Hunting for Chameleons

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Plan

- Motivation - Theoretical + Observational
- Chameleon idea and thin shell effect
- Predictions for tests in space
- Dark Energy Candidate
- Laboratory tests — See A. Chou talk next
- Exploring parameter space — In Progress

Unique chameleon features require rethinking axion bounds and experiments.

Motivation

- Massless scalar fields are abundant in String and SUGRA theories
- Massless fields generally couple directly to matter with gravitational strength

    - Unacceptably large Equivalence Principle violations
    - Coupling constants can vary
    - Masses of elementary particles can vary

Light scalar field + Gravitational strength coupling

$\Rightarrow$ Opportunity! - Connect to Cosmology

Solutions?

1. Suppress the coupling strength :

- String loop effects Damour & Polyakov

- Approximate global symmetry Carroll

2. Field acquires mass due to some mechanism :

- Invoke a potential

    - Chameleon Mechanism Khoury & A.W
    - Flux Compactification KKLT
    - Special points in moduli space - new d.o.f become light Greene, Judes, Levin, Watson & A.W

Observations

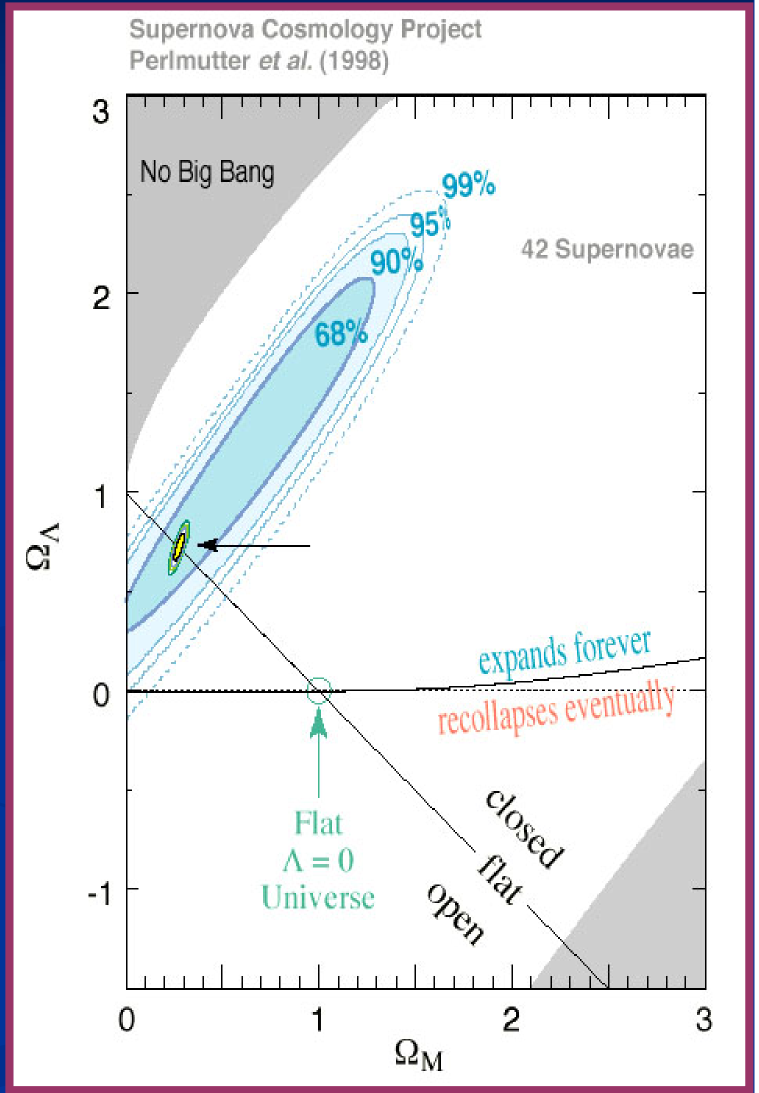
Accelerated expansion of the Universe

$$\frac{\ddot{a}}{a} = -(\rho + 3p)$$

- Dark Energy $p < 0$
- Cosmological Constant, Λ
- Dynamical e.o.s $w \neq -1$

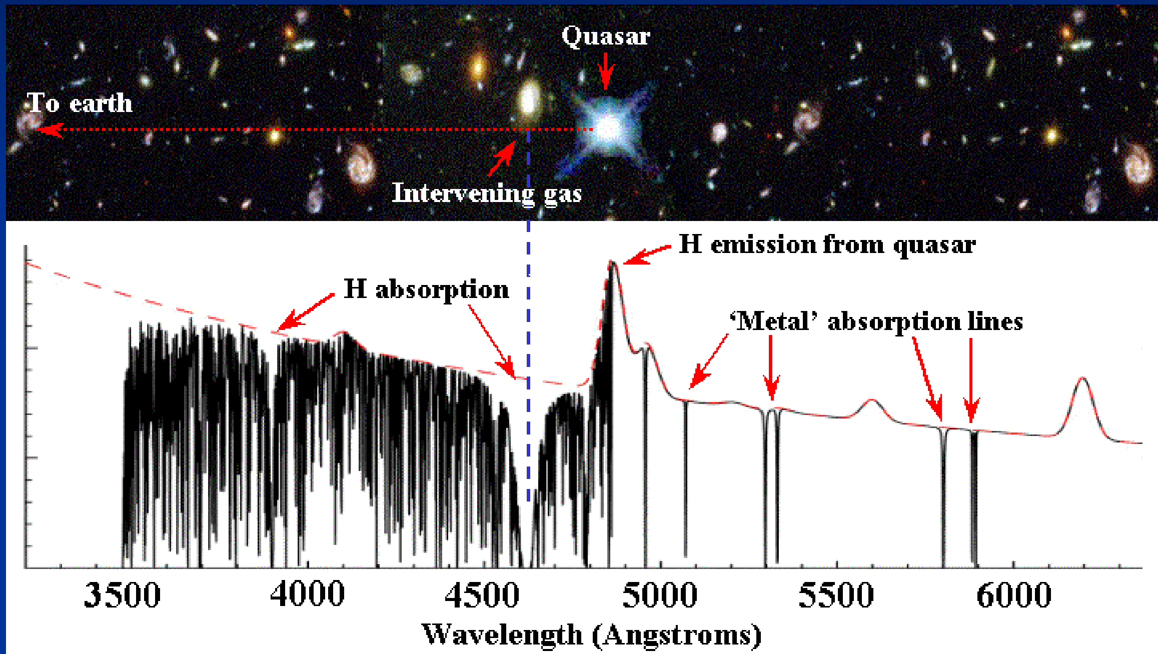
Quintessence $\rightarrow$ Need **light scalar field**

$$m_\phi < H_0 \approx 10^{-33}\mathrm{eV}$$



More Observations

Webb et. Al.



- Absorption lines in QSO spectra imply variation in fine structure constant $\Delta\alpha \sim 10^{-5}$

- Observations suggest existence of scalar fields evolving on cosmological time scales $0.2 < z < 3.7$

Chameleon Effect

astro-ph/0309300 PRL J. Khoury and A.W
astro-ph/0309411 PRD J. Khoury and A.W

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 may be a candidate for acc of universe

Approach

Scalar fields can have cosmological effects but **DO NOT** result in EP violations in lab as we live in dense environment

Use EP tests done on earth to **constrain** the parameters of the model (These give largest constraints)

Use these constraints to make **crucial predictions** for tests in **space** and in the **lab**

Could this field have **cosmological effects**?

Ingredients

astro-ph/0408415 PRD P. Brax, C. van de Bruck, J.Khoury, A. Davis and A.W

Reduced Planck Mass

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

Coupling to photons

Matter Fields

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

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

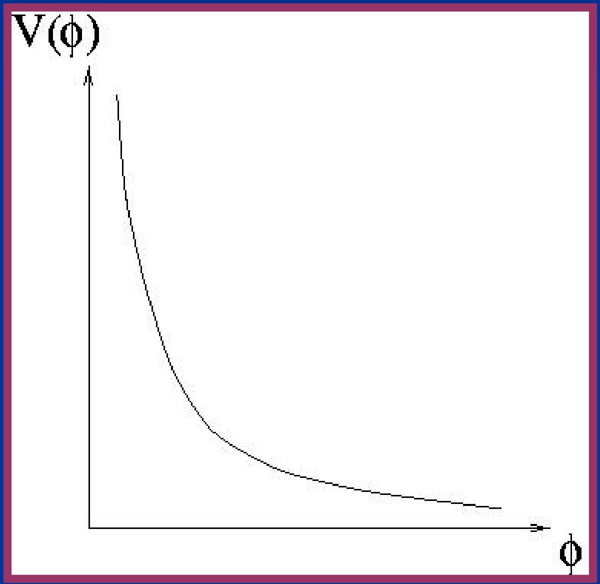
Einstein Frame Metric

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

Conformally Coupled

Potential is of the runaway form

Runaway Potential



$$\lim_{\phi\to\infty} V = 0\,, \qquad \lim_{\phi\to\infty} \frac{V_{,\phi}}{V} = 0\,, \qquad \lim_{\phi\to\infty} \frac{V_{,\phi\phi}}{V_{,\phi}} = 0 \ldots$$

$$\lim_{\phi\to 0} V = \infty\,, \qquad \lim_{\phi\to 0} \frac{V_{,\phi}}{V} = \infty\,, \qquad \lim_{\phi\to 0} \frac{V_{,\phi\phi}}{V_{,\phi}} = \infty \ldots$$

e.g. $V(\phi) = M^{4+n}\phi^{-n}$ $\quad V(\phi) = M^4 exp(\frac{M^n}{\phi^n})$

Effective Potential

Energy density in the i^{th} form of matter

Equation of motion :

$$\nabla^2\phi = V_{,\phi} + \sum_i \frac{\beta_i}{M_{Pl}} \rho_i e^{\beta_i \phi / M_{Pl}}$$

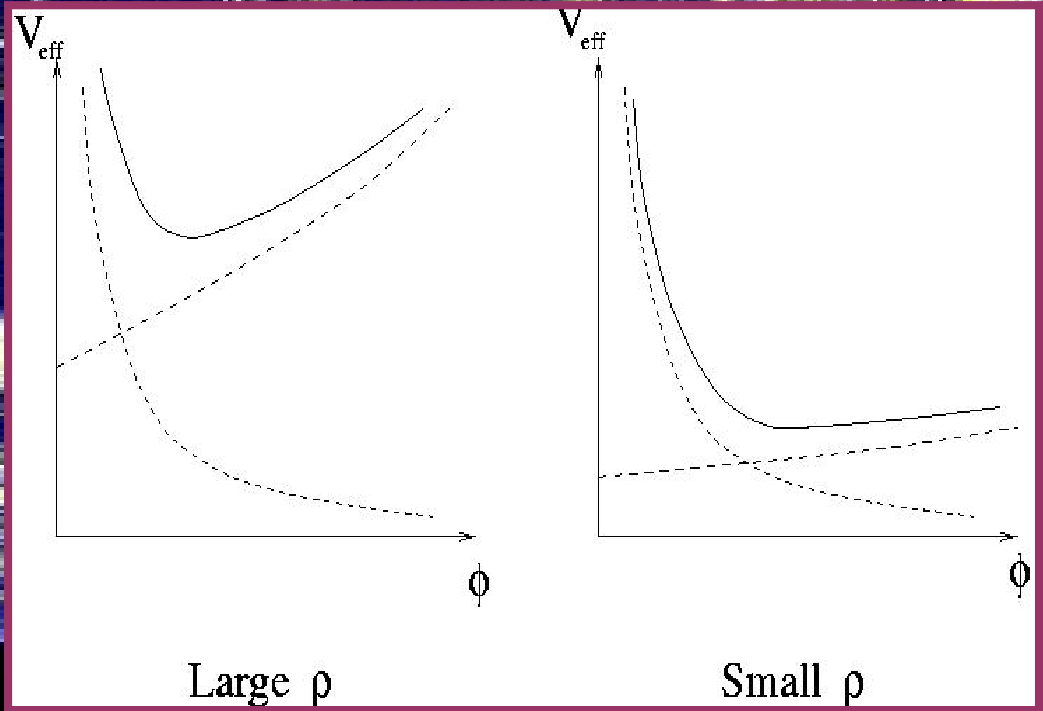
Dynamics governed by Effective potential :

$$V_{eff}(\phi) \equiv V(\phi) + \sum_i \rho_i e^{\beta_i \phi / M_{Pl}}$$

$R_E = 6 \times 10^{18} cm$

$\rho_E = 10 \mathrm{g.cm}^{-3}$

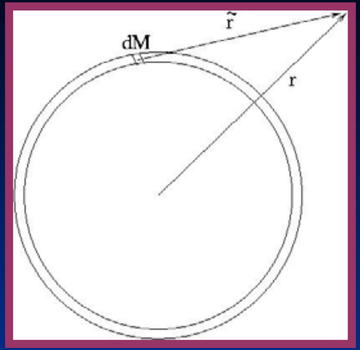
$\phi_C \ll \phi_\infty$



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

$m_C \gg m_\infty$

Exterior Solution



Thin Shell

$$\phi(r) \approx -\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_c}{R_c}\right)\frac{M_c e^{-m_\infty r}}{r} + \phi_\infty \qquad \text{if} \quad \frac{\Delta R_c}{R_c} \ll 1\,,$$

No Thin Shell

$$\phi(r) \approx -\left(\frac{\beta}{4\pi M_{Pl}}\right)\frac{M_c e^{-m_\infty r}}{r} + \phi_\infty \qquad \text{if} \quad \frac{\Delta R_c}{R_c} > 1\,;$$

$$\frac{\Delta R_C}{R_C} = \frac{\phi_\infty - \phi_C}{6\beta M_{Pl}\Phi_C}$$

Newtonian Potential

$$\frac{\Delta R_C}{R_C} \ll 1$$

Object displays thin shell effect

Thin shell $\Rightarrow$

$$\beta_{\rm eff} = 3\frac{\Delta R_C}{R_C}\beta$$

Fifth Force

5th Force: $\vec{F}_\phi = -\frac{\beta}{M_{Pl}} M \vec{\nabla}\phi$

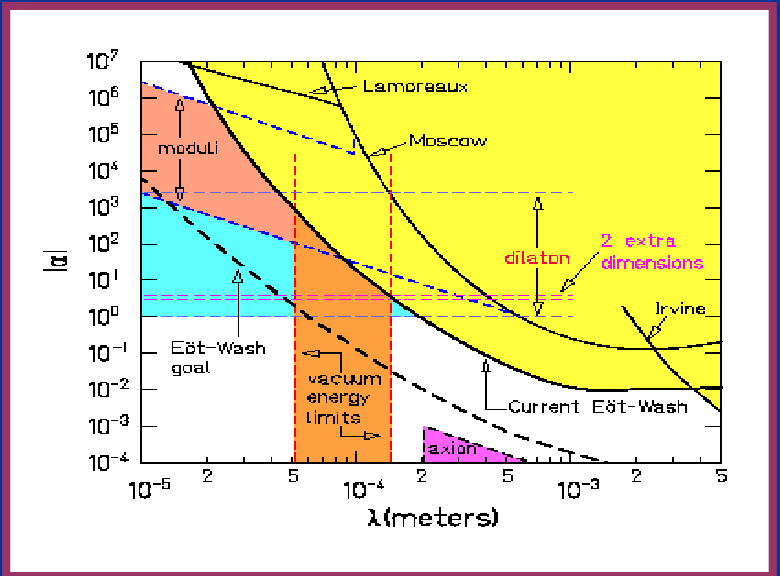
Range of interaction

Potential : $U(r) = -2\beta_1\beta_2 \frac{M_1 M_2}{8\pi M_{\rm Pl}^2} \frac{e^{-r/\lambda}}{r}$

Separation

Strength of interaction, α

Hoskins et. Al. → $\alpha < 10^{-3}$



Require both earth and atmosphere display thin shell effect

→ $\frac{\Delta R_E}{R_E} < 10^{-7}$

Constraints on Model Parameters

$$\frac{\Delta R_E}{R_E} < 10^{-7}$$

+

$$V(\phi) = M^{4+n}\phi^{-n}$$

→

$$M \leq 10^{-3}eV \approx (1mm)^{-1}$$

Coincides with Energy scale of Dark Energy

$$m_{atm}^{-1} \leq 1mm$$

$$m_G^{-1} \leq 10^4 AU$$

$$m_0^{-1} \leq 10^3 pc$$

→

$$m_{atm} \geq 10^{-3}eV$$

$$m_G \geq 10^{-21}eV$$

$$m_0 \geq 10^{-23}eV$$

Predictions for Tests in Space

New Feature !! → Different behaviour in space

Tests for UFF $\eta \equiv 2\frac{|a_1 - a_2|}{a_1 + a_2}$ 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 → $\beta^2 \cdot 10^{-19} < \eta < \beta^2 \cdot 10^{-11}$

SEE Capsule $|\vec{F}| = \frac{GM_1M_2}{r^2}(1 + 2\beta_1\beta_2)$ $10^{-15} < \Delta R_E/R_E < 10^{-7}$

Corrections of O(1) to Newton's Constant

Cosmological Evolution

astro-ph/0408415 PRD P. Brax, C. van de Bruck, J.Khoury, A. Davis and A.W

What do we need?

$$V(\phi) = M^4 exp(\frac{M^n}{\phi^n})$$

- attractor solution

→ If field starts at min, will follow the min

- ϕ must join attractor before current epoch

- ϕ Slow rolls along the attractor

- Variation in m $\rightarrow$ is constrained to be less than ~ 10%. Constrains ϕ_{BBN} $\rightarrow$ the initial energy density of the field.

→ $$\Omega_\phi^i < \frac{1}{6}$$

Weaker bound than usual quintessence → $$\Omega_\phi^i < \frac{1}{100}$$

Strong Coupling

Strong coupling not ruled out by local experiments! Mota and Shaw

Thin shell suppression $\Rightarrow$ $\beta_{\rm eff} = 3\frac{\Delta R_C}{R_C}\beta$

Remember : $\frac{\Delta R_C}{R_C} = \frac{\phi_\infty - \phi_C}{6\beta M_{Pl}\Phi_C}$

$\Rightarrow$ Effective coupling is independent of β!!

If an object satisfies thin shell condition - the ϕ force is **β independent**

Lab experiments are compatible with large β - **strong coupling!**

$\beta >> 1$ $\Rightarrow$ more likely to satisfy thin shell condition

$\Rightarrow$ Thin shell possible in space $\Rightarrow$ suppress signal

Strong coupling is not ideal for space tests - loophole

Pause…Reflect

What have we achieved so far?

- **No EP violations** on earth : agrees with gravity experiments
- Exciting **cosmological consequences** : chameleon could be causing current **accelerated expansion**
- Made **predictions** for experiments in space

BUT

- Large coupling creates a **loophole** for space tests

Opportunity?

Lab tests on earth can probe a range of parameter space that is **complementary** to space tests.

Coupling to Photons

Remember :

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

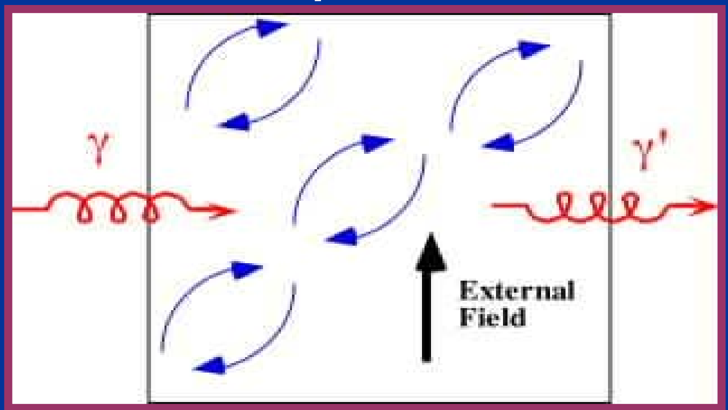
Introduces a new mass scale : $\frac{1}{M_\gamma} = \frac{\beta_\gamma}{M_{\rm Pl}}$

Effective potential :

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

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

We can probe this term in quantum vacuum experiments



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

→ Test the F^2 term

Afterglow Experiments

GammeV

“ [Photon]-[dilaton-like chameleon particle] regeneration using a "particle trapped in a jar" technique “

http://gammev.fnal.gov

A. Chou *et. Al.* 0806.2438 [hep-ex]

See also - Gies *et. Al.* + Ahlers *et. Al. (DESY)*

Alps at DESY, LIPSS at JLab, OSQAR at CERN, BMV

Idea :

- Send a laser through a magnetic field
- Photons turn into chameleons via F^2 coupling
- Turn of the laser
- Chameleons turn back into photons
- Observe the afterglow

Failing which - rule out chunks of parameter space!

GammeV

http://gammev.fnal.gov

Nd:YAG laser at 532nm, 5ns wide pulses, power 160mJ, rep rate 20Hz

Tevatron dipole magnet at 5T

Glass window

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

PMT with single photon sensitivity

Schematic

A. Uphadye

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 $m_{\text{wall}} >> m_{\text{jar}}$

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

Recasting CAST

Essential difference between the sun and a lab vacuum?

$$\rho_{\rm sun} \sim 10^{14} \rho_{\rm lab}$$

$+$

$$\frac{m_{\rm sun}}{m_{\rm lab}} \sim \left(\frac{\rho_{\rm sun}}{\rho_{\rm lab}}\right)^{\frac{n+2}{2(n+1)}}$$

→

- Far heavier
- Harder to produce

To explain PVLAS requires $m_\phi \sim \mathrm{meV}$ & $M \sim 10^6 \mathrm{GeV}$

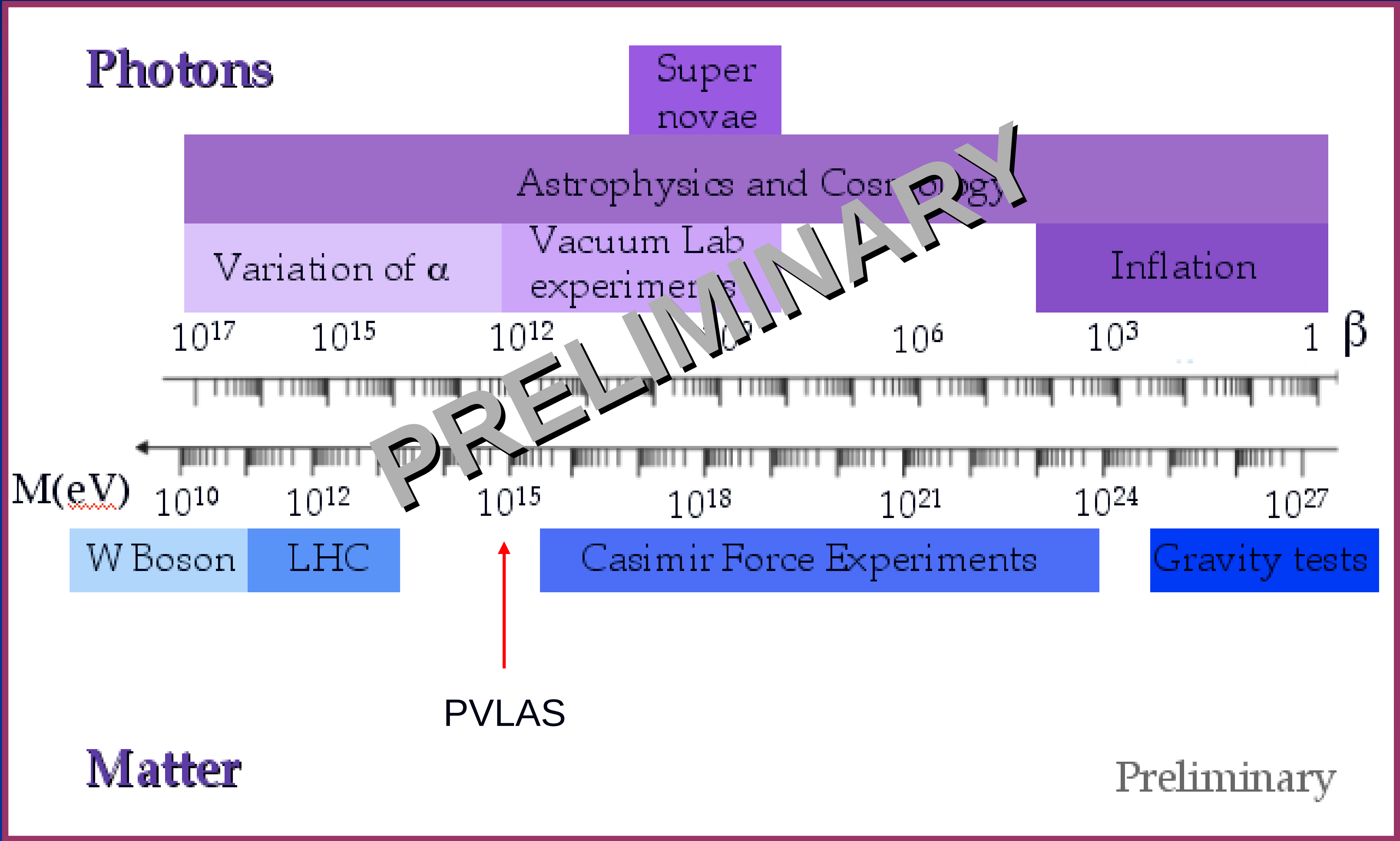
Conflicts with CAST: $m_\phi \sim \mathrm{meV}$ $\Rightarrow$ $M > 10^{10} \mathrm{GeV}$

Lab meV chameleons in the sun : $m_{\rm sun} \sim 10^{-2} \mathrm{GeV}$

Chameleons - naturally evade CAST bounds and can explain PVLAS

Brax, Davis, van de Bruck

Parameter Space Estimates



Conclusions/Outlook

- **Chameleon fields**: Concrete, testable predictions
- **Space** tests of gravity
- **Lab** tests can probe a range of parameter space that is **complementary** to space tests (qm vacuum and casimir)
- Intriguing **cosmological consequences** : chameleon could be causing current **accelerated expansion**
- New bounds from **Astrophysics** and **Cosmology**

Complementary tools of probing fundamental physics