The path of cosmology in the decade

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DESI

LSST
Large Synoptic Survey Telescope

Journée de la SFP, Division Champ & Particules
LPNHE Jussieu – July 10, 2023

Outlines

- History and Basics of Cosmology
- CMB and H_0 controversy
- BAO and Dark Energy
- Inflation
- Neutrino Masses

History and Basics of Cosmology

1929 - Expanding Universe

0.7Mpc at z=0.39

Hubble's law: $V=H_0d$

- Discovery by Lemaitre and Hubble
- Measurement of the velocity V of galaxies with **their redshift (z)**

$$z=(\lambda-\lambda_0)/\lambda_0$$

- Illustration with the SMACS 0723 galaxy cluster ($8.10^{13}m_\odot$ R_{vir}=2.4Mpc) observed by JWST

What value of H_0?

- Controversial and controverted measurement

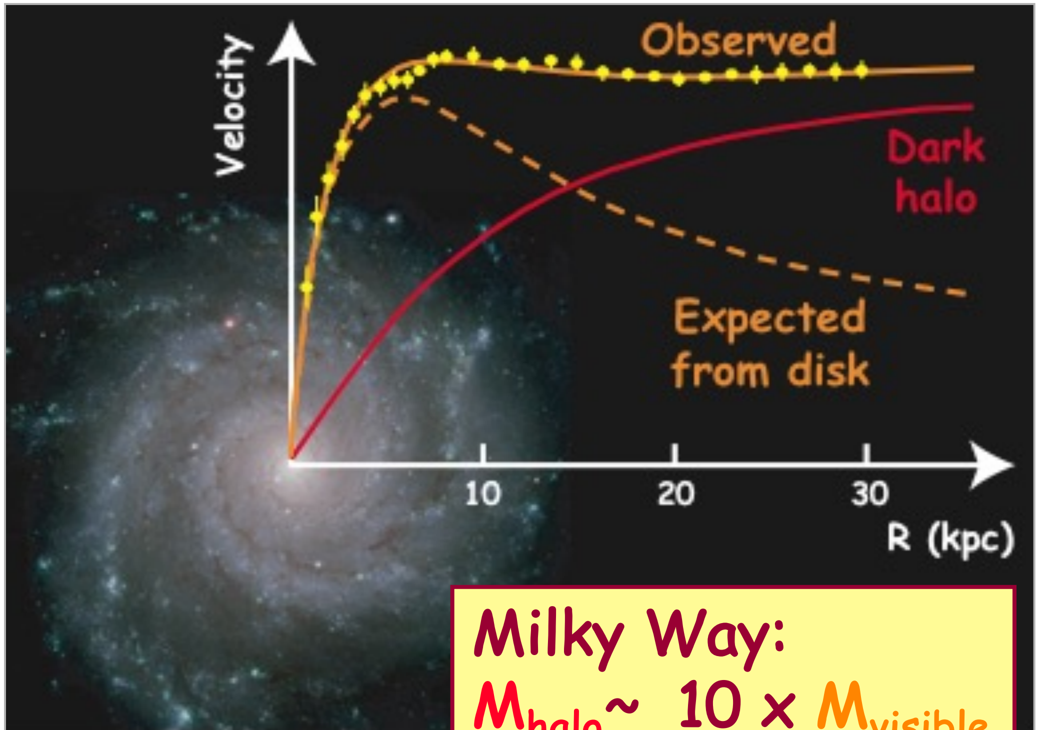
What about gravitation?

- "Ordinary" matter $\Rightarrow$ Deceleration
- "Repulsive" matter $\Rightarrow$ Acceleration

What about matter?

- SMACS 072 cluster looks transparent to matter

1970 - Dark Matter



Milky Way:
$M_{halo} \sim 10 \times M_{visible}$

Galactic rotation curves

- Final proof by measuring the velocity of stars within galaxies
- Work of Vera Rubin and Kent Ford in the 70'

Newton Law

$$E_c + E_p = 0$$

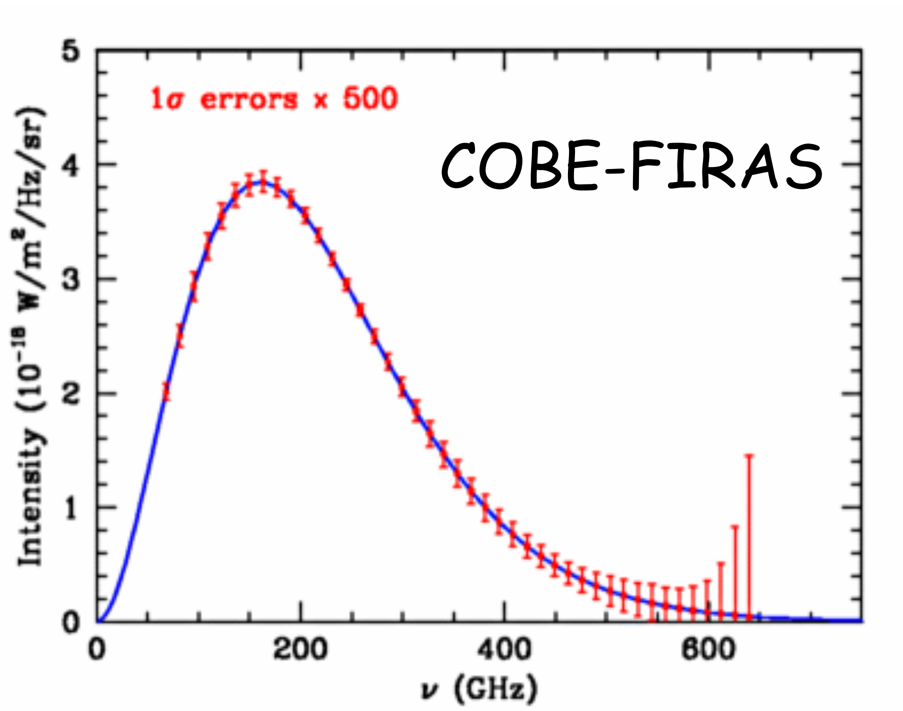
$$V_{rot} = \sqrt{\frac{2GM}{R}}$$

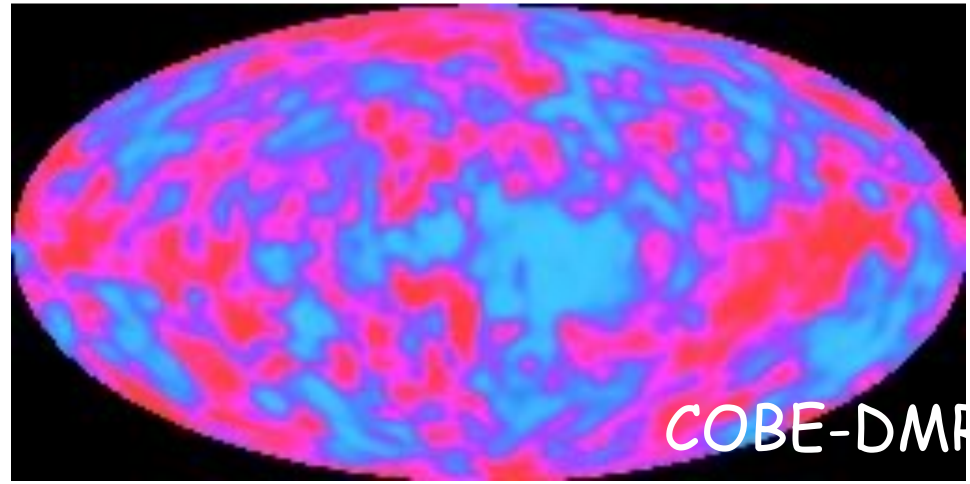
Constant rotation curve

↓

Halo of Dark Matter

1964 - CMB discovery



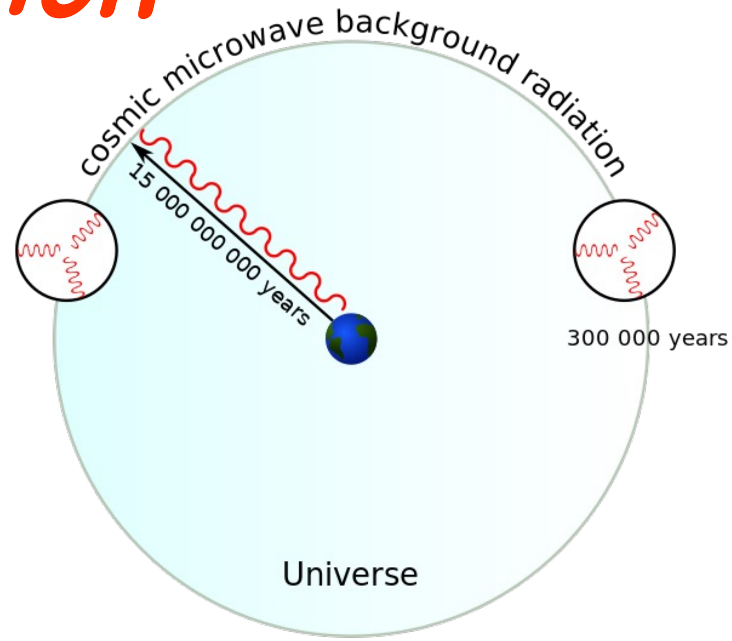


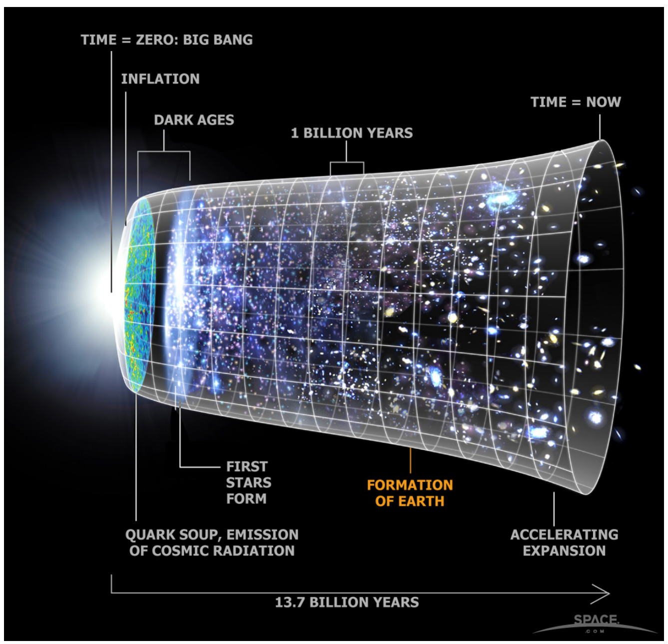
- 380 000 years: Recombination: Universe becomes transparent.
- **1964:** Discovered "by chance" by Penzias and Wilson (uniform radio "noise" at 7.5 cm ⟶ 2.7 K)
- **1989-1992:** Satellite COBE
  - Perfect black body with a temperature T=2.725K !
  - Extremely small anisotropies of 1/10000 degrees….

1979 - Inflation

Horizon problem

- Two photons in opposite direction cannot communicates between them.
- Temperature of CMB almost identical in all the directions.
- A simple solution: very fast inflation of the Universe (A. Guth 1979)





Inflation framework

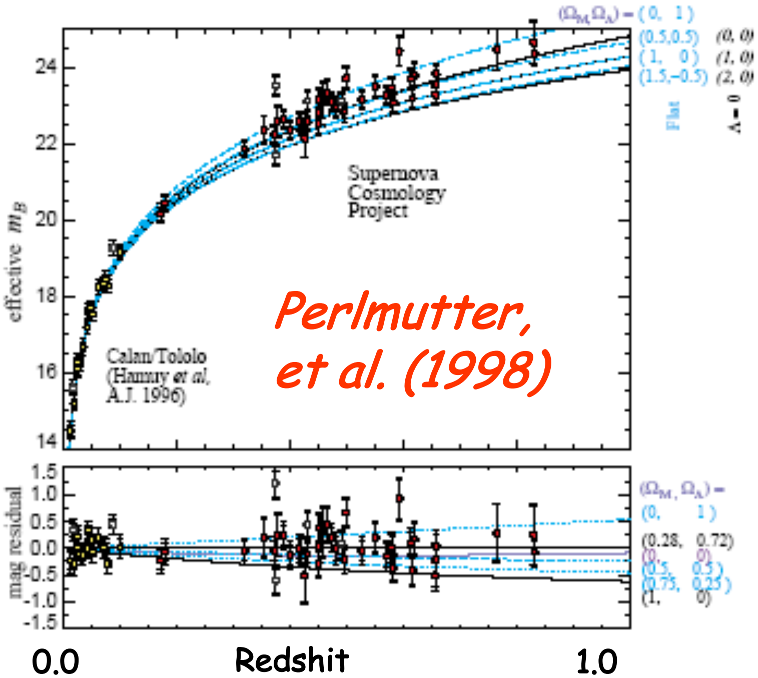
- Density energy stay almost constant

$$\frac{\dot{a}}{a} = \sqrt{8\pi G\rho/3} = \mathrm{H} = \mathrm{cste}$$

$$a \propto e^{Ht} \quad \text{with } a = 1/(1+z)$$

- Typically, the Universe expanded by a factor of about e^{60} at 10^{-36}s (after GUT)

1998 - Dark energy

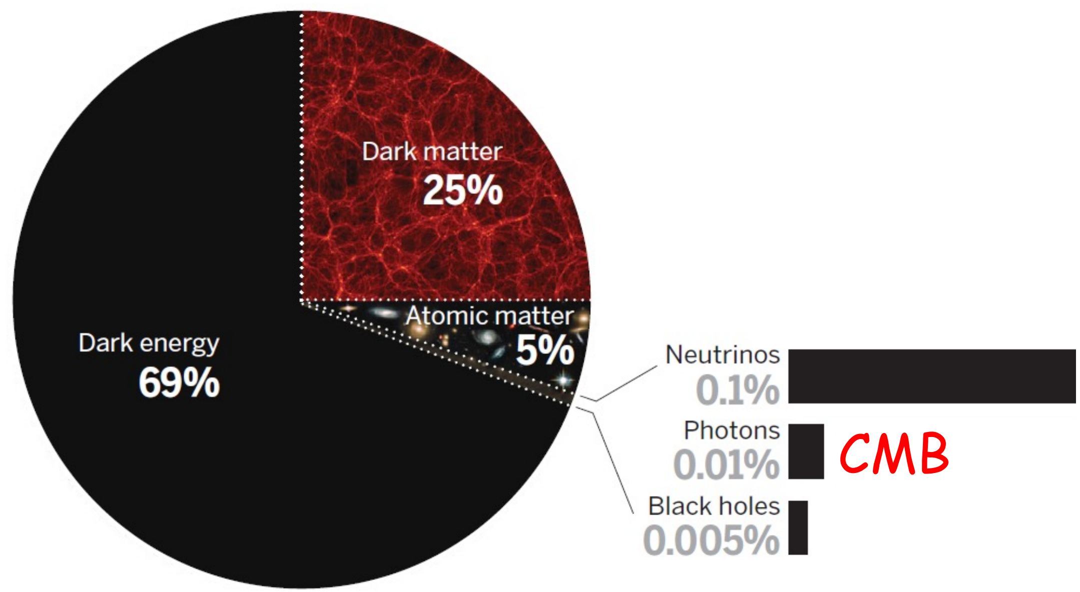


Acceleration of Universe expansion

- In 1998 revolution of cosmology with standard candles, SNIa
  - SNIa were dimmer (~0.2 mag), ~10% further away than expected with Ω_m =1 (only 'ordinary' matter)

Content of the Universe

- 2/3 of Dark Energy repulsive for gravitation
- 1/3 of "classical" matter



CMB

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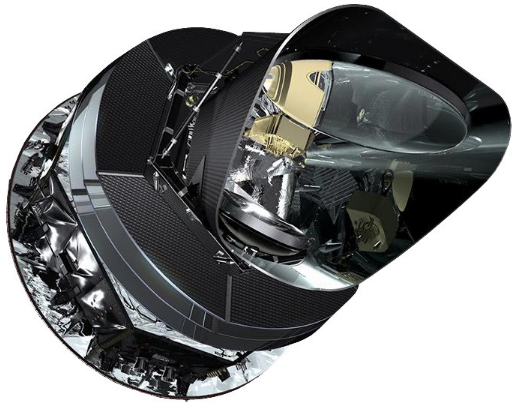
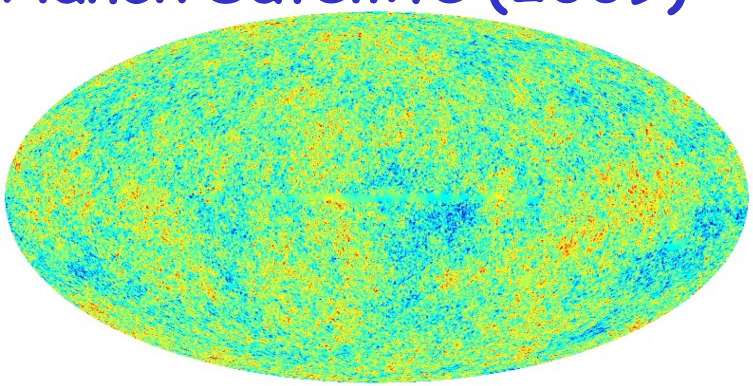
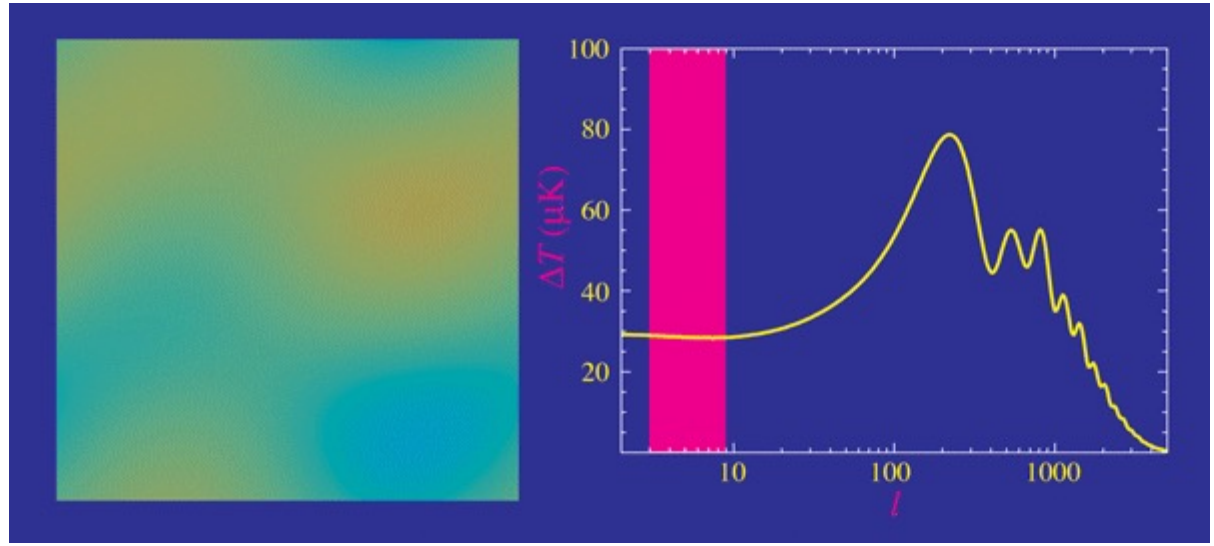
H_0 controversy

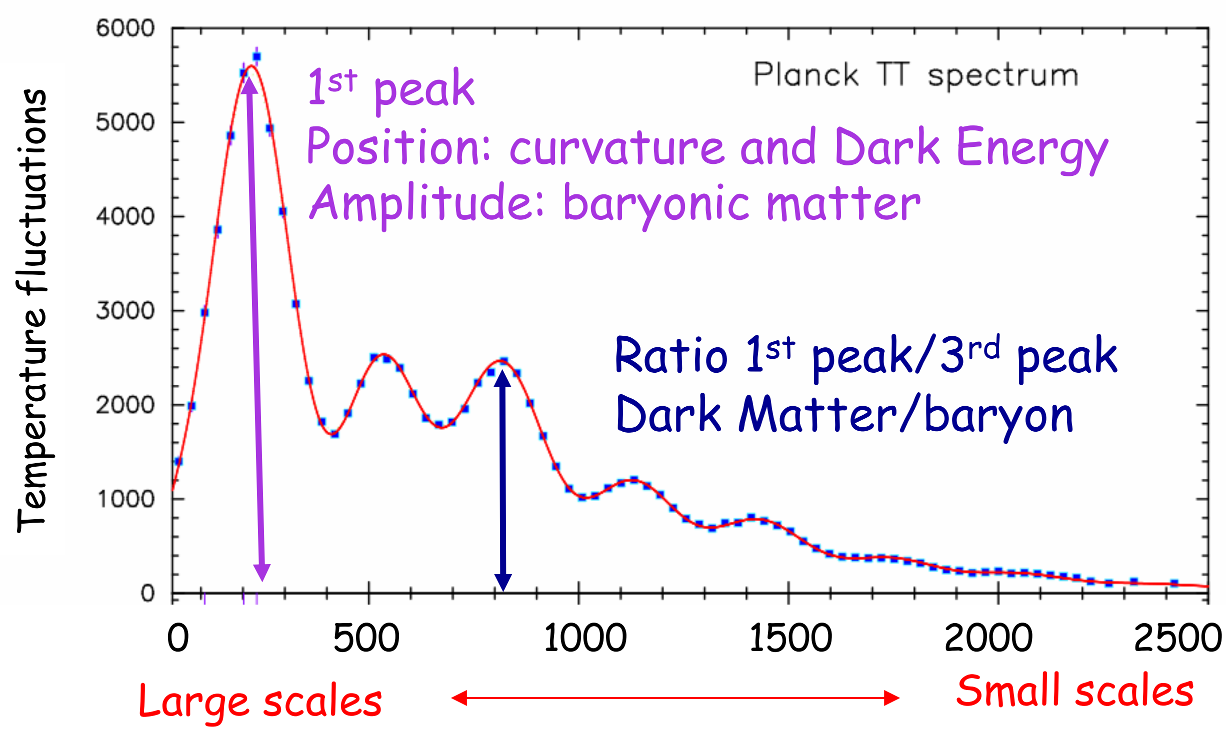
What do we learn with these maps?



Planck Satellite (2009)







CMB anisotropies

- **Angular size** of the fluctuations
- Conversion : angle $\theta \rightarrow$ multipôle $l = 180^{o}/\theta$

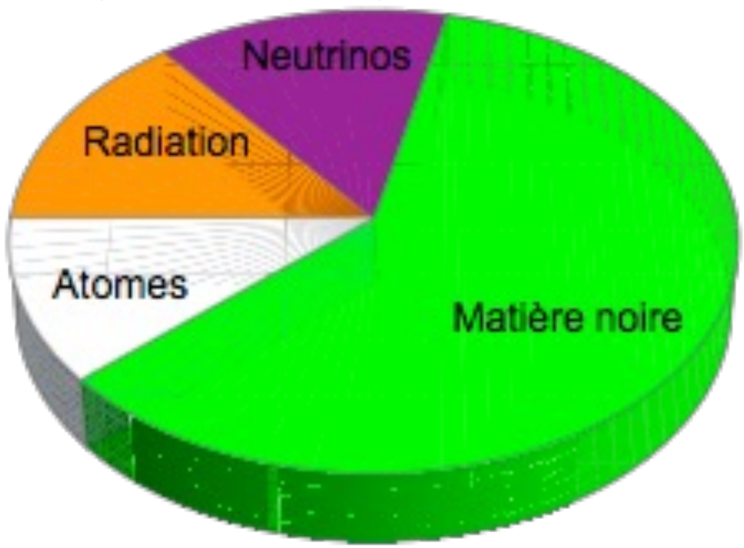
Universe content seen by Planck

- 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)



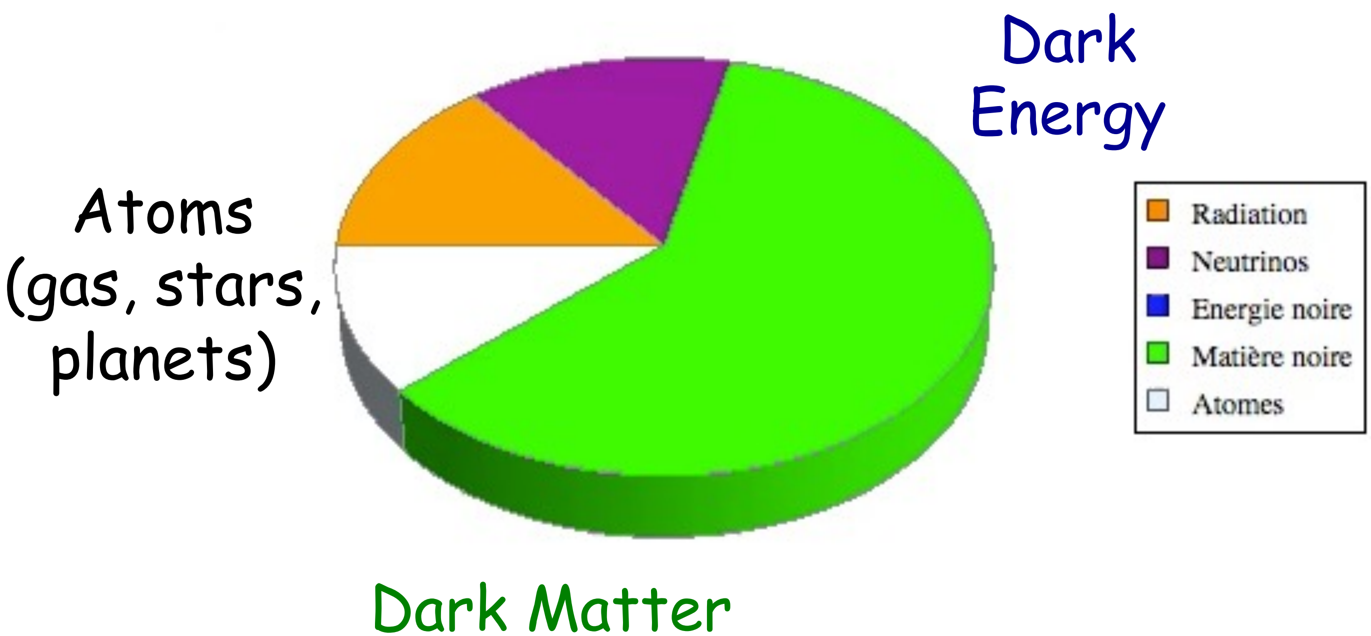
Dark Matter (SUSY, axions..)

From CMB to today

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

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

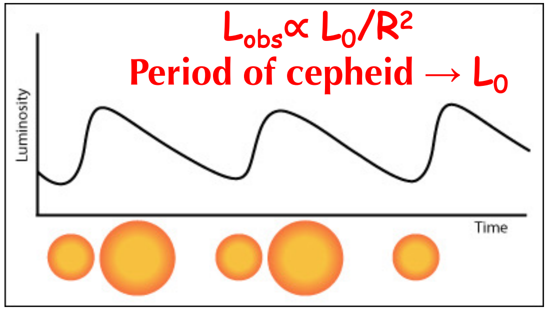
- CMB provides a prediction for H_0 that can be compared to H_0 **locally measured** by supernovae



Local measurement of H_0

Distance ladder

- Parallaxes
- Cepheids
- SN-Ia



Comparison to CMB

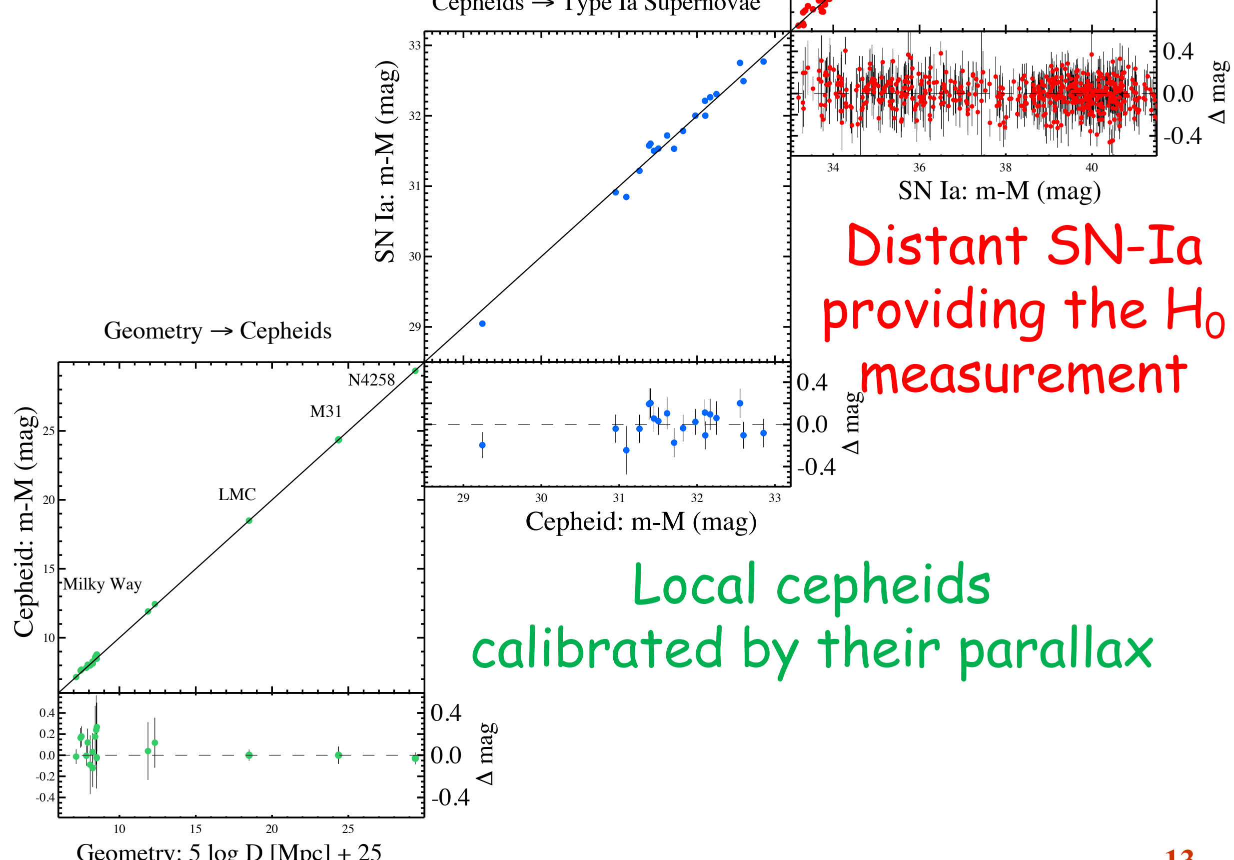
- Indirect measurement of H_0 through the evolution of the Univers assuming ΛCDM since CMB (z=1100)

5σ tension

CMB: $H_0 = 67.7 \pm 0.4$

SNIa: $H_0 = 73.0 \pm 1.0$

Riess et al., 2022

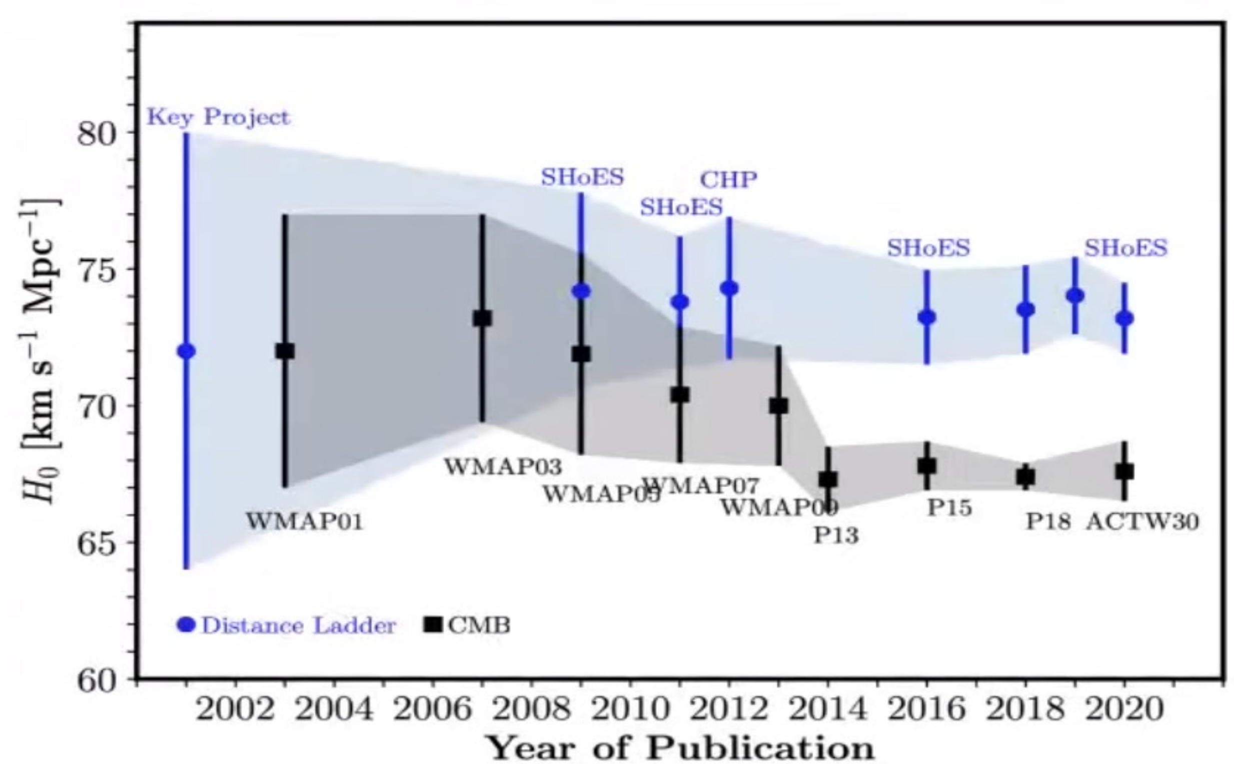


SN-Ia with cepheids in their host galaxy

Distant SN-Ia providing the H_0 measurement

Local cepheids calibrated by their parallax

Comparison CMB/Distance ladder



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 (z>3000)

$\Rightarrow$ Smaller size of the sound of horizon $\Rightarrow$ Higher value of H_0

Dark Energy

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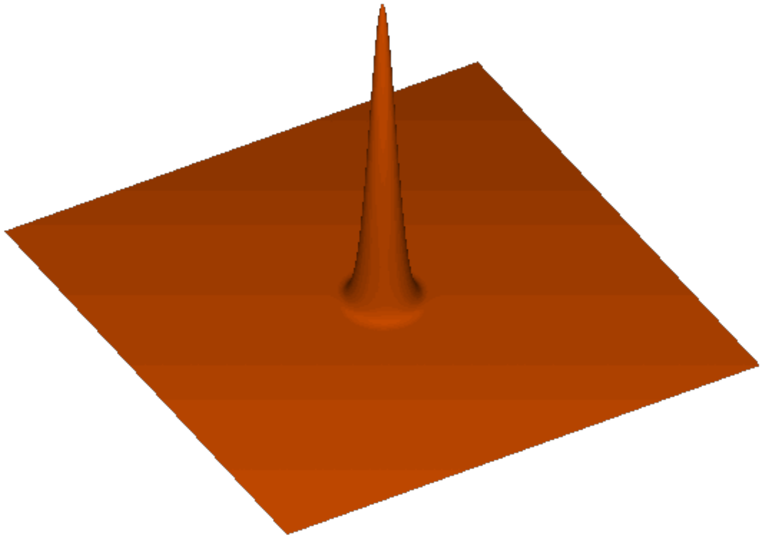
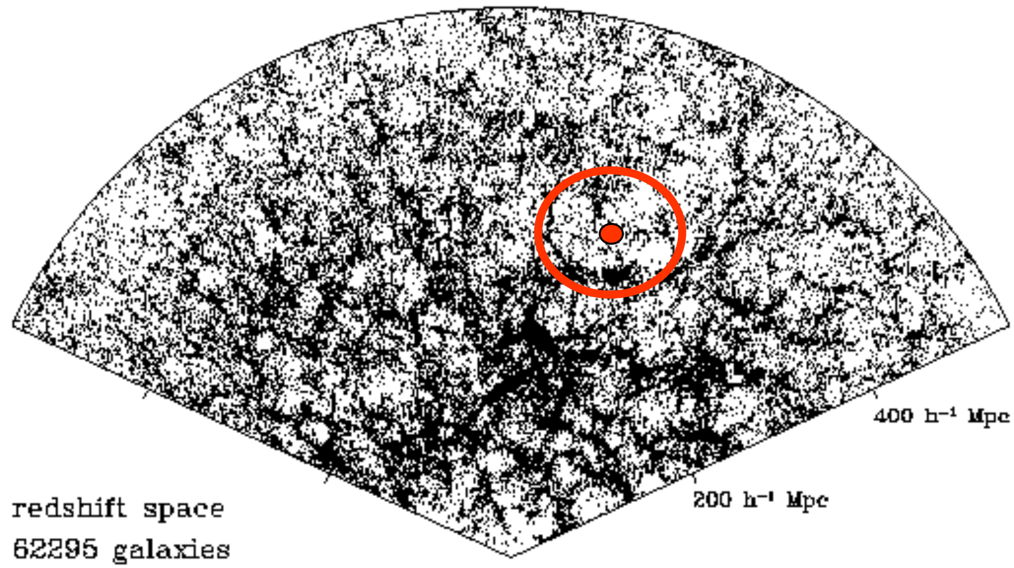
BAO

Baryonic Acoustic Oscillations





Acoustic propagation of an over-density:

- Baryon and photon perturbations travel together till recombination (z~1100) with speed $\sim c/\sqrt{3}$
- Then, the radius of the baryonic overdensity is frozen at 150 Mpc.

A special distance:

- Galaxies form in the overdense shells about 150 Mpc in radius.
- For all z, small excess of galaxies at 150 Mpc (comoving dist.)

$\Rightarrow$ Standard Ruler

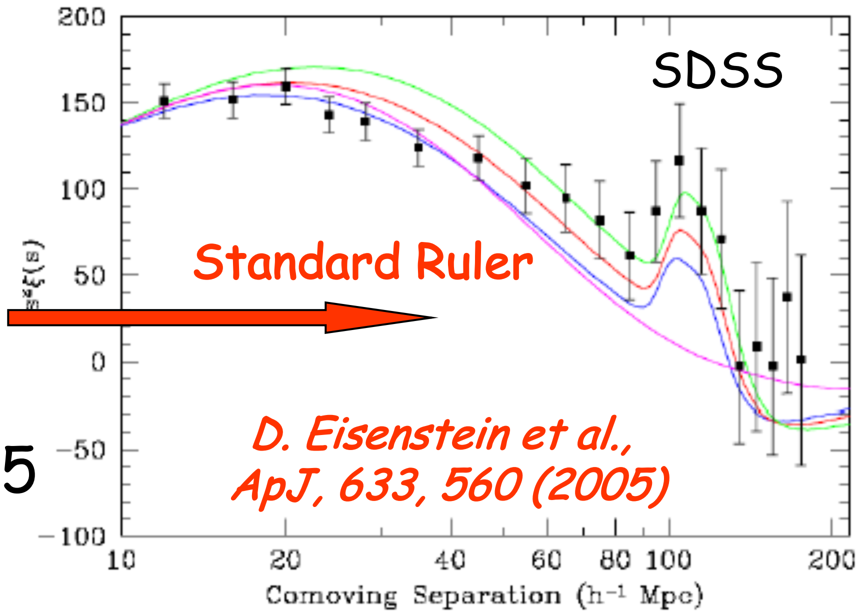
2005 - Observation of BAO

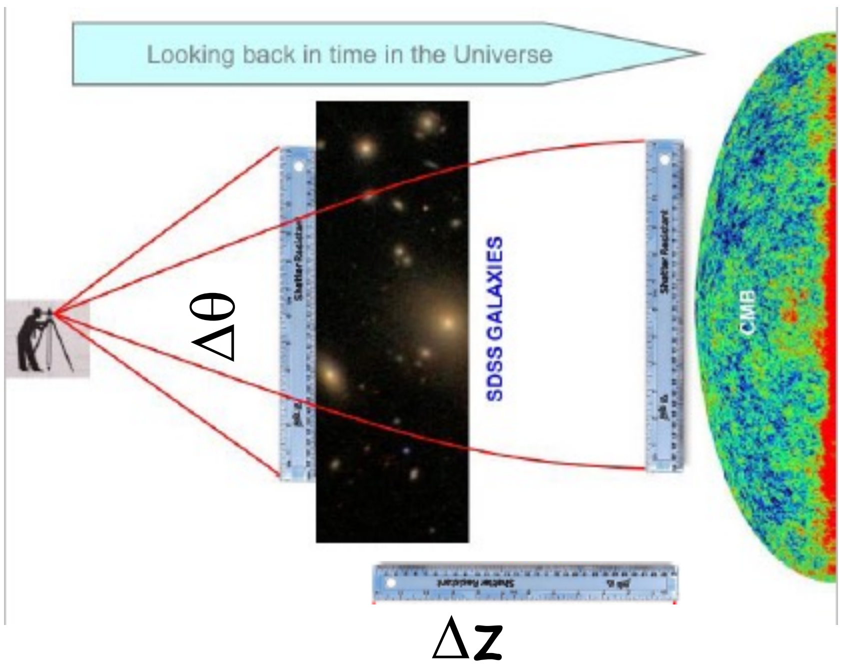
First observation:

➢ In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)

➢ SDSS observe a peak at ~150 Mpc

➢ SDSS: ~50 000 LRGs <z> ~ 0.35





A 3D measurements:

➢ Position of acoustic peak

➢ Transverse direction:

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

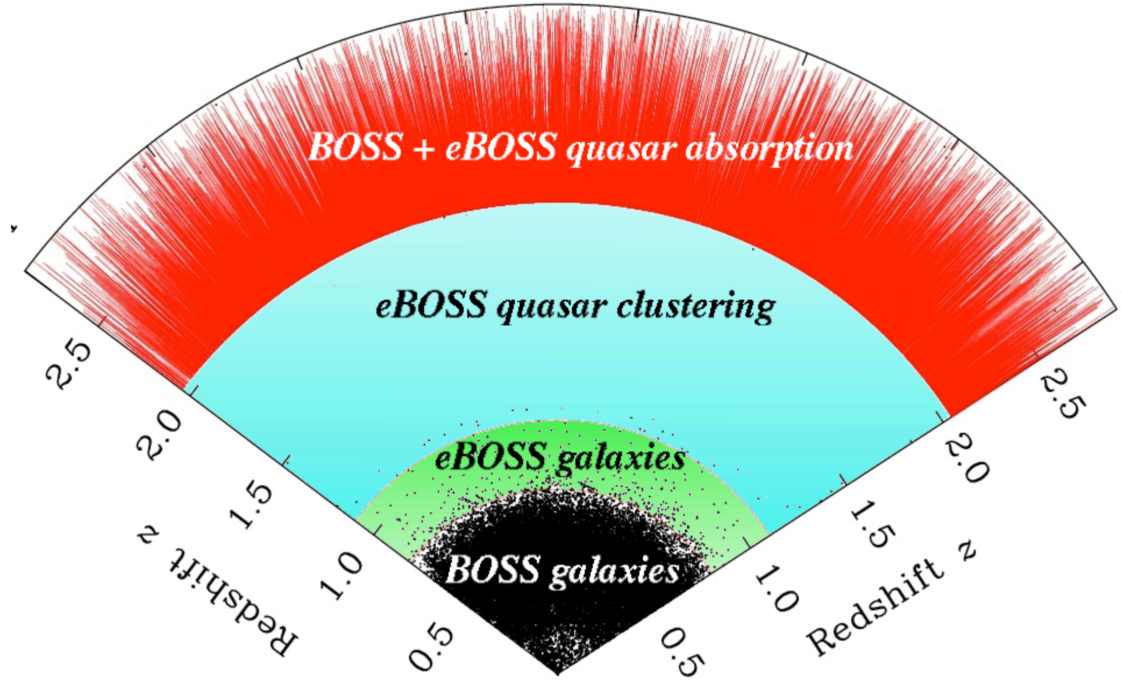
⇒ Sensitive to angular distance $D_A(z)$

➢ Radial direction (along the line of sight)

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

⇒ Sensitive to Hubble parameter H(z).

SDSS: 2009-2019



BOSS (2009→2014)

- 1.2 millions of Luminous Red Galaxies (LRG)
  - $0.15<z<0.7$
- 170 000 quasars
  - $z>2.1$, HI absorption)

eBOSS (2014→2019)

- Redshift of LRG extended to 0.8
- Emission Line Galaxies (ELG): star forming galaxies, $z\sim0.85$
- Quasars direct tracers
  - $0.9<z<2.2$

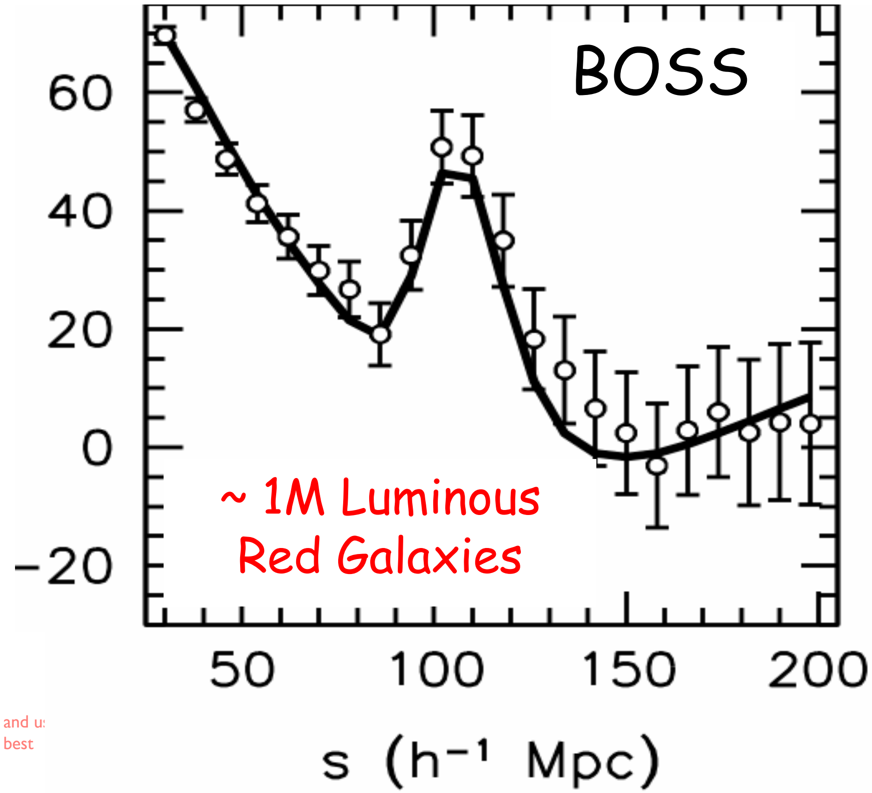
BAO with galaxies and quasars

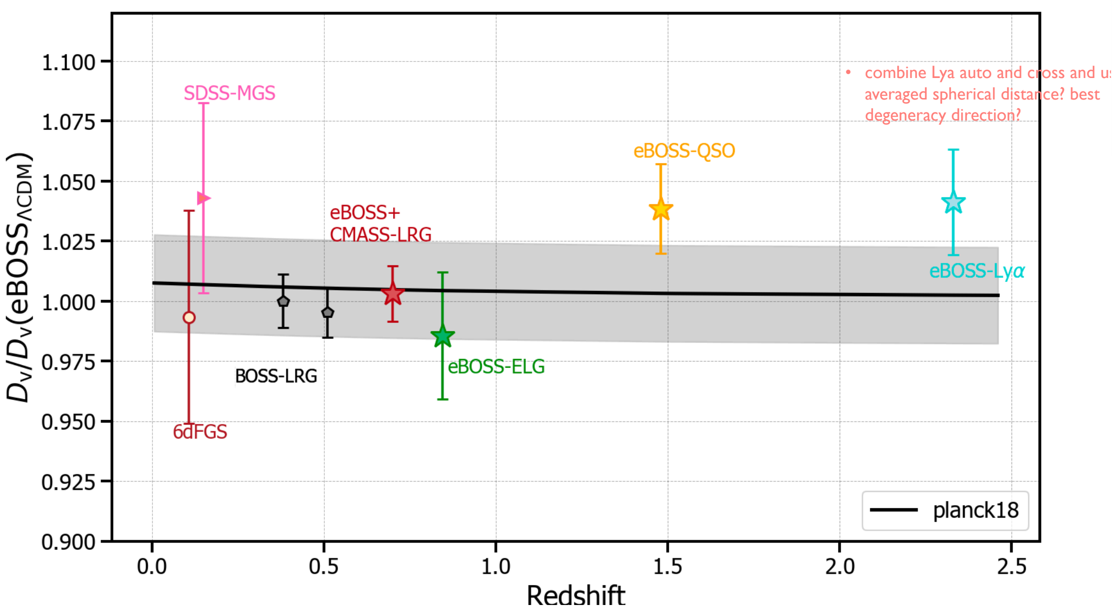
Confirmation with BOSS in 2012

- Redshift range 0.15<z<0.7
- BOSS-only 8-σ observation of BAO

Even better with eBOSS in 2020

- Redshift range 0.15<z<2.5

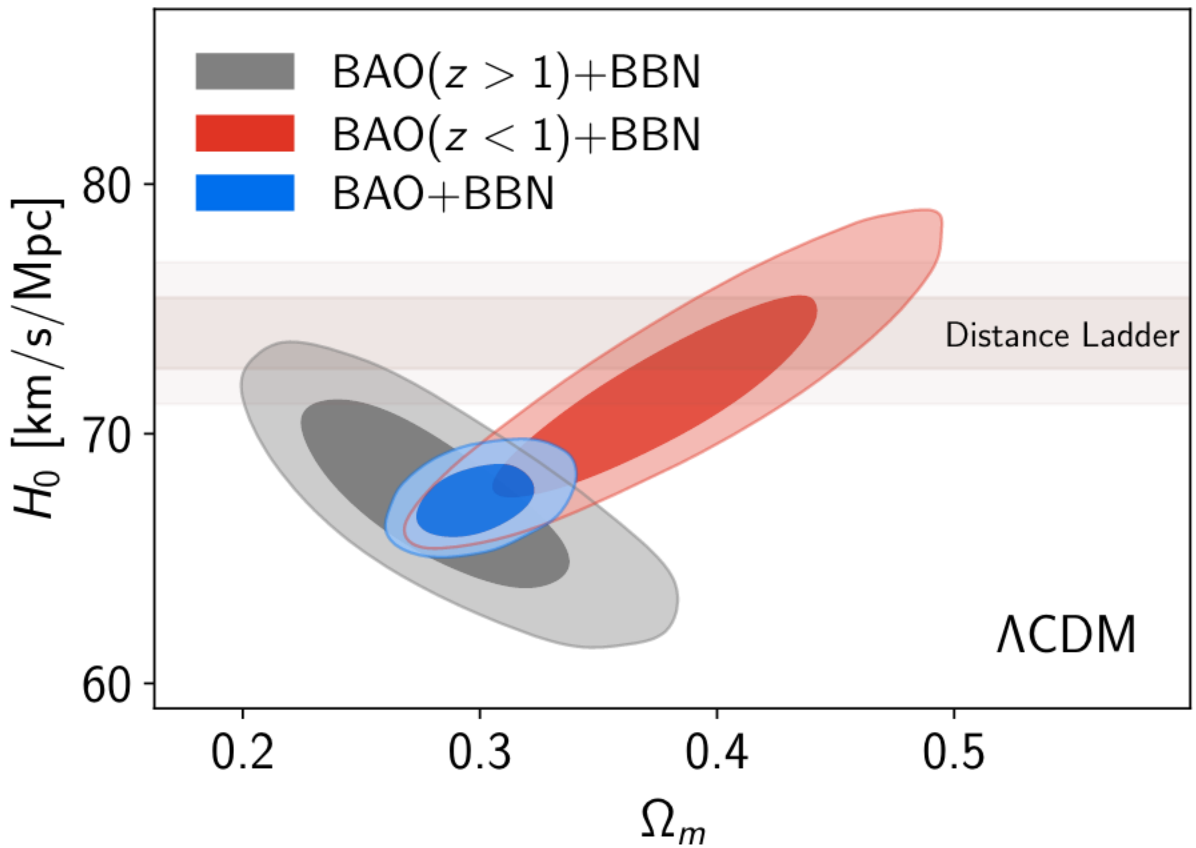




Agreement with Planck

- BAO scales consistent with Planck
- Consistency of cosmological measurements

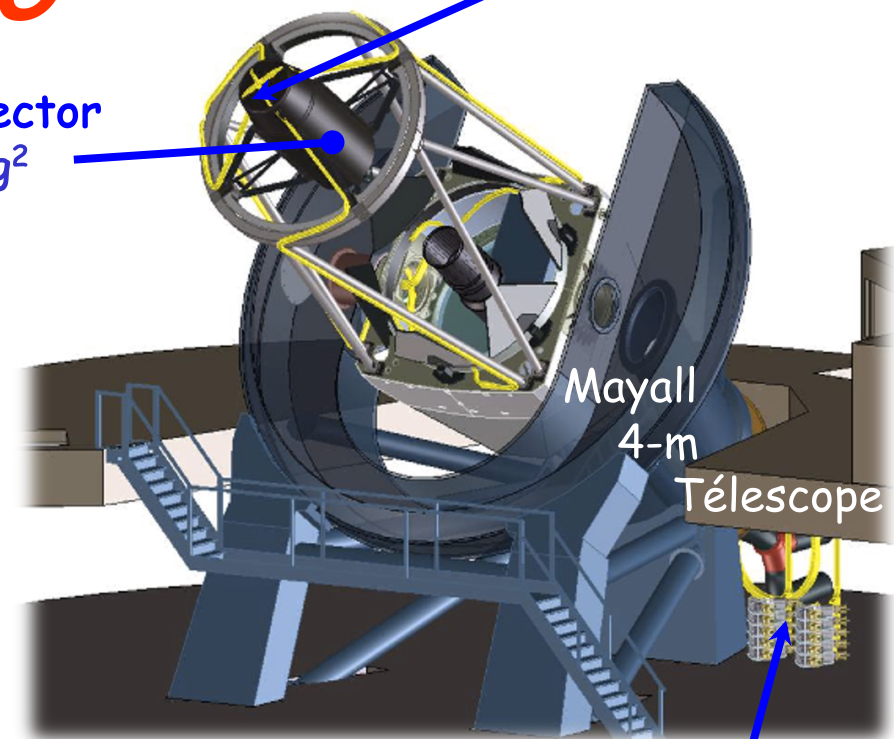
H0 controversy - Dark Energy



With BAO and Big Bang Nucleosynthesis (BBN)

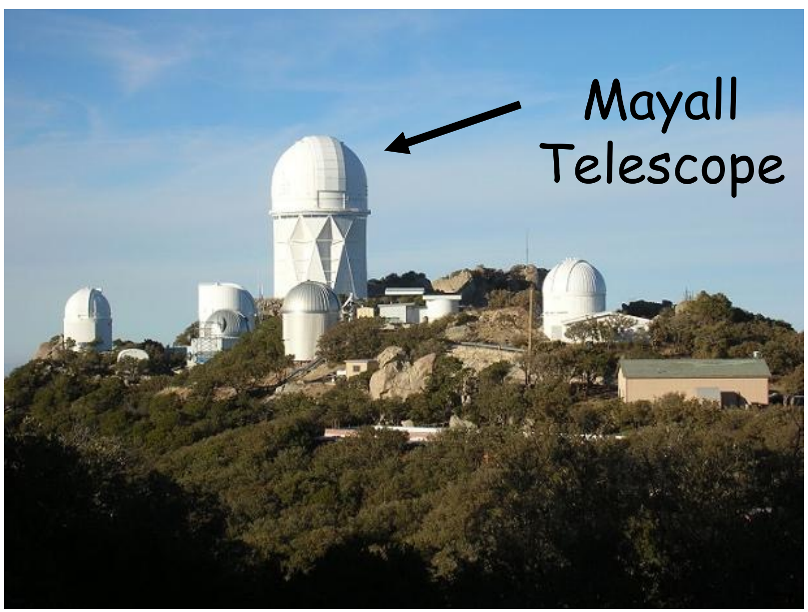
- Observation of Dark Energy (Ω_Λ~0.7)
- Confirmation of Planck value for H_0

DESI 2021-2026



Scientific Project

- 1/3 of the sky
- 3D survey for 0<z<4
- International collaboration
- 74 institutions (46 non-US)



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

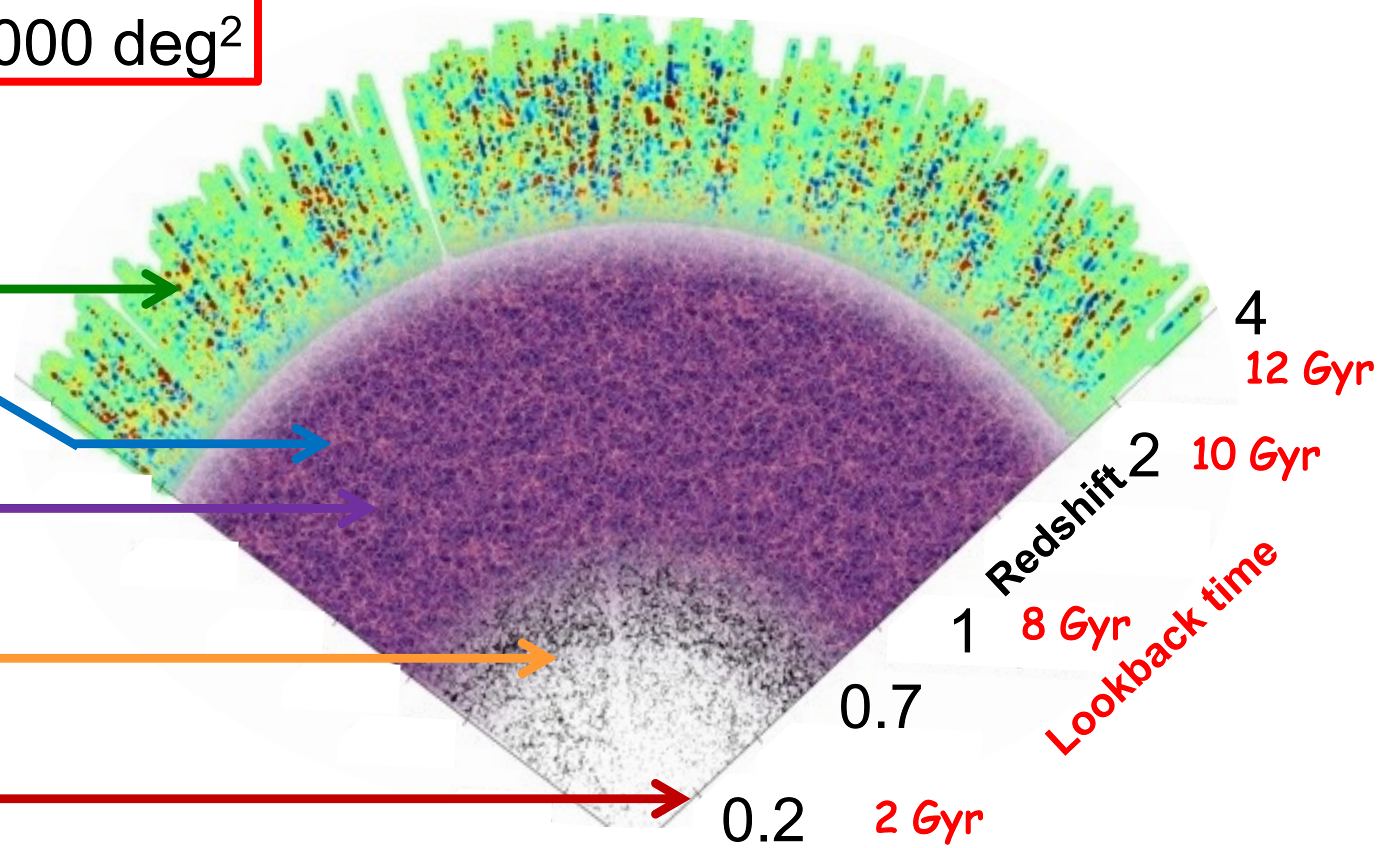
Five target classes
~40 million redshifts
in 5 years over 14000 deg^2

3 million QSOs
Ly-α $z > 2.1$
Tracers $0.9 < z < 2.1$

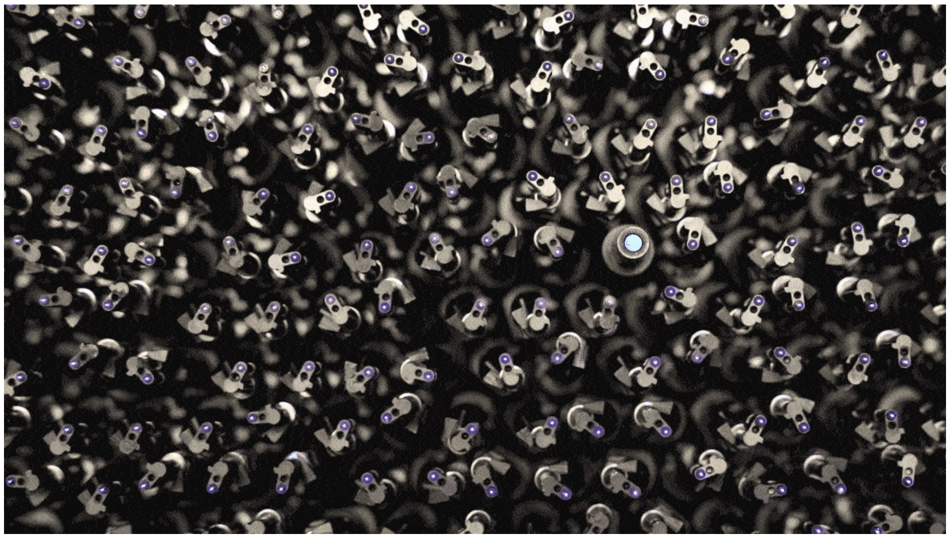
16 million ELGs
$0.6 < z < 1.6$

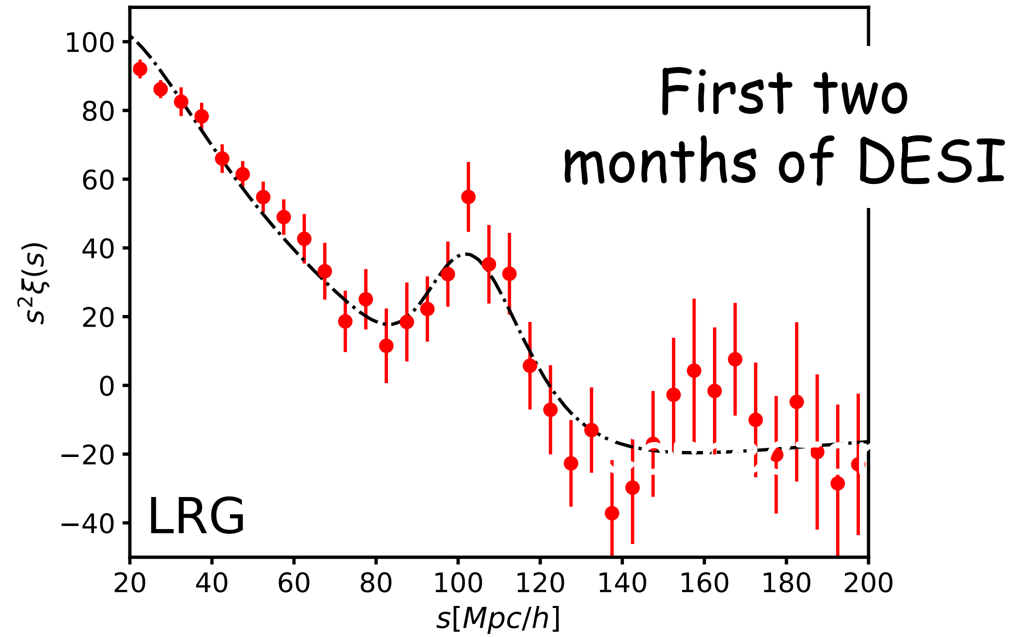
8 million LRGs
$0.4 < z < 1.0$

13.5 million
Brightest galaxies
$0.0 < z < 0.4$



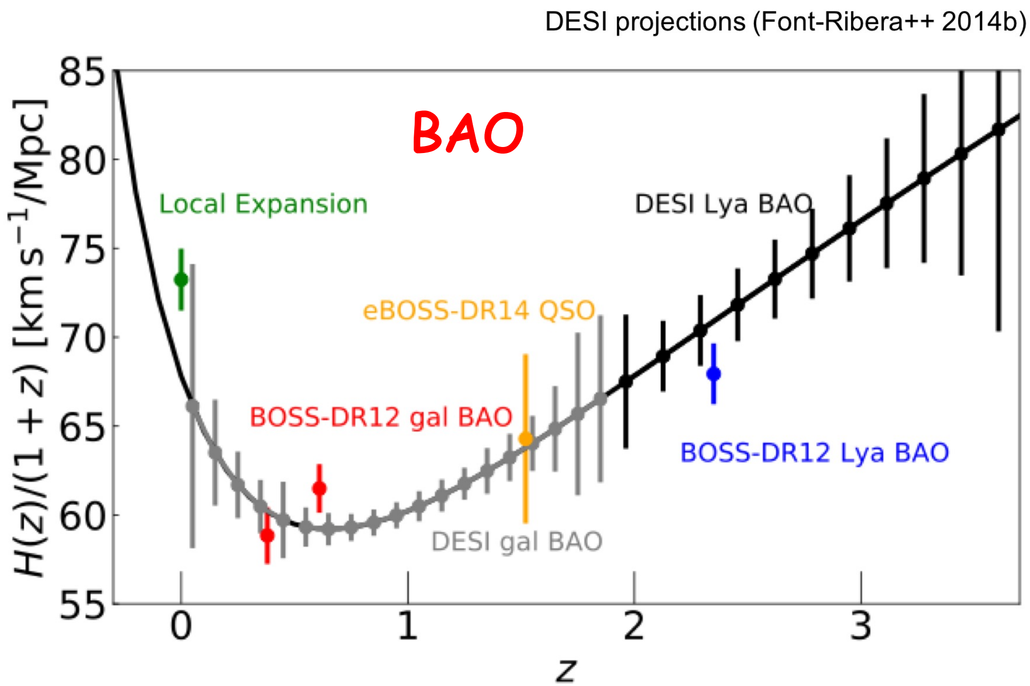
Status of DESI





- Very efficient instrument with 5000 robotic fiber positioners and 10 spectrographs built in France
- May 2021: Science Survey started!
- ~55% of the survey already covered

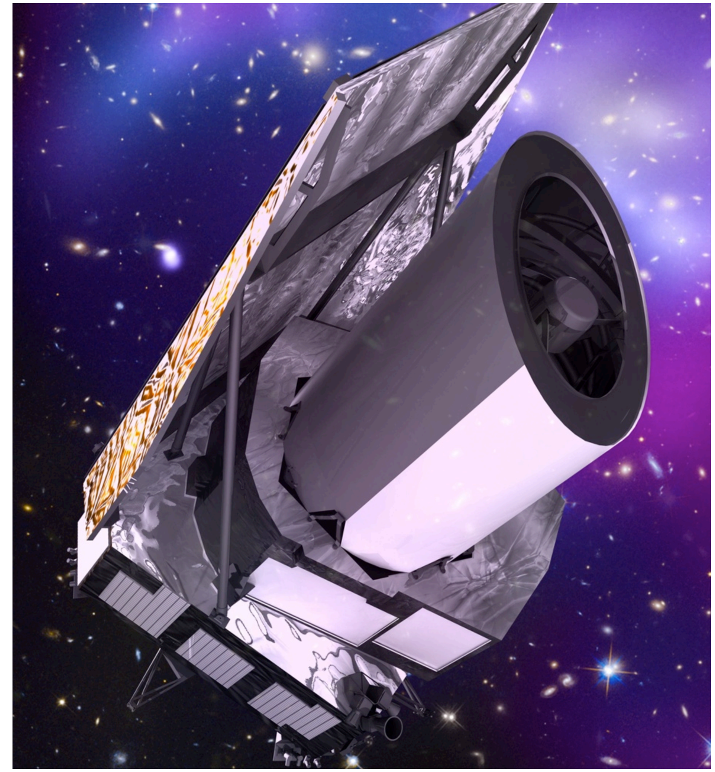
Science with DESI



Improvements compared to SDSS

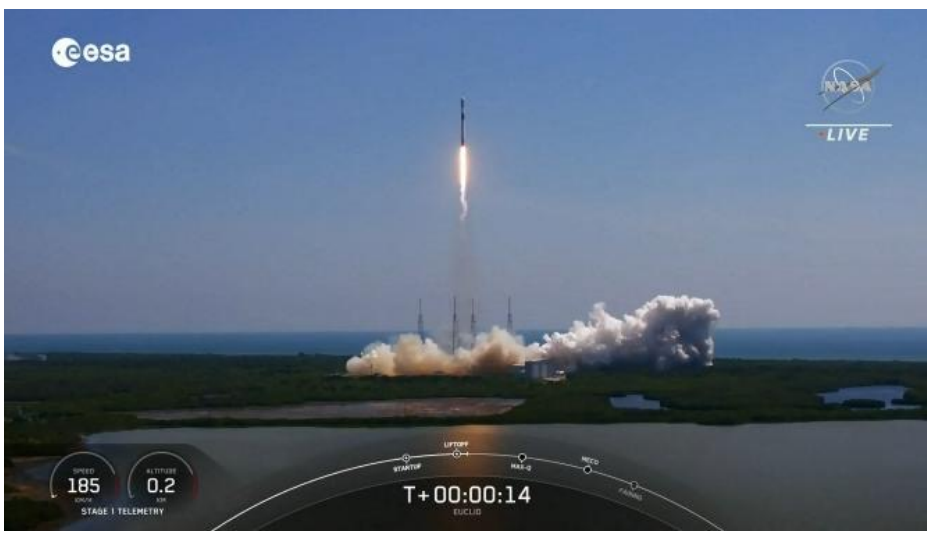
- **BAO:** 1 order of magnitude better $\sigma(\alpha)$ ~ 0.1%

Euclid 2023-2029



Instrument

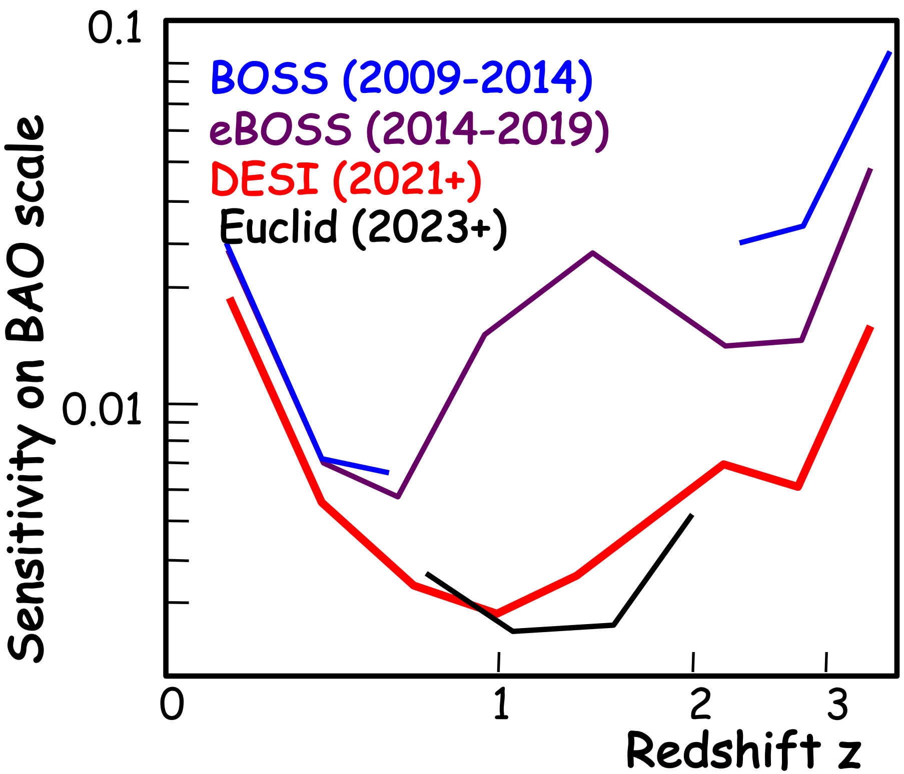
- ESA Satellite launched on July 1st to L2
- 6 year program
- 14 countries + 1100 members
- 1.2m telescope with 0.5 deg^2 FoV
- Two instruments (VIS, NISP)
- Slitless NIR spectrograph (1 blue and 3 red grisms) → 1000-2000 nm



Scientific Project

- 15000 deg^2 survey for $0.9<z<1.85$
- 50M galaxy spectra with R~250
- Redshift determined with Hα line
- Weak lensing (WL), not covered in this talk

Euclid performances in BAO



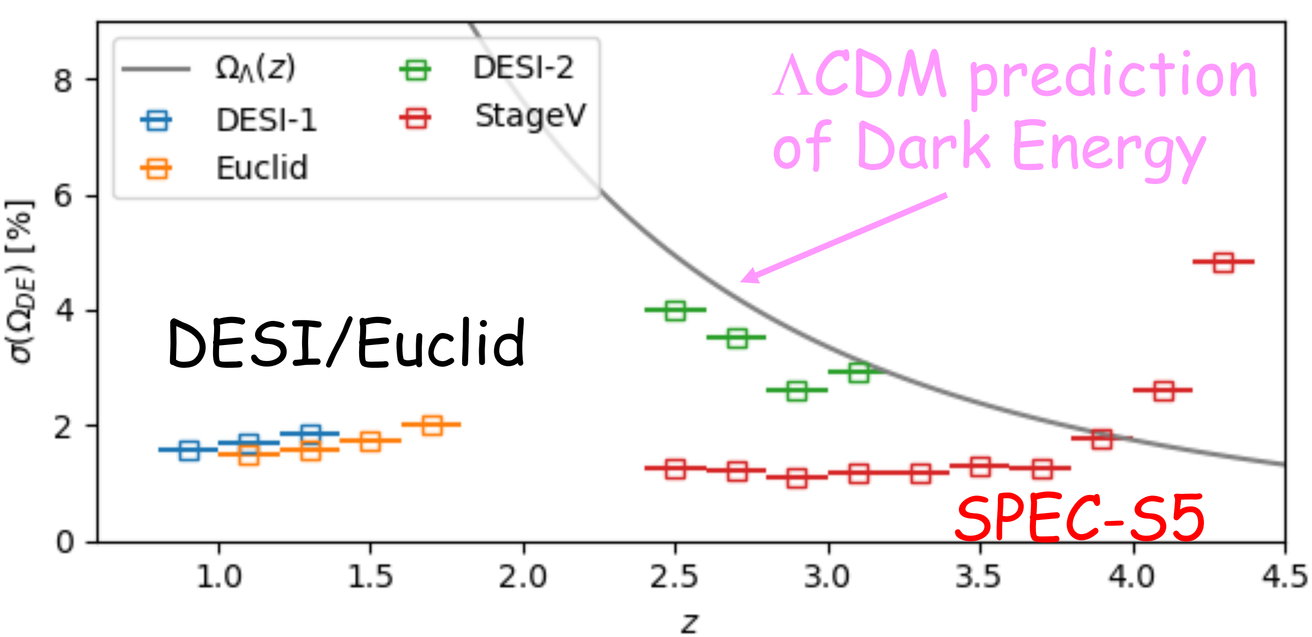
Improvements with Euclid

- For BAO in the 1<z<1.6 region (but the gain is cosmic variance limited)
- Higher in redshift, up to z~1.8 even z~2.0 (region not covered by DESI)
- More galaxies (>50M galaxies to compare to ~40M for DESI)
- Very efficient for other science not covered in this talk:
  - Redshift Space Distortion
  - Weak Lensing
  - Cross-correlation (RSDxWL)

Future Spectroscopic Surveys

SPEC-S5/MSE/WST in a nutshell

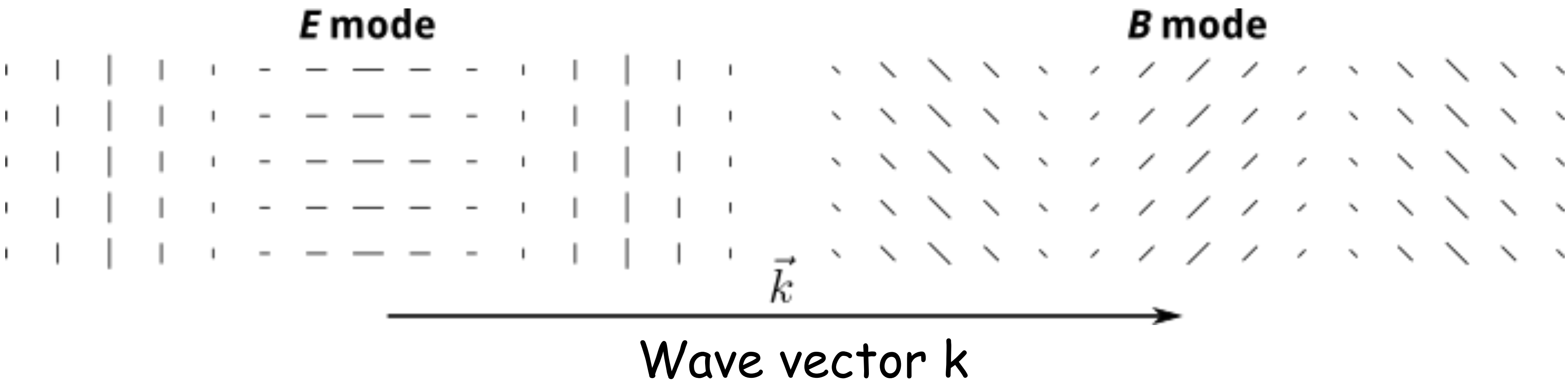
- Many projects with comparable sensitivity and topics by 2035
- ~10k to 20 k fiber positionners
- Diameter: 6.5 to 11m
- Main goal: distant Universe with tracers for 2<z<4.5



Inflation

1) CMB polarization
2) Non-gaussianities

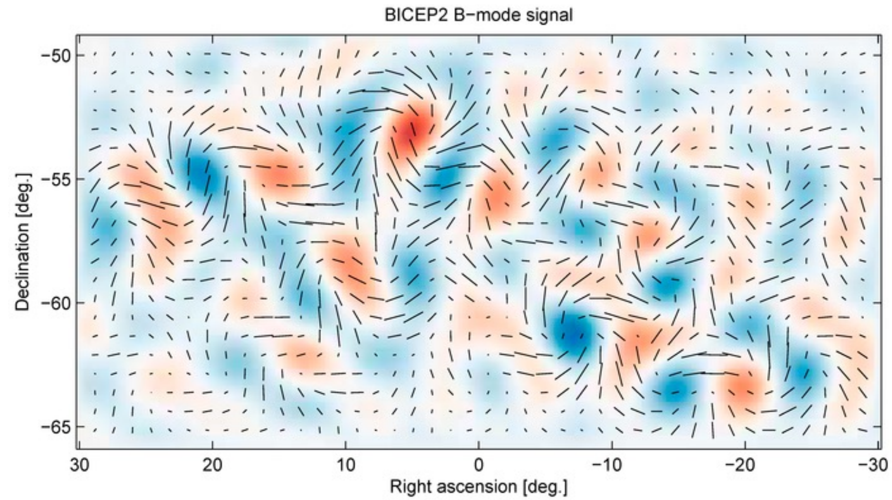
Inflation and CMB polarization

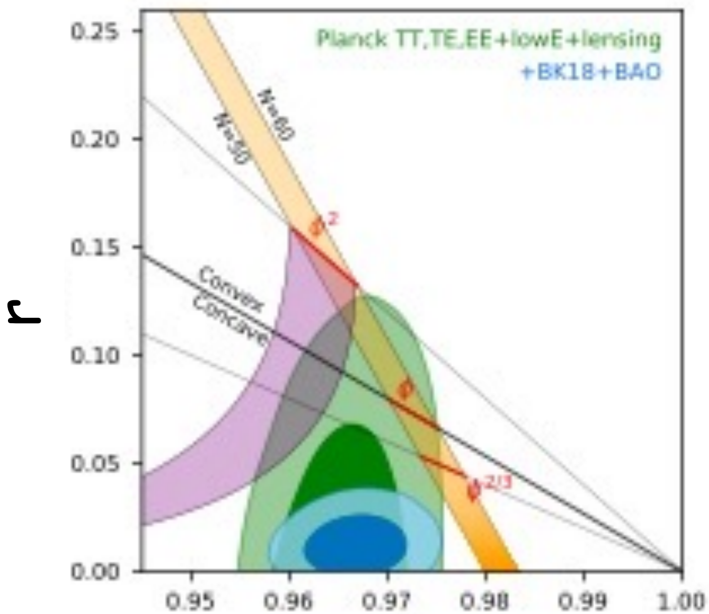


Observation of B modes

- CMB is polarized (Thomson scattering over free electrons)
- E modes: parallel or perpendicular to k
- B modes: rotated by 45° with respect to k
- Prediction of inflation: in addition, production of B-mode with GW at angular scales of a degree or larger.
- Amplitude of the B modes depends on the inflation models
- Ratio r: amplitude of tensor / amplitude of scalar

Current status on r





Spectral index: n_s

$n_s = \mathrm{d}P_{CMB}(\mathrm{k})/\mathrm{dln}(\mathrm{k})$

Constraints on inflation

- r<0.1 with Planck
- Constraint three time better with BICEP2
- Sensitivity at the order of σ_r~0.01
- Many models still possible
- Slow roll models with V''(Φ)<0 are favored
- σ_r~0.003 expected by ~2028

Future CMB programs
Complementary approach

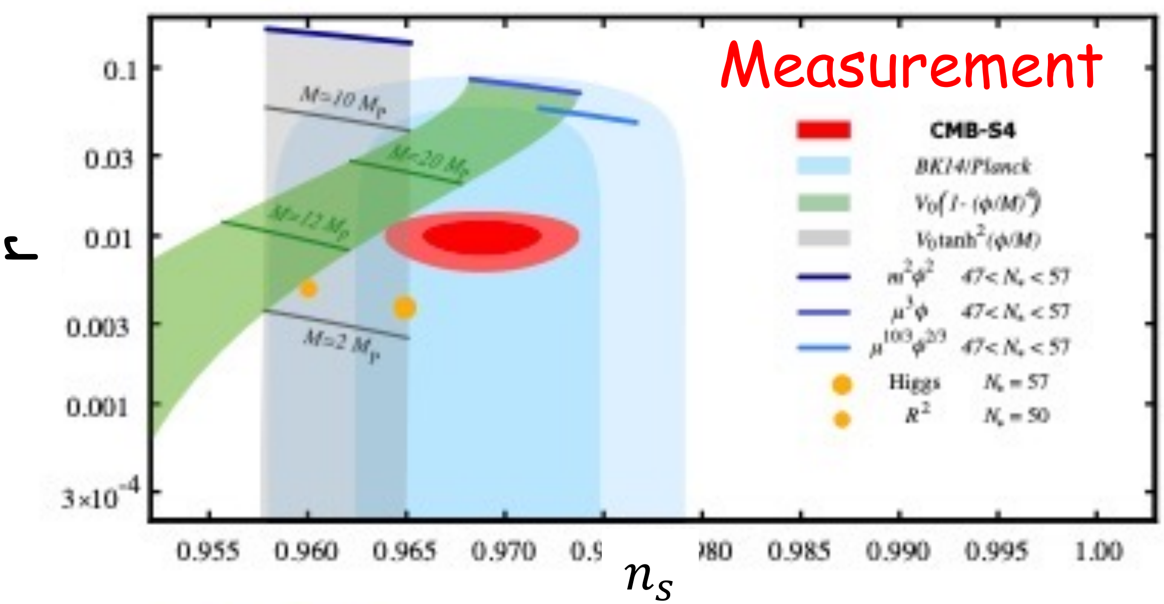
Satellite Mission: LiteBird (2029)

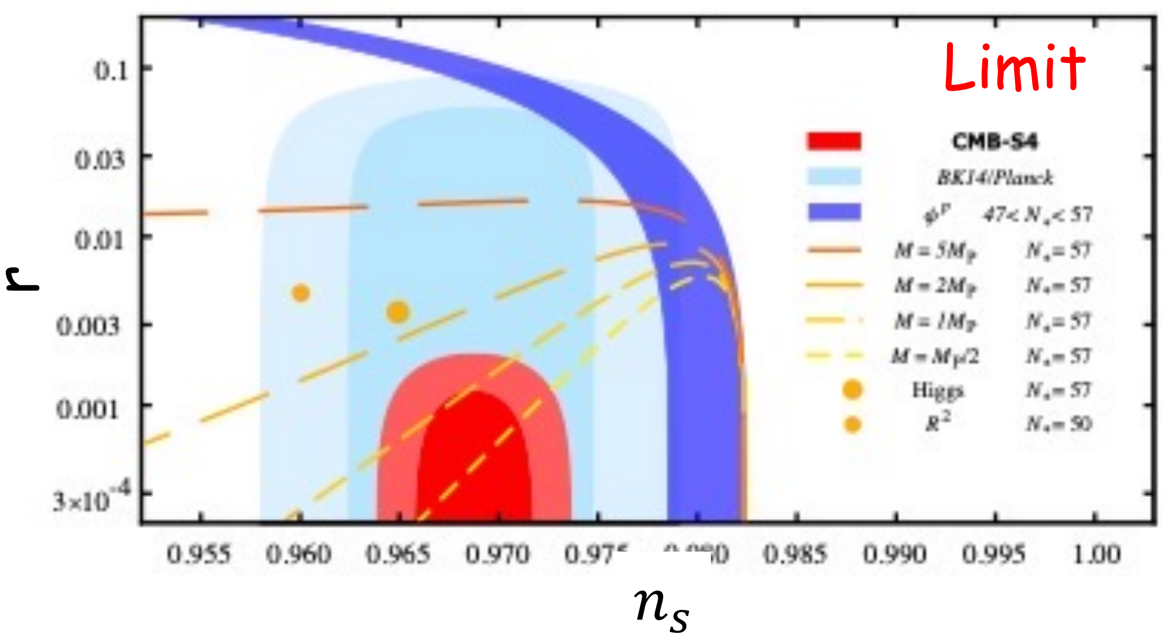
- Project selected by JAXA
- International collaboration
- Low resolution ~5′
- 15 frequencies
- 80 bolometers

Ground Mission: CMB-S4 (~2030)

- High resolution ~1′
- Only a few frequencies
- ~500 000 bolometers
- Combine several sites (SP, Atacama)
- Adiabatic evolution from existing programs (ACTPol, BICEP/Keck, Simons Obs…)

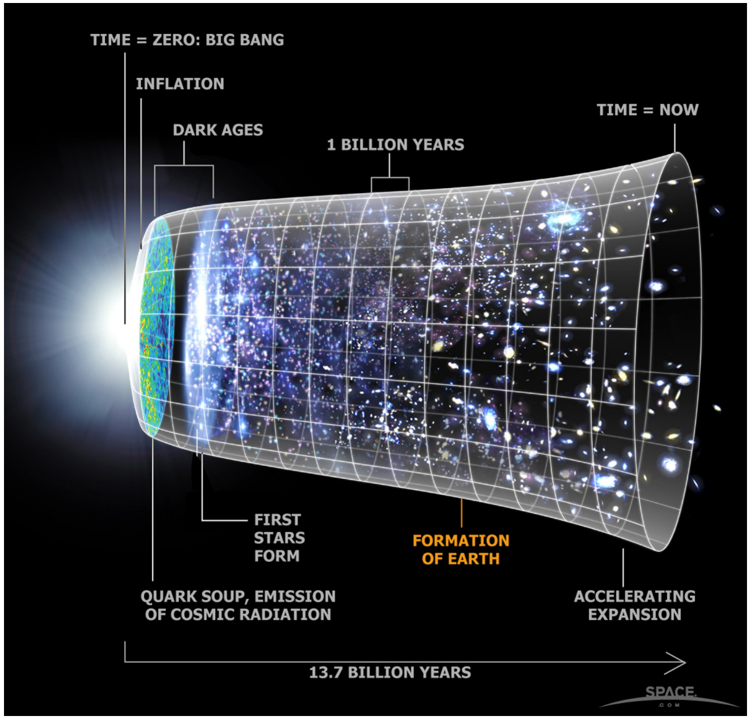
Forecasts on r





- LiteBIRD or CMB-S4 have both sensitivity at the order of σ_r~0.001
- Winning bet if 0.003<r<0.01
- In addition, LiteBIRD measures τ (see later for neutrino masses)

Inflation and non-gaussianity



Description of the primordial potential Φ

$$\Phi = \varphi + f_{NL}.(\varphi^2 - < \varphi^2 >)$$

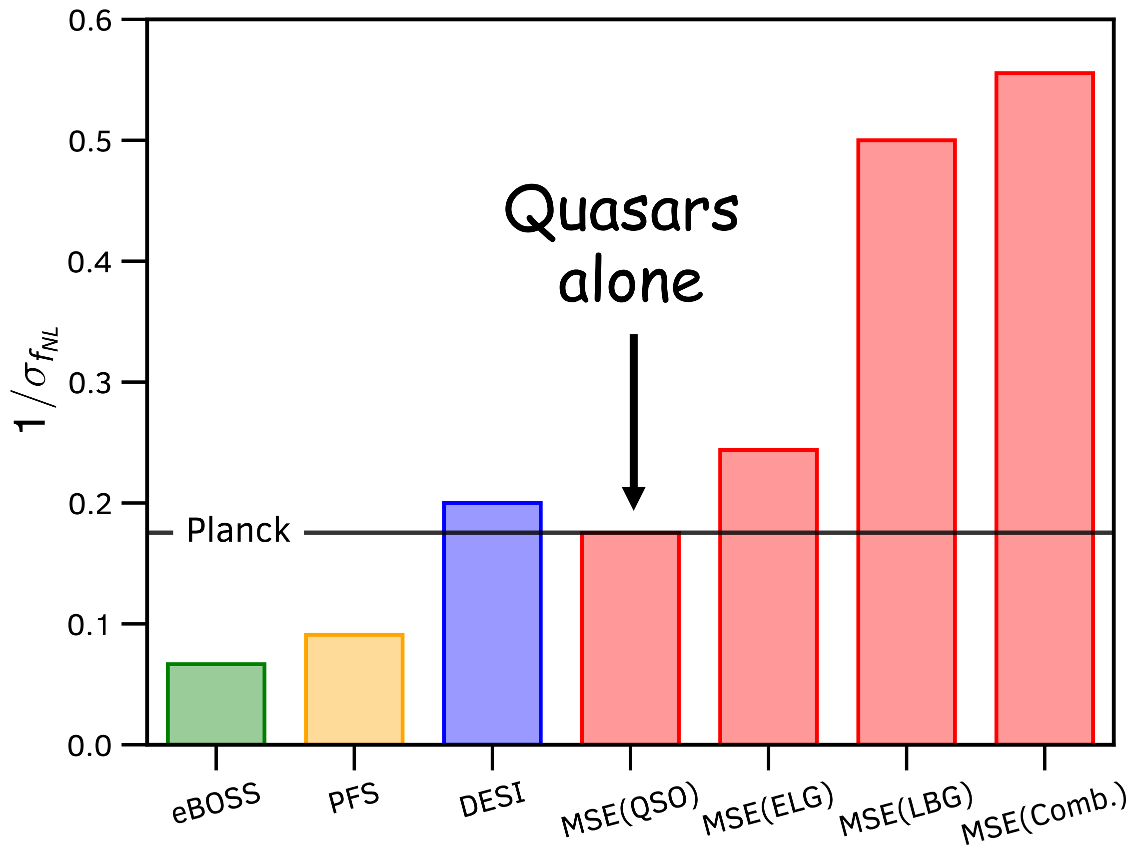
φ : a gaussian random field
f_{NL} : amplitude of the non-Gaussianity

Primordial non-gaussianities: a test of inflation

- Inflation also provides an explanation for the origin of the primordial perturbations
- Primordial fluctuations distributed almost Gaussian with the simplest slow-roll models $f_{NL} \sim O(10^{-3})$
- Alternative inflation models (multi-fields) predict $f_{NL} > 1$
- 3D galaxy surveys with a large volume can achieve $\sigma(f_{NL})$~1

Ground: Forecast for f_{NL}

SPEC-S5/MSE



A picture of primordial Universe

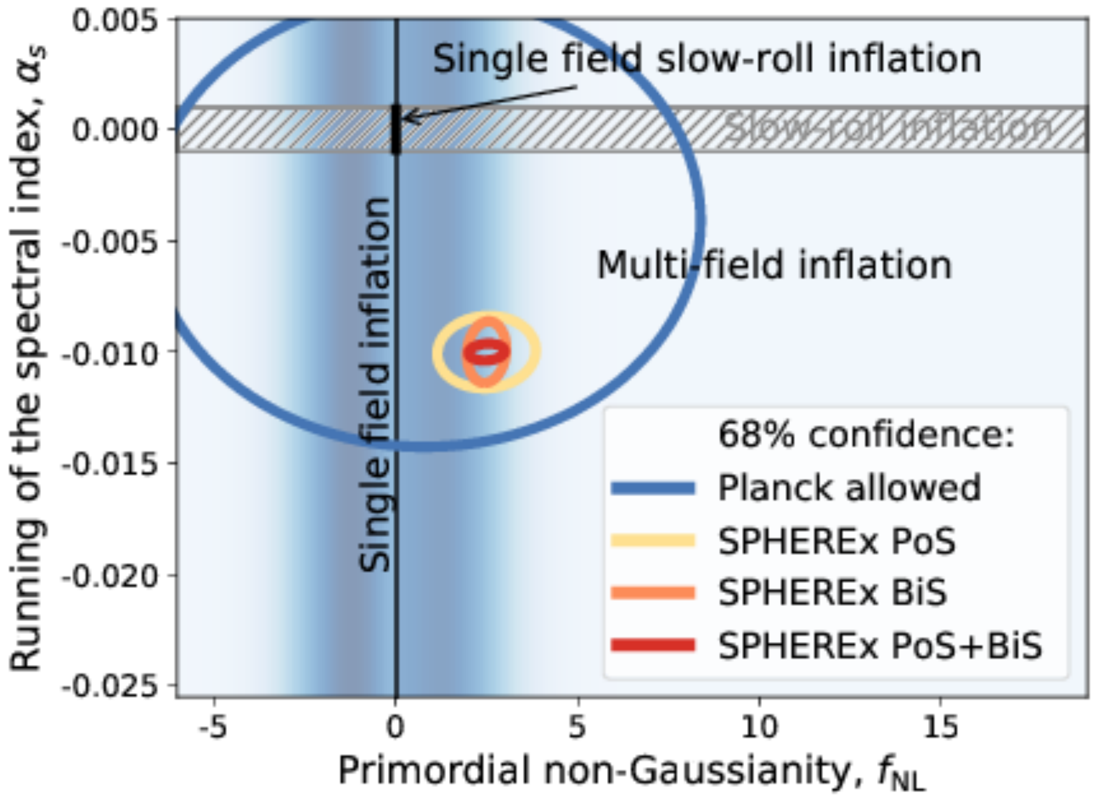
- CMB is cosmic variance limited : $\sigma(f_{NL})$~5
- f_{NL} : the SPEC-S5/MSE quasars alone are as good as all DESI tracers combined or CMB.
- All tracers combined: total accuracy $\sigma(f_{NL})$~1.8

Satellite project for f_{NL}

SPHEREx

- NASA Medium-class mission – Launch in ~2025 – 2 years
- All sky survey with a small mirror (20cm) in NIR
- Redshift expected for ~400M galaxies (low resolution in z)
- Very aggressive sensitivity, $\sigma(f_{NL})<1$
- Discriminate multi- and single-field inflation models

$$\alpha_s = d(n_s)/d\ln(k)$$



Neutrino masses with multi-probes

Cosmic neutrino background

At early times ($T_\nu \gg m_\nu$), neutrinos contribute as **radiation** $\rho_\nu \propto T_\nu^4$

At late times ($T_\nu \ll m_\nu$), neutrinos contribute as **matter** $\rho_\nu = m_\nu n_\nu$

$$\Omega_\nu = \frac{\Sigma m_\nu}{93.1 eV}$$

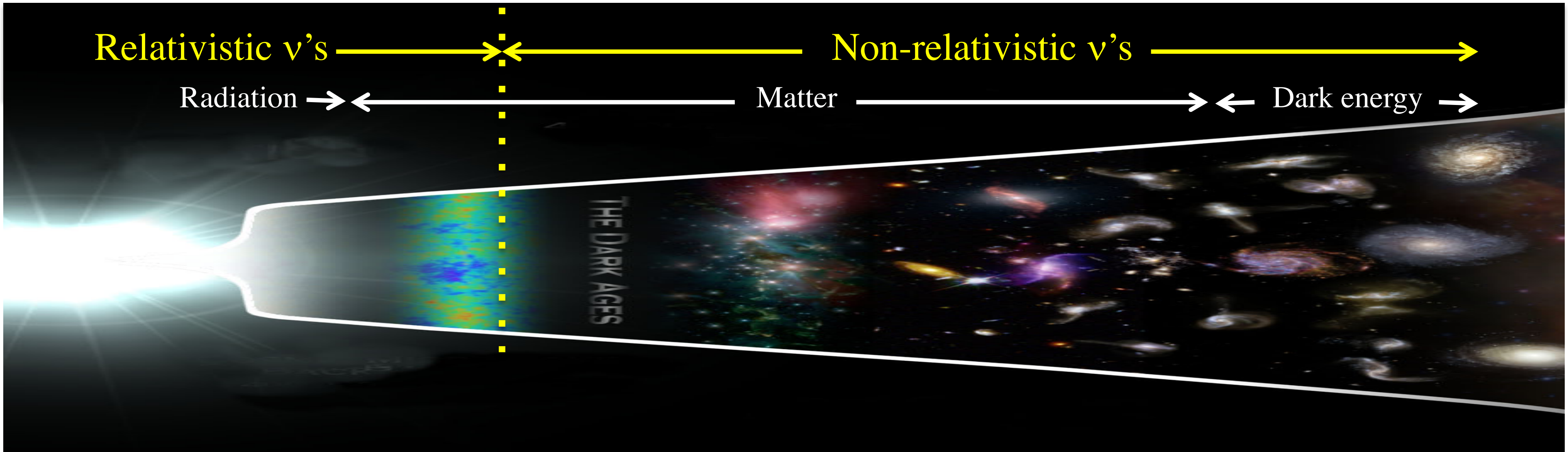
Non-relativistic transition

$$m_\nu \sim \langle p \rangle = \frac{\int p f(p) d^3p}{\int f(p) d^3p} = 3.15\, T_\nu \quad \text{with} \quad f(p) = \frac{1}{e^{p/T_\nu} + 1}$$

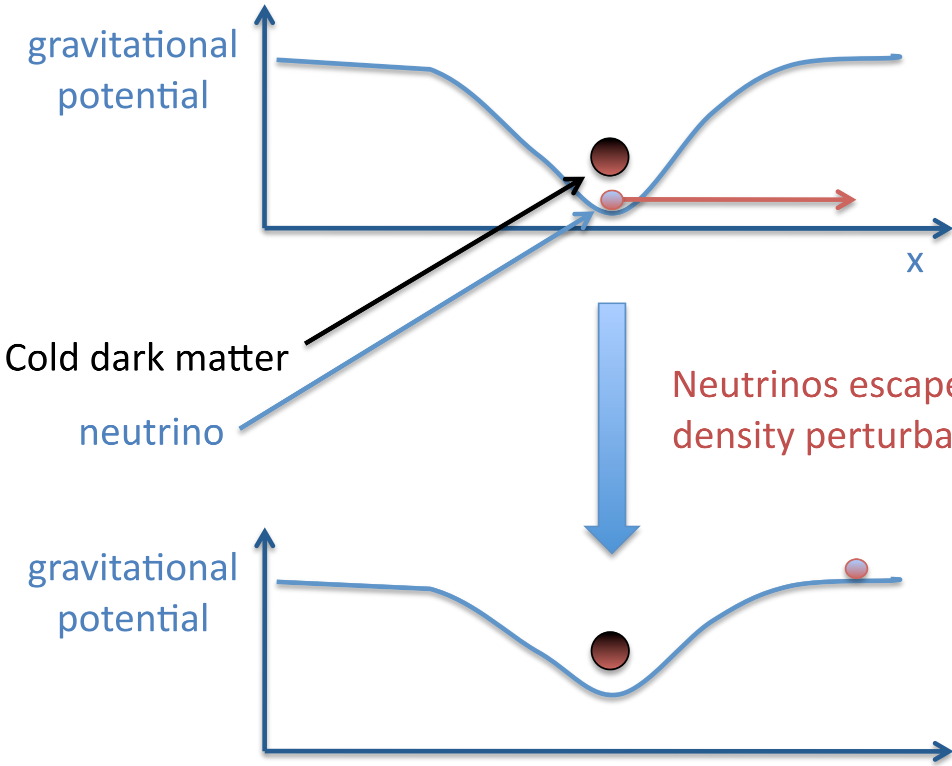
$$z_{nr} \sim 1900 \, \frac{m_\nu}{1\,\mathrm{eV}} \longrightarrow$$

At recombination

$m_\nu < 0.6$ eV ($\Sigma m_\nu < 1.7$) : relativistic
$m_\nu > 0.6$ eV ($\Sigma m_\nu > 1.7$) : matter-like



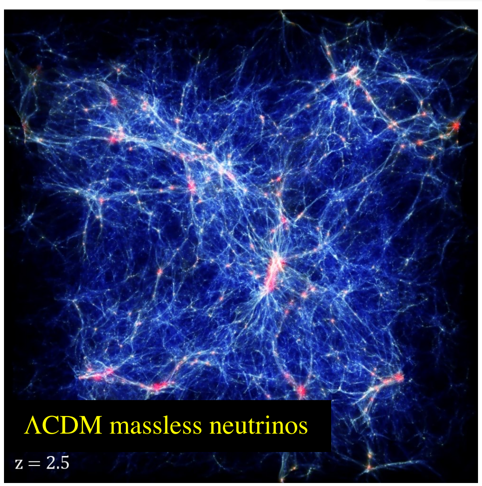
Free-streaming



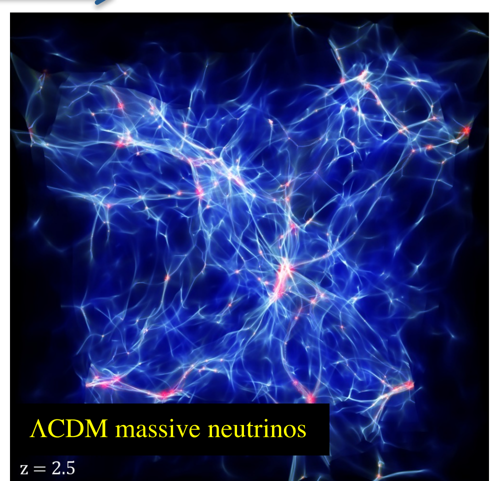
initial time

Neutrinos escape from potential well,
density perturbations get washed out

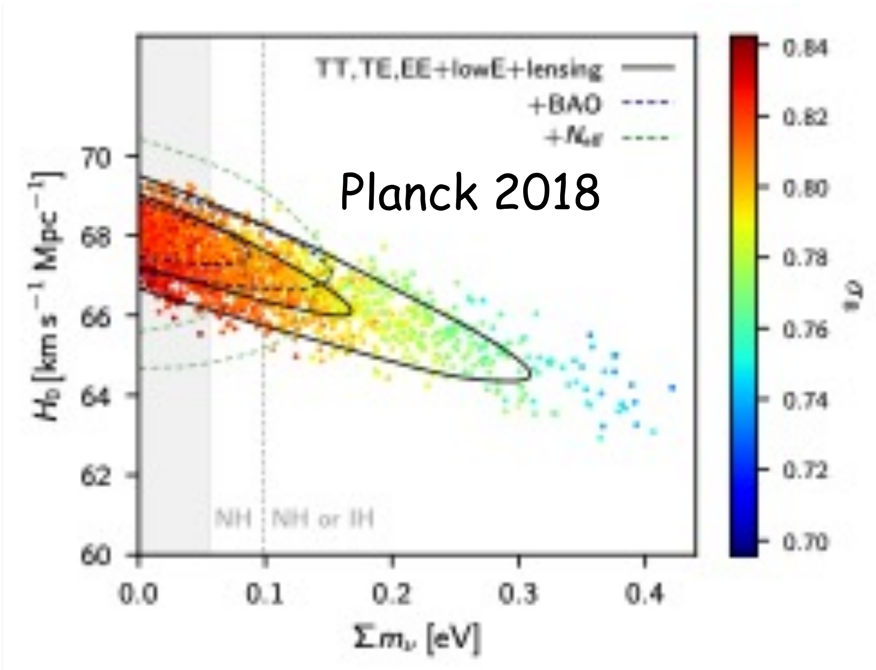
later time

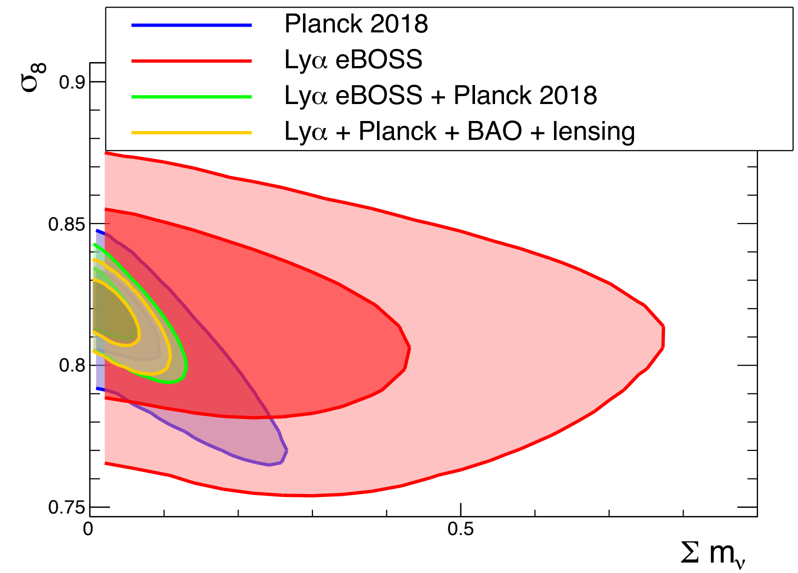


Suppression of
the small scales



Current limits on Σm_ν

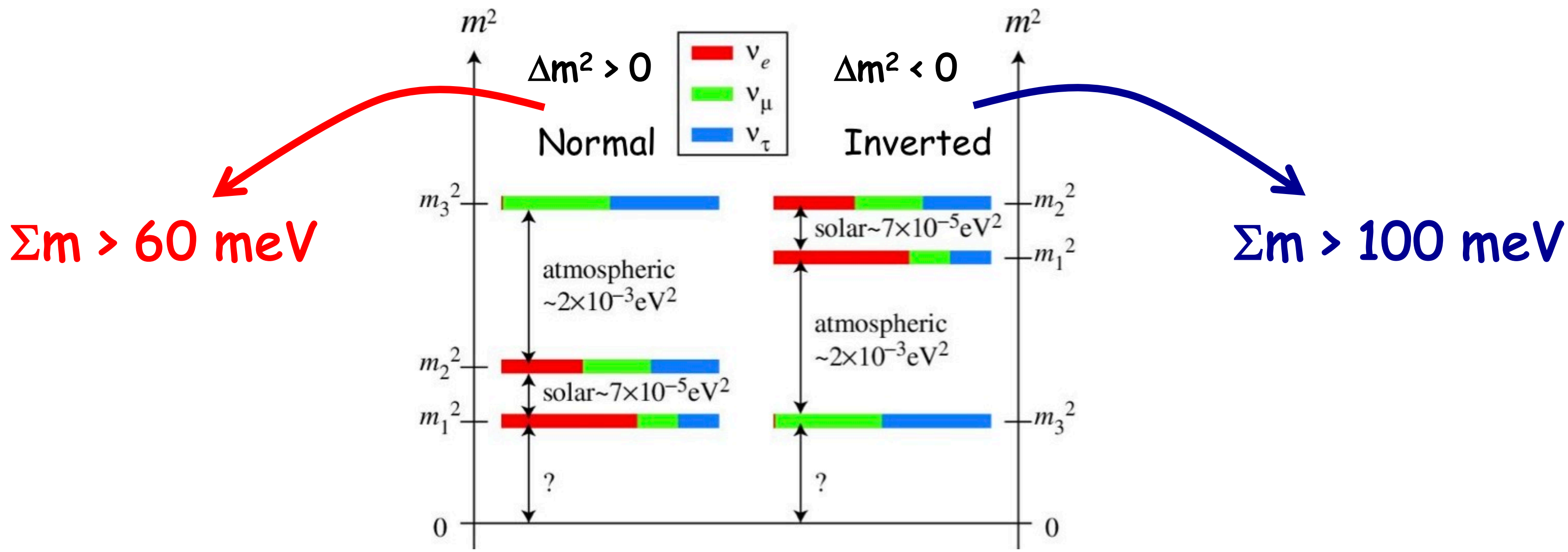




Palanque-Delabrouille , Yèche et al. (2019)

- With Planck 2018 alone:
  Σm_ν < 0.3 eV @95%CL
- Ly-α combined with Planck 2018
  Σm_ν <0.10 eV @95%CL
- BAO combined with Planck 2018
  Σm_ν <0.11 eV @95%CL

Neutrino Masses and Hierarchy



An answer to mass hierarchy with cosmological neutrinos

- Particles Physics: atmospheric and solar oscillations
- No constraint on absolute masses
- 2 possible schemes: normal vs inverted hierarchy
- With $\sigma(\Sigma m_\nu)$~20/12 meV, we measure the mass of the neutrinos with a precision better than $3\sigma/5\sigma$
- With $\sigma(\Sigma m_\nu)$~8 meV, we may have a decision at 5σ on mass hierarchy

DESI and Euclid forecast for Σm_ν

Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.56	0.19
Planck + BAO	0.087	0.18
Gal ($k_{\max} = 0.1h\,\mathrm{Mpc}^{-1}$)	0.030	0.13
Gal ($k_{\max} = 0.2h\,\mathrm{Mpc}^{-1}$)	0.021	0.083
Ly-α forest	0.041	0.11
Ly-α forest + Gal ($k_{\max} = 0.2$)	0.020	0.062

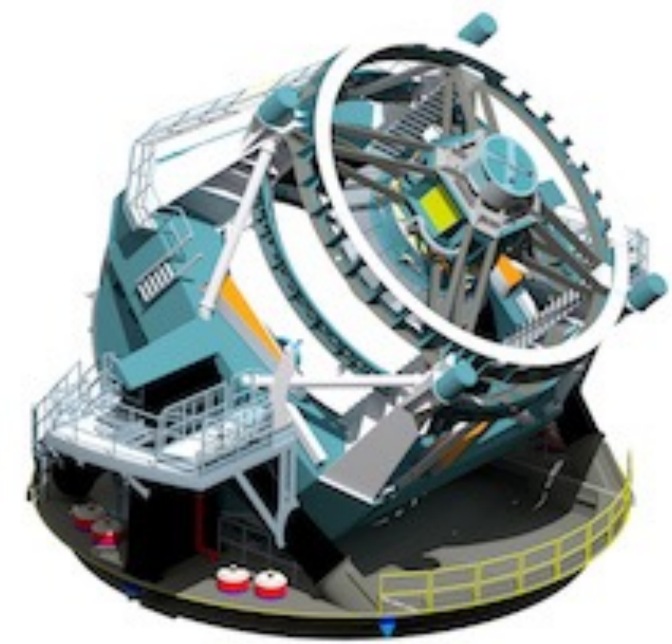
	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	*FoM*
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

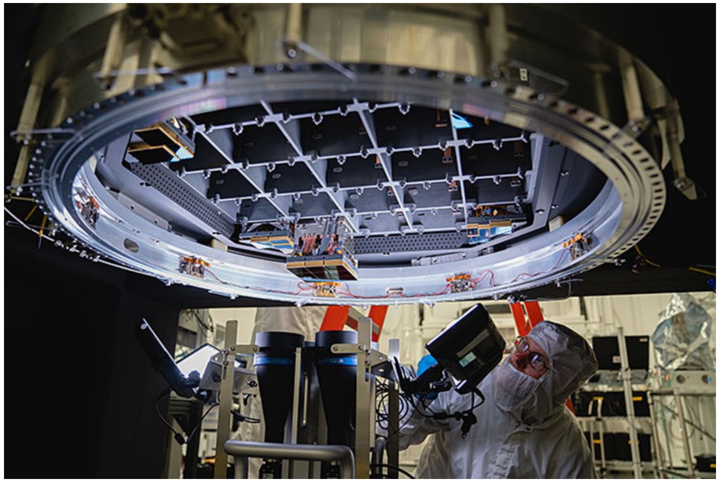
- DESI and Euclid combined with Planck give $\sigma(m_\nu)$~20 meV

Large Synoptic Survey Telescope

Rubin/LSST in a nutshell

- Site: Cerro Pachon in Chile.
- 8.4 m (~6.5m) telescope with 3.5 deg. FoV
- A 3.2-gigapixel digital camera
- 15s exposure every 20s.
- Six filters → 330-1080 nm
- Infrastructure almost completed
- Camera completed (important French participation)
- Science survey starts in 2025

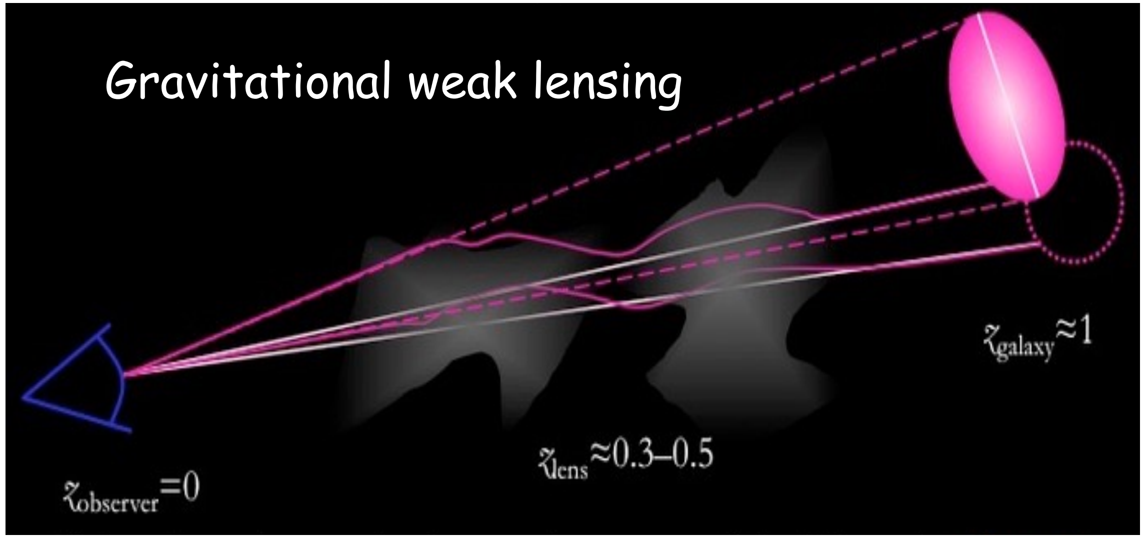


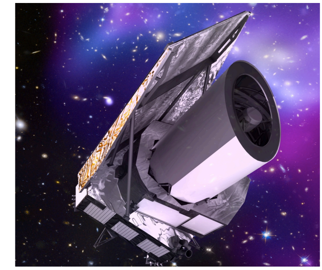


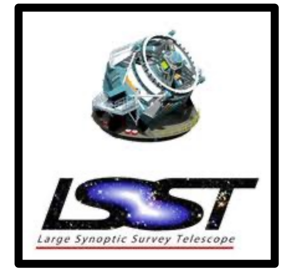
Program for cosmology:

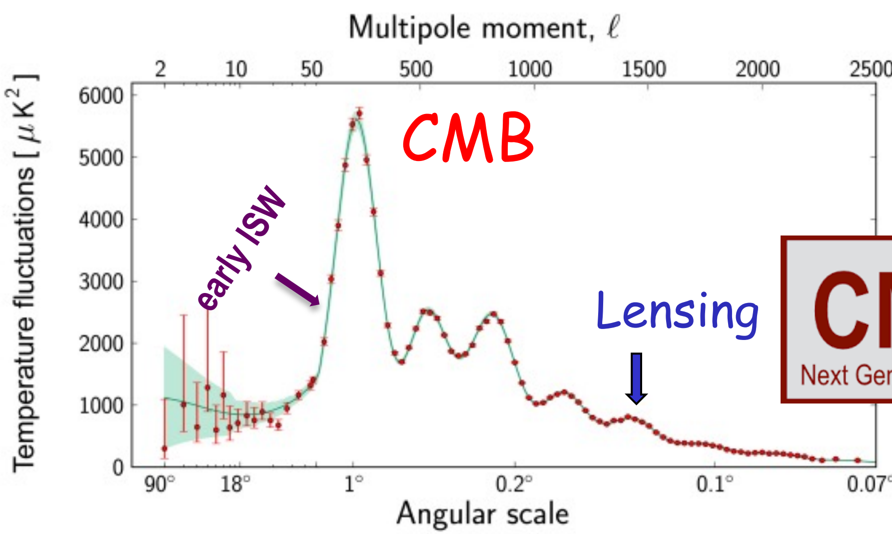
- Supernovae
- BAO with photo-z
- Weak lensing (3x2pt analyses)

Free-streaming and lensing

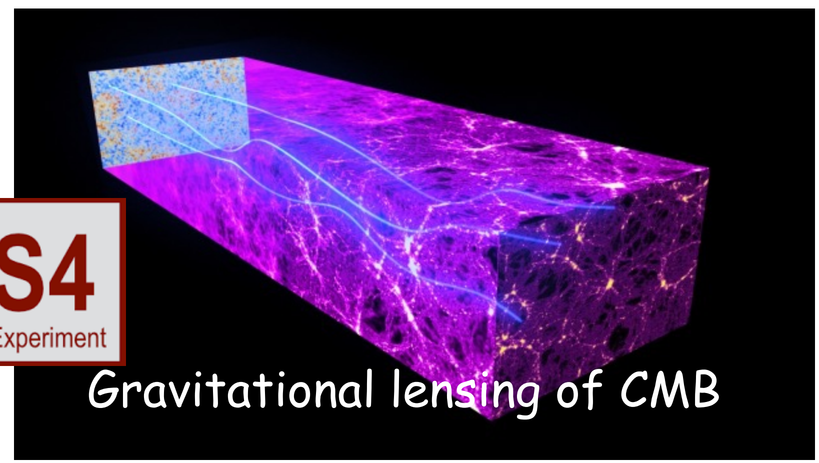




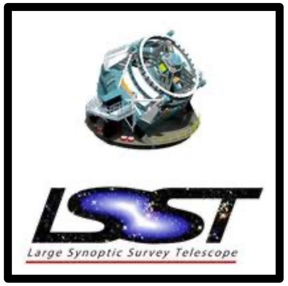




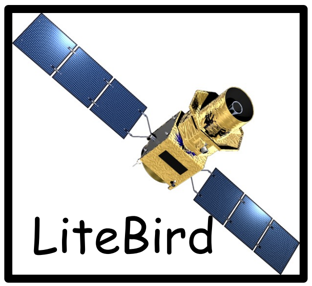
CMB-S4
Next Generation CMB Experiment



CMB-S4 and LSST forecast for Σm_ν



CMB-S4
Next Generation CMB Experiment



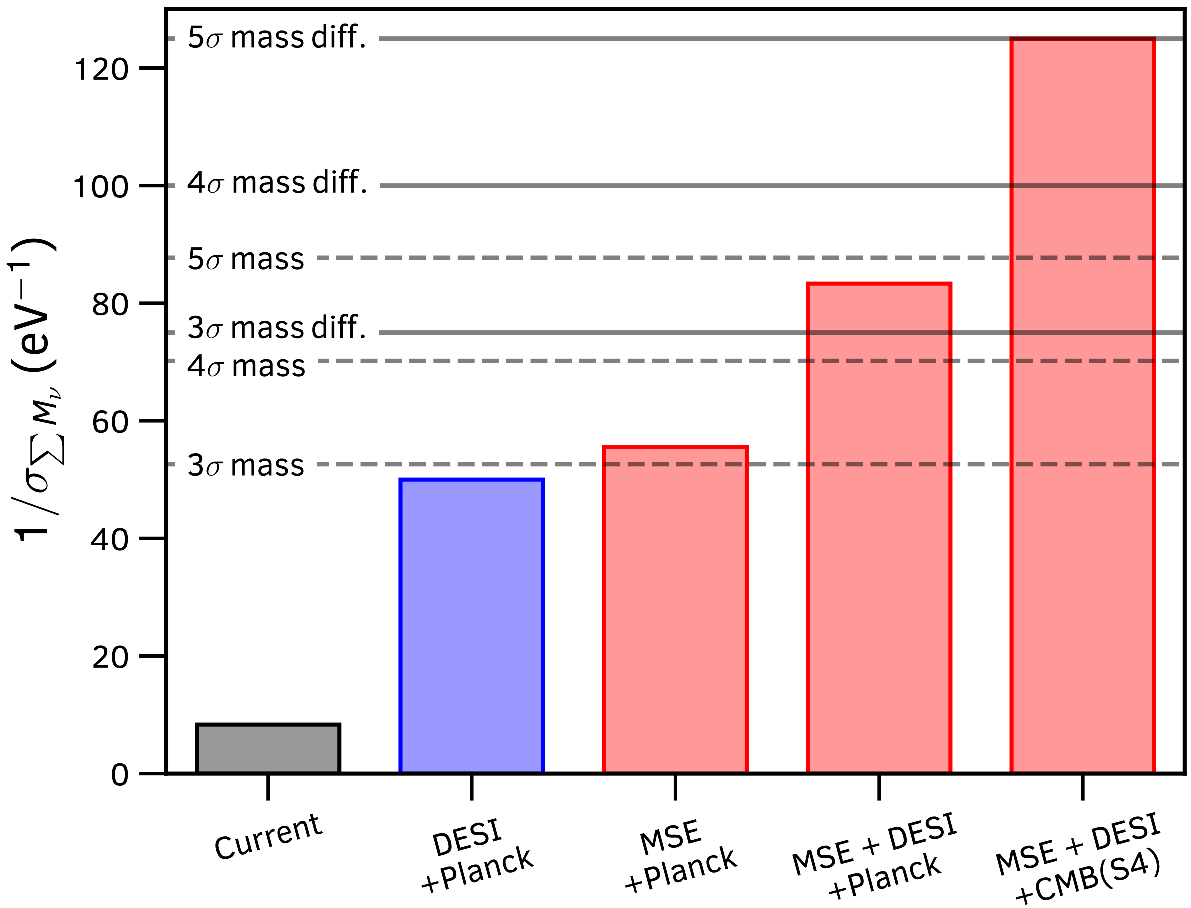
Setup	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Omega_k)$ [$\times 10^{-3}$]	$\sigma(w_0)$	$\sigma(w_a)$
S4	73	111	0.79	1.14	2.46
(+ DESI BAO)	29	76	0.48	0.13	0.41
LSST-clustering	69	91	3.33	0.42	1.22
LSST-shear	41	120	2.99	0.19	0.57
LSST-shear+clust	32	72	2.06	0.11	0.33
S4+LSST	23	28	0.49	0.10	0.26
	-	24	0.49	-	-

Setup (+CV-τ)	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Omega_k)$ [$\times 10^{-3}$]	$\sigma(w_0)$	$\sigma(w_a)$
LSST-clustering	69	91	3.3	0.42	1.20
LSST-shear	31	117	2.82	0.18	0.55
LSST-shear+clust	24	72	1.99	0.11	0.31
S4+LSST	14	21	0.49	0.10	0.26
	-	15	0.49	-	-

arXiv:1803.07561, S. Mishra-Sharma et al.

- Degeneracy with other cosmological parameters (Ω_k,w_0,w_a,...)
- Strong degeneracy between τ and m_ν for CMB lensing
- Need a measurement of τ with CMB polarization (LiteBird)
- LSST+S4+LiteBird gives **$\sigma(m_\nu)$~14 meV**

MSE :Forecast for Σm_ν



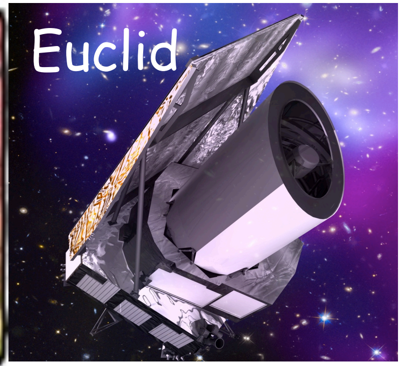
SPEC/S5/MSE

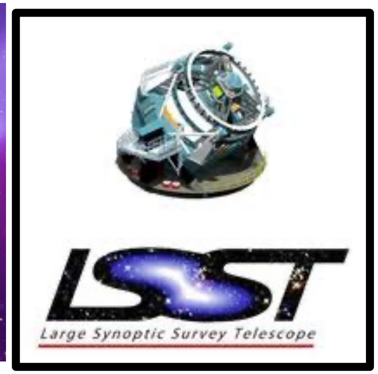
A most precise measurement of neutrino mass

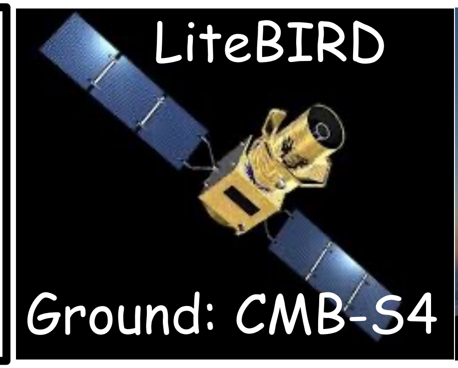
- With CMB(S4+LiteBird), accuracy on neutrino masses $\sigma(\Sigma m_\nu)$~8 meV
- Measure the neutrino masses and test the mass hierarchy
- Neutrino mass hierarchy at 5σ as precise as DUNE (ν beams)

Summary

Timeline of the projects in Cosmology







2021 — 2023 — 2025 — 2029 — 2035/2040

French community involved in all the future cosmological projects

Dark Energy - Dark Matter -2025

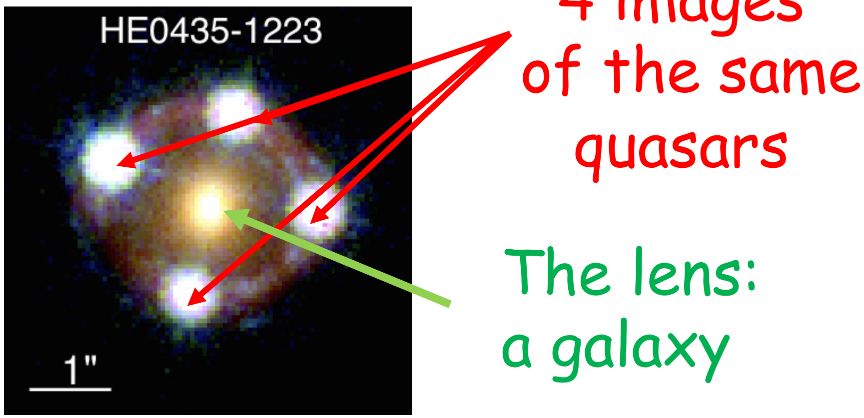
- With BAO (DESI, Euclid) and LSST (BAO-2D & WL)

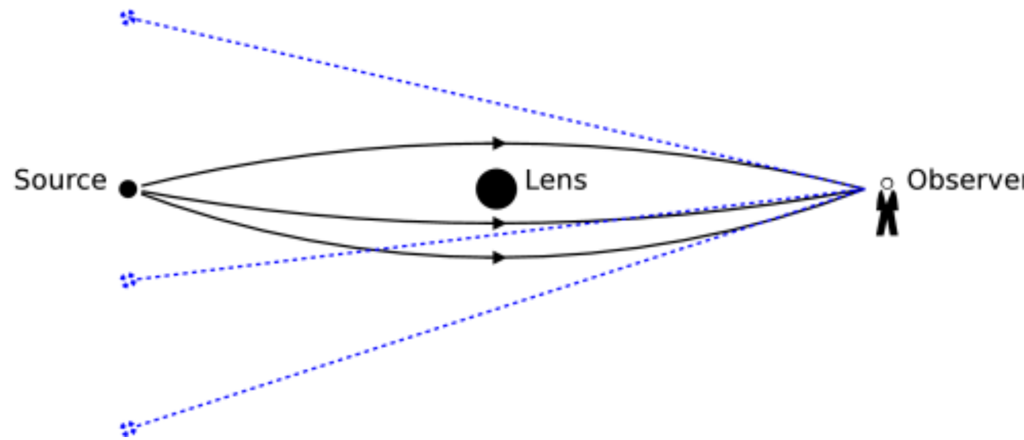
Inflation - Neutrinos - 2028-2032

- First constraints with 3D survey with DESI and Euclid
- With CMB (LiteBIRD,S4) and later SPEC-S5 (or similar)

Additional Slides

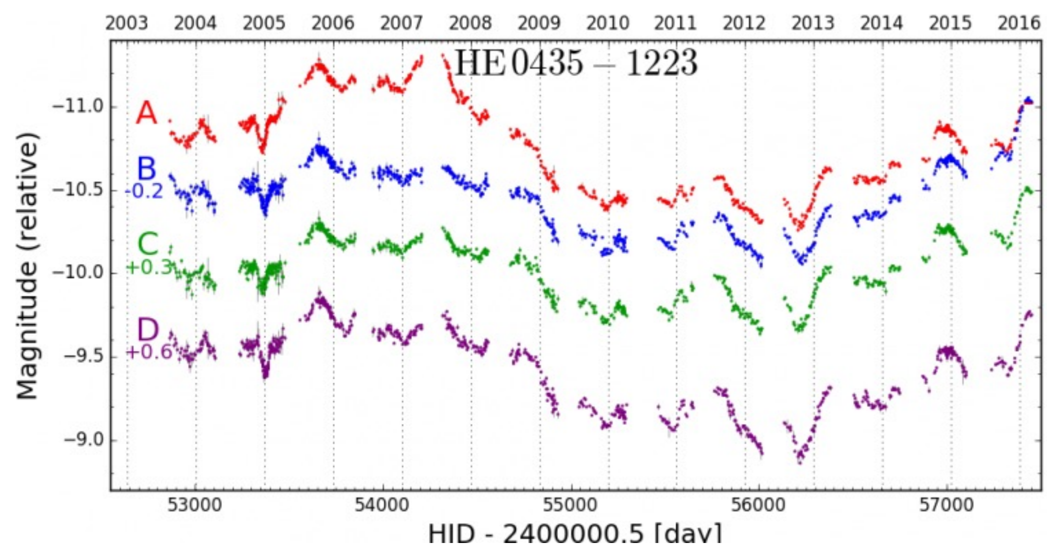
H0licow - lensed quasars



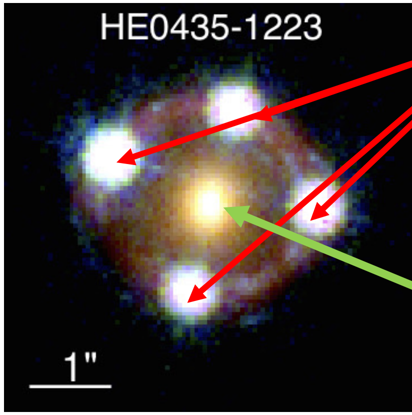


Principles

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

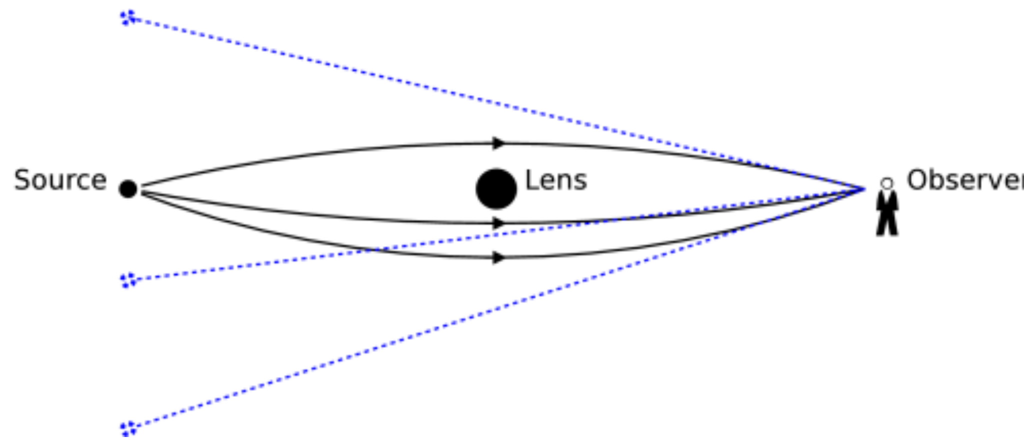


H0licow - lensed quasars



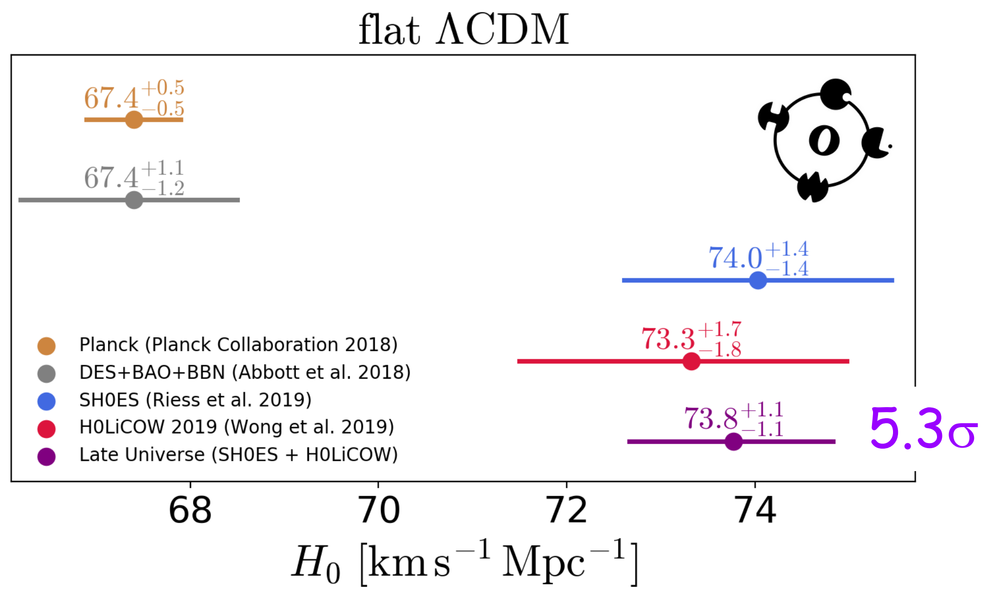
4 images of the same quasars

The lens: a galaxy

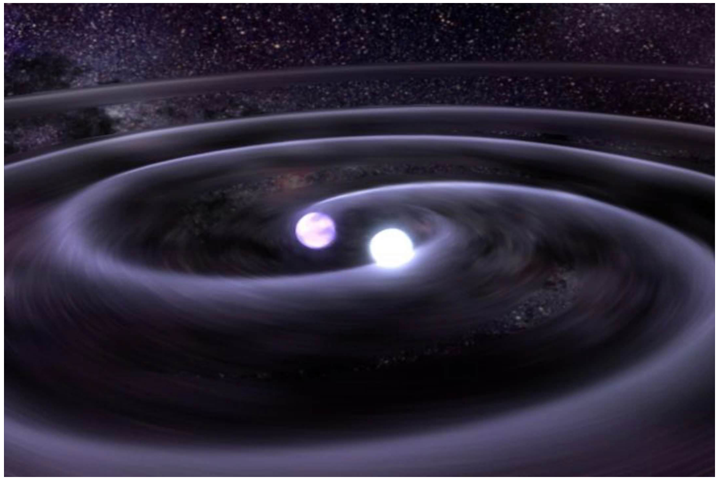


Principles

- ➢ Study of the time-delay for each image
- ➢ Several lensed quasars
- ➢ Main uncertainty: quantification of the mass profile around the lensing galaxy



H0 and Gravitational Waves?

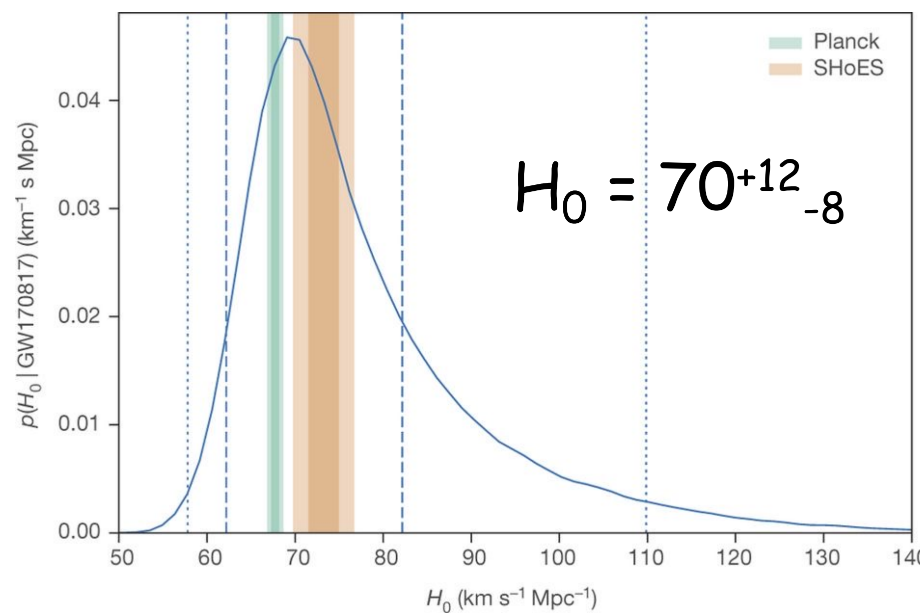


Principles

- Binary neutron star merger
- Measurement of distance with the GW
- Measurement of the redshift with the optical counterpart (host galaxy)

Prospects

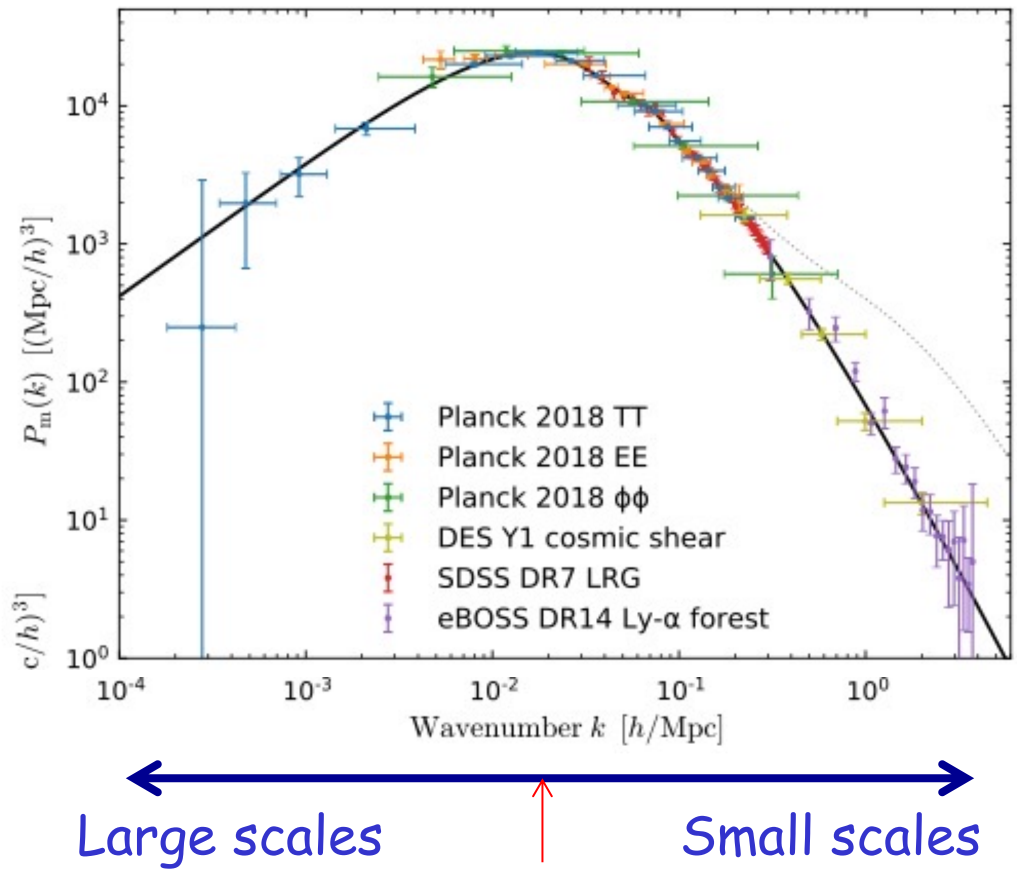
- Measurement at 10% with one BNS
- ~10 BNS merger expected by year
- In O3, since April only 2-3 BNS alerts
- Expect a few % of accuracy within a few years



Matter power spectrum

- Analogy with sound: higher at certain frequencies
- Real space ⟹ k-space (Mpc^{-1})
- Observation of "total" power spectrum with different tracers of the matter

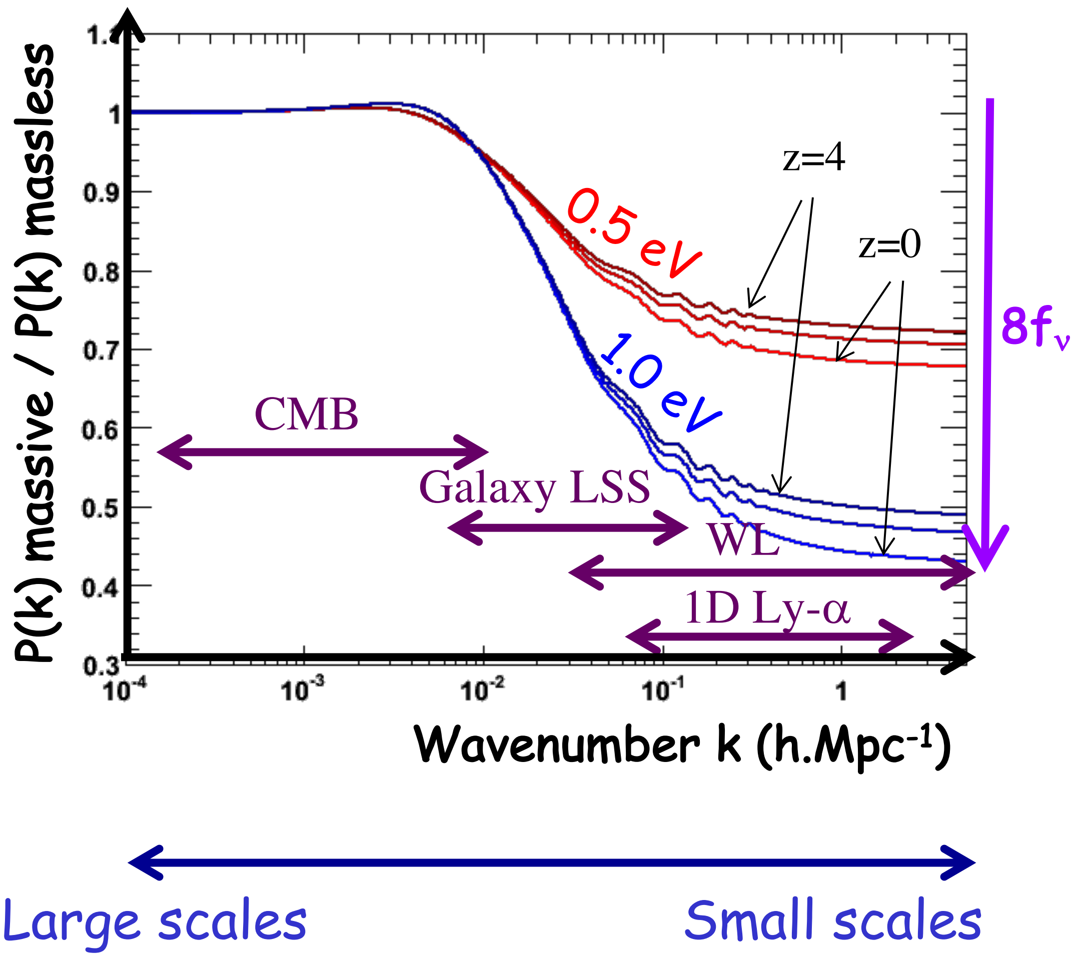
Chabanier, et al. (2019)



k_{eq}

Impact on matter power spectrum

- Impact in CMB-alone only for non-relativist neutrinos ⇒ ~1-2 eV limit



- Free-streaming:
  - Wash out the fluctuations
  - Suppression of small scales in P(k)
- Suppression factor ⇔ Σm_ν
  ⇔ $f_\nu = \Omega_\nu / \Omega_m$
- Three probes directly sensitive to free-steaming
  - Galaxy Power spectrum
  - Weak lensing
  - Ly-a absorption along the line of sight
- CMB- lensing is similarly affected by free-steaming