

Illuminating the Dark Sector

Jason H. Steffen

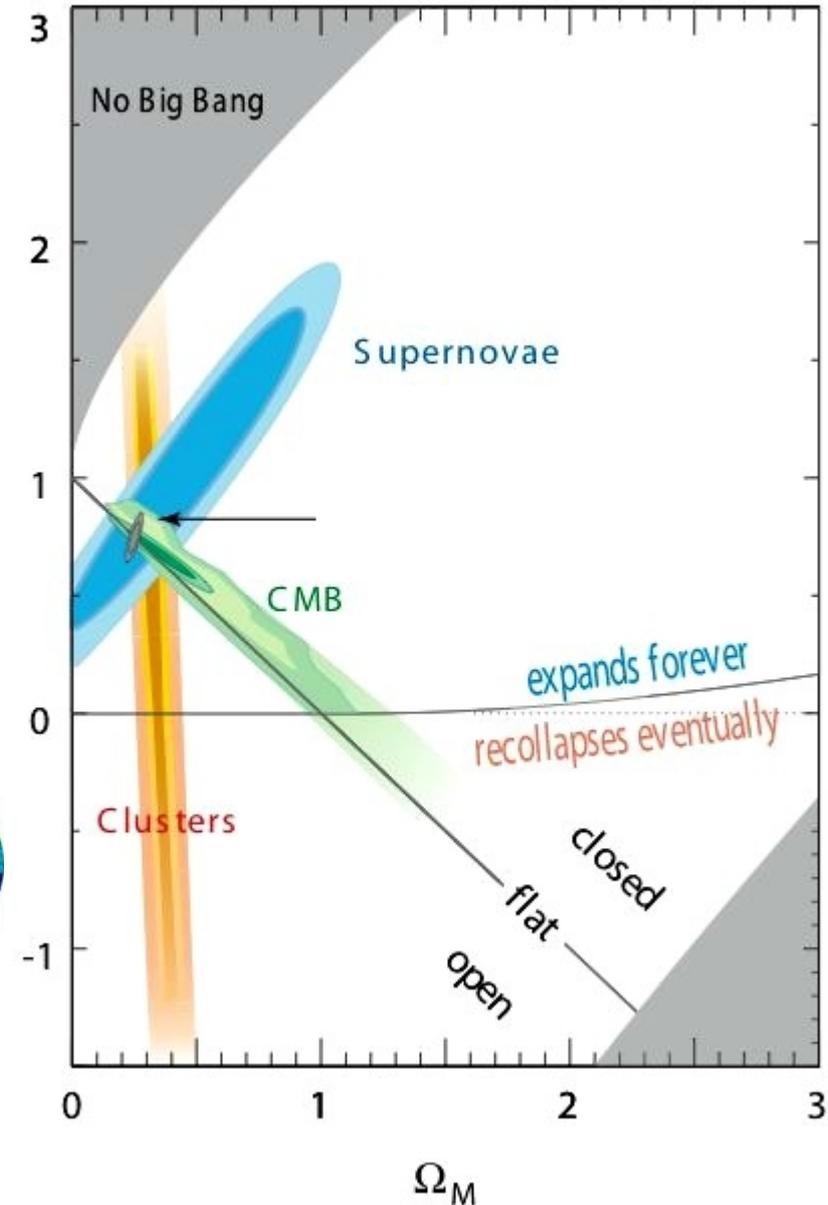
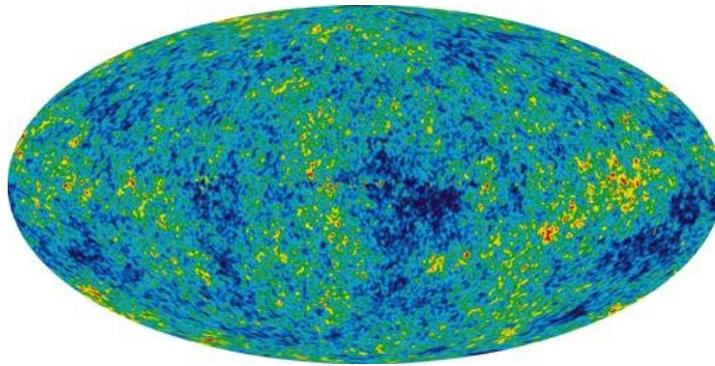
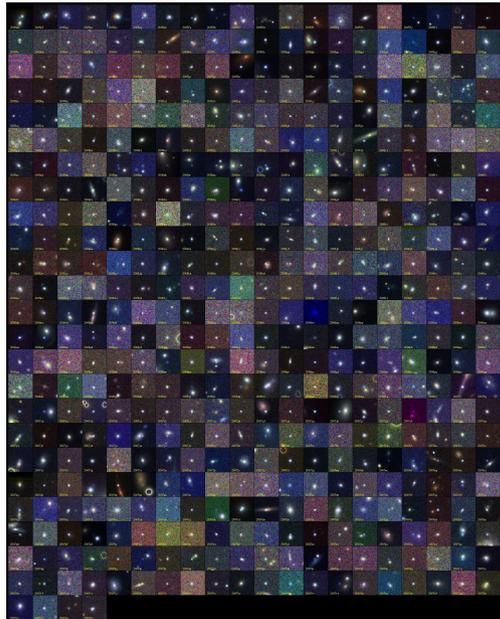
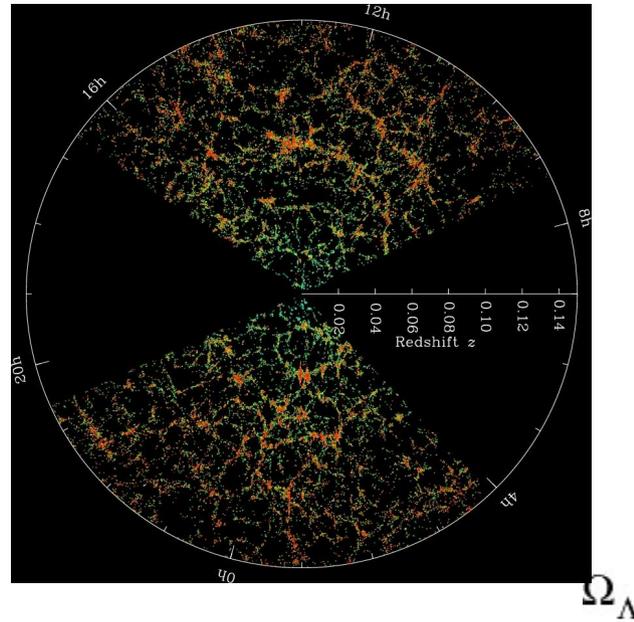
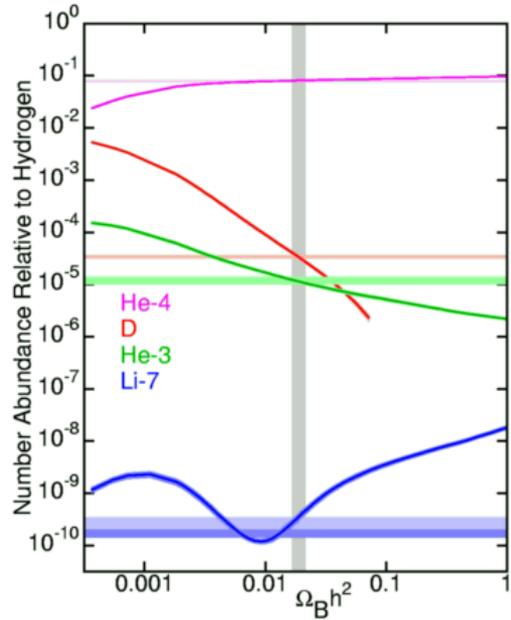
Fermilab Center for Particle Astrophysics

Fermilab

November 23, 2011

The Dark Sector

dark matter, dark energy, gravity



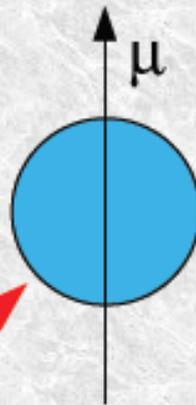
Axions, the other dark matter

The QCD Lagrangian has this

$$\mathcal{L} = -\frac{1}{4}\text{tr} F_{\mu\nu} F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2} \text{tr} F_{\mu\nu} \tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m e^{i\theta' \gamma_5})\psi$$

which should be of order unity.

This would give the neutron
an electric dipole moment.



Measurements indicate that
 θ must be less than $\sim 10^{-10}$.

This discrepancy is known as the “strong CP problem”.

Axions, the other dark matter

Peccei-Quinn ('77), Wilczek ('78), Weinberg ('78) proposed a solution:



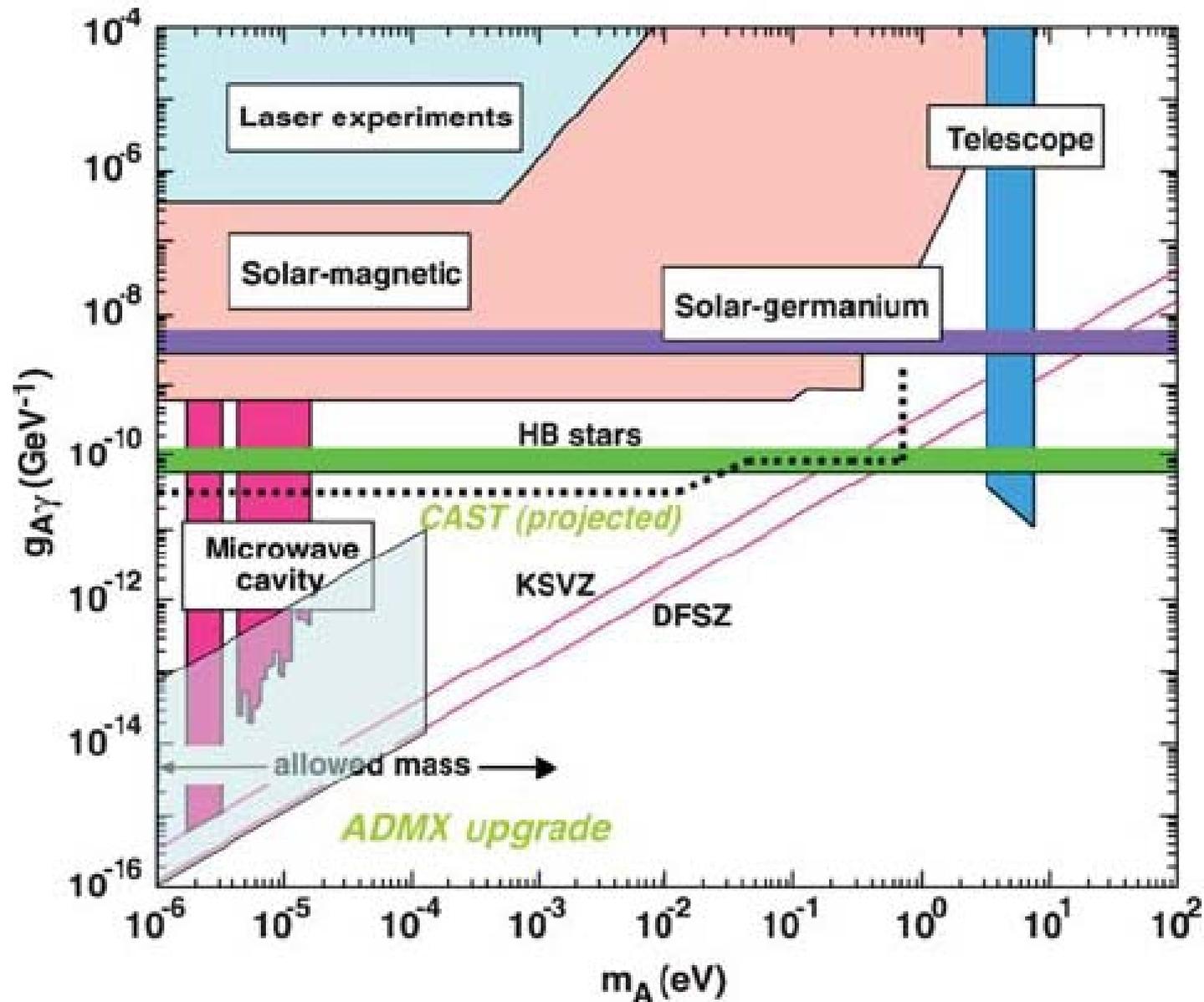
$$\mathcal{L}_{\text{int}} = -\frac{1}{4} \frac{\phi}{M} F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{\phi}{M} (\vec{E} \cdot \vec{B})$$

Pseudoscalar coupling to two photons.

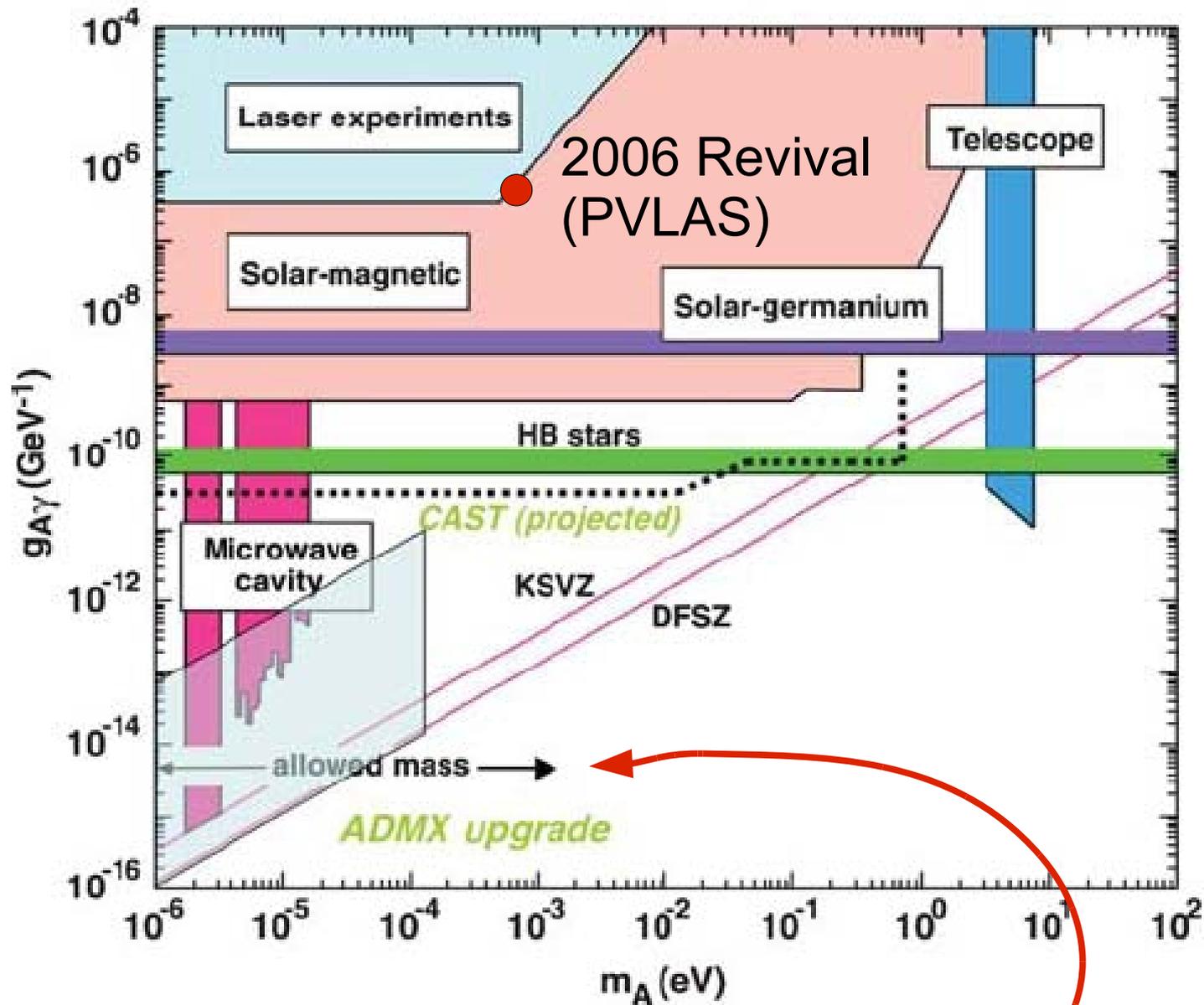
The coupling constant and mass depend upon the mass and coupling constant of the pion.
($f_a m_a = f_\pi m_\pi$)

String theories also predict a variety of scalar or pseudoscalar axion-like particles.

Axions, the other dark matter

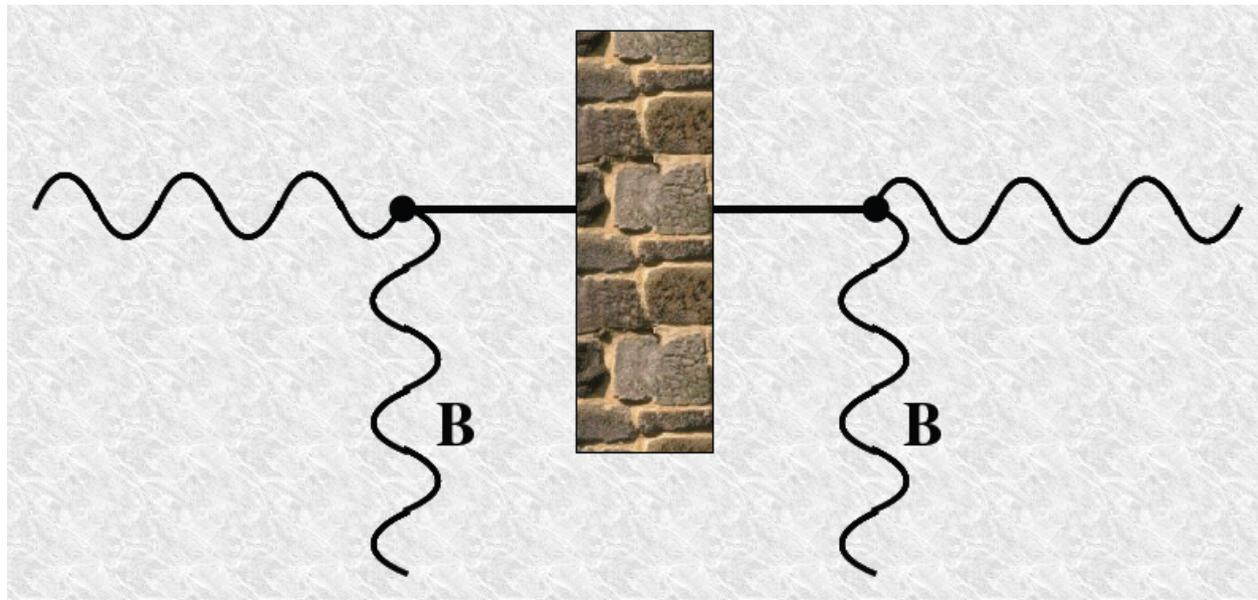
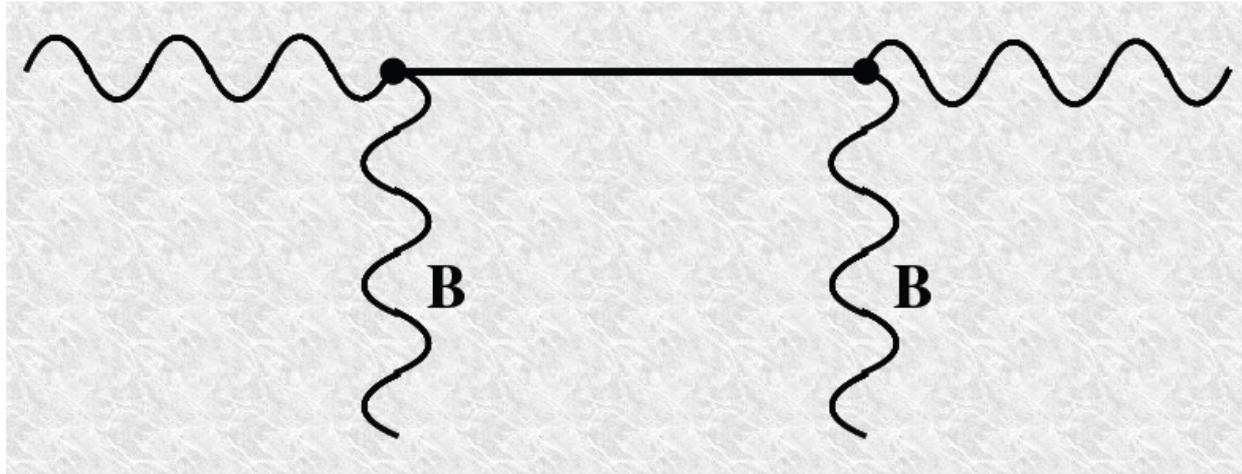


Axions, the other dark matter

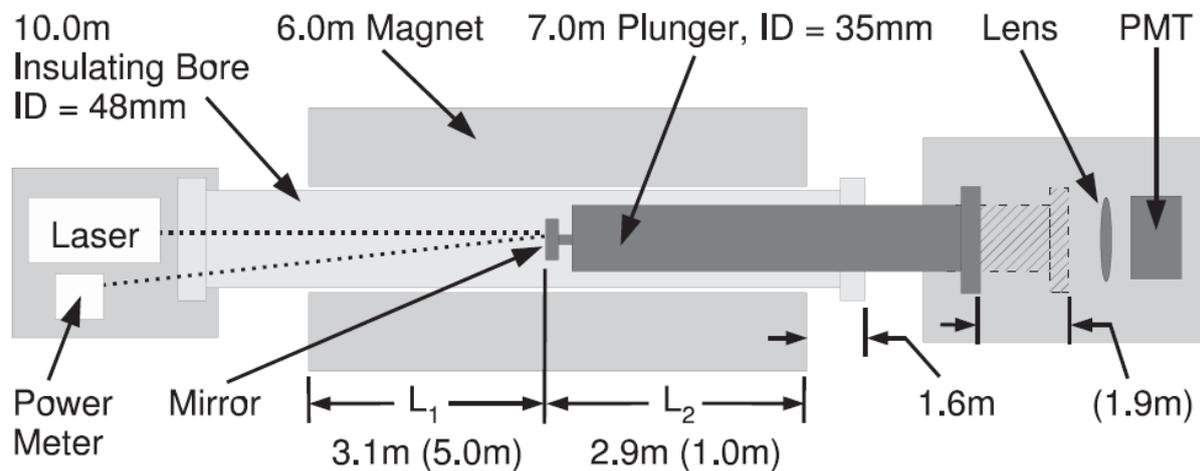
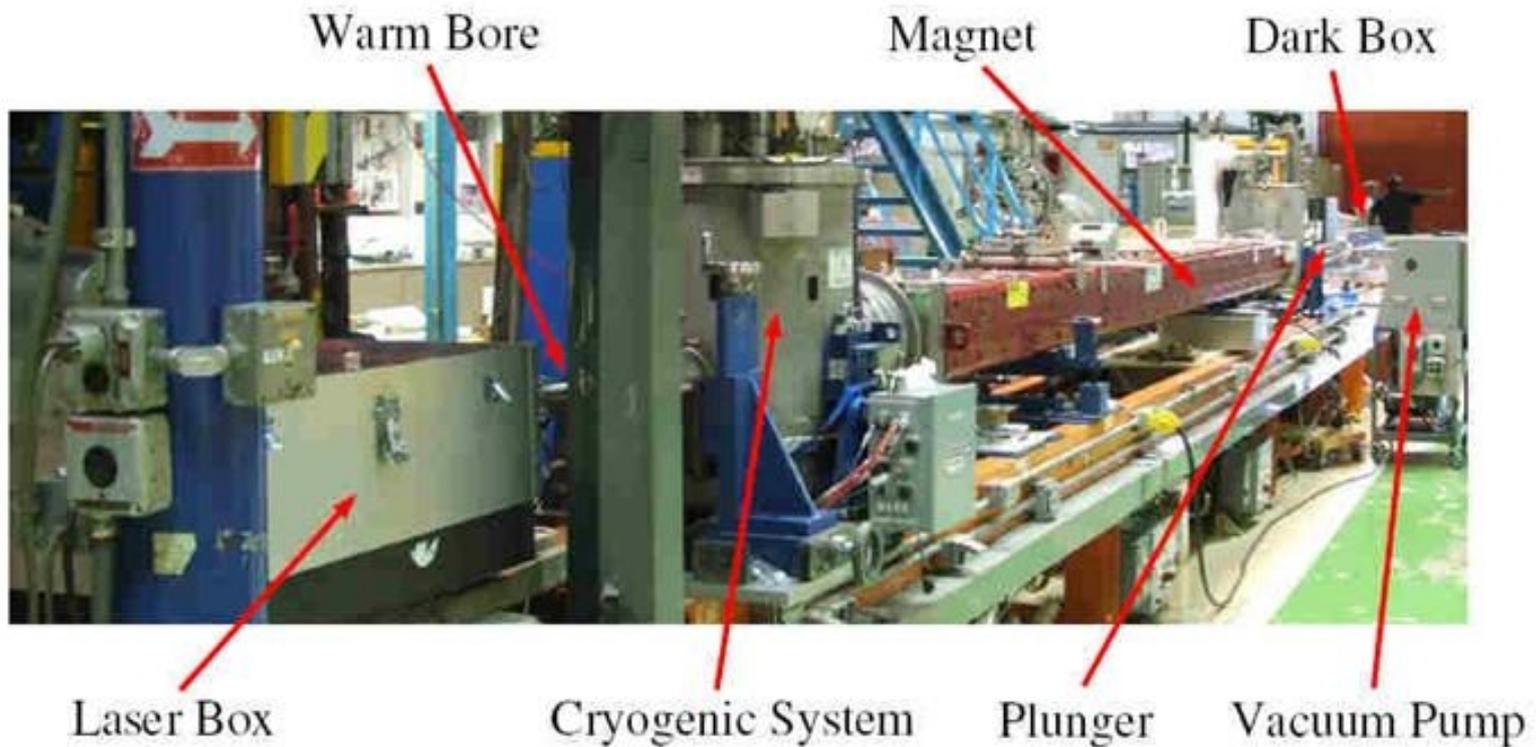


If axions are the dark matter, they would live here.

Laser searches for axion-like particles

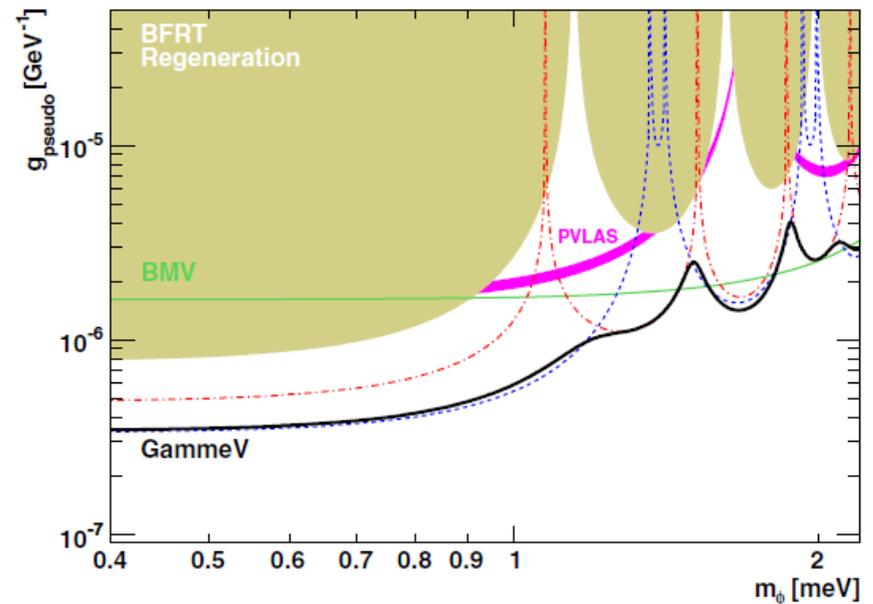
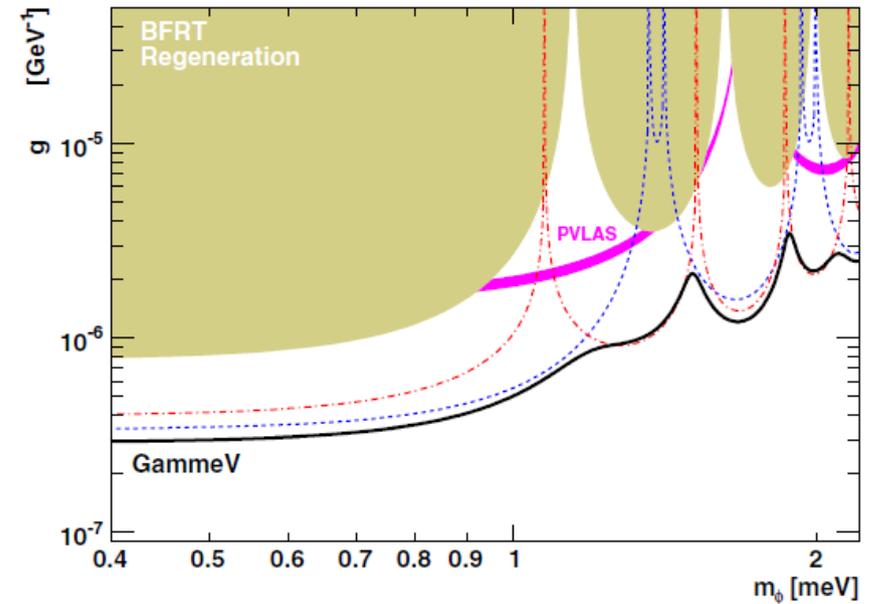
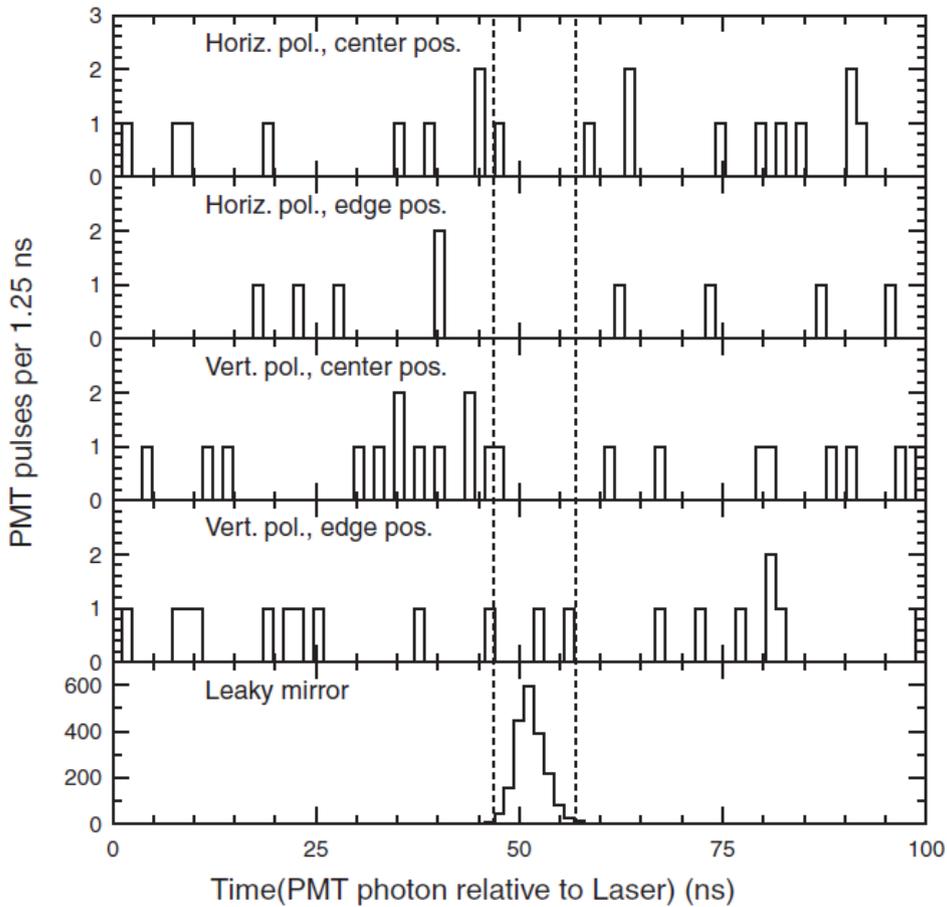


GammeV search for axion-like particles



GammeV search for axion-like particles

PRL 100, 080402 (2008)



Numerology

Dark Energy: $\Lambda = (2 \text{ meV})^4$

Neutrino Masses: $(\Delta m_{21})^2 = (9 \text{ meV})^2$
 $(\Delta m_{32})^2 = (50 \text{ meV})^2$

Weak Scale See Saw: $\text{meV} \sim \text{TeV}^2 / M_{\text{Planck}}$

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Optical Photons

Dark Energy

Situation somewhat similar to axions.

The vacuum should have some energy density,

$$E_{\text{ground}} = \frac{1}{2} \hbar \omega \quad \text{for each "smallest" box.}$$

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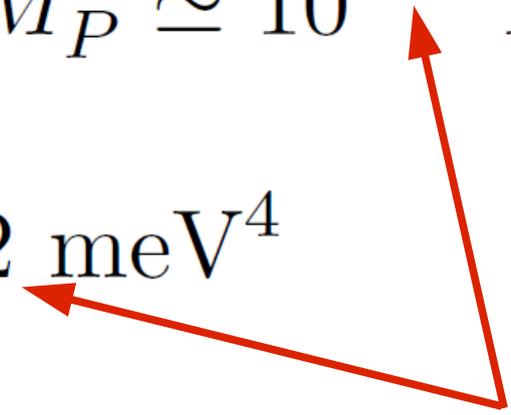
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Slight discrepancy

Dark Energy

Situation somewhat similar to axions.

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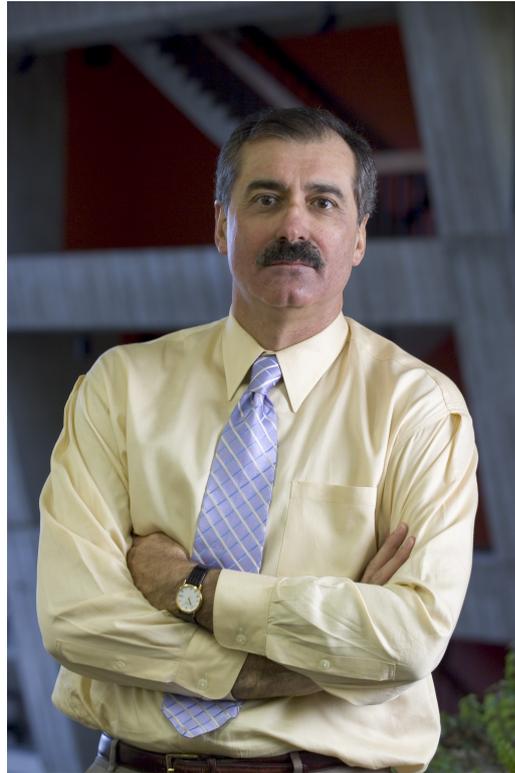
$$\Lambda_{\text{experiment}} = 2 \text{ meV}^4$$

Invoke the tooth fairy to force vacuum contribution to zero and add a new particle that will supply the measured energy density.

Physicists Toolkit

Experimentalist

Theorist



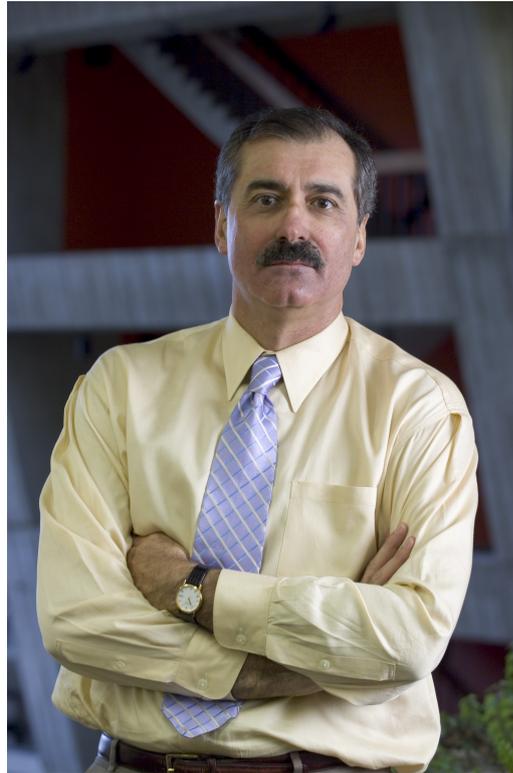
Physicists Toolkit

Experimentalist



If something should
move but it doesn't...

Theorist



Physicists Toolkit

Experimentalist

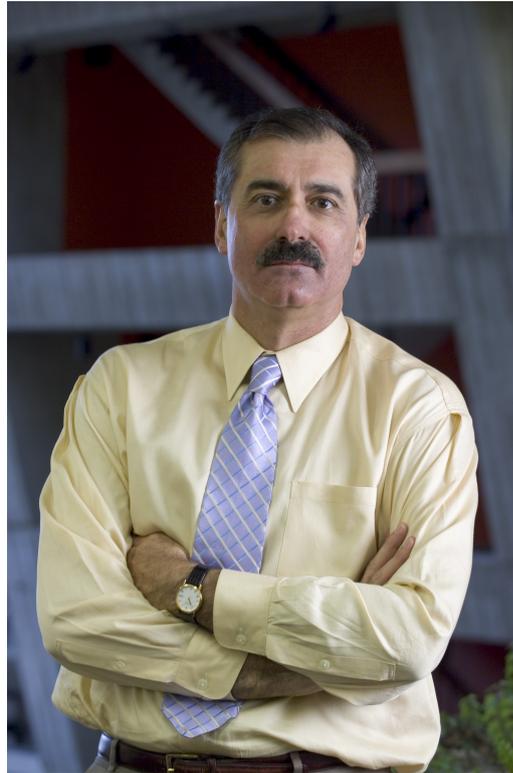


If something should move but it doesn't...



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Physicists Toolkit

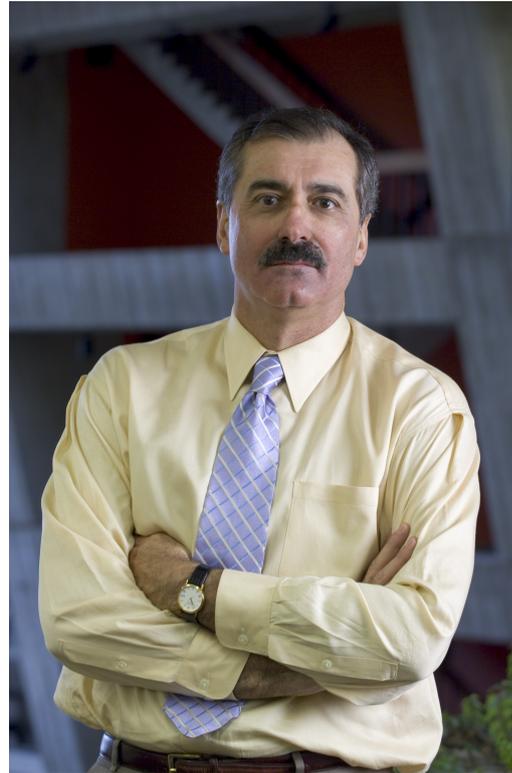
Experimentalist



If something should move but it doesn't...



If something moves but it shouldn't...



Theorist

*Sum, ergo
ita est.*

(anthropic principle)
If something moves
but it shouldn't...

Physicists Toolkit

Experimentalist



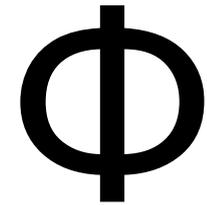
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If something moves but it shouldn't...

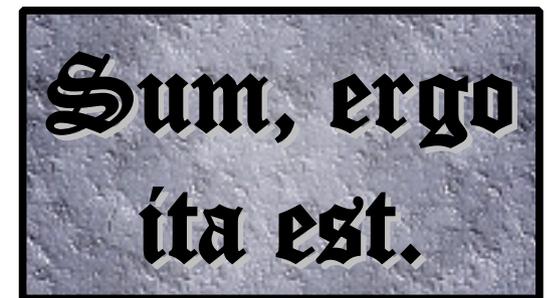


Theorist



(scalar field)

If something should move but it doesn't...



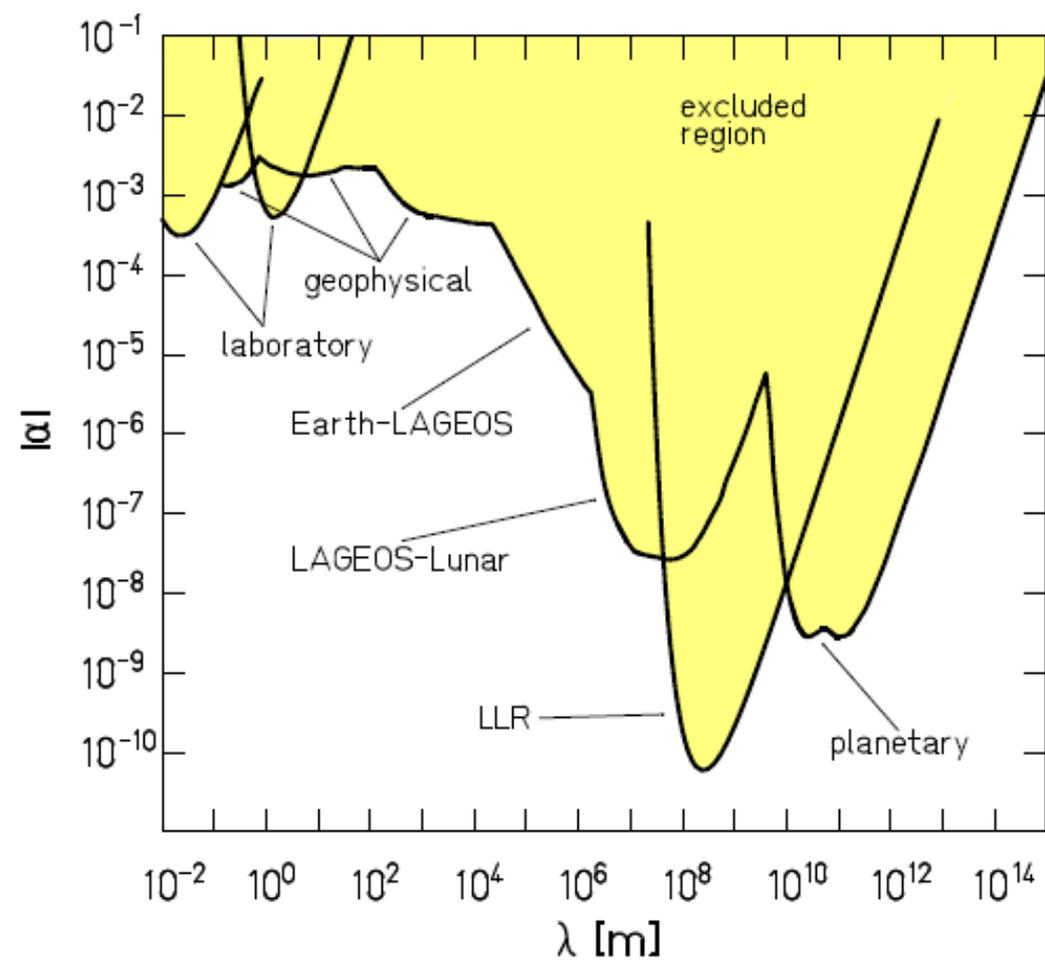
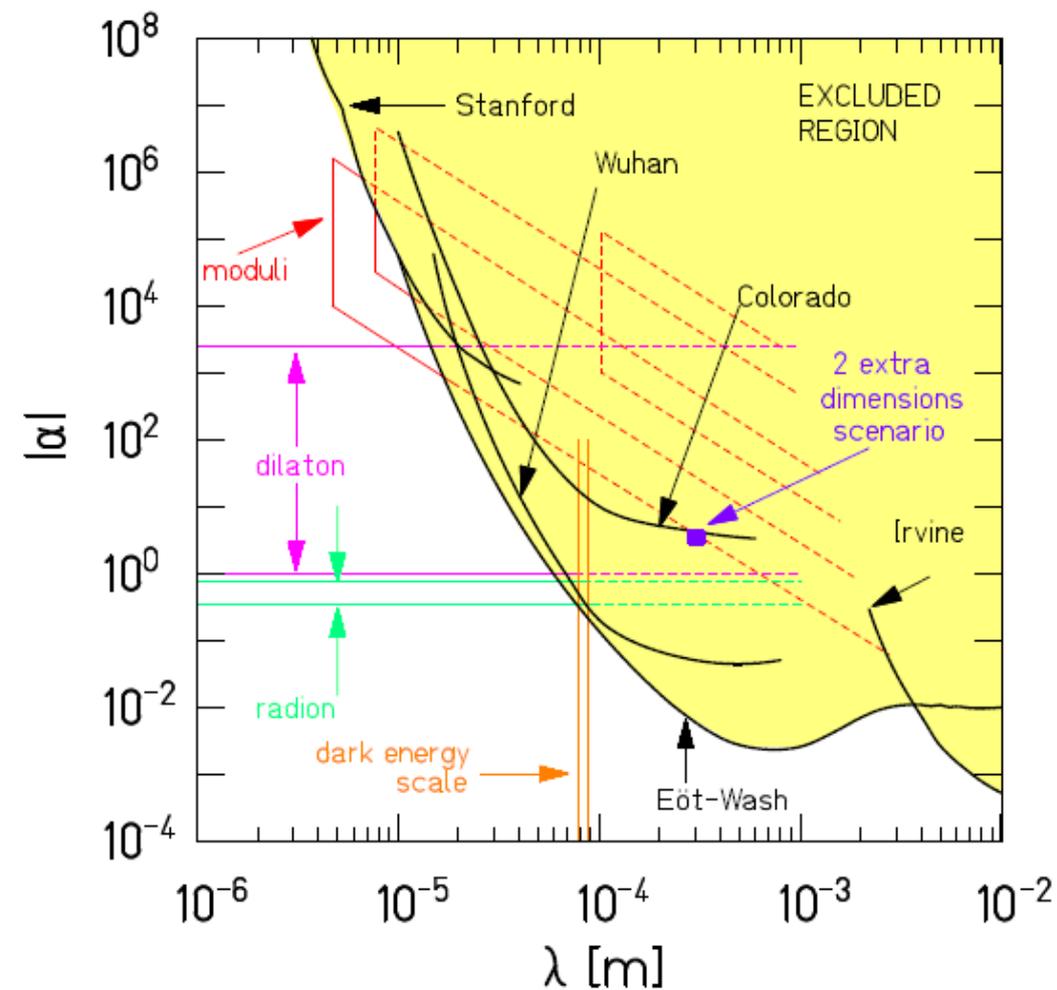
(anthropic principle)

If something moves but it shouldn't...

Experimental Evidence for Scalar Fields

Experimental Evidence for Scalar Fields

$$V = -\frac{GM}{r} \left(1 + \alpha \frac{e^{-r/\lambda}}{r} \right)$$



How do you hide a scalar field?

$$\nabla^2 \phi + m^2 \phi = \frac{g}{M_{\text{Pl}}} \rho$$

$$K(\rho) \nabla^2 \phi + m^2 \phi = \frac{g}{M_{\text{Pl}}} \rho$$

Vainshtein

$$\nabla^2 \phi + m^2 \phi = \frac{g(\rho)}{M_{\text{Pl}}} \rho$$

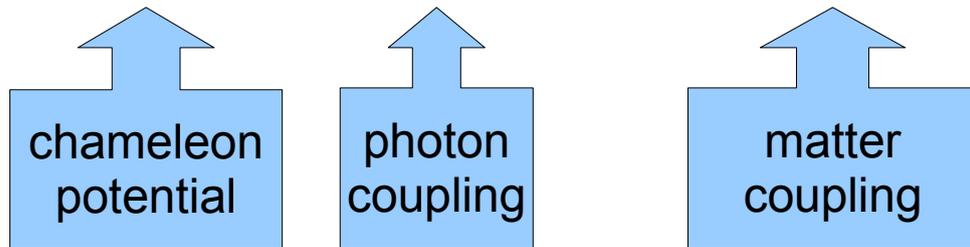
symmetron

$$\nabla^2 \phi + M^2(\rho) \phi = \frac{g}{M_{\text{Pl}}} \rho$$

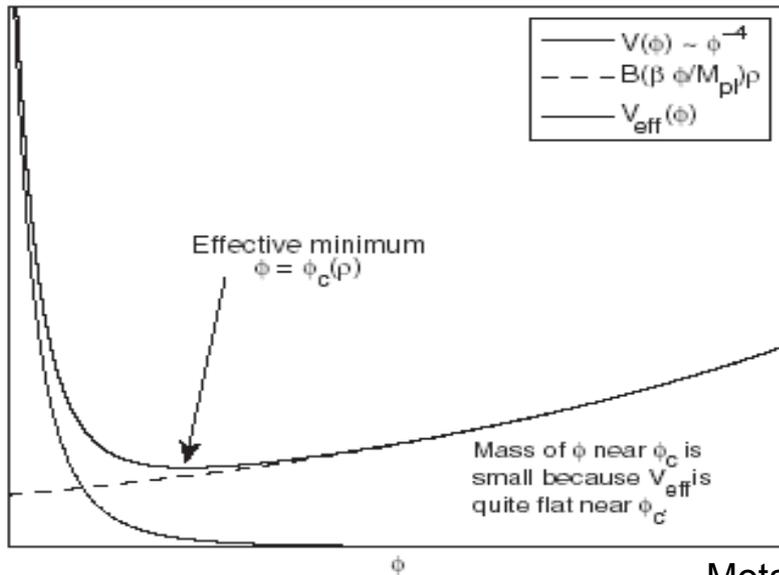
chameleon

The Chameleon Effect

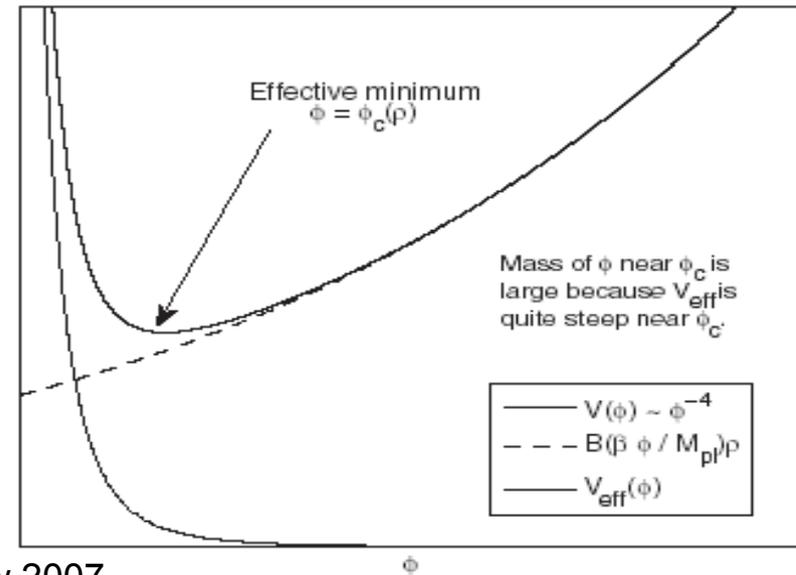
$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{1}{4} e^{\frac{\beta_\gamma \phi}{M_{\text{Pl}}}} F_{\mu\nu} F^{\mu\nu} + \mathcal{L}_m \left(e^{\frac{2\beta_m \phi}{M_{\text{Pl}}}} g_{\mu\nu}, \psi_m^{(i)} \right) \right]$$



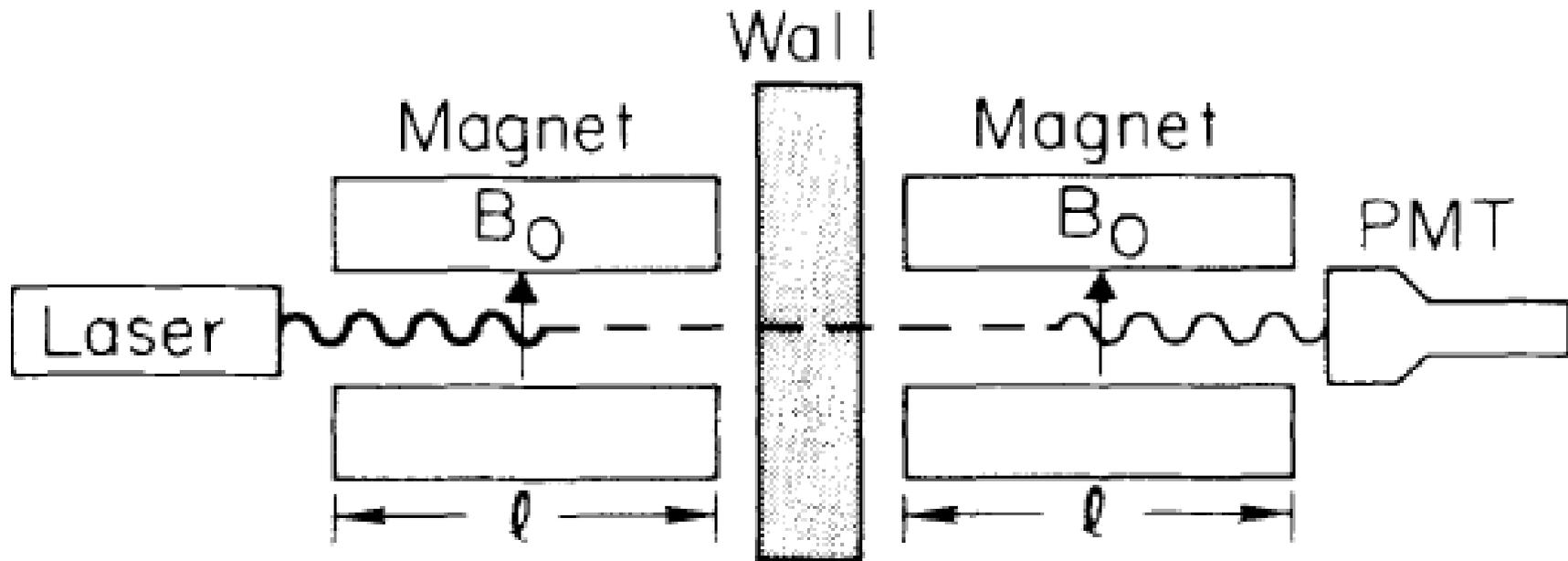
Sketch of chameleon mechanism: Low Density Background



Sketch of chameleon mechanism: High Density Background

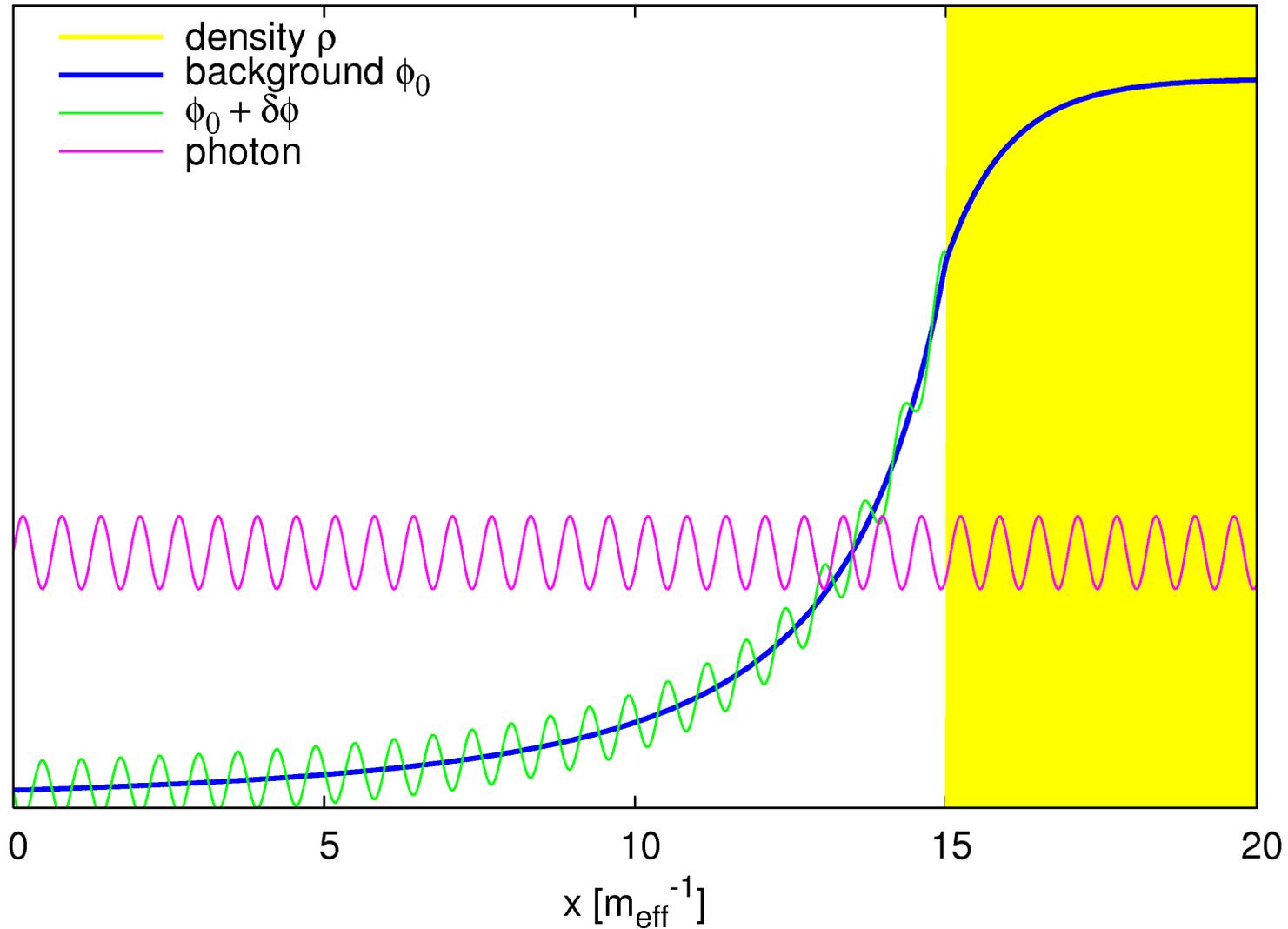


Quantum Measurement: Walls



K. Van Bibber, et. al., PRL 59, 759 (1987)

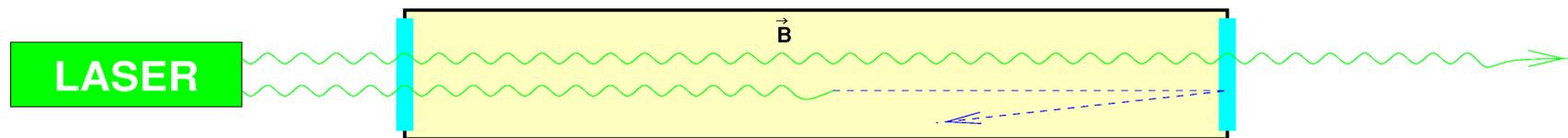
Quantum Measurement: Windows



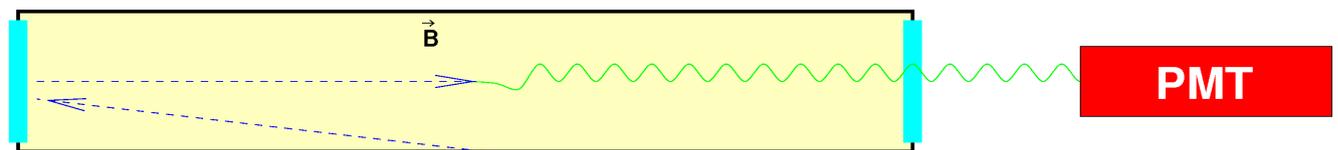
Afterglow Experiment

a) **production:** Stream photons through the magnetic field region via glass windows. Any chameleon particles produced will be trapped in the chamber.

a)

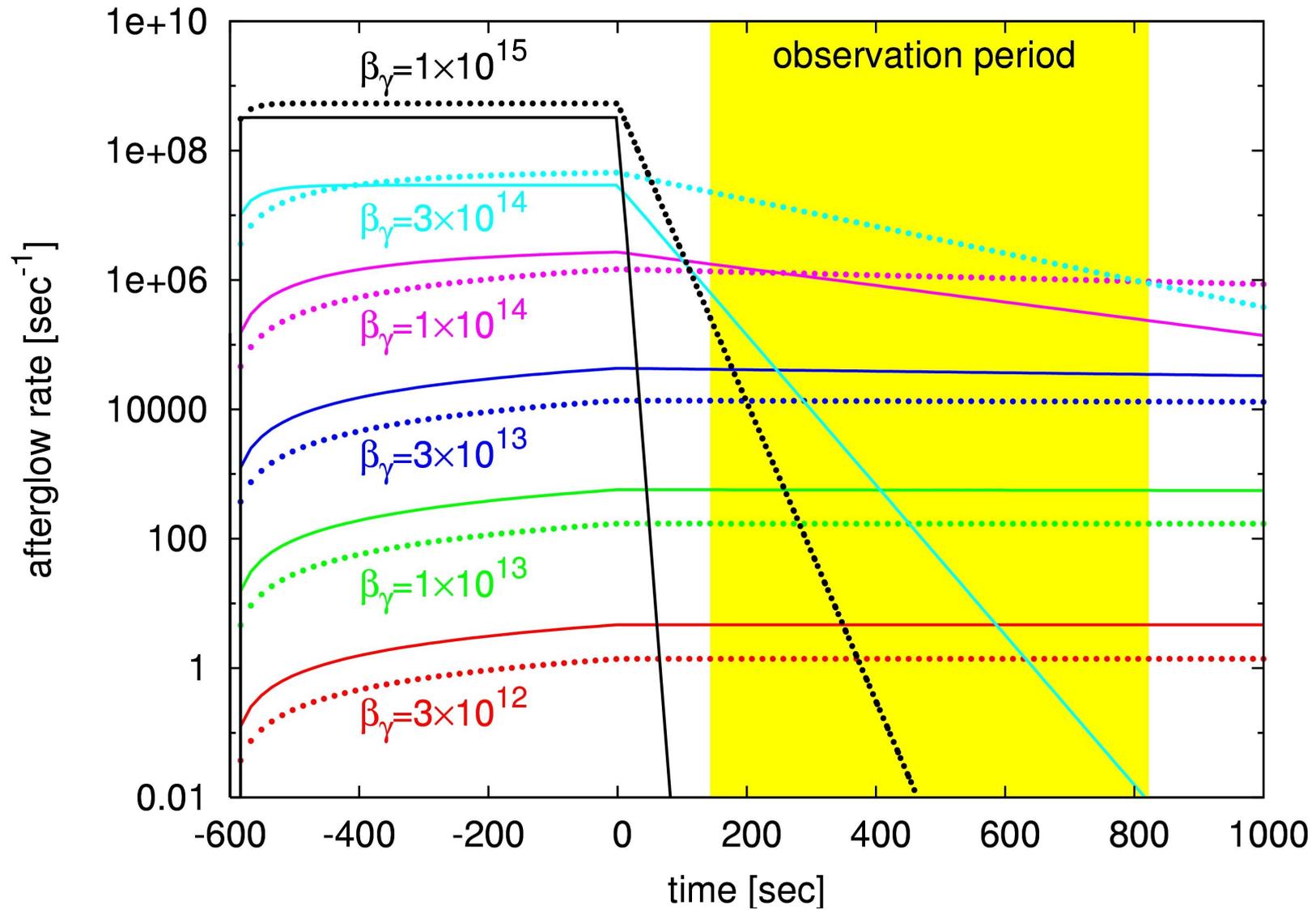


b)



b) **afterglow:** Turn off the photon source, and wait for chameleon particles to convert back into detectable photons, which emerge through the windows.

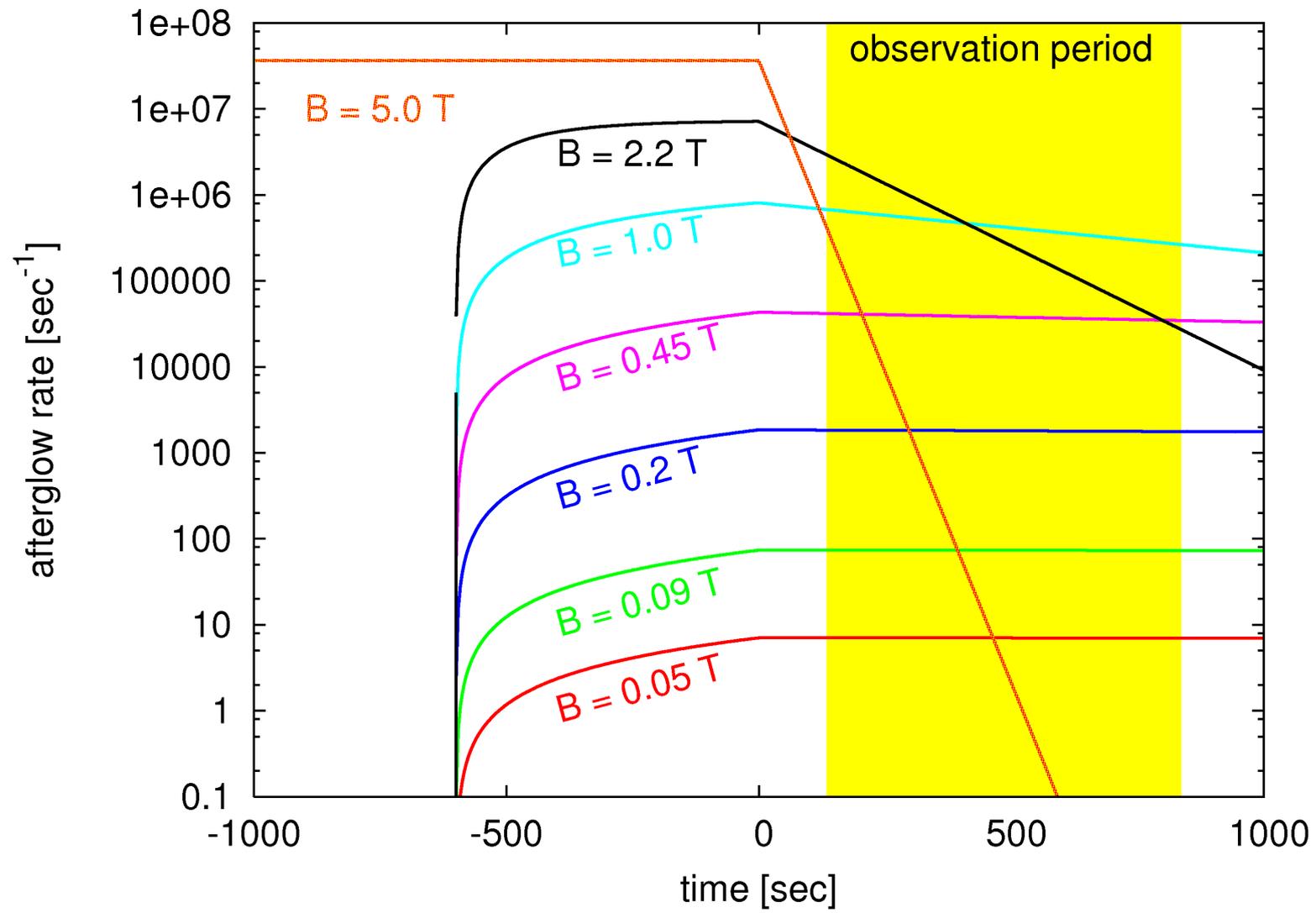
Expected Signal



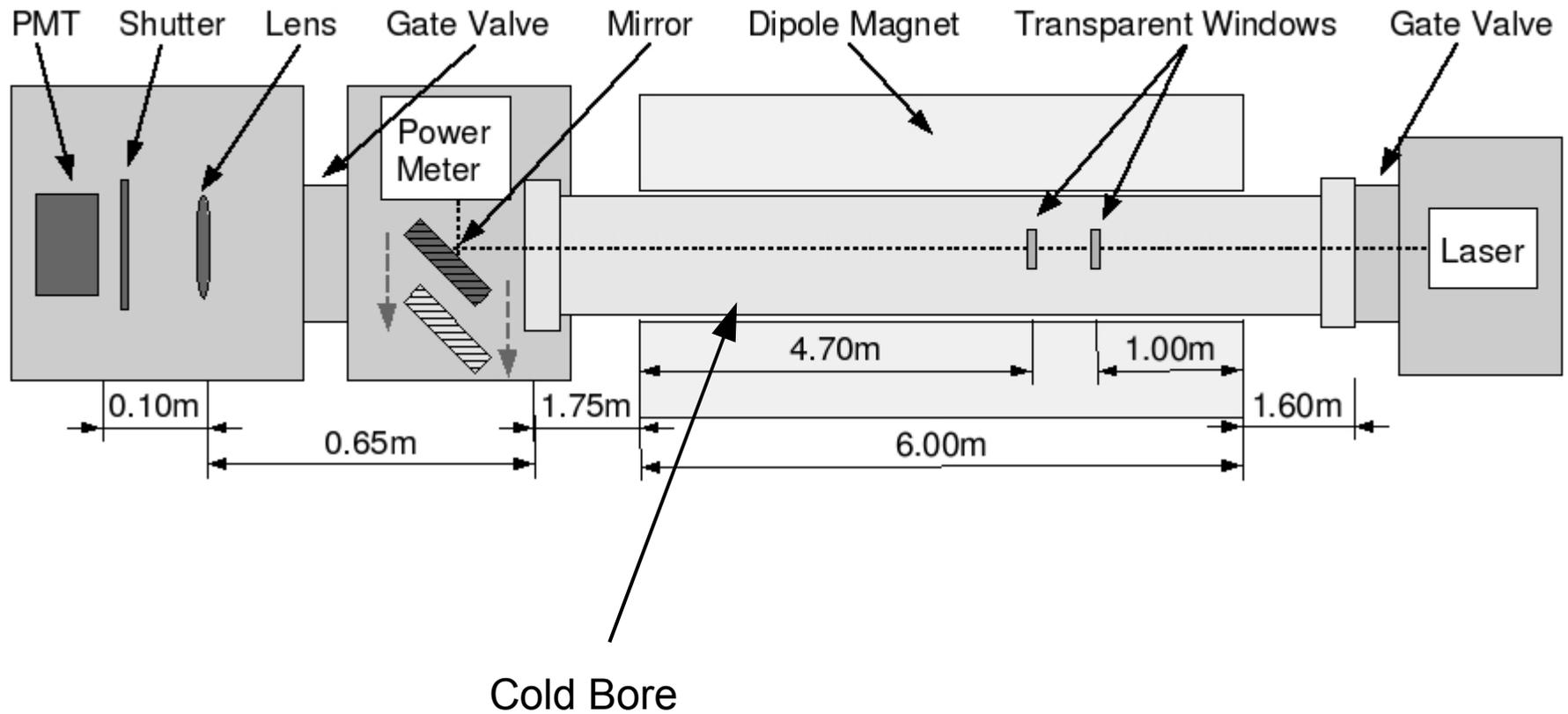
solid lines: $\xi_{\text{ref}} = 0$

dotted lines: $\xi_{\text{ref}} = \pi/3$

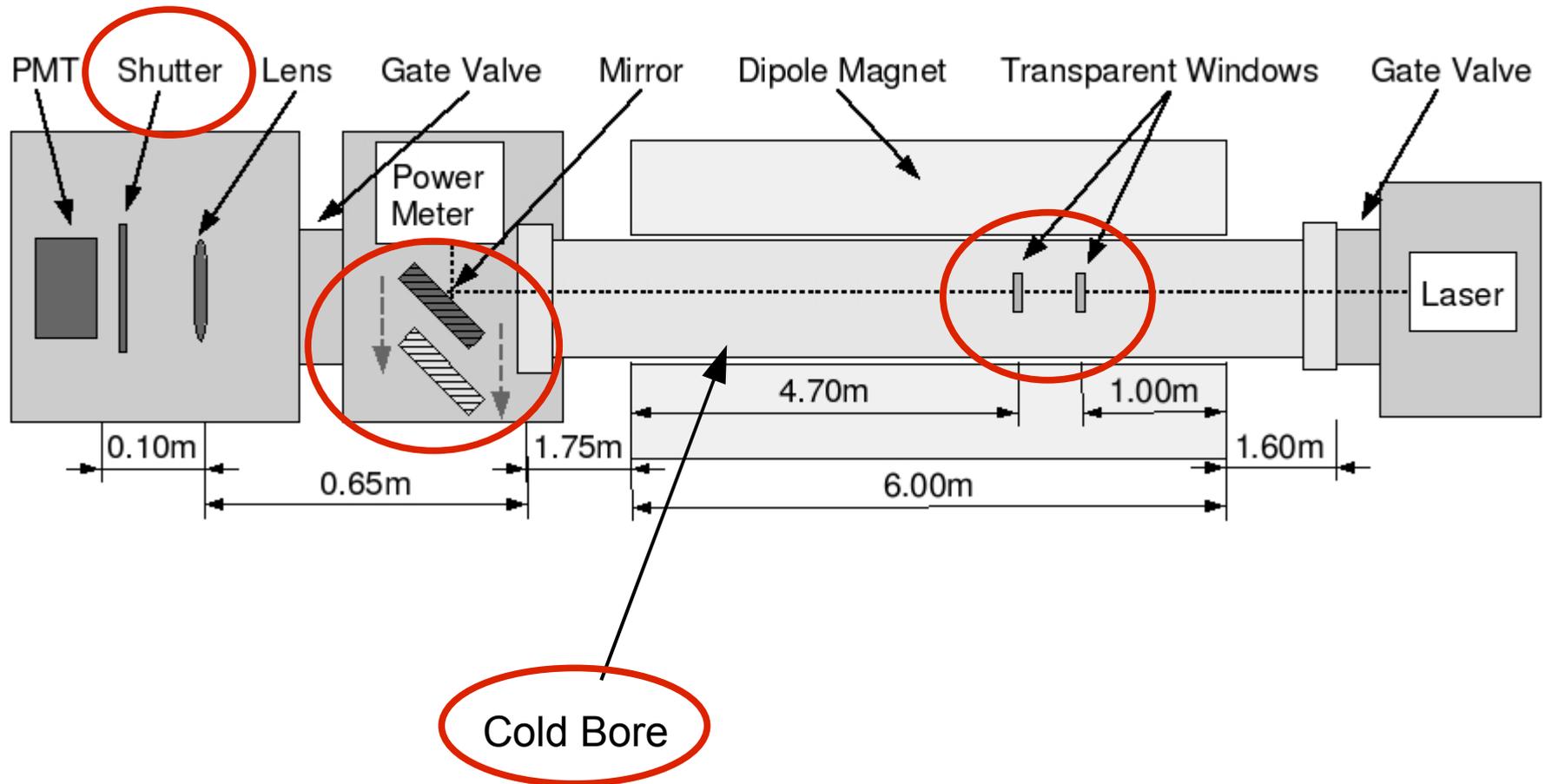
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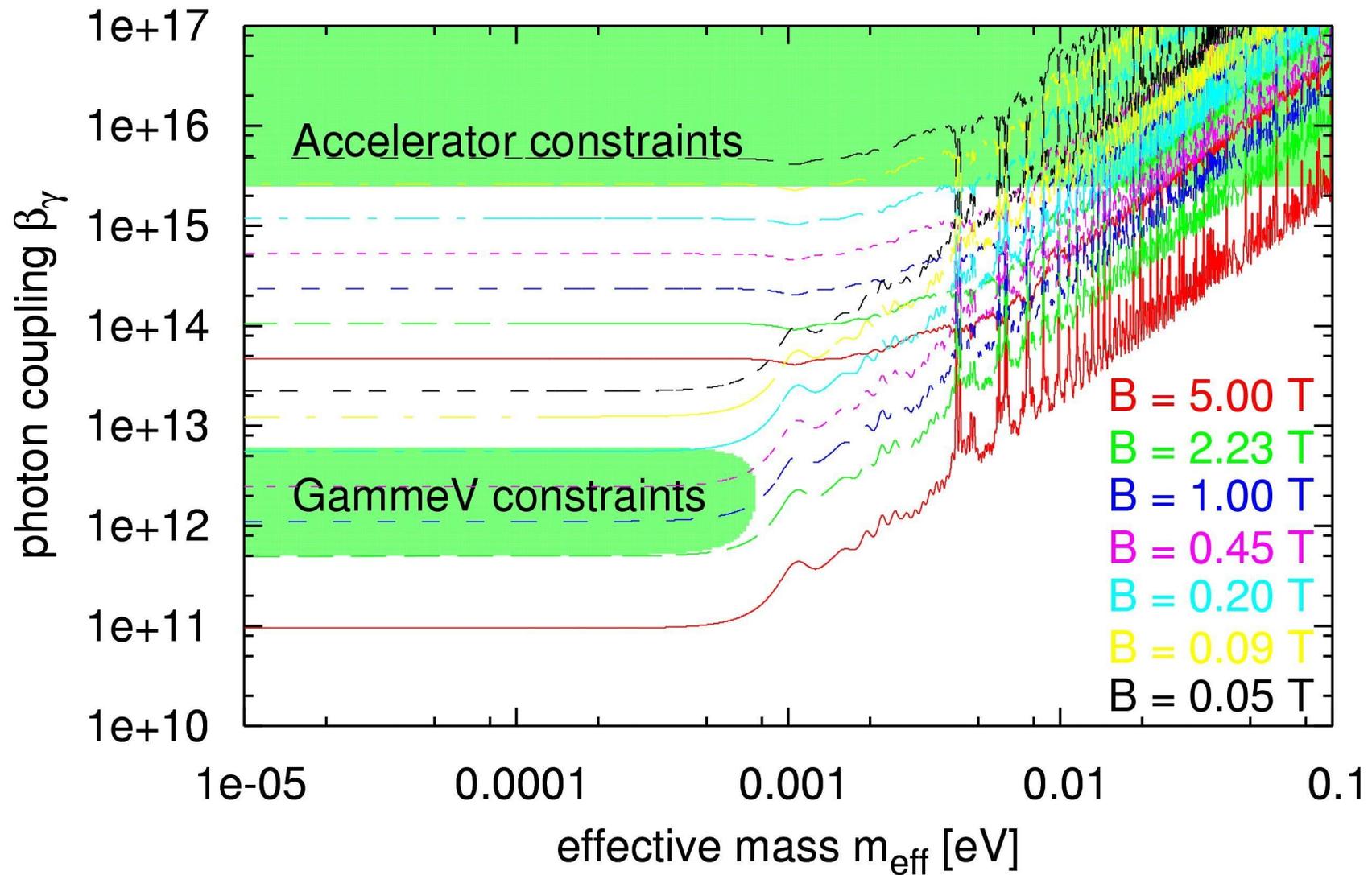
CHASE Schematic



CHASE Schematic



CHASE Experimental Approach

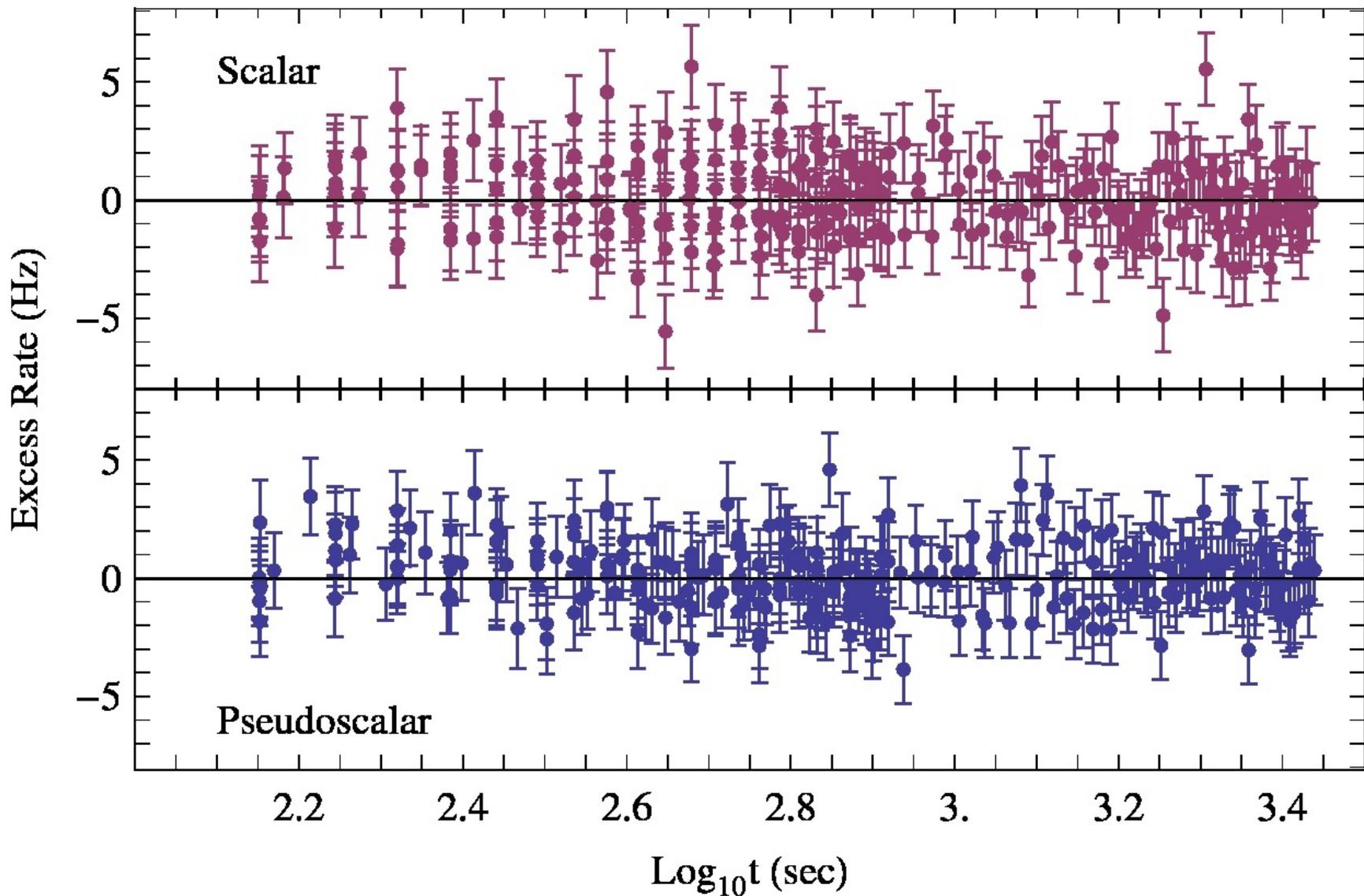


Lowering the magnetic field allows us to probe larger photon couplings and to eliminate some systematic effects.

Science Data

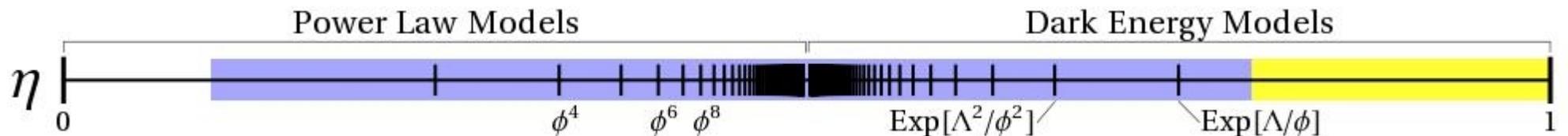
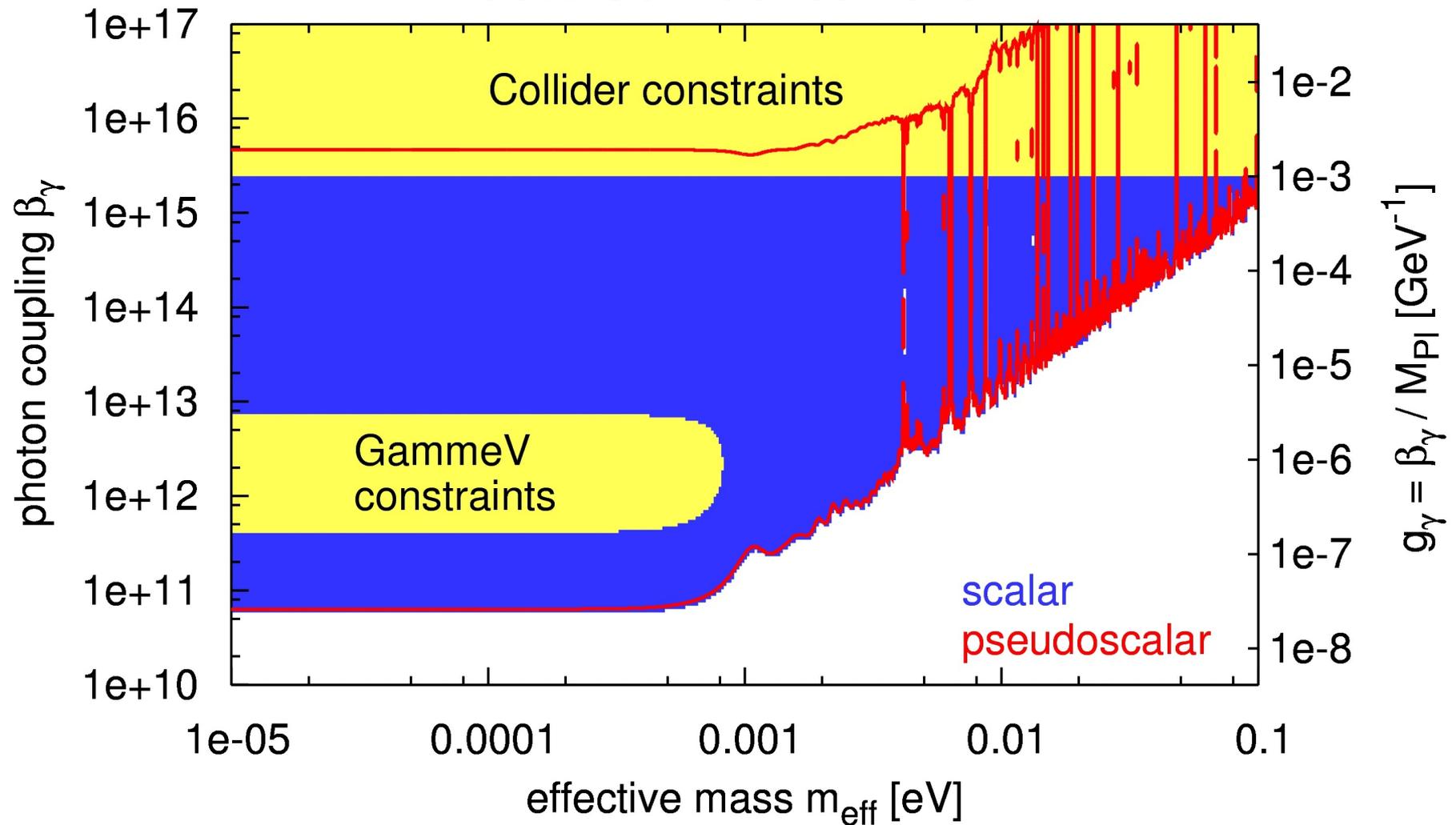
- 16 total science runs, 8 for each laser polarization
- Nominal Run
 - Fill the cavity for 10 minutes
 - Observe afterglow for 14 minutes
 - One measurement for each magnetic field
- Extended Run (for 5.0 Tesla magnetic field)
 - Fill cavity for 5 hours
 - Observe afterglow for 45 minutes
 - Repeat this measurement
- Shutter cycle is ~15 seconds on and ~15 seconds off
- 15 minute calibration run before and after each science run

CHASE Science Data



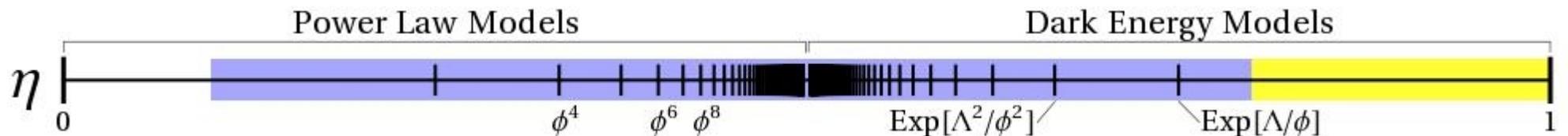
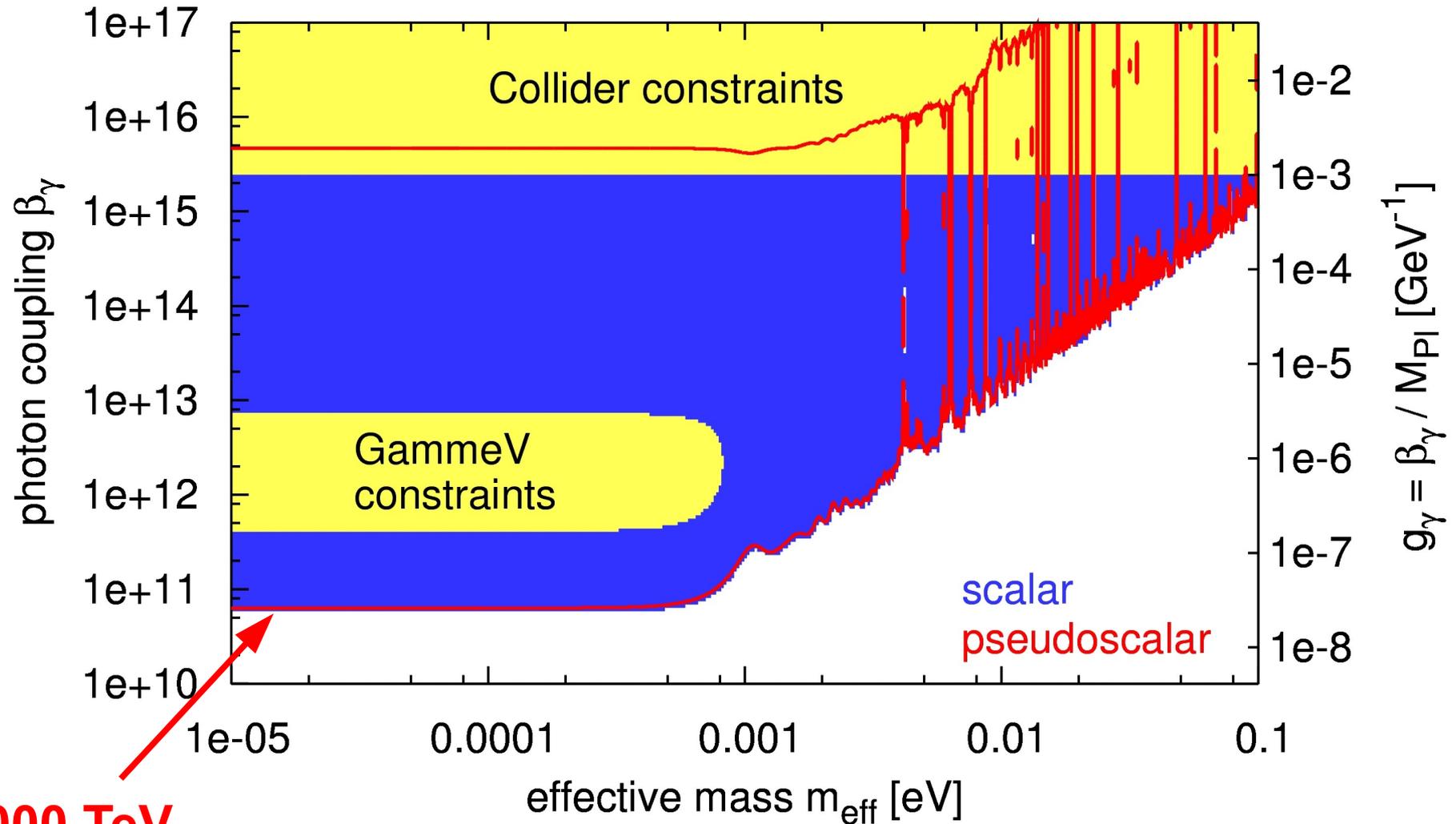
Constraints from CHASE

95% Confidence Level



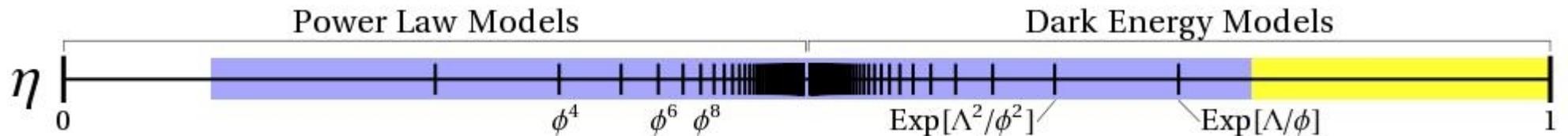
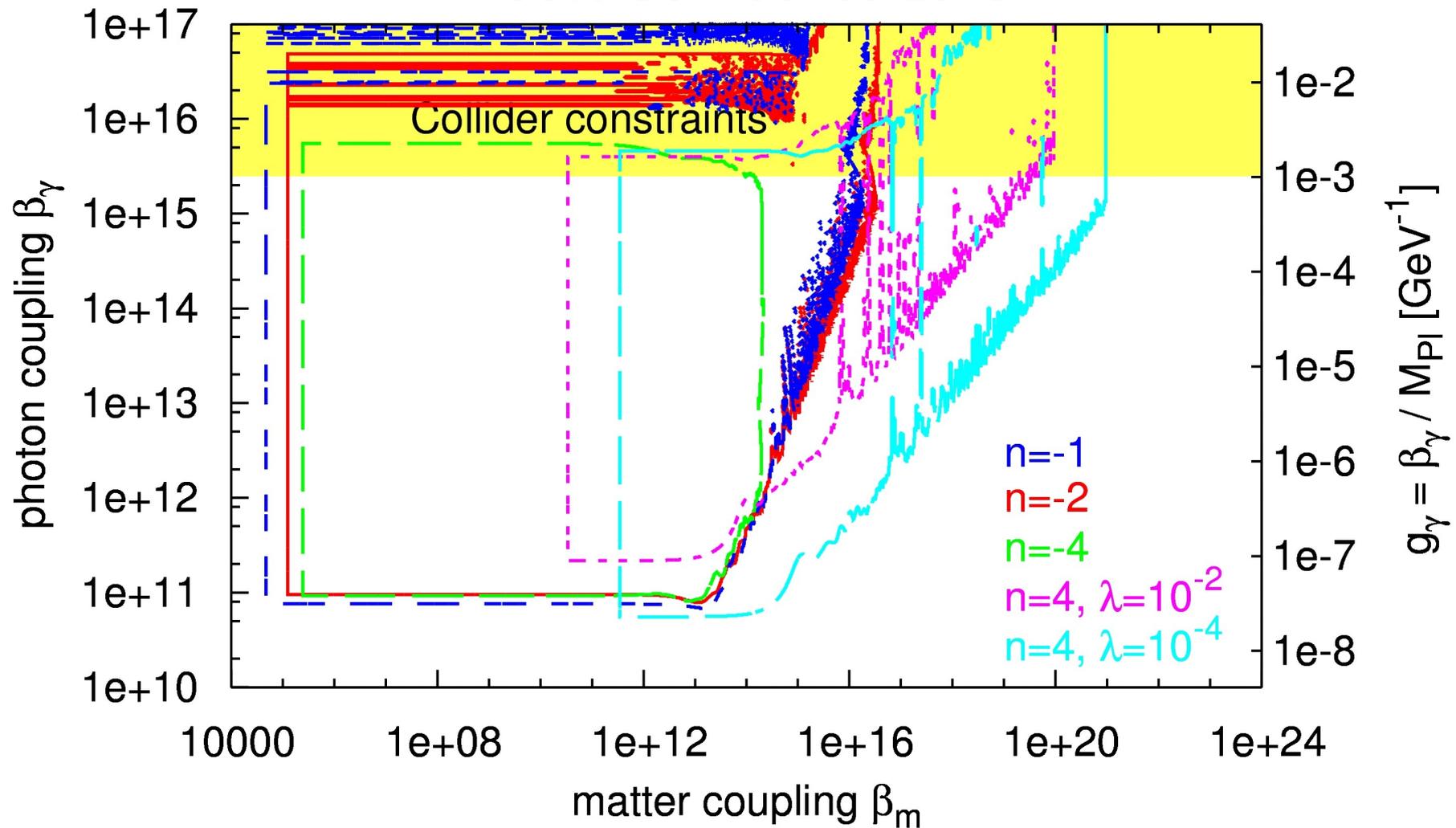
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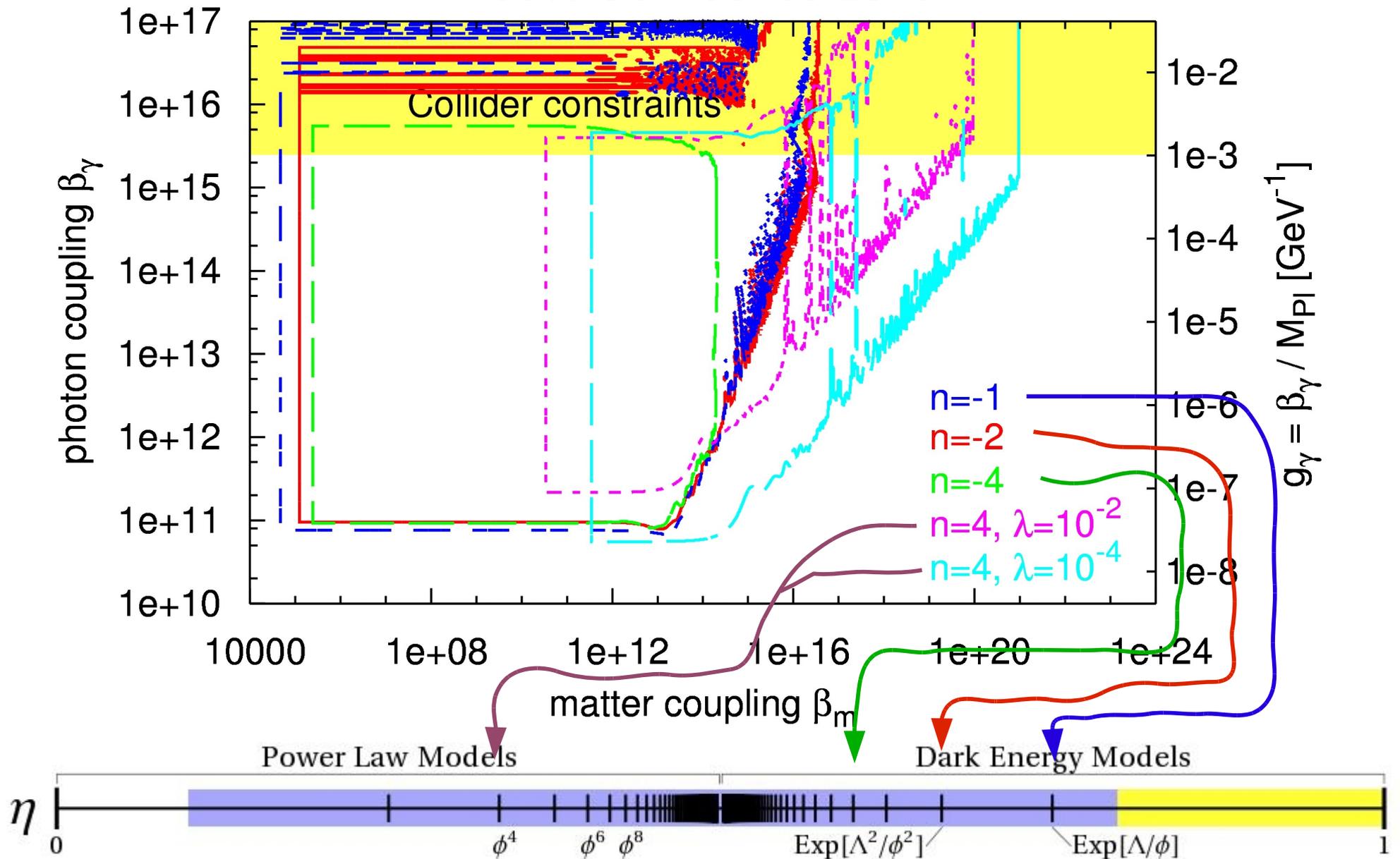
Model Dependent Results

95% Confidence Level



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95% Confidence Level



More Numerology

The Intensity Frontier:

1 Mega Watt 100 GeV proton beam $\sim 10^{14}$ protons/second

More Numerology

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1 Mega Watt 100 GeV proton beam $\sim 10^{14}$ protons/second

1 Watt eV photon beam $\sim 10^{19}$ photons/second

More Numerology

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1 Mega Watt 100 GeV proton beam $\sim 10^{14}$ protons/second

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Add a resonating cavity...

Increase power by a factor of 100 to 100,000

Power recycle for a factor of 10 to 100

More Numerology

The Intensity Frontier:

1 Mega Watt 100 GeV proton beam $\sim 10^{14}$ protons/second

1 Watt eV photon beam $\sim 10^{19}$ photons/second

Add a resonating cavity...

Increase power by a factor of 100 to 100,000

Power recycle for a factor of 10 to 100

Use an interferometer...

Angular sensitivity $\sim 10^{-12}$ radians

Differential length sensitivity $\sim 10^{-19}$ meters

The Intensity Frontier



Working groups: Heavy Quarks • Charged Leptons
Neutrinos • Photons • Proton Decay • Nucleons, Nuclei & Atoms

This workshop is an opportunity for the scientific community to identify the physics potential of the Intensity Frontier. Starting in September, six working groups will study and document the full spectrum of Intensity Frontier physics and describe the necessary facilities to realize such a program. The working groups will be open to and build upon ideas from the broader particle and nuclear physics community, and will present their preliminary findings at the workshop.

More information is available at www.intensityfrontier.org or from the workshop chairs, Jeffrey Hewett and Henry Jones, at intensity-frontier@ind.gov.



FUNDAMENTAL PHYSICS AT THE INTENSITY FRONTIER

November 30–December 2, 2011
Rockville, MD | www.intensityfrontier.org



Working group on
Hidden Sector Photons, Axions, and WISPs

Laser Test of Gravity: The Holometer

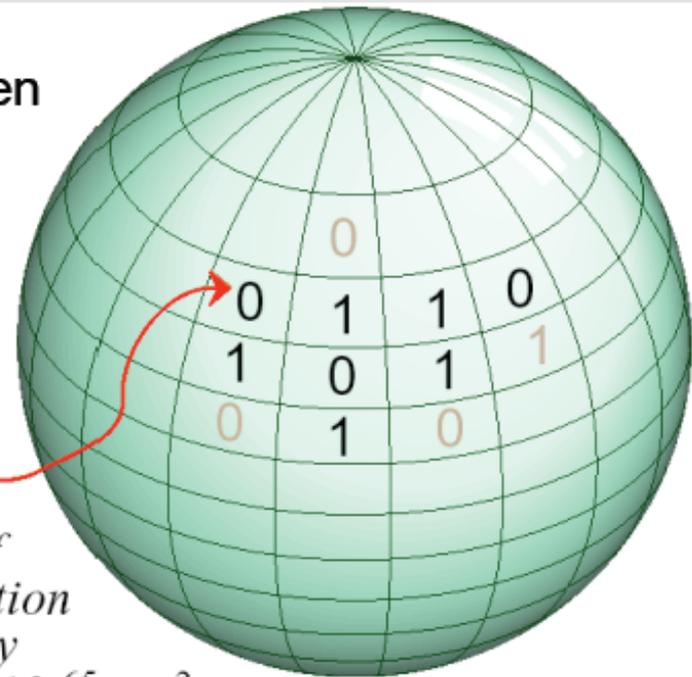
Bold idea from black hole physics: the world is a hologram

“This is what we found out about Nature’s book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size.”

-Gerard 't Hooft

Everything is written on 2D surfaces moving at the speed of light

1 bit of information on every $0.724 \times 10^{-65} \text{ cm}^2$



Are there experimental consequences of this idea?

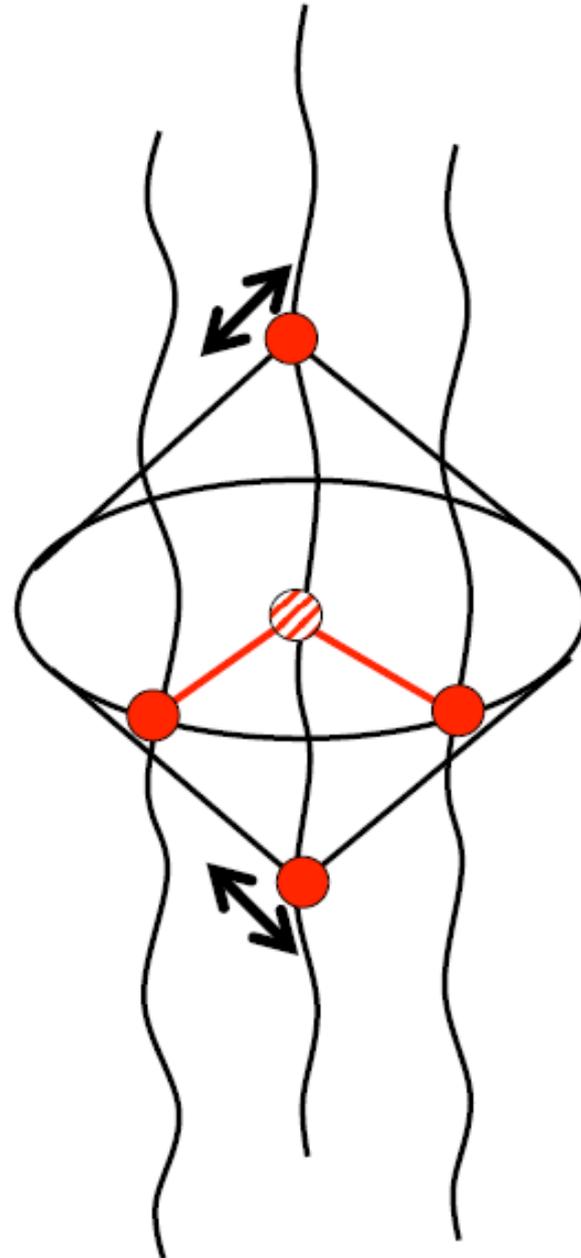
Laser Test of Gravity: The Holometer

Michelson interferometer

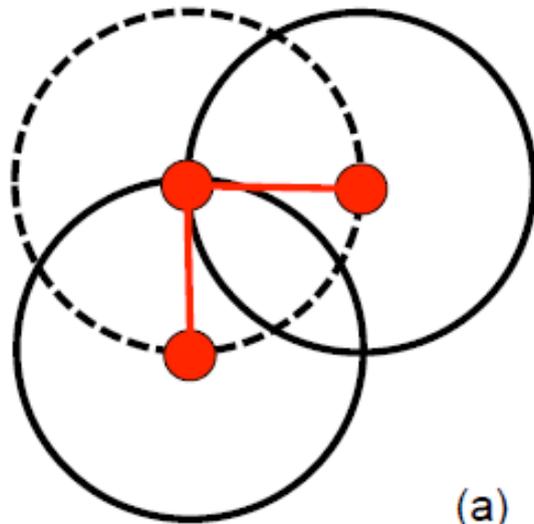
Events contributing to interferometer signal ●

On worldlines of beamsplitter and two end mirrors

Measurement is coherent, nonlocal in space and time, includes position in two directions

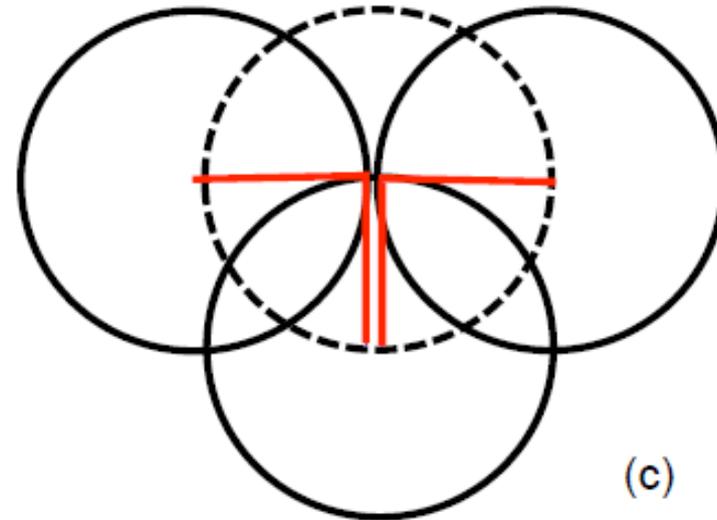


Laser Test of Gravity: The Holometer



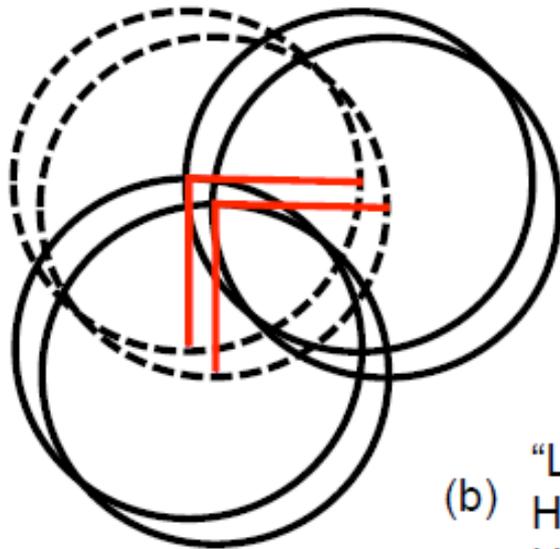
Top view of diamonds for one interferometer

(a)



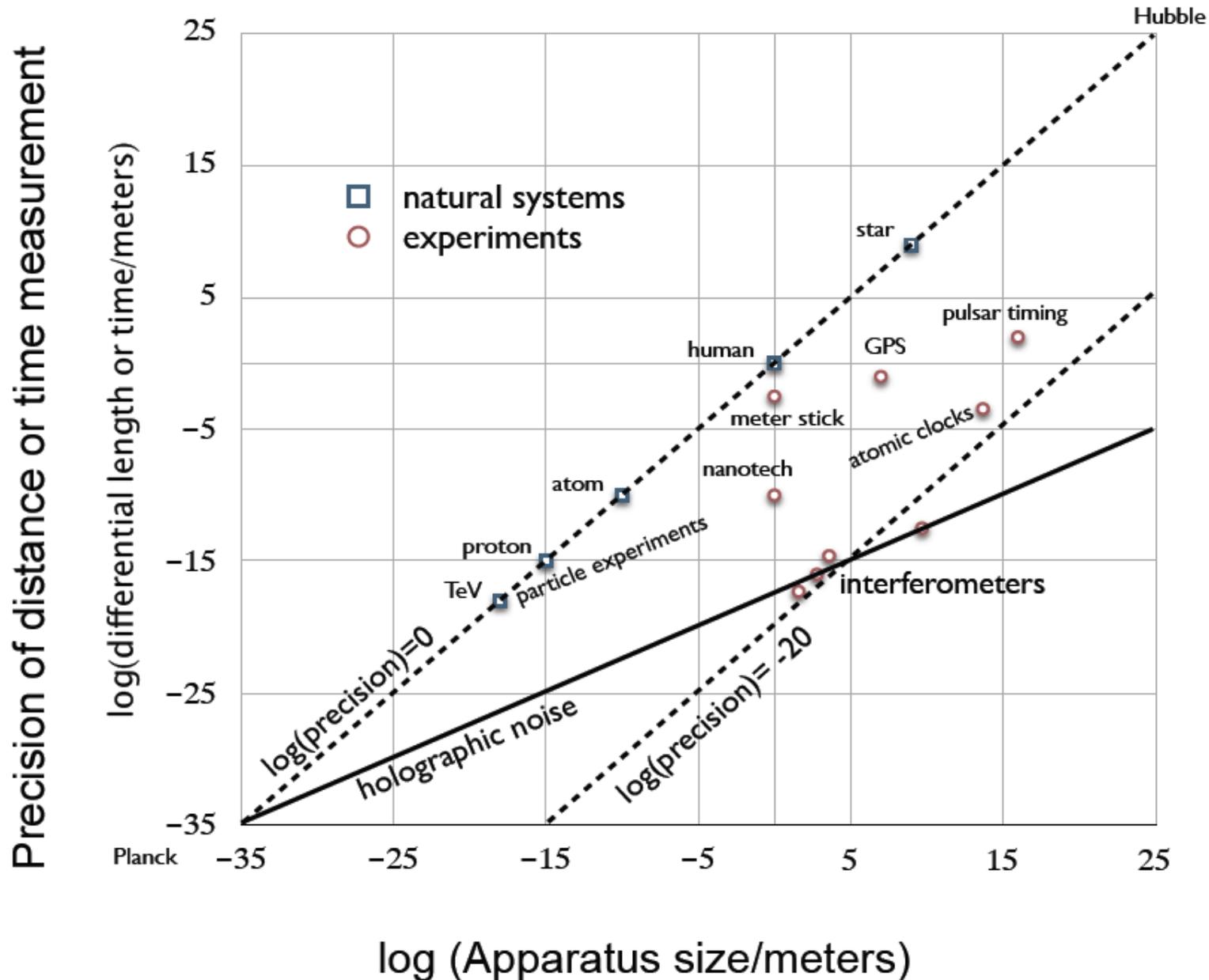
(c)

“T” configuration
No overlap of diamonds
from end mirrors
No signal correlations

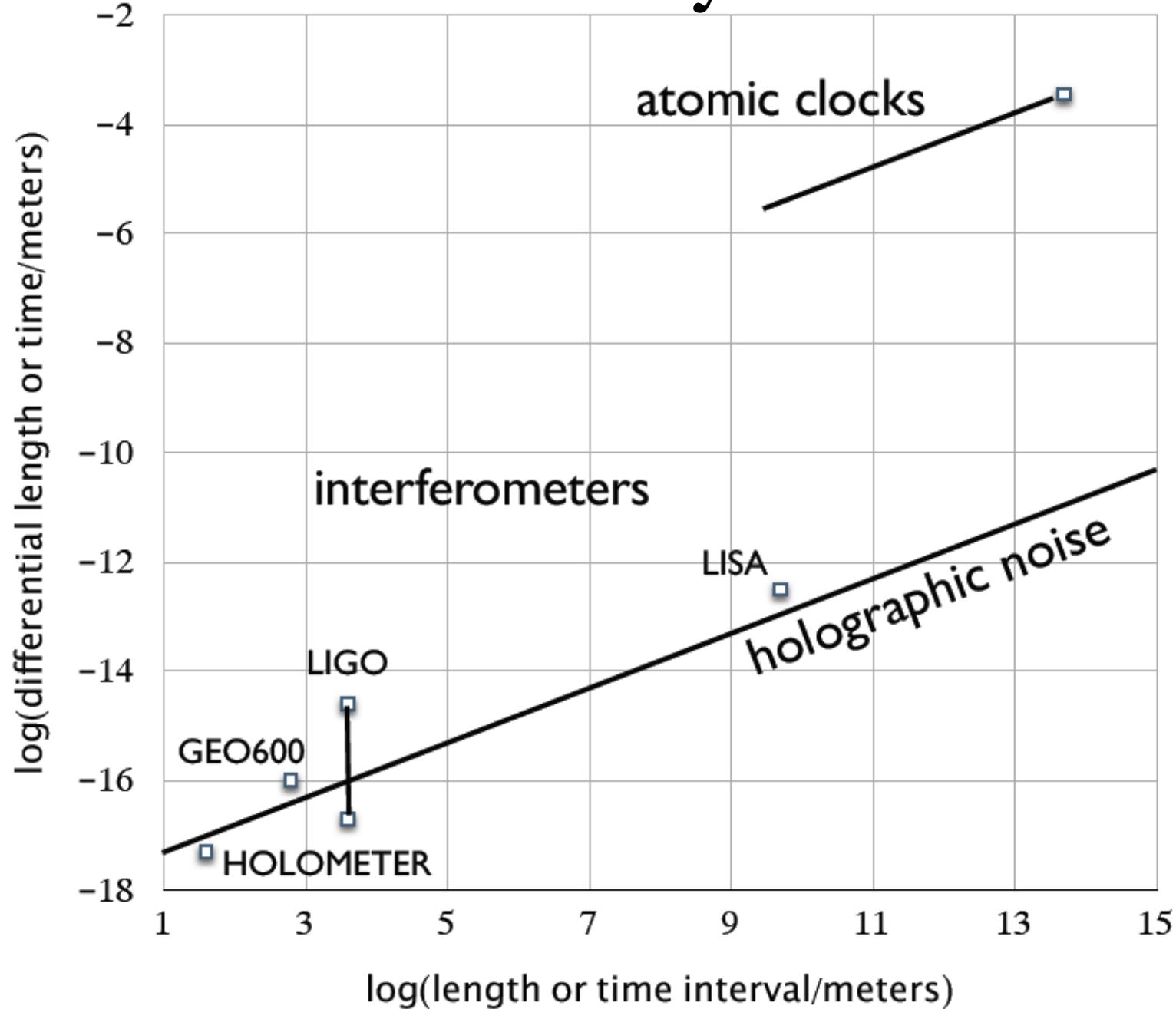


(b) “L” configuration
Highly entangled diamonds
Highly correlated signals

Laser Test of Gravity: The Holometer



Laser Test of Gravity: The Holometer



Laser Test of Gravity: The Holometer

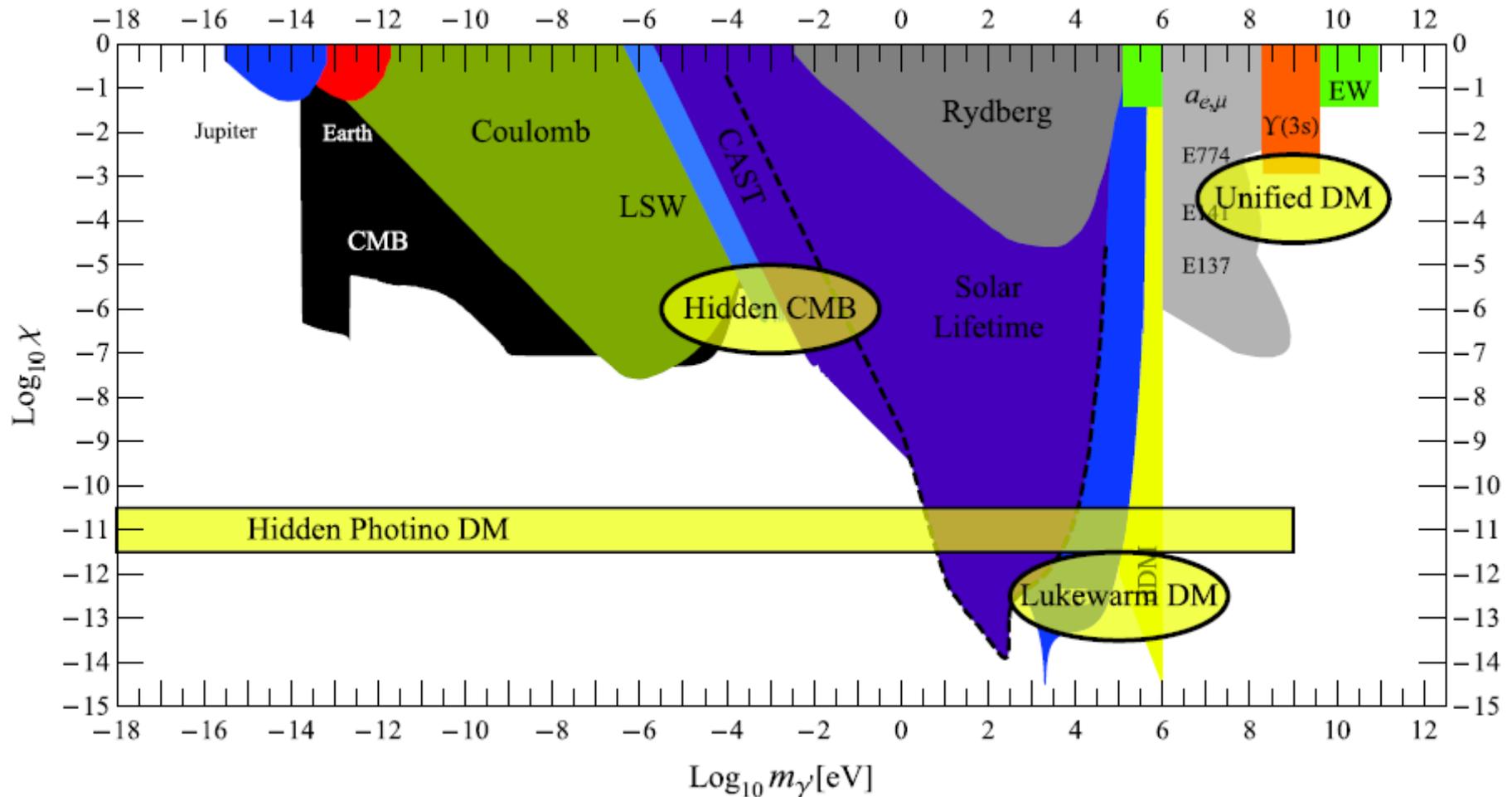


Final Slide of Numerology

$$\sqrt{\frac{\ell_P}{H_0}} \simeq \frac{1}{2} \text{ mm} \quad (4 \text{ meV})$$

Where we go from here?

Where to go: Paraphoton Search



Signatures of a Hidden Cosmic Microwave Background

Joerg Jaeckel,¹ Javier Redondo,² and Andreas Ringwald²

¹Institute for Particle Physics and Phenomenology, Durham University, Durham DH1 3LE, United Kingdom

²Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany

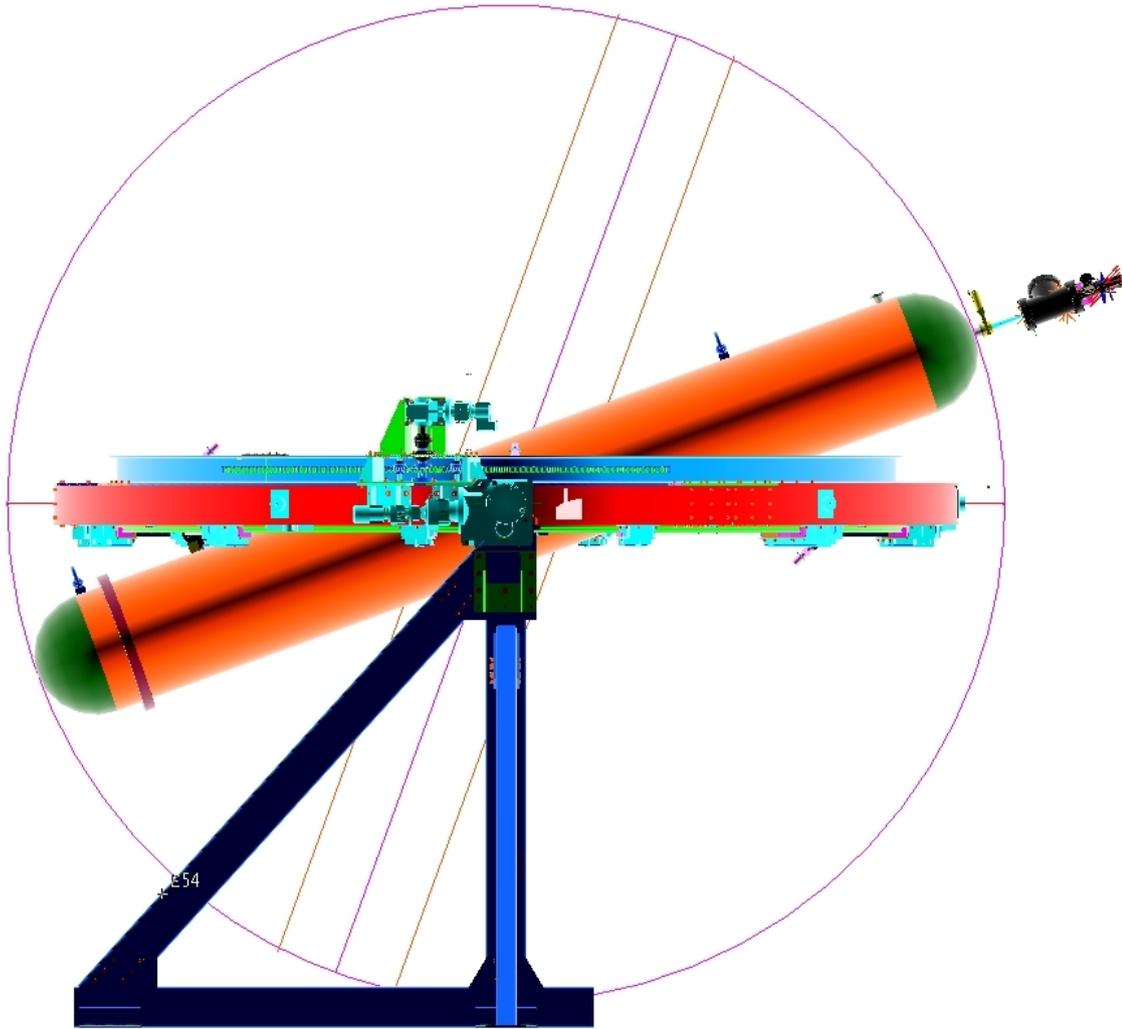
(Received 23 May 2008; published 26 September 2008)

The Case for Dark Radiation

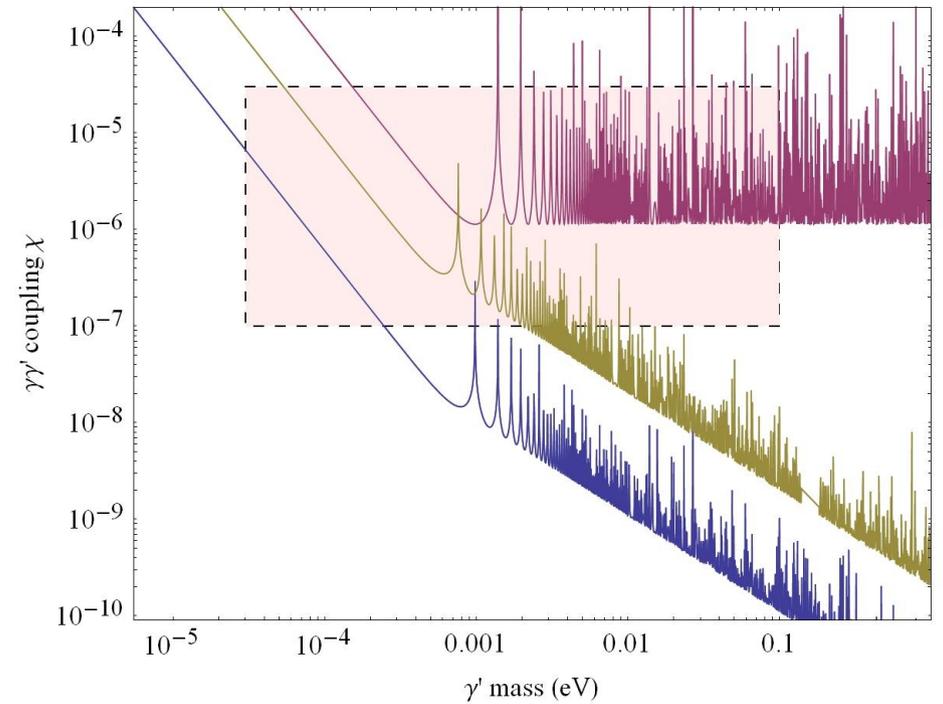
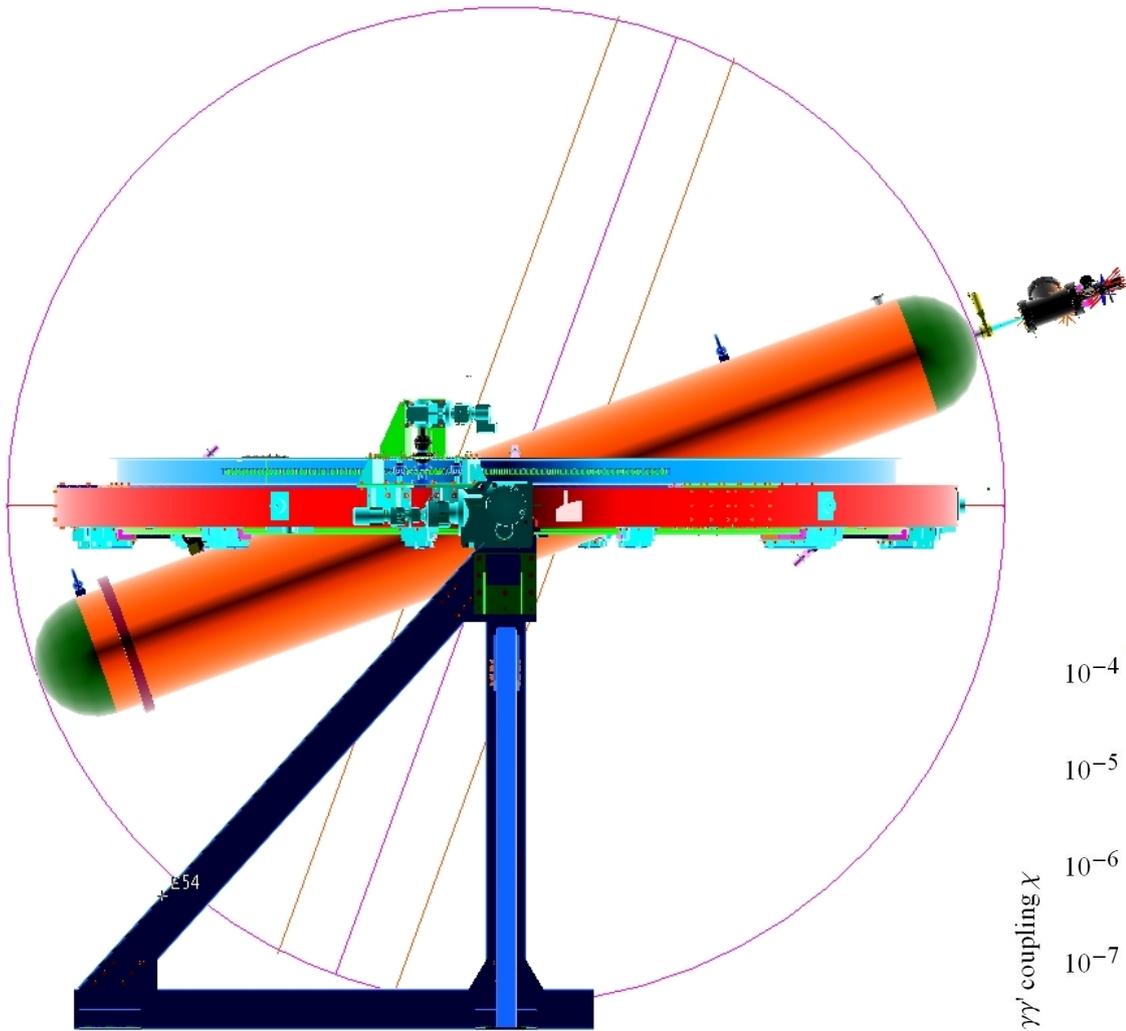
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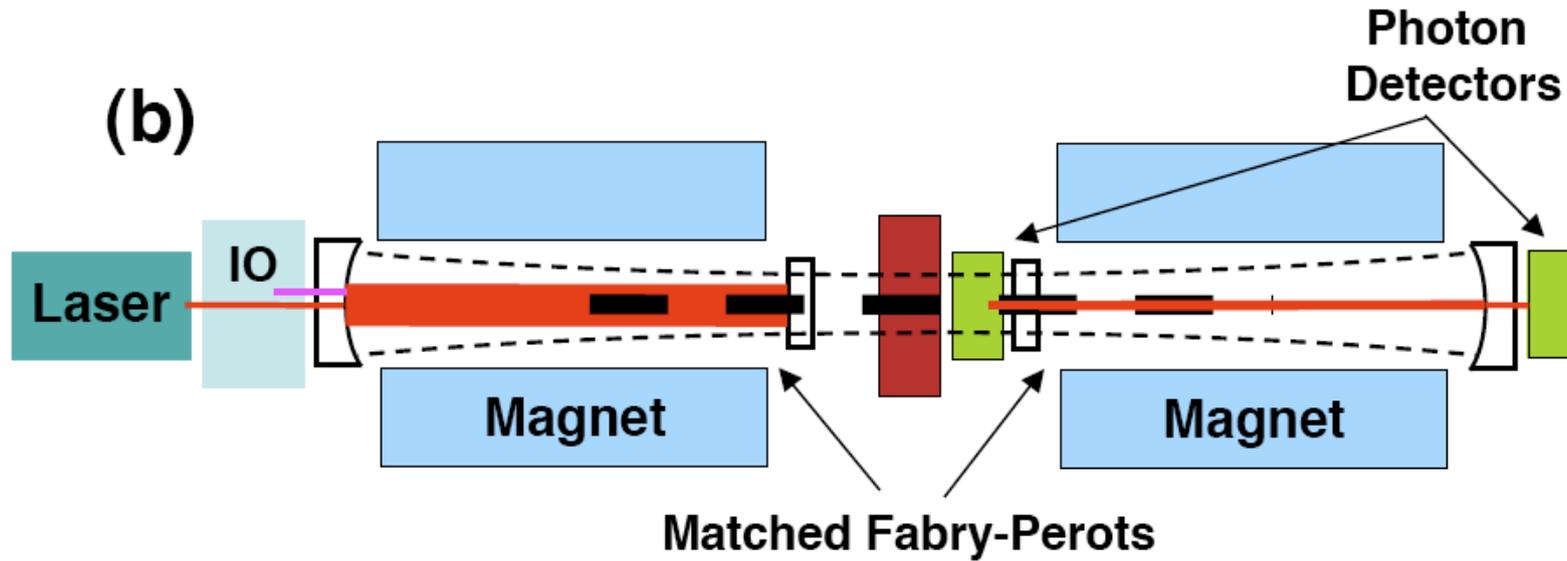
Where to go: Paraphoton Search



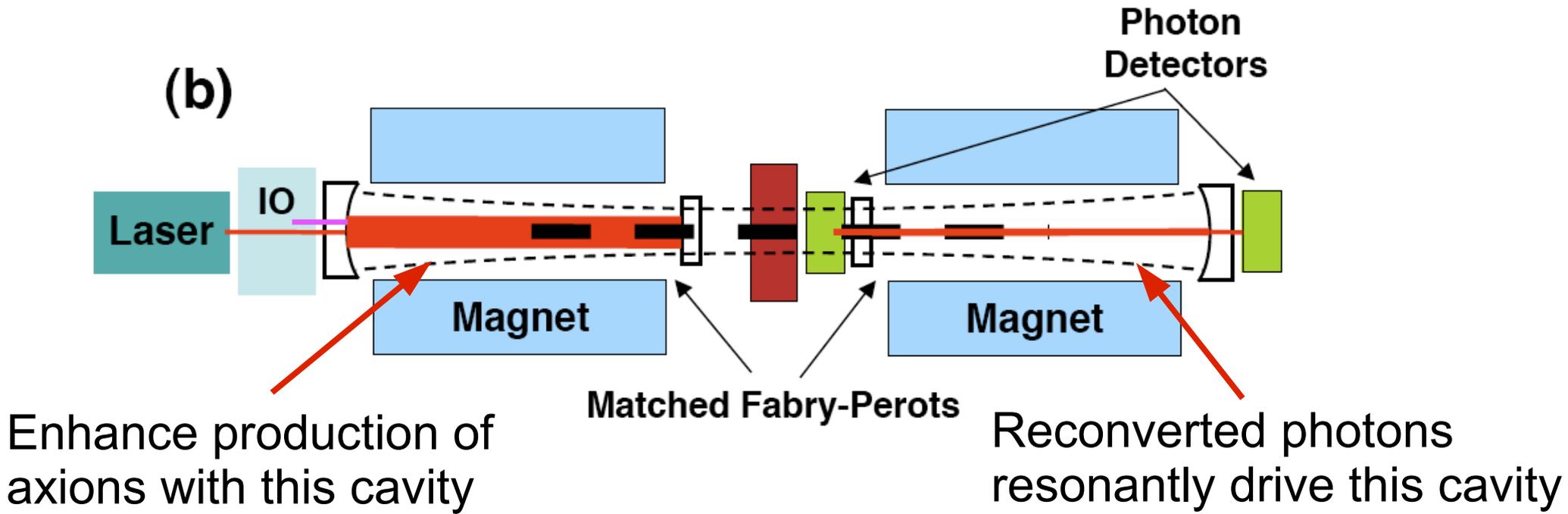
Where to go: Paraphoton Search



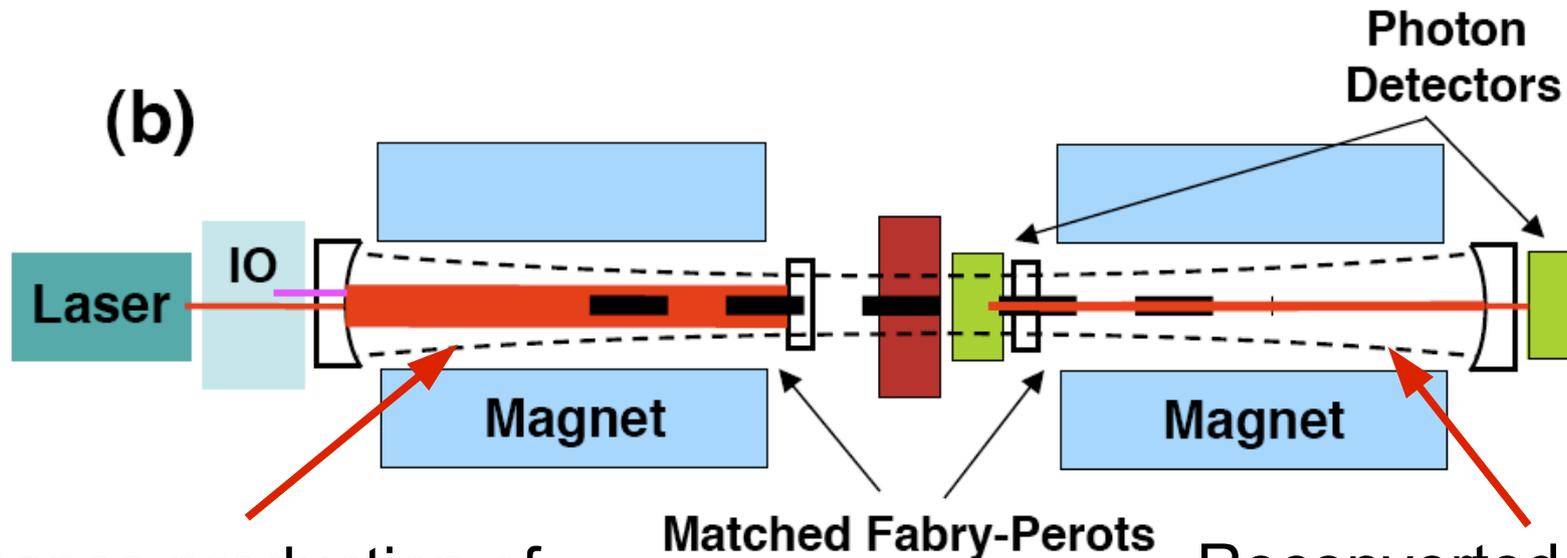
Where to go: Axion Search



Where to go: Axion Search

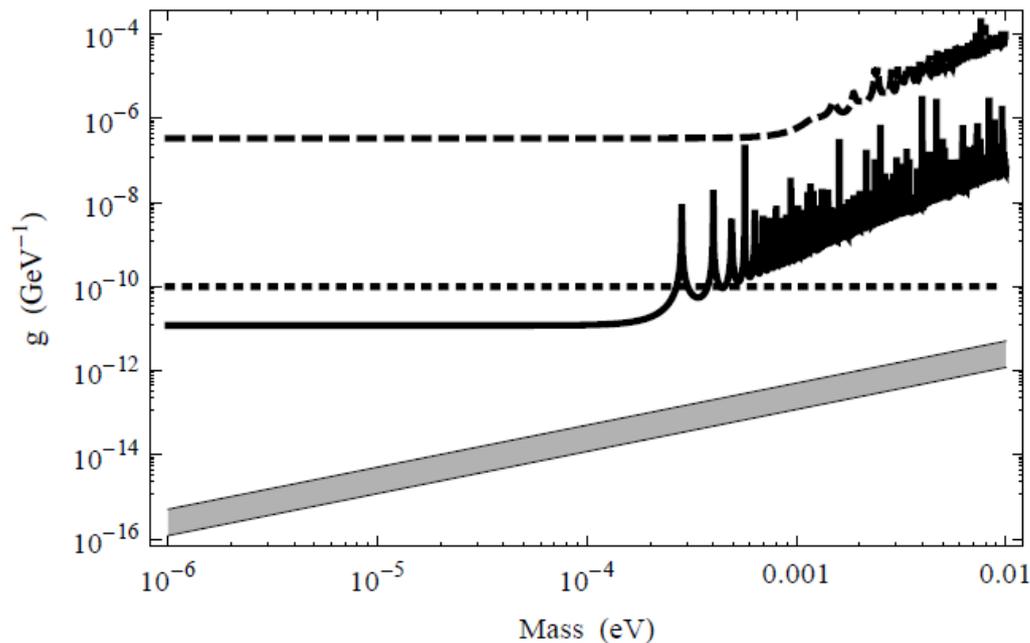


Where to go: Axion Search



Enhance production of axions with this cavity

Reconverted photons resonantly drive this cavity



Conclusions

- 96% of the universe lives in the dark sector
- Laser probes of the dark sector cover a wide variety of physics
 - Axions and axion-like particles may be dark matter constituents
 - Dark energy models with weak couplings to photons
 - The Holometer probes the fundamental nature of spacetime
- A wide variety of future experiments are being conceived
 - The Holometer (now partly constructed)
 - Resonant regeneration axion search
 - Low-mass (meV) paraphotons from the Sun
- Recent workshop on experimental tests of dark energy
 - Sizeable to-do list – perhaps reconvene in 18-24 months
- Pending workshop on the intensity frontier
 - Working group dedicated to topics discussed in this presentation

Conversion Rate

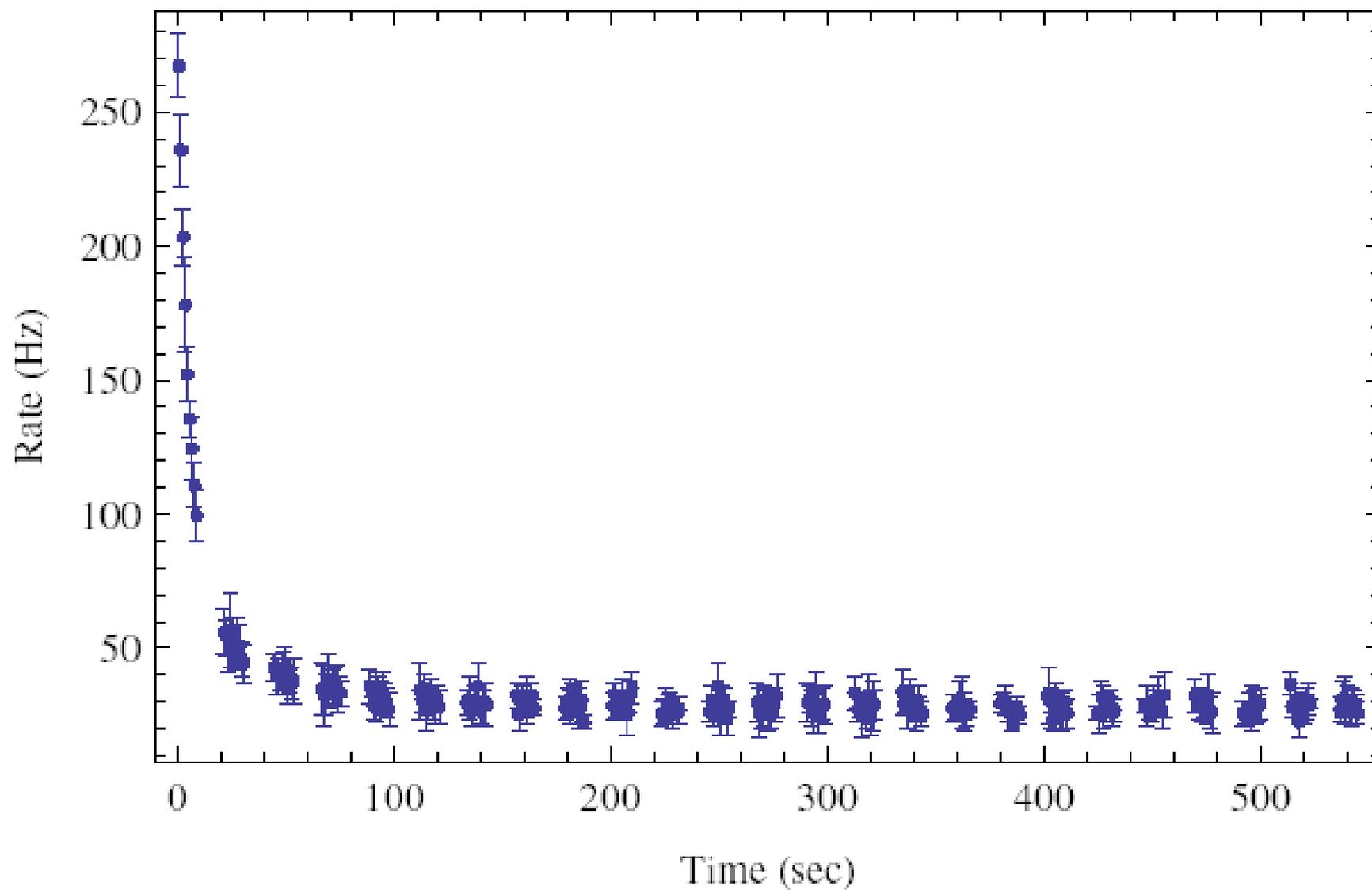
- The conversion process
 - chameleon measured at window
 - ϕ - γ superposition propagates in some direction k through magnetic field, with γ amplitude growing with time
 - particle bounces from walls, with partial reduction in photon amplitude due to nonzero absorption probability
 - particle measured again at opposite window

- Afterglow and decay rates

- Afterglow: $\Gamma_{\text{aft}} = \frac{1}{4\pi} \int d^2\hat{k} \frac{\mathcal{P}_{\gamma\leftrightarrow\phi}(\hat{k}, t(\hat{k}))}{t(\hat{k})} \times \mathcal{P}(\text{detection})$

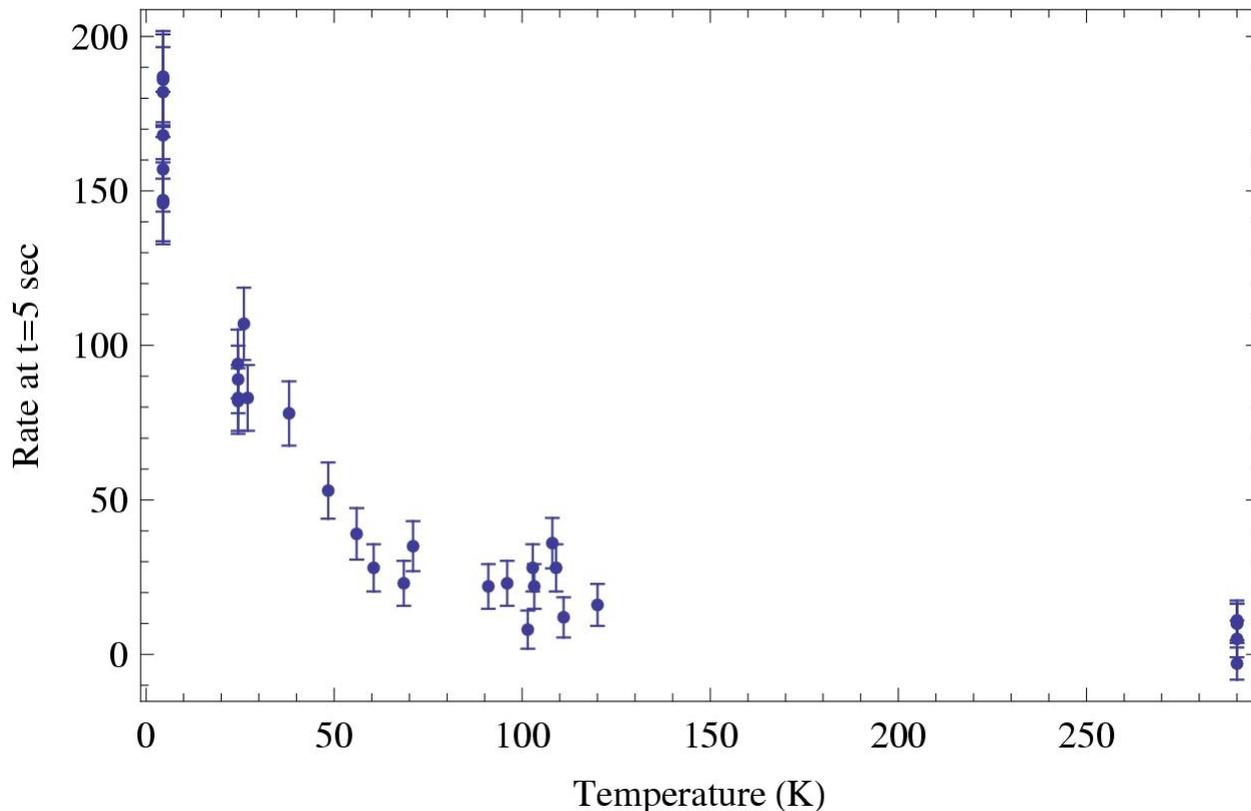
- Decay: $\Gamma_{\text{dec},\gamma} = \frac{1}{4\pi} \int d^2\hat{k} \frac{\mathcal{P}_{\gamma\leftrightarrow\phi}(\hat{k}, t(\hat{k})) + \mathcal{P}(\text{absorption})}{t(\hat{k})}$

Orange Glow



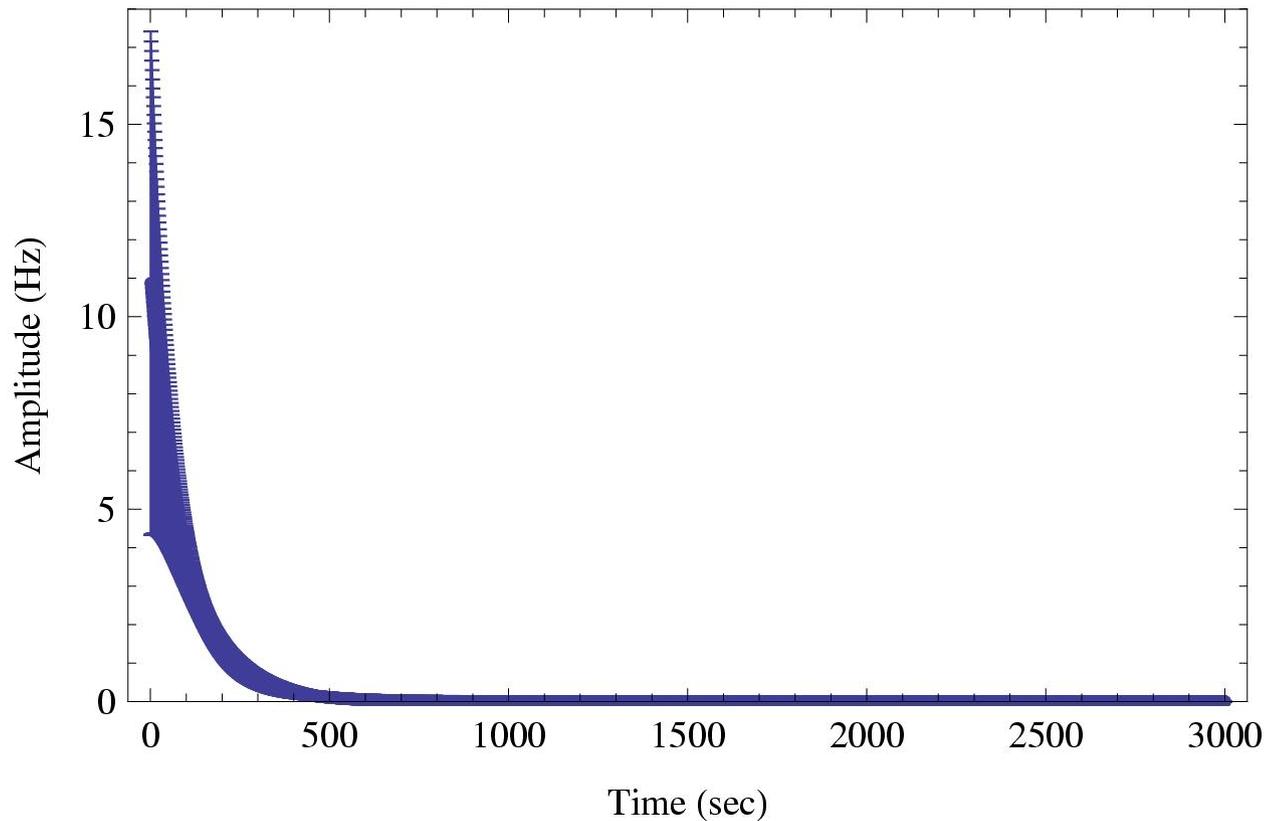
Orange Glow

- Appears in the red and orange part of the spectrum
not in the green where a chameleon signal is expected
- Independent of the magnetic field and laser polarization
unlike a chameleon signal
- Temperature dependence, also unlike a chameleon signal



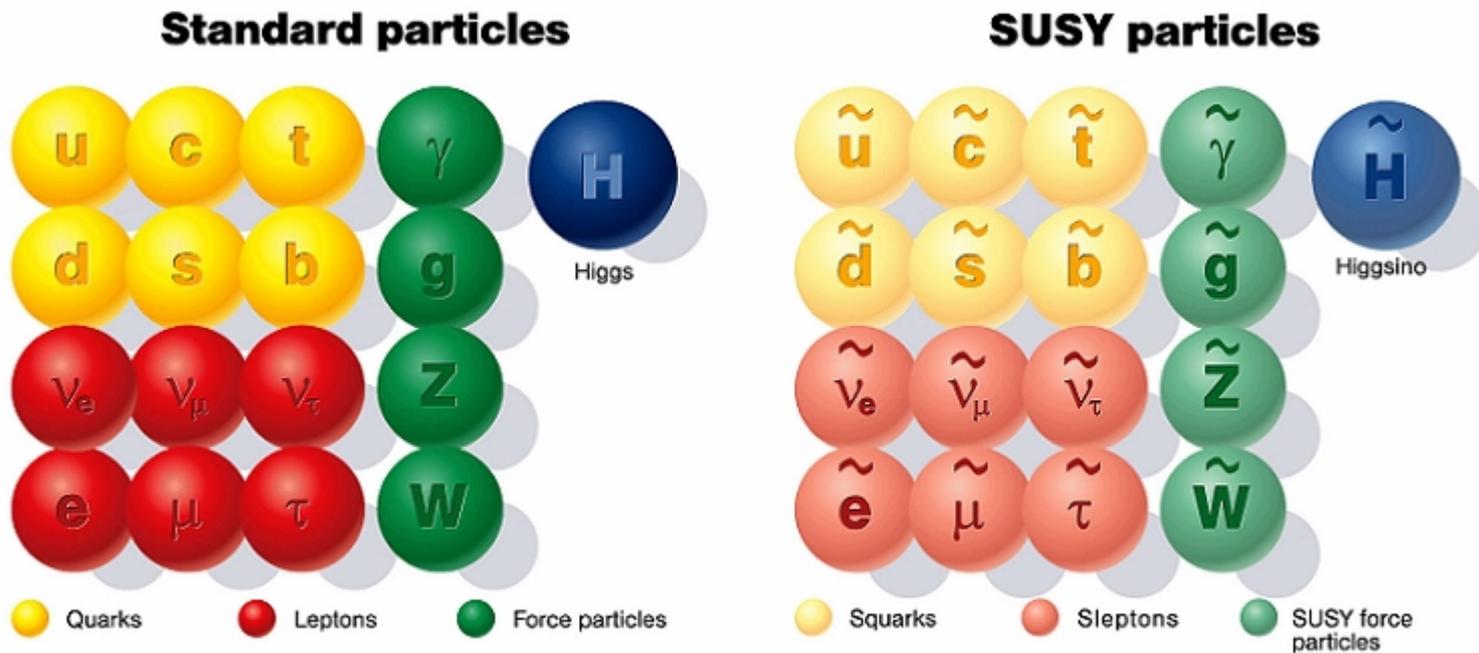
Orange Glow

- A few components are seen, only one remains after ~ 100 seconds
- Data before 120 seconds are ignored
- Orange glow and uncertainty are estimated via Monte Carlo assuming a single exponential and subtracted



Dark Matter WIMPs

A non-relativistic particle with a Weak-scale cross section naturally produces the observed amount of dark matter.



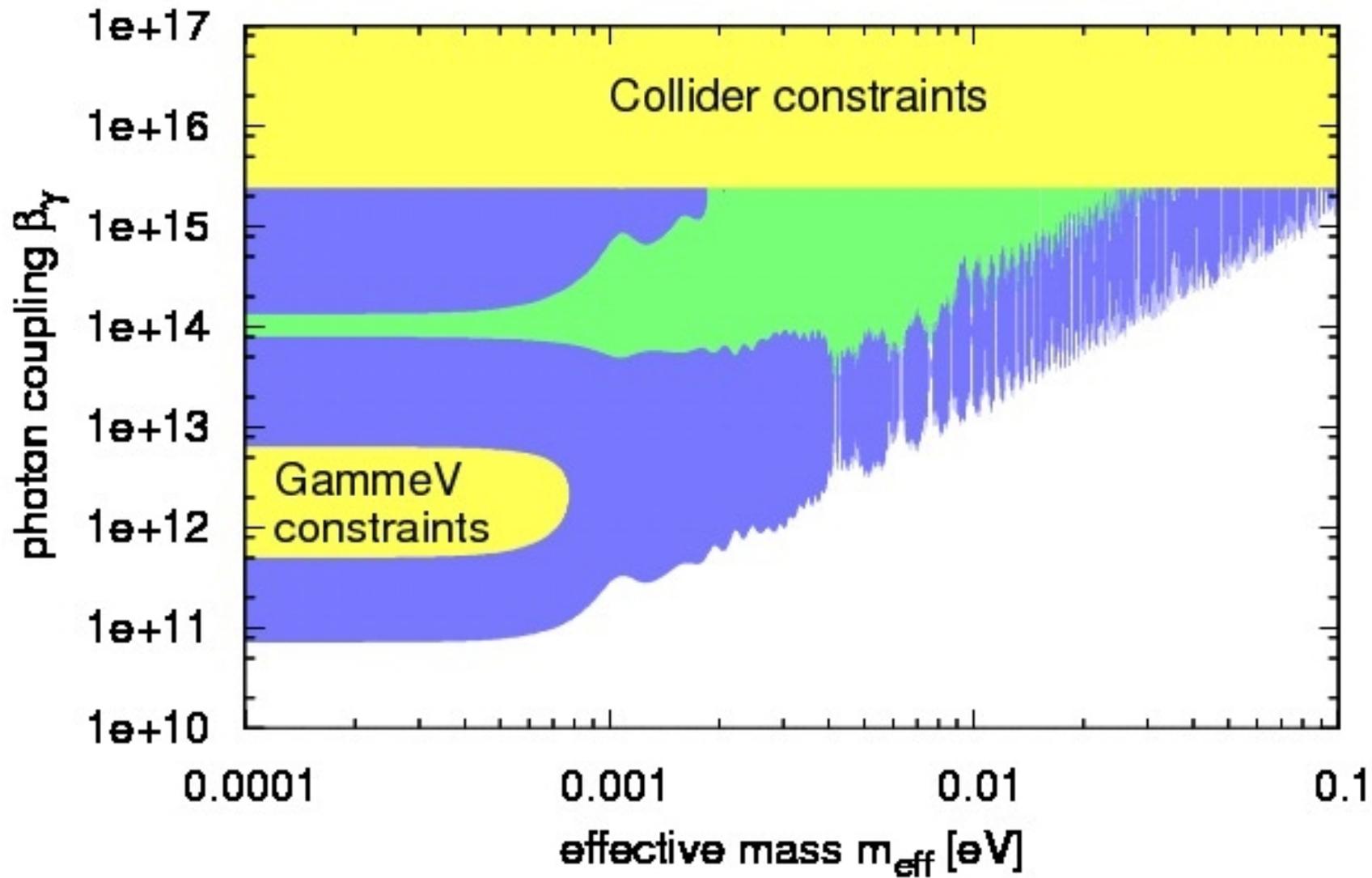
Among other things, supersymmetry:

- solves the hierarchy problem
- unifies the coupling constants of the forces
- provides a dark matter candidate (the neutralino)

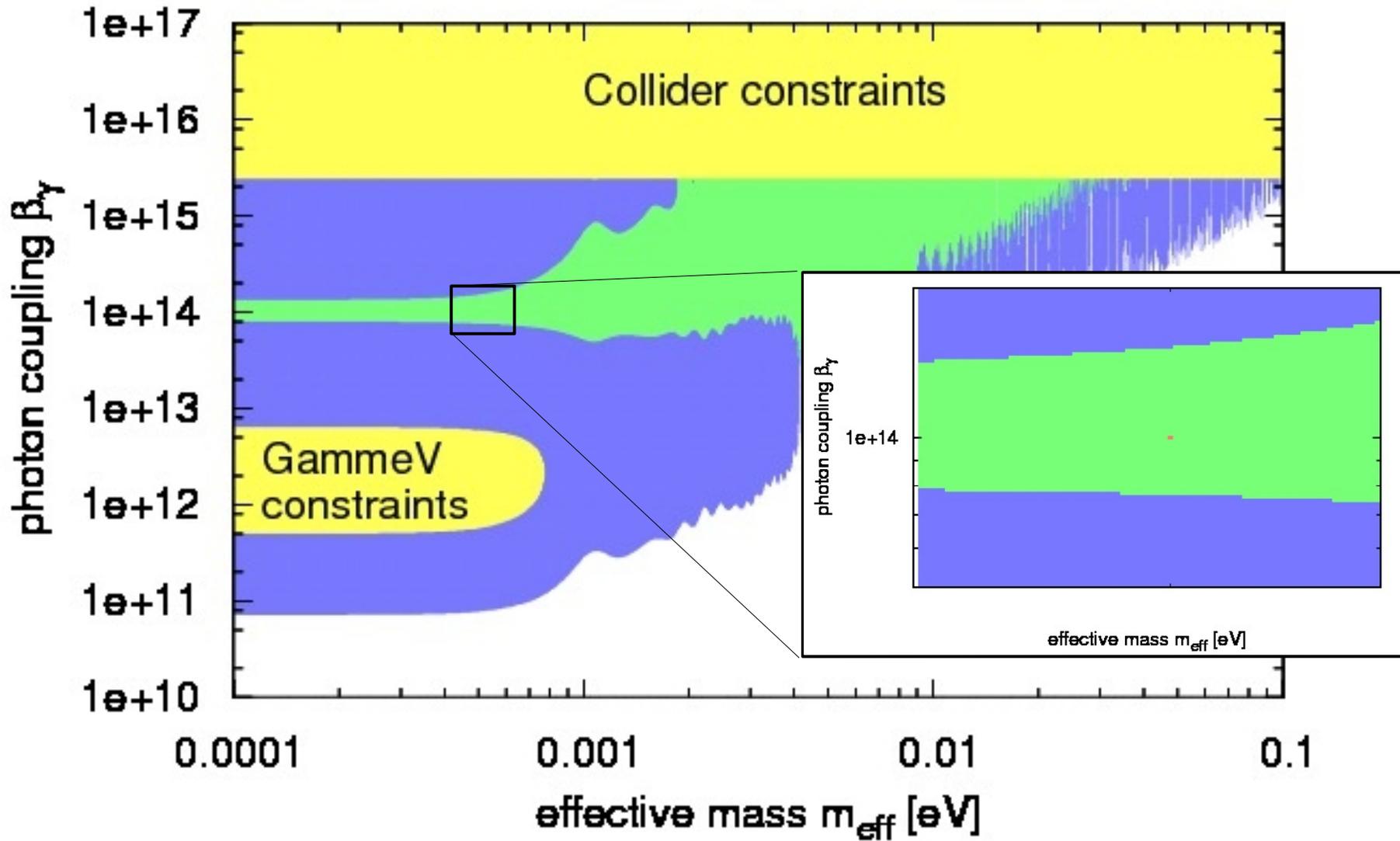
Photons and Chameleon Dark Energy

- equations of motion: $\partial_\mu \left(e^{\frac{\beta_\gamma \phi}{M_{\text{Pl}}}} F^{\mu\nu} \right) = 0$
 - the other two of Maxwell's equations stay the same
- plane wave perturbations about background fields
(assuming $\vec{B} = B_0 \hat{x}$)
 - $\left(-\frac{\partial^2}{\partial t^2} - \vec{k}^2 \right) \Psi_\phi = m_{\text{eff}}^2 \Psi_\phi + \frac{\beta_\gamma k B_0}{M_{\text{Pl}}} \hat{x} \cdot \vec{\Psi}_\gamma$
 - $\left(-\frac{\partial^2}{\partial t^2} - \vec{k}^2 \right) \vec{\Psi}_\gamma = \frac{\beta_\gamma k B_0}{M_{\text{Pl}}} \hat{k} \times (\hat{x} \times \hat{k}) \Psi_\phi$
- example: $\phi \rightarrow \gamma$ oscillations in relativistic case
 - $\mathcal{P}_{\gamma \leftrightarrow \phi} = \vec{\Psi}_\gamma \cdot \vec{\Psi}_\gamma^* = \frac{4k^2 \beta_\gamma^2 B_0^2}{m_{\text{eff}}^4 M_{\text{Pl}}^2} \sin^2 \left(\frac{m_{\text{eff}}^2 t}{4k} \right) |\hat{k} \times (\hat{x} \times \hat{k})|^2$
 - photon production rate: $\Gamma = \frac{\mathcal{P}_{\gamma \leftrightarrow \phi}(t_M)}{t_M}$

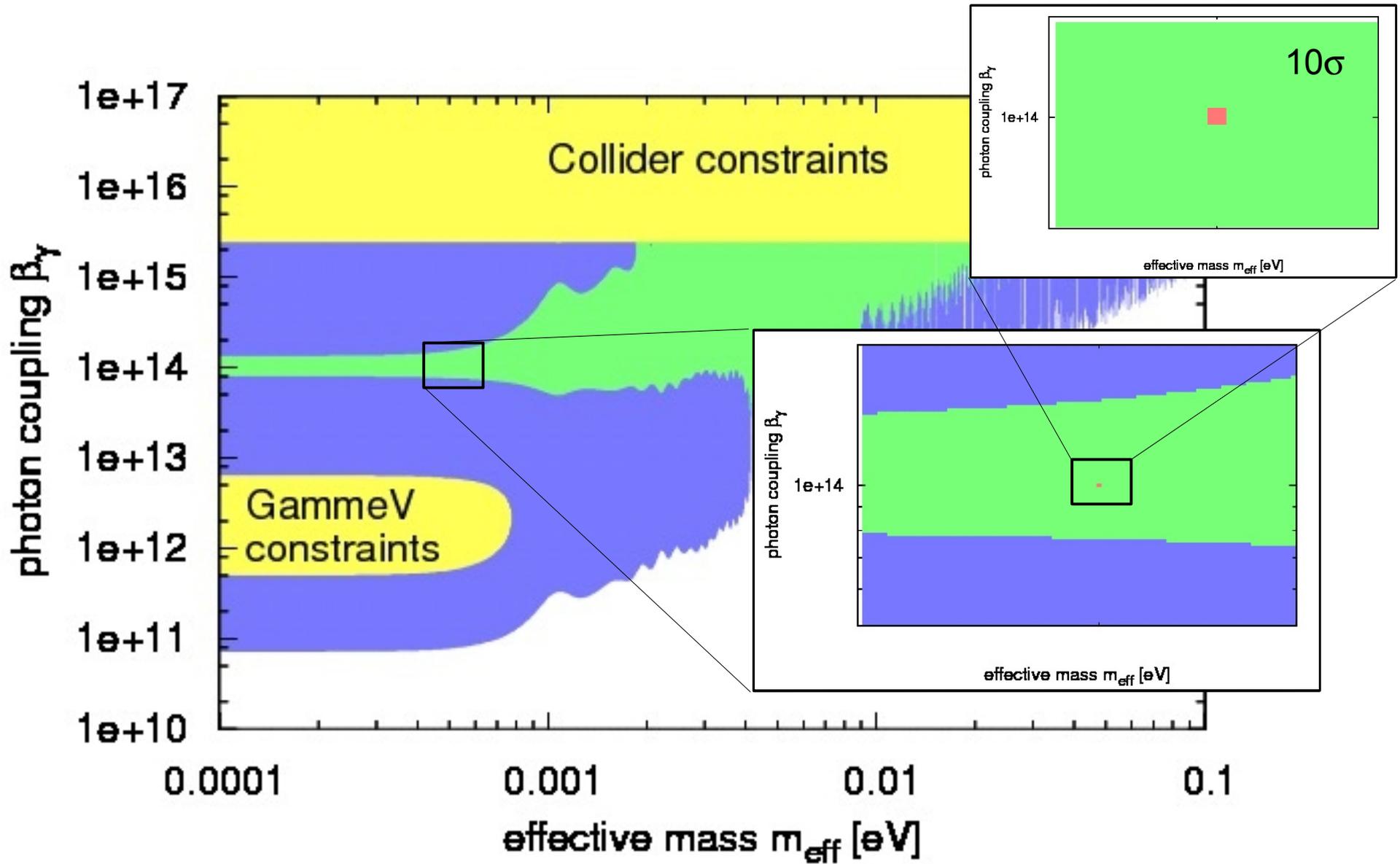
What if...



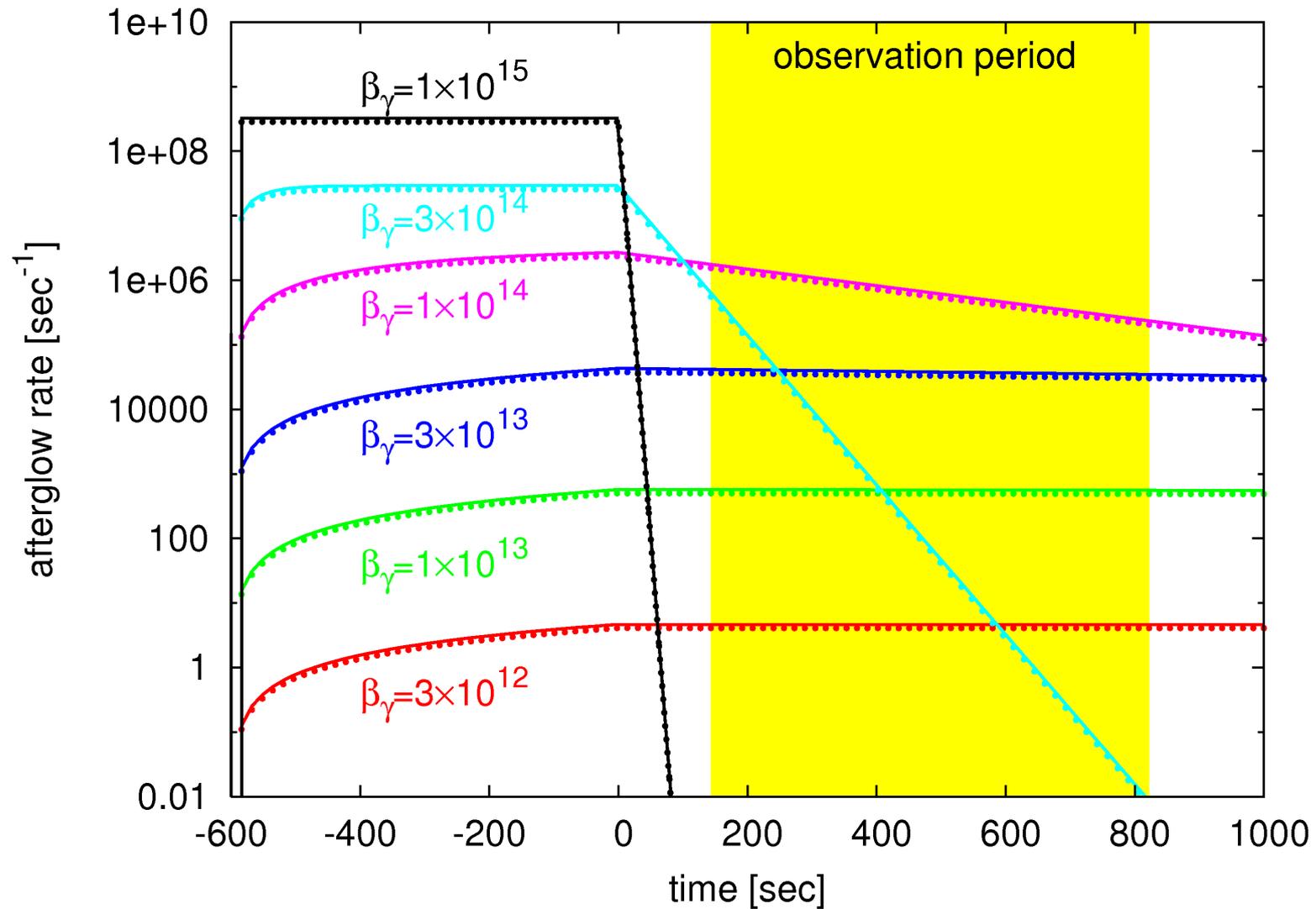
What if...



What if...



Expected Signal



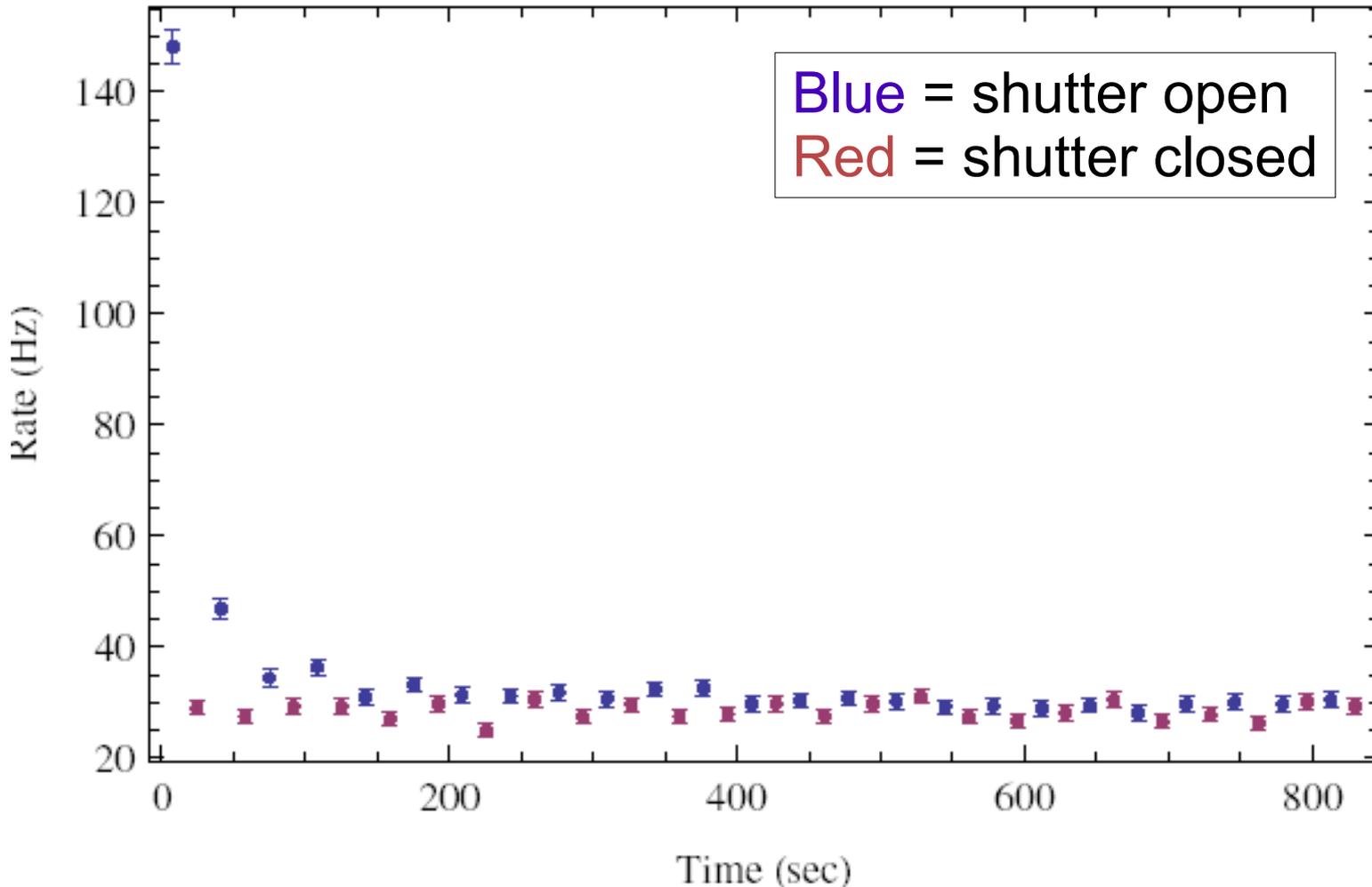
solid lines: $m_{\text{eff}} = 1 \times 10^{-4} \text{ eV}$

dotted lines: $m_{\text{eff}} = 5 \times 10^{-4} \text{ eV}$

CHASE Review

- Take data with two different laser polarizations to search for scalar and pseudoscalar chameleons
- Take data with seven different magnetic field strengths to probe a variety of photon couplings
- Three different partitions allow us to probe a larger range of chameleon masses
- PMT dark rate measured during science run using shutter-closed data
- Calibration data taken before and after (or between) each chameleon science run, excess is subtracted
- Characterized orange glow independently and subtracted it

Example of Raw Science Data



Dark rate and detector systematic variations measured using shutter-closed data.

Chameleon Dark Energy

We consider potentials of the form

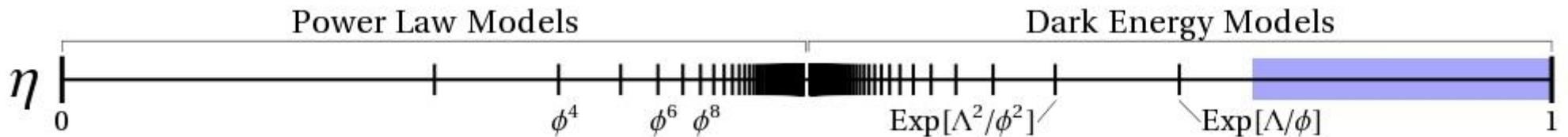
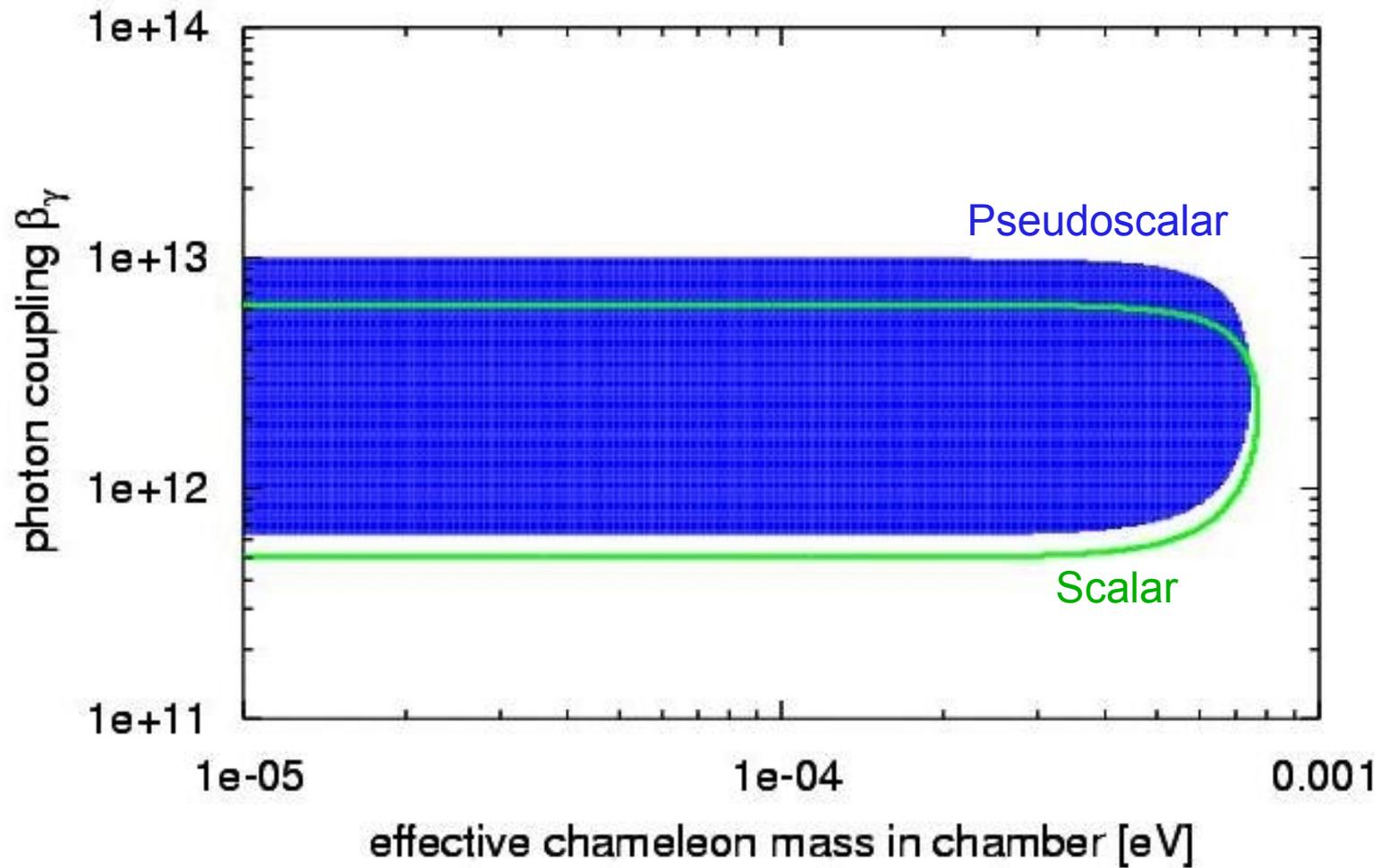
$$V(\phi) = M_{\Lambda}^4 \exp(\phi^N/M_{\Lambda}^N) \approx M_{\Lambda}^4 (1 + \phi^N/M_{\Lambda}^N)$$

- M_{Λ} is the dark energy scale, $2.4 \times 10^{-3} \text{eV}$

In bulk matter density ρ , m_{eff} scales as ρ^{η}

- $\eta = (N-2)/(2N-2)$
- $\eta = 1/3$ for ϕ^4 theory, $\eta = 3/4$ for $1/\phi$ model

Constraints from GammeV



Constraints from GammeV

