

Reionization Cross-Correlations with COMAP-Wide

Tuesday, COMAP talks

For more details on expectations for the cross-correlation signal, see Patrick's talk later this morning.



CO Mapping Array Project

COMAP Pathfinder

CO(1-0) auto @ z=3
CO(1-0) x LAE @ z=3

COMAP-*wide*

CO(2-1) x 21cm @ z=7
CO(1-0) x LAE @ z=3

COMAP-*EoR*

Planned

CO(1-0) auto @ z=5-9

CO(1-0) x CO(2-1) @ z=6-8

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<u>Long term:</u>

Wider and deeper surveys:

BAOs

e.g. Karkare et al. (2018)

Beyond LCDM

e.g. Sabla et al. (2024)

Primordial magnetic fields

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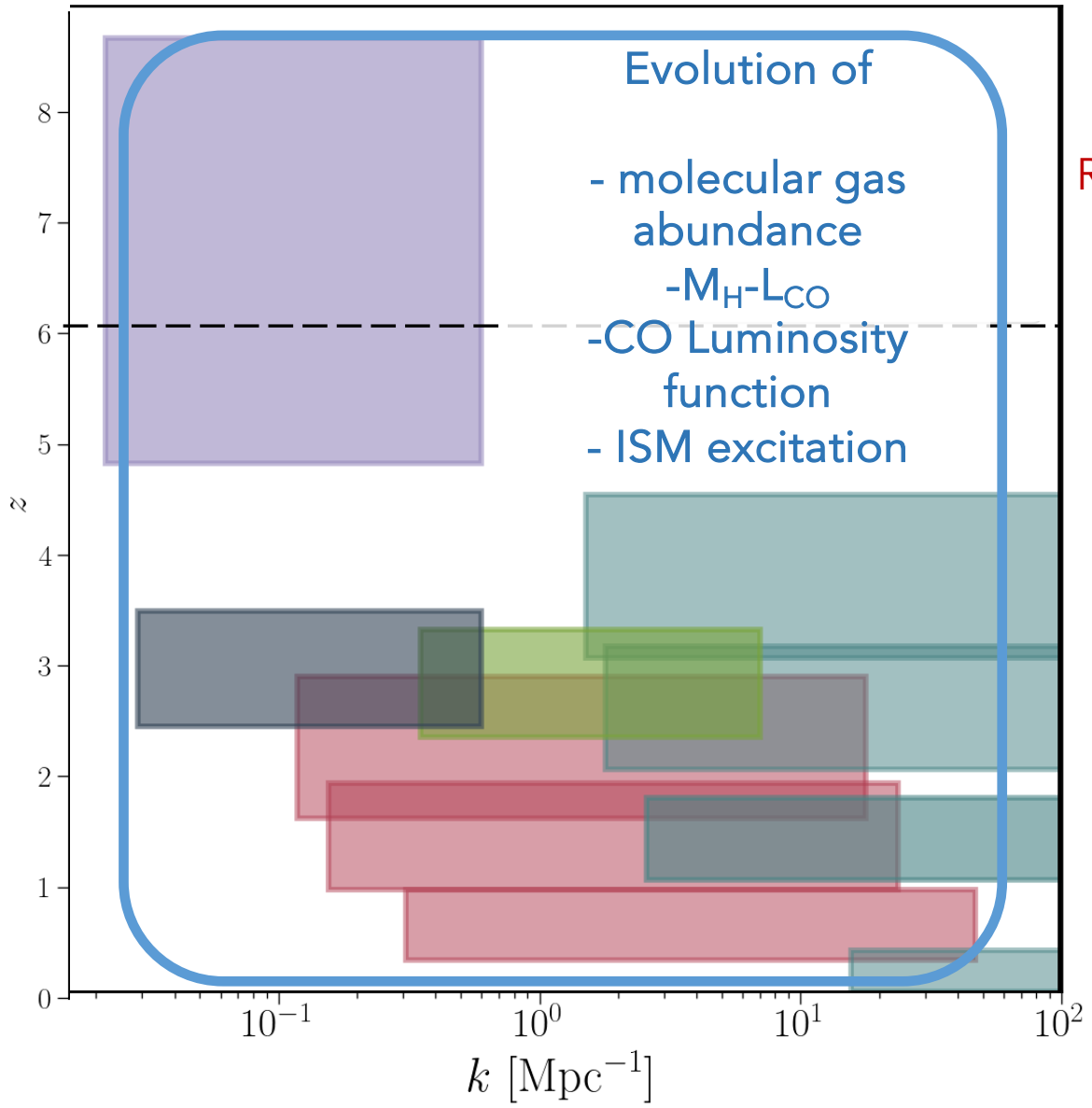
Ionization bubble scale at EoR,

e.g. Lidz et al. (2011)

Space-based observations



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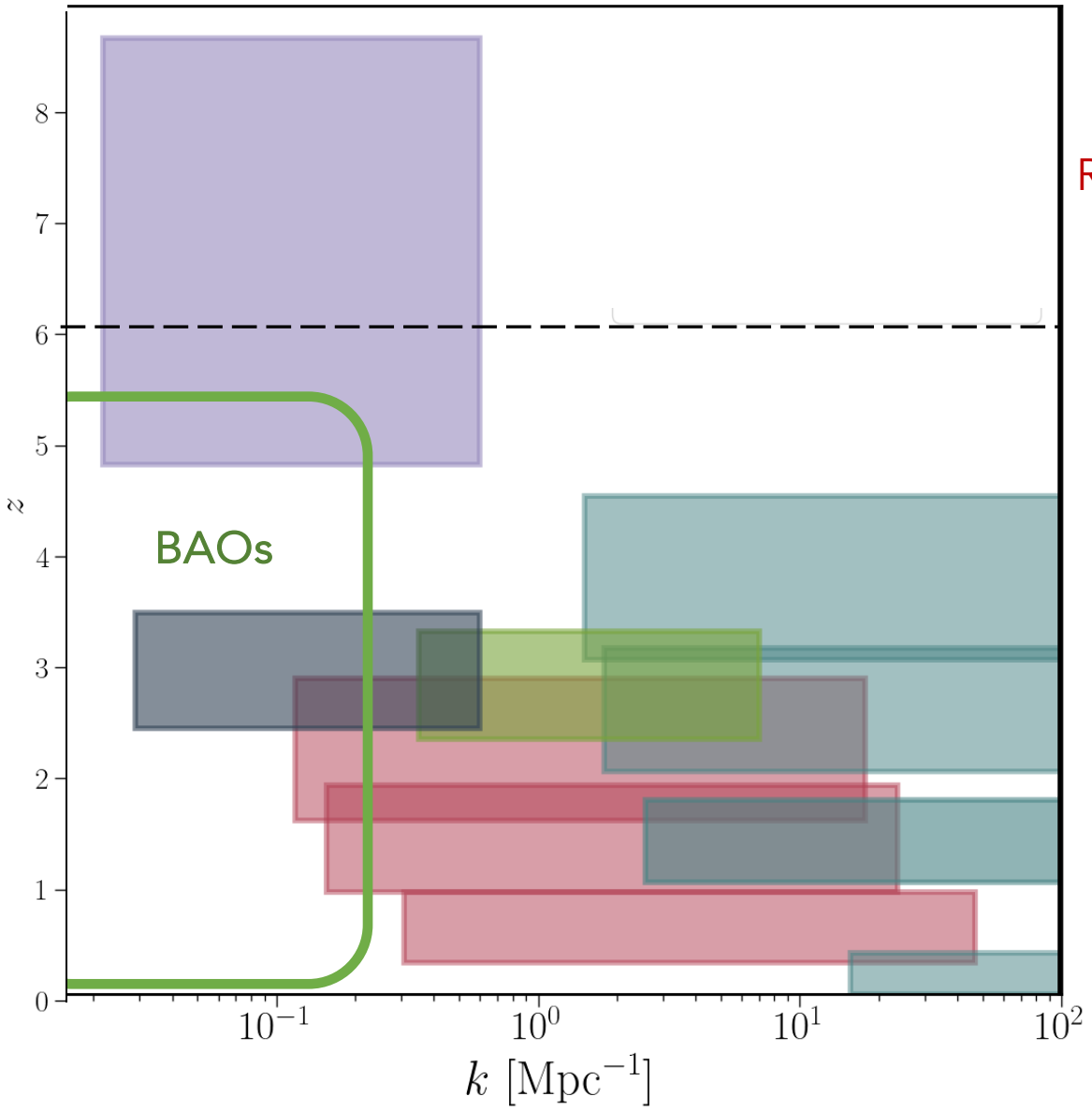

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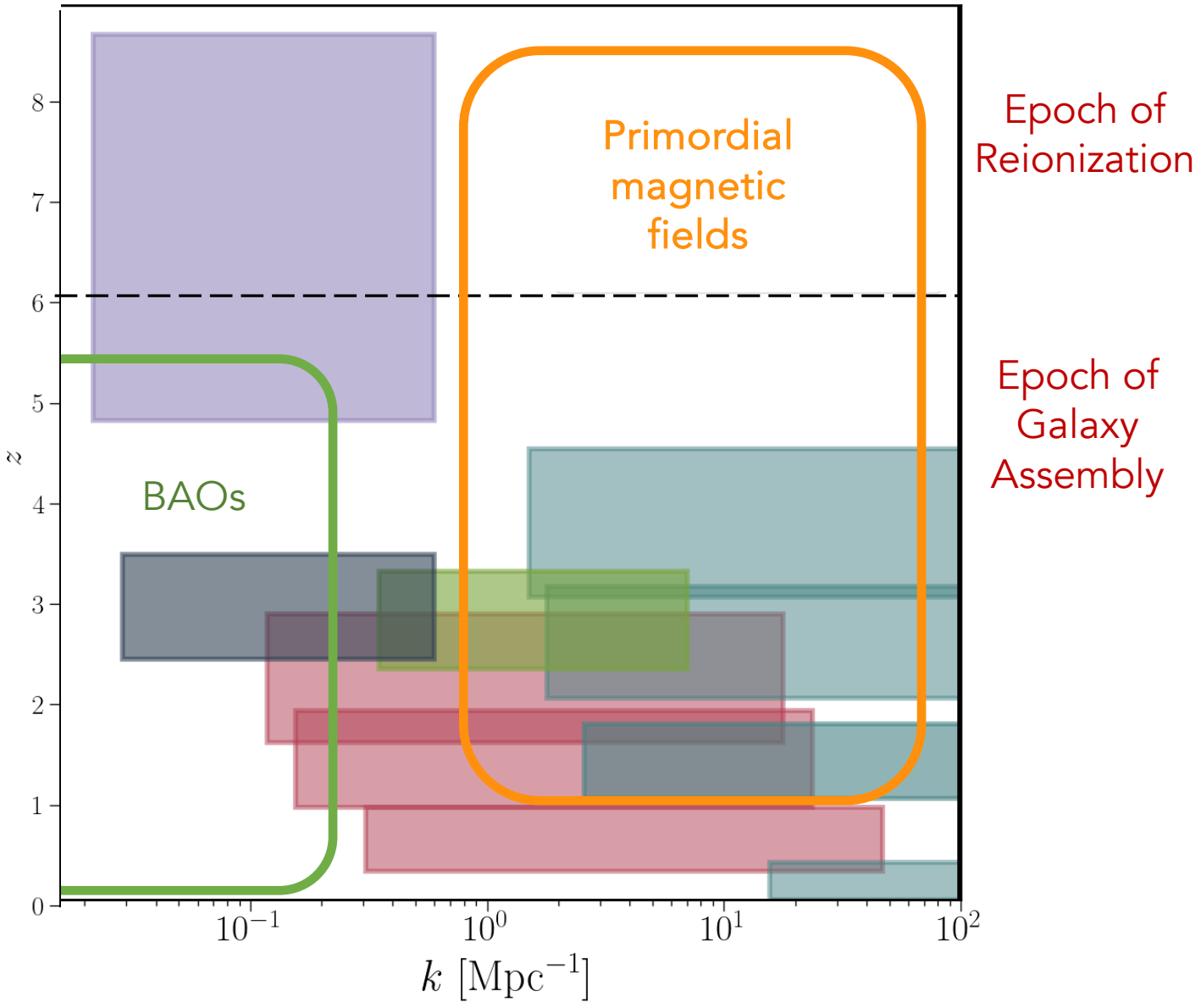

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Space-based observations

Largest scales, widest redshift coverage