Open questions in Cosmology

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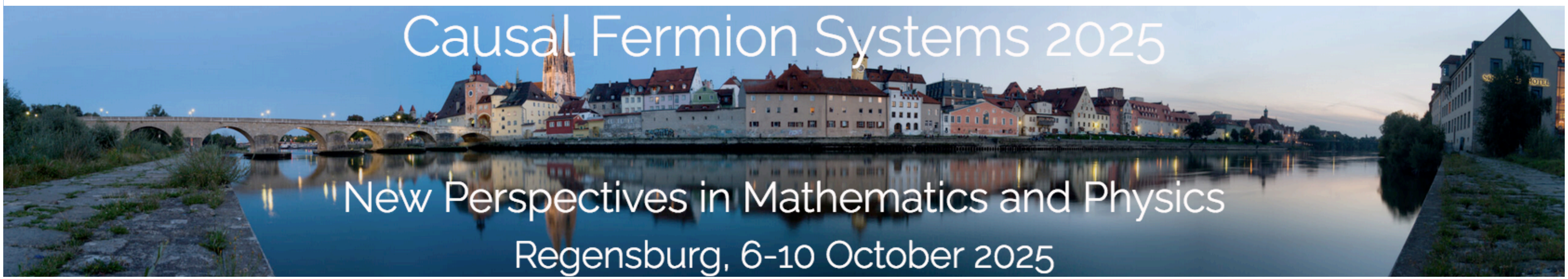
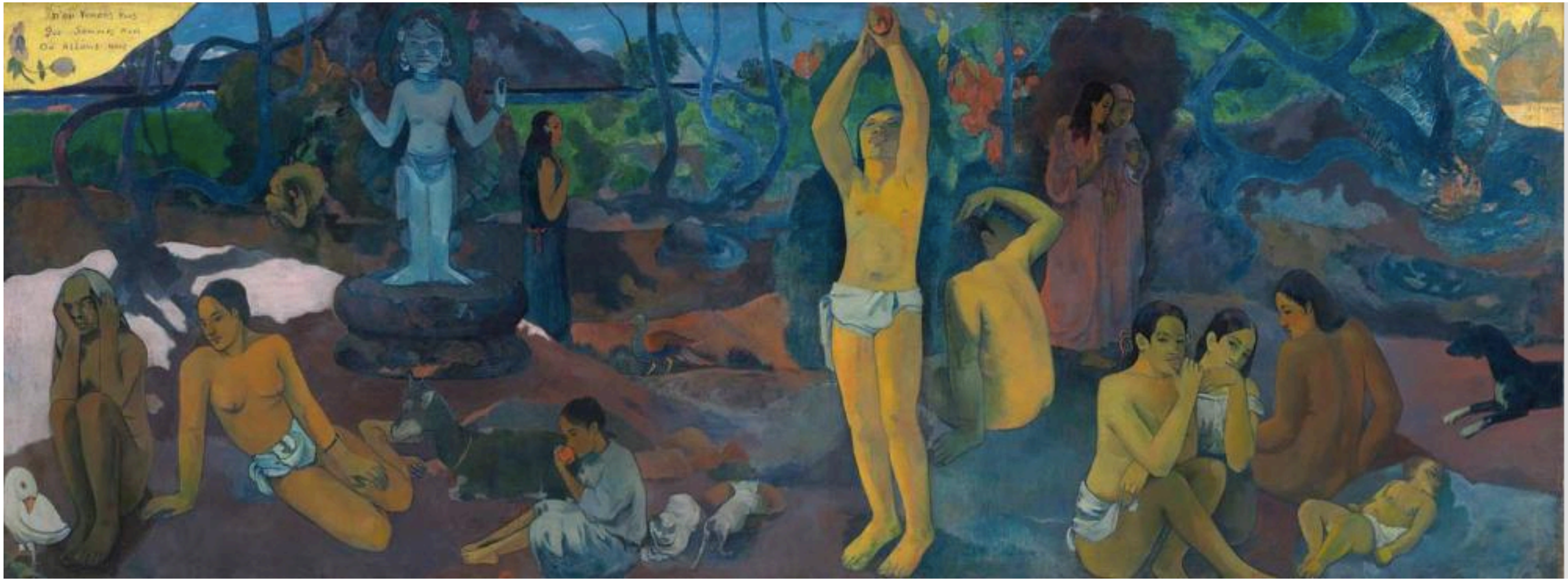
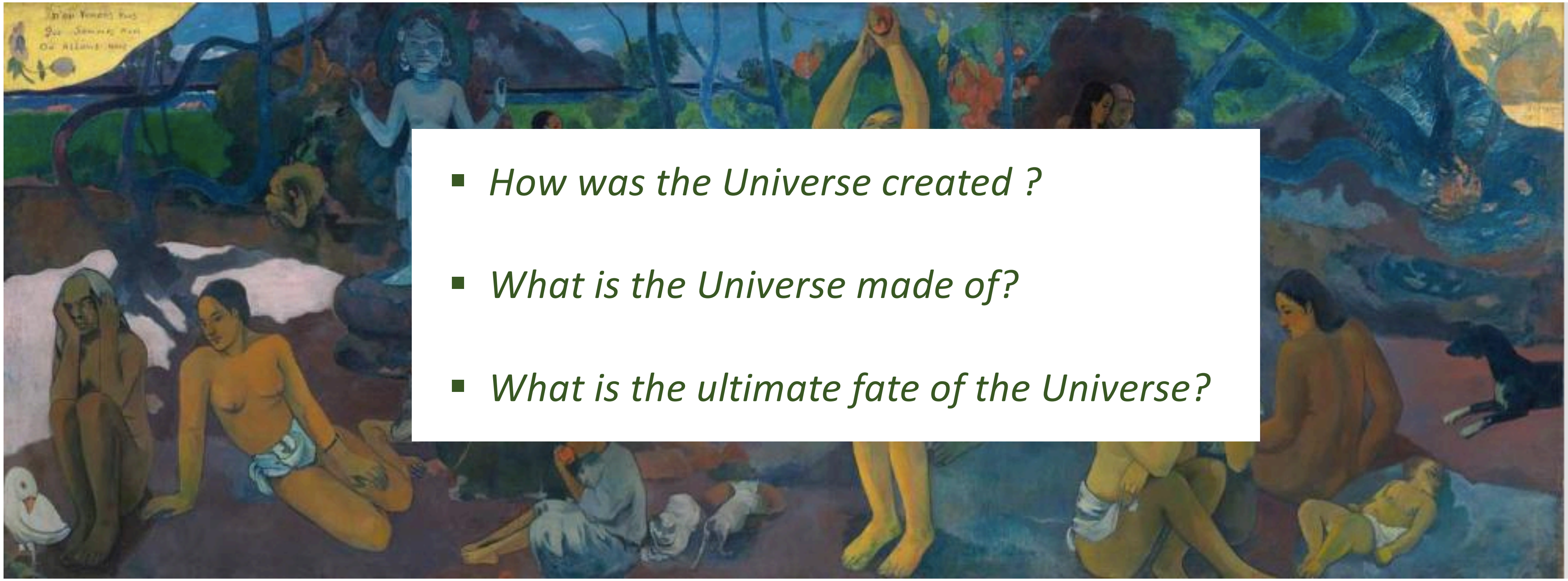
King's College London



D’où venons-nous ? / Que sommes-nous ? / Où allons-nous ?

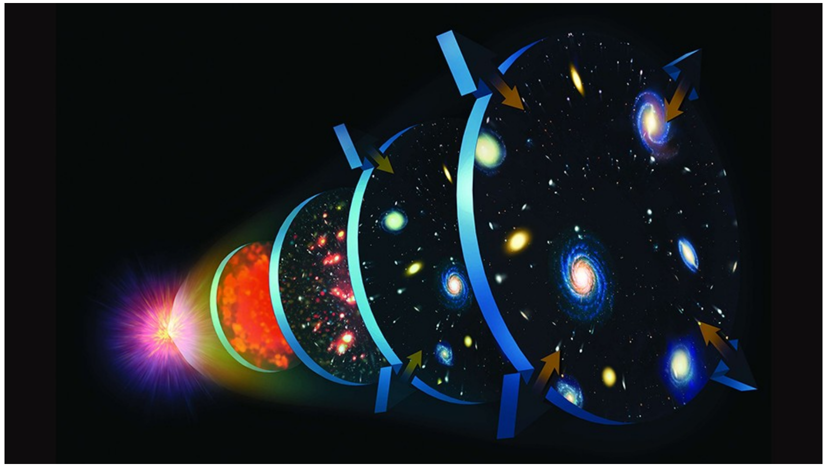




- *How was the Universe created ?*
- *What is the Universe made of?*
- *What is the ultimate fate of the Universe?*

Cosmological model

ΛCDM : phenomenological model based on GR, supplemented by CDM and dark energy, and complemented by an inflationary scenario



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General Relativity

Tests of General Relativity with GWTC-3

Phys.Rev.D (2022)

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- *The residual power, after subtracting the best fit waveform from the data, is consistent with the detector noise*

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- *All post-Newtonian deformation coefficients are consistent with the predictions from GR*

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Tests of General Relativity with GWTC-3 *Phys.Rev.D (2022)*

- *The residual power, after subtracting the best fit waveform from the data, is consistent with the detector noise*

- *All post-Newtonian deformation coefficients are consistent with the predictions from GR*

- *The spin-induced quadrupole moments Q of the BBH constituents are consistent with those of Kerr BHs in GR*

No-hair conjecture: Q take unique values for BHs given their mass and spin

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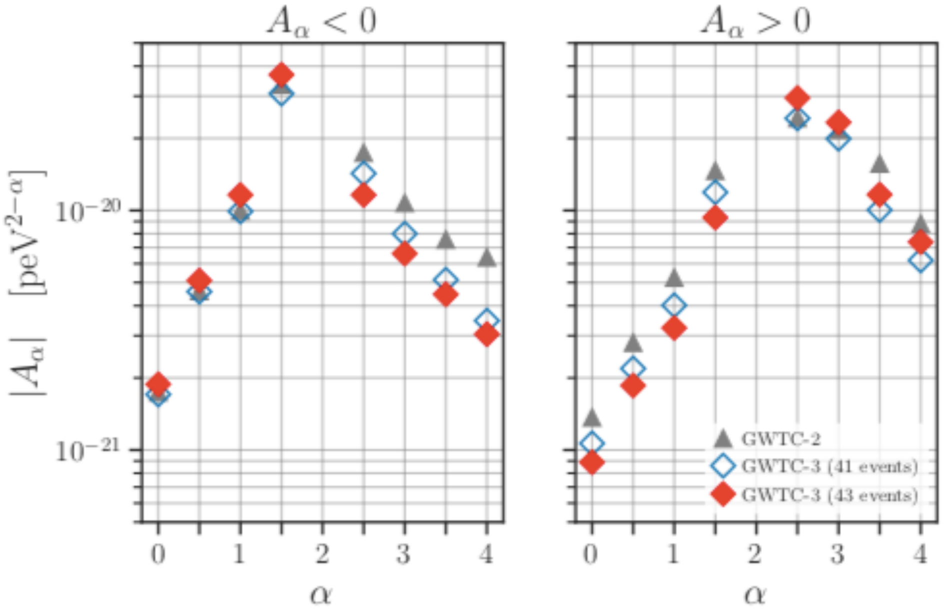

- *The residual power, after subtracting the best fit waveforr*
- *All post-Newtonian deformation coefficients are consisten*
- *The spin-induced quadrupole moments Q of the BBH consi*
- *No evidence for dispersion of GWs*

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

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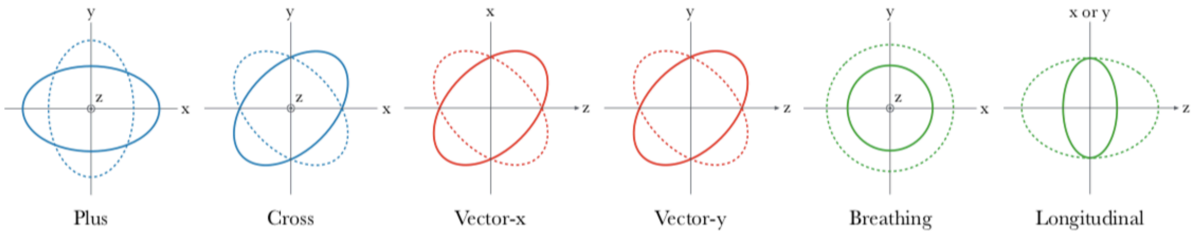
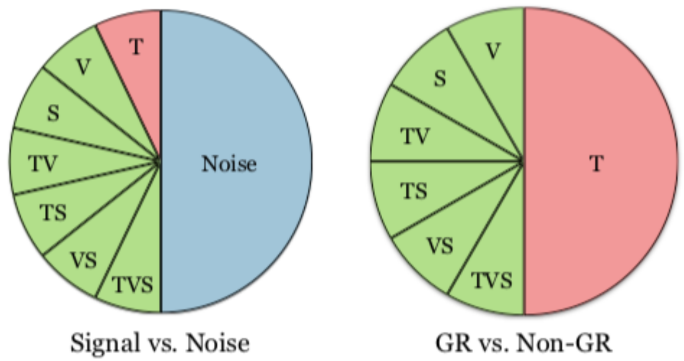
- *All post-Newtonian deformation coefficients are consistent with the predictions from GR*

- *The spin-induced quadrupole moments of the BBH constituents are*

- *No evidence for dispersion of GWs, non-GR modes of polarization*





*Callister, **Sakellariadou**, et al, PRX (2017)*

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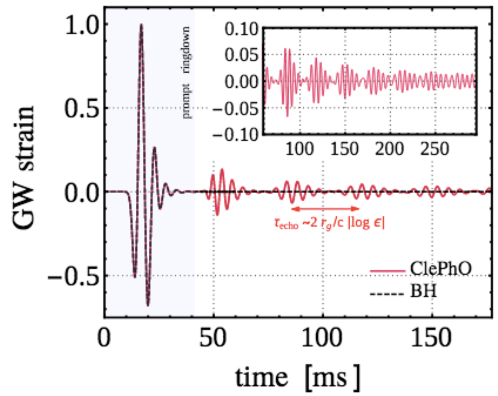

- *The residual power, after subtracting the best fit waveform from the data, is c* *oise*
- *All post-Newtonian deformation coefficients are consistent with the predictio*
- *The spin-induced quadrupole moments of the BBH constituents are consistent*
- *No evidence for dispersion of GWs, non-GR modes of polarization, or post-merger echoes*

Cardoso, Pani (2017)

Exotic Compact Objects: more massive than NS but without horizons
(ingoing GWs reflect multiple times off effective radial potential barriers, with wave packets leaking out to infinity at regular times**)**

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- *Bound on the mass of the graviton, at 90% credibility:* $m_{\mathrm{g}} \leq 1.27 \times 10^{-23} \mathrm{eV}/\mathrm{c}^2$

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- *Properties of the remnant BHs, including deviations of the quasi-normal mode frequencies and damping times, show consistency with the predictions of GR*

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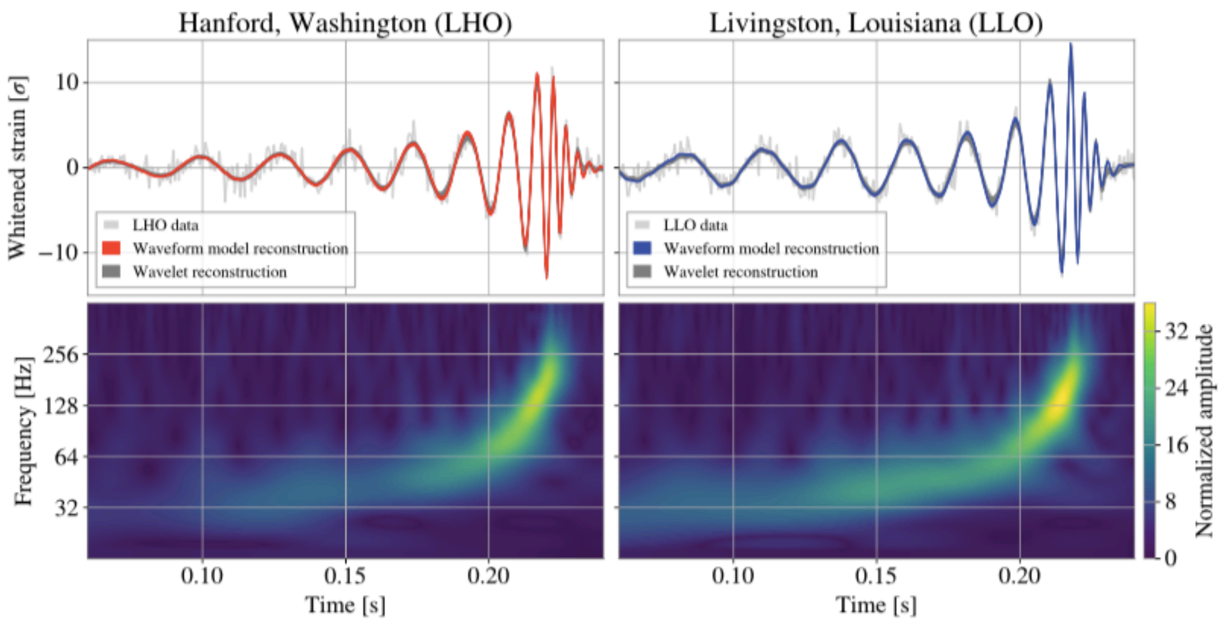
General Relativity

GW250114

GW250114 enables precise tests of both the Kerr nature of BHs and Hawking's area law:

- Post-merger data contain two distinct ringing modes of the remnant, which are consistent with the fundamental and first overtone of the quadrupolar spectrum of Kerr BH
- The remnant's event horizon area exceeds the total initial area at high credibility, in agreement with Hawking's law



Phys.Rev.Lett. 135 (2025) 11, 111403

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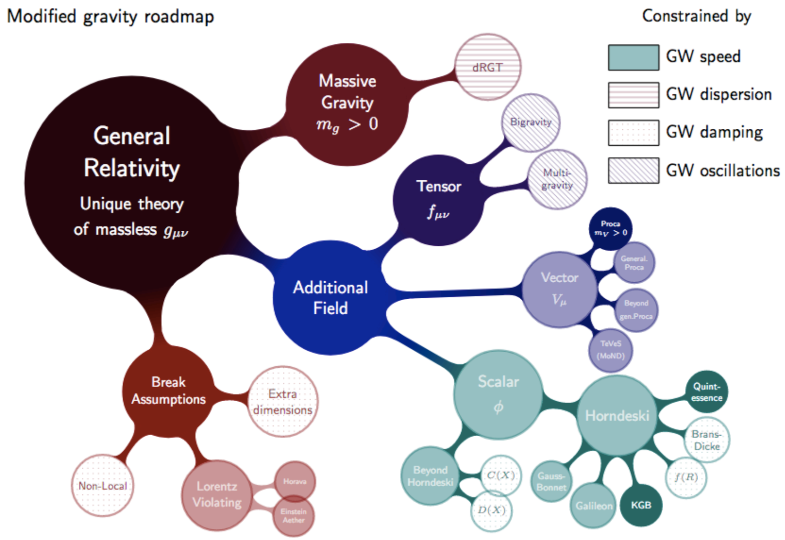
General Relativity

Is GR valid at all scales?



Credit: Ezquiaga, Zumalacarregu (2018)

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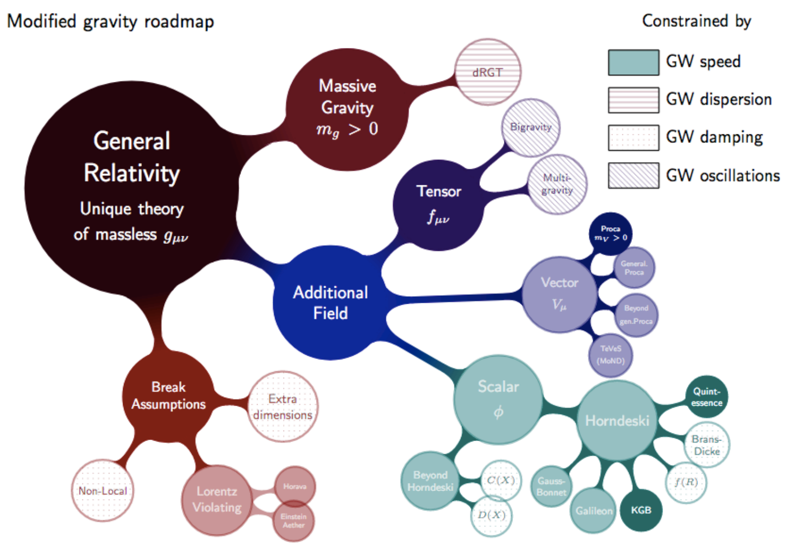
General Relativity

Is GR valid at all scales?

Approach:
Link cosmological large-scale structure, CMB, and GWs with classic PPN tests of gravity

Extremely large surveys (Euclid, SKA) will allow us to access perturbation modes close to the Hubble scale, hence test GR on ultra-large scales

Baker, Psaltis, Skordis (2015)



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General Relativity

Penrose singularity theorem (1965)

If the space-time contains a non-compact Cauchy hypersurface Σ and a closed future-trapped surface, and if the convergence condition $R_{\rho\nu}u^\rho u^\nu \geq 0$ holds for null u^μ, then there are future incomplete null geodesics

The existence of classical singularities signals the limits of the classical theory at extreme conditions, which is precisely when gravitational quantum effects will become relevant

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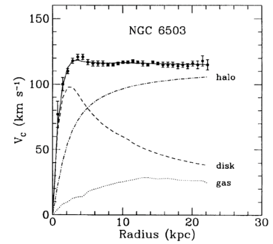
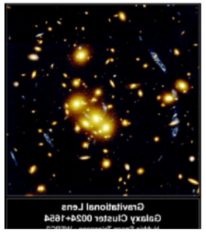
Dark matter: observations



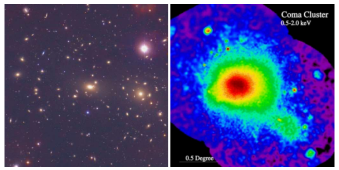
- **rotation curves** (out to tens of kpc)

Ford & Rubin (1970)

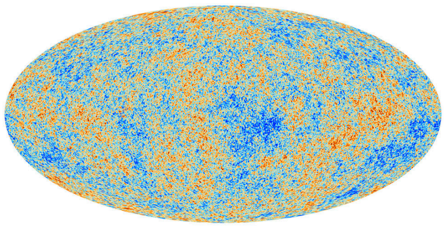
- **gravitational lens**ing (out to 200 kpc)



- **hot gas in clusters**



- **cosmic microwave background radiation**



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Dark matter: proposals

- failure of MOND/TeVeS

Milgrom (1983)
Bekenstein (2004)

*Ferreras, **Sakellariadou**, Yusaf, PRL (2012)*
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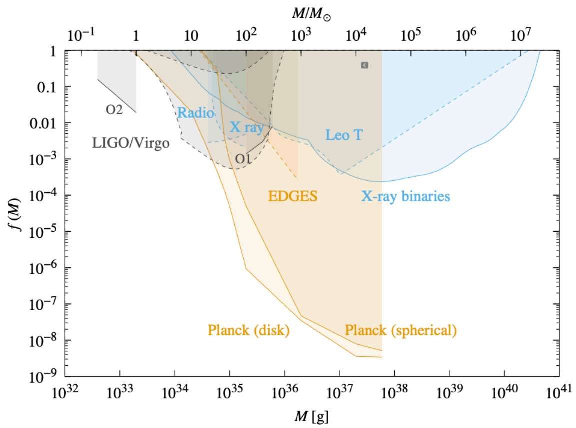
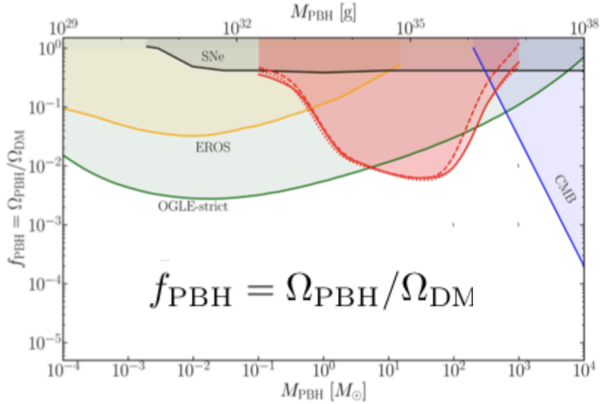


Carr, Kohri, Sendouda & Yokoyama (2016)



Boybeyi, Clesse, Kuroyanagi, **Sakellariadou**, PRD (2025)

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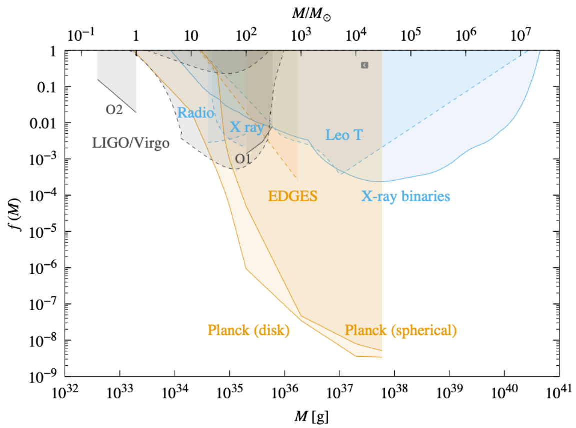
- **primordial black holes,** axion-like particles, wimpzillas, gravitinos, neutralino, sterile neutrino



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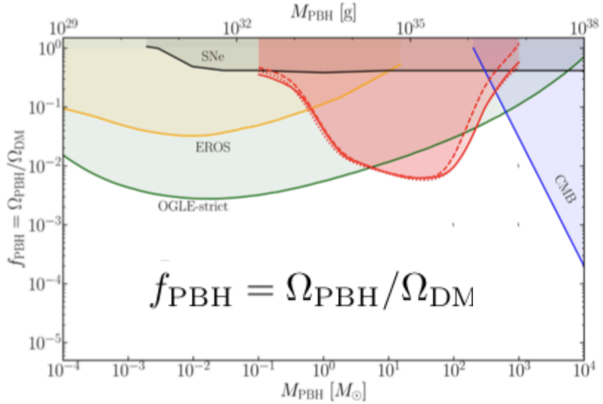

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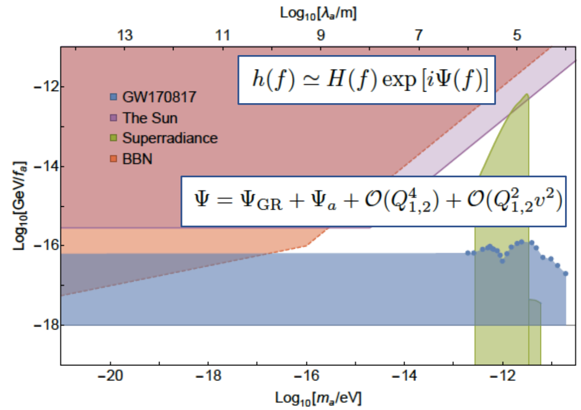

*Huang, Johnson, Sagunski, **Sakellariadou**, Zhang,* PRD (2019)

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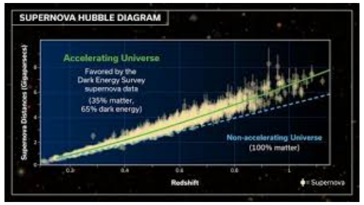
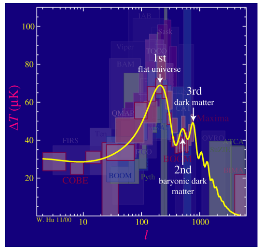
Dark energy: observations

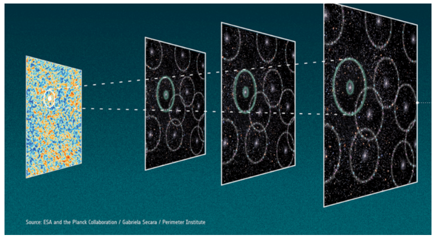
-- type Ia supernovae



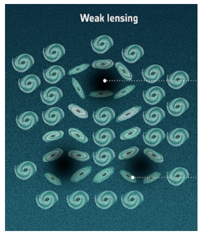
-- cosmic microwave background anisotropies



-- baryon acoustic oscillations



-- weak gravitational lensing



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Dark energy: proposals

- **cosmological constant**

$$S = -\frac{1}{16\pi G}\int d^4x\sqrt{-g}(R + 2\Lambda) + S_M,$$

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Dark energy: proposals

- **cosmological constant**
- **modified matter models**:
  - quintessence (*time varying scalar field, slowly rolling down toward its potential minimum*)

$$S = \int d^4x \sqrt{-g}\left[-\frac{1}{16\pi G}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_M.$$

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  - k-essence (*non-linear KE of scalar field drives negative pressure without help of potential terms*)

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{16\pi G} R + p(\phi, X) \right] + S_M \qquad X \equiv \frac{1}{2}(\nabla\phi)^2$$

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  - coupled dark energy and matter (example: chameleon mechanism)

$$\dot{\rho}_m + 3H(\rho_m) = \delta,$$
$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = -\delta,$$

DM

DE

energy exchange in dark sector

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- **modified gravity models** (*f(R) gravity, models with extra dim*)

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,f(R) + \int d^4x\sqrt{-g}\,\mathcal{L}_M,$$

$$S = -\frac{M_{(5)}^3}{2}\int d^5X\sqrt{-\tilde{g}}\,\tilde{R} - \frac{M_{pl}^2}{2}\int d^4x\sqrt{-g}\,R + \int d^4x\sqrt{-g}\,\mathcal{L}_m,$$

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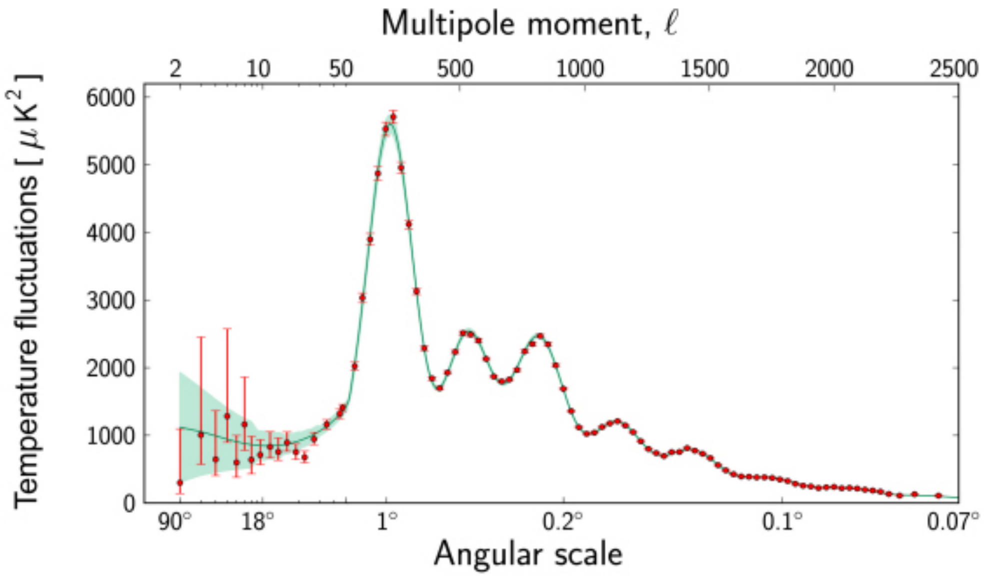
Inflationary scenario

$$\boxed{\frac{d}{dt}\left(\frac{H^{-1}}{a}\right) < 0 \quad \Rightarrow \quad \frac{d^2a}{dt^2} > 0 \quad \Rightarrow \quad \rho + 3p < 0}\,.$$



- **Adiabaticity in the CMB**

no fluctuation in relative number density of species, hence no entropy perturbations

The observation of the first CMB peak at ℓ=220± 0.8 has confirmed domination of adiabatic IC
They can arise from 1-field inflationary scenarios, which have only one degree of freedom, and therefore cannot produce entropy fluctuations

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Inflationary scenario

- **onset of inflation (initial conditions for its realisation)**

Goldwirth, Piran (1989, 1990)
*Calzetta, **Sakellariadou**, PRD (1992, 1993)*
*Gernani, Nelson, **Sakellariadou,** PRD (2007)*

- **origin of the inflaton as a matter field**

Higgs inflation: $$S_{\rm HI} = \int {\rm d}^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R + \frac{1}{2}\xi h^2 R - \frac{\lambda}{4}h^4\right) \qquad \xi^2/\lambda \approx 10^{10}$$

It requires a large non-minimal coupling to gravity

Bezrukov, Magnin, Shaposnikov, Sibiryakov (2010)

- **trans-planckian problem**

Martin, Brandenberger (2010)

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Inflationary scenario

Alternatives:

- **string gas cosmology** (*based on coupling a gas of closed string matter to a background space-time geometry*)

  Brandenberger, Vafa (1989)

- **matter bounce** (*quantum vacuum fluctuations which exit Hubble radius in a contracting matter-dominated universe*)

  Wands (1999); Finelli and Brandenberger (2002)

- **ekpyrotic scenario - cyclic universe** (*collision - once or repeated periodically- of two branes bounding an extra dim*)

  Steinhardt, Khoury, Turok, Ovrut (2001)

- How was created the Universe?

  - How did the Universe come into being?
  - What was there before the Big Bang?
  - Is the singularity real or our theory is incomplete?

Quantum Gravity is needed

The wave function of the Universe $\psi[h_{ij}(x), \phi(x)]$ satisfies WdW equation $\mathcal{H}\psi[h_{ij}, \phi] = 0\,.$

space of all 3-metrics

field configurations

2nd order differential operator in ST

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BC:

  - Hartle-Hawking no boundary proposal
  - Vilenkin's tunneling out of nothing proposal

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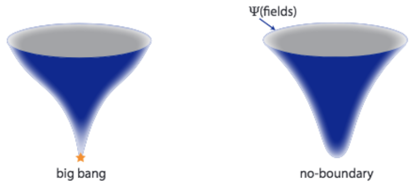
space of all 3-metrics *field configurations* *2^{nd} order differential operator in ST*

$$\psi = \int^{(h,\phi)} [dg][d\phi] \exp[-S_E(g,\phi)]$$

given by a Euclidean path integral over compact 4-geometries $g_{\mu\nu}$ (x, τ) bounded by the 3-geometry h_{ij} (x) with the field configuration φ(x)



space and time should have no boundary to our past

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is needed

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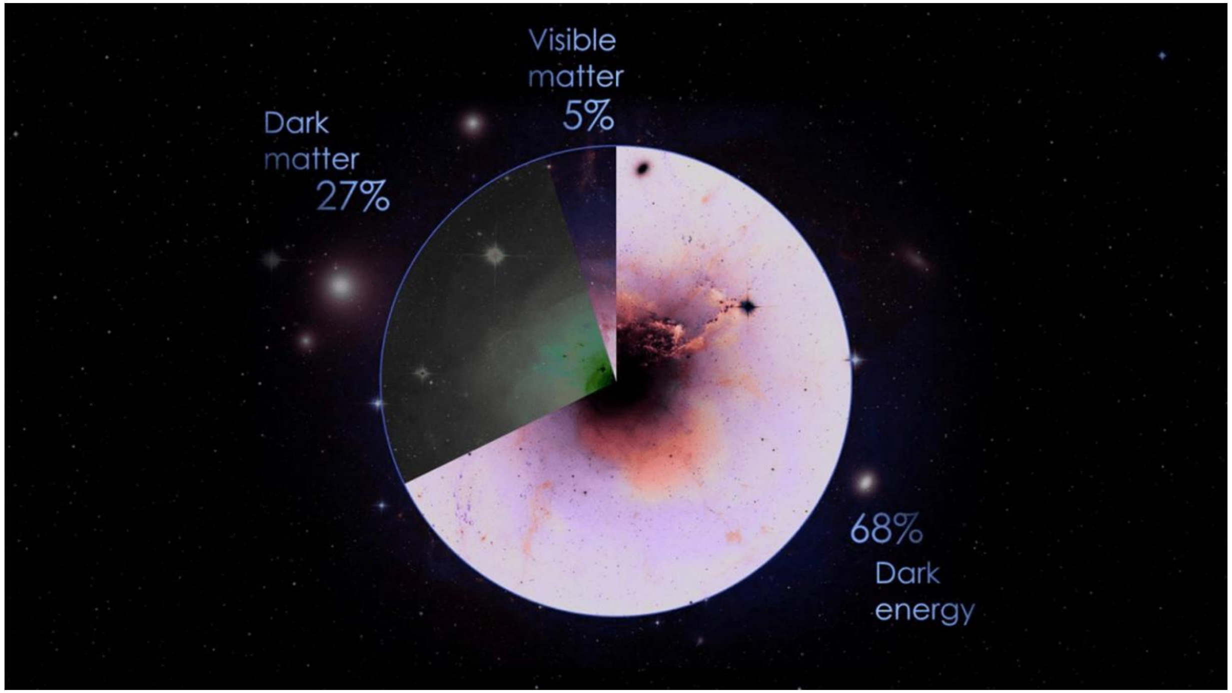
space of all 3-metrics *field configurations* *2nd order differential operator in ST*

$$\psi(h, \phi) = \int_{\emptyset}^{(h,\phi)} [dg][d\phi]e^{iS}$$

obtained by integrating over Lorentzian histories interpolating between a vanishing 3-geometry Ø and (h, φ) and lying to the past of (h, φ)

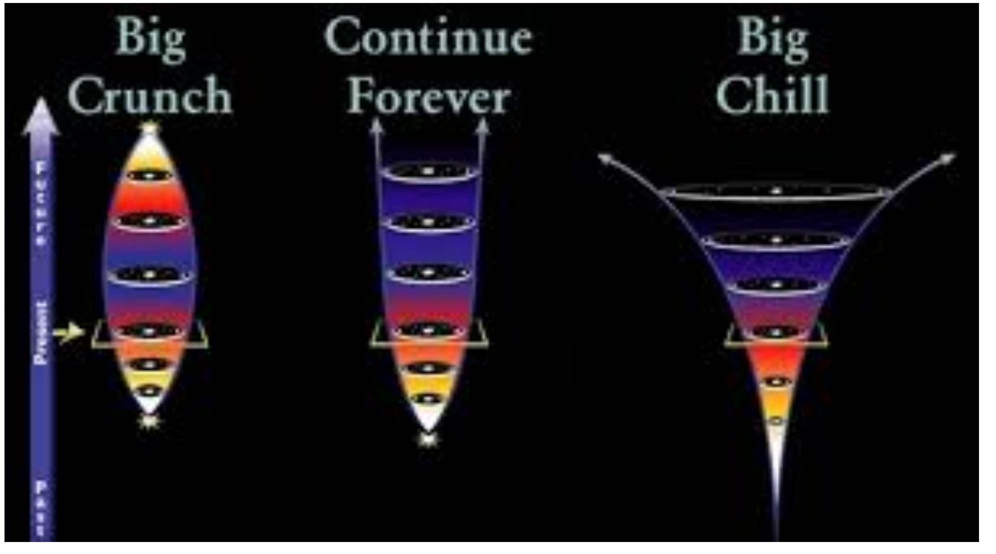
- What is the Universe made of?



Even if some reasonable candidates exist, we still have not been able to identify dark matter, 90 years after it has been first postulated by Fritz Zwicky

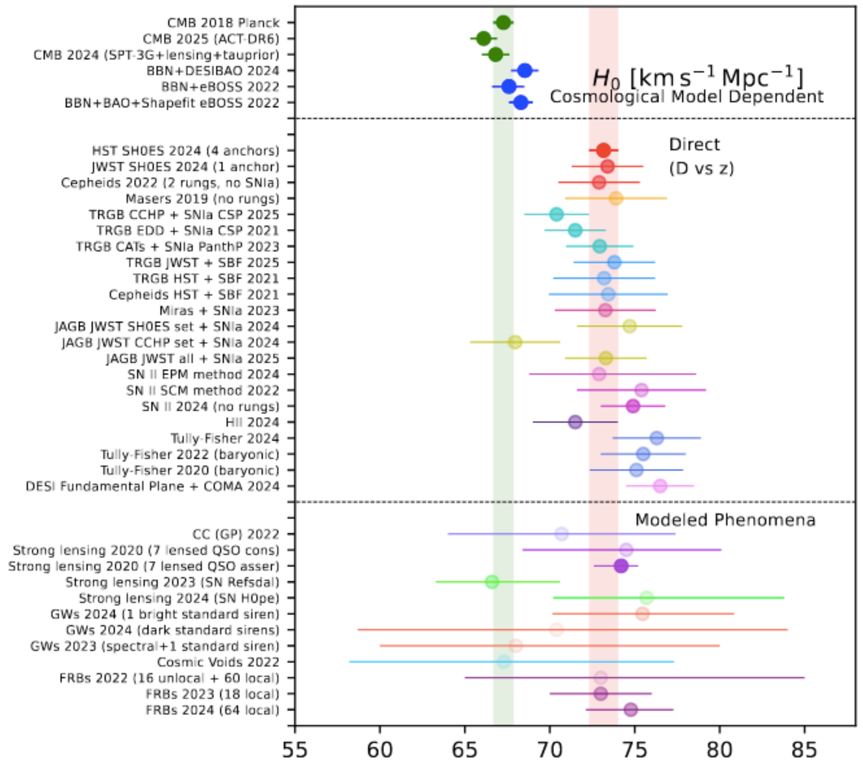
- What is the ultimate fate of the Universe?

It depends on what dark energy is



- What is the current expansion rate of the Universe (value of the Hubble constant)?

H0 tension : the persistent discrepancy between local and early-Universe measurements



The CosmoVerse network
arXiv:2504.01669

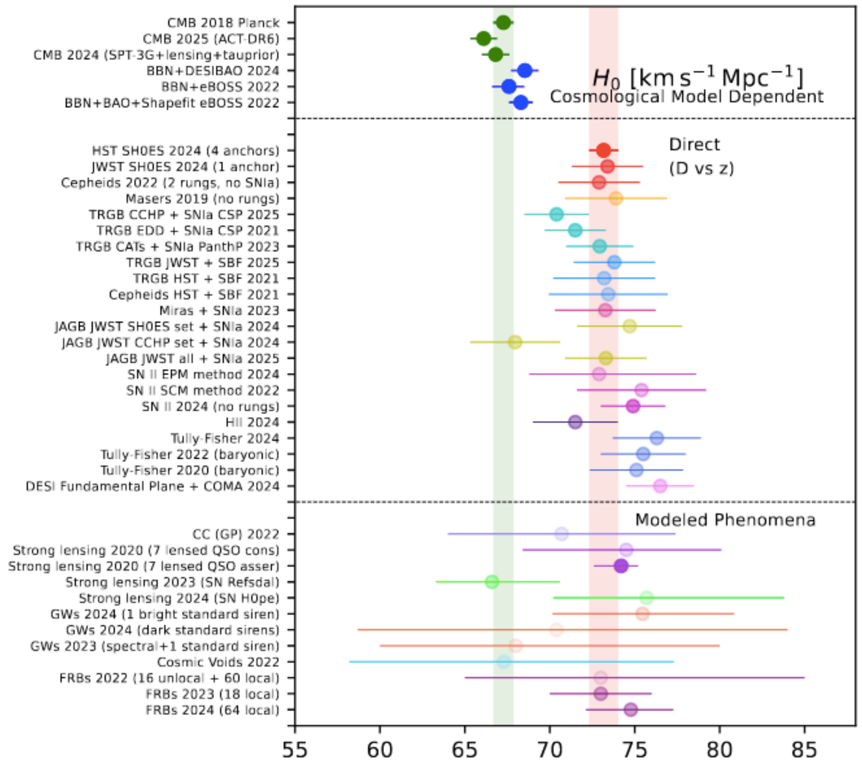
Observations of the sound horizon angular scales in CMB and BAO data
~ 67.4 km/s/Mpc

Luminosity of SNIa calibrated by Cepheids using the distance ladder technique
~73.3 km/s/Mpc

GW as standard sirens: GW170817
~ 68.7 km/s/Mpc

- What is the current expansion rate of the Universe (value of the Hubble constant)?

H0 tension : the persistent discrepancy between local and early-Universe measurements



The CosmoVerse network
arXiv:2504.01669

Efforts for a solution:

- Early DE (dominates before recombination)
- Late DE (modify expansion history at low z, z<1)
- Rapid transition in late Universe (DE from negative to positive)
- Interacting DM and DE
- Modified gravity
- Exotic scenarios and non-standard DM
- Extra relativistic species and neutrino physics
- Local void hypothesis
- Primordial magnetic fields
- Inflationary models (non-standard reheating)
- Varying fundamental constants
- Local physics solutions (new physical effects specific to the local Universe)
- Systematic uncertainties and calibration issues

Challenge to the ΛCDM concordance model

Reconcile local (late-time) measurements with global (early-time) constraints

subject to astrophysical systematics

model-dependent

GWs: independent approach free from electromagnetic systematics

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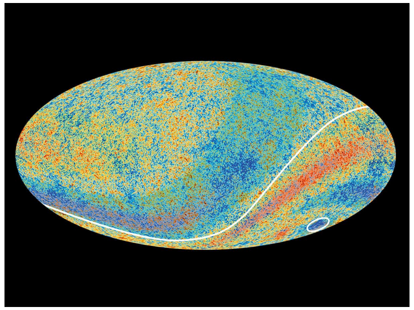
S8 (*a parameter that measures the clustering of matter in the Universe*) **tension**

Statistical discrepancy emerges in the observed values of S8 when comparing CMB-based primary anisotropy measurements with local probes such as WL, galaxy clustering, and galaxy cluster abundance studies

Moreover,

anomalies and challenges arising from the confrontation between ΛCDM and observational data (data analysis):

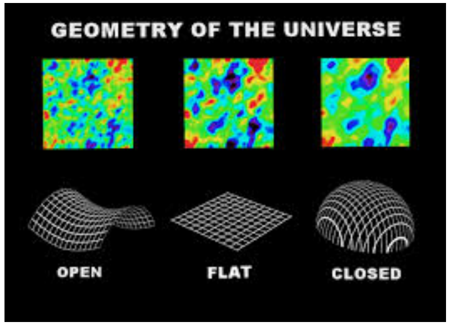
- excess lensing amplitude in the Planck data and potential deviation from ΛCDM predictions
- slight preference for a closed universe in spatial curvature parameter constraints within the ΛCDM
- low quadrupole moment and its alignment with the octupole
- hemispherical asymmetry (statistical difference in temperature fluctuations between opposite hemispheres)
- CMB cold spot



- What is the shape of the Universe?

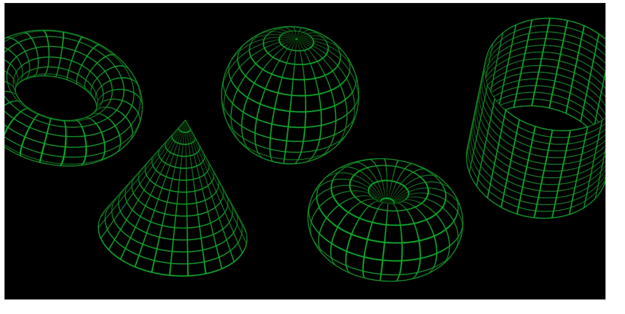
- Local geometry: spatial curvature

  The Universe is
  (first Doppler peak position)



- Global geometry: topology

  - *simply connected space?*
  - *multiply connected space?*
  - *finite or infinite?*
  - *wormholes?*



- Baryon asymmetry of the Universe

Observational evidence:

- Power spectrum of CMB $$\eta_{\mathrm{B}}^{\mathrm{CMB}} = \frac{n_{\mathrm{B}}}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}$$

- Concordance of light elements and BBN $$\eta_{\mathrm{B}}^{\mathrm{BBN}} = \frac{n_{\mathrm{B}}}{n_\gamma} = (3.4 - 6.9) \times 10^{-10}$$

Sakharov conditions (1967) for which a baryon asymmetry may successfully be generated:

- The theory should have B-violating interactions
- The interactions should violate both C and CP
- The processes of a net baryon-number generation should have a degree of irreversibility due to an out-of-thermal equilibrium dynamics

- Baryon asymmetry of the Universe

Many scenarios have been proposed, for instance:

- Baryogenesis through the decay of a heavy particle

  - Based on the out-of-equilibrium B-violating decay of a heavy GUT particle

  Yoshimura (1978) ; Dimopoulos, Susskind (1978)

  - Serious constraint difficult to overcome - strict experimental lower limit on proton's long lifetime

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- Baryogenesis at the electroweak phase transition

  - BAU is generated by (B + L)-violating sphaleron interactions at $T \sim T_c \approx 140$ GeV, through a FOPT

  Kuzmin, Rubakov, Shaposnikov (1985)

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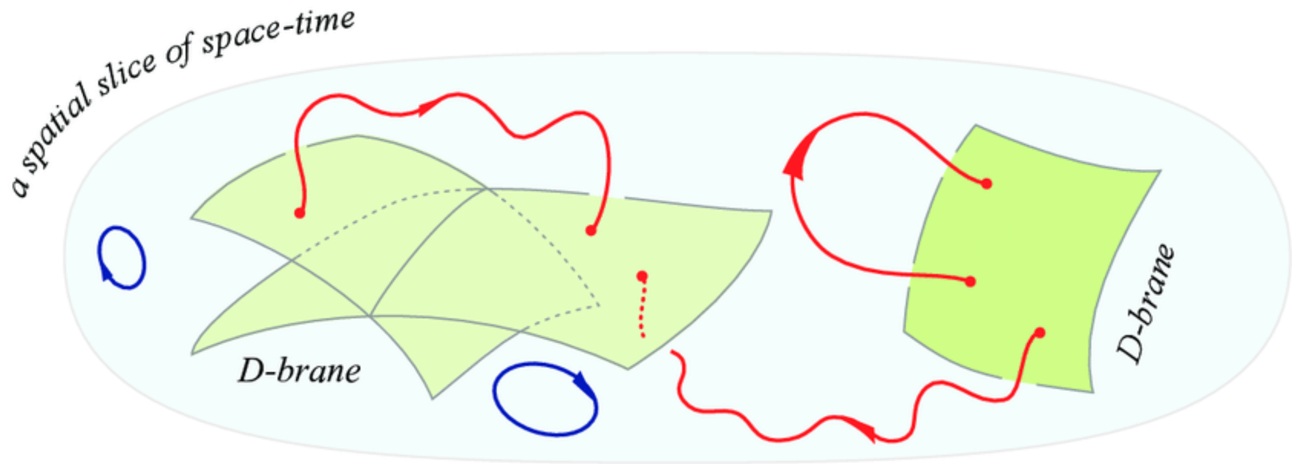
- Baryogenesis through leptogenesis
  - Leptogenesis is based on the out-of-equilibrium L-violating decays of heavy Majorana neutrinos. These decays produce a net lepton asymmetry, which is converted into the observed BAU through (B + L)-violating sphaleron interactions

    Fukugita, Yanagida (1986)

- Why do we live in (3+1)-dimensions?



Starting with a distribution of branes embedded in a higher dimensional bulk, brane interactions could naturally lead to the survival of only three-dimensional branes and one-dimensional branes (D-strings)

*Nelson, **Sakellariadou** (2009)*

Conclusions

Despite a big progress in Cosmology several questions remain open and further progress is needed.
Moreover, the (phenomenological) ΛCDM concordance model is facing challenges

Observations:

- gravitational waves (LIGO-Virgo-KAGRA, Laser Interferometer Space Antenna, Einstein Telescope & Cosmic Explorer)

- astrophysical data (James Webb Space Telescope, Fermi Gamma-ray Space Telescope, Rubin Observatory, Dark Energy Survey, Dark Energy Spectroscopic Instrument, Euclid, SKA Observatory)

Mathematics:

- Novel (more appropriate) tools