An Overview of Line Intensity Mapping at Millimeter Wavelengths

Abby Crites
Cornell University
June 26th, 2025

– mm Universe 2025 –

Outline

1. What is line intensity mapping and why this technique is promising at mm wavelengths.
    a. Ionized carbon line
    b. Carbon monoxide lines
2. Challenges and opportunities using line intensity mapping.
    a. Technology
    b. Masking and component separation
3. The experimental landscape of mm line intensity mapping.
    a. A quick overview of the landscape
    b. TIME status

The LIM Community

Yearly meetings and semi-regular status reports
Lots of the plots in this talk especially modeling and visualizations come from these reports

LIM25
LINE INTENSITY MAPPING 2025
June 2nd - 6th, Annecy - France

LABORATOIRE D'ANNECY-LE-VIEUX DE PHYSIQUE THÉORIQUE

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Line Intensity Mapping 2024

Many models for signals and few measurements!

Line-Intensity Mapping: Theory Review
with a focus on star-formation lines

J. L. Bernal · E. D. Kovetz 2206.15377

Snowmass 2021 Cosmic Frontier White Paper:
Cosmology with Millimeter-Wave Line Intensity Mapping

Kirit S. Karkare[1,2], Azadeh Moradinezhad Dizgah[3], Garrett K. Keating[4], Patrick Breysse[5], Dongwoo T. Chung[6,7], for the Snowmass 2021 Cosmic Frontier 5 Topical Group ,

Endorsers: James Aguirre[8], Zeeshan Ahmed[9,10], Adam Anderson[2], Pete S. Barry[11], Ritoban Basu Thakur[12], Bradford Benson[2,1], José Luis Bernal[13], Federico Bianchini[9,10], Simeon Bird[14], C. Matt Bradford[15,12], John E. Carlstrom[1,11], Emanuele Castorina[16], Andrea Caputo[17], Clarence Chang[11,1], Tzu-Ching Chang[15,12], Yun-Ting Cheng[12], Cyril Creque-Sarbinowski[13], Abigail T. Crites[18], Oliver Doré[15,12], Jacques Delabrouille[19,20,21], Simone Ferraro[21], Jeffrey Filippini[22], Yan Gong[23], Ely Kovetz[24], Guilaine Lagache[25], Adam Lidz[8], Abhishek S. Maniyar[5], Daniel P. Marrone[26], Jeff McMahon[1], Zhaodi Pan[11], Emmanuel Schaan[21], Erik Shirokoff[1], Sara M. Simon[2], Gordon Stacey[18], Eric R. Switzer[27], Peter Timbie[28], Joaquin Vieira[22], Gensheng Wang[11], W. L. Kimmy Wu[10], and Michael Zemcov[29]

Line-Intensity Mapping: 2017 Status Report

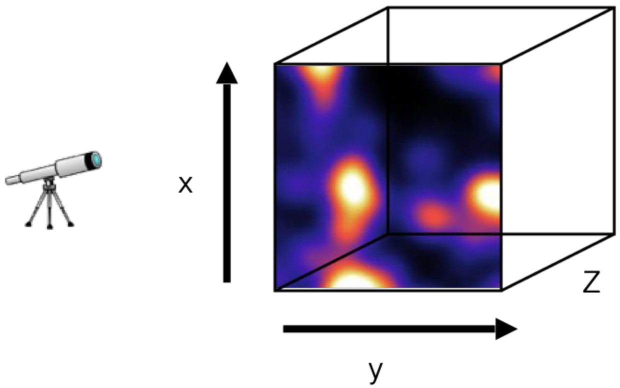
Line Intensity Mapping

Measuring the CMB or many things we've heard about here is "intensity mapping"

Map a spectral line over cosmological volume

Individual sources are not resolved –Integrate photons from many dim sources – detection threshold not required

Information extracted from the power spectrum



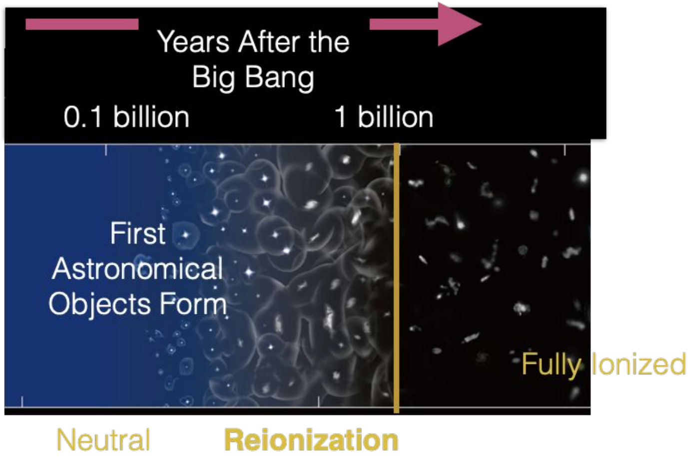
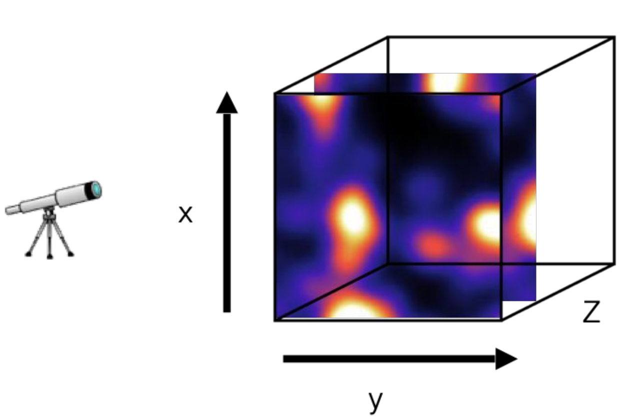
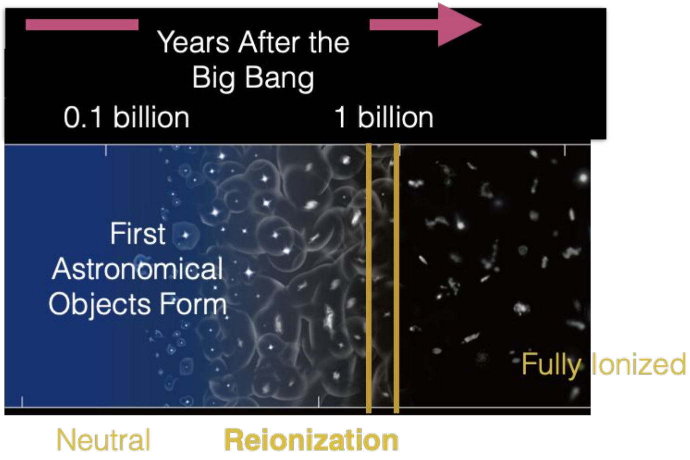


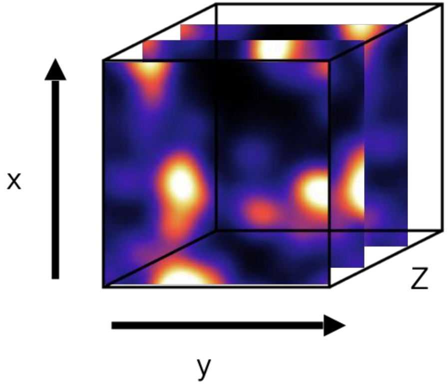
Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

Image Credit: Tony Li

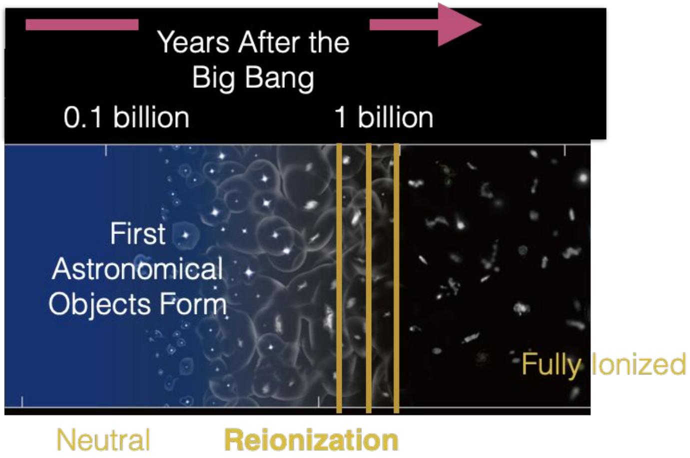
x


x
Z
y


Years After the Big Bang
0.1 billion
1 billion
First Astronomical Objects Form
Fully Ionized
Neutral
Reionization



x
y
Z



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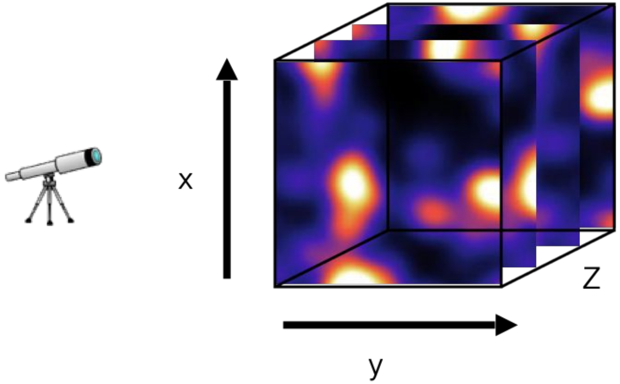
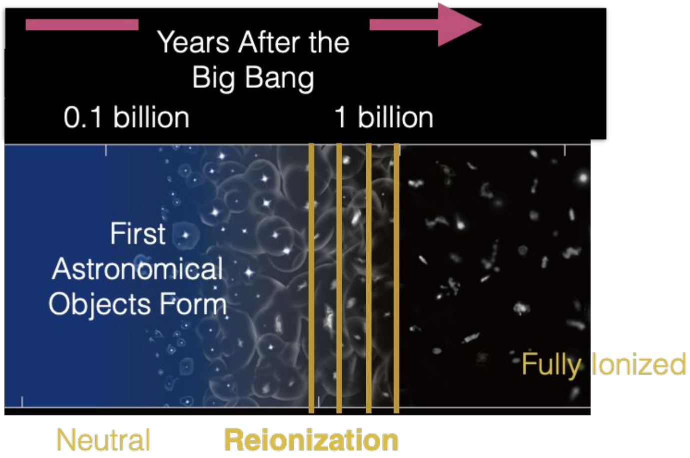

x
y
Z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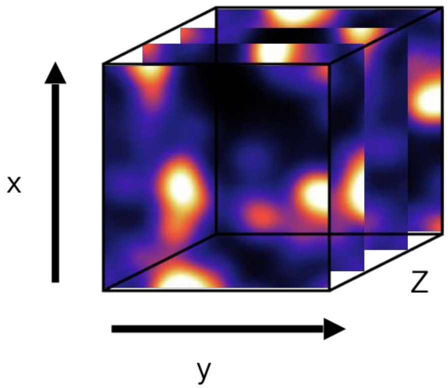
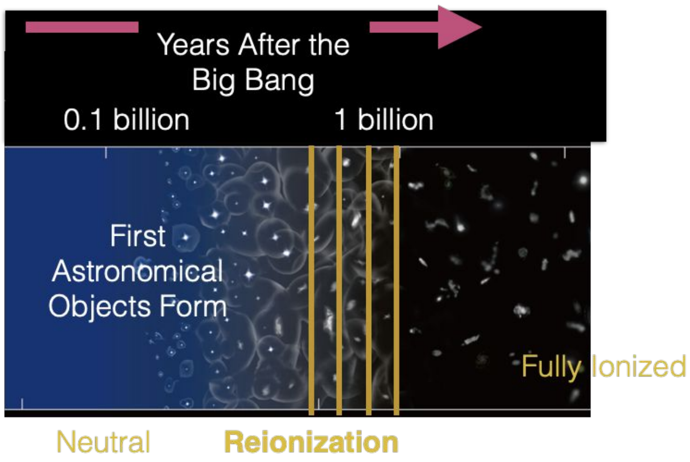

x
y
Z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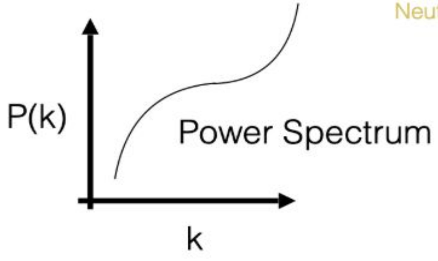
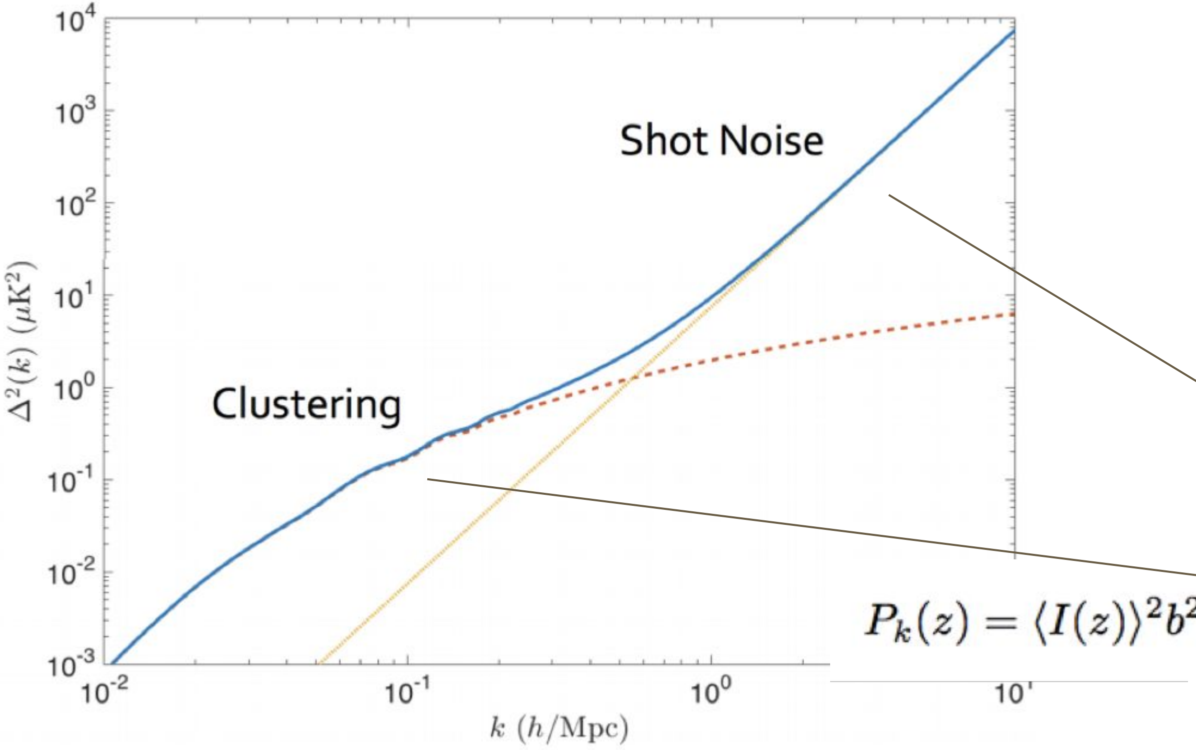

P(k)
Power Spectrum
k

What information do we get from the power spectra we measure?



$$P_k(z) = \langle I(z) \rangle^2 b^2(z) P_m(k, z) + P_{\rm shot}(z)$$

Kovetz et al 2017

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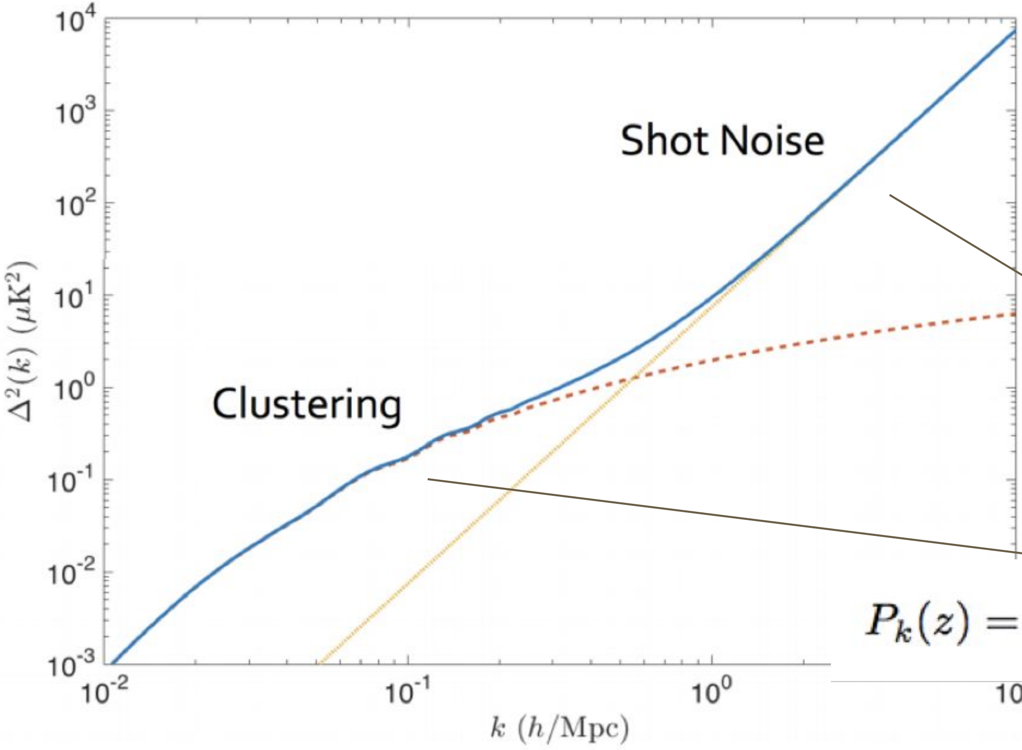
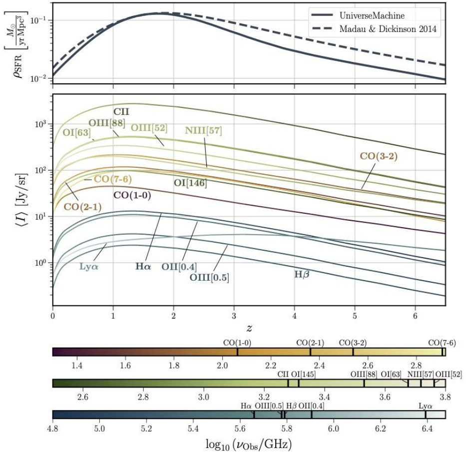


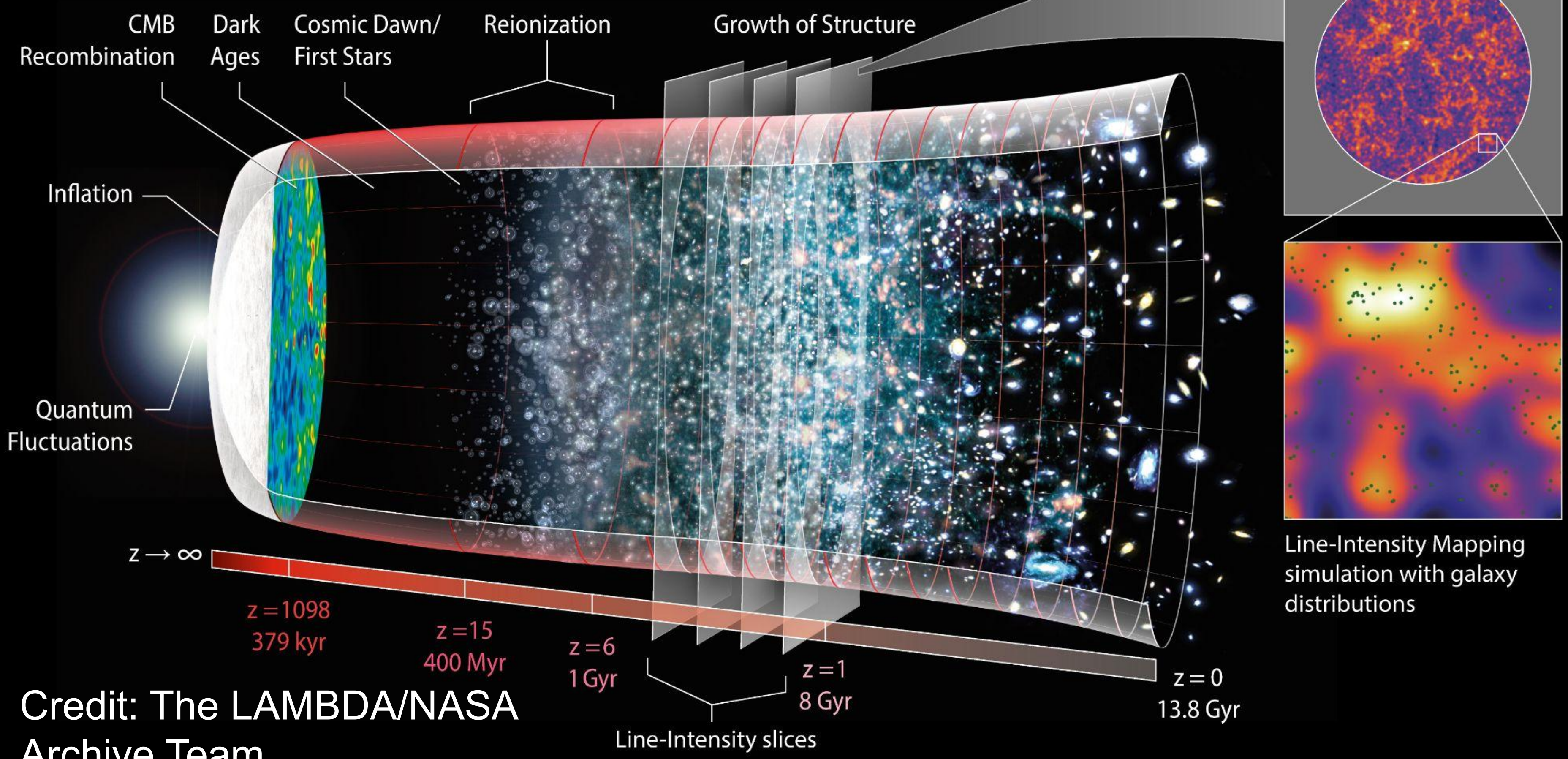


Bernal and Kovetz 2023

$$P_k(z) = \langle I(z) \rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}(z)$$

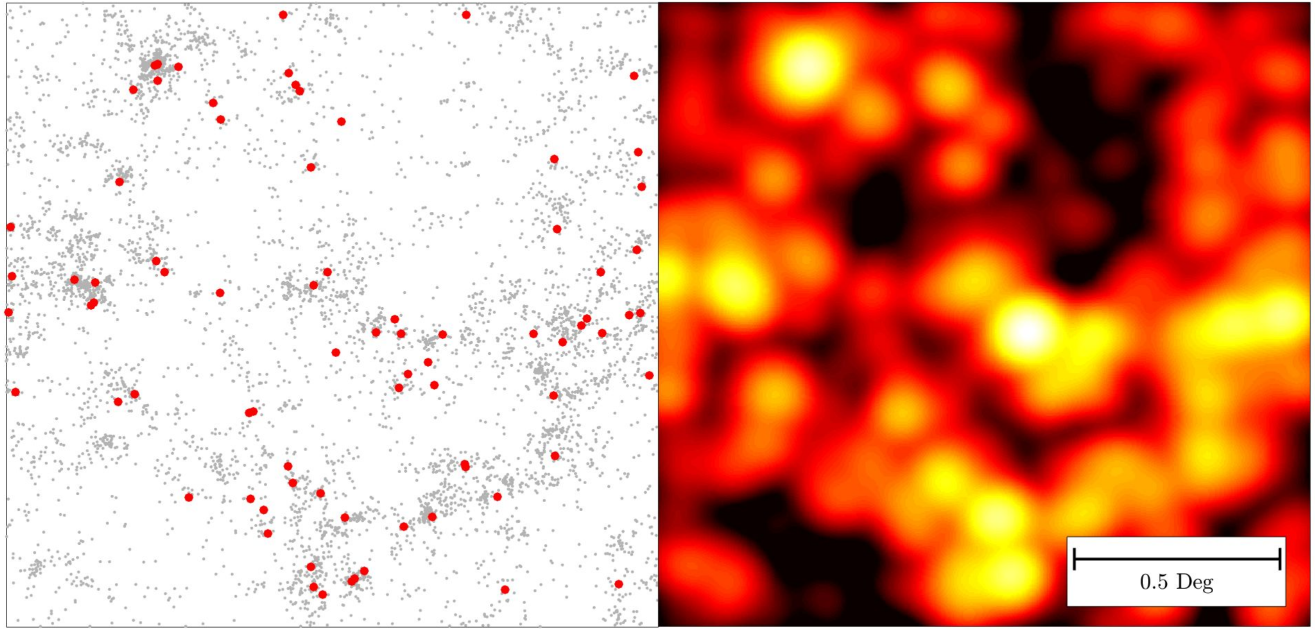
Kovetz et al 2017

Line Intensity Mapping (LIM)



Credit: The LAMBDA/NASA
Archive Team

Efficient Coverage of Cosmological Volumes



Breysse, Kovetz ++ 2017

Why LIM at mm wavelengths?

[CII], CO, and more are bright lines in galaxies and will allows us to trace structure, probe reionization, star formation, and cosmology!

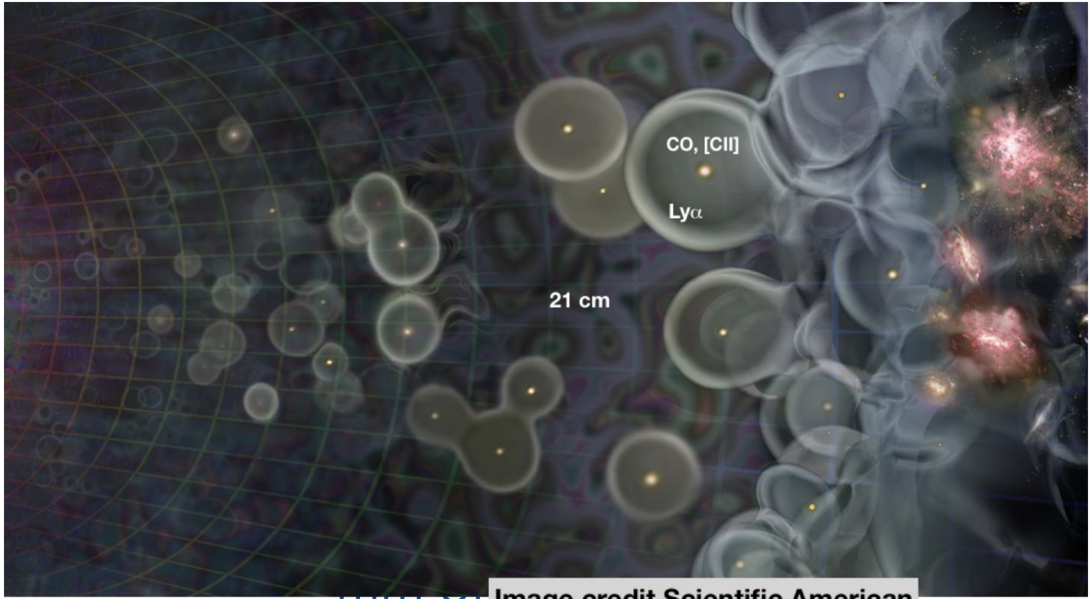
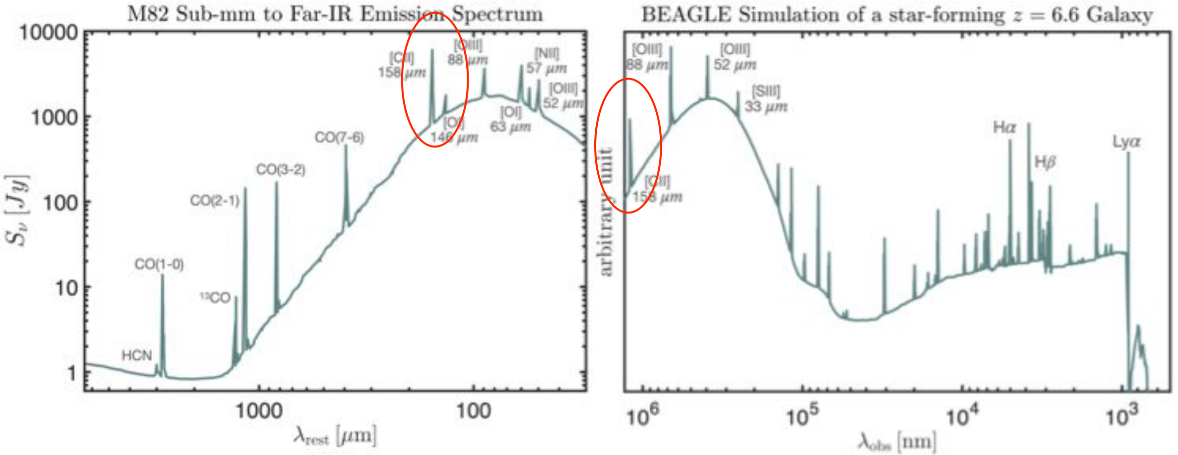


Image credit Scientific American

[CII]

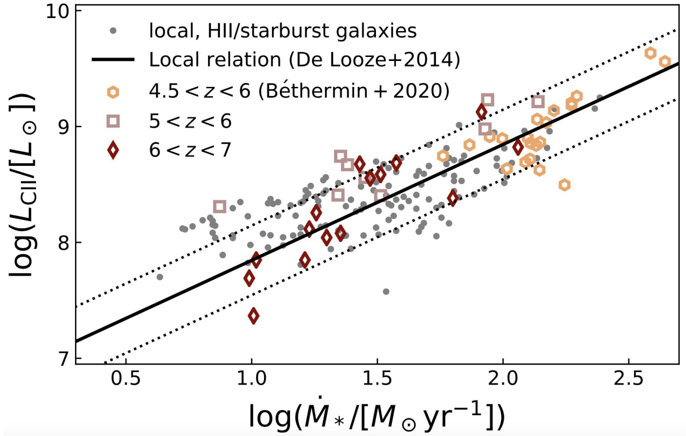
Fine structure line at 158 um

- Traces star formation
- Typically very bright
- Frequency range with technology experience



Bernal and Kovetz 2023

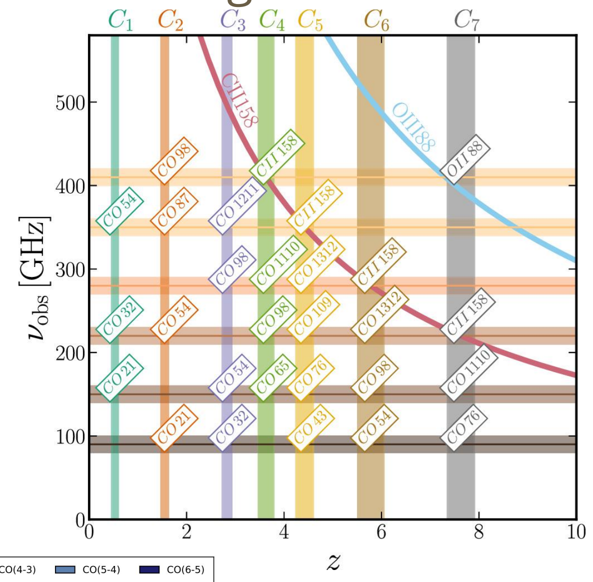
arXiv:2012.09160



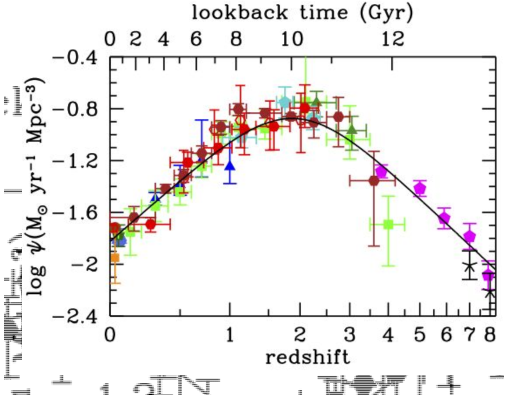
Sun et al 2021

CO

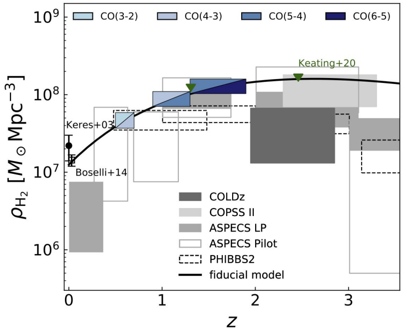
Roy and Battaglia 2024



- Molecular gas is “fuel” for star formation
- Many lines = Cross-correlation
- Probe at a range of frequencies
- Again, frequency range with technology experience



Madau and Dickenson 2014



Sun et al 2021

We can use CO and [CII] across redshifts!

Science Targets

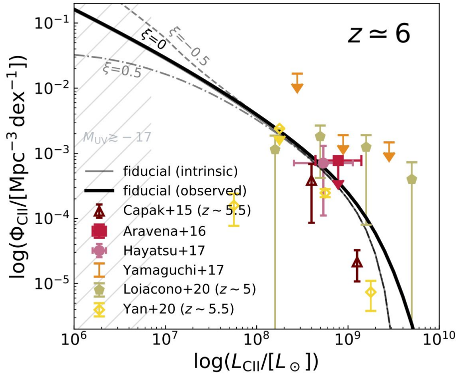
Star formation across cosmic time

Probing reionization

3D “tomography” of [CII] / CO across cosmic time

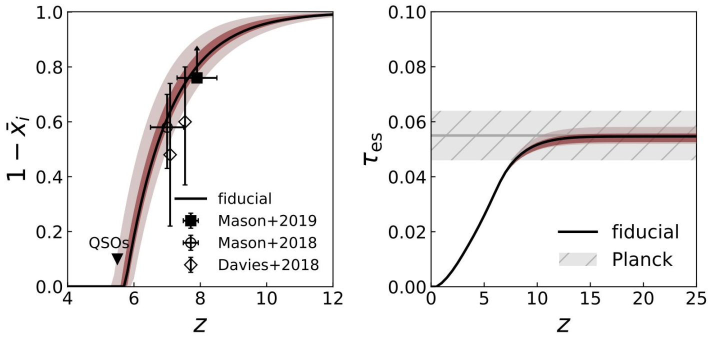
– dark energy, LSS evolution, neutrinos

[CII] Luminosity Function



Sun et al 2021

See also Gkogkou 2023 and many others



Sun et al 2021

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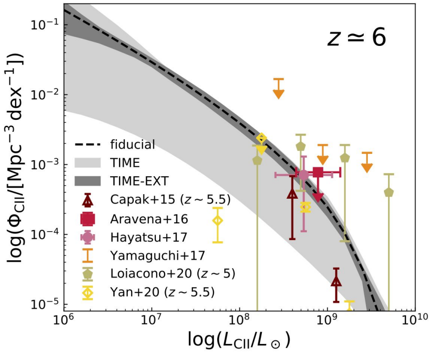

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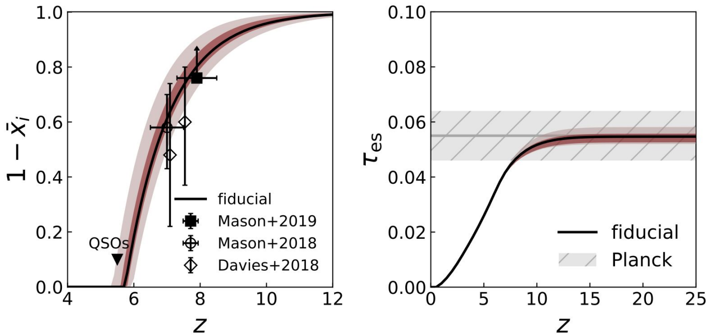


Sun et al 2021

Science Targets

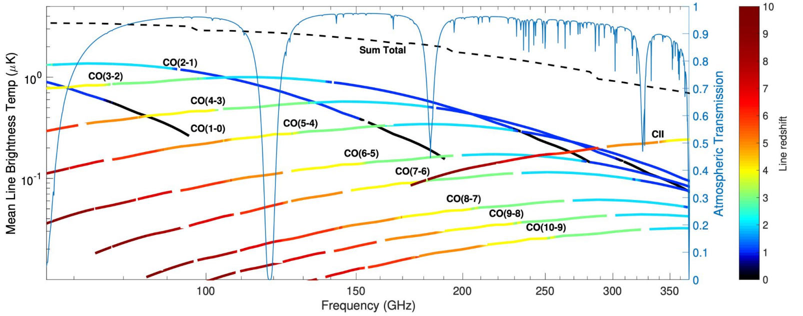
Spec-hrs	Example	Deployment Timescale	$\sigma(M_\nu)$ [eV] Int.	$\sigma(M_\nu)$ [eV] No Int.	$\sigma(N_{\rm eff})$ Int.	$\sigma(N_{\rm eff})$ No Int.
10^5	TIME	Now	0.69 (0.066)	0.48 (0.061)	2.8 (0.11)	2.0 (0.10)
10^6	TIME-EXT	3 yr	0.21 (0.047)	0.14 (0.043)	0.87 (0.087)	0.67 (0.082)
10^7	SPT-like, 1 tube	4 yr	0.066 (0.028)	0.044 (0.023)	0.27 (0.051)	0.21 (0.043)
10^8	SPT-like, 7 tubes	8 yr	0.021 (0.013)	0.014 (0.0097)	0.088 (0.023)	0.0674 (0.020)
10^9	CMB-S4-like, 85 tubes	12 yr	0.0087 (0.0068)	0.0048 (0.0041)	0.045 (0.016)	0.022 (0.013)

Star formation across cosmic time

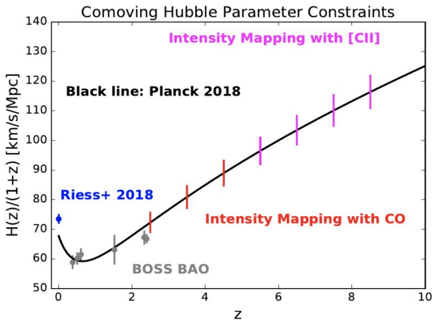
Probing reionization

3D “tomography” of [CII] / CO across cosmic time

– dark energy, LSS evolution, neutrinos



Moradinezhad Dizgah et al 2022



Karkare and Bird 2018
Moradinezhad Dizgah and Keating 2018
And more!

Need to understand and remove interlopers and have very high sensitivity

– mm Universe 2025 –

Challenges

Interloper lines

Instrument systematics

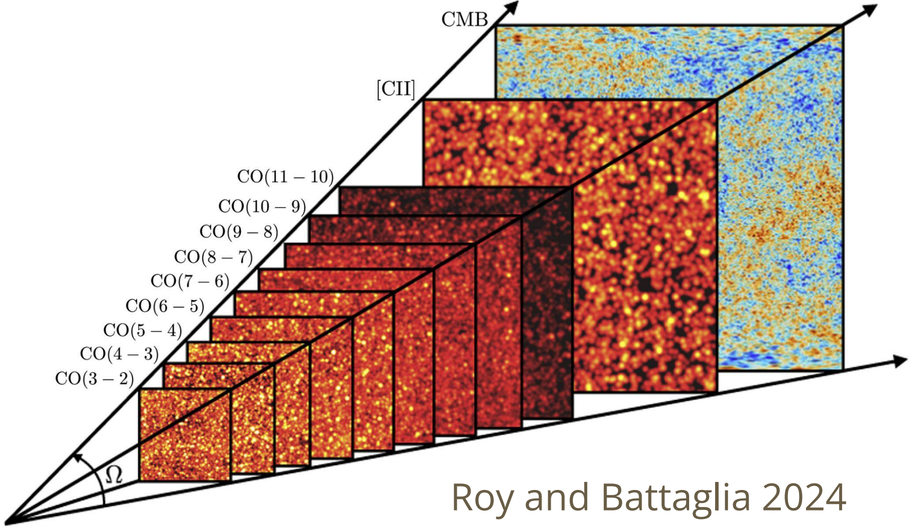
Astrophysical interpretation

Challenges

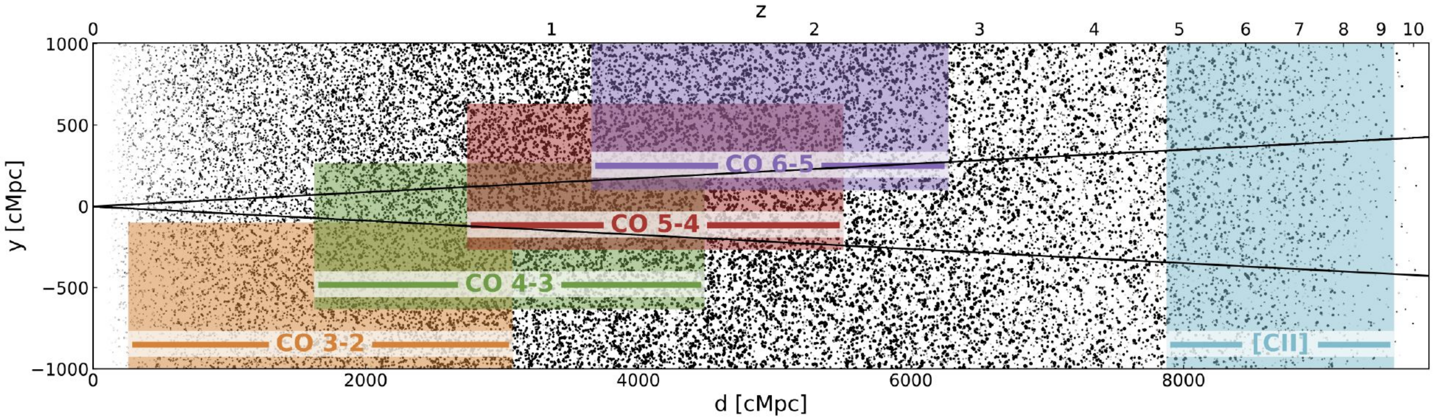
Interloper lines

Instrument systematics

Astrophysical interpretation



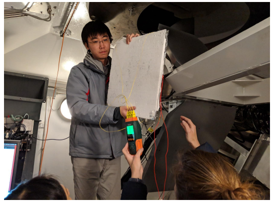
Roy and Battaglia 2024



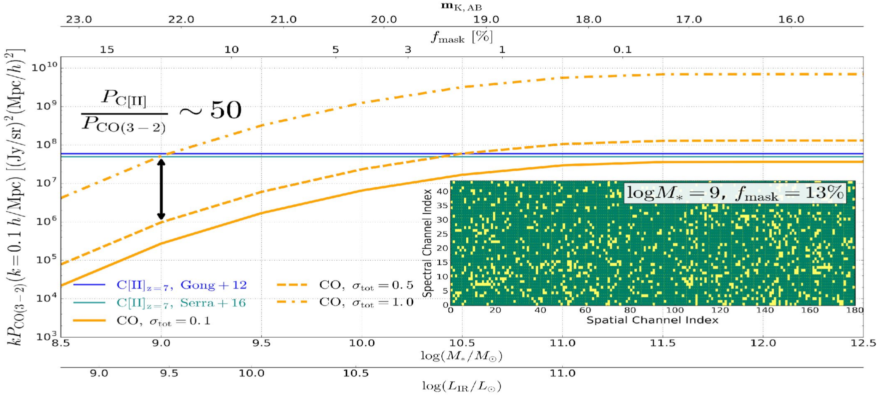
– mm Universe 2025 –

Ryan Keenan

Challenges



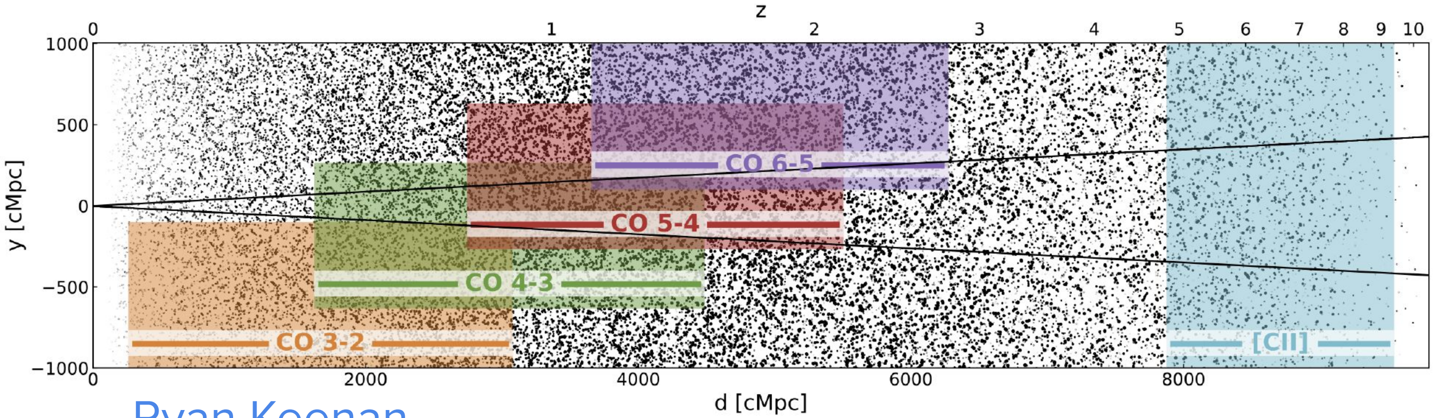
Sun+2018



Interloper lines

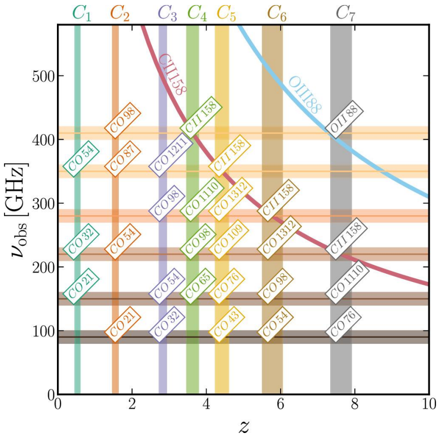
Instrument systematics

Astrophysical interpretation



Ryan Keenan

– mm Universe 2025 –



Roy and Battaglia 2024

Also C. Karoumpis et al. 2024

Challenges

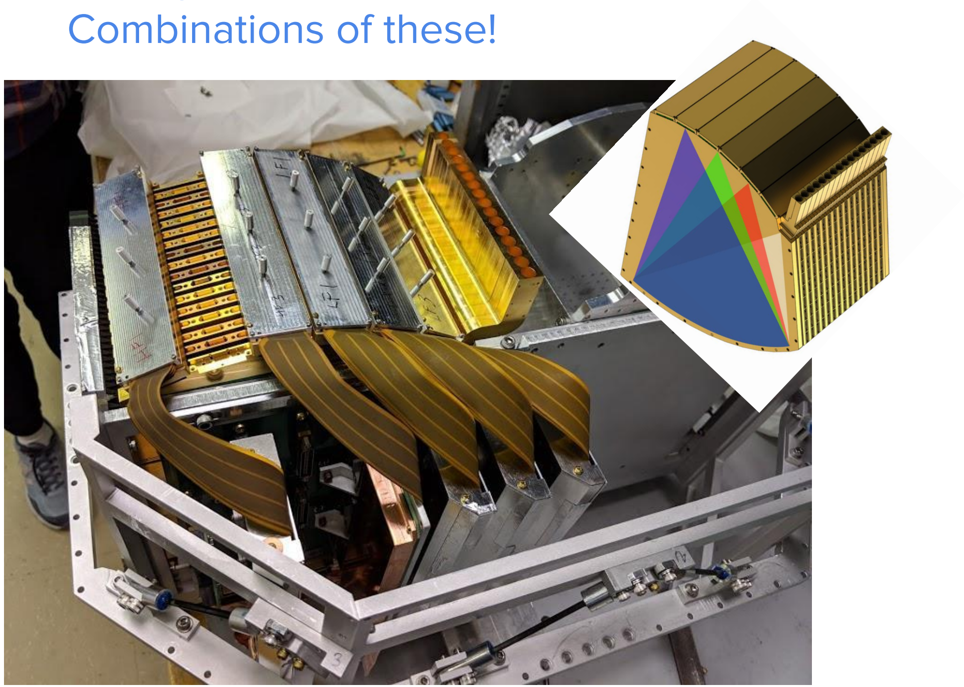
Interloper lines

Instrument systematics

Astrophysical interpretation

You need a mm-wavelength spectrometer and sensitive detectors (TES or KIDS)

Grating
On-chip spectrometers
Fabry-Perot interferometer
Fourier transform spectrometers
Waveguide spectrometers
Combinations of these!



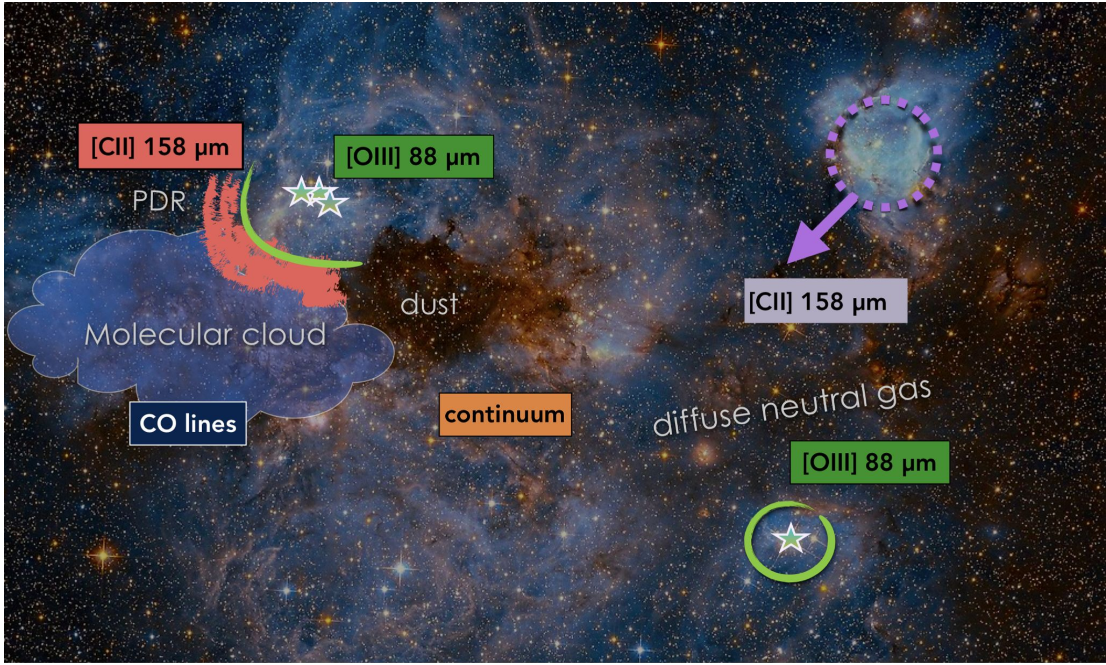
Challenges

Interloper lines

Instrument systematics

Astrophysical interpretation

We need theory / modeling as well as measurements to tease out astrophysics and cosmology



Things we don't know: escape fractions of photons, metallicity, and more.

From Livia Vallini

Quick overview of experiments

Range of technology for doing mm - THz spectroscopy

➔ Experimental systematic checks

Multiple science goals with these experiments (e.g. [CII], CO)

➔ Astrophysical systematics checks

You will hear about SPT-SLIM and COMAP right after my talk so I'll update on TIME and CCAT and touch on a few other experiments in the field in *roughly* chronological order.

Experimental Landscape

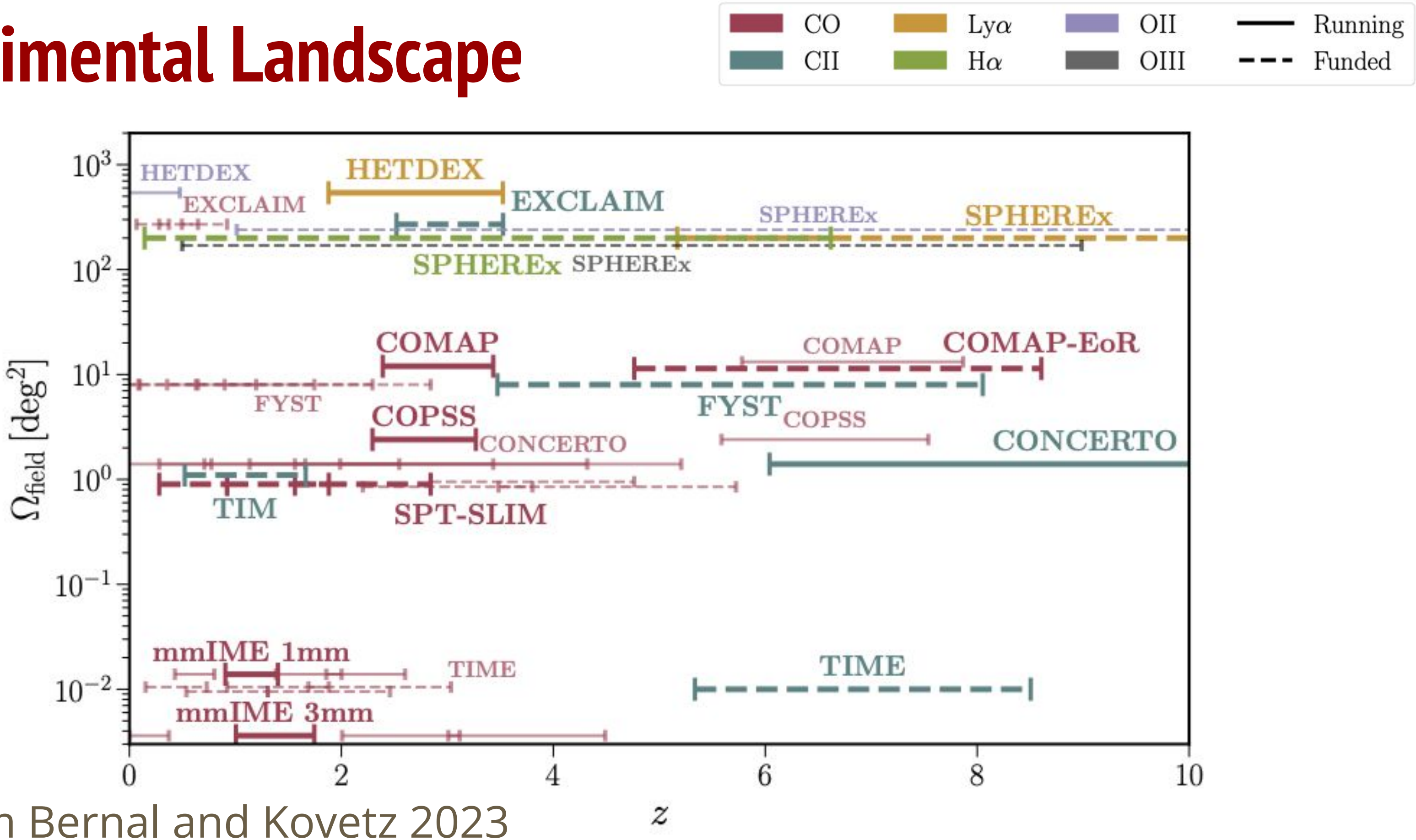
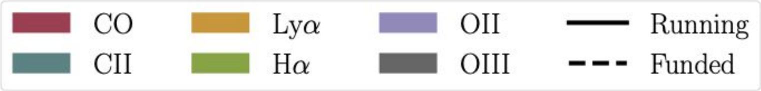


Figure from Bernal and Kovetz 2023

Experimental Landscape



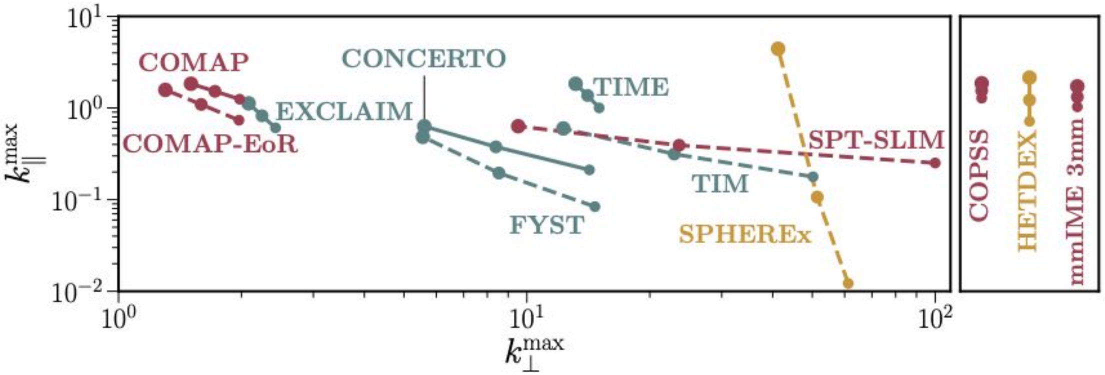
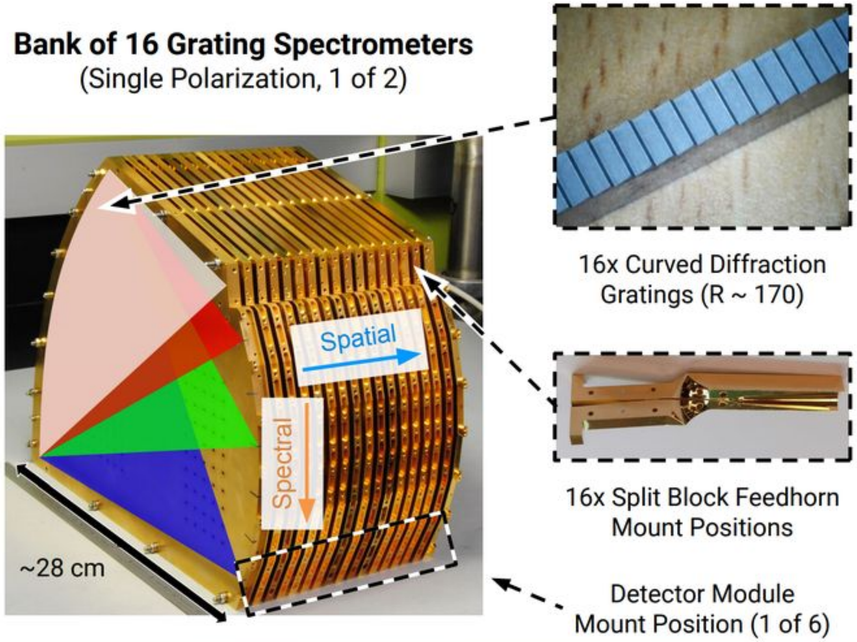
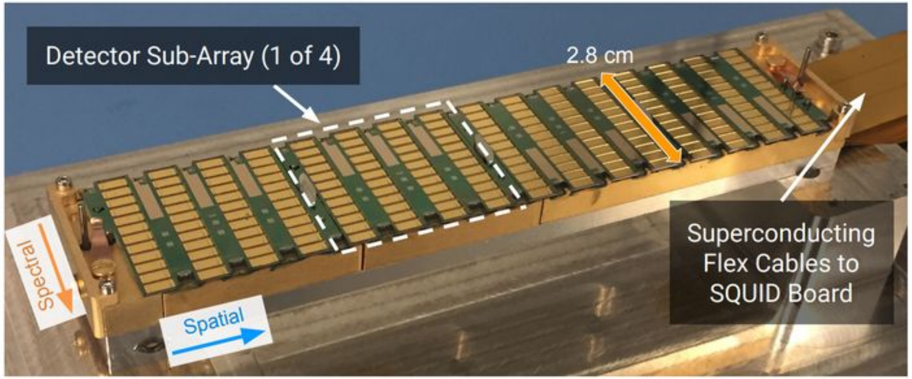


Figure from Bernal and Kovetz 2023

TIME–The Tomographic Ionized-Carbon Mapping Experiment

- 2x 16 feedhorns under a polarizer
- ~1 arcmin beam
- 2x grating spectrometers, R~100, 183-326 GHz, bw ≈ 1.5 GHz
- 3x LF/HF modules: 4 spatial × 8/12 spectral channels
- Total: 16 spatial × 60 spectral → 960 TES pairs for 1D science scans
- Arizona Radio Observatory 12m





The TIME Collaboration

Cornell University

Abigail Crites [PI]
Victoria Butler
Dongwoo Chung
Ben Vaughan
Shwetha Prakash
Selina Yang
Sophie McAtee
Sofia Pereira
Sukhman Singh

Caltech JPL

Jamie Bock
Matt Bradford
Tzu-Ching Chang
Yun-Ting Cheng
Clifford Frez
Jonathon Hunacek
Kenny Lau
Paolo Madonia
Lorenzo Moncelsi
Anthony Turner

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Chao-Te Li
Tashun Wei

The University of Arizona

Dan Marrone
Nick Emerson
Isaac Trumper
Evan Mayer
Ian Lowe

RIT Rochester Institute of Technology

Mike Zemcov
Audrey Dunn
Fiona Hufford
Tess Caze-Cortes
Caleb Greenburg

UCI University of California, Irvine

Asantha Cooray

University of Toronto

Samantha Berek
Dang Pham
Baria Khan
Lisa Nasu-Yu

Max Planck Institute for Astronomy

Ryan Keenan

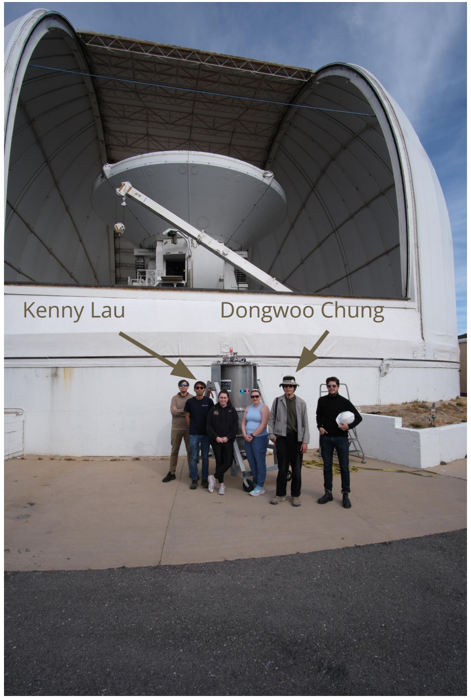
Northwestern CIERA

Guochao (Jason) Sun

supported in part by:

NSF [AST 1910598, 23080{39,40,41,42}]

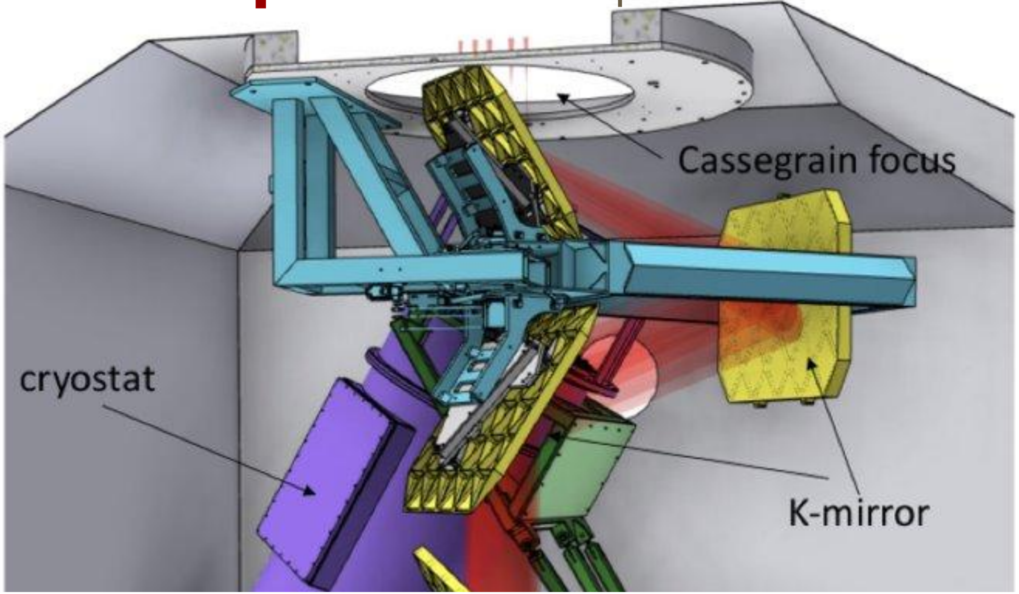
Keck Institute for Space Studies

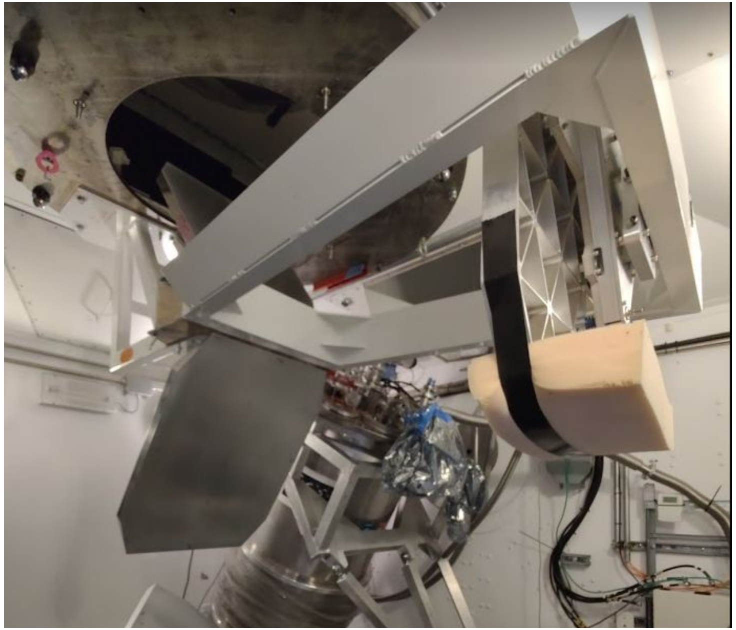


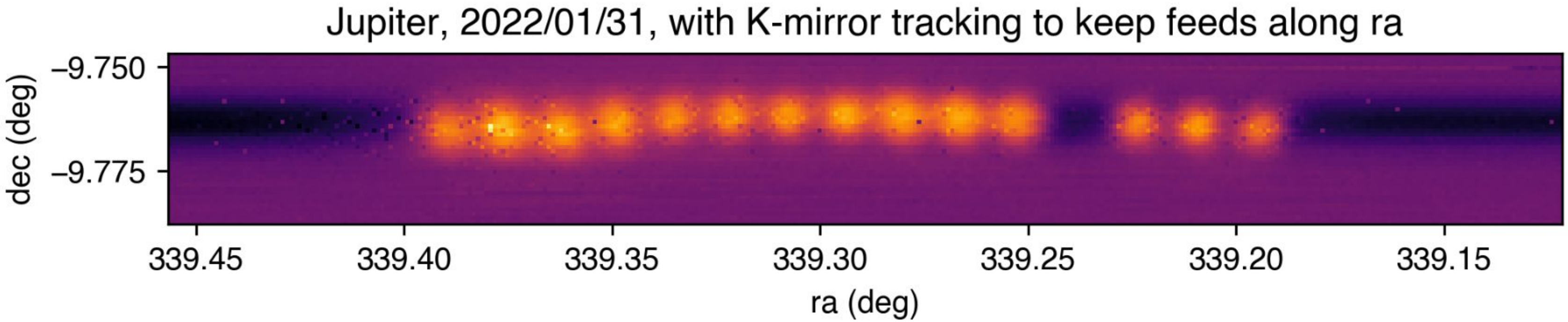
Shwetha Prakash Victoria Butler Selina Yang

TIME Optics

Marrone, Emerson, Trumper at U of A







TIME Status I

Two commissioning runs in 2022 and 2024

- operated from the Arizona Radio Observatory 12 m telescope, at Kitt Peak
- verified on-sky focus, beams with partially integrated instrument
- verified hyperspectral imaging with both continuum and spectral line sources

TIME Status II

- Currently analyzing data from observations of nearby objects to verify spectral capabilities, calibration, and the TIME data pipeline.
- We use a set of well-understood technologies combined into a pathfinding experiment for mm-wave LIM, surveying [C II] at EoR and CO rotational lines near ‘cosmic noon’, z~2.
- Our commissioning runs in 2022 and 2024 provided important tests of the TIME instrument—some avenues of clear improvement.
- We expect to begin science observations this upcoming winter.

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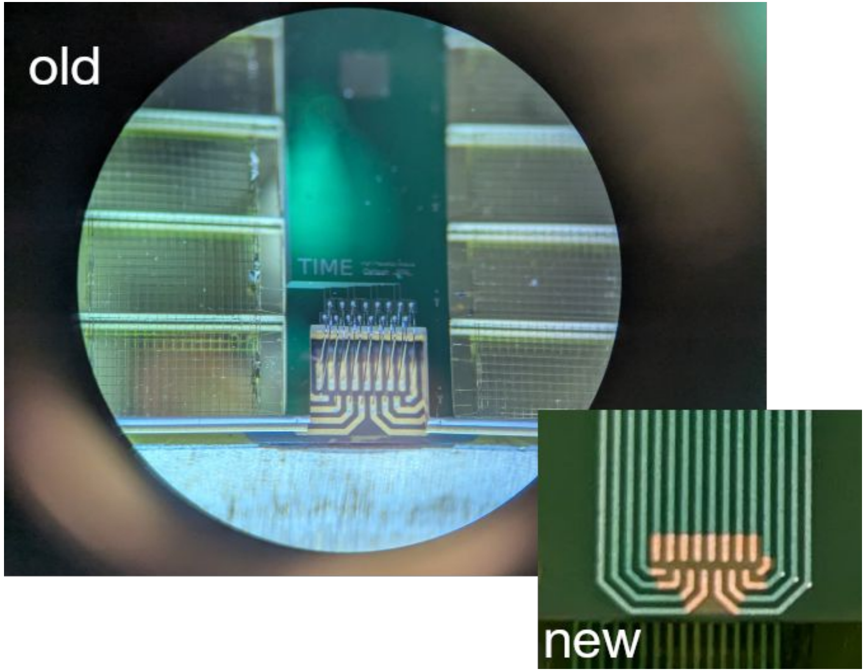
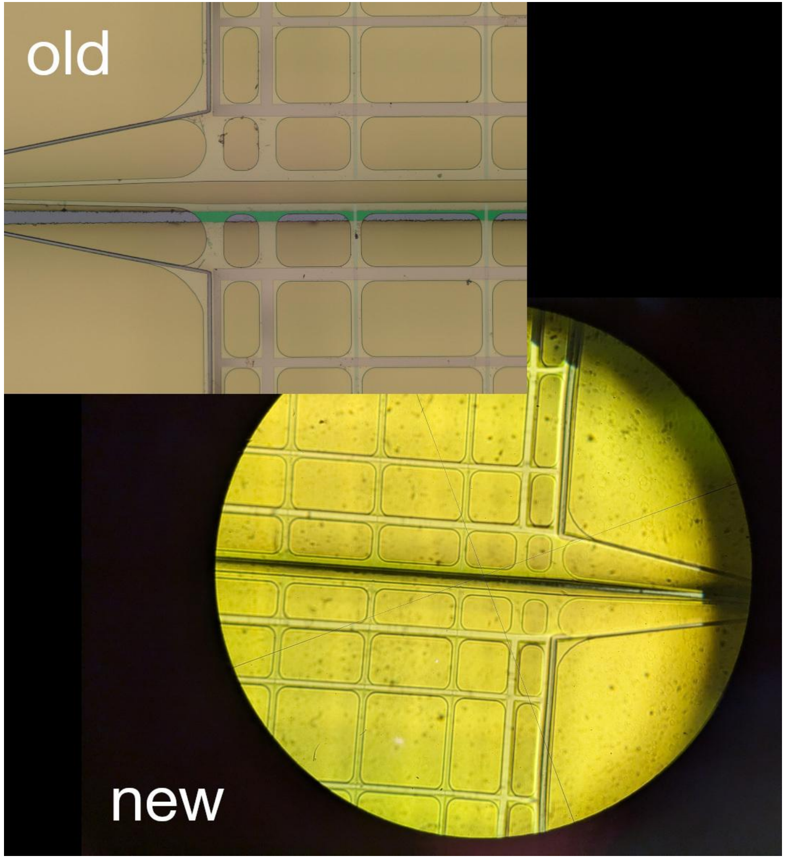
- Currently analyzing data from observations of nearby objects to verify spectral capabilities, calibration, and the TIME data pipeline.
- We use a set of well-understood tech pathfinding experiment for mm-wave rotational lines near 'cosmic noon', z~
- Our commissioning runs in 2022 and the TIME instrument—some avenues
- We expect to begin science observati

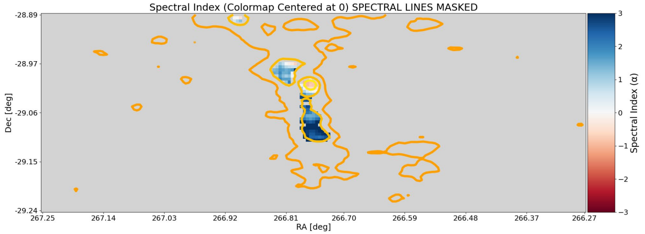
Parameter	TIME	TIME-EXT
Number of spectrometers (N_{feed})	32	32
Dish size (D_{ap})	12 m	10 m
Beam size (θ_{FWHM})[a]	0.43 arcmin	0.52 arcmin
Spectral range (ν_{min}, ν_{max})[b]	183–326 GHz	183–326 GHz
Spectral bands	LF: 200–265 GHz HF: 265–300 GHz	LF: 200–265 GHz HF: 265–300 GHz
Resolving power (R)	90–120	90–120
Observing site	ARO	LCT
Noise equivalent intensity (NEI)	5 MJy sr^{-1} s$^{1/2}$	2.5 MJy sr^{-1} s$^{1/2}$
Total integration time (t_{obs})	1000 hours	3000 hours
Survey power[c]	1	12

Hardware Upgrades





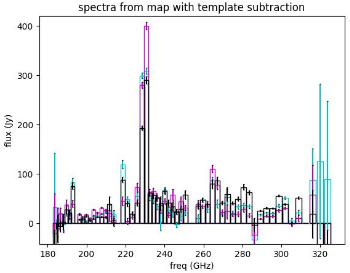
Measurements of the Galactic Center



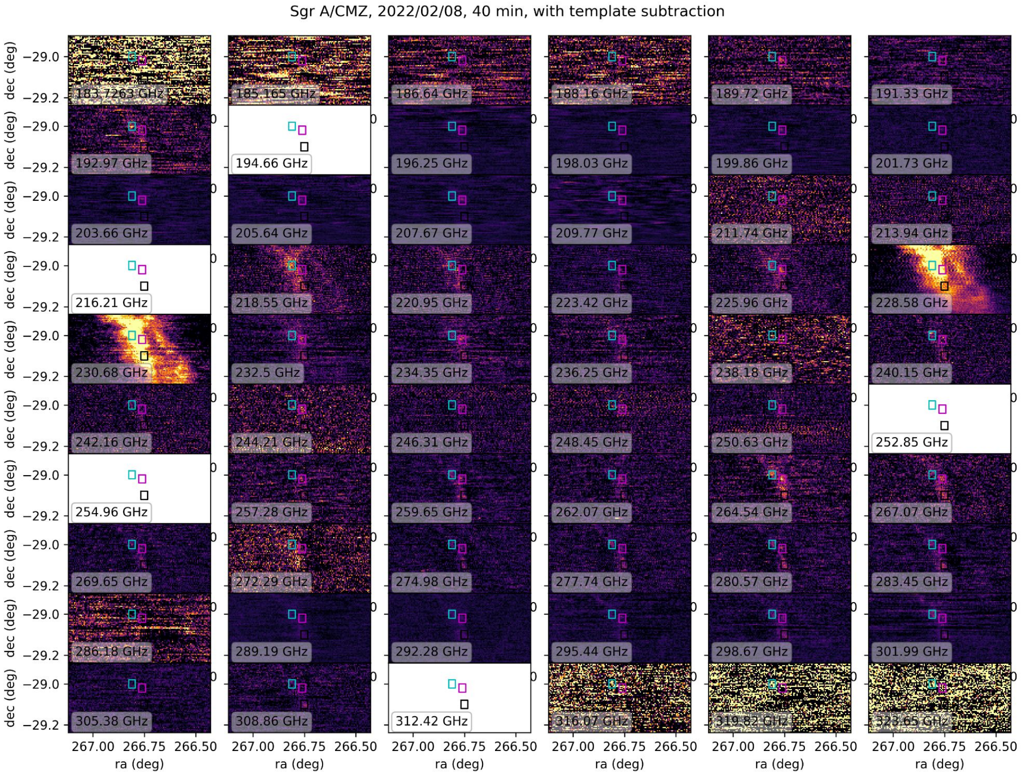
Spectral Index map

Butler et al 2024 Proceedings of the SPIE, Volume 13102, id. 131022G 11 pp. (2024).

More detailed publication in prep in measurements of the galactic center. Chung, Yang, McAtee



Spectrum

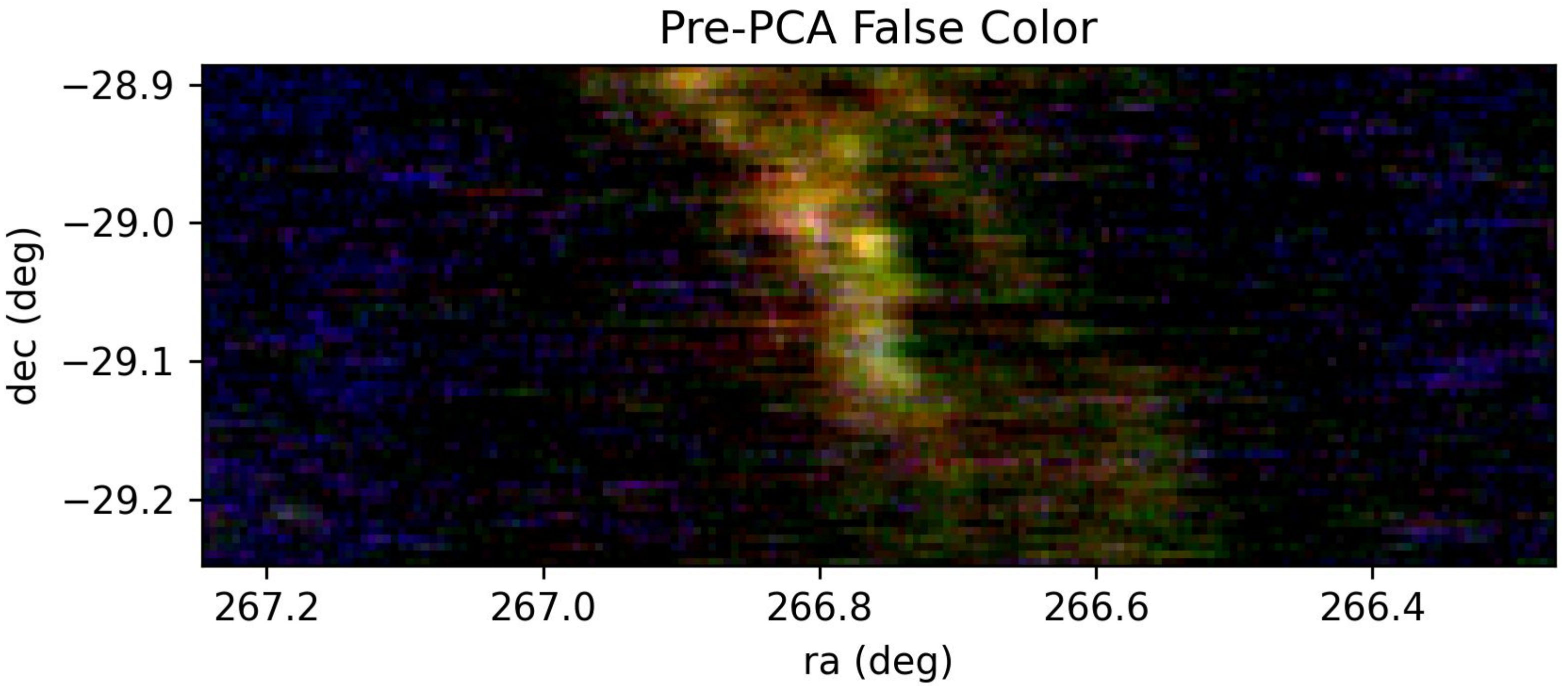


Cyan box = 50 km/s cloud

Magenta box = Circumnuclear Disk (CND)

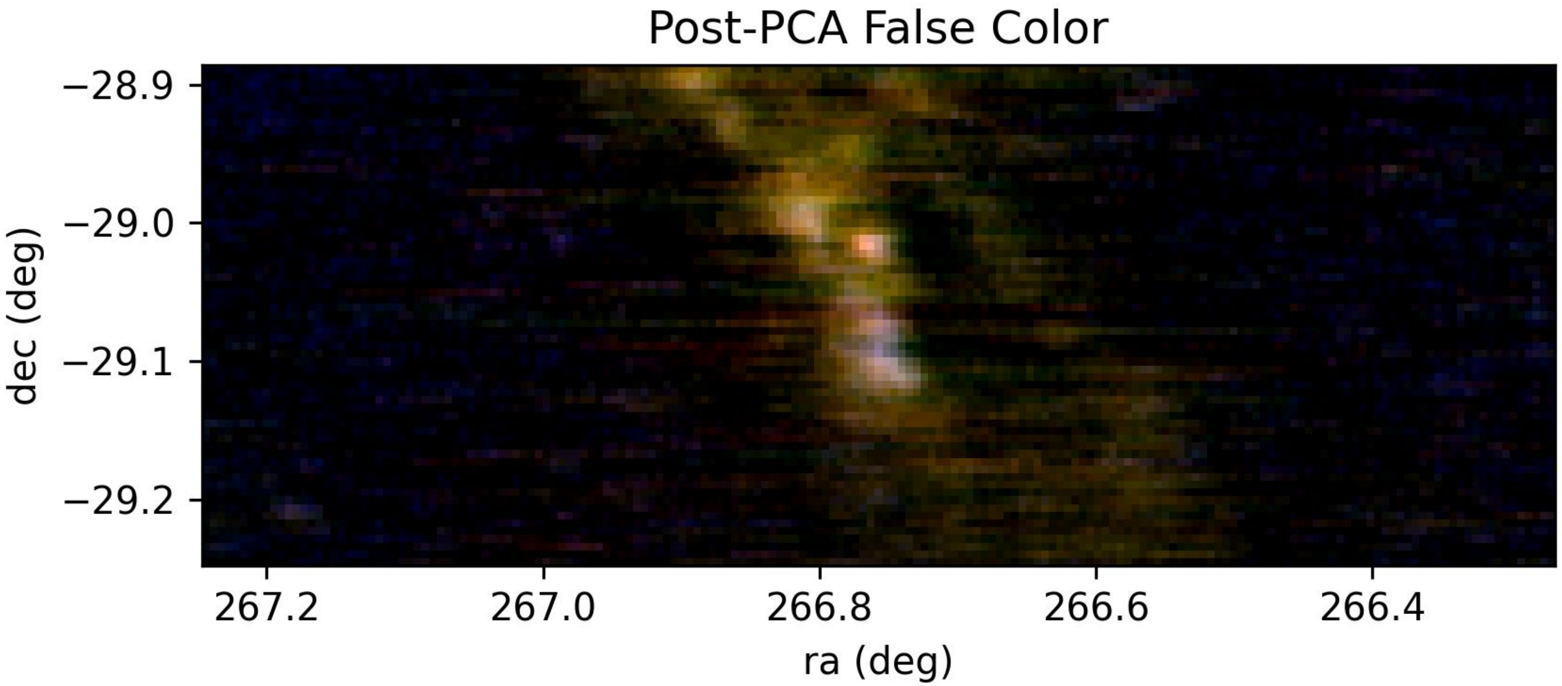
Black box = 20 km/s cloud

Exploring Atmospheric Noise Removal Strategies



Cornell Undergrad
Sophie McAtee

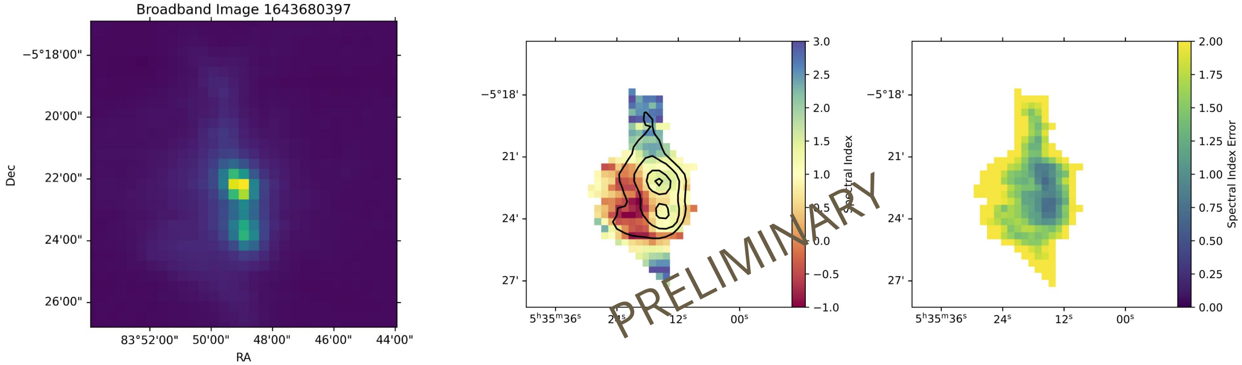
Exploring Atmospheric Noise Removal Strategies



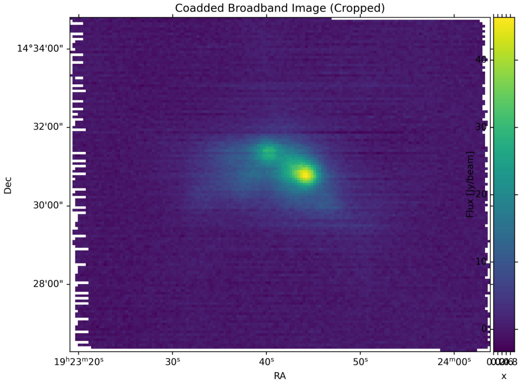
Cornell Undergrad
Sophie McAtee

OMC and other sources

OMC (Vaughan, Prakash, Butler ++ paper in prep)



G49.5-0.4 SF region



– mm Universe 2025 –

CONCERTO

CONCERTO

Fourier-Transform Spectrometer installed at APEX in Apr 2021

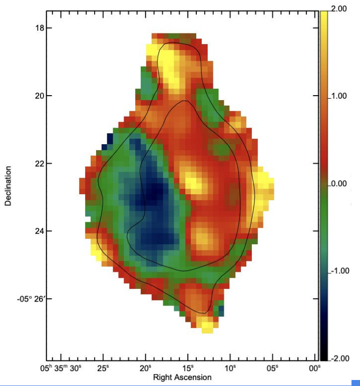
- Funded by ERC 2018 Adv. Grant (+A*MIDEX+FOCUS)
- KIDS arrays (2 arrays of 2,152 KIDS) — cooled down at 60mK
- Spectra from 130 to 310 GHz, δν up to 1.5 GHz, FOV D~18'
  - Dust continuum emission, CO lines at z<2.5, [CII] line at z>5
  - Galaxy cluster (SZ), star forming regions & molecular clouds

- Installation successful (despite covid restrictions), first light (May the 6th) rapid & wonderful!

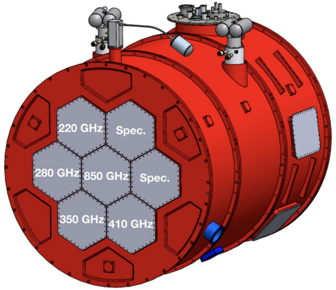
- Scientific observations from July 2021 to Dec 2022
  - 18 months of (quite smooth) operation
  - 174Tb of data (x5 uncompressed)
  - « [CII] LIM » Large Program on the COSMOS field (1.4 Sq. Deg)
  - 12 open time programs (Galactic regions, SMC, galaxy clusters)

Continuum, CO and Water vapour maps of the Orion Nebula First millimetre spectral imaging with CONCERTO

Désert et al 2025

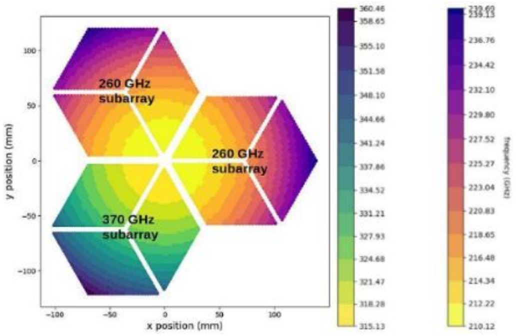


LIM on FYST: CCAT/Prime-Cam/EoR-Spec Overview

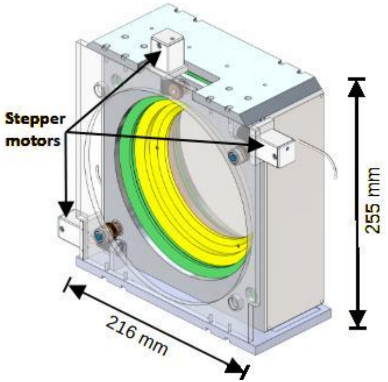


Led by Gordon Stacey

- Frequency Coverage: 210 – 420 GHz in total
  - [CII] 158 micron: z ~ 8.0 to 3.5 epoch of reionization to cosmic noon
  - [OI] 88 micron: z ~ 7.1 to 15.2 epoch of reionization
- Detector array is split:
  - two subarrays (3174 det./module) covering: 210 – 315 GHz
  - one subarray(3072 det./module) covering 315 – 420 GHz
- Spectrometer is based on a cryogenic tunable Farby-Perot Interferometer (FPI)
  - a single FPI covers both broad frequency bands simultaneously (2^{nd} and 3^{rd} order)
  - spectral resolving power: R ~ 100
- Total Field of View (FoV): ~1.3° /module

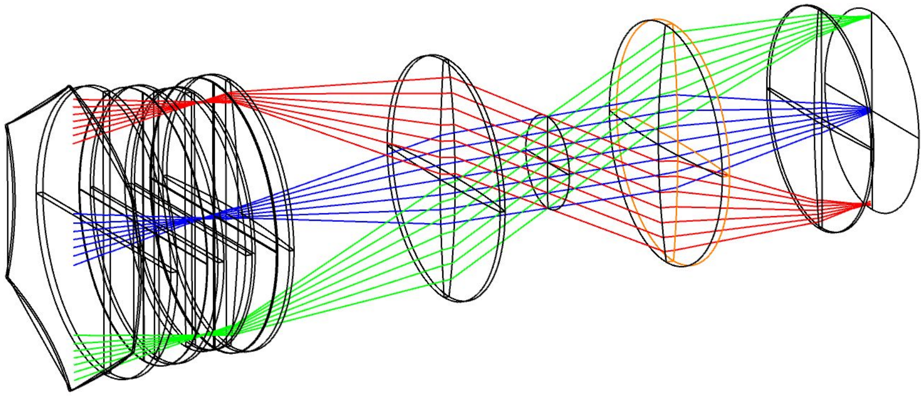


For normal incidence resonance at v_o=21

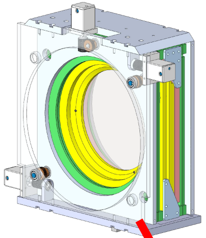


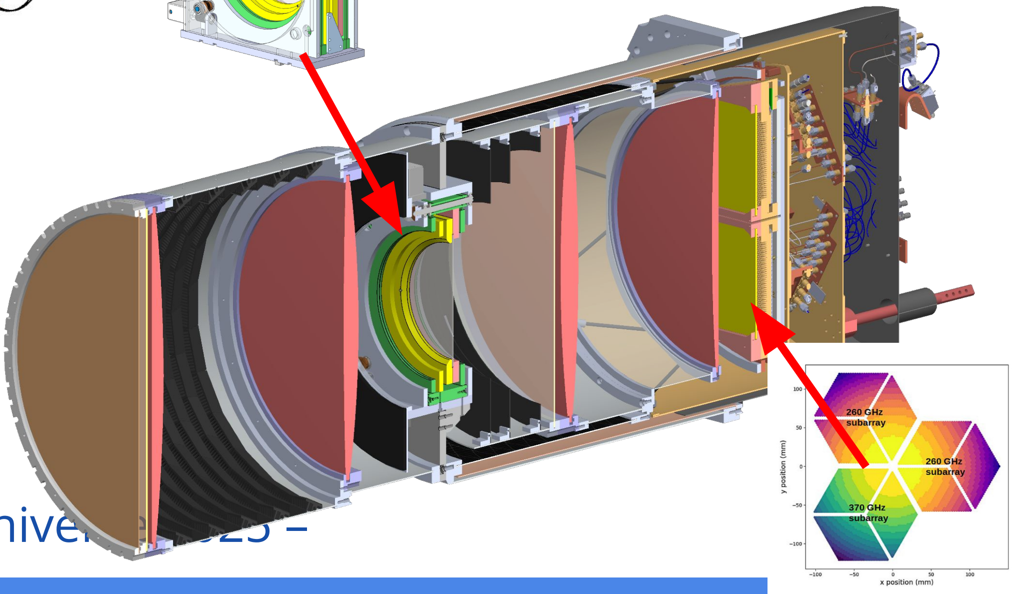
– mm Universe 2025 –

EoR-Spec Instrument module



Scanning, cryogenic Fabry-Perot Interferometer (FPI) located at the Pupil of the cold optics.





Frequency coverage: **210 - 420 GHz**
Redshift for [CII]: **z ~ 8.0 to 3.5**
(Late stages of EoR to cosmic noon)
Total Field of View (FoV): **(~1.3°/module)**
Angular resolution **30″ to 50″**
Spectral resolution **R~100**

LIM on FYST Status

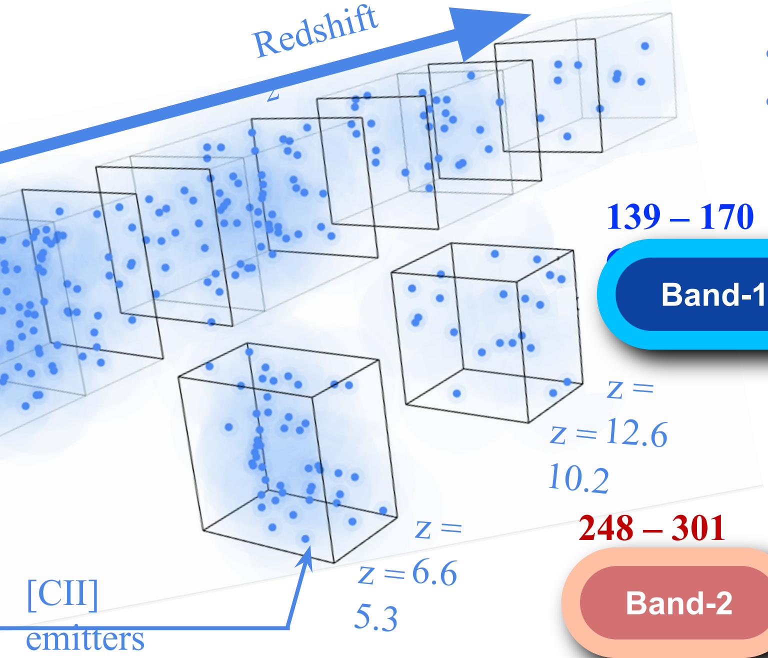
- FYST currently being assembled, first light 2026, LIM starting 2026/2027
- Focus on [CII] and CO LIM - first round of observations 210-420GHz with EoR spec
- Challenges are to isolate [CII] signal
  - Targeted Masking
  - Spectral line deconfusion
  - Cross-correlations
- Additional low frequency bands being considered for future spectrometer

https://ccatobservatory.org/

Dual-band line intensity mapping using TIFUUN

THz Integral Field Units with Universal Nanotechnology

- 100 spaxels x 100 colors (R~500) x 2 bands = 20,000 voxels in total
- Simultaneous observations of line pairs at the same redshift range
  - cross-correlation to mitigate contaminations & systematics



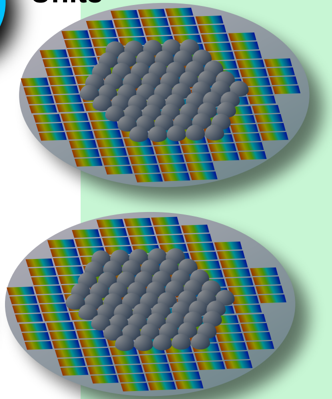
139 – 170

Band-1

248 – 301

Band-2

Integral Field Units



Redshift range	Band-1	Band-2
z = 10.2 – 12.6	[CII] 158 μm	[OIII] 88 μm
z = 1.9 – 2.2	CO(4-3), [CI](1-0)	CO(7-6), [CI](2-1)

– mm Ur

Field of view (@ASTE)
~8 arcmin (Band-1)
~5 arcmin (Band-2)

TIFUUN

	DESHIMA 1.0	DESHIMA 2.0	TIFUUN for line intensity mapping	
			Band-1	Band-2
Frequency range	332 – 377 GHz	220 – 440 GHz	139-170 GHz	248-301 GHz
Band-width	45 GHz	220 GHz	31 GHz	53 GHz
Number of spaxels	1	1	100	100
Number of spectral channels	49	347	100	100
Spectral resolution	~380	~500	~500	~500
Number of KIDs	49	347	10,000	10,000
Deploy-ment	2017	2023-2024	2026-2029	

A growing field!

https://lambda.gsfc.nasa.gov/product/expt/lim_experiments.html

Lambda hosts a list of current and future lim experiments – we are focused on the mm ones, but folks are doing lim in radio, TeraHz, IR, optical (e.g. 21 cm, SPHEREx)

LIM Overviews:

Yearly LIM conferences and summary papers

Kovetz et al 2019 arXiv:1903.04496

Bernal and Kovetz 2022 arXiv:2206.15377

COMAP Pathfinder *	CO Mapping Array Pathfinder [ADS]	CO 1-0	star formation	2019 - date	Coherent	2.4	3.4	26	34	Ground
COMAP Pathfinder *	CO Mapping Array Pathfinder [ADS]	CO 2-1	reionization	2019 - date	Coherent	5.8	7.8	26	34	Ground
CONCERTO *	CarbON CII line in post-rEionization and ReionizaTiOn epoch [ADS]	[CII]	reionization	2021-date	MKID, FTS	4.5	8.5	200	360	Ground
CONCERTO *	CarbON CII line in post-rEionization and ReionizaTiOn epoch [ADS]	CO J={2,3,4,5}	star formation	2021-date	MKID, FTS	0.3	2	200	360	Ground
COPSS	CO Power Spectrum Survey [ADS]	CO 1-0	star formation	2005-2008	Interferometer	2.3	3.3	27	35	Ground
TIME-CII *	Tomographic Ionized-Carbon Mapping Experiment [ADS]	[CII]	reionization	Future	Grating + TES	5.3	8.5	183	326	Ground
TIME-CO *	Tomographic Ionized-Carbon Mapping Experiment [ADS]	CO J={2,3,4,5}	star formation	Future	Grating + TES	5.3	8.5	183	326	Ground
YTLA *	Yuan-Tseh Lee Array	CO 3-2	star formation	2017-date	Interferometer	2.4	3	86	102	Ground
YTLA *	Yuan-Tseh Lee Array	CO 2-1	star formation	2017-date	Interferometer	1.2	1.7	86	102	Ground

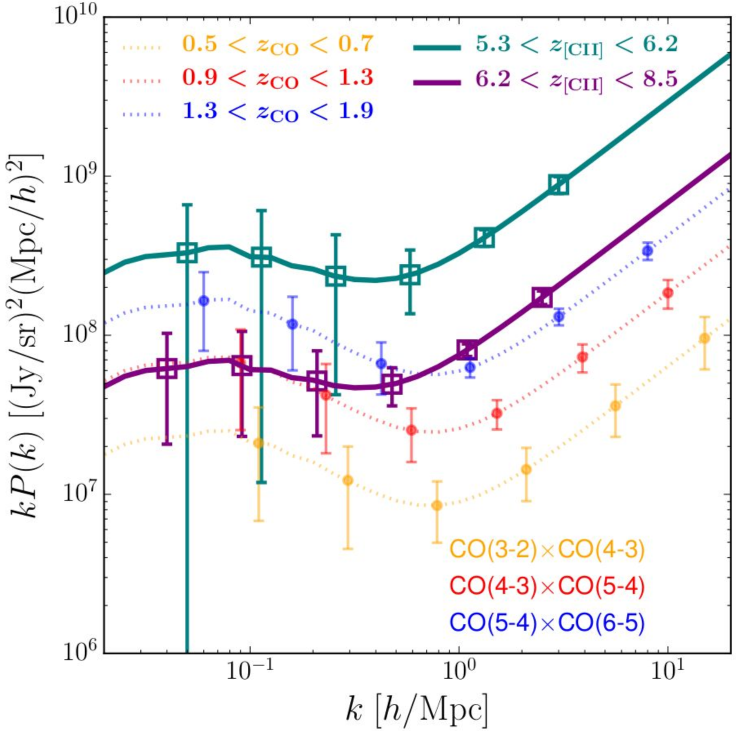
Conclusions

Line intensity mapping in the mm wavelengths will use technologies similar to the ones that have been developed in our field to probe astrophysics and cosmology over cosmic time – in particular star formation during reionization and survey molecular gas at $z \sim 2$

There are many folks working on modeling and measuring line intensity mapping signals in the mm-wavelengths using CO and [CII] and we hope to have first measurements of this signal soon

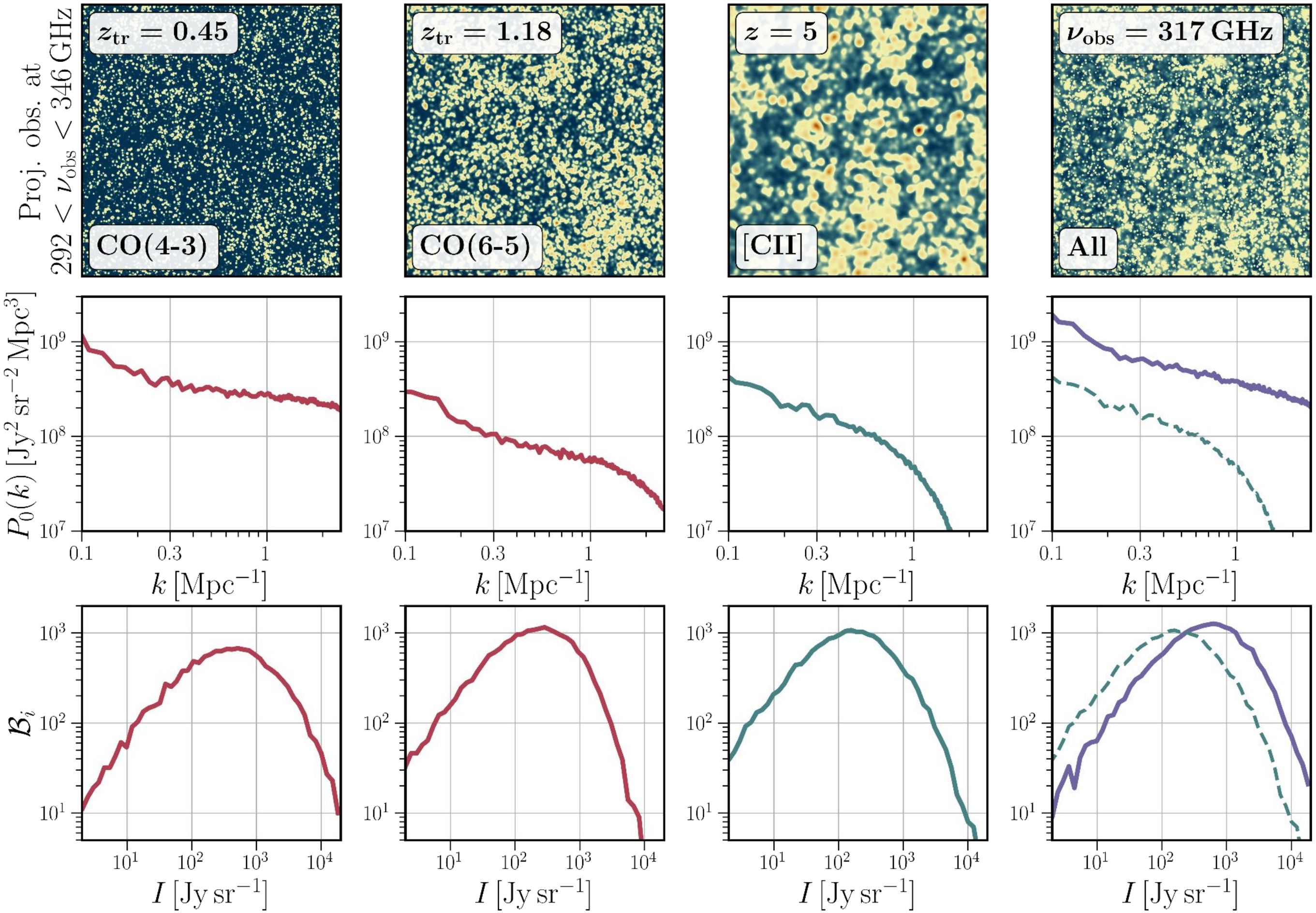
Backup Slides

TIME Predicted Power Spectrum

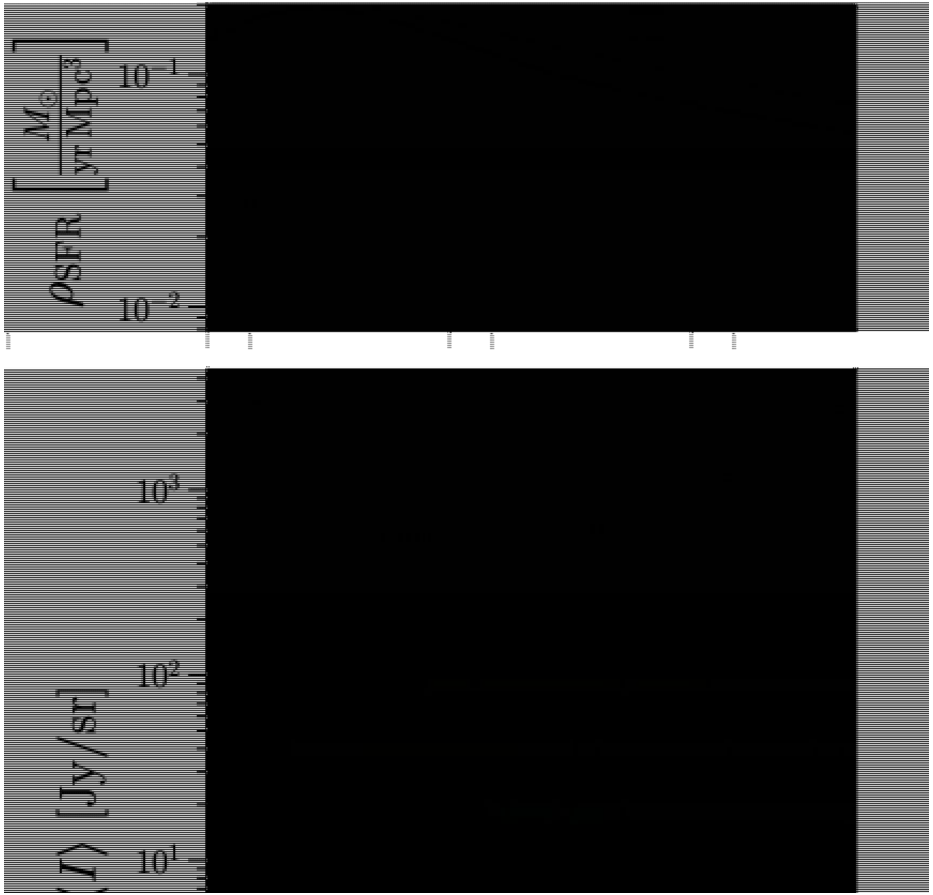


Plot by Jason Sun
Sun et al 2021

Error bars assume
1000 hr TIME survey



Bernal and Kovetz 2023



Bernal and Kovetz 2023

Parameter	TIME	TIME-EXT
Number of spectrometers (N_{feed})	32	32
Dish size (D_{ap})	12 m	10 m
Beam size (θ_{FWHM})[a]	0.43 arcmin	0.52 arcmin
Spectral range (ν_{min}, ν_{max})[b]	183–326 GHz	183–326 GHz
Spectral bands	LF: 200–265 GHz HF: 265–300 GHz	LF: 200–265 GHz HF: 265–300 GHz
Resolving power (R)	90–120	90–120
Observing site	ARO	LCT
Noise equivalent intensity (NEI)	5 MJy sr^{-1} s$^{1/2}$	2.5 MJy sr^{-1} s$^{1/2}$
Total integration time (t_{obs})	1000 hours	3000 hours
Survey power[c]	1	12