

Dark Energy Theory Overview

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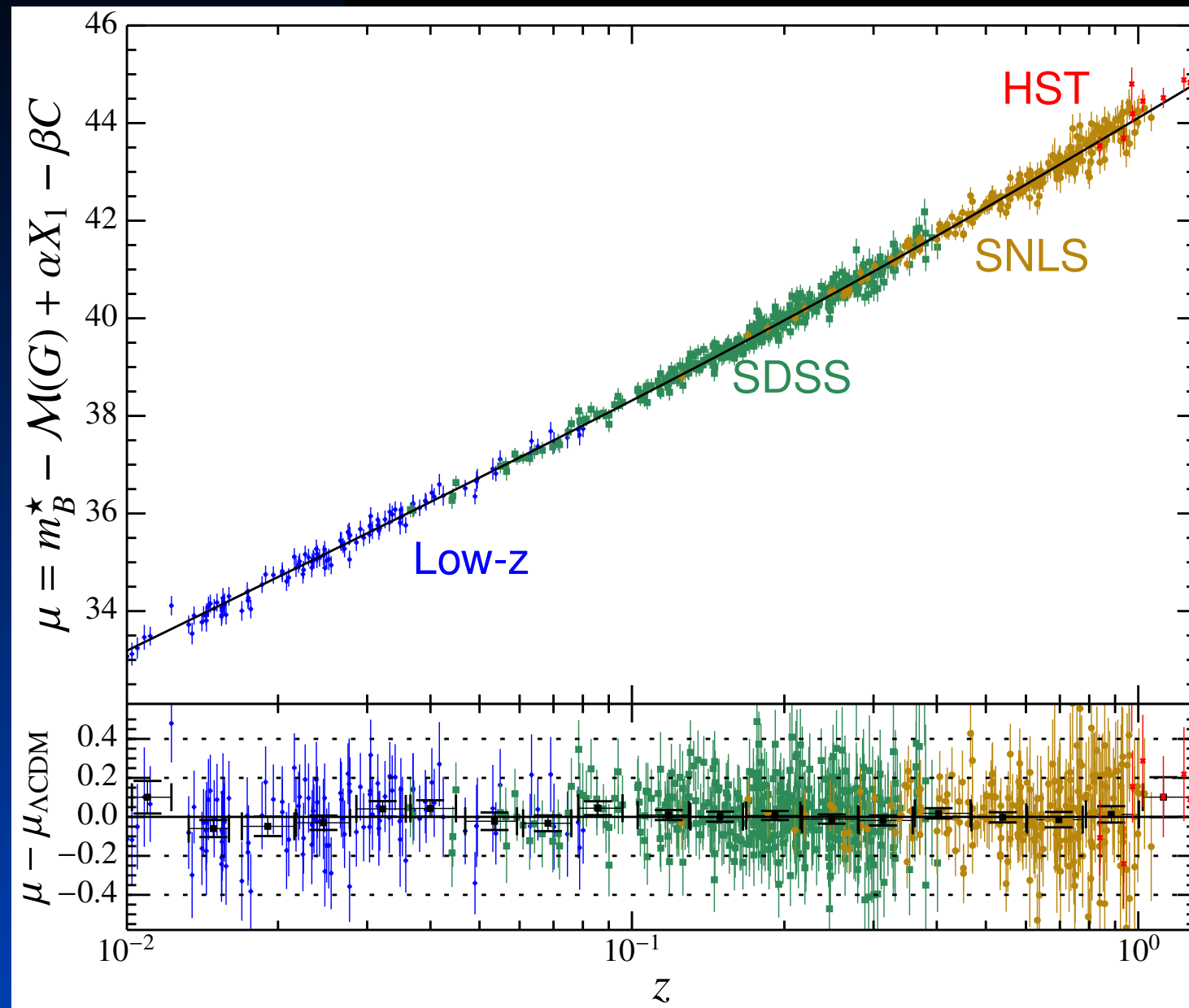
1. Brief recap of evolution of the universe: assumptions and evidence supporting them - pointing out issues where they may occur.
2. Planck and DESI evidence for dark energy.
3. Theory approaches to Dark Energy and Modified Gravity.
4. Hubble tension and Early Dark Energy
5. Impact of GW discovery on late time cosmology.
6. Dark Energy and the String Swampland
7. Recent large z results if quasars can be standard candles

UK HEP Forum 2025 - Wandering in the dark -

The Cosener's House — Oct 22nd 2025

The Big Bang – (1sec → today)

The cosmological principle -- isotropy and homogeneity on large scales



- The expansion of the Universe
 $v = H_0 d$

$$H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

(Riess et al, 2022)

$$H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

(Planck 2018)

Is there a local v global tension ?

Betoule et al 2014

$$\text{Redshift } 1 + z = \frac{a_0}{a}$$

$$H = \frac{\dot{a}}{a}$$

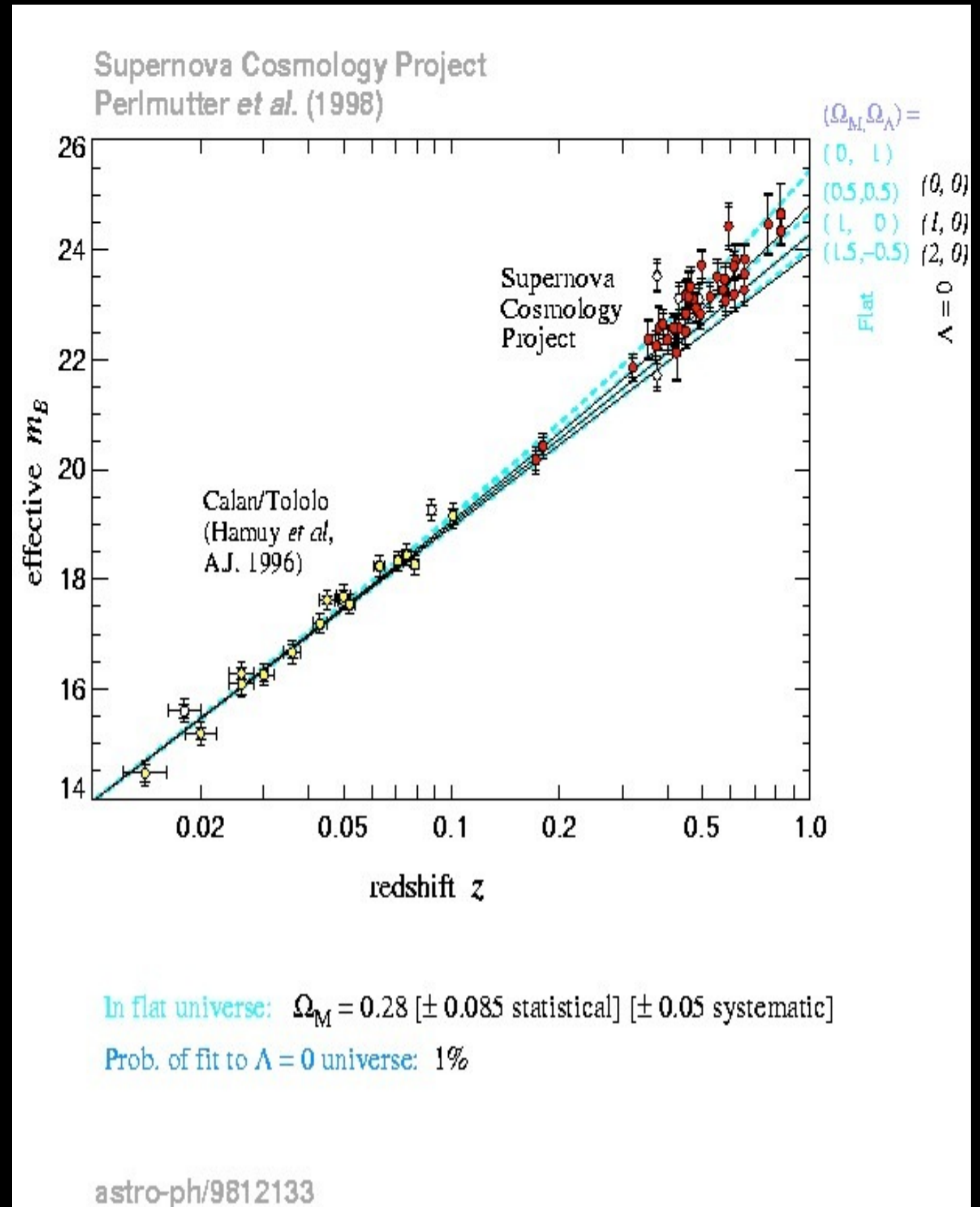
In fact the universe is accelerating !

Observations of distant supernova in galaxies indicate that the rate of expansion is increasing !

Huge issue in cosmology -- what is the fuel driving this acceleration?

We call it **Dark Energy** -- emphasises our ignorance!

Makes up 70% of the energy content of the Universe



$$G_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu} \quad \text{applied to cosmology}$$

Friedmann - the key
bgd equation:

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G \rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$a(t)$ depends on matter, $\rho(t) = \sum_i \rho_i$ -- sum of all matter contributions, rad, dust, scalar fields ...

Energy density $\rho(t)$: Pressure $p(t)$

Related through : $p = w\rho$

Eqn of state parameters: $w=1/3$ – Rad dom: $w=0$ – Mat dom: $w=-1$ – Vac dom

Eqns ($\Lambda=0$):

**Friedmann +
Fluid energy
conservation**

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G \rho - \frac{k}{a^2}$$

$$\dot{\rho} + 3(\rho + p) \frac{\dot{a}}{a} = 0$$

$$\nabla^\mu T_{\mu\nu} = 0$$

A neat equation

$$\rho_c(t) \equiv \frac{3H^2}{8\pi G} \quad ; \quad \Omega(t) \equiv \frac{\rho}{\rho_c}$$

$$\Omega > 1 \leftrightarrow k = +1$$

$$\Omega = 1 \leftrightarrow k = 0$$

$$\Omega < 1 \leftrightarrow k = -1$$



Friedmann eqn

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

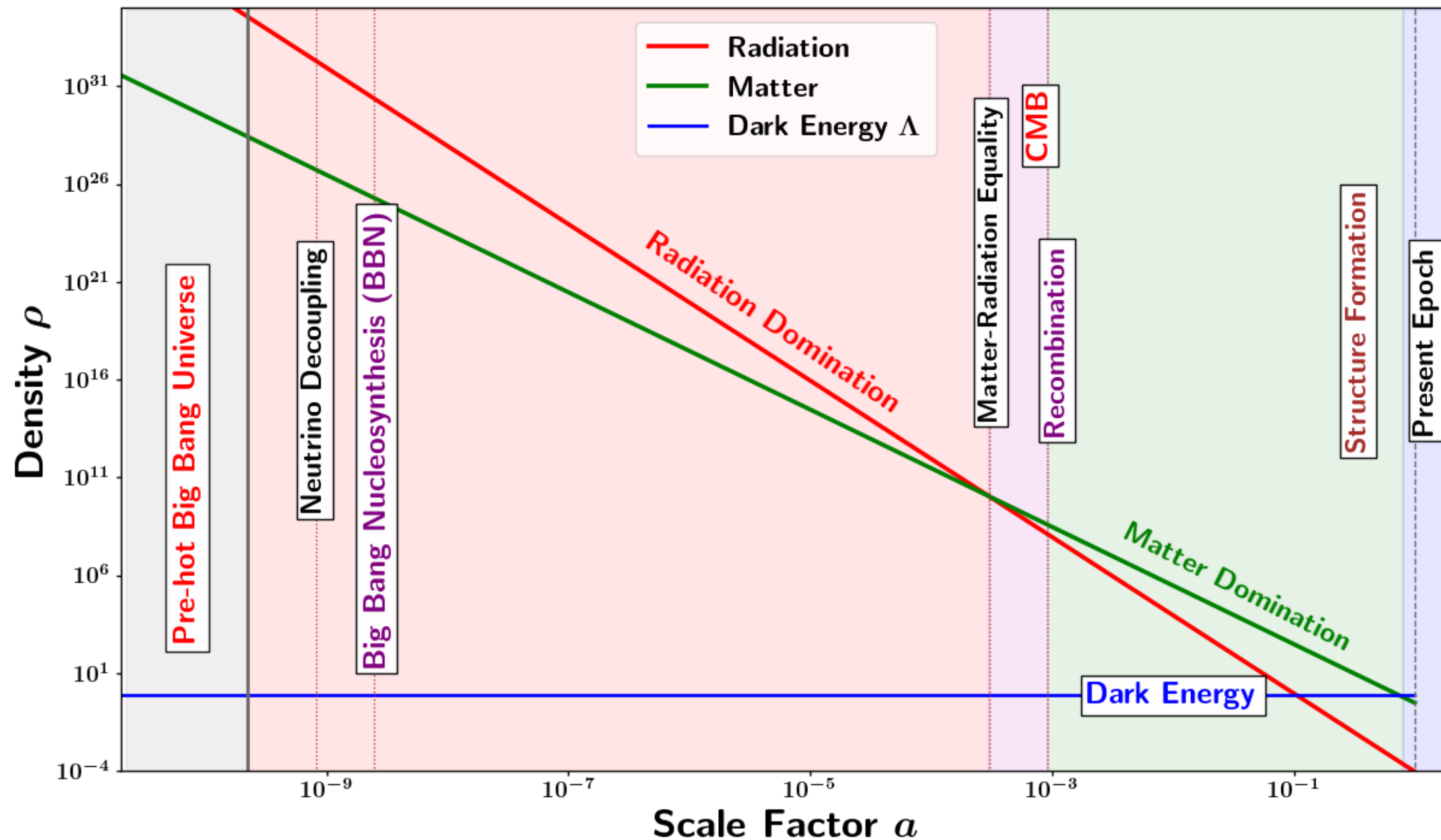
Ω_m - baryons, dark matter, neutrinos, electrons,
radiation ...

Ω_Λ - dark energy ; Ω_k - spatial curvature

$$\rho_c(t_0) \equiv 1.88h^2 * 10^{-29} \text{ g cm}^{-3}$$

Critical density

In expanding space, densities of **Matter** & **Radiation** dilute



Radiation-Domination → **Matter-Domination** → **Dark Energy Era**

See Keir's nice talk yesterday

Bounds on $H(z)$ -- Planck 2018 - (+BAO+lensing+lowE)

$$H^2(z) = H_0^2 \left(\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{de} \exp \left(3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right) \right)$$

(Expansion rate) -- $H_0 = 67.66 \pm 0.42$ km/s/Mpc

(radiation) -- $\Omega_r = (8.5 \pm 0.3) \times 10^{-5}$ - (WMAP)

(baryons) -- $\Omega_b h^2 = 0.02242 \pm 0.00014$

(dark matter) -- $\Omega_c h^2 = 0.11933 \pm 0.00091$ — (matter) - $\Omega_m = 0.3111 \pm 0.0056$

(curvature) -- $\Omega_k = 0.0007 \pm 0.0019$

(dark energy) -- $\Omega_{de} = 0.6889 \pm 0.0056$

(de eqn of state) -- $1+w = 0.028 \pm 0.032$ -- looks like a cosm const.

If allow variation of form : $w(z) = w_0 + w_a z/(1+z)$ then

$w_0 = -0.957 \pm 0.08$ and $w_a = -0.29 \pm 0.31$ (68% CL) — (Planck 2018+SNe+BAO)

Important because distance measurements often rely on assumptions made about the background cosmology.

$$w(z) = w_0 + w_a z/(1+z)$$

See
Willem's
nice talk
yesterday

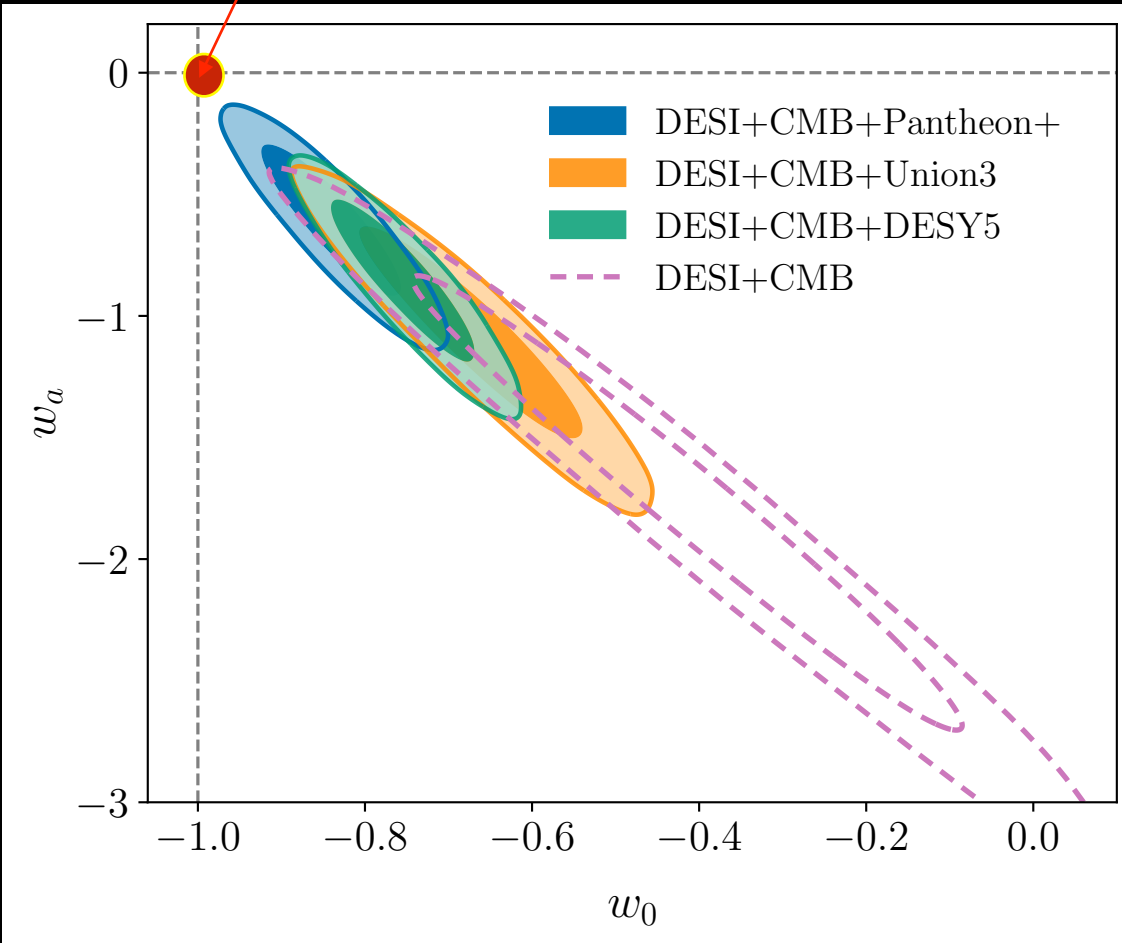
Model/Dataset	Ω_m	H_0 [km s ⁻¹ Mpc ⁻¹]	$10^3 \Omega_K$	w or w_0	w_a
wCDM					
CMB	$0.203^{+0.017}_{-0.060}$	85^{+10}_{-6}	—	$-1.55^{+0.17}_{-0.37}$	—
DESI	0.2969 ± 0.0089	—	—	-0.916 ± 0.078	—
DESI+Pantheon+	0.2976 ± 0.0087	—	—	-0.914 ± 0.040	—
DESI+Union3	0.2973 ± 0.0091	—	—	-0.866 ± 0.052	—
DESI+DESY5	0.2977 ± 0.0091	—	—	-0.872 ± 0.039	—
DESI+CMB	0.2927 ± 0.0073	69.51 ± 0.92	—	-1.055 ± 0.036	—
DESI+CMB+Pantheon+	0.3047 ± 0.0051	67.97 ± 0.57	—	-0.995 ± 0.023	—
DESI+CMB+Union3	0.3044 ± 0.0059	68.01 ± 0.68	—	-0.997 ± 0.027	—
DESI+CMB+DESY5	0.3098 ± 0.0050	67.34 ± 0.54	—	-0.971 ± 0.021	—
$w_0 w_a$CDM					
CMB	$0.220^{+0.019}_{-0.078}$	83^{+20}_{-6}	—	$-1.23^{+0.44}_{-0.61}$	< -0.504
DESI	$0.352^{+0.041}_{-0.018}$	—	—	$-0.48^{+0.35}_{-0.17}$	< -1.34
DESI+Pantheon+	$0.298^{+0.025}_{-0.011}$	—	—	$-0.888^{+0.055}_{-0.064}$	-0.17 ± 0.46
DESI+Union3	$0.328^{+0.019}_{-0.014}$	—	—	-0.70 ± 0.11	-0.99 ± 0.57
DESI+DESY5	$0.319^{+0.017}_{-0.011}$	—	—	$-0.781^{+0.067}_{-0.076}$	-0.72 ± 0.47
DESI+ $(\theta_*, \omega_b, \omega_{bc})$ CMB	0.353 ± 0.022	$63.7^{+1.7}_{-2.2}$	—	-0.43 ± 0.22	-1.72 ± 0.64
DESI+CMB (no lensing)	0.352 ± 0.021	$63.7^{+1.7}_{-2.1}$	—	-0.43 ± 0.21	-1.70 ± 0.60
DESI+CMB	0.353 ± 0.021	$63.6^{+1.6}_{-2.1}$	—	-0.42 ± 0.21	-1.75 ± 0.58
DESI+CMB+Pantheon+	0.3114 ± 0.0057	67.51 ± 0.59	—	-0.838 ± 0.055	$-0.62^{+0.22}_{-0.19}$
DESI+CMB+Union3	0.3275 ± 0.0086	65.91 ± 0.84	—	-0.667 ± 0.088	$-1.09^{+0.31}_{-0.27}$
DESI+CMB+DESY5	0.3191 ± 0.0056	66.74 ± 0.56	—	-0.752 ± 0.057	$-0.86^{+0.23}_{-0.20}$
DESI+DESY3 (3×2pt)+Pantheon+	0.3140 ± 0.0091	—	—	-0.870 ± 0.061	$-0.46^{+0.33}_{-0.29}$
DESI+DESY3 (3×2pt)+Union3	0.333 ± 0.012	—	—	-0.68 ± 0.11	$-1.09^{+0.48}_{-0.39}$
DESI+DESY3 (3×2pt)+DESY5	0.3239 ± 0.0092	—	—	-0.771 ± 0.068	$-0.82^{+0.38}_{-0.32}$

06/2

This apparent move towards phantom dark energy ($w < -1$) has generated a great deal of debate partly as it implies this can not be standard non minimally coupled quintessence .

$w(z) = -1$
LCDM

$$w(z) = w_0 + w_a z/(1+z)$$



$$\left. \begin{aligned} w_0 &= -0.838 \pm 0.055 \\ w_a &= -0.62^{+0.22}_{-0.19} \end{aligned} \right\} \text{DESI+CMB+Pantheon+,}$$

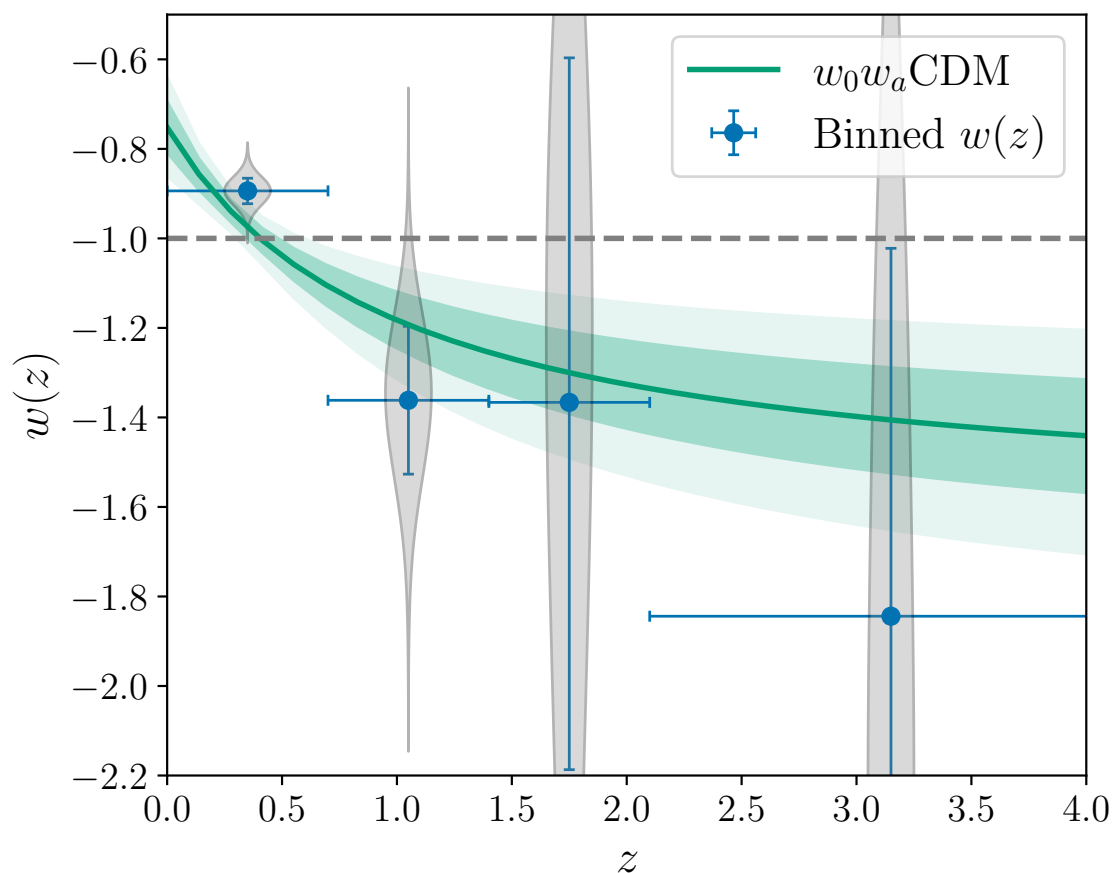
2.8 σ deviation from LCDM

$$\left. \begin{aligned} w_0 &= -0.667 \pm 0.088 \\ w_a &= -1.09^{+0.31}_{-0.27} \end{aligned} \right\} \text{DESI+CMB+Union3,}$$

3.8 σ deviation from LCDM

$$\left. \begin{aligned} w_0 &= -0.752 \pm 0.057 \\ w_a &= -0.86^{+0.23}_{-0.20} \end{aligned} \right\} \text{DESI+CMB+DESY5,}$$

4.2 σ deviation from LCDM



Standard minimally coupled quintessence has $-1 < w(z) < 1$

DESI indicates DE is getting weaker today than in LCDM

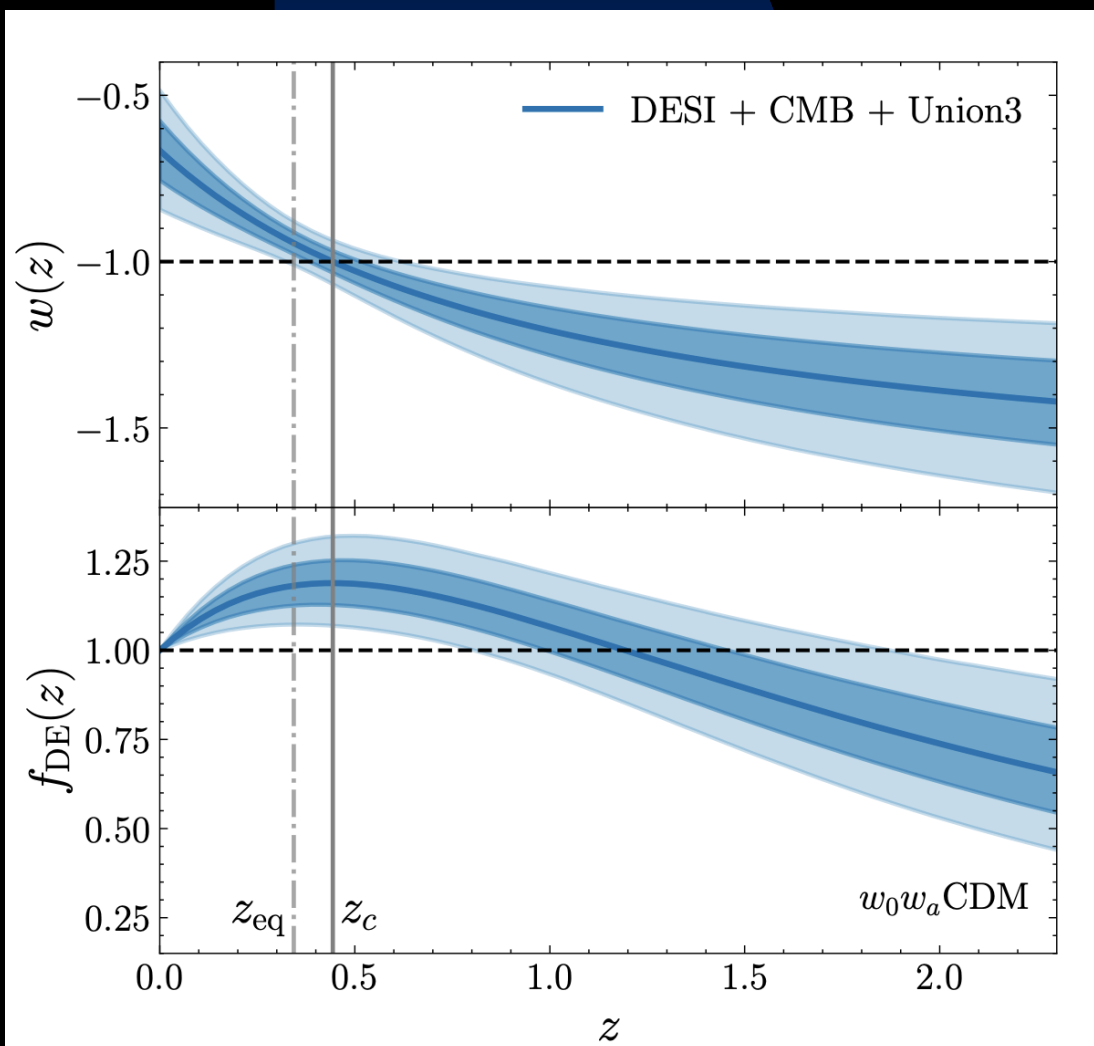
Evidence of evolution and a phantom like crossing around $z \sim 0.5$ - not same as phantom DE

Before we get too excited building models of dynamical dark energy

The main evidence, although still not that significant, seems to emerge with the SN data being included - but questions over inconsistencies between the DESY and Pantheon analysis. Pantheon is consistent with Planck LCDM whereas DESY doesn't appear to be. The low- z samples appear to be driving much of the evidence, and we require new low- z surveys to settle this.

We need to make sure we understand the systematics of the SN data in particular the Union 3 and DESY 5 samples.

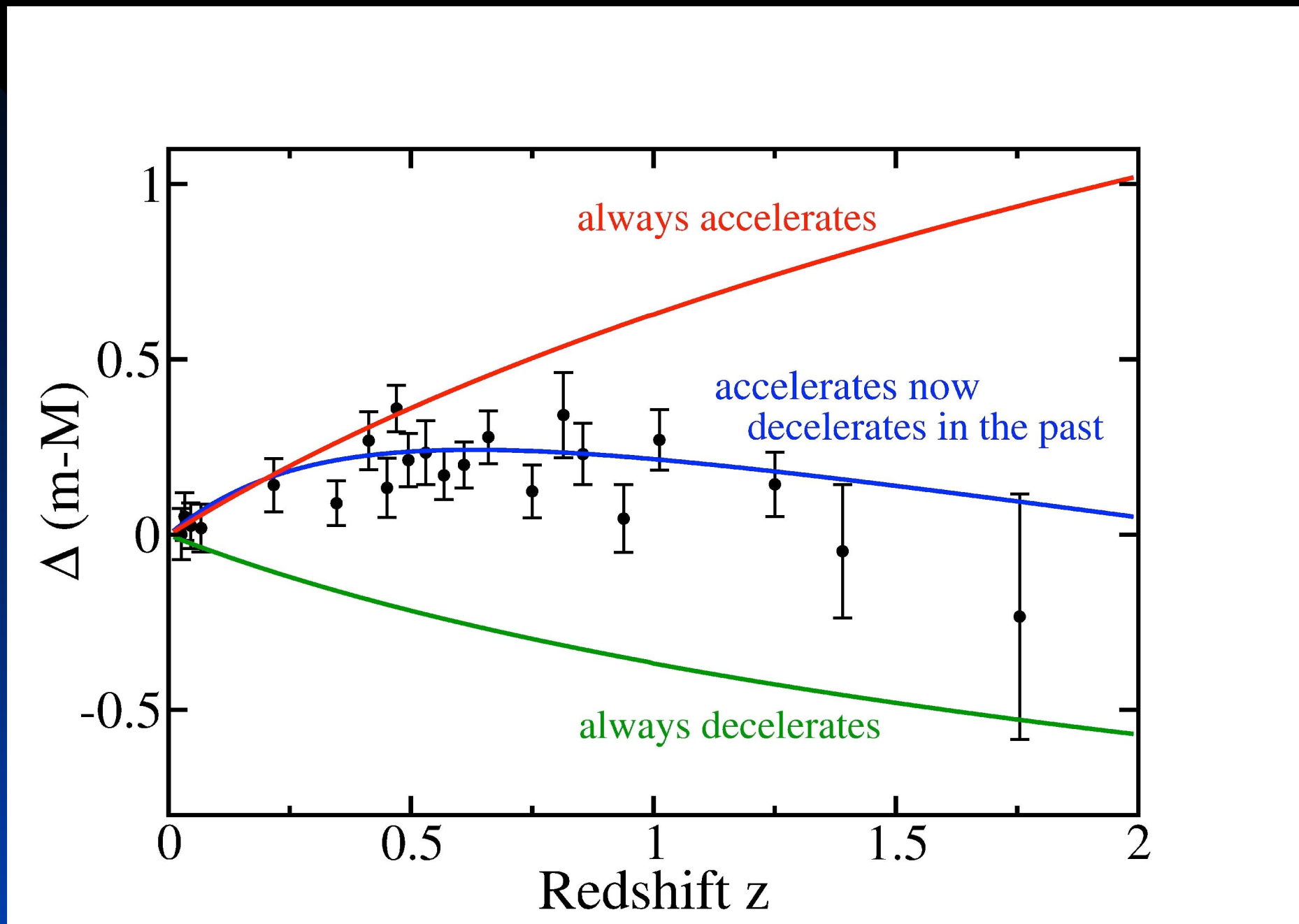
Efstathiou 2024,2025; Cortes and Liddle 2024,2025



From a theory standpoint, this is unusual behaviour of the energy density ($f(z)$), rising to a max then decreasing again.

Maybe a sign it isn't simple Quintessence, but what we are seeing is an effective energy density from modified gravity or mixed dark energy/dark matter

The acceleration has not been forever -- pinning down the turnover will provide a very useful piece of information.



Huterer 2010

Help address cosmic coincidence problem ! A region hopefully EUCLID along with DESI will also be able to probe in the coming years

Different approaches to Dark Energy include amongst many:

A true cosmological constant -- but why this value - CCP ?

Time dependent solutions arising out of evolving scalar fields -- Quintessence/K-essence.

Modifications of Einstein gravity leading to acceleration today.

Anthropic arguments.

Perhaps GR but Universe is inhomogeneous.

Hiding the cosmological constant -- its there all the time but just doesn't gravitate and something else is driving the acceleration.

Yet to be proposed ...

Brief reminder why the cosmological constant is regarded as a problem?

The CC gravitates in General Relativity:

$$\mathcal{L} = \sqrt{-g} \left(\frac{R}{16\pi G} - \rho_{\text{vac}} \right)$$
$$G_{\mu\nu} = -8\pi G \rho_{\text{vac}} g_{\mu\nu}$$

Now:

$$\rho_{\text{vac}}^{\text{obs}} \ll \rho_{\text{vac}}^{\text{theory}}$$

Just as well because anything much bigger than we have and the universe would have looked a lot different to what it does look like - Pauli realised this nearly one hundred years ago. In fact structures would not have formed in it.

Estimate what the vacuum energy should be :

$$\rho_{\text{vac}}^{\text{theory}} \sim \rho_{\text{vac}}^{\text{bare}}$$

+

zero point energies of each particle

+

contributions from phase transitions in the early universe

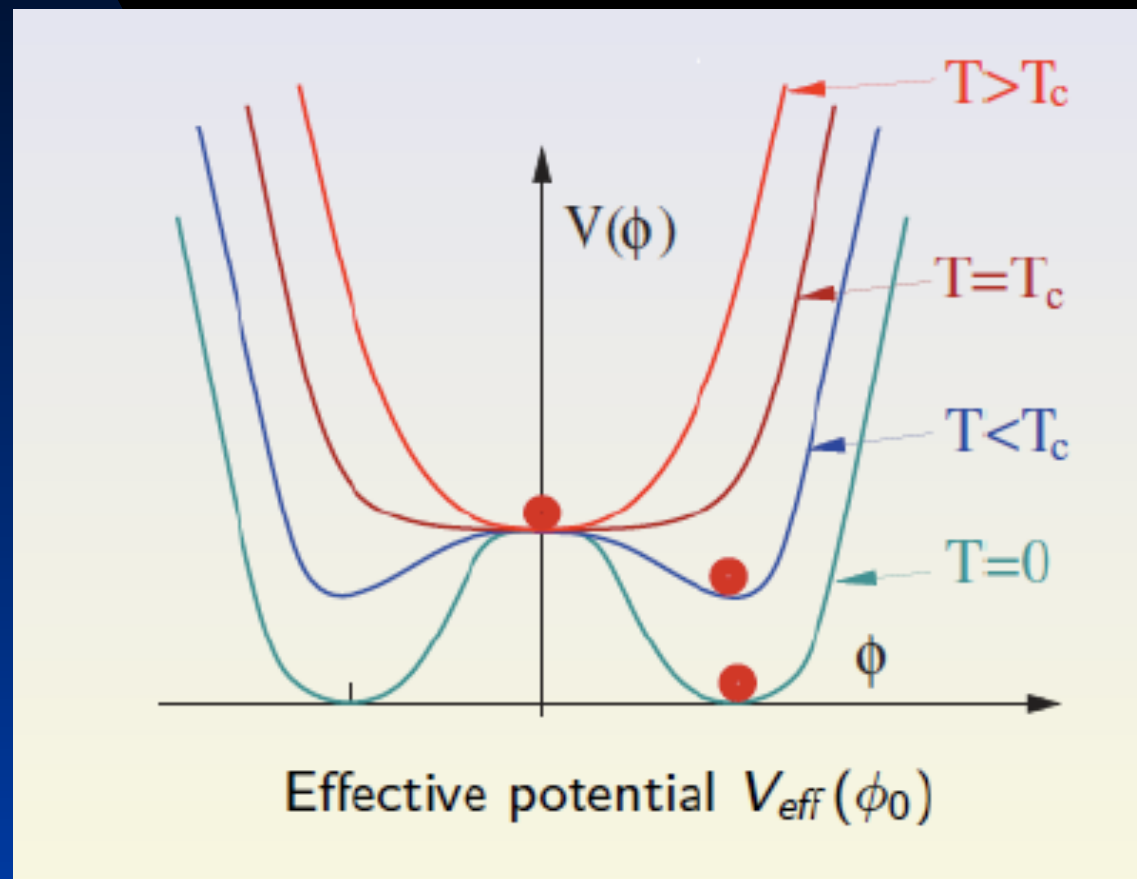
zero point energies of each particle

For many fields (i.e. leptons, quarks, gauge fields etc...):

$$\langle \rho \rangle = \frac{1}{2} \sum_{\text{fields}} g_i \int_0^{\Lambda_i} \sqrt{k^2 + m^2} \frac{d^3 k}{(2\pi)^3} \simeq \sum_{\text{fields}} \frac{g_i \Lambda_i^4}{16\pi^2}$$

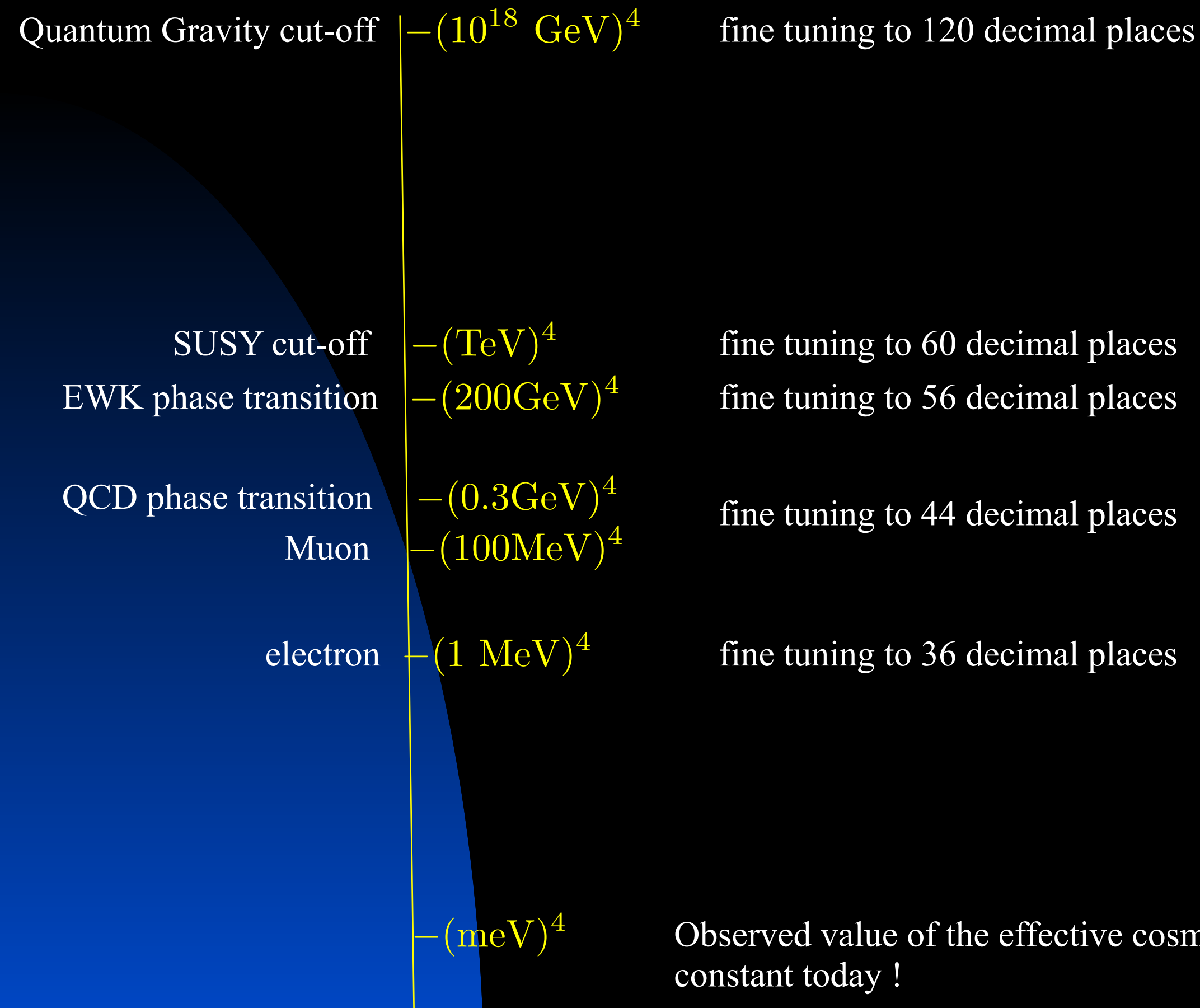
where g_i are the dof of the field (+ for bosons, - for fermions).

contributions from phase transitions in the early universe



$$\Delta V_{\text{ewk}} \sim (200 \text{ GeV})^4$$

$$\Delta V_{\text{QCD}} \sim (0.3 \text{ GeV})^4$$



String - theory -- where are the realistic models?

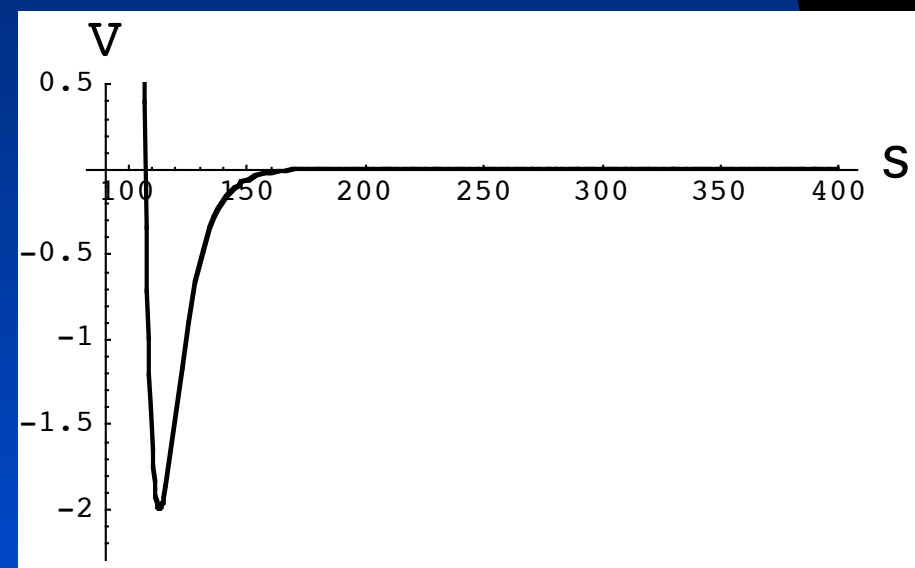
'No go' theorem: forbids cosmic acceleration in cosmological solutions arising from compactification of pure SUGRA models where internal space is time-independent, non-singular compact manifold without boundary --[Gibbons]

Avoid no-go theorem by relaxing conditions of the theorem.

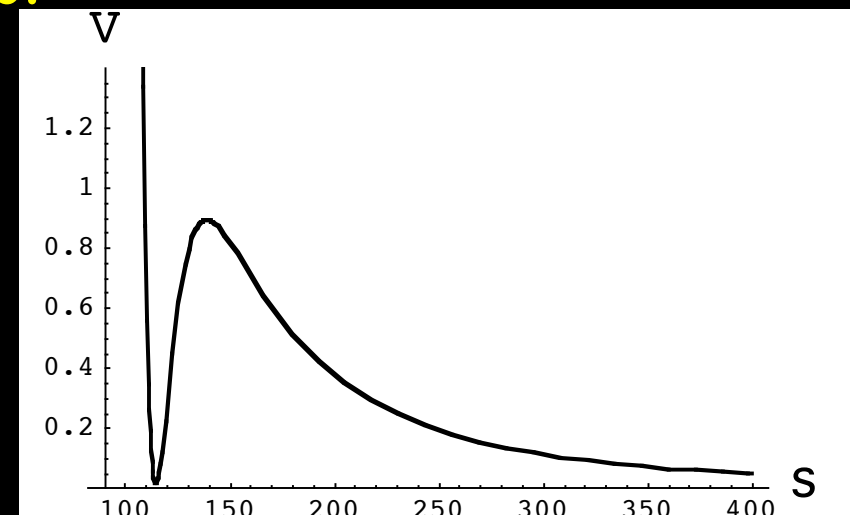
1. Allow internal space to be time-dependent scalar fields (radion)
2. Brane world set up require uplifting terms to achieve de Sitter vacua hence accn

Example of stabilised scenario: Metastable de Sitter string vacua in Type IIB string theory, based on stable highly warped IIB compactifications with NS and RR three-form fluxes. [Kachru, Kallosh, Linde and Trivedi 2003]

Metastable minima arises from adding positive energy of anti-D3 brane in warped Calabi-Yau space.



AdS minimum



Metastable dS minimum

$$V_{\text{KKLT}} = V_{\text{AdS}} + \frac{D}{\sigma^2}$$

The String Landscape approach

Type IIB String theory compactified from 10 dimensions to 4.

Internal dimensions stabilised by fluxes. Assumes natural AdS vacuum uplifted to de Sitter vacuum through additional fluxes !

Many many vacua $\sim 10^{500}$! Typical separation $\sim 10^{-500} \Lambda_{pl}$

Assume randomly distributed, tunnelling allowed between vacua --> separate universes .

Anthropic : Galaxies require vacua $< 10^{-118} \Lambda_{pl}$ [Weinberg] Most likely to find values not equal to zero!

Landscape gives a realisation of the multiverse picture.

There isn't one true vacuum but many so that makes it almost impossible to find our vacuum in such a Universe which is really a multiverse.

So how can we hope to understand or predict why we have our particular particle content and couplings when there are so many choices in different parts of the universe, none of them special ?

1. SUSY large extra dimensions and Lambda - Burgess et al 2013, 2015

Soln to 6D Einstein-Maxwell-scalar with chiral gauged sugr.

In more than 4D, the 4D vac energy can curve the extra dimensions.

Proposal: Physics is 6D above 0.01eV scale with SUSY bulk. We live in 4D brane with 2 extra dim. 4D vac energy cancelled by Bulk contributions - quintessence like potential generated by Qu corrections leading to late time accn.

2. Sequestering Lambda - Kaloper and Padilla and others 2013-2016

IR soln to the problem - initial version adds a global term to Einstein action and fix $\langle R \rangle$ by global constraints.

In particular promote Λ and M_P to be global variables. Varying wrt these, and separating $T_{\mu\nu}$ into vacuum energy and local excitations find that vacuum energy drops out at each order.

$$\kappa^2 G_{\mu\nu} = T_{\mu\nu}^{\text{local}} - \frac{1}{4} \langle T^{\text{local}} \rangle g_{\mu\nu}$$

where

$$\langle Q \rangle = \frac{\int d^4x \sqrt{-g} Q}{\int d^4x \sqrt{-g}}$$

Local version of sequestering can accommodate infinite universe [Kaloper et al 2015]

3. Self tuning

In GR the vacuum energy gravitates, and the theoretical estimate suggests that it gravitates too much.

Basic idea is to use self tuning to prevent the vacuum energy gravitating at all.

The cosmological constant is there all the time but is being dealt with by the evolving scalar field.

Most general scalar-tensor theory with second order field equations:

[G.W. Horndeski, Int. Jour. Theor. Phys. 10 (1974) 363-384]

The action which leads to required self tuning solutions is such that

the self tuning can be seen to reside in terms of four arbitrary potential functions of ϕ coupled to the curvature terms.

Covers most scalar field related modified gravity models studied to date.

See also:

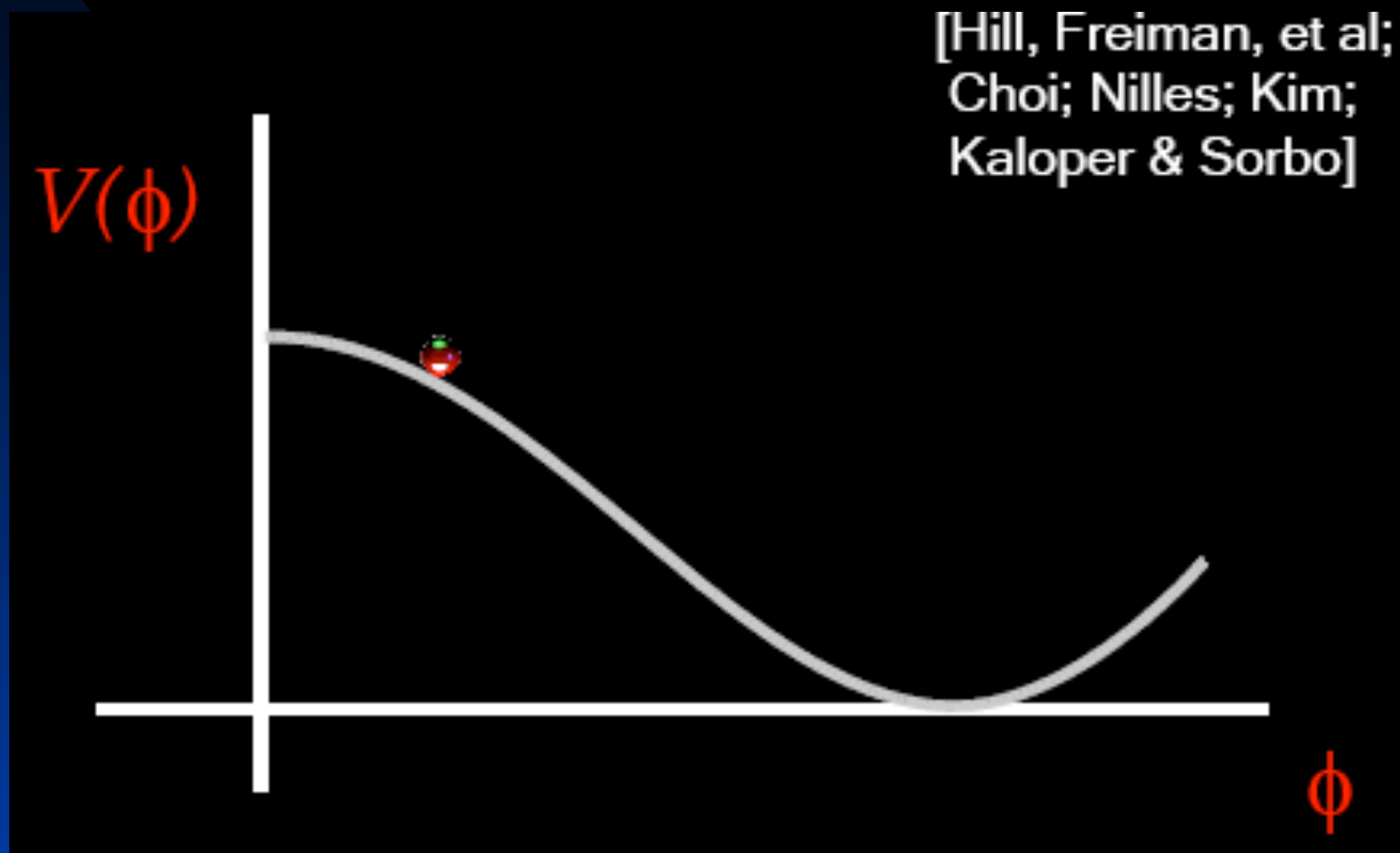
Appleby et al JCAP 1210 (2012) 060; Amendola et al PRD 87 (2013) 2, 023501; Martin-Moruno et al PRD 91 (2015) 8, 084029; Babichev et al arXiv:1507.05942 [gr-qc] ; Emond et al JCAP 05 (2019) 038

See
Martin's
nice talk
yesterday

Particle physics inspired models of dark energy ?

Pseudo-Goldstone Bosons -- approx sym $\phi \rightarrow \phi + \text{const.}$

Leads to naturally small masses, naturally small couplings



Barbieri et al

See Yoga model of
Burgess et al 2021 for
approach to solving the
CCP via relaxation
mechanism and
obtaining dynamical DE

$$V(\phi) = \lambda^4 (1 + \cos(\phi/F_a))$$

Axions could be useful for strong CP problem, dark matter and dark energy — ex. Quintessential Axion.

Axions could be useful for strong CP problem, dark matter and dark energy.

Strong CP problem intro axion : $m_a = \frac{\Lambda_{\text{QCD}}^2}{F_a}$; F_a — decay constant

Maybe not original PQ axion but invisible axion still allowed:

$$10^9 \text{ GeV} \leq F_a \leq 10^{12} \text{ GeV}$$

Sun stability CDM constraint

String theory has lots of antisymmetric tensor fields in 10d, hence many light axion candidates.

Can have $F_a \sim 10^{17}-10^{18} \text{ GeV}$

Quintessential axion -- dark energy candidate [Kim & Nilles].

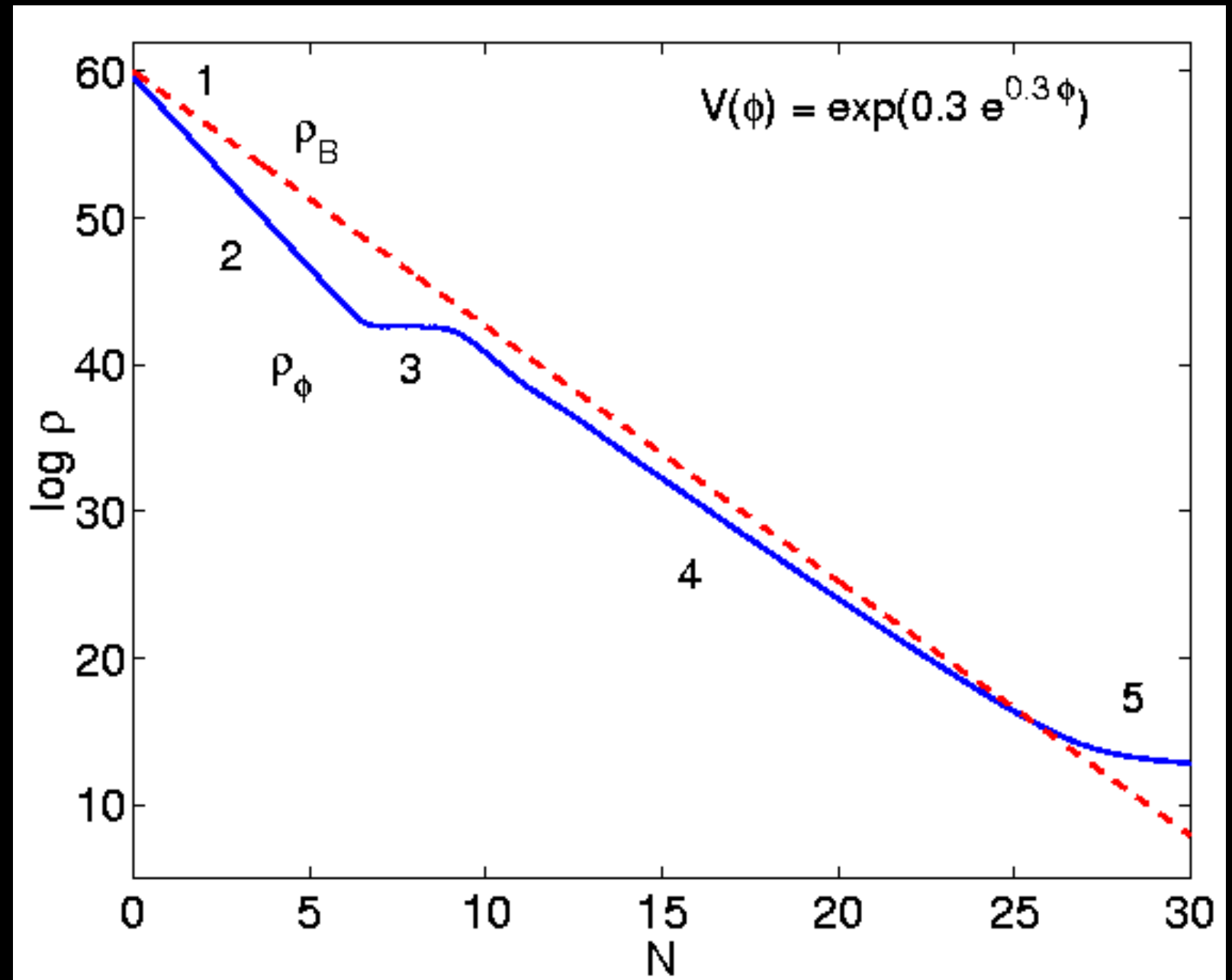
Requires $F_a \sim 10^{18} \text{ GeV}$ which can give:

$$E_{\text{vac}} = (10^{-3} \text{ eV})^4 \rightarrow m_{\text{axion}} \sim 10^{-33} \text{ eV}$$

Because axion is pseudoscalar -- mass is protected, hence avoids fifth force constraints

Slowly rolling scalar fields Quintessence

1. PE $\rightarrow$ KE
2. KE dom scalar field energy den.
3. Const field.
4. Attractor solution: almost const ratio KE/PE.
5. PE dom.



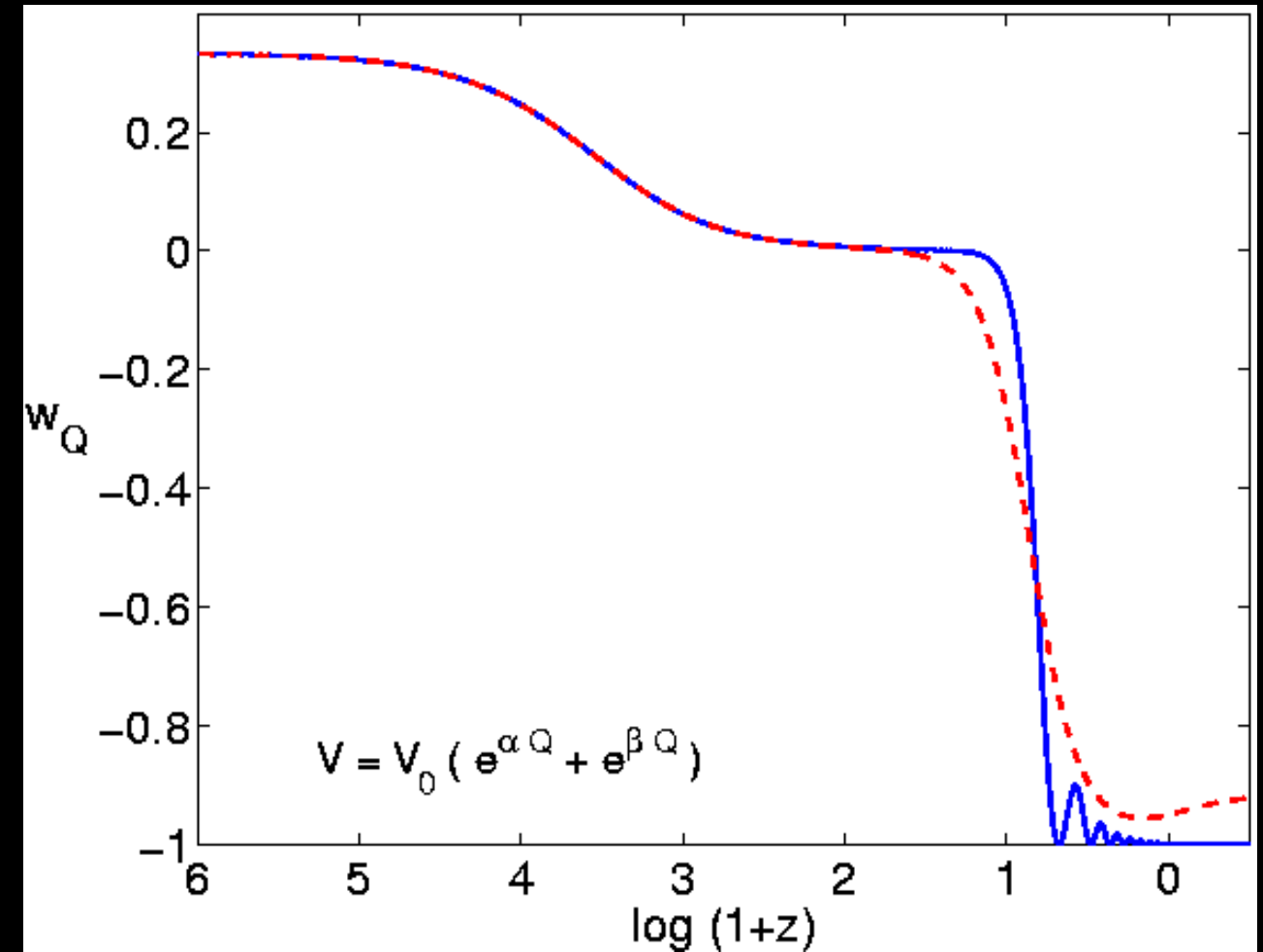
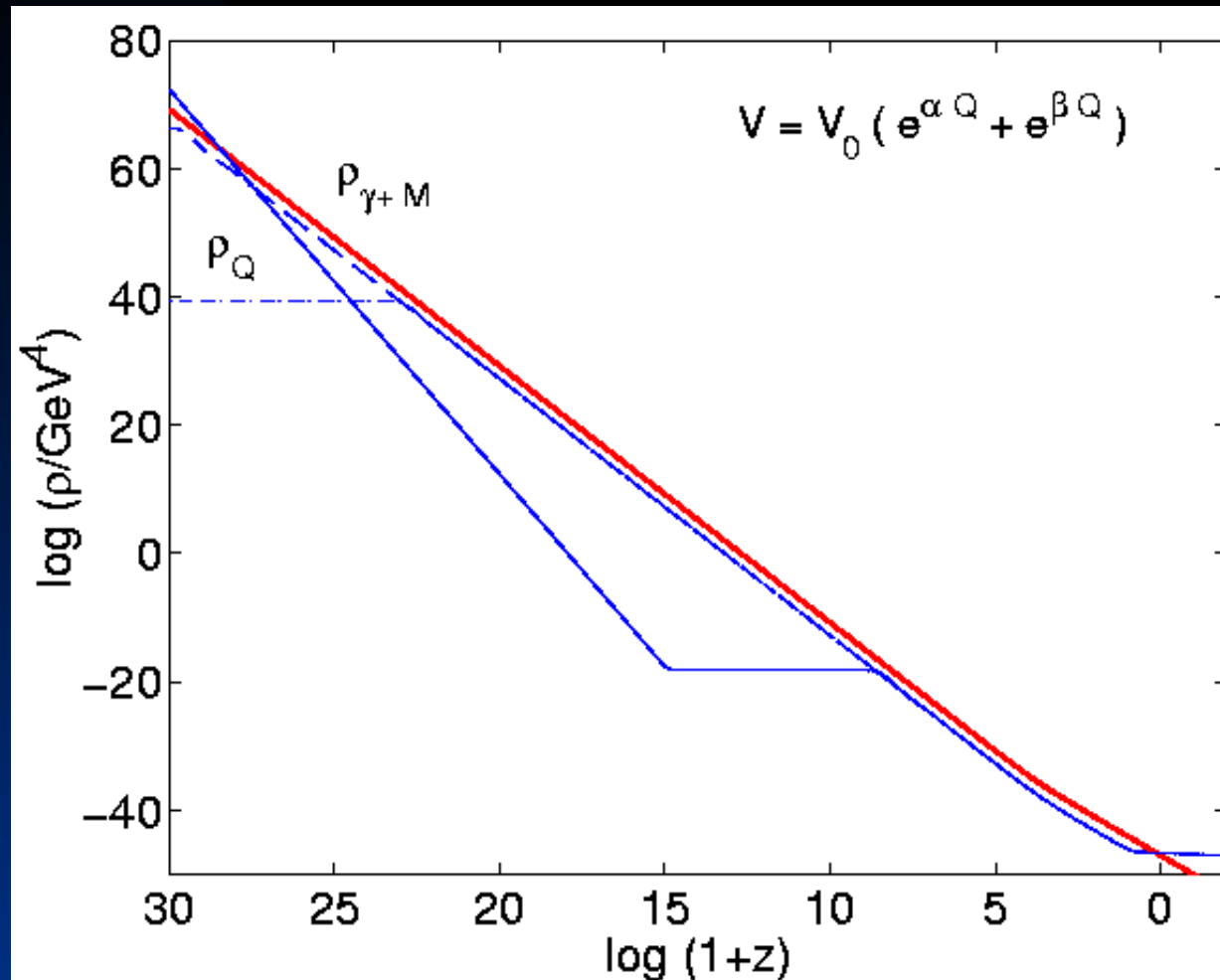
Nunes

Attractors make initial conditions less important

$$V(\phi) = V_1 + V_2$$

$$= V_{01} e^{-\kappa \lambda_1 \phi} + V_{02} e^{-\kappa \lambda_2 \phi}$$

Barreiro, EJC and Nunes 2000



$$\alpha = 20; \beta = 0.5$$

Scaling for wide range of i.c.

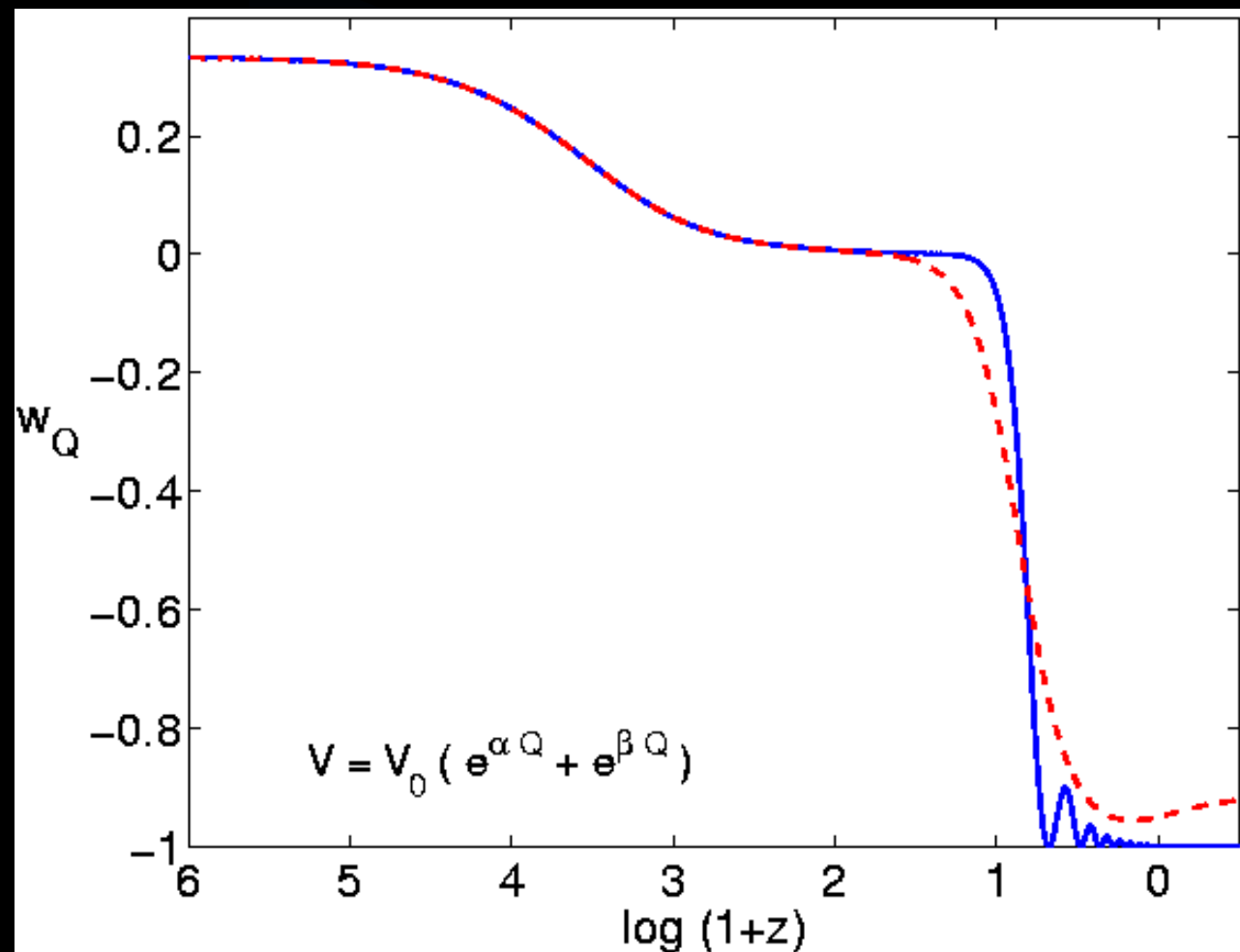
Fine tuning: $V_0 \approx \rho_\phi \approx 10^{-47} \text{ GeV}^4 \approx (10^{-3} \text{ eV})^4$

Mass:

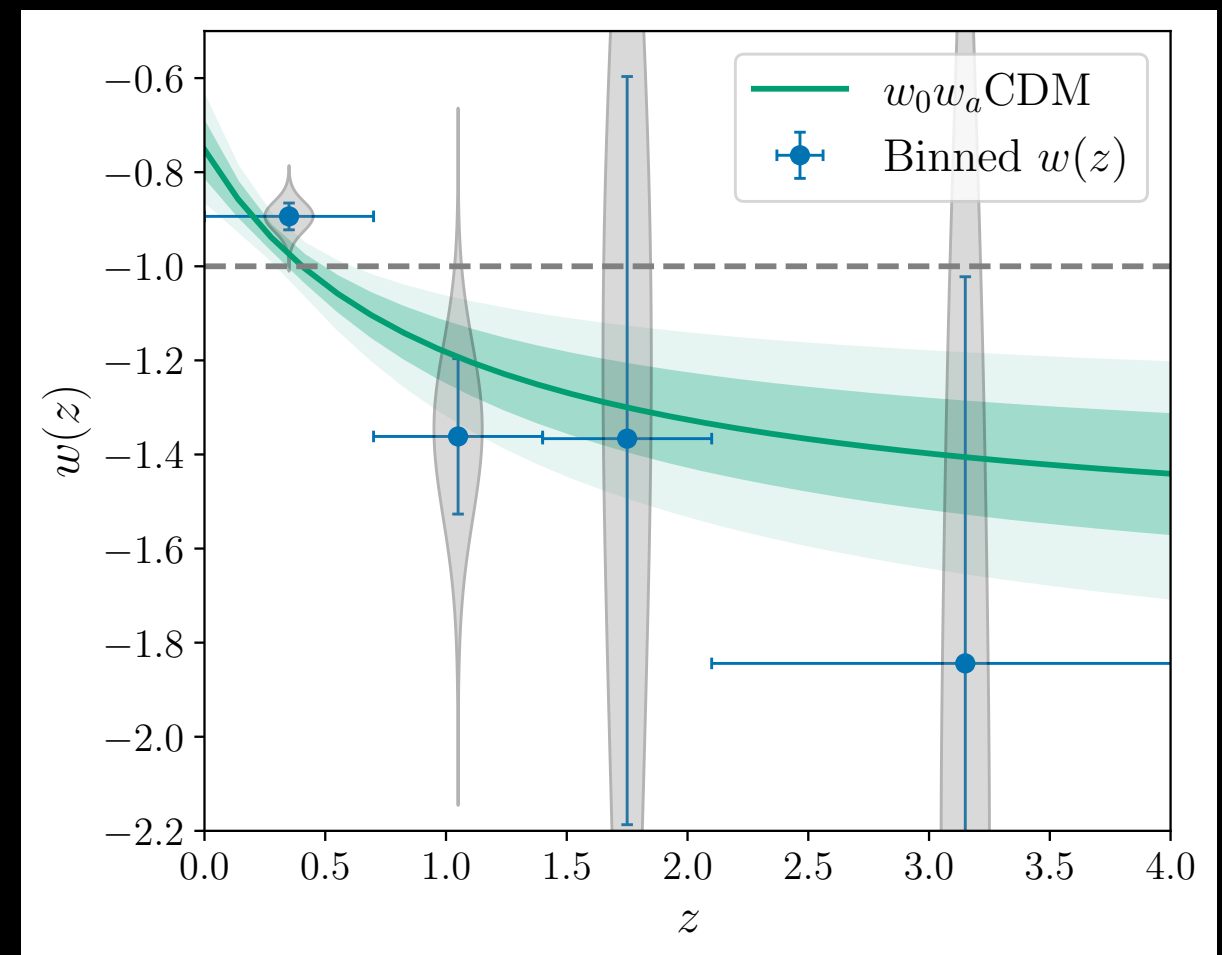
$$m \approx \sqrt{\frac{V_0}{M_{\text{pl}}^2}} \approx 10^{-33} \text{ eV}$$

Generic issue Fifth force - require screening mechanism!

Typical Quintessence eos $w \sim -1$
today and was always $w > -1$



DESI eos $w > -1$ today but was
earlier in $w < -1$ region



DESI seems to prefer a phantom
like region.

Phantom Dark Energy - a way to get $w < -1$ — [Caldwell 2002]

Recall a canonical
homogeneous scalar field

$$\rho = -T_0^0 = \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad p = T_i^i = \frac{1}{2}\dot{\phi}^2 - V(\phi).$$

Eqn of state

$$w_\phi = \frac{p}{\rho} = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}.$$

Bounded $-1 < w < 1$ - Quintessence

Intro ghost field (negative KE)

$$w_\phi = \frac{p}{\rho} = \frac{\dot{\phi}^2 + 2V(\phi)}{\dot{\phi}^2 - 2V(\phi)}. \quad \text{can now satisfy } w < -1$$

Curvature of the universe grows towards infinity within a finite
time if dominated by a phantom field — leads to a Big Rip

UV Quantum instabilities - energy density unbounded from below, vacuum
unstable against production of ghosts and normal (positive energy) fields.

Even if the ghosts are decoupled from matter fields, they couple to
gravitons which mediate vacuum decay: vacuum $\longrightarrow$ 2 ghosts + 2 photons

But DE doesn't have to be actually an unstable phantom field for $w < -1$

Is modified gravity the way forward ? [Wolf et al - arXiv 2504.07679]

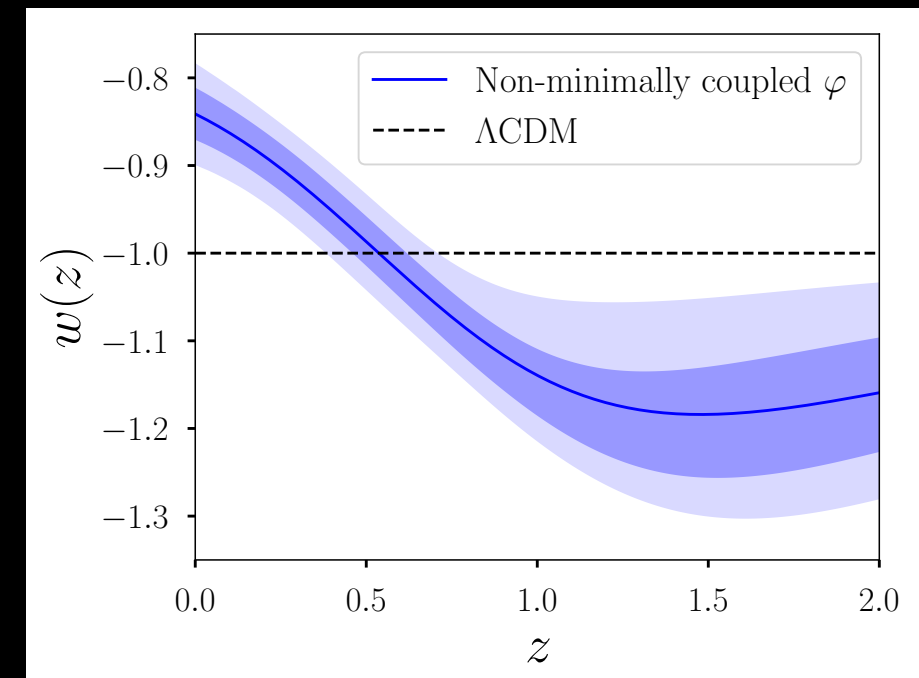
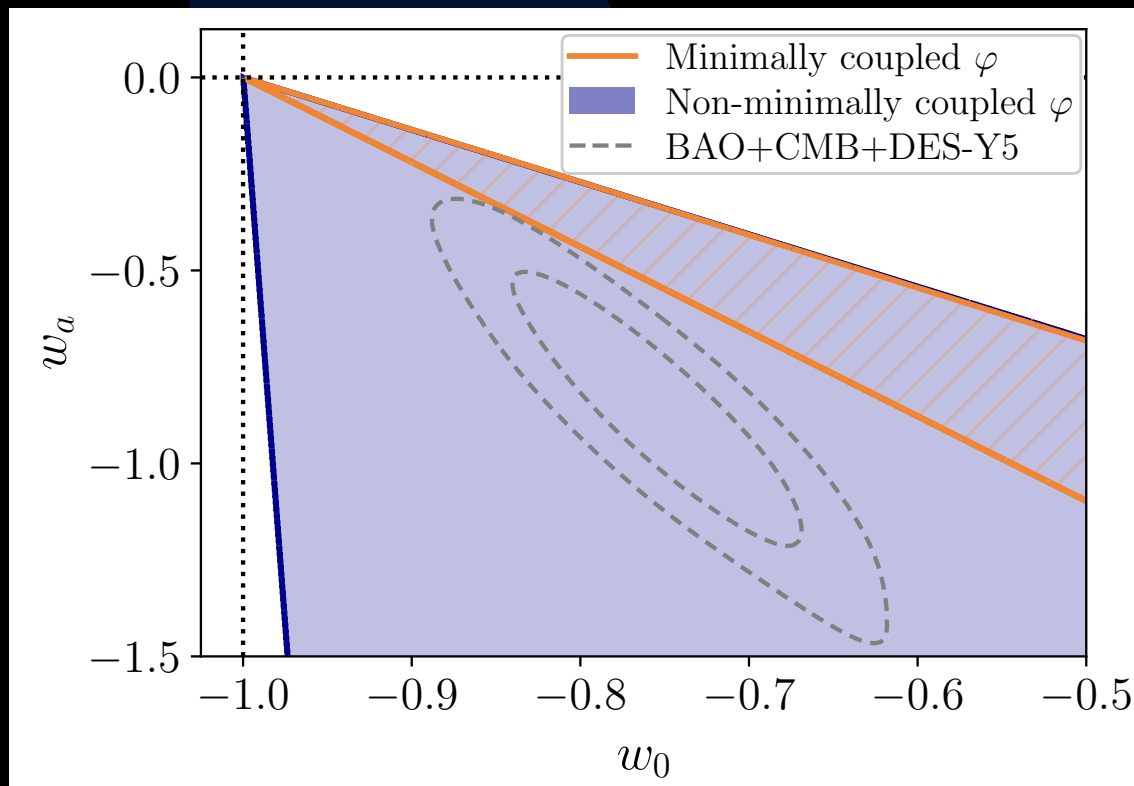
$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} F(\varphi) R - \frac{1}{2} G(\varphi) X - V(\varphi) - J(\varphi) X^2 + \mathcal{L}_M(g_{\alpha\beta}, \psi_M) \right],$$

$$X = \partial_\mu \varphi \partial^\mu \varphi$$

where

$$F(\varphi) \simeq 1 - \xi \frac{\varphi^2}{M_{\text{Pl}}^2},$$

$$V(\varphi) \simeq V_0 + \beta \varphi + \frac{1}{2} m^2 \varphi^2,$$



So a thawing ($m^2 < 0$) non-min coupled quintessence model can fit DESI - but severely constrained by fifth force experiments because field so light !

06/23/2008

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Need to then screen them, but even then severely constrained - its not easy. Or maybe couple DE and DM so as to avoid the issue of baryons coupling in. [See Elisa's talk]

The problem of coupling DE and DM directly with scalars

[D'Amico, Hamil & Kaloper 2016; Marsh 2016]

Generate loop corrections to the DE mass.

Consider Yukawa type coupling between
DE scalar and DM fermion

$$g\phi\bar{\psi}\psi$$

Now since it is DE:

$$m_\phi \simeq H \sim 10^{-33} eV$$

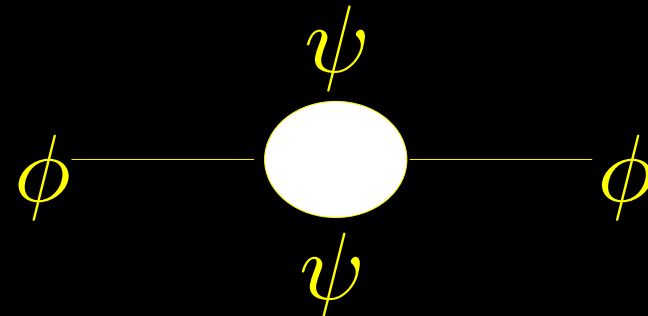
Very light so long range
attractive 5th force:

$$Pot : \Phi(r) \sim g^2 / r$$

Must be less than grav attraction of
DM particles by say factor 10

$$g < m_\psi / (10m_{pl})$$

Loop correction to DE mass from DM



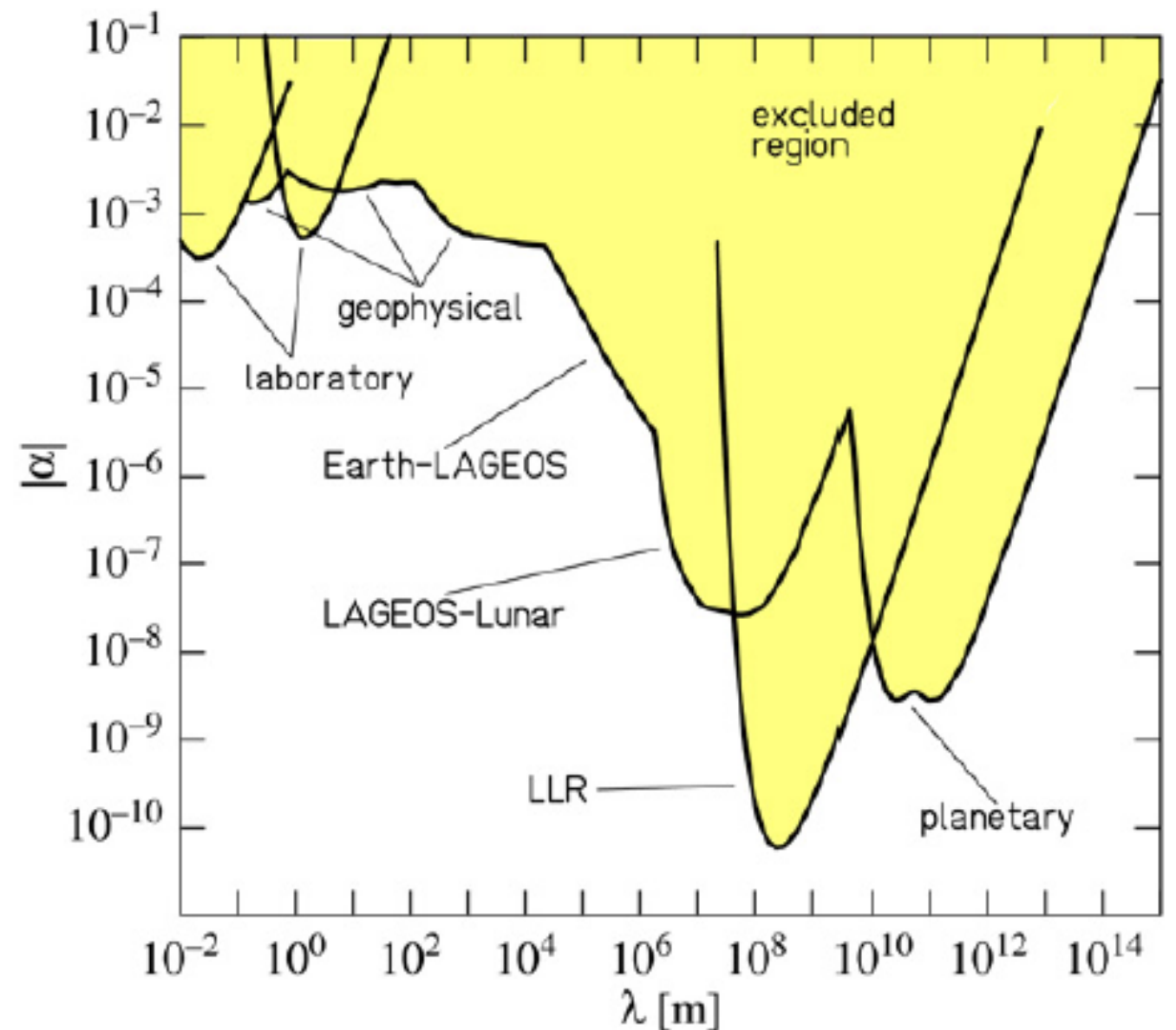
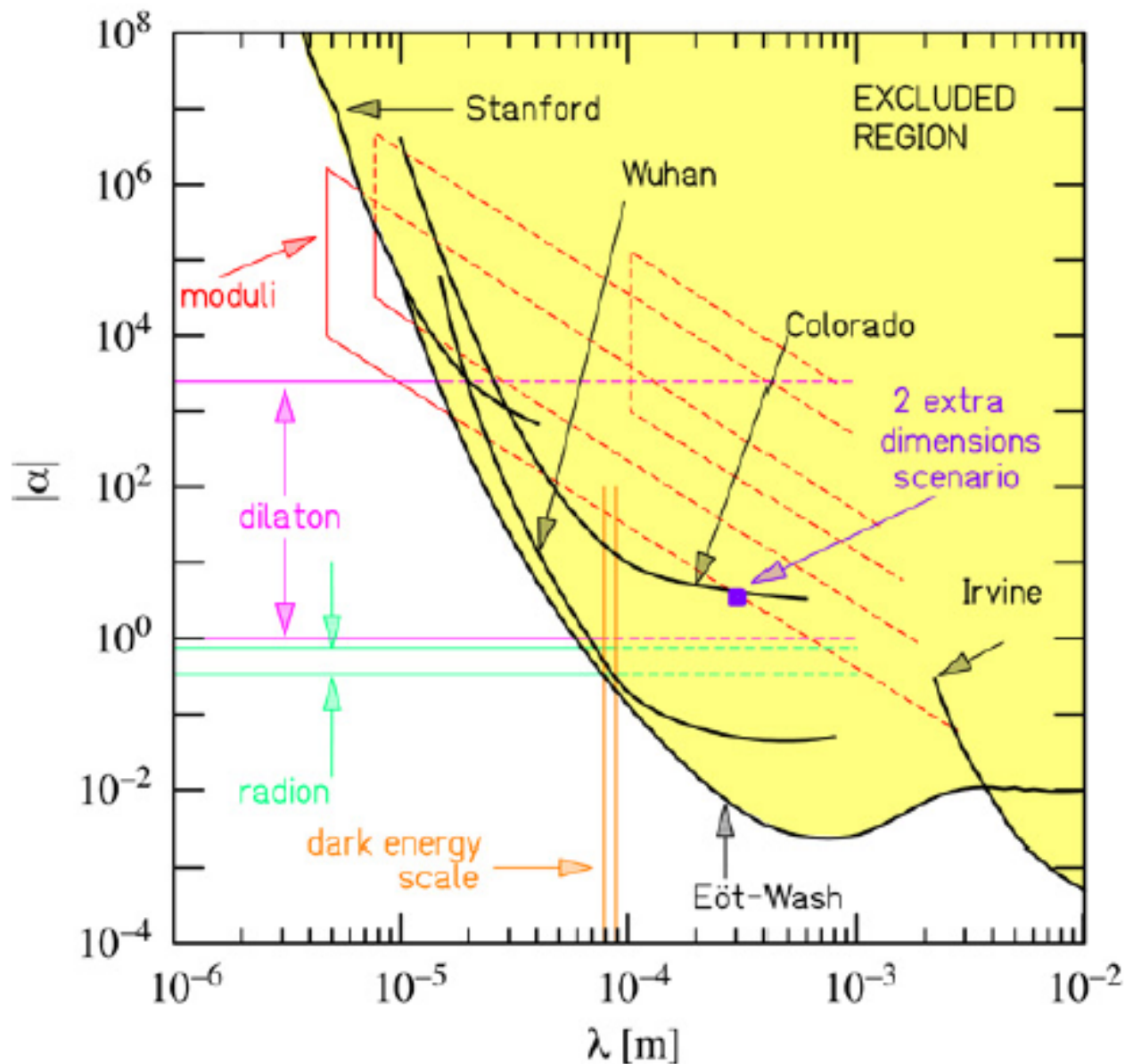
$$\delta m_\phi^2 \simeq g^2 m_\psi^2 < m_\psi^4 / (10m_{pl})^2$$

Require: $\delta m_\phi^2 < H_0^2$ implying: $m_\psi < 10^{-3} eV$

But then the required light DM isn't cold - or go for an axion with a
protected mass or a different coupling between DM and DE

Quintessence tends to lead to existence of Yukawa Fifth Force - very tightly constrained.

$$F(r) = G \frac{m_1 m_2}{r^2} \left[1 + \alpha \left(1 + \frac{r}{\lambda} \right) e^{-r/\lambda} \right]$$



Screening mechanisms - a route to hide the fifth forces

1. Chameleon fields [Khoury and Weltman (2003) ...]

Non-minimal coupling of scalar to matter in order to avoid fifth force type constraints on Quintessence models: the effective mass of the field depends on the local matter density, so it is massive in high density regions and light ($m \sim H$) in low density regions (cosmological scales).

2. K-essence [Armendariz-Picon et al ...]

Scalar fields with non-canonical kinetic terms. Includes models with derivative self-couplings which become important in vicinity of massive sources. The strong coupling boosts the kinetic terms so after canonical normalisation the coupling of fluctuations to matter is weakened -- screening via Vainshtein mechanism

Similar fine tuning to Quintessence -- vital in brane-world modifications of gravity, massive gravity, degeneration models, DBI model, Galileon's,

3. Symmetron fields [Hinterbichler and Khoury 2010 ...]

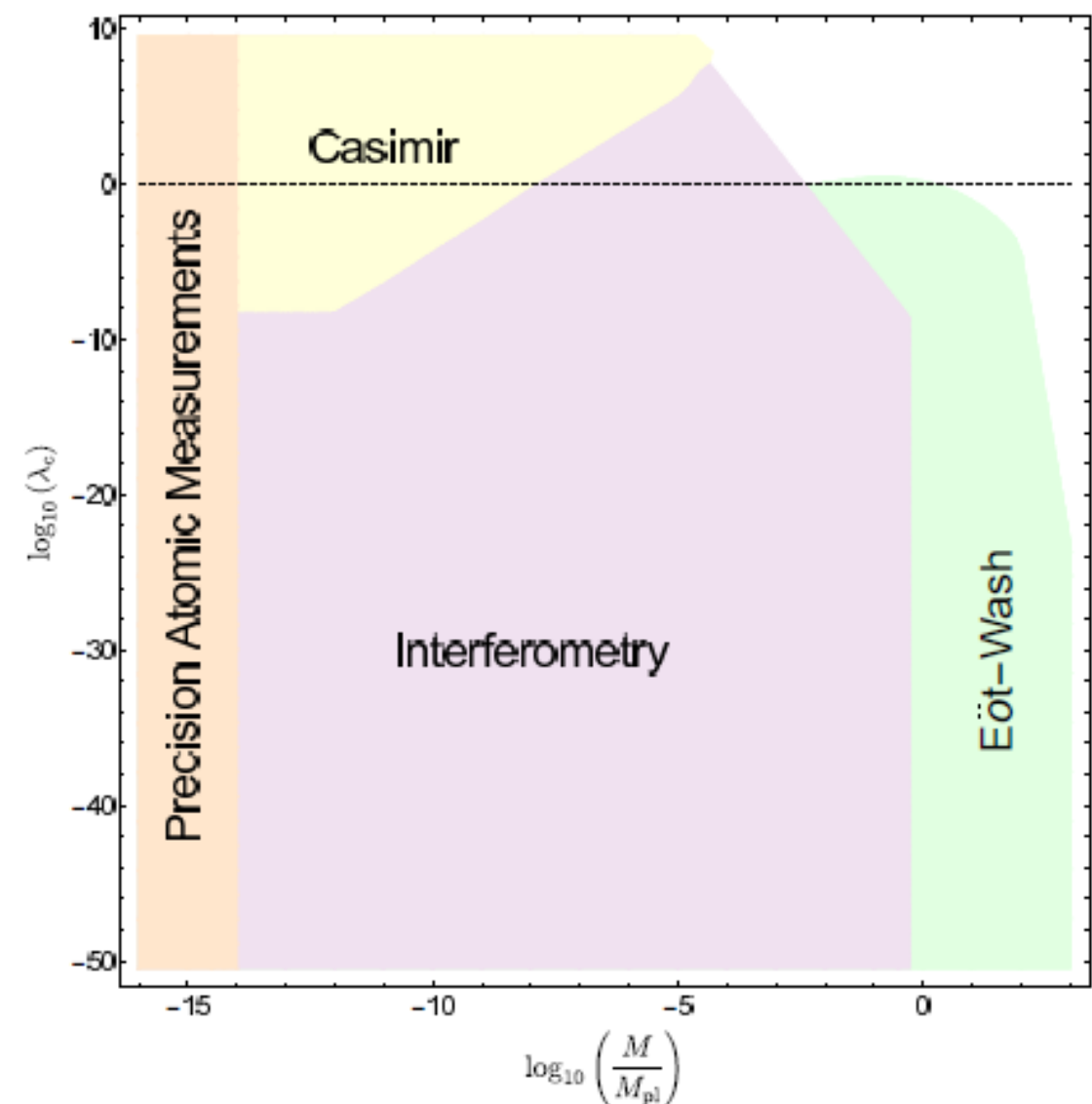
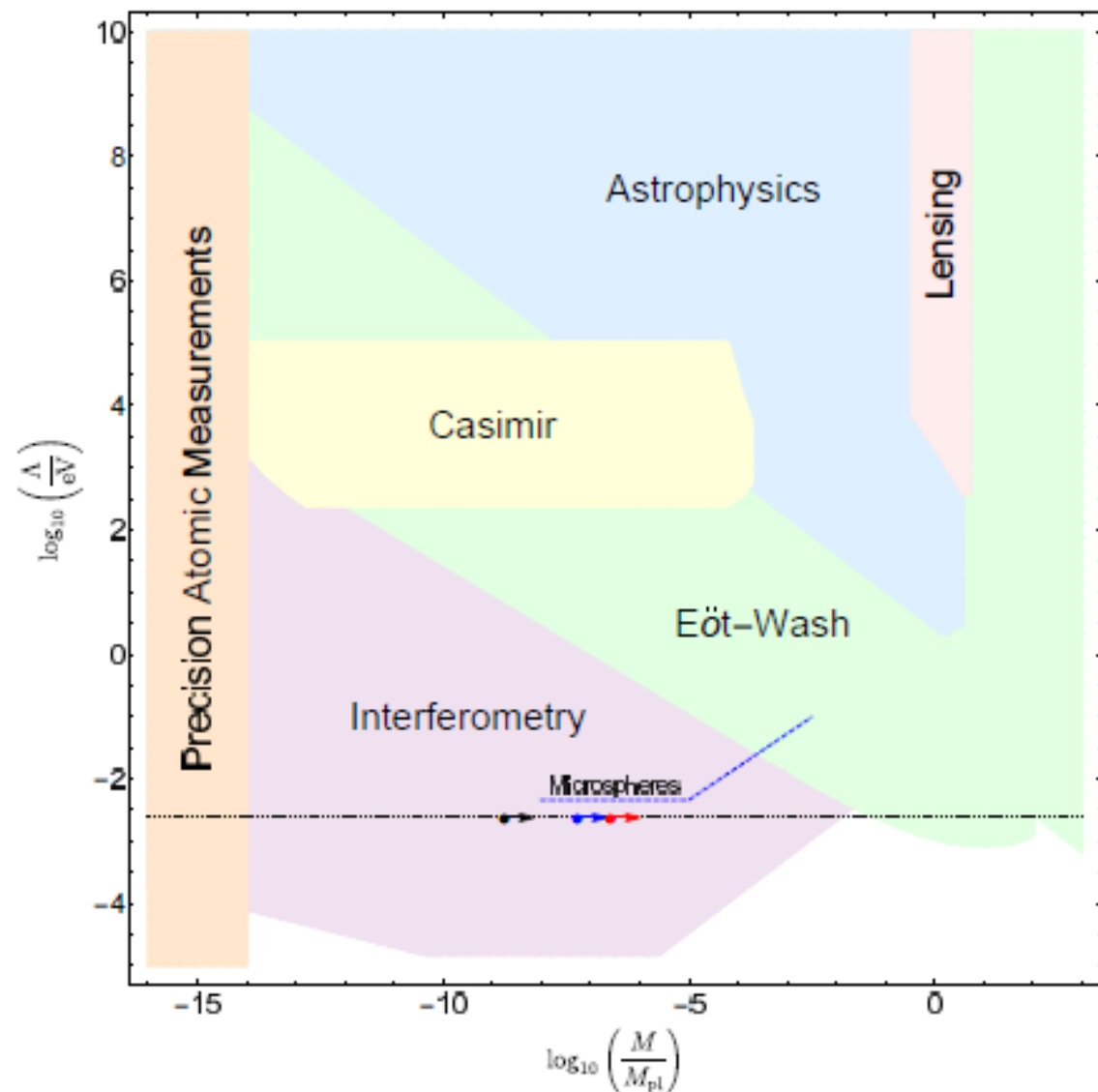
vev of scalar field depends on local mass density: vev large in low density regions and small in high density regions. Also coupling of scalar to matter is prop to vev, so couples with grav strength in low density regions but decoupled and screened in high density regions.

Combined chameleon constraints [Burrage & Sakstein 2017]

$$V_{\text{eff}}(\phi) = V(\phi) + \left(\frac{\phi}{M}\right) \rho$$

$$V(\phi) = \frac{\Lambda^5}{\phi}$$

$$V(\phi) = \frac{\Lambda}{4} \phi^4$$



Modifying Gravity rather than looking for Dark Energy - non trivial

Any theory deviating from GR must do so at late times yet remain consistent with Solar System tests. Potential examples include:

- $f(R)$, $f(G)$ gravity -- coupled to higher curv terms, changes the dynamical eqns for the spacetime metric. Need chameleon mechanism [Starobinski 1980, Carroll et al 2003, Joyce et al 2015...]

- Modified source gravity -- gravity depends on nonlinear function of the energy.
- Gravity based on the existence of extra dimensions -- DGP gravity

We live on a brane in an infinite extra dimension. Gravity is stronger in the bulk, and therefore wants to stick close to the brane -- looks locally four-dimensional.

Tightly constrained -- both from theory [ghosts] and observations

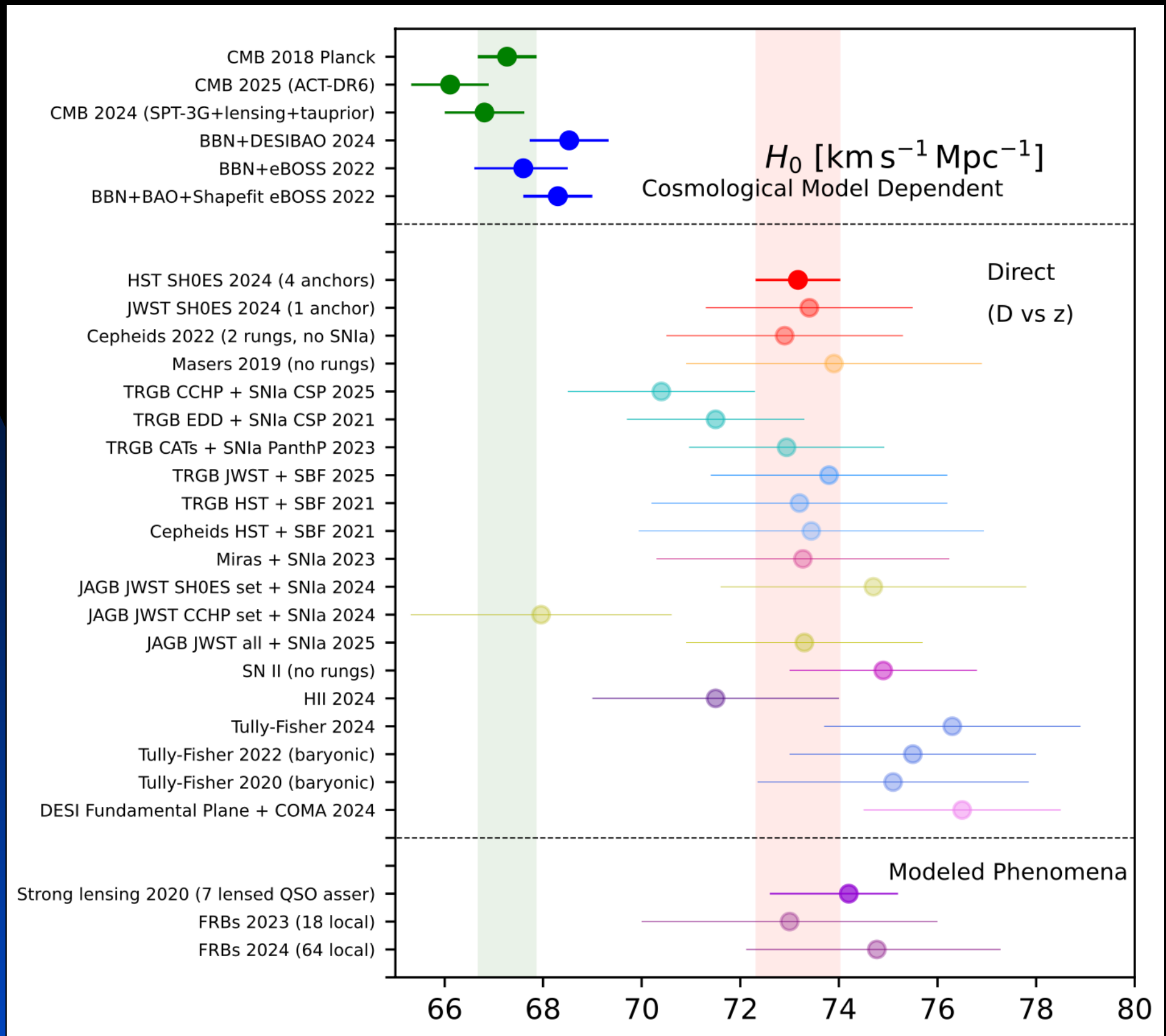
- Scalar-tensor theories including higher order scalar-tensor lagrangians -- examples include Galileon models
- Massive gravity theories dRGT [de Rham et al 2011...]

Return to Hubble tension - local v global - Early Dark Energy

See
Eleanora's
nice talk
yesterday

Lots of
approaches
being taken to
determine H_0

Has it
anything to do
with today's
Dark Energy ?



CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

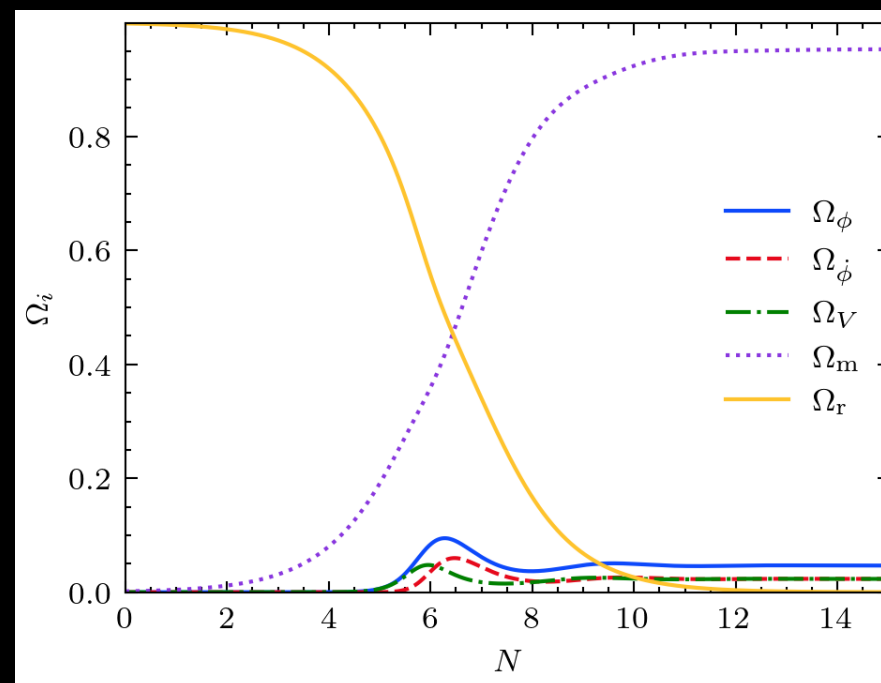
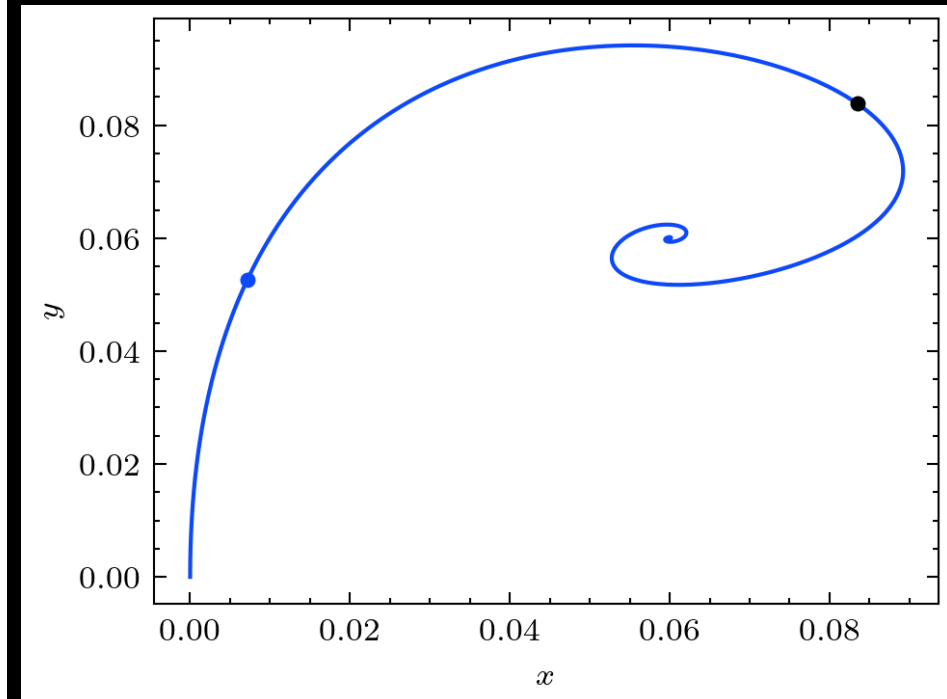
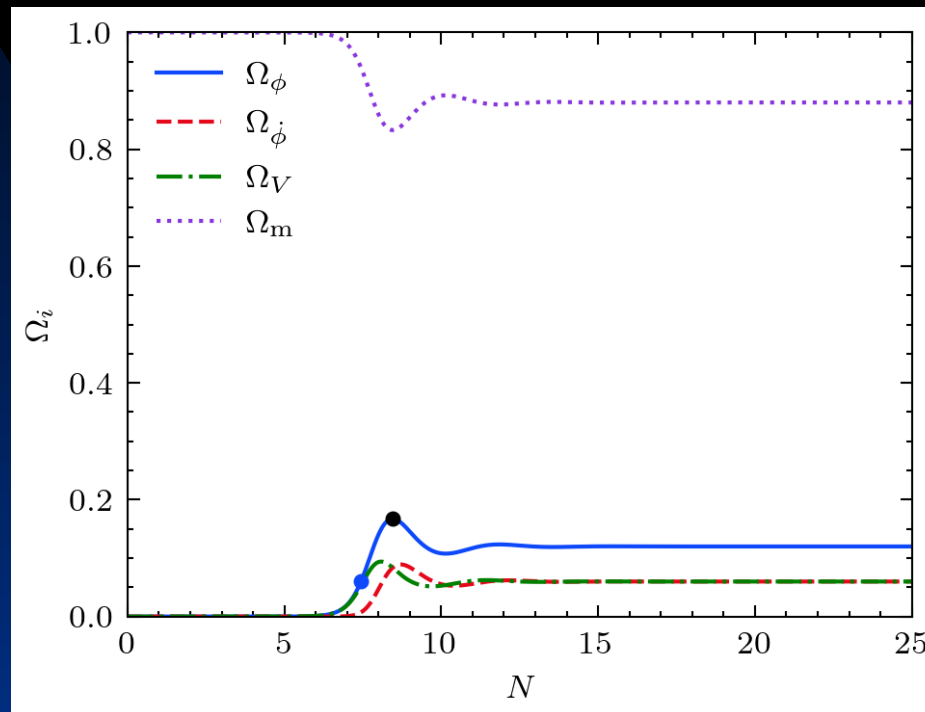
$H_0 = 67.4 \pm 0.5$ km s⁻¹ Mpc⁻¹ (Planck) v $H_0 = 73.2 \pm 1.3$ km s⁻¹ Mpc⁻¹ (SH0ES)

A nice feature of scaling solutions - they tend to generate bumps in their energy density as they approach their attractor solutions

$$H^2 = \frac{\kappa^2}{3} \left(\rho_r + \rho_m + \rho_{cc} + \frac{\dot{\phi}^2}{2} + V(\phi) \right)$$

$$x = \frac{\kappa \dot{\phi}}{\sqrt{6}H}$$

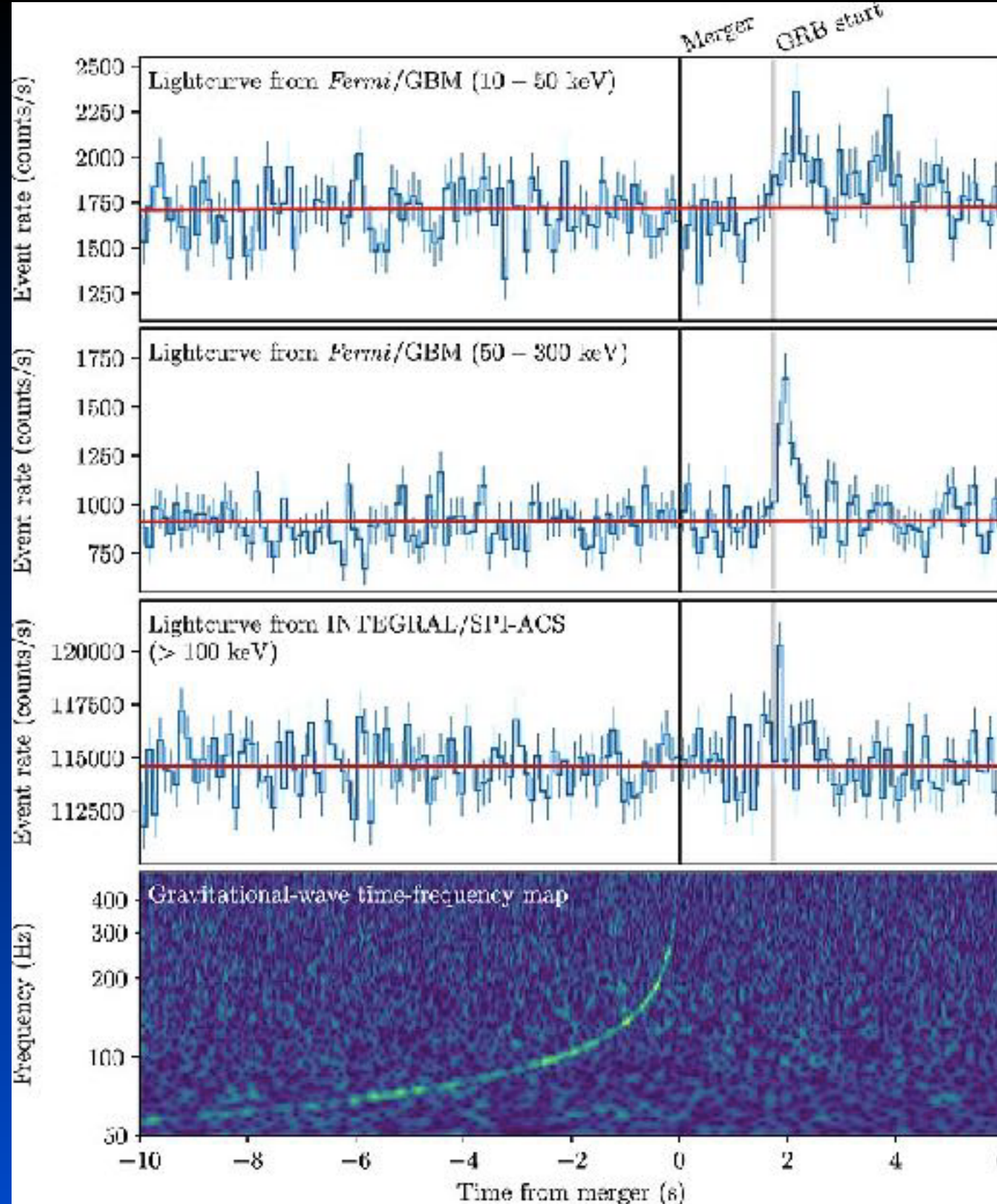
$$y = \frac{\kappa \sqrt{V}}{\sqrt{3}H} : \Omega_\phi = \frac{\kappa^2 \rho_\phi}{3H^2} = x^2 + y^2 : V(\phi) = V_0 \exp(-\kappa \lambda \phi)$$



Quintessence peak around matter-radiation equality

[EJC, A. Moss, S. Sevilano Muñoz, J.D. White 2023]

The impact of the simultaneous detection of GWs and GRBs on Modified Gravity models !



GW 170817 and GRB 170817A

speed of GW waves

$$c_T^2 = 1 + \alpha_T$$

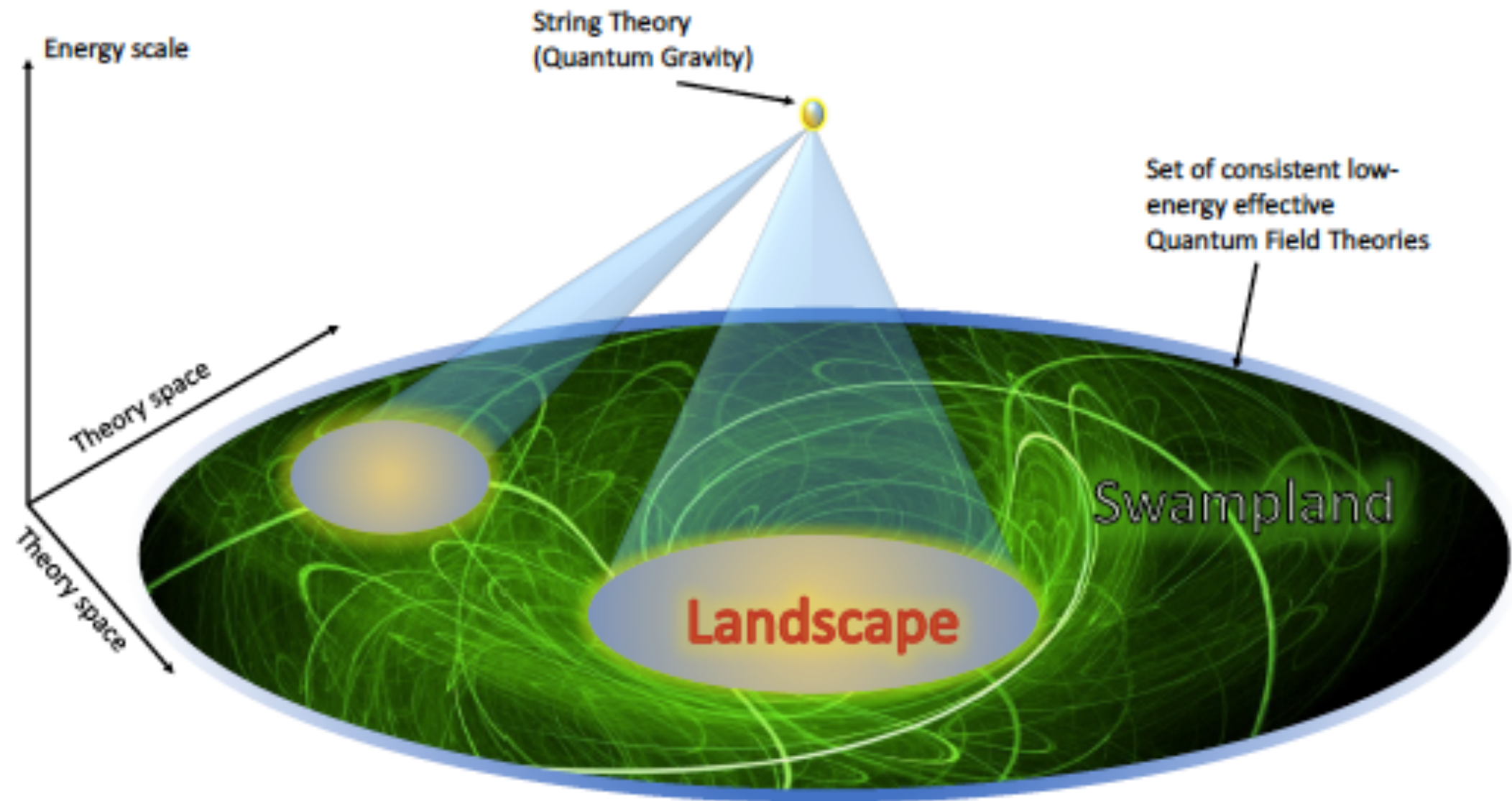
$$\Delta t \simeq 1.7s$$

$$\rightarrow |\alpha_T| \leq 10^{-15}$$

Ruled out many Horndeski models which naturally had differing speeds of GW and photons. But not all of them !

Creminelli & Vernizzi (2017), Baker et al (2017), Sakstein & Jain (2017), Ezquiaga & Zumalacárregui (2017)

Dark Energy and the String Swampland [Agrawal et. al. 2018]



String Swampland [Vafa 2005]

[Credit: E. Palti 2018]

The class of theories that appear perfectly acceptable as low energy QFT but can not be in the Landscape of string theories at high energies.

Dark Energy and the String Swampland [Agrawal et. al. 2018]

They make use of 2 main criteria:

1. The Swampland Distance Conjecture. Range traversed by a scalar field in field space is bounded by

$$\frac{|\Delta\phi|}{M_{\text{Pl}}} < \Delta < O(1)$$

If go large distance D in field space, a tower of light modes appear with mass scale

$$m \sim M_{\text{Pl}} \exp(-\alpha D), \quad \alpha \sim O(1)$$

which invalidates the effective action being used.

2. There is a lower bound on $\frac{|\nabla_\phi V(\phi)|}{V(\phi)} > c \sim O(1)$, when $V > 0$

motivated by difficulty in obtaining reliable deS vacua, and string constructions of scalar potentials.

The constants are not well constrained yet. But if constraint 2 is accepted (which it isn't yet by many), it would clearly rule out Λ CDM as the source of the current acceleration.

Quintessence type models work well though with model independent constraints of $c < 0.6$, $c < 3.5$ Δ .

$$V(\phi) = V_1 e^{\lambda_1 \phi / M_{\text{Pl}}} + V_2 e^{\lambda_2 \phi / M_{\text{Pl}}} \quad [\text{Barreiro, EC, Nunes 2000}]$$

$$\lambda_1 \gg \sqrt{3}, \quad \lambda_2 = c = 0.6$$

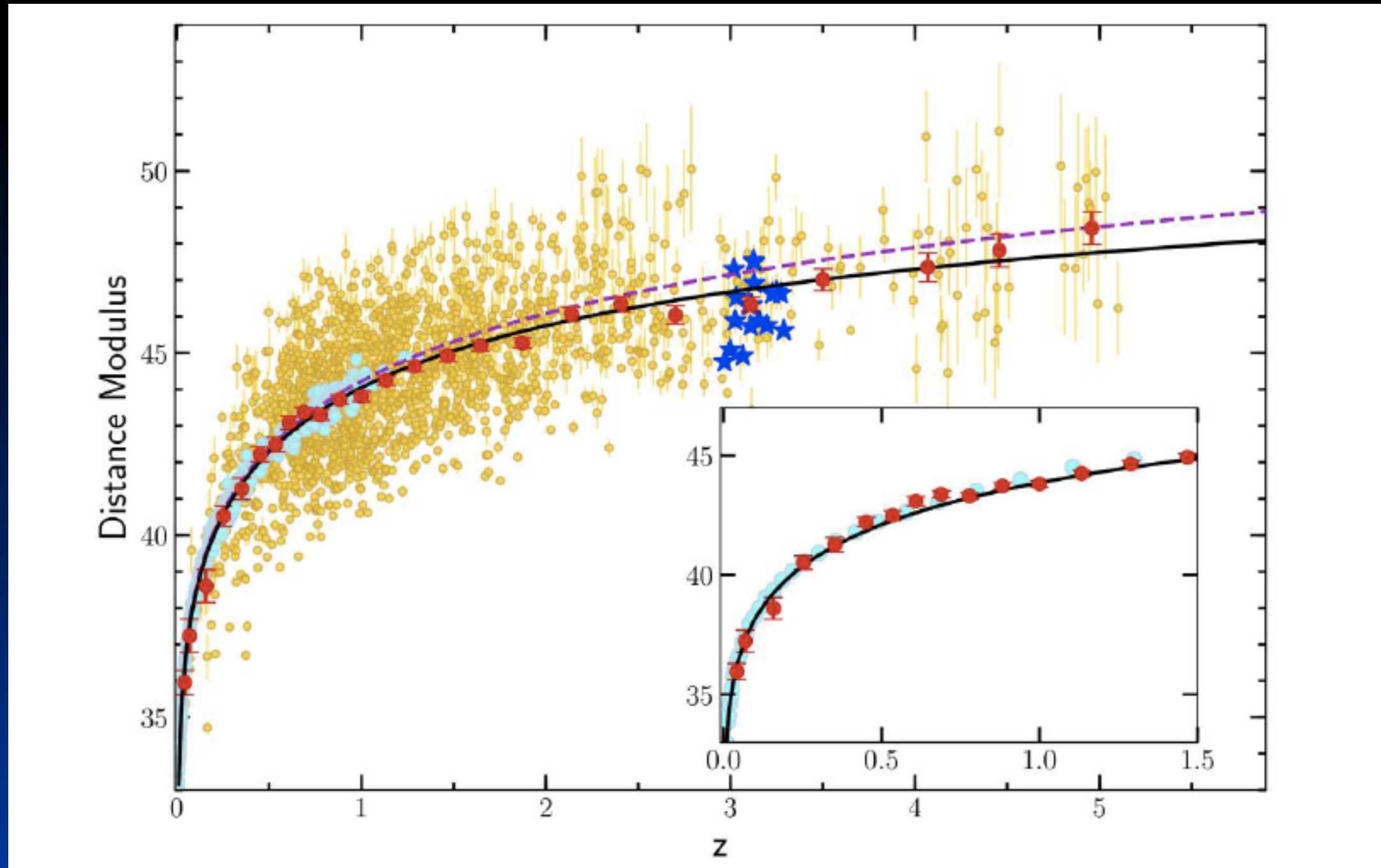
For a range of initial conditions, evolves so that it initially scales with the background matter density and then at late times comes to dominate whilst satisfying criteria 1 and 2. In fact they find:

$$\Delta \geq \frac{1}{3} c \Omega_\phi^0$$

Early days but might lead to genuine new constraints on the nature of dark energy - still somewhat unclear how robust the bound is.

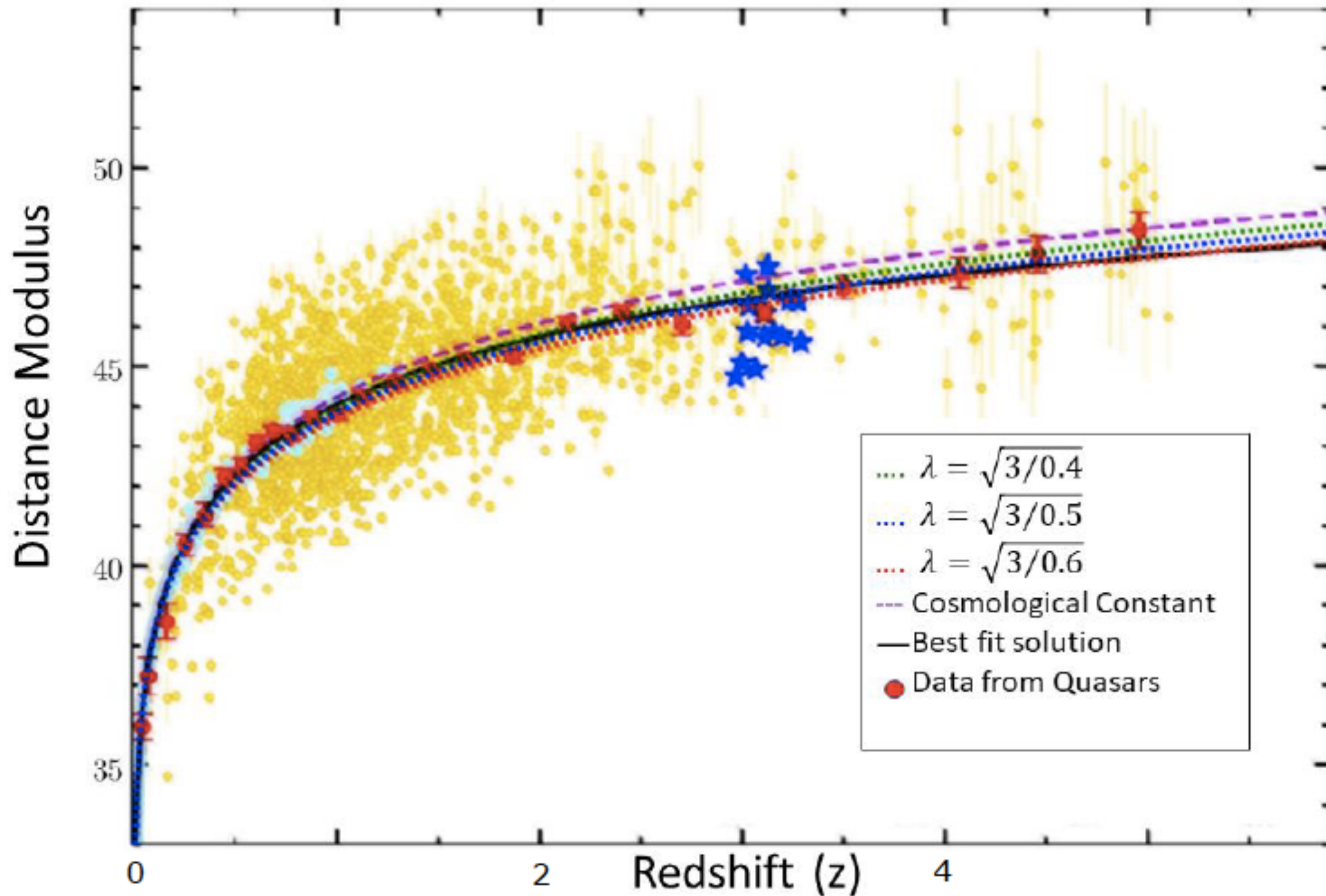
For the most complete analysis of quintessence in the swampland motivated from moduli evolution in string theory see Cicoli et al 2021

Quasars as Standard Candles ? [Risaliti & Lusso. Nat. Astron. 2019]



Developed a technique they argue allows quasars to be treated as std candles. Here of order 1600 quasars (yellow, blue) out to $z \sim 5$. Inset is comparison to SN (cyan) showing good agreement to $z \sim 1.4$ with dashed magenta line is Λ CDM with $\Omega_M \sim 0.31 \pm 0.05$ - extrapolated out to $z \sim 5$.

Evolving Dark Energy ?



Ex: $V(\phi) = V_1 \exp(\sqrt{2}\phi/2) + V_2 \exp(\lambda\phi), \quad \sqrt{5} < \lambda < \sqrt{7.5}$

Early days - key is are quasars standard candles !

Conclusions

1. A natural explanation of the cosmological constant remains challenging. Quintessence type approaches to the nature of dark energy and the current acceleration of the Universe provides alternative to Landscape.
2. DESI has provided potential evidence for DDE, but wait - it doesn't look to be quintessence ! So what is it if it survives the test of time?
3. Need to screen DE fields which leads to models such as axions, chameleons, non-canonical kinetic terms etc.. -- many of these have their own issues.
4. Emergence of GW and multi-messenger astronomy opens up a new direction to constrain and rule out modified gravity models, but we need to be careful how we do it. [see Baker et al Rev Mod Phys 2021]
5. Is the Hubble tension telling us something about dark energy or MG? Time will tell - maybe LIGO will tell us over the coming years !
6. Is the Swampland telling us something about dark energy?
7. How can we go locally beyond SN1a ? Quasars ?