Unimodular Gravity and diffusion processes in the dark sector: a possible solution to the H_0 tension

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Based on: https://arxiv.org/abs/2009.10268

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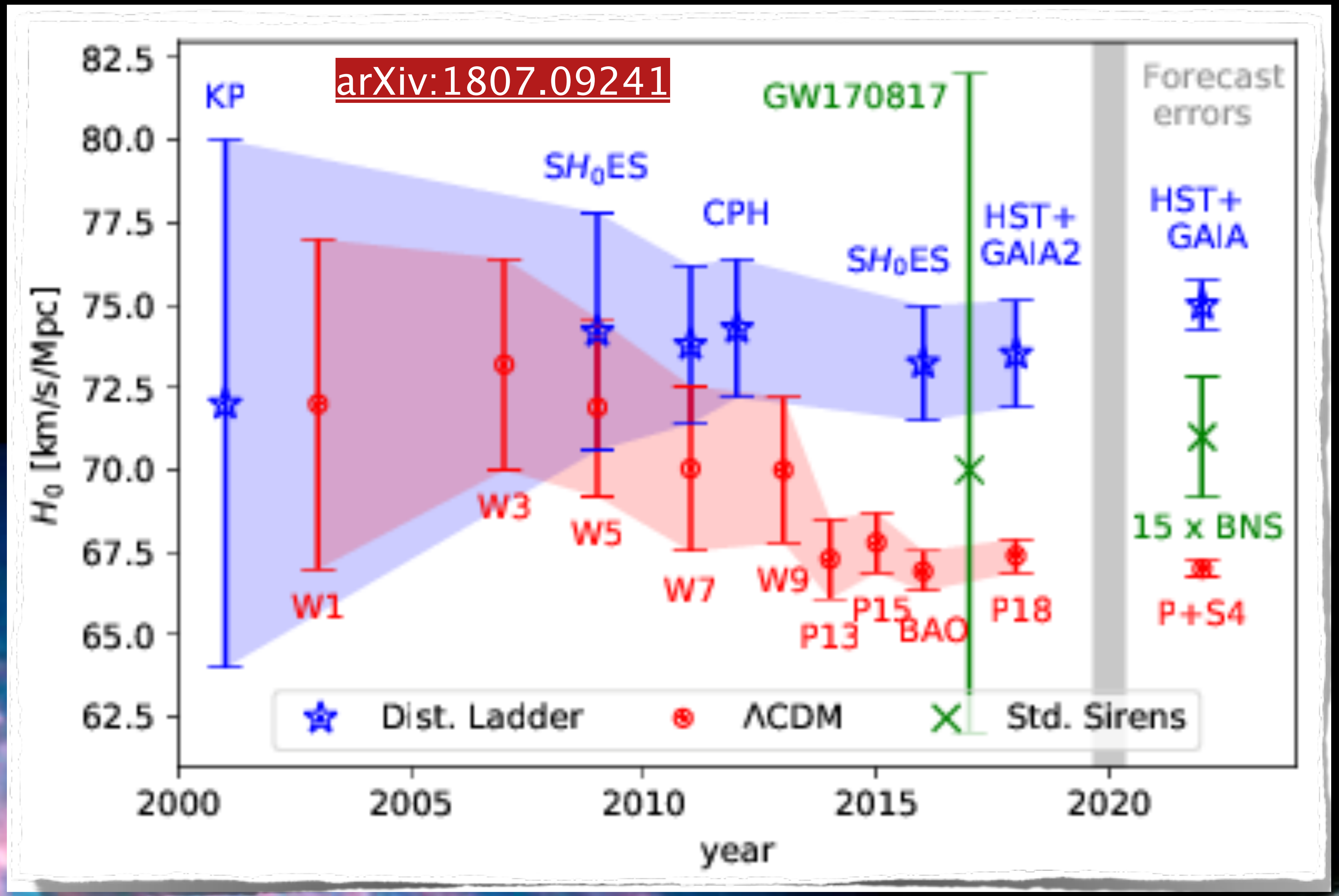
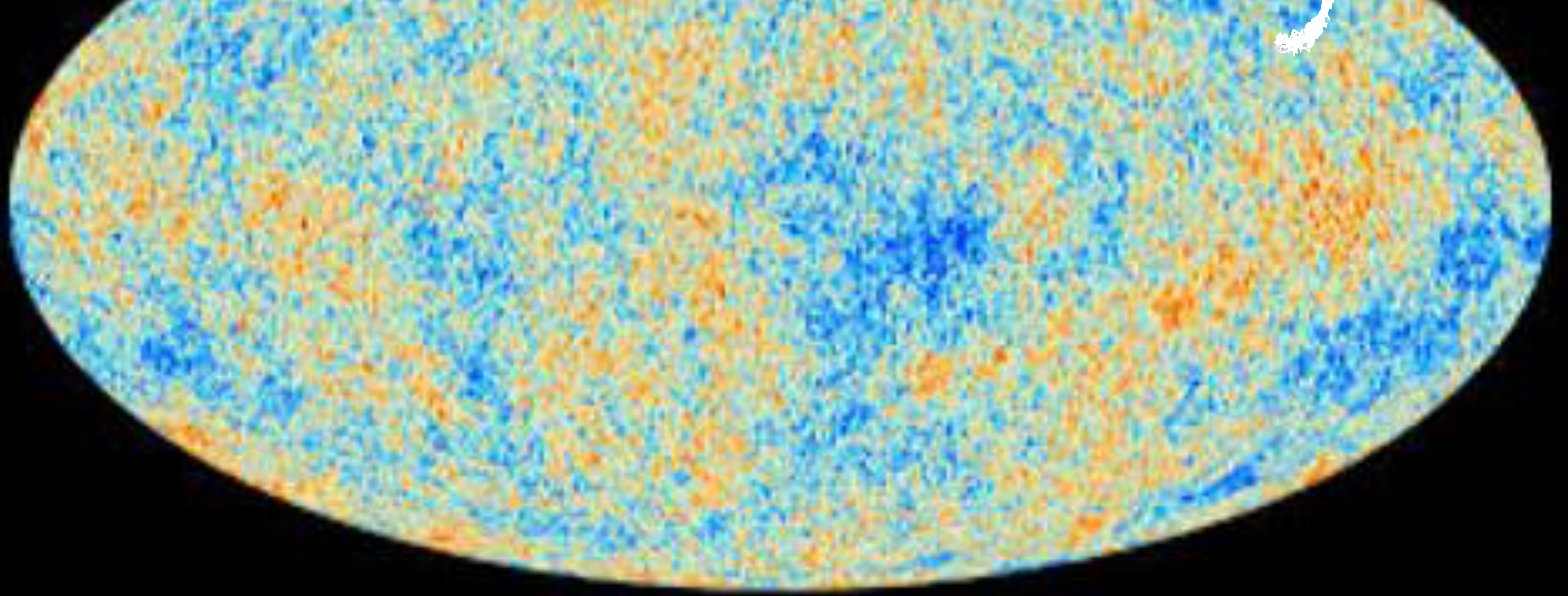
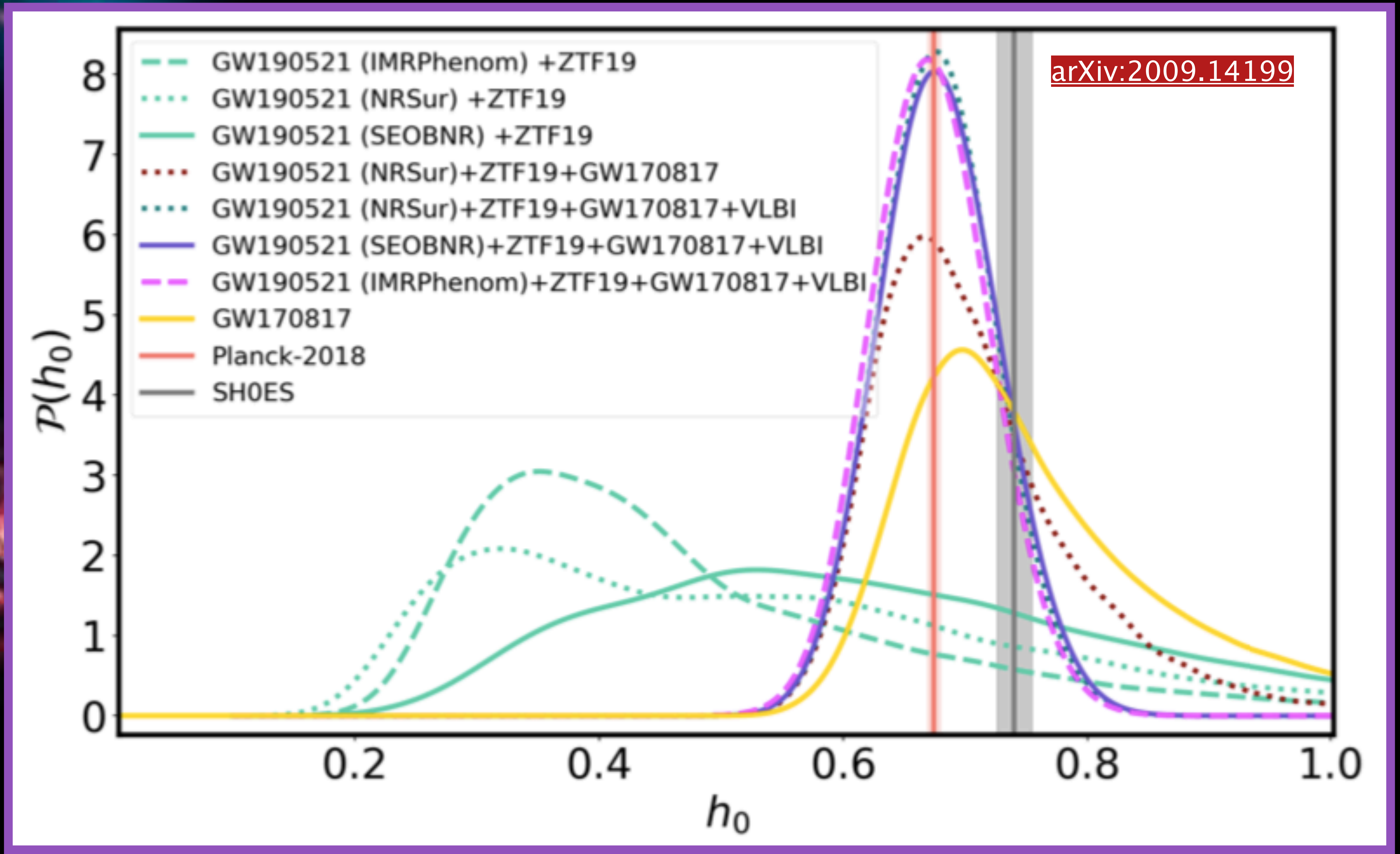
Outline

- H_0 tension: introduction to the controversy.
- Unimodular Gravity: interaction between CDM and Λ.
- Diffusion in the dark sector: phenomenological models.
- Results: numerical solutions and statistical analysis.
- Final remarks.

H_0 tension: introduction to the controversy



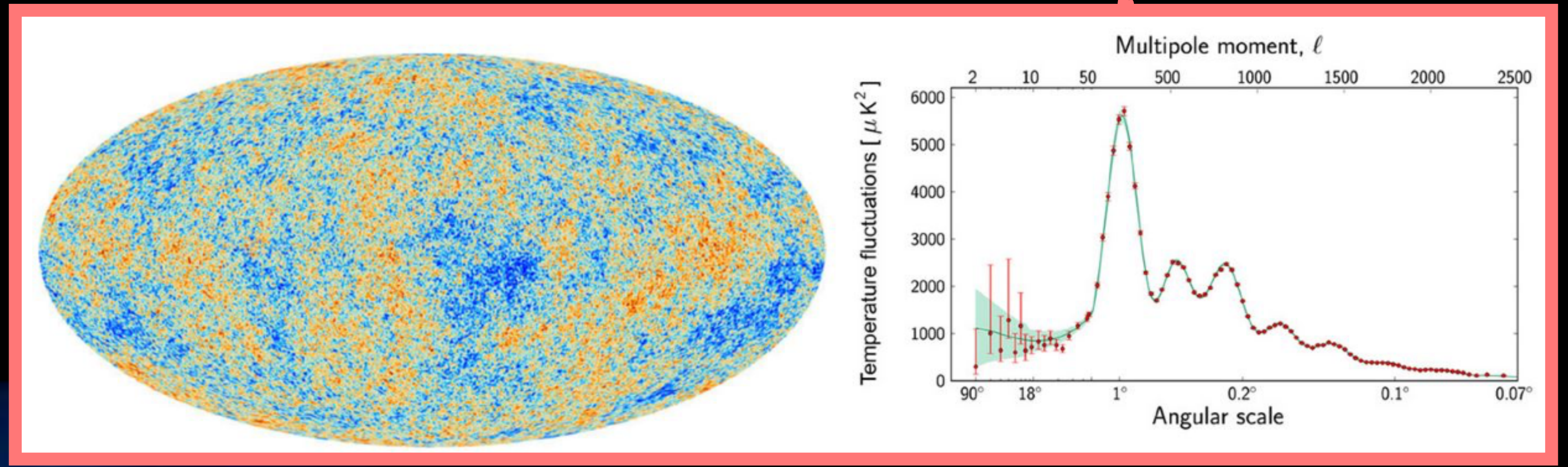




https://www.agenciasinc.es/en/News/The-measurements-of-the-expansion-of-the-universe-don-t-add-up

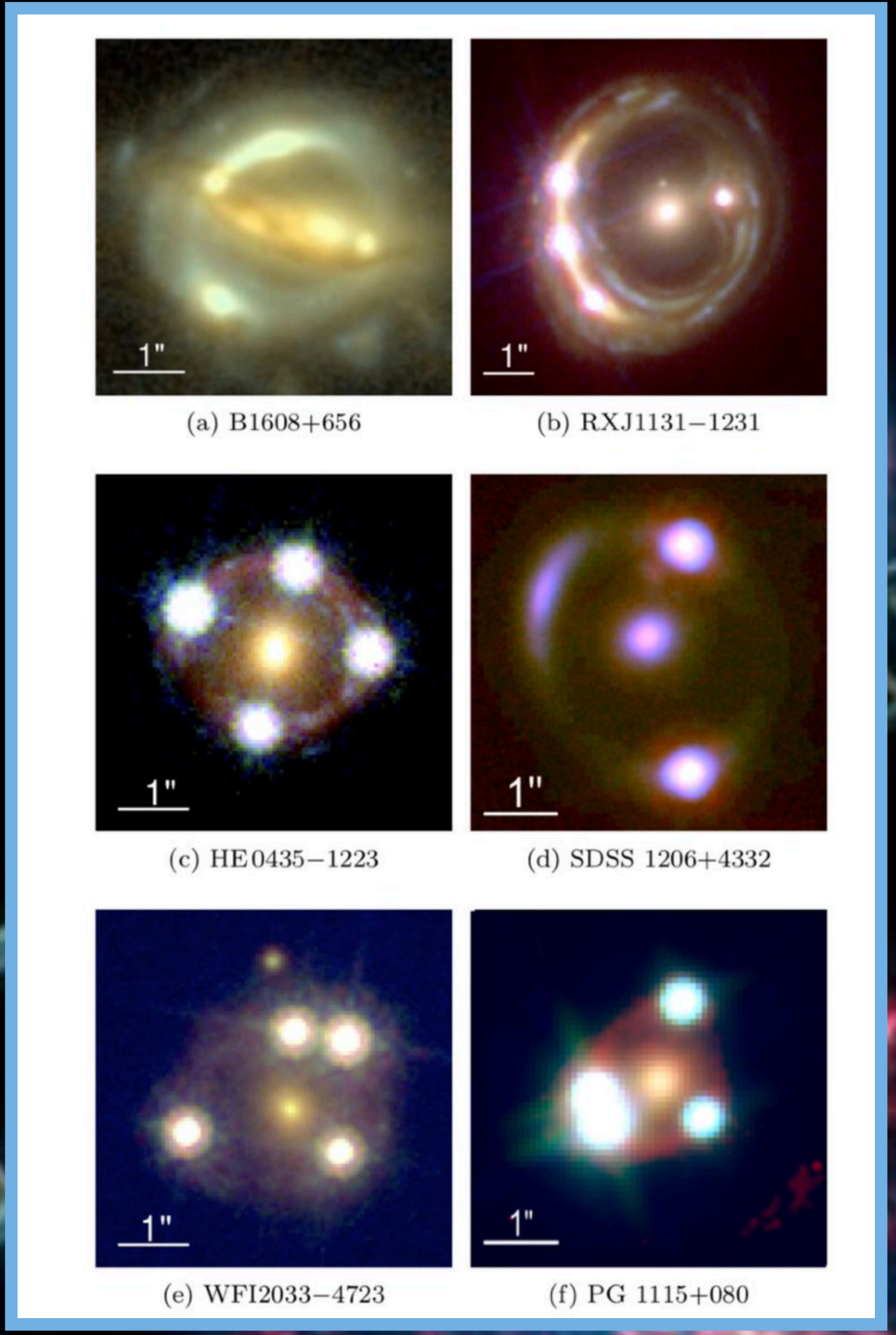
H_0 tension: introduction to the controversy

CMB Anisotropies



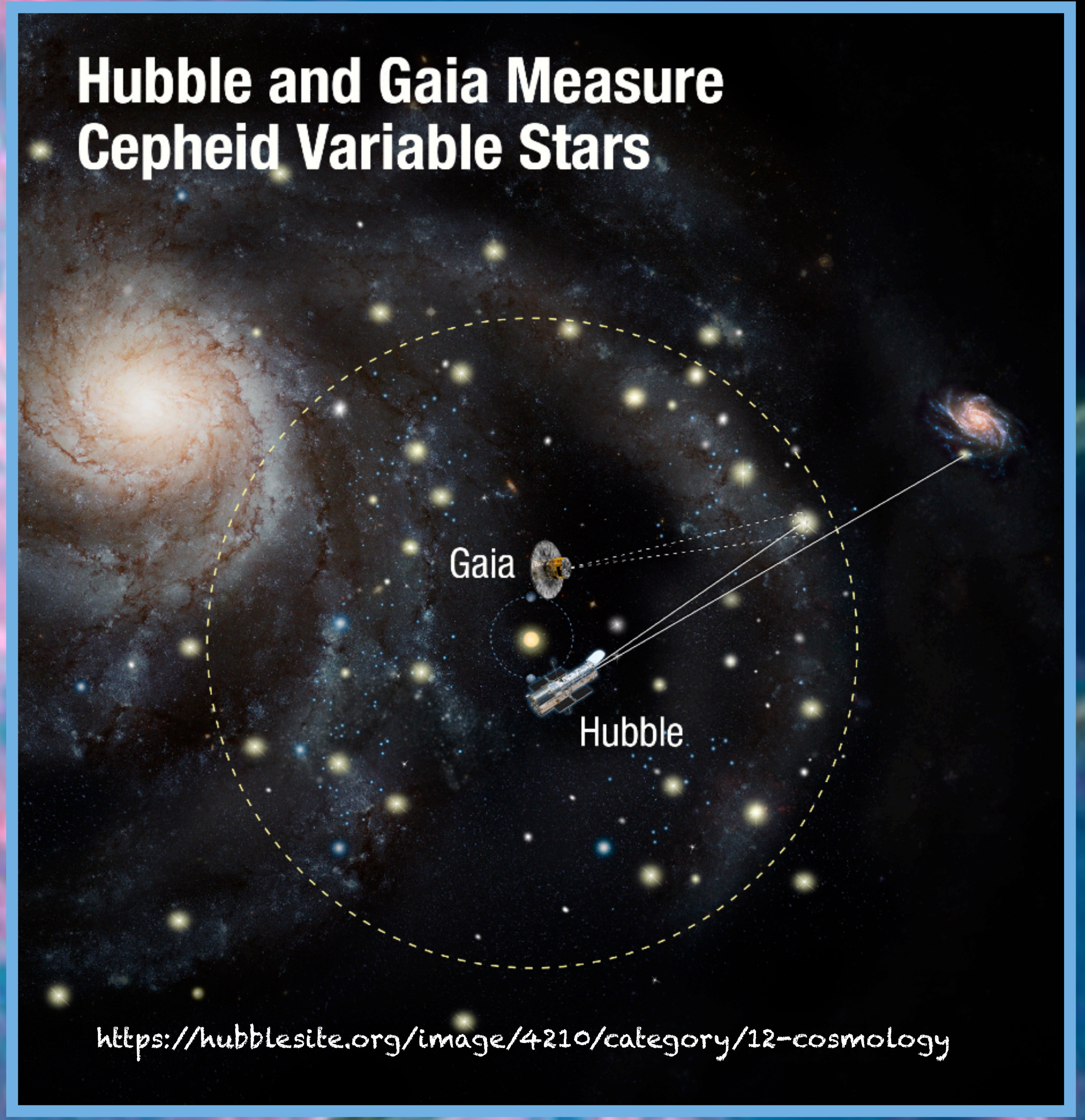
https://lerma.obspm.fr/spip.php?article55&lang=fr

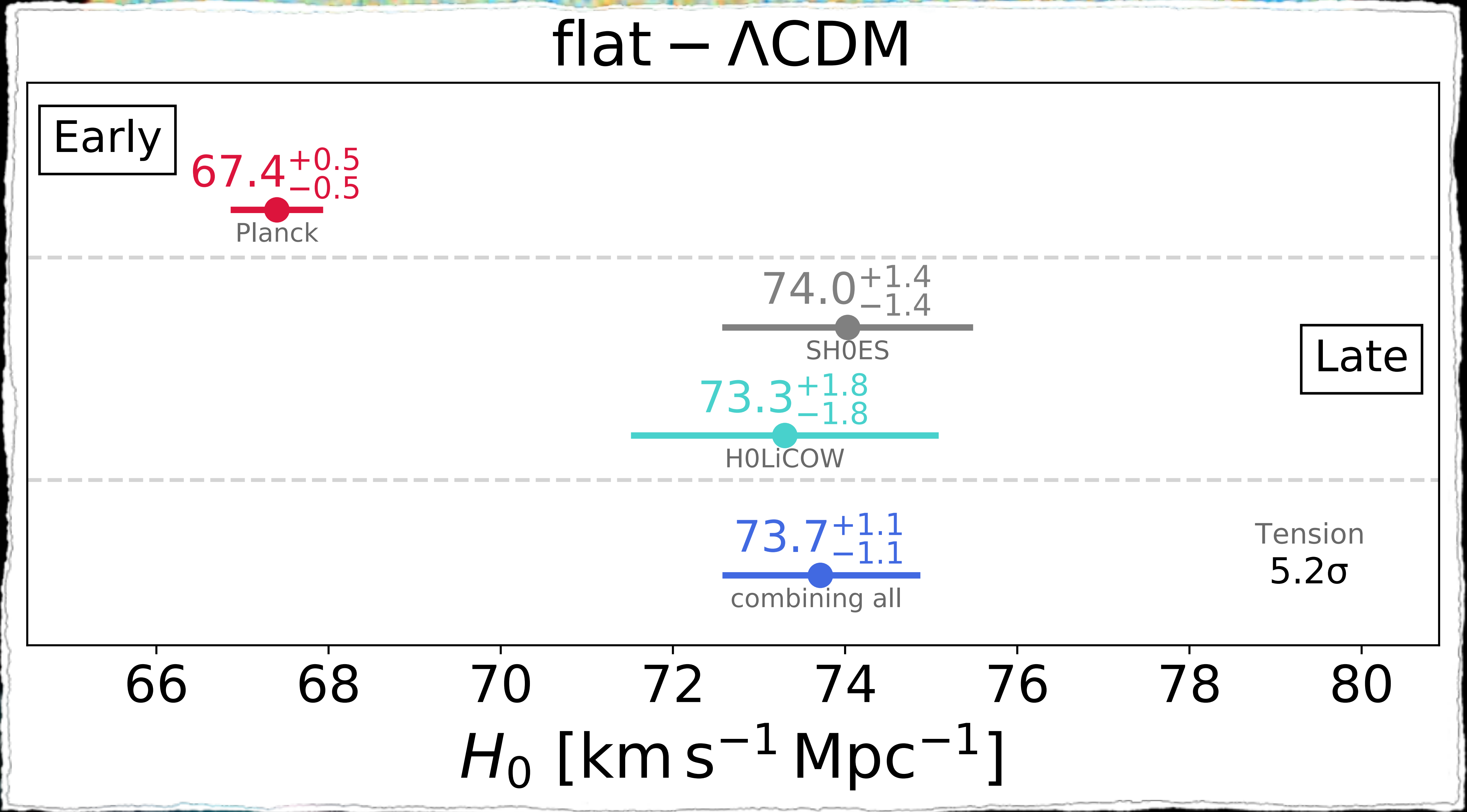
Lensed quasars



arXiv:1907.04869

Cepheids





(This Figure is a reduced version of arXiv:1907.10625)

$$T_{H_0} = \frac{|\mu_{early} - \mu_{late}|}{\sqrt{\sigma^2_{early} + \sigma^2_{late}}},$$ arXiv:1805.09900

H_0 tension: introduction to the controversy.

CMB: $l_A = (1+z_*)\pi \frac{d_A(z_*)}{r_s(z_*)}\,, \quad R = (1+z_*)\frac{\Omega_{0,m}^{1/2} H_0}{c} d_A(z_*)\,,$

arXiv:1808.05724

with $d_A(z) = \frac{c}{H_0(1+z)}\int_0^z \frac{dz'}{E(z')}\,,$ for $\Omega_k = 0\,,$ and $r_s(z) = \frac{1}{H_0}\int_z^\infty \frac{c_s(z')dz'}{E(z')}\,.$ $c_s(z) = c\left[3\left(1+\frac{3\Omega_b}{4\Omega_r(1+z)}\right)\right]^{-1/2}\,.$

Lensed quasars: $\Delta t_{ij} = t(\theta_i,\beta) - t(\theta_j,\beta) = \frac{D_{\Delta t}}{c}\Delta\phi_{ij}\,,$ with $D_{\Delta t} = (1+z_d)\frac{D_d D_s}{D_{ds}}\,.$

arXiv:1907.04869

SNe Ia: $\mu(z) = 5\log\left[\frac{d_L(z)}{10\mathrm{pc}}\right]\,,$ with $d_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{E(z')}\,.$

arXiv:1710.00845

Cepheids: $d_c(z) = \frac{cz}{H_0}\,.$

arXiv:1903.07603

$$E(z) \equiv \frac{H(z)}{H_0} = \sqrt{\Omega_{0,r}(1+z)^4 + \Omega_{0,b}(1+z)^3 + \Omega_{cdm}(1+z)^3 + \Omega_\Lambda}\,.$$

Unimodular Gravity: interaction between CDM and Λ.

A simple way to introduce the framework of Unimodular Gravity (UG) is by regarding the Einstein-Hilbert action plus a volume-preserving diffeomorphism term:

$$S = \frac{1}{\kappa^2}\int d^4x\left[\sqrt{-g}R + \lambda(x)\left(\sqrt{-g} - f\right) + \mathscr{L}_m\right],$$

where $f = f(x)$ is a fixed scalar density. After variations with respect to the inverse of the metric tensor we have

$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \lambda g_{\mu\nu} = \kappa^2 T_{\mu\nu}$, and taking the trace we found λ to be $\lambda = \frac{1}{4}\left(R + \kappa^2 T\right)$.

Eliminating λ, we have the trace-free version of the Einstein field equations:

$$\boxed{R_{\mu\nu} - \frac{1}{4}Rg_{\mu\nu} = \kappa^2\left(T_{\mu\nu} - \frac{1}{4}Tg_{\mu\nu}\right). \quad \text{UG field equations!!}}$$

https://aapt.scitation.org/doi/10.1119/1.1986321

Unimodular Gravity: interaction between CDM and Λ.

One of the main features of this theory can be obtained when replacing the Lagrange multiplier in the UG field equations and applying the Bianchi identities,

$$R^{\mu}{}_{\nu} - \frac{1}{2}R\delta^{\mu}{}_{\nu} + \frac{1}{4}\left(R + \kappa^2 T\right)\delta^{\mu}_{\nu} = \kappa^2 T^{\mu}{}_{\nu} \Rightarrow \overbrace{\nabla_{\mu}\left(R^{\mu}{}_{\nu} - \frac{1}{2}R\delta^{\mu}{}_{\nu}\right)}^{\equiv 0} + \frac{1}{4}\nabla_{\nu}\left(R + \kappa^2 T\right) = \kappa^2 \nabla_{\mu} T^{\mu}{}_{\nu}\,.$$

The energy-momentum tensor is no longer conserved!!

$$\kappa^2 \nabla_{\mu} T^{\mu}{}_{\nu} = \frac{1}{4}\partial_{\nu}\left(R + \kappa^2 T\right) \quad \Rightarrow \quad \lambda(x) \equiv \Lambda + \int_l J\,, \quad \text{with} \quad J_{\nu} \equiv \kappa^2 \nabla_{\mu} T^{\mu}{}_{\nu}\,.$$

The function J is the energy-momentum current violation.

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} + \underbrace{\left(\Lambda + \int_l J(x)\right)}_{\Lambda(x)} g_{\mu\nu} = \kappa^2 T_{\mu\nu}\,.$$

Effective cosmological "constant"

https://aapt.scitation.org/doi/10.1119/1.1986321

Unimodular Gravity: interaction between CDM and Λ.

In a spatially-flat FRW Universe, and in presence of a perfect fluid for ordinary matter, we have

$$\boxed{\begin{gathered} H^2 = \frac{\kappa^2}{3}\left(\rho_\gamma + \rho_\nu + \rho_b + \rho_{cdm} + \rho_{\Lambda(t)}\right) , \\ \dot{H} = -\frac{\kappa^2}{2}\left[(\rho_\gamma + p_\gamma) + (\rho_\nu + p_\nu) + (\rho_b + p_b) + (\rho_{cdm} + p_{cdm})\right] , \\ \dot{\rho}_\gamma = -3H(\rho_\gamma + p_\gamma) , \qquad \dot{\rho}_\nu = -3H(\rho_\nu + p_\nu) , \qquad \dot{\rho}_b = -3H(\rho_b + p_b) , \\ \dot{\rho}_{cdm} = -3H(\rho_{cdm} + p_{cdm}) - \frac{\dot{\Lambda}(t)}{\kappa^2} . \end{gathered}}$$

The latter equation can be written as

$$\dot{\rho}_{cdm} = -3H(\rho_{cdm} + p_{cdm}) - \dot{Q}(t) , \qquad Q(t) \equiv \frac{1}{\kappa^2}\int_l J(t) .$$

arXiv:2009.10268

Diffusion in the dark sector: phenomenological models.

- Model 1: Sudden Transfer model

$$\rho_{cdm}(z) = \rho_{0,cdm}(1+z)^3 \times \begin{cases} 1 & \text{if} \quad z \geq z^\star , \\ 1-\alpha & \text{if} \quad z < z^\star , \end{cases}$$

$$\Lambda(z) = \begin{cases} \Lambda & \text{if} \quad z \geq z^\star , \\ \Lambda + 3H_0^2\alpha(1+z^\star)^3\Omega_{0,cdm} & \text{if} \quad z < z^\star . \end{cases}$$

arXiv:2001.07536

- Model 2: Anomalous Decay of the Matter Density

$$\rho_{cdm}(z) = \rho_{0,cdm}(1+z)^3 \times \begin{cases} 1 & \text{if} \quad z \geq z^\star , \\ \left(\frac{1+z}{1+z^\star}\right)^\gamma & \text{if} \quad z < z^\star , \end{cases}$$

$$\Lambda(z) = \begin{cases} \Lambda & \text{if} \quad z \geq z^\star , \\ \Lambda - \frac{3\gamma}{\gamma+3}H_0^2\left[\left(\frac{1+z}{1+z^\star}\right)^\gamma(1+z)^3 - (1+z^\star)^3\right]\Omega_{0,cdm} & \text{if} \quad z < z^\star . \end{cases}$$

- Model 3: Barotropic model

$$Q \equiv x_i \rho_i ,$$

$$\rho_{cdm}(z) = \rho_{cdm}(1+z)^{\frac{3(\omega_{cdm}+1)}{x_{cdm}+1}} .$$

arXiv:2005.06052

- Model 4: Continuous Spontaneous Localization model

$$\dot{Q} = -\,\xi_{CSL}\,\rho_{cdm} , \quad \text{with} \quad Q(t) = Q_i - \xi_{CSL}\int_0^t \rho_{cdm}(t')dt' ,$$

$$\rho_{cdm}(z) = \rho_{cdm}(1+z)^3 e^{\xi_{CSL} t} .$$

Diffusion in the dark sector: phenomenological models.

arXiv:2009.10268

- Model 1: Sudden Transfer model

$$E(z) \equiv \frac{H(z)}{H_0} = \sqrt{\Omega_{0,r}(1+z)^4 + \Omega_b h^2(1+z)^3 + \Omega_{cdm}(1+z)^3\left[1-\alpha+\alpha\left(\frac{1+z^\star}{1+z}\right)^3\right] + \Omega_\Lambda}\,, \quad \text{for} \quad z < z^\star\,.$$

- Model 2: Anomalous Decay of the Matter Density

$$E(z) \equiv \frac{H(z)}{H_0} = \sqrt{\Omega_{0,r}(1+z)^4 + \Omega_b h^2(1+z)^3 + \Omega_{cdm}(1+z)^3\left[\frac{3}{3+\gamma}\left(\frac{1+z}{1+z^\star}\right)^\gamma + \frac{\gamma}{3+\gamma}\left(\frac{1+z^\star}{1+z}\right)^3\right] + \Omega_\Lambda}\,, \text{for} \quad z < z^\star\,.$$

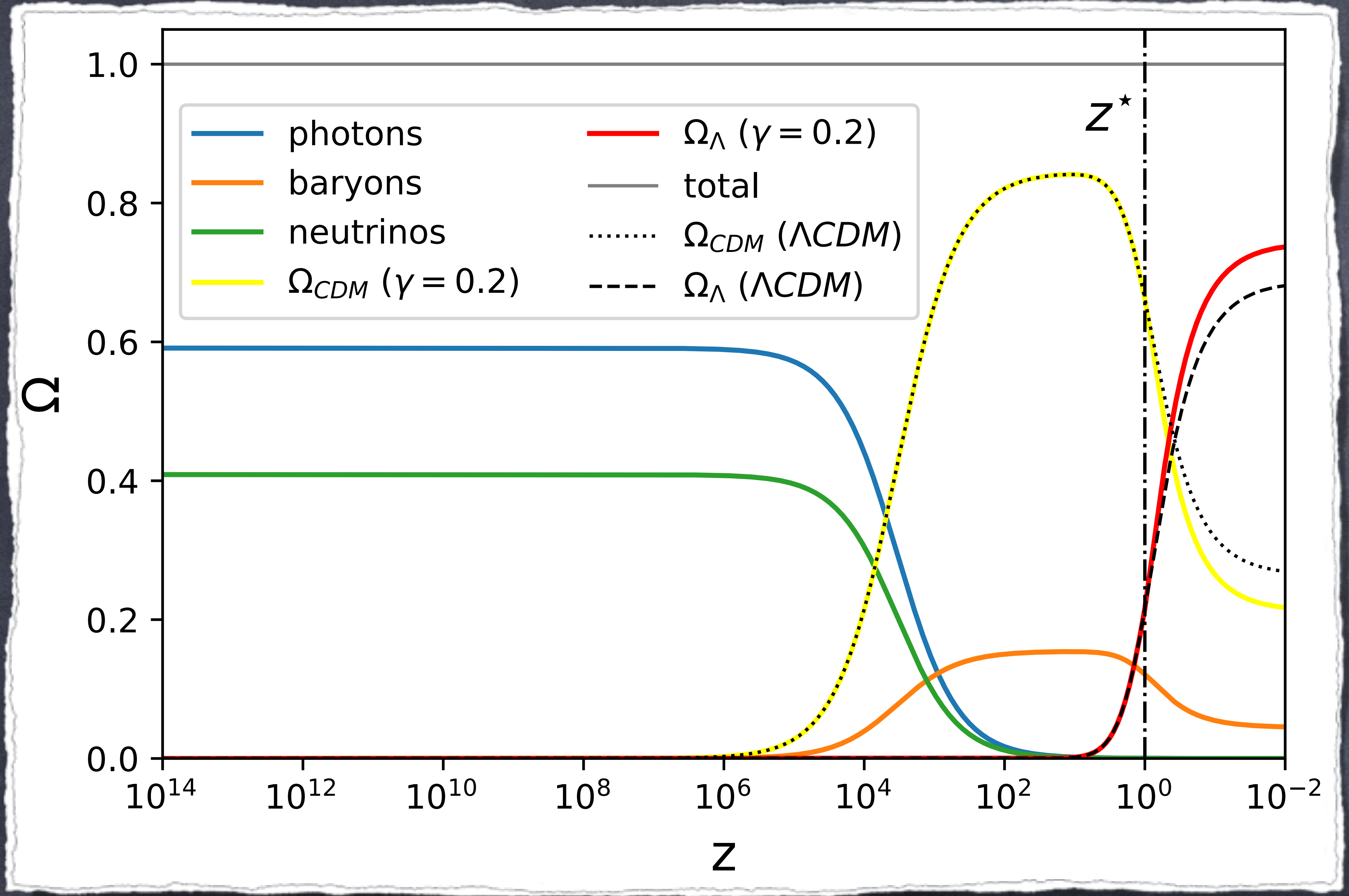
- Model 3: Barotropic model

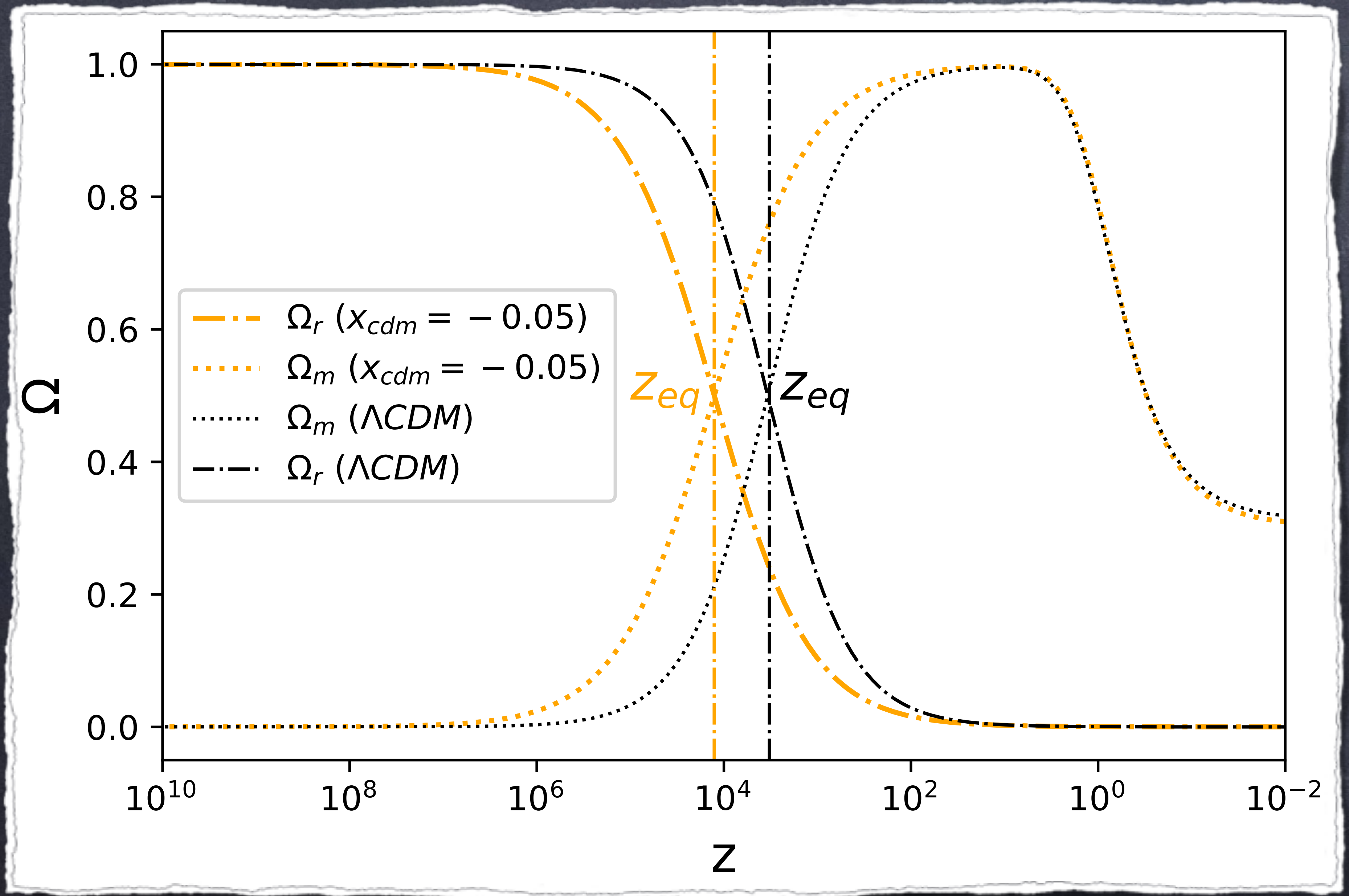
$$E(z) \equiv \frac{H(z)}{H_0} = \sqrt{\Omega_{0,r}(1+z)^4 + \Omega_{0,b}(1+z)^3 + (1+x_{cdm})\Omega_{cdm}(1+z)^{\frac{3}{x_{cdm}+1}} + \Omega_\Lambda}\,.$$

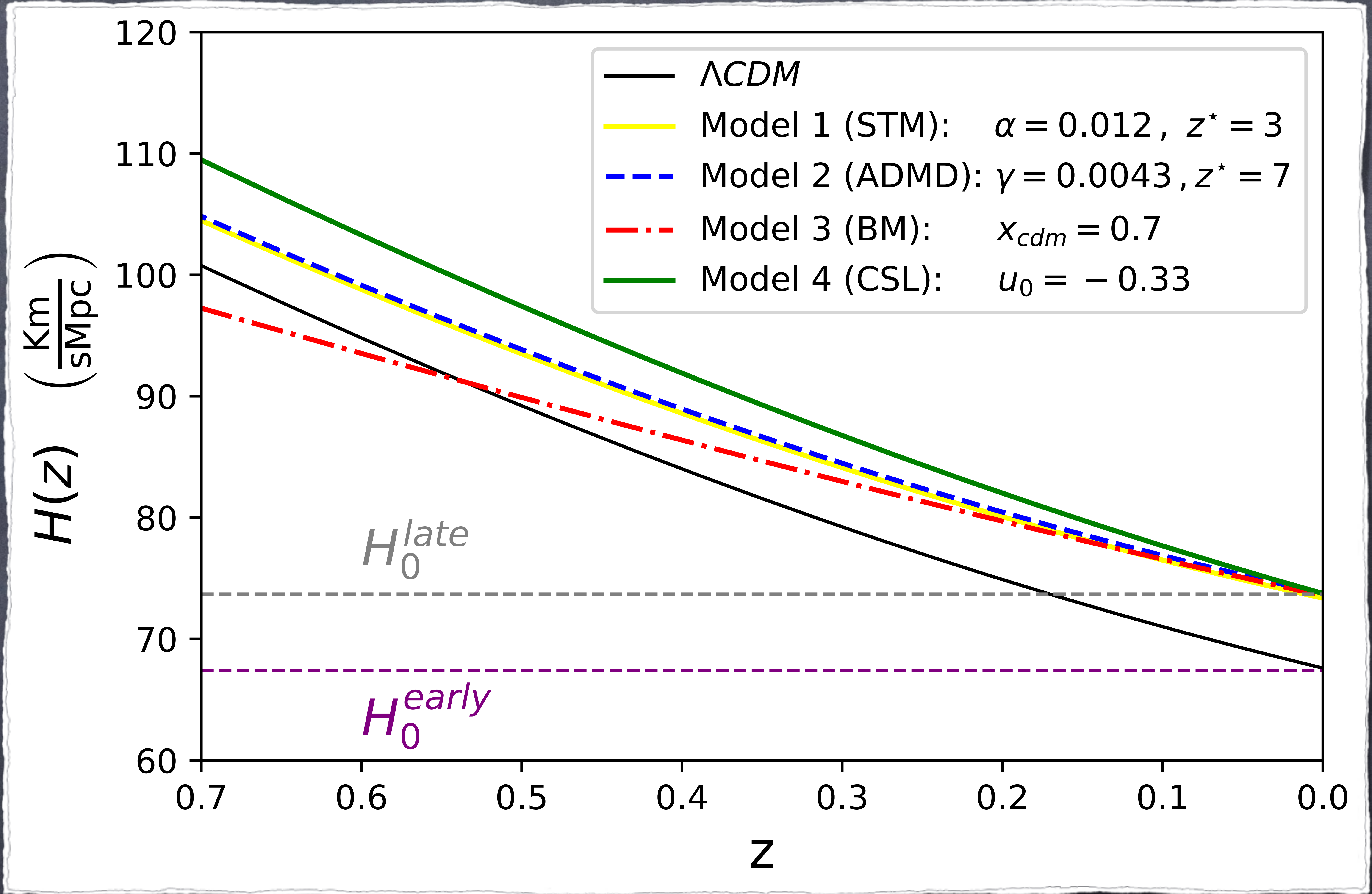
- Model 4: Continuous Spontaneous Localization model

$$E(z) \equiv \frac{H(z)}{H_0} = \sqrt{\Omega_{0,r}(1+z)^4 + \Omega_b h^2(1+z)^3 + \Omega_{cdm}\left[e^{\xi_{CSL}t}(1+z)^3 - \xi_{CSL}\int_0^t e^{\xi_{CSL}t'}[1+z(t')]^3 dt'\right] + \Omega_{\Lambda_{eff}}}\,, \quad \text{with} \quad \Omega_{\Lambda_{eff}} \equiv \Omega_\Lambda + \frac{\kappa^2 Q_i}{3H_0^2}\,.$$

Results: numerical solutions and statistical analysis.







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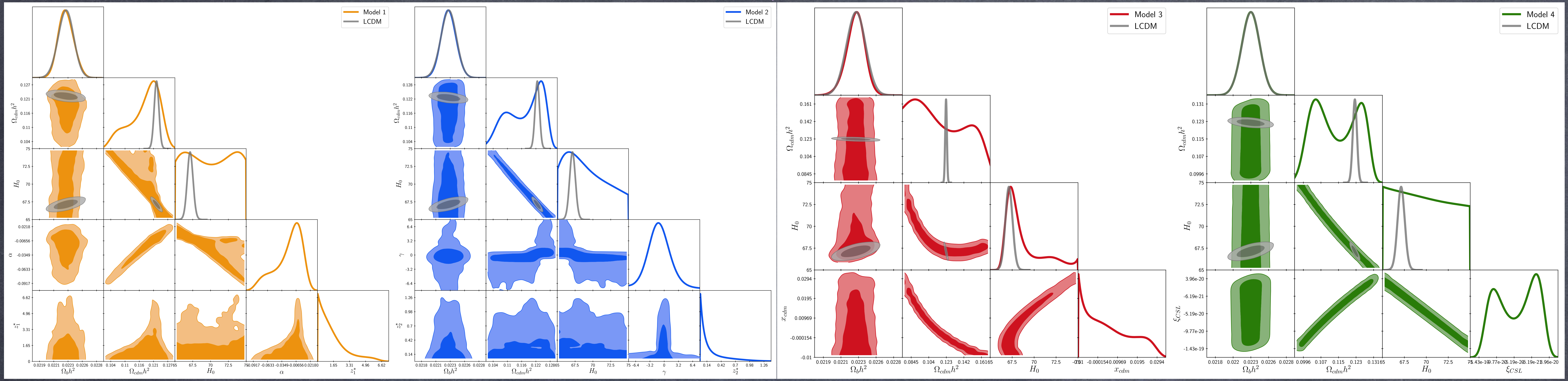
Results: numerical solutions and statistical analysis.

CMB



CMB+SHOES+HOLICOW+PANTHEON

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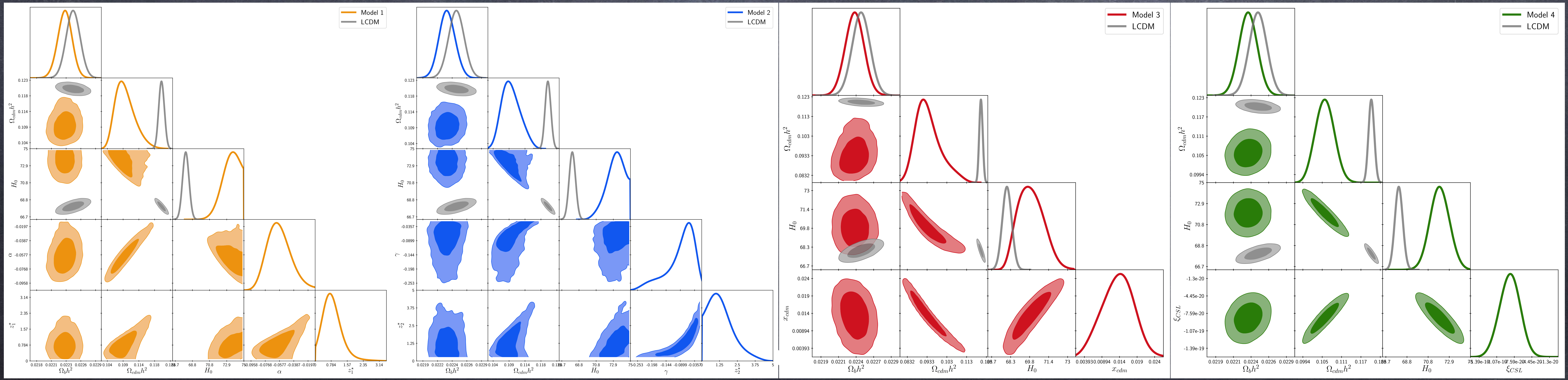

Final remarks.

- Difussion processes between CDM and Λ are naturally allowed within the framework of Unimodular Gravity.

- The tension on H_0 is eased at 0.2σ for Model 1, 0.3σ for Model 2, 2.4σ for Model 3, and 1.1σ for Model 4.

- A deeper comprehension of the physical mechanisms driving the diffusion processes is needed in order to have a complete description of the non-gravitational interaction between the dark sector components.

- Unimodular Gravity offers not only an answer to the origin of the cosmological constant, but we have shown that it can be a compelling candidate to solve the H_0 tension as well.

Gracias!!!

Thank you!!!

¿Questions?