A Hubble parameter estimate $H_0 = \left(73.37 \pm 0.54\right)\ \mathrm{km\,s^{-1}Mpc^{-1}}$ from the late-time Universe and the BAO

Maurice H.P.M. van Putten
Physics and Astronomy, Sejong University, Seoul

Based on

van Putten 2021 **PLB** 823 136737
Abchouyeh & van Putten 2021 **PRD** 104 083511
O Colgain, van Putten, Yavartanoo, 2019 **PLB** 126

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- “*What’s the choice of vacuum*?” (G. ’t Hooft, MG15 meeting)
- Finite temperature in cosmology
- *Missing term* in FRW-equations: heat
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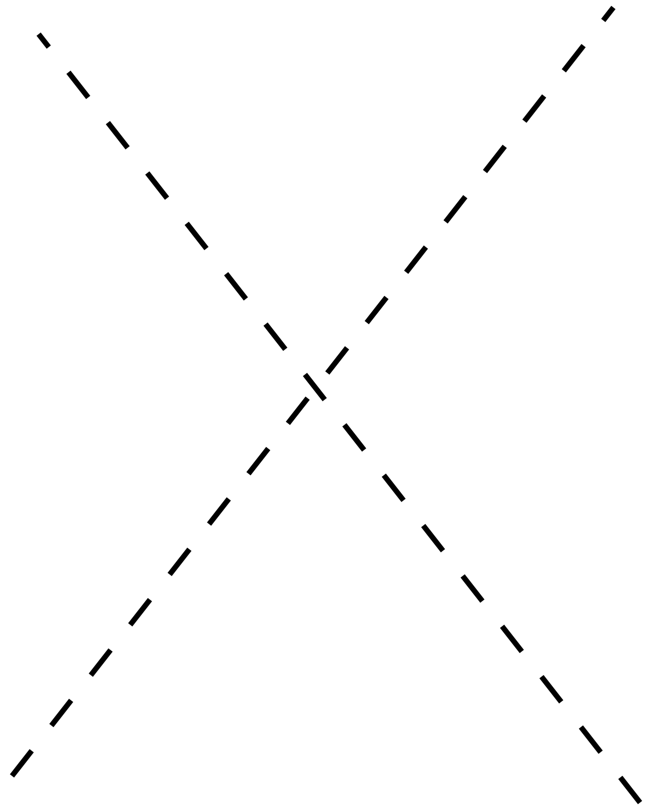
Minkowski spacetime

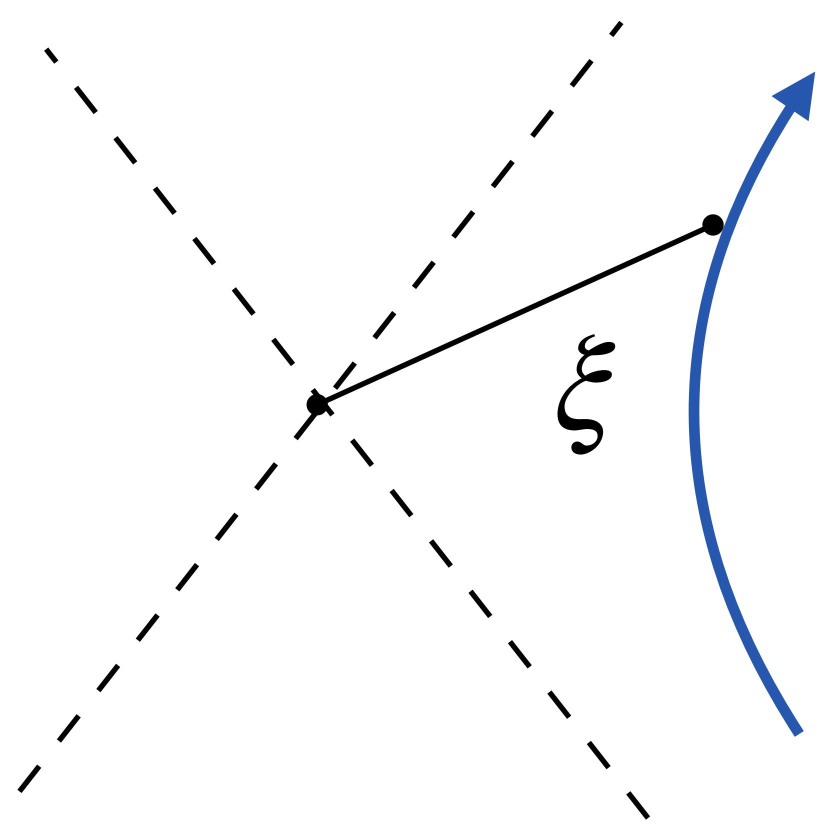
Minkowski spacetime $\mathscr{M}$



Zero temperature limit for geodesic observers

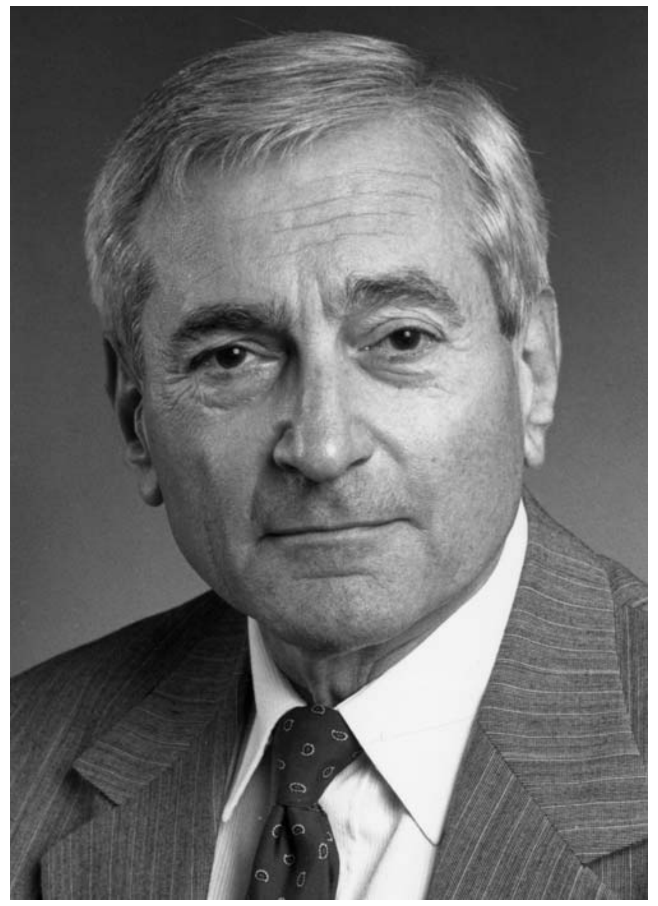
… seen along a hyperbolic trajectory

Minkowski spacetime $\mathscr{M}$



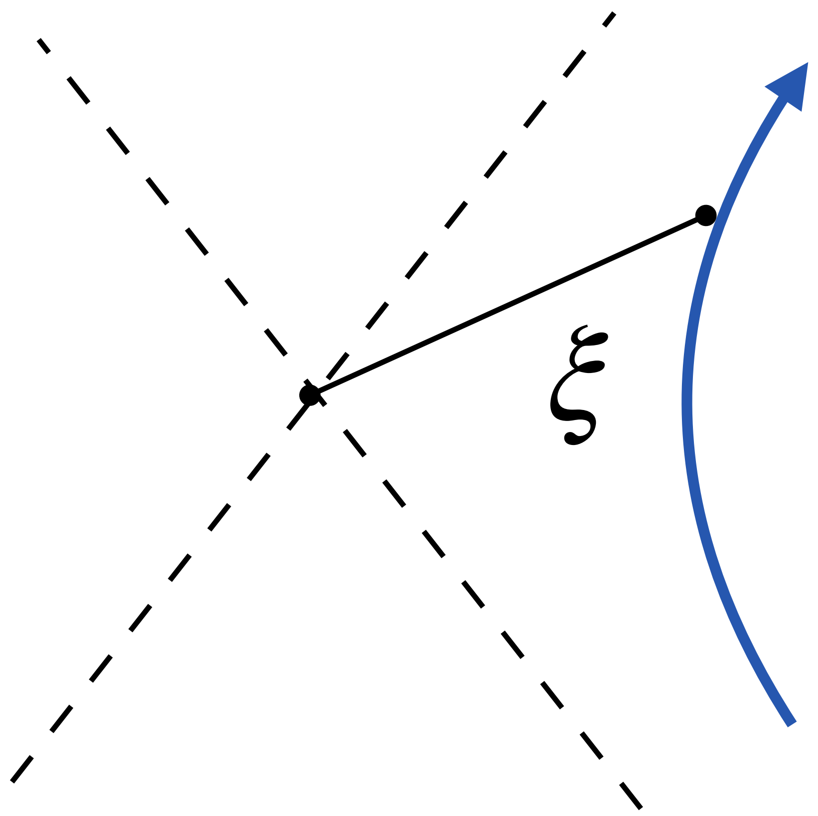
Observer at constant acceleration α

… in Rindler spacetime



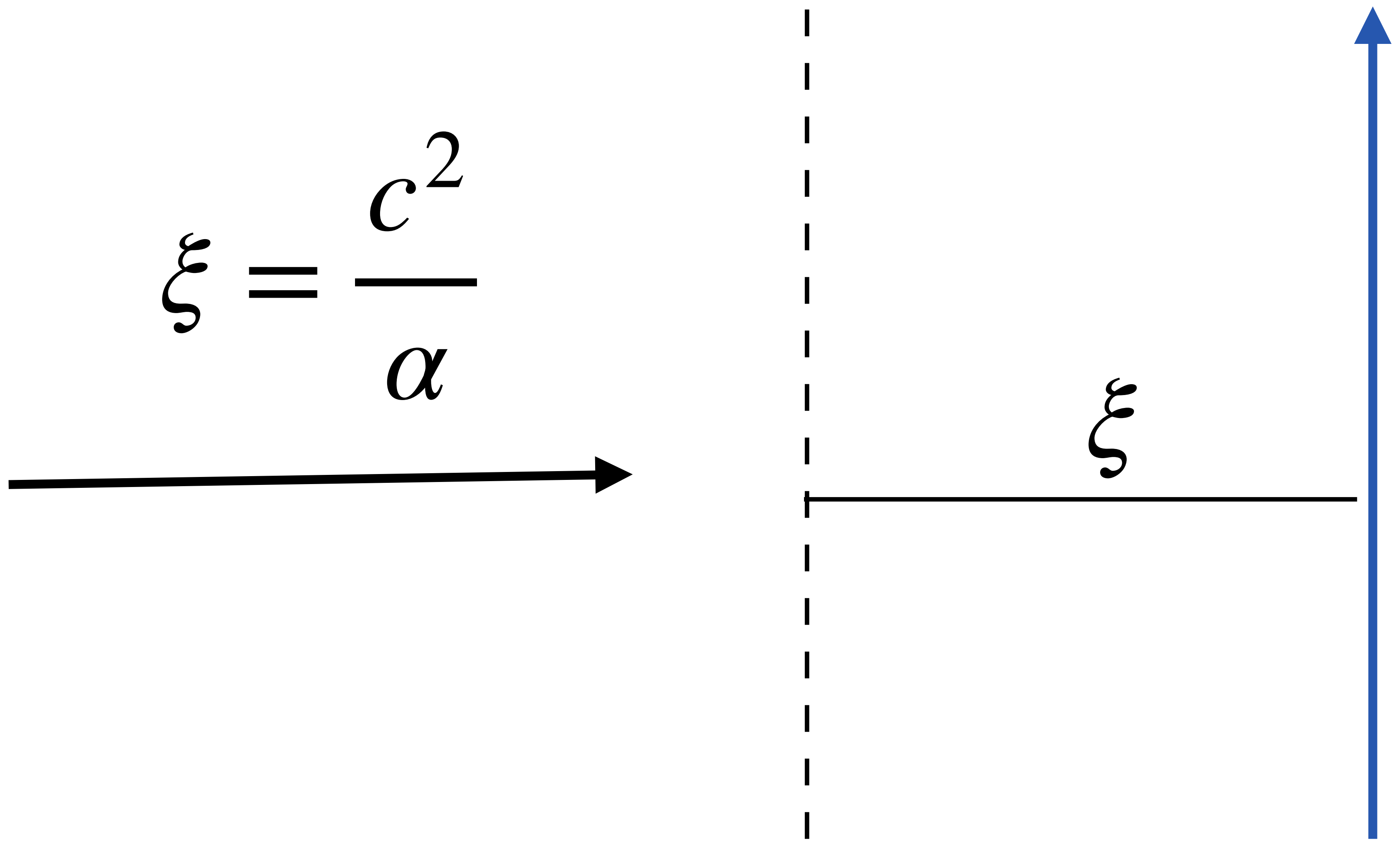
W. Rindler

Minkowski spacetime $\mathscr{M}$



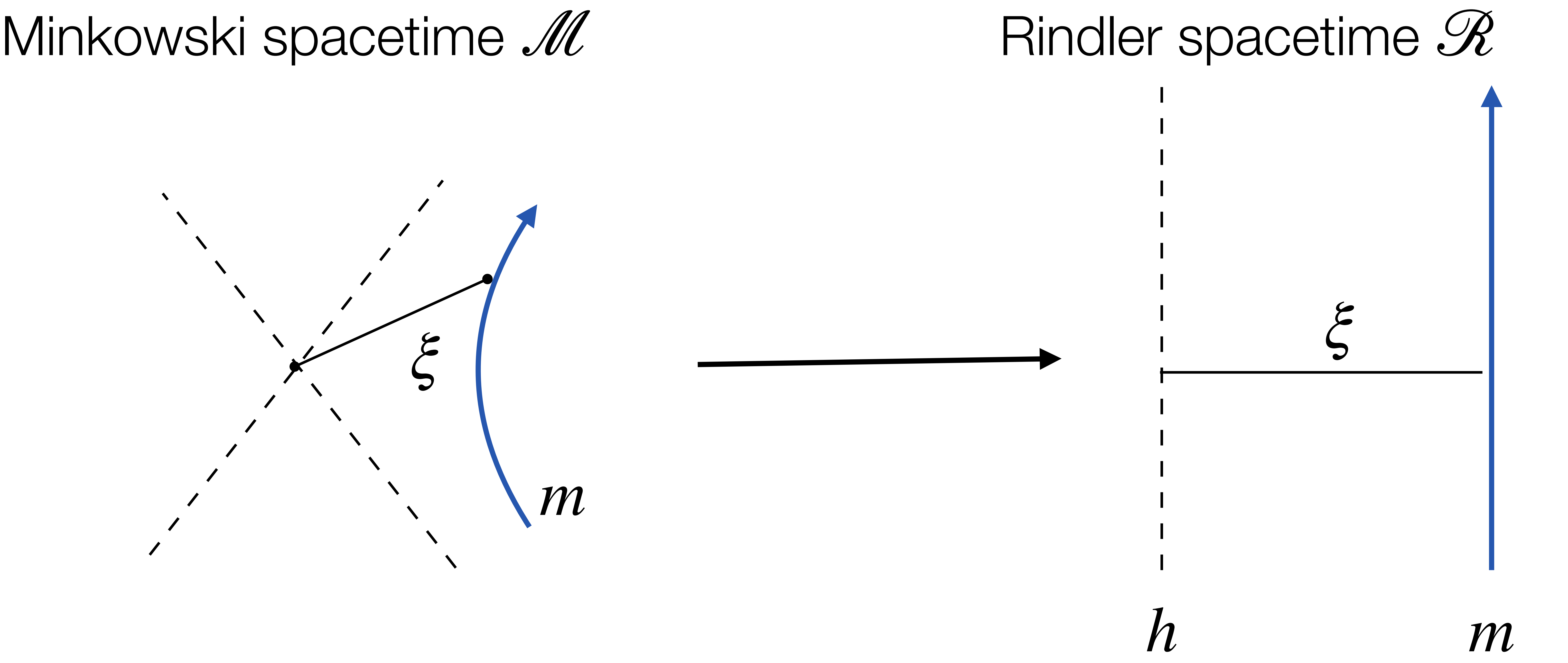
$$\xi = \frac{c^2}{\alpha}$$

Rindler spacetime $\mathscr{R}$



Rindler horizon h

Thermodynamic temperature



$$S = 2\pi\varphi_C$$

(Bekenstein 1973)

$$T = \frac{\alpha\hbar}{2\pi c}$$

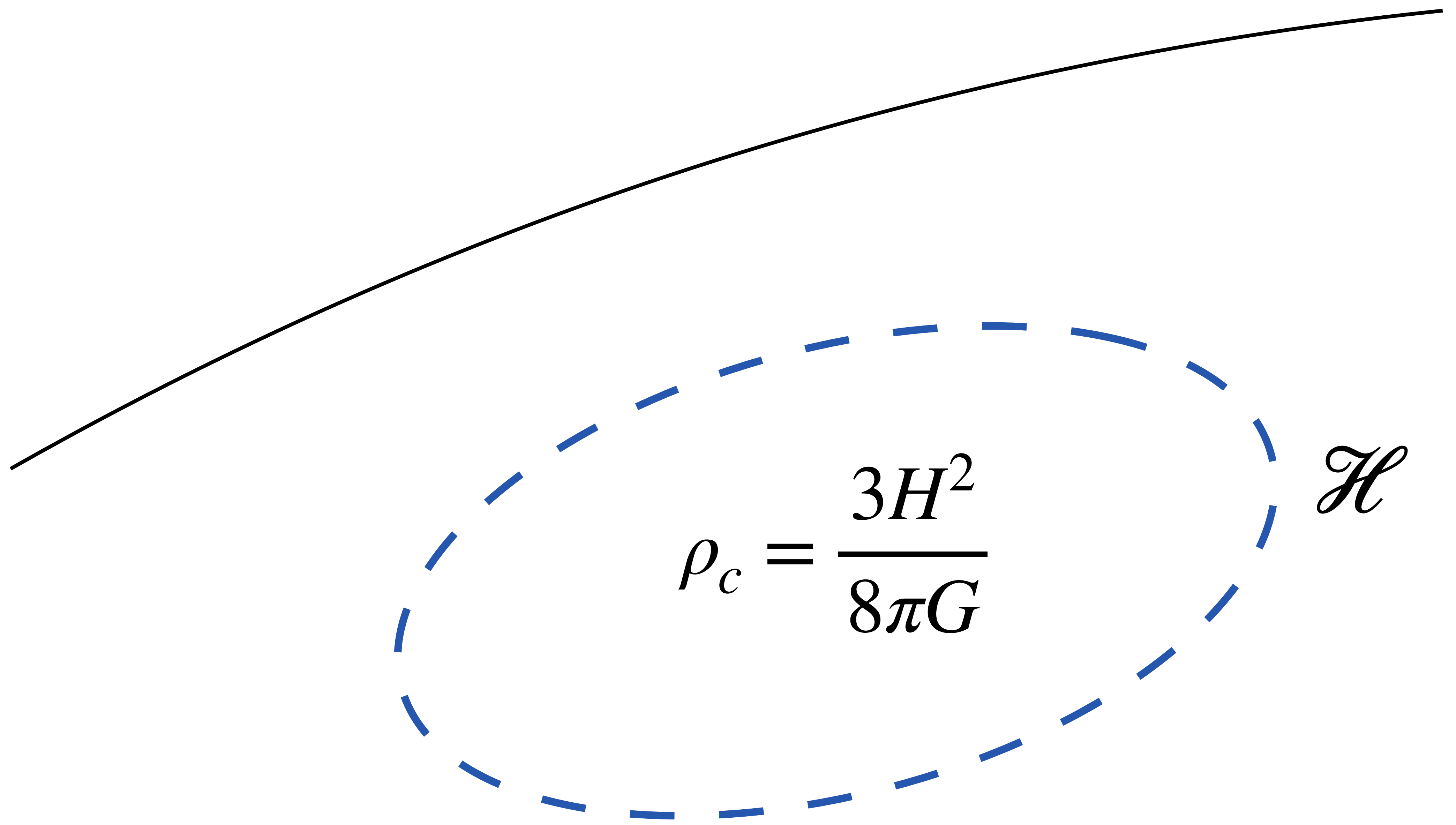
(Unruh 1976)

Spacetime with finite gravitational field carries heat $Q = \int_0^\xi T dS = mc^2$

de Sitter cosmology: constant *H*

$$k_B T_H = \frac{H\hbar}{2\pi}$$

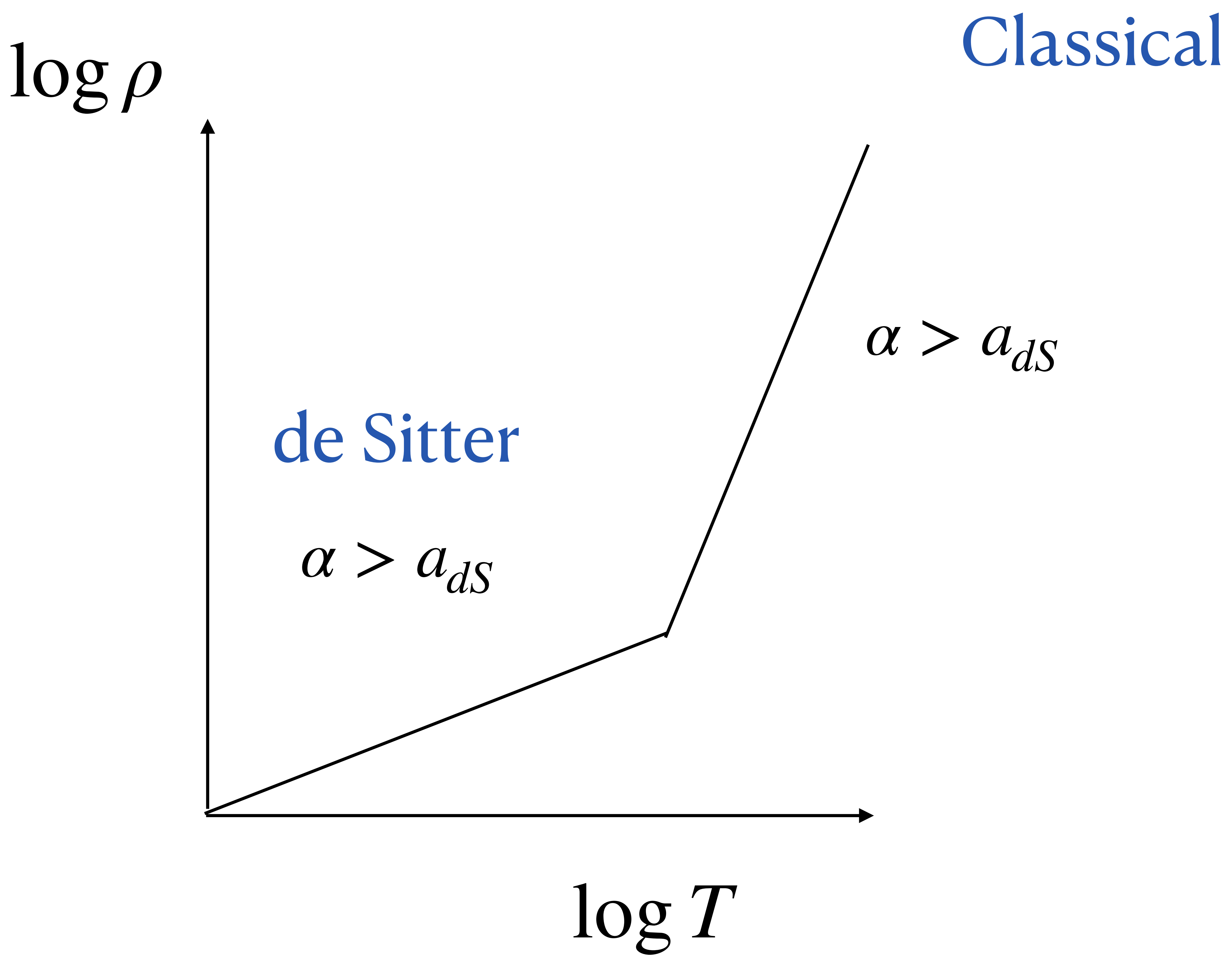
(Gibbons & Hawking 1977)



de Sitter scaling

$$\rho_c c^2 = A T_H^2$$

$$A = \frac{3\pi k_B^2}{2 l_p^2 \hbar c}$$



Heat density reduces to closure density at $a_{dS} = cH$

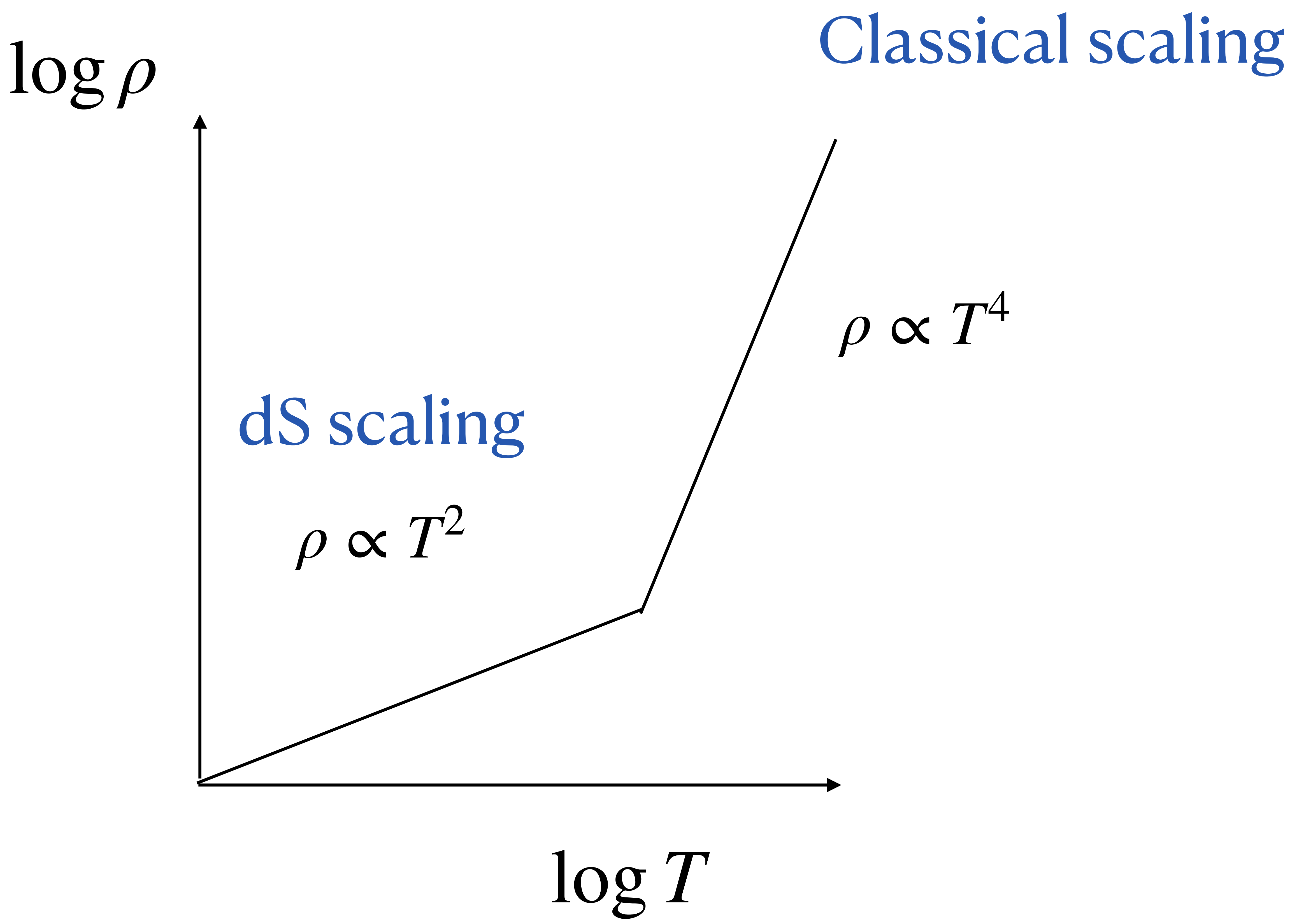
.. picked up in late-time $H(z)$ data

Fit to Hubble data

$$\rho_U = BT^\alpha + \sigma T^4$$

$$\alpha = 1.94 \pm 0.46$$

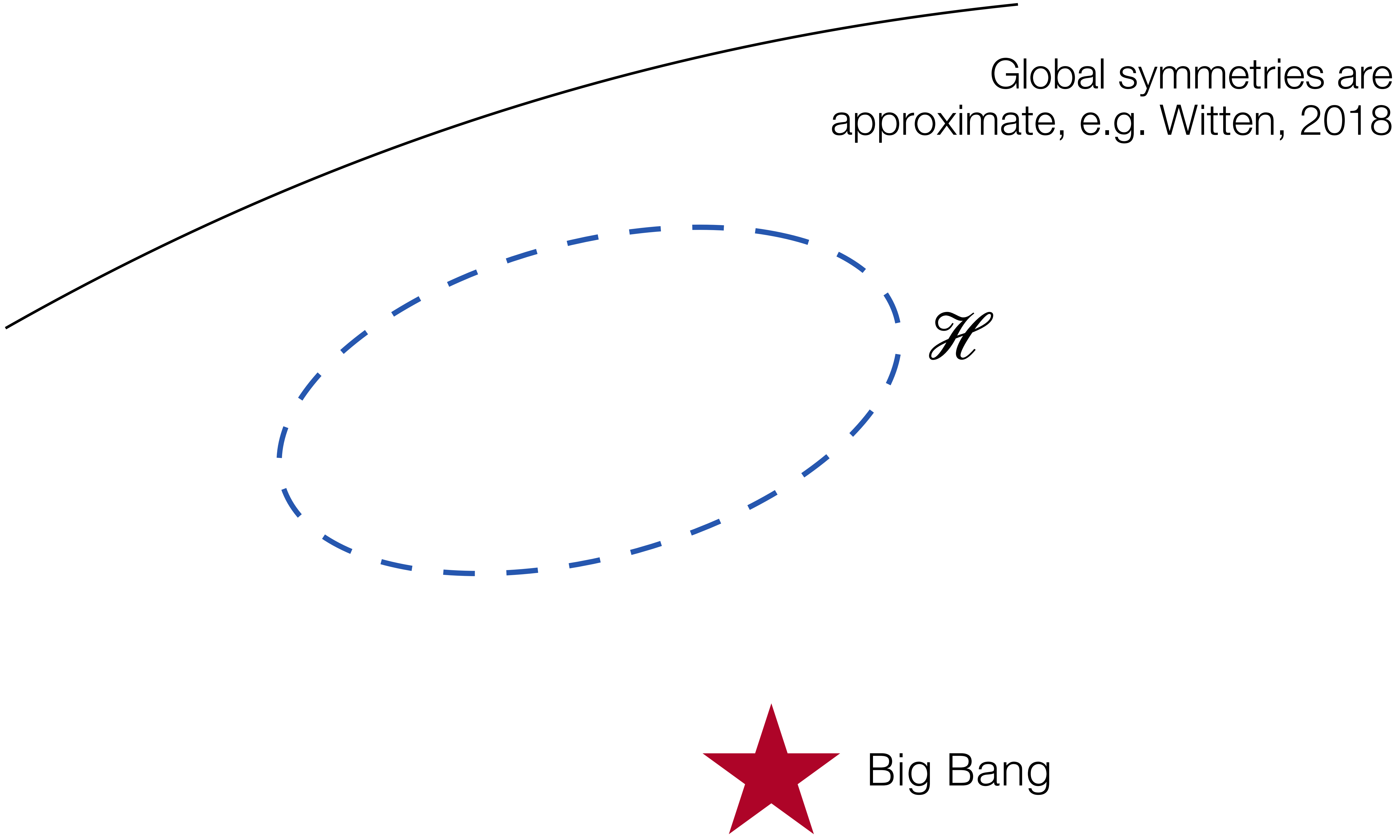
(Abchouyeh & van Putten 2021)



Big Bang

Time-translation invariance broken on a Hubble time-scale

Equivalently, asymptotically flat $\mathscr{M}$ absent in the face of the Hubble horizon $\mathscr{H}$.



Beyond de Sitter

Propagator $e^{i\left(\Phi - \Phi_0\right)}$ now includes phase reference $\Phi_0\left[\mathscr{H}\right]$ - dynamic!

van Putten, 2020, MNRAS, 491, L6

Missing term in FLRW

Friedmann scale factor a of a background cosmology:

$\Phi_0\left[\mathscr{H}\right] = \int 2\Lambda$ with equivalent $\Lambda = \lambda R(a, \dot{a})$:

$$\boxed{\Lambda = g(1-q)H^2}$$

van Putten, 2021, PLB, 823, 136737

Allow gravitational coupling $g \lesssim 1$ (not necessarily universal).

... in heat

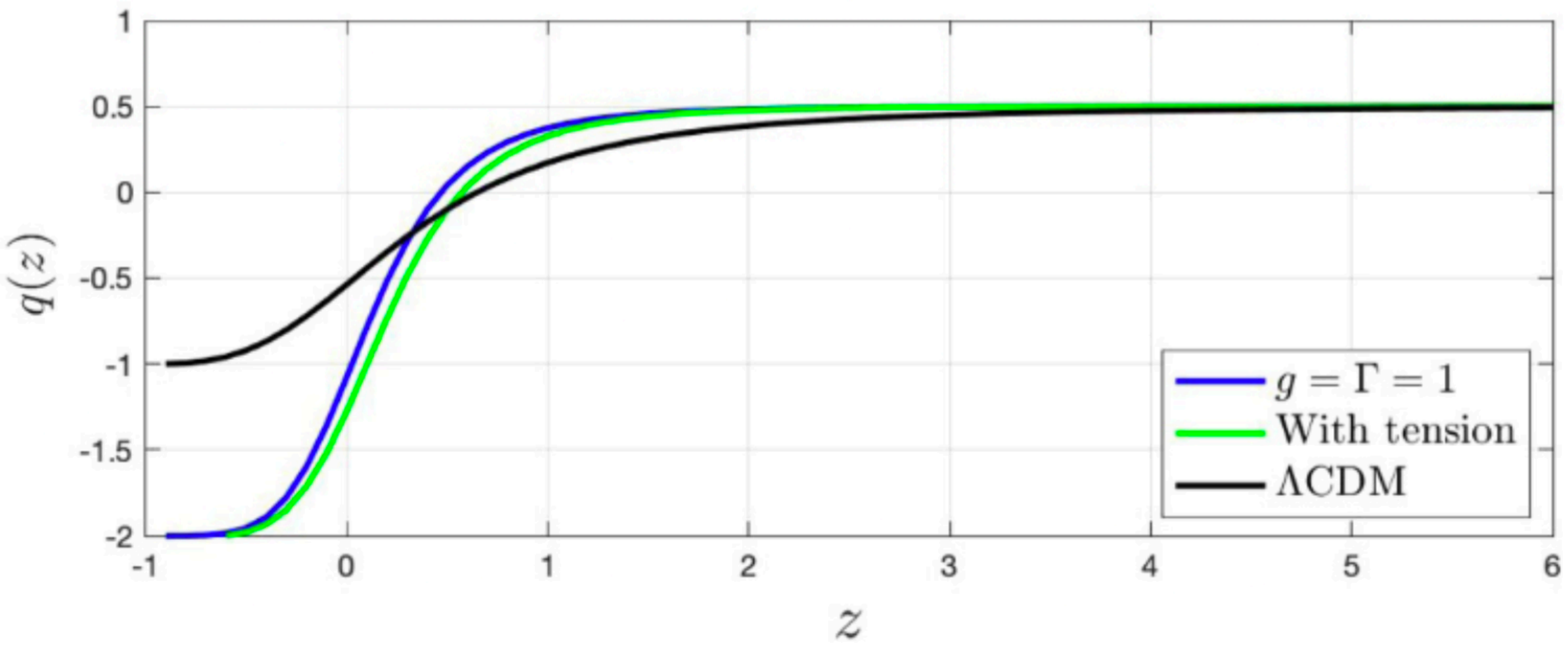
Include generalized *Ansatz* $\Lambda = \Lambda_0 + g(1-q)H^2$:

$$h(z) = \frac{\sqrt{1+A(z)}}{(1+z)^{\frac{\gamma+1}{2}}} \quad \left(\gamma = \frac{6}{g} - 5\right)$$

$A(z) = A_0(z) + A_r(z) + A_M(z) + A_K(z)$ in $Z_n = (1+z)^n - 1$:

$$A_0(z) = \frac{3\Omega_{\Lambda_0}}{3-2g} Z_{1+\gamma}(z),\ A_r(z) = \Omega_r Z_{5+\gamma}(z),\ A_M(z) = \frac{6\Omega_{M,0}}{6-g} Z_{4+\gamma}(z),\ A_K(z) = \frac{3\Omega_{K,0}}{3-g} Z_{3+\gamma}(z)$$

Analytical solutions



Zero temperature: ΛCDM $\left(\Lambda = \Lambda_0, g = 0\right)$

$$h(z) = \sqrt{1 + \Omega_{M,0} Z_3(z)}$$

Standard Friedmann equations

$$q_0 = \frac{1}{2}\Omega_{M,0} - \Omega_{\Lambda_0} \sim -\frac{1}{2}$$

Finite temperature: $\left(\Lambda_0 = 0, g = 1\right)$:

$$h(z) = \frac{\sqrt{1 + \frac{6}{5}\Omega_{M,0} Z_5(z)}}{1 + z}$$

Friedmann equations with heat

$$q_0 = 2q_{0,\Lambda\mathrm{CDM}} \simeq -1$$

Deceleration is twice what is expected in zero temperature limit

H_0-tension

H_0-tension between Planck-ΛCDM and the Local Distance Ladder

- Planck-ΛCDM: $H_0' = \left(67.4 \pm 0.5\right)\ \mathrm{km\,s^{-1}Mpc^{-1}}$

Planck ΛCDM analysis of CMB (2020)
("primed")

- Local Distance Ladder: $H_0 = (73.2 \pm 1.3)\ \mathrm{km\,s^{-1}Mpc^{-1}}$

Riess et al. 2021 ApJ 908 L6
Wong et al. 2020 MNRS 498 1420

$$\Gamma = \frac{H_0}{H_0'} = 1.0861 \times (1 \pm 0.019)$$

8.6% tension

Two observational constraints

C1: Age of the Universe T_U from oldest stars in Globular Clusters of Milky Way

Valcin et al., 2020, JCAP 12, 162
O'Malley et al., 2017, ApJ, 838, 162
Jimenez et al. 2019, JCAP, 03, 043

C2: Baryon Acoustic Oscillations (BAO) in CMB:

$$\theta_{*,\mathrm{Planck}} = (1.04109 \pm 0.00030) \times 10^{-2}$$

most precise observational constraint in modern cosmology

Planck ΛCDM analysis of CMB (2020)

Two integral constraints

$H(z) = H_0 h(z)$ and normalize constraints C1-2 to ΛCDM solutions:

C1. $$T_U \equiv H_0^{-1} T_{U,0},\ T_{U,0} = \int_0^\infty \frac{dz}{(1+z)h(z)}:$$

$$\frac{T_{U,0}}{T'_{U,0}} = \frac{H_0}{H'_0} = \Gamma$$

Correlates $(H_0, \Omega_M)^*$

C2. $$\theta_* = \frac{c^{-1}\int_{z_*}^\infty c_s h(z)^{-1} dz}{\int_0^{z_*} h(z)^{-1} dz}:$$

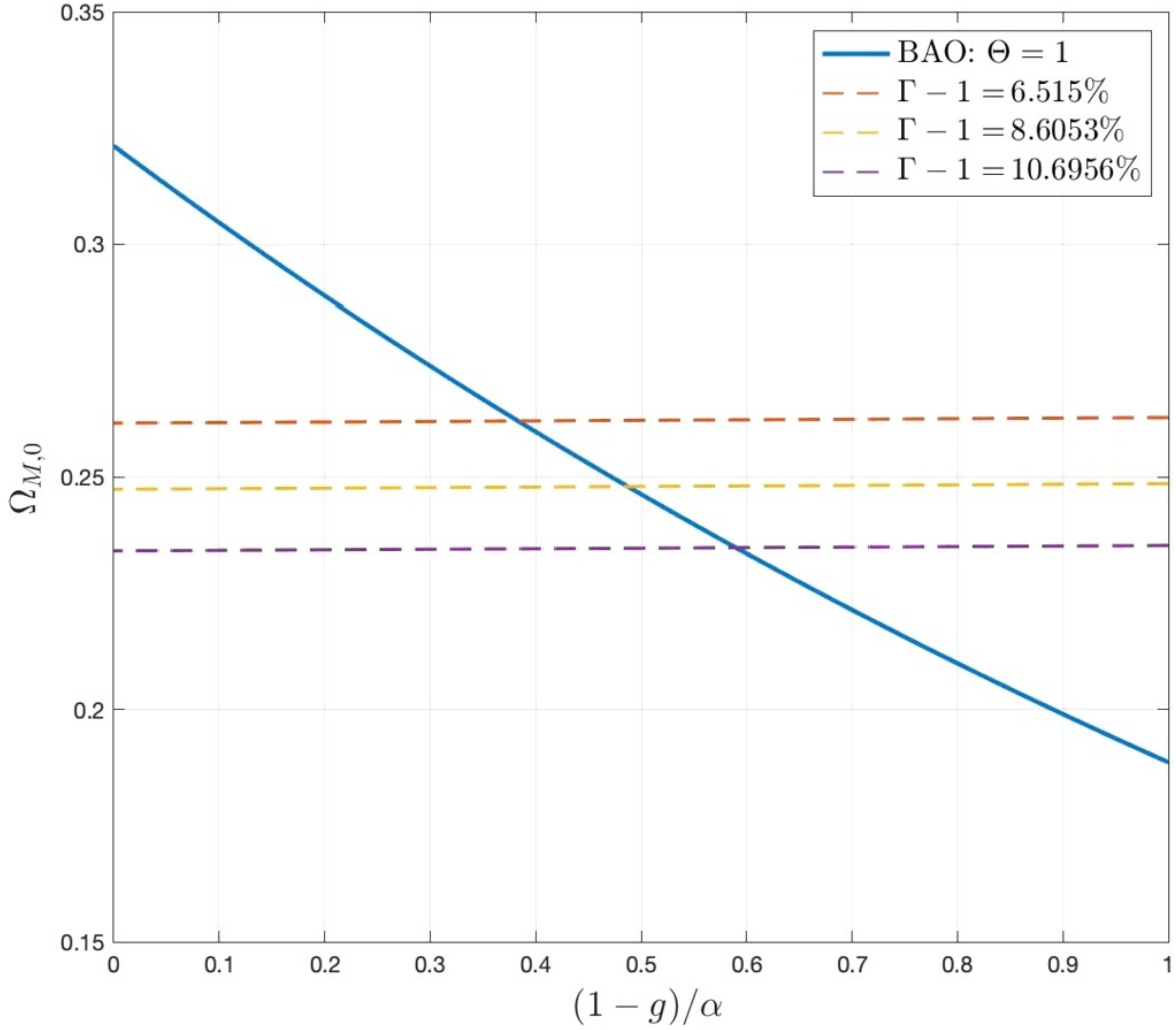
$$\theta_* = \theta_{*,\mathrm{Planck}}$$

Largely fixes Ω_M^*

cf. Jedamzik, Pogoslan & Zhang, 2021, Commun. Phys. 4 , 123

*For a given model cosmological background evolution

Solving C1-2



$$g = 1 - \xi\alpha \quad \left(\alpha \simeq \frac{1}{137}\right)$$

Impose $\Gamma - 1 = 8.64\,\%$:

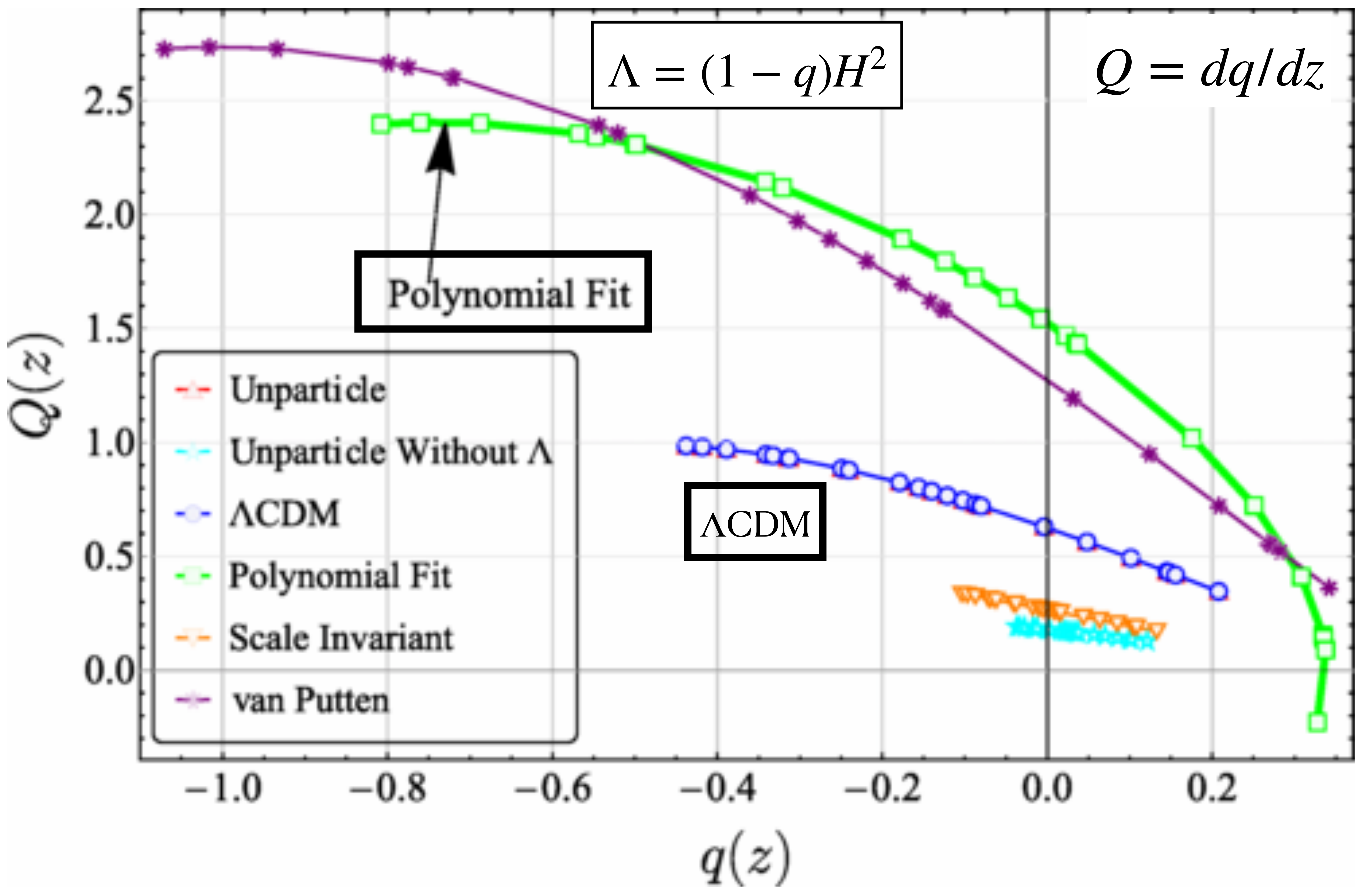
$$\xi = 0.49 \pm 0.1$$

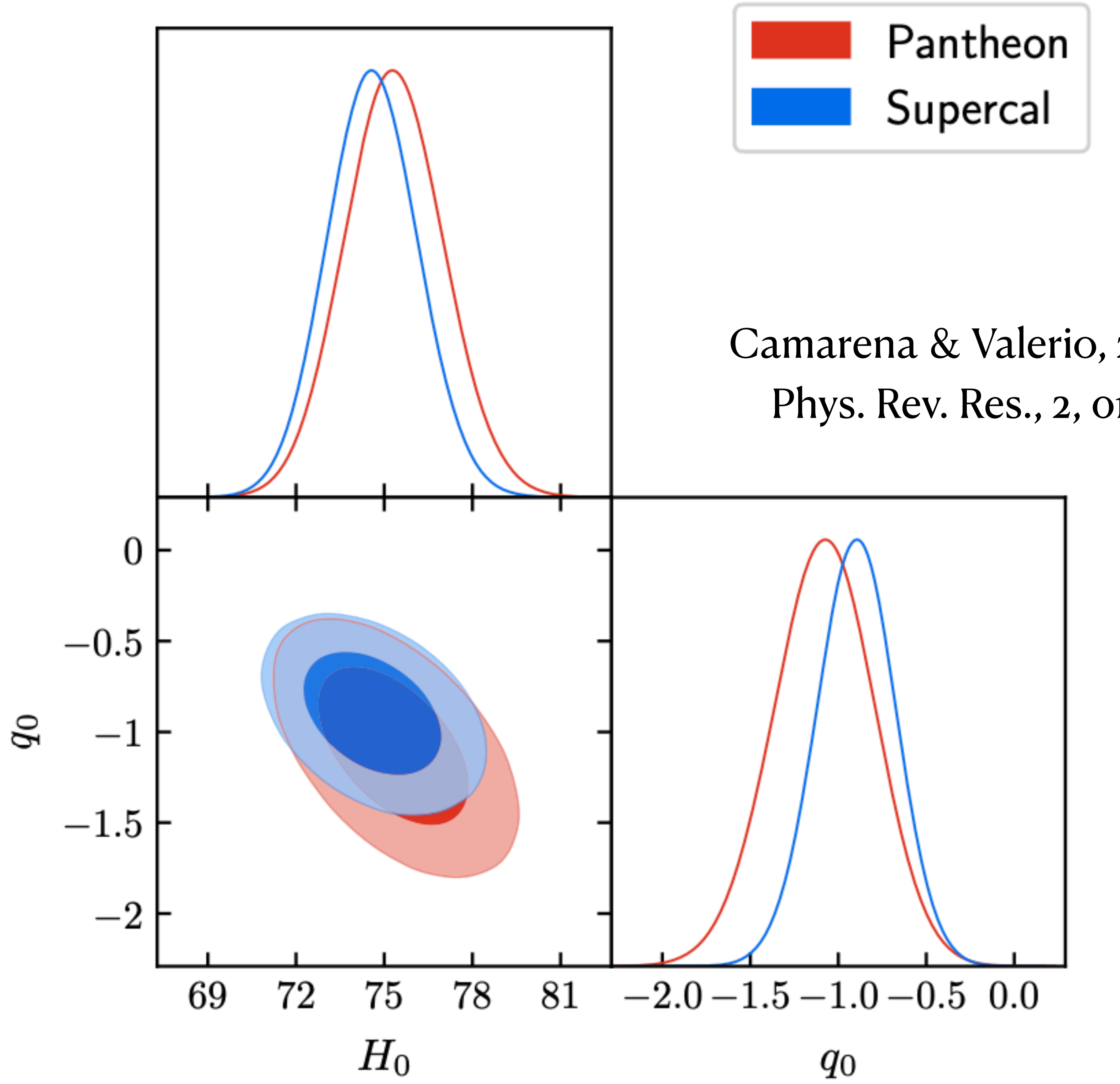
$\Omega_M = 0.2480 \pm 0.014$ consistent with 0.2719 ± 0.028 in fit to late-time $H(z)$-data of Farooq et al. (2017)

van Putten, 2017, ApJ, 848, 28

qQ-diagram

Abchouyeh & van Putten 2021 PRD 104 083511





Camarena & Valerio, 2020, Phys. Rev. Res., 2, 013028

$$q_0 = 2q_{0,\Lambda\mathrm{CDM}} \simeq -1 \qquad\qquad q_0 = -1.08 \pm 0.29$$

Conclusions

H_0 larger than expected *by including heat* to FLRW-equations:

$$\Lambda = \left(1 - \xi\alpha\right)\left(1 - q\right)H^2$$

$\xi = 0.49 \pm 0.1$ (preserving age of the Universe and BAO)

Conceivably $\xi = \frac{1}{2}$: $H_0 = \left(73.37 \pm 0.54\right)\ \mathrm{km\,s^{-1}Mpc^{-1}}$

cf. $(73.30 \pm 1.04)\ \mathrm{km\,s^{-1}Mpc^{-1}}$

Riess et al. 2021, arXiv:2112.04510v2