Dark Energy and Where to find it

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Cosmology at the Beach
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Chameleon Dark Energy

What is a chameleon?

Why are chameleons compelling?

Where to find chameleons?

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What is a Chameleon?

Khoury & Weltman 2004

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

Mass of scalar field depends on local matter density

In region of high density → mass is large ⇒ EP viol suppressed

In solar system → density much lower ⇒ fields essentially free

On cosmological scales → density very low ⇒ $m \sim H_0$

Field is a candidate for acceleration of the universe

Ingredients

Reduced Planck Mass **Coupling to photons** **Matter Fields**

$$M_{Pl} = (8\pi G)^{-1/2}$$

$$S = \int d^4x\sqrt{-g}\left(\frac{M_{Pl}^2}{2}R - (\partial\phi)^2 - V(\phi) - \frac{e^{\frac{\beta_\gamma\phi}{M_{Pl}}}}{4}F^{\mu\nu}F_{\mu\nu}\right) + S_m\left(g_{\mu\nu}^{(i)}, \psi_m^{(i)}\right)$$

$$g = det g_{\mu\nu}$$

$$g_{\mu\nu}^{(i)} = e^{2\beta_i\phi/M_{Pl}}g_{\mu\nu}$$

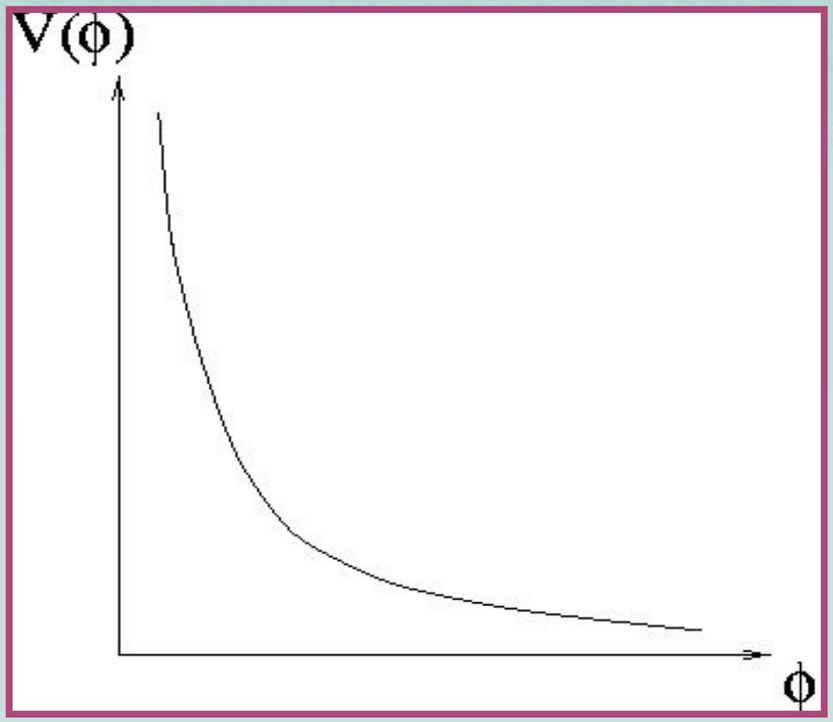
Einstein Frame Metric **Conformally Coupled**

Potential is of the runaway form

This field couples to all matter types - and in a different way to regular gravity

Potential

Runaway potential



Energy density in ith form of matter

Dynamics governed by effective potential :

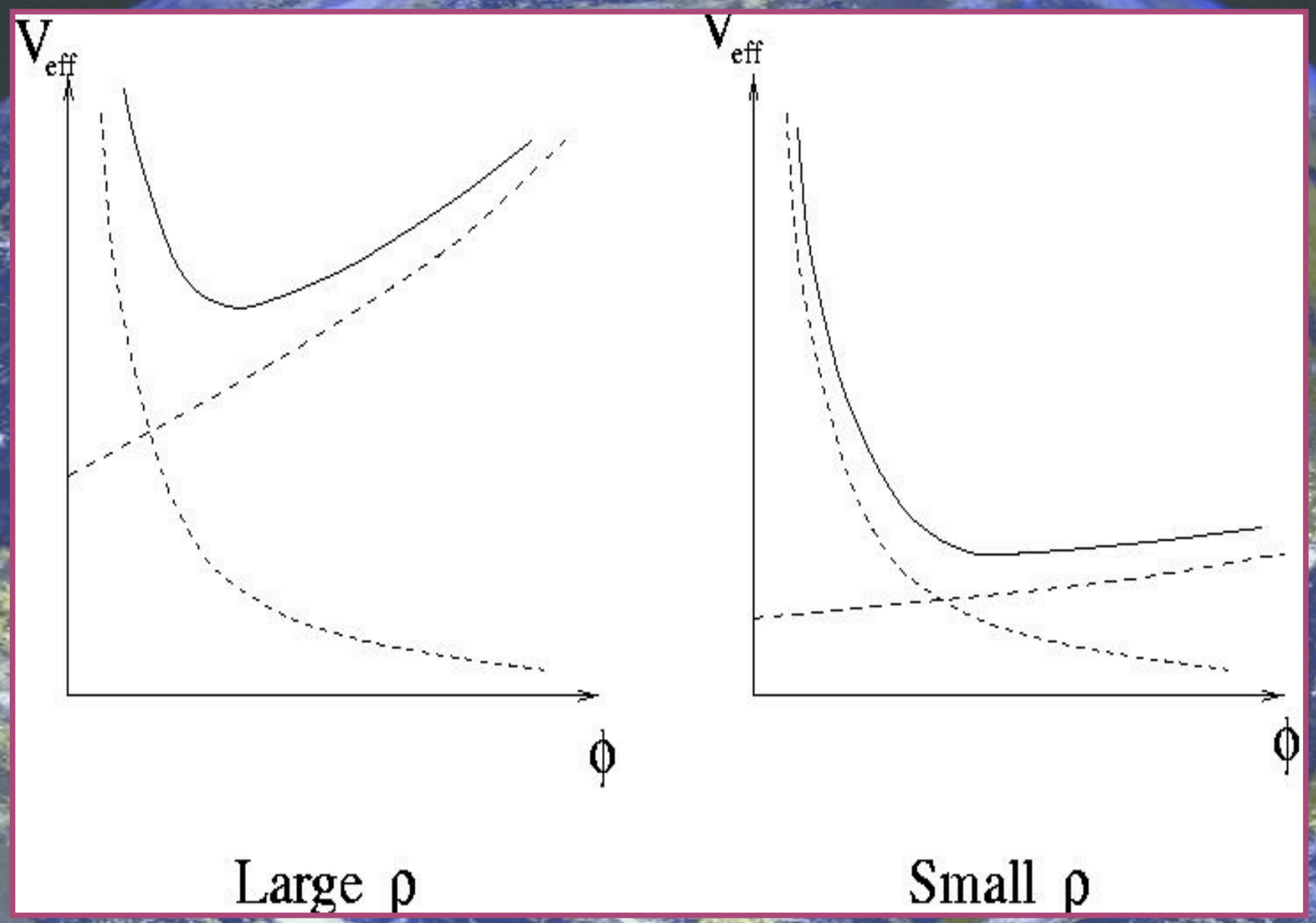
$$V_{\rm eff}(\phi) = V(\phi) + \sum_i \rho_i e^{\frac{\beta_i \phi}{M_{\rm PL}}}$$

$$\boxed{V_{\rm eff}(\phi) = V(\phi) + \rho e^{\frac{\beta \phi}{M_{\rm PL}}}}$$

Earth

$\rho_{\mathbf{E}} = 10\mathrm{g.cm}^{-3}$

$\rho_{\mathbf{g}} = 10^{-24}\mathrm{g.cm}^{-3}$



$\mathbf{m_E} \gg \mathbf{m_g}$

$\phi_{\mathbf{E}} \ll \phi_{\mathbf{g}}$

Why are Chameleons compelling?

- May solve the moduli stabilisation problem
- No violations of BBN, local gravity tests etc
- Predictions for tests in space
- Predictions for lab tests
- Astrophysical effects
- A dark energy theory we can test outside of cosmology

We can probe fundamental physics using low energy and low cost techniques complementary to HEP - e.g. astrophysics, space tests of gravity, quantum vacuum lab

Predictions for Tests in Space

New Feature !! → Different behaviour in space

Tests for UFF $\eta = 2\frac{|a_1 - a_2|}{a_1 + a_2}$

Eöt-Wash Bound $\eta < 10^{-13}$

Near- future experiments in space :

STEP	$\eta \sim 10^{-18}$
GG	$\eta \sim 10^{-17}$
MICROSCOPE	$\eta \sim 10^{-15}$

We predict → $\beta^2 10^{-19} < \eta < \beta^2 10^{-11}$

SEE Capsule $F = \frac{G M_1 M_2}{r^2}(1 + 2\beta_1\beta_2)$

⇒ Corrections of O(1) to Newton's Constant

Coupling to Photons

Effective potential :

$$V_{\text{eff}}(\phi, \vec{x}) = V(\phi) + \rho_m(\vec{x}) e^{\frac{\phi}{M_m}} + \rho_\gamma(\vec{x}) e^{\frac{\phi}{M_\gamma}}$$

$$\rho_\gamma \equiv \frac{1}{2}(B^2 - E^2)$$

In the presence of a magnetic field photons convert to chameleons

Transition Probability: $P \sim \beta_\gamma^2 B^2 L^2$

Path length

Flux of photons

Chameleons produced: $N_\phi = F_\gamma P t_{\text{int}}$

Integration time

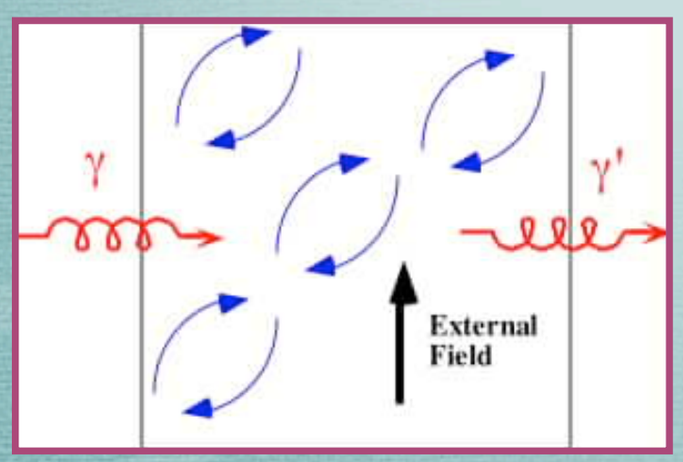
Lab vs Sky

To maximise conversions:

- Large B field
- Large path length, L
- Large flux of photons
- Large integration time

Astro tests require finding sources that satisfy some of the above

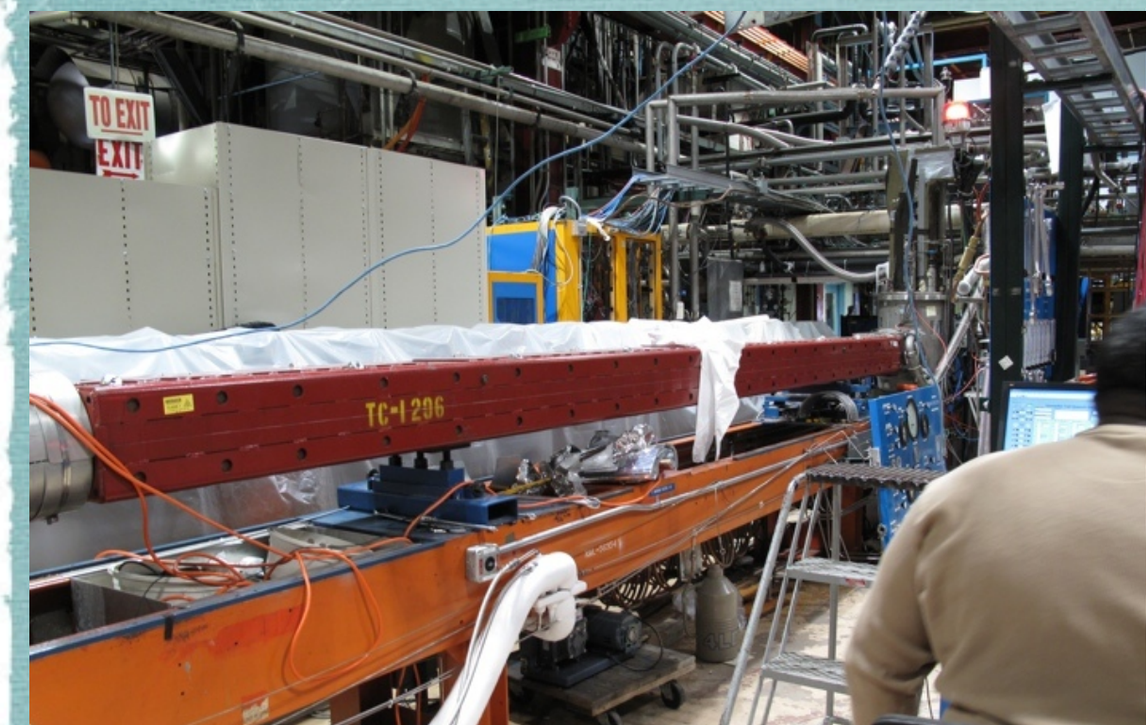
We can control these parameters in quantum vacuum experiments

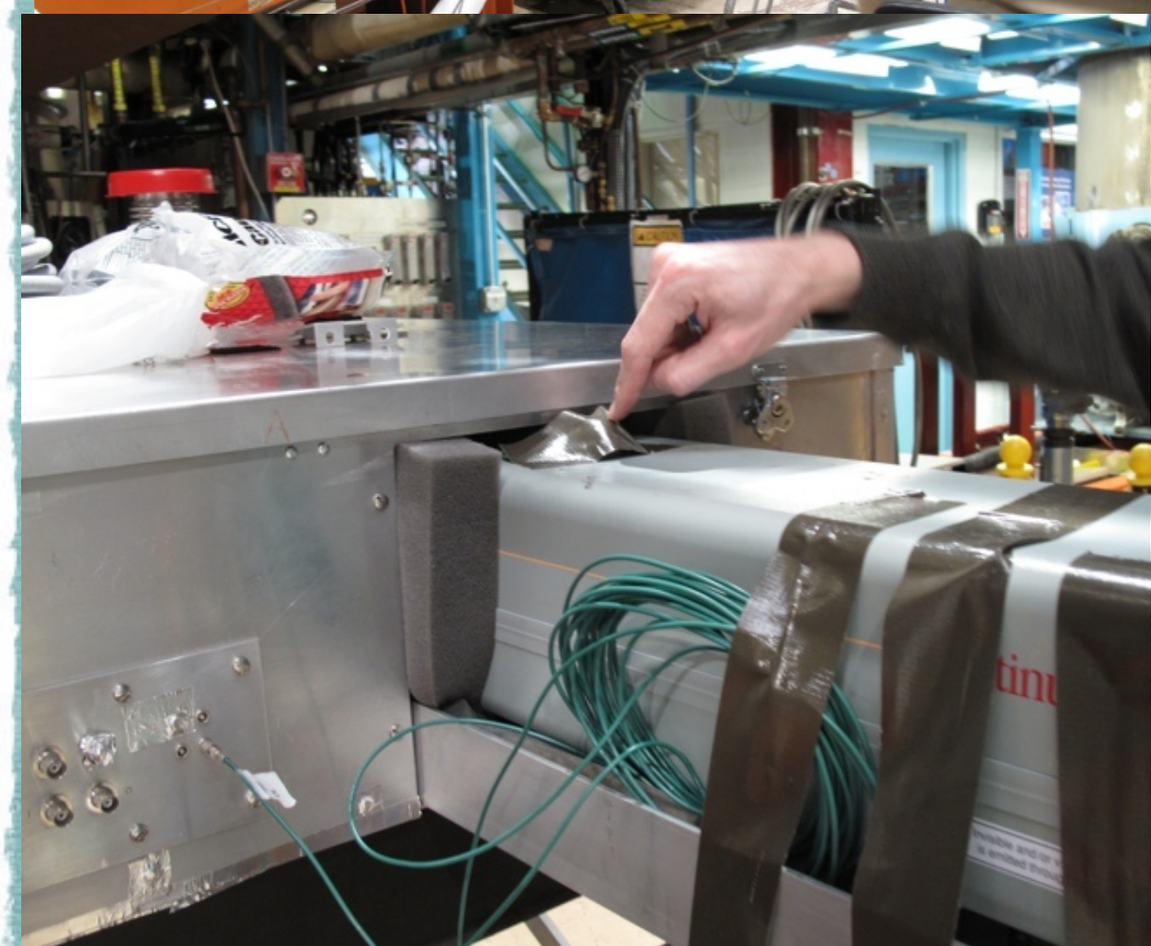


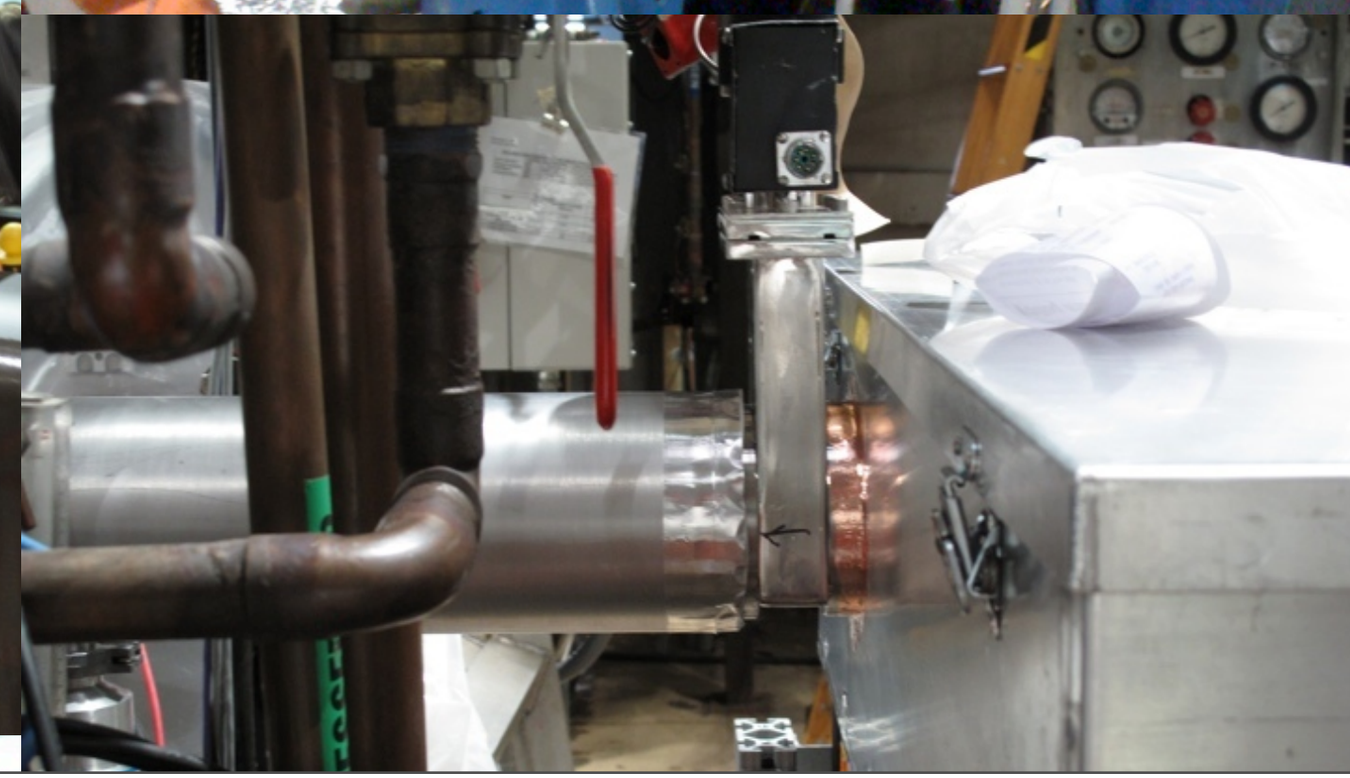
- Use a magnetic field to disturb the vacuum
- Probe the disturbance with photons

→ Test chameleon photon coupling

GammeV CHASE

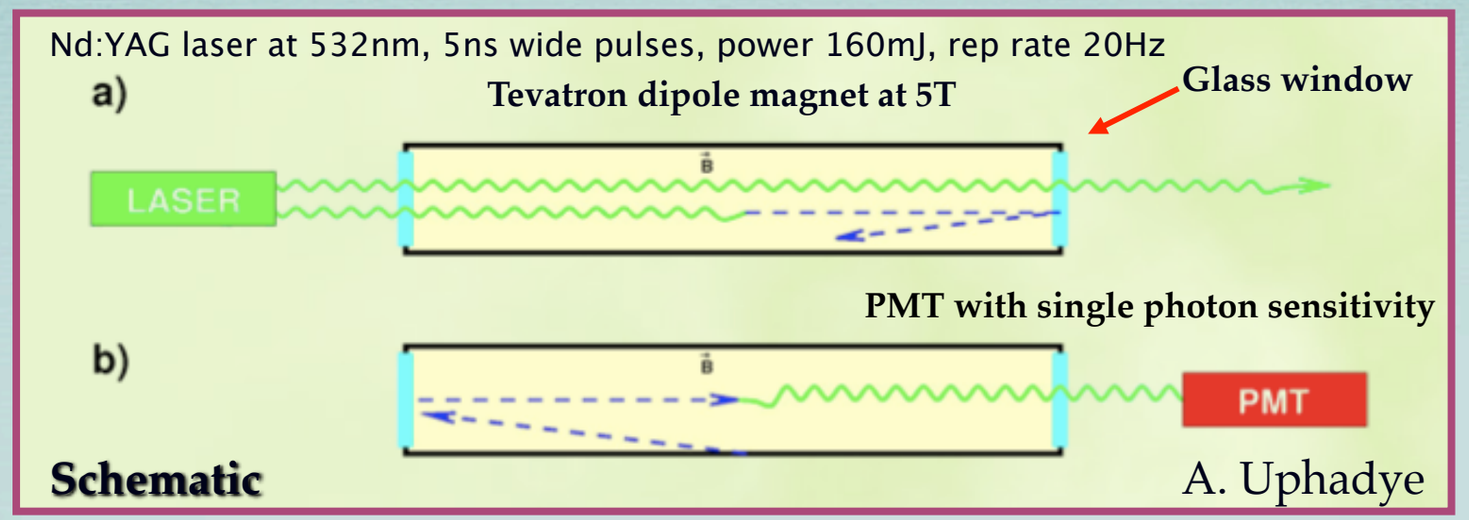






GammeV CHASE

http://gammev.fnal.gov

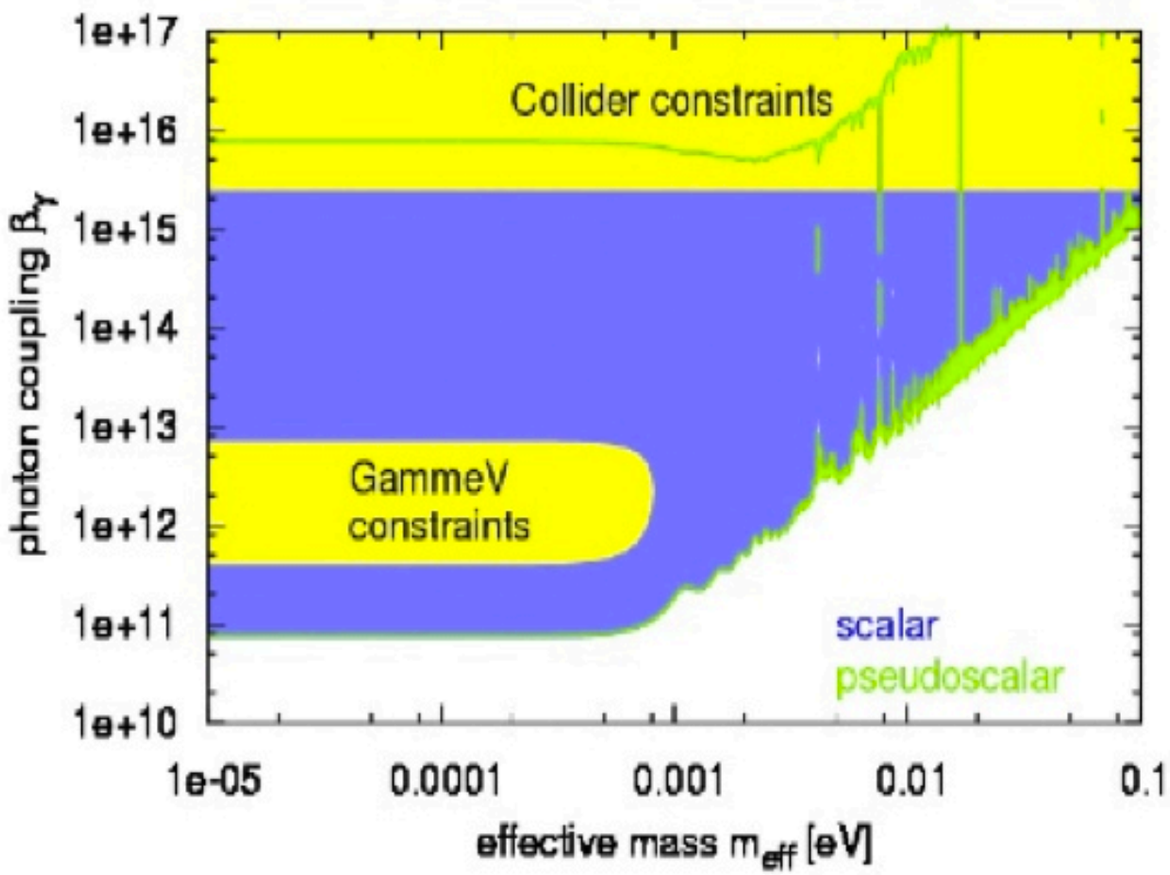


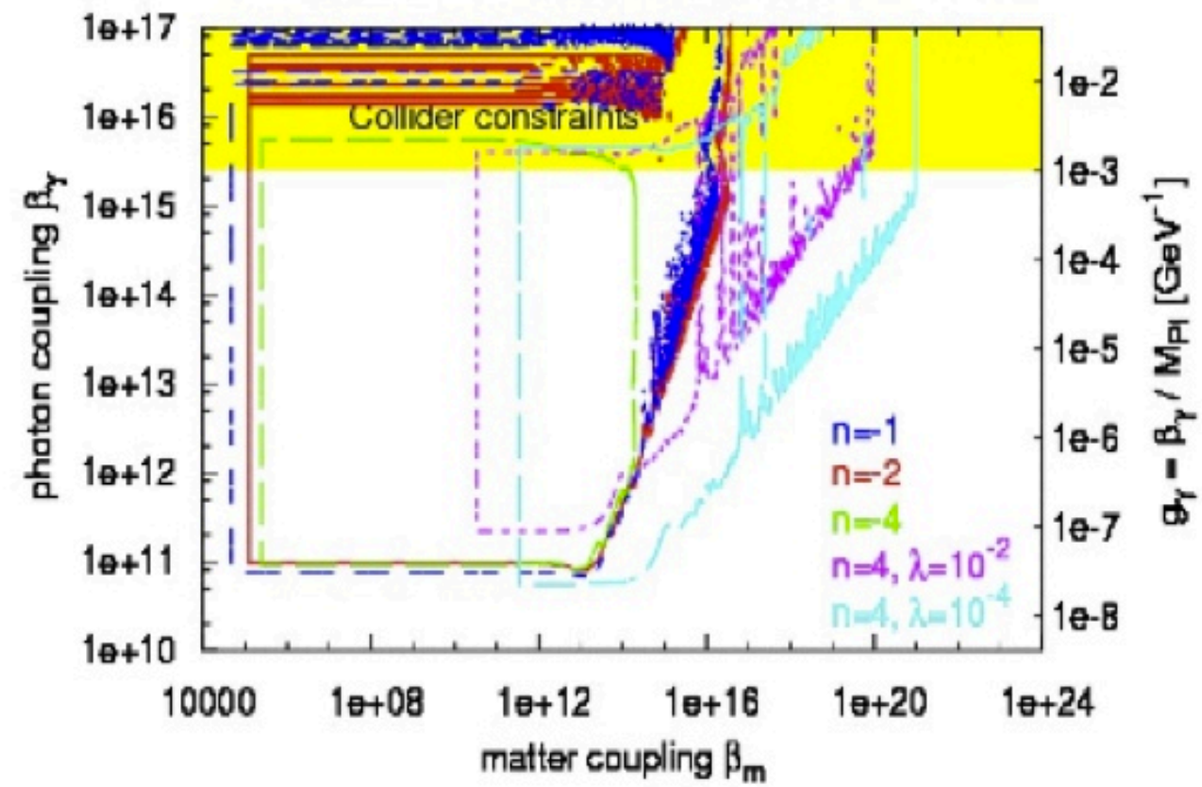
a) Chameleon production phase: photons propagating through a region of magnetic field oscillate into chameleons

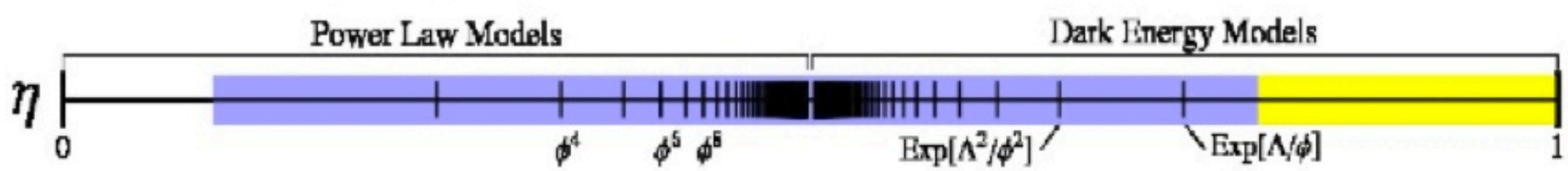
- Photons travel through the glass
- Chameleons see the glass as a wall - trapped

b) Afterglow phase: chameleons in chamber gradually decay back into photons and are detected by a PMT

GammeV Chase Constraints







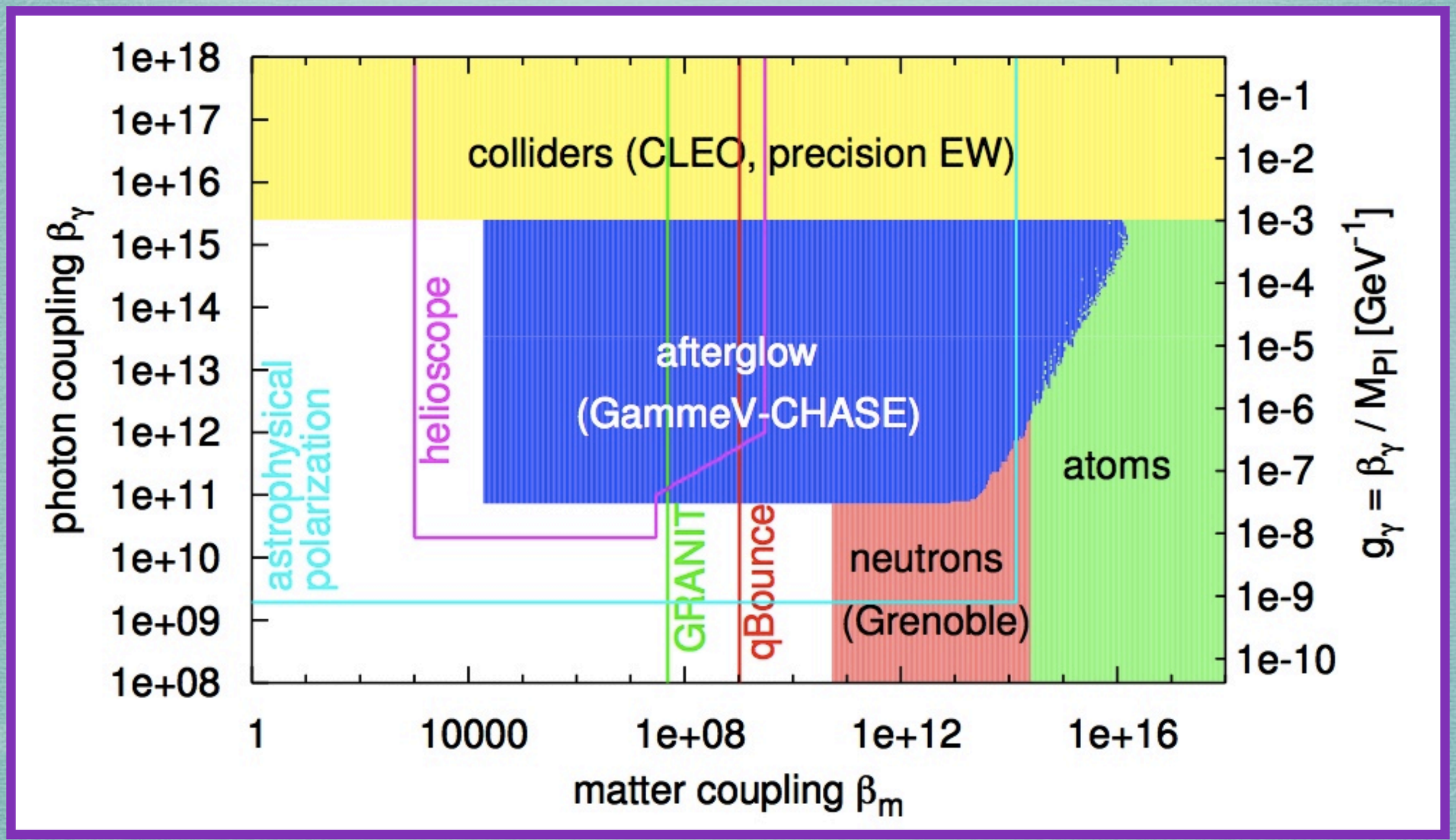
Whats next?

Top down :
- Derivation from fundamental theory
- Include the coupling and potential

Hinterbichler, Khoury and Nastase 2011

Bottom up :
- Experiment to observe the effect
- Distinguish clearly from other models
- Constrain the parameters using complementary searches
- Afterglow searches (GammeV, JLab, DESY etc)
- Helioscope at CAST
- Electroweak at colliders
- Neutrons at Grenoble
- Casimir force experiments
- Torsion pendula experiments
- Astrophysical sources
- Astronomical effects

Constraints and Projections



Why do chameleons still excite me?

There are only 3 known ways to hide Dark Energy from local gravity tests

- Weak couplings - e.g. Λ, tracking quintessence models with no matter couplings

  Not interesting?

- Effectively weak couplings locally - e.g effective 4 theory from a DGP braneworld model

  Not well understood

- Effectively large masses - Chameleon effect

Experiments can be done and eventually the theory can be **ruled out**

Possibilities with Astrophysics

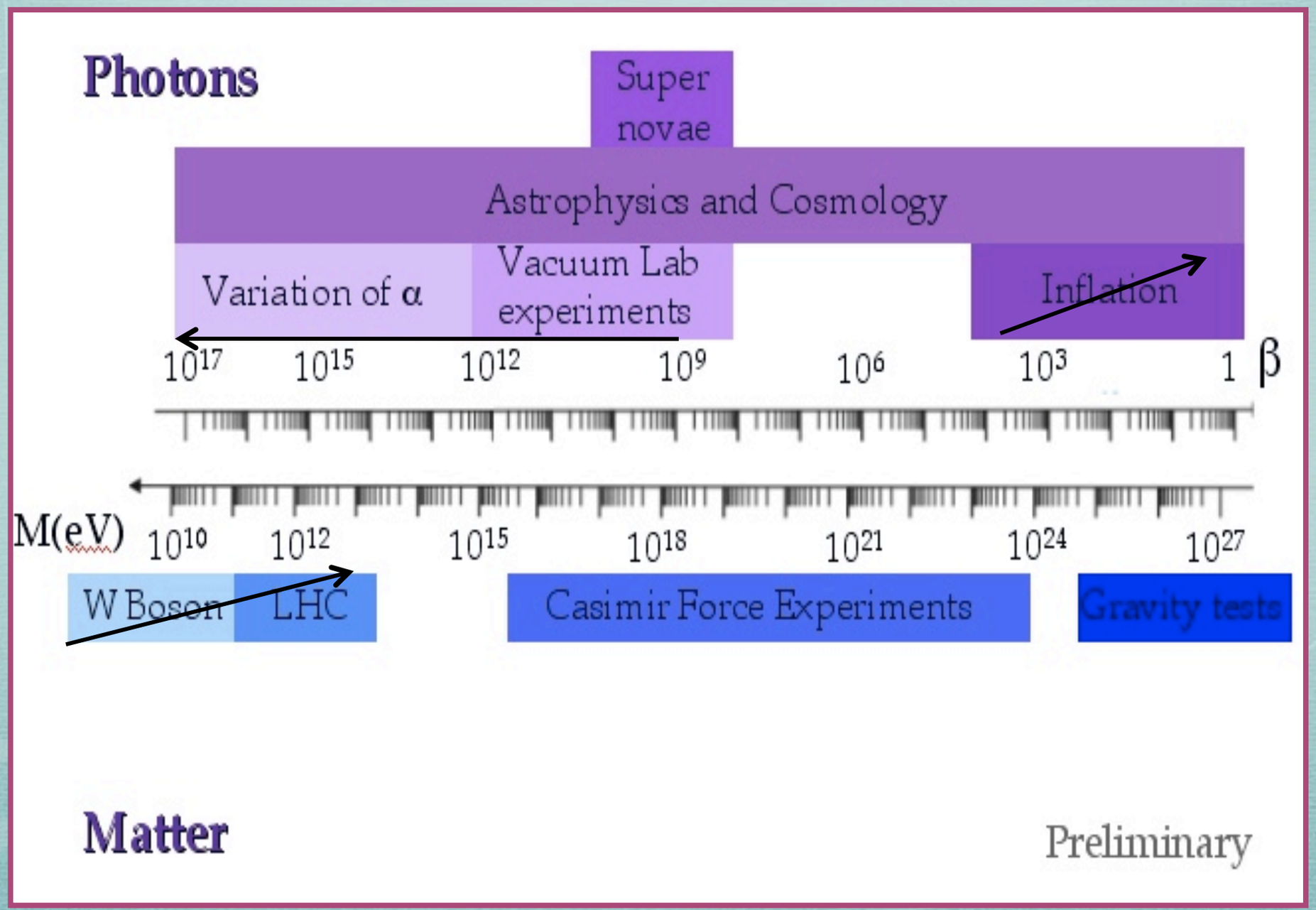
- **Supernova Brightening from Chameleon-Photon Mixing. C. Burrage**
  Effect: photon to chameleon conversion in SN + chameleon-photon mixing in the intergalactic magnetic field
  Result : supernovae brightening + fits observations of std candles and std rulers

- **Detecting Chameleons: The Astronomical Polarization Produced by Chameleon-like Scalar Fields. C. Burrage et. al.**
  Effect : linear and circular polarization
  Result : "a tentative statistical detection of a chameleon-like scalar field from observations of starlight polarization in our galaxy."

- **Active Galactic Nuclei shed light on Axion-like-Particles. C. Burrage et. al.**
  Effect: scatter in luminosity relations of astro objects
  Result : ''we find evidence strongly suggestive of the existence of a very light ALP''

Can also study other objects and systems eg. pulsars, the CMB etc.

...and with Astronomy

- **Searching for chameleon-like scalar fields with the ammonia method. S.A. Levshakov et. al.**
  Goal: probe the dependence of $\mu = \frac{m_e}{m_p}$ on ambient matter density using radio astronomical observations
  $$\frac{\Delta\mu}{\mu} = 2.2 \times 10^{-8}$$
- **Searching for spatial variations of alpha^2/mu in the Milky Way. S.A. Levshakov et. al.**
  $$\frac{\Delta\alpha}{\alpha} < 2 \times 10^{-7}$$
- **Equivalence Principle Implications of Modified Gravity Models. L.Hui *et. al.***
  Claims : Small galaxies should accelerate faster than large galaxies.
  Voids defined by small galaxies would appear larger compared to expectations.
  Lensing and dynamical mass estimates should agree for large galaxies but disagree for small ones.
  Stars and diffuse gas in small galaxies should have different velocities, even if they are on the same orbits - effect could be 30% or more - best to look in voids.

Parameter Space Estimates