Dark energy and early dark energy - what could they be?

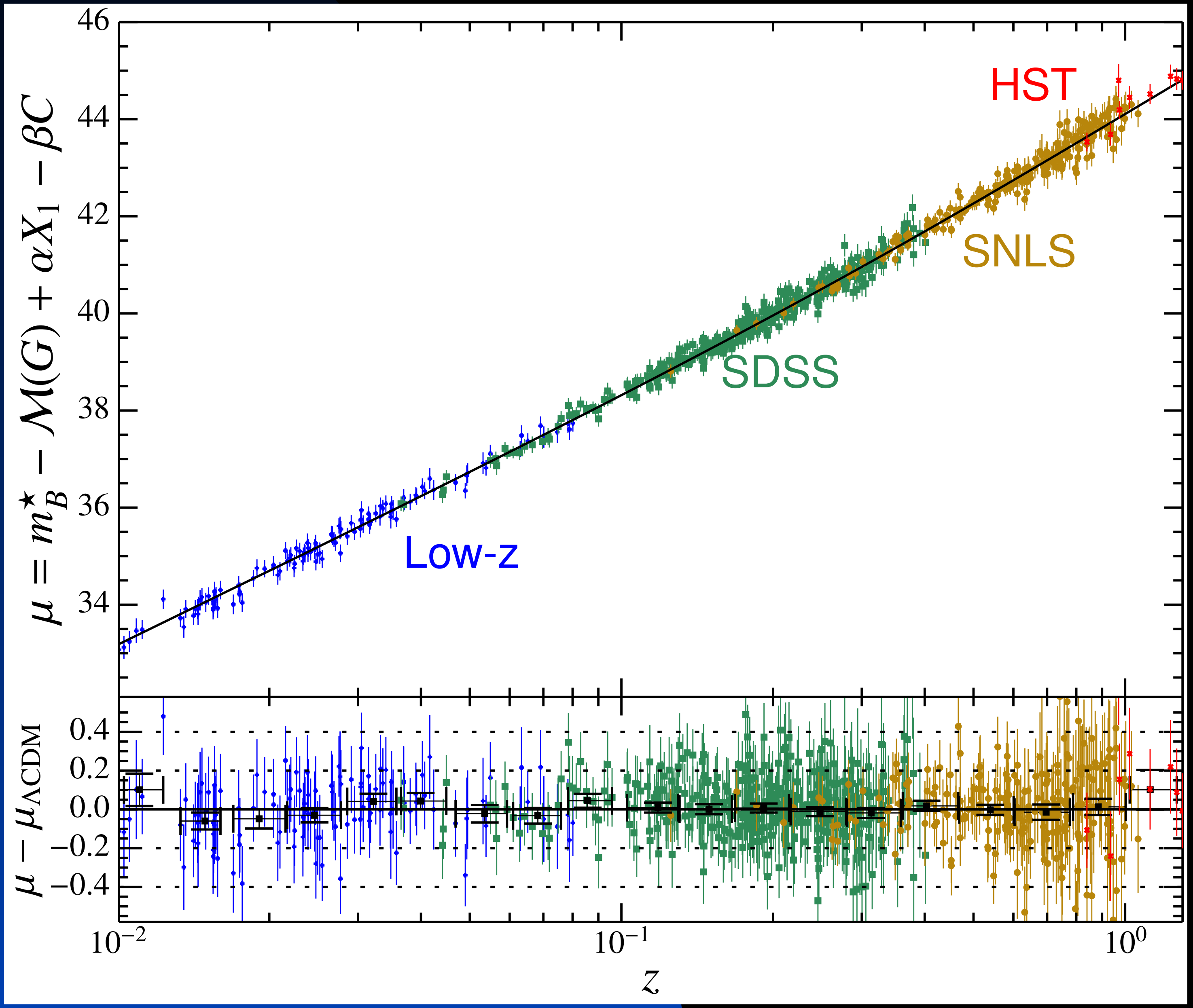
Ed Copeland -- Nottingham University

1. Approaches to Dark Energy and Modified Gravity.
2. Testing screening mechanisms in the laboratory.
3. Screening fields and the Radial Acceleration Relation
4. Searching for fifth forces in colliders.
5. Hubble tension and approaches to Early Dark Energy
6. Dark Energy and the String Swampland
7. Recent large z results if quasars can be standard candles

DΛrk Energy — Frascati — Sept 15th 2023

The Big Bang – (1sec → today)

The cosmological principle -- isotropy and homogeneity on large scales



- **The expansion of the Universe $v=H_0d$**

H_0=73.04±1.04 km s^{-1} Mpc^{-1}

(Riess et al, 2022)

H_0=67.4±0.5 km s^{-1} Mpc^{-1}

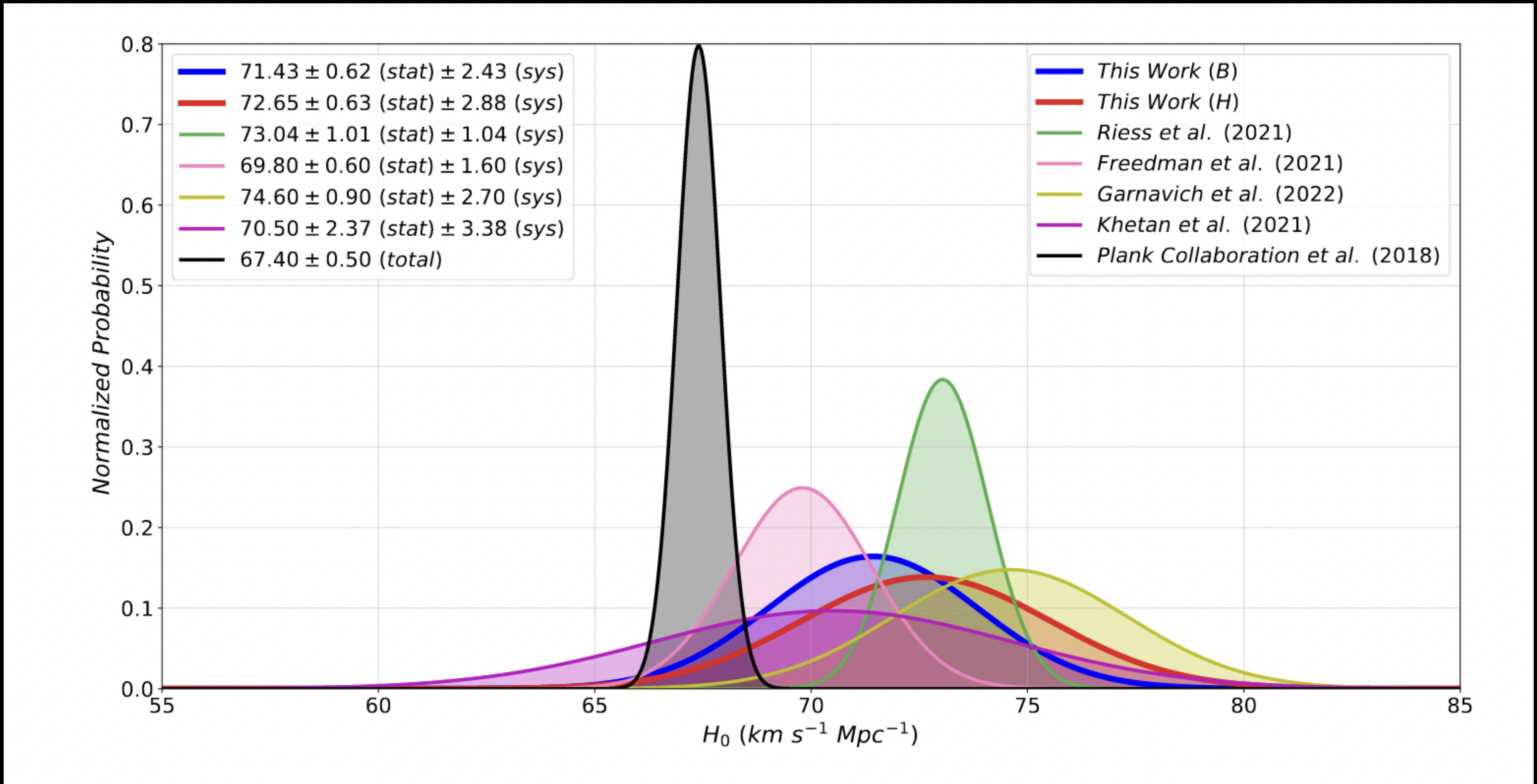
(Planck 2018)

Is there a local v global tension ?

Betoule et al 2014

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

JWST may have something to say on the Hubble tension - higher resolution should allow it to address crowding of cepheids



W.L Freedman and B.F. Madore - arXiv:2309.05618

`` the current outstanding question … revolves around the *uncertainty in the uncertainty..*" local measurements need to reach 1% before true comparison can be made with cmb

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

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

(Expansion rate) -- H_0=67.66 ± 0.42 km/s/Mpc

(radiation) -- Ω_r = (8.5 ± 0.3) x 10^{-5} - (WMAP)

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

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

(curvature) -- Ω_k =0.0007 ± 0.0019

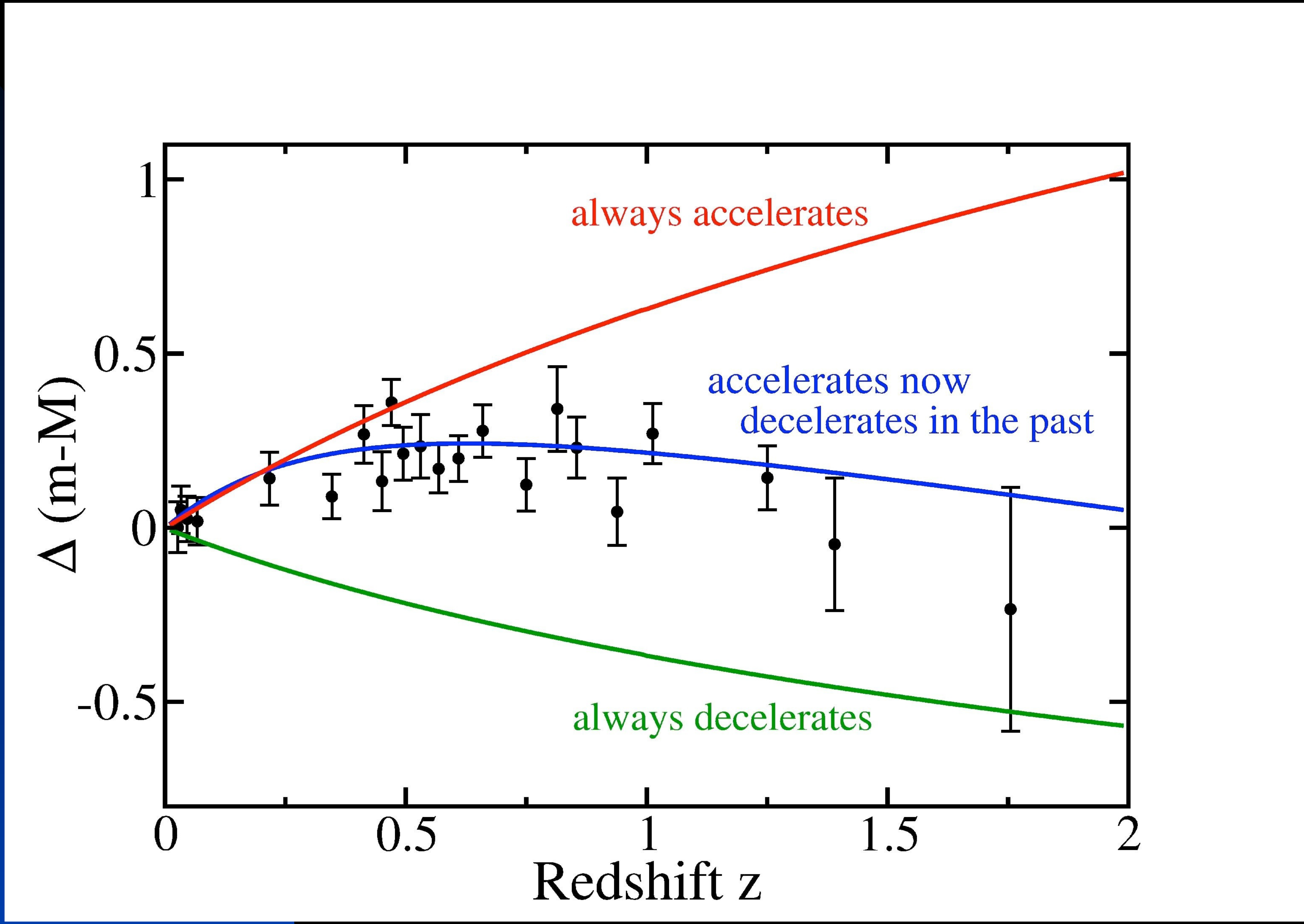
(dark energy) -- Ω_{de} = 0.6889 ± 0.0056 -- Implying univ accelerating today

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

If allow variation of form : w(z) = w_0+ w' z/(1+z) then
w_0=-0.961 ±0.077 and w'=-0.28 ± 0.31 (68% CL) — (WMAP)

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

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 will be able to probe in a few months. Will it see evidence for either $w \neq -1$ or $w(z)$ - that would be huge.

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 ...

One approach - accept there may be a large Λ —Self tuning

with Charmousis, Padilla and Saffin: PRL 108 (2012) 051101; PRD 85 (2012) 104040

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 :

$$\begin{aligned}
\mathcal{L}_{john} &= \sqrt{-g}V_{john}(\phi)G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi \\
\mathcal{L}_{paul} &= \sqrt{-g}V_{paul}(\phi)P^{\mu\nu\alpha\beta}\nabla_\mu\phi\nabla_\alpha\phi\nabla_\nu\nabla_\beta\phi \\
\mathcal{L}_{george} &= \sqrt{-g}V_{george}(\phi)R \\
\mathcal{L}_{ringo} &= \sqrt{-g}V_{ringo}(\phi)\hat{G}
\end{aligned}$$

In other words it can be seen to reside in terms of the four arbitrary potential functions of ϕ coupled to the curvature terms.

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

fab four cosmology

TABLE I: Examples of interesting cosmological behaviour for various fixed points with $\sigma = 0$.

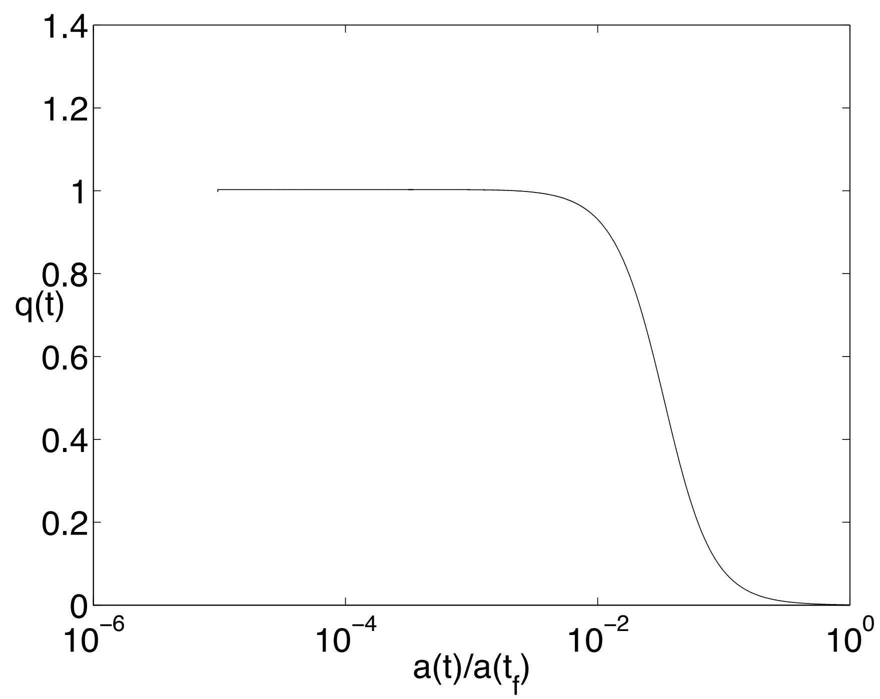
Case	cosmological behaviour	$V_j(\phi)$	$V_p(\phi)$	$V_g(\phi)$	$V_r(\phi)$
Stiff fluid	$H^2 \propto 1/a^6$	$c_1\phi^{\frac{4}{\alpha}-2}$	$c_2\phi^{\frac{6}{\alpha}-3}$	0	0
Radiation	$H^2 \propto 1/a^4$	$c_1\phi^{\frac{4}{\alpha}-2}$	0	$c_2\phi^{\frac{2}{\alpha}}$	$-\frac{\alpha^2}{8}c_1\phi^{\frac{4}{\alpha}}$
Curvature	$H^2 \propto 1/a^2$	0	0	0	$c_1\phi^{\frac{4}{\alpha}}$
Arbitrary	$H^2 \propto a^{2h}, \quad h \neq 0$	$c_1(1+h)\phi^{\frac{4}{\alpha}-2}$	0	0	$-\frac{\alpha^2}{16}h(3+h)c_1\phi^{\frac{4}{\alpha}}$

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

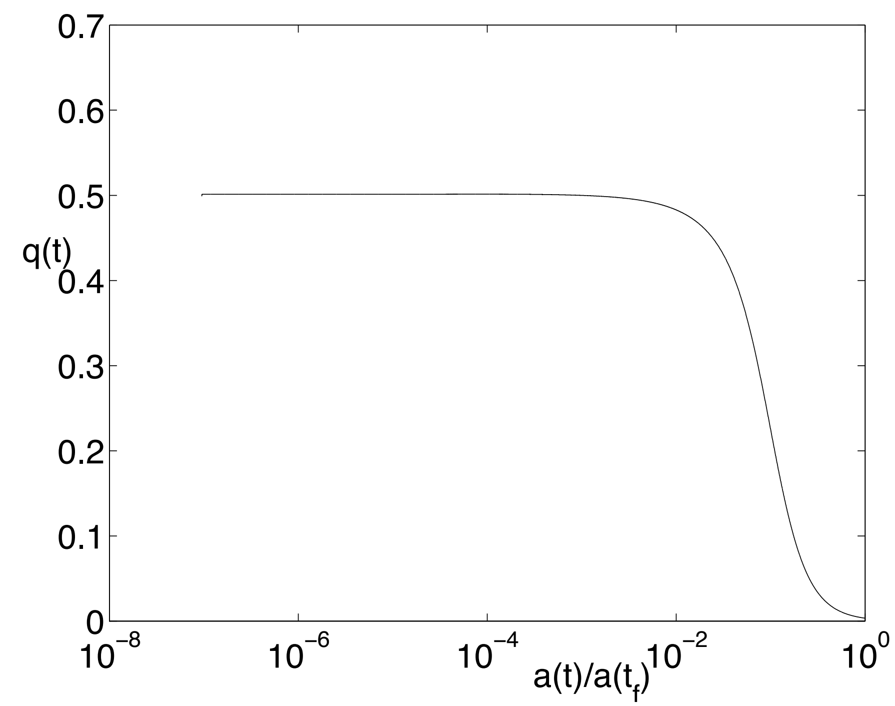
$$a \sim t^p \sim t^{-1/h}$$

$$q = -\frac{p(p-1)}{p^2} = -(1+h)$$

"radiation"



"matter"



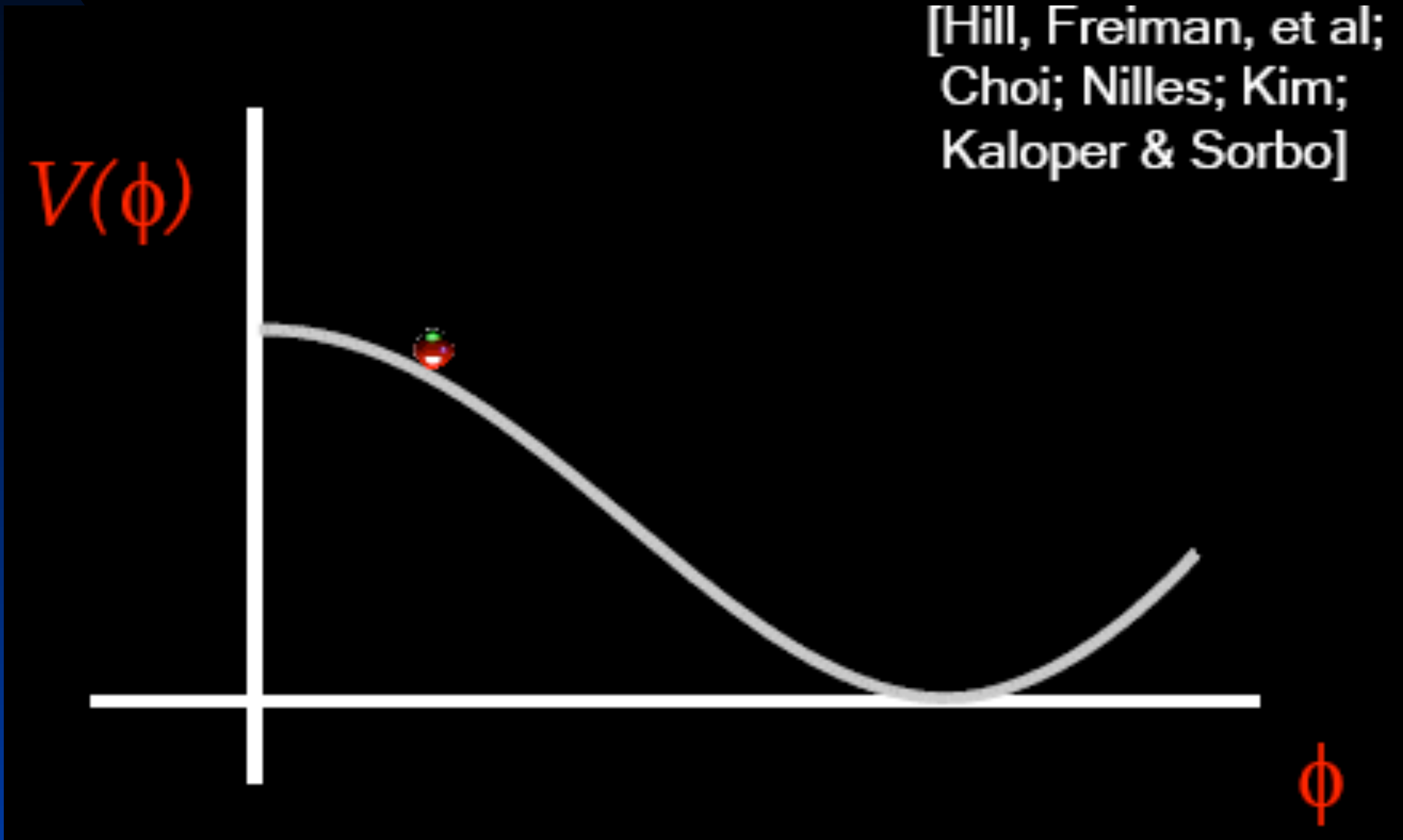
See also:

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

Particle physics inspired models of dark energy ?

Pseudo-Goldstone Bosons -- approx sym ϕ --> ϕ + const.

Leads to naturally small masses, naturally small couplings



Barbieri et al

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

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

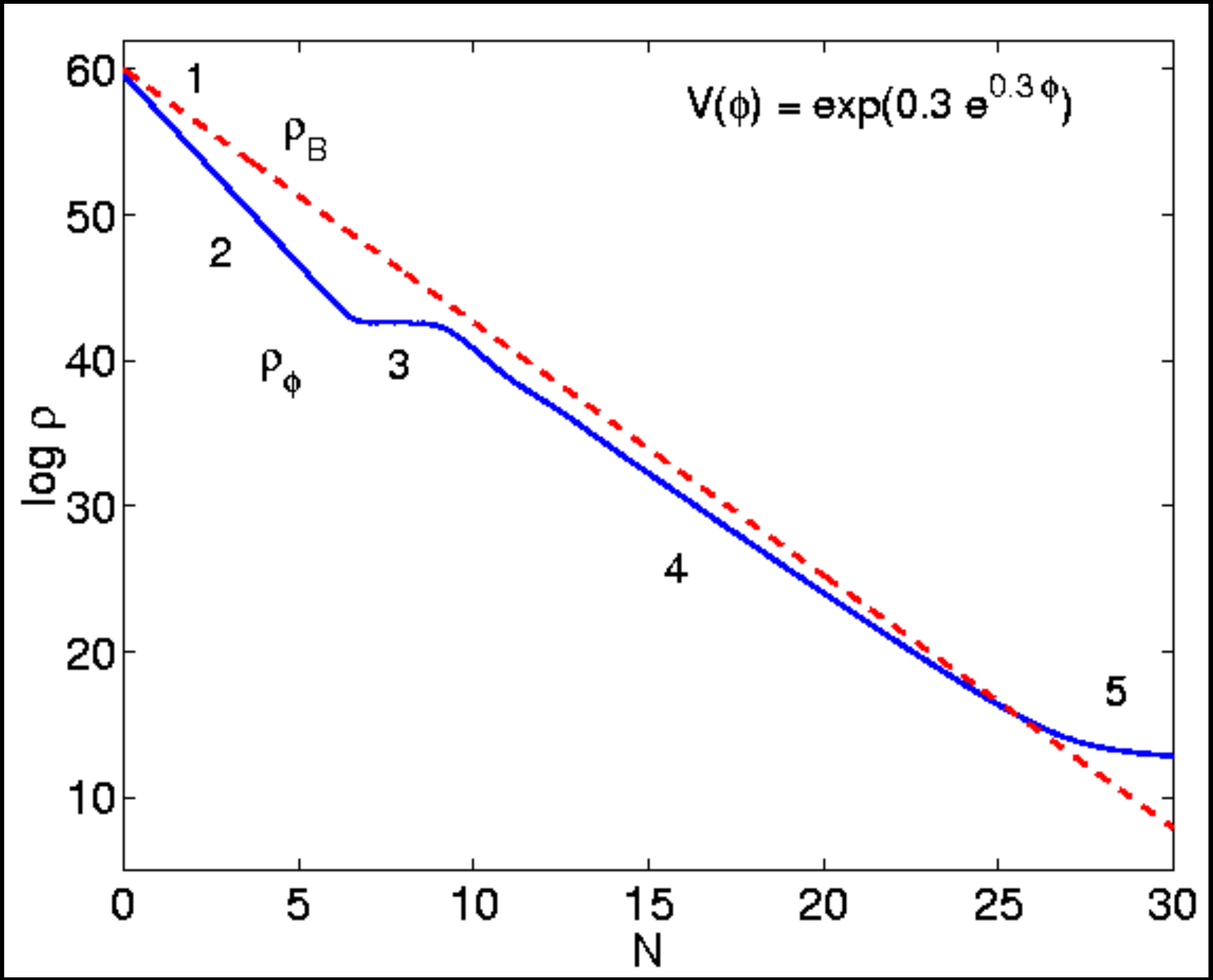
Axions could be useful for strong CP problem, dark matter and dark energy — ex. Quintessential Axion.

Dynamical Dark Energy

Wetterich 1987,
Caldwell et al 1998

Slowly rolling scalar fields Quintessence

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

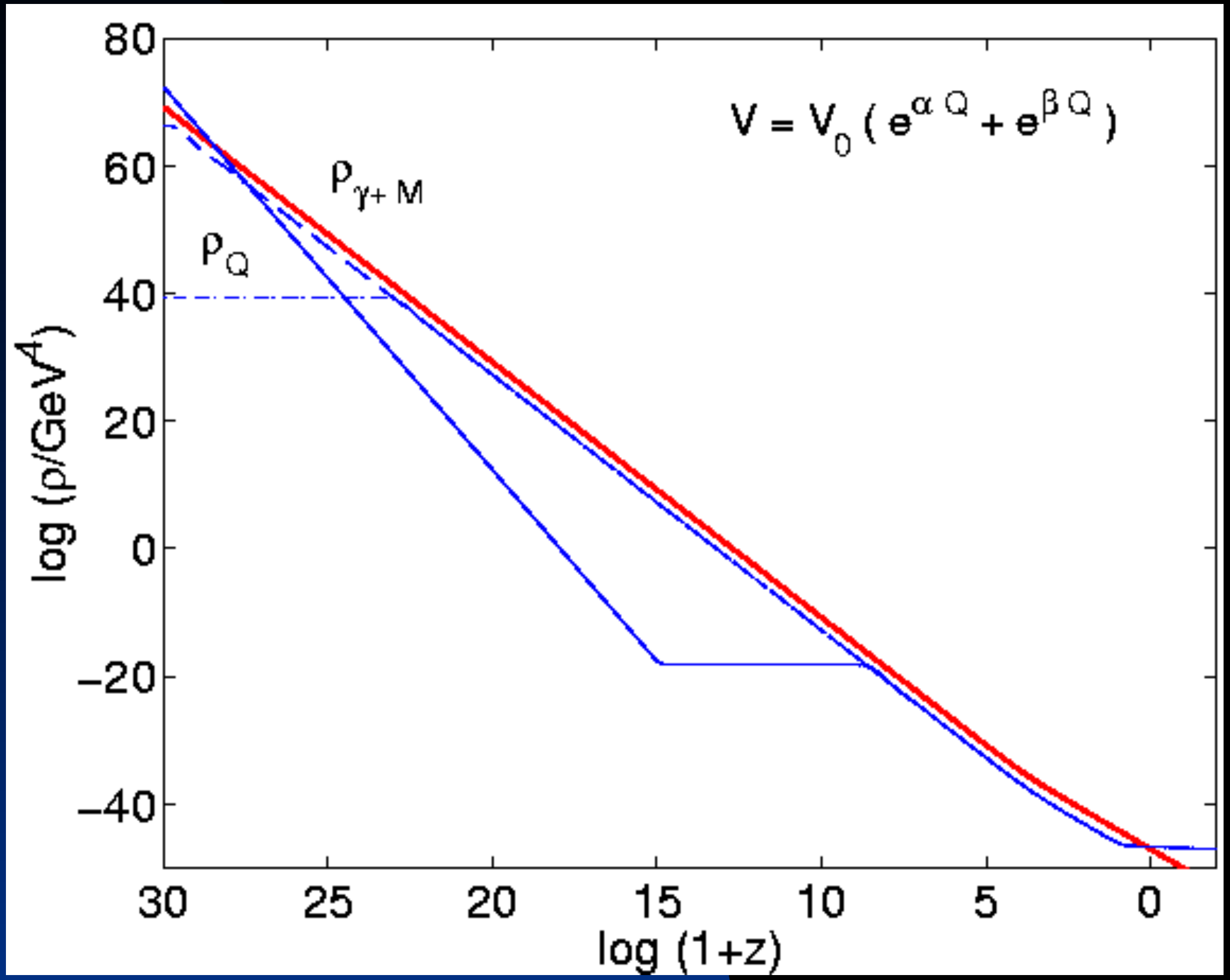


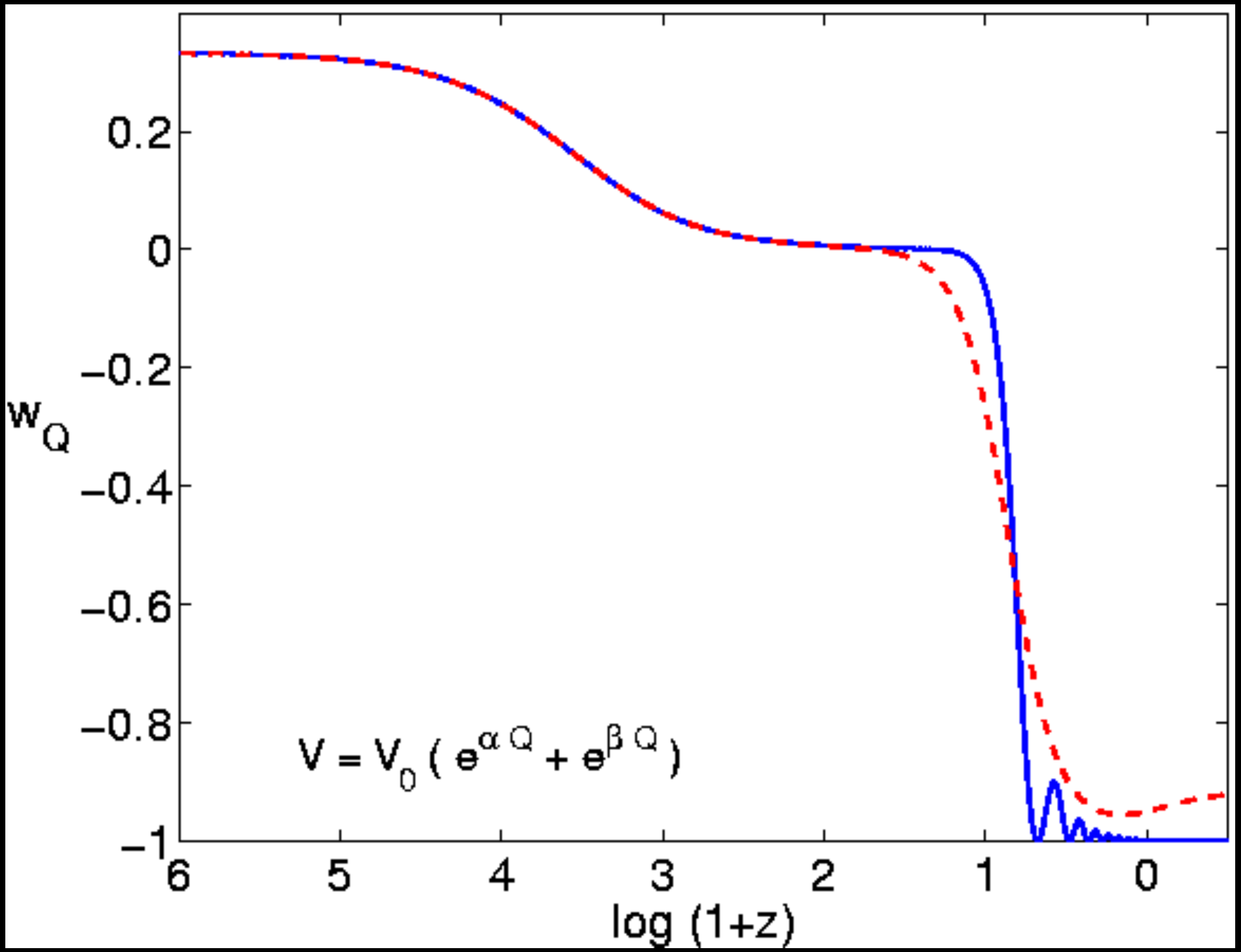
Nunes

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

Generic issue Fifth force - require screening mechanism!

The problem of coupling DE and DM directly with scalars

Generate loop corrections to the DE mass.

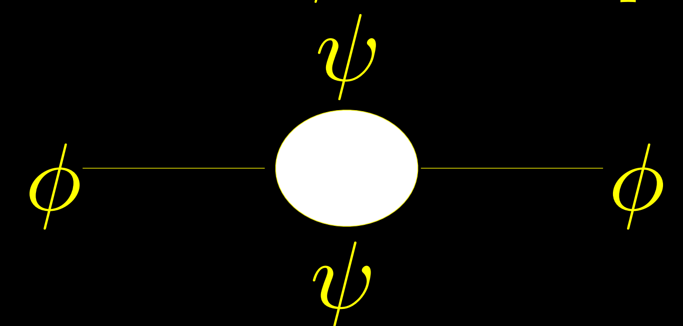
Consider Yukawa type coupling between DE scalar and DM fermion $g\phi\bar{\psi}\psi$

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

Loop correction to DE mass from DM



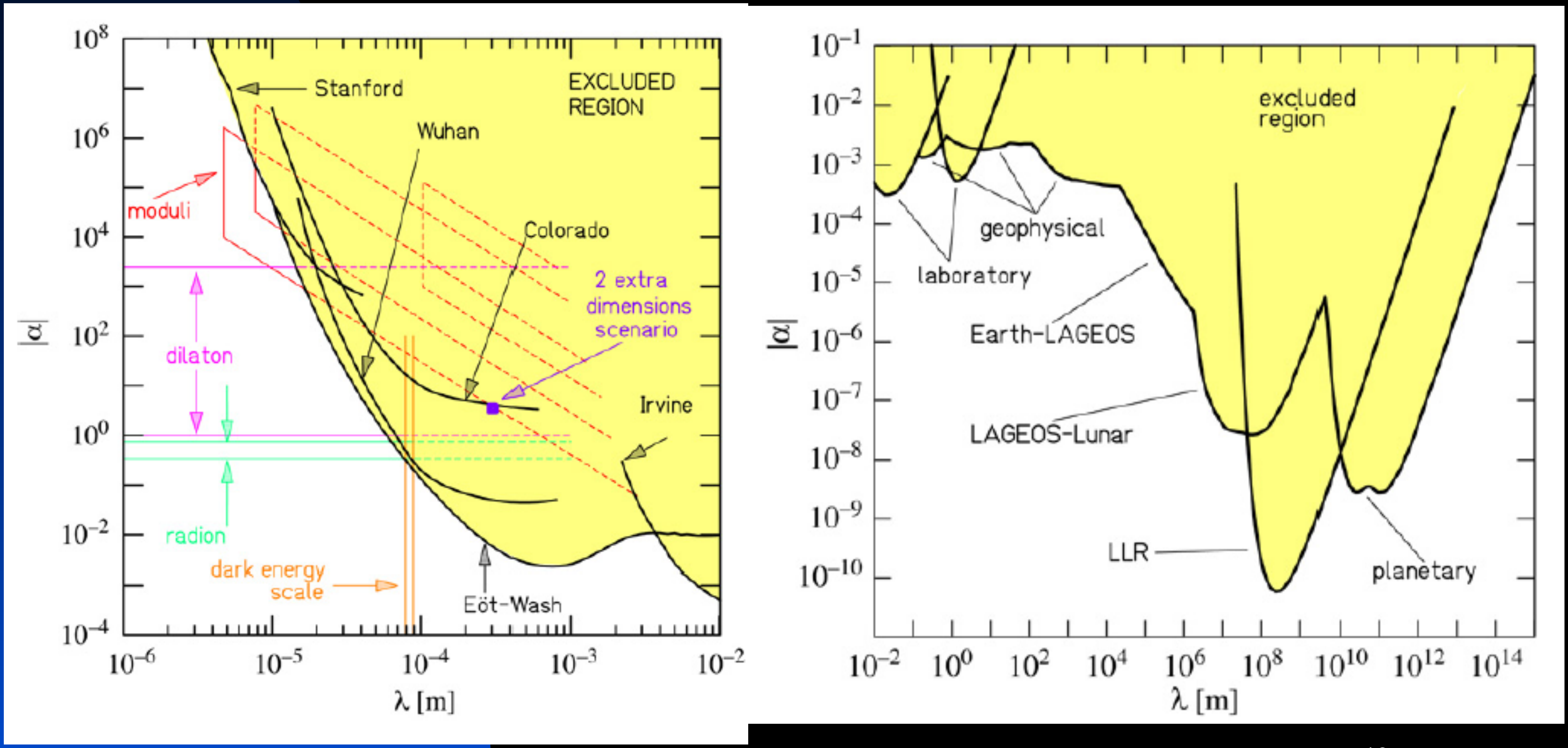
$$\delta m_\phi^2 \simeq g^2 m_\psi^2 < m_\psi^4/(10 m_{\rm pl})^2$$

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.

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



Adelberger 2009.

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~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, degravitation models, DBI model, Galileon's, ...

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

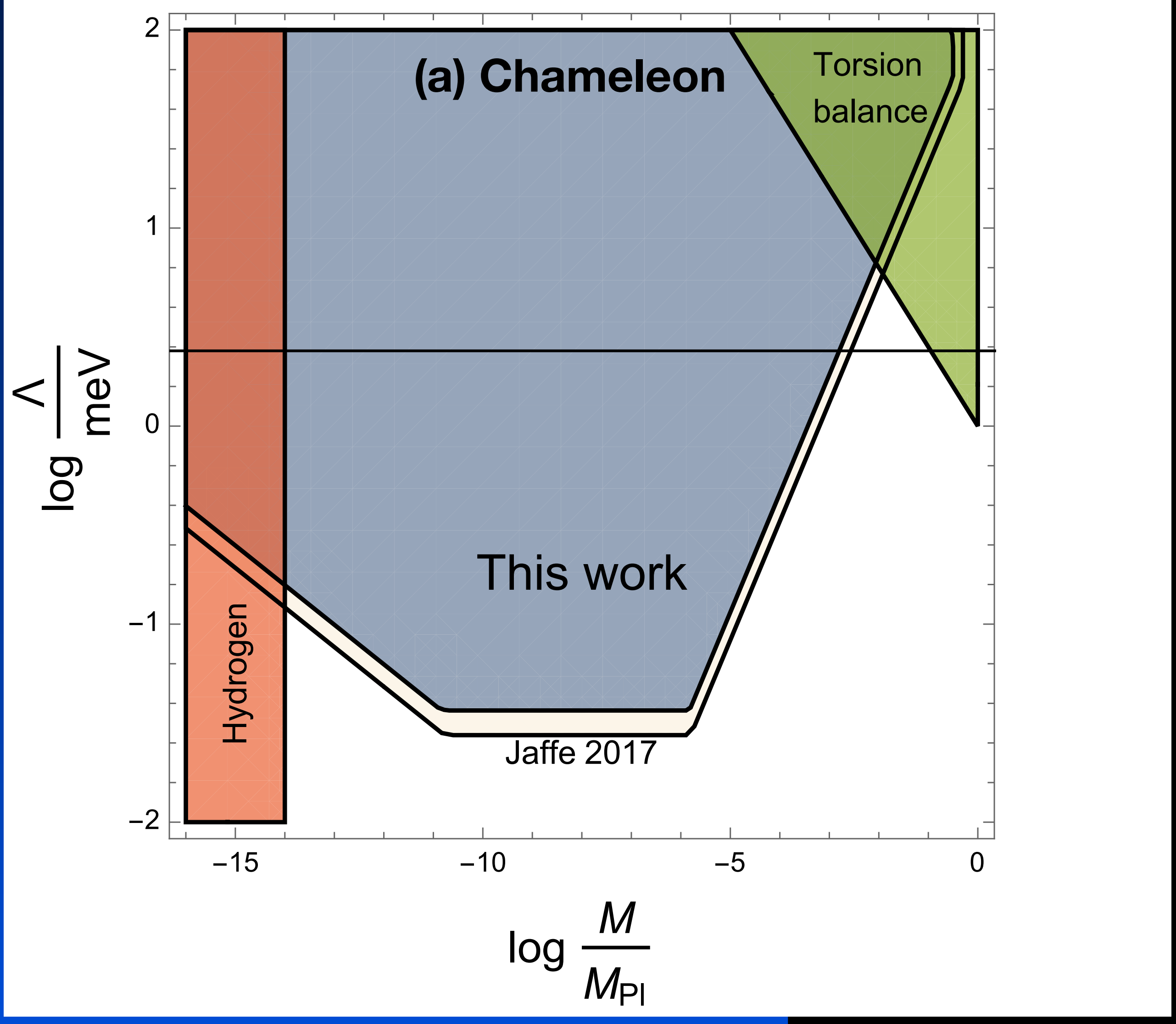
vev of scalar field depends on local mass density: vev large in low density regions and small in high density regions. Also coupling of scalar to matter is prop to vev, so couples with grav strength in low density regions but decoupled and screened in high density regions.

Dark Energy Direct Detection Experiment [Burrage, EC, Hinds 2015,Hamilton et al 2015]

We normally associate DE with cosmological scales but here we use the lab !

Atom Interferometry - testing Chameleons Idea: Individual atoms in a high vacuum chamber are too small to screen the chameleon field and so are very sensitive to it - can detect it with high sensitivity. Can use atom interferometry to measure the chameleon force - or more likely constrain the parameters !

$$\nabla^2\phi = -\frac{\Lambda^2}{\phi^2} + \frac{\rho}{M}$$



$$F_r = \frac{G M_A M_B}{r^2}\left[1 + 2\lambda_A\lambda_B\left(\frac{M_P}{M}\right)^2\right]$$

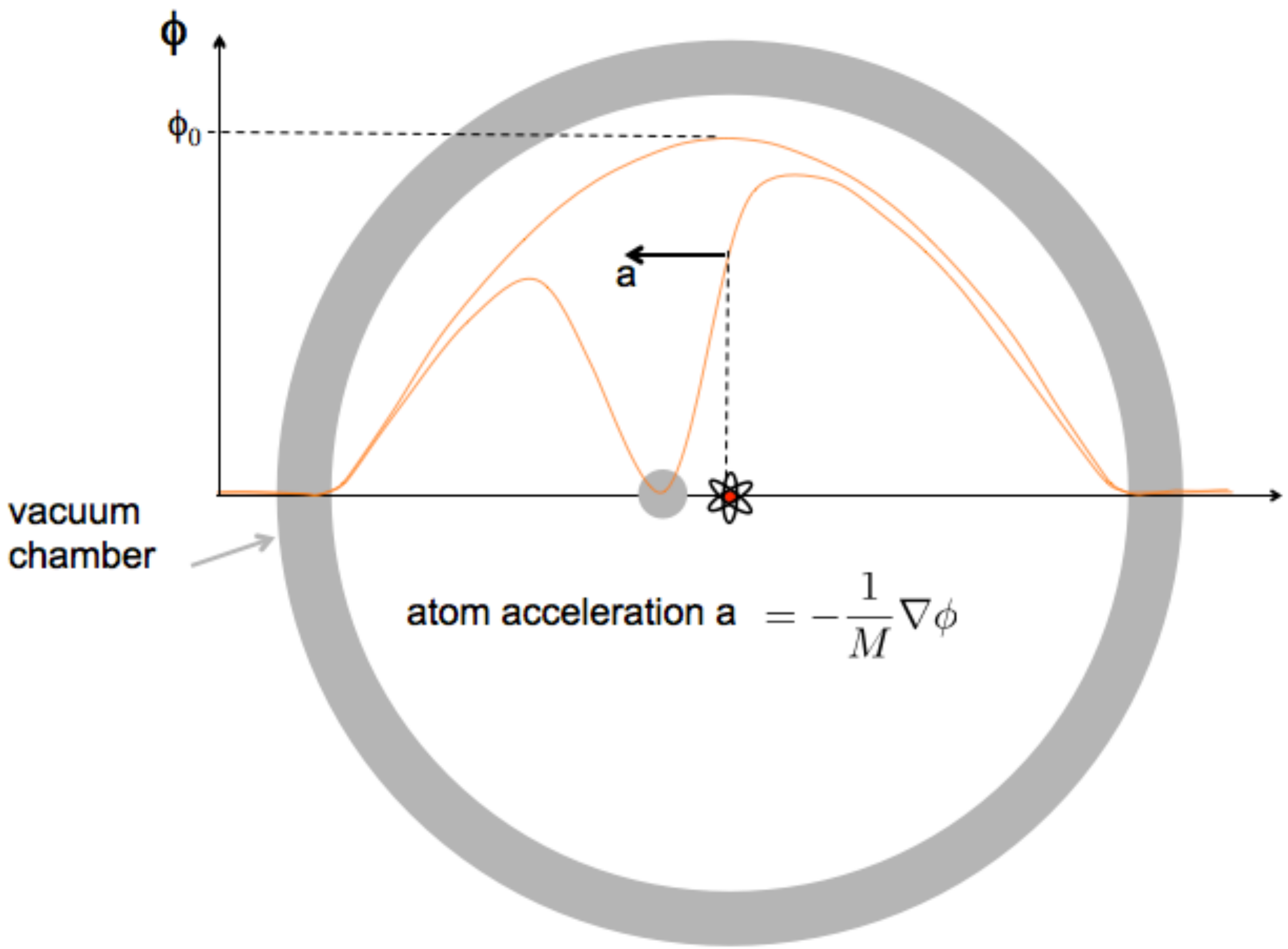
$$\lambda_i = 1 \text{ for } \rho_i R_i^2 < 3M\phi_{bg}$$

$$\lambda_i = \frac{3M\phi_{bg}}{\rho_i R_i^2} \text{ for } \rho_i R_i^2 > 3M\phi_{bg}$$

Sph source A and test object B near middle of chamber experience force between them - usually ƛ<<1 in cosmology but for atom ƛ=1 - reduced suppression

[Sabulsky et al 2019]

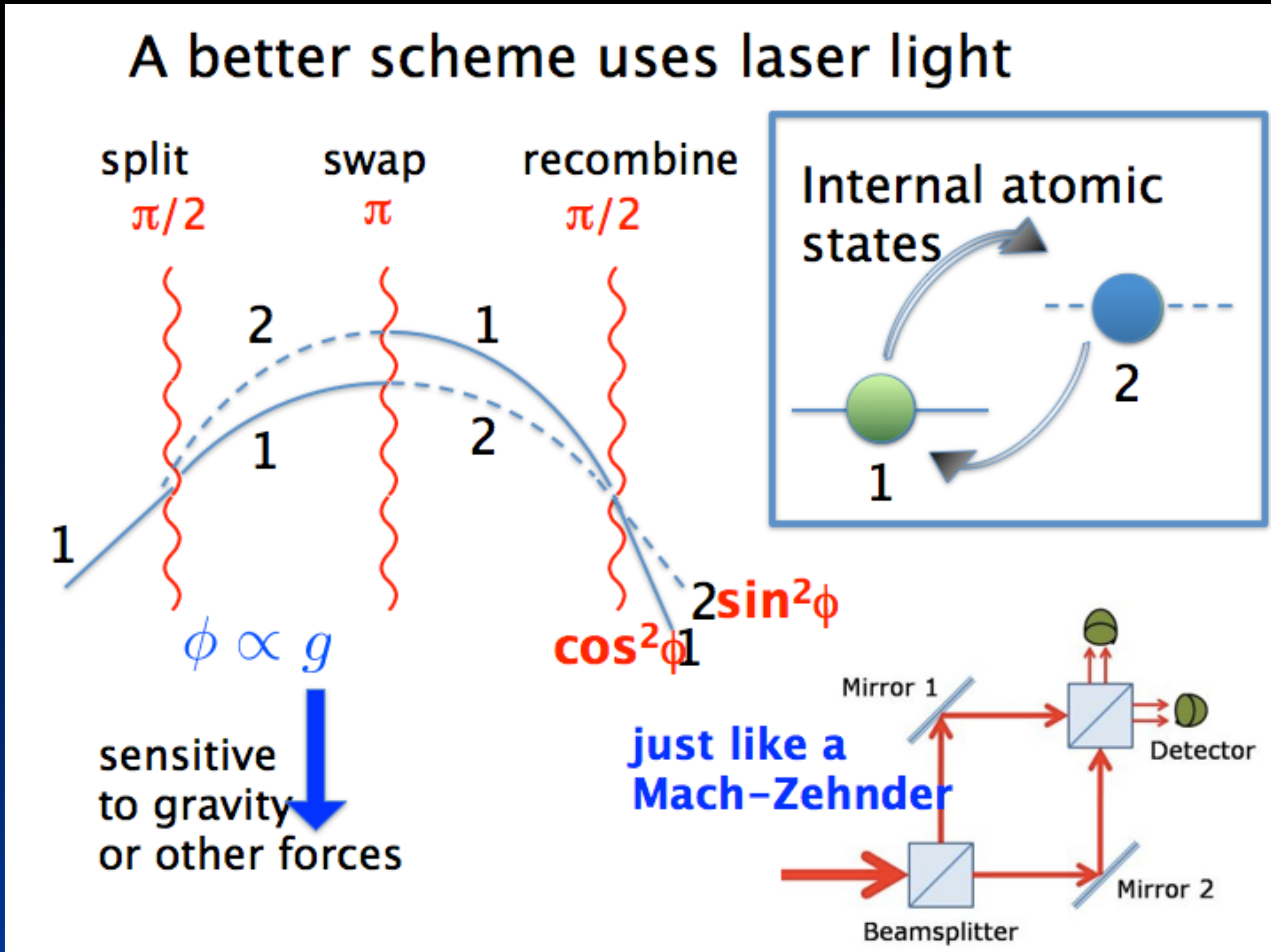
Measure ϕ in a high vacuum chamber



atom acceleration a $= -\frac{1}{M}\nabla\phi$

Ed Hinds

Use Atom Interferometry of atoms in free fall [Burrage, EC, Hinds 2015]



Raman interferometry uses a pair of counter-proagating laser beams, pulsed on three times, to split the atomic wave function, imprint a phase difference, and recombine the wave function.

The output signal of the interferometer is proportional to $\cos^2 \varphi$, with

$$\varphi = (\underline{k}_1 - \underline{k}_2).\underline{a}T^2$$

Ed Hinds

$\underline{k}_{1,2}$ – –wavevectors of the 2 beams

T – –time interval between pulses

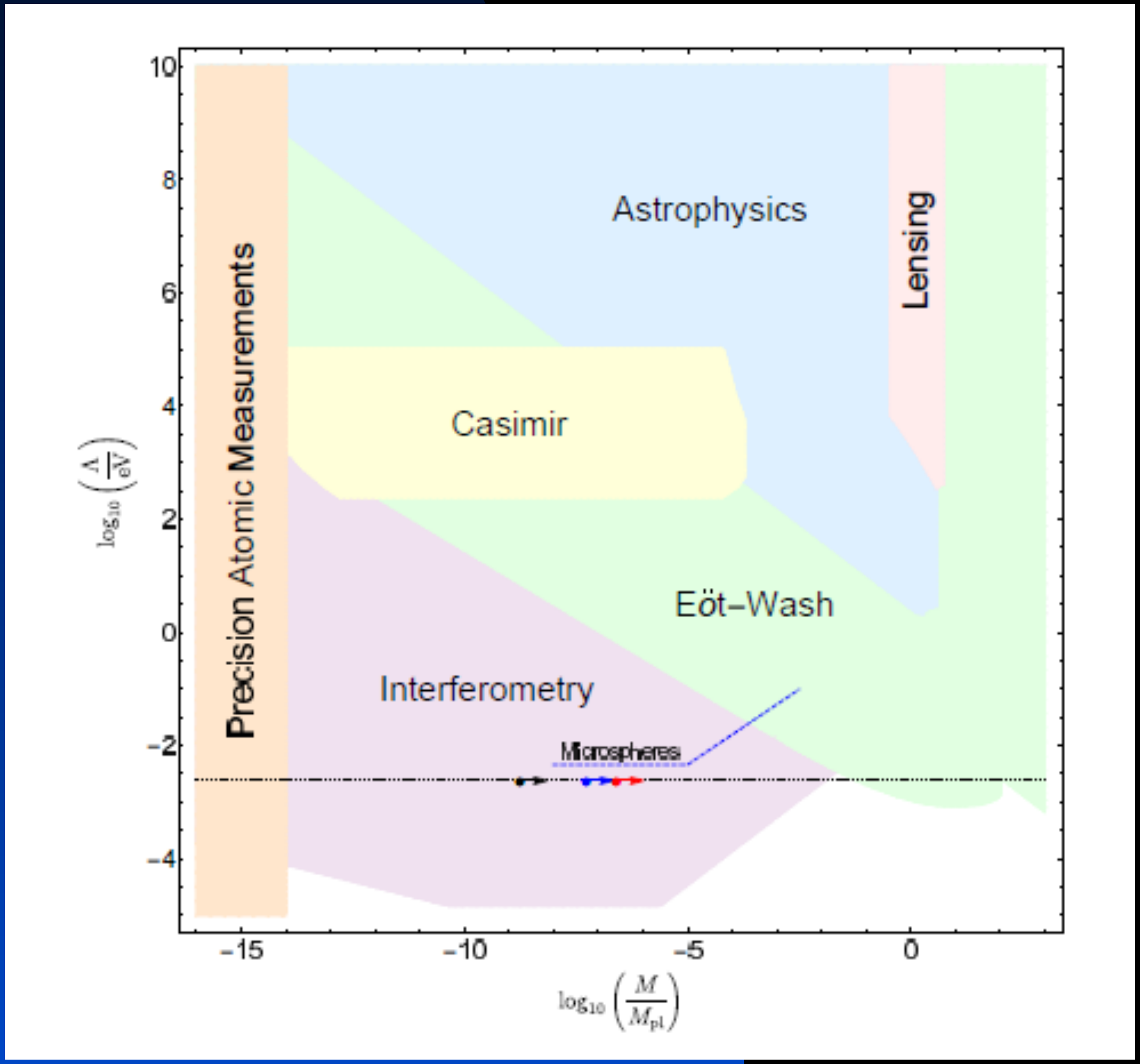
$\underline{a}$ – –acceleration of the atom

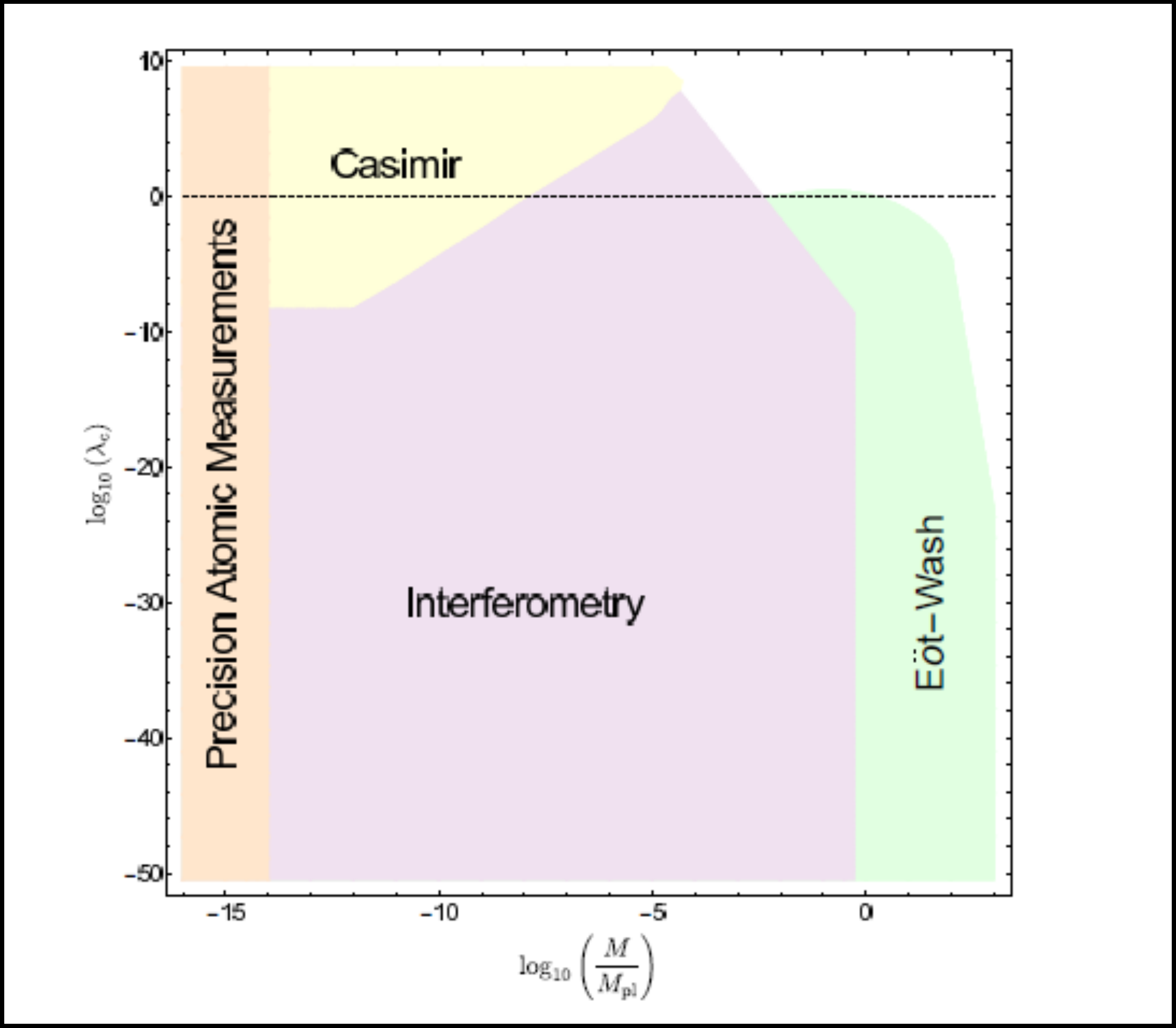
Combined chameleon constraints [Burrage & Sakstein 2017]

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

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

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





Screening mechanisms - Symmetron [Hinterbichler & Khoury 2010]

Model:

$$\tilde{V}(\varphi) \equiv V(\varphi) - \mathcal{L}_m[g] = -\frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\varphi^4 - \mathcal{L}_m[g],$$

Scalar field conformally coupled to matter through Jordan frame metric $g_{\mu\nu}$ related to Einstein frame metric $\hat{g}_{\mu\nu}$:

$$g_{\mu\nu} = A^2(\varphi)\tilde{g}_{\mu\nu}$$

with

$$A(\varphi) = 1 + \frac{\varphi^2}{2M^2} + \mathcal{O}\left(\frac{\varphi^4}{M^4}\right),$$

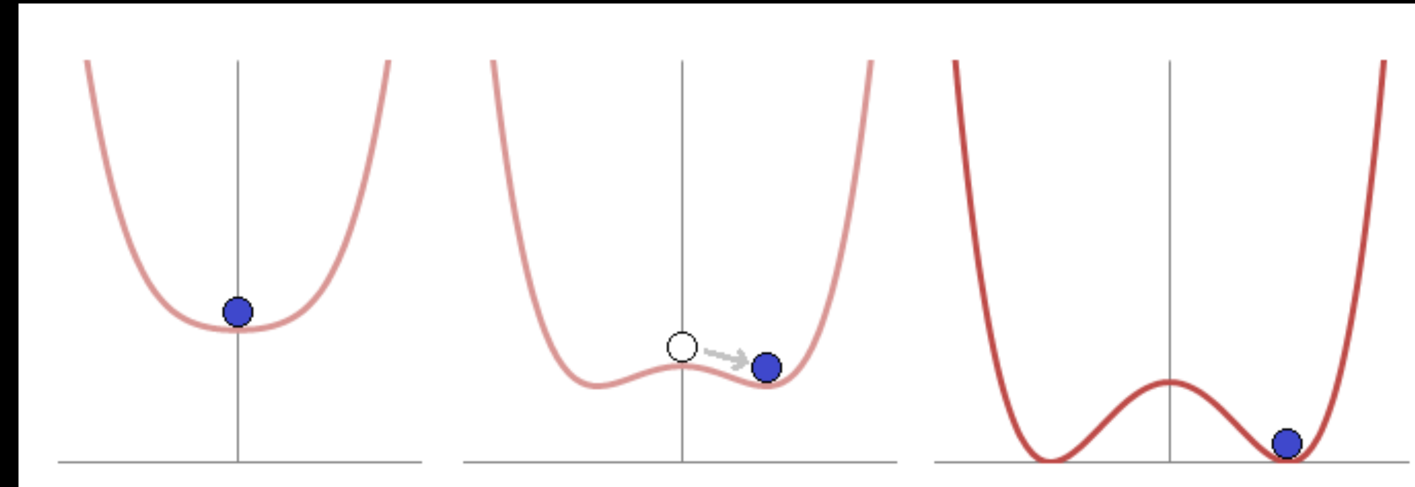
Coupling to matter leads to a fifth force which vanishes as $\varphi \to 0$

$$\vec{F}_{\mathrm{sym}} = \vec{\nabla}A(\varphi) = \frac{\varphi}{M^2}\vec{\nabla}\varphi.$$

Treating matter fields as a pressure less perfect fluid we obtain the classical Einstein frame potential

$$\tilde{V}(\varphi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\varphi^2 + \frac{1}{4}\lambda\varphi^4,$$

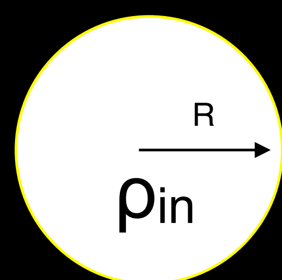
$$\tilde{V}(\varphi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\varphi^2 + \frac{1}{4}\lambda\varphi^4,$$



High density: $\rho/M^2 > \mu^2$:

Low density: $\rho/M^2 < \mu^2$:

Spherical source radius R:



ρ_{out}

with $\rho_{in}/M^2 > \mu^2$ and $\rho_{out}/M^2 < \mu^2$

Define:

$$m_{\rm in}^2 = \rho_{\rm in}/M^2 - \mu^2 > 0, \quad m_{\rm out}^2 = 2(\mu^2 - \rho_{\rm out}/M^2) > 0, \quad v \equiv m_{\rm out}/\sqrt{\lambda},$$

Assuming $m_{out}\, r \ll 1$ we find:

$$\varphi(r) = \frac{\pm v}{m_{\rm in} r}\begin{cases} \dfrac{\sinh m_{\rm in} r}{\cosh m_{\rm in} R}, & 0 < r < R \\ \left[\dfrac{\sinh m_{\rm in} R}{\cosh m_{\rm in} R} + m_{\rm in}(r - R)\right], & R < r. \end{cases}$$

Symmetrons & rotation curves - screening in galaxies [Burrage, EC & Millington 2017]

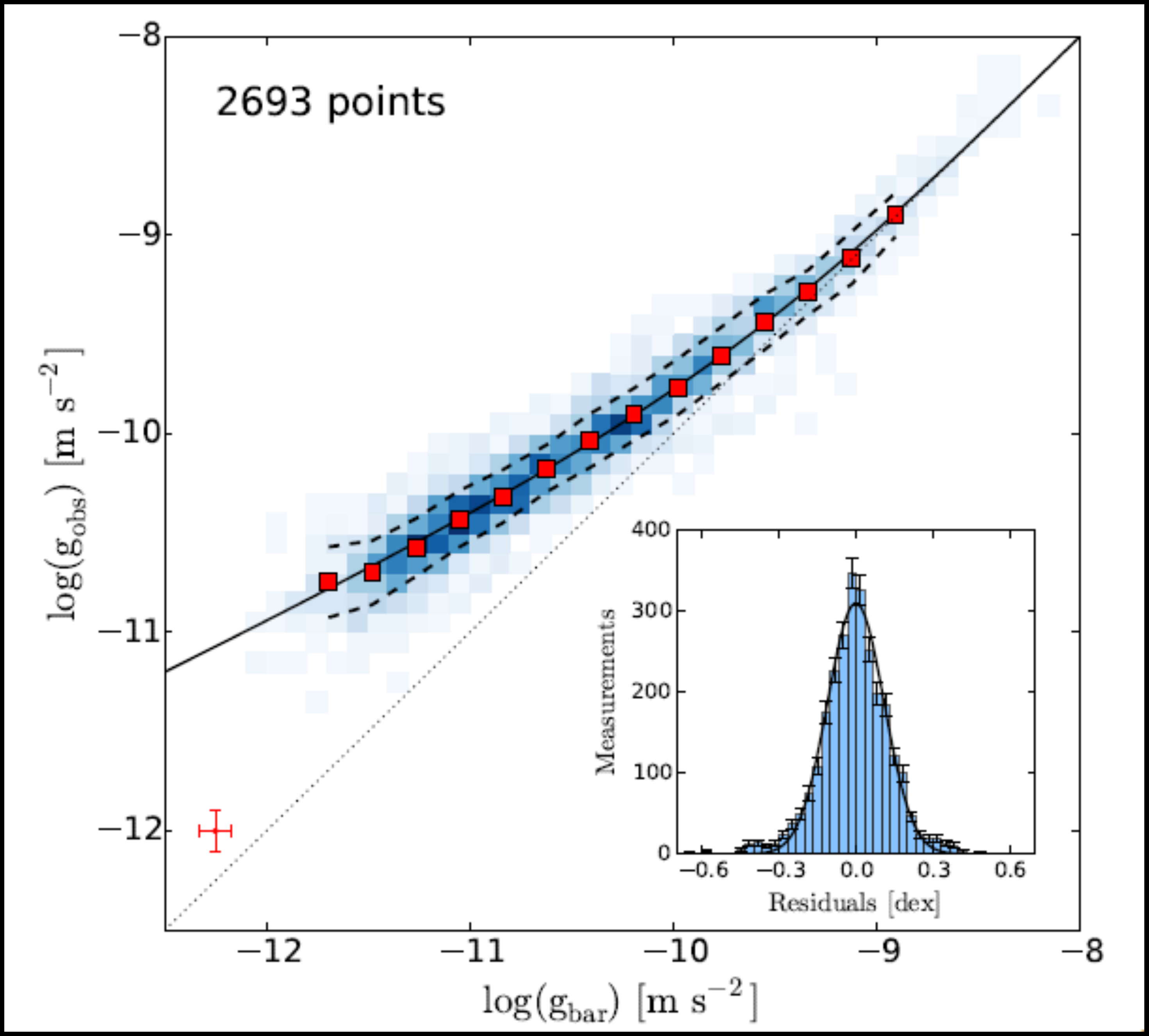
Radial acceleration relation from 153 galaxies (also known as mass discrepancy acceleration relation) [McGaugh et al PRL 2016]

$$g_{\rm obs(bar)}(r) = \frac{V^2_{\rm obs(bar)}(r)}{r} = \frac{GM_{\rm obs(bar)}(r)}{r^2}$$

Empirical fit:

$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_\dagger}}}$$

where $g_\dagger = 1.20 \pm 0.02(\text{rand}) \pm 0.24(\text{sys}) \times 10^{-10}\ \text{ms}^{-2}$.



Explanations include: MOND [Milgrom 2016], MOG [Moffat 2016], Emergent Gravity [Verlinde 2016], Dissipative DM [Keller & Waldsley 2016], Superfluid DM [Hodson et al 2016], some weird thing called ΛCDM [Ludlow et al PRL 2017] + us + others …

Symmetron explanation [Burrage, EC and Millington 2017]

$$\boxed{g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_\dagger}}}}$$

$$g_{\rm obs(bar)}(r) = \frac{V^2_{\rm obs(bar)}(r)}{r} = \frac{GM_{\rm obs(bar)}(r)}{r^2}$$

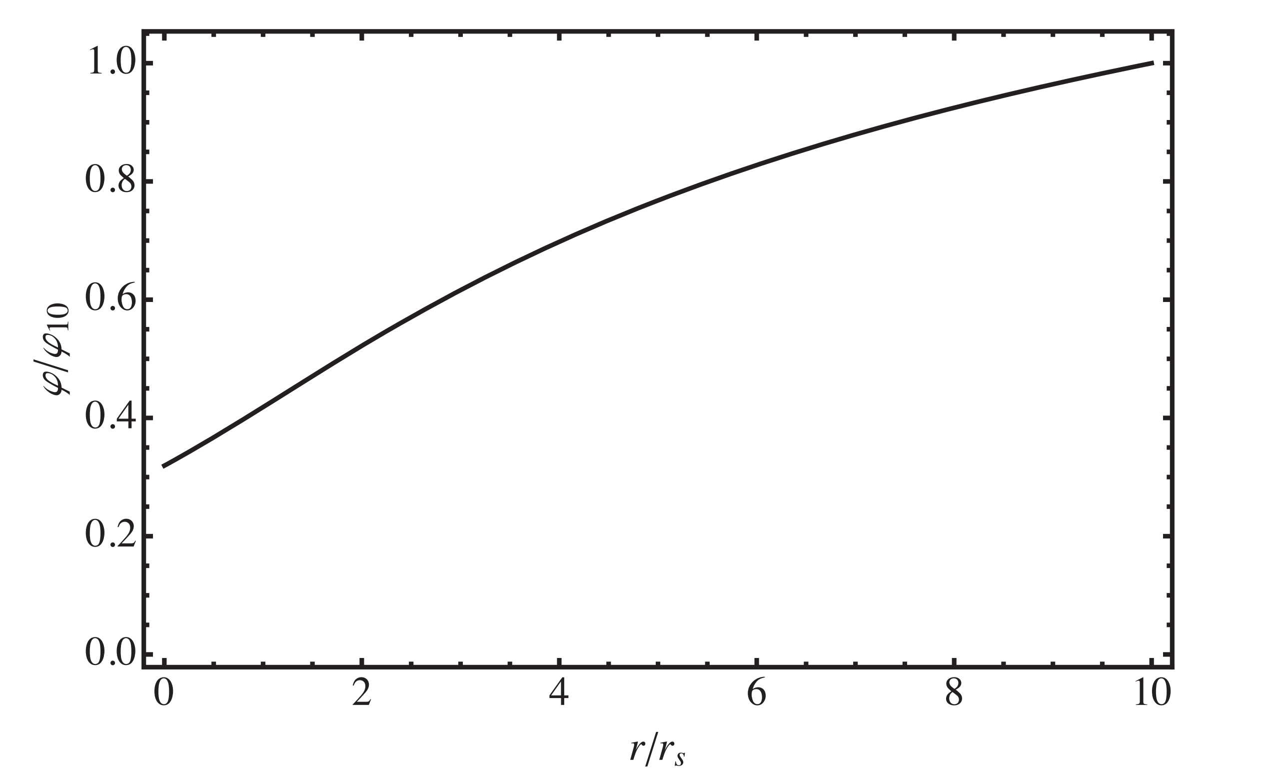
Rotation curve explained if symmetron profile satisfies:

$$g_{\rm sym}(r) = \frac{c^2}{2}\frac{d}{dr}\left(\frac{\varphi(r)}{M}\right)^2 = \frac{g_{\rm bar}(r)}{e^{\sqrt{g_{\rm bar}(r)/g_\dagger}} - 1}$$

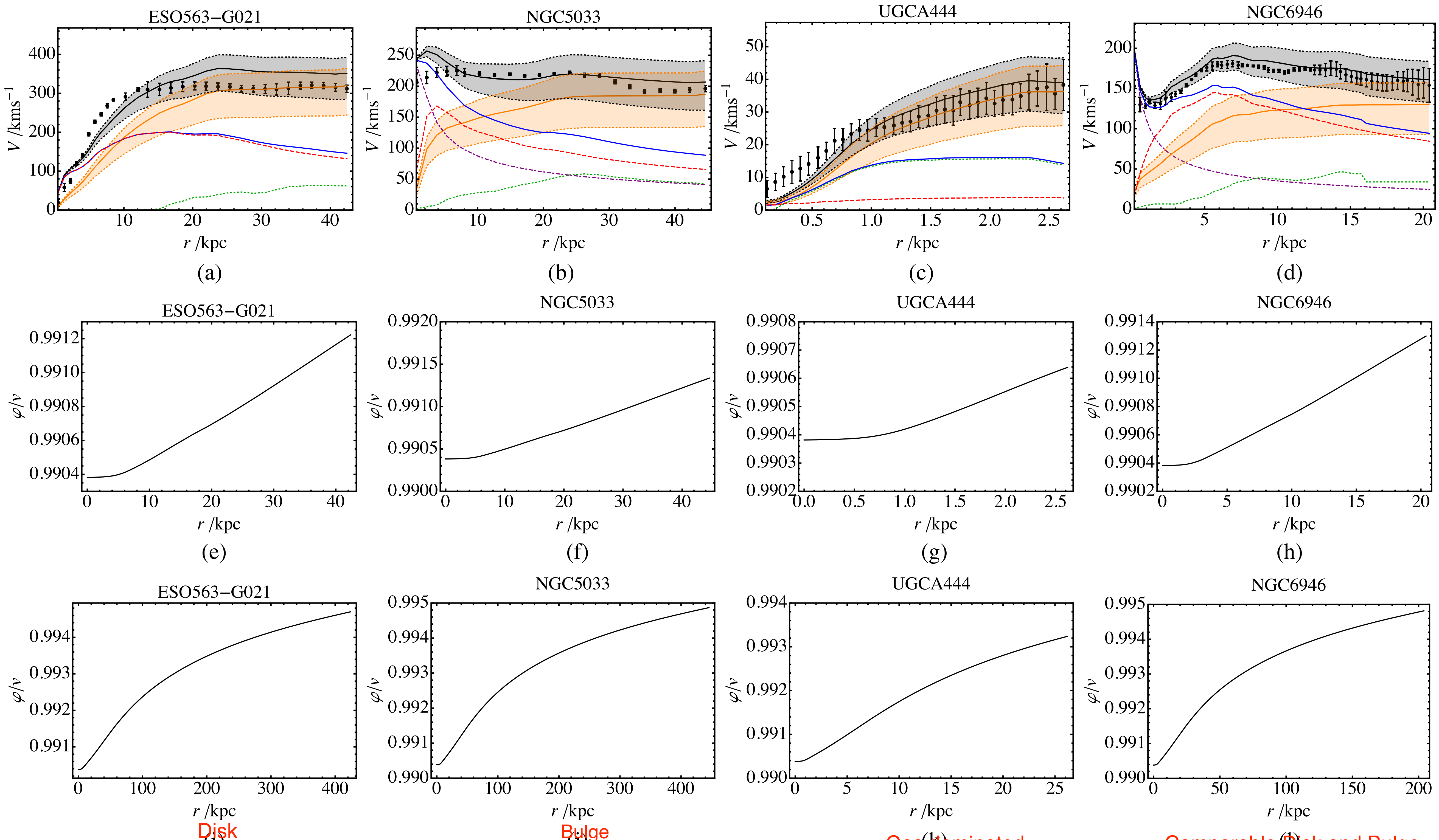
Assuming an exponential disc profile for the galaxy $\boxed{\Sigma(r) = \Sigma_0 e^{-r/r_s}}$ we obtain:

$$\mathcal{M}_{\rm bar}(r) = \mathcal{M}_0 \int_0^r \frac{{\rm d}r'}{r_s}\frac{r'}{r_s} e^{-r'/r_s} = \mathcal{M}_0\left[1 - e^{-r/r_s}\left(1 + \frac{r}{r_s}\right)\right],$$

Hence the required symmetron profile to explain observed accn without dark matter



Real galaxies in the SPARC dataset [Burrage, EC & Millington 2017, SPARC, Lelli et al 2016]



Disk dominated

Bulge dominated

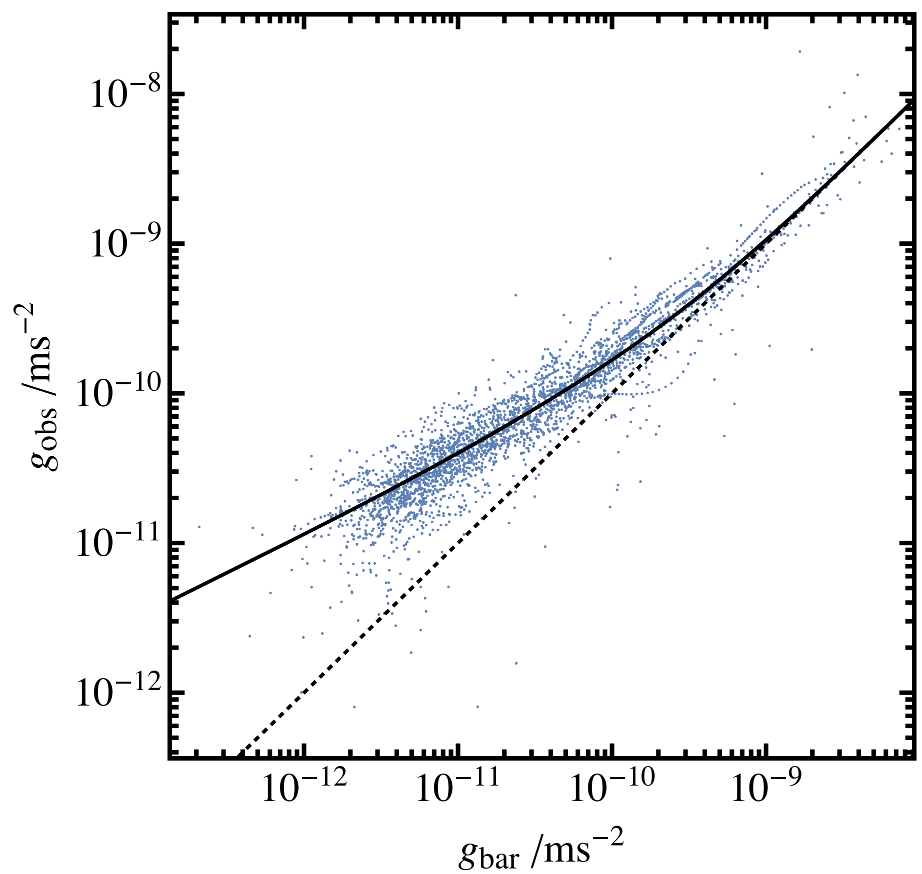
Gas dominated

Comparable Disk and Bulge

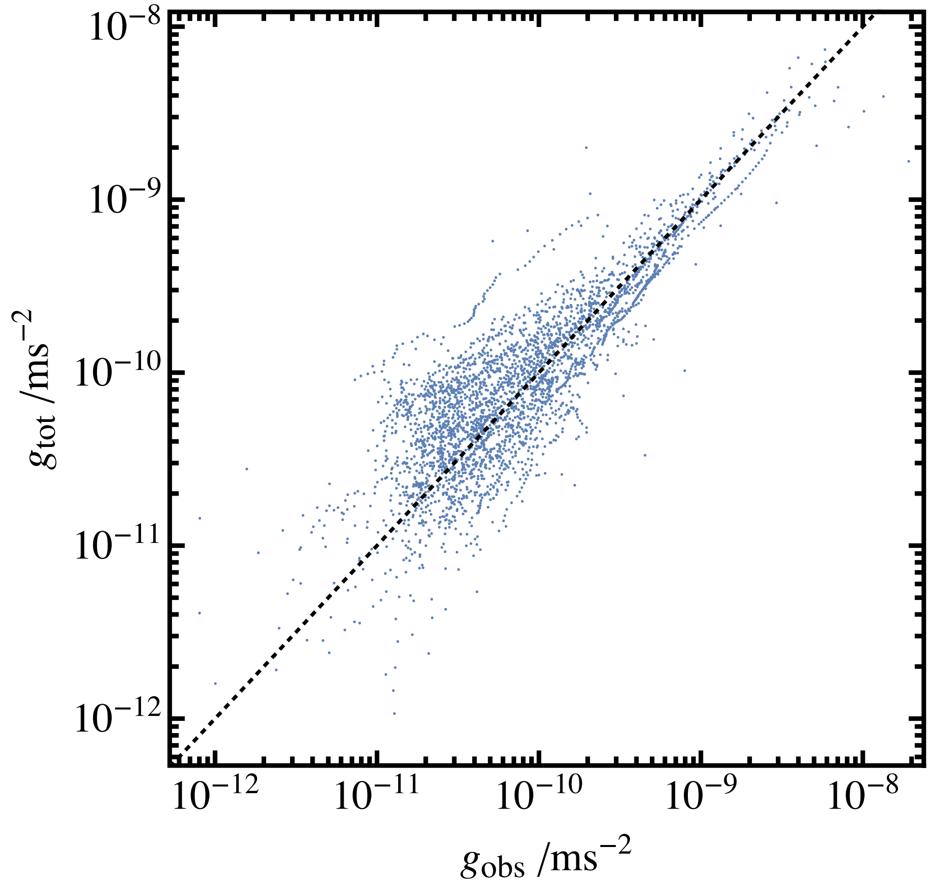
$$M = M_{\rm Pl}/10 \text{ and } \bar{\rho}_0 = 1\ M_\odot\,\text{pc}^{-3},\ v/M = 1/150, \text{ and } \mu = 3\times10^{-39}\ \text{GeV}:$$

Comparison with real data

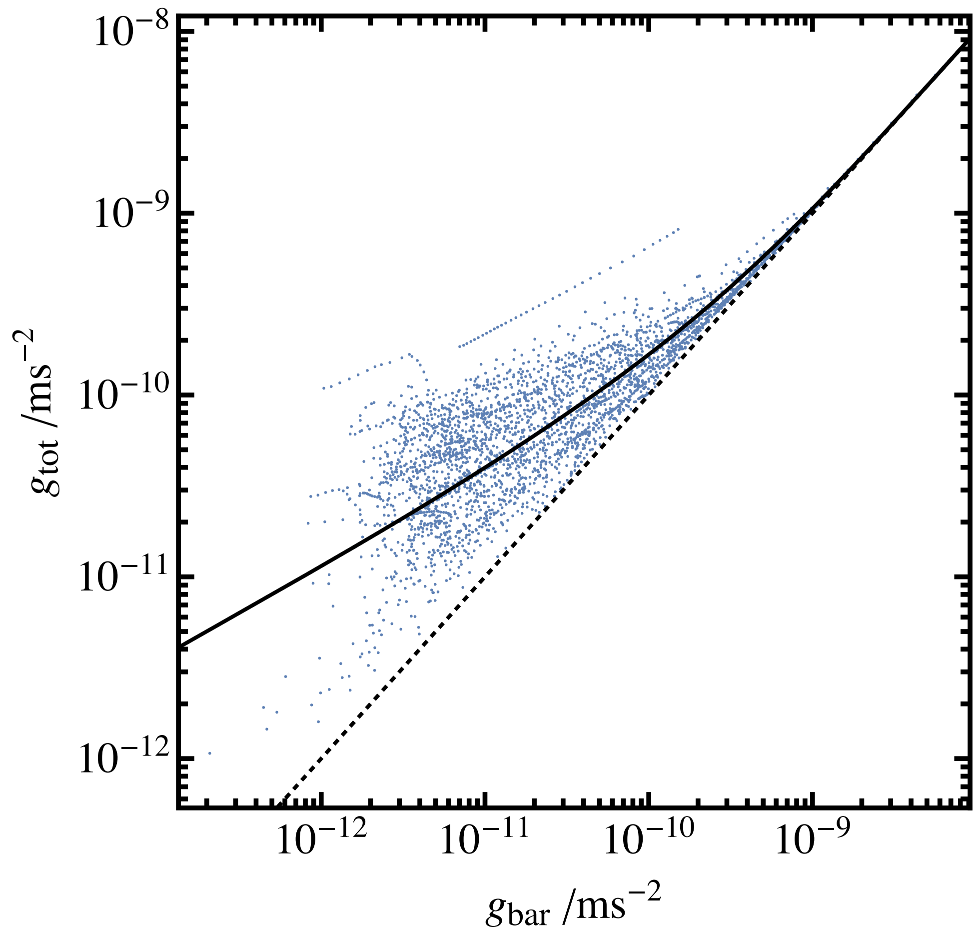
[Burrage, EC and Millington 2017]



(a) observed versus baryonic



(b) symmetron prediction versus observed



(c) symmetron prediction versus baryonic

Recent result — this radial acceleration relation (RAR) is the fundamental correlation governing the radial (in-disk) dynamics of late type galaxies. It can not be tightened - it sounds to me as if it is an important relation for any model to predict.

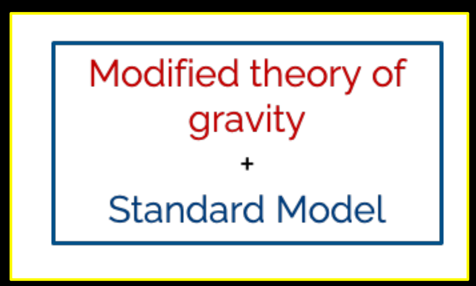
[R. Stiskalek and H. Desmond — arXiv:2305.19978017]

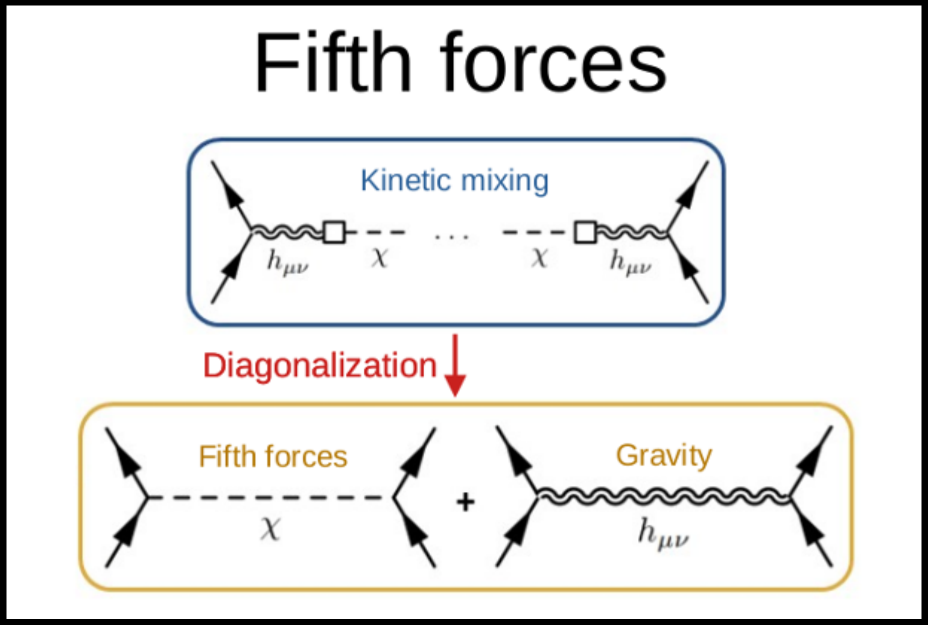
Modified Gravity models can couple to the standard model particles - we can use particle collisions to look for fifth forces [Brax et al (2016), Aaboud et al (2019), S.Sevillano Munoz et al (2022)]

Brans Dicke
$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{F(X)}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu X\partial_\nu X - U(X) + \mathcal{L}_\mathrm{m}\{\psi_i, \phi_i, g_{\mu\nu}, ...\}\right]$$

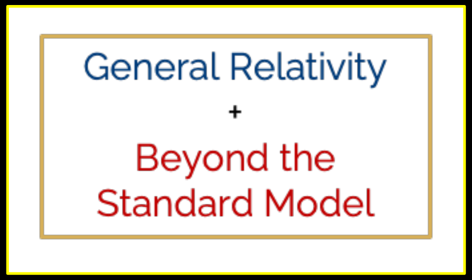
Expand around Mink space
$$\begin{aligned} g_{\mu\nu} &= \eta_{\mu\nu} + h_{\mu\nu} + \cdots \\ g^{\mu\nu} &= \eta^{\mu\nu} - h^{\mu\nu}, \end{aligned}$$

Fifth forces leak into the system via a kinetic mixing with gravity





[credit: Sergio Sevillano Munoz]



Once we have BSM description we can calculate from quantum corrections the scattering amplitudes. But they are long and tedious to do. They require: expanding of gravity, canonical normalisation, expanding around non-trivial vevs, obtaining the kinetic mixings to graviton and then mass mixings

In flat space, particle phenomenologists use FeynRules - Mathematica package that goes from a Lagrangian gives Feyn Rules and phenomenology.

What about Gen Rel plus BSM ?

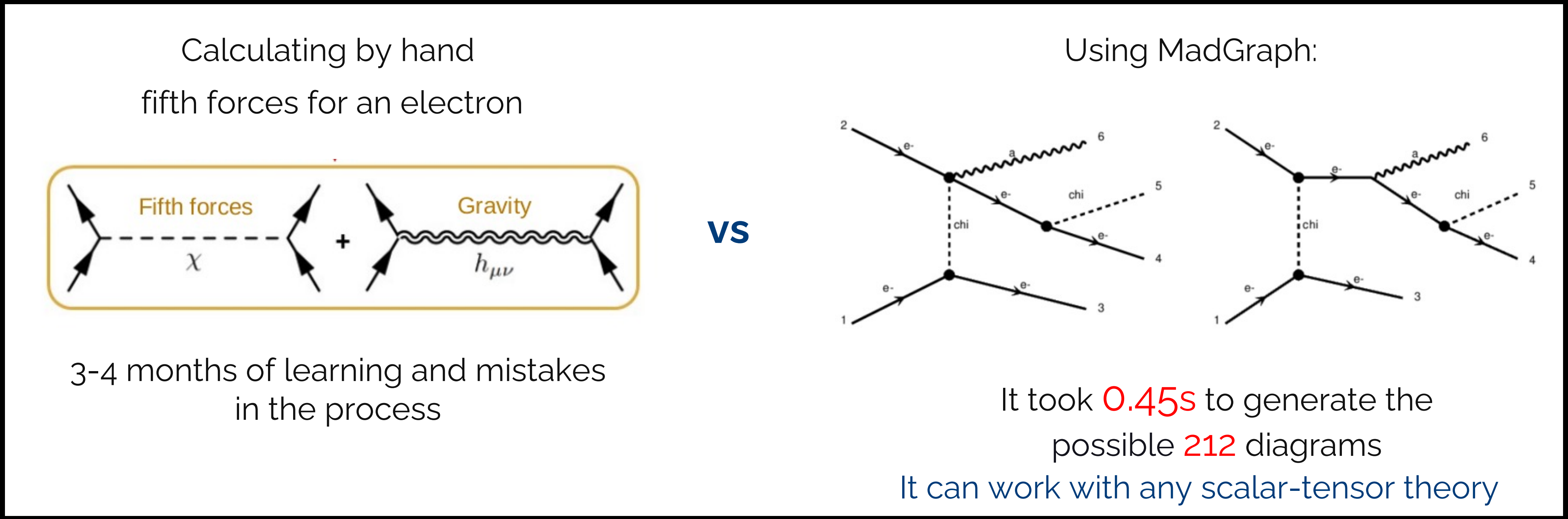
Enter FeynMG written primarily by Sergio Sevillano Munoz

A sub package of Feyn Rules

[S.Sevillano Munoz et al, arXiv:2211.14300]

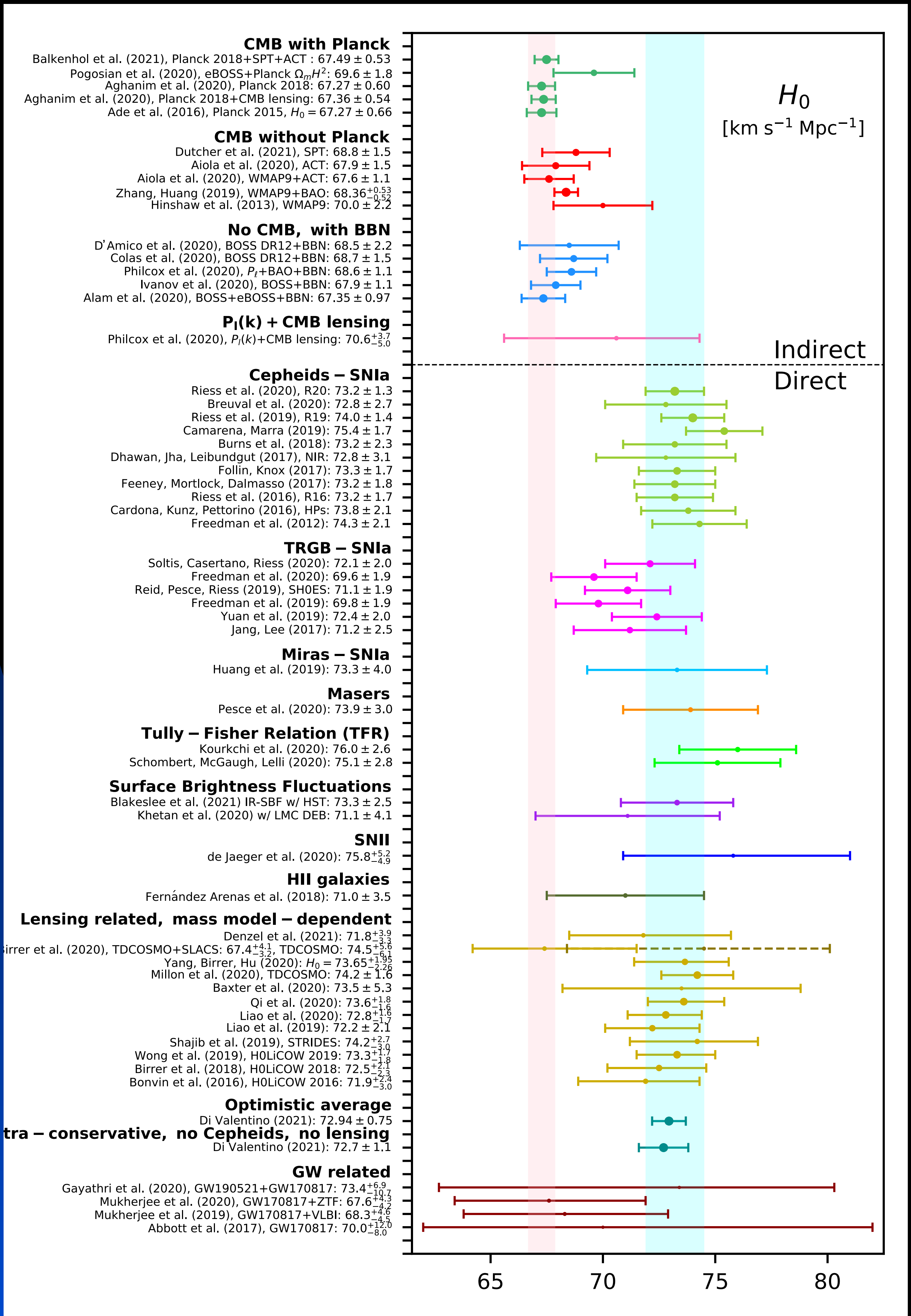
Allows user to insert new scalar dof and any grav theory. Can then perform the necessary operations to calculation the BSM description.

Test scalar-tensor theories in colliders



[credit: Sergio Sevillano Munoz]

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



[Di Valentino et al 2019]

Lots of approaches being taken to determine H_0

H_0=67.4±0.5 km s^{-1} Mpc^{-1} (Planck) v H_0=73.04±1.04 km s^{-1} Mpc^{-1} (Riess et al 2022)

Assuming the tension is a sign of new physics - many theoretical approaches.

Most of them make use of the standard ruler imprinted in the cmb maps - the Sound Horizon - the distance sound waves could propagate in a plasma from t=0 to t=1100.

Measure the angular size on the cmb, so have a distance and redshift to cmb.

One approach - use new physics early on to reduce the physical size of the sound horizon, hence decrease the distance we infer to the cmb (rem we measure the angular separation) - implying the H_0 we infer increases !

$$r_s^* = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(z) \quad \rightarrow D_A \sim \frac{r_s^*}{\theta_s^*} \quad \rightarrow H_0$$

Recall $D_A \sim 1/H_0$

So the idea, have new physics early on, alter the energy density, change H(z). Concentrate here on EDE but also possible to have late time modifications to resolve the tension [Zhao et al, Nature Ast 2017; Wang et al, Astro J. Lett 2018]

The particle cosmologists tool of choice — a (pseudo) scalar field - ϕ

ϕ initially frozen on its potential c/o Hubble friction - like DE with w=-1

As H~m, rolls down potential and oscillates.

Need late time w>0, so EDE energy density decays faster than matter.

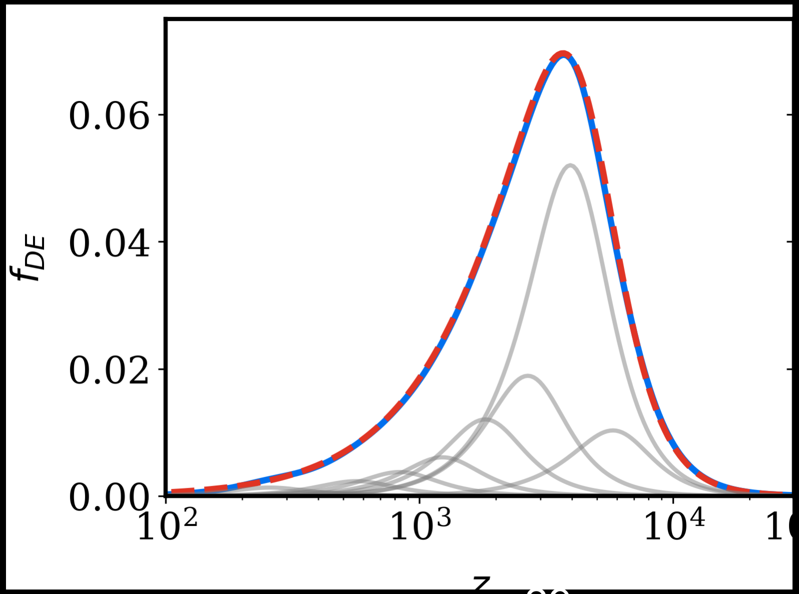
Three EDE examples:

axion EDE [Poulin et al, PRL 2019]

$$V(\phi) = m^2 f^2 (1 - \cos(\phi/f))^n, \quad m \sim 10^{-27} eV, \;\; f \sim 10^{26} eV, \;\; n = 3$$

Near minimum - eos - $w_\phi = \dfrac{n-1}{n+1} = \dfrac{1}{2} > 0$

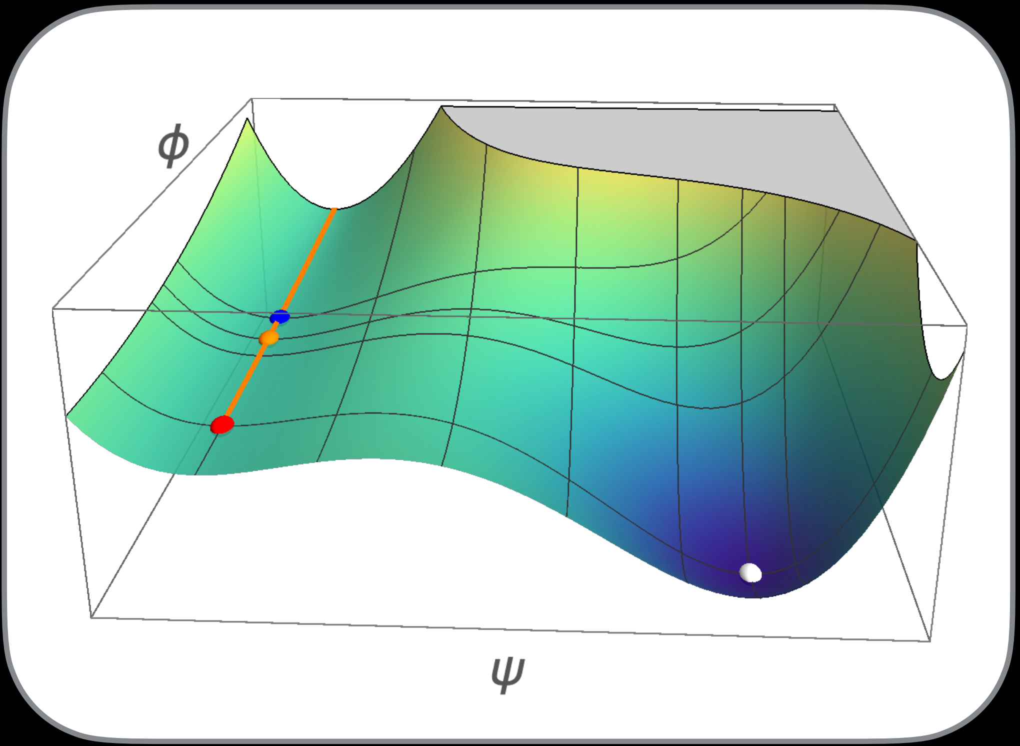
Note occurs around matter radiation equality



[Moss et al, 2021]

New EDE — driven by a first order phase transition [Niedermann and Sloth, PRD 2021]

$V(\psi,\phi) = \frac{\lambda}{4}\psi^4 + \frac{1}{2}\beta M^2\psi^2 - \frac{1}{3}\alpha M\psi^3 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\tilde{\lambda}\phi^2\psi^2,$ ψ is tunneling field, ϕ trigger field



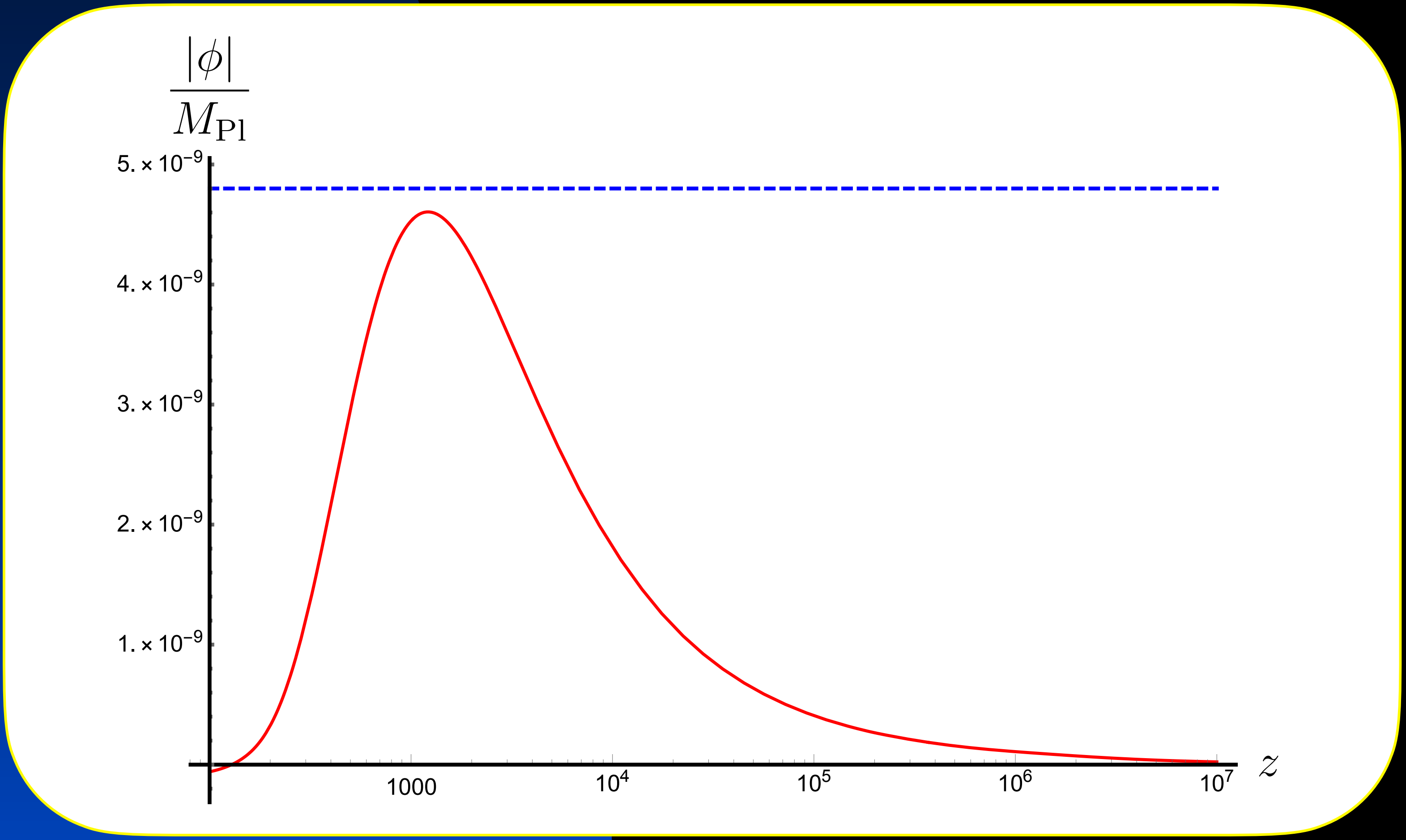
False vacuum decay of ψ from cosm const source to decaying field with const eos w>0 around eV scale.

$H_0 = 71.4 \pm 1.0 kms^{-1}Mpc^{-1}$, with decay at $z_* = 4920^{+620}_{-730}$ and with $f_{NEDE} = 0.126^{+0.03}_{-=.03}$

Massive neutrino driven EDE — [Sakstein and Trodden, PRL 2020, for earlier related work see Amendola et al 2008]

Idea: If EDE field ϕ is coupled to neutrinos with strength β, it receives a large injection of energy around the time that neutrinos become non-relativistic, which is when their temp ~ their mass, just before matter-rad equality.

Nice feature - neutrino decoupling provides trigger for EDE by displacing ϕ from min of it's potential $V(\phi) = \lambda\phi^4/4$.



$m_\nu = 0.5eV,\ \beta = 4 \times 10^{-4},\ \lambda = 10^{-75}$

For approaches resolving the Hubble tension using impact of screened fifth forces on the distance ladder see [Desmond et al, PRD 2019, Baker et al, Rev Mod Phys 2021]

More general approach to DE - spike model

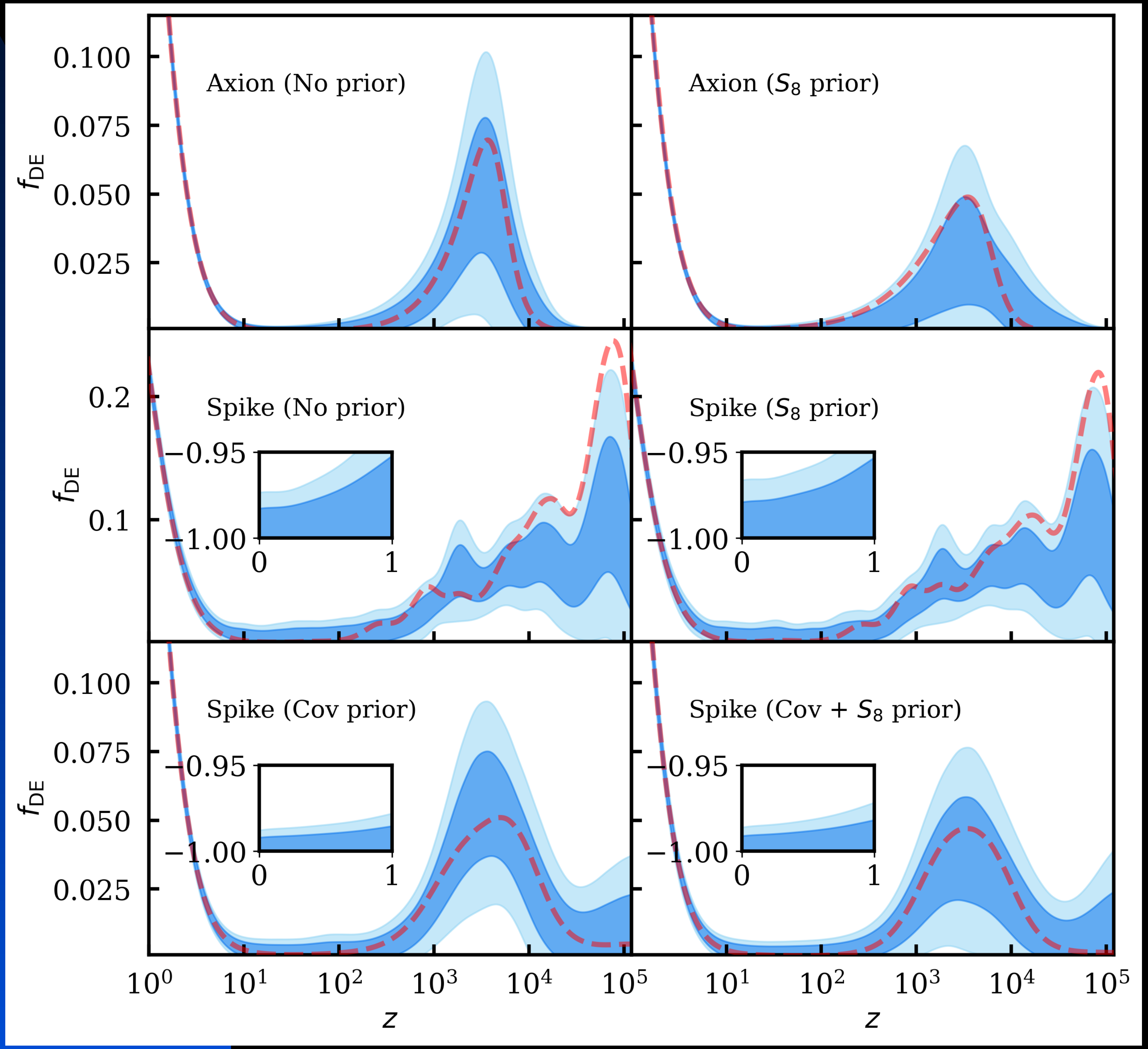
[Moss, EJC, Bamford and Clarke 2021 - for similar approach see also Lin et al 2019 and Hojjati et al 2013]

Model DE by perfect fluid with series of bins in energy density, with eos $-1 \leq w \leq 1$. Combine with cmb, BAO and local H_0 data obtain improvement over ΛCDM with DE contributing significantly between $z \sim 10^4 - 10^5$ and $c_s^2 \sim 1/3$.

$\Delta\chi^2 = -10.8$

$\Delta\chi^2 = -34.4$

$\Delta\chi^2 = -14.0$



inc DES S_8 prior

$S_8 = 0.776 \pm 0.017$

A few details

Parameter	ΛCDM	Axion Fluid	Spike	Spike (+ Covariance Prior)
H_0	68.48 ± 0.32 (68.44)	$70.03^{+0.81}_{-1.1}$ (70.95)	$72.25^{+0.93}_{-1.2}$ (73.59)	$70.9^{+1.0}_{-1.3}$ (71.29)
Ω_m	0.3001 ± 0.0041 (0.3006)	$0.2975^{+0.0044}_{-0.0049}$ (0.2950)	$0.3027^{+0.0062}_{-0.0055}$ (0.2978)	0.2948 ± 0.0054 (0.2952)
n_s	0.9729 ± 0.0030 (0.9728)	$0.9810^{+0.0060}_{-0.0073}$ (0.9834)	0.9703 ± 0.0083 (0.9636)	$0.9805^{+0.0081}_{-0.0063}$ (0.9833)
c_s^2	-	-	$0.334^{+0.021}_{-0.039}$ (0.3125)	$0.401^{+0.10}_{-0.090}$ (0.4153)
w_n	-	$0.475^{+0.087}_{-0.18}$ (0.3523)	-	-
z_c	-	10240^{+2000}_{-8000} (5460)	-	-
$f_\mathrm{EDE}(z_\mathrm{c})$	-	$0.0272^{+0.0097}_{-0.021}$ (0.03609)	-	-
S_8	0.8075 ± 0.0077 (0.8073)	0.814 ± 0.010 (0.8133)	0.8182 ± 0.0099 (0.8183)	$0.812^{+0.011}_{-0.0094}$ (0.8151)
χ^2_H0	15.5	4.7 (**-10.8**)	0.1 (**-15.4**)	3.7 (**-11.8**)
χ^2_Planck	1017.0	1020.0 (3.0)	1009.2 (**-7.8**)	1018.3 (1.3)
χ^2_ACT	240.7	235.3 (**-5.4**)	225.3 (**-15.4**)	234.4 (**-6.3**)
χ^2_S8	3.4	4.8 (1.4)	6.2 (2.8)	5.3 (1.9)
χ^2_data	2316.7	2305.9 (**-10.8**)	2281.4 (**-35.4**)	2302.8 (**-14.0**)
χ^2_prior	0.0	0.0	0.0	3.8
$\Delta \ln E$	-	-	-	5.0

The high z behaviour of EDE changes the radiation driving envelope that modifies the high *l* CMB power spectrum, potentially alleviating the tension between Planck and ACT data -see [Hill et al 2021]

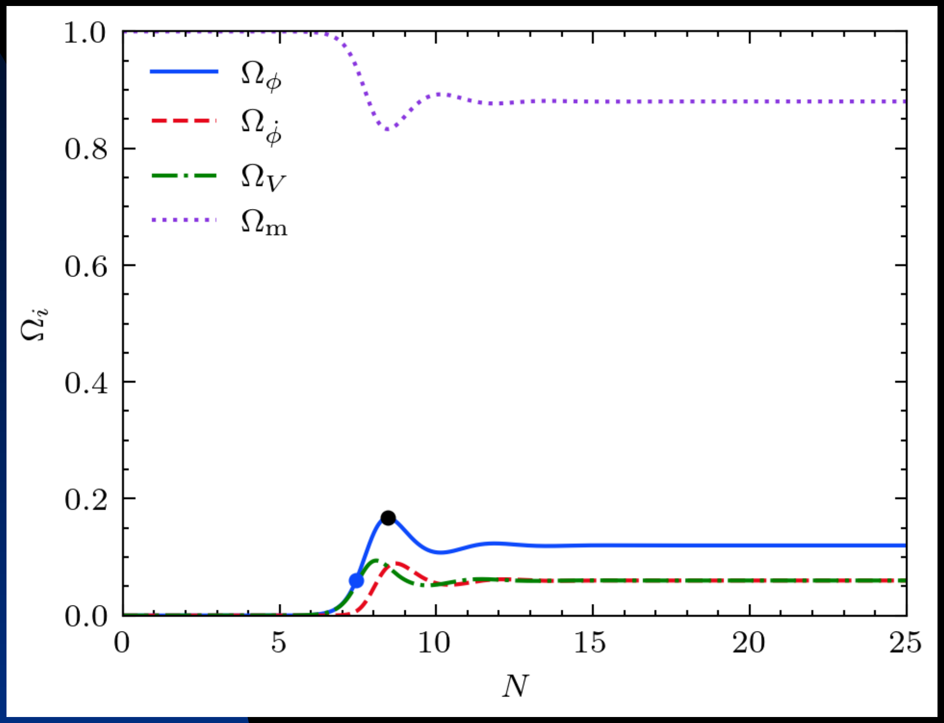
Note - none of these models really address the S_8 tension - cmb v lss

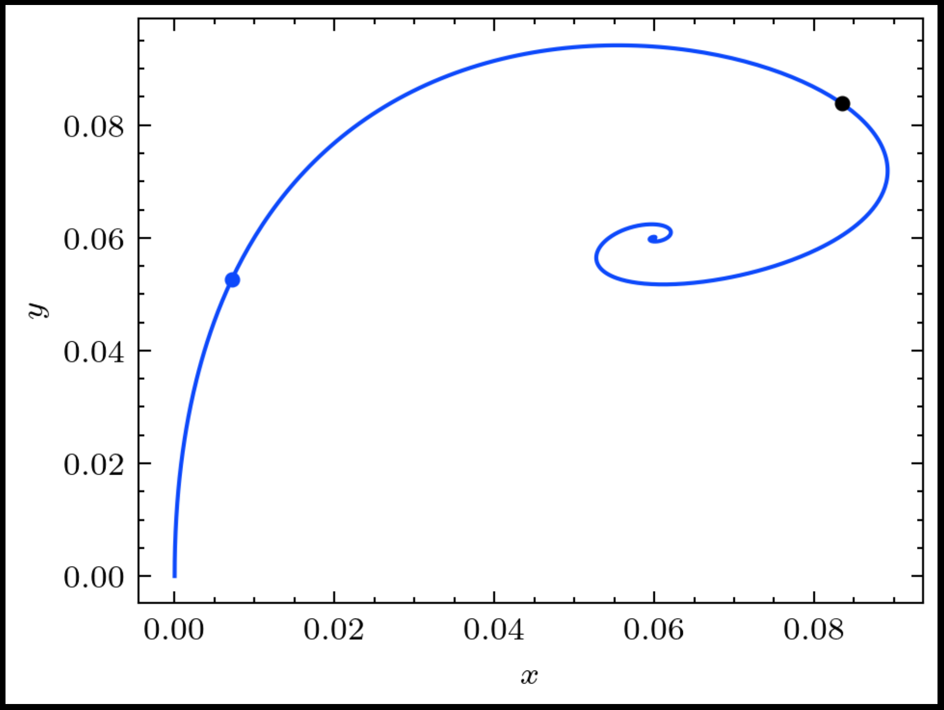
Once the 33 spike parameters inc, find moderate Bayesian evidence for EDE [following the approach developed in [Crittendon et al, JCAP 2012; Zhao et al, PRL 2012]]

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

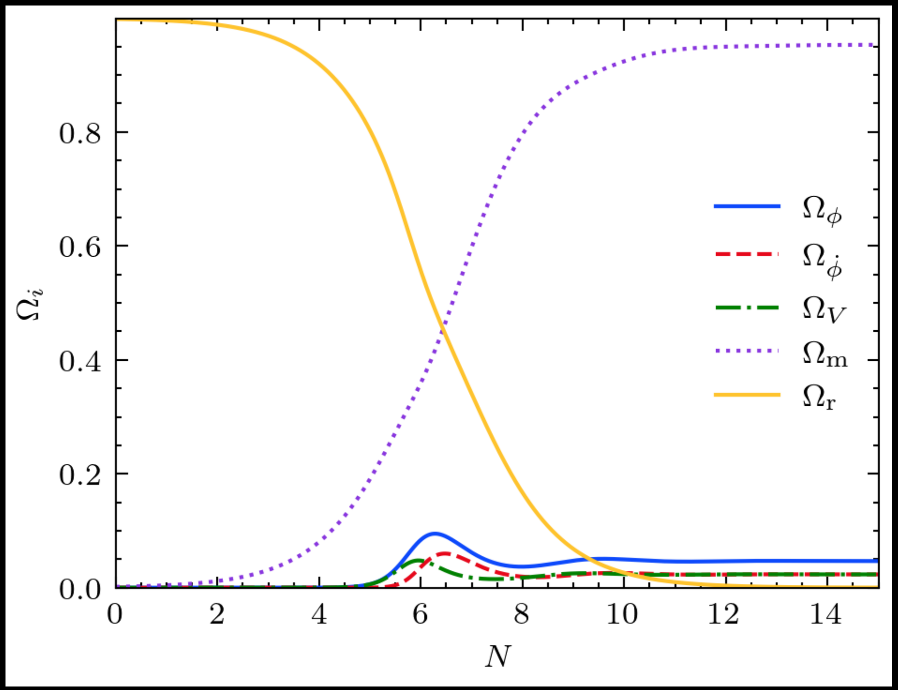
$$H^2 = \frac{\kappa^2}{3}\left(\rho_r + \rho_m + \rho_{cc} + \frac{\dot{\phi}^2}{2} + V(\phi)\right)$$

$$x = \frac{\kappa\dot{\phi}}{\sqrt{6}H} \qquad y = \frac{\kappa\sqrt{V}}{\sqrt{3}H} \ : \ \Omega_\phi = \frac{\kappa^2\rho_\phi}{3H^2} = x^2 + y^2 \ : V(\phi) = V_0 \exp(-\kappa\lambda\phi)$$





Quintessence peak around matter-radiation equality

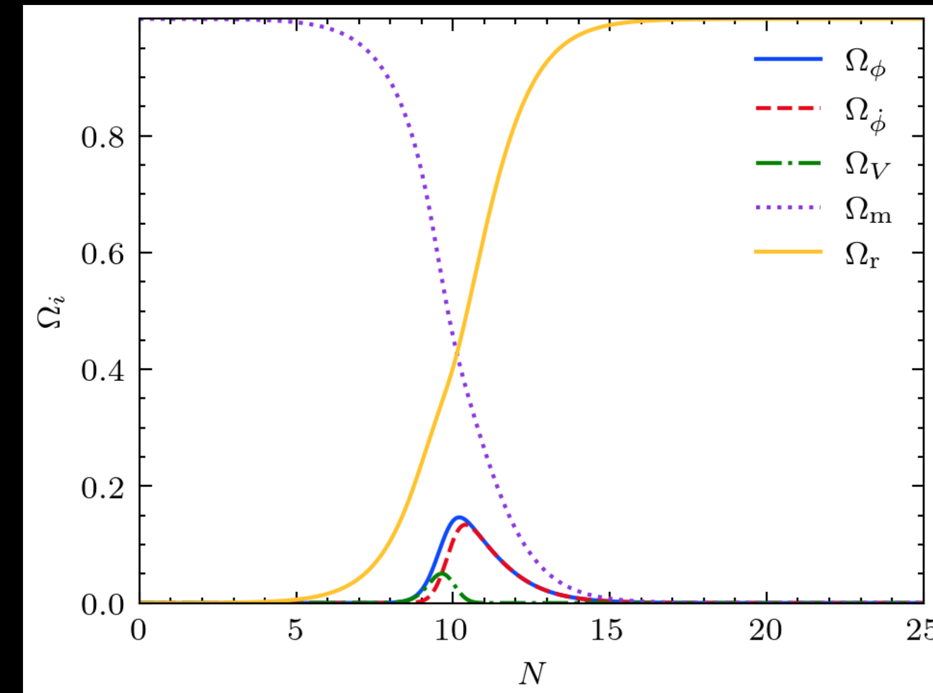


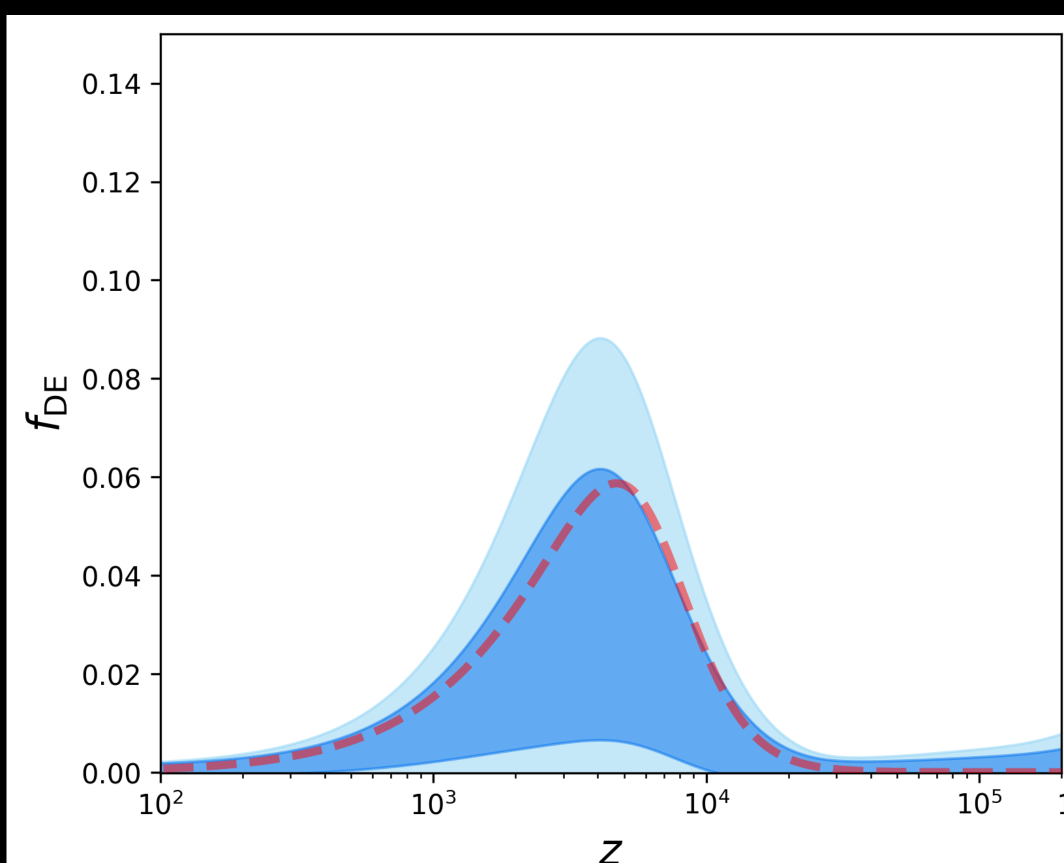
[EJC, A. Moss, S. Sevillano Muńoz, J.D. White 2023]

Also for K-essence type behaviour, as long as there is an attractor it wants to go to.

$$\mathcal{L} = \frac{X(\dot\phi)^n}{M^{4(n-1)}} - V(\phi) \quad : \quad X(\dot\phi) \equiv \frac{1}{2}\dot\phi^2 \quad : \quad V(\phi) = V_0 \exp\left(-\kappa\lambda\phi\right)$$

n=2

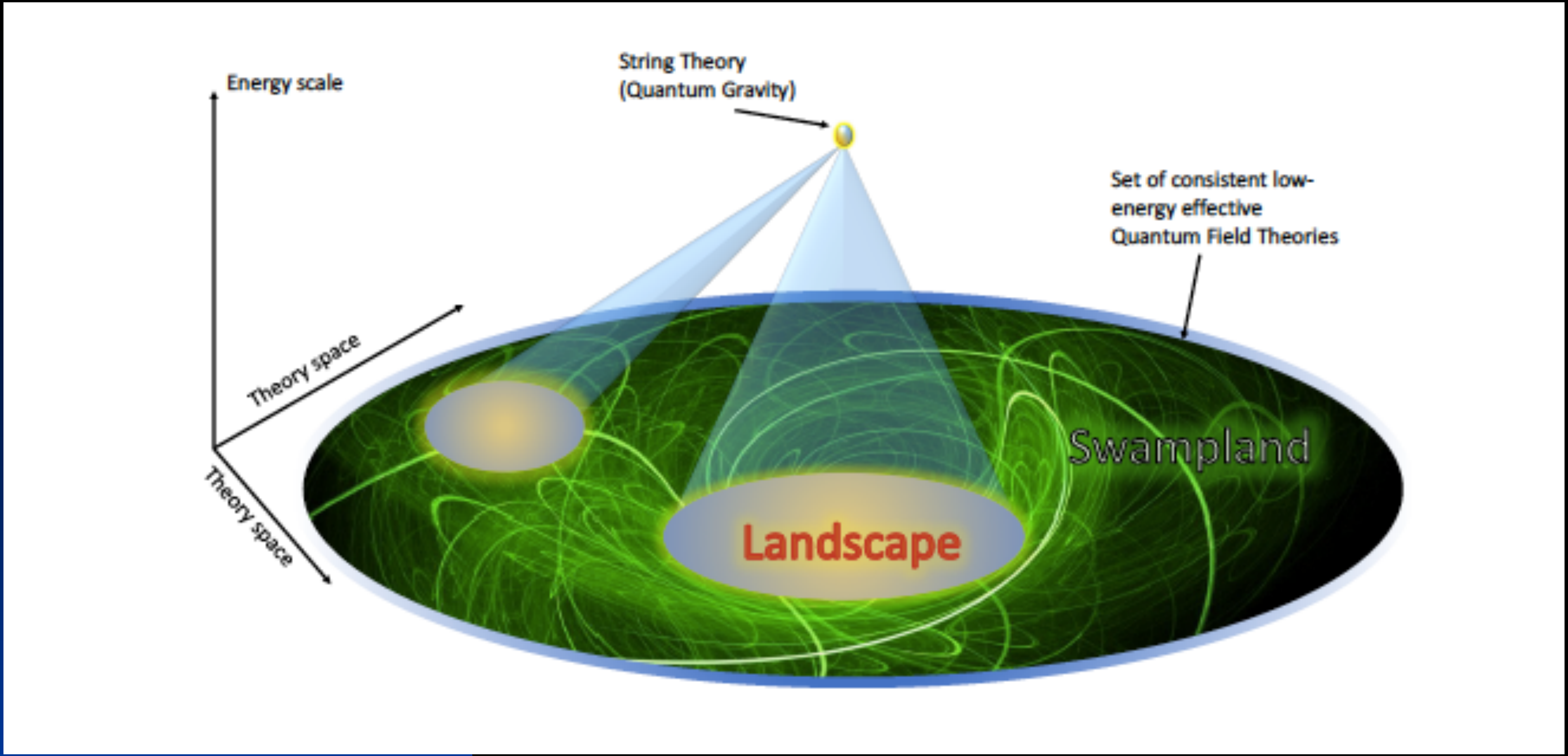




Parameter	ΛCDM	K-essence	Fang
H_0	68.16 ± 0.34 (68.17)	69.6 ± 1.1 (70.45)	$68.15^{+0.40}_{-0.35}$ (68.15)
$\Omega_{\rm b}h^2$	$0.02247^{+0.00011}_{-0.000094}$ (0.02248)	$0.02248^{+0.00014}_{-0.00016}$ (0.02251)	0.02247 ± 0.00012 (0.02246)
$\Omega_{\rm c}h^2$	0.11829 ± 0.00077 (0.1183)	$0.1237^{+0.0039}_{-0.0044}$ (0.1278)	0.11830 ± 0.00084 (0.1183)
$n_{\rm s}$	0.9715 ± 0.0030 (0.9715)	0.9804 ± 0.0078 (0.9873)	0.9716 ± 0.0032 (0.9720)
$\log(10^{10}A_{\rm s})$	$3.056^{+0.012}_{-0.013}$ (3.052)	$3.064^{+0.013}_{-0.017}$ (3.058)	3.057 ± 0.014 (3.056)
$\tau_{\rm reio}$	$0.0586^{+0.0060}_{-0.0068}$ (0.05654)	$0.0574^{+0.0064}_{-0.0083}$ (0.05122)	0.0586 ± 0.0071 (0.05881)
$r_d h$	100.50 ± 0.60 (100.5)	100.71 ± 0.70 (100.5)	100.47 ± 0.64 (100.5)
S_8	0.8181 ± 0.0091 (0.8161)	$0.829^{+0.013}_{-0.014}$ (0.8378)	0.8183 ± 0.0095 (0.8182)
$\chi^2_{\rm H0}$	17.0	6.3 (**-10.7**)	17.1 (0.1)
$\chi^2_{\rm Planck}$	1014.7	1017.1 (2.4)	1015.1 (0.4)
$\chi^2_{\rm ACT}$	240.4	234.4 (**-6.0**)	240.3 (-0.2)
$\chi^2_{\rm data}$	2312.2	2297.9 (**-14.3**)	2312.5 (0.3)

MCMC fit : constraints on Quintessence from sound speed and K-essence from rate at which energy density drops

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



[Credit: E. Palti 2018]

String Swampland [Vafa 2005]

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

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

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

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

which invalidates the effective action being used.

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

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 ΛCDM as the source of the current acceleration.

Quintessence type models can work, though with model independent constraints of $c < 0.6$, $c < 3.5\,\Delta$.

$$V(\phi) = V_1 e^{\lambda_1 \phi / M_{\mathrm{Pl}}} + V_2 e^{\lambda_2 \phi / M_{\mathrm{Pl}}}$$

[Barreiro, EC, Nunes 2000]

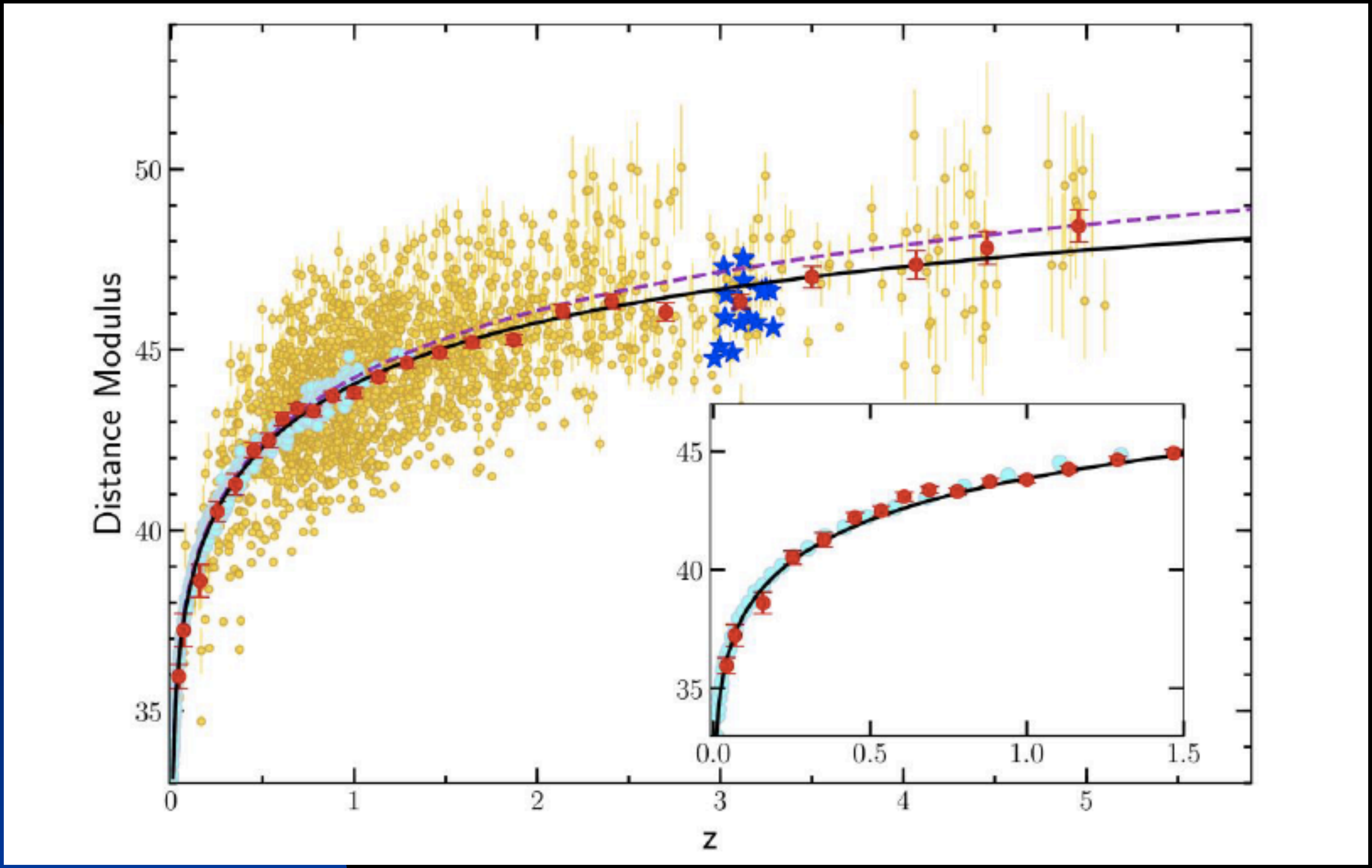
$$\lambda_1 \gg \sqrt{3}, \quad \lambda_2 = c = 0.6$$

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:

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

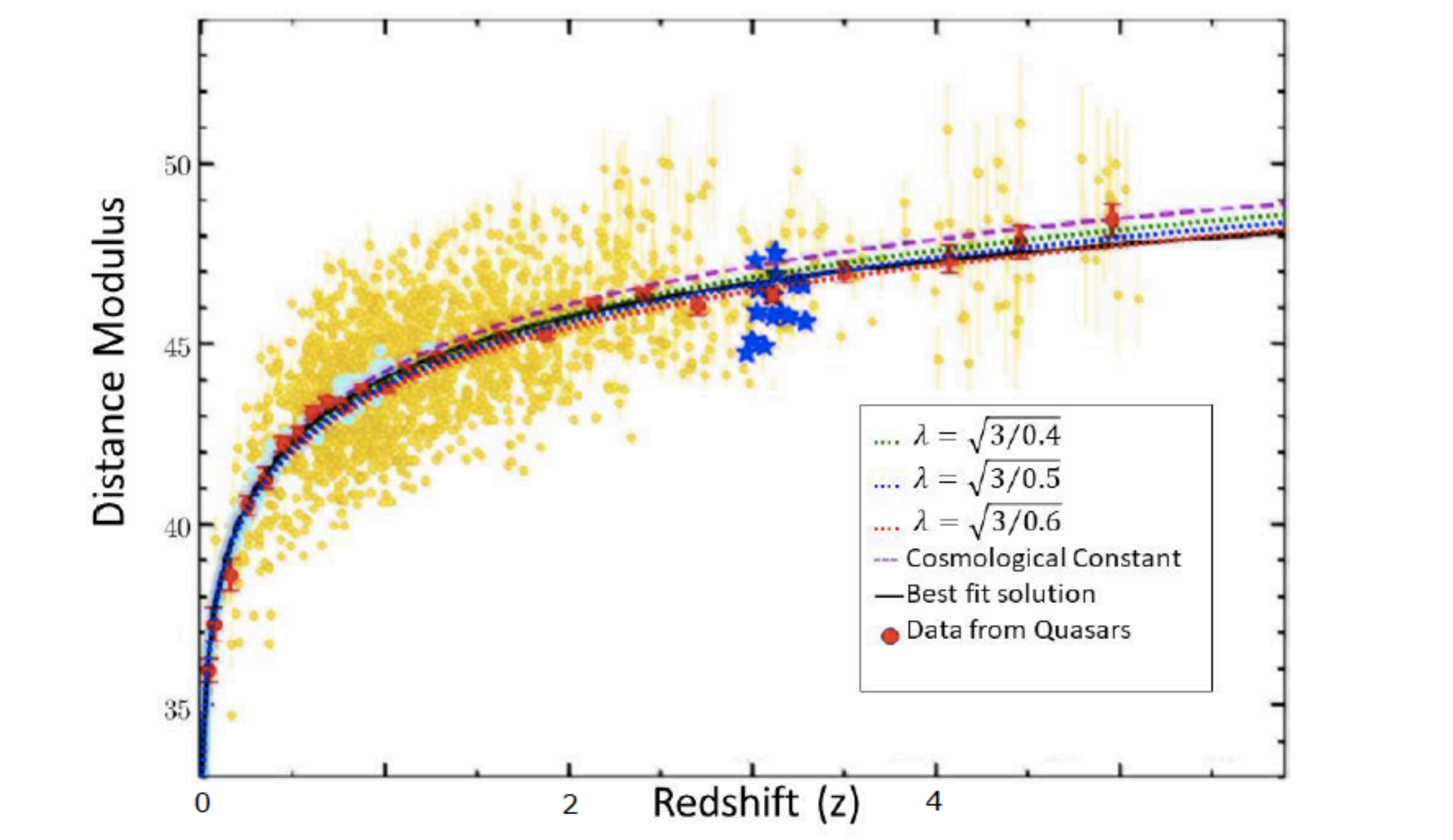
Early days but might lead to genuine new constraints on the nature of dark energy - still somewhat unclear how robust the bound is.

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~5. Inset is comparison to SN (cyan) showing good agreement to z~1.4 with dashed magenta line is ΛCDM with $\Omega_M \sim 0.31 \pm .05$ - extrapolated out to z~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. Quintessence type approaches to the nature of dark energy and the current acceleration of the Universe provides alternative to Landscape - but does not solve the CCP.

2. Need to screen this which leads to models such as axions, Higgs-dilatons, chameleons, non-canonical kinetic terms etc.. -- many of these have their own issues.

3. Atoms are small enough that the chameleon or symmetron field can't react to it quickly enough and they remain unscreened in high vacuum.

4. Galaxy dynamics offer a probe of modified gravity (RAR curve)

5. Higgs portal interactions provide a way of searching for fifth forces through FeynMG.

6. Is the Hubble tension telling us something about dark energy or MG? Time will tell - maybe JWST or LIGO will tell us over the coming years !

7. Is the Swampland telling us something about dark energy?

8. How can we go locally beyond SN1a ? Quasars ?