What gravitational waves can tell us about Cosmology?

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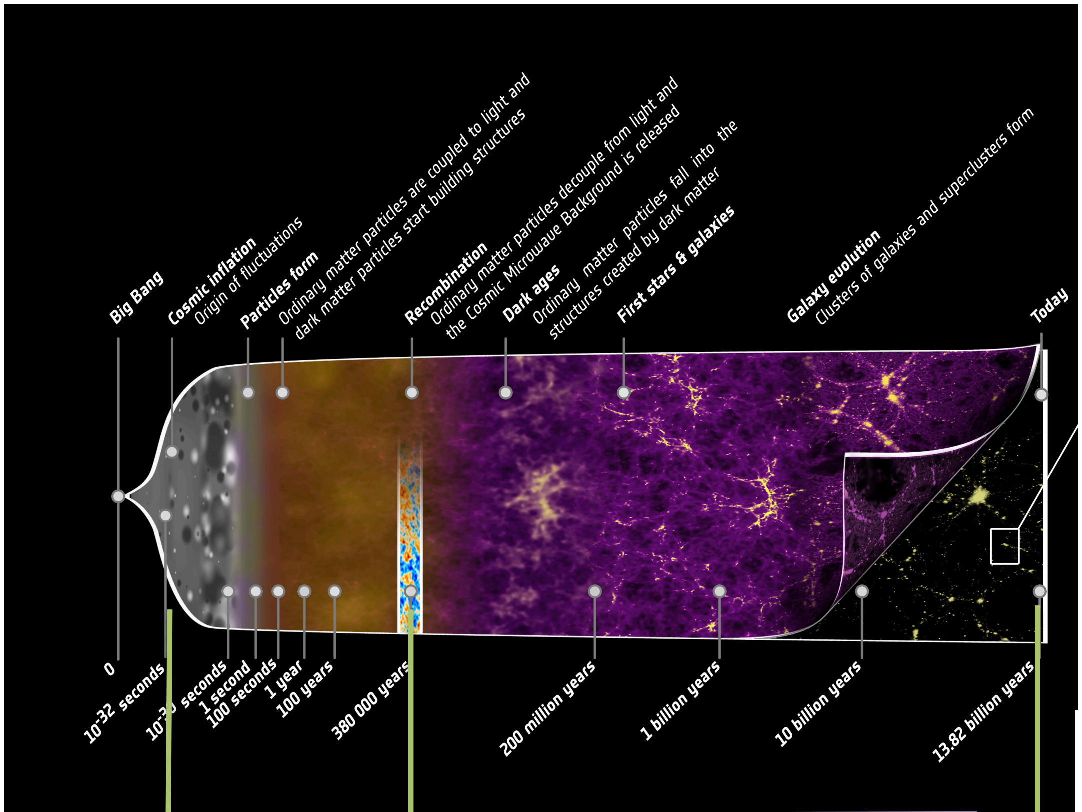
Outline

- *Cosmological implications of GW170817: constraints on the speed of GWs and H_0*
- *Prospects for the future: the birth of a new branch in cosmology?*
- *Conclusions*

GW170817: implications for Dark Energy

$$
\begin{aligned}
\mathcal{L}_2 &= c_2 X\,, \qquad \mathcal{L}_3 = 2\frac{c_3}{M^3}\,X\Box\phi \\
\mathcal{L}_4 &= \left(\frac{M_p^2}{2} + \frac{c_4}{M^6}X^2\right)R + 2\frac{c_4}{M^6}X\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right] \\
\mathcal{L}_5 &= \frac{c_5}{M^9}X^2\,G_{\mu\nu}\nabla^\mu\nabla^\nu\phi \; - \frac{1}{3}\frac{c_5}{M^9}X\left[(\Box\phi)^3 - 3\,(\nabla_\mu\nabla_\nu\phi)^2\,\Box\phi + 2\,(\nabla_\mu\nabla_\nu\phi)^3\right]
\end{aligned}
$$

Dark Energy

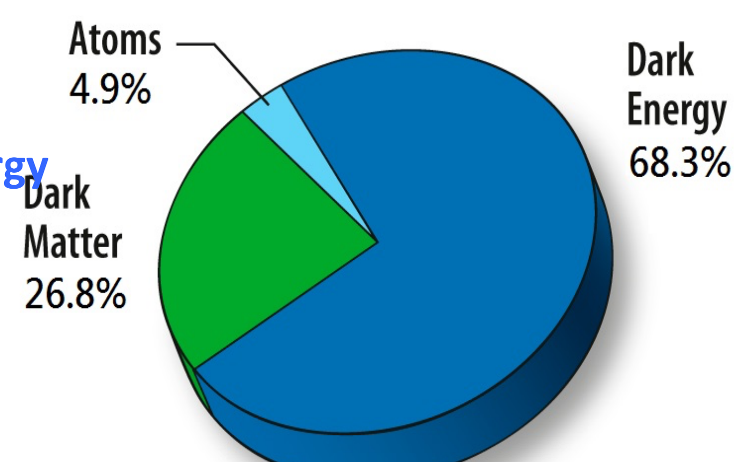


Radiation domination | **Matter domination** | **Dark energy**

Inflation | CMB is released | Present accelerated expansion

What is dark energy??

- A cosmological constant? It provides the best fit to data (standard cosmological model ΛCDM).
- Or a dynamical component? Alternative models to ΛCDM include models of gravity modified w.r.t. General Relativity (with additional degrees of freedom)



GWs: testing dark energy and modified gravity

The extremely strong constraint on the speed of GWs

$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 6 \cdot 10^{-16}$$

has already ruled out many classes of modified gravity models which have been proposed in the past years to explain the present acceleration of the universe.

GWs: testing dark energy and modified gravity

GWs are tensor perturbations of the metric. In cosmology: describe their evolution over a flat Friedmann-Robertson-Walker background

(disregarding scalar and vector modes)

$$ds^2 = -dt^2 + a^2(t)\,[(\delta_{ij} + h_{ij}(\underline{x},\tau))\,dx^i\,dx^j]$$

where h_{ij} are tensor modes which have the following properties

$h_{ij} = h_{ji}$ (symmetric)

$h^i_{\ i} = 0$ (traceless)

$h^i_{\ j|i} = 0$ (transverse)

$$\ddot{h}_{ij} + (3+\alpha_M)H\dot{h}_{ij} + (1+\alpha_T)k^2 h_{ij} = 0$$

$$\alpha_T = c_g^2 - 1$$

GWs: many models of modified gravity ruled out!

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

Also ruled out by GW170817:

- Vector Dark Energy
- Einstein Aether theories
- TeVeS
- MOND-like theories
- some sectors of Horava gravity
- Generalized PROCA theories

See, e.g., Ezquiaga & Zumalacarregui ’17
Baker et al. ‘17
Creminelli & Vernizzi ‘17

GWs: testing dark energy and modified gravity

➢ ***An example: Galileon models***

$$S_H = \int d^4x\sqrt{-g}\mathcal{L}_H = \int d^4x\sqrt{-g}\sum_{n=0}^{3}\mathcal{L}_n$$

$$\mathcal{L}_2 \;=\; c_2 X\,, \qquad \mathcal{L}_3 \;=\; 2\frac{c_3}{M^3}\,X\Box\phi$$

$$\mathcal{L}_4 \;=\; \left(\frac{M_p^2}{2} + \frac{c_4}{M^6}X^2\right)R + 2\frac{c_4}{M^6}X\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$

$$\mathcal{L}_5 \;=\; \frac{c_5}{M^9}X^2\,G_{\mu\nu}\nabla^\mu\nabla^\nu\phi \;-\frac{1}{3}\frac{c_5}{M^9}X\left[(\Box\phi)^3 - 3\,(\nabla_\mu\nabla_\nu\phi)^2\,\Box\phi + 2\,(\nabla_\mu\nabla_\nu\phi)^3\right]$$

$$X = -1/2\nabla_\mu\varphi\nabla^\mu\varphi$$

GWs: testing dark energy and modified gravity

- these models provide self-accelerating solutions at late time (i.e. no need to put by hand a cosmological constant)
- non-linear derivative interactions:

  - allow for self-acceleration

  - allow for so called screening mechanism
- enjoy stability properties (no ghosts, coefficients of the action protected from quantum corrections)
- compatible with data until last week......

  (in fact, able to relieve the tension on H_o)

GWs: testing dark energy and modified gravity

An example: Galileon models

$$
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\end{aligned}
$$

$$c_g \neq 1$$

$$-3\cdot 10^{-15}\leq c_g/c-1\leq 6\cdot 10^{-16} \quad \Rightarrow \quad \begin{aligned} |c_4| &< \sim 2.8\cdot 10^{-17} \\ |c_5| &< \sim 3.8\cdot 10^{-17}\end{aligned}$$

GWs: testing dark energy and modified gravity

- An example: Galileon models

$$\mathcal{L}_2 = c_2 X\,, \qquad \mathcal{L}_3 = 2\frac{c_3}{M^3}X\Box\phi \longrightarrow \text{“Cubic Galileons”}$$

$$\mathcal{L}_4 = \left(\frac{M_p^2}{2}+\frac{c_4}{M^6}X^2\right)R + 2\frac{c_4}{M^6}X\left[(\Box\phi)^2-(\nabla_\mu\nabla_\nu\phi)^2\right]$$

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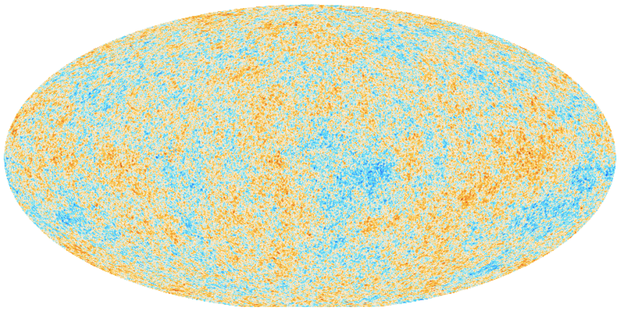
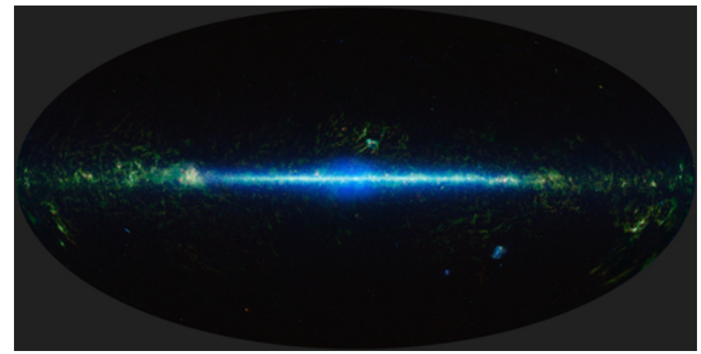
Exploiting CMB and LSS data

But……Cubic Galileon is ruled out at more than 7σ by the ISW-LSS cross-correlation



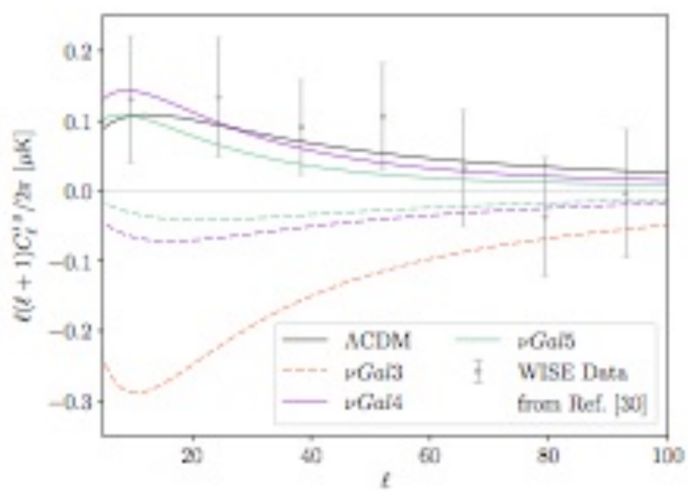
Integrated Sachs-Wolfe effect (ISW)

$$\frac{\Delta T}{T}(\hat{\mathbf{n}}) = -2\int_0^{z_{rec}} dz\,\frac{d\Phi(r\hat{\mathbf{n}},z)}{dz}$$



Evolution of Large-Scale-Structures (LSS)

$$-k^2\Phi = -4\pi G a^2\rho\,\delta$$



Renk et al. '17.

GWs: testing dark energy and modified gravity

- An example: Galileon models

$$\xcancel{\mathcal{L}_2 = c_2 X\,, \qquad \mathcal{L}_3 = 2\frac{c_3}{M^3} X \Box\phi}$$

“Cubic Galileons”

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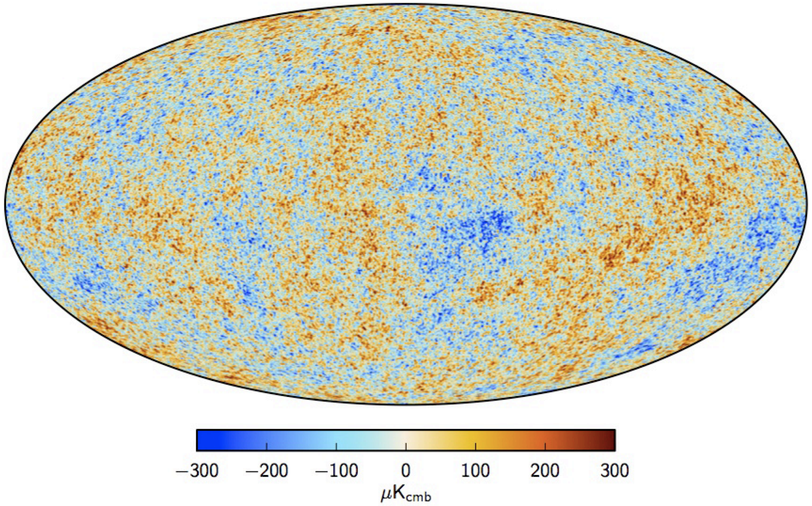
\end{aligned}}$$

A clear example of multimessenger physics



Measurements of H_0

$$H_0 = 70.0^{+12.0}_{-8.0} \quad \mathrm{km\,s^{-1}\,Mpc^{-1}}$$ from GW170817

- How this compares with the present direct measurements and with measurements from CMB?

- Why it would be important to increase the precision of measurements of H_0 from GWs?

Measurements of H_0

$$H_0 = 66.88 \pm 0.91$$ From CMB** (Planck15+SIMlow_HFI)

$$H_0 = 73.24 \pm 1.74$$ From local, low redshift direct measurements using SNIa (Riess et al. 2016).

3.1σ tension

****N.B.: this is not a *Planck tension, this is a tension between CMB inferred value of H_0 and late-time cosmology.***

The values measured by Planck and WMAP are fully consistent

$$H_0 = 69.7 \pm 2.1$$ WMAP

$$H_0 = 68.1 \pm 0.7$$ WMAP9+BAO (BOSSDR11+6dFGS+Lyman α)+high-z SNIa; 2.7σ tension (Aubourg+ 2015)

$$H_0 = 69.3 \pm 0.7$$ WMAP9+ACT+SPT + BAO (BOSSDR11+6dFGS) 1.9σ tension (Bennet+ 2014)

Measurements of H_0

- this tension might indicate either the presence of some systematics or *new physics*

- in any case, such a tension is a clear indication that we are living in a precision cosmology epoch, and because of that we are moving towards an epoch of "accuracy" cosmology

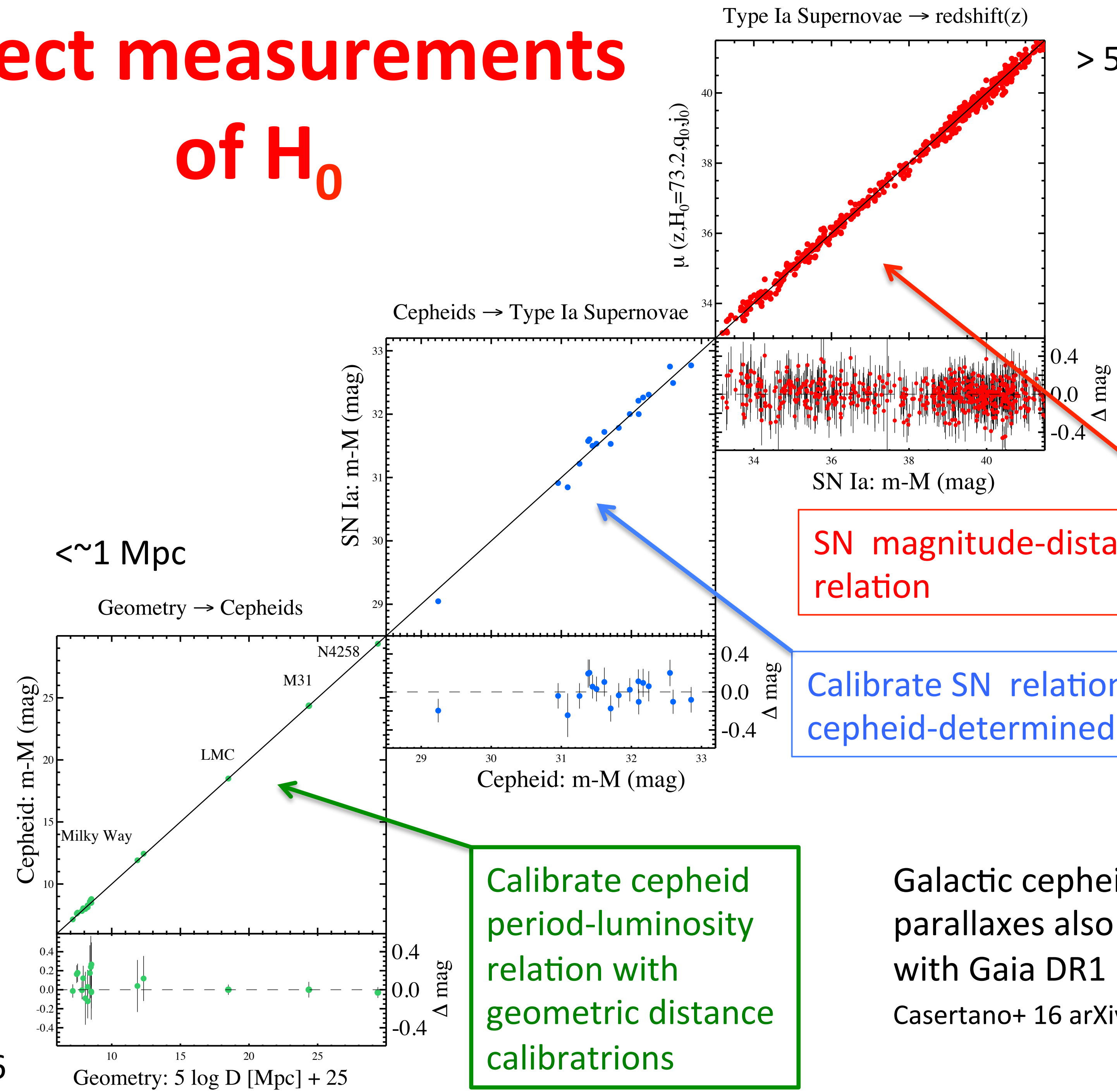
Direct measurements of H_0

Luminosity distance:

$$\boxed{d_L(z) = c\,(1+z)\int_0^z \frac{1}{H(z')}dz'}$$

- For low redshifts z<<1: $D_L(z) \approx c\,z/H_0$
- For higher redshifts z> 1: $D_L(z)$ depends the evolution of H(z) and hence on cosmological parameters like Ω_m and the equation state parameters, dark energy evolution.

Direct measurements of H_0



> 50 Mpc

<~1 Mpc

SN magnitude-distance relation

Calibrate SN relation with cepheid-determined distances

Calibrate cepheid period-luminosity relation with geometric distance calibratrions

Galactic cepheids parallaxes also checked with Gaia DR1 release

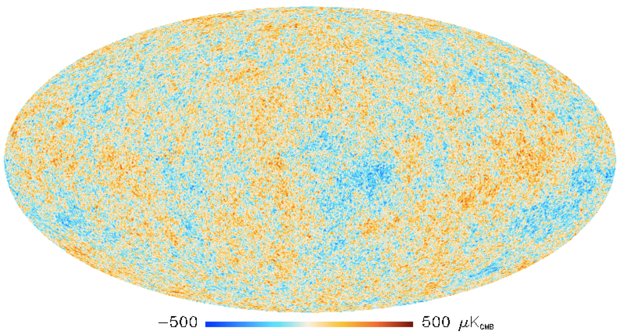
Casertano+ 16 arXiv:1609.05175

Riess+2016

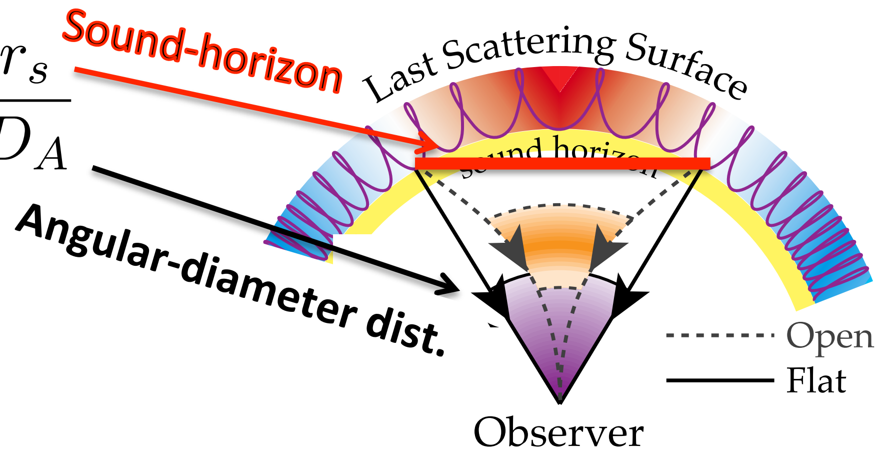
H_0 measurements from CMB

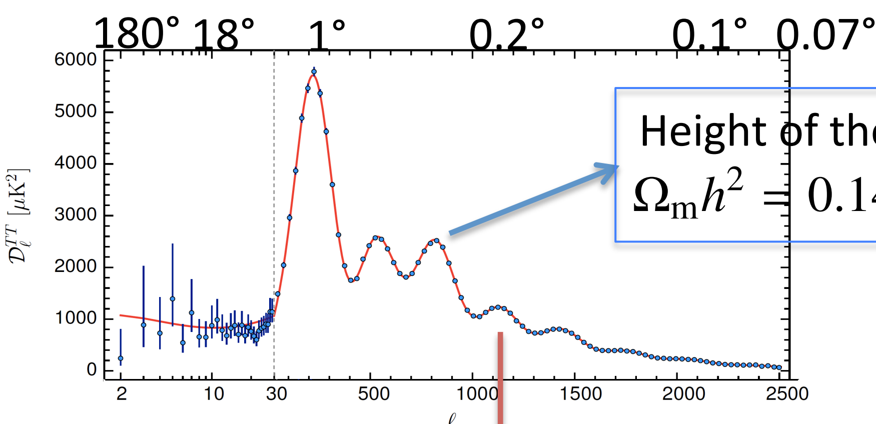
Acoustic oscillations of CMB photons+baryons at last scattering z~1100: ***acoustic scale ϑ_****

$$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724^\circ \pm 0.00038^\circ$$



$$\theta_* = \frac{r_s}{D_A}$$

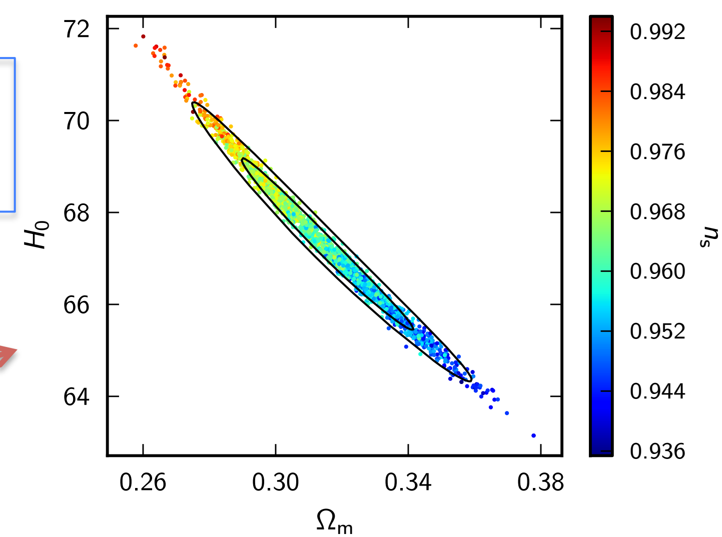




Height of the peaks
$\Omega_m h^2 = 0.1423 \pm 0.0029$

Positions of the acoustic peaks

$\boxed{\Omega_m h^3 = 0.0959 \pm 0.0006}$



Binaries as standard sirens

$$d_L(z) = c\,(1+z)\int_0^z \frac{1}{H(z')}dz'$$

- The measured GW waveform depends directly on the luminosity distance of the source
- If subsequent electromagnetic observations are able to identify an EM counterpart, then one is able to obtain a measure of the source redshift and thus a point in the distance-redshift space.
- One can map out the universe expansion history (H_0, dark energy equation of state, Ω_{CDM}, Ω_{DE}).

Binaries as standard sirens

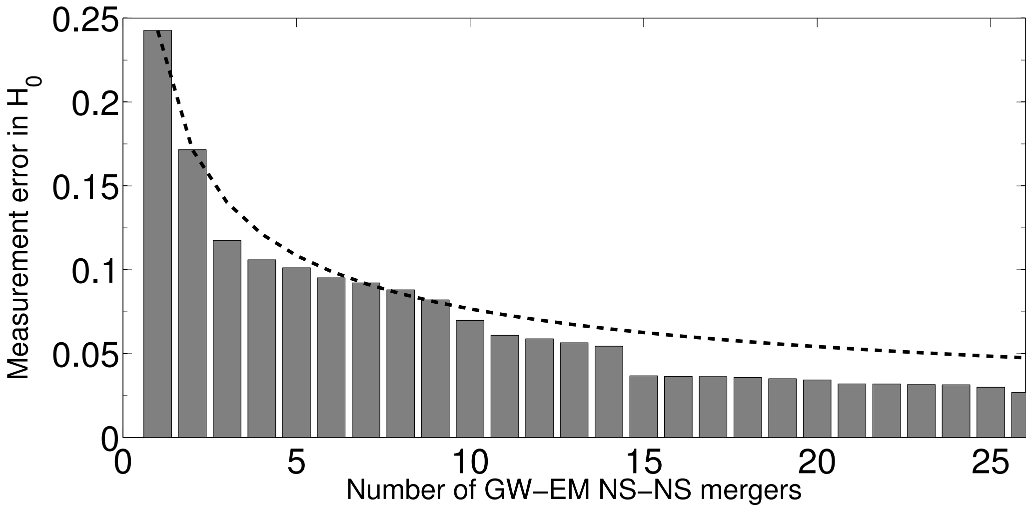
$$d_L(z) = c\,(1+z)\int_0^z \frac{1}{H(z')}dz'$$

- no calibration needed
  (the only calibration needed is
  the assumption that general relativity
  describes the binary system)
  → ***no need to construct a distance ladder!***
- ***different systematics w.r.t to CMB and local direct measurements (e.g. SNIa)***
- ***A % precision is needed to help in fixing the tension***
  (almost ~50 events of neutron
  star binaries to have a 2.5% precision,
  Guidorzi et al. '17)

Binaries as standard sirens

Prospects for the (near?) future…….

LIGO+VIRGO



Nissanke et al. 2013

- Of course the error on H_0 depends critically on number of events and hence, among various factors, merging-rate, sensitivity and number of GW interferometers in network

- The timescale to reach % precision on H_0 depends critically on the precise merging rate $(1.5^{+3.2}_{-1.2}) \times 10^{-6}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$

in the optimistic case a ~4.2 % precision with third run??
(e.g., Seto & Kyutoku '17)

Prospects for the future

The future is bright! Many new ideas and observational constraints on many diverse cosmological issues.

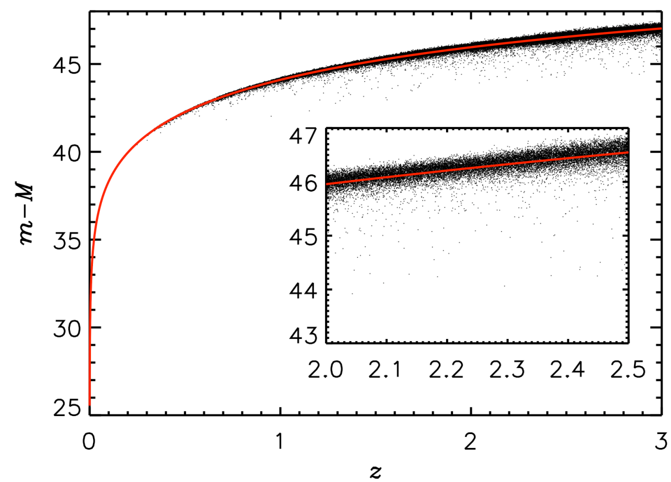
Here I just mention a list, focusing on some details for a couple of examples

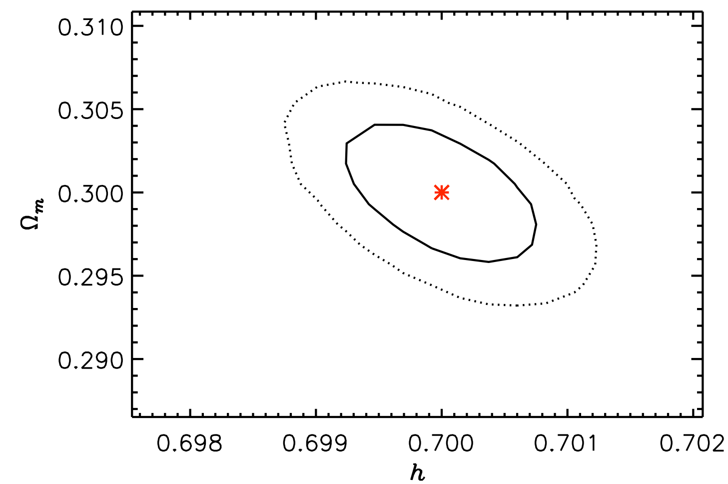
- Precision cosmology on standard cosmological parameters (e.g., H_0, Ω_m, the equation state parameter, dark energy evolution, …)
- Tests on GR and modified gravity models
- Tests of fundamental physics (equivalence principle, tests of parity violation,…..)
- Impact of cosmological Large-Scale Structures on GW sources
  → inference of lensing convergence and growth of structures from GW standard sirens
- Primordial non-Gaussianity from inflation
- Black holes as dark matter
- Gravitational waves from inflation

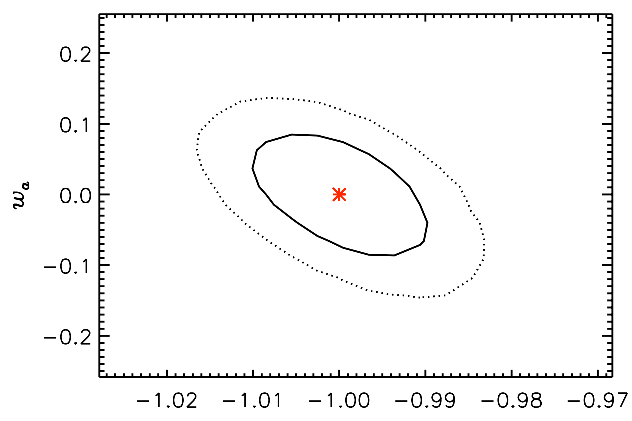
Binaries as standard sirens

And futuristic prospects…….ultra-high precision cosmology!

e.g.: with BBO (Big-Bang Observer) a 0.1% accurate determination of H_0





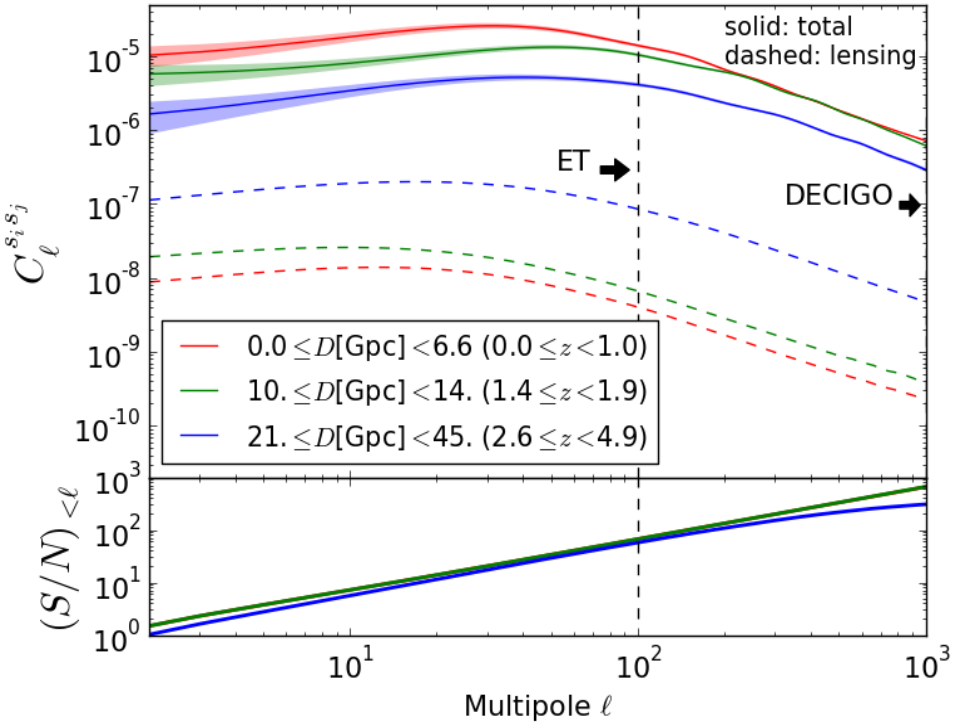


1% precision on w_0 and 10% on w_a

$w_{DE}(a)=w_0+w_a(1-a)$

Cutler and Holz 09

Anisotropies of GW standard sirens



- exploit ***clustering of NS binaries*** due to the underlying cosmological gravitational potential fluctuations

- ***LSS also induces gravitational lensing***
→ Luminosity distance is modified

- ***This would be a method that does not require redshift information (i.e. an EM counterpat)!***

Namikawa+, 2016 (see also: Bertacca, Raccanelli, N.B., Matarrese '17, Laguna et al. 09; Contaldi '16; Dai et al. '16; Bonvin et al. '16 for related issues).

Cosmological applications:

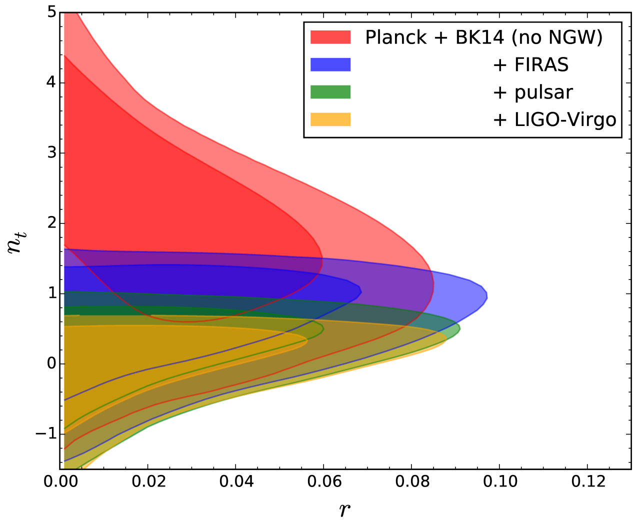
- e.g., primordial non-Gaussianity, can reach $f_{NL=}0.5$!! (now Planck error is 5.7)
- Cross-correlation with other cosmological probes (CMB lensing and weak lensing of LSS galaxy surveys)

Primordial GWs from inflation

- Inflation predicts a stochastic background of gravitational waves, a smoking-gun of inflation: they are the result of quantum mechanical fluctuations of the metric

$$\mathcal{P}_T(k) = A_T \left(\frac{k}{k_*}\right)^{n_\mathrm{T}} \qquad r = \frac{\mathcal{P}_T(k_*)}{\mathcal{P}_\zeta(k_*)}$$

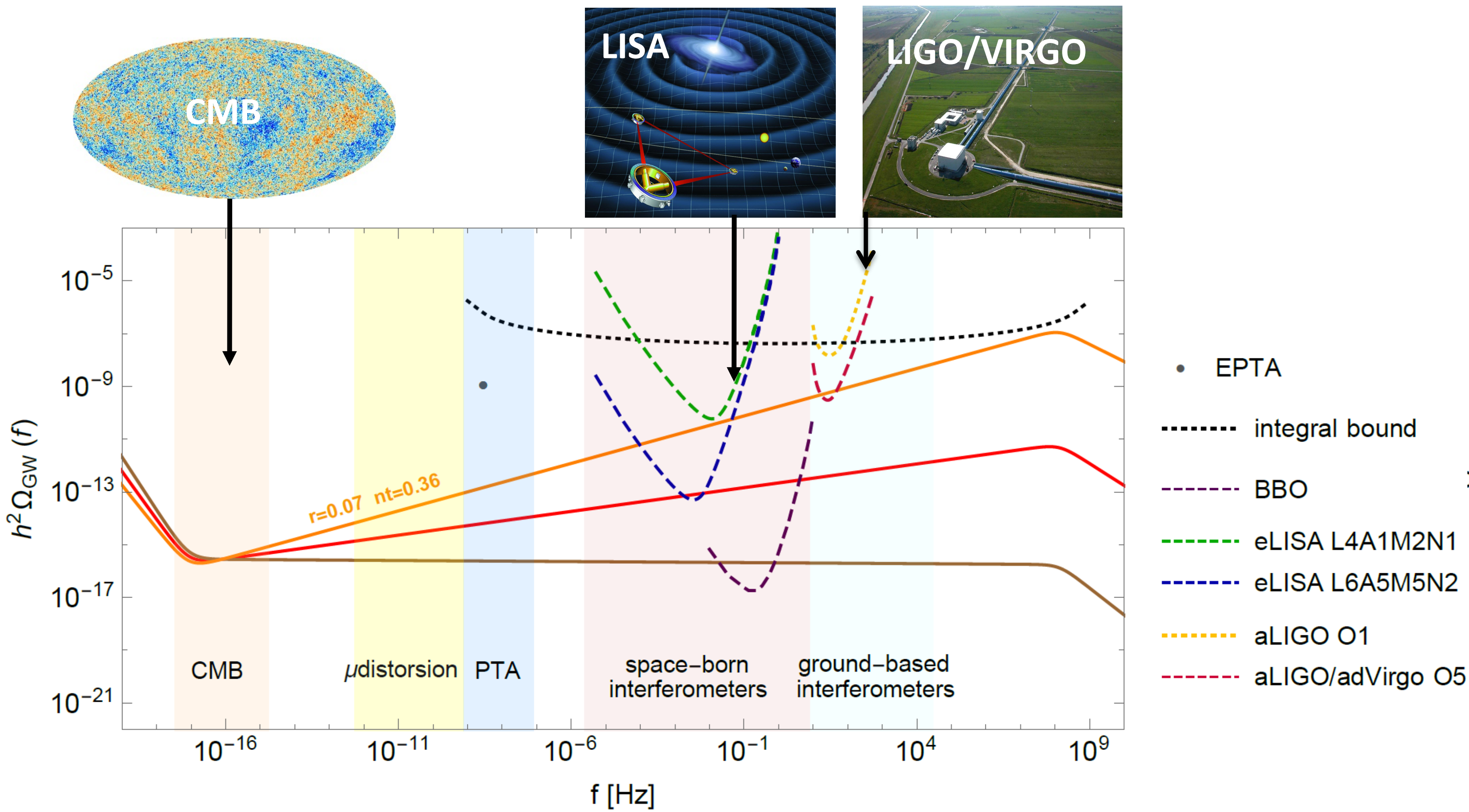
- Data from interferometers have already provided useful constraints.



$$r < 0.085 \quad n_T = 0.04^{+0.61}_{-0.85} \quad (95\%\ \mathrm{C.L.})$$

G. Cabass, L. Pagano et al. 2015

SYNERGY BETWEEN CMB AND INTERFEROMETERS



From M.C. Guzzetti, N.B., M. Liguori, S. Matarrese, ``Gravitational waves from Inflation'', arXiv:1605.01615

The nature or primordial GWs

GW PRODUCTION	Discriminant	Specific discriminant	Examples of specific models	Produced GW
Vacuum oscillations quantum fluctuations of the gravitational field stretched by the accelerated expansion	**theory of gravity**	General Relativity	*single-field slow-roll*	*broad spectrum*
			all other models in GR	broad spectrum
		MG/EFT approach	G-Inflation	broad spectrum
			Potential-driven G-Inflation	broad spectrum
			EFT approach	broad spectrum
Classical production second-order GW generated by the presence of a source term in GW equation of motion	**source term**	vacuum inflaton fluctuations	*all models*	*broad spectrum*
		fluctuations of extra scalar fields	inflaton+spectator fields	broad spectrum
			curvaton	broad spectrum
		gauge particle production	pseudoscalar inflaton+gauge field	broad spectrum
			scalar infl.+pseudoscalar+gauge	broad spectrum
		scalar particle production	scalar inflaton+ scalar field	peaked
		particle production during preheating	chaotic inflation	peaked
			hybrid inflation	peaked

From M.C Guzzetti, N.B., M. Liguori, S. Matarrese, ``Gravitational waves from Inflation'', arXiv:1605.01615

- ✓ A detection of GW would not by itself determine the precise mechanism generating the the tensor modes
- ✓ In addition to the standard quantum vacuum amplification of tensor perturbations on cosmological scales various mechanisms exist that produce during inflation (or immediately after inflation) a ***classical background of gravitational waves.***
- ✓ ***Case studies have been proposed in ``Science with the space-based interferometer LISA. IV: Probing inflation with gravitational waves''*** , N.B., C. Caprini, V. Domcke, D. Figueroa, J. Garcia-Bellido, M. C. Guzzetti. et al. (including M.Liguori & S. Matarrese)

Conclusions

- A new era of gravitational wave astronomy (and multimessenger physics) has just started!

- ***The consequences of GW170817 for cosmology are (up to now) impressive:*** different classes of modified gravity models (proposed as dark energy) have been ruled out in just one day!

- Improving the precision on H_0 using standard sirens can be very interesting to better understand the present (slight) tension on H_0 measurements.

- ***The future is bright:*** a new branch of high-precision cosmology might start, with very exciting new ideas and new, alternative observables to investigate the universe, from low-redshift up the very first moments of the universe (inflation).

H_0 and Number of relativistic species

- Combining Planck TT with a gaussian prior 73 ± 1.8 Km/s/Mpc as from Riess+ 16, in LCDM+Neff model H_0 prior pushes Neff high, but
- Planck χ^2 worsens when combining with Riess both in LCDM and LCDM+Neff model, high Neff
- This is because for Planck alone, even in LCDM+Neff H_0=68+-2.8, i.e. the tension is still at the 2.4σ level
- A modification of the early-time physics to include a component of dark radiation with an effective number of species N_{eff}~ 0.4 would reconcile the CMB-inferred constraints, and the local H_0 and standard ruler determinations. The inclusion of the “preliminary” high-l Planck CMB polarisation data disfavours this solution.