Dark Energy and Modified Gravity

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Outline:

The Accelerated Universe

Dark Energy / Modified Gravity Theories

Observables

The Cosmological Constant

The Einstein equations can be extended to include a cosmological constant

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

In a FRW universe filled with a perfect fluid the resulting Friedmann equation is

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

The Accelerating Universe

The deceleration parameter:

$$q = -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\ddot{a}}{a}\frac{1}{H^2}$$

In a flat universe:

$$q = \frac{1}{2} - \frac{3}{2}\Omega_\Lambda$$

where

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H^2}$$

If the cosmological constant contributes sufficiently to the energy budget of the universe it will accelerate

The Accelerating Universe

If the universe is dominated by a perfect fluid, with equation of state

$$p = w\rho c^2$$

The acceleration equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3\frac{p}{c^2}\right)$$

tells us that the expansion of the universe will accelerate if

$$w < -1/3$$

Type 1a Supernovae

A white dwarf in a binary system accretes material from its companion

- As the mass approaches ~1.4 solar masses it becomes unstable, and runaway thermo-nuclear reactions result in an explosion

The Pinwheel Galaxy and SN2011fe. Image Credit: BJ Fulton

Type 1a Supernovae

A white dwarf in a binary system accretes material from its companion

- As the mass approaches ~1.4 solar masses it becomes unstable, and runaway thermo-nuclear reactions result in an explosion

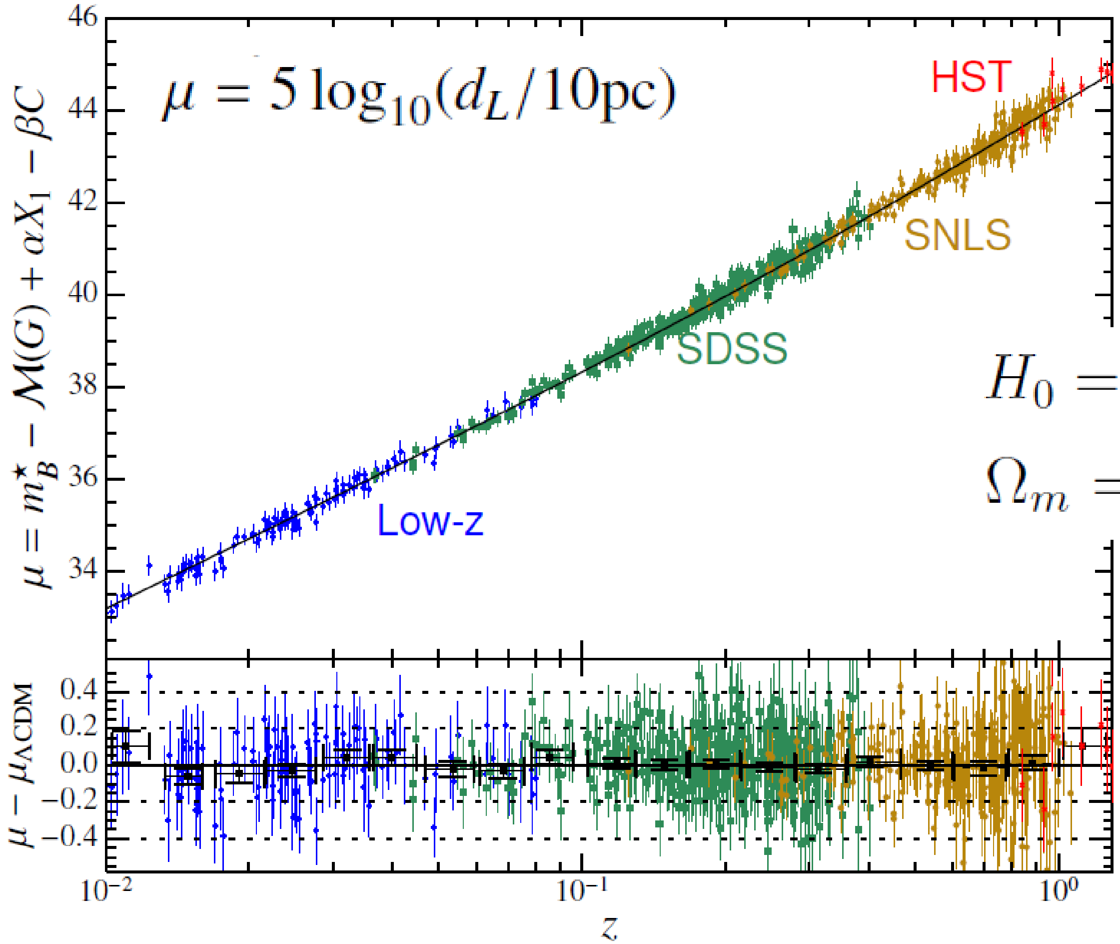
Type 1a Snae are standardizable candles

- This allows us to determine their luminosity distance from the inverse square law

$$\mathrm{Flux} = \frac{\mathrm{Luminosity}}{4\pi d_L^2}$$

Supernova Hubble Diagram - 2014

740 Type 1a Supernovae

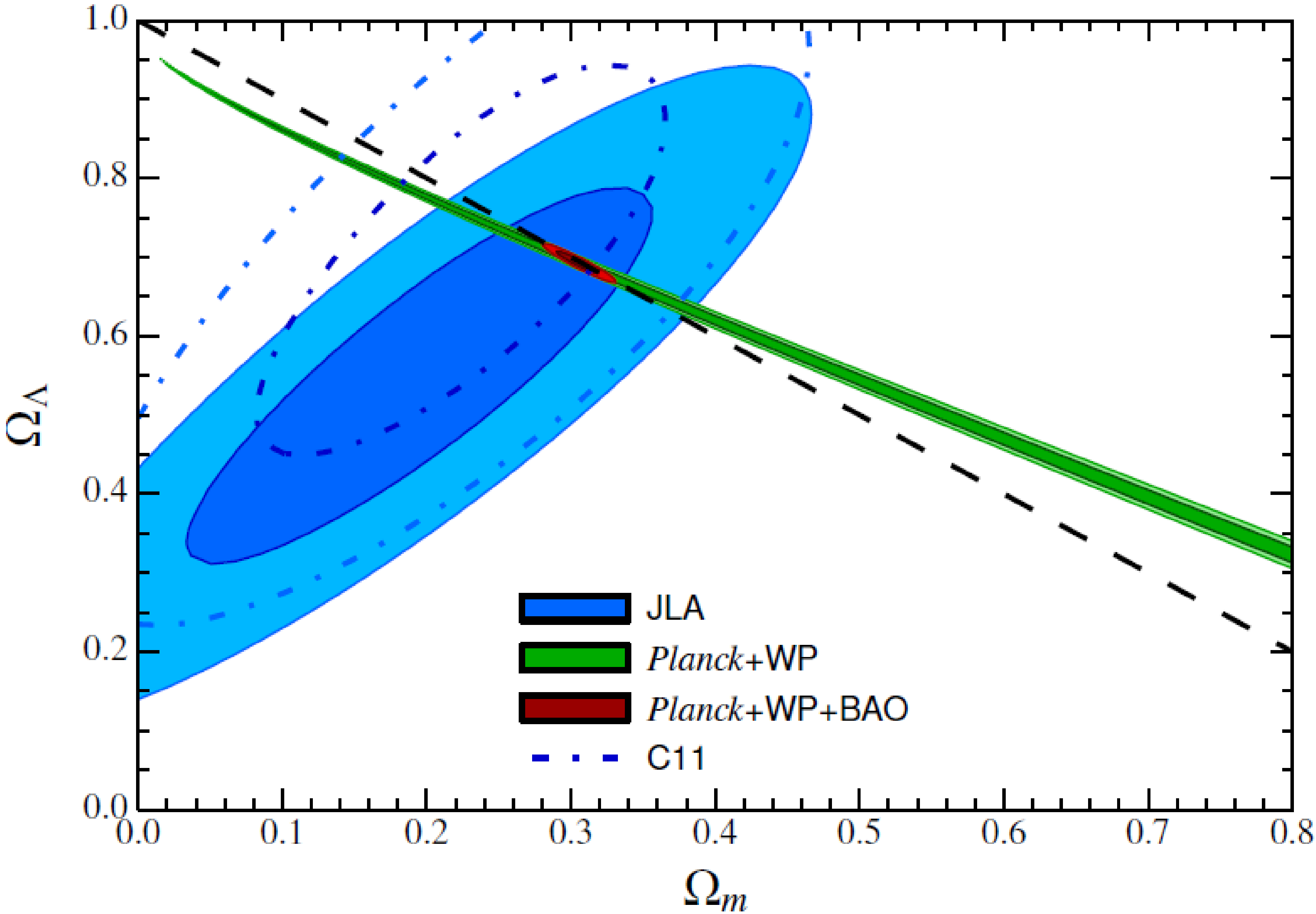


$$H_0 = 70\ \text{kms}^{-1}\text{Mpc}^{-1}$$

$$\Omega_m = 0.295$$

Betoule et al. 2014

The Contents of the Universe - 2014

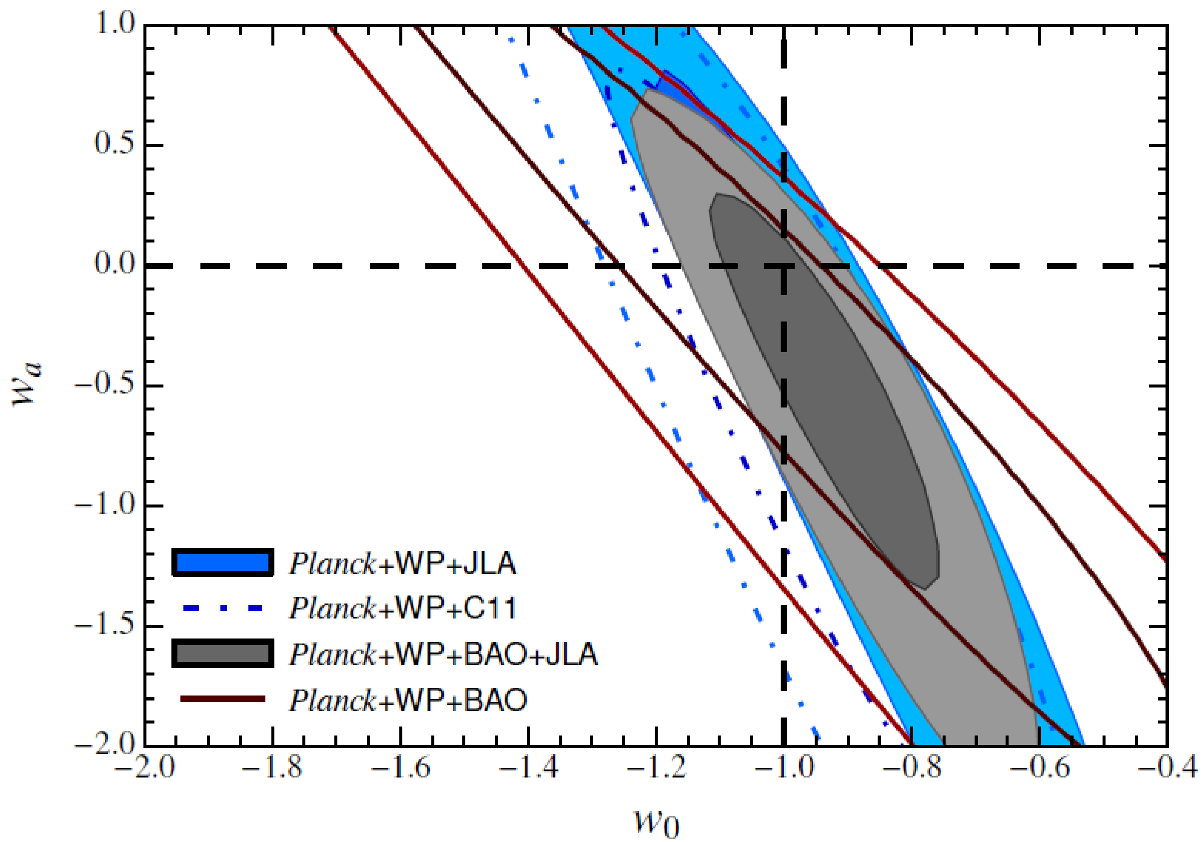


Betoule et al. 2014

Is it Really a Cosmological Constant?

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

Dashed lines = cosmological constant



Betoule et al. 2014

We still don't have a good theory

Cosmological Constant: Why is the value non-zero but so small

Expected:

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

Observed:

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

Phase transitions in the early universe induce large changes in the vacuum energy

Such a large hierarchy is not protected in a quantum theory

The Cosmological Constant Problem

Field Theory Prediction:

$$\Omega_\Lambda = \frac{M^4}{3H_0^2 M_P^2}$$

The old cosmological constant problem:

Why don't we see an enormous cosmological constant?

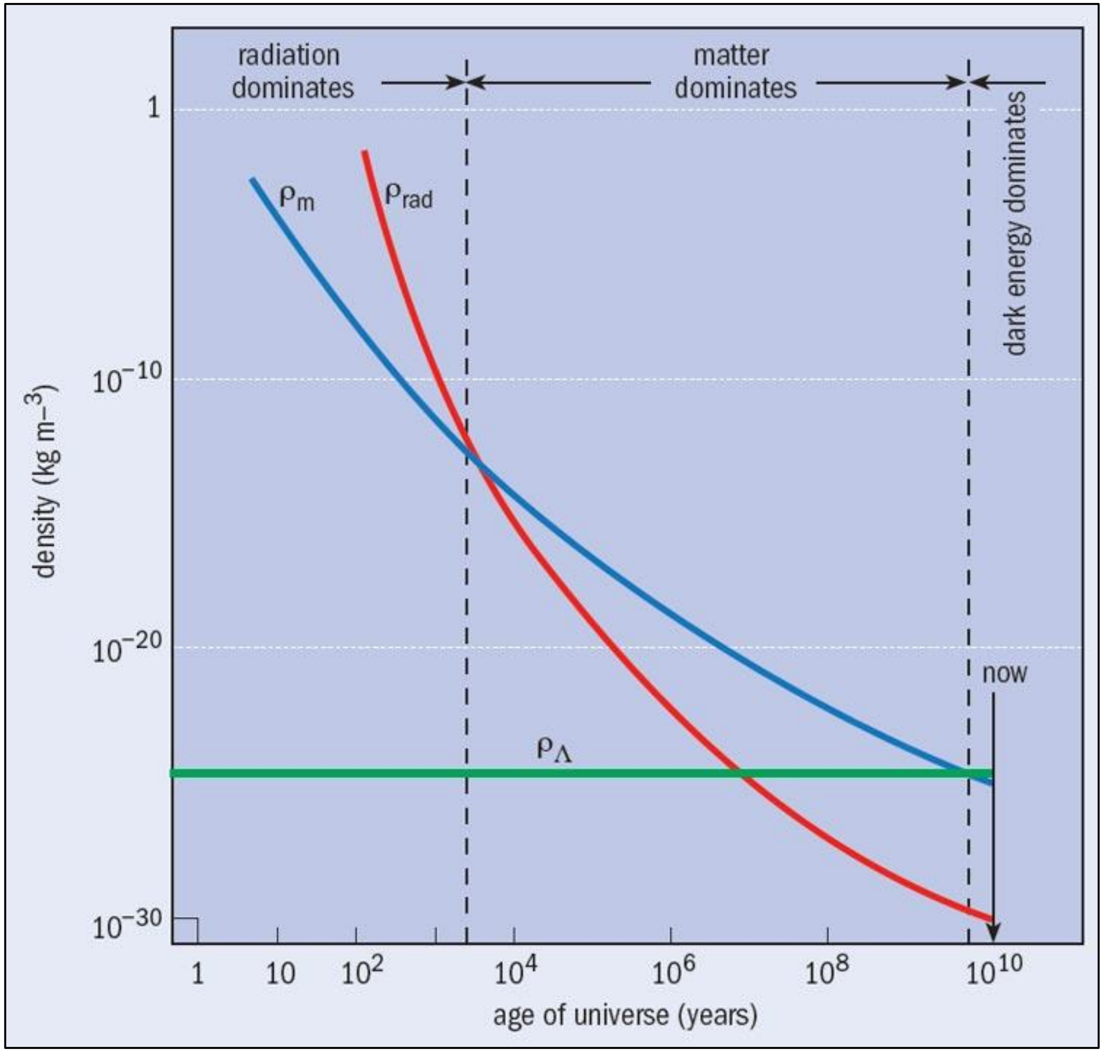
The new cosmological constant problem:

Why is the cosmological constant small but not zero?

The coincidence problem:

Why is the value chosen so that the cosmological constant dominates today?

The Cosmological Constant Problem



Calder, Lahav. Physics World 2010

Solutions to the Cosmological Constant Problem

There are new types of matter in the universe

- A perfect fluid can cause acceleration if

$$w < -1/3$$

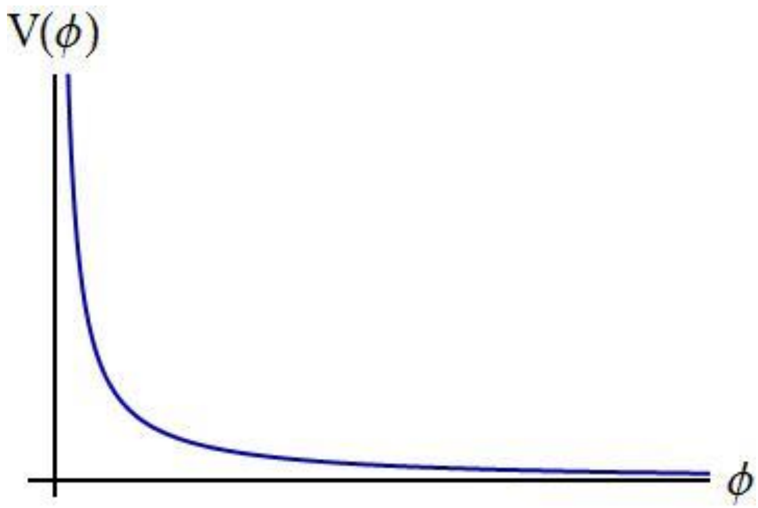
- But no matter species that we know of satisfy this

The theory of gravity is wrong

- General relativity is not a good description of gravity over very large distance scales
- E.g. the graviton could have mass and so there is a maximum distance (the Compton wavelength) over which gravitational information can be sent

Quintessence

The universe is dominated by a new type of matter described by a scalar field



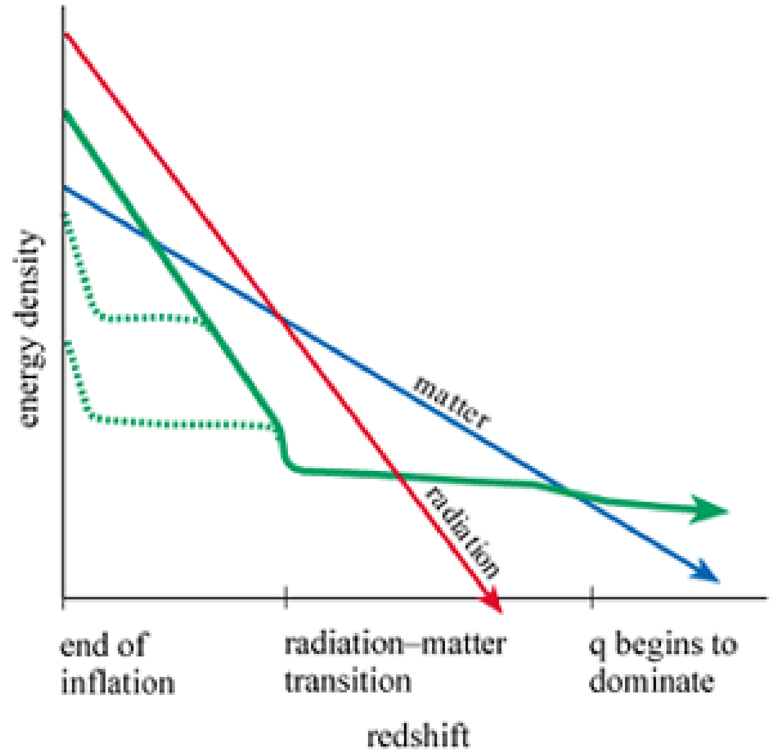
$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

The scalar field evolves according to

$$\ddot{\phi} + 3H\dot{\phi} = \frac{dV}{d\phi}$$

Quintessence



Solves the coincidence problem, but doesn't explain why the cosmological constant is not huge

- Still have to tune the parameters to match observations

Caldwell. Physics World 2000

Degravitation

Sources of size larger than a characteristic scale do not source a gravitational field

- Similar to a band pass filter in electromagnetism

The cosmological constant is constant over all of time and space

- Would be filtered out of the gravitational field

Can be done if the graviton has a mass – but this is a difficult thing to include in the theory

Small value protected from quantum effects

Dvali, Hoffman, Khoury. 2007

Problem: New fields and New Forces

Trying to solve the cosmological constant problem introduces new scalar fields/particles

These fields will interact with normal matter

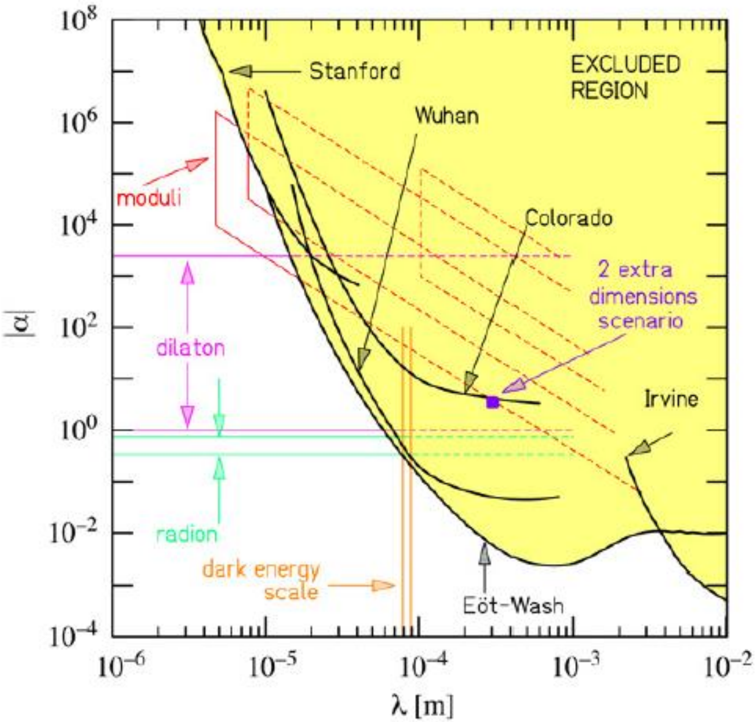
As they are scalars (spin 0) this means that there would be a new, 5th force in the Universe

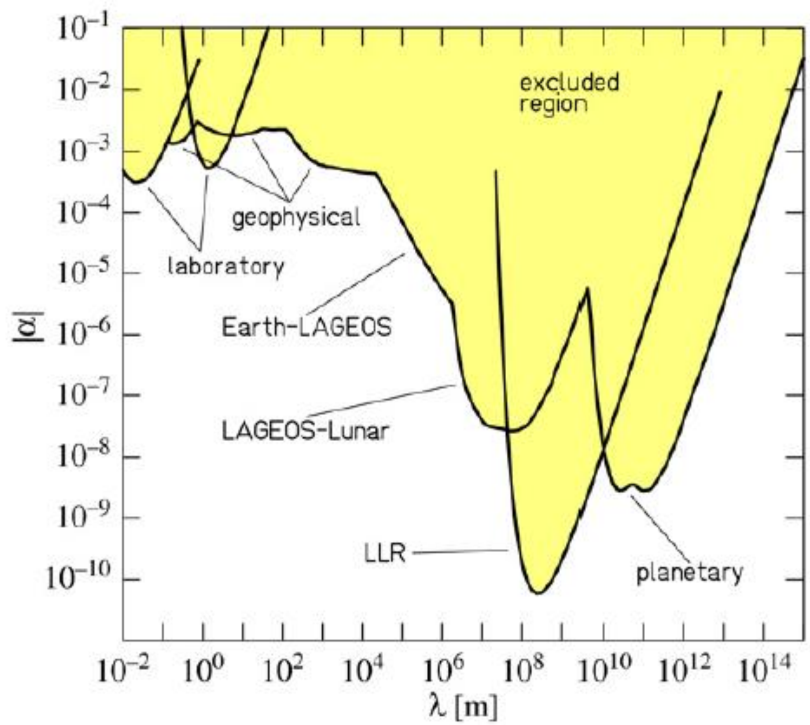
Why haven't we seen it?

Dark Energy Scalar Fields

The existence of a fifth force is excluded to a high degree of precision

$$V(r) = -\frac{G\alpha m_1 m_2}{r} e^{-m_\phi r}$$





Adelberger et al. (2009)

The Chameleon

or

Scalar field theory with non-trivial self interactions and coupling to matter

The spherically symmetric, static equation of motion is

$$\frac{1}{r^2}\frac{d}{dr}[r^2\phi(r)] = \frac{dV}{d\phi} + \frac{\rho(r)}{M} \equiv V_{\rm eff}(\phi)$$

Chameleon screening relies on a non-linear potential,

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

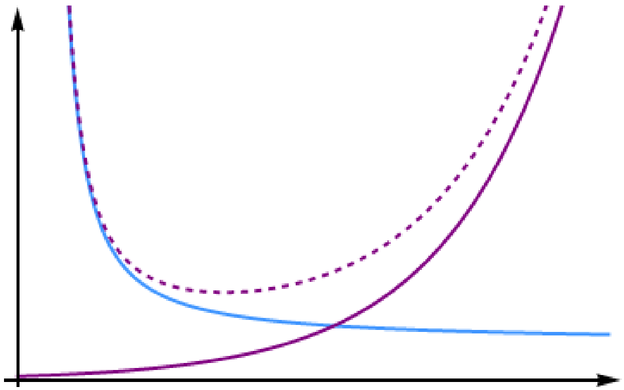
Khoury, Weltman. (2004). Image credit: Nanosanchez

Varying Mass

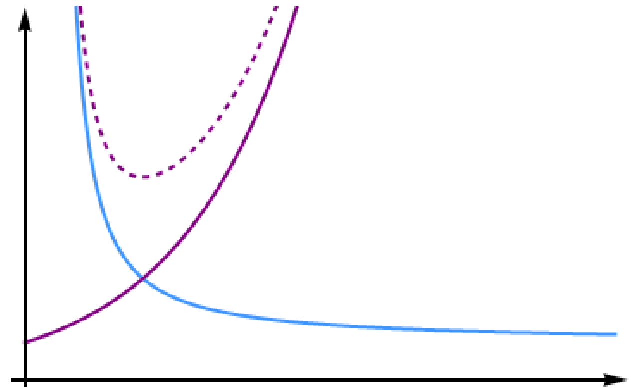
The mass of the chameleon changes with the environment

Field is governed by an effective potential

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



Low density

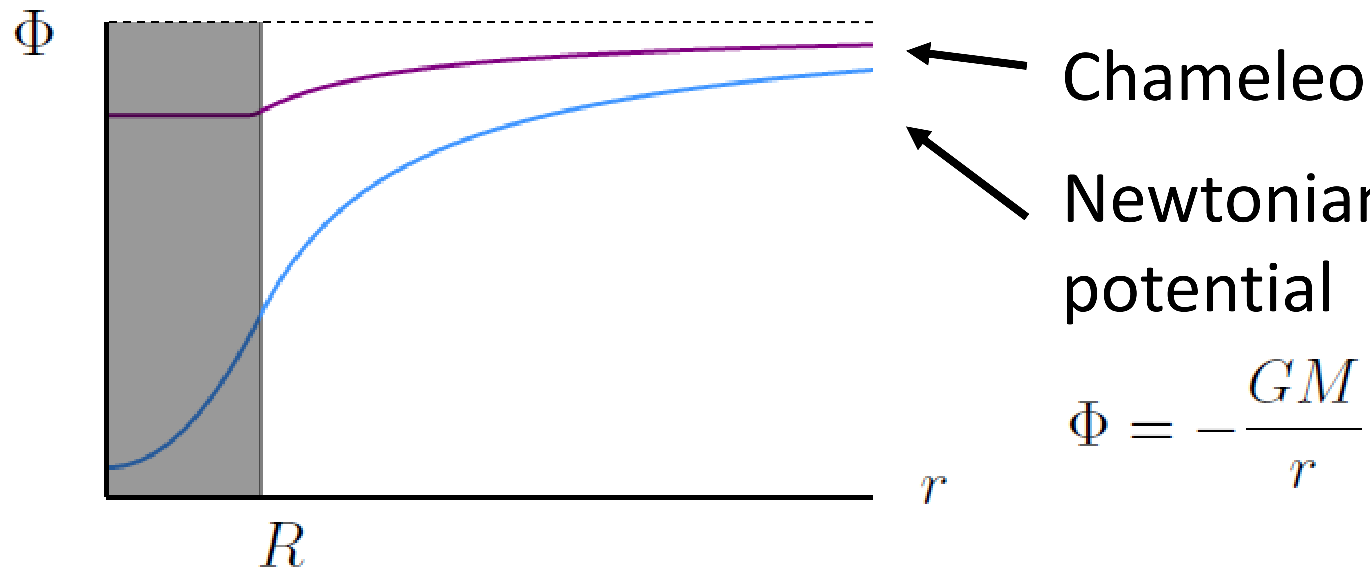


High density

Warning: Relies on non-renormalisible operators, no protection from quantum corrections

Chameleon Screening

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



The chameleon potential well around ‘large’ objects is shallower than for standard light scalar fields

The Scalar Potential

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

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

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

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

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

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

The Galileon

On flat space-time the Lagrangian is

$$\mathcal{L} = -\frac{1}{2}(\partial\pi)^2 - \frac{c_3}{2\Lambda^3}\Box\pi(\partial\pi)^2 + \frac{c_4}{\Lambda^6}\mathcal{L}_4(\pi) + \frac{c_5}{\Lambda^9}\mathcal{L}_5(\pi) + \pi T\ .$$

$$\begin{aligned}\mathcal{L}_4(\pi) &= (\partial\pi)^2\left([\Pi]^2 - [\Pi^2]\right)\ ,\\ \mathcal{L}_5(\pi) &= (\partial\pi)^2\left([\Pi]^3 - 3[\Pi][\Pi^2] + 2[\Pi^3]\right)\ .\end{aligned} \qquad \Pi_{\mu\nu} = \partial_\mu\partial_\nu\pi.$$

The Lagrangian respects (up to total derivatives) the symmetry

$$\pi(x) \to \pi(x) + b_\mu x^\mu + c,$$

Nicolis, Rattazzi, Trincherini 2009

The Galileon

The equations of motion are

$$[\Pi] + \frac{c_3}{\Lambda^3}\left([\Pi]^2 - [\Pi^2]\right) - \frac{c_4}{\Lambda^6}\left([\Pi]^3 - 3[\Pi][\Pi^2] + 2[\Pi^3]\right)$$
$$- \ \frac{c_5}{\Lambda^9}\left([\Pi]^4 - 6[\Pi]^2[\Pi^2] + 8[\Pi][\Pi^3] + 3[\Pi^2]^2 - 6[\Pi^4]\right) = -T\ .$$

$$\Pi_{\mu\nu} \ = \ \partial_\mu\partial_\nu\pi.$$

There are never more than two derivatives on a field

This avoids Ostrogradski ghosts

Fifth forces & the Vainshtein effect

Spherically symmetric, static equations of motion, near an object of mass M_c

$$c_2\left(\frac{\pi'}{r}\right)+2c_3\left(\frac{\pi'}{r}\right)^2+2c_4\left(\frac{\pi'}{r}\right)^3=\frac{M_c}{4\pi r^3}$$

The force can be made substantially weaker than gravity if non-linearities become important

$$\pi'=\frac{M_c}{4\pi c_2 r^2}g(r)$$

$$R_1^3\sim\frac{c_3M_c}{c_2^2}$$

The equation of motion becomes

$$g+\left(\frac{R_1}{r}\right)^3g^2+\left(\frac{R_2}{r}\right)^6g^3=1.$$

$$R_2^6\sim\frac{c_4M_c^2}{c_2^3}$$

CB, Seery. 2010

Observational constraints

Matching the cosmological background expansion can lead to variations in Newton's constant G

This is potentially in conflict with

–Lunar laser ranging observations

–The history of structure formation

Initial conditions which lead to small changes in G lead to large evolutions in the equation of state of the scalar field in the recent universe

This leads to a significant tension with observations

Babichev, Deffayet, Esposito-Farese 2011. Appleby, Linder 2011,2012

Observations – What do we need?

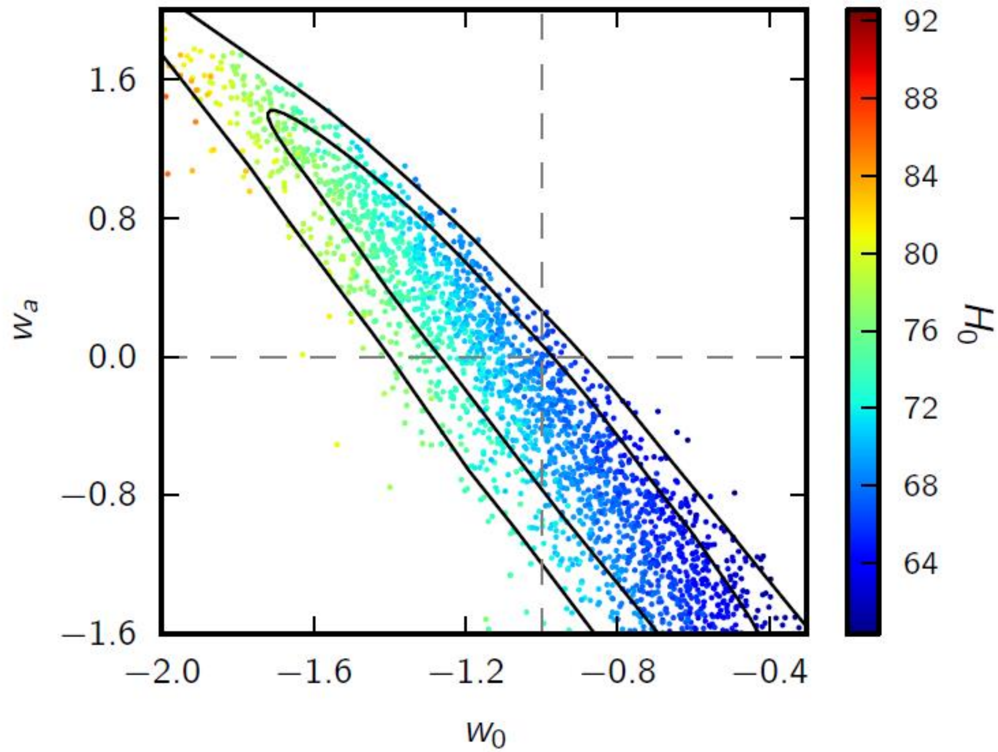
Better understanding of the expansion history of the universe

Other ways to test whether gravity works as expected on large distance scales

Direct ways to look for new fields in the laboratory

The Expansion History of the Universe

The cosmic microwave background light has travelled through (almost) the whole history of the universe



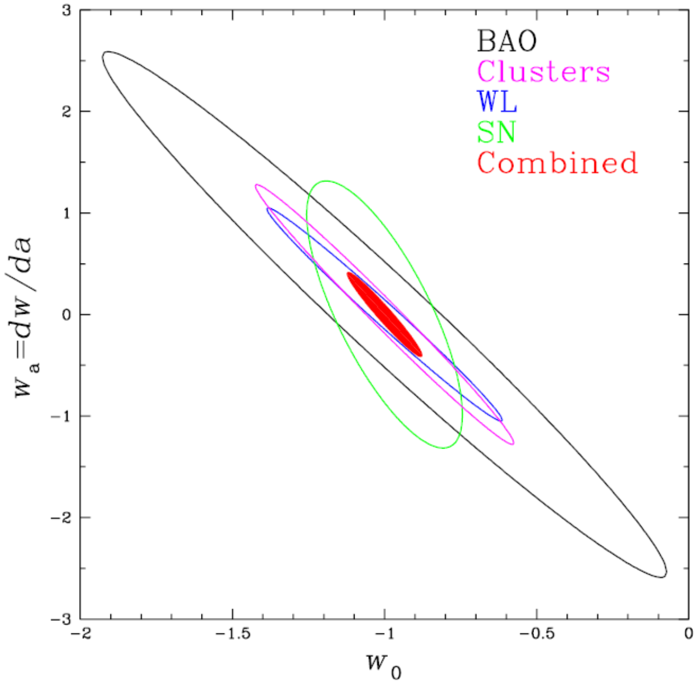
CMB only constraints, no supernova data

Planck 2013 results XVI. Cosmological Parameters.

Near Future for Supernovae Observations

Dark Energy Survey, (Blanco Telescope, Chile)

- Will measure around 4,000 type 1a supernovae out to redshift ~ 1
- Five year mission. First year of data being analysed now



Dark Energy Survey Science Program

Gravitational Lensing

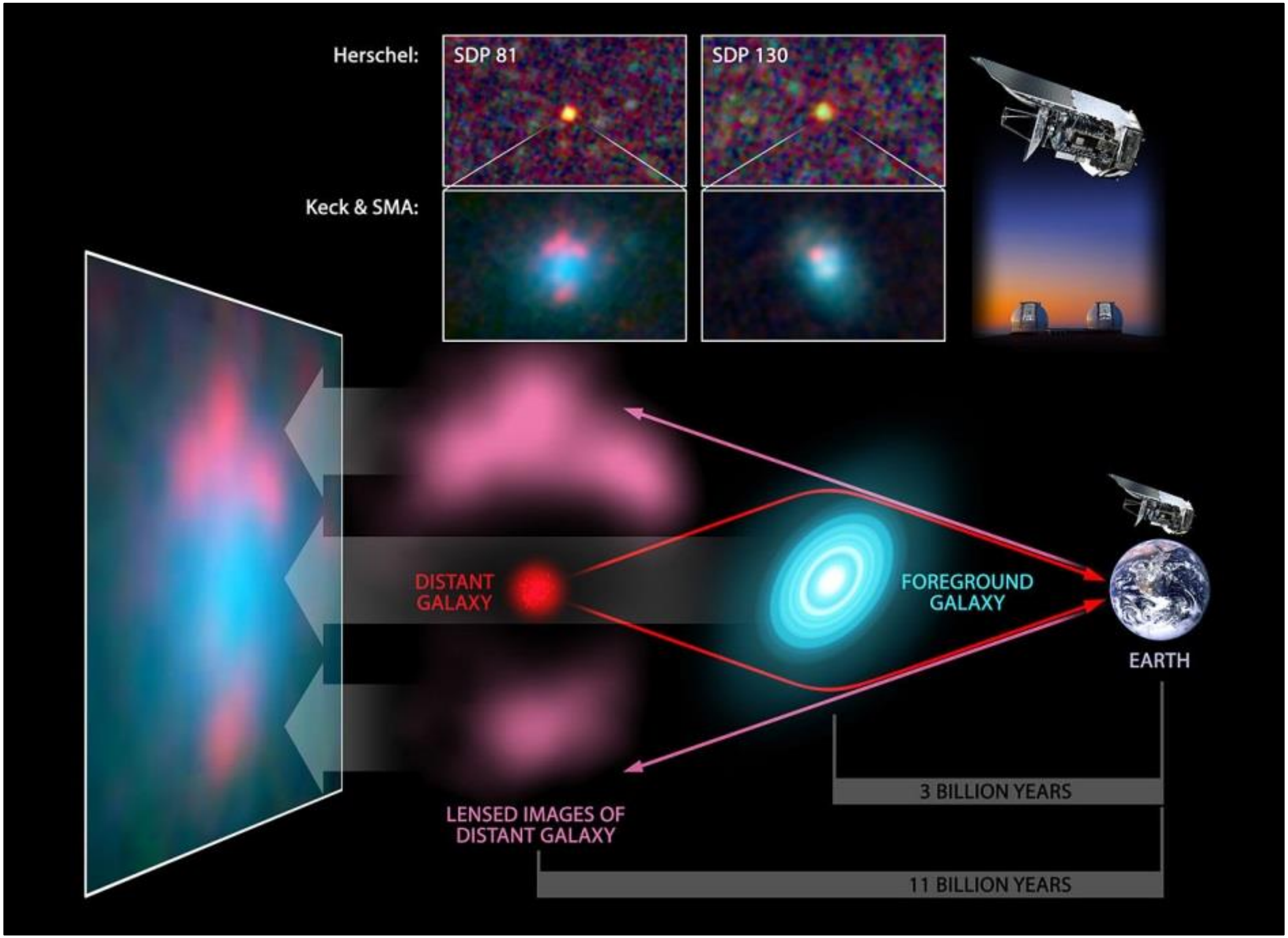


Image credit: NASA/JPL-Caltech/T. Pyle

Weak Lensing

Most galaxies we see are lensed by about 1%

- No useful physics from looking at one galaxy (especially as not all galaxies have the same shape)

Look for alignments:

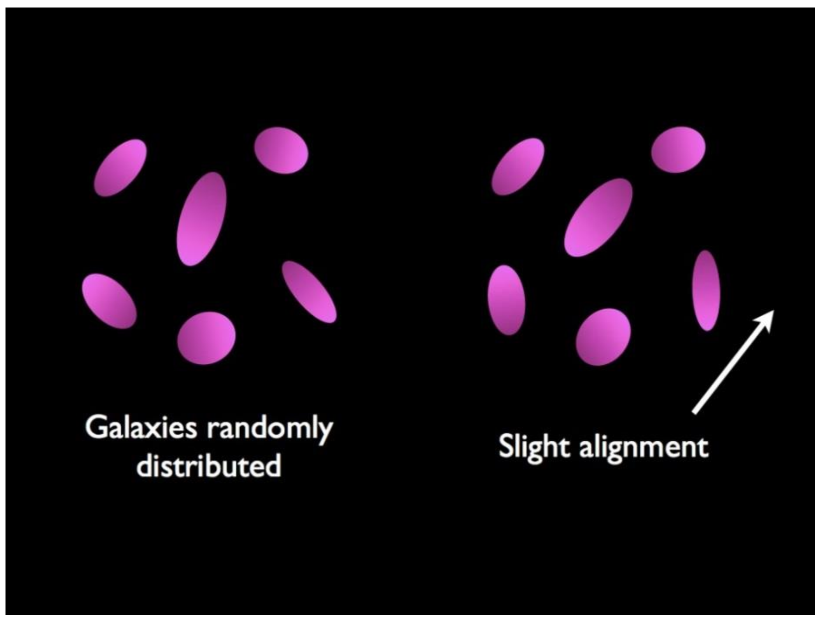
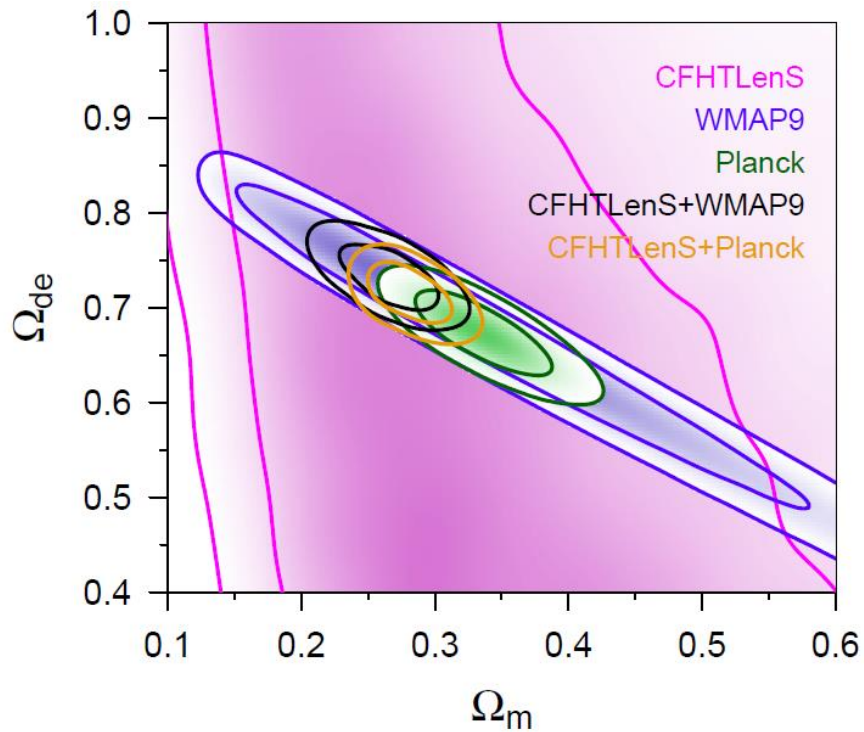


Image credit: E Grocutt, IfA, Edinburgh

Weak Lensing

Weak lensing tells us about:

- The distribution of dark matter in the universe
- The background evolution of the universe (does lensing change with time?)



Fu et al. 2014

Redshift Space Distortions

Does gravity affect matter and light in the same way?

- Anisotropic stress / slip:

$$ds^2 = -(1+2\Psi)dt^2 + a(t)^2(1+2\Phi)d\vec{x}^2$$

$$\eta(k,a) = -\frac{\Phi}{\Psi}$$

The gravitational attraction between a cluster and surrounding galaxies causes them to fall towards the cluster (peculiar velocities)

- This changes their apparent redshift, but only for motion along the line of sight

Redshift Space Distortions

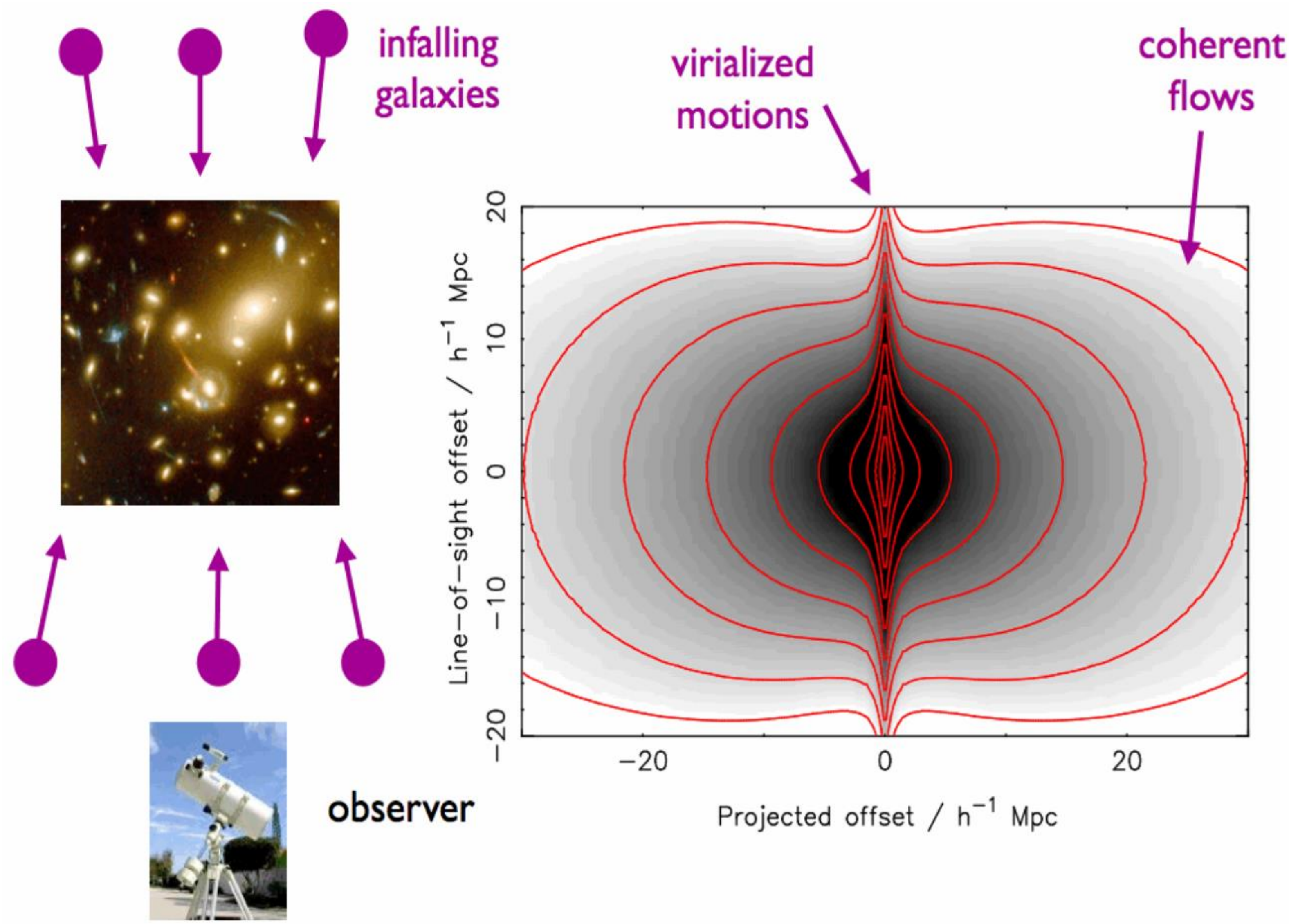


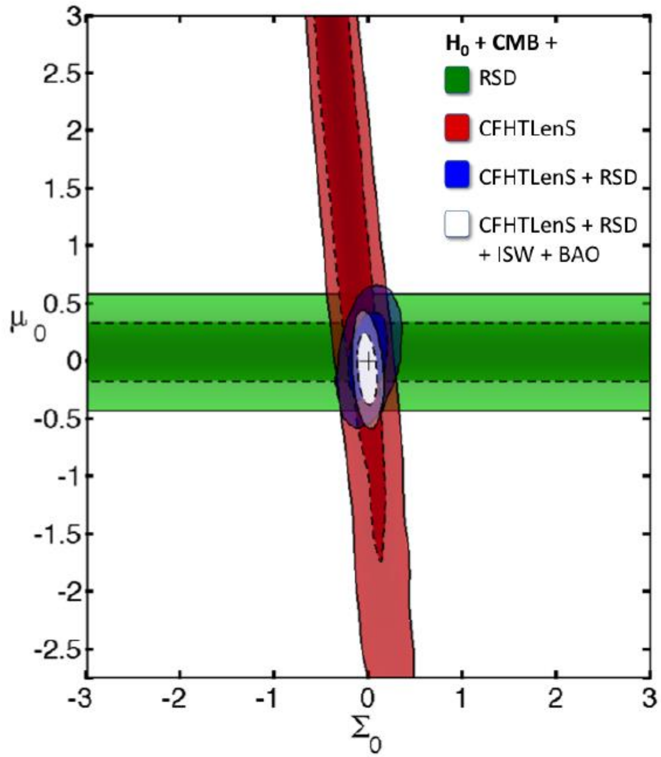
Image credit: David Parkinson

Constraints on Modified Gravity

Combining weak lensing and redshift space distortions

$$\Psi(k,a) = [1+\mu(k,a)]\,\Psi_{\rm GR}(k,a)$$

$$[\Psi(k,a)+\Phi(k,a)] = [1+\Sigma(k,a)]\,[\Psi_{\rm GR}(k,a)+\Phi_{\rm GR}(k,a)]$$



Simpson et al. 2013

The Future of Cosmological Observations

Euclid satellite – launch planned for 2020

Will use all of these techniques (and more)

Better sensitivity and don't have to see through the atmosphere

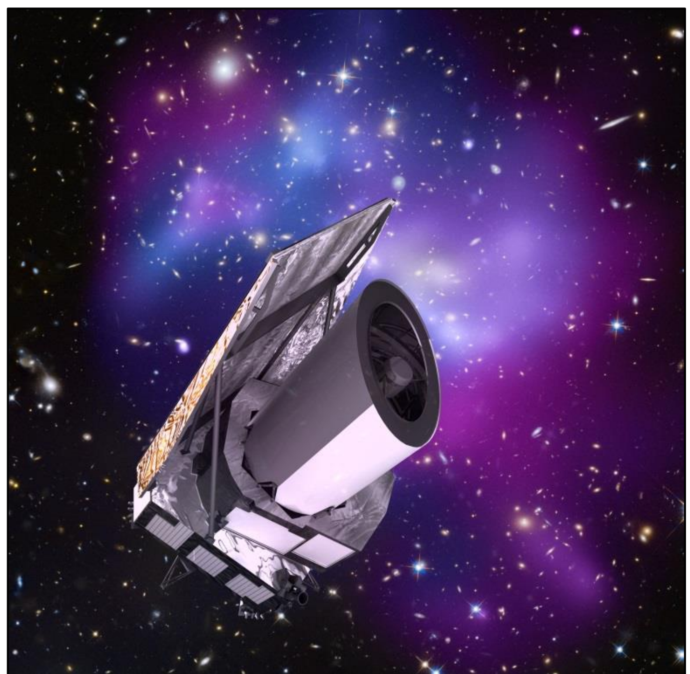
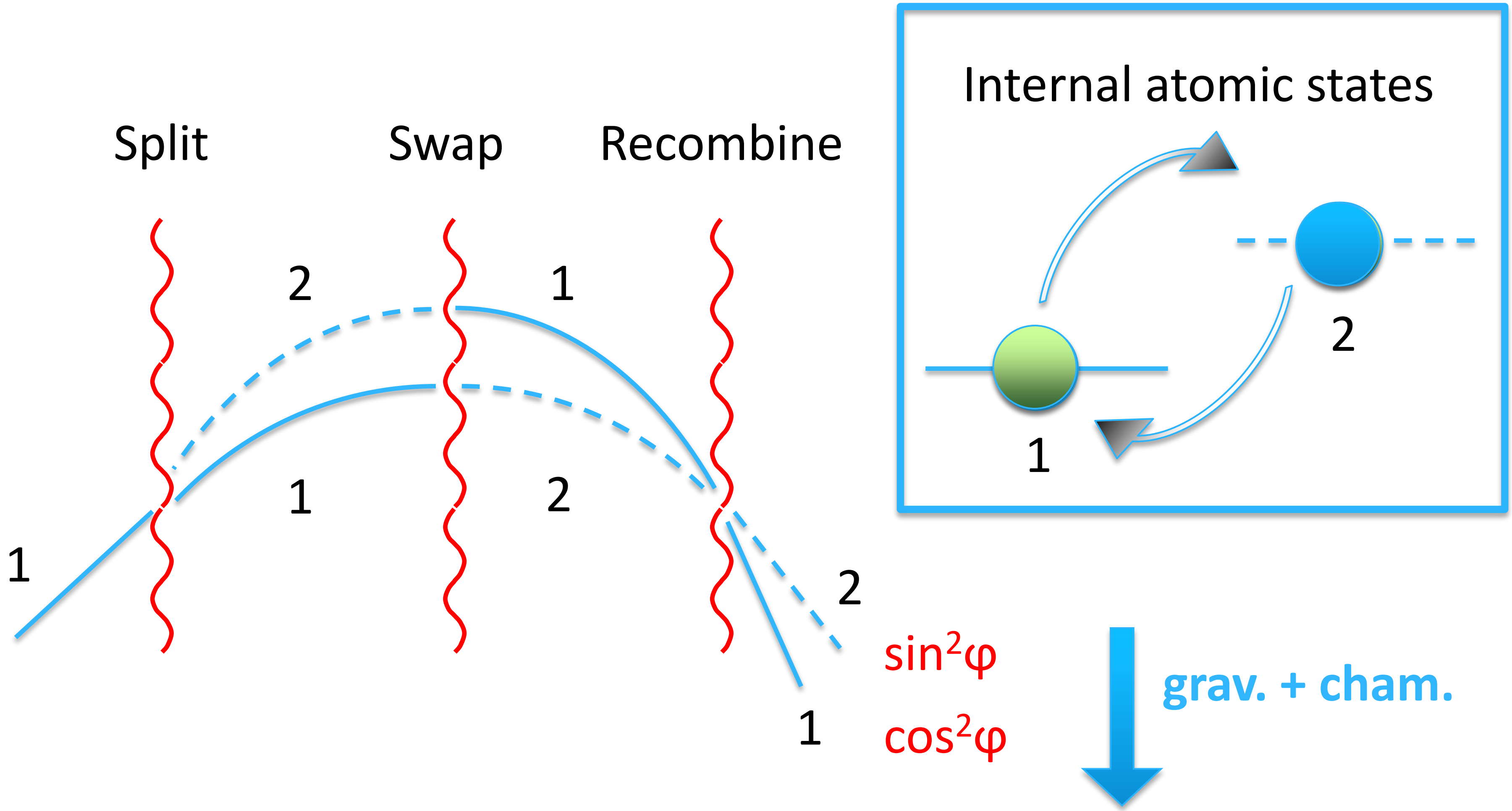


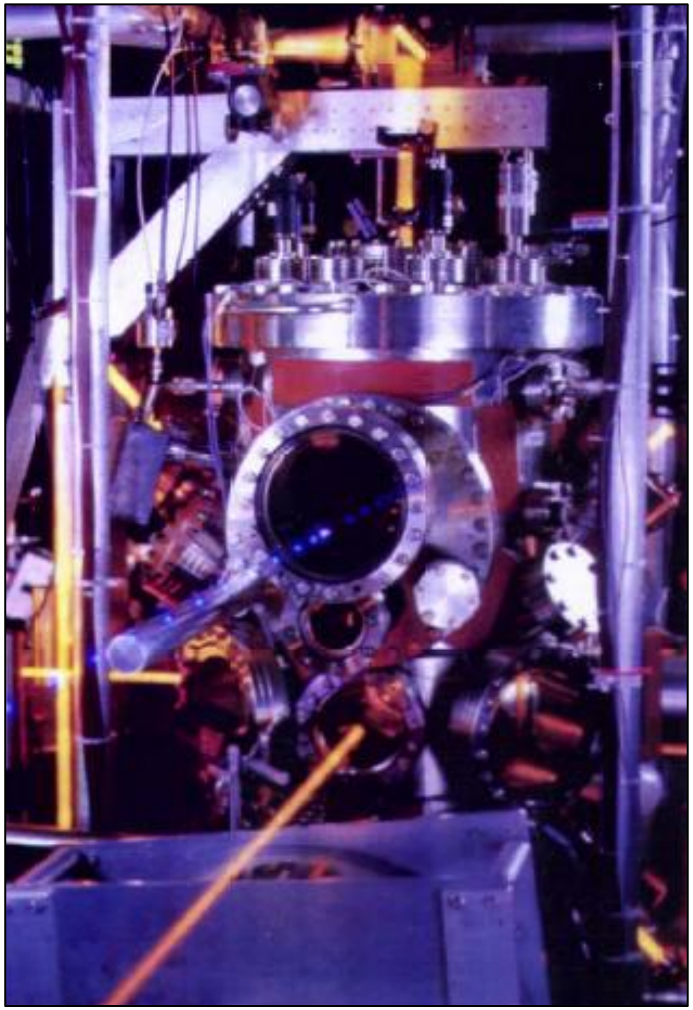
Image Credit: Euclid Consortium

Detecting Chameleons with Atom Interferometry



Force acting on atoms induces phase difference
Determines whether atoms come out in state 1 or 2

Proposed Chameleon Experiment



Launch Rb atoms in a fountain, height 5 mm, held 1 cm from a source mass of 1 cm radius

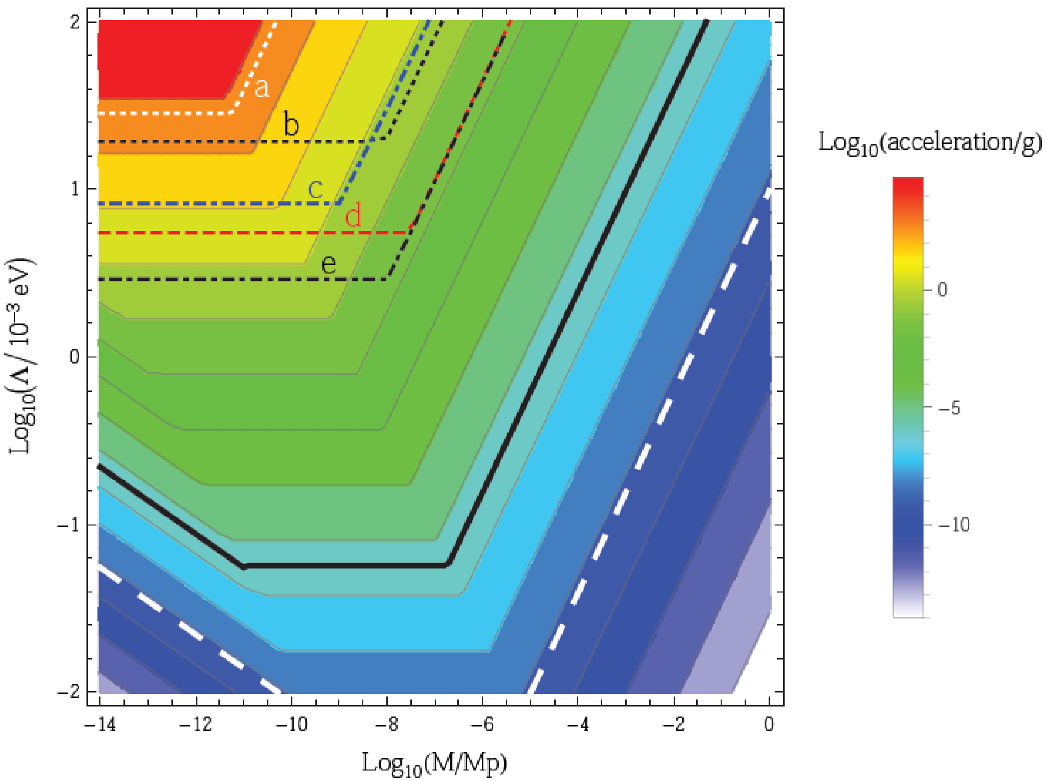
- Accelerations of 10^{-6} g produce a detectable, $^{1}/_{7}$ radian, phase shift
- Stark effect, Zeeman effect, phase shifts due to scattered light and movement of beams all negligible at this level

Image credit: Center for Cold Matter, Imperial College

Expected Sensitivity

Atoms are ‘small’, and therefore unscreened

They are sensitive probes of the chameleon field



CB, Copeland & Hinds 2014

Summary

Dark energy makes up ~ 70% of the Universe

- Could be a cosmological constant
- Theory predicts a value 120 orders of magnitude larger than is observed

We do not currently have a theory that explains the acceleration of the expansion of the universe

- Ideas include introducing new types of matter and modifying gravity
- Introduces new forces that are also not seen

Many new possibilities to search for study detect dark energy in the next decade