

CO Intensity Mapping for Capturing the Star-formation History in the Early Universe

김준한 Junhan Kim (junhan@kaist.ac.kr)

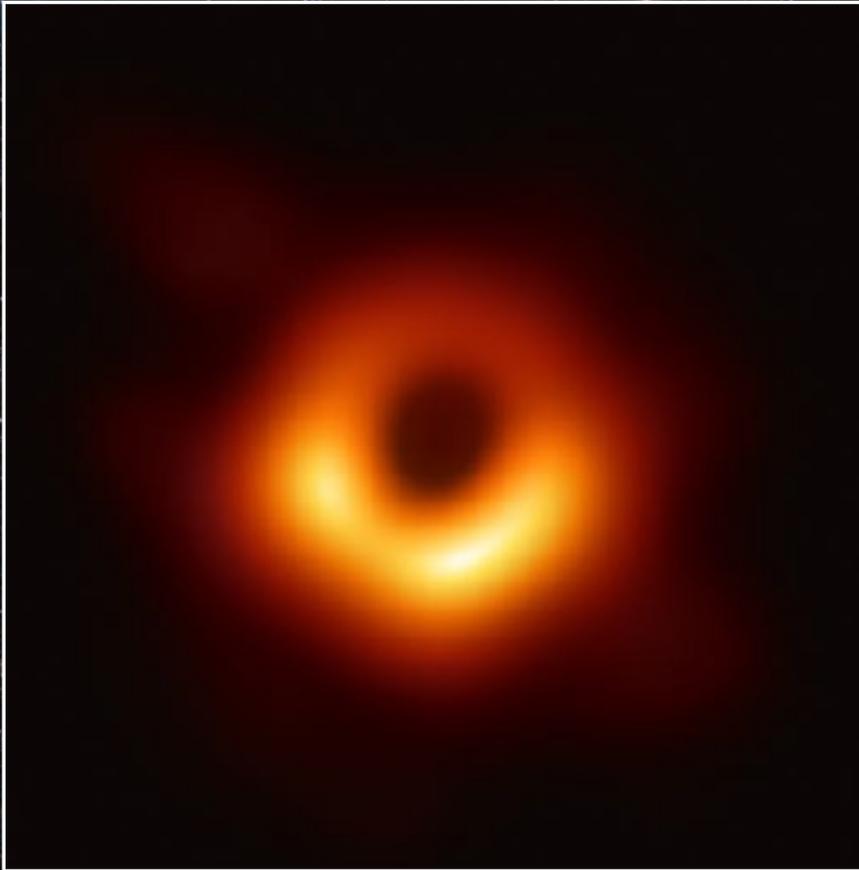
Department of Physics

Korea Advanced Institute of Science and Technology (KAIST)

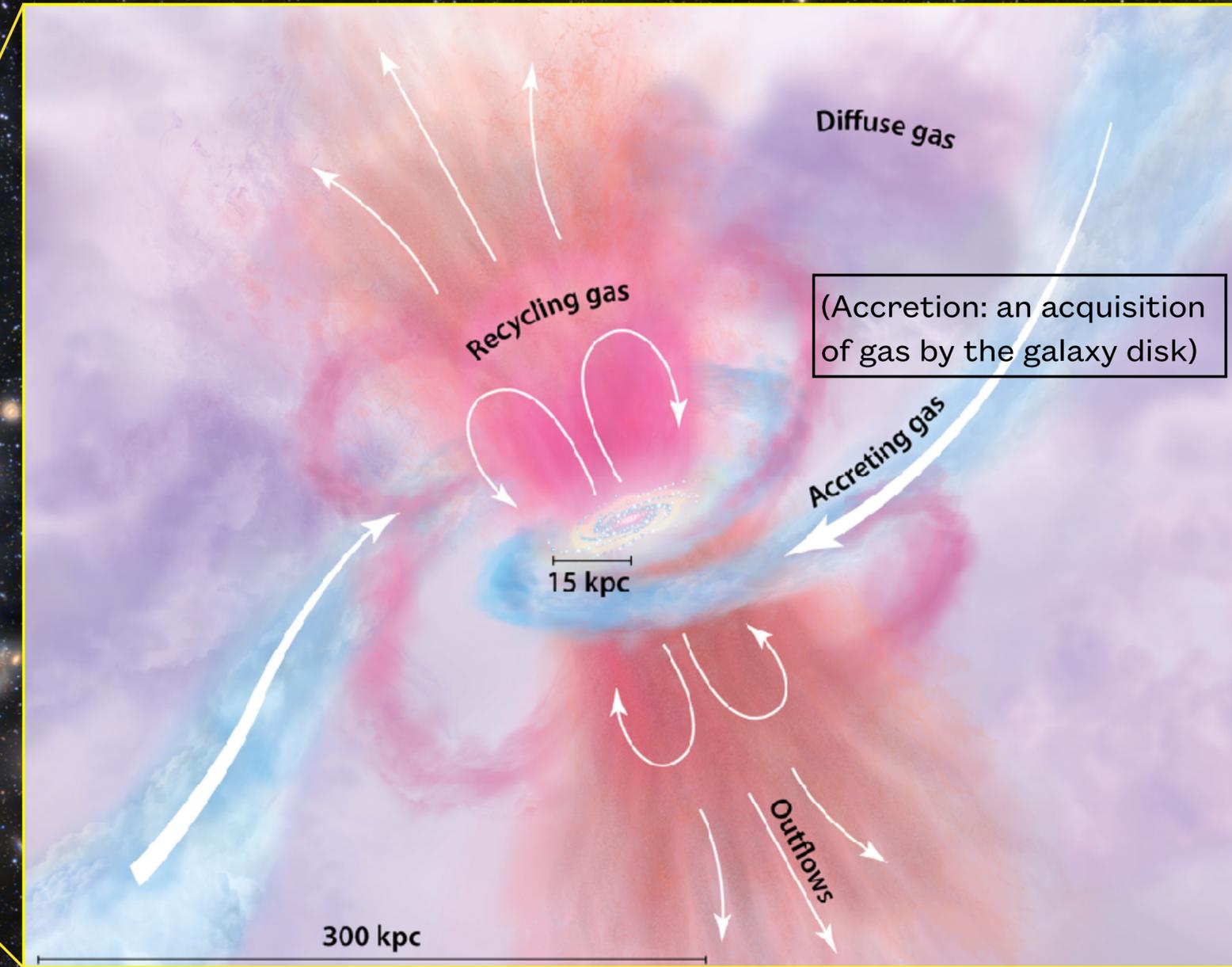


Circumgalactic/Intergalactic/Intracluster medium

Supermassive black holes



M87

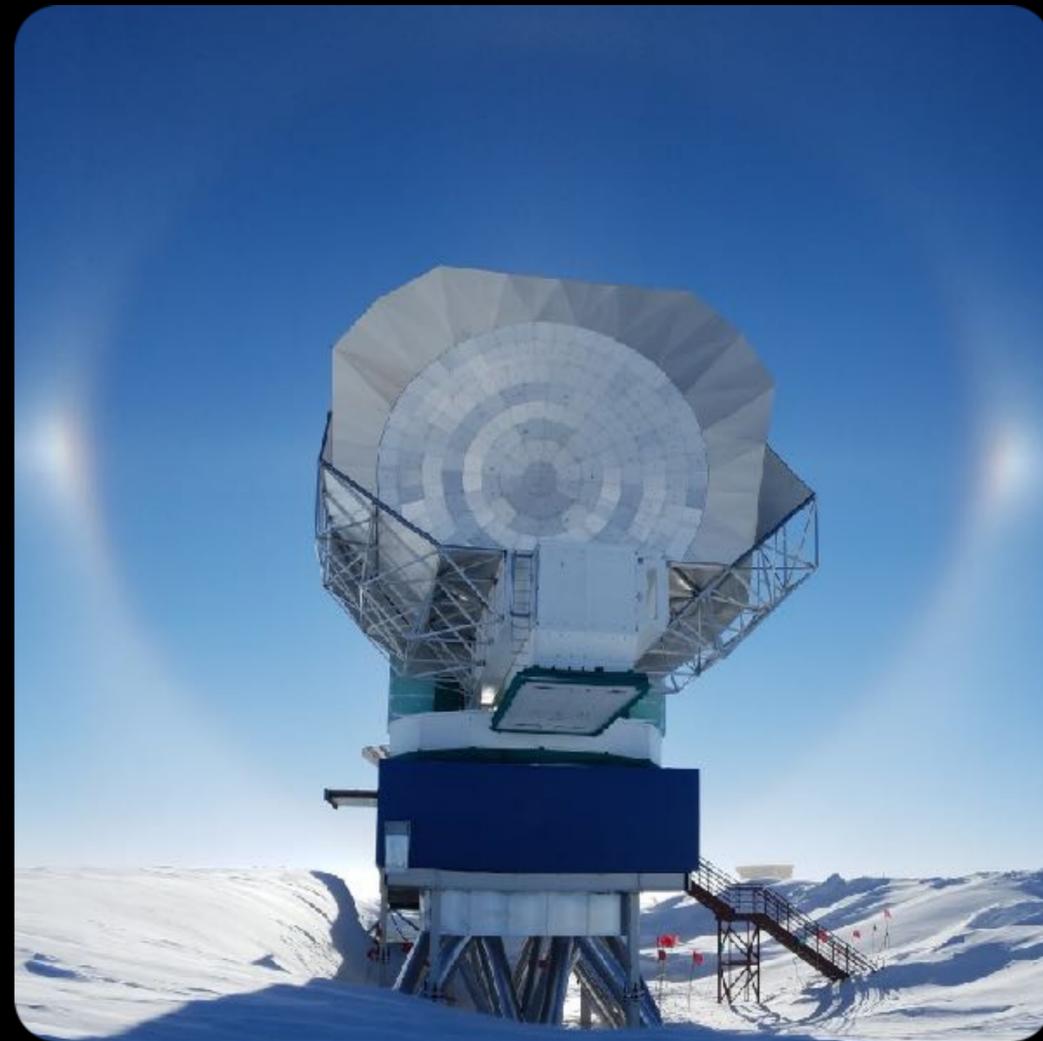


(Accretion: an acquisition of gas by the galaxy disk)

Tumlinson, Peeples, Werk (2017)

Studying Baryonic Flow Across the Cosmic Scales Using *Radio and Millimeter Wavelength Experiments*

Event Horizon Telescope VLBI:
Supermassive black holes



South Pole Telescope
(South Pole Station, Antarctica)

Line-intensity mapping with CO:
Spatial distribution of galaxies



COMAP (Owens Valley
Radio Observatory, California)

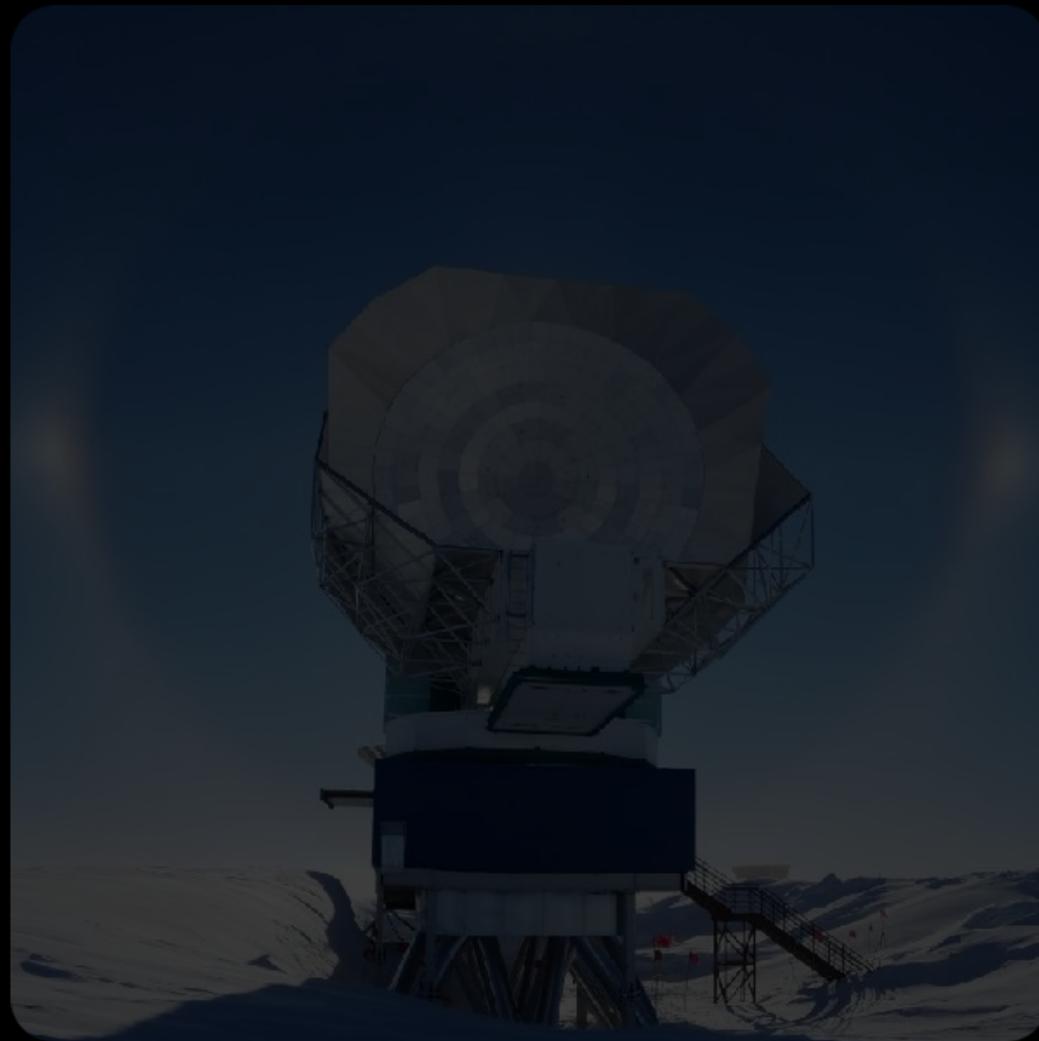
Sunyaev-Zel'dovich effect:
Circumgalactic & intracluster media



Leighton Chajnantor Telescope
(Mauna Kea, Hawaii → Atacama desert, Chile)

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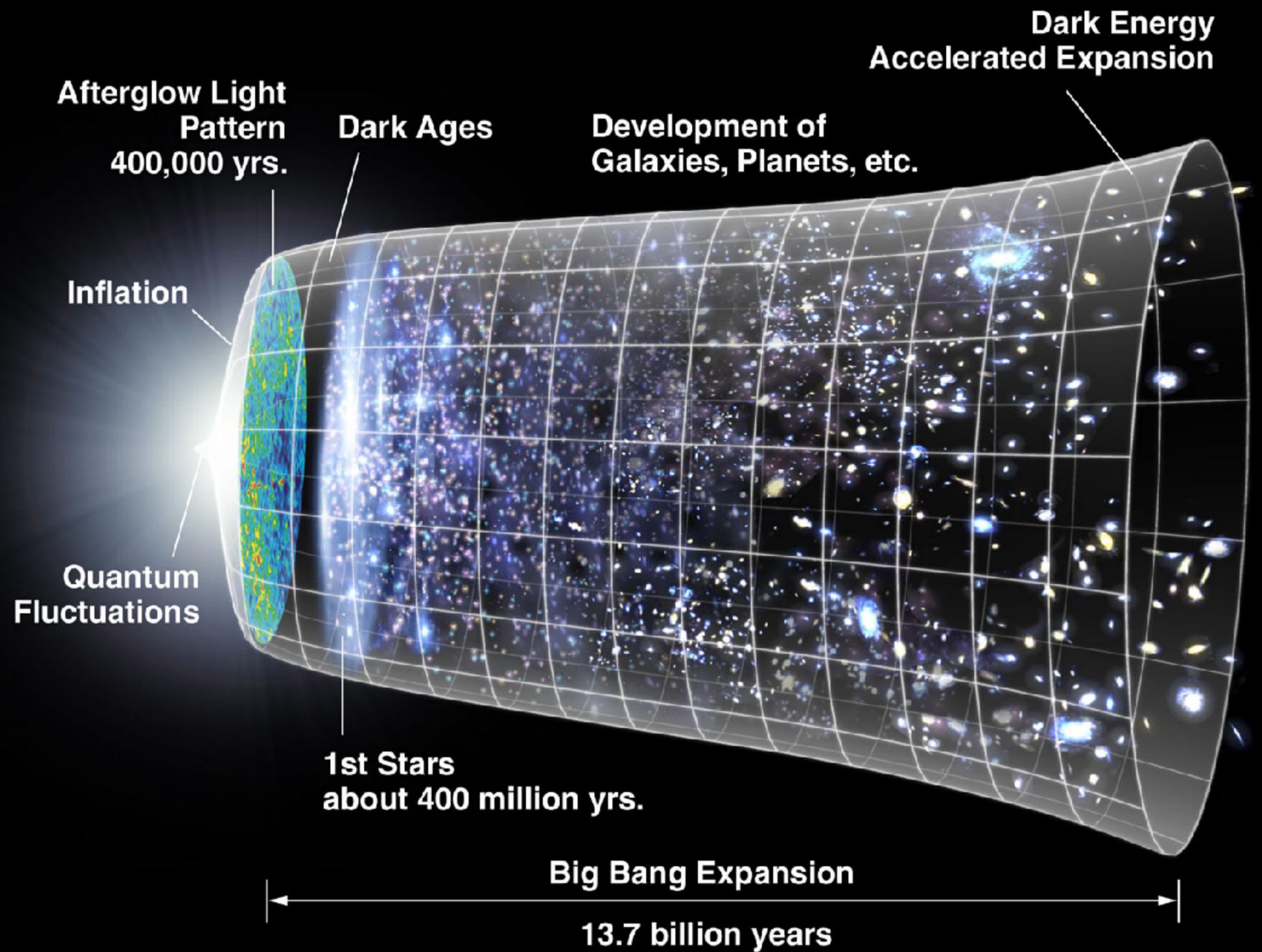


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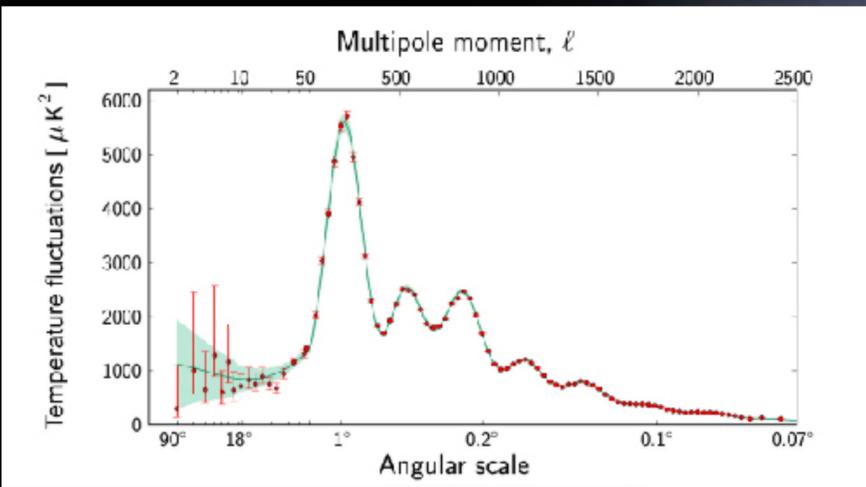
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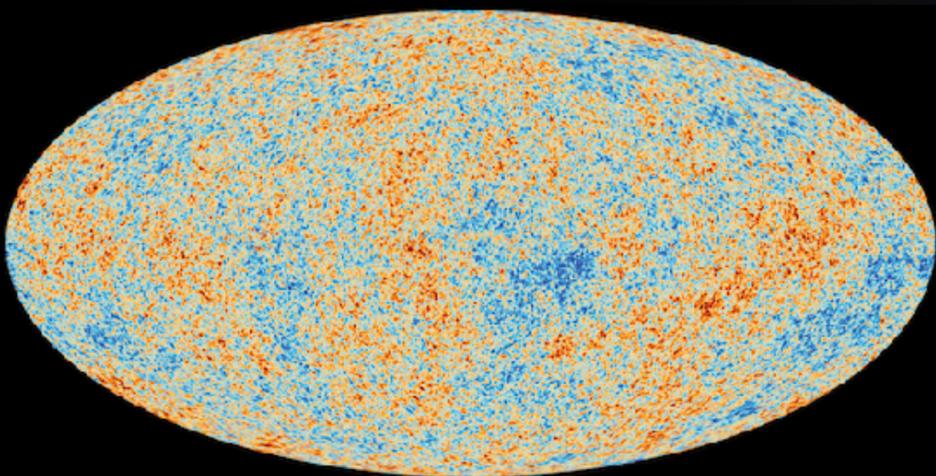


Afterglow Light
Pattern
400,000 yrs.



Fluctuations

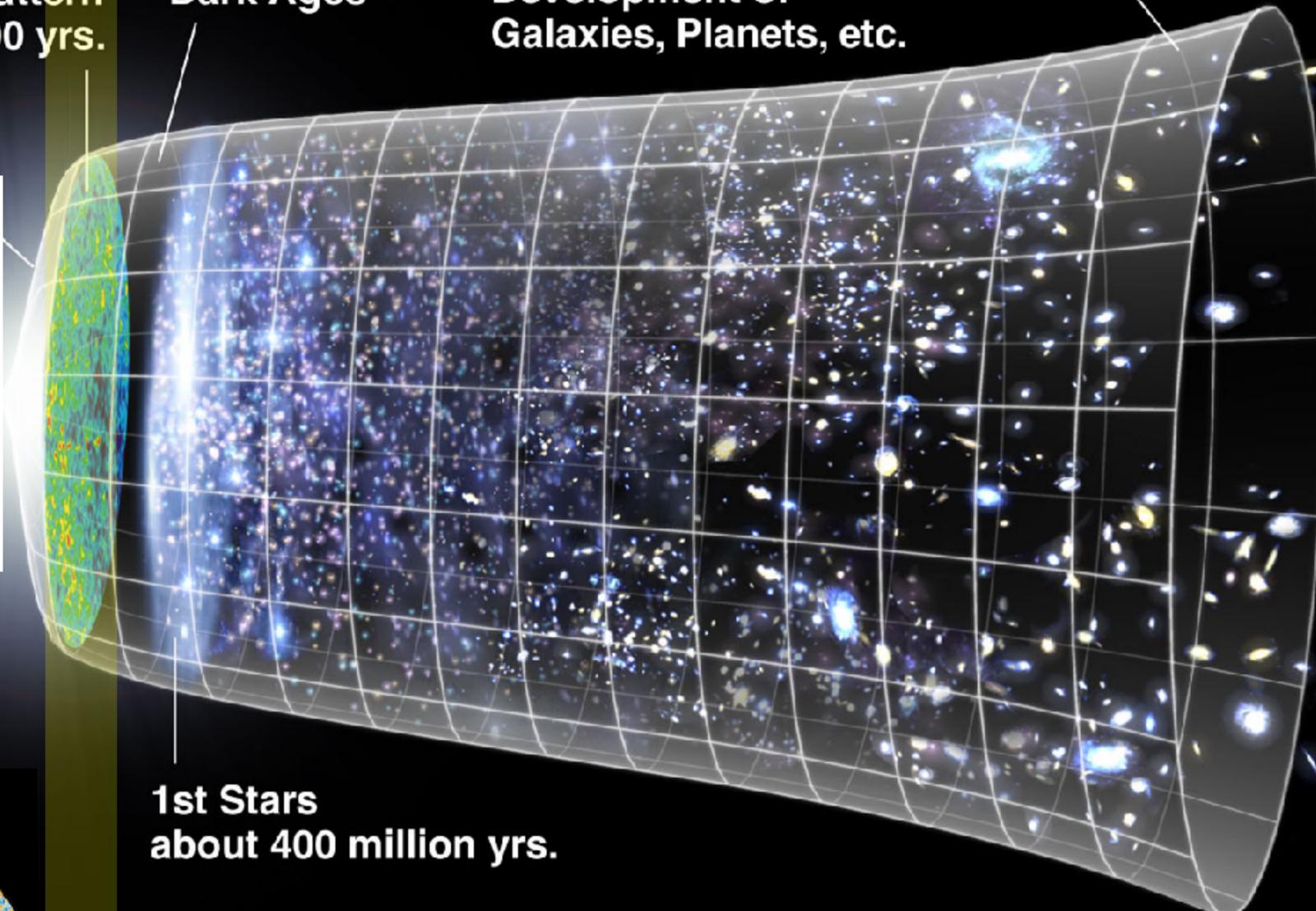
Cosmic Microwave
Background (CMB)



Dark Ages

Development of
Galaxies, Planets, etc.

Dark Energy
Accelerated Expansion



1st Stars
about 400 million yrs.

Big Bang Expansion

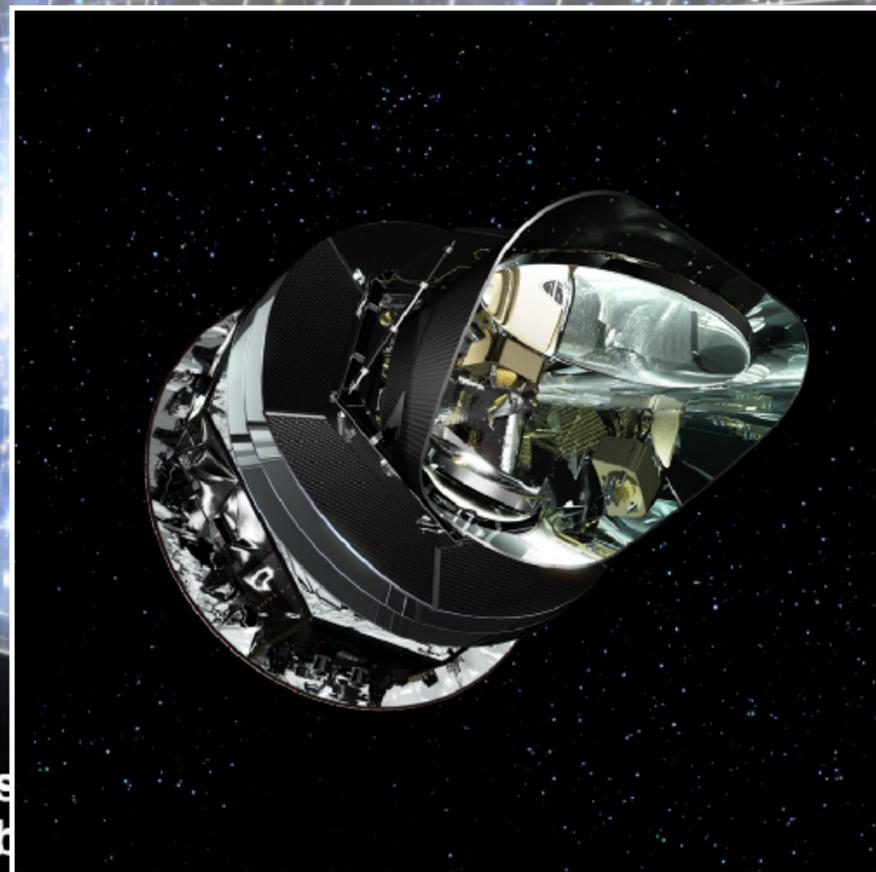
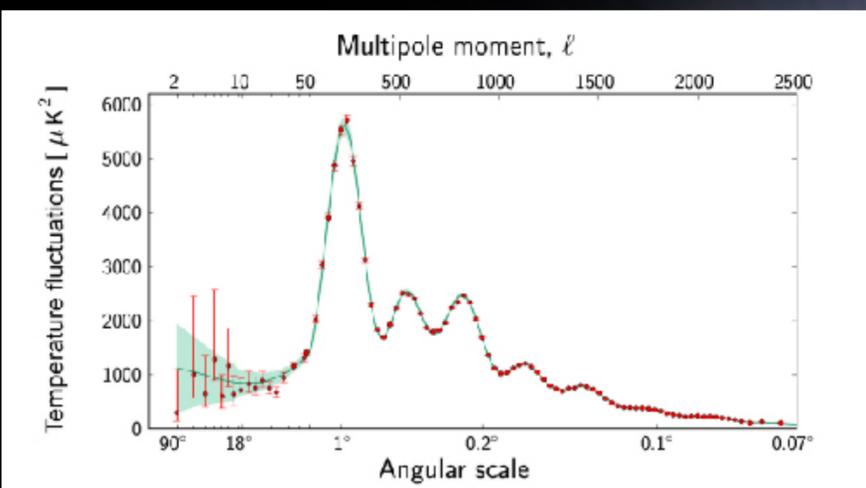
13.7 billion years

Afterglow Light
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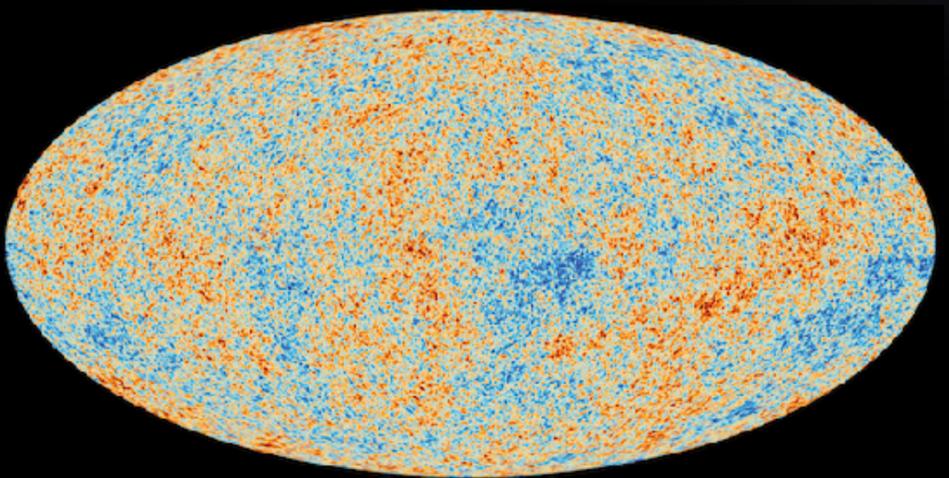
Accele



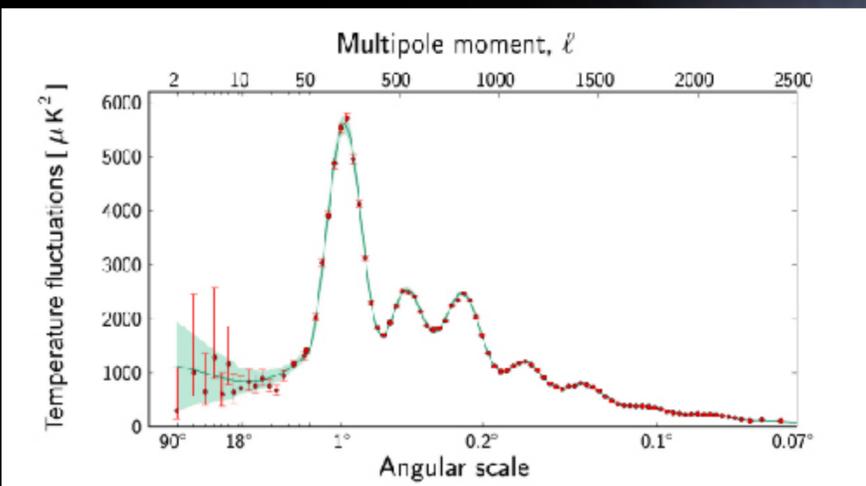
1s
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Fluctuations
Cosmic Microwave
Background (CMB)

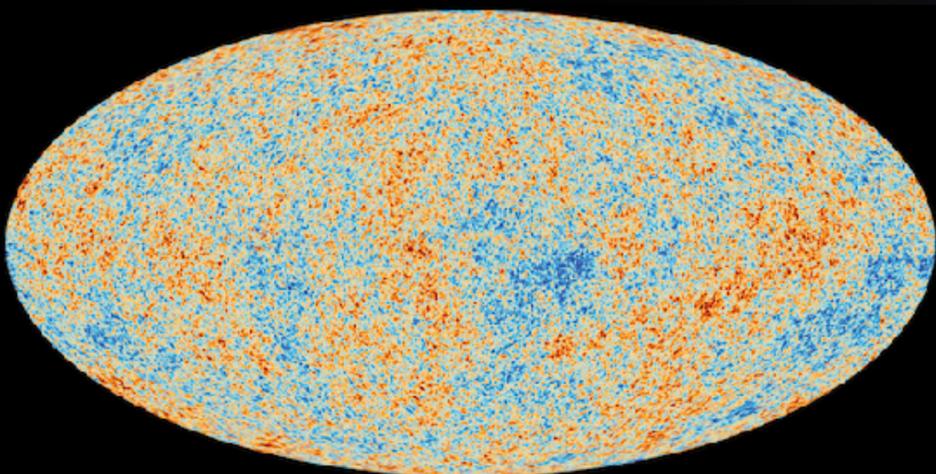


Afterglow Light
Pattern
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Fluctuations

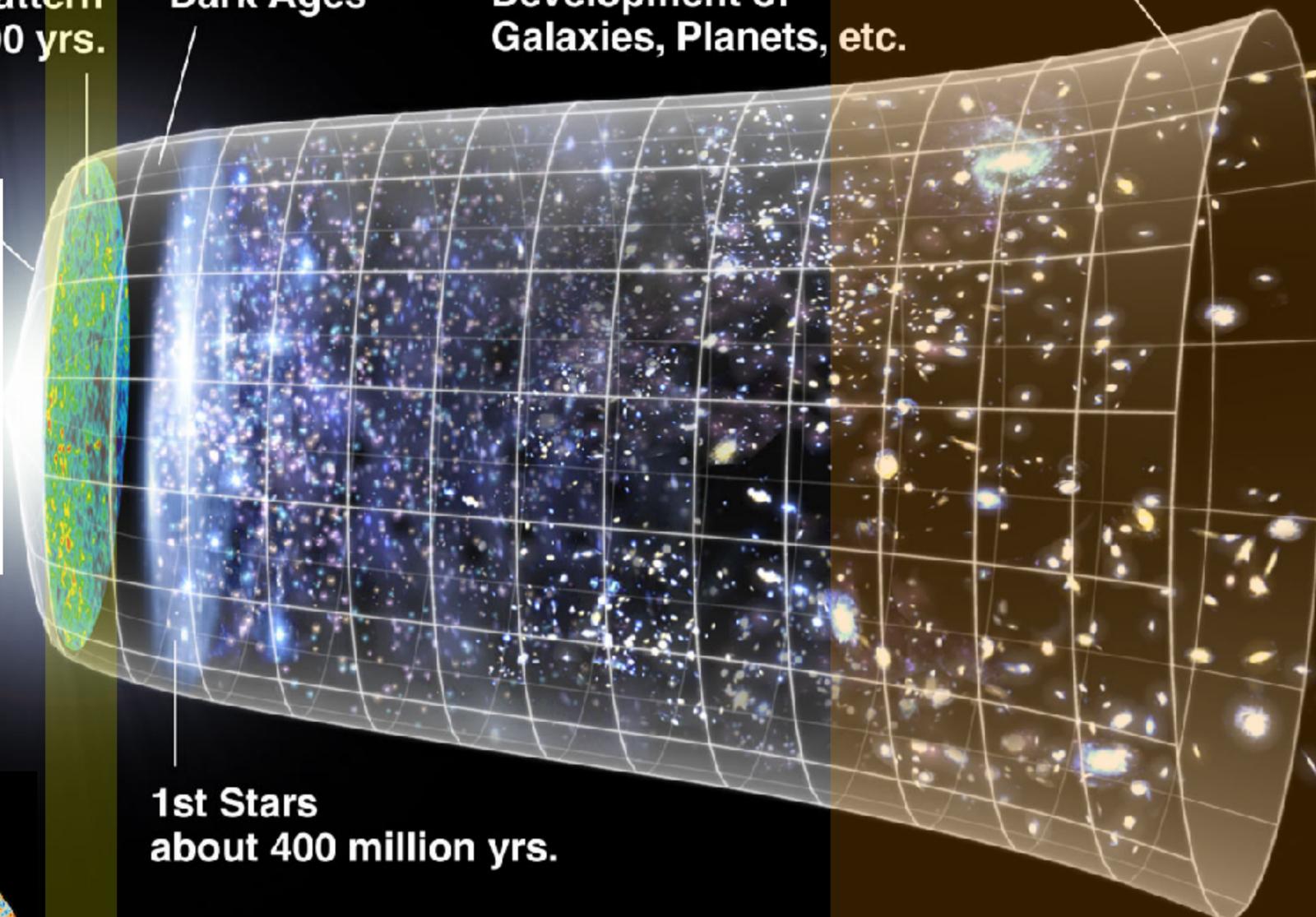
Cosmic Microwave
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Dark Ages

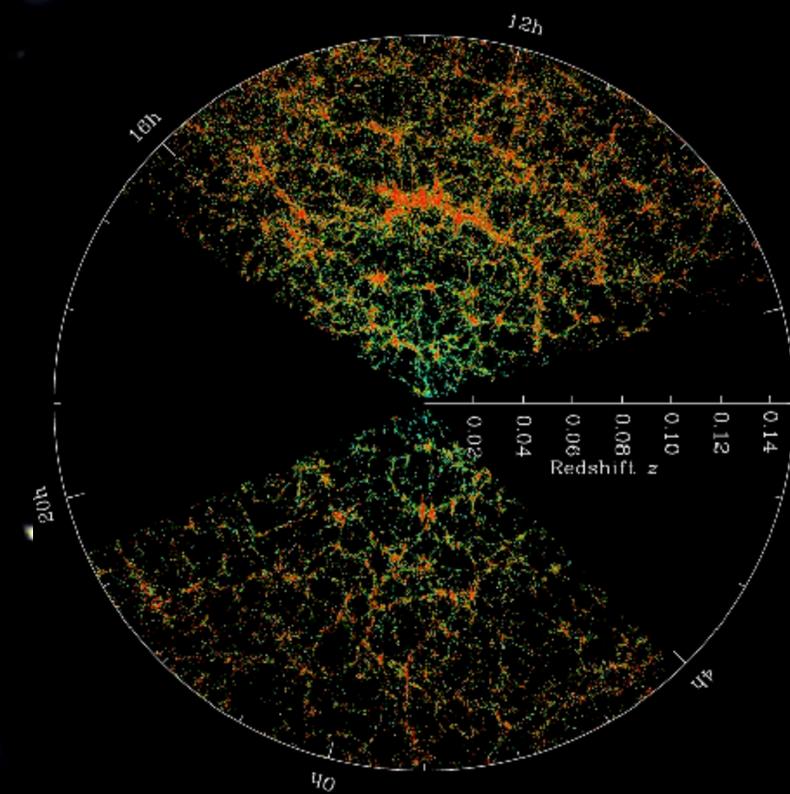
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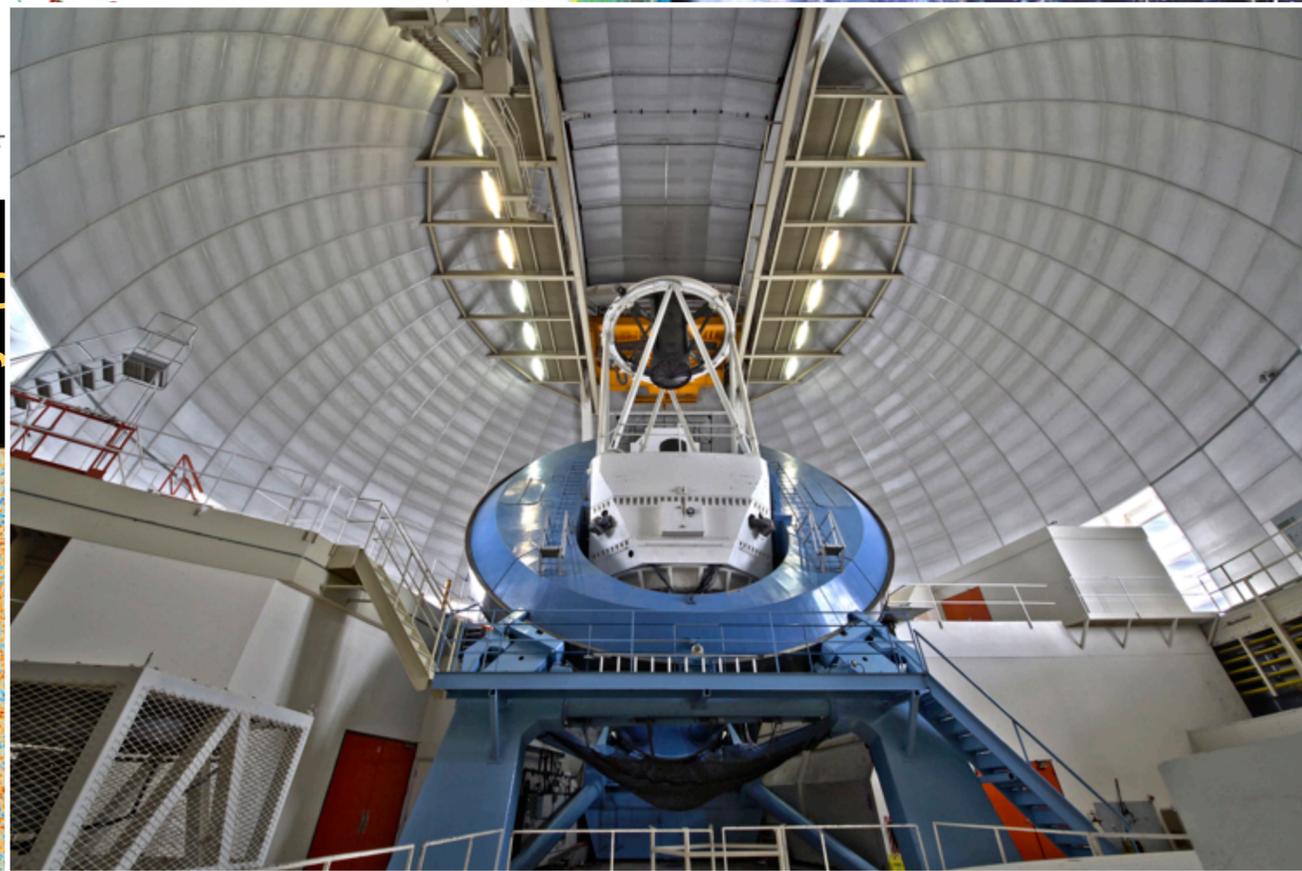
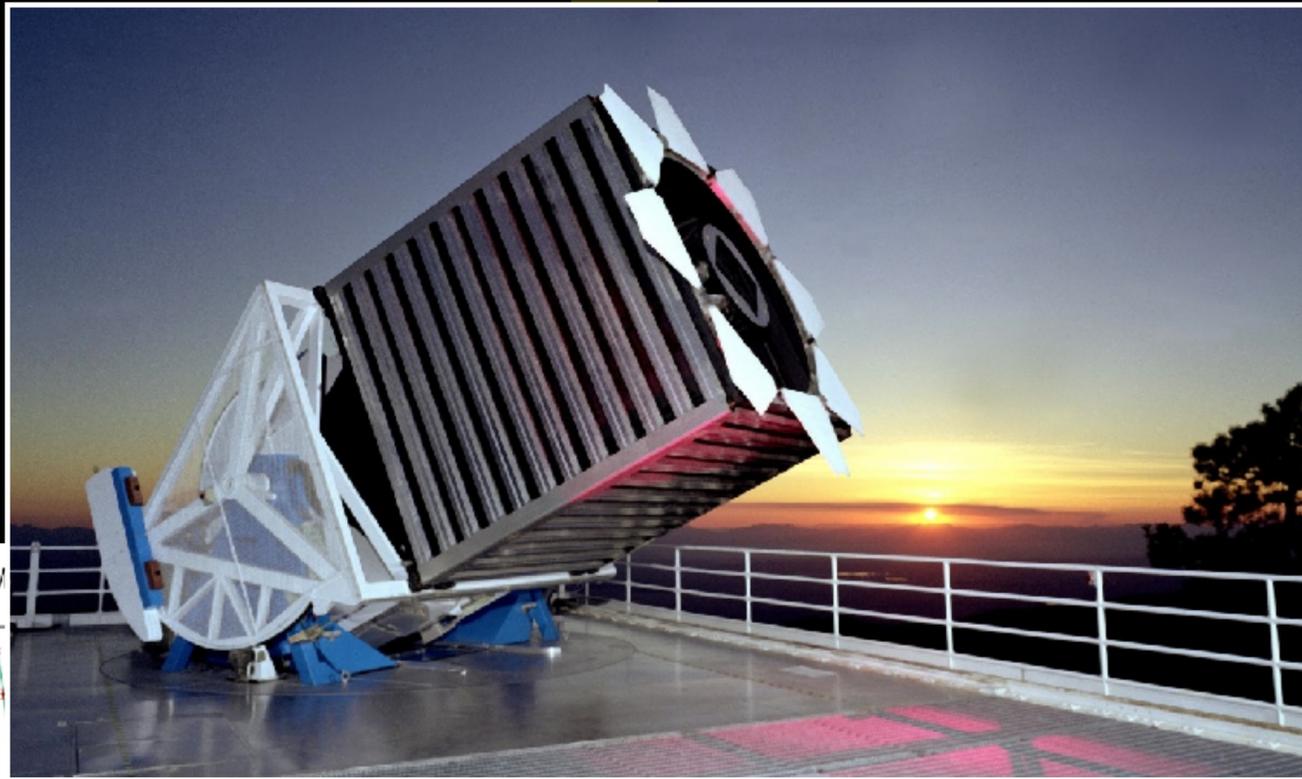
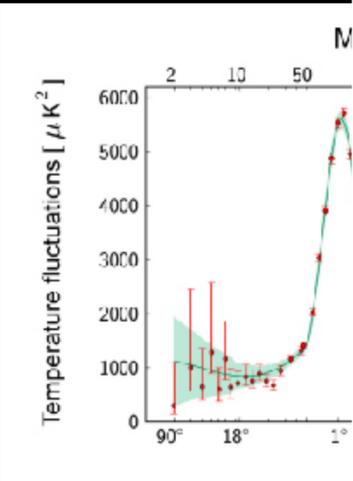


1st Stars
about 400 million yrs.

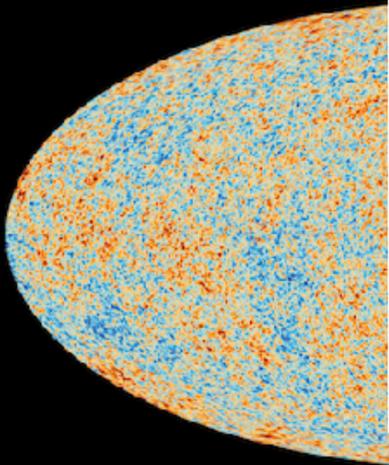
Big Bang Expansion
13.7 billion years



Galaxy surveys
 $z = 0-1+$



Cosmic
Background

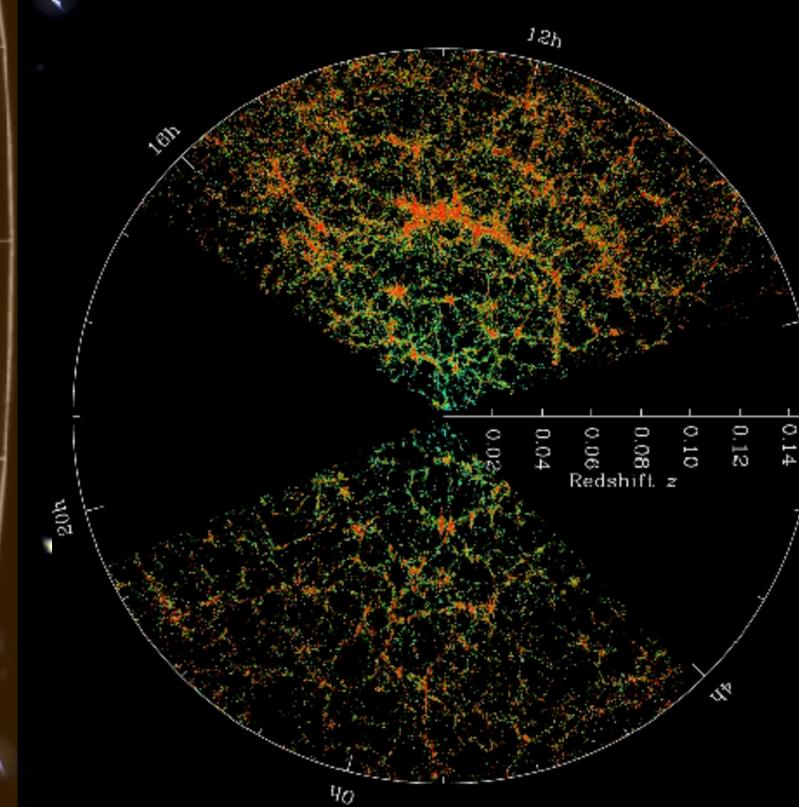


Dark Energy
Accelerated Expansion

Expansion of
Galaxies, Planets, etc.

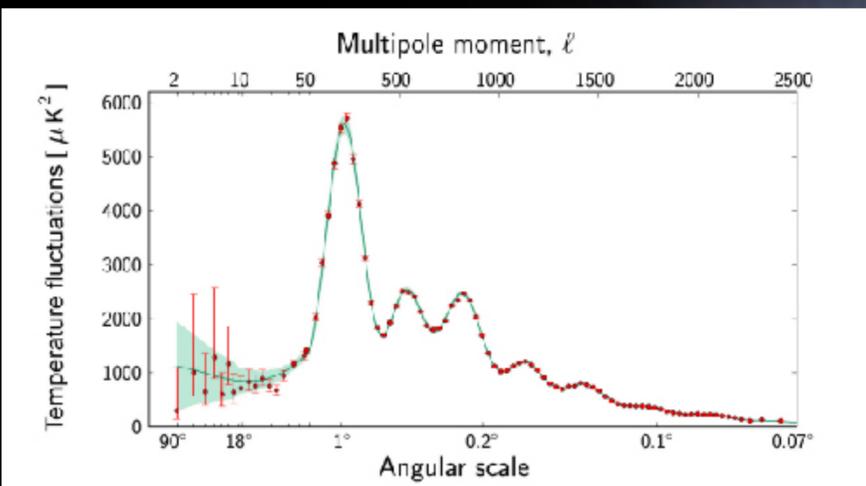


Expansion
in years

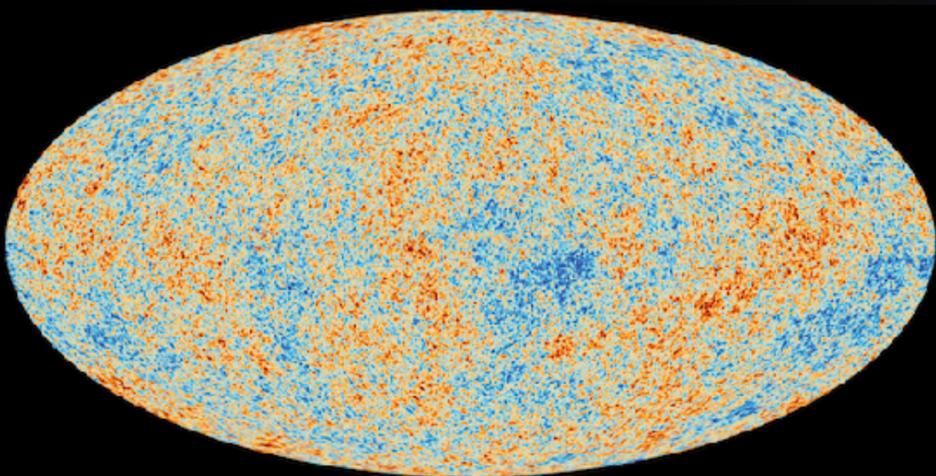


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Afterglow Light
Pattern
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Fluctuations
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Dark Ages

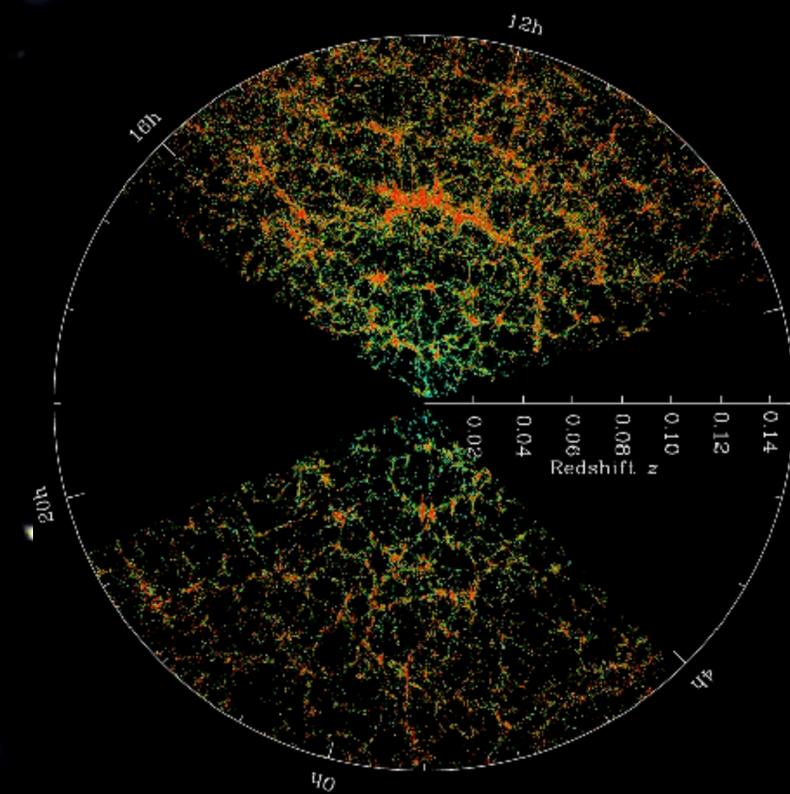
Development of
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Dark Energy
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?

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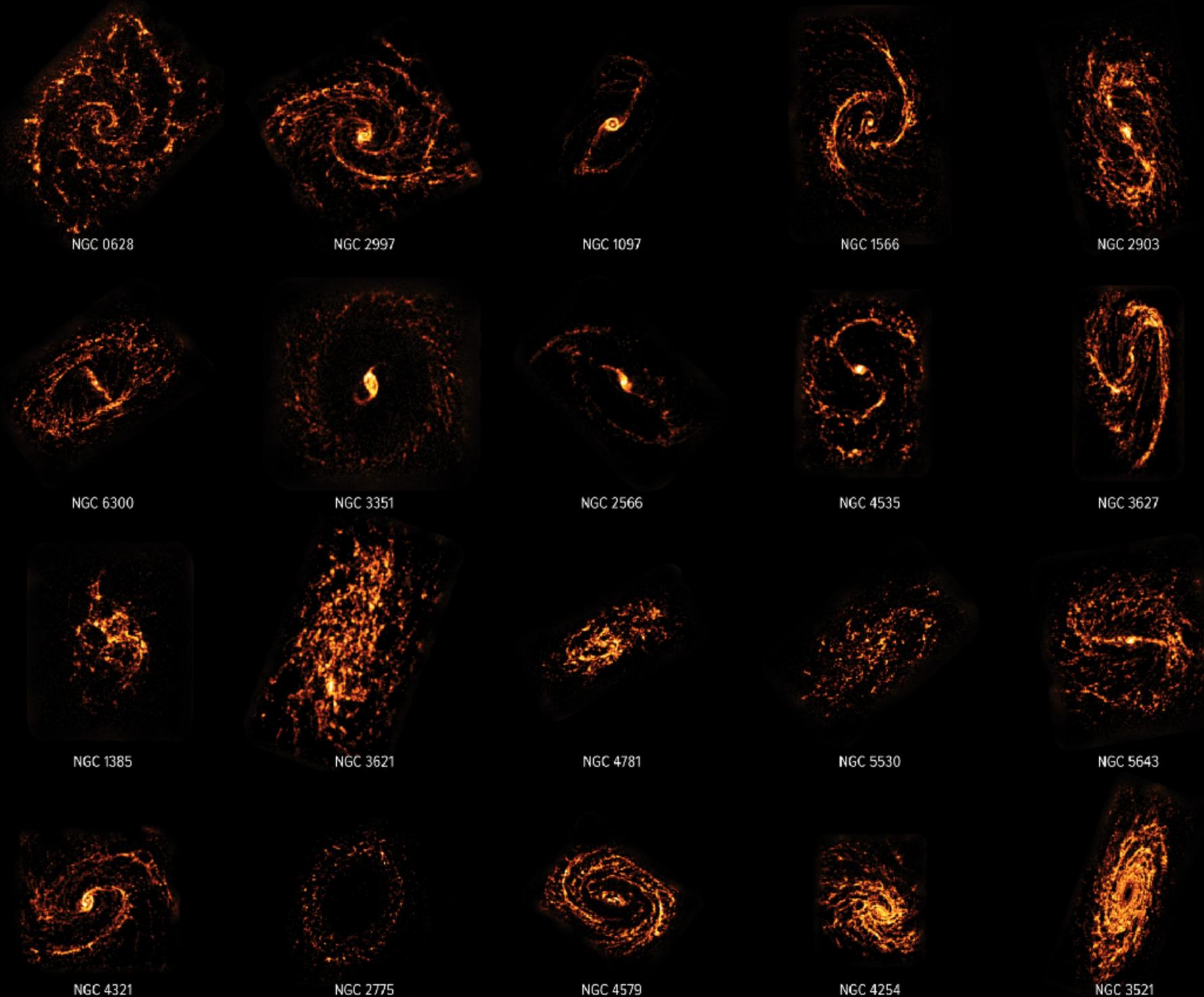
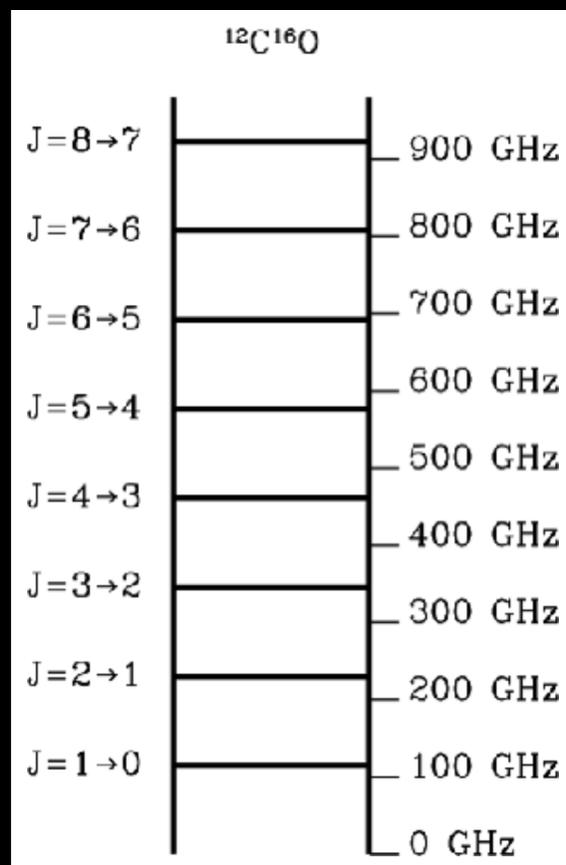
Big Bang Expansion
13.7 billion years



Galaxy surveys
 $z = 0-1+$

Carbon Monoxide (CO)

- Tracer of cold molecular gas, the fuel for star formation.
- The second most abundant molecule in the gas phase.
- Line emissions at multiples of ~115 GHz.



Credit: ALMA (ESO/NAOJ/NRAO)/PHANGS, S. Dagnello (NRAO)

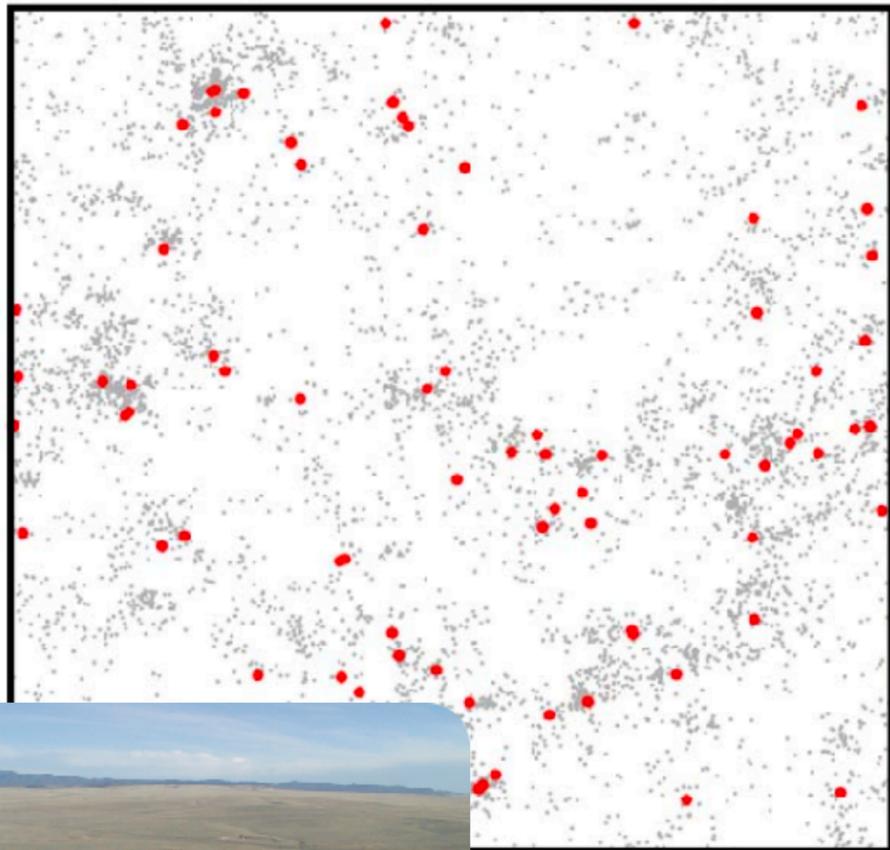
Line Intensity Mapping (LIM, ‘선 세기 매핑’)

- LIM is sensitive to the “aggregate line emission from all galaxies in the line of sight”.

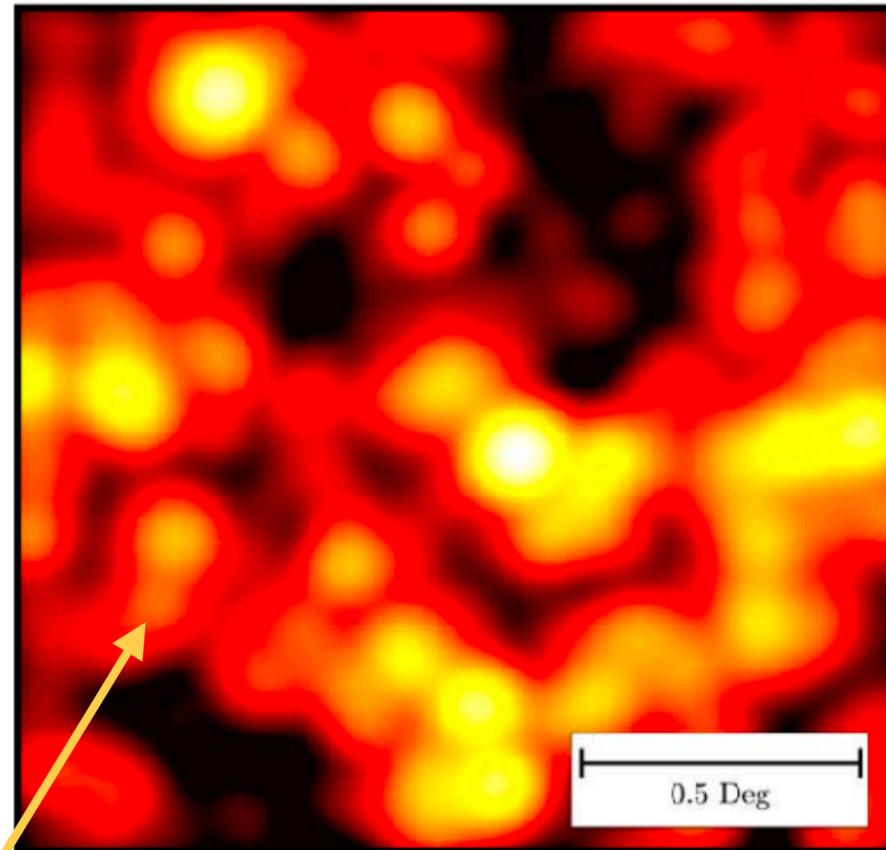
CO(1-0) at $z \sim 3$

(convolved with ~ 5 arcmin beam)

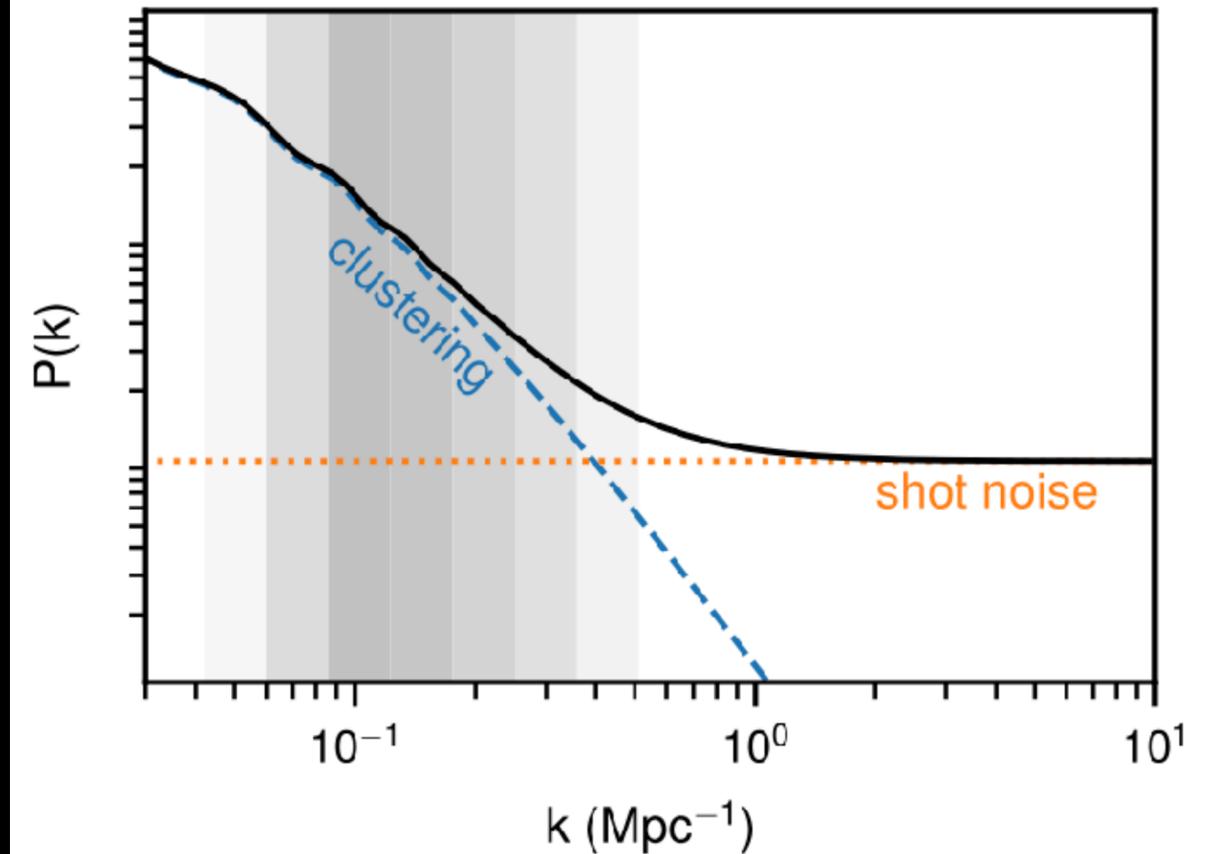
CO Galaxies



CO Intensity Map



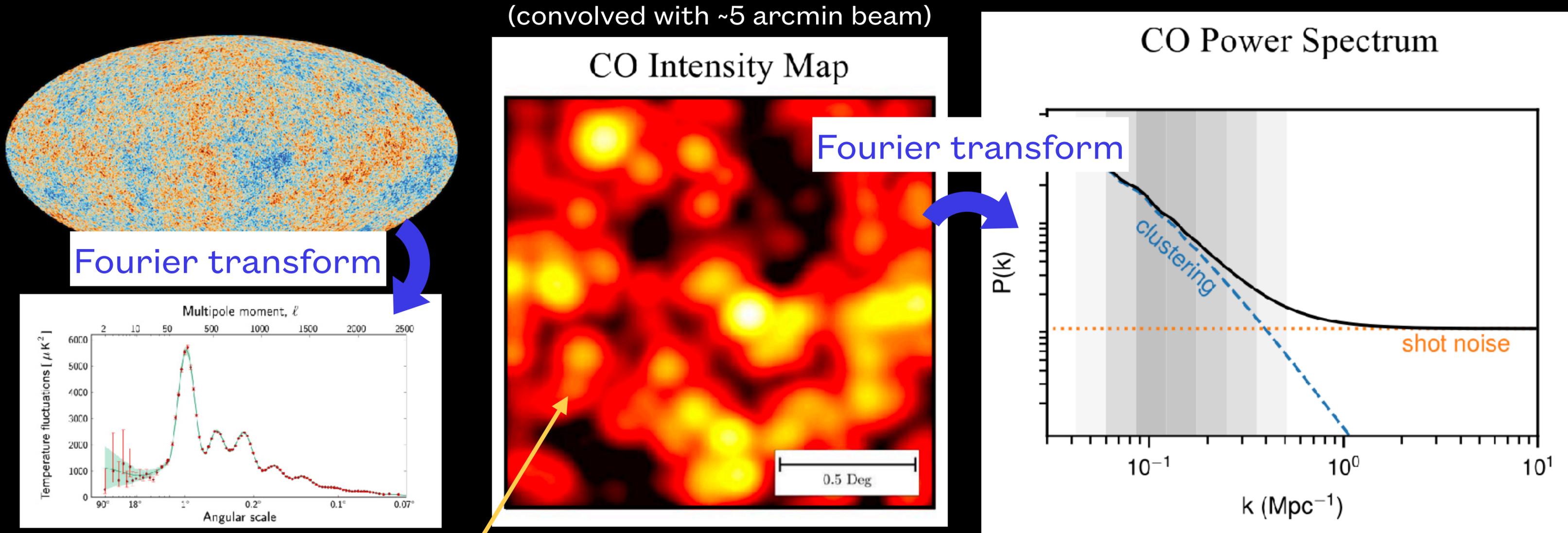
CO Power Spectrum



all of the photons!

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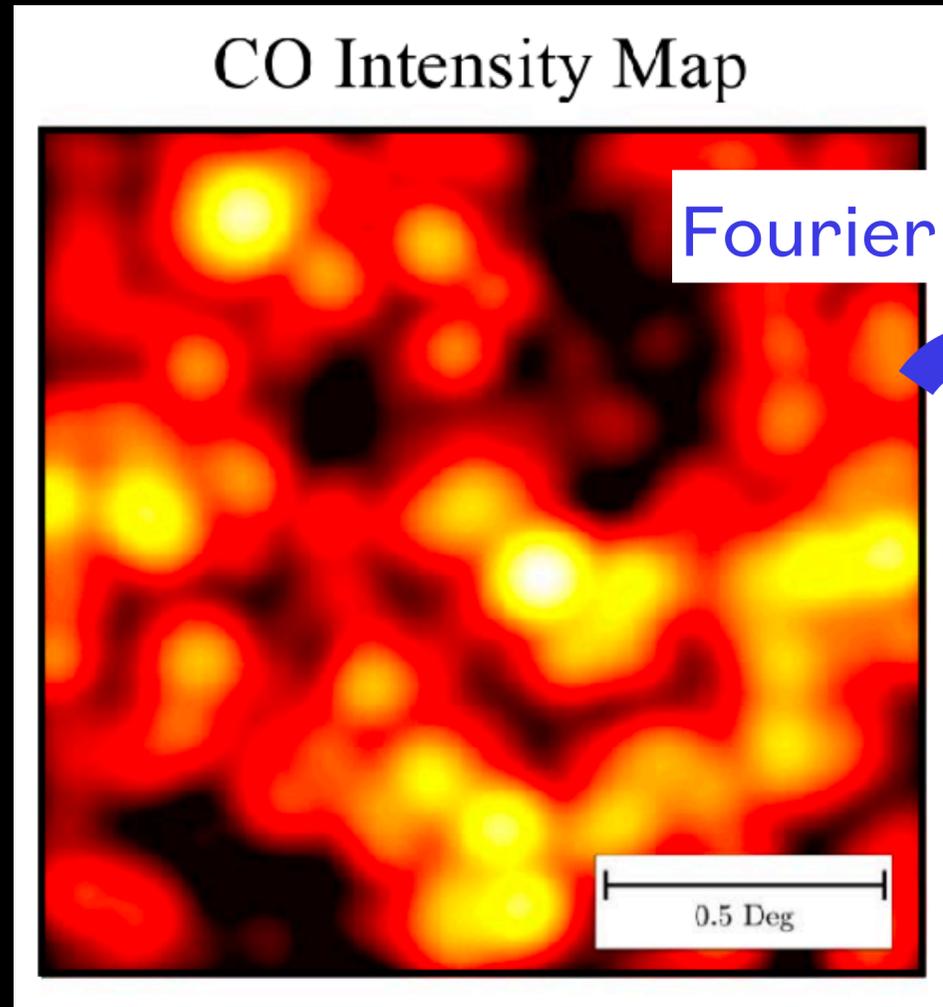


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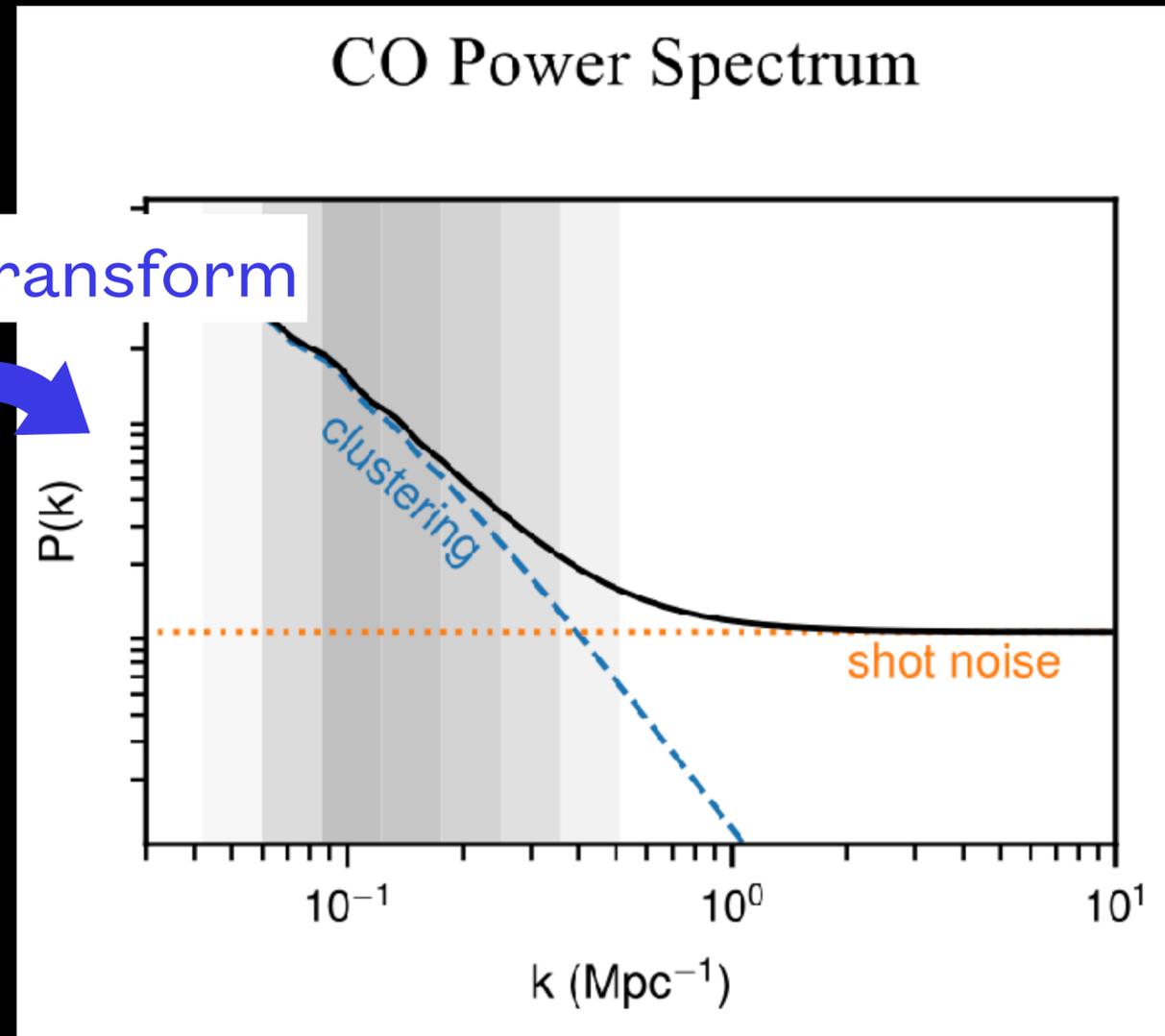
Line Intensity Mapping (LIM, ‘선 세기 매핑’)

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(convolved with ~5 arcmin beam)



Fourier transform



Clustering amplitude \times
(Underlying matter
power spectrum)

=

+

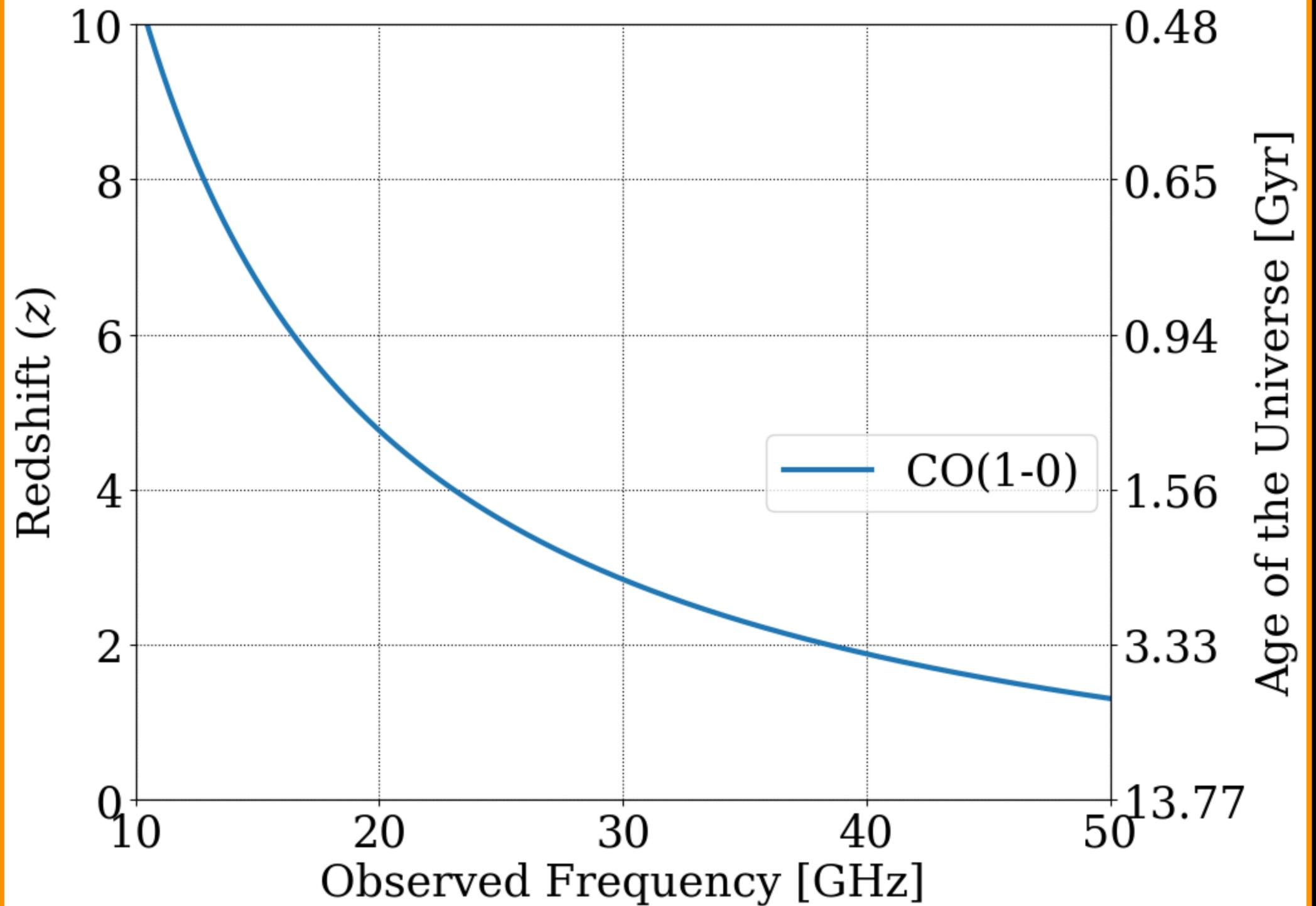
shot noise

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

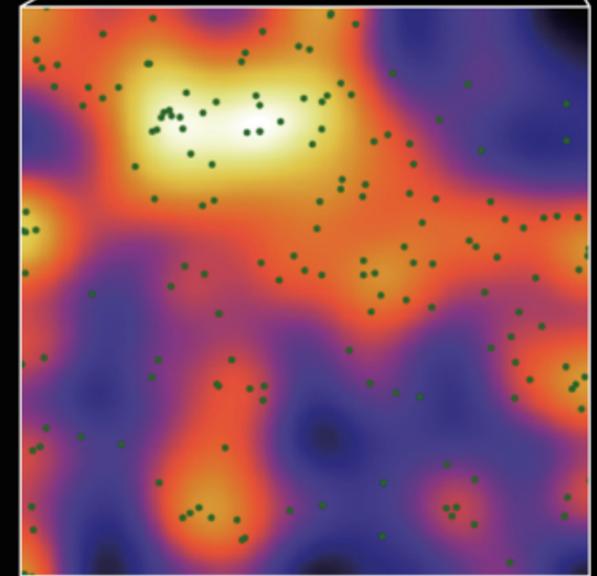
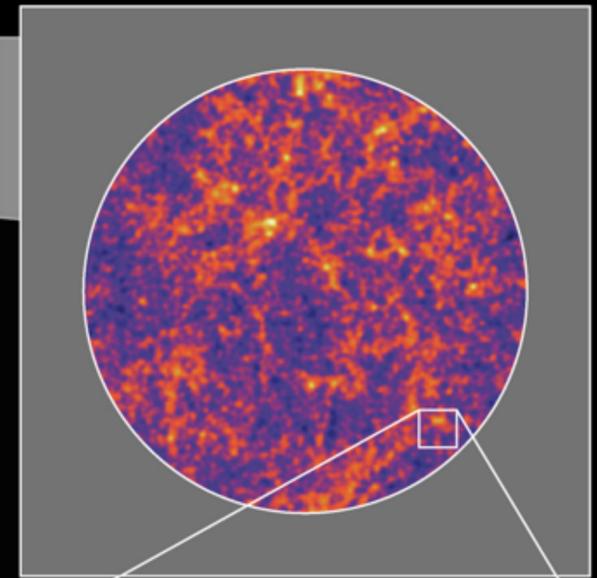
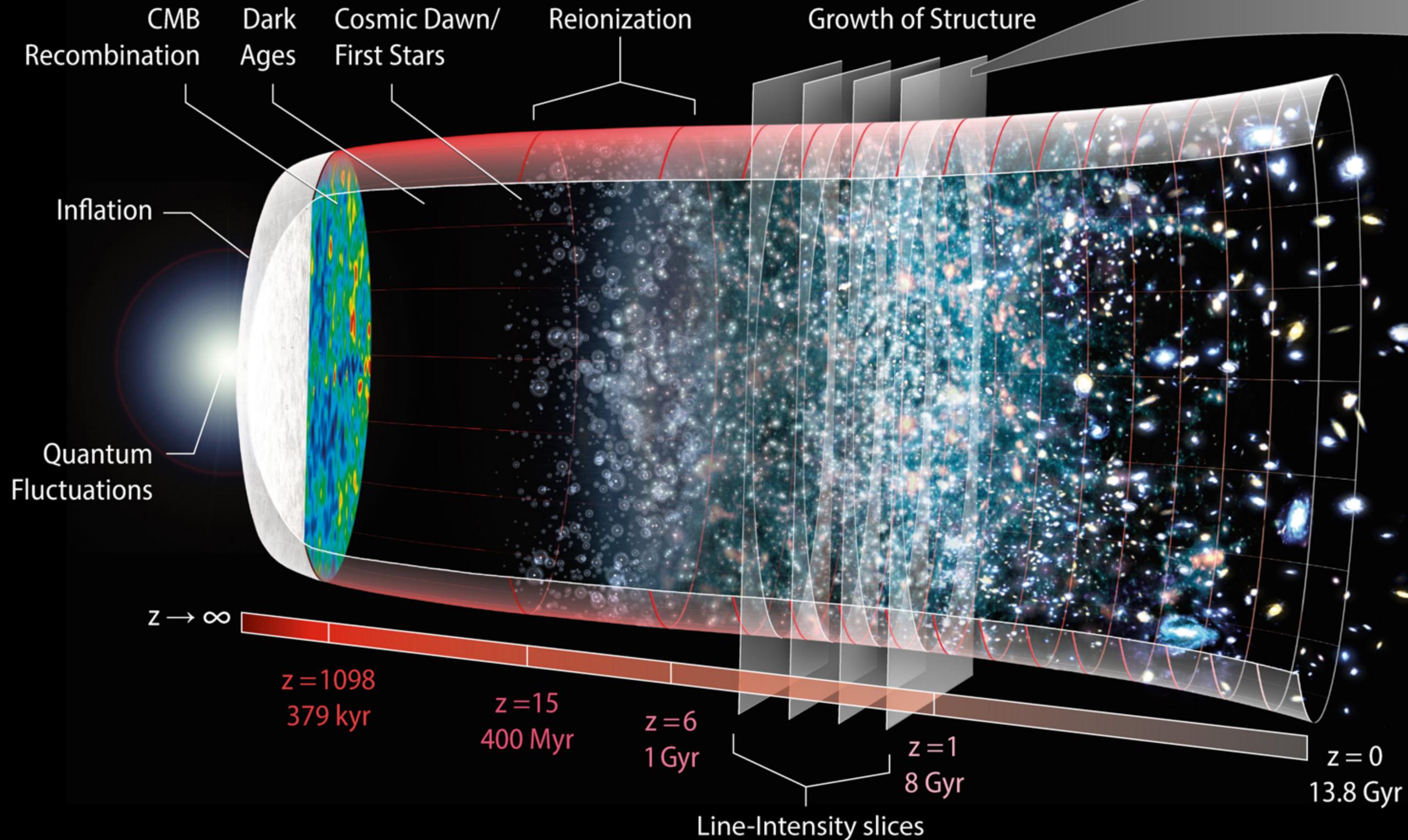
- **Cosmological Redshift:** The observed frequency of a specific spectral line corresponds to the redshift, which in turn indicates the age of the Universe!

CO(1-0): 115.27 GHz
(2.6 mm)

$$\nu_{\text{obs}} = 115.27 \text{ GHz} / (1 + z)$$

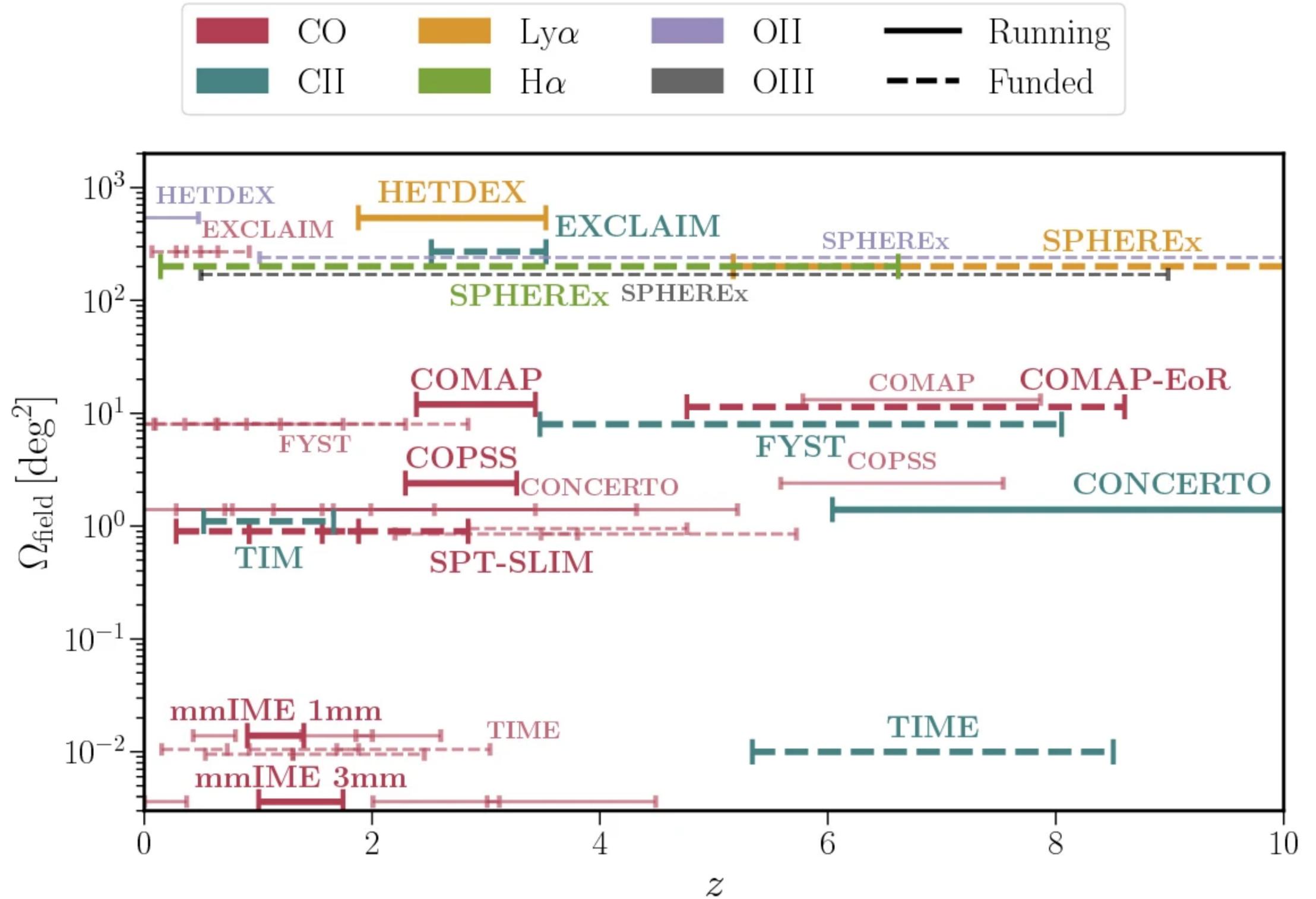


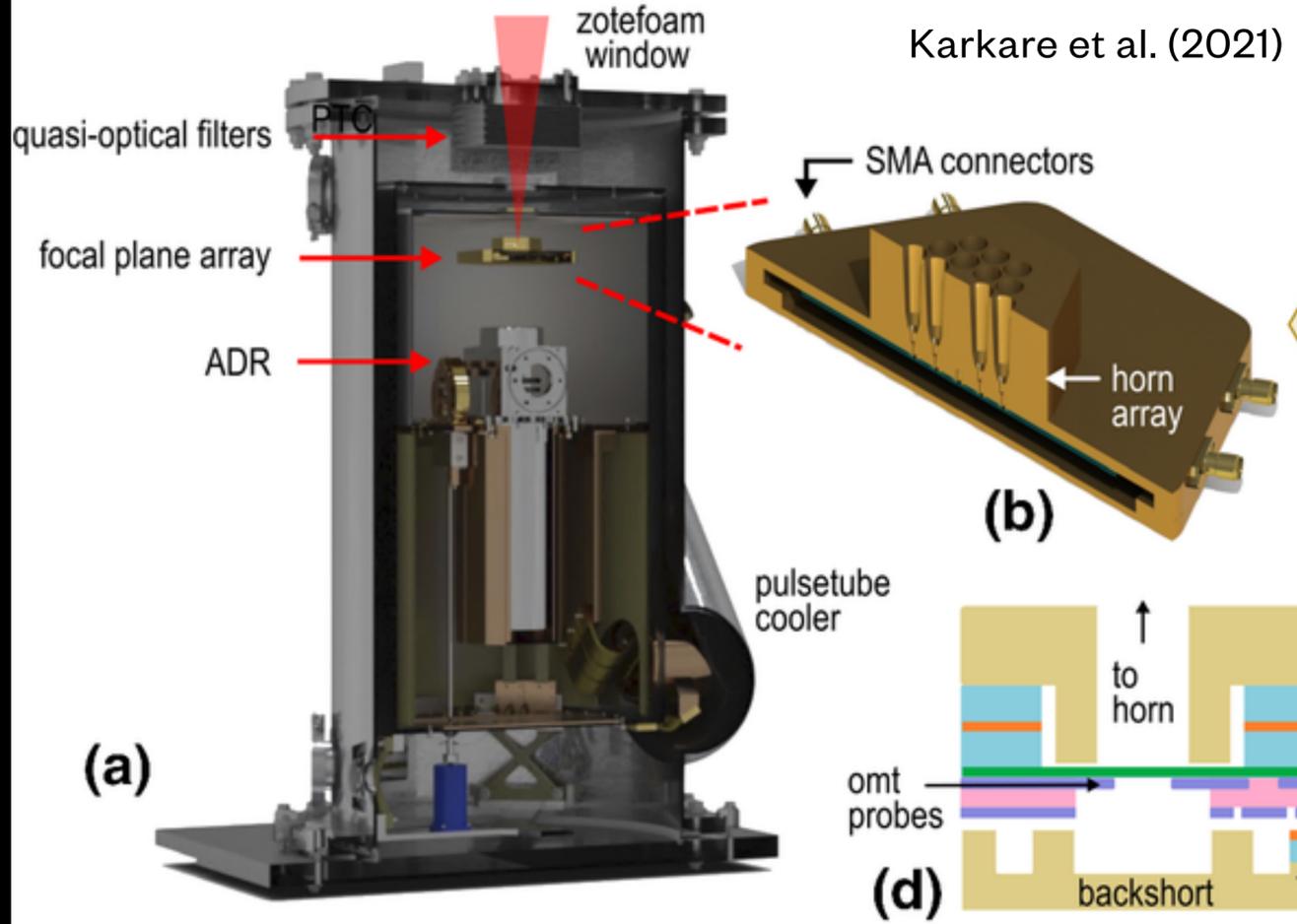
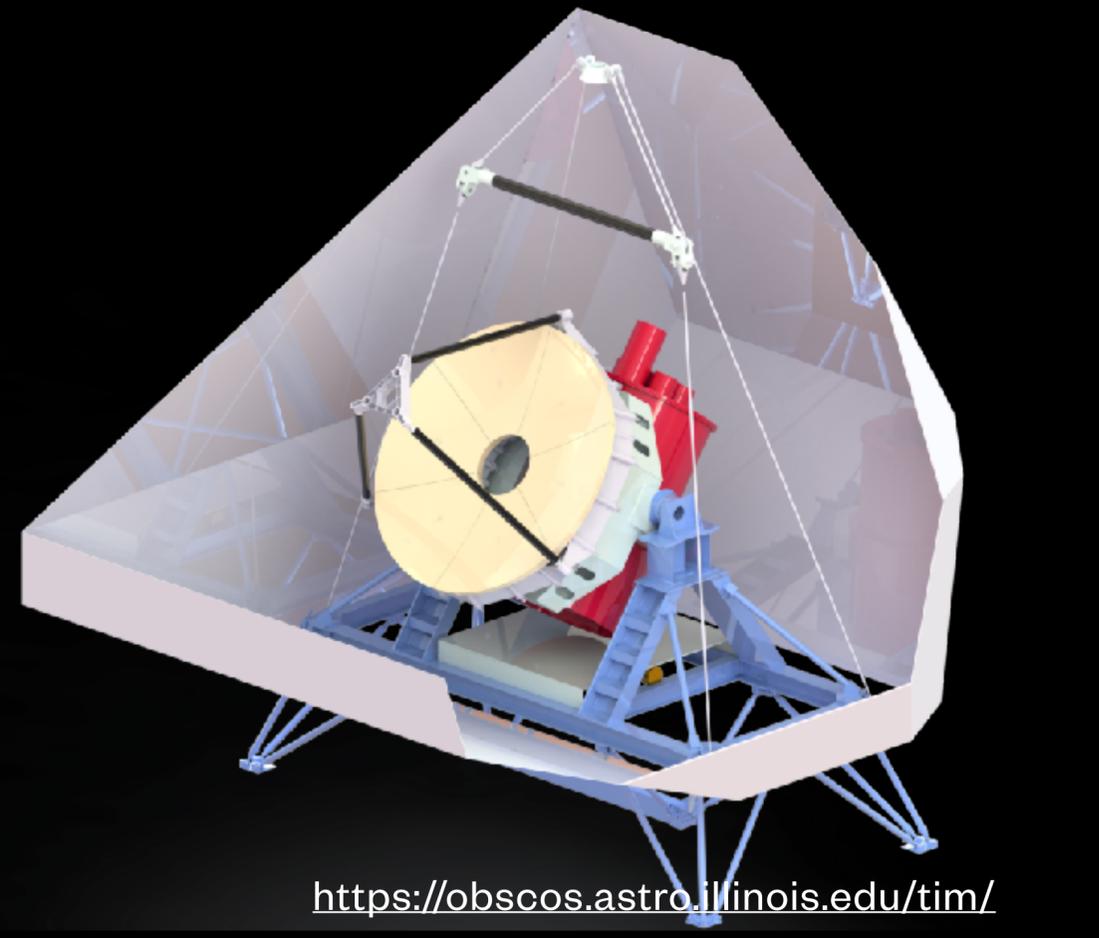
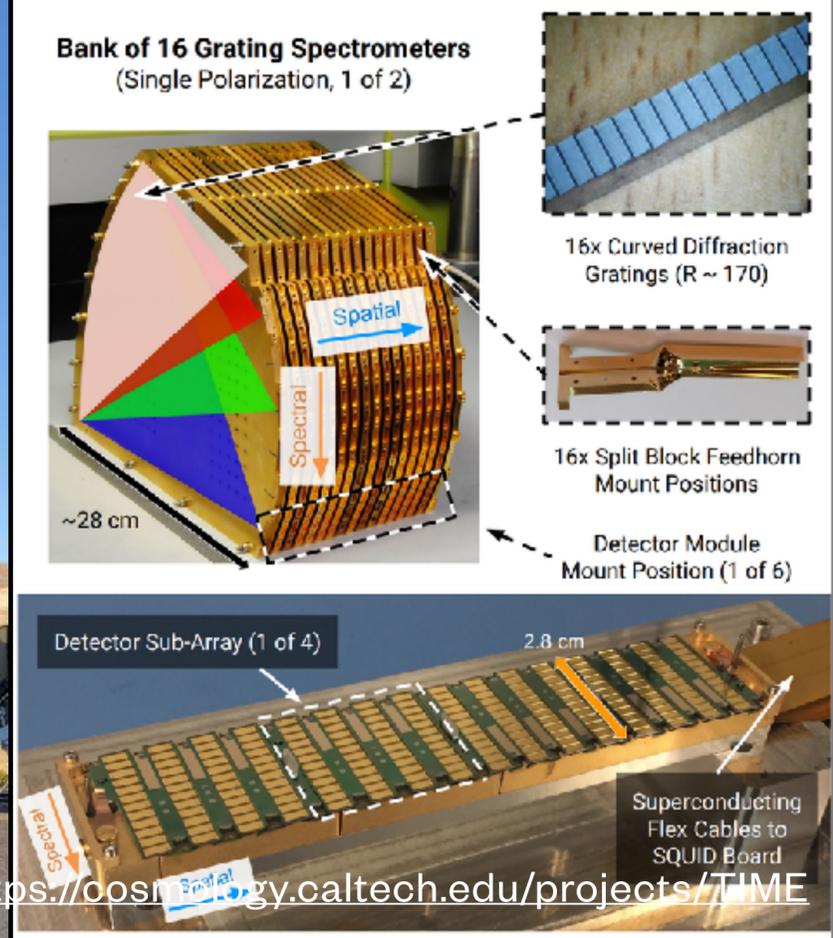
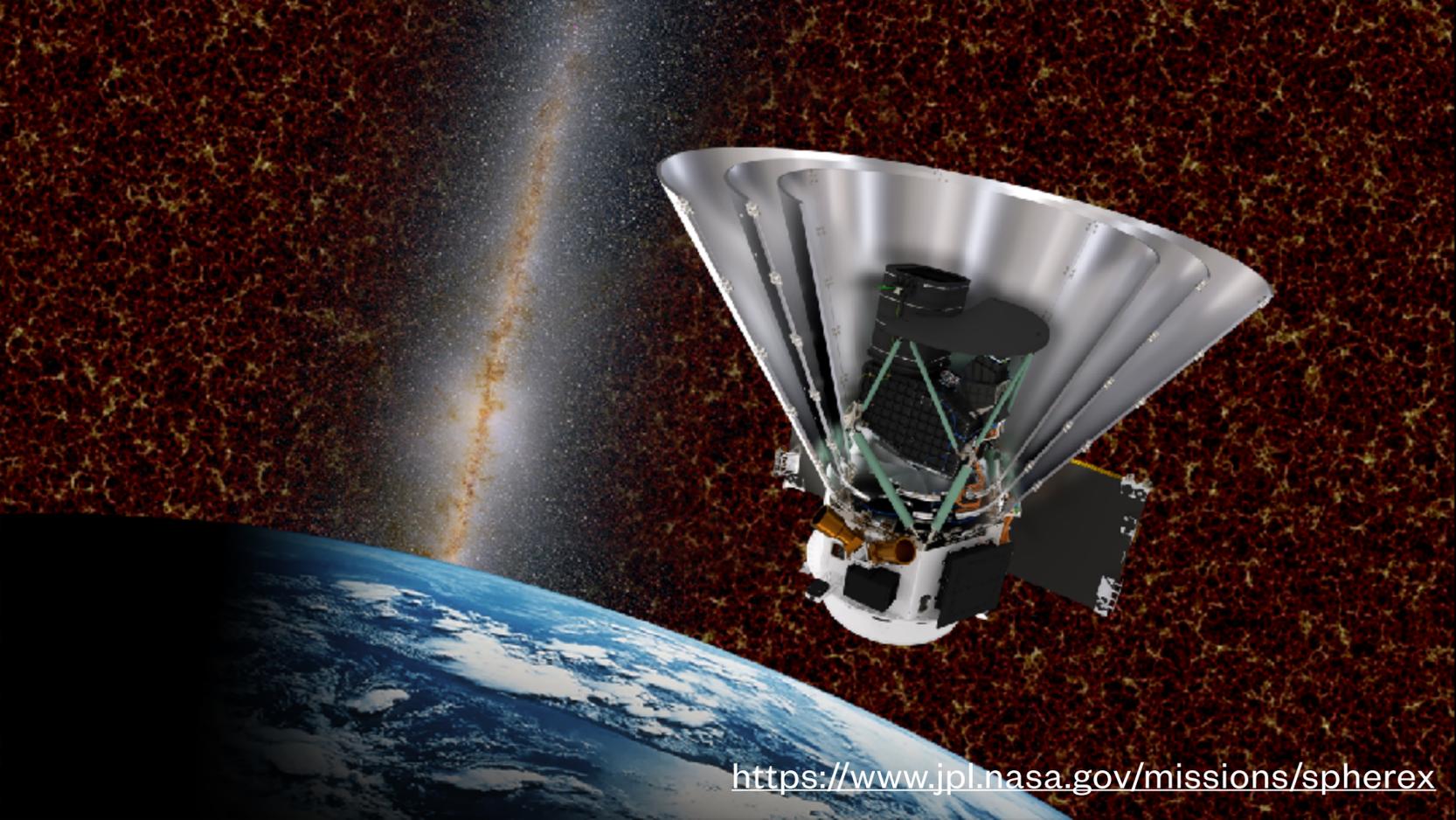
Line Intensity Mapping (LIM)



Line-Intensity Mapping simulation with galaxy distributions

- Sub-mm: Rotational carbon-monoxide (CO) transitions
 - Far-IR: Bright fine-structure lines such as [CII]
 - Optical/UV: Hydrogen H α and Ly α lines
- +
- Radio: HI 21 cm line originating from the neutral hydrogen





CO Mapping Array Project (COMAP)

Caltech

Kieran Cleary (PI)
Delaney Dunne
Rick Hobbs
James Lamb
Timothy Pearson
Anthony Readhead
David Woody

UiO : Universitetet i Oslo

Ingunn Wehus
Hans Kristian Eriksen
Jonas Lunde
Nils-Ole Stutzer

SMU

Patrick Breysse



Cornell University

Dongwoo Chung

MANCHESTER
1824
The University of Manchester

Clive Dickinson
Stuart Harper

KAIST

Junhan Kim



THE UNIVERSITY
OF BRITISH COLUMBIA

Thomas Rennie



UNIVERSITÉ
DE GENÈVE

Hamsa Padmanabhan



Richard Bond
Norman Murray
Doğa Tolgay

U UNIVERSITY
OF MIAMI

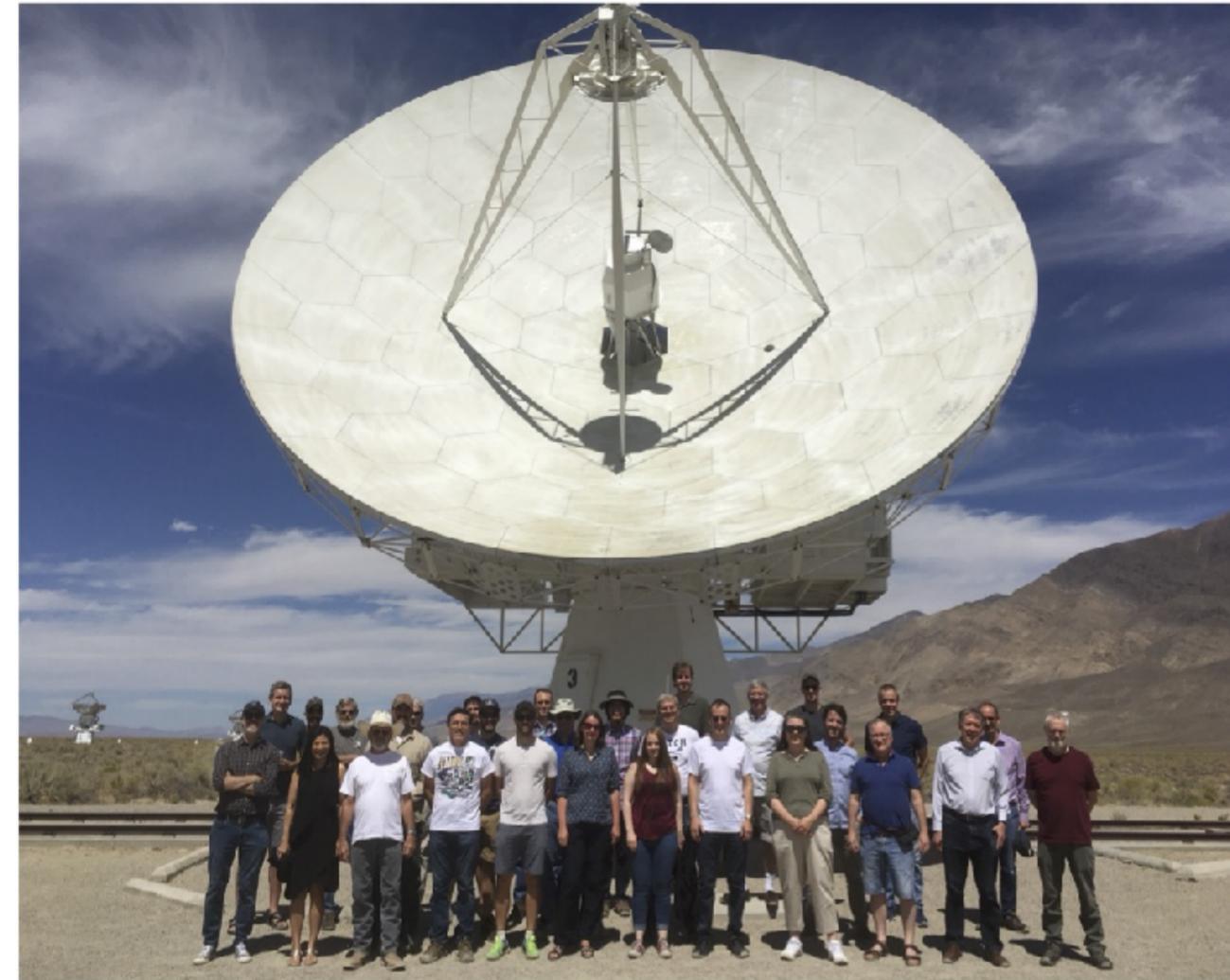
Joshua Gundersen

**UNIVERSITY OF
MARYLAND**

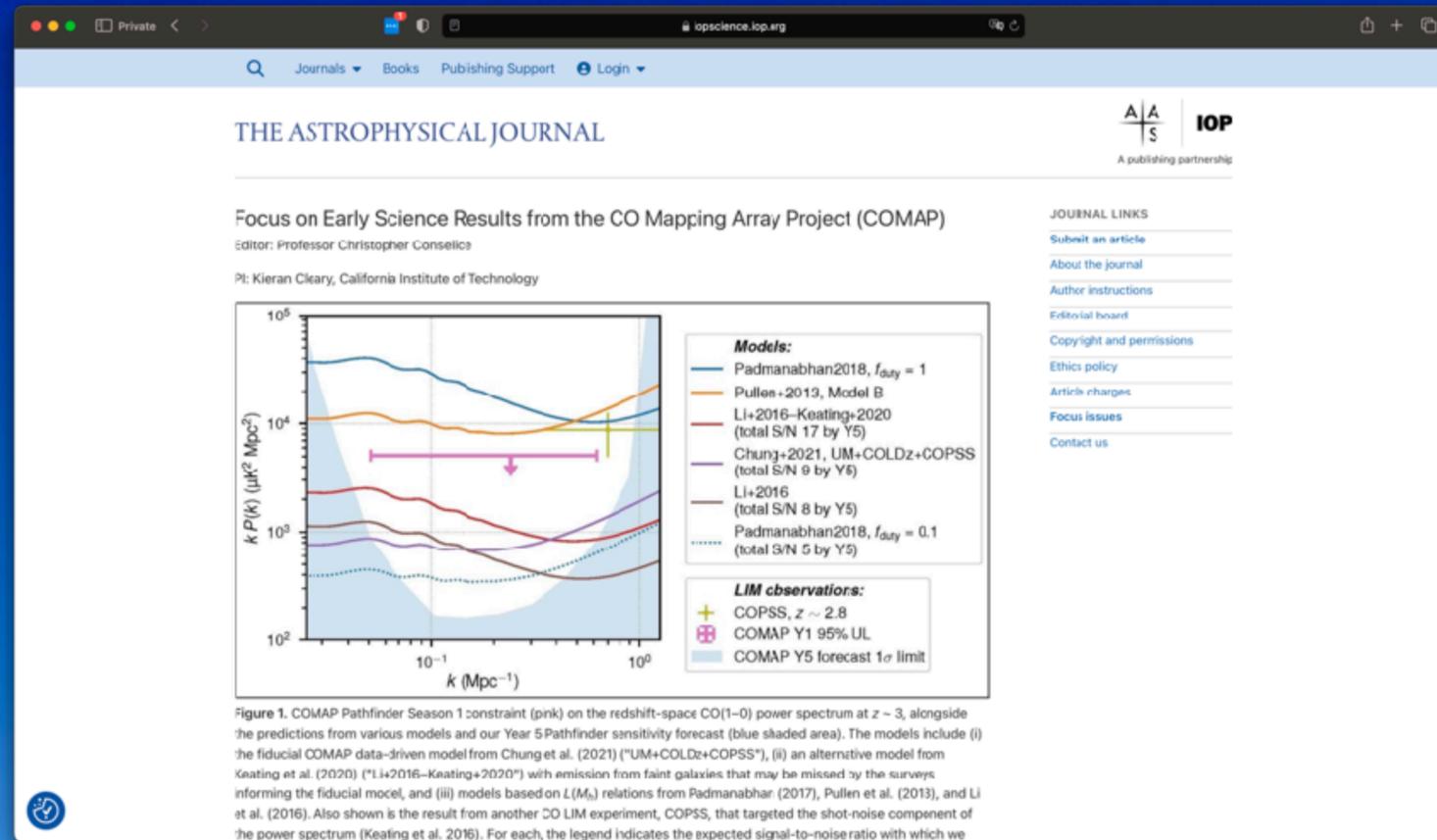
Andrew Harris

JPL
Jet Propulsion Laboratory
California Institute of Technology

Charles Lawrence
Todd Gaier
Brandon Hensley
Joseph Lazio



COMAP Early Science Results

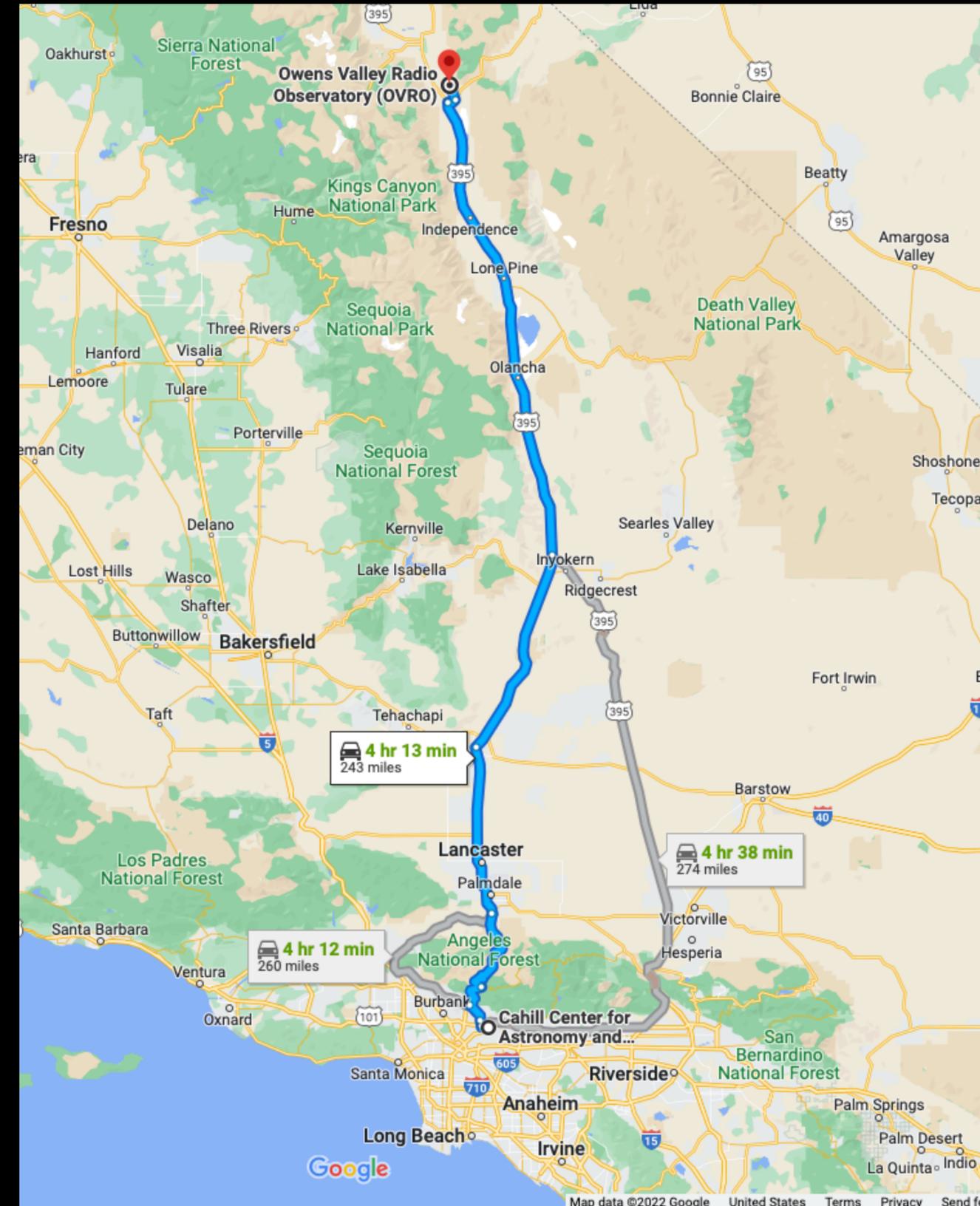


COMAP
Pathfinder



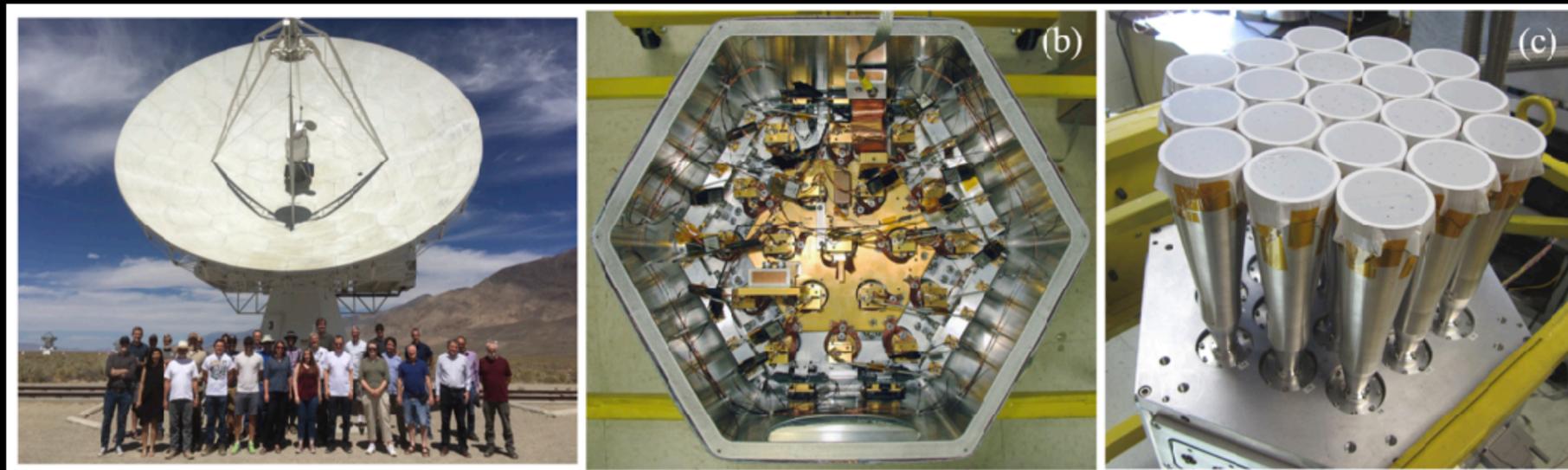
COMAP Pathfinder

- Site: Owens Valley Radio Observatory (OVRO), CA
- Telescope: “Leighton” dish (10.4 m)
- Receiver: **26-34 GHz ($z=2.4-3.4$)**
 - 19-pixel, single-polarization focal plane array
 - High electron mobility transistor (HEMT) amps
- Backend digitization
 - 38 ROACH2 spectrometers, 2 MHz resolution



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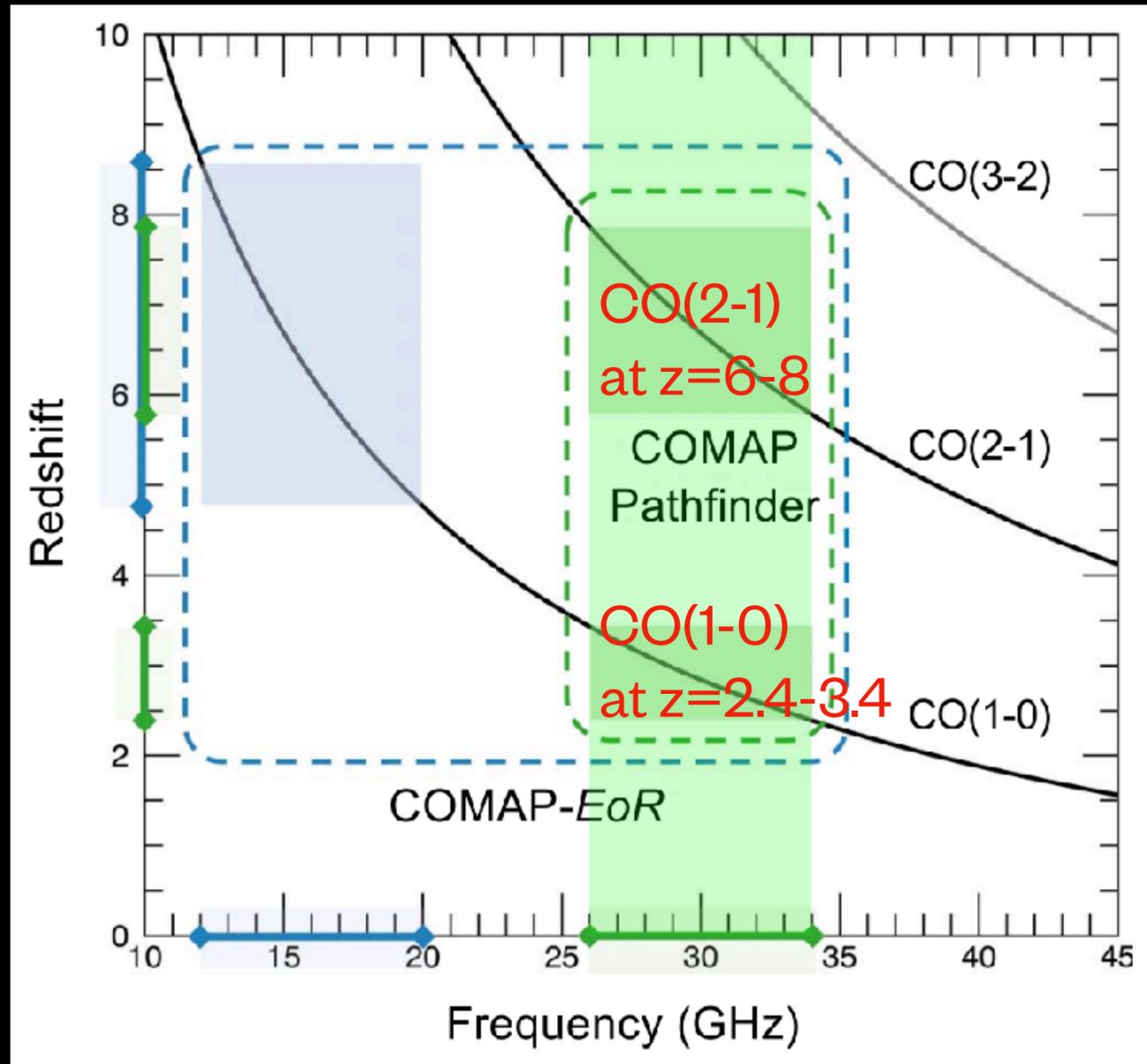
Cleary et al. (2022), Lamb et al. (2022)



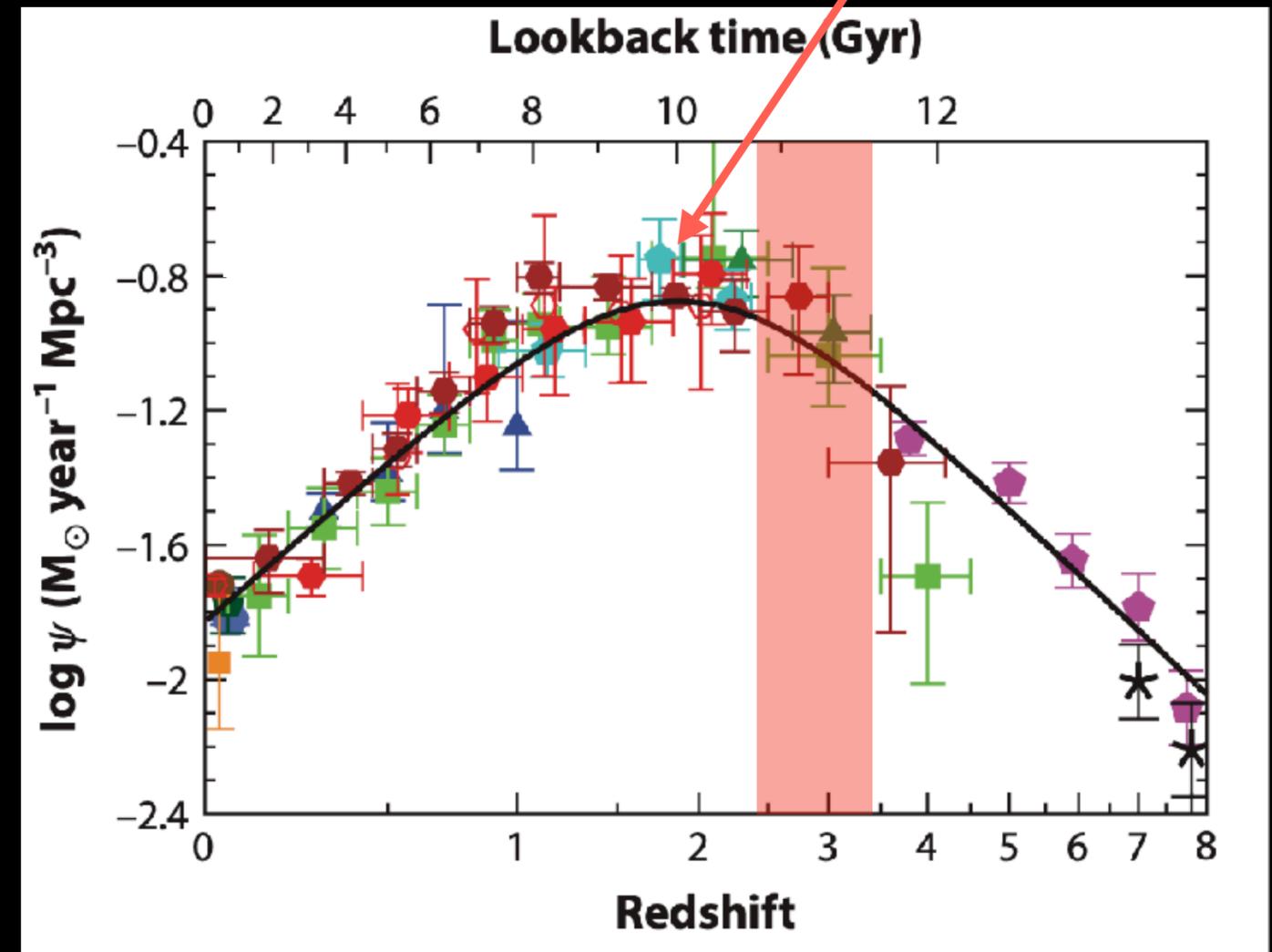
COMAP Pathfinder

- CO probes cold molecular gas, the fuel for star formation.

Peak of the
Star-formation History

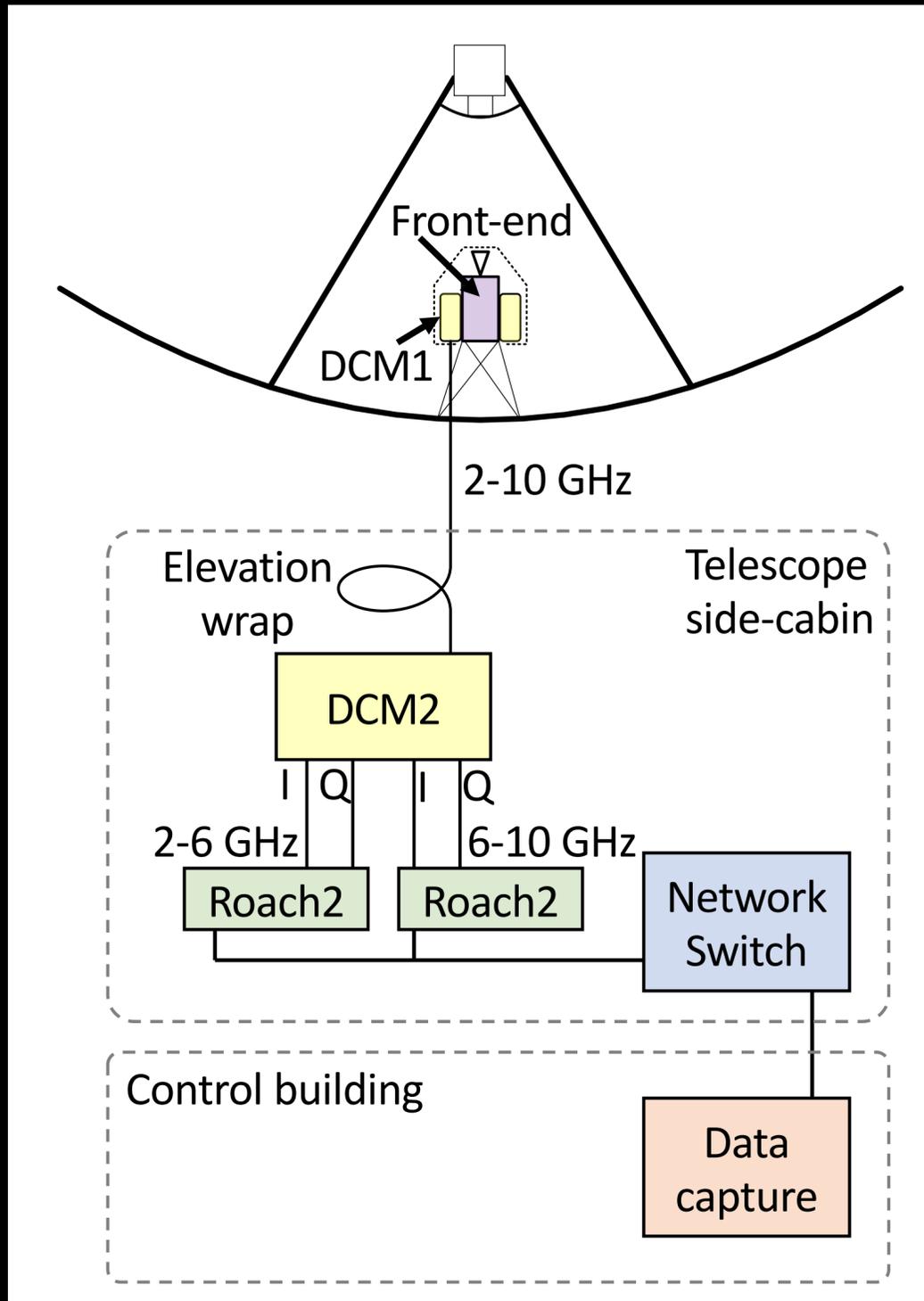


Cleary et al. (2022)

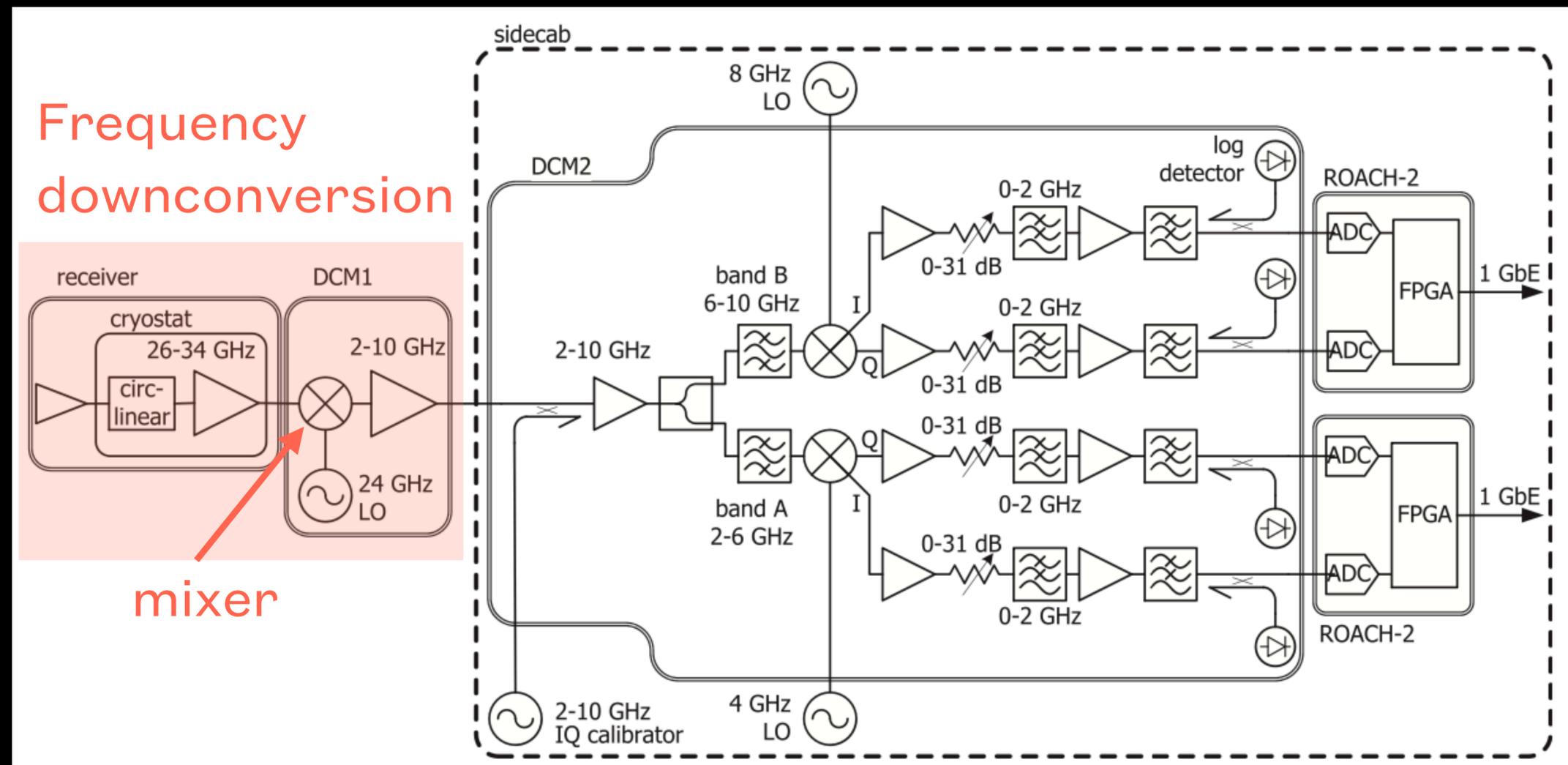
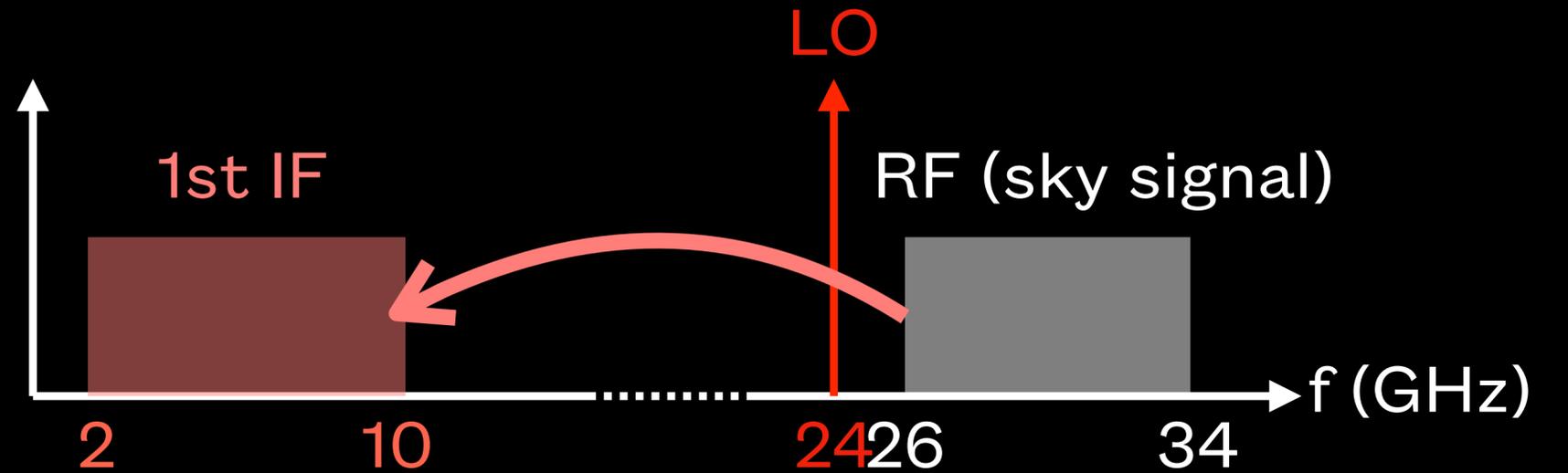


Madau & Dickinson (2014)

COMAP Pathfinder: Instrument



Lamb et al. (2022)

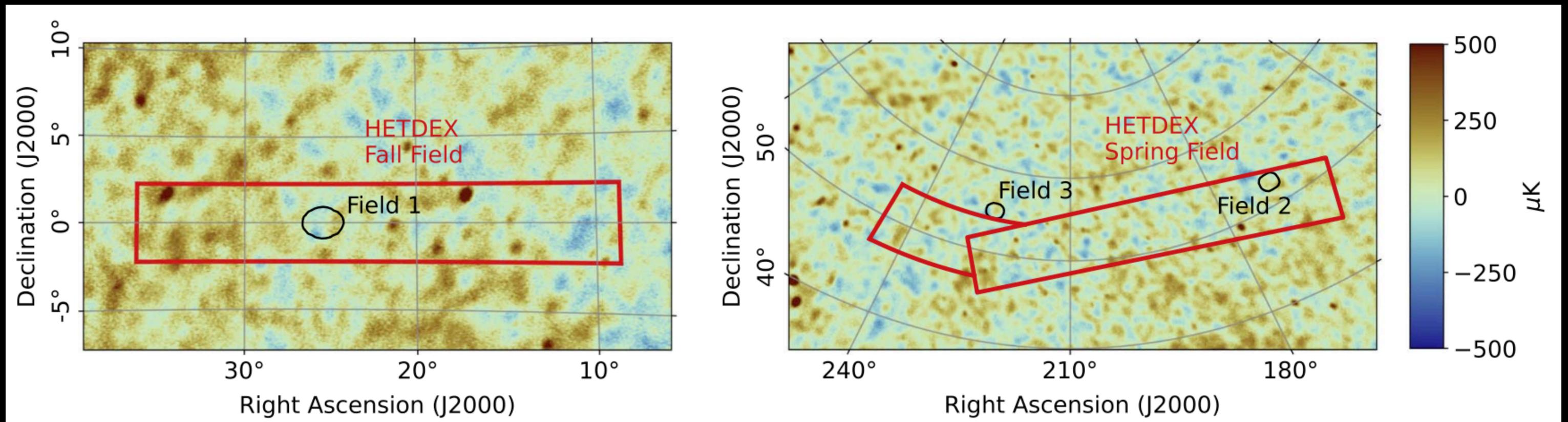


Frequency
downconversion

mixer

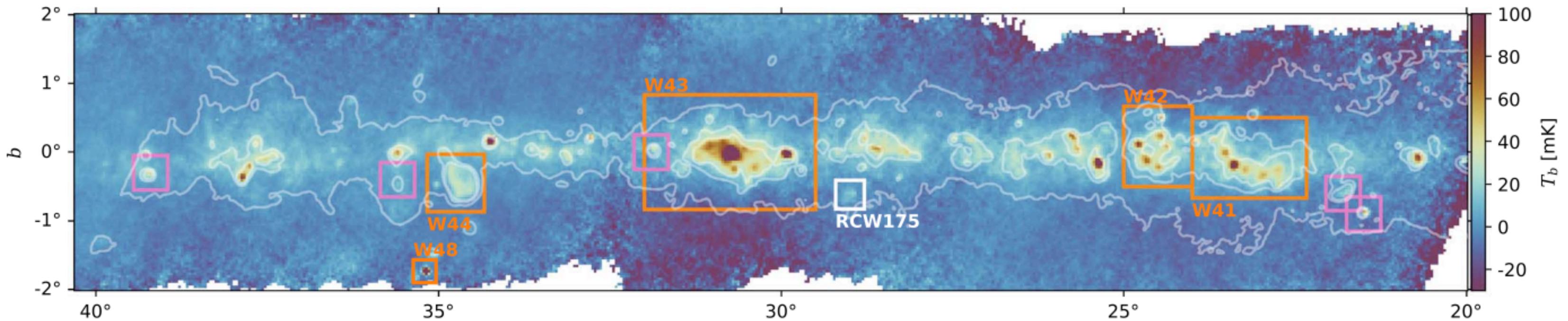
COMAP Pathfinder: Observation

- 5-year observing campaign (started 2019)
- Three observing fields (~4 deg²)
 - Distributed in R. A. to maximize observing efficiency
 - Overlap with Hobby-Eberly Telescope Dark Energy Experiment (HETDEX; Gebhardt et al. 2021, Hill et al. 2021)



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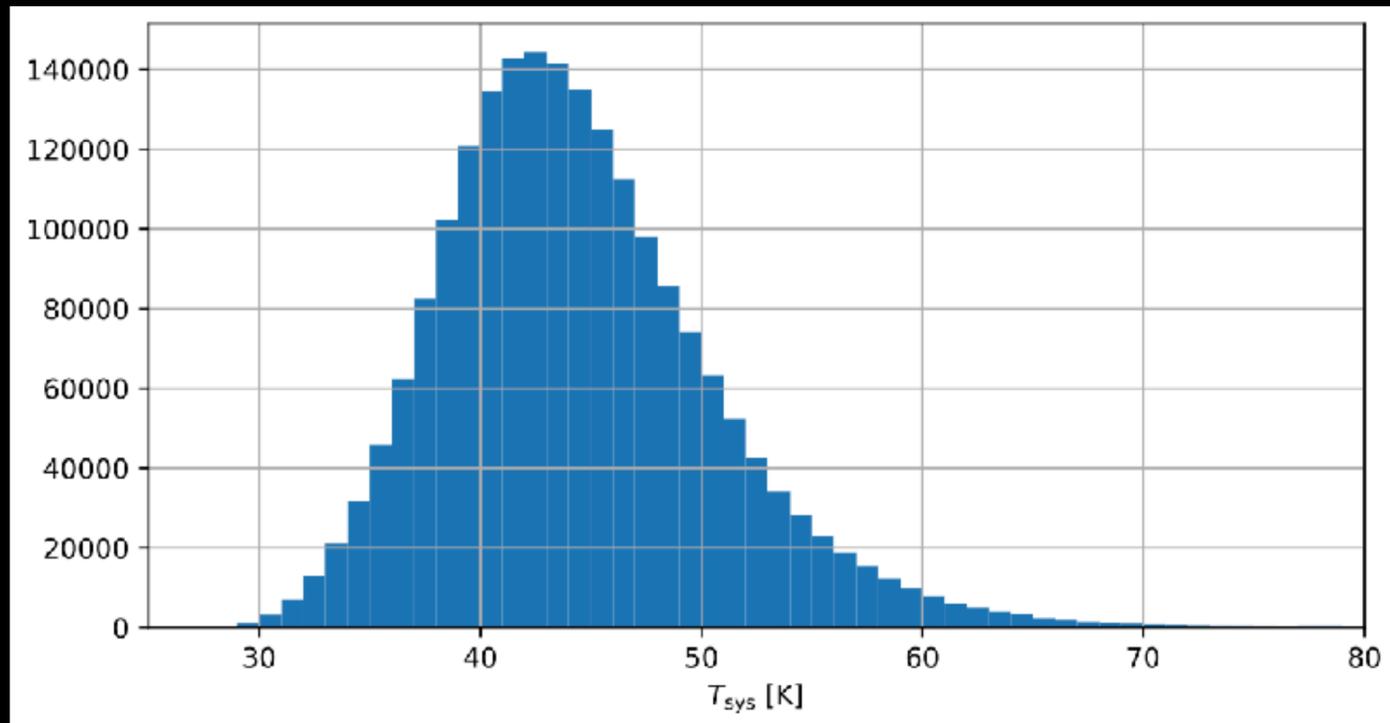


COMAP Pathfinder: Calibration

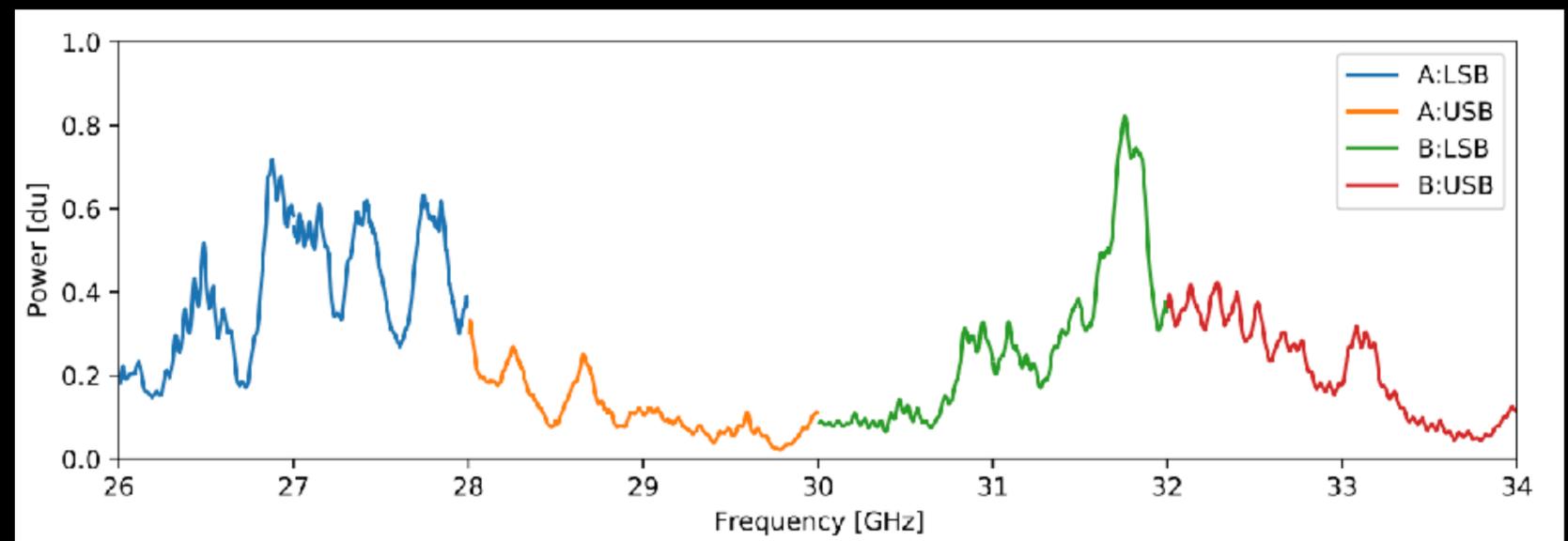
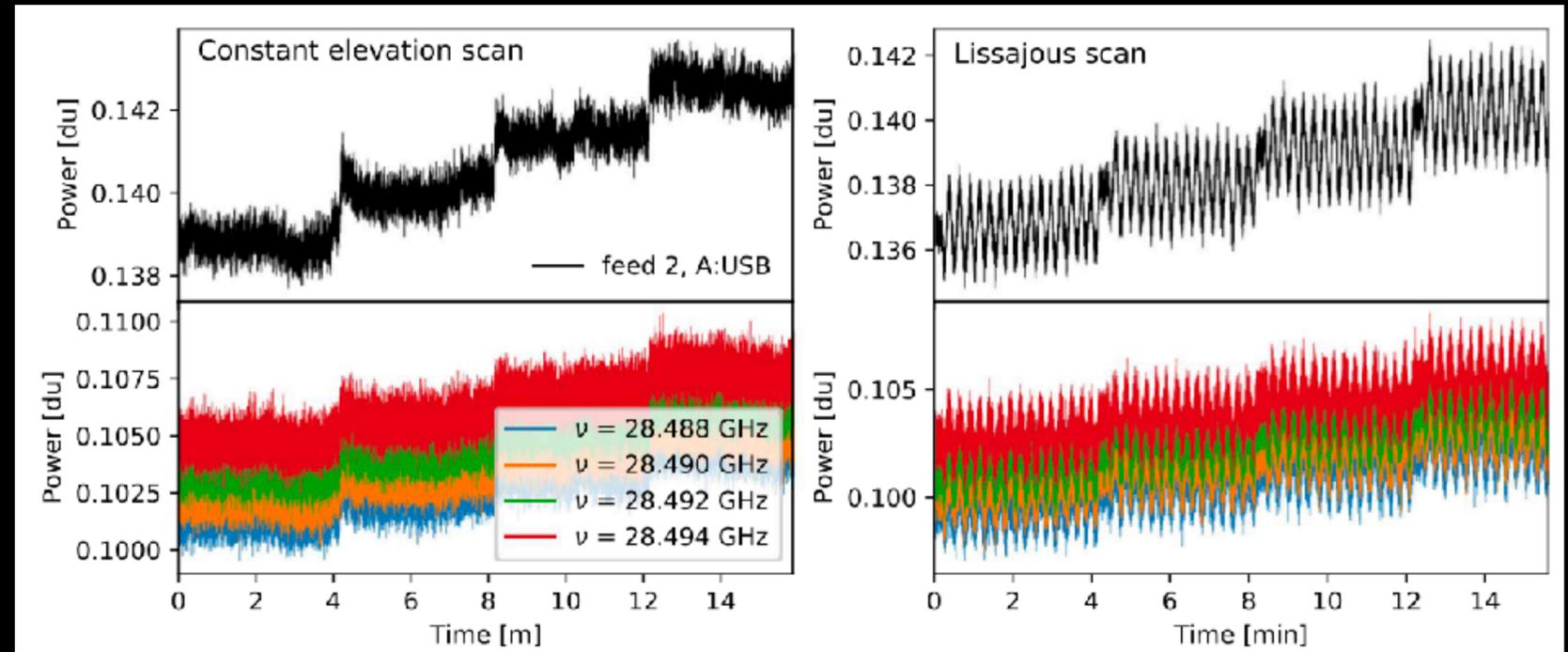
$$T_{\text{sys}} = T_{\text{receiver}} + T_{\text{atmosphere}} + T_{\text{ground}} + T_{\text{CMB}} + T_{\text{foregrounds}} + T_{\text{CO}}$$

(~10-30 K) (~15-25 K) (~5-6 K) (2.7K) (~1 mK) $\mathcal{O}(1 \mu\text{K})$

Radiometer Equation: $\sigma_T = \frac{T_{\text{sys}}}{\sqrt{\Delta\nu T}}$



Foss et al. (2022)



normalization

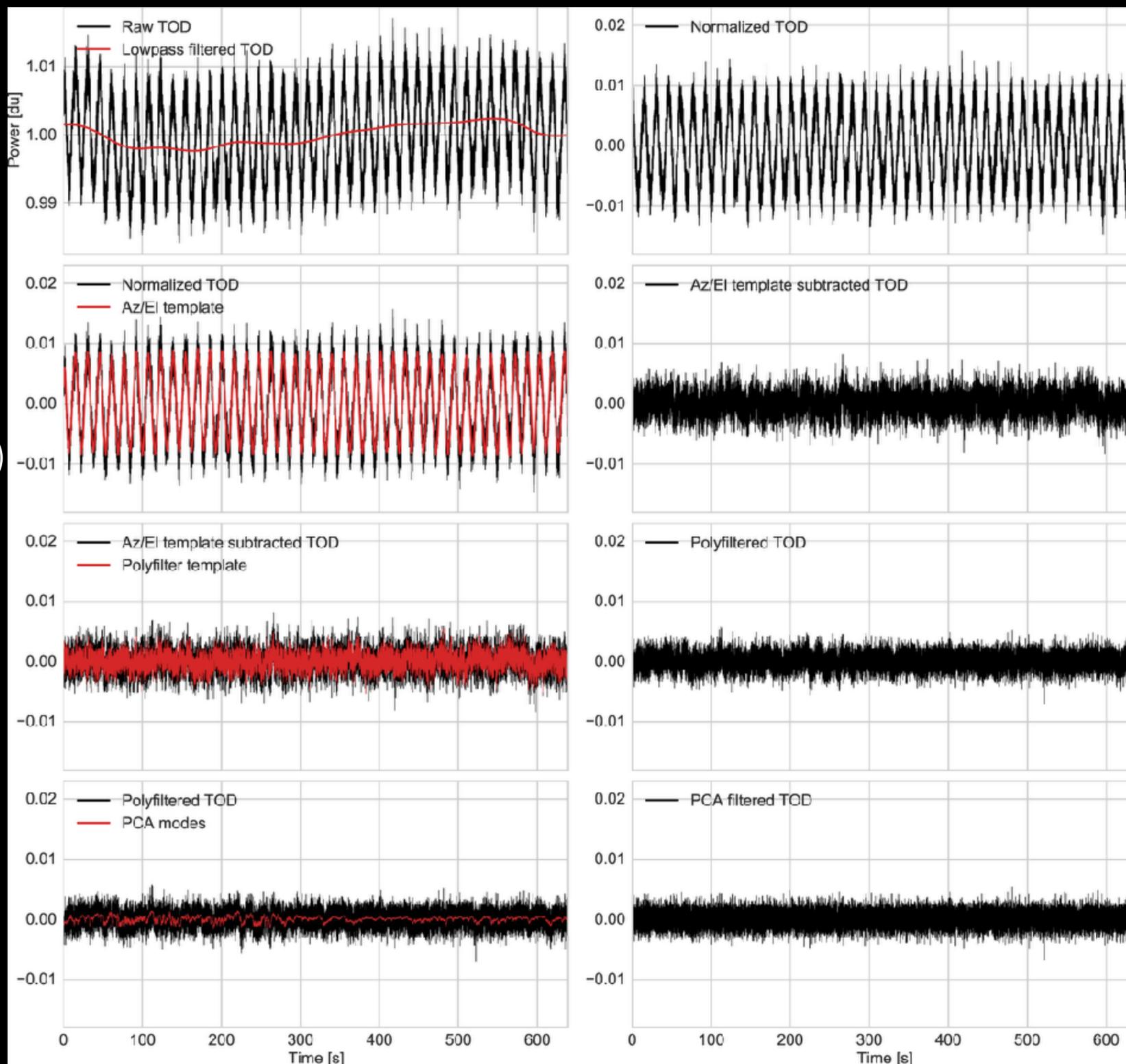
atmospheric
template

$$\tau(e_l) = \tau_0 / \sin(e_l)$$

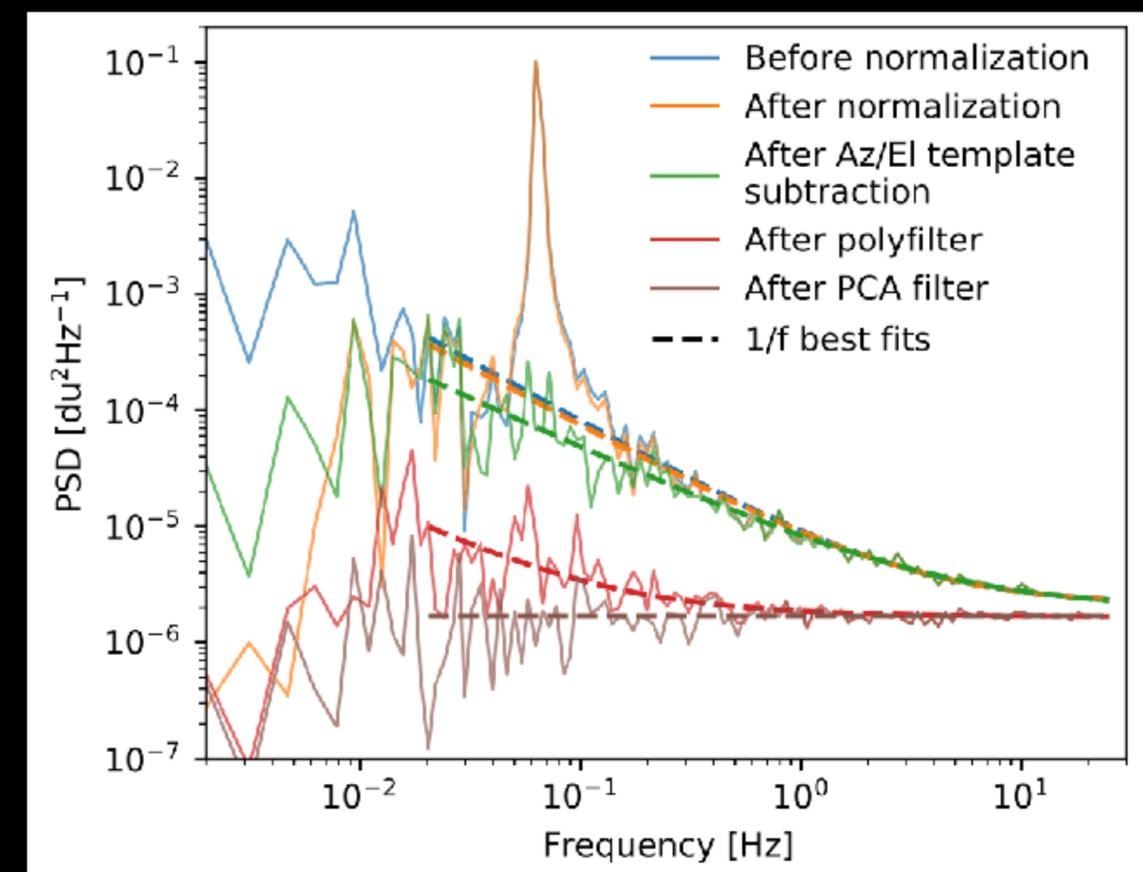
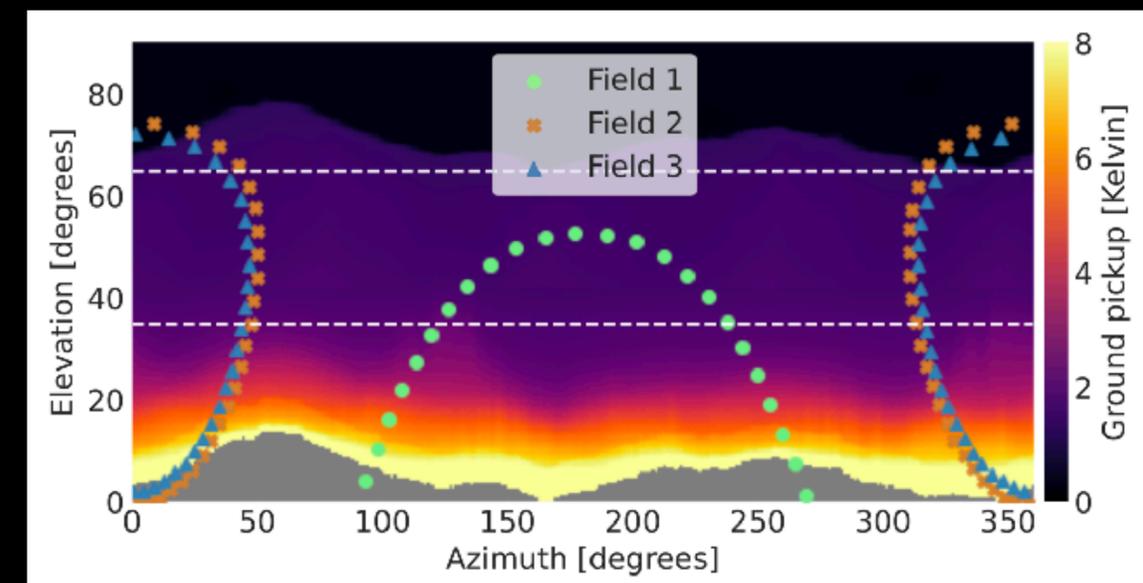
low-order
polynomial

$$d_\nu = c_0 + c_1\nu + c_2\nu^2 + \dots$$

PCA filter



Foss et al. (2022)



Cleary et al. (2022)

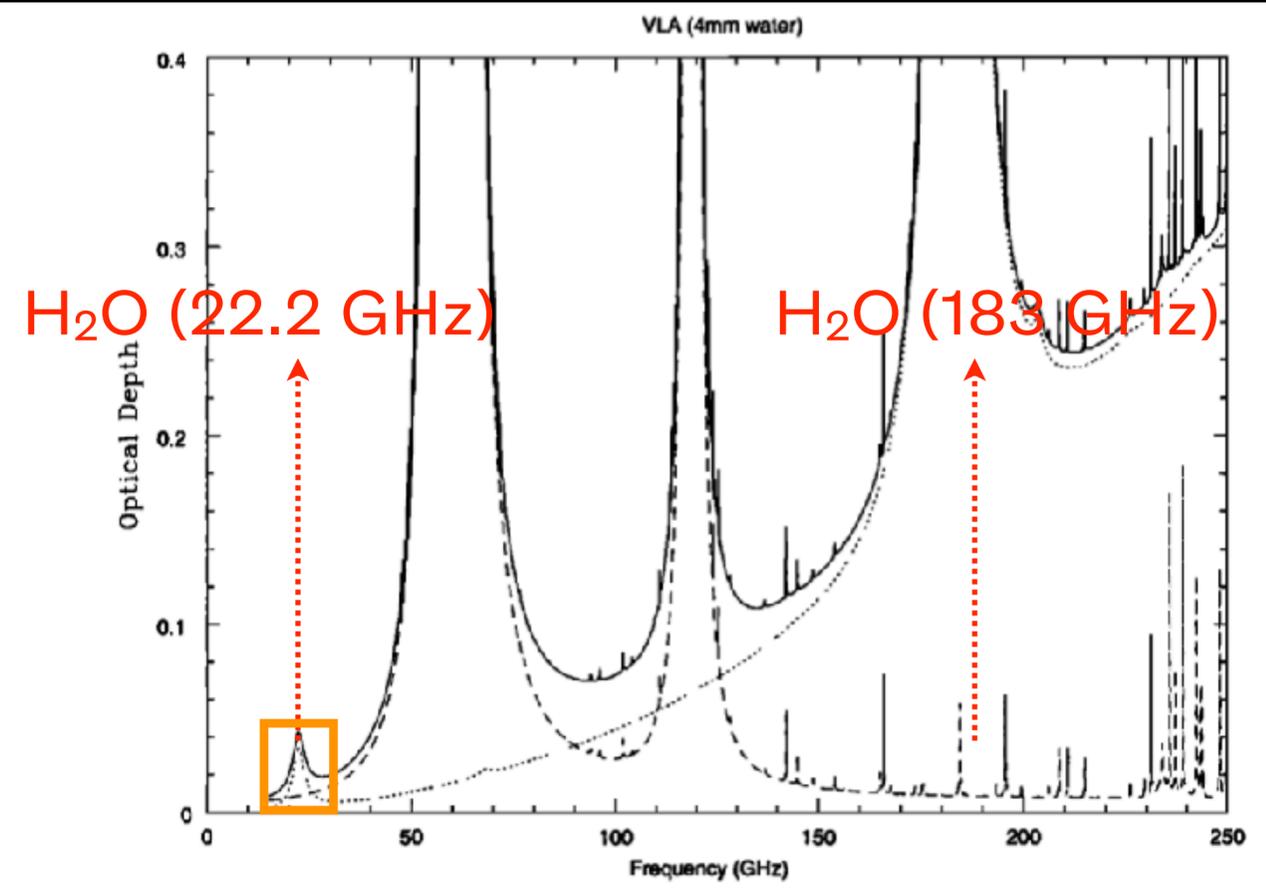
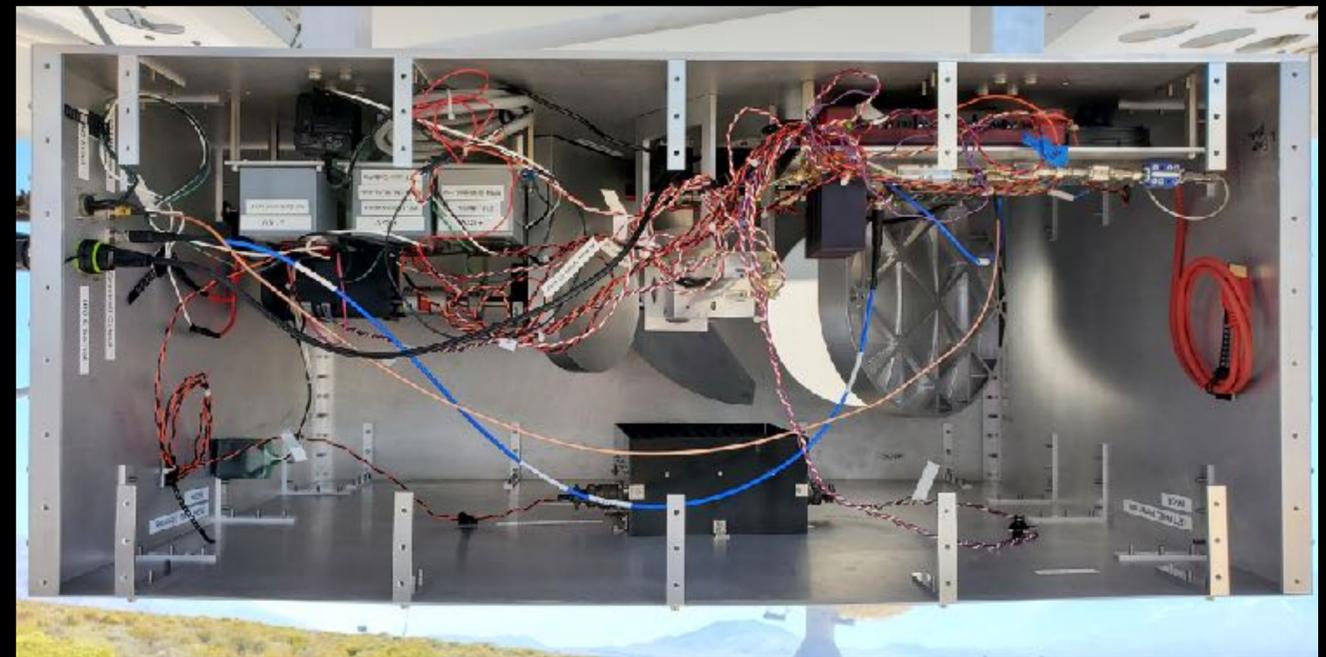
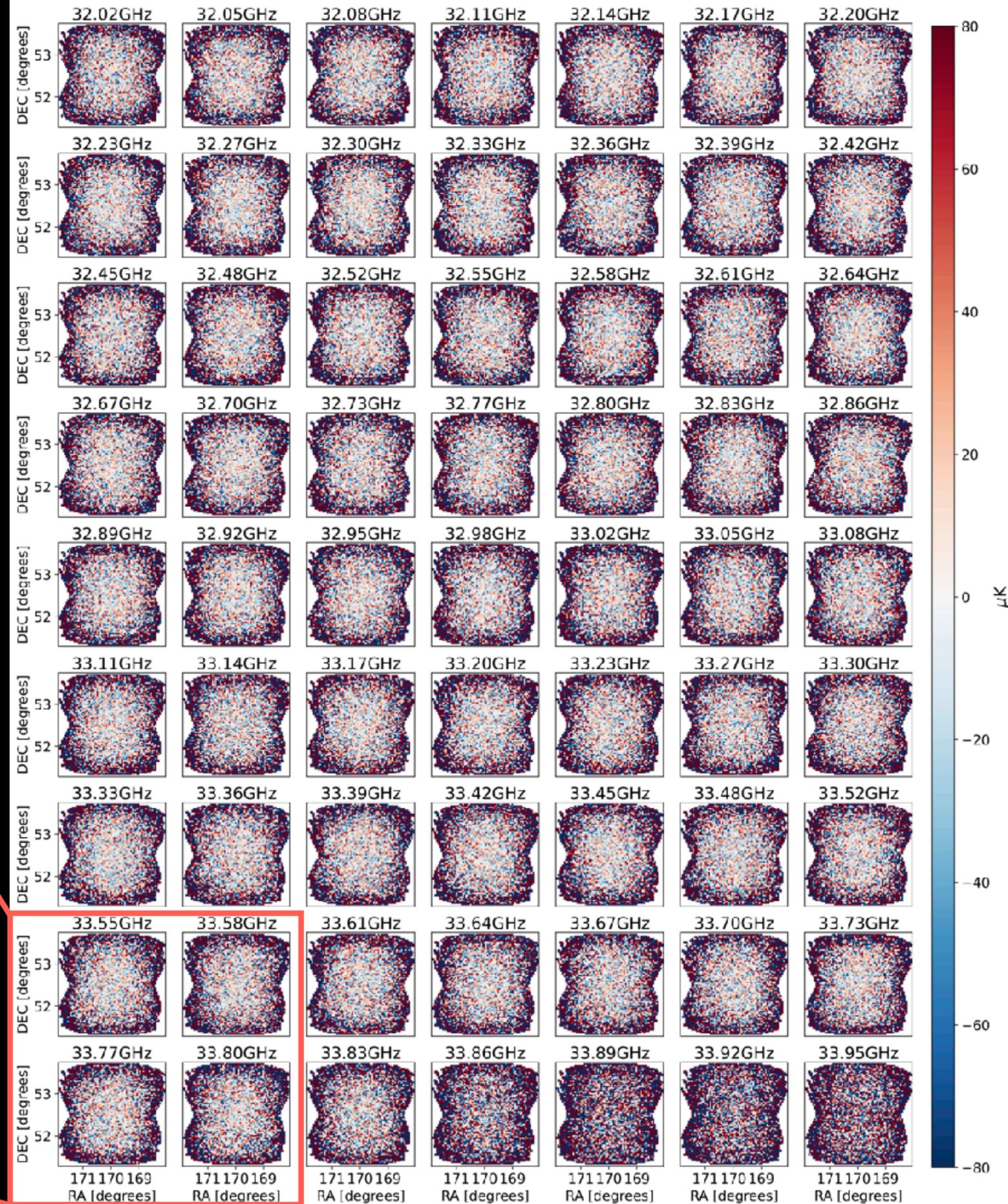
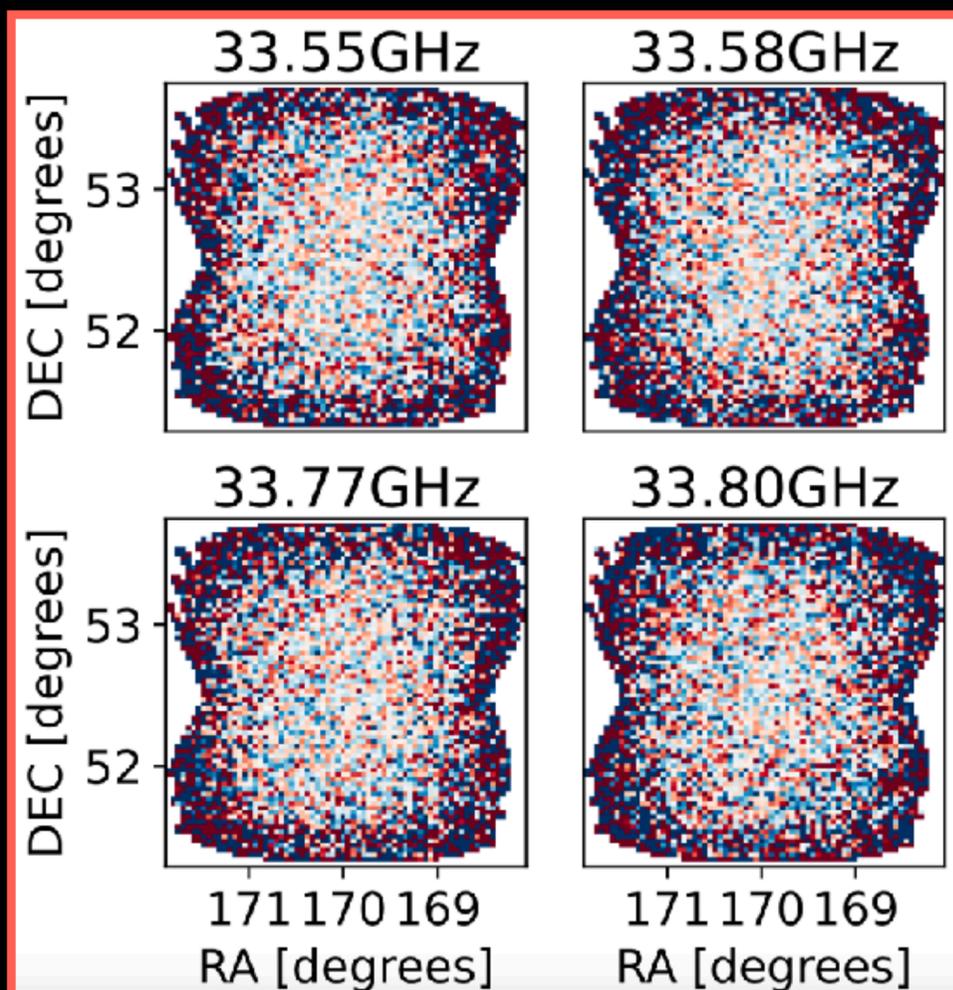


Figure 2. The optical depth for the VLA site assuming $w_0 = 4$ mm. The solid line is the total optical depth. The dotted line is the optical depth due to water vapor. The dashed line is the optical depth due to dry air (O_2 and other trace gases).

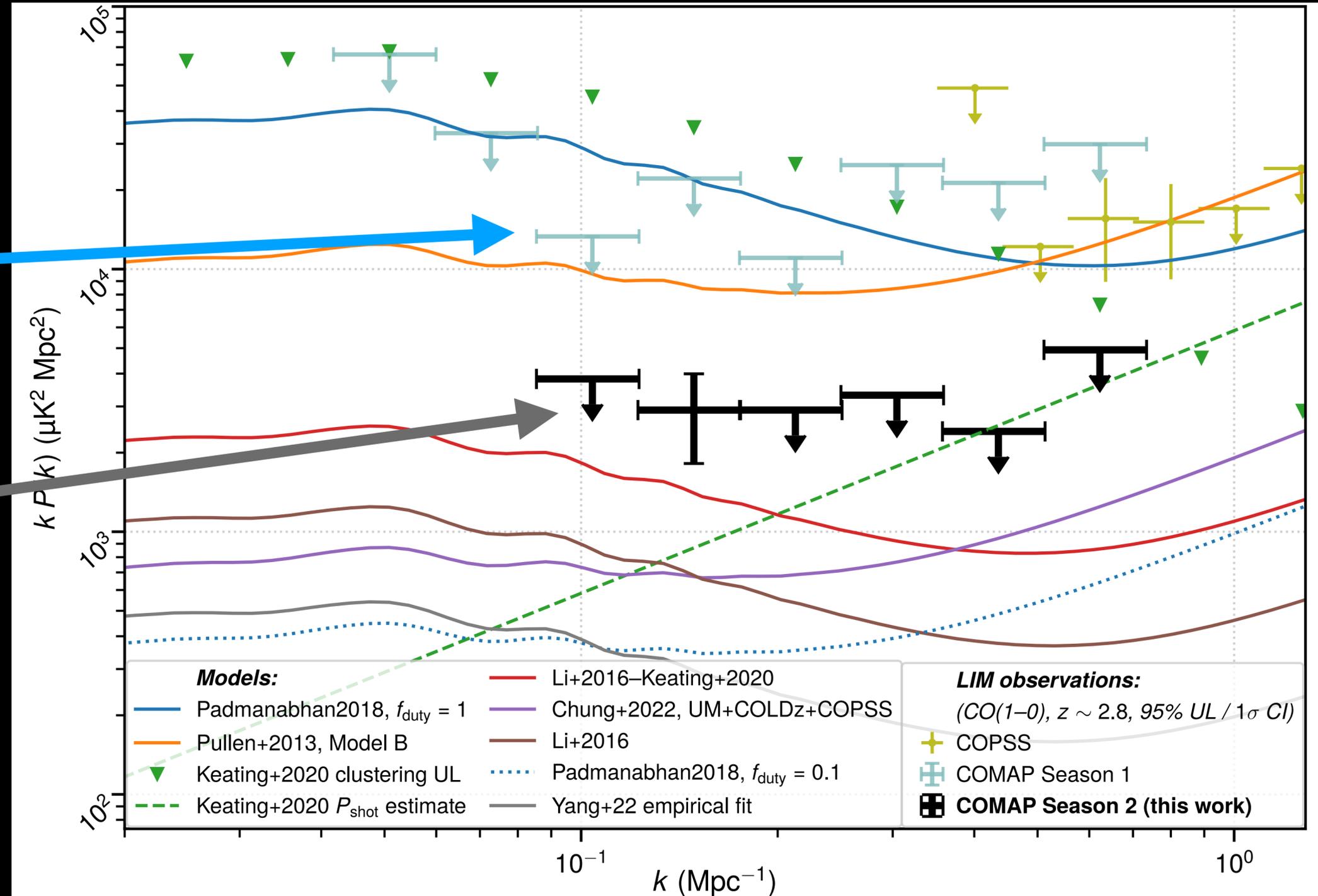
31.25 MHz frequency channel maps
8 GHz / 31.25 MHz ~ 250 channels

$$\Delta z/z = 0.004$$



COMAP Pathfinder: Season 2 Results

- Season 1 (May 2019 - August 2020; 5,200 on-sky observation hours)
- Season 2 (November 2020 - November 2023; 12,300 on-sky observation hours)



COMAP Pathfinder: Season 2 Results

$$\langle T_{\text{CO}} \rangle = 0.72_{-0.30}^{+0.45} \mu\text{K}$$

(mean CO temperature)

$$\alpha_{\text{CO}} = 3.6 M_{\odot} (\text{K km s}^{-1} \text{ pc}^{-2})^{-1}$$

$$\rho_{\text{H}_2} = 5.0_{-2.1}^{+3.1} \times 10^7 M_{\odot} \text{Mpc}^{-3}$$

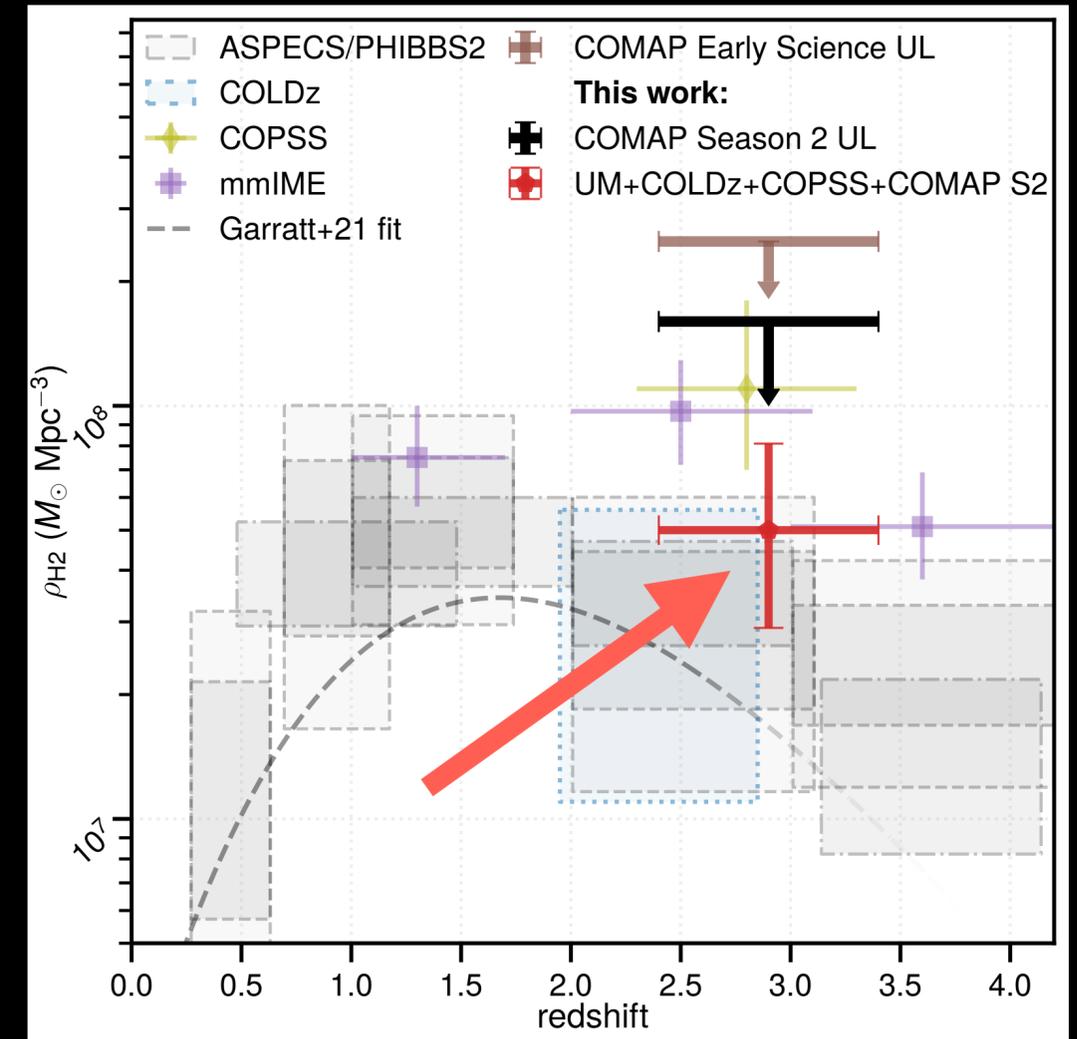
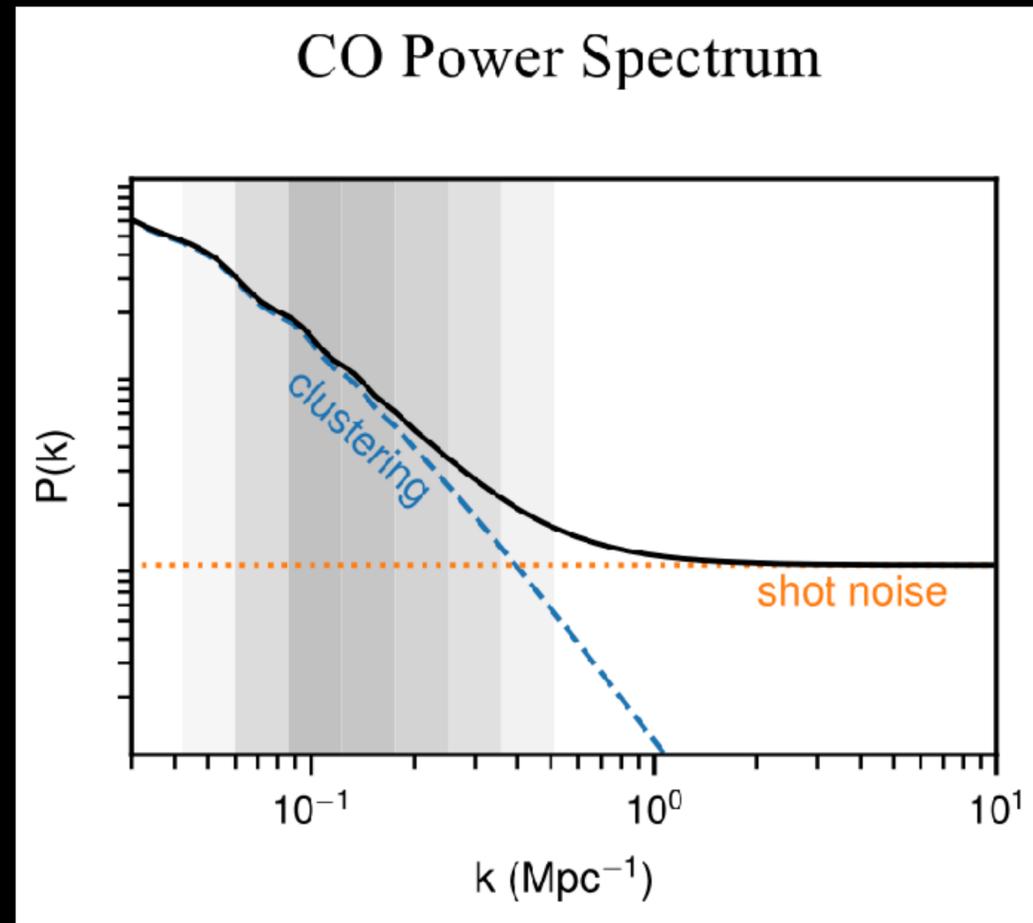
(molecular gas abundance)

Clustering amplitude \times
(Underlying matter
power spectrum)

+

shot noise

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



COMAP Pathfinder: Early Science Results (2022, 2024)

THE ASTROPHYSICAL JOURNAL

Focus on Early Science Results from the CO Mapping Array Project (COMAP)

Editor: Professor Christopher Conselice

PI: Kieran Cleary, California Institute of Technology

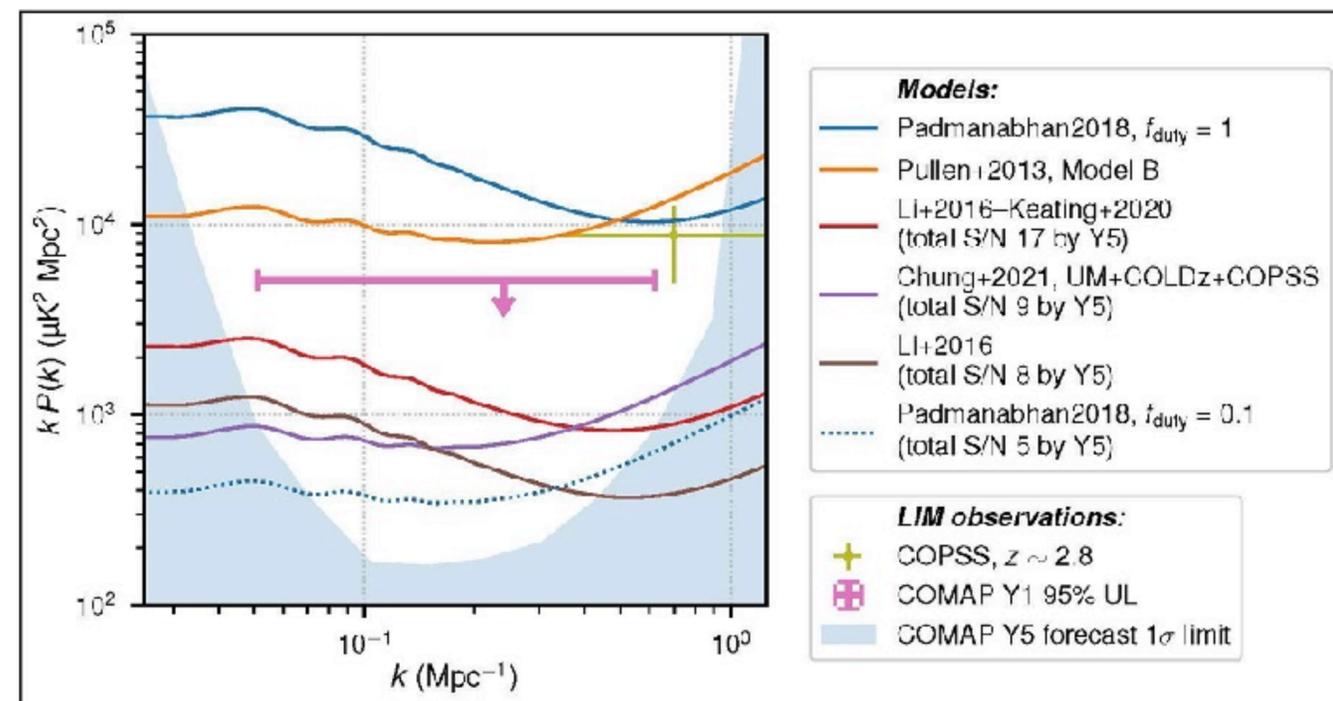


Figure 1. COMAP Pathfinder Season 1 constraint (pink) on the redshift-space CO(1-0) power spectrum at $z \sim 3$, alongside the predictions from various models and our Year 5 Pathfinder sensitivity forecast (blue shaded area). The models include (i) the fiducial COMAP data-driven model from Chung et al. (2021) ("UM+GOLDz+COPSS"), (ii) an alternative model from Keating et al. (2020) ("Li+2016-Keating+2020") with emission from faint galaxies that may be missed by the surveys informing the fiducial model, and (iii) models based on $L(M_H)$ relations from Padmanabhan (2017), Pullen et al. (2013), and Li et al. (2016). Also shown is the result from another CO LIM experiment, COPSS, that targeted the shot-noise component of the power spectrum (Keating et al. 2016). For each, the legend indicates the expected signal-to-noise ratio with which we would reject the null hypothesis (i.e., excluding sample variance from the calculation).

Grid of 16 abstracts from The Astrophysical Journal, 2024, Volume 912, Number 1, pages 1-16.

- COMAP Early Science. I. Overview** (Pages 1-10)
- COMAP Early Science. II. Full-Field Instrument** (Pages 11-20)
- COMAP Early Science. III. CO Data Processing** (Pages 21-30)
- COMAP Early Science. IV. Power Spectrum Methodology and Results** (Pages 31-40)
- COMAP Early Science. V. Constraints and Forecasts at $z \sim 3$** (Pages 41-50)
- COMAP Early Science. VI. A First Look at the COMAP Galactic Plane Survey** (Pages 51-60)
- COMAP Early Science. VII. Prospects for CO Intensity Mapping at Redshift $z \sim 3$** (Pages 61-70)
- COMAP Early Science. VIII. A Joint Stacking Analysis with eROS-Q** (Pages 71-80)

Each abstract includes a title, authors, and a brief summary of the paper's content.

COMAP Pathfinder: Season 2 Results (2024)

Lunde et al. 2024
(A&A, 691, A335)

Stutzer et al. 2024
(A&A, 691, A336)

Chung et al. 2024
(A&A, 691, A337)

A&A, 691, A335 (2024)
<https://doi.org/10.1051/0004-6361/202451121>
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Astronomy
& Astrophysics

COMAP Pathfinder – Season 2 results

I. Improved data selection and processing

J. G. S. Lunde^{1,*}, N.-O. Stutzer¹, P. C. Breysse^{5,7}, D. T. Chung^{3,4,5}, K. A. Cleary², D. A. Dunne², H. K. Eriksen⁸, S. E. Harper¹⁰, H. T. Ihle⁹, J. W. Lamb⁹, T. J. Pearson², L. Philip^{12,15}, I. K. Wehus¹⁰, D. P. Woody⁹, J. R. Bond^{1,4,15}, S. E. Church¹¹, T. Gaier¹², J. O. Gundersen¹⁸, A. I. Harris¹⁹, R. Hobbs⁹, J. Kim¹³, C. R. Lawrence¹², N. Murray^{1,4,15}, H. Padmanabhan⁴, A. C. S. Readhead², J. Kim¹³, T. J. Rennie^{10,11}, and D. Tolgay^{3,14} (COMAP Collaboration)

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ABSTRACT

The CO Mapping Array Project (COMAP) Pathfinder is performing line intensity mapping of CO emission to trace the distribution of unresolved galaxies at redshift $z \sim 3$. We present an improved version of the COMAP data processing pipeline and apply it to the first two seasons of observations. This analysis improves on the COMAP Early Science (ES) results in several key aspects. On the observational side, all second season scans were made in constant-elevation mode, after noting that the previous Lissajous scans were associated with increased systematic errors; those scans accounted for 30% of the total Season 1 data volume. In addition, all raw observations were restricted to an elevation range of 35–65 degrees to minimize sidelobe ground pickup. On the data processing side, more effective data cleaning in both the time and map domain allowed us to eliminate all data-driven power spectrum-based cuts. This increases the overall data retention and reduces the risk of signal subtraction bias. However, due to the increased sensitivity, two new pointing-correlated systematic errors have emerged, and we introduced a new map-domain PCA filter to suppress these errors. Subtracting only five out of 255 PCA modes, we find that the standard deviation of the cleaned maps decreases by 67% on large angular scales, and after applying this filter, the maps appear consistent with instrumental noise. Combining all of these improvements, we find that each hour of raw Season 2 observations yields on average 3.7 times more cleaned data compared to the ES analysis. Combining this with the increase in raw observational hours, the effective amount of data available for high-level analysis is a factor of eight higher than in the ES analysis. The resulting maps have reached an uncertainty of 35–50 K per voxel, providing by far the strongest constraints on cosmological CO line emission published to date.

Key words. methods: data analysis – methods: observational – galaxies: high-redshift – diffuse radiation – radio lines: galaxies

1. Introduction

Line intensity mapping (LIM) is an emerging observational technique in which the integrated spectral line emission from many

unresolved galaxies is mapped in 3D as a tracer of the cosmological large-scale structure (e.g., Kovetz et al. 2017, 2019). It represents a promising and complementary cosmological probe to, say, galaxy surveys and cosmic microwave background (CMB) observations. In particular, LIM offers the potential to survey vast cosmological volumes at high redshift in a manner that is

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& Astrophysics

COMAP Pathfinder – Season 2 results

II. Updated constraints on the CO(1–0) power spectrum

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ABSTRACT

We present updated constraints on the cosmological 3D power spectrum of carbon monoxide CO(1–0) emission in the redshift range 2.4–3.4. The constraints are derived from the two first seasons of Carbon monoxide Mapping Array Project (COMAP) Pathfinder line intensity mapping observations aiming to trace star formation during the epoch of galaxy assembly. These results improve on the previous Early Science results through both increased data volume and an improved data processing methodology. On the methodological side, we now perform cross-correlations between groups of detectors (“feed groups”), as opposed to cross-correlations between single feeds, and this new feed group pseudo power spectrum (FGPXS) is constructed to be more robust against systematic effects. In terms of data volume, the effective mapping speed is significantly increased due to an improved observational strategy as well as a better data selection methodology. The updated spherically- and field-averaged FGPXS, $\xi(k)$, is consistent with zero, at a probability-to-exceed of around 34%, with an excess of 2.7 σ in the most sensitive bin. Our power spectrum estimate is about an order of magnitude more sensitive in our six deepest bins across $0.99 \text{ Mpc}^{-1} < k < 0.73 \text{ Mpc}^{-1}$, compared to the feed feed pseudo power spectrum (FPXS) of COMAP ES. Each of these bins individually constrains the CO power spectrum to $\Delta P_{\text{CO}}(k) < 2400\text{--}4500 \mu\text{K}^2 \text{ Mpc}^3$ at 95% confidence. To monitor potential contamination from residual systematic effects, we analyzed a set of 312 difference-map null tests and found that these are consistent with the instrumental noise prediction. In sum, these results provide the strongest direct constraints on the cosmological 3D CO(1–0) power spectrum published to date.

Key words. methods: data analysis – methods: observational – galaxies: high-redshift – diffuse radiation – radio lines: galaxies

1. Introduction

By collecting the combined redshift-dependent line emission from all sources, both diffusely emitting gas and all galaxies,

bright and faint, line intensity mapping (LIM) aims to map the Universe from large to small scales in three dimensions (see Madec et al. 1997; Batyè et al. 2004; Peterson et al. 2006; Loeb & Wyithe 2008; Kovetz et al. 2017, 2019, and references therein for details on LIM). Several emission lines of interest have been proposed, among them 21 cm, carbon monoxide (CO), ionized

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COMAP Pathfinder – Season 2 results

III. Implications for cosmic molecular gas content at $z \sim 3$

D. T. Chung^{1,2,3,*}, P. C. Breysse^{4,5}, K. A. Cleary⁶, D. A. Dunne⁷, J. G. S. Lunde⁷, H. Padmanabhan⁸, N.-O. Stutzer⁹, D. Tolgay¹⁰, J. R. Bond^{1,9,10}, S. E. Church¹¹, H. K. Eriksen⁷, T. Gaier¹², J. O. Gundersen¹³, S. E. Harper¹⁴, A. I. Harris¹⁵, R. Hobbs¹⁶, H. T. Ihle¹⁷, J. Kim¹⁸, J. W. Lamb¹⁶, C. R. Lawrence¹², N. Murray^{1,9,10}, T. J. Pearson⁹, L. Philip¹³, A. C. S. Readhead¹⁰, T. J. Rennie^{14,19}, I. K. Wehus¹⁰, and D. P. Woody¹⁴ (COMAP Collaboration)

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ABSTRACT

The Carbon monoxide Mapping Array Project (COMAP) Pathfinder survey continues to demonstrate the feasibility of line-intensity mapping using high-redshift carbon monoxide (CO) line emission traced at cosmological scales. The latest COMAP Pathfinder power spectrum analysis is based on observations through the end of Season 2, covering the first three years of Pathfinder observations. We use our latest constraints on the CO(1–0) line intensity power spectrum at $z \sim 3$ to update corresponding constraints on the cosmological clustering of CO line emission and trace the cosmic molecular gas content at a key epoch of galaxy assembly. We first mirror the COMAP Early Science interpretation, considering how Season 2 results translate to limits on the shot noise power of CO fluctuations and the bias of CO emission as a tracer of the underlying dark matter distribution. The COMAP Season 2 results place the most stringent limits on the CO tracer bias to date, at $\langle b \rangle < 4.8$ (which translates to a molecular gas density upper limit of $\rho_{\text{CO}} < 1.6 \times 10^7 \text{ M}_{\odot} \text{ Mpc}^{-3}$ at $z \sim 3$ given additional model assumptions). These limits narrow the model space significantly compared to previous CO line intensity mapping results while maintaining consistency with small volume intercometric surveys of resolved line card data. The results also express a weak preference for CO emission models used to guide fiducial forecasts from COMAP Early Science, including our data-driven priors. We also consider directly constraining a model of the halo–CO connection, and show qualitative hints of capturing the total contribution of faint CO emitters through the improved sensitivity of COMAP data. With continued observations and matching improvements in analysis, the COMAP Pathfinder remains on track for a detection of cosmological clustering of CO emission.

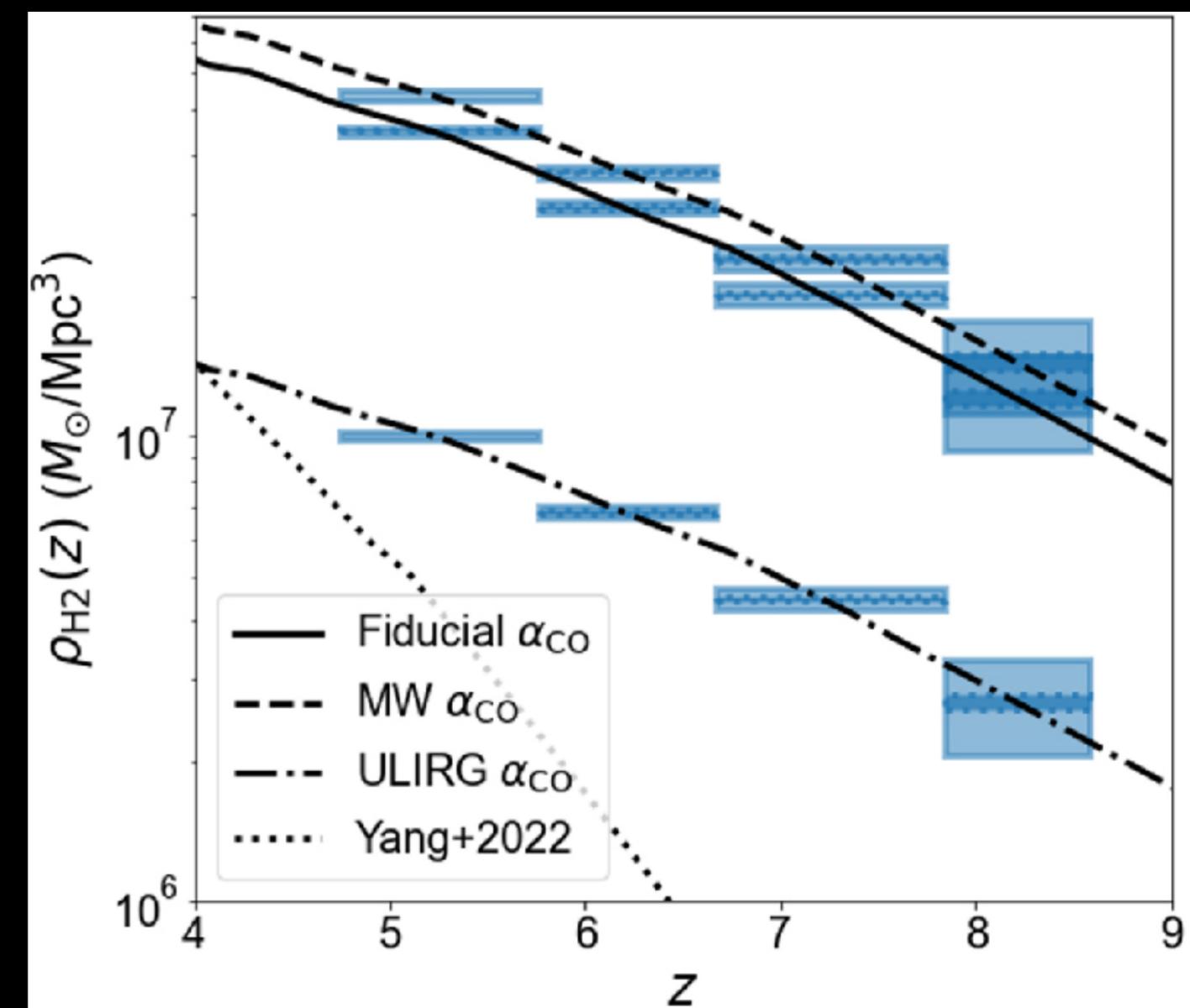
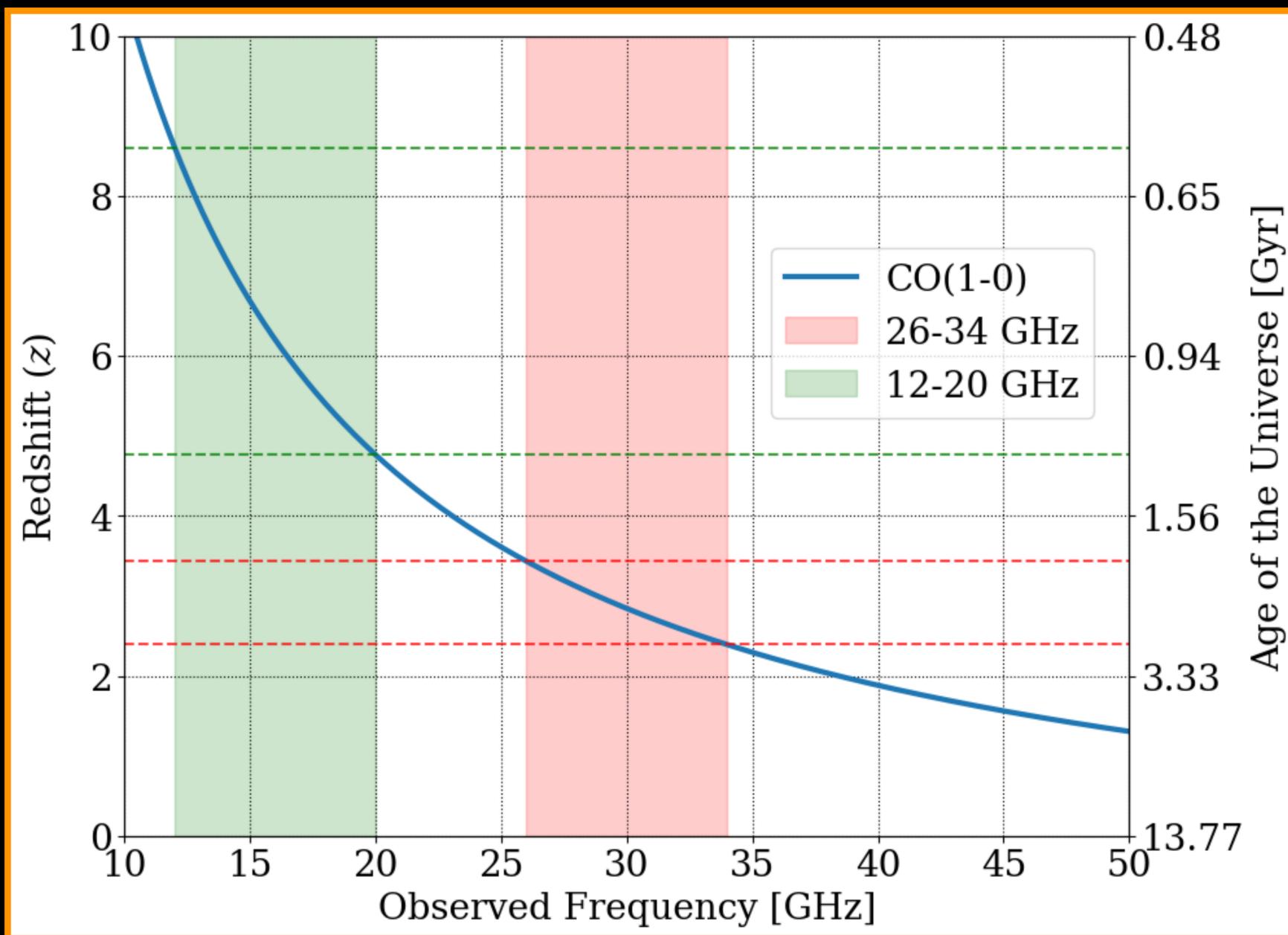
Key words. galaxies: high-redshift – diffuse radiation – radio lines: galaxies

1. Introduction

Line intensity mapping (LIM) surveys map the large-scale structure of the Universe in large cosmological volumes, but not

through discrete resolved tracer sources. Rather, LIM surveys achieve this through unresolved emission in specific spectral lines, including lines associated with different phases of the star-forming interstellar medium (ISM) such as carbon monoxide (CO) and the [C II] line from singly ionized carbon (see

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Breysse et al. (2022)

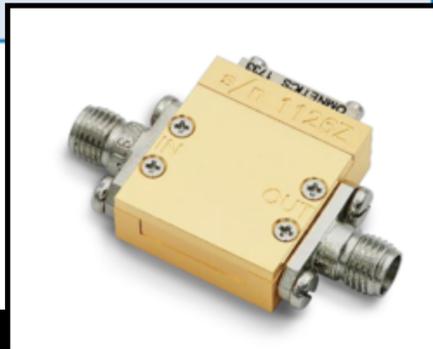
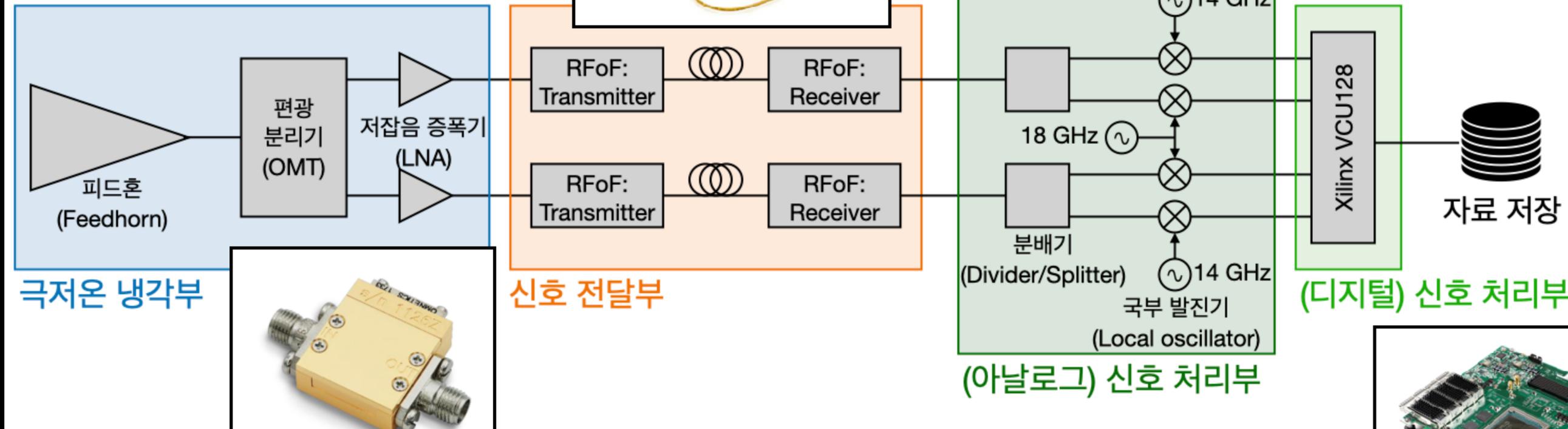
COMAP EoR: 12-20 GHz (Ku-band)

Taeduk Radio Astronomy Observatory (TRAO) 13.7 m

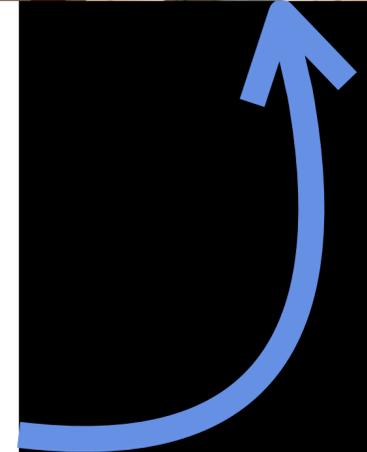


- Probing Epoch of Reionization: **CO LIM @12-20 GHz (z=4.8-8.6)**
- Development of a prototype receiver at KAIST (NRF funded)

RF over Fiber (20 GHz)



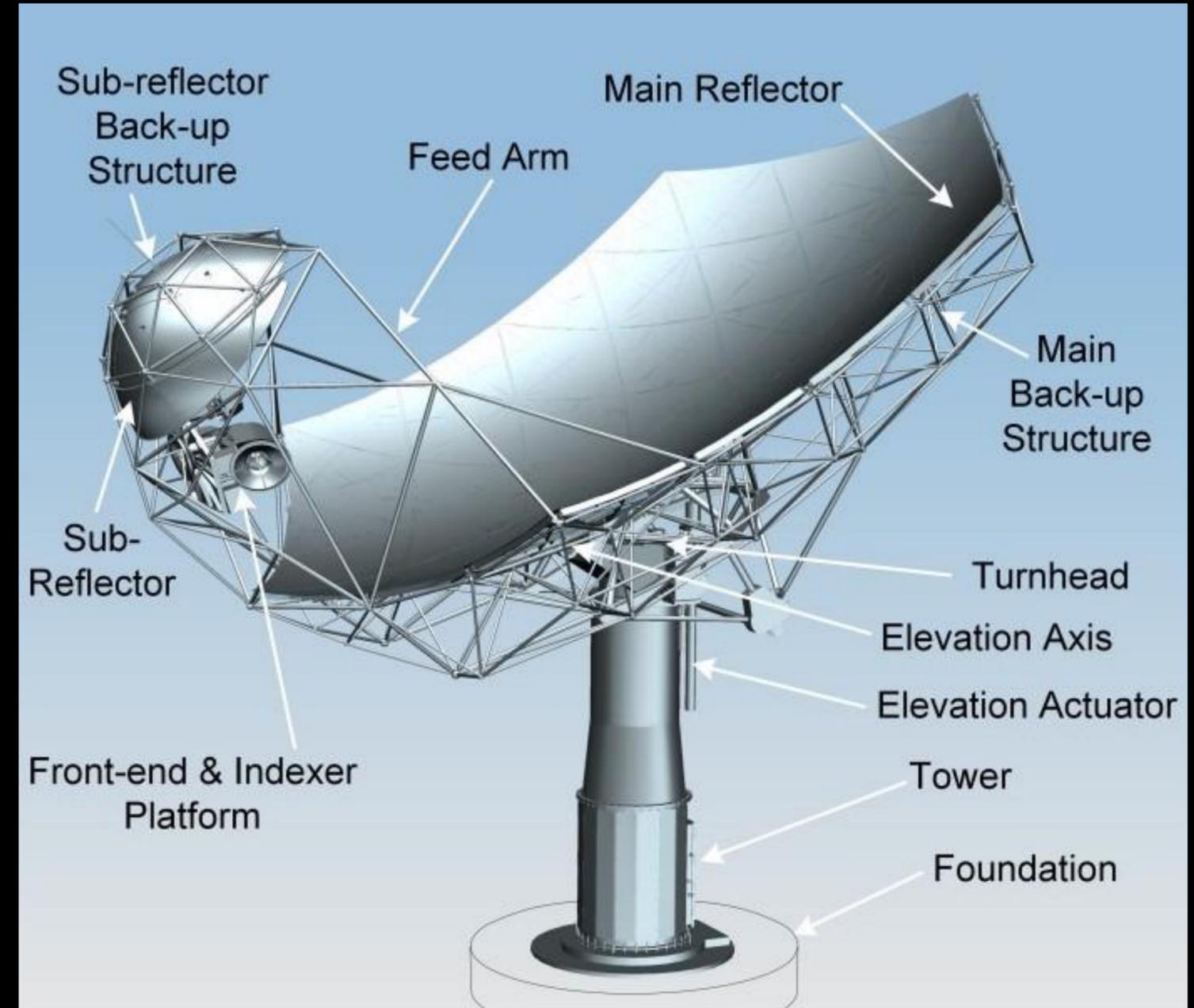
LNF-LNC6_20C Cryogenic LNA





(Future) Telescope Idea: SKA-Mid

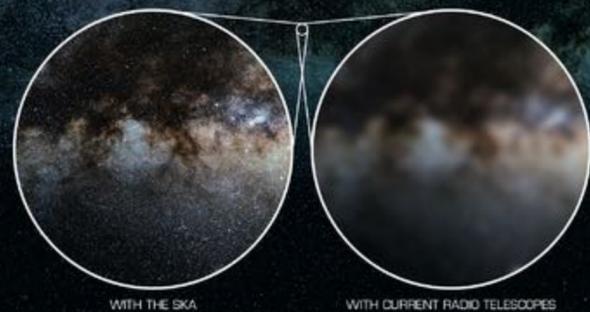
- The first prototype dish of the (15 m) SKA-Mid telescope constructed on site in South Africa has achieved first light.
- Frequency range: 350 MHz - 15.4 GHz (with a goal of 24 GHz)
- Focal plane array (~19 pixels) available
- Off-axis design: Standing wave ↓, Sidelobe performance ↑
- Southern hemisphere: Cross-correlation with SKA observations (or the other galaxy surveys)



How will SKA1 be better than today's best radio telescopes?



Astronomers assess a telescope's performance by looking at three factors - **resolution**, **sensitivity**, and **survey speed**. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.

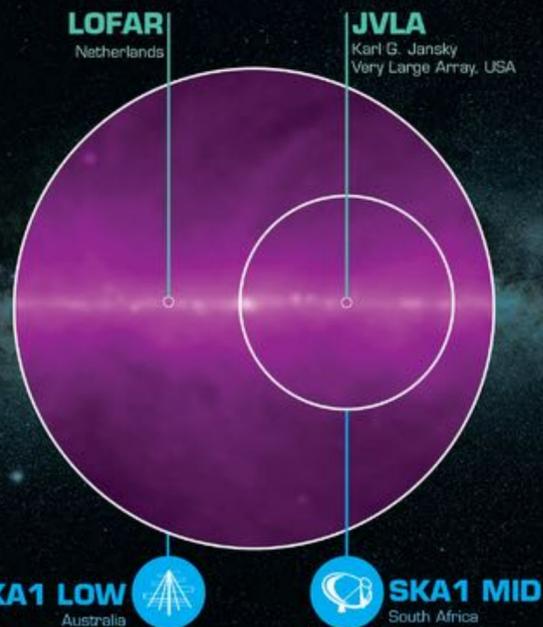


SKA1 LOW x1.2 LOFAR NL
SKA1 MID x4 JVLA

RESOLUTION

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

www.skatelescope.org | Square Kilometre Array | @SKA_telescope | The Square Kilometre Array



SKA1 LOW x135 LOFAR NL
SKA1 MID x60 JVLA

SURVEY SPEED

Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.

The **Square Kilometre Array (SKA)** will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - **SKA1 MID** and **SKA1 LOW** - observing the Universe at different frequencies.



SKA1 LOW x8 LOFAR NL
SKA1 MID x5 JVLA

SENSITIVITY

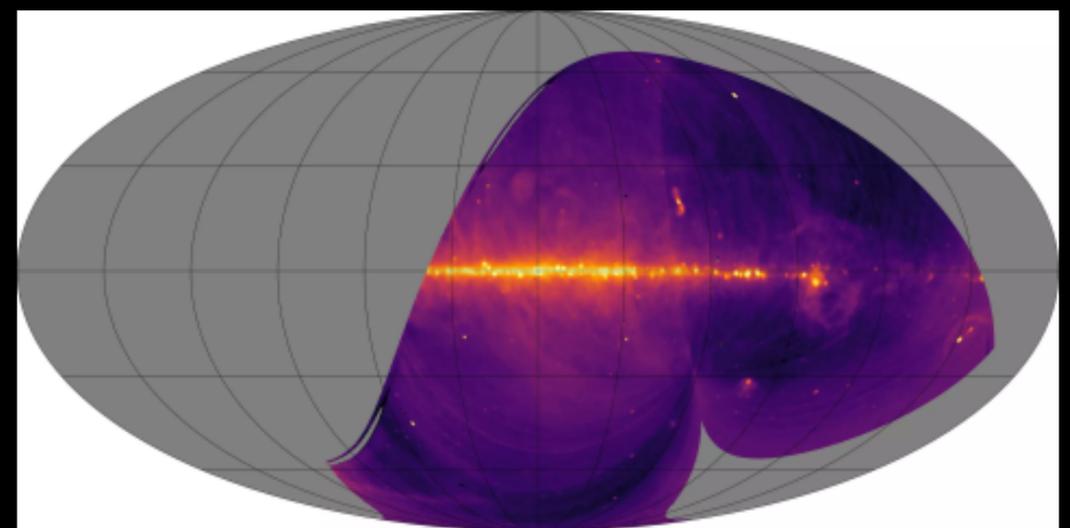
Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

As the SKA isn't operational yet, we use an optical image of the Milky Way to illustrate the concepts of increased sensitivity and resolution.

SKA-Mid prototype dish creates first light image

NEWS on 25 January 2024

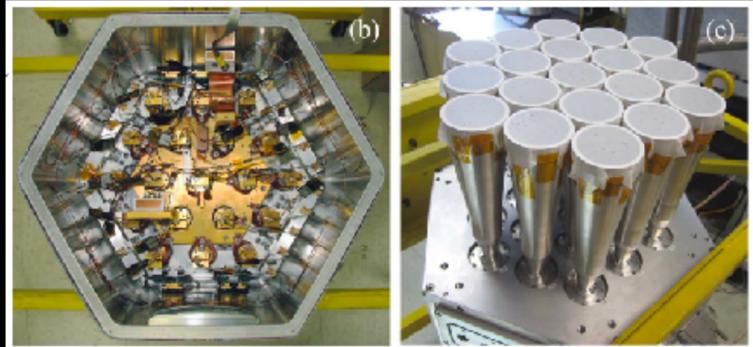
The first prototype dish of the SKA-Mid telescope constructed on site in South Africa has achieved first light.



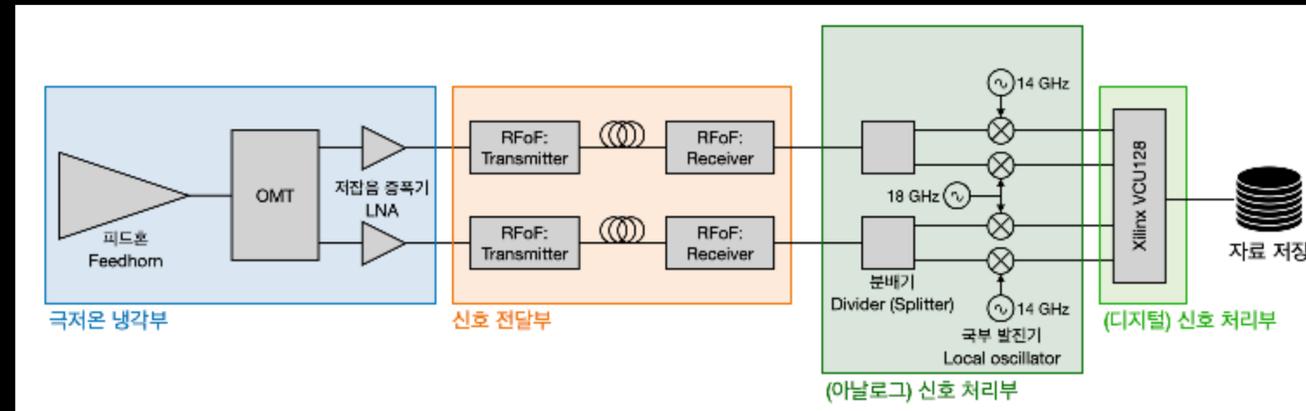
<https://www.roe.ac.uk/vdod2021/crawford-building/ska.html>

<https://www.skao.int/en/news/512/ska-mid-prototype-dish-creates-first-light-image>

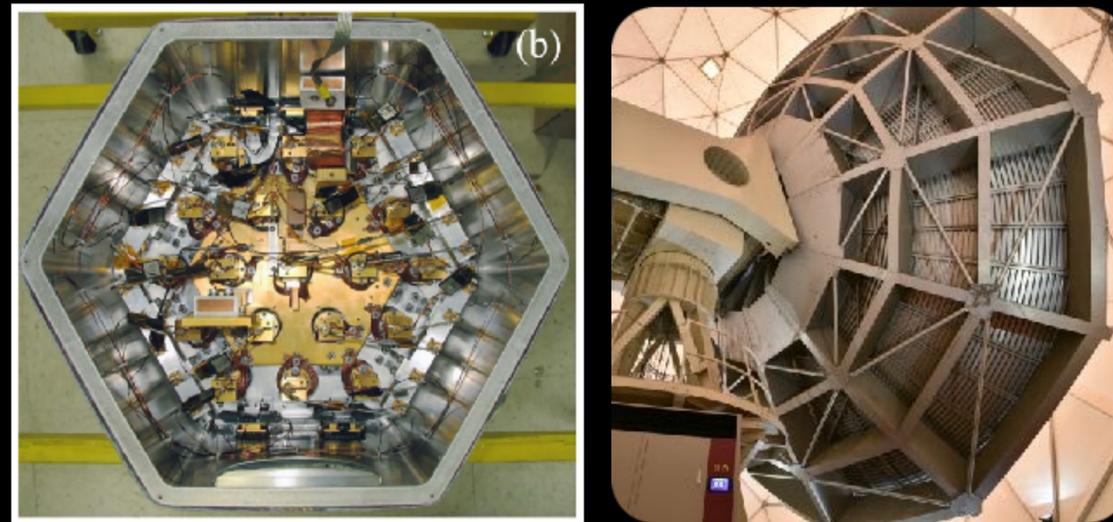
COMAP Pathfinder 26-34 GHz ($z=2.4 - 3.4$)



(1) Ku-band Prototype Receiver Development



(2) Testing Signal Chain + Observation



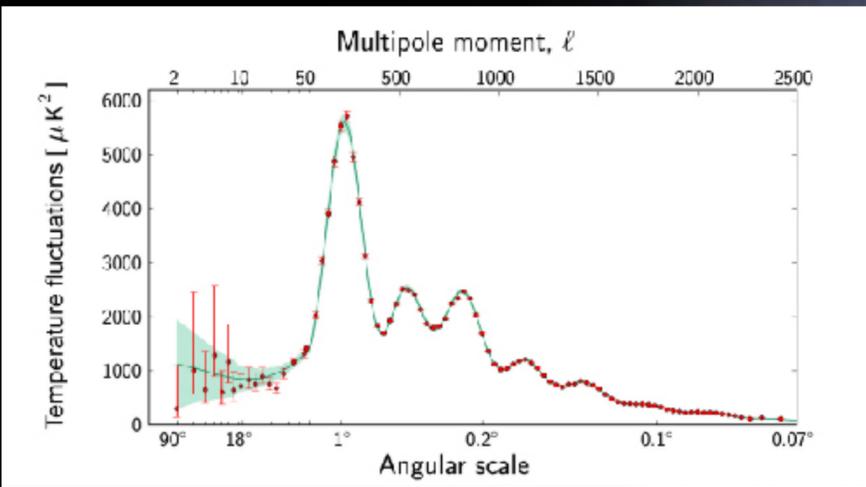
COMAP EoR 12-20 GHz ($z=4.8 - 8.6$)



- Focal plane array
- CO LIM using single-dish radio telescopes (e.g., ngVLA, SKA)

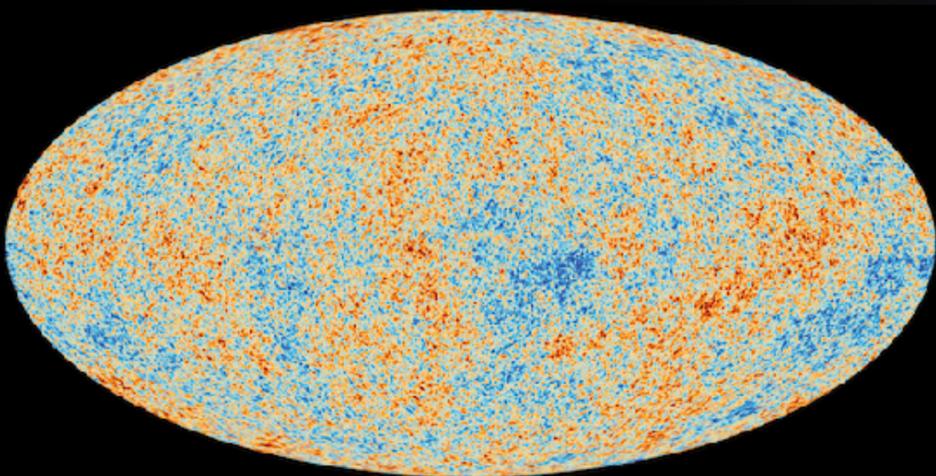
**Exploring the History of Star and Galaxy
Formation in the Early Universe from $z=2.4$ to 8.6 ,
Probing the 3D Large-Scale Structure**

Afterglow Light
Pattern
400,000 yrs.



Fluctuations

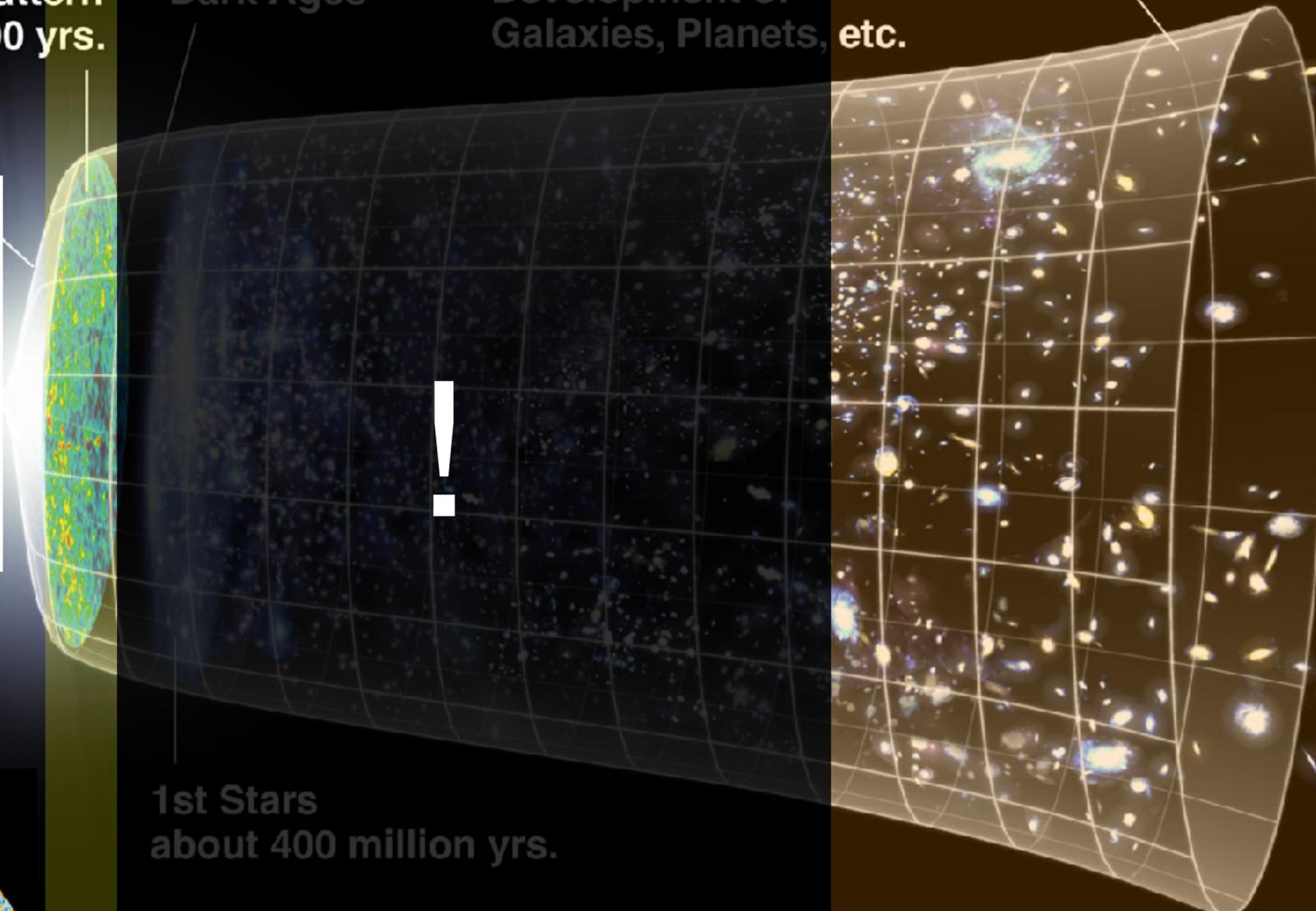
Cosmic Microwave
Background (CMB)



Dark Ages

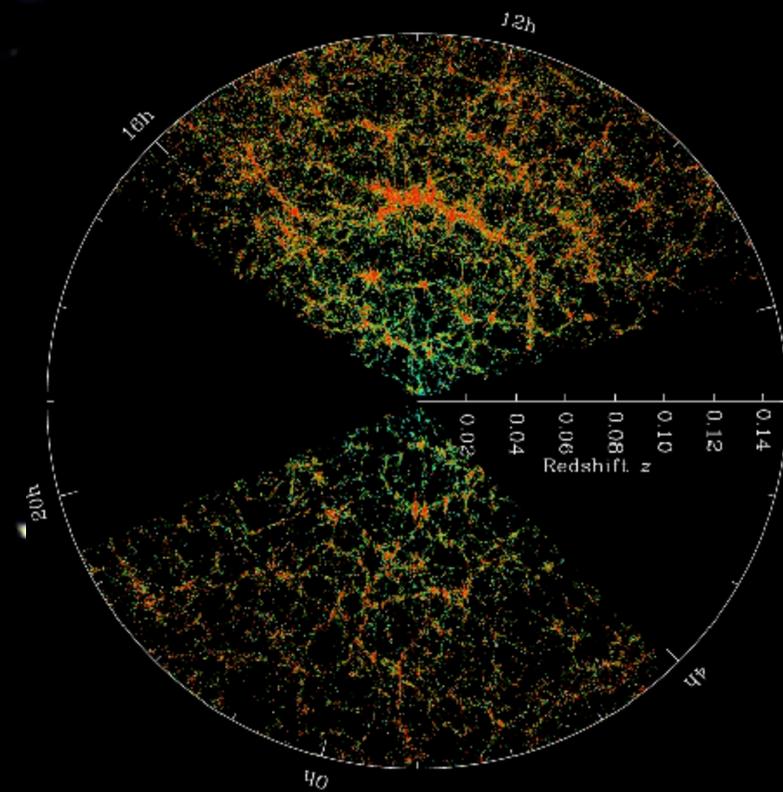
Development of
Galaxies, Planets, etc.

Dark Energy
Accelerated Expansion



1st Stars
about 400 million yrs.

Big Bang Expansion
13.7 billion years



Galaxy surveys
 $z = 0-1+$