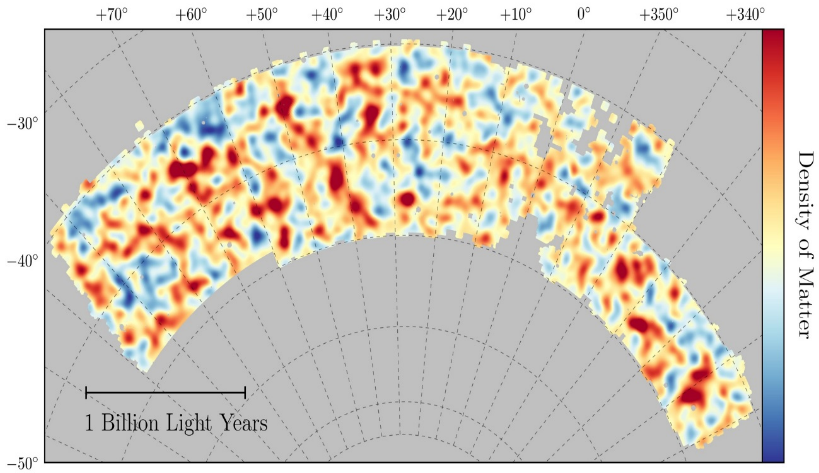
Dark Energy from Large Galaxy Surveys

Ofer Lahav (University College London)



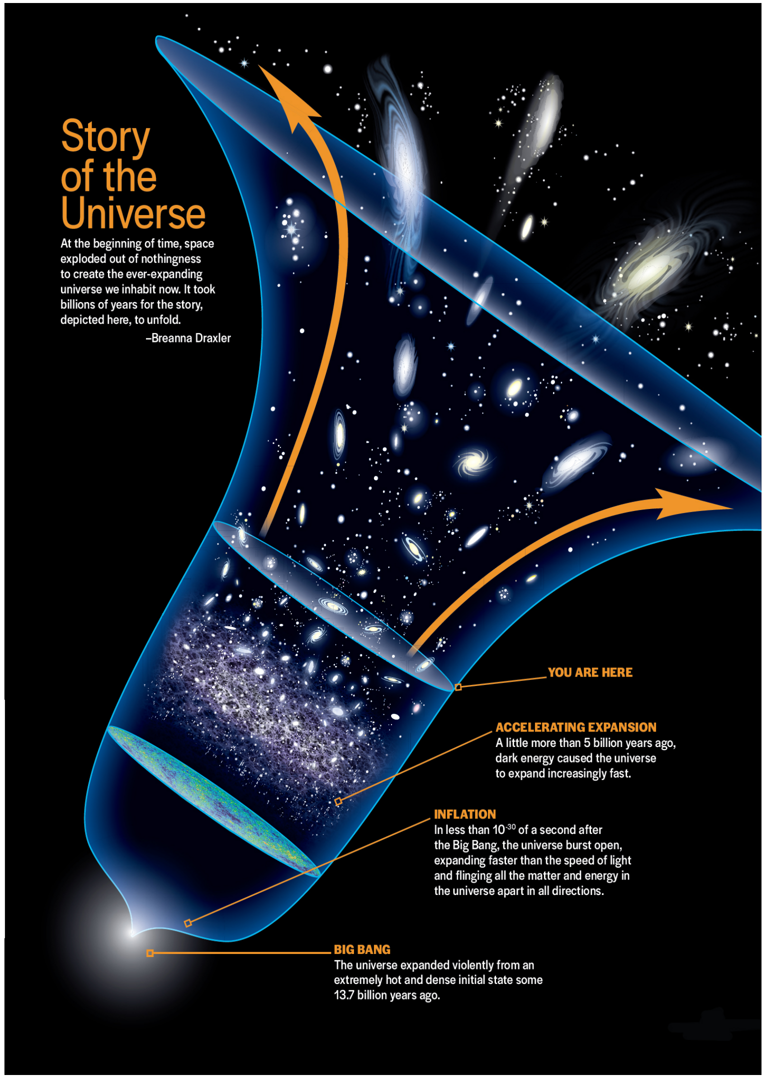
DES mass map from weak lensing

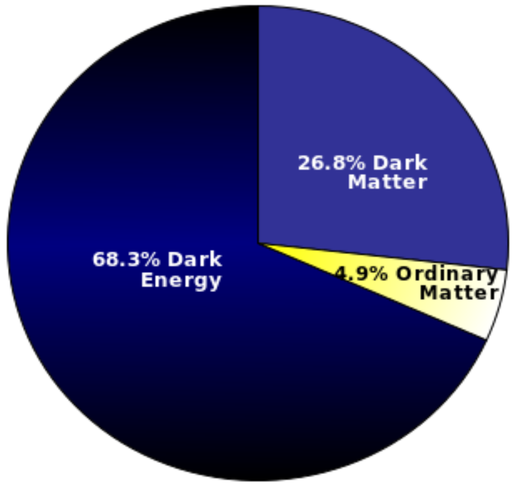
Outline

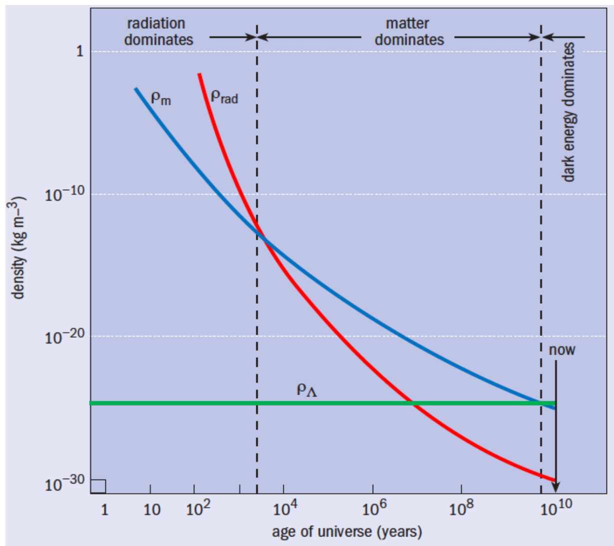
- 100 years of the Cosmological Constant
- Current and future galaxy surveys
- New Cosmology results
- The path to Neutrino mass
- Spin-offs:

- Gravitational Waves and Multi-messengers
- Big Data

What accelerates the Universe?

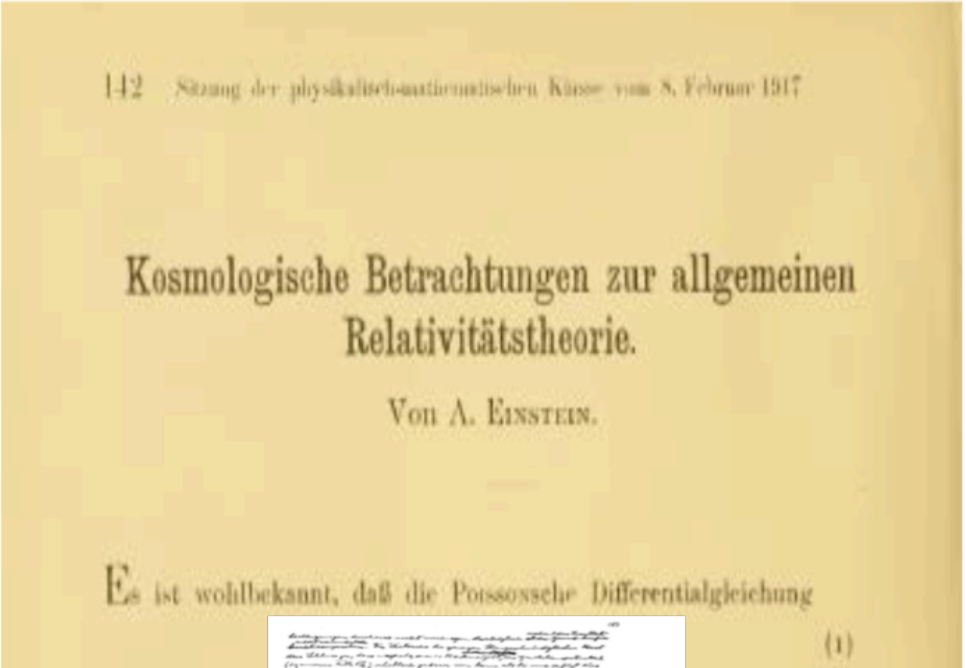






"a simple but strange universe"

Einstein 1917 Lambda



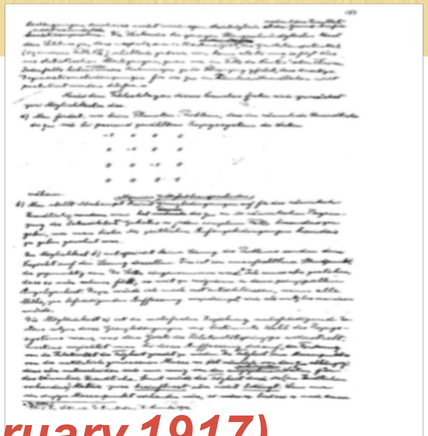
142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

(1)



Modified Newtonian

$$\nabla^2\phi - \lambda\phi = 4\pi\kappa\rho$$

Modified GR

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)$$

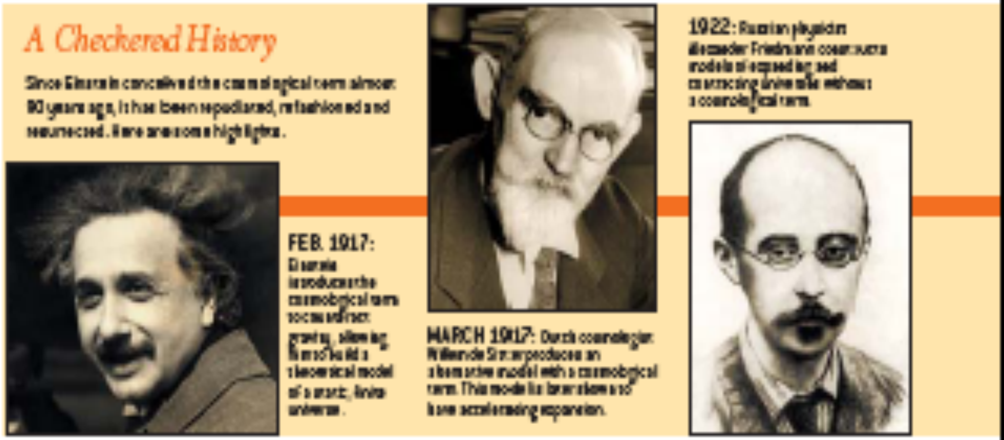
In a static universe:

$$\lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2}.$$

Einstein (February 1917)

English translation: http://einsteinpapers.press.princeton.edu/vol6-trans/433?ajax

The Chequered History of the Cosmological Constant Λ



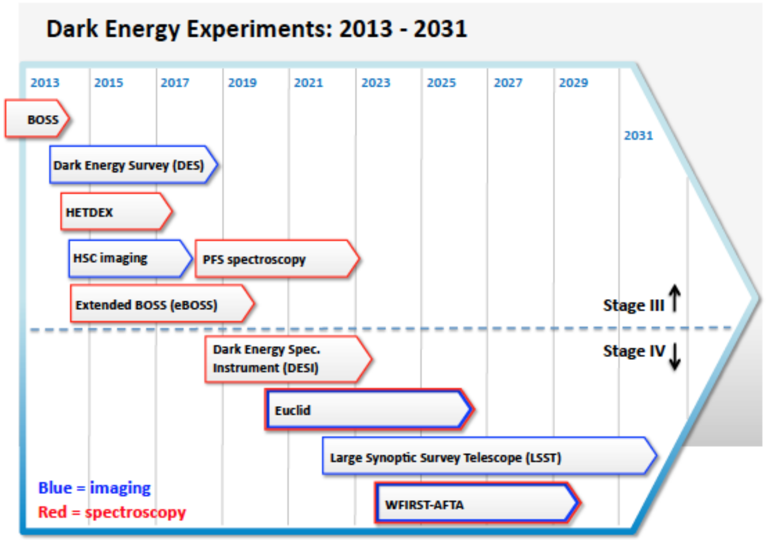
The old problem:
Theory exceeds observational limits on Λ by 10^{120} !
New problems:
- Is Λ on the LHS or RHS?

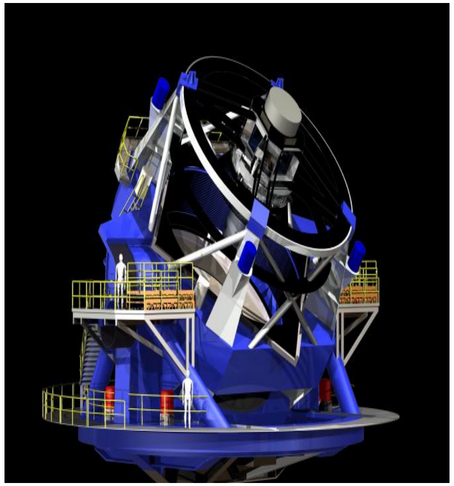
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

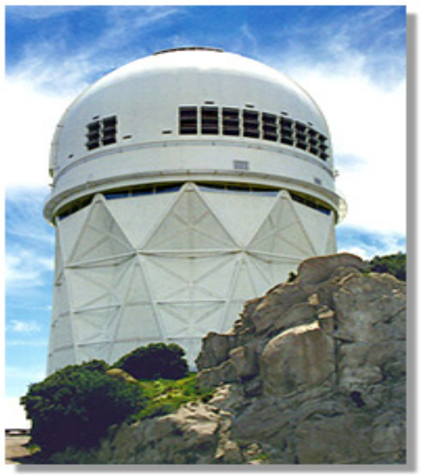
- Why are the amounts of Dark Matter and Λ so similar at present?

DE equation of state: Pressure/density = $w(a) = w_0 + w_a (1-a)$
$w=-1$ correspond to *Λ*

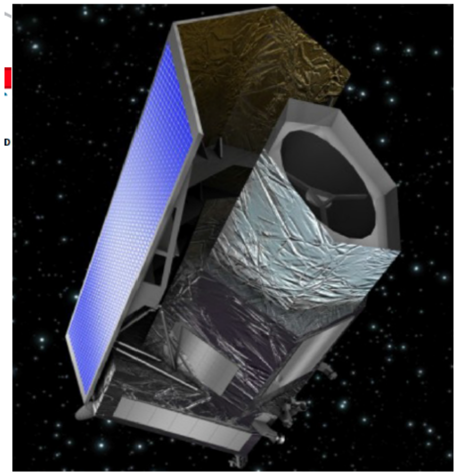
Galaxy surveys timeline





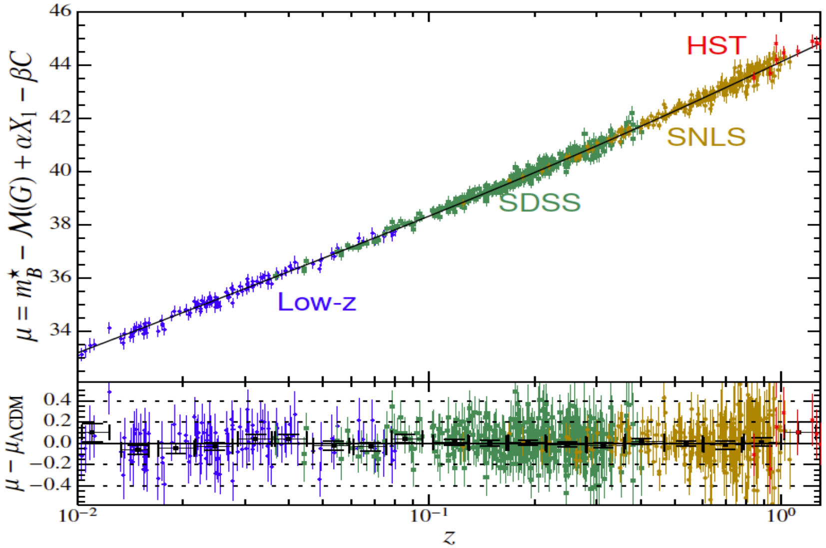


Mayall 4-Meter Telescope

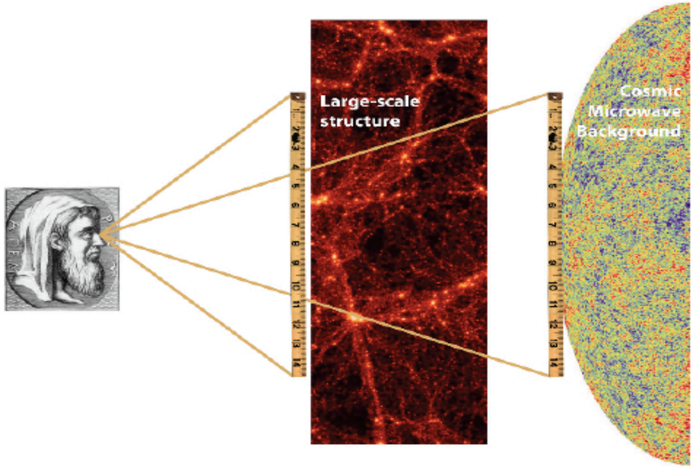


Probes of Dark Energy

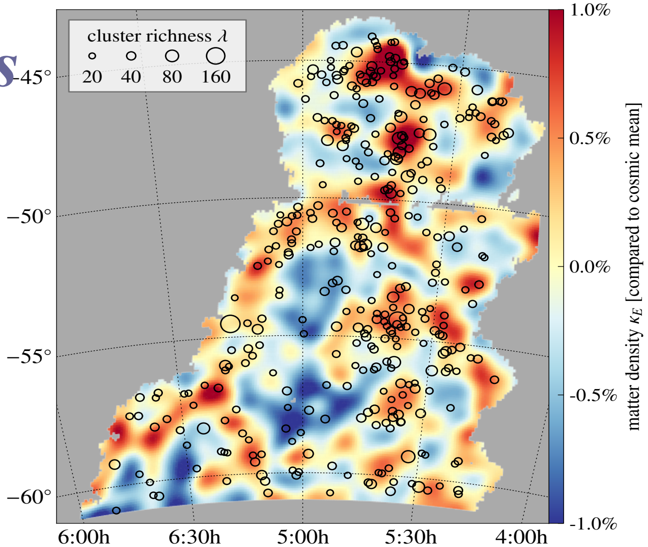
Standard candles



Standard rulers

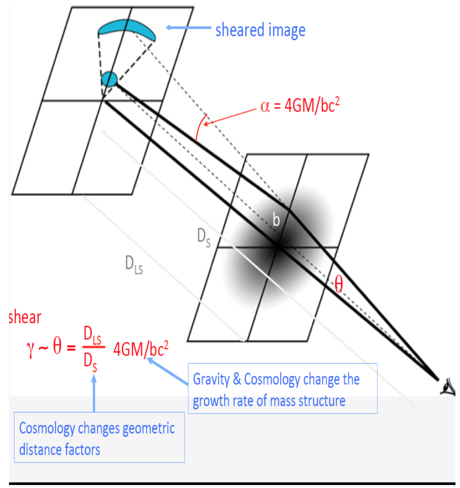


Clusters

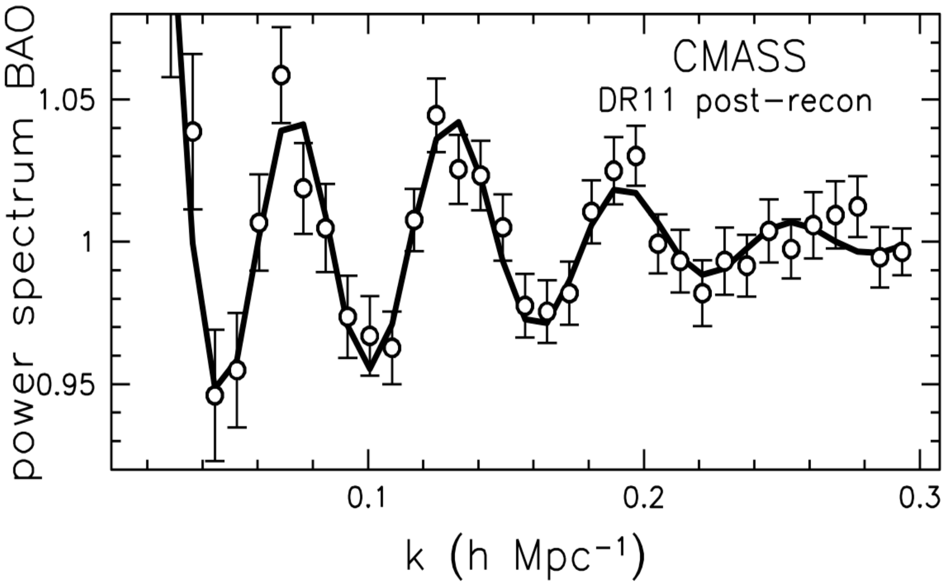


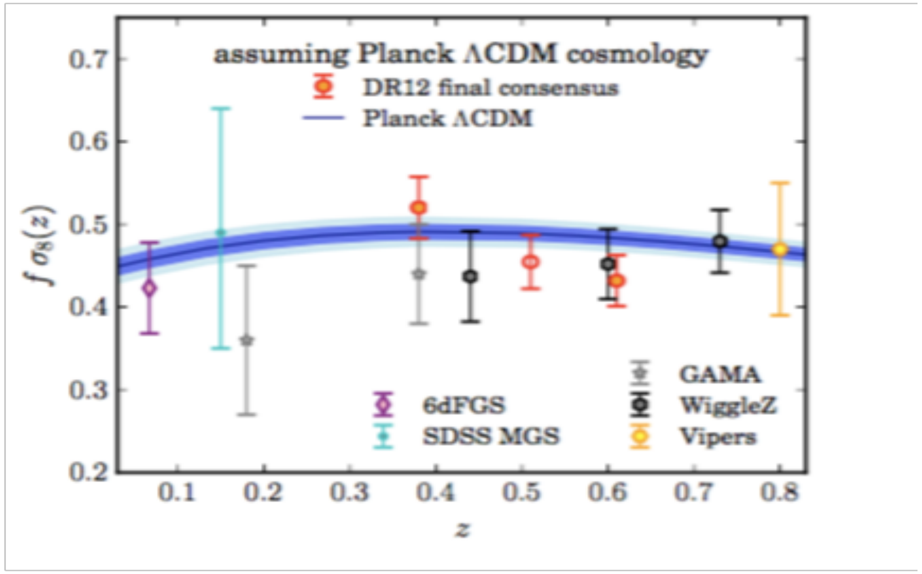
DES SV mass map (Chang et al. 2016)

Gravitational Lensing



BAOs and redshift distortion



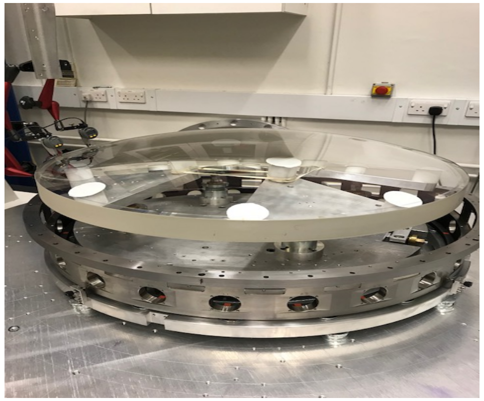


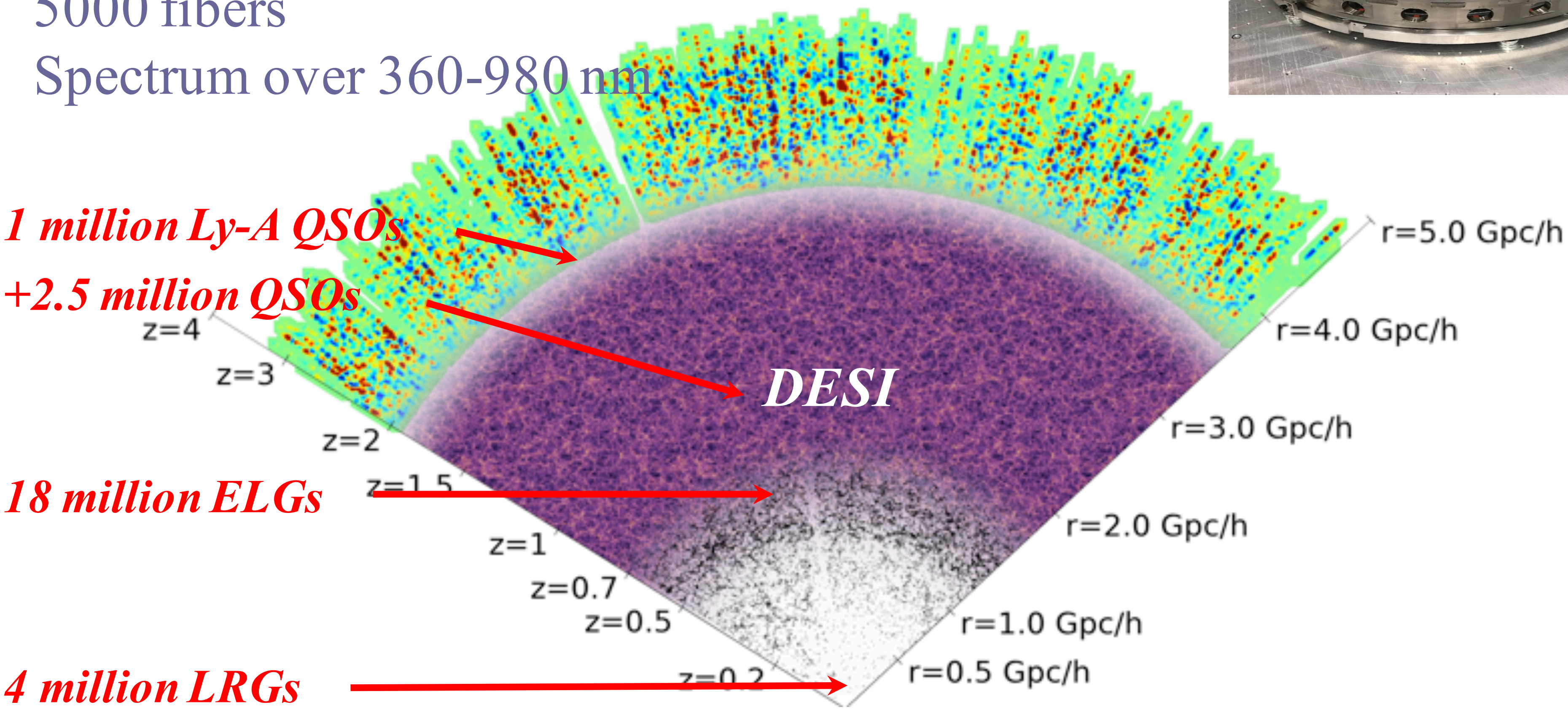
BOSS - Anderson et al. (2013) ***Alam et al. (2016)***

BAOs first detected in 2005 by 2dF and SDSS

Dark Energy Spectroscopic Instrument (DESI)

- Main goal: Baryon Acoustic Oscillation (BAO)
- Spectra of 35 million galaxies and quasars over 14,000 deg^2 in 5 years.
- 5000 fibers
- Spectrum over 360-980 nm





Current and planned Large Surveys

Project	Dates	Area/deg^2	Data	Spec-z Range	Methods
BOSS	2008-2014	10,000	Opt-S	$0.3-0.7$ (gals)	BAO/RSD
				$2-3.5$ (LyαF)	
DES	2013-2018	5000	Opt-I	——	WL/CL
					SN/BAO
eBOSS	2014-2020	7500	Opt-S	$0.6-2.0$ (gal/QSO)	BAO/RSD
				$2-3.5$ (LyαF)	
SuMIRE	2014-2024	1500	Opt-I		WL/CL
			Opt/NIR-S	$0.8-2.4$ (gals)	BAO/RSD
HETDEX	2014-2019	300	Opt-S	$1.9 < z < 3.5$ (gals)	BAO/RSD
DESI	2019-2024	14,000	Opt-S	$0-1.7$ (gals)	BAO/RSD
				$2-3.5$ (LyαF)	
LSST	2020-2030	20,000	Opt-I	——	WL/CL
					SN/BAO
Euclid	2020-2026	15,000	Opt-I		WL/CL
			NIR-S	$0.7-2.2$ (gals)	BAO/RSD
WFIRST	2024-2030	2200	NIR-I		WL/CL/SN
			NIR-S	$1.0-3.0$ (gals)	BAO/RSD

RPP 2017

The Dark Energy Survey

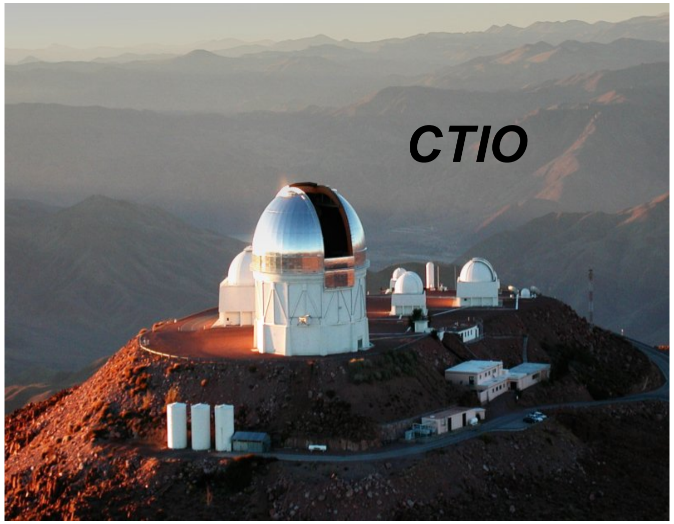
* Multi-probe approach
  Wide field: Cluster Counts,
  Weak Lensing, Large Scale Structure
  Time domain: Supernovae

* Survey strategy
  300 million photometric redshifts (grizY)
  over 5000 deg^2
  + 2500 SN Ia over 27 sq deg fields
  overlaps with other surveys

* Currently 5th (last) year of observations

* Over 140 DES papers on the arXiv

* Over 400 scientists from 7 countries



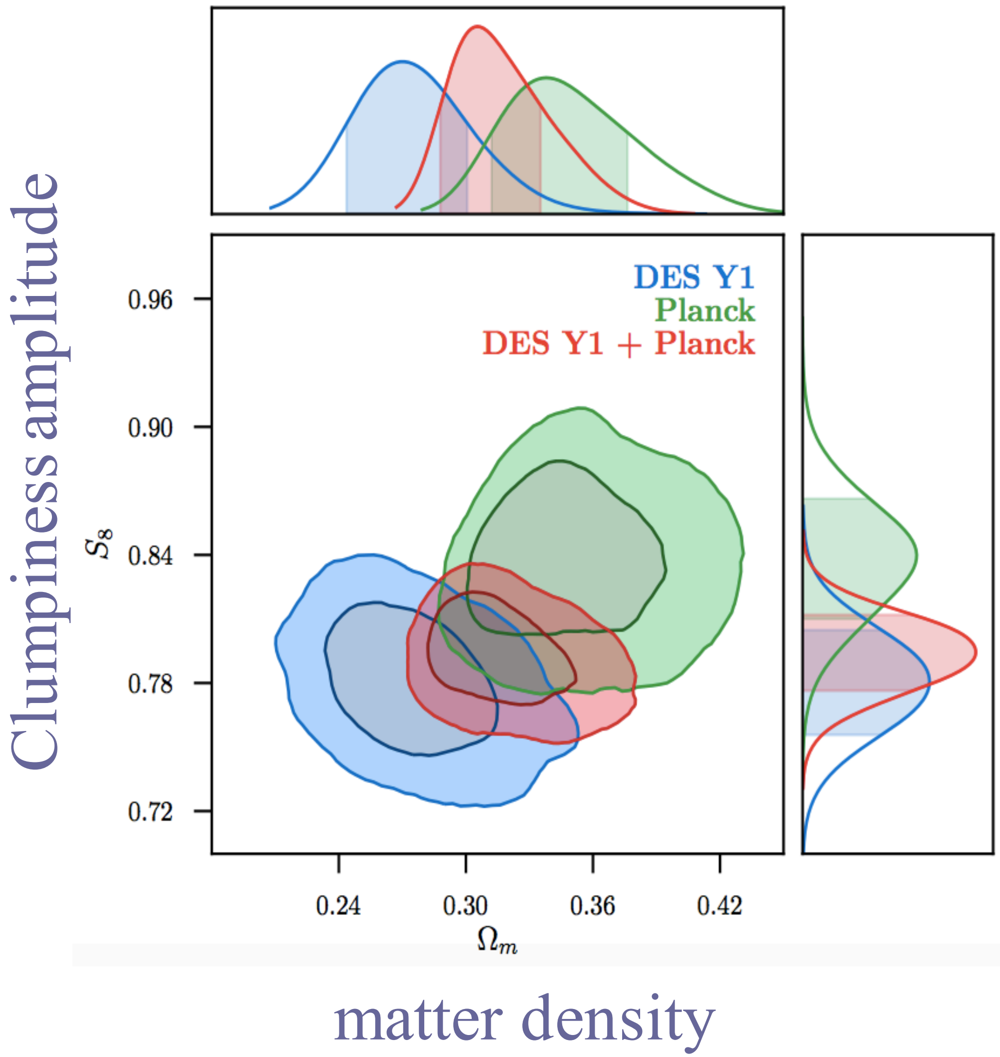
DES Year 1 results from galaxy clustering and weak lensing

- DES vs Planck CMB:
  differ in central values,
  but consistent according
  to Bayesian Evidence in the full
  parameter space

- DES final (Year 5) analysis will
  include ~4 times Year 1 data
  and additional probes (clusters,
  supernovae)

DES Collaboration 2017

arXiv:1708.01530



Tension in LCDM?

- Hubble constant:

h = 0.67 (Planck) or

h = 0.73 (Cepheids +SN IA) ?

- The amplitude Sigma8 in Planck vs WL
- Anomalies: the CMB Cold Spot
- Tests of GR on large scales => Modified Gravity?

Possible outcomes of ongoing and future surveys

W = -1.00 +- 0.01

e.g.
W = 0.12 +- 0.01
or e.g.
W = -1.23 +- 0.01
or
W(z)

The Unknown Unknown

???

Back to Lambda

Back to fundamental Physics

Anthropic Principle?

'Accuracy' vs 'Precision'

Back to systematics/Astrophysics
Blinding

Then fundamental Physics

A new paradigm shift?

Open Questions on Dark Energy

DE equation of state:

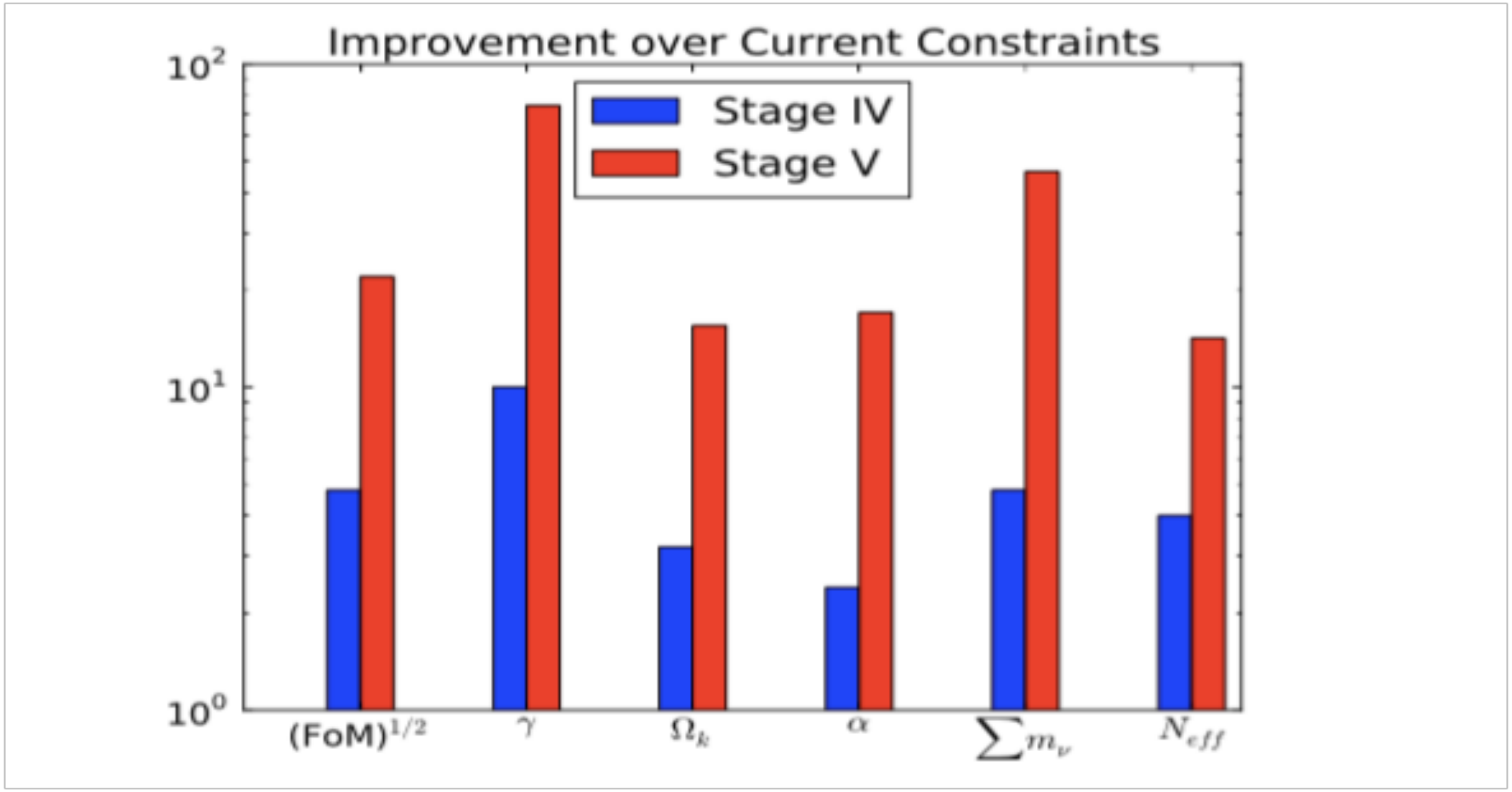
Pressure/density = $w(a) = w_0 + w_a\,(1\text{-}a)$

- Is there a fundamental reason for **w=-1** (Lambda)?
- Is it on the **LHS or RHS** of Einstein's equation?
- Is there a physical case for **w<-1**?
- What is the case for a time-dependent **w(z)** ?
- When should we **stop** with w?

(note **'precision'** vs **'accuracy'**, cf. curvature)

- Does **Anthropic reasoning** make sense?
- Is a **higher level theory** to be discovered, connecting GR to Quantum Mechanics and Thermodynamics? Will it take **another 100 years** ?

Cosmic Vision forecast



arXiv:1604.07626

The Big Neutrino Questions

- What is the absolute sum of neutrino mass?

(given the lower limit 0.06 eV from oscillations)

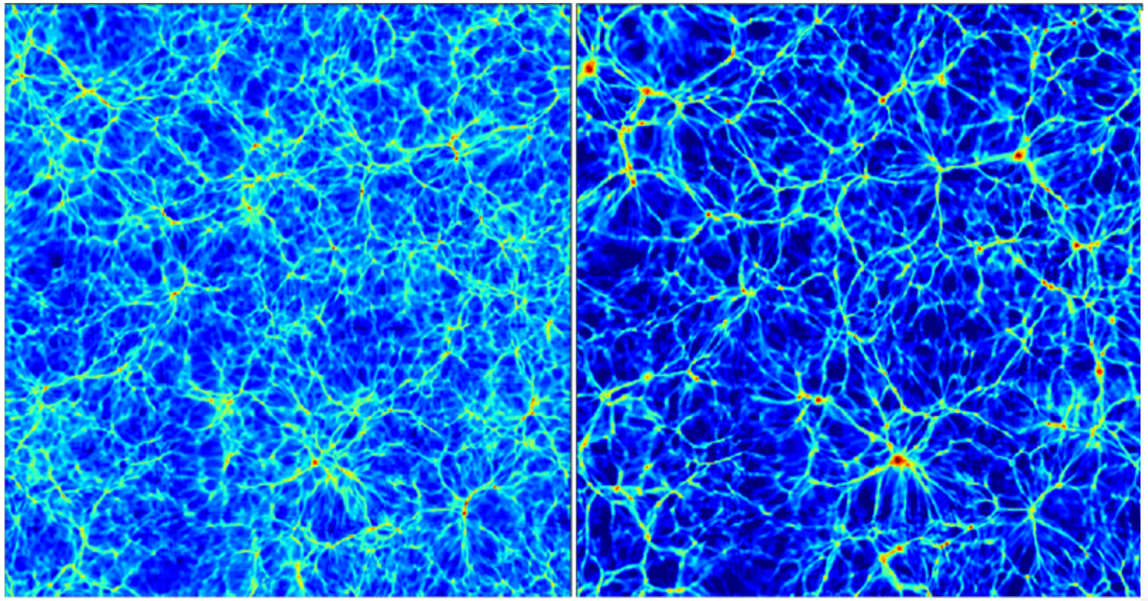
- What is the hierarchy – Normal or Inverted?
- Is N_{eff} = 3.045, or larger (Sterile neutrino /'dark radiation')?
- Is the neutrino its anti-particle (Majorana)?

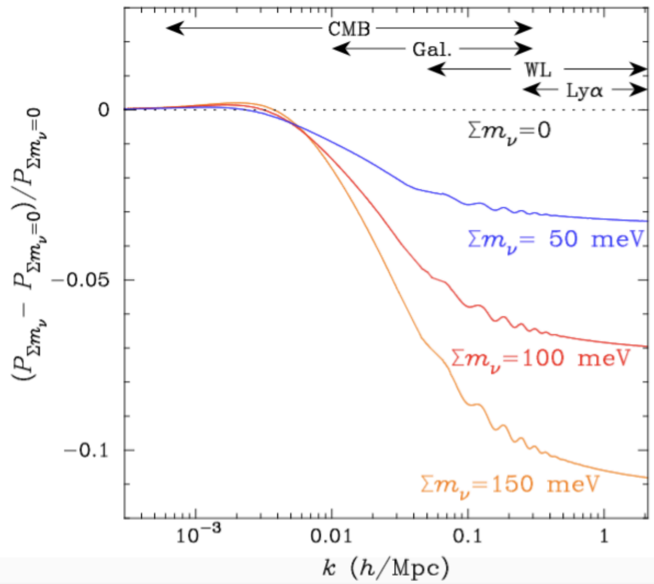
Neutrino Mass from Cosmology

Neutrinos decoupled when they were still relativistic, hence they wiped out structure on small scales

$k > k_{nr} = 0.018\ (m_\nu /1\ \text{eV})^{1/2}\ \Omega_m^{1/2}\ h/\text{Mpc}$

$\Omega_\nu\ h^2 = M_\nu/(93\ \text{eV})$

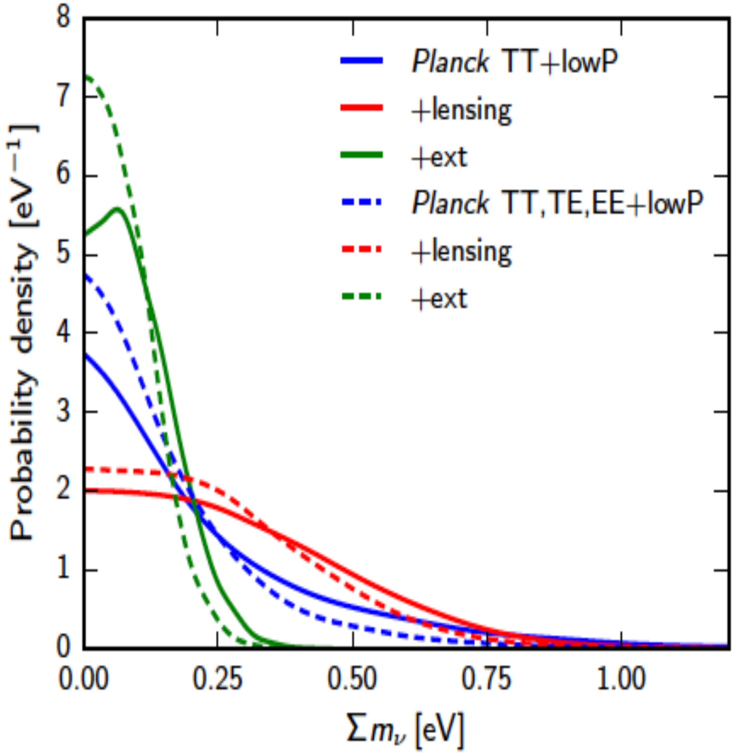




CDM+ 1.9 eV neutrinos. structure 'washed out' ***CDM***

Agarwal & Feldman 2010

Planck 2015 ++ (arXiv:1502.01589)



$$\left.\begin{array}{l}\sum m_\nu < 0.23\ \text{eV} \\ \Omega_\nu h^2 < 0.0025\end{array}\right\}\ 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+ext.}$$

N_{eff} = 3.15 +- 0.46 (95% CL)
Consistent with standard 3.045

2-sigma Neutrino mass upper limits from existing data

Data	Authors	$M_\nu = \Sigma\, m_i$
2dFGRS	Elgaroy, OL et al. (2002)	< 1.8 eV
MegaZ-LRG + WMAP	Thomas et al. (2010)	< 0.28 eV
Planck13+robust surveys	Leistedt et al. (2014)	< 0.3 eV
Planck15++	Planck collaboration 2015	< 0.23 eV
BOSS Ly-alpha + Planck15	Palanque-Delabrouille et al. (2015)	< 0.12 eV
DES Y1 + Planck15+JLA+BAO	DES collaboration (2017)	< 0.29 eV

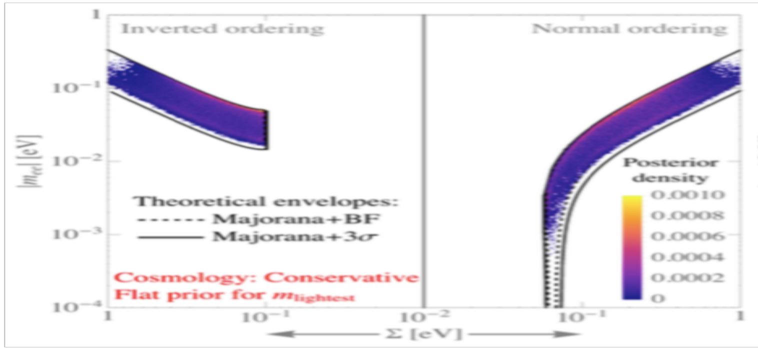
All upper limits 95% CL, but different assumed priors !

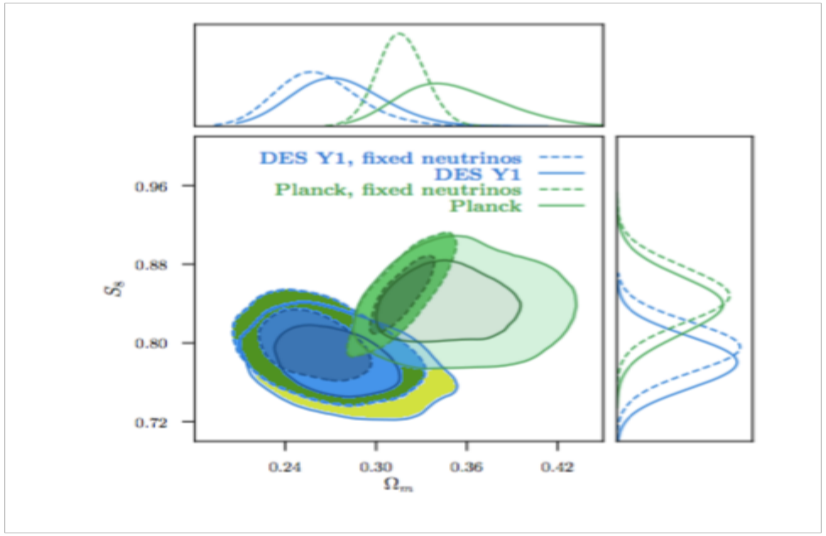
2-sigma errors on Neutrino mass – forecast for future surveys

Data	Authors	Error (Σ)
DES (LSS) + Planck DES (LSS+WL) + Planck	OL et al. (2010) Font-Ribera et al. (2014)	0.1 eV 0.08 eV
Euclid (LSS/WL) + Planck	Amendola et al. 2016	0.04 eV 0.05 eV
LSST (WL) +Planck	Abazajian et al. 2014	0.04 eV
DESI++	Font-Ribera et al. 2014	0.04 eV
SKA++	Abdalla & Rawling 2007	0.05 eV

Errors 95% CL, but different assumed priors !

Combining Neutrino and Cosmology experiments





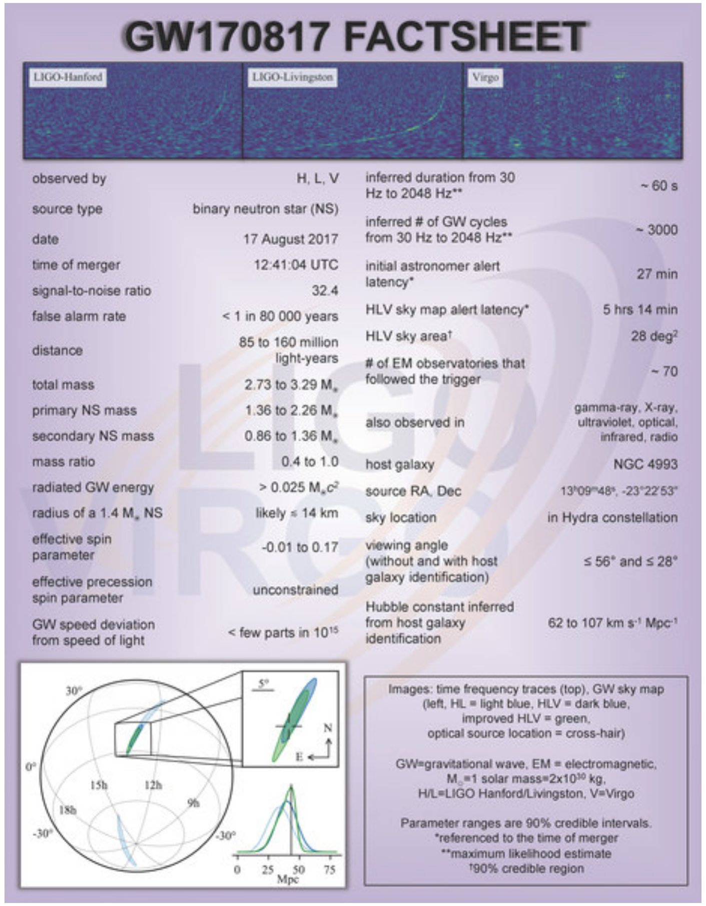
A global Bayesian analysis of neutrino mass from Double Beta Decay, Oscillations & Cosmology

To fix or not to fix to minimal oscillations M_{nu} = 0.06 eV ?

Caldwell et al., arXiv:1705.01945
Agostini et al. arXiv:1705.02996

DES collaboration arXiv:1708.01530

First Binary Neutron Star discovered in both GW and light



GW170817 FACTSHEET

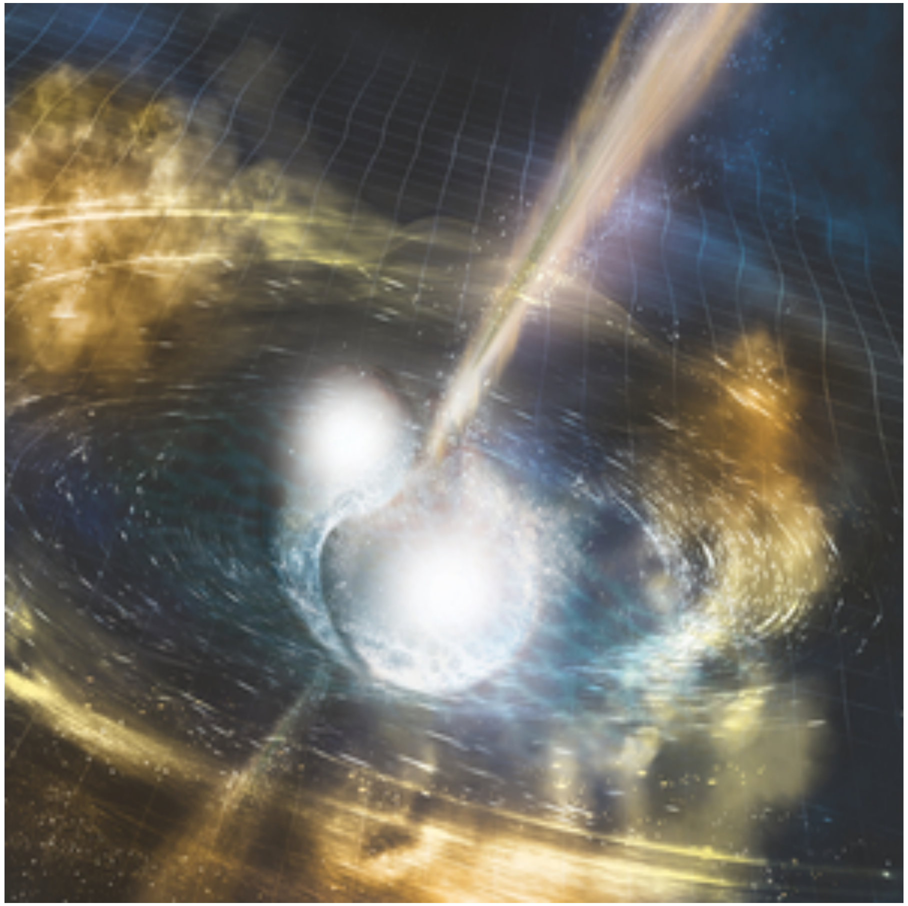
LIGO-Hanford | LIGO-Livingston | Virgo

observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≤ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}
inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22′53″
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}

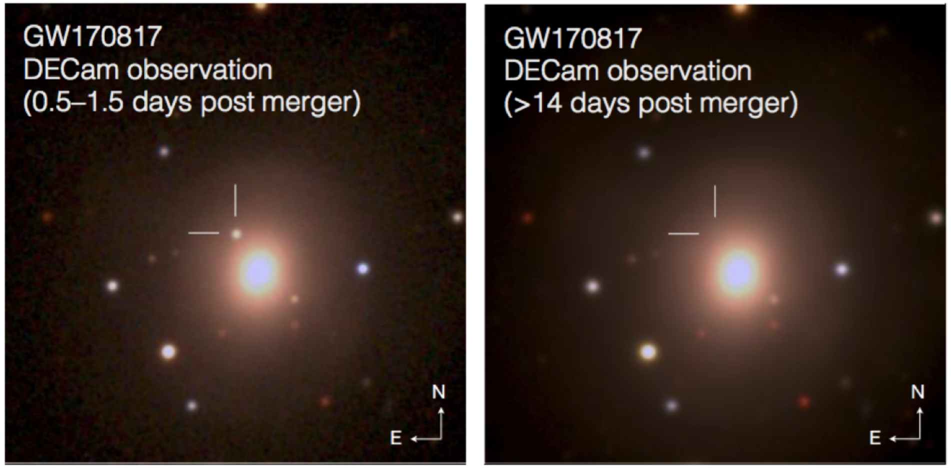
Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

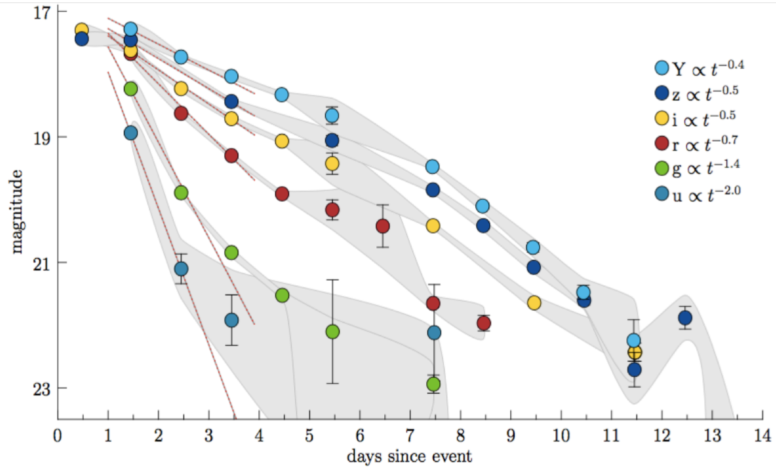
GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2×10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

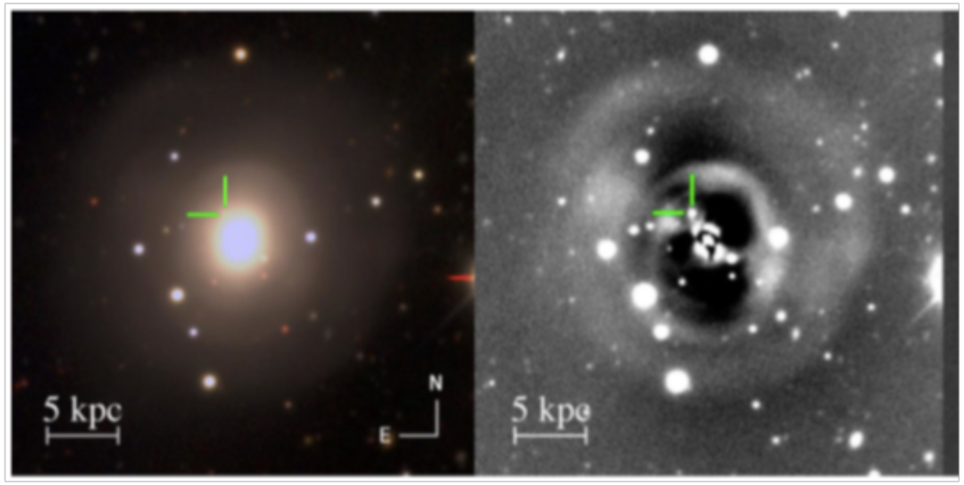
Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region



DECam/DES image of GW170817 in galaxy NGC4993 (40 Mpc away)



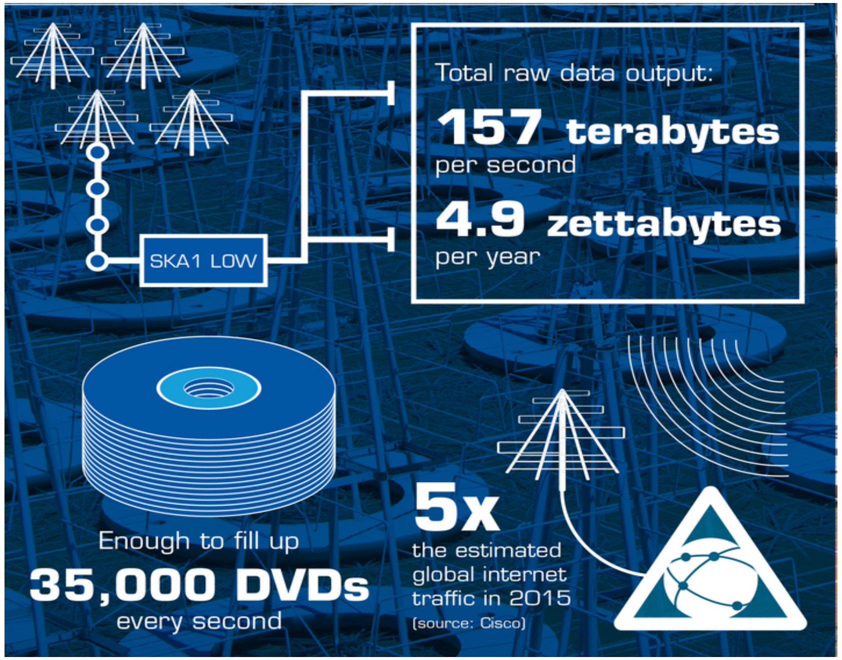




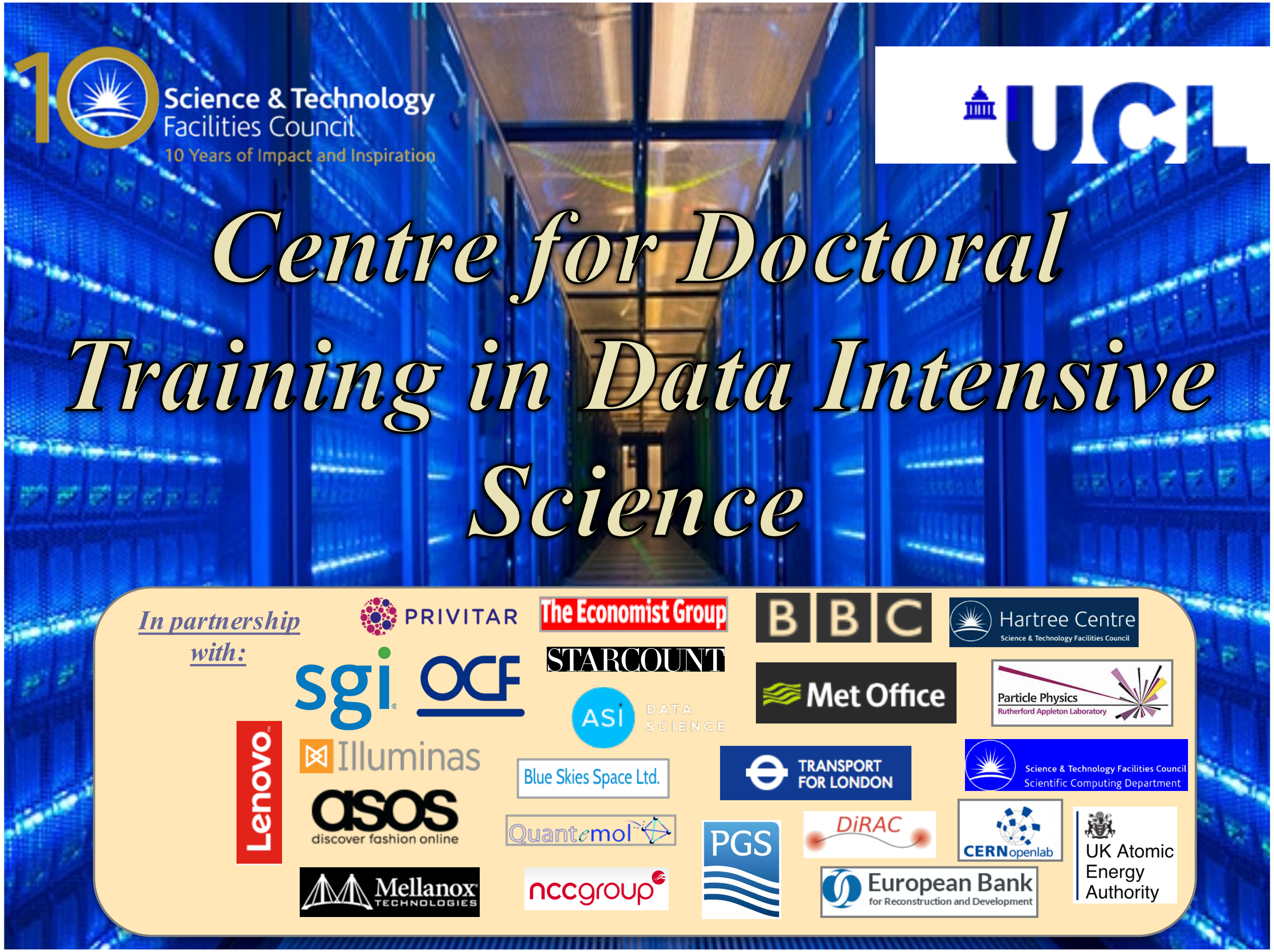
Soares-Santos & DES
arXiv:1710.05459

Palmese & DES
arXiv:1710.06748

SKA Big Data Challenge



www.skatelescope.org



- UCL + 7 other CDT-DIS funded by STFC
- 122 PhD students in data science started in October

Summary

- **27 years of LCDM**: supported by most current observations.
- Important to test LCDM further (e.g. local dynamics, CMB Cold Spot, gravitational redshift, parameter 'tension')
- Timeline: **past** (APM, 2dF & SDSS,WMAP, Planck, …), **present** (BOSS, DESI, HSC, …), **future** (LSST, DESI, Euclid, WFIRST, SKA,…)
- What are the prospects for **a new paradigm shift**, beyond LCDM, eg w(z) or ModGrav ?
- **Spin-offs: GW multi-messengers, Big Data, …**

Extra slides

Planck++ parameters

	Planck TT+lowP+lensing	*Planck* TT+lowP+lensing+ext
$\Omega_b h^2$	0.02226 ± 0.00023	0.02227 ± 0.00020
$\Omega_c h^2$	0.1186 ± 0.0020	0.1184 ± 0.0012
$100\,\theta_{MC}$	1.0410 ± 0.0005	1.0411 ± 0.0004
n_s	0.968 ± 0.006	0.968 ± 0.004
τ	0.066 ± 0.016	0.067 ± 0.013
$\ln(10^{10} \Delta^2_{\mathcal{R}})$	3.062 ± 0.029	3.064 ± 0.024
h	0.678 ± 0.009	0.679 ± 0.006
σ_8	0.815 ± 0.009	0.815 ± 0.009
Ω_m	0.308 ± 0.012	0.306 ± 0.007
Ω_Λ	0.692 ± 0.012	0.694 ± 0.007

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$M_{nu} = m_1 + m_2 + m_3$ from Planck++

Table 1.2: Summary of $\sum m_\nu$ constraints.

	Model	95%CL	Ref.
CMB alone			
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$	< 0.72 eV	[23]
Pl15[TT,TE,EE+lowP]	ΛCDM+$\sum m_\nu$	< 0.49 eV	[23]
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.73 eV	[24]
Pl16[TT+SimLow]	ΛCDM+$\sum m_\nu$	< 0.59 eV	[26]
Pl16[TT,TE,EE+SimLow]	ΛCDM+$\sum m_\nu$	< 0.34 eV	[26]
CMB + probes of background evolution			
Pl15[TT+lowP] + BAO	ΛCDM+$\sum m_\nu$	< 0.21 eV	[23]
Pl15[TT,TE,EE+lowP] + BAO	ΛCDM+$\sum m_\nu$	< 0.17 eV	[23]
Pl15[TT+lowP] + JLA	ΛCDM+$\sum m_\nu$	< 0.33 eV	[24]
Pl15[TT+lowP] + BAO	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.27 eV	[24]
CMB + probes of background evolution + LSS			
Pl15[TT+lowP+lensing]	ΛCDM+$\sum m_\nu$	< 0.68 eV	[23]
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.25 eV	[24]
Pl15[TT+lowP+lensing] + P(k)$_{\rm DR12}$	ΛCDM+$\sum m_\nu$	< 0.30 eV	[28]
Pl15[TT+lowP+lensing] + P(k)$_{\rm DR12}$ + HST	ΛCDM+$\sum m_\nu$	< 0.16 eV	[28]
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$\sum m_\nu$	< 0.59 eV	[23]
Pl15[TT,TE,EE+lowP] + BAO+ P(k)$_{\rm WZ}$	ΛCDM+$\sum m_\nu$	< 0.14 eV	[31]
Pl15[TT,TE,EE+lowP] + BAO+ P(k)$_{\rm DR7}$	ΛCDM+$\sum m_\nu$	< 0.13 eV	[31]
Pl15[TT,TE,EE+lowP] + BAO+ P(k)$_{\rm DR12}$	ΛCDM+$\sum m_\nu$	< 0.16 eV	[30]
Pl15[TT+lowP+lensing] + Lyα	ΛCDM+$\sum m_\nu$	< 0.12 eV	[29]
Pl16[TT+SimLow+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.17 eV	[26]
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+Ω_k	< 0.37 eV	[24]
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+w	< 0.37 eV	[24]
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.32 eV	[23]
Pl15[TT,TE,EE+lowP]+BAO+P(k)$_{\rm DR12}$+JLA	ΛCDM+$\sum m_\nu$+Ω_k+w	< 0.31 eV	[30]
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$\sum m_\nu$+5-params.	< 0.66 eV	[32]

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N_{eff} from Planck++ [vs. standard N_{eff} =3.045]

Table 1.1: Summary of $N_{\rm eff}$ constraints.

	Model	68%CL	Ref.
CMB alone			
Pl15[TT+lowP]	ΛCDM+$N_{\rm eff}$	3.13 ± 0.32	[23]
Pl15[TT,TE,EE+lowP]	ΛCDM+$N_{\rm eff}$	2.99 ± 0.20	[23]
Pl15[TT+lowP]	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	3.08 ± 0.31	[24]
CMB + probes of background evolution			
Pl15[TT+lowP] + BAO	ΛCDM+$N_{\rm eff}$	3.15 ± 0.23	[23]
Pl15[TT,TE,EE+lowP] + BAO	ΛCDM+$N_{\rm eff}$	3.04 ± 0.18	[23]
Pl15[TT+lowP] + JLA	ΛCDM+$N_{\rm eff}$	$3.18^{+0.28}_{-0.32}$	[24]
Pl15[TT+lowP] + BAO	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	$3.18^{+0.24}_{-0.27}$	[24]
CMB + probes of background evolution + LSS			
Pl15[TT+lowP+lensing]	ΛCDM+$N_{\rm eff}$	$3.13^{+0.29}_{-0.34}$	[24]
— + BAO	ΛCDM+$N_{\rm eff}$	$3.08^{+0.22}_{-0.24}$	[24]
— + BAO + JLA + HST	ΛCDM+$N_{\rm eff}$	3.41 ± 0.22	[25]
— + BAO	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	3.2 ± 0.5	[23]
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$N_{\rm eff}$+5-params.	$2.93^{+0.51}_{-0.48}$	[32]

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