The Hubble parameter of the Local Distance Ladder from dynamical dark energy with no free parameters

Maurice H.P.M. van Putten

References:

van Putten, 2023, submitted
Abchouyeh & van Putten, 2021
O'Colgain, van Putten & Yavartano (2019)
van Putten (2017, 2019, 2021)

Corfu2023 Tensions in Cosmology
Sept 12 2023

Outline

- Hubble parameter and data-structure of observables
- Evolution in quantum cosmology:
  - ✤ H_0 bootstrapped from ΛCDM and H_0-tension
- q_0 inferred from baryonic Tully Fisher'
- Conclusions and Outlook

Hubble parameter and data structure

Cosmological expansion

Homogeneous and isotropic Universe

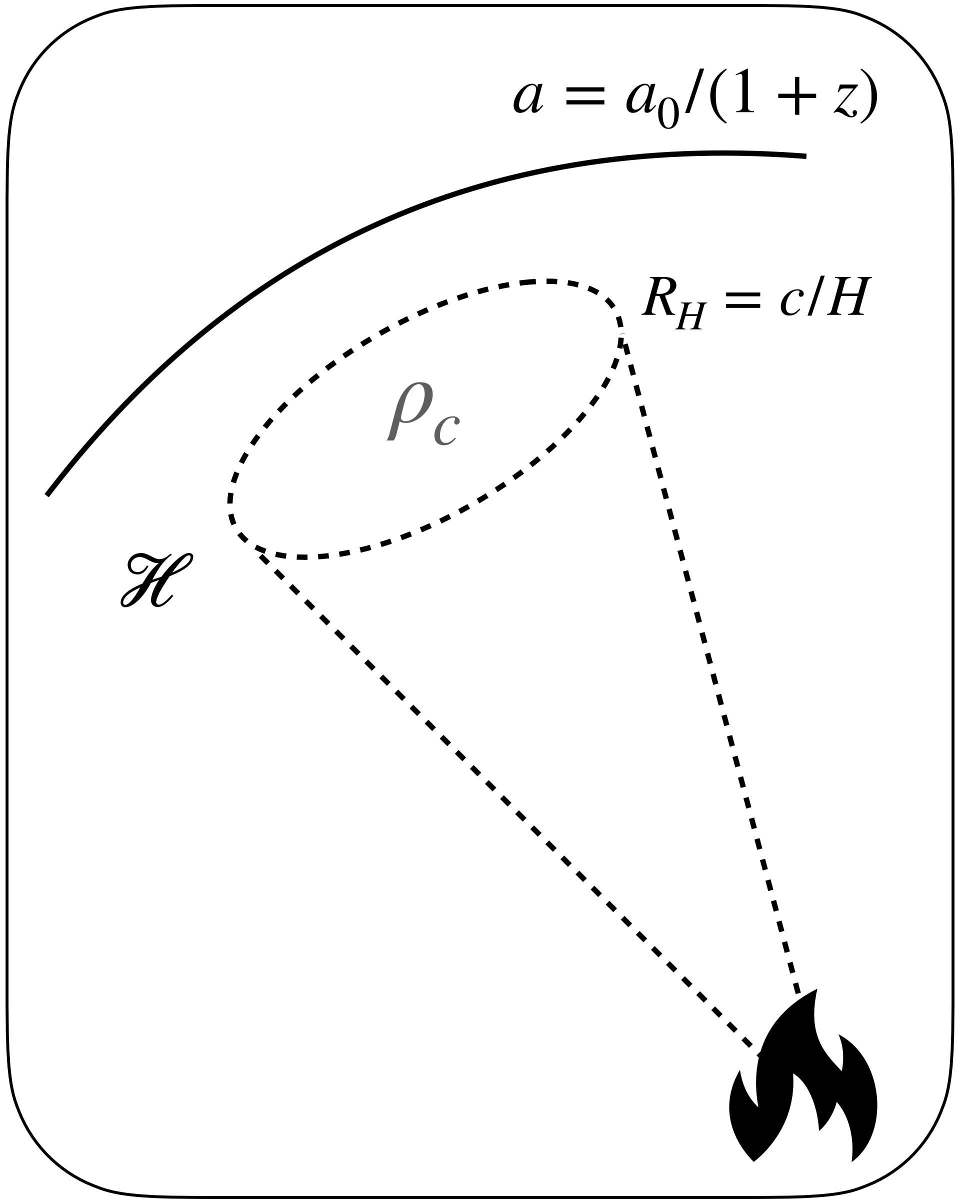
$$ds^2 = -c^2dt^2 + a(t)^2\left(dx^2 + dy^2 + dz^2\right)$$

Friedmann scale factor $a(t)$

$$H = \frac{\dot{a}}{a},\ q = -\frac{\ddot{a}a}{\dot{a}^2}$$

with closure density $\rho_c = \dfrac{3H^2}{8\pi G}$.

$a(t)$ evolves by 2nd-order system:



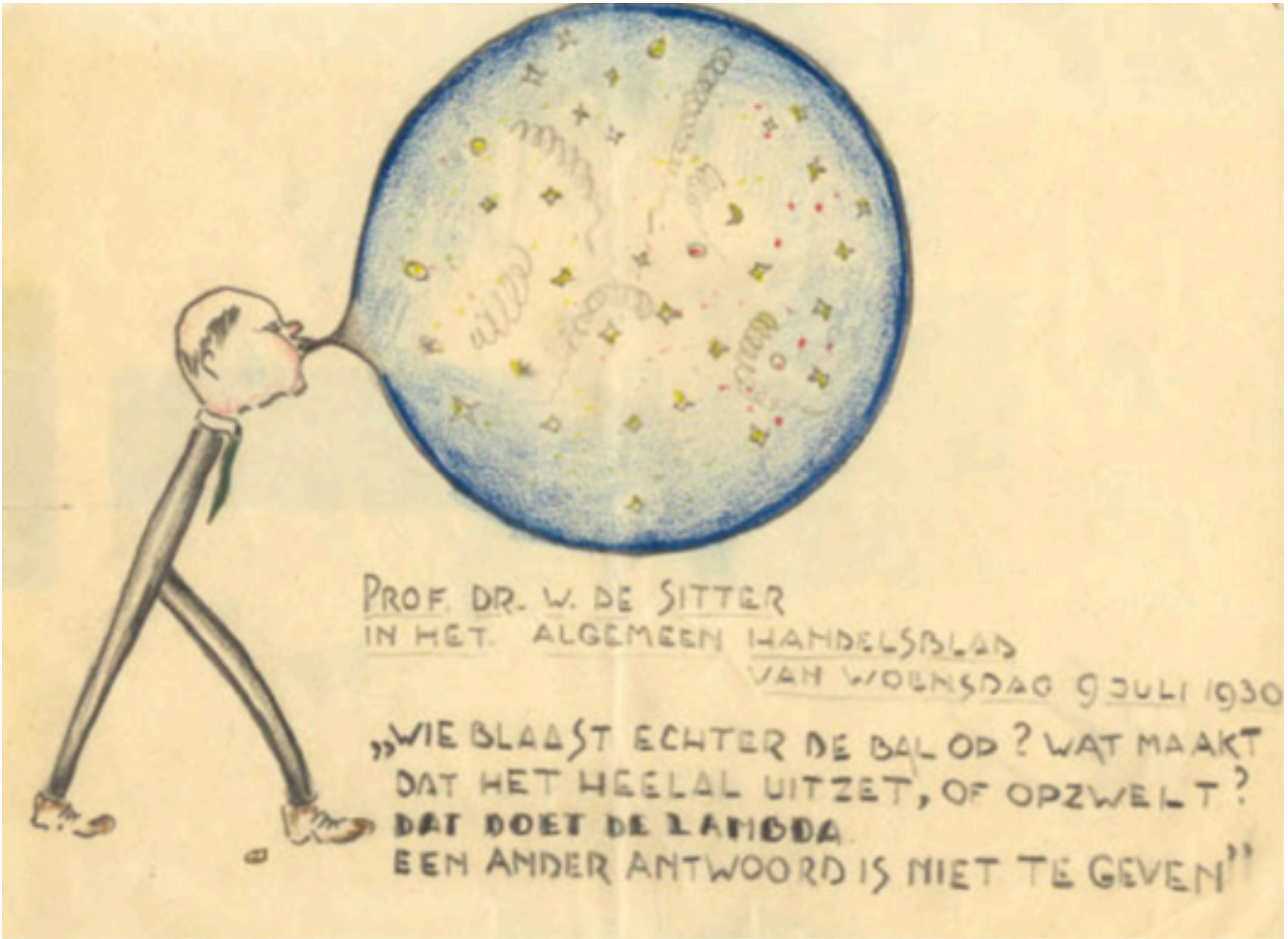
Late-time cosmology parameterized by $\left(H_0, q_0\right)$

Sandage (1961, 1970)

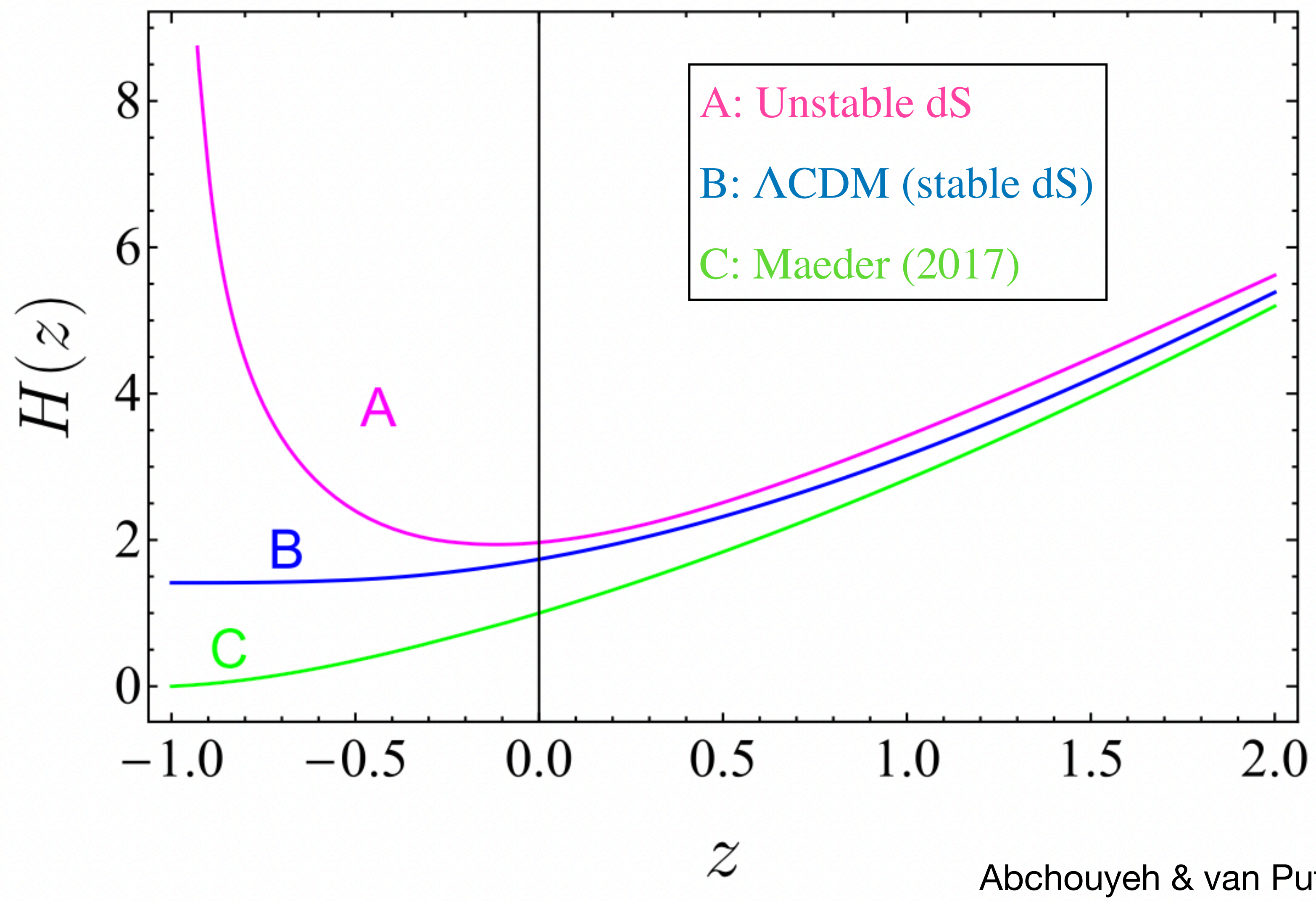
Cosmological expansion - de Sitter 1936

accelerated

"Who, however, inflates the balloon? What causes the Universe to expand or swell?
That does the Λ.
A different answer cannot be given."



Futures of cosmological expansion

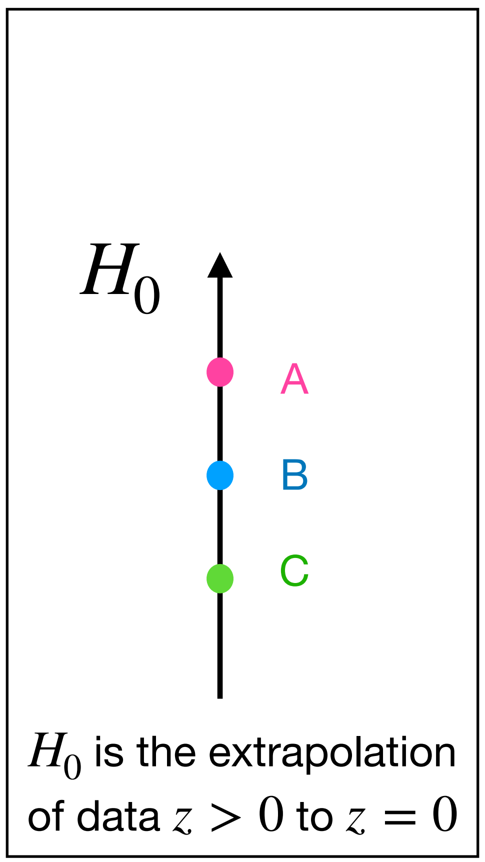


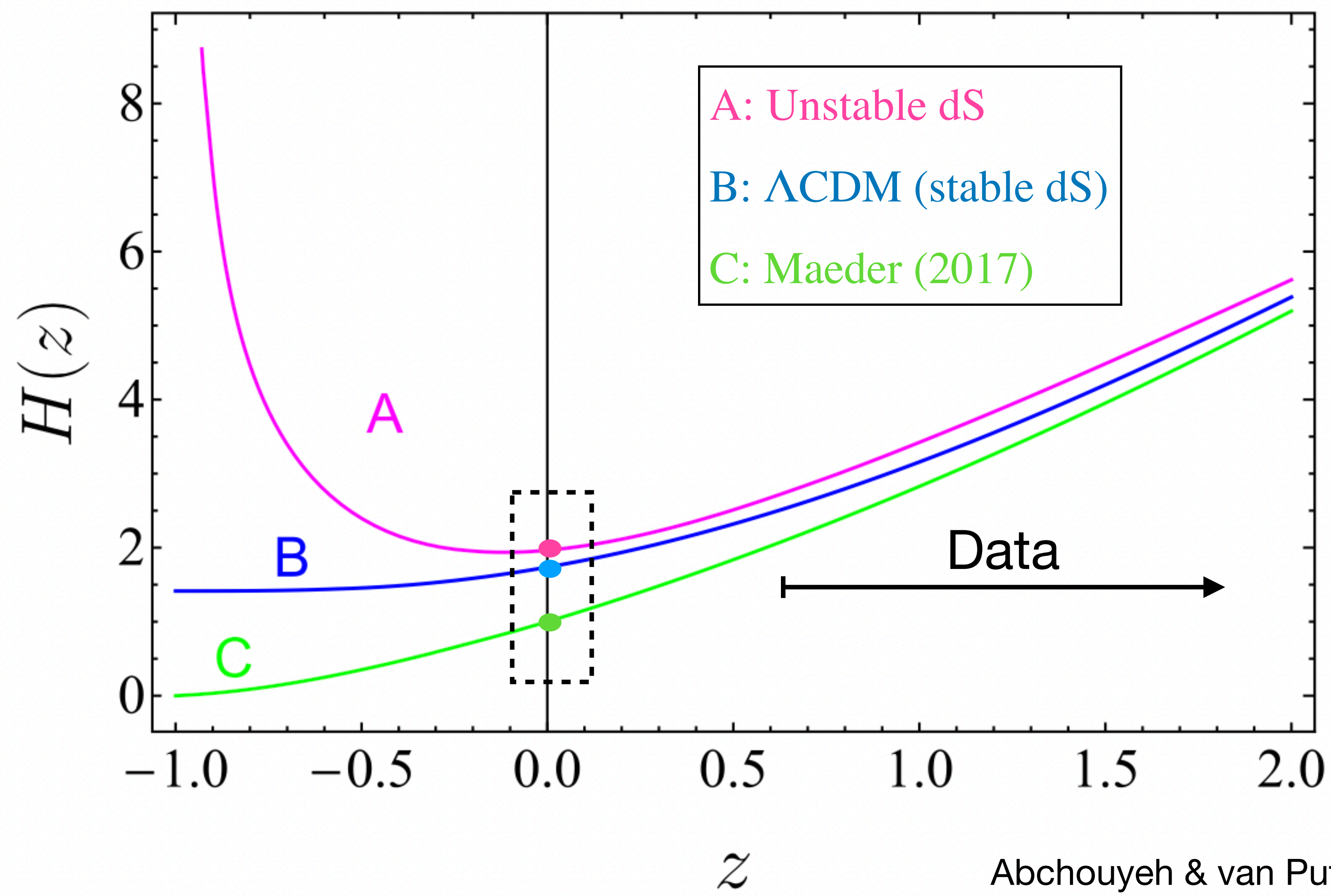
Abchouyeh & van Putten (2021)

Tensions from the future

Future is stable dS in ΛCDM,
unstable dS favors higher H_0

van Putten (2017)
O'Colgain, van Putten & Yavartano (2019)
ΛCDM in swampland (Agrawal, Obied, Steinhardt & Vafa, 2018





Abchouyeh & van Putten (2021)

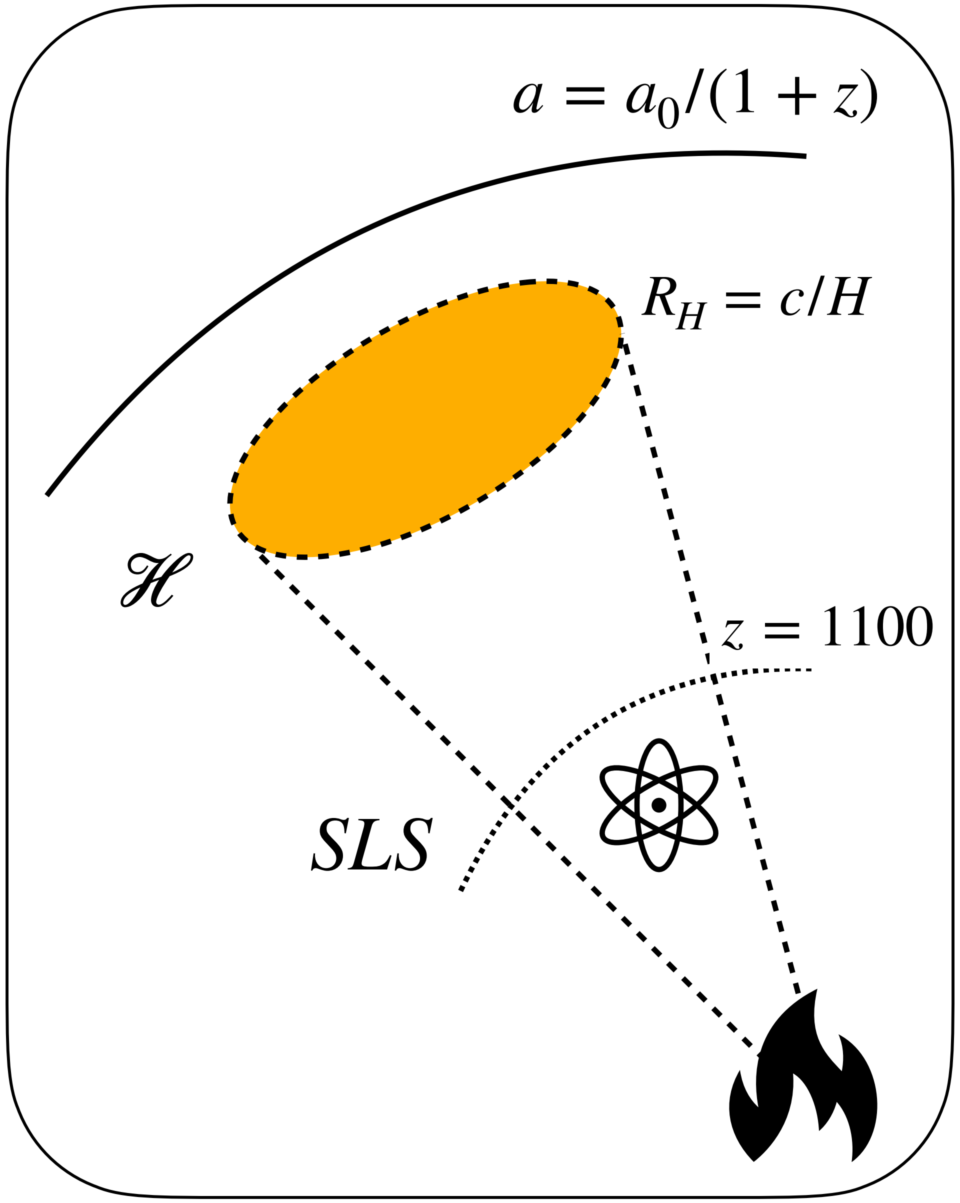
H_0 estimates are sensitive to future (in)stability of de Sitter space

Data-structure

Principle observables (H_0, q_0) with primary observational constraints:

- Baryon Acoustic Oscillations (BAO)
- Astronomical Age of the Universe

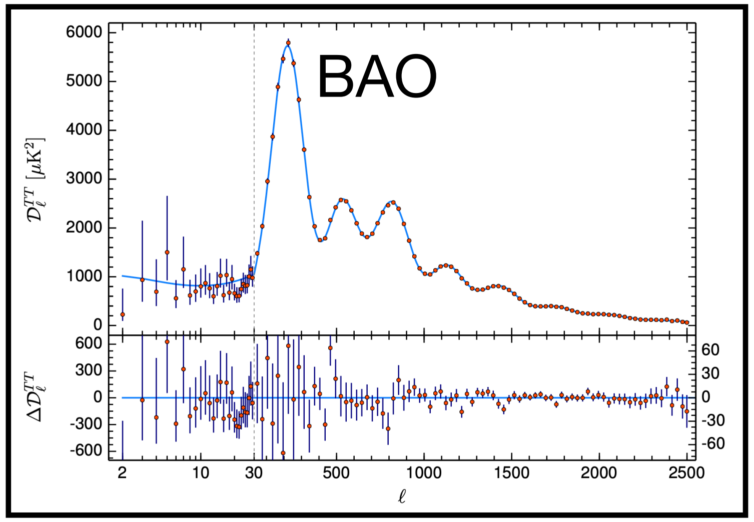
Model-dependent parameter $\Omega_{M,0}$ with secondary observational constraint S_8



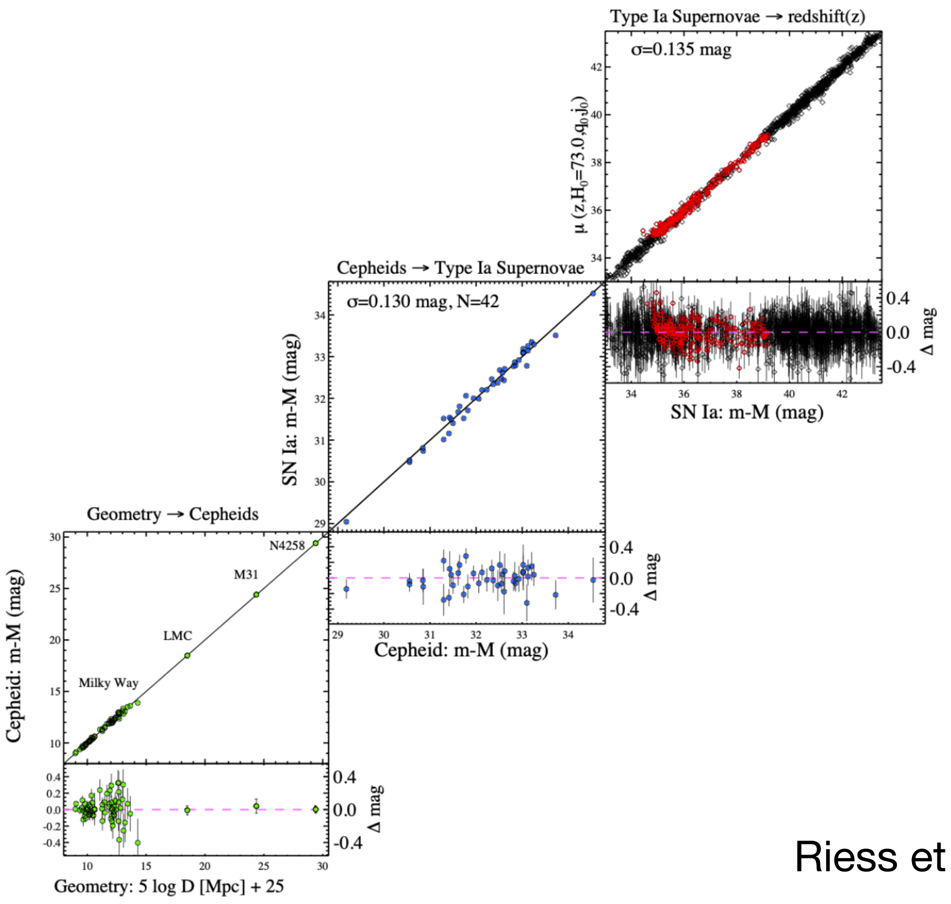
Jedamzik, Pogosian & Zhang (2021), Di Valentino et al.(2021), Vagnozzi (2023), Cimatti & Moresco (2023), Dainotti et al.(2023), Murakami et al. (2023), D'Agostino & Nunes (2023), Basilakos et al.(2023), Riess & Breuval (2023), Wang et al.(2023), Valcin et al. (2020), O'Malley et al. (2017), Jimenez et al. (2019), Planck (2020), …

Planck-ΛCDM versus Local Distance Ladder

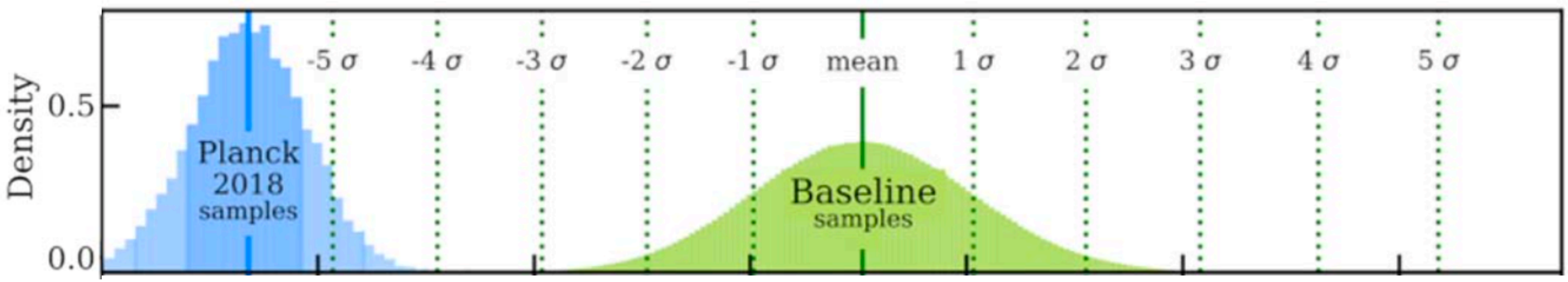
$l = 0$



Planck 2020



Riess et al. 2022



Riess et al. 2022

$$H_0 = (67.4 \pm 0.5)\ \mathrm{km\,s^{-1}Mpc^{-1}}$$

$$H_0 = (73.30 \pm 1.04)\ \mathrm{km\,s^{-1}Mpc^{-1}}$$

Age of the Universe

Astronomical age of the Universe from oldest stars in globular clusters

$$T_U = 13.5^{0.16}_{0.14}\text{Gyr(stat)} \pm 0.23(0.33)\text{Gyr(sys)}$$

Valcin et al. 2021
O'Malley et al 2017
Jimenez et al. 2019

Planck ΛCDM analysis of CMB

$H(z) = H_0 h(z)$:

$$T_U = H_0^{-1} \int_0^\infty \frac{dz}{(1+z)h(z)} = H_0^{-1}(1-\epsilon) \simeq 13.8 \pm 0.02 \text{ Gyr}$$

Aghanim et al. 2020

Consistent ages within measurement uncertainties

How old is the Universe?

Universe today at 26.5 Gyr ? (Gupta 2022, 2023)

Covarying decay $G \sim c^3 \sim \hbar^3 \sim k_B^{3/2}$ with cosmic time

Black holes provide an arrow of time by their entropy

$$S \sim k_B \left(\frac{M}{m_p} \right)^2$$

and the second law of thermodynamics $\delta S \geq 0$:

$$\frac{\dot{k}_B}{k_B} \geq 2 \left(\frac{\dot{m}_p}{m_p} \right).$$

van Putten (2023, submitted)

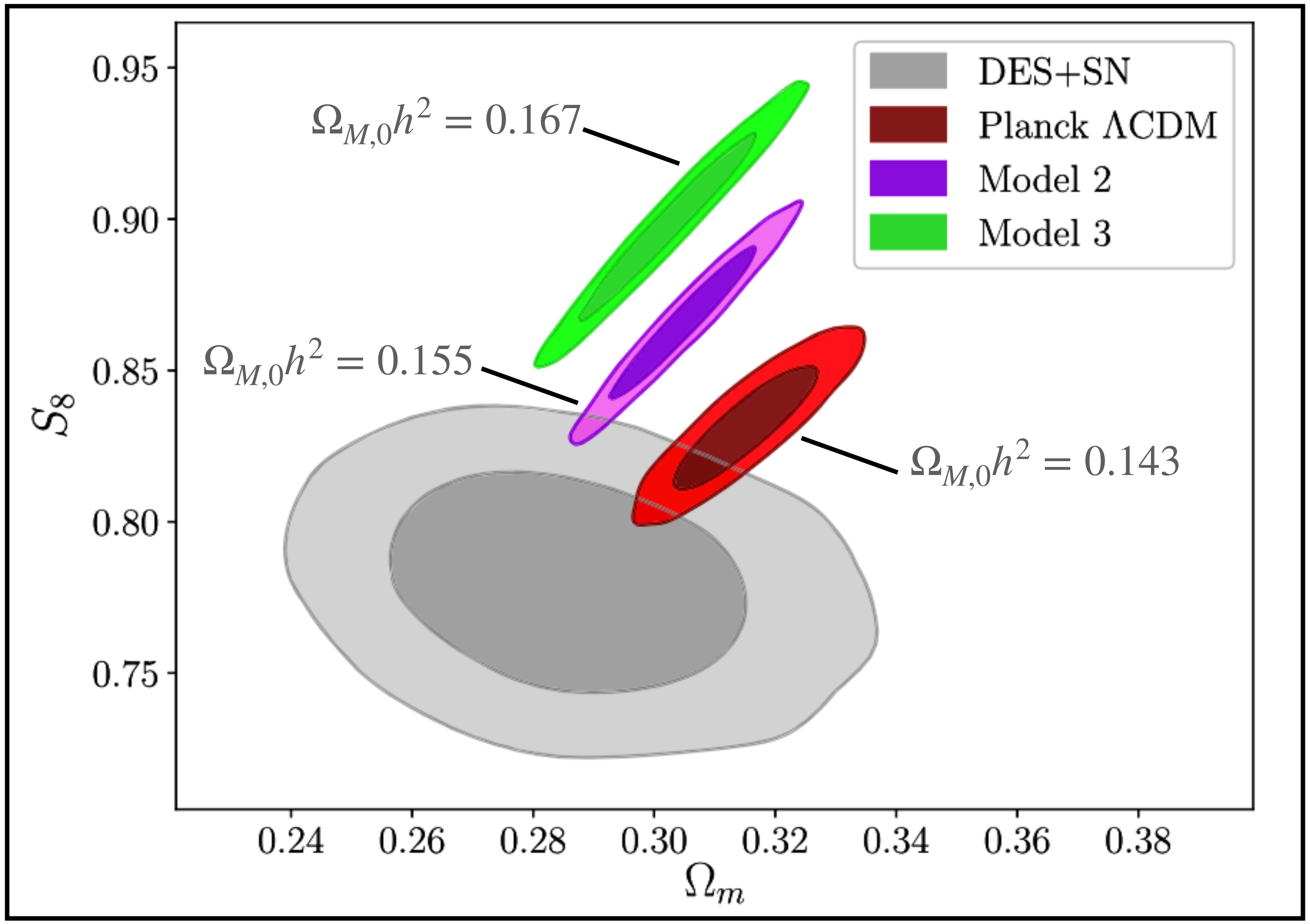
Nobel Prize 2020 awarded to Penrose, Genzel & Ghez for SMBH at SgrA*

Stephen W. Hawking (à g.) et Jacob David Bekenstein
https://www.israelscienceinfo.com/en/physique/la-controverse-hawking-bekenstein-sur-le-trou-noir-inspire-les-chercheurs-israeliens/

Gupta's proposal implies $S \sim c^3$ decays with cosmic time $\Rightarrow\Leftarrow$

Matter density and S_8

$$S_8 = \sigma_8 \sqrt{\Omega_{M,0}/0.3}:$$



Jedamzik, Pogosian & Zhang, 2021

Lessons from black hole thermodynamics

Closure density

Schwarzschild black hole of mass M shows equivalence of mass-energy and holographic heat:

$$Q = Mc^2 = \int T_H dS$$

given the Hawking temperature T_H and Bekenstein-Hawking entropy S. Thermodynamics of the horizon defines the maximal mass-density

$$\rho = \frac{M}{\frac{4\pi}{3}R_S^3} = \frac{3c^2}{8\pi G R_S^2}$$

saturating the Bekenstein bound. A three-flat Universe $\Omega = 1$ satisfies the same scaling:

$$\rho_c = \frac{3H^2}{8\pi G} = \frac{3c^2}{8\pi R_H^2}.$$

Observational evidence from $\delta \simeq -2$ in data fits to $\rho_{\mathcal{U}} = cT^{4+\delta}$, $k_B T \sim H\hbar$: the holographic limit of unparticle cosmology (Abchouyeh & van Putten (2021)

Closure density is an extremum by thermodynamic properties of a horizon.

van Putten, 2020, MNRAS, 491, L6

de Sitter temperature

Hubble horizon at $R_H = c/H$ is a relic of the Big Bang $1/H$ in the past. It breaks global symmetries in space and time.

Global symmetries are approximate, e.g. Witten, 2018

Breaking asymptotic flatness at spatial infinity:

$$\left(\frac{k_B T_{dS}}{c}\right) R_H \simeq \frac{1}{2}\hbar$$

Cosmic time is no longer a Killing vector:

$$k_B T_{dS} H^{-1} \sim \frac{1}{2}\hbar$$

$k_B T_{dS} \sim H\hbar$ from broken global symmetries by the Big Bang

The de Sitter acceleration $a_{dS} = cH$ is the surface gravity of the Hubble horizon $\mathscr{H}$. With topology S^2, $\mathscr{H}$ assumes the Unruh temperature

$$k_B T_{dS} = \frac{a\hbar}{2\pi c} = \frac{H\hbar}{2\pi}.$$

Gibbons & Hawking (1977)

T_{dS} derives from the de Sitter acceleration of cosmological spacetime

de Sitter energy density

Hubble horizon with area $A_H = 4\pi R_H^2$ contains Planck sized units $l_p^2 = G\hbar/c^3$ of area

$$N = S/k_B = \frac{1}{4} A_H / l_p^2$$

Each excited at $k_B T_{dS} = H\hbar/2\pi$, collectively contain the heat

$$Q = Nk_B T_{dS} = \pi R_H^2 \left(\frac{H\hbar}{2\pi}\right)\left(\frac{c^3}{G\hbar}\right) = \frac{1}{2} R_H c^4/G.$$

with equivalent density

$$\epsilon \equiv \frac{Q}{(4\pi/3)R_H^3} = \frac{3c^4}{8\pi G R_H^2} = \rho_c c^2$$

de Sitter heat carries an energy density at closure density

Modified de Sitter temperature

Hubble horizon has a surface gravity

$$a = \frac{H}{2}\left(1 - q\right).$$

Cai & Kim (2005)

The Hubble horizon has ordinary point-set topology S^2 with associated Unruh temperature

$$k_B T_H = \frac{a\hbar}{2\pi c} = \frac{H\hbar}{2\pi c}\left(\frac{1-q}{2}\right) = T_{dS}\left(\frac{1-q}{2}\right).$$

van Putten (2015)

In a holographic interpretation, this comes with a *phantom pressure*

$$-p = A_H^{-1} T_H \frac{dS}{dR} = \frac{k_B T_H}{2 R_H l_p^2}.$$

Easson, Framptomn & Smoot (2011)

Modified Friedmann equations

Hubble horizon is a Lorentz invariant, whereby $\rho_\Lambda = -p$ and so

$$\Omega_\Lambda = \frac{2}{3}\left(\frac{1-q}{2}\right).$$

van Putten (2015)

Now include $\Lambda = 8\pi\rho_\Lambda = (1-q)\,H^2$ in the Einstein equations:

$$G_{ab} = 8\pi T_{ab} - (1-q)\,H^2 g_{ab}.$$

$\mathscr{H}$ defined in geometric optics limit, is transparent to super-horizon scale fluctuations:

$$T_{ab} = \left[(1-q)\,\pi^-_{ab} + q\pi^+_{ab}\right]\rho_c$$

is the sum of on- and off-shell fluctuations $\pi^\pm = \text{dia}\left[1, \pm 1/3, \pm 1/3. \pm 1/3\right]$ with tr $\pi^\pm_{ab} = 1 \mp (-1)$ in the metric signature $(-,+,+,+)$ from $\Omega_M = (1/3)(2+q)$, $\Omega_\Lambda = (1/3)(1-q)$ with phantom pressure $\Omega_p = p/\rho_c, q = 3\Omega_p = \Omega_M - 2\Omega_\Lambda$.

Modified Friedmann equations

Hubble horizon is a Lorentz invariant, whereby $\rho_\Lambda = -p$ and so

$$\Omega_\Lambda = \frac{2}{3}\left(\frac{1-q}{2}\right).$$

Now include $\Lambda = 8\pi\rho_\Lambda = \left(1-q\right)H^2$ in the Einstein equations:

$$G_{ab} = 8\pi T_{ab} - \left(1-q\right)H^2 g_{ab}.$$

The first and second Friedmann equations become

$$\frac{\ddot{a}}{a} = 2h^2 - 3\Omega_{M,0}a^{-3}$$

The Hamiltonian energy constraint becomes second-order in time - a singular perturbation away from ΛCDM

$$q = \Omega_p.$$

Phantom pressure

$\tau = H_0 t,\ H(z) = H_0 h(z).$

van Putten (2015, 2020)

Dark energy from T-duality

Define the curvature operator $D(u) \equiv \frac{\ddot{u}u}{\dot{u}}$. With $\kappa = 1/a$, obtain

$$D(\kappa) = 3\Omega_M$$

$$D(a) = -3\Omega_p$$

with EOS $w = (2q-1)/(1-q)$.

This formulation satisfies

$$D(a) + D(\kappa) = 2.$$

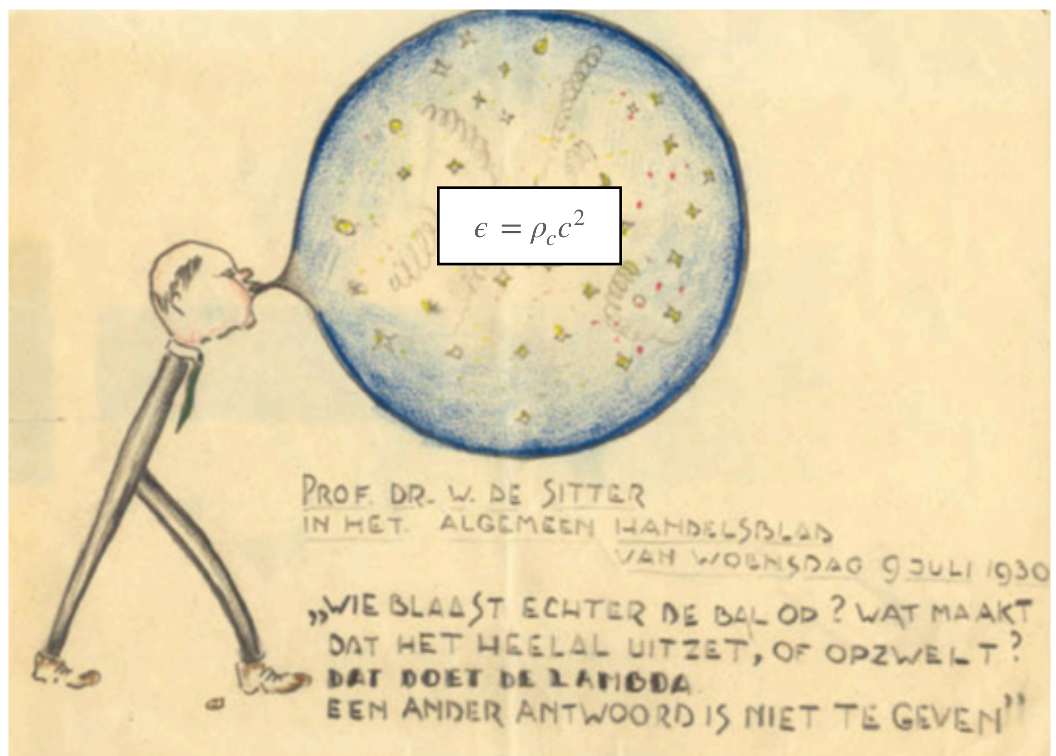
van Putten (2021)

YITP Workshop Strings and Fields 2021
https://meetings.aps.org/Meeting/APR21/Session/L18.7

What happened?

Heat content at finite temperature by breaking global symmetries

Black hole → *de Sitter*



Nature finds a new symmetry in T-duality in the Friedmann scale factor a

Analytic solution

Rewrite the first Friedmann equation in $y(z) = \log h(z)$:

$$y'(z) = 3\,(1+z)^2\,\Omega_{M,0}e^{-2y(z)} - \frac{1}{1+z}.$$

Solution:

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

in $Z_n = (1+z)^n - 1$

van Putten (2017, 2021)

O'Colgain, van Putten & Yavartanoo (2019)

Evolution in quantum cosmology

Quantum cosmology in the face of the Hubble horizon

The Hubble horizon is a relic of the Big Bang: *variational principle runs over two scales: sub- versus super-Hubble scale variations.*

Propagator $e^{i\Phi}$ derives from the action: $\Phi = S/\hbar$, $S = \int \mathscr{L}\sqrt{-g}\,d^4x$ e.g. Wald 1984

$\mathscr{L} = R + \cdots$ by the Ricci scalar R and contributions from matter and fields.
Sub-Hubble scale variations define the Einstein equations.

Super-Hubble scale variations $(k \sim 0)$ require a global phase reference $\Phi_0 = \Phi_0\left[\mathscr{H}\right]$. *With no asymptotically flat Minkowski spacetime in FLRW:*

$$\Phi_0 \not\equiv 0$$

Normalized propagator:

$$e^{i(\Phi - \Phi_0)} = \frac{e^{i\Phi}}{e^{i\Phi_0}}$$

van Putten, 2020, MNRAS, 491, L6

Λ from Φ_0

On a background cosmology, write

$$\Phi_0\left[\mathscr{H}\right] = \int 2\Lambda\sqrt{-g}\,d^4x$$

Global phase reference for super-Hubble scale variations $\left(k \sim 0\right)$:

$$\Lambda = \lambda R\left(a,\dot{a}\right) \equiv g(1-q)H^2.$$

Φ_0 has equivalent density with coupling $g \lesssim 1$

van Putten (2021)

In conventional action principle (variations on sub-Hubble scale), this Λ sources the Friedmann equations …

Analytic solution

Generalized expression $\Lambda = \Lambda_0 + g(1-q)H^2$:

$$H(z) = H_0 \frac{\sqrt{1 + A(z)}}{(1+z)^{\frac{\gamma+1}{2}}}$$

New solution with the same cosmological parameters as ΛCDM

$A(z) = A_0(z) + A_r(z) + A_M(z) + A_K(z)$, $Z_n = (1+z)^n - 1$, $\gamma = 6/g$:

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

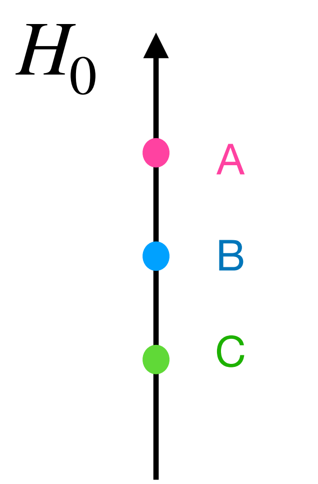
What is the H_0 value?

ΛCDM vs. new model

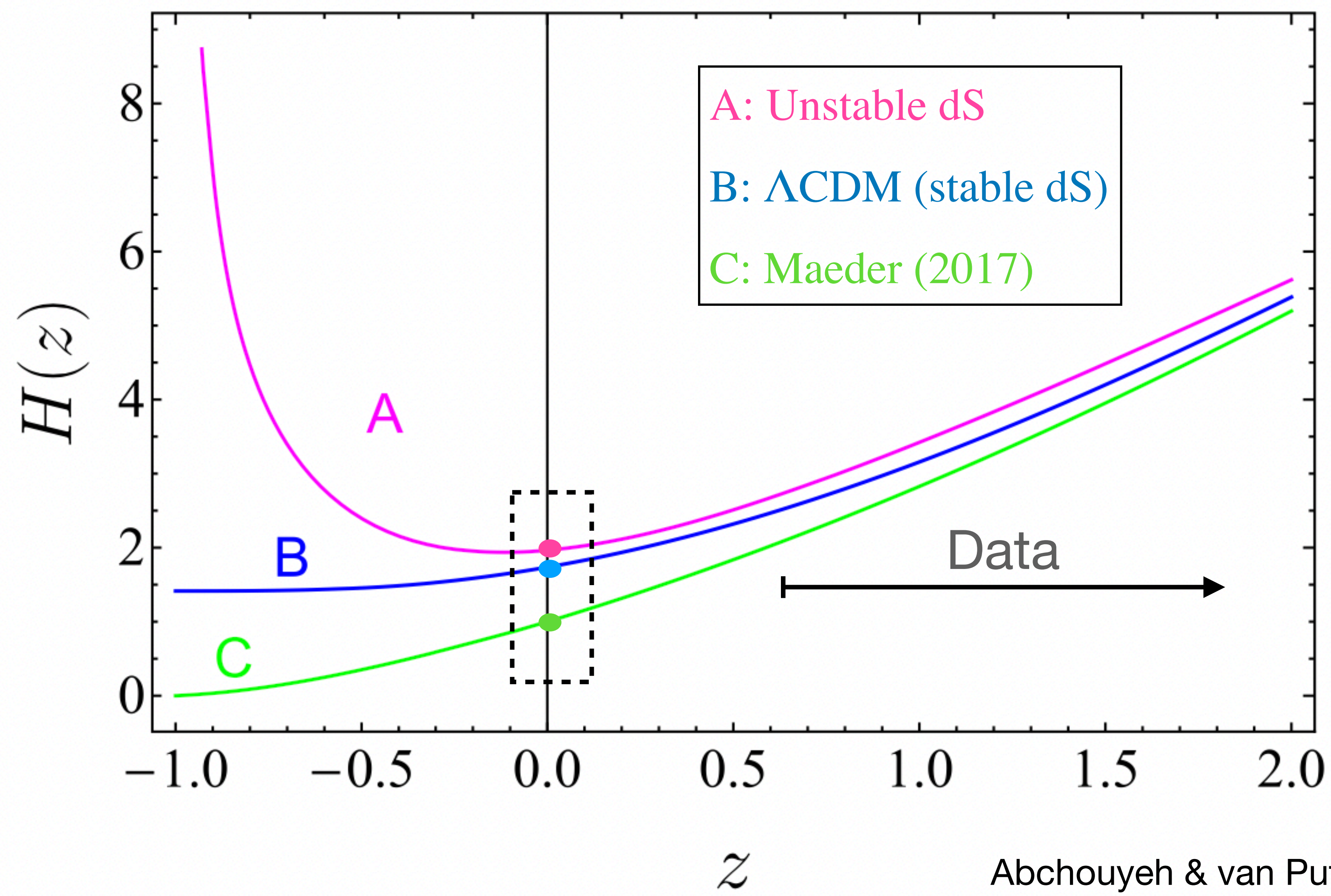
H_0 from Case A

ΛCDM assumes stable dS,
unstable dS favors higher H_0

van Putten (2017)
O'Colgain, van Putten & Yavartano (2019)



H_0 is the extrapolation of data $z > 0$ to $z = 0$



Abchouyeh & van Putten (2021)

H_0 estimates are sensitive to future (in)stability of de Sitter space

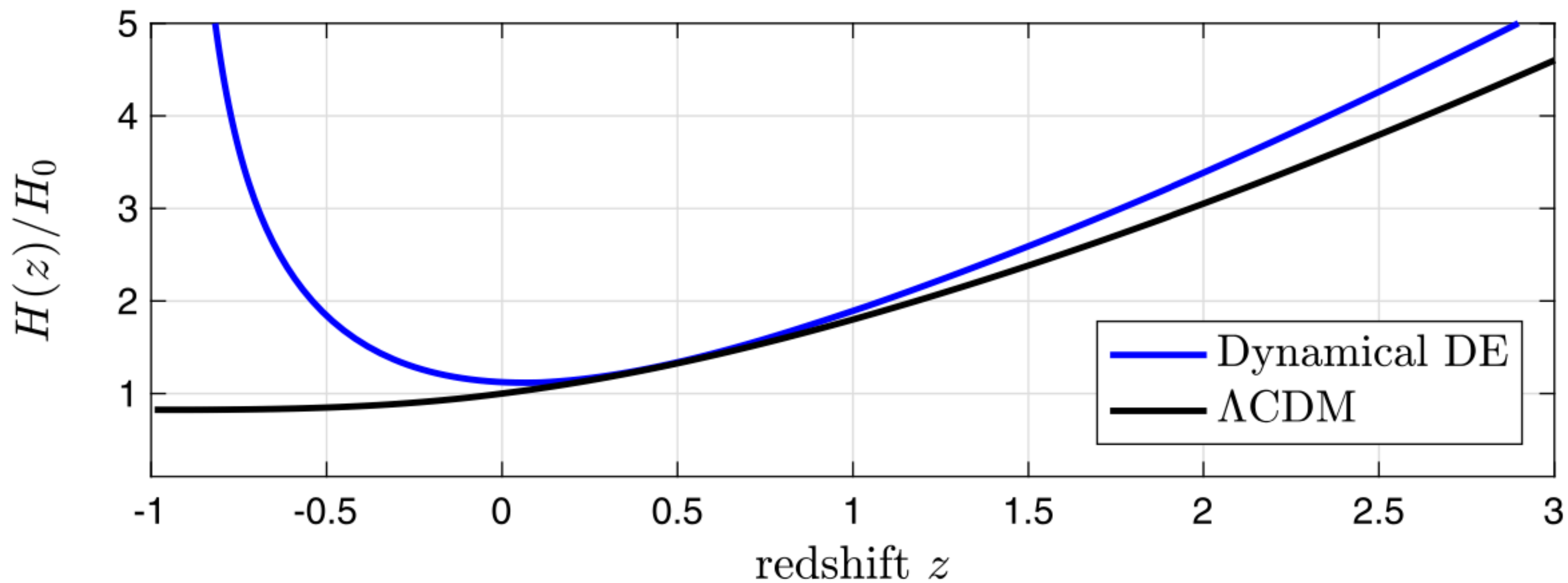
... compare with ΛCDM

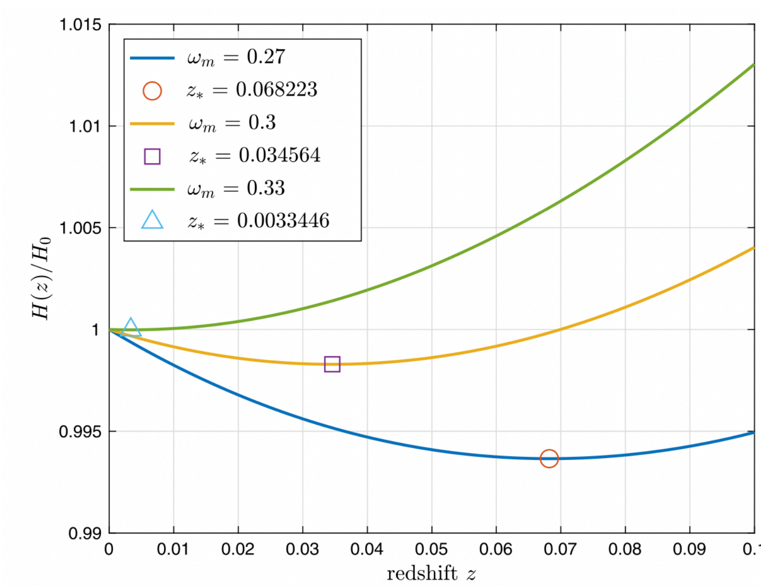
Our model

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

ΛCDM

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





Turning point in $H(z)$ at $z_* = \left(\frac{5 - 6\Omega_{M,0}}{9\Omega_{M,0}}\right)^{\frac{1}{5}} - 1 \gtrsim 0 \quad (\Omega_{M,0} \lesssim 1/3)$

O'Colgain, van Putten & Yavartanoo (2019)

... compare with ΛCDM

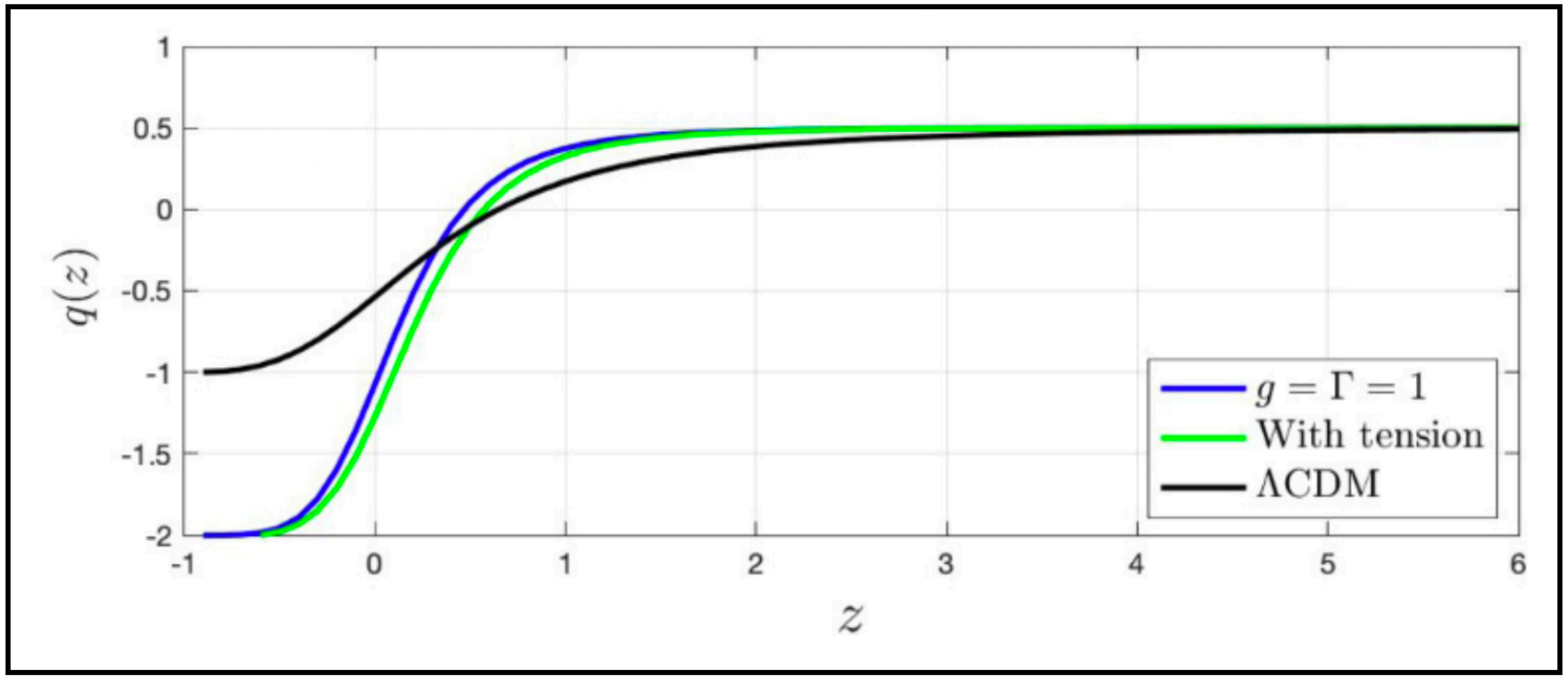
Our model

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

ΛCDM

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

$$w = \frac{2q-1}{1-q}$$



van Putten (2017, 2019)

… reduced matter density

BAO angle $\theta_* = r_*/D(z_*)$ depends on $h(z)$, not on H_0.

Asymptotic behavior

$$h(z) \sim \sqrt{\frac{6}{5}\Omega_{M,0}}\,(1+z)^{3/2} \simeq 0.9126\sqrt{\Omega_{M,0}}\,(1+z)^{3/2}$$

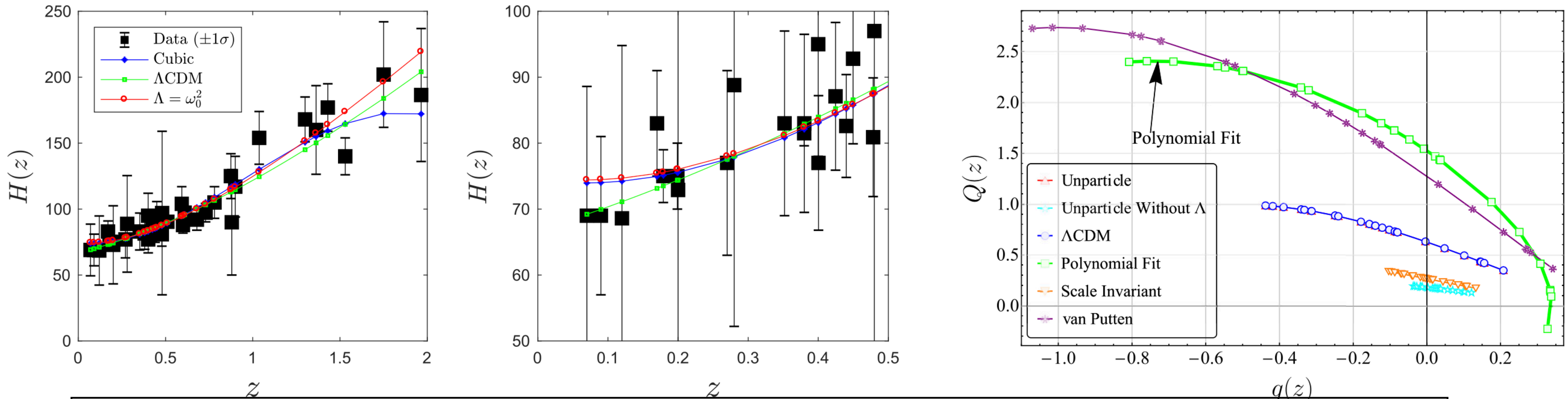
$$h(z) \sim \sqrt{\Omega'_{M,0}}\,(1+z)^{3/2} \quad (\Lambda\text{CDM})$$

Keeping similar shapes at high redshift:

Expect 10-20% reduction in $\Omega_{M,0}$ compared to ΛCDM

... confrontation with data

Data of Farooq et al. (2017):



With no free parameters:

$$H_0 = 74.9 \pm 2.6\,\text{km s}^{-1}\,\text{Mpc}^{-1}, \quad \Omega_{M,0} = 0.2719 \pm 0.028,$$
$$q_0 = -1.18 \pm 0.084$$

Encouraging anti-correlated departure from ΛCDM:

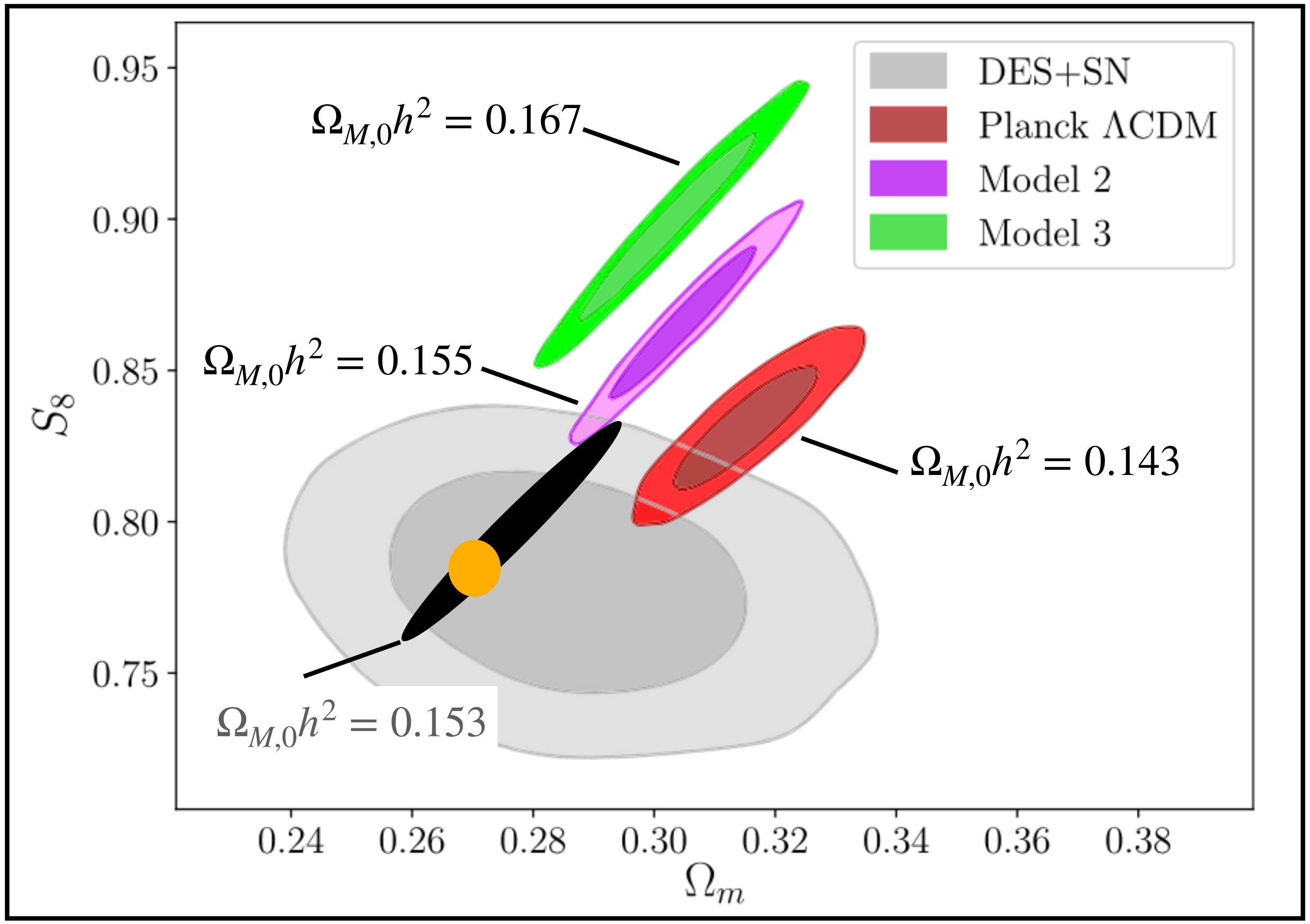
H_0 moves to the value of the Local Distance Ladder

$\Omega_{M,0}$ drops below the Planck value of ΛCDM

Van Putten (2017)
O'Colgain, van Putten & Yavartanoo (2019)

... implications for S_8

$S_8 = \sigma_8\sqrt{\Omega_{M,0}/0.3}$ along $\Omega_{M,0}h^2 = 0.153$:



Jedamzik, Pogosian & Zhang, 2021

Data-structure

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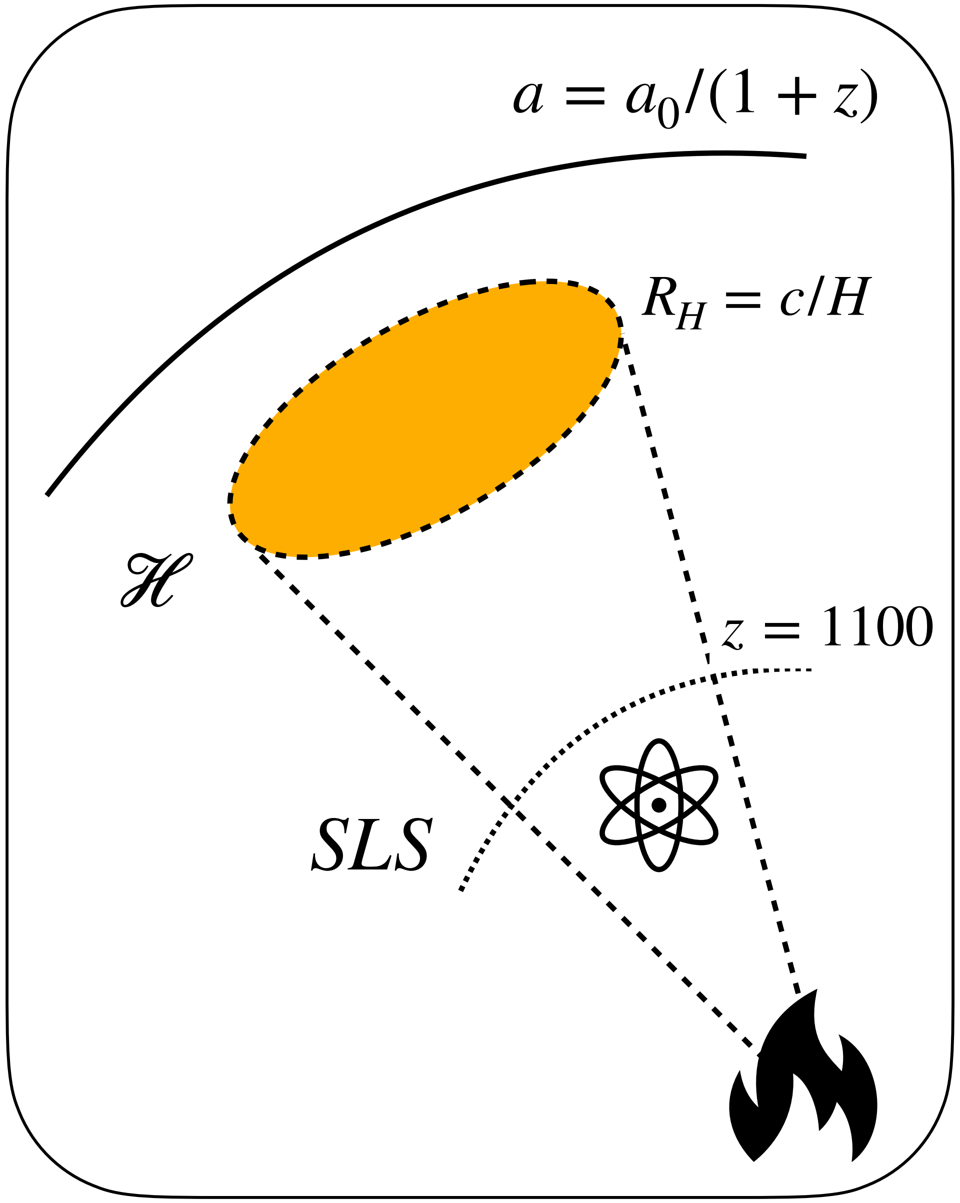


Estimate H_0

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

Riess et al. 2022
Wong et al. 2020

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

$$H_0 = (73.2 \pm 1.3)\ \mathrm{km\,s^{-1}Mpc^{-1}}$$ Local Distance Ladder (Riess et al. 2021)

8.6% H_0-tension:

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

Primed values: Planck ΛCDM analysis of CMB

Primary constraints

Valcin et al., 2020, JCAP 12, 162
O'Malley et al., 2017, ApJ, 838, 162
Jimenez et al. 2019, JCAP, 03, 043
Planck ΛCDM analysis of CMB (2020)

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

T_U from oldest Globular Clusters of the Milky Way

Primary constraints

Valcin et al., 2020, JCAP 12, 162
O'Malley et al., 2017, ApJ, 838, 162
Jimenez et al. 2019, JCAP, 03, 043
Planck ΛCDM analysis of CMB (2020)

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

$$\theta_* = \frac{c^{-1} \int_{z_*}^{\infty} c_s h(z)^{-1} dz}{\int_0^{z_*} h(z)^{-1} dz}: \qquad \theta_* = \theta_{*,\mathrm{Planck}}$$

Fixes $\Omega_{M,0}$ for a given modal

Adapted from Jedamzik, Pogoslan & Zhang (2021)

Age of the Universe $T_U = H_0^{-1} t_U$

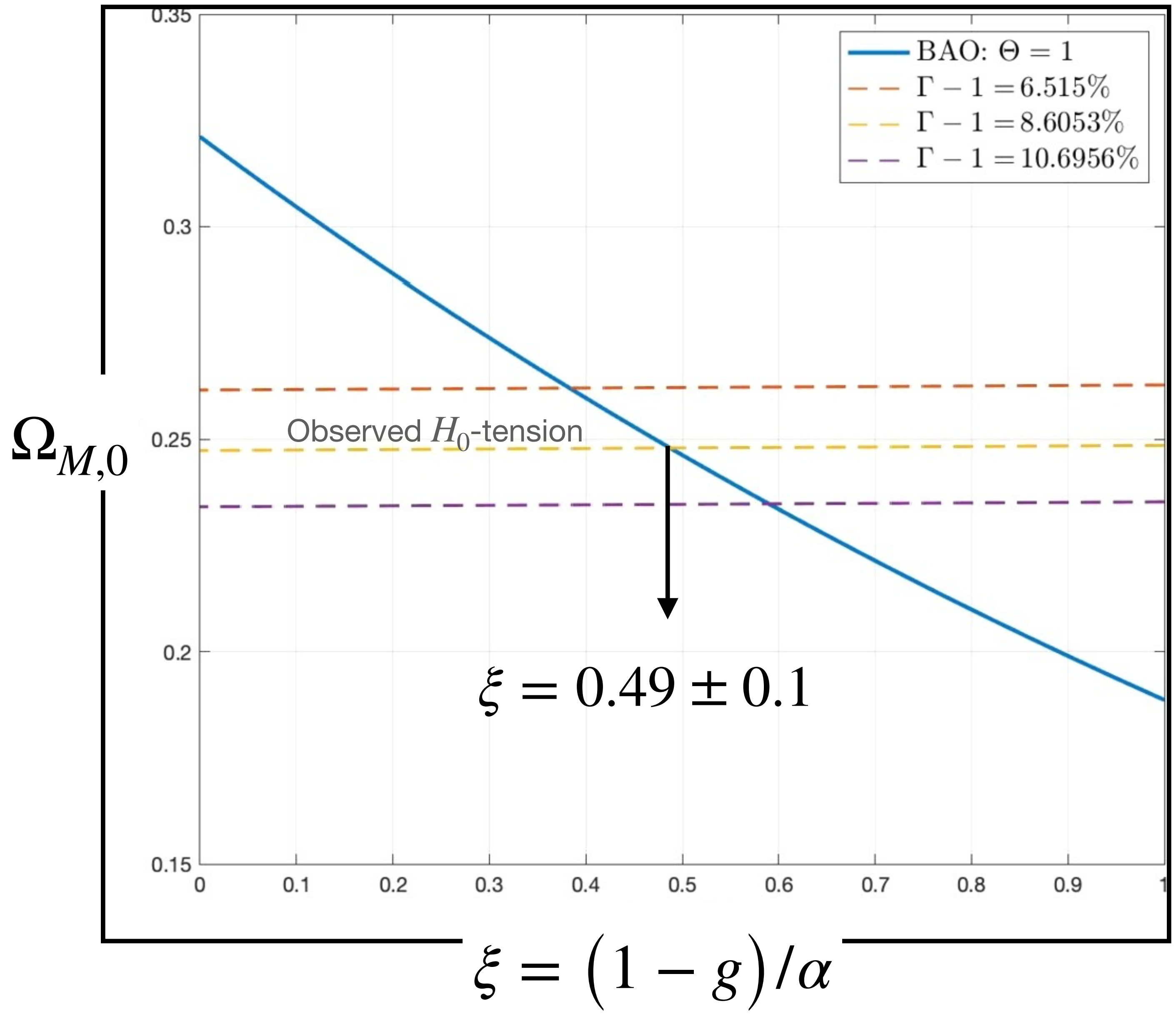
$$t_U = \int_0^{\infty} \frac{dz}{(1+z)h(z)}: \qquad \frac{t_U}{t'_U} = \frac{H_0}{H'_0} = \Gamma$$

Correlates $\left(H_0, \Omega_M\right)^*$

Two constraints on $\left(g, \Omega_{M,0}\right)$

Numerical root finding

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

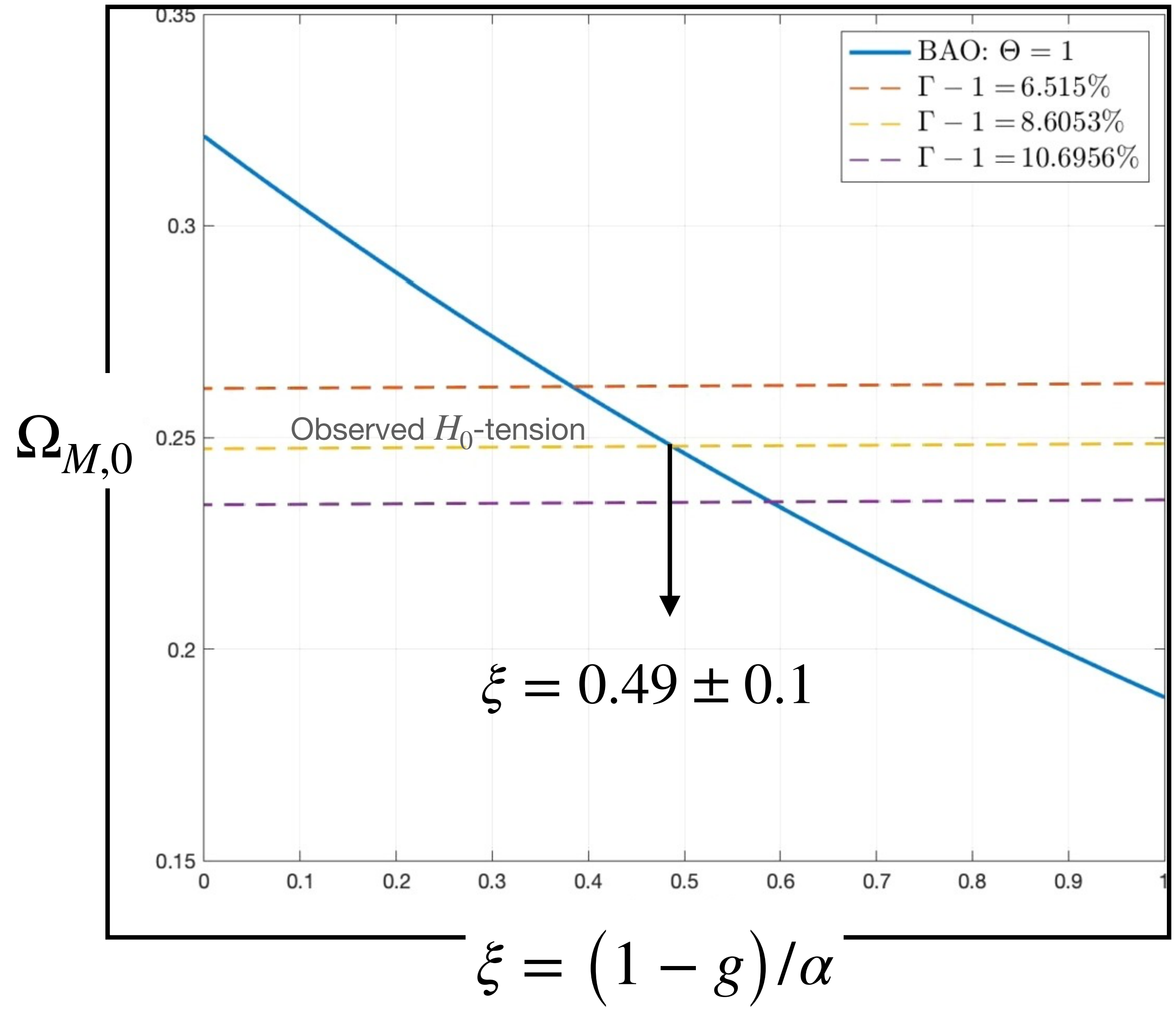


$$\Omega_{M,0} = 0.2480 \pm 0.014$$

consistent with $\Omega_{M,0} = 0.2719 \pm 0.028$ (fit to late-time $H(z)$-data Farooq et al. 2017 in van Putten 2017)

Numerical root finding

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



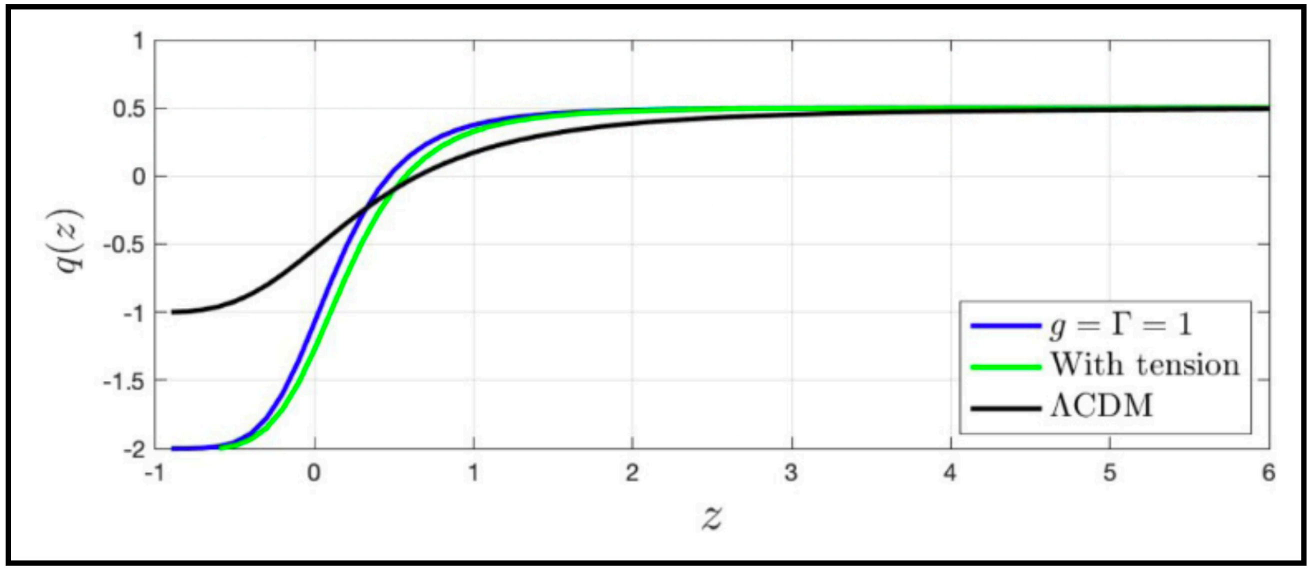
For $\xi = 1/2$:

$$H_0 = (73.37 \pm 0.54)\ \mathrm{km\,s^{-1}Mpc^{-1}}$$

consistent with $H_0 = 74.9 \pm 2.6$ km s^{-1} Mpc^{-1} (fit to late-time $H(z)$-data Farooq et al. 2017 in van Putten 2017)

Deceleration parameter

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



$$\Omega_{M,0} = \frac{1}{3}\left(2+q\right), \Omega_{\Lambda} = \frac{1}{3}\left(1-q\right)$$

$$w = \frac{2q-1}{1-q}$$

ΛCDM in general relativity: $q_0 = \frac{1}{2}\Omega_{M,0} - \Omega_{\Lambda_0} \simeq -0.55$

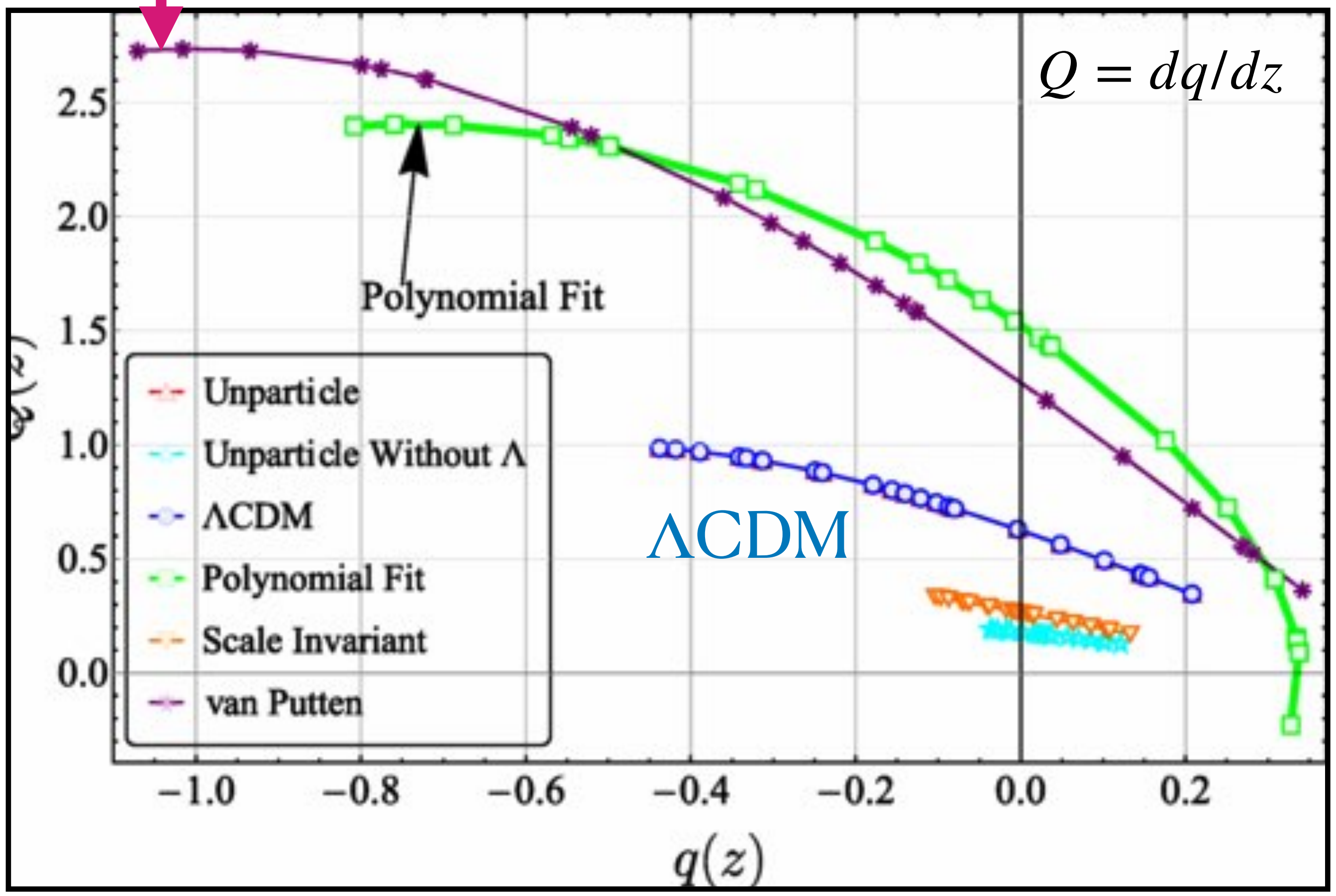
Modified to

$$q_0 = \Omega_{M,0} - 2\Omega_{\Lambda} \simeq 2q_{0,\Lambda\text{CDM}} \simeq -1.1$$

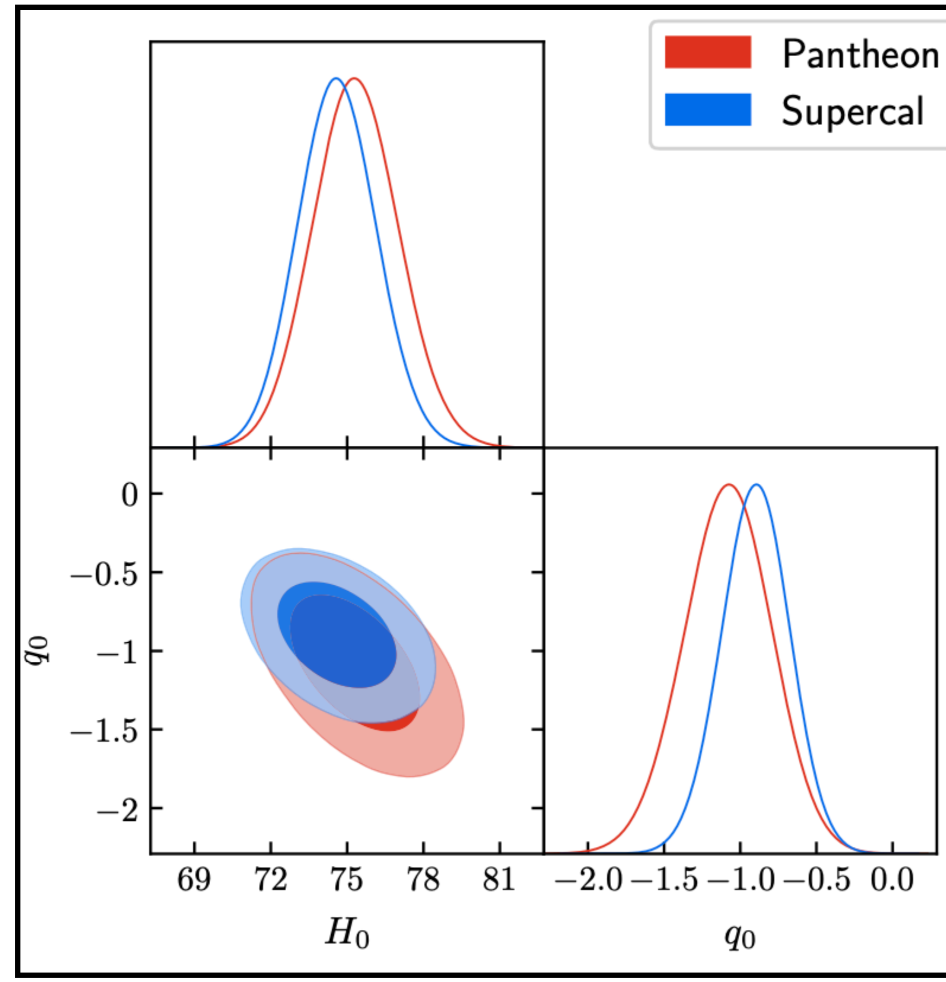
Deceleration parameter

New

Abchouyeh & van Putten (2021)



Camarena & Valerio (2020)



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

$$q_0 = -1.08 \pm 0.29$$

Consistent with prediction but tension in q_0 is modest: 1.8σ relative to ΛCDM due to large uncertainty. Can we do better?

q_0 from baryonic Tully-Fisher relation

Galaxies to probe cosmology

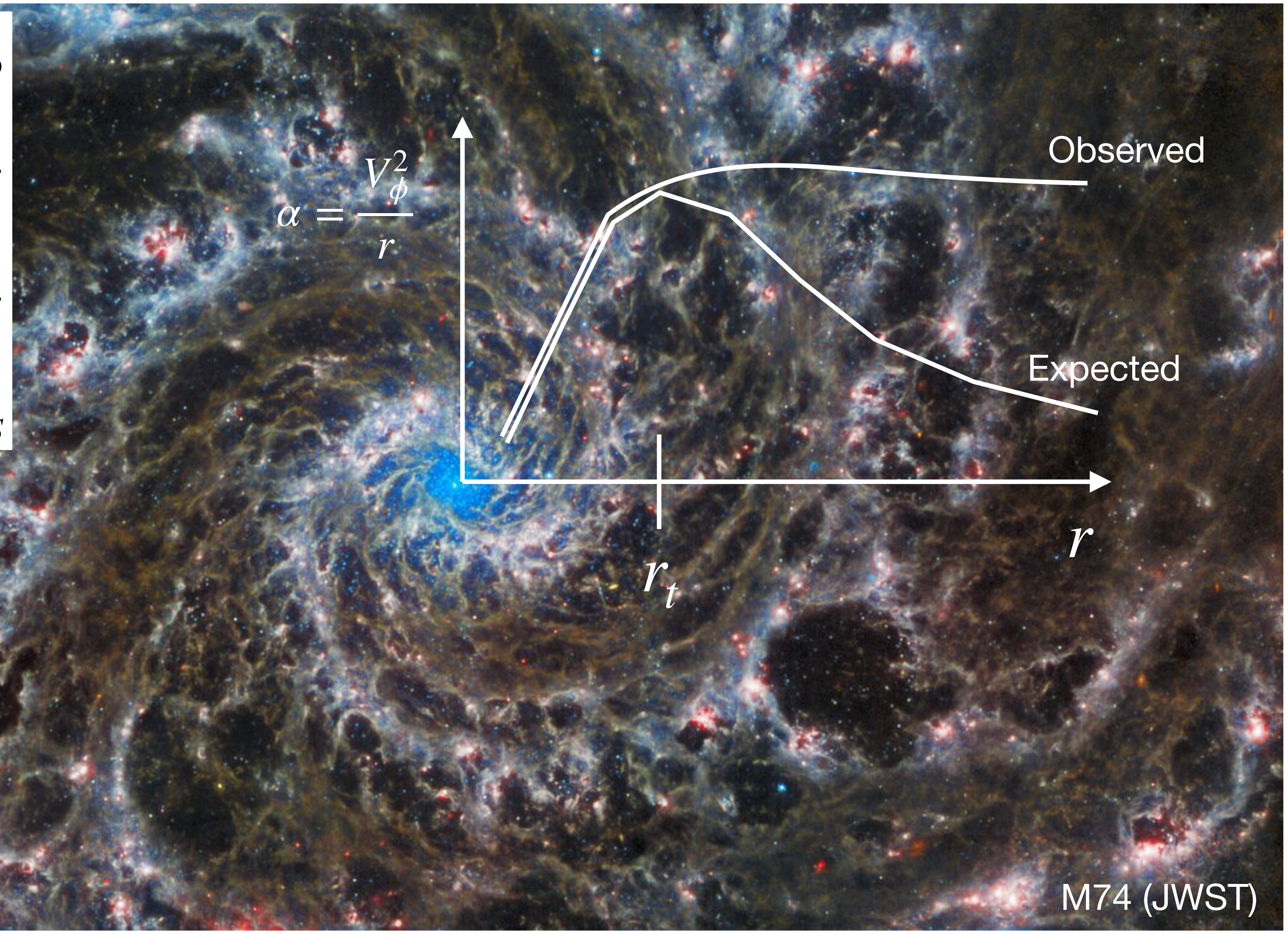
Anomalous galaxy dynamics below the de Sitter scale of acceleration $a_{dS} = cH$

$M_G = M_{11} 10^{11} M_\odot$

$R_G = \frac{GM_G}{c^2}$

$R_H = \frac{c}{H}$

$R_H = c^2 / a_{dS}$

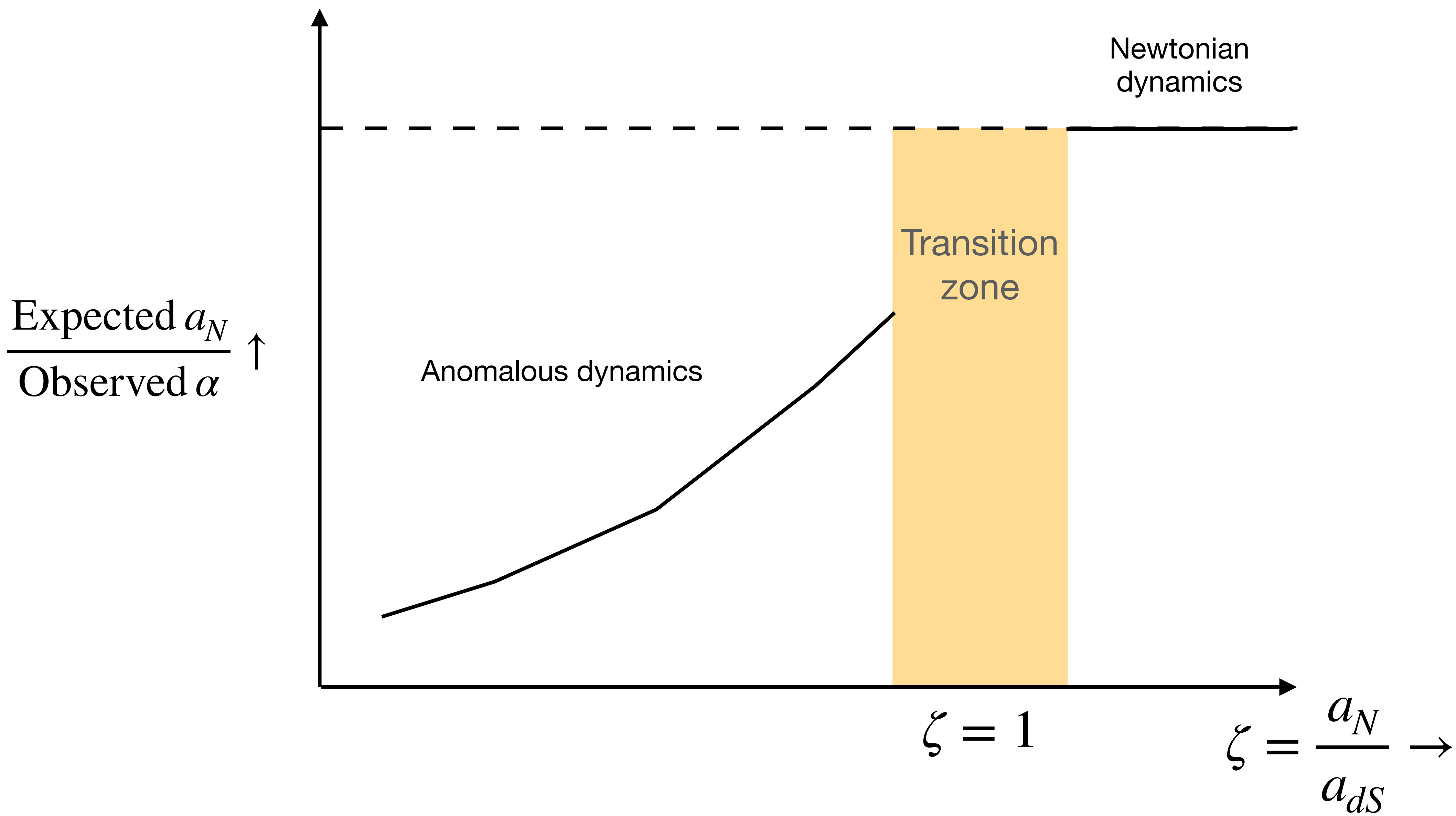


$$r_t = \sqrt{R_H R_G} \simeq 4.5\,\mathrm{kpc} \sqrt{M_{G,11} / H_{0,73}}$$

van Putten 2017 ApJ 848 28

Diagram of normalized accelerations

Spectroscopic versus photometric data on radial acceleration ($\alpha = V_c^2/r$) vs expected Newtonian acceleration $a_N = \dfrac{GM_b}{r^2}$

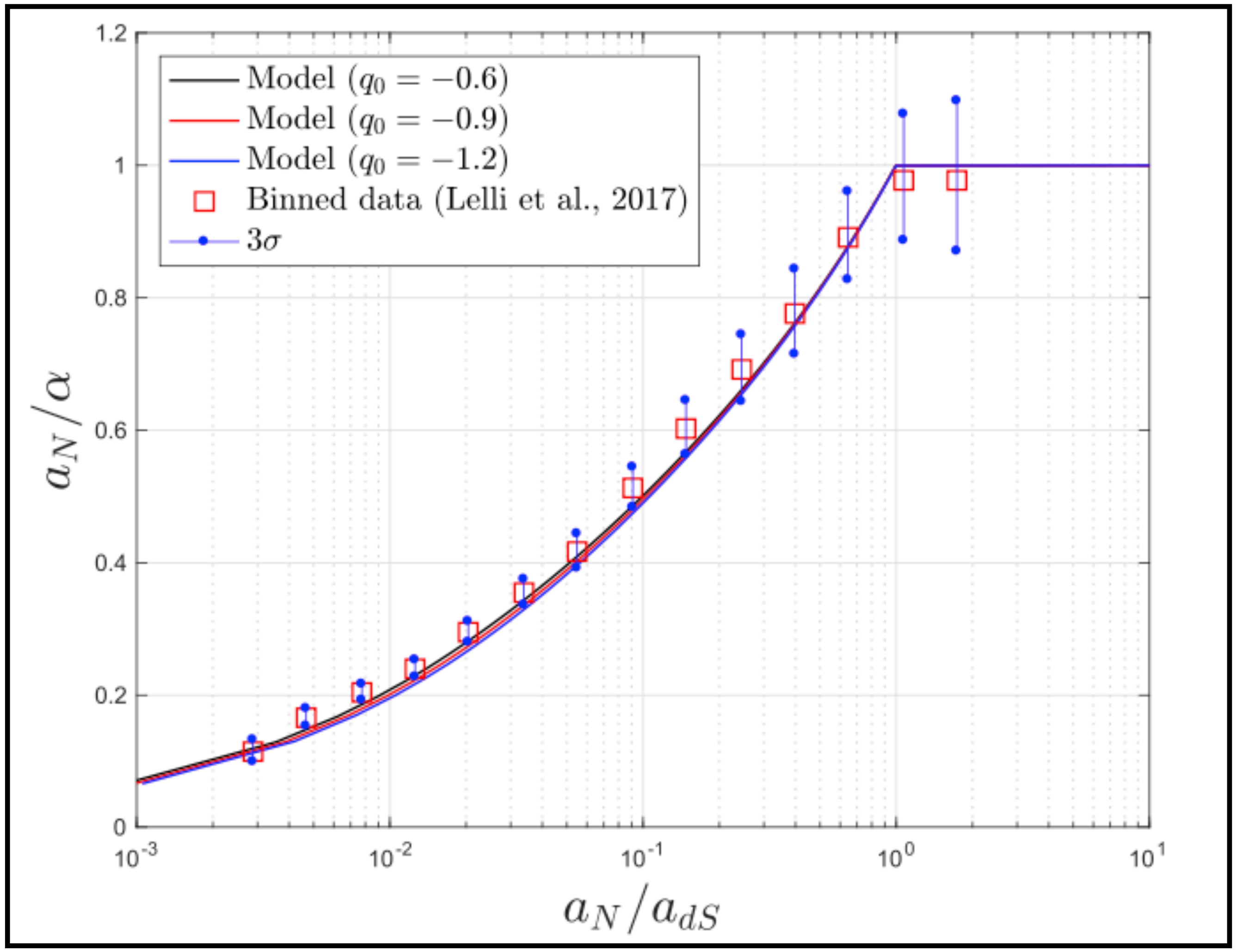


Results from SPARC

SPARC: Spitzer Photometry & Accurate Rotation Curves

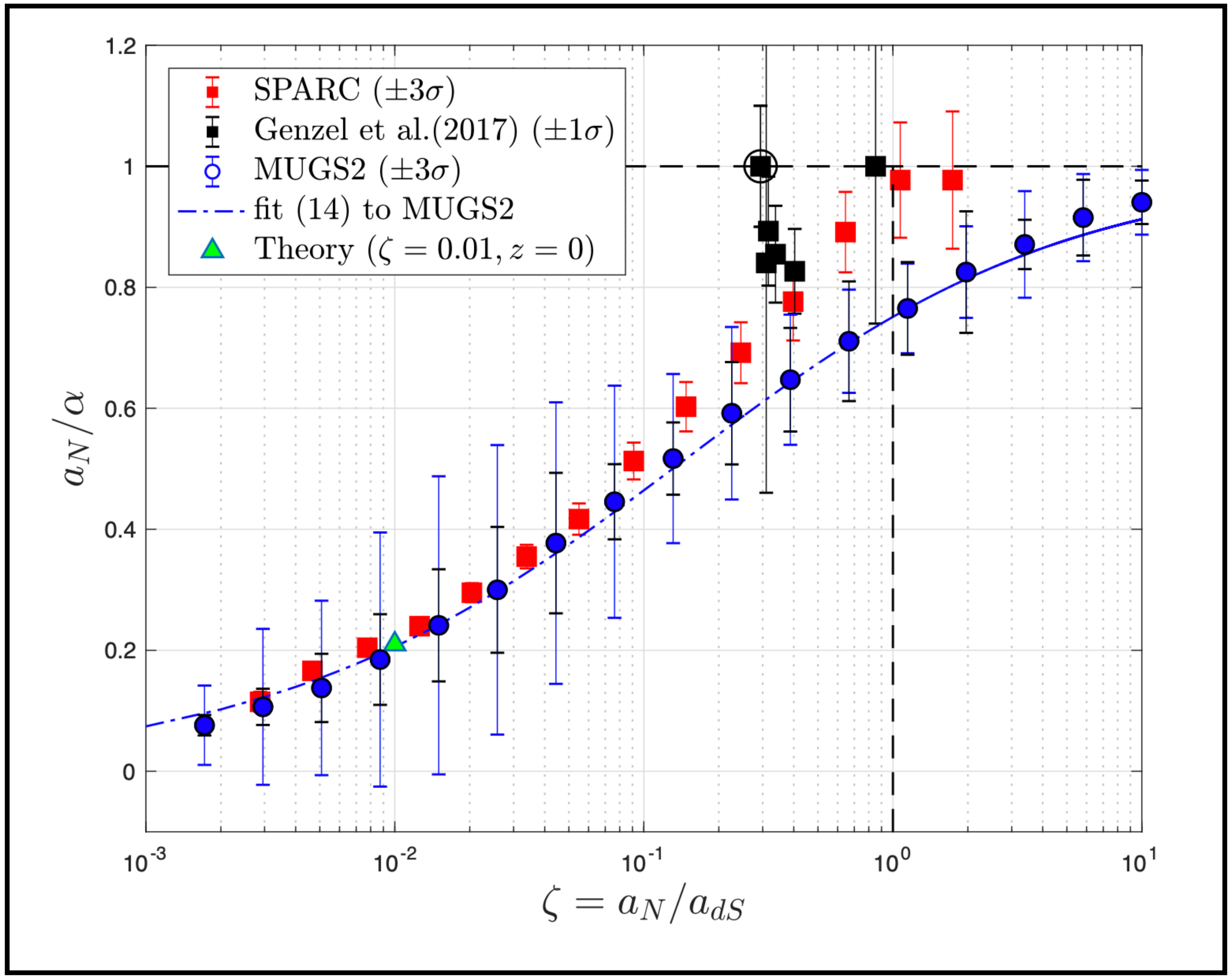
C^0-transition in galaxy dynamics across a_{dS}

Crossing of Rindler and Hubble horizon



van Putten 2017 ApJ 848 28

SPARC versus MUGS2 ΛCDM-galaxy models

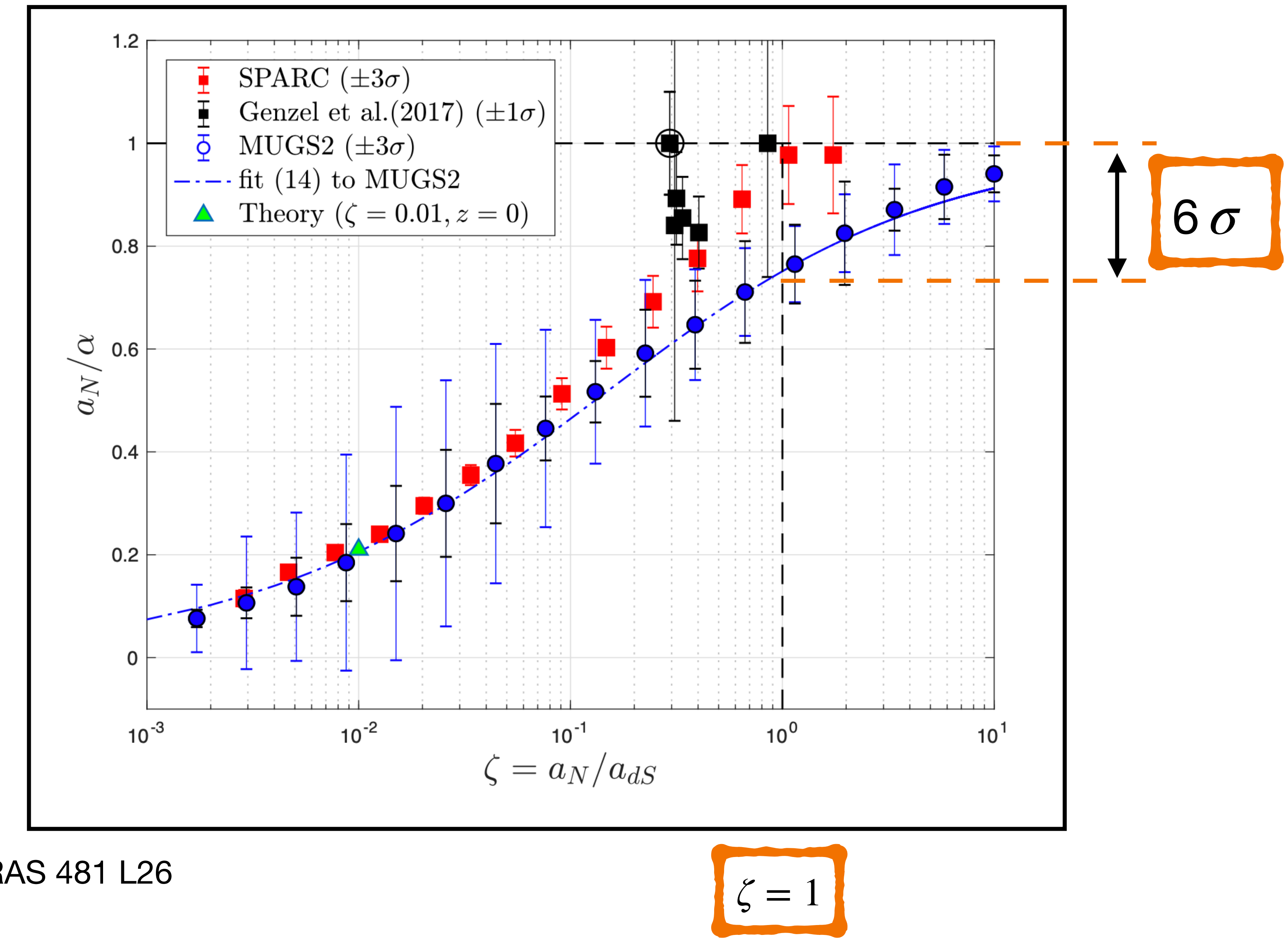


van Putten 2018 MNRAS 481 L26

$\zeta = 1$

SPARC versus MUGS2 ΛCDM-galaxy models

ΛCDM galaxy models in MUGS2 versus SPARC:



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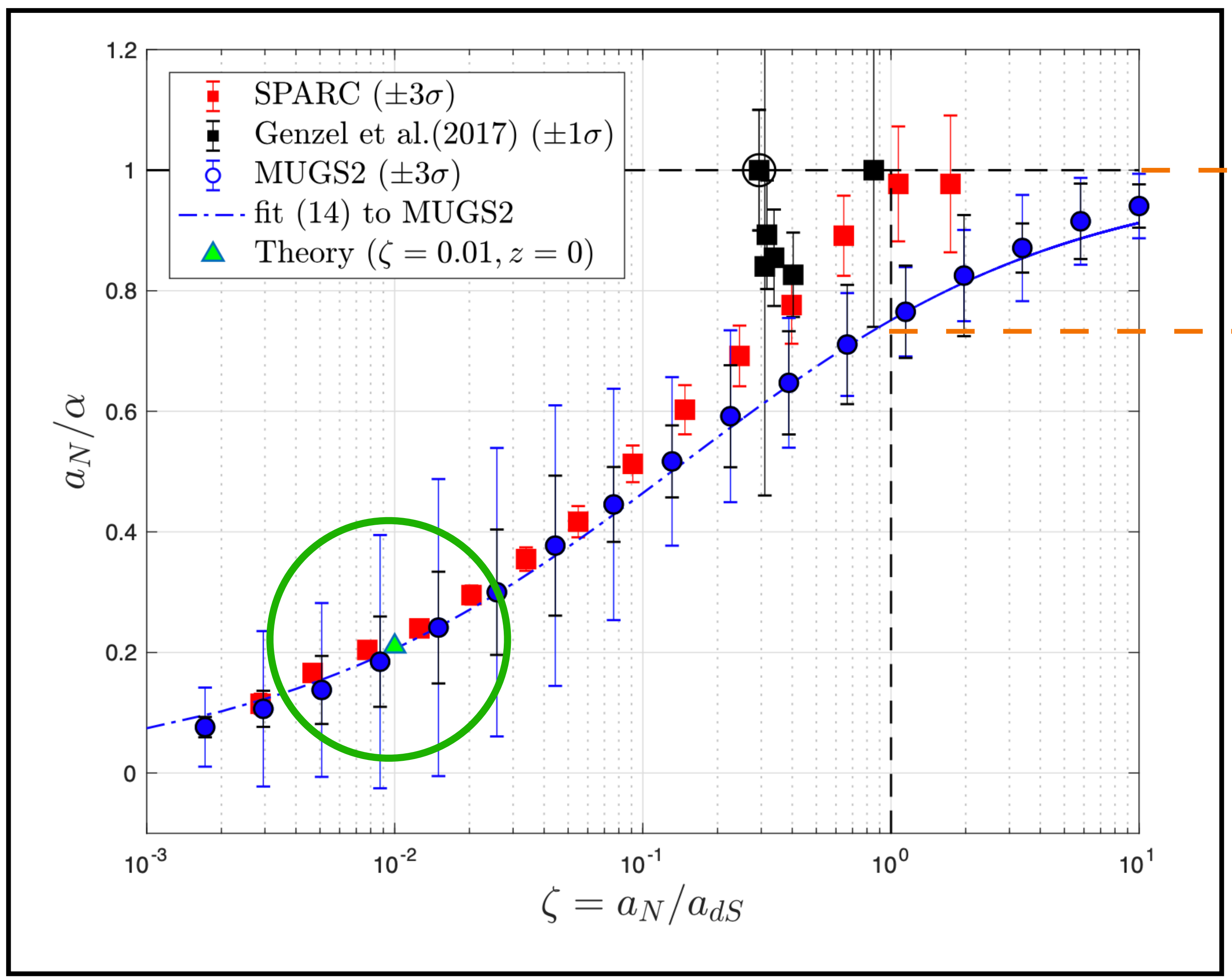
Asymptotic behavior

$$\frac{a_N}{\alpha} = \frac{\text{expected radial acceleration}}{\text{observed radial acceleration}} = \sqrt{2\pi}\,(1-q_0)^{-1/4}\,\zeta^{1/2} \simeq 2.1\zeta^{\frac{1}{2}}$$



$6\,\sigma$

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$\zeta = 1$

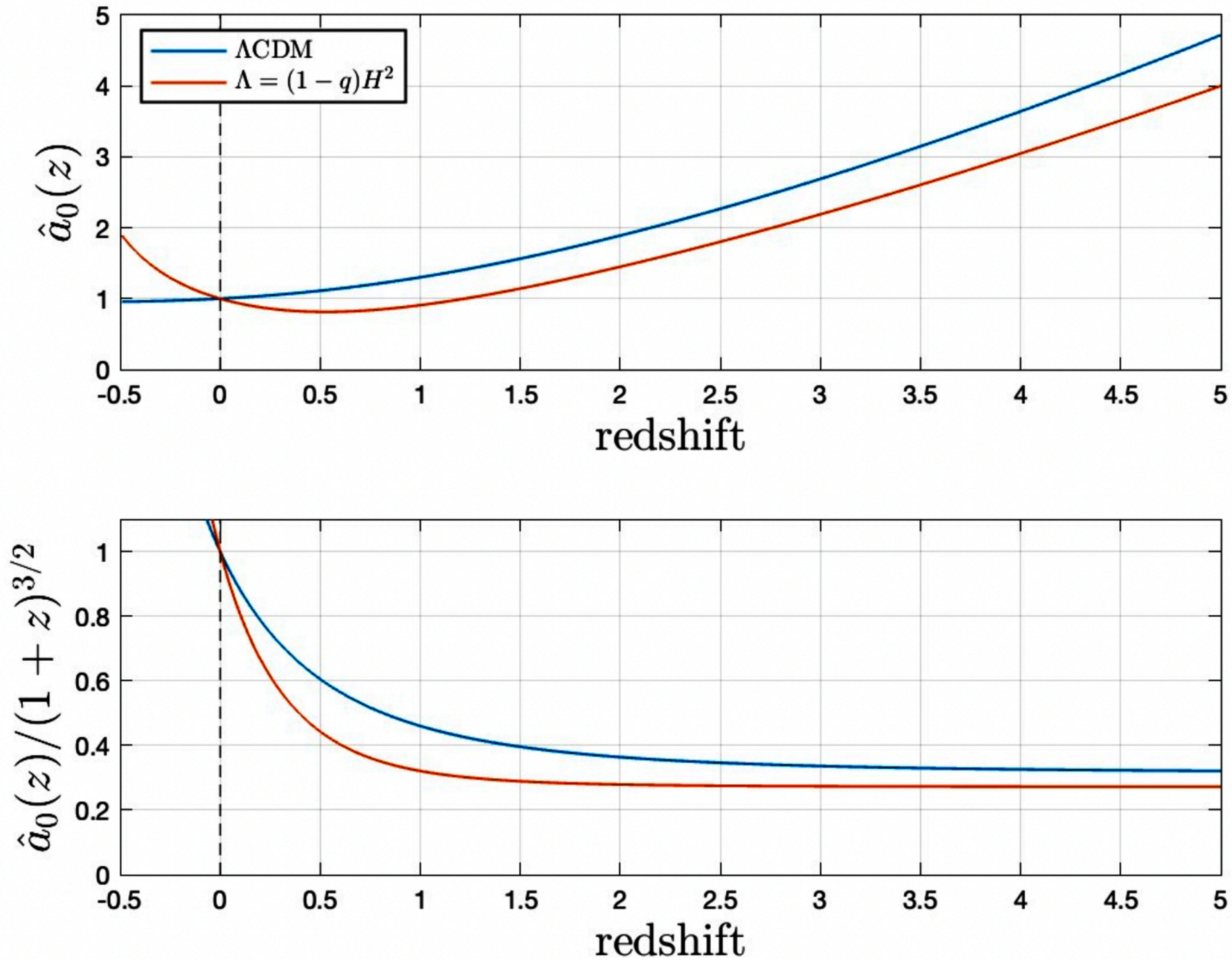
Milgrom parameter

Milgrom parameter (1984)

$$\alpha = \sqrt{a_0 a_N}$$

Can show

$$a_0(z) = \frac{\sqrt{1-q(z)}}{2\pi} a_{dS}$$



van Putten (2017-2018)

q_0-tension

Baryonic Tully Fisher relation

$$M_b = AV_c^4 \text{ with}$$
$$A = (47 \pm 6)\, M_\odot \left(\text{km s}^{-1}\right)^{-4}$$

Milgrom parameter

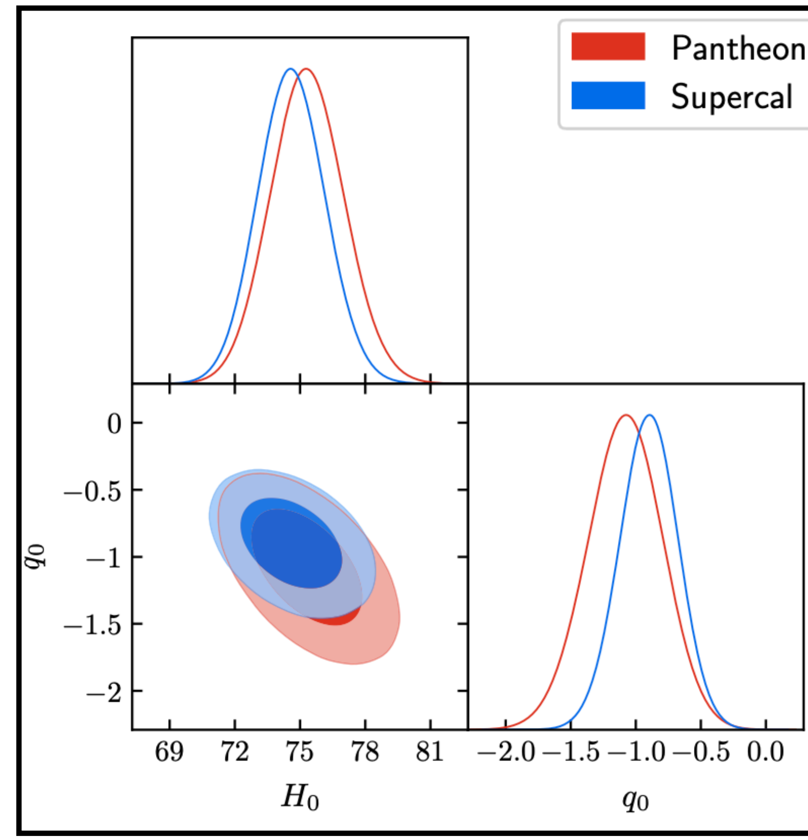
$$GAa_0 = 1$$

McGaugh (2012)

Inverting $a_0(z)$:

$$q_0 = 1 - \left(\frac{2\pi}{GAa_{dS}}\right)^2 = -0.98^{+0.60}_{-0.42}$$

Camarena & Valerio (2020)



Local Distance Ladder:

$$q_0 = -1.08 \pm 0.29$$

van Putten (submitted)

$$q_0 = -1.03 \pm 0.17$$
3σ departure from Planck value $q_0 = -0.5275$

Conclusions

$\left(H_0, q_0, S_8\right)$-tensions due to finite-temperature cosmology with a de Sitter density of heat:

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

Primary constraints T_U and BAO imply $\xi = 0.49 \pm 0.1$ in $g = \left(1 - \xi\alpha\right)$.

For $\xi = 1/2$:

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

Baryonic Tully-Fisher + supernova data:

$$q_0 = -1.03 \pm 0.17 \quad (3\sigma \text{ tension with Planck})$$

S_8-tension alleviated at reduced $\Omega_{M,0} \simeq 0.26 \pm 0.15$

van Putten (2021)

$(73.30 \pm 1.04)\ \mathrm{km\,s^{-1}Mpc^{-1}}$
Riess et al. (2022)

van Putten (2023, submitted)

$q_0 = -1.18 \pm 0.084$ in model fit to $H(z)$ data of Farooq et al. (2017), van Putten (2017)

Cosmological expansion

"Who, however, inflates the balloon? What causes the Universe to expand ~~or swell~~ accelerated or swell?"

That does de Sitter heat in $\Lambda = g\left(1-q\right)H^2$

New symmetry in T-duality in $a = 1/(1+z)$, compensating for loss of global symmetries due to the Big Bang


Gracias
Merci
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Kòp kun
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SPASIBO
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Thank you
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TAKK
DANK U
DYÁKUYU
TODA
Tak
Sepaas gozaaram
Arigatō gozaimasu
Dziękuję
Tack
XIÈXIÈ NǏ
Dhanyavaad
Teşekkürler
Köszönöm
Obrigado
Cảm ơn
SHUKRAN LAK
Efcharistó