Cosmology in the multimessenger era: an overview

PUMA22
Sestri Levante
25/09/2022

Enzo Branchini

Charles Dickens
1812-1870

A Tale of Two Cities.

1859

Over 200 million copies

One of the best selling novels of all times.

It was the best of times,
it was the worst of times,
it was the age of wisdom,
it was the age of foolishness,
it was the epoch of belief,
it was the epoch of incredulity,
it was the season of Light,
it was the season of Darkness,
it was the spring of hope,
it was the winter of despair,

Cosmology is the scientific study of the Universe as a unified whole, from its earliest moments through its evolution to its ultimate fate. (Britannica)

Physical Cosmology deals with the observable Universe. Which is assumed to be a realization of a stationary random process. A fair sample. *One only*. To compare our models with.

Hence the importance for Cosmology to go **multi-wavelength**, **multi-probe** and now **multi-messenger**.

ΛCDM "standard" model. Observational pillars. Hubble law.

Redshifts from optical spectra

Distance indicator: Cepheids

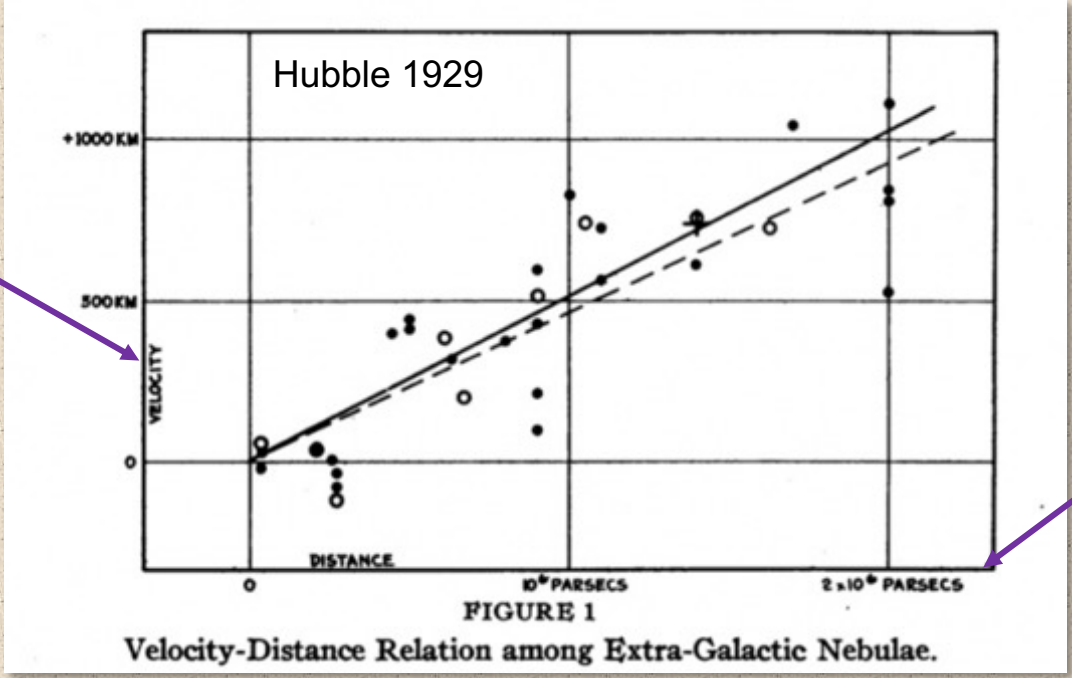
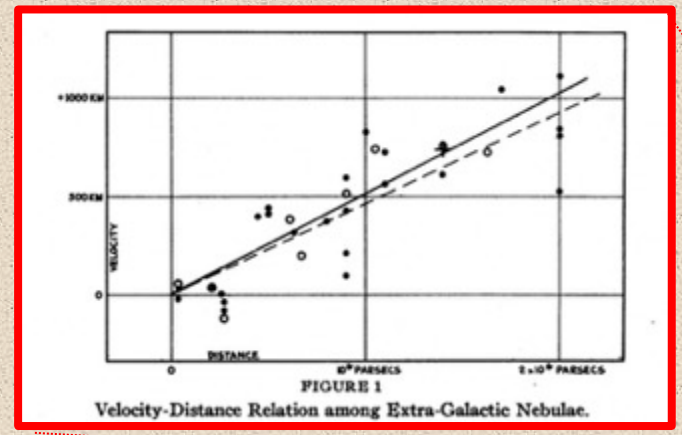


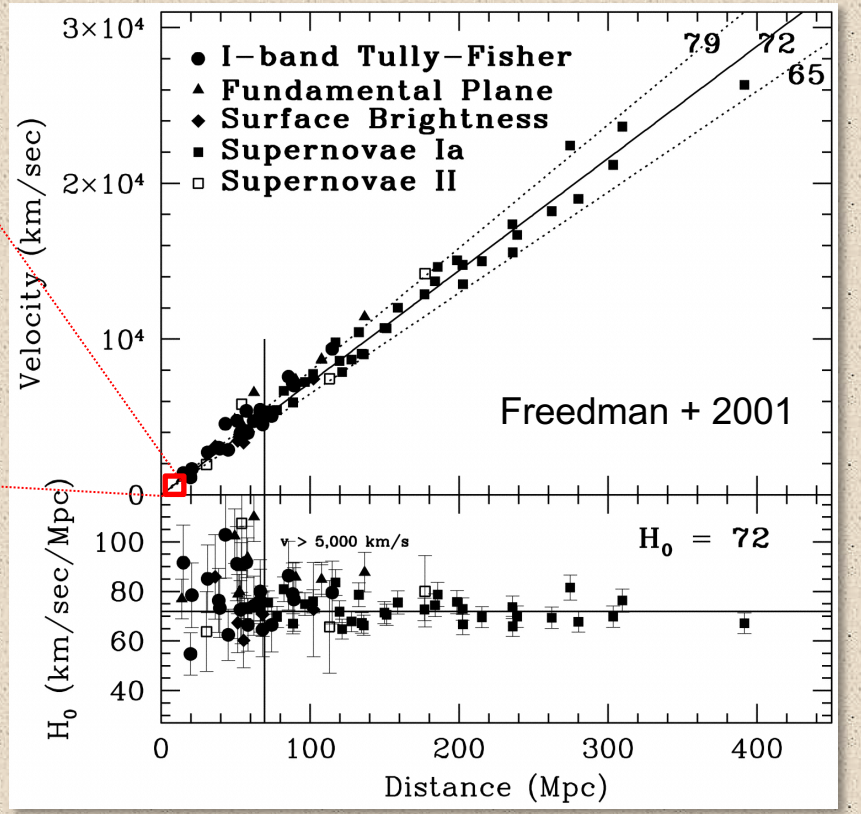
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Distances from Optical photometry

ΛCDM "standard" model.
Observational pillars. Hubble Law.

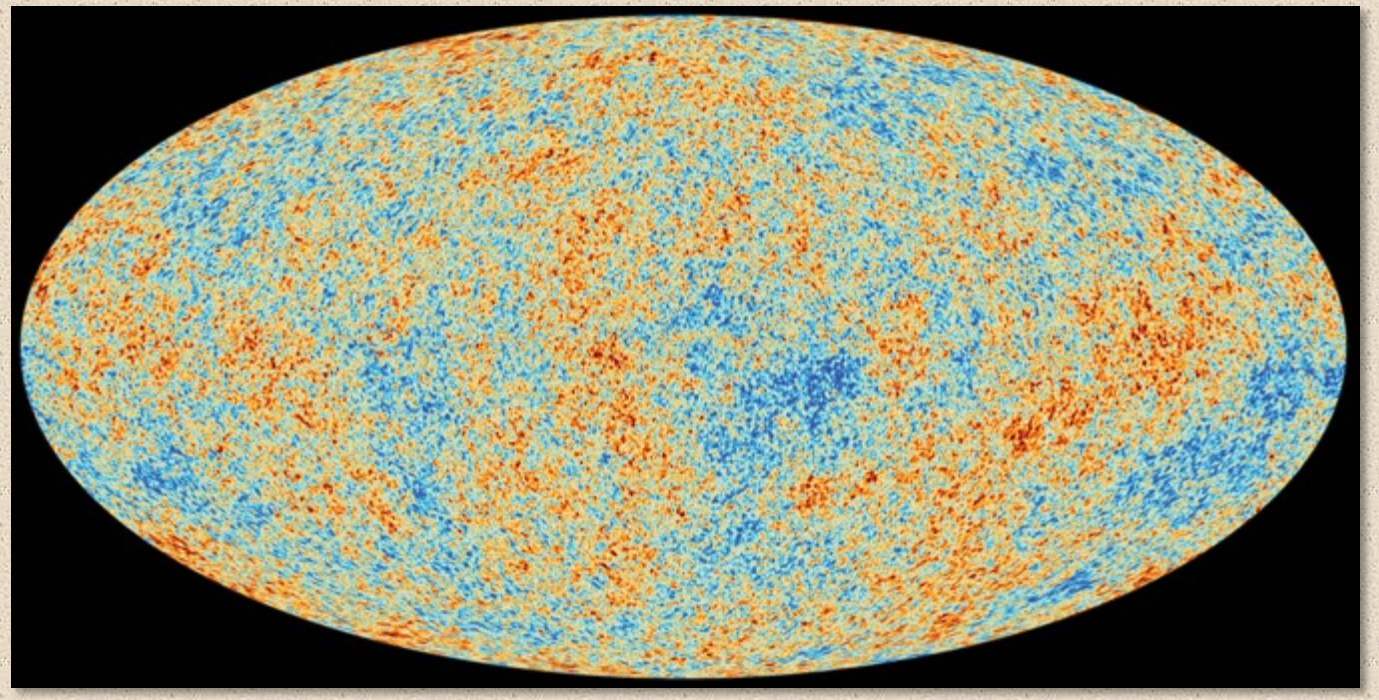




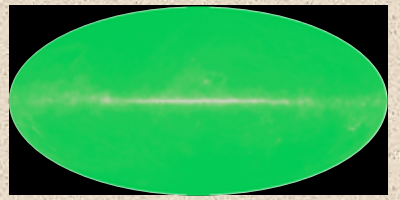
Optical + Near Infrared

Several distance indicators

ΛCDM "standard" model. Observational pillars. CMB.

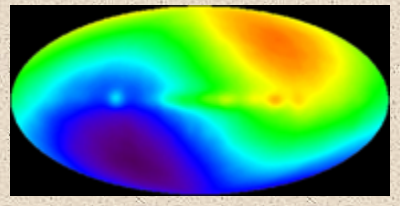


-



Monopole

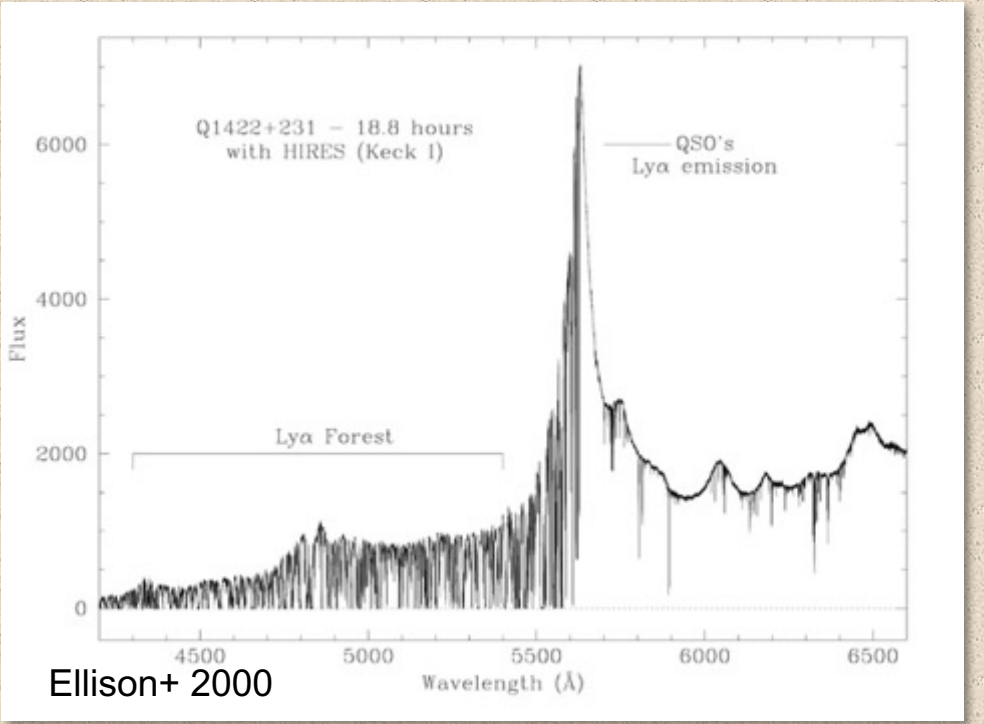
-



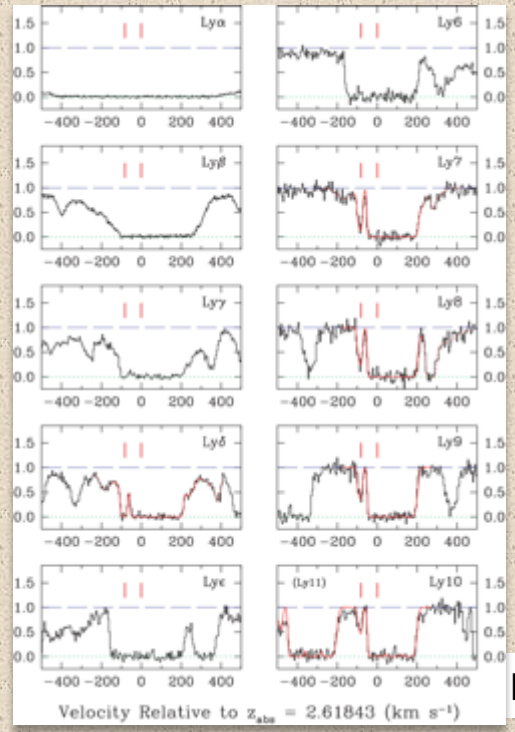
Dipole

Microwave band

ΛCDM "standard" model. Observational pillars. Nucleosynthsis.



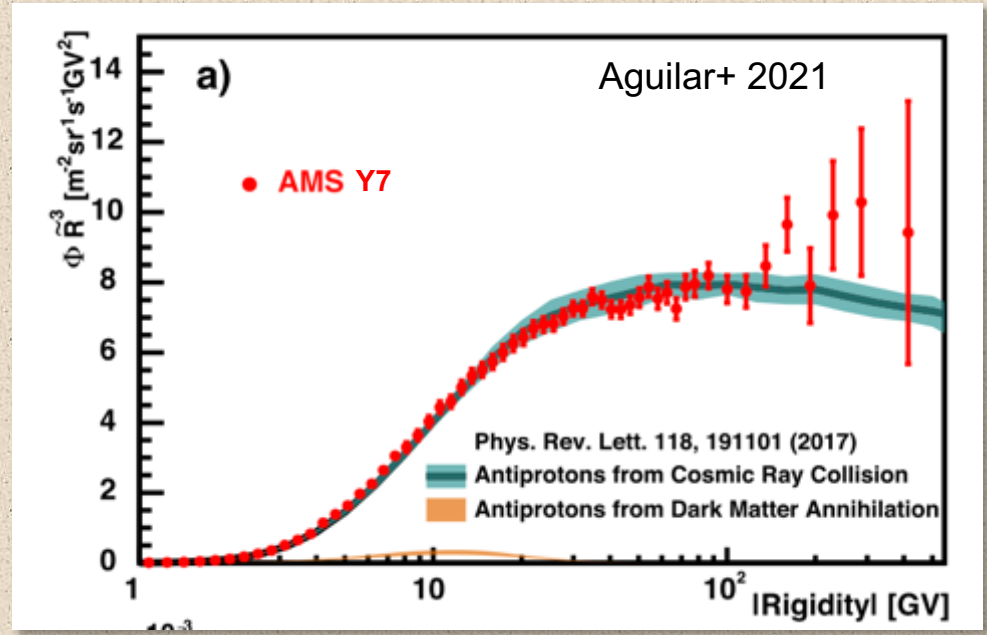
Ellison+ 2000



Pettini+ 2008

Optical and UV spectra

ΛCDM "standard" model.
Key observations. Antimatter abundance.



Charged particles

ΛCDM

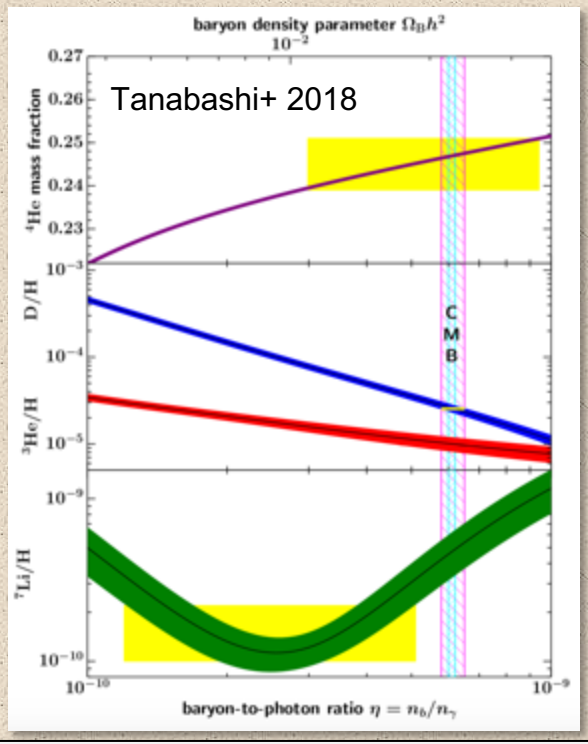
Ω_b, Ω_M, Ω_γ, Ω_Λ, A_s, n_s, H_0, τ | $\Omega_\nu \sim 0$, Inflation

ΛCDM is a simple and yet very successfull model.
It is described by a small number of free parameters.
Is it correct ? Is it satisfactory ?

«…..the empirical case that the ΛCDM theory is a good approximation to reality remains compelling. But....we have empirical evidence that there is a still better theory to be found.»

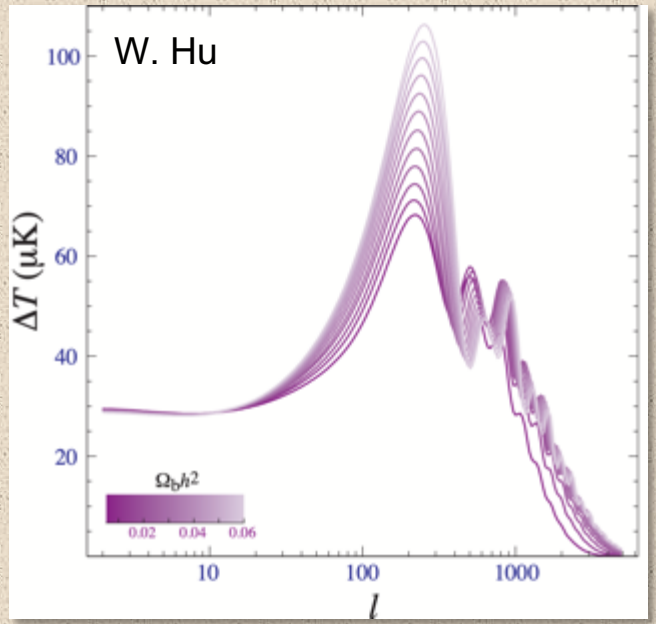
J. Peebles 2022

ΛCDM predictions consistently agrees with a wide range diverse observations. Ex 1. baryon density.

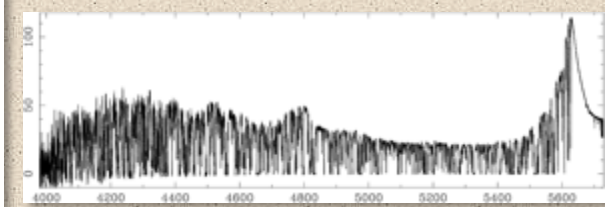


Light elements abundance z~10^9

$\Omega_b h^2 = 0.02237 \pm 0.00015$

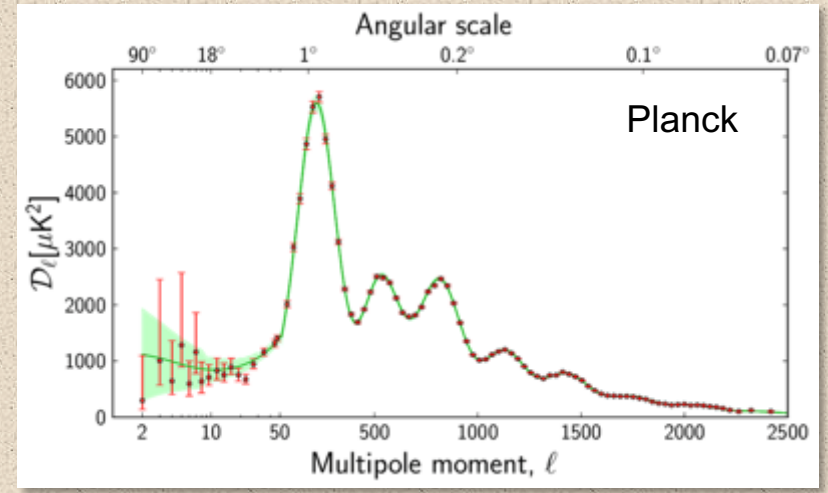


CMB angular spectrum z~10^3

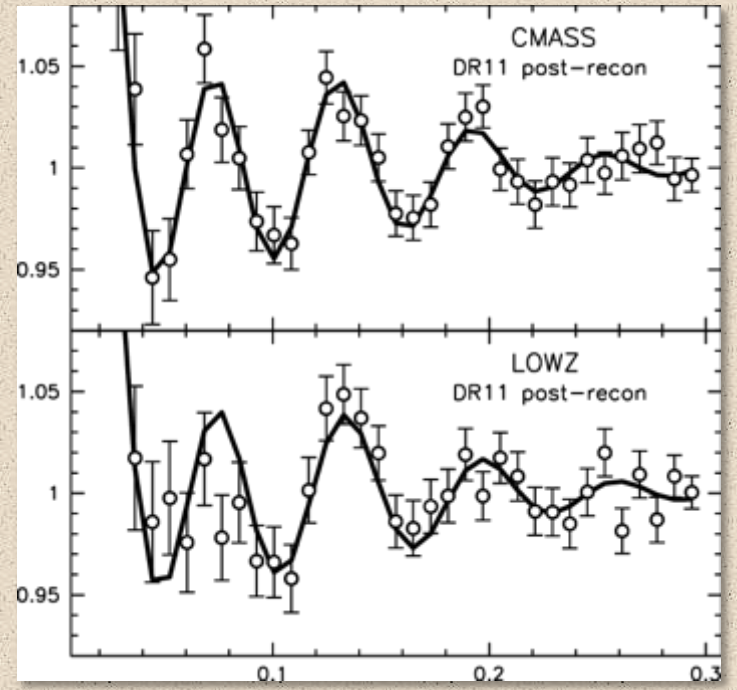


Lyman-α forest z~1

ΛCDM predictions consistently agrees with a wide range diverse observations. Ex 2. BAOs



In the plasma @ z O(1000)



In the spatial distribution of galaxies @ z O(1)

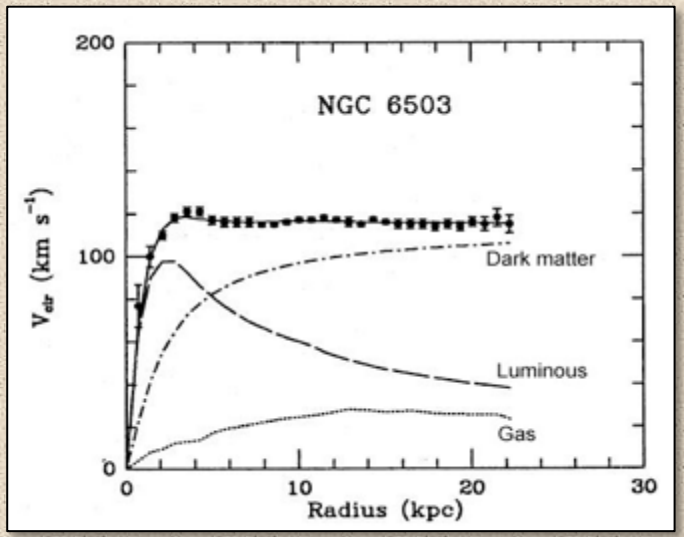
ΛCDM

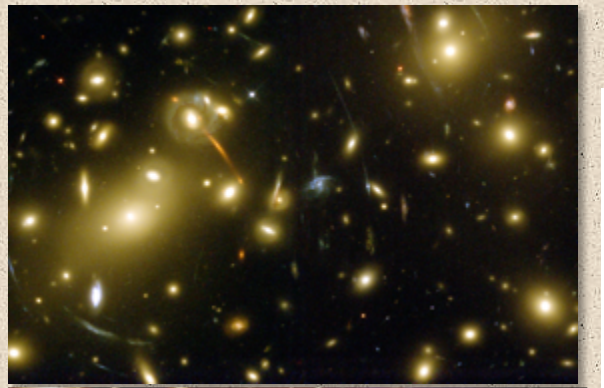
…provides a good description to a large number of independent observations over a broad range of spatial and temporal scales.

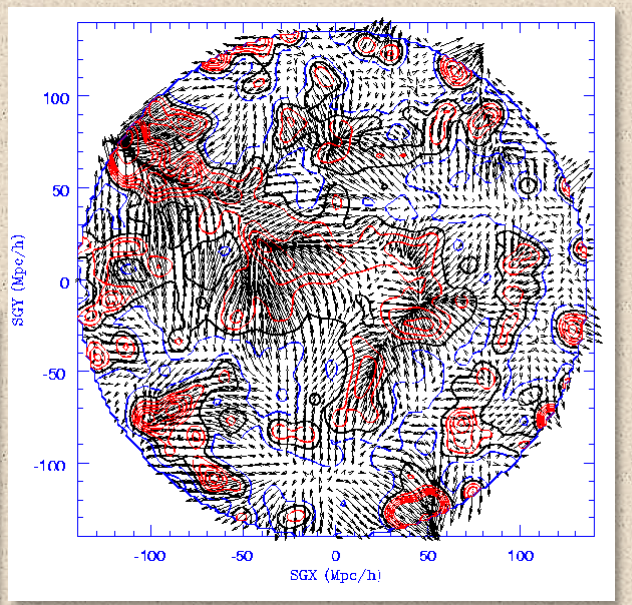
Λ + CDM

….but it relies on two fundamental ingredients of which we have convincing phenomenological evidence but little physical understanding.

ΛCDM







+ clustering evolution…

ΛCDM

Compelling evidence from dynamical anomalies on a broad range of scales.

Some phenomenological constraints (~collisionless, massive, ~stable, cold).

No detections from either direct or indirect searches so far.

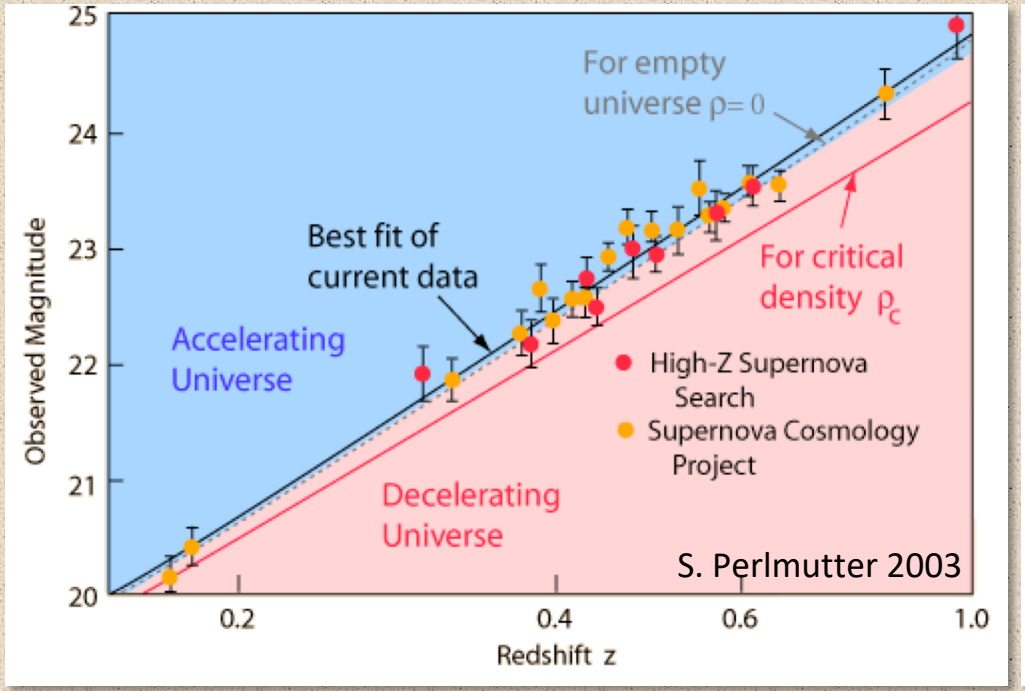
No unique theoretical prediction.

Are we capturing the complexity of the dark sector ?

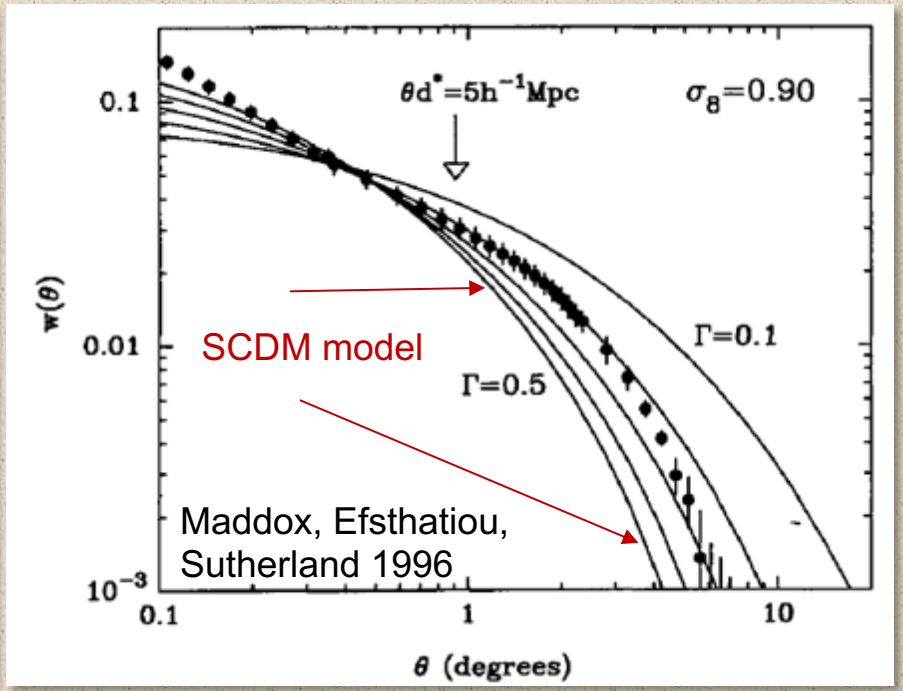
Open issue of fundamental importance

ΛCDM

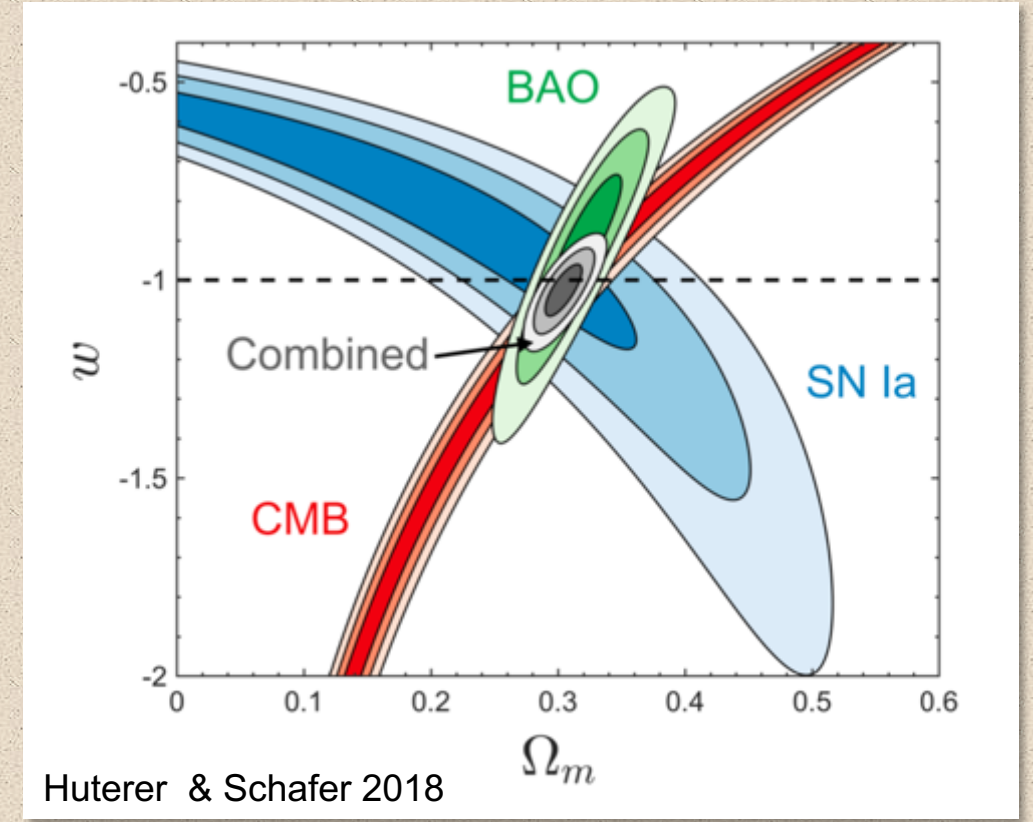
SN1a - distances



Galaxies - clustering



ΛCDM



Huterer & Schafer 2018

ΛCDM

Compelling evidence from different probes.

Some observational constraints.

Broad range of theoretical predictions, from Dark Energy to Modified Gravity models.

2 separate issues: the nature of the accelerated expansion and cosmological relevance of the zero-point vacuum fluctuations.

Open issue of fundamental importance

ΛCDM

ΛCDM theory is probably a good
but unsatisfactory approximation to reality.

How good this approximation is ?

Anomalies, tensions, inconsistencies, if genuine,
can show the way to a better model.

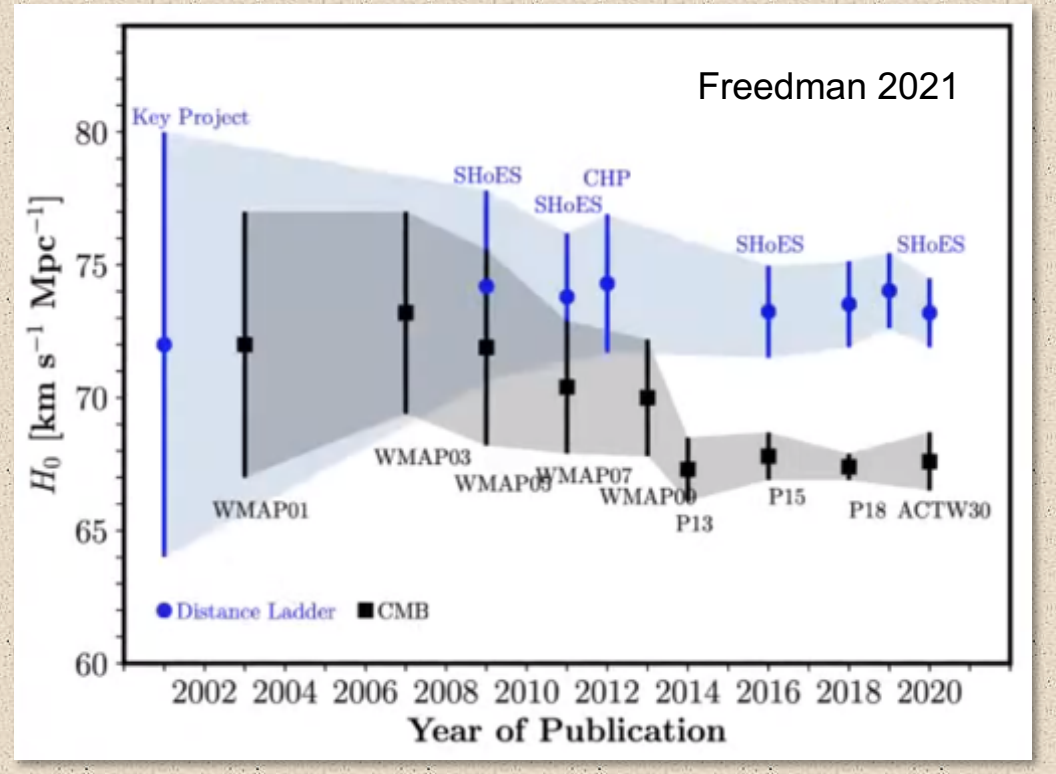
The many ΛCDM crises, tensions and anomalies.

- H_0 tension.
- σ_8 tension.
- CMB anomalies.
- Cosmological dipoles and bulk flows.
- Missing baryons.
- Too big to fail / substructures abundance.
- Core-cusp problem.
- Supermassive black holes.
- Lithium abundance.
- ……..

The many ΛCDM crises, tensions and anomalies.

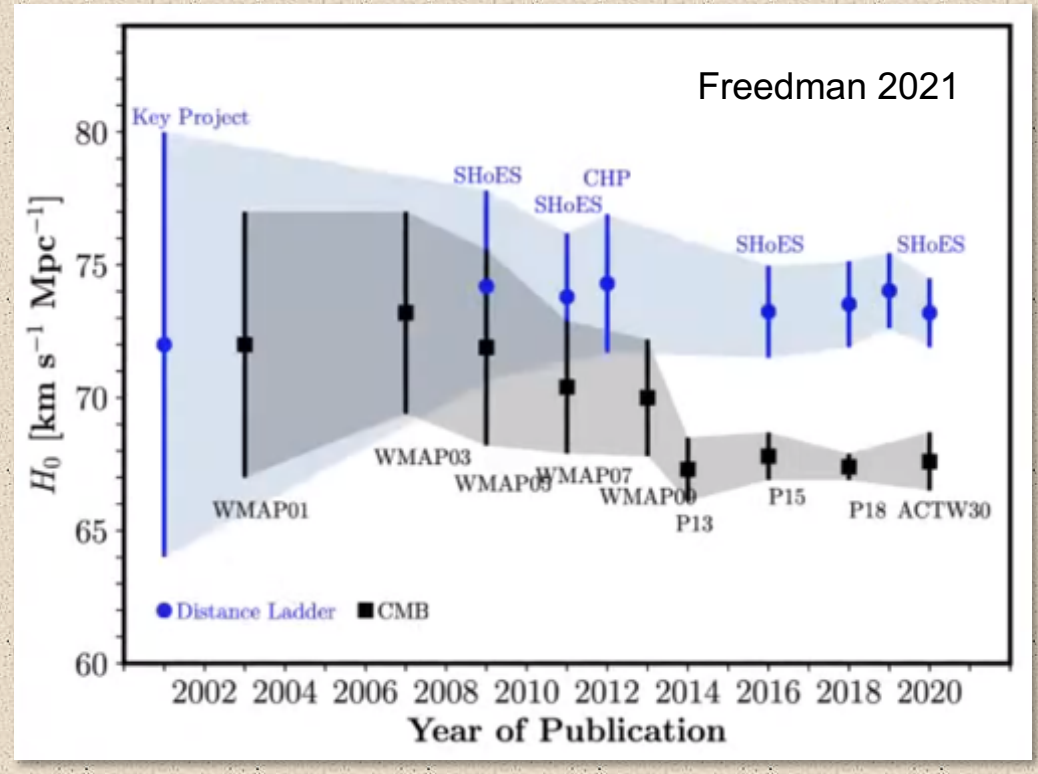
- **H_0 tension.**
- σ_8 tension.
- CMB anomalies.
- Cosmological dipoles and bulk flows.
- Missing baryons.
- Too big to fail / substructures abundance.
- Core-cusp problem.
- Supermassive black holes.
- Lithium abundance.
- ……..

ΛCDM crises, tensions and anomalies.



H_0 tension.

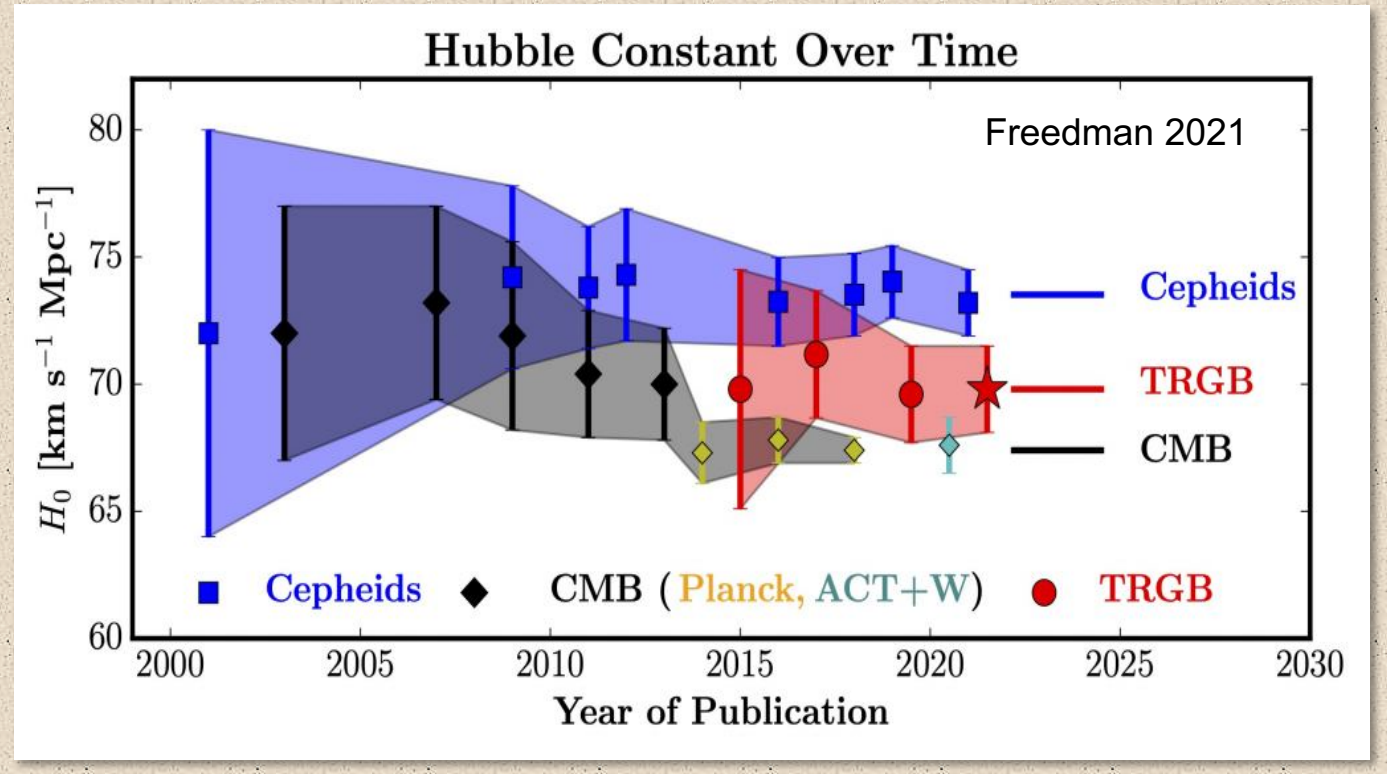
ΛCDM crises, tensions and anomalies.



H_0 tension.

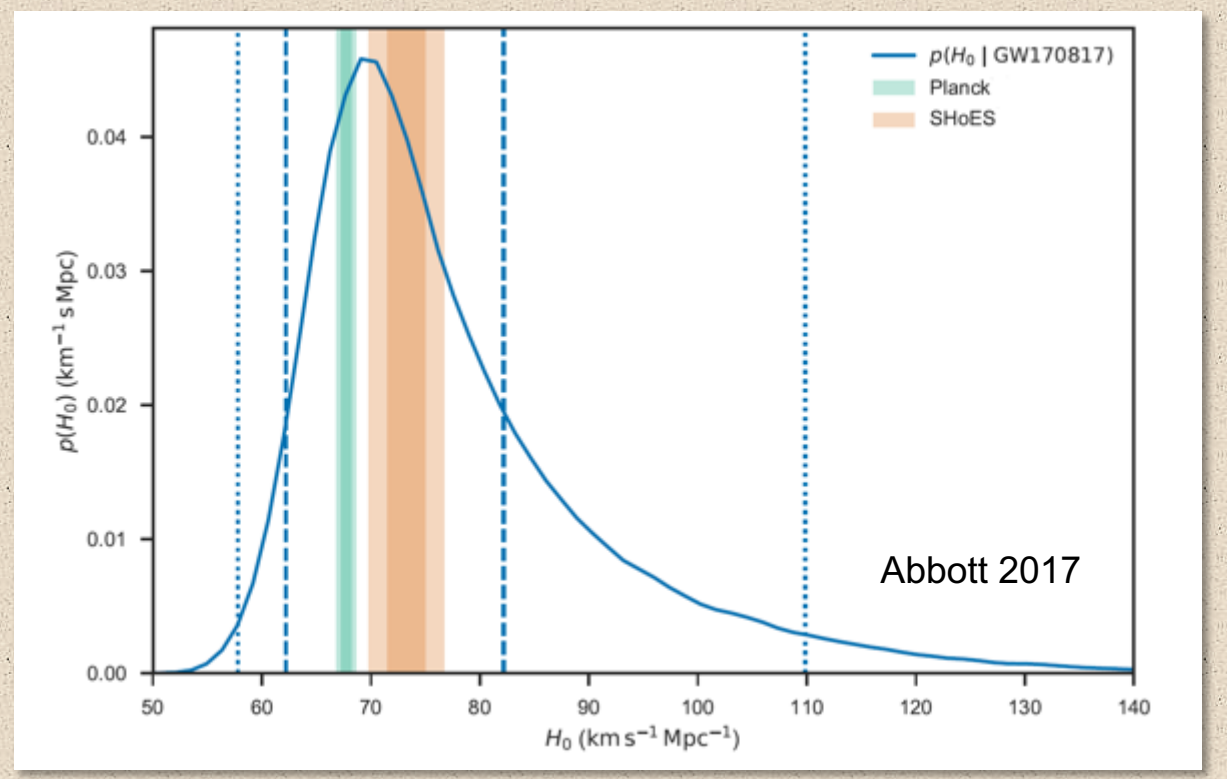
This is a 10% discrepancy over a factor 1000 in the cosmic expansion !!!!!

ΛCDM crises, tensions and anomalies.



H_0 tension.

ΛCDM crises, tensions and anomalies.

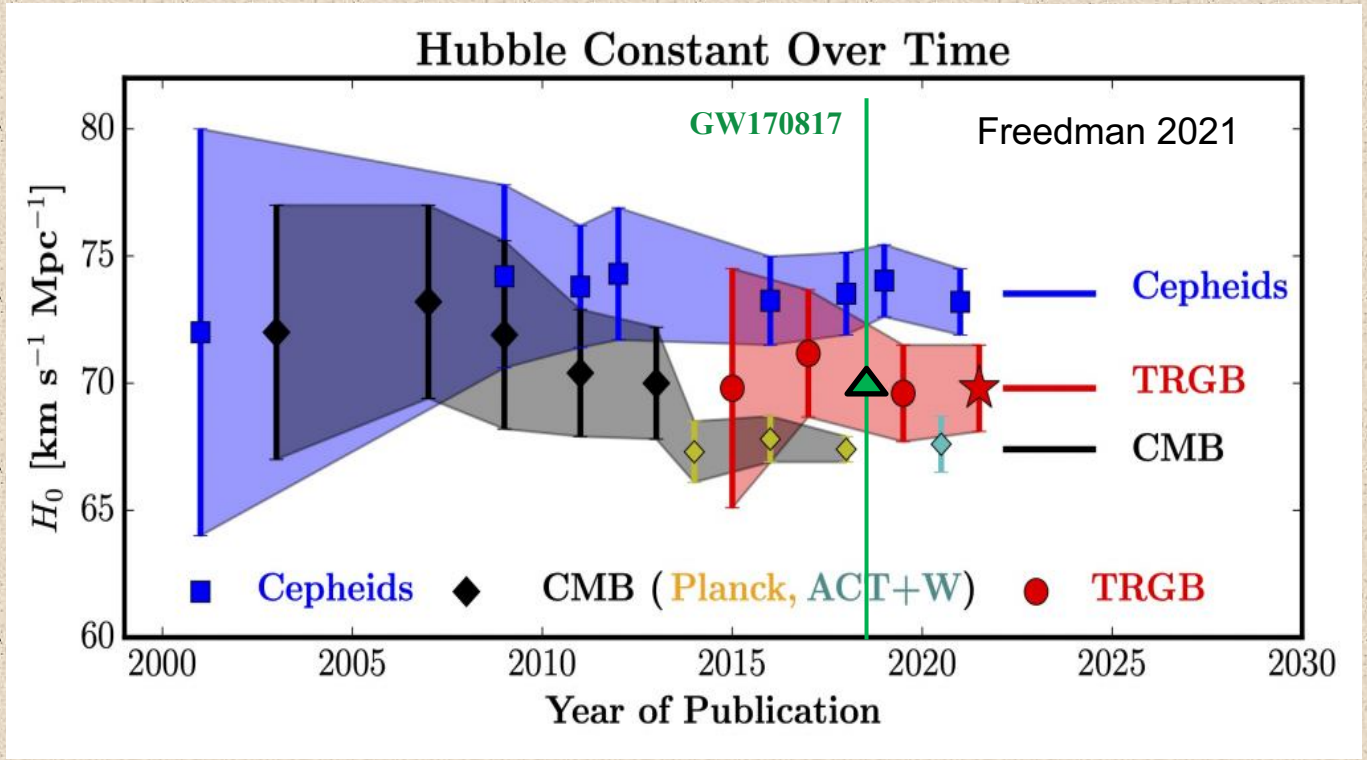


H_0 tension.

GW from bright and dark sirens

ΛCDM crises, tensions and anomalies.

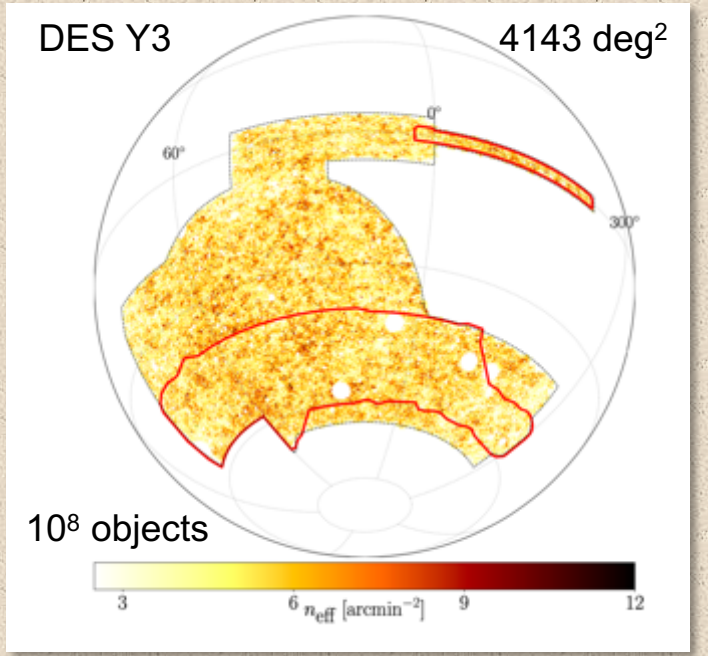
H_0 tension.

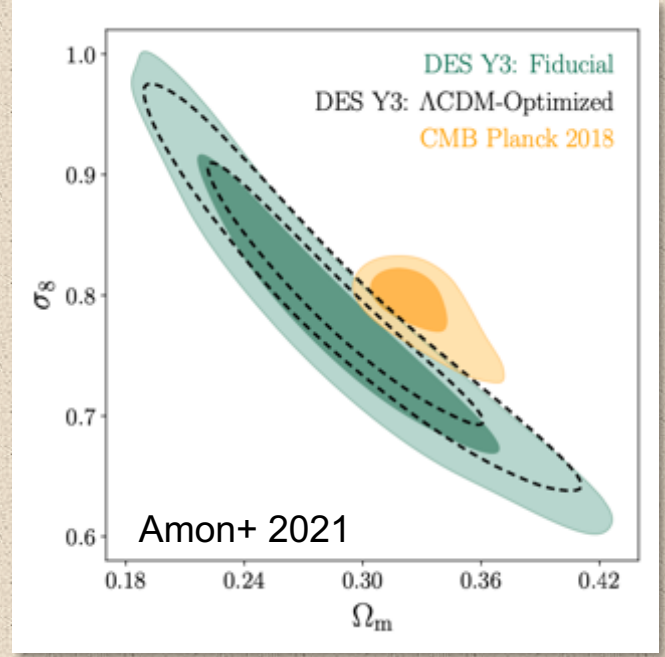


The many ΛCDM crises, tensions and anomalies.

- H_0 tension.
- **σ_8 tension.**
- CMB anomalies.
- Cosmological dipoles and bulk flows.
- Missing baryons.
- Too big to fail / substructures abundance.
- Core-cusp problem.
- Supermassive black holes.
- Lithium abundance.
- ……..

ΛCDM crises, tensions and anomalies.





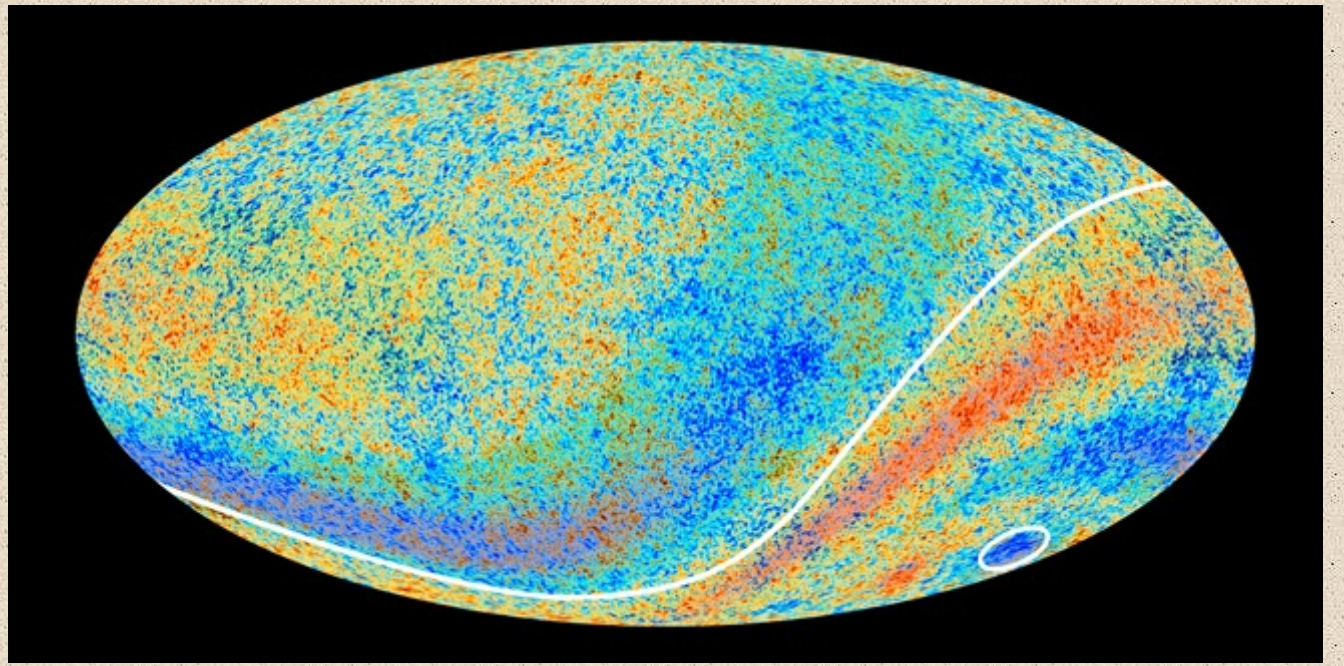
σ_8 tension.

Same tension found from weak lensing analyses of independent datasets i.e. KiDS.

The many ΛCDM crises, tensions and anomalies.

- H_0 tension.
- σ_8 tension.
- **CMB anomalies.**
- Cosmological dipoles and bulk flows.
- Missing baryons.
- Too big to fail / substructures abundance.
- Core-cusp problem.
- Supermassive black holes.
- Lithium abundance.
- ……..

ΛCDM crises, tensions and anomalies.



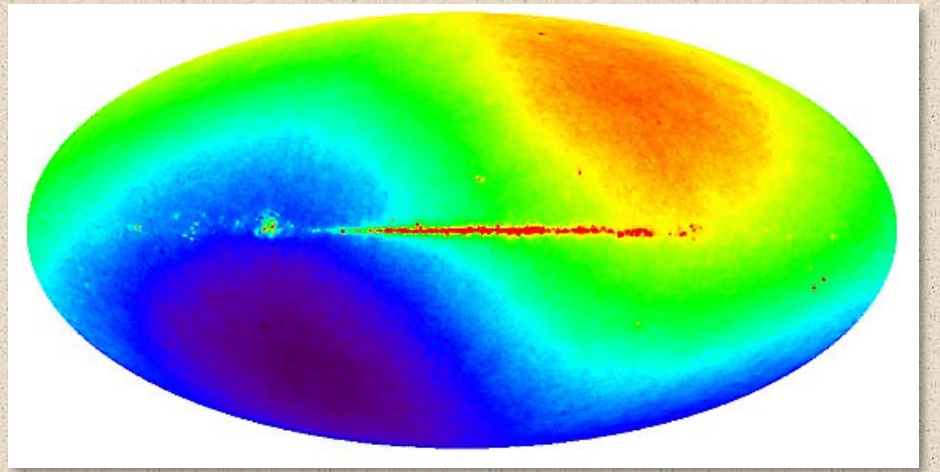
CDM anomalies
Cold spot.
Hemispheric asymmetry.
Low quadrupole.

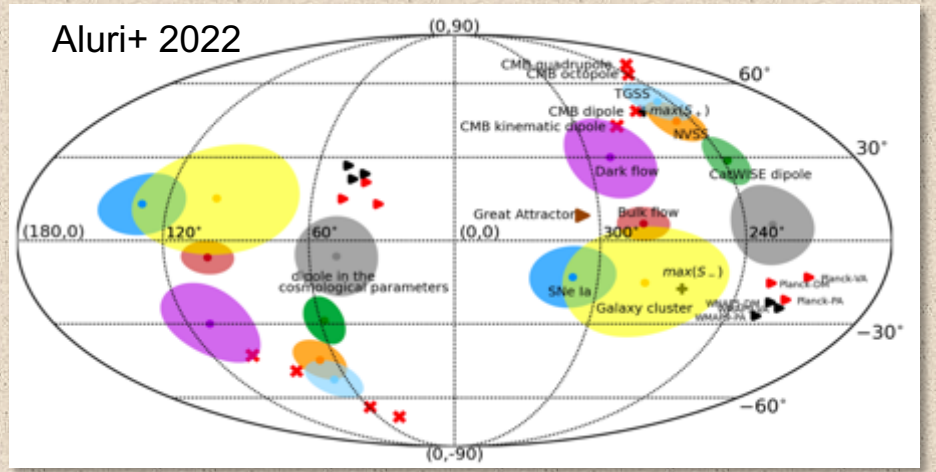
ESA Archive

The many ΛCDM crises, tensions and anomalies.

- H_0 tension.
- σ_8 tension.
- CMB anomalies.
- **Cosmological dipoles and bulk flows.**
- Missing baryons.
- Too big to fail / substructures abundance.
- Core-cusp problem.
- Supermassive black holes.
- Lithium abundance.
- ……..

ΛCDM crises, tensions and anomalies.





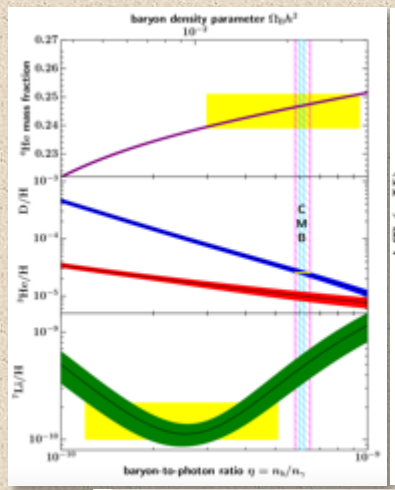
Anomalies: Kinematic Dipole, Galaxy Dipole, Bulk Flow

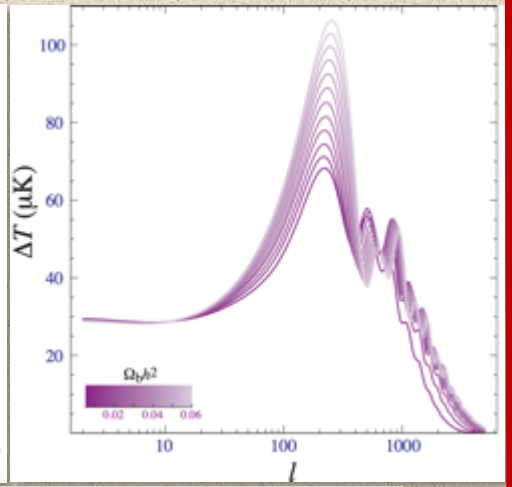
The many ΛCDM crises, tensions and anomalies.

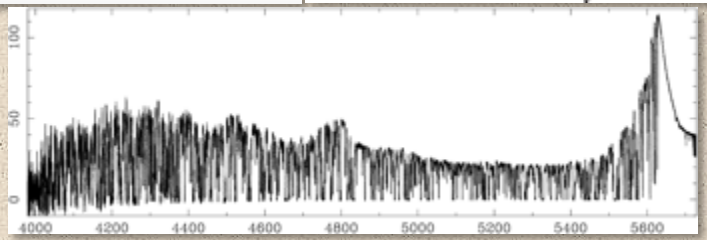
- H_0 tension.
- σ_8 tension.
- CMB anomalies.
- Cosmological dipoles and bulk flows.
- **Missing baryons.**
- Too big to fail / substructures abundance.
- Core-cusp problem.
- Supermassive black holes.
- Lithium abundance.
- ……..

ΛCDM crises, tensions and anomalies.

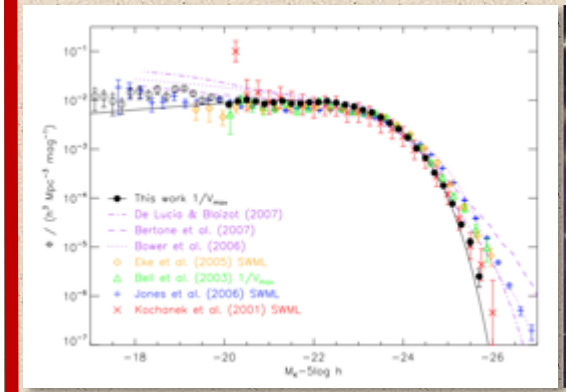
z>1 Consistent baryon density

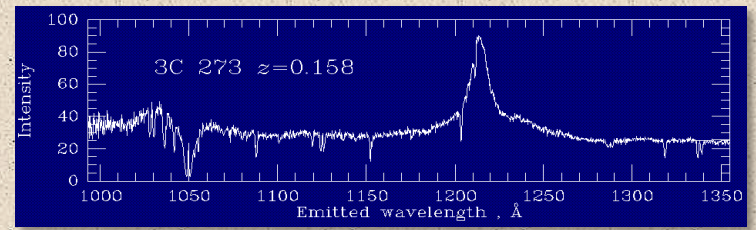




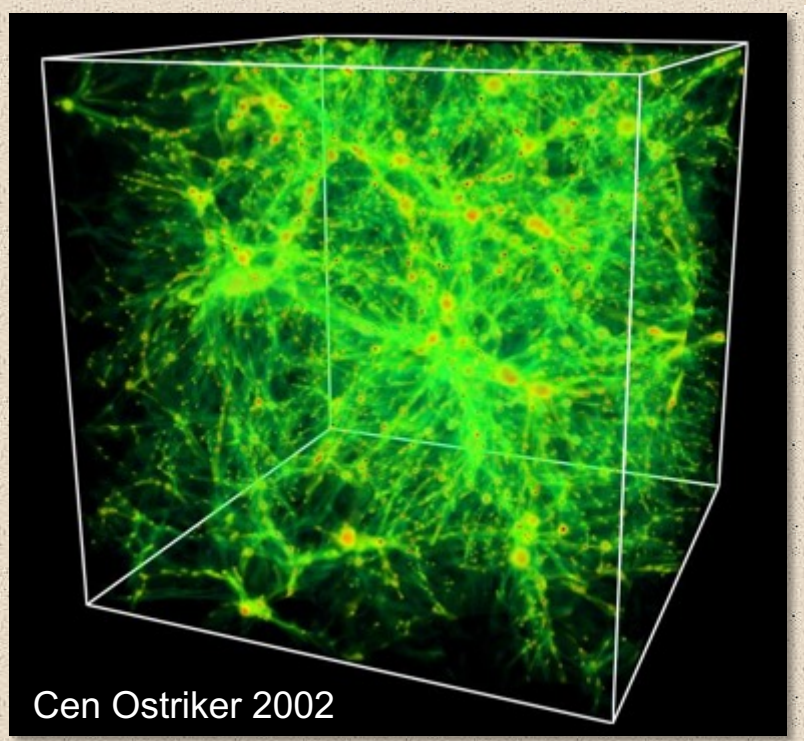


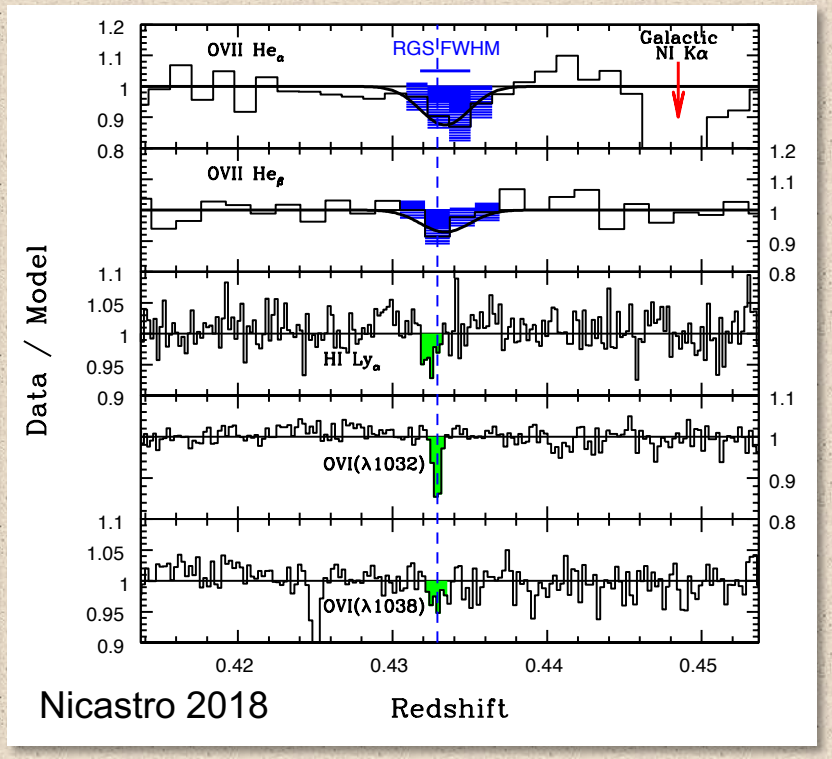
z<1 Missing baryons



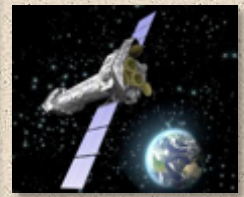


ΛCDM crises, tensions and anomalies.





Missing baryons



From precision cosmology to accurate cosmology

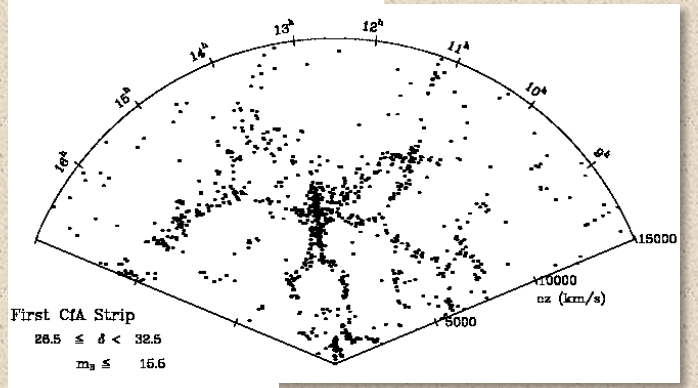
To effectively investigate the reality of these tensions an exquisite control of systematic errors is required.

% accuracy and precision is the goal

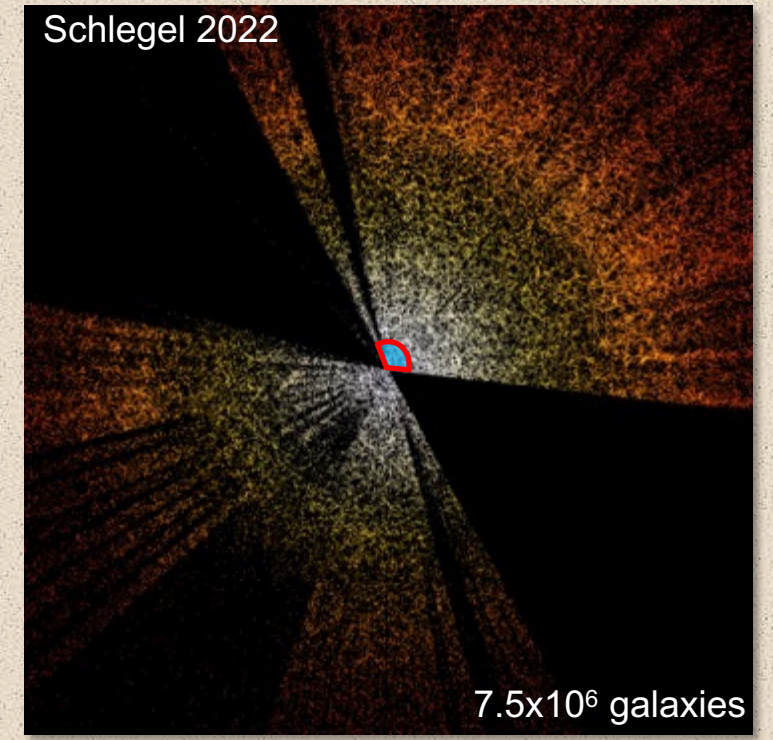
- Optimized observational strategies.
- Combination of different probes (and possibly messangers).
- Efficient and unbiased data compression methods.
- Theoretical predictions of matching accuracy.
- Effective data vs. model comparisons.

Optimizing observational strategies: DESI

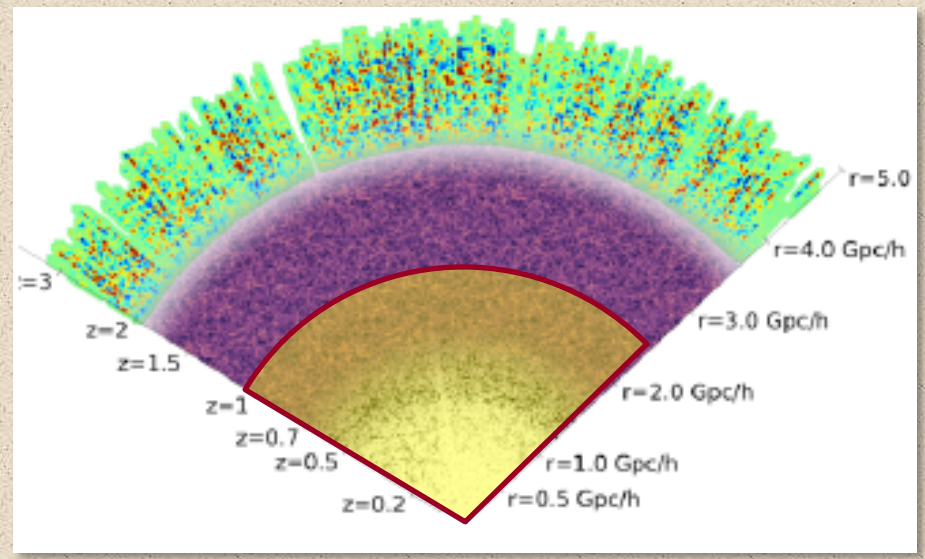
de Lapparent+ 1985

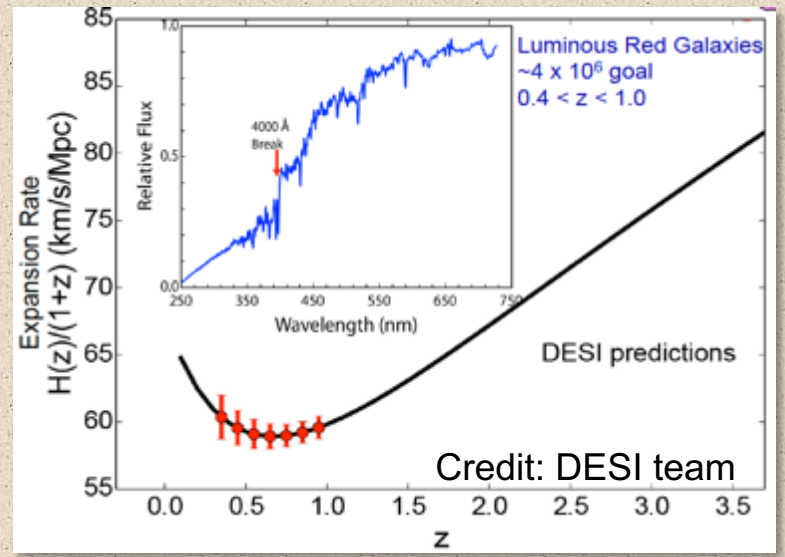


1100 galaxies

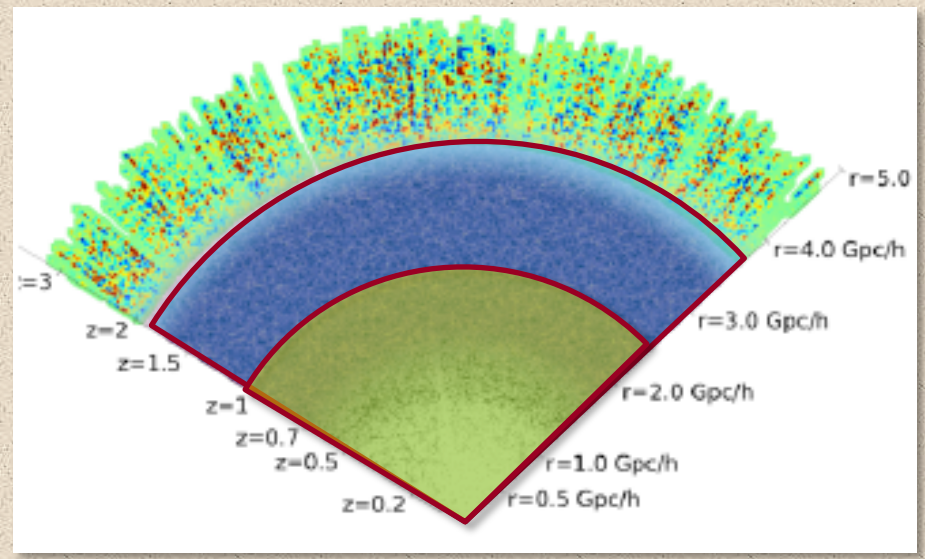


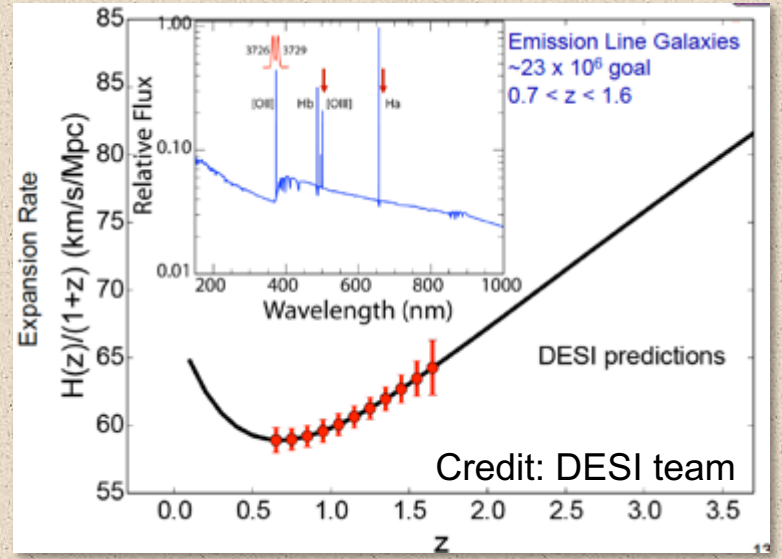
Optimizing observational strategies: DESI



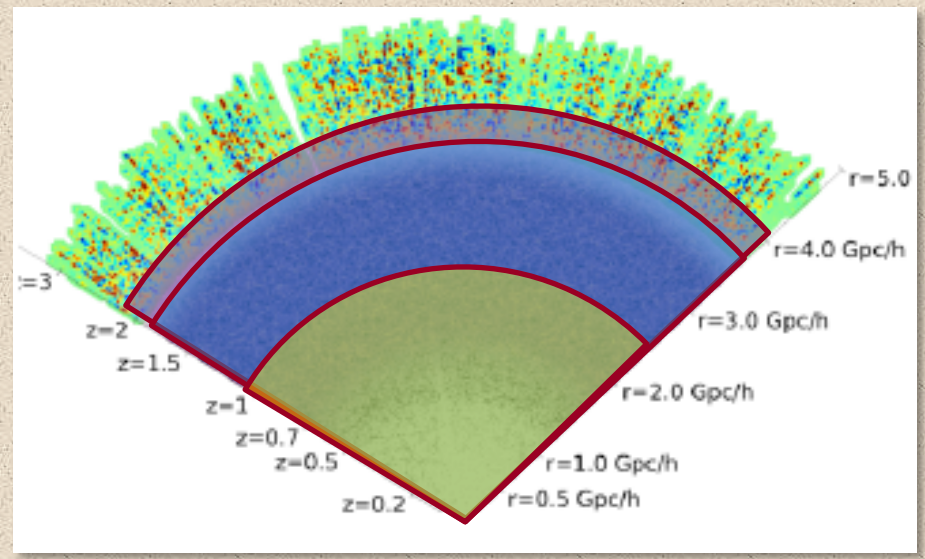


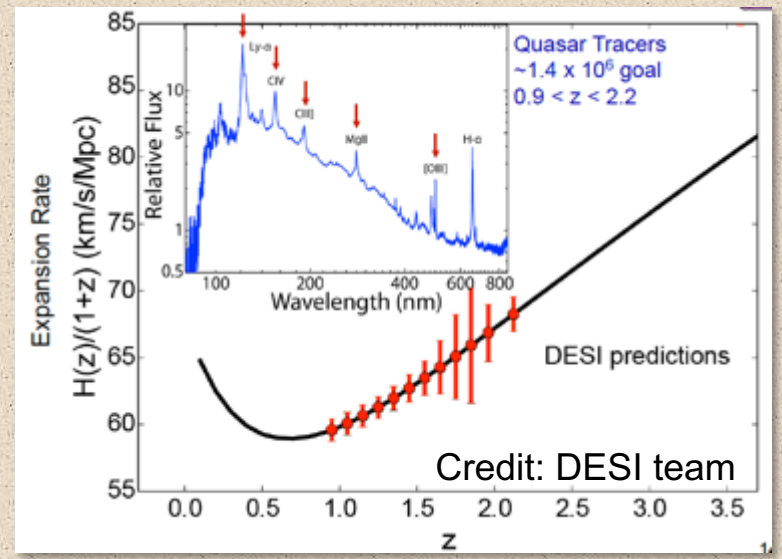
Optimizing observational strategies: DESI



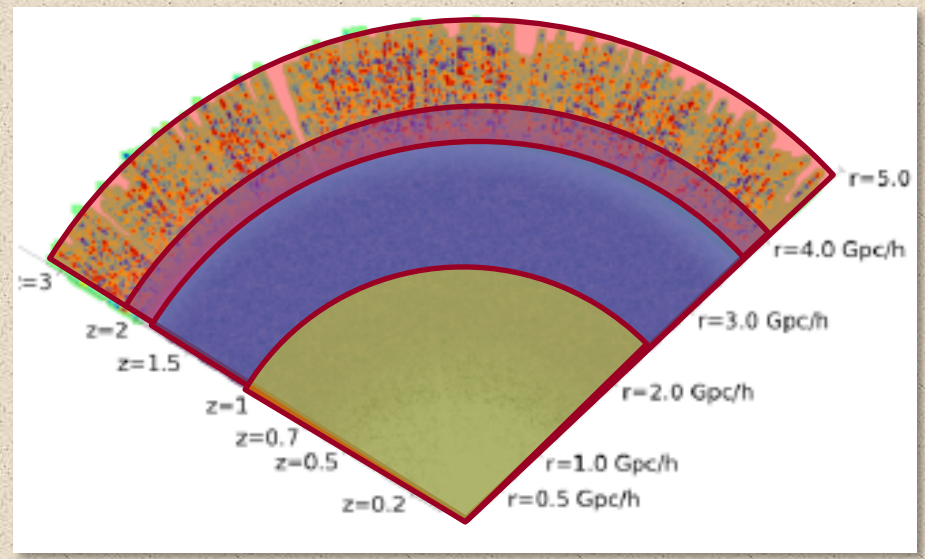


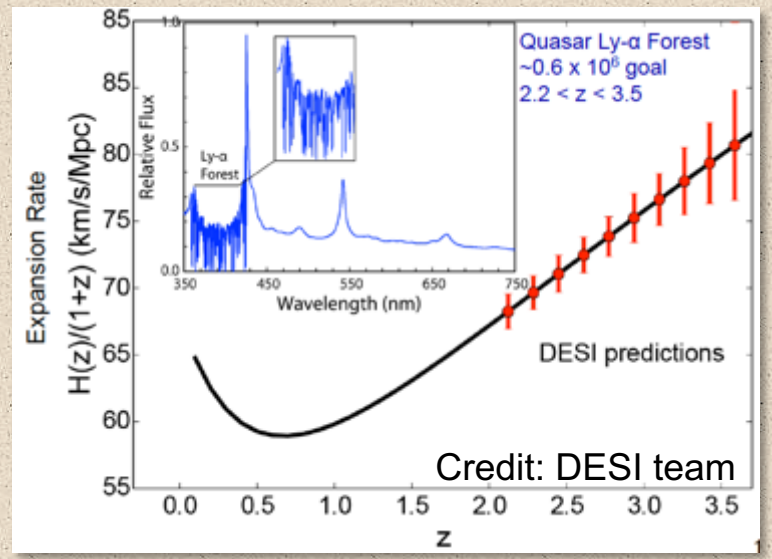
Optimizing observational strategies: DESI





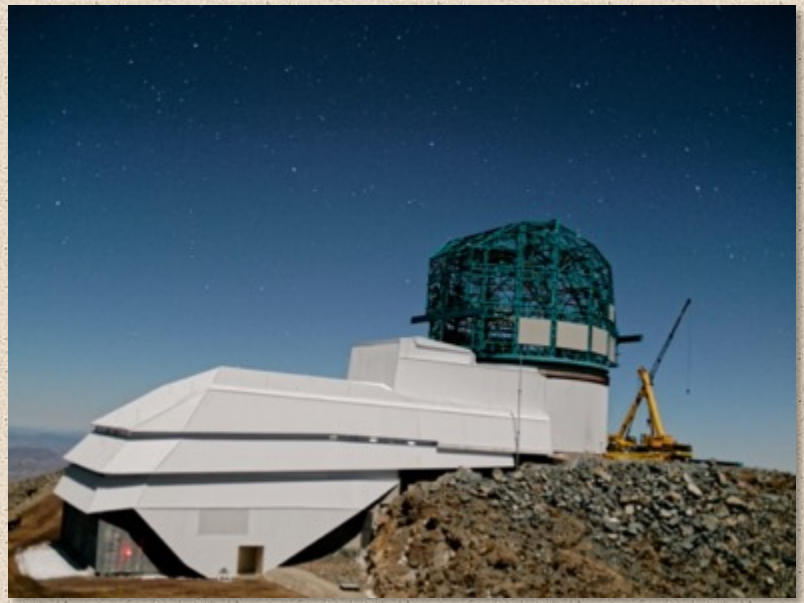
Optimizing observational strategies: DESI





Combining probes: clustering and (weak) lensing

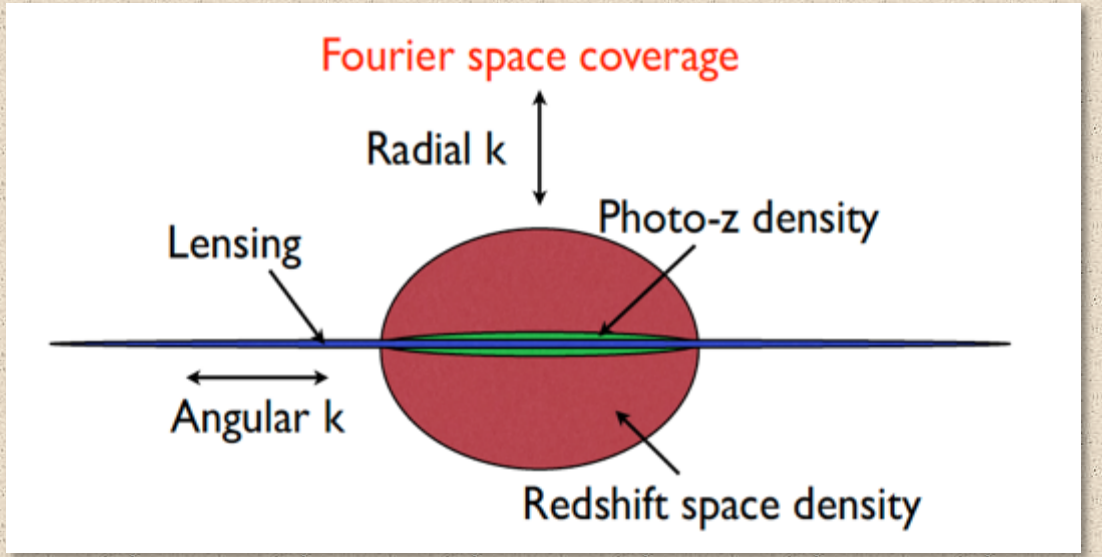
Combining probes: clustering and (weak) lensing
(beyond Euclid)

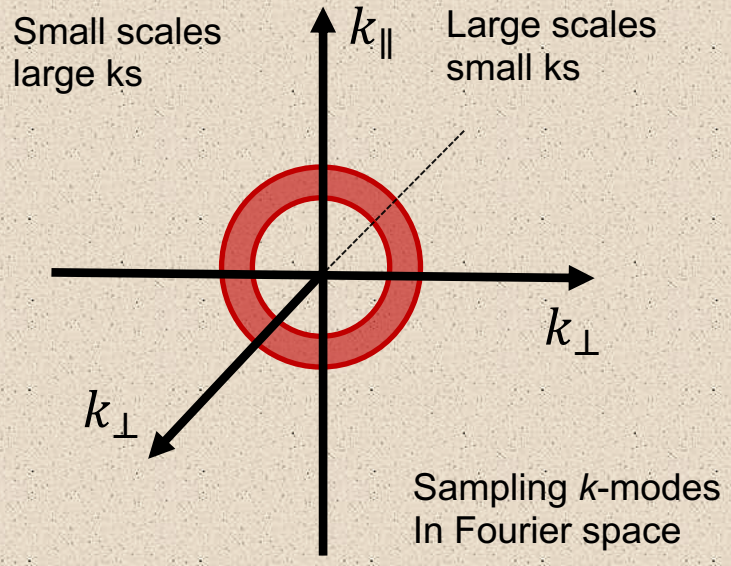


Vera C. Rubin Observatory (2024)
20B galaxies

Nancy Grace Roman Space telescope (2027)
1B photometry 15M spectroscopy

Combining probes: clustering and (weak) lensing





To wrap up.

- ΛCDM is a very effective model.
- A better theory is still to be found.
- ΛCDM is probably a good starting point.
- Investigating tensions is the best way to proceed.
- High accuracy is required.
- Combining probes and messengers is the key.
- Ongoing and future observational campaigns are being designed accordingly.

To wrap up.

Is it the best of times ? Maybe not.

Is it the worst of times ? Certainly not.

Is it exciting times ? Definitely.