Dark Energy: Theoretical Developments

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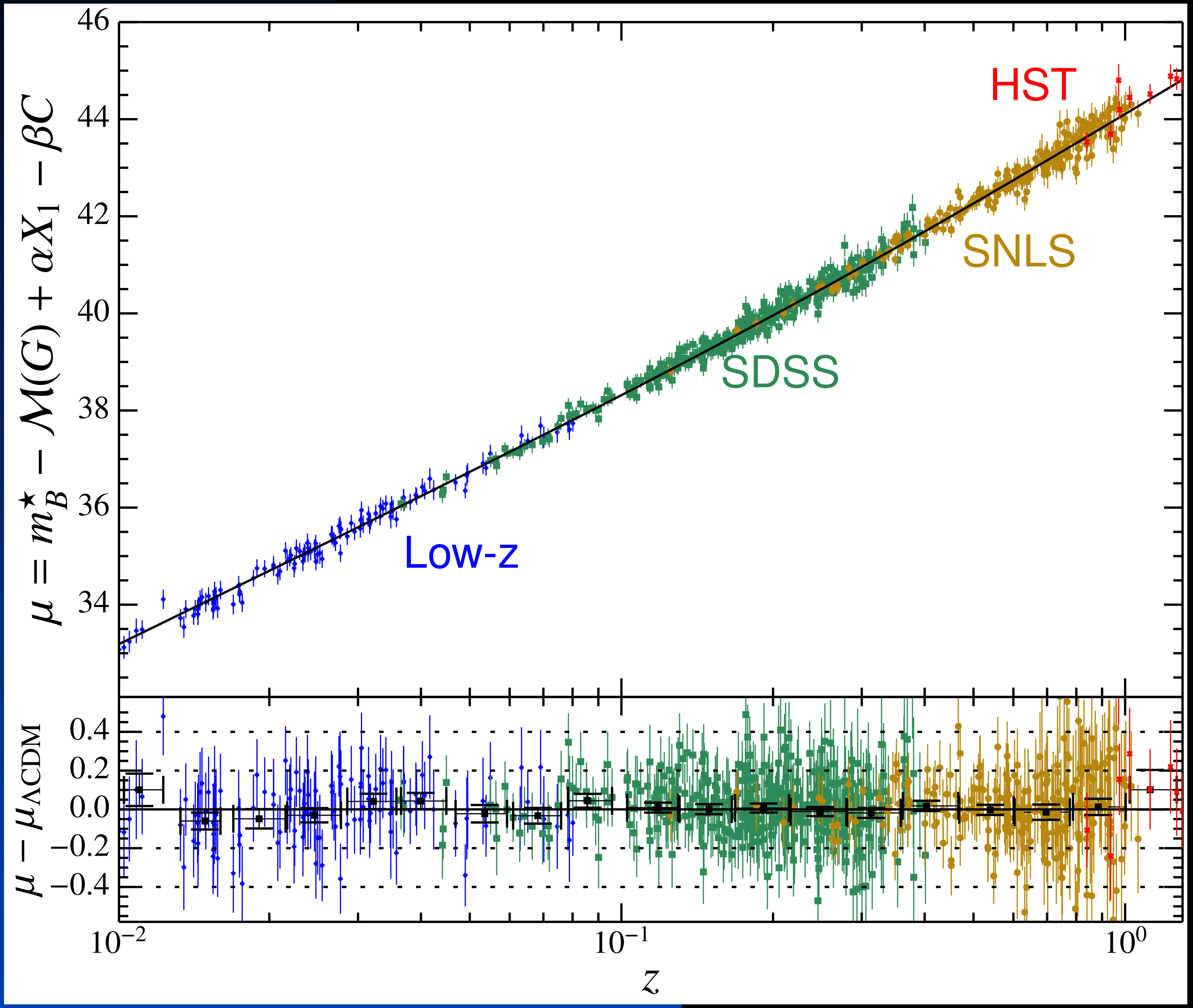
1. Brief recap of evolution of the universe: assumptions and evidence supporting them - pointing out issues where they may occur.
2. Approaches to Dark Energy and Modified Gravity.
3. Testing screening mechanisms in the laboratory.
4. Hubble tension and impact of GW discovery on cosmology.
5. Dark Energy and the String Swampland
6. Recent large z results based on using quasars as standard candles

31st Rencontres de Blois: Particle Physics and Cosmology

June 7th 2019

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=74.03±1.42 km s^{-1} Mpc^{-1}

(Riess et al, 2019)

H_0=67.4±0.5 km s^{-1} Mpc^{-1}

(Planck 2018)

Is there a local v global difference emerging in $\mathbf{H_0}$?

Betoule et al 2014

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

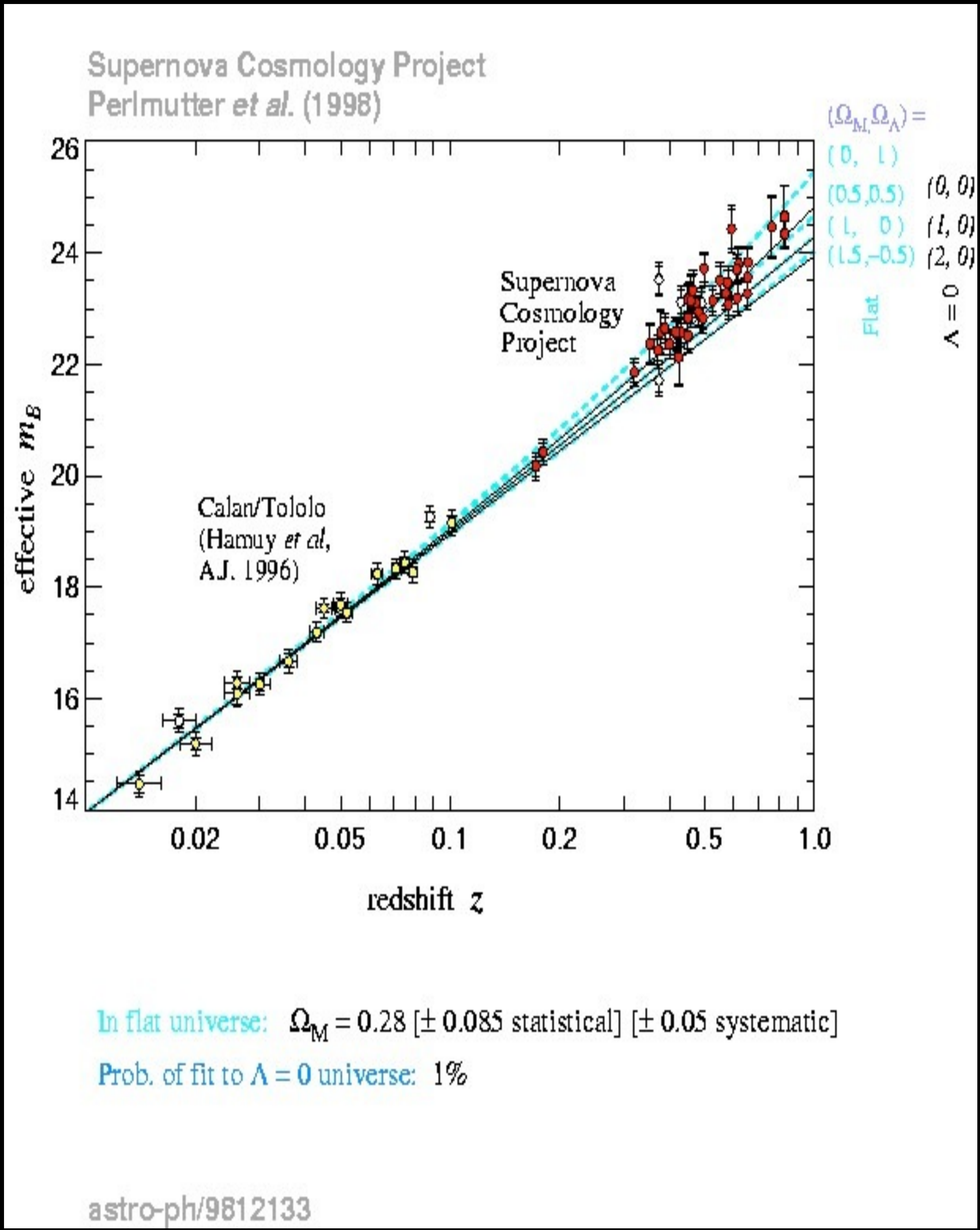
In fact the universe is accelerating !

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



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

Friedmann - the key bgd equation:

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

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

$$\boxed{\begin{array}{c}\text{Energy density } \rho(t): \quad \text{Pressure } p(t) \\ \text{Related through}: p = w\rho\end{array}}$$

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

Eqns (Λ=0):

Friedmann + Fluid energy conservation

$$\boxed{\begin{array}{l} H^2 \equiv \dfrac{\dot{a}^2}{a^2} = \dfrac{8\pi}{3} G\rho - \dfrac{k}{a^2} \\ \dot{\rho} + 3(\rho + p)\dfrac{\dot{a}}{a} = 0 \end{array}}$$

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

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

$$\rho_c(t_0) \equiv 1.88h^2 * 10^{-29}\, gcm^{-3}$$

Critical density

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.

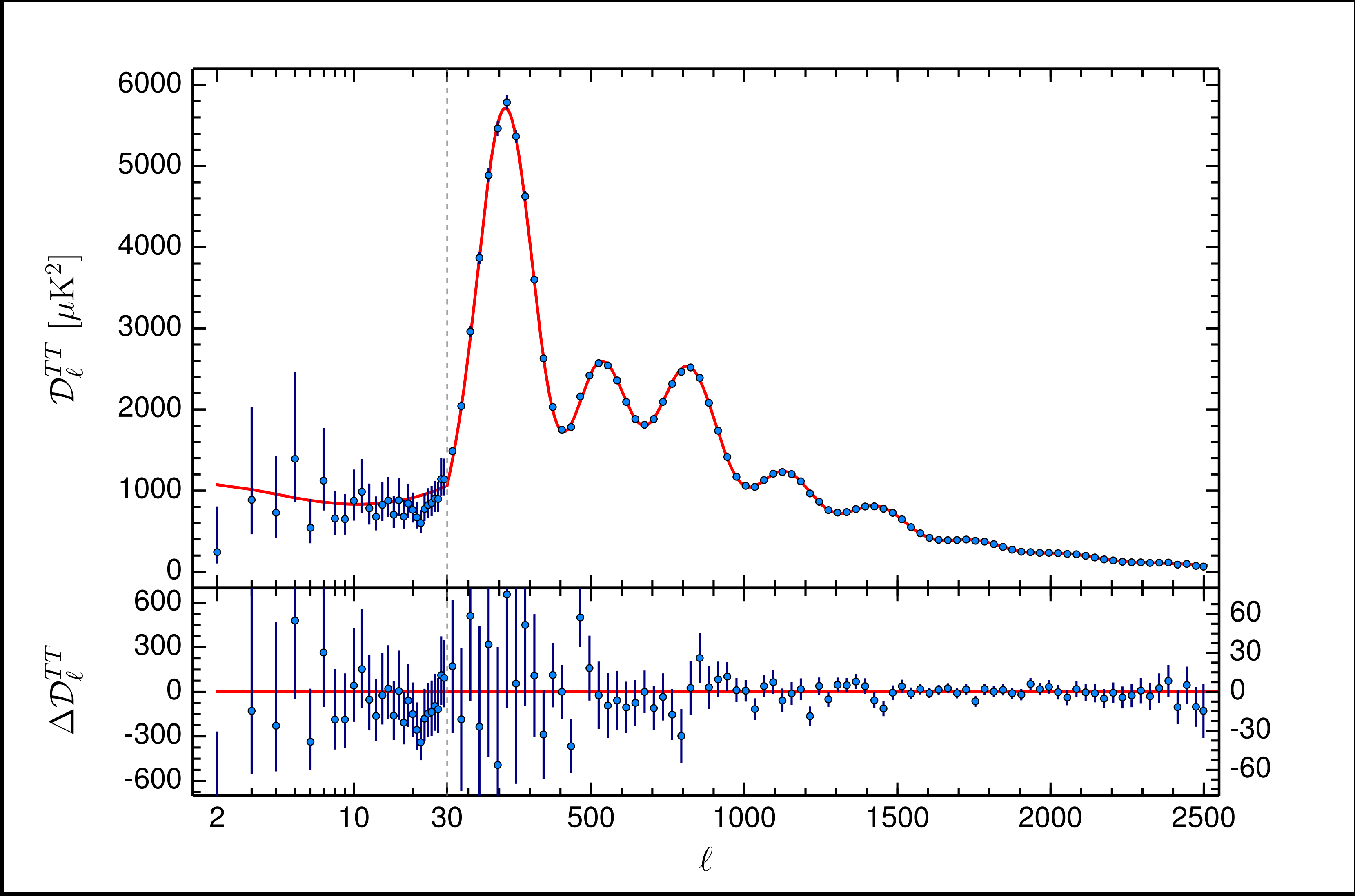
Evidence for Dark Energy?

Enter CMBR:

$$3.\ \Omega_0 = \Omega_m + \Omega_\Lambda$$

Provides clue. 1st angular peak in power spectrum.

$$l_{\text{peak}} \approx \frac{220}{\sqrt{\Omega_0}}$$



Planck TT spectrum (2015)

$$\Omega_k = 0.000 \pm 0.005 \ (95\%\ \text{CL})$$

Planck + Lensing+ BAO consortium 2015

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

Yet to be proposed ...

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 ~ 10^{500} ! Typical separation ~ $10^{-500}\,\Lambda_{pl}$

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 ?

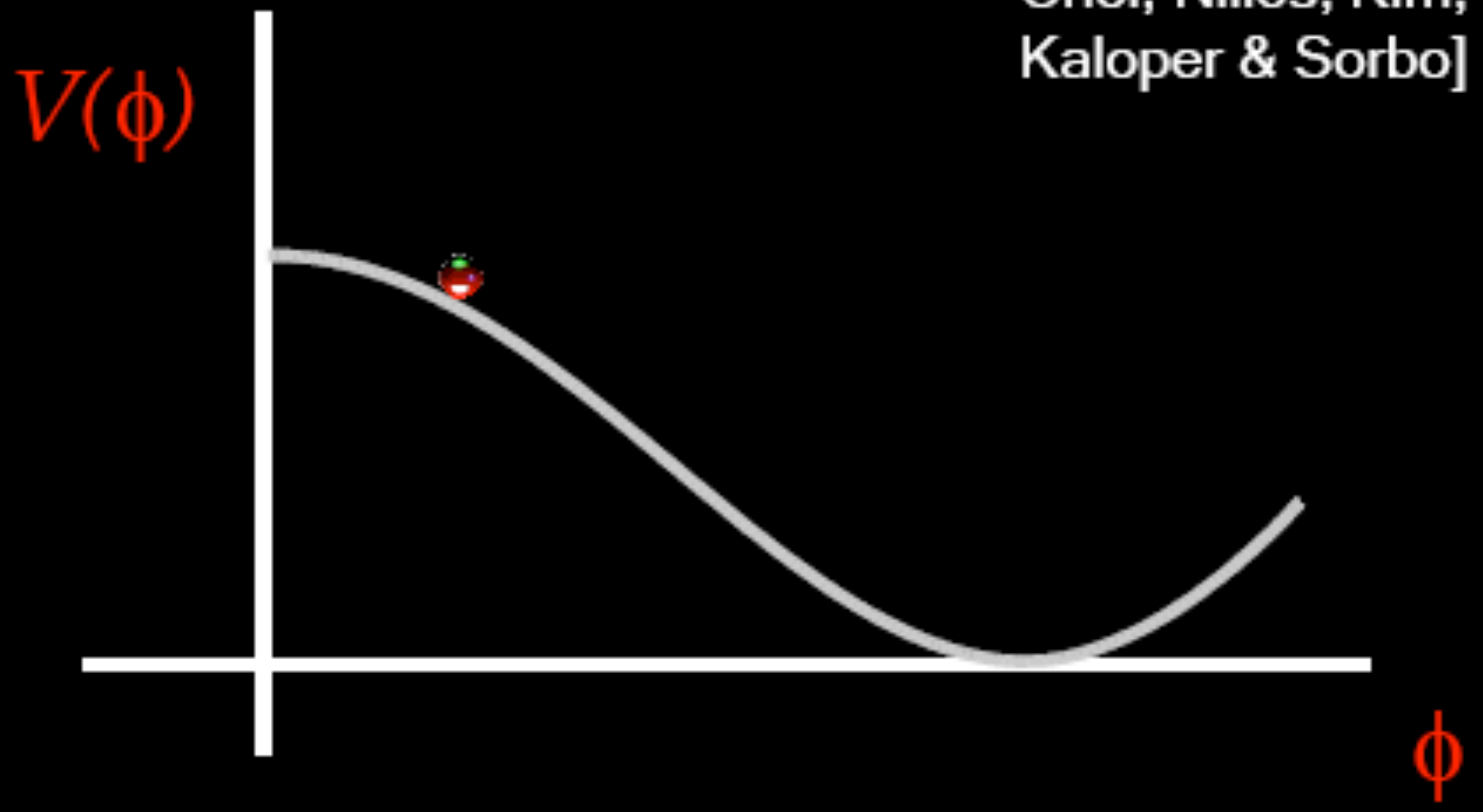
Particle physics inspired models of dark energy ?

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

Leads to naturally small masses, naturally small couplings

[Hill, Freiman, et al; Choi; Nilles; Kim; Kaloper & Sorbo]

Barbieri et al

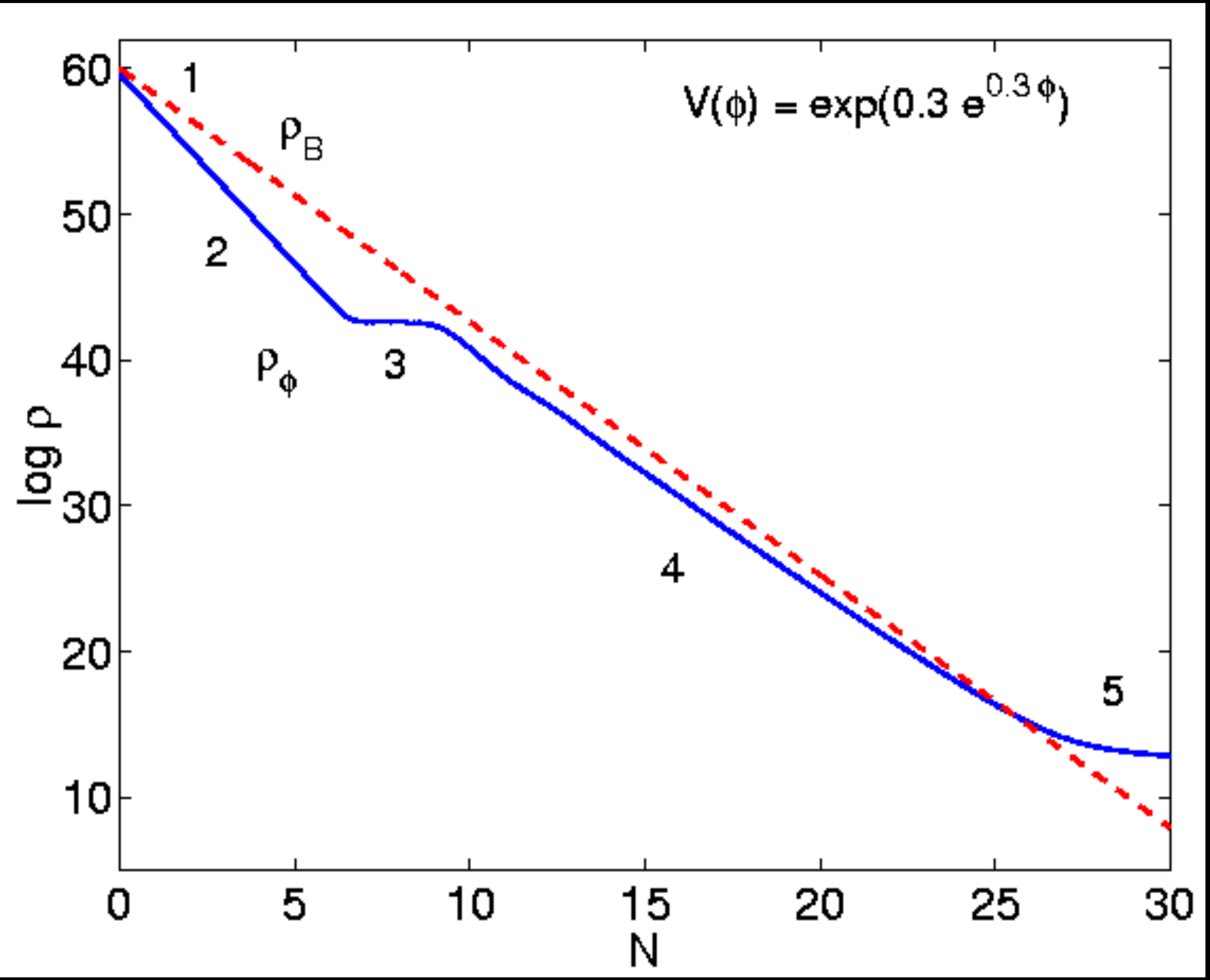


$$V(\phi) = \lambda^4 (1 + \cos(\phi / F_a))$$

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

Slowly rolling scalar fields Quintessence - Generic behaviour

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

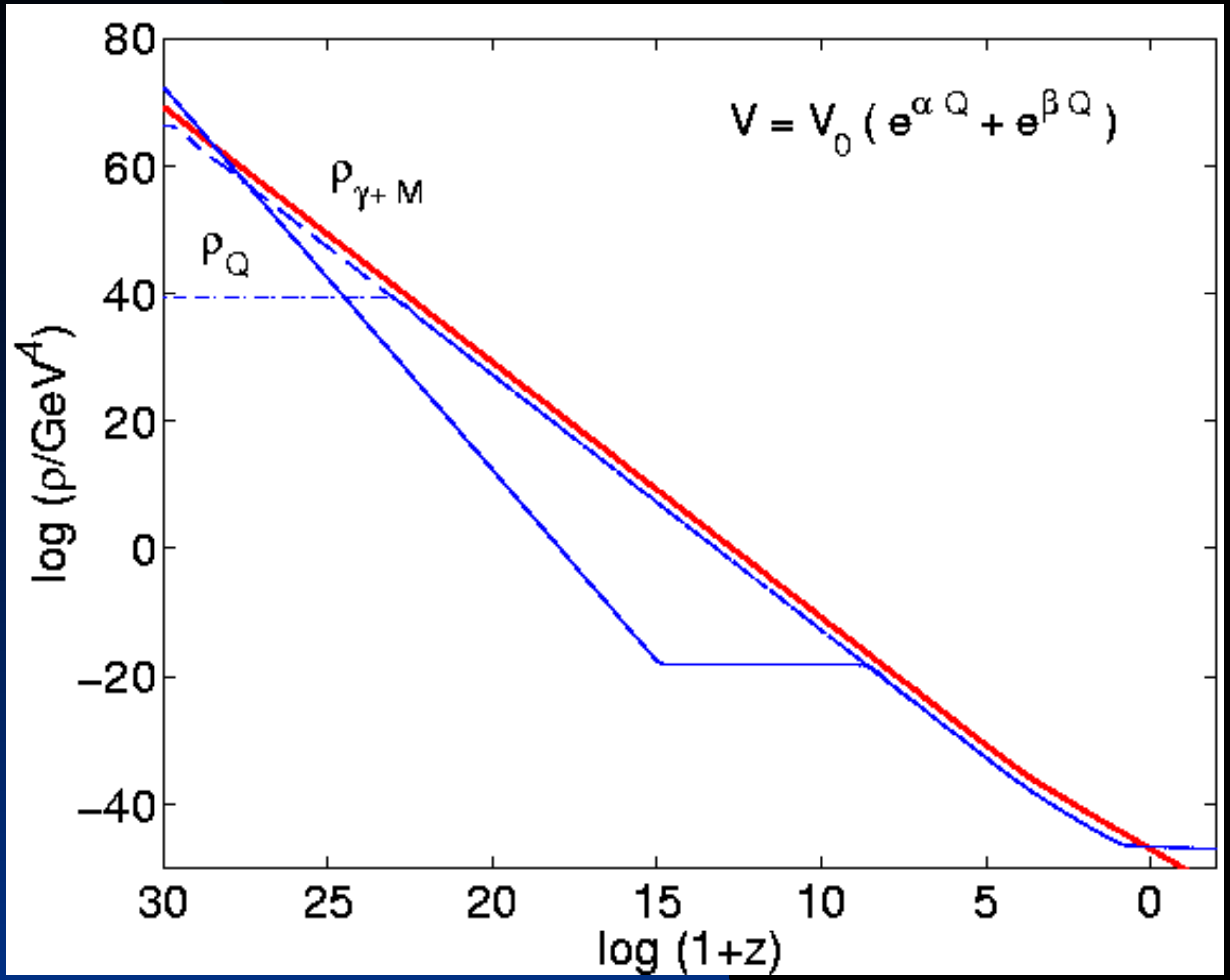


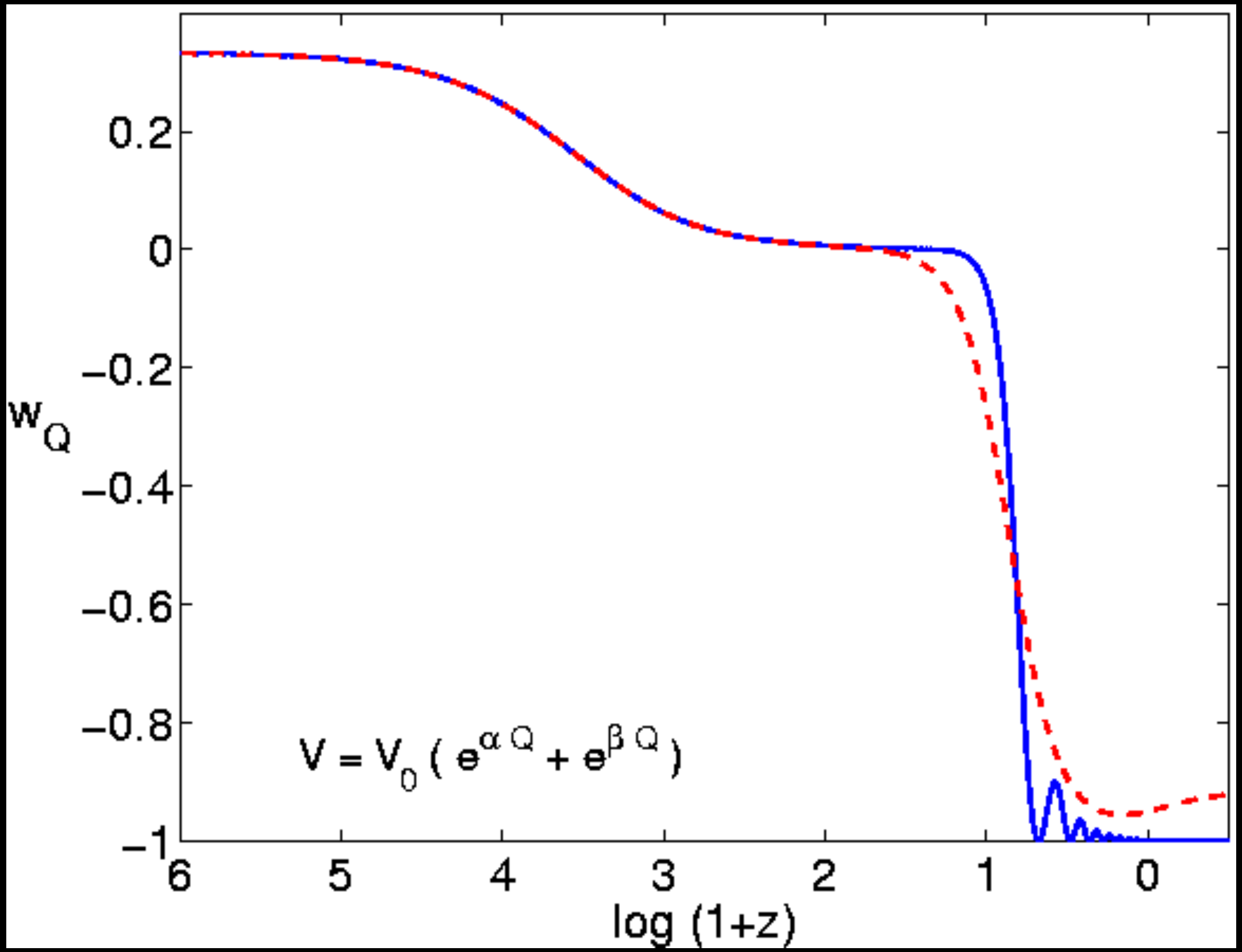
Nunes

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.

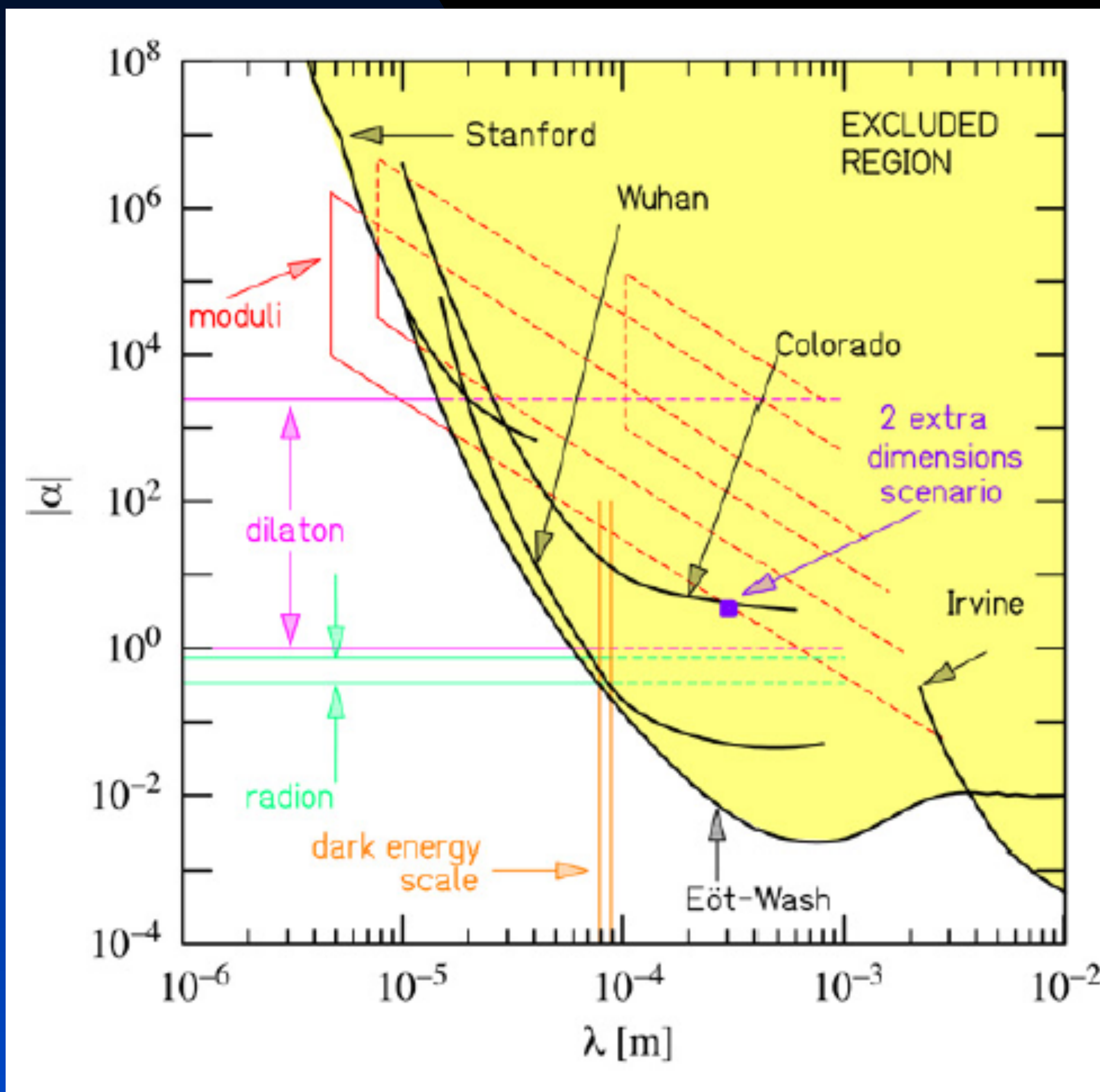
Fine tuning: $V_0 \approx \rho_\phi \approx 10^{-47}\ \mathrm{GeV}^4 \approx (10^{-3}\ \mathrm{eV})^4$

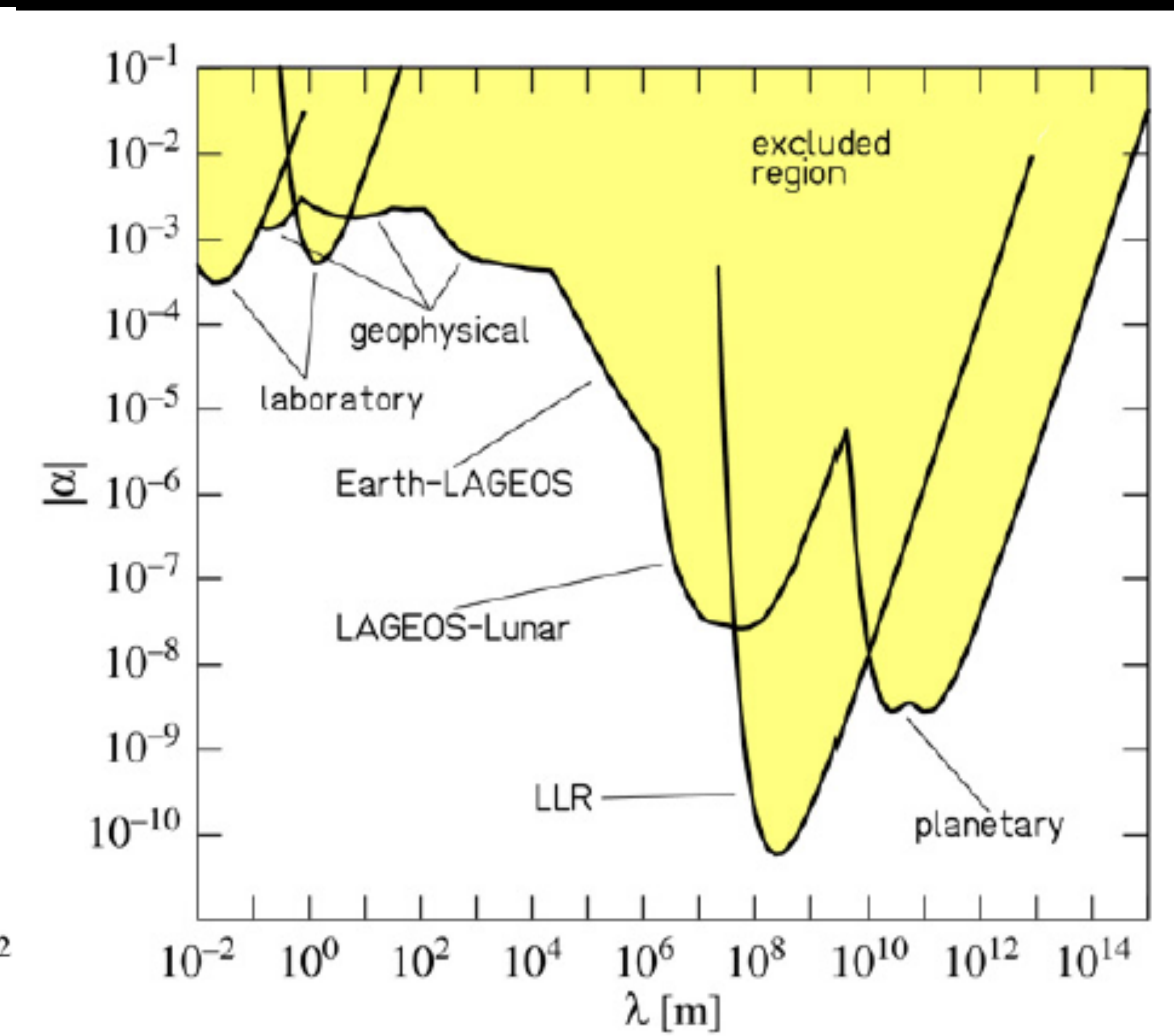
Mass: $m \approx \sqrt{\frac{V_0}{M_{pl}^2}} \approx 10^{-33}\ \mathrm{eV}$

Generic issue Fifth force - require screening mechanism!

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

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 ...]

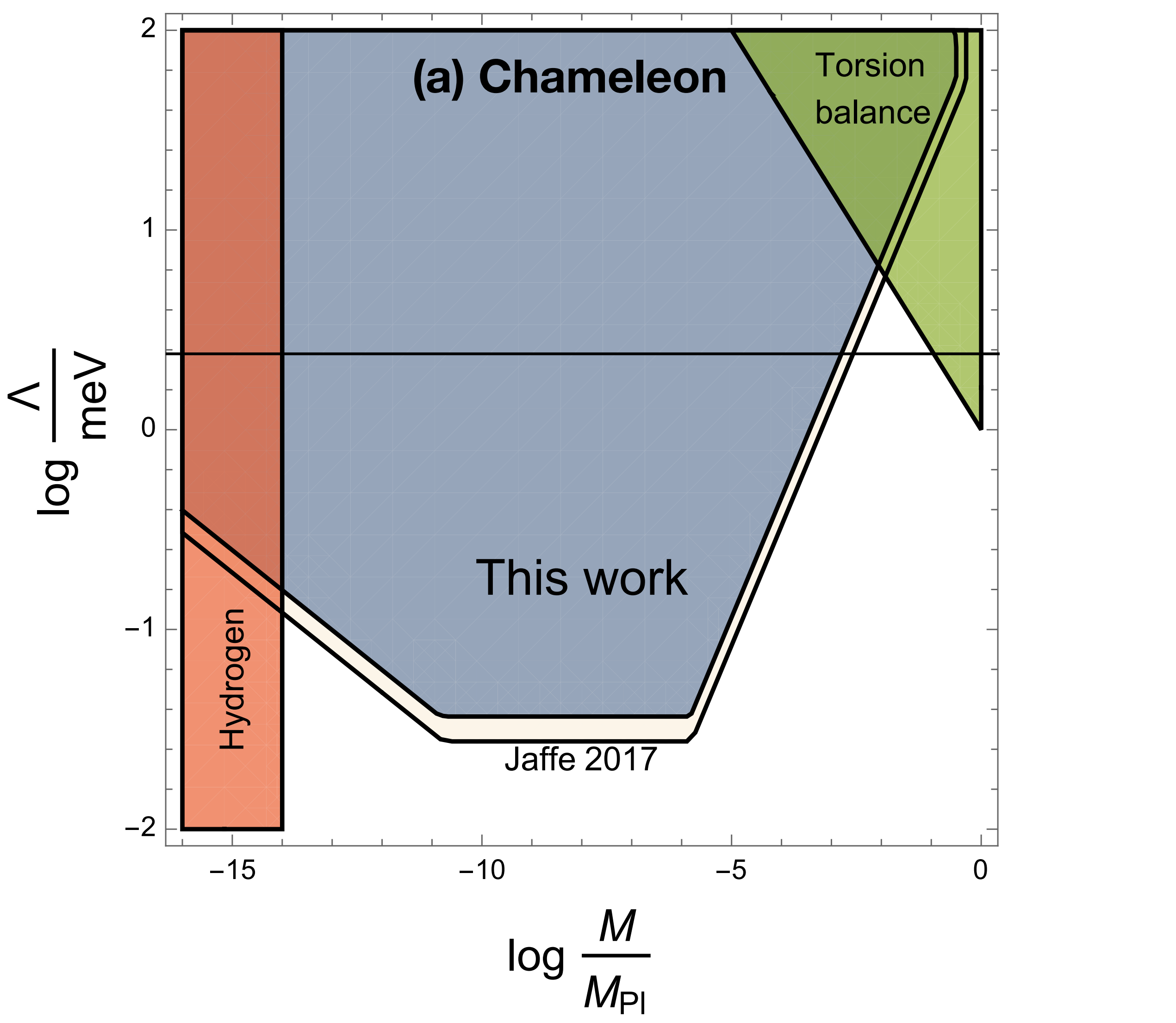
vev of scalar field depends on local mass density: vev large in low density regions and small in high density regions. Also coupling of scalar to matter is prop to vev, so couples with grav strength in low density regions but decoupled and screened in high density regions.

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 !

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



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

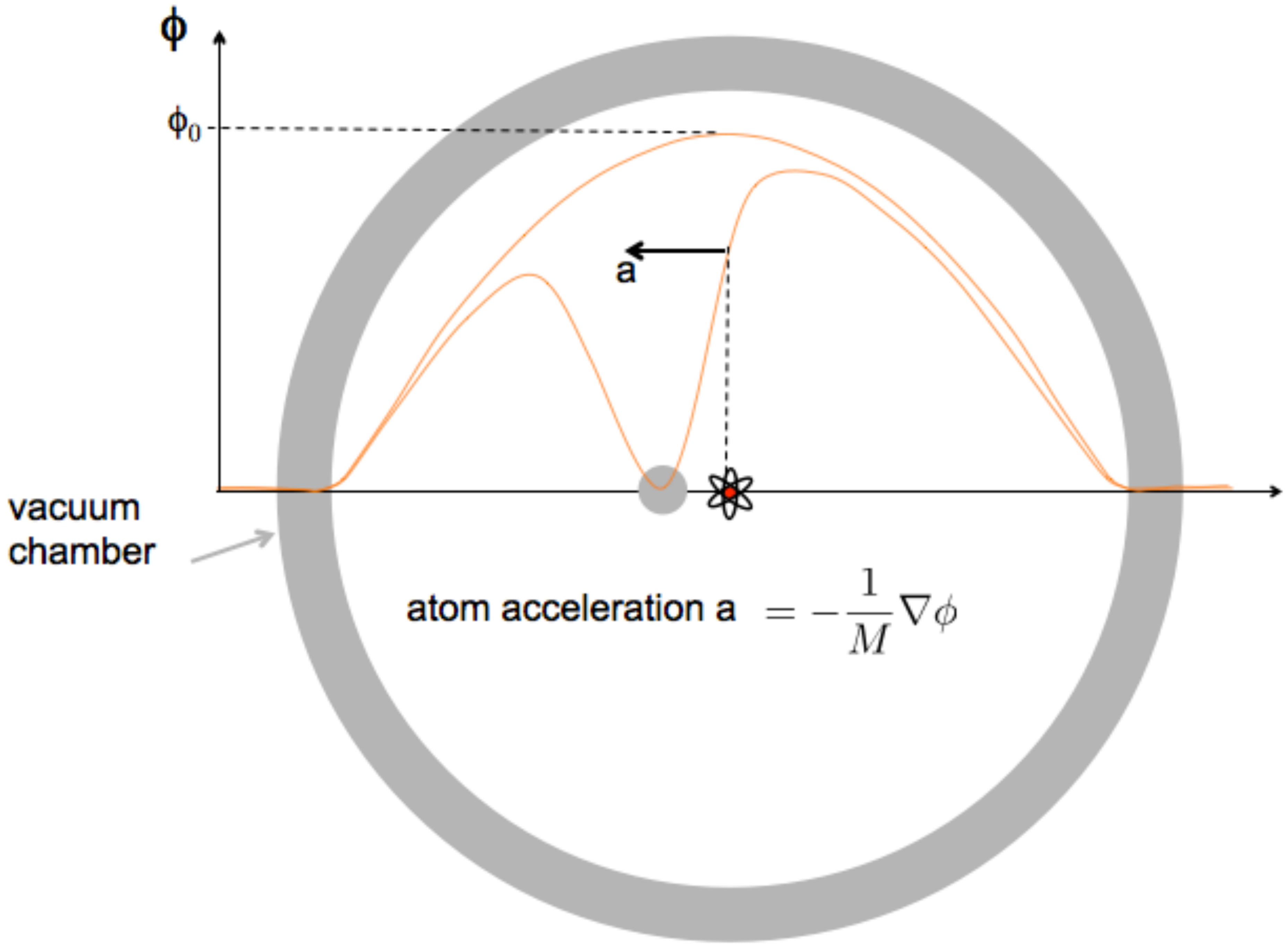
$$\lambda_i = 1 \text{ for } \rho_i R_i^2 < 3M\phi_{bg}$$

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

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

[Sabulsky et al 2019]

Measure ϕ in a high vacuum chamber



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

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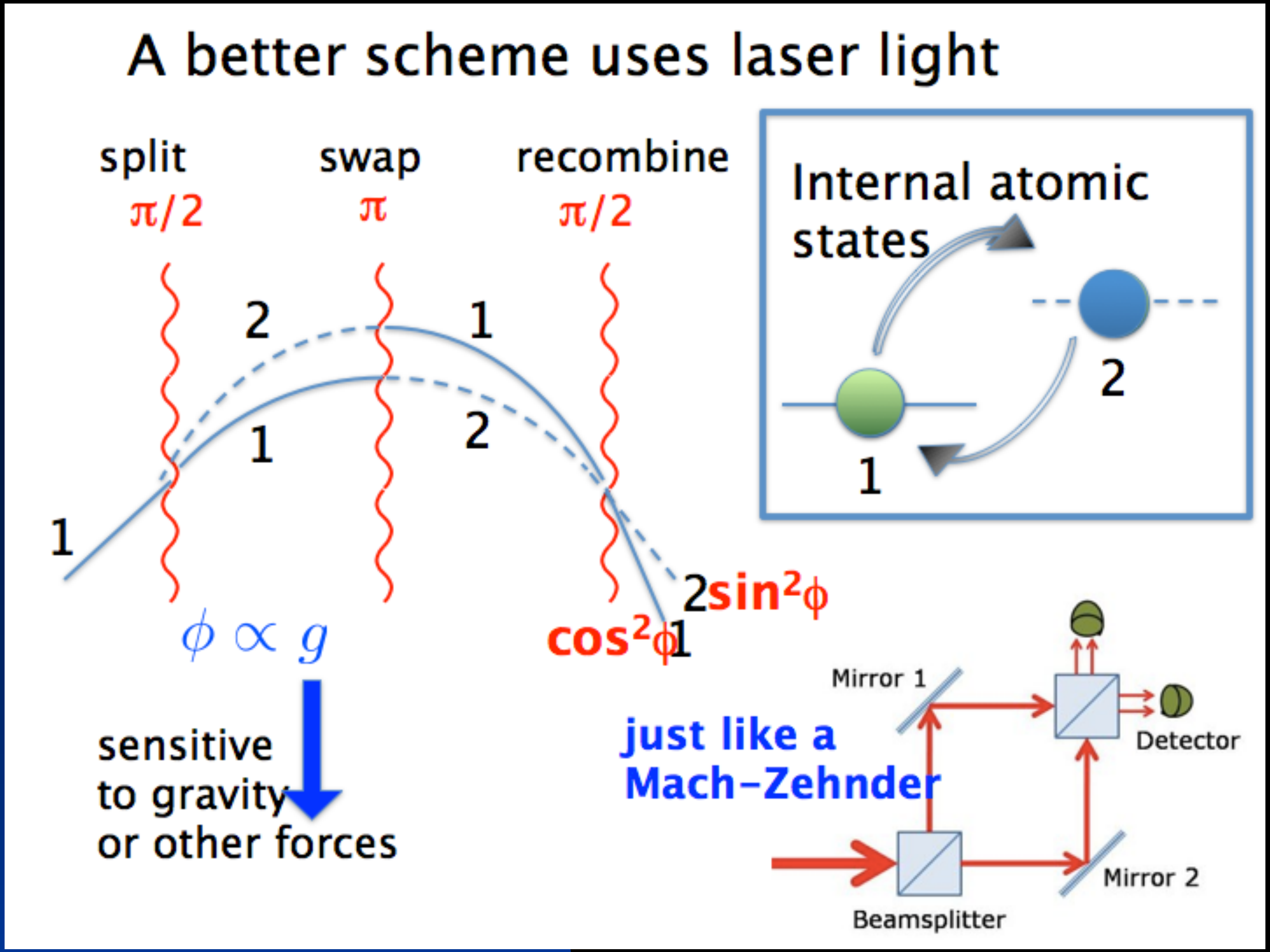
Our proposal uses Atom Interferometry of atoms in free fall [Burrage, EC, Hinds 2015]



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

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

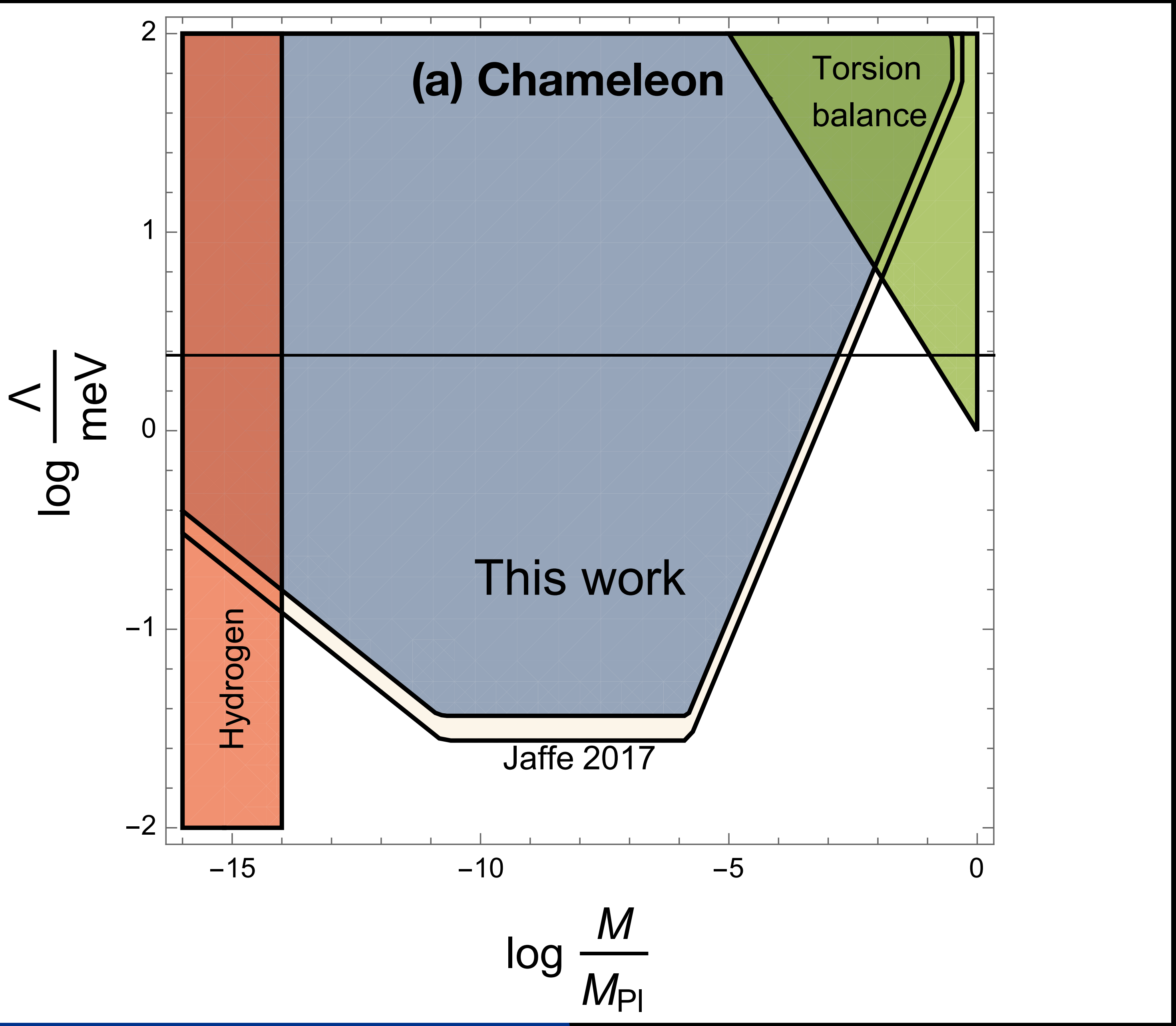
Ed Hinds

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

T – –time interval between pulses

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

Sensitivity to acc'n of rubidium atoms due to sphere placed in Chamber radius 10cm, Pressure 10^{-10} Torr



[Sabulsky et al 2019]

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

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

Systematics:

Stark effect, Zeeman effect, Phase shifts due to scattered light, movement of beams - negligible at 10^{-6} g and controllable for 10^{-9} g

Accn due to chameleon force outside an Al sphere of radius R_A = 19mm and screening factor $\lambda_A \ll 1$.

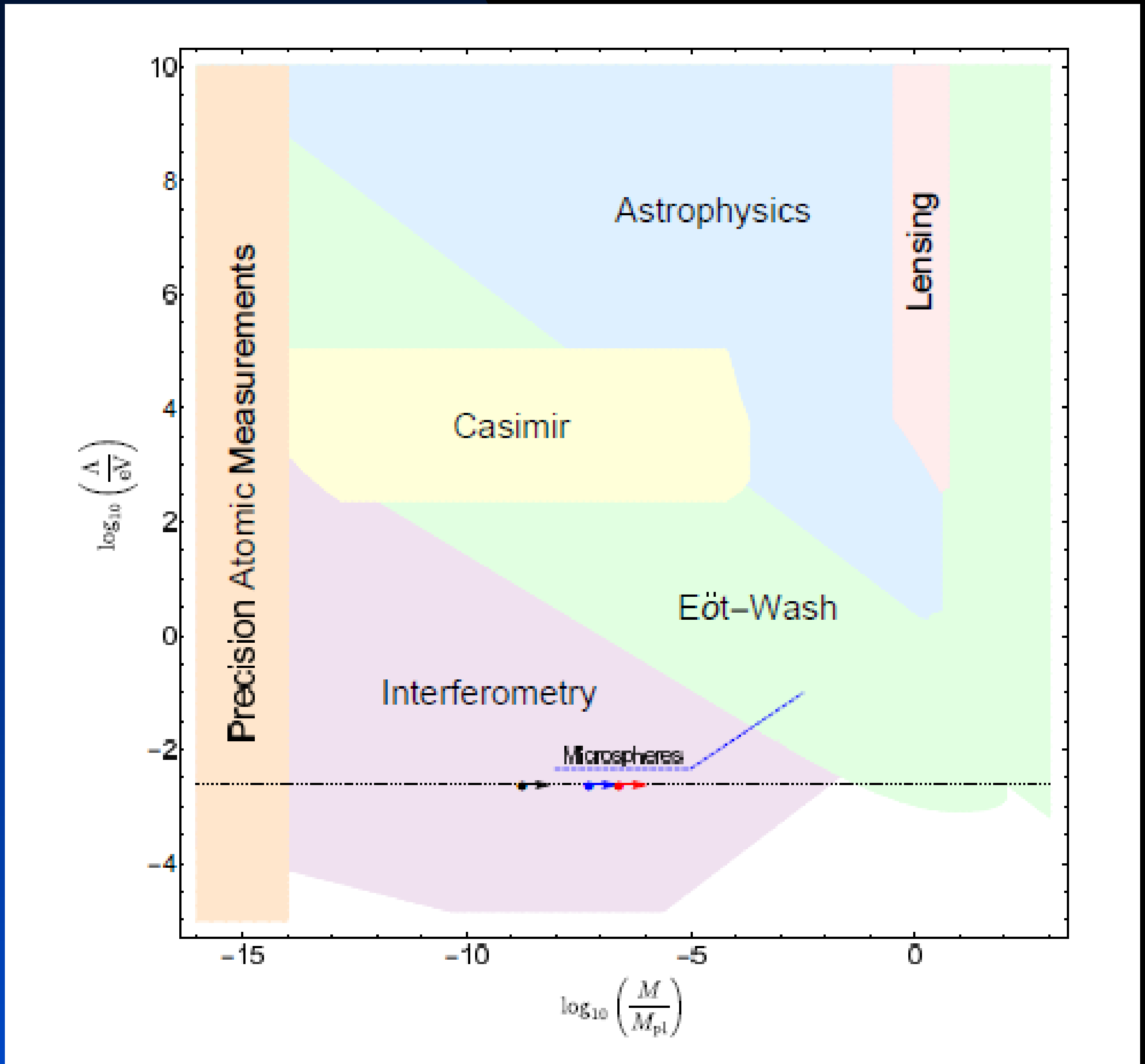
Λ-M area above solid black line excluded by atom interferometry expt measuring 10^{-6} g - easy !

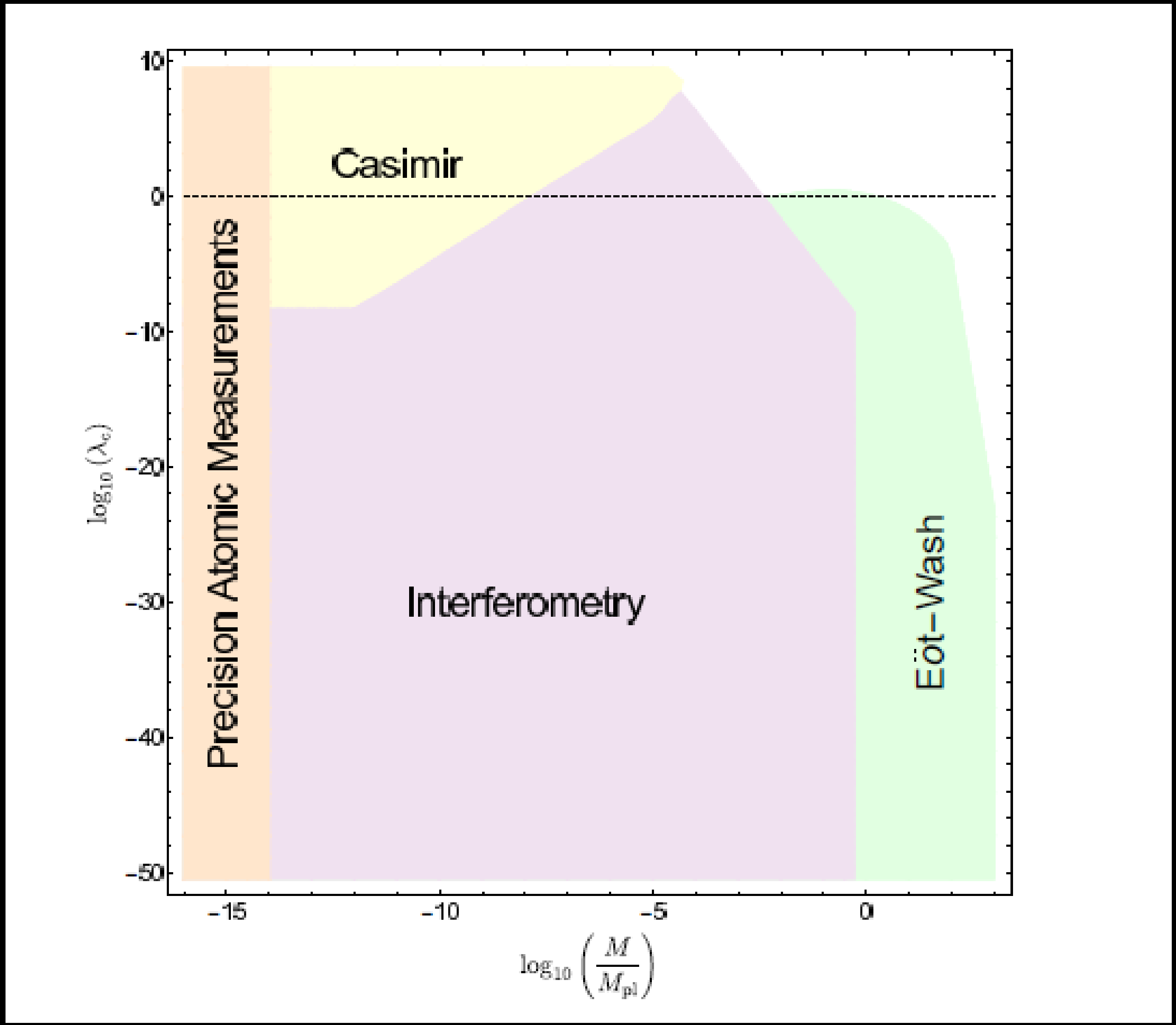
Our result indicates acceleration due to chameleon < 18 x10^{-9} g (90% CL) - can reach M_P !

Combined chameleon constraints [Burrage & Sakstein 2017]

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

$$V(\phi) = \frac{\Lambda^5}{\phi} \qquad\qquad V(\phi) = \frac{\Lambda}{4}\phi^4$$





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, ...]

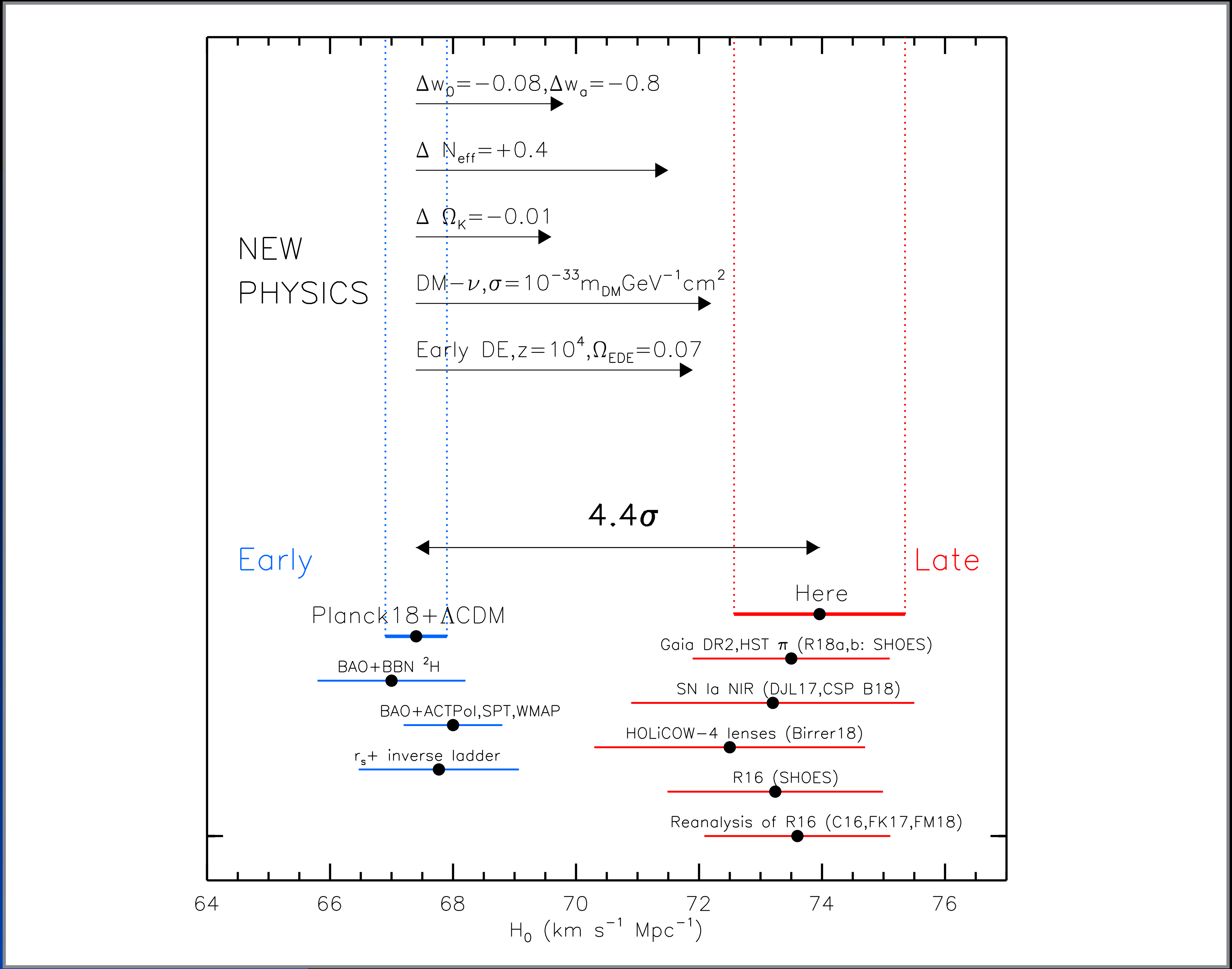
- Modified source gravity -- gravity depends on nonlinear function of the energy.
- Gravity based on the existence of extra dimensions -- DGP gravity

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 -- recent examples being Galileon models

Brief return to Hubble tension - local v global

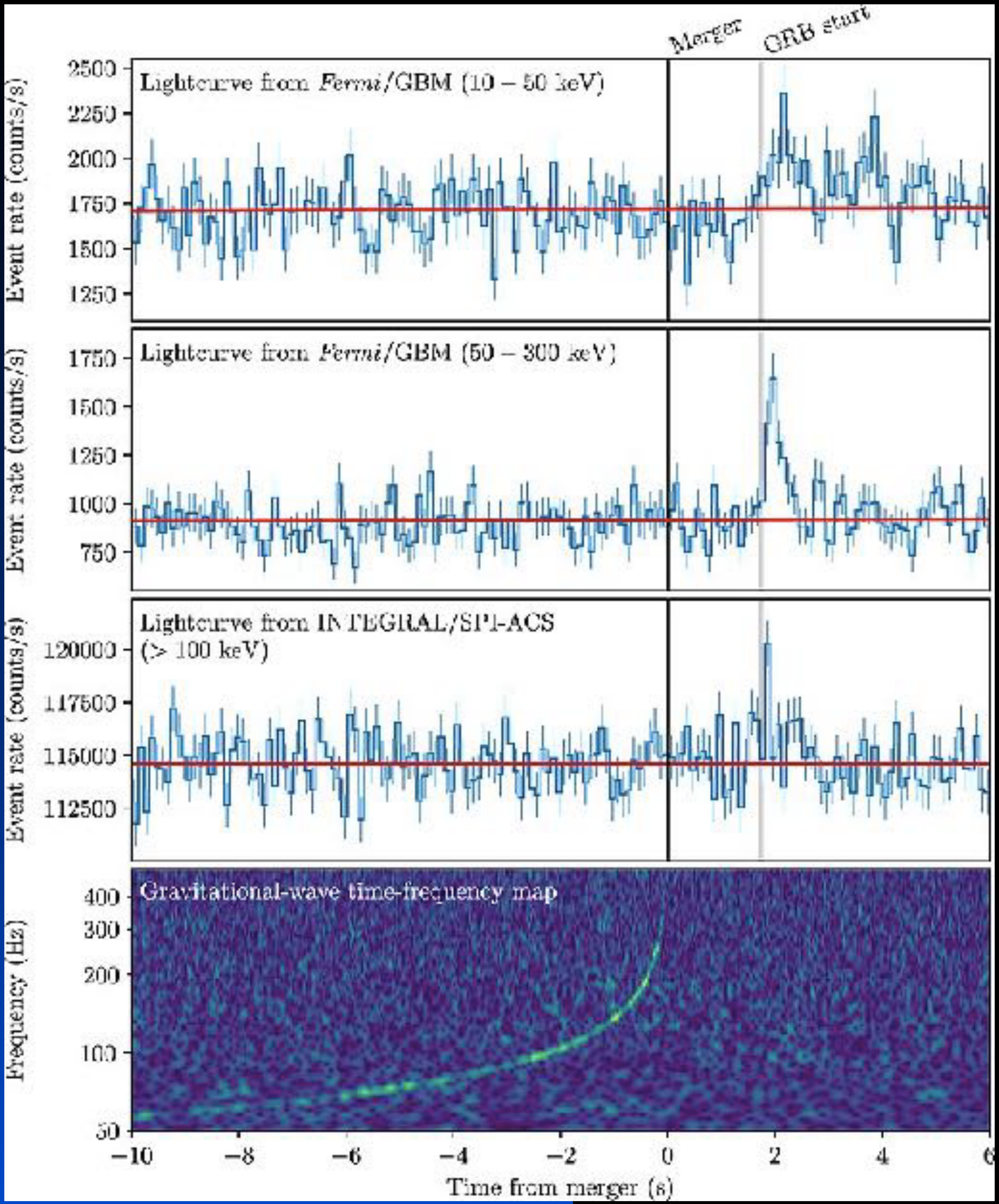


[Riess et al 2019]

H_0=67.4±0.5 km s^{-1} Mpc^{-1} (Planck) v H_0=74.03±1.42 km s^{-1} Mpc^{-1} (Riess)

Can the two values be reconciled with MG or Dynamical DE for example? There are models out there doing it, for example early dark energy but is it a real tension ?

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



GW 170817 and GRB 170817A

speed of GW waves

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

$$\Delta t \simeq 1.7s$$

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

Credit: LIGO-VIRGO Collaboration.

Implication for scalar-tensor theories - [Horndeski (1974), Deffayet et al 2011]

Lagrangian couples field and curvature terms: $\mathcal{L} = \sum_{i=2}^{5} \mathcal{L}_i$

$$\mathcal{L}_2 = K \qquad \mathcal{L}_3 = -G_3 \Box\phi$$

$$\mathcal{L}_4 = G_4 R + G_{4,X}\left[(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\right]$$

$$\mathcal{L}_5 = G_5 G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,X}\left[(\nabla\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\phi\Box\phi + 2\nabla^\nu\nabla_\mu\phi\nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi\right]$$

where $G_i = G_i(\phi, X)$ and $X = -\nabla^\mu\phi\nabla_\mu\phi/2$

Linearise theory and map to alpha parameter :

$$M_*^2 \alpha_T = 2X\left[2G_{4,X} - 2G_{5,\phi} - (\ddot{\phi} - H\dot{\phi})G_{5,X}\right]$$

$$M_*^2 = 2(G_4 - 2XG_{4,X} + XG_{5,\phi} - H\dot{\phi}XG_{5,X})$$

Recall:

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

Many authors assumed the following saying they held barring fine-tuned cancellation:

$$G_{4,X} = G_{5,\phi} = G_{5,X} = 0$$

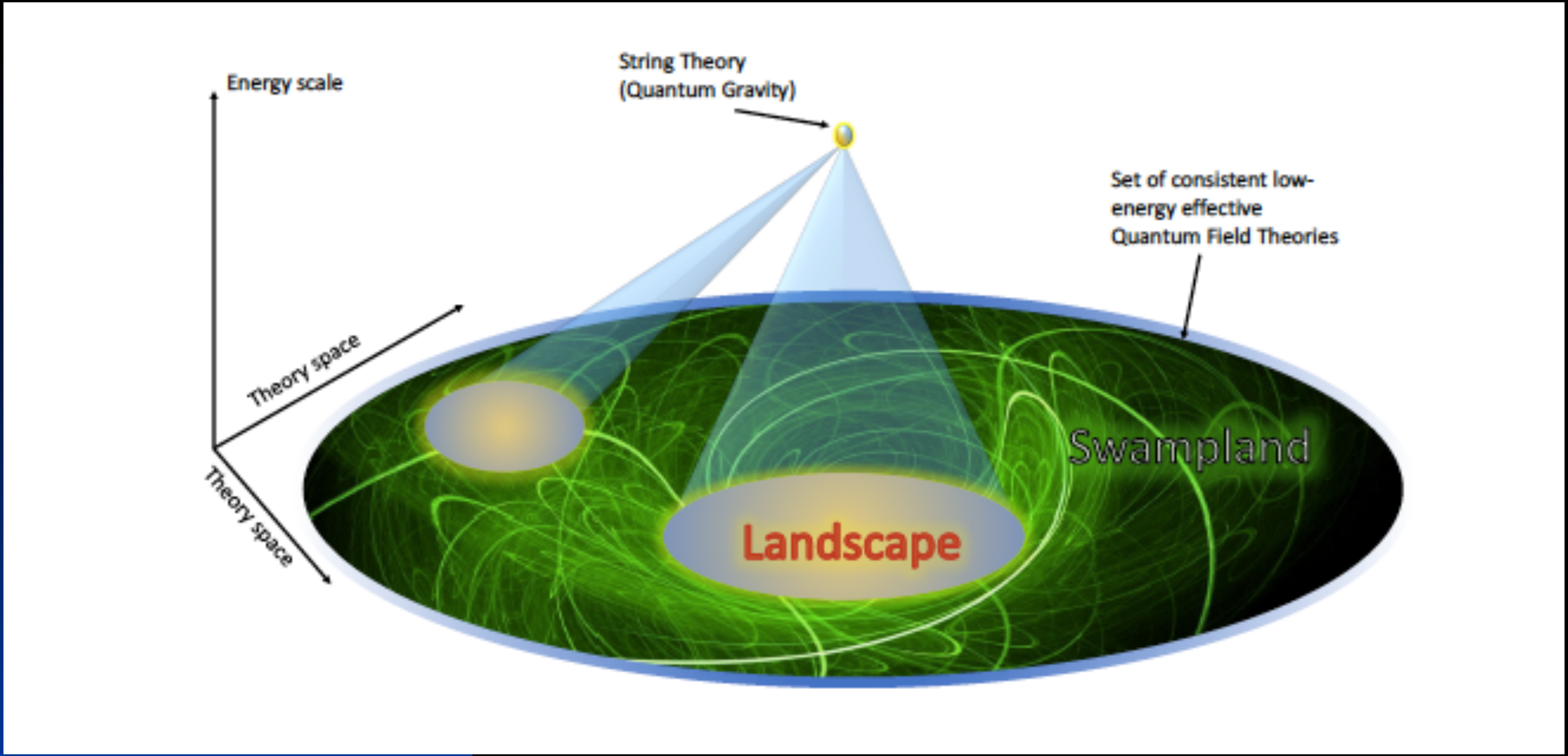
This of course satisfies the bound meaning any model that satisfies those conditions (such as GR, f(R), Quintessence) is perfectly viable.

Creminelli & Vernizzi (2017), Baker et al (2017), Sakstein & Jain (2017), Ezquiaga & Zumalacárregui (2017) — all same edition of PRL (2018)

Crucially though it does not imply that models that do not satisfy the assumptions are ruled out !

Copeland et al, PRL (2019)

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 work well 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]

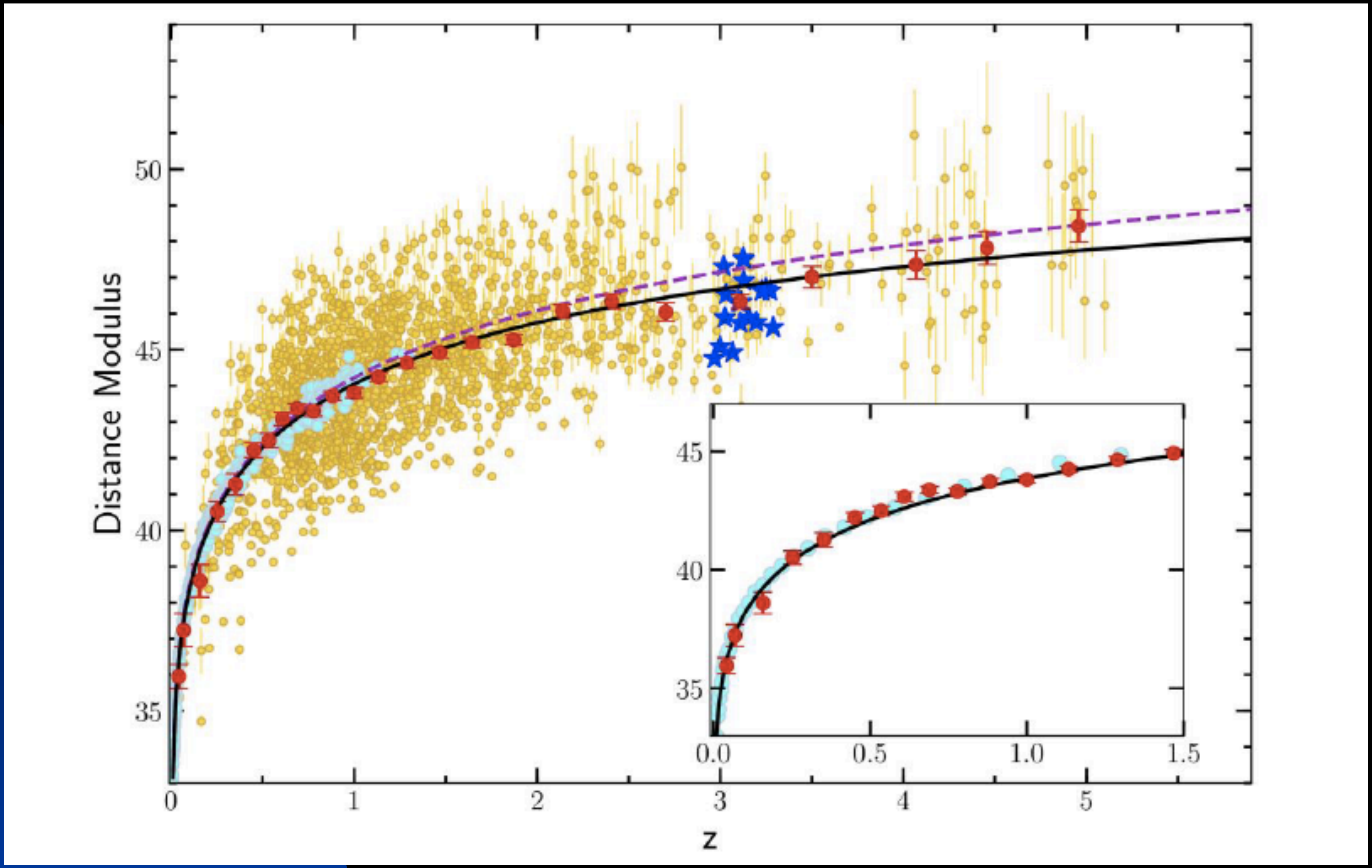
$$\lambda_1 \gg \sqrt{3}, \quad \lambda_2 = c = 0.6$$

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:

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

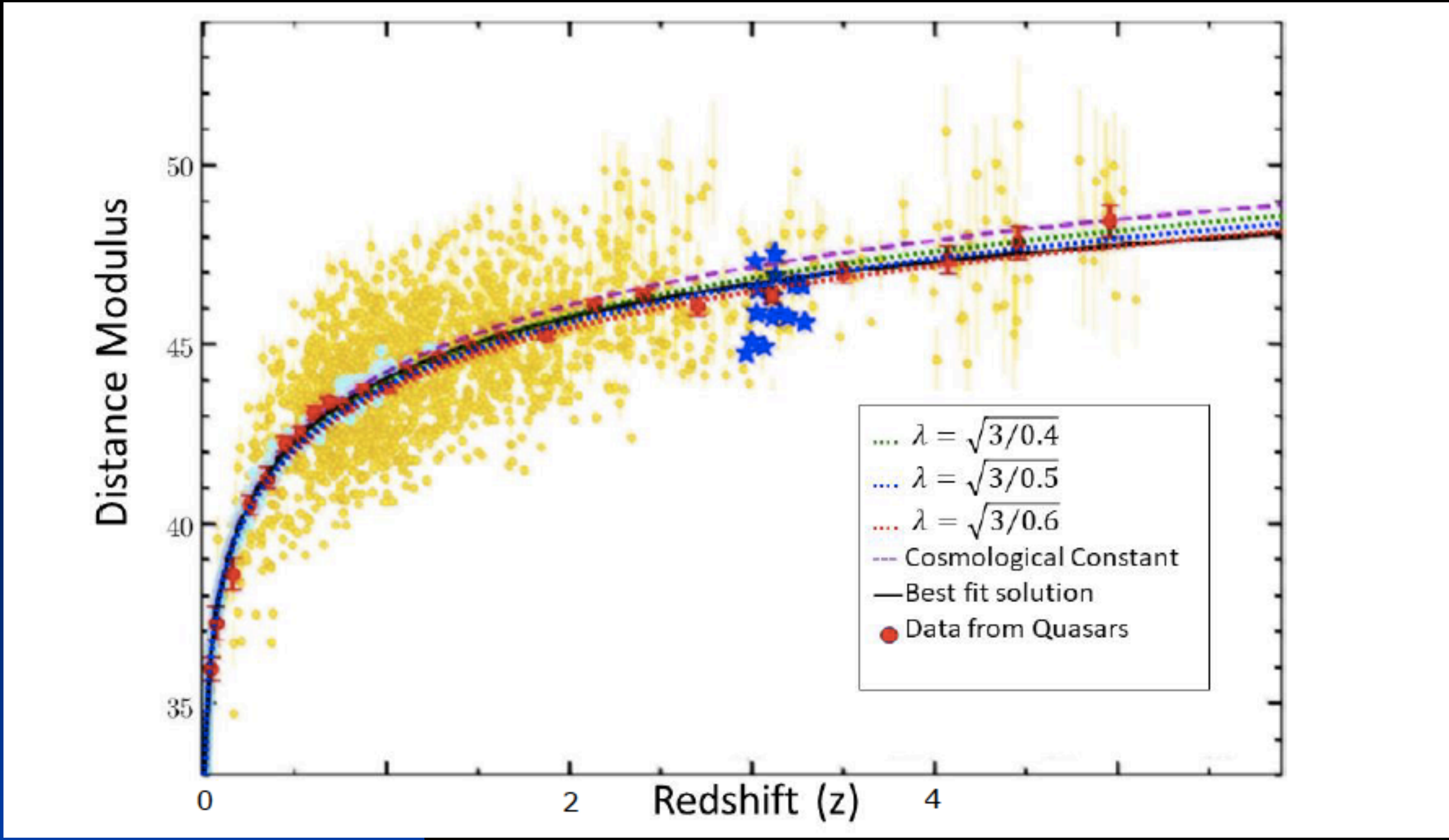
Early days but might lead to genuine new constraints on the nature of dark energy - still somewhat unclear how robust the bound is.

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 !

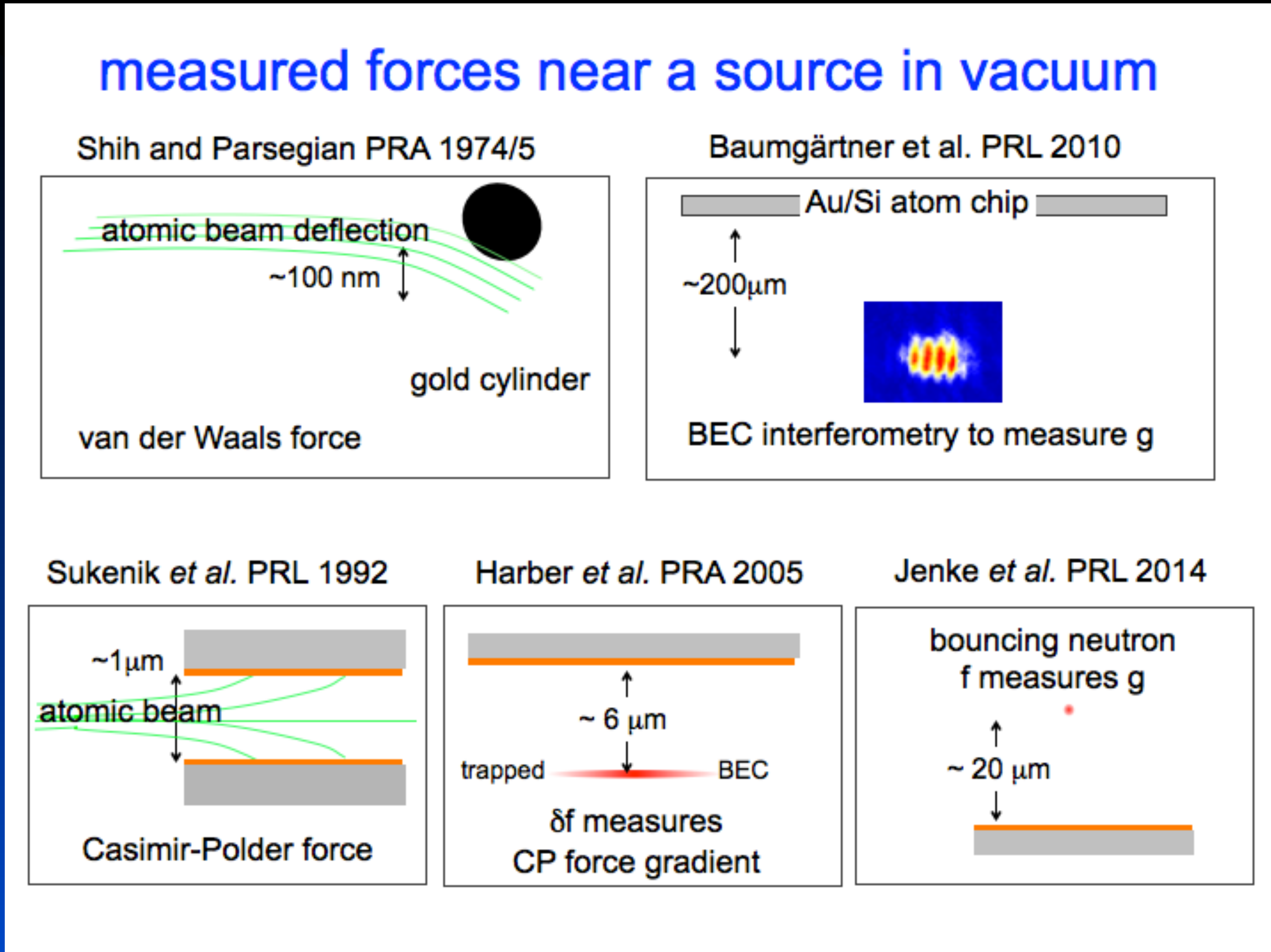
Conclusions

1. Quintessence type approaches to the nature of dark energy and the current acceleration of the Universe provides alternative to Landscape.
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 field can't react to it quickly enough and they remain unscreened in high vacuum.
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.
5. Is the Hubble tension telling us something about dark energy or MG? Time will tell - maybe LIGO will tell us !
6. Is the Swampland telling us something about dark energy?
7. How can we go locally beyond SN1a ? Quasars ?

Thankyou for listening.

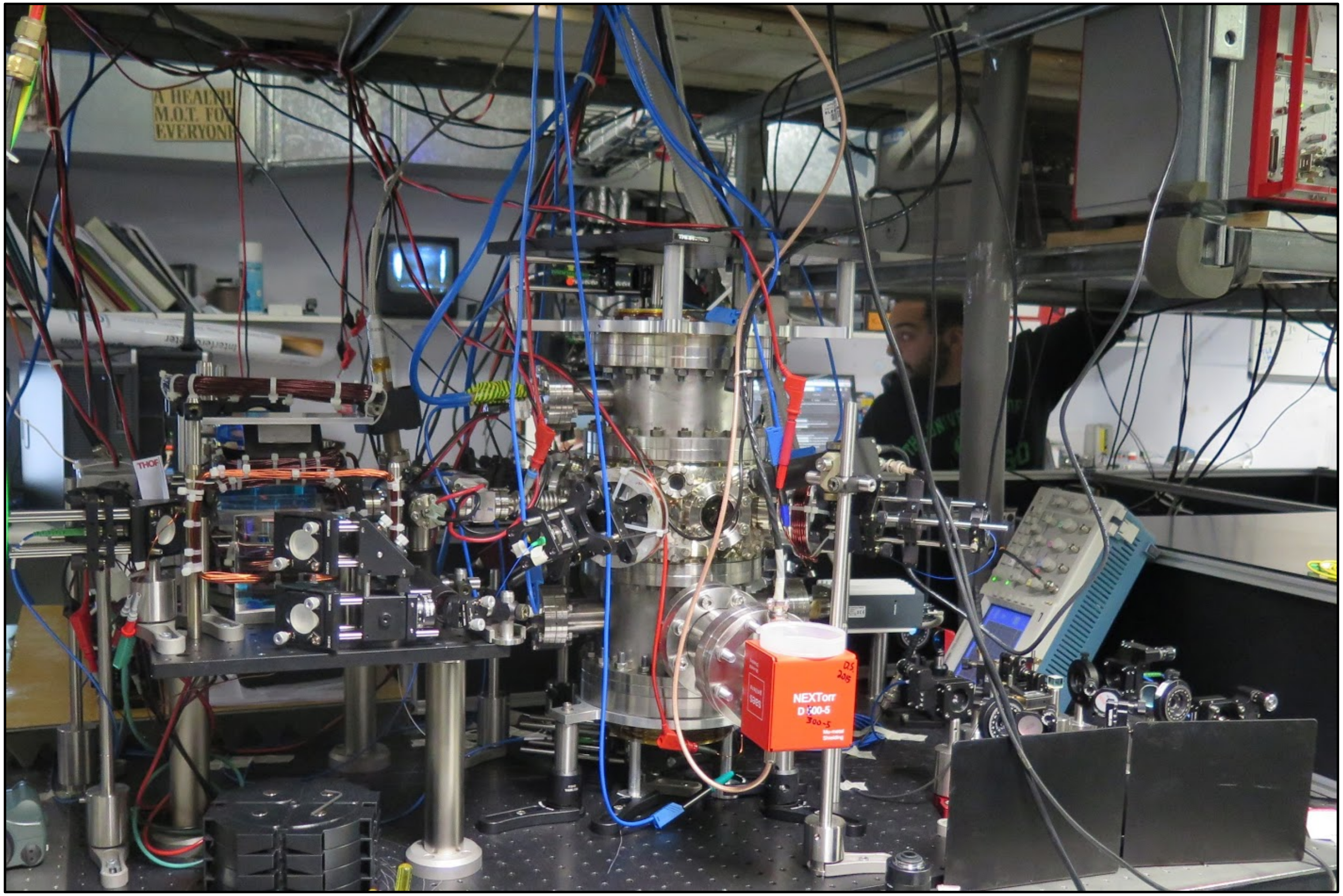
Extra slides in case of emergency

We can constrain the chameleon with any measurement of interactions between atoms and macroscopic objects/surfaces in high vacuum environments



Chameleon experiment constructed at Imperial College

Centre for Cold Matter (Ed Hinds group)



Experiment rotated by 90 degrees from the Berkeley experiment - no sensitivity to Earth's gravity

[Dylan Sabulsky, Indranil Dutta and Ed Hinds]

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

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

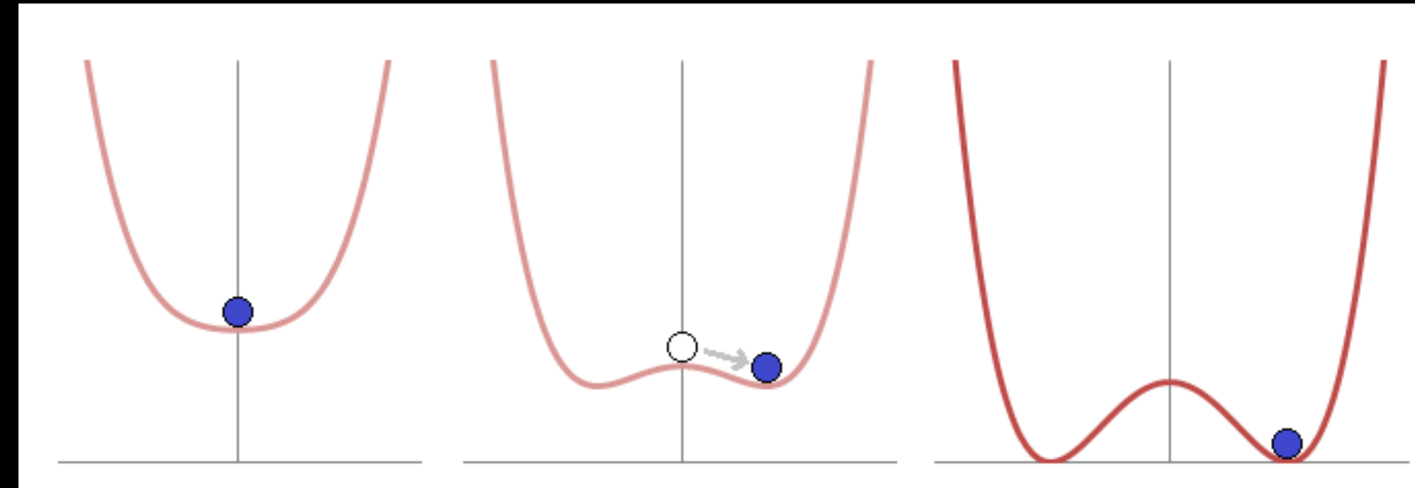
Coupling to matter leads to a fifth force which vanishes as $\varphi \to 0$

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

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

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

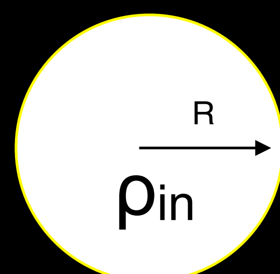
$$\tilde{V}(\varphi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\varphi^2 + \frac{1}{4}\lambda\varphi^4,$$



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:

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

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

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

Radiatively Stable Symmetron [Burrage, EC, Millington, PRL 2016]

Renormalised one loop potential for symmetron field

Radiative screening mechanism

ρ

symmetry restored: one global minimum; fifth force screened.

$$\left(\frac{\lambda}{8\pi}\right)^2 e^{4/3}\, m^2\, M^2$$

critical point:
one global minimum and two inflection points.

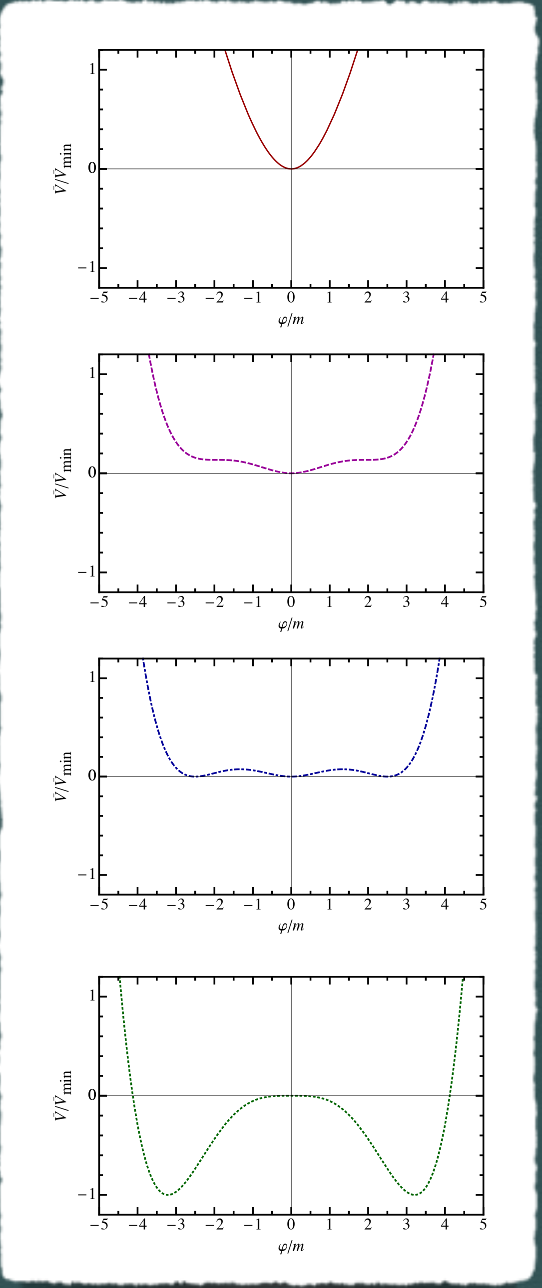
Tunneling to global symmetric minimum.

$$\frac{1}{2}\left(\frac{\lambda}{8\pi}\right)^2 e^{11/6}\, m^2\, M^2$$

degenerate point:
three degenerate global minima.

Tunneling to global symmetry-breaking minima.

symmetry broken: two global minima and a flat maximum.



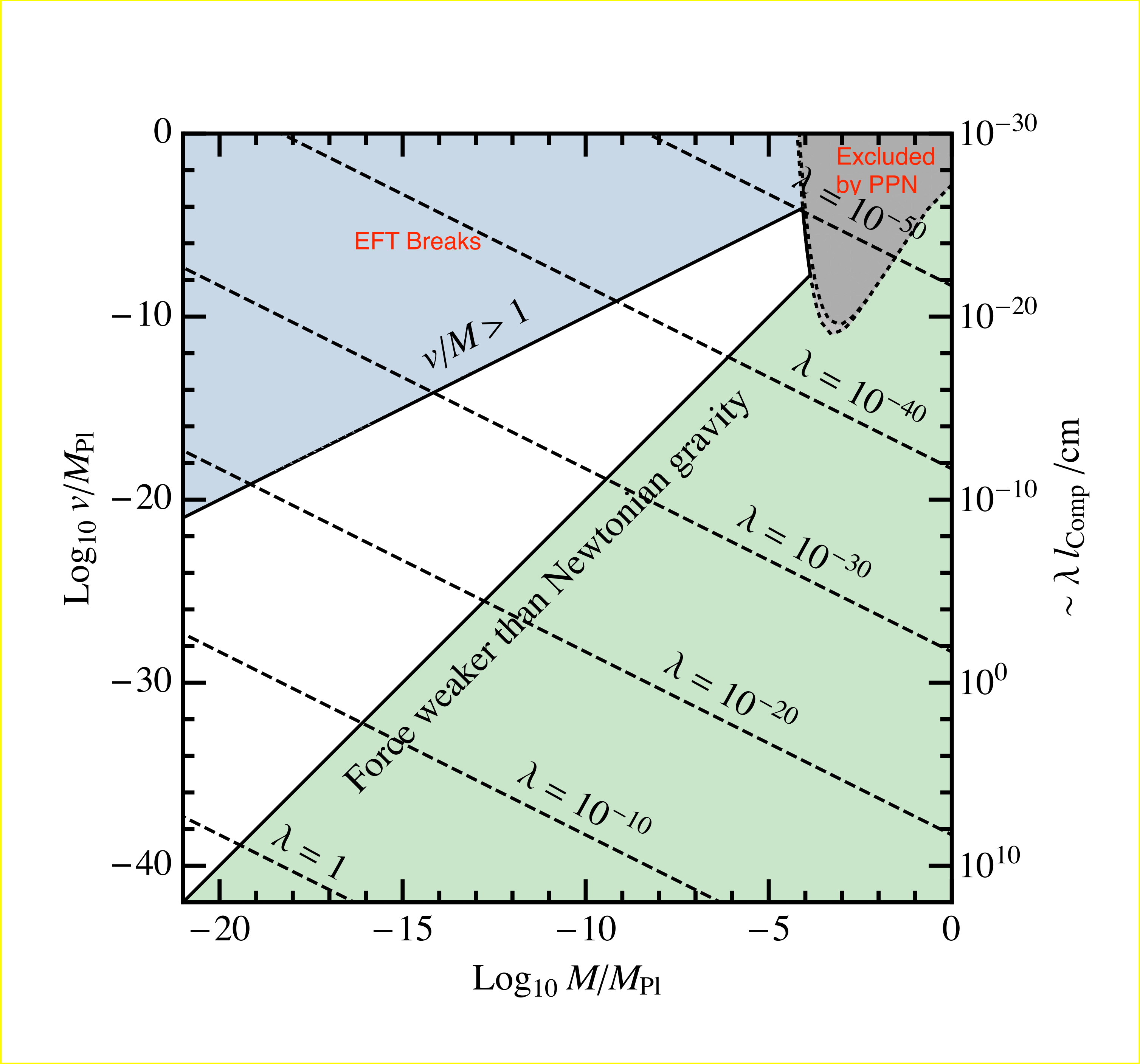
Fun dynamics - five roots, symmetry restored as density of matter increases.
Potential low temperature first order phase transitions, bubbles and domain walls !

Pete Millington

Constraints

Radiatively stable if: $\phi_{min}/M < 1$ $\lambda > (v_H/M_{Pl})^2$

Also satisfy Eöt-Wash and be in sym broken phase in current cosmological vacuum



Benchmark values : $\lambda \sim 10^{-18}$ $v \sim 10^3$ TeV $M \sim 10^{-5}\, M_{Pl}$

gives $l_{Comp} \sim$ 1cm — tabletop fifth force experiment scales.

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

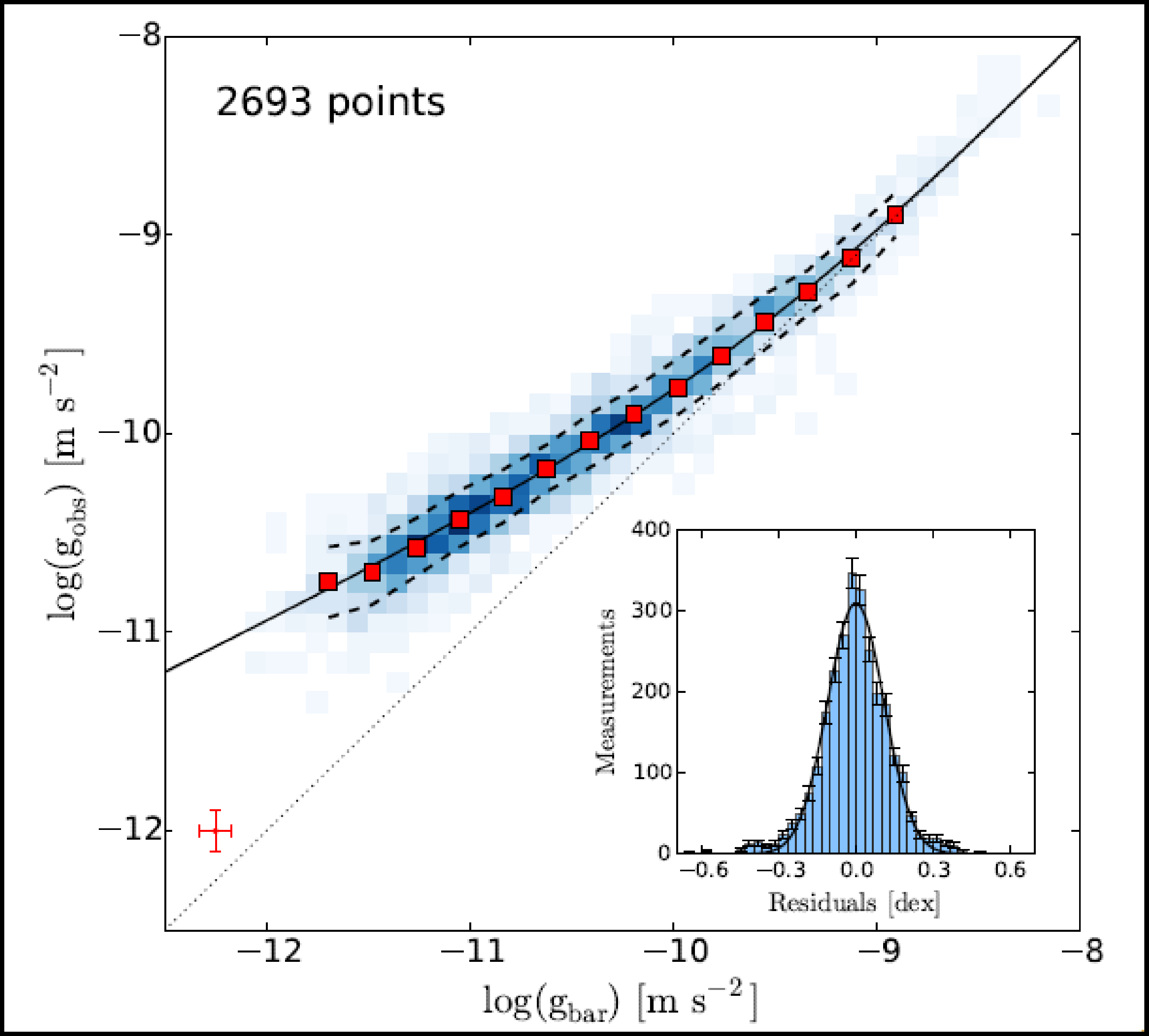
Radial acceleration relation from 153 galaxies (also known as mass discrepancy acceleration relation) [McGaugh et al PRL 2016]

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

Empirical fit:

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

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



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]

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

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

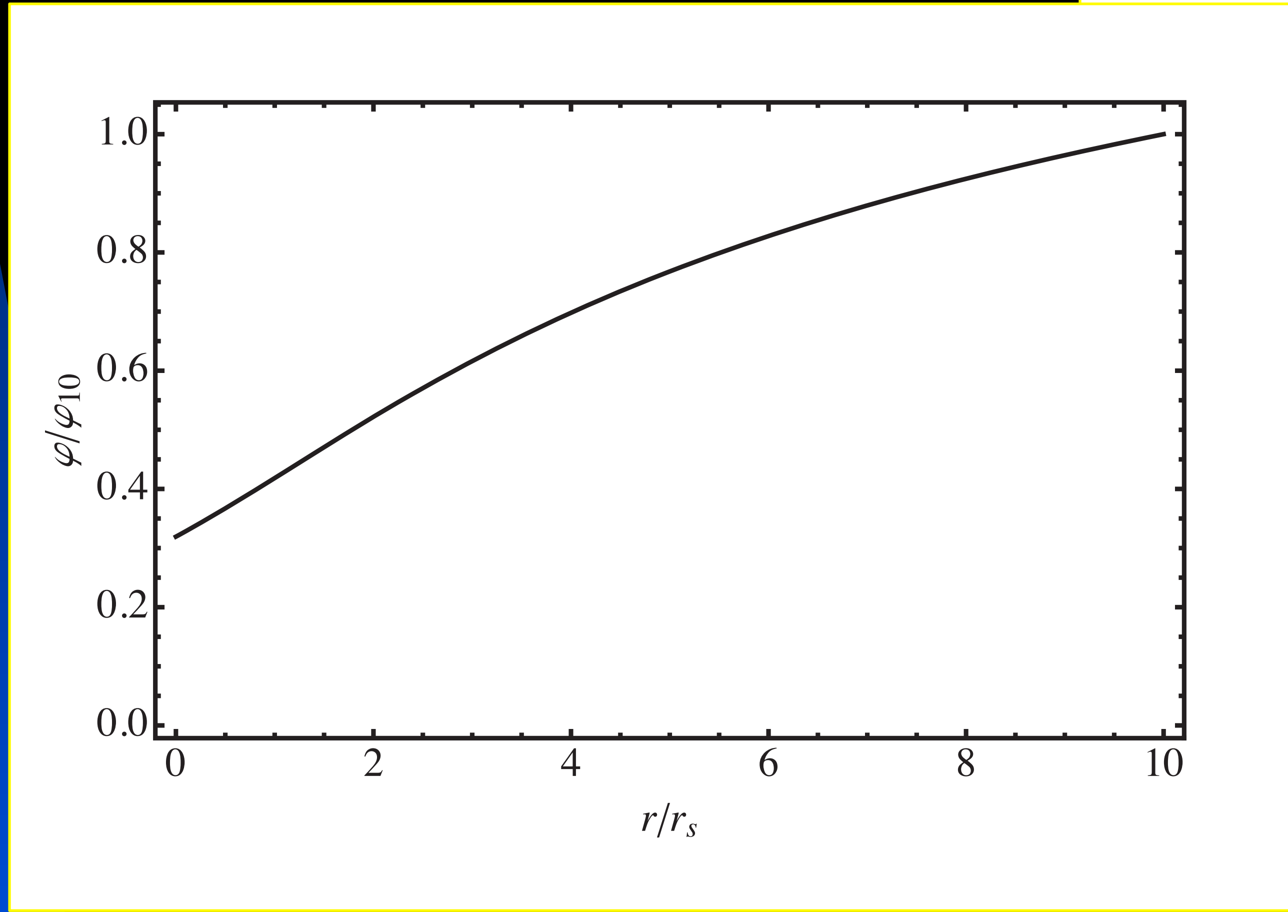
Rotation curve explained if symmetron profile satisfies:

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

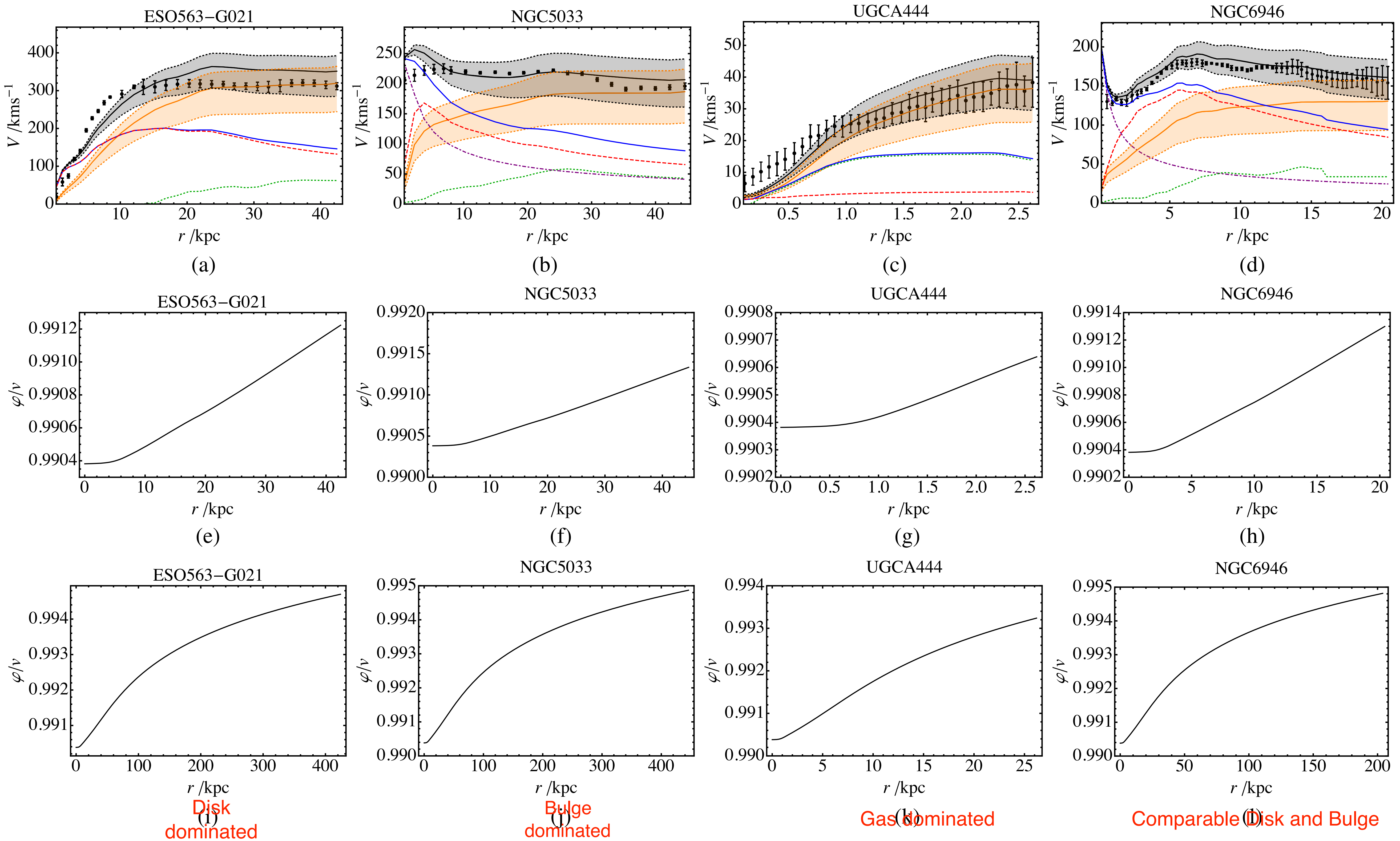
Assuming an exponential disc profile for the galaxy $\Sigma(r) = \Sigma_0 e^{-r/r_s}$ we obtain:

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

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



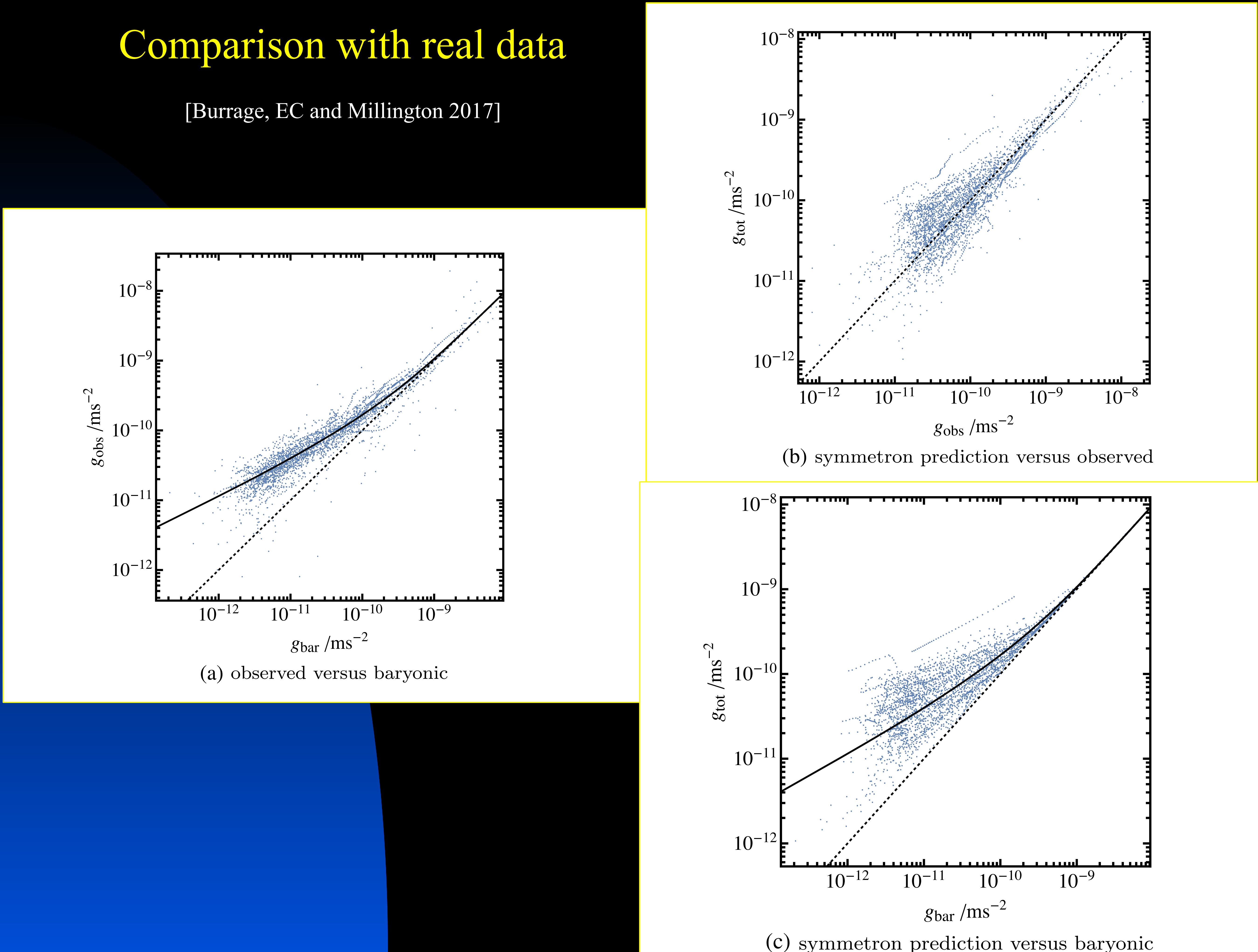
Real galaxies in the SPARC dataset [Burrage, EC & Millington 2017, SPARC, Lelli et al 2016]



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

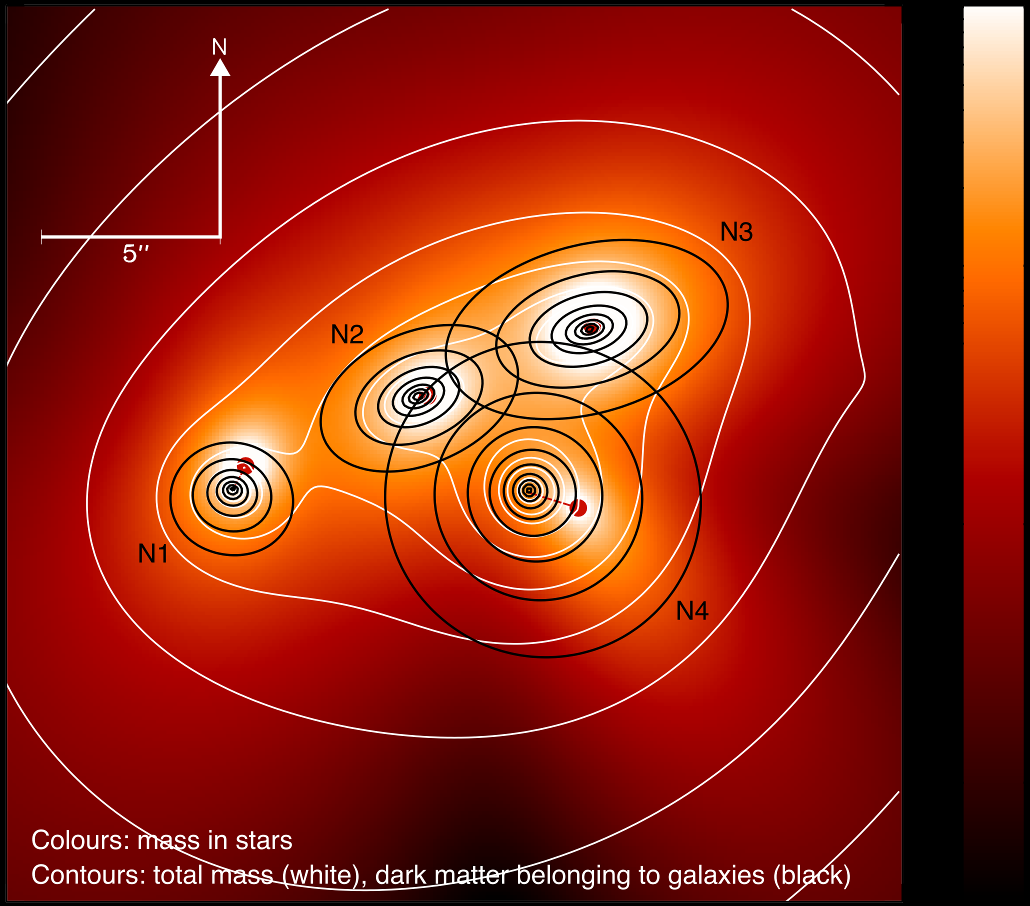
Comparison with real data

[Burrage, EC and Millington 2017]



Other interesting aspects [Burrage, EC and Millington 2017]

`Kink-kink' interactions of the symmetron profiles, as well as the response of the symmetron field to the change in the gas distribution may produce an offset between the stellar and DM components in colliding systems such as observed in Abell 2827



[Taylor et al 2017]

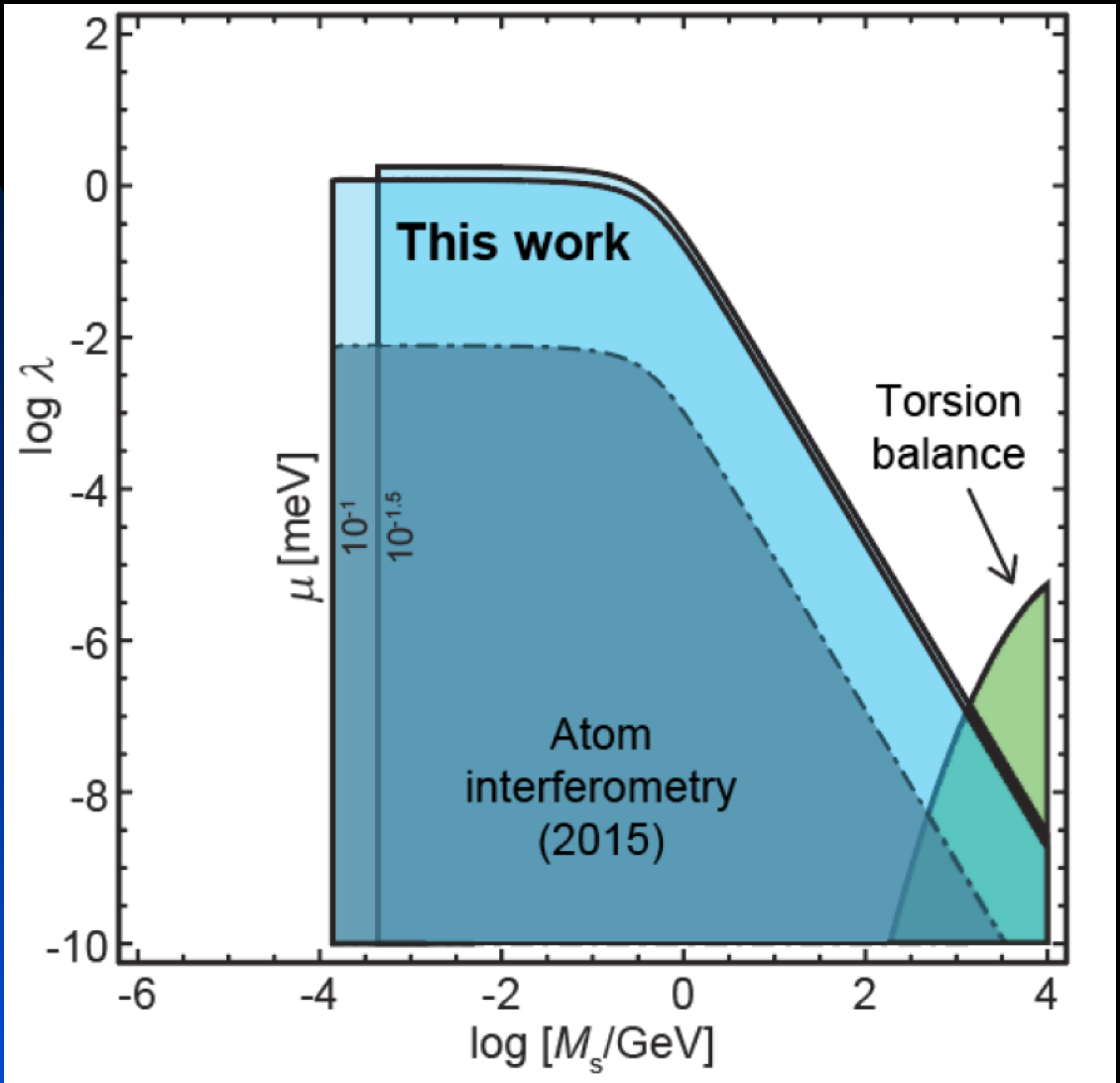
Disk Stability - known that baryonic component alone insufficient to stabilise disks of galaxies to barlike modes, spherical DM halo fixes that.

Energy stored in symmetron field has similar stabilising effect. Requires constraint

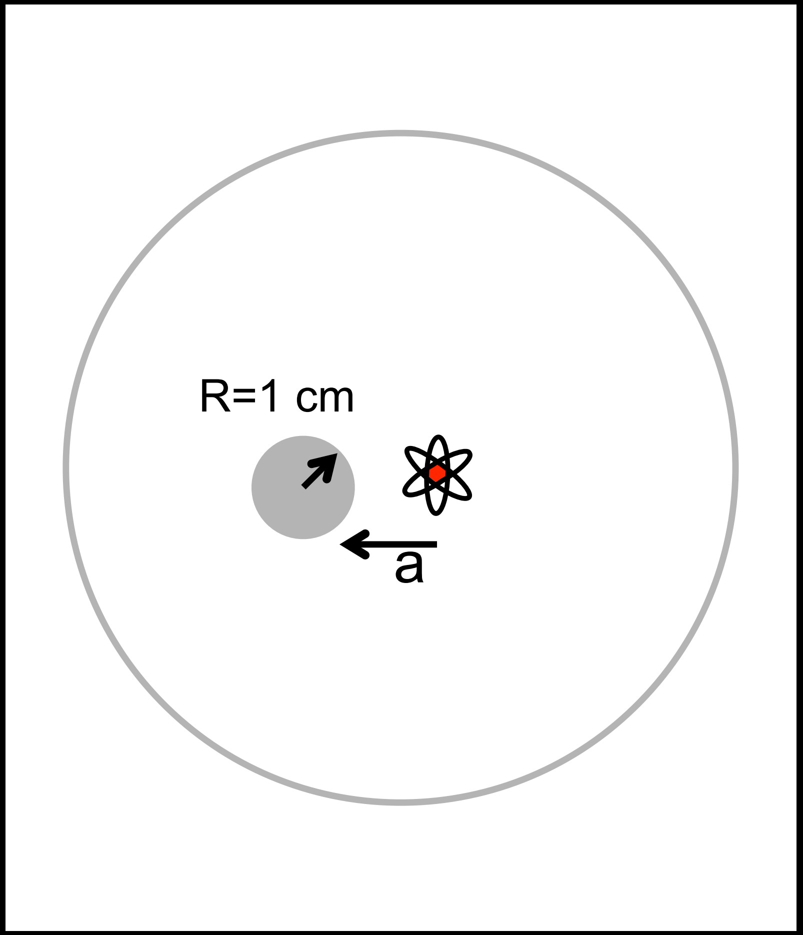
$$\frac{\mu}{\mathrm{GeV}} \gtrsim \frac{2\times 10^{-41}}{\sqrt{\alpha n}}\left(\frac{v}{M_{\rm Pl}}\right)^{-1},$$

Symmetron constraints [Jaffe et al 2016; Burrage et al 2106, Brax & Davis 2016]

$$V_{\text{eff}}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4}\phi^4$$



Consider now a source object A and test object B (atom) near the middle of the chamber. The force between uniform spheres a distance r apart, due to the combined effect of gravity and the chameleon field is :



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

where

$$\lambda_i = \begin{cases} 1 & \rho_i R_i^2 < 3M\phi_{\rm bg} \\ \frac{3M\phi_{\rm bg}}{\rho_i R_i^2} & \rho_i R_i^2 > 3M\phi_{\rm bg} \end{cases}$$

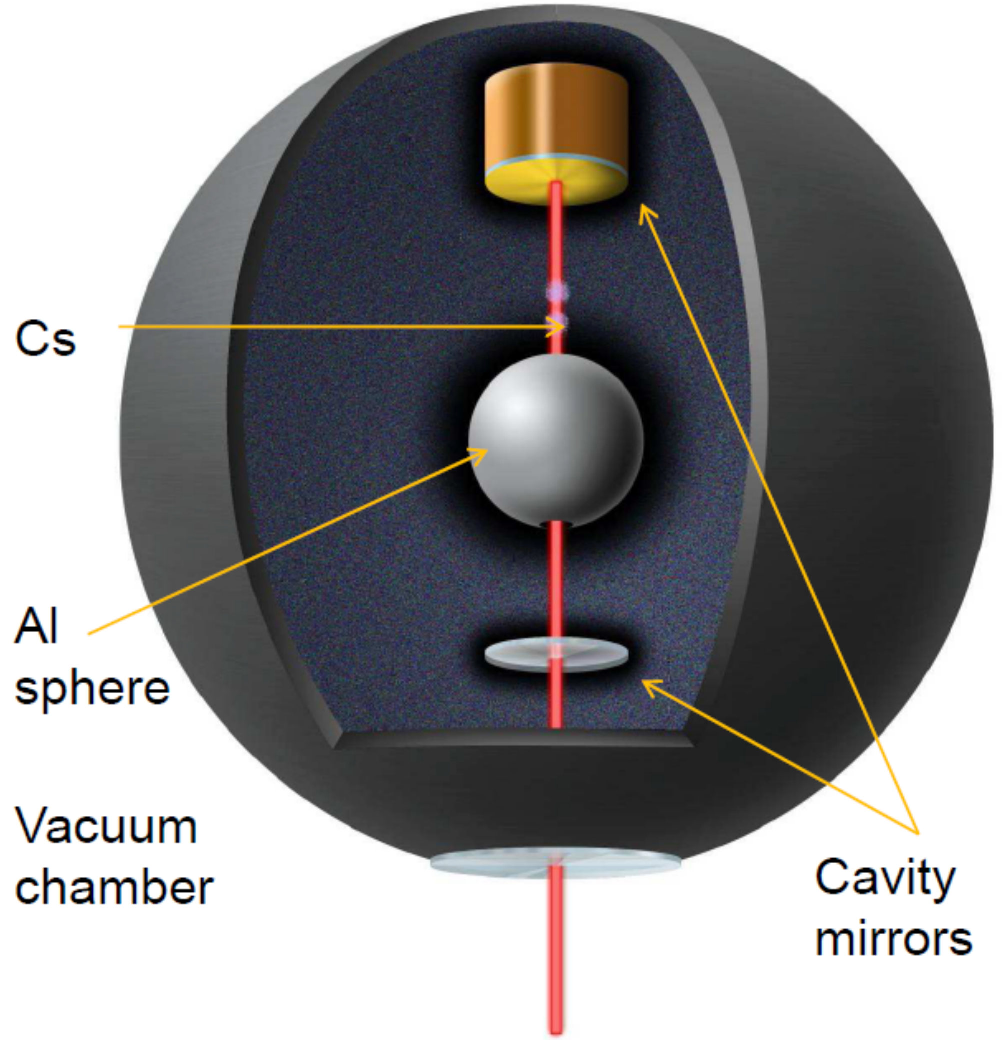
Fifth force experiments to date tend to have $\lambda_A \ll 1$ and $\lambda_B \ll 1$ because the objects are large and dense and ϕ_{bg} is small in the high terrestrial bgd density. Resulting double suppression of the force is so strong, expt bounds are not very stringent.

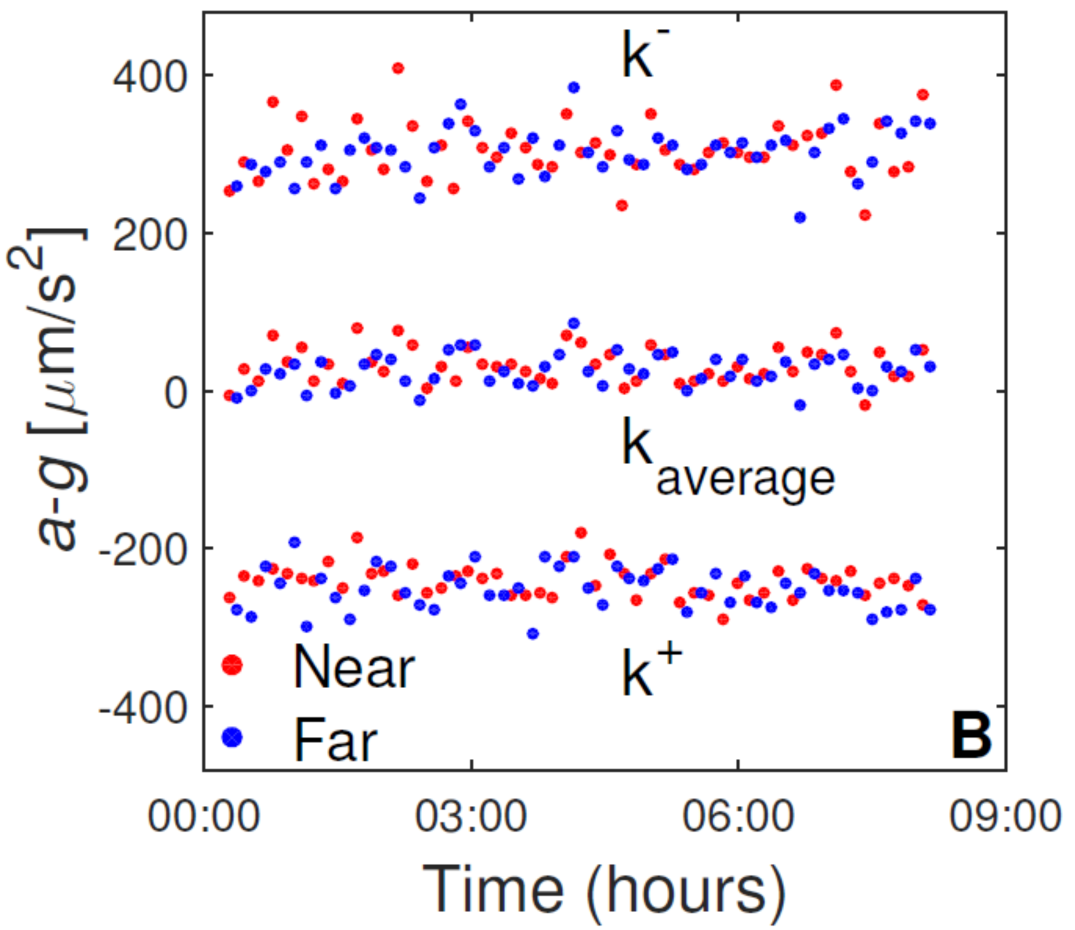
However, can achieve $\lambda_B = 1$ by using an atom in high vacuum where $\rho_B R^2{}_B << M\ \phi_{bg}$

Then the acceleration towards a macroscopic test mass is only singly suppressed and atom interferometry can easily detect it.

Berkley Experiment

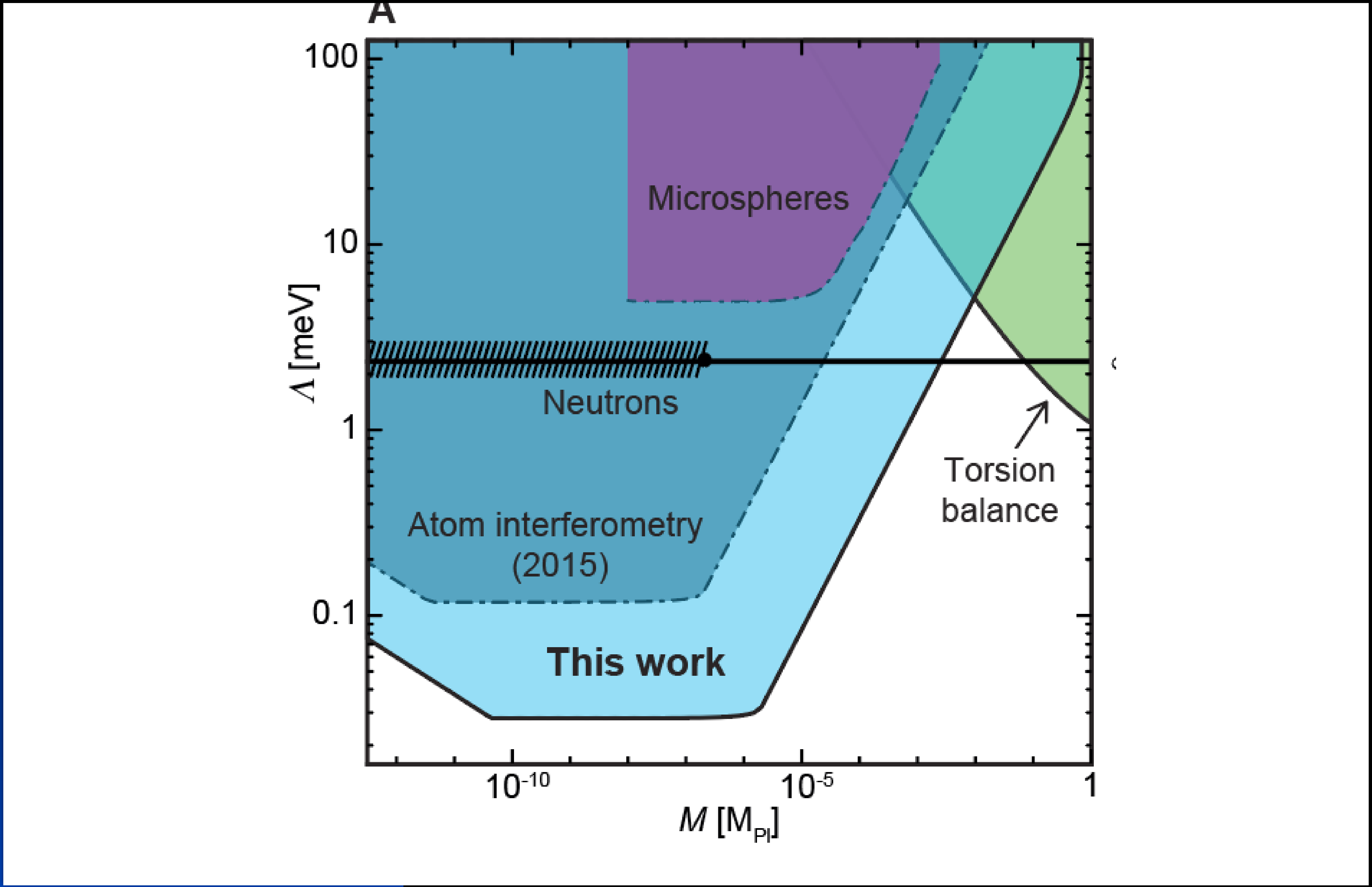
Using an existing set up with an optical cavity
The cavity provides power enhancement, spatial filtering, and a precise beam geometry





Hamilton et al. (2015)

Berkeley Experiment



Hamilton et al 2015, Jaffe et al 2016 - already increased limits on Chameleons by over two orders of magnitude.

Ex: Fab Four - self tuning solutions with a large Cosmological Constant:

$$G_X^{(2)} = V^{(J)} - 2V_\phi^{(P)} X + 4V_{\phi\phi}^{(R)} \left(1 - \ln|8\pi G X|\right)$$

$$G_\phi^{(3)} = \frac{1}{2}V_\phi^{(P)} X + \frac{2}{3}V_{\phi\phi}^{(R)} \ln|8\pi G X|$$

$$G_X^{(3)} = \frac{1}{2}V^{(P)} + \frac{2}{3}V_\phi^{(R)} \frac{1}{X}$$

Four arbitrary potentials- John, Paul, Ringo, George

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

$$\left[\frac{3}{2}V^{(P)} X + 2V_\phi^{(R)}\right]\left(\ddot{\phi} - H\dot{\phi}\right) = -V^{(J)} X - V_\phi^{(P)} X^2 - 4V_{\phi\phi}^{(R)} X$$

Cosmological Solutions : [EJC,Padilla, Saffin and Skordis 2018]

Case	behaviour	$V^{(J)}$	$V^{(P)}$	$V^{(G)}$	$V^{(R)}$
Stiff	$H^2 = H_0^2/a^6$	$c_1\phi^{4/\alpha-2}$	$c_2\phi^{6/\alpha-3}$	0	0
Radiation	$H^2 = H_0^2/a^4$	$c_1\phi^{4/\alpha-2}$	0	$c_2\phi^{2/\alpha}$	$-\frac{\alpha^2}{8}c_1\phi^{4/\alpha}$
Curvature	$H^2 = H_0^2/a^2$	0	0	0	$c_1\phi^{4/\alpha}$
Arbitrary $w \neq -1$	$H^2 = H_0^2 a^{-3(1+w)}$	$-\frac{1}{2}c_1(1+3w)\phi^{4/\alpha-2}$	0	0	$\frac{9\alpha^2(1-w^2)}{64}c_1\phi^{4/\alpha}$
Matter-I	$H^2 = H_0^2 a^{-3}$	$c_1\phi^{n+4}$	$c_2\phi^{n+6}$	0	$\frac{2n-3}{16(2n+7)(n+6)}c_1\phi^{n+6}$
Matter-II	$H^2 = H_0^2 a^{-3}$	$c_1\phi^{n+4}$	0	$c_2\phi^{n+3}$	$-\frac{(n+3)(2n+5)}{8(2n+7)(n+6)}c_1\phi^{n+6}$
Matter-III	$H^2 = H_0^2 a^{-3}$	$-\frac{1}{2}c_1\phi^4$	0	0	$\frac{1}{16}c_1\phi^6$
Matter-IV	$H^2 = H_0^2 a^{-3}$	$-45\sqrt{2}\phi^5$	$-\frac{75067}{225}\frac{1}{M^2}\phi^7$	$-M^2\phi^4$	$\frac{143}{168}\sqrt{2}\phi^7$

Table 1: Table of solutions from Copeland-Padilla-Saffin

All of these solutions except Stiff fluid satisfy the GW bound and in doing so determine either the coefficient alpha or n in the potentials.