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TWEAKING GRAVITY

Tiago B. Gonçalves
(IA-U.Lisboa)

with **Francisco S.N. Lobo** (IA-U.Lisboa) & **João Luís Rosa** (U.Tartu)

7th PhD Student workshop

LIP & IDPASC

COIMBRA, JULY 6-7

LIP LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

IDPASC

Acknowlegments: UIDB/04434/2020 & UIDP/04434/2020, PTDC/FIS-OUT/29048/2017, PTDC/FIS-AST/0054/2021, PRT/BD/153354/2021.

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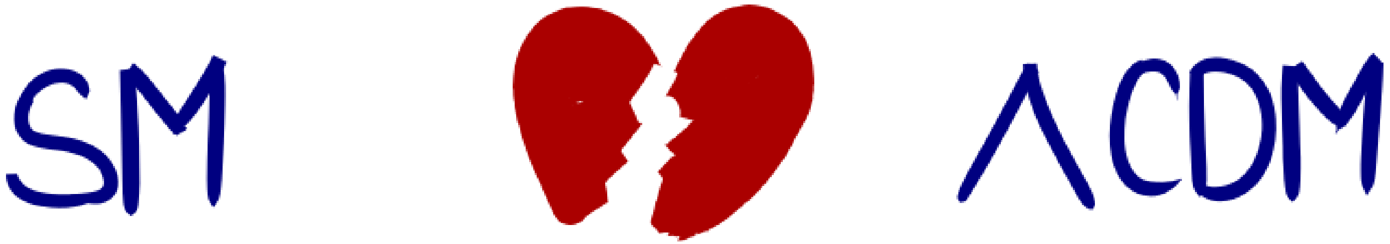
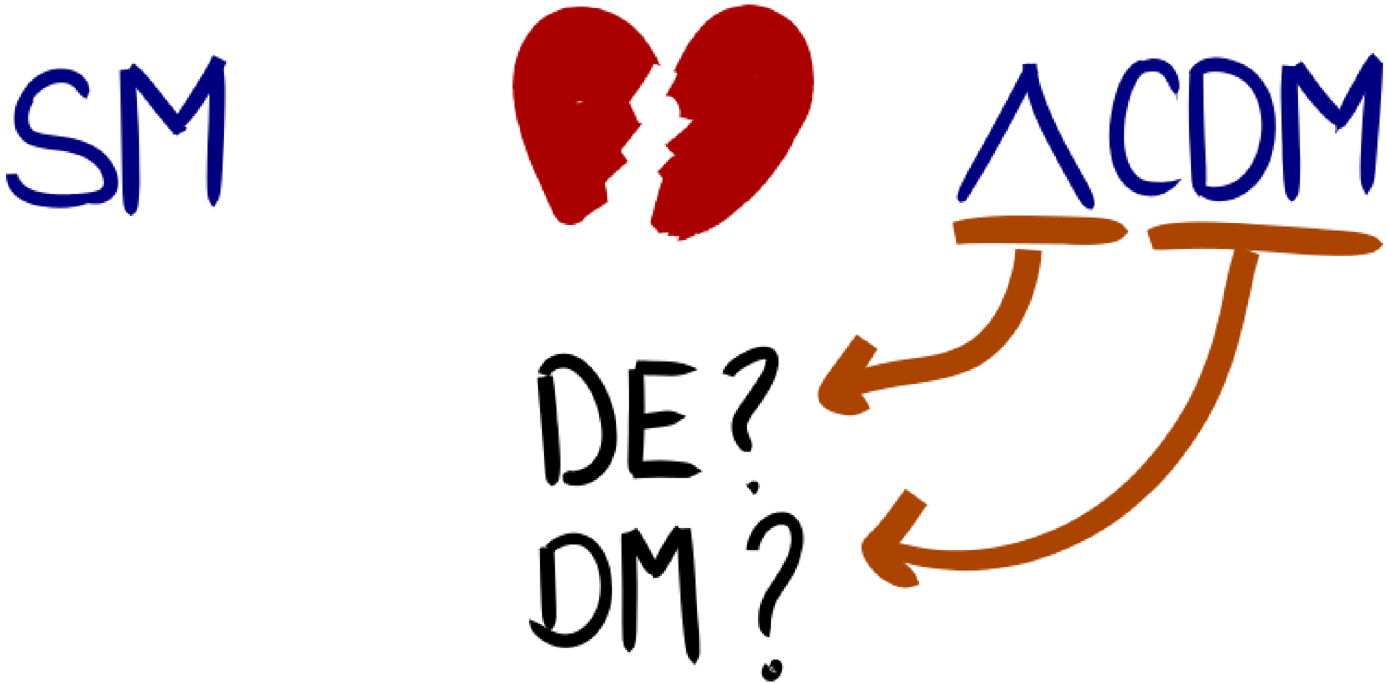
Why tweak gravity?

SM ♥ ΛCDM

Why tweak gravity?



Why tweak gravity?



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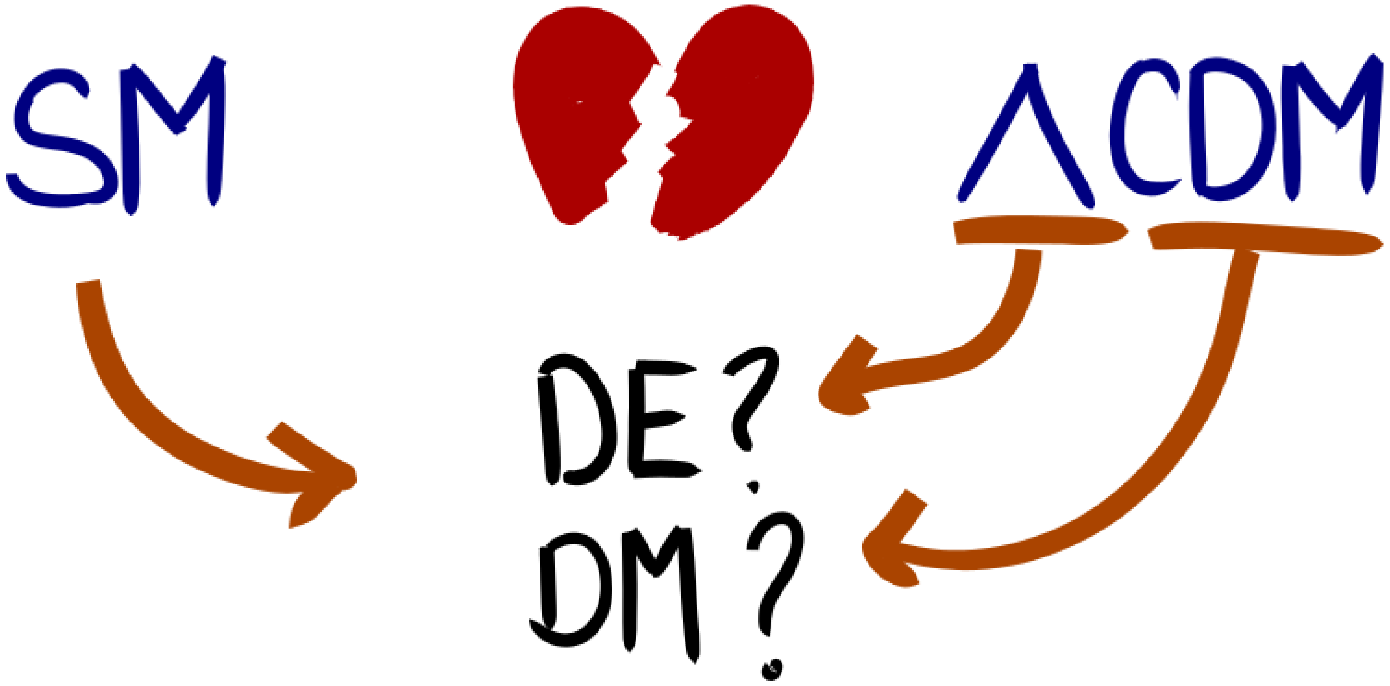

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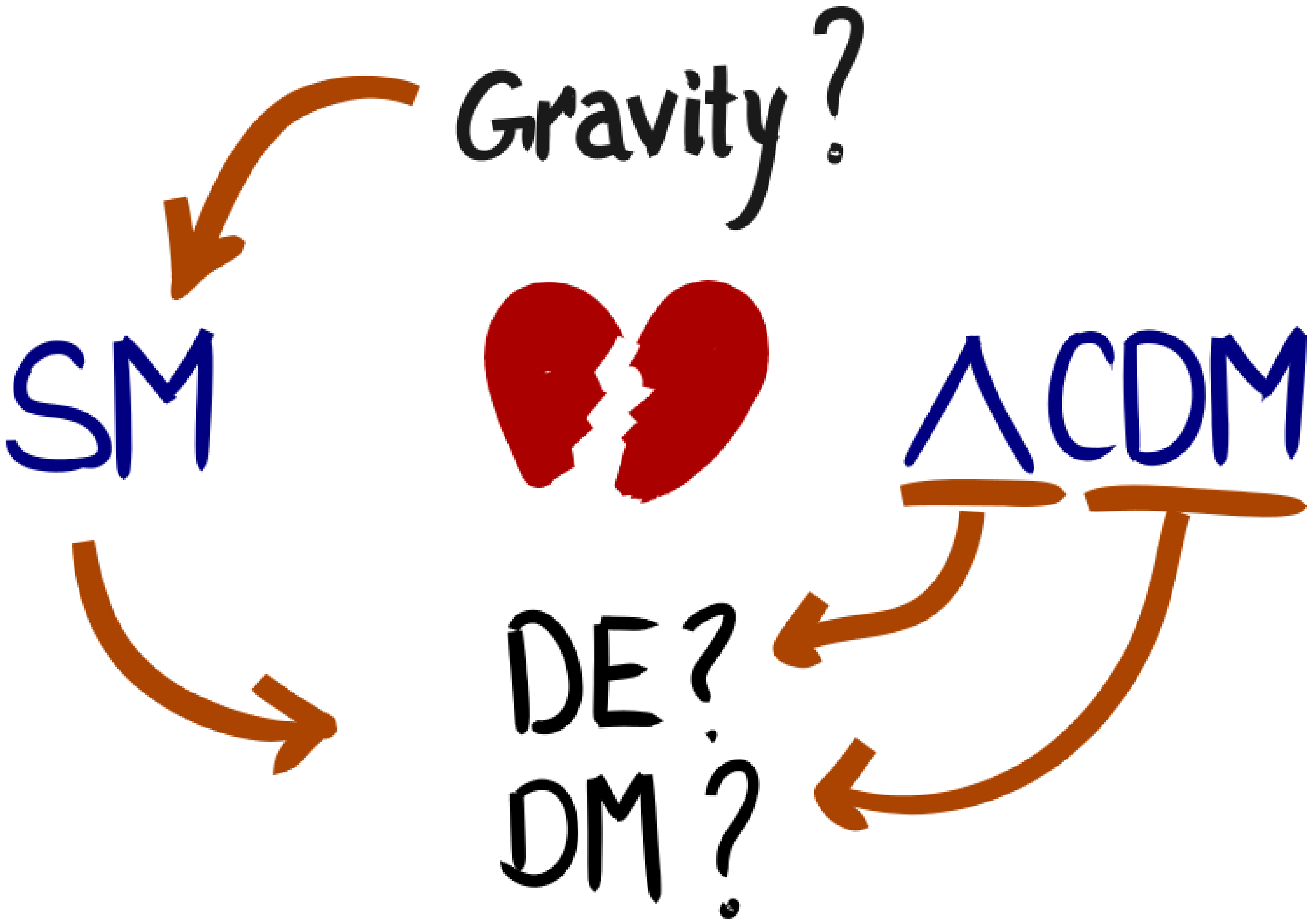

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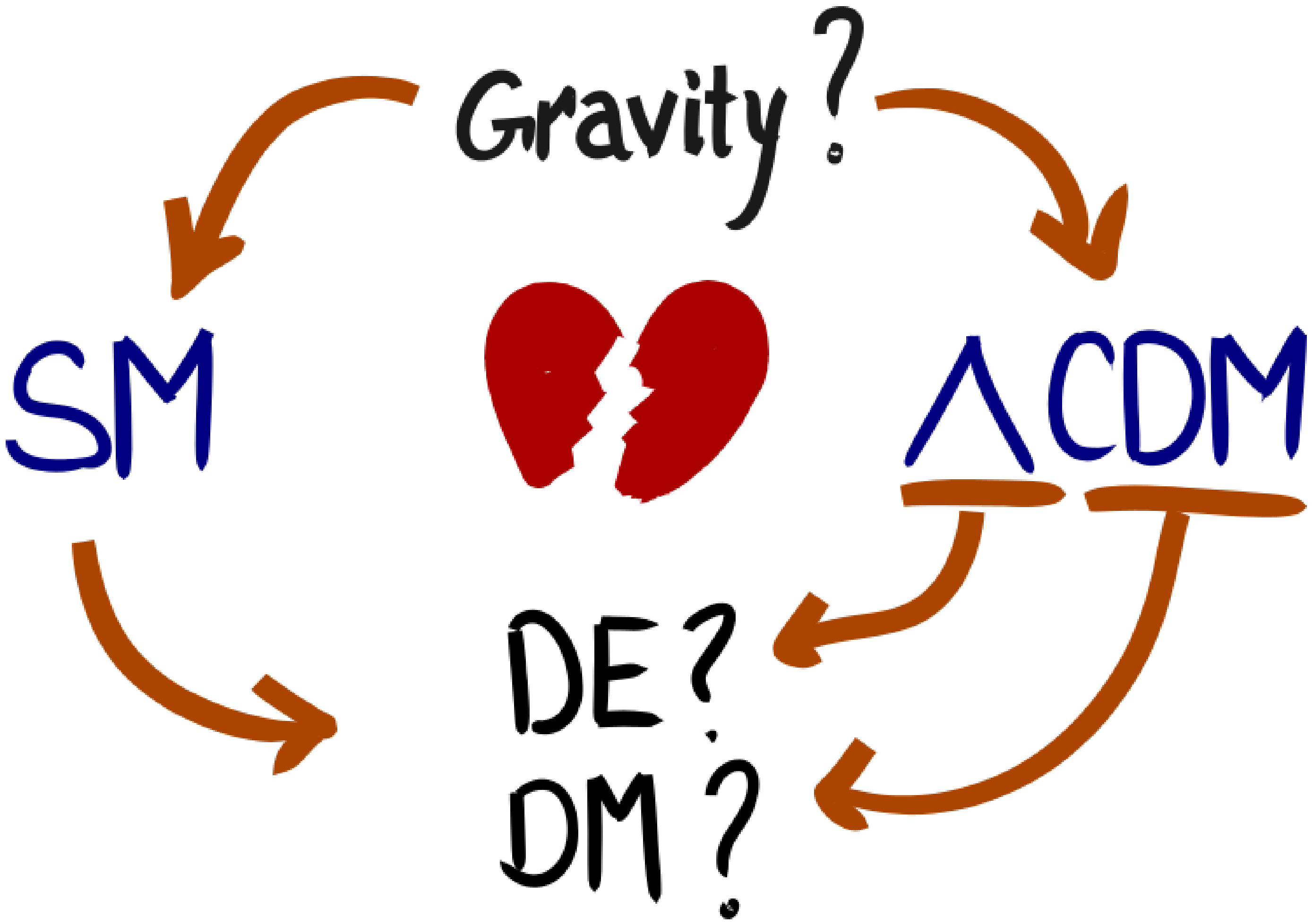
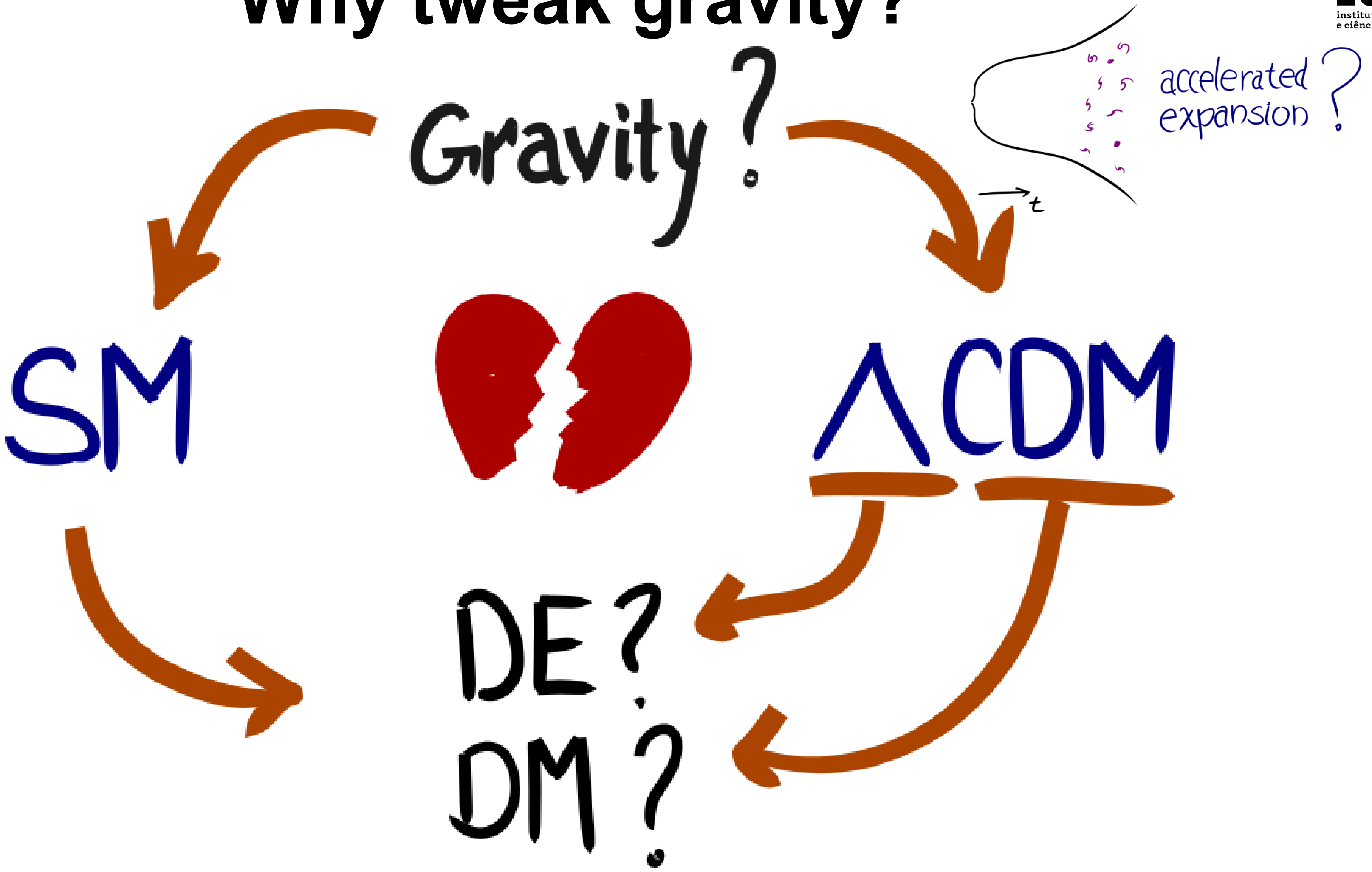


Why tweak gravity?



How to tweak gravity?

Einstein-Hilbert action:

$$S = \frac{1}{2\kappa^2}\int \underbrace{\boxed{R}}_{\text{curvature scalar}} \sqrt{-g}d^4x + \int \mathcal{L}_m \sqrt{-g}d^4x$$

How to tweak gravity?

Einstein-Hilbert action:

$$S = \frac{1}{2\kappa^2}\int \boxed{R}\,\sqrt{-g}d^4x + \int \mathcal{L}_m\sqrt{-g}d^4x$$

curvature scalar

$$\downarrow$$

$f(R)$

How to tweak gravity?

Einstein-Hilbert action:

$$S = \frac{1}{2\kappa^2}\int R \sqrt{-g} d^4x + \int \mathcal{L}_m \sqrt{-g} d^4x$$

curvature scalar

$f(R)$

f(R,T) gravity [Harko & al. 1104.2669]:

$$S = \frac{1}{2\kappa^2}\int f(R,T) \sqrt{-g} d^4x + \int \mathcal{L}_m \sqrt{-g} d^4x$$

trace stress-energy

The f(R,T) tweak

Geometrical representation [Harko & al. 1104.2669]

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

Scalar-tensor representation [Rosa 2103.11698]

$$\varphi \equiv \frac{\partial f}{\partial R} \qquad \psi \equiv \frac{\partial f}{\partial T} \qquad V(\varphi,\psi) \equiv -f(R,T) + \varphi R + \psi T$$

$$S = \frac{1}{16\pi G_N}\int \sqrt{-g}\left[\varphi R + \psi T - V(\varphi,\psi)\right] d^4x + \int \sqrt{-g}\mathcal{L}_m d^4x$$

The f(R,T) tweak

Modified equations:

$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

The f(R,T) tweak

Modified equations:

$$\varphi G_{\mu\nu} = 8\pi G_N T_{\mu\nu} - \left[\psi\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T + \Theta_{\mu\nu}\right) + (g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu)\varphi + \frac{1}{2}g_{\mu\nu}V\right]$$

$$\frac{\partial V}{\partial \varphi} = R$$

$$\frac{\partial V}{\partial \psi} = T$$

$$\varphi \equiv \frac{\partial f}{\partial R} \qquad \psi \equiv \frac{\partial f}{\partial T} \qquad \Theta_{\mu\nu} \equiv g^{\rho\sigma}\frac{\delta T_{\rho\sigma}}{\delta g^{\mu\nu}} \qquad \Box \equiv \nabla^\sigma\nabla_\sigma$$

The f(R,T) tweak

Modified equations:

$$\varphi G_{\mu\nu} = 8\pi G_N T_{\mu\nu} - \left[\psi\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T + \Theta_{\mu\nu}\right) + \left(g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu\right)\varphi + \frac{1}{2}g_{\mu\nu}V\right]$$

$$\frac{\partial V}{\partial \varphi} = R$$

$$\frac{\partial V}{\partial \psi} = T$$

CAN HAVE NON-CONSERVATION OF MATTER!

$$\nabla^\mu T_{\mu\nu} = \frac{1}{(8\pi G_N - \psi)}\left\{\left(T_{\mu\nu} + \Theta_{\mu\nu}\right)\nabla^\mu\psi + \psi\nabla^\mu\Theta_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\left[R\nabla^\mu\varphi + \nabla^\mu\left(\psi T - V\right)\right]\right\}$$

$$\varphi \equiv \frac{\partial f}{\partial R} \qquad \psi \equiv \frac{\partial f}{\partial T} \qquad \Theta_{\mu\nu} \equiv g^{\rho\sigma}\frac{\delta T_{\rho\sigma}}{\delta g^{\mu\nu}} \qquad \Box \equiv \nabla^\sigma\nabla_\sigma$$

What happens after tweaking?

f(R,T) gravity

Background Cosmology

Reconstruction

$a \propto \{e^t, t^{2/3}, t^{1/2}\}$

$k = \{\ ,\ ,\ \}$

$w = [-1, 1]$

[Gonçalves & al. 2112.02541]

Sudden Singularities

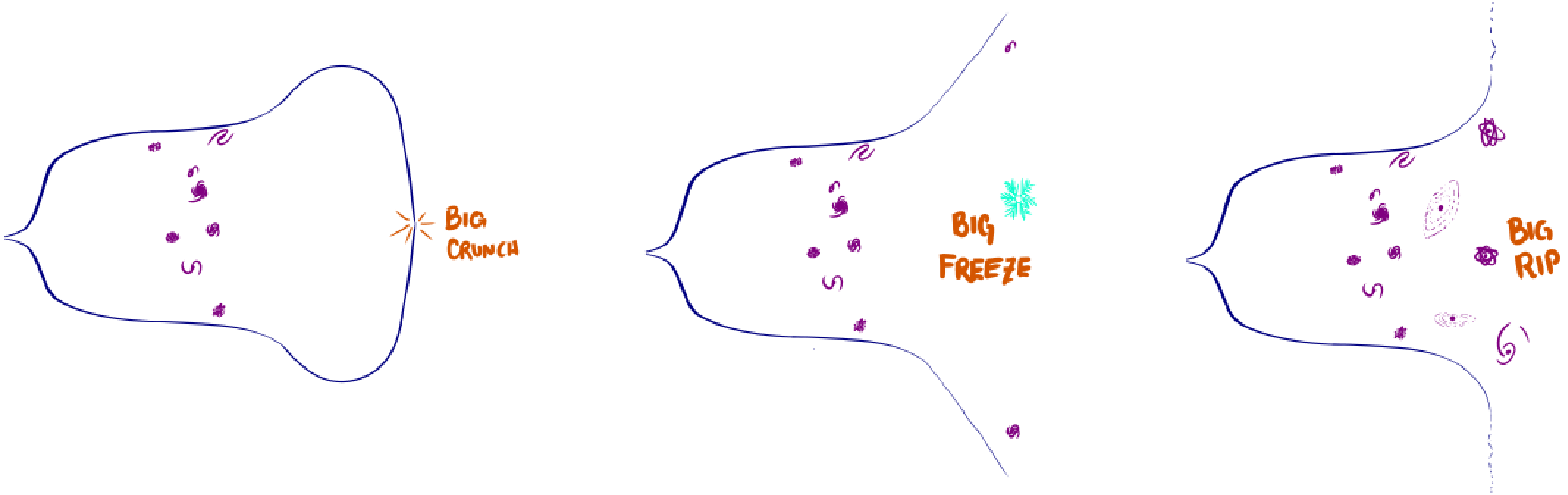
$$\begin{cases} \text{None}, & \text{if } \nabla_\nu T^{\mu\nu} = 0 \\ \dddot{a} \to \infty, & \text{if } \nabla_\nu T^{\mu\nu} \neq 0 \end{cases}$$

[Gonçalves et al. 2203.11124]

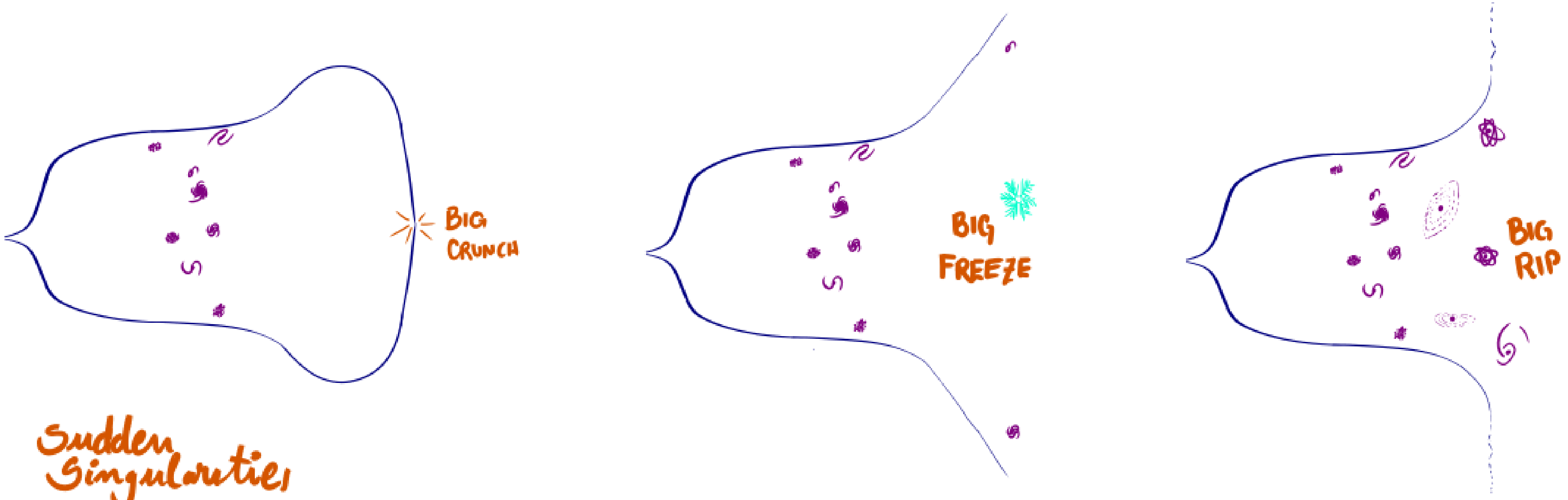
BBN Constraints

$$\frac{H_{modified}}{H_{standard}} = 0.99 \pm 0.55$$

Future singularities



Future singularities



Sudden Singularities

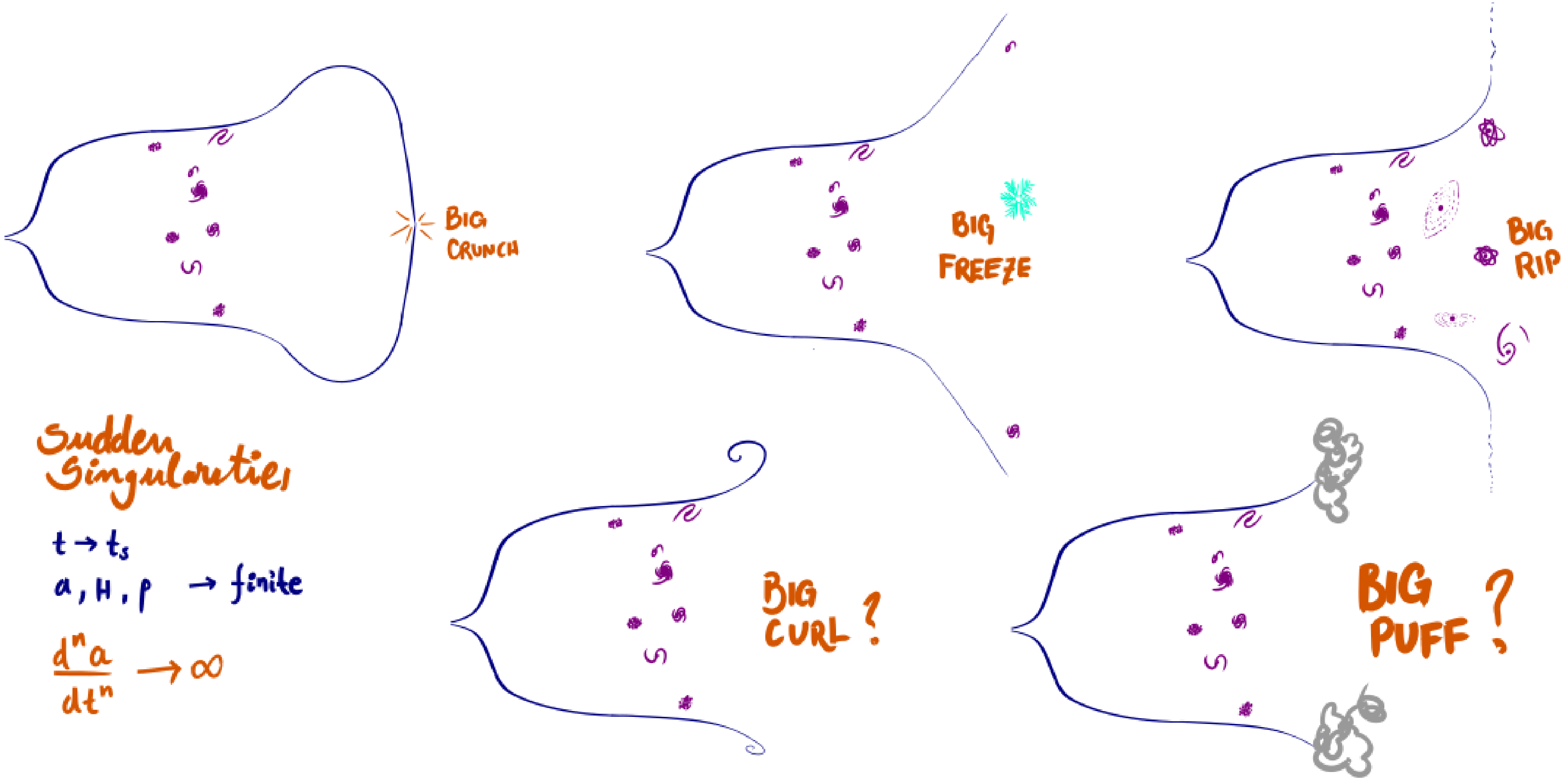
$t \to t_s$

$a, H, \rho \to$ finite

$\frac{d^n a}{dt^n} \to \infty$

[Barrow gr-qc/0403084 & 0409062; Nojiri & al. hep-th/0501025]
E.g. sudden singularities in Generalized Hybrid Metric-Palatini Gravity [Rosa & al. 2103.02580]

Future singularities



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E.g. sudden singularities in Generalized Hybrid Metric-Palatini Gravity [Rosa & al. 2103.02580]

Future singularities

Sudden singularities f(R,T) gravity [Gonçalves et al. 2203.11124]:

Assuming:

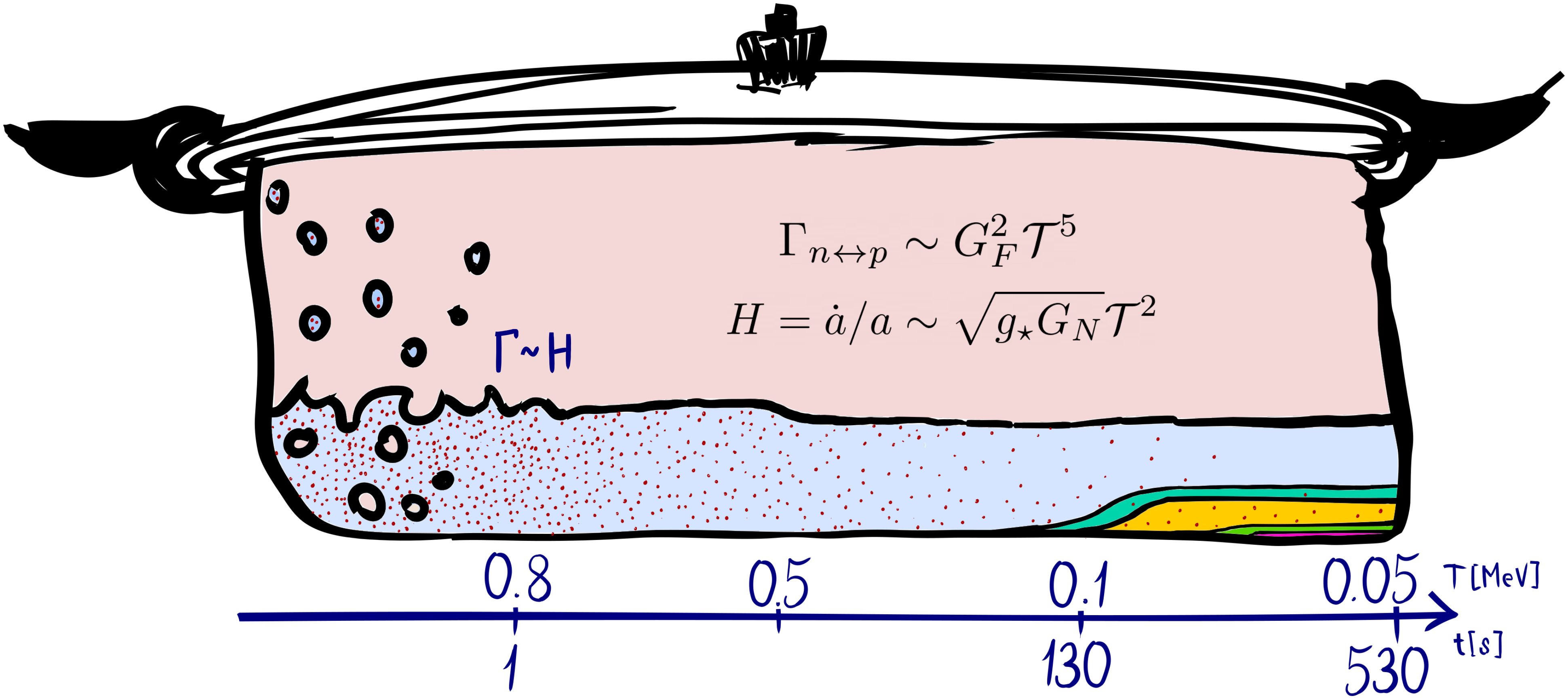
- FLRW metric
- Perfect fluid
- $\mathcal{L}_m = p$
- $f(R,T)$ is C^∞ function $\Rightarrow$ $R, T, \varphi, \psi, V, \ldots$ all regular

$\nabla_\nu T^{\mu\nu} = 0$ $\longrightarrow$ <u>NO</u> sudden singularities

$\nabla_\nu T^{\mu\nu} \neq 0$ $\longrightarrow$ $\dddot{a}$ lowest derivative with sudden singularities

BBN in a nutshell

(or in a pressure pot)



BBN with tweaked Hubble expansion

$$\xi = \frac{H'}{H_{SBBN}}$$

$$^{4}\mathrm{He:}\quad Y_{\mathrm{p}} = (0.2381 \pm 0.0006) + 0.0016\,[\eta_{10} + 100\,(\xi - 1)] + 0.0002\,(\tau_n - 881.5)$$

$$\mathrm{D/H} = 2.60\,(1 \pm 0.06)\left[\frac{6}{\eta_{10} - 6\,(\xi - 1)}\right]^{1.6} \times 10^{-5}$$

$$^{7}\mathrm{Li/H} = 4.82\,(1 \pm 0.10)\left[\frac{\eta_{10} - 3\,(\xi - 1)}{6}\right]^{2} \times 10^{-10}$$

$$\eta_{10} = \frac{n_b}{n_\gamma} \times 10^{10}$$

[Kneller & Steigman astro-ph/0406320; Steigman 0712.1100; Steigman 1208.0032]

BBN with tweaked Hubble expansion

$$\xi = \frac{H'}{H_{SBBN}}$$

$$106\,(\xi - 1) = \frac{Y_\mathrm{p} - (0.2374 \pm 0.0006)}{0.0016} - 6\left[\frac{(2.60 \pm 0.16) \times 10^{-5}}{(\mathrm{D/H})}\right]^{1/1.6}$$

[Kneller & Steigman astro-ph/0406320; Steigman 0712.1100; Steigman 1208.0032]
[Particle Data Group Review – Sec. 24 ‘Big Bang Nucleosynthesis’ (2021 update)]
[Bhattacharjee et al. 2004.04684]

$$\xi = 0.99 \pm 0.05$$

$$\Delta N_\nu = 43\left(\xi^2 - 1\right)/7 = -0.15^{+0.63}_{-0.60}$$

$$G'/G_N = \xi^2 = 0.98 \pm 0.10$$

BBN with tweaked Hubble expansion

GR, assuming:

- FLRW metric
- Perfect fluid

$$H^2 = \frac{8\pi G_N}{3}\rho \qquad\qquad - \frac{k}{a^2}$$

BBN with tweaked Hubble expansion

f(R,T), assuming:

- FLRW metric
- Perfect fluid
- $\mathcal{L}_m = p$

[Gonçalves et al. 2112.02541]

$$H^2 = \frac{1}{\varphi}\left[\frac{8\pi G_N}{3}\rho - H\dot{\varphi} + \frac{\psi}{2}\left(\rho - \frac{1}{3}P\right) + \frac{1}{6}V\right] - \frac{k}{a^2}$$

- $T = 0$ during BBN?
- Numerical predictions still the same?
- Inferring abundances observationally changed by modified gravity model?

BBN with tweaked Hubble expansion

f(R,T):

$$H^2 = \frac{1}{\varphi}\left[\frac{8\pi G_N}{3}\rho - \boxed{H\dot{\varphi}} + \frac{\psi}{2}\left(\rho - \frac{1}{3}P\right) + \boxed{\frac{1}{6}V}\right] - \boxed{\frac{k}{a^2}}$$

$$H^2 \simeq \frac{1}{\varphi}\left(\frac{8\pi G_N}{3} + \frac{4}{9}\psi\right)\rho_r$$

$$\varphi \equiv \frac{\partial f}{\partial R} \qquad \psi \equiv \frac{\partial f}{\partial T}$$

BBN with tweaked Hubble expansion

f(R,T):

$$H^2 \simeq \frac{1}{\varphi}\left(\frac{8\pi G_N}{3} + \frac{4}{9}\psi\right)\rho_r$$

$$f(R,T) = R + \alpha R + \beta T + \gamma R T$$

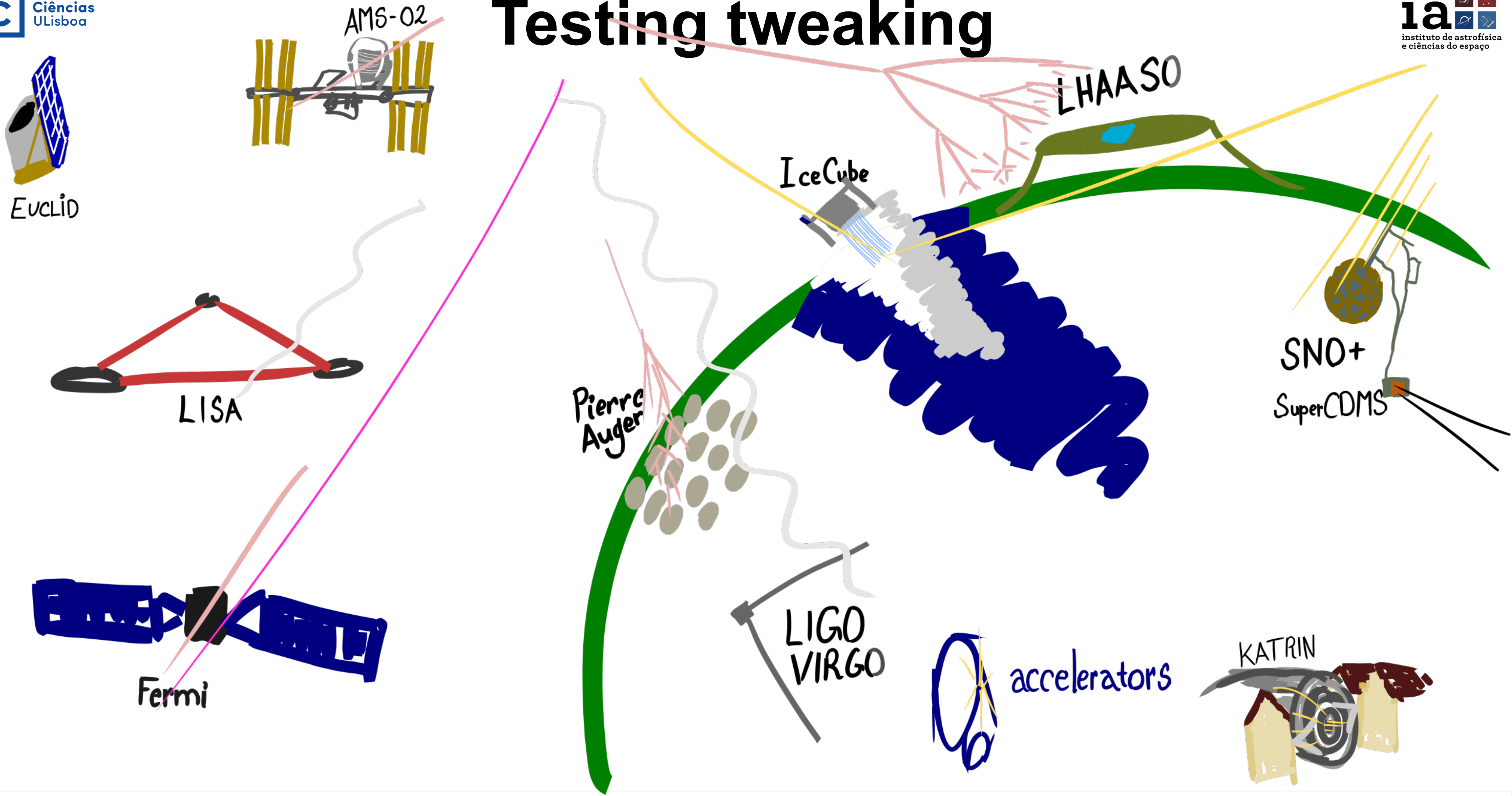
if $\beta = 0$

$\alpha = 0.0 \pm 0.1$

if $\alpha = 0$

$\beta = (-0.015 \pm 0.074)\, 8\pi G_N$

Testing tweaking



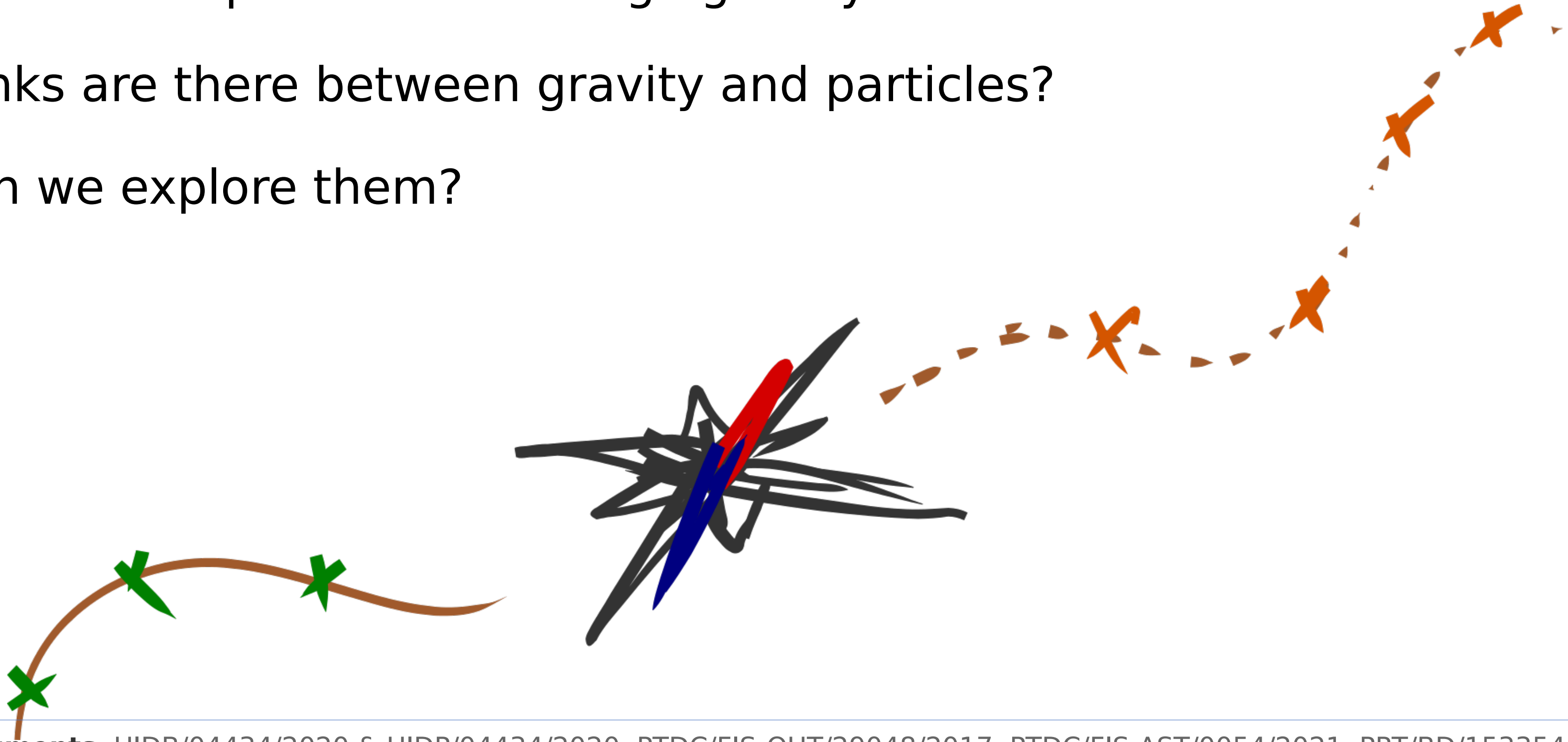
Concluding remarks

Where to go?

Do we add more particles or change gravity? Or both?

What links are there between gravity and particles?

How can we explore them?



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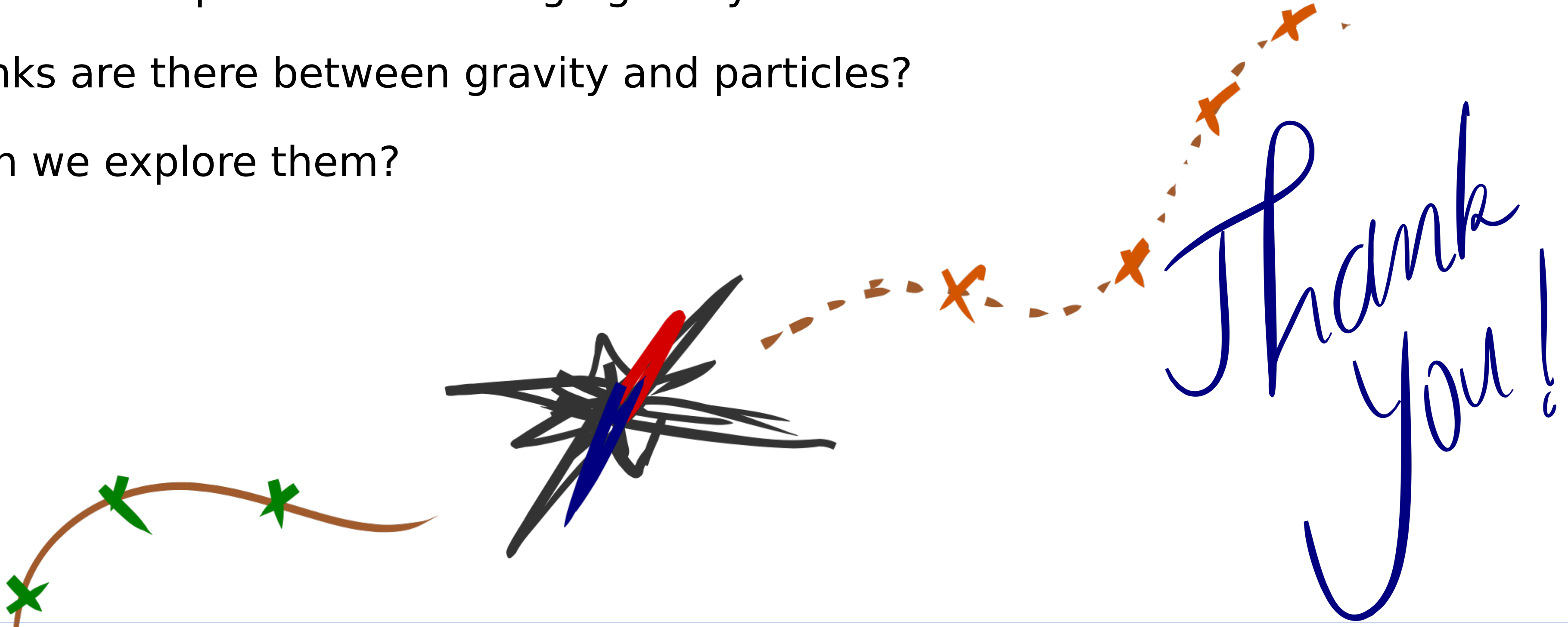

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Background evolution

Cosmology in scalar-tensor f(R,T) gravity [Gonçalves et al. 2112.02541]:

$$a \propto \left\{ e^{t},\ t^{2/3},\ t^{1/2} \right\}$$

$$k = \left\{ \ ,\ \ ,\ \ \right\}$$

$$w = [-1,\ 1]$$

$$\left\{ \Lambda,\ \ ,\ \ \right\}$$

Background evolution

Cosmology in scalar-tensor f(R,T) gravity [Gonçalves et al. 2112.02541]:

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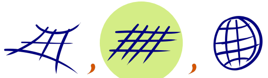
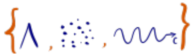
$k = \{$  $\}$

$$w = [-1 , 1]$$



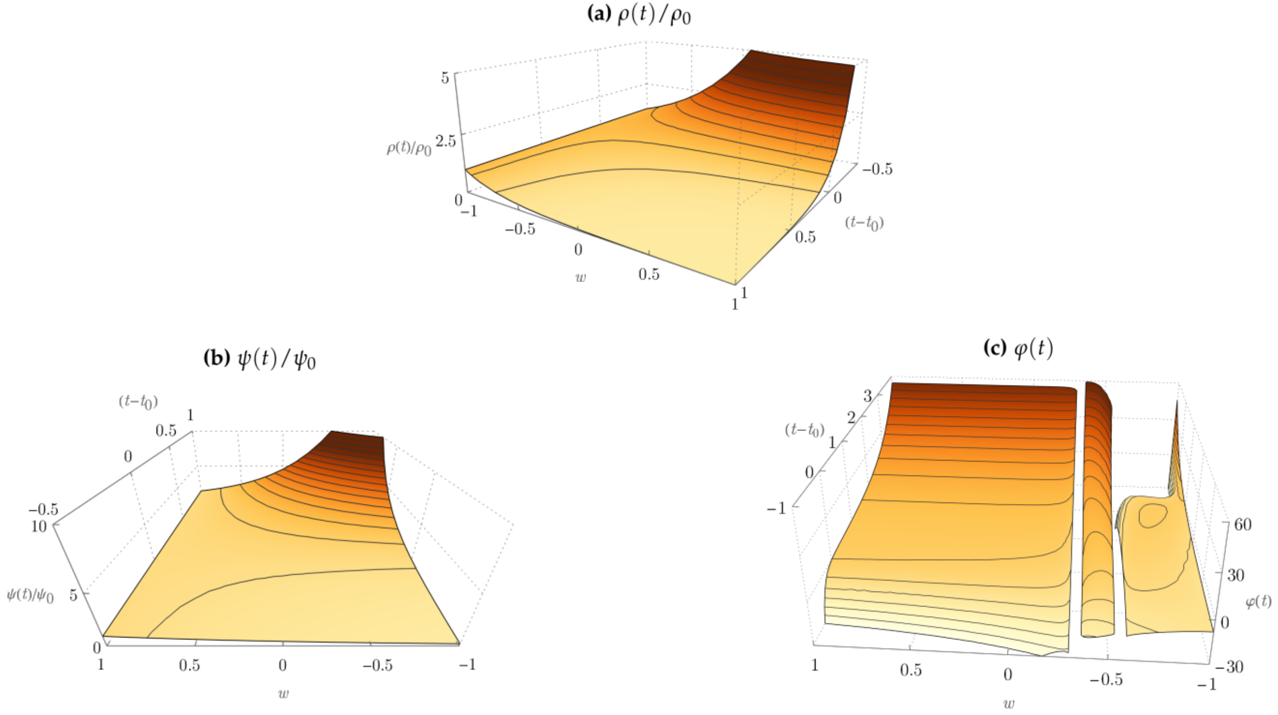


Figure 1. Energy density $\rho(t)$ (top panel), scalar field $\psi(t)$ (left panel) and scalar field $\varphi(t)$ (right panel), in the particular case of a de Sitter scale factor $a \propto e^t$, for a range of values of the equation of state parameter w, setting $k = 0$ and $\Lambda = 1$.

A. Helium-4

$$Y_{\mathrm{P}}^{FIT} \equiv 0.2384 \pm 0.0006 + 0.0016\eta_{10} + 0.16(S-1).$$

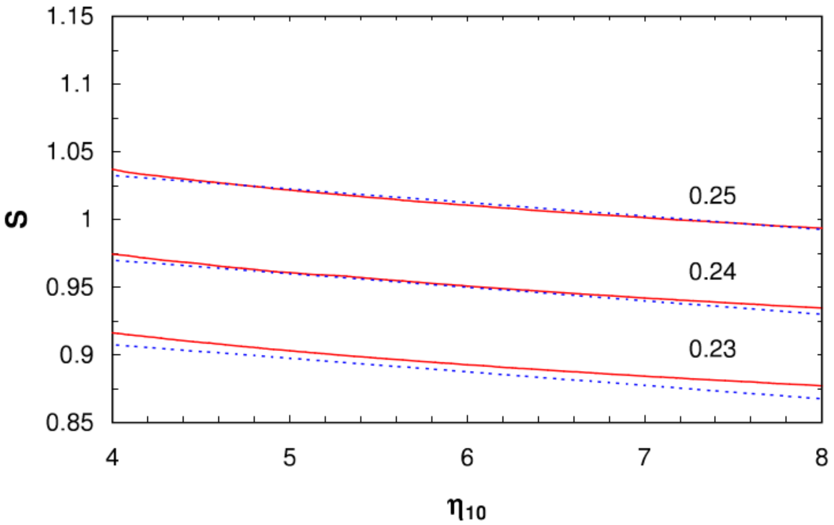


FIG. 3: BBN-predicted isoabundance curves for ^{4}He in the expansion-rate parameter (S), baryon density parameter (η) plane. From bottom to top, $Y_P = 0.23, 0.24, 0.25$. The solid curves are the BBN-predicted results, while the dotted curves are our fits (see the text).

[Kneller & Steigman astro-ph/0406320; Steigman 0712.1100; Steigman 1208.0032]

Modified Hubble expansion

$$\xi = \frac{H'}{H_{SBBN}}$$

Table 1. Summary of primordial abundance of elements inferred from observations [5] and the corresponding theoretical predictions (Eqs. (9)–(11) based on Ref. [42]), using $\eta_{10} = 6.104 \pm 0.058$ from CMB (with no BBN correction) [5], and the recent measurement $\tau_n = 877.75 \pm 0.50$ s [39]. Constraints on a modified Hubble parameter as given by ξ are obtained by equating observations with predictions.

	$Y_\mathbf{p}$	$\mathbf{D/H} \times 10^5$	$^7\mathbf{Li/H} \times 10^{10}$
Observations	0.245 ± 0.003	(2.547 ± 0.025)	(1.6 ± 0.3)
Predictions	$(0.2471 \pm 0.0006) + 0.1600\,(\xi - 1)$	$\frac{(2.60\pm0.16)}{[(1.017\pm0.010)-(\xi-1)]^{1.6}}$	$(4.82 \pm 0.48)\left[(1.017 \pm 0.010) - \frac{(\xi-1)}{2}\right]^2$
ξ	0.987 ± 0.019	1.00 ± 0.19	1.9 ± 0.3

[5] PDG Review – Sec. 24 'Big Bang Nucleosynthesis' (2021 update)
[39] F. M. Gonzalez et al. [UCNτ] 2106.10375
[42] Kneller & Steigman astro-ph/0406320; Steigman 0712.1100 & 1208.0032

[Lithium problem: see also Bruno Carrazedo's talk tomorrow]

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Modified Friedmann equation

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$$H^2 \simeq \frac{1}{\varphi}\left(\frac{8\pi G_N}{3} + \frac{4}{9}\psi\right)\rho_r$$

$\psi = 0$

e.g. $f(R,T) = R + A\,R$

$\varphi = 1$

e.g. $f(R,T) = R + BT$

$\varphi = 1.0 \pm 0.1$

$\psi = 8\pi G_N(-0.015 \pm 0.074)$

$f(R,T) = R + CRT$

$$f(R,T) = R + \mathcal{A}R^{\alpha} + \mathcal{B}T^{\beta} + \mathcal{C}R^{\gamma}T^{\delta}$$

$$\varphi = 1 + \alpha\mathcal{A}R^{\alpha-1} + \gamma\mathcal{C}R^{\gamma-1}T^{\delta}$$

$$\psi = \beta\mathcal{B}T^{\beta-1} + \delta\mathcal{C}R^{\gamma}T^{\delta-1}$$

$$V = (\alpha-1)\,\mathcal{A}R^{\alpha} + (\beta-1)\,\mathcal{B}T^{\beta} + (\gamma+\delta-1)\,\mathcal{C}R^{\gamma}T^{\delta}$$