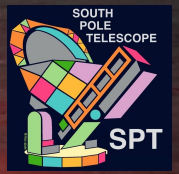
Cosmology with Line Intensity Mapping from Antarctica with SPT-SLIM and TIM

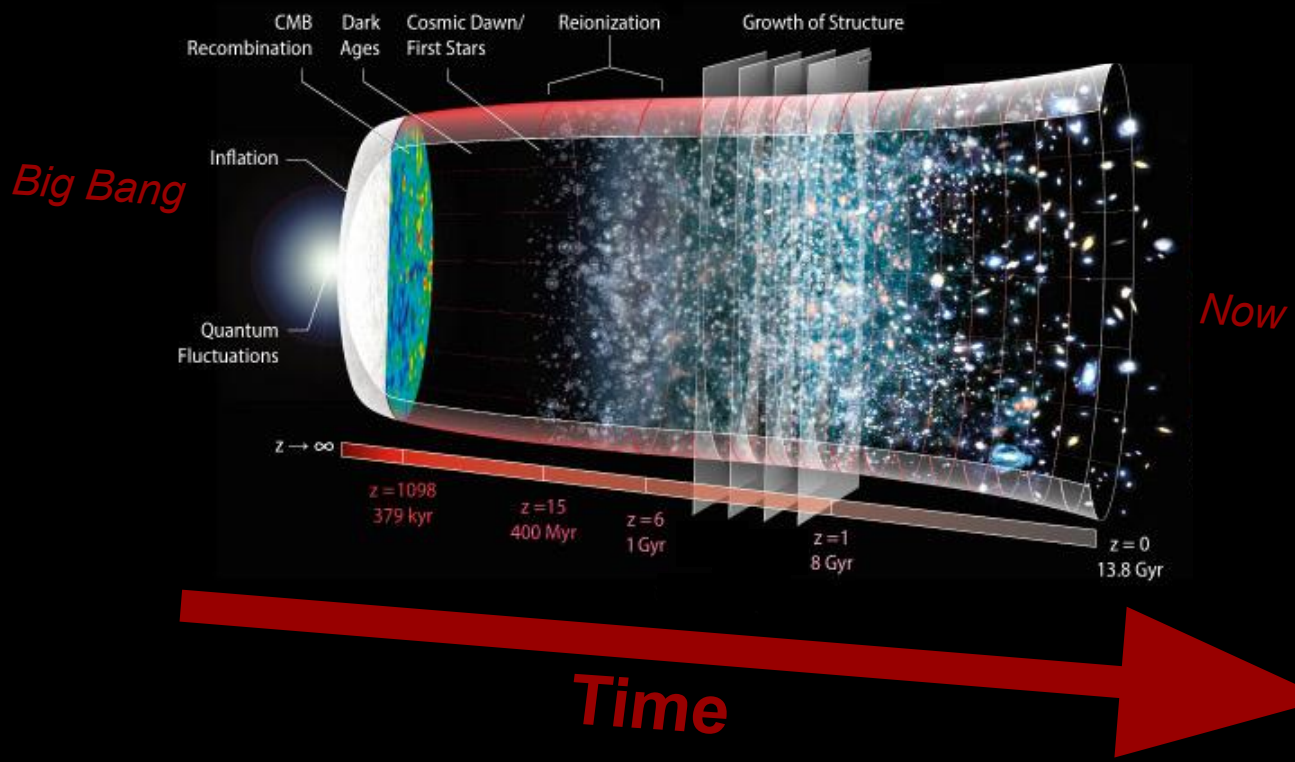
Jessica Avva Zebrowski
University of Chicago

Rencontres du Vietnam
8-11-25



Video: Matt Young

The Observable Universe



Unsolved Mysteries

What is dark energy?

What mechanism drove inflation?

How did the first galaxies and stars form?

Image Credit: NASA / LAMBDA Archive Team

The Observable Universe

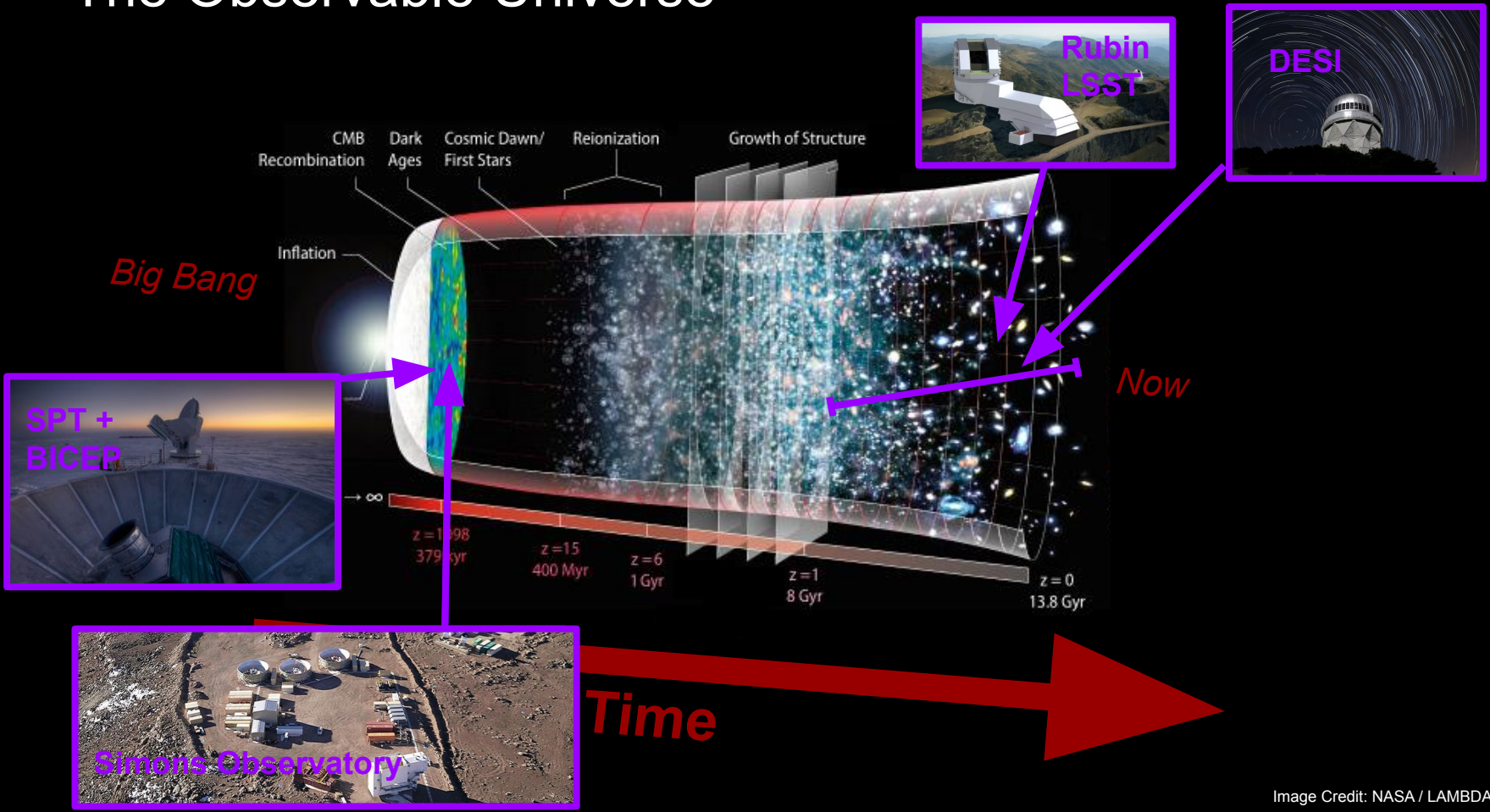
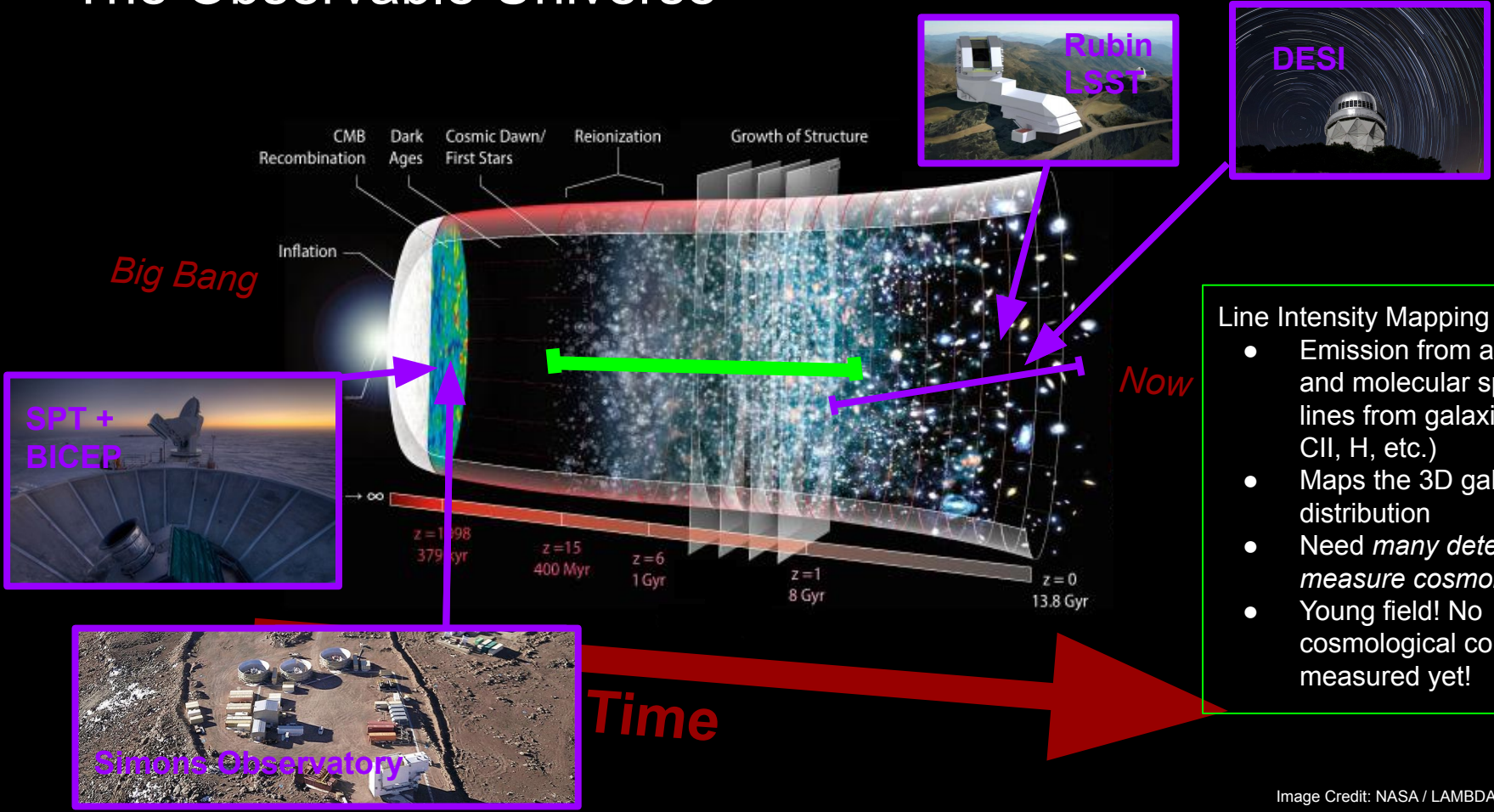


Image Credit: NASA / LAMBDA Archive Team

The Observable Universe

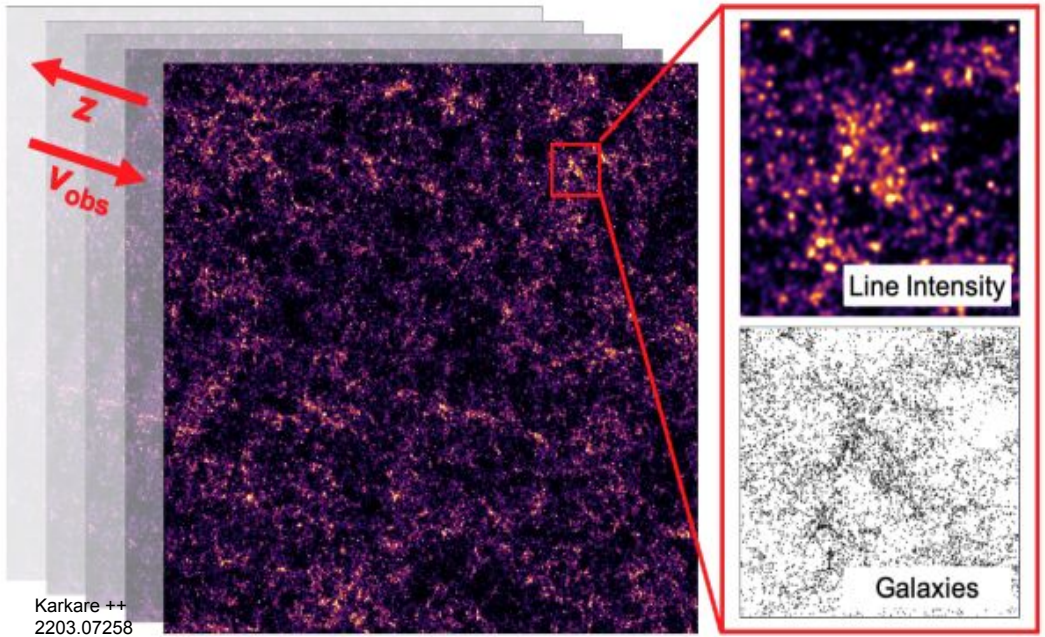


Line Intensity Mapping (LIM)

- Emission from atomic and molecular spectral lines from galaxies (CO, CII, H, etc.)
- Maps the 3D galaxy distribution
- Need *many detectors to measure cosmology*
- Young field! No cosmological constraints measured yet!

Image Credit: NASA / LAMBDA Archive Team

Line Intensity Mapping - The Measurement



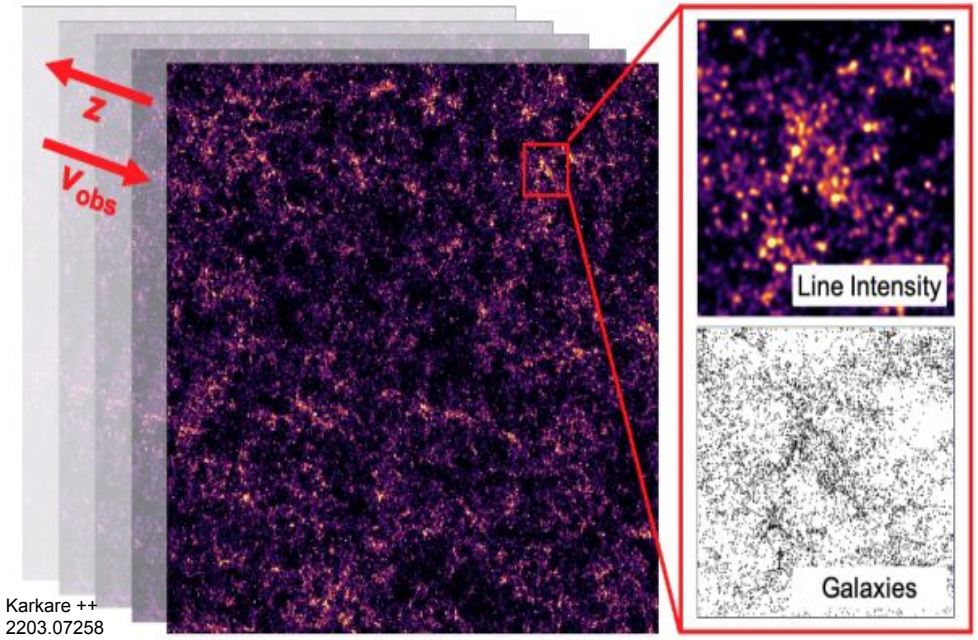
What you measure

low-resolution intensity map of atomic or molecular spectral line emission x multiple frequencies

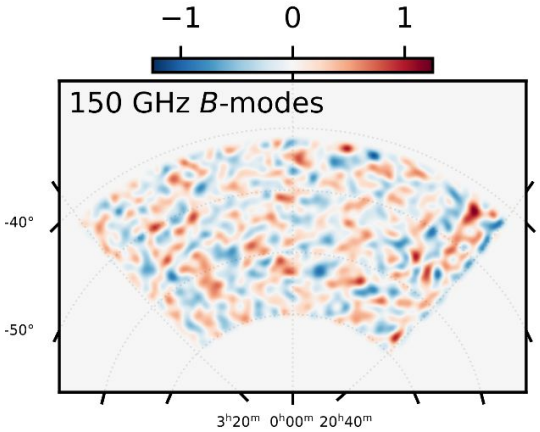
What this traces

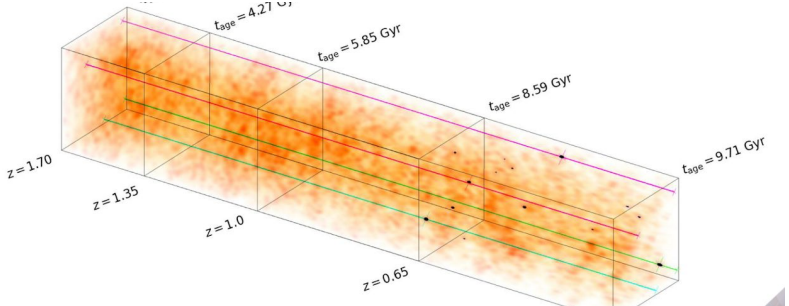
large-scale structure in the underlying galaxy population/dark matter distribution as it evolves over time as the spectral line redshifts

Complementarity with ***the CMB***

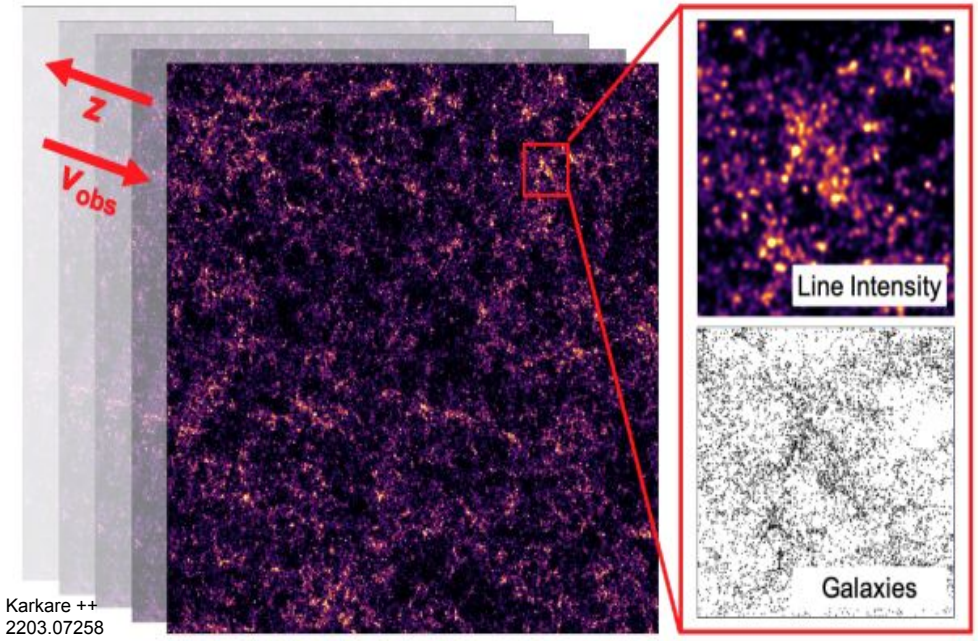


Karkare ++
2203.07258





- The “surface” of last scattering - Only one cosmological epoch
- Different number of modes
- Breaks degeneracies in CMB
- Same intuition for cosmology analysis!



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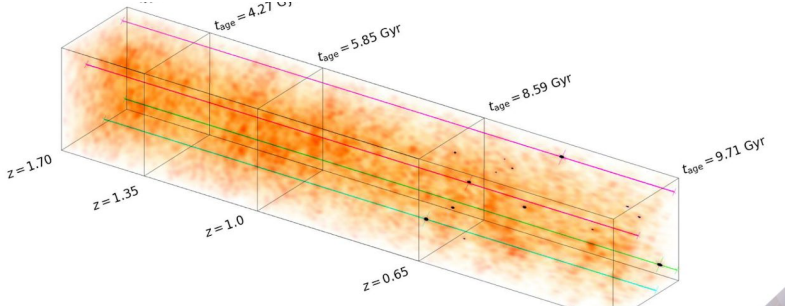
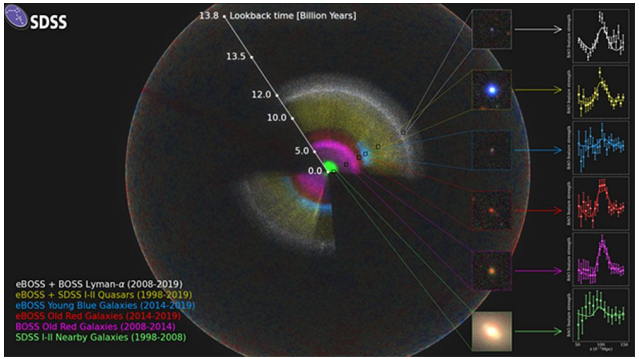
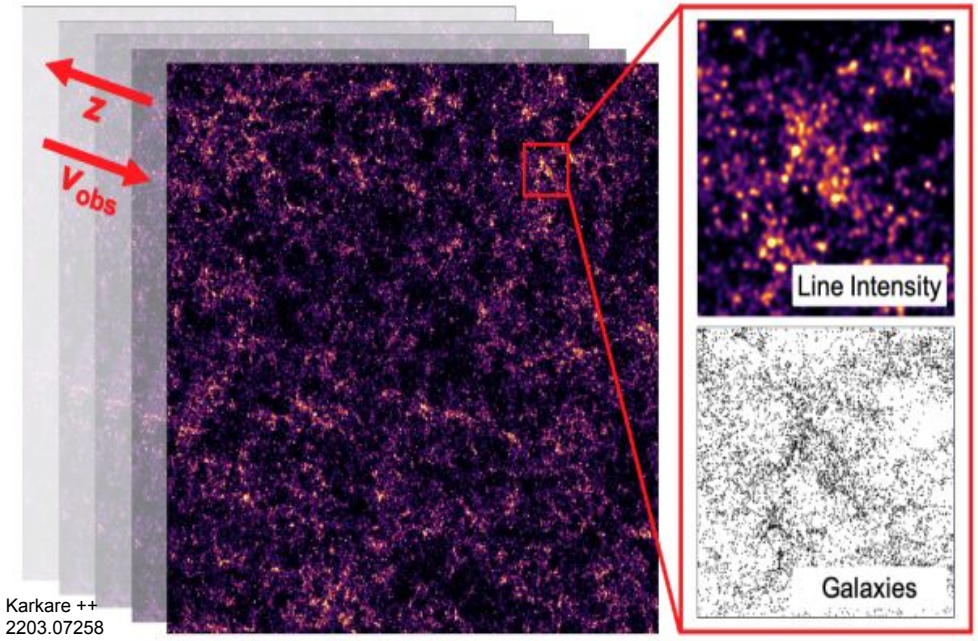


Complementarity with ***Optical Galaxy Surveys***



- Fundamentally different tracer - cold gas vs. optical light
- Potential for higher redshift
- All of the integrated emission
- Cross Correlation



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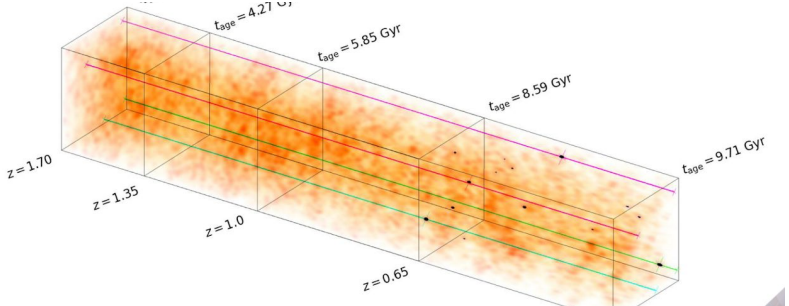
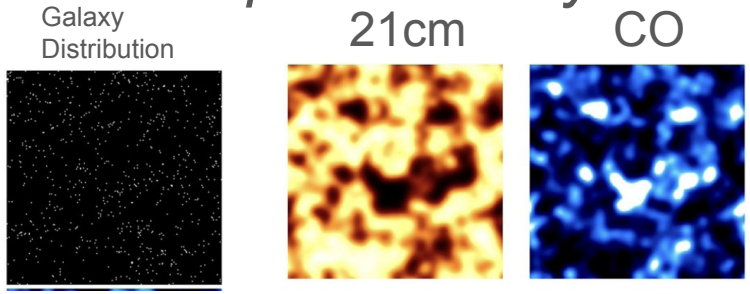


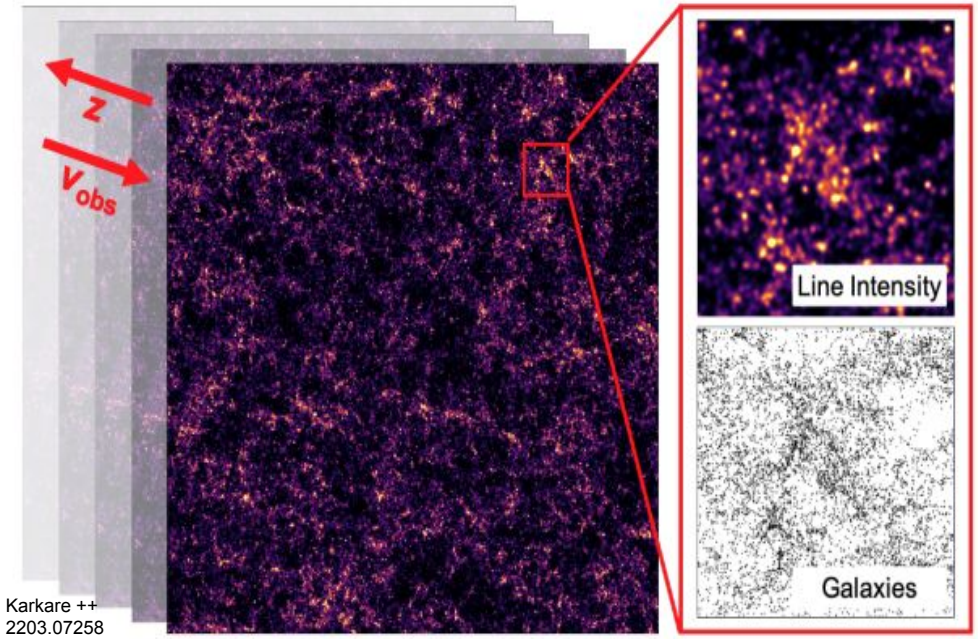
Multi-Line

Complementarity



Figures: Adapted from Pritchard and Loeb (2012)

- Each atomic species reflects different properties of the host galaxies
- E.g. many galaxies == ionized the IGM, a “hole” in the 21cm map. Many galaxies == star formation and produced metals, a bright spot in the CO map.
- Different instrumentation systematics
- Cross Correlation



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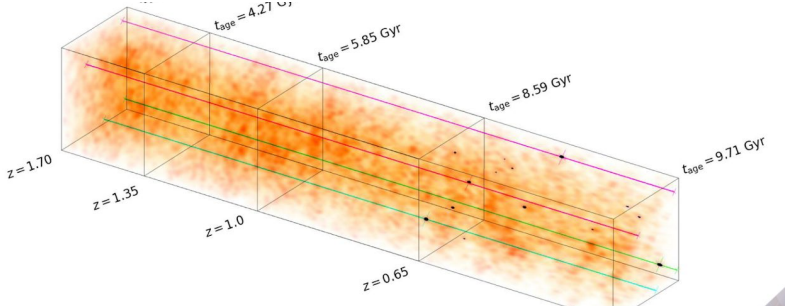

LIM is truly a new window into our universe, spanning back to cosmic dawn!

Line Intensity Mapping - The Motivation

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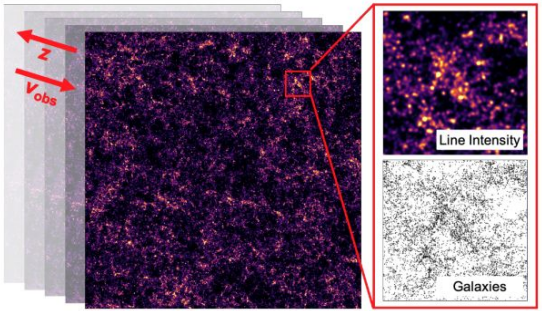
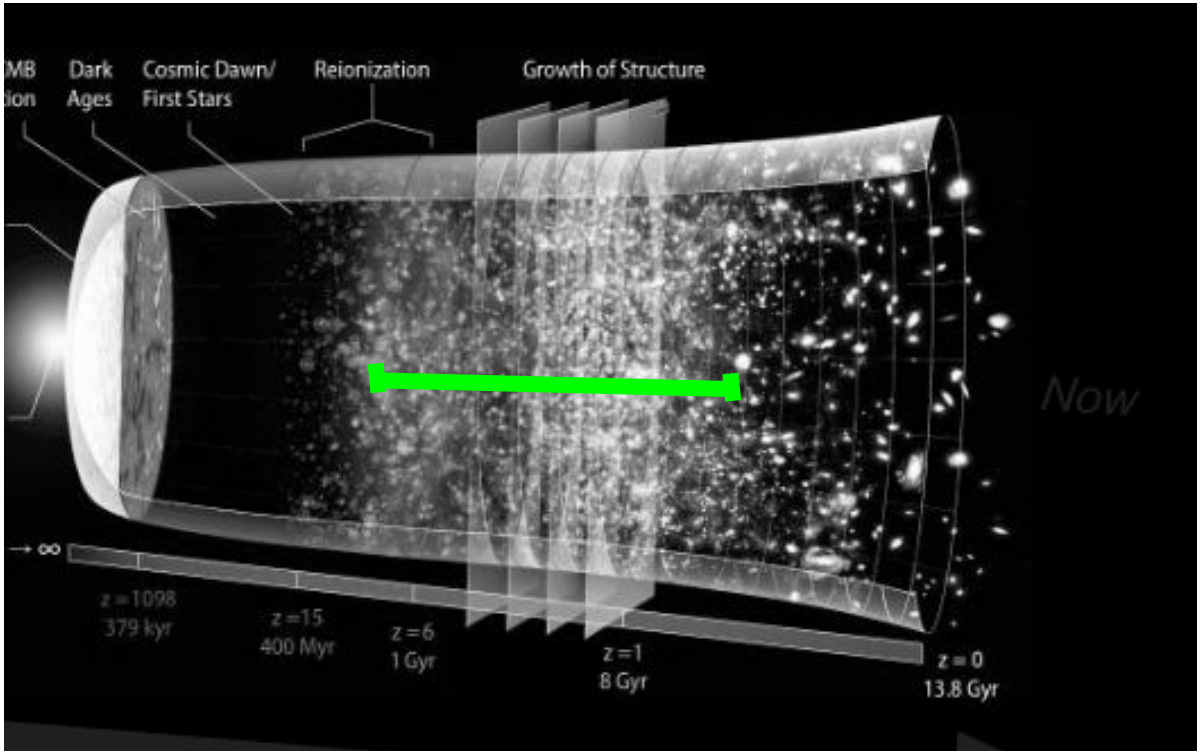


You can constrain…
astrophysics of the high redshift universe



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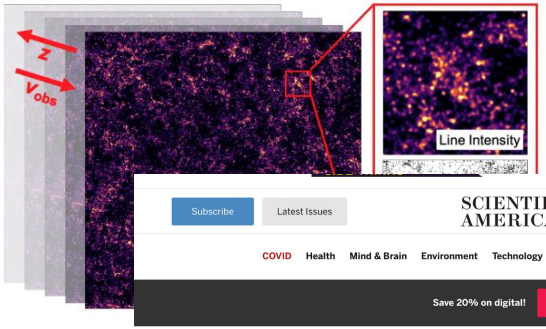

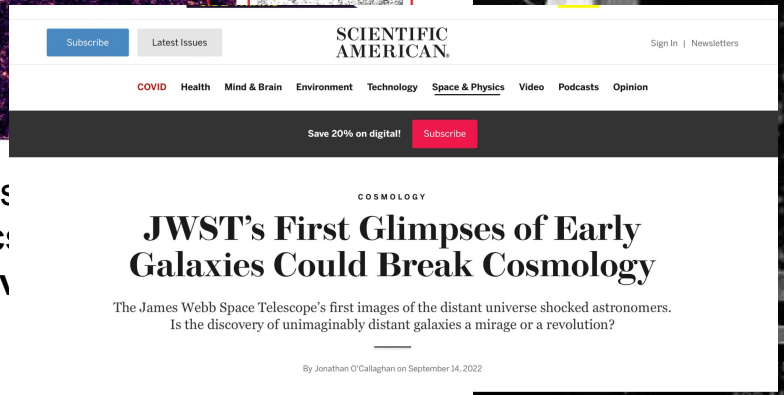
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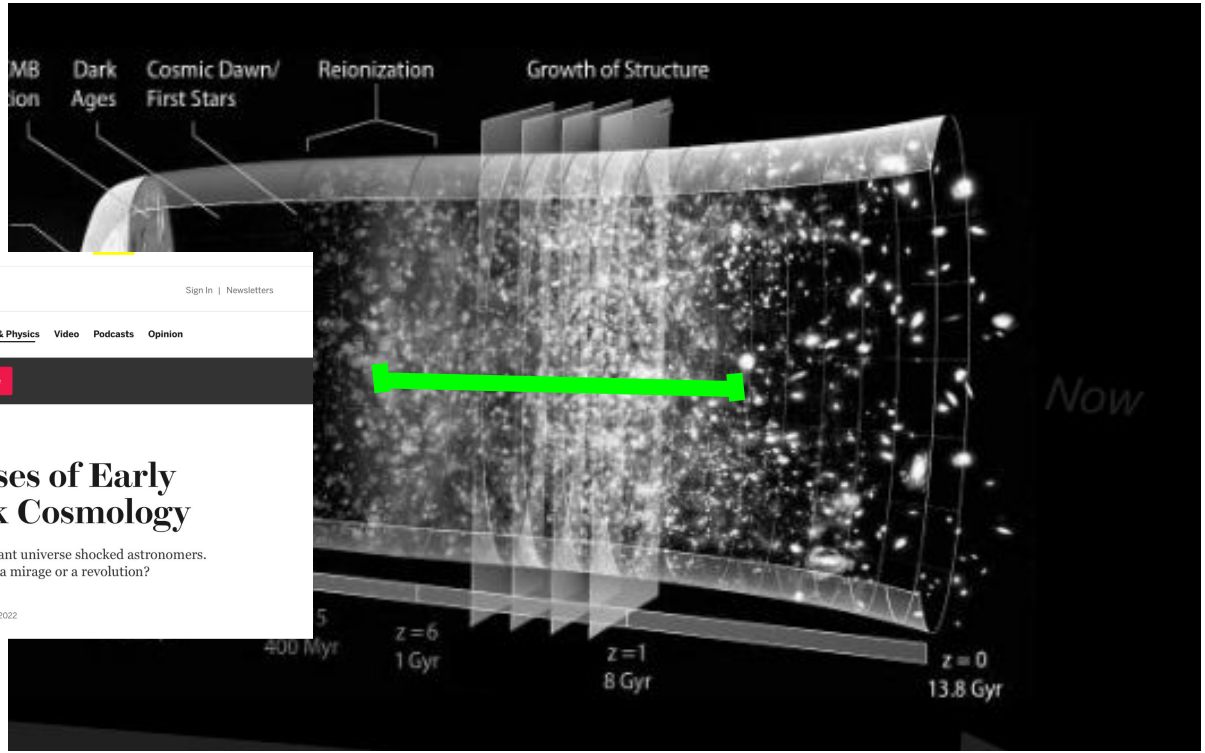
By Jonathan O'Callaghan on September 14, 2022



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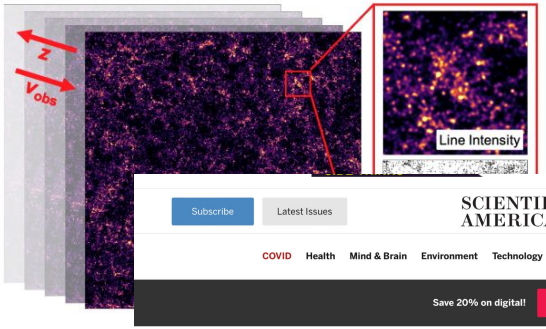

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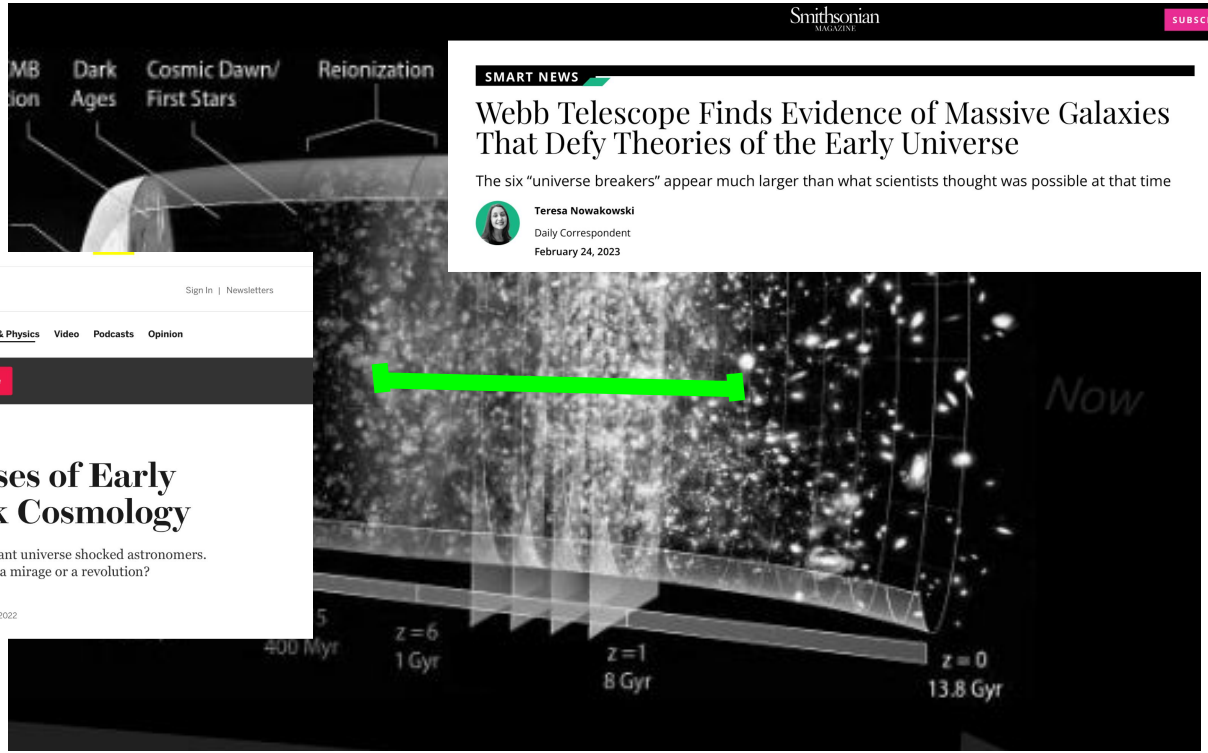

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Webb Telescope Finds Evidence of Massive Galaxies That Defy Theories of the Early Universe

The six "universe breakers" appear much larger than what scientists thought was possible at that time

Teresa Nowakowski
Daily Correspondent
February 24, 2023

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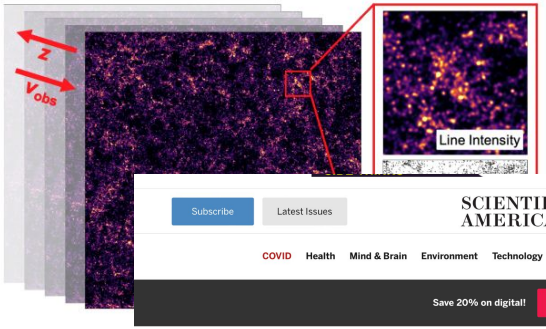

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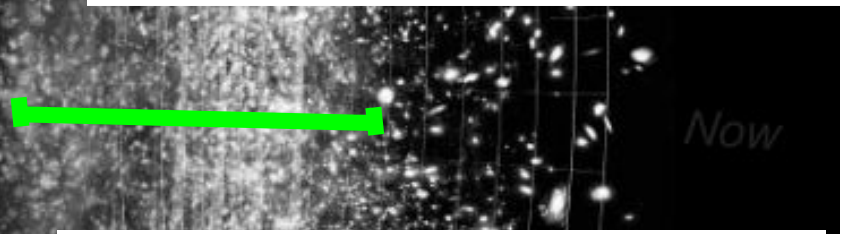

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The James Webb Space Telescope discovers enormous distant galaxies that should not exist

By Tereza Pultarova published February 22, 2023

Giant, mature galaxies seem to have filled the universe shortly after the Big Bang, and astronomers are puzzled.

Comments (45)

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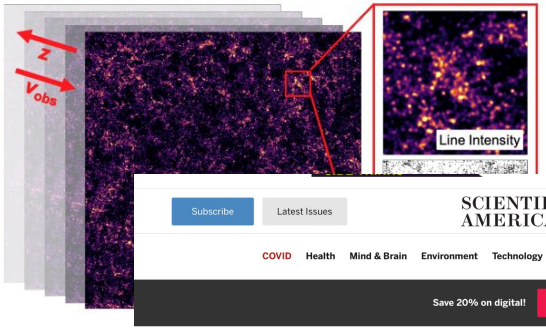

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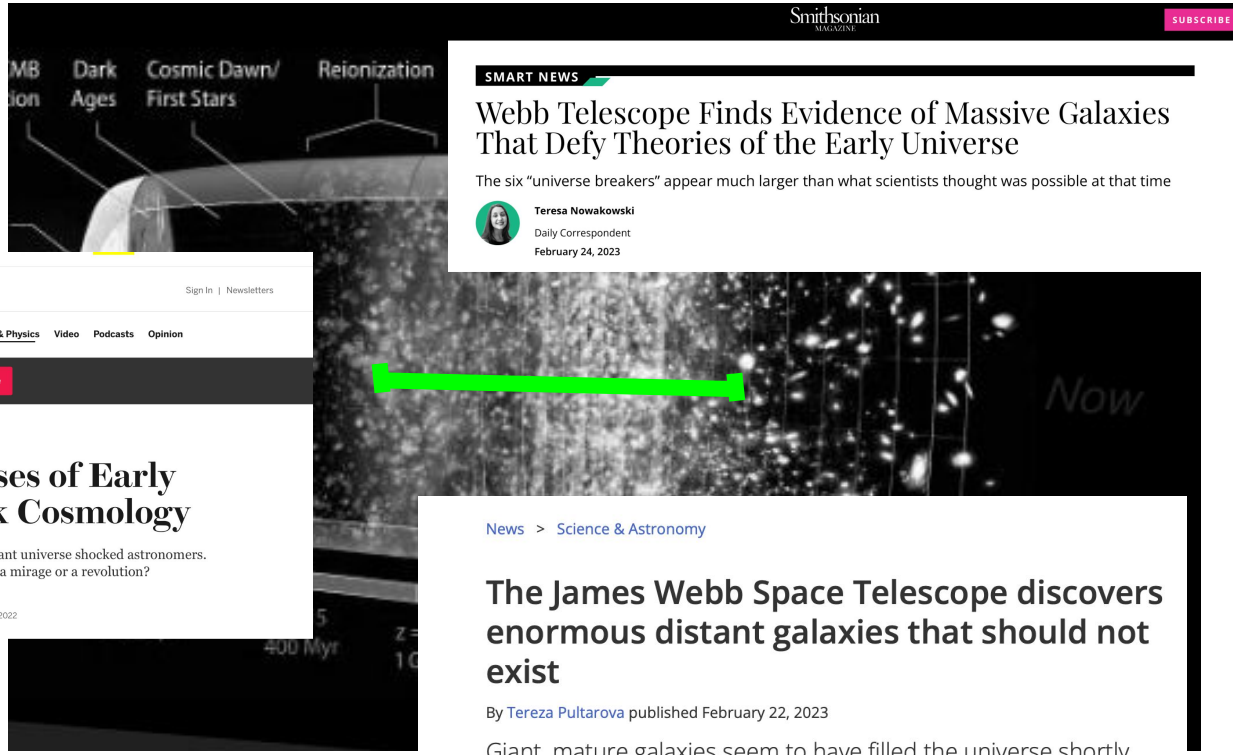

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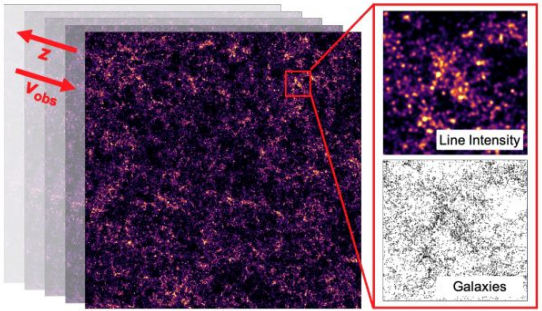
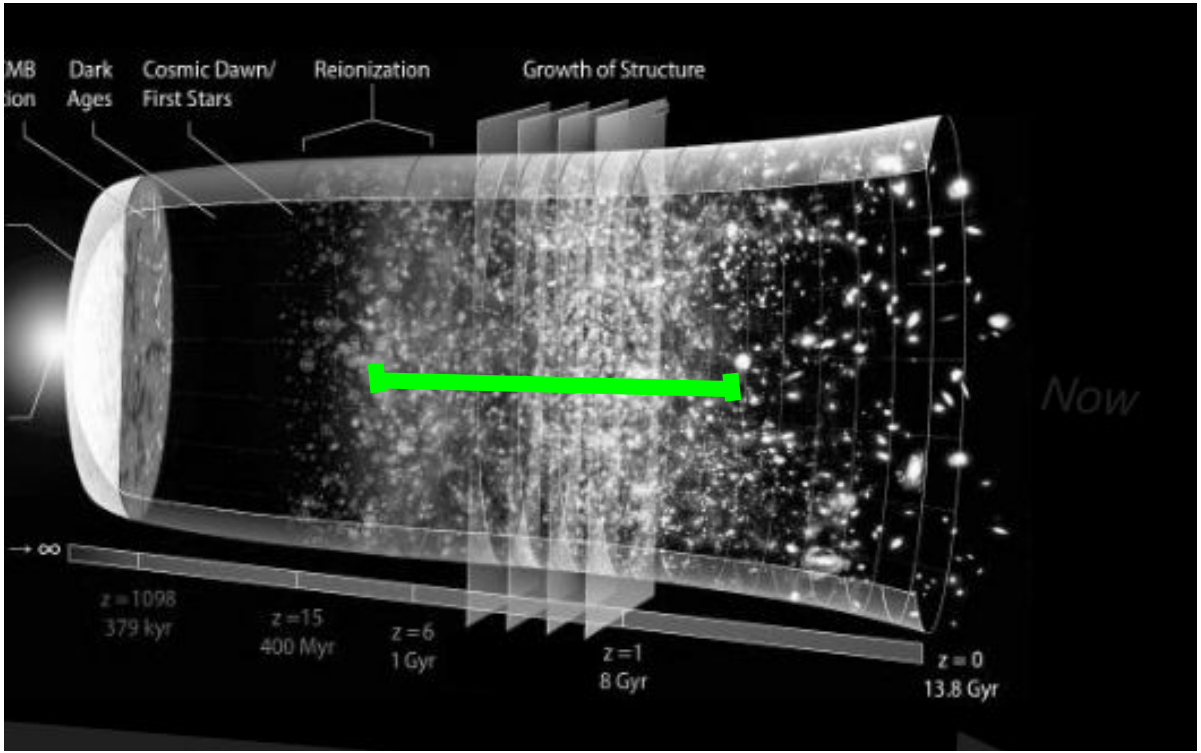


You can constrain…
astrophysics of the high redshift universe

- Integrated map of CO/CII (cold gas) as a function of redshift
- Galaxy formation and evolution
  - One of the ONLY near term (and cheap) ways to probe cold gas phase of the ISM



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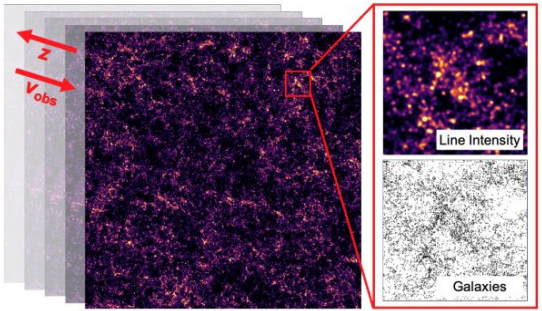
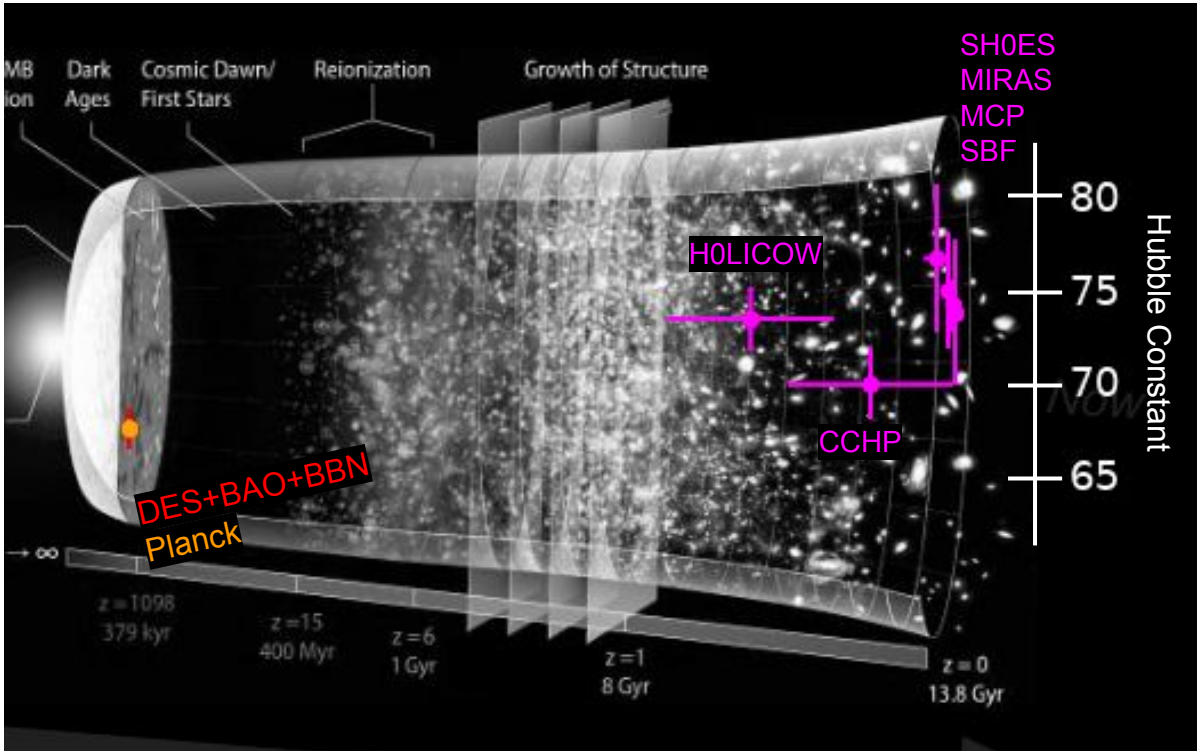


You can constrain… **cosmology**

- Hubble Constant



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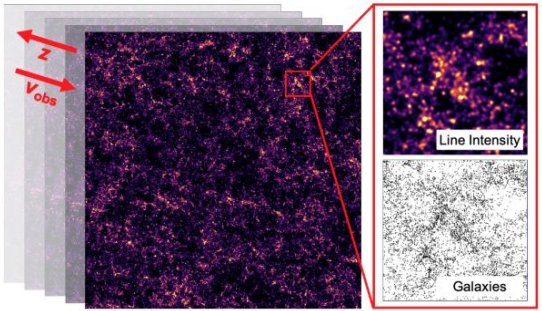
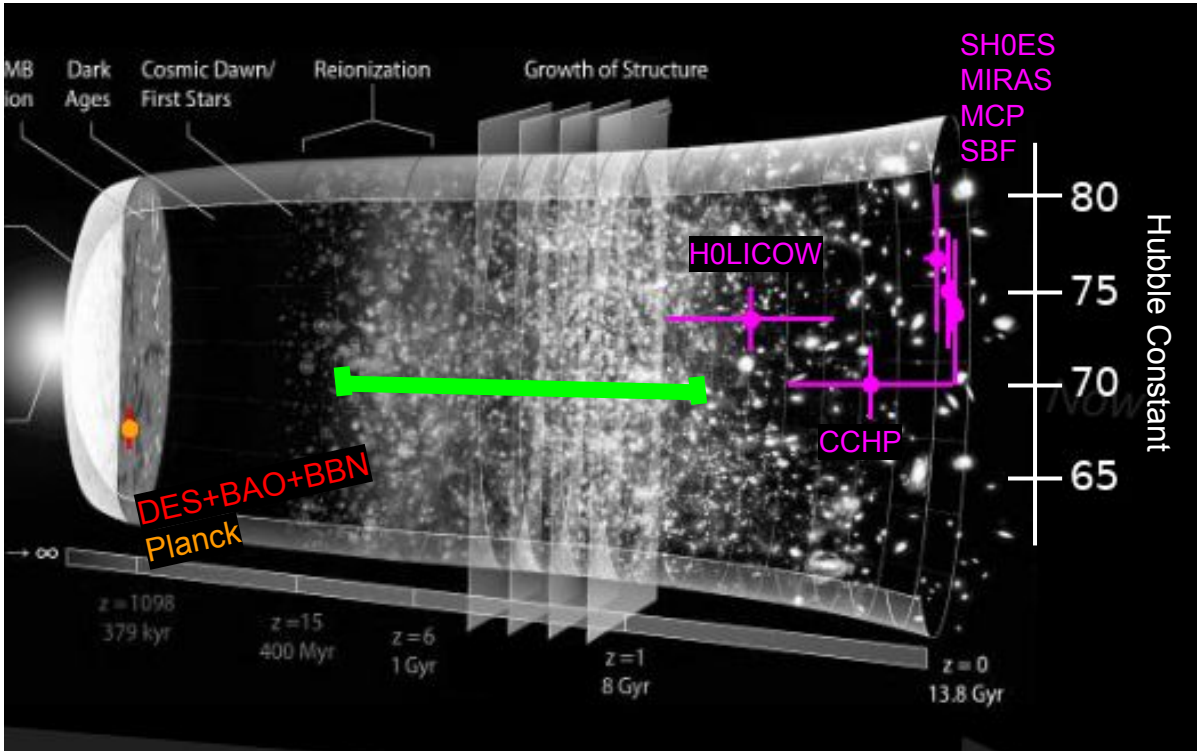


You can constrain… **cosmology**

- Hubble Constant
  - Independent measurement at higher redshifts



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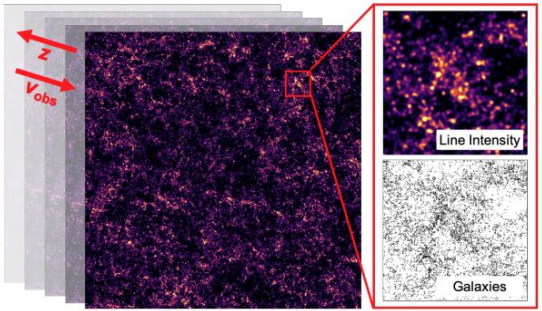
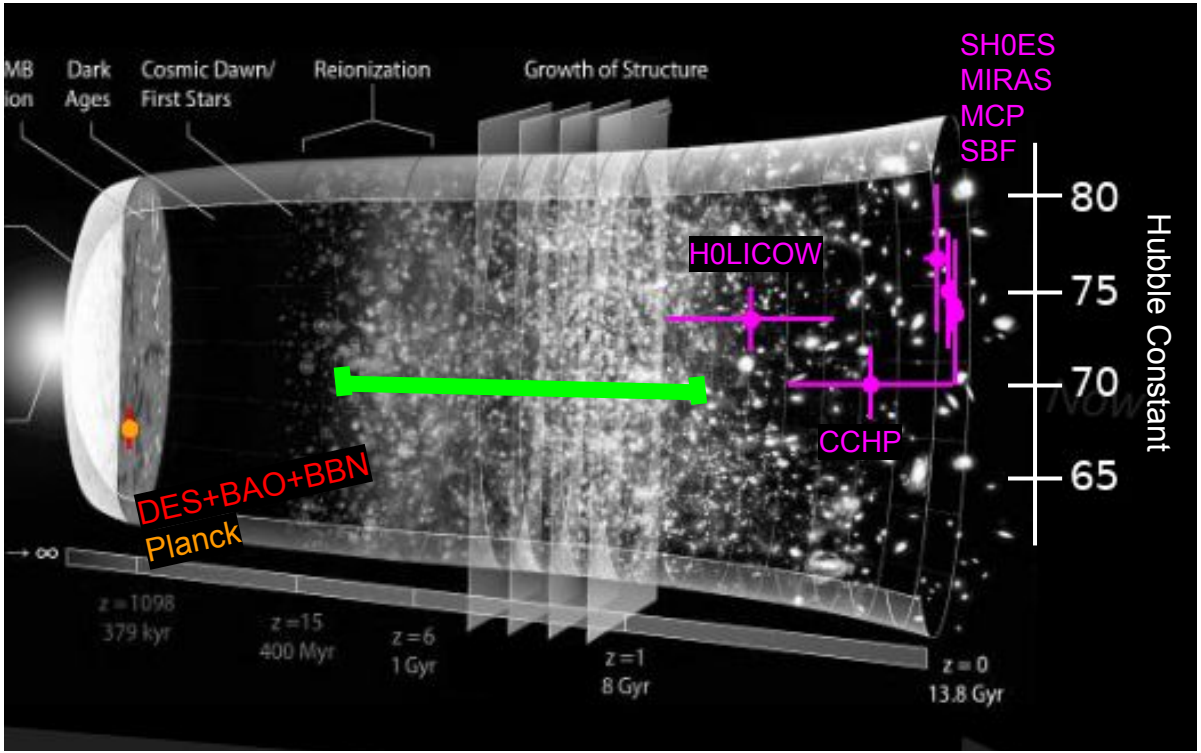


You can constrain… **cosmology**

- Hubble Constant
- Dark Energy
  - Constrain expansion history



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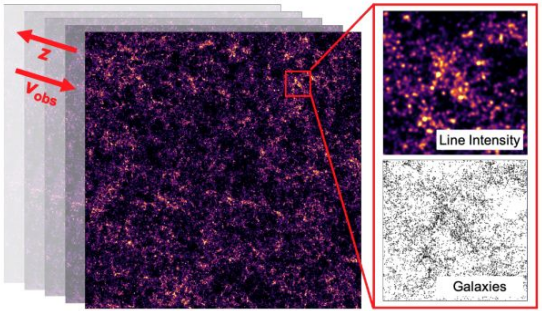
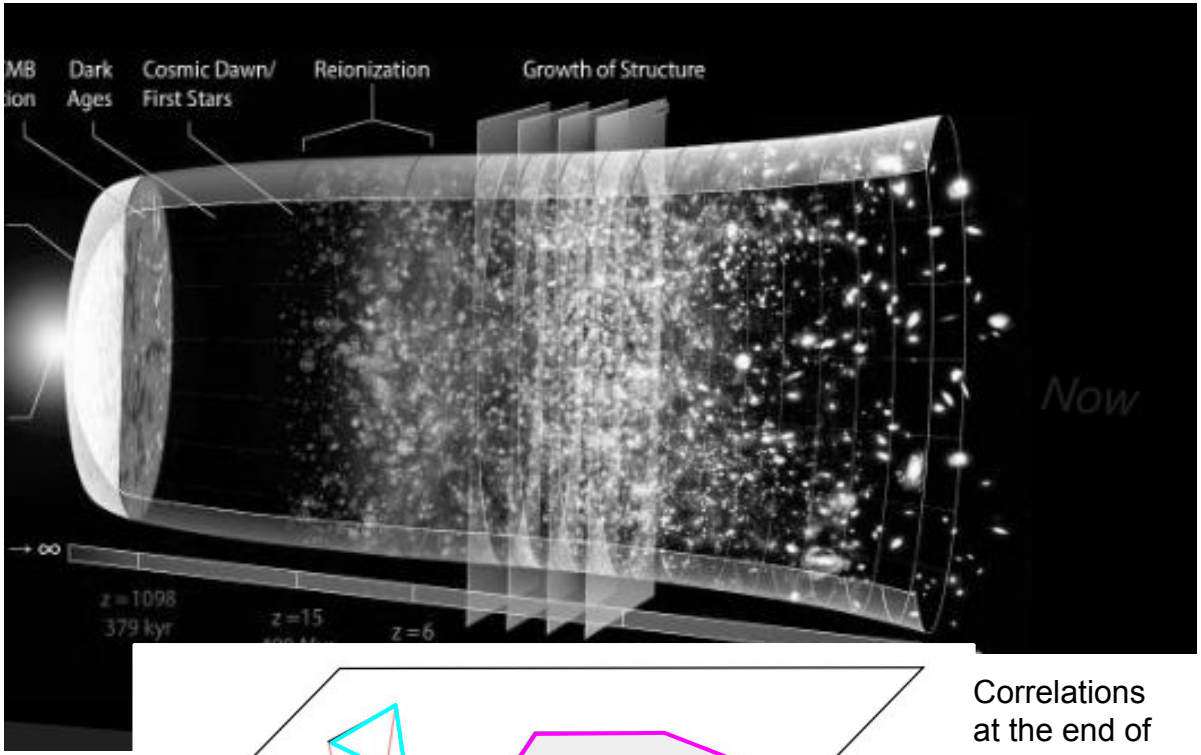


You can constrain… **cosmology**

- Hubble Constant
- Dark Energy
- Inflation



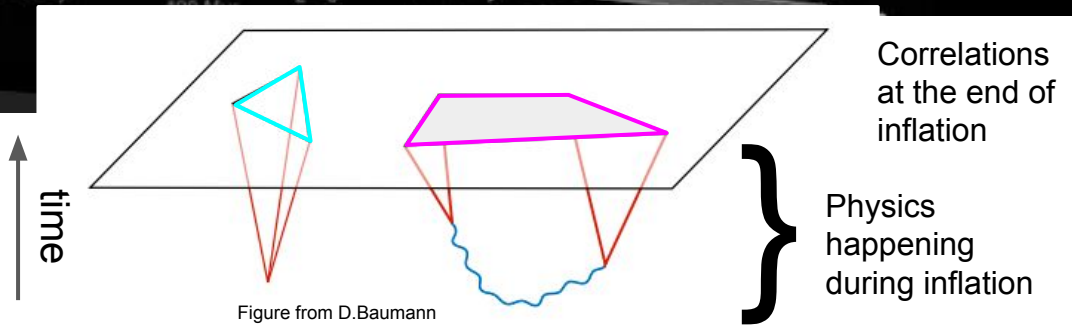


Figure from D.Baumann

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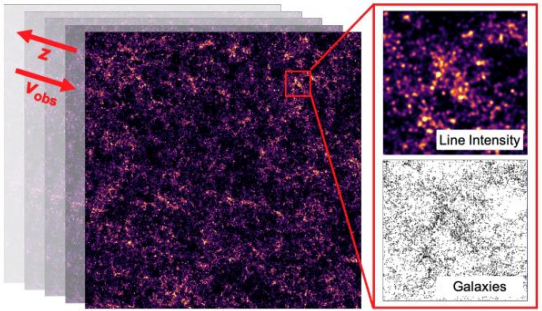

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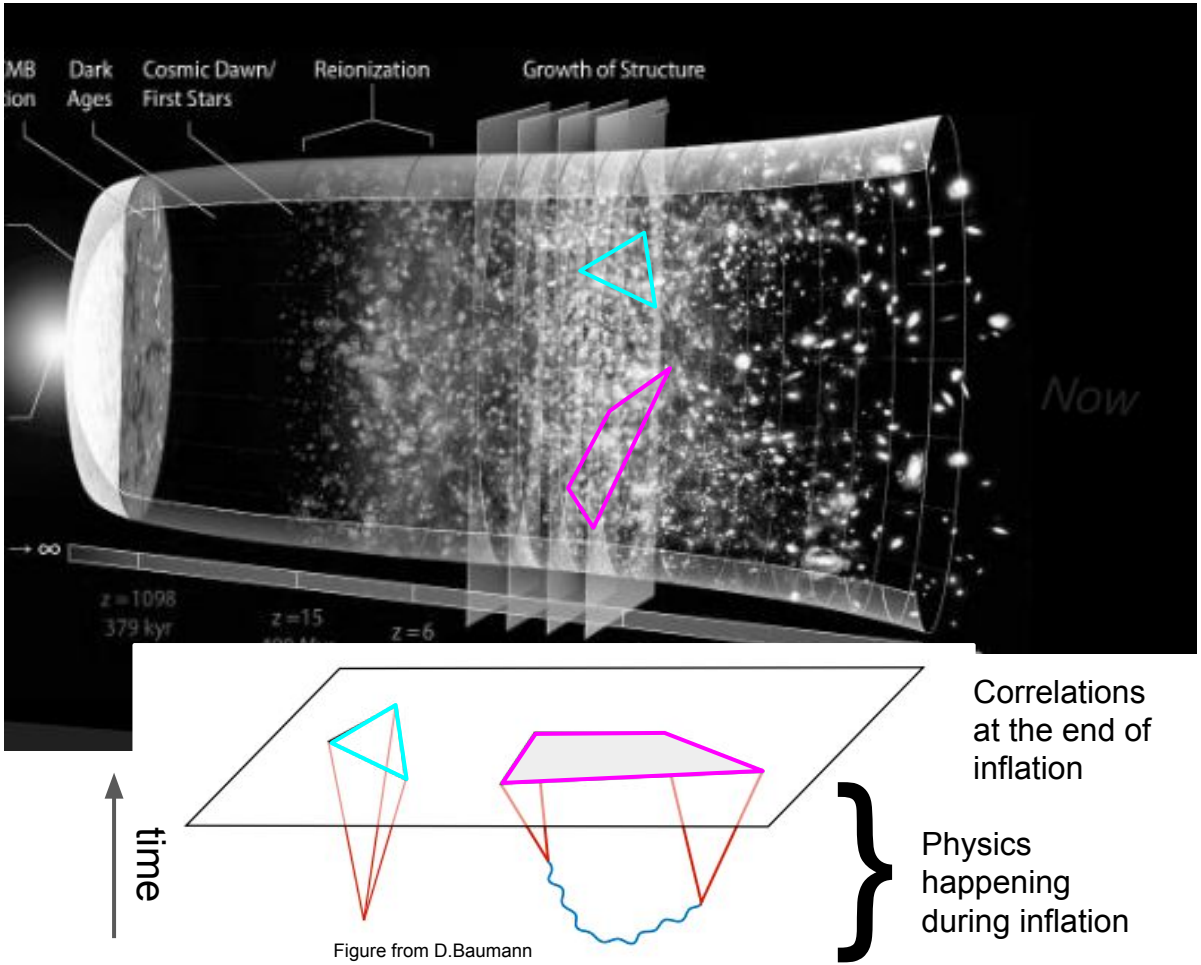

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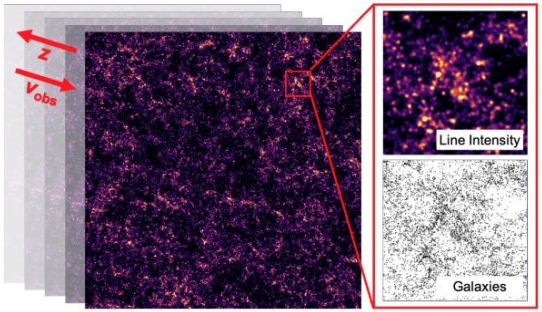
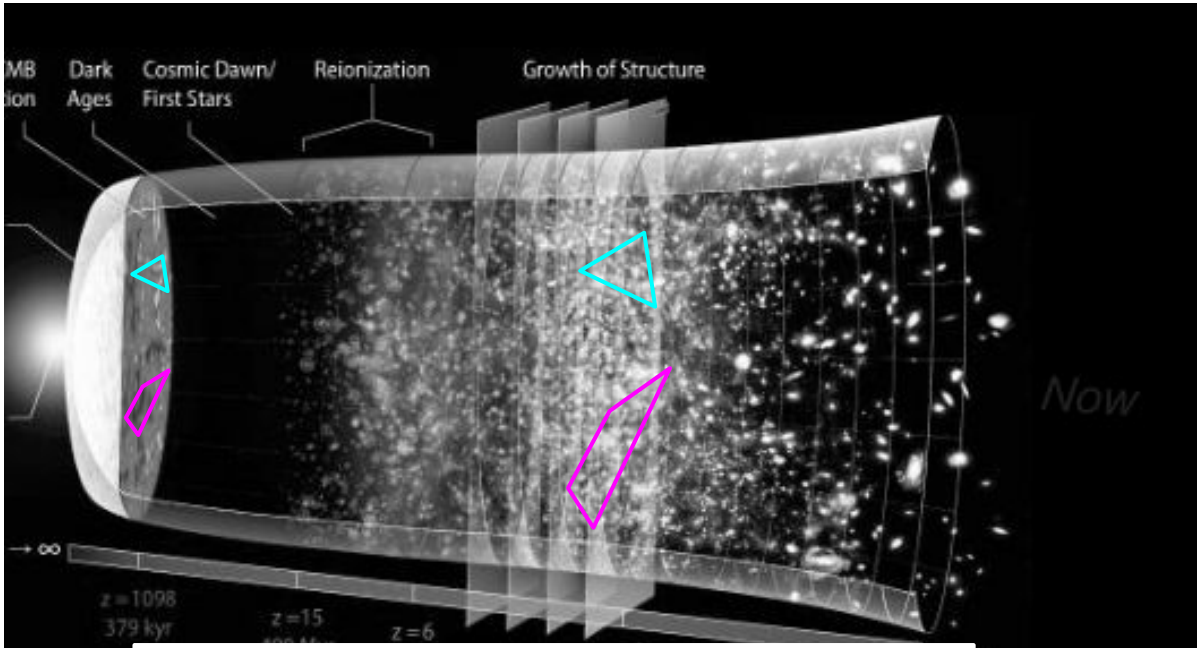
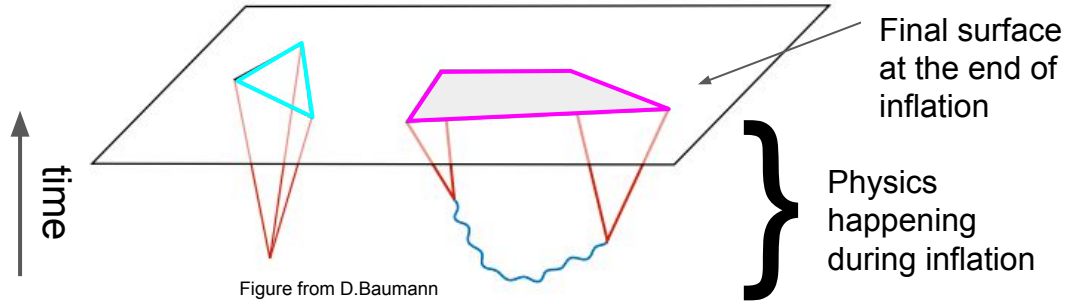




You can constrain… **cosmology**

- Hubble Constant
- Dark Energy
- Inflation
  - f_{NL} = parameter describing non-gaussianity
  - Single-field inflation
    Predicts only $f_{NL} < 1$
  - For multi-field inflation
    learn from shape dynamics of inflationary field and of other particles that may have been interacting with the inflation at the time
  - Unique advantage of LIM: large amount of linear modes



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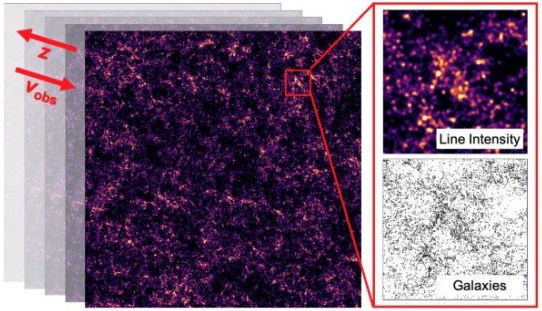

You can constrain… **cosmology**

- Hubble Constant
- Dark Energy
- Inflation
- Search for New Light Particles
  - N_{eff} corresponds to number of relativistic species in early universe - sensitive to number of neutrinos, sterile neutrinos, light dark matter, axions, etc.
  - Smears out structure within the free-streaming scale

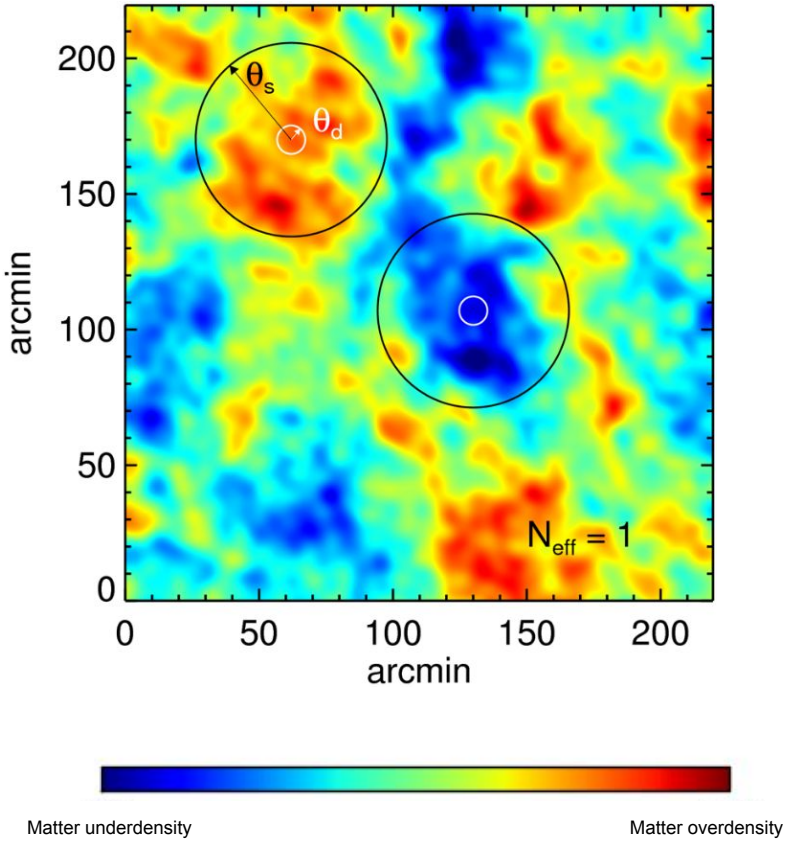

Figure: Z. Hou, L. Knox

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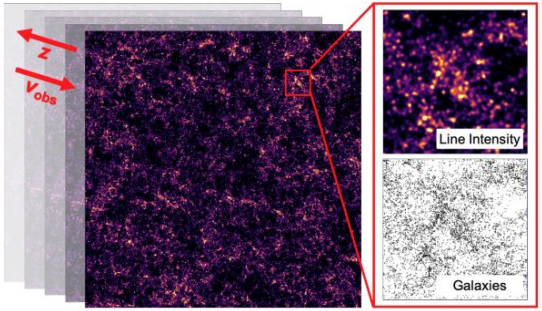

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  - N_{eff} corresponds to number of relativistic species in early universe - sensitive to number of neutrinos, sterile neutrinos, light dark matter, axions, etc.
  - Smears out structure within the free-streaming scale

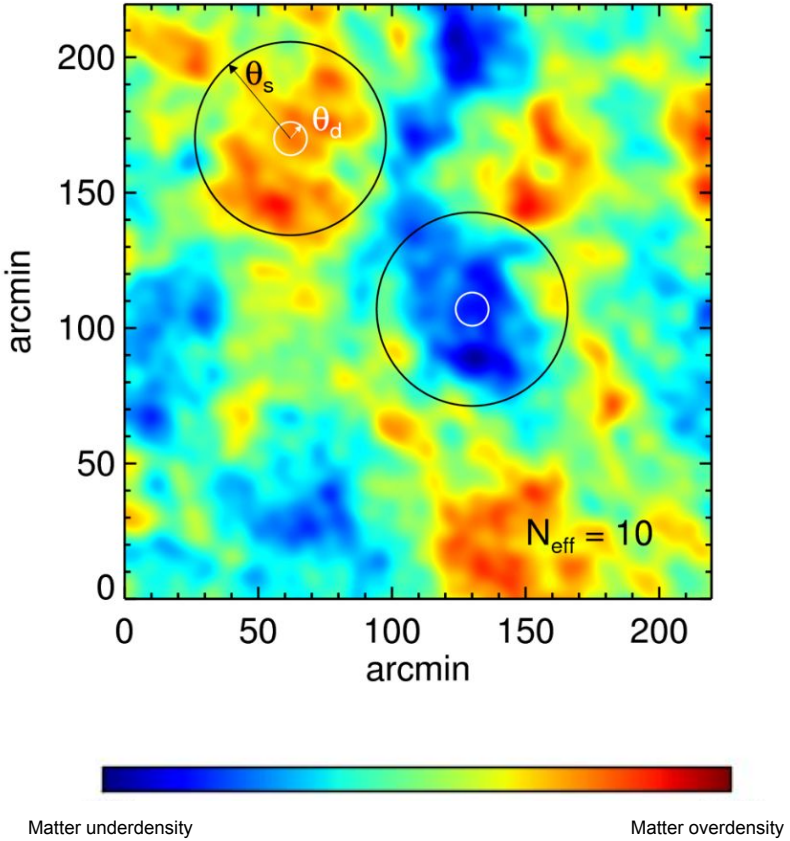


Figure: Z. Hou, L. Knox

LIM as a New Cosmological Probe

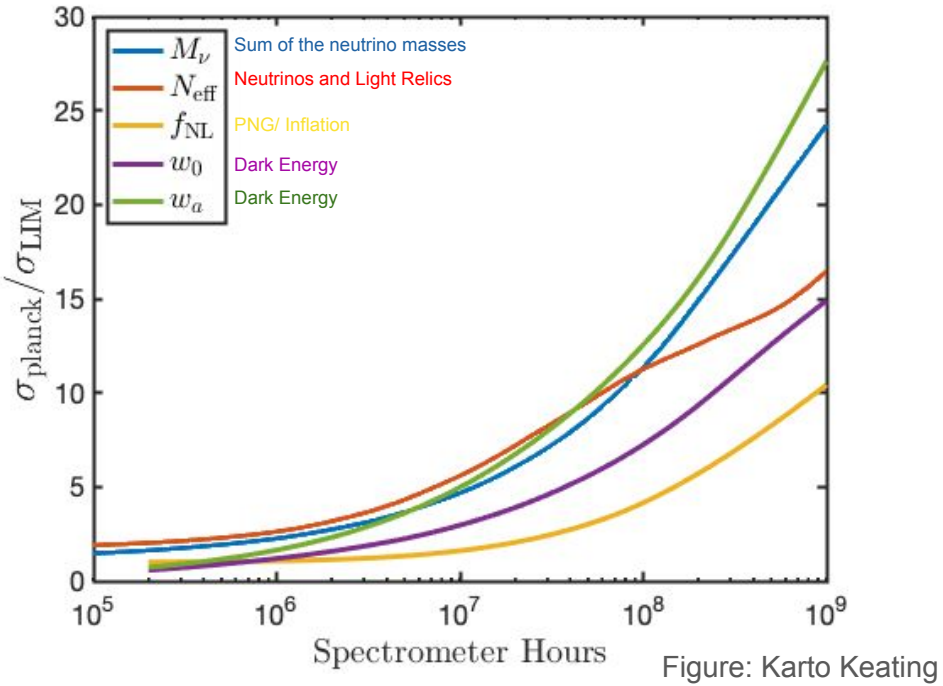
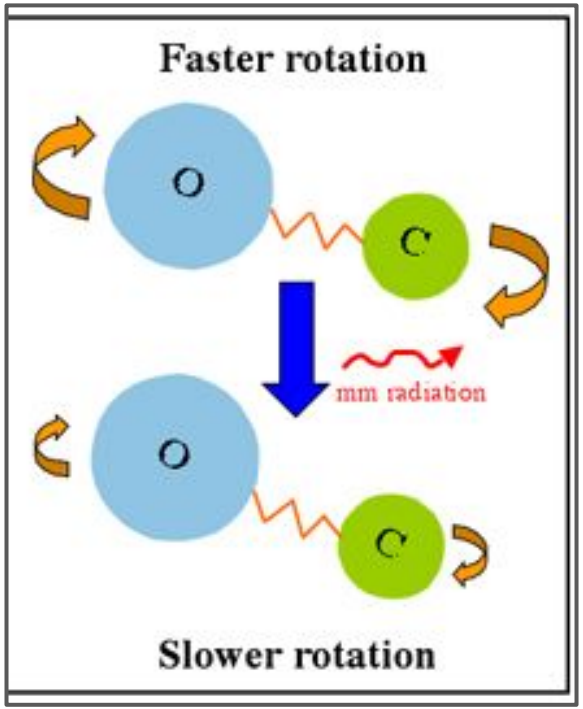


Figure: Karto Keating

Improvement over Planck comes from large volume of modes and breaking of parameter degeneracies in CMB data

Basics of Line Emission

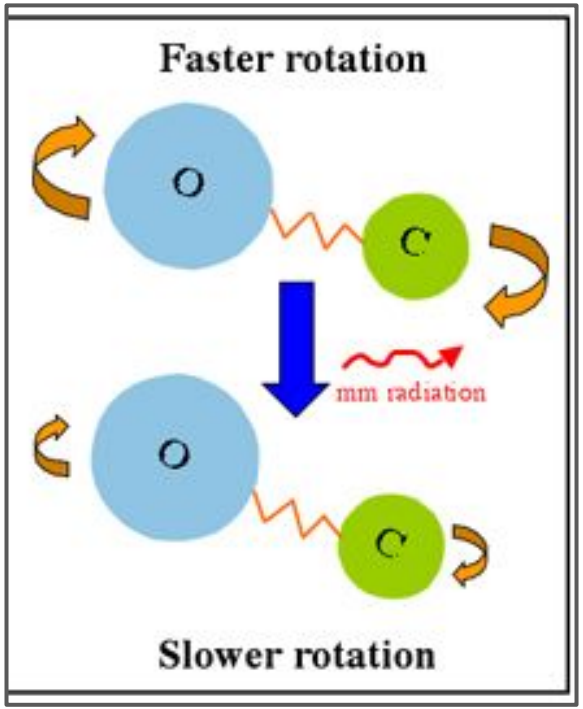
Emission from atomic and molecular spectral lines from galaxies

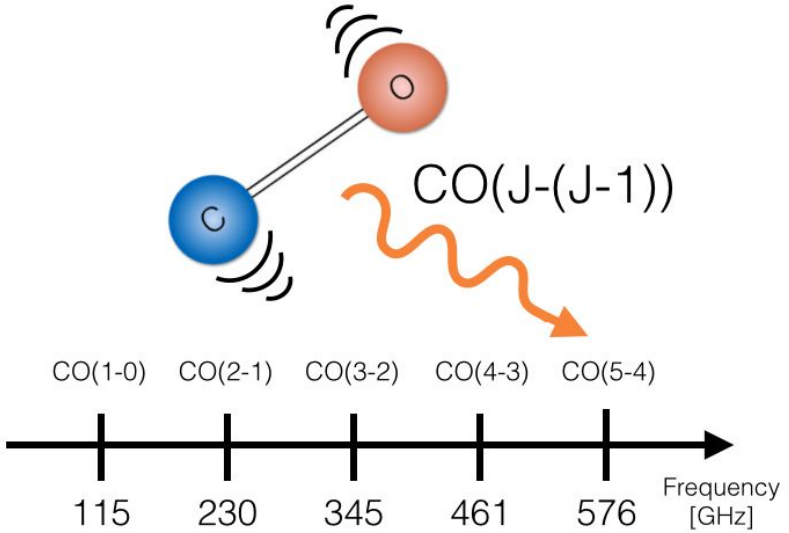


- In an atom, electrons can only exist at specific energy levels → need to absorb or release photons to transition
- Similarly, molecules can only rotate and vibrate and certain rates
- When CO changes its rotational state, it absorbs or emits a photon in the mm-wavelengths

Basics of Line Emission

Emission from atomic and molecular spectral lines from galaxies





K. Olsen

Basics of Line Emission

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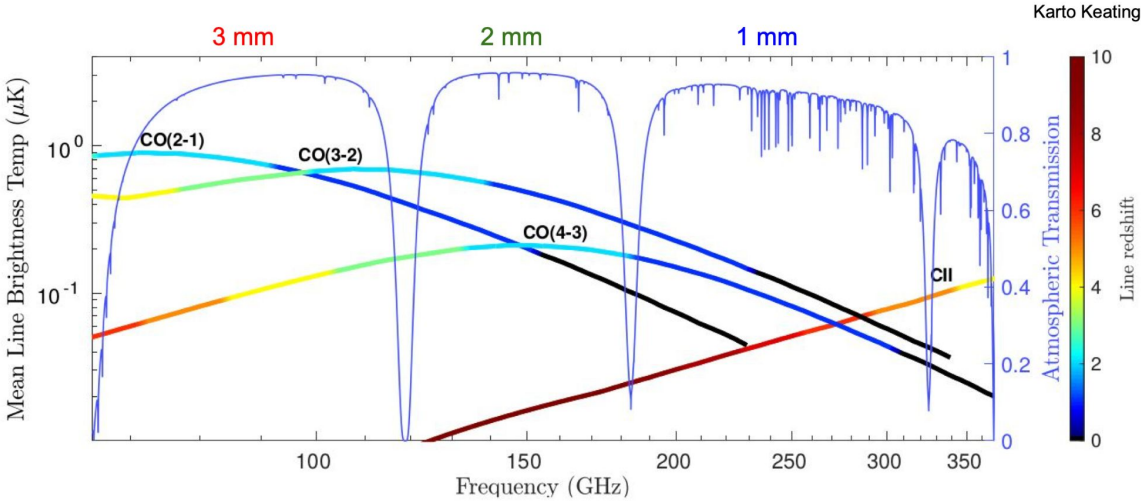
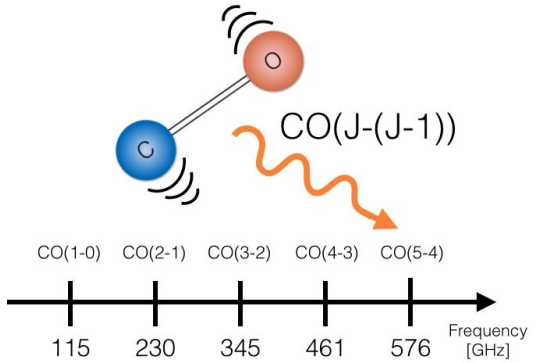
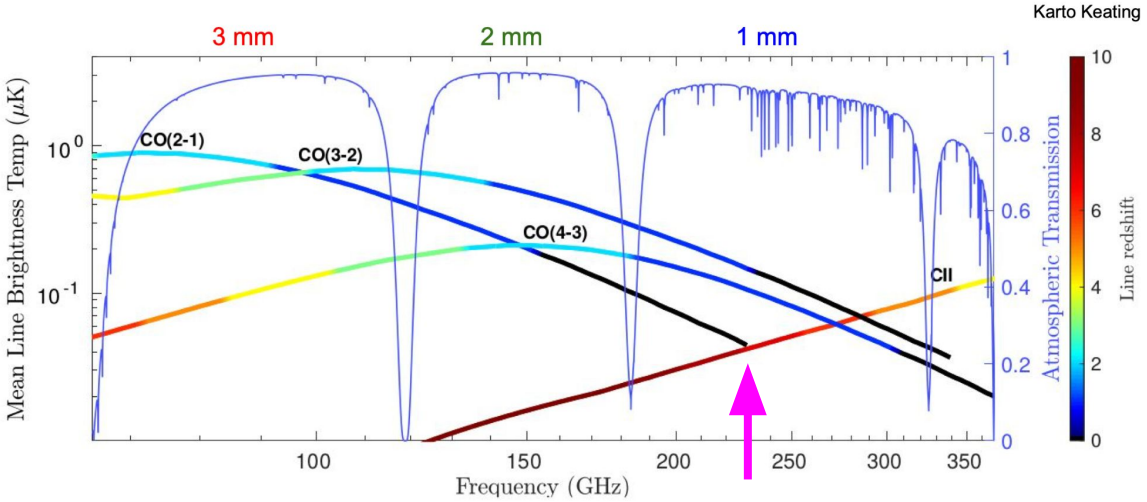


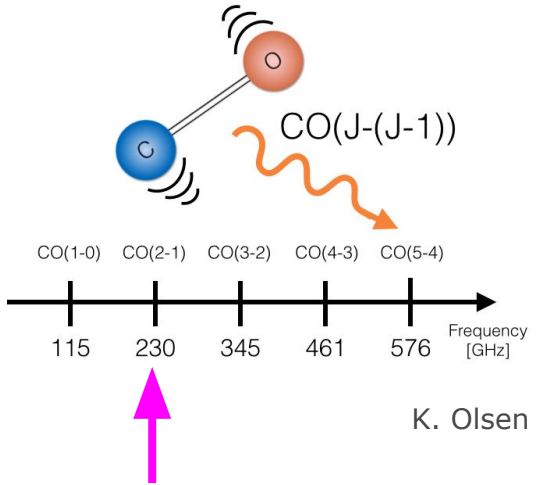


K. Olsen

Basics of Line Emission

Emission from atomic and molecular spectral lines from galaxies





Basics of Line Emission

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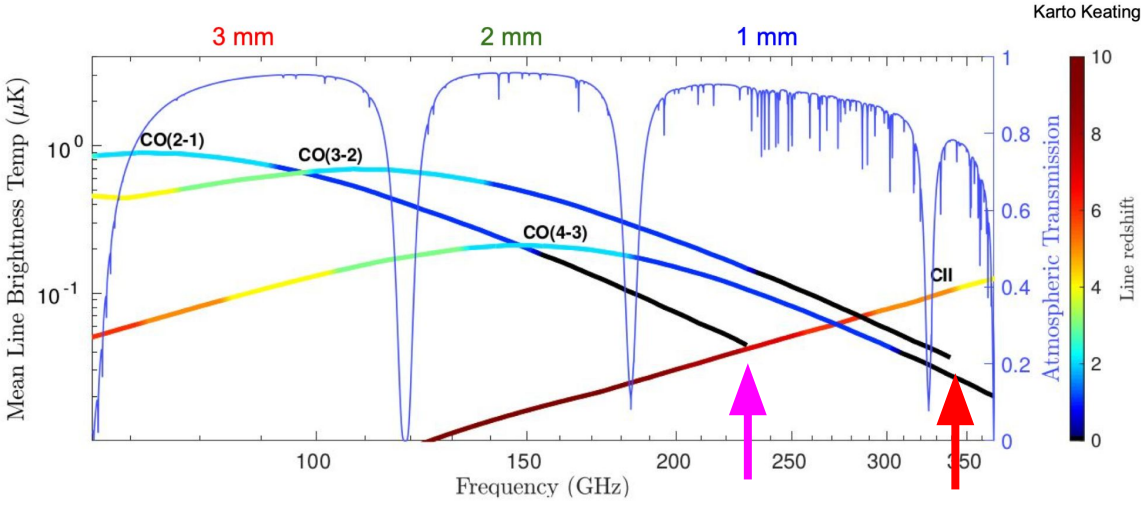
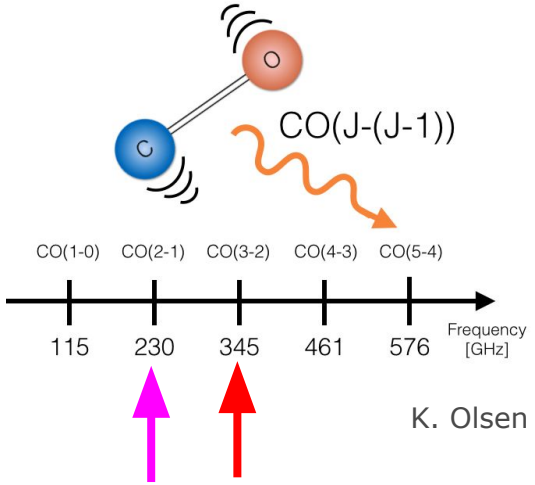
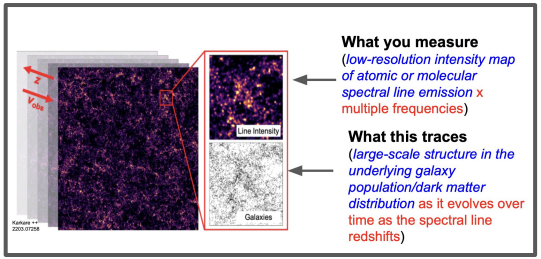






Which line to pick?

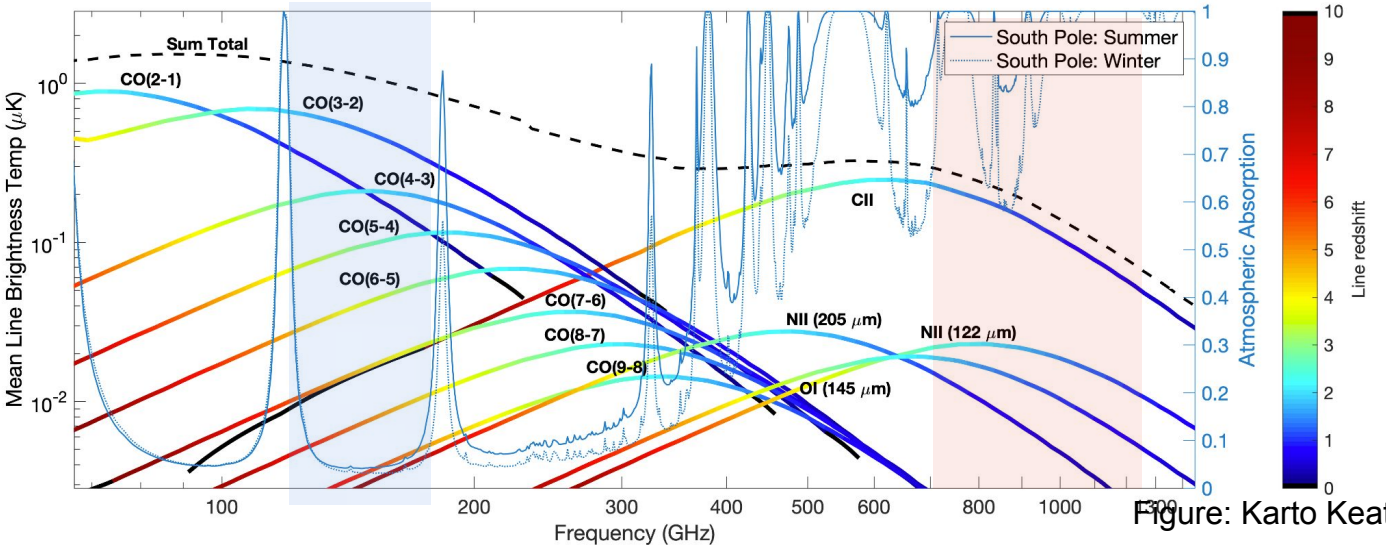


Figure: Karto Keating

CO
Maximum *Signal*
GHz (Can do from the ground)

CII
Maximum *Signal-to-Noise*
THz (From Space)

Which line to pick?

balloon

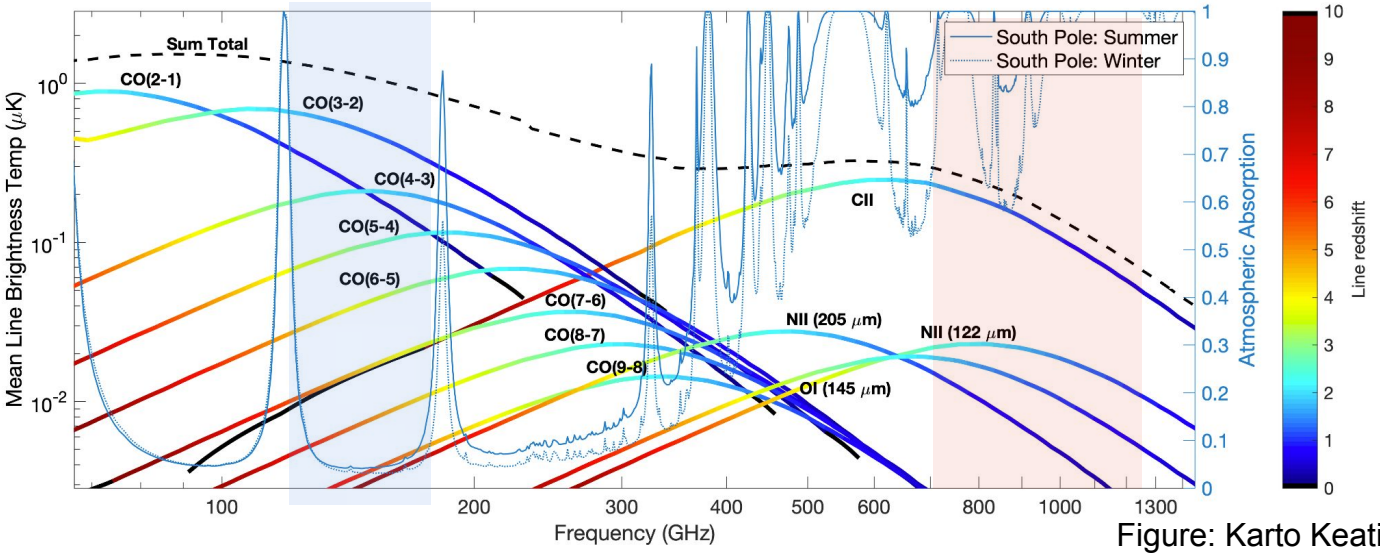
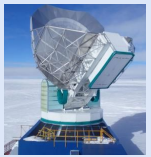
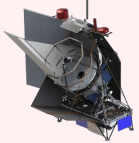


Figure: Karto Keating

CO
Maximum *Signal*
GHz (Can do from the ground)
SPT-SLIM



CII
Maximum *Signal-to-Noise*
THz (From Space)
TIM (Terahertz Intensity Mapper)



balloon

Two Big Challenges for the Field of Line Intensity Mapping:

Instrumentation Challenge:

How do we build instruments with the raw sensitivity to make competitive cosmological constraints?

Data Analysis Challenge:

New techniques needed to be developed and perfected for these sensitive instruments!

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Maximum *Signal*
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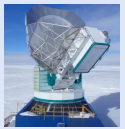

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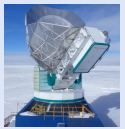


CII
Maximum *Signal-to-Noise*
THz (From Space)
TIM (Terahertz Intensity Mapper)

The Terahertz Intensity Mapper: An Antarctic Balloon to Map the Universe in CII

Flight Slot Winter 2026-2027 from McMurdo Station, Antarctica

Photo: Ian Lowe

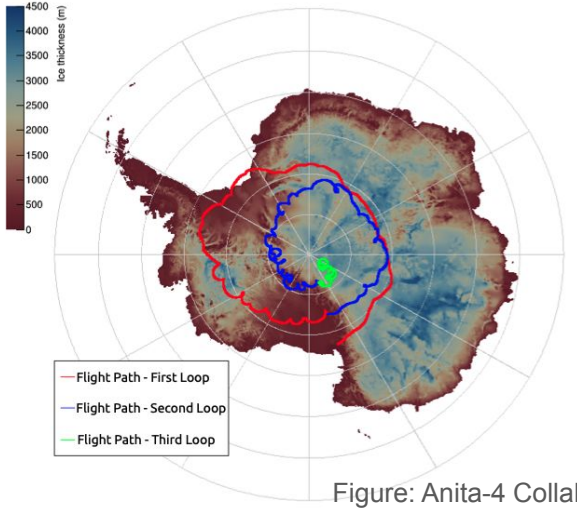


Figure: Anita-4 Collaboration, Gorham et al (2019)

The power of a balloon-based platform for a telescope:

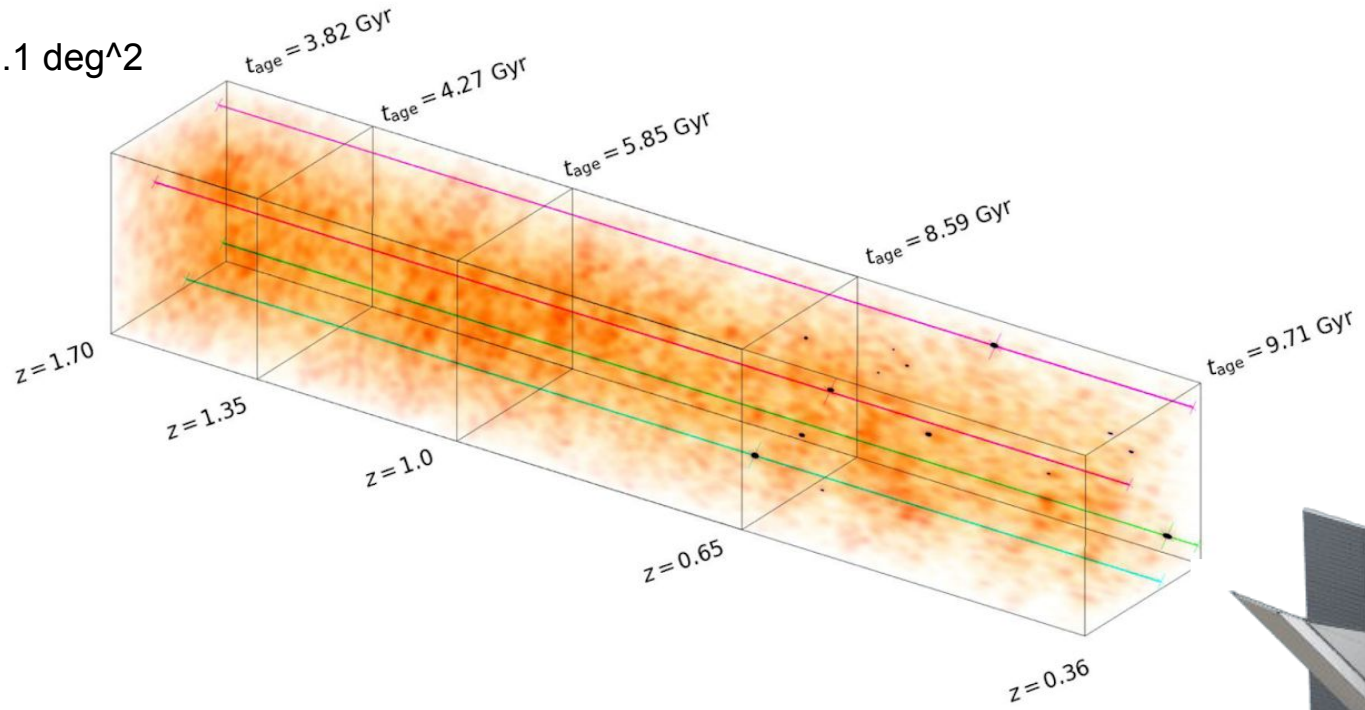
- Space-like environment
  - ".3% of the atmosphere for 1% of the cost of a satellite!"
- View of the same patch of sky for up to a month flight
- TRL pathway to space

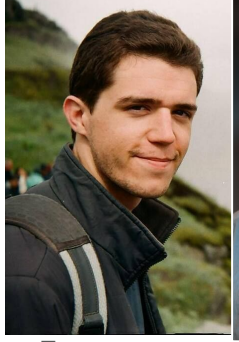
The Terahertz Intensity Mapper

University of Illinois **J. Vieira (PI),** J. Filippini, J. Alameda, H. Athreya**,** B. Brendal, J. Fu, M. Kowalik, R. Nie, V. Razavimaleki
Caltech/JPL **R. Janssen**, **M. Bradford**, S. Hailey-Dunsheath, B. Bumble, L.-J. Liu
Arizona State University **C. Groppi,** D. Joralmon, P. Mauskopf, T. Saeid
University of Arizona **D. Marrone,** R. Dominguez, N. Emerson, V. Gasho, **I. Lowe**, E. Mayer, I. Trumper
University of Pennsylvania **J. Aguirre**, S. Agrawal, J. Bracks, A. Manduca
Max Planck Institute for Astronomy R. Keenan
Harvard & Smithsonian **G. Keating**
University of Chicago **J. Zebrowski**

ILLINOIS JPL Jet Propulsion Laboratory California Institute of Technology ASU THE UNIVERSITY OF ARIZONA Penn

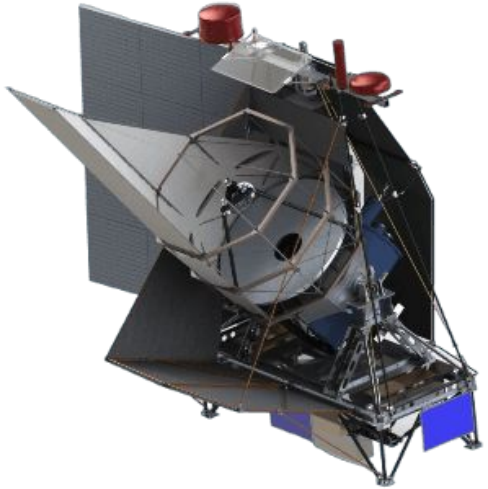
~0.1 deg^2



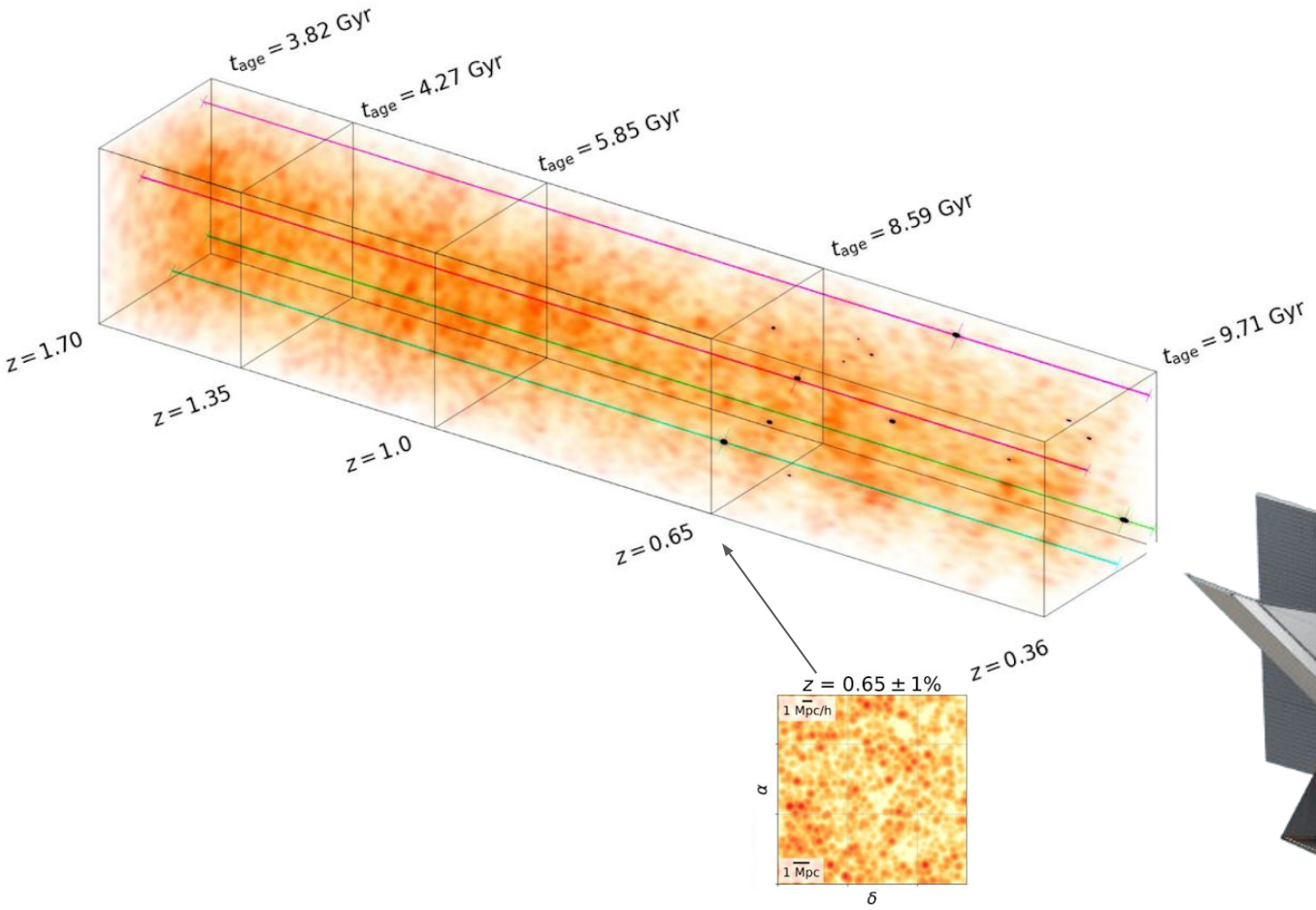


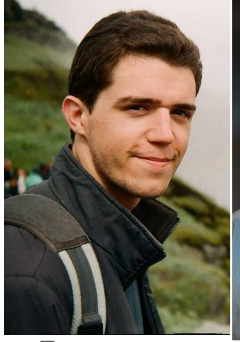
Evan Mayer

Shubh Agrawal



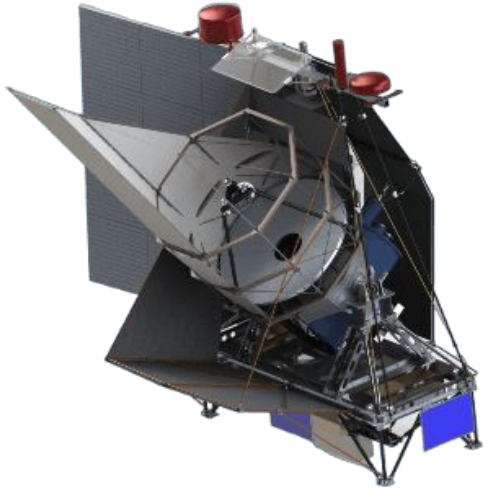
A “pencil beam survey”-like lightcone tracing [CII] in a volume 2 x 10 Mpc^3 across 4.5 Gyr of evolution across *cosmic noon* (**peak of star formation**).

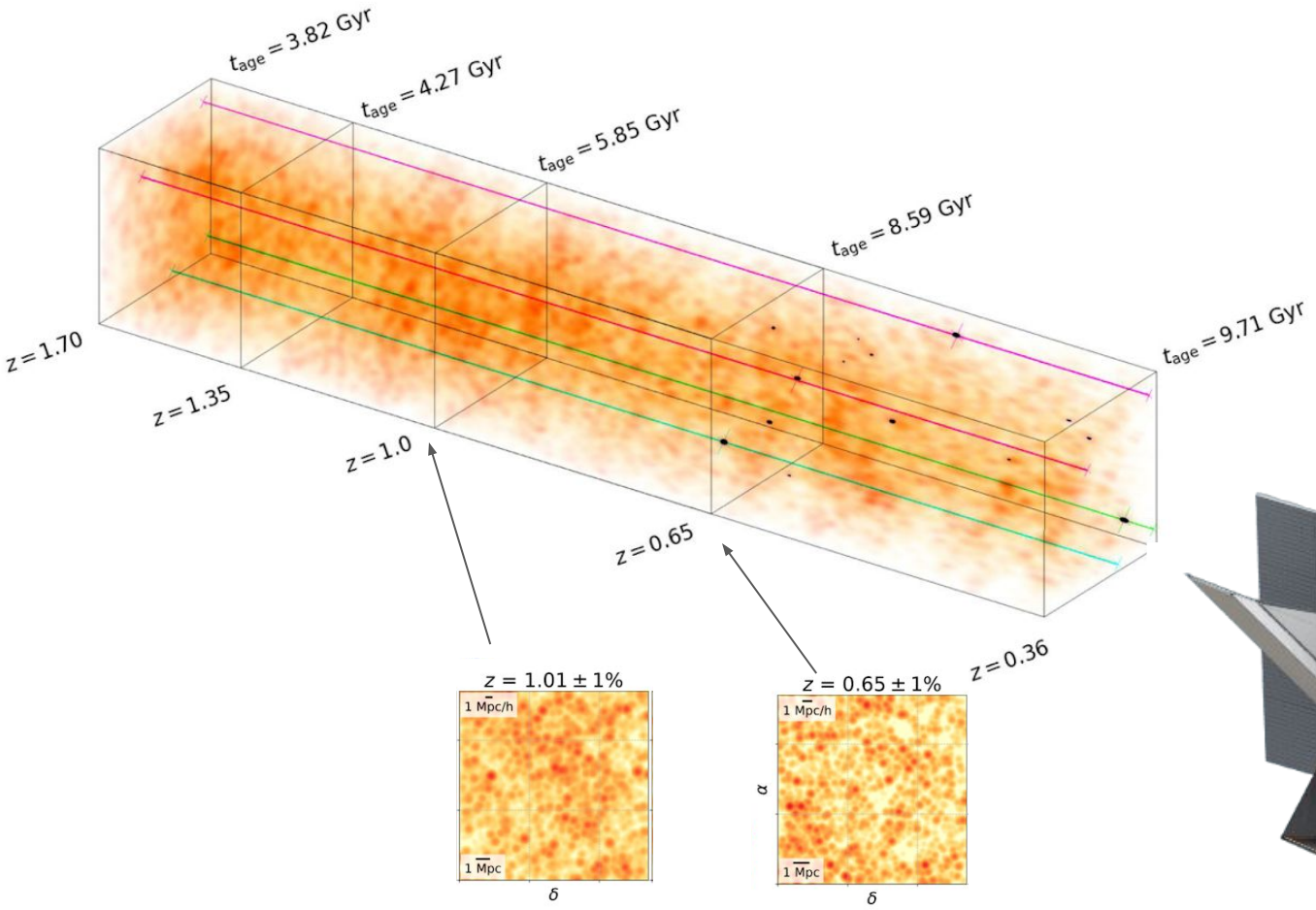


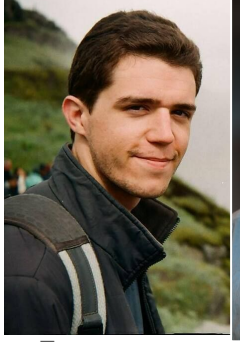


Evan Mayer

Shubh Agrawal

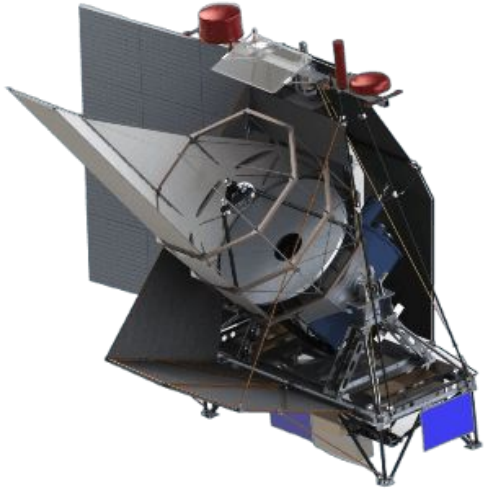


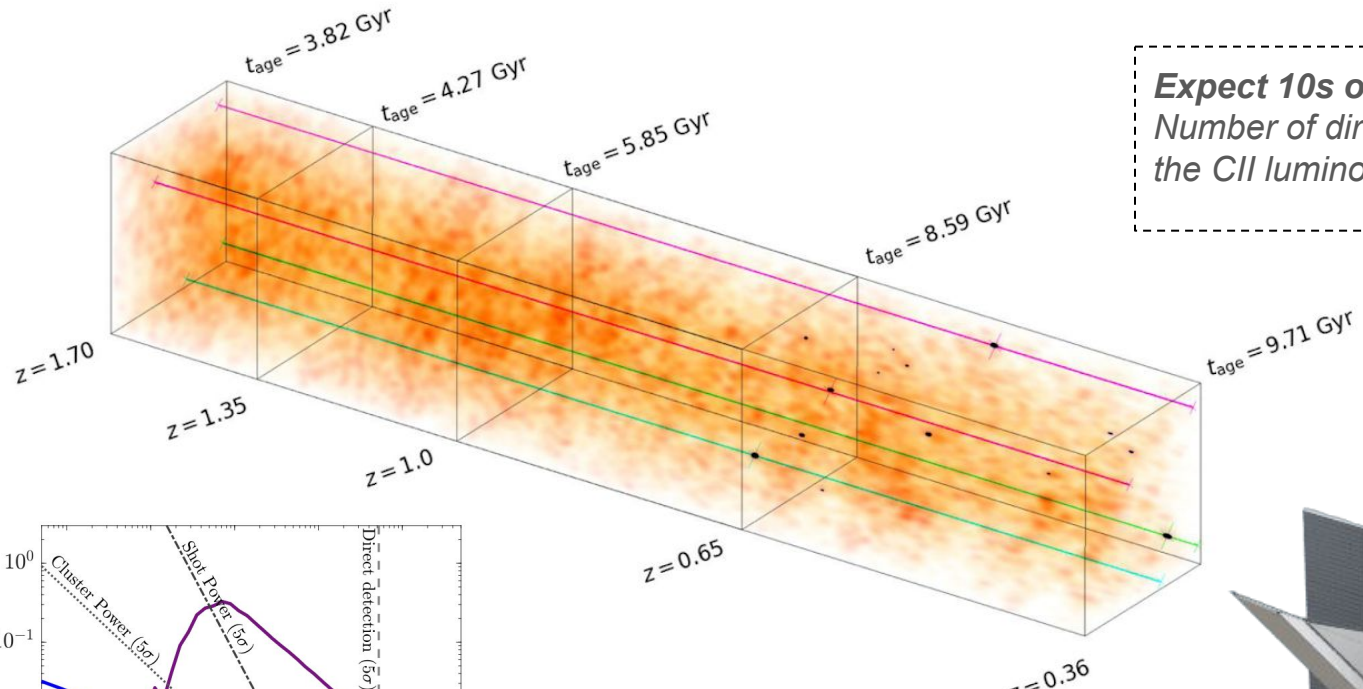




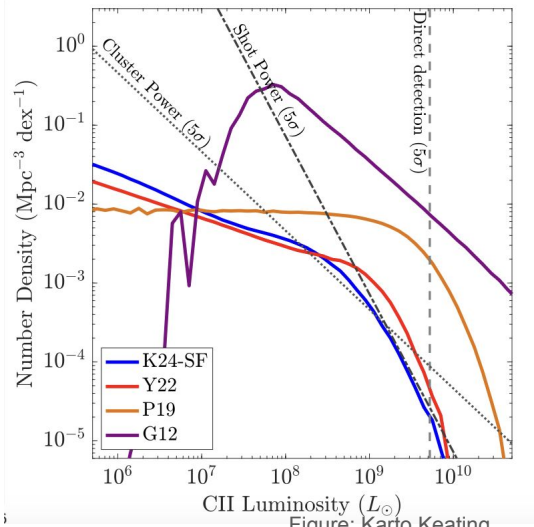
Evan Mayer

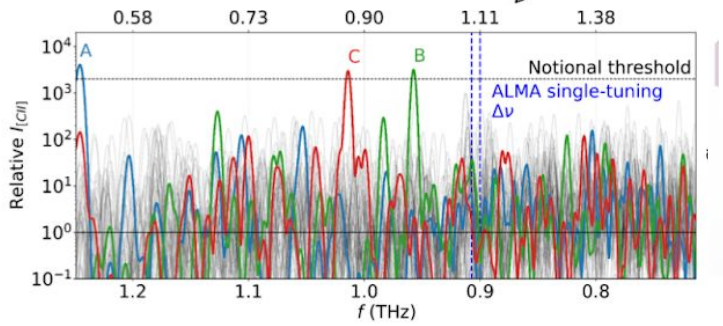
Shubh Agrawal





Expect 10s of direct detections
Number of direct detections constrains the CII luminosity function





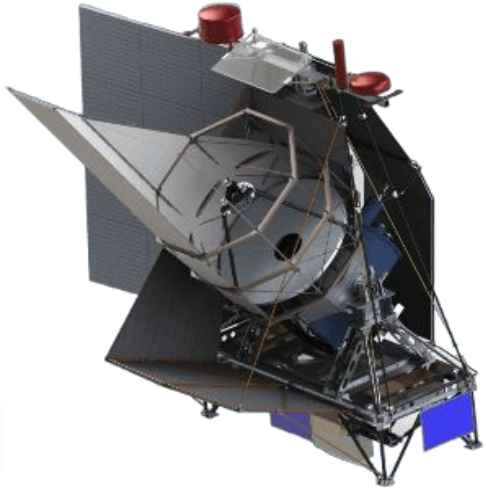
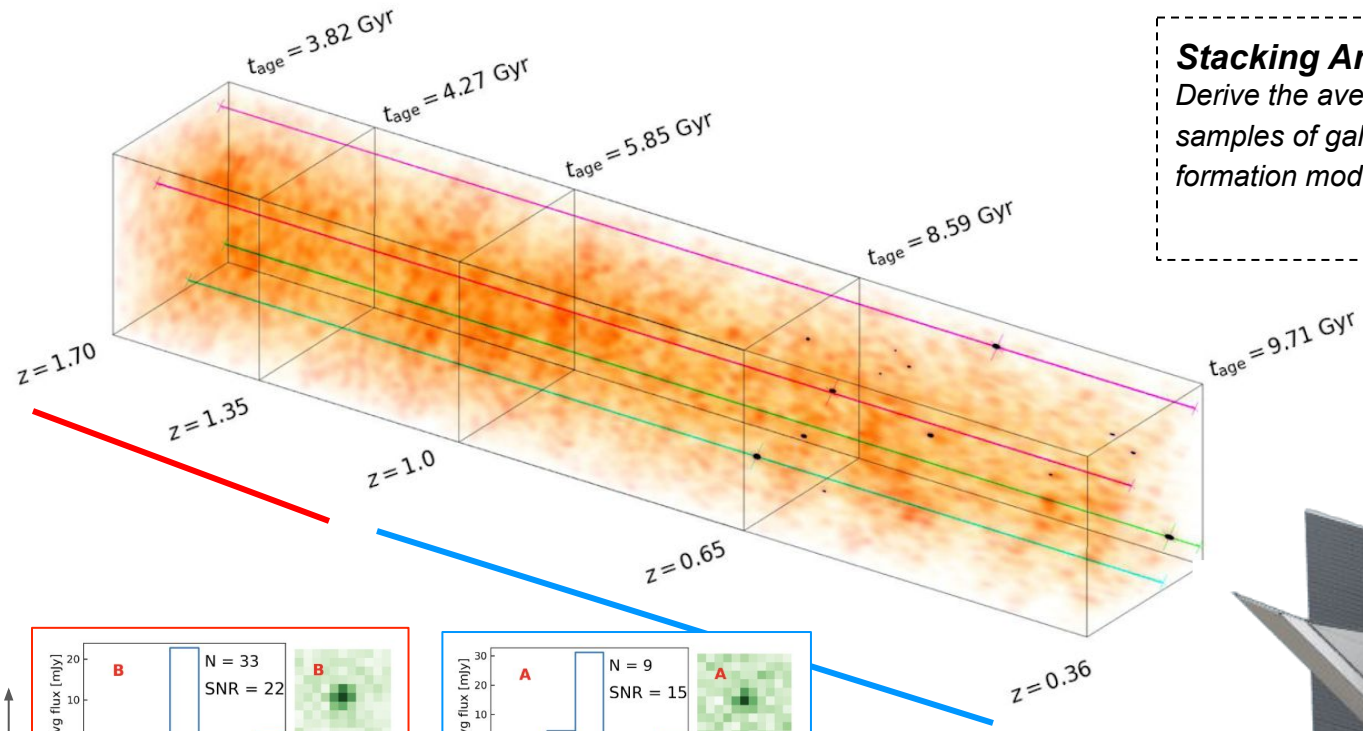
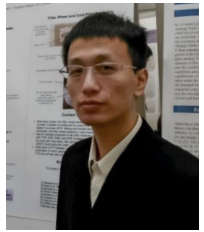


Figure: Karto Keating

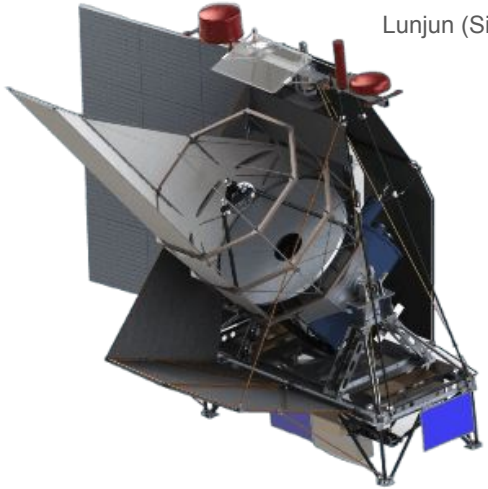


Stacking Analysis

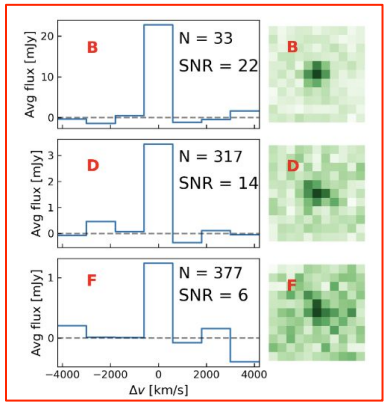
Derive the average FIR spectral properties of samples of galaxies e.g. metallicity, star formation modes, specific star formation rate

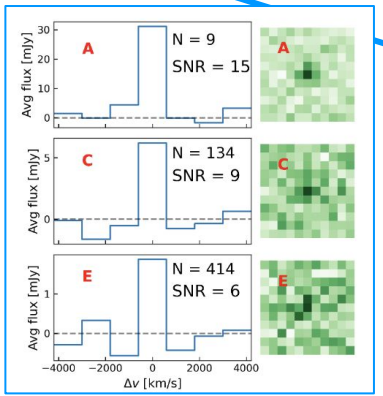


Lunjun (Simon) Liu



SFR





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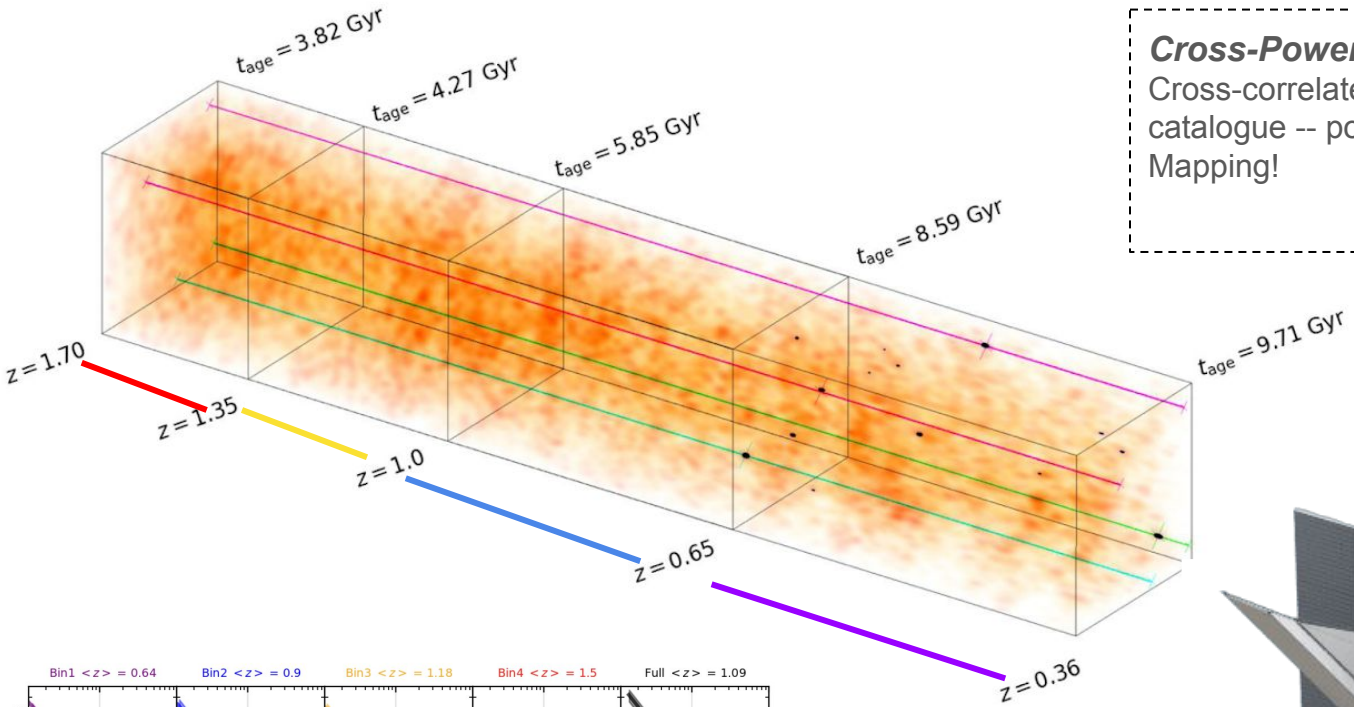
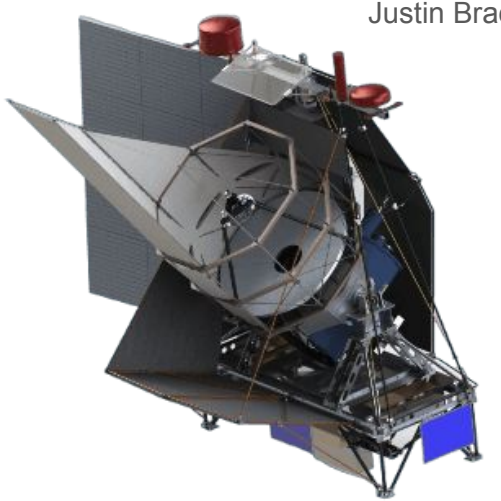
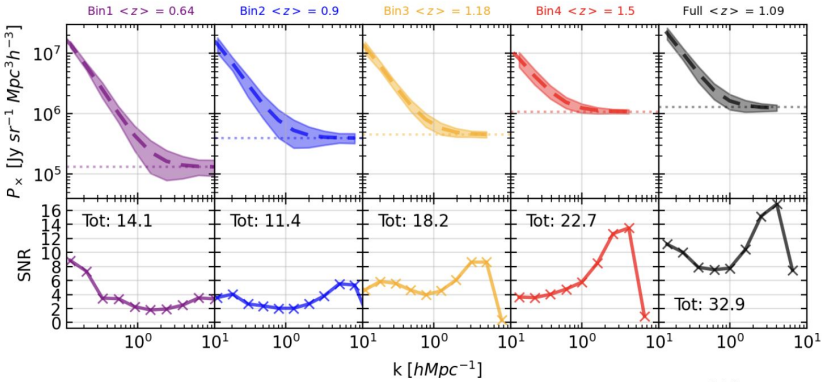


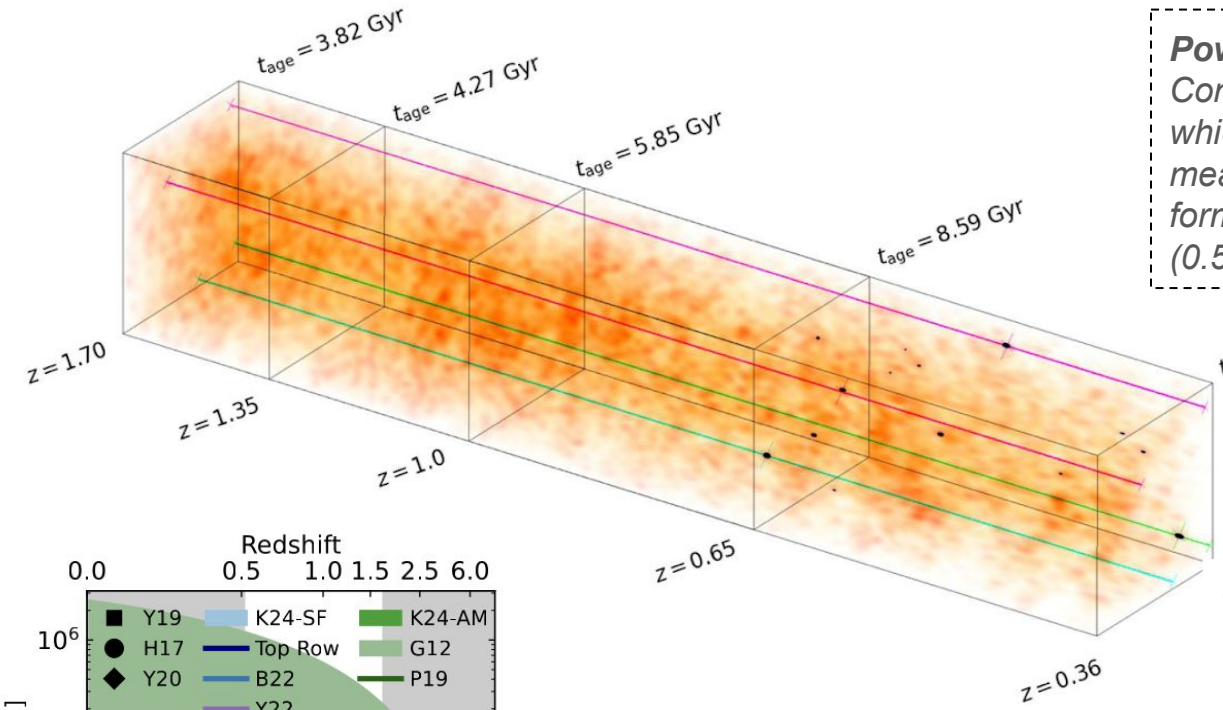
Cross-Power Spectrum

Cross-correlate with ASTRODEEP catalogue -- powerful proof of Line Intensity Mapping!

Justin Bracks



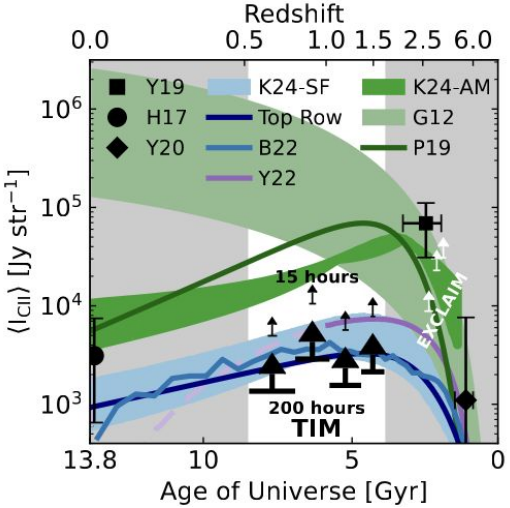


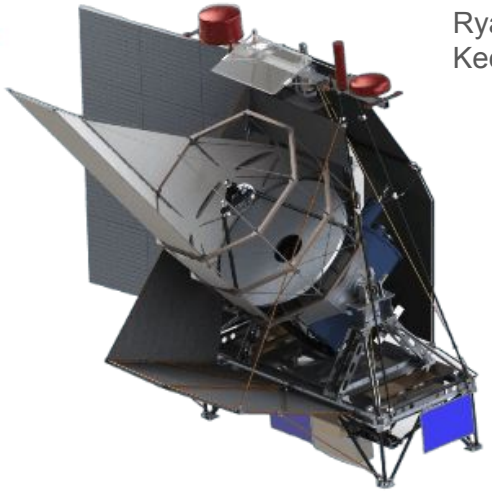


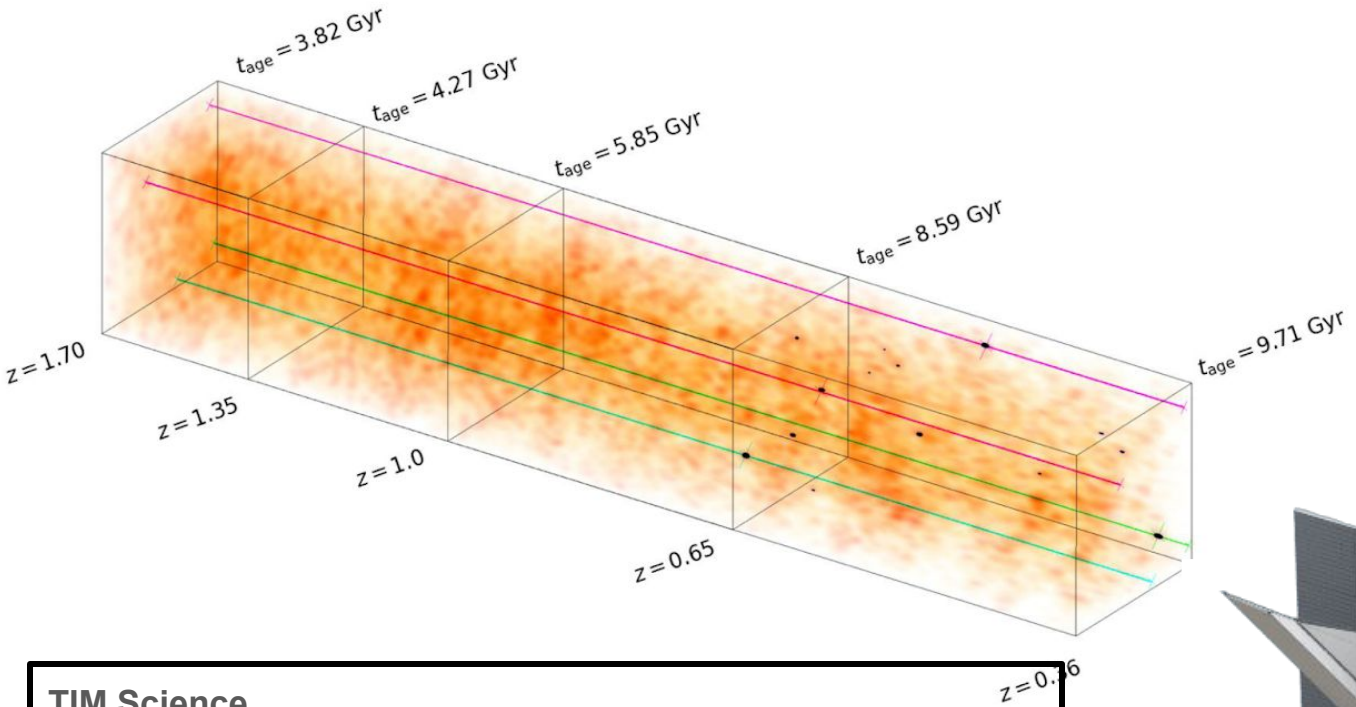
Power Spectrum

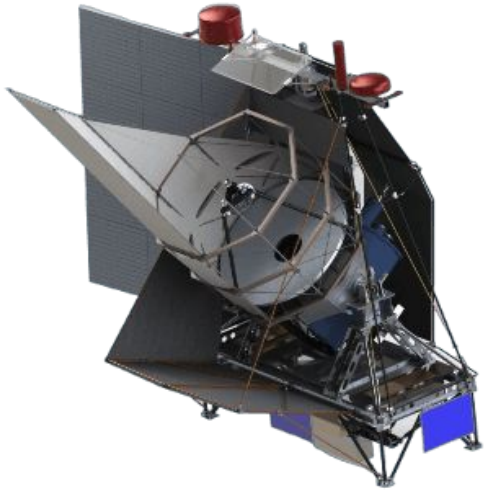
Constrain the CII Luminosity Function which can be translated to a measurement of the cosmic star formation rate density at cosmic noon (0.5<z<1.7)

Ryan Keenan









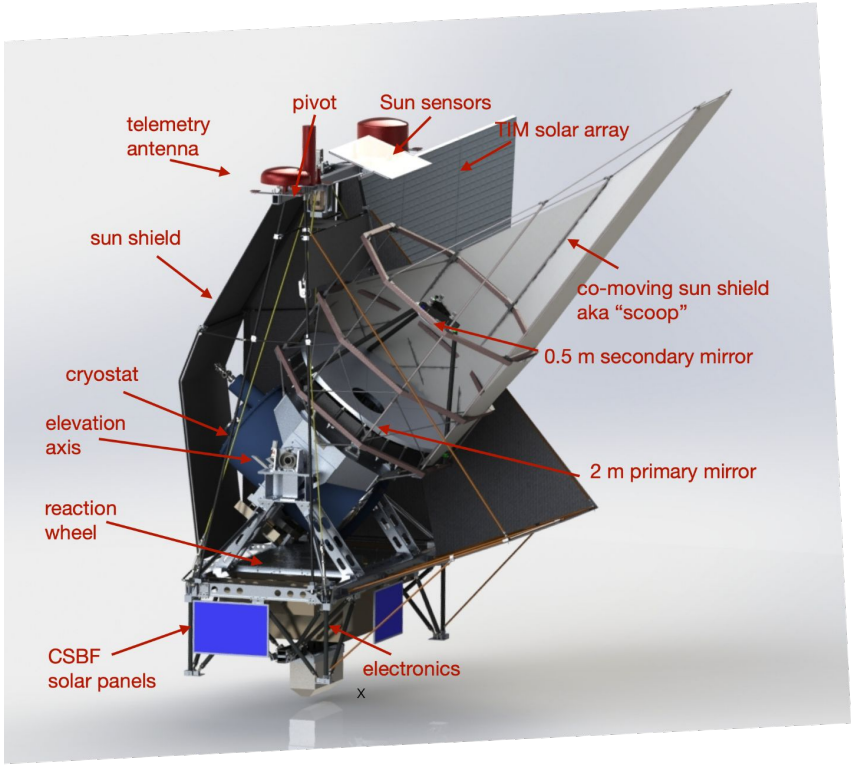
TIM Science

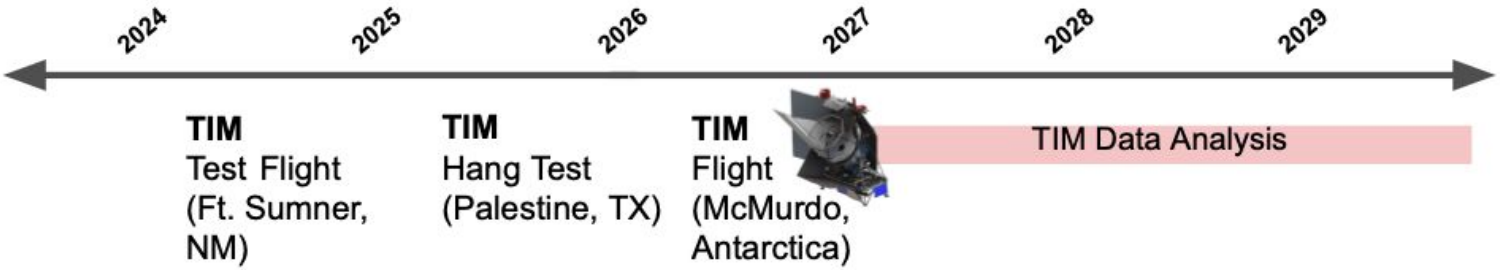
- Direct Detection
- Stacking
- Cross-Power Spectrum
- Auto-Spectrum

Learn about galaxy and star formation from this dataset!
Precursor to cosmology w/ LIM!

TIM at a glance

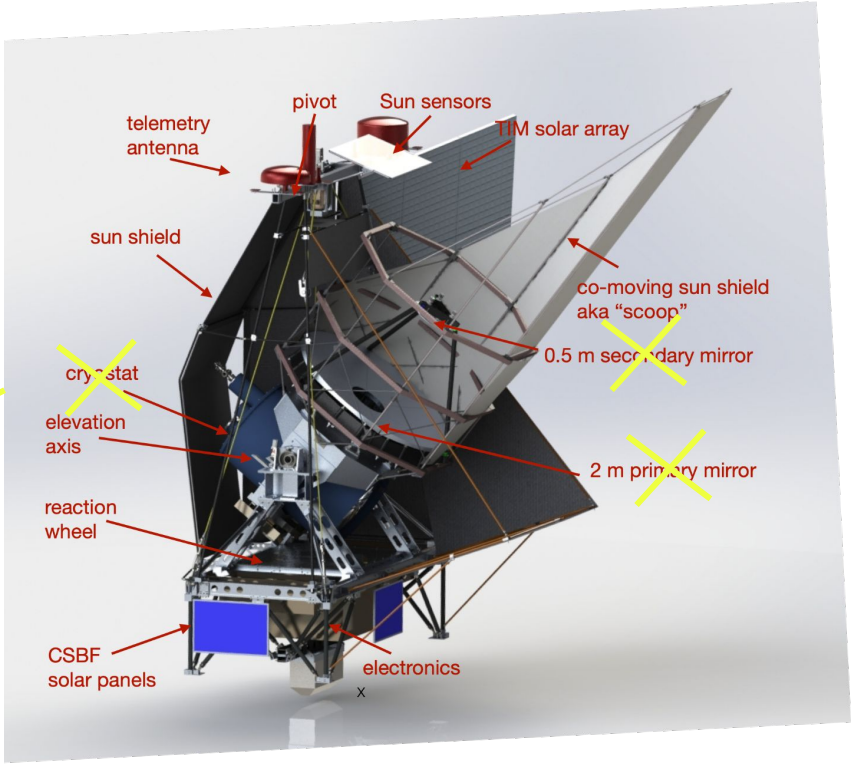
- 2m primary mirror
  - ~25” resolution at 240μm
- Two grating spectrometers
  - 240 – 317 & 317 - 420 μm at R~250
- 2x arrays with ~3600 detectors each





TIM Test Flight

- A NASA milestone to prove communications, drive train, and launch readiness
- Don’t fly anything expensive!



2024 2025 2026 2027 2028 2029

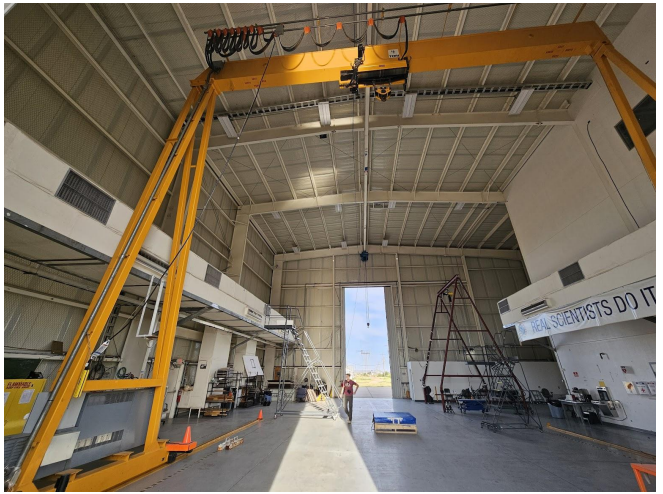
TIM ✅
Test Flight (Ft. Sumner, NM)

TIM
Hang Test (Palestine, TX)

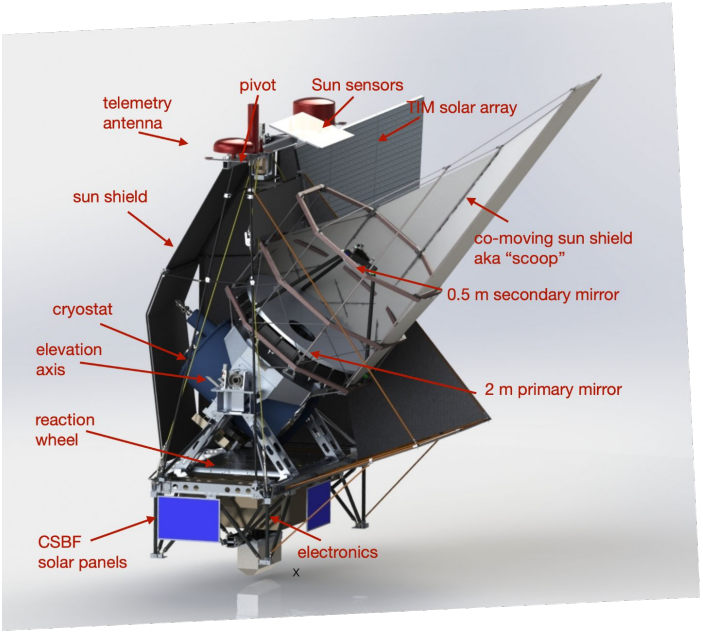
TIM
Flight (McMurdo, Antarctica)

TIM Data Analysis

The beginning : An empty hangar in Ft. Sumner, NM



August 2024 : Building TIM's Gondola



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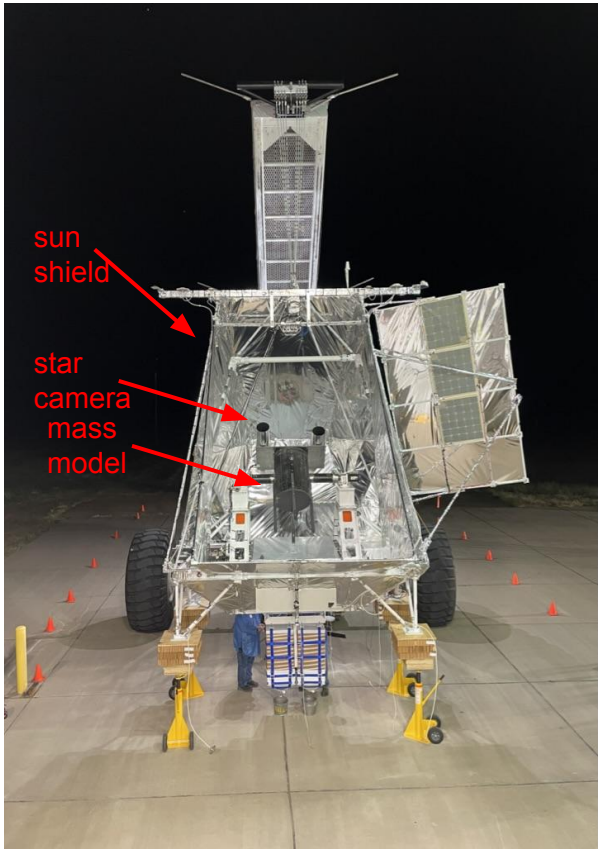
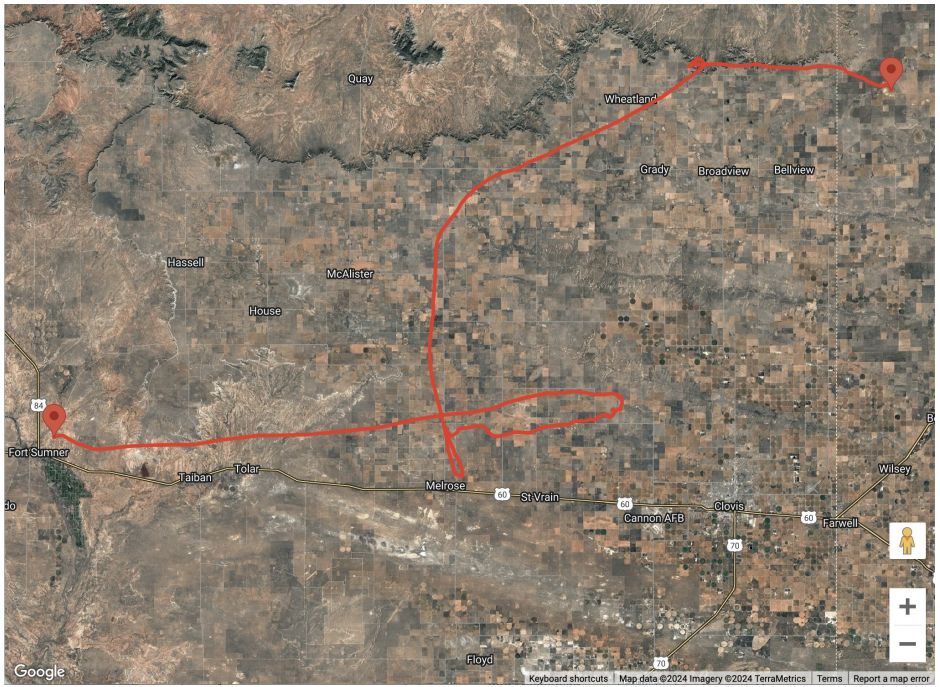


Launch Day: September 23rd, our 9th attempt

Successful Flight : 4 Hours, all NASA Milestones Passed



Data Analysis Pipeline Development

2024 2025 2026 2027 2028 2029

TIM ✅
Test Flight
(Ft. Sumner, NM)

TIM
Hang Test
(Palestine, TX)

TIM
Flight
(McMurdo, Antarctica)

TIM Data Analysis

Robust calibration, focusing, data quality checks, and online-mapmaking for during flight

TIM Science

- Direct Detection
- Stacking
- Cross-Power Spectrum
- Auto-Spectrum

Learn about galaxy and star formation from this powerful dataset!
Precursor to cosmology w/ LIM!

Two Big Challenges for the Field of Line Intensity Mapping:

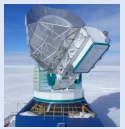
Instrumentation Challenge:

How do we build instruments with the raw sensitivity to make competitive cosmological constraints?

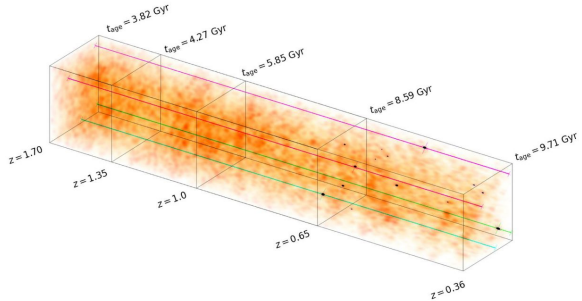
Data Analysis Challenge:

New techniques needed to be developed and perfected for these sensitive instruments!

CO
Maximum *Signal*
GHz (Can do from the ground)
SPT-SLIM



CII
Maximum *Signal-to-Noise*
THz (From Space)
TIM (Terahertz Intensity Mapper)



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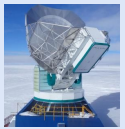

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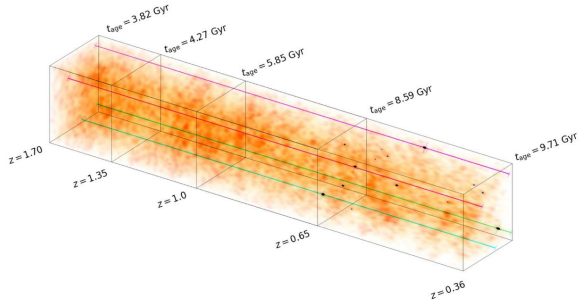
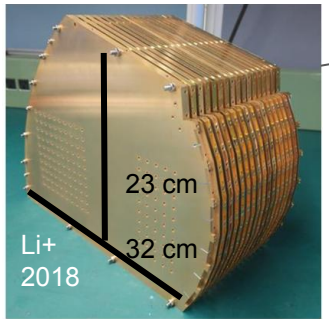


Cosmology with mm-wave Line Intensity Mapping

LIM can potentially constrain cosmological parameters beyond current CMB and galaxy survey constraints:

- Inflation and the history of the very early universe
- Neutrino masses
- New light relic particles
- Dark energy



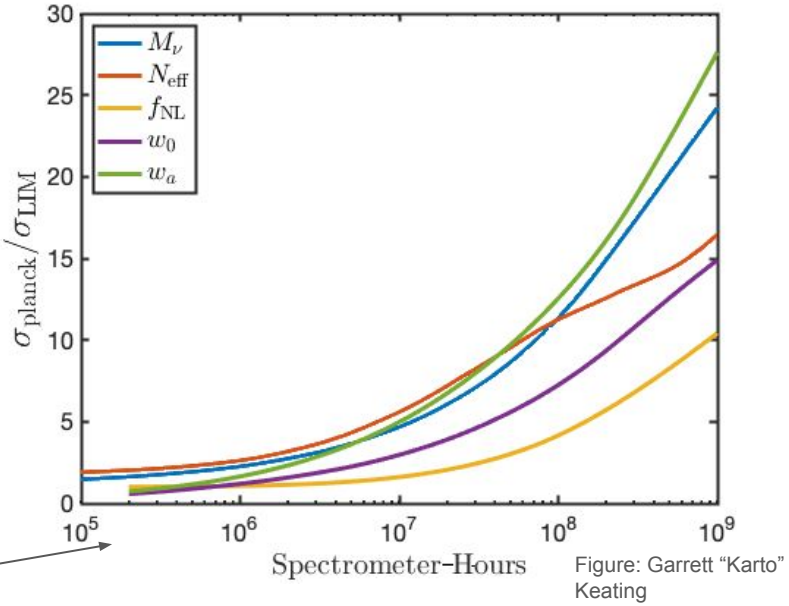
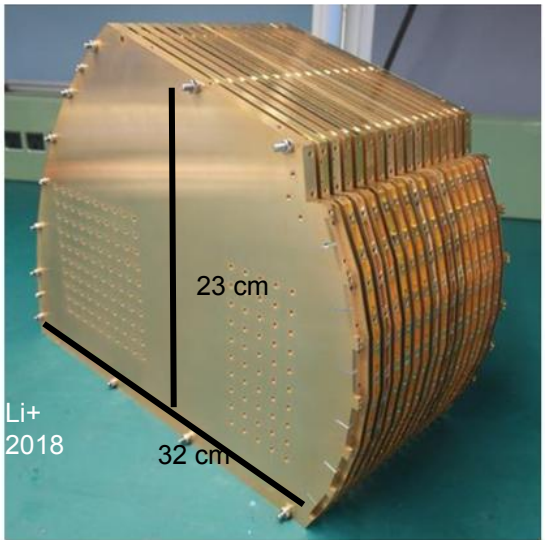
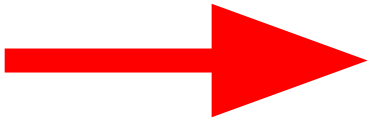


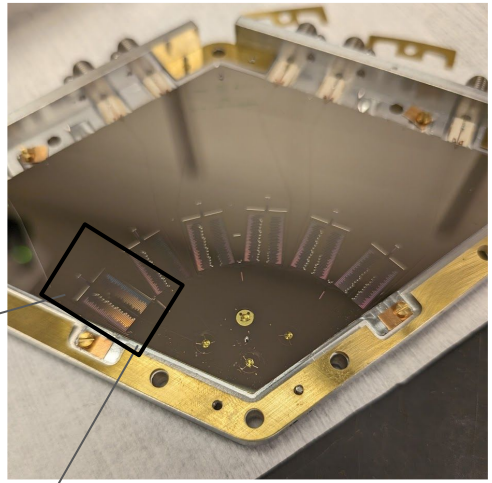
Figure: Garrett "Karto" Keating

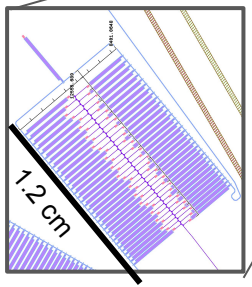
Need to increase instantaneous sensitivity

On-Chip Spectrometers: A Scalable Technology









TIME grating: R = 100, 60 spectral channels
32 x 23 x 1 cm = **~ 736 cm^3**

SPT-SLIM Filterbank: R = 100, 65 spectral channels
1.26 x .84 x 0.05 cm= **~ 0.5 cm^3**

SPT-SLIM: SPT Shirokoff Line Intensity Mapper

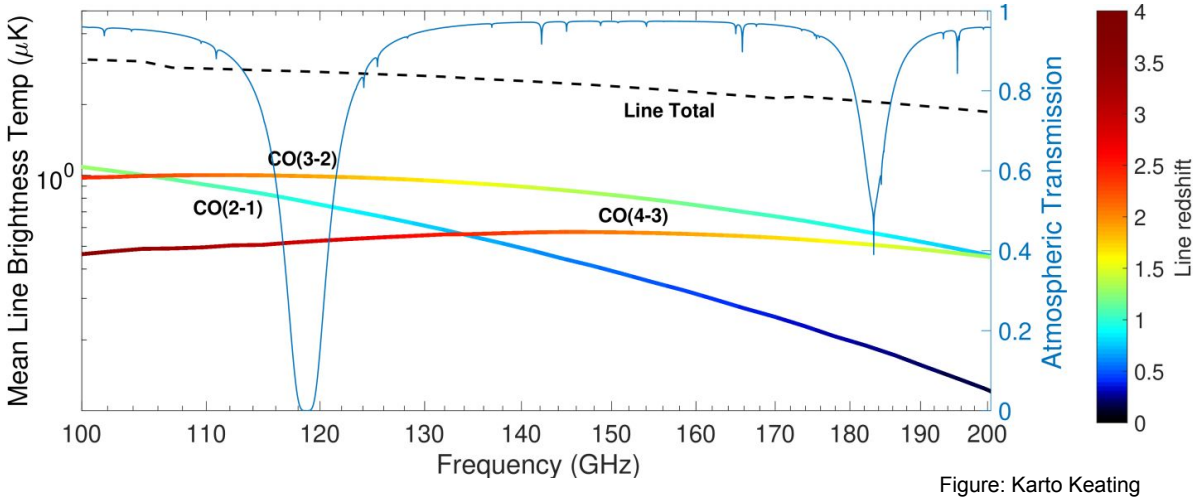
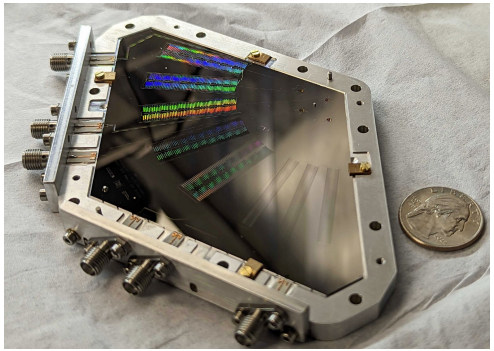
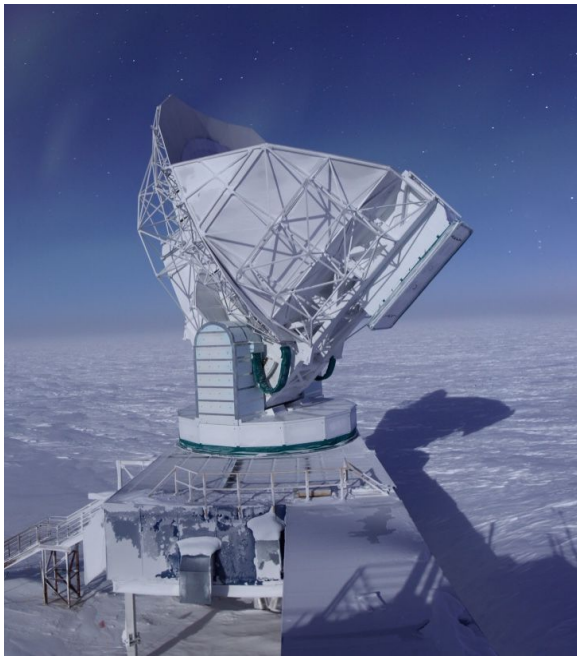


Figure: Karto Keating



- Demonstrate the LIM measurement using on-chip mm-wave spectrometers -- **scalable, a unique technological advantage in the field!**
- a high-density, 9-pixel dual-polarization focal plane
- 120-180 GHz, sensitive to CO at $0.5 < z < 2$
- Deployed Nov 2024 to the South Pole Telescope

SPT-SLIM: SPT Shirokoff Line Intensity Mapper



Argonne NATIONAL LABORATORY — T. Cecil, C. Chang, M. Lisovenko, V. Yefremenko, C. Yu

BOSTON UNIVERSITY — **K. Karkare,** A Lapuente

CARDIFF UNIVERSITY / PRIFYSGOL CAERDYDD — **P. S. Barry,** C. Benson, G. Robson

Fermilab — **A. Anderson**, B. Benson, M. Young

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN — G. Keating

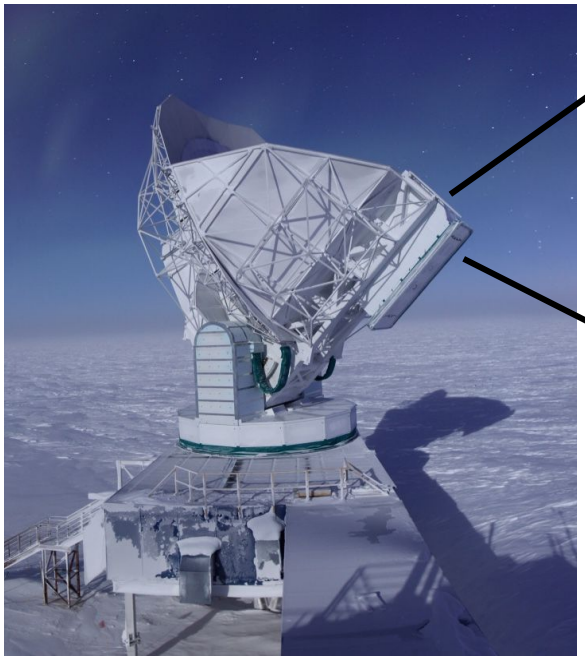
McGill — M. Adamic, M. Dobbs, J. Montgomery, M. Rouble, G. Smecher

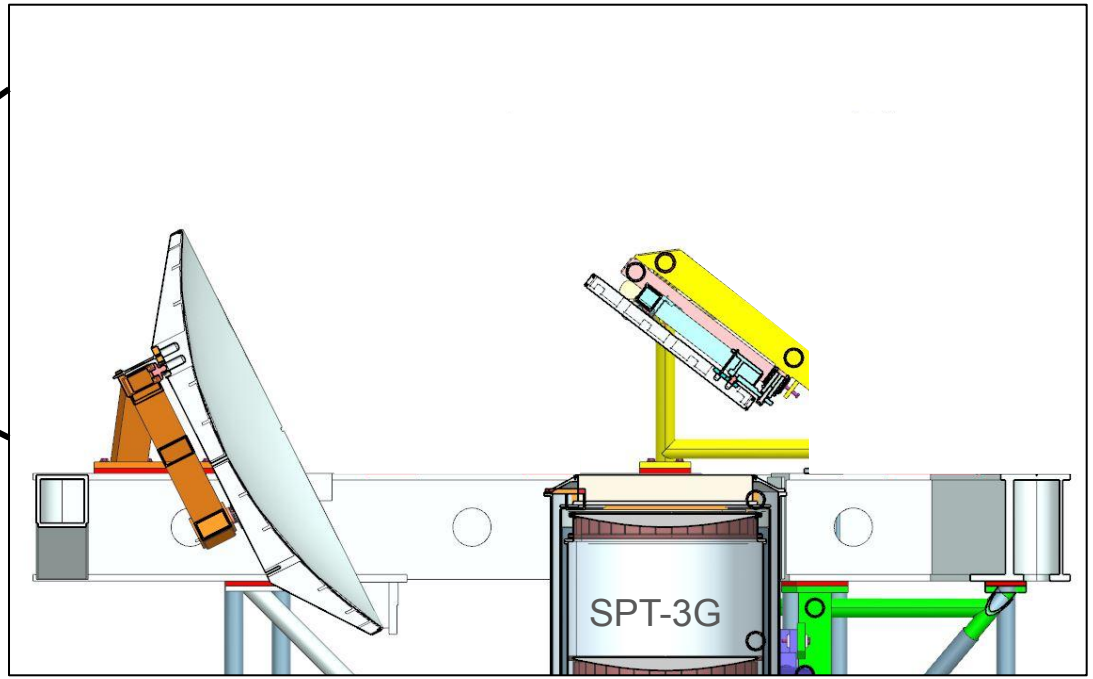
SLAC — C. Zhang

THE UNIVERSITY OF ARIZONA — D. Marrone, D. Kim, H. Tailor

THE UNIVERSITY OF CHICAGO — E. Brooks, J. Carlstrom, K. Dibert, K. Fichman, T. Natoli, A. Rahlin, J. Zebrowski

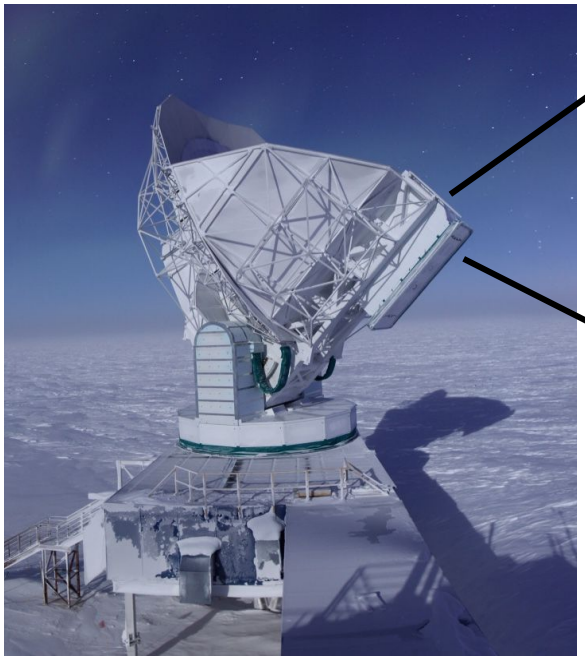
SPT-SLIM: SPT Shirokoff Line Intensity Mapper

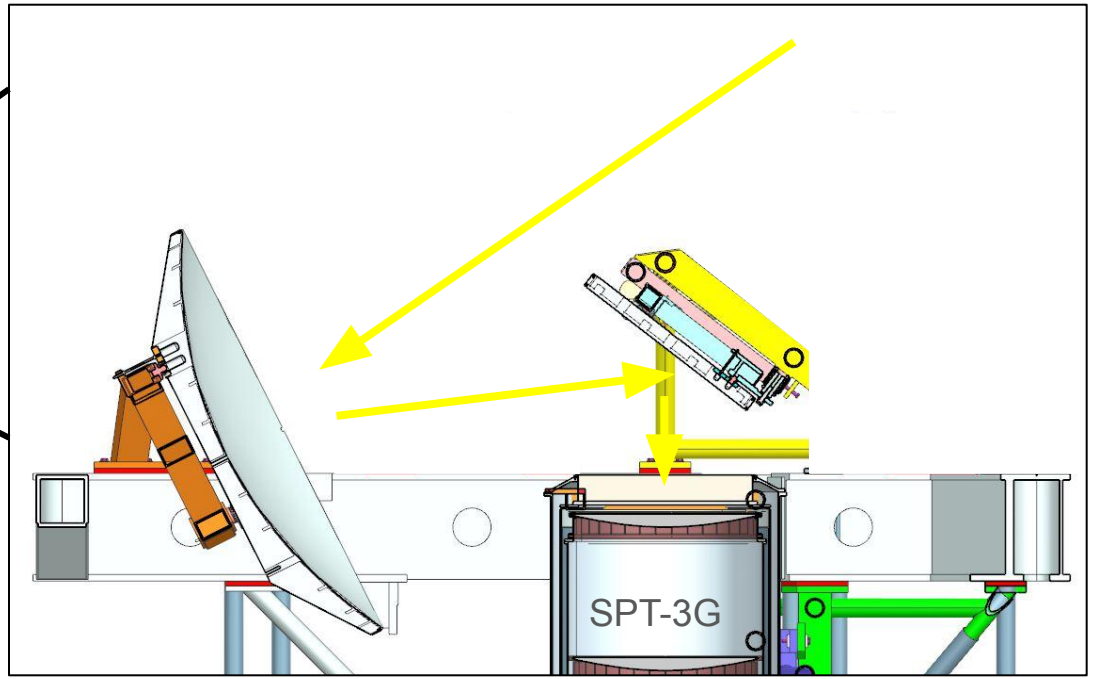




The South Pole Telescope: a 10-m off-axis gregorian telescope at Amundsen-Scott South Pole Station

SPT-SLIM: SPT Shirokoff Line Intensity Mapper





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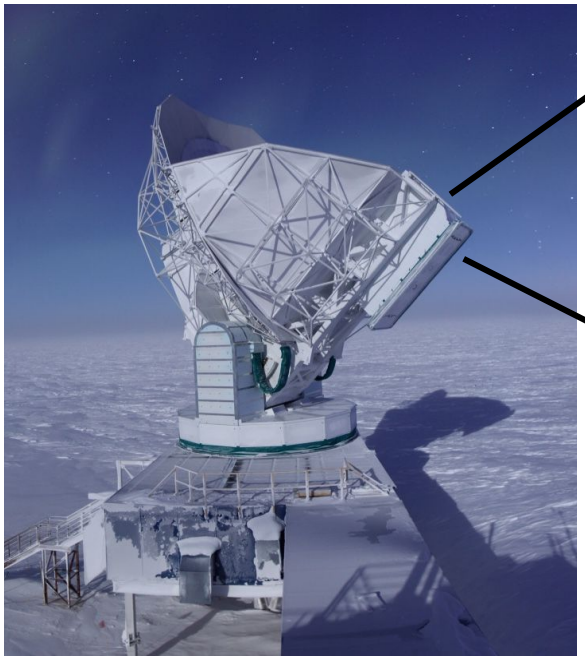
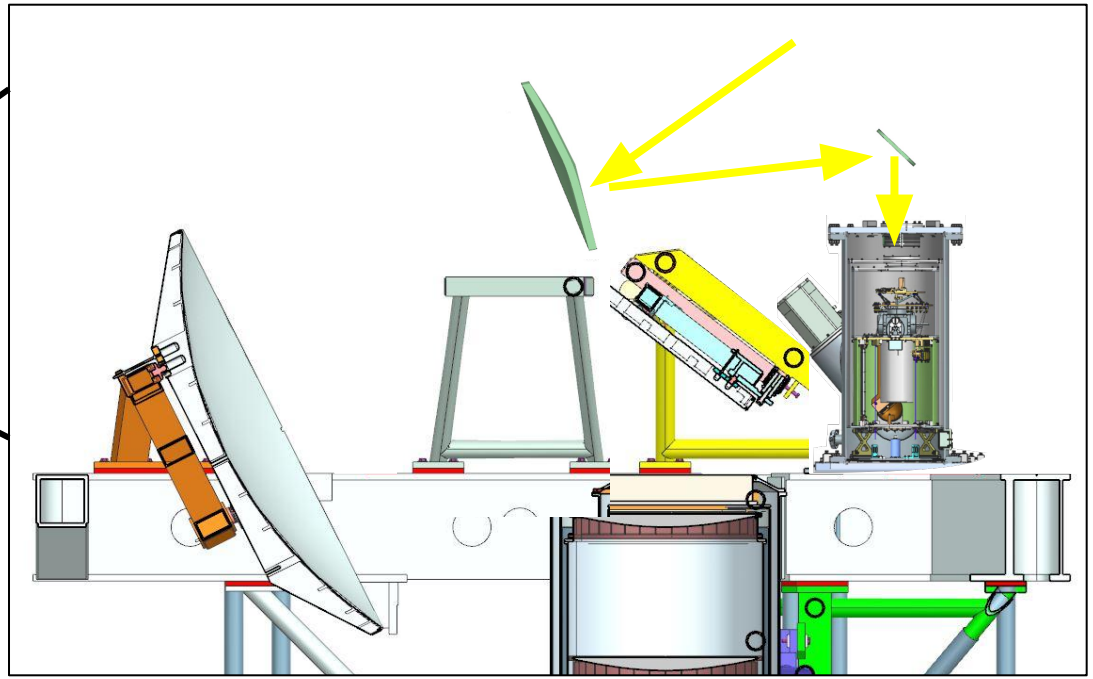
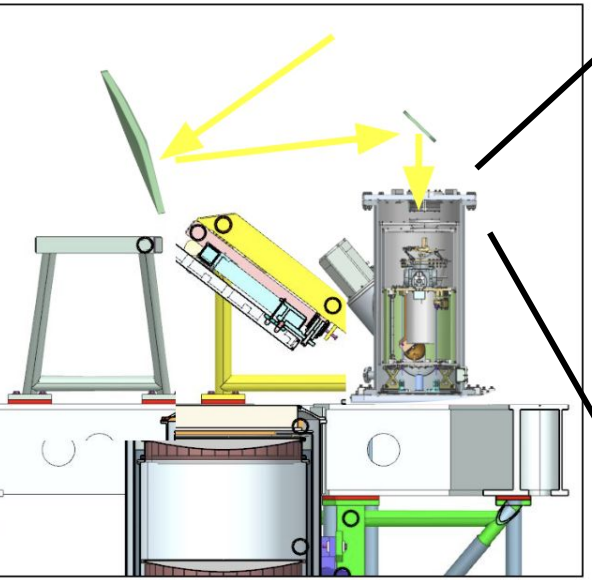
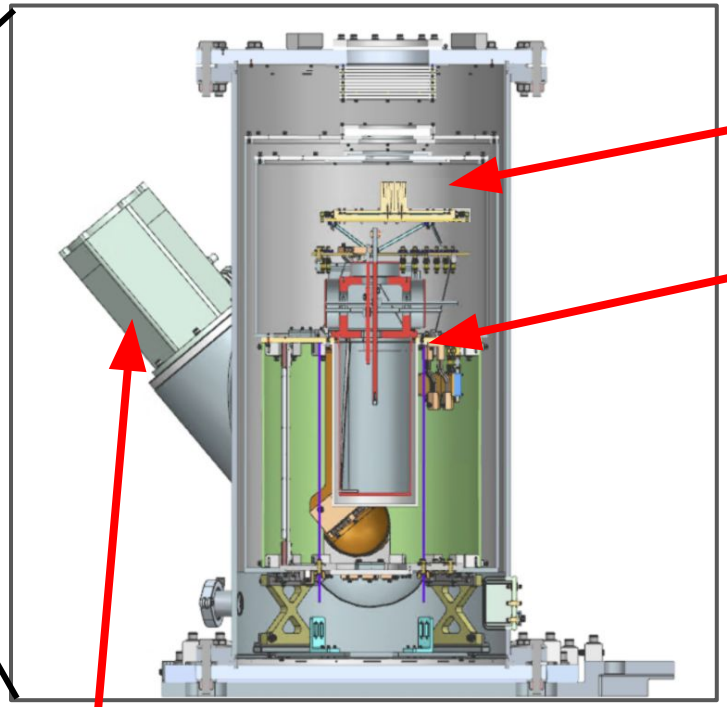




SPT-SLIM has two auxiliary mirrors to pick off the main SPT beam, while not disturbing the SPT-3G CMB experiment

SPT-SLIM: SPT Shirokoff Line Intensity Mapper



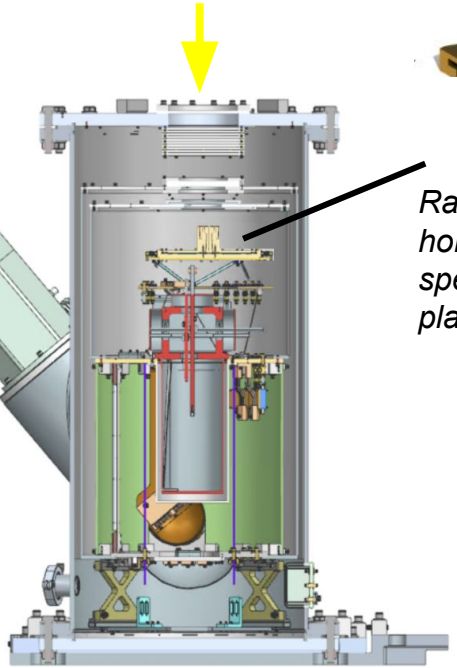


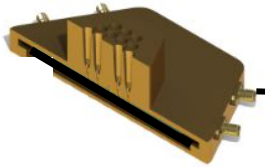
Focal Plane

ADR (Adiabatic Demagnetization Refrigerator) - *cools focal plane to 150 mK*

Pulse Tube Cooler - *cools to 4K*

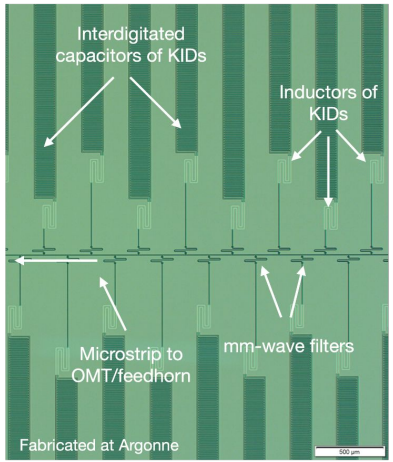
SPT-SLIM: SPT Shirokoff Line Intensity Mapper



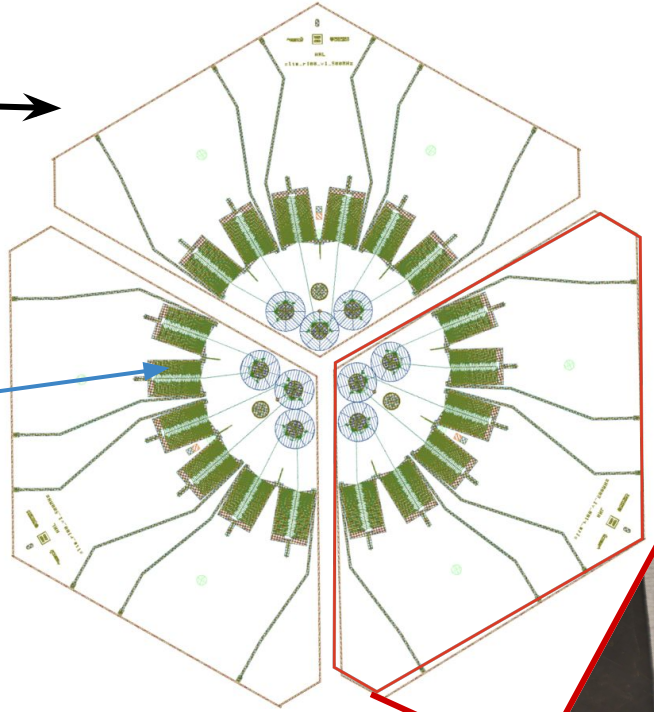


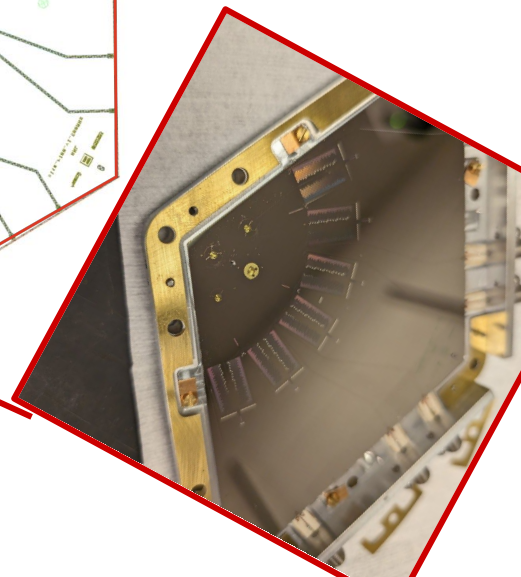
Radiation admitted by conical horns and coupled to spectrometer filterbanks by a planar OMT

KID filterbanks

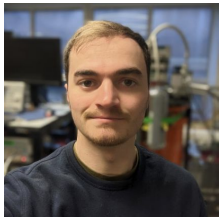


Fabricated at Argonne (C. Chang ++)





Focal plane consists of 3x "submodules" each with 3 pixels / 6 filter banks, tiled together in a scalable package.



Designed at Cardiff
(P.Barry, G. Robson)

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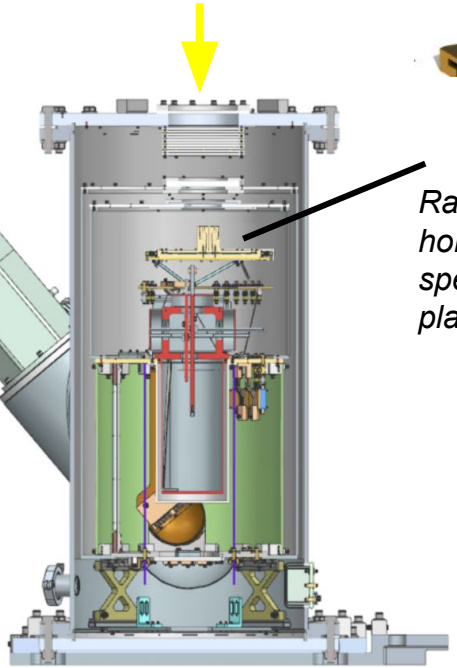

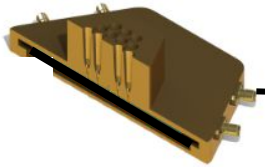

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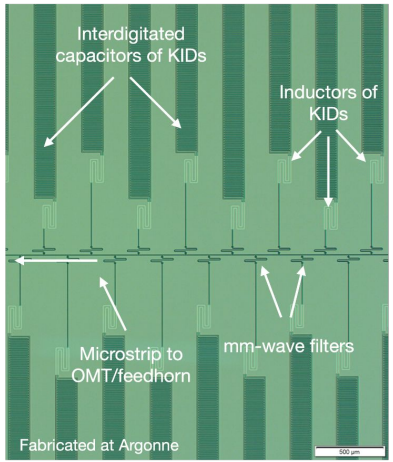

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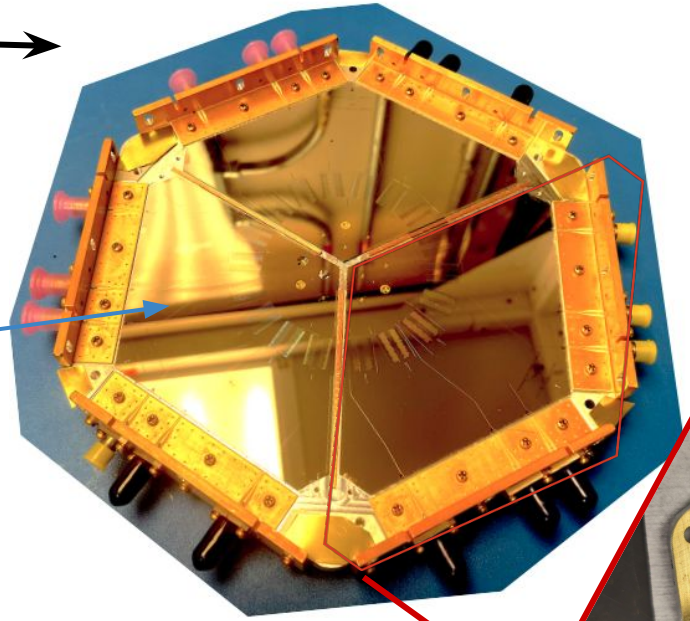

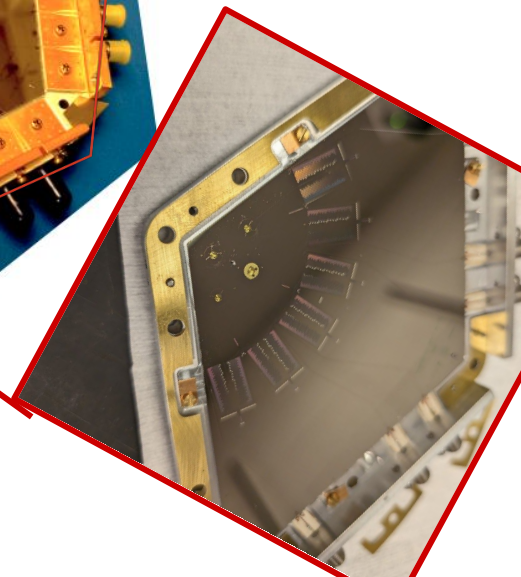

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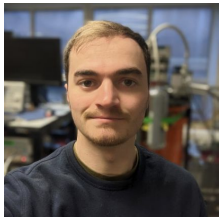

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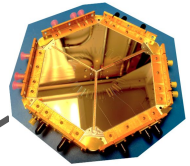
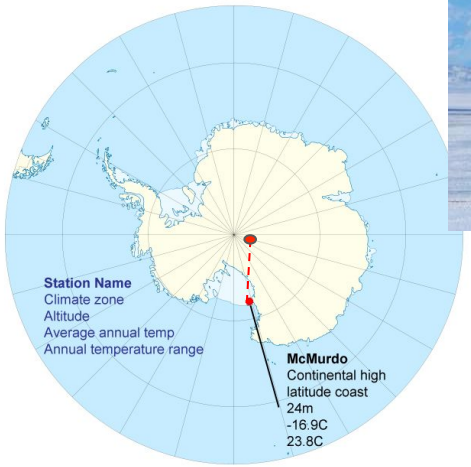


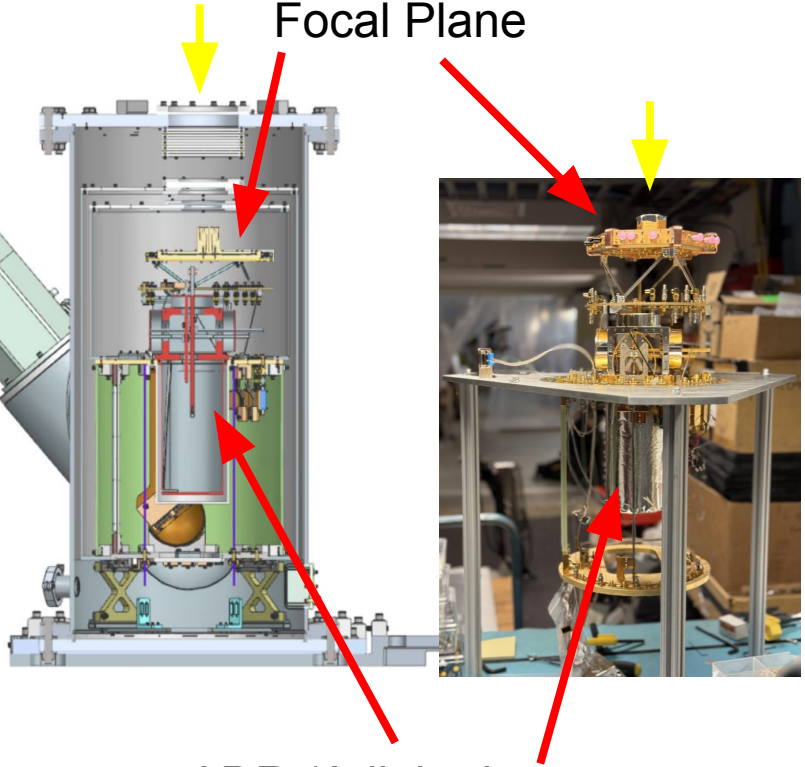
Fragile equipment
carried by hand

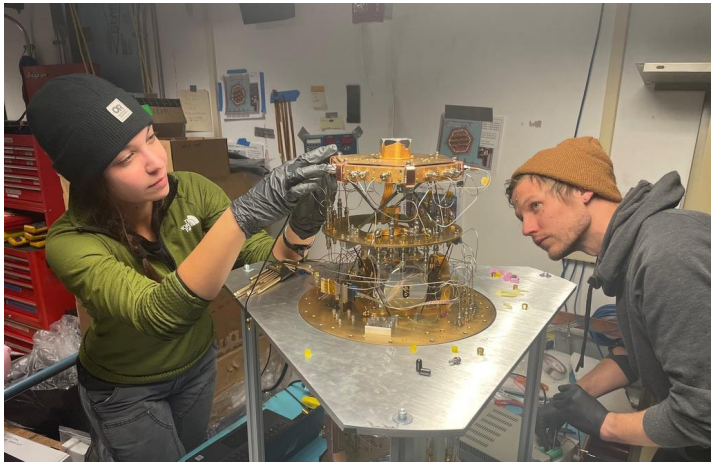


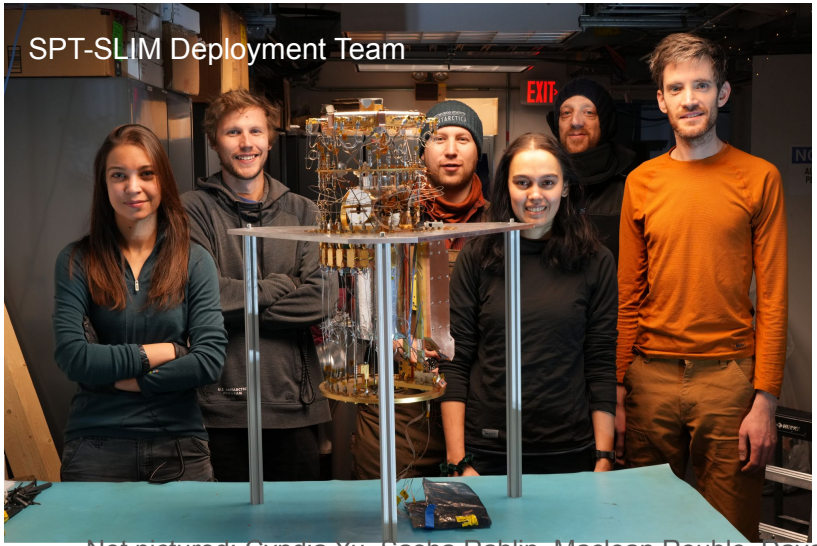
Rest of the equipment
in the cargo hold

Cargo Arrived: Dec 3rd, 2024

SPT-SLIM Cryostat Assembly

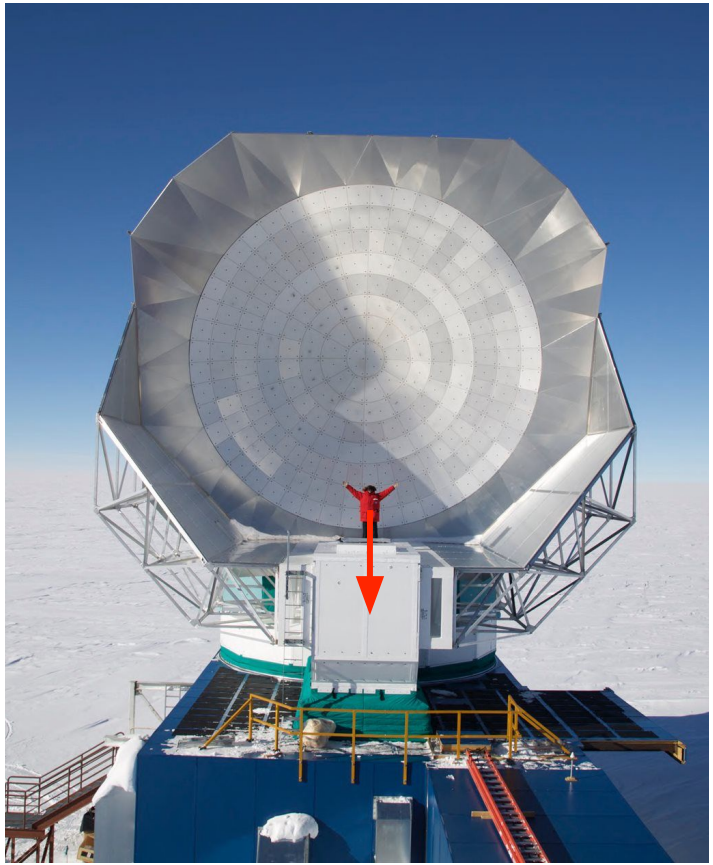




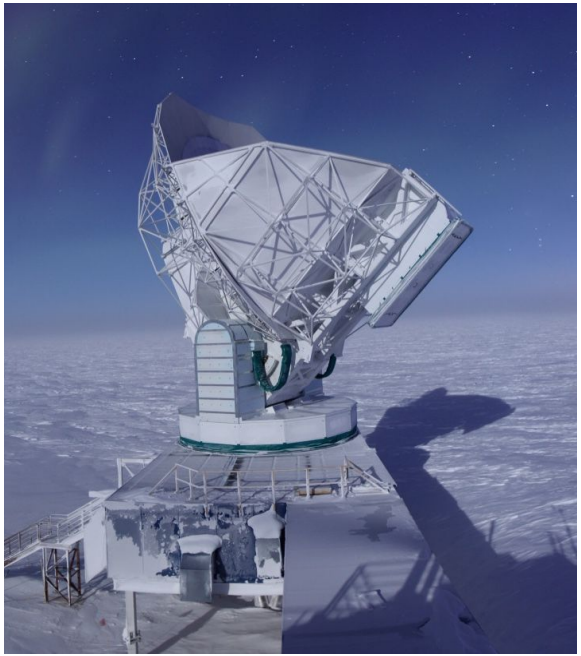


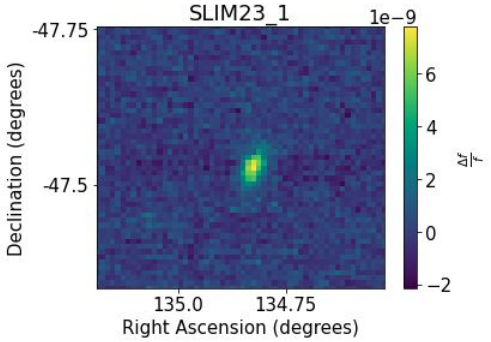
Not pictured: Cyndia Yu, Sasha Rahlin, Maclean Rouble, Dave Pernic

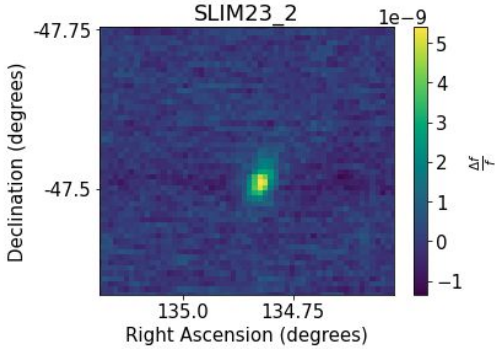
Lifting SPT-SLIM into the Telescope

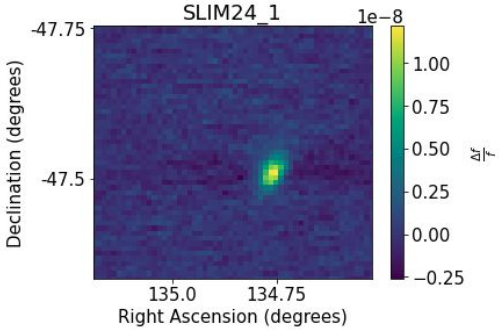


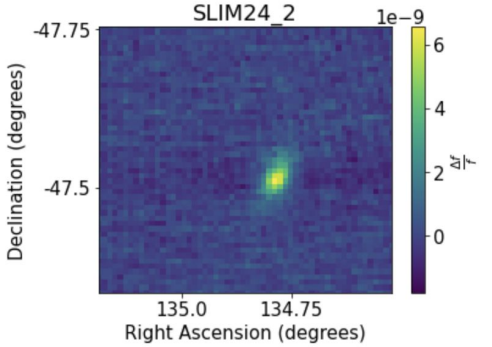
Jan 15th SPT-SLIM First Observed Source: RCW 38





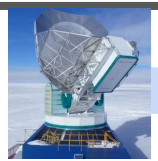






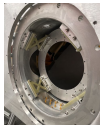
SPT-SLIM: This is just the start for on-chip spectrometers!

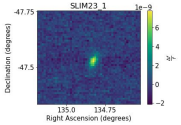
2024 2025 2026 2027 2028 2029



SPT-SLIM Y1
Deployment:
CO Data

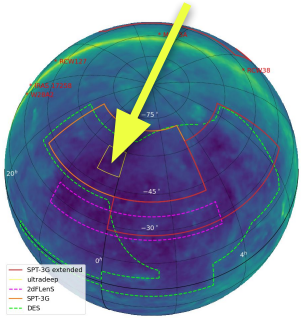
- Deployment of mm-wave on-chip spectrometers for line intensity mapping





SPT-SLIM Y2
Deployment SPT-SLIM Data Analysis

- Deployment of more sensitive detectors and a deeper field survey



How do we get orders of magnitude improvement for cosmology?

Spec-hrs	Example	Time-scale
10^5	TIME, CCAT-p, SPT-SLIM	2025
10^6	TIME-EXT	2026
10^7	SPT-like 1 tube	2028
10^8	SPT-like 7 tubes	2031
10^9	CMB-S4-like 85 tubes	2037

Karkare 2022

How do we get orders of magnitude improvement for cosmology?

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10^9	CMB-S4-like 85 tubes	2037

Karkare 2022

LIM becomes competitive with galaxy surveys in the ~10^7 spectrometer-hour range

How do we get orders of magnitude improvement for cosmology?

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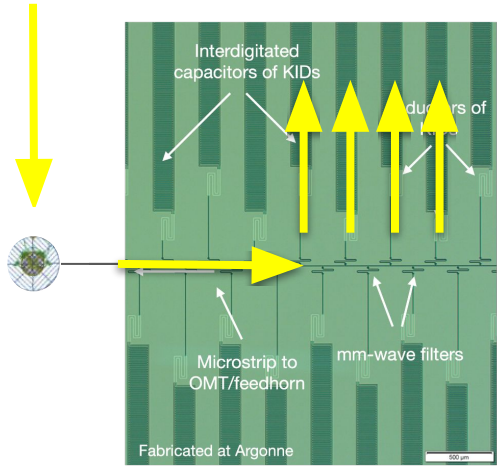
Karkare 2022

Limiting factor #1 is dielectric loss



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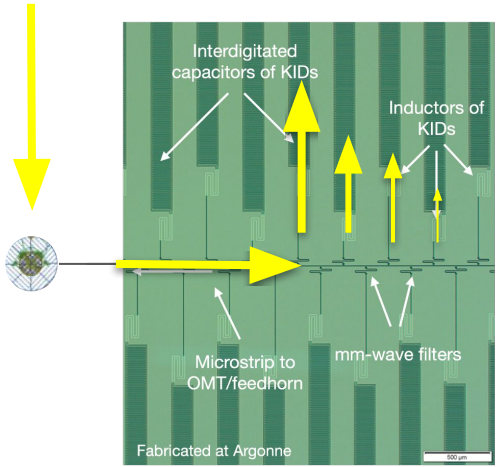

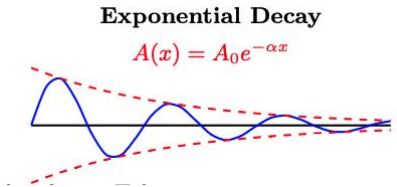

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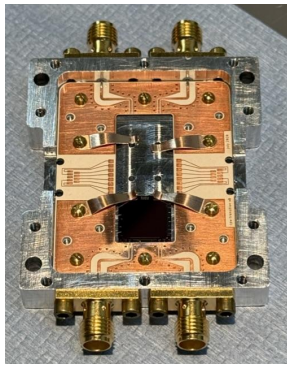
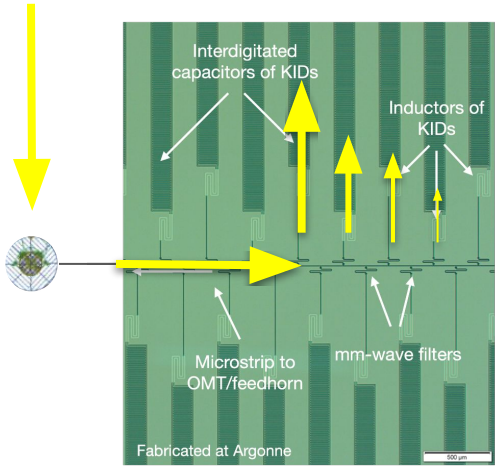
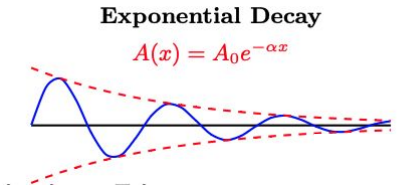
LANCE

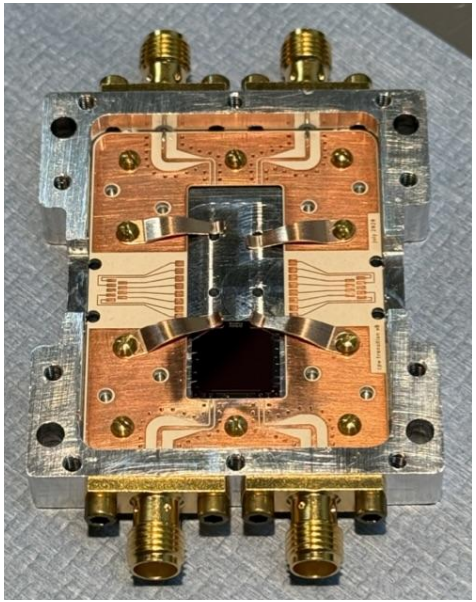


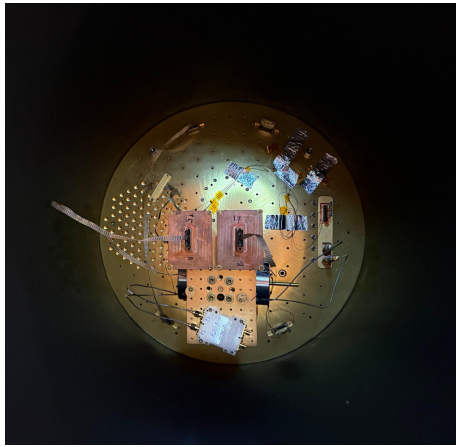


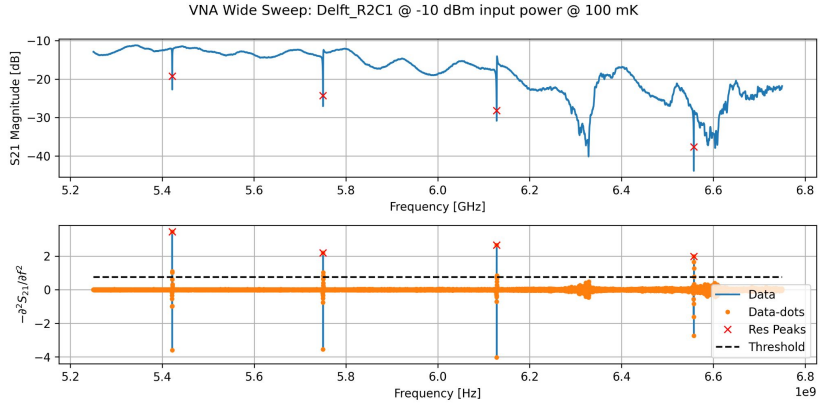


LANCE: Leveraging Advancements in Nanotechnology for Cosmology Experiment

Using methods developed for cosmology to test new dielectrics for next-generation cosmology instrumentation using materials developed for quantum transduction







THE KAVLI FOUNDATION

Argonne: James Cornelison, Clarence Chang, Tom Cecil
UChicago: Jessica Zebrowski, Hrushi Athreya
TU Delft: Maz Ali, Roald van der Kolk, Mischa Mykhaylov

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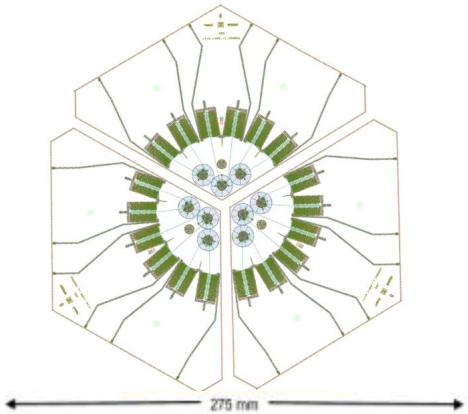

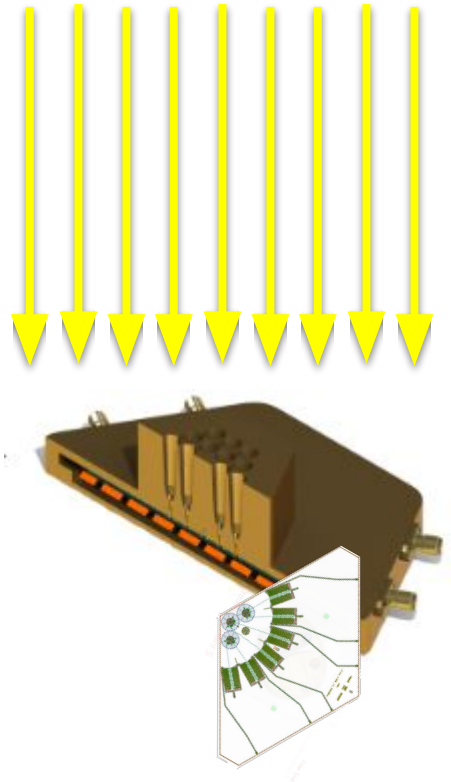

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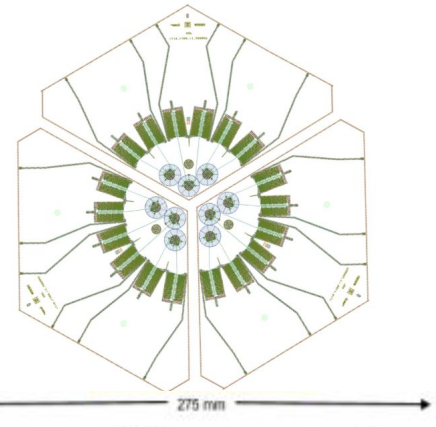

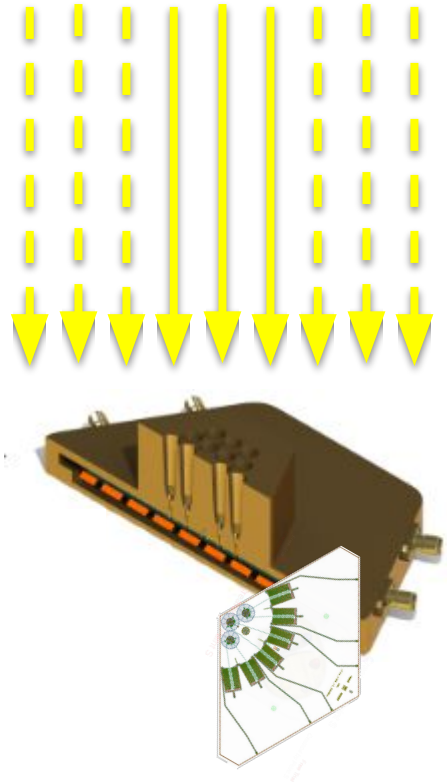

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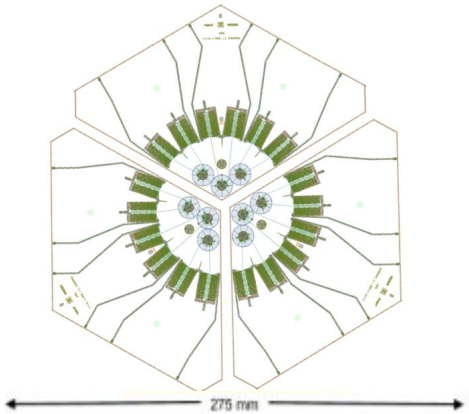

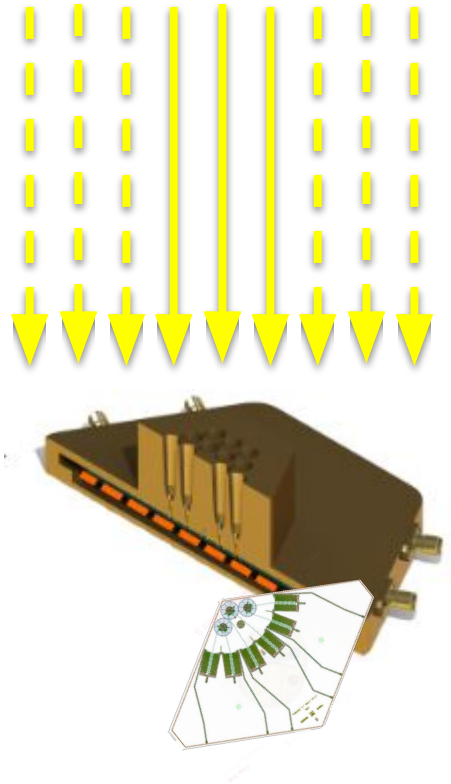

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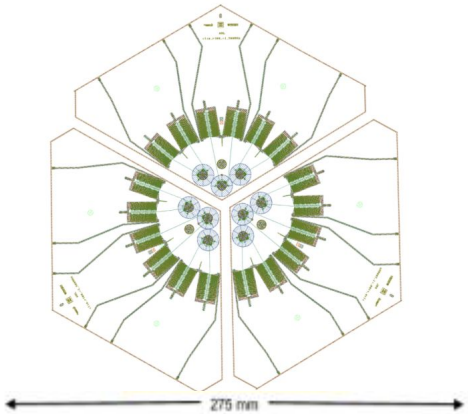

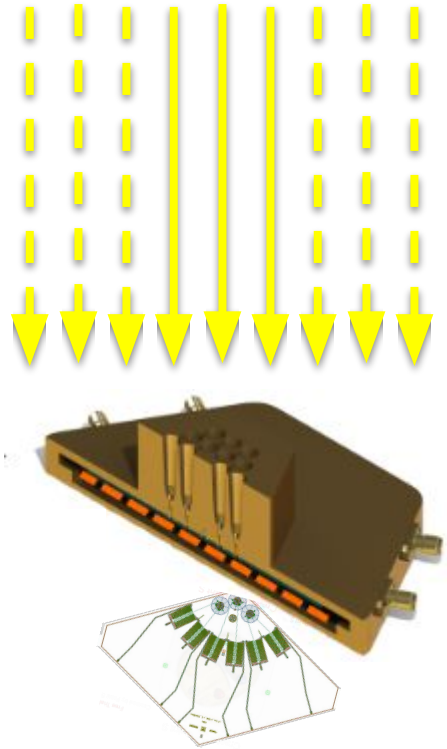

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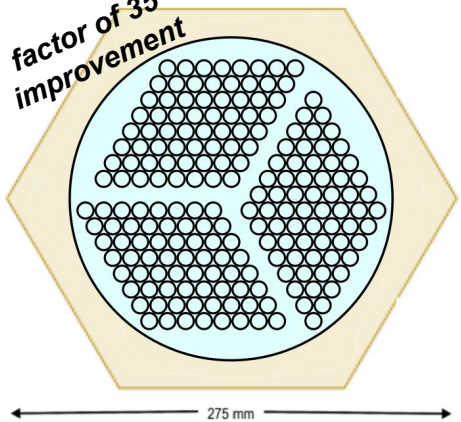
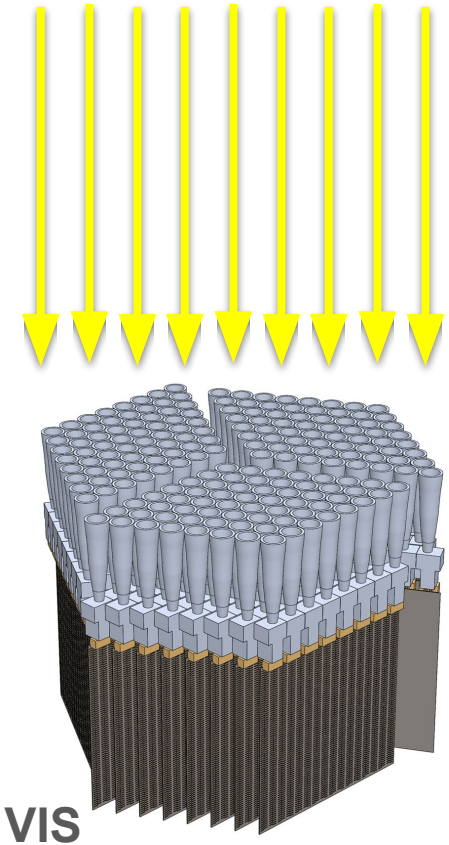




Two Big Challenges for the Field of Line Intensity Mapping:

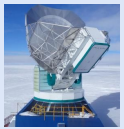
Instrumentation Challenge:

How do we build instruments with the raw sensitivity to make competitive cosmological constraints?

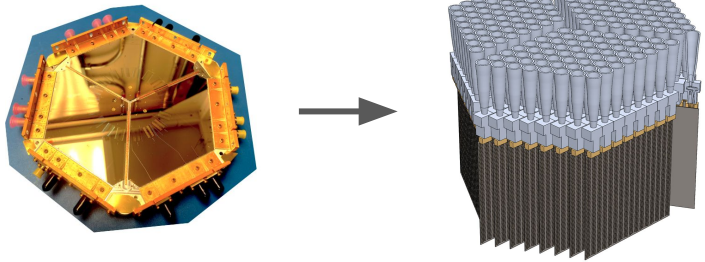
Data Analysis Challenge:

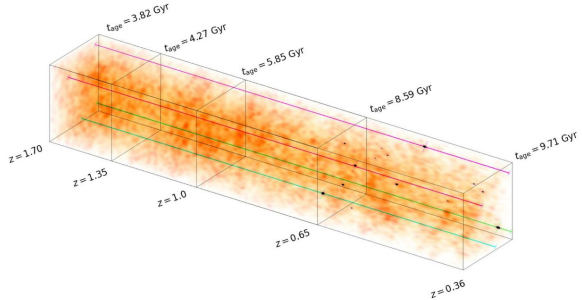
New techniques needed to be developed and perfected for these sensitive instruments!

CO
Maximum *Signal*
GHz (Can do from the ground)
SPT-SLIM



CII
Maximum *Signal-to-Noise*
THz (From Space)
TIM (Terahertz Intensity Mapper)





My Dream for the Future of Line Intensity Mapping

LIM **wide** survey in the Atacama Desert: constrain *dark energy equation of state, the Hubble constant, and inflation via primordial non-gaussianity*

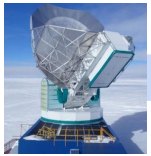
LIM **space** mission to gain sensitivity to lines you can't access from the ground, and remove atmospheric contamination

LIM **deep** survey at the South Pole: constrain *the matter power spectrum, galaxy bias, and galaxy formation and evolution*

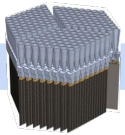
Summary: We're just at the beginning for Line Intensity Mapping!

2024 2025 2026 2027 2028 2029

SPT-SLIM
Deployment:
CO Data!

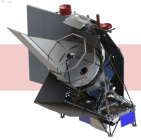


- CO Power spectrum
- Deployment of mm-wave on-chip spectrometers for line intensity mapping



Next-Gen CO LIM Focal Plane

TIM
Flight:
CII Data!



LIM Space Probe

- CII Power spectrum
- Direct Detection
- Stacking
- Cross-Correlation
- Auto-correlation