Dark Energy Screening Mechanisms

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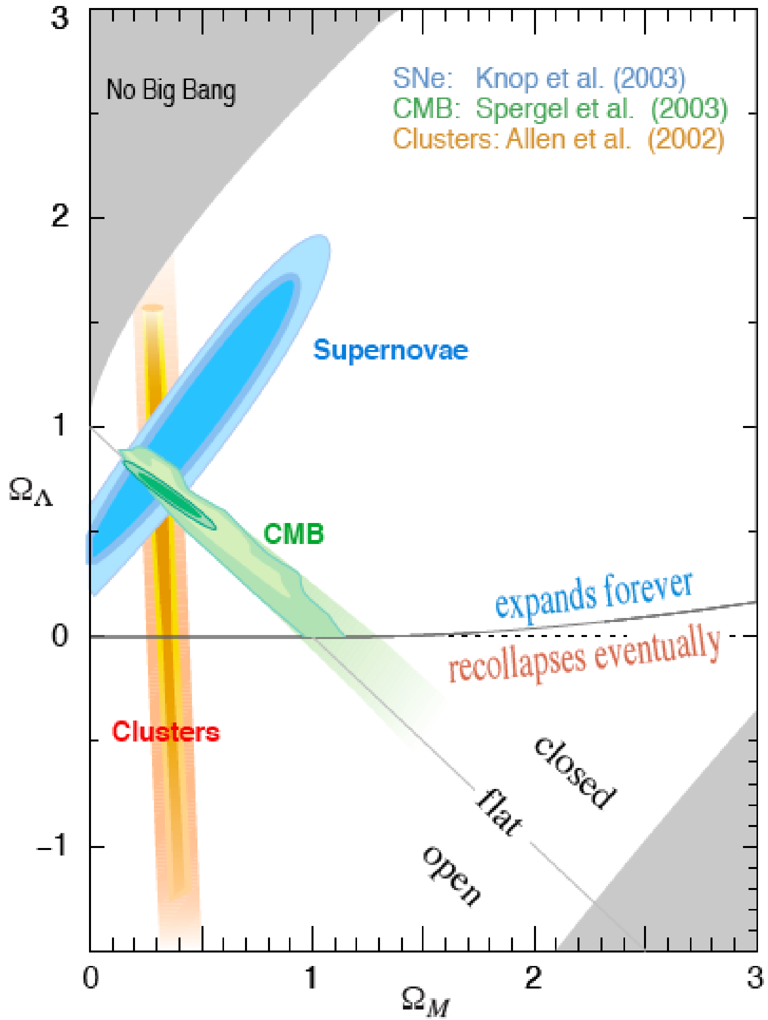
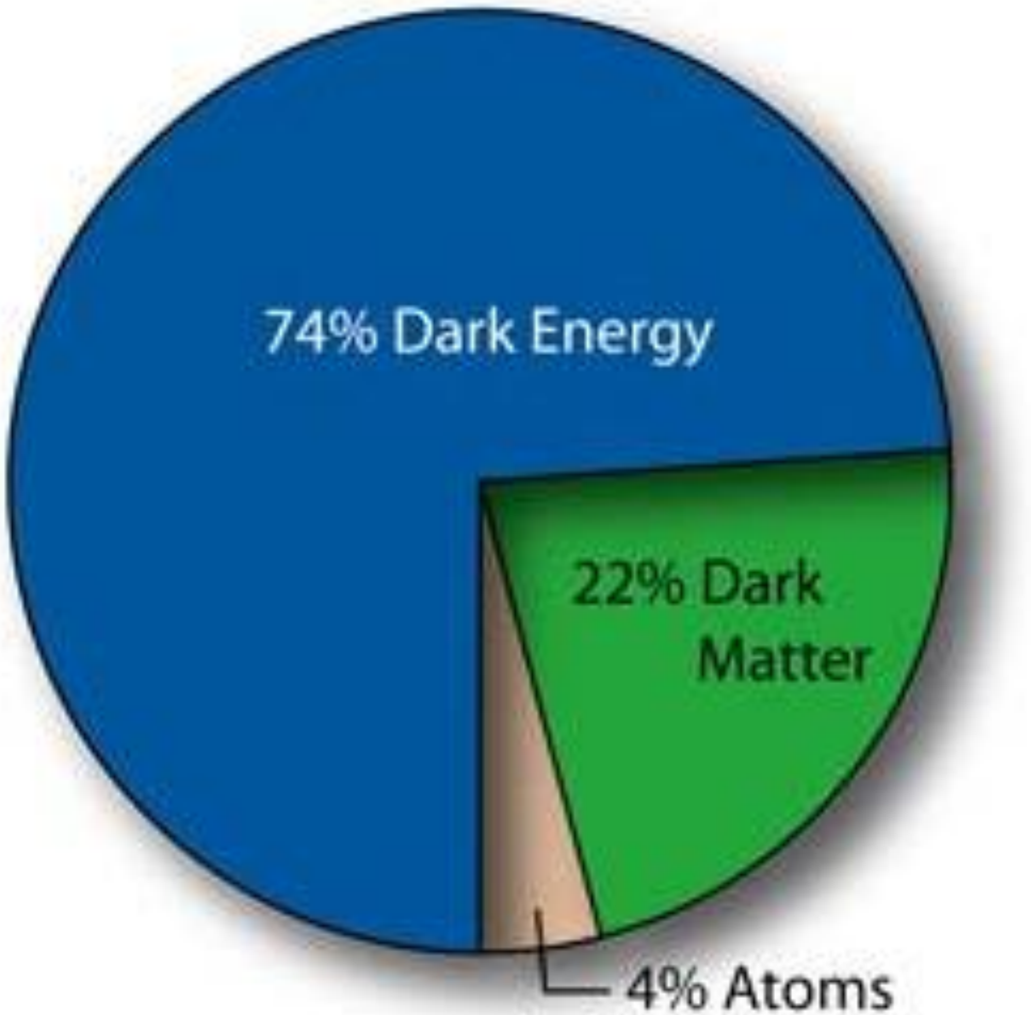
The expansion of the Universe is accelerating



"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

The Universe today



The cosmological constant problem

The Einstein equations:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

The energy density of the vacuum looks like a cosmological constant

$$\langle T^{vac}_{\mu\nu} \rangle = \langle \rho^{vac} \rangle g_{\mu\nu}$$

$$\Lambda_{eff} = \Lambda + 8\pi G \langle \rho^{vac} \rangle$$

Contributions from phase transitions and quantum loops

Expected value:

$$\rho^{vac} \sim M^4$$

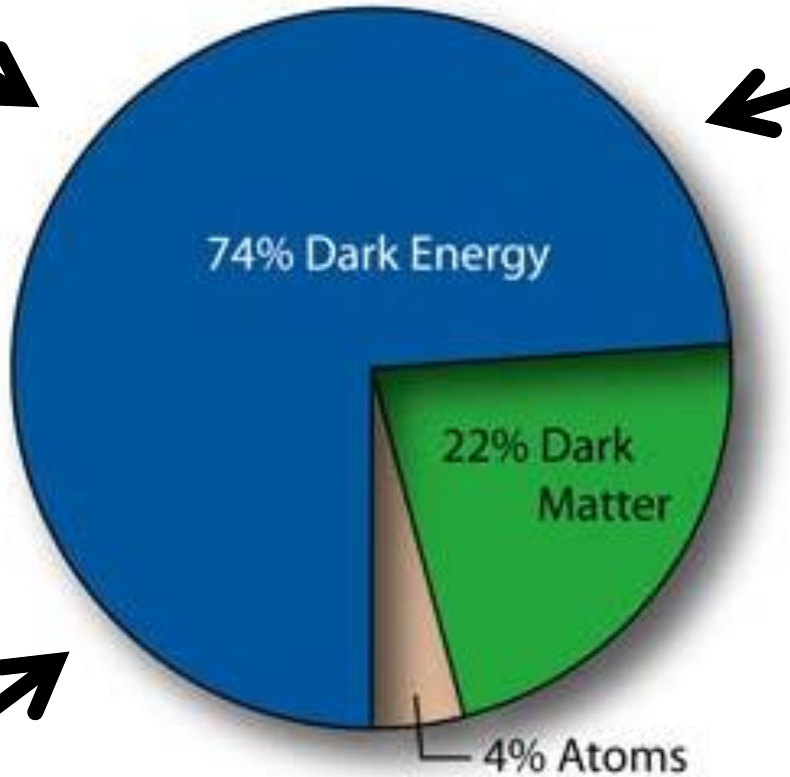
Observed value:

$$\rho_\Lambda \sim (10^{-3}\ \mathrm{eV})^4$$

The Universe today

Cosmological constant?

New scalar field?



Modification of gravity?

Dark energy vs. modified gravity

Is this an unnecessary distinction?

$$G_{\mu\nu} = -8\pi G T_{\mu\nu}$$

Changes on the gravity side of the equation can be mapped to equivalent changes on the matter side

Typically modifications introduce a new scalar degree of freedom

Dark energy vs. modified gravity

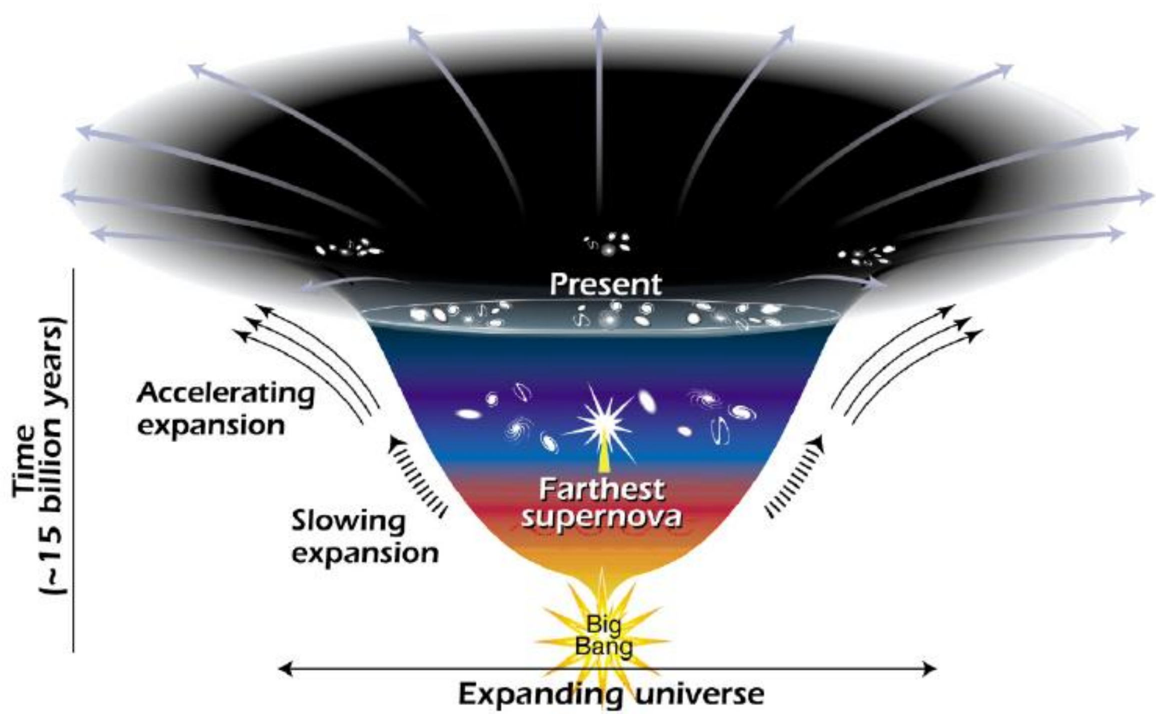
A massive graviton has more degrees of freedom than a massless one

- One of these behaves like an additional scalar mode

f(R) theories contain an extra scalar degree of freedom because of the presence of higher derivatives

In many brane world models there is an extra scalar mode corresponding to the position of the brane in the extra dimension

Light scalar fields



Whatever is causing the acceleration of the expansion of the universe today must be coherent across the observable universe

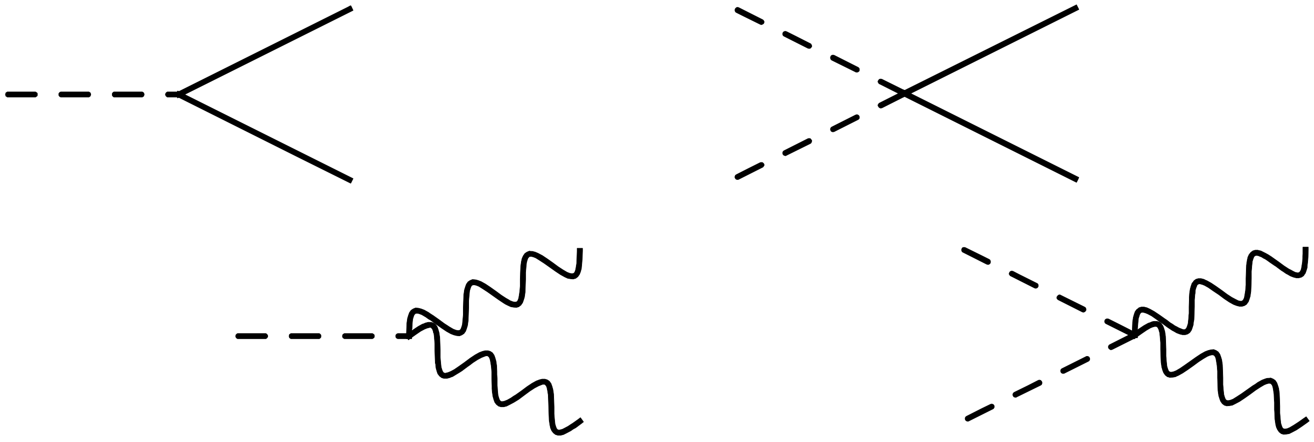
- This corresponds to very light masses

DARK ENERGY AND MATTER

Interactions with matter are unavoidable

No symmetry can prevent all couplings to the Standard Model

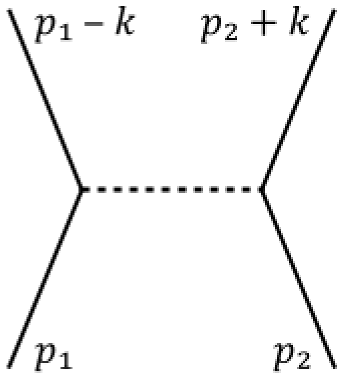
Even if dark energy is in a ‘dark sector’ there will still be interactions mediated by gravity



What's the problem with scalar fields?

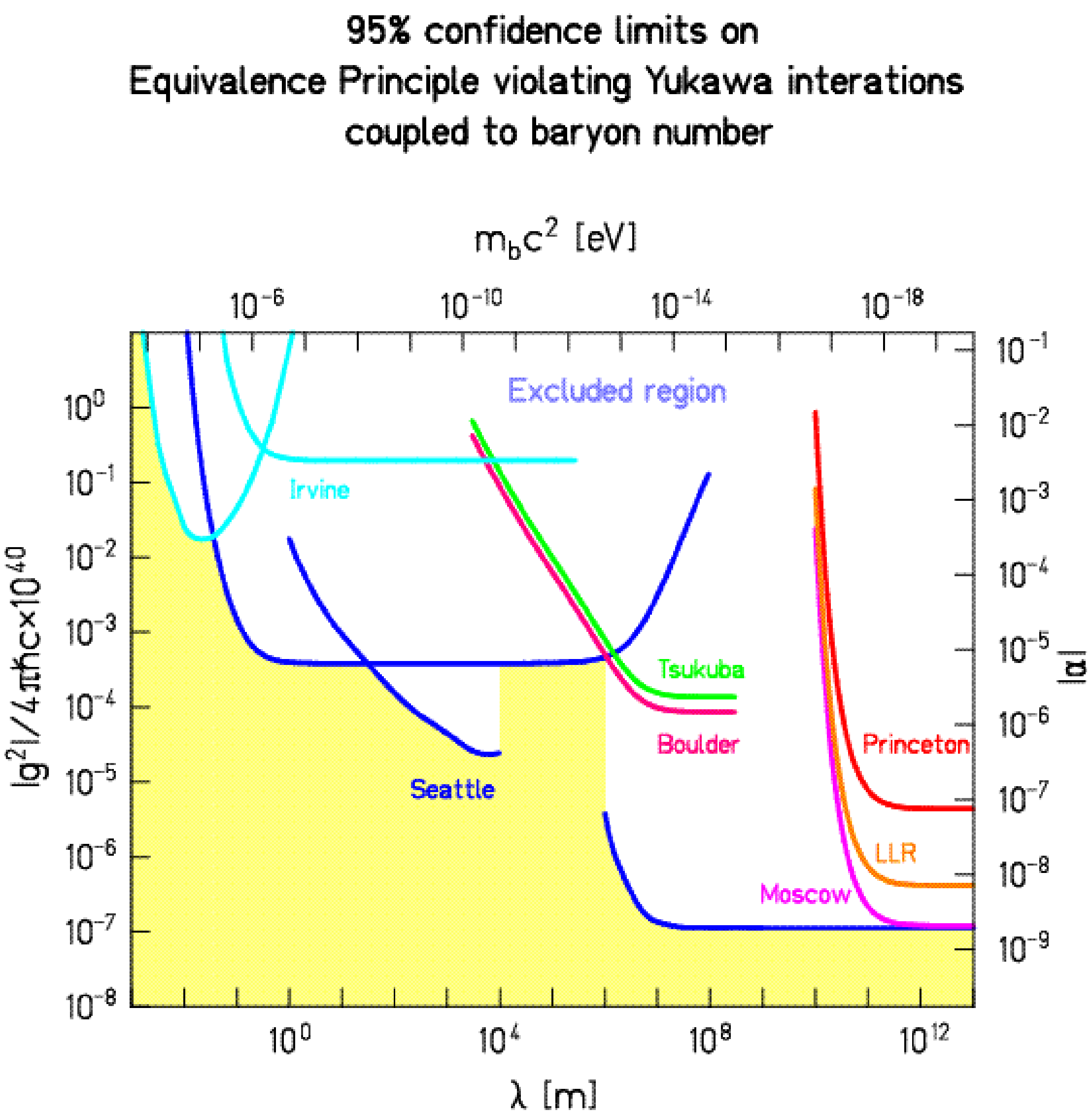
It is hard to introduce a new scalar field that does not couple to matter fields at least at the Planck scale

Bosons that couple to matter mediate forces



- In the non-relativistic limit: $\vec{F} \sim \dfrac{1}{|\vec{x}|^2}$

We do not see any fifth forces or modifications of gravity in the laboratory or in the Solar System



Results of the Eöt-Wash experiment at the University of Washington

Is Dark Energy a chameleon?

Picture credit: Habib M’henni

The chameleon

A scalar field theory

- With self interactions
- Which couples to matter

$$\mathcal{L}_\phi = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + B(\phi)T^\mu_\mu$$

$$V(\phi) = \Lambda^4 e^{\Lambda/\phi} \qquad\qquad B(\phi) = e^{\beta\phi/M_P}$$

Evading fifth force constraints requires $\Lambda \lesssim 0.01 \text{ eV}$

The screening mechanism is relevant if $\beta \gtrsim 0.01$

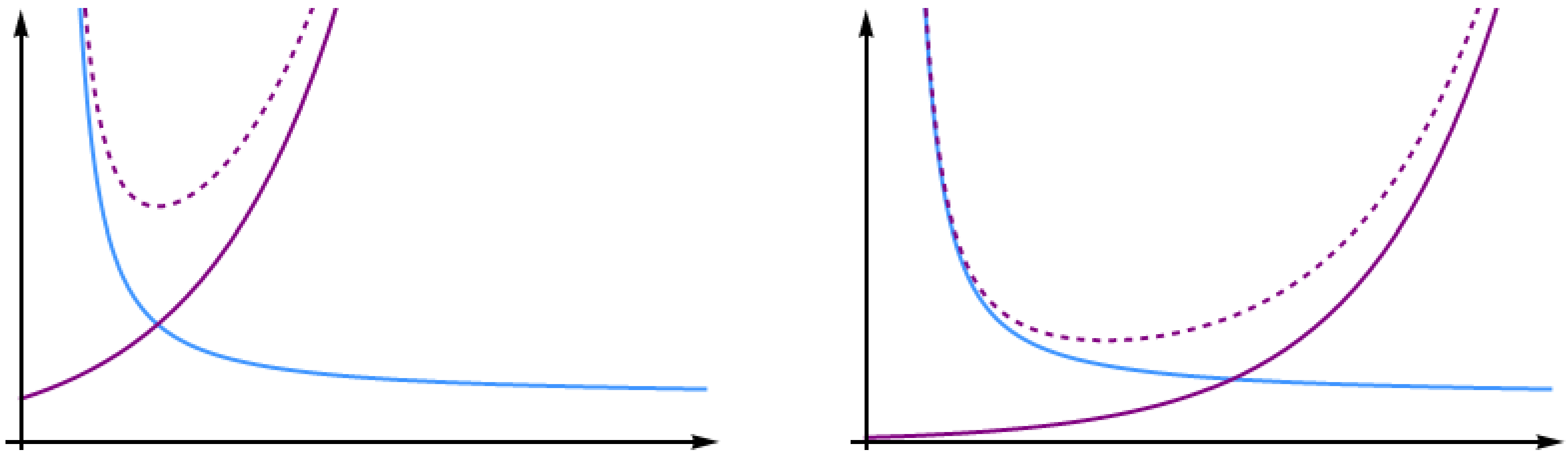
f(R) modifications of gravity correspond to

$$\beta = \frac{1}{\sqrt{6}}$$

Khoury, Weltman. 2004

The effective potential

$$V_{\mathrm{eff}} = \Lambda^4 e^{\Lambda/\phi} + (\rho - 3p)e^{\beta\phi/M_P}$$



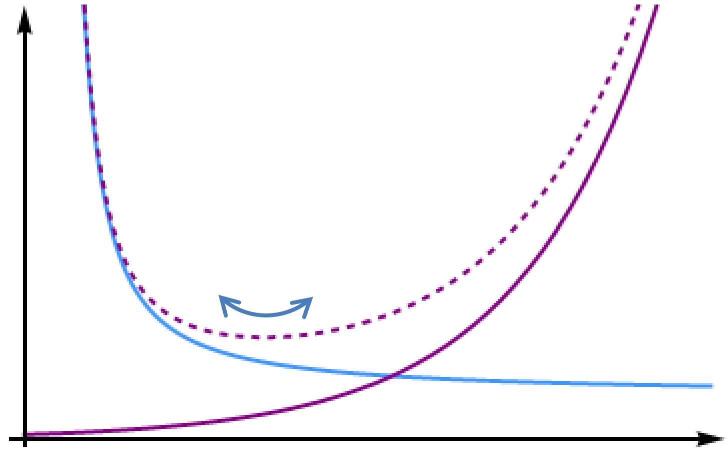
High density, no pressure

Low density, no pressure

The mass of the chameleon changes depending on its environment

‘Small’ Objects

The object only causes a small perturbation of the scalar field



Find a gravity like form for the scalar potential

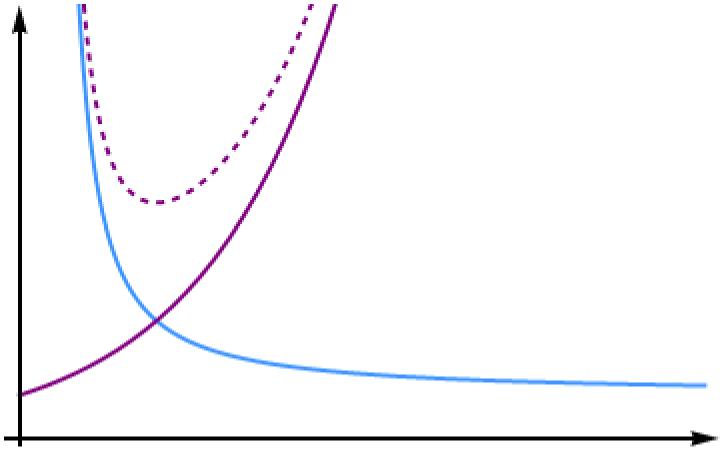
$$\phi = \phi_\infty - \beta \frac{M_c}{4\pi M_P r} e^{-m_\infty (r - R_c)}$$

- The force is the gradient of the potential

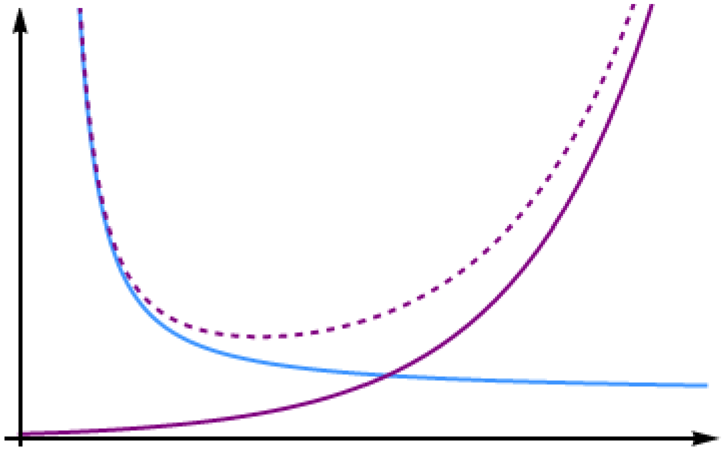
$$\vec{F} = \frac{1}{M} \vec{\nabla} \phi$$

‘Large’ Objects

$$\frac{\phi_\infty}{M_P} < \beta \frac{M_c}{M_P^2 R_c}$$



Inside

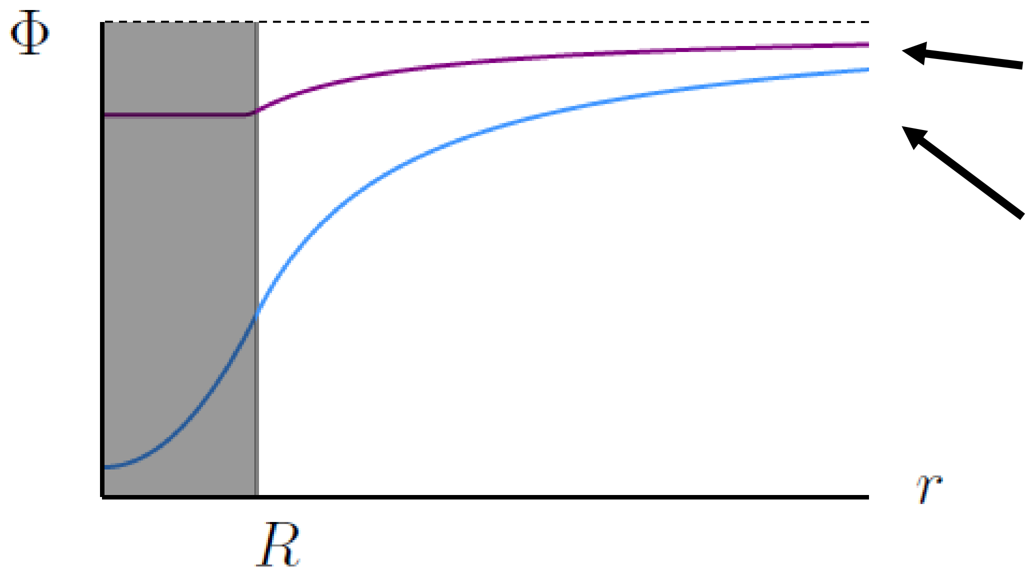


Outside

$$\phi = \begin{cases} \phi_c & 0 < r < R_{\rm roll} \\ \phi_c + \beta \frac{M_c}{8\pi M_p R_c}\left[\left(\frac{r}{R_c}\right)^2 + 2\frac{R_{\rm roll}^3}{r R_c^2} - \left(\frac{R_{\rm roll}}{R_c}\right)^2\right] & R_{\rm roll} < r < R_c \\ \phi_\infty - (\phi_\infty - \phi_c)\frac{R_c}{r} e^{-m_\infty (r - R_c)} & R_c < r \end{cases}$$

Suppressing the fifth force

The increased mass makes it hard for the chameleon field to adjust its value



Chameleon

Newtonian potential

$$\Phi = -\frac{GM}{r}$$

The chameleon potential well around massive objects is shallower than for standard light scalar fields

Chameleon fluctuations

The chameleon Lagrangian is non-linear

$$\mathcal{L}_\phi = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + B(\phi)T^\mu_\mu$$

$$V(\phi) = \Lambda^4 e^{\Lambda/\phi} \qquad\qquad B(\phi) = e^{\beta\phi/M_P}$$

This makes the mass of chameleon fluctuations depend on the background configuration

$$\phi = \phi_0 + \delta\phi$$

$$\mathcal{L}_{\delta\phi} \supset -\frac{1}{2}(\partial\delta\phi)^2 - \left(\frac{3\Lambda^4}{2\phi_0^2}e^{\Lambda/\phi_0} - \frac{T_0}{2\phi_0^2}e^{\beta\phi_0/M_P}\right)\delta\phi^2 + \frac{e^{\beta\phi_0/M_P}}{\phi_0}\delta\phi\delta T$$

Screening mechanisms

Start with a non-linear scalar field theory

- Solve the equations of motion for the background

The Lagrangian for fluctuations (to second order):

$$\mathcal{L} \supset -\frac{Z(\phi_0)}{2}(\partial\delta\phi)^2 + \frac{m^2(\phi_0)}{2}\delta\phi^2 + \frac{\beta(\phi_0)}{M_P}\delta\phi\delta T$$

Large Z makes it hard for the scalar to propagate
- Galileons
- Massive gravity
- Vainshtein mechanism

Large m means the scalar only propagates over shorter distances
- Chameleon

Small β makes the interaction with matter fields weaker
- Symmetron

TESTING DARK ENERGY WITH SCREENING MECHANISMS

Interactions with Standard Model fields

Dark energy interacts with the trace of the energy-momentum tensor of matter fields

Interactions with photons (and other gauge fields) are also generated

$$\mathcal{L}_E \supset \frac{\delta\phi}{M_\gamma} F^{ab} F_{ab}$$

Predictions for the energy scales of the couplings are very model dependent

- Can be Planck scale
- Can be much lower, e.g. in massive gravity the disformal coupling of the scalar component has energy scale

$$M \sim \sqrt{M_P m_{\text{grav}}} \sim 10^{-1}\ \text{eV}$$

Searches for dark energy interactions

Interactions with dark energy strongest in diffuse environments

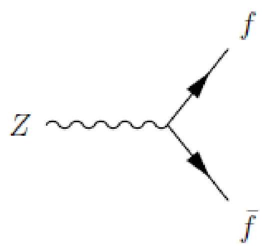
Constraints from high precision experiments performed in near vacuum

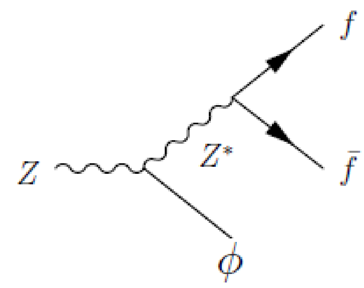
Can exploit:

- Particle physics experiments
- High precision photon measurements (e.g. axion searches)
- Atomic structure measurements

Scalar Bremsstrahlung

Contribution to the width of Z decay





$$\frac{\Gamma(Z \to \phi f \bar{f})}{\Gamma(Z \to f\bar{f})} = \frac{1}{16\pi^3}\frac{m_Z^2}{M_\gamma^2} I_{\phi f \bar{f}} \qquad I_{\phi f \bar{f}} \approx 0.2$$

- Prediction from the Standard Model:

$$\Gamma_Z \;=\; 2.4952 \;\; \text{GeV}$$

- Measurement at LEP:

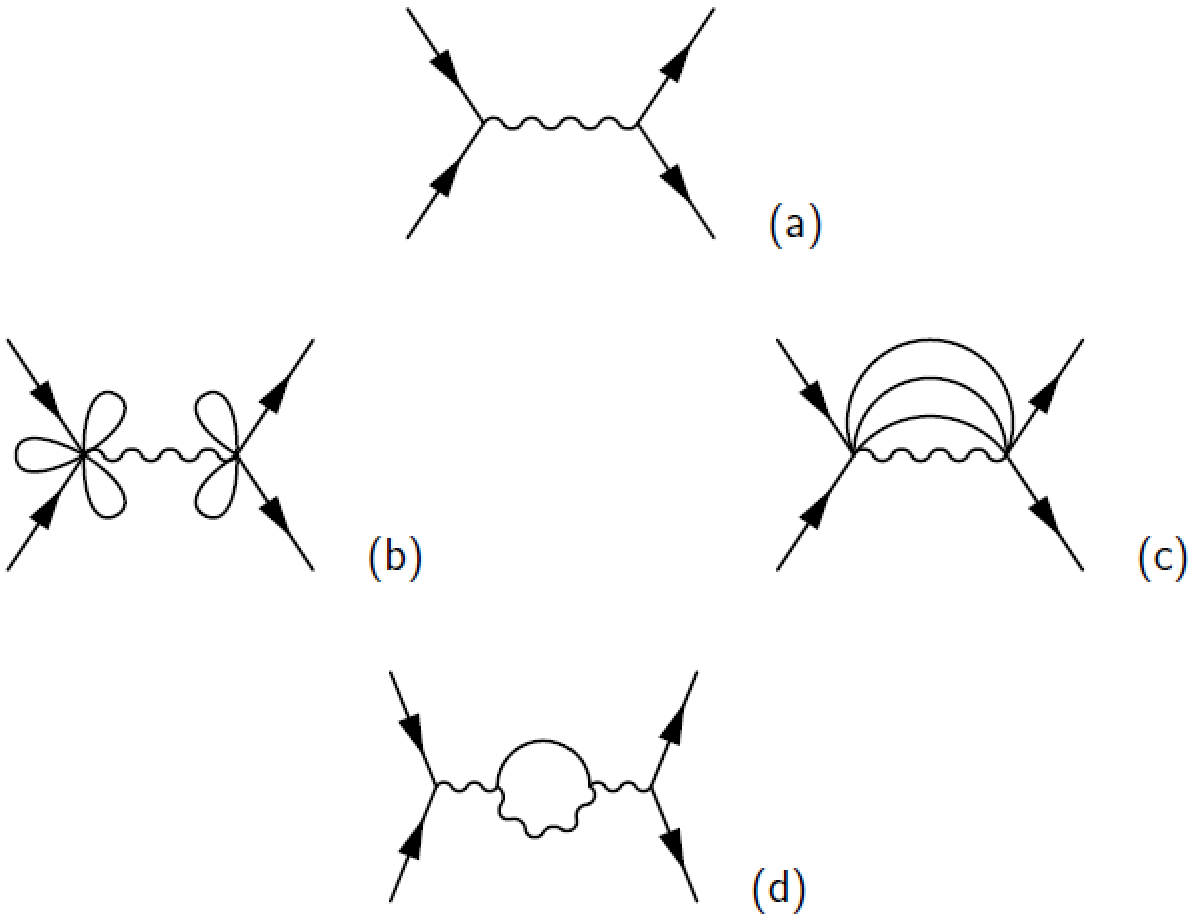
$$\Gamma_Z \;=\; (2.4952 \pm 0.0023) \;\; \text{GeV}$$

Dark Energy correction negligible if

$$M_\gamma \gtrsim 10^2 \;\text{GeV}$$

Brax, CB, Davis, Seery, Weltman. 2009

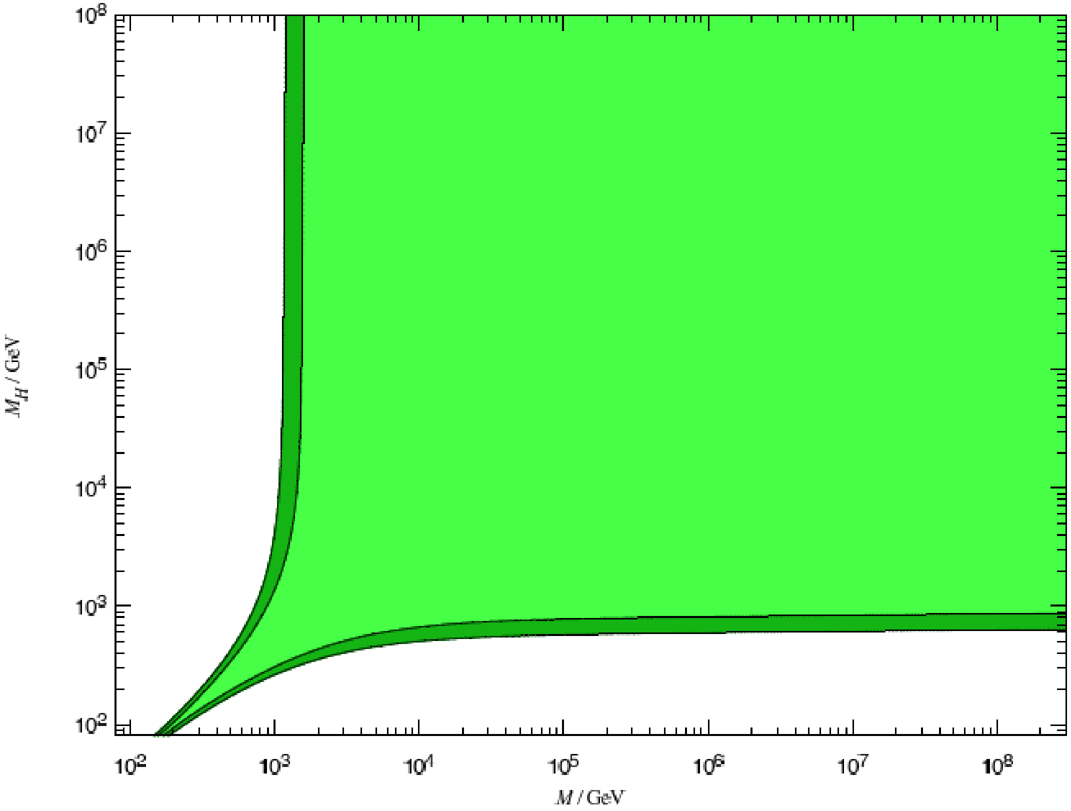
Corrections to Electroweak Processes



Brax, CB, Davis, Seery, Weltman. 2009

Electroweak precision observables

Constraints on scalar couplings from EW precision observables at LEP



Brax, CB, Davis, Seery, Weltman. 2009

Local EP violation

The Lagrangian that we started with respects the equivalence principle

We have separated objects into two classes screened (large) and unscreened (small)

The parameter which controls the suppression of the dark energy force

$$\epsilon = \frac{\phi_\infty}{M}\frac{M^2 R_c}{M_c} < 1$$

Is the scalar charge of the object

Local EP violation

The total force felt by a object O caused by a source S is

$$F = -\frac{2GM_S M_O}{r^2}\left(1 + \frac{M_P^4}{M^4}\epsilon_O \epsilon_S\right)$$

Where:

Unscreened

$$\epsilon = 1$$

Screened

$$\epsilon = \frac{\phi_\infty}{M}\frac{R_c M^2}{M_c}$$

Screened and unscreened objects will fall at different rates

Hui, Nicolis, Stubbs. 2009

Proposed EP Violation Tests

The gas in dwarf galaxies may be unscreened but the stars are screened

- They will fall differently towards local over densities

Jain, VanderPlas. 2011

Can use diffuse clouds of cold atoms to measure gravity in the laboratory

- These may be unscreened objects, and so would feel a different ‘gravity’ compared to macroscopic test masses used to date

CB, Copeland, Hinds. (to appear)

SCREENING MECHANISMS IN EFFECTIVE FIELD THEORY

f(R) chameleons

Attempt to modify gravity to explain accelerated expansion

$$S_{f(R)} = \int \mathrm{d}^4 x \sqrt{-g}\frac{M_{\mathrm{Pl}}^2}{2} f(R) + S_{\mathrm{matter}}[g_{\mu\nu}, \Psi_i]$$

Field equations are second order in derivatives of R

- Fourth order in derivatives of the metric
- By Ostrogradski's theorem there are hidden degrees of freedom

Make the extra degree of freedom explicit

$$\exp\left(-\frac{2\beta\phi}{M_{\mathrm{Pl}}}\right) = f'(R)$$

Corresponds to Einstein vs. Jordan frame description

f(R) chameleons

Define Einstein frame metric

$$\bar{g}_{\mu\nu} = e^{-\frac{2\beta\phi}{M_{\rm Pl}}} g_{\mu\nu}$$

Action becomes

$$S_{\rm ST} = \int {\rm d}^4 x \sqrt{-\bar{g}} \left(\frac{M_{\rm Pl}^2}{2}\bar{R} - \frac{1}{2}\bar{g}^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi - V(\phi) \right)$$
$$+ S_{\rm matter}[e^{\frac{2\beta\phi}{M_{\rm Pl}}}\bar{g}_{\mu\nu}, \Psi_i],$$

$$V(\phi) = \frac{M_{\rm Pl}^2 \left(R f'(R) - f(R)\right)}{2 f'(R)^2} \qquad \beta = \sqrt{1/6}$$

Only f(R) theories with a chameleon mechanism are observationally acceptable

Hu, Sawicki 2007. Brax, van de Bruck, Davis, Shaw 2008

String theory chameleons

The scalar field is the complexified volume modulus of a KKLT compactification

Get an N=1 SUSY set-up by gluing a K-S throat on to the Calabi-Yau CY_3

- Obtain a suitable scalar potential
- No a-priori rule for how to couple to matter fields, but chameleon-like couplings an allowed choice
- However parameter controlling the coupling enters with the wrong sign

Picture credit: June Gilbank

Hinterbichler, Khoury, Nastase. 2011

Screening mechanisms

Theories with screening mechanisms rely on non-linearities

- Controlled by higher order operators
- Theory only valid up to a cut-off

Parameters required to satisfy fifth force experiments may require fine tuning

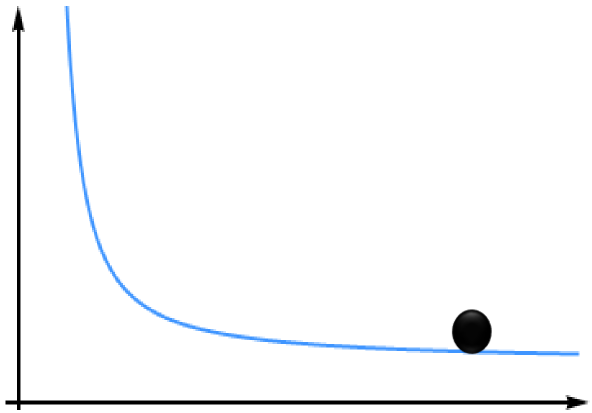
Have to check that we can evolve the theory through all standard physical scenarios without quantum corrections becoming important

Example: Chameleon cosmology

The trace of the energy-momentum tensor of a relativistic fluid vanishes

During radiation domination the chameleon is initially frozen due to Hubble friction

$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi) - \frac{\beta}{M_p}(\rho - 3p)$$



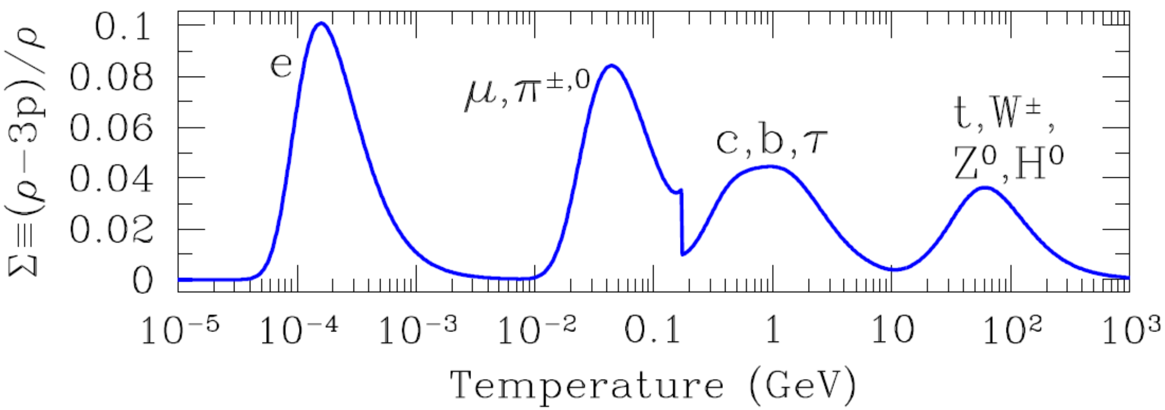
Generically will sit at a very large field value - incompatible with BBN

Example: Chameleon cosmology

Trace of the energy momentum tensor becomes non-zero when a SM particle falls out of thermal equilibrium

This turns on the growing part of the chameleon effective potential

'Kicks' the chameleon towards smaller values



Helps avoid BBN constraints

Brax, van de Bruck, Davis, Khoury, Weltman. 2004

The old story

The kicks drive the chameleon towards the minimum of the potential by the time of BBN

But this neglects

Feedback of the scalar field on the temperature

Velocity at which the minimum is reached

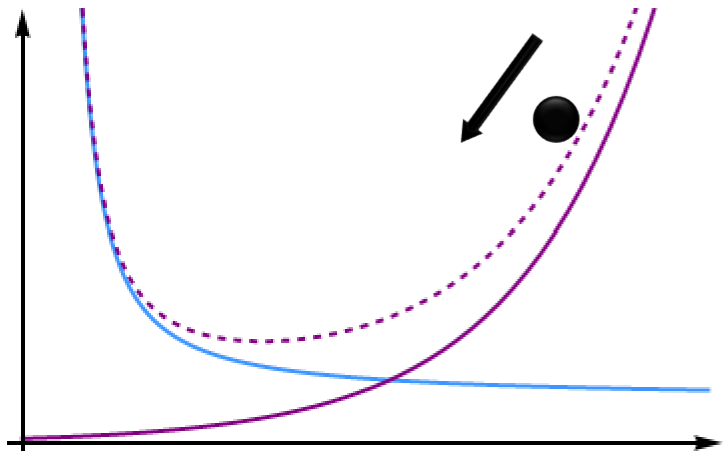
Quantum Corrections

We find new solutions where the chameleon ‘surfs’ the kick all the way to the minimum of the effective potential

Barnaby, CB, Erickcek, Huang. 2013

Example: Chameleon cosmology

The surfer carries the chameleon towards the steep part of the potential with high velocity



Classically the field rapidly climbs up the potential and falls back down

Quantum particle production

The production of quantum fluctuations is governed by their effective mass

$$m_\phi^2(t) \equiv V''_{\text{eff}}\left[\bar{\phi}(t)\right] \simeq V''\left[\bar{\phi}(t)\right]$$

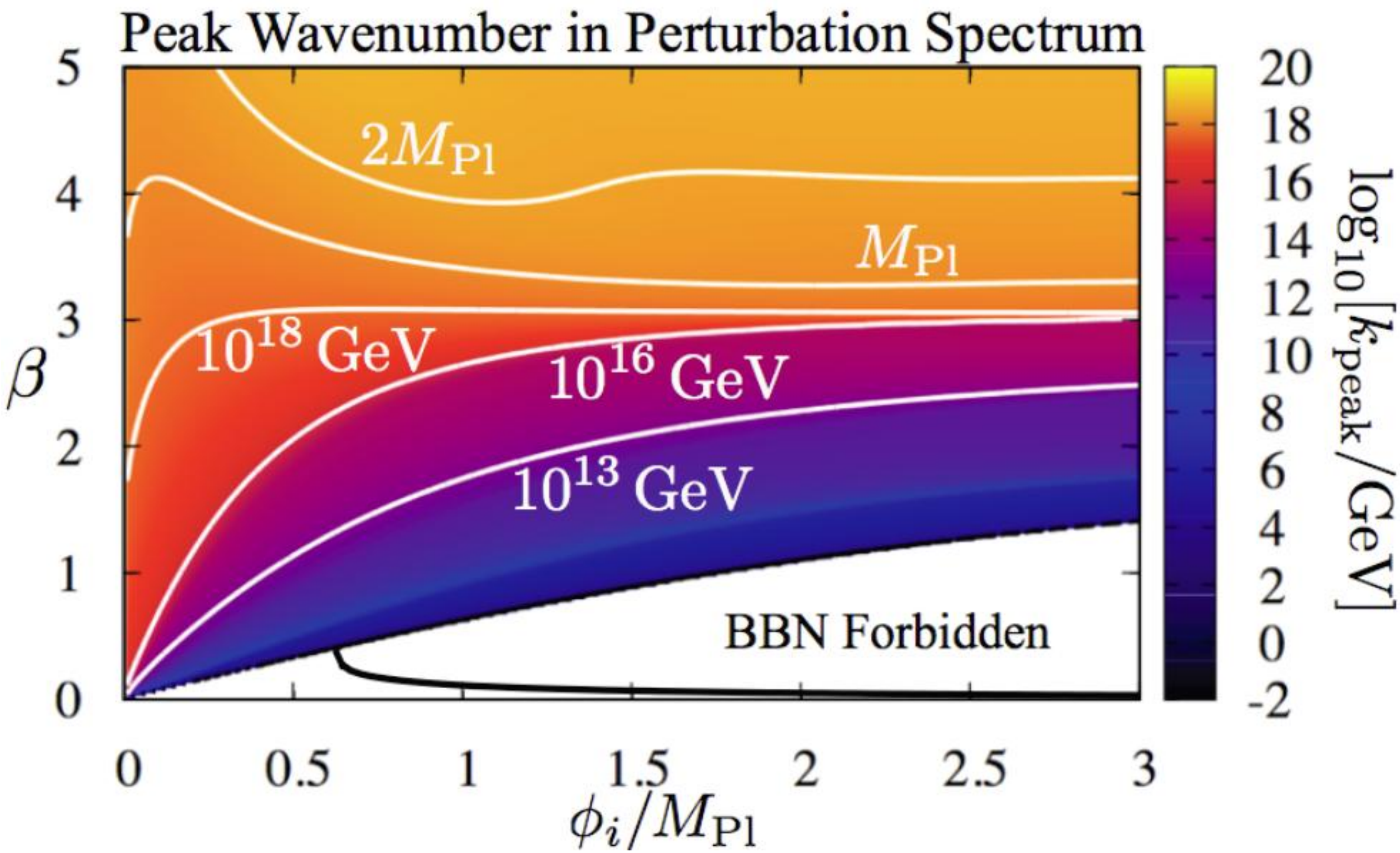
Mass changes significantly at moment of reflection, on timescales

$$\Delta t \sim V''/(V'''\dot{\phi}_M)$$

Non-adiabatic variation excites modes with

$$k \lesssim (\Delta t)^{-1} \sim |\dot{\phi}_M|/M$$

A chameleon catastrophe



Conclusions

Dark energy couples to Standard Model particles

This typically leads to problematically strong fifth forces unless the theory has a screening mechanism

Relies on the non-linearities

Leads to many new possible ways to detect dark energy

May also lead to uncontrollably large quantum corrections