

Cosmology

Session Overview

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Journées rencontres jeunes chercheurs — October 2021

Introduction to Cosmology

The energy content of the Universe

Estimating the Hubble constant

With type Ia Supernovae (standard candles)

With gravitational waves (standard sirens)

A multi-probe / multi-messenger era

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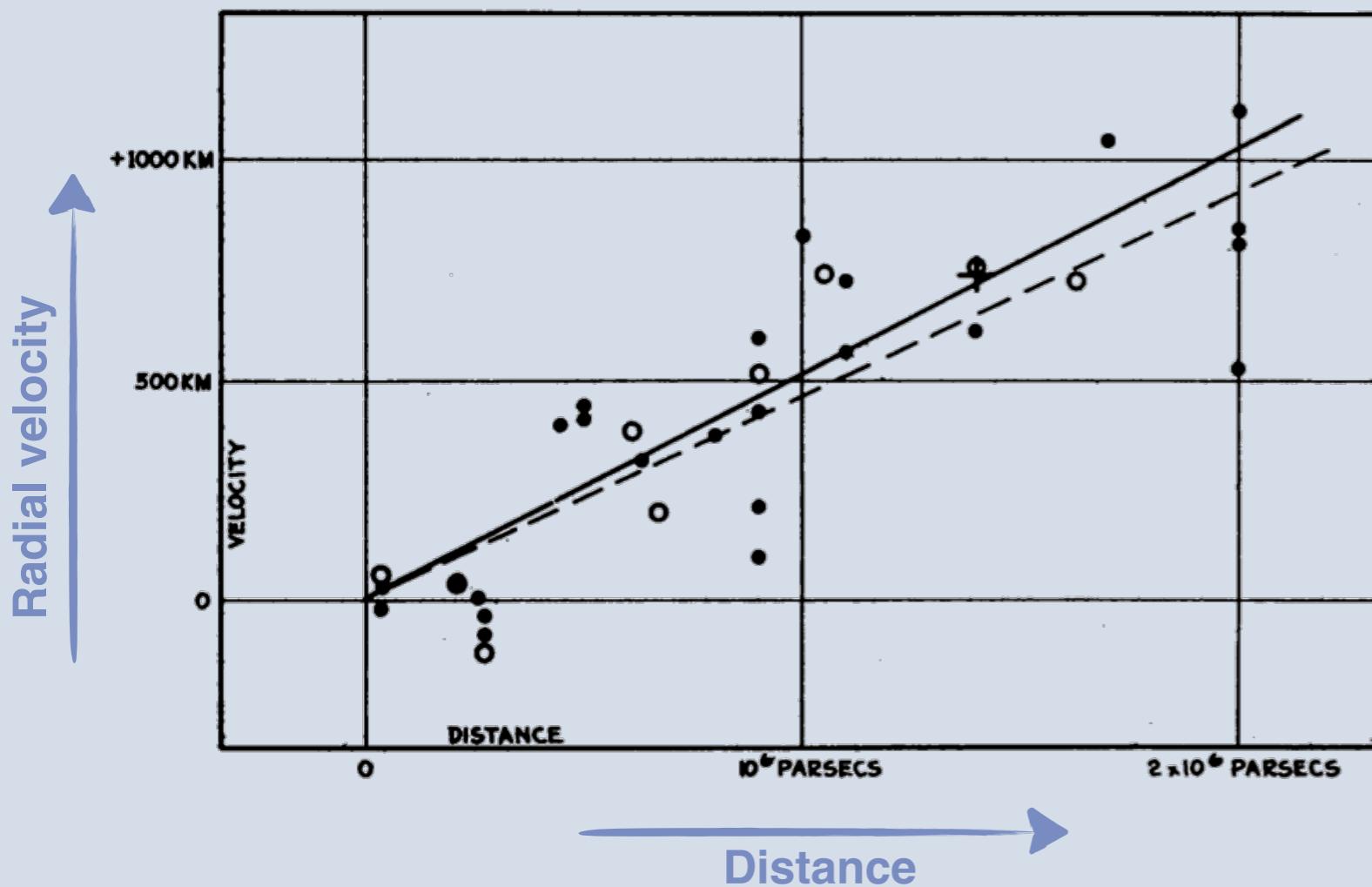
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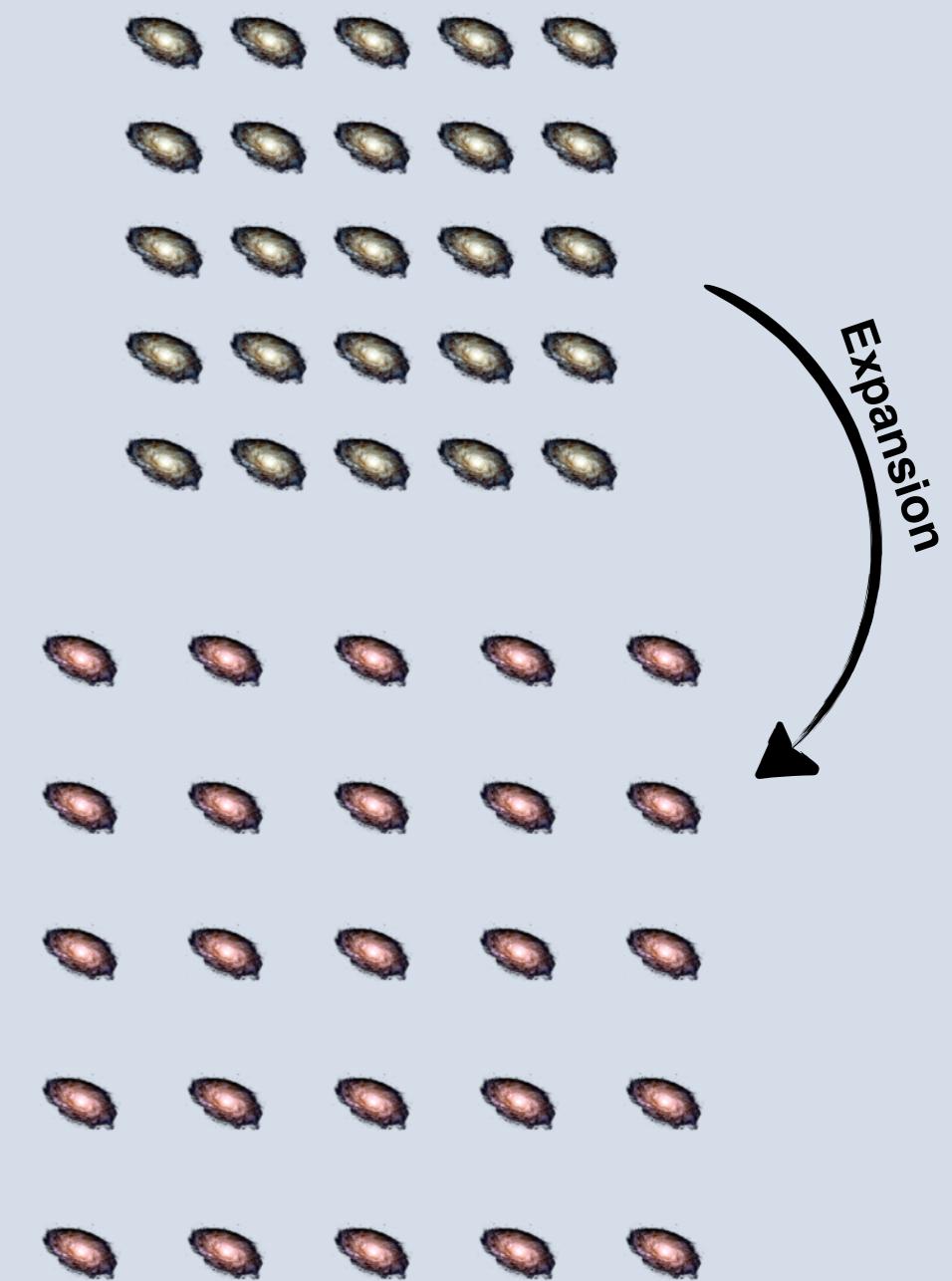
A multi-probe / multi-messenger era

Expansion of the Universe

Edwin Hubble, 1929



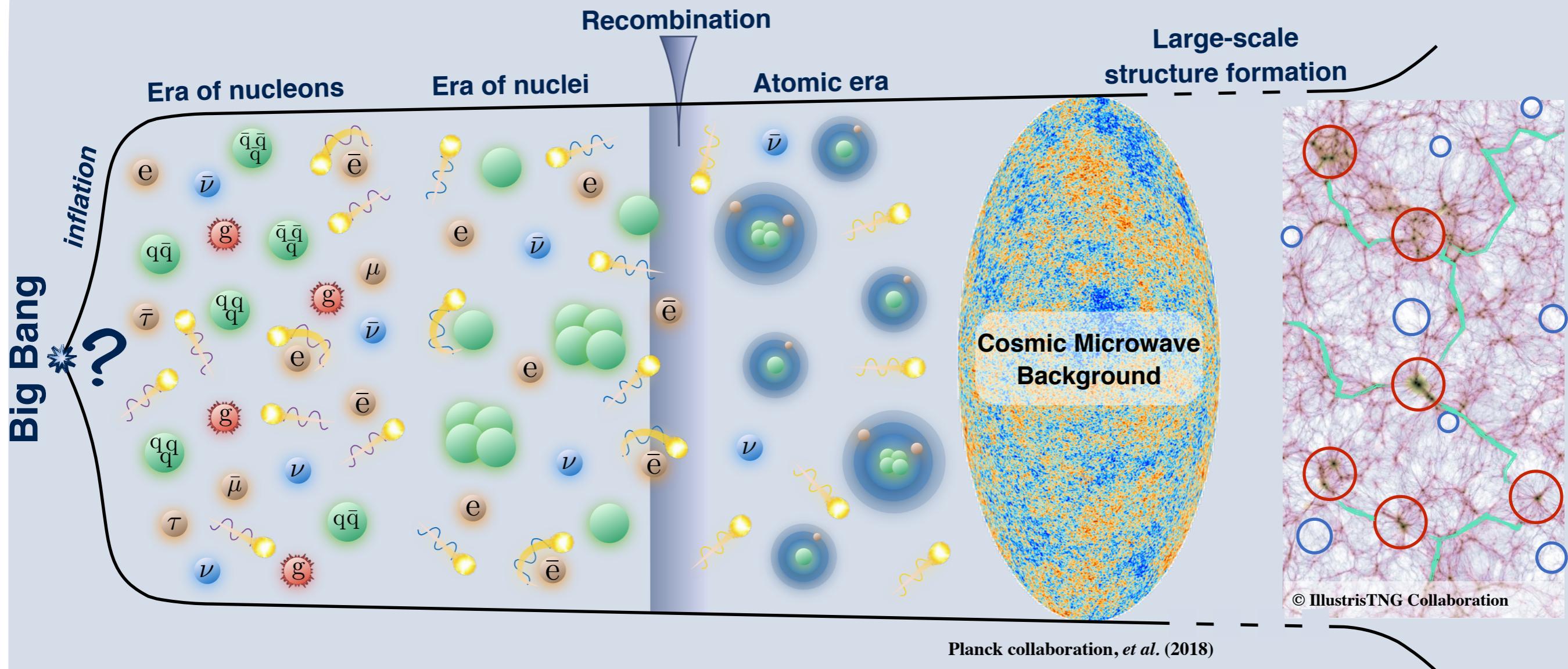
Galaxy distribution



Going back in time:

Universe had to be extremely dense and hot at some point (*big bang*)

A brief history of the Universe



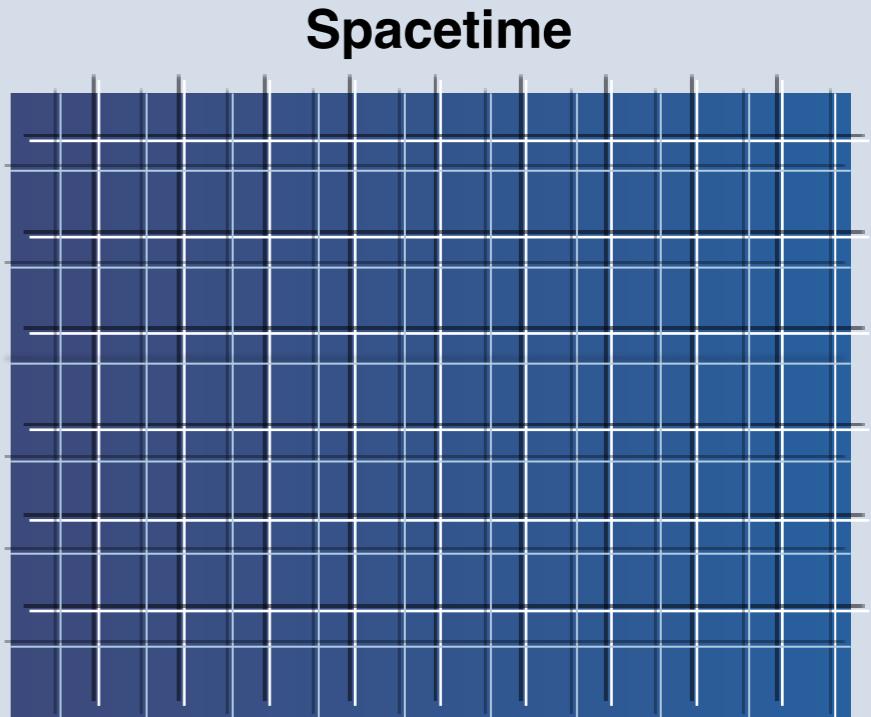
- Young universe: fully **opaque** plasma
- Recombination: Cosmic Microwave Background (**CMB**) emission
- CMB anisotropies: seeds of the **large-scale structures** of the universe
- **Cosmic web:** galaxy clusters (nodes), voids, filaments

Standard model of Cosmology

Einstein field equations

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

→ Links spacetime curvature ($G_{\mu\nu}$) to energy content ($T_{\mu\nu}$)



First Friedmann equation

Universe: spatially homogeneous and isotropic at large scales → metric: $ds^2 = a(t)^2 ds_3^2 - c^2 dt^2$

Solve Einstein field equations for a perfect fluid:

$$H^2 = H_0^2 [\Omega_r a^{-4} + \Omega_m a^{-3} + (1 - \Omega_{\text{tot}}) a^{-2} + \Omega_\Lambda] \quad \text{with} \quad H \equiv \frac{\dot{a}}{a} \quad \text{the Hubble parameter}$$

Hubble's constant
(expansion rate measured today)

$$\Omega_i = \frac{\rho_i}{\rho_c} \quad \text{and} \quad \rho_c = \frac{3H_0^2}{8\pi G}$$

$$\Omega_{\text{tot}} = \sum_i \Omega_i$$

Evolution of the Universe

$$H^2 = H_0^2 \left[\Omega_r a^{-4} + \Omega_m a^{-3} + (1 - \Omega_{\text{tot}}) a^{-2} + \Omega_\Lambda \right]$$

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Need to estimate Ω_r , Ω_m , Ω_Λ , Ω_{tot} , and H_0 to solve the equation

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Cosmological parameters: Matter power spectrum

- Power spectrum of the matter distribution:

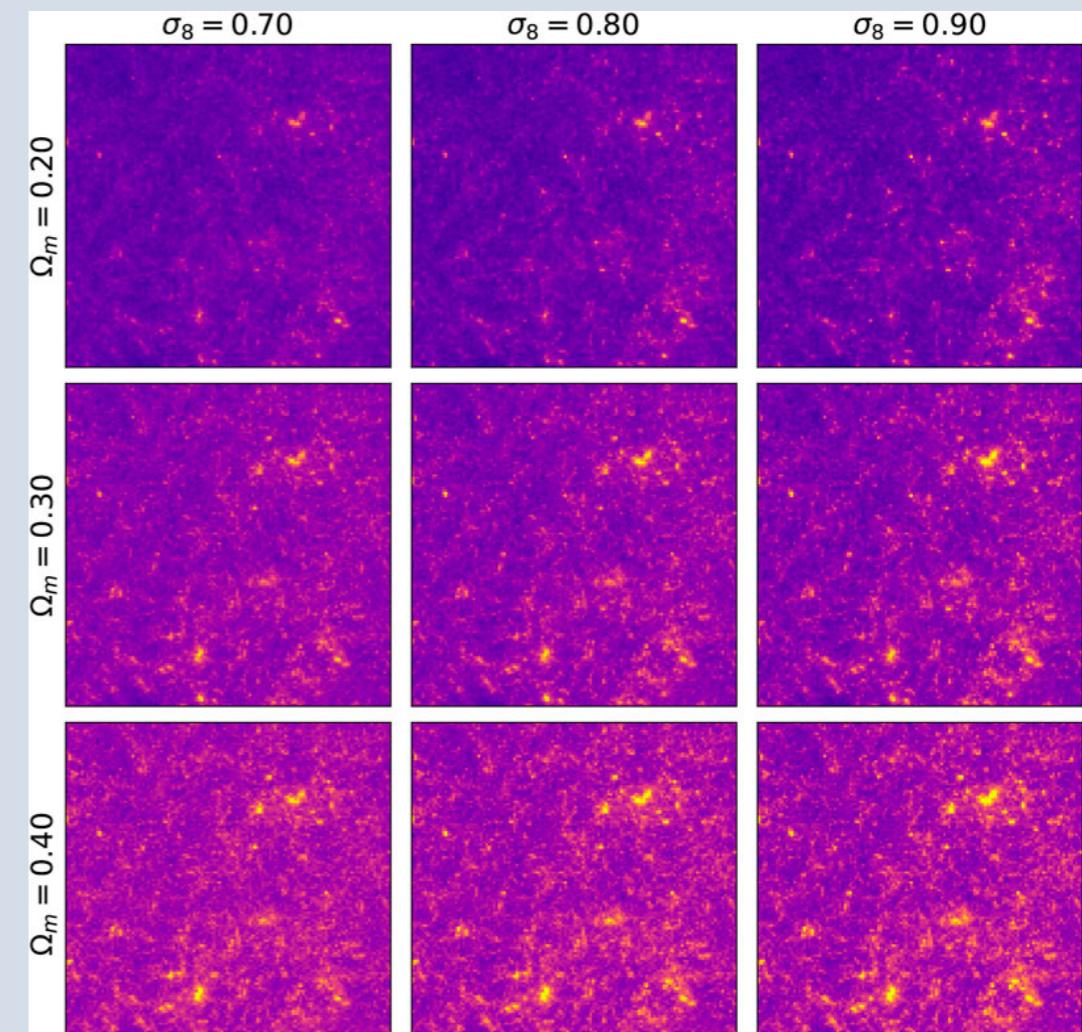
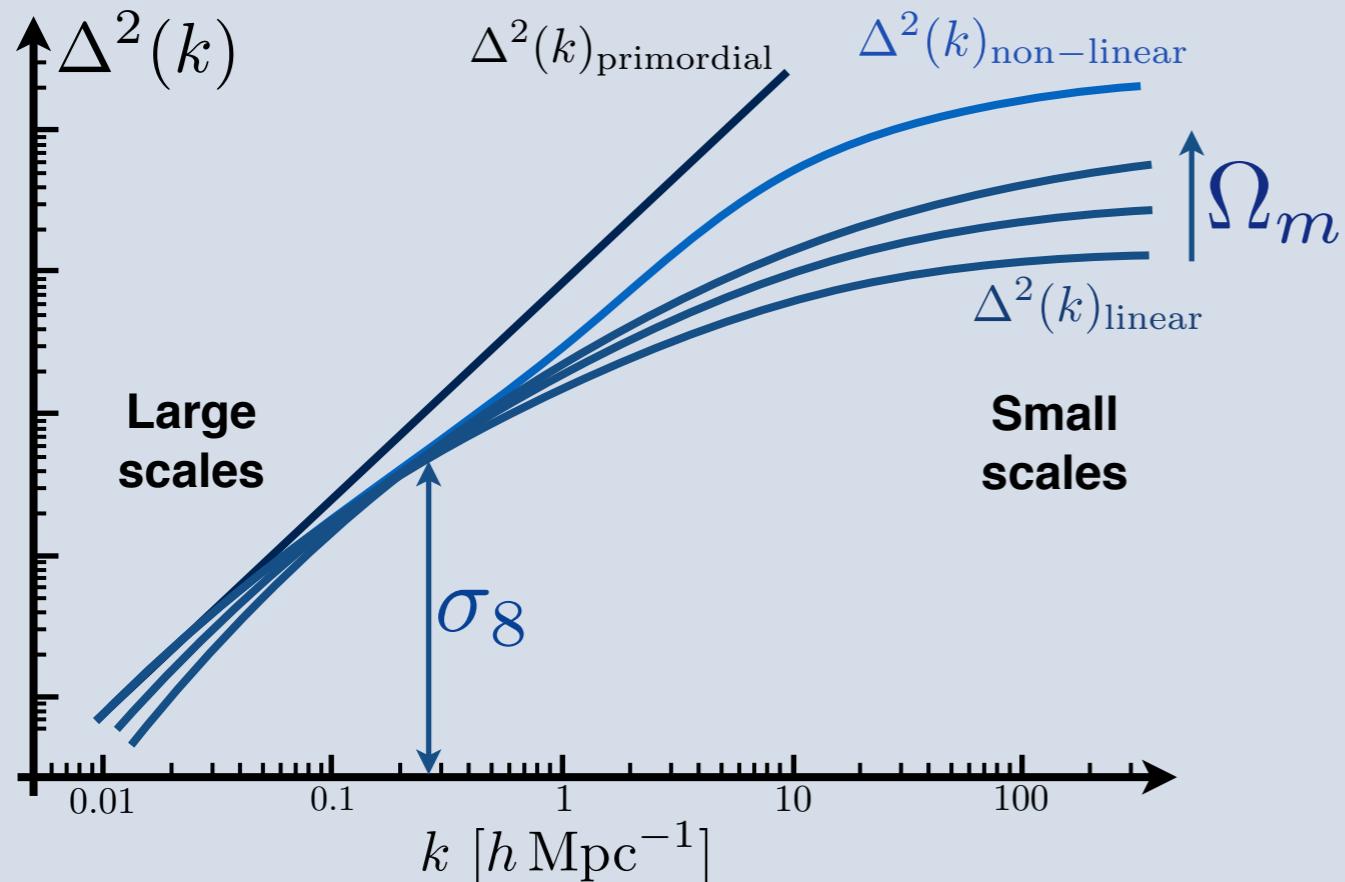
Fourier transform of the two point correlation function: $\Delta^2(k) = \text{TF}[\xi(r)]$

$\xi(r)$: probability to find two over-densities in volumes δV separated by a distance r

See Sara's talk

Depends on:

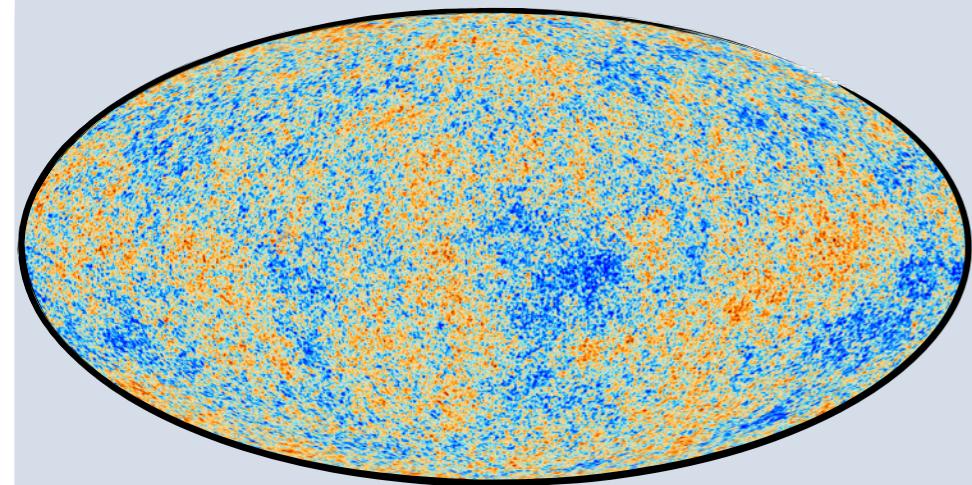
- the expansion of the universe
- the growth of primordial over-densities



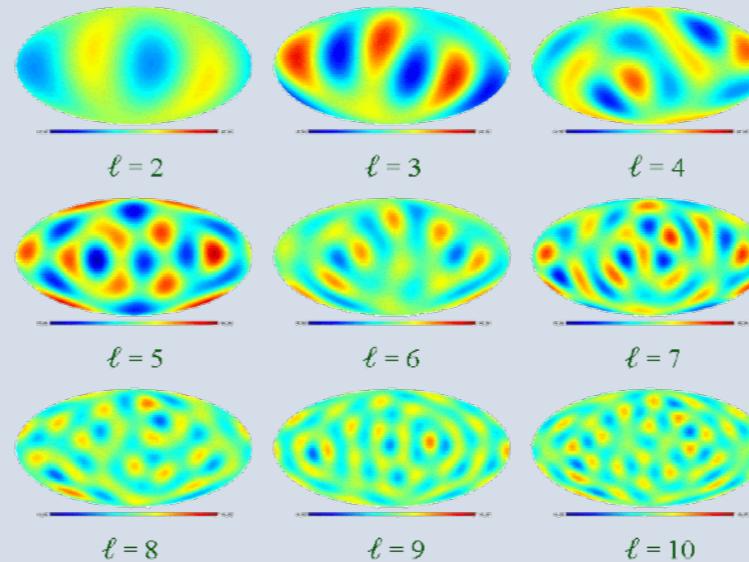
Perraudin et al. 2020

Cosmological parameters: CMB power spectrum

CMB temperature fluctuations



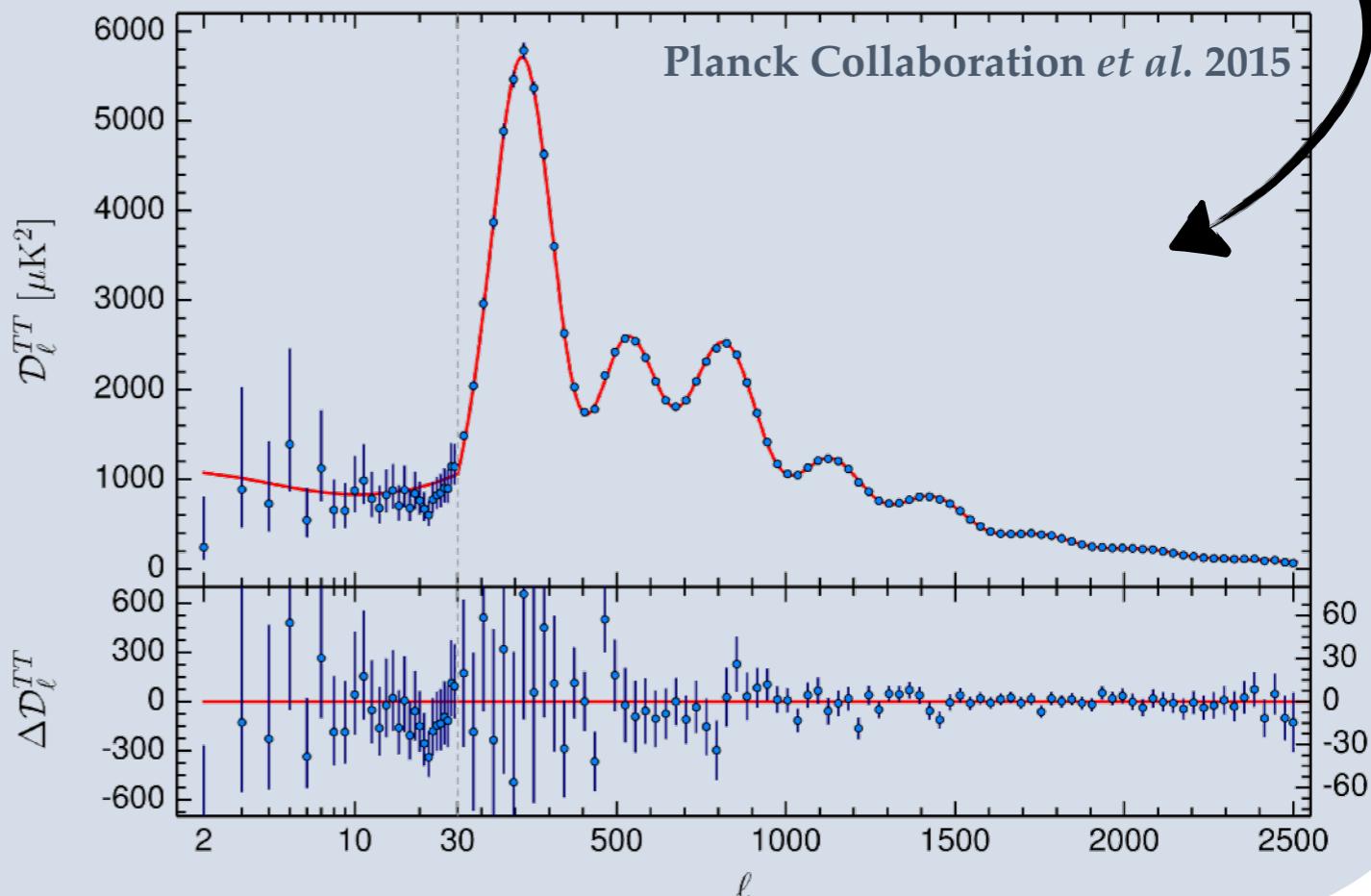
Spherical harmonic expansion



$$T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

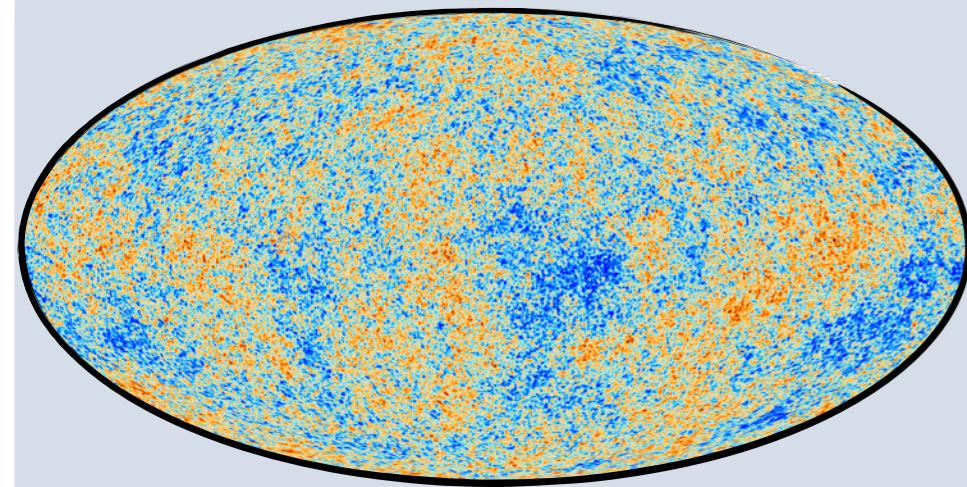
$$C_{\ell} = \frac{1}{2\ell + 1} \sum_{-\ell < m < \ell} |a_{\ell m}|^2$$

$$D_{\ell} = \frac{\ell(\ell + 1)}{2\pi} C_{\ell}$$

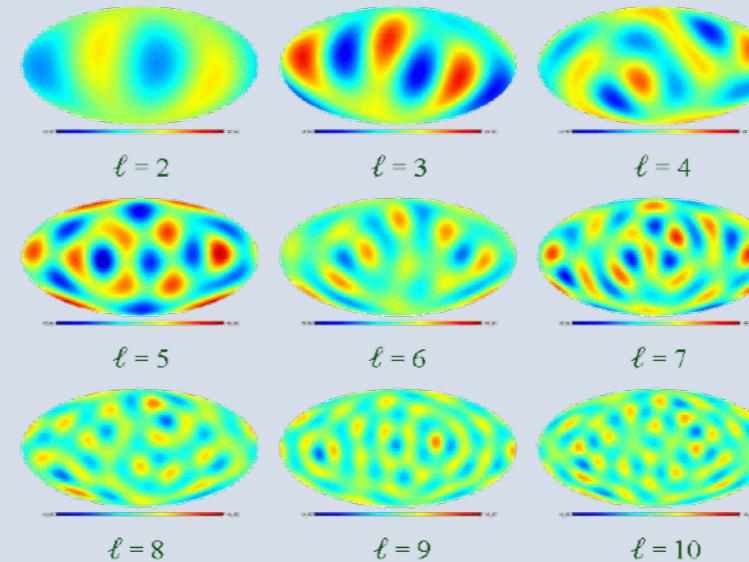


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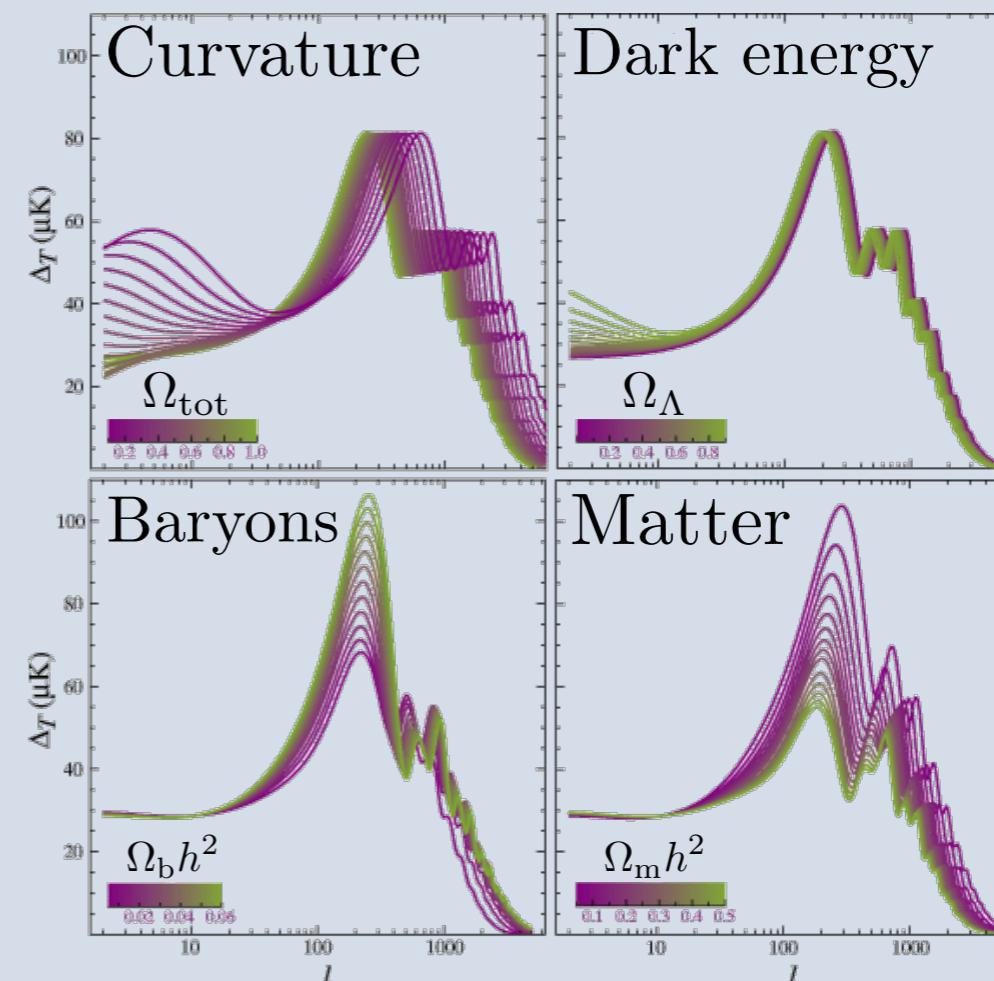
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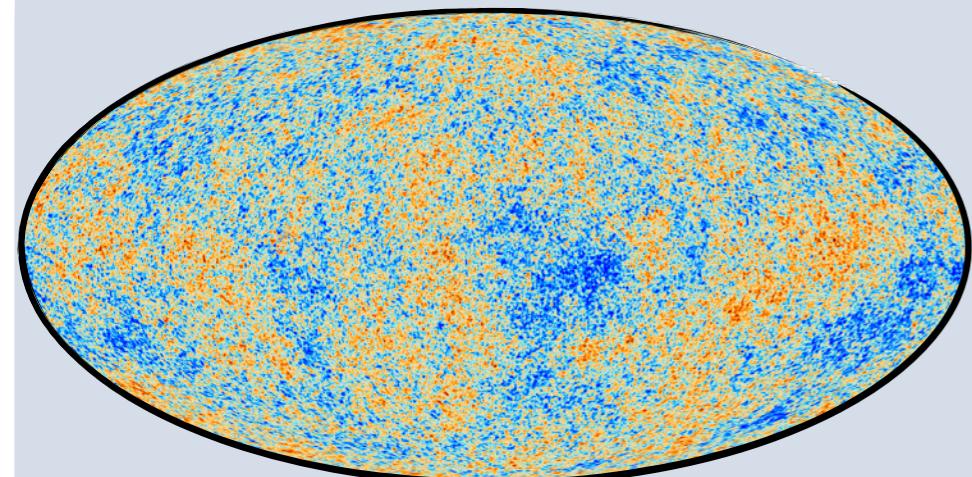
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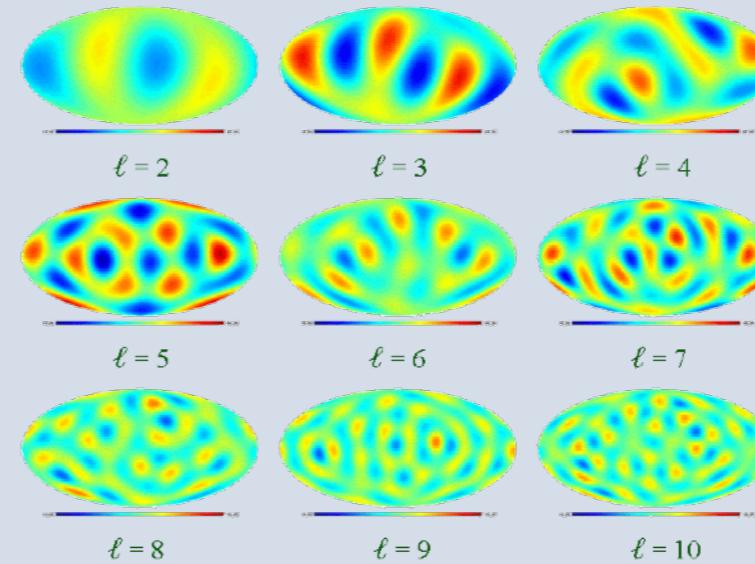


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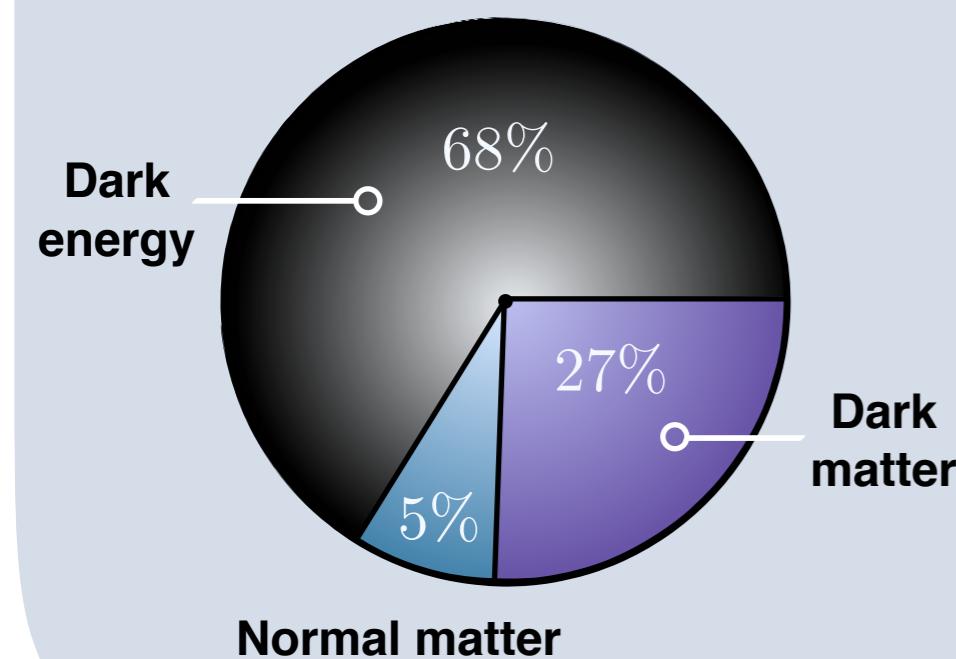
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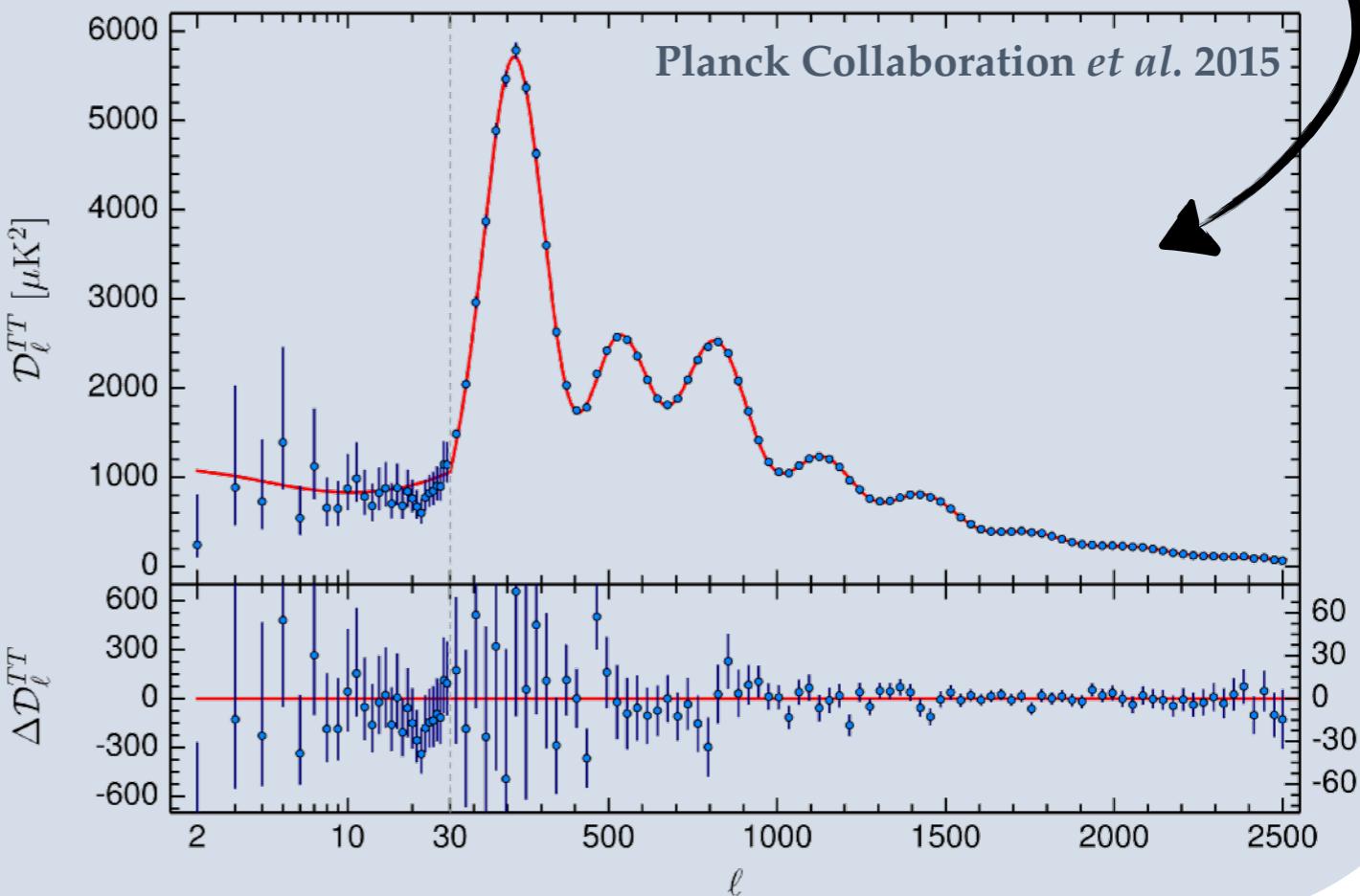
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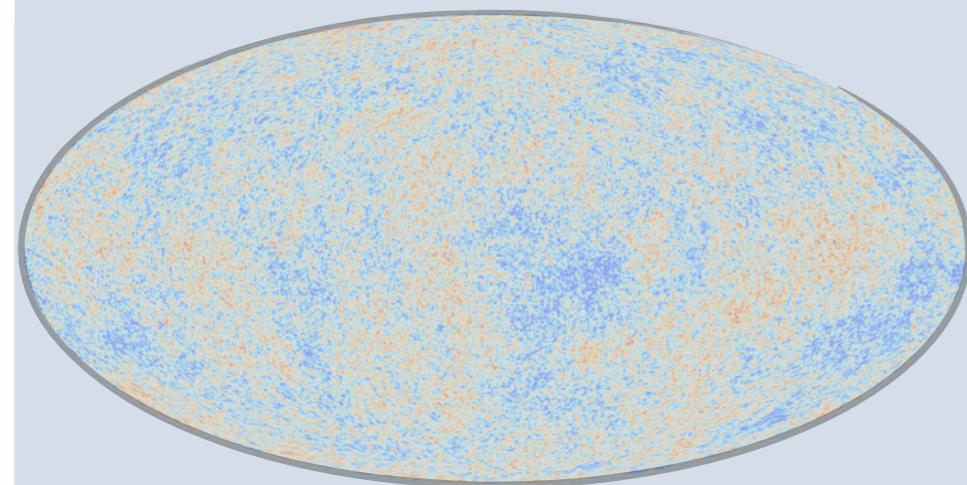


$$+ \Omega_{\text{tot}} = 1 \text{ (i.e. flat universe)}$$

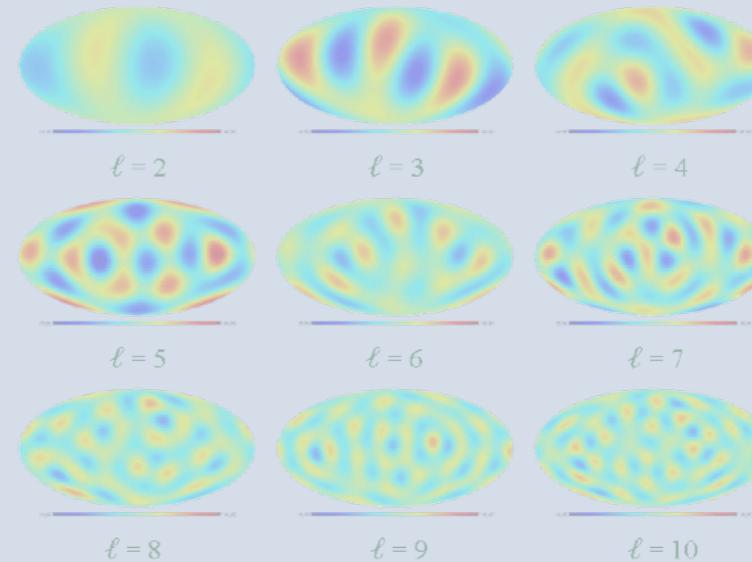


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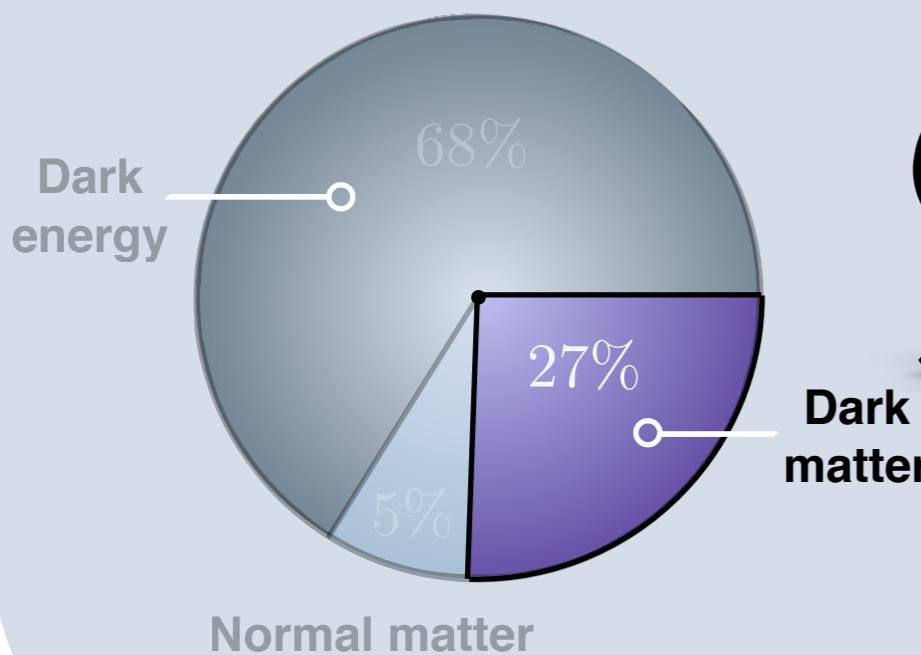
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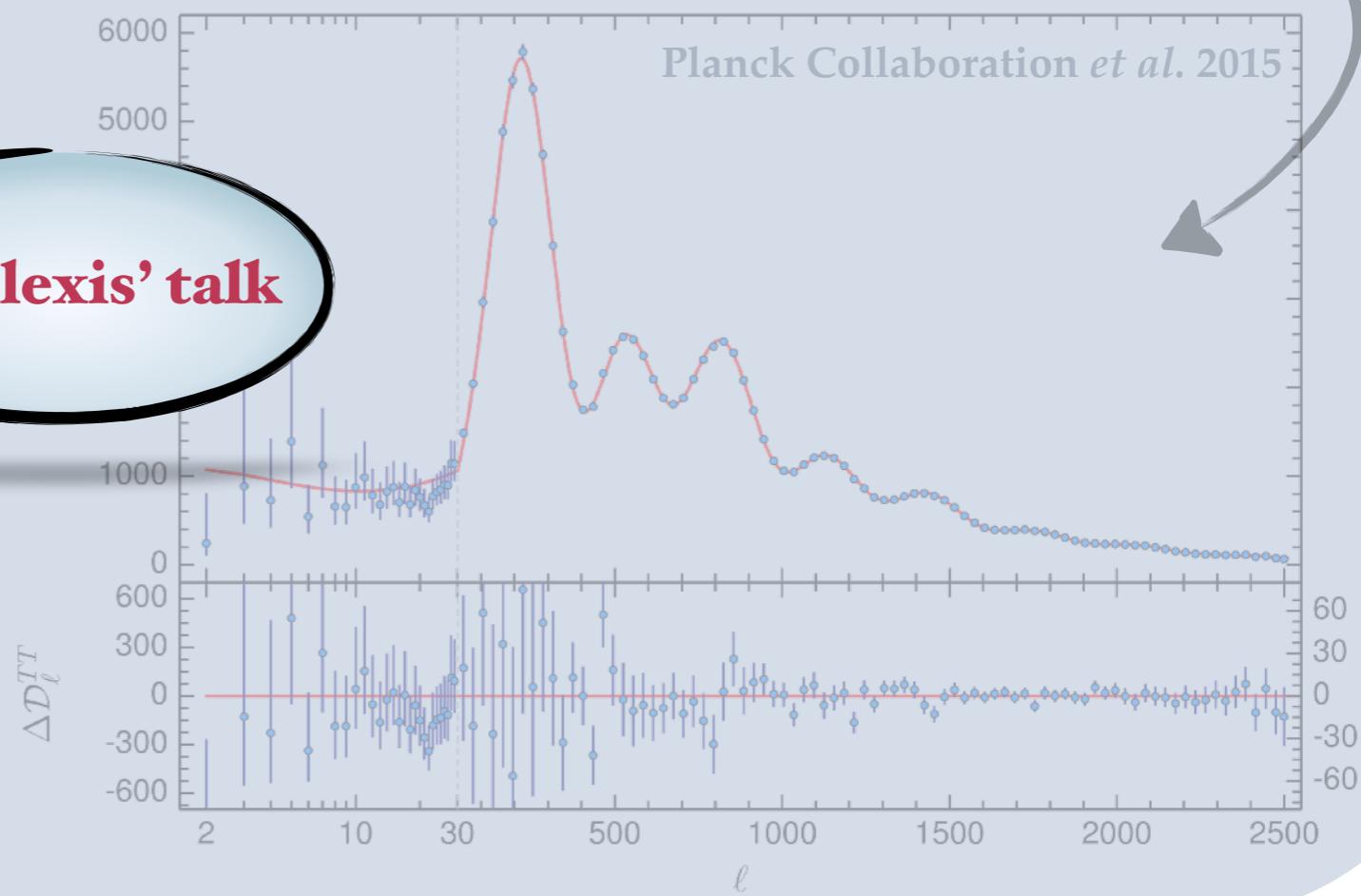
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$$+ \Omega_{\text{tot}} = 1 \text{ (i.e. flat universe)}$$

See Alexis' talk



Evolution of the Universe

$$H^2 = H_0^2 \left[\Omega_r a^{-4} + \Omega_m a^{-3} + (1 - \Omega_{\text{tot}}) a^{-2} + \Omega_\Lambda \right]$$

$$H \equiv \frac{\dot{a}}{a} \quad \Omega_i = \frac{\rho_i}{\rho_c} \quad \rho_c = \frac{3H_0^2}{8\pi G} \quad \Omega_{\text{tot}} = \sum_i \Omega_i$$

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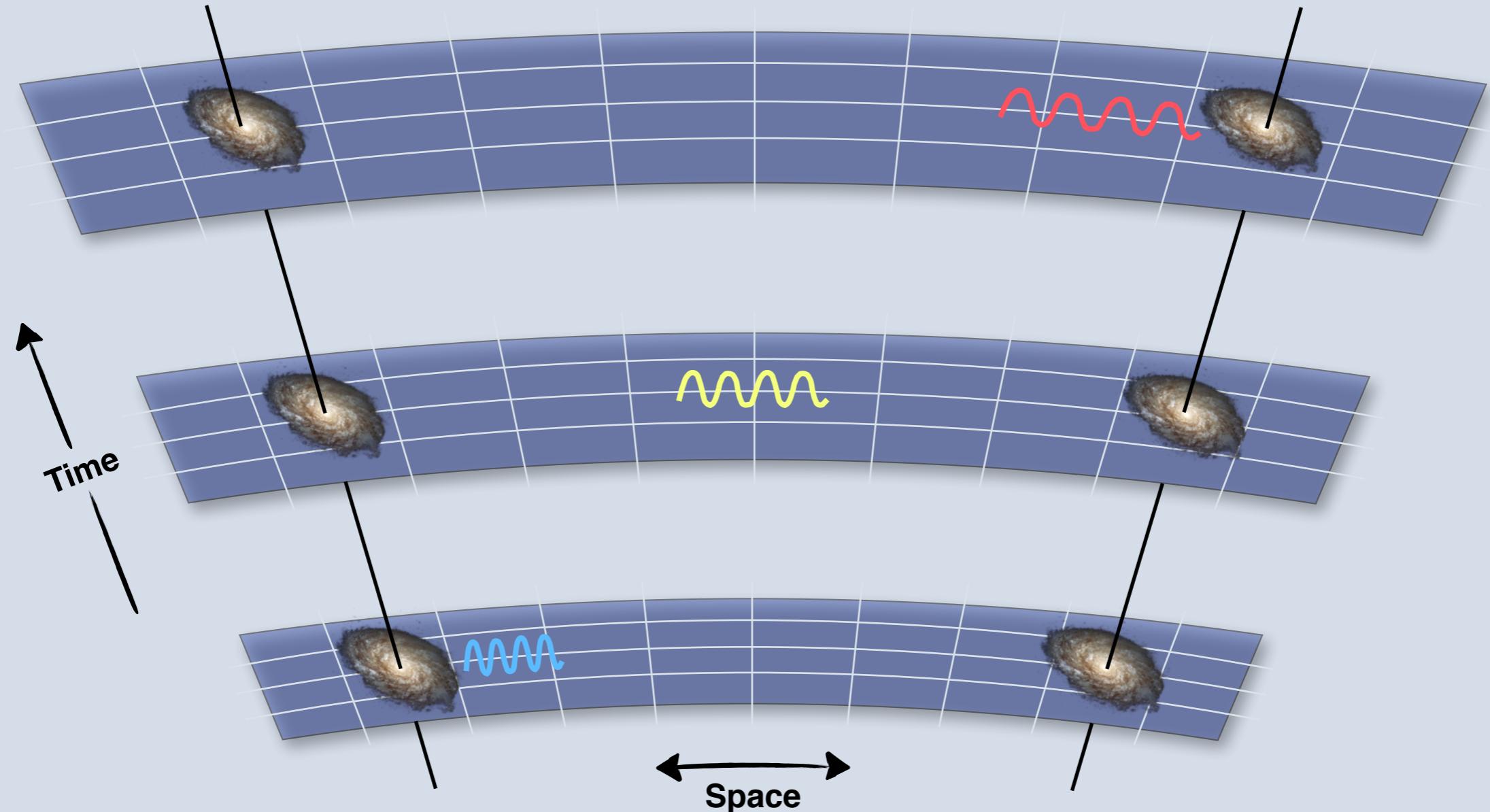
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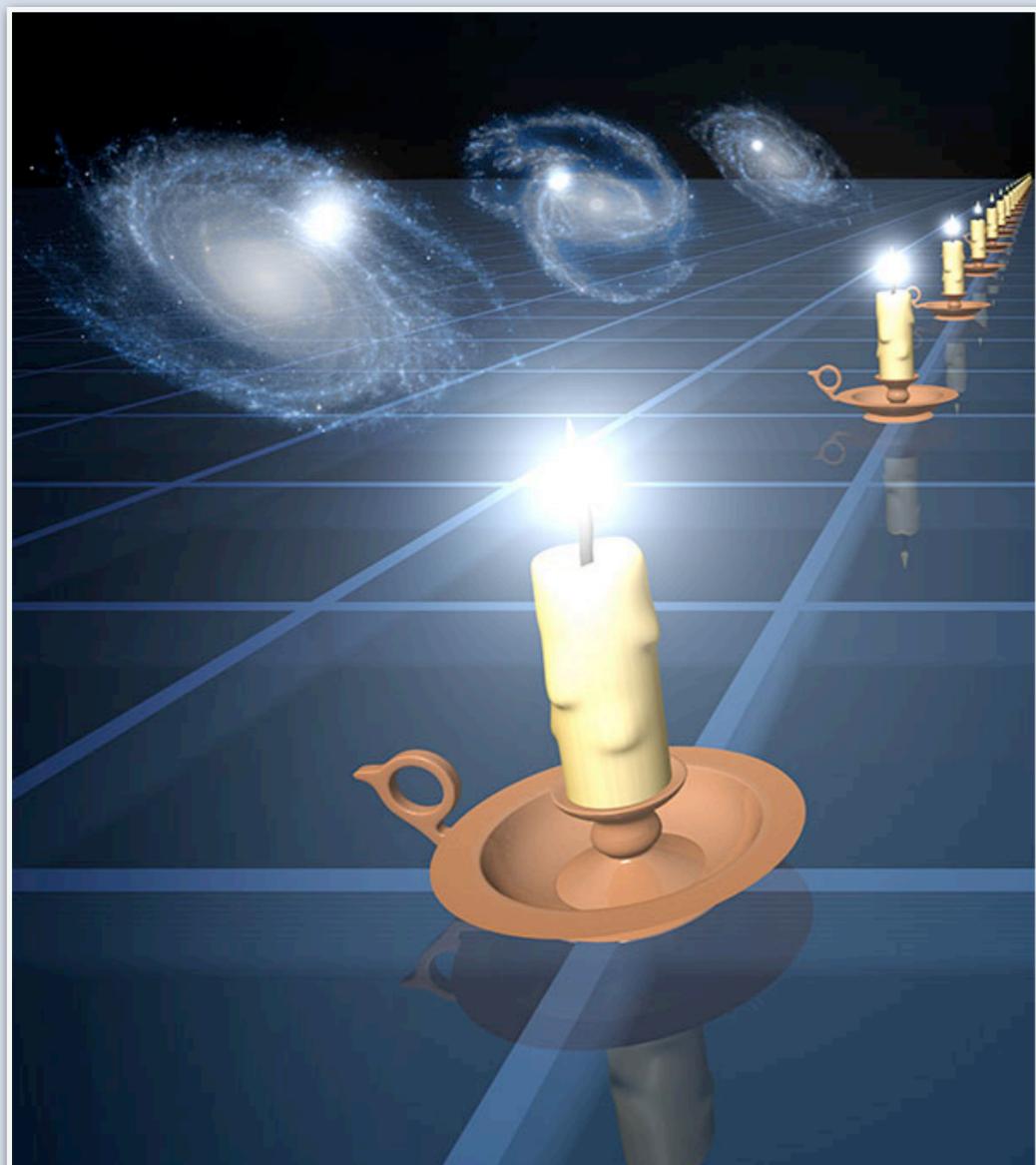
A multi-probe / multi-messenger era

The redshift as an expansion tracer



- Redshift definition: $1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} \quad (\text{what we measure})$
- Photon wavelength stretched by the expansion of the Universe: $a = (1 + z_{\text{cosmo}})^{-1}$
- Doppler shift due to peculiar motion: $1 + z_{\text{pec}} = \gamma \left(1 + \frac{v_{\text{pec},\parallel}}{c}\right)$

Type Ia supernovae: standard candles



See Mélissa's talk

Type Ia Supernova (SNIa)

- White dwarf: stellar core remnant
- Perturbation induced by unknown astrophysical process
- Initiation of carbon fusion in the core
- Runaway reaction → supernova explosion

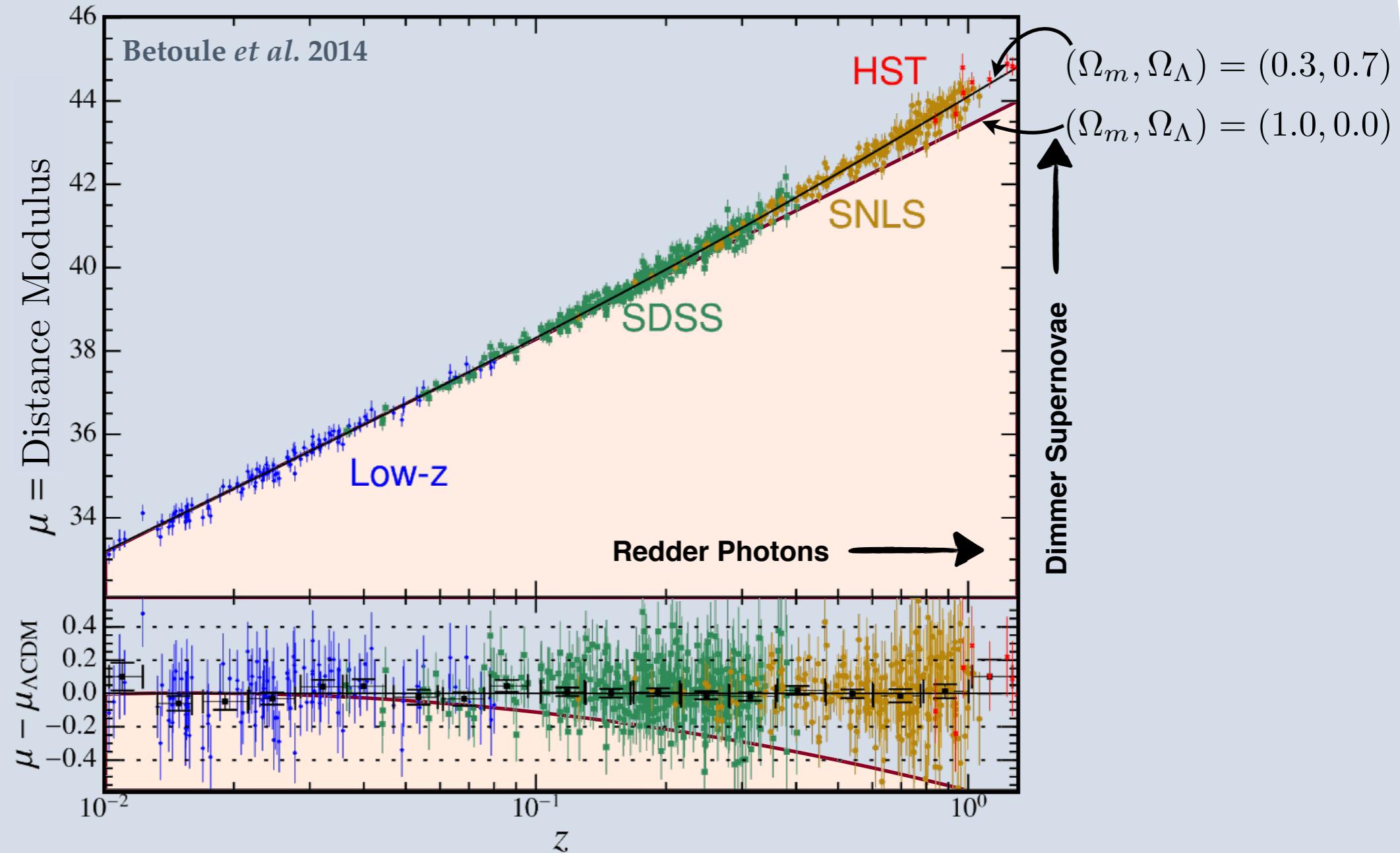
Peak luminosity L can be standardized

What we measure

- SNIa redshift: \mathcal{Z} (*Affected by peculiar motions*)
- SNIa flux: $F = \frac{L}{4\pi d_L^2}$ with $d_L \simeq \frac{cz}{H_0}$ for $z \ll 1$

Knowing L , F , and \mathcal{Z} we can estimate H_0 at low redshift

Constraining H_0 with SNIa



Hubble constant: overall amplitude of the relation (*complete degeneracy with SNIa luminosity*)

$$H_0 = (73.2 \pm 1.3) \text{ km s}^{-1} \text{ Mpc}^{-1} \quad \text{Riess et al. 2021}$$

Deviation at high redshift: acceleration of the expansion of the Universe (*dark energy*)

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Gravitational waves: origin

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. EINSTEIN.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist. Ich wurde hierauf aufmerksam durch eine briefliche Mitteilung des Astronomen DE SITTER, der fand, daß man durch eine andere Wahl des Bezugssystems zu einem einfacheren Ausdruck des Gravitationsfeldes eines ruhenden Massenpunktes gelangen kann, als ich ihm früher gegeben hatte¹. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

¹ Sitzungsber. XLVII, 1915, S. 833.

Approximate integration of the field equations of gravitation

A. Einstein, 1916

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

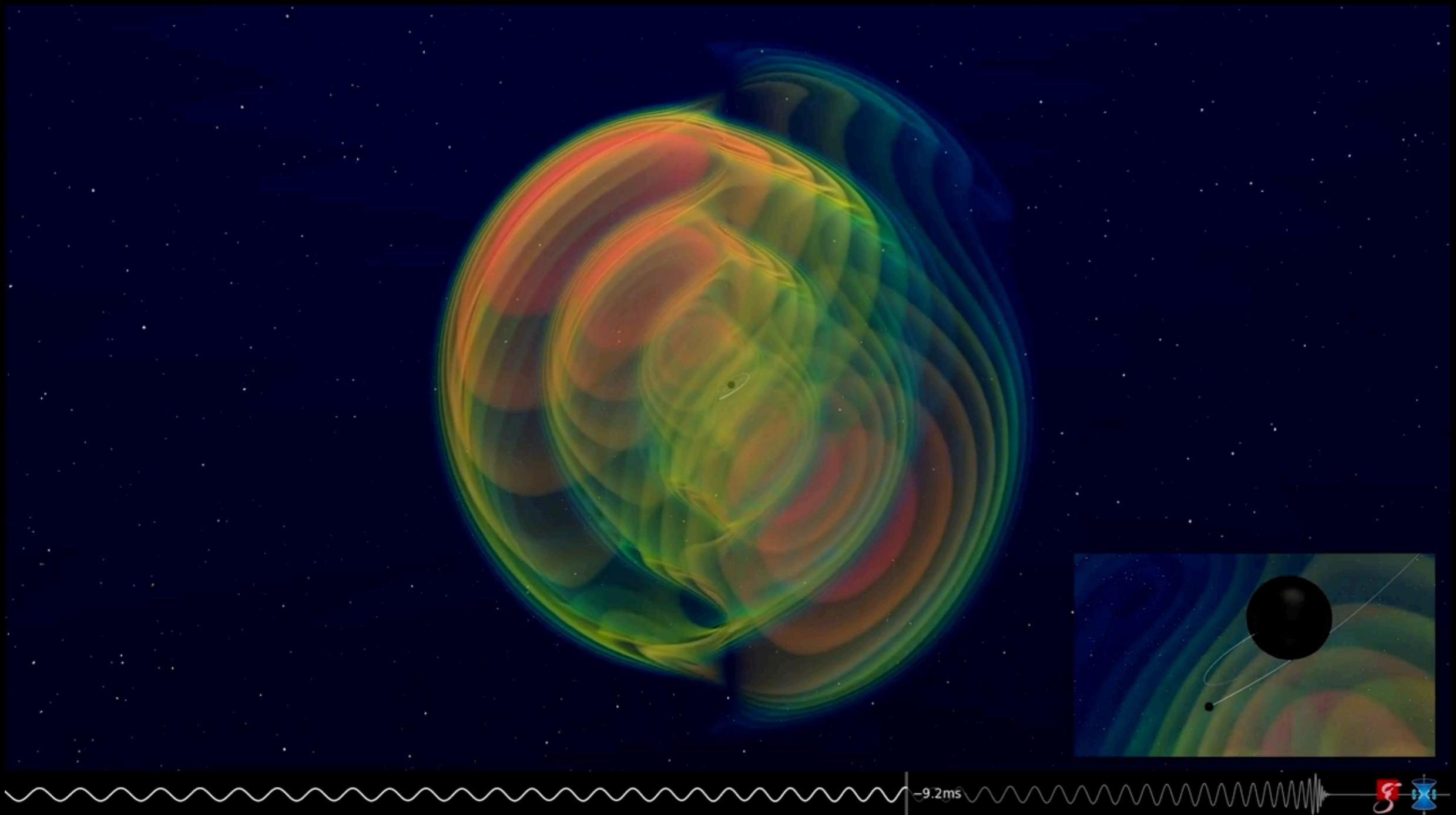
$$\downarrow$$
$$g_{\mu\nu} = \eta_{\mu\nu} + \epsilon h_{\mu\nu} \quad \text{with} \quad \epsilon \ll 1$$

$$\square h_{\mu\nu} = 0 \quad \text{In the vacuum (where } T_{\mu\nu} = 0)$$

System of decoupled wave equations!

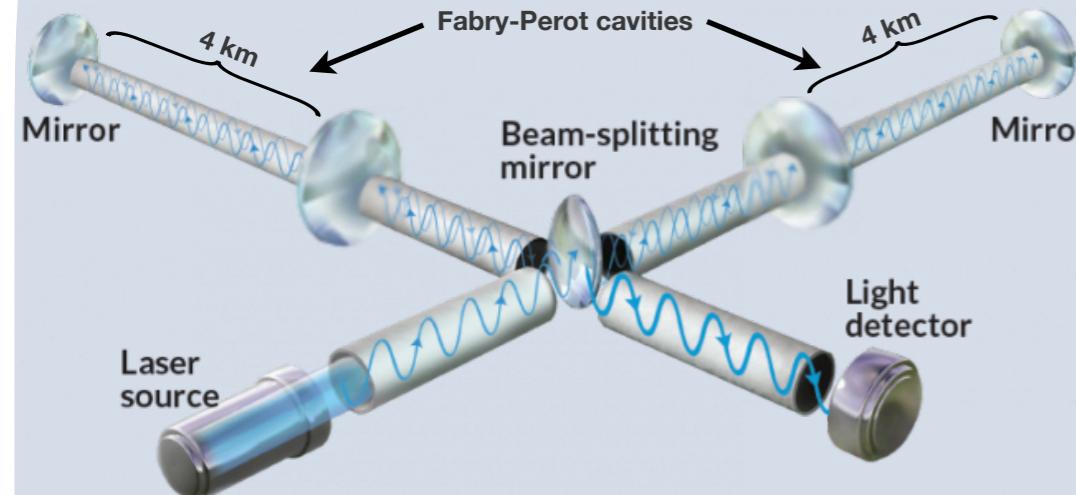
- Origin: acceleration of masses
- Propagation: speed of light
- Effect: modifies the proper distance between objects

Binary Black Hole Merger



© N. Fischer, H. Pfeiffer, A. Buonanno (Max-Planck-Institut für Gravitationsphysik)

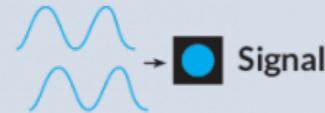
Detecting gravitational waves



Normal situation



Gravitational wave detection



© NICOLLE RAGER FULLER

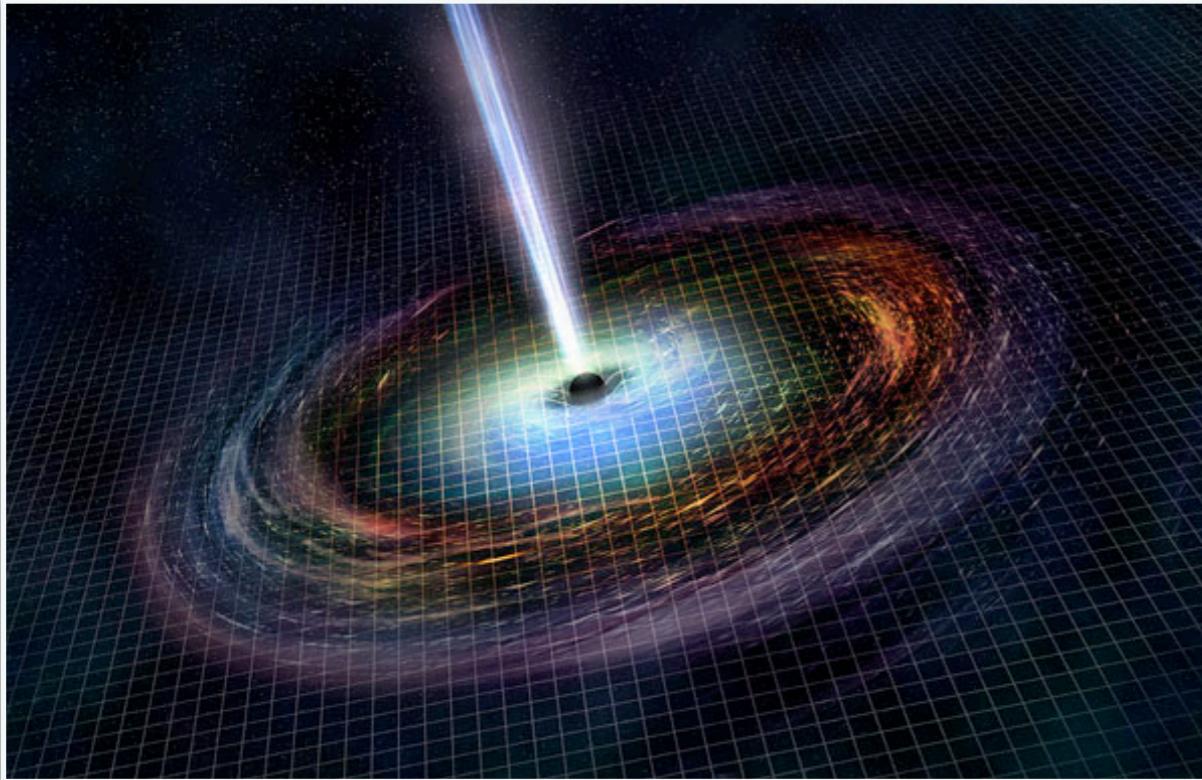


- Michelson interferometers with km-scale arms
- Fabry-Perot cavities:
 - increase distance by 300
 - build up the light
- Destructive interference if no GW (*no fringe*)
- If GW passes: space stretched in one arm and compressed in the other one

First detection in 2015: GW150914 binary black hole merger

Abbott *et al.* 2016

Gravitational waves: standard sirens



© NASA/CXC/M.Weiss — artist impression of jet emission after neutron star merger

What we measure from GW

- Amplitude: $h \propto \mathcal{M}^{5/3} f^{2/3} d_L^{-1}$
- Frequency variations: $\dot{f} \propto \mathcal{M}^{5/3} f^{11/3}$

with $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

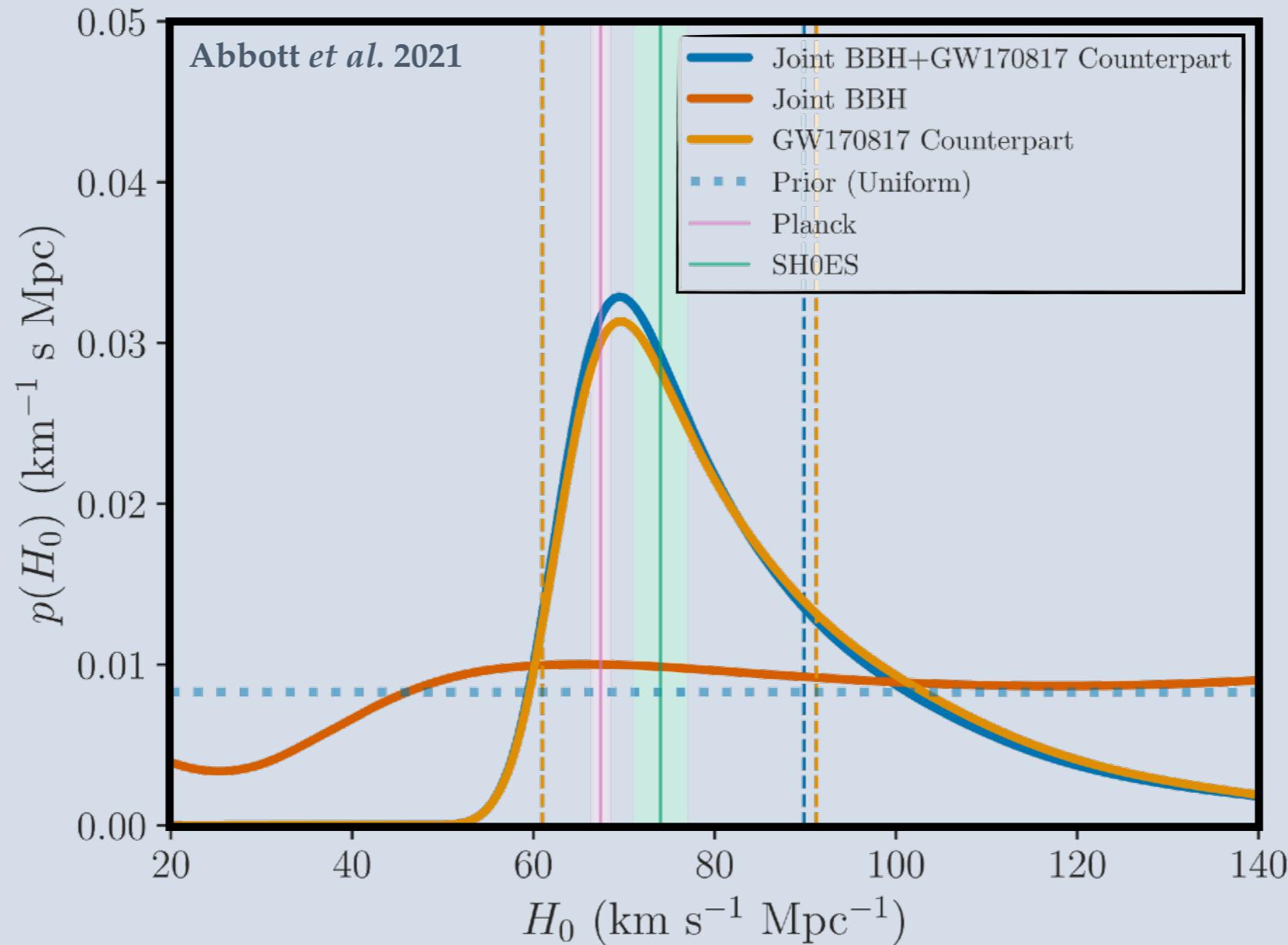
By measuring h , f , and \dot{f} we can estimate \mathcal{M} and d_L

Redshift estimate

- Electromagnetic counterpart to neutron star mergers (*short gamma-ray burst*) → Redshift of host galaxy
- Precise event triangulation → Use galaxy surveys

Knowing d_L and \mathcal{Z} we can estimate H_0

Constraining H_0 with gravitational waves



- First constraint of H_0 with one GW event + gamma-ray counterpart: $H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{Mpc}^{-1}$ **Abbott et al. 2017**
- Addition of 6 BBH events + galaxy survey: improves the constraint on H_0 by 4%
- Perspectives: relative uncertainty on H_0 of 1% with $\mathcal{O}(100)$ events

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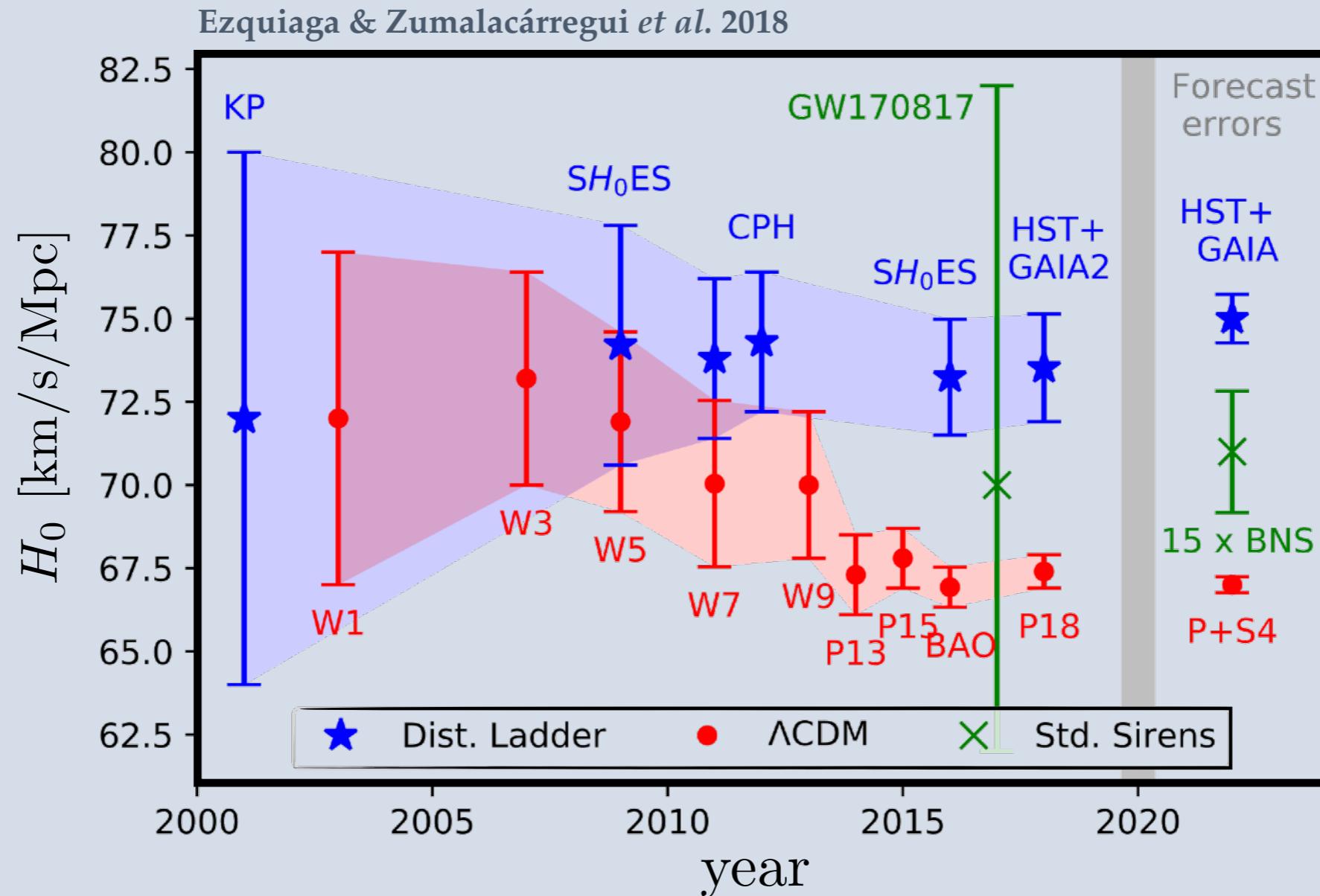
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Current tension between H_0 constraints



- Tension of 4.2σ between direct measurements and extrapolation from Λ CDM model (*CMB - BAO - Clusters*)
- Hint of new physics or systematic effects? → Need better understanding of astrophysical processes
- GW: new cosmological probe that will help solving the tension

Conclusions / Perspectives

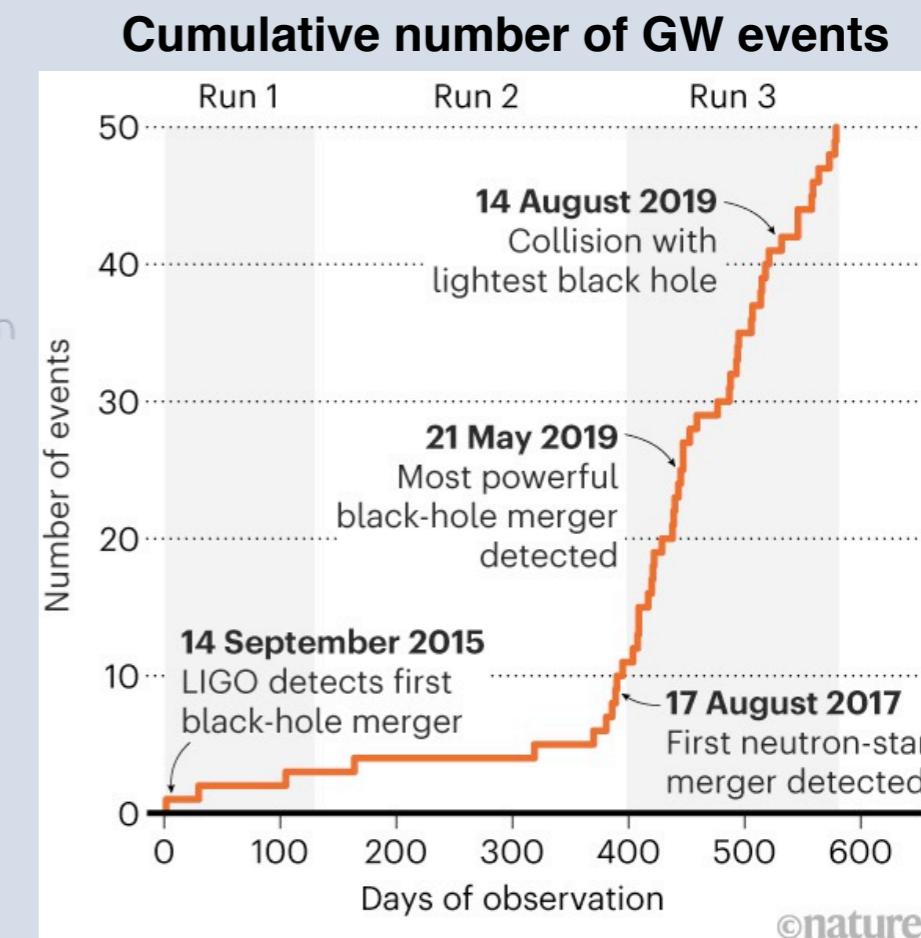
- Cosmology enters a multi-messenger era
- With more precision comes new discrepancies → Potential weaknesses of our standard models
- The future is bright on the statistical side...



$\mathcal{O}(10^9)$ Galaxies



$\mathcal{O}(10^5)$ Clusters



- ... but currently all hints of new physics can be explained by underestimated systematic effects

Understanding systematic effects from instrument / analysis / astrophysics is crucial



Thank you

