Unravelling Cosmic Acceleration with Gravitational Waves and Large-Scale Structure

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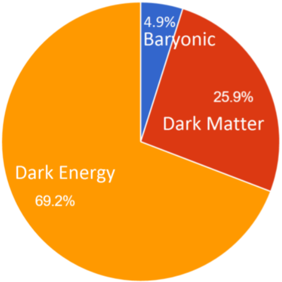
12 Jul 2019

Cosmological constant



- Cosmic acceleration at late times

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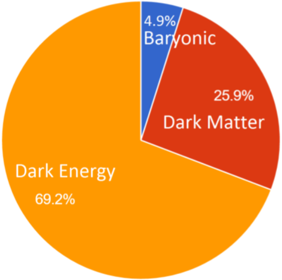

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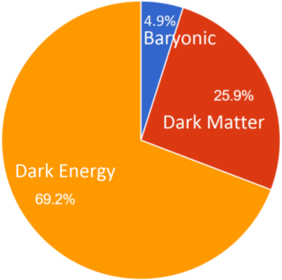

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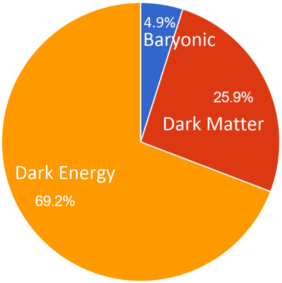

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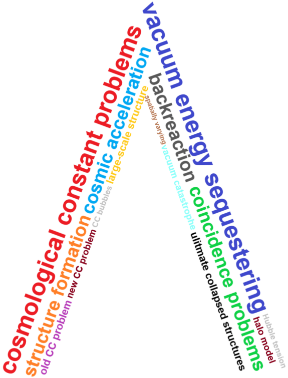
- $\Lambda = 0$ & DE or MG?

Cosmological constant



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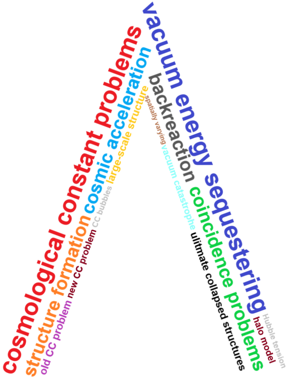

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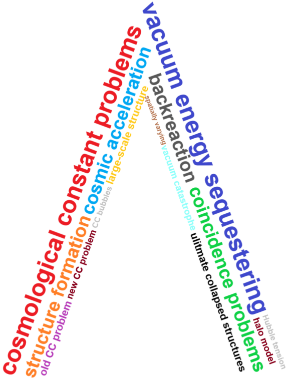

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- Genuine MG self-acceleration challenged by GW170817
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Horndeski scalar-tensor action (simplest MG)

- Horndeski action:

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\begin{aligned}
S \;=\; & \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,\Big\{ G_2(\varphi,X) - G_3(\varphi,X)\Box\varphi \\
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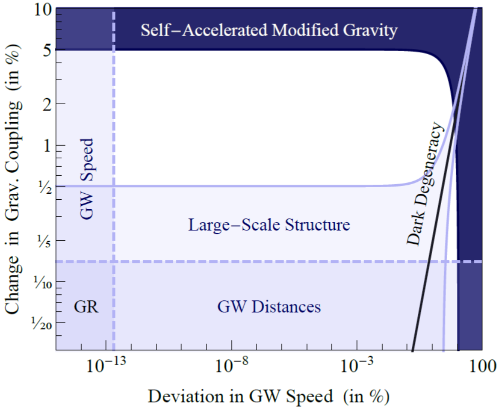
& + \mathcal{L}_{\mathrm{m}}(g_{\mu\nu},\psi_i)\Big\},
\end{aligned}
$$

where $X \equiv -\frac{1}{2}(\partial_\mu\varphi)^2$

[Horndeski 1974; Deffayet, Gao, Steer, Zahariade 2011; Kobayashi, Yamaguchi, Yokoyama 2011]

Breaking the Dark Degeneracy with GWs



[L & Taylor (2015)]

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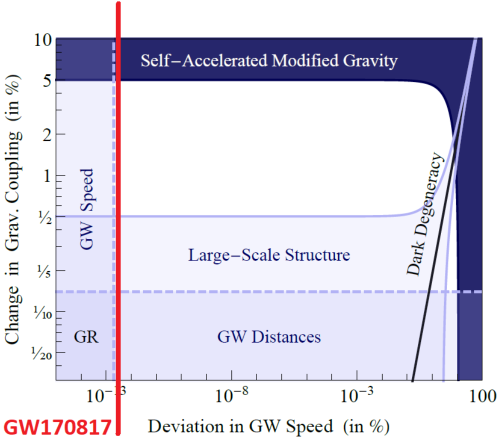

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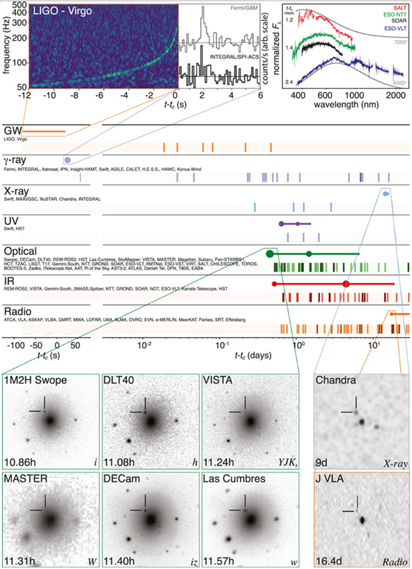
GW170817



[Abbott *et al.* 2017]

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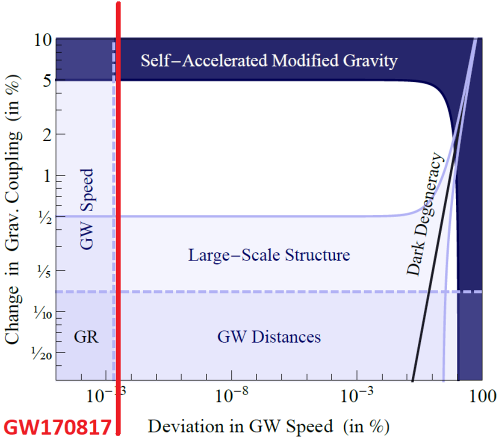

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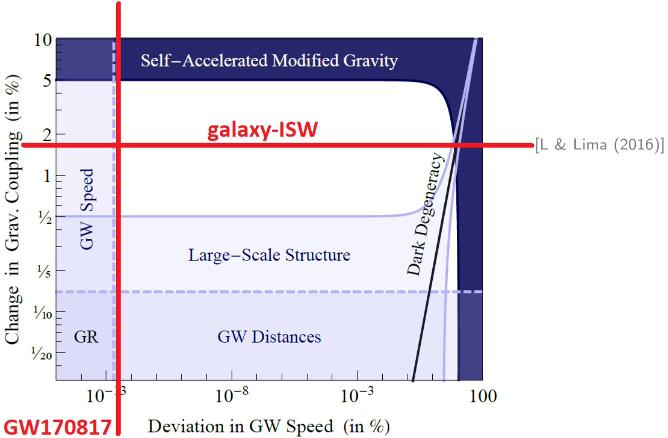

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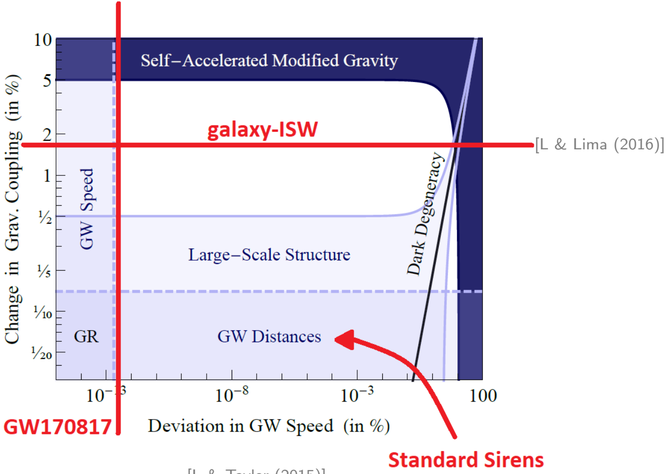

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Outlook – *Standard Sirens*

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NATURE | LETTER

日本語要約

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTER Collaboration

Affiliations | Contributions | Corresponding authors

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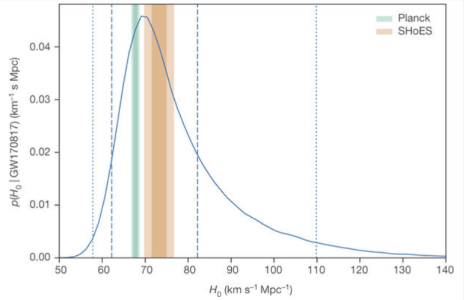
Received 26 September 2017 | Accepted 05 October 2017 | Published online 16 October 2017

PDF | Citation | Rights & permissions | Article metrics

On 17 August 2017, the Advanced LIGO[1] and Virgo[2] detectors observed the gravitational-wave event GW170817—a strong signal from the merger of a binary neutron-star system[3].

Figure 1: GW170817 measurement of H_0.



The marginalized posterior density for H_0, $p(H_0 \mid \mathrm{GW170817})$, is shown by the blue curve. Constraints at 1σ (darker shading) and 2σ (lighter shading) from Planck[20] and SHoES[21] are shown in green and orange, respectively. The maximum a posteriori value and minimal 68.3% credible interval from this posterior density function is $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\ s^{-1}\,Mpc^{-1}}$. The 68.3% (1σ) and 95.4% (2σ) minimal credible intervals are indicated by dashed and dotted lines, respectively.

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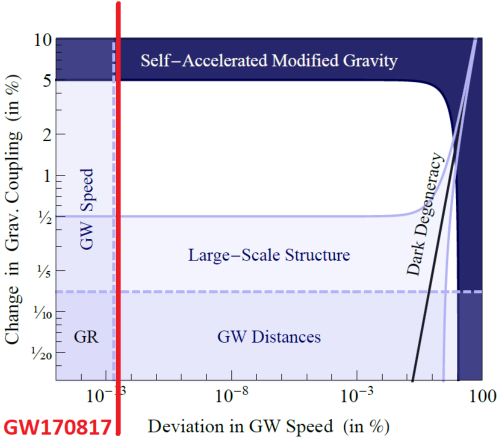

[L & Taylor (2015)]

Remaining viable Horndeski (at low z)

- Horndeski action:

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also see: [Ezquiaga & Zumalacárregui (2017); Creminelli & Vernizzi (2017); Sakstein & Jain (2017); Baker, Bellini, Ferreira, Lagos, Noller, Sawicki (2017); . . .]

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[Creminelli *et al.* (2018)]

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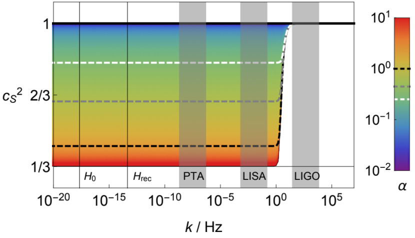
Linear shielding for GWs



[de Rham & Melville (2018)]

- Scale-dependent propagation of GWs:

$$h_{ij}'' + \left(3 + \frac{H'}{H} + \frac{{}^{(0)}\alpha_{\rm M} + {}^{(1)}\alpha_{\rm M}\, w(a) k_H^2}{1 + w(a) k_H^2}\right) h_{ij}' + \left(1 + \frac{{}^{(0)}\alpha_{\rm T} + {}^{(1)}\alpha_{\rm T}\, w(a) k_H^2}{1 + w(a) k_H^2}\right) k_H^2 h_{ij} = 0$$

with GW170817 $\Rightarrow$ ${}^{(1)}\alpha_{\rm T} \simeq 0$ as $k_H \sim 10^{19}$

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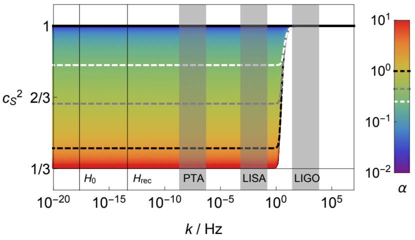

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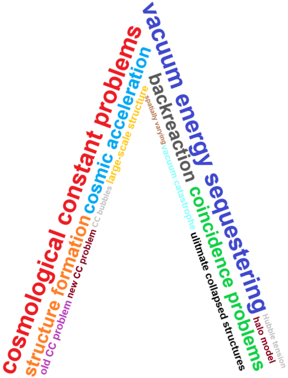
- Self-acceleration driven by

$$\left|\frac{\Omega'}{\Omega}\right| = \left|{}^{(0)}\alpha_{\rm M} + \frac{{}^{(0)}\alpha_{\rm T}'}{1 + {}^{(0)}\alpha_{\rm T}}\right| \gtrsim \mathcal{O}(1)$$

(cf. linear shielding for GWs) [L & Taylor (2014)]

Cosmological constant



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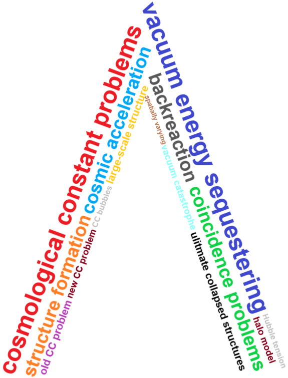

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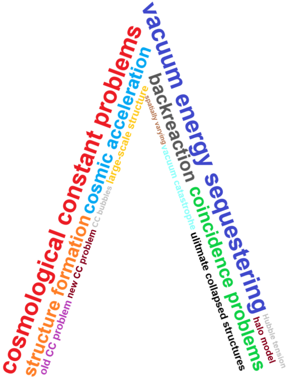

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- Back to Λ? Cosmological constant problem?

Planck mass variation

- Einstein-Hilbert action

$$S = M_{\mathrm{Pl}}^2 \int d^4x \sqrt{-g} \left(\frac{R}{2} - \Lambda \right) + \int d^4x \sqrt{-g} \mathcal{L}_{\mathrm{m}}(g_{\mu\nu}, \Phi_{\mathrm{m}})$$

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- Field and constraint equations

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = M_{\rm Pl}^{-2} T_{\mu\nu}\,, \qquad \int dV_4\left(\frac{R}{2}-\Lambda\right) = 0$$

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$$G_{\mu\nu} + \frac{1}{2} M_{\mathrm{Pl}}^{-2}\langle T\rangle g_{\mu\nu} = M_{\mathrm{Pl}}^{-2} T_{\mu\nu}\,, \qquad M_{\mathrm{Pl}}^2\,\Lambda = \frac{1}{2}\frac{\int dV_4\, T}{\int dV_4} \equiv \frac{1}{2}\langle T\rangle$$

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[L (2019)] (also see, e.g., vacuum energy sequestering, unimodular gravity, Barrow & Shaw (2011), 4-form field strength of a 3-form gauge field, δ-function from scalar-vector term, multiverse type II, higher-dimensional scalar-tensor theory, supergravity, string theory . . .)

Old cosmological constant problem

- Combined field equations: $\int dV_4 \, (R - 2\Lambda) = 0$, $M_{\rm Pl}^2 \, \Lambda = \frac{1}{2} \frac{\int dV_4 \, T}{\int dV_4} \equiv \frac{1}{2} \langle T \rangle$

$$G_{\mu\nu} + \frac{1}{2} M_{\rm Pl}^{-2} \langle T \rangle g_{\mu\nu} = M_{\rm Pl}^{-2} T_{\mu\nu}$$

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  (1-loop: $m_i\to\lambda_i M_{\rm Pl}$; Wheeler space-time foam [Wang, Zhu & Unruh (2017)])

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  - Example 2: $M_{\rm Pl}^2\Lambda_{\rm vac}\propto M_{\rm Pl}^{2\alpha}M^{4-2\alpha}$ ($\alpha=1$; $\alpha=0$ local sequestering)

$$G_{\mu\nu}+\frac{1}{2-\alpha}\left[(1-\alpha)\Lambda+\frac{M_{\rm Pl}^{-2}\langle T\rangle}{2}\right]g_{\mu\nu}=M_{\rm Pl}^{-2}T_{\mu\nu}$$

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  - Example 3: expansion of $\Lambda_{\rm vac}$ in $M_{\rm Pl}^2$ cancelled by expansion of classical Λ

New cosmological constant problem

- Value of the cosmological constant, $M_{\mathrm{Pl}}^2\,\Lambda = \frac{1}{2}\frac{\int dV_4\,T}{\int dV_4} \equiv \frac{1}{2}\langle T\rangle$

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- Universe is inhomogeneous on small scales (*backreaction*)

  (final conditions clearer than initial conditions: ultimate critical matter cells)

$$S_{\rm m} = \sum_i \int_{\mathcal{U}_i} dV_4 \mathcal{L}_{{\rm m},i} + \int_{\mathcal{M}\setminus\bigcup_i\mathcal{U}_i} dV_4 \mathcal{L}_{\varnothing}$$

Matching Λ between $\mathcal{U}_i$ and $\mathcal{M}\setminus\bigcup_i\mathcal{U}_i$: $\mathcal{L}_{\varnothing} = M_{\rm Pl}^2(\Lambda/n + M_{\rm Pl}^{2n}\bar{\Lambda}_{\varnothing})$

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- Spherical collapse equation from energy-momentum conservation in matter cell

$$y'' + \left(2 + \frac{H'}{H}\right) y' + \frac{1}{2}\Omega_{\rm m}(a)(y^{-3} - 1)y = 0$$

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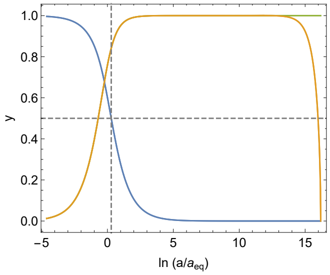
- Standard field equations (w/ non-gravitating vacuum)

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_{\rm obs} = M_{\rm Pl}^{-2}T_{\mu\nu}$$

New cosmological constant problem



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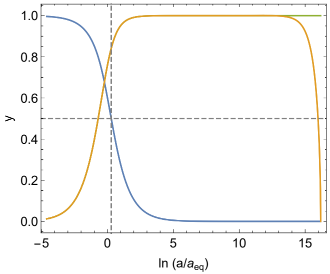
New cosmological constant problem



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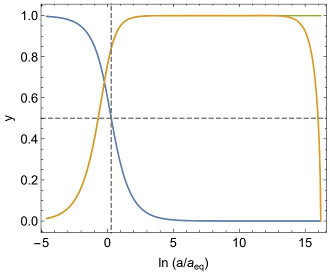

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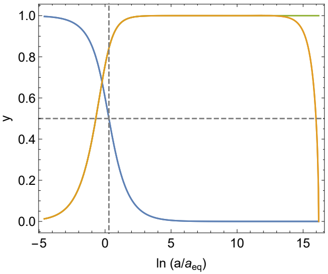

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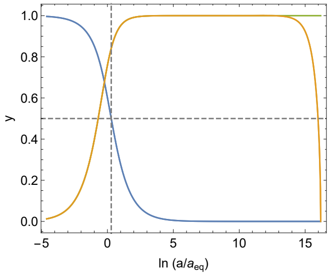

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- 1σ & 3σ agreement w/ DES & *Planck*

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Conclusions

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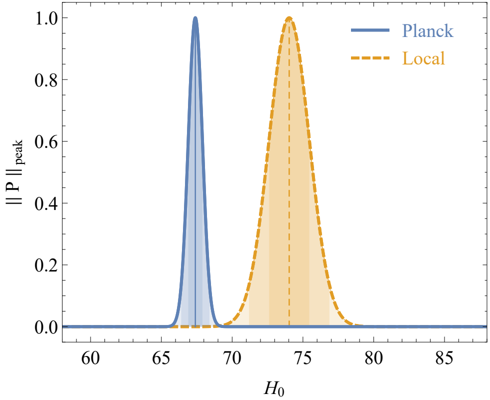
- Evaluation of the constraint equation for matter patches that form ultimate critical cells yields backreaction effect that predicts $\Omega_\Lambda = 0.704$, giving rise to cosmic late-time acceleration & coincident current $\Omega_{\mathrm{m}} \sim \Omega_\Lambda$ (*new* Λ problem).
- No problem with the cosmological constant.

Hubble tension?

But what about the 4.4σ H_0 tension?



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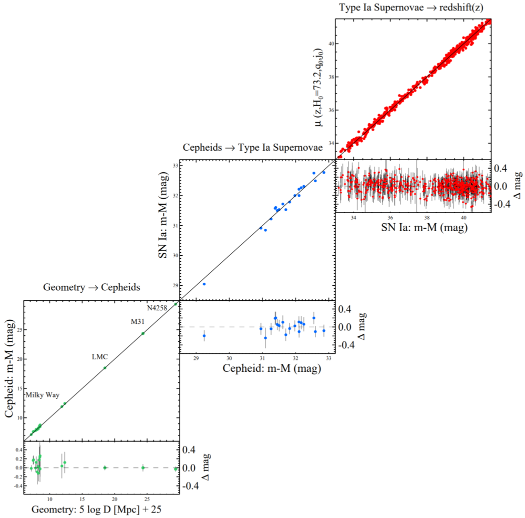

[Riess *et al.* (2016)]

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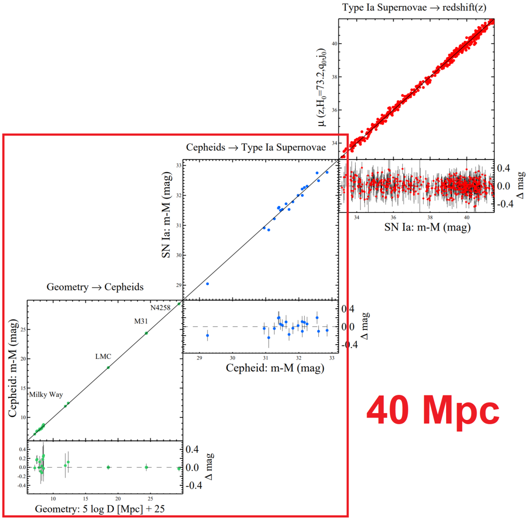

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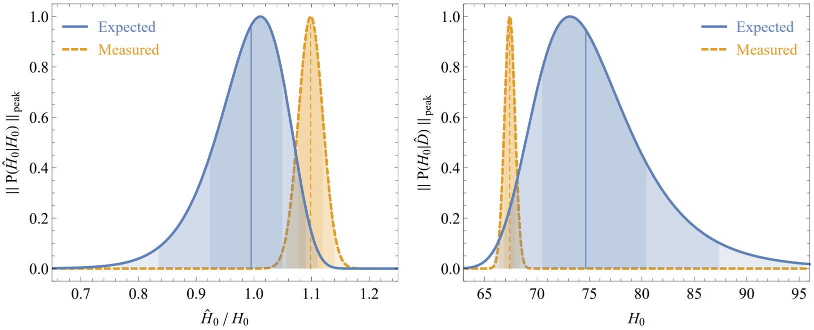

[L (2019)]

$$\hat{B}_{eq} = 4$$

Thank you!