Comprendre l'Infiniment Grand

-

Introduction to Cosmology

-

Part III

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Summary of Part II

FLRW metric

Homogeneous and isotropic Universe ⇒
Friedmann, Lemaitre, Robertson, Walker metric

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

- isotropic
- scale factor *R(t)* due to expansion
- dimensionless scale factor : $a(t)=R(t) / R(t_0)$

now $a(t_0) = 1$
in the past $a(t) < 1$
Big Bang $a(t) = 0$

Friedman equation

- Einstein Eq => $\left(\frac{\dot{R}}{R}\right)^2 + \frac{k}{R^2} = \frac{8\pi\rho}{3}$ (Friedmann Eq.)

- Critical density today

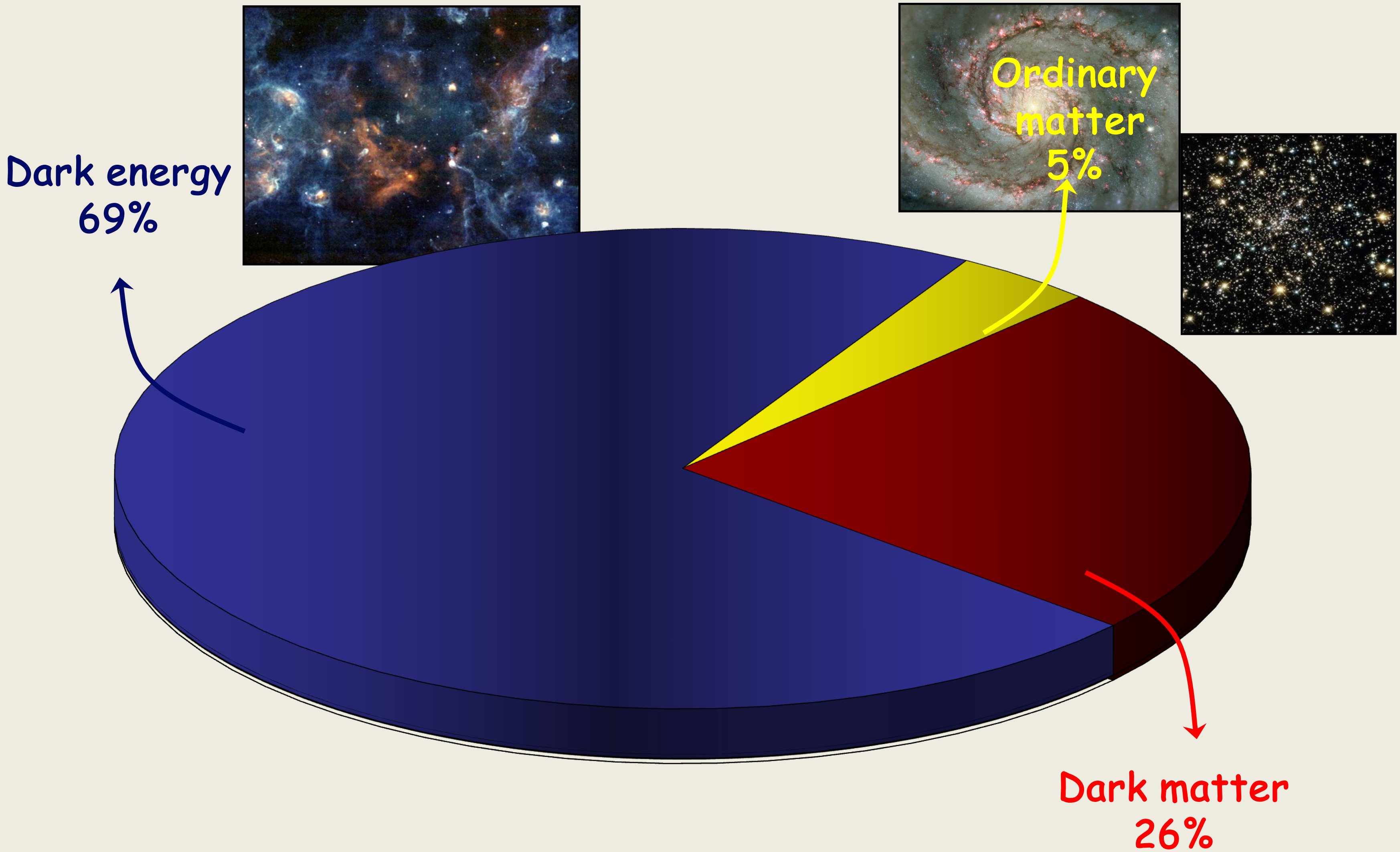
$$\rho_c = \frac{3H_0^2}{8\pi} = 1.88 \times 10^{-29} h^2 \text{ g/cm}^3 \sim 5 \text{ protons / m}^3$$

- We introduce $\Omega_m \equiv \frac{\rho_m(t_0)}{\rho_c}, \quad \Omega_r \equiv \frac{\rho_r(t_0)}{\rho_c}, \quad \Omega_v \equiv \frac{\rho_v(t_0)}{\rho_c}$

$\Omega_T = \Omega_m + \Omega_r + \Omega_v = \rho_0 / \rho_c$

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_v + (1 - \Omega_T)a^{-2}\right]$$

Content of the Universe



Observational Cosmology - Part III

1. **Standard candles**
    - SNLS

2. **Cosmic Microwave Background**
    - History
    - Planck Satellite

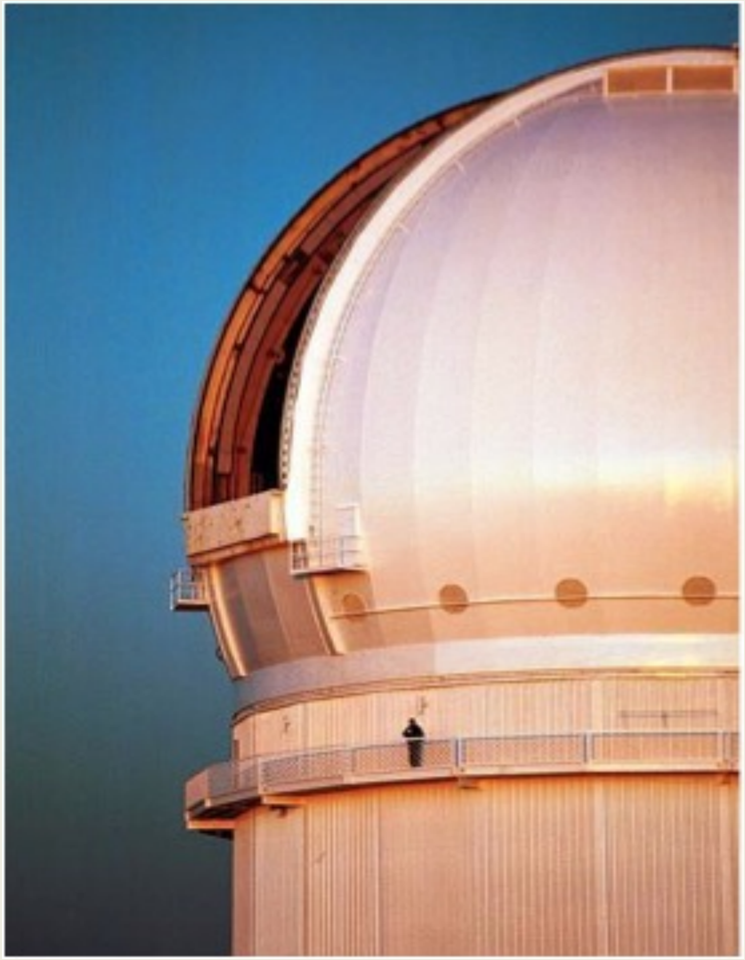
3. **Standard ruler - BAO**
    - DESI

4. **The H_0 puzzle**

Standard candles

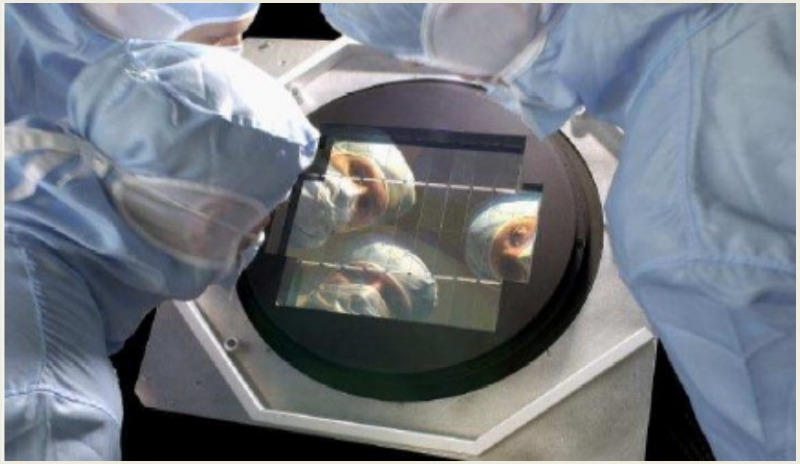
SNI-a

SNLS: SuperNova Legacy Survey



MegaCam:

- designed and built by CEA/Irfu
- Biggest camera CCD in the world till 2010:
  36 CCD 2k × 4.5k pixels.
- Wide field: 1 deg^2

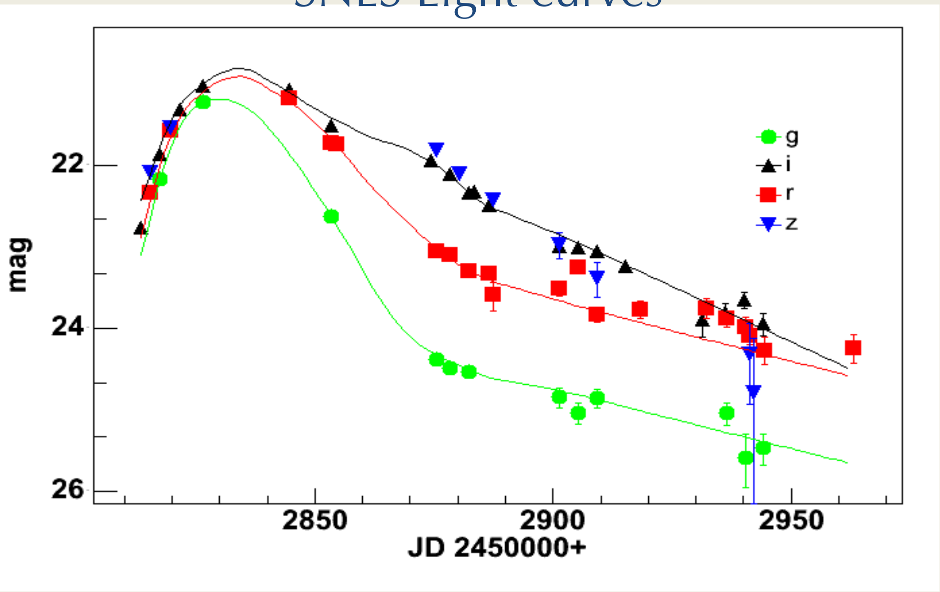


SNLS:

- 3.6m telescope (CFHT) at Hawaï equipped with **MegaCam**
- 400 SN Ia over 2003-2008

SNLS: The method

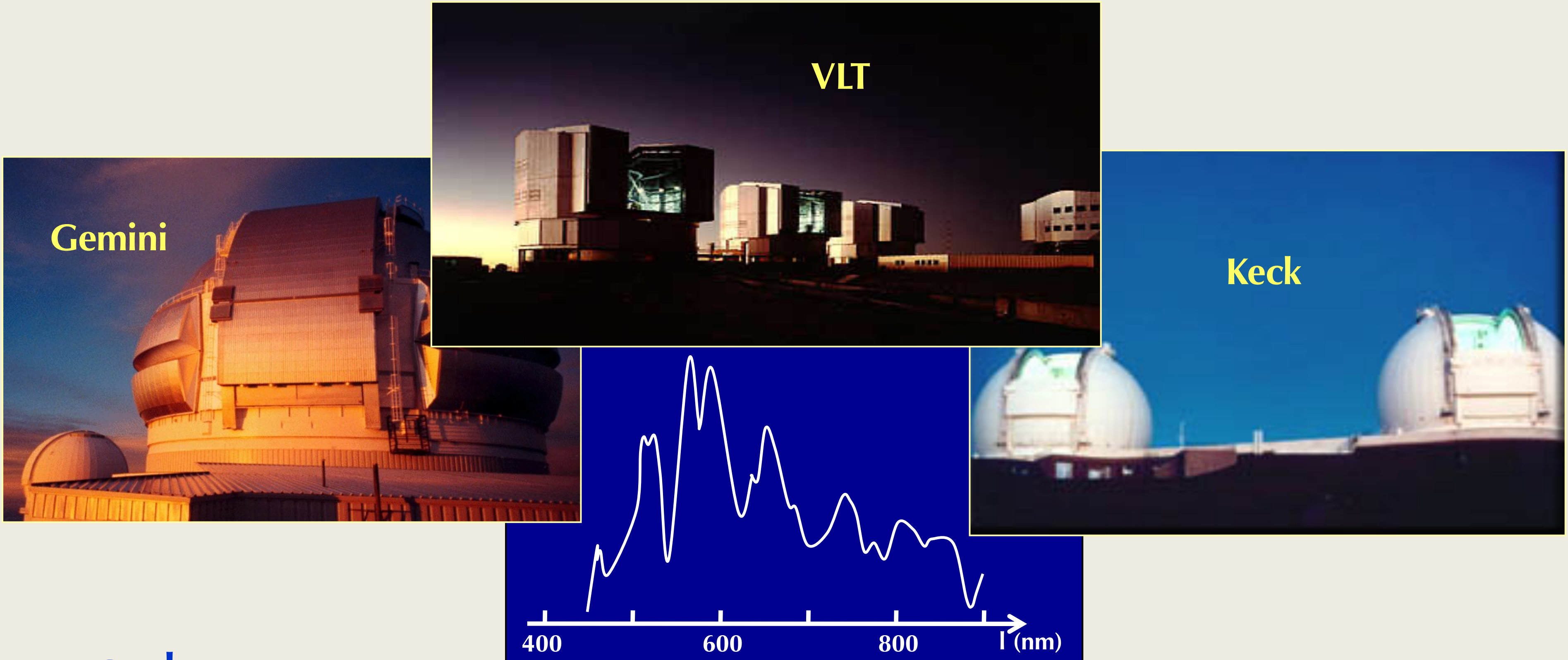
SNLS Light curves



1st Stage

- ➢ Measurement of photon flux every 3-4 days
- ➢ On-the-fly detection of SN explosions

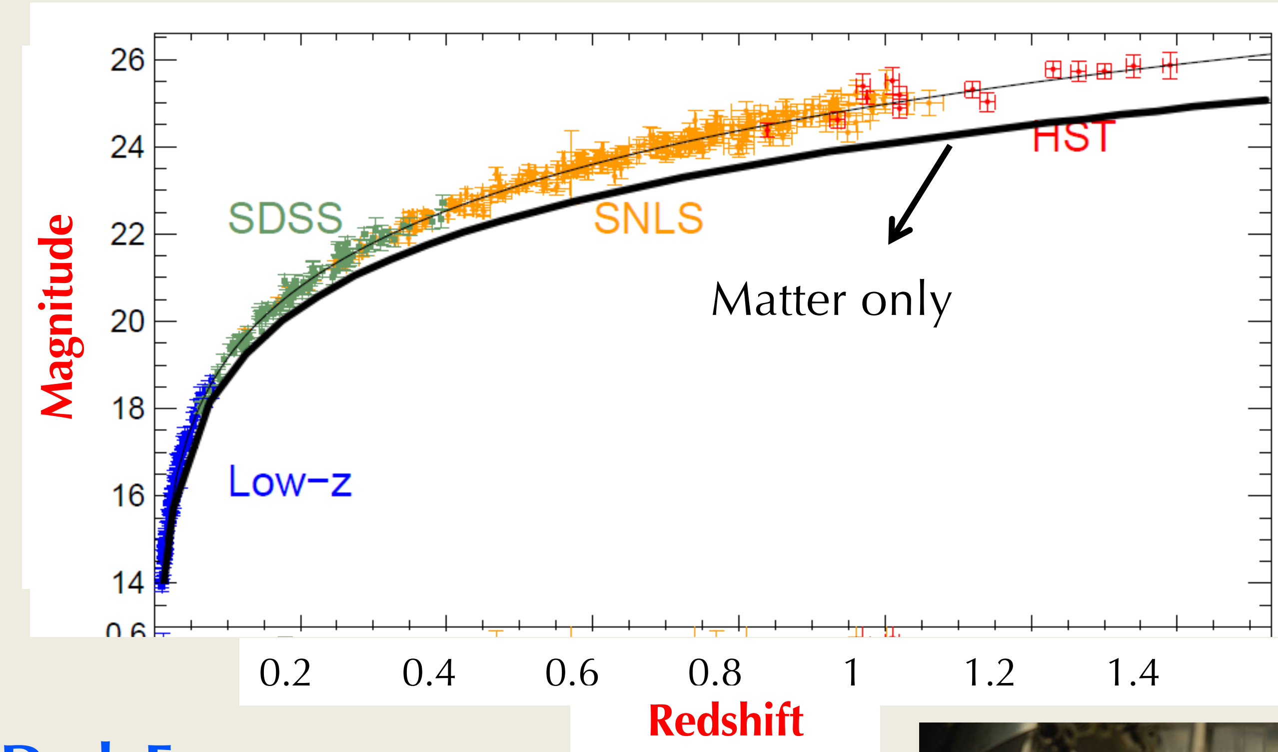
SNLS: the method



2nd stage

- ➢ Observation of SN spectra with 8m telescope (VLT, Keck, Gemini…).
- ➢ Confirmation of SN type (Ia, Ib..).
- ➢ Measurement of redshift.

Standard Candles - Status

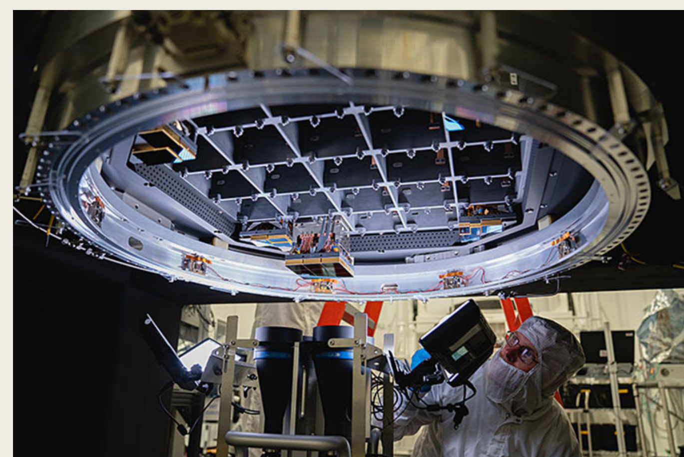


Proof of Dark Energy

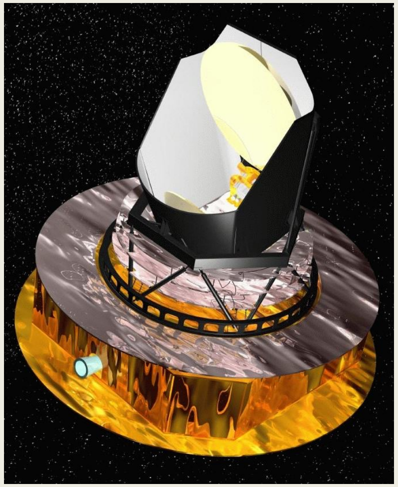
➢ Almost one thousand SNIa used in the new Hubble diagram

➢ Clear demonstration since 1999

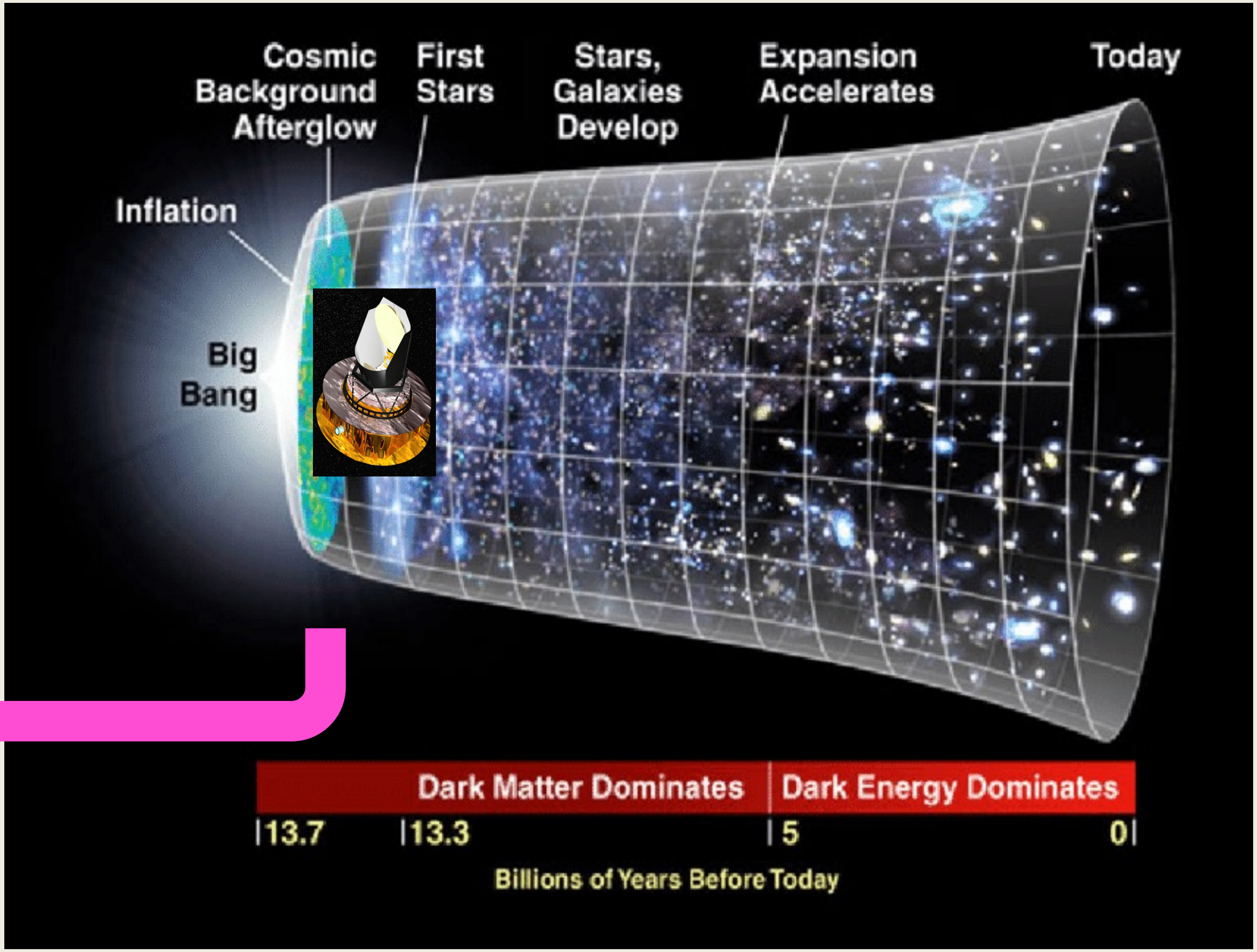
➢ SNIa machine in preparation with LSST (first light in 2023) in Chile



A picture
of the primordial Universe
-
Cosmic Microwave Background



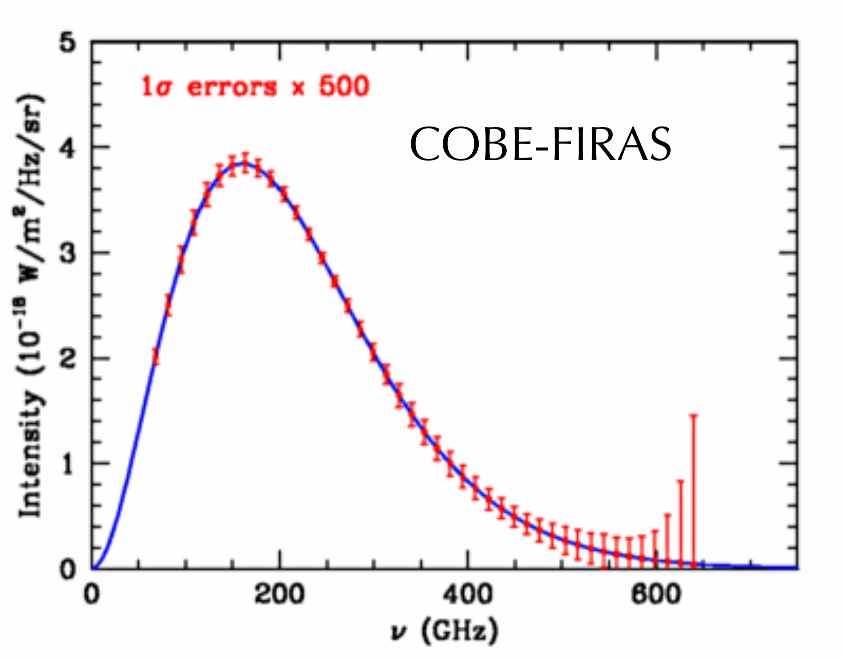
The Big-Bang

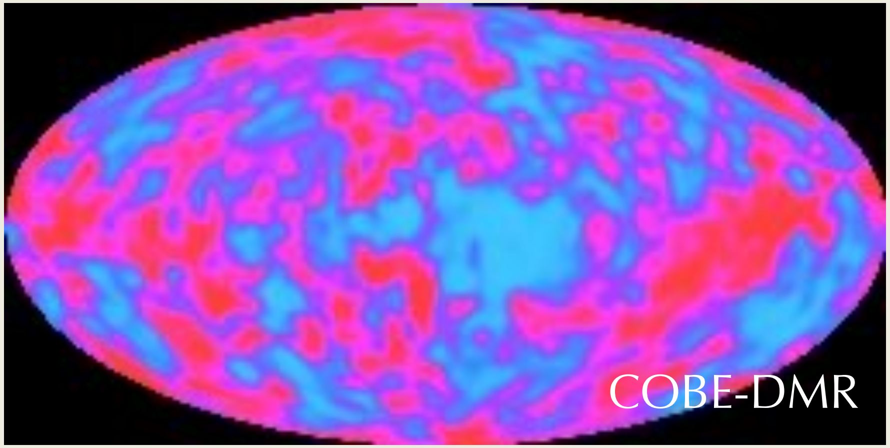


~10^{-10}-10^{-5}s
Elementary particles
⇒ LHC

- Expanding Universe is slowly cooling
- 3mns : End of nucleo-synthesis
- 380 000 years: Recombination : Universe becomes transparent

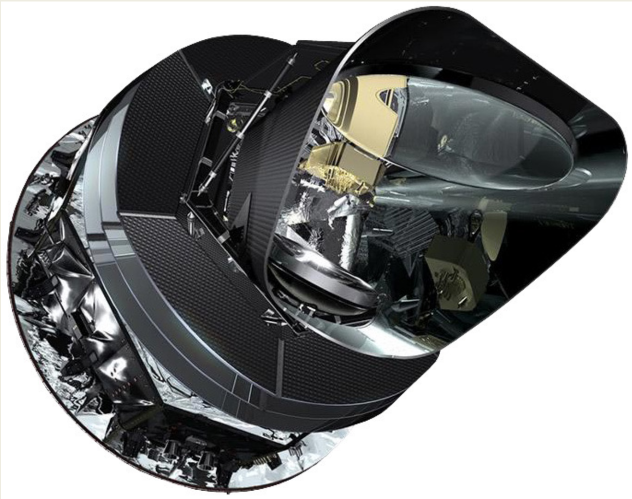
CMB discovery





- **1964:** Discovered "by chance" by Penzias and Wilson (uniform radio "noise" at 7.5 cm ⟶ 2.7 K)
- **1989-1992:** Satellite COBE
  - Perfect black body with a temperature T=2.725K !
  - Extremely small anisotropies of 0.00001 degrees….

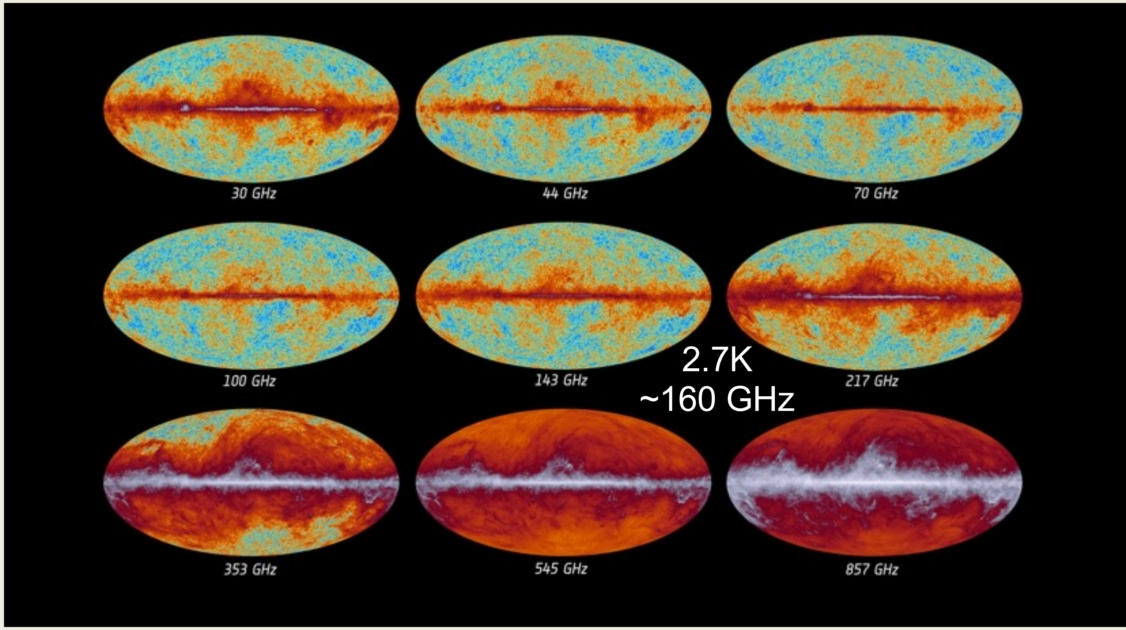
Planck more and more precise measurements



- ESA/CNES satellite launched in May 2009 toward L2 (1.5 M km from Earth)
- Measurement of T_{FDC}=2.7K at 1/100 000
- Bolometers cooled at 0.1 K
- ~3-year observation program

Planck maps

- Maps of the whole sky for 9 different frequencies
- Separation of the components (CMB, galactic dust, experimental noise…).

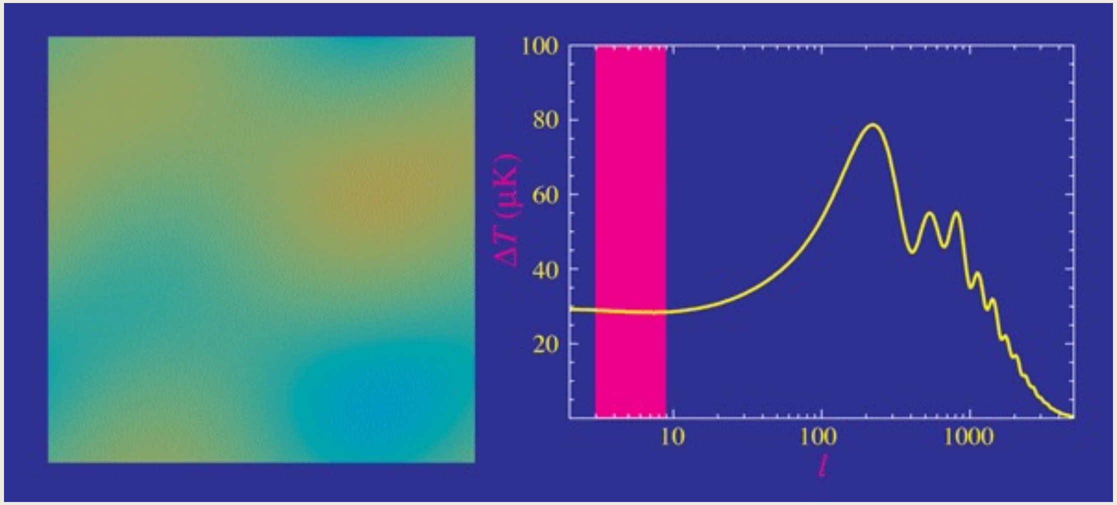


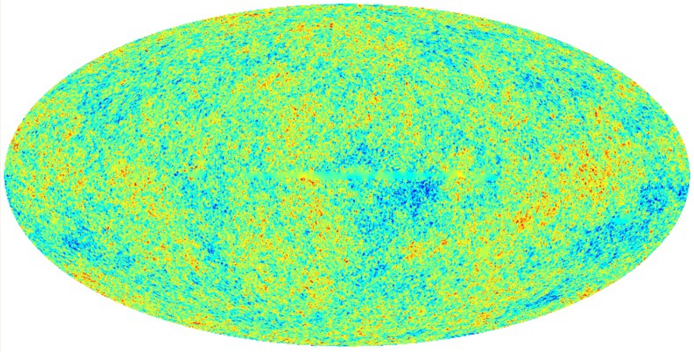
What do we learn with these maps?

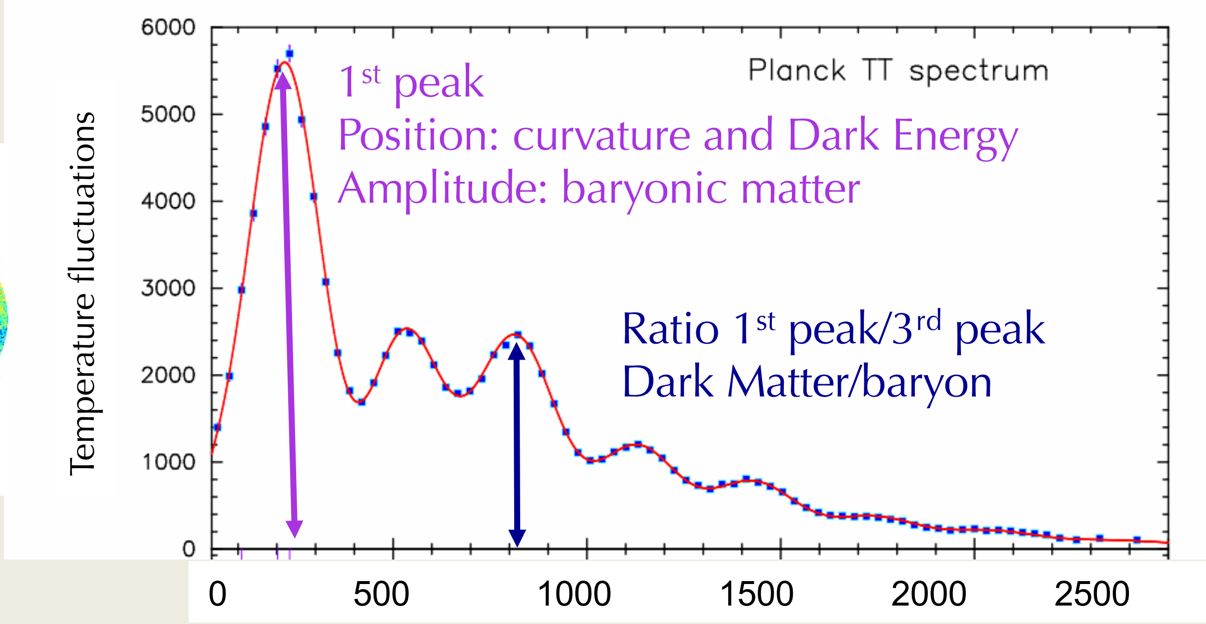
CMB anisotropies

➢**Angular size** of the fluctuations

➢ Conversion : angle $\theta \rightarrow$ multipole $l = 180^{O}/\theta$







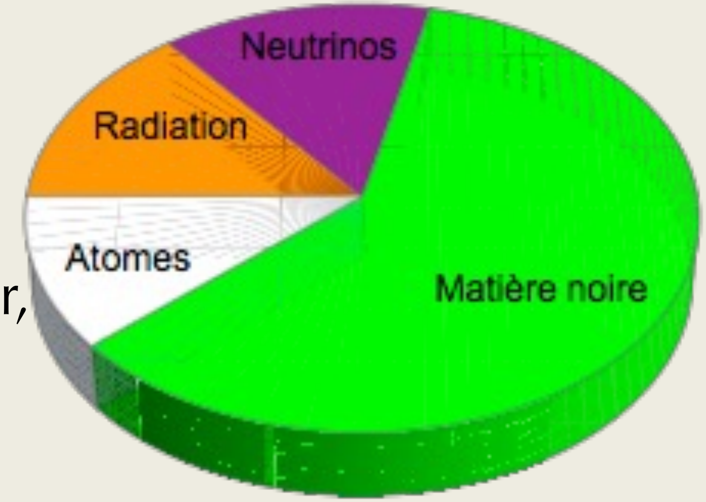
Universe content seen by Planck

- Starting from power spectrum (acoustic oscillations), we derive the content of the Universe, 380 000 years ago.

Light particles
relativistic
(neutrinos)

Radiation
(photons)

Atoms
(ordinary matter,
hydrogen,
helium)



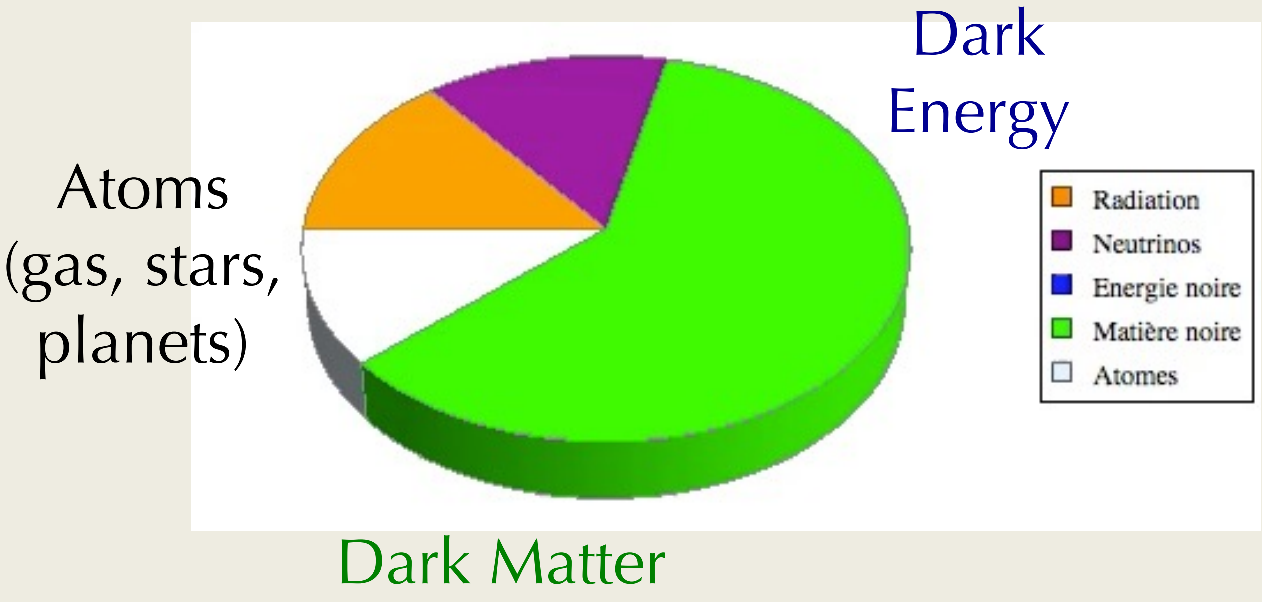
Dark Matter
(SUSY,
axions..)

From CMB to today

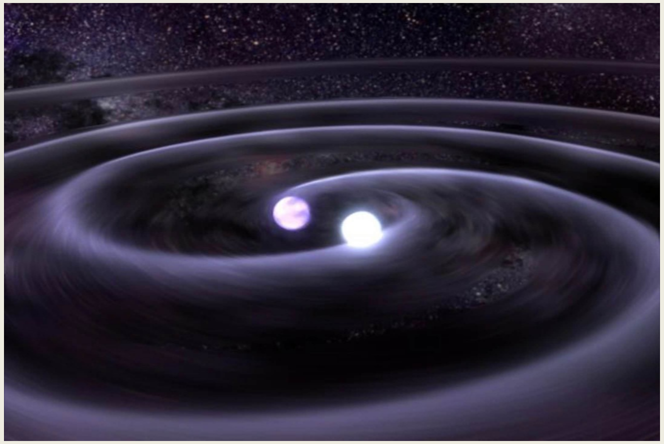
- From Friedmann equation, we can predict the evolution of Universe components

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3} \qquad a \propto \frac{1}{1+z}$$

- Consistent with Universe observed by supernovae



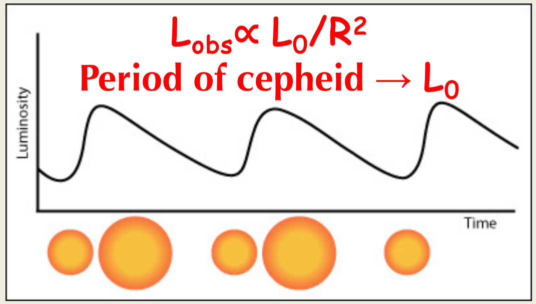
The H_0 puzzle
-
Future standard sirens



Local measurement of H_0

Distance ladder

- Parallaxes
- Cepheids
- SN-Ia



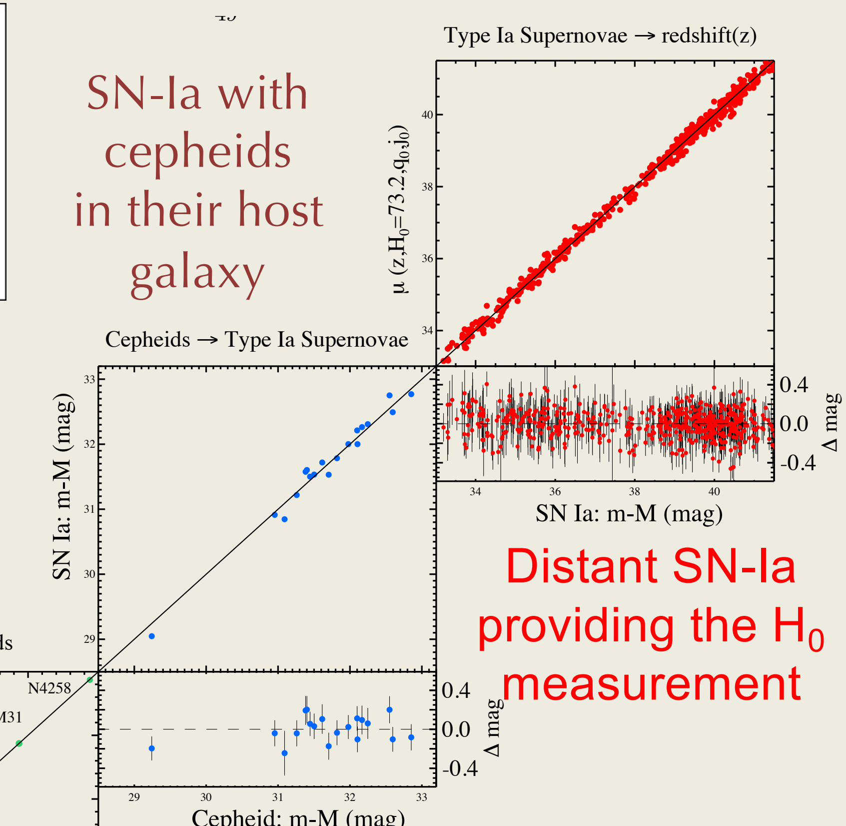
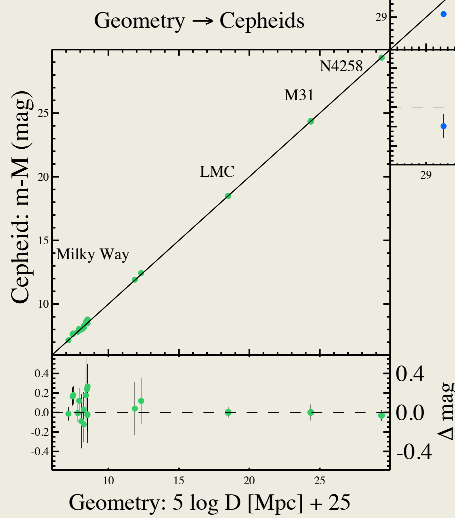
Comparison to CMB

- Indirect measurement of H_0 through the evolution of the Univers assuming LCDM since CMB (z=1100)

4.4σ tension

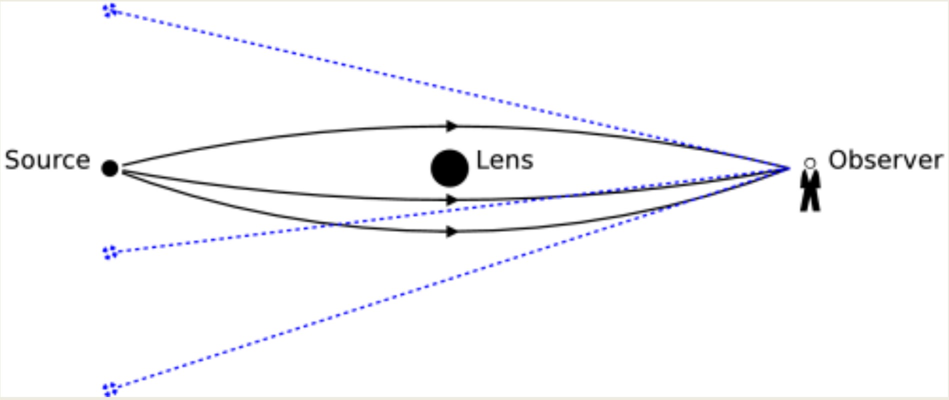
- CMB: $H_0 = 67.4 \pm 0.5$
- SNIa: $H_0 = 74.0 \pm 1.4$

Riess et al., 2022

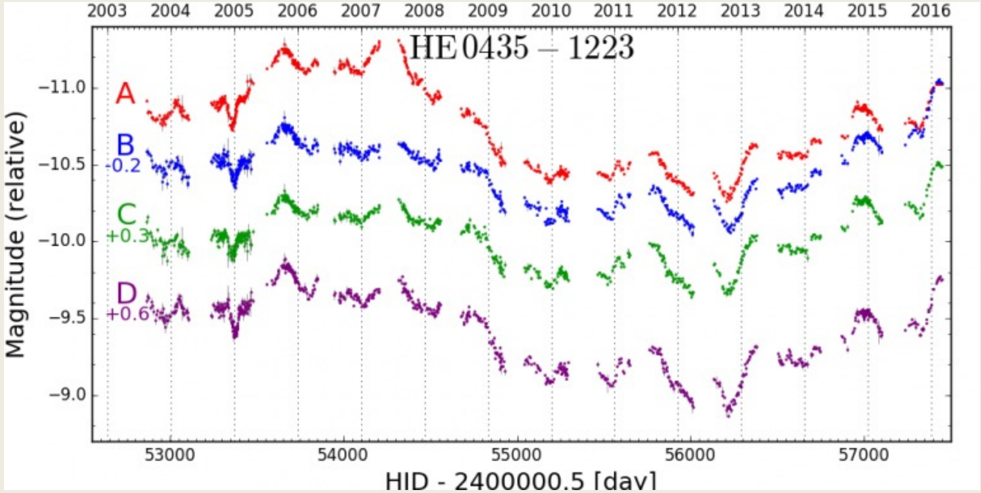
SH0es, Riess et al., 2019

H0licow – lensed quasars



Principles

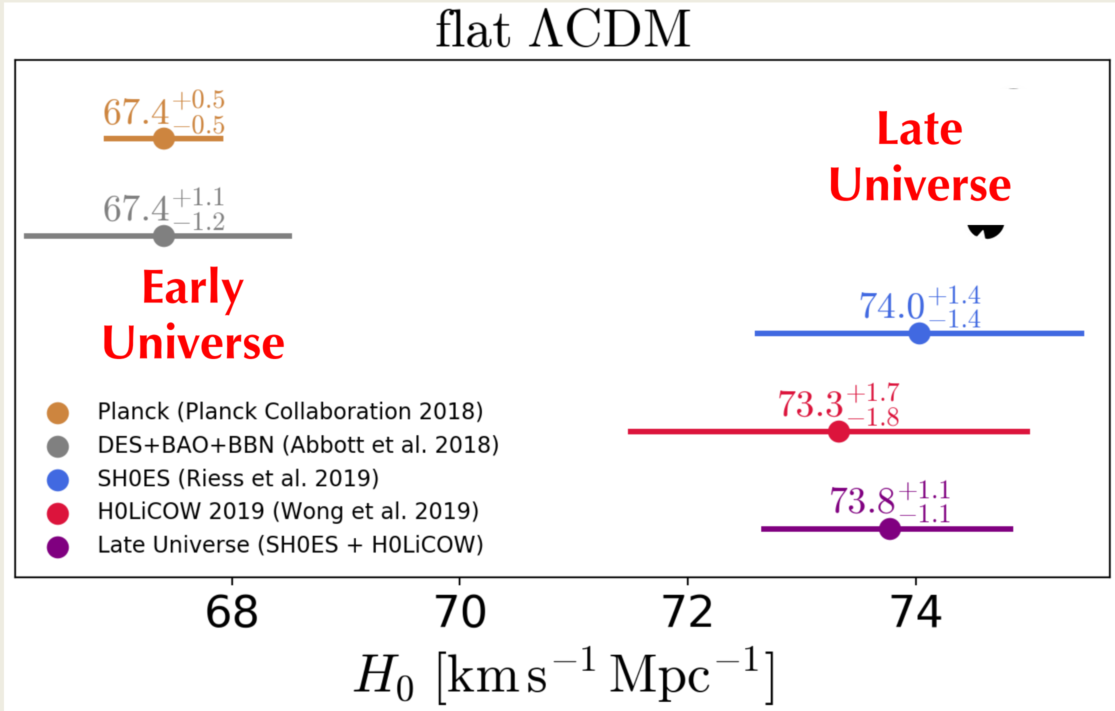
- ➢ Study of the time-delay for each image
- ➢ Several lensed quasars
- ➢ Quasar variability makes time delays measurable
- ➢ Time delays: ~10 days



Comparison late/early Universe

CMB-Planck

BAO+BBN



SNIa

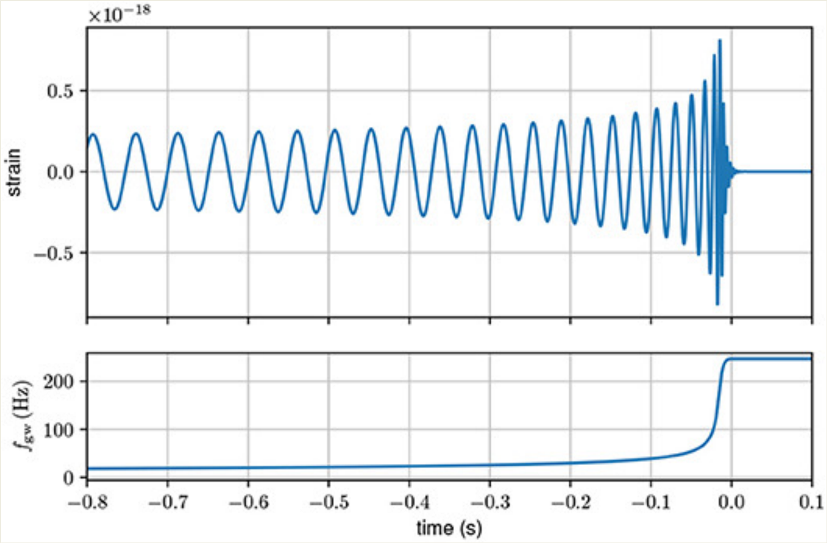
Quasar Lensing

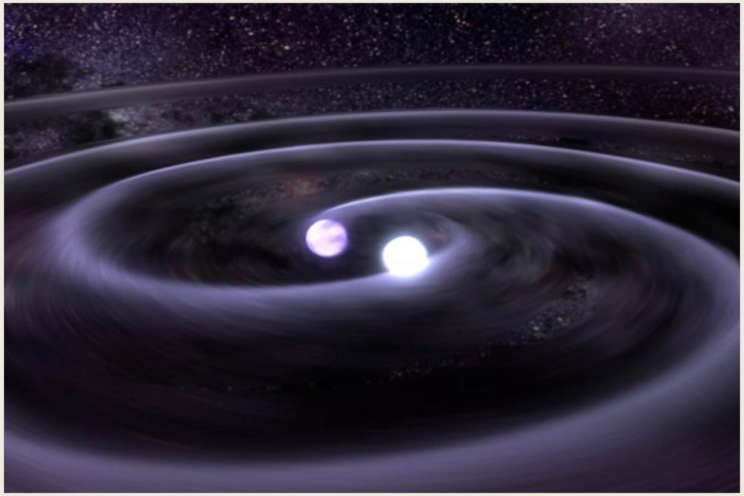
Combined

Interpretation

- Significant discrepancy >5σ, so-called the "H_0 tension"
- Underestimate of systematic uncertainties
- New models to describe cosmology, typically with evolving Dark Energy model… Early Dark Energy

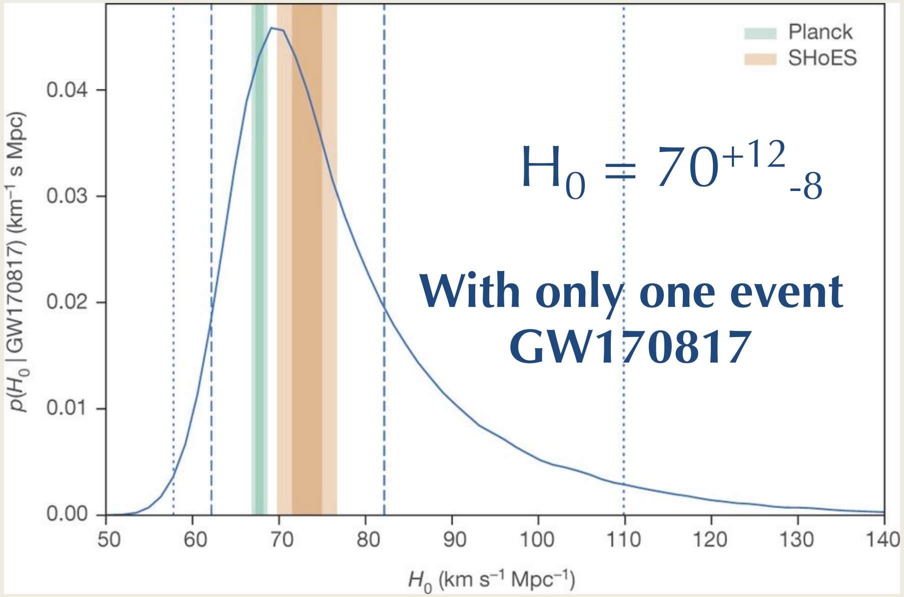
H_0 and Gravitational Waves?



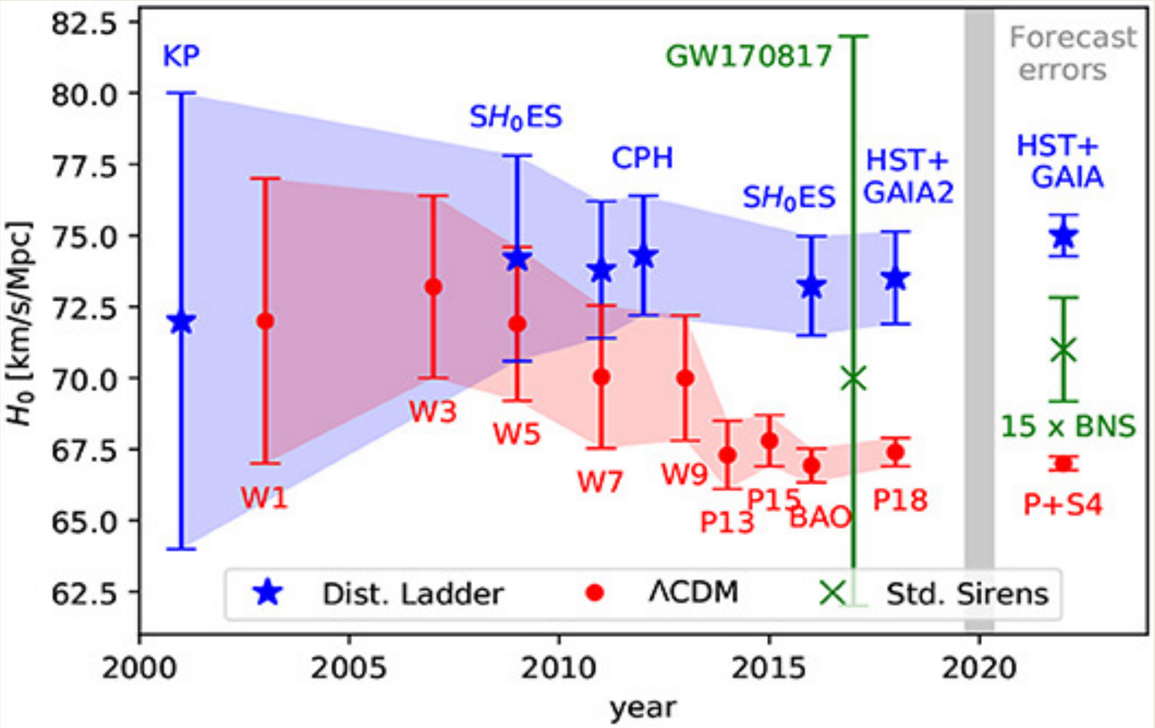


Principles

- Binary neutron star merger
- Measurement of distance with the GW amplitude (strain)
- Measurement of the redshift with the optical counterpart (host galaxy)
- **Standard sirens**



Future with standard sirens

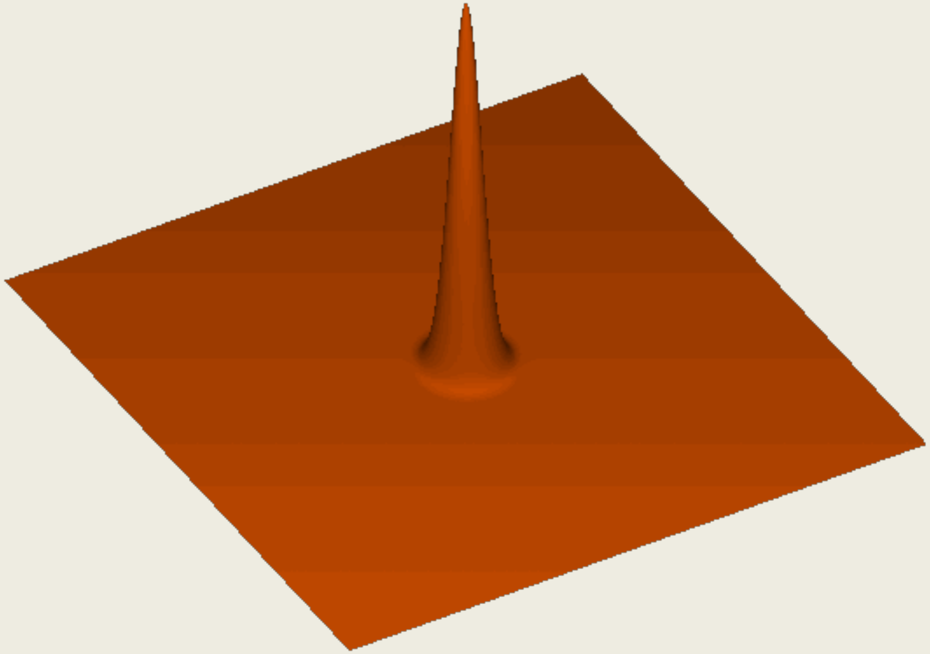


Prospects

- ➢ Measurement at 10% with one BNS (GW170817)
- ➢ Several BNS merger expected by year
- ➢ Expected a few % of accuracy within a few years
- ➢ But, in O3: April 2019-March 2020, none with EM counterpart
- ➢ O4 started in May 2023 for 2 years (nothing so far…)

Standard Ruler
Baryonic Acoustic Oscillations

A probe for Dark Energy: Baryonic Acoustic Oscillations



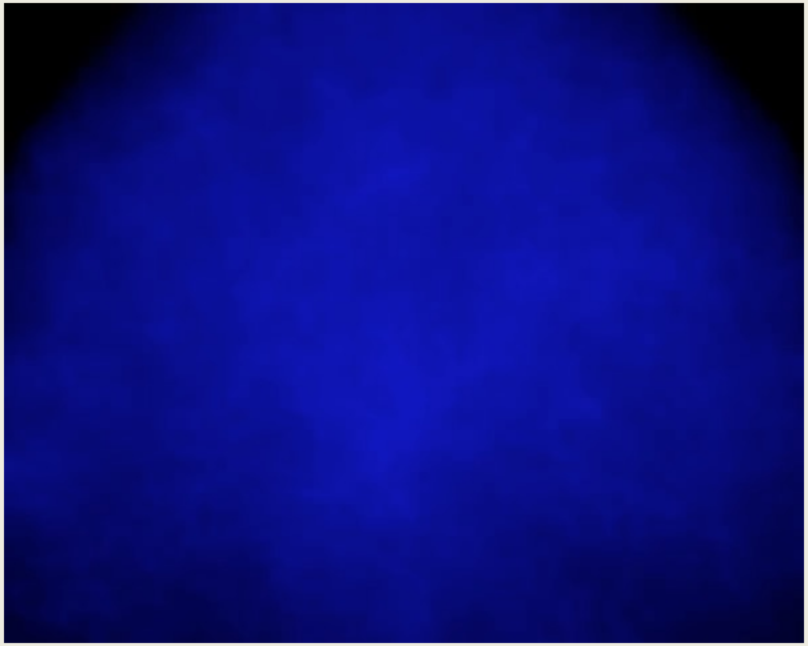
Acoustic propagation of an overdensity:

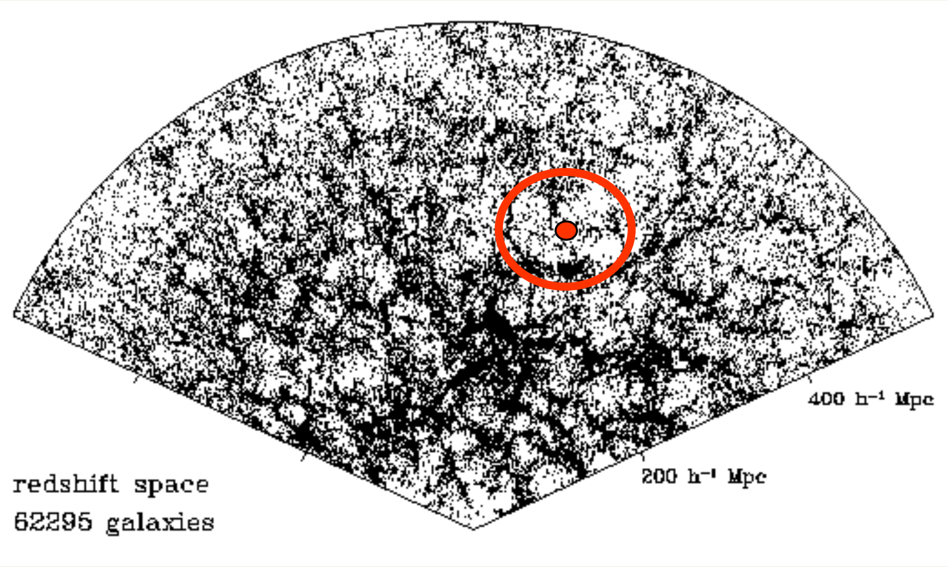
➢ Sound wave through relativistic plasma (baryons, electrons, photons).

➢ Baryon and photon perturbations travel together till recombination (z~1100).

➢ Then, the radius of the baryonic overdensity is frozen at 150 Mpc.

Baryonic Acoustic Oscillations





A special distance:

➢ Galaxies form in the overdense shells about 150 Mpc in radius.

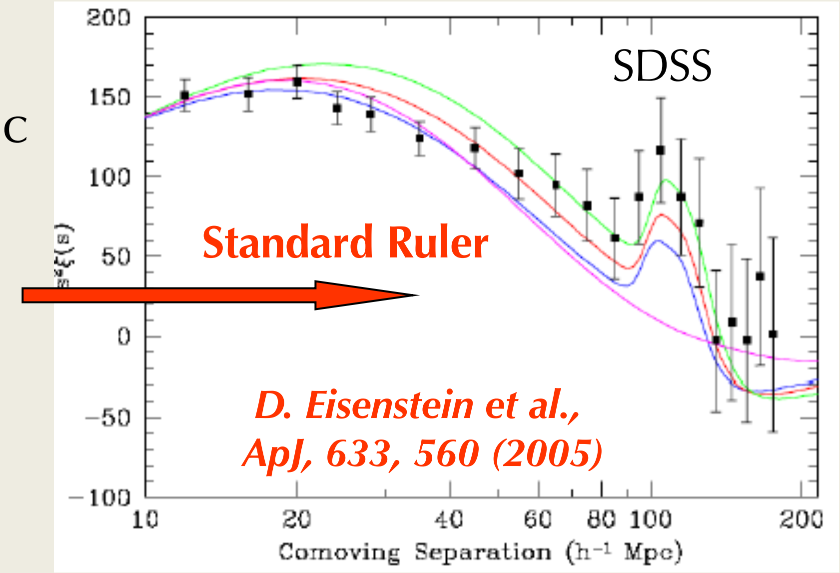
➢ For all z, small excess of galaxies 150 Mpc (in comoving coordinates) away from other galaxies.

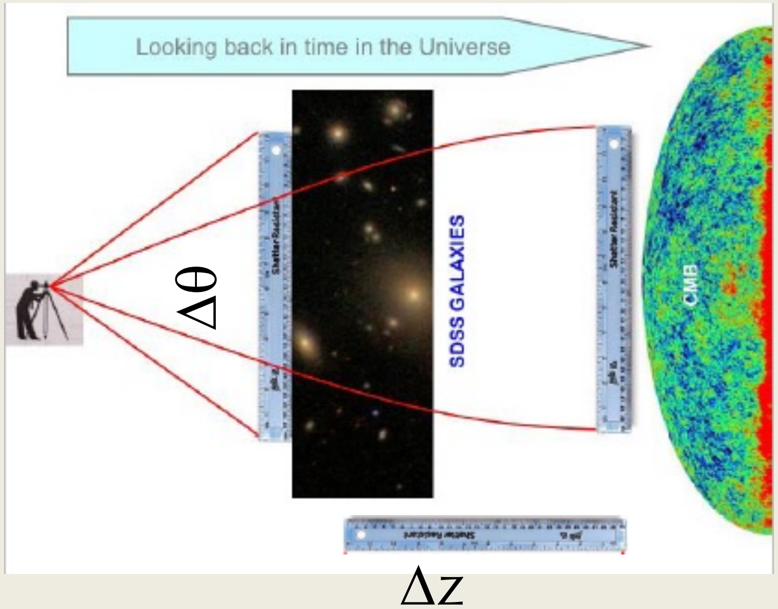
⇒ **Standard Ruler**

Observation of baryonic acoustic peak

First observation:

- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at ~150 Mpc
- SDSS: ~50 000 LRGs
  "Luminous Red Galaxies"
  <z> ~ 0.35





A 3D measurements:

- Position of acoustic peak
- **Transverse direction:**

$\Delta\theta = r_d/(1+z)/D_A(z)$

$\Rightarrow$ Sensitive to angular distance $D_A(z)$

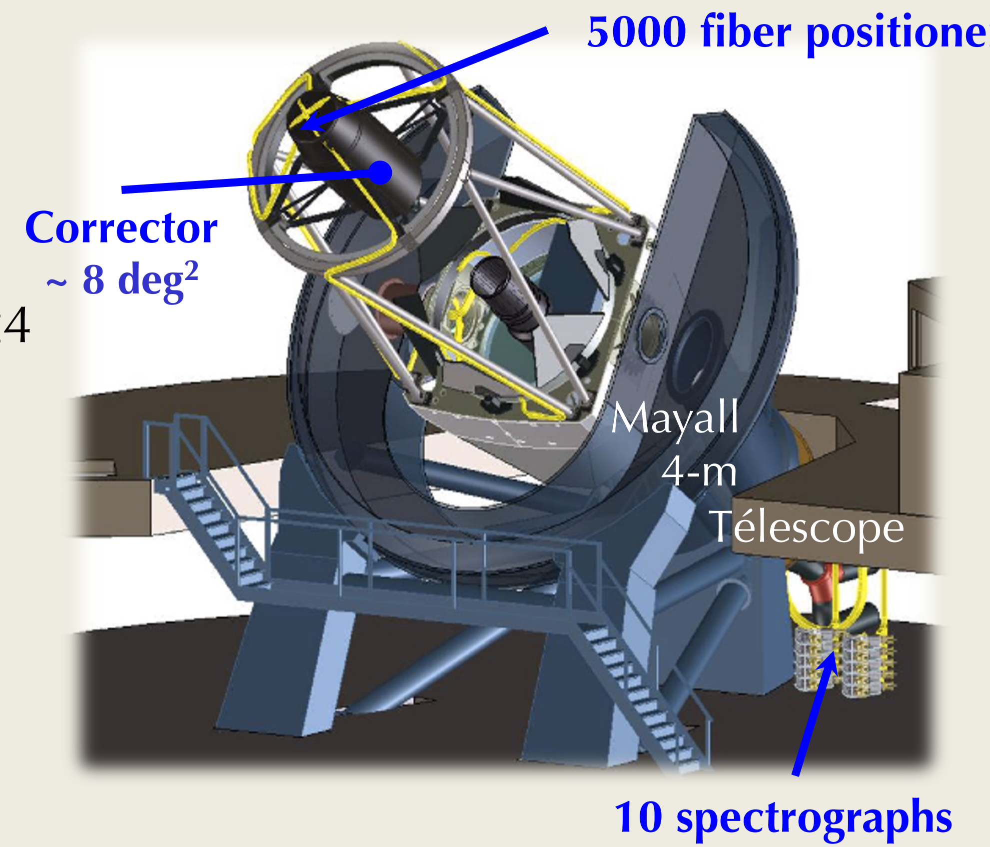
- **Radial direction** (along the line of sight):

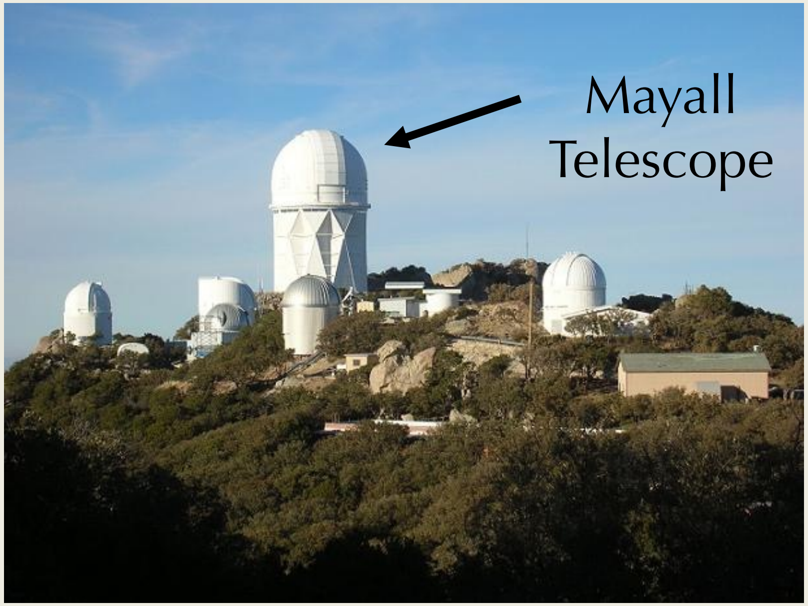
$\Delta z = r_d \cdot H(z)/c$

$\Rightarrow$ Sensitive to Hubble parameter $H(z)$.

DESI Project

- **Scientific project**
  - 14000 deg^2 3D survey for 0<z<4
  - International collaboration
  - 74 institutions (46 non-US)
  - 650 members





- **Instrument**
  - 4-m telescope at Kitt Peak (Arizona)
  - Wide FoV (~ 8 deg^2)
  - Robotic positioner with 5000 fibers
  - 10 spectrographs x 3 bands (blue, visible, red-NIR) →360-1020 nm

DESI tracers of the Matter

Five target classes

~40 million redshifts

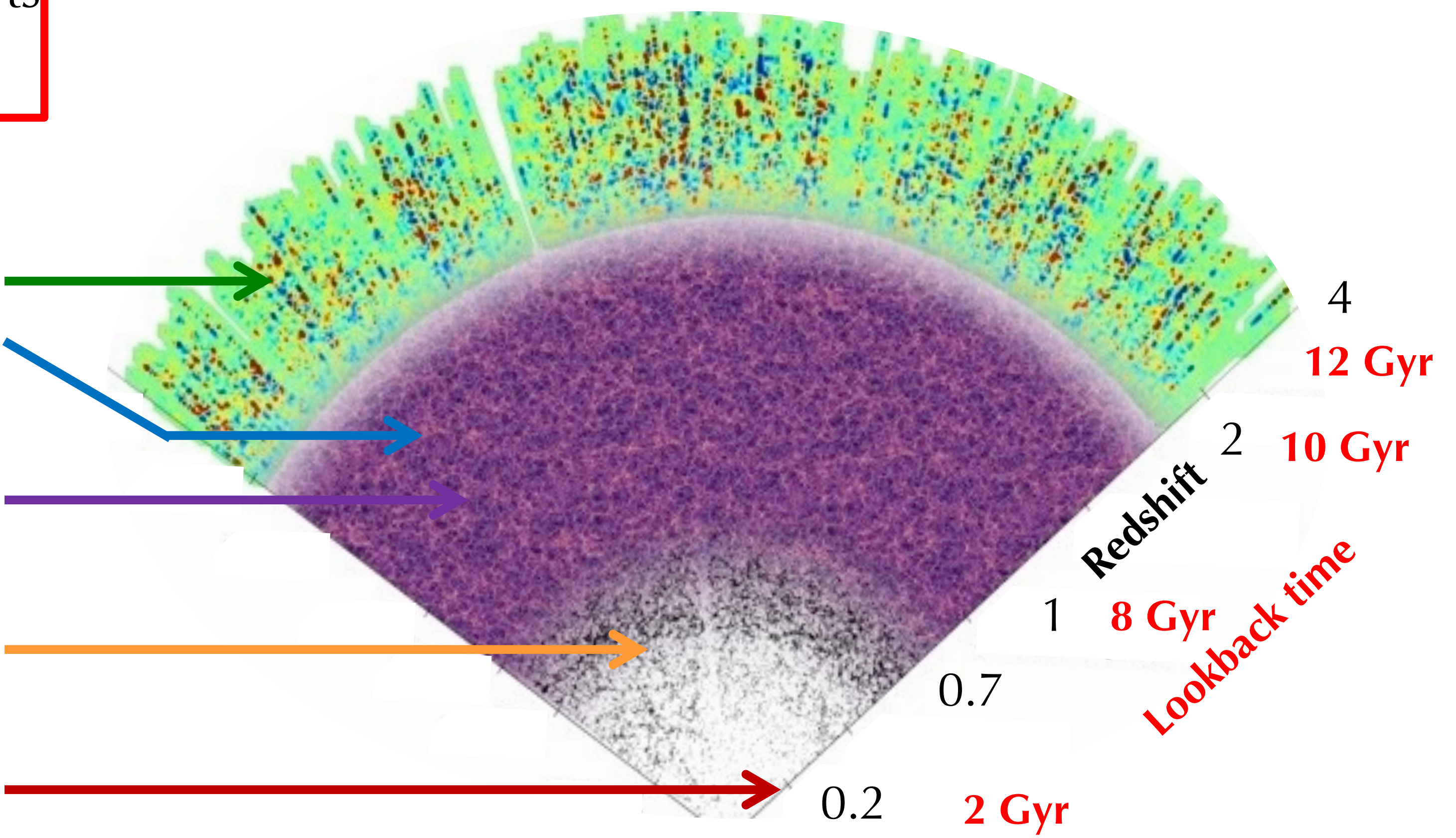
in 5 years

3 million QSOs
Ly-a z > 2.1
Tracers 0.9 < z < 2.1

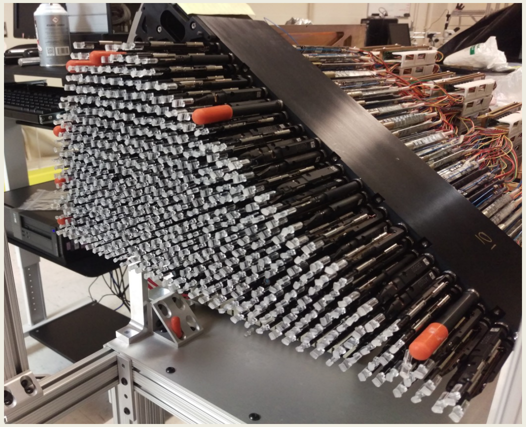
16 million ELGs
0.6 < z < 1.6

8 million LRGs
0.4 < z < 1.0

13.5 million Brightest galaxies
0.0 < z < 0.4

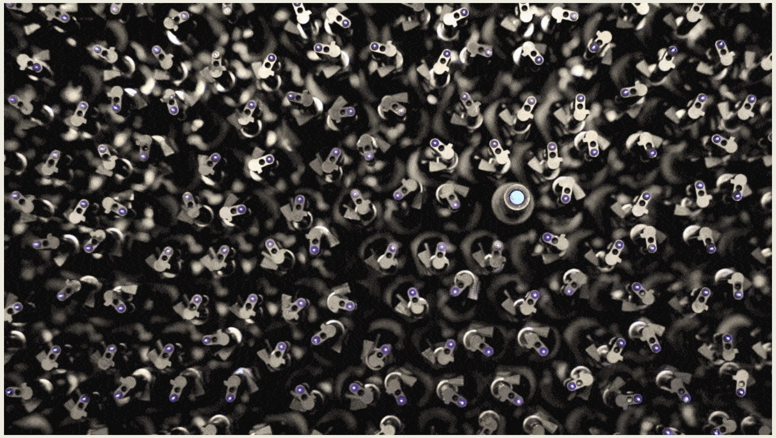


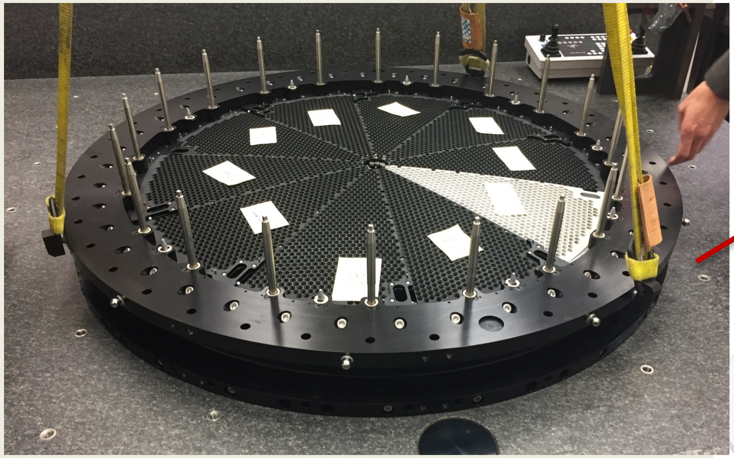
5000 robotic fiber positioners

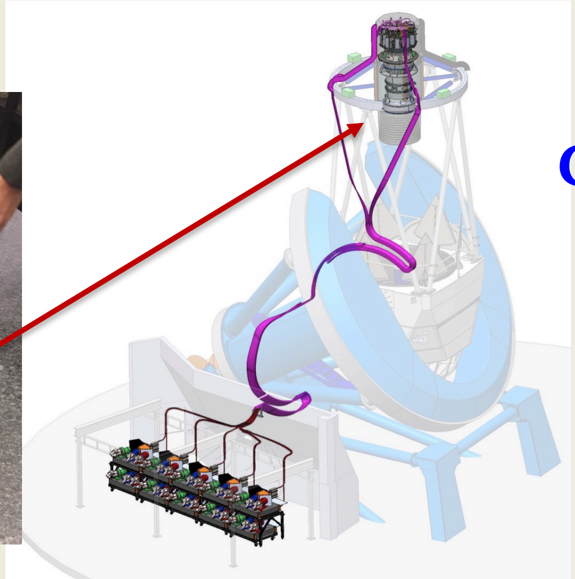


Configuration

- 10 petals in focal plane
- 500 fibers each petal
- 5000 total
- 10.4 mm pitch
- 2 motors per positioner







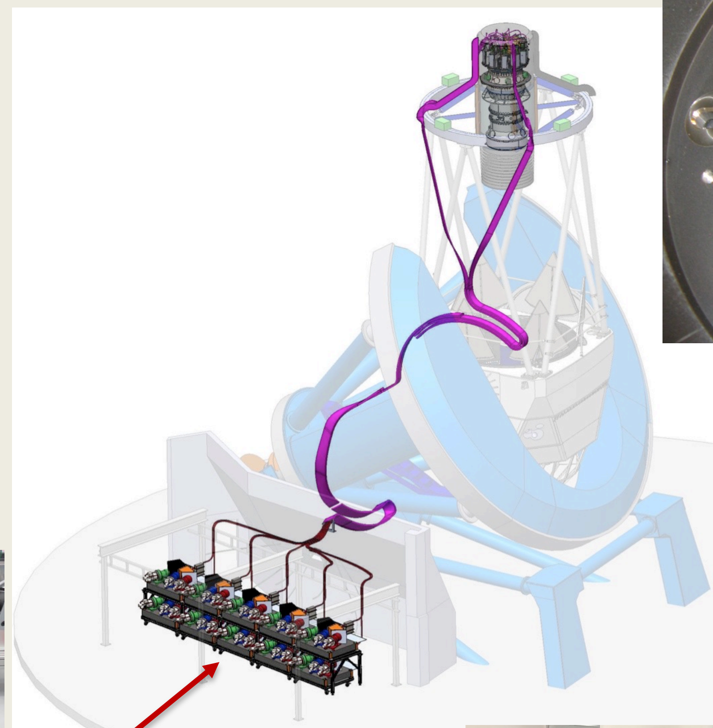
Challenge

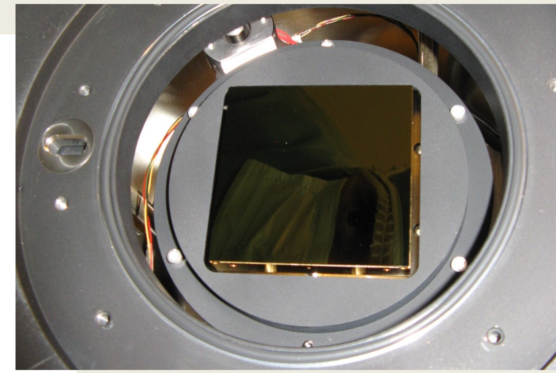
– Reposition the 5000 fibers in less than 2mns
– Position of each fiber better than 15 mm

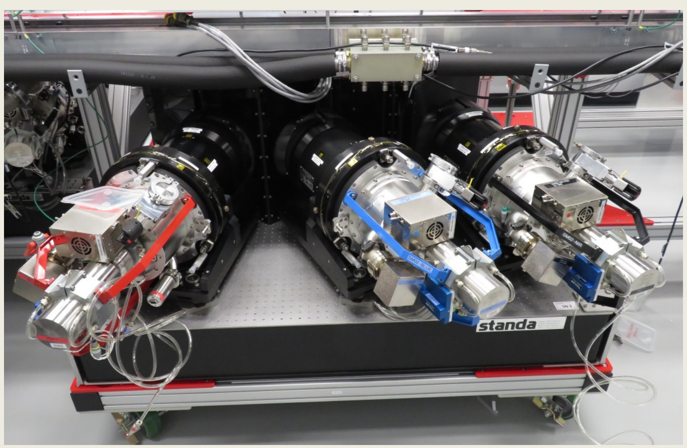
Ten spectrographs

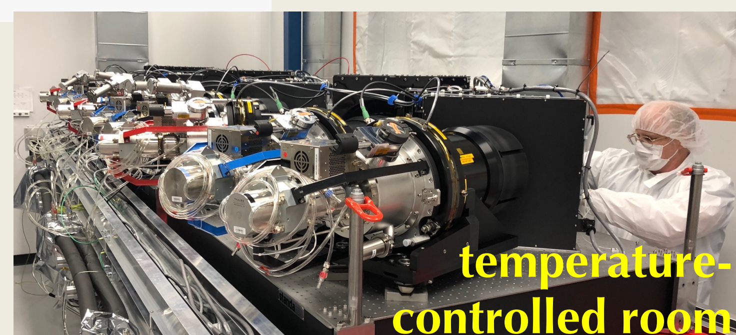
Ten 3-channel spectrographs

l = 360 nm to 980 nm





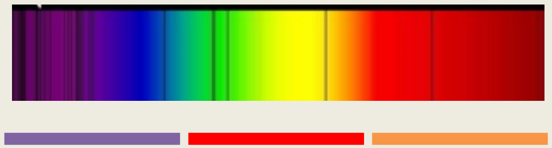




Ten spectrographs

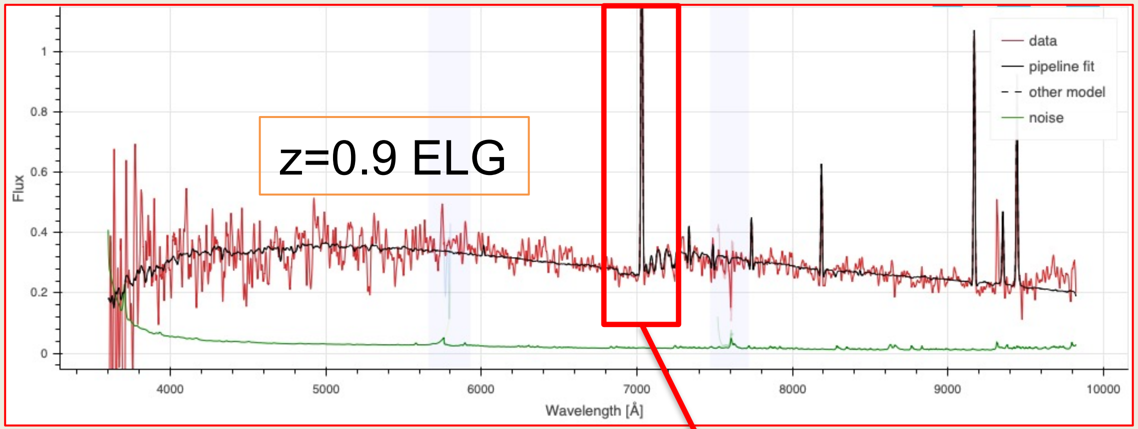
Ten 3-channel spectrographs

λ = 360 nm to 980 nm



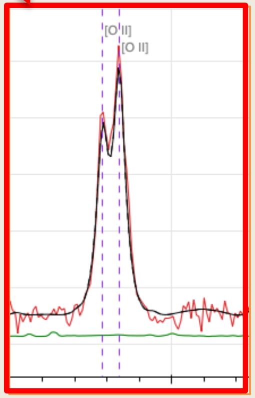
$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

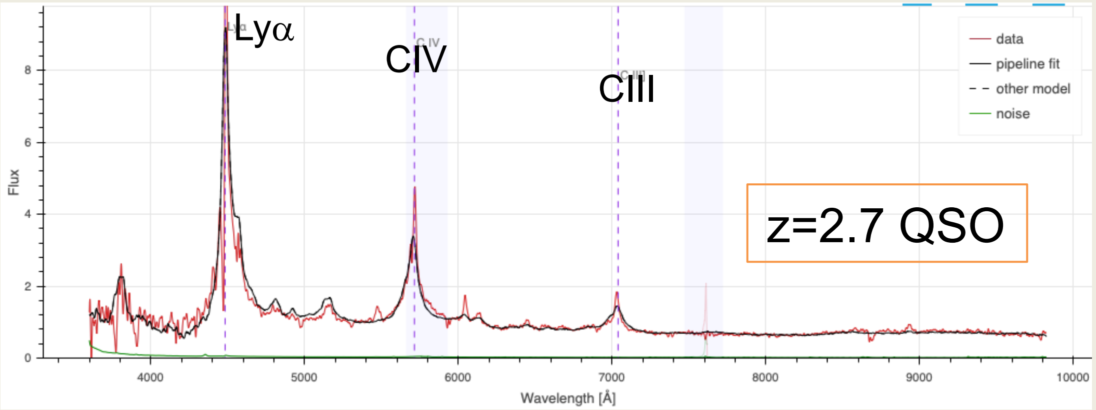
[OII] 373 nm
up to z = 1.6



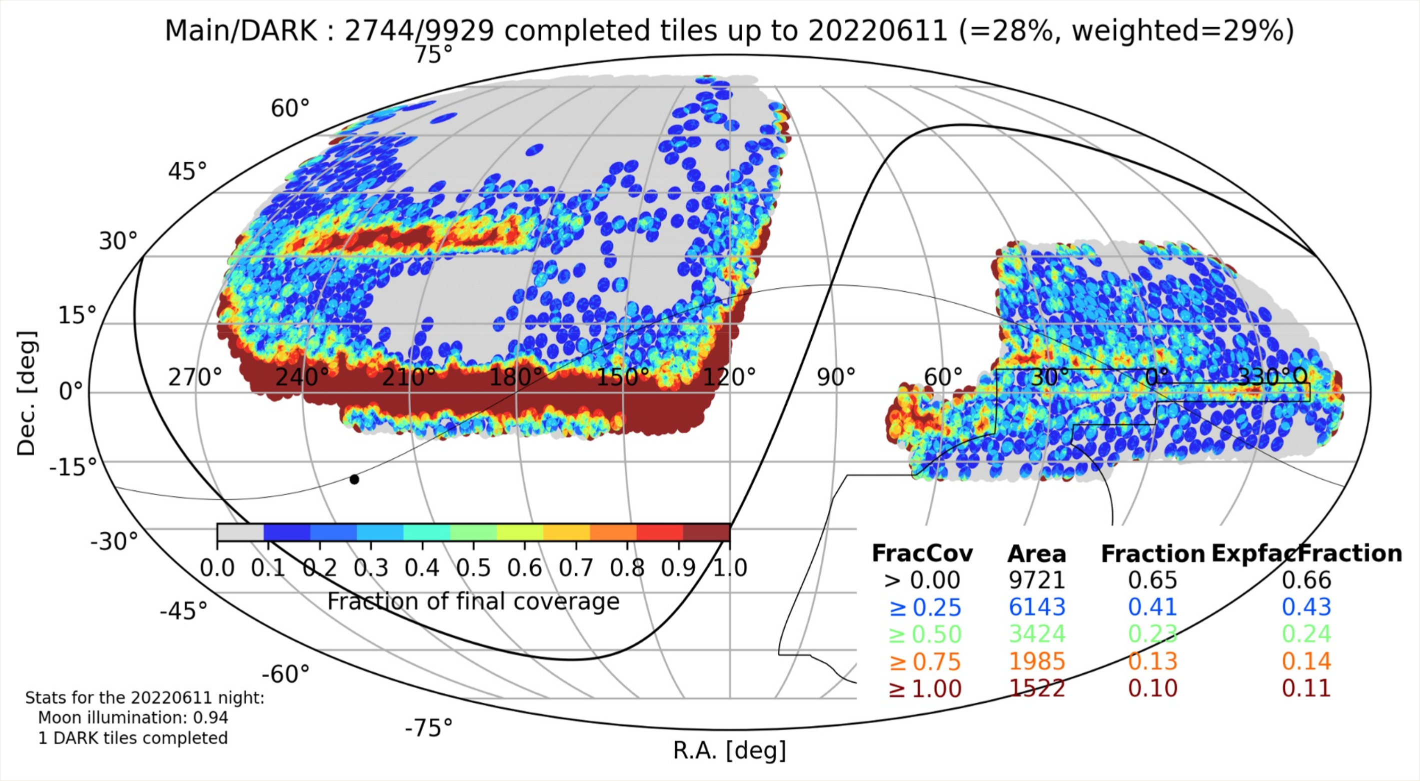
Ly-α 121.6 nm
down to z = 2.0

[OII] doublet



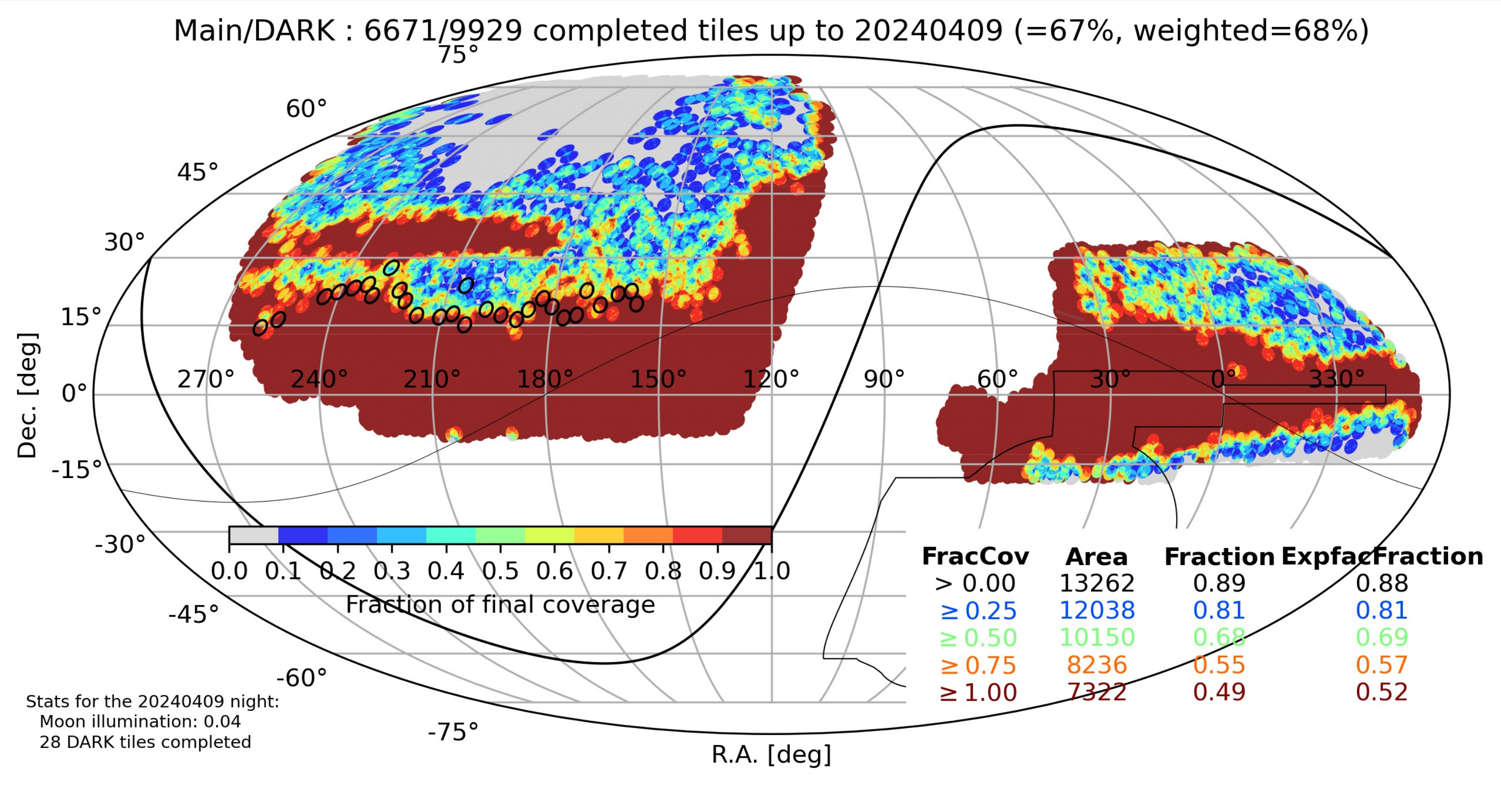


DESI Y1footprint



- Grey area: DESI footprint over 5 years, ~14000 deg^2
- On average 5 passes
- In Y1, only 1500 deg^2 with 5 passes

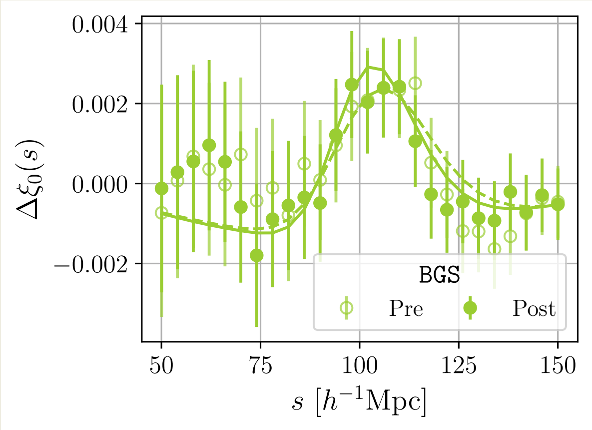
Observations: current status



- In April 2024, Y3 dataset is completed and frozen
- ~70% of the final dataset (much more ELGs)
- In Y3, already 7300 deg^2 with 5 passes

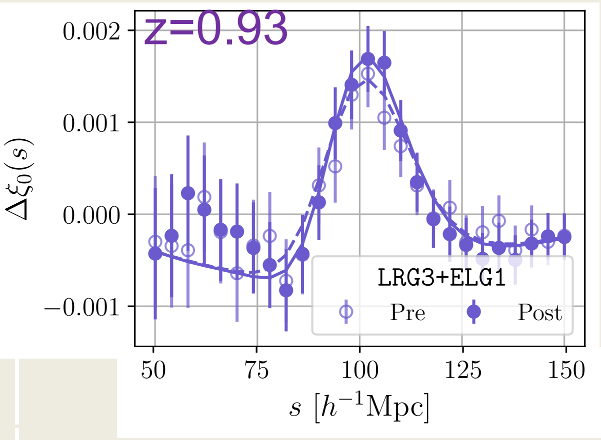
First results

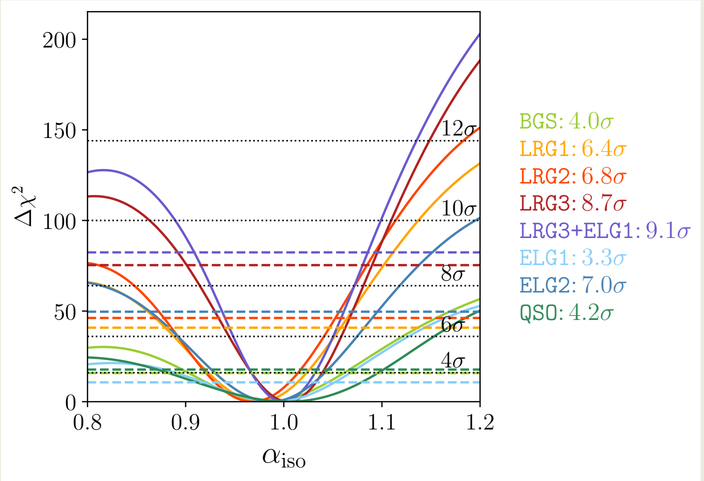
BGS z=0.30



LRG3+ELG1

z=0.93





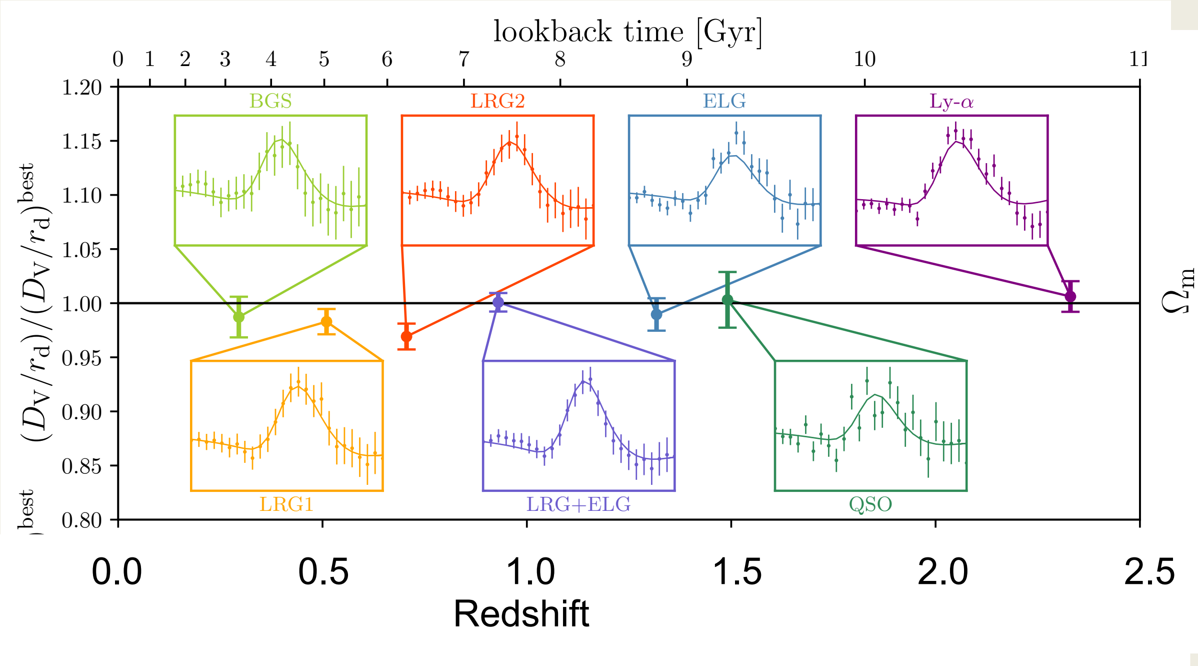
Significance: 4.0σ
Precision: 1.85%

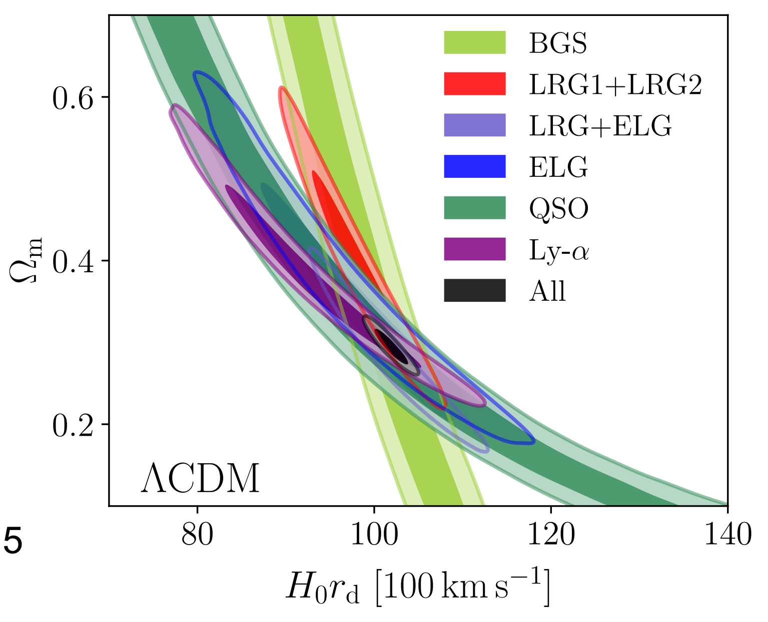
Significance: 9.1σ
Precision: 0.81%

- **Dilation compared to a fiducial cosmology**
  - Perpendicular or parallel to the line of sight, $\alpha_\perp$ and $\alpha_{||}$
  - Combined through $\alpha_{\mathrm{iso}} = (\alpha_\perp^2 \alpha_{||})^{1/3}$
- 6 bins in redshifts covering the redshift range, 0.1<z<2.1
- Bin with lowest significance 4.0

Measurement of Ω_m

$$\alpha_\perp = \frac{D_M}{r_d}\frac{r_d^{fid}}{D_M^{fid}} \qquad \alpha_{||} = \frac{H^{fid} r_d^{fid}}{H r_d} \qquad \alpha_{iso} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$$

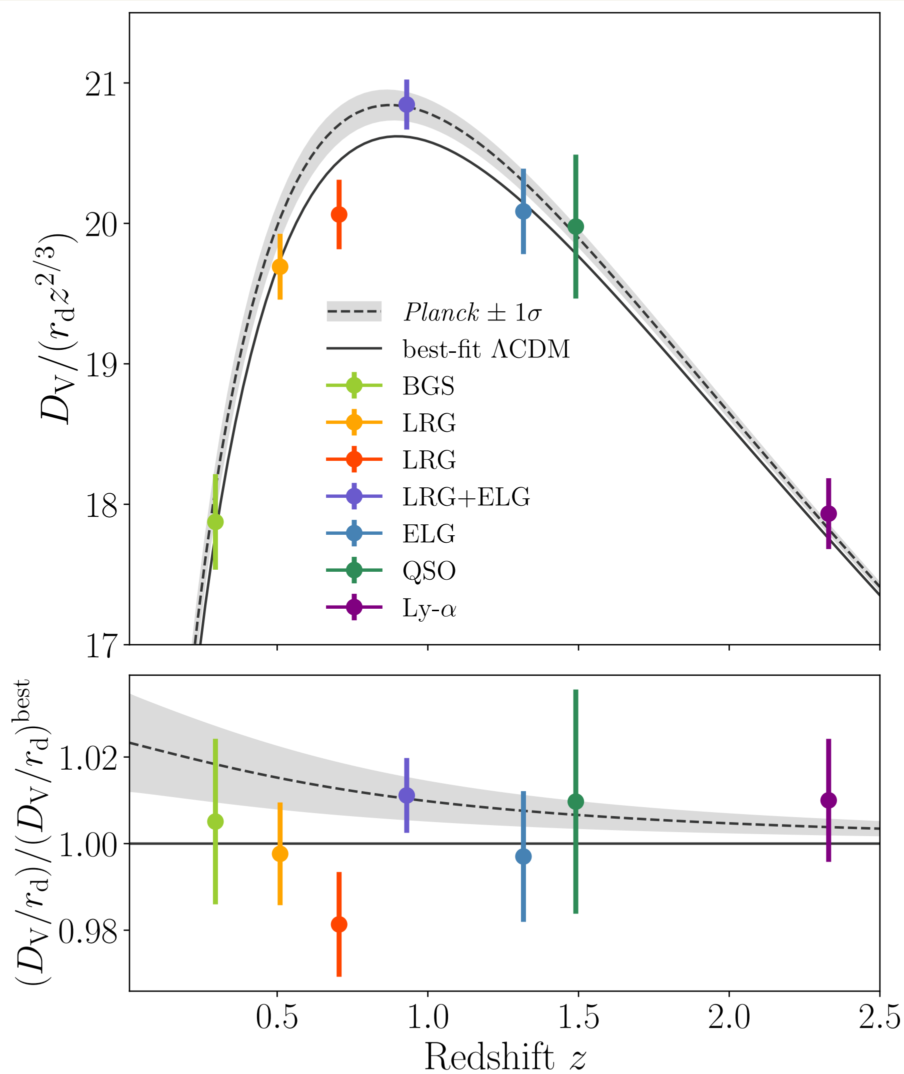




- Different dependence as a function of redshift (Ω_m, r_d)
- Break the degeneracy without knowing r_d

$$\Omega_m = 0.3069 \pm 0.0050\ (1.6\%)$$

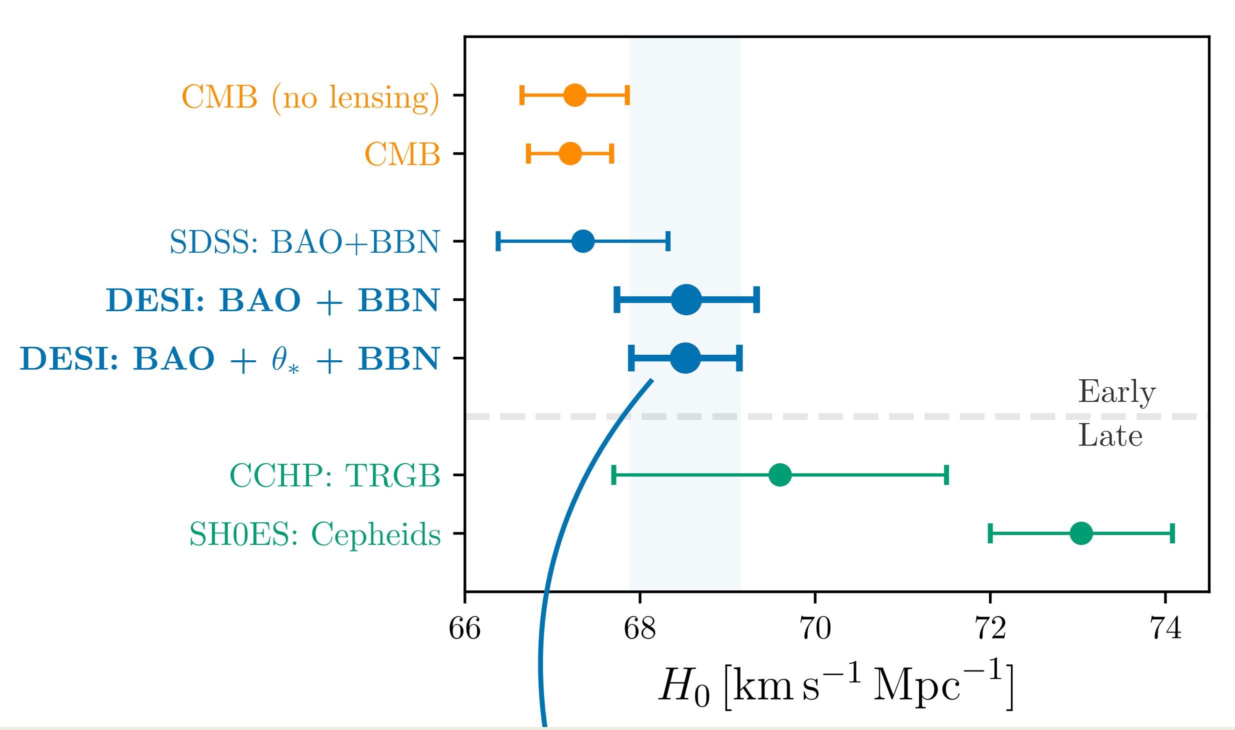
Hubble diagram



- ~6M discrete tracers
- 0.1<z<2.1
- 3 times bigger than SDSS

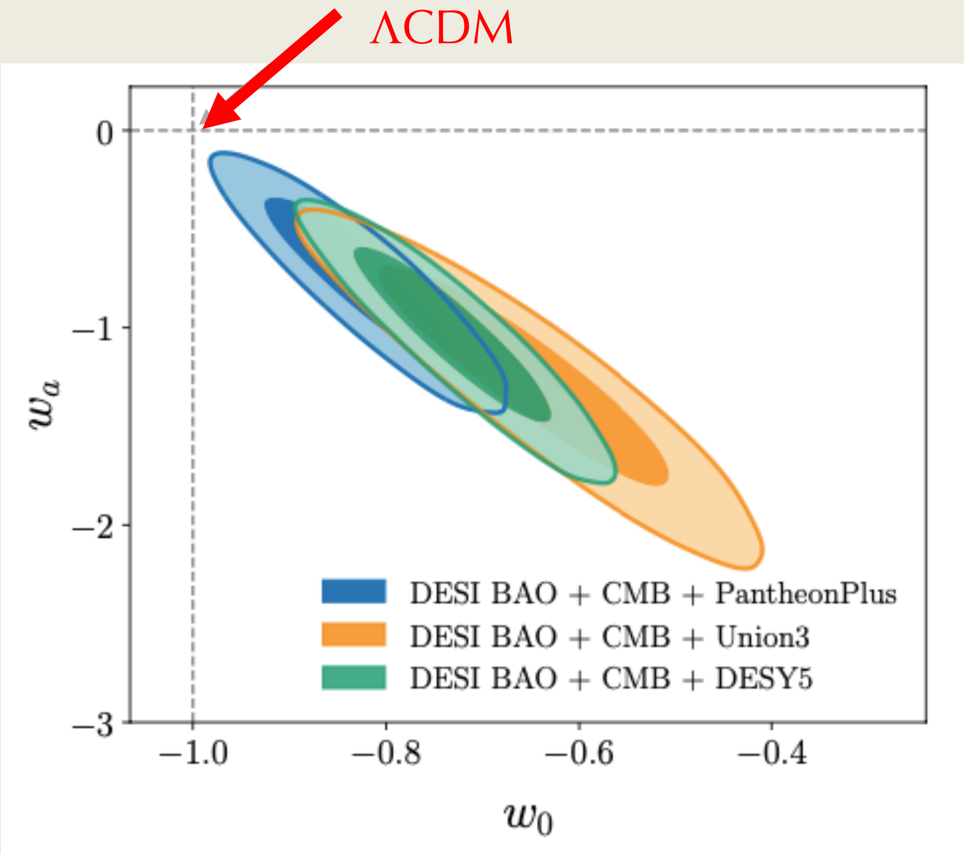
- Total precision on BAO: 0.52%
- Consistent with ΛCDM
- Agreement with Planck: 1.9σ
- BAO ~almost systematic free measurements

Measurement of H_0



- Big Bang Nucleosynthesis can be used to measure r_d
- BAO peak in CMB (θ_*) can constrain r_d too!
- Consistency with CMB: 2.1σ
- Consistency with SNIa (SH0ES): 3.7σ

Beyond ΛCDM



Dark Energy Equation of State

$$w(z) = \frac{p(z)}{\rho(z)}$$

$$w(z) = w_0 + \frac{z}{1+z} w_a$$

- For ΛCDM, we expect w=-1, i.e. w_0=-1 and w_a=0
- Combining DESI+CMB+SN: 2.5σ to 3.9σ effect depending on the SN samples
- **Indication of dynamical dark energy with DESI???**