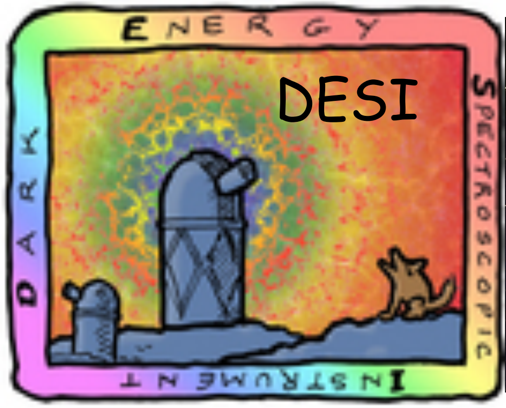
Cosmology in the next decade

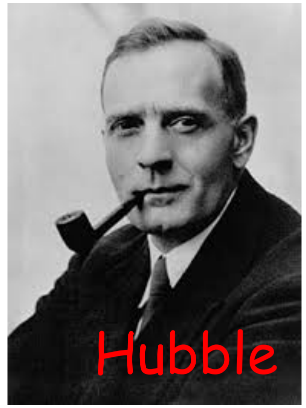
Ch. Yèche (CEA-Saclay Irfu)



Ecole de Gif - Palaiseau - September 06, 2019

A brief history of cosmology

Expanding Universe



History of the discovery

- 1914, Slipher: farther the « nebula » (galaxy) is from us, the more it seems to be escaping away
- 1927, Lemaître: solutions of Einstein General Relativity for a non static universe ⇒ velocity proportional to distance.

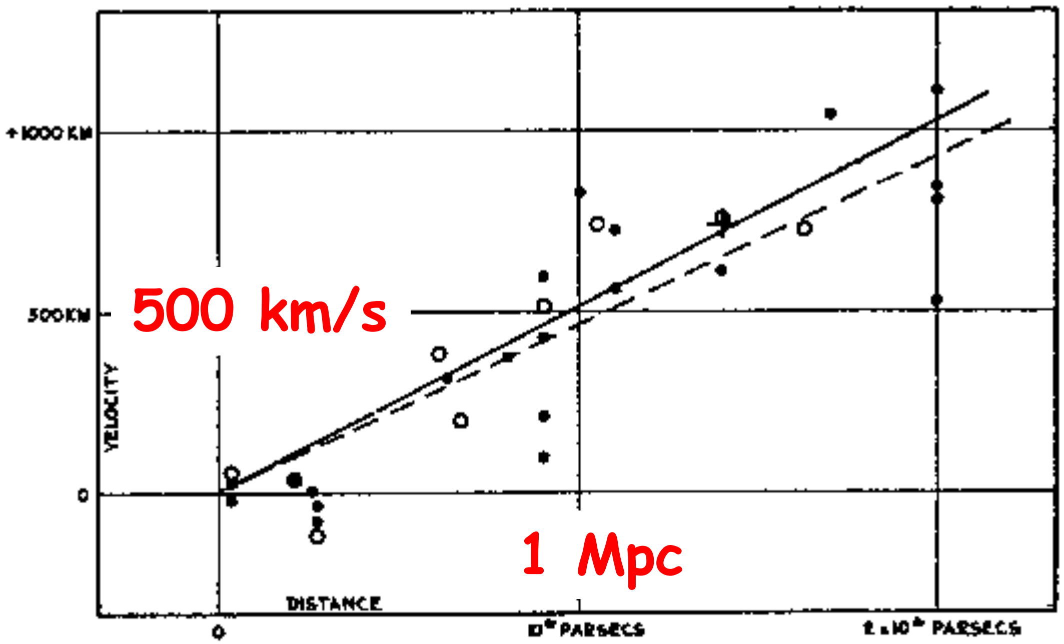


FIGURE 1

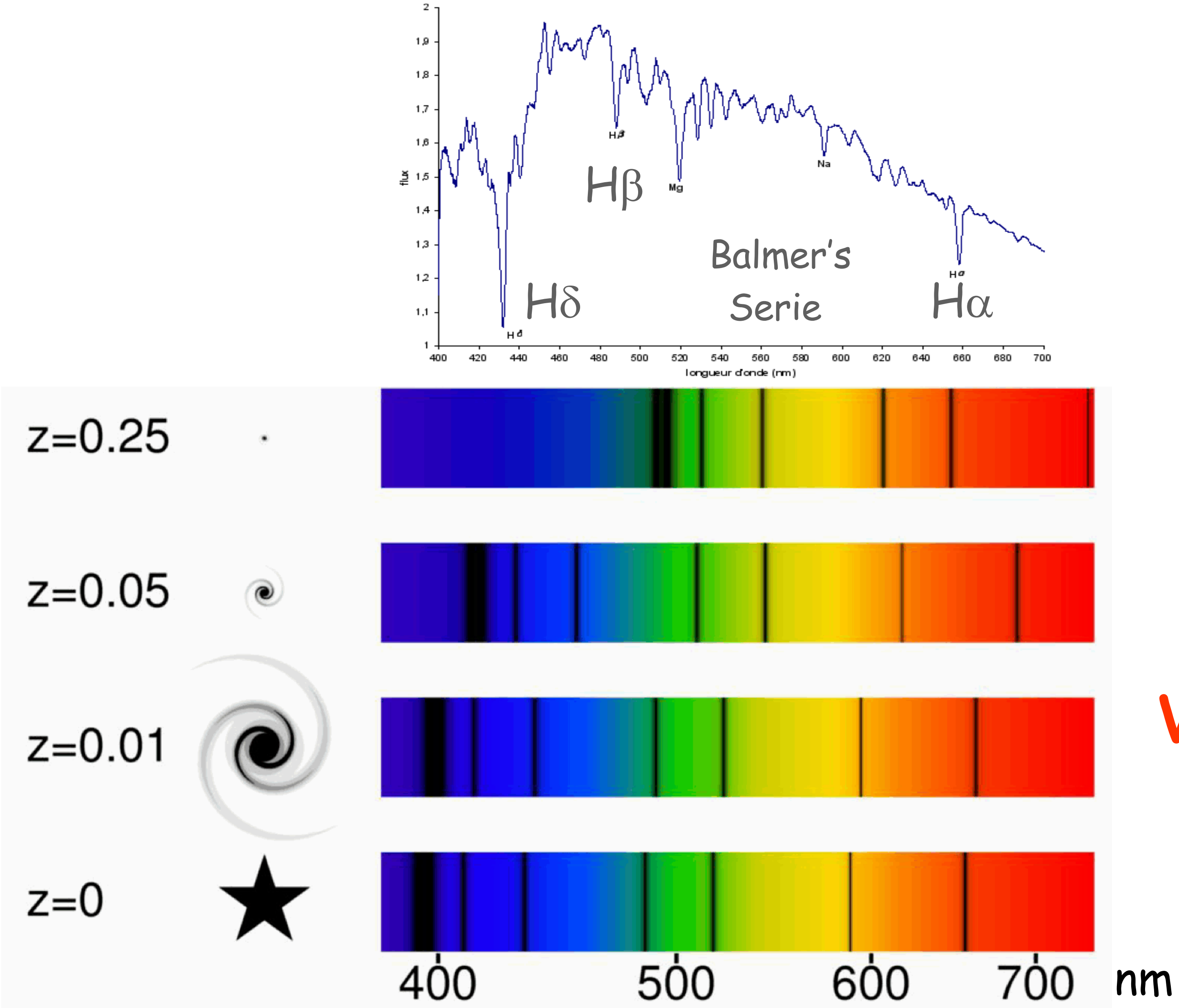
1 parsec= 3 light years

- 1929, Hubble: Relation distance – velocity thanks to cepheid in extragalactic "nebula "

$L_{obs} \propto L_0/R^2$

Period of cepheid → L_0

How do we measure velocity?



Stars spectra

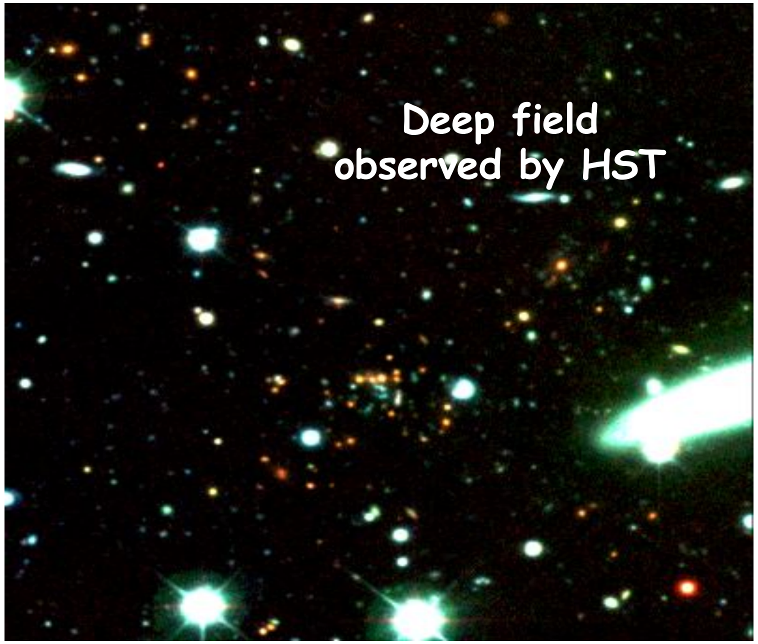
absorption lines

Redshift

Doppler effect

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

Expanding Universe



Hubble's law

$$V = H_0 d$$

- Measurement of the velocity of galaxies with **their redshift (z)**
Doppler effect : $V/c = (\lambda - \lambda_0)/\lambda_0 = z$
- Increasing z $\Rightarrow$ Back in time

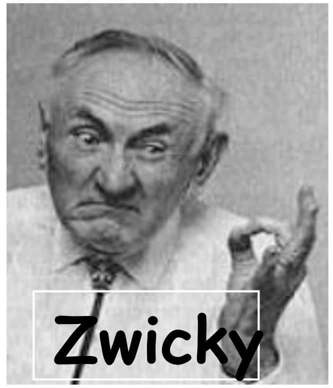
What value of H_0?

- Controversial and controverted measurement.

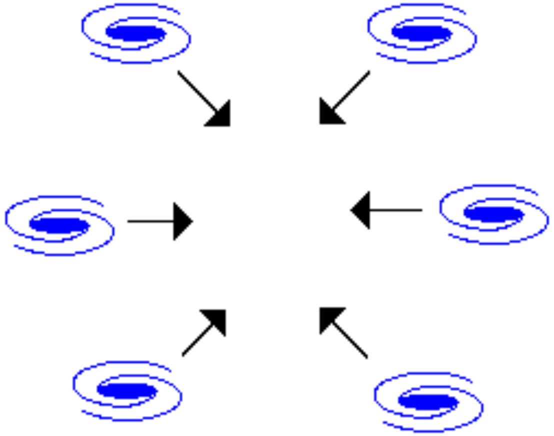
What about gravitation?

- It will slow the expansion of the universe for dark matter - Deceleration.
- It will accelerate the expansion of the universe for "repulsive" matter - Acceleration.

Discovery of Dark Matter



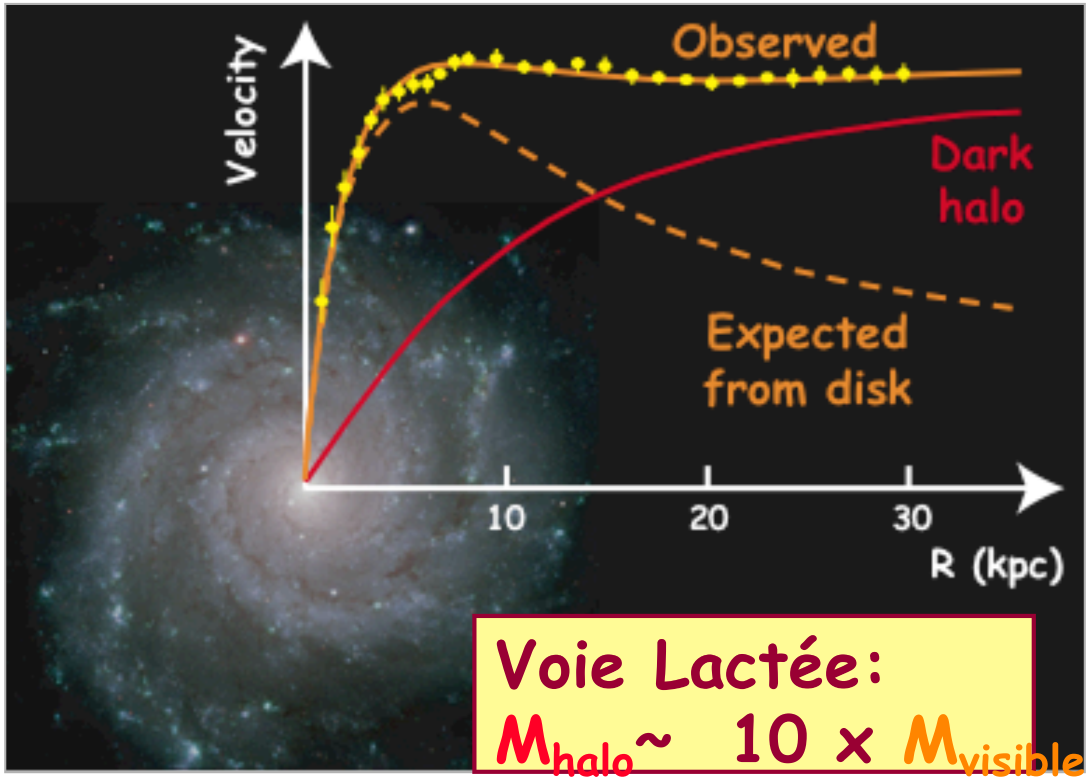
Zwicky, 1933



"Invisible" matter

- Galaxy cluster.
- Peculiar velocity of galaxies too high.
- Viriel theorem.
- Galaxies are about 1-10% of the total mass.

1970: how to weigh galaxies?



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

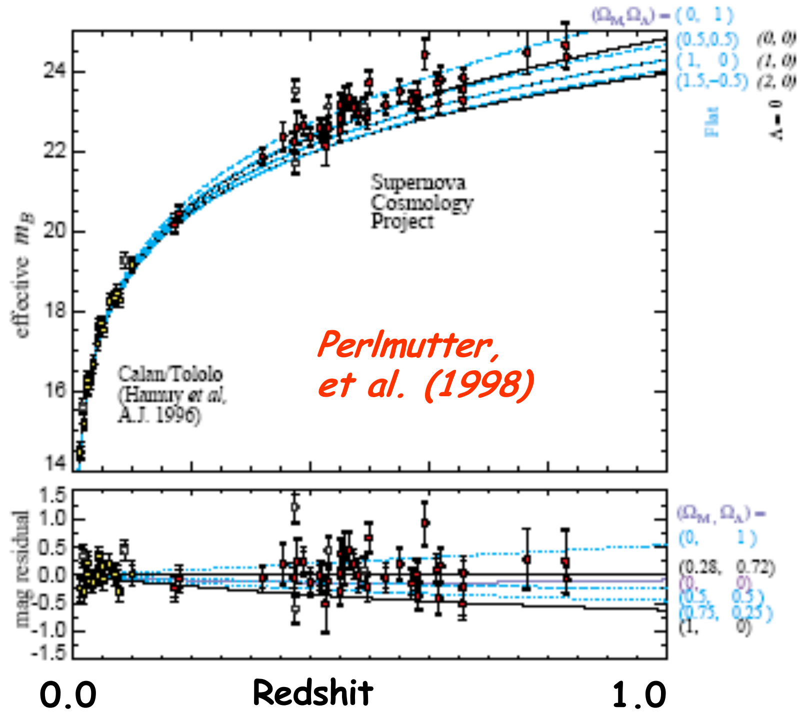
$$\boxed{\begin{aligned} &E_c + E_p = 0 \\ &V_{rot} = \sqrt{\frac{2GM}{R}} \end{aligned}}$$

Constant rotation curve

↓

Halo of Dark Matter

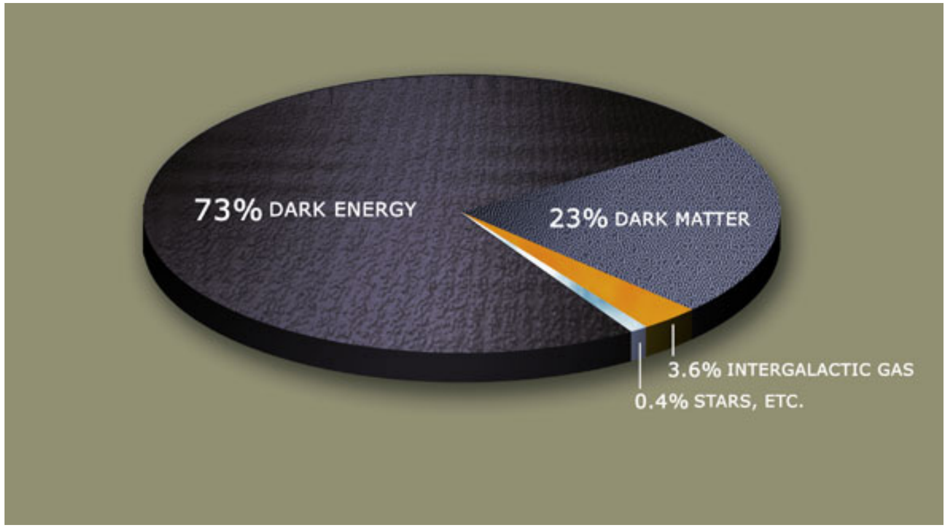
Dark energy



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



Concordance Model

➢ ΛCDM with GR

➢ Study of the nature of DE

$$\boxed{w = P_{DE}/\rho_{DE} = w_0 + w_a z/(1+z)}$$

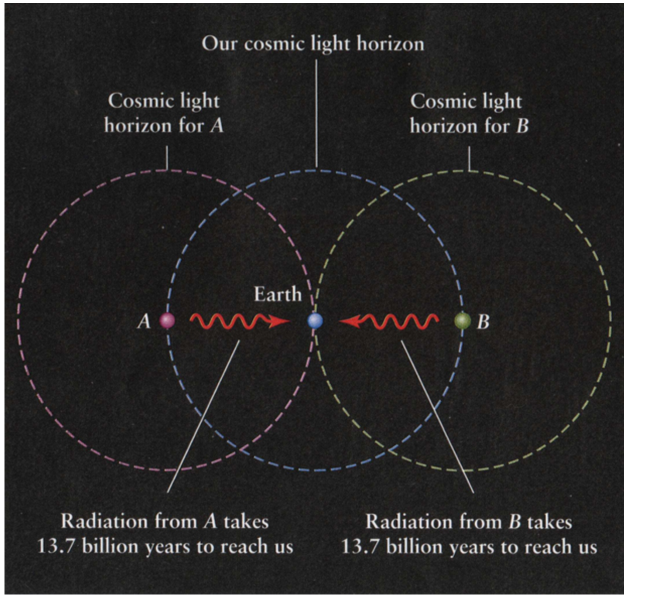
Inflation

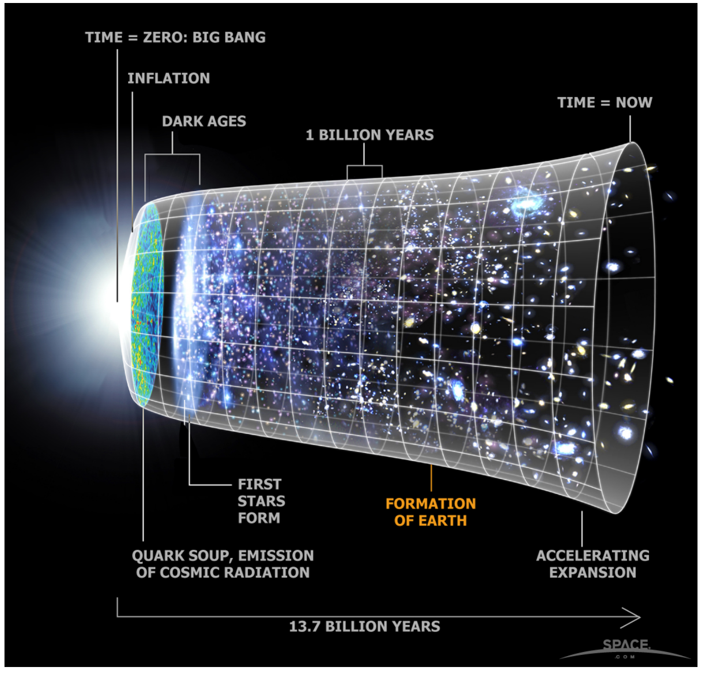
Horizon problem

➢ 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 to keep causality of photons (A. Guth 1979)





Inflation framework

➢ Density energy stay almost constant ("slow roll" model)

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

$$a \propto e^{Ht}$$

➢ Typically, the Universe expanded by a factor of about e^{60}

Open questions in Cosmology

H_0

- Tension between local measurement and CMB

Dark Energy

- BAO: the new standard ruler

Gravitation

- RSD: Test of GR at cosmological distances

Inflation

- Non-gaussianities with 3D survey and CMB
- Polarization of B modes in CMB

Mass of neutrinos

- Multi-probe approach, CMB, WL….

Many topics not covered in this talk

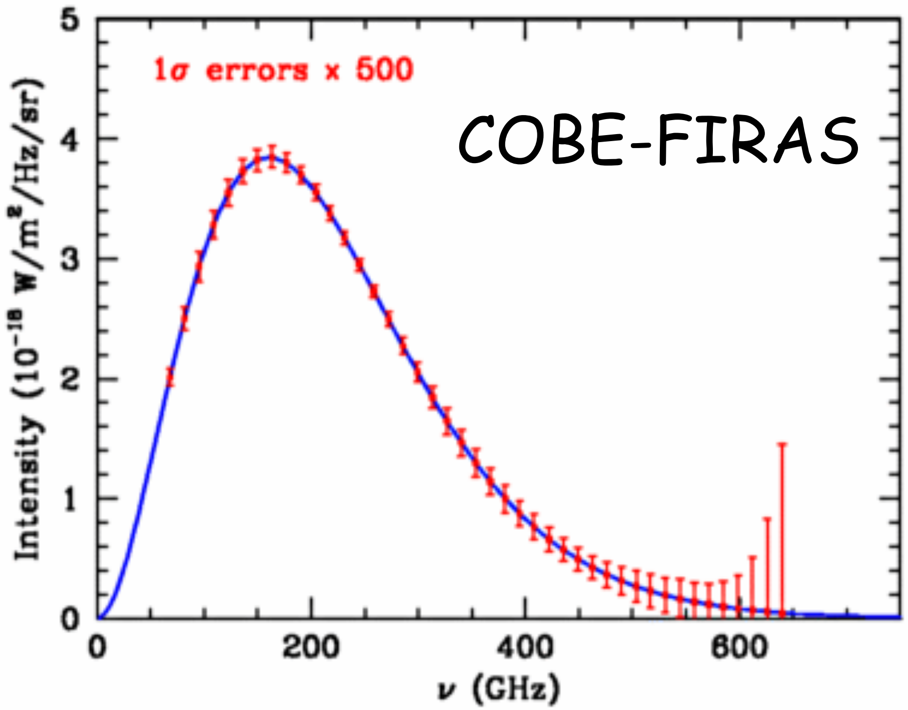
- Dark matter, Warm Dark matter, Galaxy evolution…

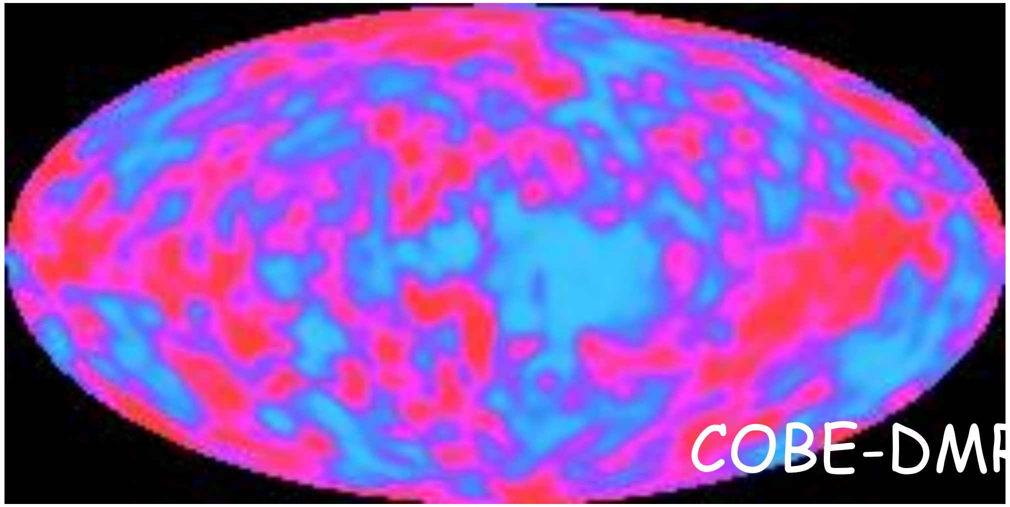
CMB

–

H_0 contreversy

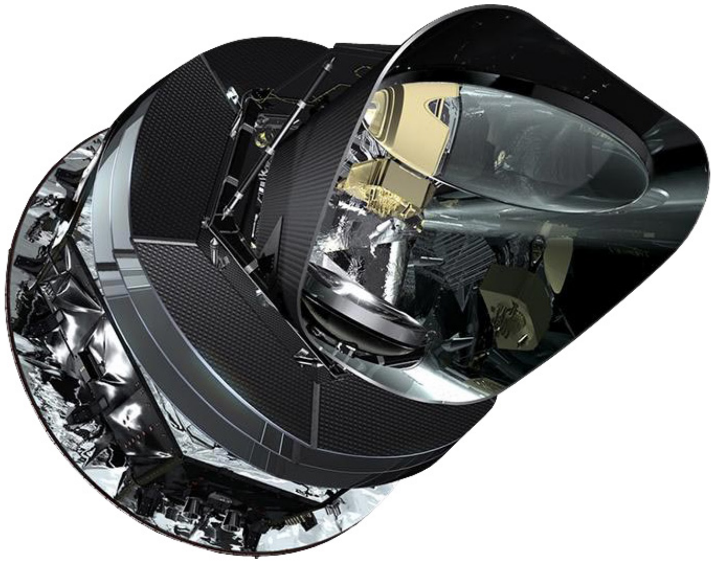
CMB discovery





- 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….

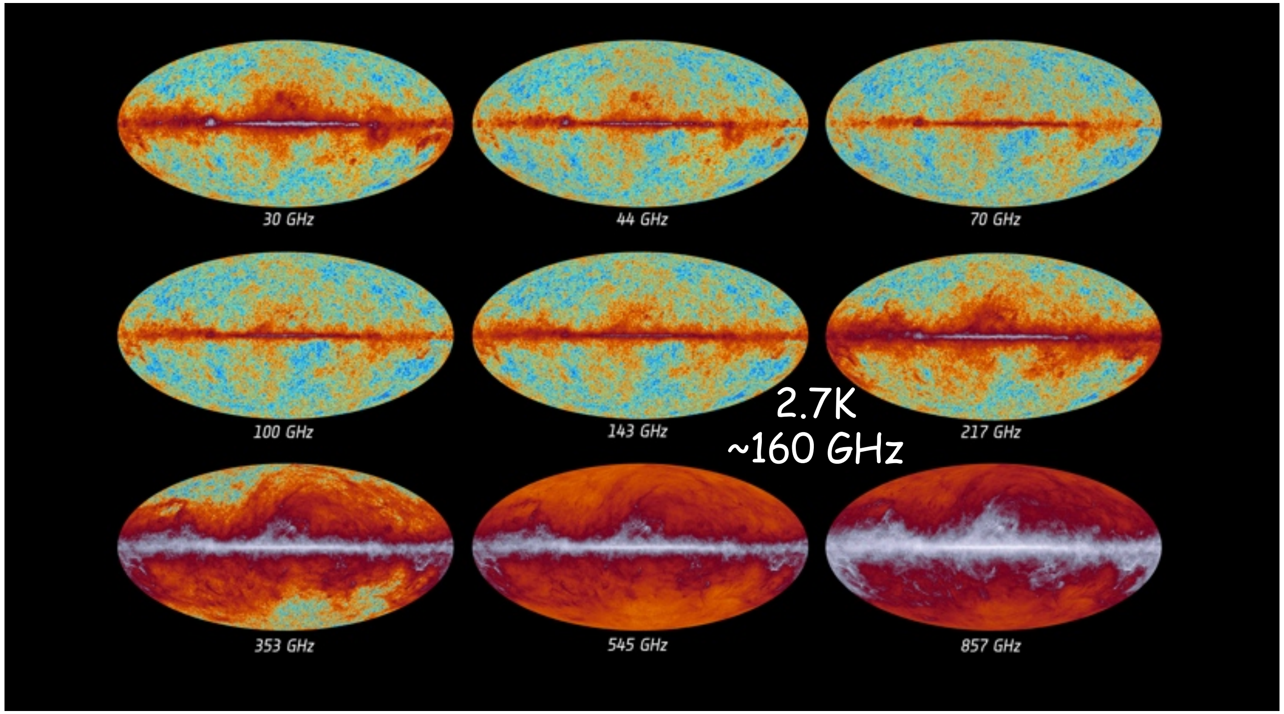
Planck: more and more precise measurements



- 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

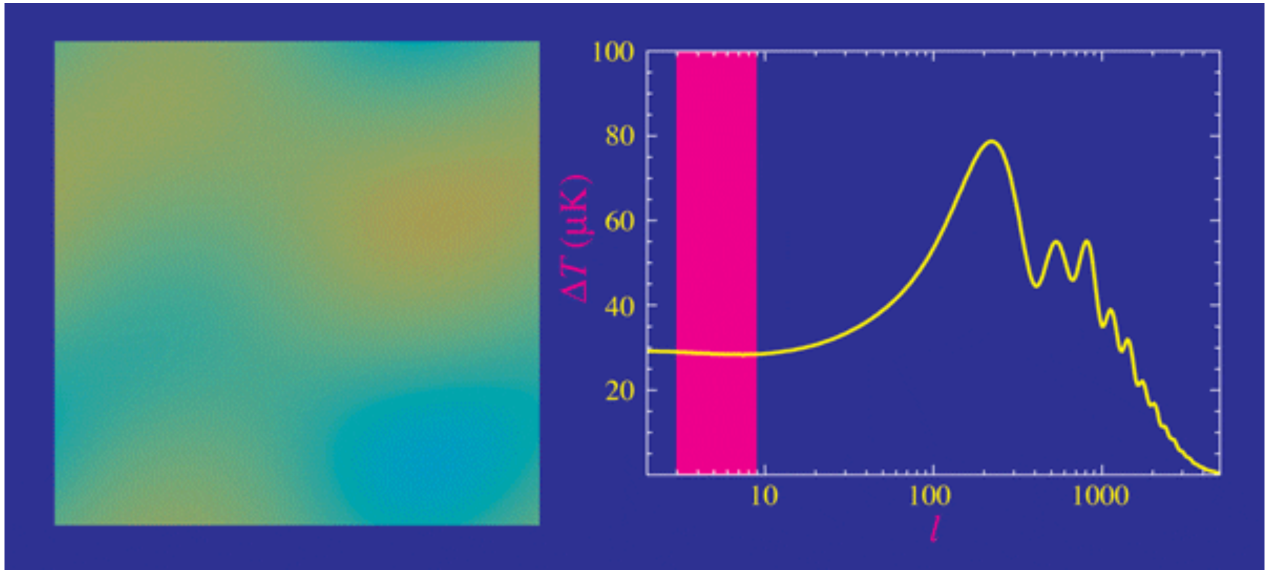
- Maps of the whole sky for 9 different frequencies
- Separation of the components (CMB, galactic dust, experimental noise…).

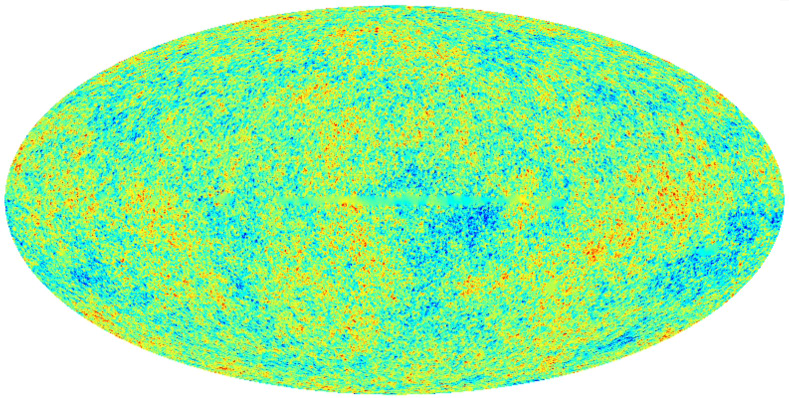


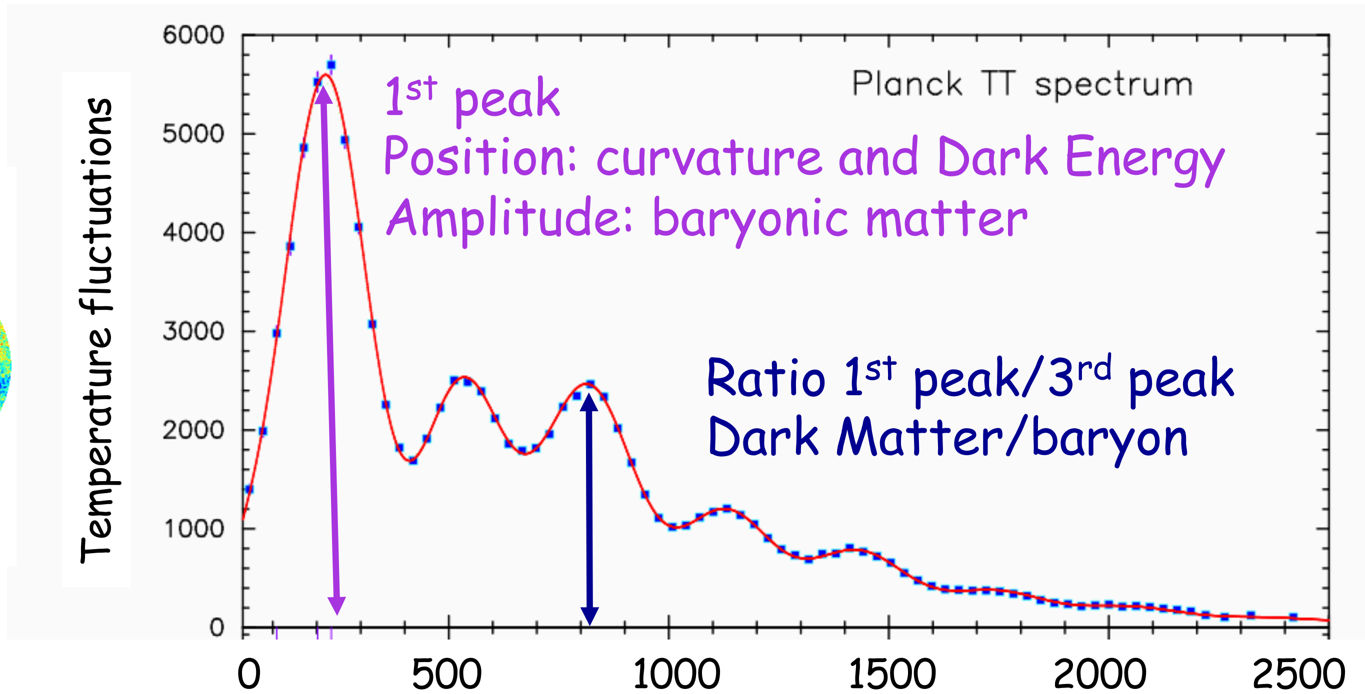
What do we learn with these maps?

CMB anisotropies

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







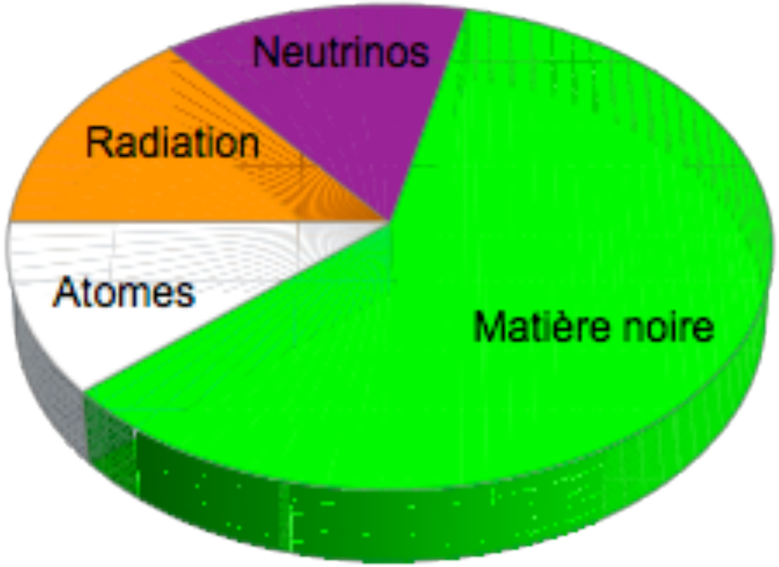
Universe content seen by Planck

➢ 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)



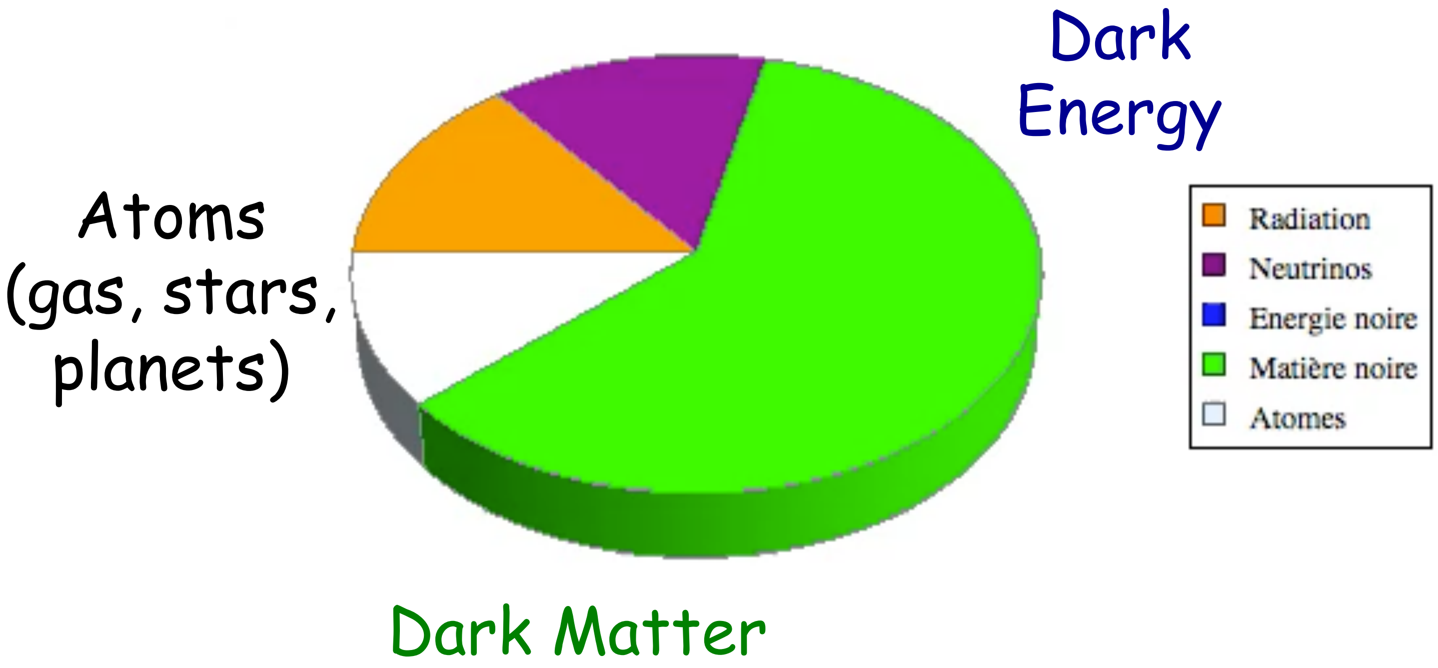
Dark Matter (SUSY, axions..)

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



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)

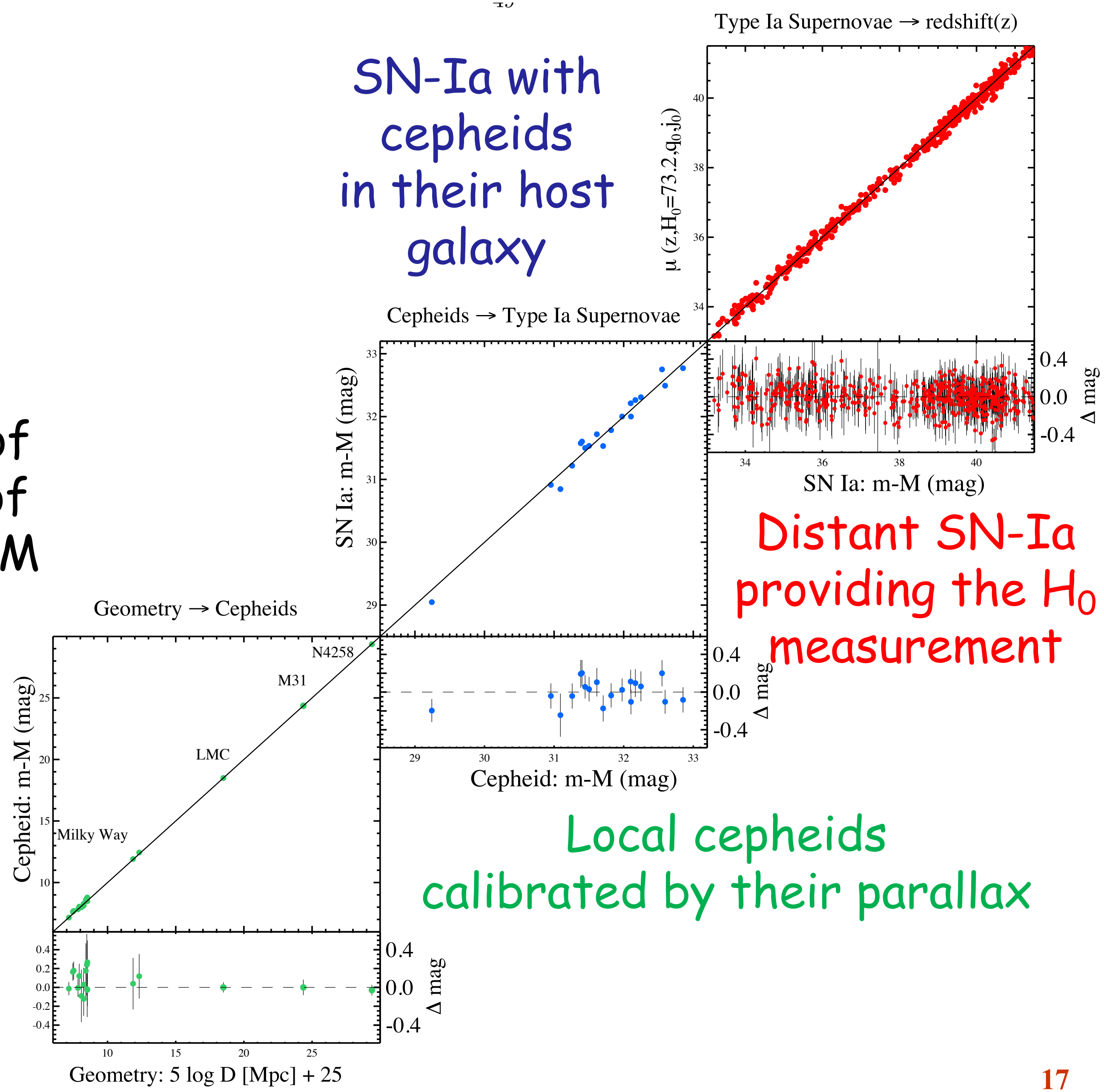
4.4σ tension

CMB: $H_0 = 67.4 \pm 0.5$

SNIa: $H_0 = 74.0 \pm 1.4$

SH0es, Riess et al., 2019

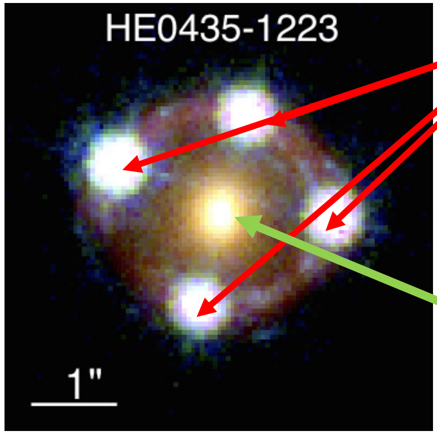
SN-Ia with cepheids in their host galaxy



Distant SN-Ia providing the H_0 measurement

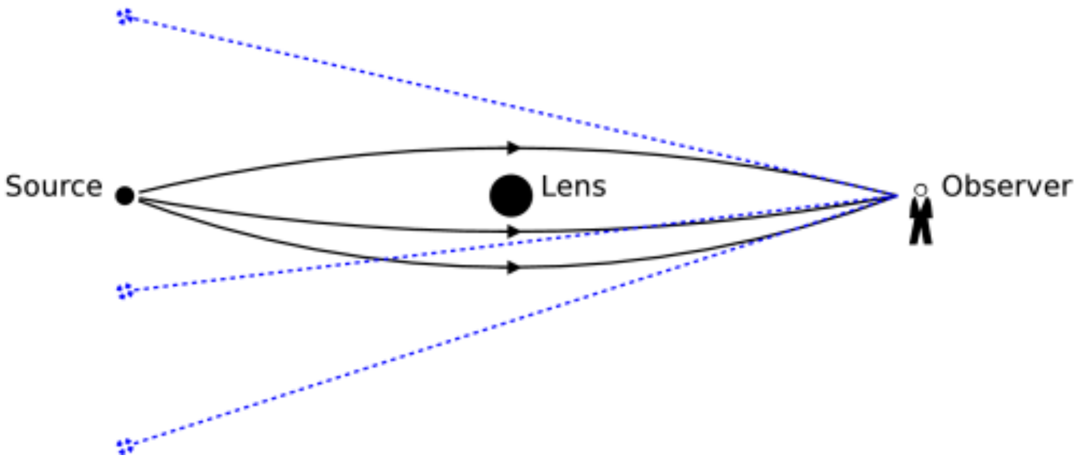
Local cepheids calibrated by their parallax

H0licow – lensed quasars



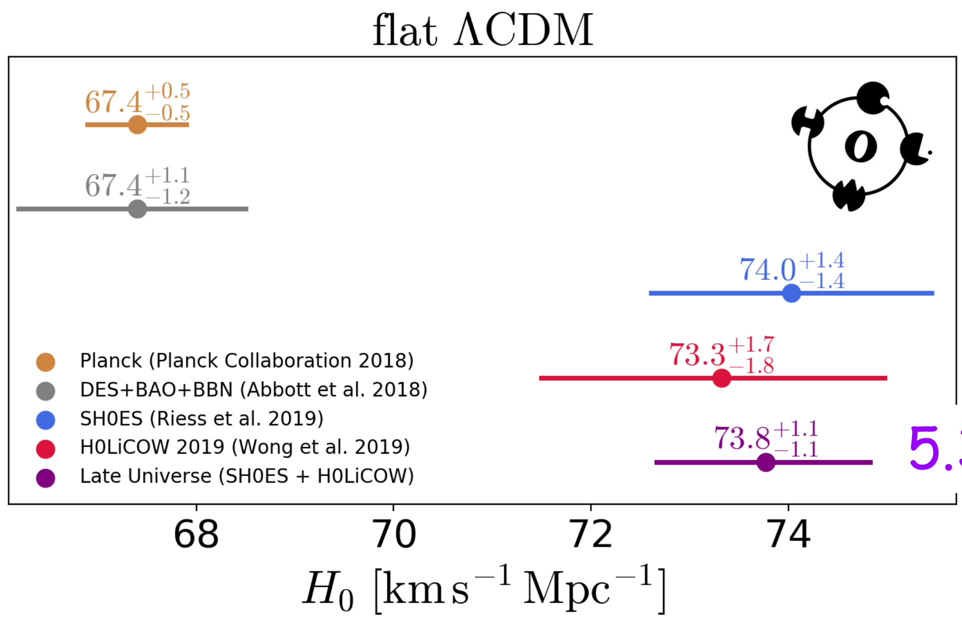
4 images of the same quasars

The lens: a galaxy



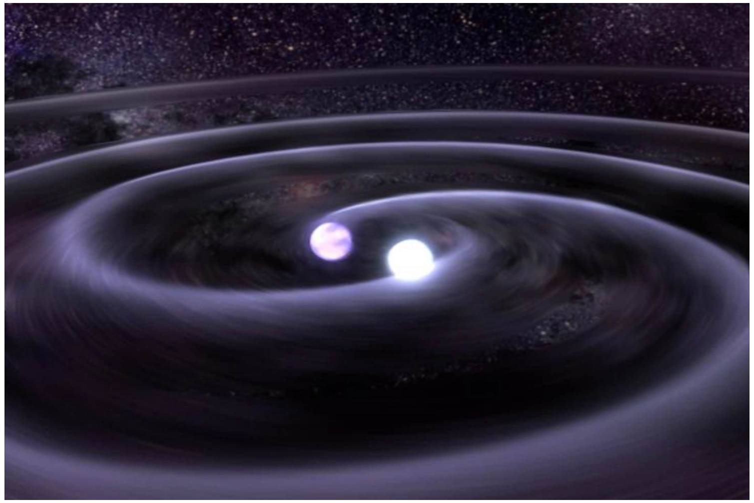
Principles

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



5.3σ

H0 and Gravitational Waves?

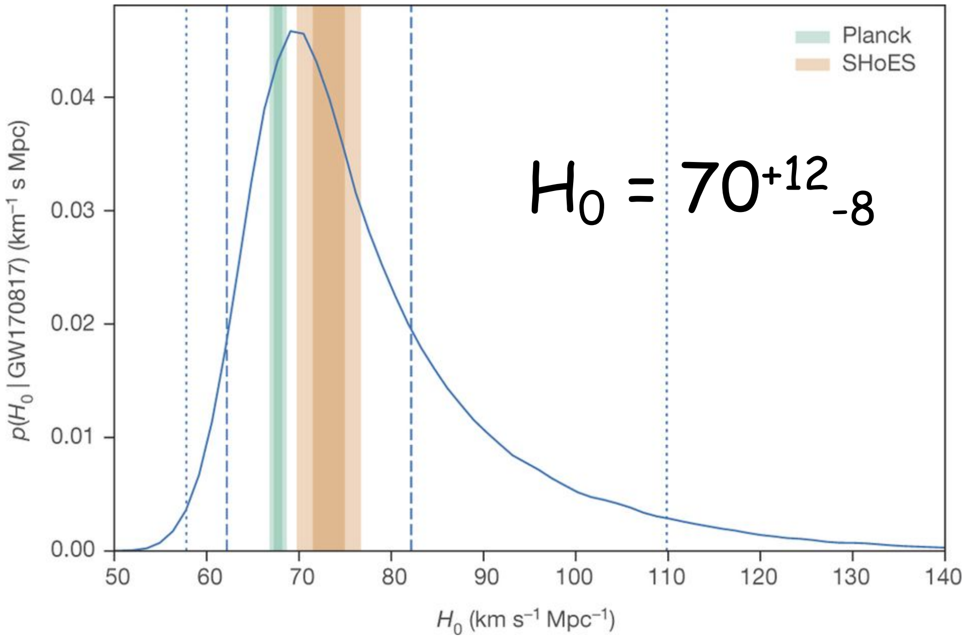


Principles

- 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



$H_0 = 70^{+12}_{-8}$

Dark Energy and GR

–

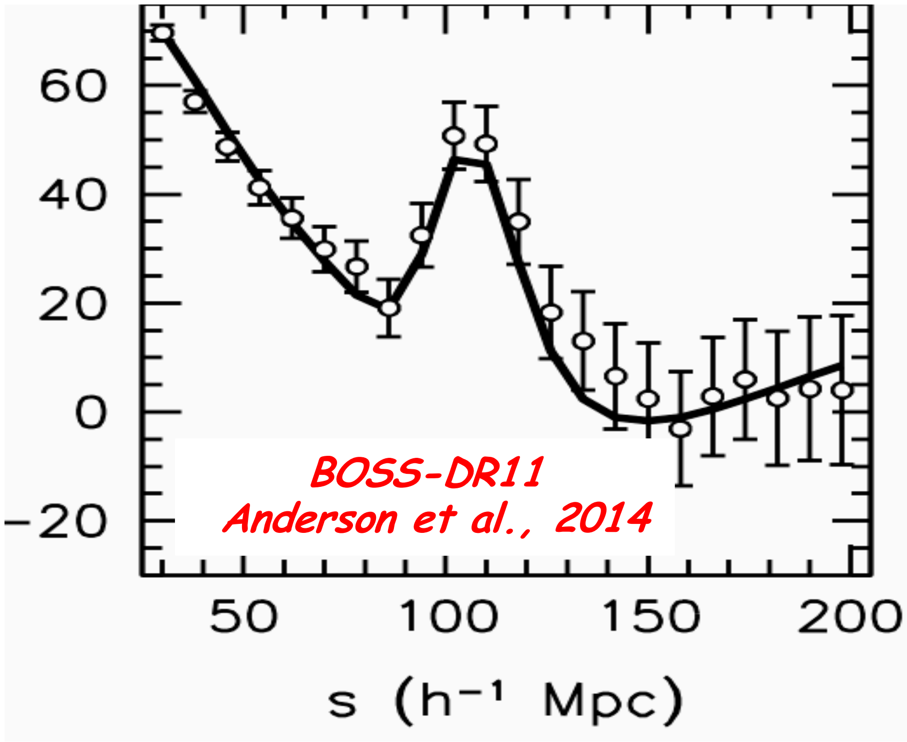
BAO and RSD

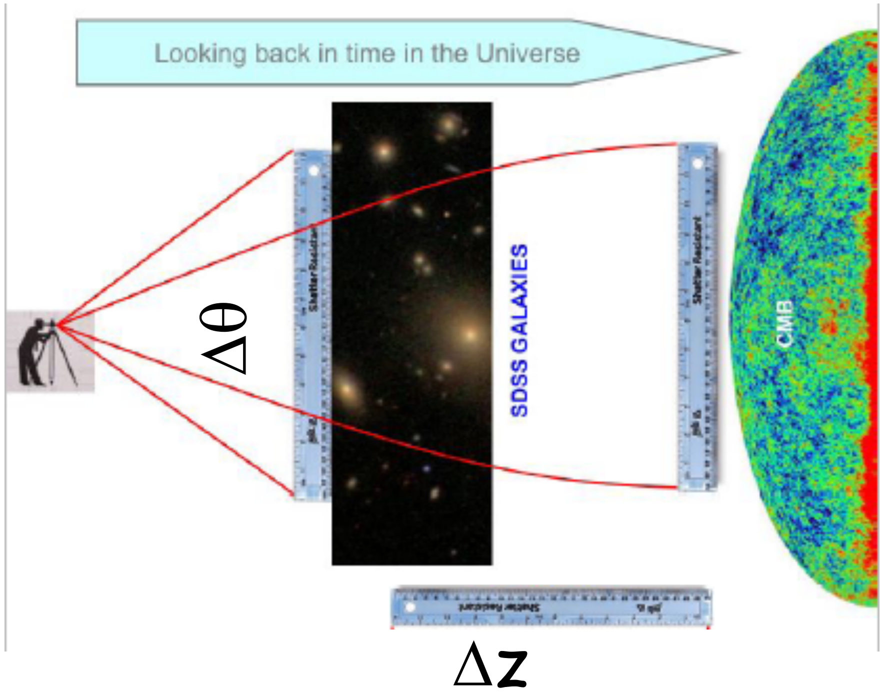
Baryonic Acoustic Oscillations (BAO)

BAO distance

- Non-uniform distribution of galaxies, they form in overdense shells about 100 Mpc.h^{-1} in radius.
- Excess in the correlation function at ~100 Mpc.h^{-1}

$\Rightarrow$ Standard Ruler





A 3D measurements

- Position of acoustic peak
- Transverse direction:

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

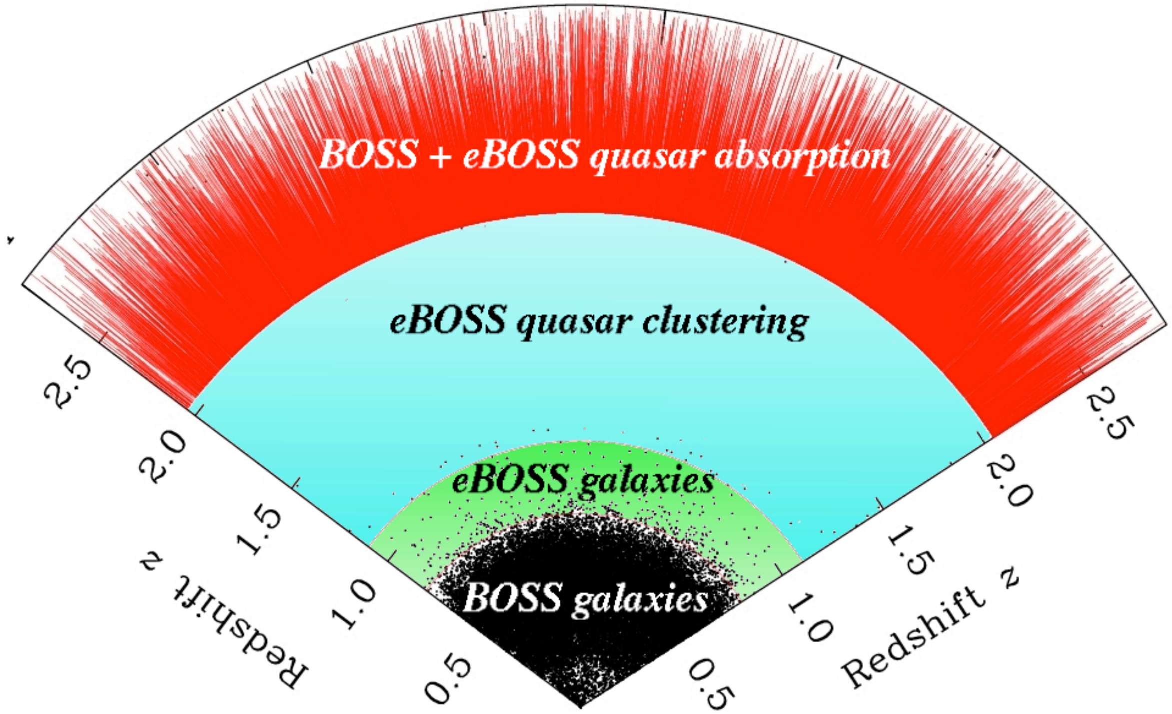
$\Rightarrow$ Sensitive to angular distance $D_A(z)$

- Radial direction (along the line of sight):

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

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

SDSS: BOSS/eBOSS 2009-2019



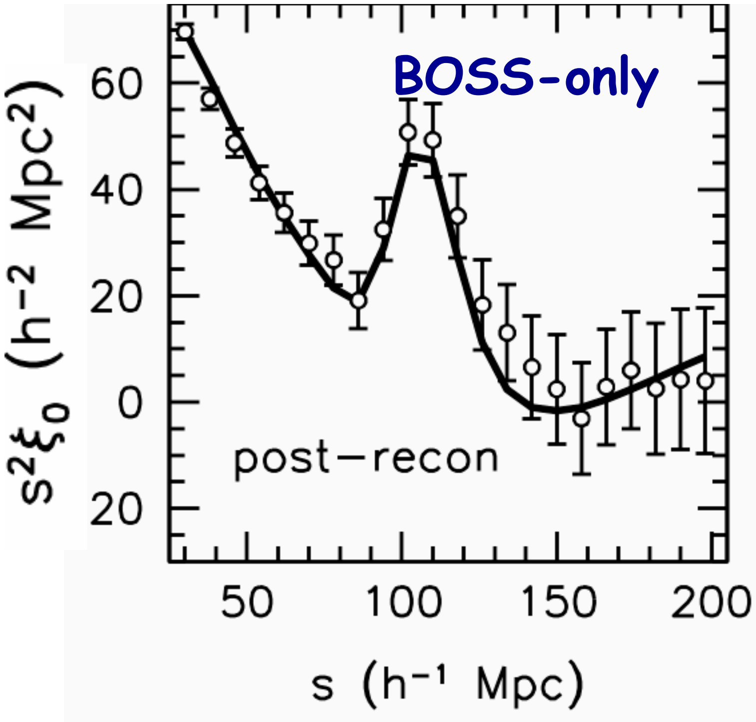
BOSS (2009→2014)

- 1.2 millions of Luminous Red Galaxies (LRG)
  - LOW-z: $0.15<z<0.43$
  - CMASS: $0.43<z<0.7$
- 170 000 quasars ($z>2.1$, HI absorption in Ly-α forests)

eBOSS (2014→2019)

- Redshift of LRG extended to 0.8
- Emission Line Galaxies (ELG): star forming galaxies, $z\sim0.85$
- Quasars direct tracers, $0.9<z<2.2$
- More ($z>2.1$) quasars with Ly-α forest

BAO in Correlation Function



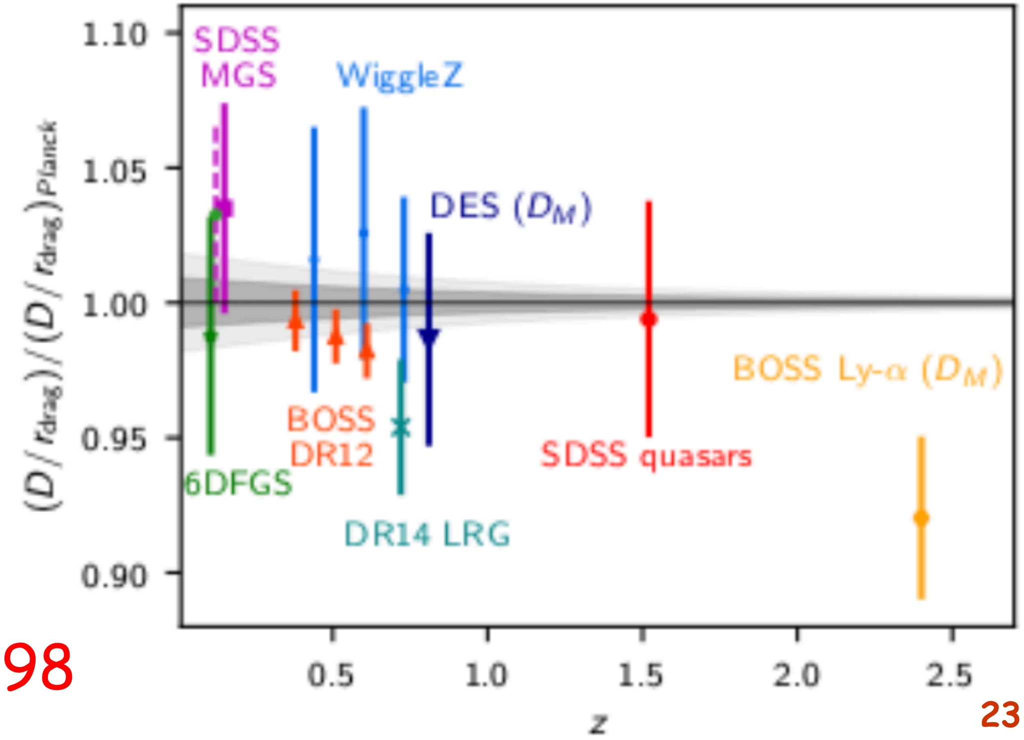
BOSS-DR11. Anderson et al., 2014

- BOSS-only 8-σ observation
- One percent measurement of BAO scale for CMASS-only !!!
  - Low-z (z~0.3): α=1.018 ±0.021
  - CMASS (z~0.6): α=1.0144 ±0.0098

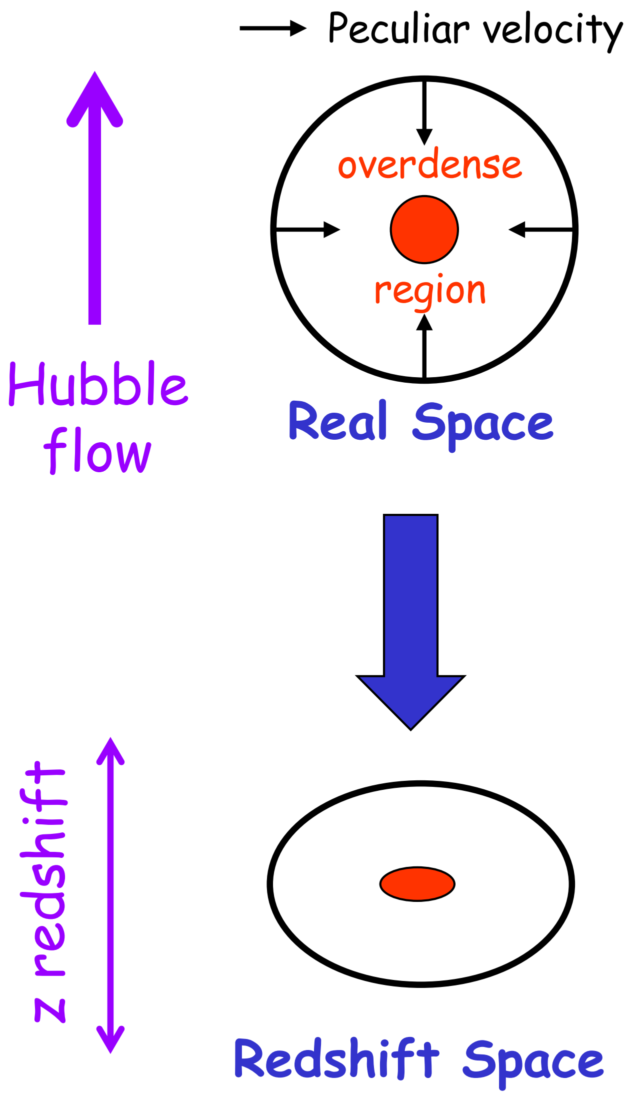
- Use a fiducial model to compare against observed features in spherical average statistics.
- Departures quantified by dilatation scales α:

  ➡Fit of $\xi(\alpha r)$

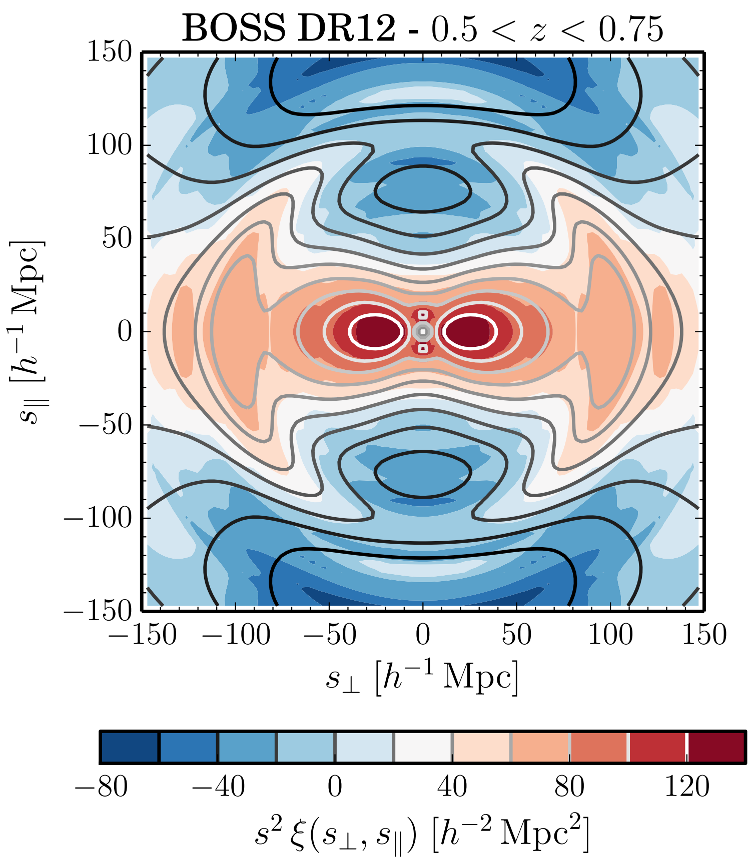
Planck 2018. VI. cosmological parameters



Redshift Space Distortions (RSD)



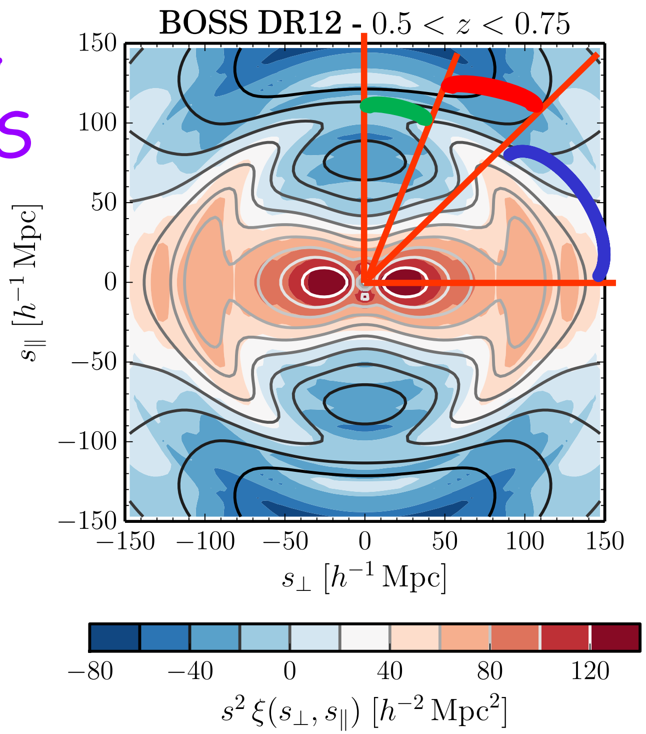
- Acceleration toward overdense regions
- Flattening in radial direction from real space to redshift space (over tens Mpc)
- Allow us to measure action of gravity (5-40 Mpc) at cosmological distance (Gpc)



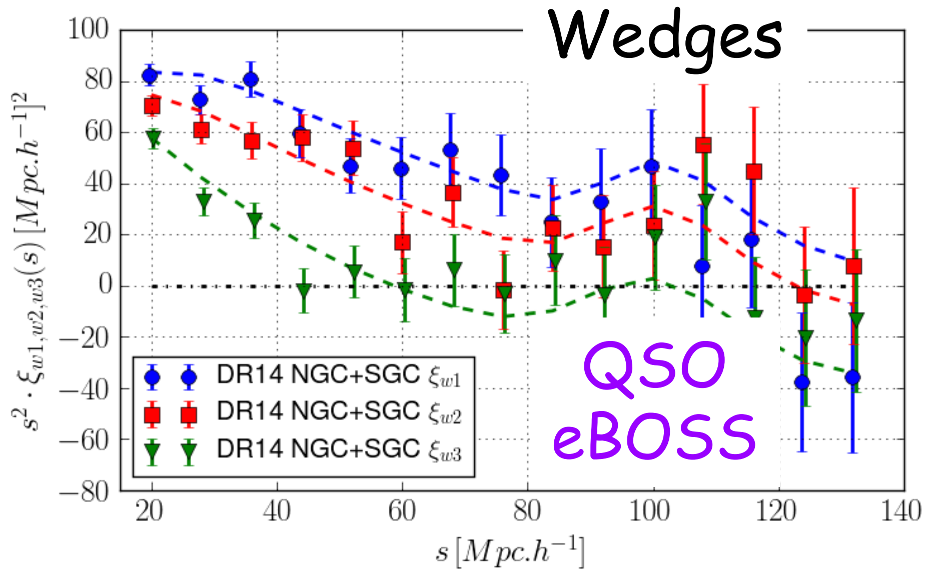
BOSS Collaboration
Alam et al. (2016)

Redshift Space Distortions

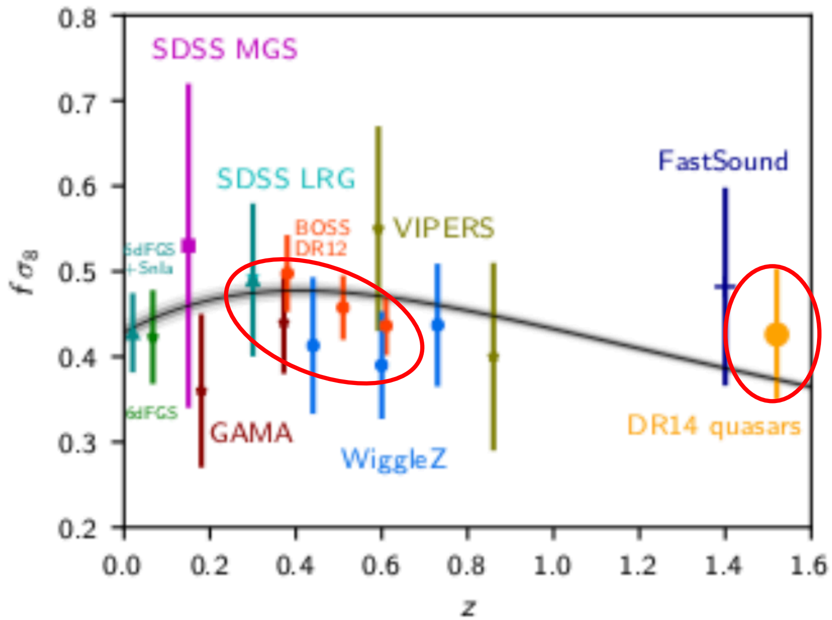
LRG
BOSS



BOSS Collaboration Alam et al. (2016)



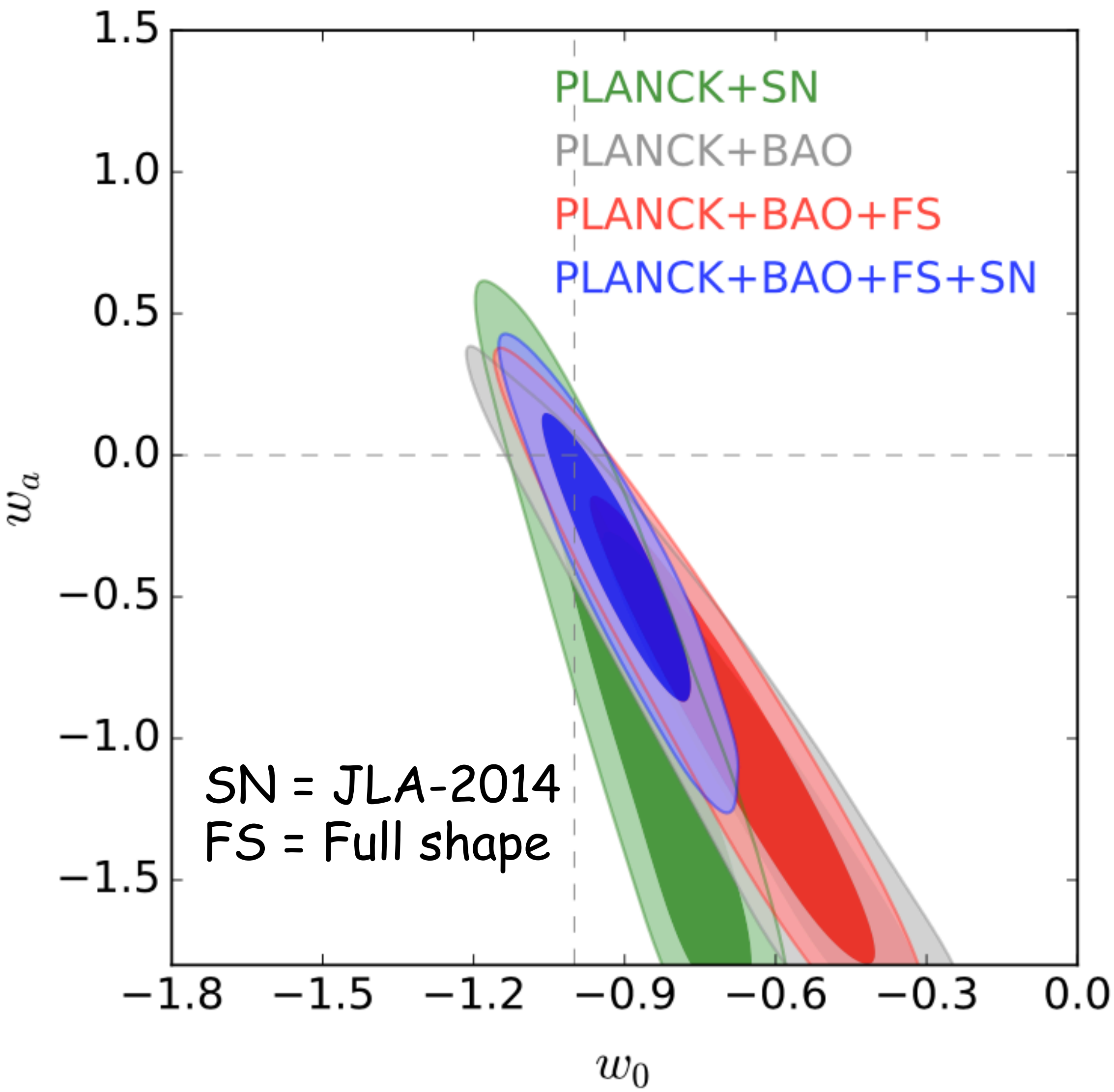
Zarrouk et al., (2018)



Planck 2018. VI. cosmological parameters

- Test with different tracers
  - BOSS: LRGs z~0.6
  - eBOSS: QSOs z~1.5
- RSD clearly visible with the wedges splitting
- Perfect agreement with GR

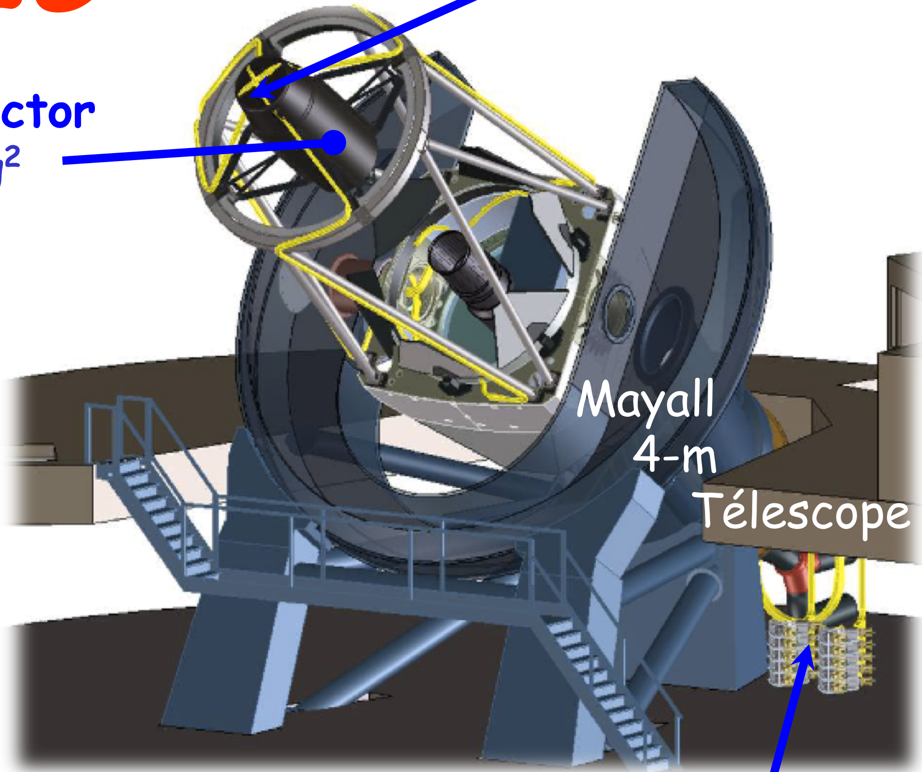
Dark Energy: Equation of state



BOSS-DR12 Alam et al. (2016)

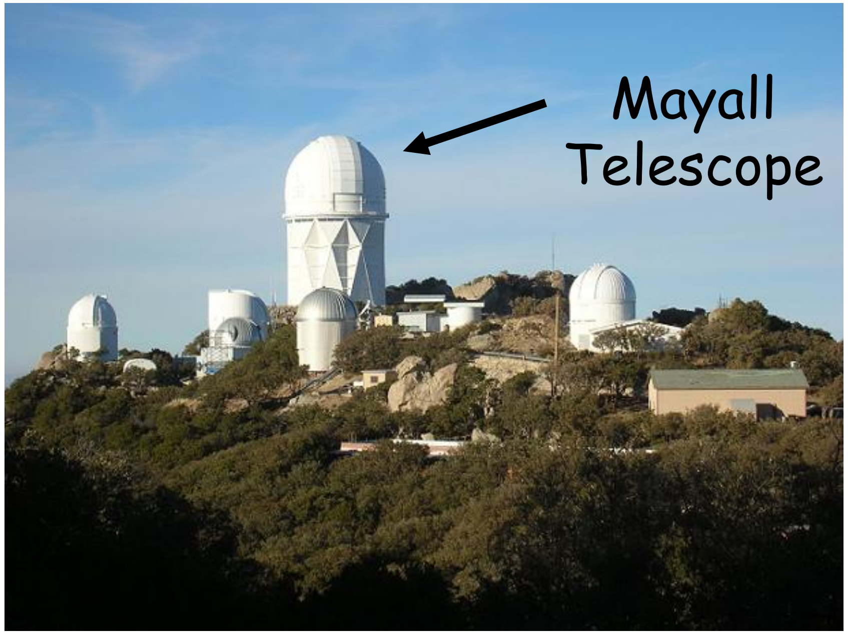
- Eq. of state: $w=P/\rho$
  $w(z)=w_0+z/(1+z).w_a$
- For ΛCDM:
  $w_0 = -1$
  $w_a = 0$
- Planck+BAO:
  $w_0 = -0.63\pm0.20$
  $w_a = -1.16\pm0.55$
- Planck+BAO+FS+SN:
  $w_0 = -0.91\pm0.10$
  $w_a = -0.39\pm0.34$

DESI 2020-2025



Scientific Project

- 14000 deg^2 survey for $0.05<z<3.7$
- Main scientific goals : RSD and BAO
- International collaboration
- 74 institutions (46 non-US)
- 630 members
- ~40 French scientists and engineers



Instrument

- 4-m telescope at Kitt Peak (Arizona)
- Wide FoV (~ 7 deg^2)
- Robotic positioner with 5000 fibers
- 10 spectrographs x 3 bands (blue, visible, red-NIR) → 360-1020 nm

DESI tracers of the Matter

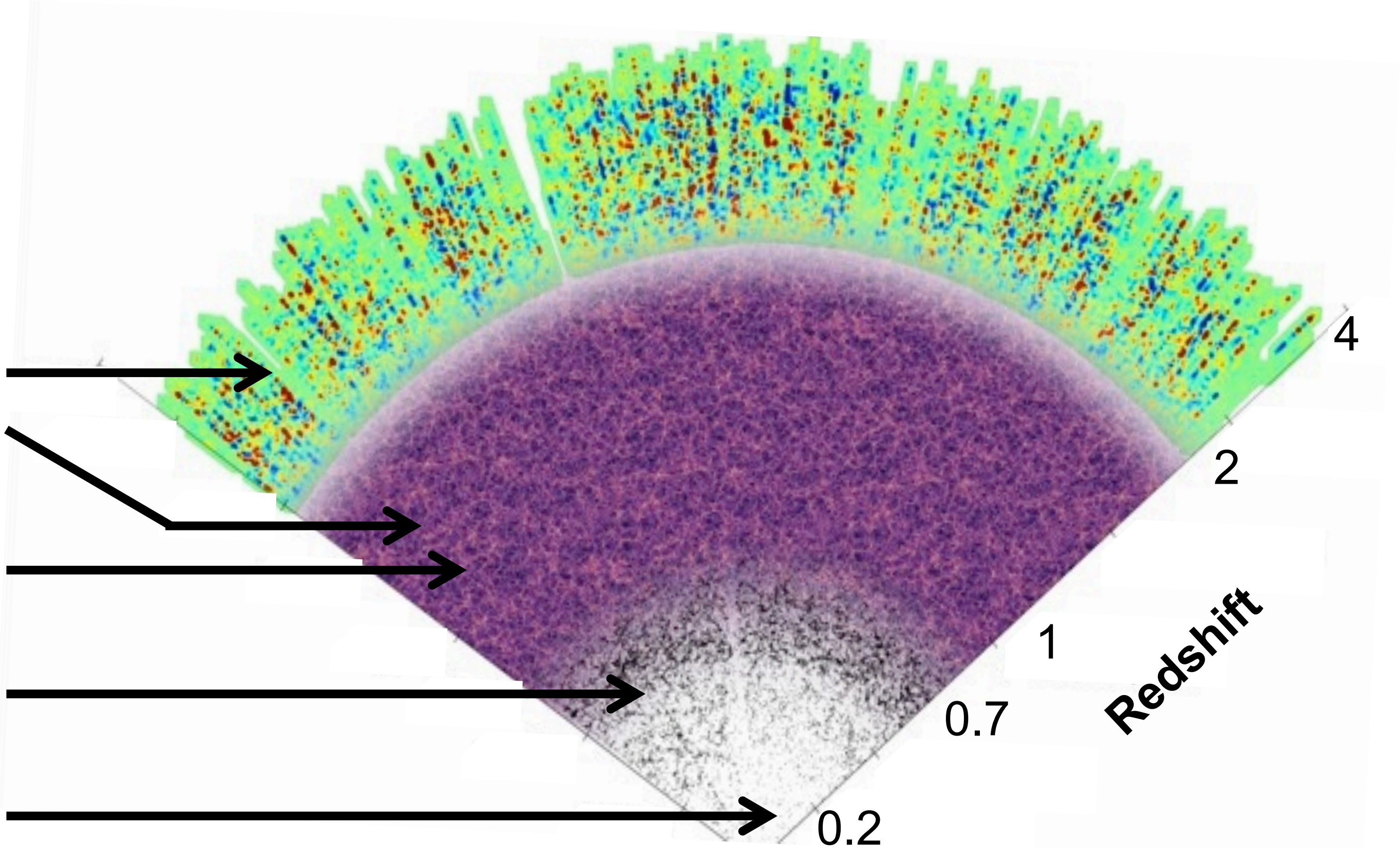
Five target classes spanning redshifts z=0.05 → 3.7 for clustering
DESI will explore a x30 larger volume than the SDSS map
~35 million redshifts over 14,000 sq. degrees in five years

2.4 million QSOs
Lya $z > 2.1$
Tracers $1.0 < z < 2.1$

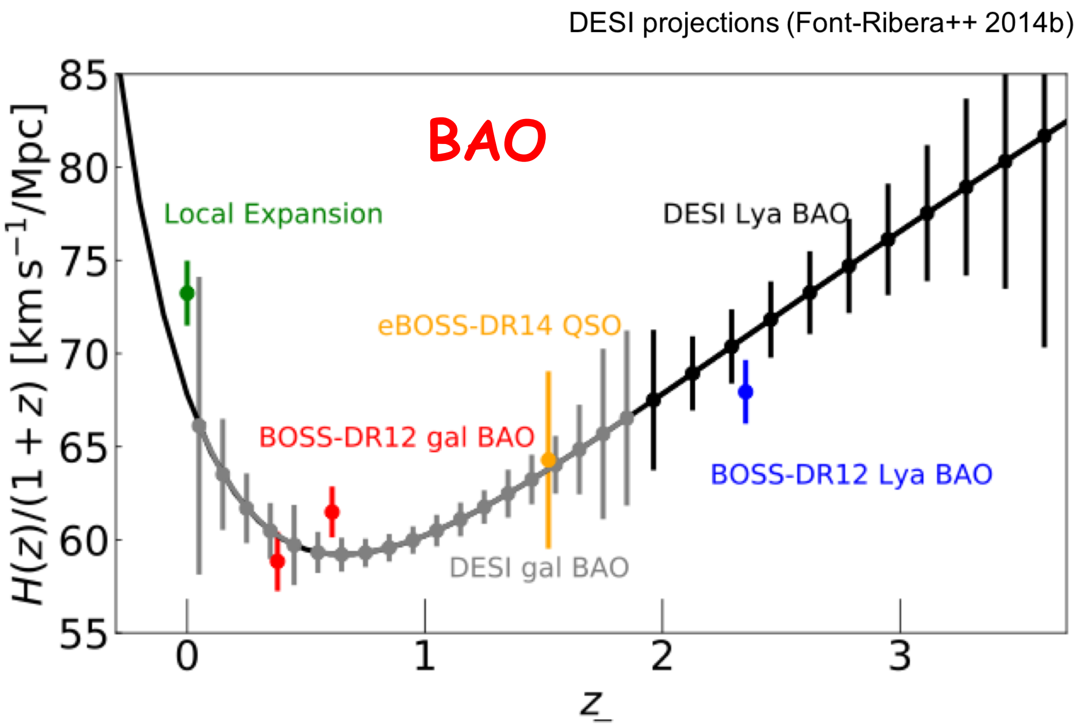
17 million ELGs
$0.6 < z < 1.6$

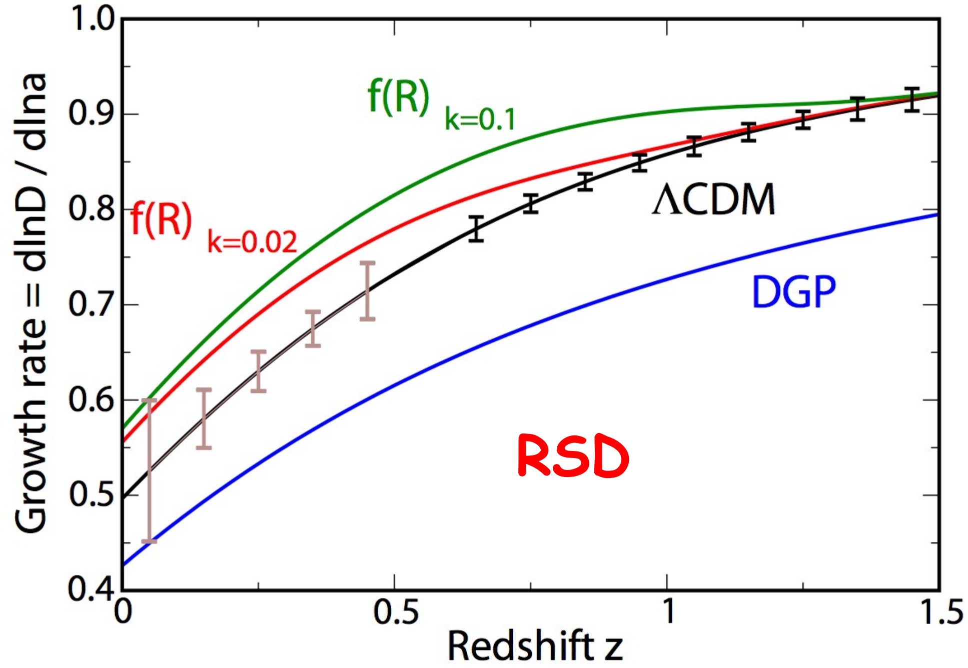
6 million LRGs
$0.4 < z < 1.0$

10 million
brightest galaxies
$0.05 < z < 0.4$



Science with DESI



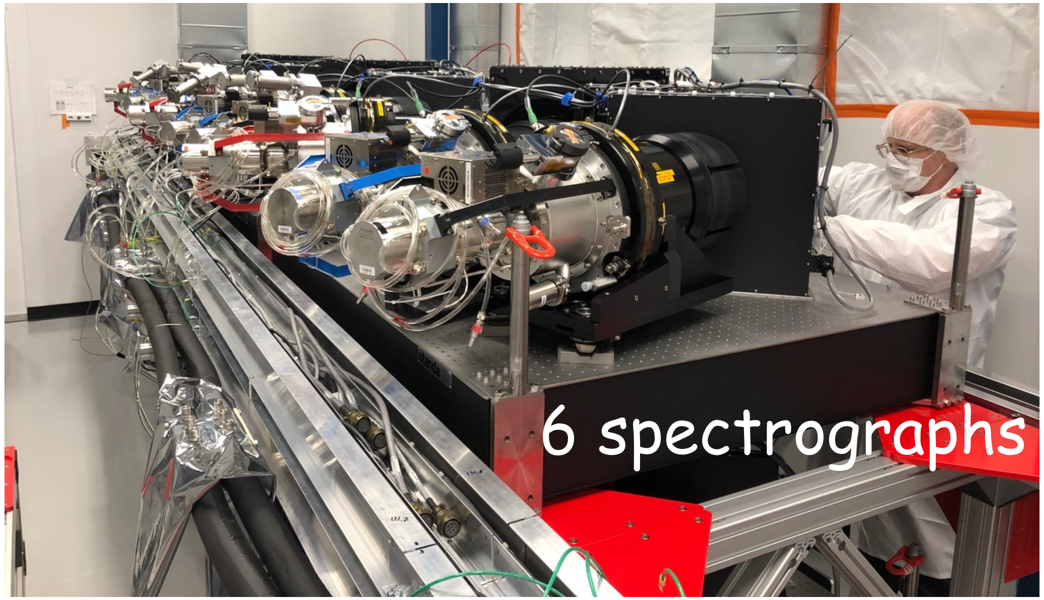


Improvements compared to SDSS

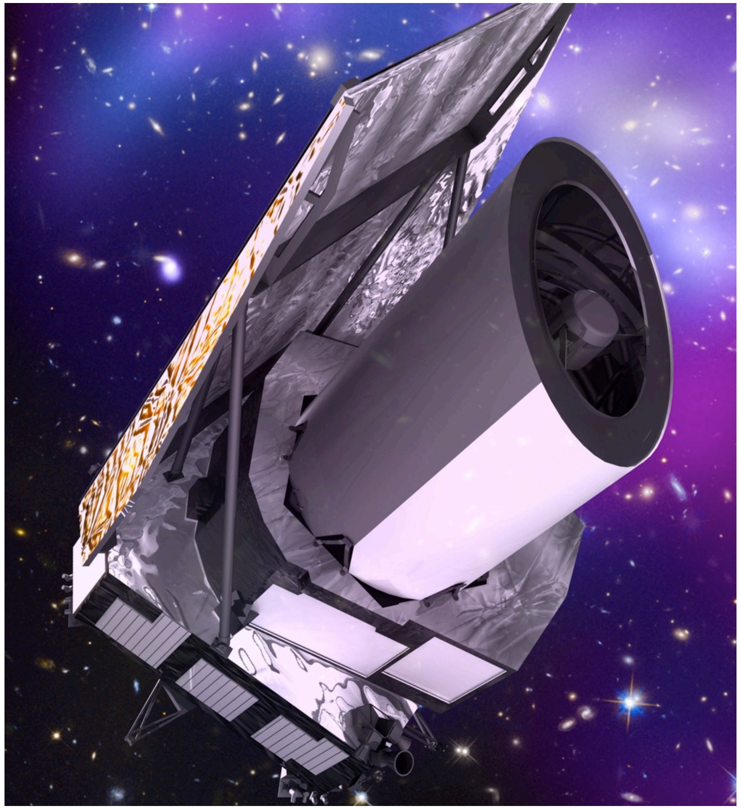
- **BAO:** 1 order of magnitude better $\sigma(\alpha)$ ~ 0.1%
- **RSD:** better than 1% over the full redshift range

Status of DESI

- Optical and NIR imaging for Target Selection is completed
- Optical corrector is installed and commissioned
- Focal plane with positioner installed and in test
- 6/10 spectrographs in operation
- October 2019: Commissioning of DESI with spectrographs
- Feb. 2020: Survey Validation
- **June 2020: Science Survey starts!!!**

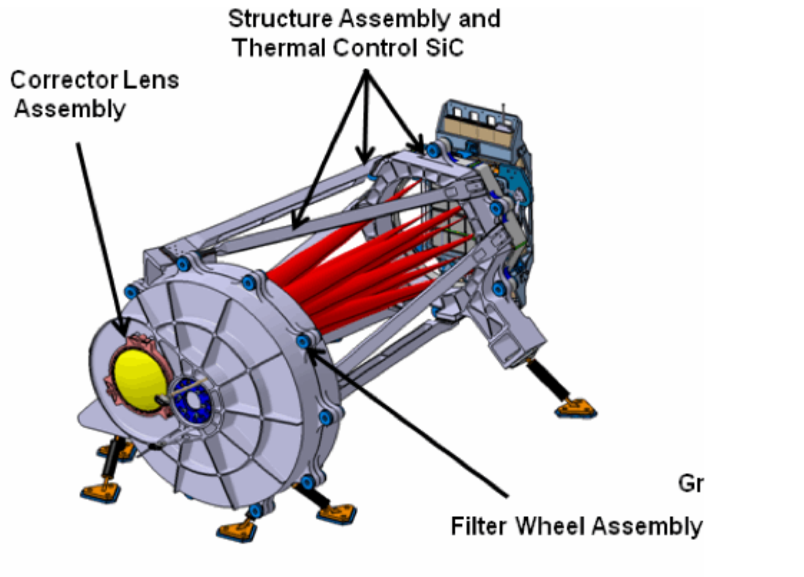


Euclid 2022-2028



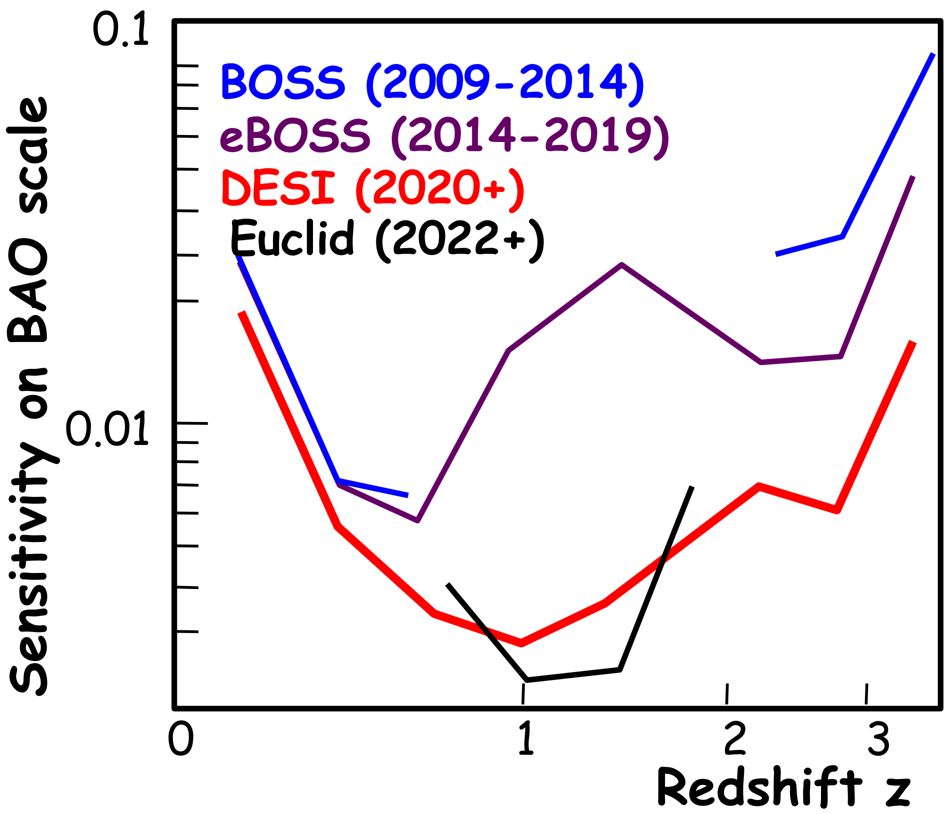
Instrument

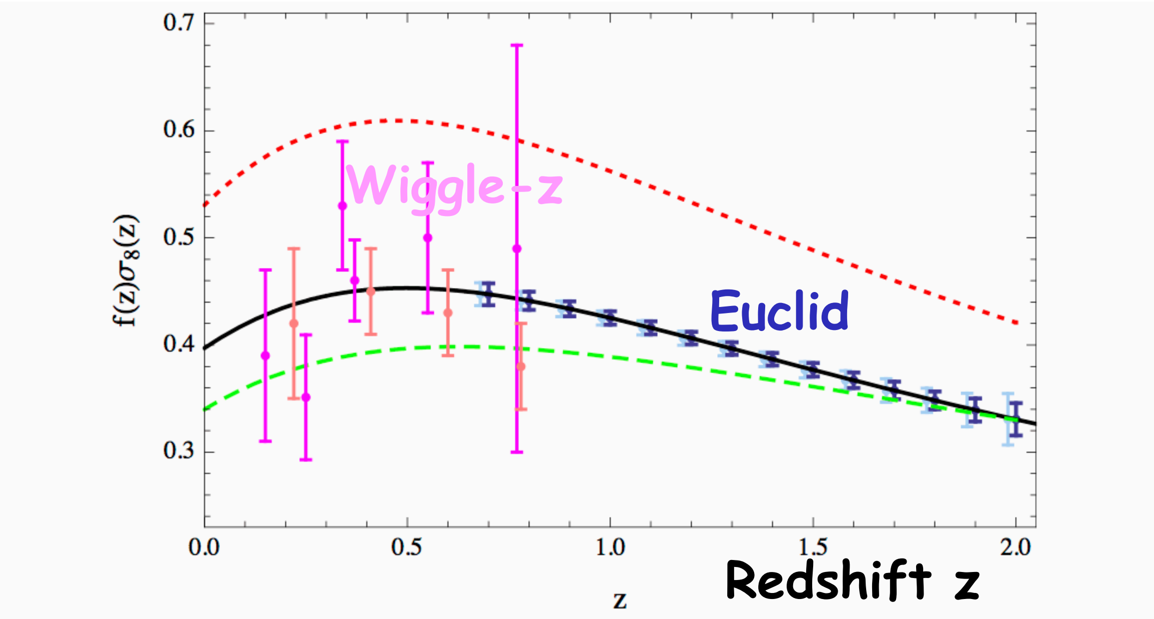
- ESA Satellite (launch in 2022) at L2
- 6 year program
- 14 countries + 1100 members
- 1.2m telescope with 0.5 deg^2 FoV
- Two instruments (VIS, NISP)
- Slitless NIR spectrograph (1 blue and 3 red grisms) →1000-2000 nm



Scientific Project

- 15000 deg^2 survey for $0.9<z<1.85$
- For BAO and RSD: 50M galaxy spectra with R~250
- Redshift determined with Hα line
- Weak lensing (WL), see later in this talk



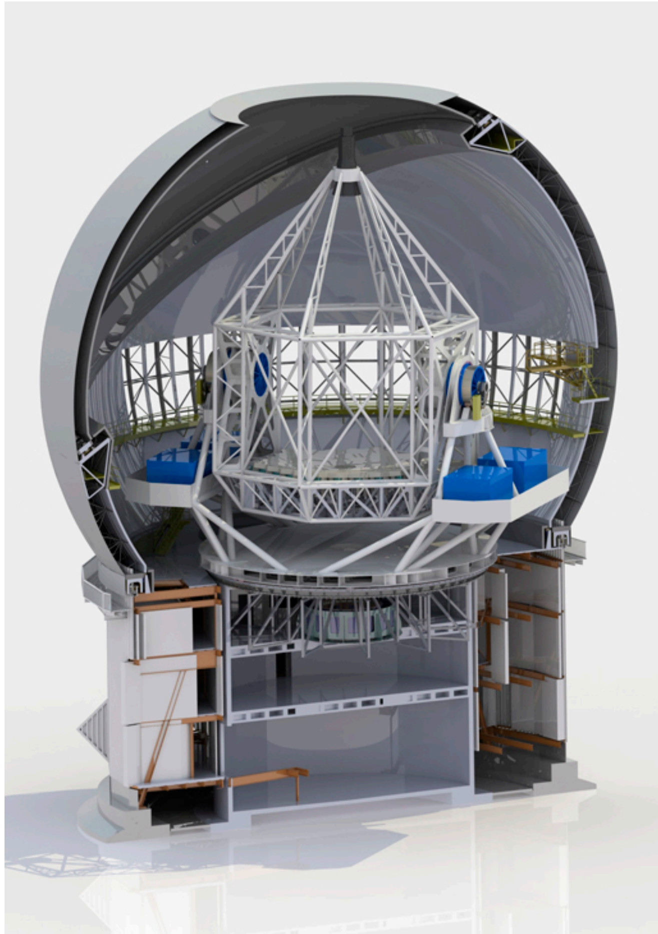


Euclid performances

Improvements with Euclid

- For BAO in the 1<z<1.6 region (but the gain is cosmic variance limited)
- Much impressive gain for RSD (50M galaxies to compare to ~35M for DESI)
- Higher in redshift, up to z~1.8 even z~2.0 (region not covered by DESI)

Maunakea Spectroscopic Explorer



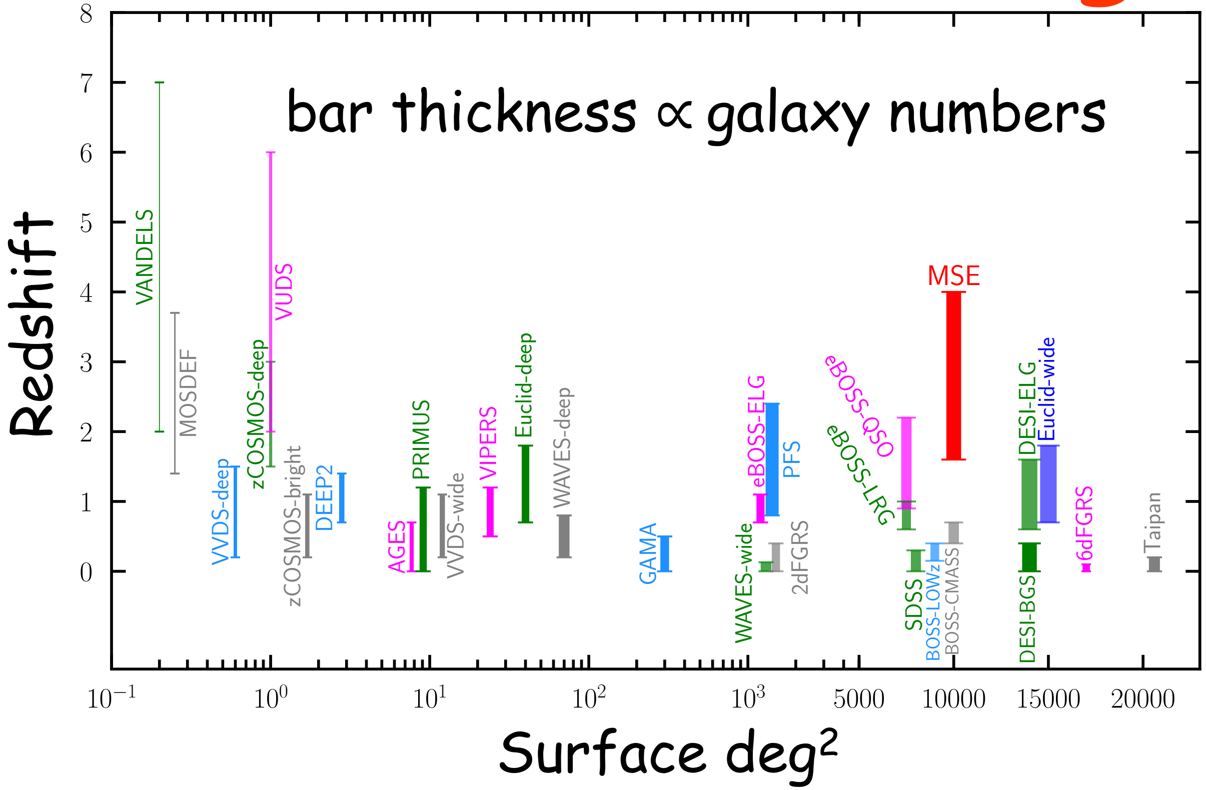
MSE in a nutshell:

- It will replace the 3.6-m Canada-France-Hawaii Telescope
- 11.2 m telescope with 1.5 deg. FoV
- Fully dedicated to spectroscopy
- Positioner with 4332 fibers
- Low and moderate resolution:
  R: 2500 → 6000
- Wavelength range:
  Visible + NIR (J and H bands)

Program for cosmology:

- A large-volume survey of high-redshift galaxies and quasars
- Forecasts based on the white paper:
  W. Percival, Ch. Yèche et al., arXiv:1903.03158

A wide and distant cosmological survey



MSE

Probing primordial Universe with SF galaxies and quasars

- Wide survey: 10,000 deg^2 with ~500 observation nights
- Three tracers covering 1.6<z<4.0:
  - Emission line galaxy (ELG): 1.6<z<2.4
  - Lyman break galaxy (LBG): 2.4<z<4.0
  - Quasars with Ly-α forests: 2.1<z<4.0

Forecast for BAO and RSD

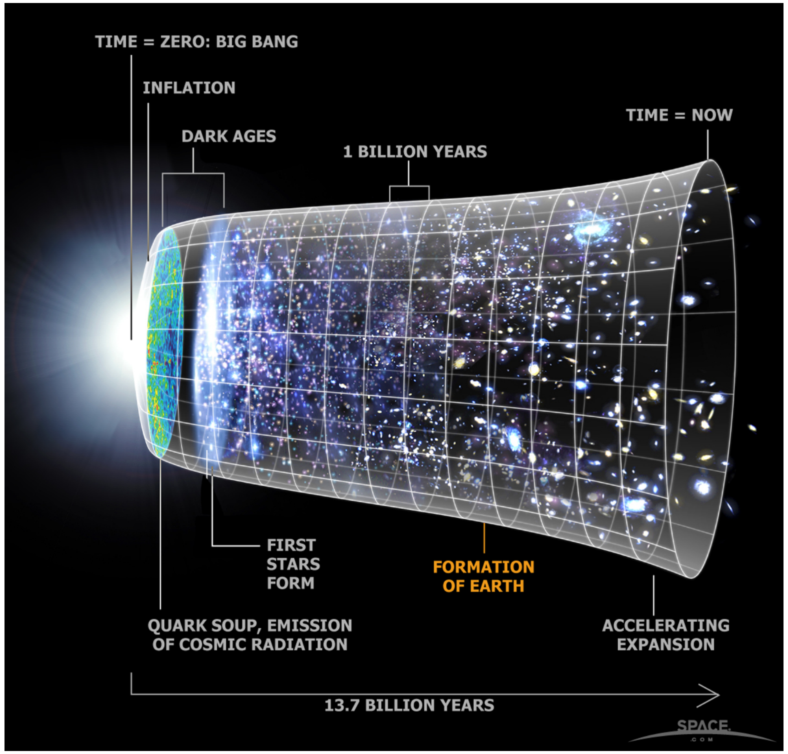
Sample	z	$\bar{n}$ $[10^{-4}\mathrm{h}^3/\mathrm{Mpc}^3]$	V $[\mathrm{Gpc}^3/\mathrm{h}^3]$	σ_{D_A}/D_A [%]	σ_H/H [%]	σ_{D_V}/D_V [%]	$\sigma_{f\sigma_8}/f\sigma_8$ [%] $k_{\mathrm{max}} = 0.1[\mathrm{h/Mpc}]$
ELGs	1.6 – 2.0	1.8	15.56	0.81	1.43	0.56	1.86
	2.0 – 2.4	1.8	16.20	0.74	1.30	0.51	2.05
LBGs	2.4 – 2.8	1.1	16.27	0.96	1.59	0.64	2.68
	2.8 – 3.2	1.1	16.00	0.94	1.54	0.63	2.94
	3.2 – 3.6	1.1	15.54	0.93	1.52	0.62	3.23
	3.6 – 4.0	1.1	14.99	0.94	1.52	0.62	3.59

Matter-dominated Era for 1.6<z<4.0

- 6 independent measurements at ~0.6% of BAO scale
- Benchmark to test exotic early Dark Energy models
- RSD measurements from 1.9% to 3.6%
- Growth rate f~1 at z=4 → Pure measurement of σ_8

Inflation

Inflation and non-gaussianity



Description of the primordial potential Φ

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

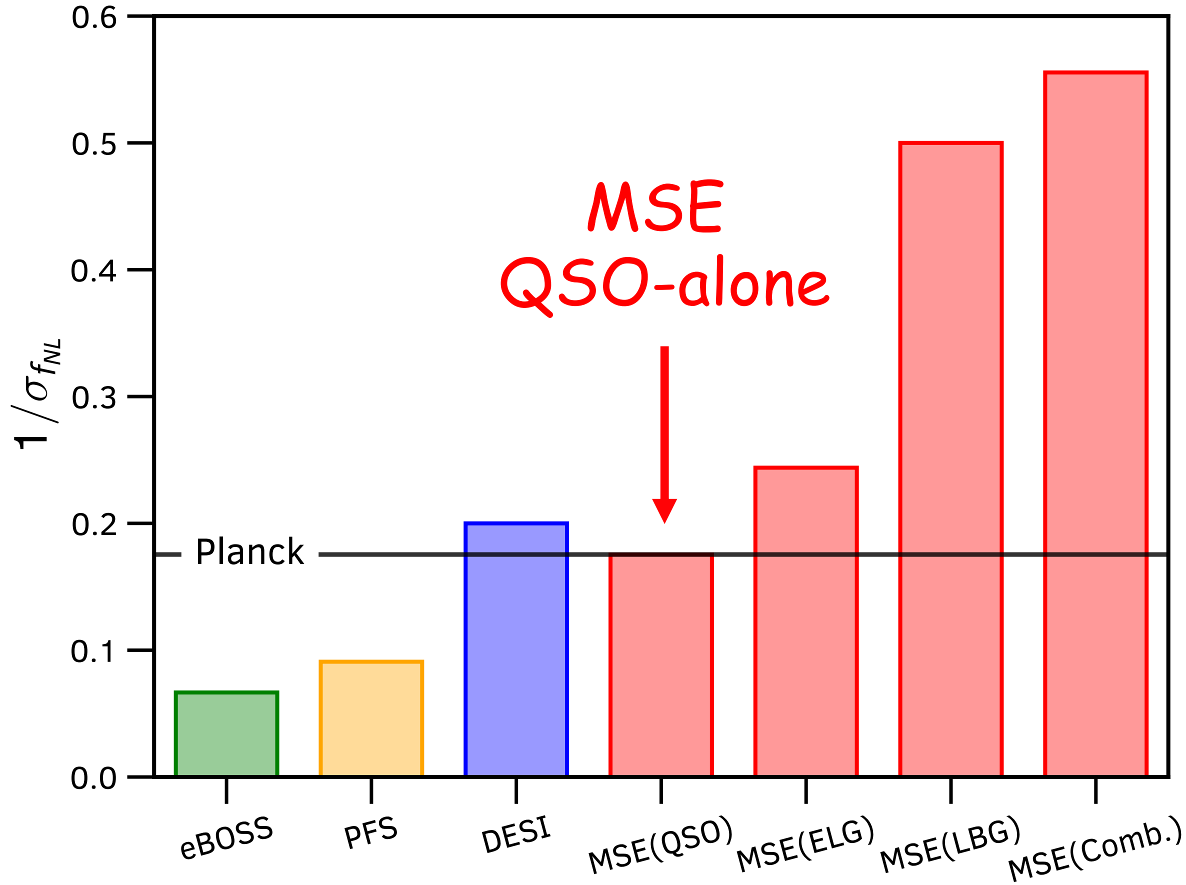
φ : a gaussian random field
f_{NL} : amplitude of the non-Gaussianity

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 $f_{NL} > 1$
- Galaxy surveys with a large volume can achieve $\sigma(f_{NL}) \sim 1$

Forecast for f_{NL}

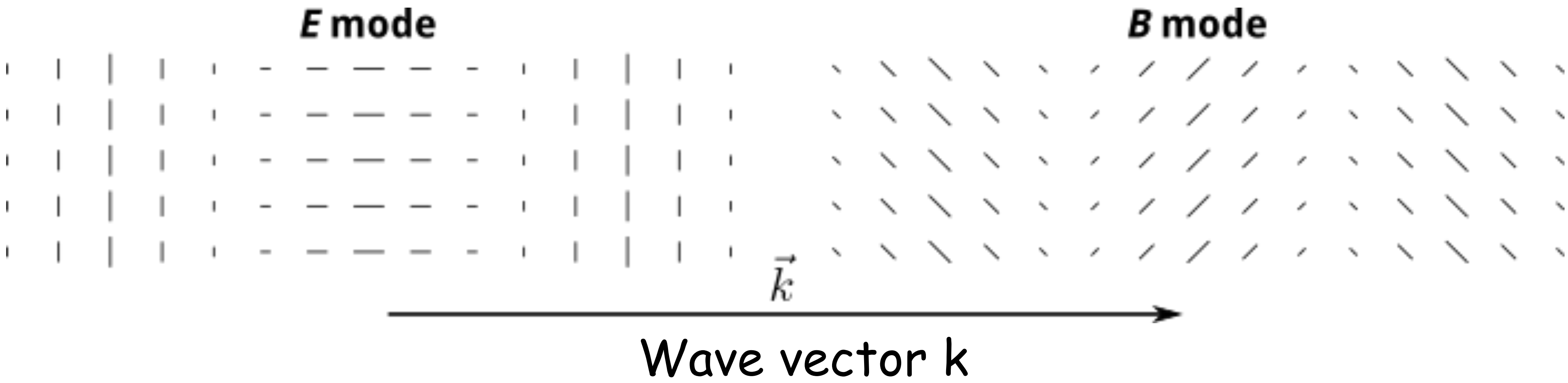
MSE



A picture of primordial Universe

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

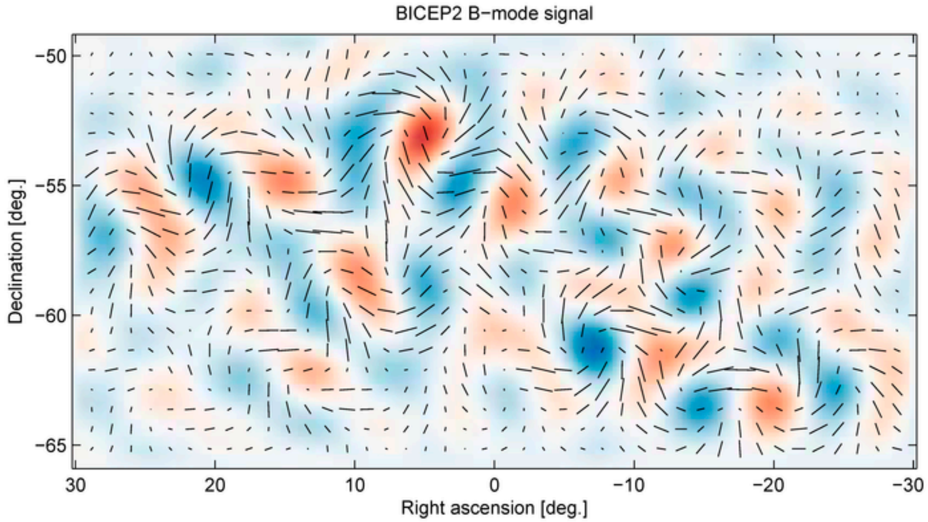
Inflation and CMB

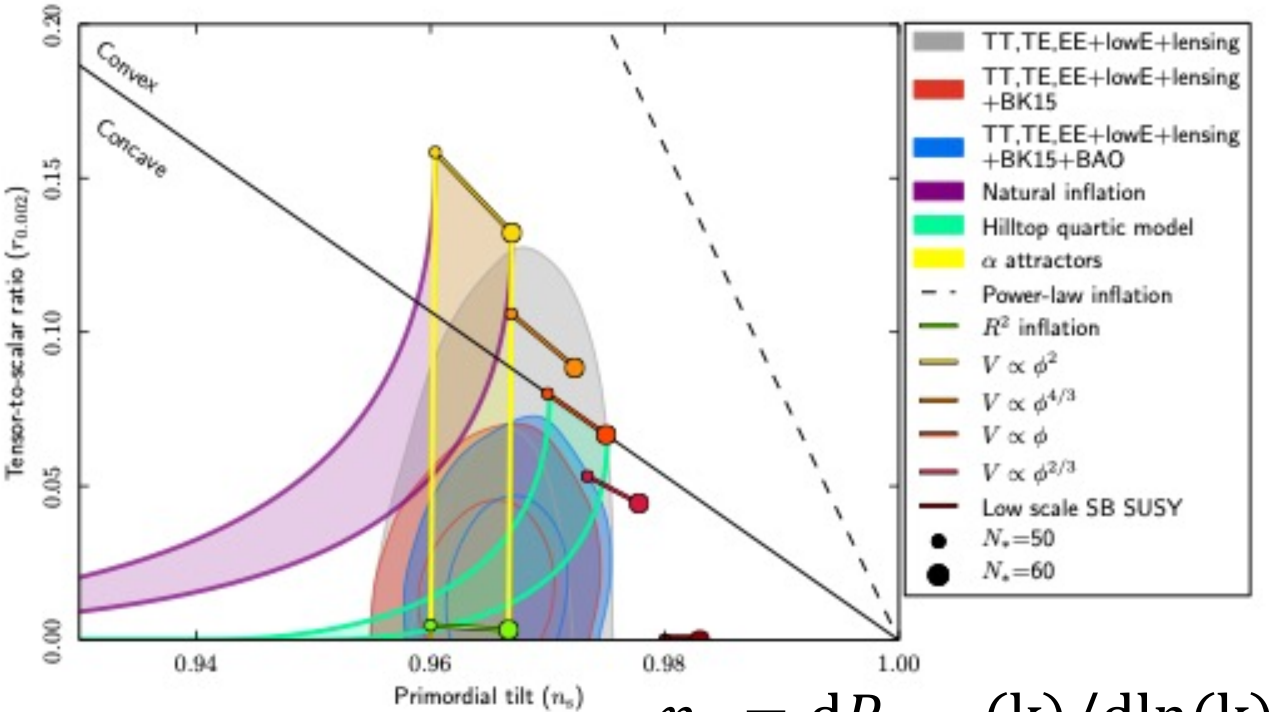


Observation of B modes

- CMB is polarized
- E modes: parallel or perpendicular to k
- B modes: rotated by 45° with respect to k
- Prediction of inflation: 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





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

Constraints on inflation

- r<0.1 with Planck
- Constraint twice better with BICEP2
- Many models still possible
- Slow roll models with V''(Φ)<0 are favored

Future CMB programs
Complementary approach

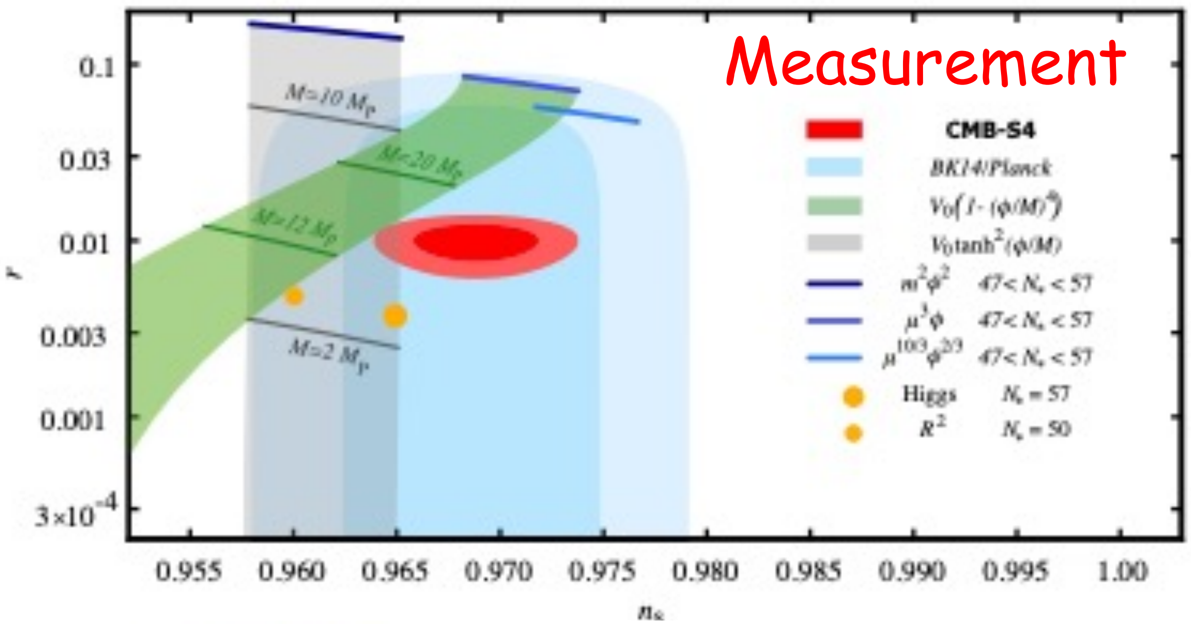
Satellite Mission: LiteBird (2027)

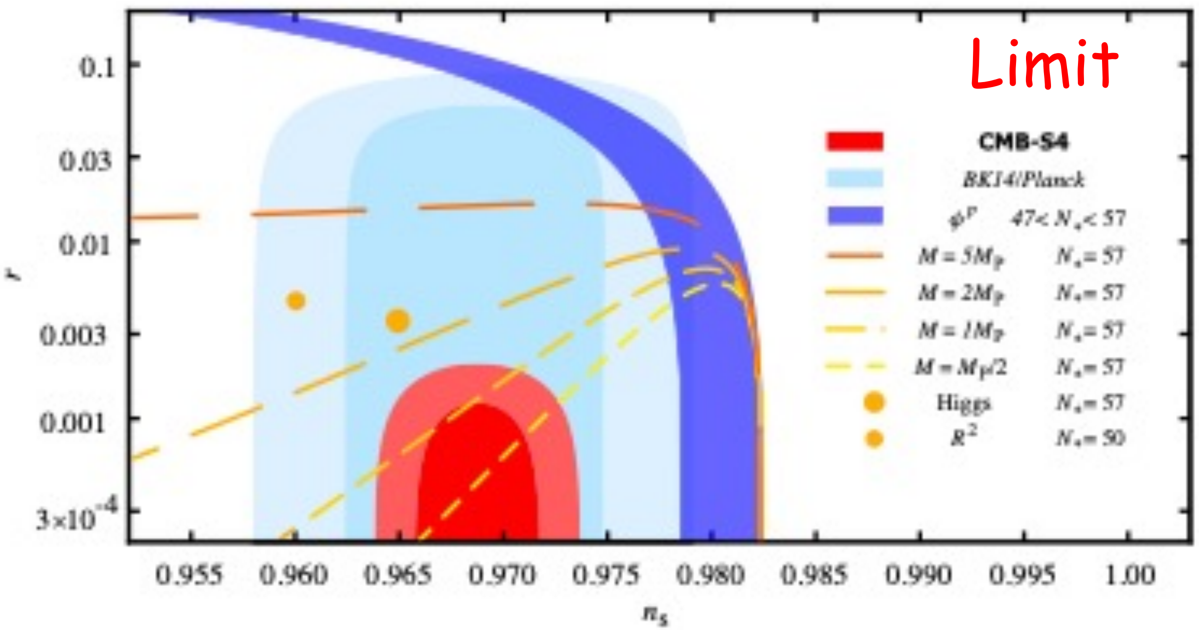
- Project selected by JAXA
- International collaboration
- Low resolution ~5′
- 15 frequencies
- 80 bolometers

Ground Mission: CMB-S4 (2025)

- 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 $\sigma_r \sim 0.001$

- Winning bet
  if $0.003 < r < 0.01$

- In addition, LiteBIRD measures τ (see later for neutrinos masses)

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

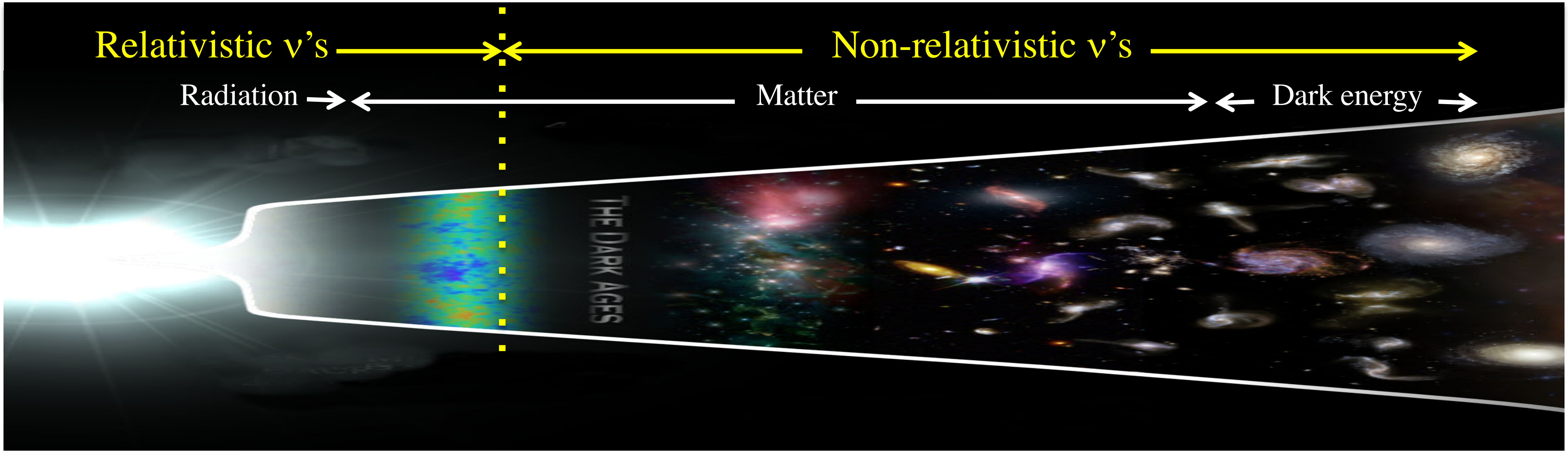
$$m_\nu \sim \langle p \rangle = \frac{\int p f(p) d^3 p}{\int f(p) d^3 p} = 3.15\, T_\nu \quad \text{with} \quad f(p) = \frac{1}{e^{p/T_\nu} + 1}$$

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

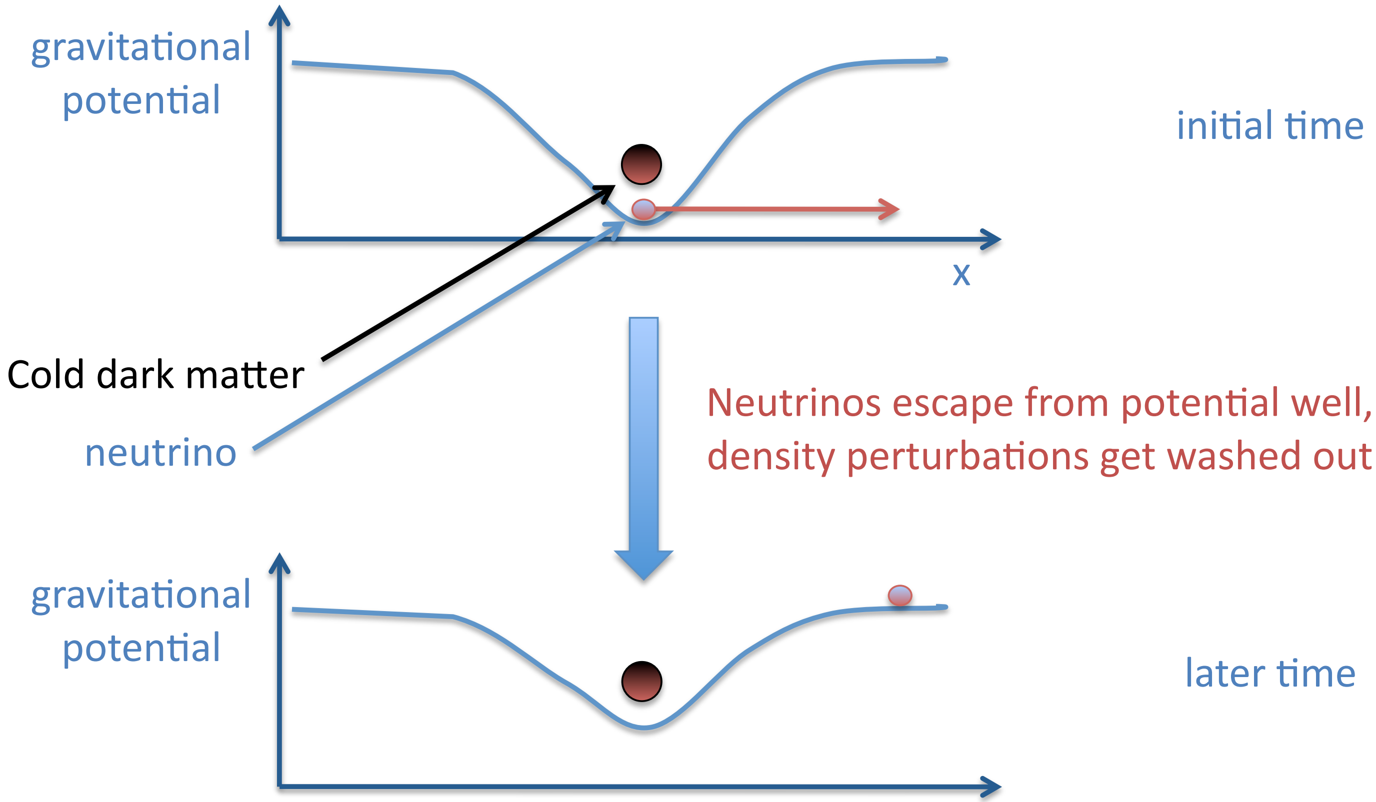
At recombination

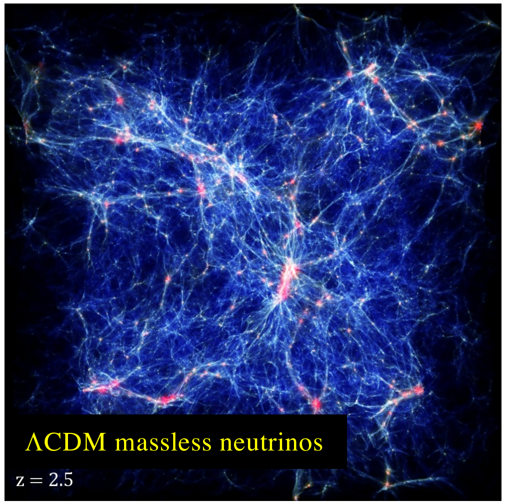
$m_\nu < 0.6$ eV ($\Sigma m_\nu < 1.7$) : relativistic

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

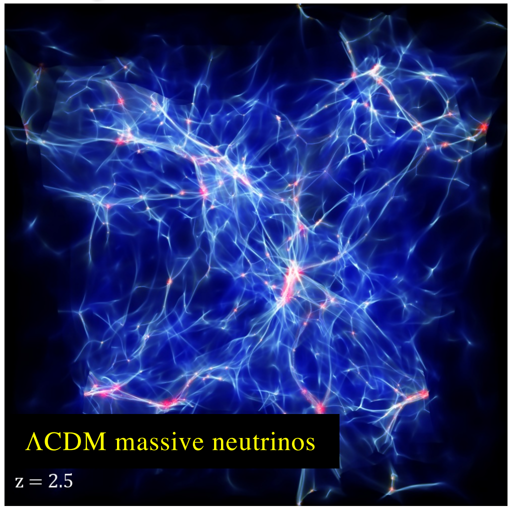


Free-streaming





Suppression of the small scales



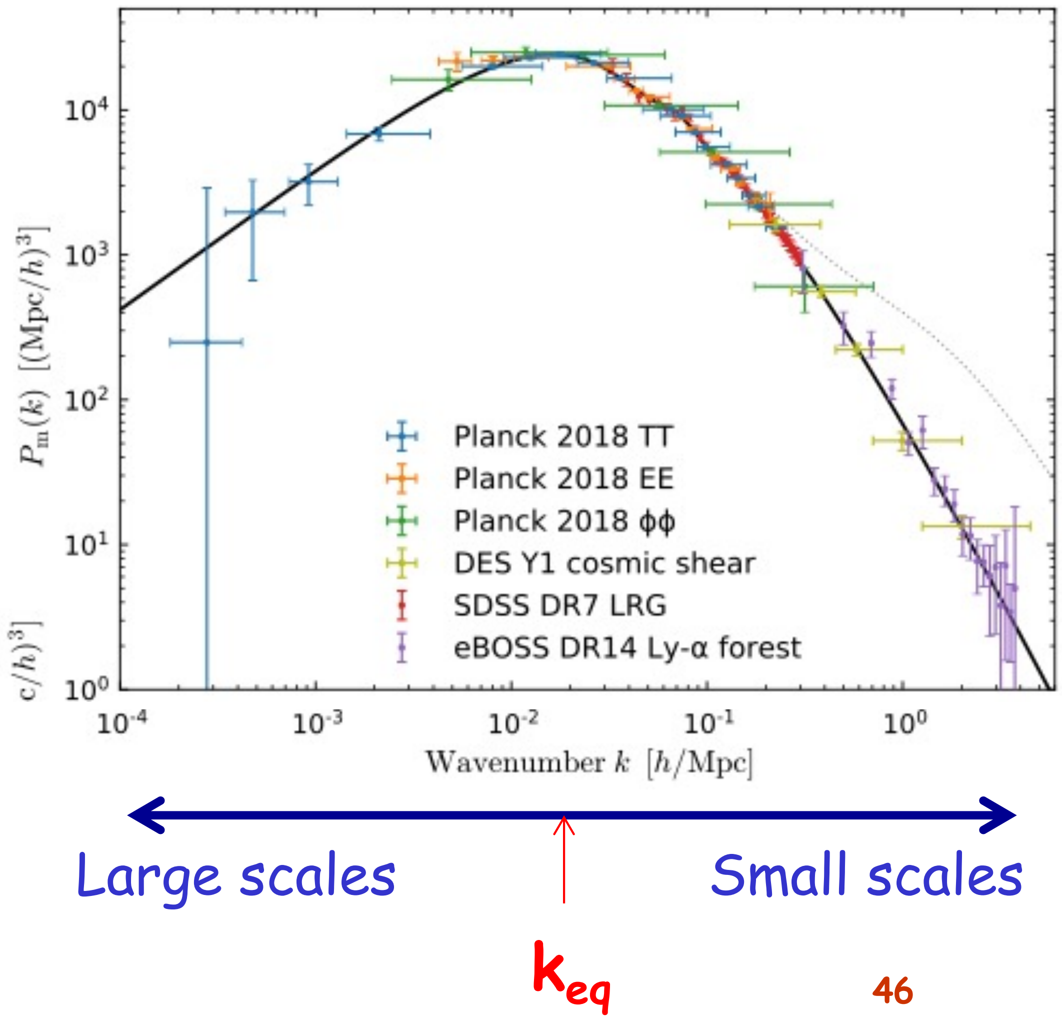
Matter power spectrum

- Analogy with sound: higher at certain frequencies

- Real space $\Rightarrow$ k-space (Mpc^{-1})

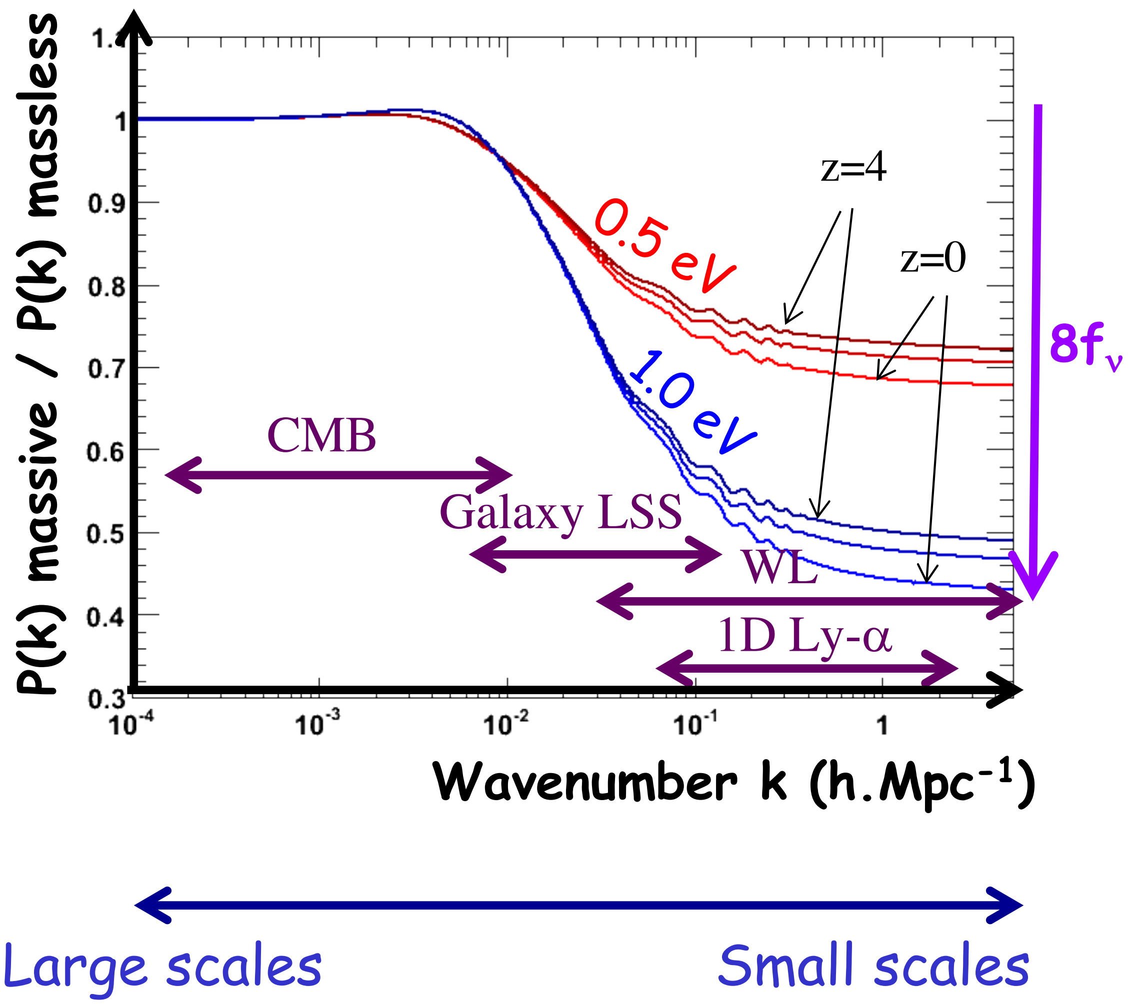
- Observation of "total" power spectrum with different tracers of the matter

Chabanier, et al. (2019)



Impact on matter power spectrum

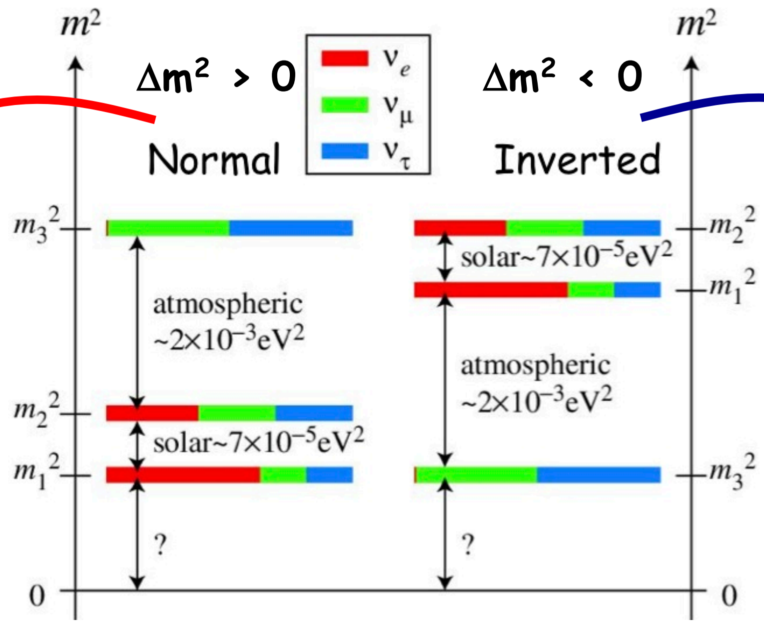
- Impact in CMB-alone only for non-relativist neutrinos ⇒ ~1-2 eV limit



- 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

Neutrino Masses and Hierarchy

$\Sigma m > 60$ meV

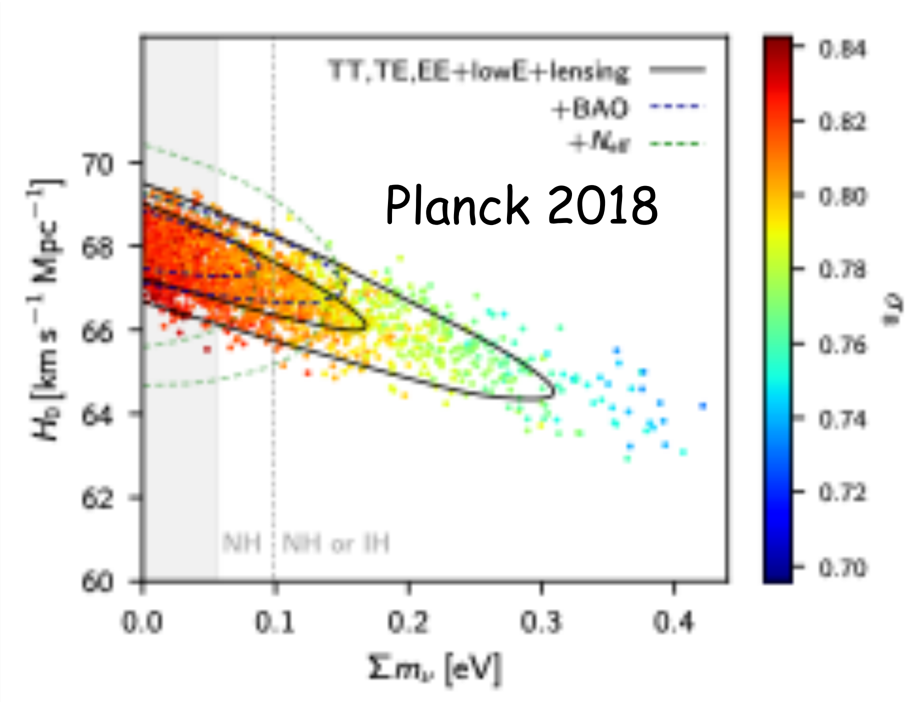


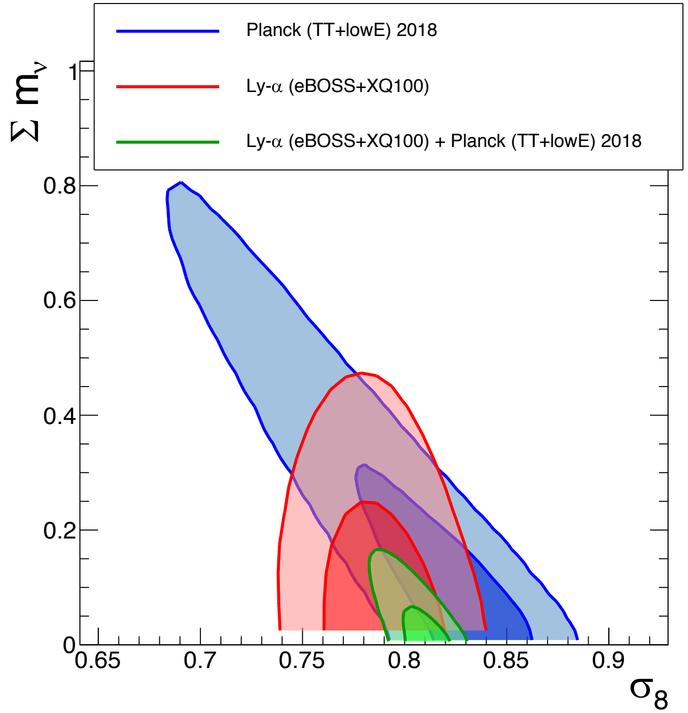
$\Sigma m > 100$ meV

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

Current limits on Σm_ν



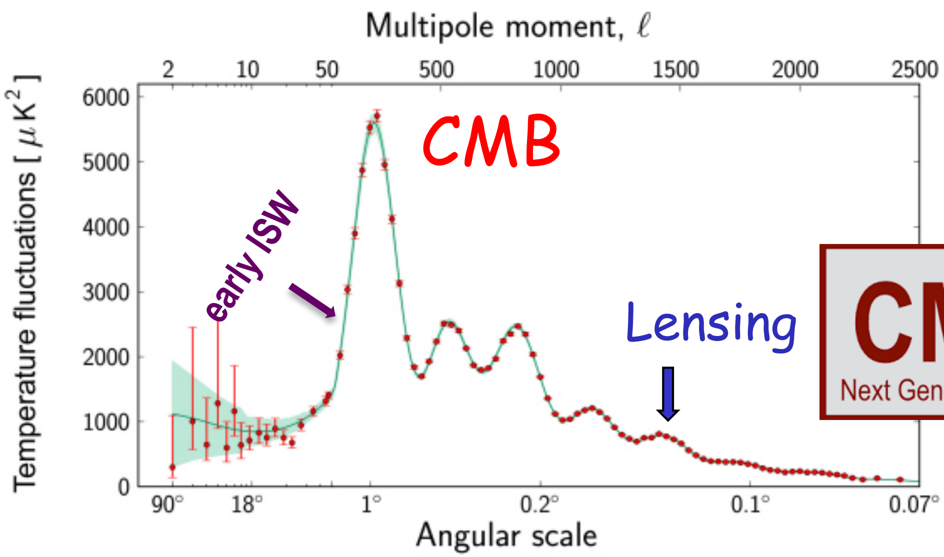


Palanque-Delabrouille et al. (2015)

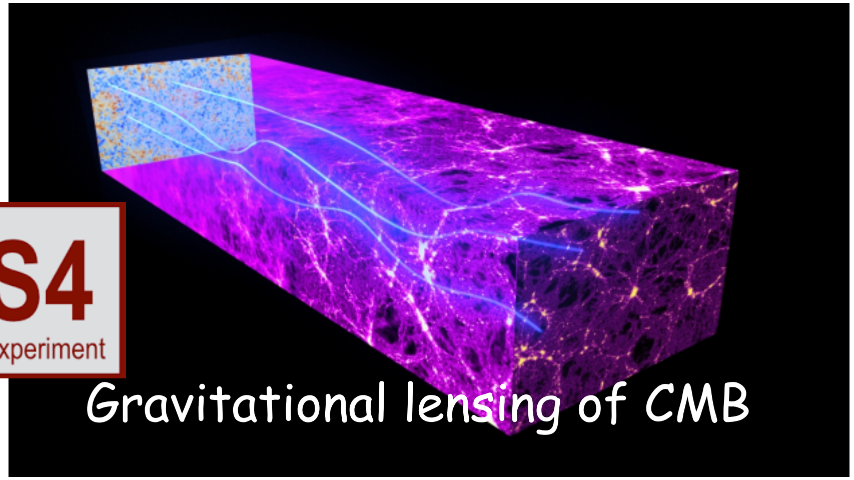
Yèche, et al. (2017)

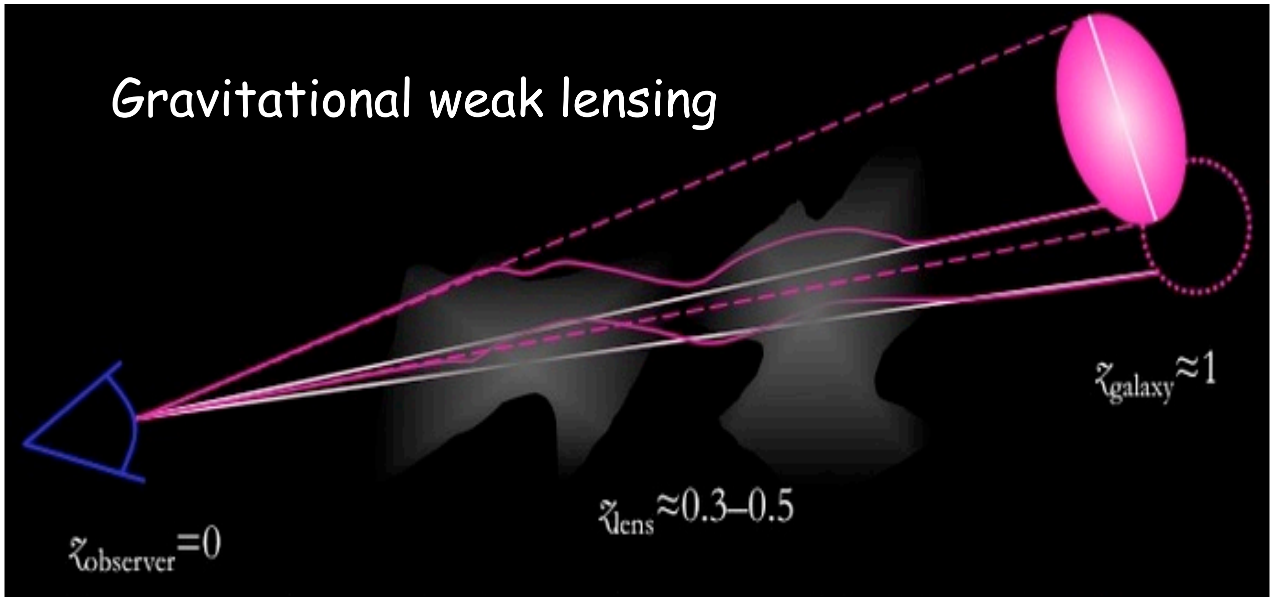
- With Ly-α alone (SDSS/eBOSS+VLT/XQ100):
  Σm_ν < 0.35 eV @95%CL
- With Planck 2018 alone:
  Σm_ν < 0.54 eV @95%CL
- Ly-α combined with CMB (Planck 2018) (just TT)
  Σm_ν <0.12 eV @95%CL
- BAO combined with CMB (Planck 2018) (TT,TE,EE and lensing)
  Σm_ν <0.12 eV @95%CL

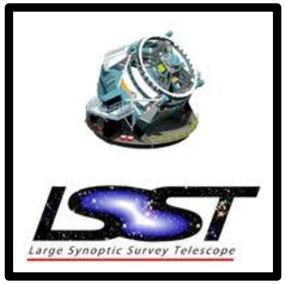
Probes –Projects



CMB-S4
Next Generation CMB Experiment



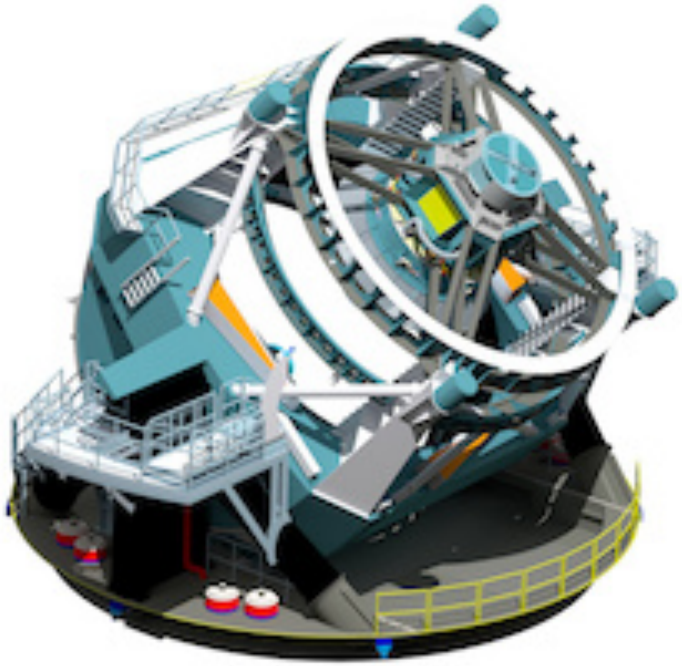


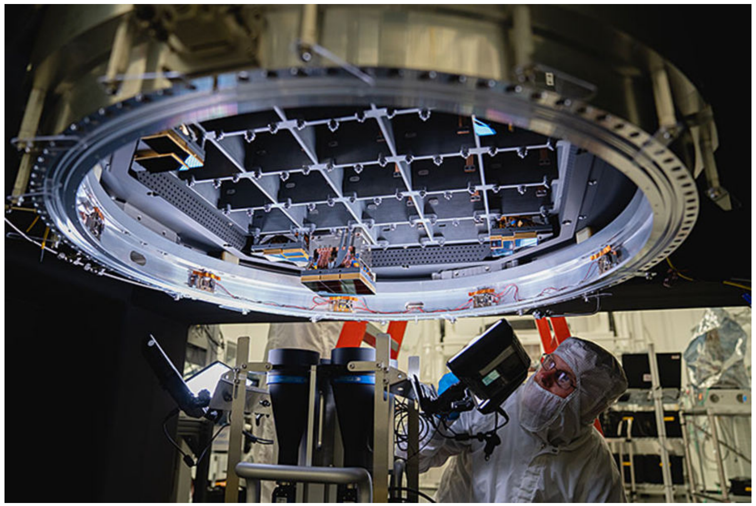


Large Synoptic Survey Telescope

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 still in construction
- The assembly of the telescope begins in Oct. 2019.
- Camera almost completed
- Science survey starts in 2023

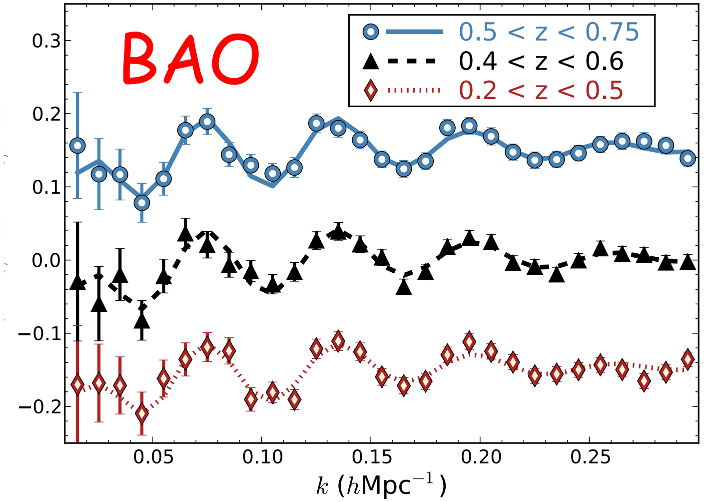


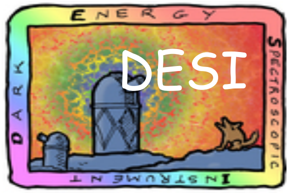


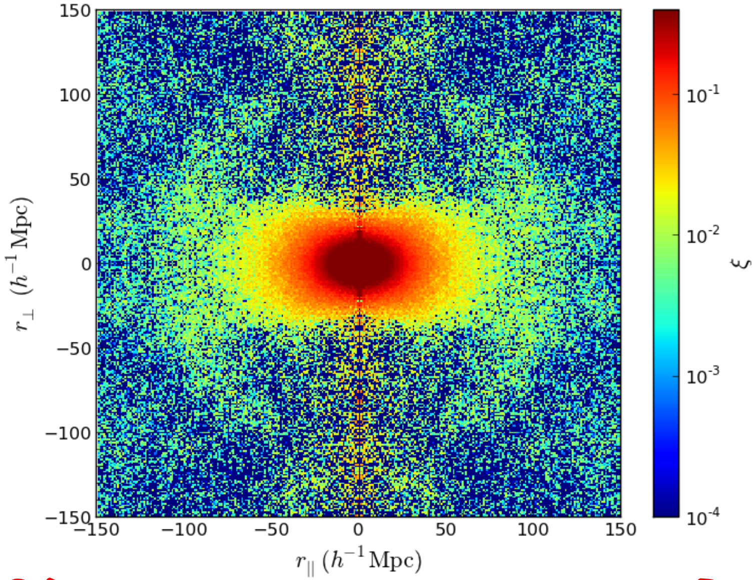
Program for cosmology:

- Supernovae
- BAO with photo-z
- Weak lensing

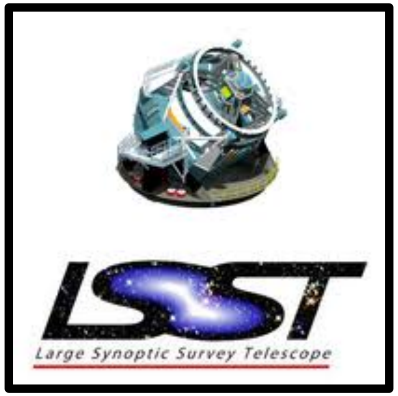
Probes - Projects

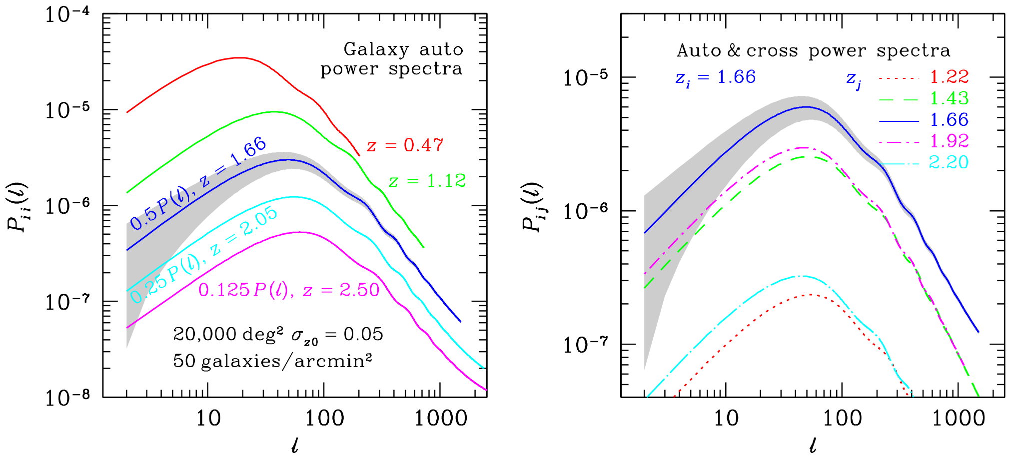






3D power spectrum - RSD





Angular power spectrum

DESI and Euclid forecast for Σm_ν

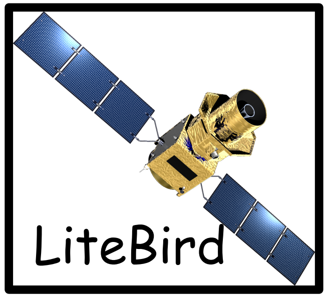
Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.56	0.19
Planck + BAO	0.087	0.18
Gal ($k_{\max} = 0.1h\,\mathrm{Mpc}^{-1}$)	0.030	0.13
Gal ($k_{\max} = 0.2h\,\mathrm{Mpc}^{-1}$)	0.021	0.083
Ly-α forest	0.041	0.11
Ly-α forest + Gal ($k_{\max} = 0.2$)	0.020	0.062

	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

CMB-S4 and LSST forecast for Σm_ν

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	-	-

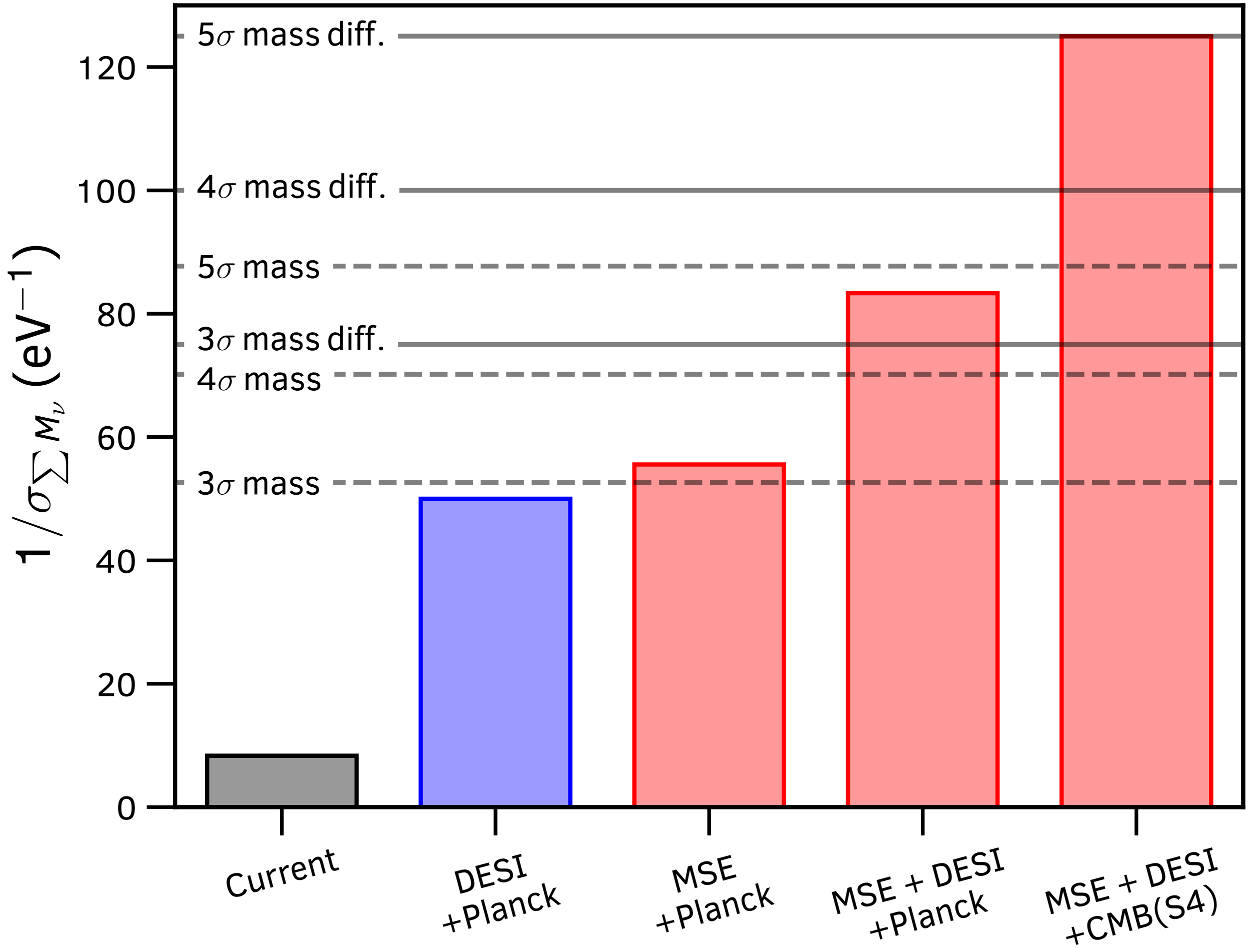


Setup (+CV-τ)	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Omega_k)$ [$\times 10^{-3}$]	$\sigma(w_0)$	$\sigma(w_a)$
LSST-clustering	69	91	3.3	0.42	1.20
LSST-shear	31	117	2.82	0.18	0.55
LSST-shear+clust	24	72	1.99	0.11	0.31
S4+LSST	14	21	0.49	0.10	0.26
	-	15	0.49	-	-

arXiv:2803.07561, 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

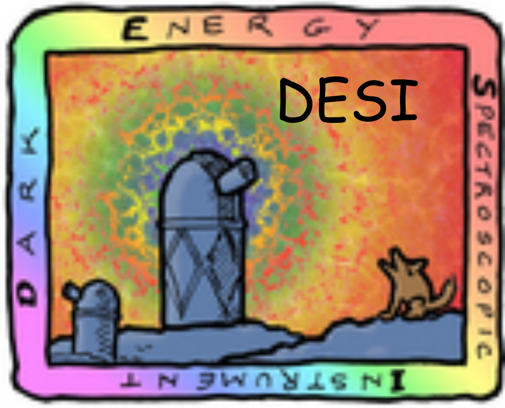


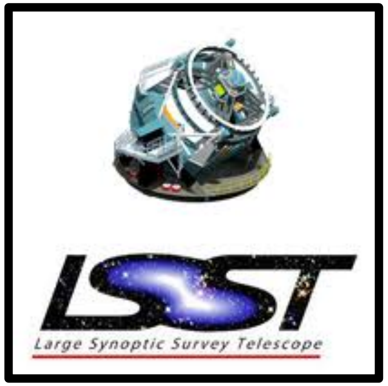
MSE

A most precise measurement of neutrino mass

- With CMB(S4), 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





2020 2023 2027 2030

Dark Energy - Dark Matter -2025

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

General Relativity - New models of Gravity 2025

- With RSD (DESI, Euclid) and LSST (WL)

Inflation - Neutrinos - 2028-2032

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