Probing the Middle Ages of Cosmic History with Line Intensity Mapping

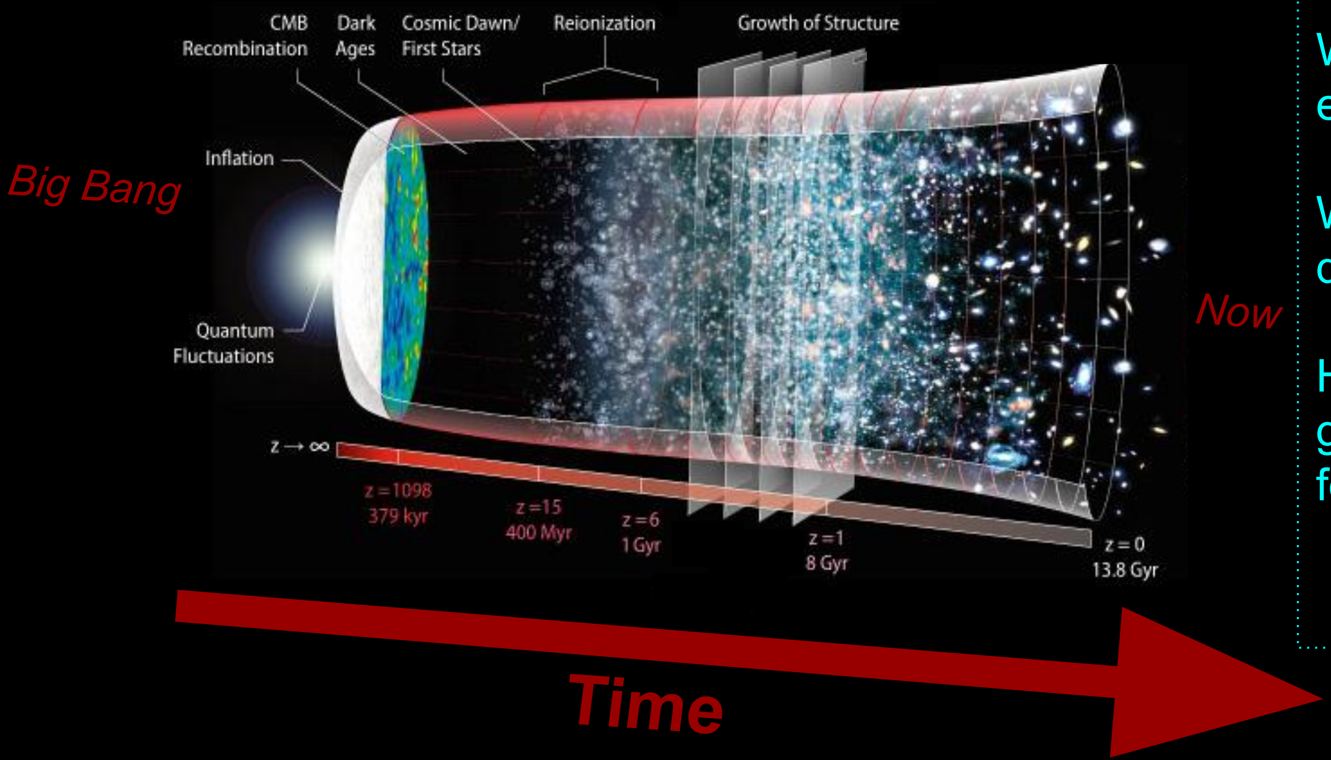
Jessica Zebrowski (UChicago) , NHFP Symposium , 9/16/2024

The Terahertz Intensity Mapper Test Flight : The Hopes and Heartbreak of Scientific Ballooning

A Line Intensity Mapping Story

Jessica Zebrowski (UChicago) , NHFP Symposium , 9/16/2024

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

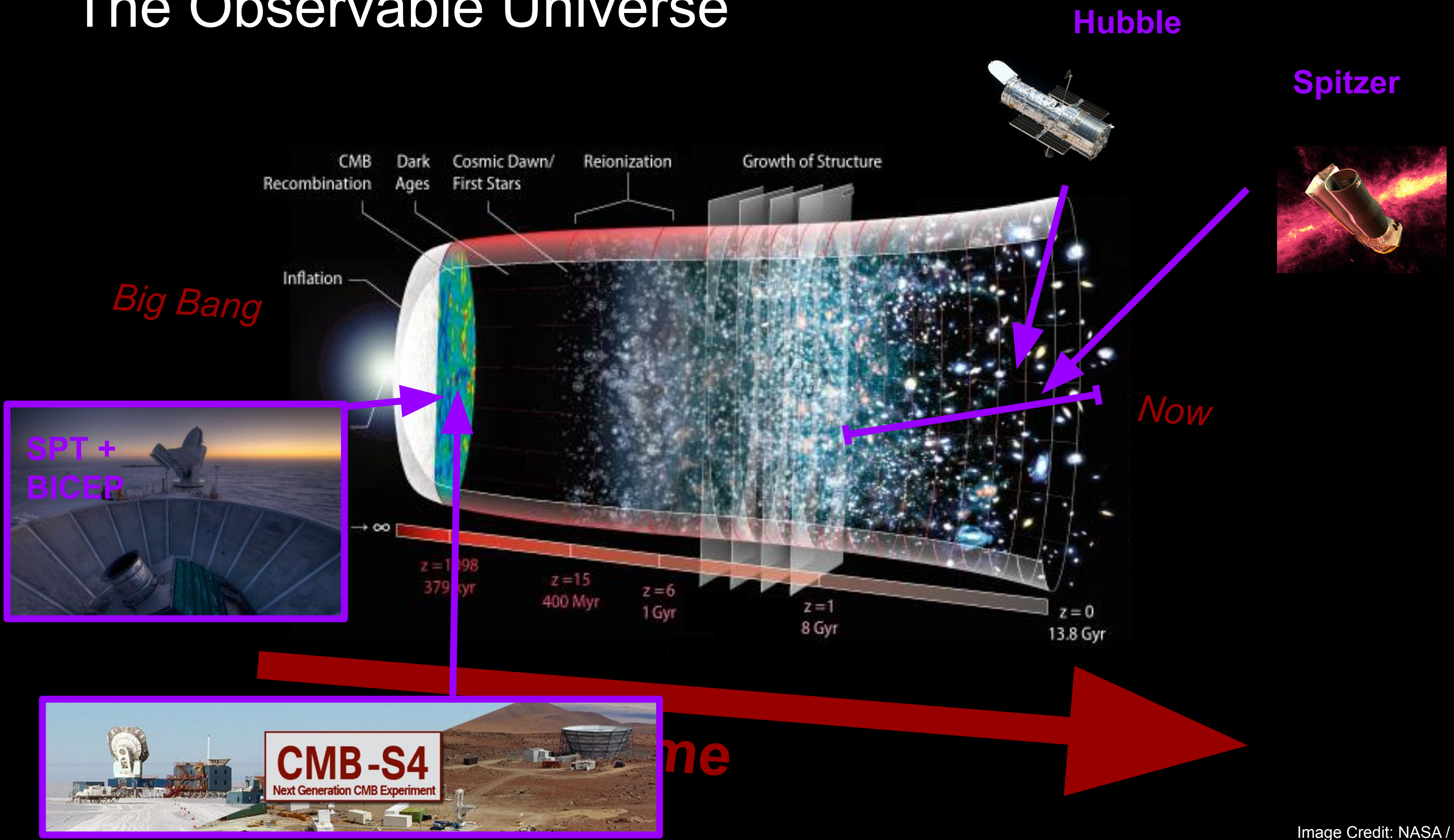
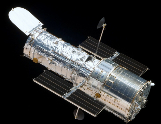


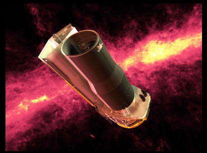
Image Credit: NASA / LAMBDA Archive Team

The Observable Universe

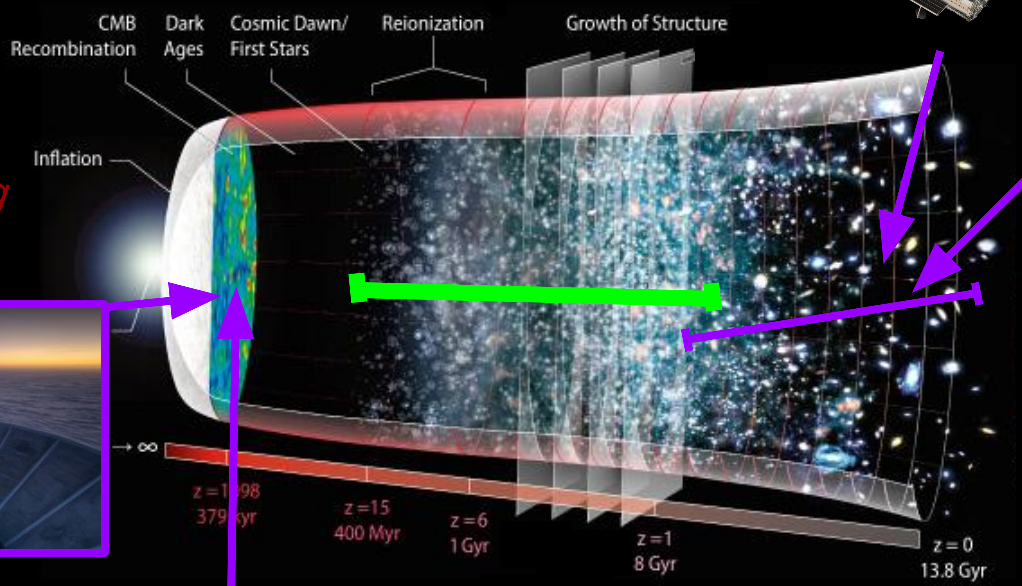
Hubble



Spitzer



Big Bang



Now

Line Intensity Mapping (LIM)

- Emission from atomic and molecular spectral lines from galaxies (CO, CII, H, etc.)
- Maps the 3D galaxy distribution

me

Image Credit: NASA / LAMBDA Archive Team

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

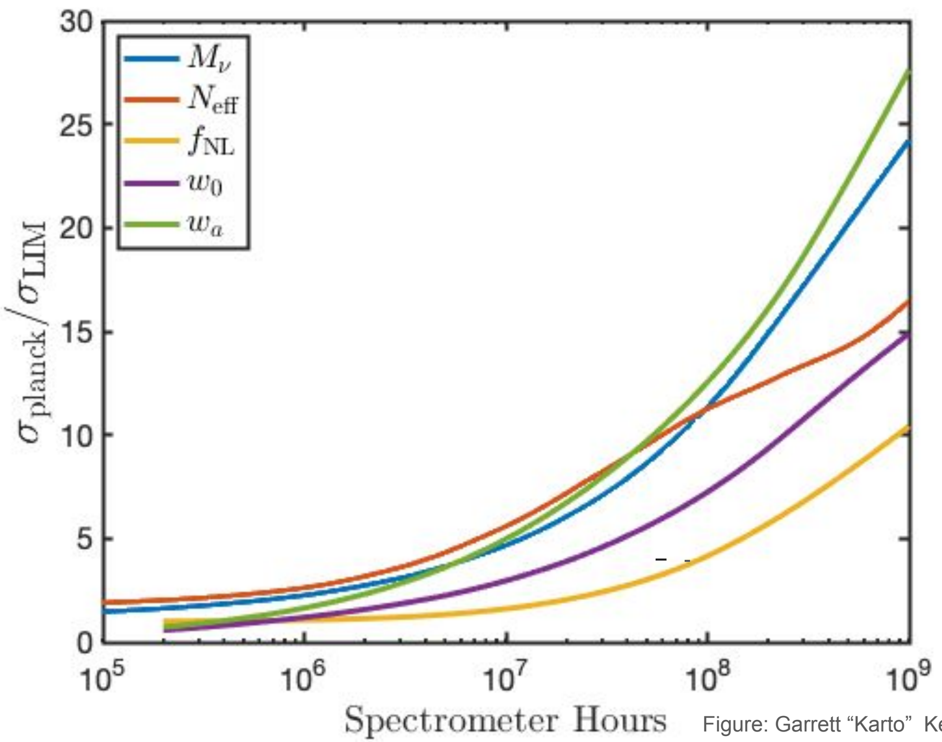


Figure: Garrett “Karto” Keating

Need to increase instantaneous sensitivity

Which line to pick?

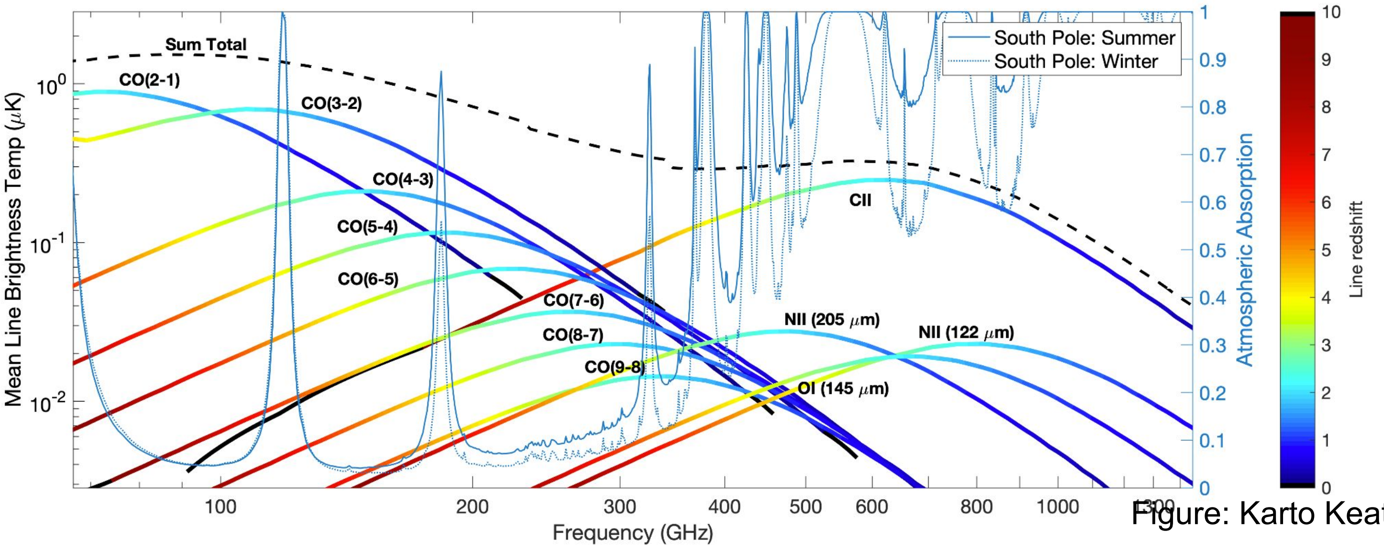


Figure: Karto Keating

Which line to pick?

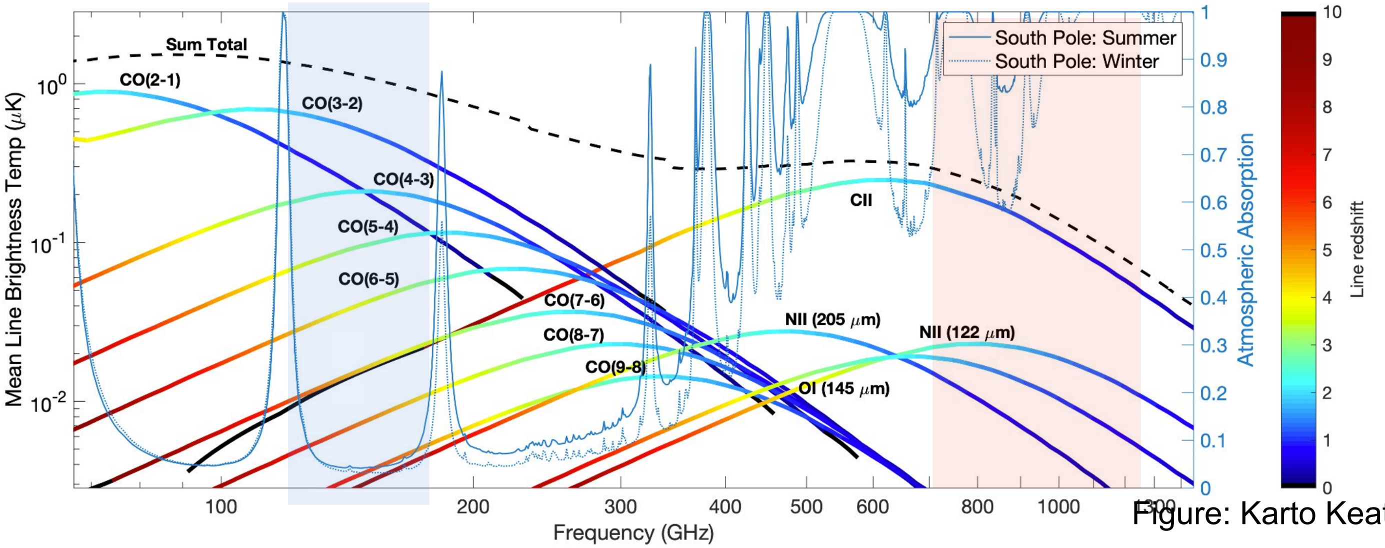


Figure: Karto Keating

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

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

Which line to pick?

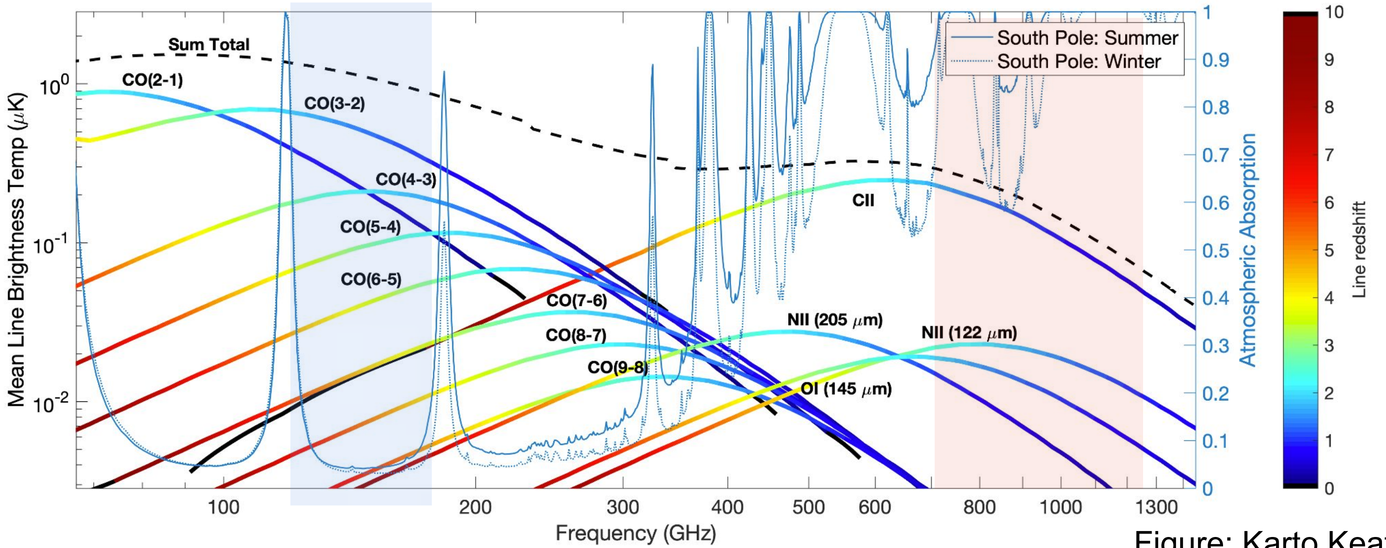
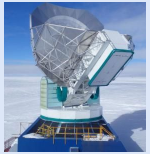


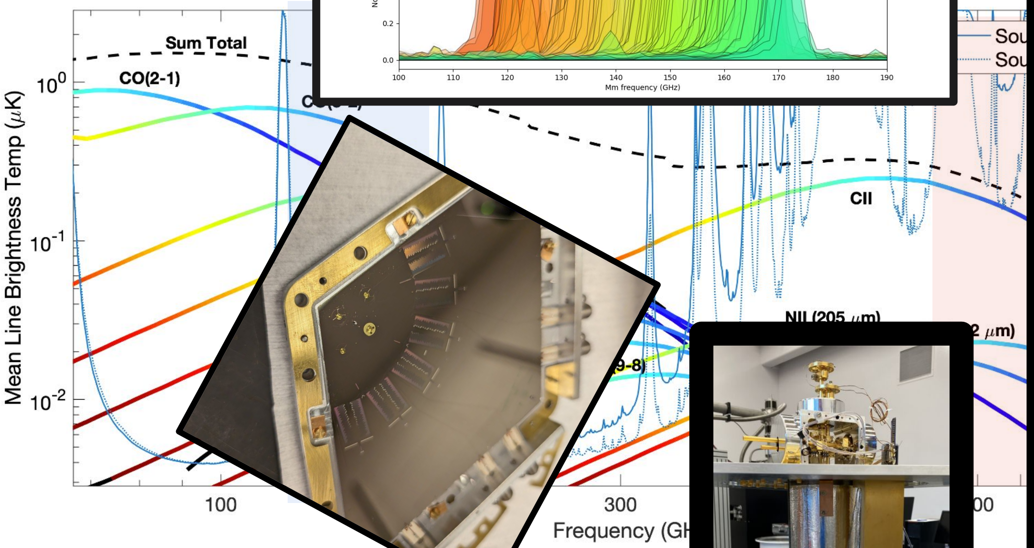
Figure: Karto Keating

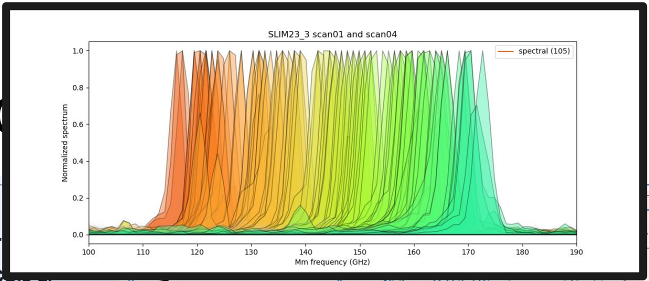
CO
Maximum *Signal*
GHz (Can do from the ground)
SPT-SLIM

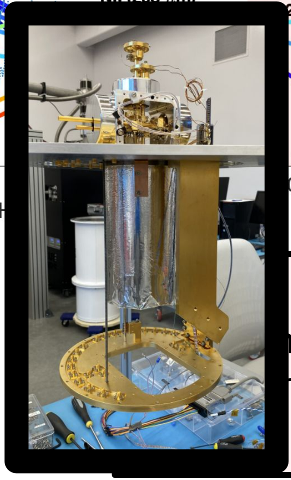


CII
Maximum *Signal-to-Noise*
THz (From Space)

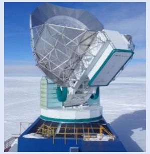
Which line to pi





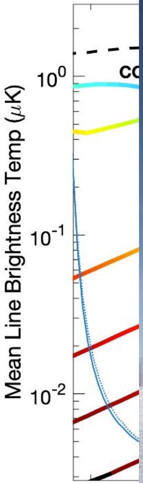


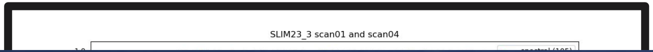
CO
Maximum *Signal*
GHz (Can do from the ground)
SPT-SLIM

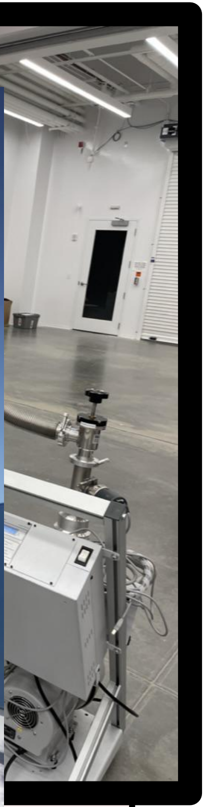


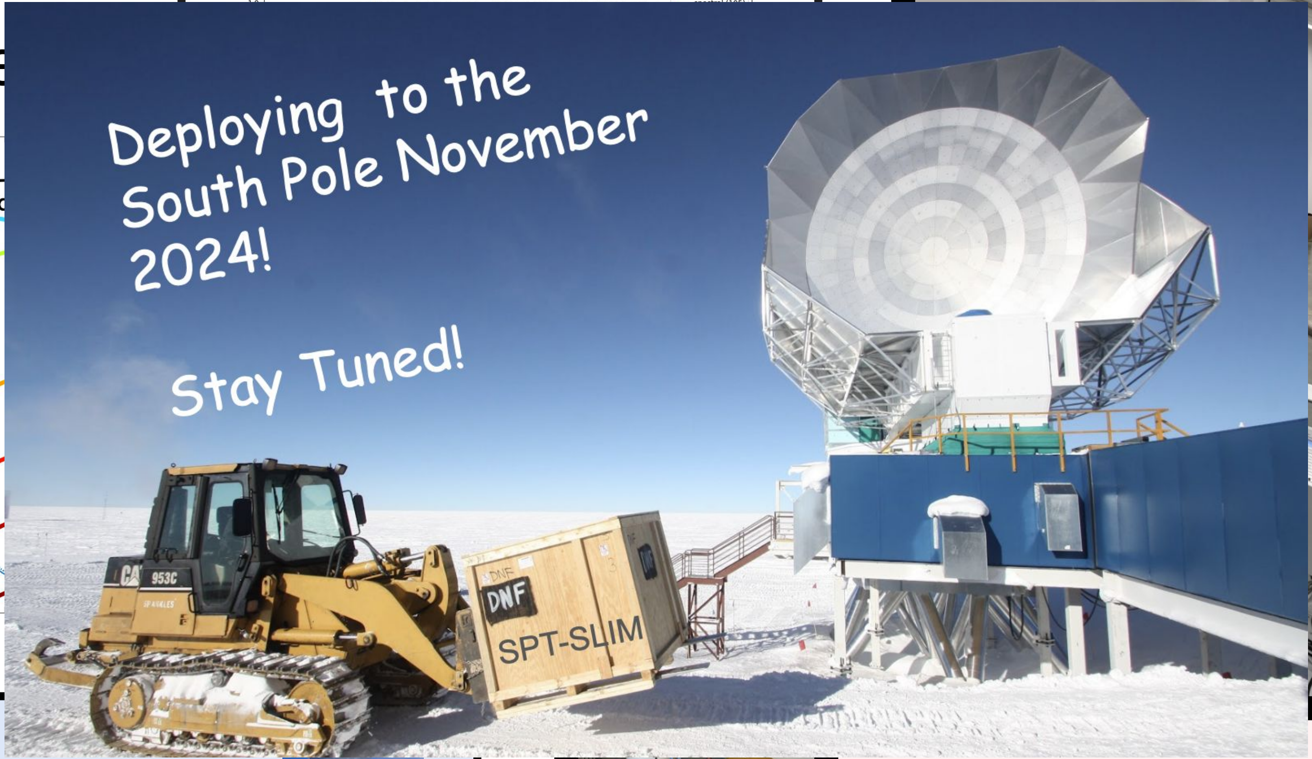
n *Signal-to-Noise*
m Space)

Which line

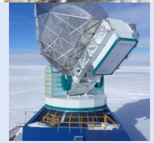


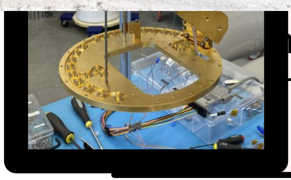






CO
Maximum *Signal*
GHz (Can do from the ground)
SPT-SLIM





n *Signal-to-Noise*
m Space)

Which line to pick?

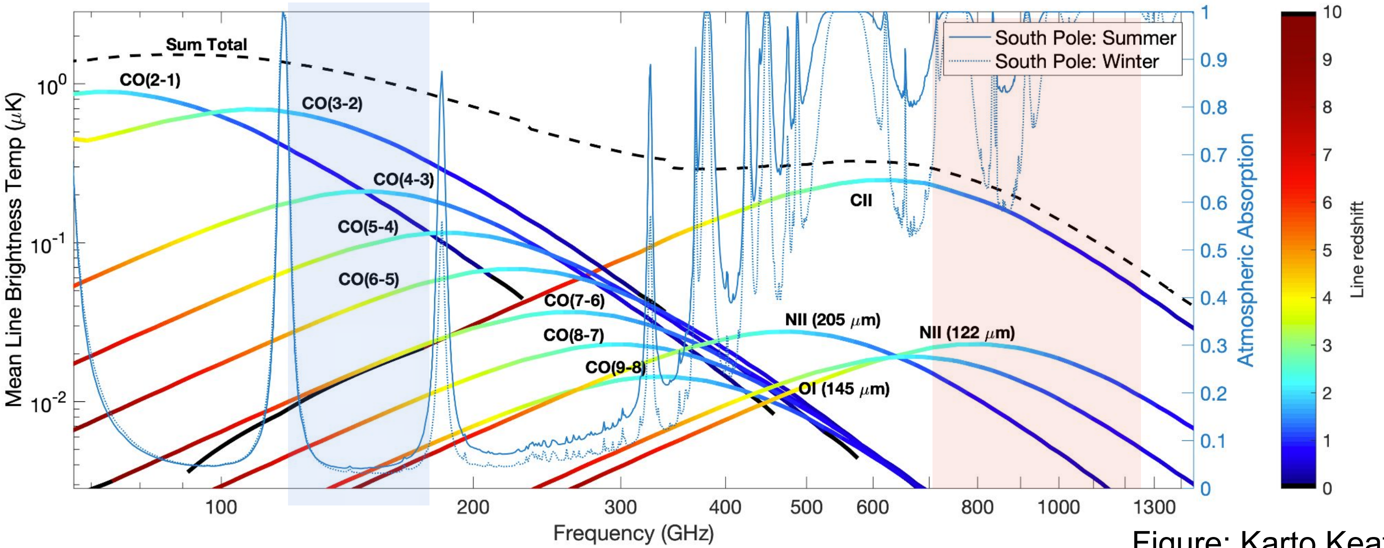
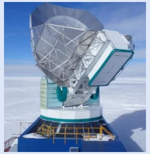


Figure: Karto Keating

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



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

Which line to pick?

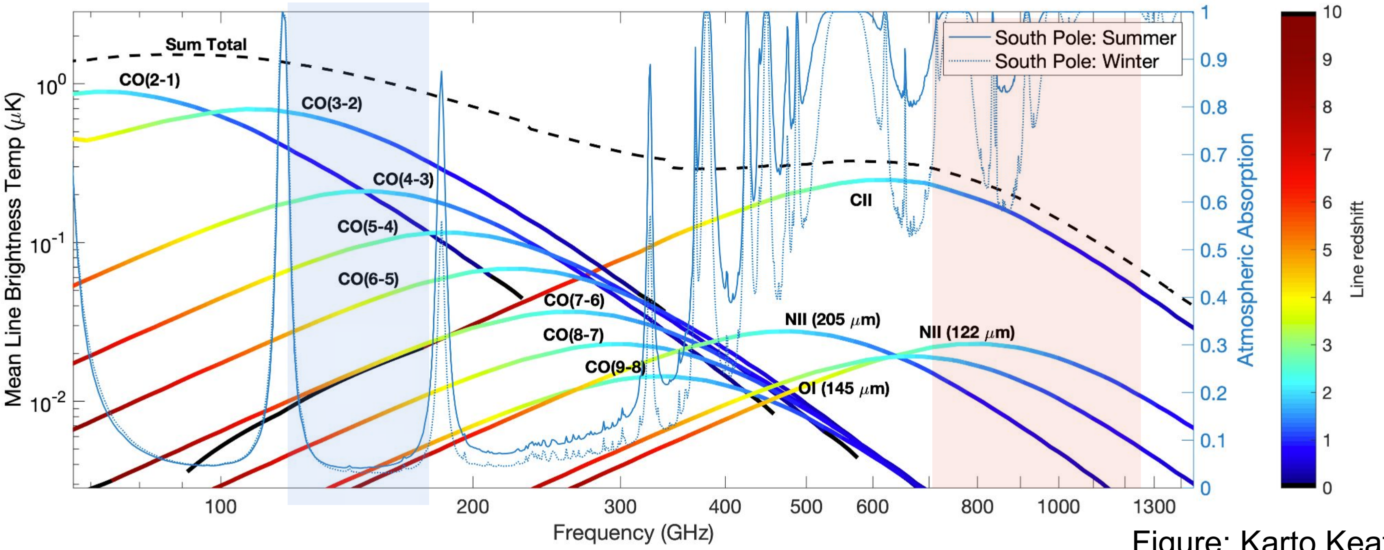
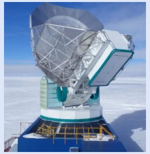
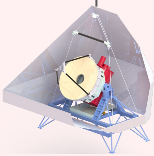


Figure: Karto Keating

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



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



The Terahertz Intensity Mapper

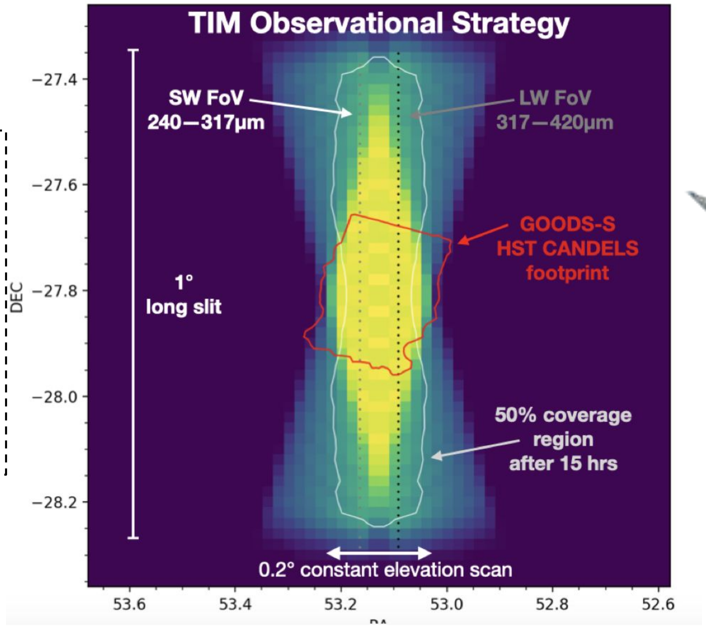
University of Illinois **J. Vieira (PI),** J. Filippini, J. Alameda, **H. Athreya,** B. Brendal, J. Fu, M. Kowalik, R. Nie, V. Razavimaleki
Caltech/JPL R. Janssen, M. Bradford, S. Hailey-Dunsheath, B. Bumble, L.-J. Liu
Arizona State University **C. Groppi,** D. Joralmon, P. Mauskopf, T. Saeid
University 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

Figure: Jianyang (Frank) Fu

TIM Deep Observations

Deep Field
~0.1 deg^2
GOODS-S (3.5hr, -28deg)
Wants as small of a field as to have the lowest noise, but we have a large FoV



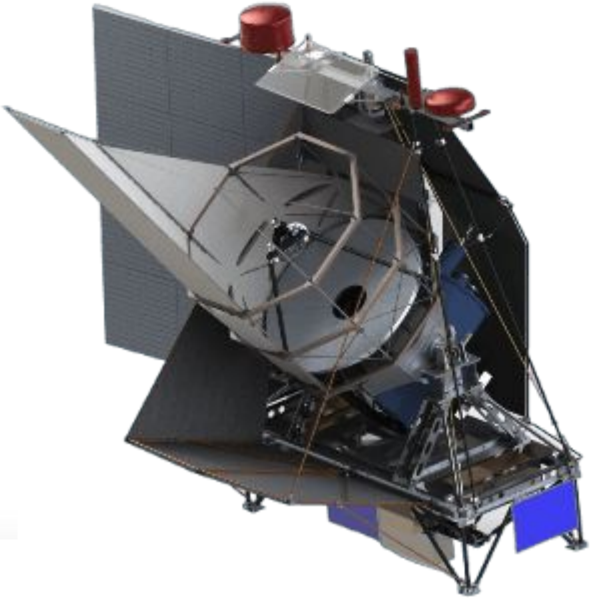
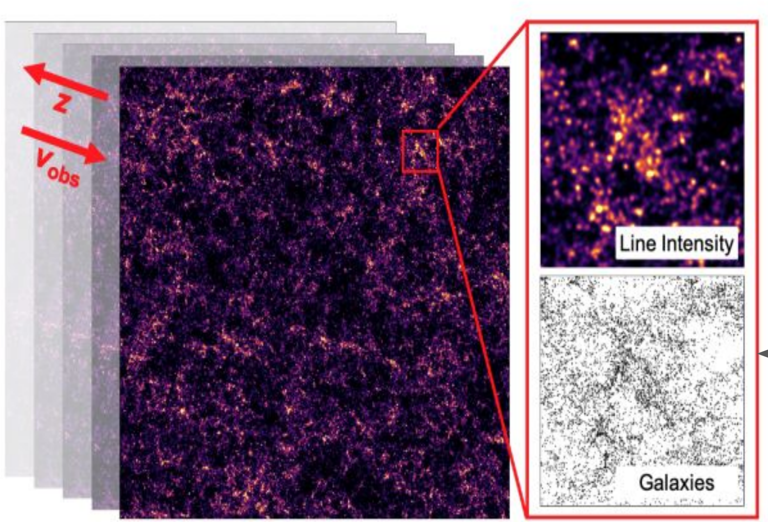


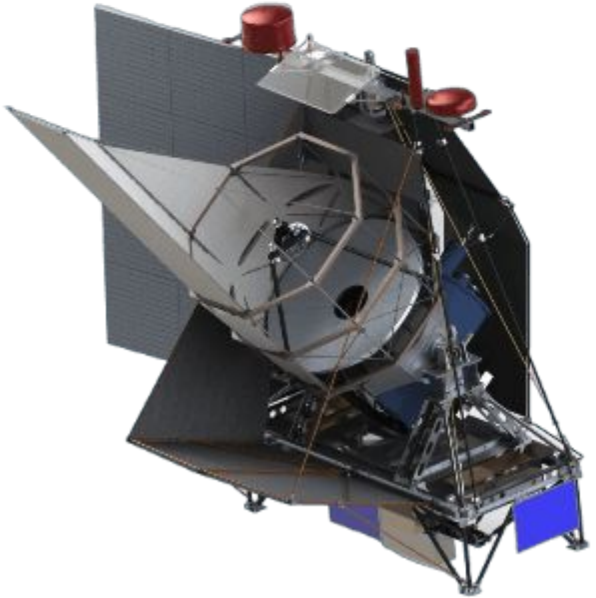
Figure: Talia Saeid

TIM Deep Observations

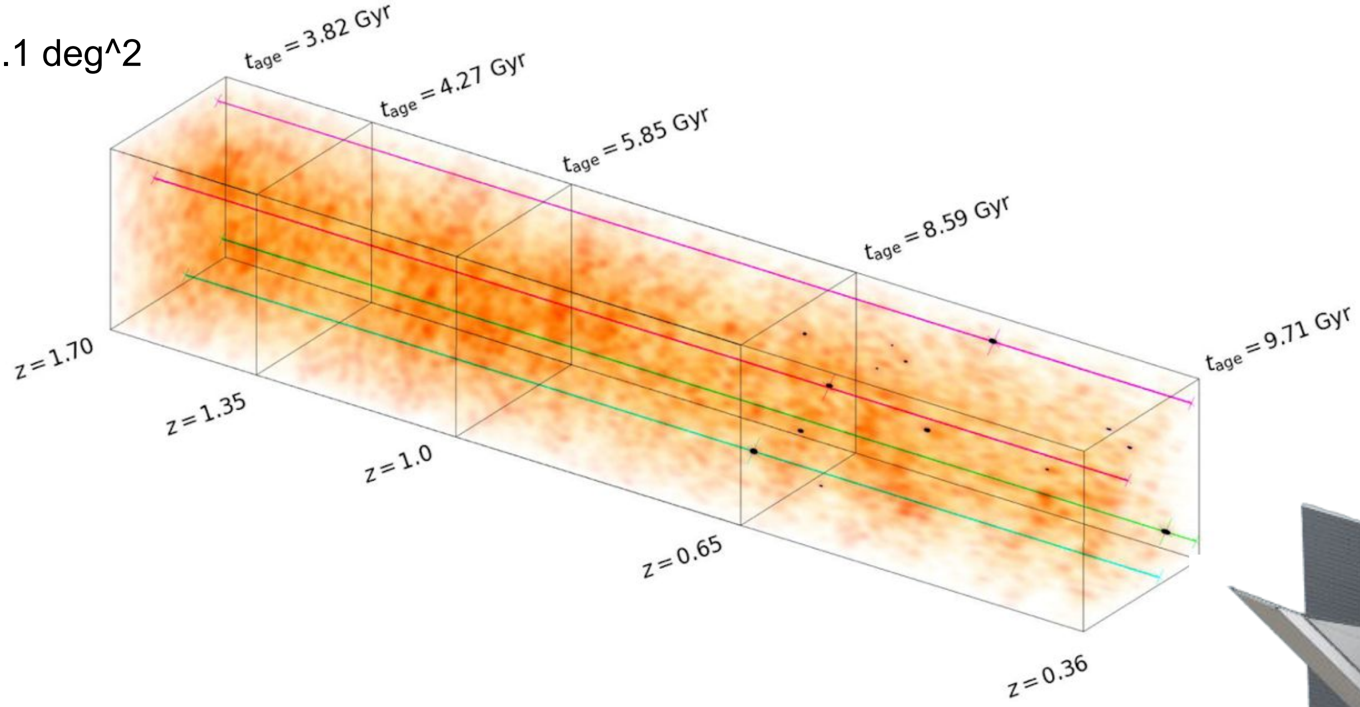


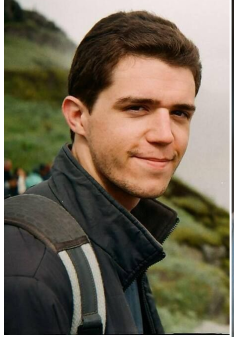
What you measure
(*low-resolution intensity map of CII* x multiple frequencies)

What this traces
(*large-scale structure in the underlying galaxy population/dark matter distribution* as it evolves over time as the spectral line redshifts)



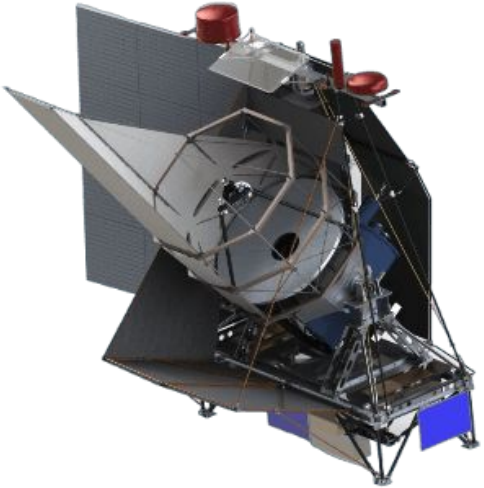
~0.1 deg^2

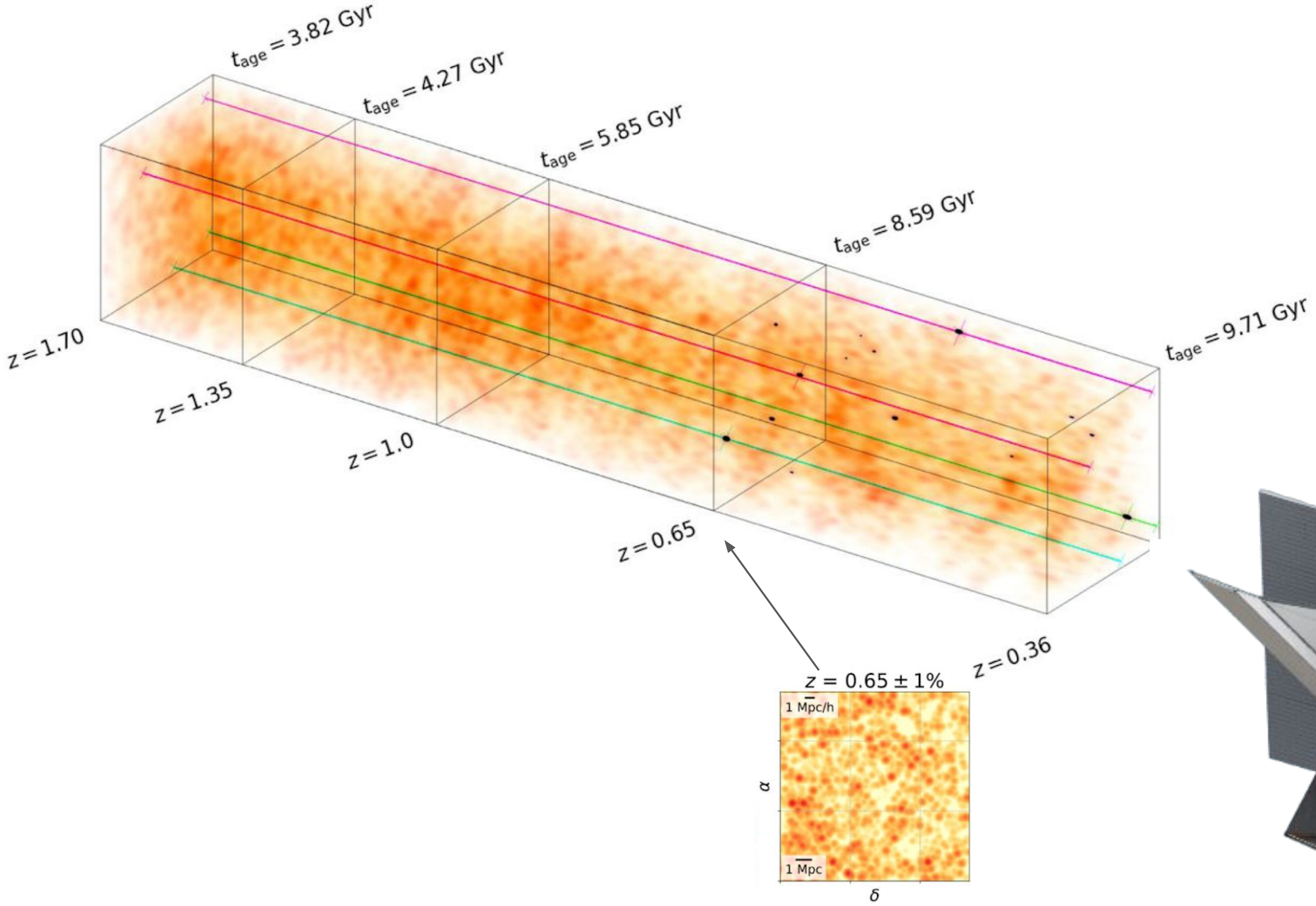


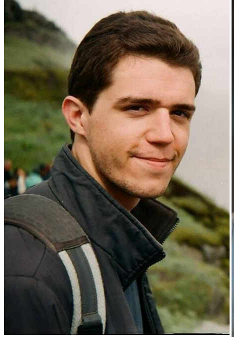


Evan Mayer

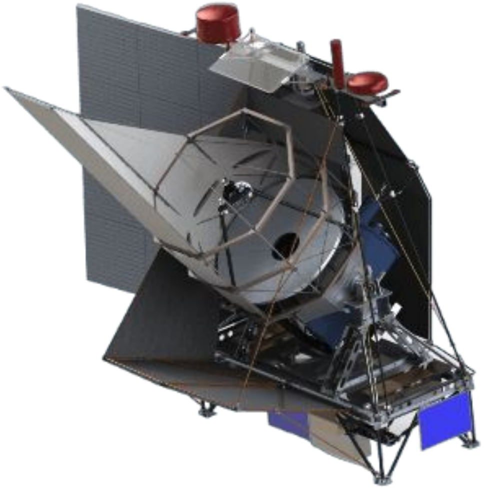
Shubh Agrawal

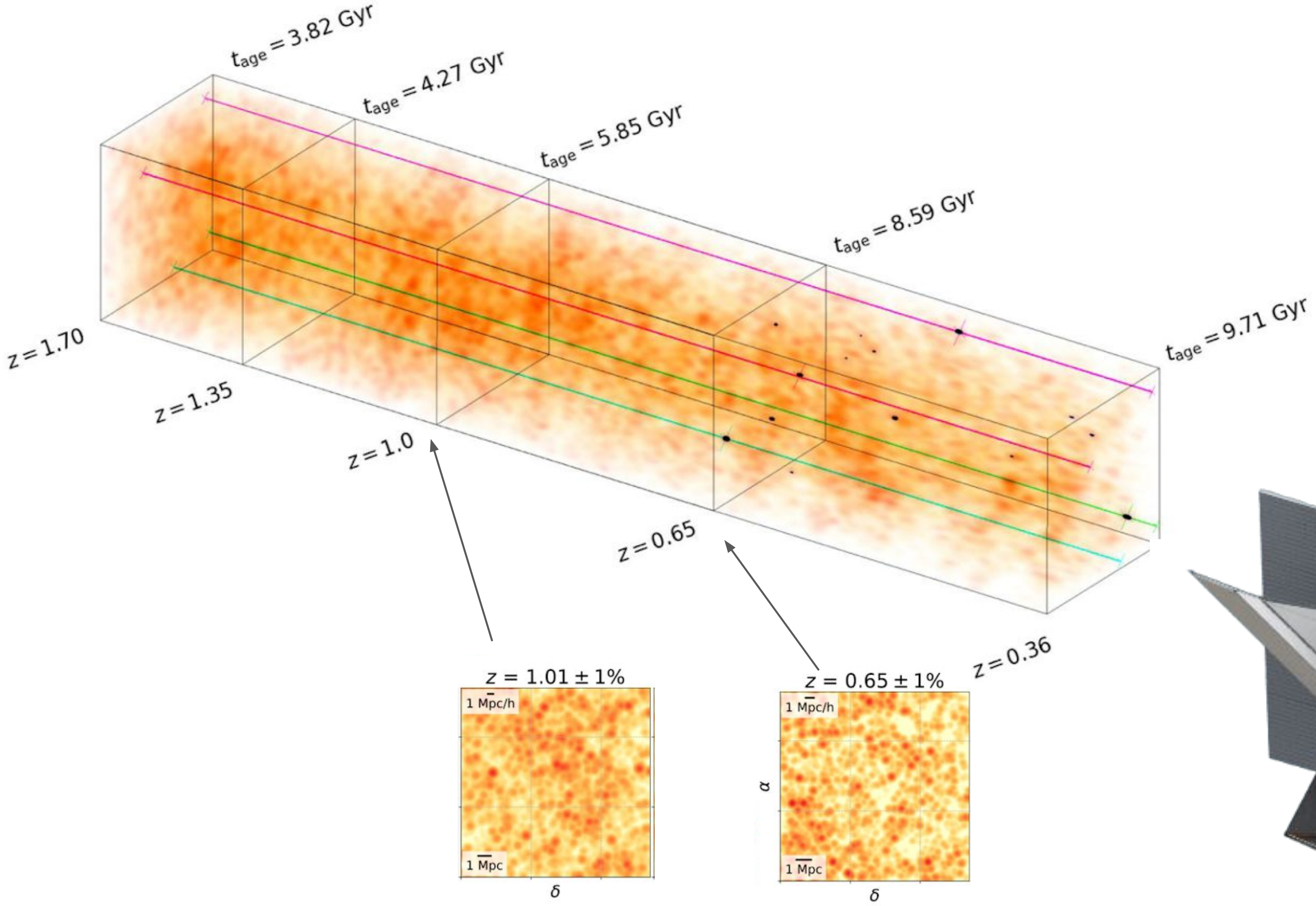


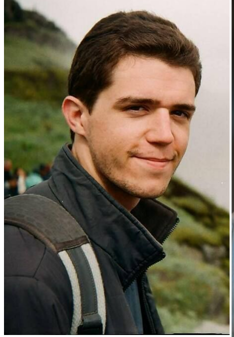



Evan Mayer

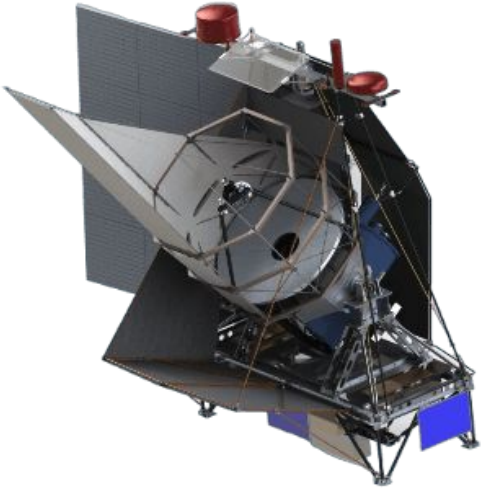

Shubh Agrawal

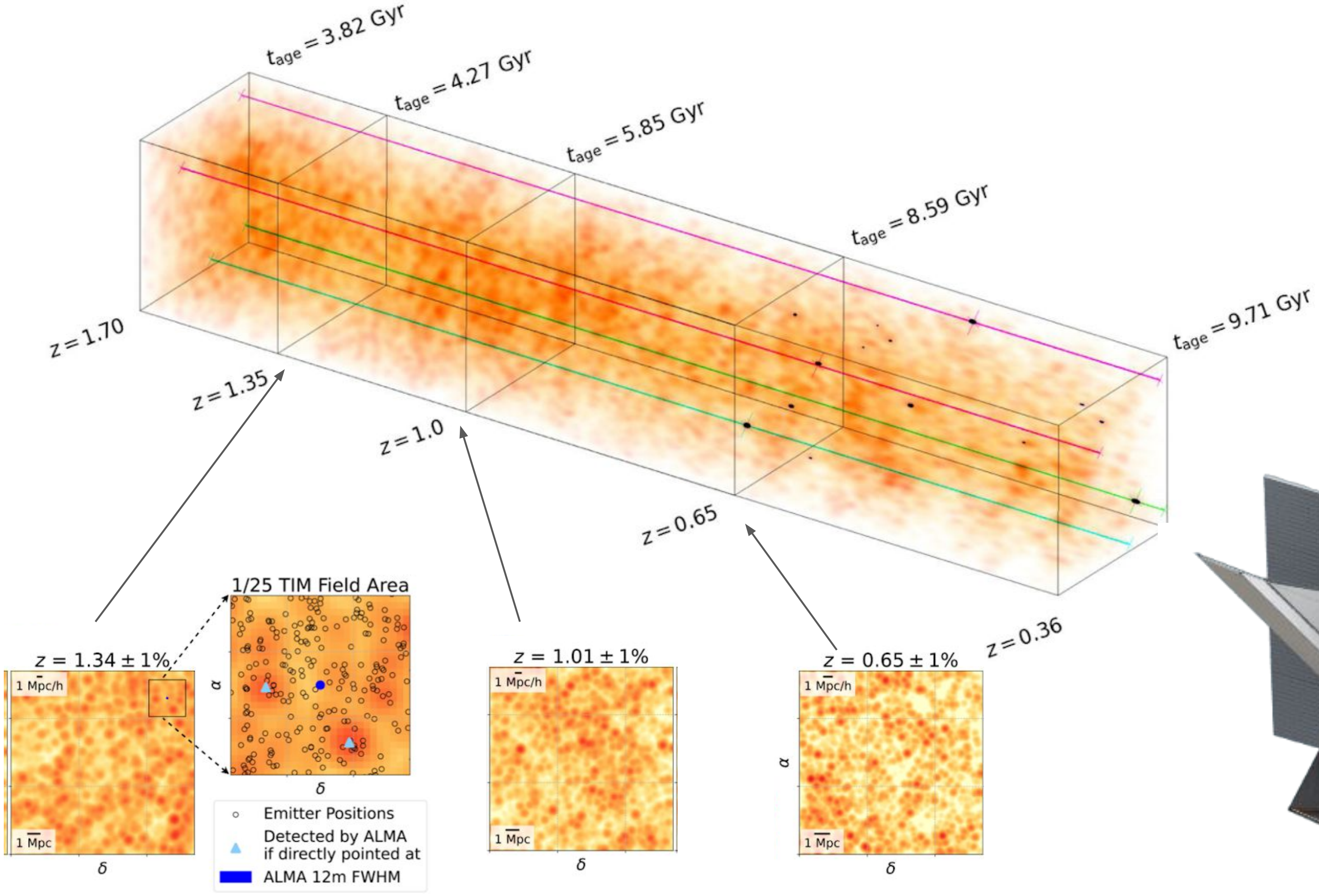


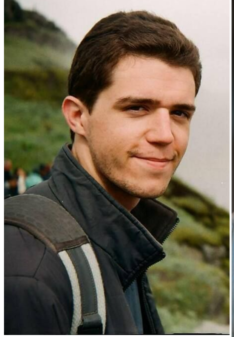



Evan Mayer

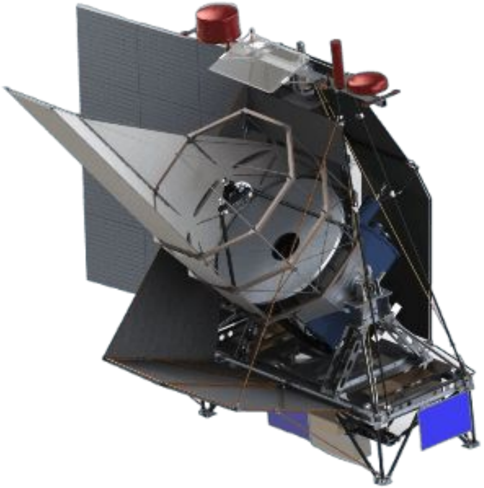

Shubh Agrawal



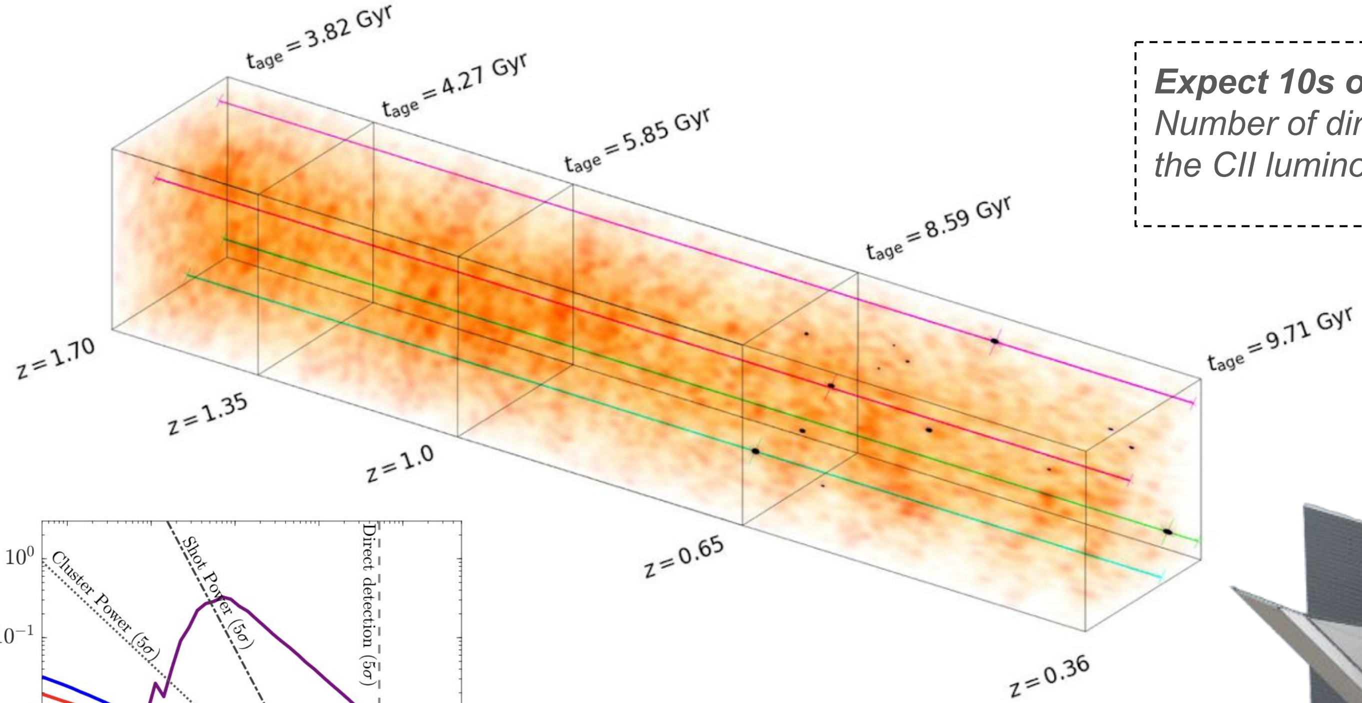


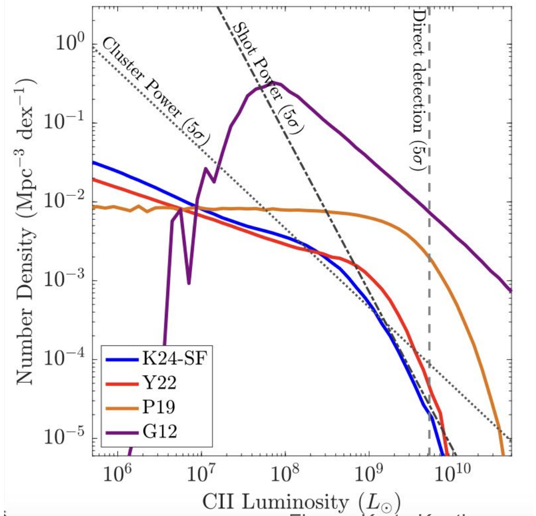

Evan Mayer

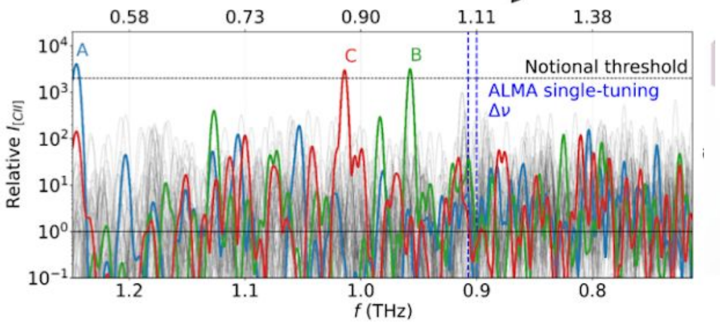

Shubh Agrawal



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







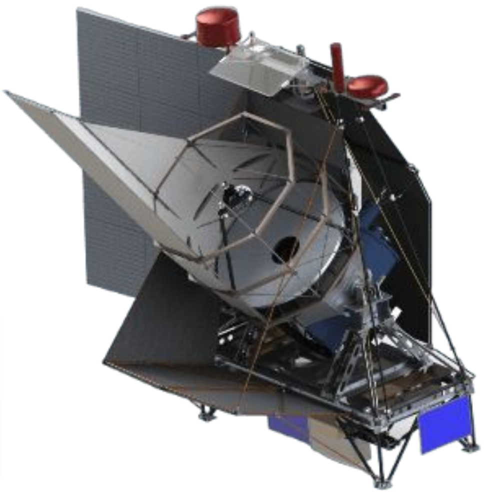
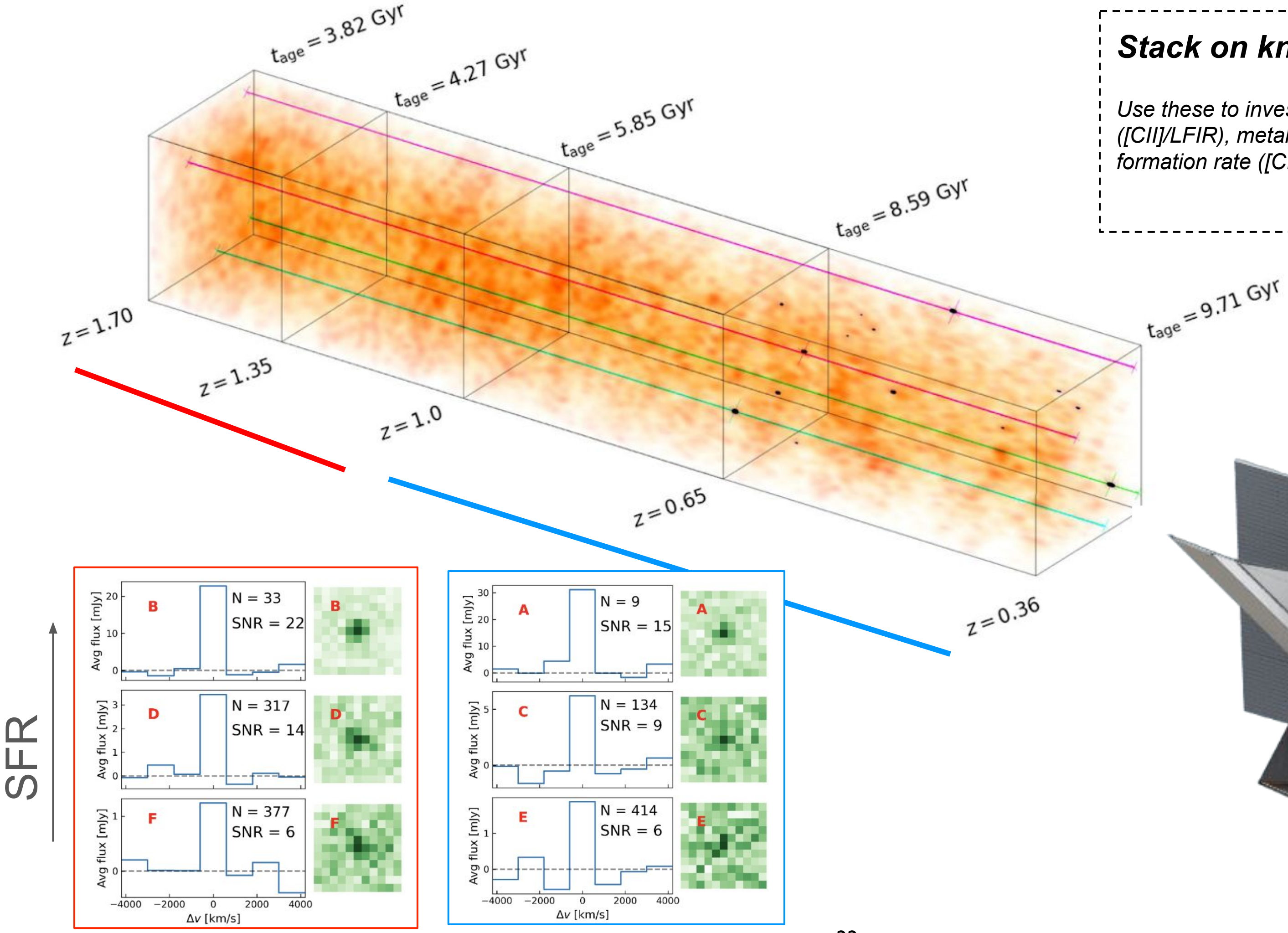


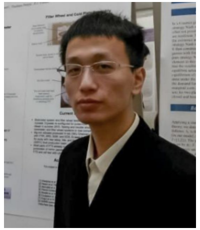
Figure: Karto Keating

Stack on known locations of galaxies

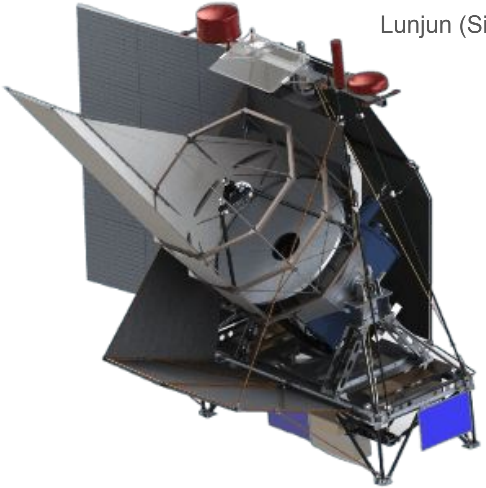
Use these to investigate changes in star formation modes ([CII]/LFIR), metallicity ([NII]/[CII]), and specific star formation rate ([CII]/M_star)

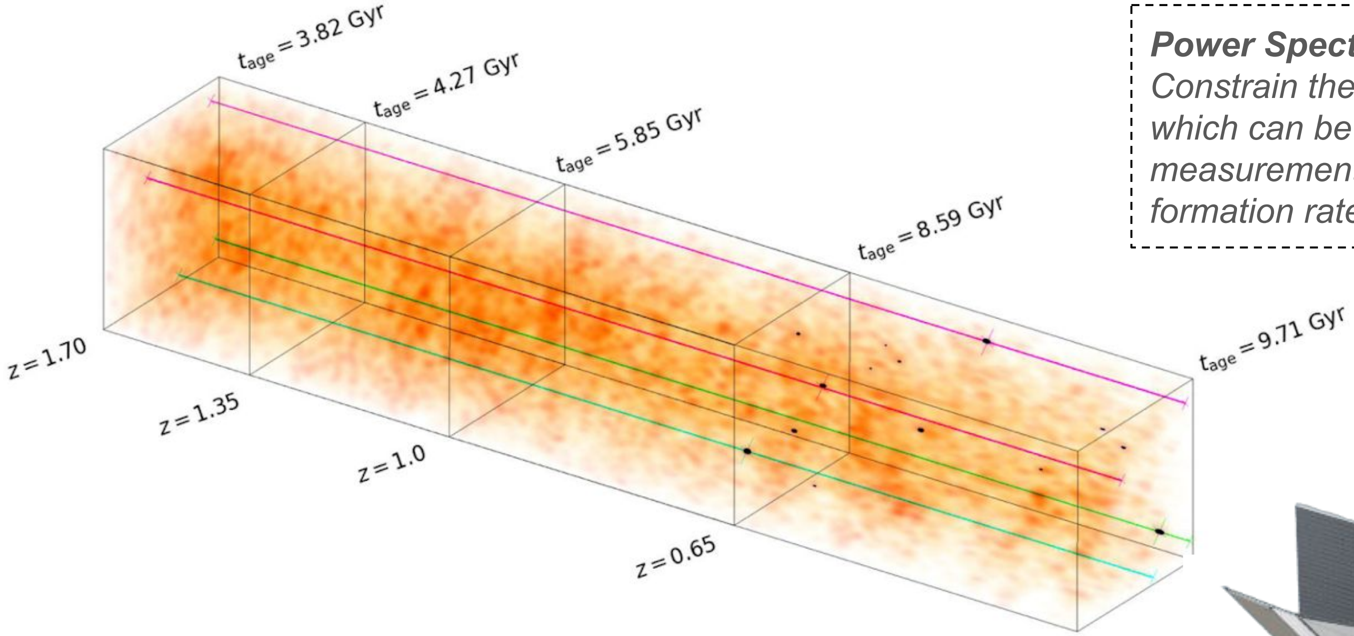


Lunjun (Simon) Liu



Lunjun (Simon) Liu

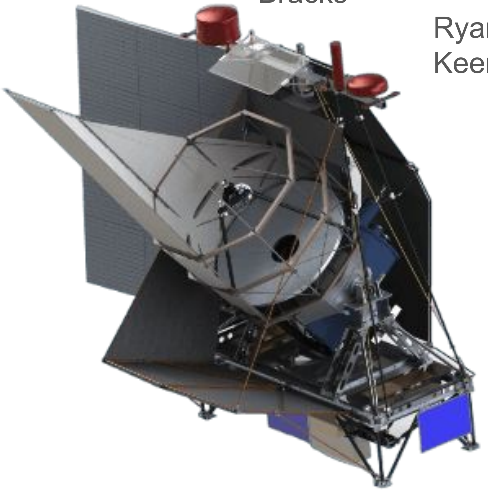


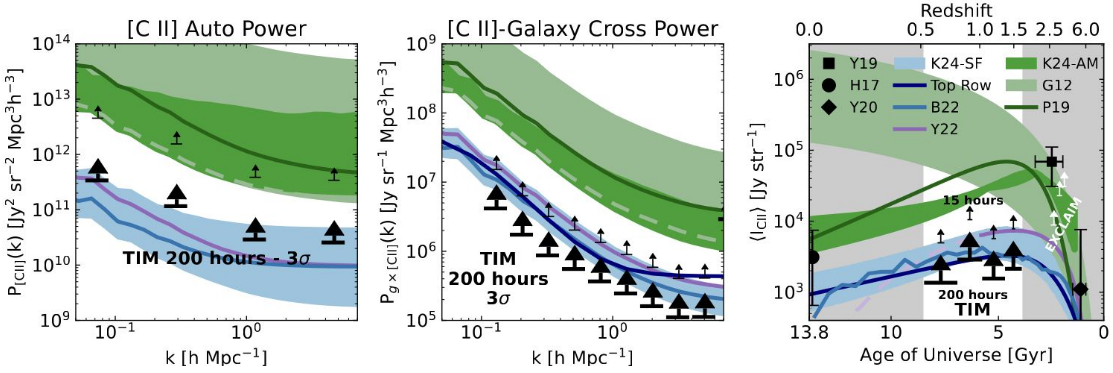


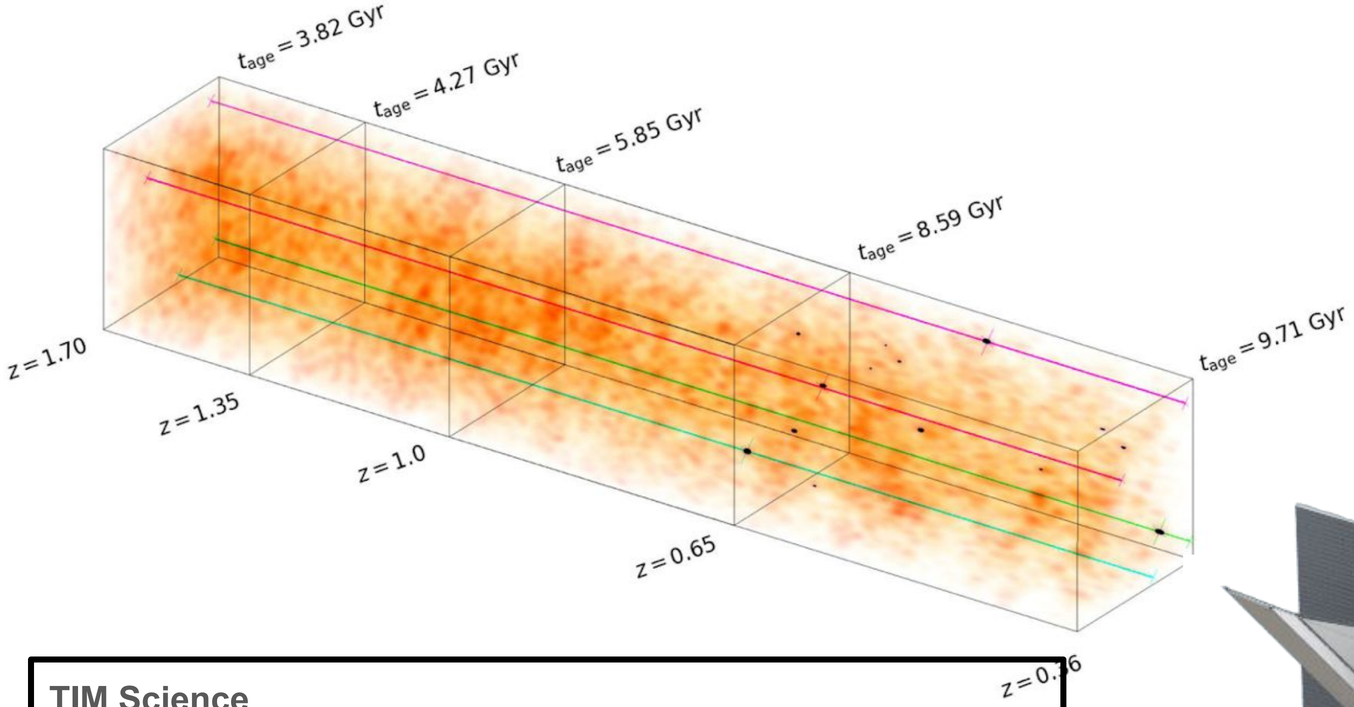
Power Spectrum
Constrain the CII Luminosity Function which can be translated to a measurement of the cosmic star formation rate density at 0.5<z<1.7

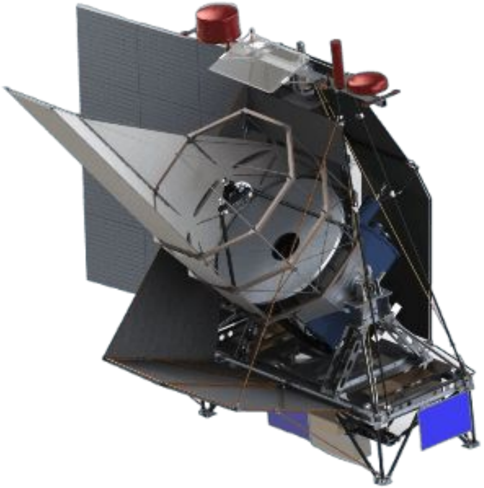
Justin Bracks

Ryan Keenan









TIM Science

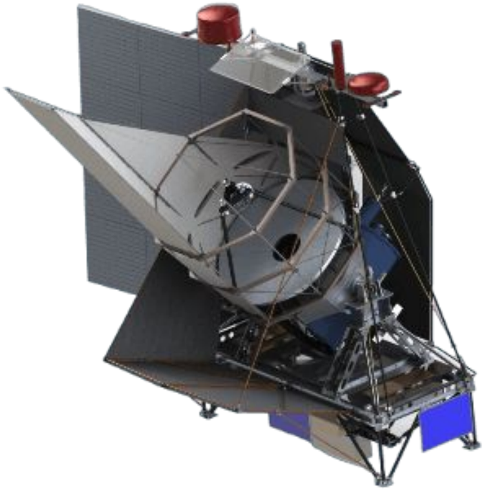
- Direct Detection
- Stacking
- Cross-Power Spectrum
- Auto-Spectrum

Learn about galaxy and star formation from this powerful dataset!

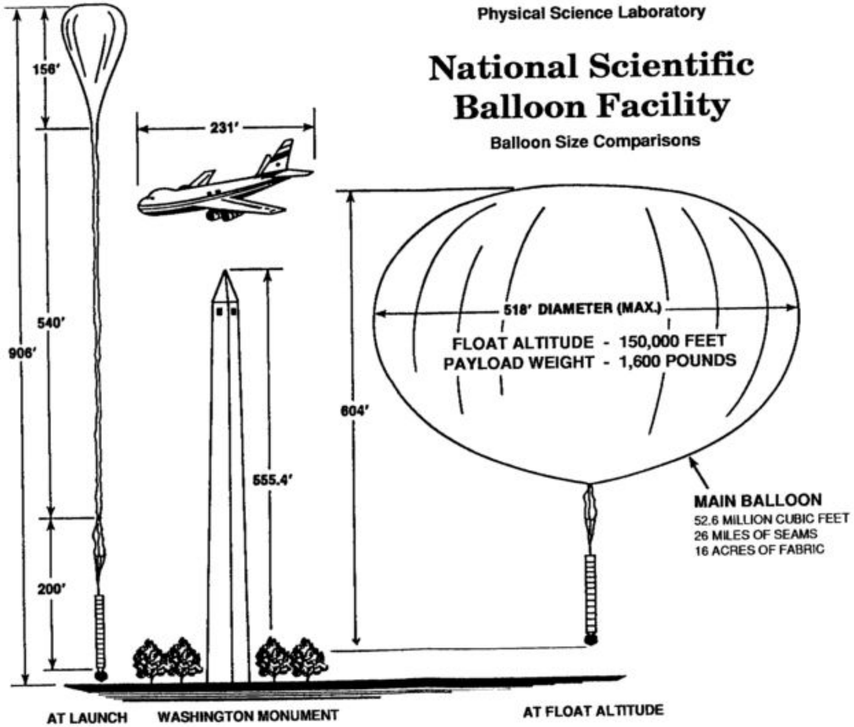
~~Precursor to cosmology w/ LIM!~~

The Terahertz Intensity Mapper (TIM) Instrument at a Glance

- Antarctic Stratospheric Balloon (‘26/’27 Austral summer launch)
- 2m primary mirror, Cassegrain design
- Liquid-Helium cryostat with sorption cooler (~250mK)
- Two grating spectrometers
    - 240 – 317 & 317 - 420 μm at R~250
    - 1 degree slit length
- 2x MKID arrays with ~3600 detectors each



Scientific Ballooning



Images: NASA

Schedule for Scientific Ballooning

Name	Location	Date	Payload Flies	Cryostat Cold	Comms Function	Take Science Data
Test Flight	Ft. Sumner, NM	Summer 2024	✅	❌	✅	❌
Hang Test	Palestine, TX	Summer 2026	❌	✅	✅	❌
Science Flight	McMurdo, Antarctica	Austral Summer 2026-2027	✅	✅	✅	✅

Test Flight Schedule

Name	Location	Date	Payload Flies	Cryostat Cold	Comms Function	Take Science Data
Test Flight	Ft. Sumner, NM	Summer 2024	✅	❌	✅	❌

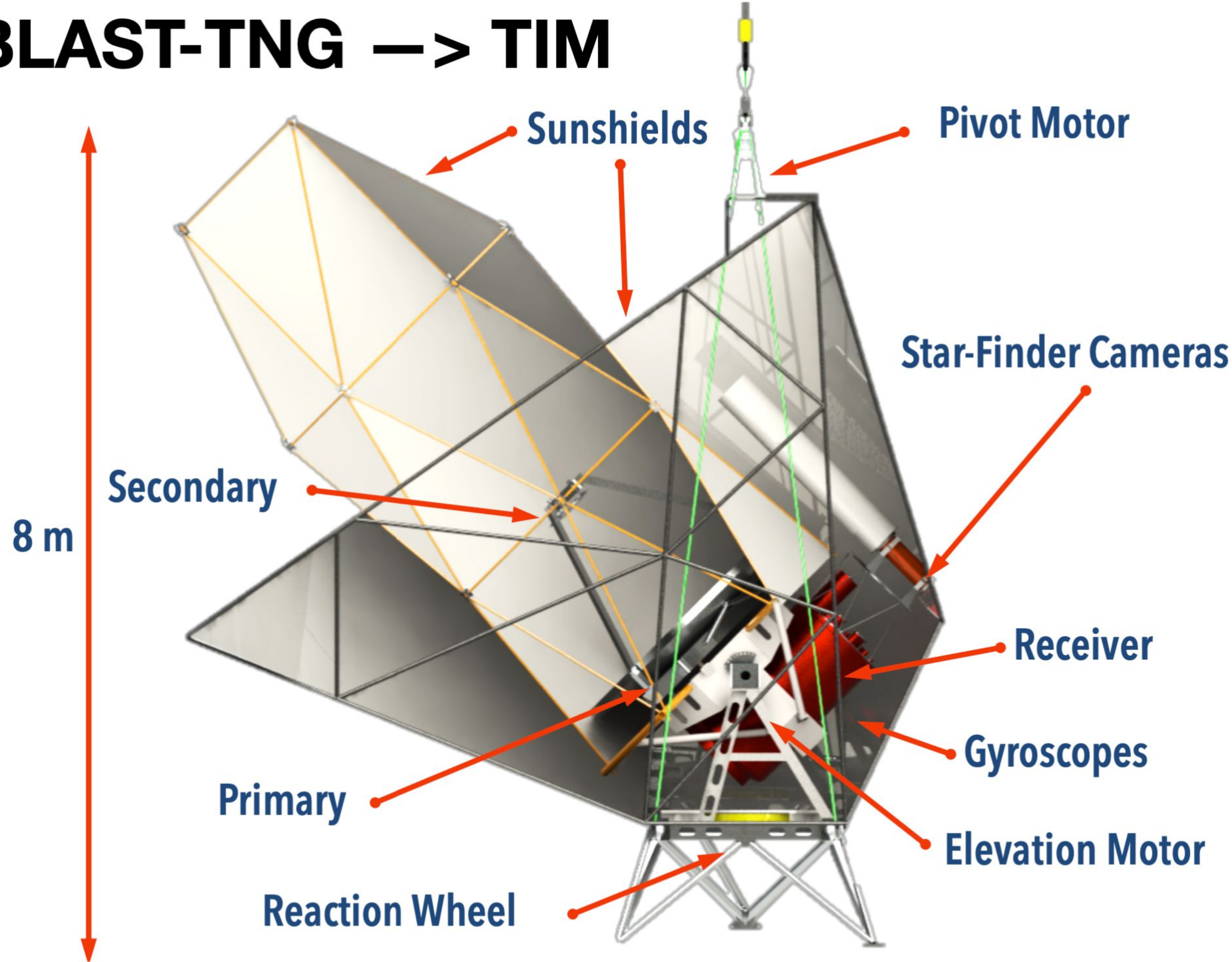
Q: Where is Ft. Sumner, NM?
A: The middle of nowhere.

The Nice Hotel in town:

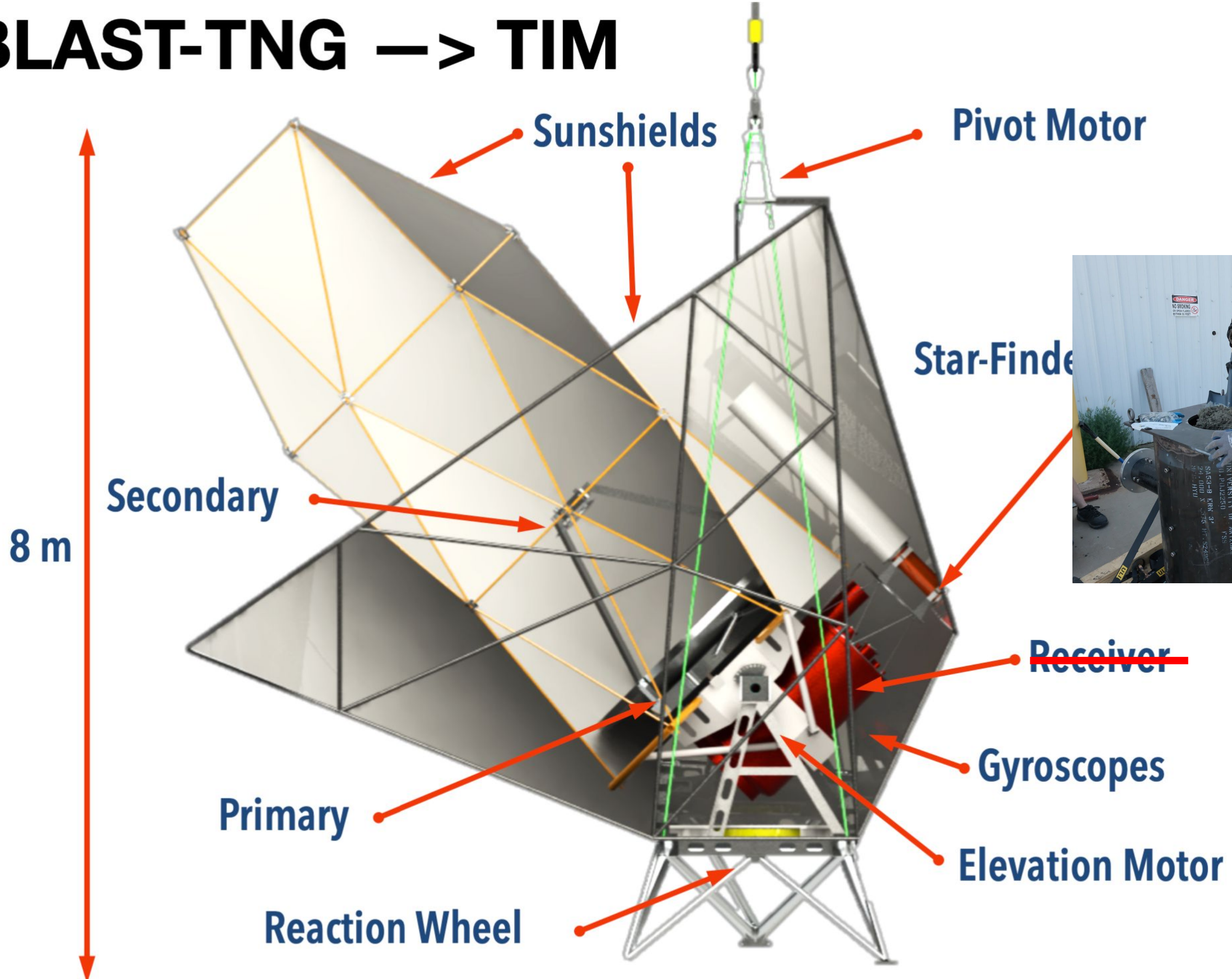
The only place open for dinner on a sunday night:

NASA Hangar in Ft. Sumner

BLAST-TNG —> TIM

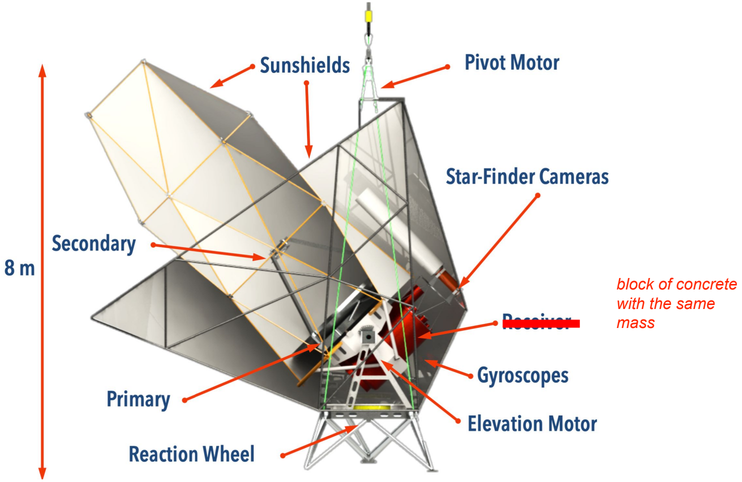


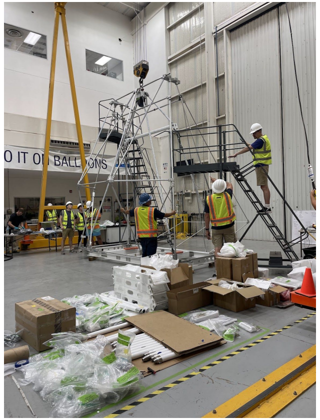
BLAST-TNG —> TIM



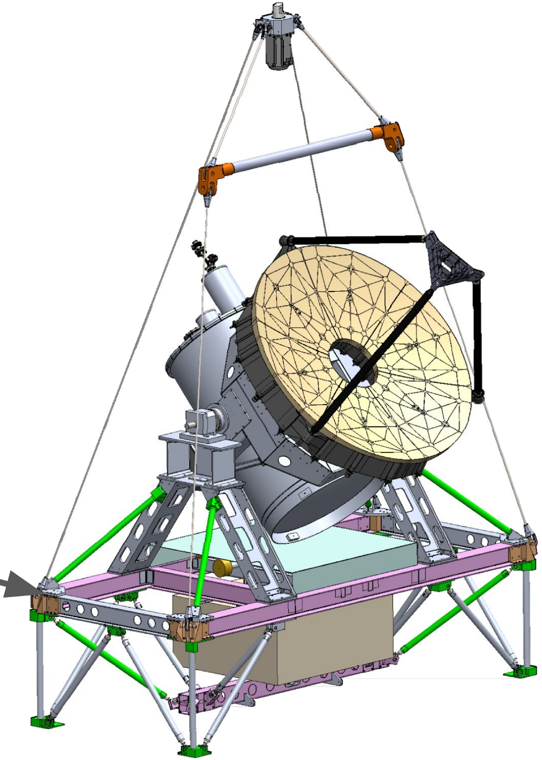
block of concrete with the same mass

Assembling the Sun Shields

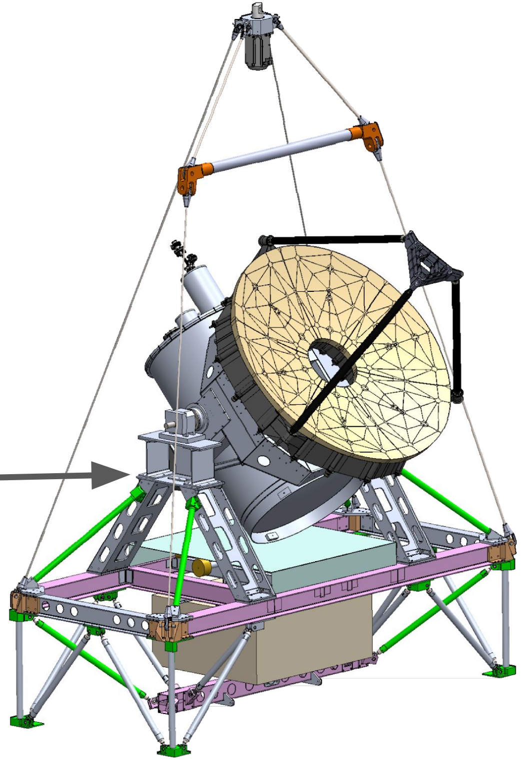




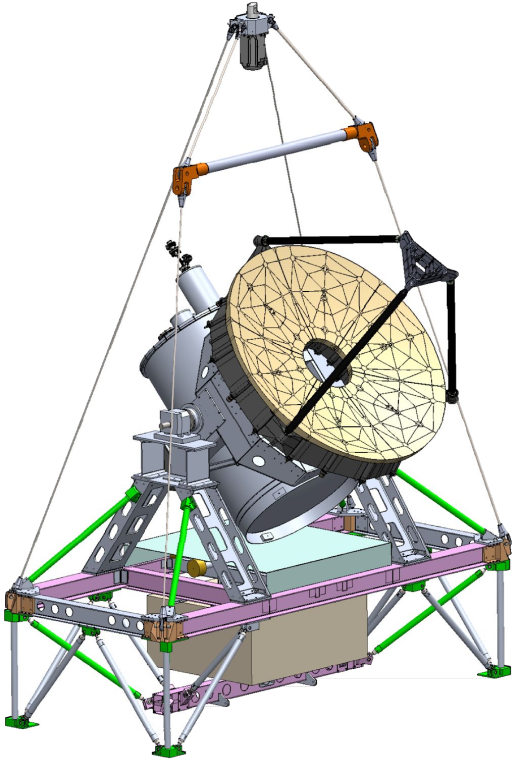
Building up the gondola



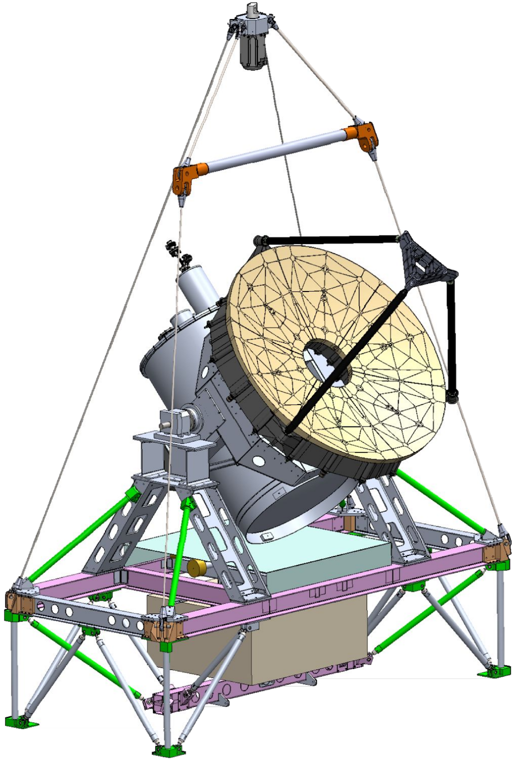
Building up the gondola

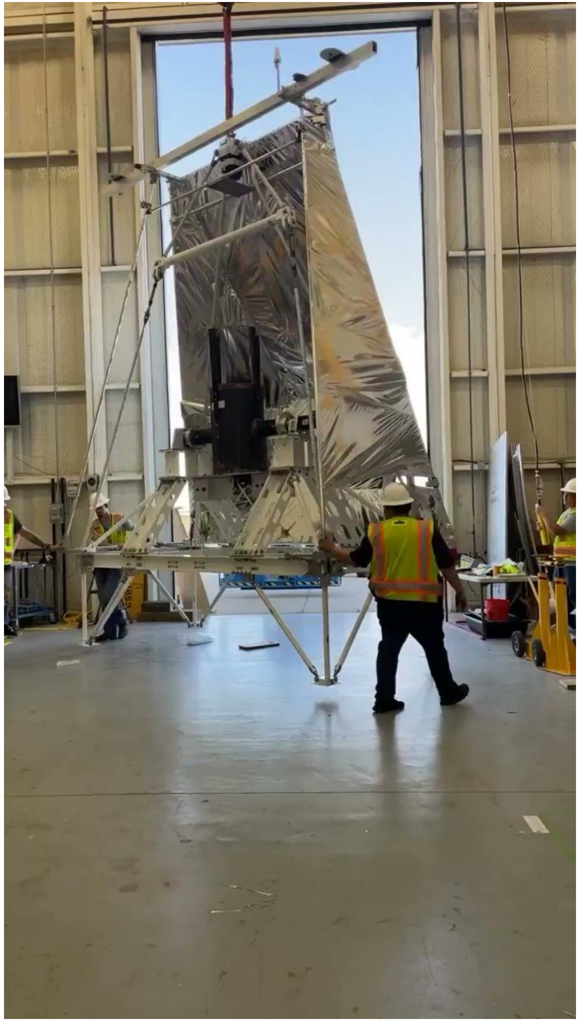


Building up the gondola



Building up the gondola





Fully built TIM gondola ready for launch

A typical launch night:

11 pm - show up and prep payload
1 am - science is ready to go, safety check
2 am - electronics integrated
3 am - hang on the launch vehicle with weather all-clear
4 am - inflate the balloon
7 am - launch


Image: Chris Walker

A typical launch *attempt* night:

11 pm - show up and prep payload
1 am - science is ready to go, safety check
2 am - electronics integrated
3 am - hang on the launch vehicle with weather all-clear
4 am - ~~inflate the balloon~~ wait for weather to clear (it doesn't')
7 am - ~~launch~~ pack in the payload and go get a sad brunch at the only diner in town, sleep until 3pm, rinse and repeat

Sunday launch *attempt*:

11 pm - show up and prep payload

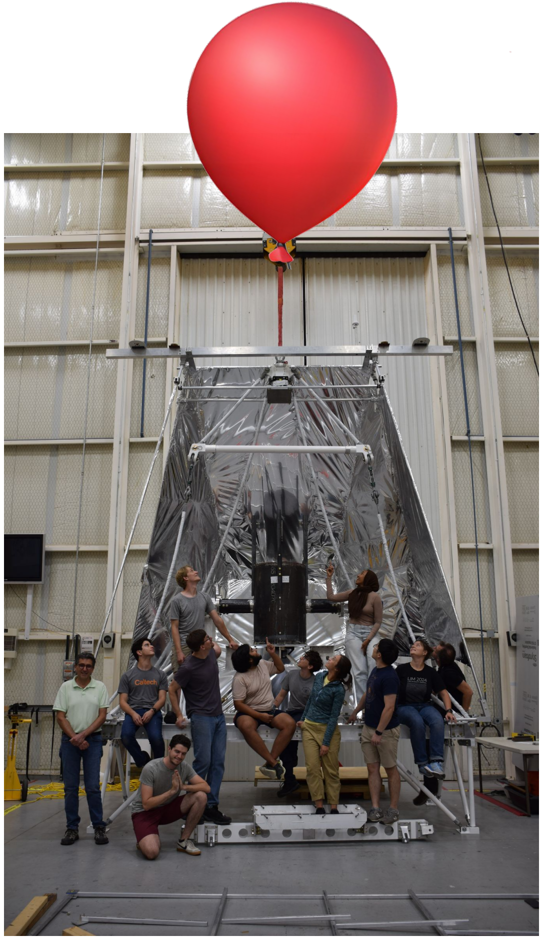
1 am - science is ready to go, safety check

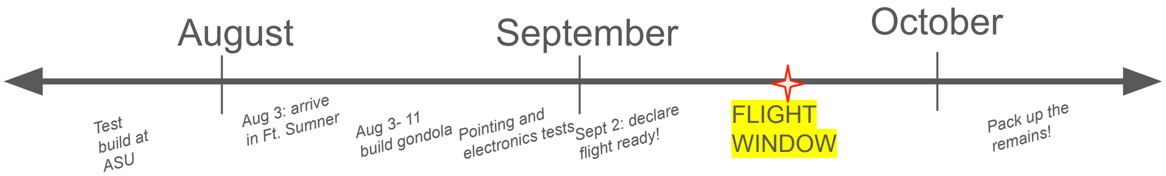
2 am - electronics integrated

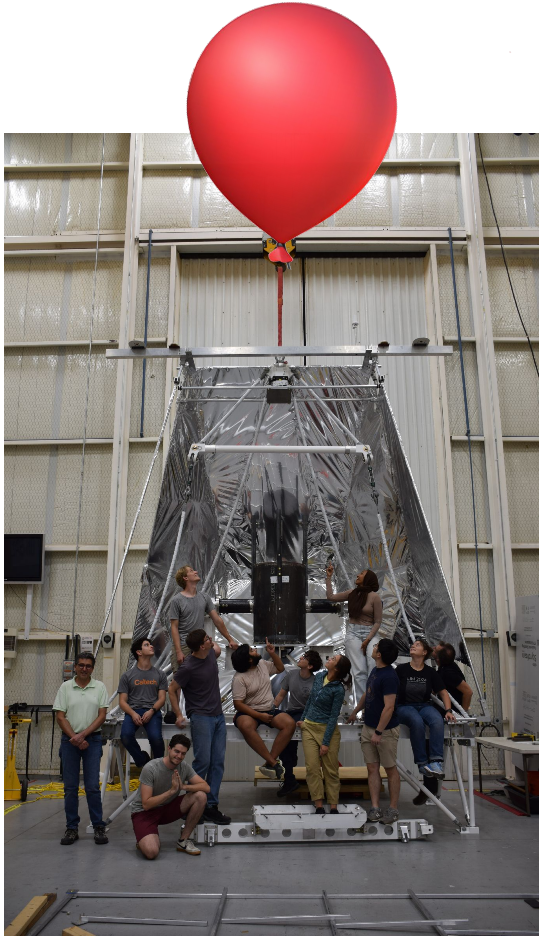
3 am - hang on the launch vehicle with weather all-clear

4 am - ~~inflate the balloon~~ wait for weather to clear (it doesn't)

7 am - ~~launch~~ pack in the payload **and book a ticket to LA to go to the NHFP Symposium**




August
September
October
Test build at ASU
Aug 3: arrive in Ft. Sumner
Aug 3- 11 build gondola
Pointing and electronics tests
Sept 2: declare flight ready!
FLIGHT WINDOW
Pack up the remains!

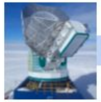


August — September — October

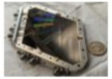
- Test build at ASU
- Aug 3: arrive in Ft. Sumner
- Aug 3- 11 build gondola
- Pointing and electronics tests
- Sept 2: declare flight ready!
- FLIGHT WINDOW
- Pack up the remains!

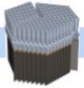
2024 — 2025 — 2026 — 2027 — 2028 — 2029

SPT-SLIM
Deployment:
CO Data!



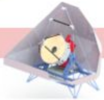
- CO Power spectrum
- First demonstration of mm-wave on-chip spectrometers for line intensity mapping





Next-Gen CO Focal Plane?

TIM
Flight:
CII Data!



Space Probe?

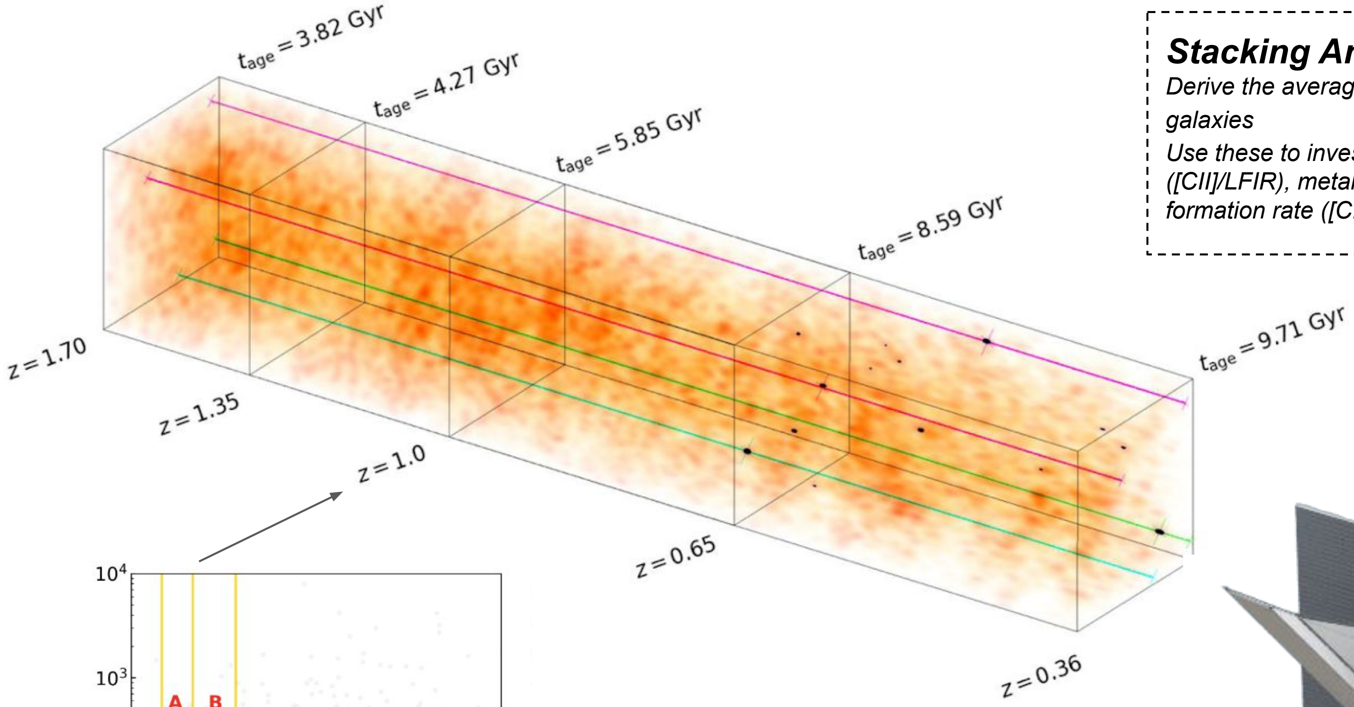
- Lensed Single Galaxy
- CII Power spectrum
- Blind Galaxy Detection + ALMA follow up
- Galaxy Survey x-corr w/ Euclid
- SPT-SLIM x TIM CO x CII x-corr

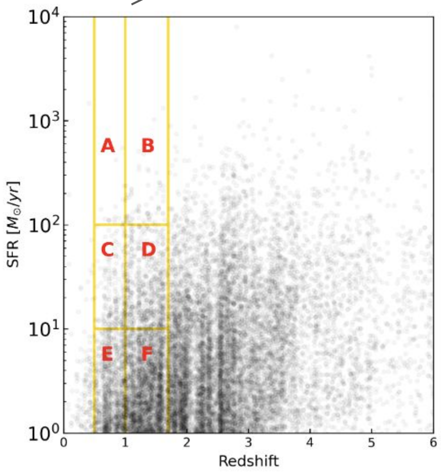
Backup

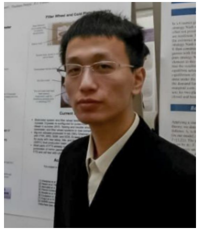
Stacking Analysis

Derive the average FIR spectral properties of samples of galaxies

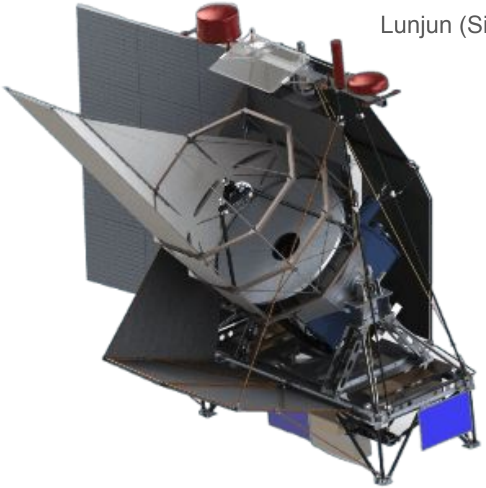
Use these to investigate changes in star formation modes ([CII]/LFIR), metallicity ([NII]/[CII]), and specific star formation rate ([CII]/M_star)







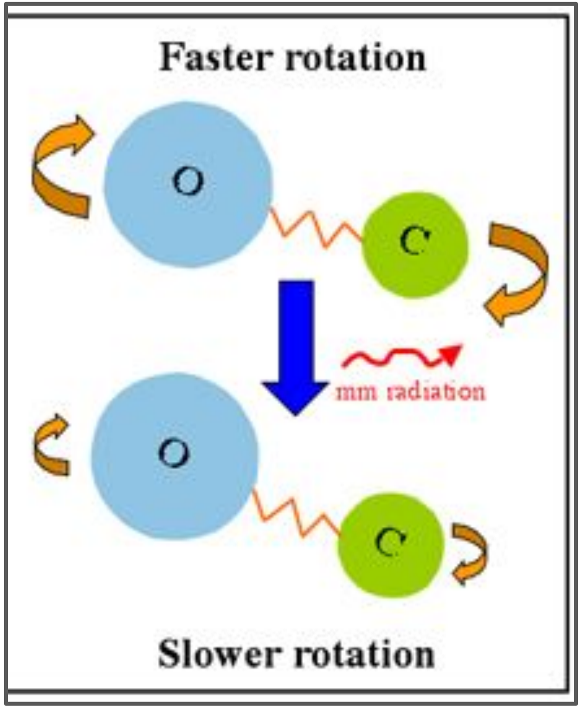
Lunjun (Simon) Liu



~1, 700 spectroscopic samples are available for stacking from the ASTRODEEP catalogue, which are binned by spectroscopic redshift and SFR, labeled A – F.

Basics of Line Emission

Emission from atomic and molecular spectral lines from galaxies

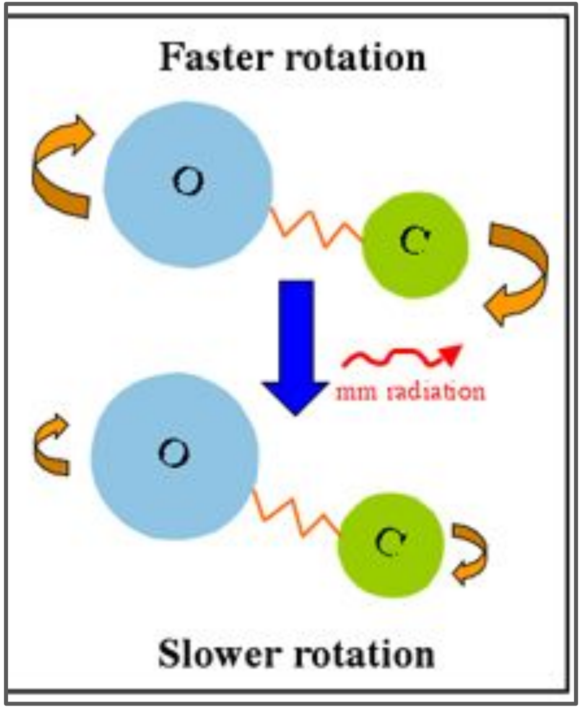


Swinburne University of Technology

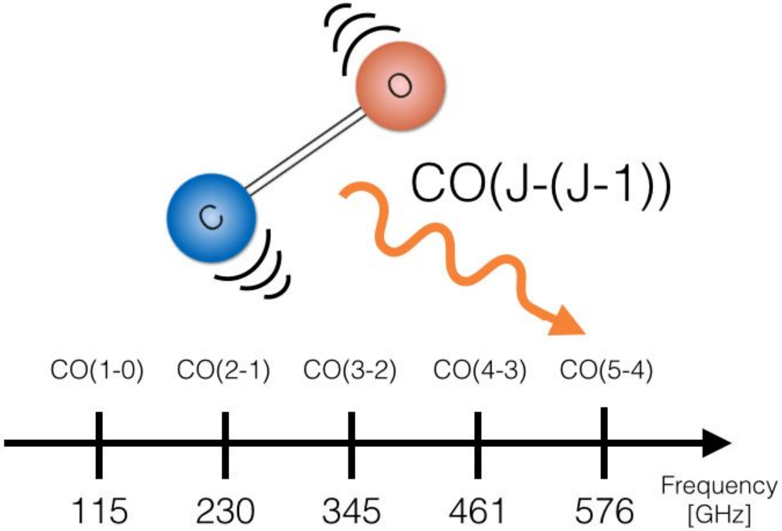
- In an atom, electrons can only exist at specific energy levels → need to absorb or release photons to transition
- Similarly, molecules can only rotate and vibrate and certain rates
- When CO changes it's rotational state, it's absorbs or emits a photon in the mm-wavelengths
- [CII] fine structure transition at 158 μm

Basics of Line Emission

Emission from atomic and molecular spectral lines from galaxies



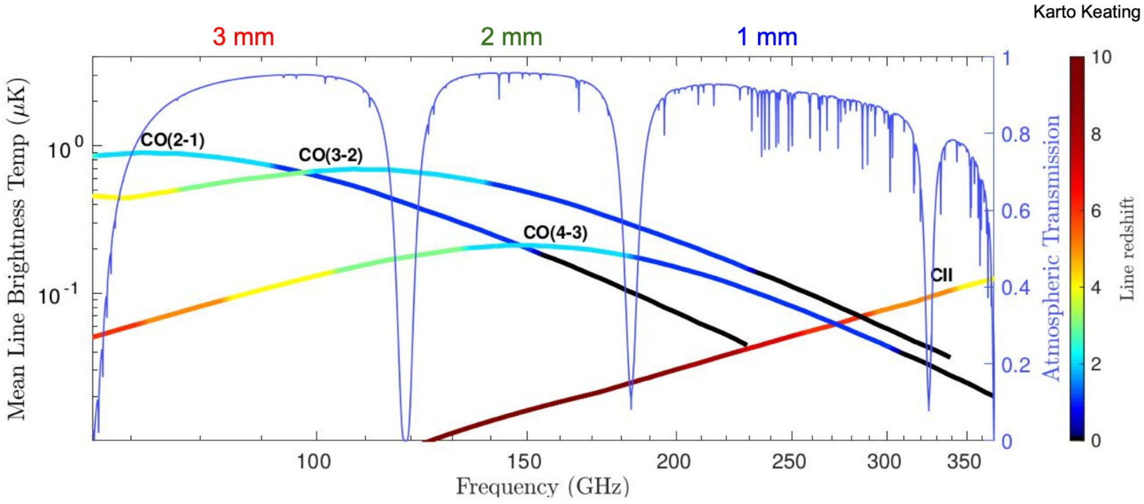
Swinburne University of Technology

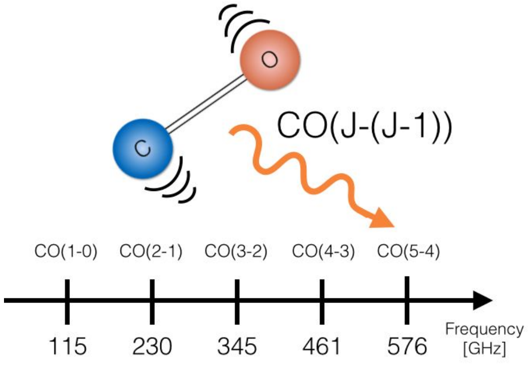


K. Olsen

Basics of Line Emission

Emission from atomic and molecular spectral lines from galaxies

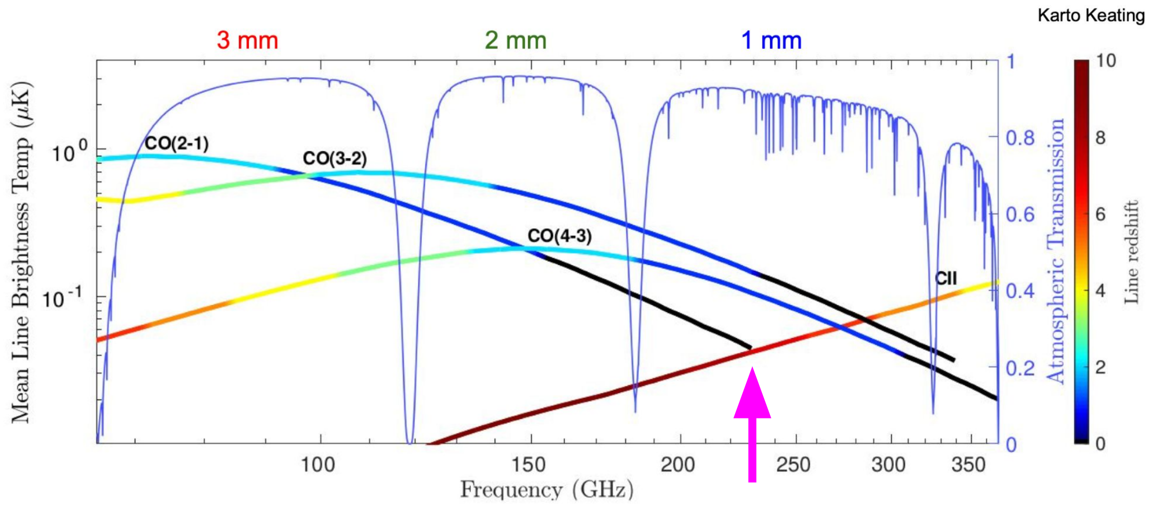


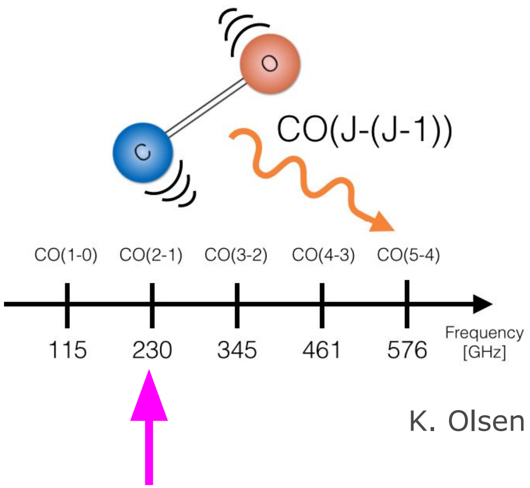


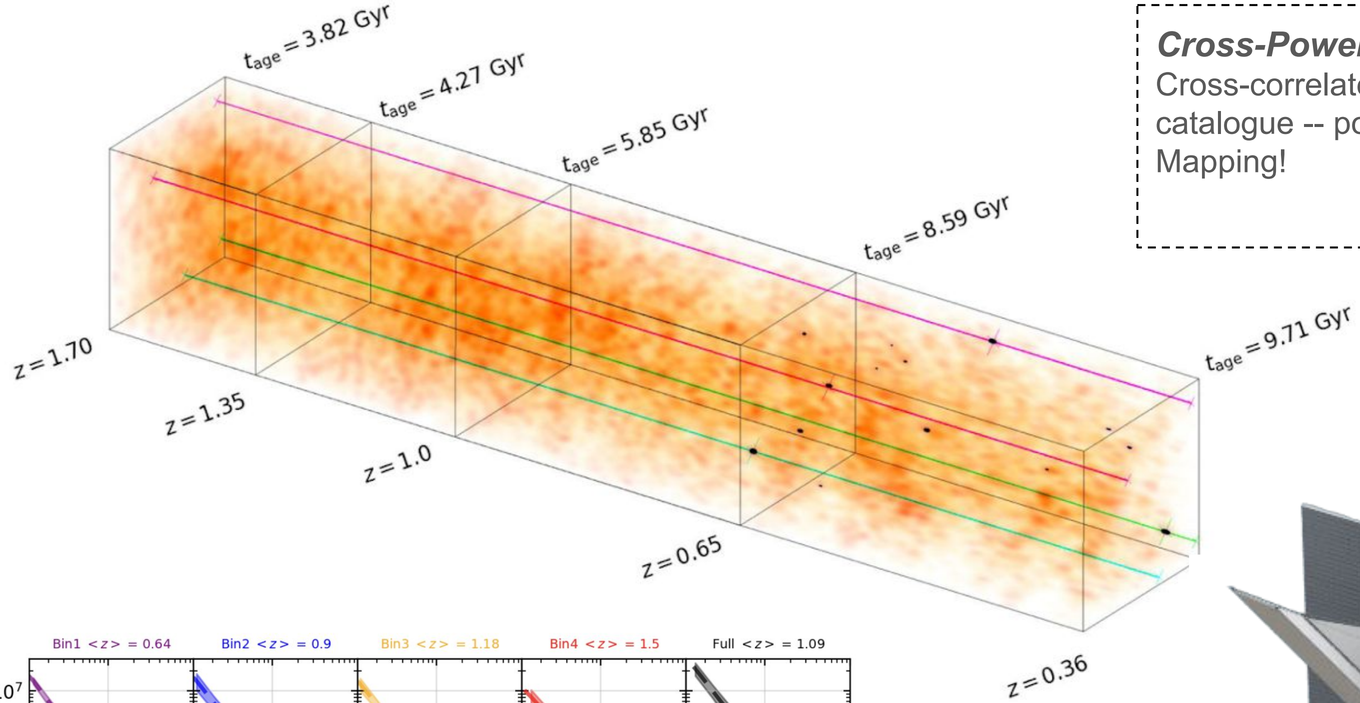
K. Olsen

Basics of Line Emission

Emission from atomic and molecular spectral lines from galaxies

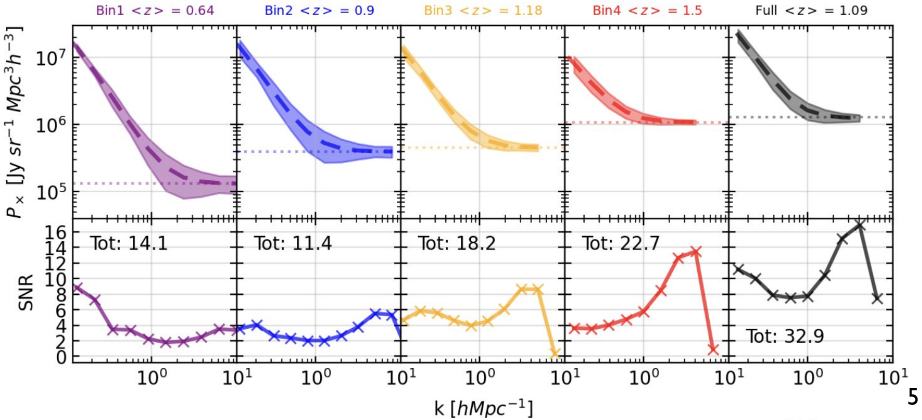




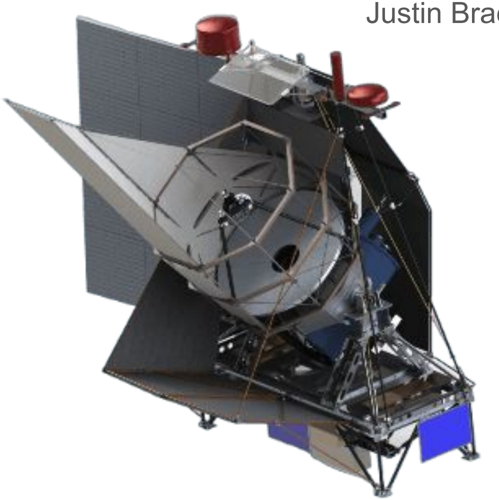


Cross-Power Spectrum

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

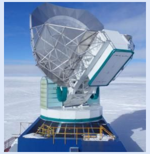


Justin Bracks

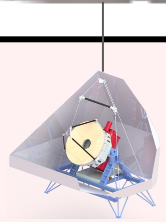


Why should I, as a SPT-SLIM collaborator, care about TIM? (And what is the difference)

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



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

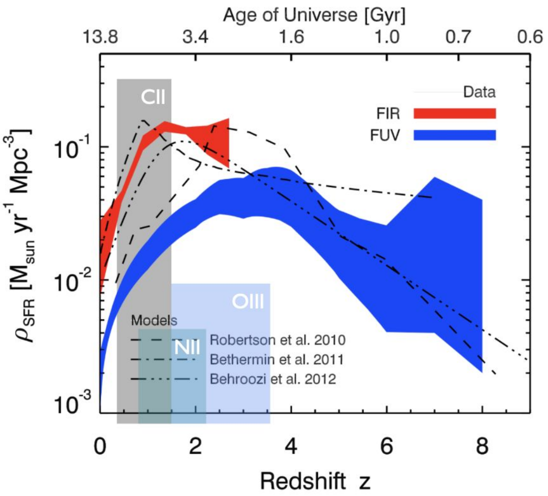


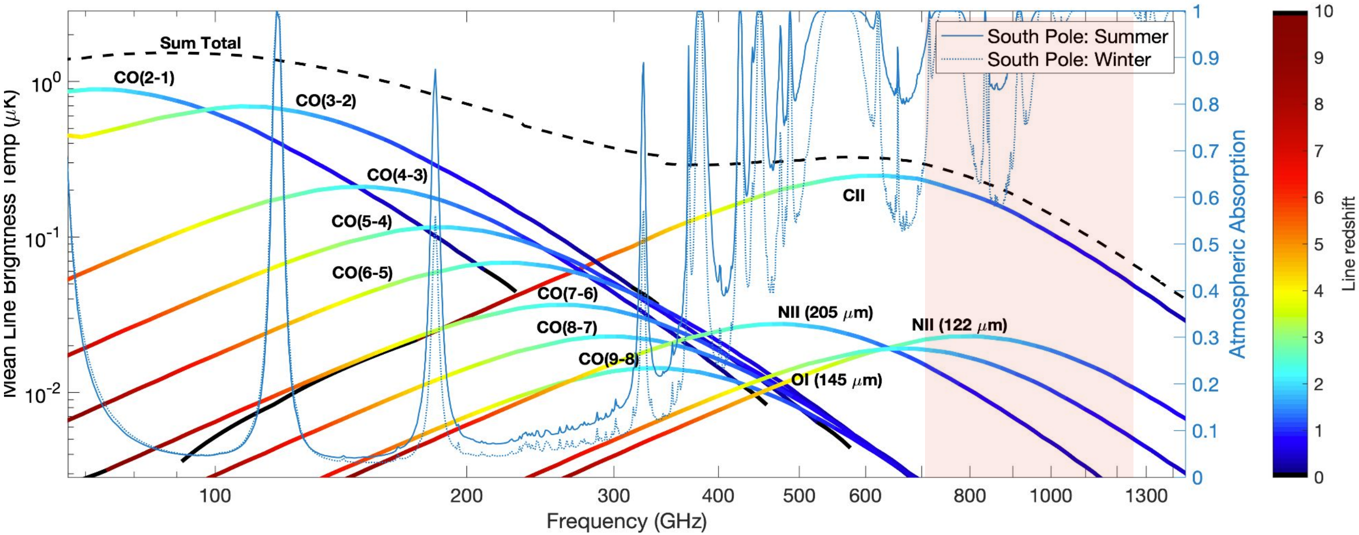
CO traces **cold** gas of molecular clouds, which is an excellent tracer of star formation since molecular clouds are the dense regions in galaxies where new stars form -- the “fuel” of star formation

CII directly traces the signatures of star formation, because it originates from photon-dominated regions around **hot** stars - it is an effective proxy for the total infrared galaxy luminosities

Note: neither says “traces dark matter!” -- both a biased tracer. Much can be learned by cross correlating maps of both, and looking at line ratios at different redshifts!

Line Intensity Mapping with [C II] and CO(1-0) as Probes of Primordial Non-Gaussianity by Azadeh Moradinezhad Dizgah and Garrett Karto Keating : https://iopscience.iop.org/article/10.3847/1538-4357/aafd36





The TIM redshift range: *perfect for studying galaxy and star formation*

0.7-1.2 THz (240-420μm)

[CII] 158μm   0.5 < z < 1.6

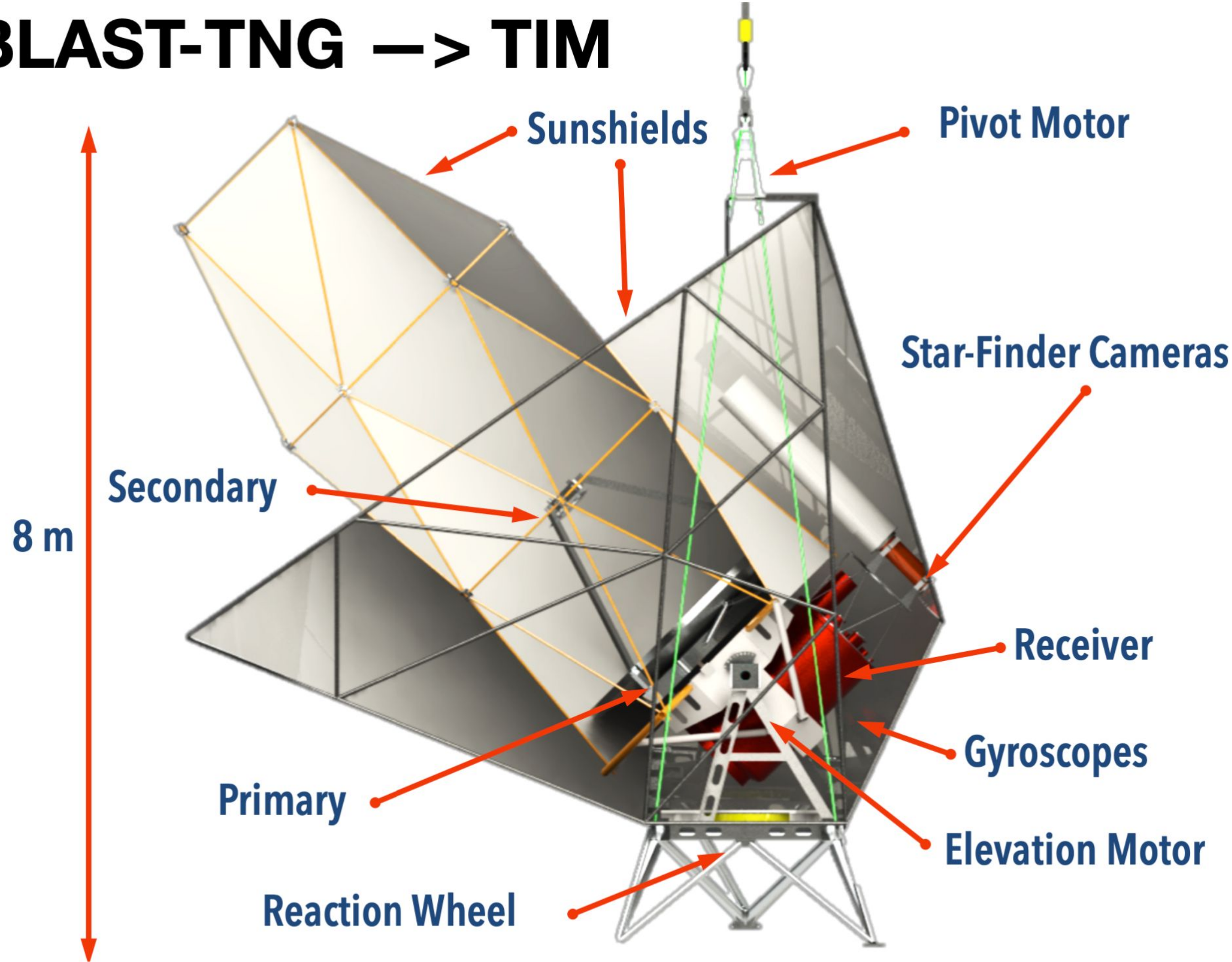
[OIII] 88μm   1.8 < z < 3.5

[OI] 63μm   3.0 < z < 5.0

TIM connects [CII] intensity mapping to galaxy studies in local universe

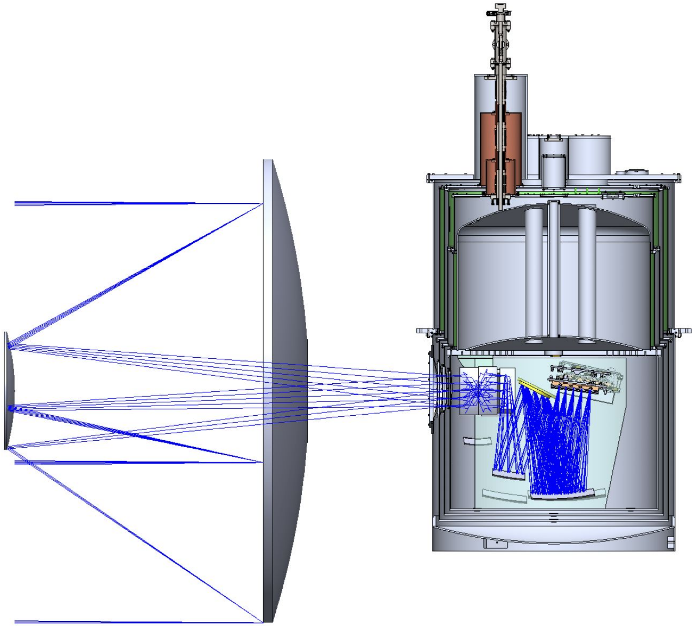
- Ionized Carbon [CII] 158μm (or C+) is one of the major coolants for the interstellar medium and can be ~0.1% of the total luminosity of a galaxy
- C+ is a (mostly) extinction-free probe of the physical conditions of gas and radiation fields
- Can be used as a tracer of large scale structure and of the cosmic star formation history

BLAST-TNG —> TIM



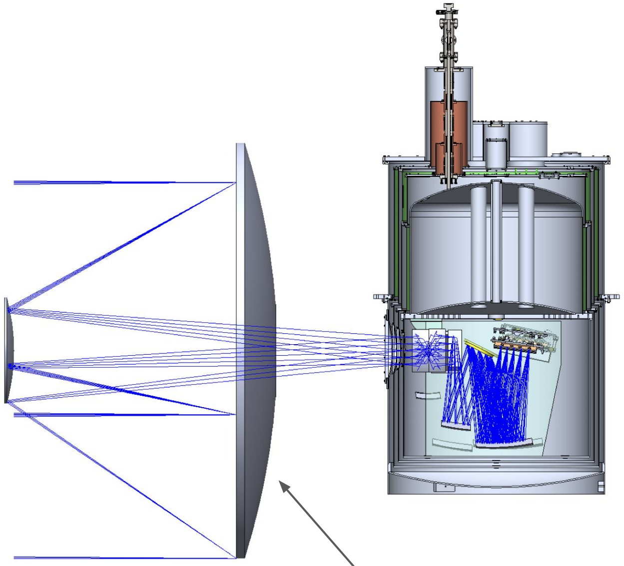
Optical Design & Cryostat

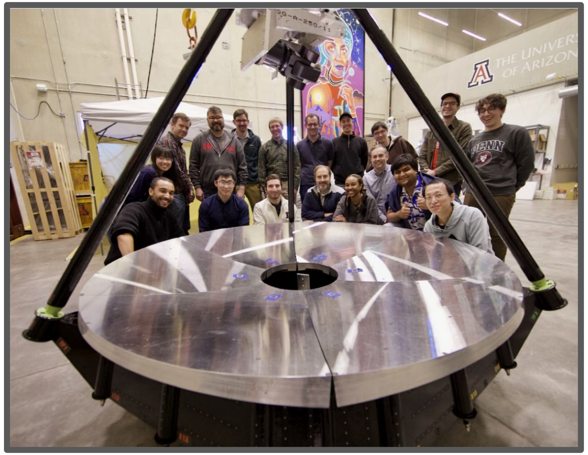
- 2m primary
- 1.3 deg diffraction-limited FoV
- Separately optimized LW/SW spectrometers
- 45-60% efficiency (Filters not included)
- Liquid Helium cooled with He10 sorption fridge



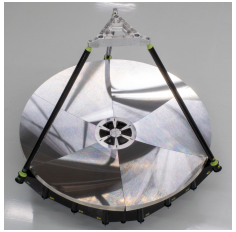
Optical Design & Cryostat

- 2m primary
- 1.3 deg diffraction-limited FoV
- Separately optimized LW/SW spectrometers
- 45-60% efficiency (Filters not included)
- Liquid Helium cooled with He10 sorption fridge



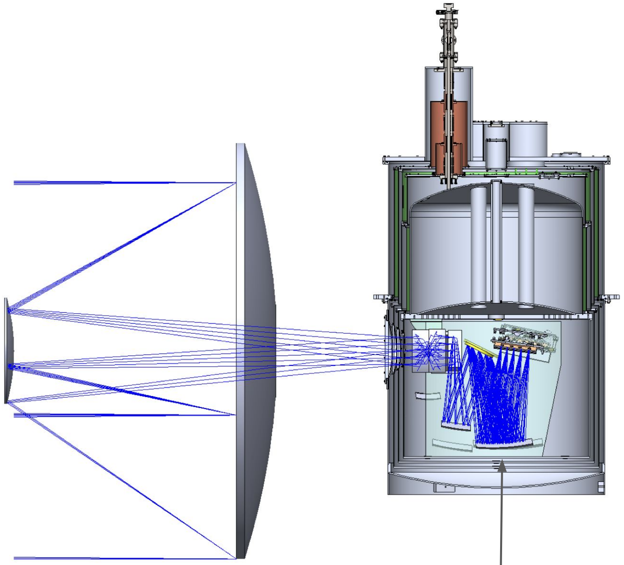


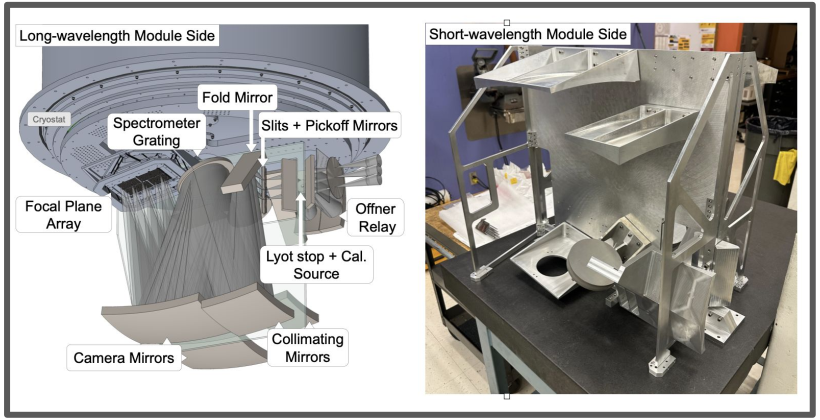
- Fabricated in 6 wedges by mtex Antenna Technology -- surface ~5 um rms



Optical Design & Cryostat

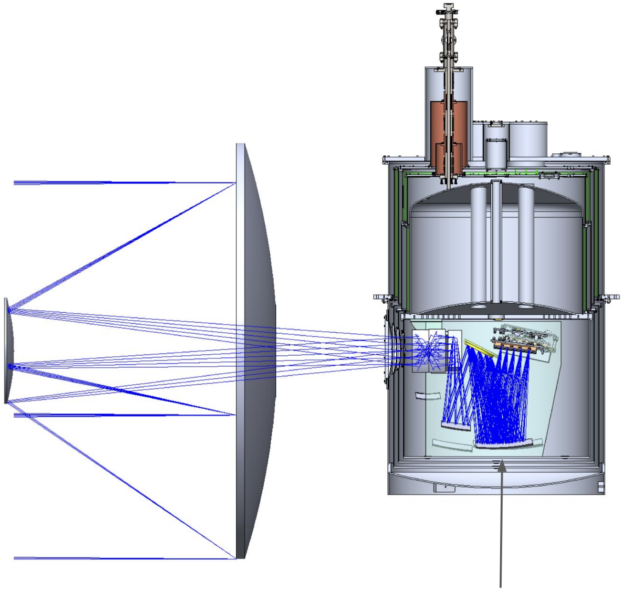
- 2m primary
- 1.3 deg diffraction-limited FoV
- Separately optimized LW/SW spectrometers
- 45-60% efficiency (Filters not included)
- Liquid Helium cooled with He10 sorption fridge

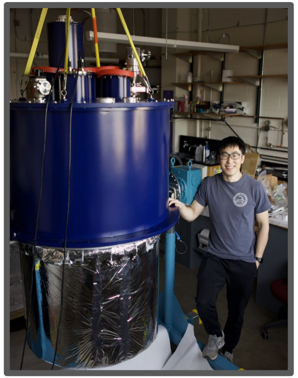




Optical Design & Cryostat

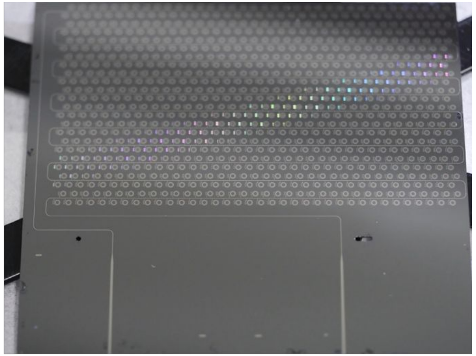
- 2m primary
- 1.3 deg diffraction-limited FoV
- Separately optimized LW/SW spectrometers
- 45-60% efficiency (Filters not included)
- Liquid Helium cooled with He10 sorption fridge

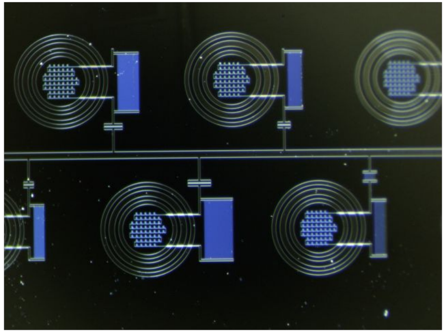


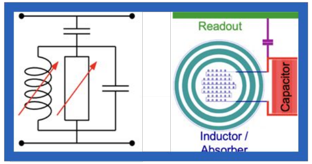


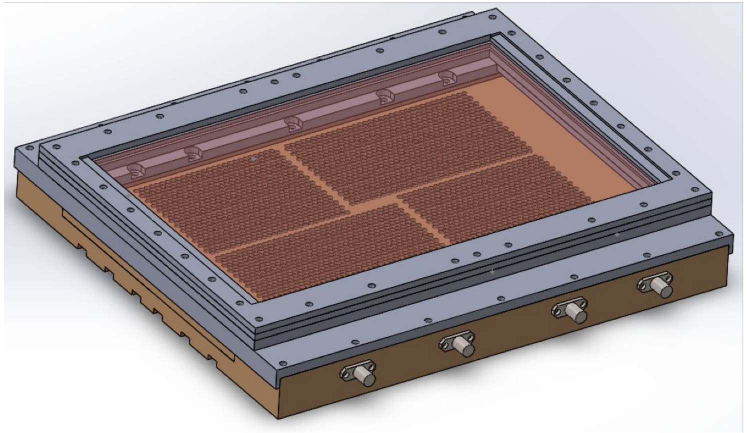
Detectors

- 2x ~3600 Aluminum Kinetic Inductance Detectors (KIDs)
- Detectors exceed sensitivity requirements
  - NEP = 3.5 x 10-18 W/Hz0.5 at 250mK
  - 2-3x better than needed
- First arrays >95% fabrication yield
- Coupled through horn array plate









What's different about ballooning?

Things we have to consider

- Build to withstand 8g+ shocks
- Soft "weight envelope" - costs altitude
- Hard size envelope to launch
- Harsh solar radiation + Earth Limb to avoid
- Radiative only heat dissipation
- DIY power systems
- Low-overhead flight software
- Attitude determination and control

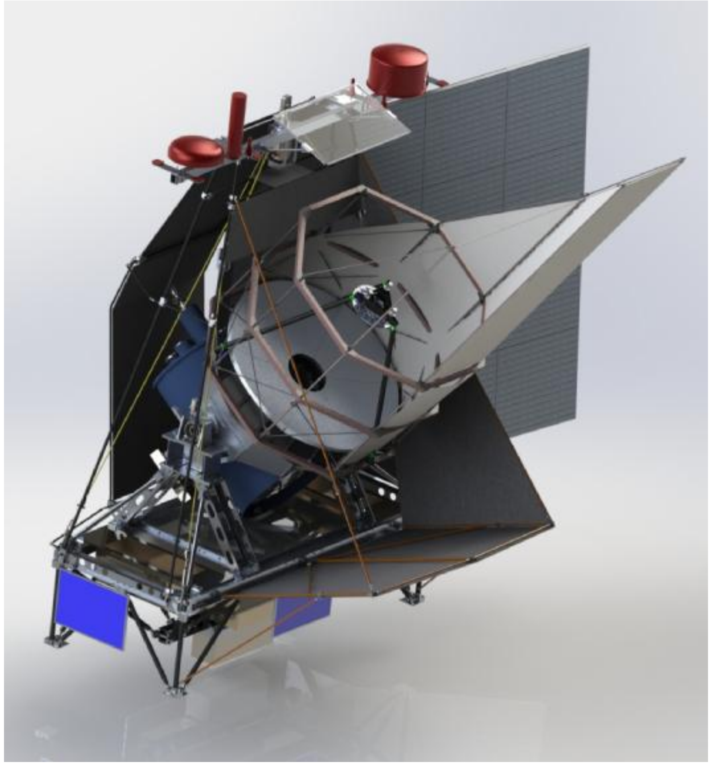


Figure: Talia Saeid