Theoretical Models for Dark Energy: A Brief Review

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Laboratory Tests of Dark Energy
Fermilab
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Overview

- Cosmic Acceleration - Dark Energy - Modified Gravity
- Central question: How do new degrees of freedom couple to Standard Model + Dark Matter
- Categorizing Models of Dark Energy
- Example Theoretical Constructions

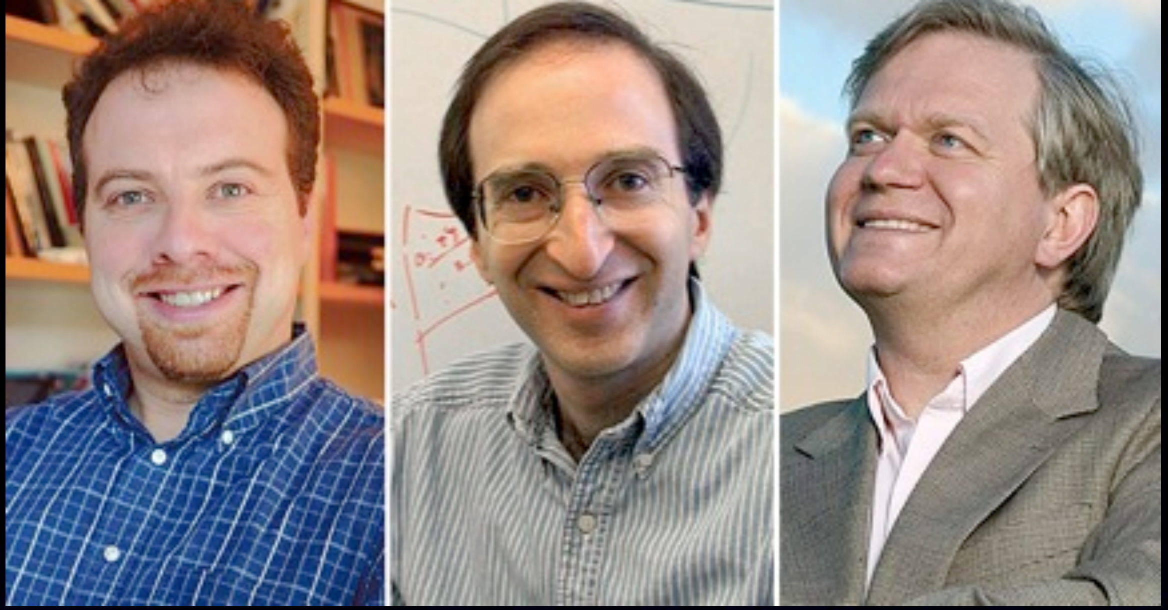
Cosmic Acceleration

Dark Energy?

Modified Gravity?

Cosmological constant?

Cosmic Acceleration



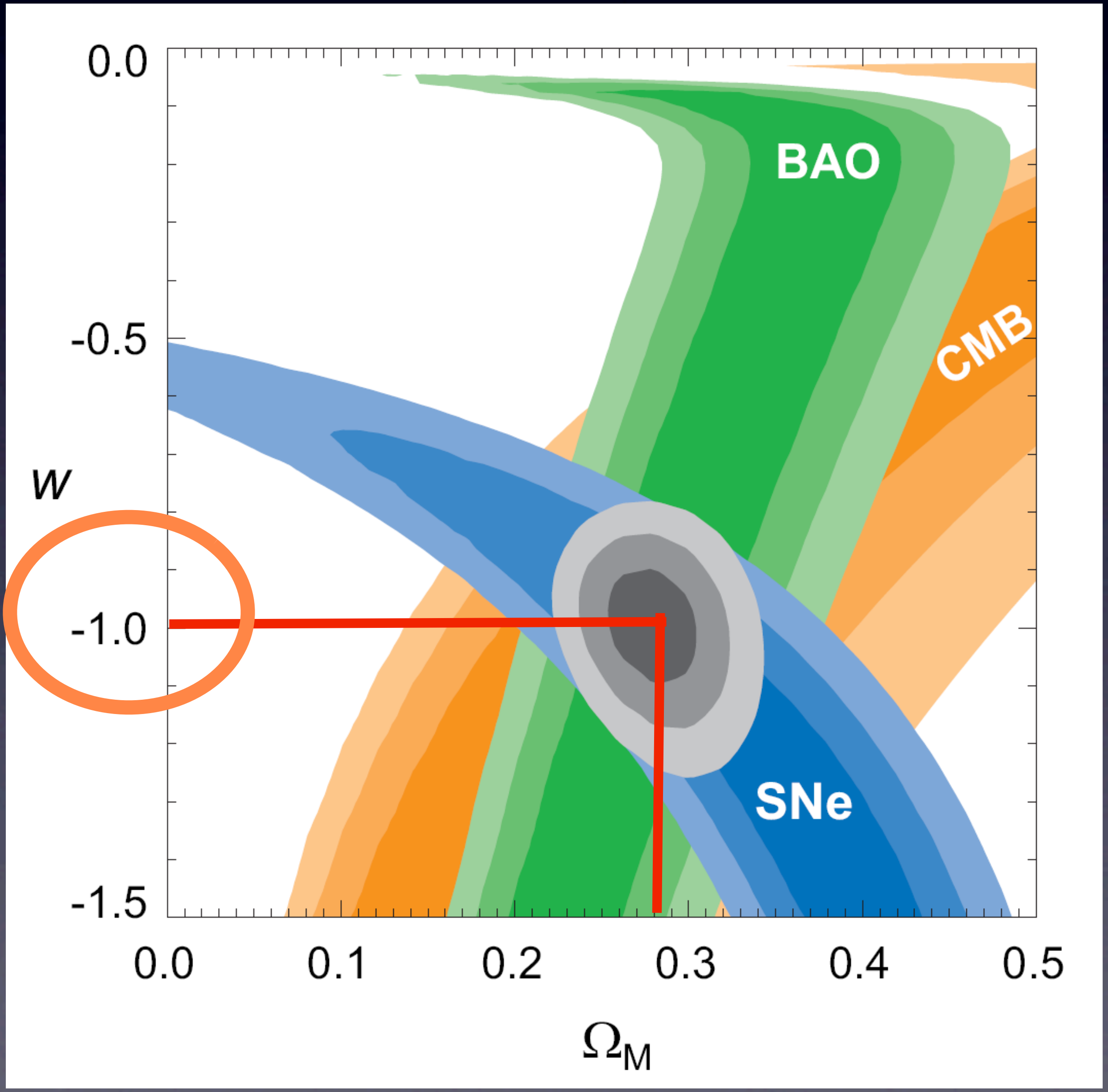
2011 Nobel Prize in Physics

Riess, Perlmutter, Schmidt

The Universe is Accelerating!
Acceleration can only occur if

$$w = \frac{p}{\rho} < -1/3$$

Data points tantalizingly close to $w = -1$



$$w = -0.94 \pm 0.1$$

Frieman *et al.* (2008) Ann.Rev.Astron.Astrophys

Why are we so concerned?

New physics at Hubble scales?

New physics at a millimeter scales?

Cosmic Coincidence Problem

Cosmological Constant Problem

Scales of Dark Energy

There are two natural scales associated with Dark Energy

$$H^2 = \frac{8\pi G}{3}\rho$$

Curvature scale

$$\boxed{\Lambda \sim m^2 \sim \frac{1}{R^2}}$$

$$m = 10^{-33}\mathrm{eV}$$

$$R \sim 3800\,\mathrm{Mpc}$$

Cosmological scale

Energy scale

$$\boxed{\rho_\Lambda = \frac{1}{8\pi G}\Lambda \sim m^4}$$

$$L = 0.1\,\mathrm{mm}$$

$$m = 1\,\mathrm{meV}$$

Submillimeter scale

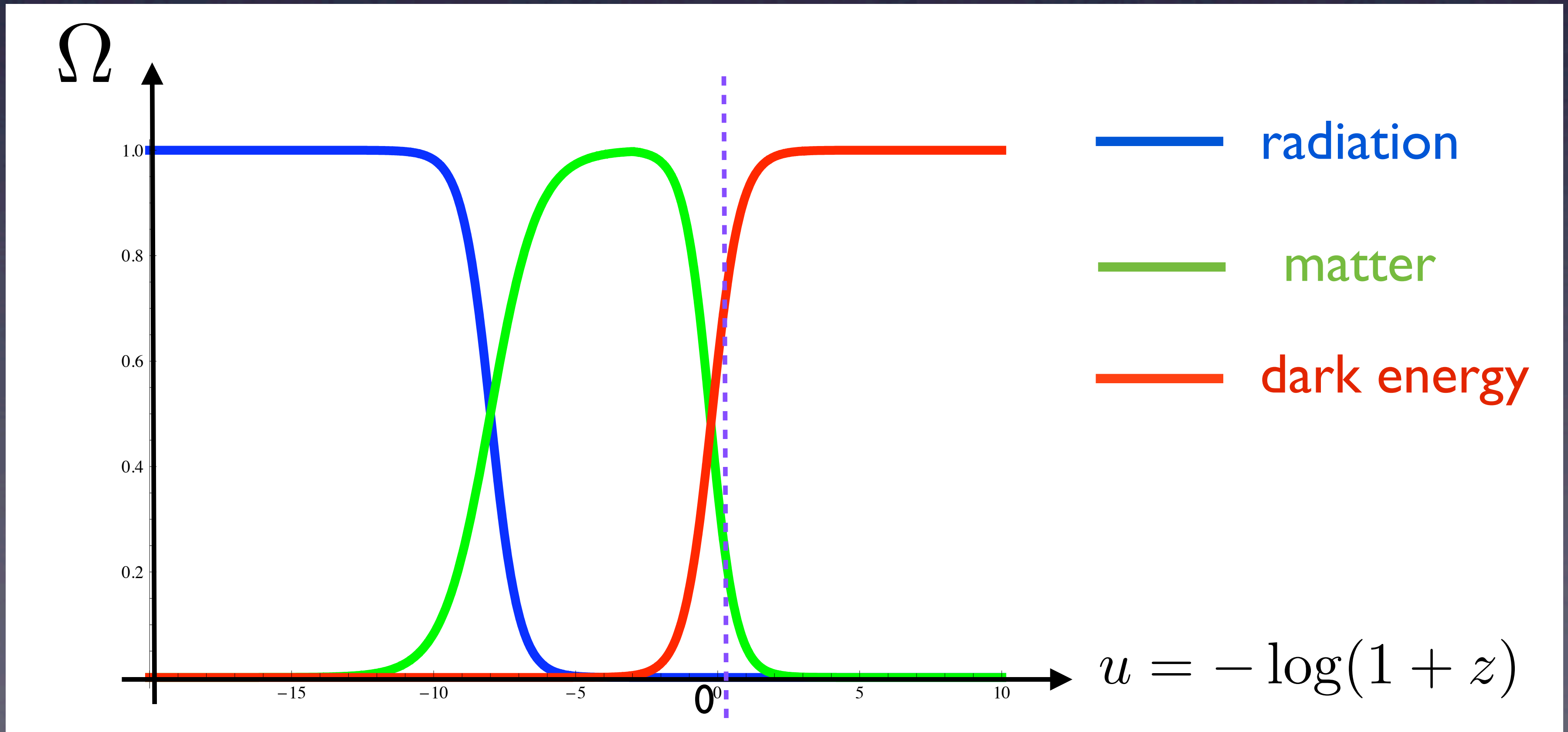
Cosmic Coincidence problem

Why does dark energy come to dominate today? around the time of structure formation?

Universe began accelerating about redshift z~0.4 and age 10 Gyr

Also seems coincidental that visible and dark matter are only a few orders of magnitude away from each other today

$$\frac{\Omega_{\mathrm{d.e.}}}{\Omega_{\mathrm{M}}} \sim a^3$$



Cosmological constant problem

Why is Λ so un(technically) naturally small?

C.C. is leading 'relevant operator' in action for gravity

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{16\pi G}\Lambda + \frac{1}{16\pi G} R + \mathcal{L}_M \right)$$

Despite being most relevant operator: most UV sensitive!

$$\Delta\rho_\Lambda = \frac{8\pi G}{3}\Delta\Lambda \sim \sum m_i^4 \ln(m_i/\mu)$$

$m_e^4/\rho \sim 10^{36}$ $m_W^4/\rho \sim 10^{56}$

Cosmological constant problem

Why doesn't Lambda pick up a large contribution from Phase Transitions?

Examples:

Potential energy of Higgs field $V \sim (100GeV)^4$

QCD condensate energy in presence of qqbar bilinears (chiral symmetry breaking) $V \sim (100MeV)^4$

Even if we resolve zero-point fluctuations,
we have to classically tune away these large contributions

Cosmological Constant *versus* Dynamical Dark Energy

$$w = -1$$

↓

Cosmological constant

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

$$w \neq -1$$

↓

Dynamical Dark Energy

existence of new d.o.f.
i.e. new particles
beyond gravity + SM (+DM)

Categorizing Dark Energy/ Modified Gravity Models via Screening

New Degrees of Freedom

Cosmological constant is the `unique' large distance modification to GR that does not introduce any new degrees of freedom

Dynamical Models of Dark Energy or Modified Gravity will be distinguished by new d.o.f. (i.e. dynamical perturbations!)

New degrees of freedom must necessarily by incredibly light!

$$m_{\rm d.e.} \leq 10^{-33} {\rm eV}$$

New gravitational degrees of freedom that coupled to matter are highly constrained

Fifth Forces (solar system)

Equivalence Principle Tests etc.

Binary Pulsar Timing

Nucleosynthesis

Cosmological Moduli Problems

Need some kind of screening mechanism to hide extra d.o.f.

Why are new d.o.f. *nearly* always scalars?

If theory Lorentz invariance, new d.o.f characterized by spin

Must be effectively bosonic (even if fundamentally fermionic)

(=GR!)

Massive spin 2 = Massless spin 2 + Massless spin 1 + Scalar

Massive spin 1 = Massless spin 1 + Scalar

Massless spin 1 must coupled to conserved vector but $\partial_\mu T^\mu{}_\nu = 0$

~ always some range of energies for which every D.E./modified gravity theory looks like GR plus scalars!

Interactions of new d.o.f.

Imagine a scalar $\phi = \phi_b + \delta\phi$

coupled to the energy density $\rho = \rho_b + \delta\rho$

Generic form of effective action for perturbations:

$$S_2 = \int d^4x - \frac{1}{2} Z(\phi_b, \rho_b)(\partial\delta\phi)^2 - \frac{1}{2} m^2(\phi_b, \rho_b)\delta\phi^2 + \frac{\beta(\phi_b, \rho_b)}{M_{\rm Pl}}\delta\rho\,\delta\phi$$

kinetic term mass term coupling to matter

Fifth force contribution

$$S_2 = \int d^4x - \frac{1}{2} Z(\phi_b, \rho_b)(\partial \delta\phi)^2 - \frac{1}{2} m^2(\phi_b, \rho_b)\delta\phi^2 + \frac{\beta(\phi_b, \rho_b)}{M_{\rm Pl}} \delta\rho\, \delta\phi$$

$$\downarrow$$

Force between two masses:

$$F \approx \frac{m_1 m_2}{M_{\rm Pl}^2 r^2} \frac{\beta(\phi_b, \rho_b)}{\sqrt{Z(\phi_b, \rho_b)}} \exp(-m(\phi_b, \rho_b) r)$$

Fifth force constraints: screening

To ensure fifth forces are small

$$\frac{\beta(\phi_b, \rho_b)}{\sqrt{Z(\phi_b, \rho_b)}} \exp(-m(\phi_b, \rho_b) r) \ll 1$$

Only three independent possibilities!

(a) Coupling is small $\beta(\phi_b, \rho_b) \ll 1$

(b) Mass is large $m(\phi_n, \rho_b) \gg \frac{1}{r_{exp}}$

(c) Kinetic term is large $Z(\phi_b, \rho_b) \gg 1$

Screening Mechanisms

I. `Screening without Screening' - make coupling to matter universally small - e.g. Quintessence

$$\beta(\phi_b, \rho_b) \ll 1$$

$$F \approx \frac{m_1 m_2}{M_{\rm Pl}^2 r^2} \frac{\beta(\phi_b, \rho_b)}{\sqrt{Z(\phi_b, \rho_b)}} \exp(-m(\phi_b, \rho_b) r)$$

Screening Mechanisms

I. `Screening without Screening' - make coupling to matter universally small - e.g. Quintessence

II. Make coupling to matter environmental (small in high density envinments, large in low density environments) - e.g. Symmetron

at high densities: $\beta(\phi_b, \rho_b) \ll 1$

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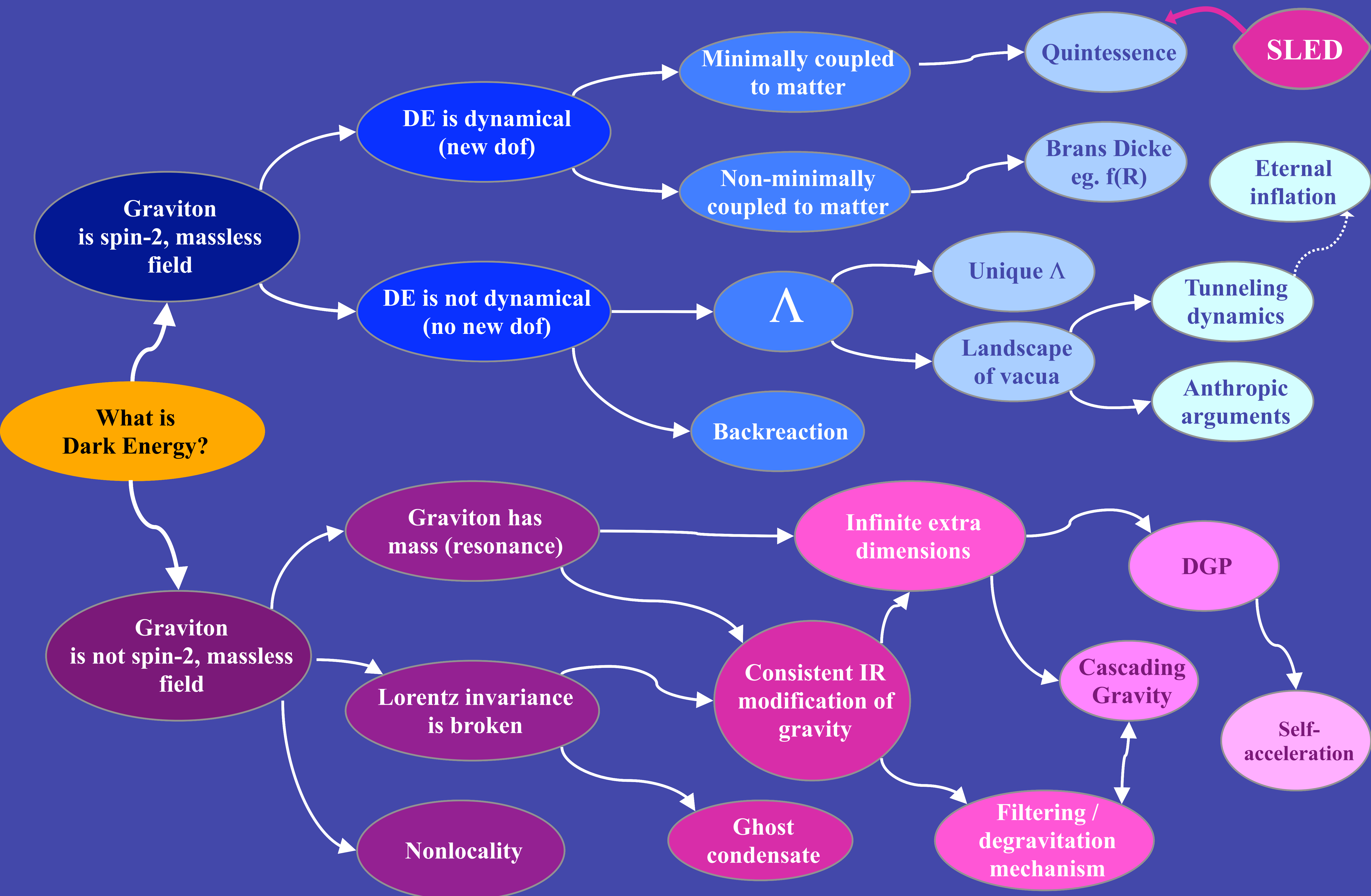
IV. Make kinetic term environmental (large in high density environments, small in low density environments)- e.g.Vainshtein mechanism - Massive Gravity, Galileon

$$Z(\phi_b, \rho_b) \gg 1$$

Constructing Models of Dark Energy



de Rham & AJT, Lectures on Dark Energy and the Cosmological Constant Challenge, Nordita 2008

1. Making the coupling small universally

Theoretical Models: $\beta(\phi_b, \rho_b) \ll 1$

Quintessence and its multifarious generalizations!!!

These are the *Vanilla* models of Dark Energy

Quintessence

Canonical Example: Scalar field with no direct coupling to matter

$$S = \int d^4x \sqrt{-g} \left(\frac{M_{\rm pl}^2}{2} R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) \right) + S_{\rm m}$$

Dark energy contributes to the background evolution, and plays an indirect role in perturbations, additional isocurvature modes

Can tolerate a very small coupling (e.g. one protected by a shift symmetry)

Brax et al. 0904.3471

Tuning/Technical Naturalness

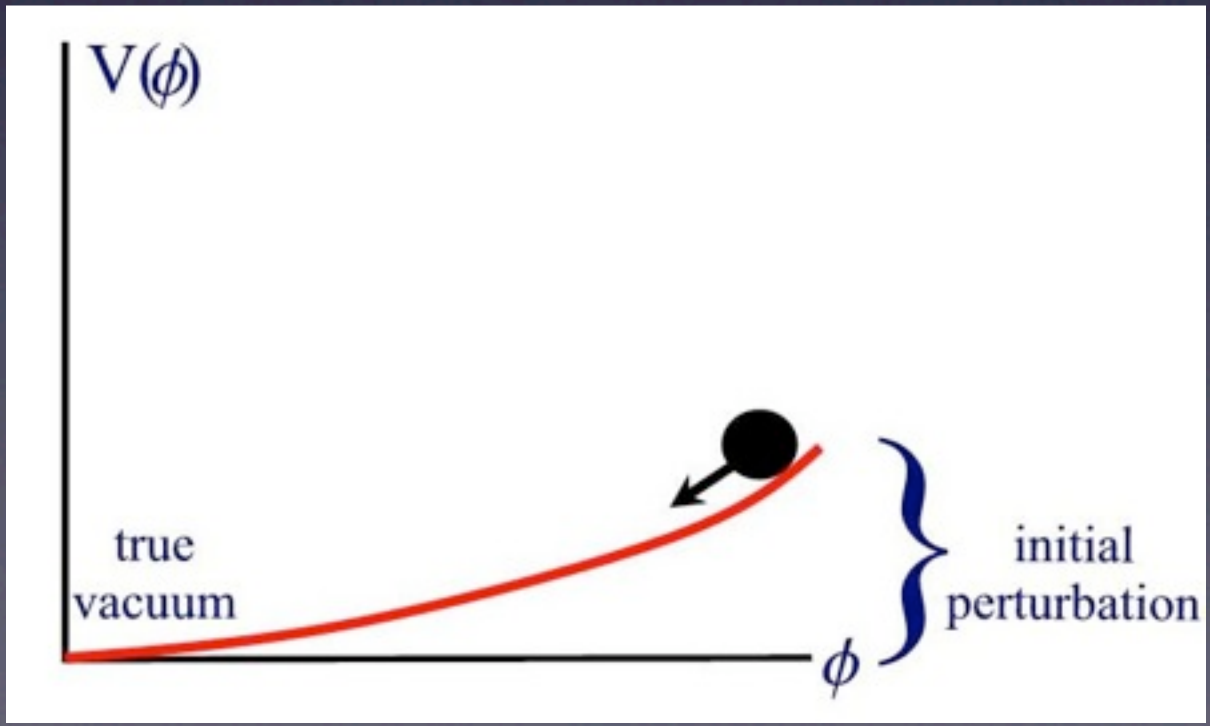
Typically not technically natural (Eta problem in Inflation) - significantly worse for Dark Energy

$$\Delta V \sim V(\phi)\frac{\phi^2}{M_{\rm pl}^2}$$

Closely akin to Higgs mass/gauge hierarchy problem

dim 6 operators

mass quadratically divergent, pick up mass comparable to heaviest particle



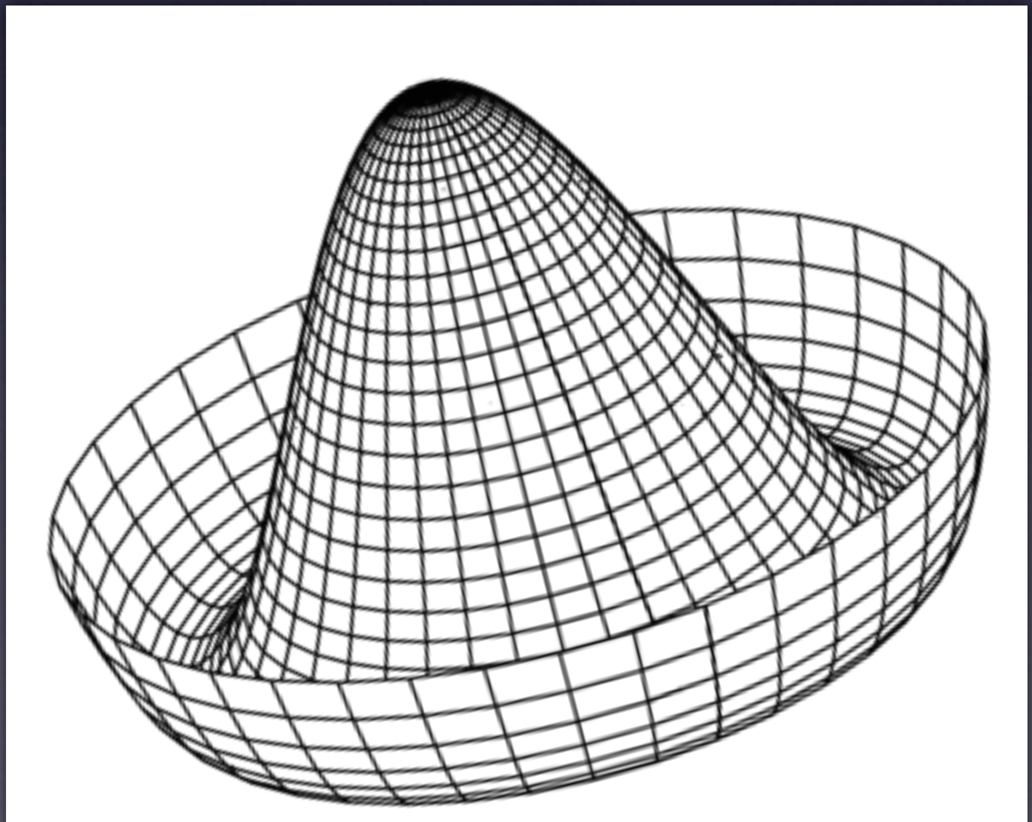
Scalars kept light by an approximate shift symmetry

- Technically natural Scalar Field arises as a *pseudo-Nambu-Goldstone* field associated with an approximately broken continuous global symmetry

$$\phi \to \phi + C$$

Explicitly broken but by a small amount

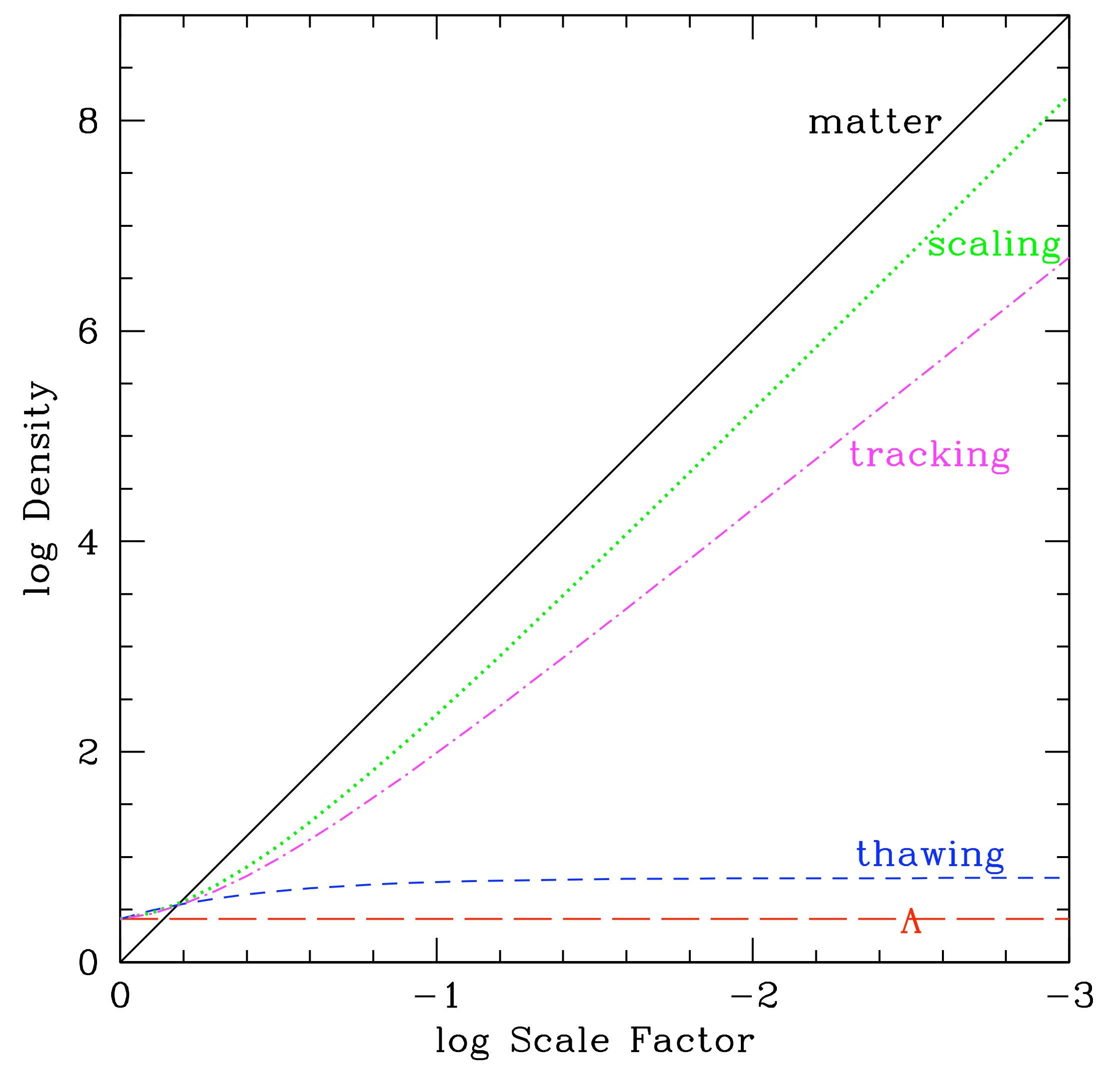
e.g. U(1) symmetry of mexican hat



Freezing Models

Freezing: Field rolls to minimum during deceleration (w>-1,w'<0), slows down as comes to dominate universe

Linder 0801.2968



Scaling fields: Attractor of Autonomous System, D.E. constant fraction of total

Tracking fields: Attractor in sense of independence of initial conditions, D.E. has different equation of state to total

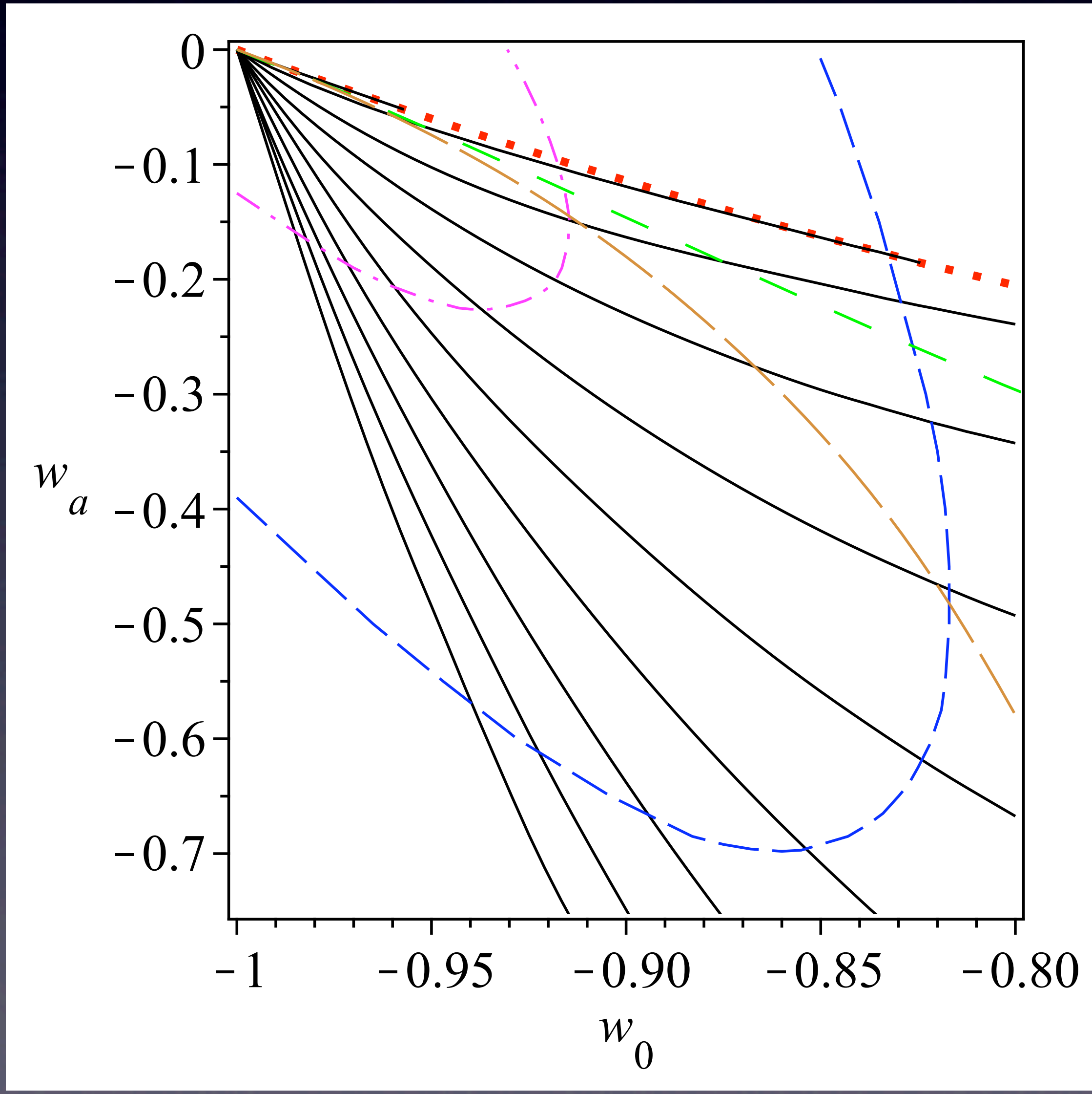
see e.g. Copeland et al. review hep-th/0603057

Thawing Models

Thawing: Field frozen away from minimum at early times by Hubble damping (w~-1) then thaw w'>0

Thawing must be slow to be consistent with observations

$$w(a) = w_0 + w_a(1-a)$$



Clemson+Liddle, 0811.4676

Natural generalizations of quintessence:

k-essence

Armendariz-Picon et al.2000

(modify kinetic term of quintessence field)

Assisted Quintessence

Kim et al. 2005

(many fields evolving in tandem)

Many attempts for example at embeddings in Low Energy Supergravity Models

e.g. Brax and Martin 1999

Many generalizations can be incorporated into a unified EFT approach for perturbations

Creminelli et al. 2008

Quintessence with a hint of modified gravity

Constraints on coupling of dark energy to visible matter are very strong (in absence of (kinetic) chameleon effects) but not so to dark matter!!

Vanilla model of dark sector interaction:

$$S = \int d^4x\sqrt{-g}\left(\frac{M_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm visible}[g_{\mu\nu},\chi_i] + S_{\rm dark}[\beta(\phi)g_{\mu\nu},\xi_i]$$

N.B. Although we dont require the chameleon mechanism to be active here, that doesn't mean it wont take place!

or for example:

$$S_{\rm dark} = \int d^4x\sqrt{-g}\left(-m(\phi)\bar{\psi}\psi + \mathcal{L}_{kin}(\psi)\right)$$

II. Making the coupling small environmentally

Theoretical Models: $\beta(\phi_b, \rho_b) \ll 1$

Symmetron - as yet no other explicit example

Symmetron

Consider a scalar with

Khoury and Hinterbichler 2010

1. Symmetry
2. Symmetry breaking potential
3. Non-minimal coupling to matter density

example

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda\phi^4 + \frac{1}{2}\mu^2\phi^2 + \mathcal{L}_M(g_{\mu\nu}(1+\phi^2/M^2))\right)$$

Z2 symmetry

$$\phi \to -\phi$$

Broken symmetry vev

$$\phi^2 = \mu^2/\lambda$$

Symmetron - effective potential

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda\phi^4 + \frac{1}{2}\mu^2\phi^2 + \mathcal{L}_M(g_{\mu\nu}(1+\phi^2/M^2))\right)$$

As a result of non-minimal coupling, effective potential is

$$V_{\rm eff}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4 \qquad \beta \sim \frac{\phi M_{\rm PL}}{M^2}$$

At low densities symmetry broken, coupling large

$$\rho < \mu^2 M^2 \qquad \phi \sim \mu^2/\lambda \qquad \beta \sim \frac{\mu^2 M_{\rm Pl}}{\lambda M^2}$$

At high densities symmetry recovered, coupling small

$$\rho > \mu^2 M^2 \qquad \phi \sim 0 \qquad \beta \sim 0$$

$$M \leq 10^{-3} M_{\rm Pl} \qquad \mu^{-1} \sim Mpc$$

III. Making the mass large environmentally

Theoretical Models:

Chameleon, Generalized Branes-Dicke models, f(R)

$$m(\phi_n, \rho_b) \gg \frac{1}{r_{exp}}$$

Chameleon effect

starts with same idea:

Khoury and Weltman, 2003

$$S_{\rm cham} = \int \mathrm{d}^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}\left[g\ \ \mathrm{e}^{2\beta\phi/M_{\rm Pl}}\right]$$

$$V_{\rm eff}(\phi) = V(\phi) + \rho\ e^{\beta\phi/M_{\rm Pl}}$$

$$m_{\rm eff}^2 = V_{,\phi\phi}(\phi_{\rm min}) + \frac{\beta^2}{M_{\rm Pl}^2}\rho\ e^{\beta\phi/M_{\rm Pl}}$$

Chameleon effect

$$m_{\text{eff}}^2 = V_{,\phi\phi}(\phi_{\text{min}}) + \frac{\beta^2}{M_{\text{Pl}}^2}\rho\, e^{\beta\phi/M_{\text{Pl}}}$$

Conditions necessary for chameleon mechanism to take place: $\beta > 0$

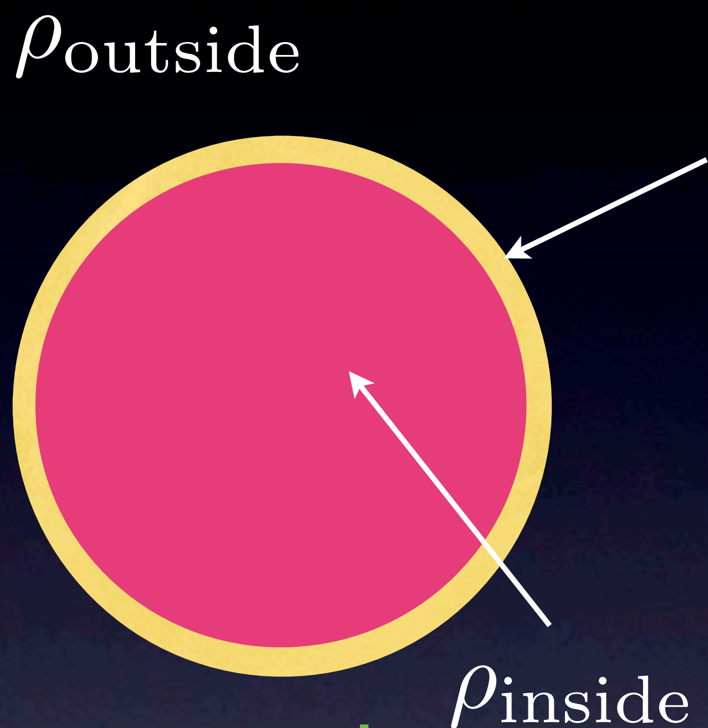
Balance	Stability	*m* increase with density
$V_{,\phi} < 0$	$V_{,\phi\phi} > 0$	$V_{,\phi\phi\phi} < 0$

easy to satisfy, e.g. $V(\phi) \sim \frac{M^{4+n}}{\phi^n}$

To satisfy fifth force

$$M < 1meV$$

Thin shell effect



Thin shell of gradient energy

$$\frac{\Delta R}{R} = \frac{1}{6\beta M_{\text{pl}}} \frac{\phi_{\text{outside}} - \phi_{\text{inside}}}{\Phi_N}$$

Khoury and Weltman 2004

For most objects only a thin shell around the edge of the object contributes to the Newtonian potential

Cosmologically chameleon behaves like matter at early times and c.c. at late times (Like a freezing model)

If chameleons couple to photons (such couplings can be generated via loops) they affect astronomical observations of polarization and luminosity

Chameleons Issues

Naively not *technically natural*

$$m_\phi \sim \beta \frac{\Lambda_{UV}^2}{M_{\rm pl}} \sim 1meV$$

when $\beta \sim O(1)$

$\Lambda_{UV} \sim TeV$

Adiabatic Instability (for strongly coupled chameleons)

Bean et al. 2007

$c_s^2 < 0$

Type of Jeans instability, exponential growth of small scale modes

IV. Making the kinetic term large environmentally

$$Z(\phi_b, \rho_b) \gg 1$$

Theoretical Models:

Vainshtein (or kinetic chameleon) mechanism:

Massive Gravity, DGP, Cascading Gravity, Galileon models and their generalizations!

Mechanism relies on a nontrivial reorganization of effective field theory to allow for large kinetic terms - arguably only natural in the context of massive gravity/DGP/Cascading

Vainshtein (Kinetic Chameleon) effect

$$\Lambda^3 \sim m^2 M_{\rm Pl}$$

Allow in the action Irrelevant kinetic operators

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 + \frac{\phi}{M_{\rm pl}}\rho\right)$$

Expanding around background solution, generates large kinetic term

schematically: $\Box\phi \sim \dfrac{\rho}{M_{\rm pl}} \longrightarrow \quad Z \approx 1 + \dfrac{\rho}{\Lambda^3 M_{\rm Pl}}$

$Z(\phi_b, \rho_b) \gg 1$ *when* $\rho_b \gg \Lambda^3 M_{\rm Pl} \sim m^2 M_{\rm Pl}^2$

Galileon - a model that relies on Vainshtein

Logic: write down every term in action consistent with symmetry

$$\pi \to \pi + c$$
$$\pi \to \pi + v_\mu x^\mu$$

$$\begin{aligned}
\mathcal{L}_1 &= \pi \\
\mathcal{L}_2 &= -\tfrac{1}{2}\,\partial\pi\cdot\partial\pi \\
\mathcal{L}_3 &= -\tfrac{1}{2}\,[\Pi]\,\partial\pi\cdot\partial\pi \\
\mathcal{L}_4 &= -\tfrac{1}{4}\big([\Pi]^2\,\partial\pi\cdot\partial\pi - 2\,[\Pi]\,\partial\pi\cdot\Pi\cdot\partial\pi - [\Pi^2]\,\partial\pi\cdot\partial\pi + 2\,\partial\pi\cdot\Pi^2\cdot\partial\pi\big) \\
\mathcal{L}_5 &= -\tfrac{1}{5}\big([\Pi]^3\,\partial\pi\cdot\partial\pi - 3[\Pi]^2\,\partial\pi\cdot\Pi\cdot\partial\pi - 3[\Pi][\Pi^2]\,\partial\pi\cdot\partial\pi + 6[\Pi]\,\partial\pi\cdot\Pi^2\cdot\partial\pi \\
&\quad +2[\Pi^3]\,\partial\pi\cdot\partial\pi + 3[\Pi^2]\,\partial\pi\cdot\Pi\cdot\partial\pi - 6\,\partial\pi\cdot\Pi^3\cdot\partial\pi\big)
\end{aligned}$$

$$\Pi^\mu_\nu = \partial^\mu\partial_\nu\pi$$

Nicolis et al. 0811.2197

Self-acceleration without ghosts!

Massive Gravity leads to light scalars

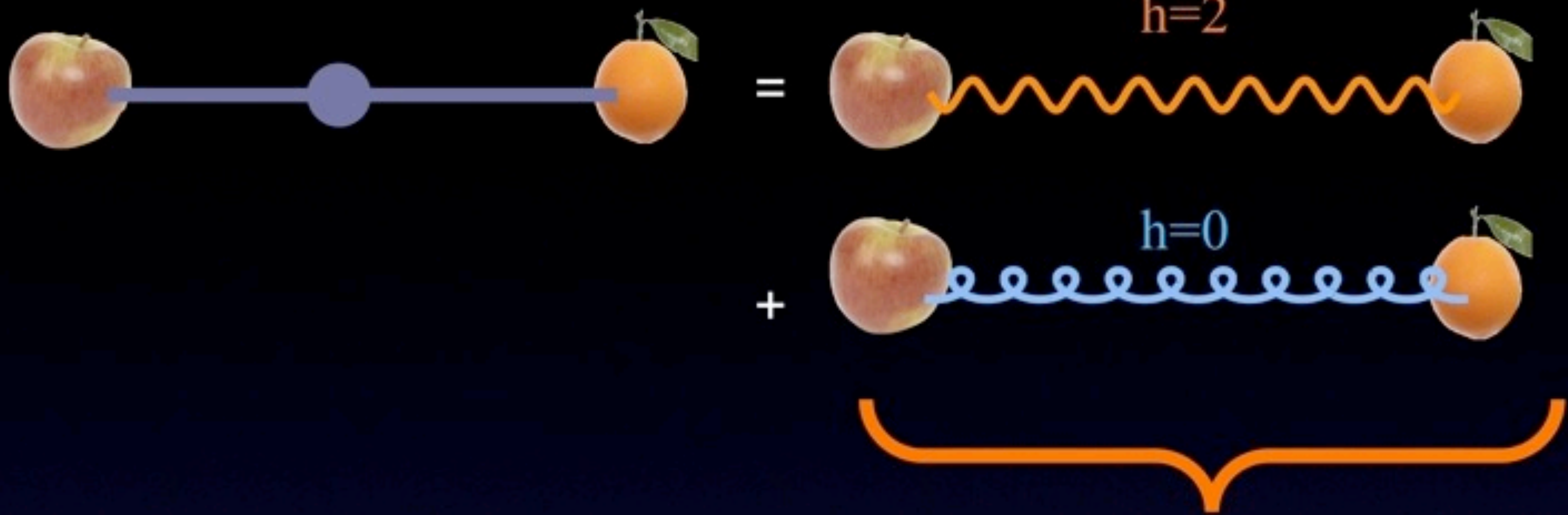
Massive spin-2 field, has 5 dof

$$h_{\mu\nu} \sim \frac{G_N}{\Box_4 - m^2} T_{\mu\nu}$$

$$2 \oplus 1 \oplus 2$$

$$h_{\mu\nu} = h'_{\mu\nu} + \pi \eta_{\mu\nu}$$

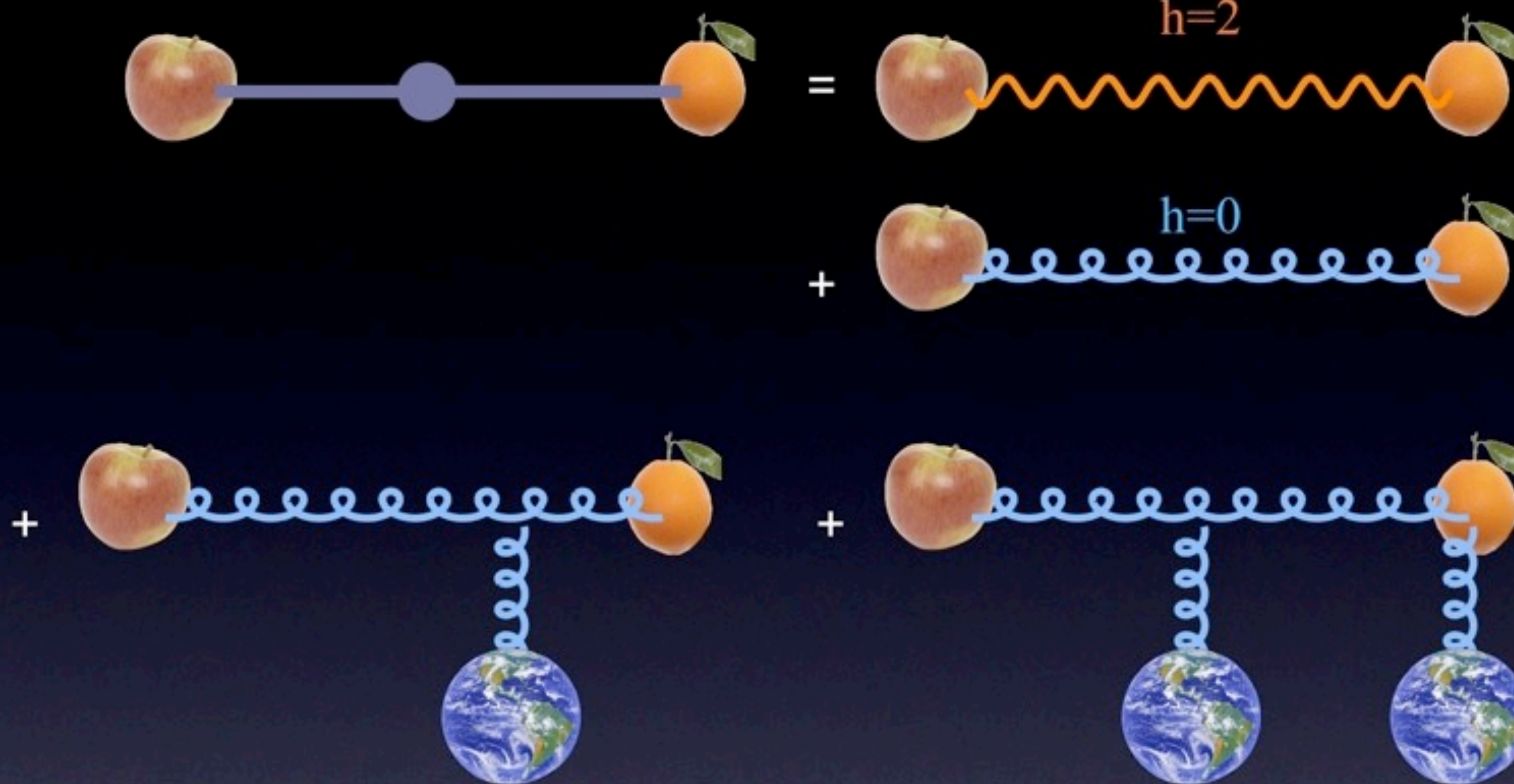
New scalar degree of freedom, exhibits Galileon symmetry and Galileon interactions

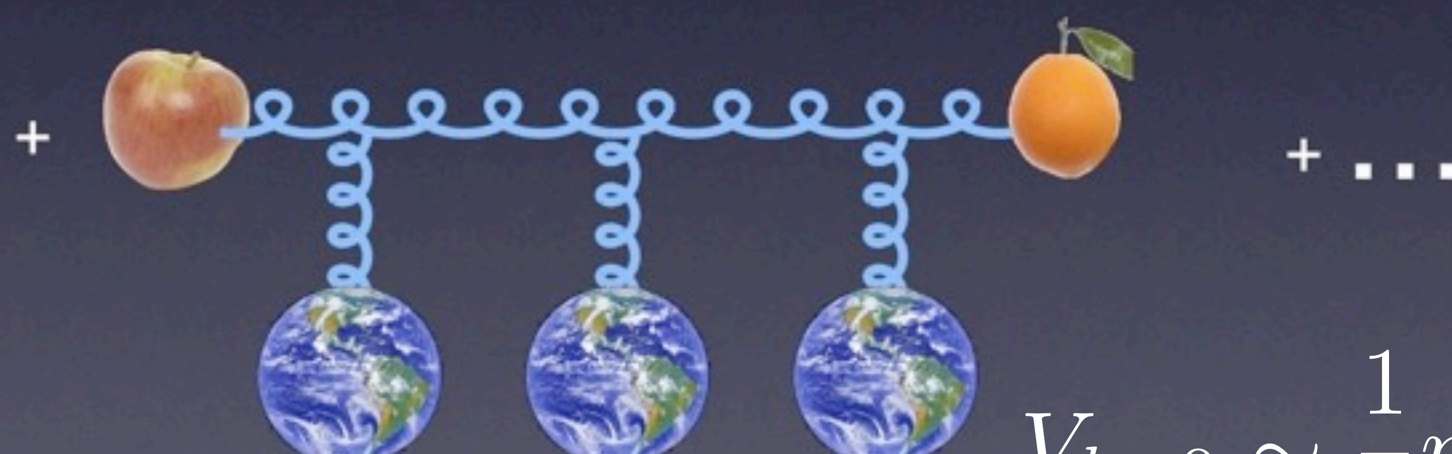


Additional fifth force from scalar mode

$$V_{h=0} = \frac{1}{3} m_{\mathrm{a}} m_{\mathrm{o}} G \frac{e^{-mr}}{r}$$

at first sight such theories are ruled out!





Force now vanishes as

$$V_{h=0} \sim \frac{1}{3} m_{\mathrm{a}} m_{\mathrm{o}} G \frac{e^{-mr}}{r} \frac{1}{1 + \frac{\bar{\rho}_{\mathrm{e}}}{m^2 M_{\mathrm{pl}}^2}}$$

Vainshtein effect is strongly scale and density dependent

Characteristic radius from source
- Vainshtein radius
- helicity zero version of Schwarzschild radius

Strong coupling region $r \ll r_V$ $Z \gg 1$

$$r_V = (r_s m^{-2})^{1/3} \qquad \Lambda^3 \sim m^2 M_{\rm Pl}$$

Weak coupling region $r \gg r_V$ $Z \sim 1$

For Sun $r_V \sim 250pc$ $r_s \sim 3km$ $m^{-1} \sim 4000Mpc$