

Guest Lecture of Physical Cosmology – 2024/11/27

Probes in Observational Cosmology

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L Outline

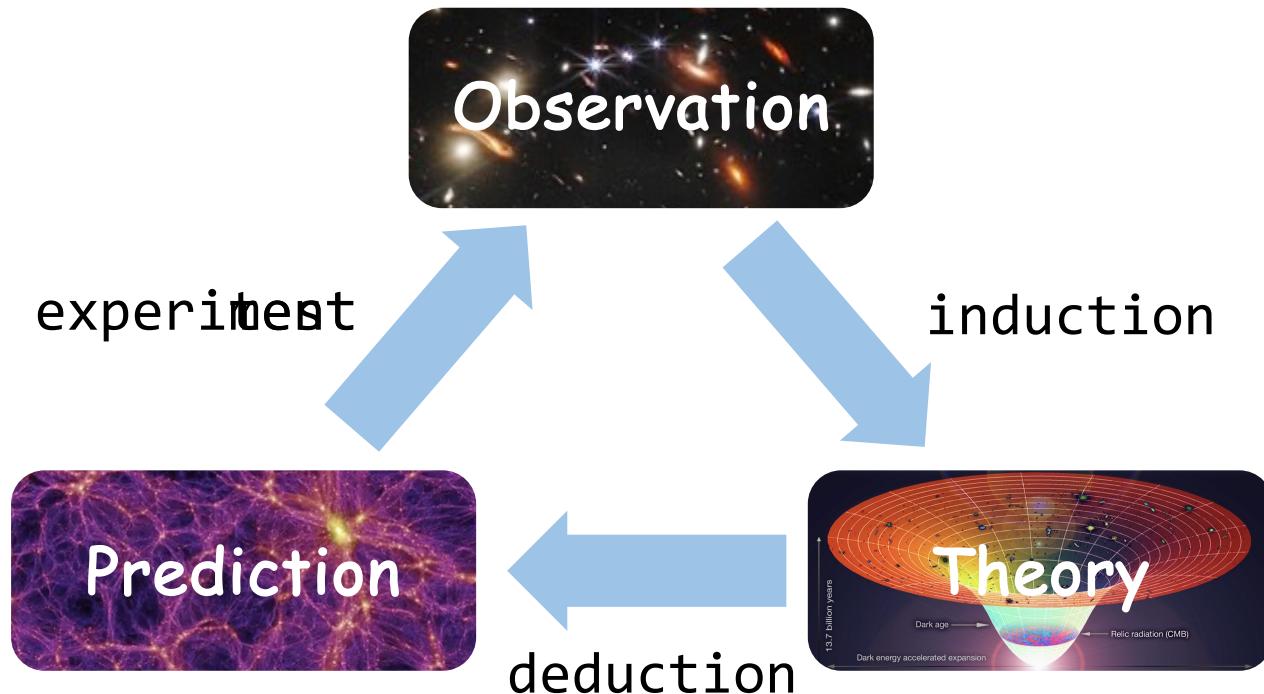
- Introduction to observational cosmology: a historical review
- Cosmological probes
 - Distance ladder
 - Type Ia supernova
 - Cosmic microwave background
 - Galaxy clustering
 - Gravitational lensing
- Combination of probes
- Future prospective

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Observational

- The study of the structure, the evolution, and the origin of the entire Universe
- Use of scientific method:

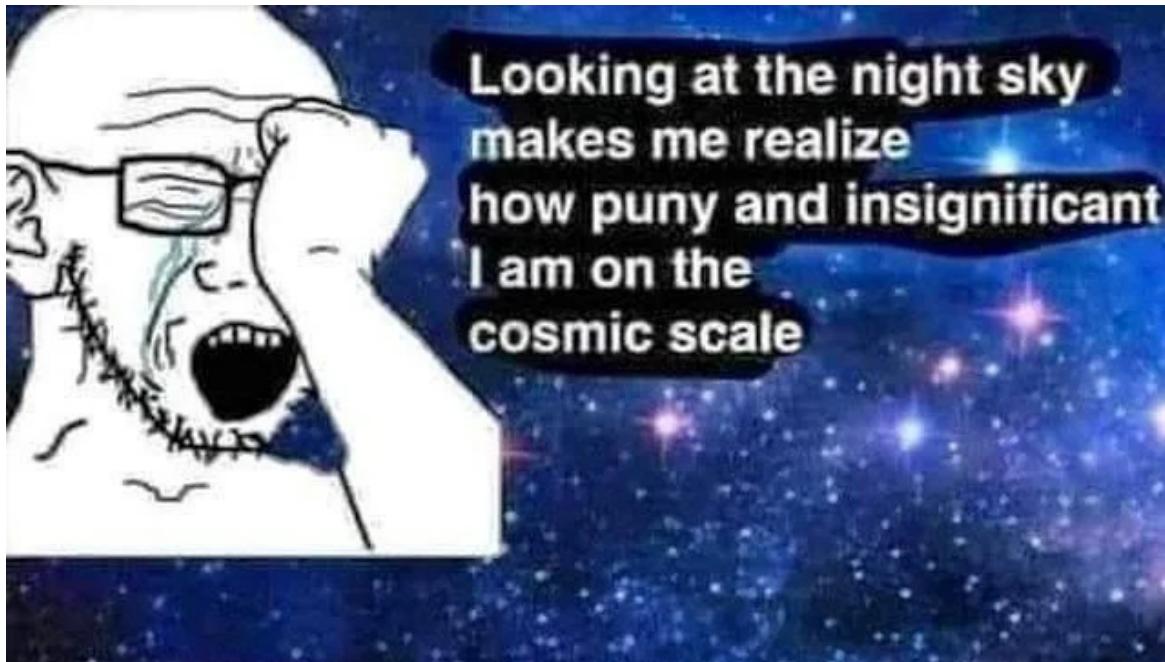


L Observational Cosmology

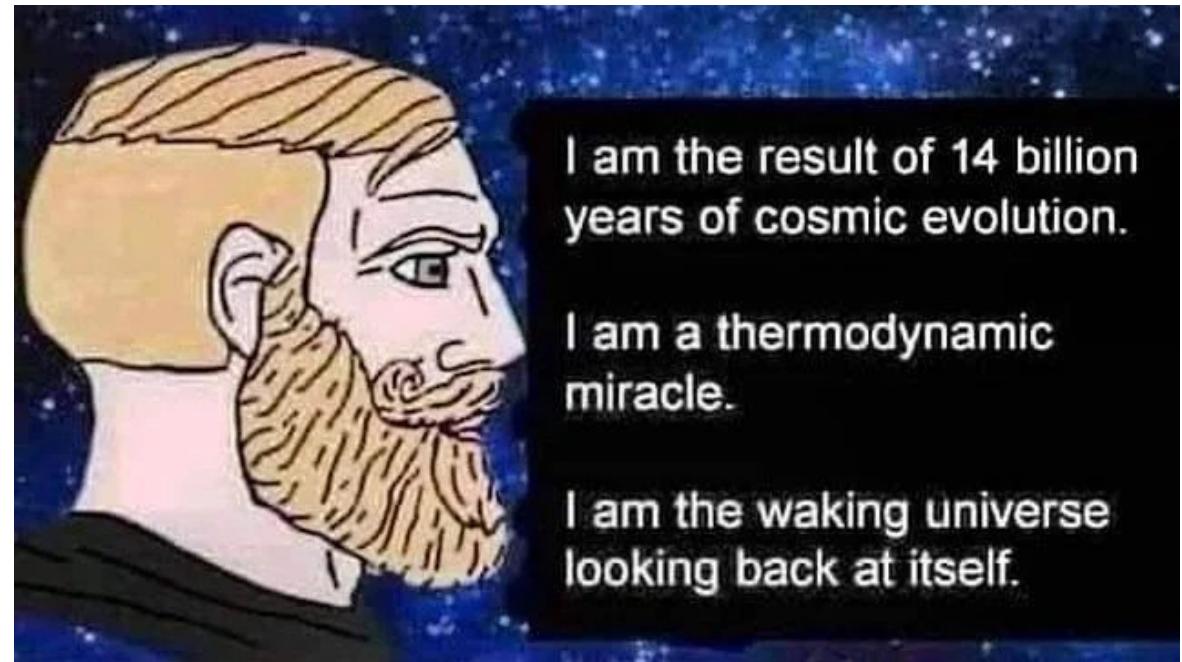
- The study of the entire Universe through **observation**, using **instruments** such as telescopes
- What have we observed and concluded so far?
- Do we really understand the observations?



L Observational Cosmology: a real epic



Looking at the night sky
makes me realize
how puny and insignificant
I am on the
cosmic scale



I am the result of 14 billion
years of cosmic evolution.

I am a thermodynamic
miracle.

I am the waking universe
looking back at itself.

L Historical Visions of the Universe

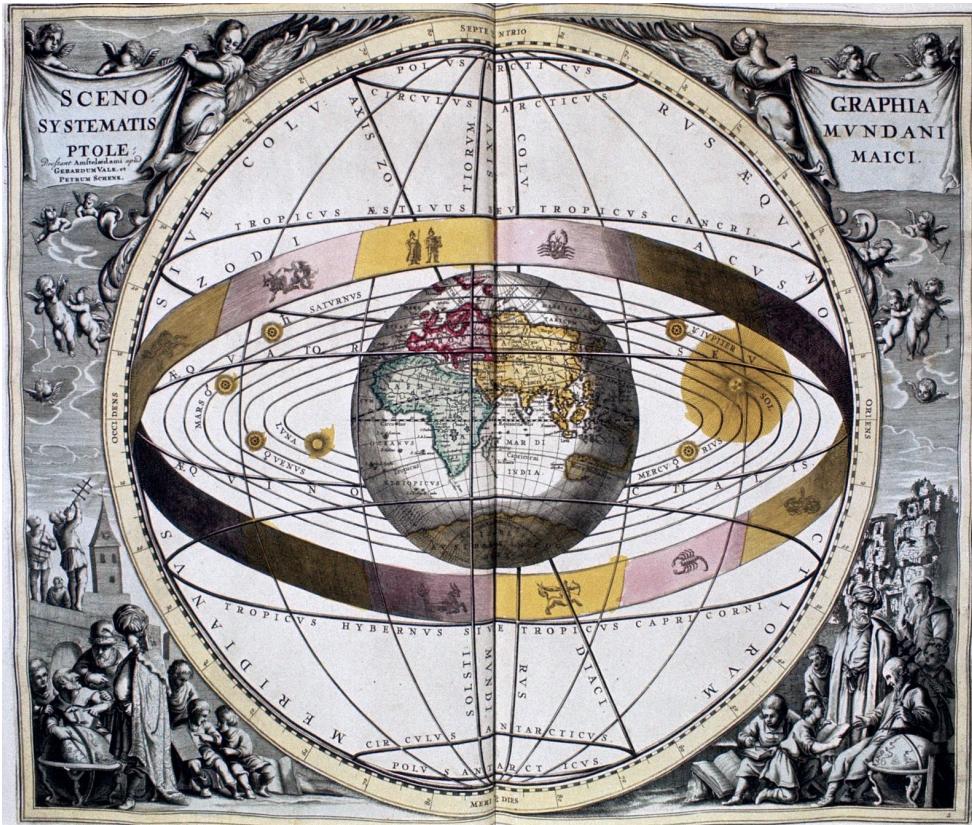
- The cosmos as seen by naked eyes



Polaris

Historical Visions of the Universe

Ptolemaic System



Ancient Chinese Cosmos

盖天说



天圆像张开的伞，地方像棋盘

浑天说



“天之包地，犹壳之裹黄”

Earth at the centre of the Universe



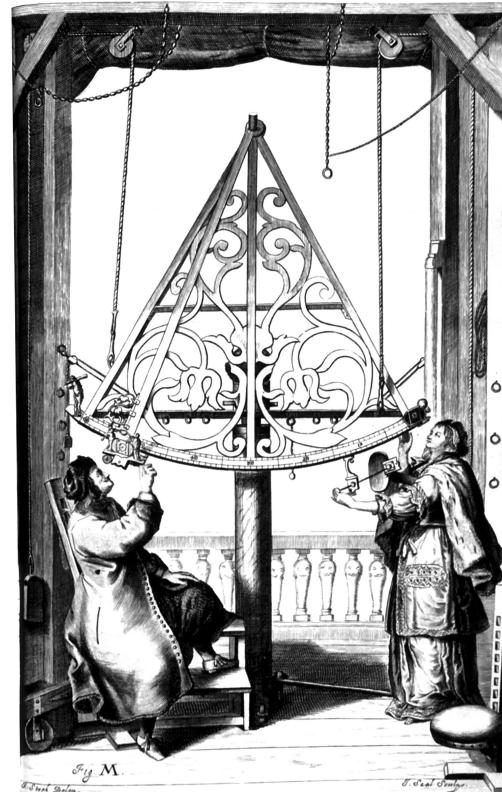
Instrumental development

- The cosmos as seen by naked eyes *with the help of instruments*

Armill



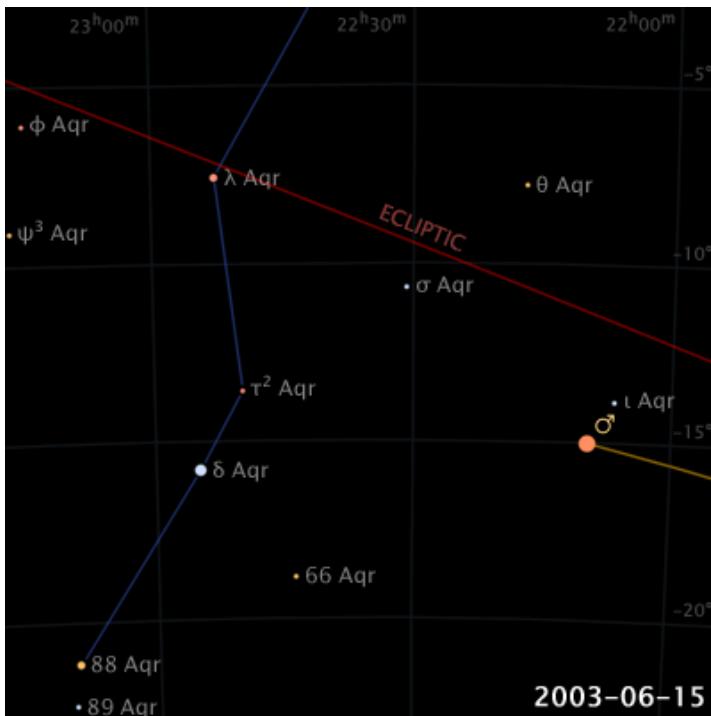
Sextant



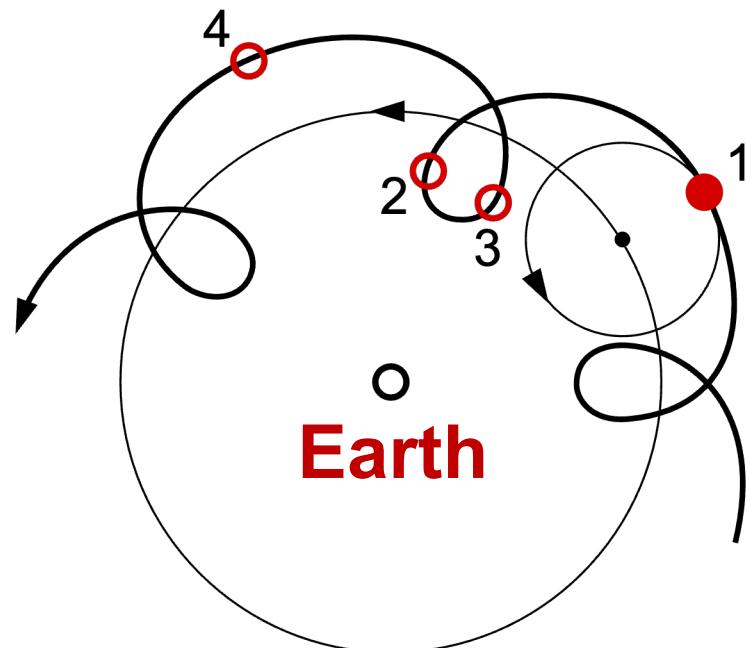
~ degree – arcmin precision

L Deferent and epicycle

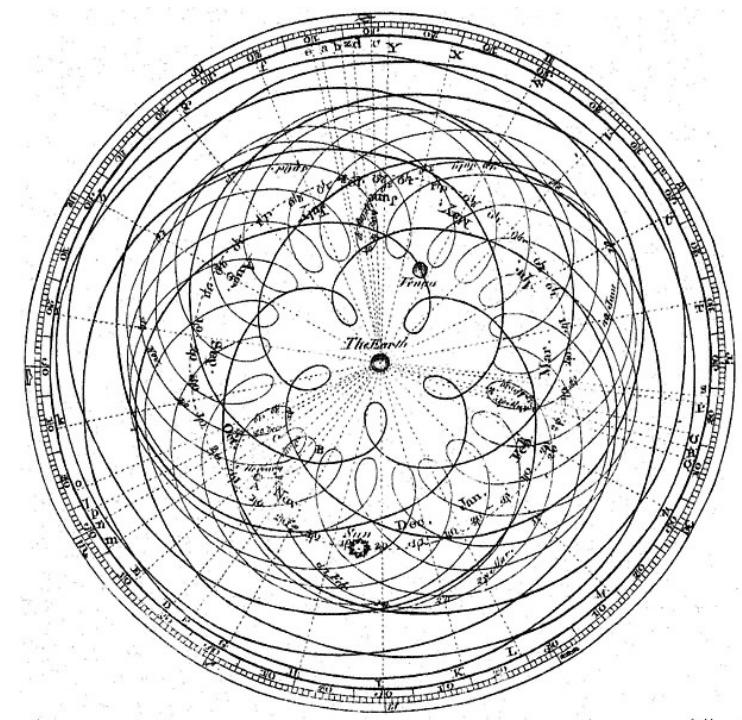
- The cosmos as seen by naked eyes *with the help of instruments*



*Retrograde motion
of planets*

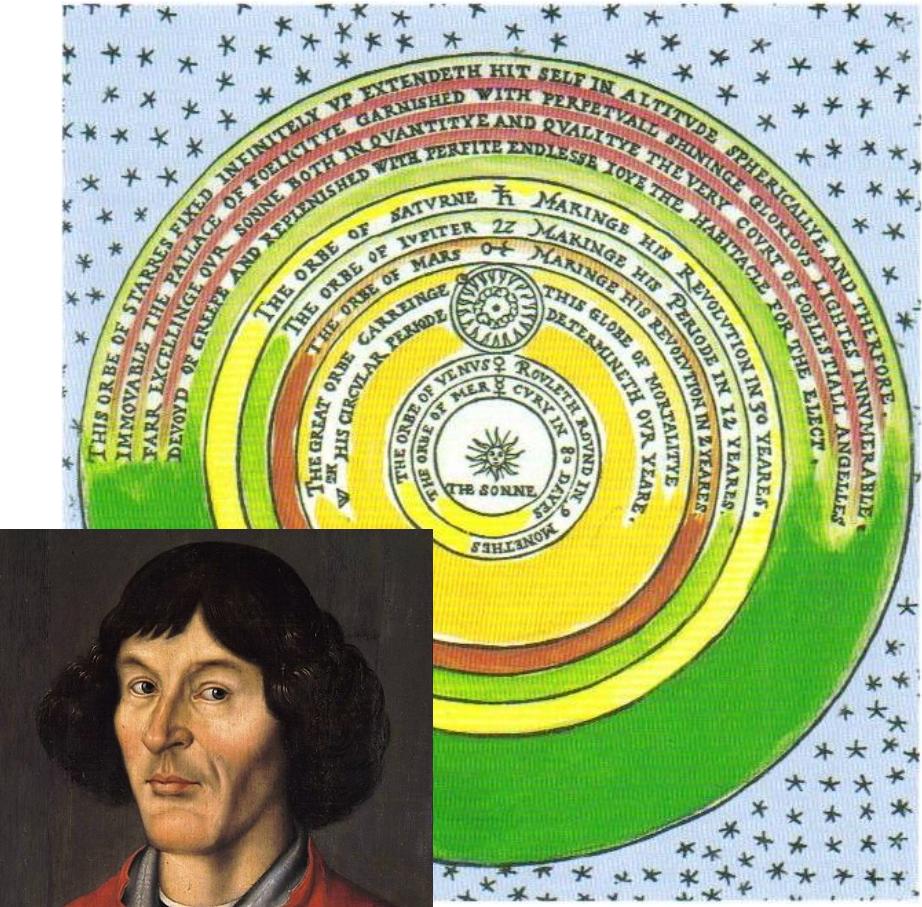
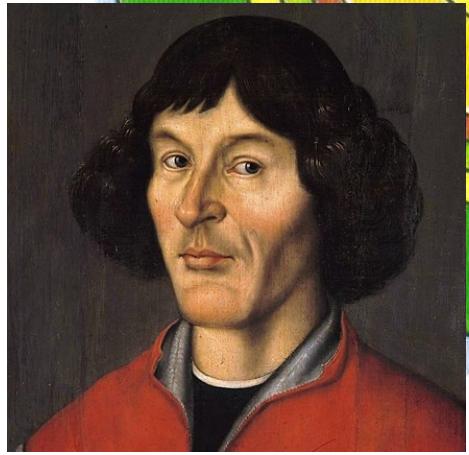


Deferent and epicycle

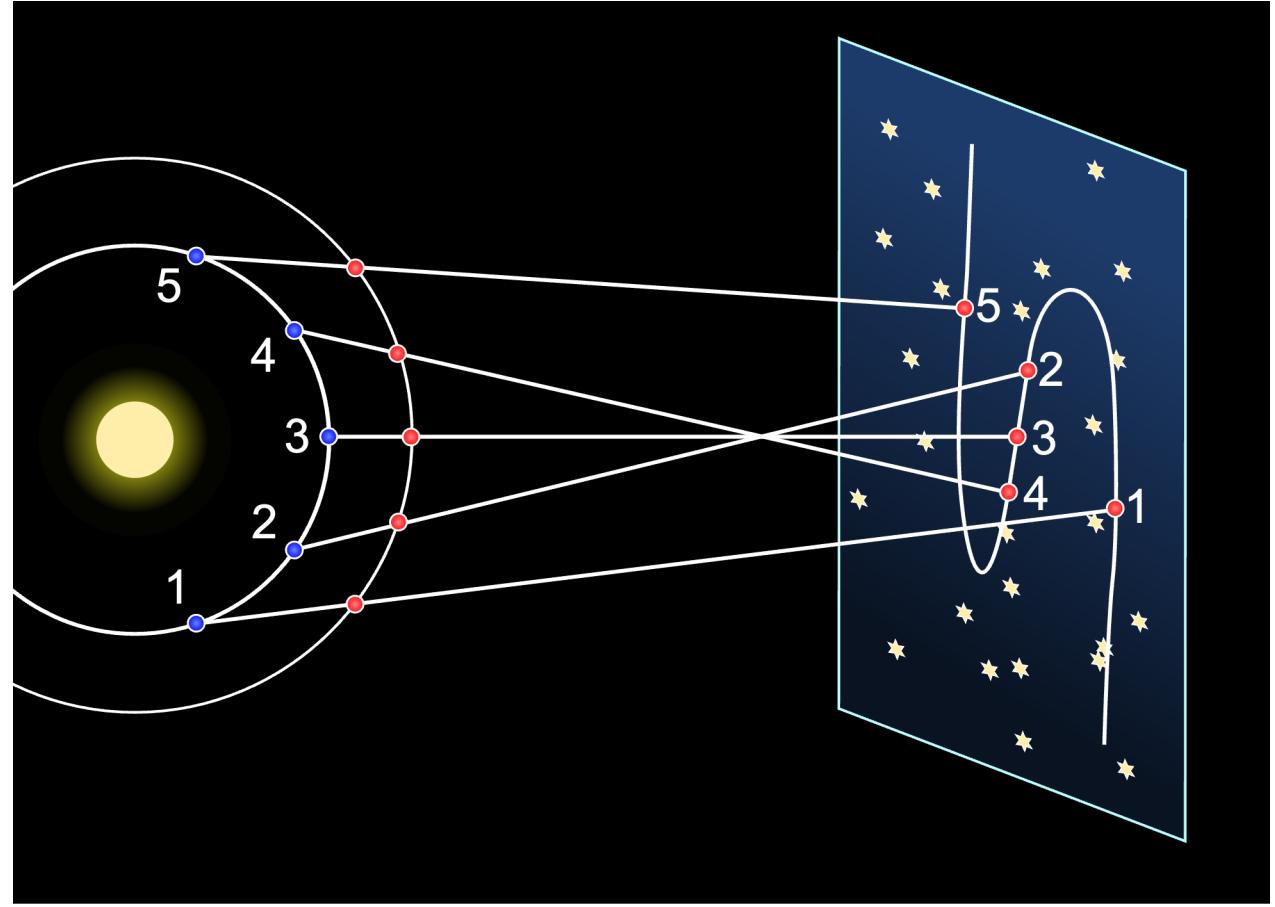


*The complexity
of the theory*

Copernicus Revolution (1543)



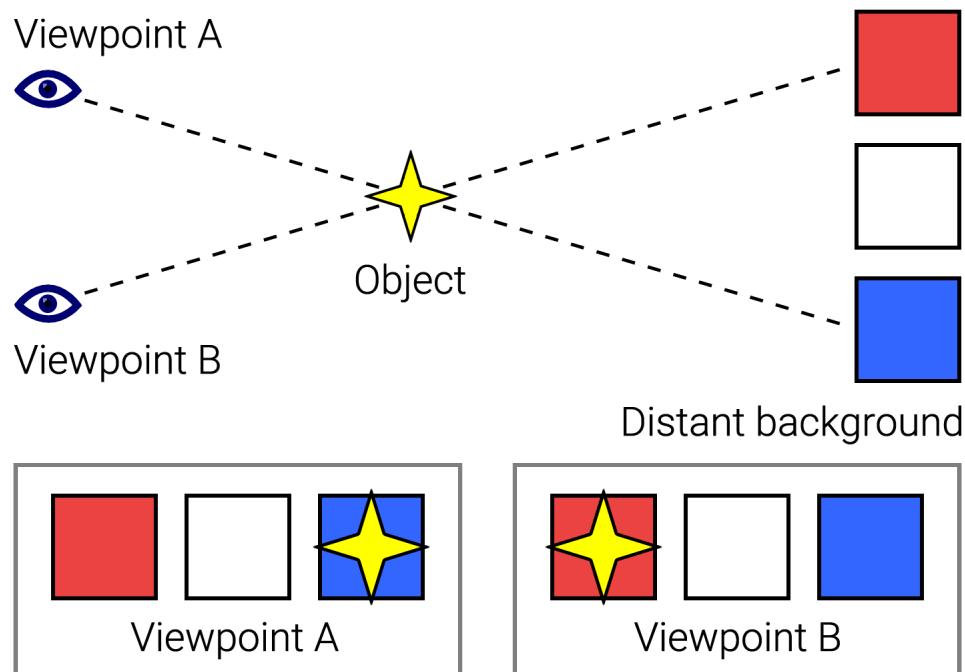
Heliocentric model



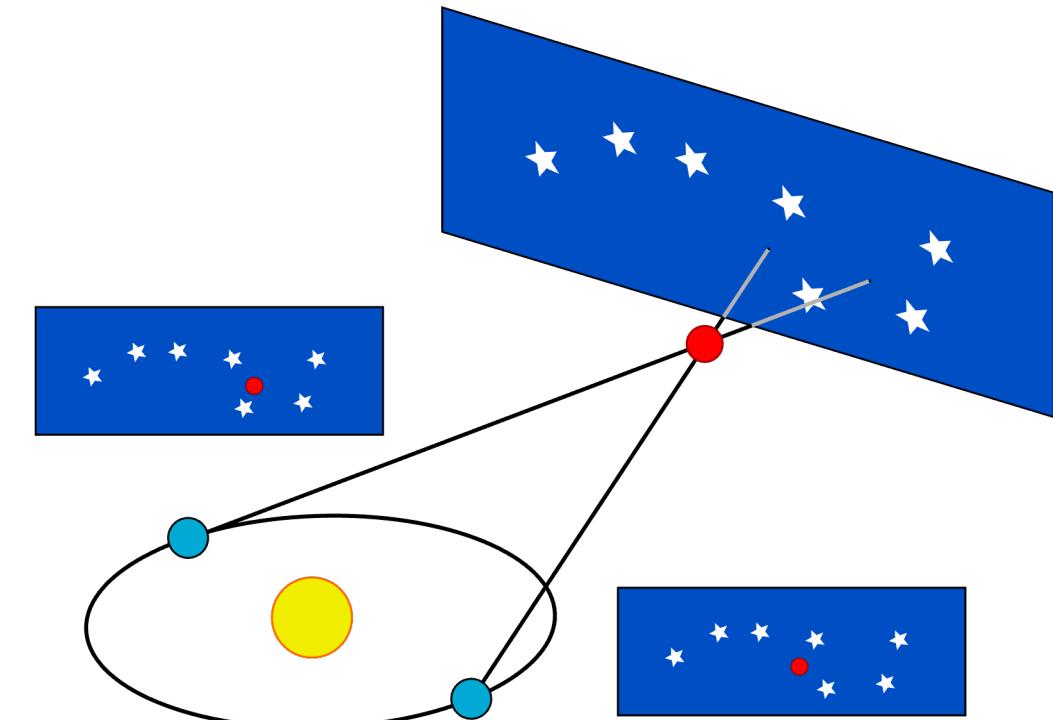
*The simplified explanation of
retrograde motion*



Tycho's argument: parallax (1600s)



*Distances of stars measurable given a long enough **baseline***



Heliocentric model offers a much longer baseline than the size of the earth



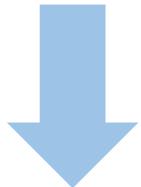
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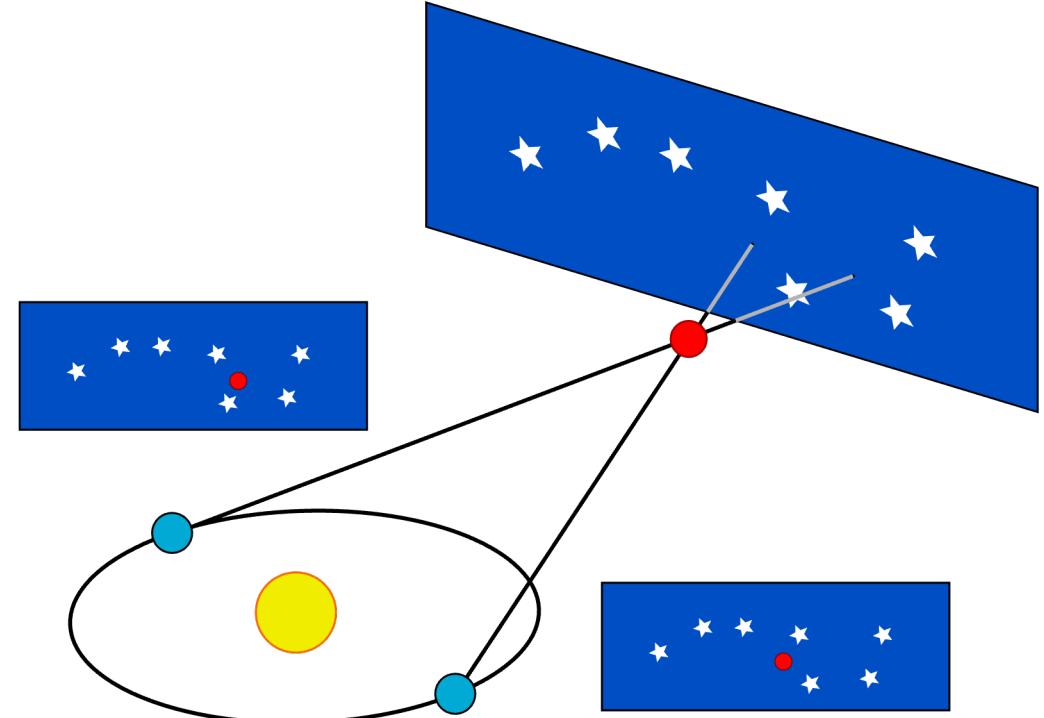
No detection



Stars cannot be so distant



Copernicus' model **rejected**

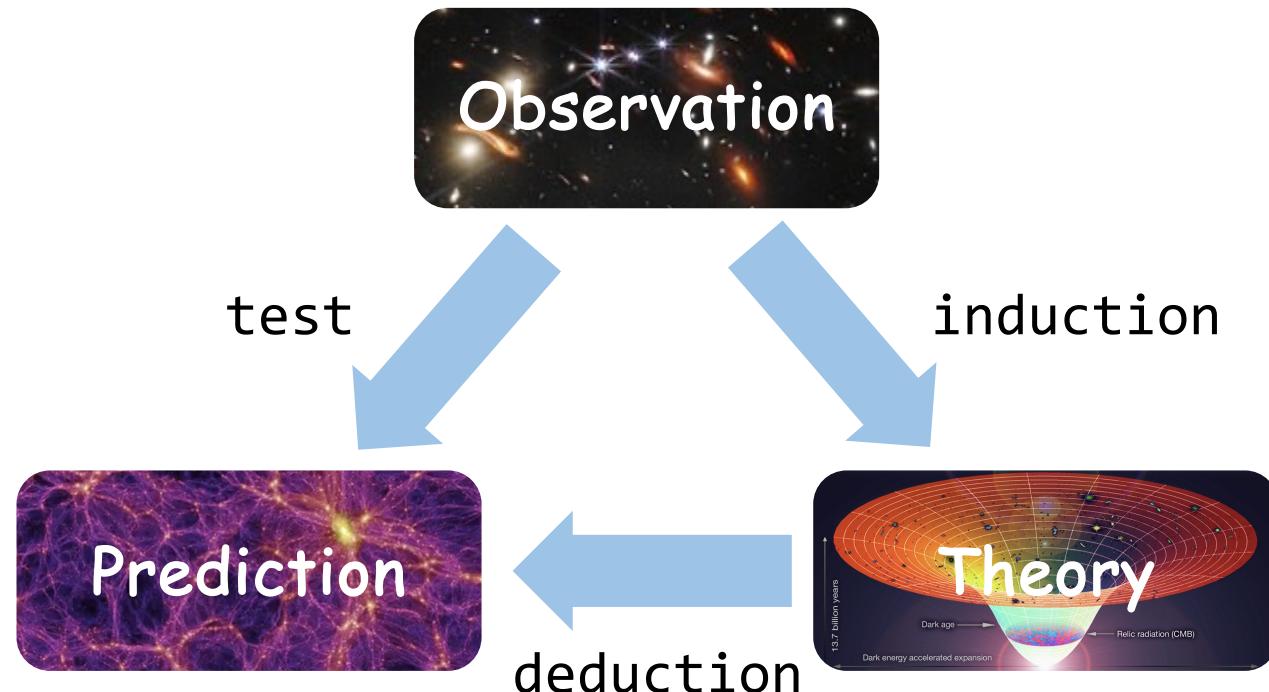


Heliocentric model offers a much longer baseline than the size of the earth



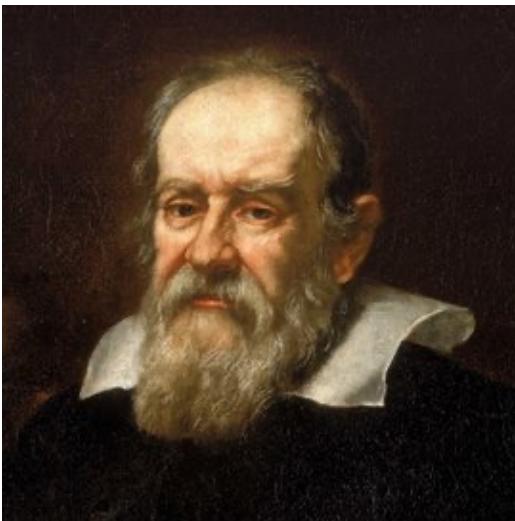
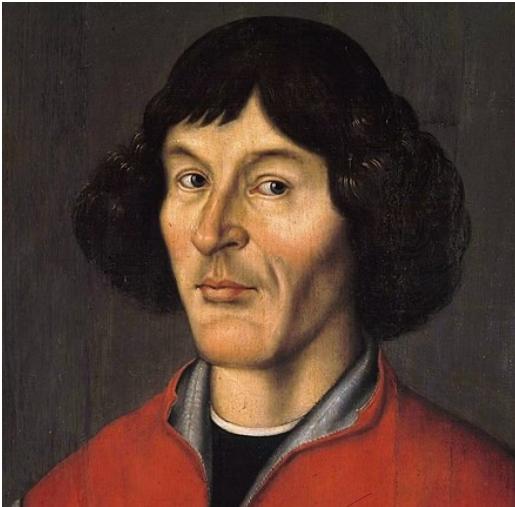
Acceptance of the Heliocentric Model

- Detailed analysis of **observational data**: *Kepler's law*
- New **instrument**: *Galileo's telescope*
- New **theory**: *Newton's universal gravity*



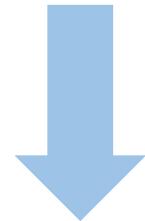


Copernicus-Galileo Revolution (1500-1650)



Modern extension:

Humans, on the Earth or in the Solar System, are not privileged observers of the Universe

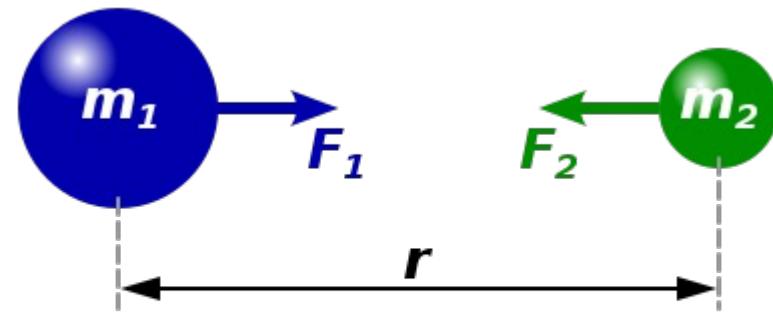
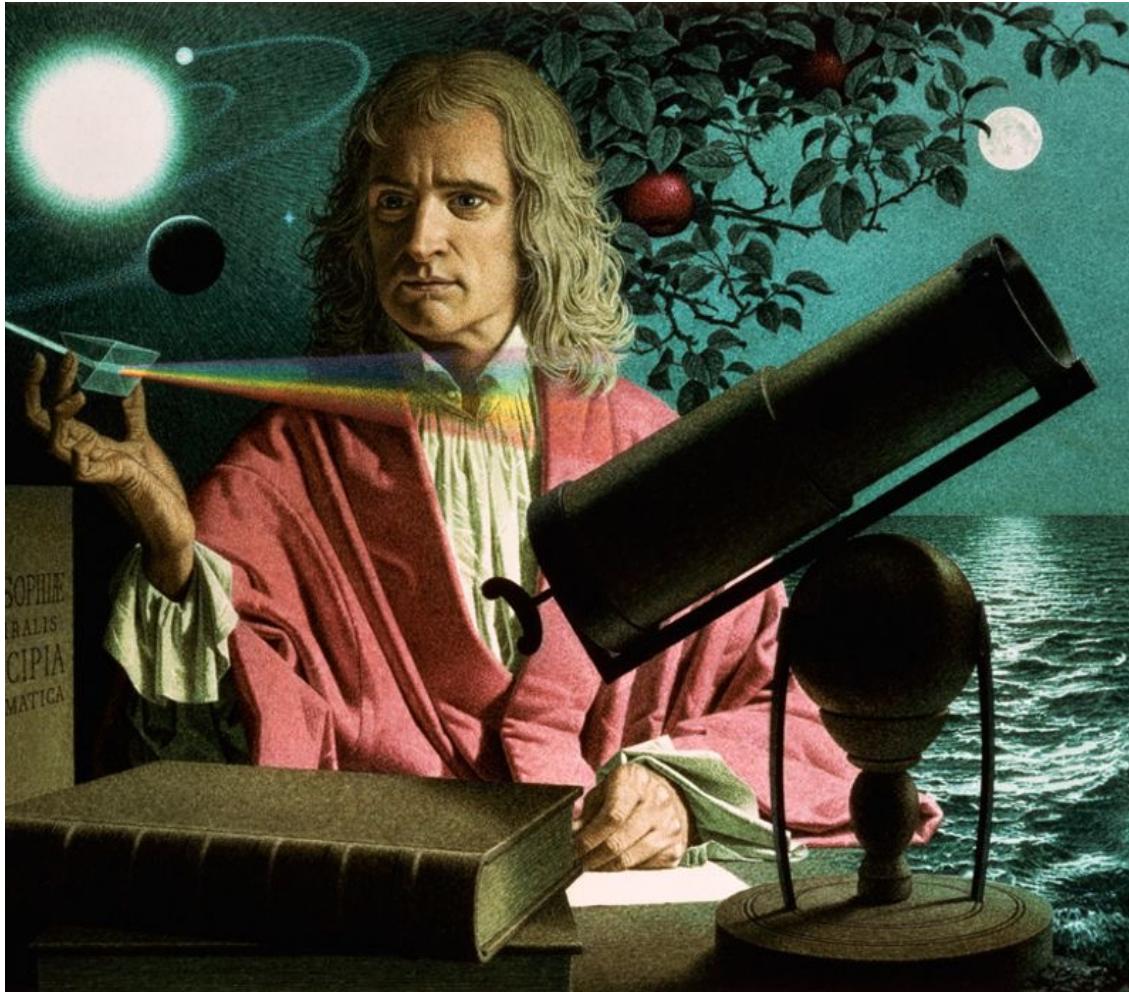


Observations from the Earth are representative of observations from the **average position** in the Universe

Basis of cosmology as a science

L

Newton's law of universal gravitation (1687)



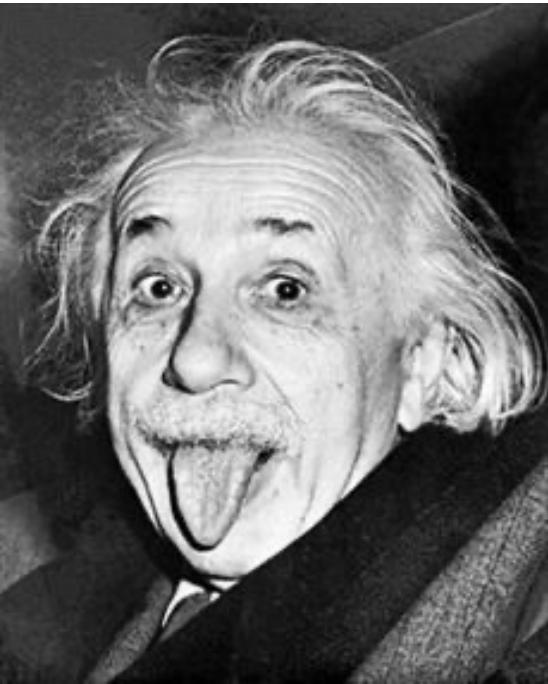
$$F_1 = F_2 = G \frac{m_1 \times m_2}{r^2}$$

Motions of celestial bodies became understandable

First physical law for cosmology



Einstein's General Relativity (1915)



Massive objects cause space-time to curve

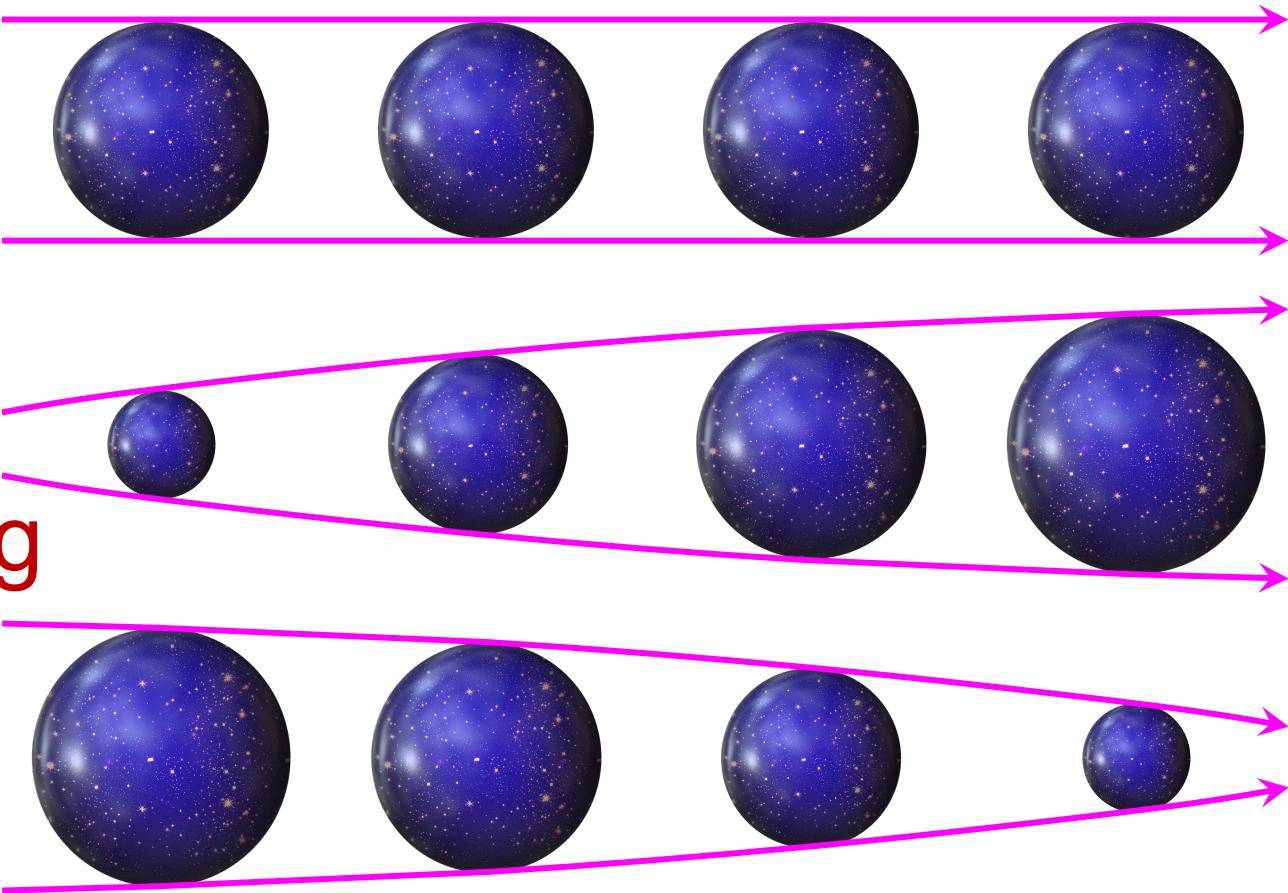


Physical law for modern cosmology

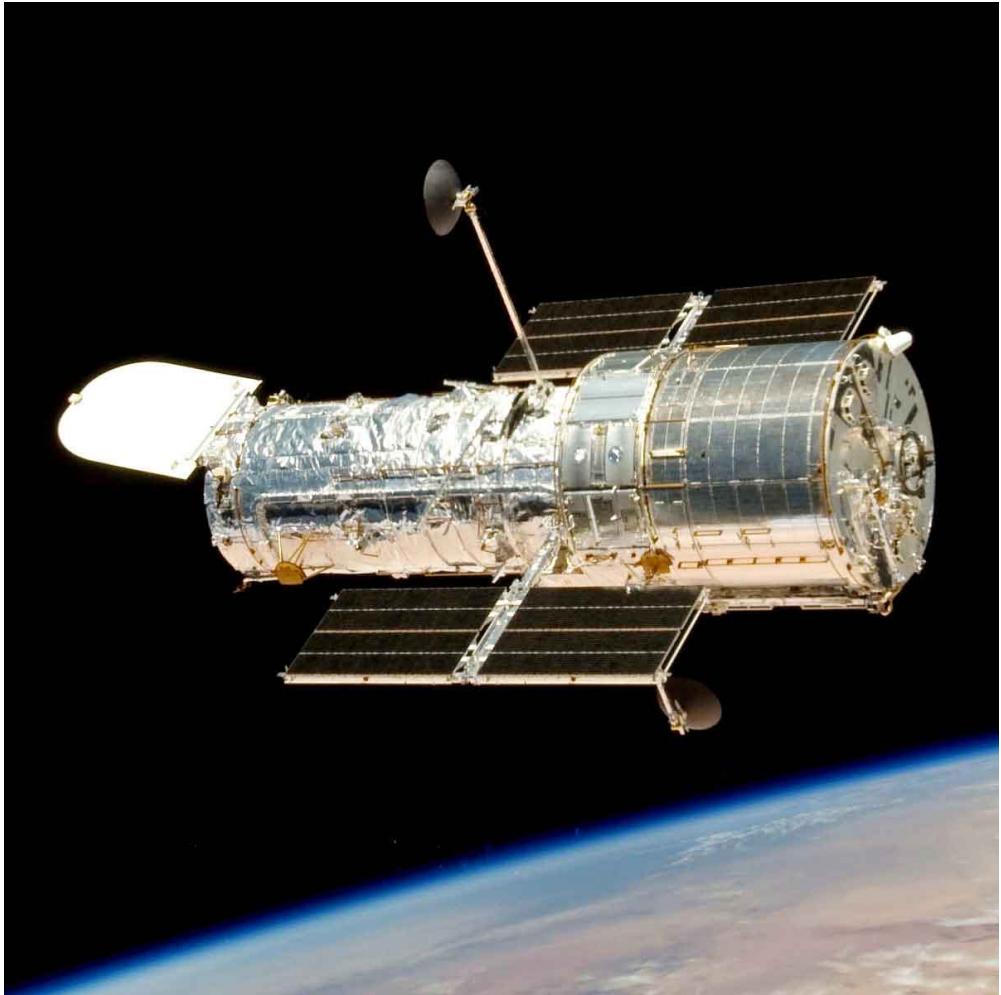
Quiz

With only gravity, is the Universe:

- Static ~~Static~~
- Expanding but decelerating
- Collapsing



Hubble's Discoveries



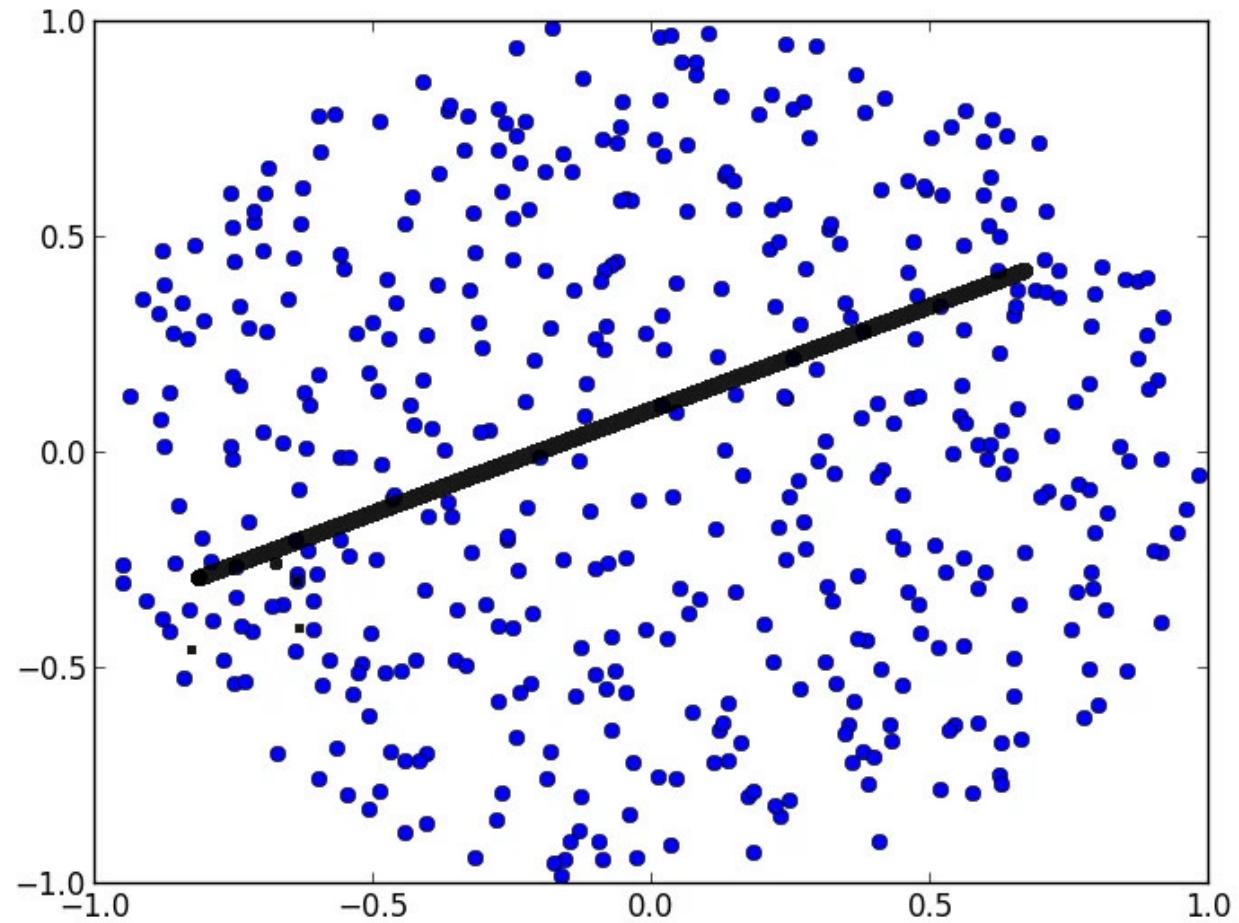
*No, not the telescope
but the person...*

Hubble's Discoveries (1920s)

Scientists be like



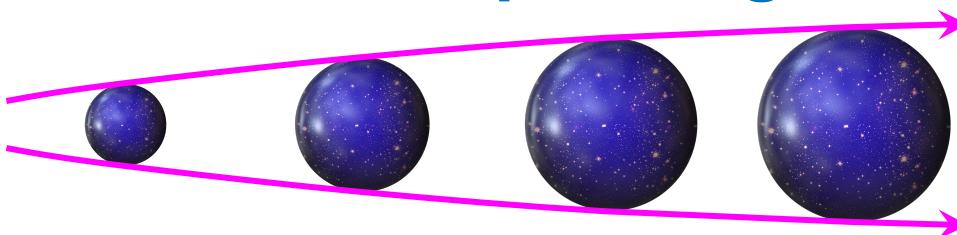
Recession Velocity



Hubble's Discoveries (1920s)

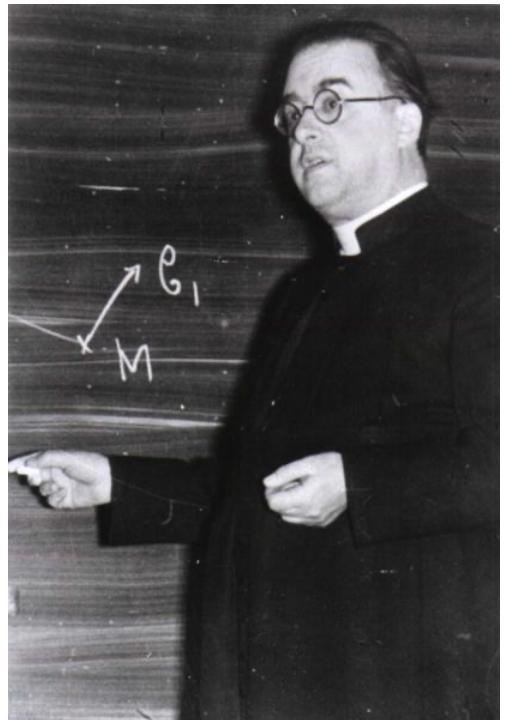


- Confirmed the existence of extragalactic sources and ended the “Great debate” (Milky Way is the entirety of the Universe vs. “universe islands”)
- **Hubble’s law:** galaxies are moving away from Earth at speeds proportional to their distance → **first observational evidence of an expanding Universe**

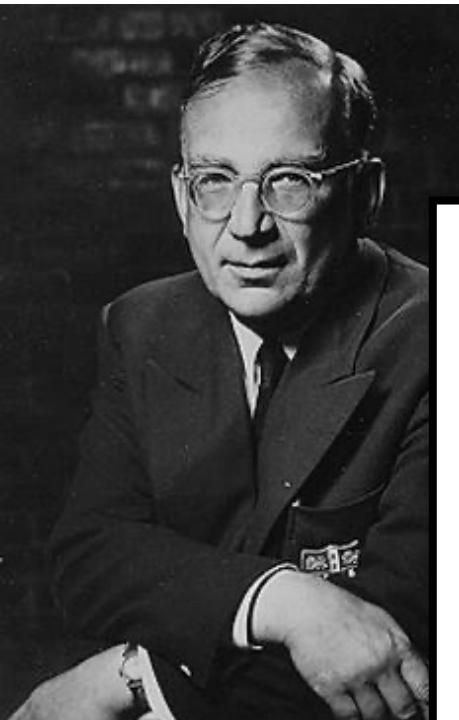


Must be decelerating

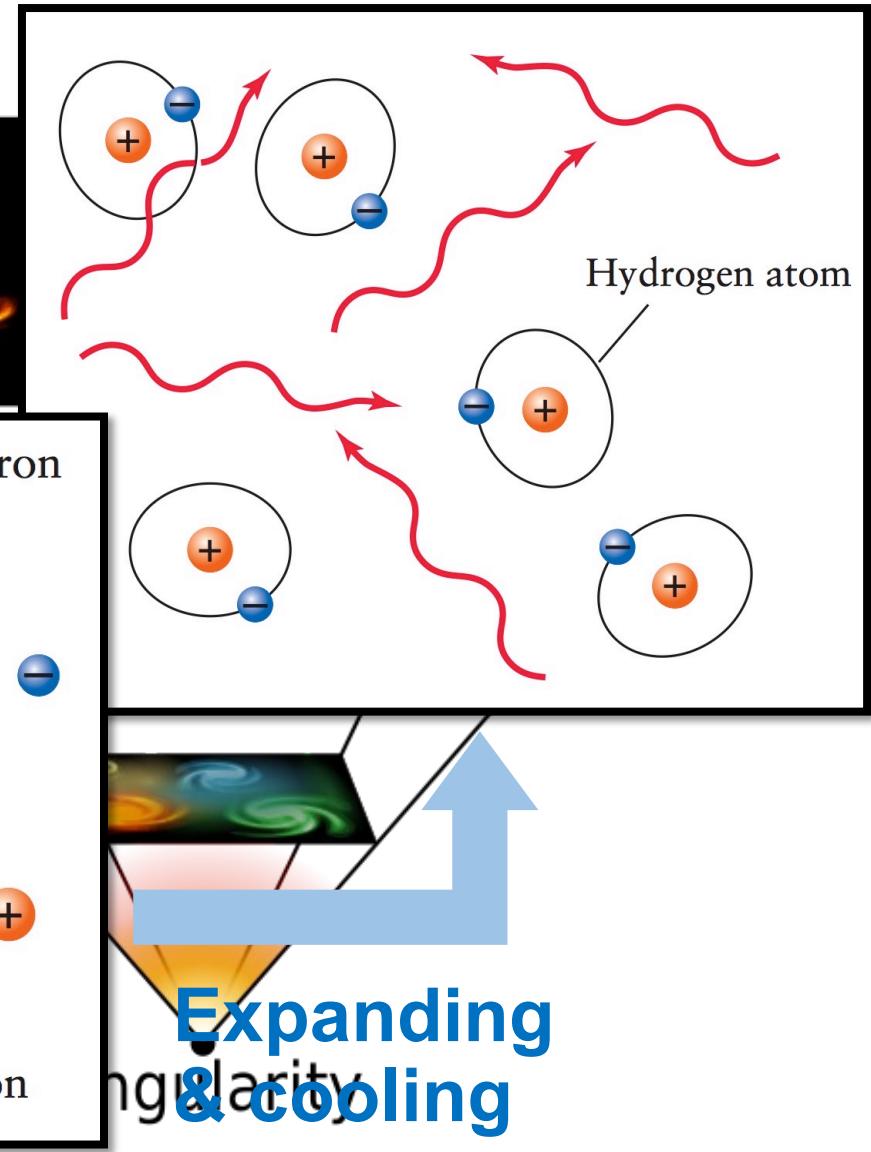
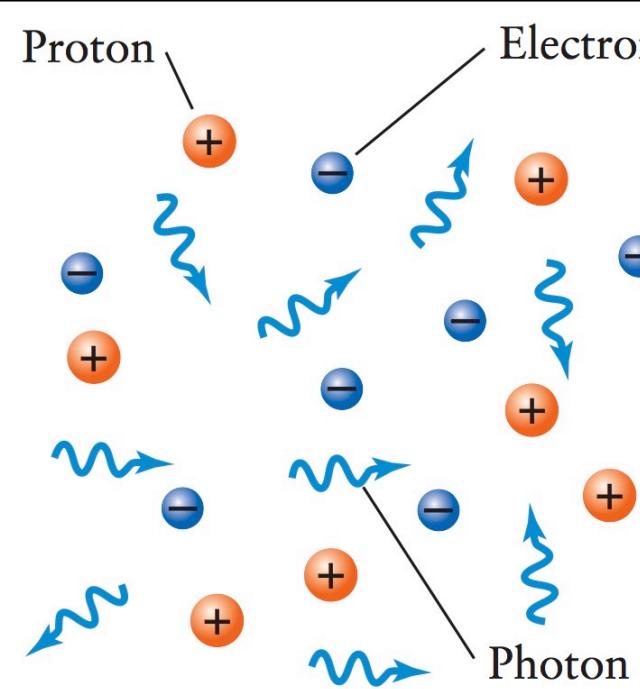
Big Bang Theory (since 1927)



Georges
Lemaître



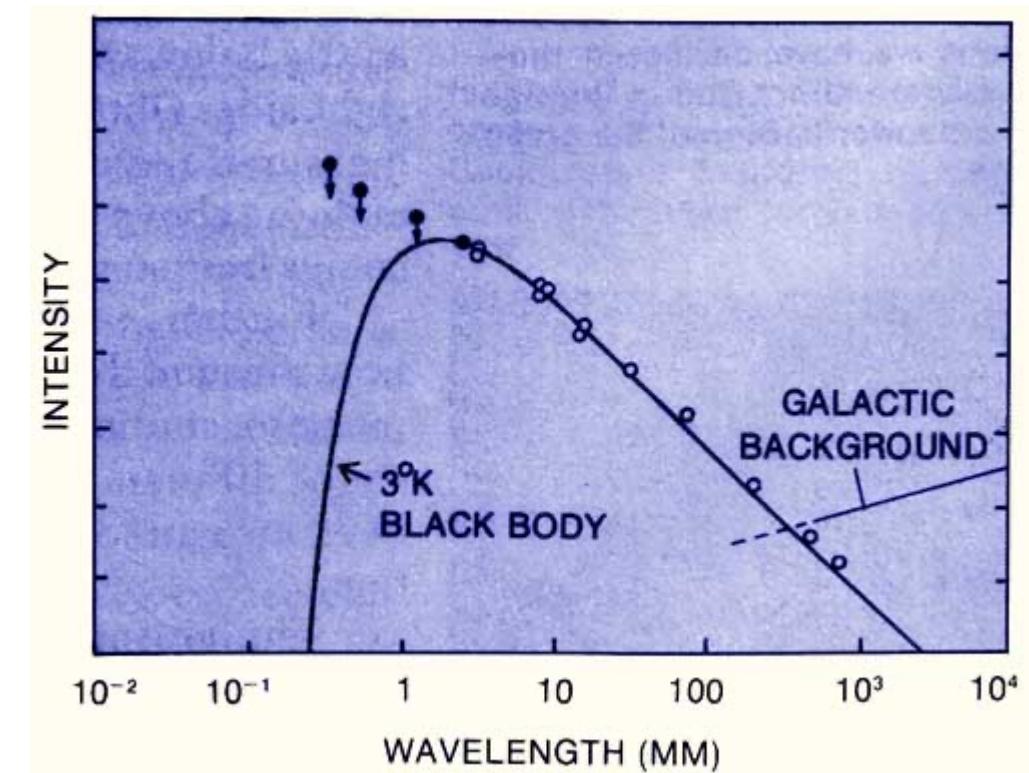
George
Gamow



Cosmic Microwave Background (1964)

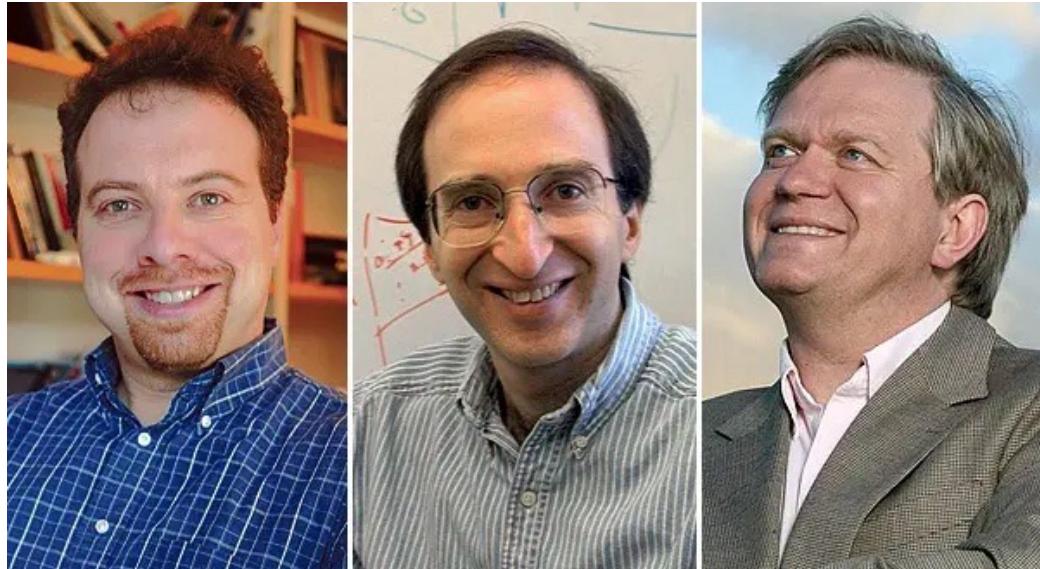


Arno Penzias and Robert Wilson



1978
Nobel Prize in Physics

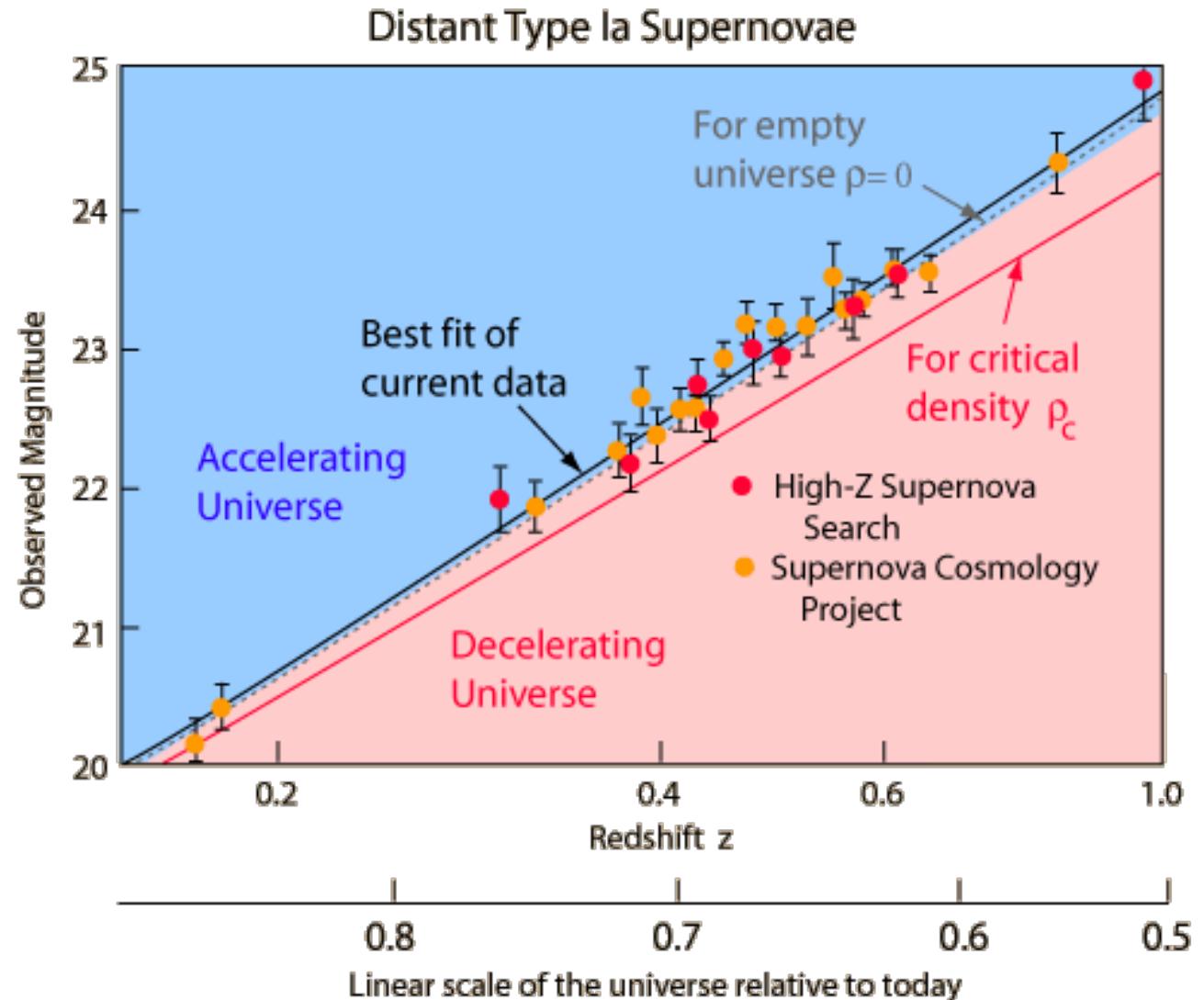
Accelerating Expansion (1998)



Adam
Riess

Saul
Perlmutter

Brian
Schmidt



L Observational Cosmology

- New **instruments** and **observations** always revolutionize our view of the Universe
- Cosmology is (still) an observational driven science
→ **Do observe!**



Déjà vu?

Does the ***logic*** of the **geocentric model** differ from that of **modern cosmology**?

- Reasonable induction based on **observational data**
- Continuous discovery of **anomalies**
- Add **new components** of the model to address anomalies
- **Complication** of the model over time
- Will there be a new “Copernican model” for modern cosmology?
→ **Keep critical thinking and collecting new observational evidences with instrumental developments!**

Questions?

Hopefully I have convinced you that observations are vital for cosmology

Observational Cosmology

- New observations always revolutionize our view of the Universe
- Cosmology is (still) an observational driven science
- But what to observe? → **Probes in observational cosmology**



"Cosmic question mark" by JWST

L Observational Cosmology

- New observations always revolutionize our view of the Universe
- Cosmology is (still) an observational driven science
- But what to observe? → **Probes in observational cosmology**

However...

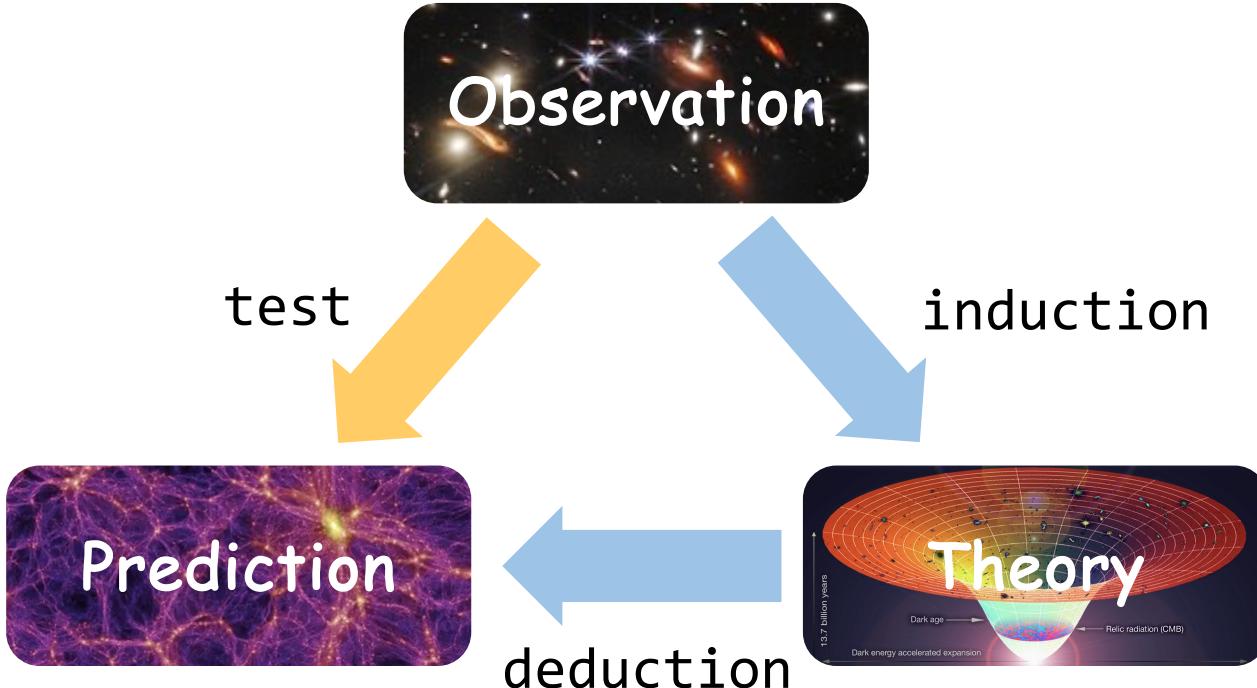
- Only one sky and no controlled measurements
- **Use combination of cosmological probes**

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L What to probe?

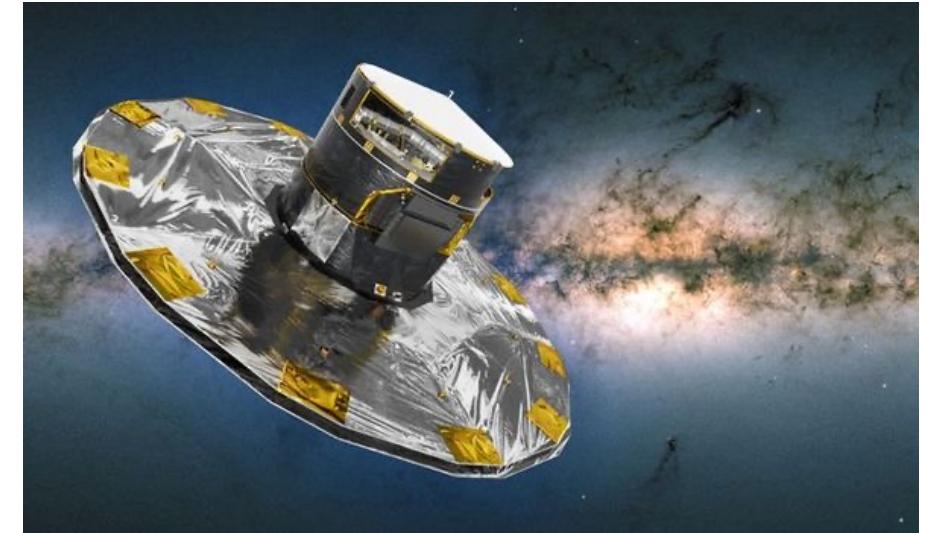
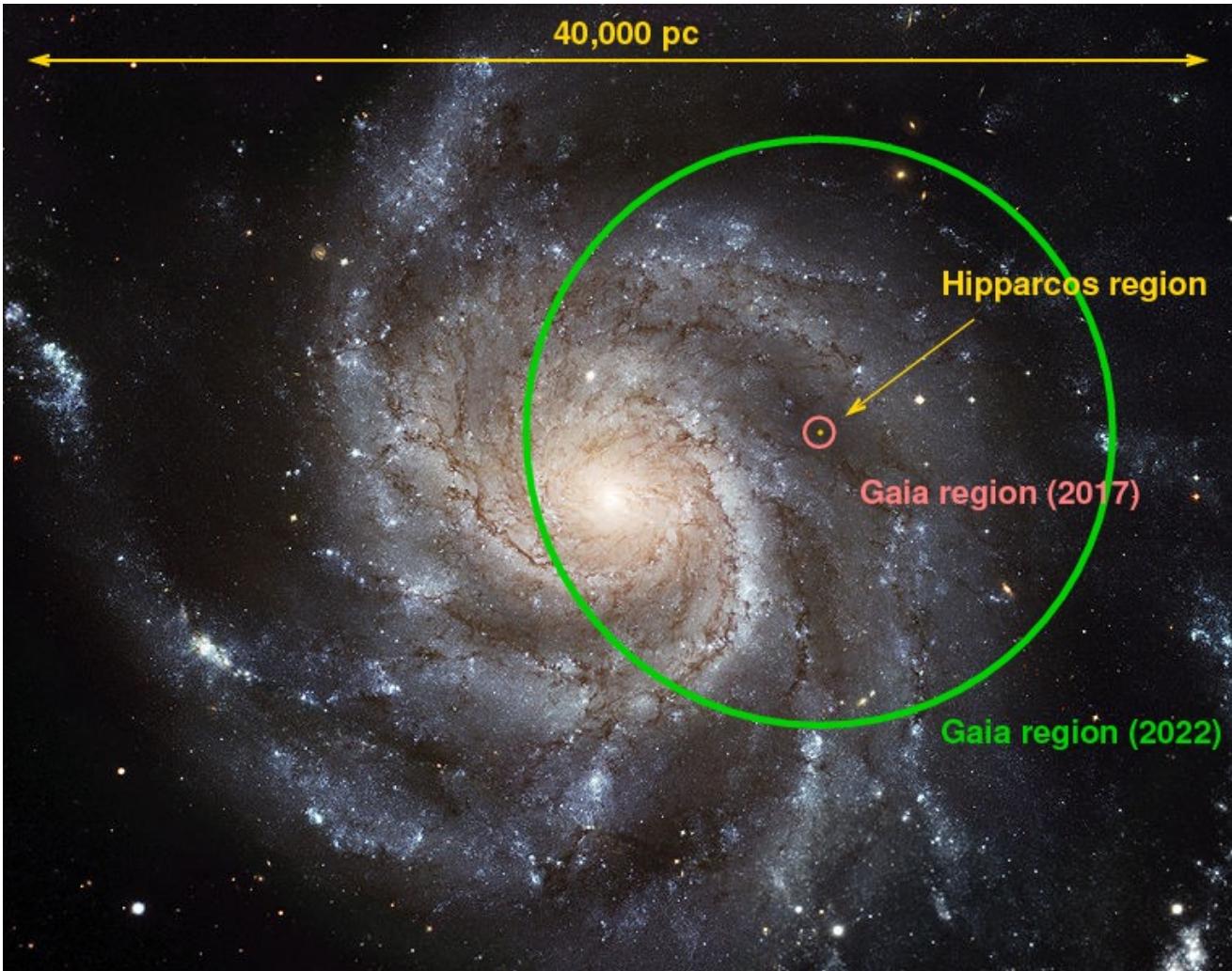
- Background equation: $H^2(a) = H_0^2 (\Omega_m a^{-3} + \Omega_\Lambda + \dots) \rightarrow \text{geometry}$
- Perturbation equations: *growth of perturbations* $\rightarrow \text{clustering}$



L Cosmological Probes

- Distance Ladder
- Type Ia Supernova
- Cosmic Microwave Background (CMB)
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Distance Ladder: Parallax



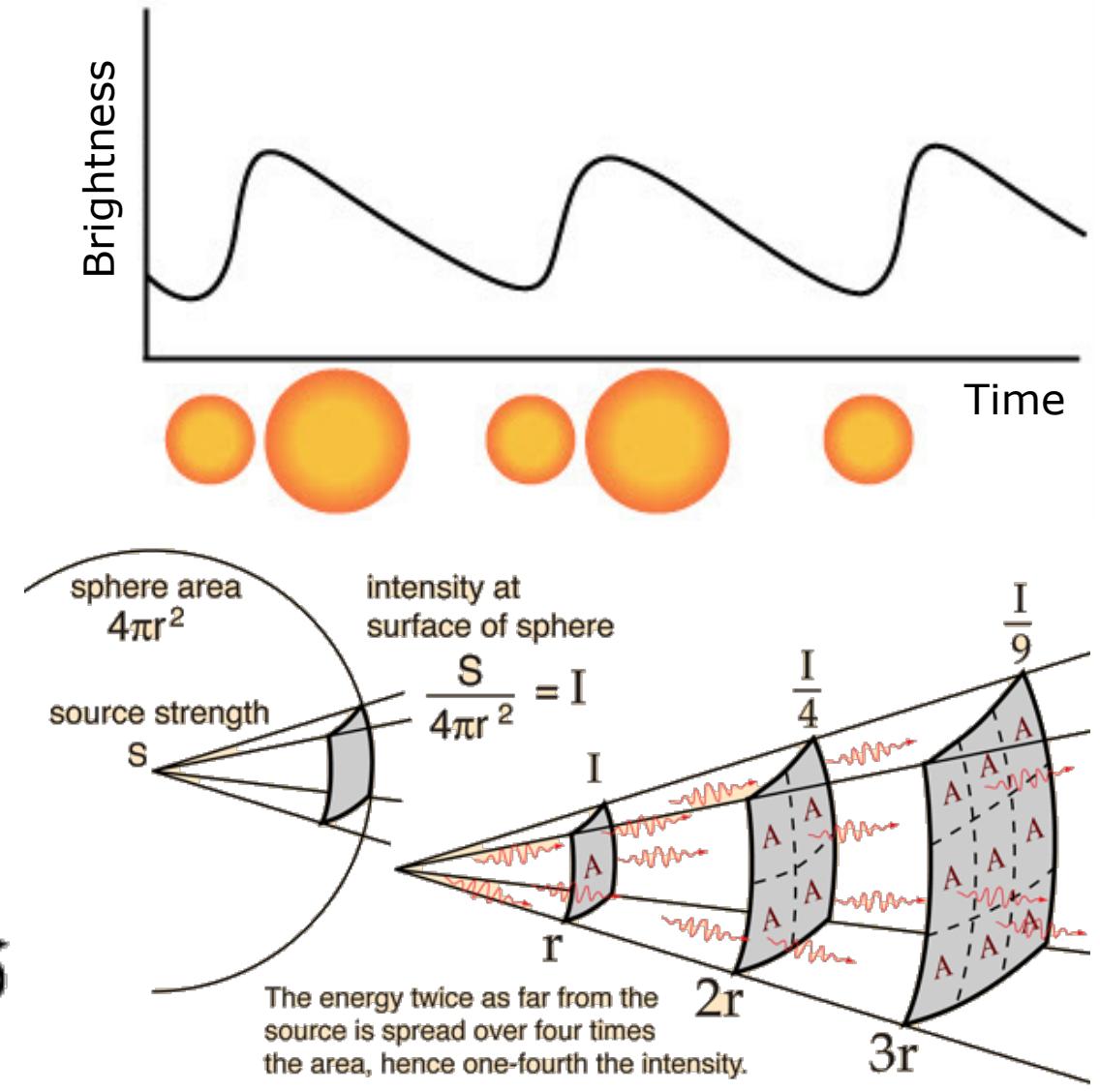
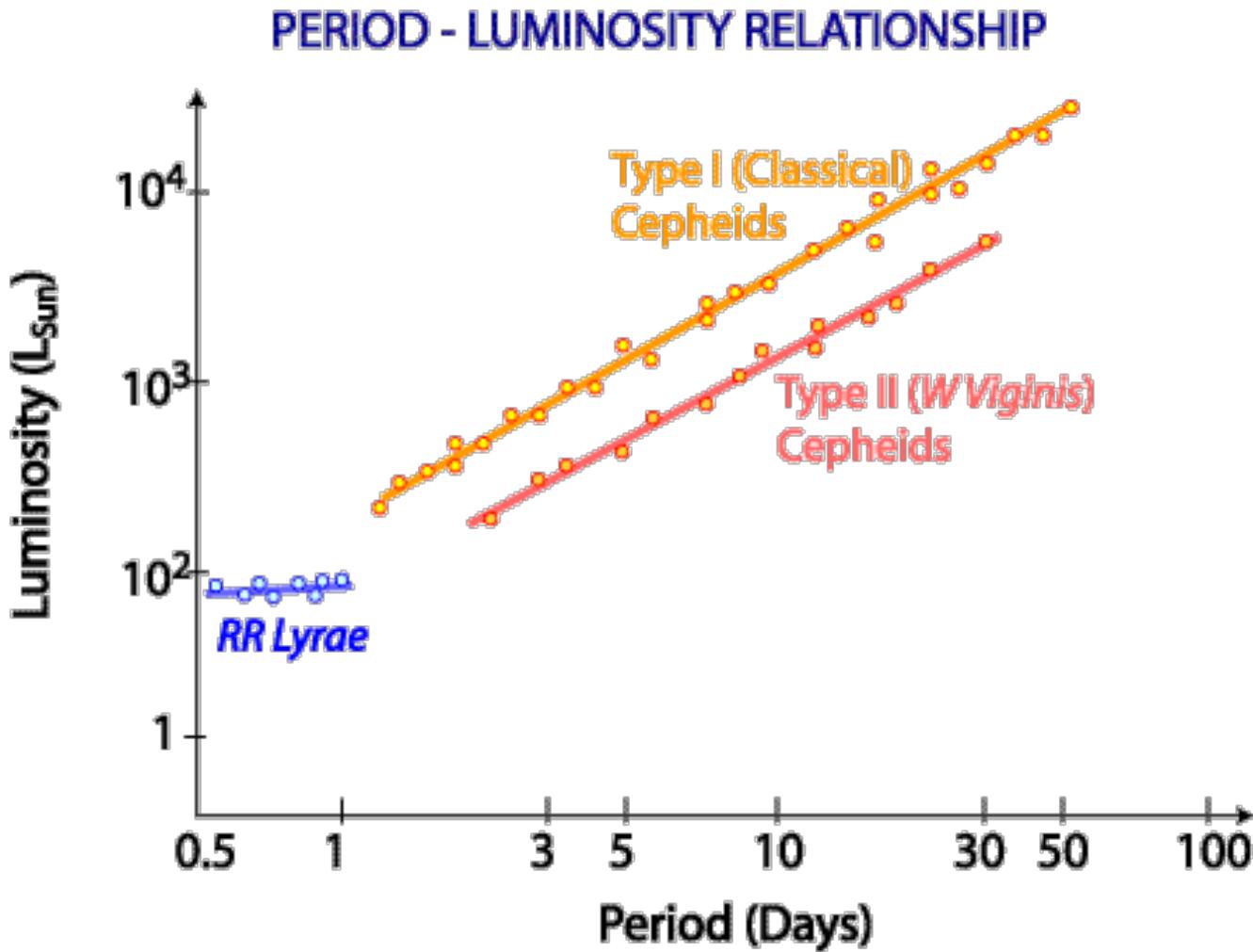
Gaia Mission

Distances of ~1.4 billion stars
up to ~10 kpc as of 2020

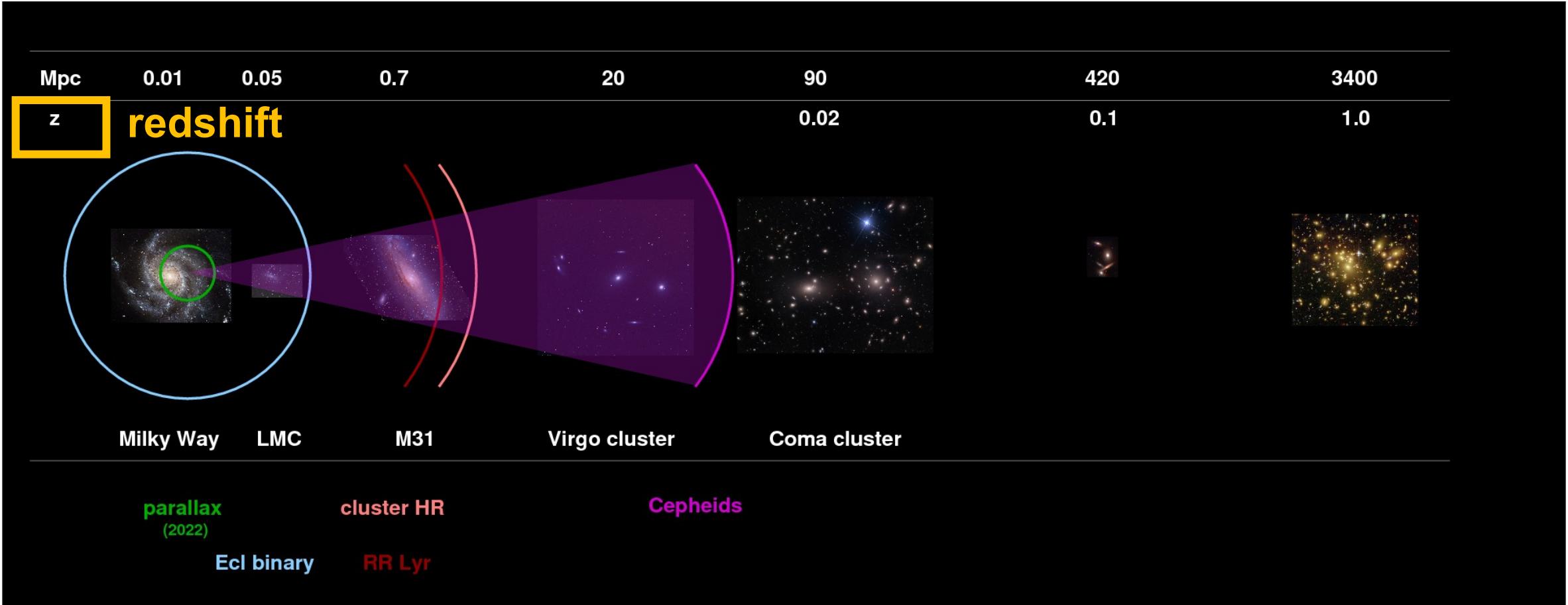
Reference:

<https://arxiv.org/abs/2012.05220>

L Distance Ladder: Variable Stars

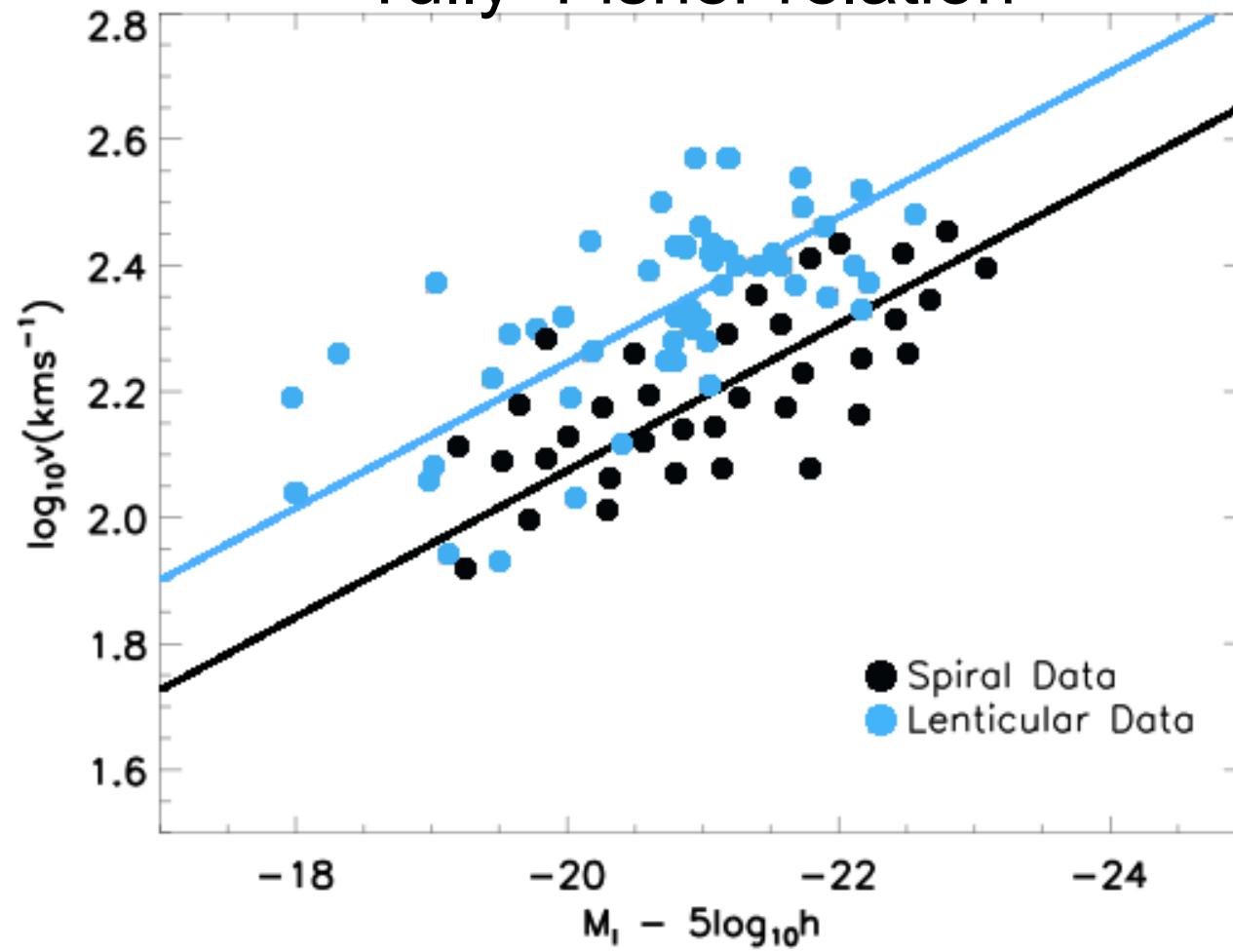


L Distance Ladder: Variable Stars

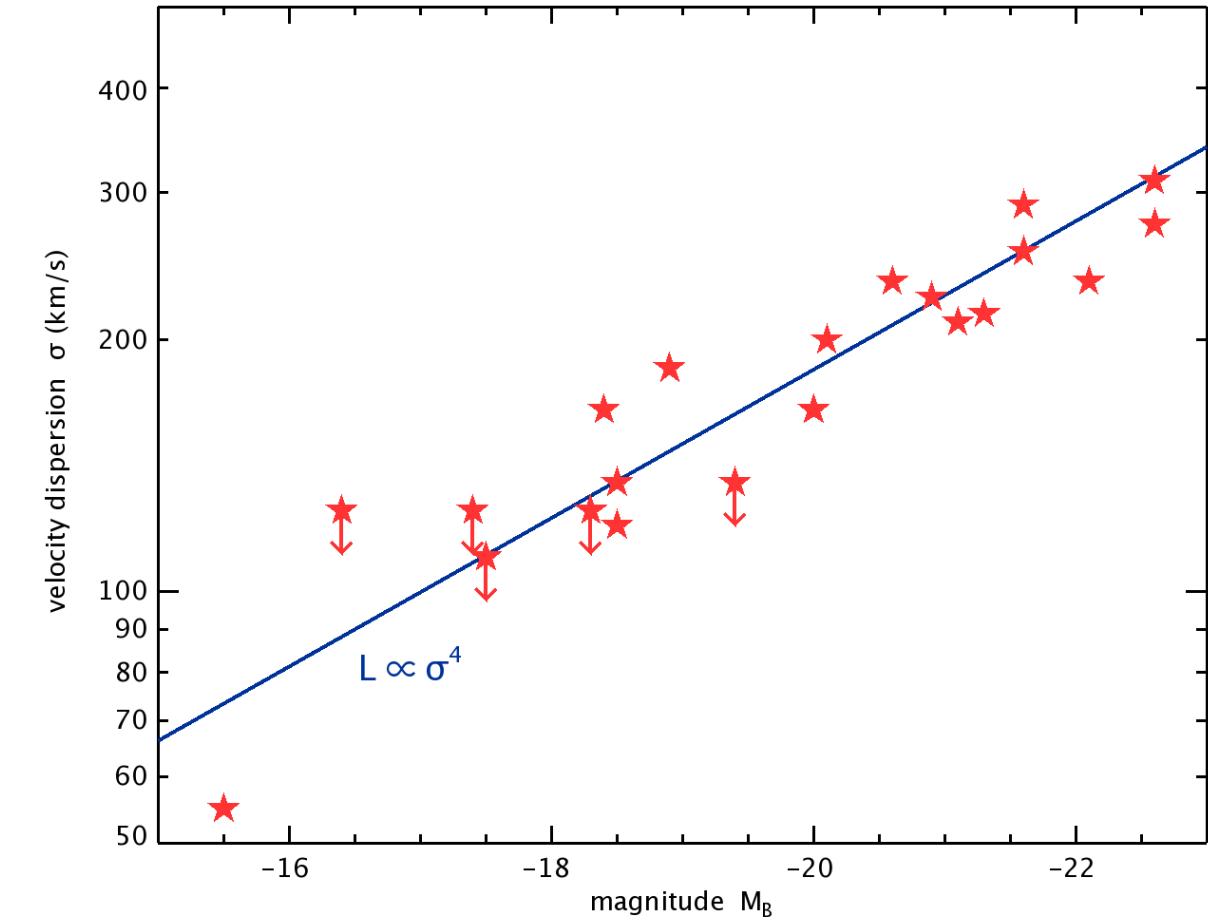


Distance Ladder*: Galaxy Properties

Tully–Fisher relation

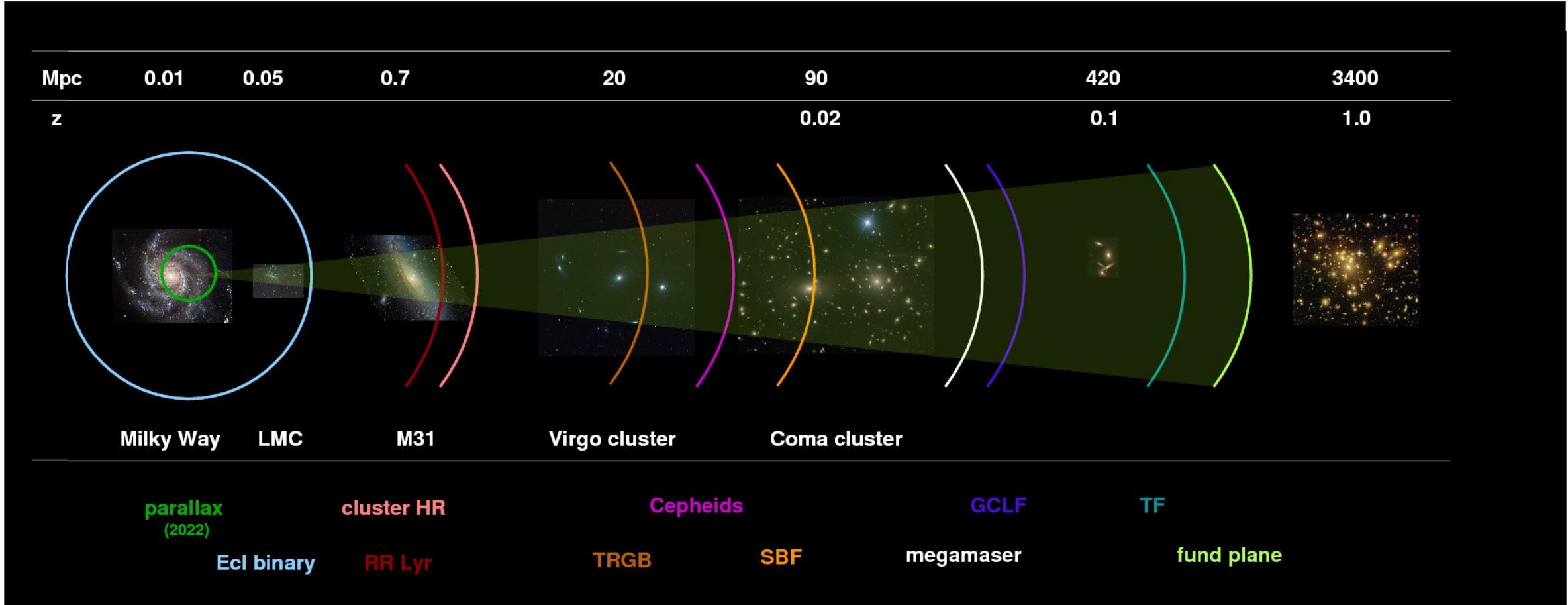


Faber–Jackson relation



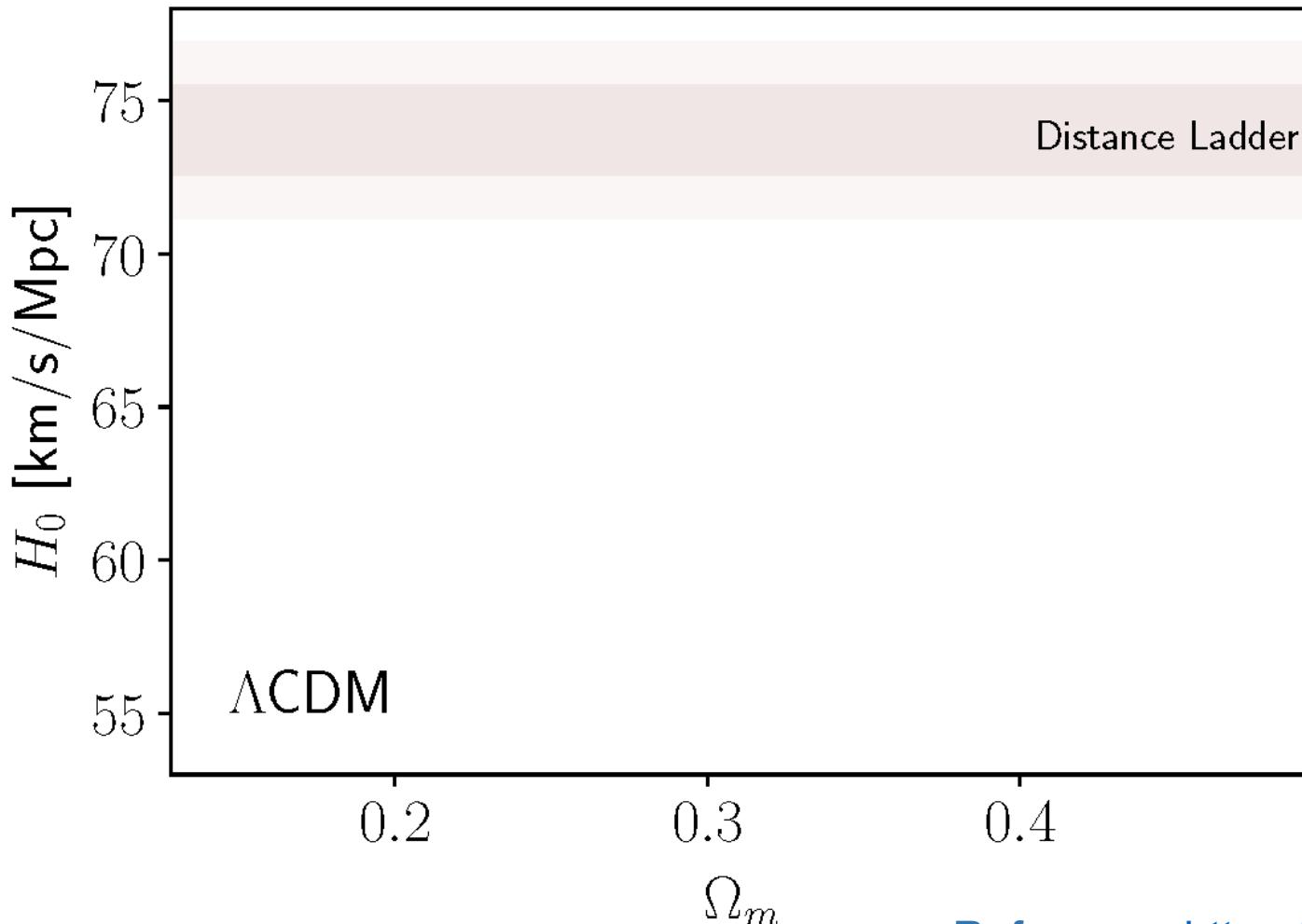


Distance Ladder*: Galaxy Properties





Distance Ladder: Constraints



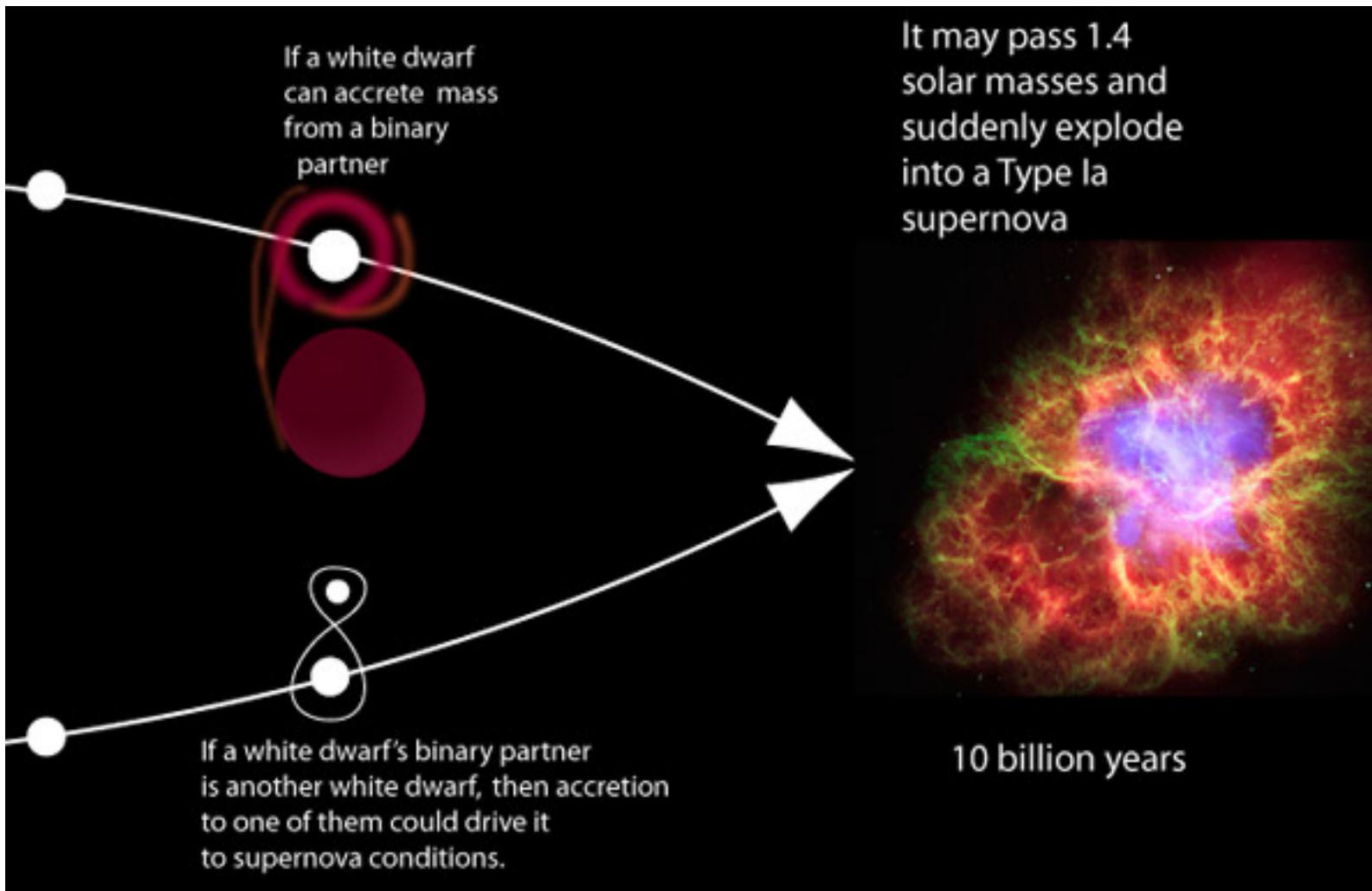
Reference: <https://arxiv.org/abs/2007.08991>



Cosmological Probes

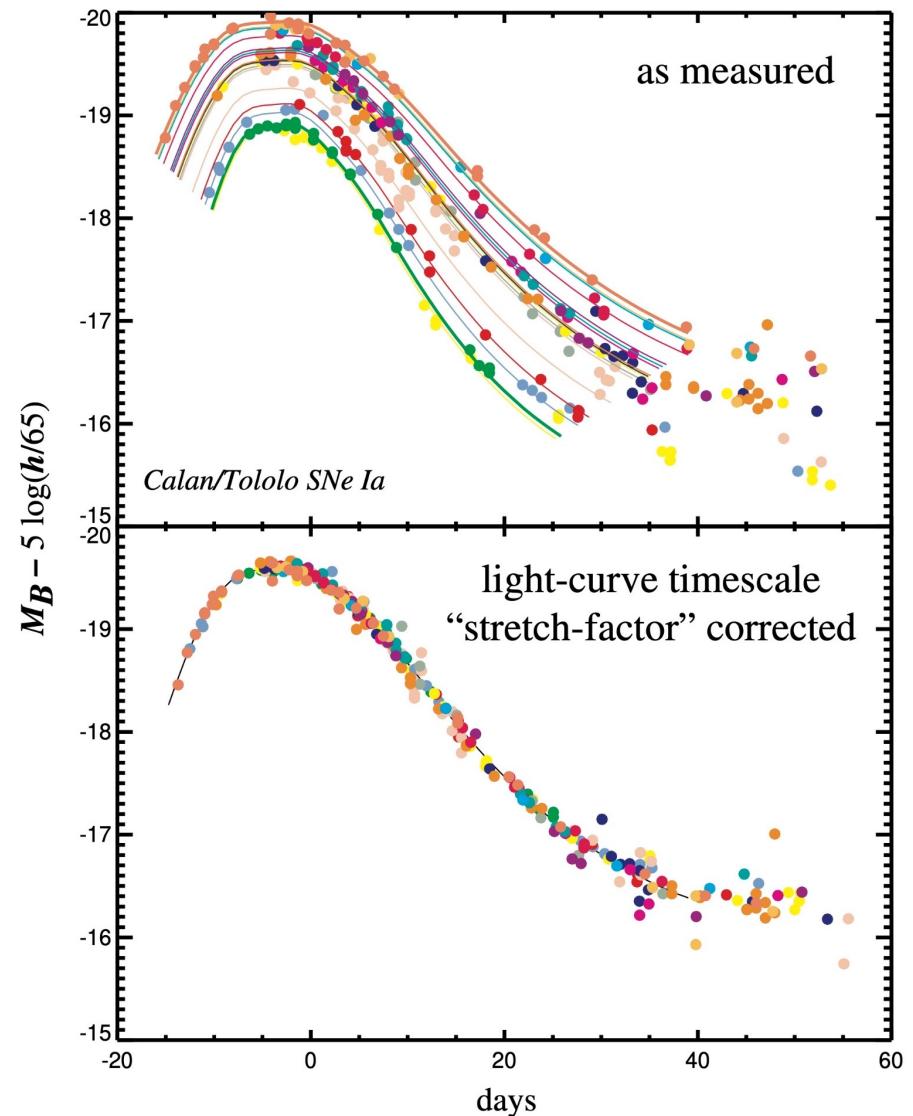
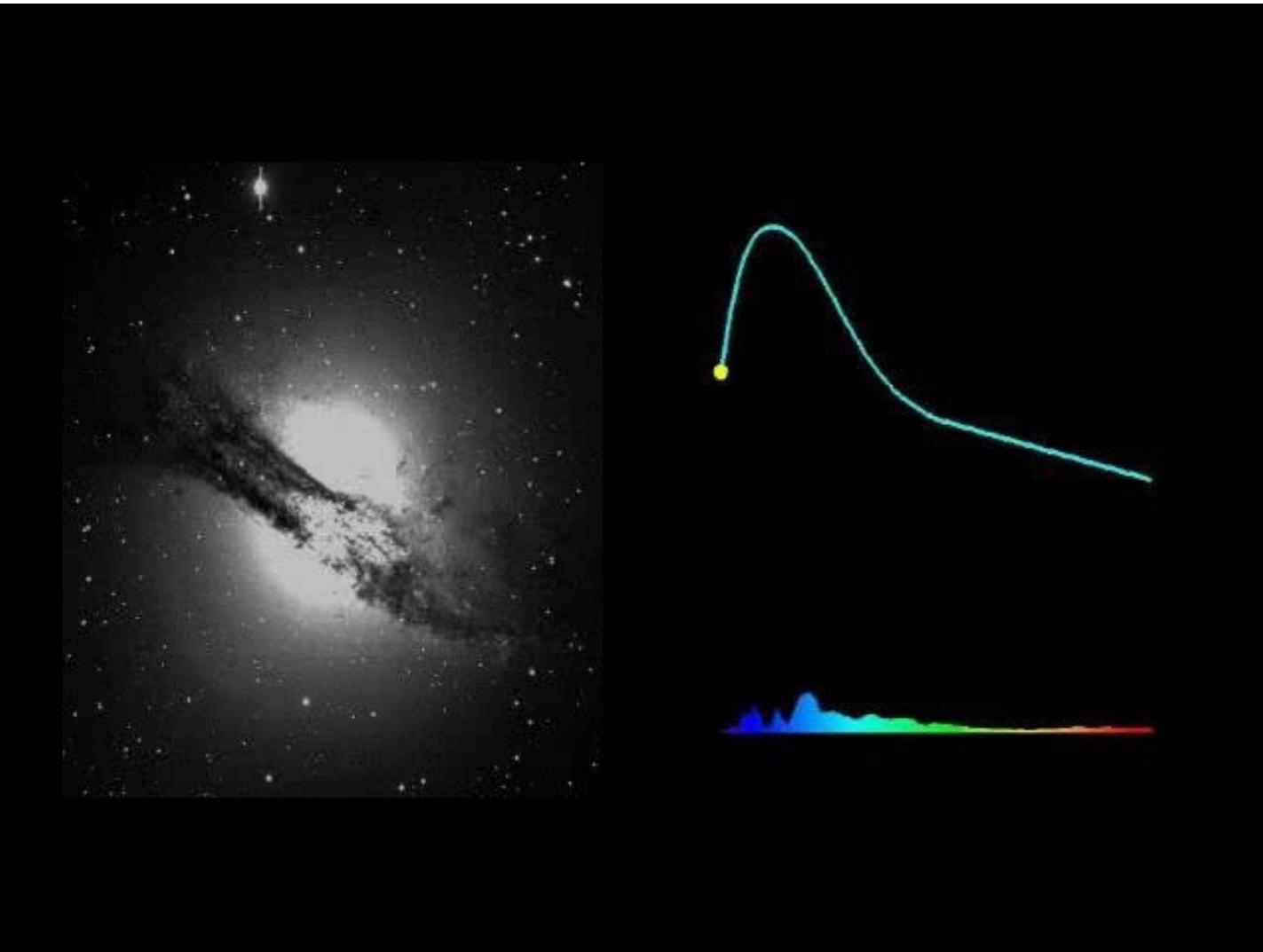
- Distance Ladder
- Type Ia Supernova
- Cosmic Microwave Background (CMB)
- Galaxy Clustering
- Gravitational lensing

Type Ia Supernova: Standardisable Candle

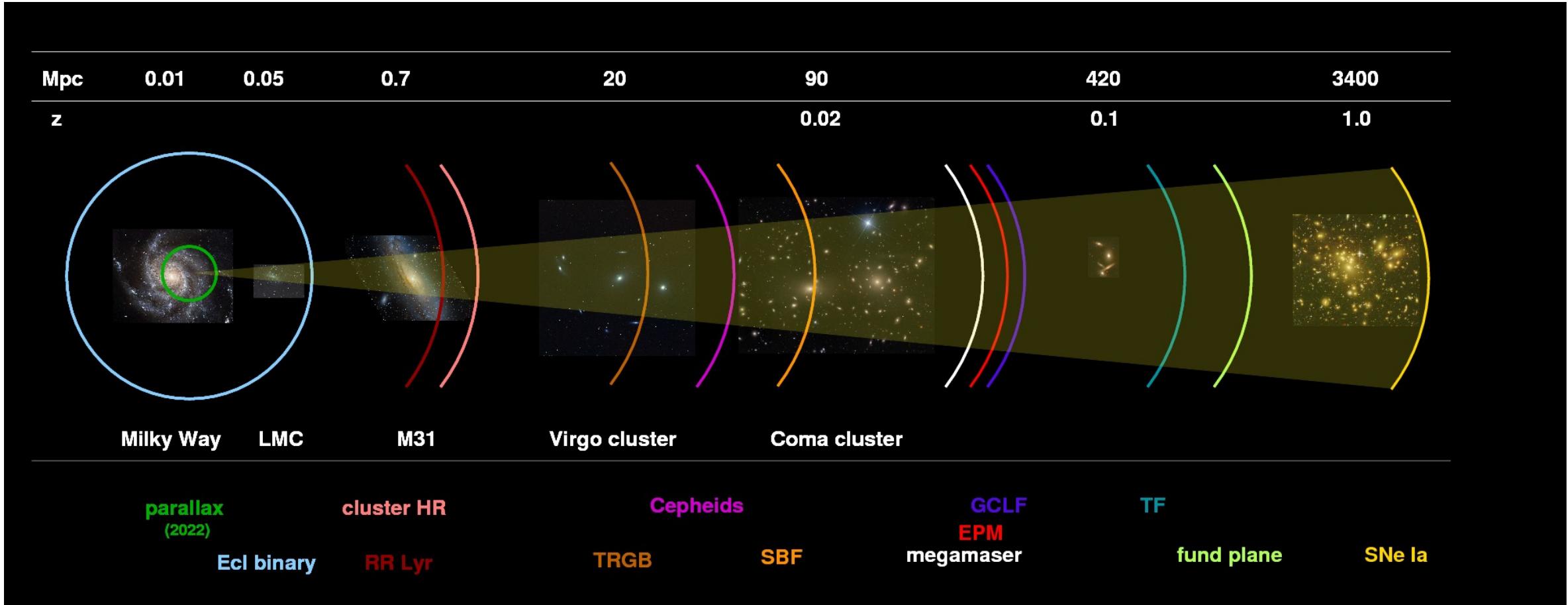


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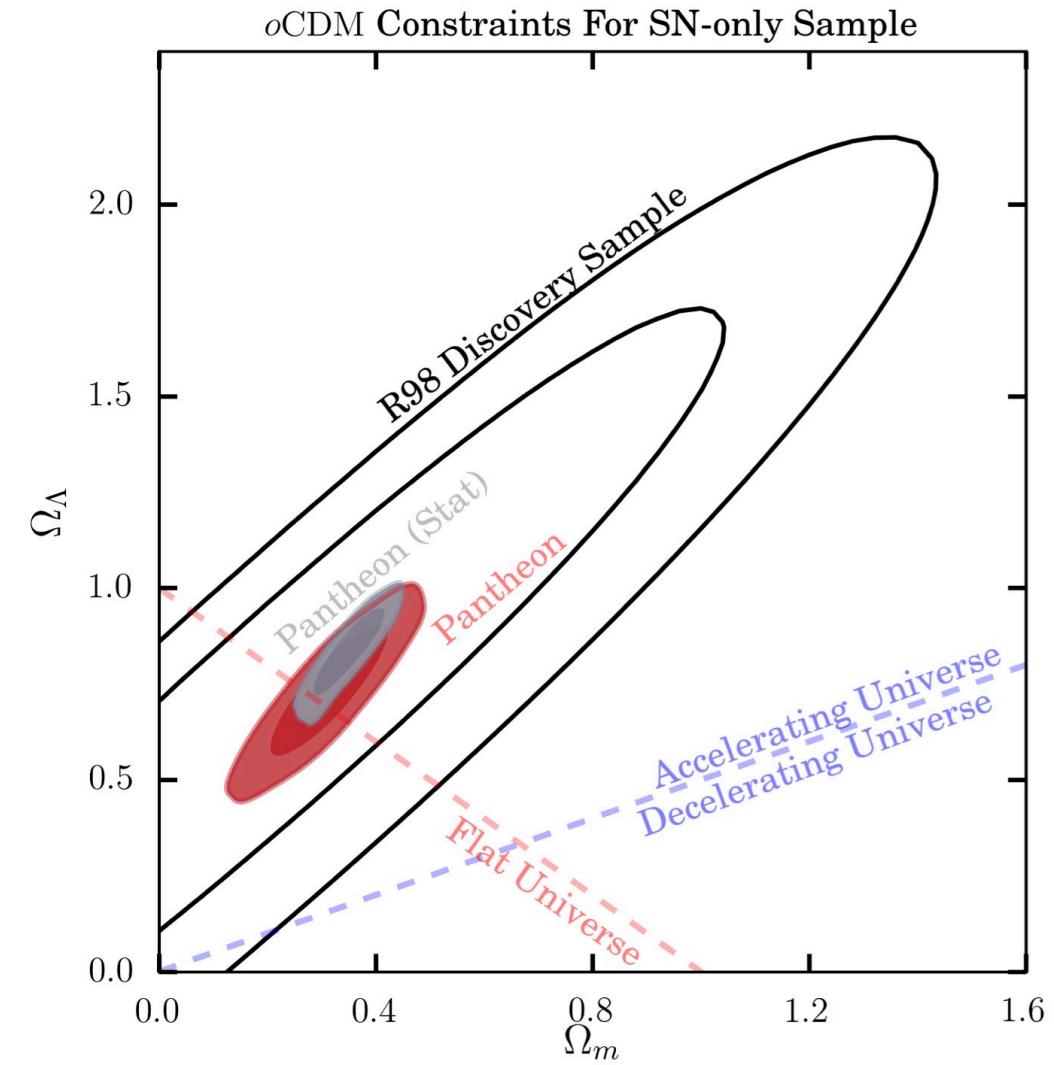
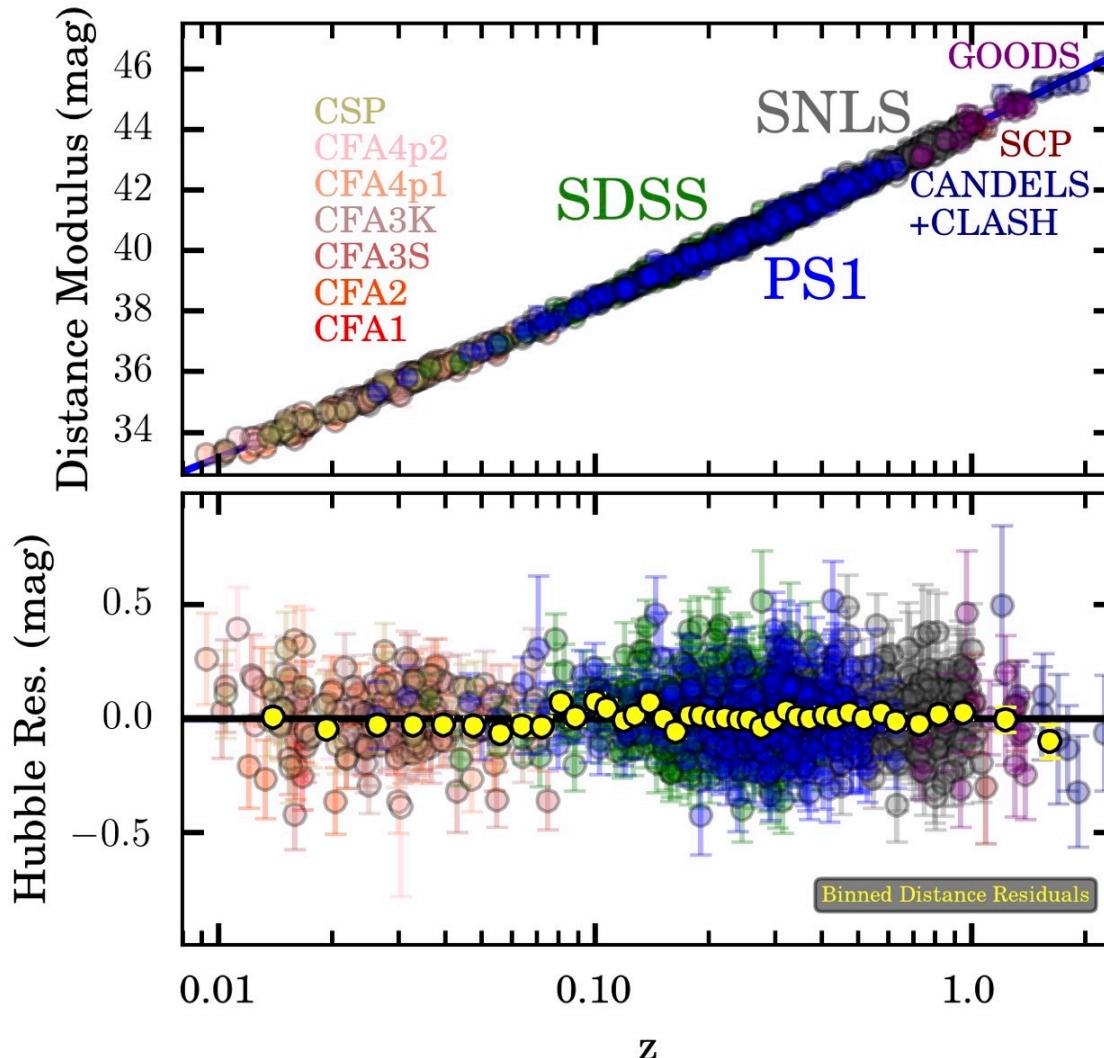
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Type Ia Supernova: Standardisable Candle



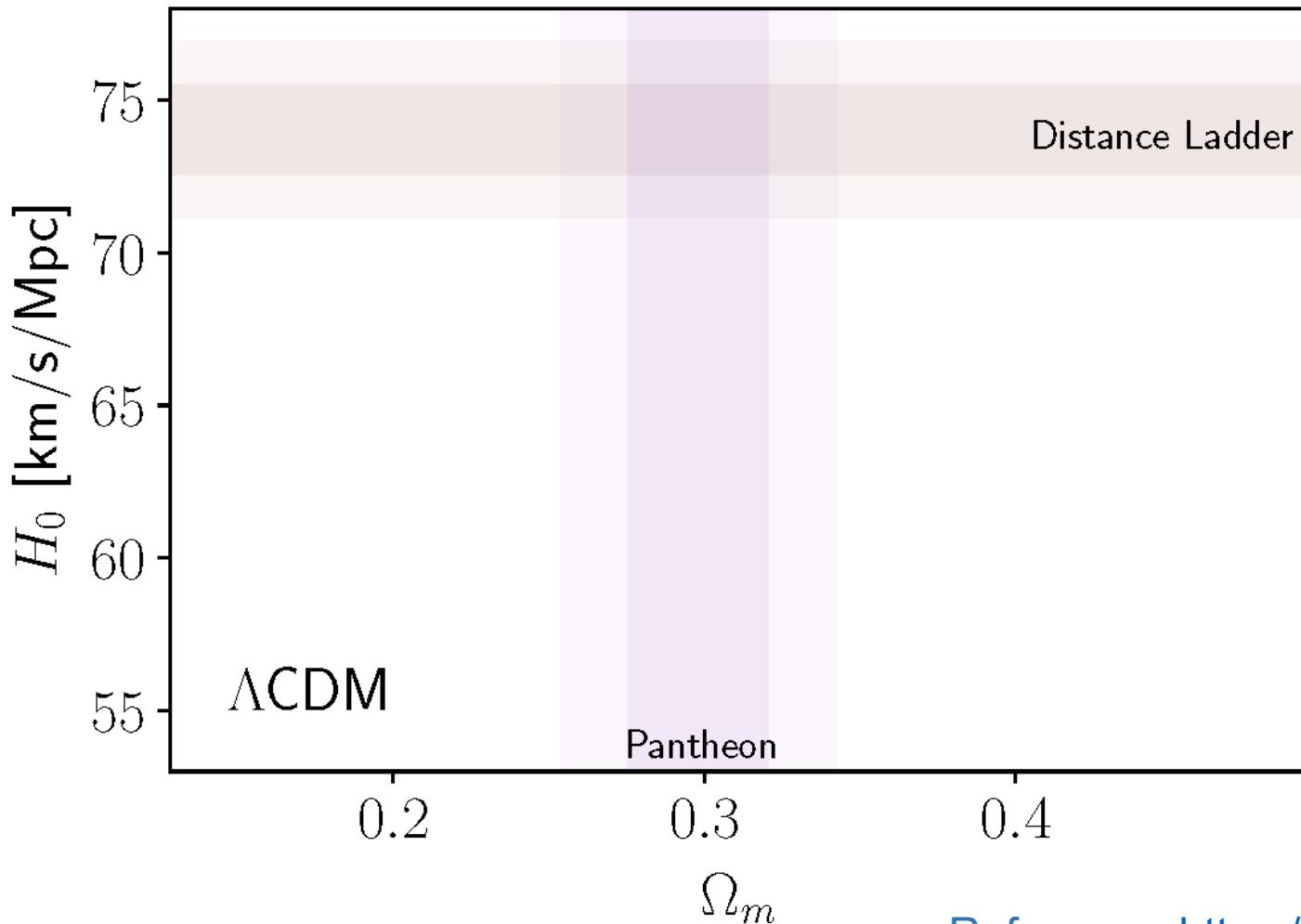
Type Ia Supernova: Standardisable Candle



Reference: <https://arxiv.org/abs/1710.00845>



Type Ia Supernova: Constraints



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L Cosmological Probes

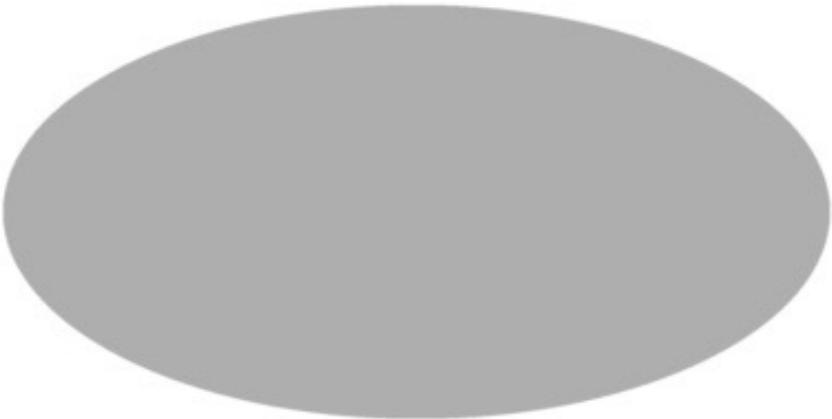
- Distance Ladder
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CMB: Temperature Maps

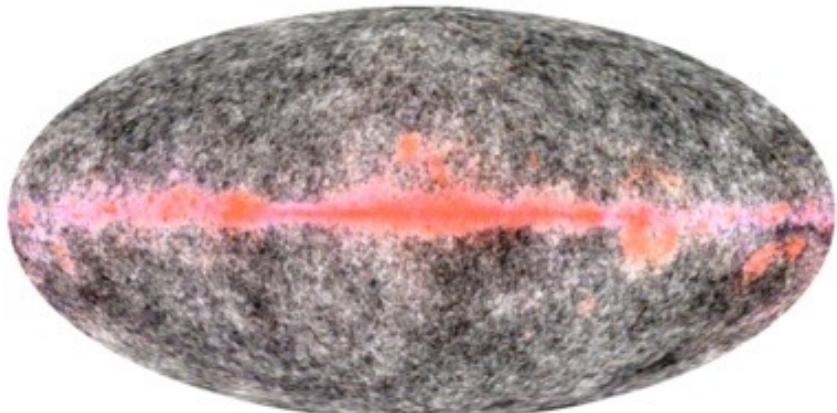
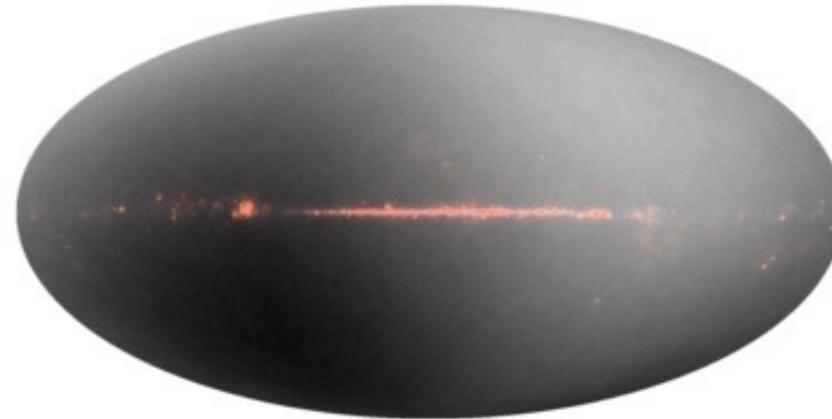
Monopole

$\sim 2.7\text{K}$

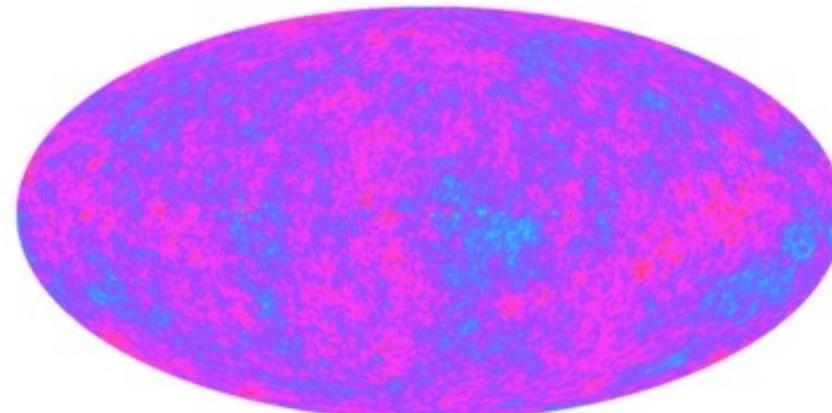


Dipole

Local Motion



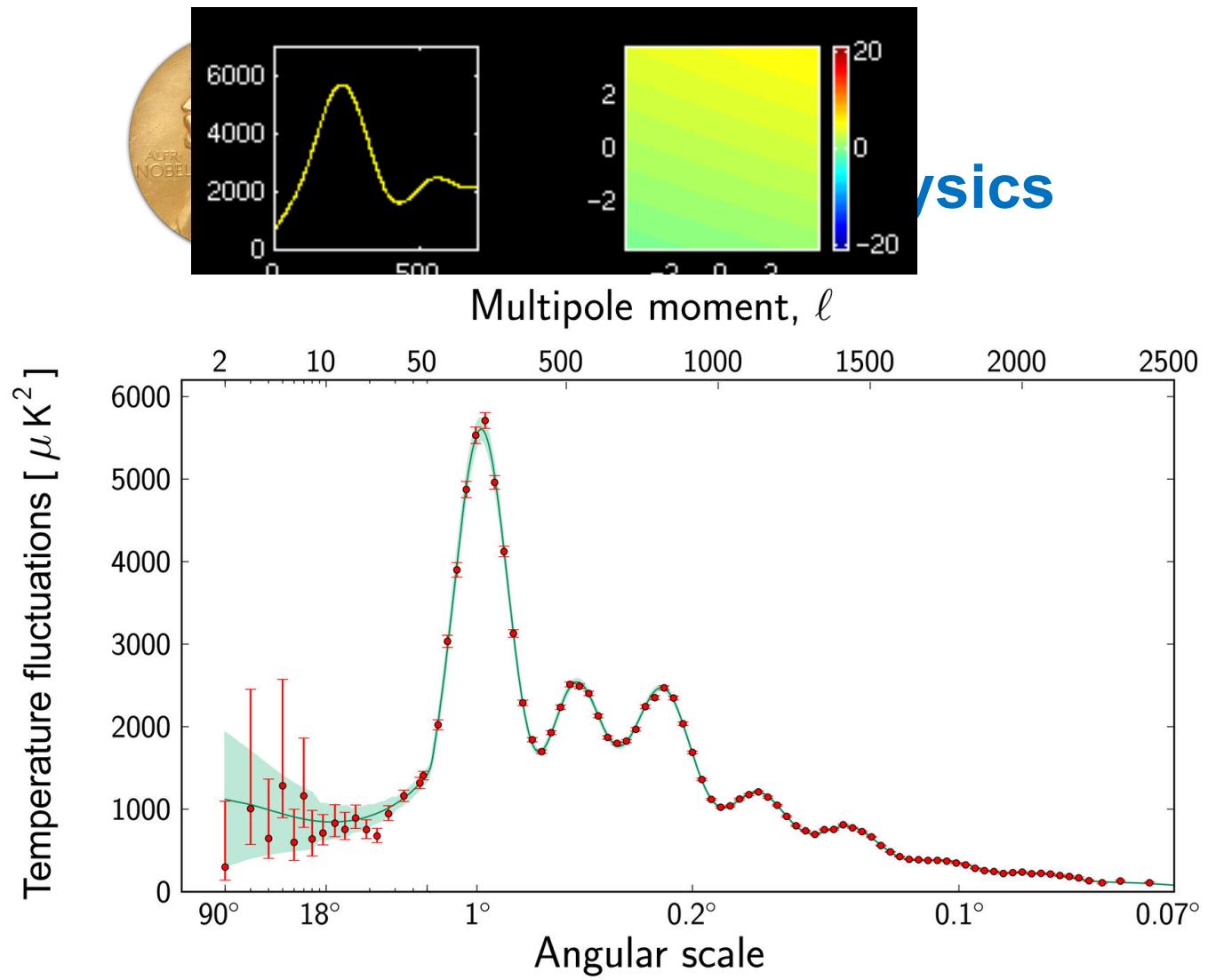
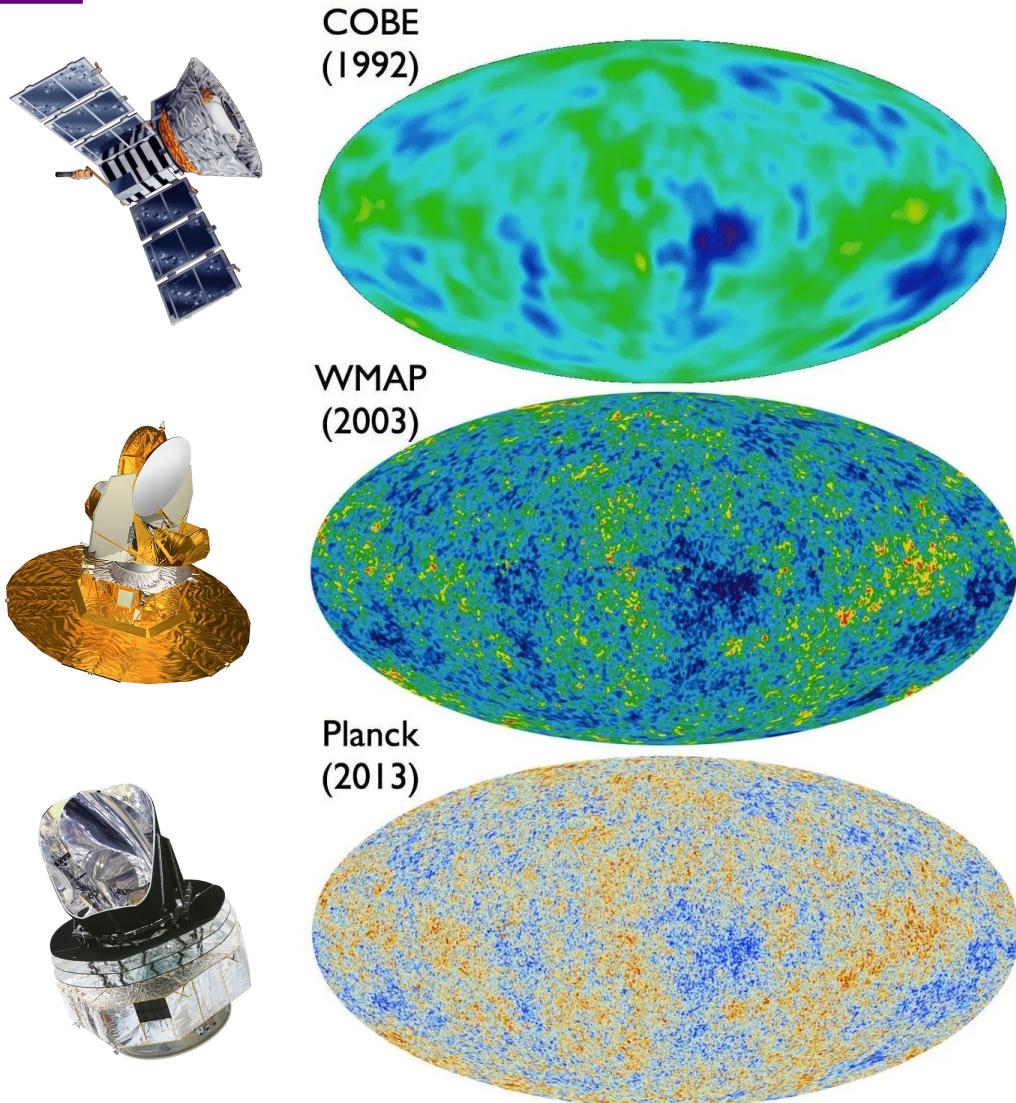
Multipole (with Milky Way)



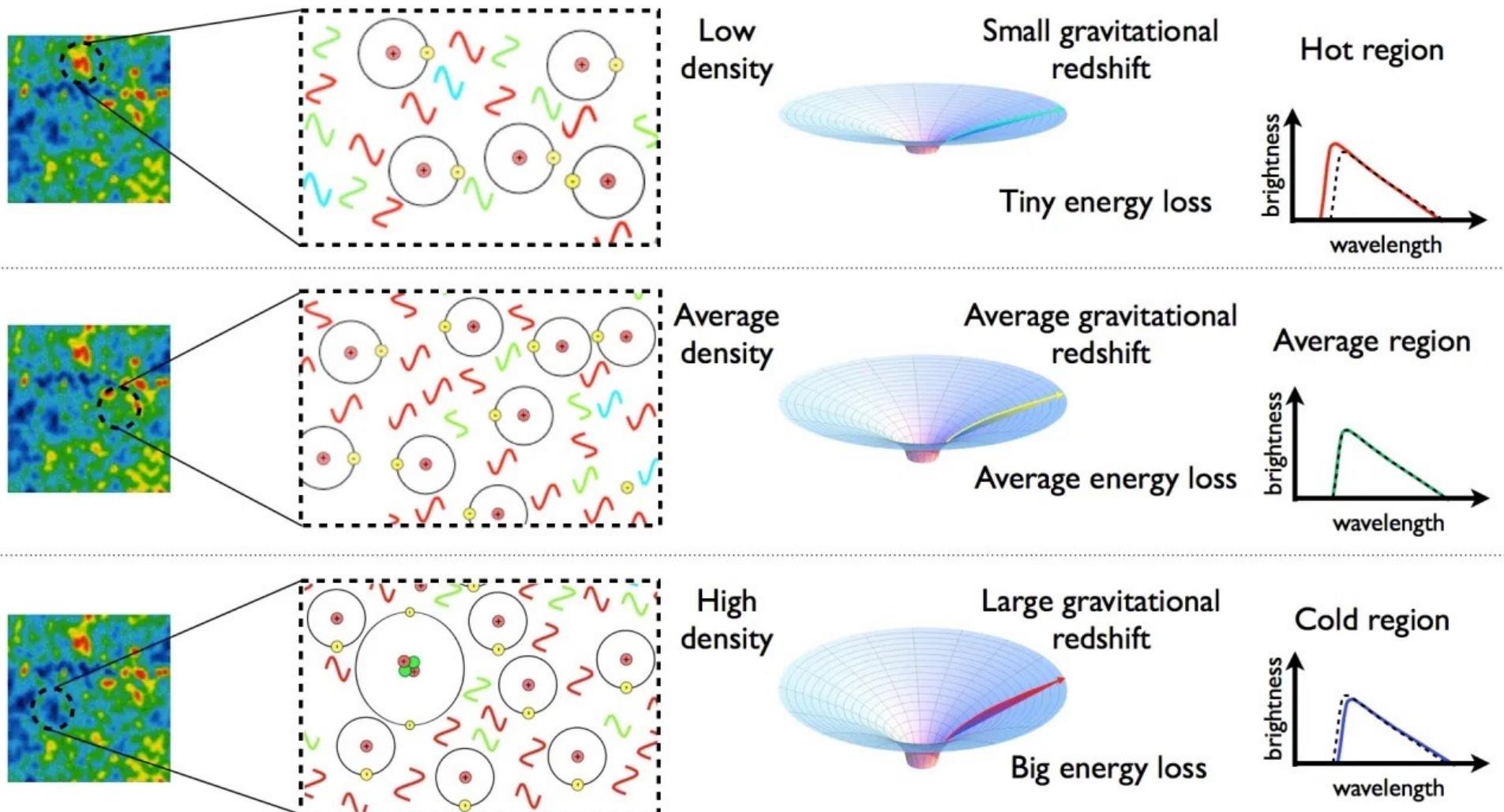
$\sim 10^{-5}$

Multipole (Milky Way subtracted)

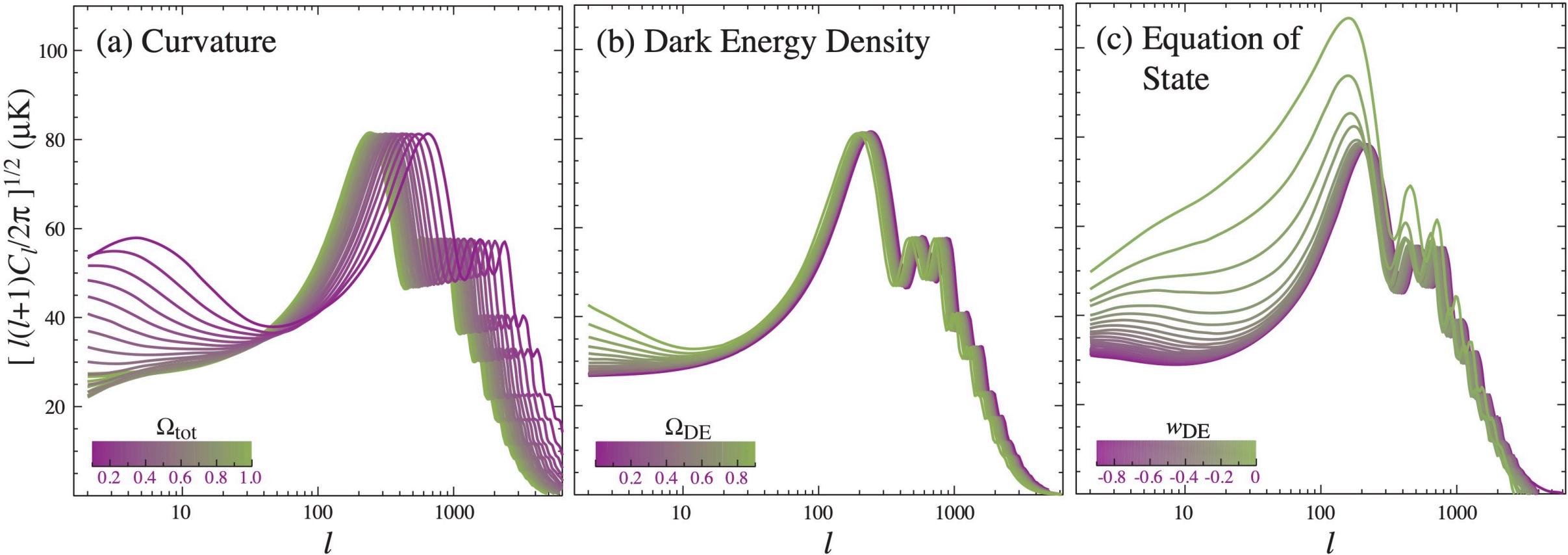
CMB: Power Spectrum



L CMB: Matter Fluctuations

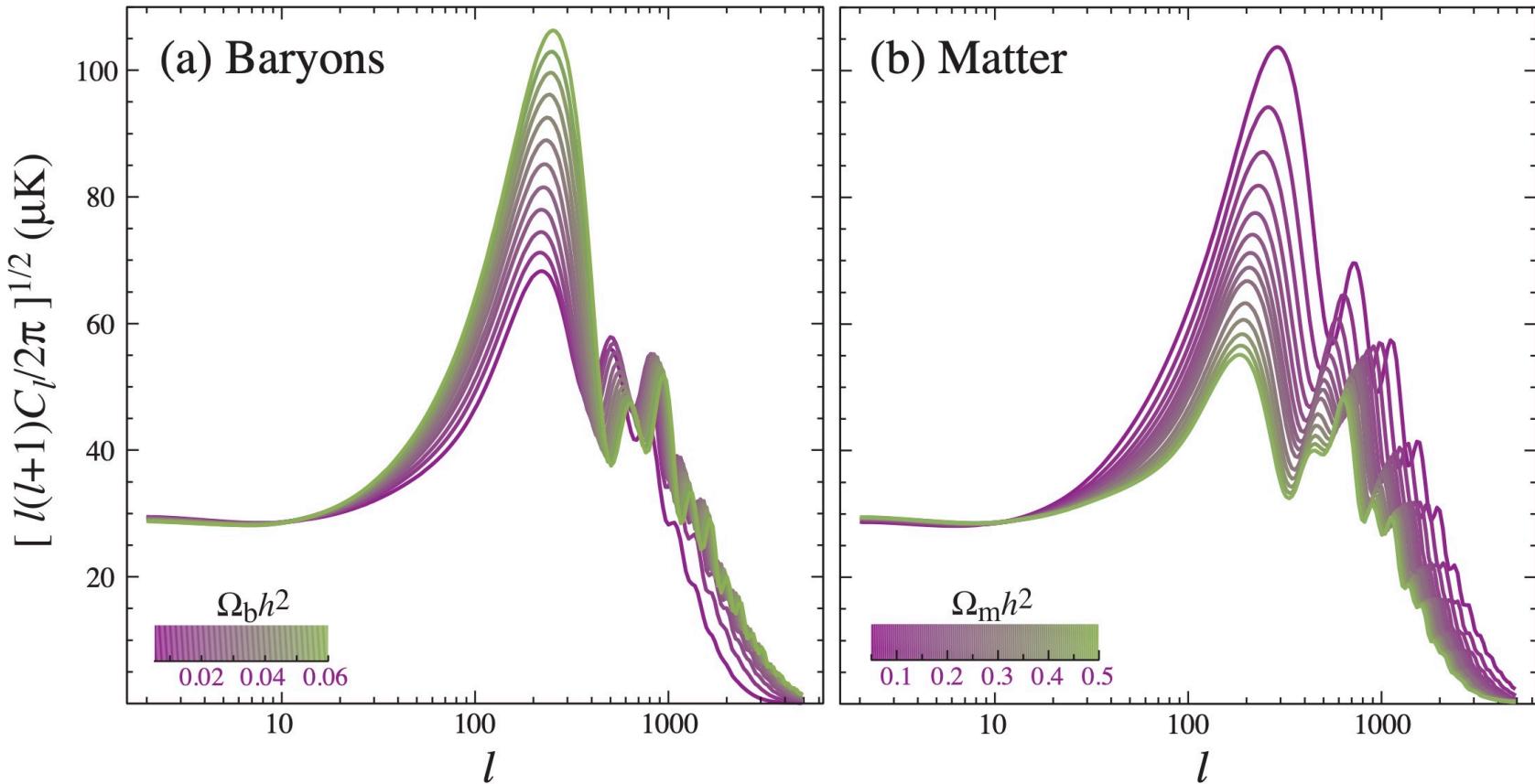


CMB: Cosmological Parameters



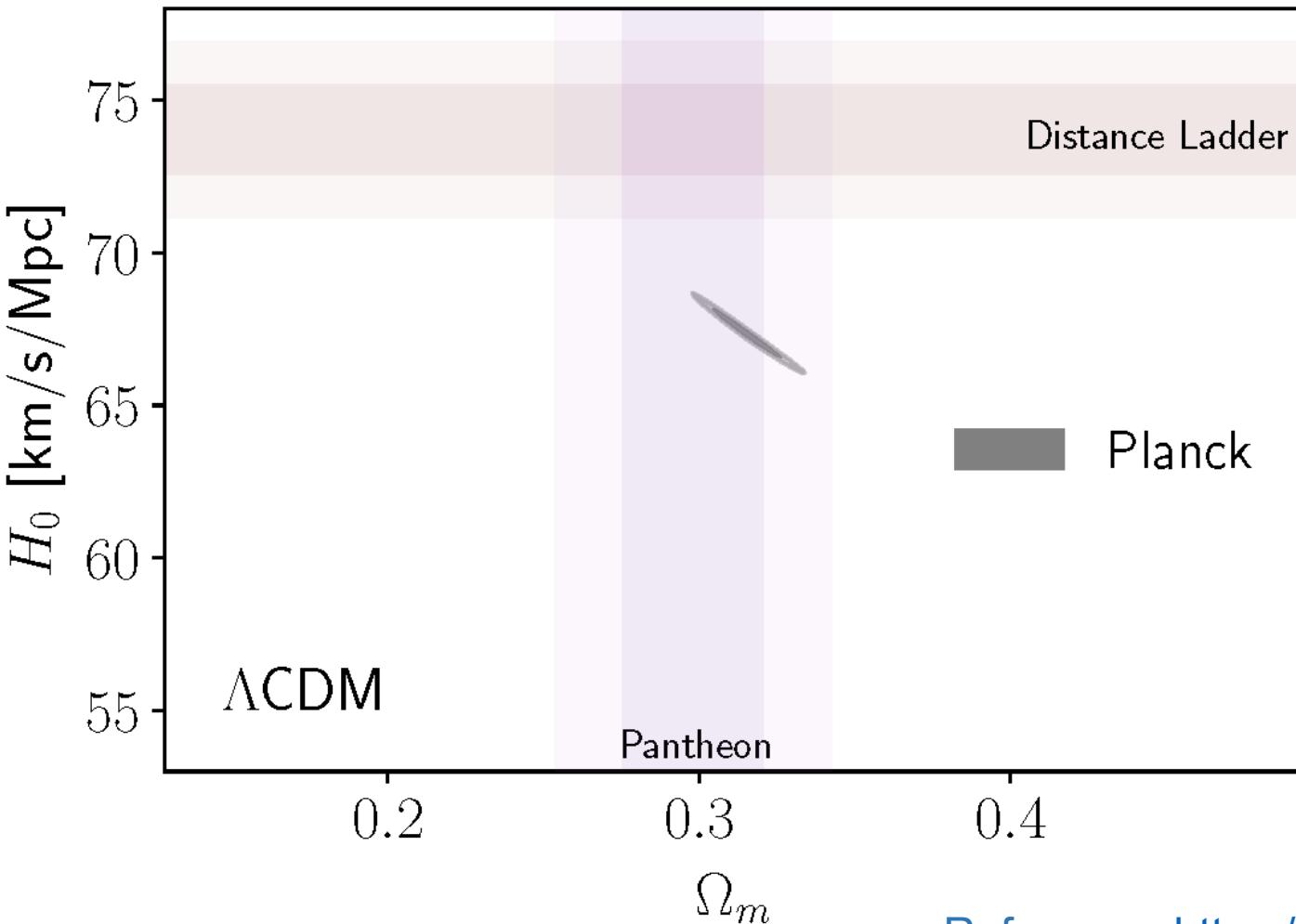
Reference: <https://arxiv.org/abs/0802.3688>

CMB: Cosmological Parameters

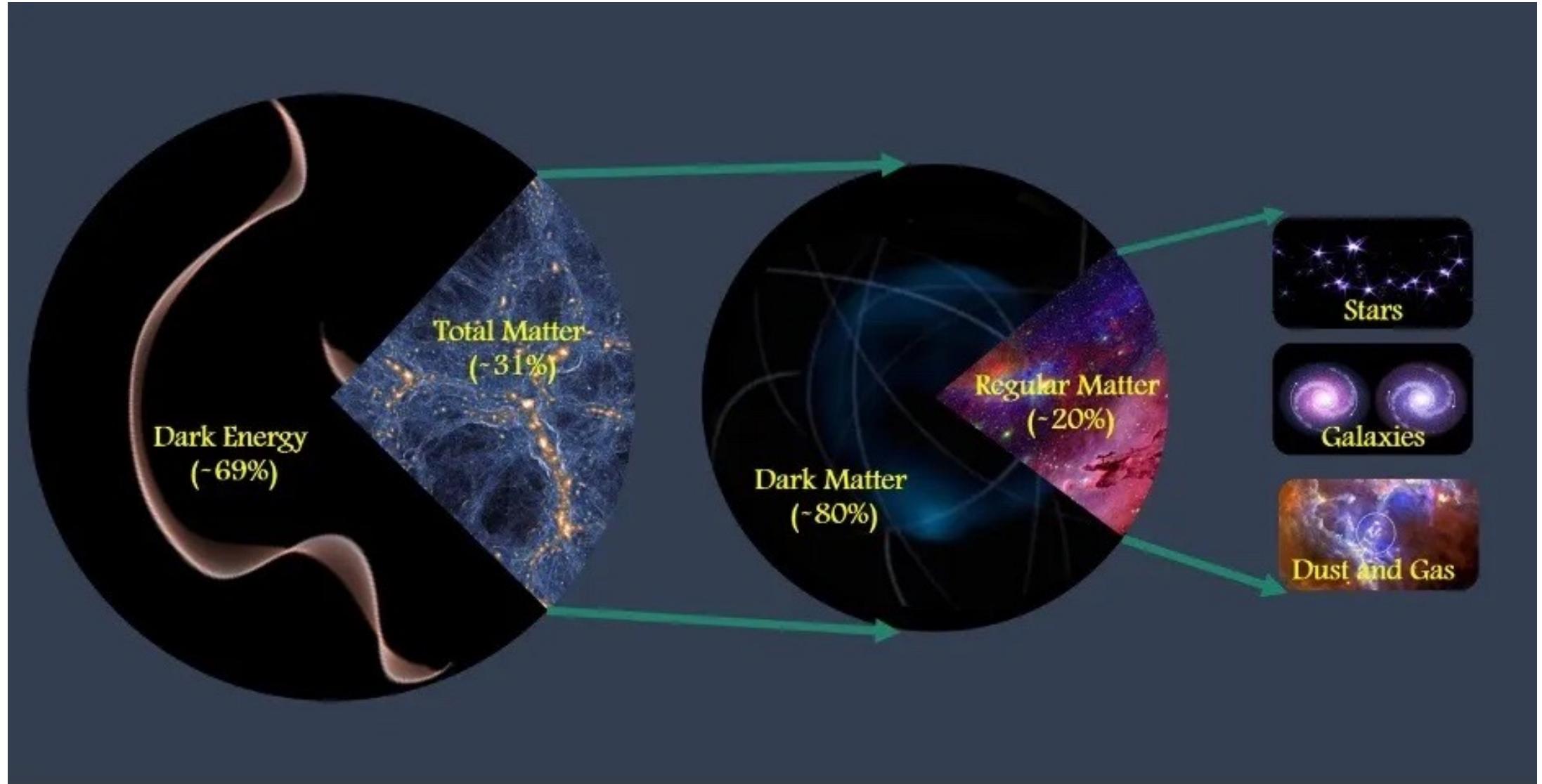


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CMB: Constraints



CMB: Components of the Universe



L Quiz

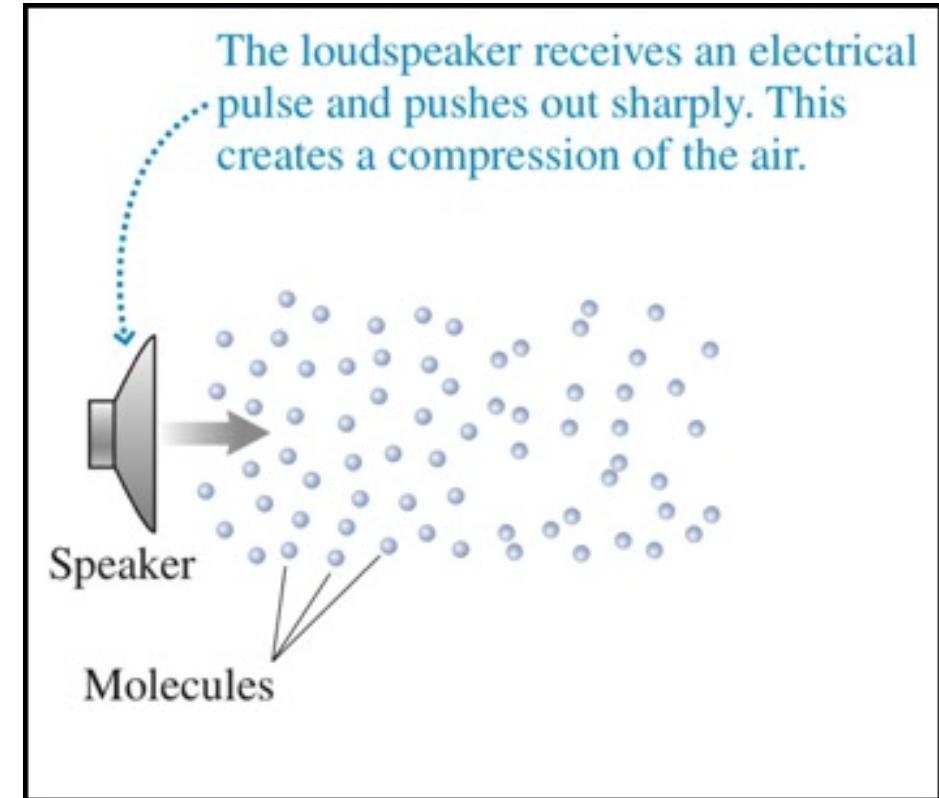
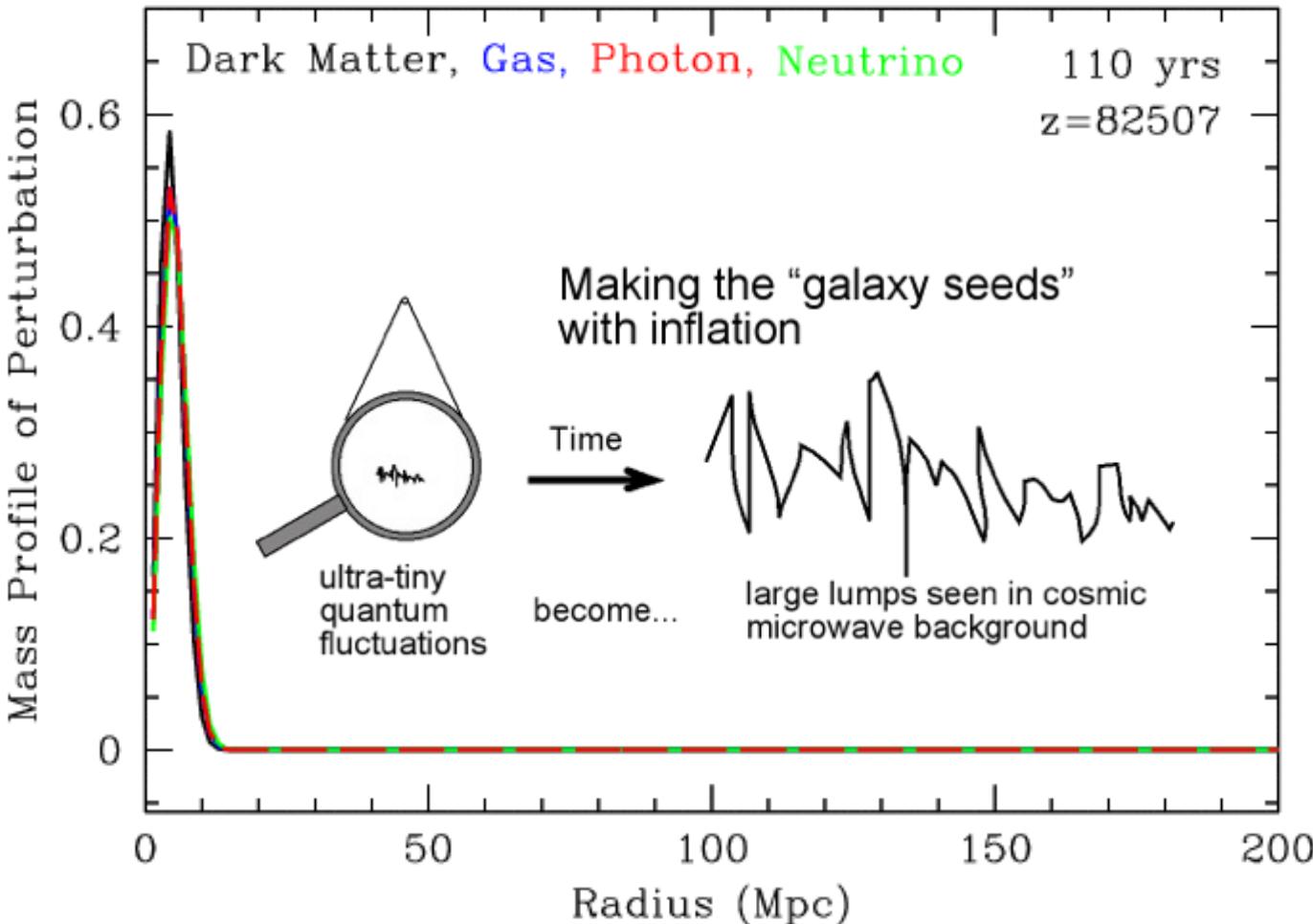
Given that the Universe was “opaque” before recombination, does the CMB last scattering surface defines the size of the observable Universe?

- Yes
only for photons
- No
There are multiple messengers, e.g. neutrinos and gravitational wave

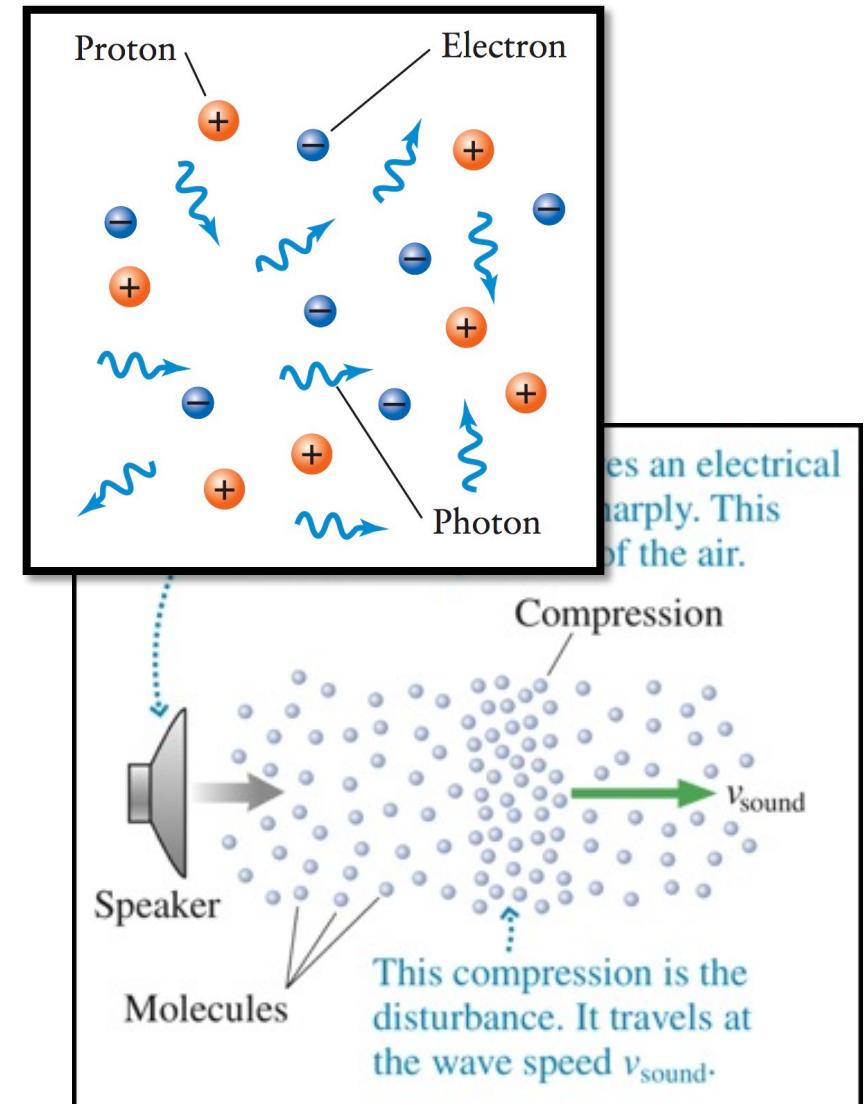
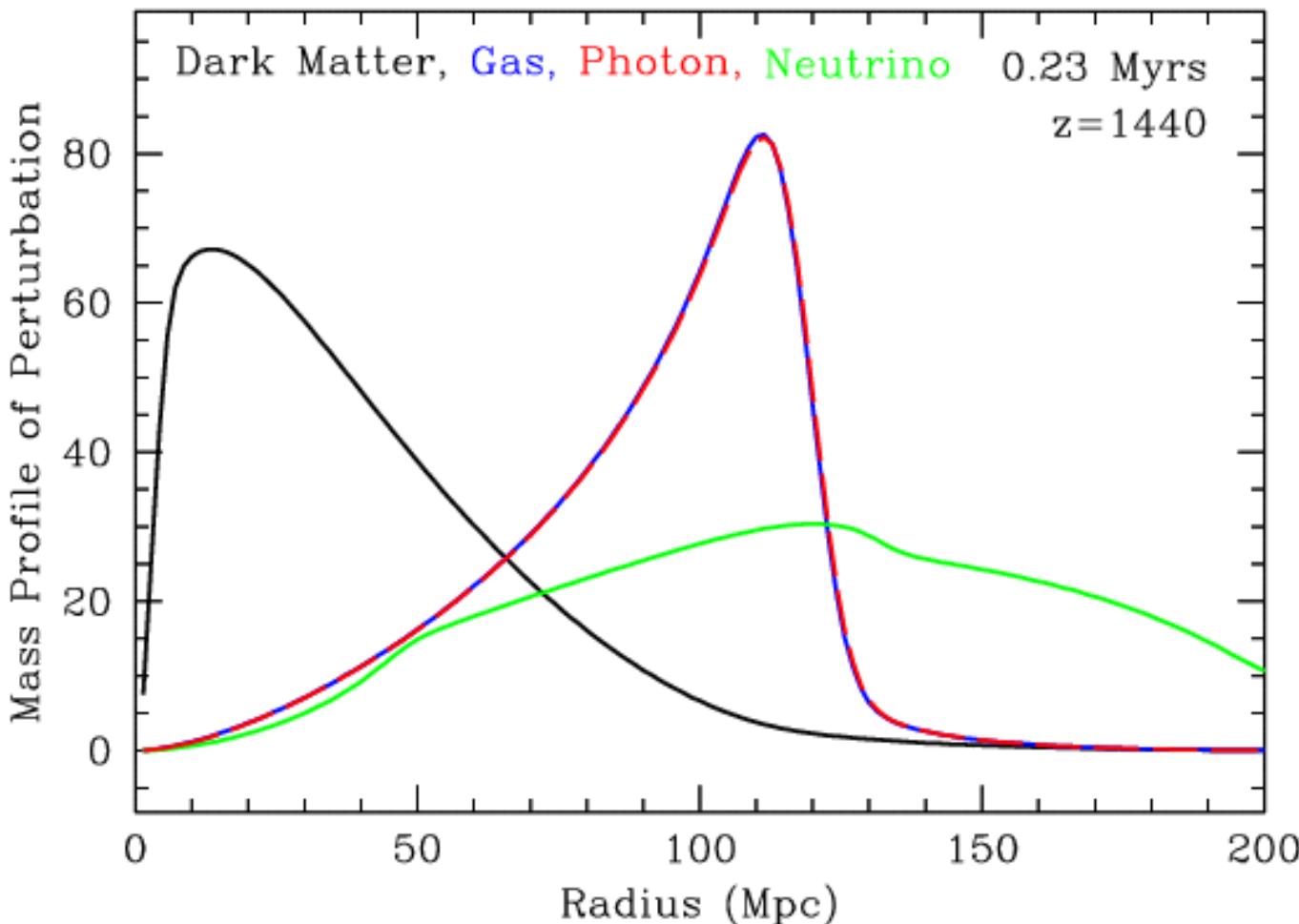
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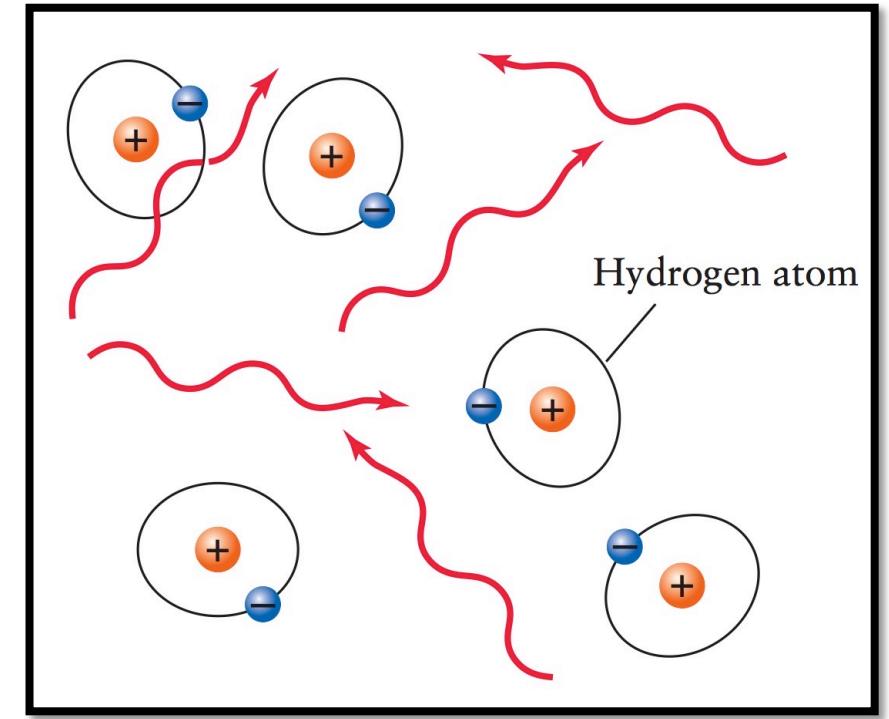
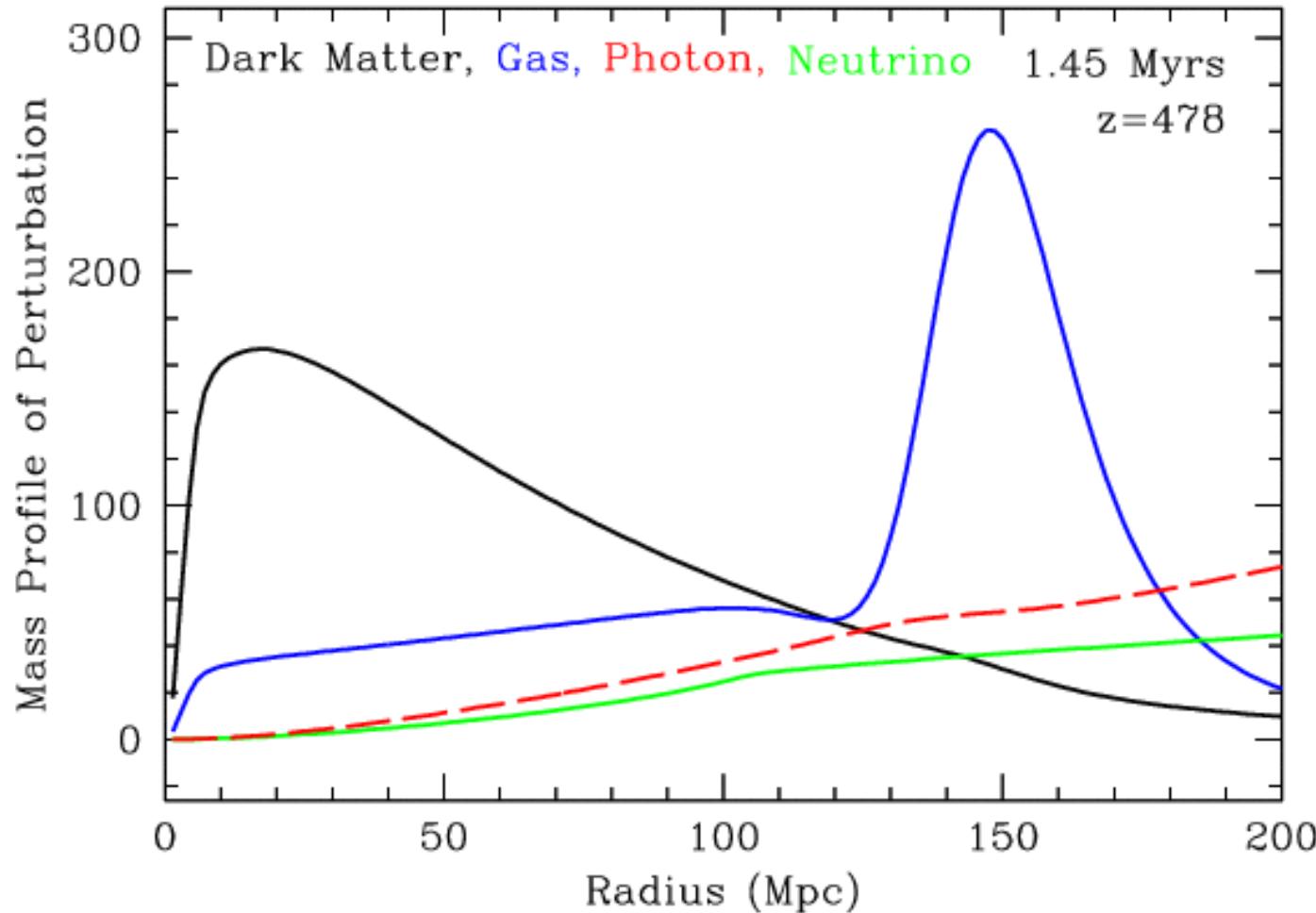
Baryon Acoustic Oscillation (BAO)



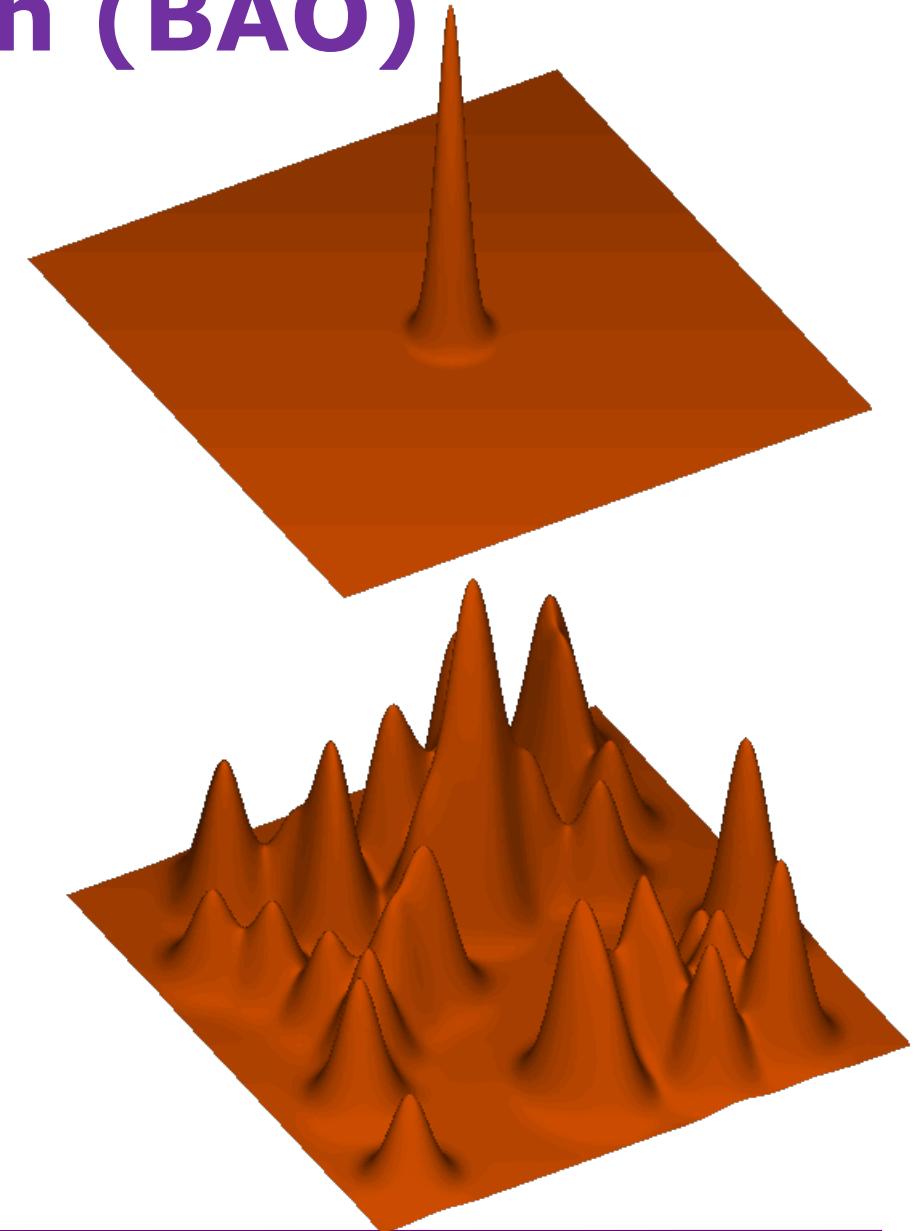
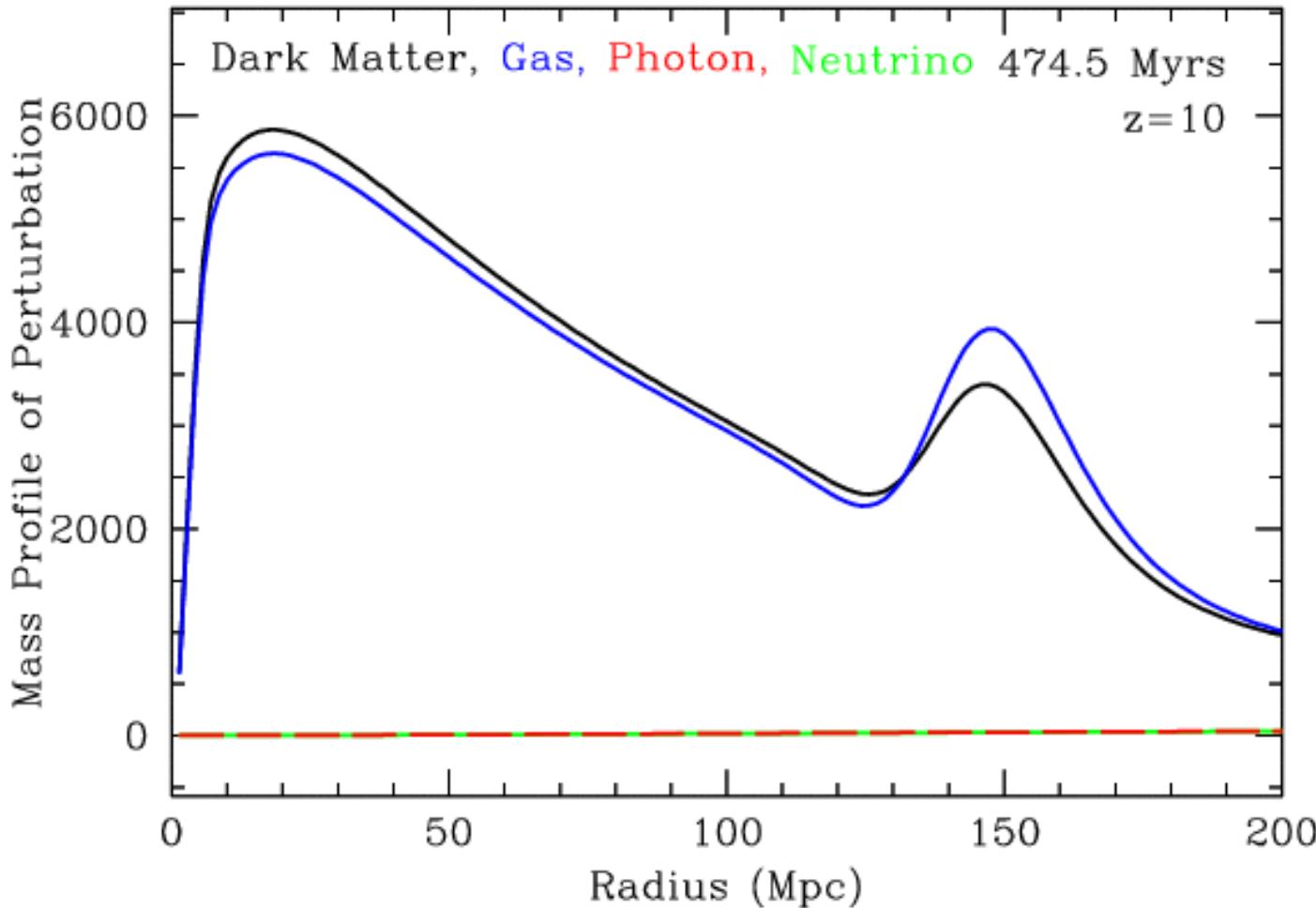
Baryon Acoustic Oscillation (BAO)



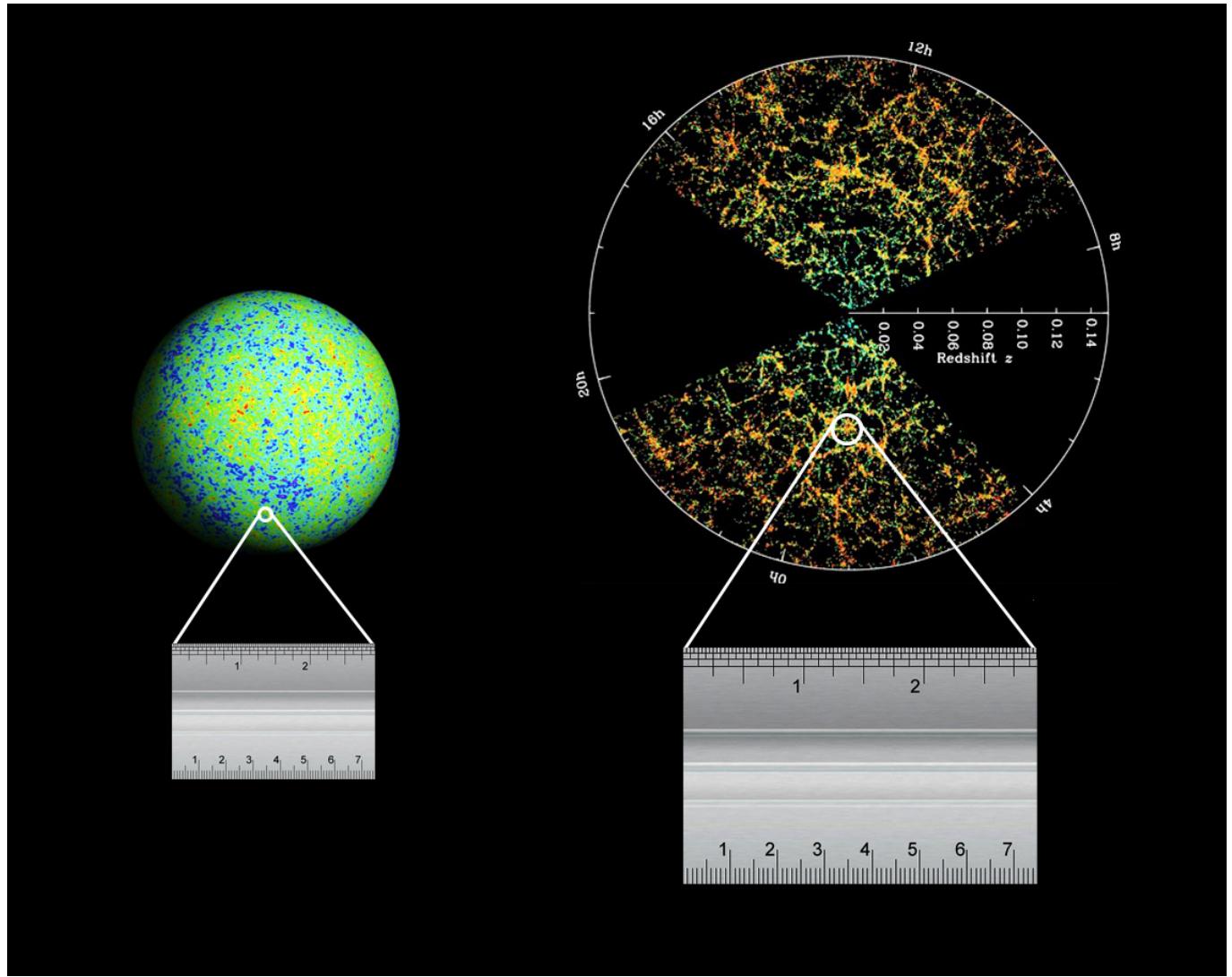
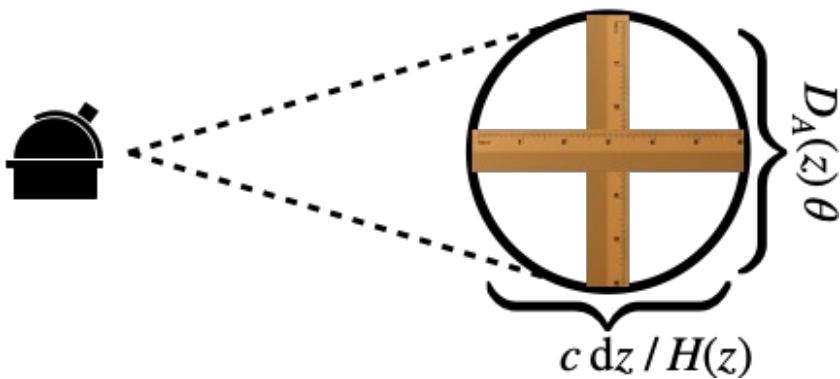
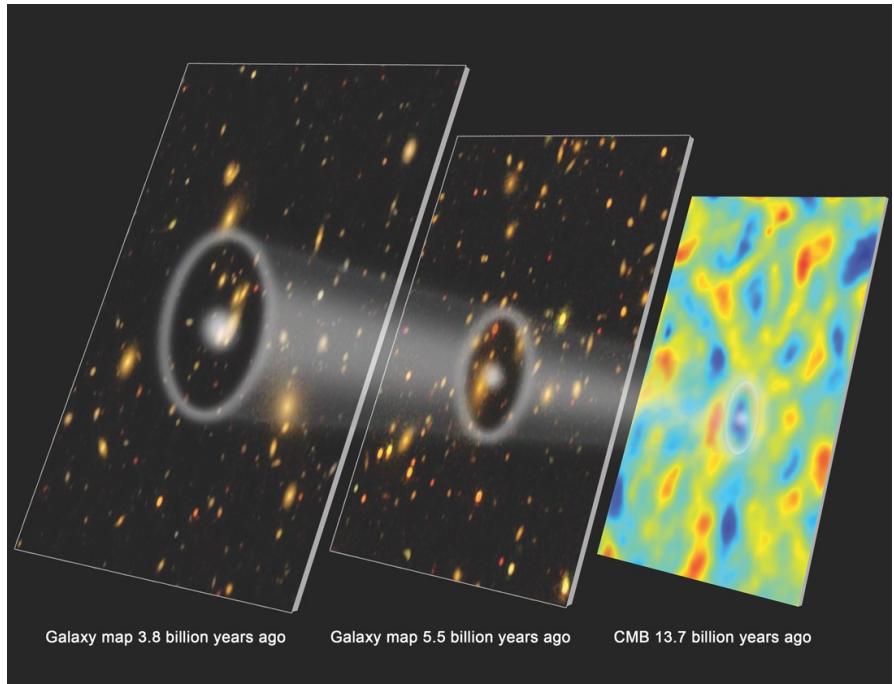
Baryon Acoustic Oscillation (BAO)



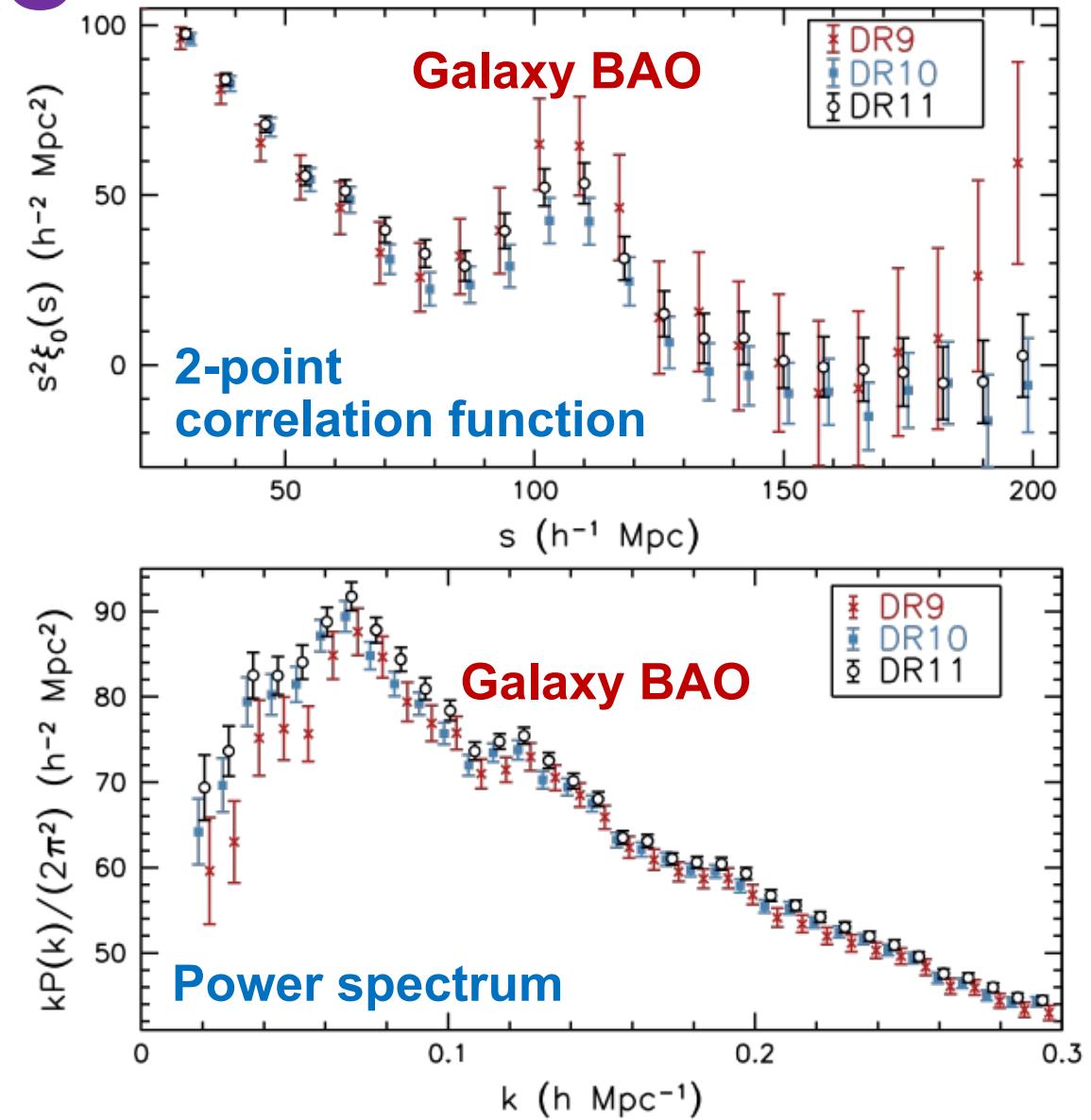
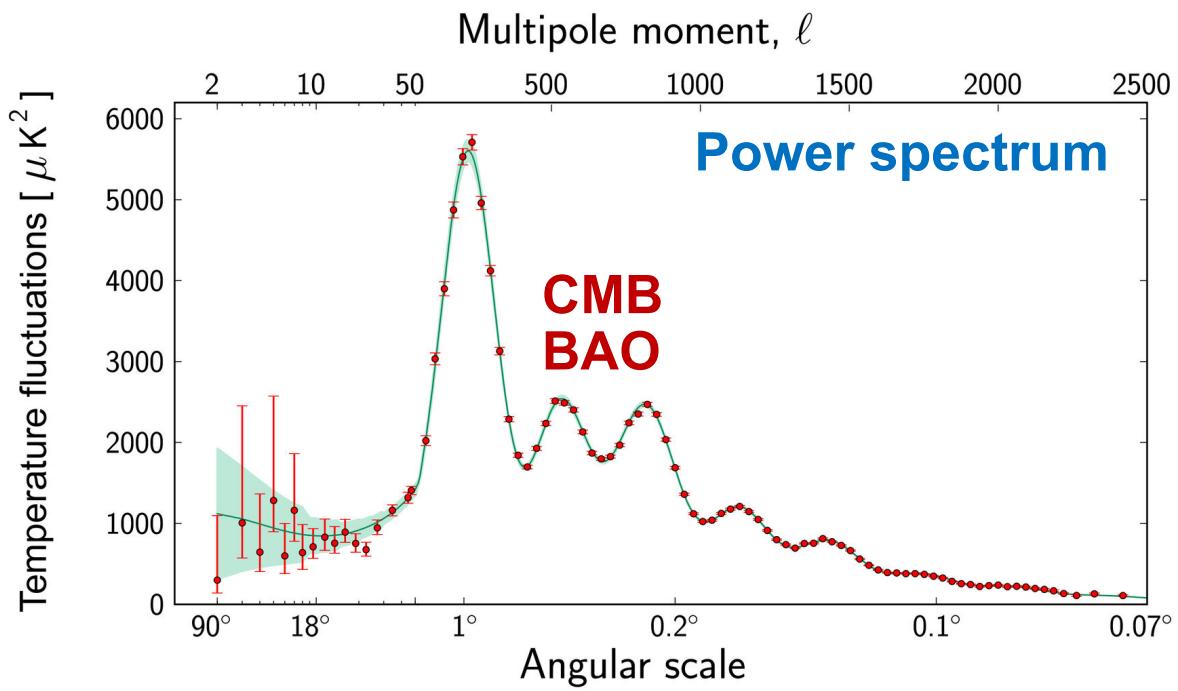
Baryon Acoustic Oscillation (BAO)



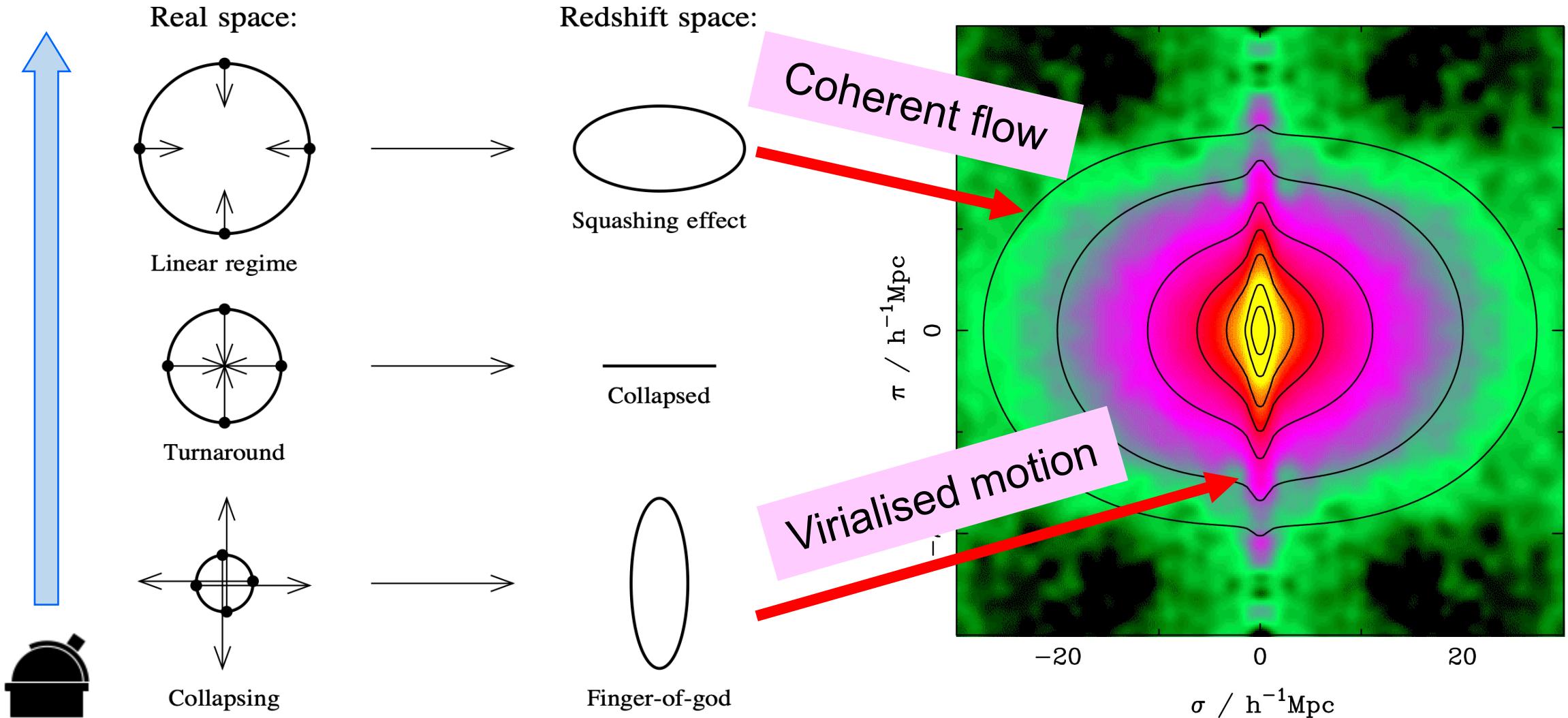
Baryon Acoustic Oscillation: Standard Ruler



Galaxy Clustering: BAO

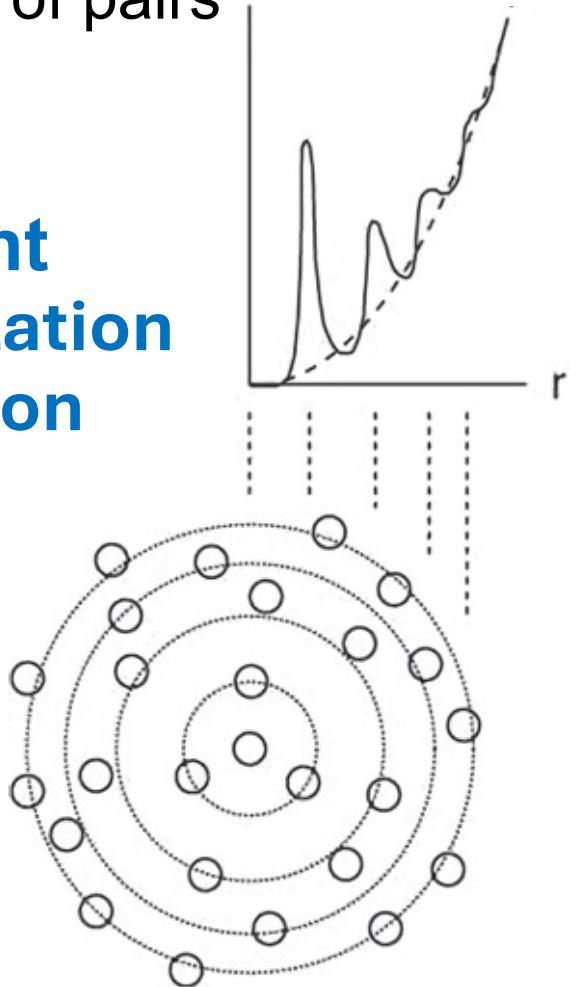


Redshift-space Distortion

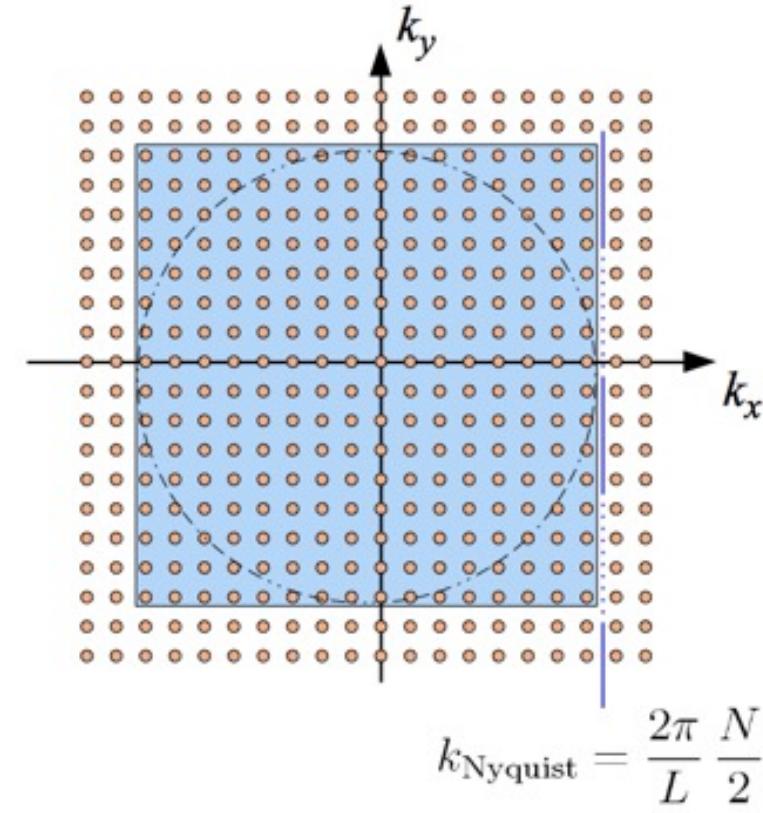


Galaxy Clustering Measurements

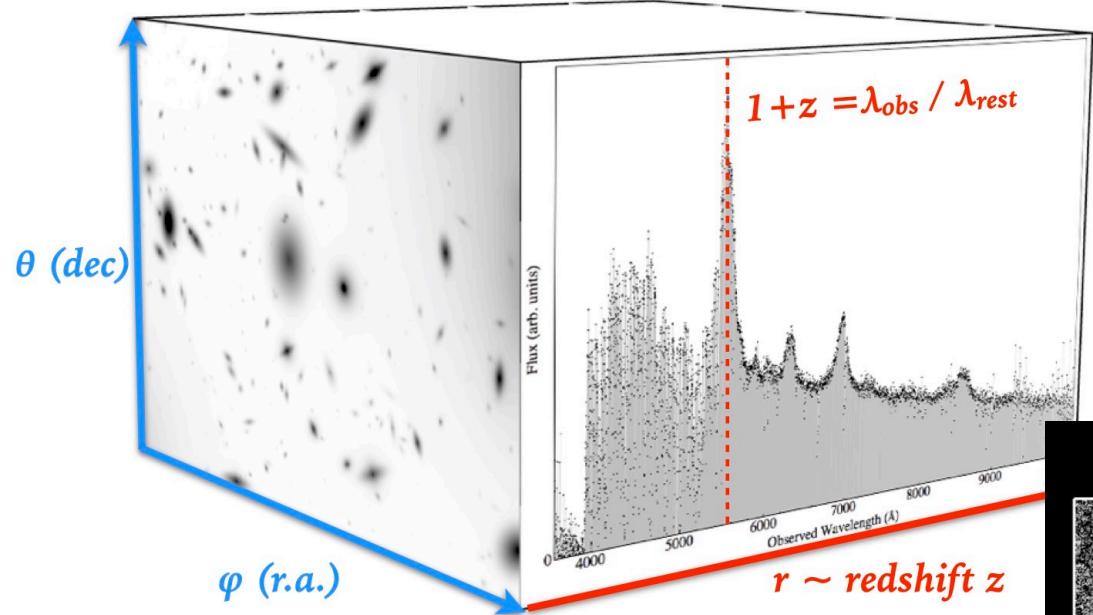
of pairs
2-point correlation function



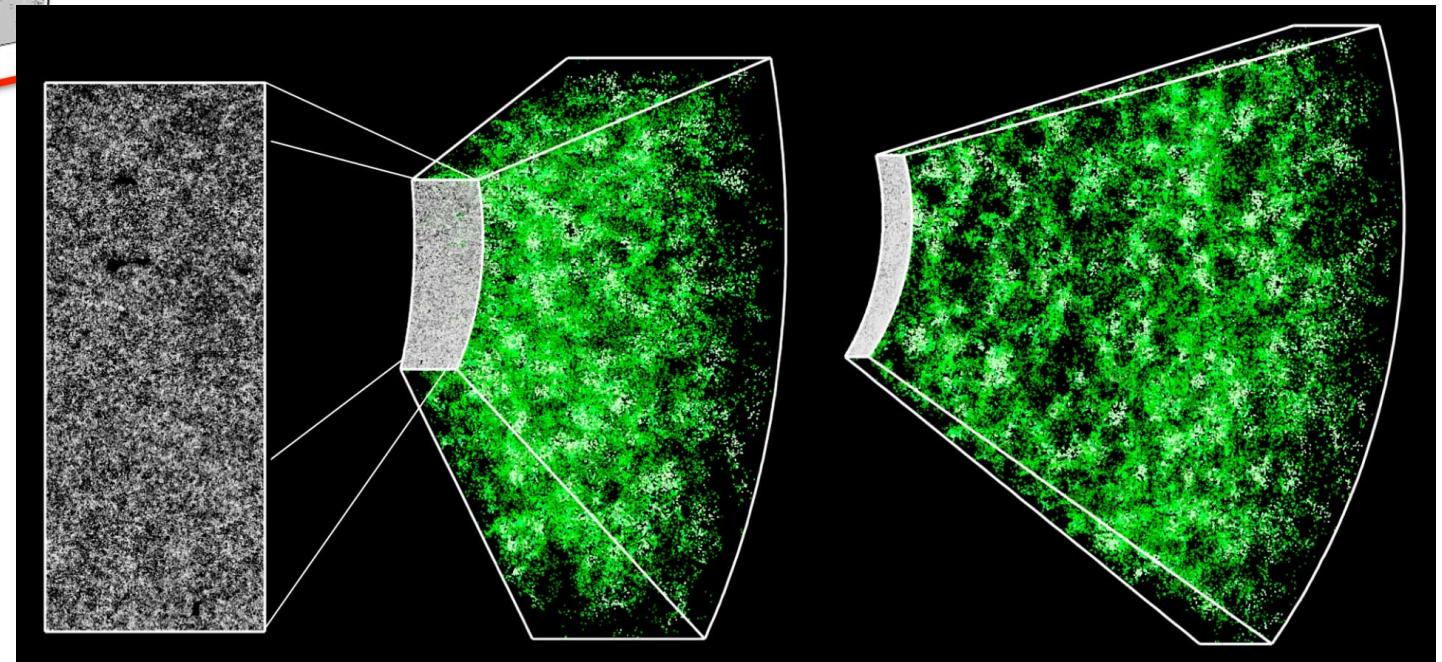
Power spectrum



Galaxy Spectroscopy

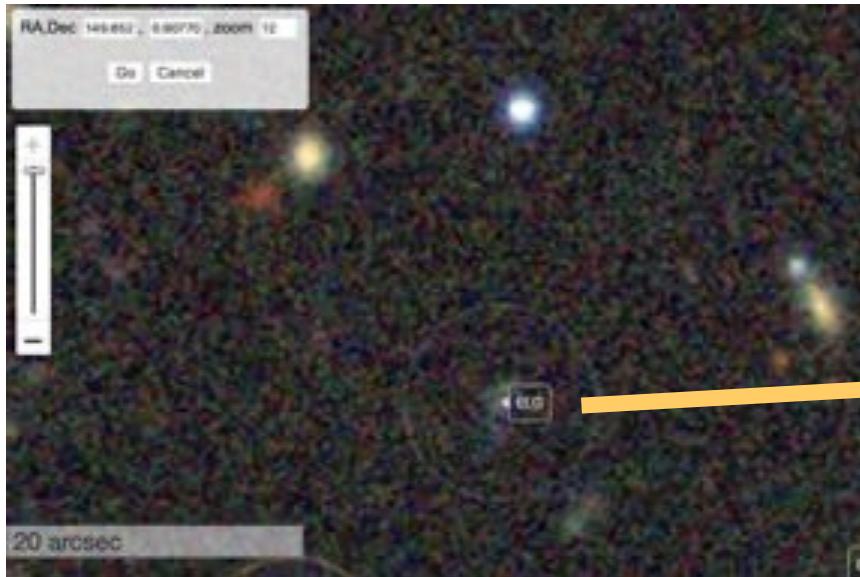


The optical sky is a data cube: $\theta \times \varphi \times r$

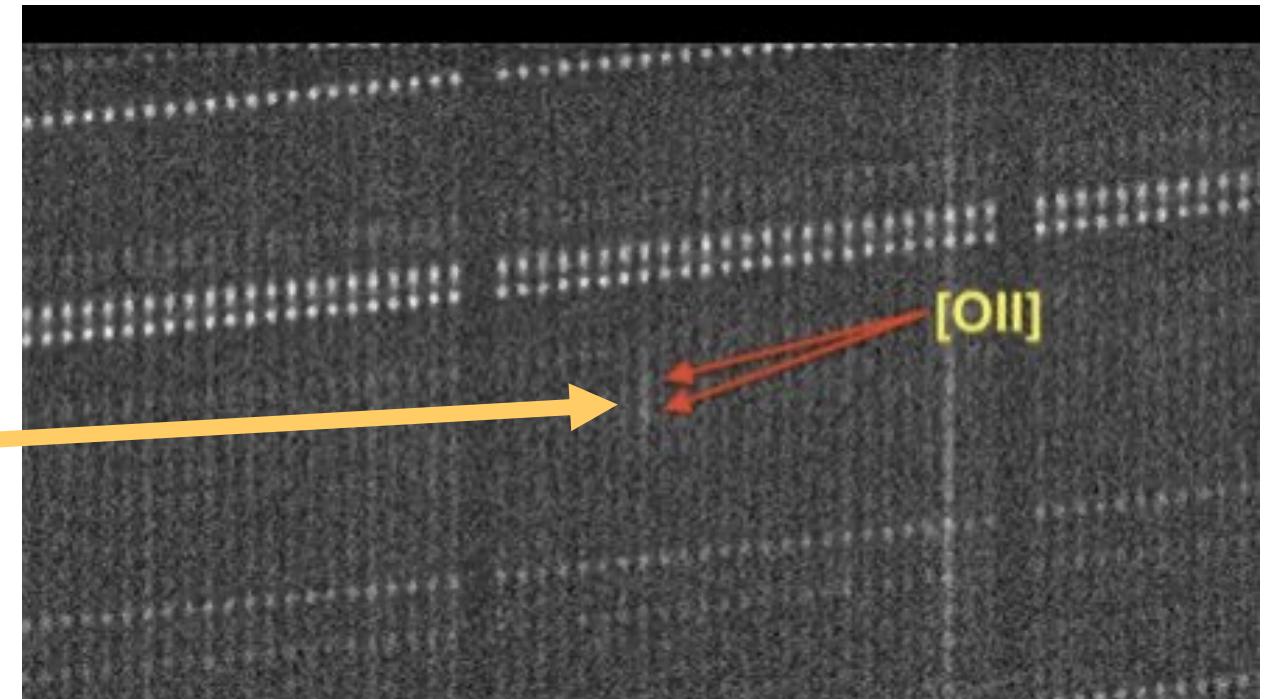


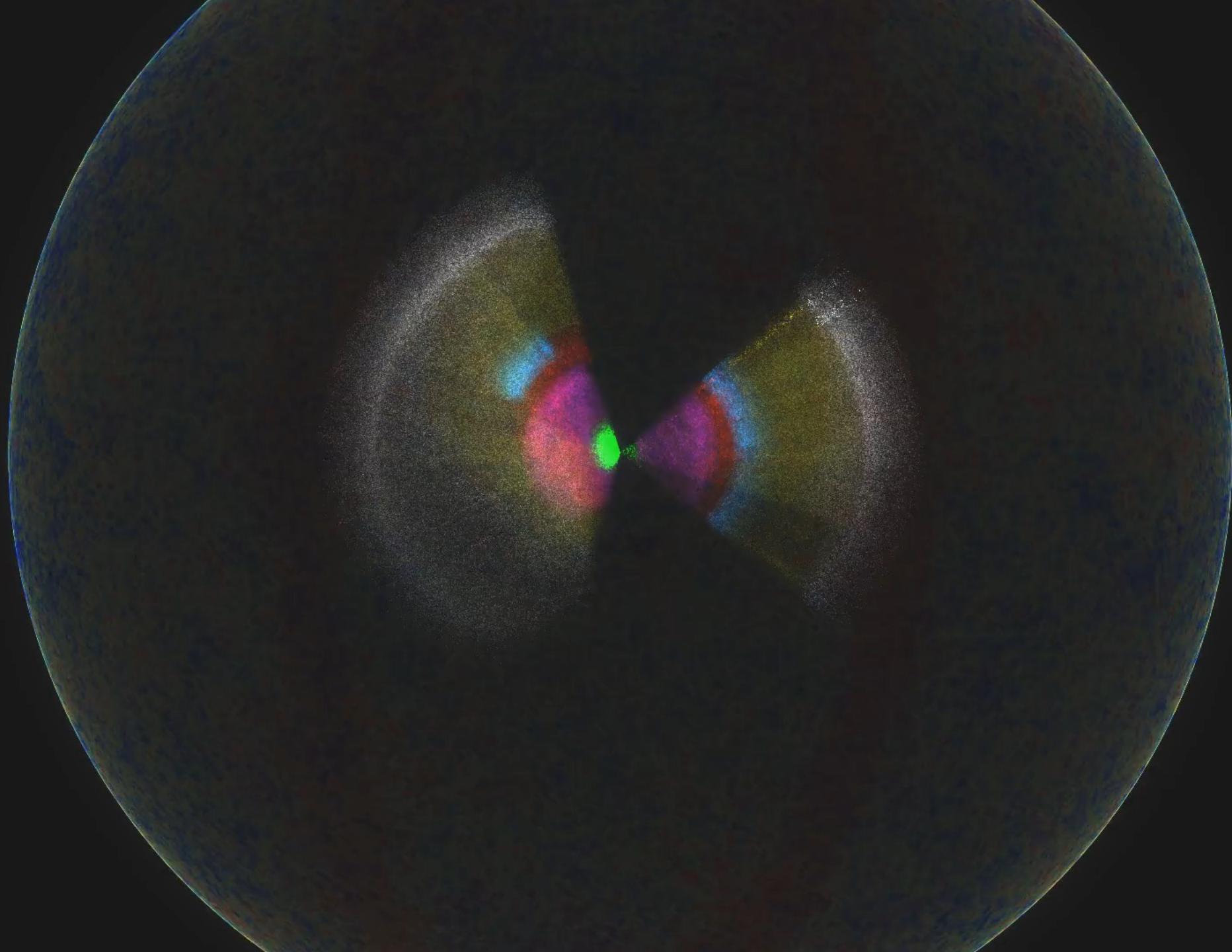
Galaxy Spectroscopic Survey

Imaging survey



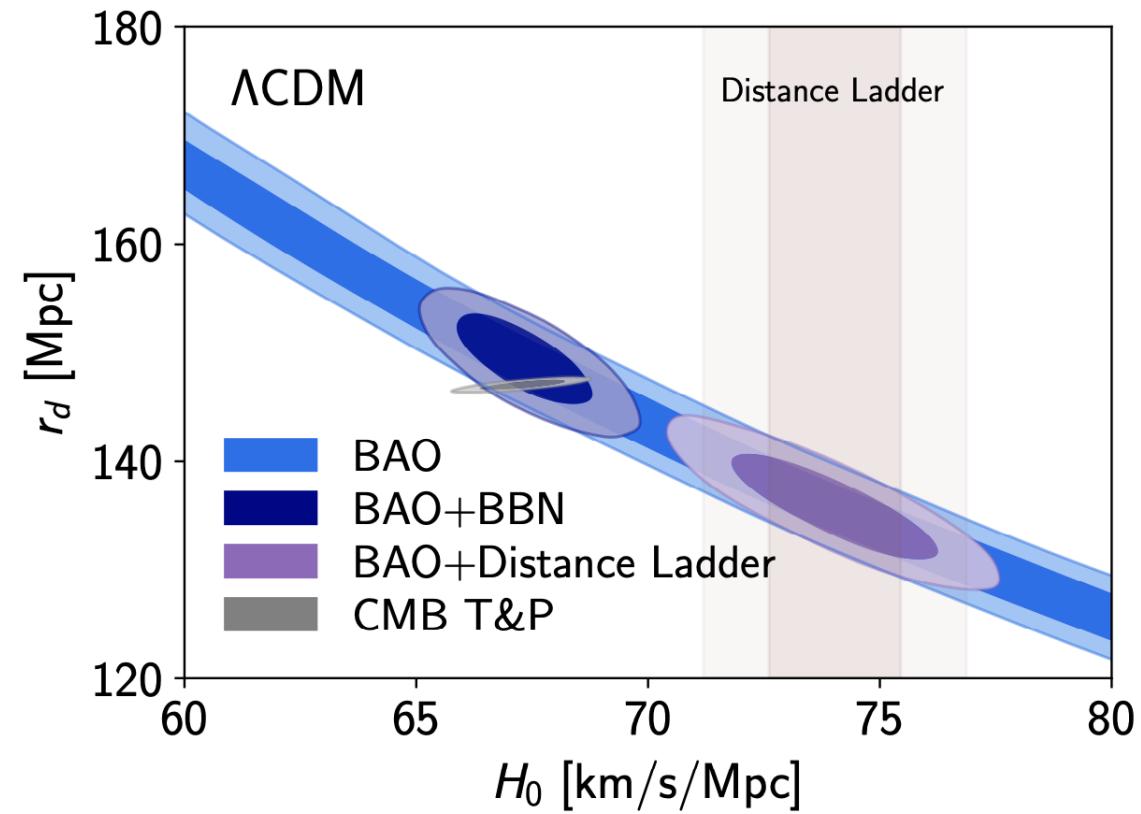
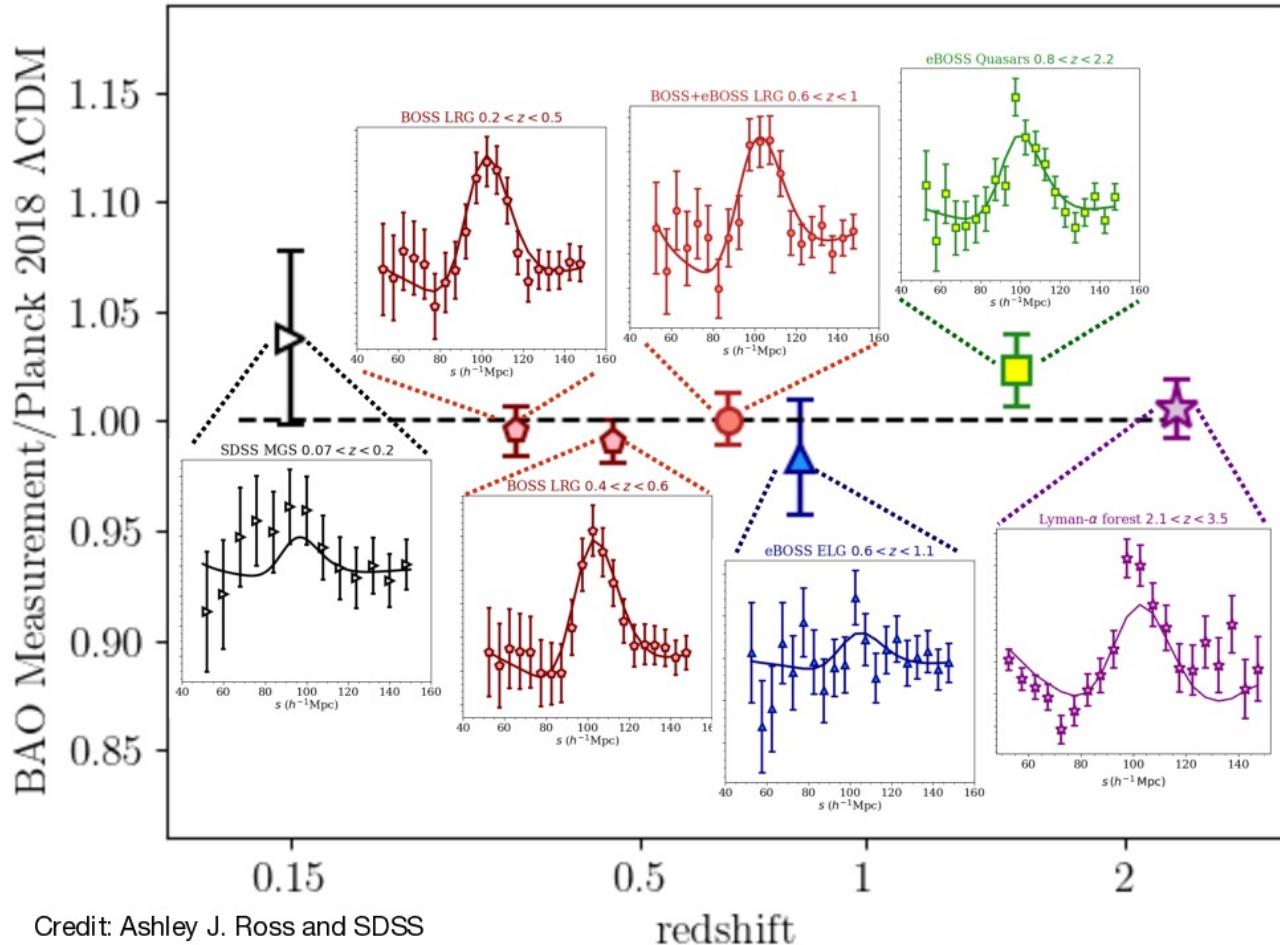
CCD of spectrograph





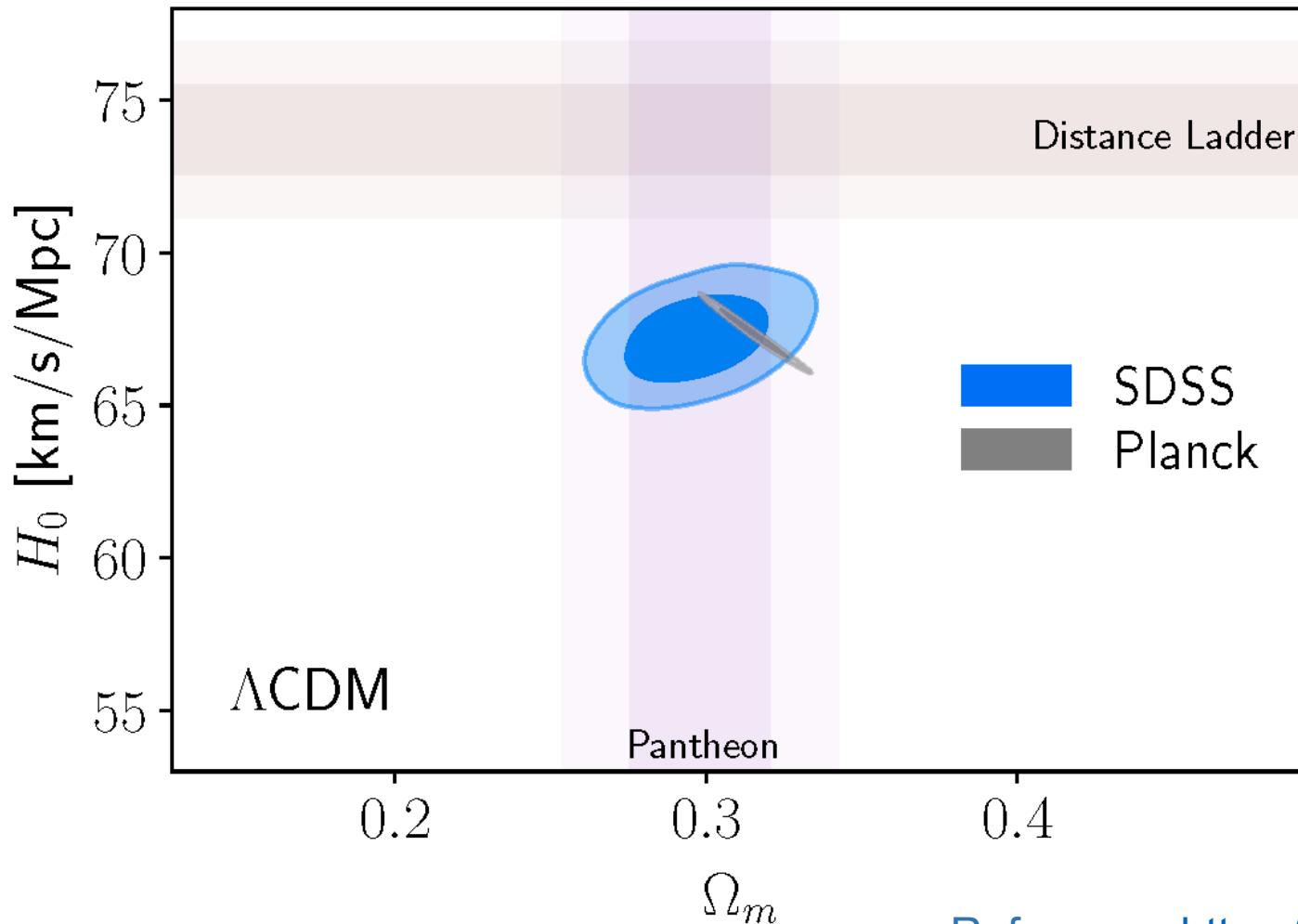
Galaxy Clustering: BAO

SDSS BAO Distance Ladder



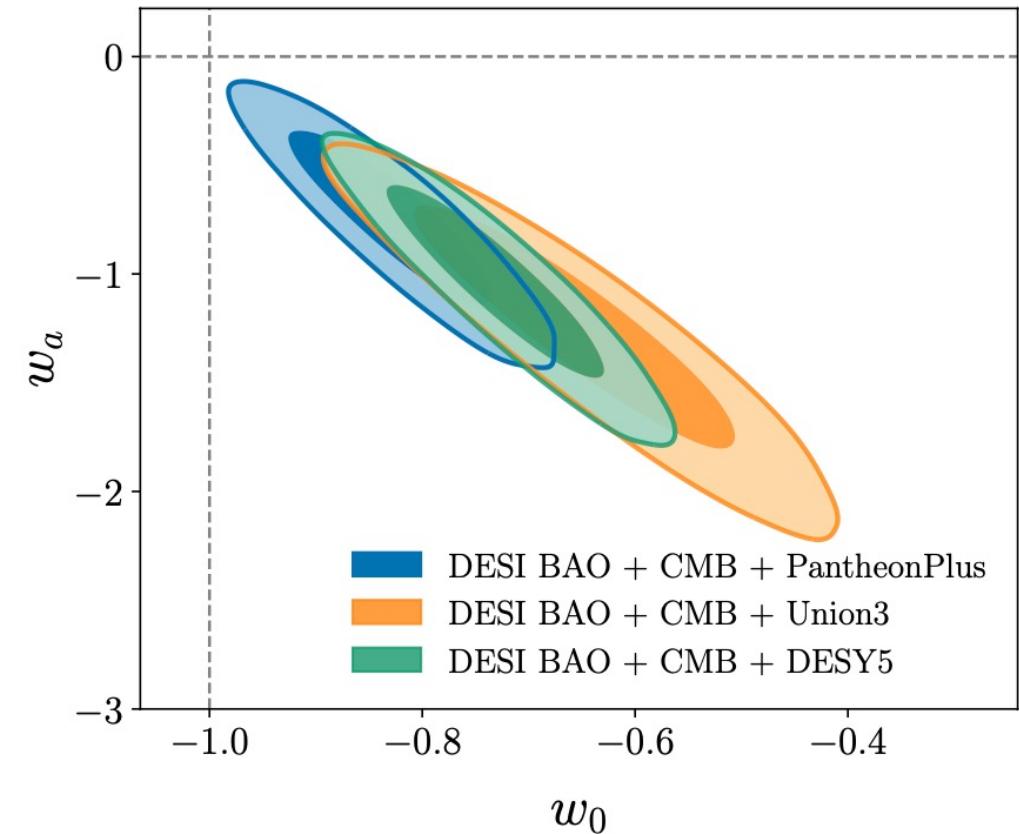
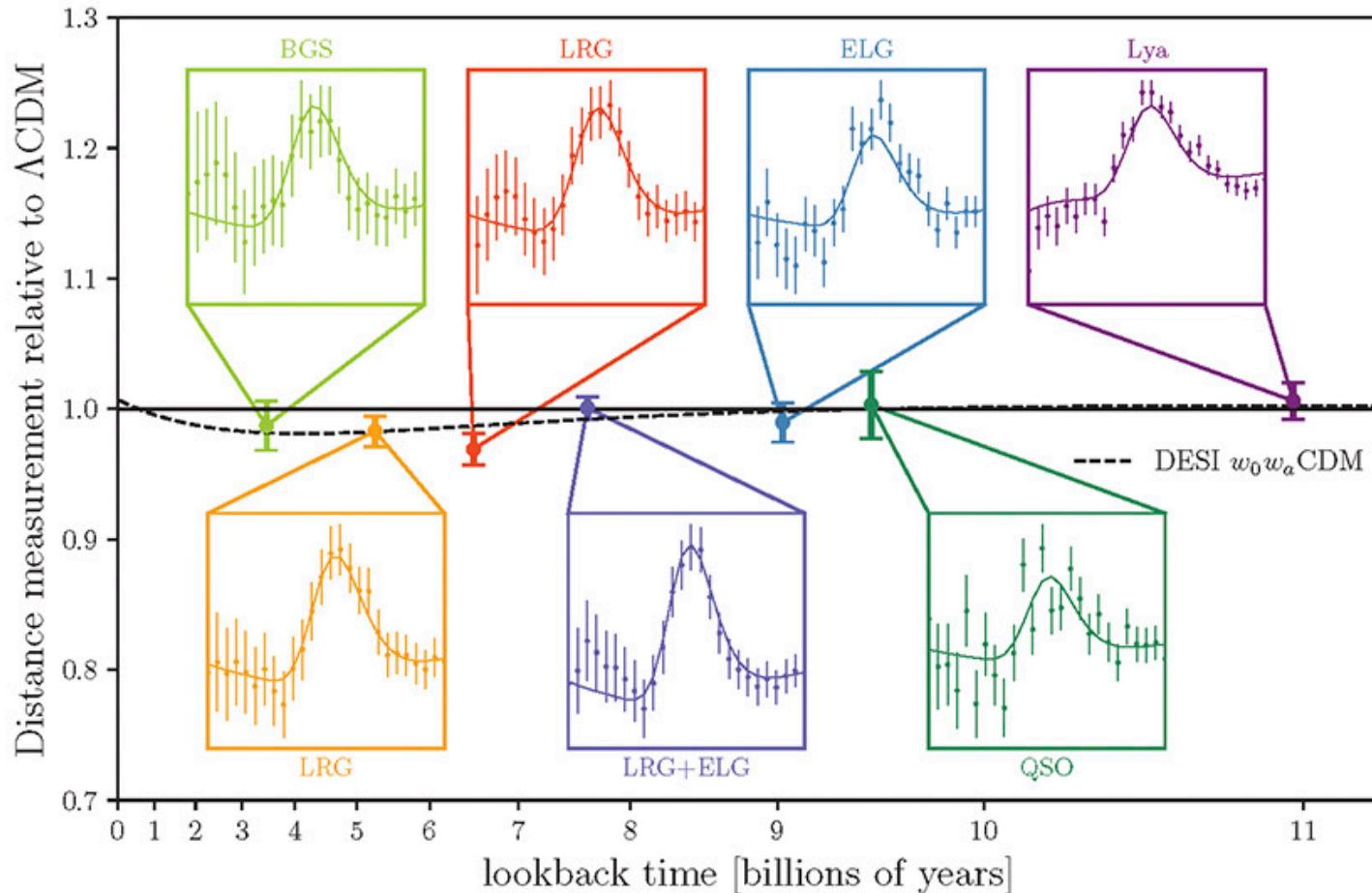
Reference: <https://arxiv.org/abs/2007.08991>

Galaxy Clustering: Constraints



Galaxy Clustering: BAO

DESI first-year results



Dynamic dark energy?

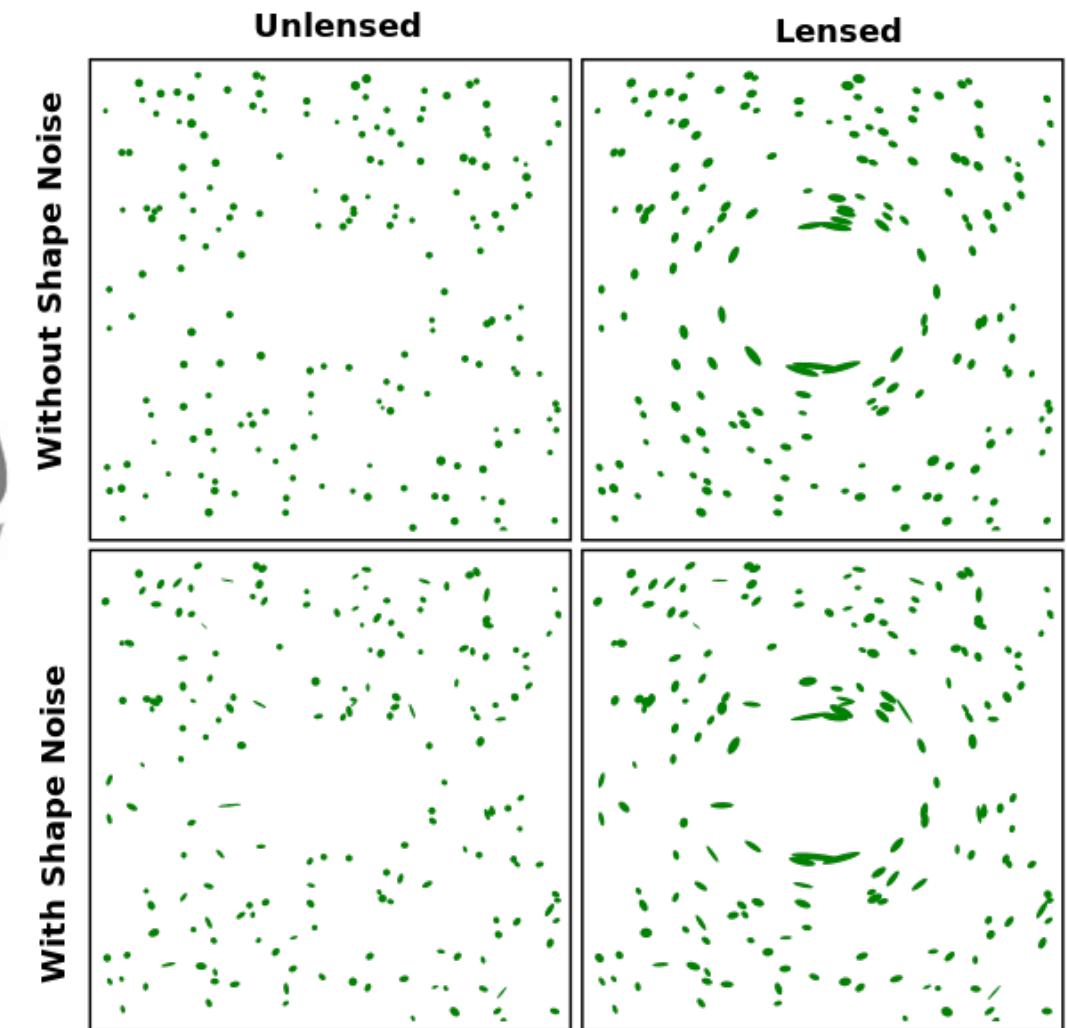
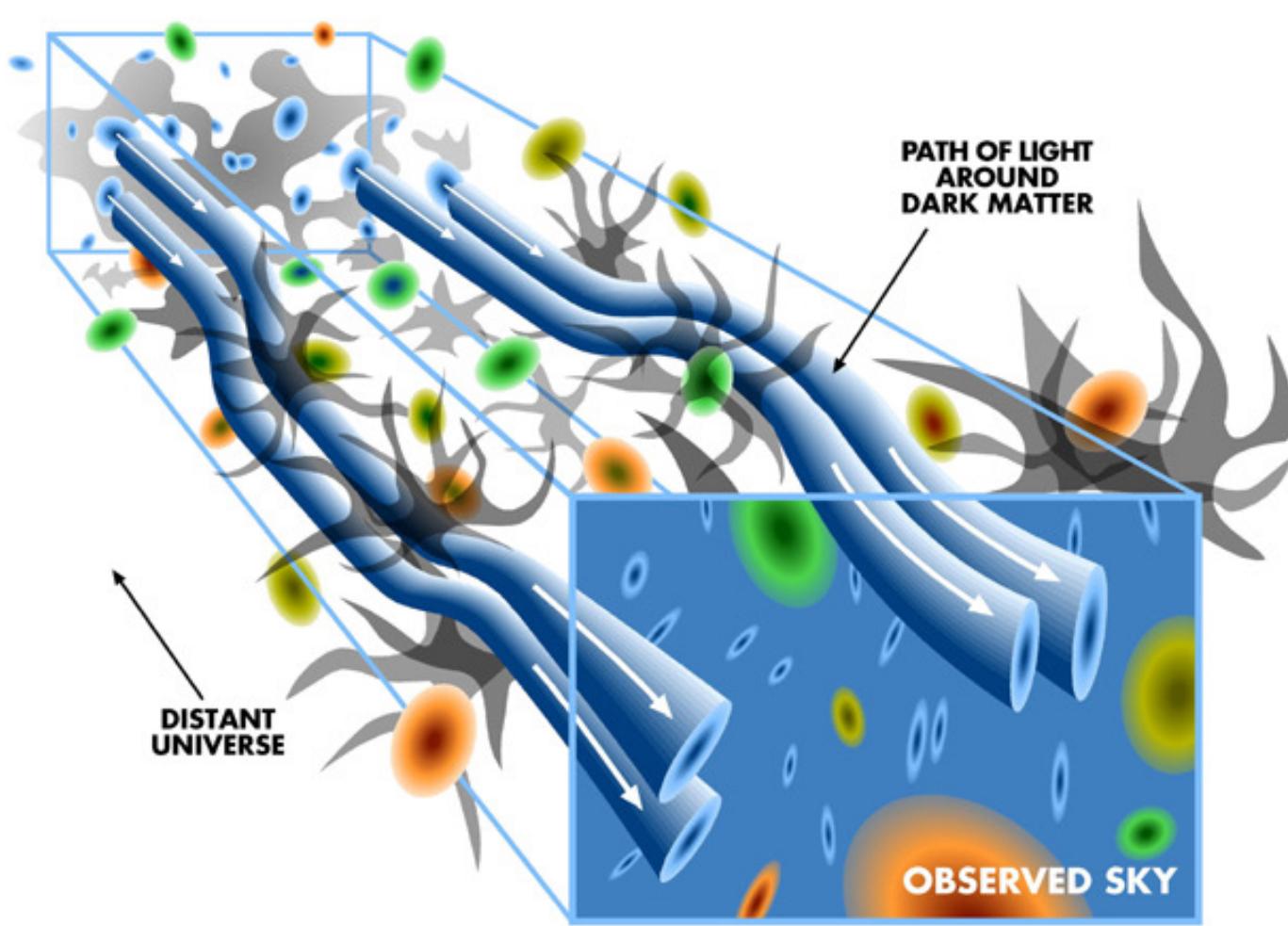
Reference: <https://arxiv.org/abs/2404.03002>



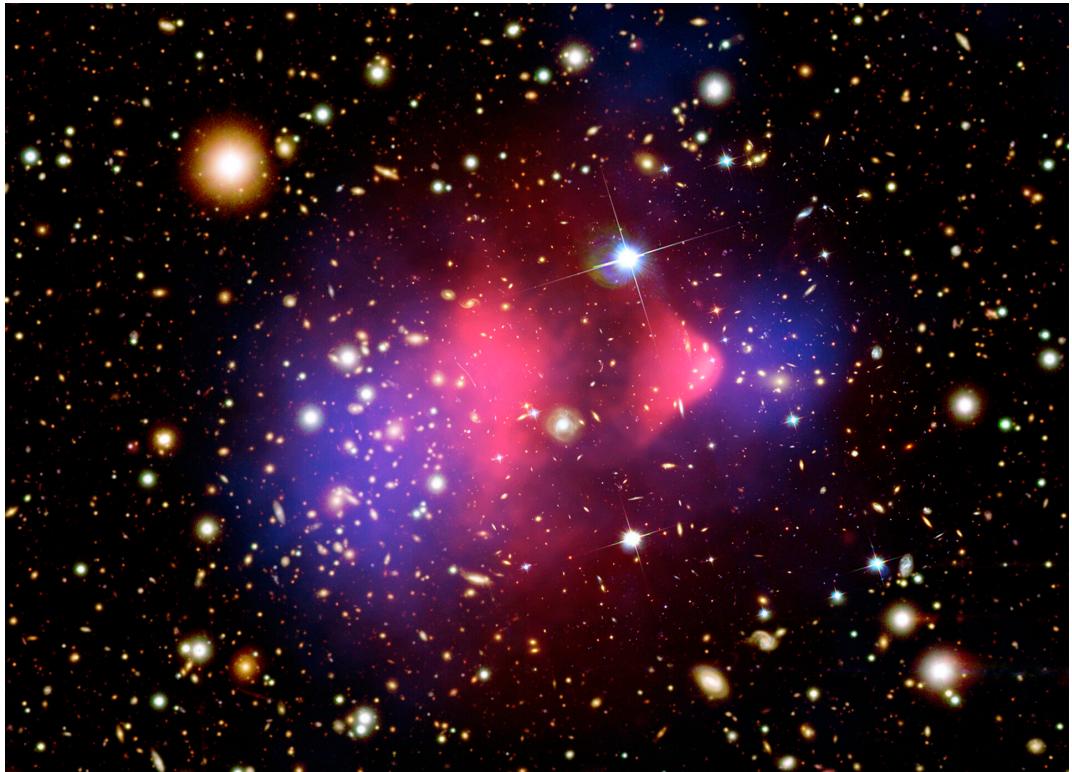
Cosmological Probes

- Distance Ladder
- Type Ia Supernova
- Cosmic Microwave Background (CMB)
- Galaxy Clustering
- Gravitational lensing

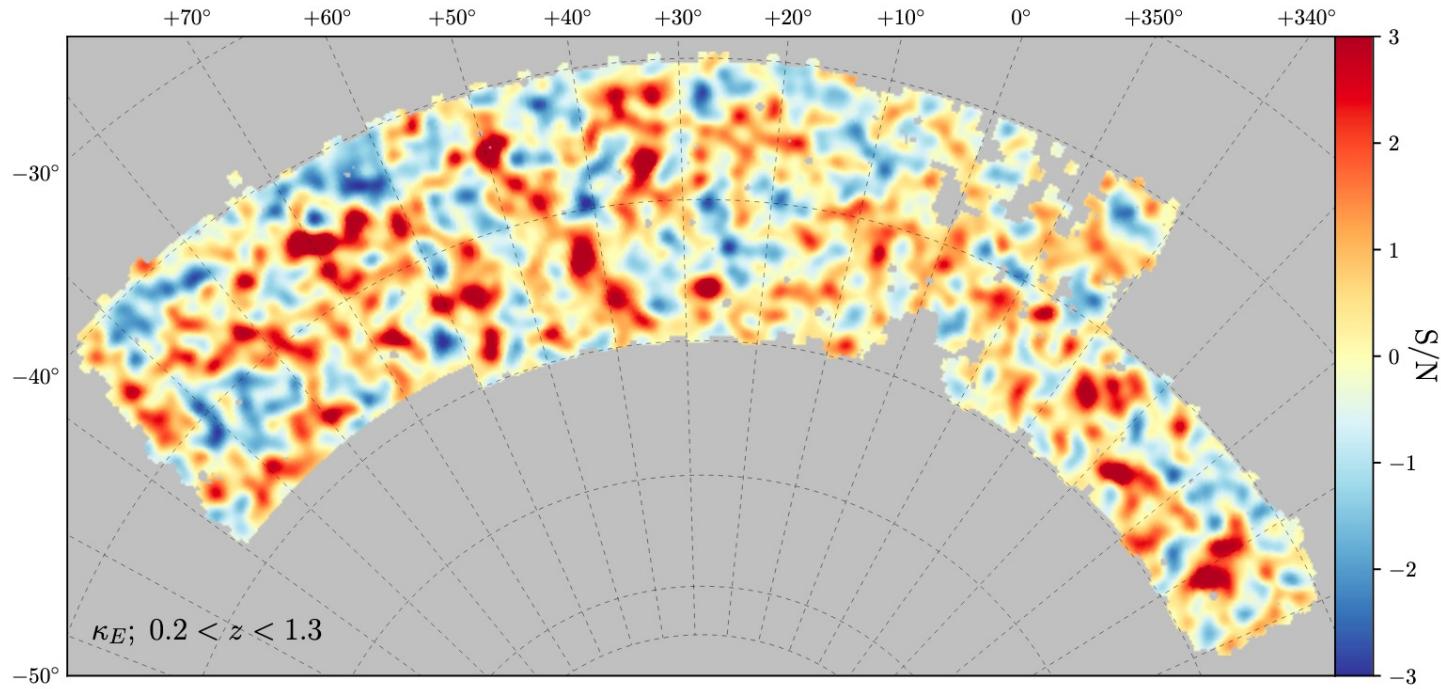
L Weak Gravitational Lensing



L Weak Gravitational Lensing

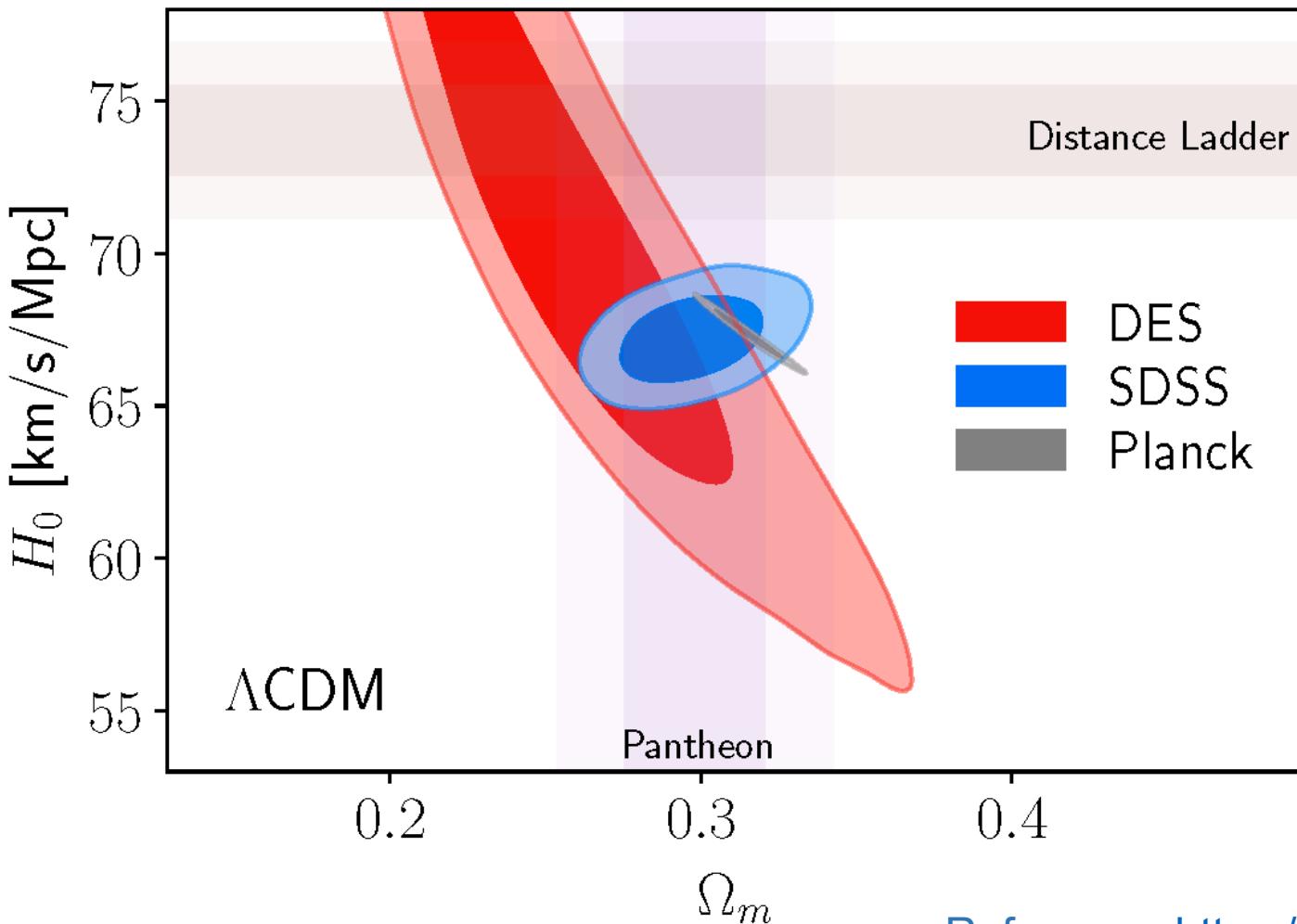


Bullet cluster:
evidence of dark matter



Dark Energy Survey (DES):
large-scale matter distribution

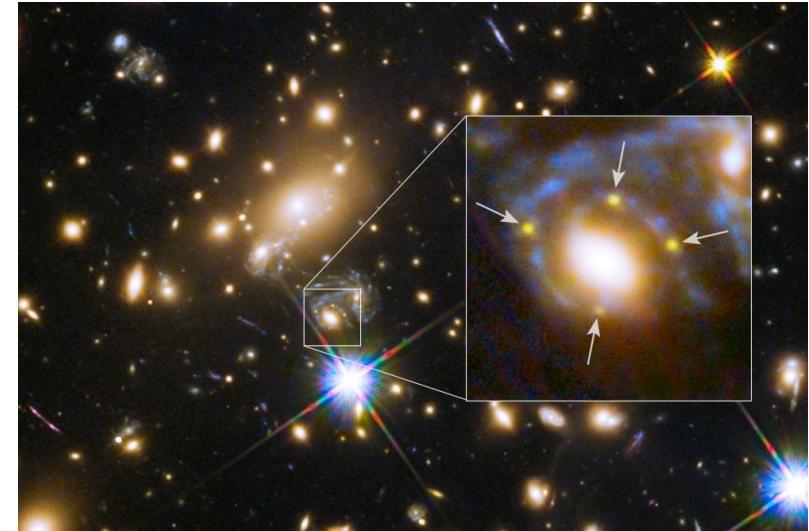
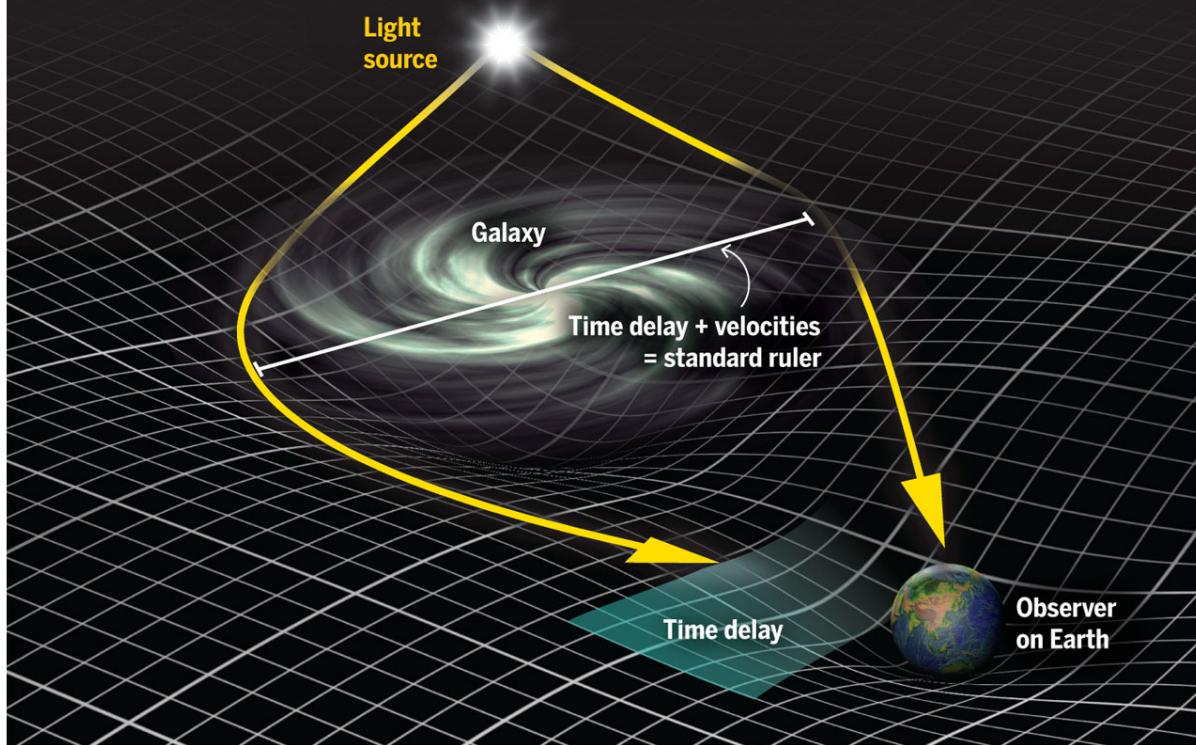
Weak Gravitational Lensing: Constraints



L Strong Gravitational Lensing

Multiple paths to Hubble's constant

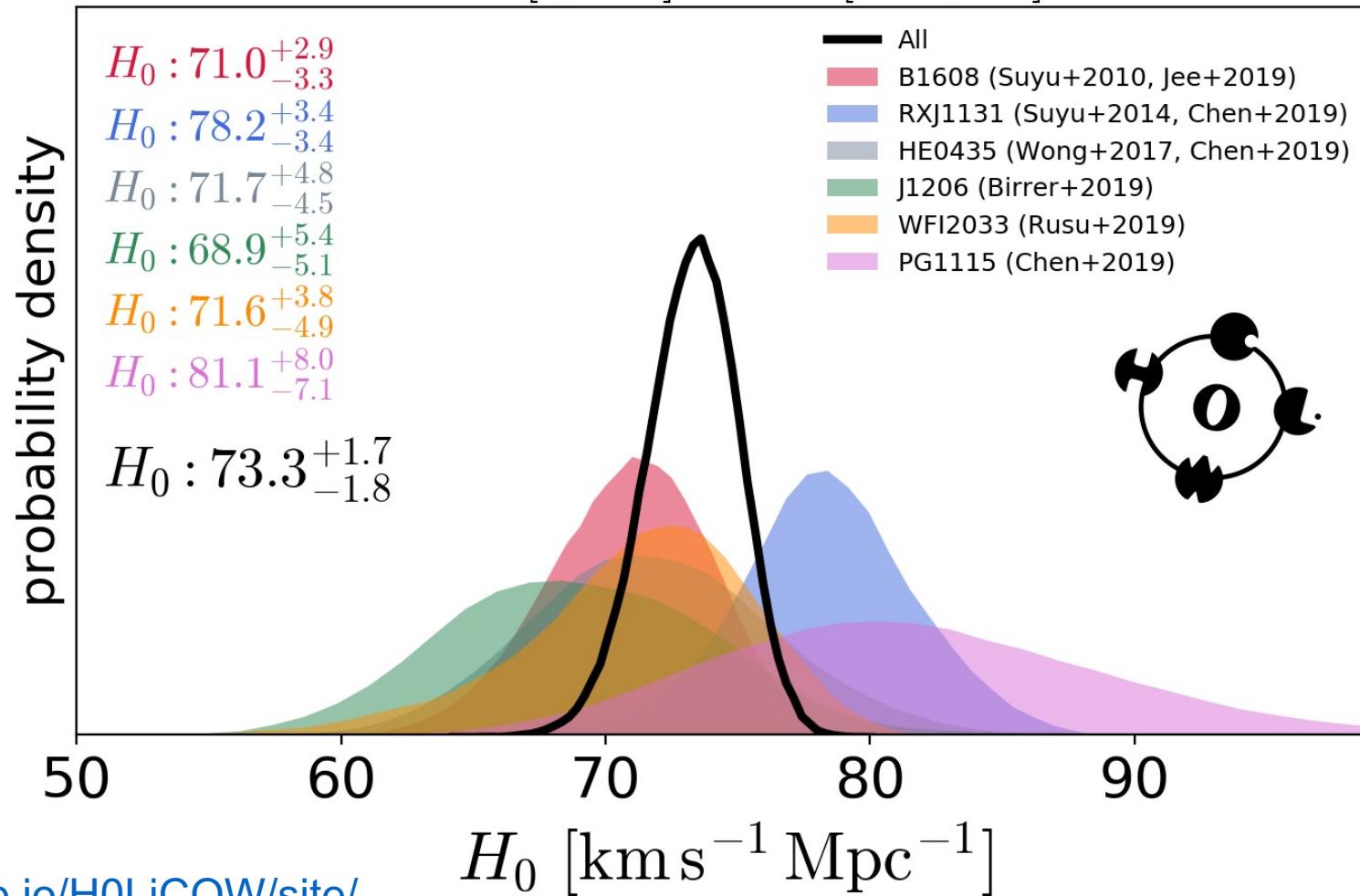
The strong foreground lens, a galaxy, bends the path of light from a background supernova, so that light arrives at Earth by two routes of different lengths. Thus, the observer detects one image before the other. This time difference allows calculation of the lens's mass. The velocity of stars orbiting in the lens galaxy reveals the gravitational potential. Together, these values yield the lensing system's radius (a standard ruler). Jee *et al.* used this method to derive H_0 .





Strong Gravitational Lensing: Constraints

$$H_0 \in [0, 150] \quad \Omega_m \in [0.05, 0.5]$$



Reference:

<https://shsuyu.github.io/H0LiCOW/site/>

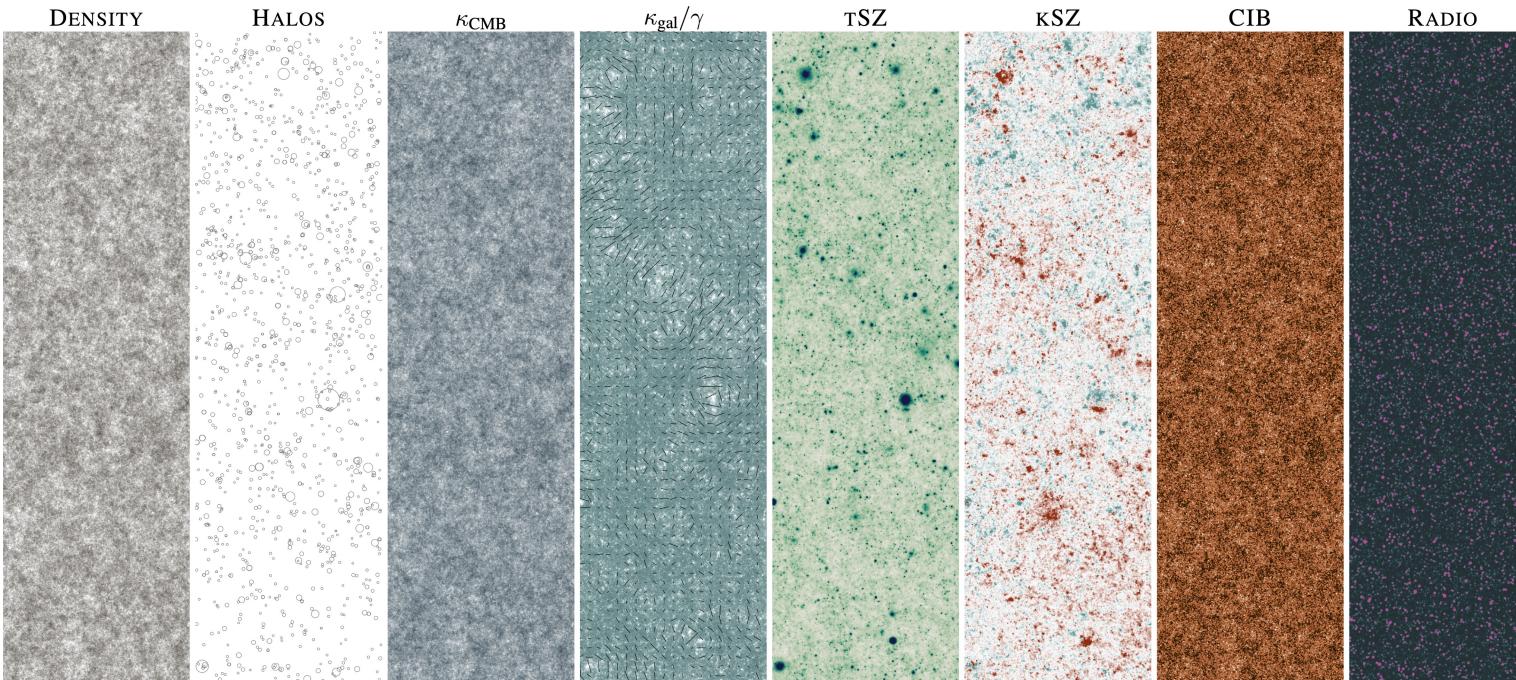
L Outline

- Introduction to observational cosmology: a historical review
- Cosmological probes
 - Distance ladder
 - Type Ia supernova
 - Cosmic microwave background
 - Galaxy clustering
 - Gravitational lensing
- Combination of probes
- Future prospective

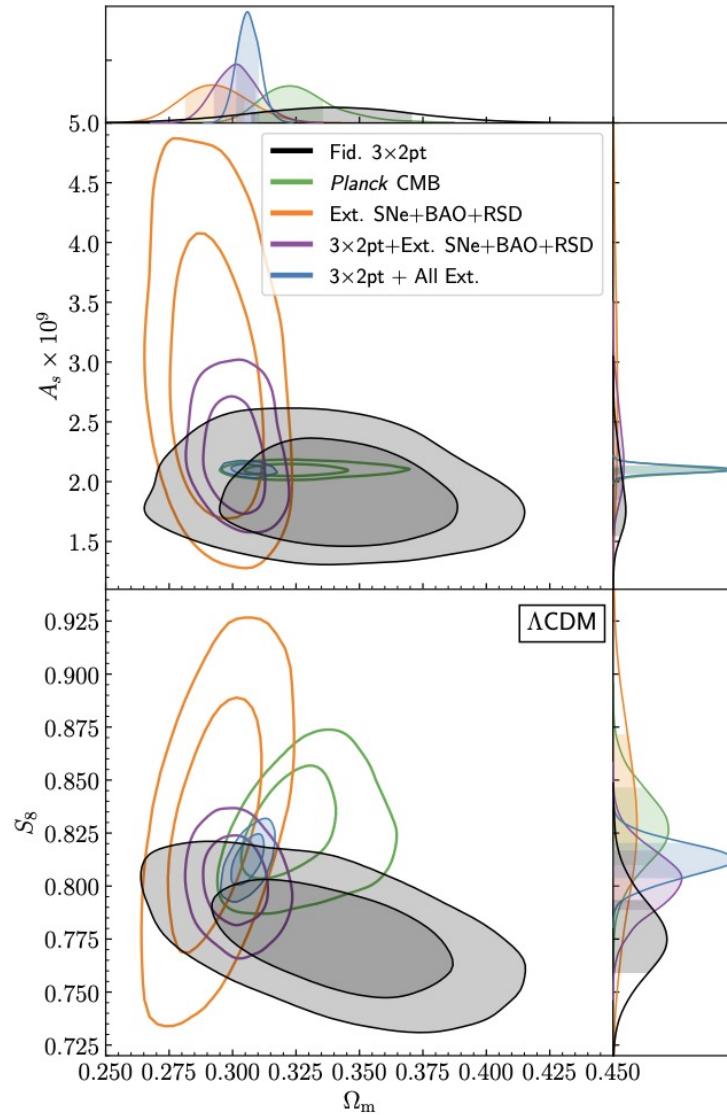
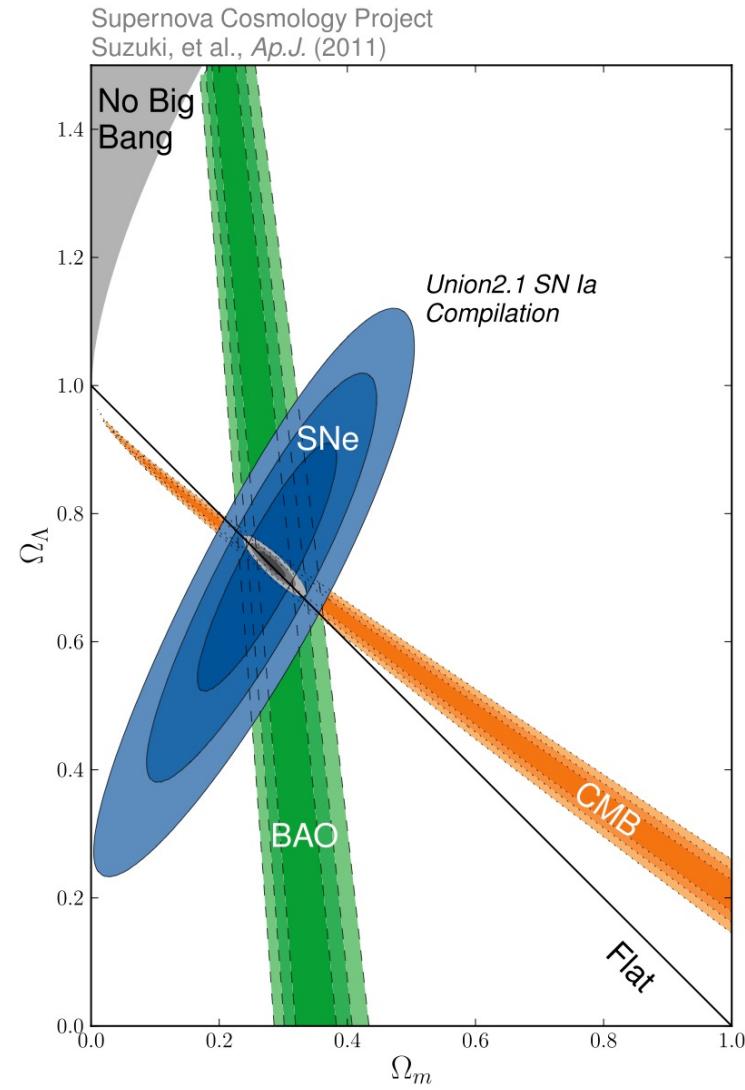


Multi-probe Combination: Why?

- Only one sky and no controlled measurements
- Break of parameter degeneracy
- Mitigation of probe-specific systematics

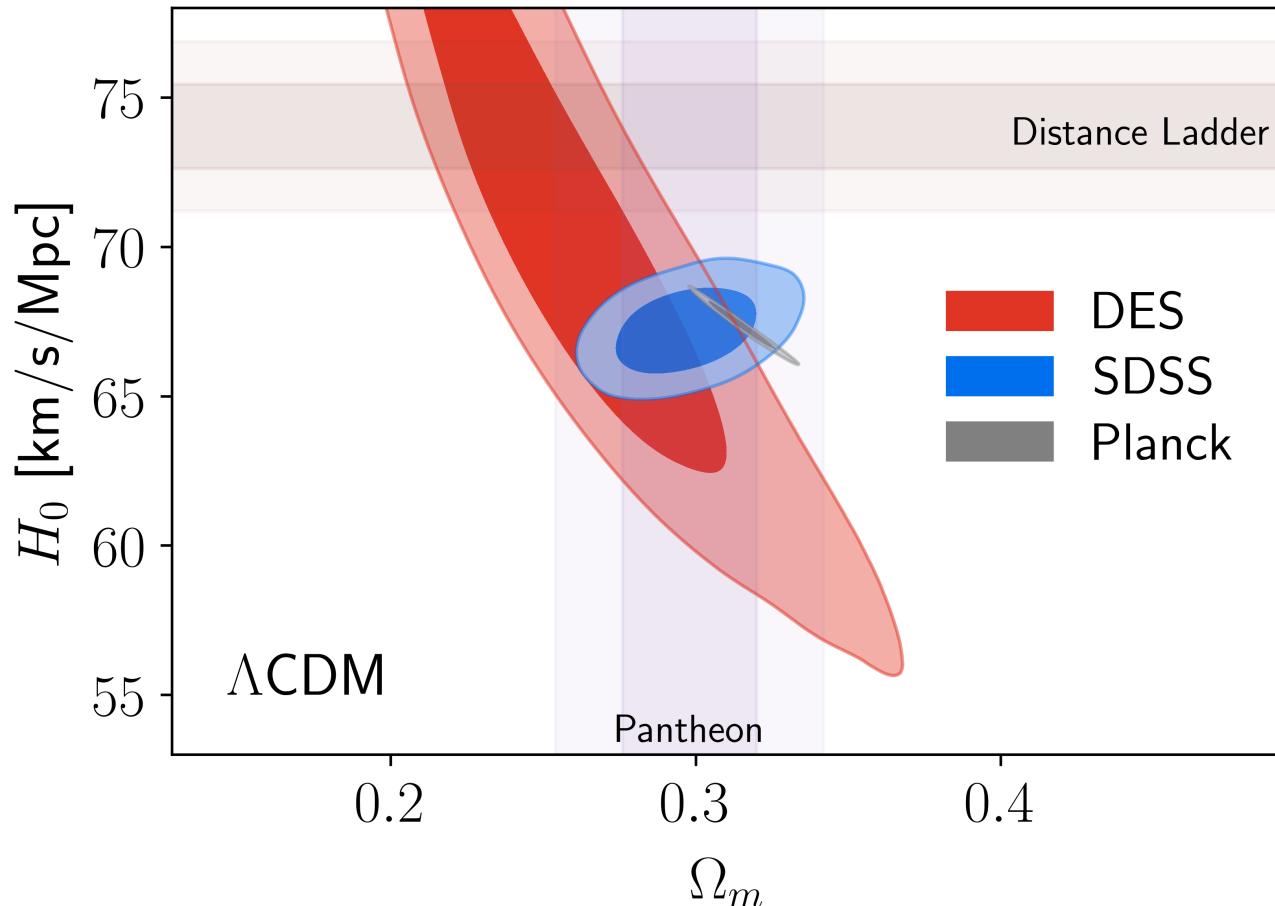


Multi-probe Combination



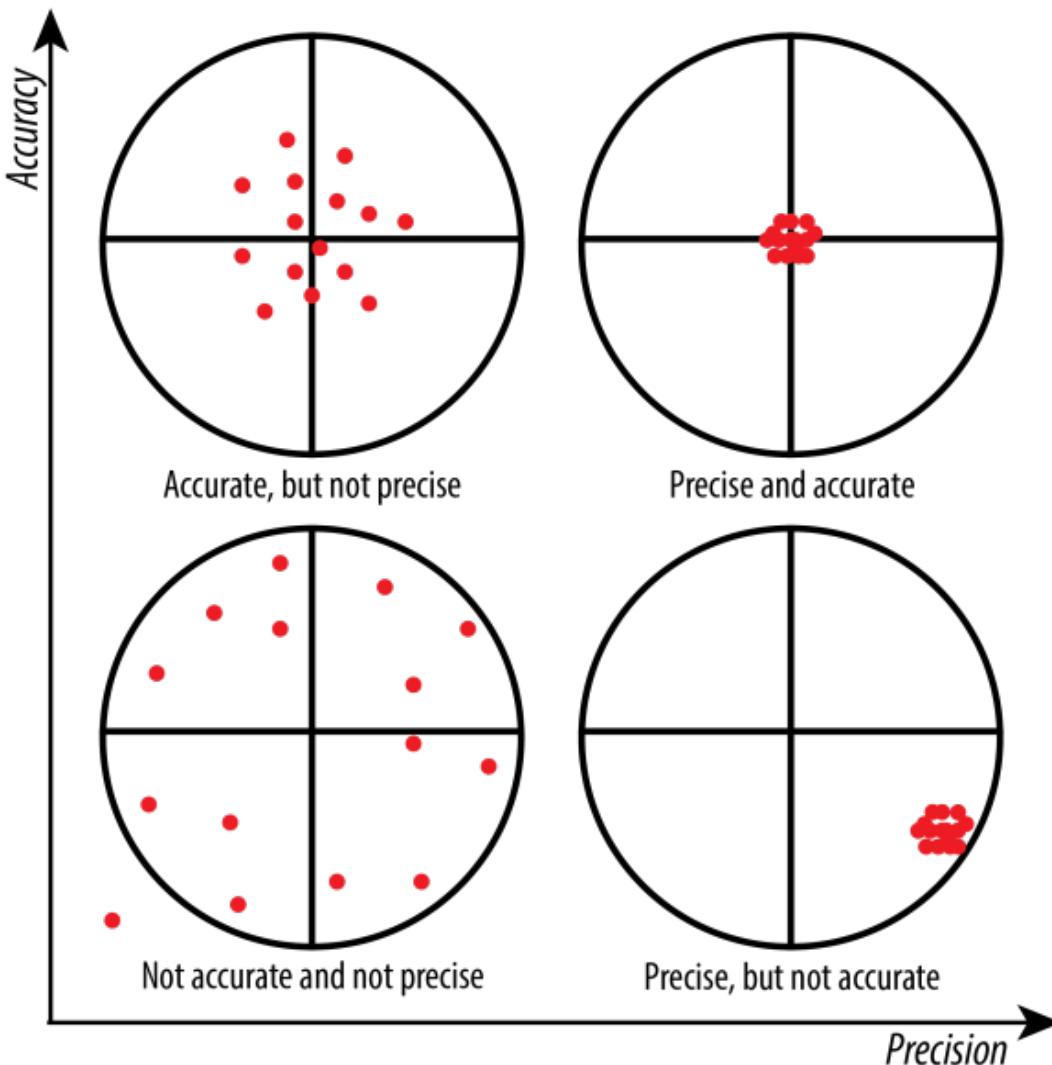
L Quiz

Is it fine to combine all the probes?



- Yes
- No

L Multi-probe Combination: Caveat

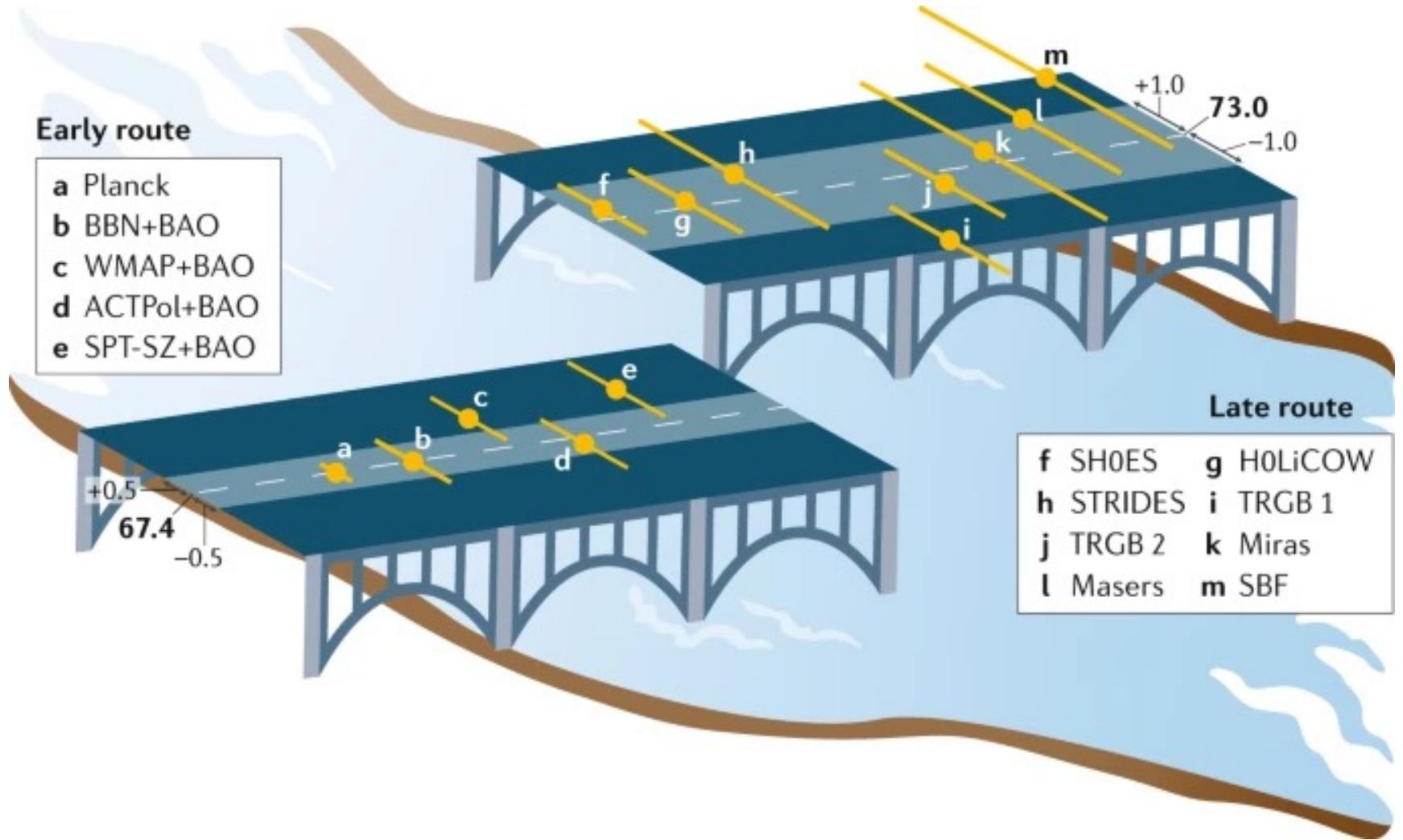


Crisis: Hubble Tension

New physics?

or

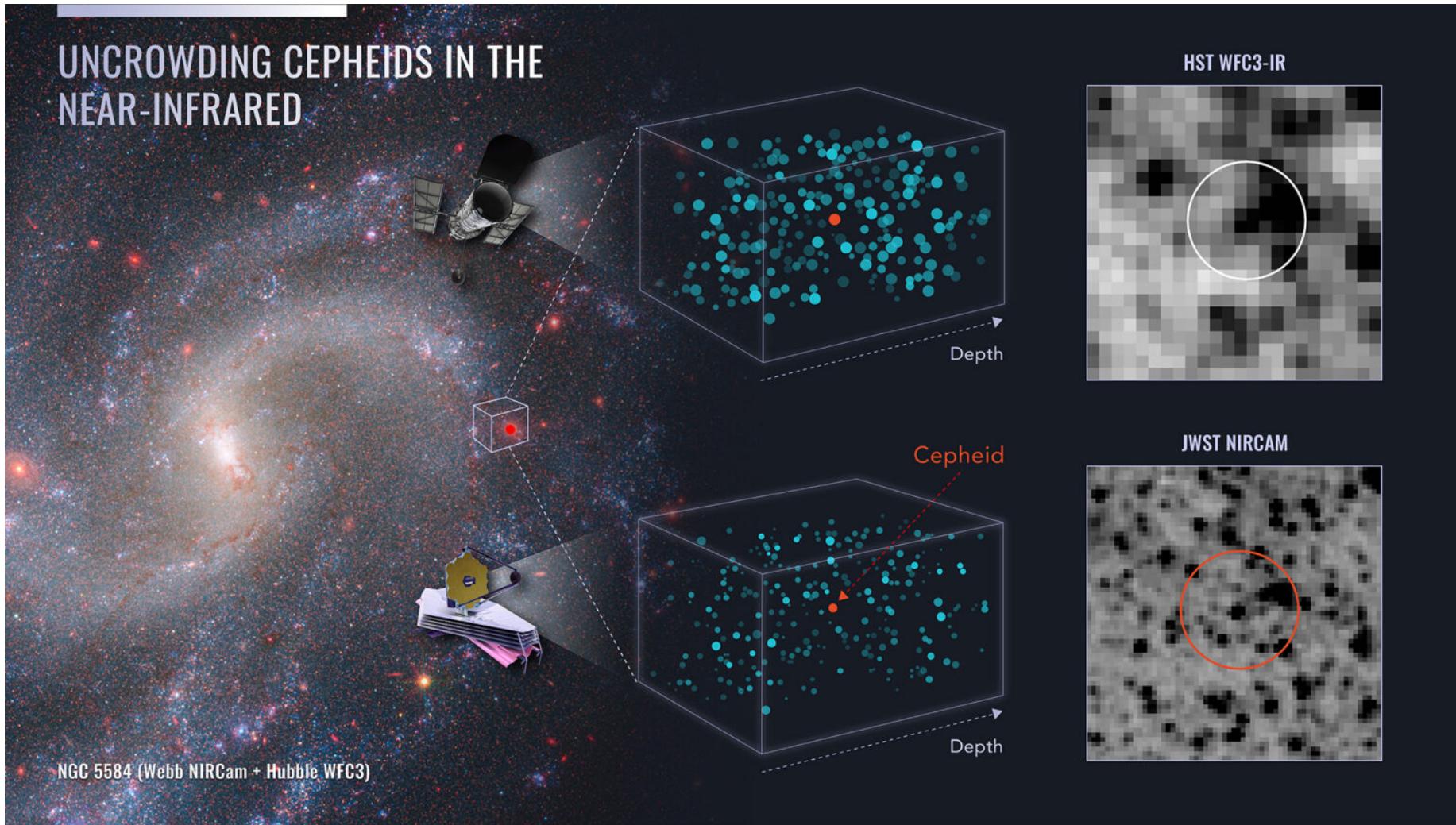
Unknown
systematics?



L Outline

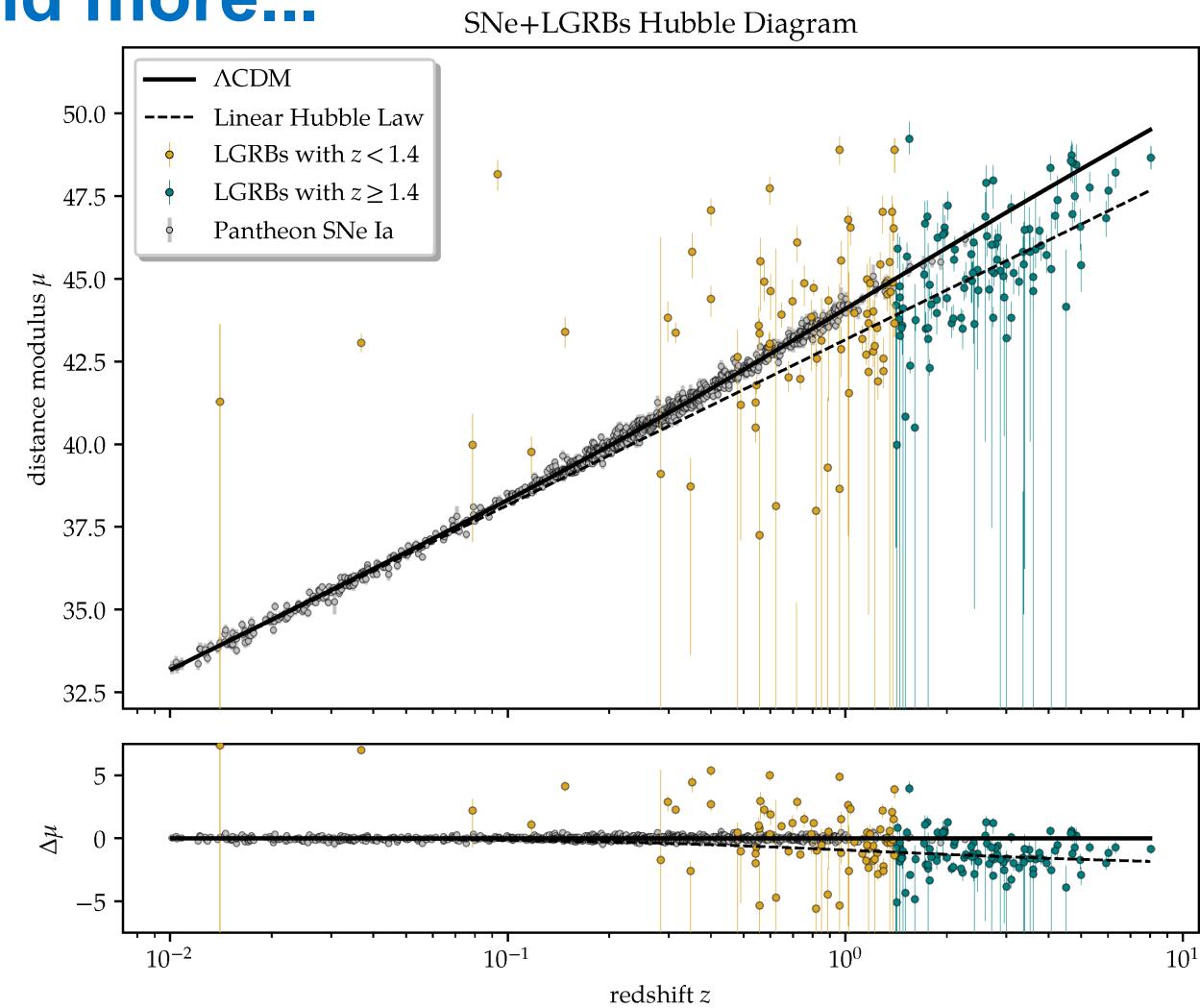
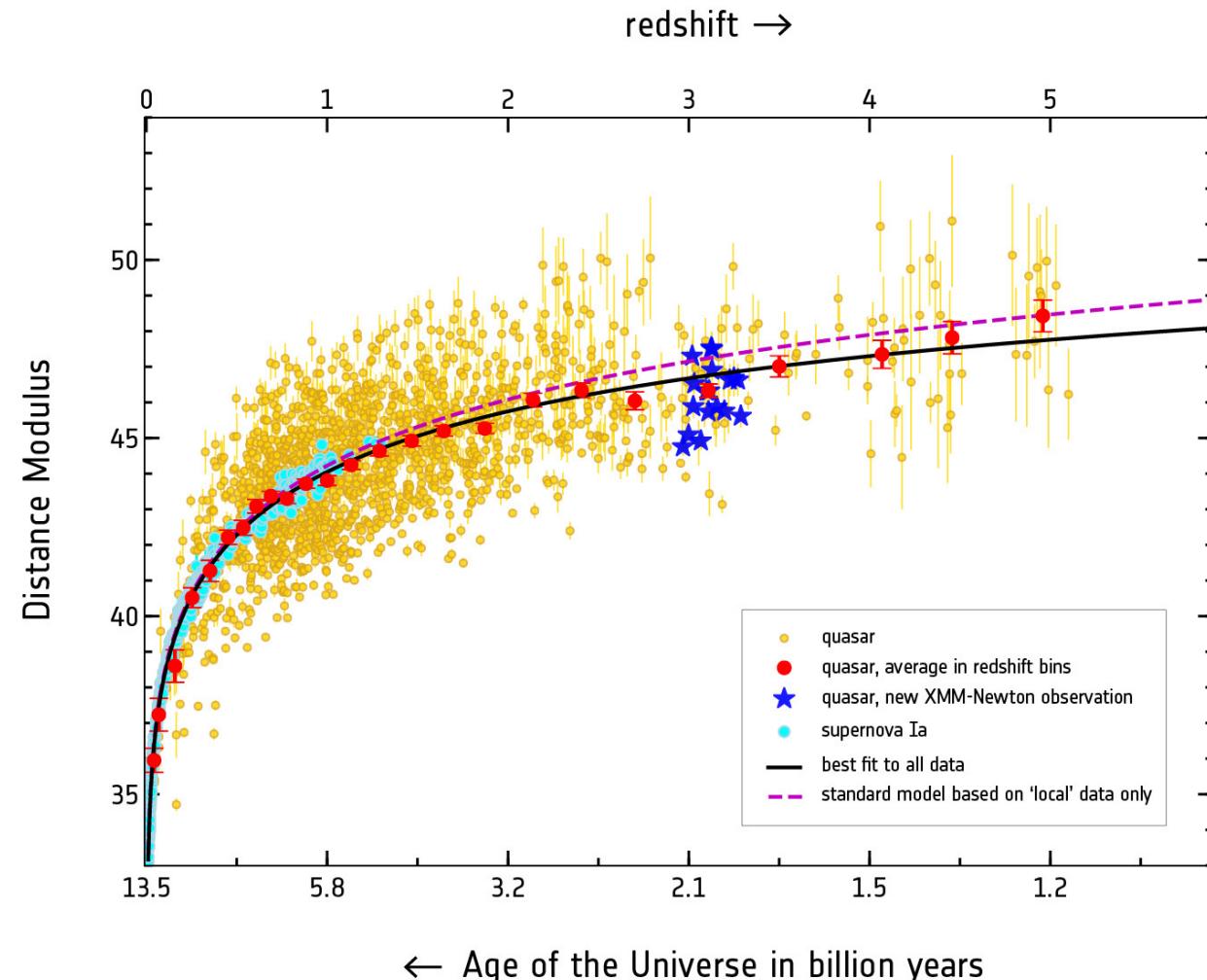
- Introduction to observational cosmology: a historical review
- Cosmological probes
 - Distance ladder
 - Type Ia supernova
 - Cosmic microwave background
 - Galaxy clustering
 - Gravitational lensing
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- Future prospective

Future Prospective: Distance Ladder

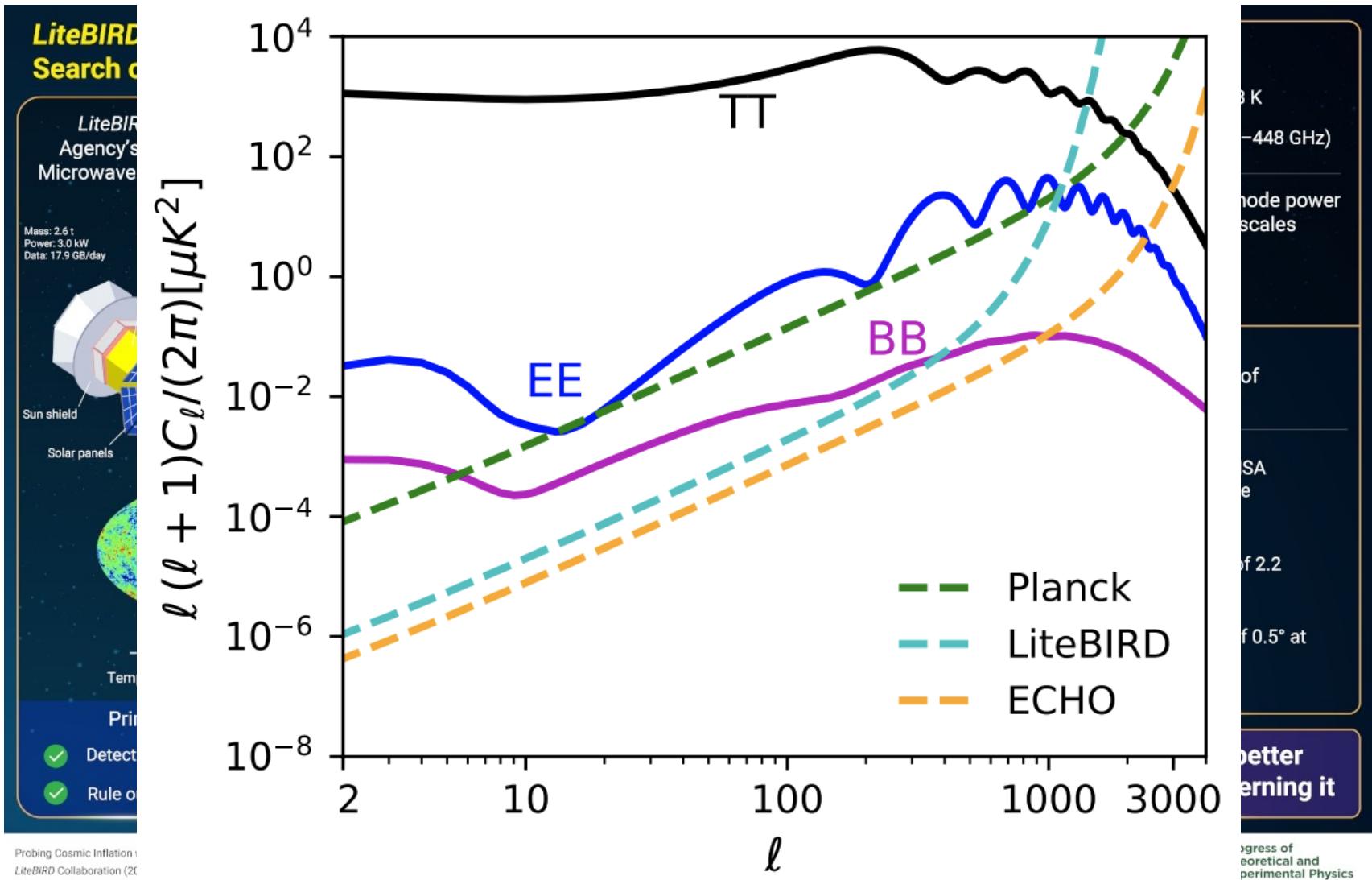


Future Prospective: Standardisable candles

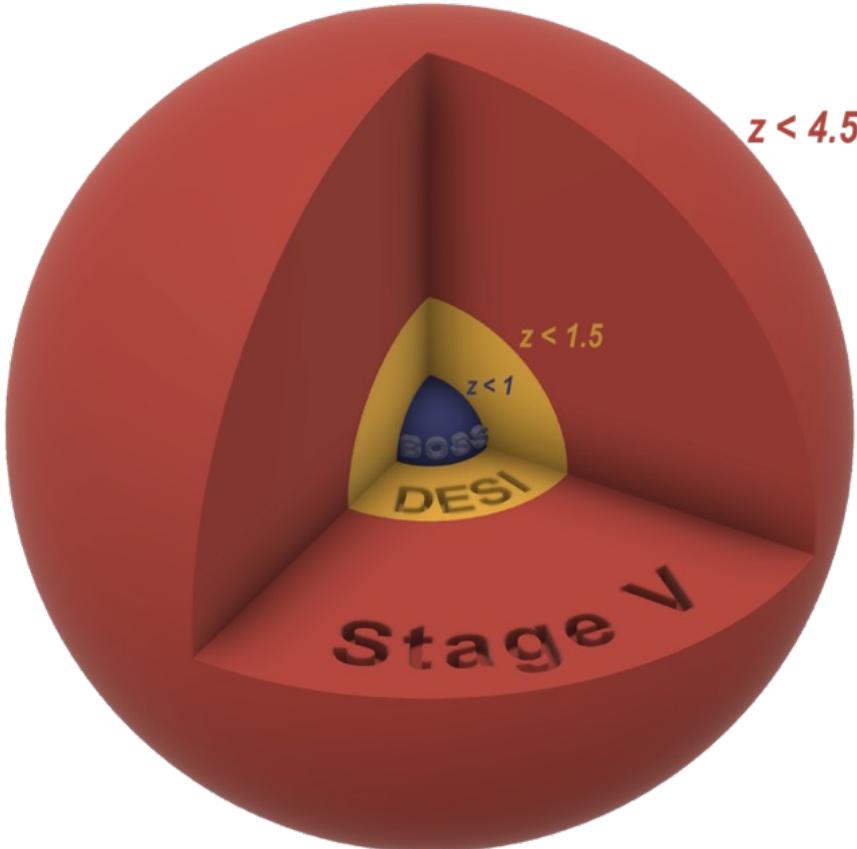
SNIa, quasar, GRB, and more...



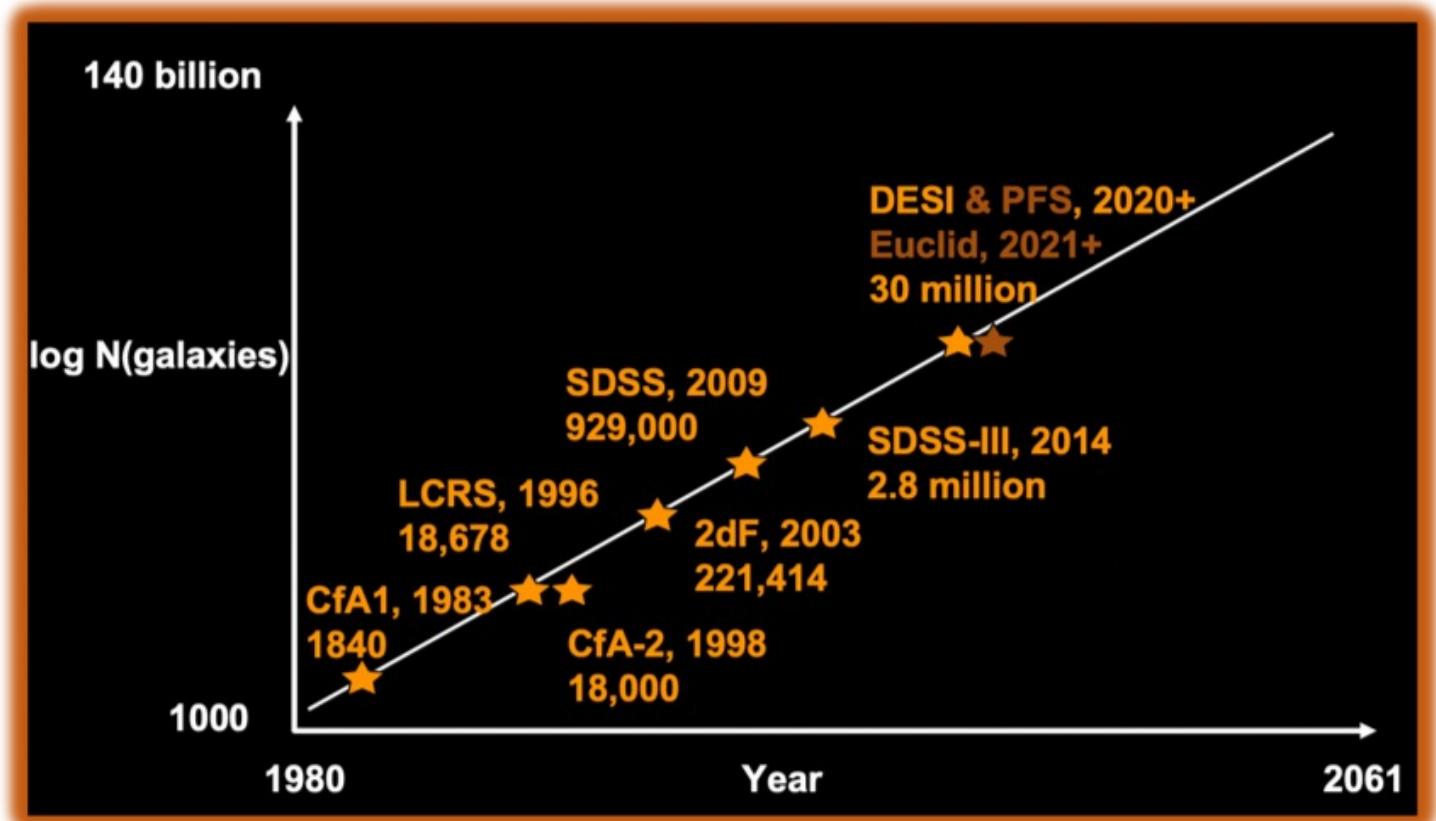
Future Prospective: CMB



Future Prospective: Galaxy Clustering



Larger volume



More tracers

Galaxy Clustering: Future Survey – MUST

<https://must.astro.tsinghua.edu.cn/>

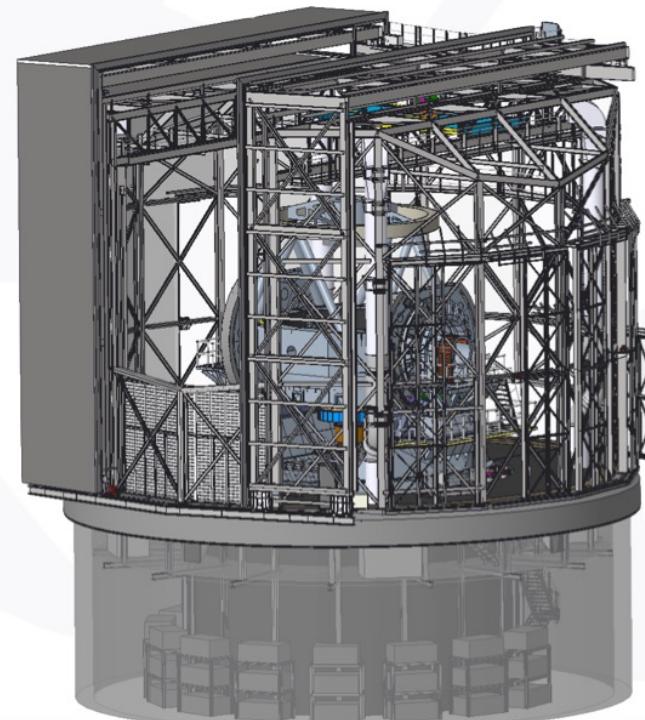
- MUST aims to carry out the world's **First Stage-V** spectroscopic survey for Cosmology and create the **Largest 3-D Map of the Universe**.
- MUST will constrain cosmological models with unprecedented precision and strive for breakthroughs in **Fundamental Physical Problems**, such as the primordial condition of the Universe, the origin and evolution of Dark Energy, and the nature of Dark Matter.

6.5m Primary

2.4m Secondary

1.6m Lens for WFC

7deg² FoV



20,000 Fiber Positioners

MODULAR Focal Plane

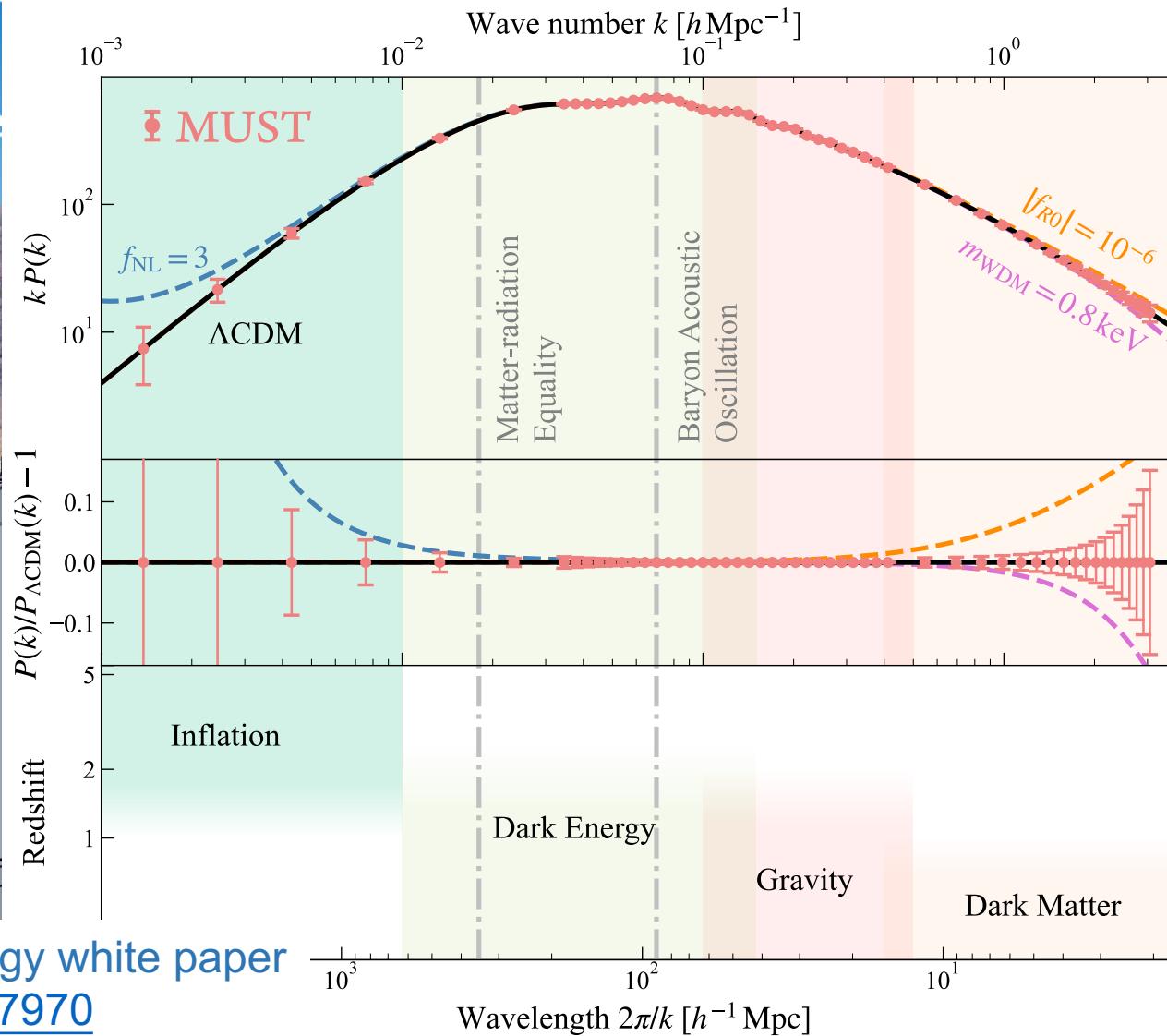
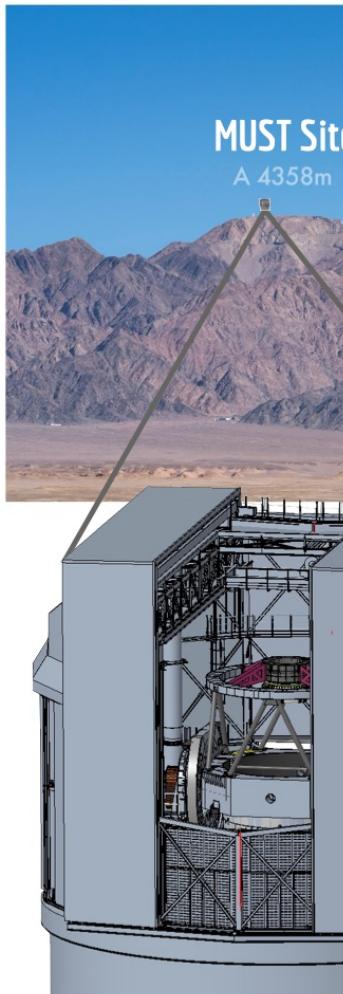
40 Spectrographs

0.37-0.98 micron

R~2000-4000

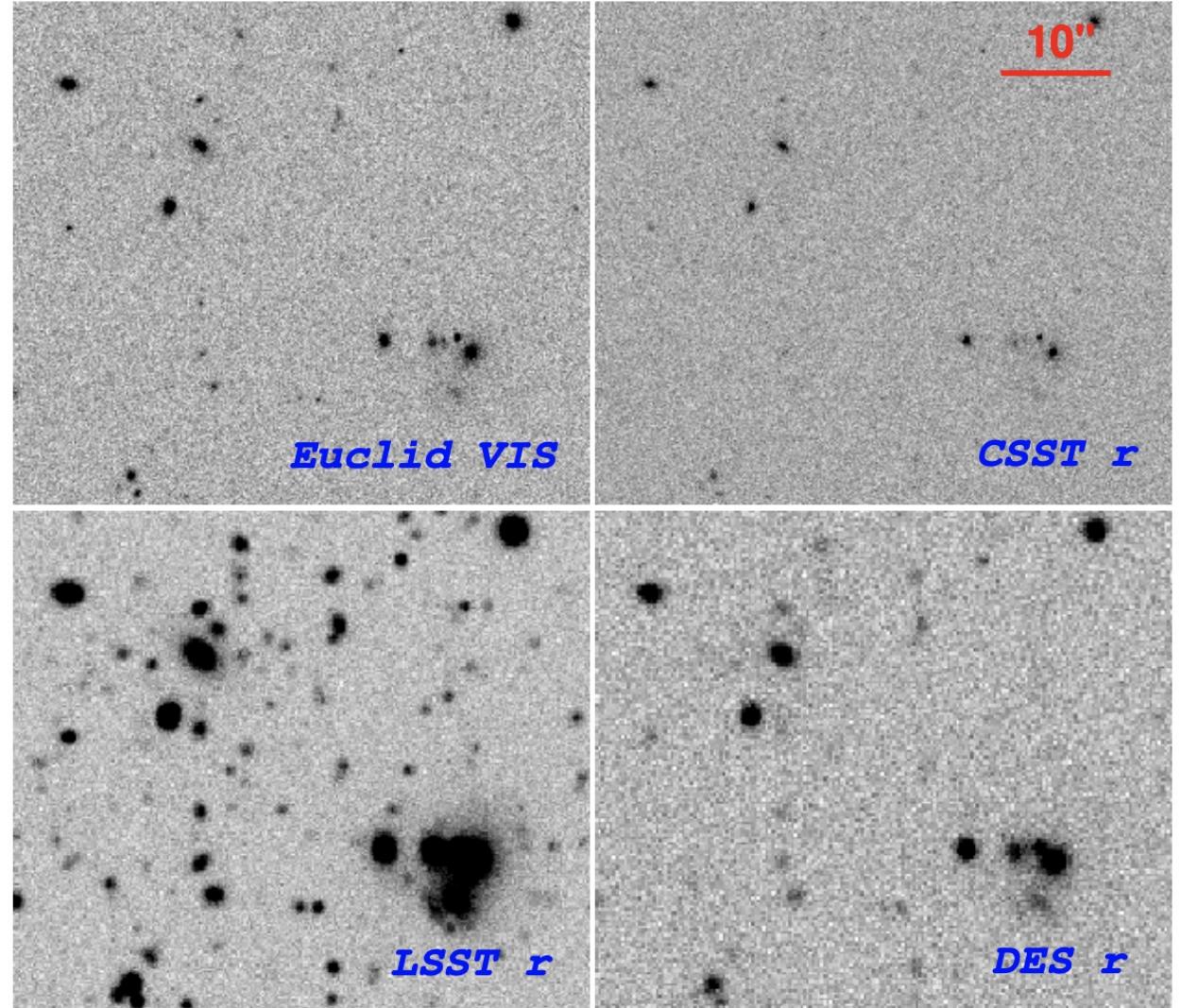
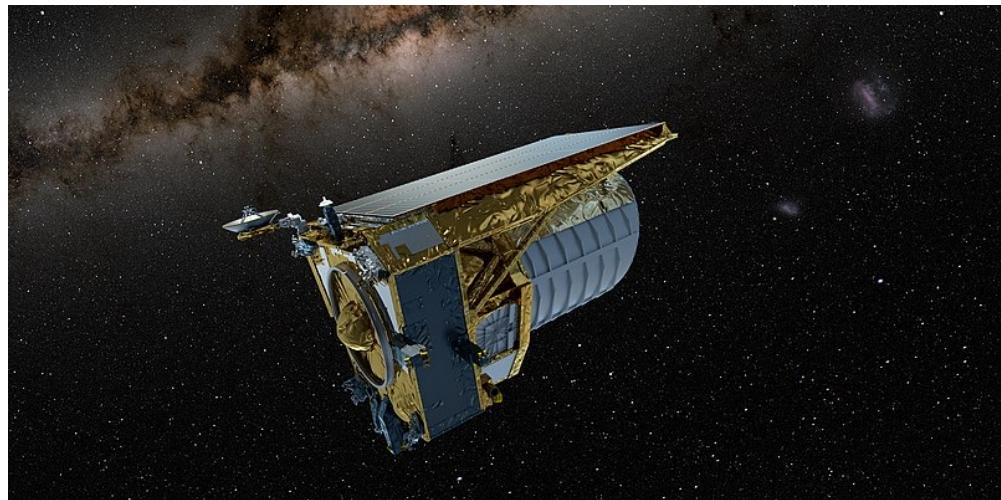
Credit: MUST Team

Galaxy Clustering: Future Survey – MUST



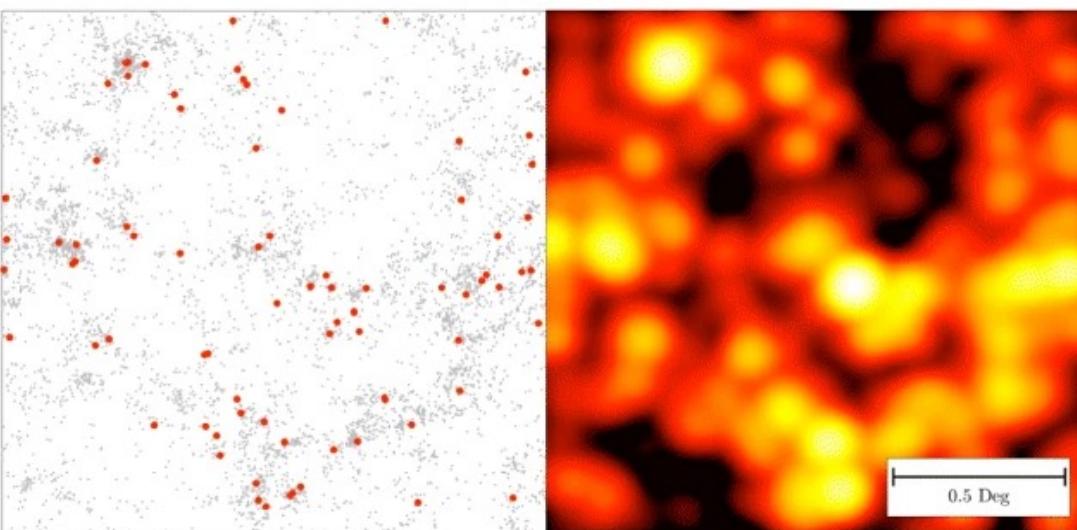
L

Future Prospective: Weak Lensing



Future Prospective: Line Intensity Mapping

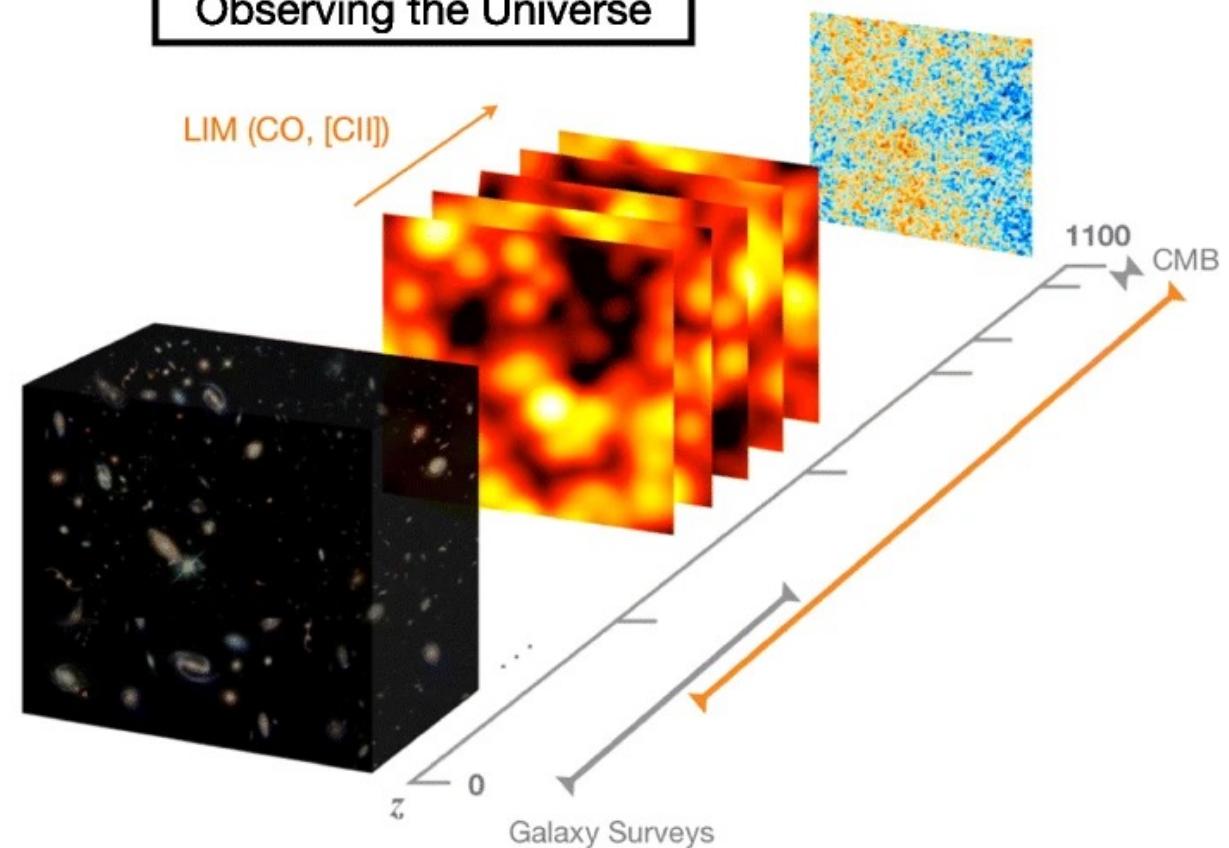
Comparison between LIM and discrete surveys



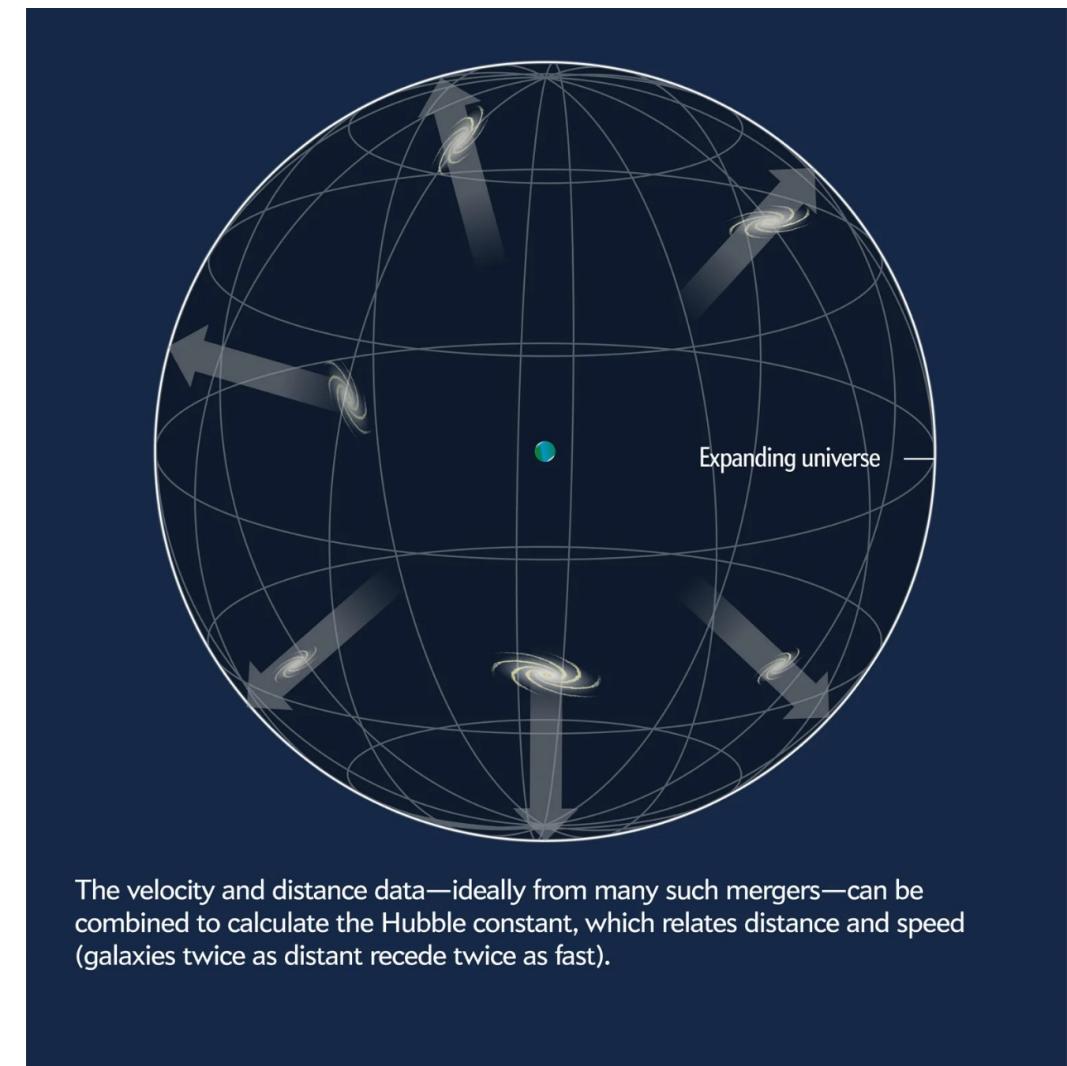
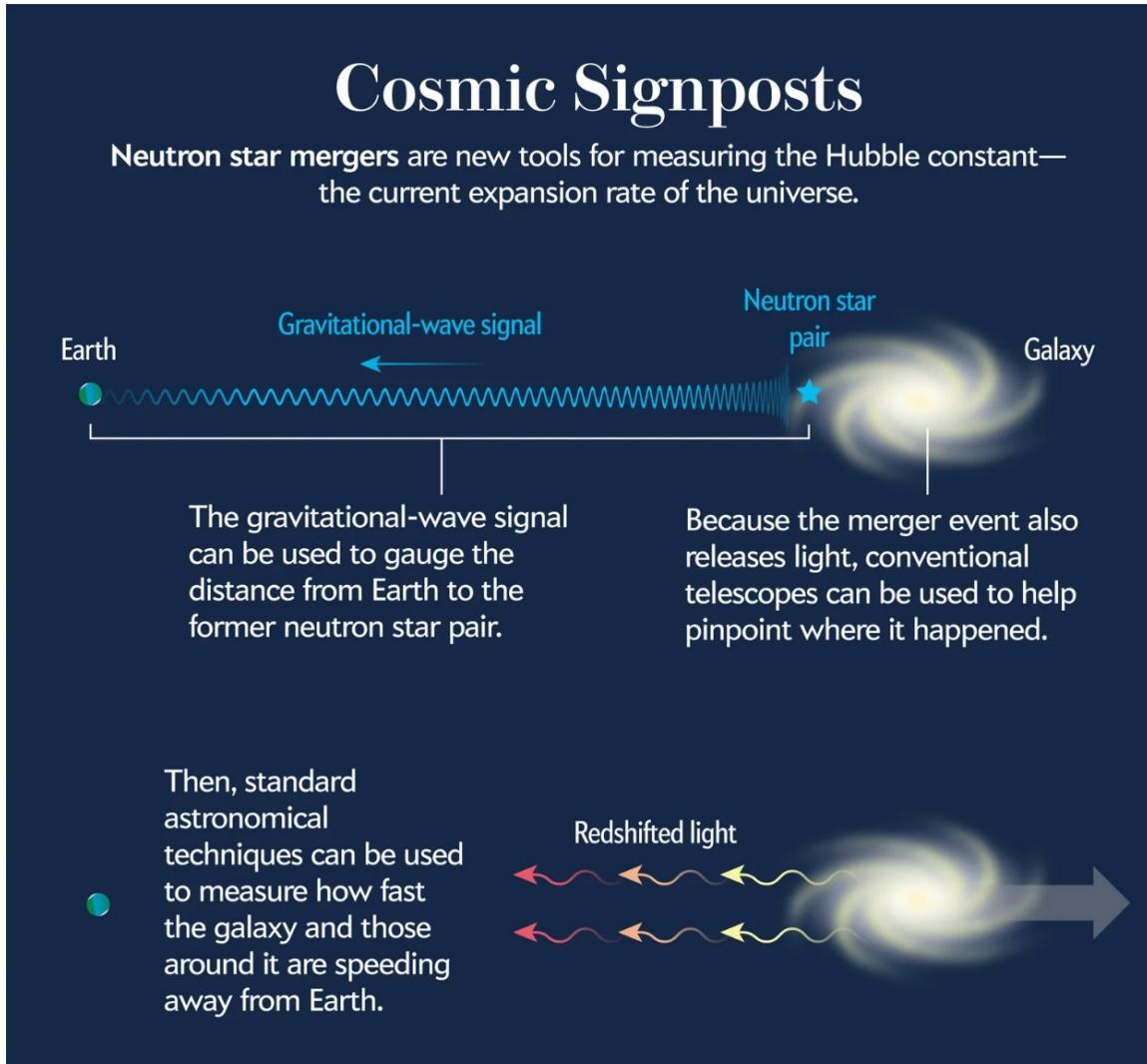
Bright galaxies

LIM (CO, [CII]...)

Observing the Universe



Future Prospective: Standard Siren



Future Prospective





Further Reading

- The Cosmological Distance Ladder:
<http://spiff.rit.edu/classes/ladder/ladder.html>
- Introduction to the first BAO detection:
<https://lweb.cfa.harvard.edu/~deisenst/acousticpeak/>
- Hubble tension:
<https://arxiv.org/abs/1907.10625>
<https://arxiv.org/abs/2105.05208>
- Snowmass Cosmic Frontier report:
<https://arxiv.org/abs/2211.09978>
- P5 report:
<https://www.usparticlephysics.org/2023-p5-report/>
- MUST cosmology:
<https://arxiv.org/abs/2411.07970>

Thank you