Dark energy and table-top experiments

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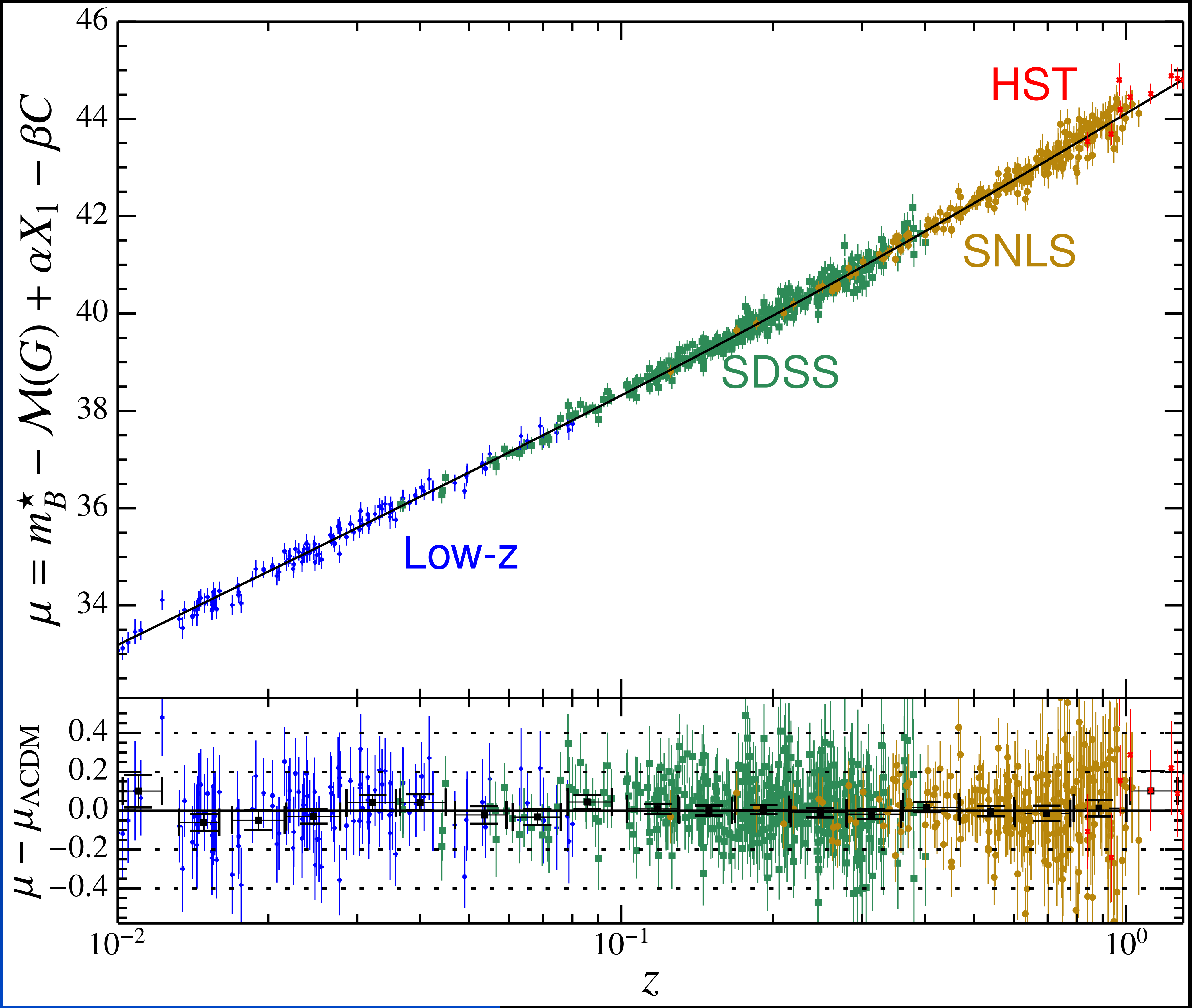
1. Models of Dark Energy
2. Chameleon and laboratory tests
3. Symmetron and laboratory tests

UK HEP Forum: Cosmology, Gravitation and Particle Physics

Cosener's House - November 28th 2017

Brief recap on Dark Energy



The Universe is accelerating and yet we still really have little idea what is causing this acceleration.

Is it a cosmological constant, an evolving scalar field, evidence of modifications of General Relativity on large scales or something yet to be dreamt up ?

Betoule et al 2014

Friedmann with Λ:

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

a(t) depends on matter.

Energy density ρ(t) : Pressure p(t)

Related through : p = wρ

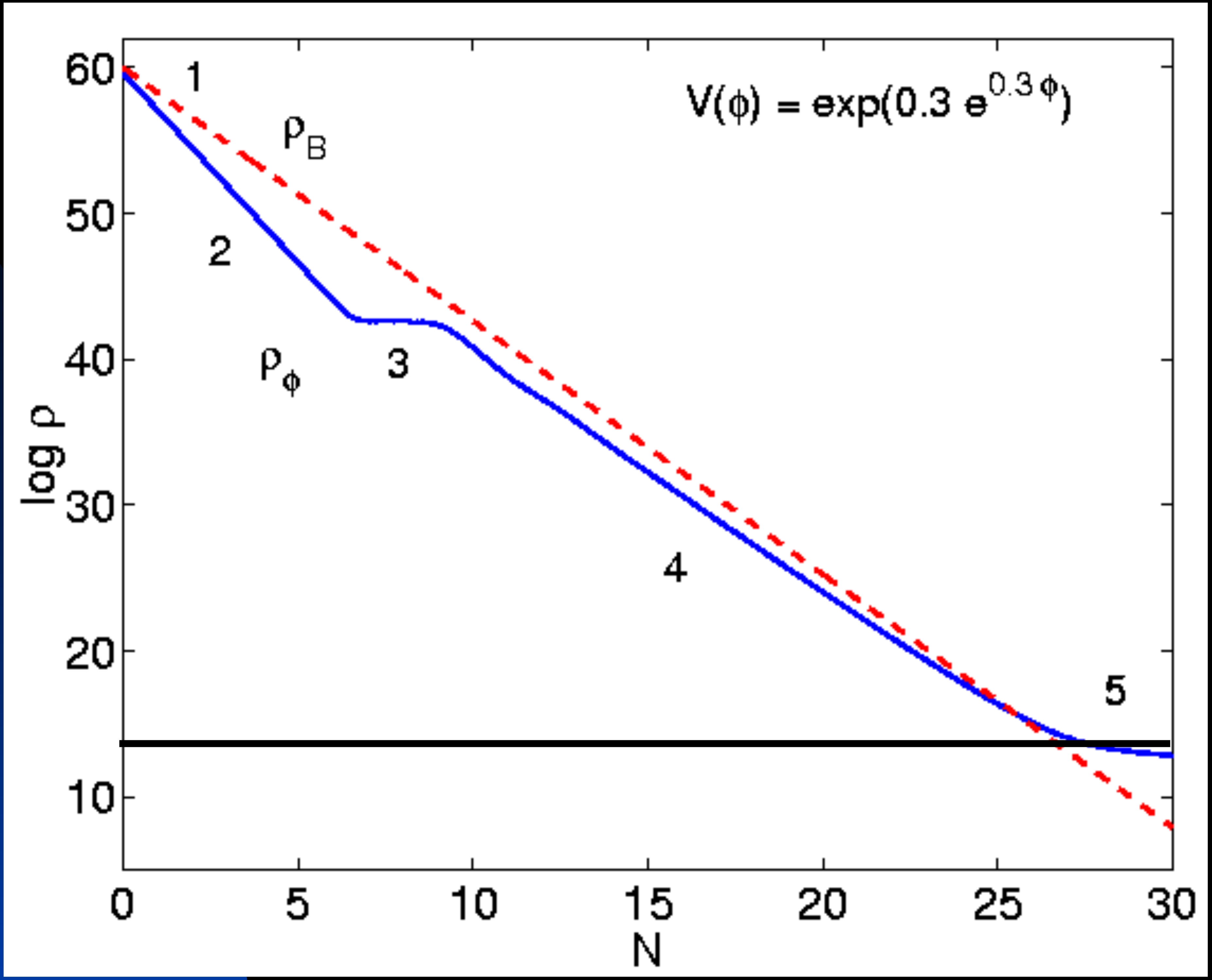
w=1/3 – Rad dom: w=0 – Mat dom: w=-1– Vac dom

$$w(a) \equiv \frac{P}{\rho} = w_0 + (1-a) w_a$$ Typical parameterisation

Friedmann with evolving dark energy:

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

Evolving energy densities



Dashed line - radiation and matter

Solid blue line - Dynamical Dark Energy - Quintessence

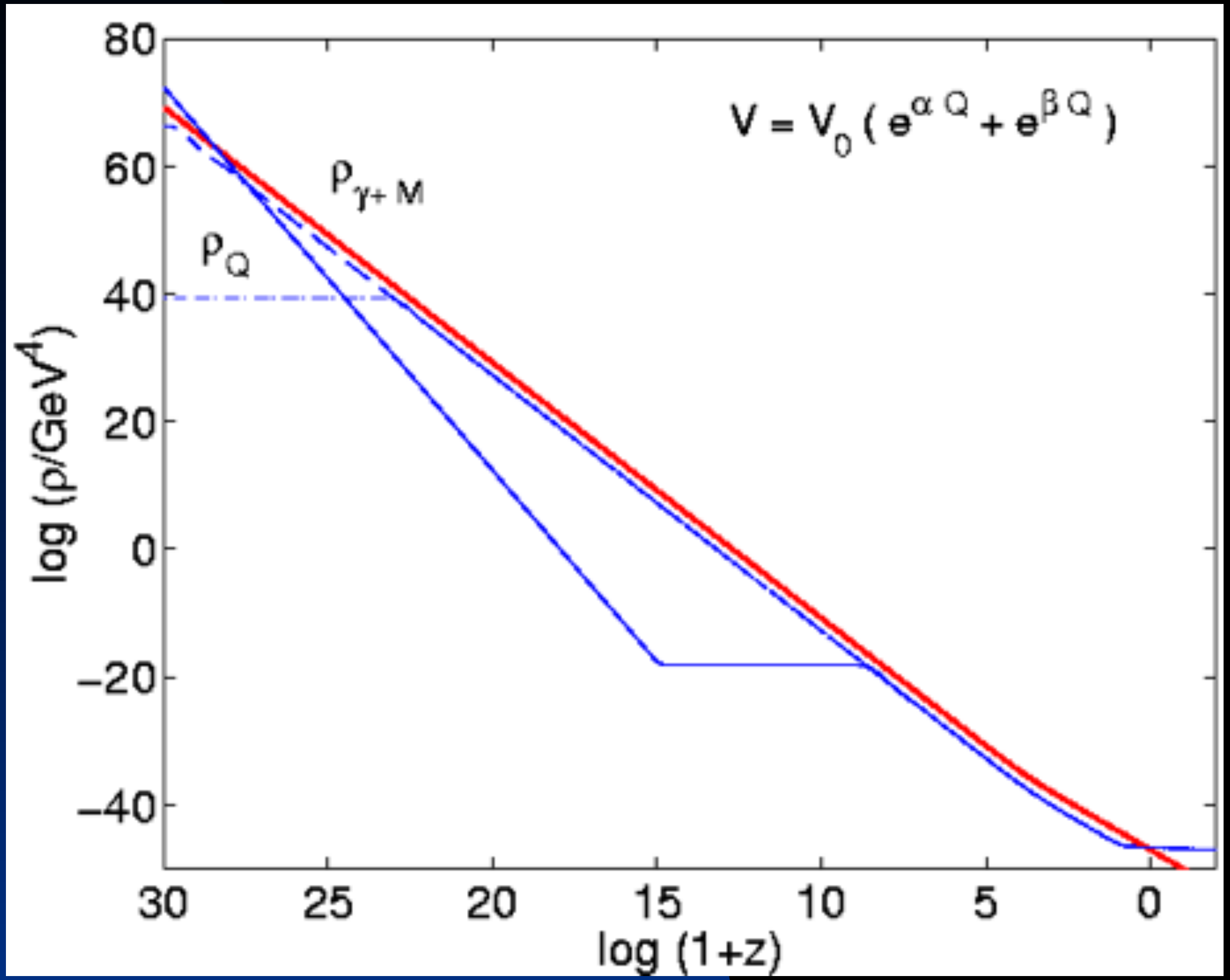
Solid black line - cosmological constant

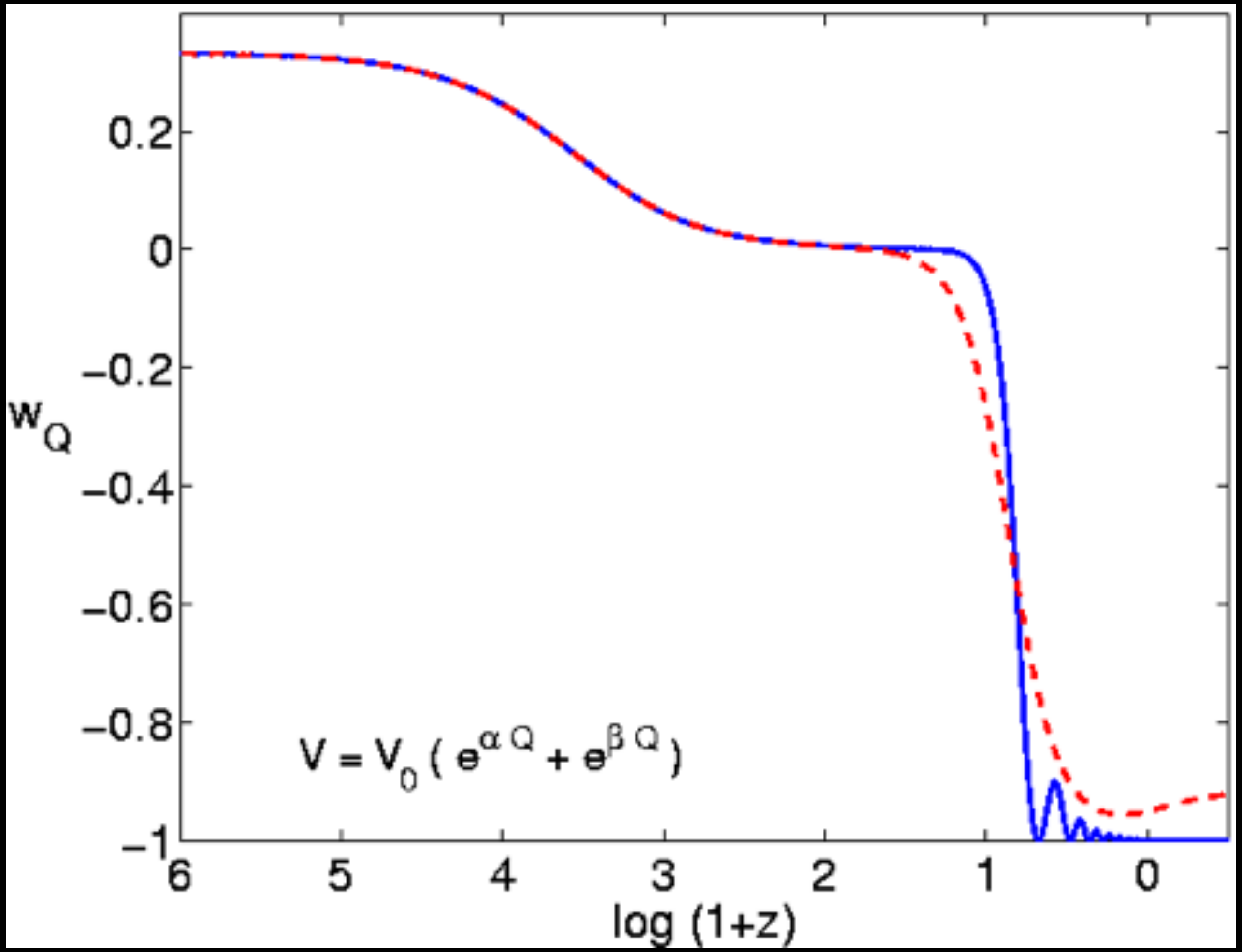
Approaches to Dark Energy:

- A true cosmological constant -- but why this value?
- Time dependent solutions arising out of evolving scalar fields -- Quintessence/K-essence.
- Modifications of Einstein gravity leading to acceleration today.
- String Landscape.
- Anthropic arguments.
- Perhaps GR but Universe is inhomogeneous.
- Yet to be proposed ...

Evolving scalar field - Quintessence:

$$V(\phi) = V_1 + V_2 = V_{01}e^{-\kappa\lambda_1\phi} + V_{02}e^{-\kappa\lambda_2\phi}$$





$\alpha = 20; \beta = 0.5$

Scaling for wide range of i.c.

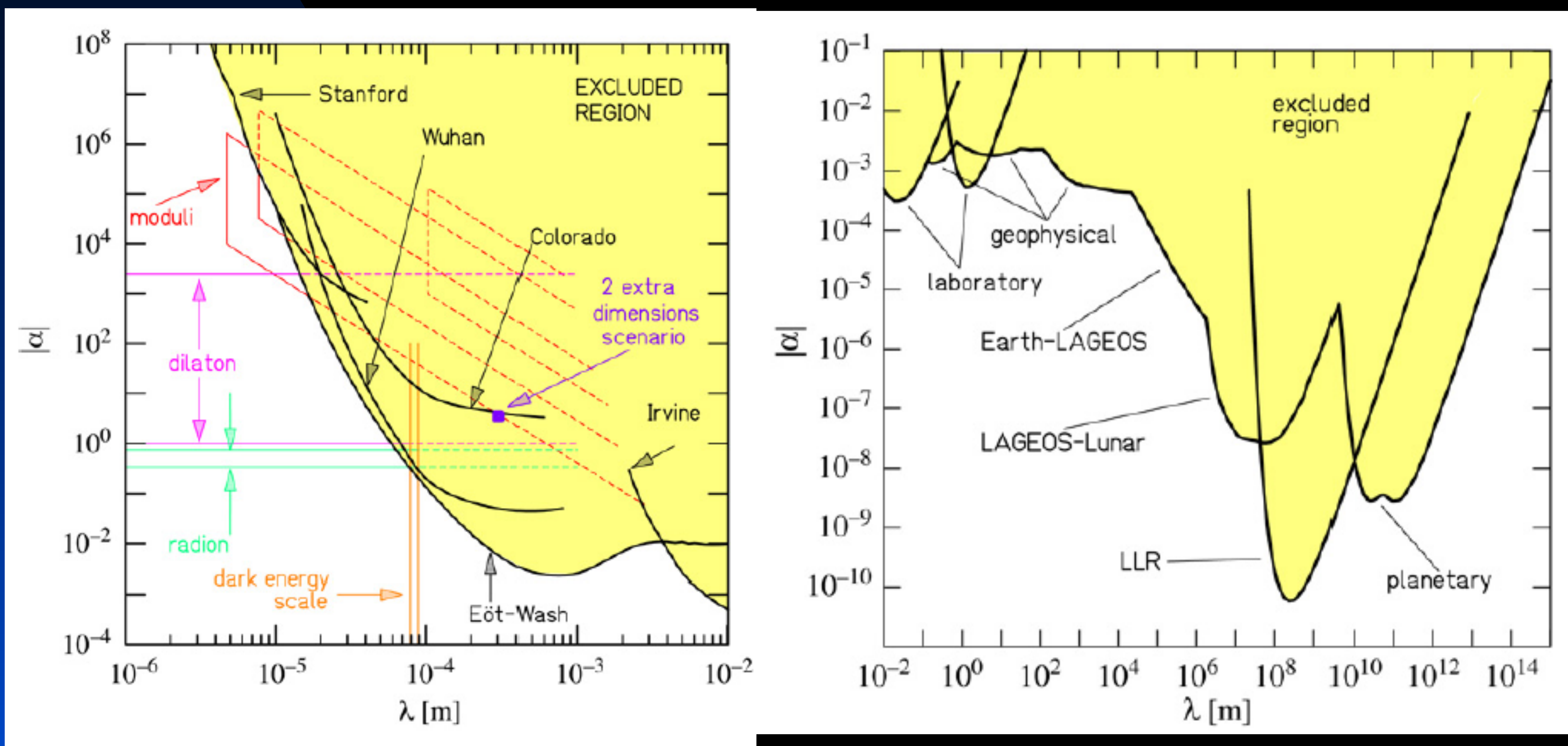
Fine tuning: $V_0 \approx \rho_\phi \approx 10^{-47}\ \mathrm{GeV}^4 \approx (10^{-3}\ \mathrm{eV})^4$

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

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.

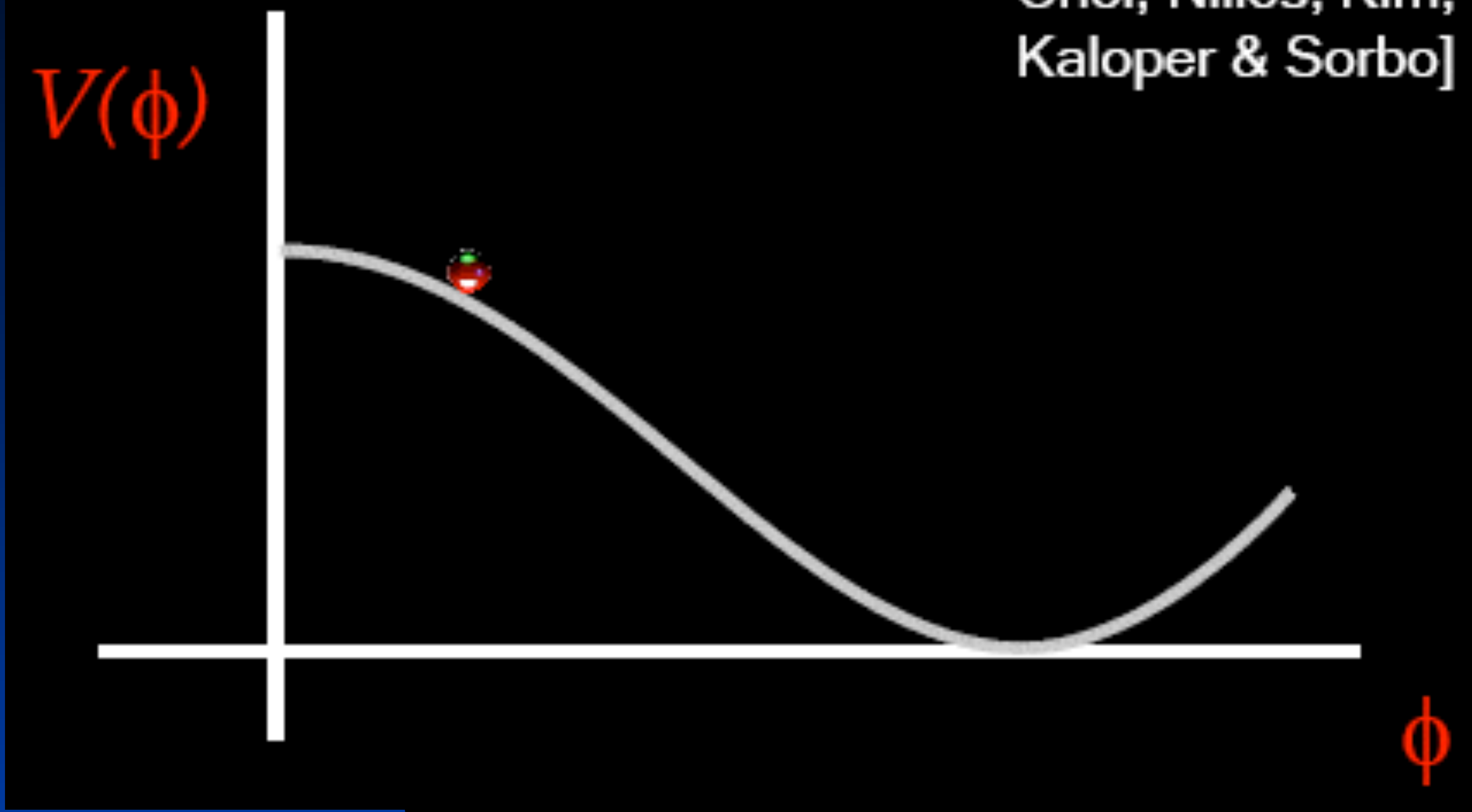
Particle physics inspired models of Dark Energy ?

Pseudo-Goldstone Bosons -- approx sym ϕ --> ϕ + 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 - see also recent work by D'Amico, Hamil & Kaloper 2016.

Approaches to 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. Vainshtein [Vainshtein 1972]

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, Gallileons, ...

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.

Concentrate on a class of models known as Chameleon Fields

[Khoury and Weltman, PRL 93 171104 (2004)]

$$S = \int d^4x \sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)\right] + \int d^4x\, \mathcal{L}_{(m)}(\psi_{(m)}, \Omega^{-2}(\phi)g_{\mu\nu}) \,.$$

$V(\phi)$ – –Chameleon potential

$S_m = \int d^4x \mathcal{L}_{(m)}(\psi_{(m)}, \Omega^{-2}(\phi)g_{\mu\nu})$ – –matter action

Matter fields move on geodesics of the conformally rescaled metric $\tilde{g}_{\mu\nu} = \Omega^{-2}(\phi)g_{\mu\nu}$

$\Omega(\phi)$ determines the coupling between the matter and ϕ

For a static spherically symmetric configuration sourced by non-rel matter eom:

$$\frac{1}{r^2}\frac{d}{dr}\left[r^2\frac{d\phi(r)}{dr}\right] = \frac{dV}{d\phi} + \frac{\rho(r)}{M} \equiv \frac{d}{d\phi}V_{\rm eff}(\phi) \,, \quad \text{where} \quad \frac{\partial \ln \Omega^2}{\partial\phi} = -\frac{2}{M}$$

Assume energy scale M constant and $\phi/M \ll 1$, allows us to consider the chameleon moving in a density dependent potential.

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

Typical chameleon bare non-linear potential

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

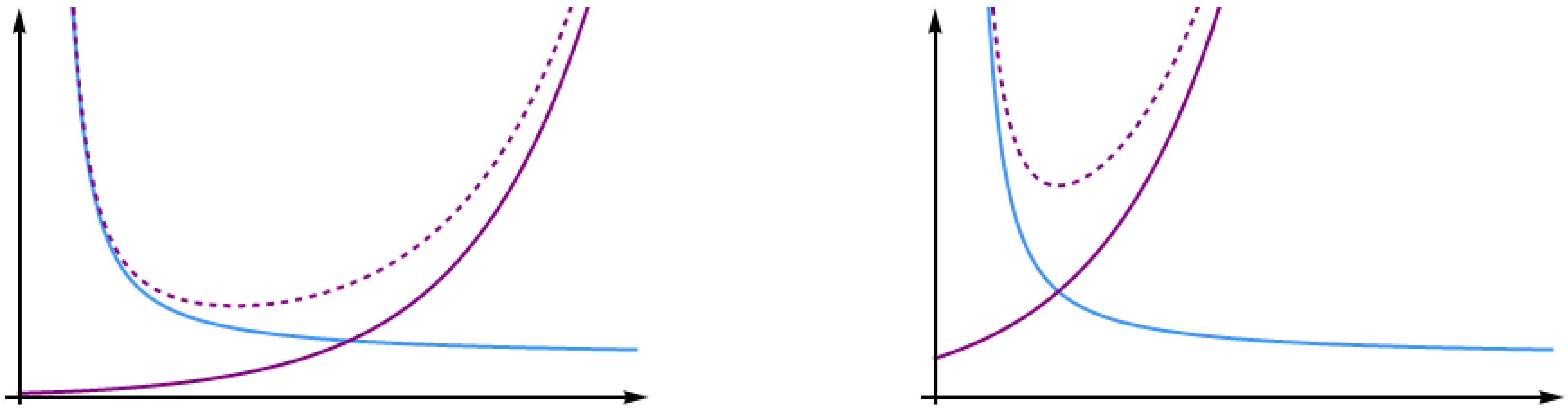
with self-interaction strength Λ

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

The mass of the chameleon changes with the environment

Field is governed by an effective potential

$$V_{\rm eff} = \frac{\Lambda^5}{\phi} + \frac{\phi}{M}\rho$$



Low density High density

$$\phi_{\rm min}(\rho) = \left(\frac{\Lambda^5 M}{\rho}\right)^{1/2},$$

$$m_{\rm min}(\rho) = \sqrt{2}\left(\frac{\rho^3}{\Lambda^5 M^3}\right)^{1/4}.$$

coupling constants

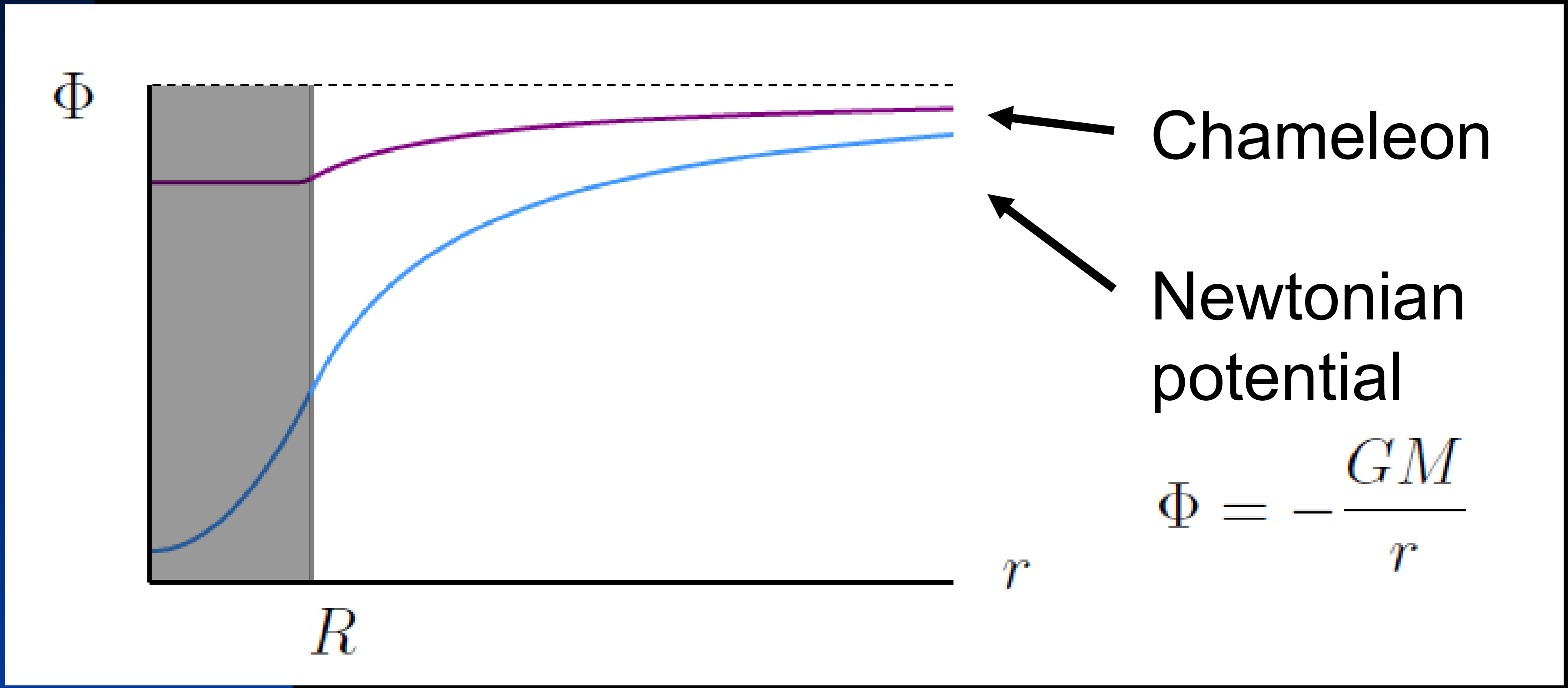
$10^{-5} eV < \Lambda < 10^{-1} eV$

$10^{-14} M_p < M < M_p$

How does this type of potential help with the fifth force constraints?

The fact it is density (or environment) dependent means that in less dense areas it is light (as required for dark energy) and in denser regions it is massive (as required by solar system tests).

The increased mass makes it harder for the Chameleon field to adjust its value, leads to the associated force being screened.



The Chameleon potential well around a massive object is shallower than for standard light scalar fields - hence the associated force is reduced.

The sources we consider for the chameleon field are const density and spherically symmetric.

$$\rho(r) = \rho_A \Theta(R_A - r) + \rho_{\rm bg}\Theta(r - R_A) \ ,$$

ρ_A, R_A − −density and radius of the source

ρ_{bg} − −density of bgd env surrounding the ball

There is a universal form for the scalar potential which comes from solving the eom in all the regimes and matching across boundaries - suitable for weakly and strongly perturbing objects:

$$\phi = \phi_{\rm bg} - \lambda_A \frac{1}{4\pi R_A}\frac{M_A}{M}\frac{R_A}{r}e^{-m_{\rm bg} r}$$

$$\lambda_A = \begin{cases} 1 \ , & \rho_A R_A^2 < 3M\phi_{\rm bg} \\ 1 - \frac{S^3}{R_A^3} \approx 4\pi R_A \frac{M}{M_A}\phi_{\rm bg} \ , & \rho_A R_A^2 > 3M\phi_{\rm bg} \end{cases}$$

$$m_{\rm bg}^2 = d^2 V_{\rm eff}/d\phi^2|_{\phi_{\rm bg}}$$

The parameter λ determines how responsive an object is to the chameleon field.

For small m_{bg} r the ratio of the acceleration of a test particle due to chameleon and gravity is

$$\frac{a_\phi}{a_N} = \frac{\partial_r \phi}{M}\frac{r^2}{GM_A} = 3\lambda_A \left(\frac{M_P}{M}\right)^2$$

If λ =1 this could be a big effect ! On cosmological scales though λ << 1

And so we begin to think about measuring this effect in Laboratory experiments.

We see that the chameleon effects are not screened for `small' objects that do not probe the scalar non-linearities. This will be the case if $\lambda = 1$ or:

$$\frac{1}{4\pi R_A}\frac{M_A}{M} \ll \phi_{\rm bg}$$

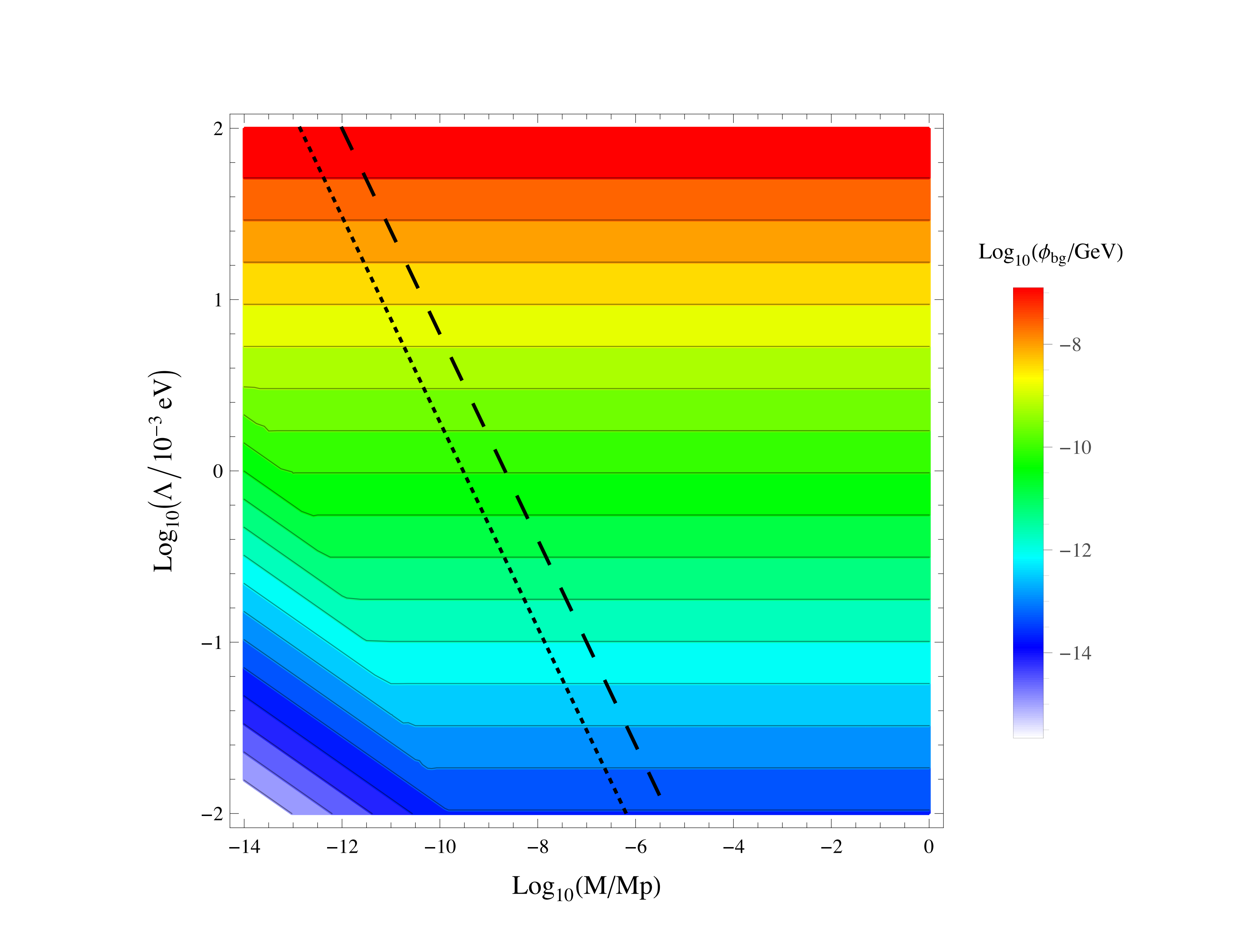
To achieve this we either require an expt with:

$$\phi_{\rm bg} \text{ is large } -- \text{ high quality vacuum}$$

$$\frac{M_A}{R_A} << 1 -- \text{ atoms}$$

The idea is to use a vacuum chamber with walls thick enough so that the interior can be screened from external chameleon field fluctuations

Are atoms screened ?



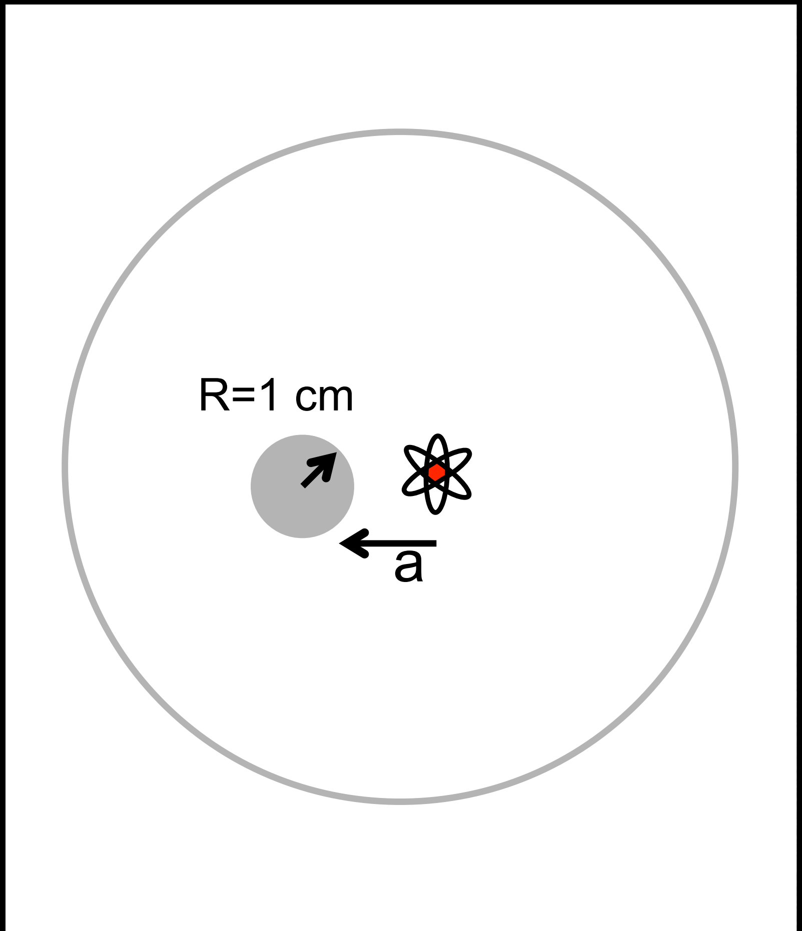
The value of ϕ_{bg} , the value of the chameleon field at the centre of a spherical vacuum chamber as a function of Λ and M.

Chamber radius 10cm, Pressure 10^{-10} Torr

Force unscreened by the atoms above black lines (λ =1) - dashed line for caesium atom and dotted line for lithium atoms

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

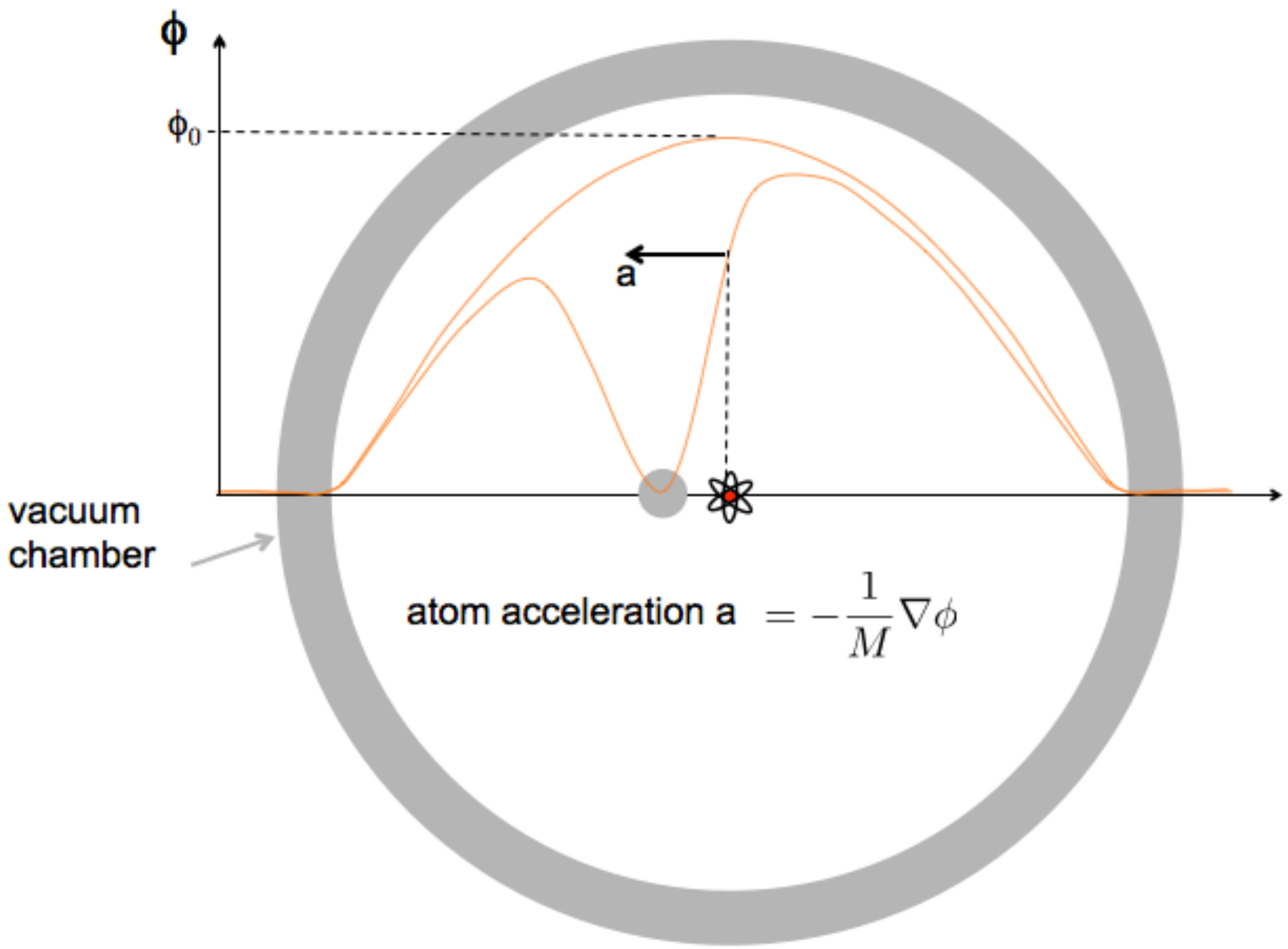
$$\lambda_i = \begin{cases} 1 & \rho_i R_i^2 < 3M\phi_{\rm bg} \\ \frac{3M\phi_{\rm bg}}{\rho_i R_i^2} & \rho_i R_i^2 > 3M\phi_{\rm bg} \end{cases}$$

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.

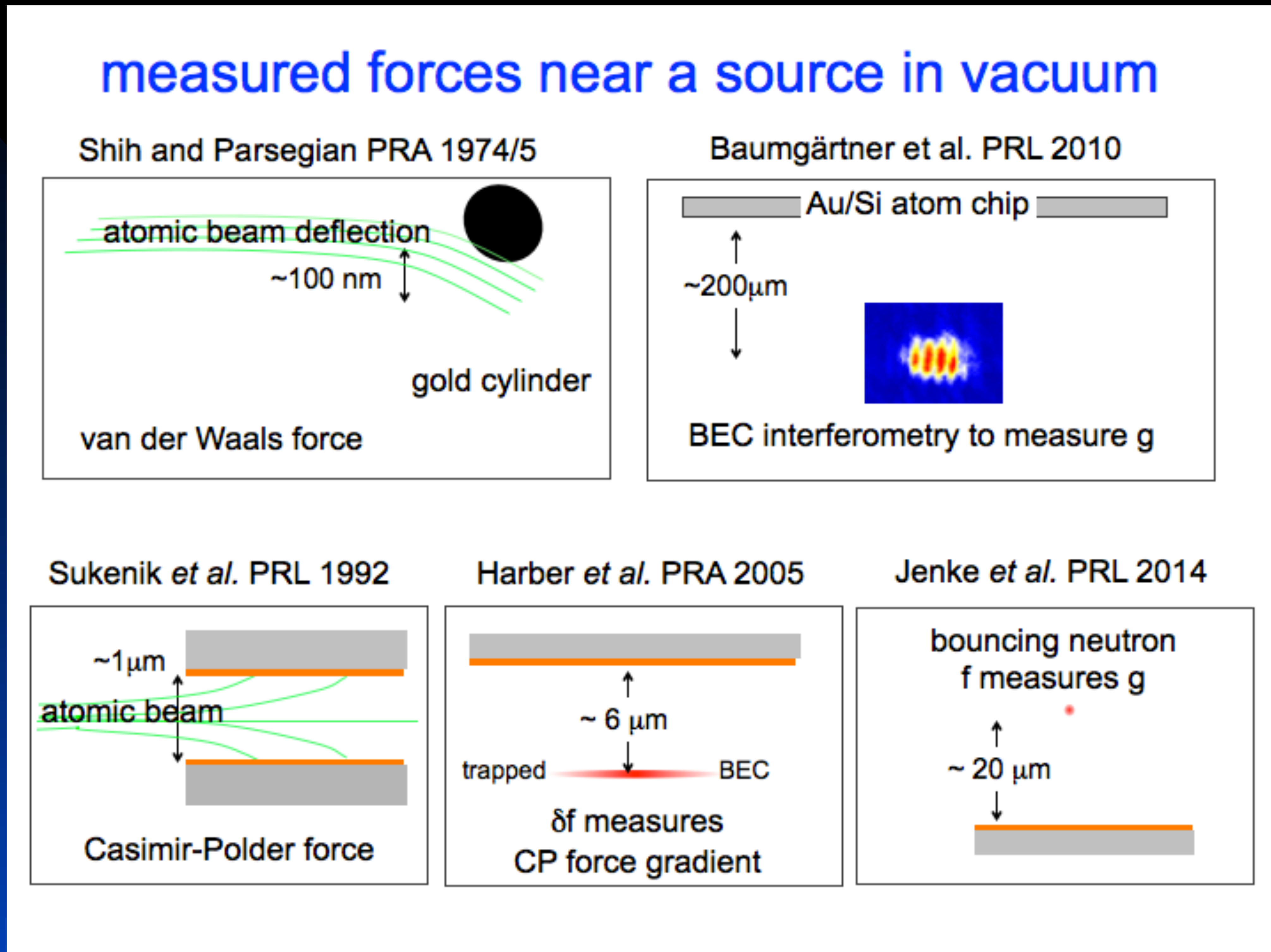
Measure ϕ in a high vacuum chamber



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

Ed Hinds

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



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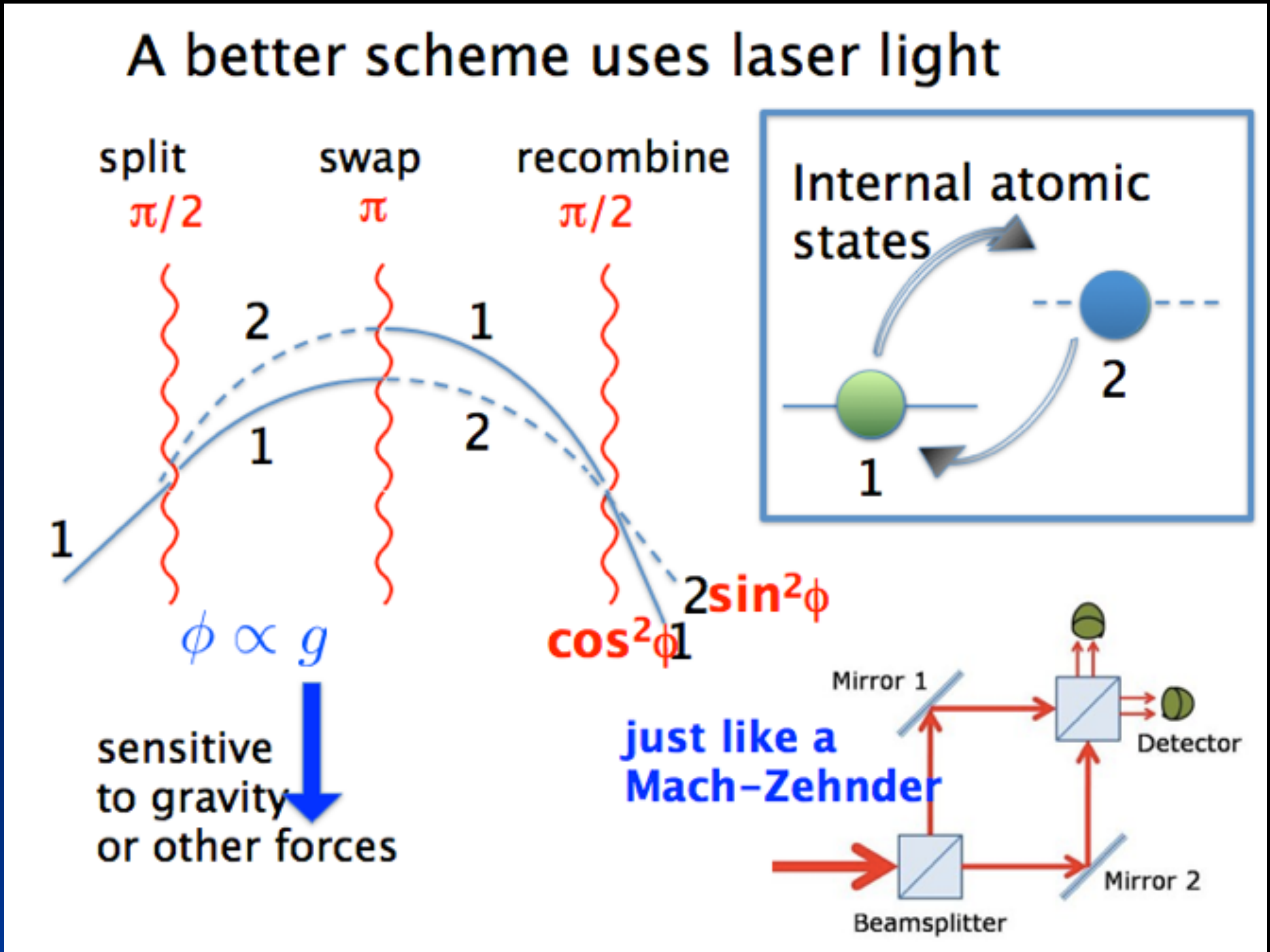
Our proposal uses Atom Interferometry of atoms in free fall [Burrage, EC, Hinds 2015]



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

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

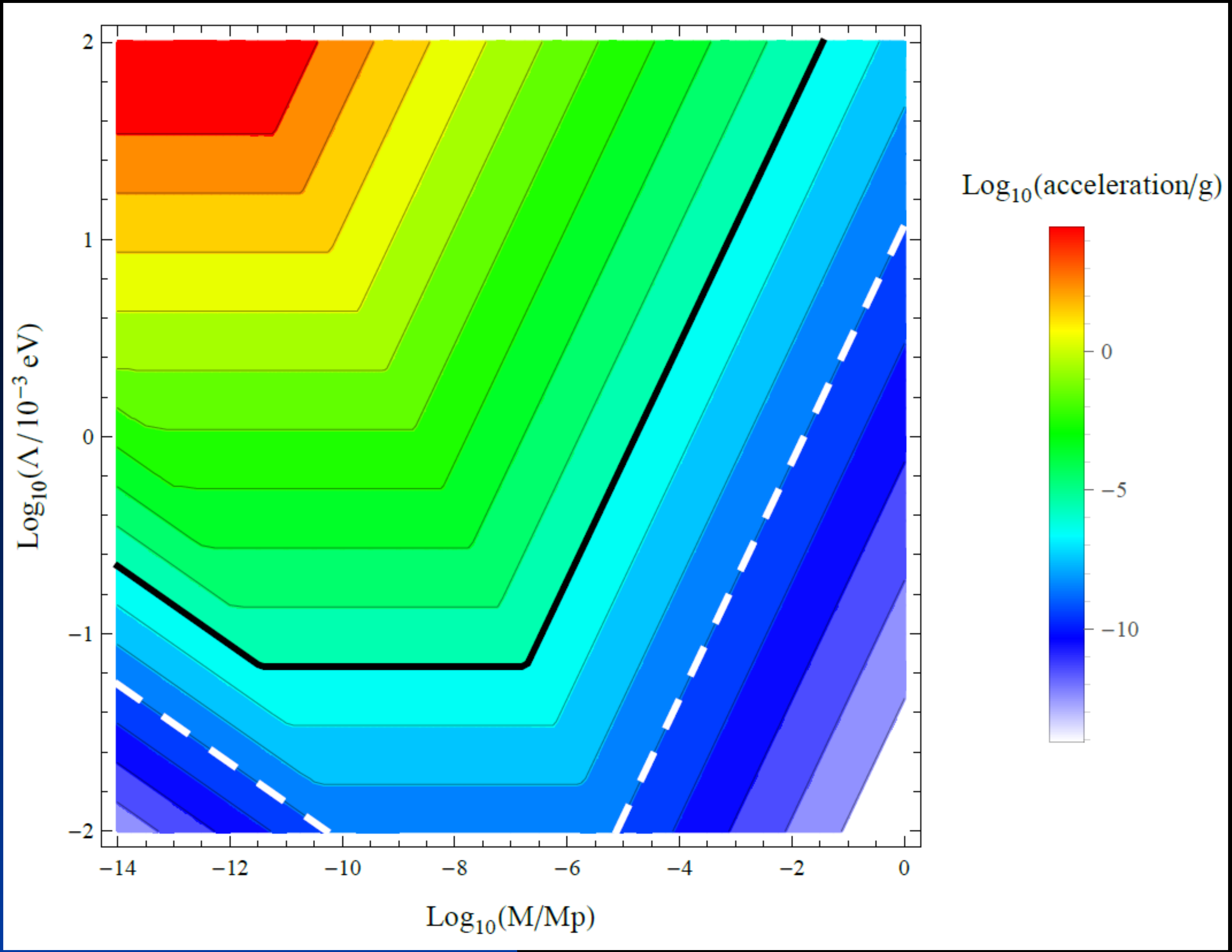
Ed Hinds

$\underline{k}_{1,2}$ — —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



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

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

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

Acceleration due to chameleon force outside a sphere of radius R_A = 1cm and screening factor $\lambda_A \ll 1$.

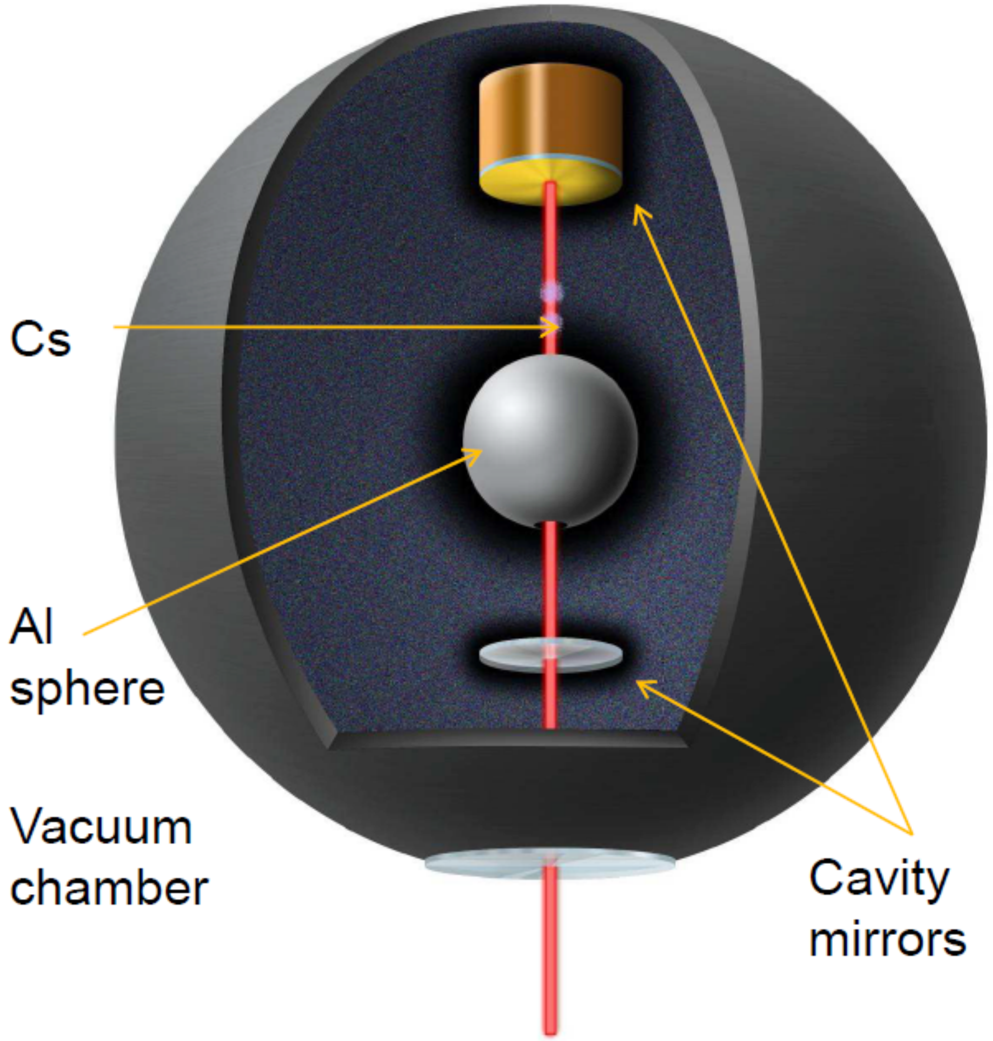
Λ-M area above solid black line excluded by atom interferometry expt measuring 10^{-6} g - easy !

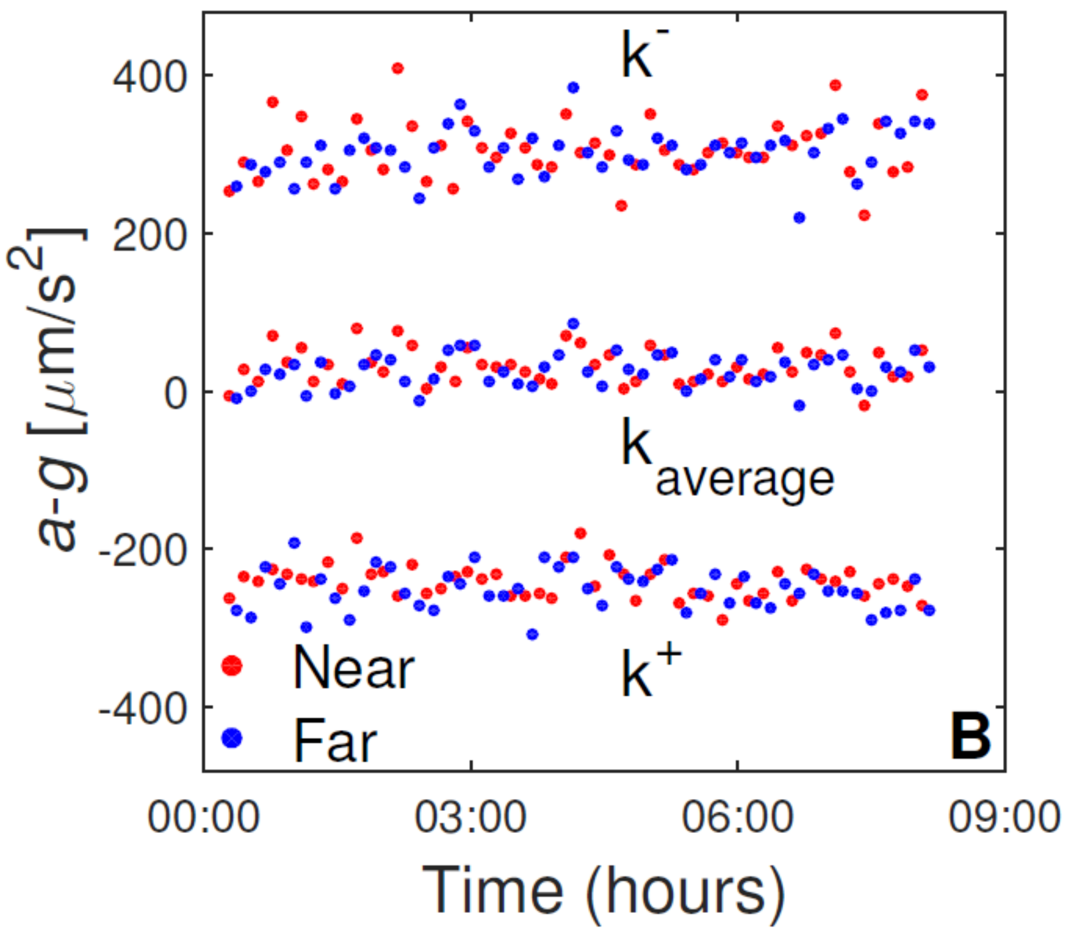
Above white dashed line excluded with expt measuring 10^{-9} g - achievable - can reach M_P !

The experiment was performed in Berkeley within a few months of the proposal

Berkley Experiment

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

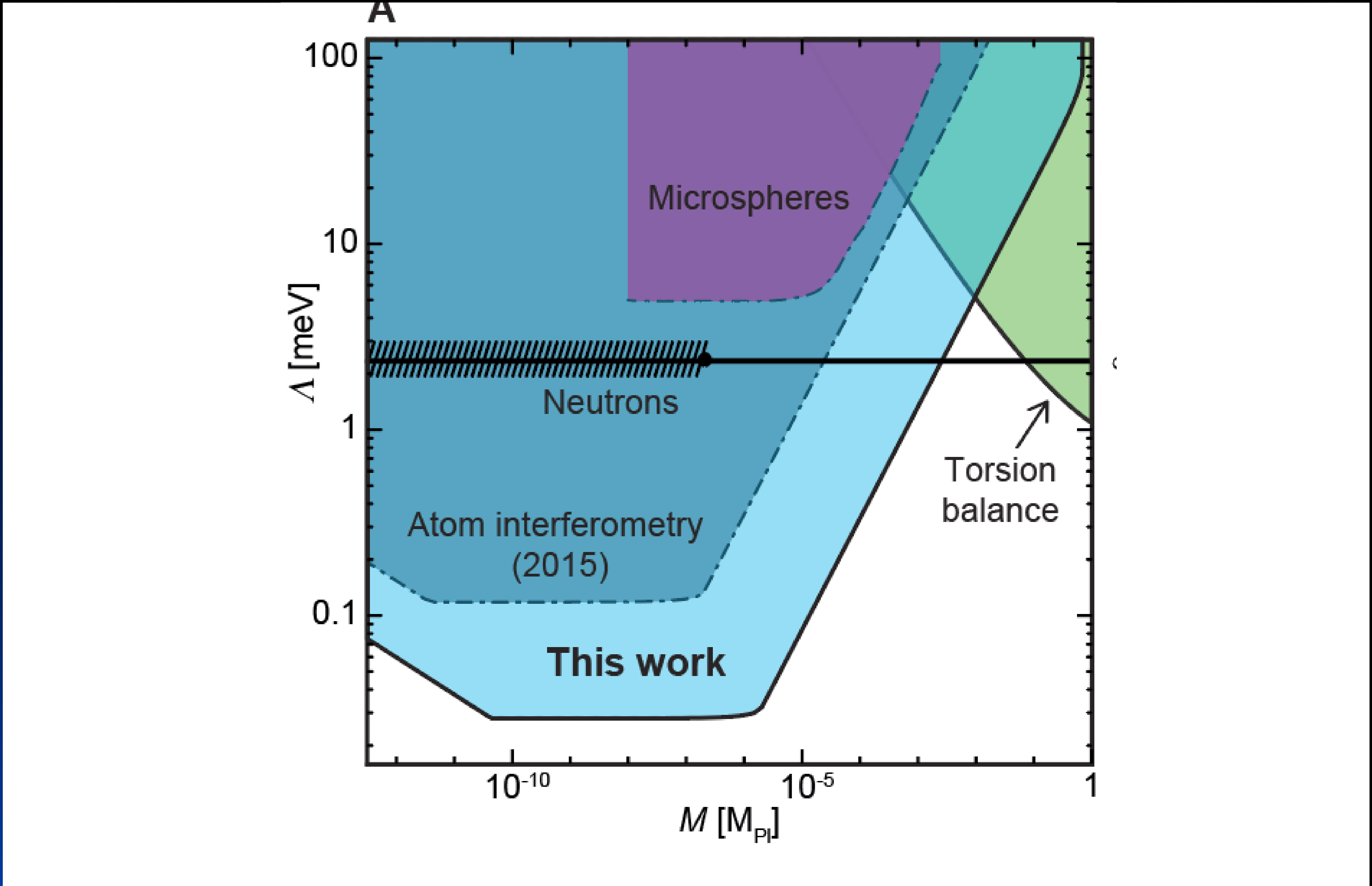




Hamilton et al. (2015)

Slide thanks to Clare Burrage

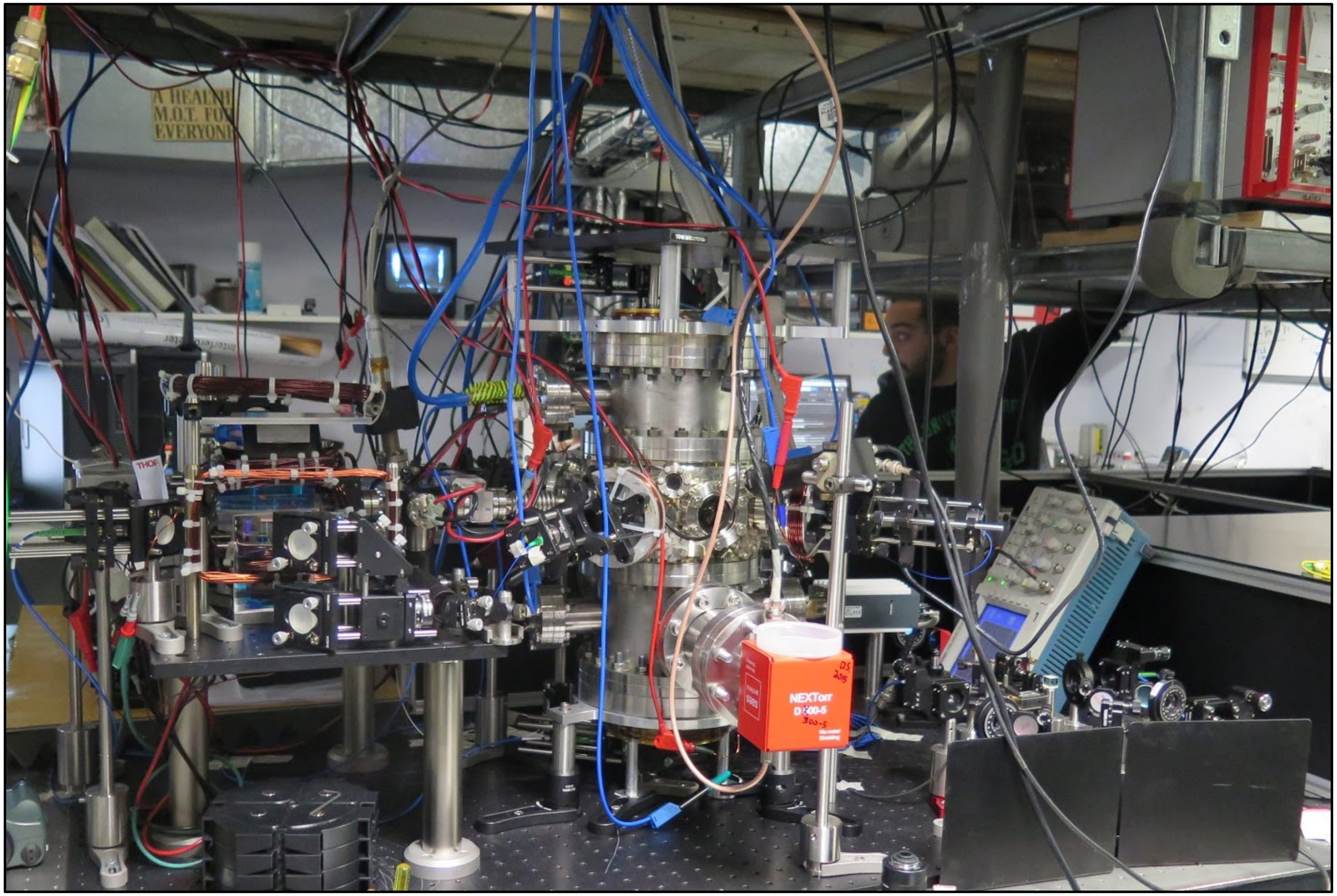
Berkeley Experiment



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

Chameleon experiment being constructed at Imperial College

Centre for Cold Matter (Ed Hinds group)



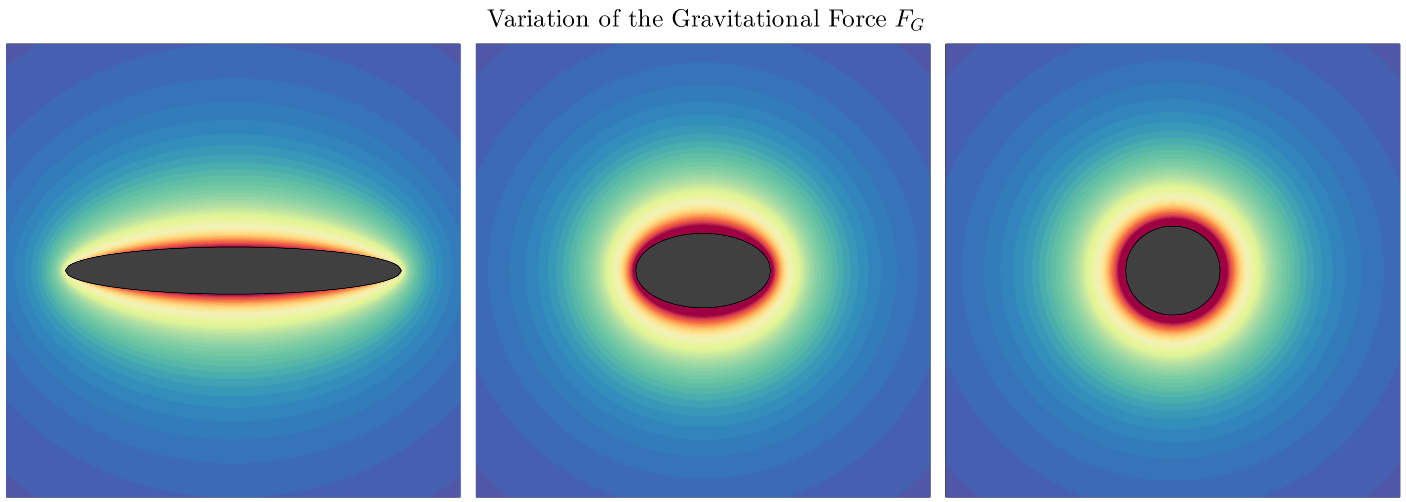
Experiment rotated by 90 degrees from the Berkeley experiment - no sensitivity to Earth's gravity - hope for results in late 2017

So far just considered spherical sources - are they the best shape? [Burrage et al 2014,2017]

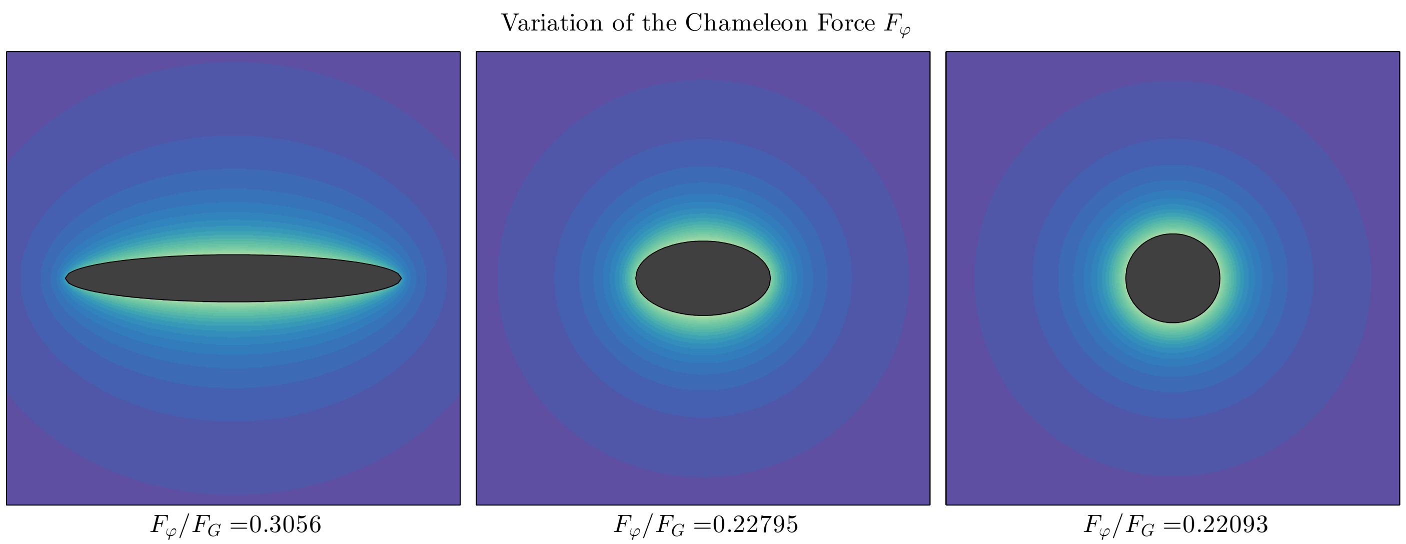
The non-linear self-interactions mean that the chameleon responds to changes in the shape of the source differently to gravity.

Have looked at ellipsoidal departures from spherical symmetry and obtained the full form of the chameleon force, comparing its shape dependence to gravity.

Find enhancement of the chameleon force by up to 40% when deforming sphere to an ellipsoid of the same mass, with compression factor 0.14



(a) The shape dependence of the gravitational force. This also represents the shape dependence of the unscreened chameleon force around objects that do not have a thin shell.

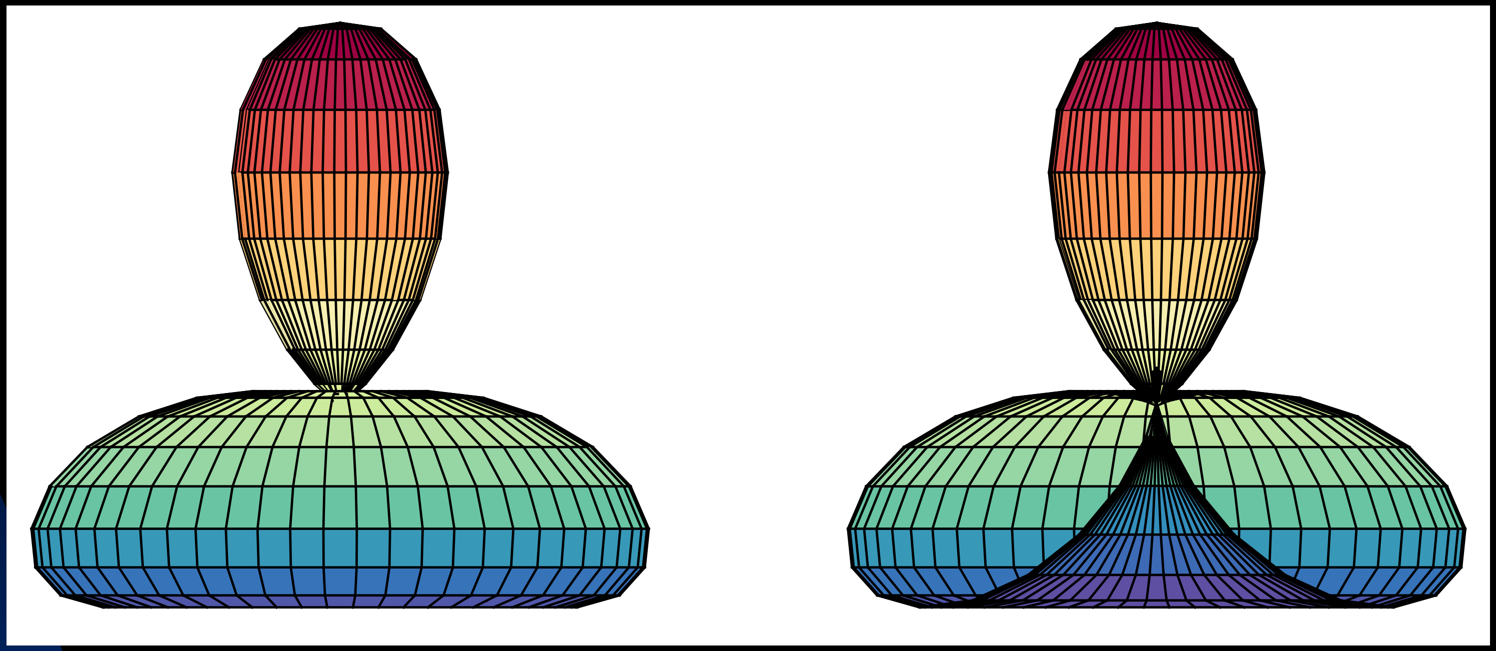


(b) The shape dependence of the chameleon force characteristic of objects for which a shell region has developed.

Red-strongest force

Blue - weakest force

Generalised approach with Legendre Polynomials leads to enhancement by factor of 3 [Burrage et al, 2017].

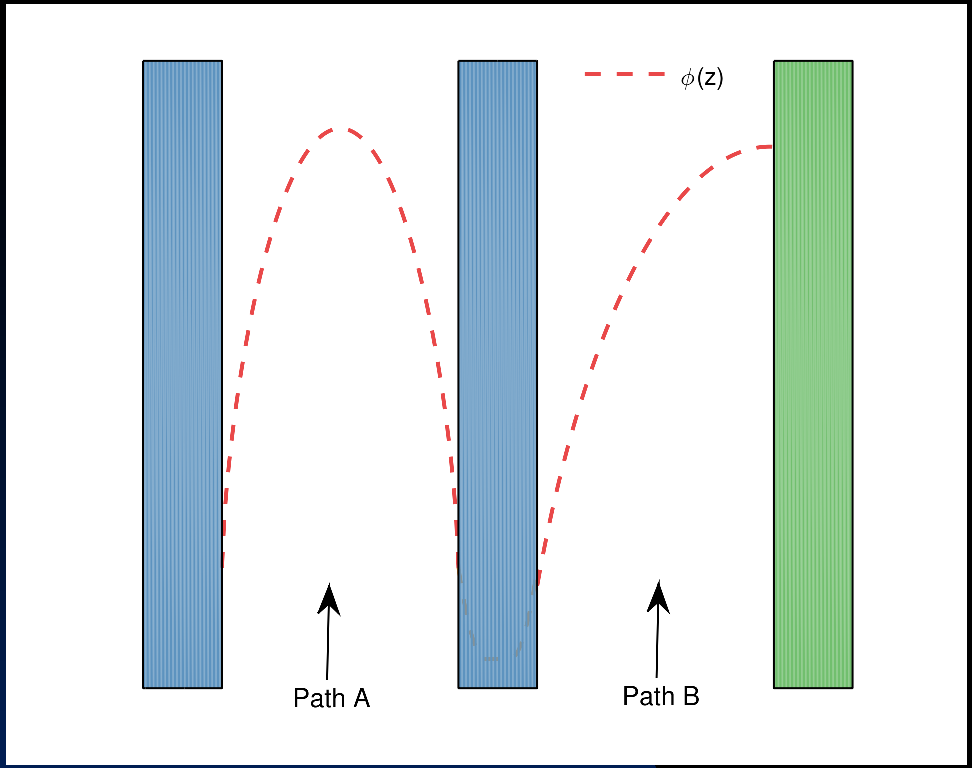


Full 3D image

Cross section from slicing object in half

Raises interesting possibilities for addressing optimal shapes given capability of 3D printing and possible use of machine learning to test out best shapes.

Chameleon searches using Asymmetric Parallel Plates [Burrage,EC,Stevenson 2016]

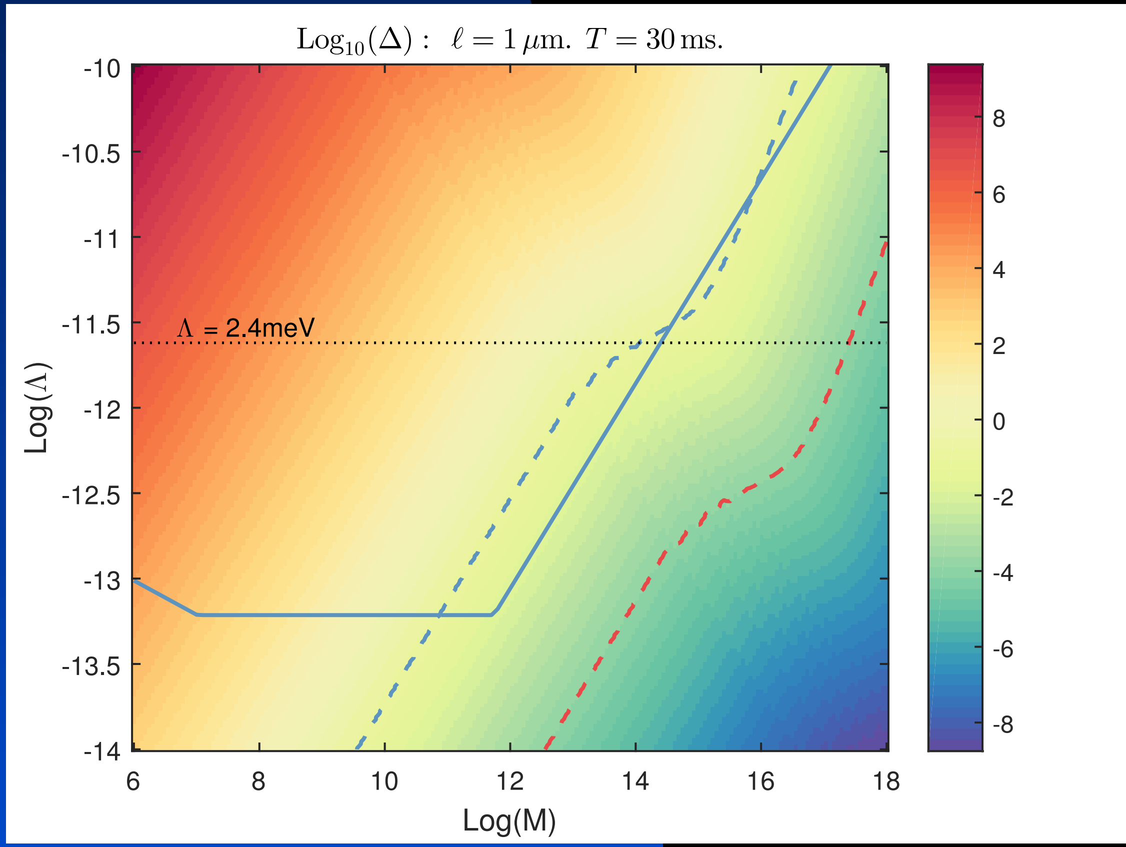


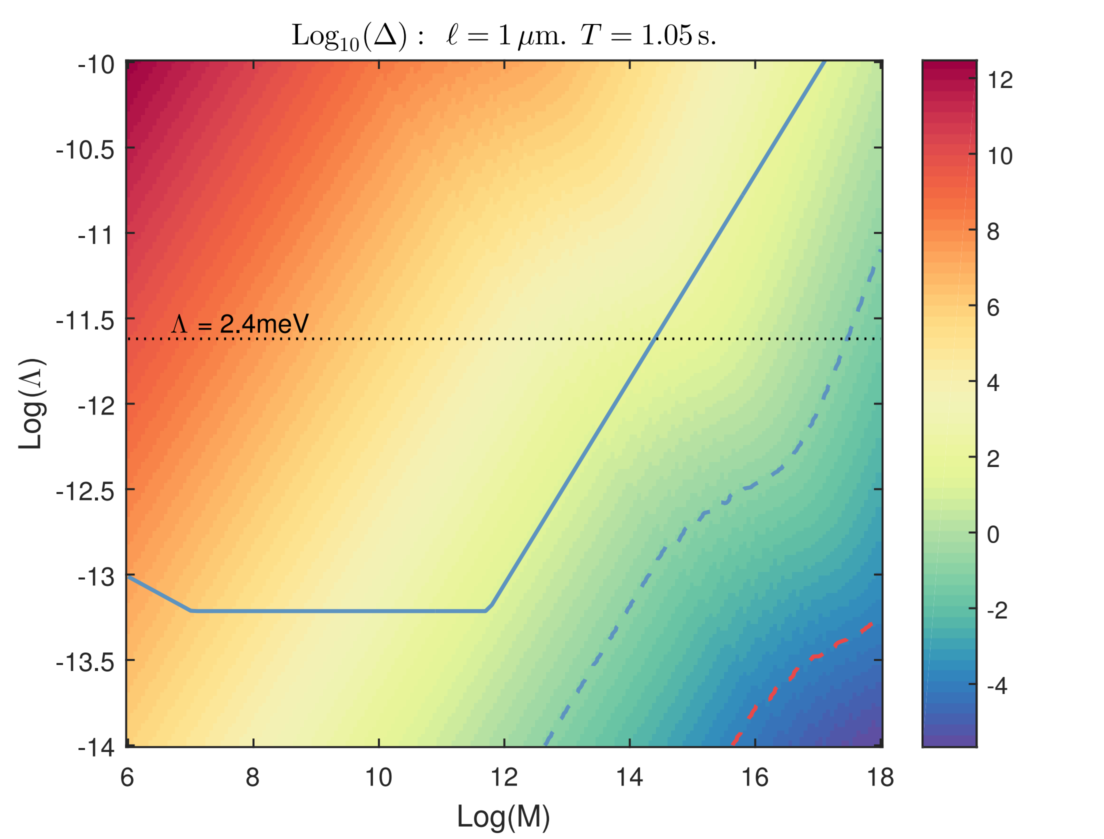
$$\nabla^2\phi = -\frac{\Lambda^2}{\phi^2} + \frac{\rho}{M}$$

Use in conjunction with an Atom Interferometry expt:

Green plate less dense than the blue plates - but same mass. Fire incident atoms along both paths - the wave function describing an atom divides into a superposition of states traversing both paths. The phase of each state experience different paths and recombine to give interference fringes.

Phase difference of wave function for plates separated by a micron and exposure times of 30ms and 1.05s





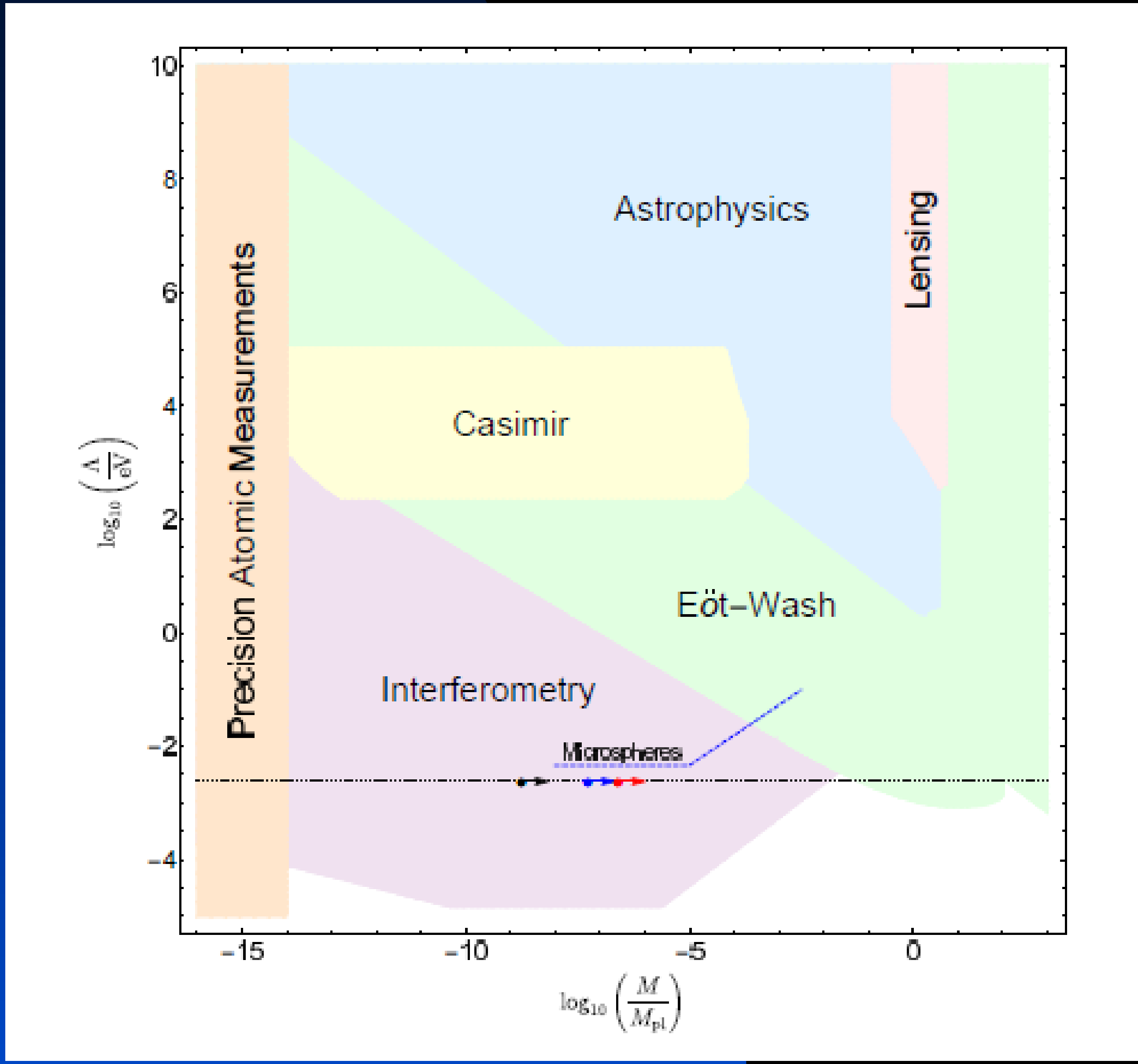
dashed blue line for accelerations down to 10^{-6}g and dashed red line for 10^{-9}g

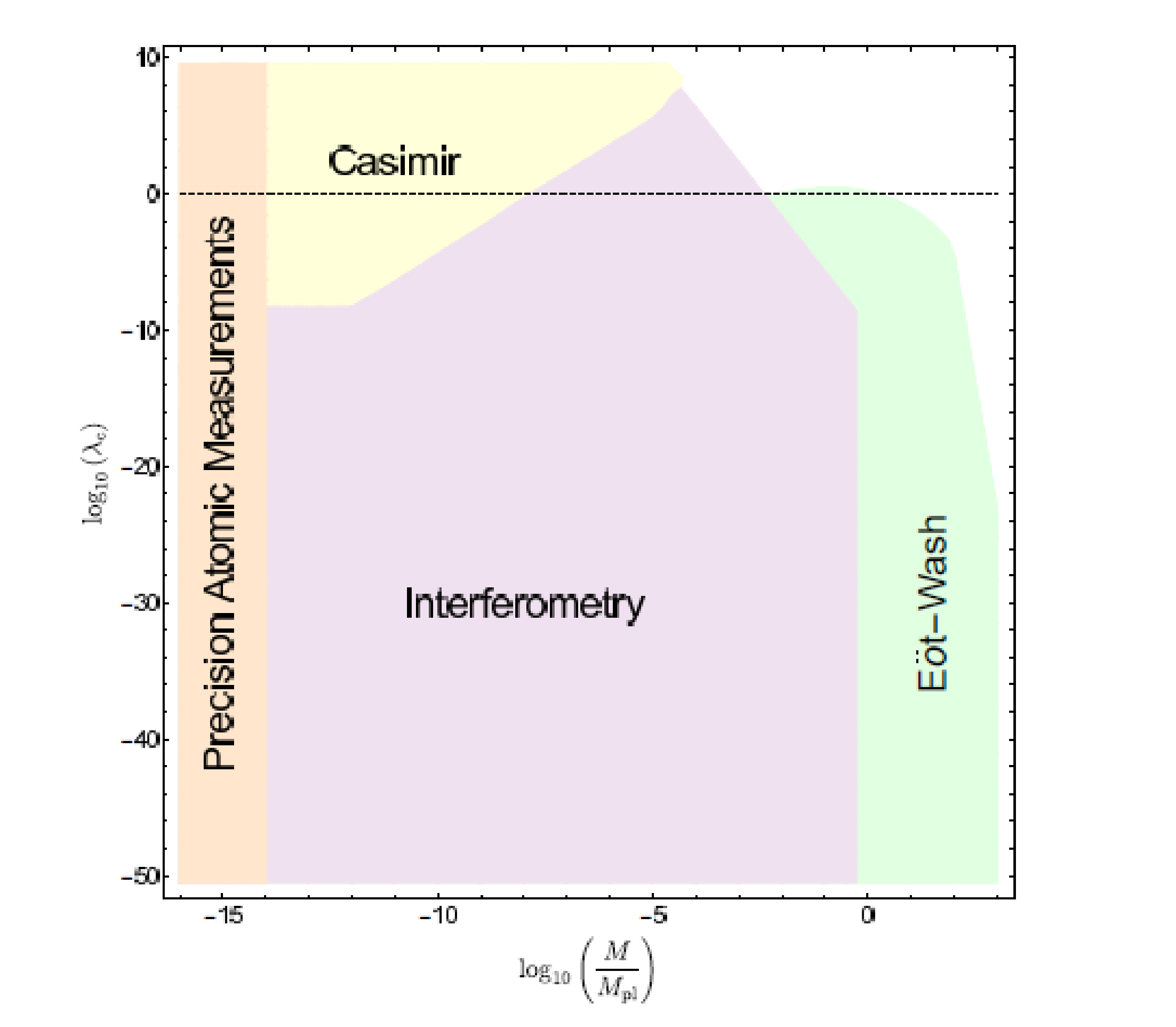
Combined chameleon constraints [Burrage & Sakstein 2017]

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

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

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





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

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

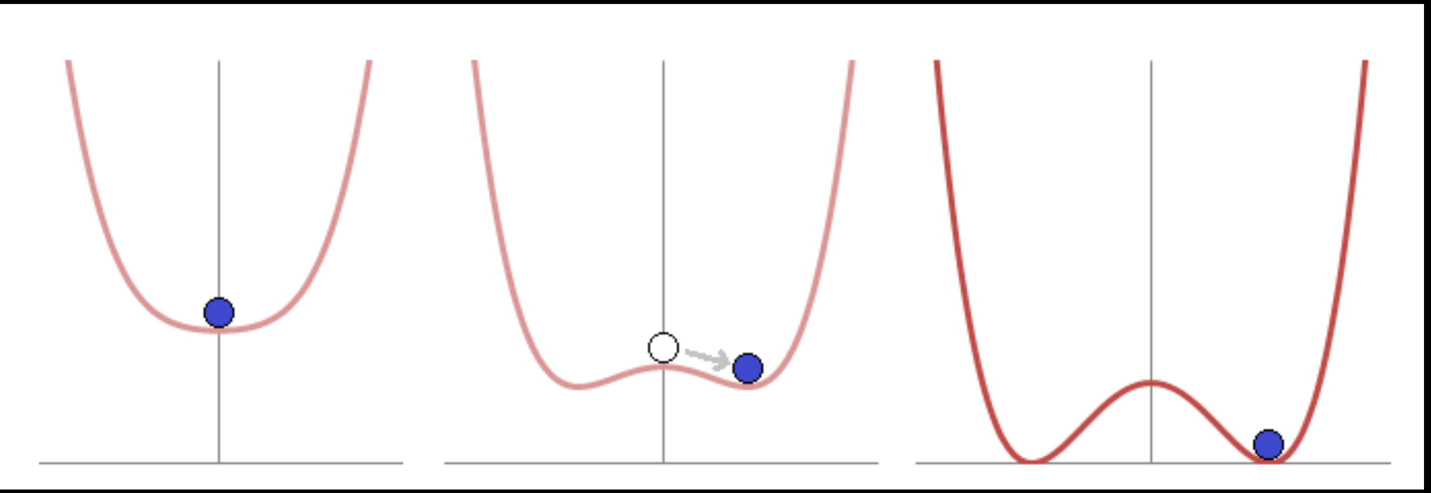
Coupling to matter leads to a fifth force which vanishes as $\varphi \to 0$

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

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

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

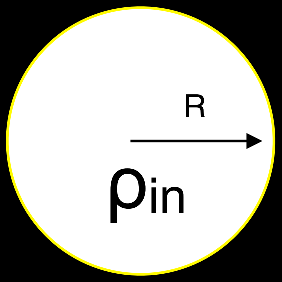
$$\tilde{V}(\varphi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\varphi^2 + \frac{1}{4}\lambda\varphi^4,$$



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:

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

Screened regime: $m_{in} R \gg 1$ (source much bigger than Compton wavelength of symmetron)

Symmetry restored as $r \to 0$ and for $r \gg R$ we find

$$\frac{F_{\rm sym}}{F_N} = \frac{6v^2}{\rho_{\rm in} R^2}\left(\frac{M_{\rm Pl}}{M}\right)^2\left(1 - \frac{R}{r}\right) \ll 1,$$

when $\frac{\nu}{M^2} \sim \frac{1}{M_{\rm pl}}$ symmetron force in vacuum is approx gravitational strength

Unscreened regime: $m_{in} R \ll 1$ (source smaller than Compton wavelength of symmetron)

Symmetry not fully restored as $r \to 0$ and for $r \gg R$ we find

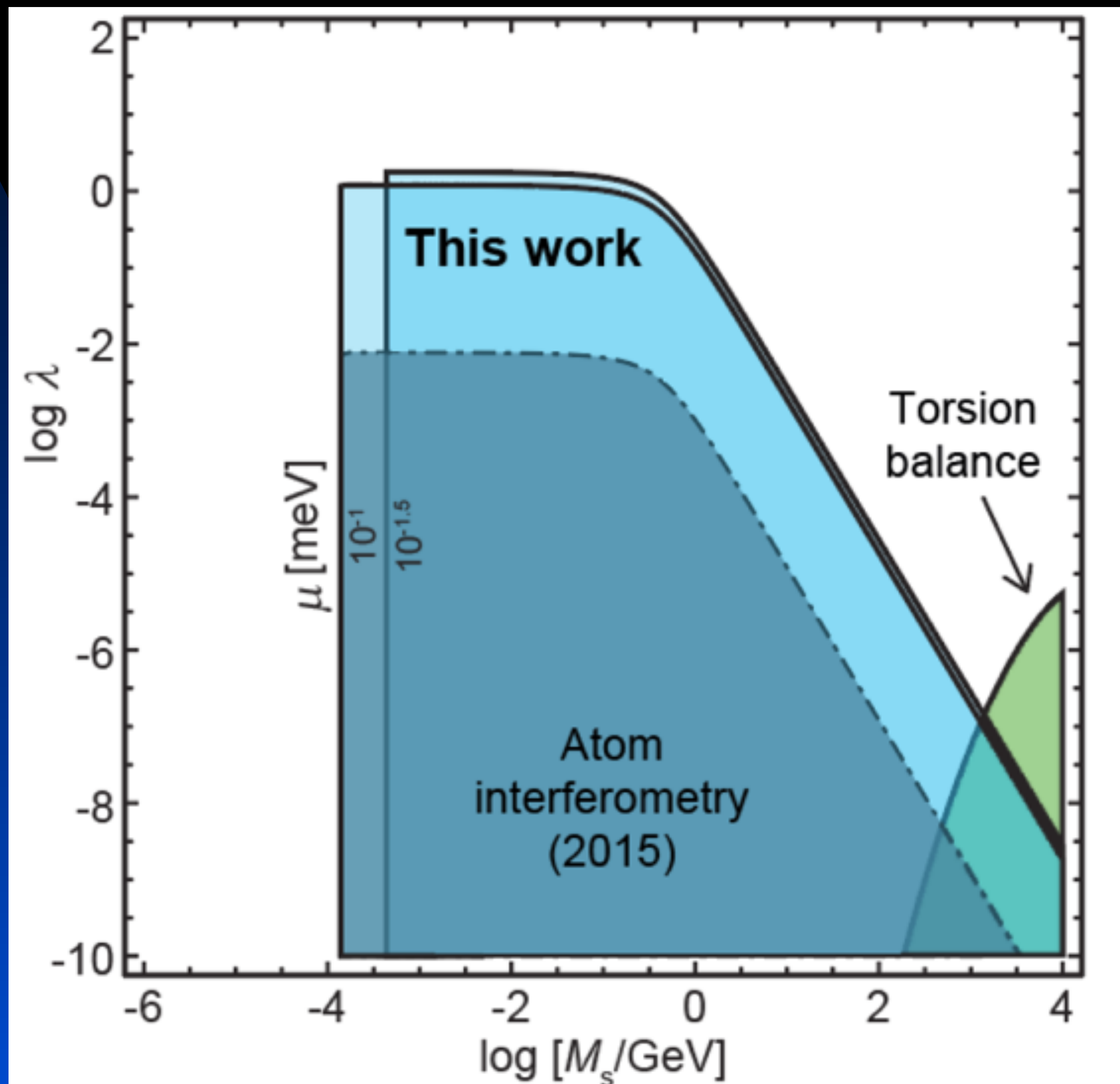
$$\frac{F_{\rm sym}}{F_N} = \frac{2v^2}{M^2}\left(\frac{M_{\rm Pl}}{M}\right)^2 \approx 2.$$

when $\frac{\nu}{M^2} \sim \frac{1}{M_{\rm pl}}$

Note constraints on strength of matter coupling from Lunar ranging is $M/M_{Pl} \lesssim 10^{-4}$! If this is satisfied then can have gravitational strength symmetron force in vacuum between test particles.

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

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



Summary

1. Quintessence type approaches to understanding the nature of dark energy and the current acceleration of the Universe require light scalars which bring with them fifth force constraints that need satisfying.
2. Need to screen this which leads to models such as axions, chameleons,non-canonical kinetic terms etc.. -- these have their own issues.
3. The chameleon mechanism relies on the mass of the scalar field varying with the density of the environment.
4. Atoms are small enough that chameleon field can't react to it quickly enough and they remain unscreened in high vacuum.
5. Opens up possibility of detecting a force in atom interferometry expts.
6. Current expts can provide a significant scan of the Λ-M parameter space and the Planck scale could be within reach.
7. The approach is applicable to other scenarios like symmetron and dilaton fields.
8. Amazing thought - the humble atom can constrain the physics of the Cosmos.

Extra slides in case of emergency

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

The CC gravitates in General Relativity:

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi G} - \rho_{\rm vac}\right)$$

$$G_{\mu\nu} = -8\pi G \rho_{\rm vac} g_{\mu\nu}$$

Now:

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

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. In fact structures would not have formed in it.

Estimate what the vacuum energy should be :

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

$$+$$

zero point energies of each particle

$$+$$

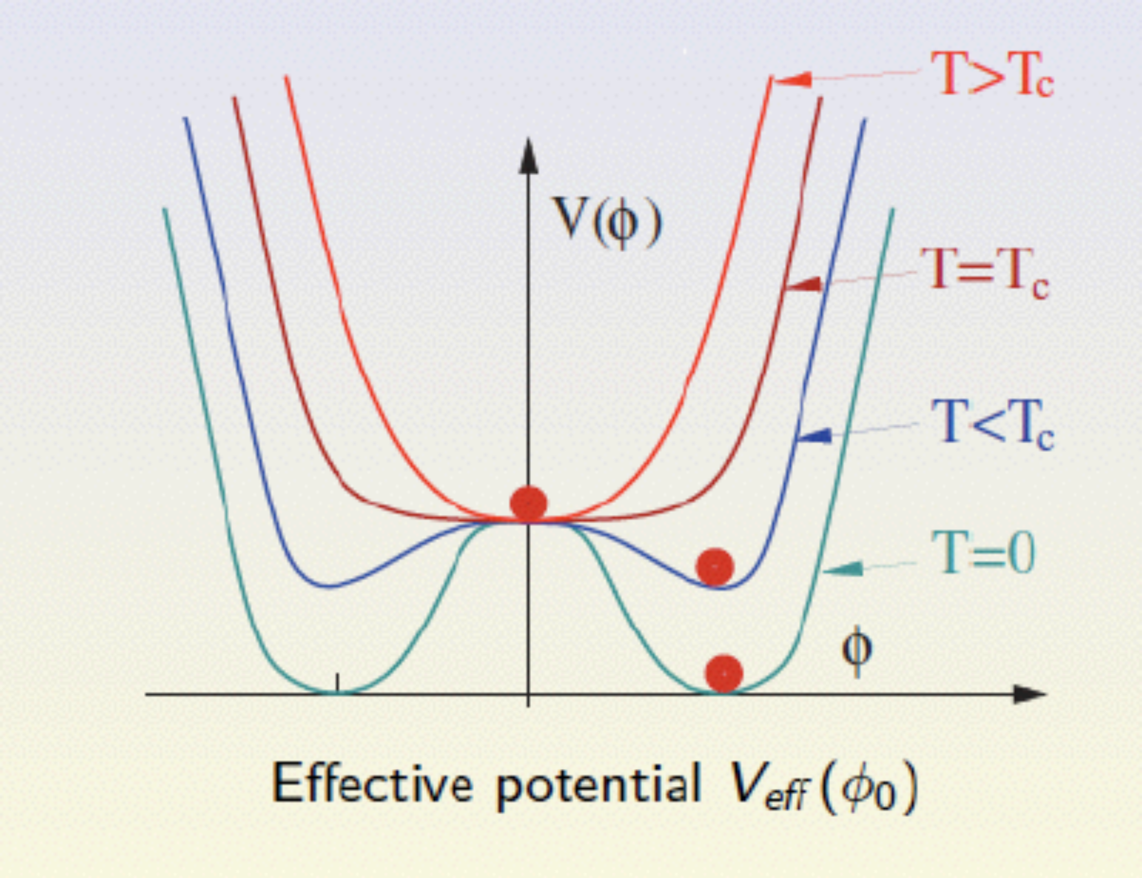
contributions from phase transitions in the early universe zero point energies of each particle

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

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

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

contributions from phase transitions in the early universe



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

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

Quantum Gravity cut-off	$-(10^{18}\ \text{GeV})^4$	fine tuning to 120 decimal places
SUSY cut-off	$-(\text{TeV})^4$	fine tuning to 60 decimal places
EWK phase transition	$-(200\text{GeV})^4$	fine tuning to 56 decimal places
QCD phase transition	$-(0.3\text{GeV})^4$	fine tuning to 44 decimal places
Muon	$-(100\text{MeV})^4$	
electron	$-(1\ \text{MeV})^4$	fine tuning to 36 decimal places
	$-(\text{meV})^4$	Observed value of the effective cosmological constant today !

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 $\varphi \to 0$

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

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

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

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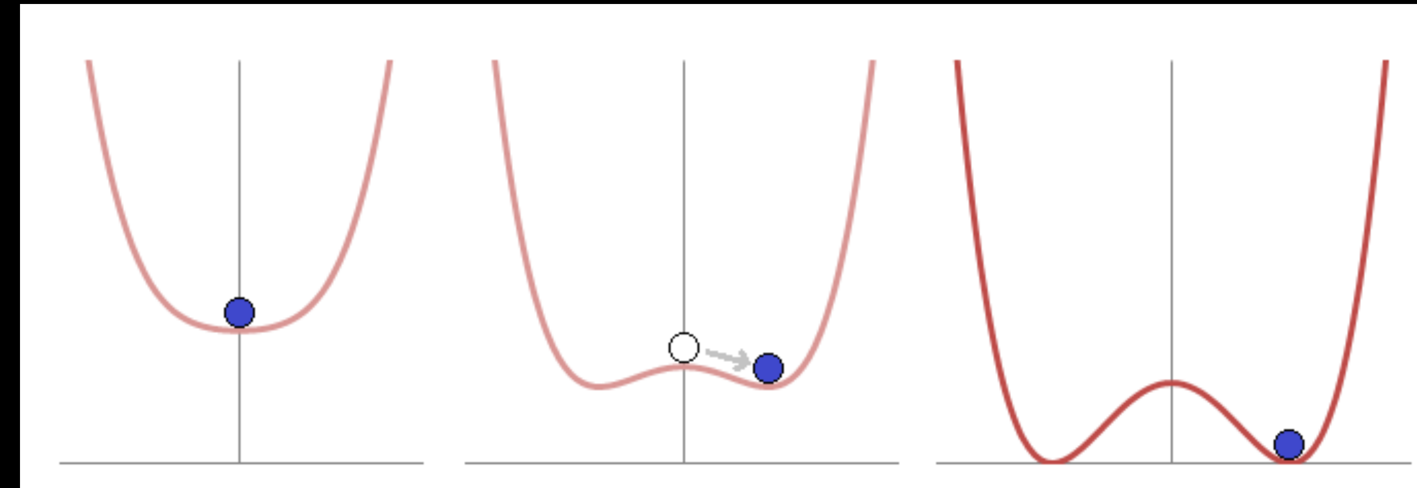
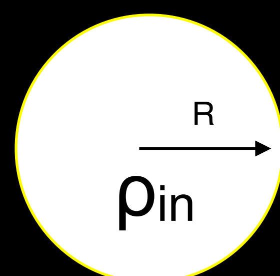


High density: $\rho/M^2 > \mu^2$:

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:

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

Screened regime: $m_{in} R \gg 1$ (source much bigger than Compton wavelength of symmetron)

Symmetry restored as $r \to 0$ and for $r \gg R$ we find

$$\frac{F_{\rm sym}}{F_N} = \frac{6v^2}{\rho_{\rm in} R^2}\left(\frac{M_{\rm Pl}}{M}\right)^2\left(1 - \frac{R}{r}\right) \ll 1,$$

when $v/M^2 \sim 1/M_{Pl}$:

symmetron force in vacuum is approx gravitational strength

Unscreened regime: $m_{in} R \ll 1$ (source smaller than Compton wavelength of symmetron)

Symmetry not fully restored as $r \to 0$ and for $r \gg R$ we find

$$\frac{F_{\rm sym}}{F_N} = \frac{2v^2}{M^2}\left(\frac{M_{\rm Pl}}{M}\right)^2 \approx 2.$$

when $v/M^2 \sim 1/M_{Pl}$

Note constraints on strength of matter coupling from Lunar ranging is $M/M_{Pl} \lesssim 10^{-4}$! If this is satisfied then can have gravitational strength symmetron force in vacuum between test particles.

This is a classical result. We need to think about the radiative stability.

The problem of coupling DE and DM directly with scalars

[D'Amico, Hamil & Kaloper 2016]

Generate loop corrections to the DE mass.

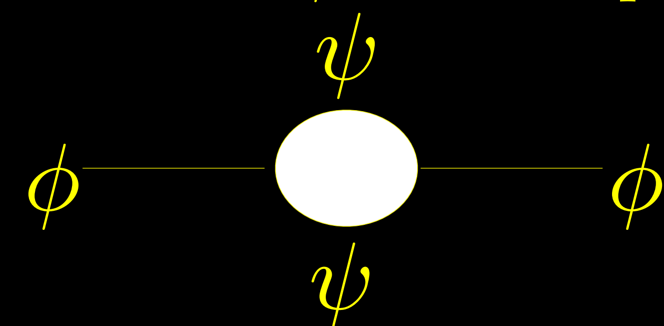
Consider Yukawa type coupling between DE scalar and DM fermion $\quad g\phi\bar{\psi}\psi$

Now since it is DE: $\quad m_\phi \simeq H \sim 10^{-33} eV$

Very light so long range attractive 5th force: $\quad Pot : \Phi(r) \sim g^2/r$

Must be less than grav attraction of DM particles by say factor 10 $\quad g < m_\psi/(10 m_{\rm pl})$

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

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

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

Idea: rather than symmetry breaking at tree level in regions of low density, sym breaking arises radiatively in similar regions via CW mechanism.

Begin with scale invariant model minimally coupled to gravity in Jordan Frame

$$S = \int d^4x \sqrt{-g}\left[\frac{1}{2}F(\phi)\mathcal{R} - \Lambda + \mathcal{L} + \mathcal{L}_m\right],$$

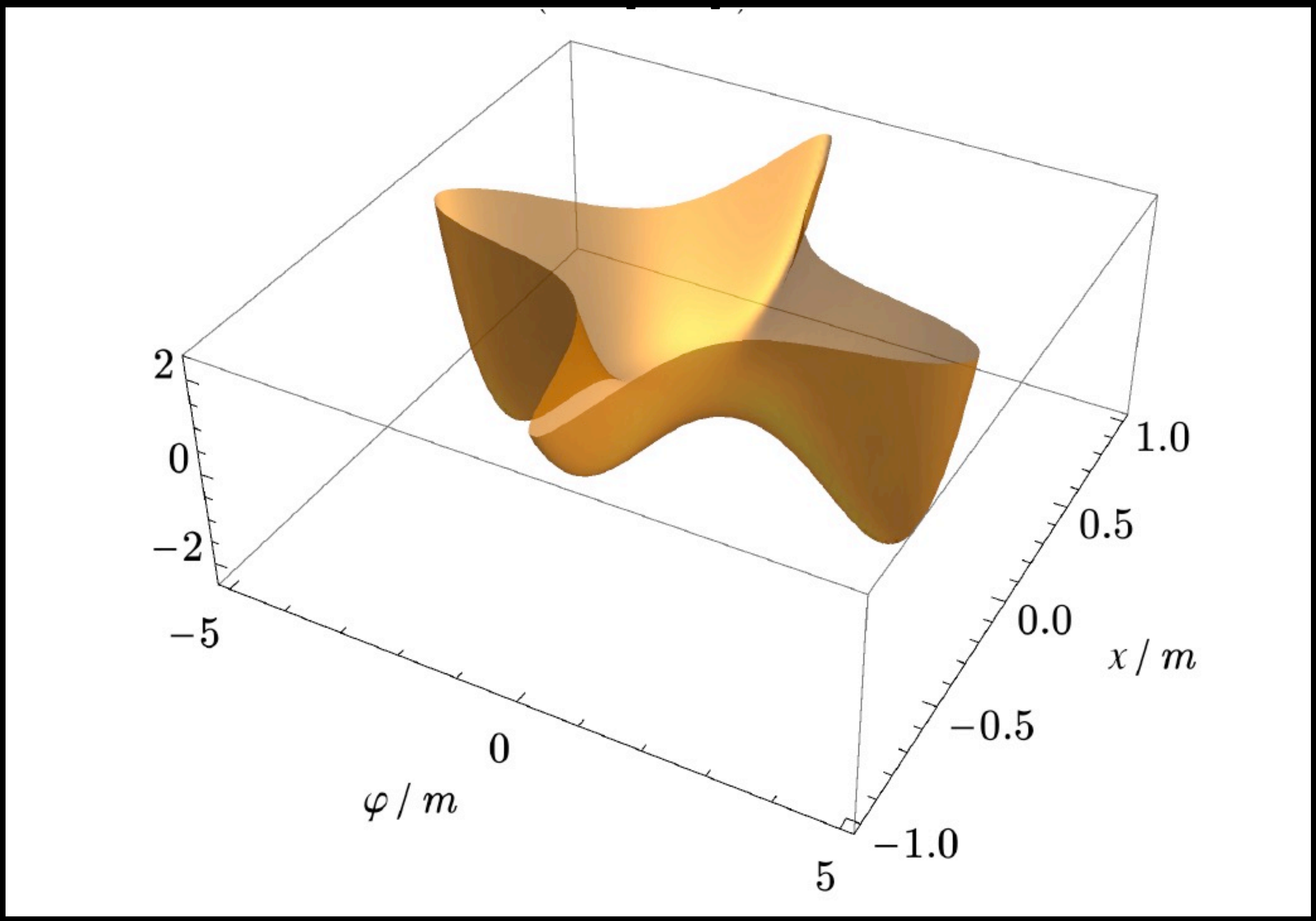
$$-\mathcal{L} = \frac{1}{2}\phi_{,\mu}\phi^{,\mu} + \frac{1}{2}X_{,\mu}X^{,\mu} + \frac{\lambda}{4}\phi^2 X^2 + \frac{\kappa}{4!}X^4,$$

$$F(\phi) = 1 + \frac{\phi^2}{M^2},$$

One Loop Effective Potential

Assuming: gravitational sector is a classical source so neglect all gravitational perturbations; neglect gradient effects so Mink bgd, constant field profiles in loop integrals; treat matter as p=0 perfect fluid

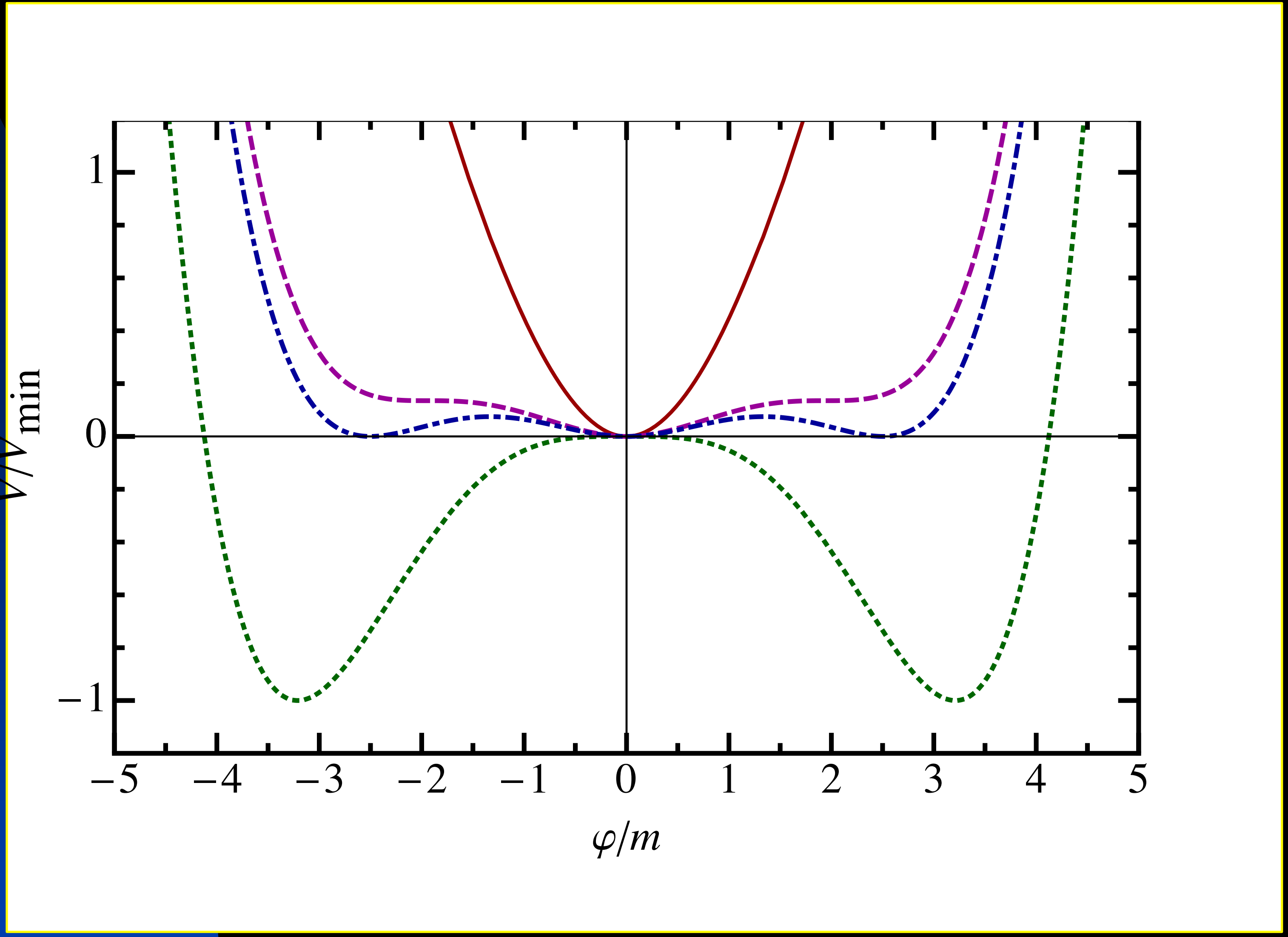
Global minimum along χ=0



[Garbrecht, Millington 2015, Burrage et al 2016]

Renormalised one loop potential for symmetron field when λ=κ

$$V(\varphi) = \frac{1}{2}F(\varphi)\mathcal{R} + \left(\frac{\lambda}{16\pi}\right)^2 \varphi^4 \left(\ln\frac{\varphi^2}{m^2} - \frac{17}{6}\right).$$



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

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.

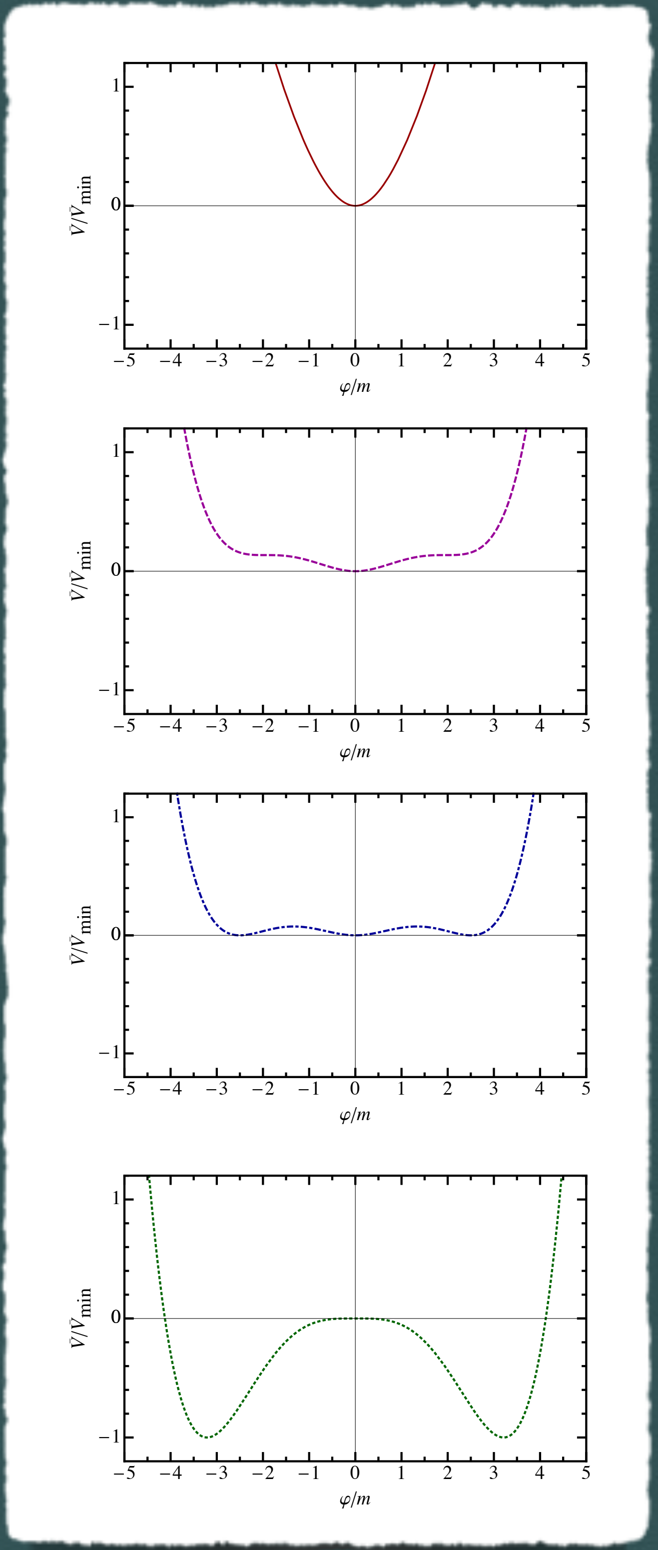
Tunneling to global symmetric minimum.

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

degenerate point:
three degenerate global minima.

Tunneling to global symmetry-breaking minima.

symmetry broken: two global minima and a flat maximum.

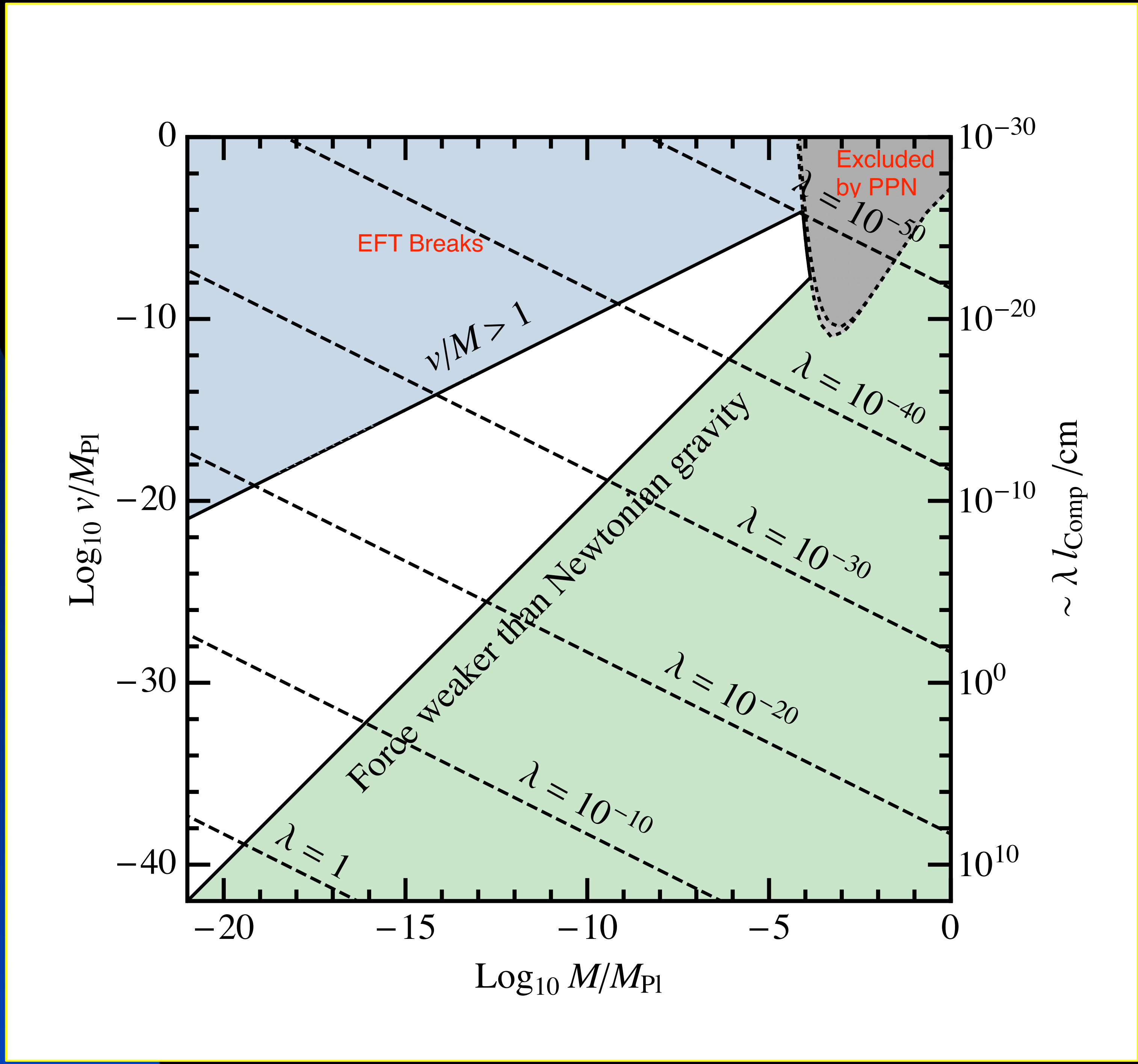


With thanks to Pete Millington

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]

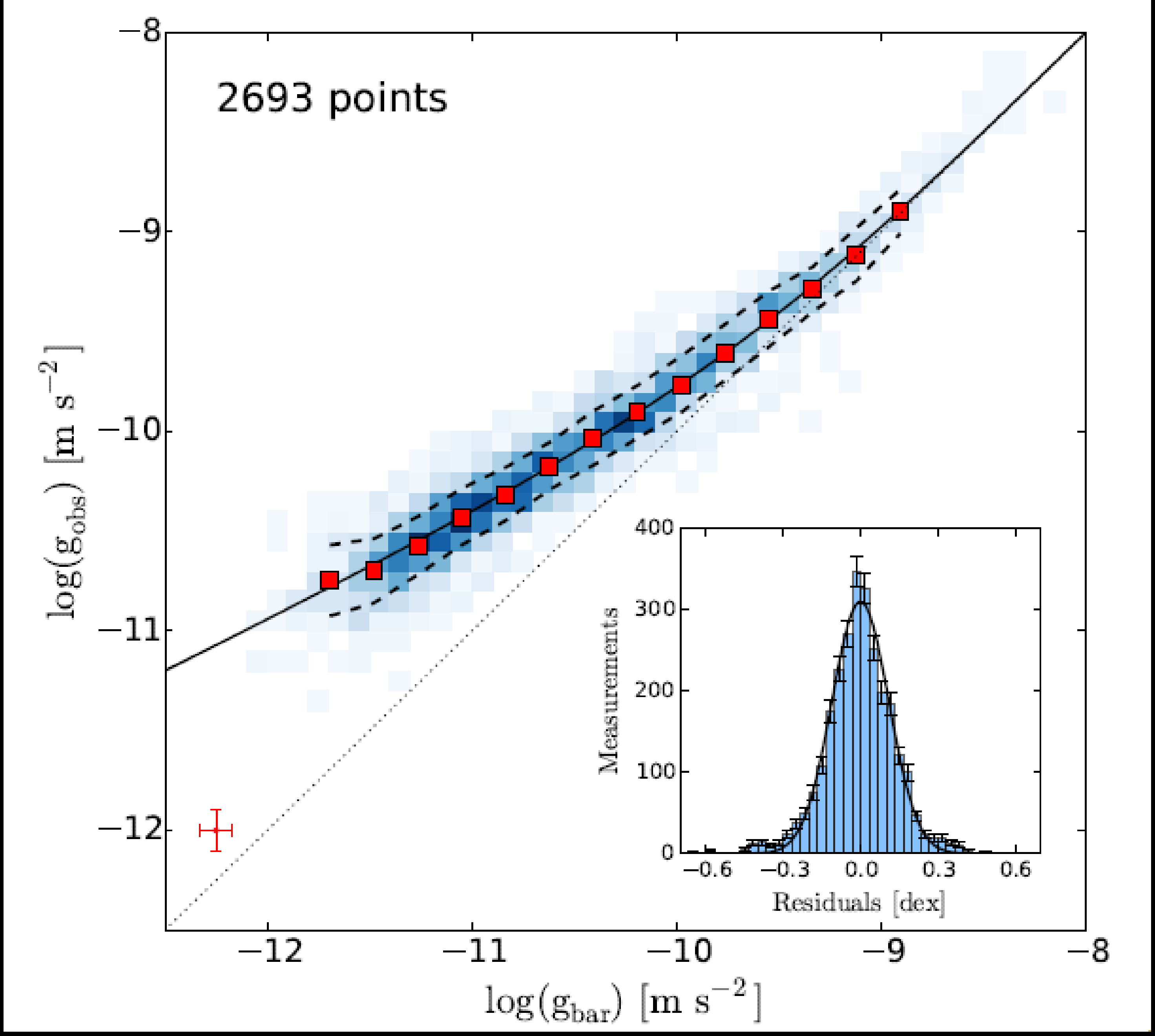
Radial acceleration relation from 153 galaxies (also known as mass discrepancy acceleration relation) [McGaugh et al PRL 2016]

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

Empirical fit:

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

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]

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

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

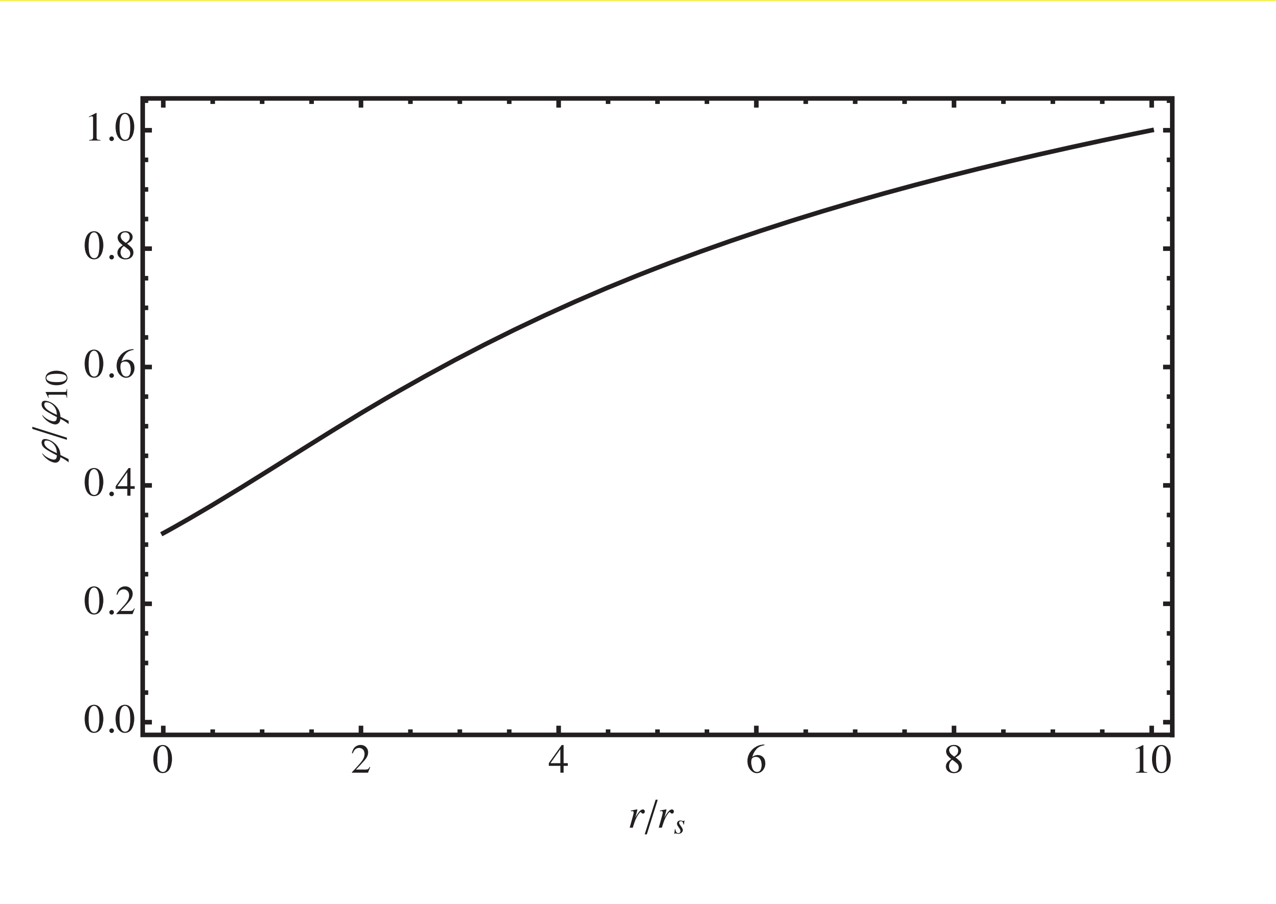
Rotation curve explained if symmetron profile satisfies:

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

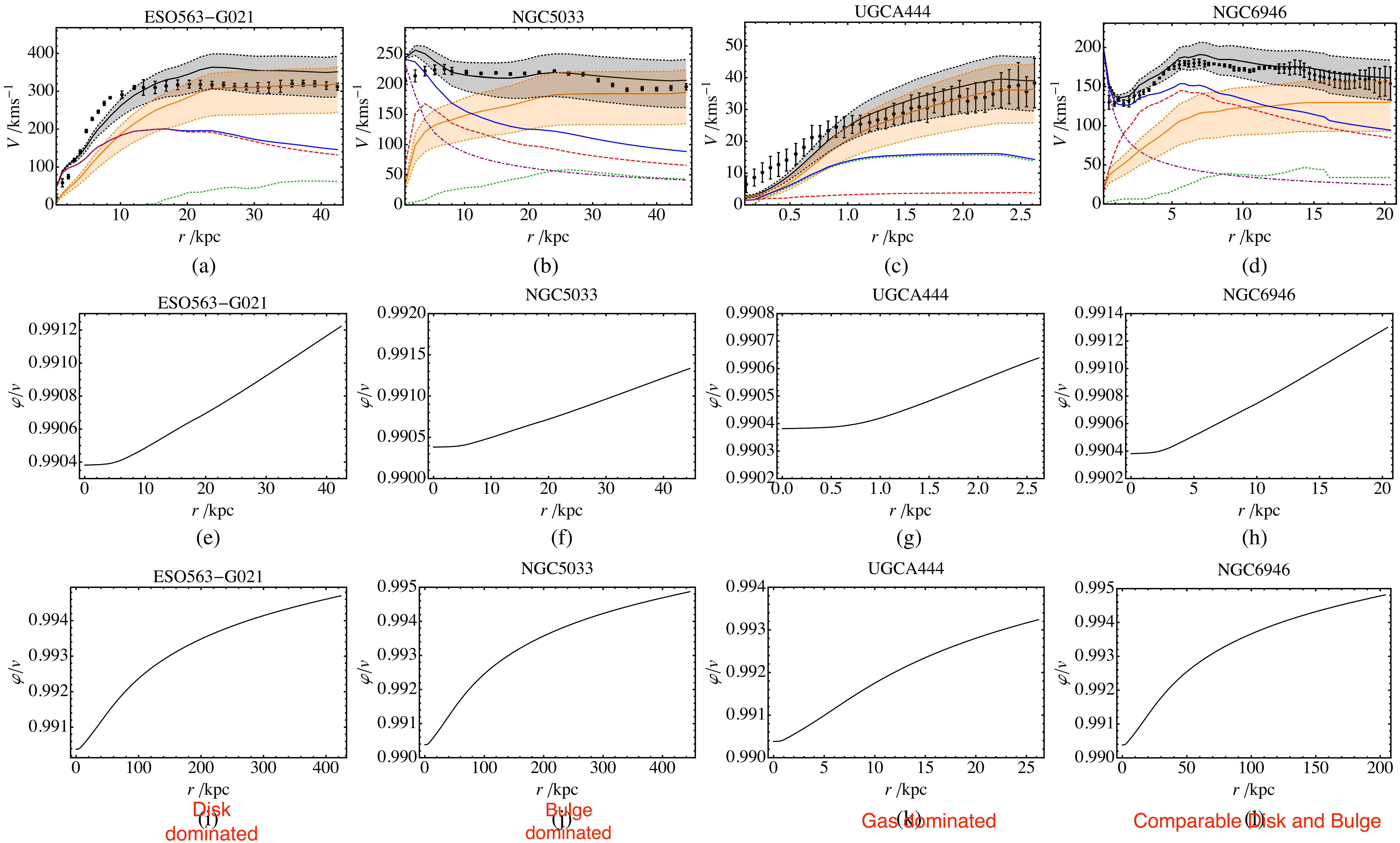
Assuming an exponential disc profile for the galaxy $\Sigma(r) = \Sigma_0 e^{-r/r_s}$, we obtain:

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

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



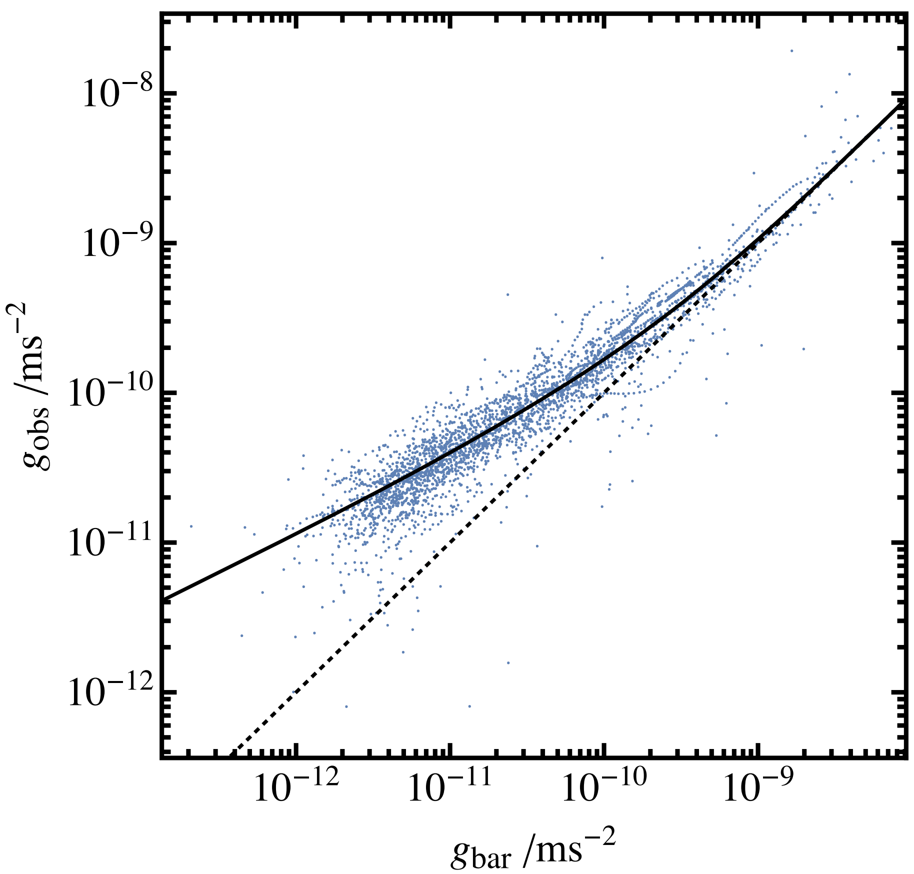
Real galaxies in the SPARC dataset [Burrage, EC & Millington 2017, SPARC, Lelli et al 2016]



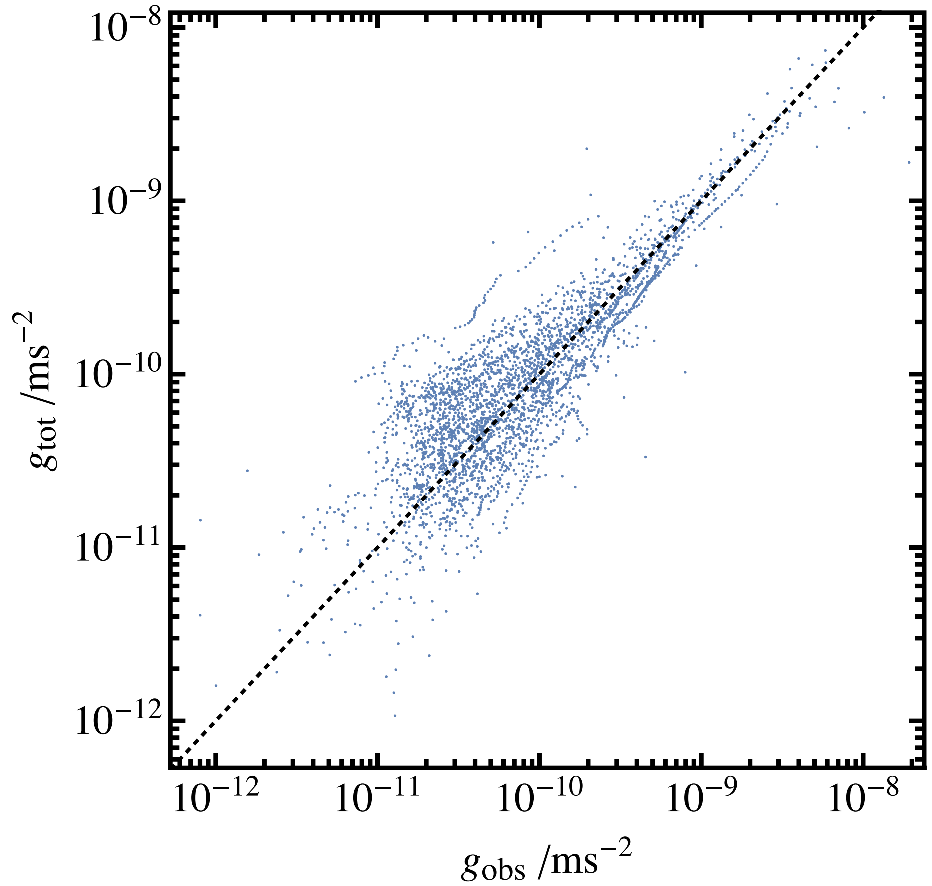
$$M = M_{\rm Pl}/10 \text{ and } \bar{\rho}_0 = 1\ M_\odot\,{\rm pc}^{-3},\ v/M = 1/150, \text{ and } \mu = 3\times 10^{-39}\ {\rm GeV}:$$

Comparison with real data

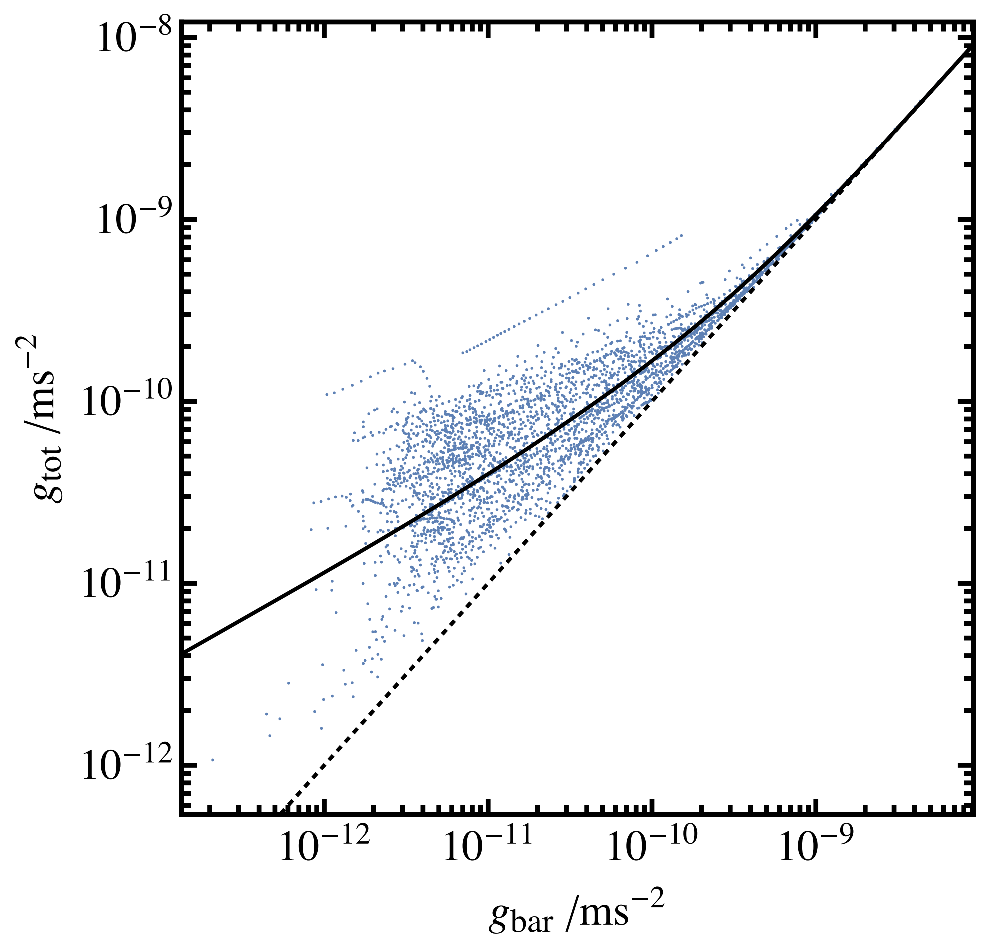
[Burrage, EC and Millington 2017]



(a) observed versus baryonic



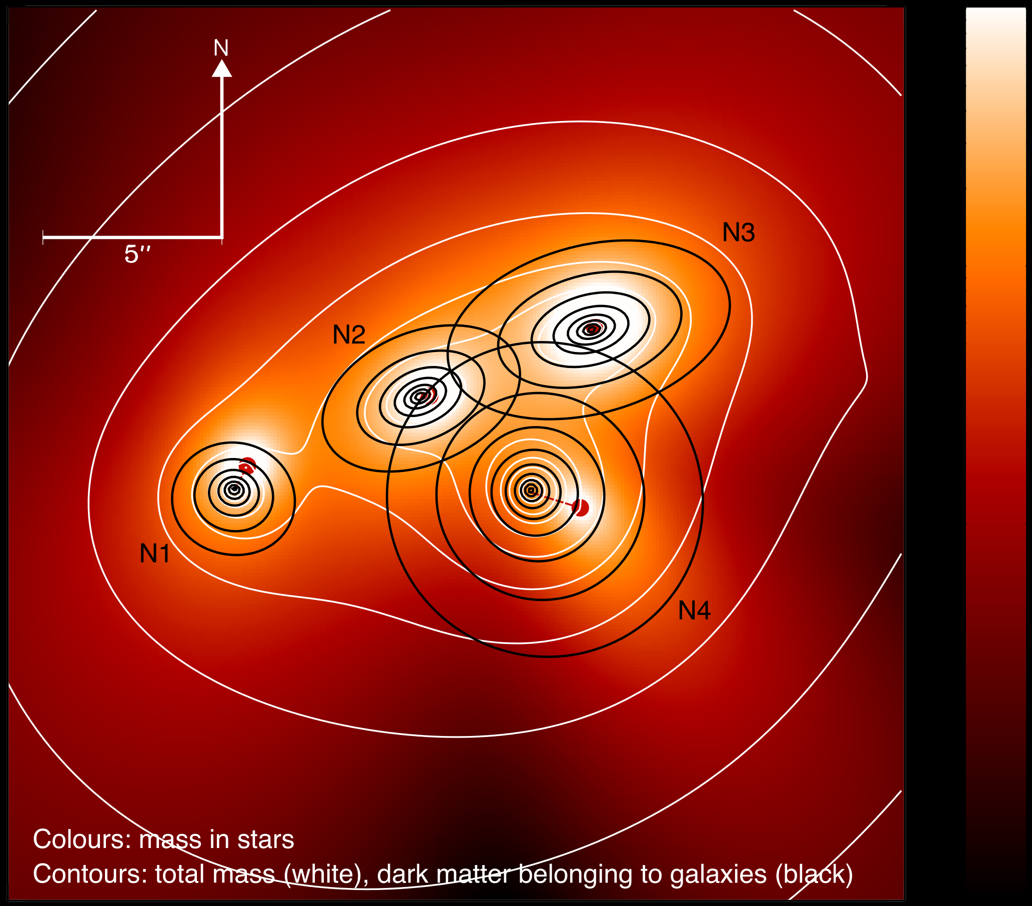
(b) symmetron prediction versus observed



(c) symmetron prediction versus baryonic

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

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

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

Strong CP problem intro axion : $m_a = \frac{\Lambda^2_{\rm QCD}}{F_a}$; F_a – decay constant

PQ axion ruled out but invisible axion still allowed:

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

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} GeV

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

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

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

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