한국고에너지물리학회 2024 가을 학술대회
11/30/2024

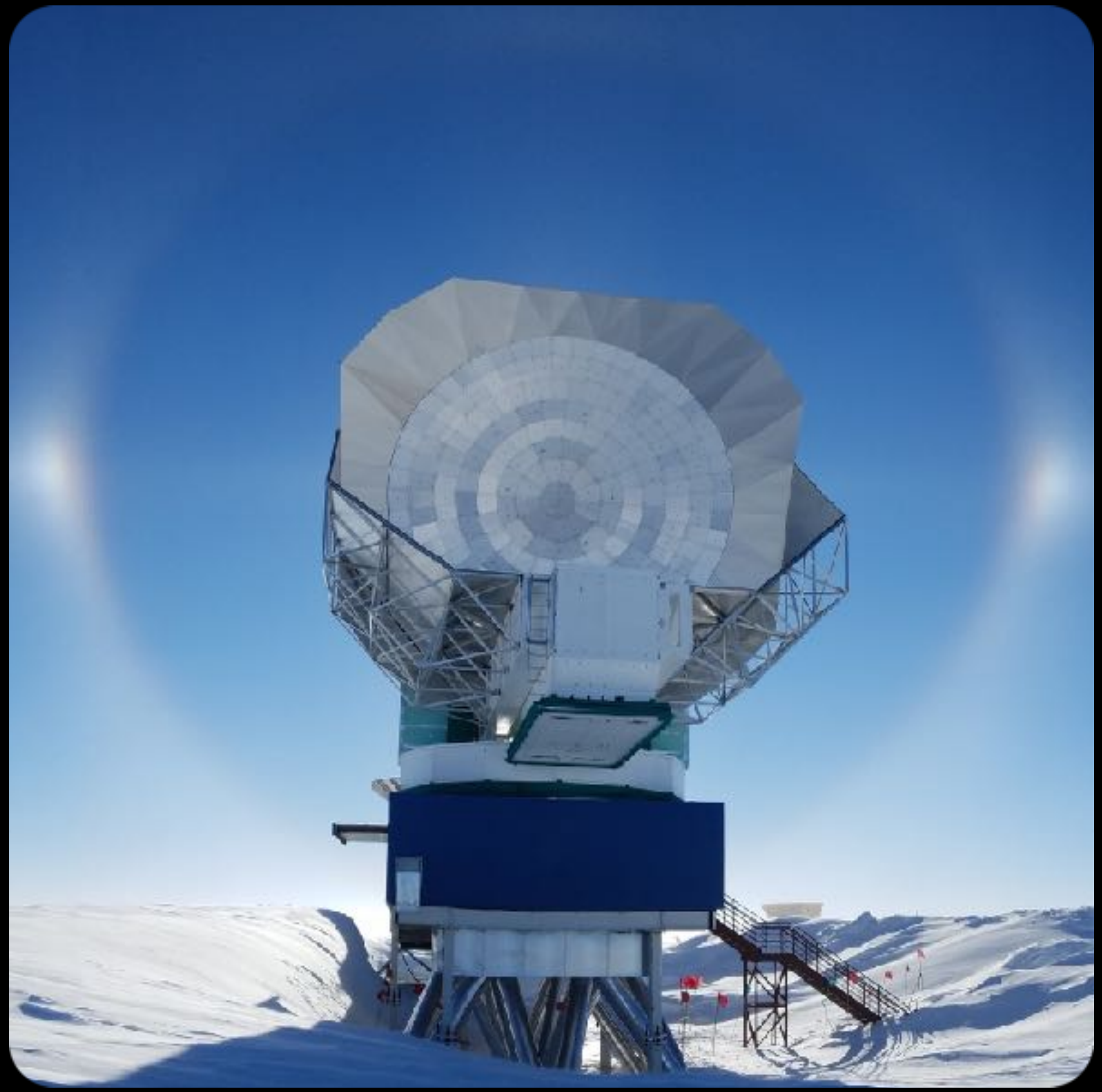
CO Intensity Mapping for Capturing the Star-formation History in the Early Universe

김준한 Junhan Kim (junhan@kaist.ac.kr)
Department of Physics
Korea Advanced Institute of Science and Technology (KAIST)


Circumgalactic/Intergalactic/Intracluster medium
Diffuse gas
Recycling gas
(Accretion: an acquisition of gas by the galaxy disk)
Accreting gas
15 kpc
Outflows
300 kpc
Tumlinson, Peeples, Werk (2017)
Supermassive black holes
M87
Rogelio Bernal Andreo
Credit & Copyright: Rogelio Bernal Andreo (https://apod.nasa.gov/apod/ap150804.html)
DeepSkyColors.com

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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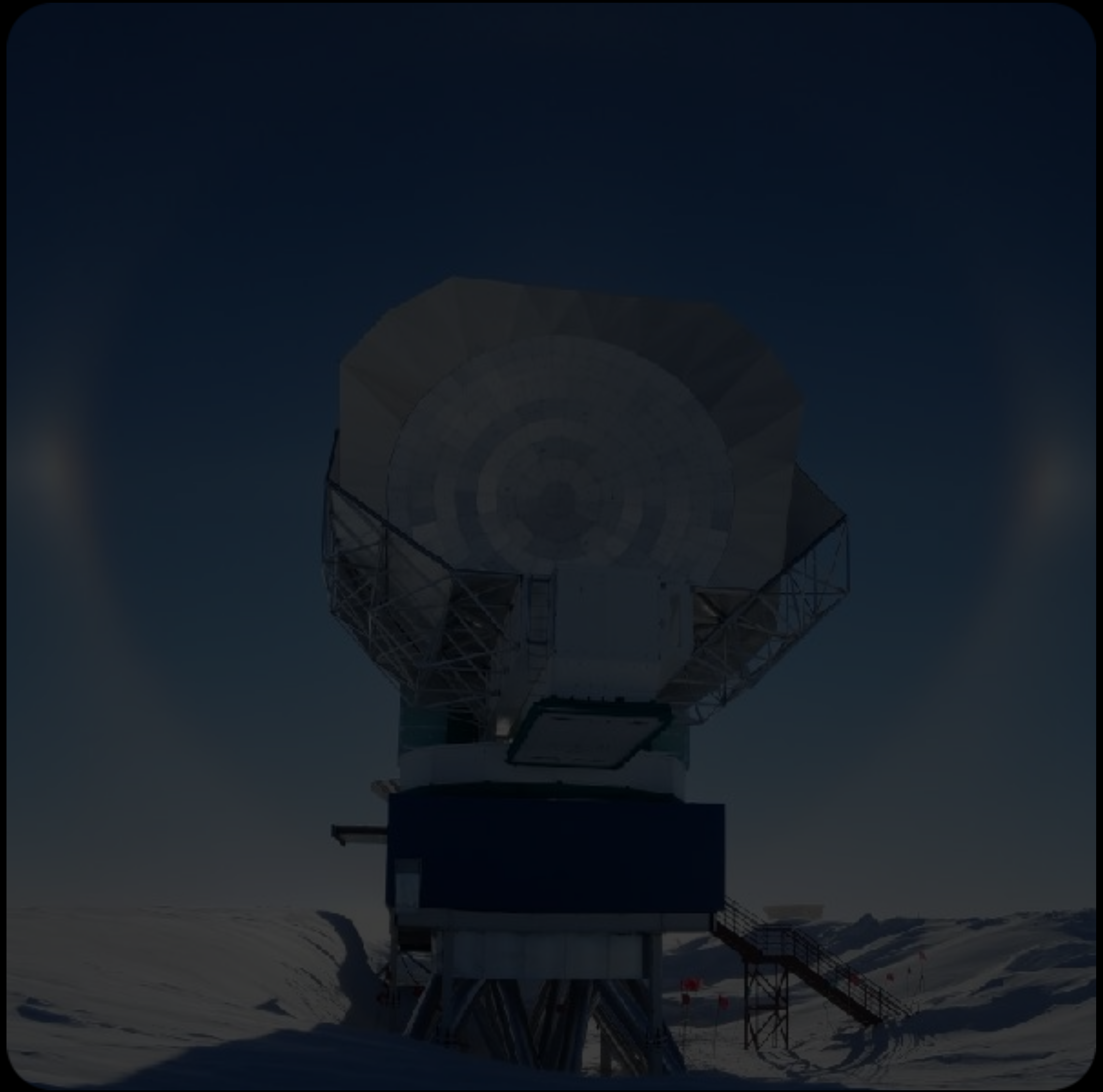

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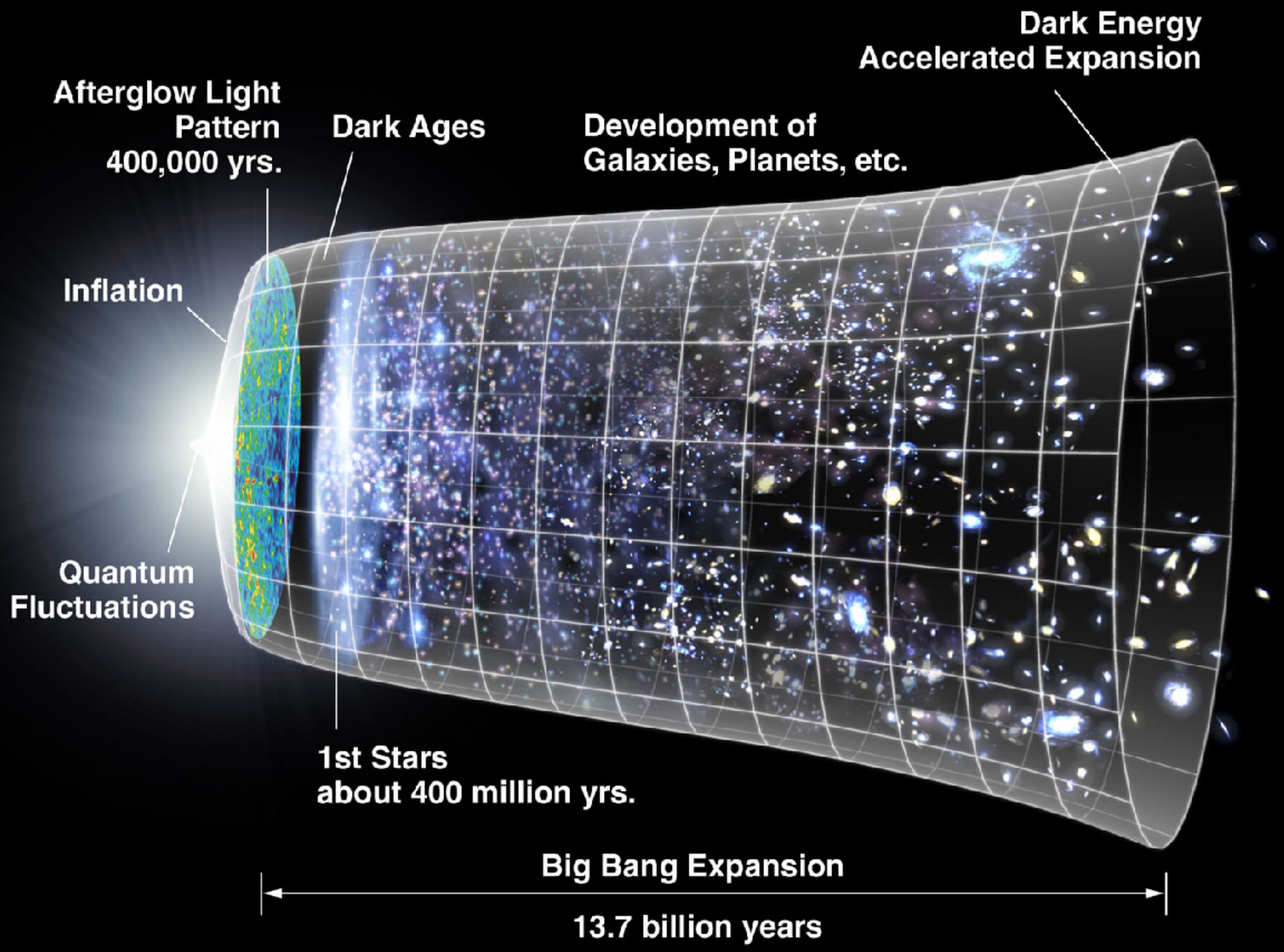
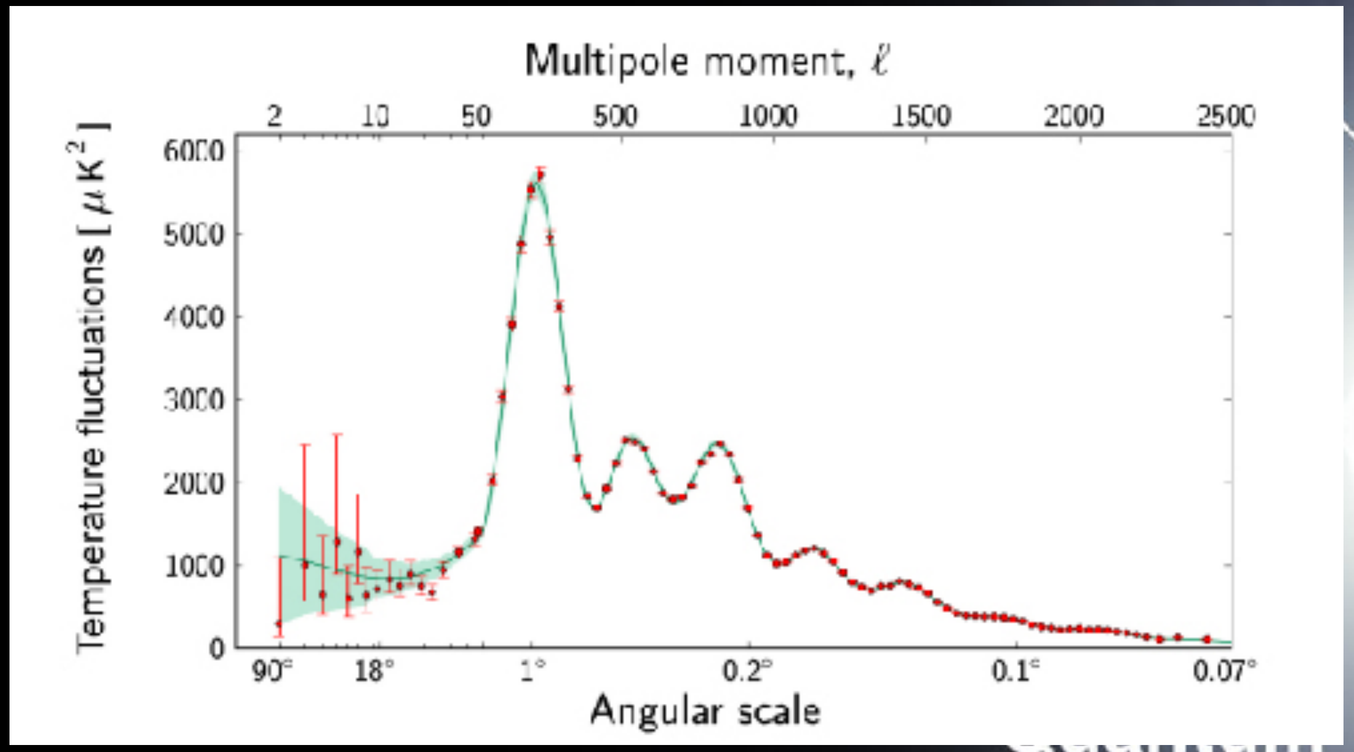
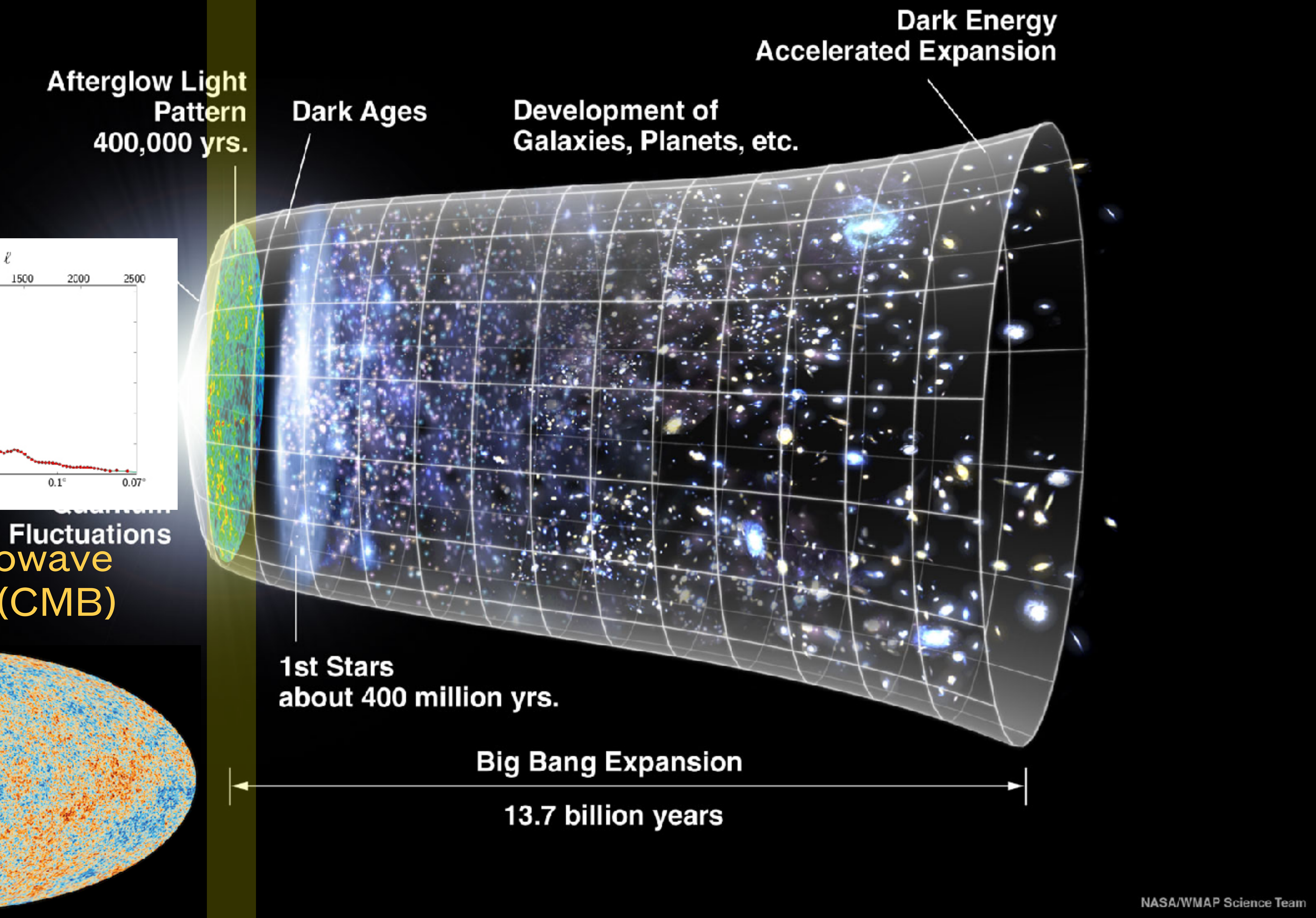
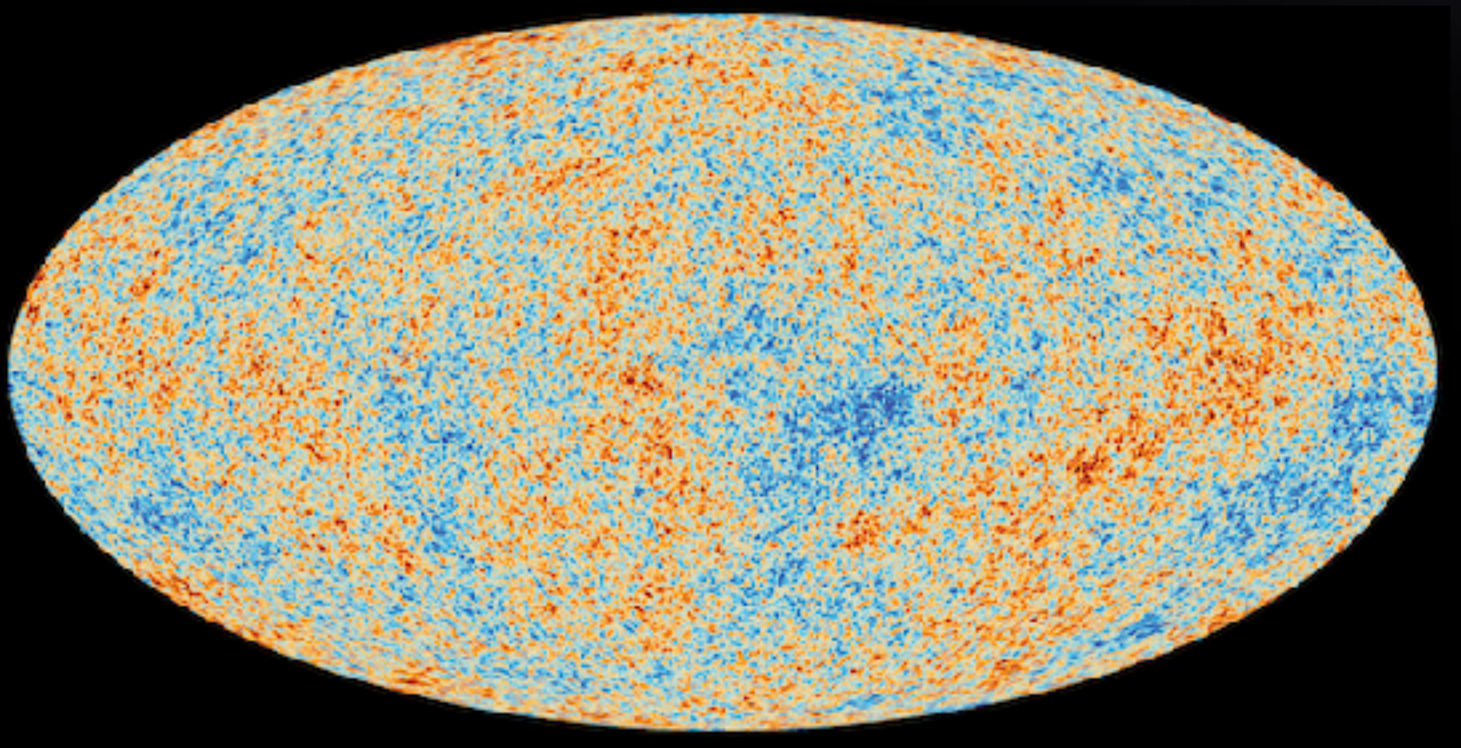


https://map.gsfc.nasa.gov/media/060915/index.html





Cosmic Microwave
Background (CMB)



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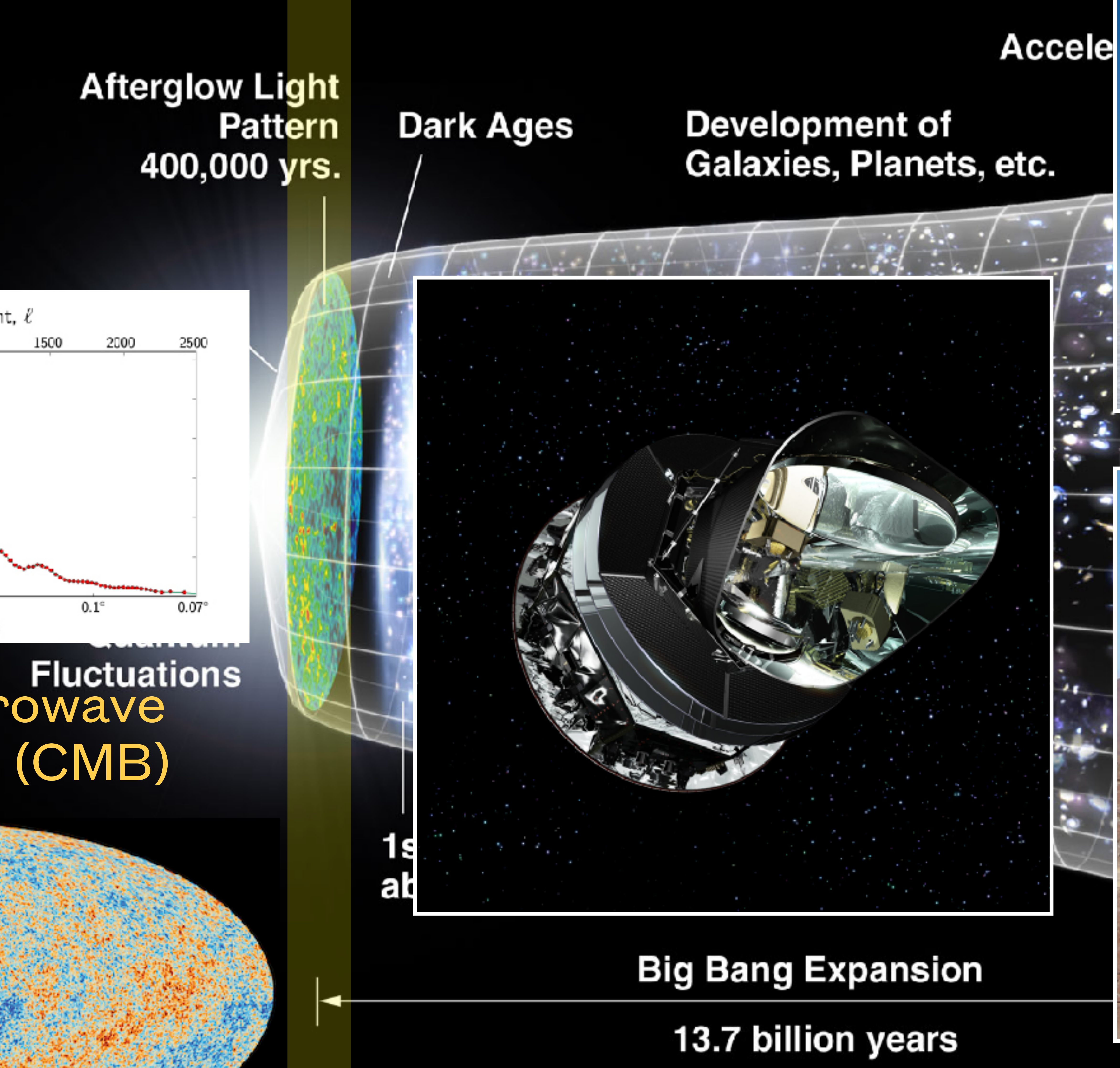
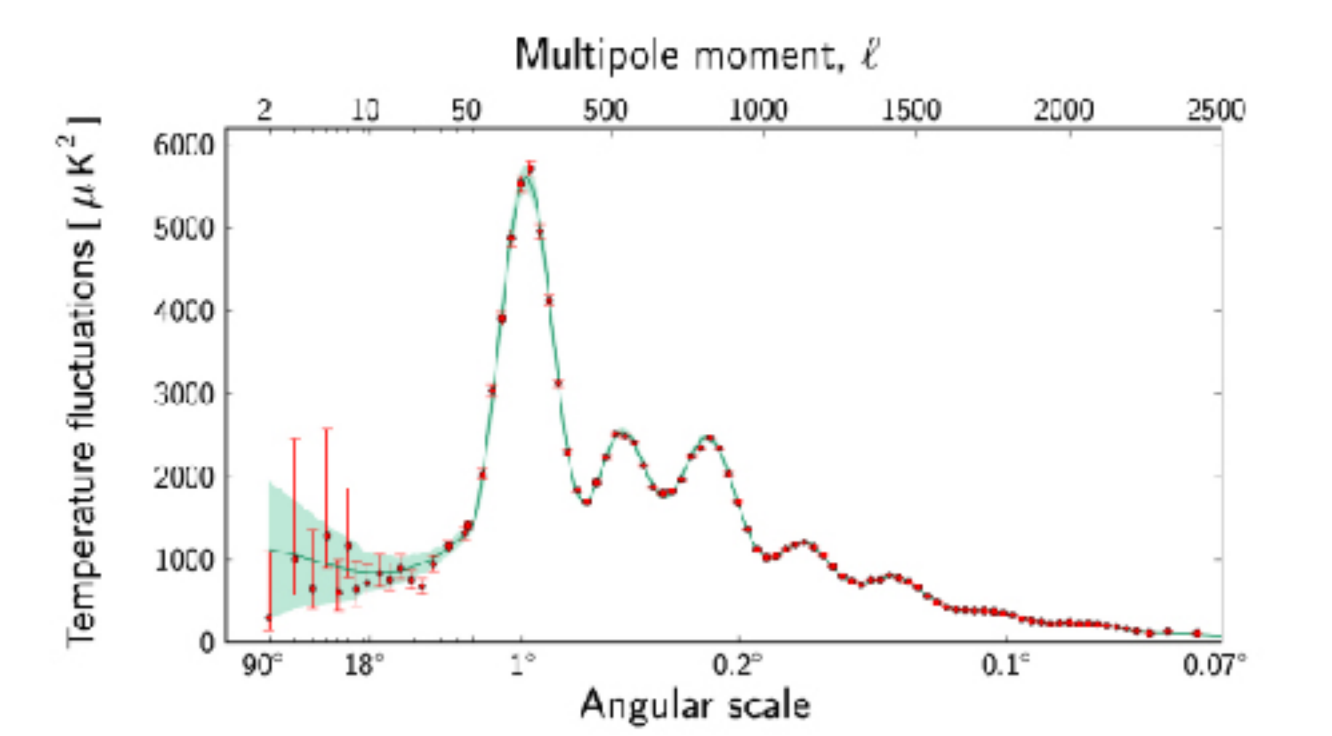
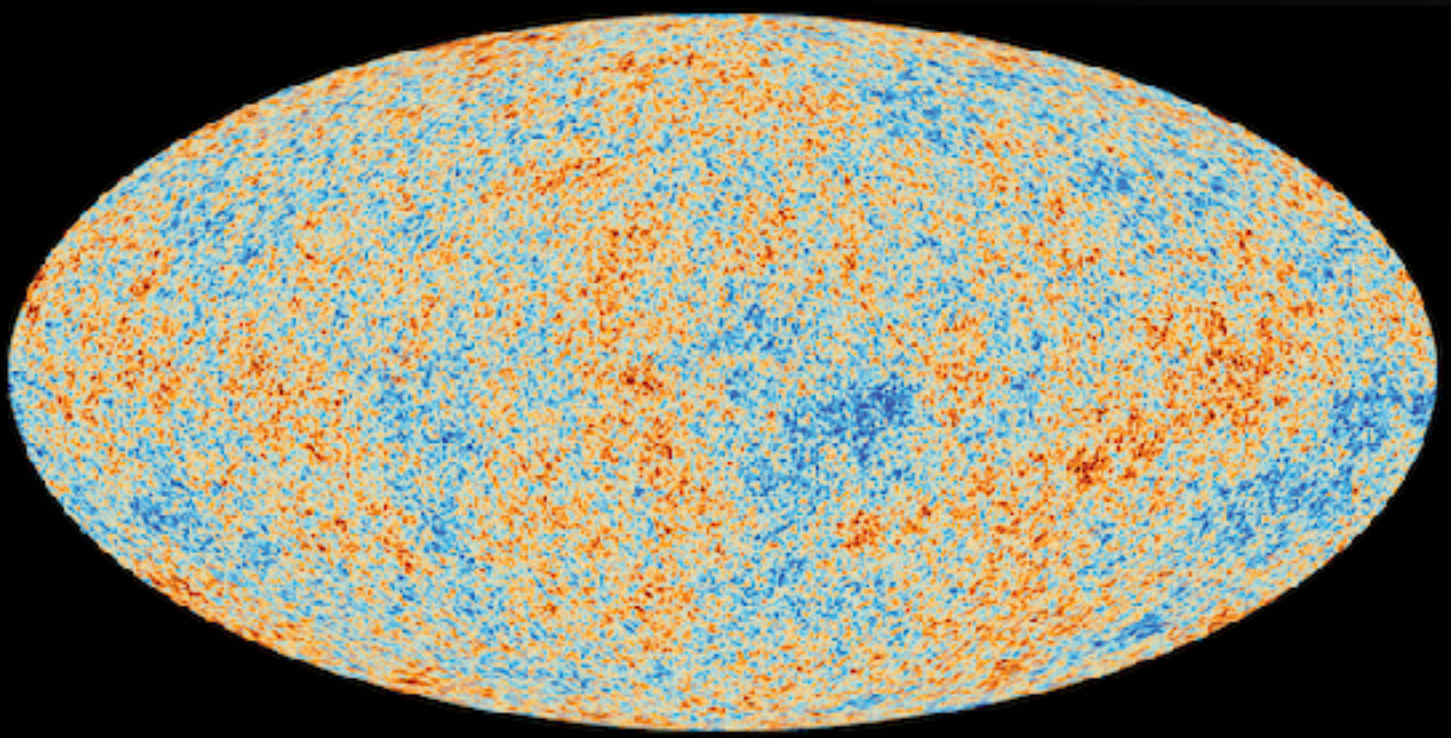
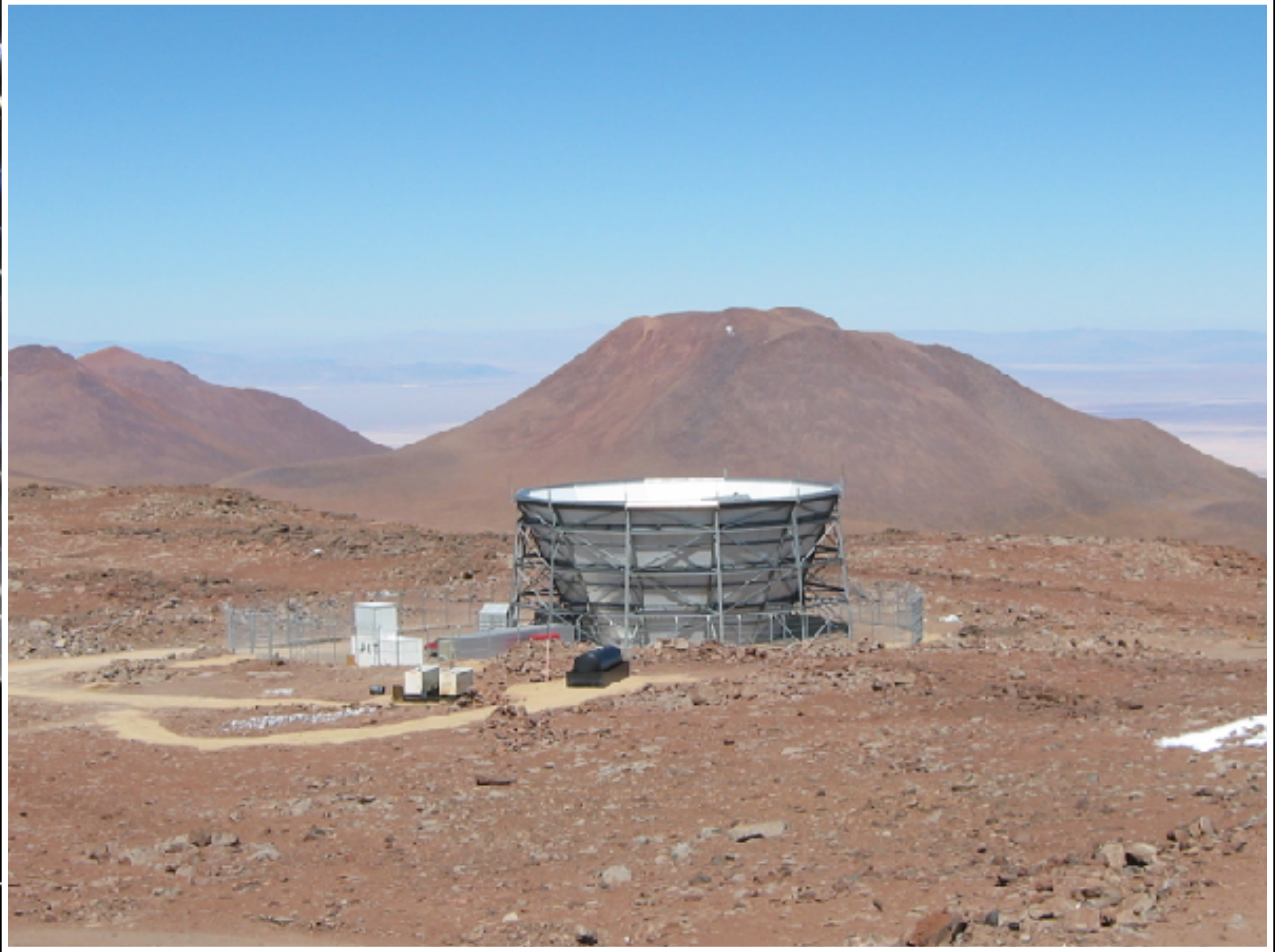
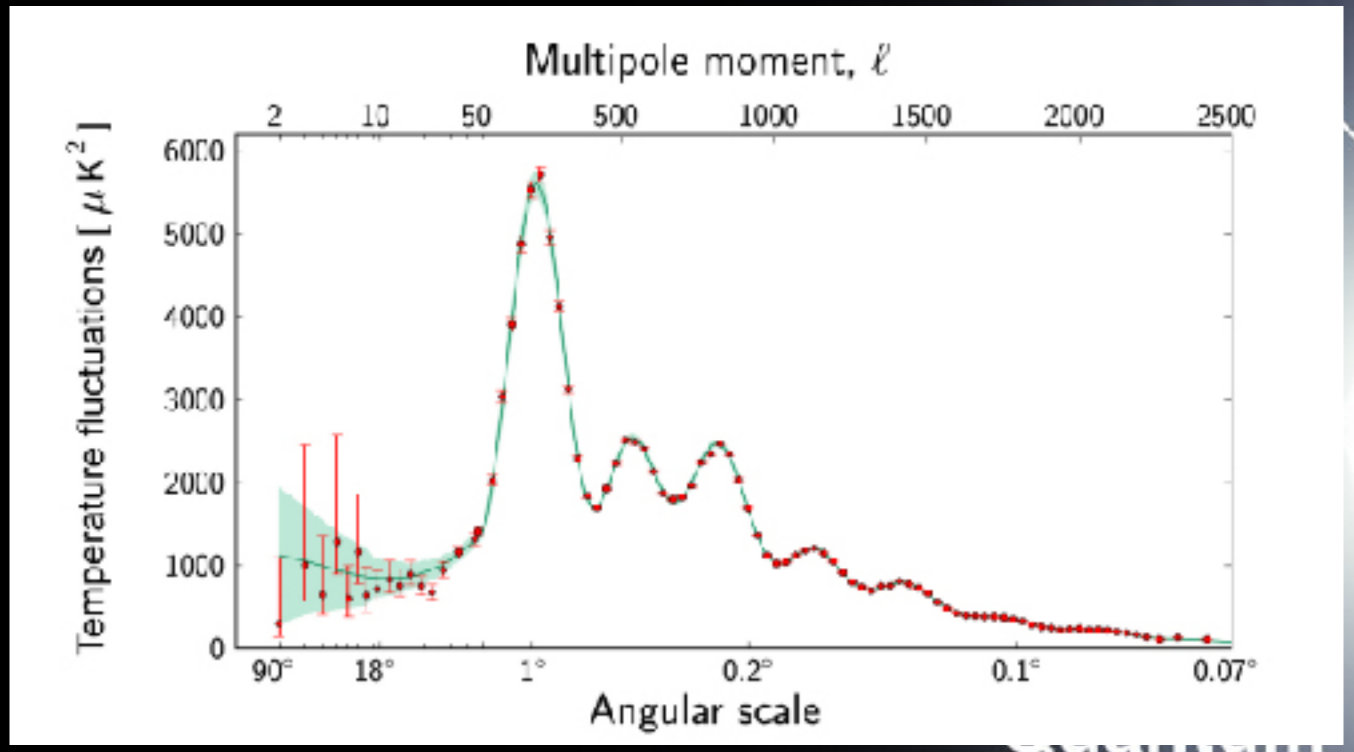


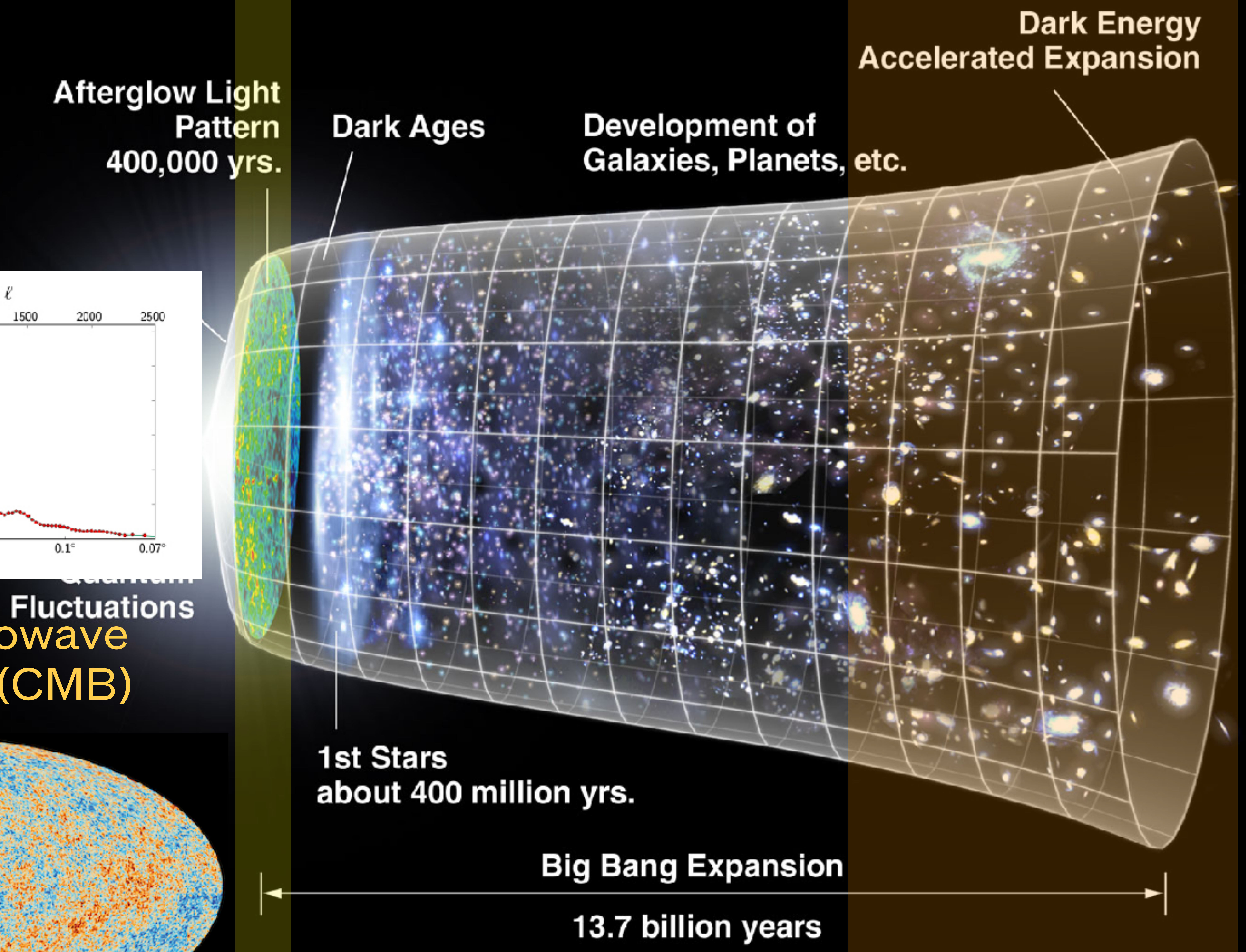






NASA/WMAP Science Team





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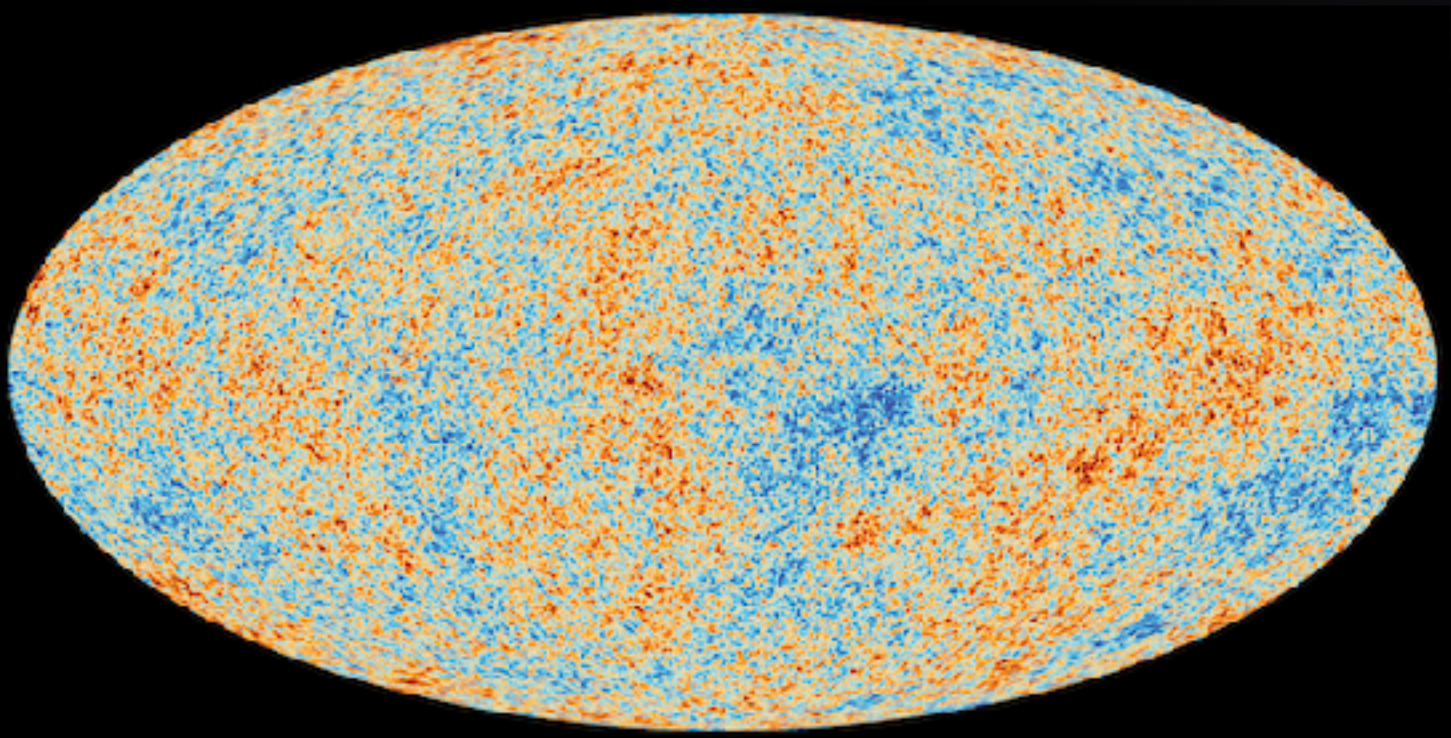
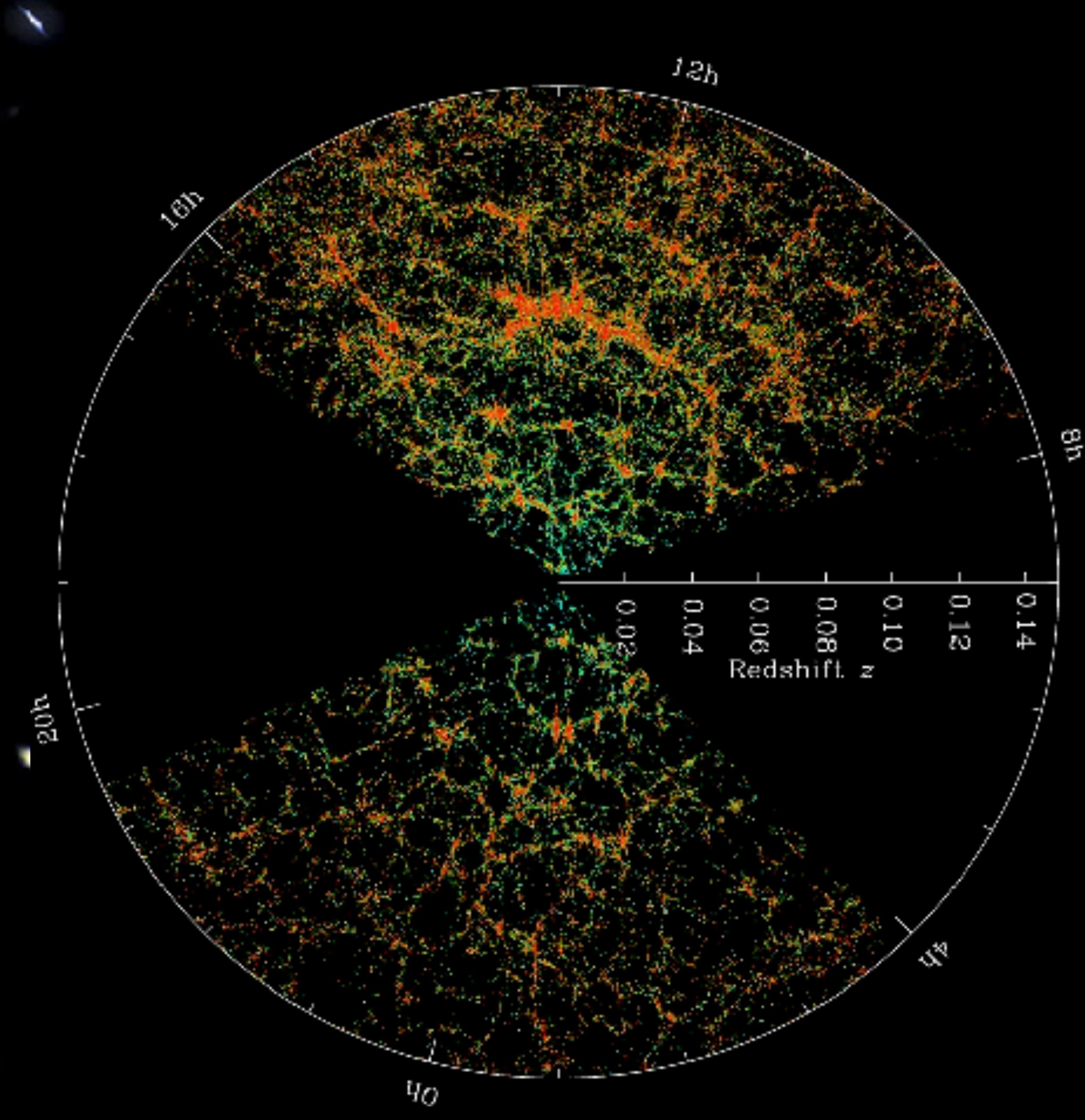
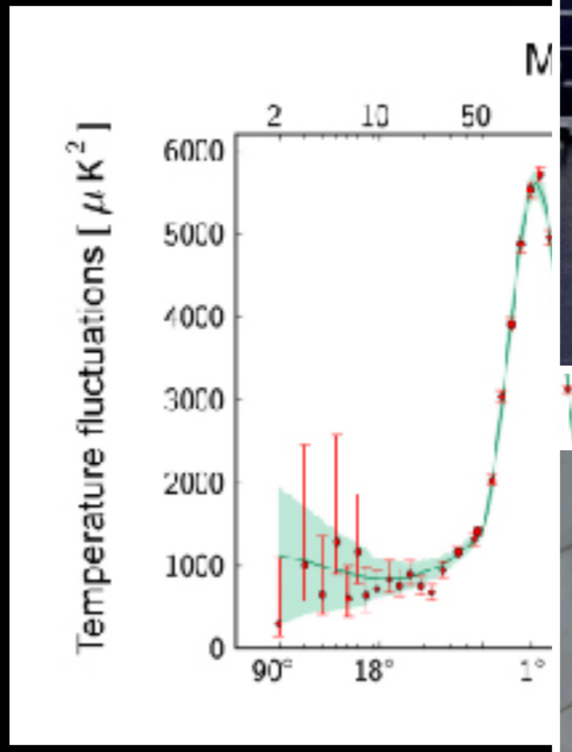


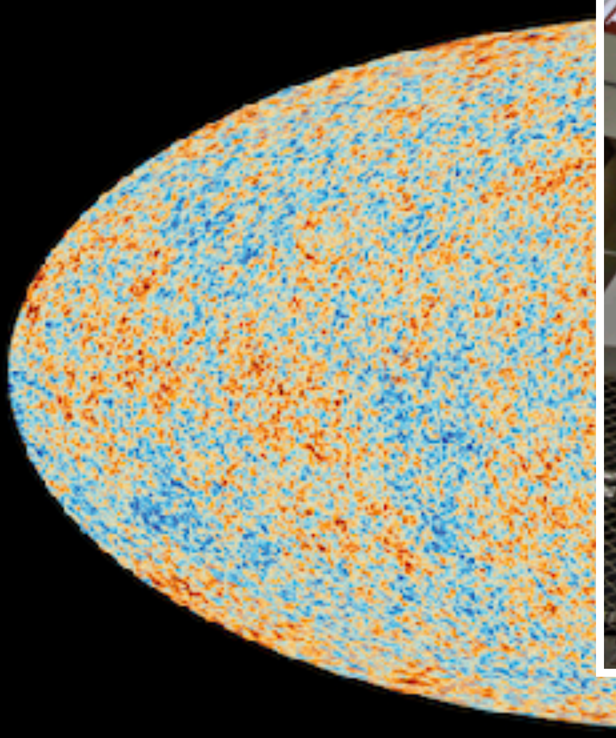


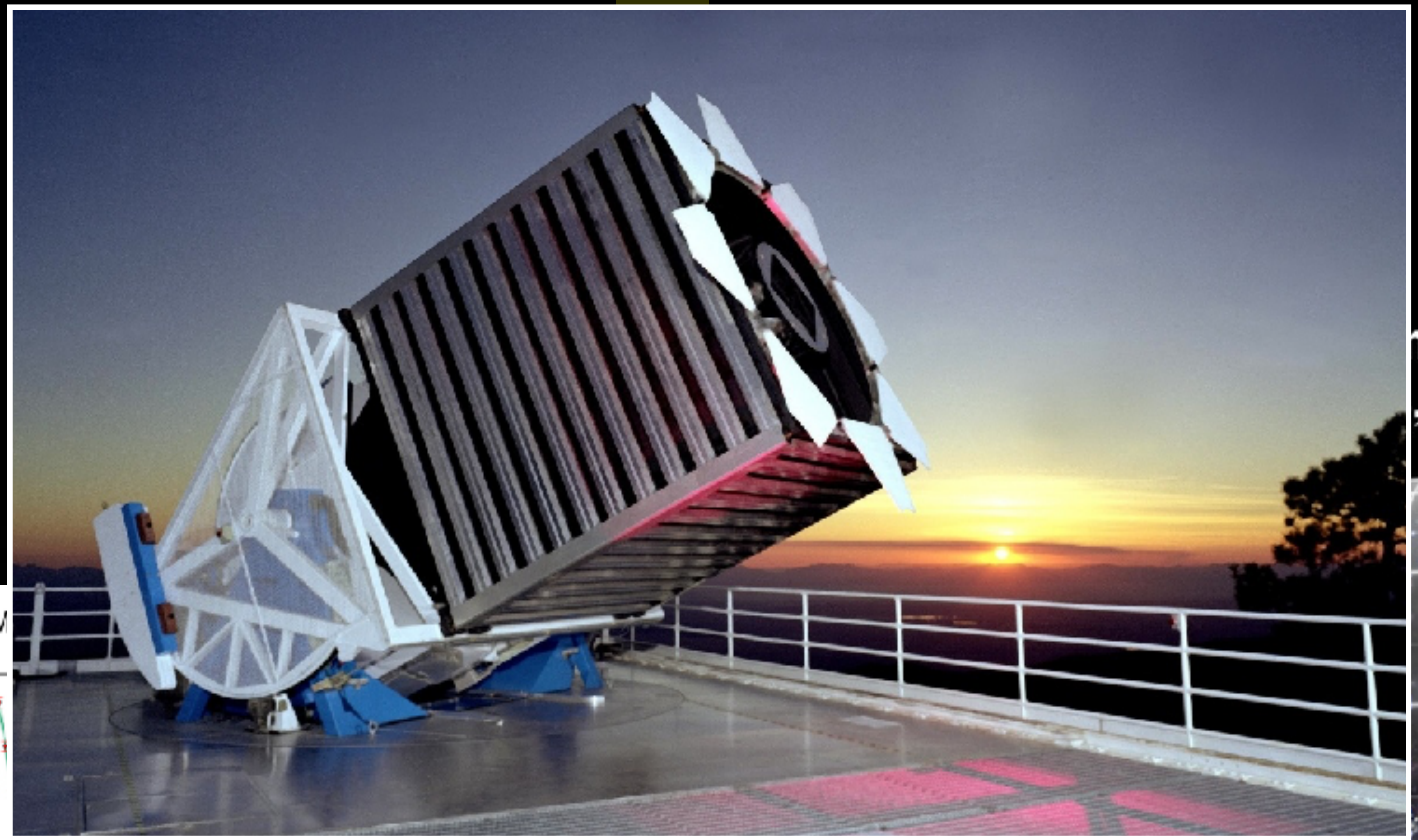
Galaxy surveys
z = 0-1+

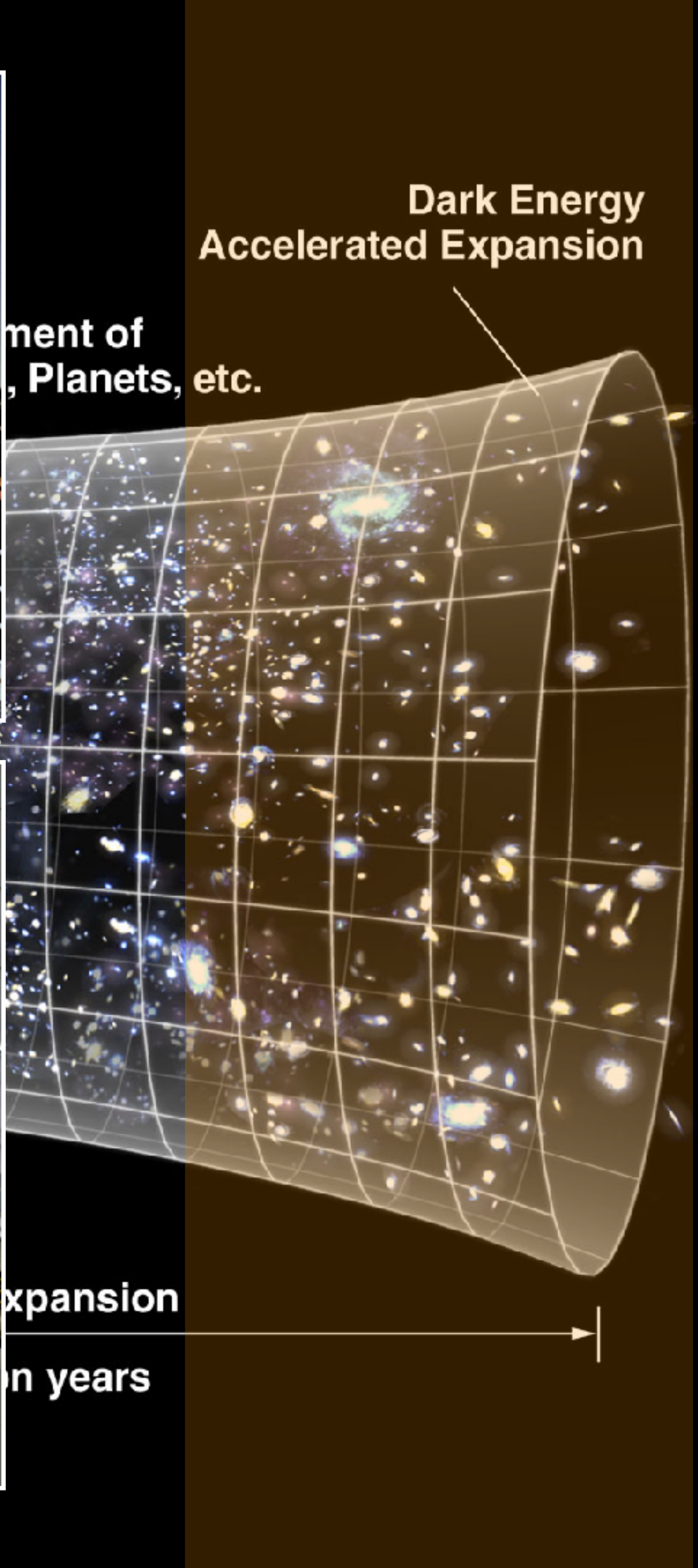
NASA/WMAP Science Team

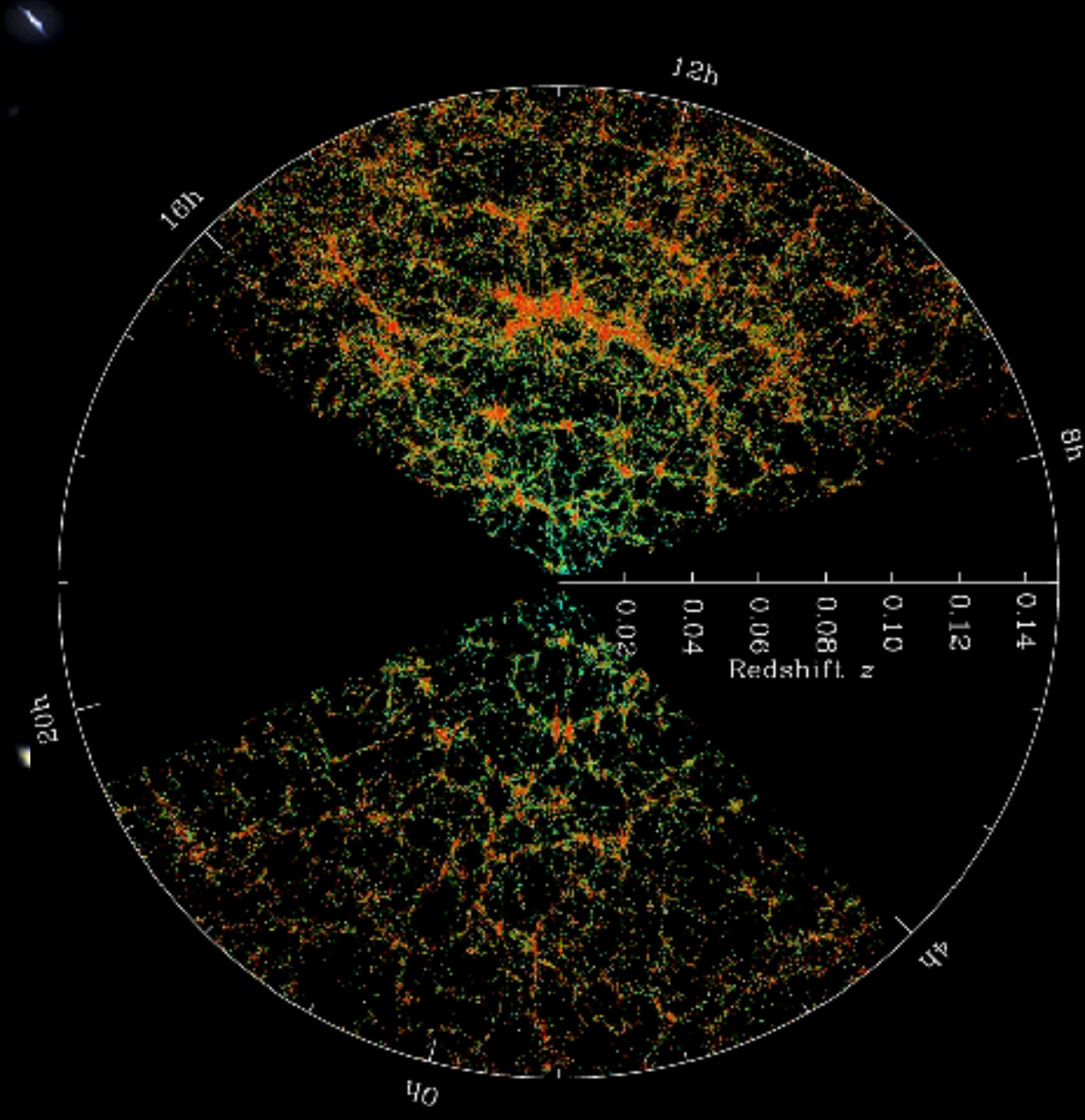


Cosmic
Backgr









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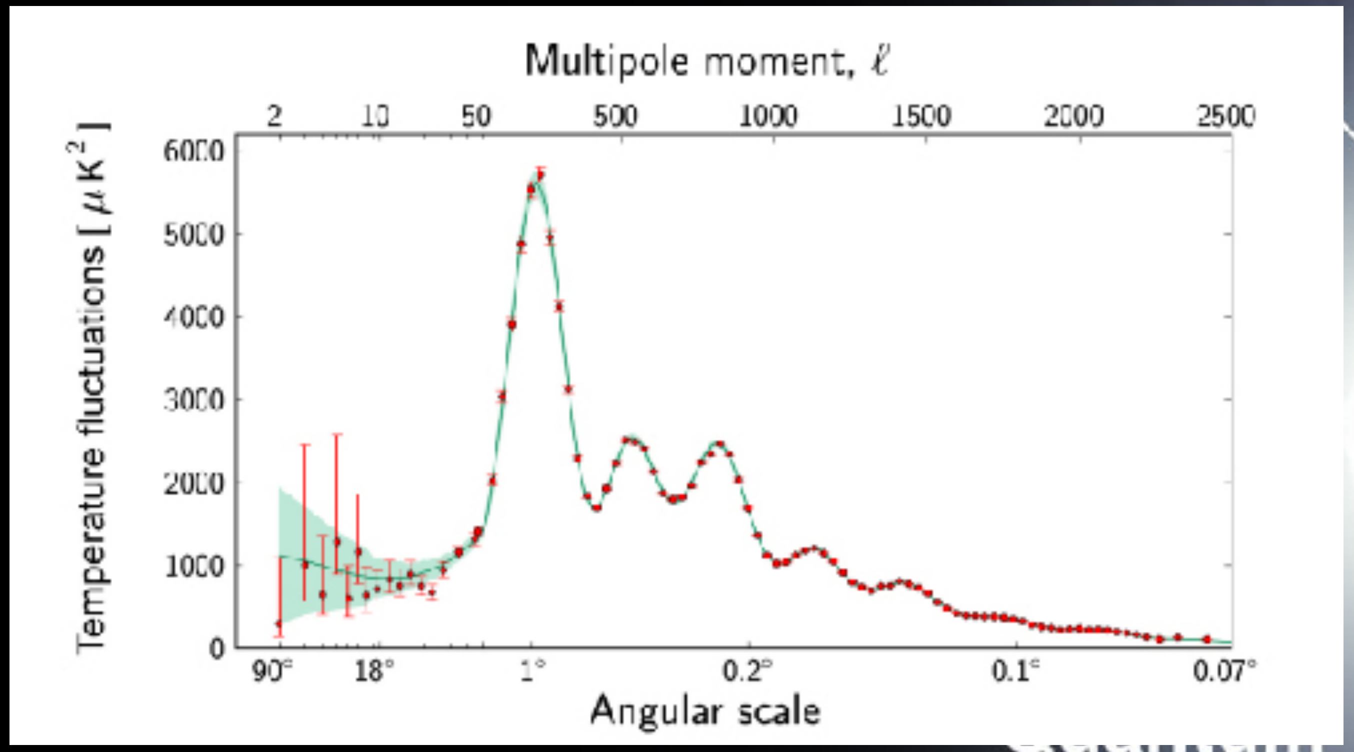
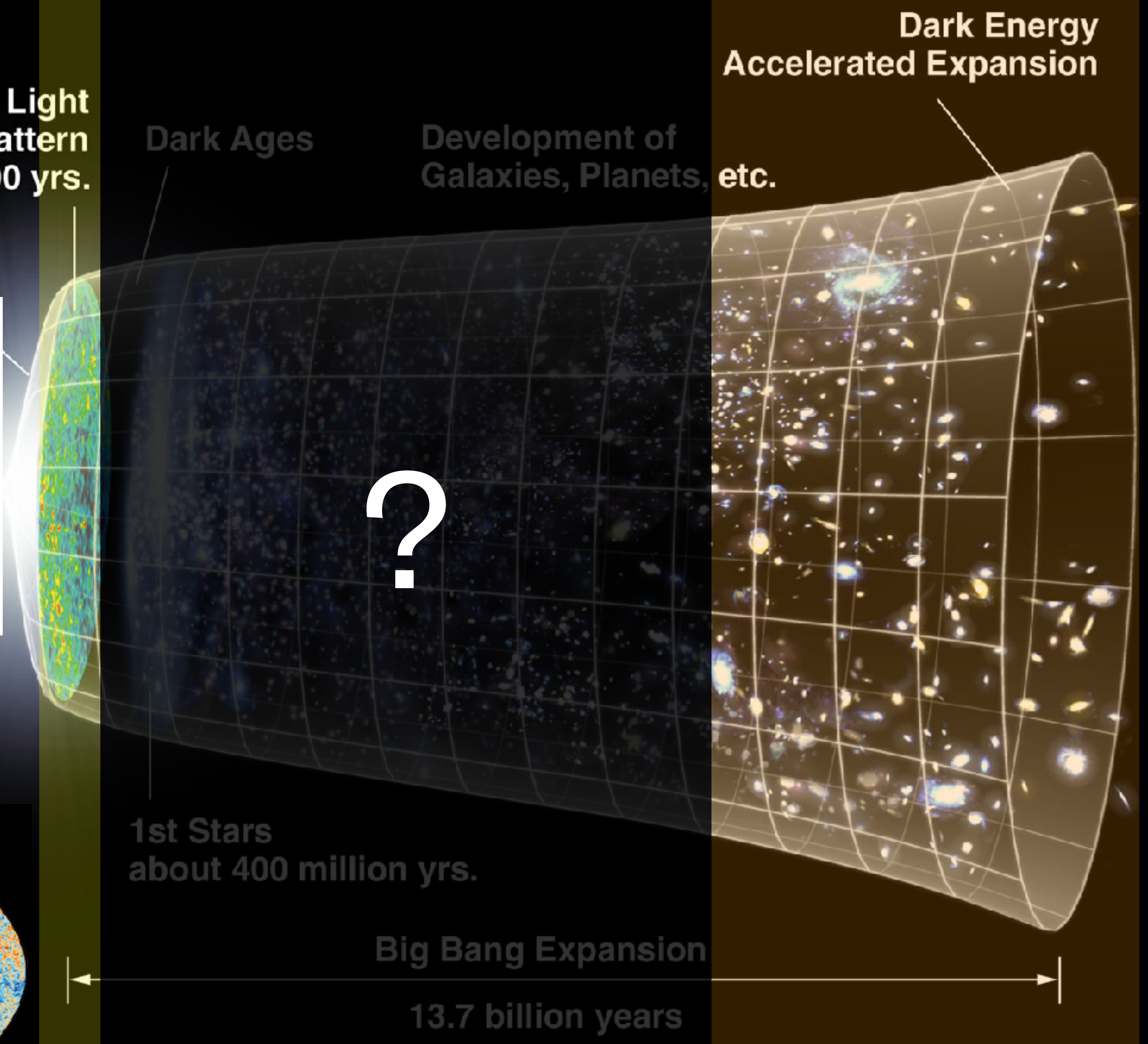
NASA/WMAP Science Team





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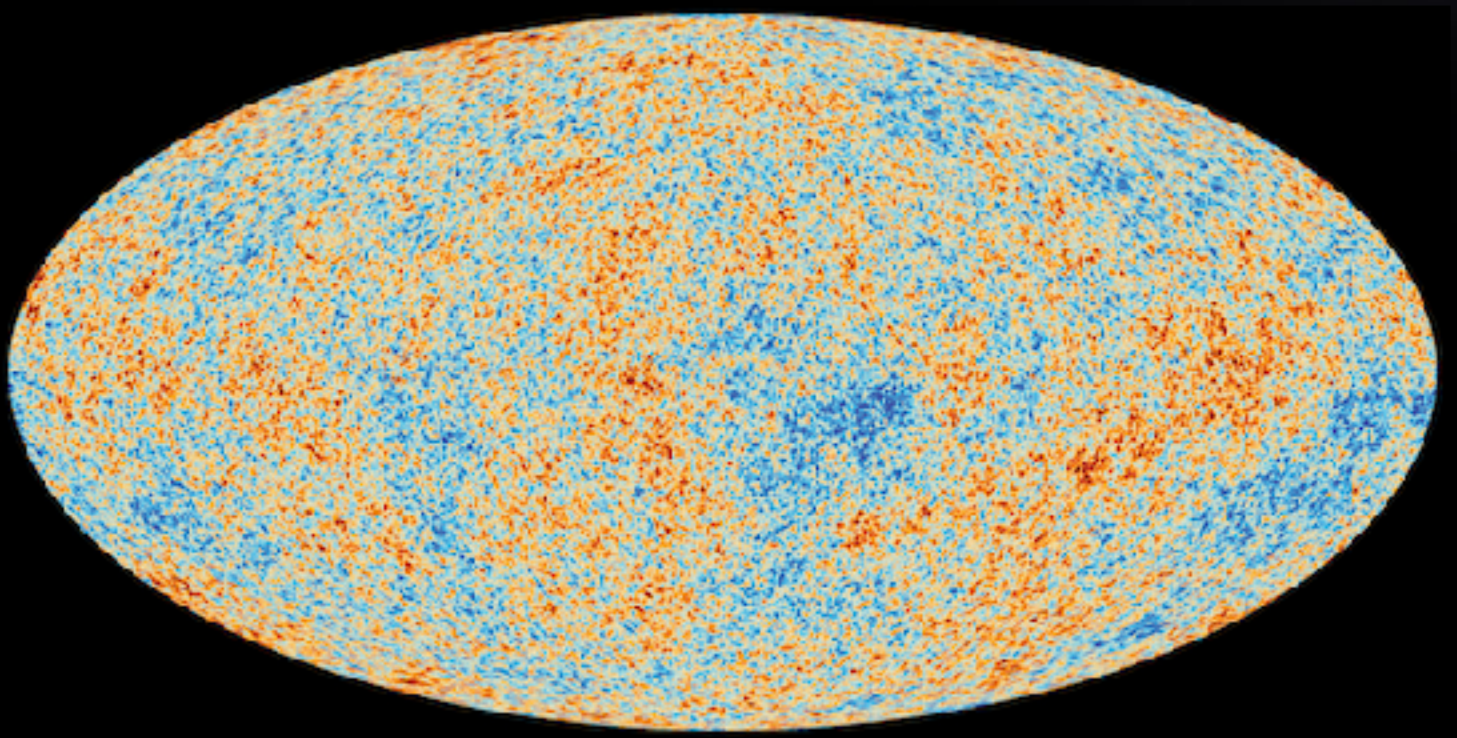
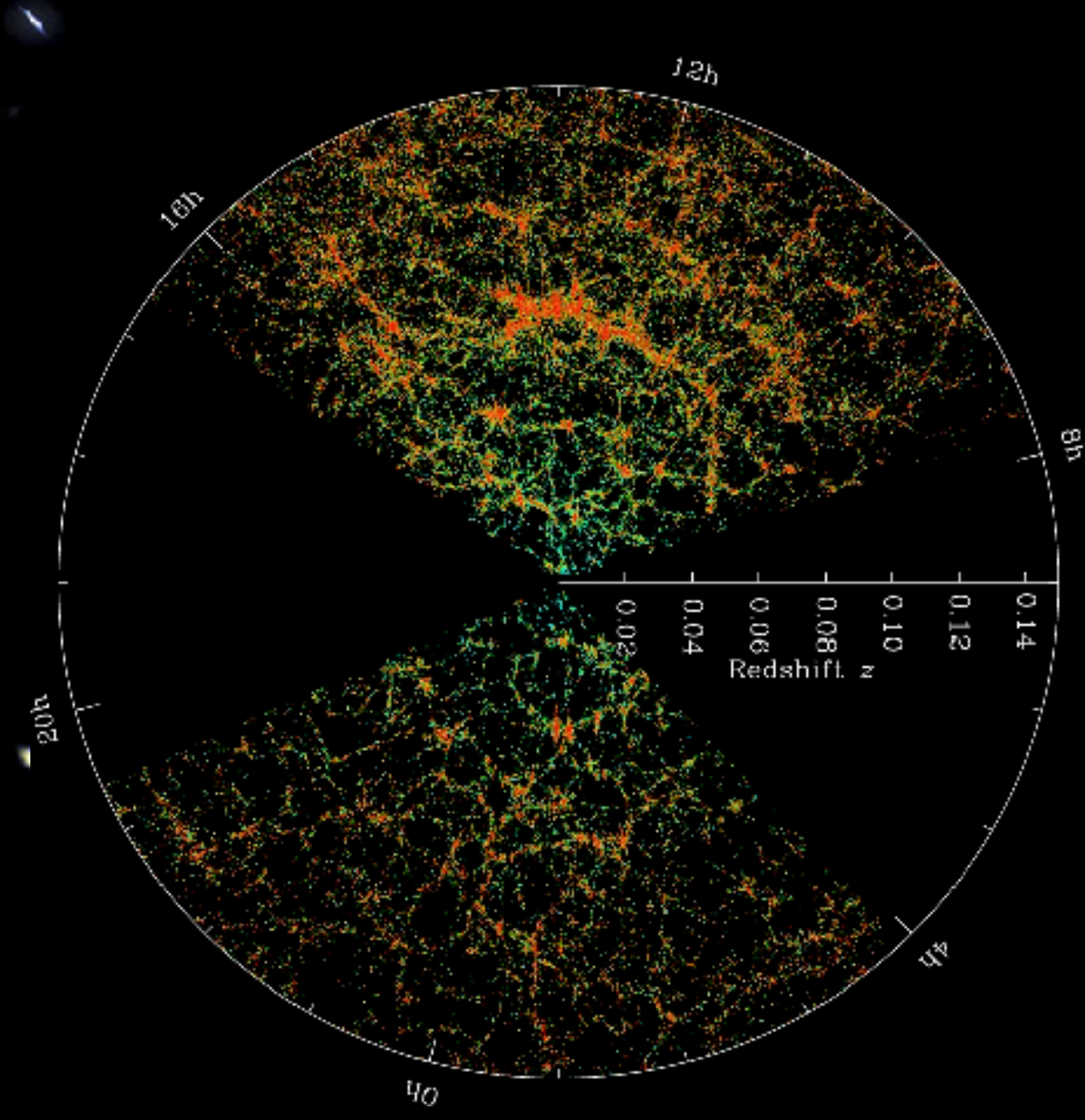


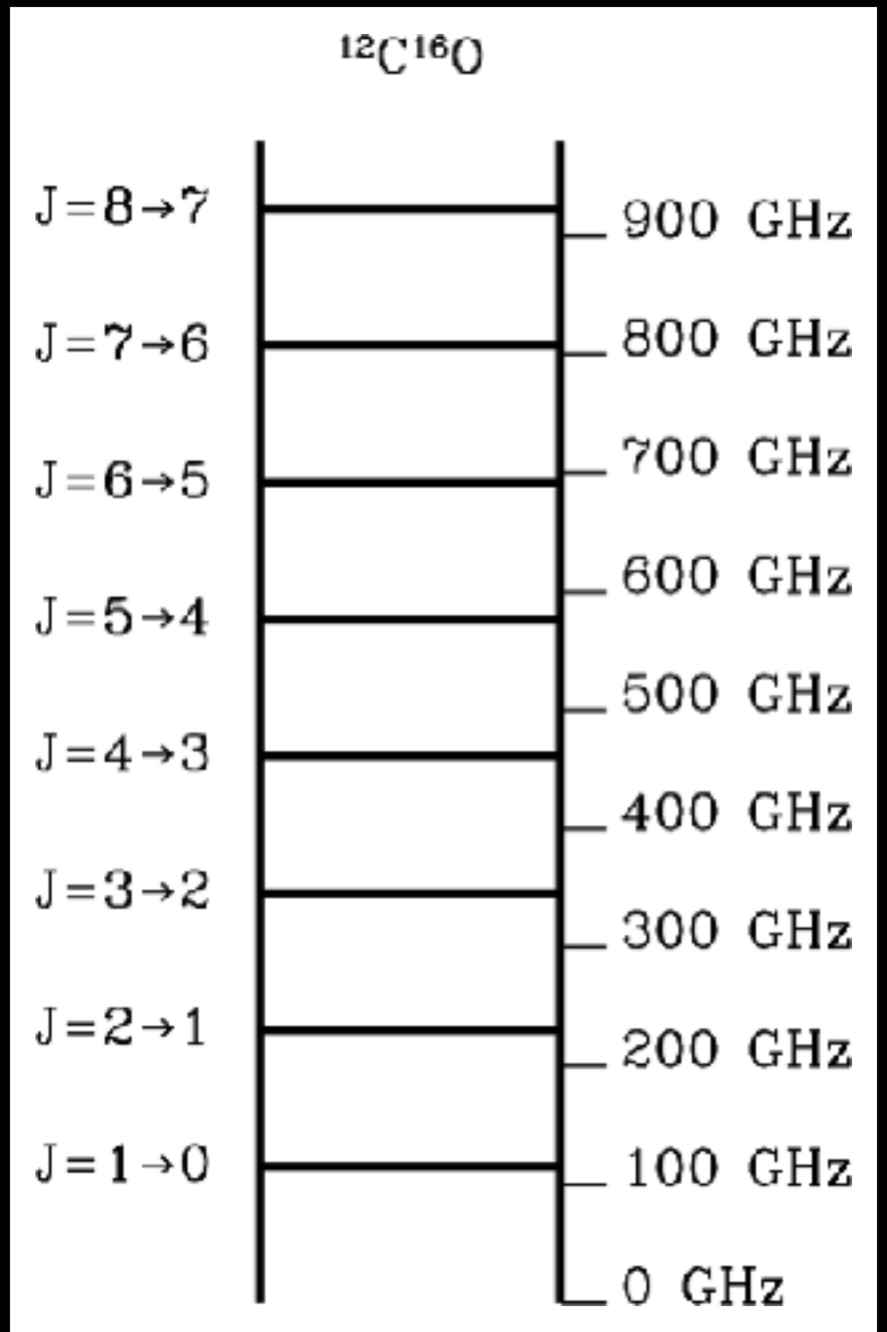


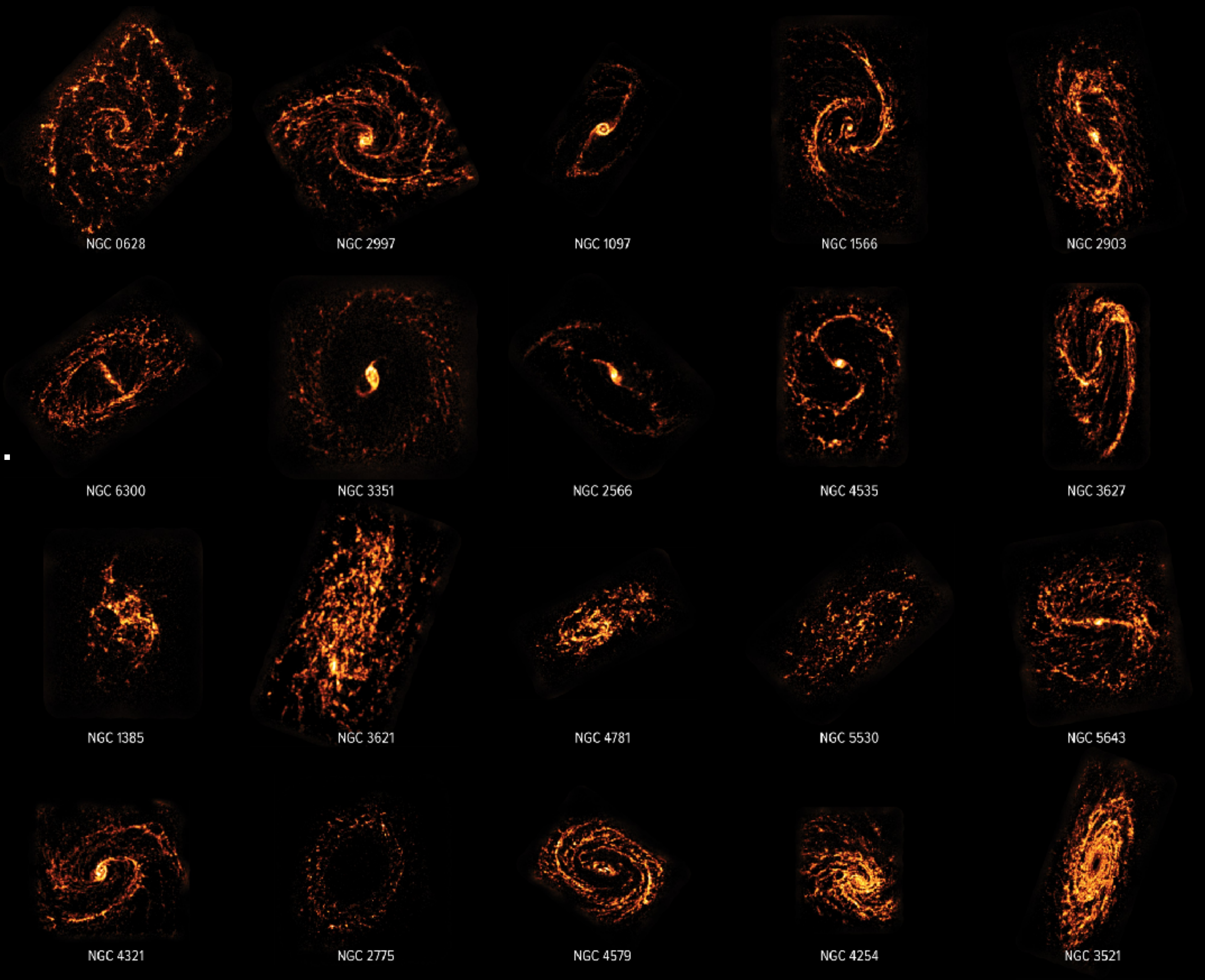
Galaxy surveys
z = 0-1+

NASA/WMAP Science Team

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.



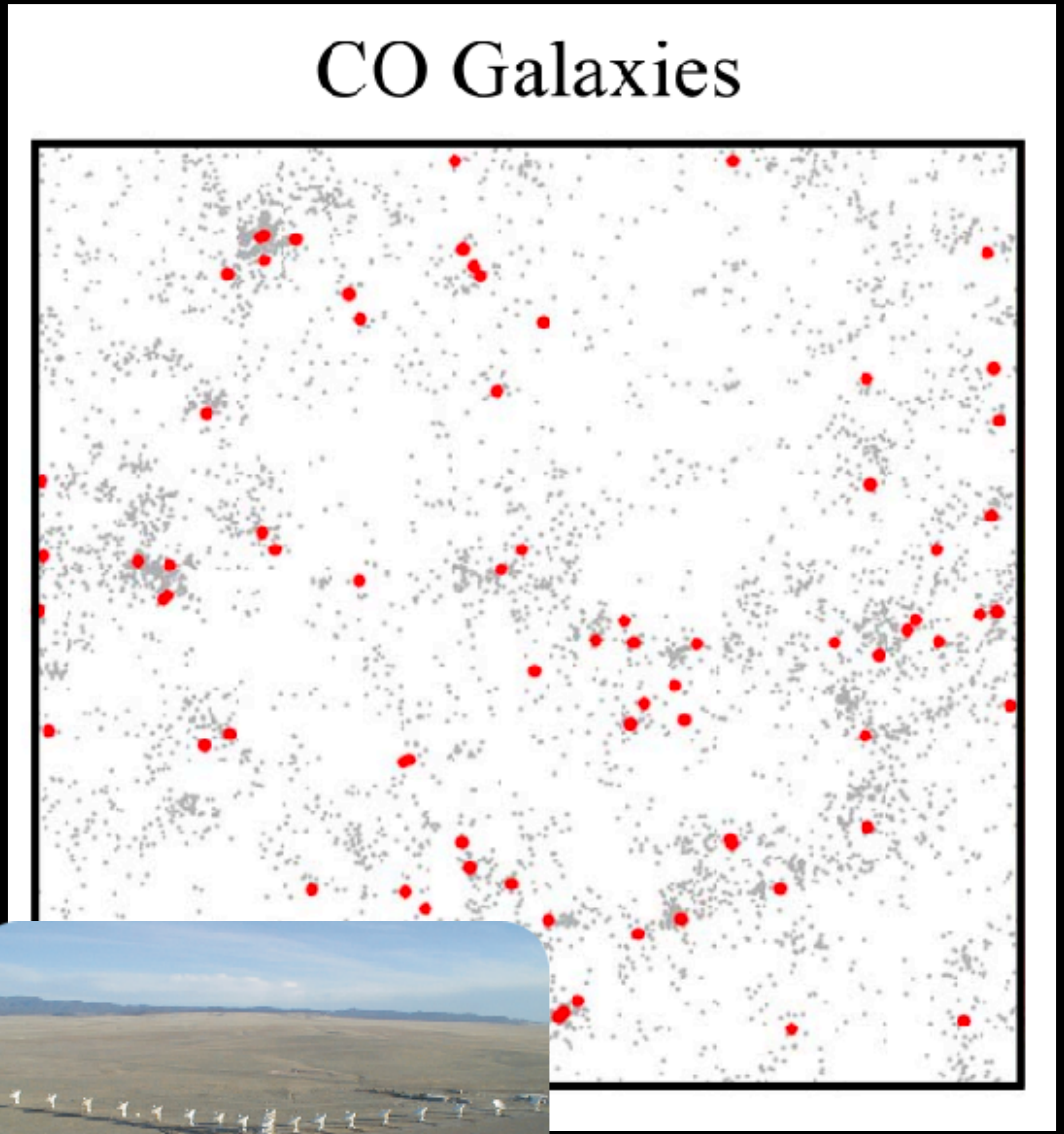


Credit: ALMA (ESO/NAOJ/NRAO)/PHANGS, S. Dagnello (NRAO)

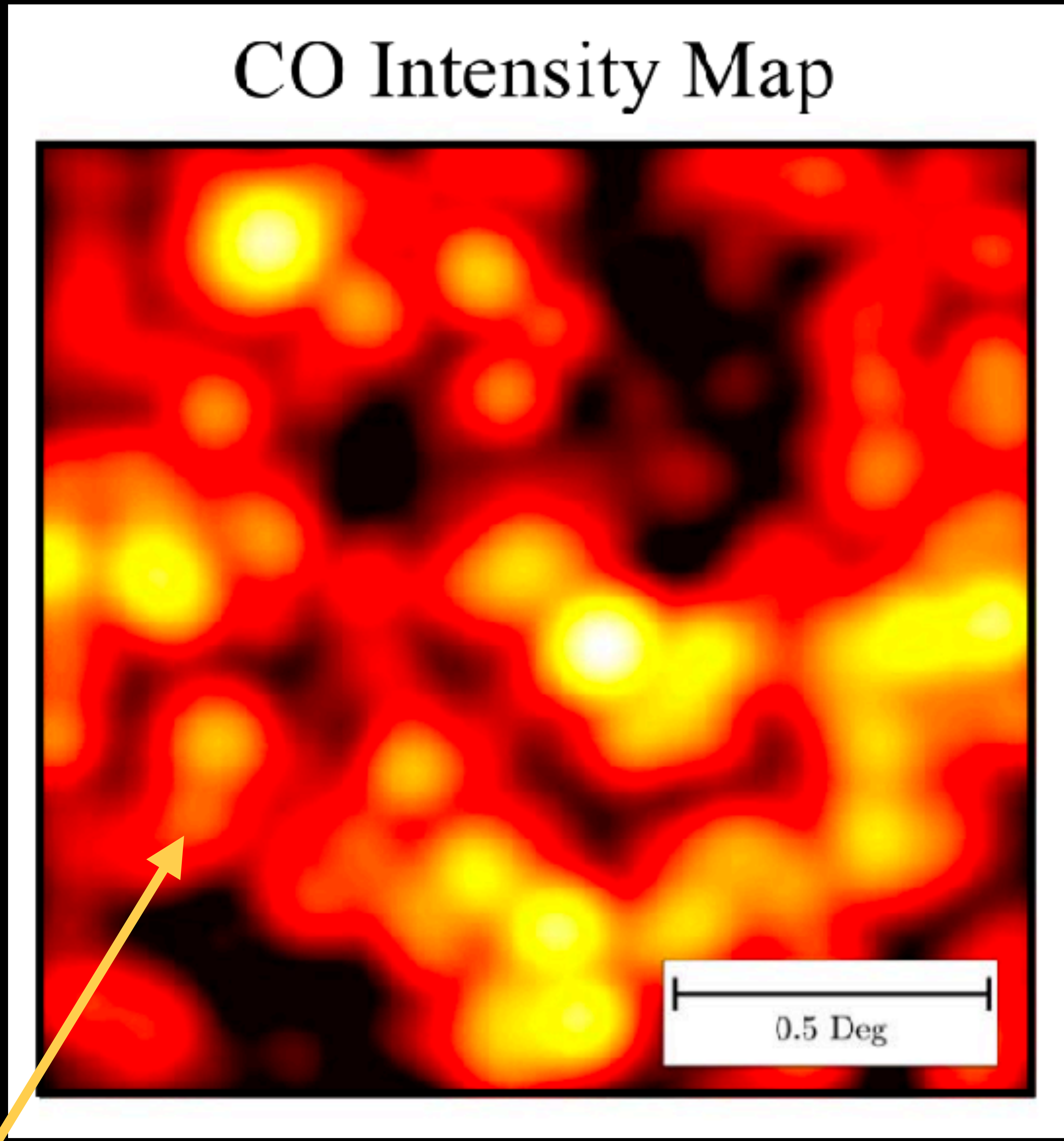
Line Intensity Mapping (LIM, ‘선 세기 매핑’)

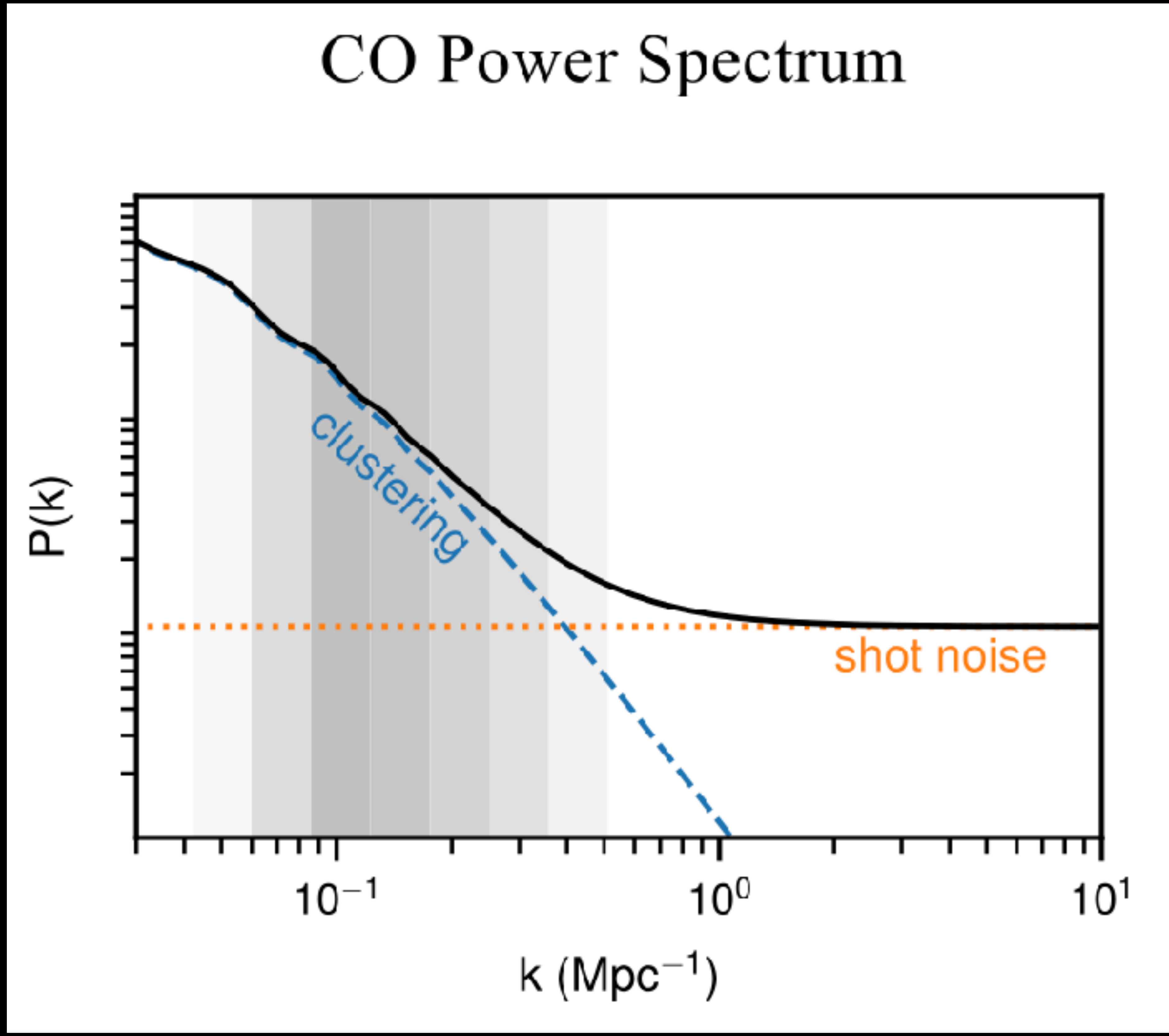
- LIM is sensitive to the “aggregate line emission from all galaxies in the line of sight”.

CO(1-0) at z~3



(convolved with ~5 arcmin beam)





all of the photons!

Kovetz et al. (2017), Cleary et al. (2022), Credit: Patrick Breysse & Dongwoo Chung

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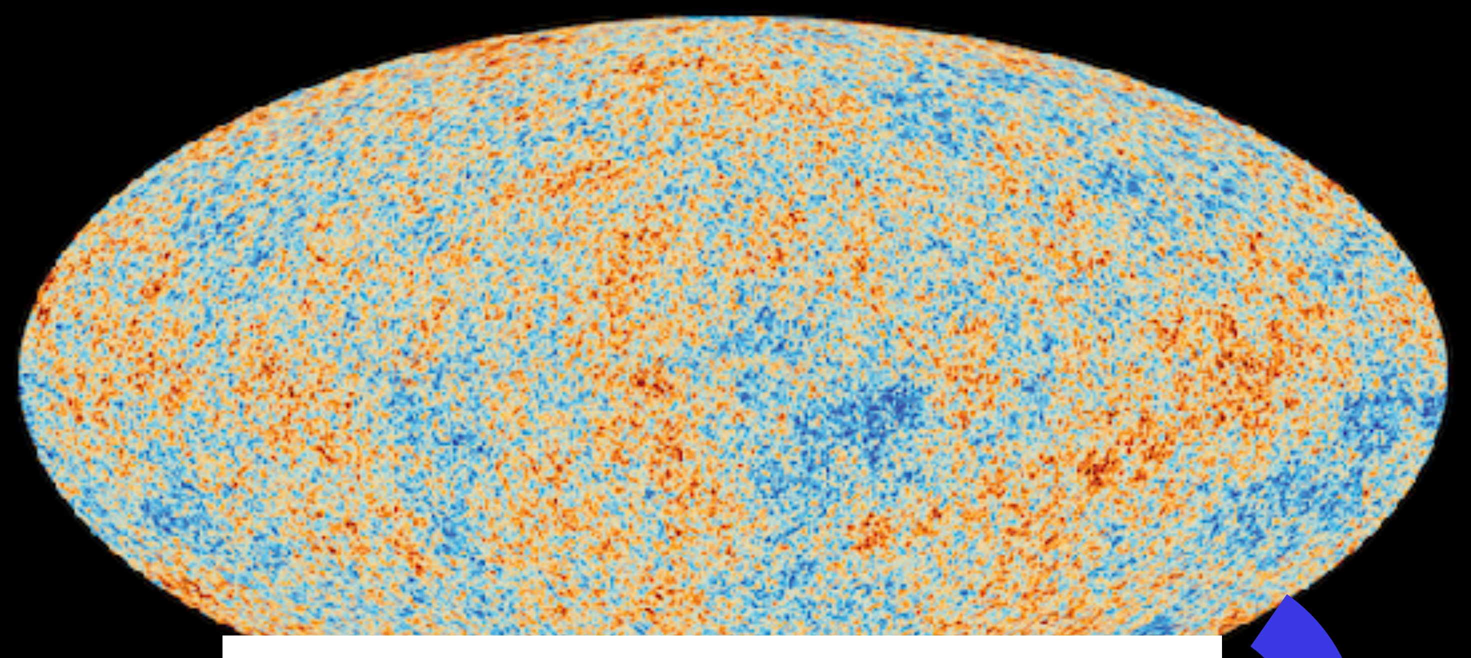
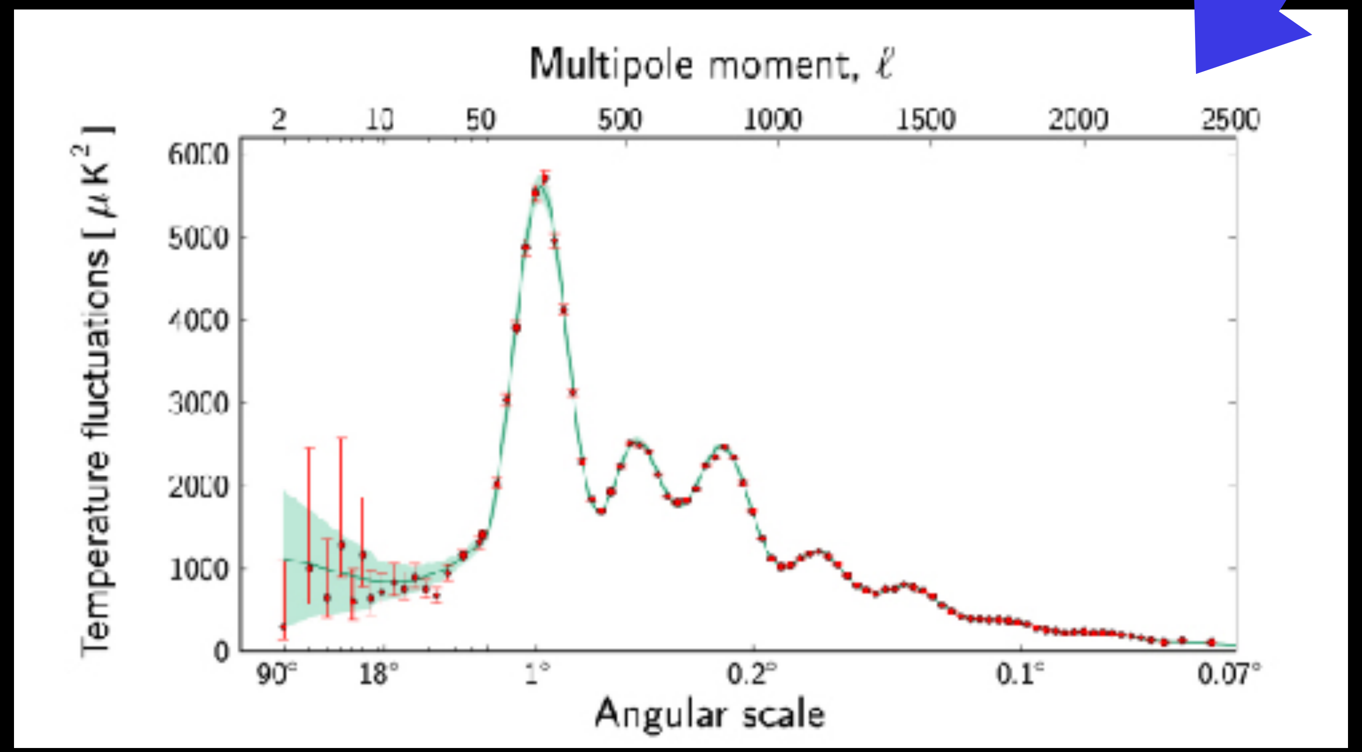


Fourier transform



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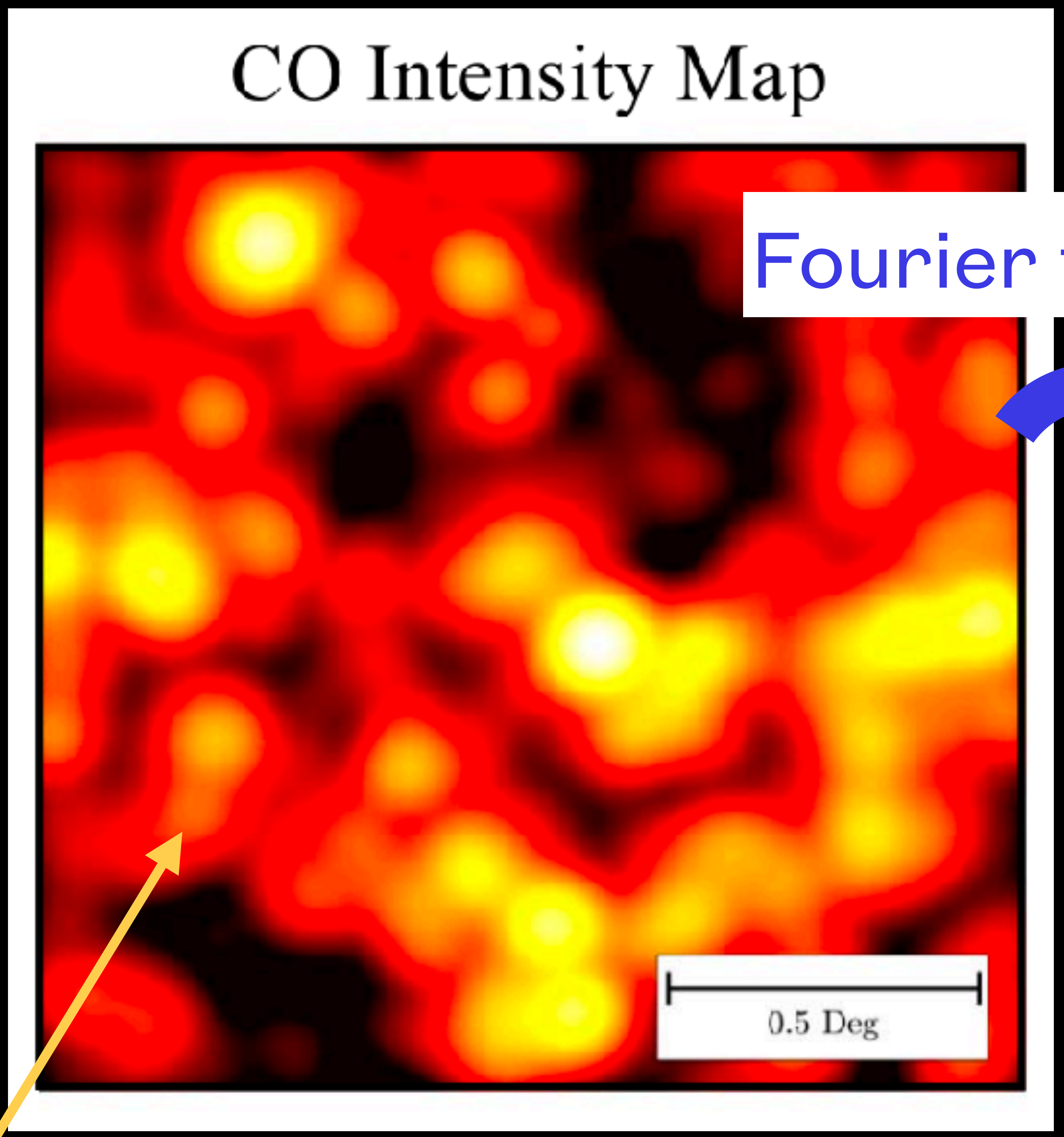
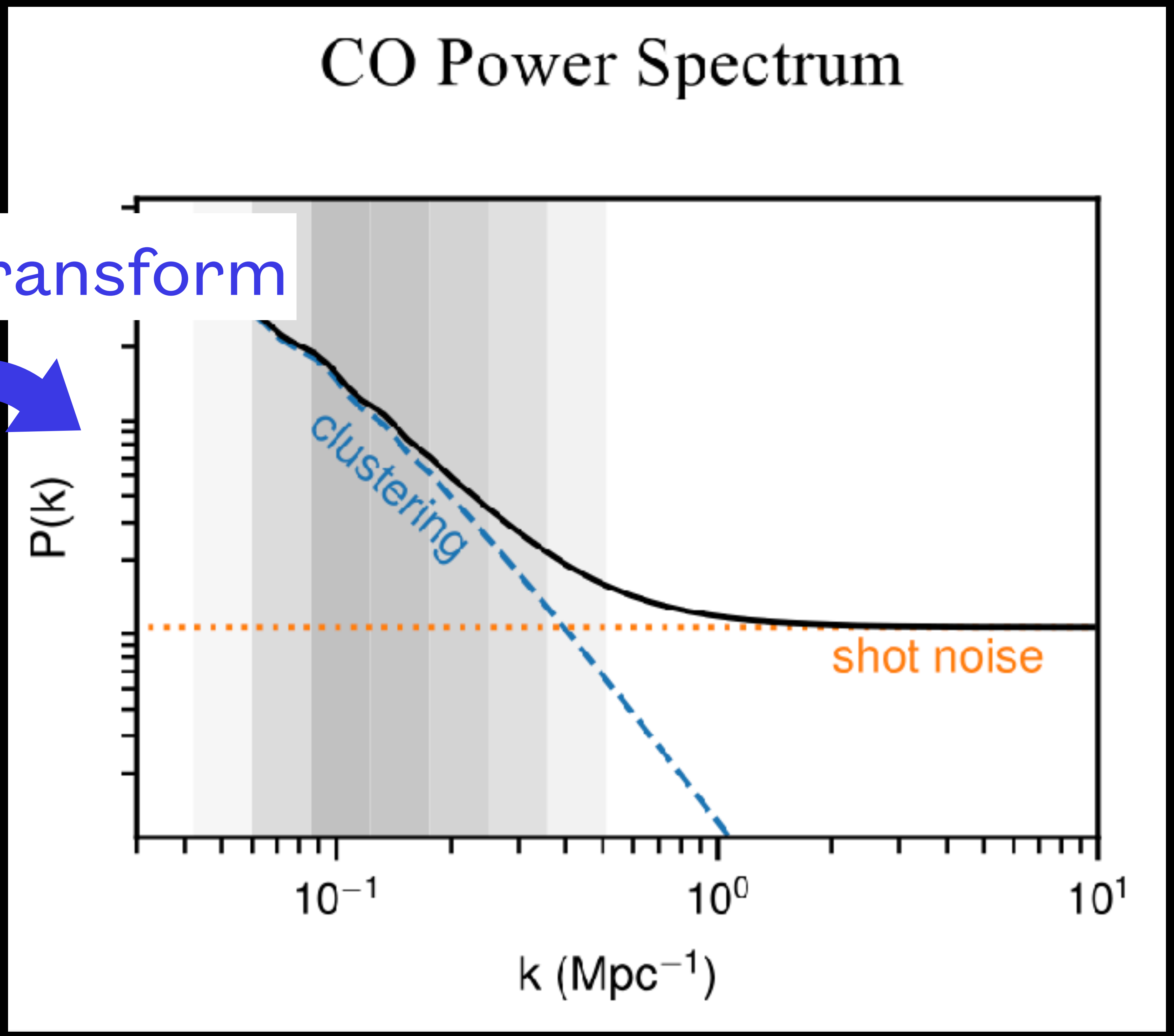


Fourier transform



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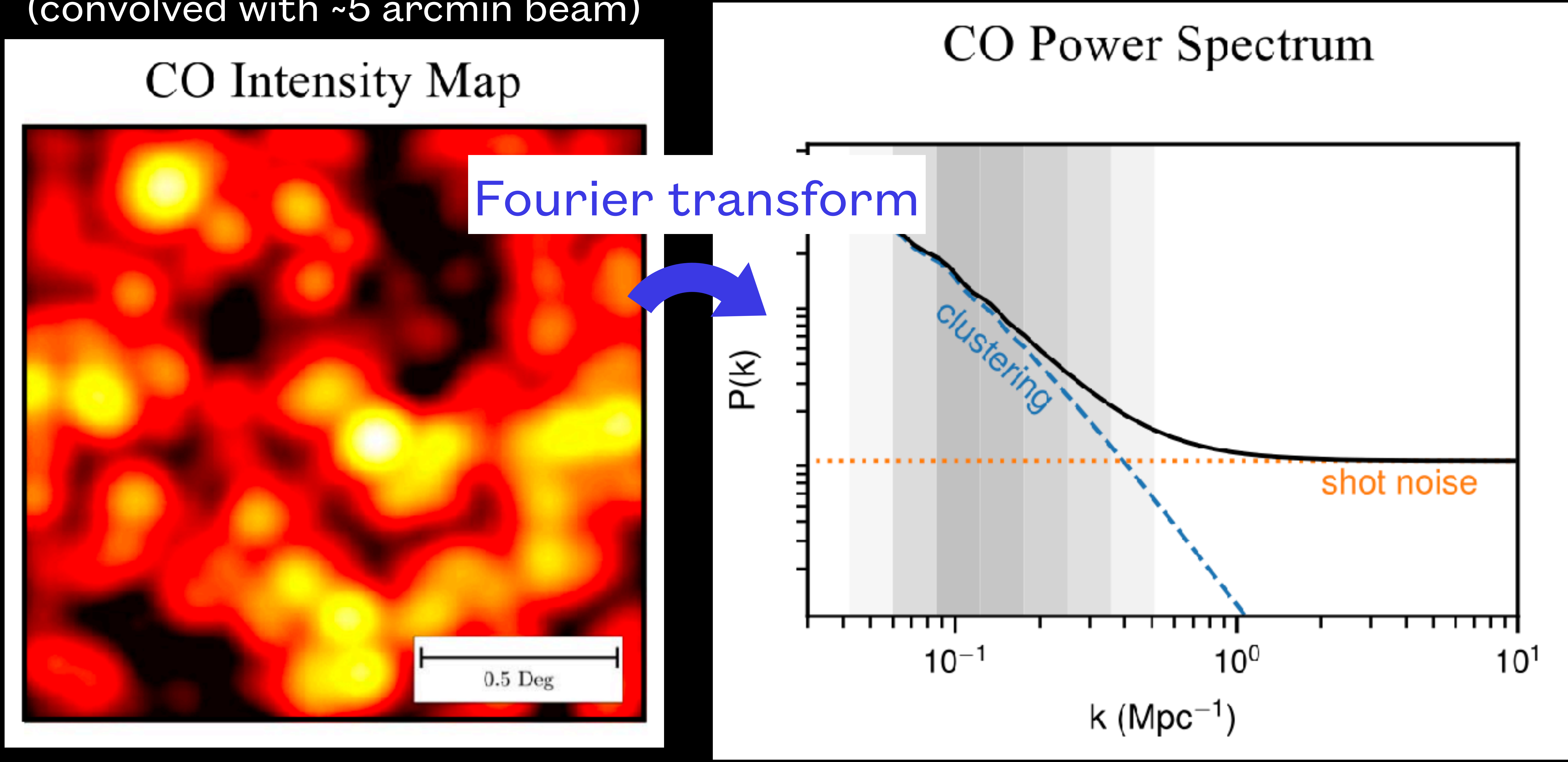


= Clustering amplitude × (Underlying matter power spectrum) + shot noise

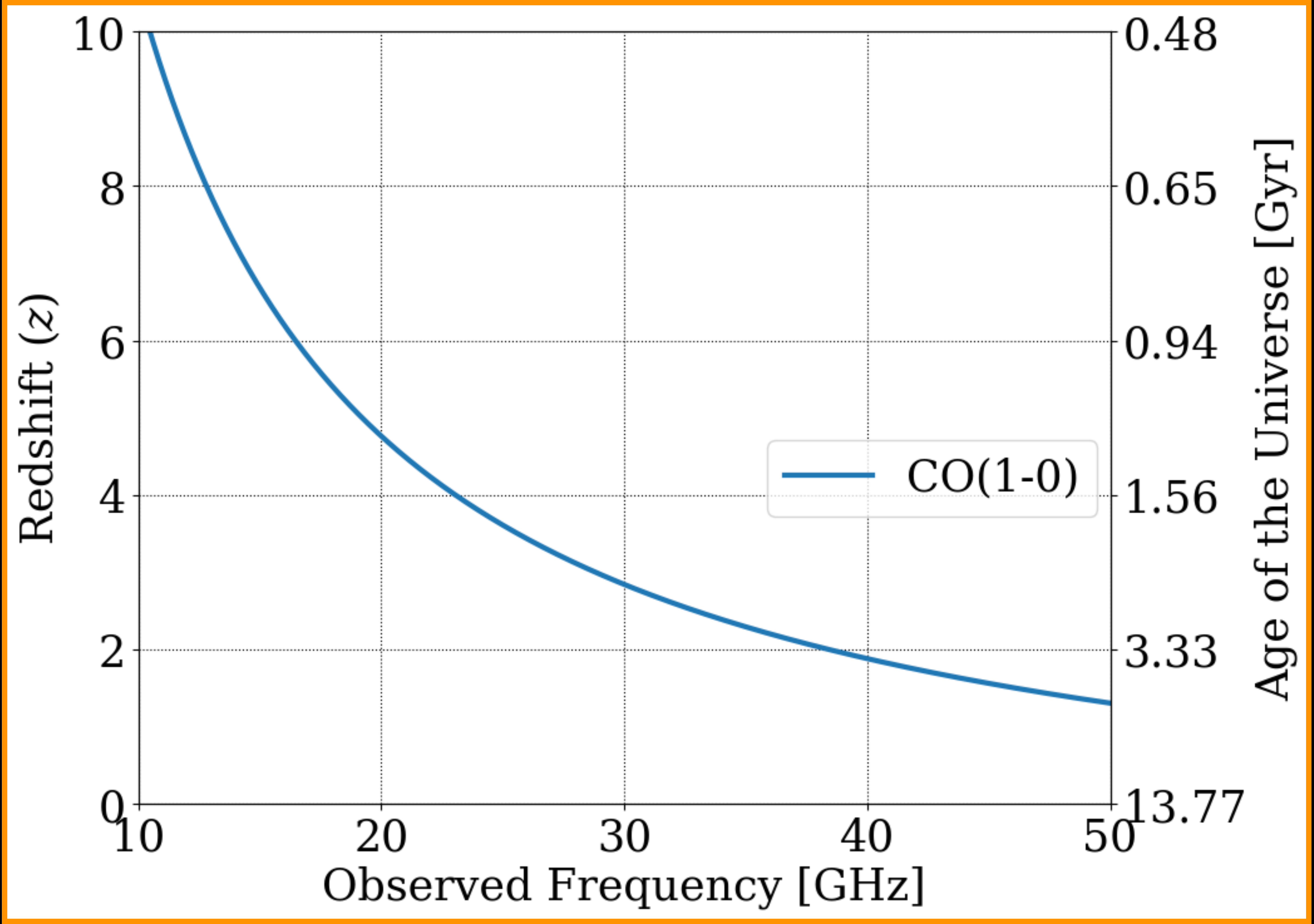
$$P_{\rm CO}(k) = A_{\rm clust} P_m(k) + P_{\rm shot}$$

Kovetz et al. (2017), Cleary et al. (2022), Credit: Patrick Breysse & Dongwoo Chung

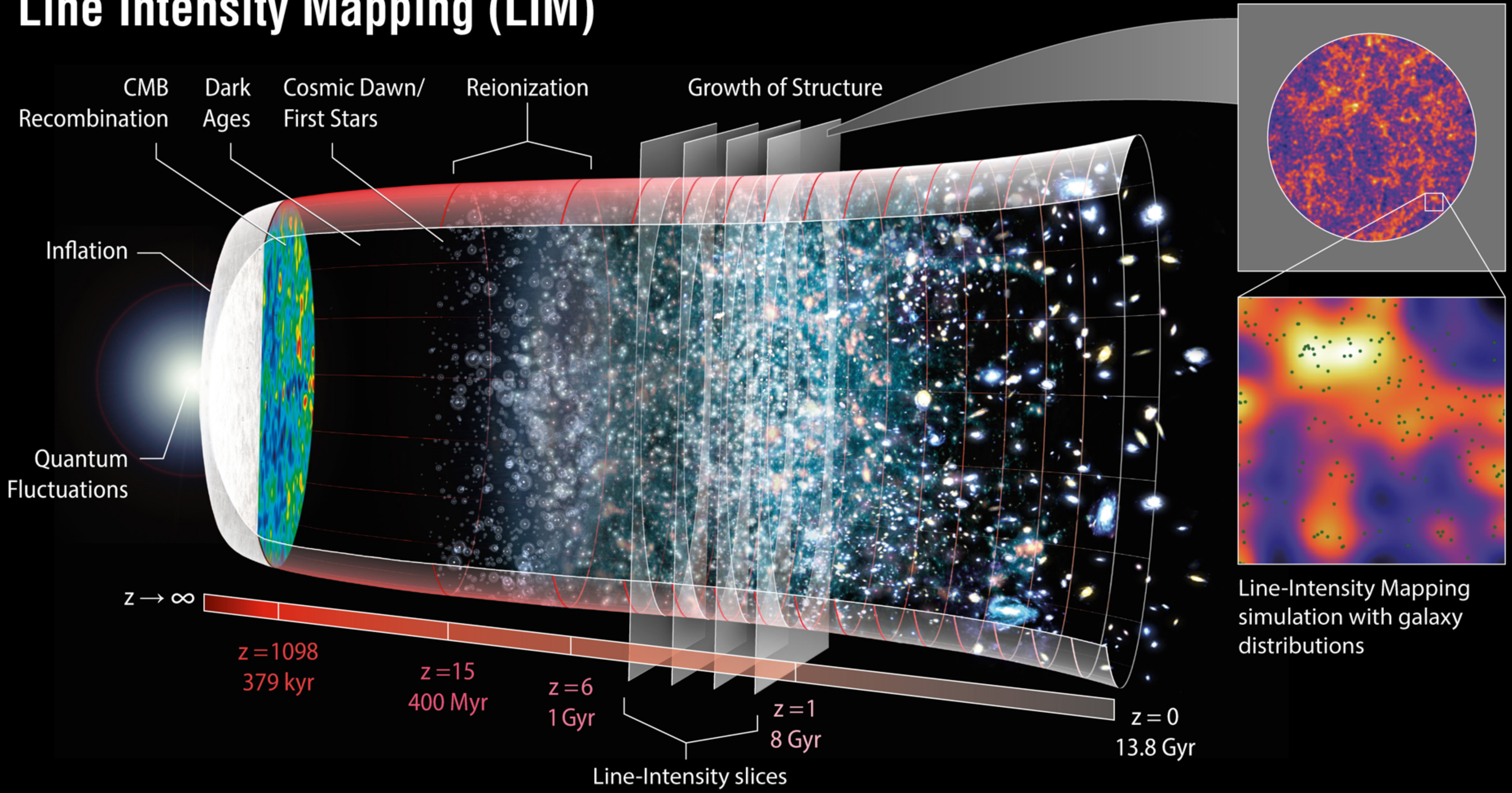
- Cosmological Redshift: The observed frequency of a specific spectral line corresponds to the redshift, which in turn indicates the age of the Universe!

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

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



Line Intensity Mapping (LIM)

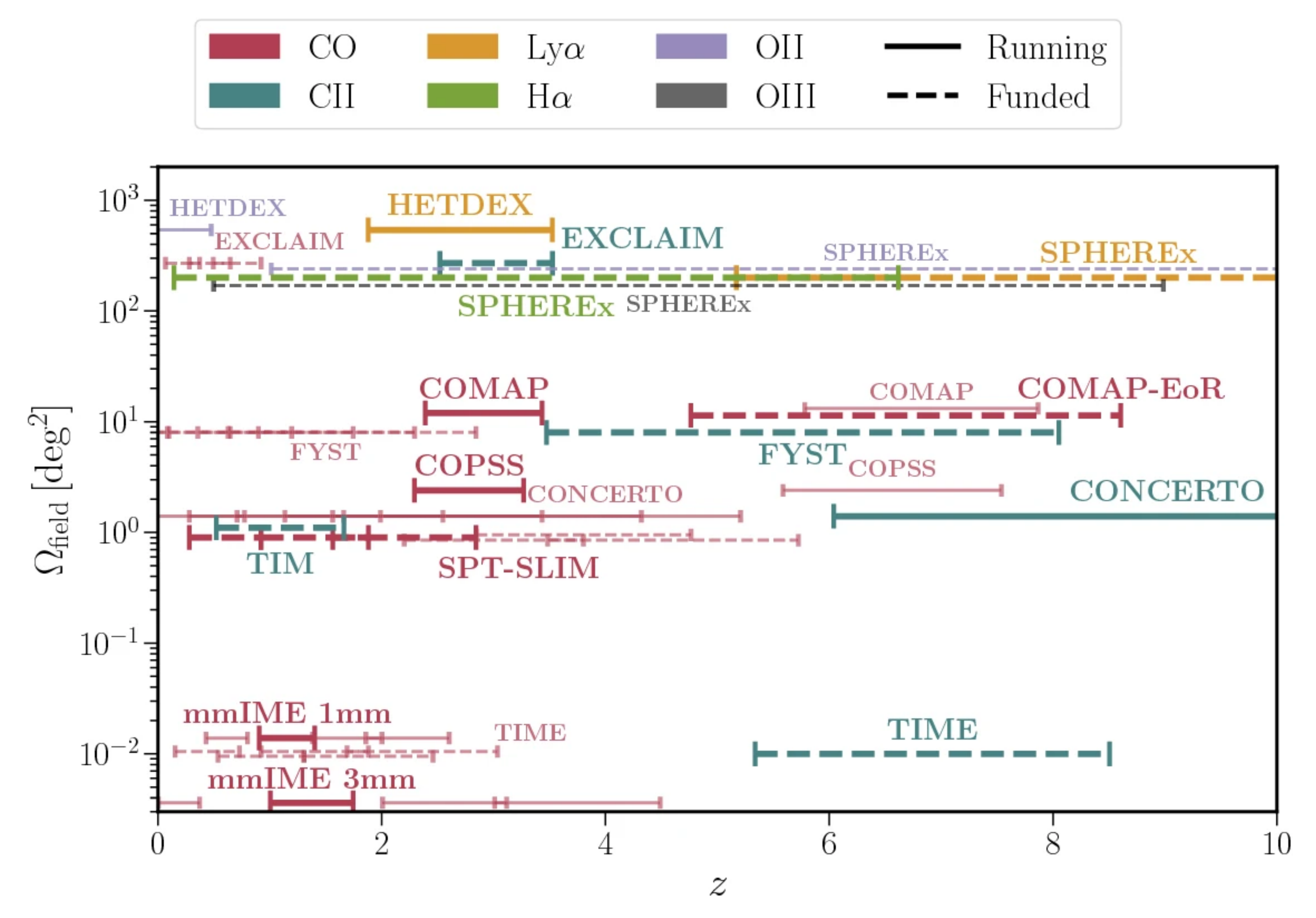


https://lambda.gsfc.nasa.gov/education/graphic_history/intensitymapping.html

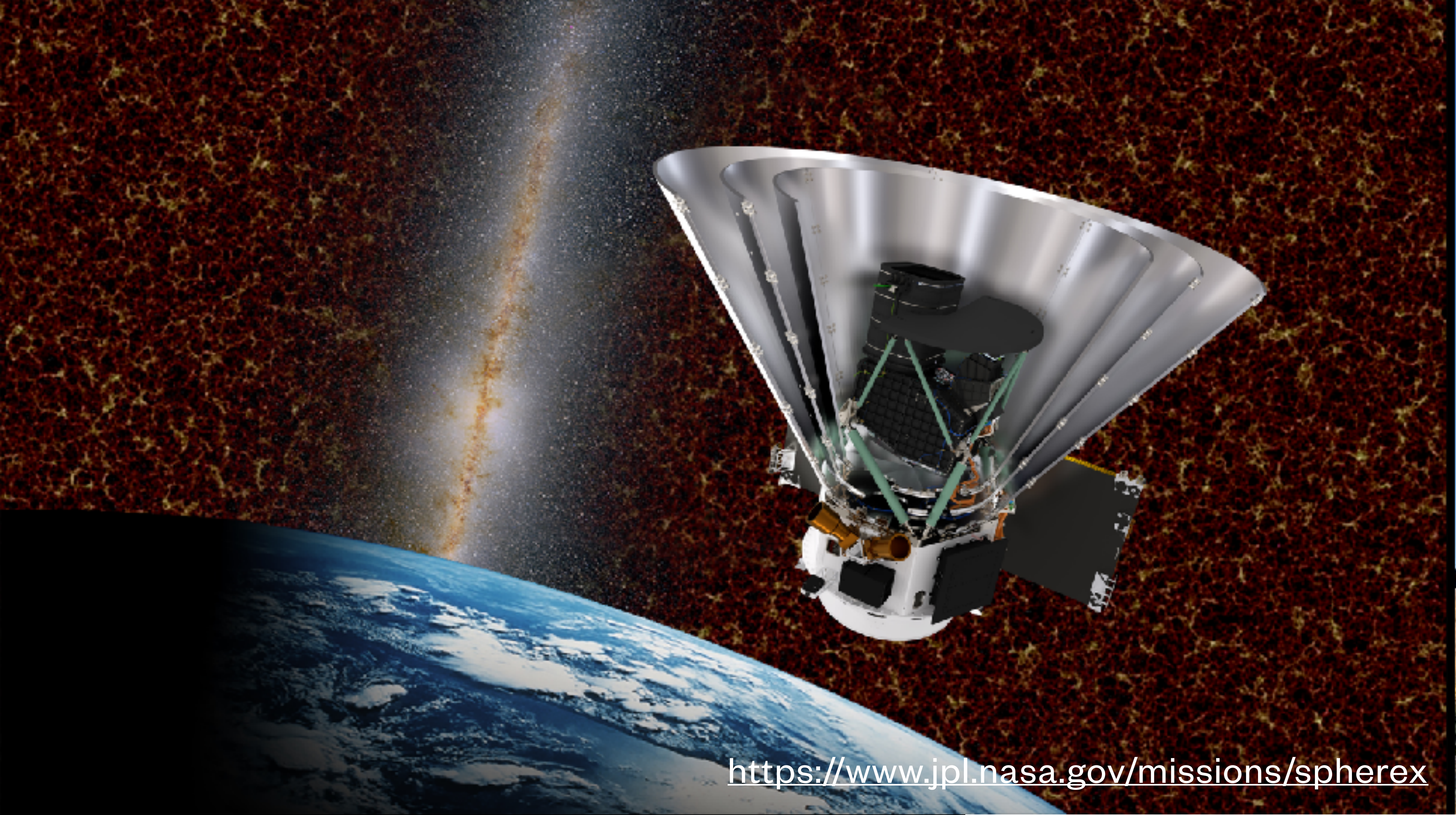
- Sub-mm: Rotational carbon-monoxide (CO) transitions
- Far-IR: Bright fine-structure lines such as [CII]
- Optical/UV: Hydrogen Hα and Lyα lines

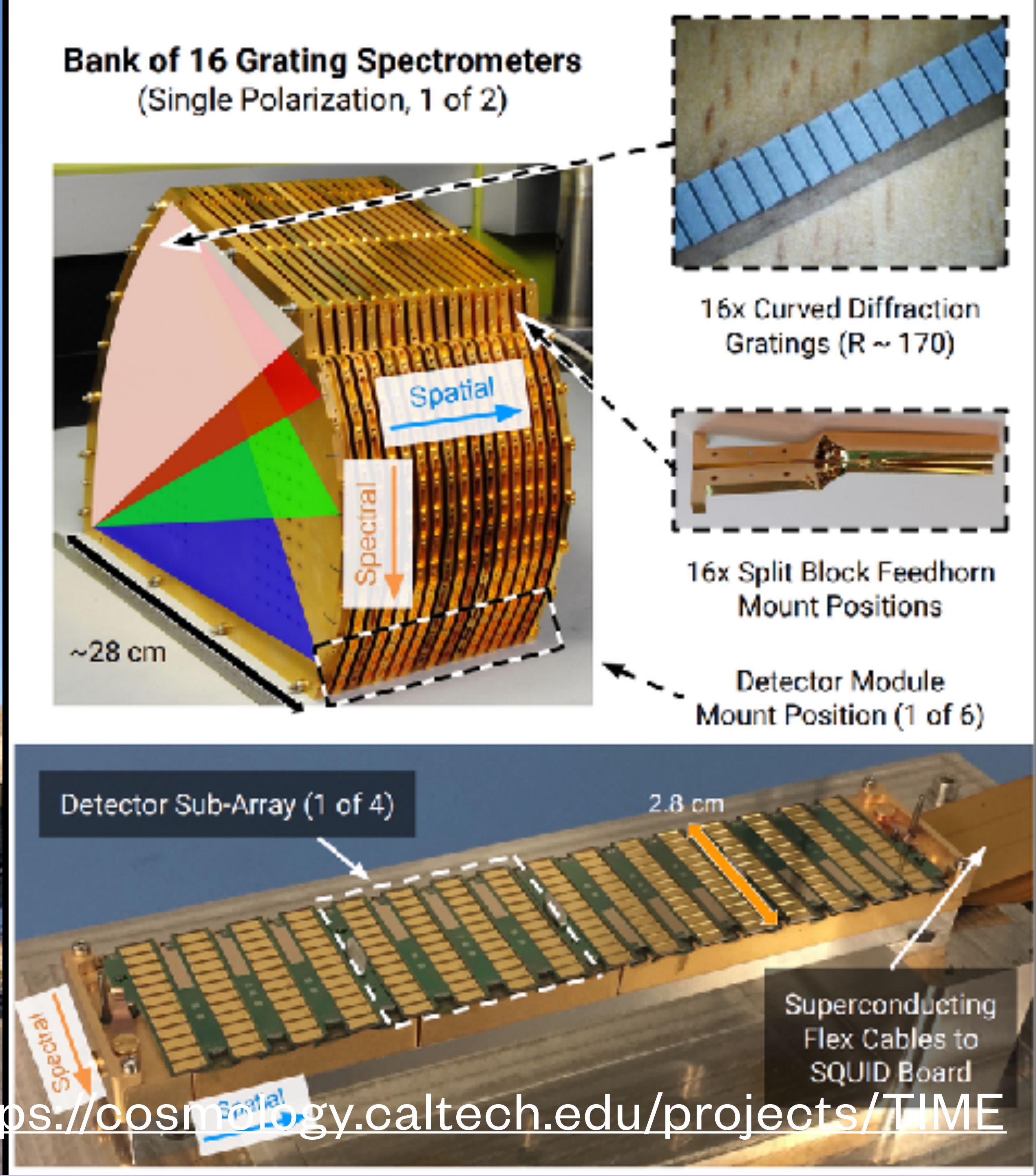
+

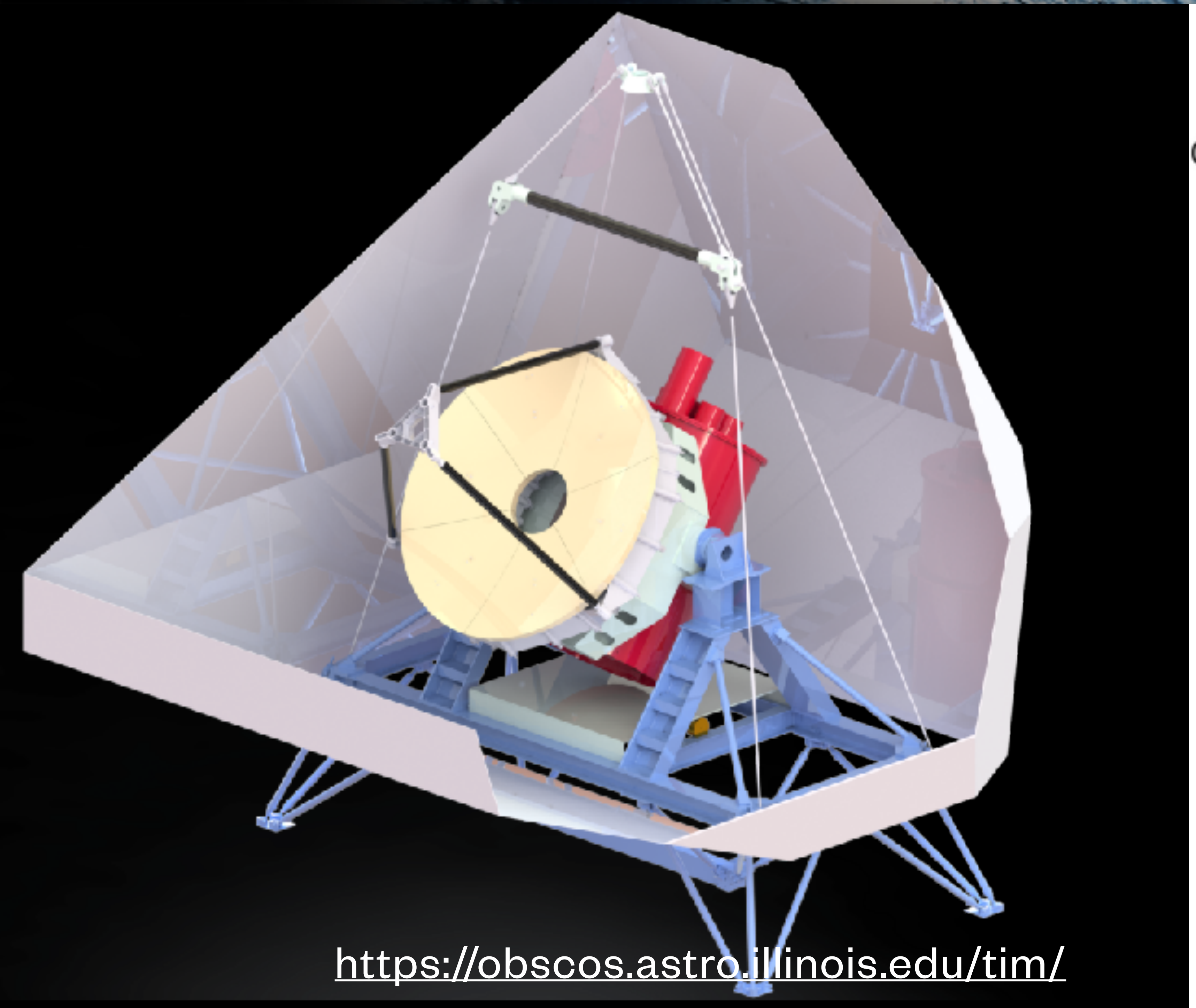
Radio: HI 21 cm line originating from the neutral hydrogen

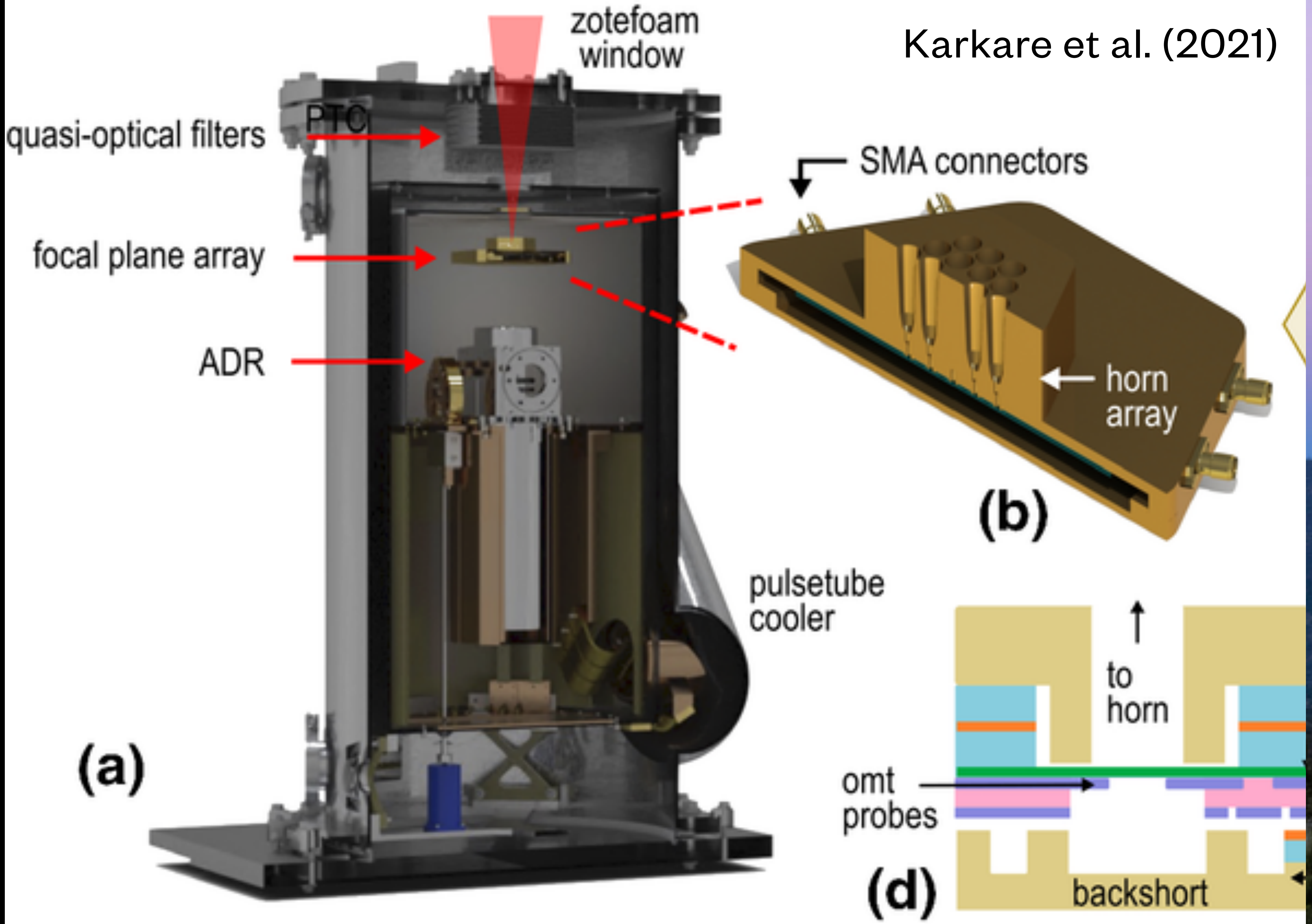


Bernal & Kovetz (2022)


https://www.jpl.nasa.gov/missions/spherex


Bank of 16 Grating Spectrometers
(Single Polarization, 1 of 2)
16x Curved Diffraction Gratings (R ~ 170)
Spatial
Spectral
16x Split Block Feedhorn Mount Positions
~28 cm
Detector Module Mount Position (1 of 6)
Detector Sub-Array (1 of 4)
2.8 cm
Superconducting Flex Cables to SQUID Board
https://cosmology.caltech.edu/projects/TIME


https://obscos.astro.illinois.edu/tim/


zotefoam window
Karkare et al. (2021)
quasi-optical filters
PTC
focal plane array
ADR
SMA connectors
horn array
(b)
pulsetube cooler
(a)
to horn
omt probes
(d)
backshort


Credit: Ethan Tweedie https://hetdex.org

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

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The University of British Columbia
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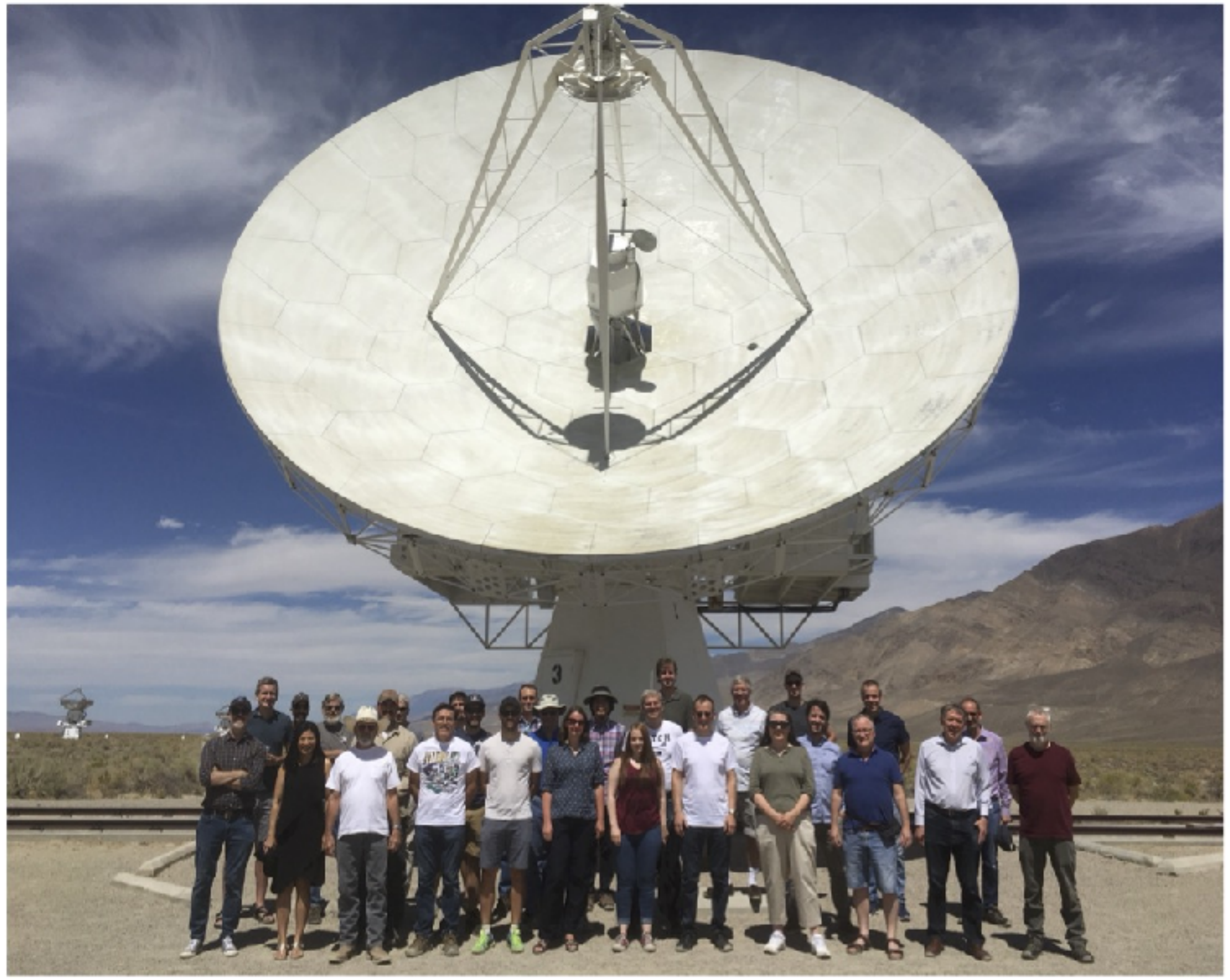
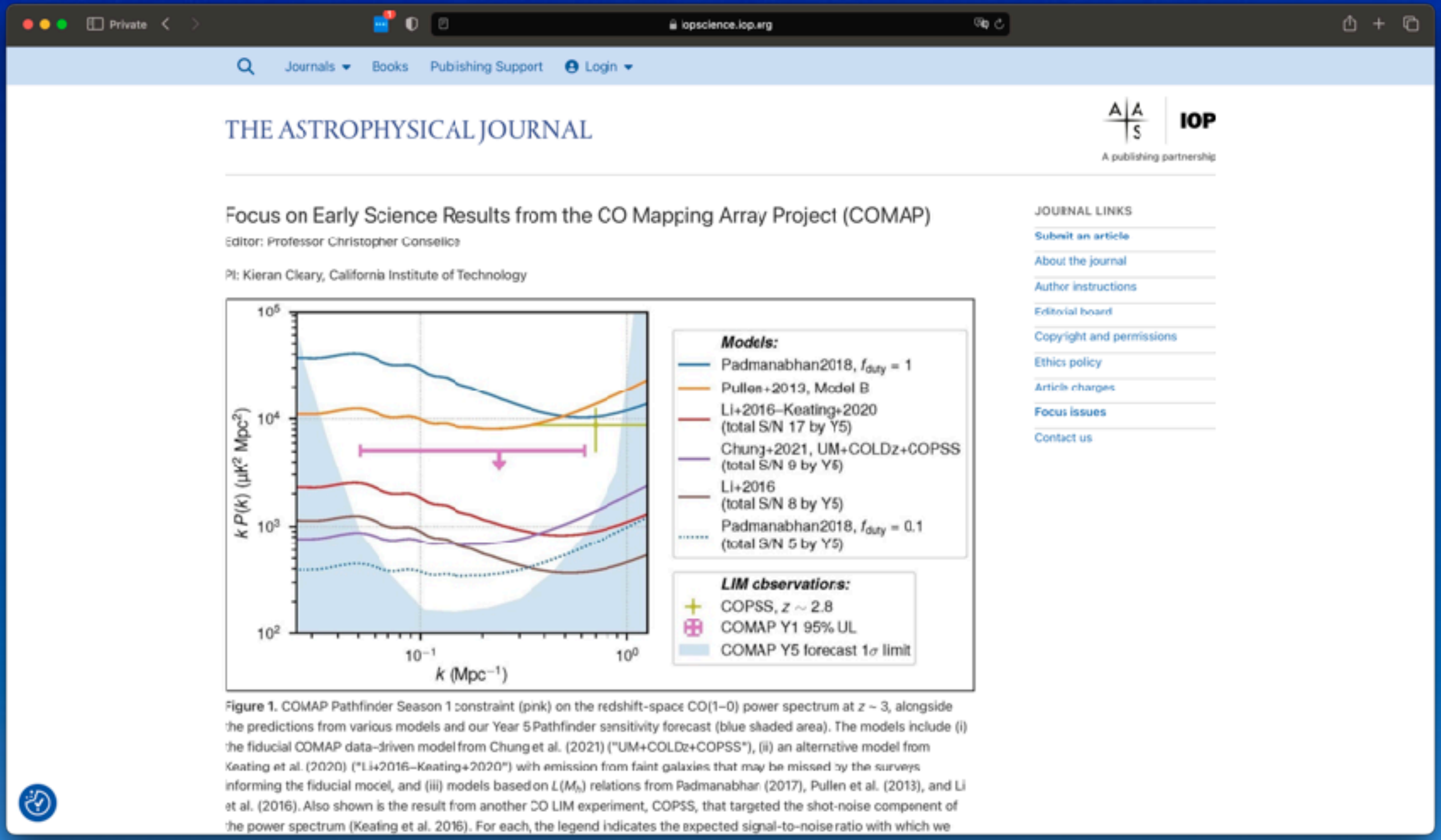
Todd Gaier
Brandon Hensley
Joseph Lazio



https://comap.caltech.edu/team.html#

COMAP Early Science Results



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THE ASTROPHYSICAL JOURNAL

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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+COLDz+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

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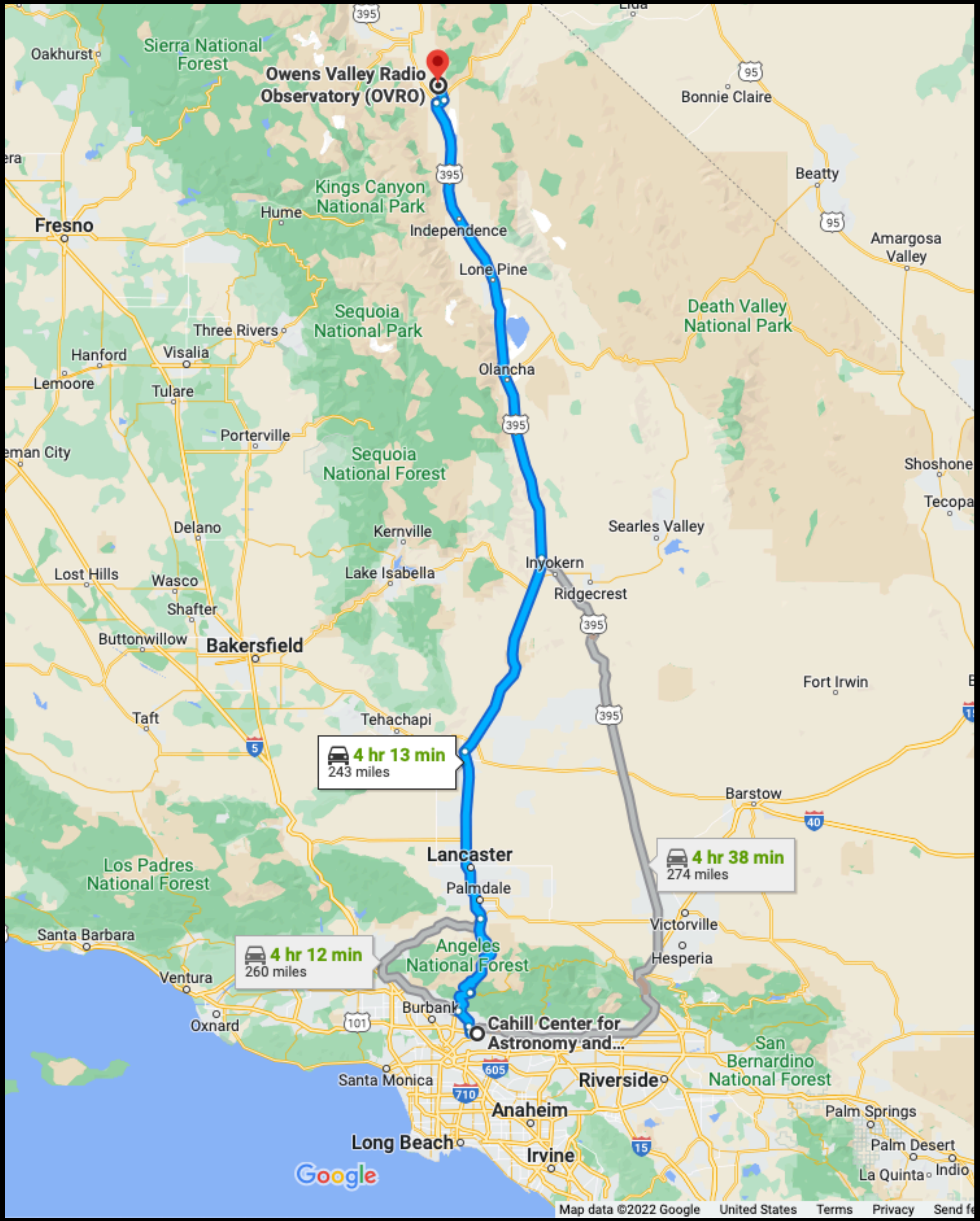
COMAP Pathfinder

- 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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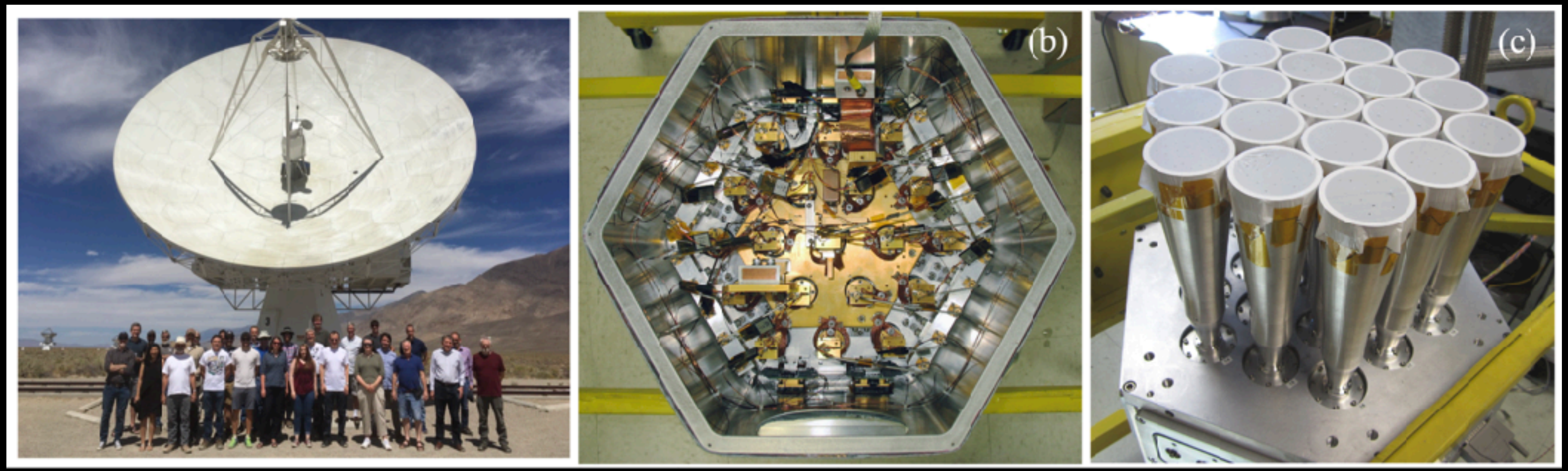
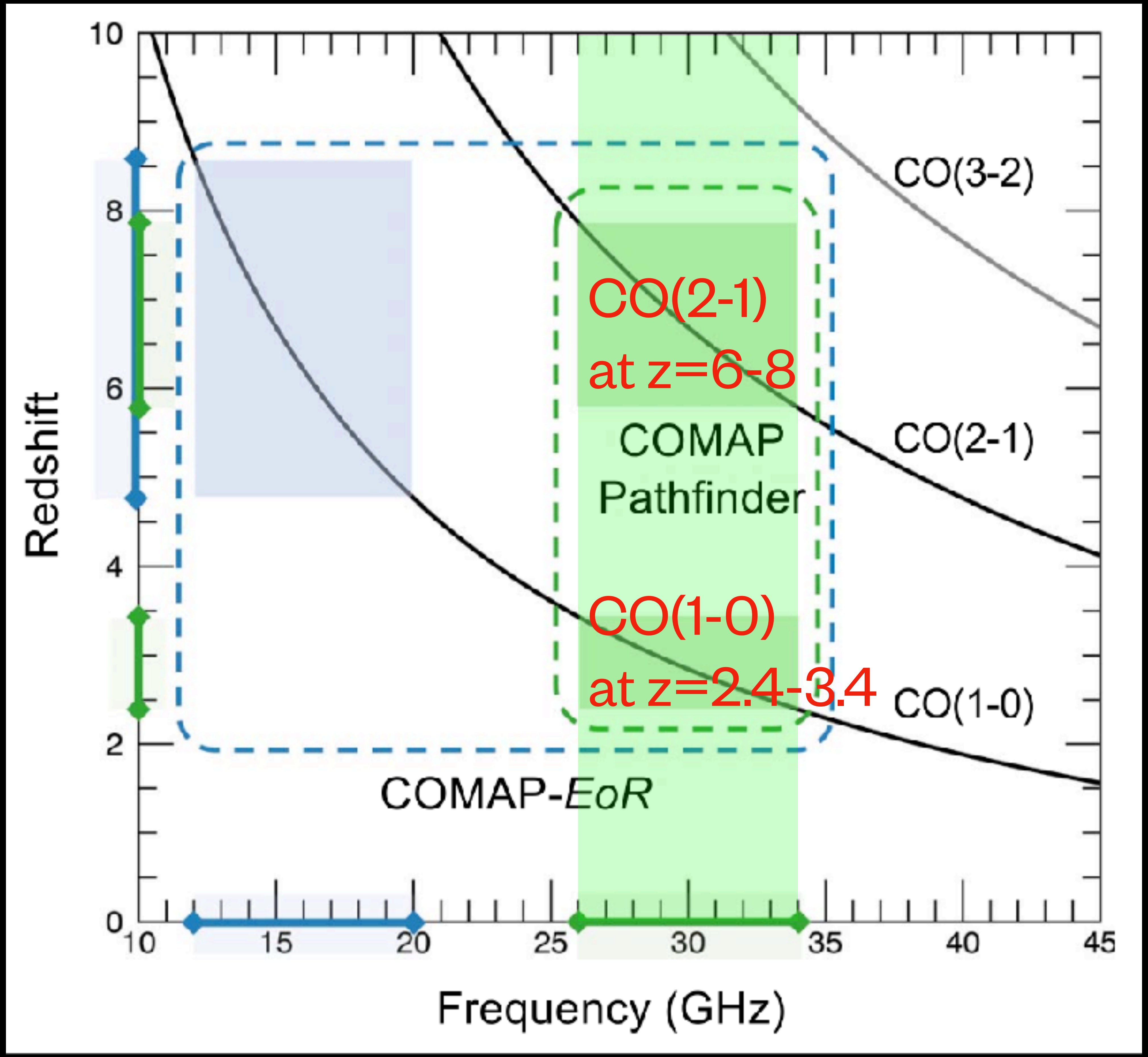


Cleary et al. (2022), Lamb et al. (2022)

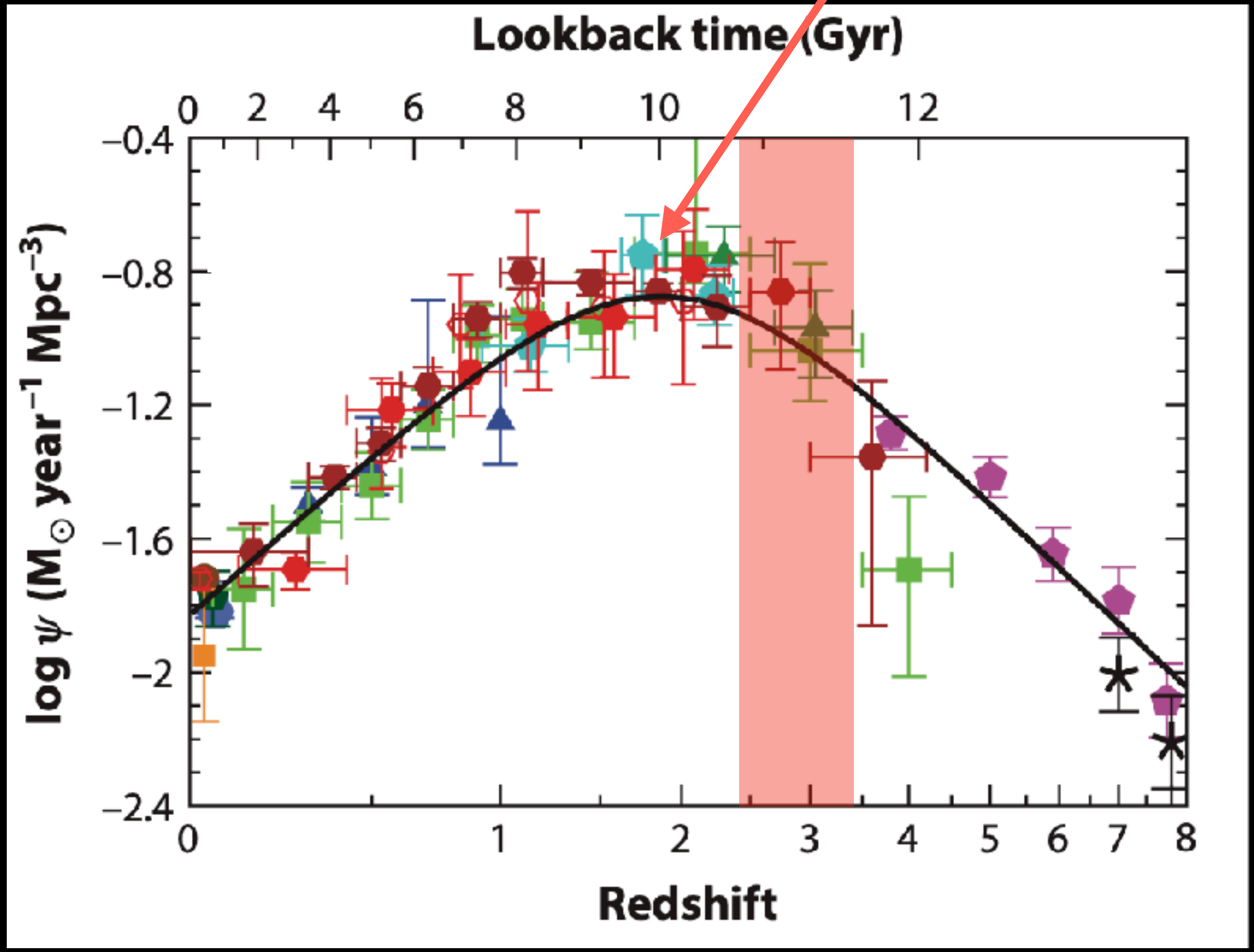
COMAP Pathfinder

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



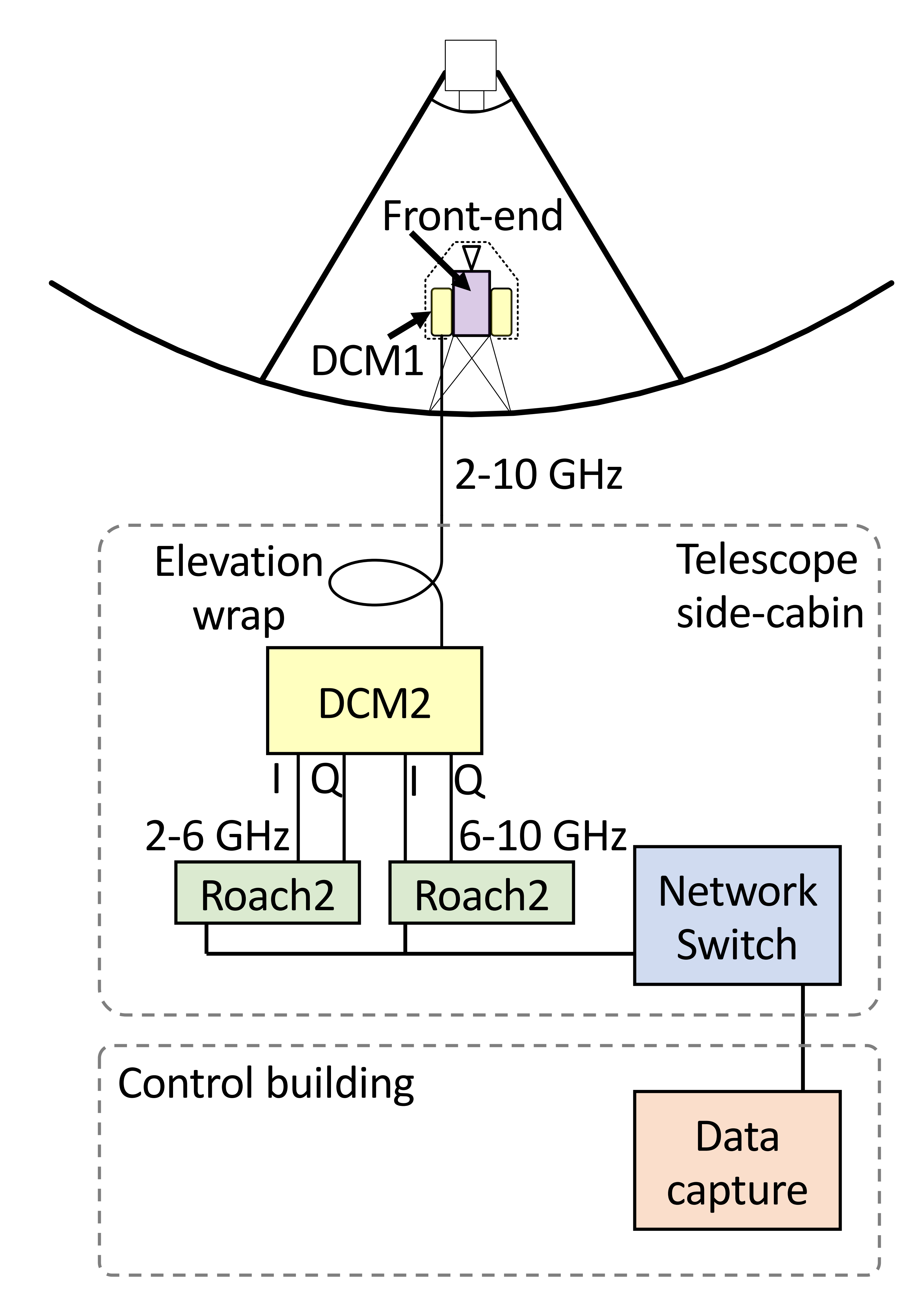
Cleary et al. (2022)

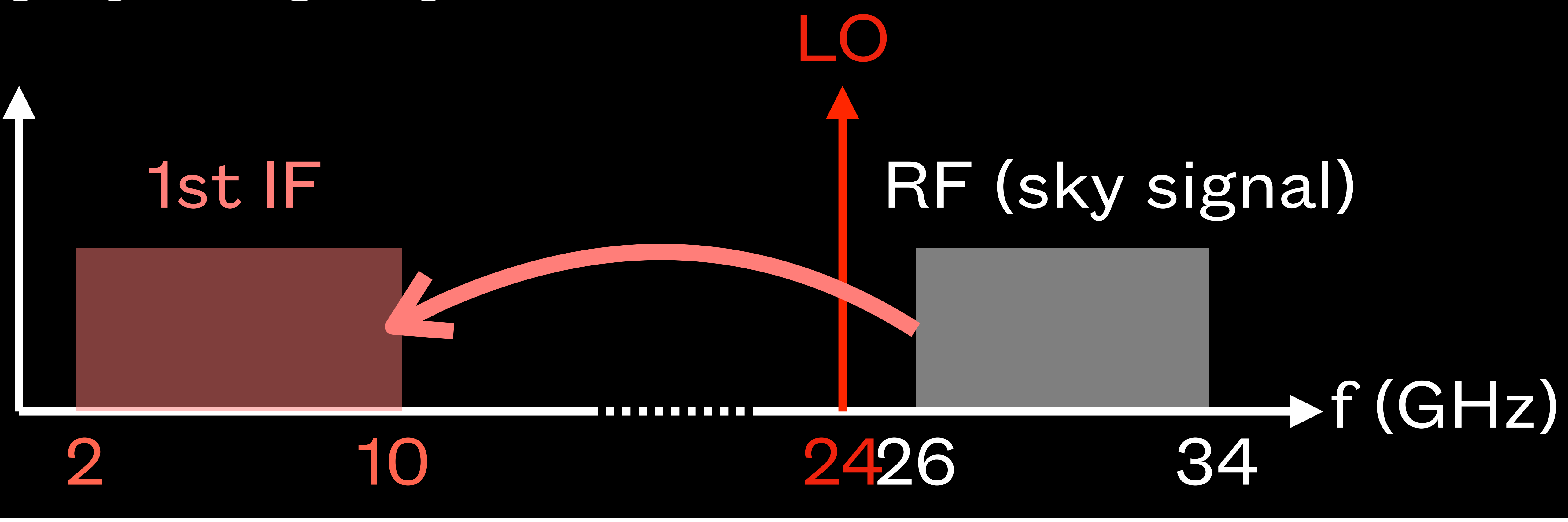
Peak of the
Star-formation History

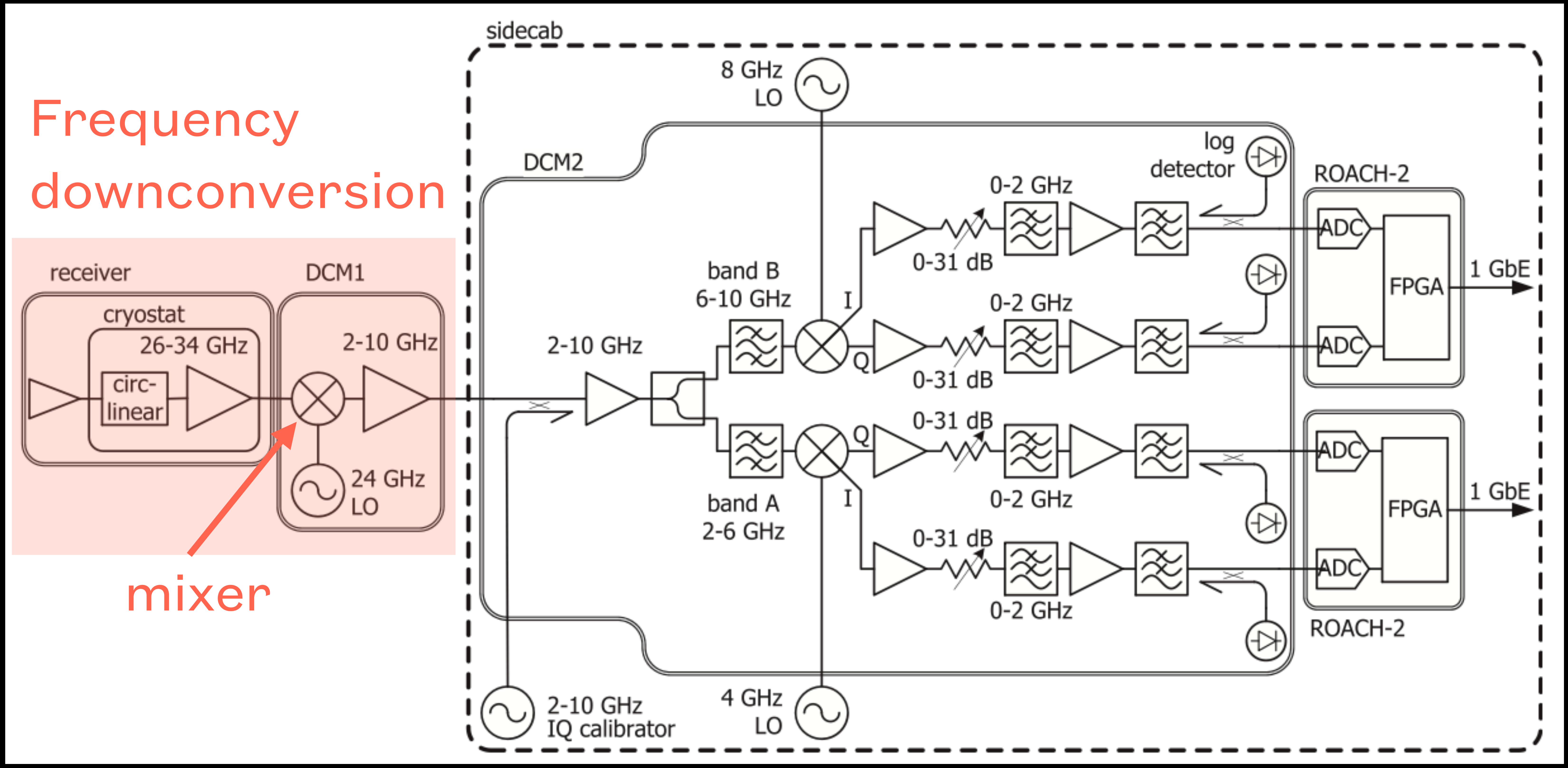


Madau & Dickinson (2014)

COMAP Pathfinder: Instrument



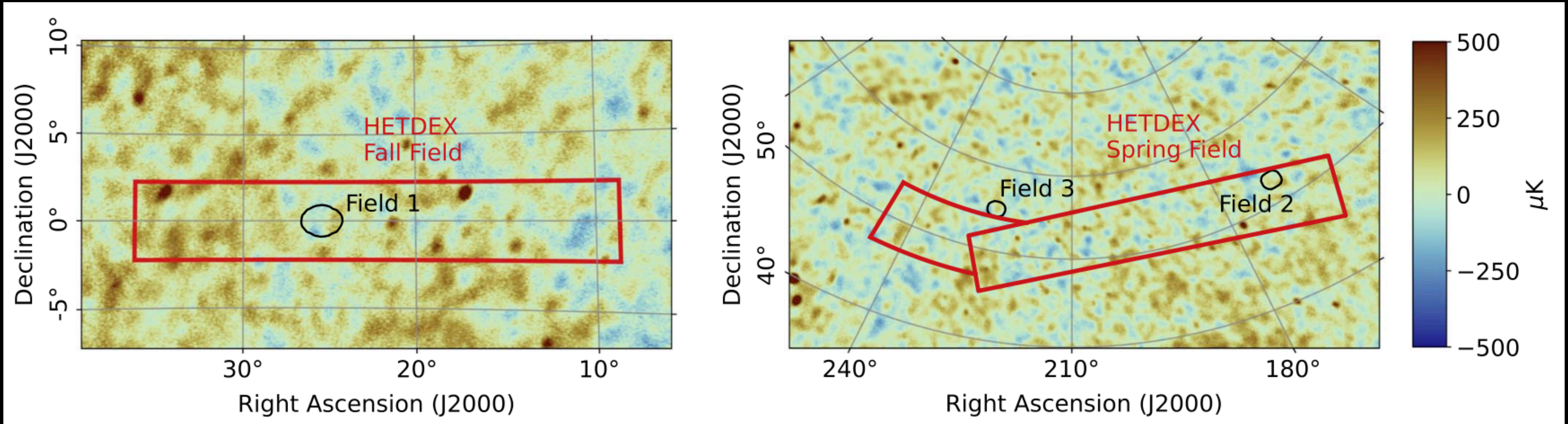




Lamb et al. (2022)

COMAP Pathfinder: Observation

- 5-year observing campaign (started 2019)
- Three observing fields (~4 deg^2)
  - 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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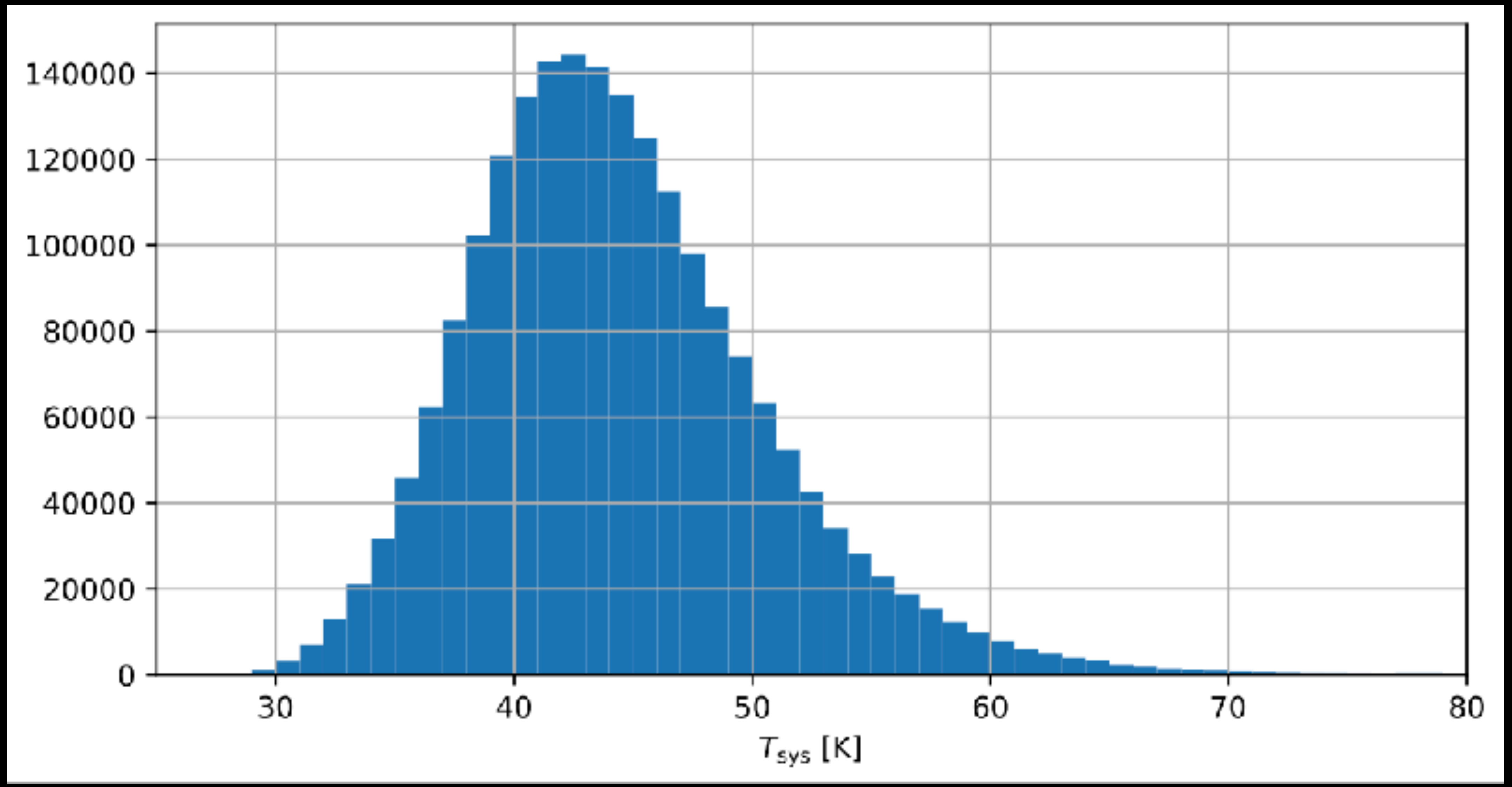
Cleary et al. (2022)

COMAP Pathfinder: Calibration

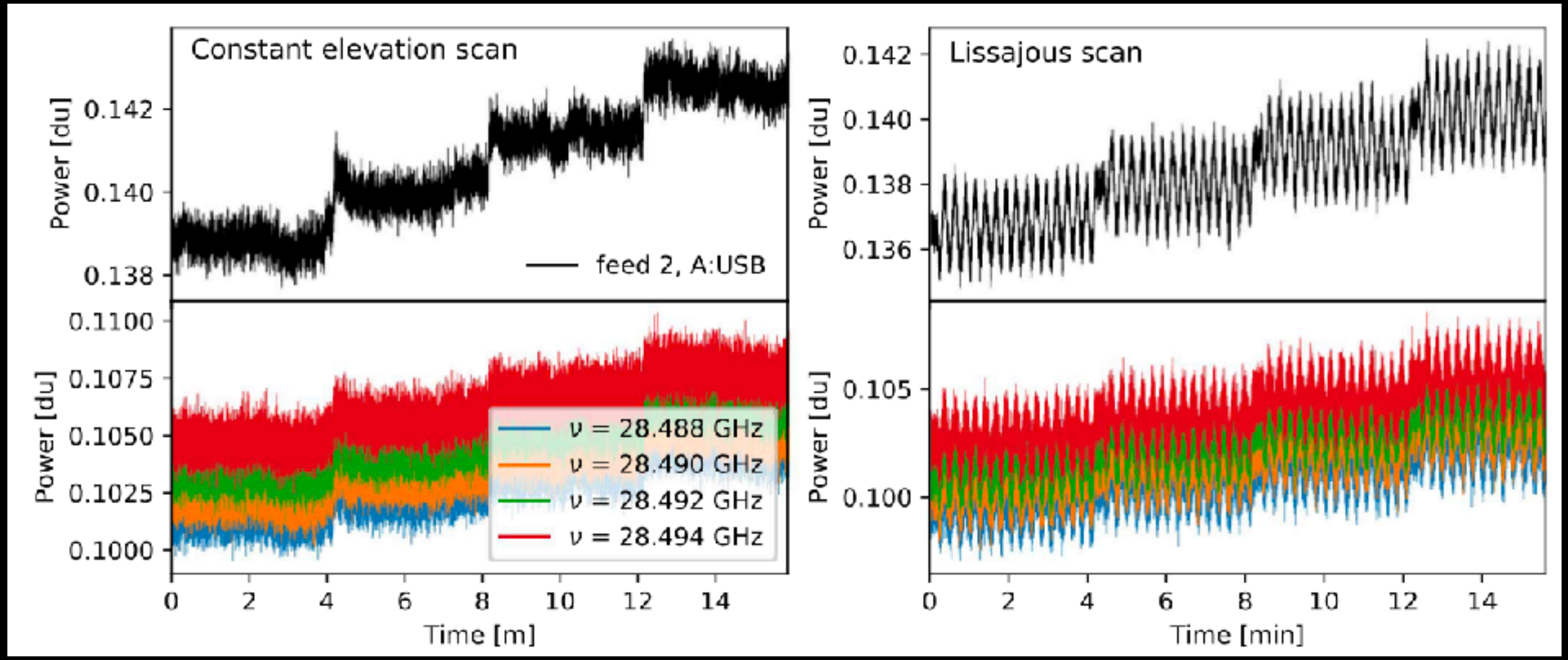
$$T_{\text{sys}} = T_{\text{receiver}} + T_{\text{atmosphere}} + T_{\text{ground}} + T_{\text{CMB}} + T_{\text{foregrounds}} + T_{\text{CO}}$$

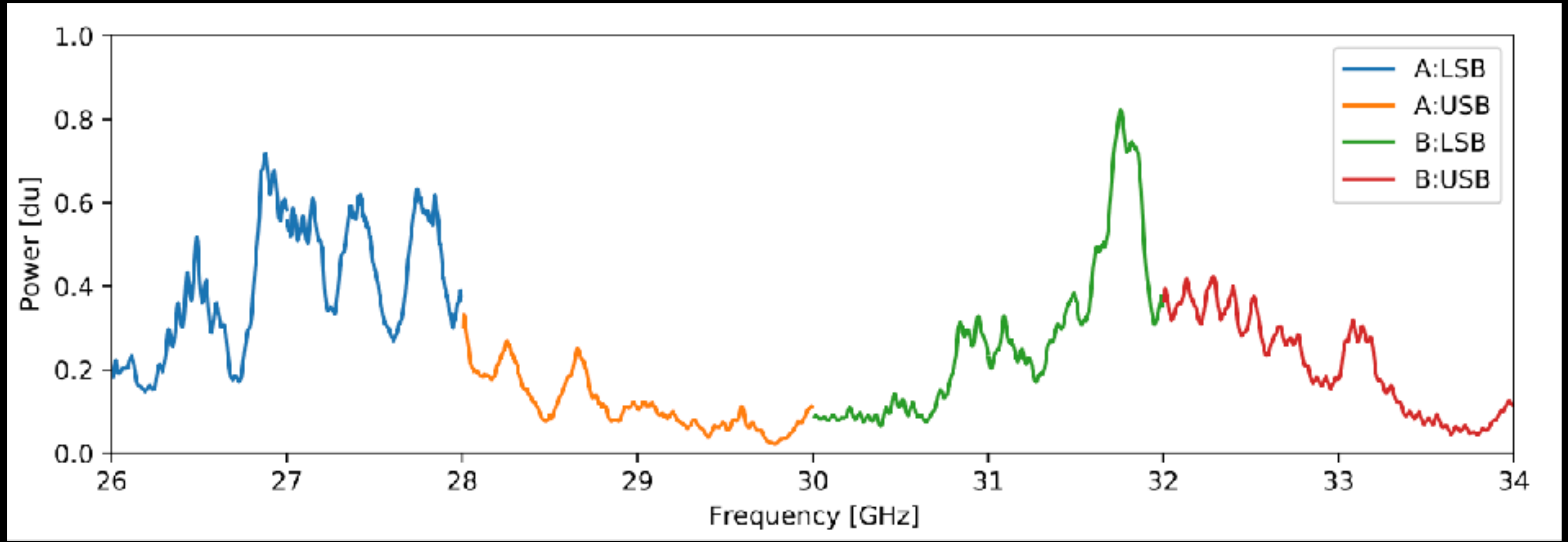
(~10-30 K) (~15-25 K) (~5-6 K) (2.7K) (~1 mK) $\mathcal{O}(1\ \mu\text{K})$

Radiometer Equation: $\sigma_T = \dfrac{T_{\text{sys}}}{\sqrt{\Delta\nu\tau}}$



Foss et al. (2022)





normalization

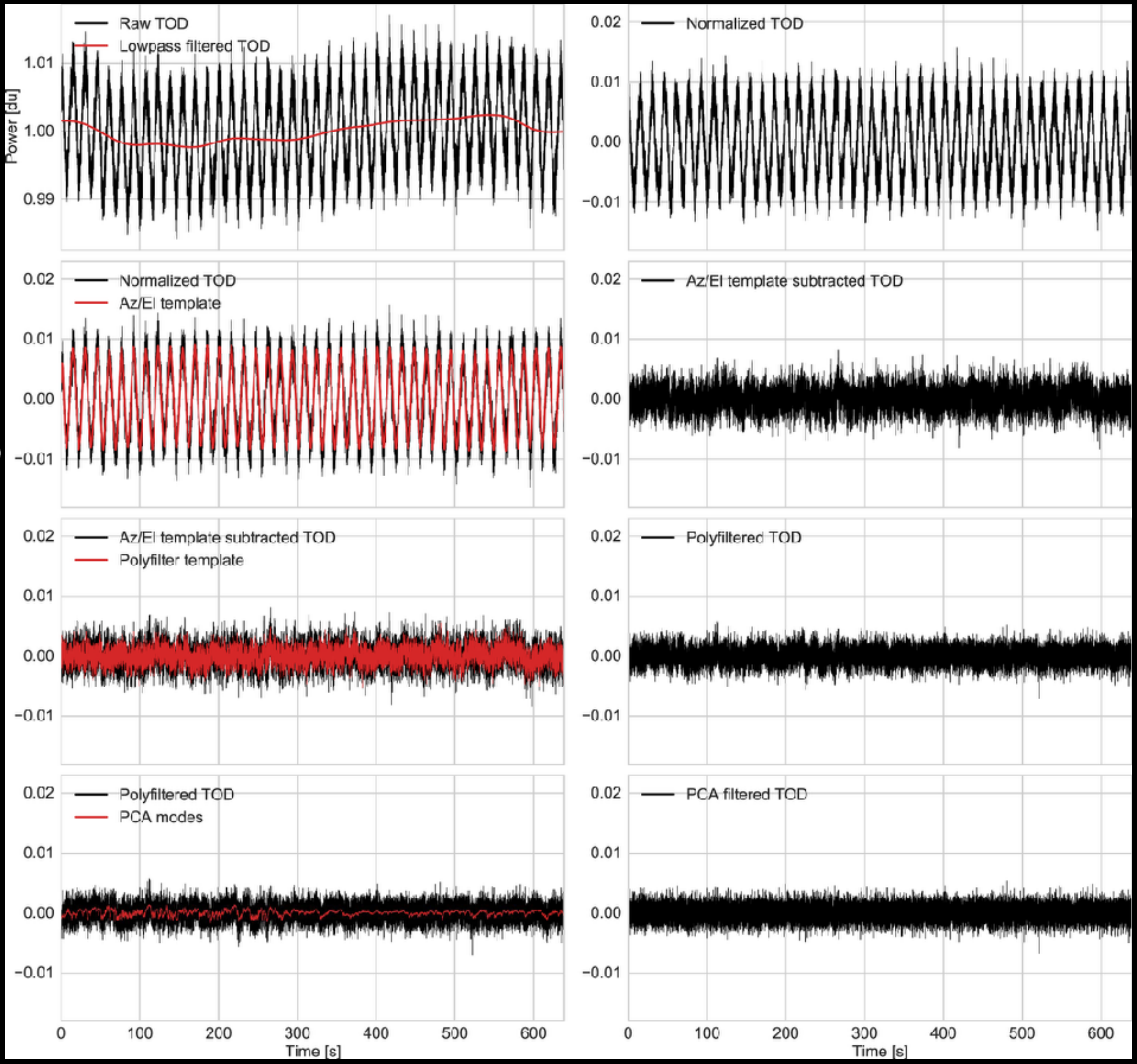
atmospheric template

$\tau(\mathrm{el}) = \tau_0 / \sin(\mathrm{el})$

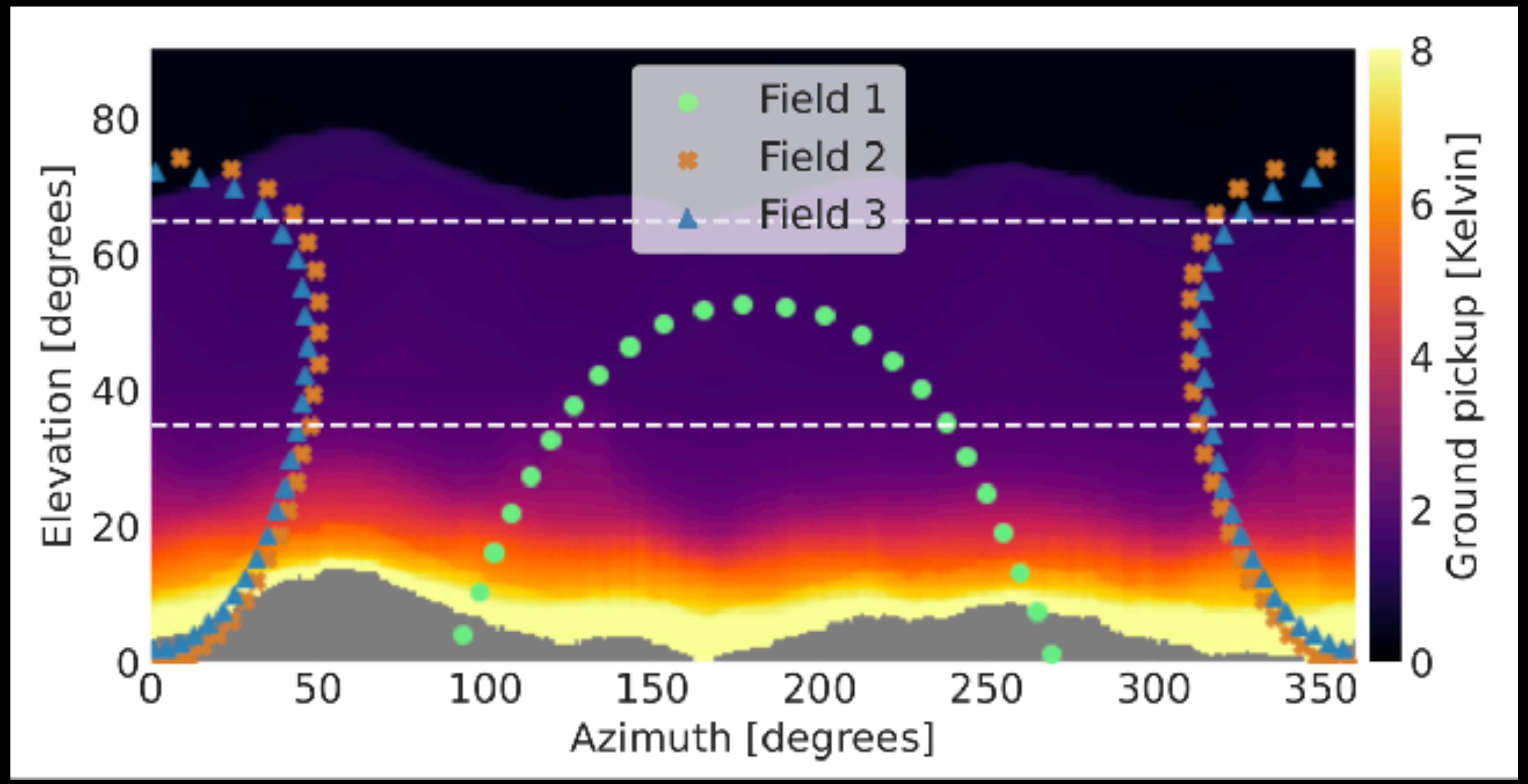
low-order polynomial

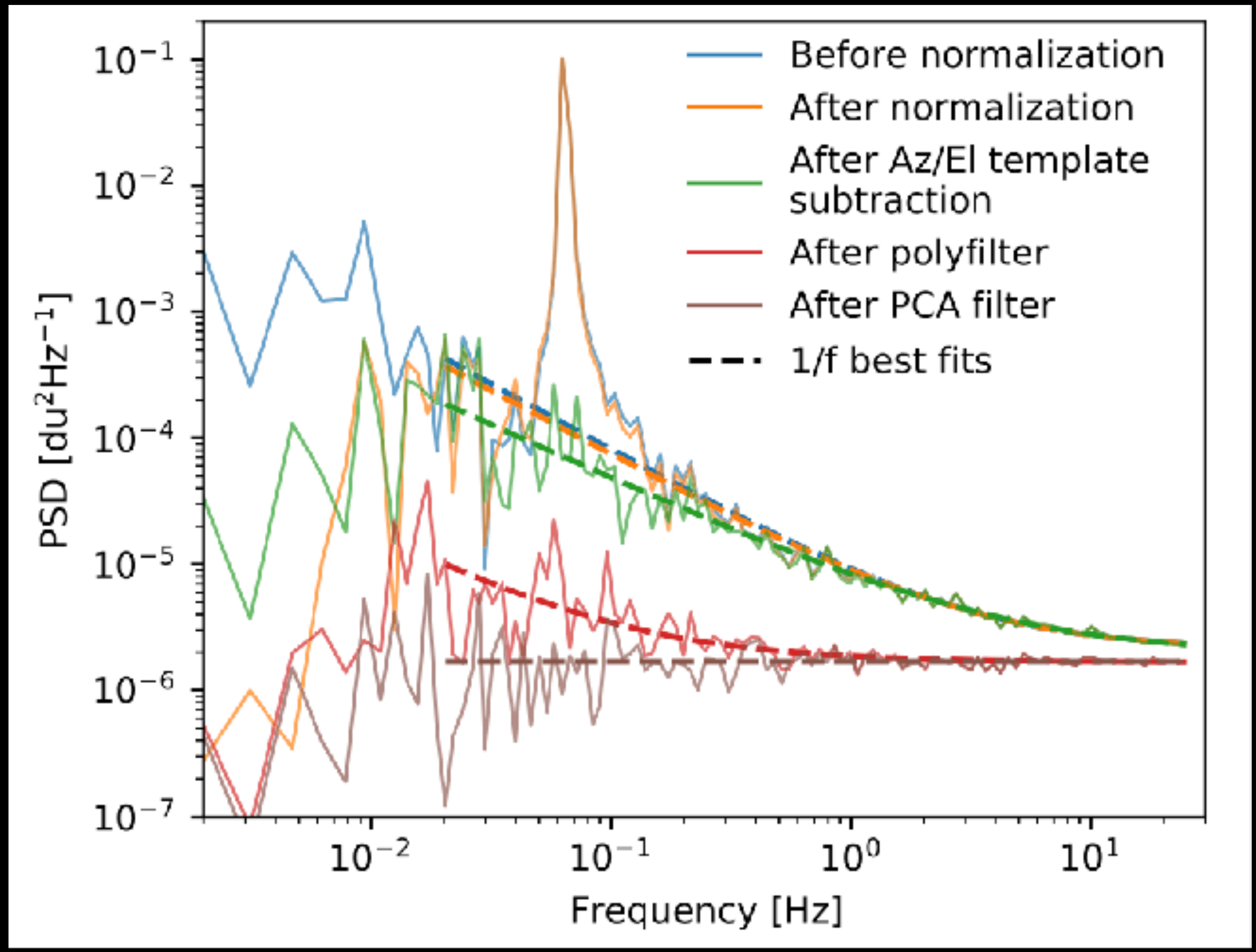
$d_\nu = c_0 + c_1\nu + c_2\nu^2 + \ldots$

PCA filter

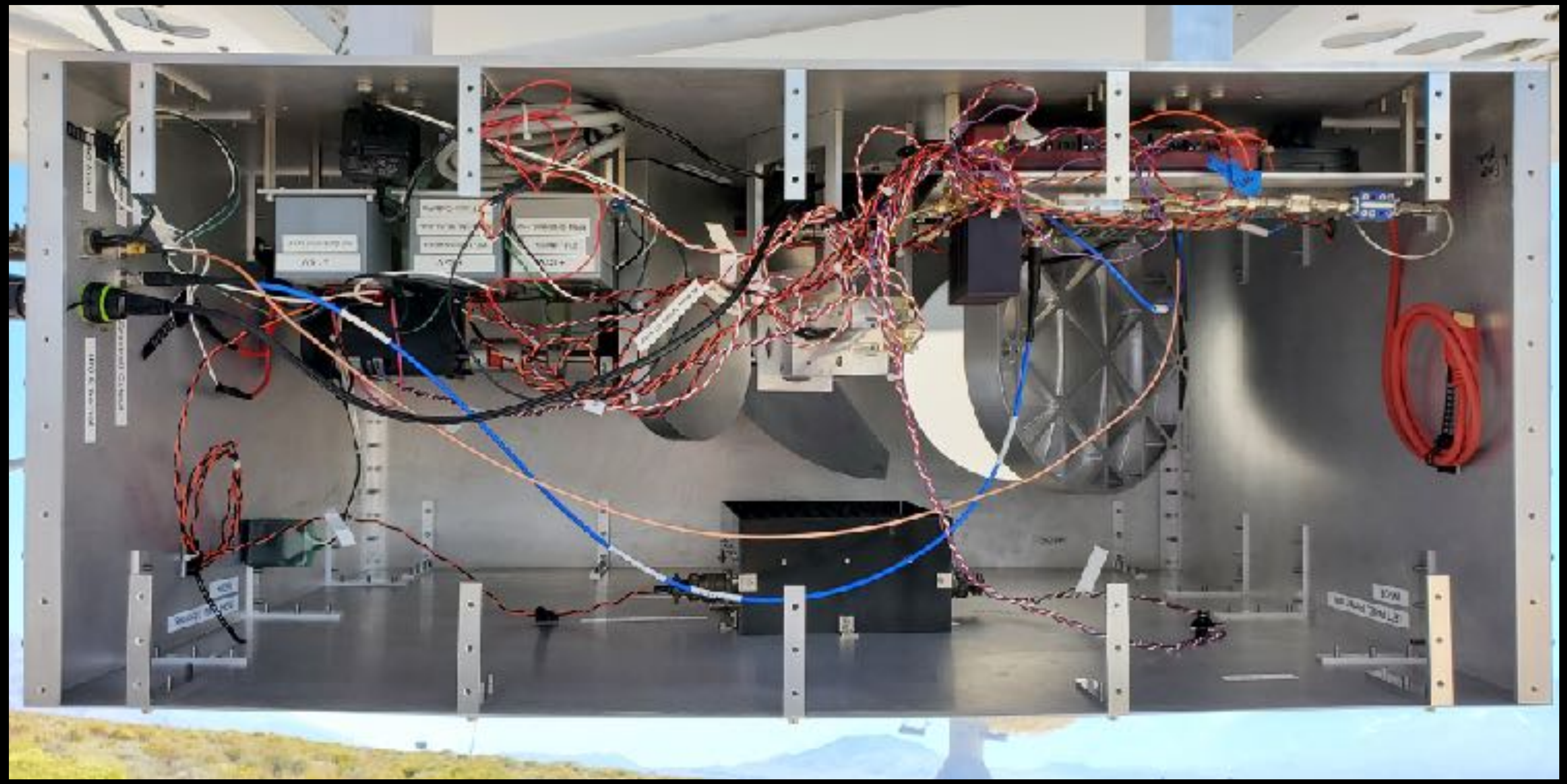


Foss et al. (2022)





Cleary et al. (2022)



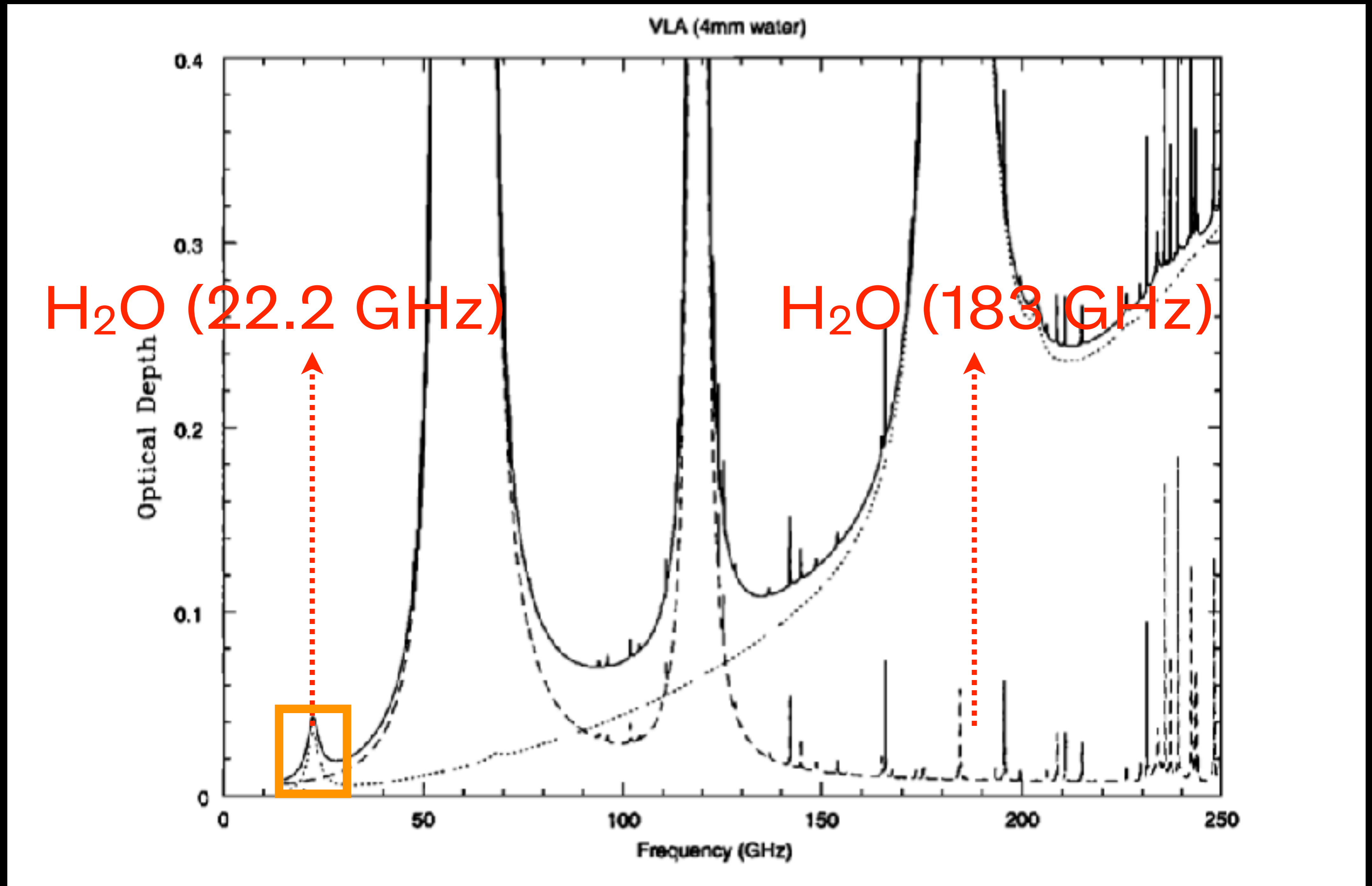


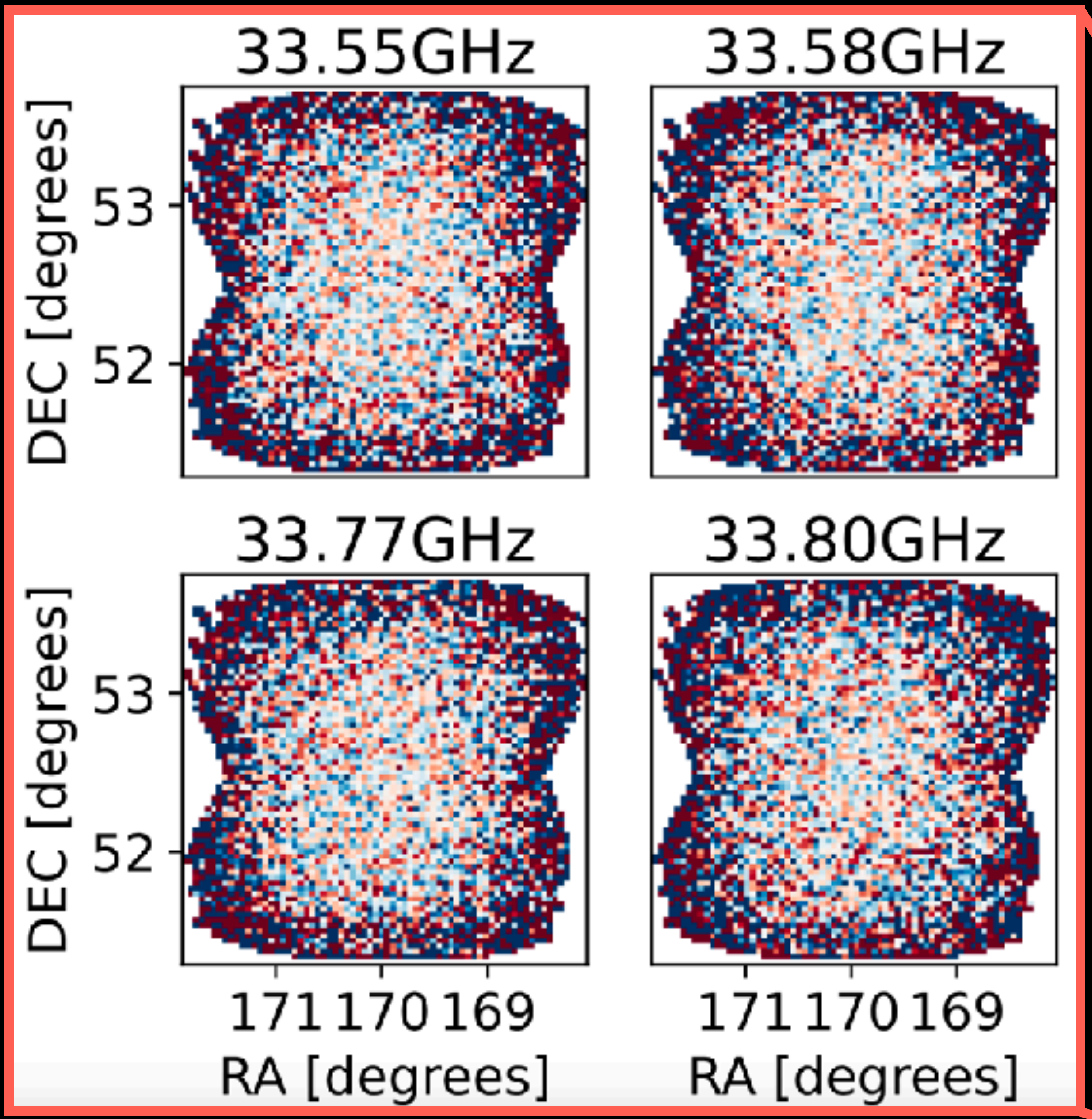
Figure 2. The optical depth for the VLA site assuming w_o = 4 mm. The solid line is the total optical depth. The dotted line is the optical depth due to water vapor. The dashed line is the optical depth due to dry air (O_2 and other trace gases).

Carilli & Holdaway (1999)

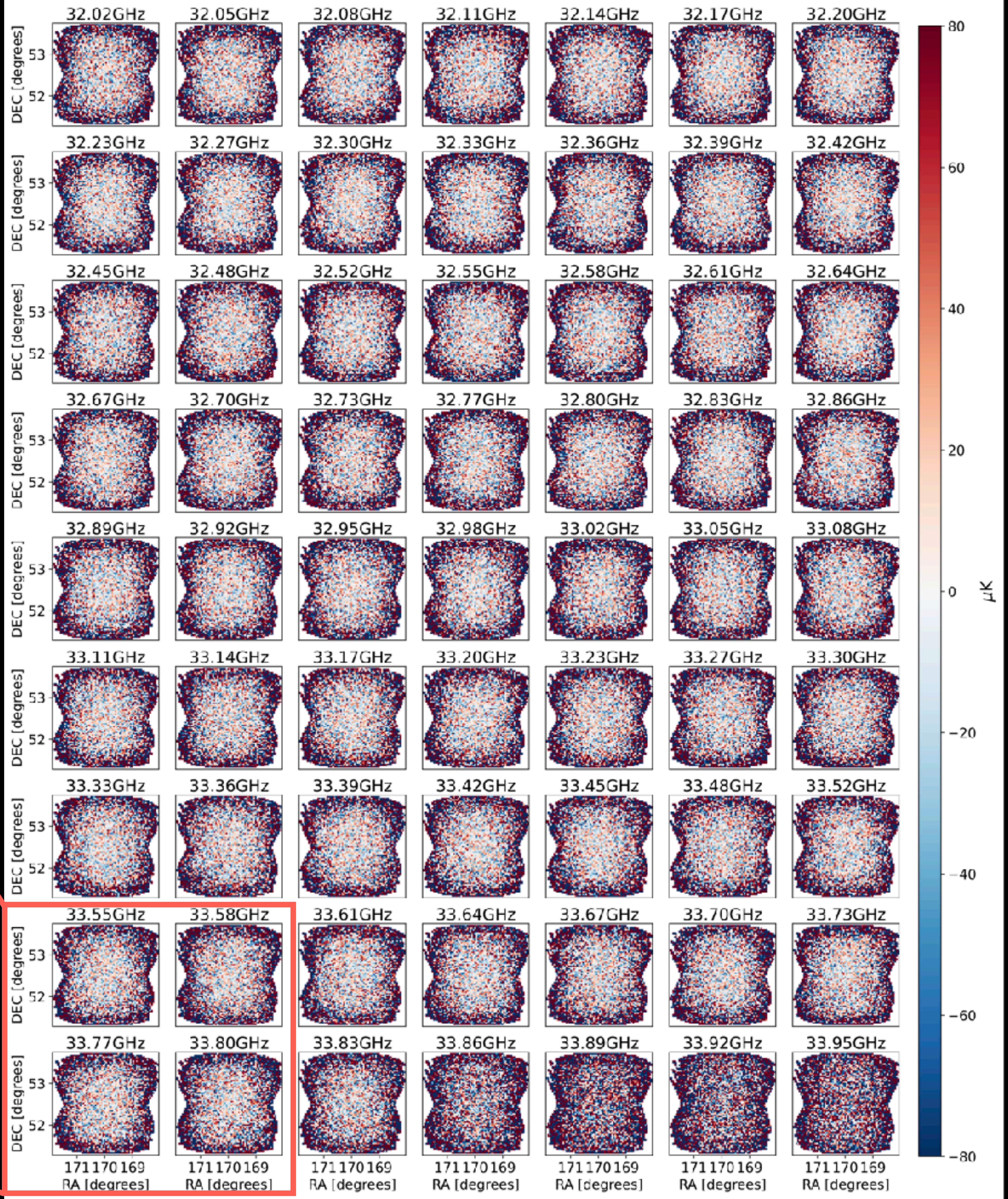
31.25 MHz frequency channel maps

8 GHz / 31.25 MHz ~ 250 channels

$$\Delta z / z = 0.004$$

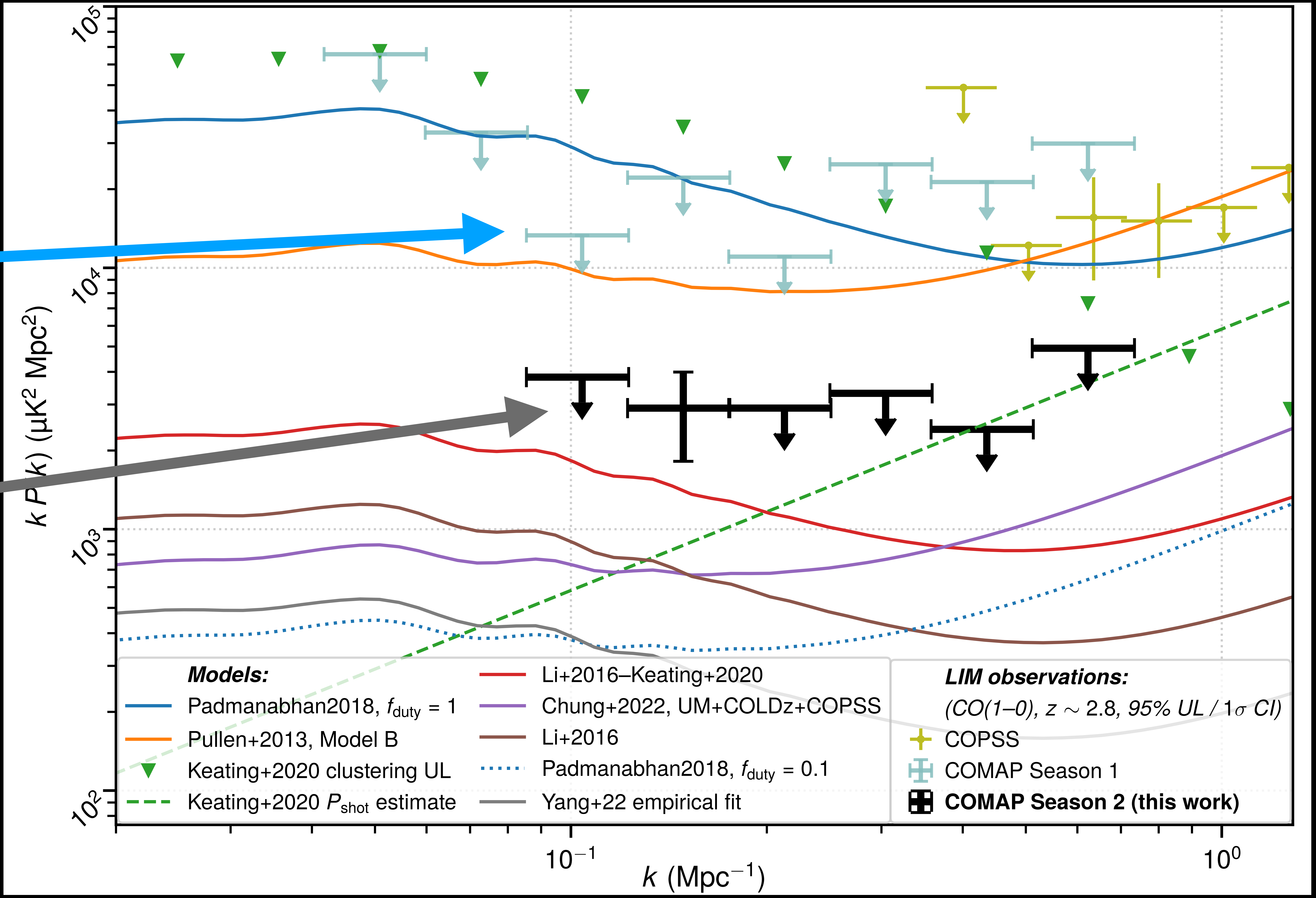


Lunde et al. (2024)



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)



Chung et al. (2024)

COMAP Pathfinder: Season 2 Results

$$\langle T_{CO} \rangle = 0.72^{+0.45}_{-0.30} \mu K \xrightarrow{\alpha_{CO} = 3.6 M_\odot (K\ km\ s^{-1}\ pc^{-2})^{-1}} \rho_{H2} = 5.0^{+3.1}_{-2.1} \times 10^7 M_\odot Mpc^{-3}$$

(mean CO temperature)

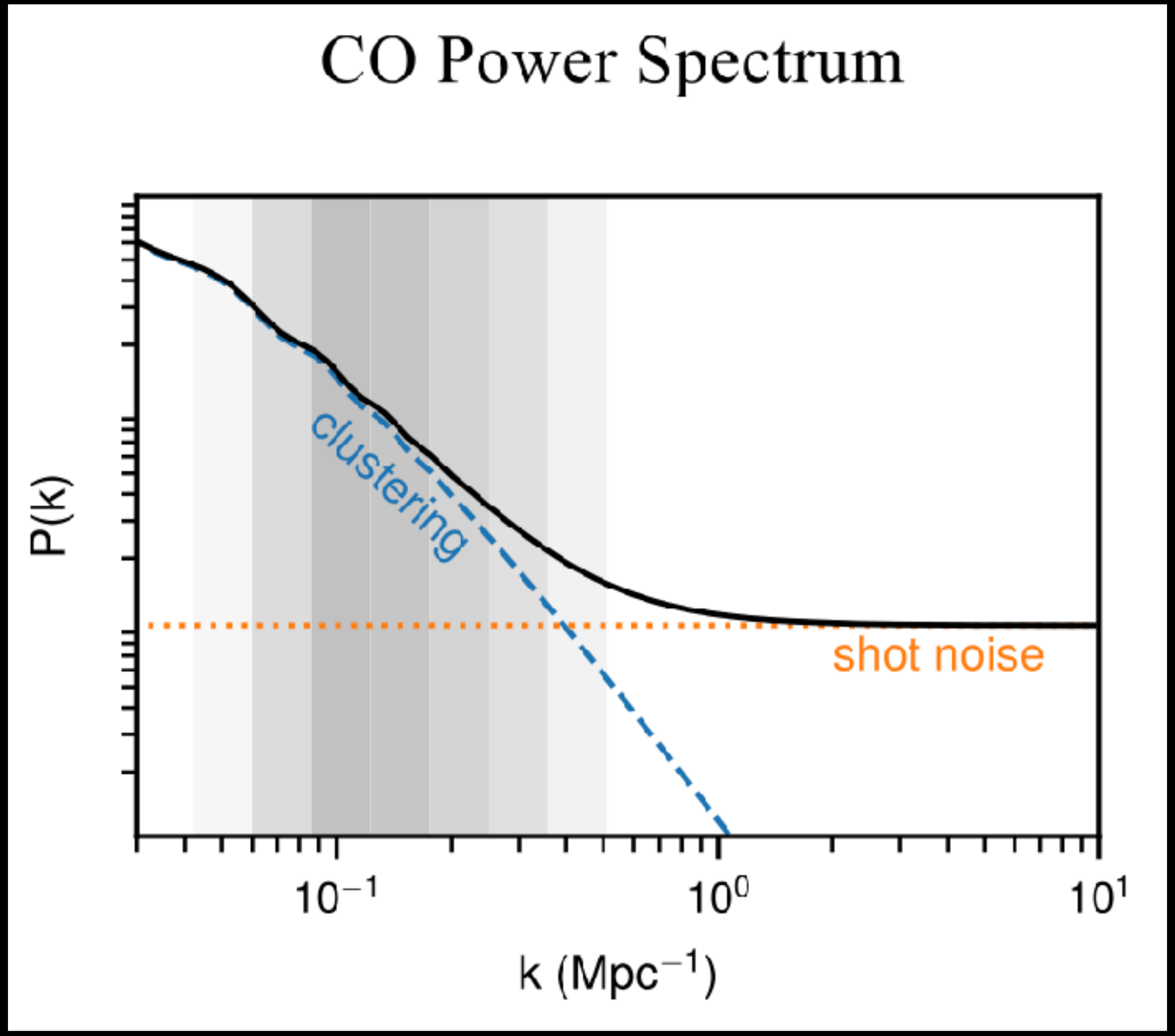
(molecular gas abundance)

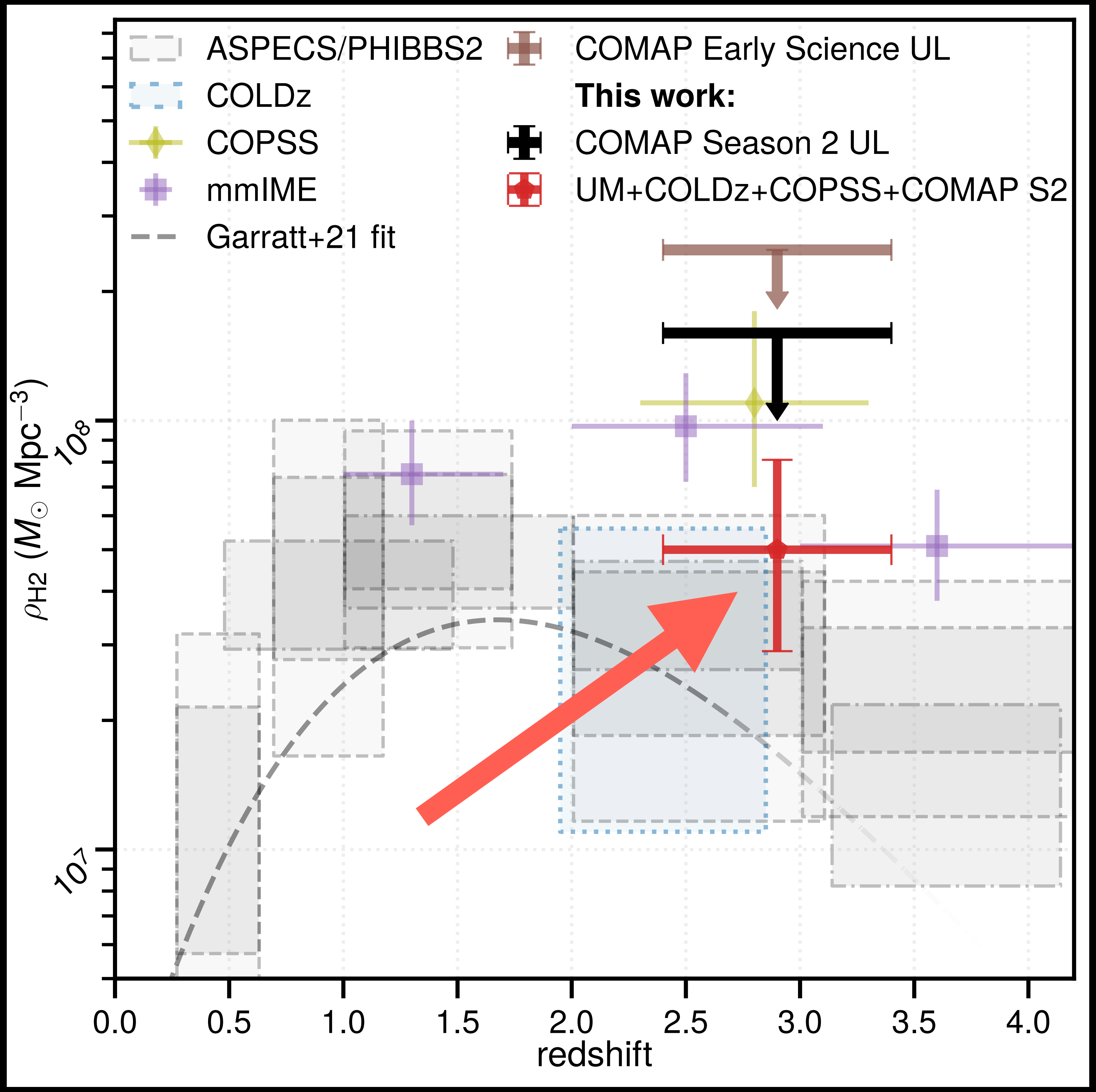
Clustering amplitude × (Underlying matter power spectrum)

+

shot noise

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





Chung et al. (2024)

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

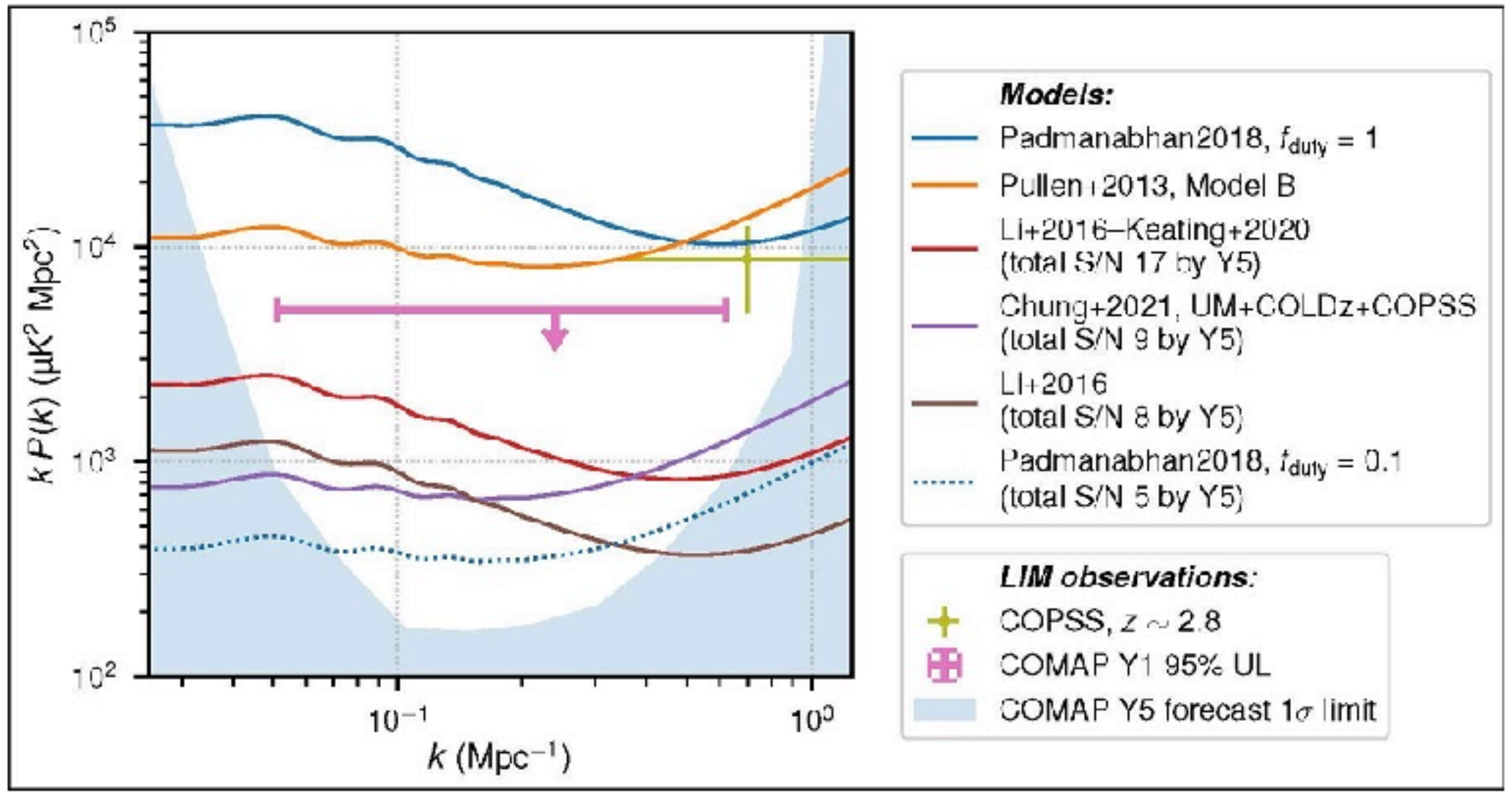
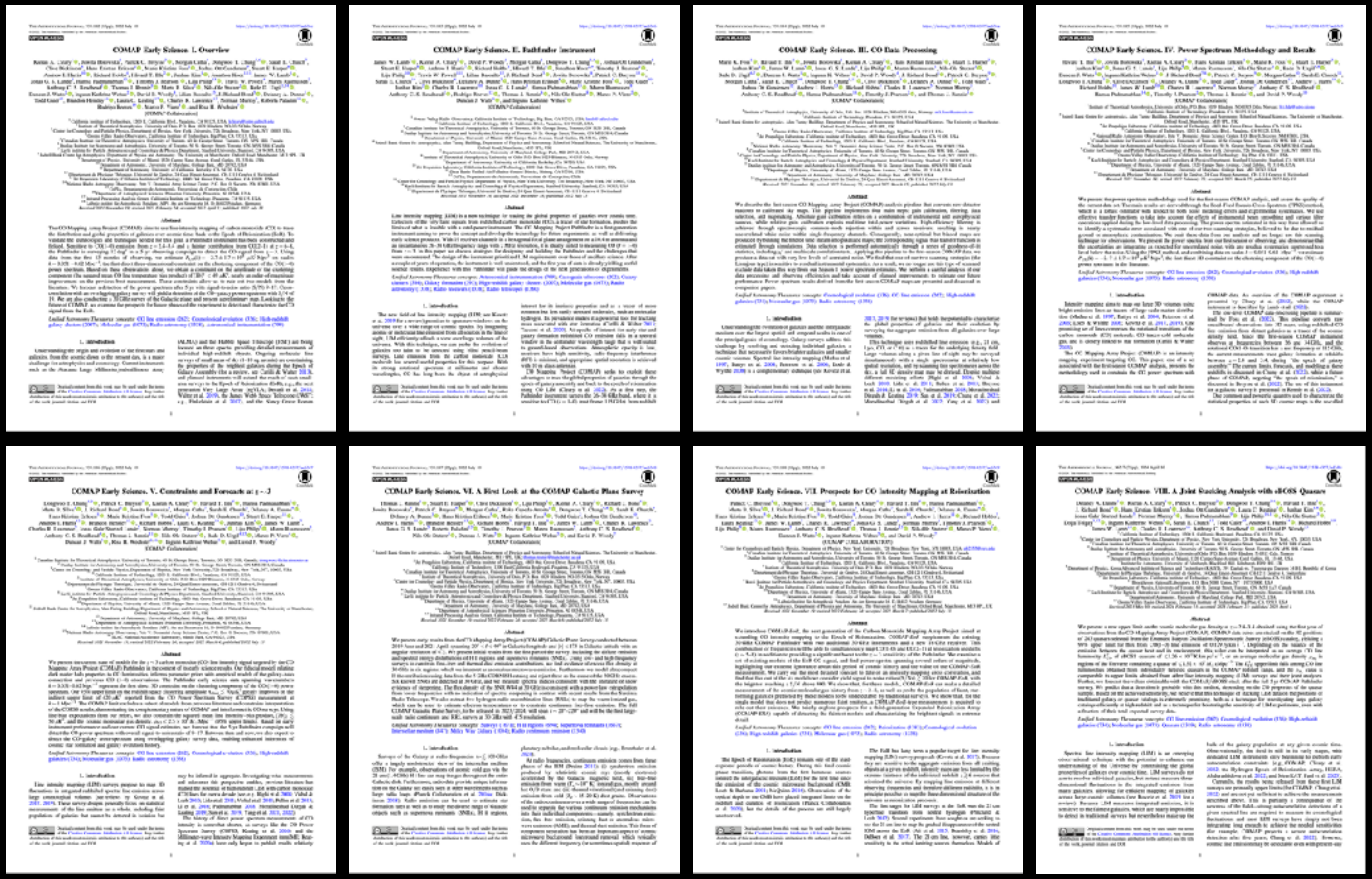


Figure 1. COMAP Pathfinder Season 1 constraint (pink) on the redshift-space CO(1–0) power spectrum at $z \sim 3$, alongside the predictions from various models and our Year 5 Pathfinder sensitivity forecast (blue shaded area). The models include (i) the fiducial COMAP data-driven model from Chung et al. (2021) ("UM+COLDz+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).



https://iopscience.iop.org/journal/0004-637X/page/comap

COMAP Pathfinder: Season 2 Results (2024)

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

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

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

A&A, 691, A336 (2024)
https://doi.org/10.1051/0004-6361/202451123
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Astronomy & Astrophysics

COMAP Pathfinder – Season 2 results

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

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

A&A, 691, A337 (2024)
https://doi.org/10.1051/0004-6361/202451122
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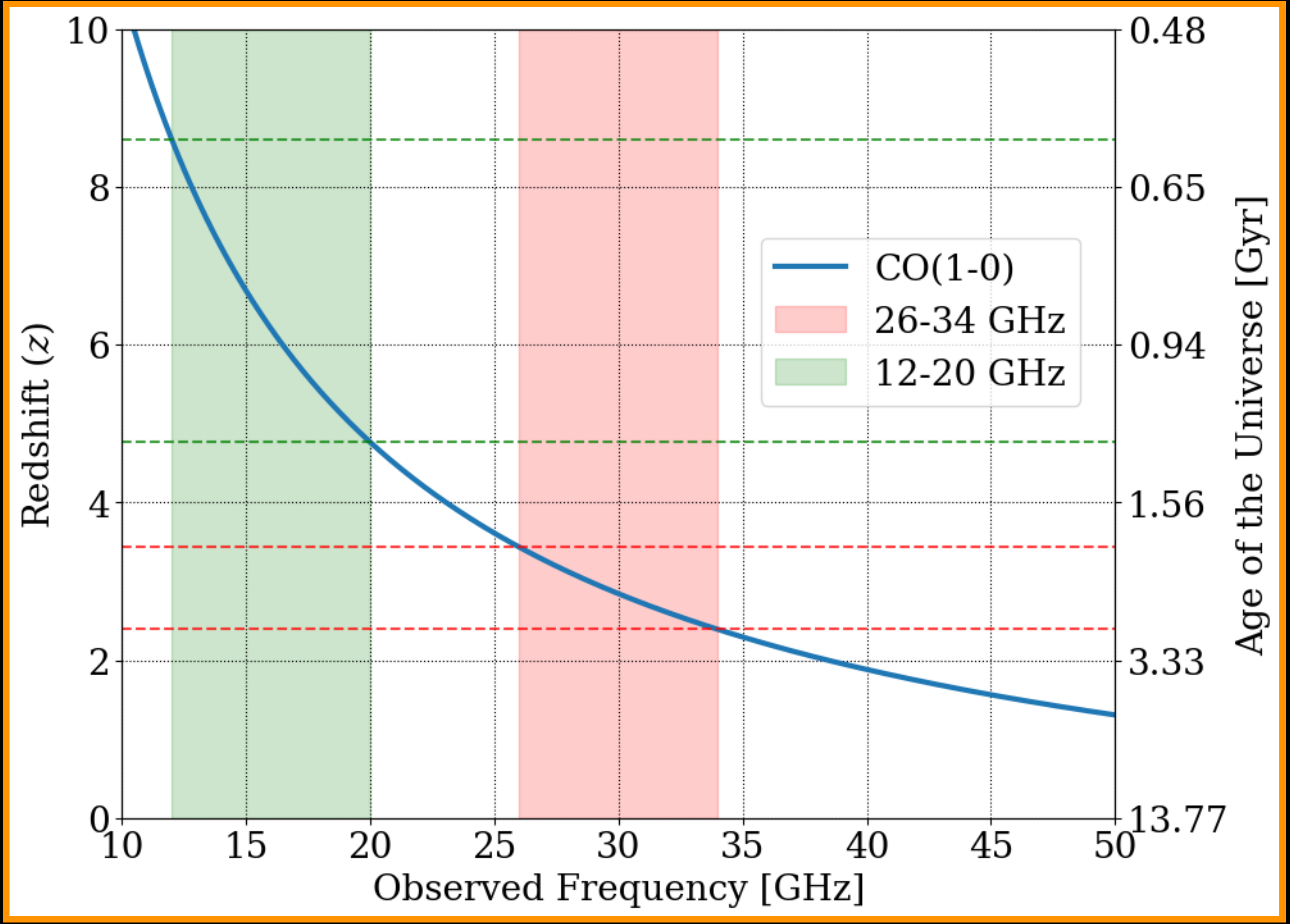
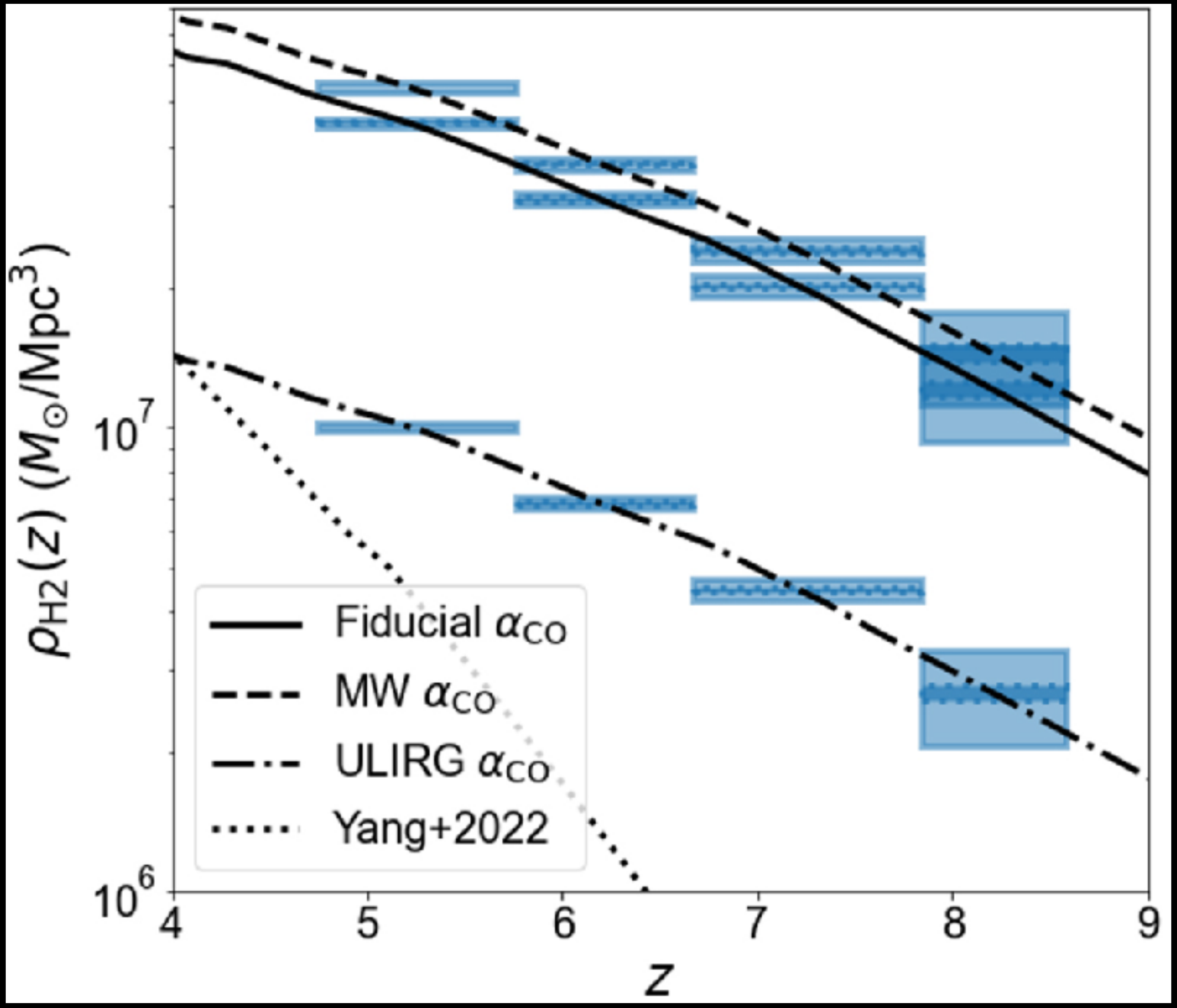
Astronomy & Astrophysics

COMAP Pathfinder – Season 2 results

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





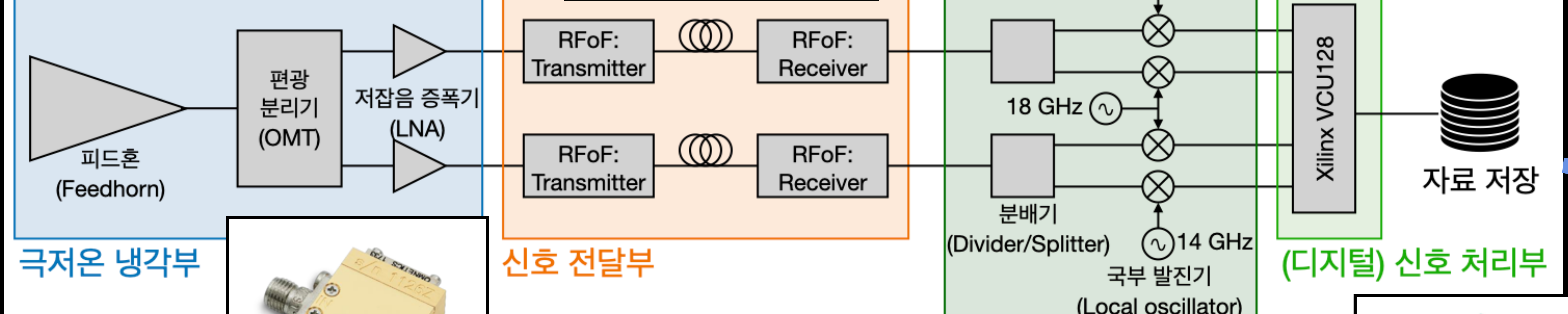
Breysse et al. (2022)

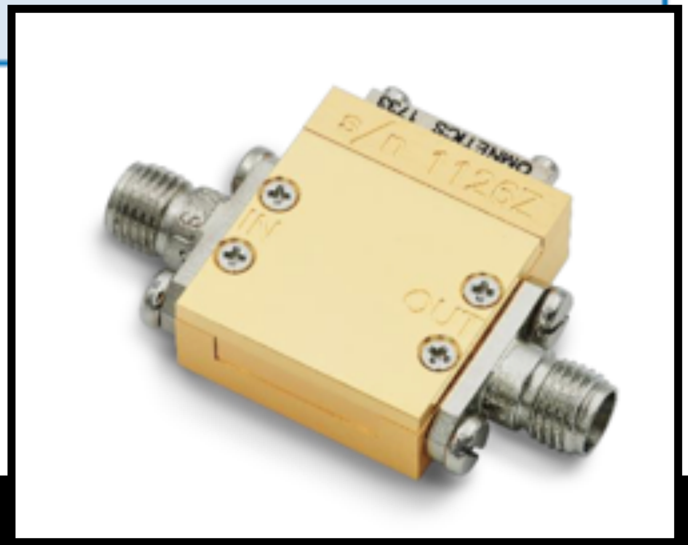
COMAP EoR: 12-20 GHz (Ku-band)

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

Taeduk Radio Astronomy Observatory (TRAO) 13.7 m

RF over Fiber (20 GHz)

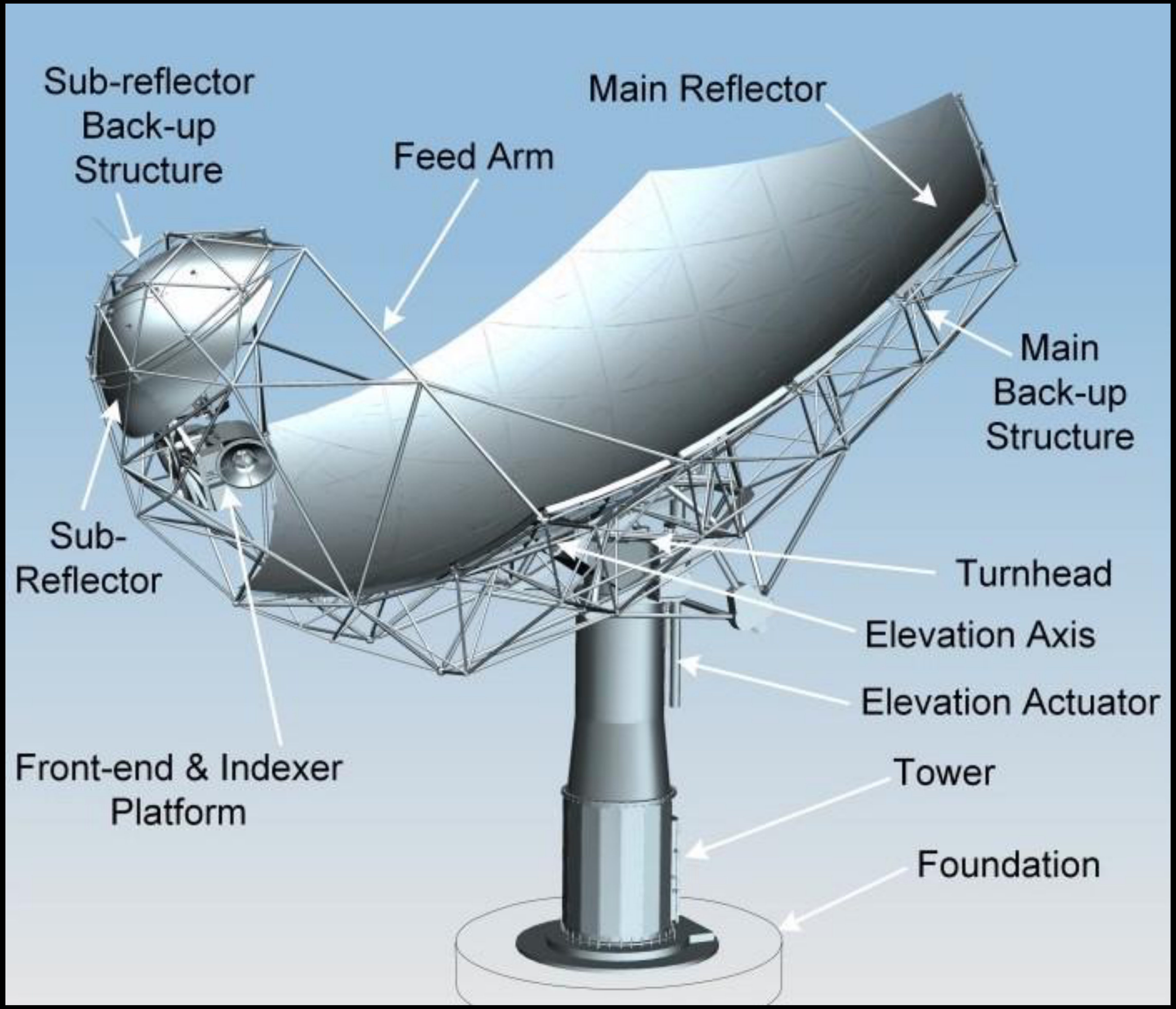




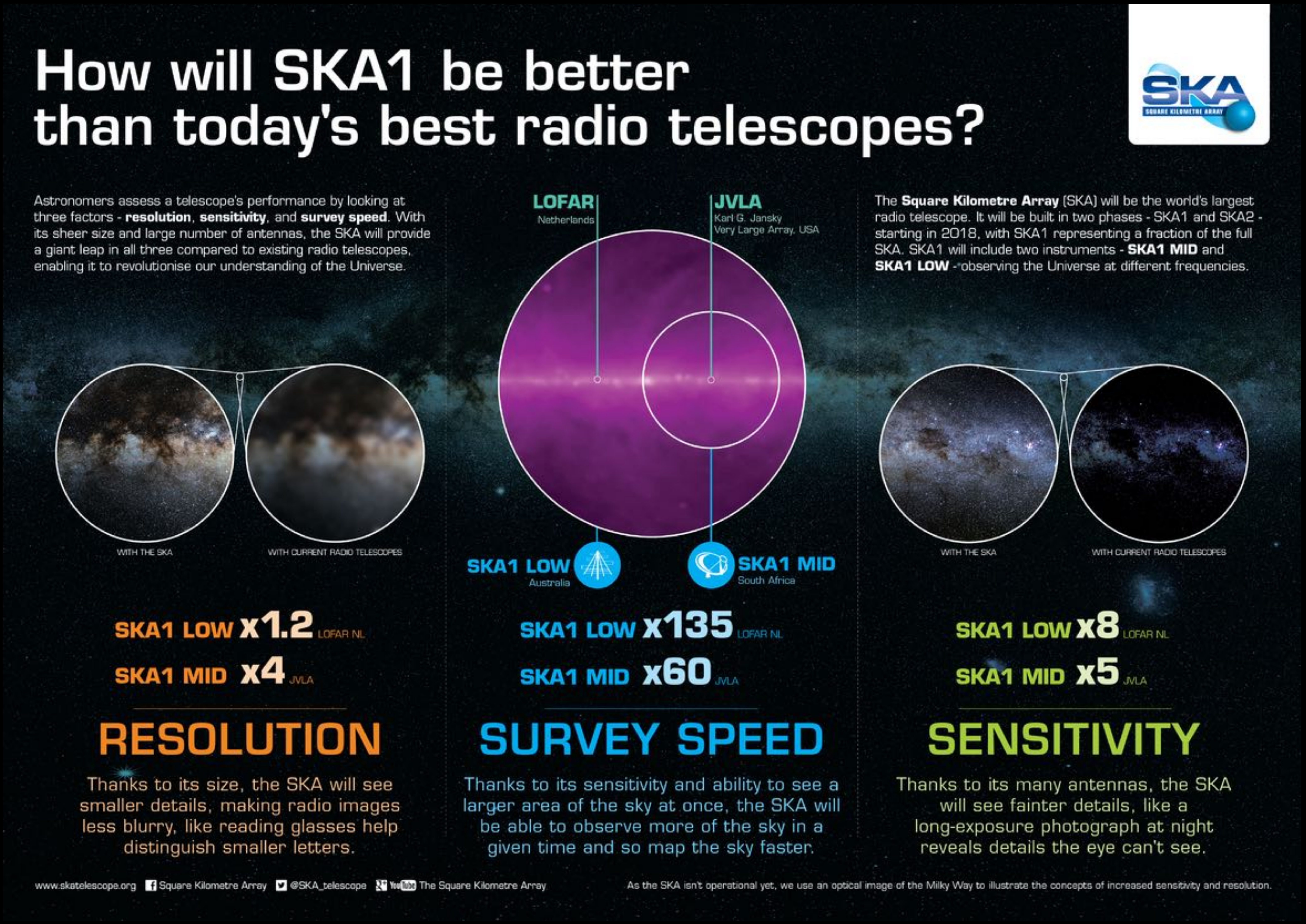
LNF-LNC6_20C Cryogenic LNA

(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)



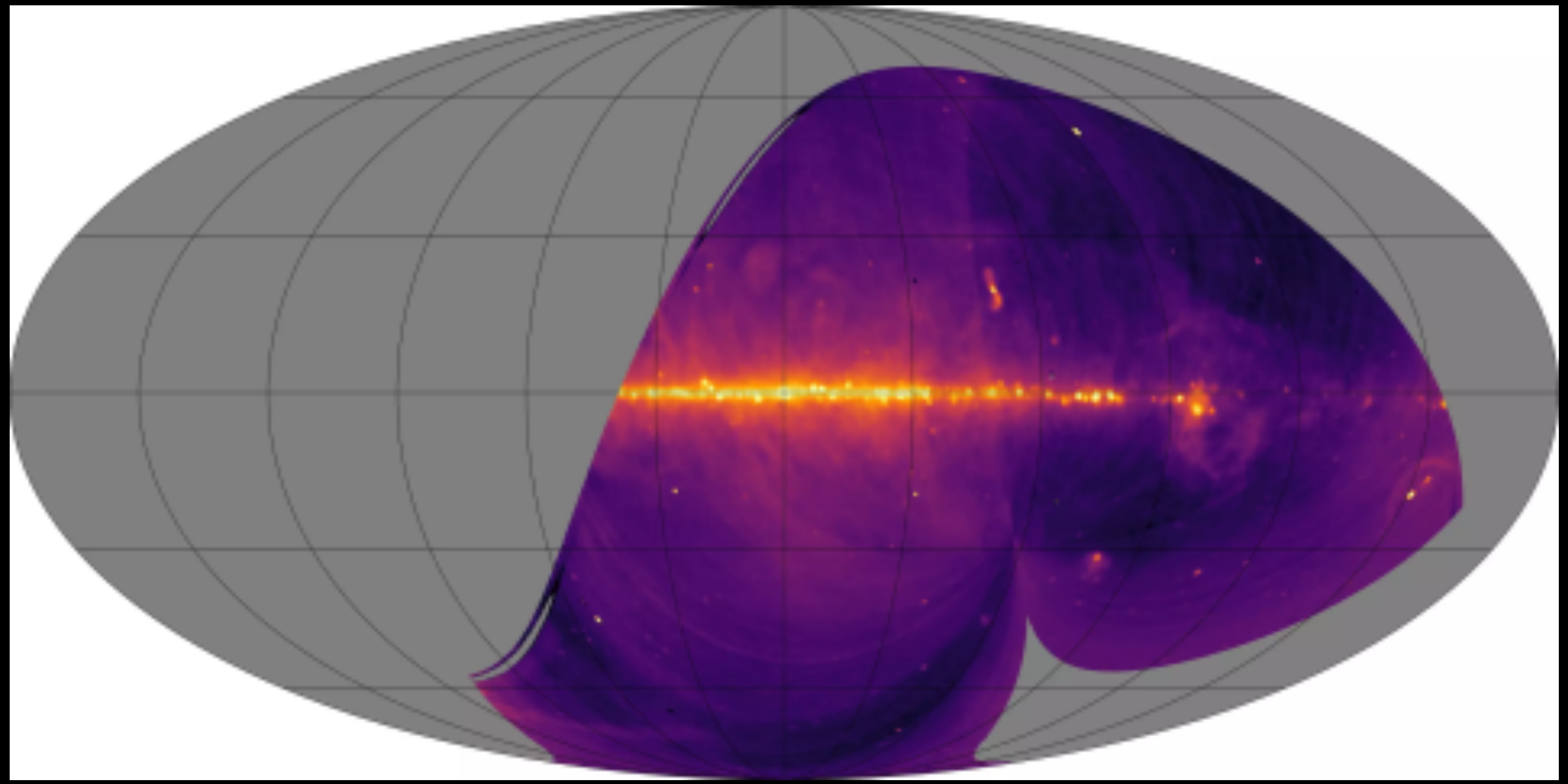
https://www.skao.int/en/explore/telescopes/ska-mid



SKA-Mid prototype dish creates first light image

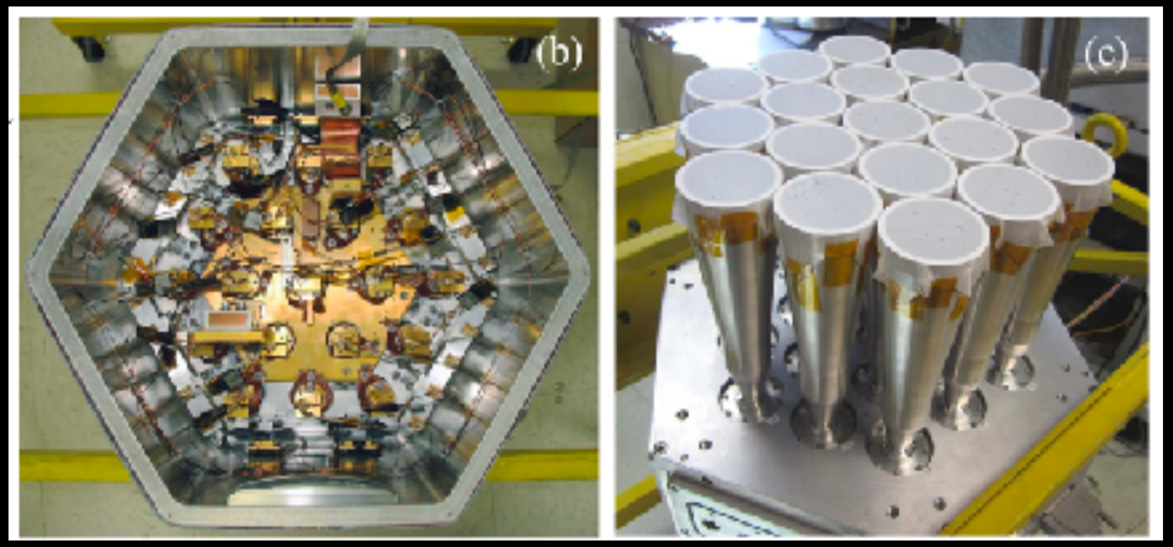
NEWS
on 25 January 2024

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

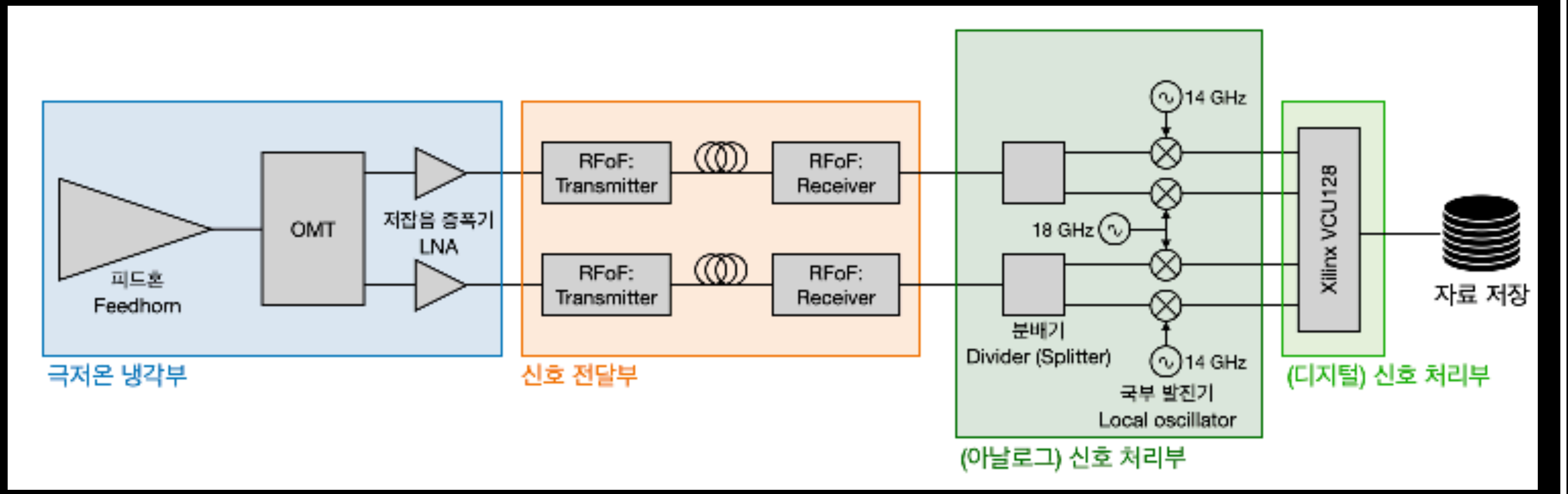


https://www.roe.ac.uk/vdod2021/crawford-building/ska.html
https://www.skao.int/en/news/512/ska-mid-prototype-dish-creates-first-light-image

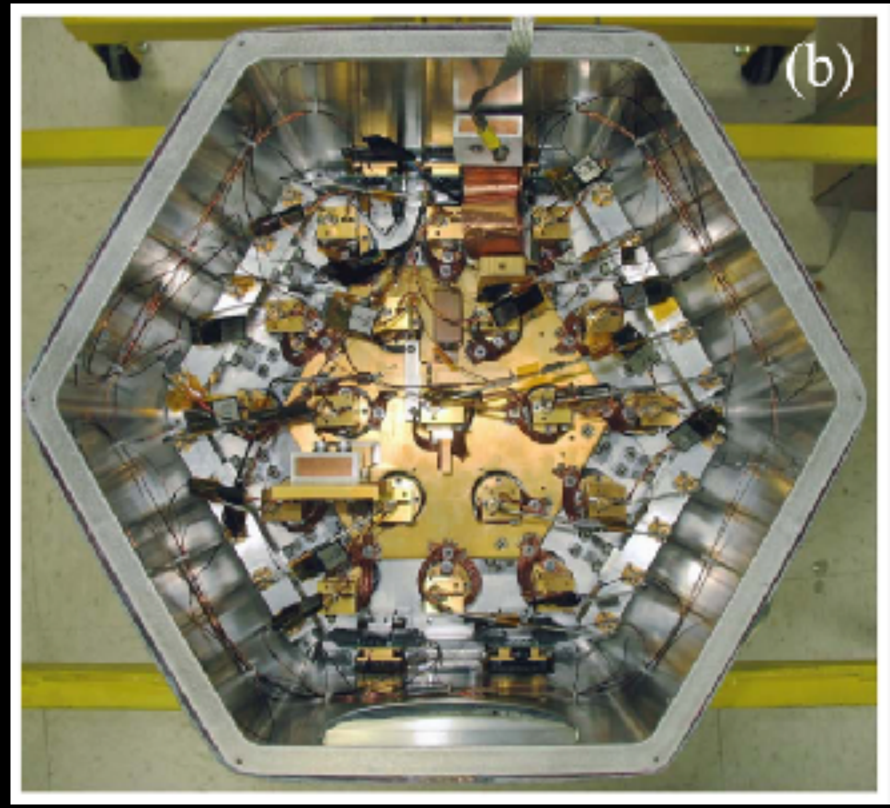
COMAP Pathfinder
26-34 GHz (z=2.4 – 3.4)



(1) Ku-band Prototype Receiver Development



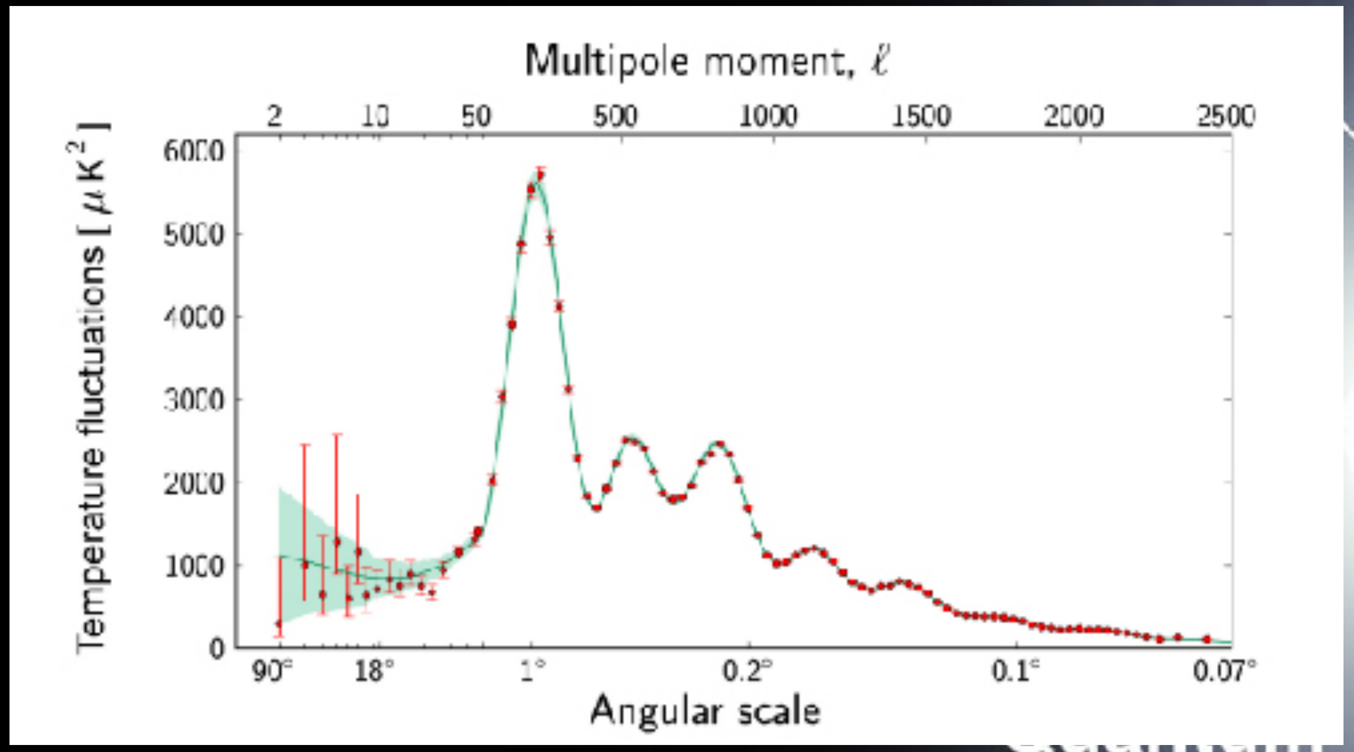
(2) Testing Signal Chain + Observation



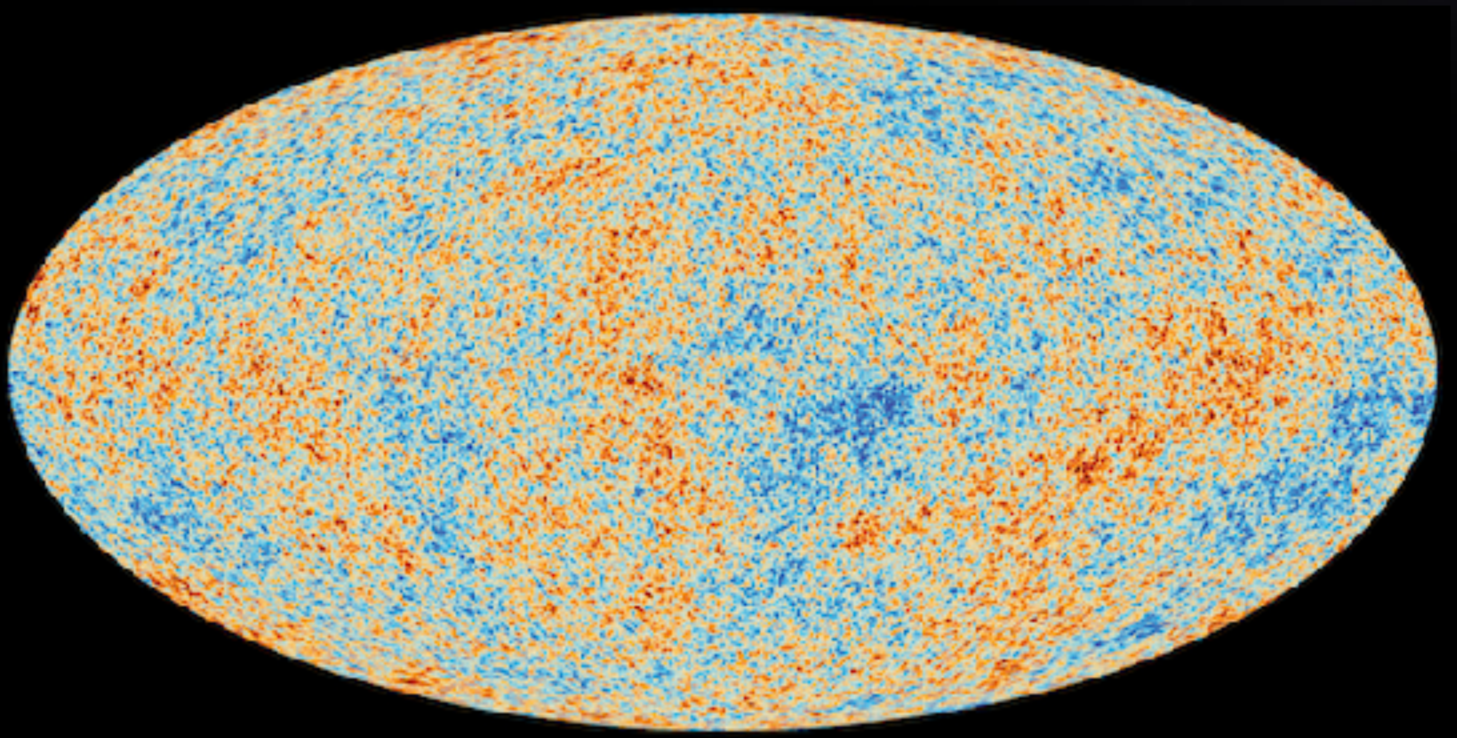
COMAP EoR
12-20 GHz (z=4.8 – 8.6)

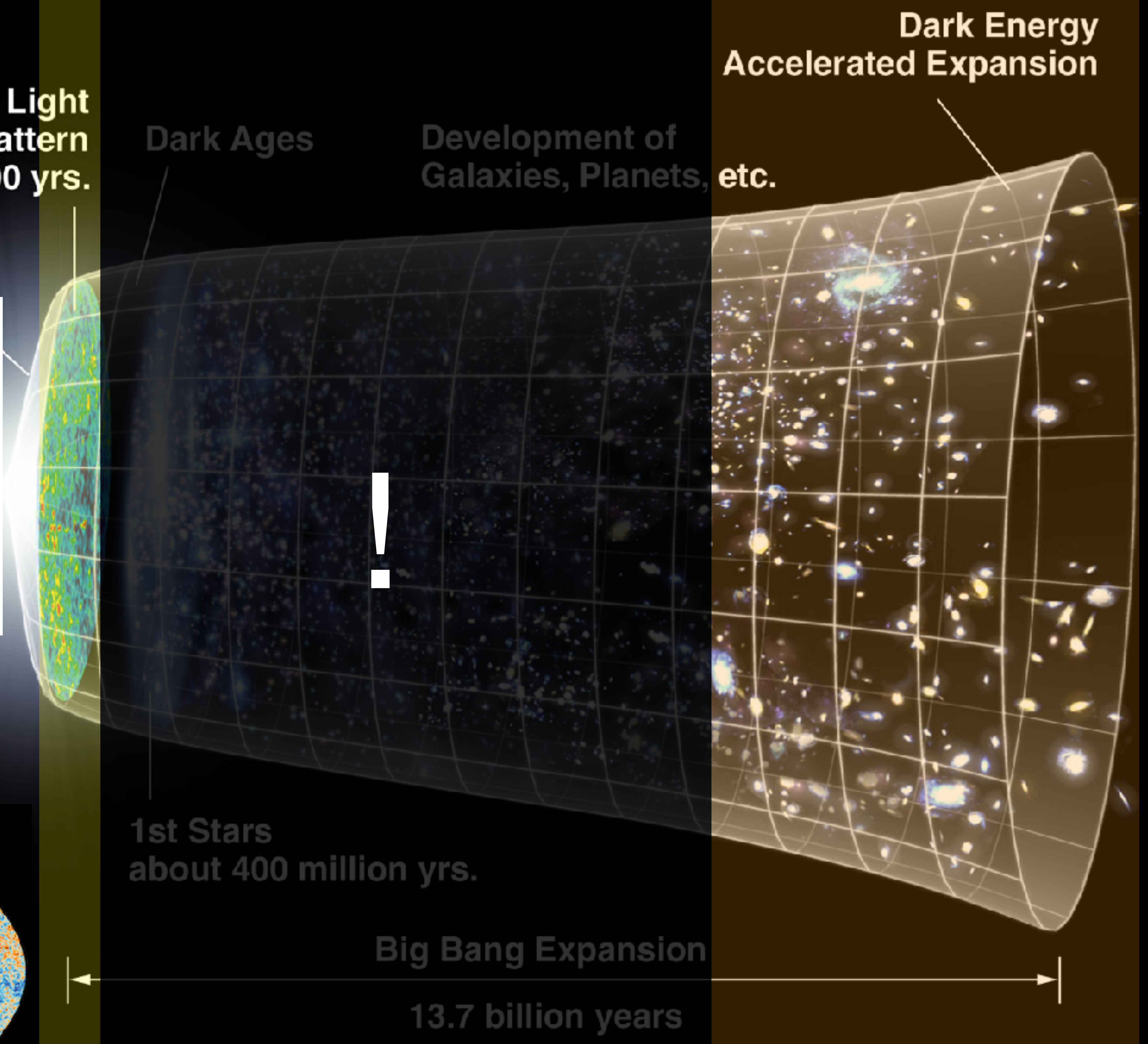
- Focal plane array
- CO LIM using single-dish radio telescopes (e.g., ngVLA, SKA)

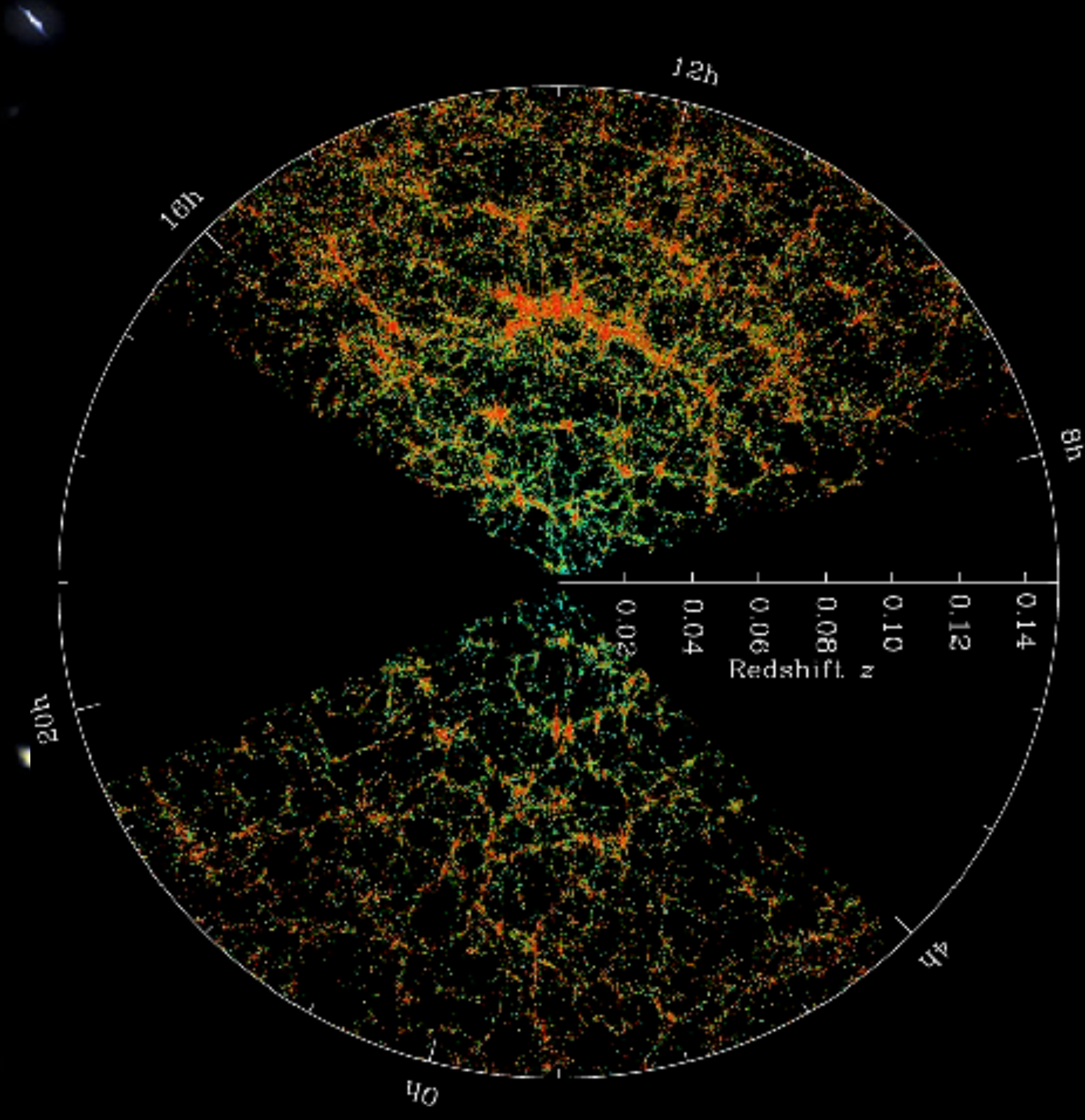
Exploring the History of Star and Galaxy Formation in the Early Universe from z=2.4 to 8.6, Probing the 3D Large-Scale Structure



Cosmic Microwave Background (CMB)







Galaxy surveys
z = 0-1+

NASA/WMAP Science Team