Understanding Cosmic Acceleration

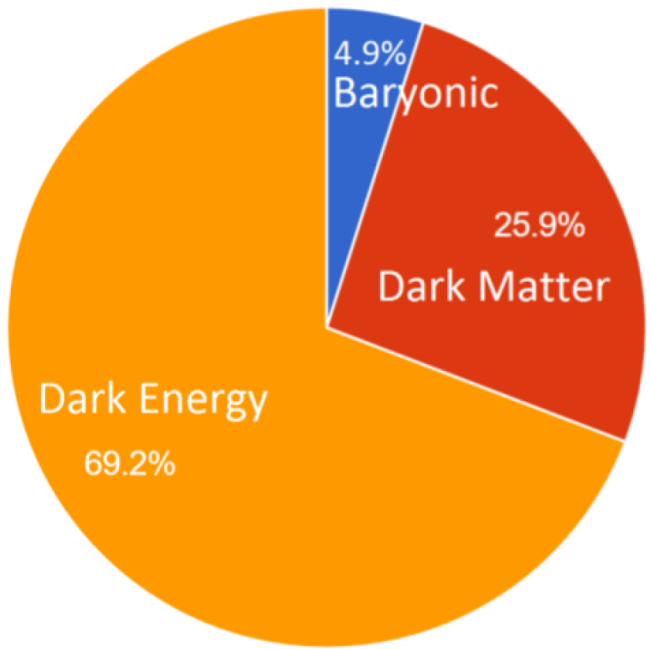
A Question of Life, the Universe and Everything?

Lucas Lombriser

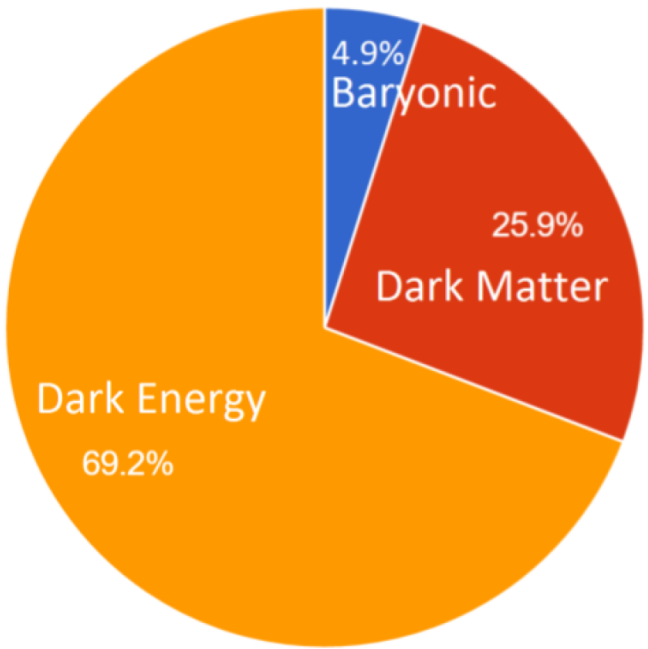
Université de Genève

Copernicus Webinar

7 Sep 2021



- Cosmic acceleration at late times



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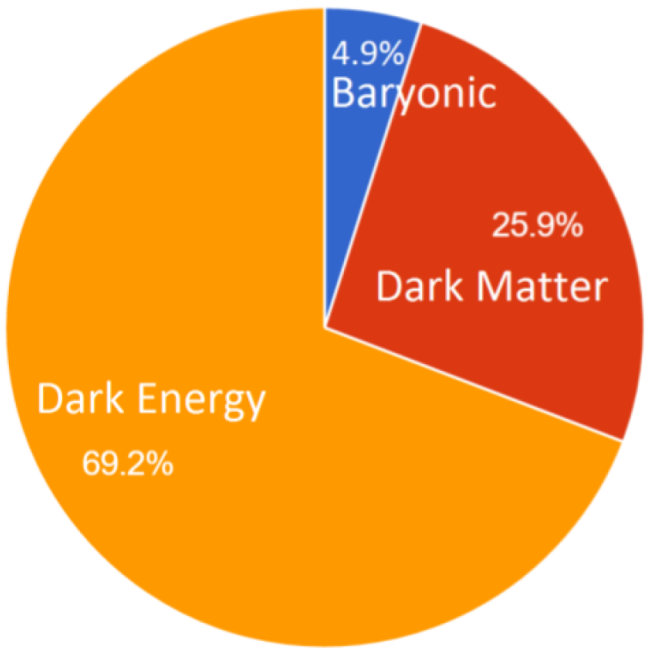
- Best candidate:
  $R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = M_{\rm Pl}^{-2} T_{\mu\nu}$



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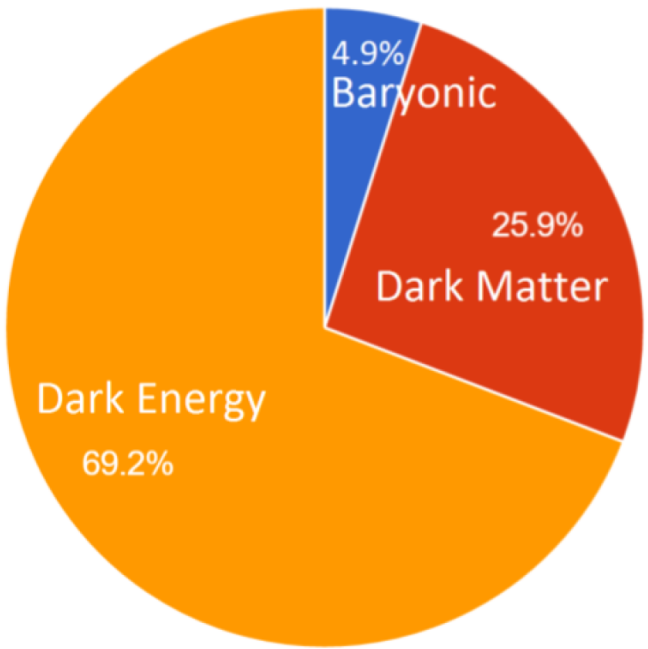

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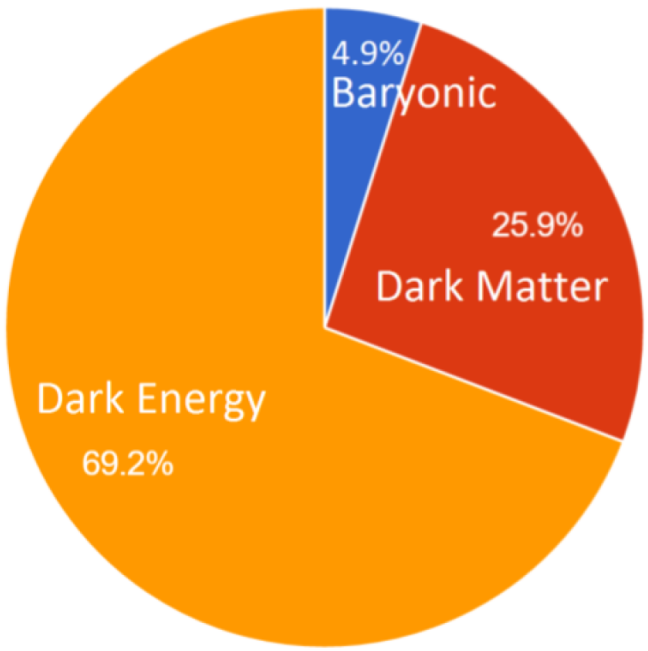
- $\Lambda = 0$ & DE or MG?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Baryonic
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Dark Matter
Dark Energy
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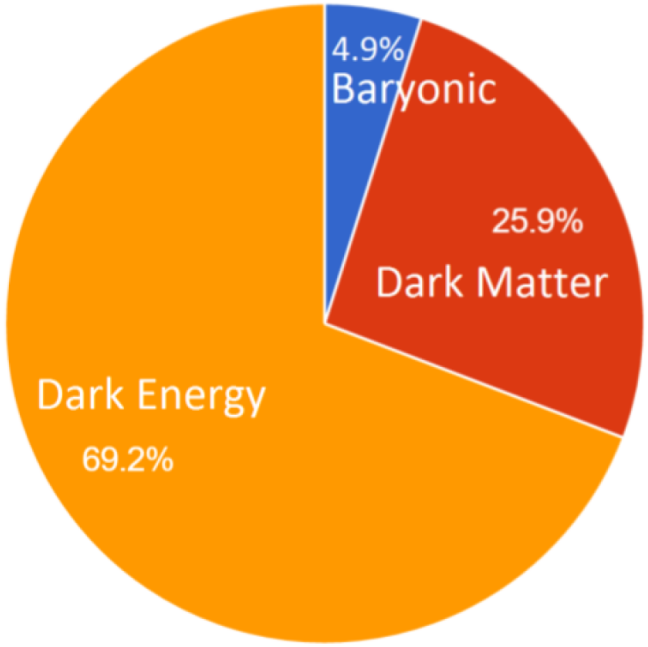
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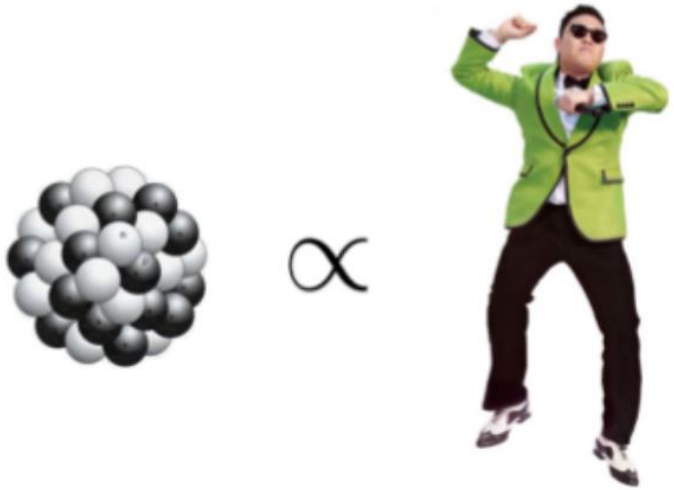
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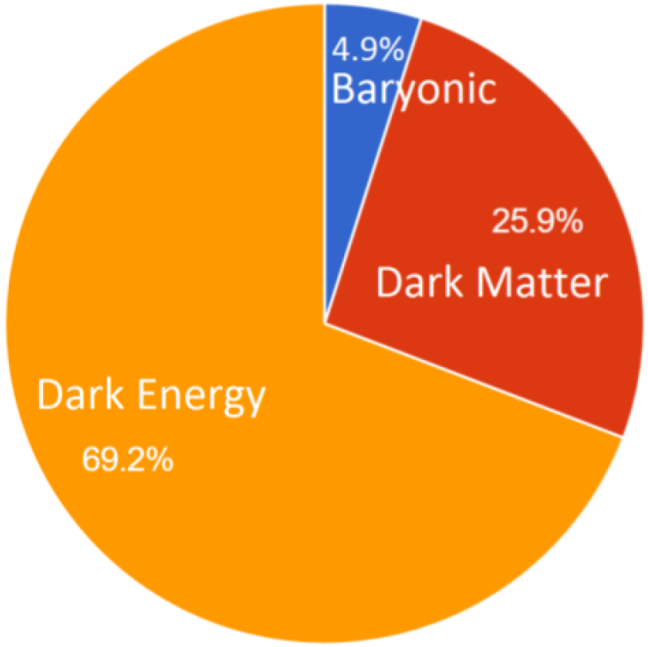

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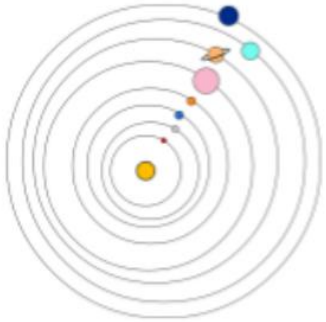

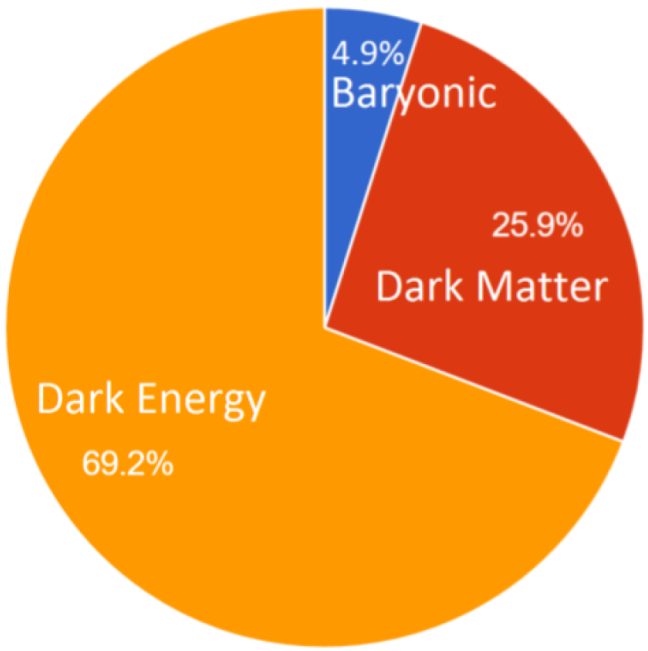
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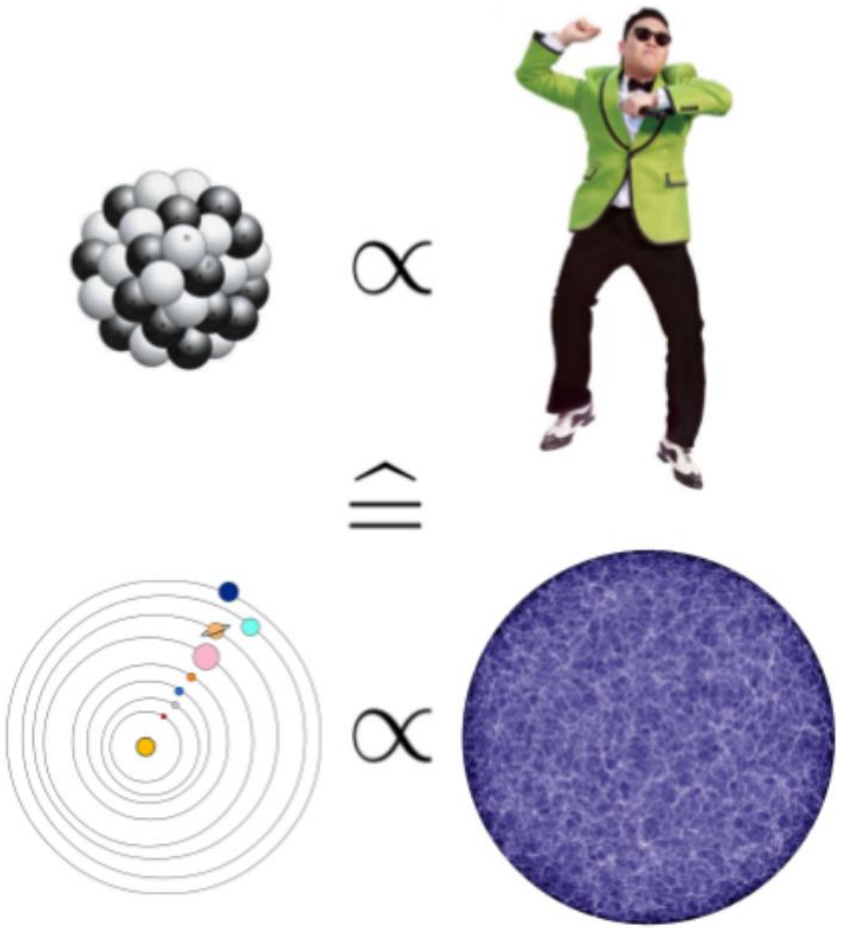
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Horndeski scalar-tensor action (simplest MG)

- Horndeski action:

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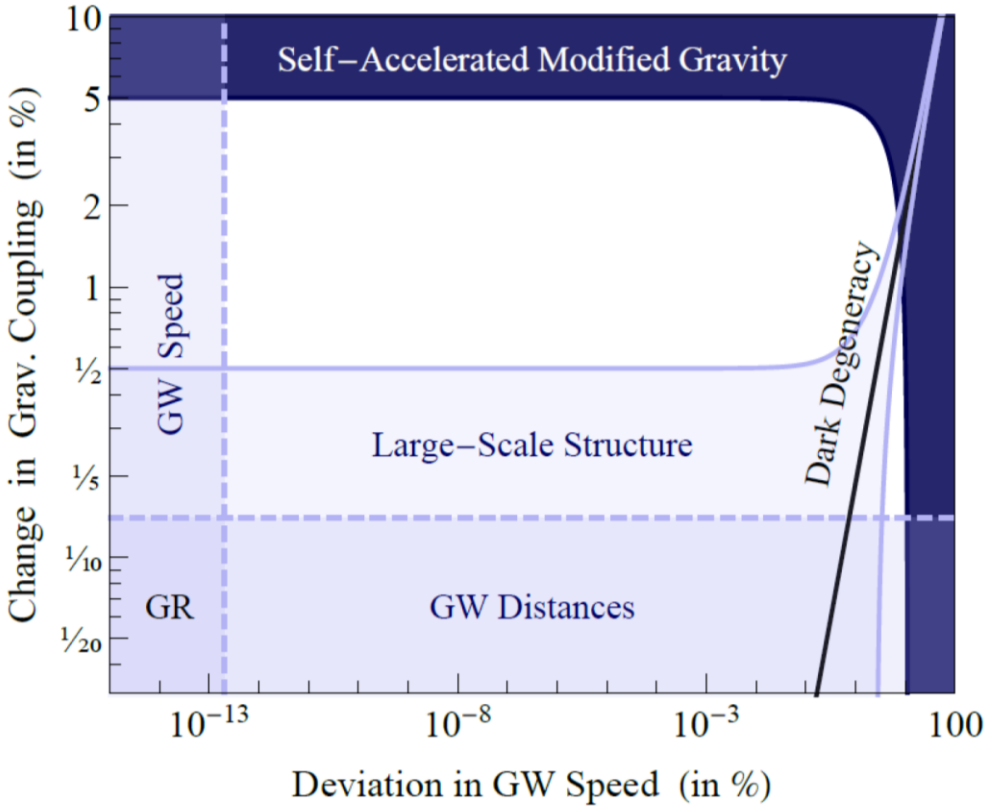
& + \mathcal{L}_{\rm m}(g_{\mu\nu},\psi_i)\Big\},
\end{aligned}
$$

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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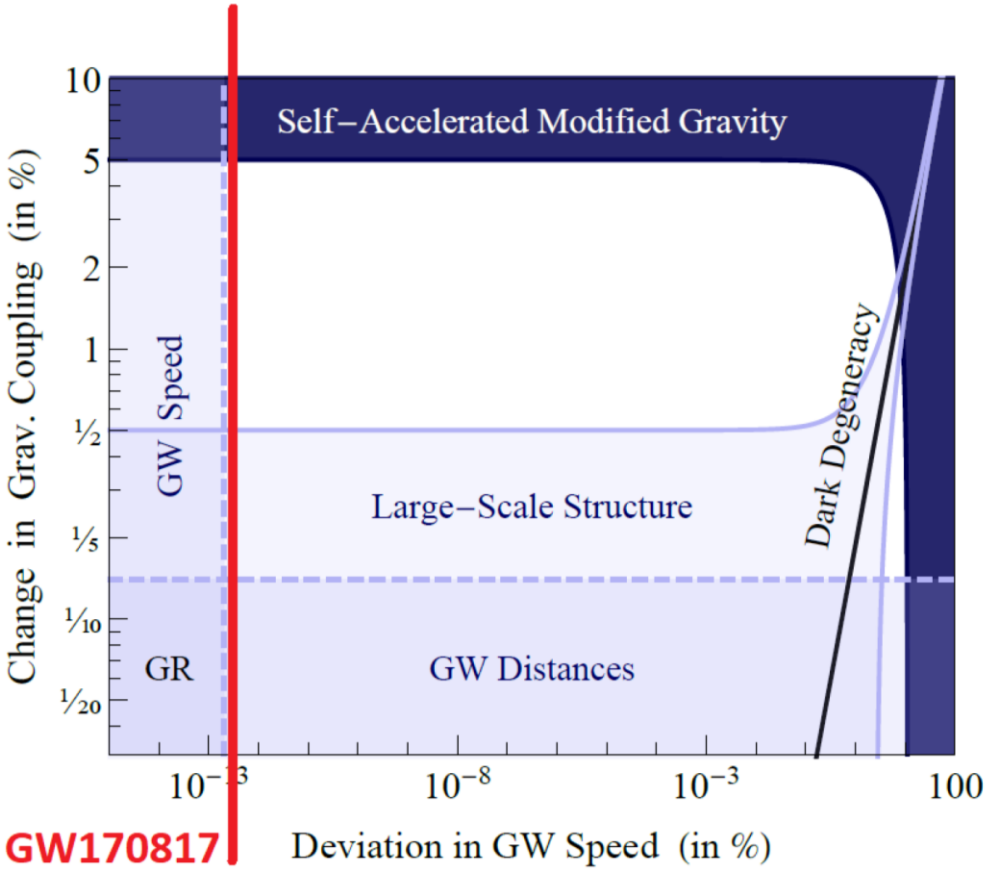

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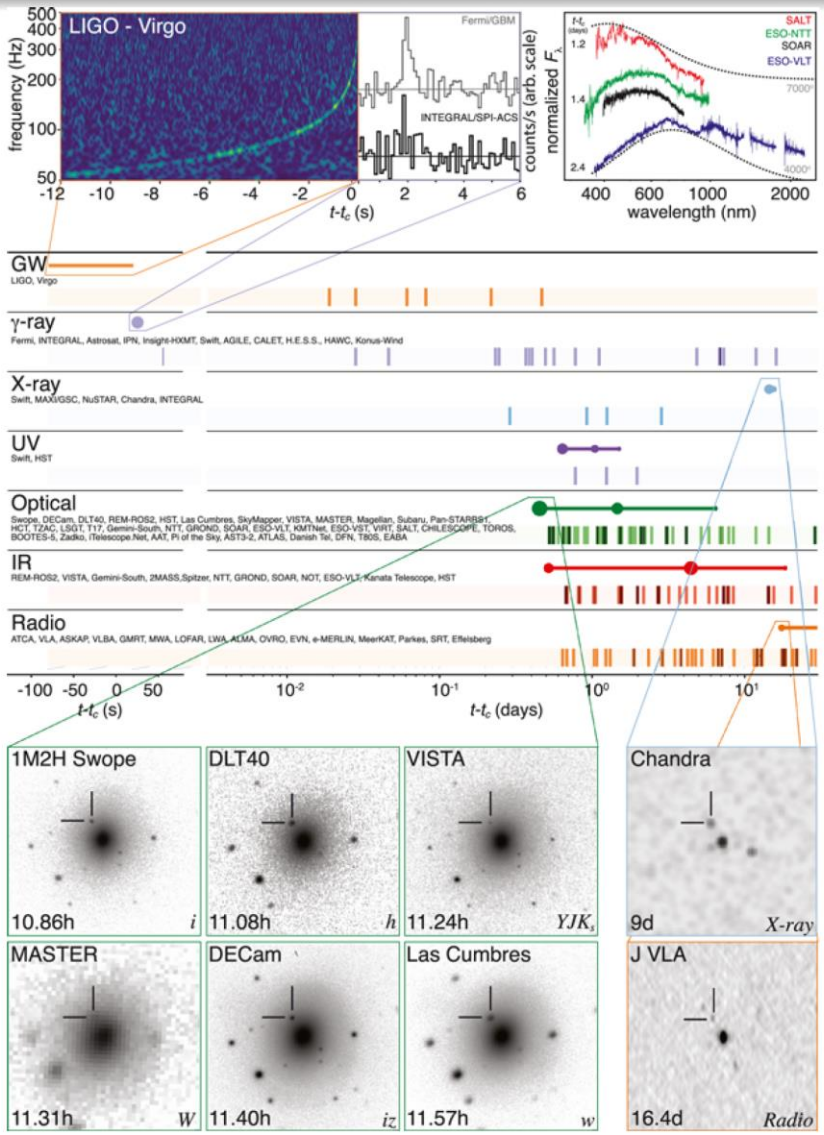
GW170817



[Abbott *et al.* 2017]

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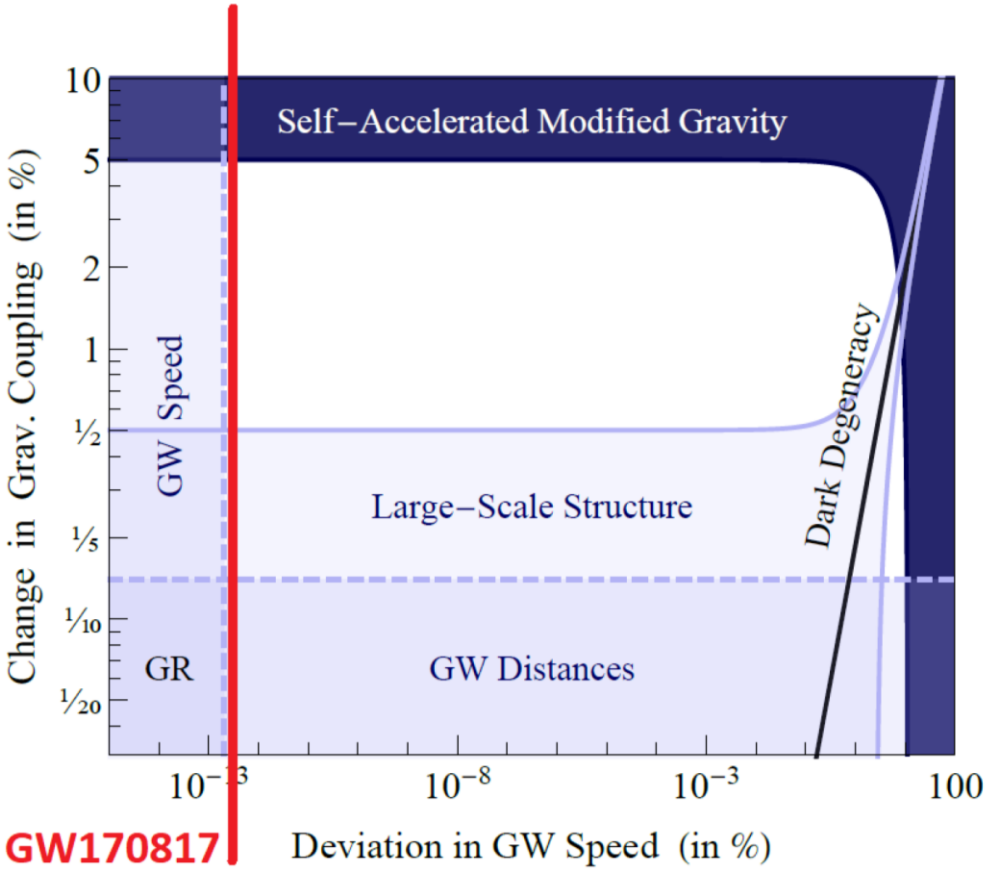

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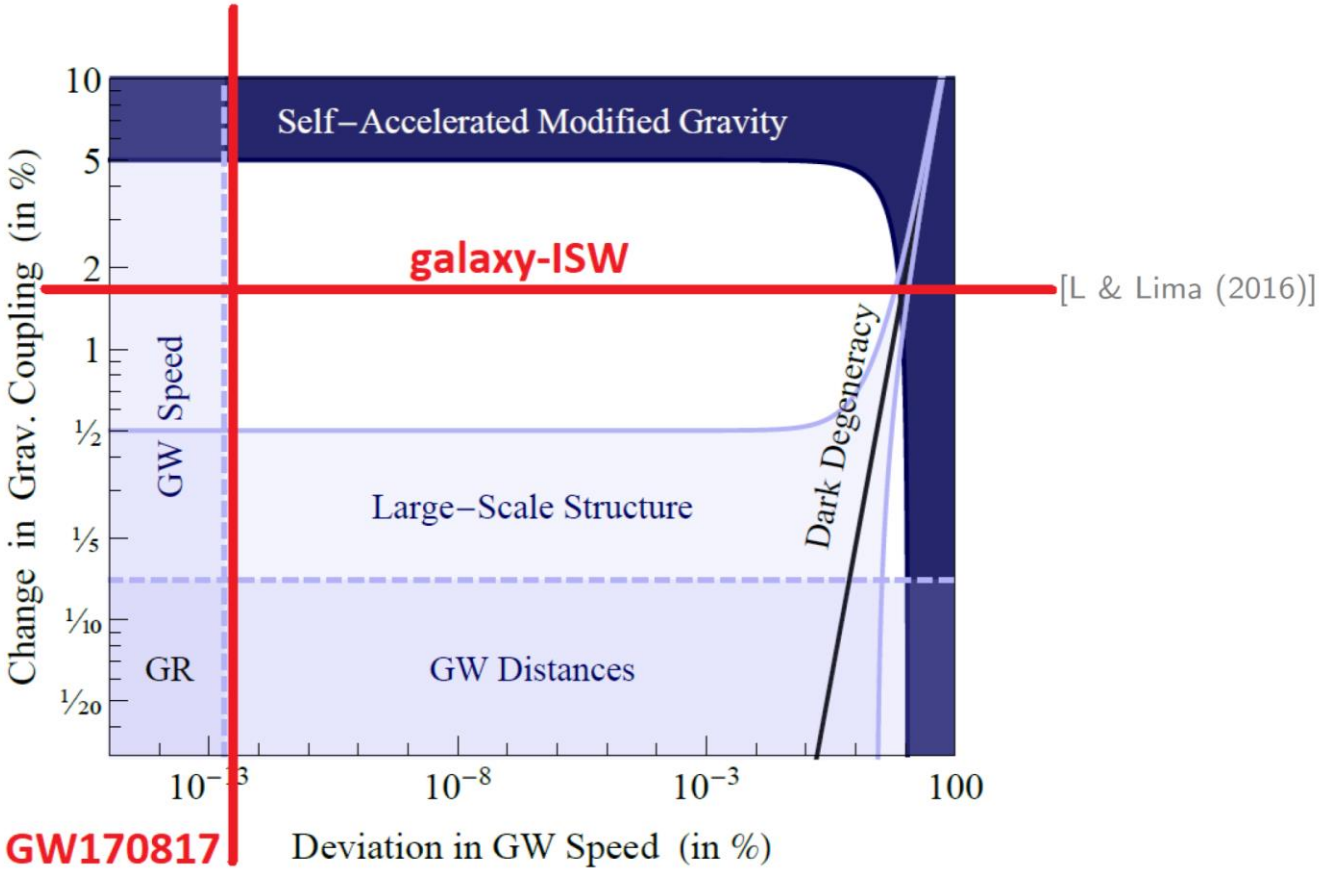

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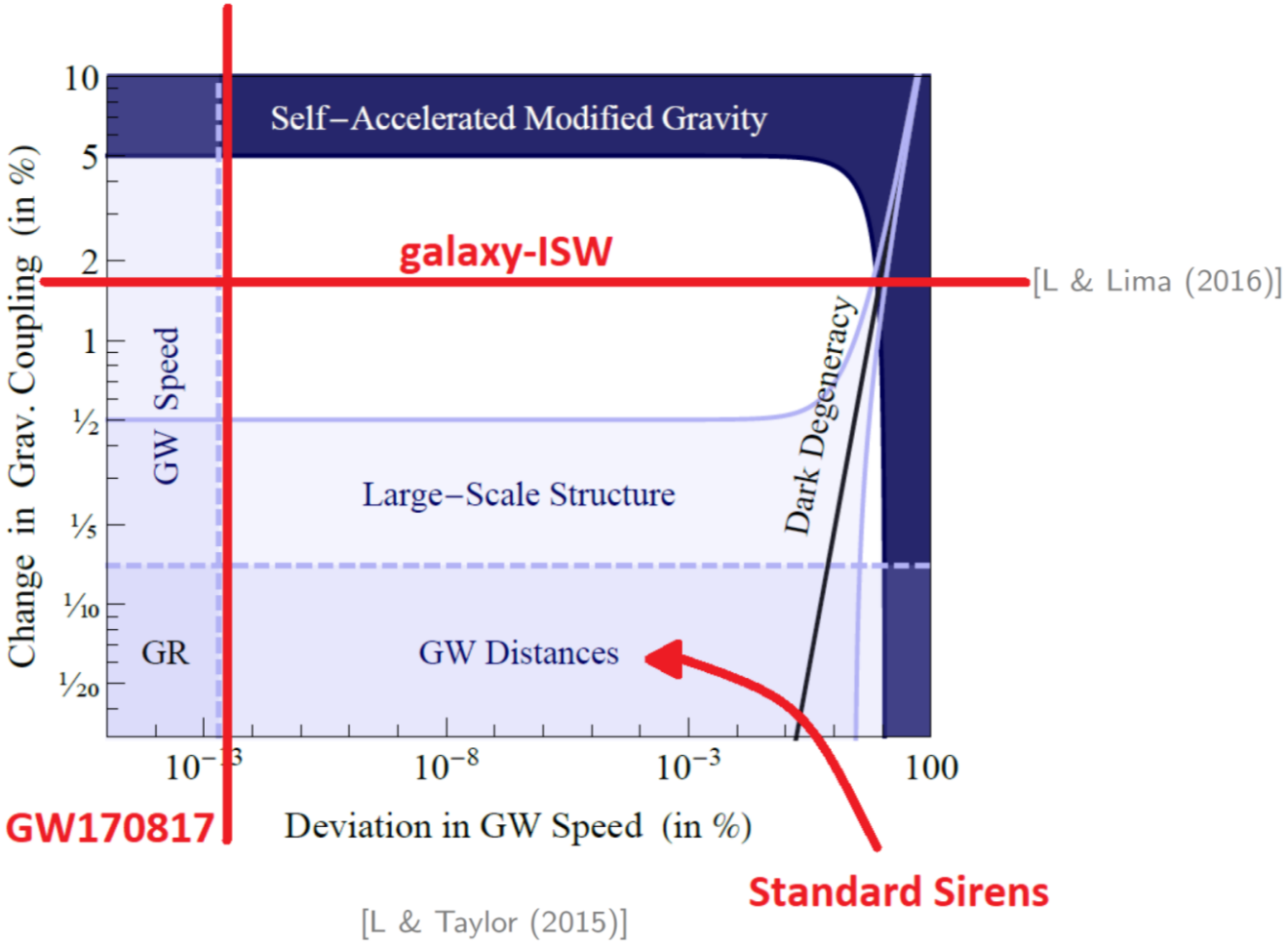

Outlook – *Standard Sirens*

nature International weekly journal of science

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

Nature **551**, 85–88 (02 November 2017) | doi:10.1038/nature24471

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

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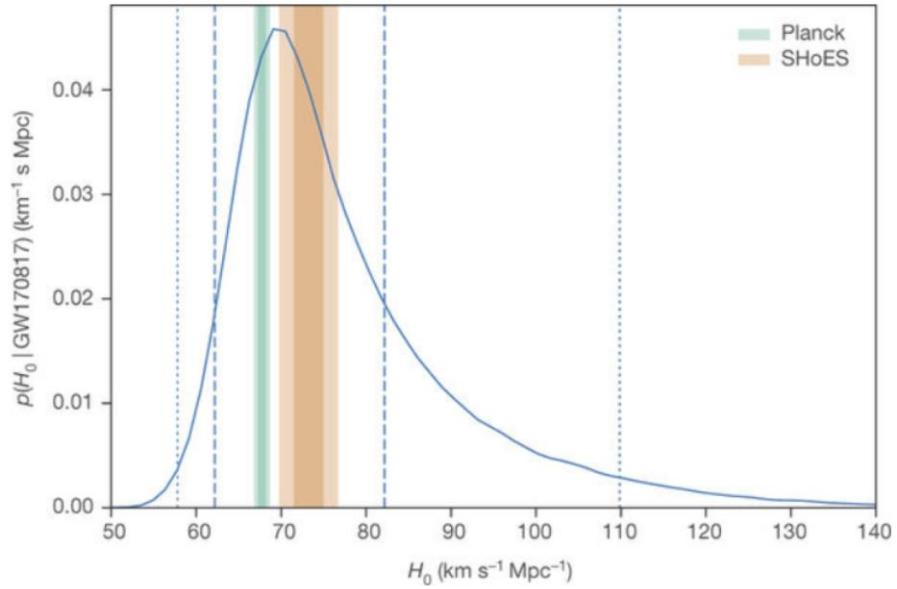
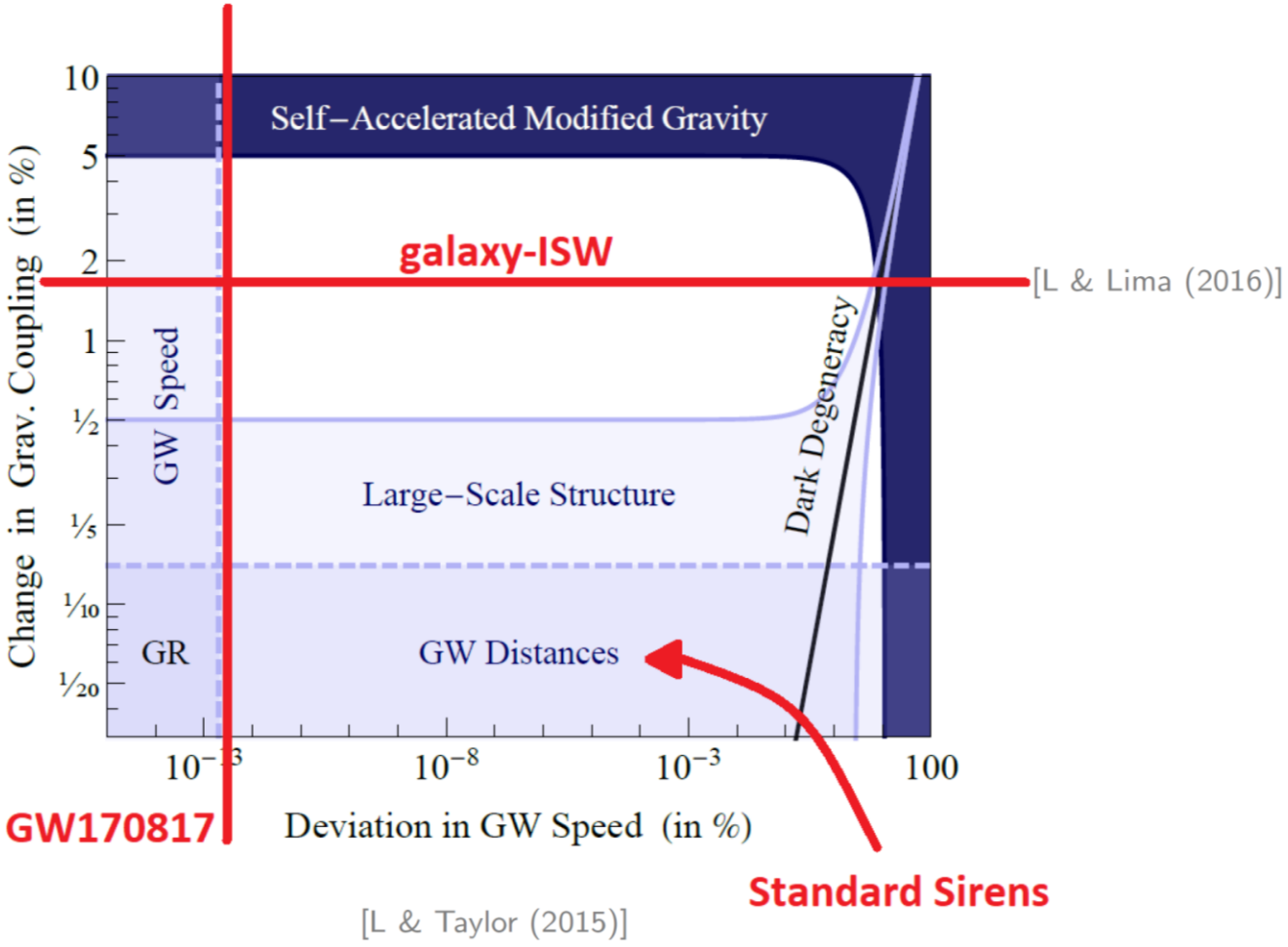
On 17 August 2017, the Advanced LIGO[1] and Virgo[2] detectors observed the gravitational-wave event GW170817—a strong signal from the merger of a binary neutron-star system[3].

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% ($1\sigma$) and 95.4% ($2\sigma$) minimal credible intervals are indicated by dashed and dotted lines, respectively.

Breaking the Dark Degeneracy with GWs



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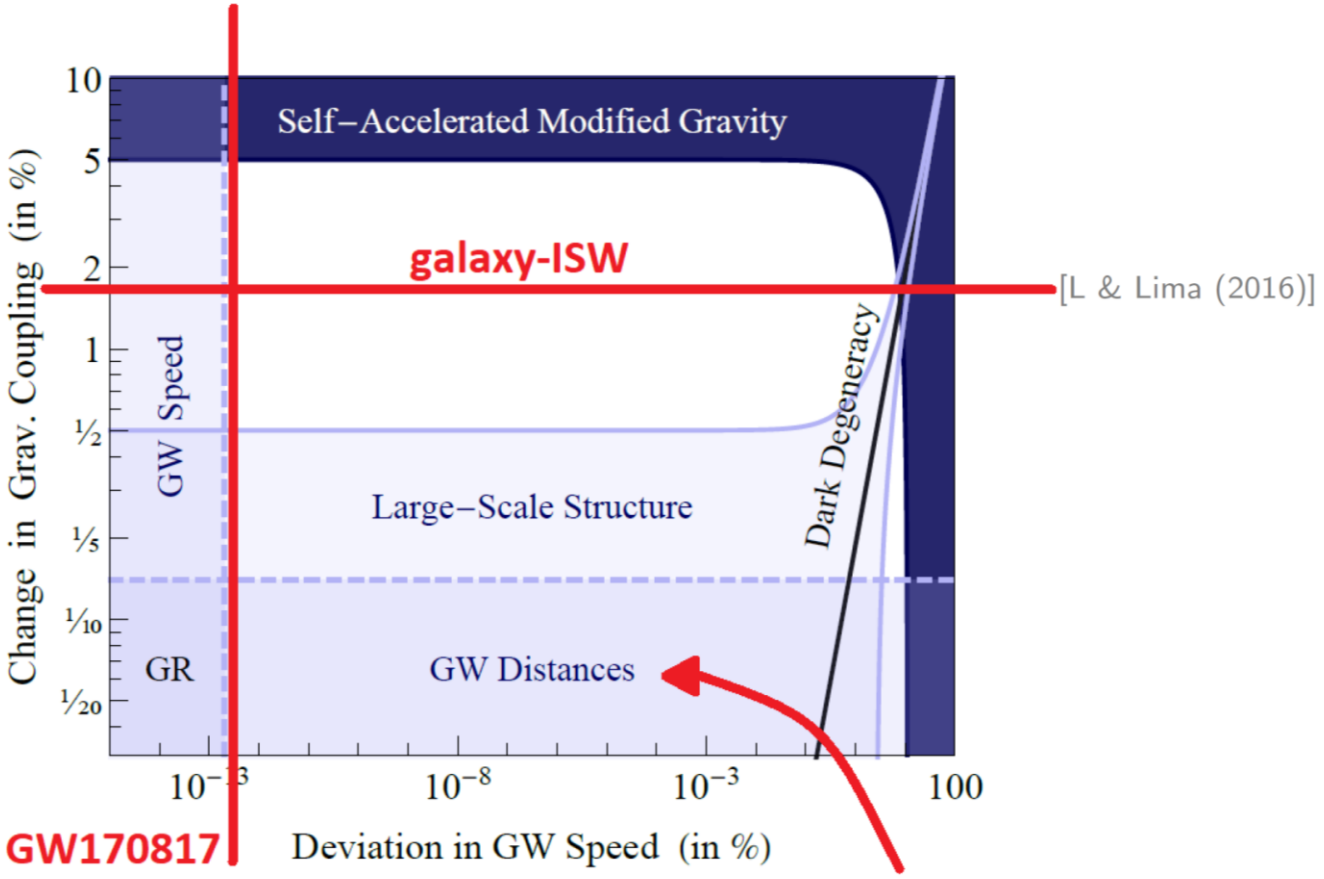

[L & Lima (2016)]

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Standard Sirens

- Dalang & L (2019); Dalang, Fleury & L (2019)

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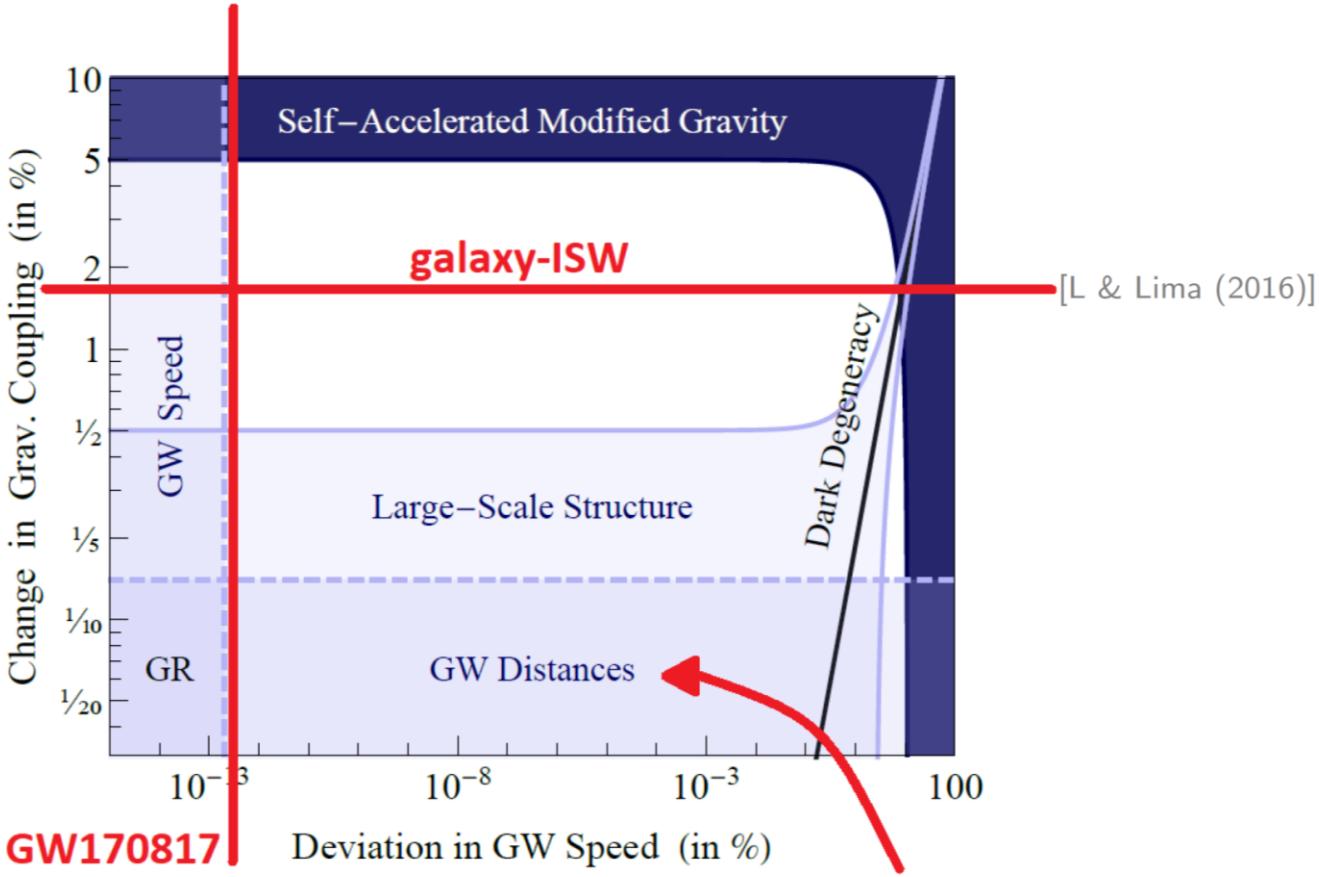

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- Renevey, McManus, Dalang & L (2021)

Remaining viable Horndeski (at low z)

- Horndeski action:

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Remaining viable Horndeski (at low z)

- Horndeski action: Dalang, Fleury & L (*in prep.*)

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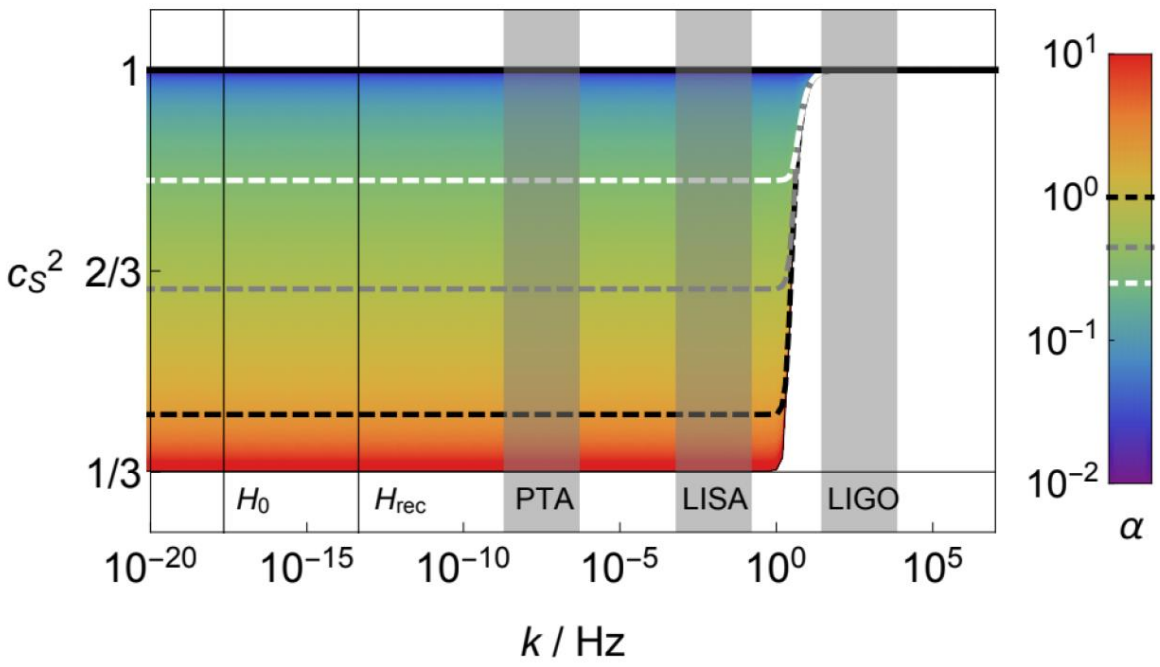

[de Rham & Melville (2018)]

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  [Kennedy, L & Taylor (2019)]
- Genuine MG self-acceleration challenged by GW170817
  [L & Taylor/Lima (2015/16)]
- DE & MG models typically do not address *old* Λ problem

Planck mass variation (*global* version)

L (2019)
cf. sequestering

- Einstein-Hilbert action

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

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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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Note: Just one example. For details see L (2019); Sobral Blanco & L (2020a,b). The Planck mass variation can be realised in generic local scalar-tensor theories with coupling to a three-form gauge field.

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

Note: Just one example. For details see L (2019); Sobral Blanco & L (2020
The Planck mass variation can be realised in generic local scalar-ten
with coupling to a three-form gauge field.

Solves old Cosmological Constant Problem!

New cosmological constant problem

L (2019)

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

  assume spatially perfectly homogeneous matter-only universe with instantaneous collapse at $t_{\rm end}$

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Important consequence: The future observable Universe will reduce to the maximally gravitationally bound structure (Local Group). Everything else will be redshifted away in finite time.

New cosmological constant problem

L (2019)

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

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

where $y \equiv (\rho_{\mathrm{m}}/\bar{\rho}_{\mathrm{m}})^{-1/3}$ and primes denote derivatives wrt $\ln a$

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- Self-consistent

$$\frac{\frac{1}{2}M_{\rm Pl}^{-2}\langle T\rangle}{\Lambda_{\rm obs}} = \frac{\Omega_{\rm m}}{4(1-\Omega_{\rm m})}\frac{t_{\rm max}}{\int_0^{t_{\rm turn}} dt\, a^3 y^3} > \frac{t_{\rm max}}{2t_{\rm turn}} = 1$$

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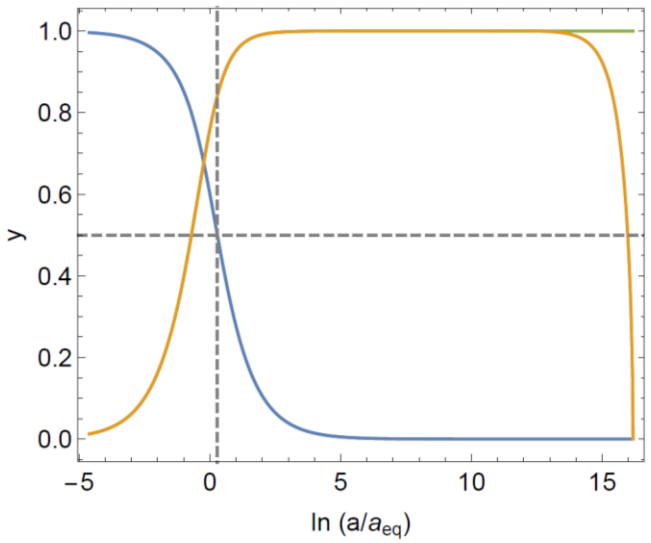
- Standard field equations (w/ non-gravitating vacuum)

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

New cosmological constant problem

L (2019)



- Measure for likelihood for our location in process: $y \in [0, 1)$.

New cosmological constant problem

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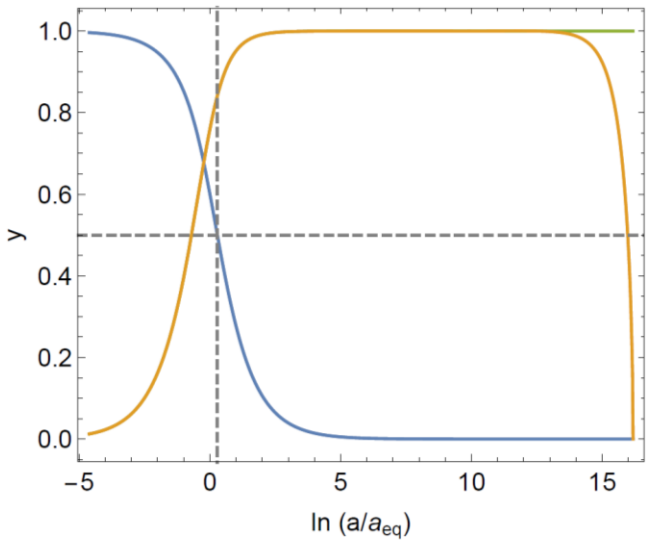

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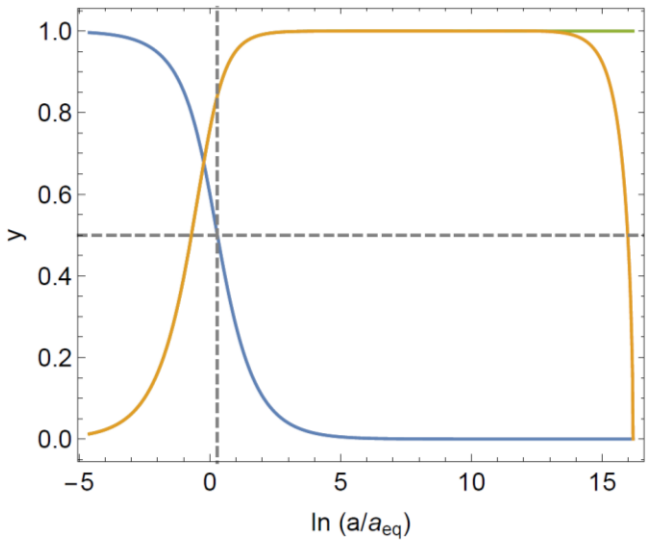

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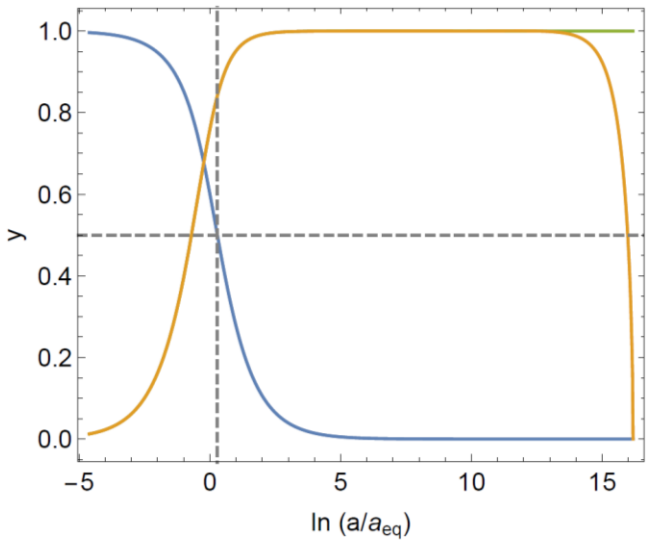

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$$\boxed{\Rightarrow \Omega_\Lambda = 0.704}$$

New cosmological constant problem

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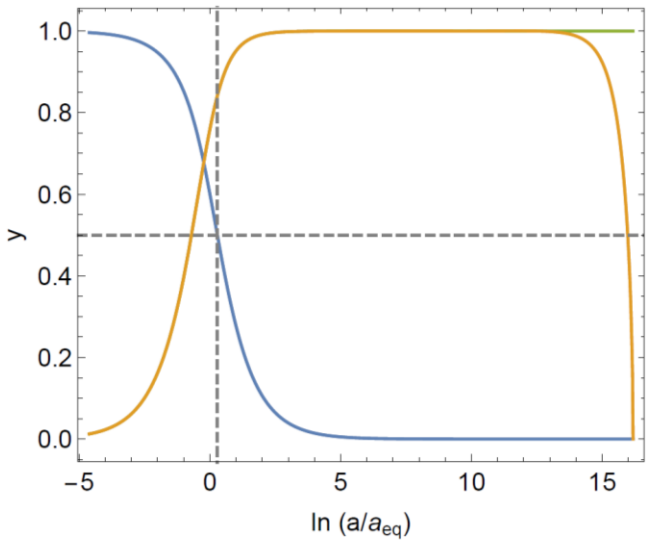

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New cosmological constant problem

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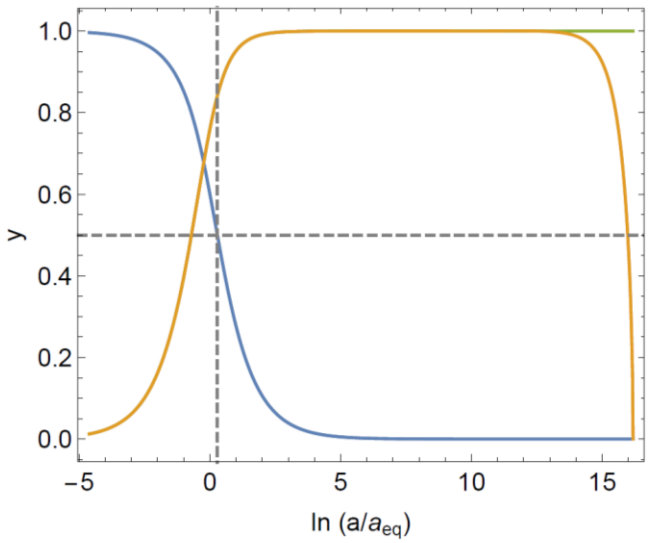

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Solves *new* Cosmological Constant Problem!

Planck mass variation (manifestly *local* version)

L (2019); Sobral Blanco & L (2020a,b)

cf. sequestering

$$S = \int_{\mathcal{M}} d^4x\sqrt{-g}\left[\frac{1}{2}\varphi R - V(\varphi) + \mathcal{L}_m(g_{\mu\nu}, \Psi_m)\right]$$

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$$S_{\mathrm{A}} = \frac{1}{4!}\int_{\mathcal{M}} d^4x\, \epsilon^{\mu\nu\rho\sigma}\, \sigma(\varphi)\, F_{\mu\nu\rho\sigma}\,, \quad F_{\mu\nu\rho\sigma} = \partial_{[\mu}A_{\nu\rho\sigma]} \qquad \mathcal{L}_m = \bar{\mathcal{L}}_m - M_P^2(\Lambda_{\mathrm{vac}} + \Lambda_B)$$

$$\tau_{\mu\nu}$$

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$$\varphi G_{\mu\nu} + \left[V(\varphi) + M_P^2\Lambda_{\rm vac}(\varphi)\right] g_{\mu\nu} = (\nabla_\mu\nabla_\nu - g_{\mu\nu}\Box)\varphi + \tau_{\mu\nu}$$

$$\int_{\mathcal{M}} d^4x\sqrt{-g}\left[\frac{1}{2}R - V'(\varphi) - M_P^2\Lambda'_{\rm vac}(\varphi) + \frac{\sigma'(\varphi)}{4!}\frac{\varepsilon^{\mu\nu\rho\gamma}}{\sqrt{-g}}F_{\mu\nu\rho\gamma}\right] = 0$$

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$$G_{\mu\nu} + \frac{1}{2-\alpha}\left[(\beta-\alpha)M_P^{-2}\Delta V + \frac{M_P^{-2}}{2}\langle\tau\rangle + \Delta\Lambda\right] g_{\mu\nu} = M_P^{-2}\tau_{\mu\nu}$$

$$\alpha \equiv \partial\ln\Lambda_{\rm vac}/\partial\ln\varphi \qquad \beta \equiv \partial\ln\Delta V/\partial\ln\varphi \qquad \Delta V = V - V_c$$

$$\frac{M_P^2}{\varphi}\Delta\Lambda \equiv -\frac{\sigma'}{4!}\left\langle\frac{\varepsilon^{\mu\nu\rho\gamma}}{\sqrt{-g}}F_{\mu\nu\rho\gamma}\right\rangle = -\frac{\sigma'}{4!}\frac{\int d^4x\varepsilon^{\mu\nu\rho\gamma}F_{\mu\nu\rho\gamma}}{\int d^4x\sqrt{-g}}$$

Planck mass variation (manifestly *local* version)

L (2019); Sobral Blanco & L (2020a,b)

$$S = \int_{\mathcal{M}} d^4x\sqrt{-g}\left[\frac{1}{2}\sum_{i=2}^{5}\mathcal{L}_i(g_{\mu\nu},\varphi) + \mathcal{L}_m(g_{\mu\nu},\Psi_m)\right]$$

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$$\begin{aligned} S \;=\; & \int d^4x\sqrt{-g}\,(\mathcal{L}_{\rm gravity}(g_{\mu\nu},\phi) - V(\phi,\varphi_i,\Phi_i)) \\ & + \sum_i \int d^4x\sqrt{-g}B_i(\varphi_i,\chi_i)\mathcal{L}_{m_i}\left(\psi_{m_i}; A_i^2(\Phi_i,\xi_i)g_{\mu\nu} + D_i^2(\Phi_i,\xi_i)\partial_\mu\Phi_i\partial_\nu\Phi_i\right) \\ & + \frac{1}{4!}\int d^4x\epsilon^{\mu\nu\rho\sigma}\left(\sigma(\phi)F_{\mu\nu\rho\sigma} + \sum_i \sigma_i(\varphi_i)(F_i)_{\mu\nu\rho\sigma} + \hat{\sigma}_i(\Phi_i)(\hat{F}_i)_{\mu\nu\rho\sigma}\right) \end{aligned}$$

$$\frac{1}{4!}\int d^4x\epsilon^{\mu\nu\rho\sigma}\sigma(\phi)F_{\mu\nu\rho\sigma} \to \frac{1}{4!}\int d^4x\Theta(\phi-\phi_0)\epsilon^{\mu\nu\rho\sigma}\sigma(\phi)F_{\mu\nu\rho\sigma}$$

Search for *New Physics* in the nonlinear Cosmos

Search for *New Physics* in the nonlinear Cosmos

New galaxy surveys

- DESI, Euclid, LSST/VRO, SKA

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$P(k)$ to $\sim$10 h/Mpc with new physics

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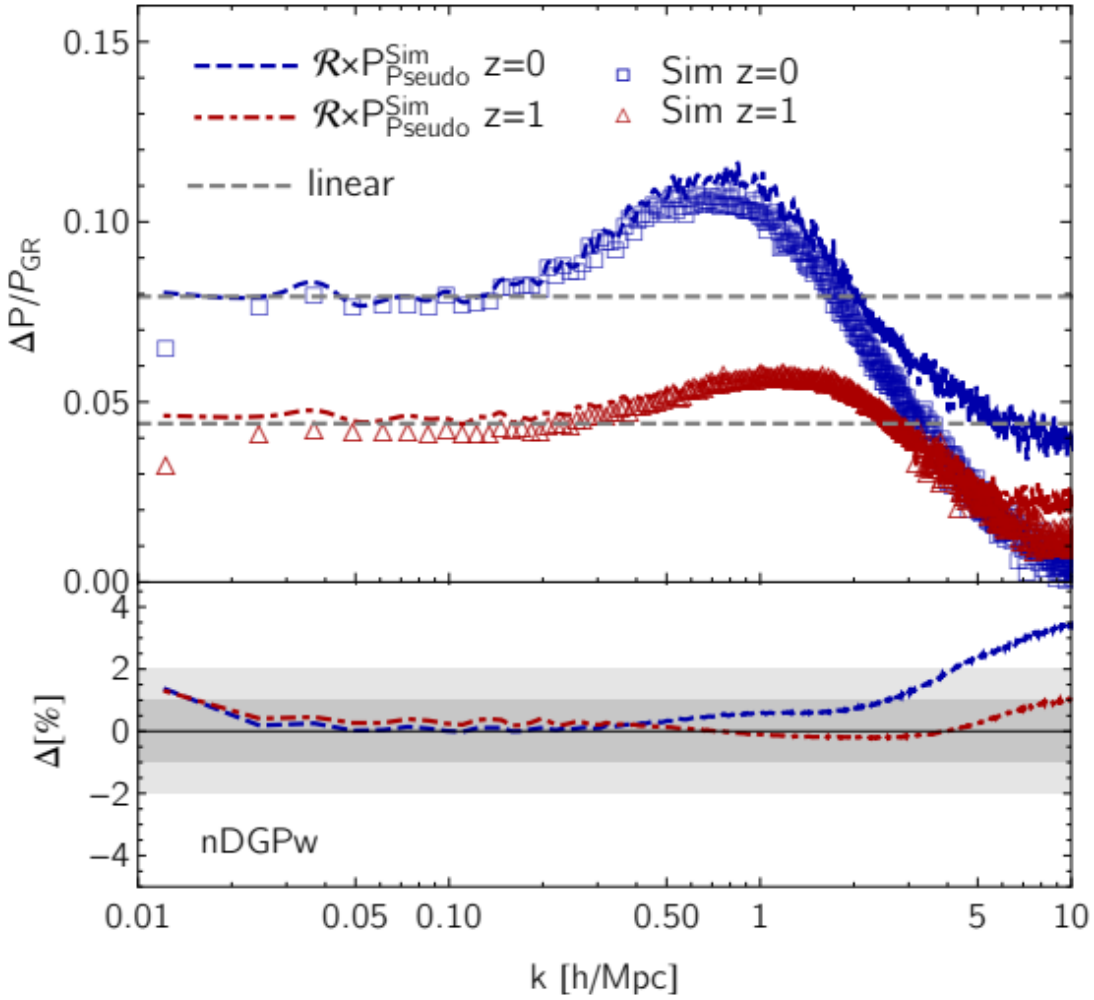

Reaction: Cataneo, L, Heymans, Mead, Barreira, Bose, Li (2019)
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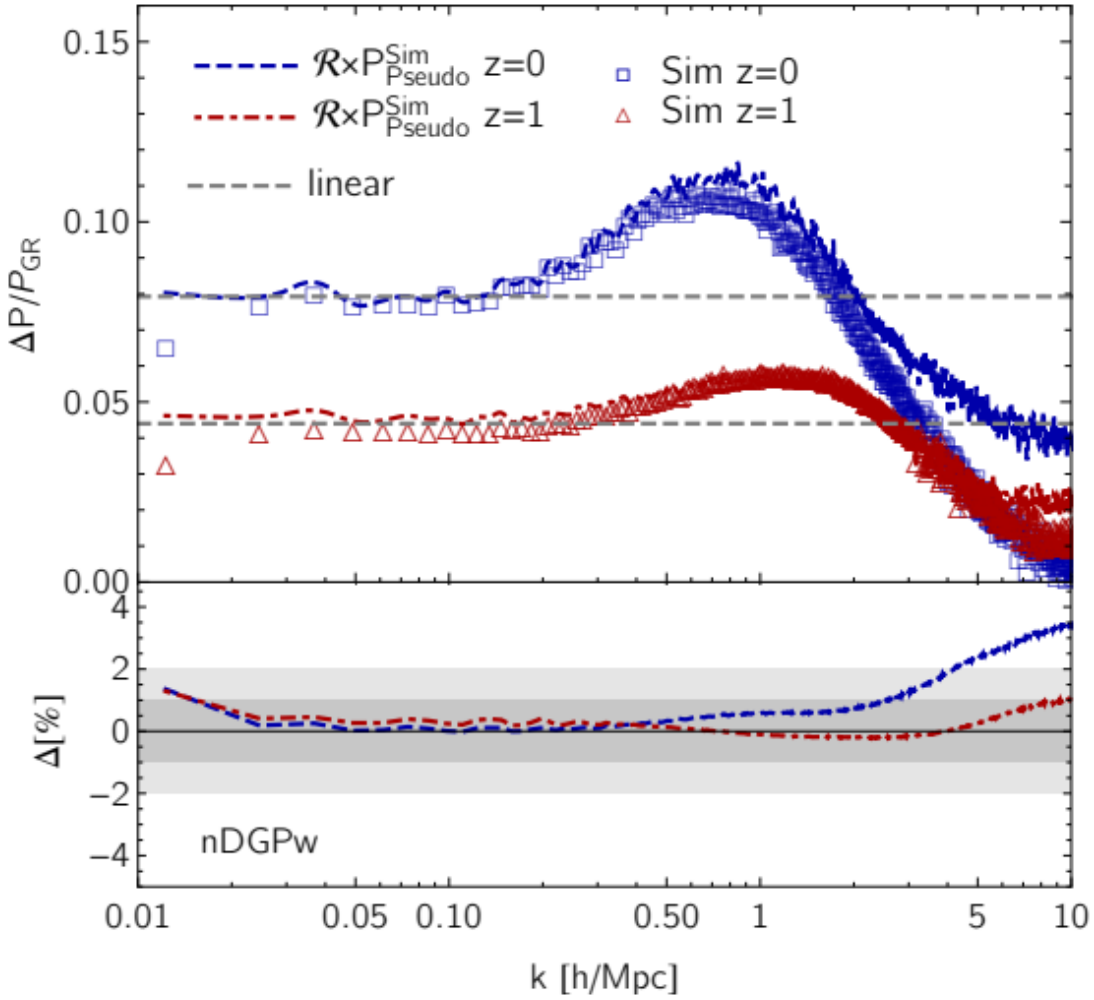

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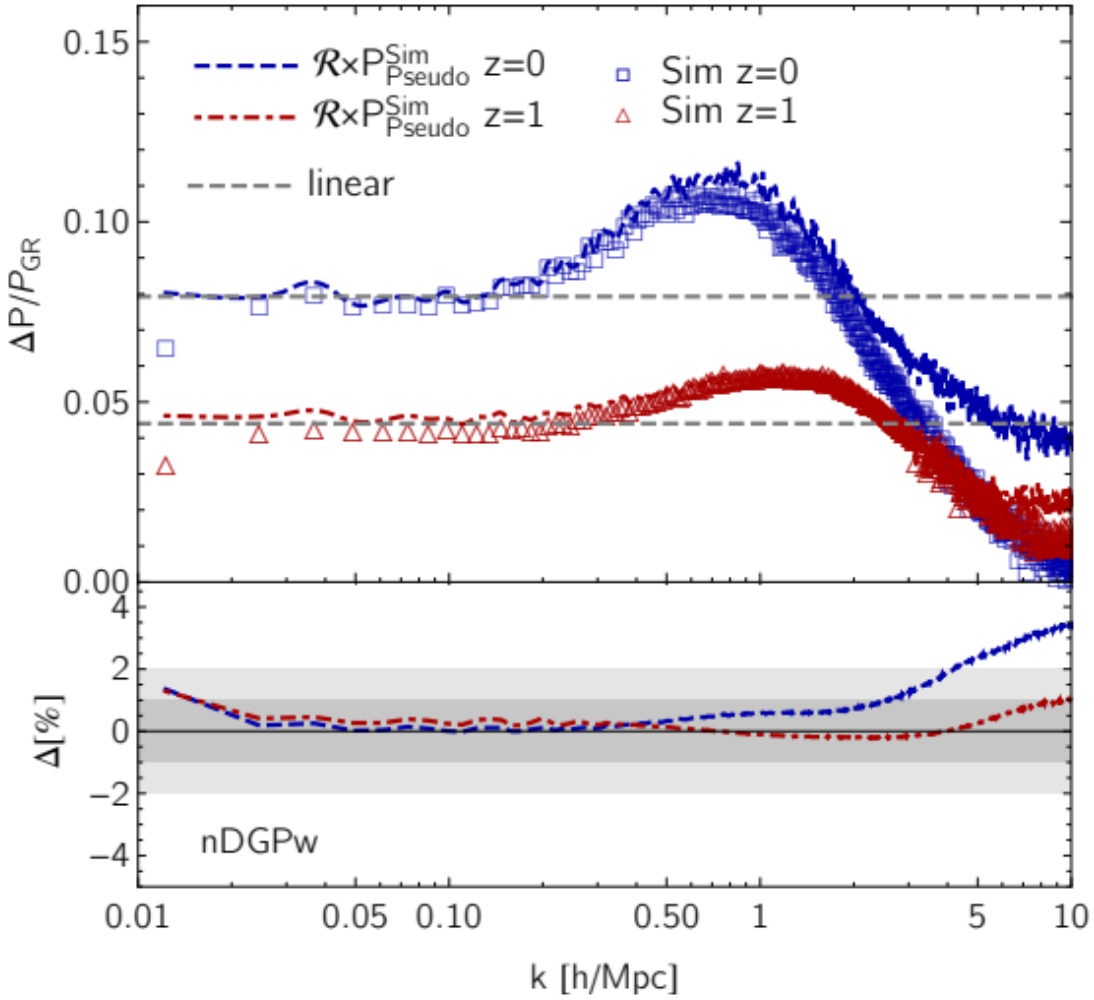
Galaxy power spectrum

- HyPk (Gaussian Streaming Model)



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Work in progress
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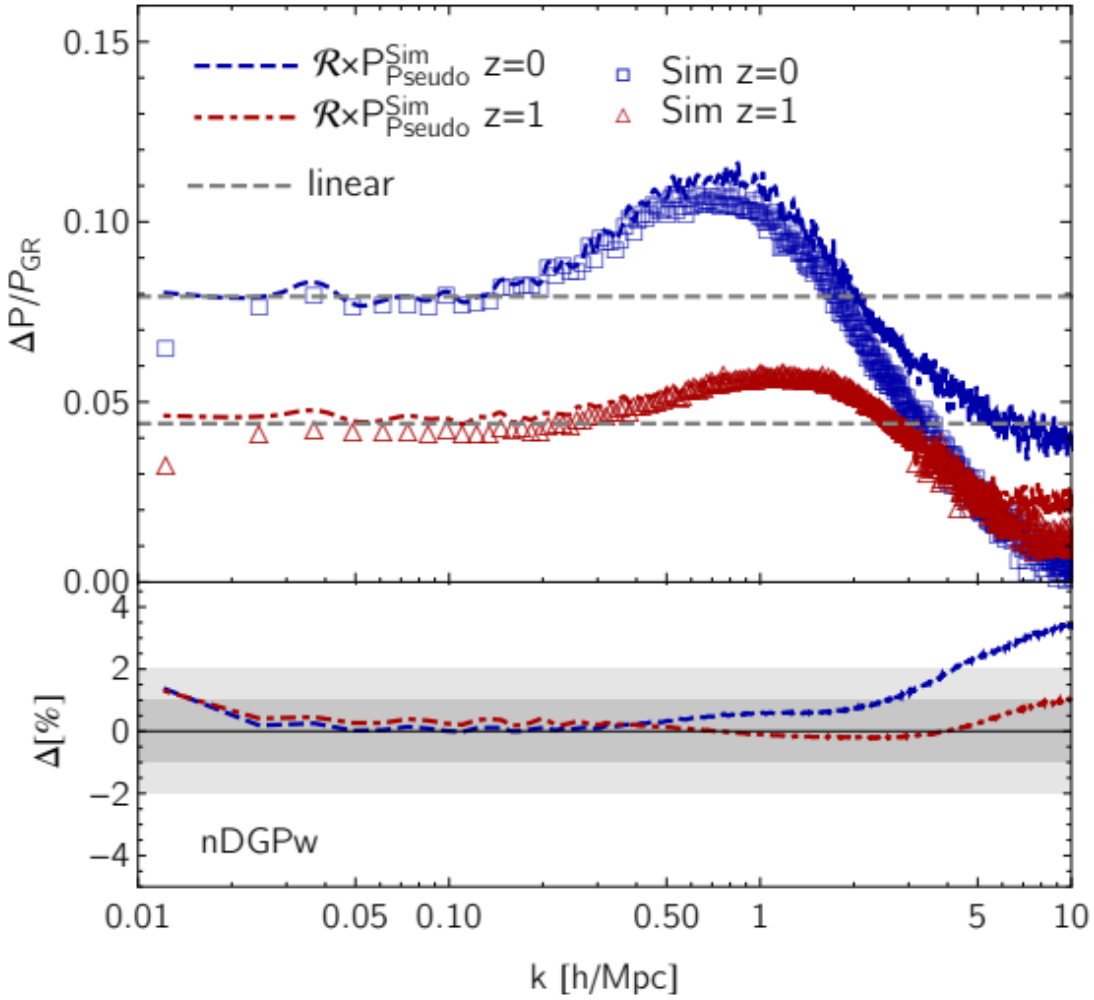

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Work in progress
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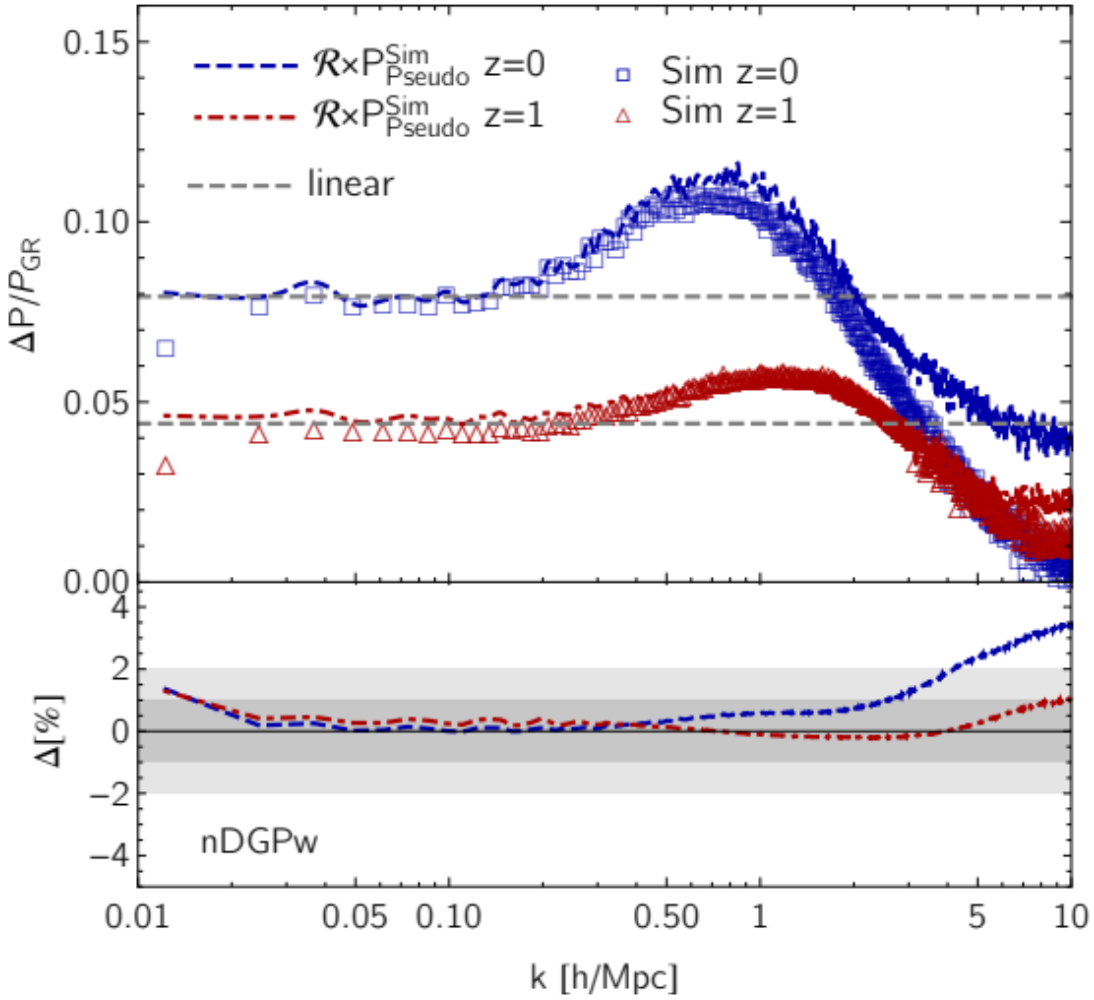
Efficient detection of new physics
- BaCoN (Bayesian Neural Network)



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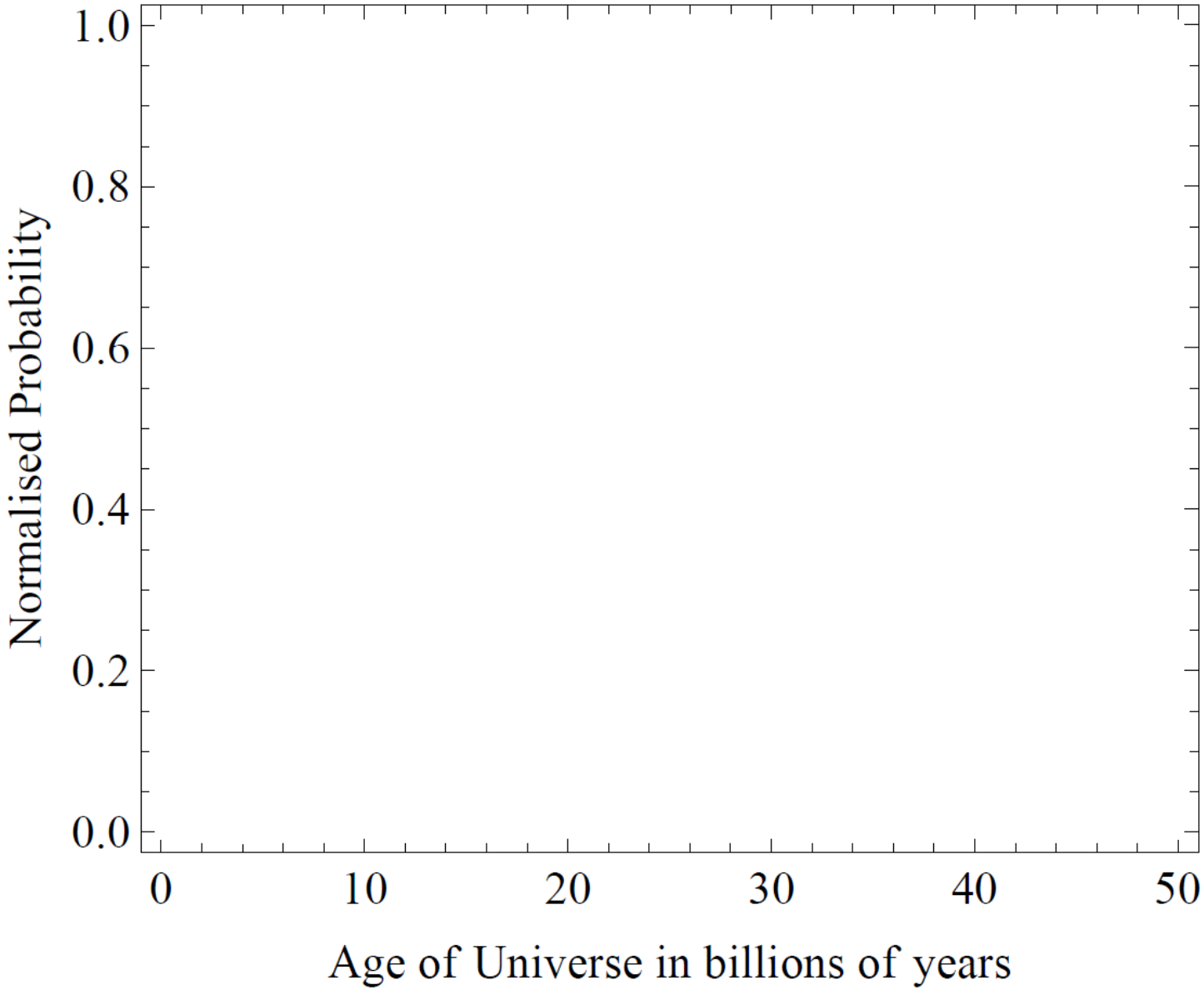
BaCoN: Mancarella, Kennedy, Bose, L (2020)

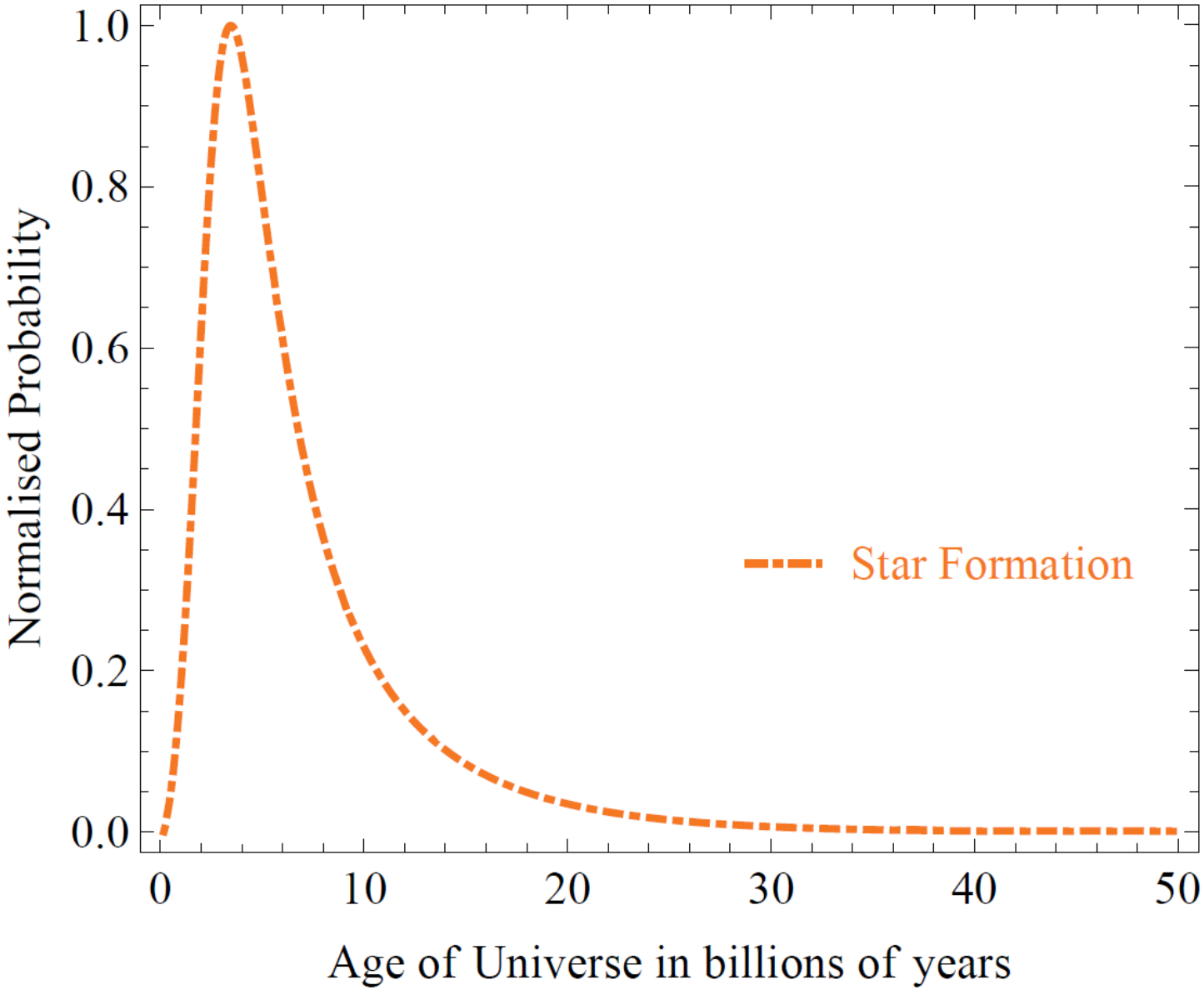
Cosmological constant

Cosmological constant

Why Now?



Sobral Blanco & L (2020b)



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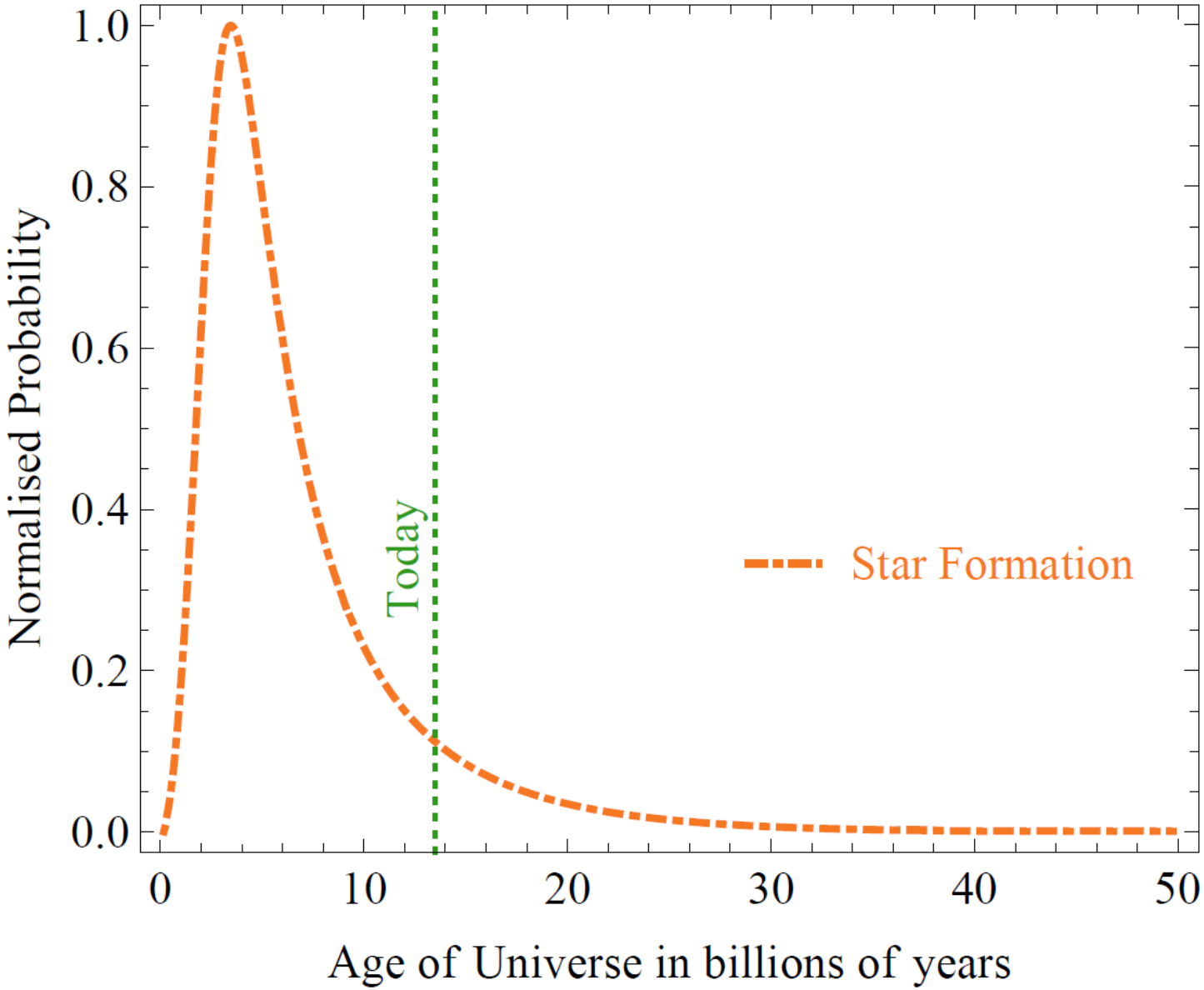

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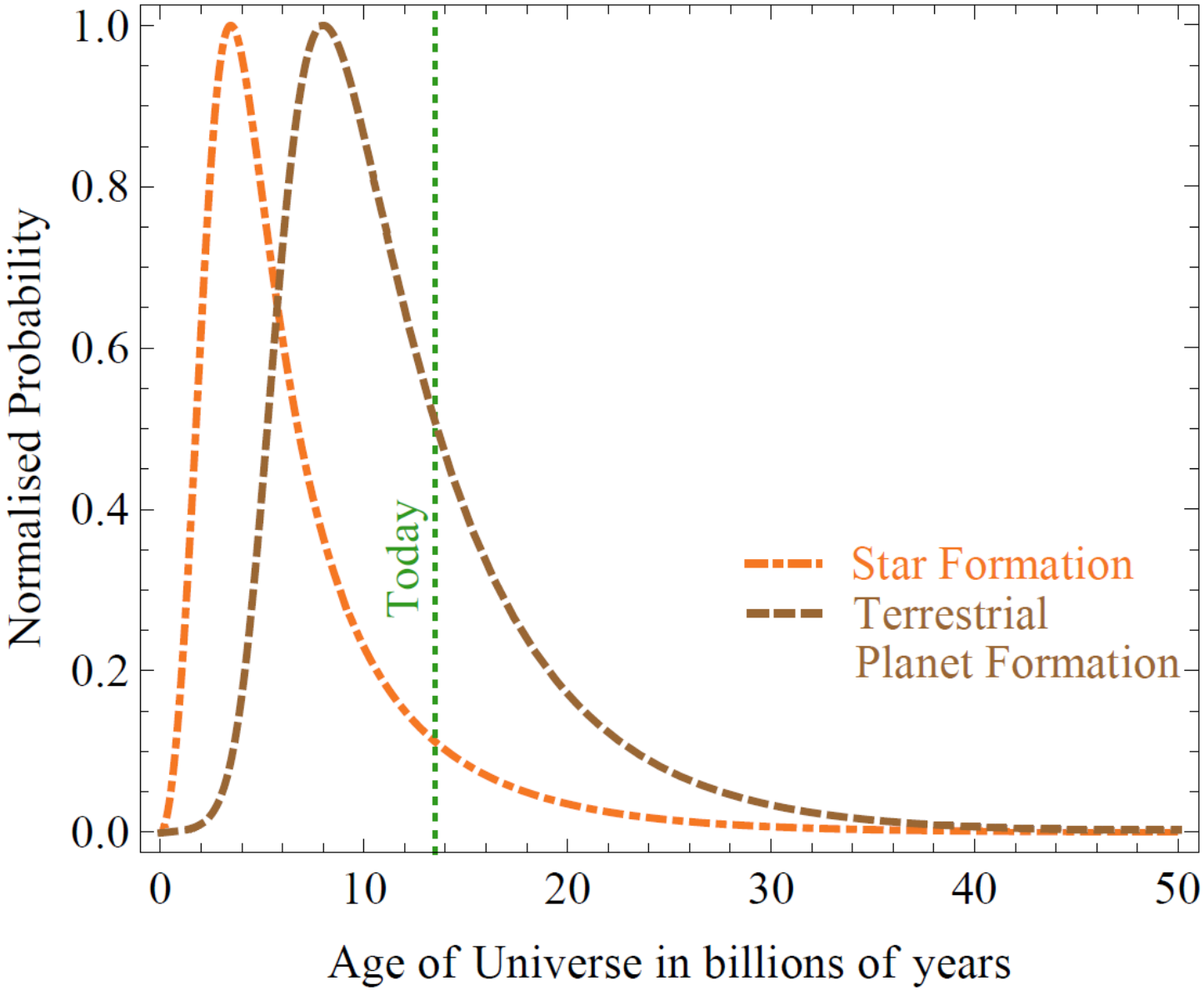
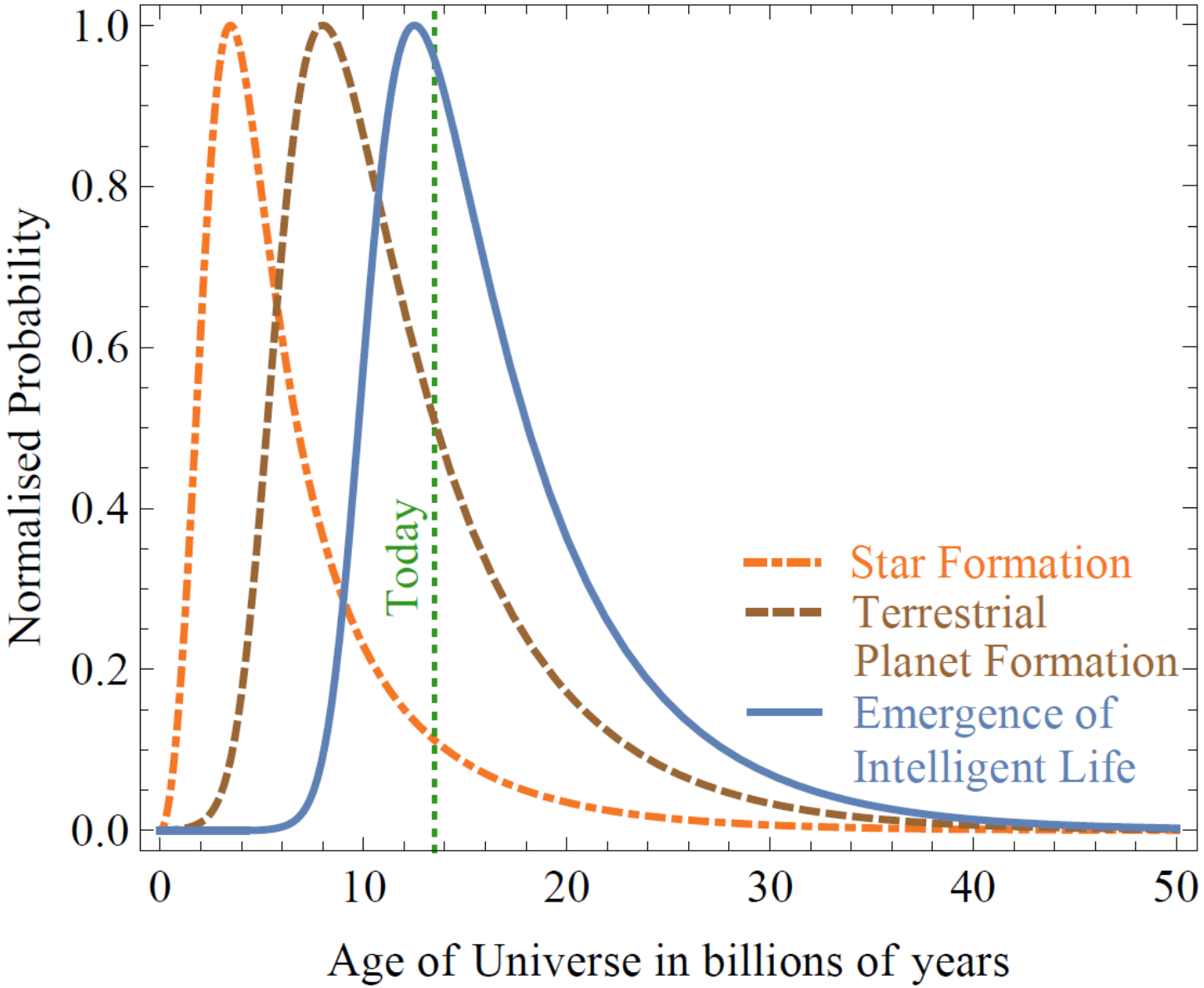
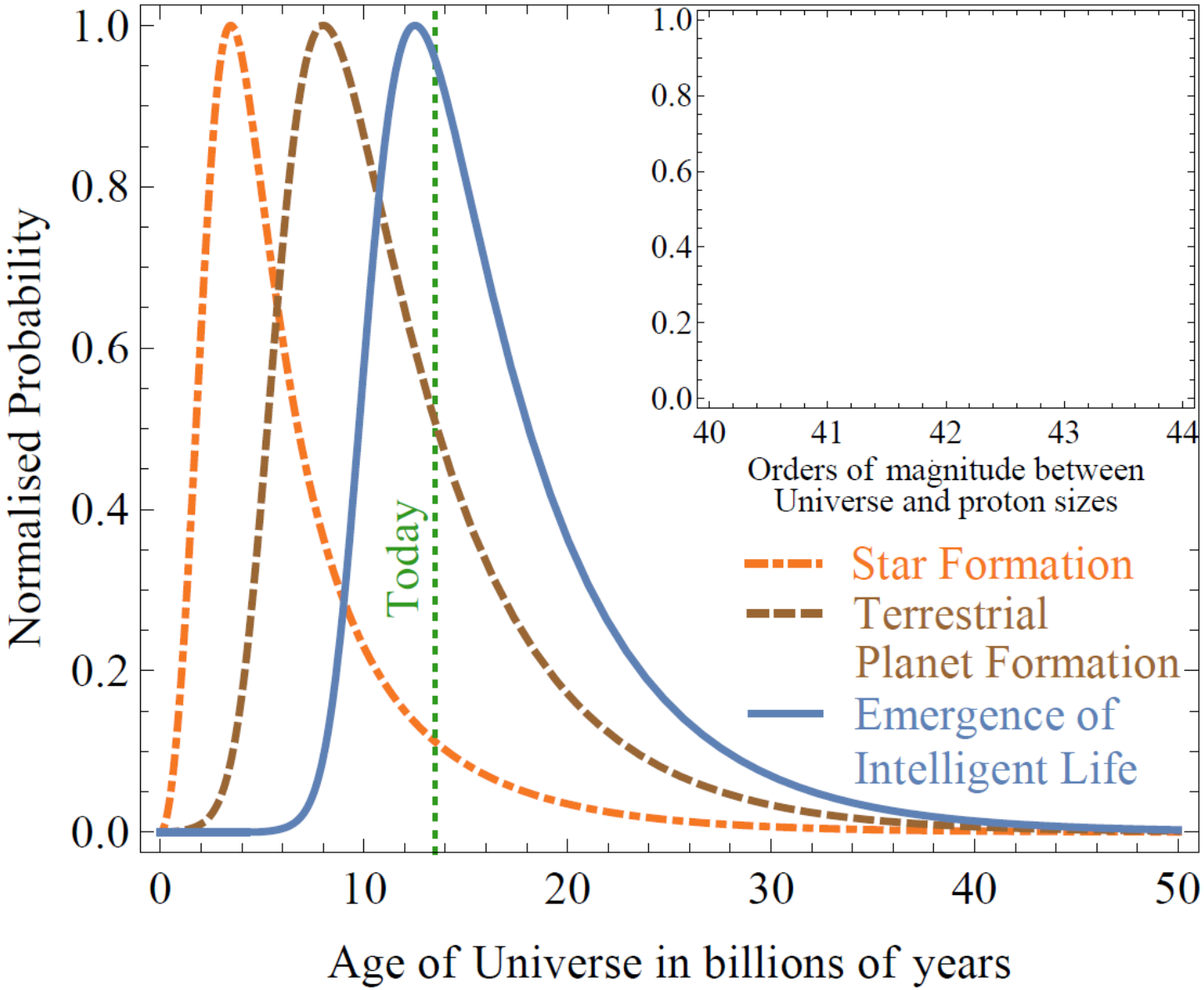
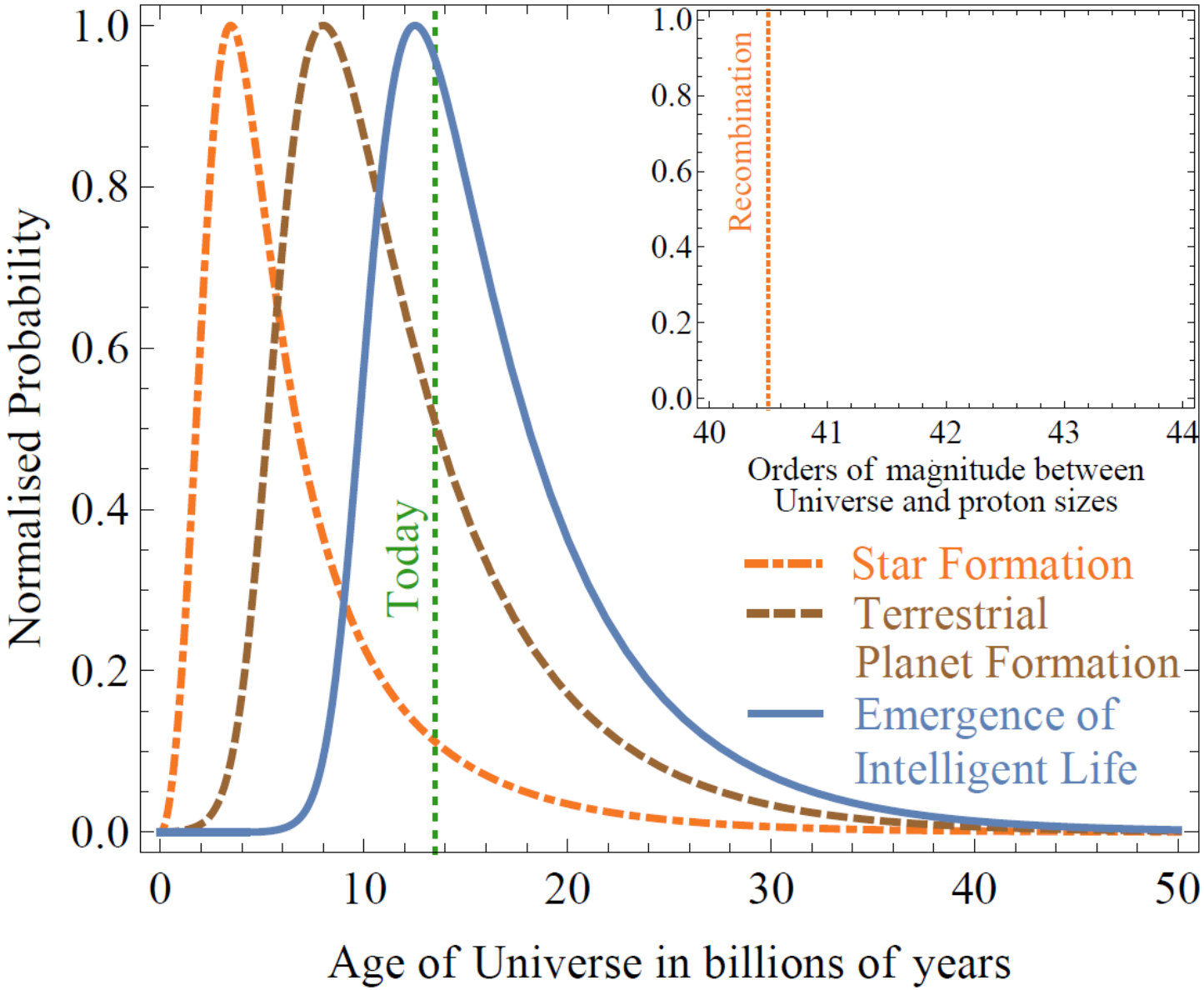


Sobral Blanco & L (2020b)

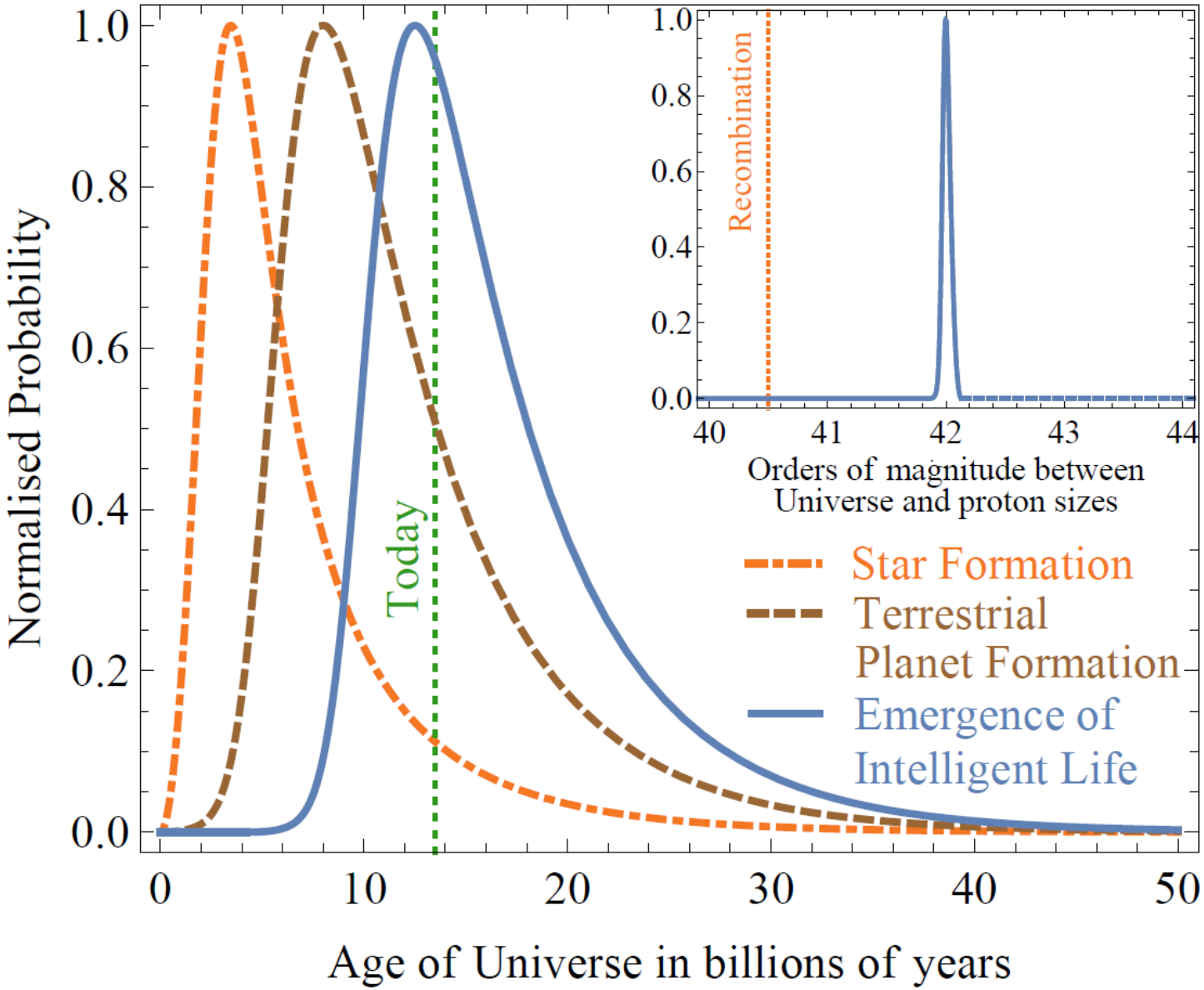


Sobral Blanco & L (2020b)

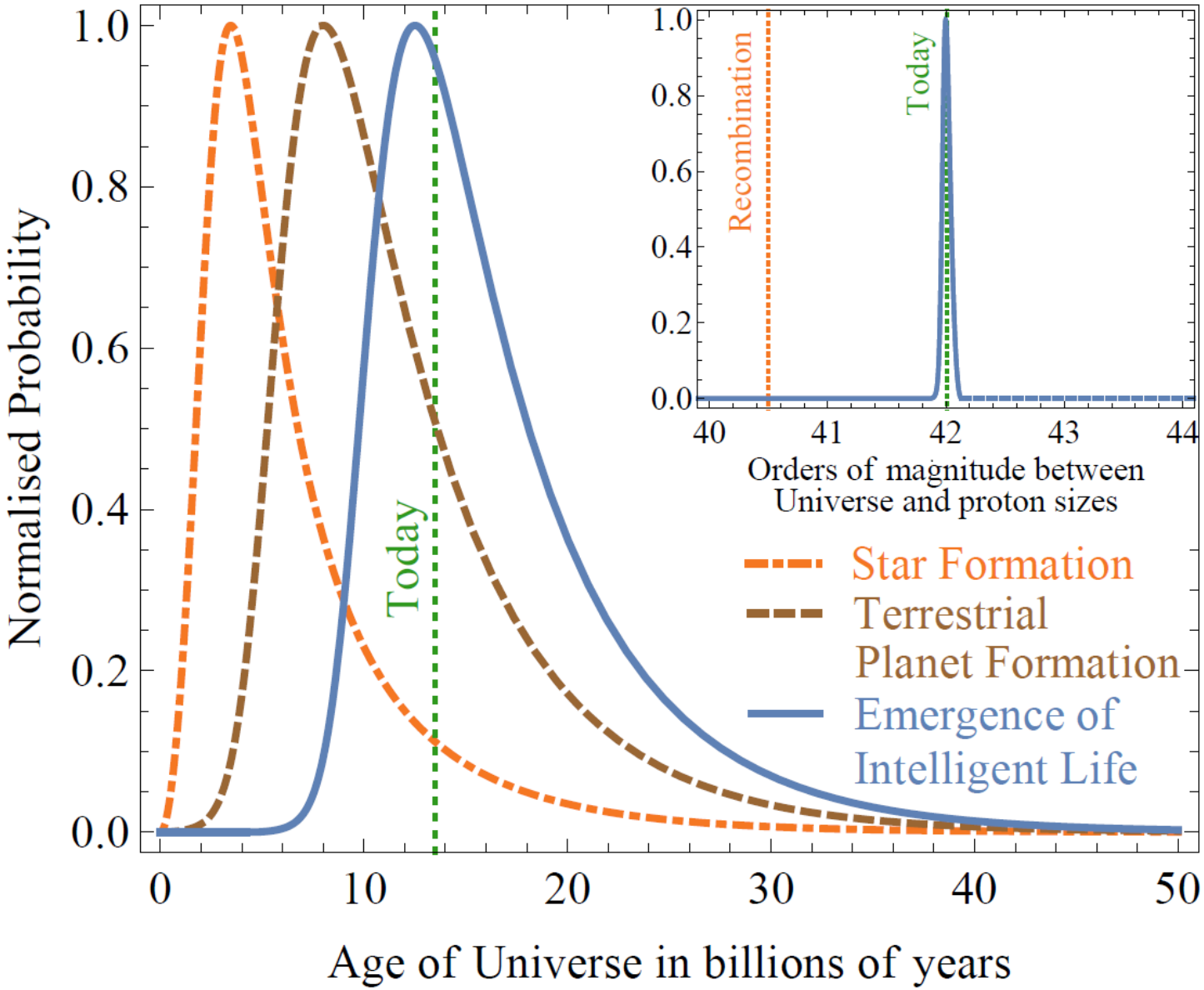

Normalised Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
Age of Universe in billions of years
Today
Star Formation
Terrestrial Planet Formation
Emergence of Intelligent Life
1.0
0.8
0.6
0.4
0.2
0.0
40
41
42
43
44
Orders of magnitude between Universe and proton sizes



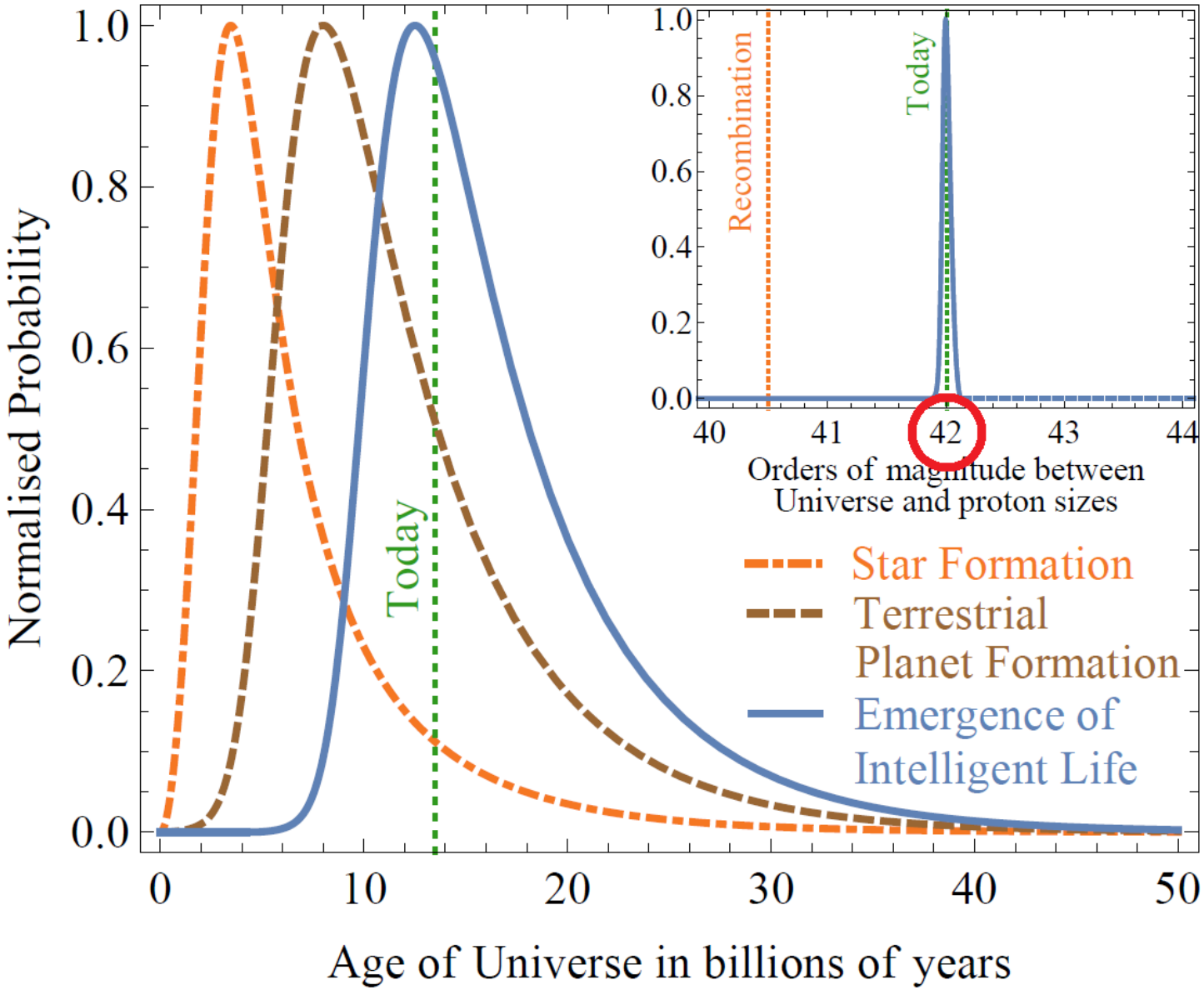
Sobral Blanco & L (2020b)



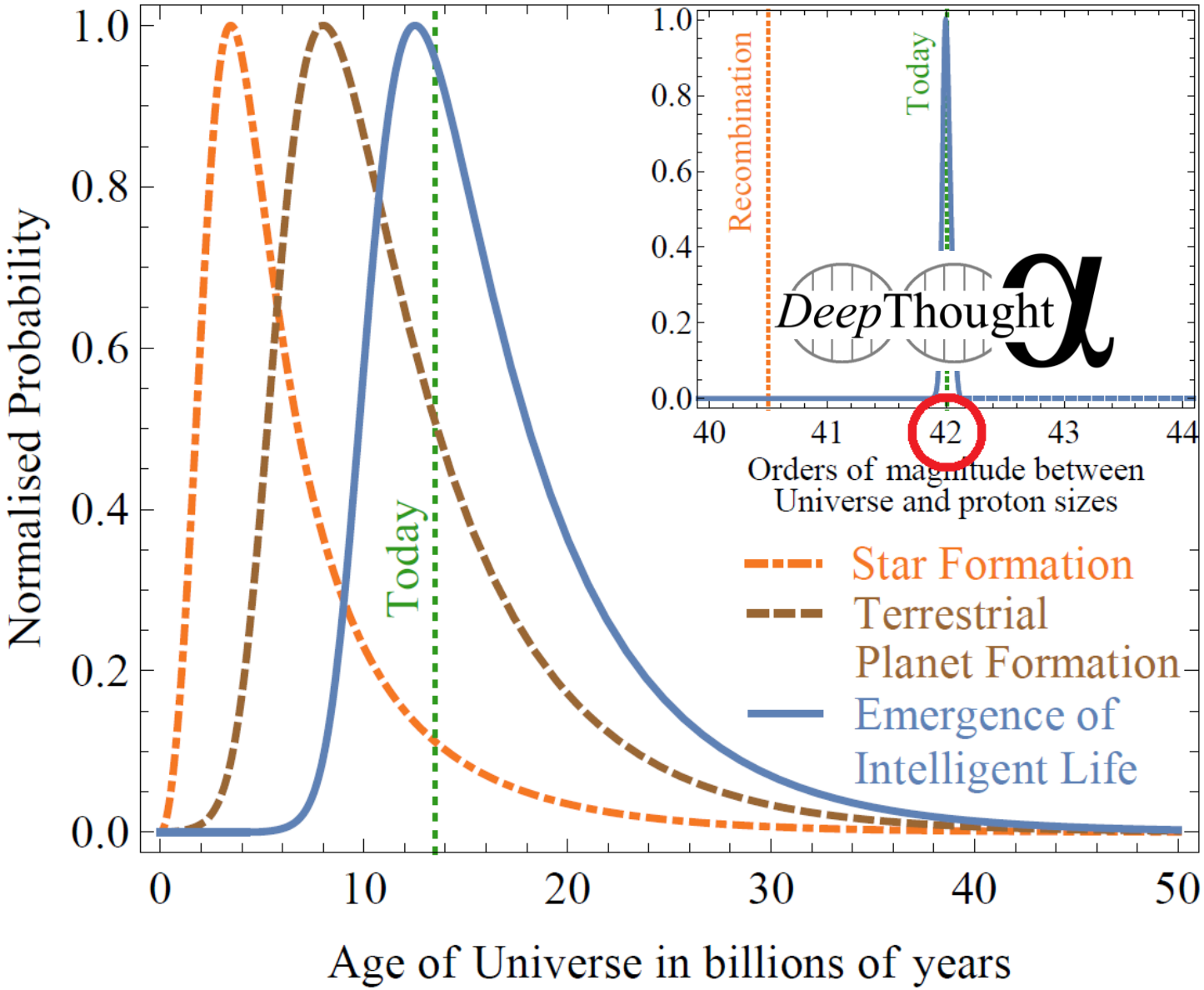
Sobral Blanco & L (2020b)



Sobral Blanco & L (2020b)

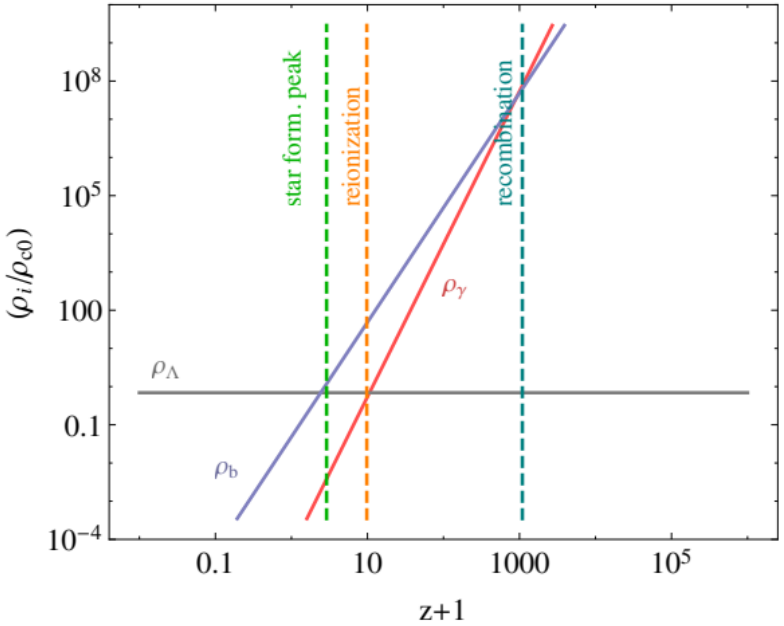


Sobral Blanco & L (2020b)



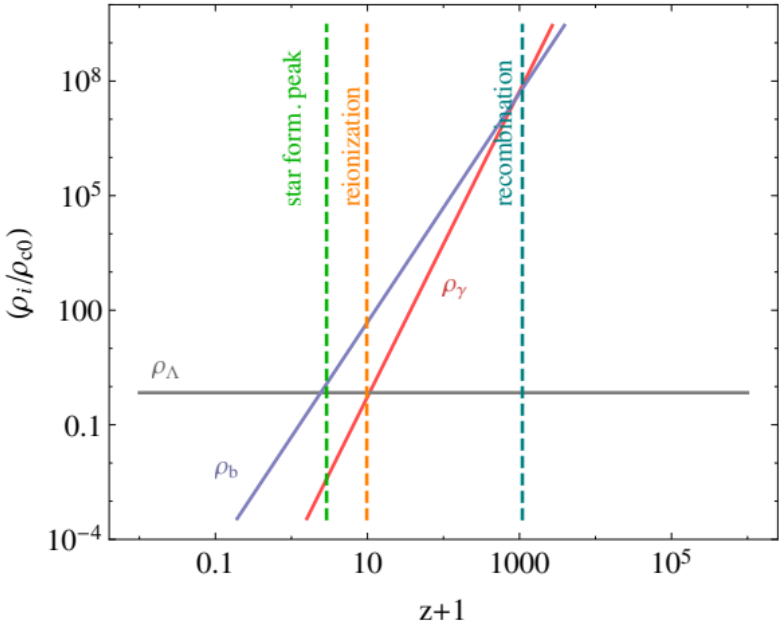
Sobral Blanco & L (2020b)

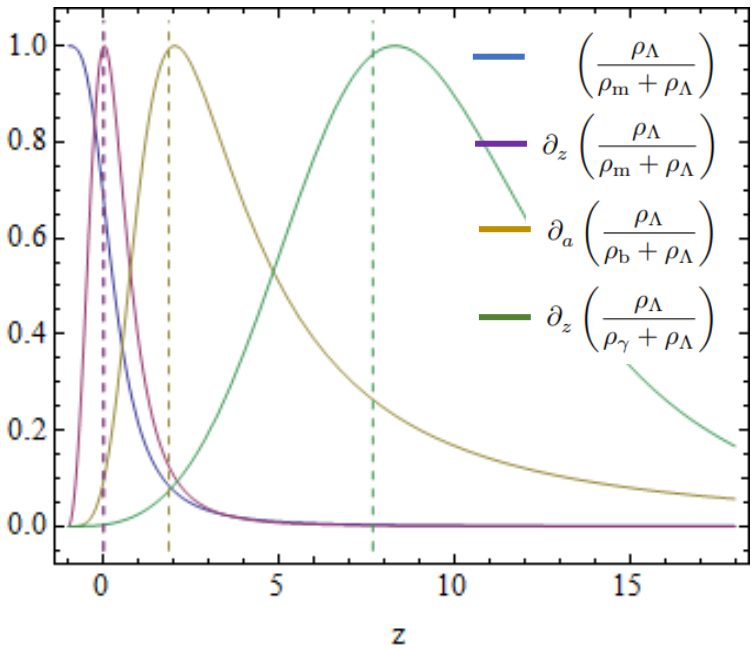
Example: Cosmic Coincidences across the Multiverse



Smer-Barreto & L (2017)

Example: Cosmic Coincidences across the Multiverse





Smer-Barreto & L (2017)

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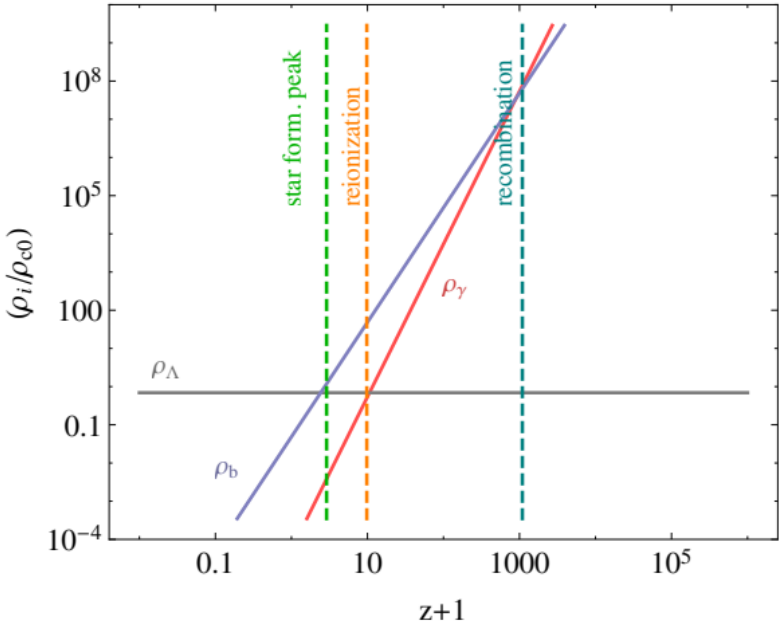
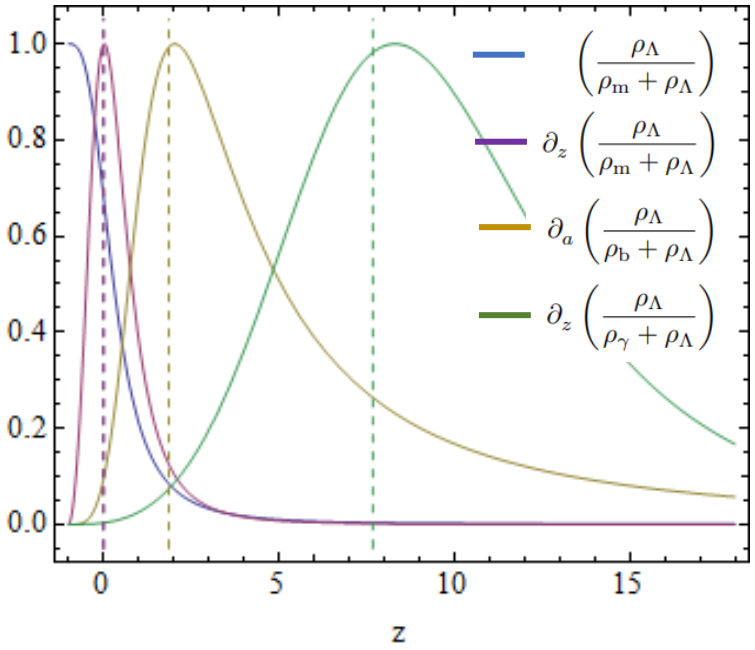
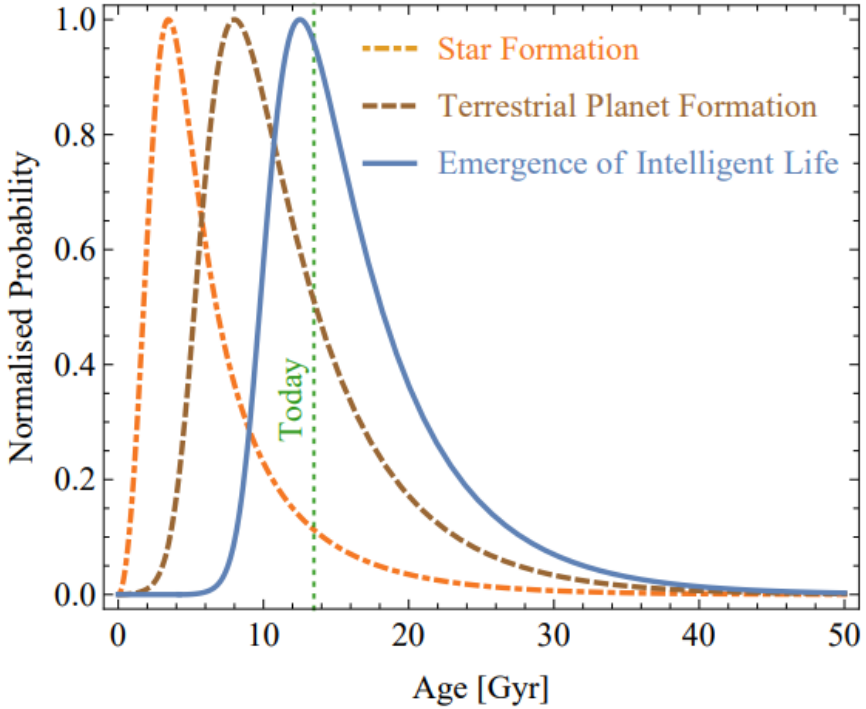


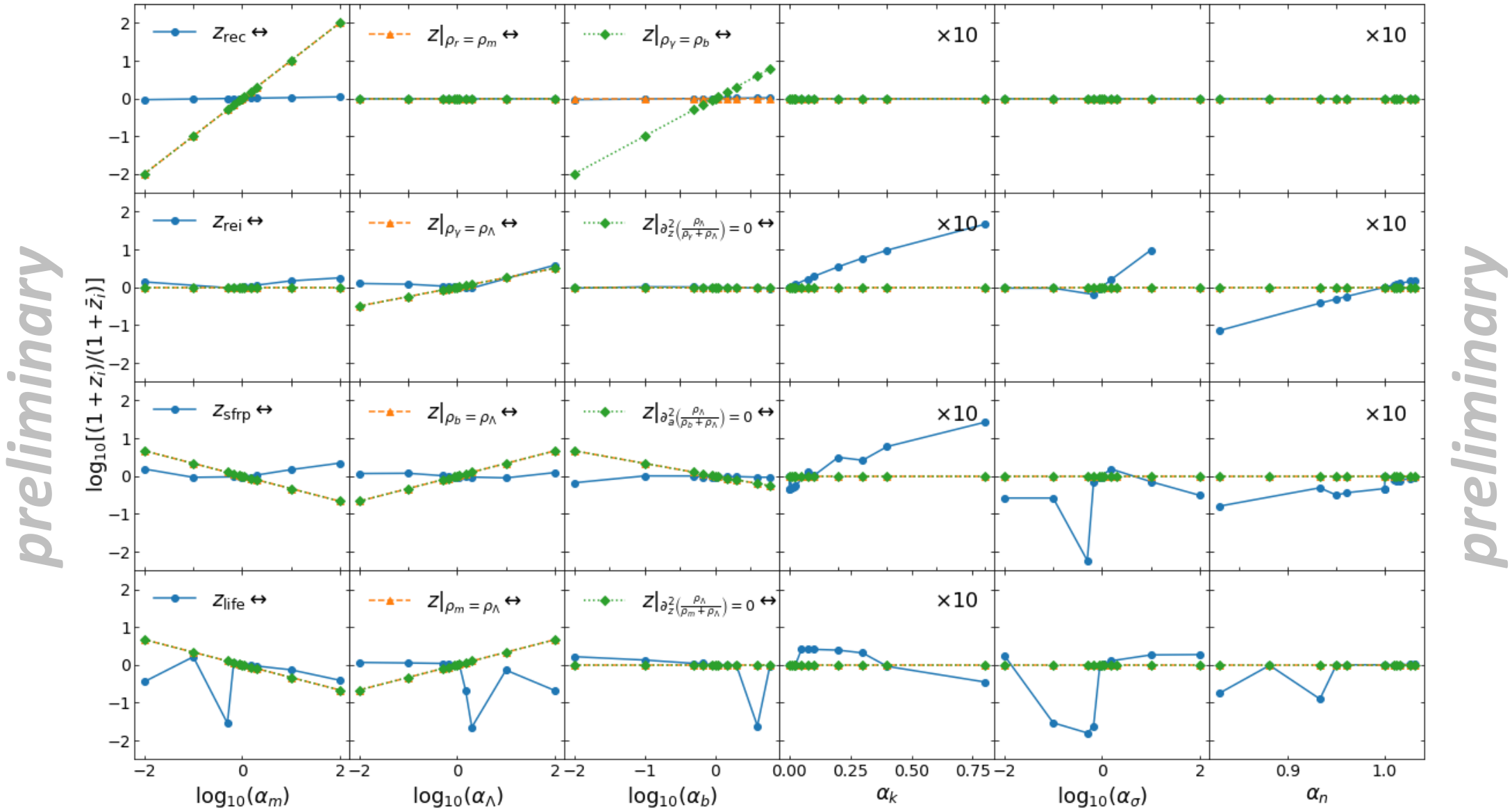
Smer-Barreto & L (2017)



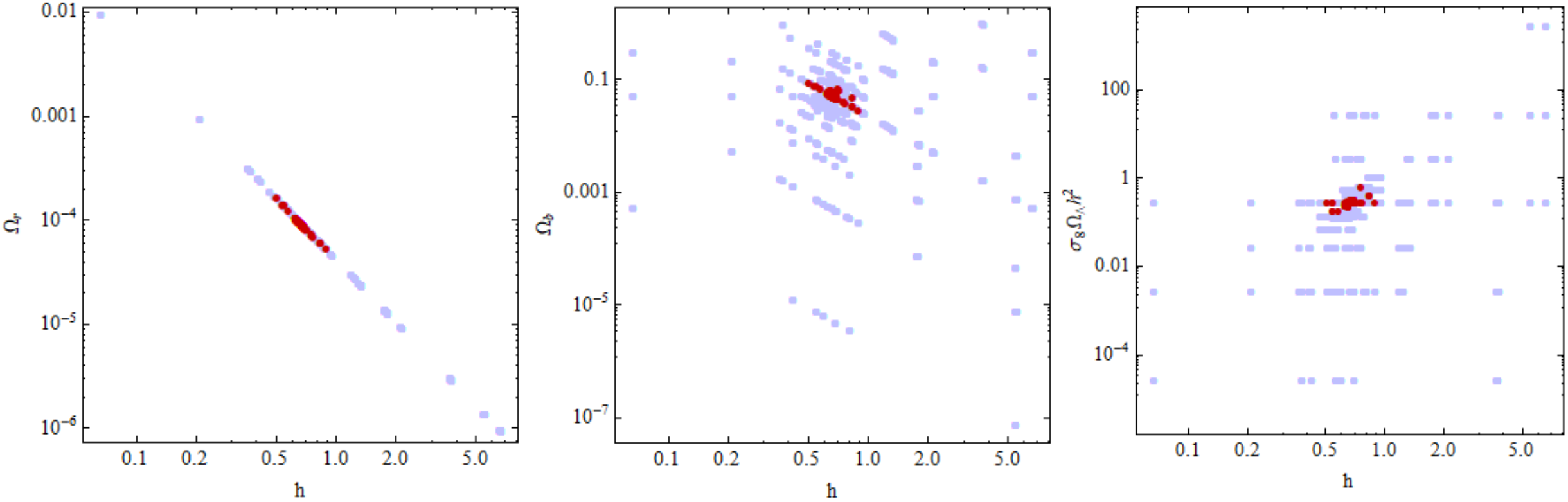


Sobral Blanco & L (2020b)

Example: Cosmic Coincidences across the Multiverse



Example: Cosmic Coincidences across the Multiverse



preliminary

Conclusions

Cosmic late-time acceleration from alternatives to GR is difficult

We can build a toy model solution to the Cosmological Constant Problem

Need accurate tools for general tests for New Physics in the nonlinear Cosmos

There is no *Why Now?* Problem in our Universe

Cosmic coincidences not unique to our Universe but appear in restricted set

Thank you!