Laser Probes of the Dark Sector

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CERN
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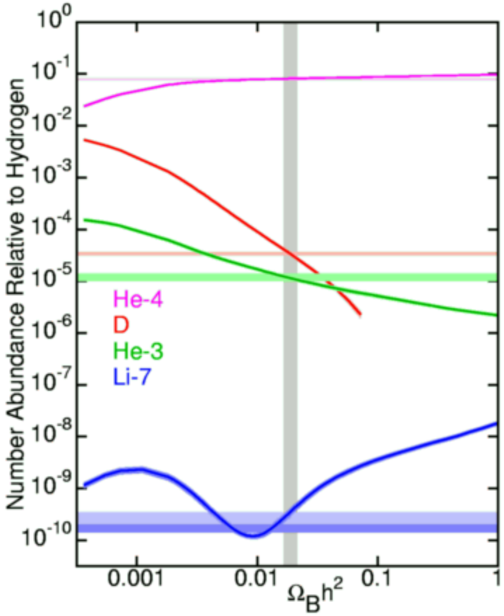
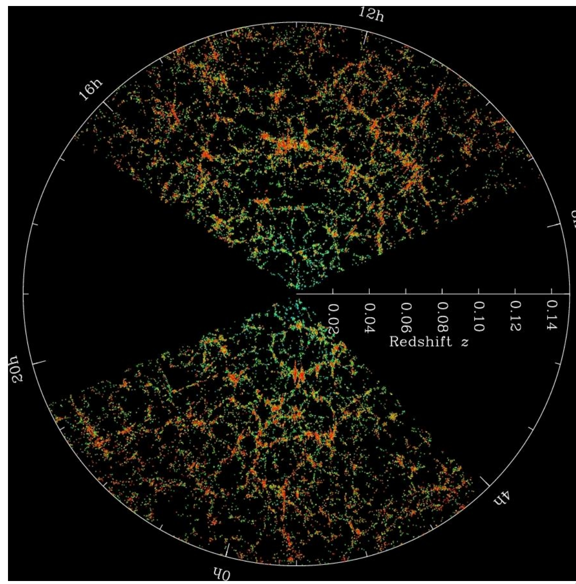
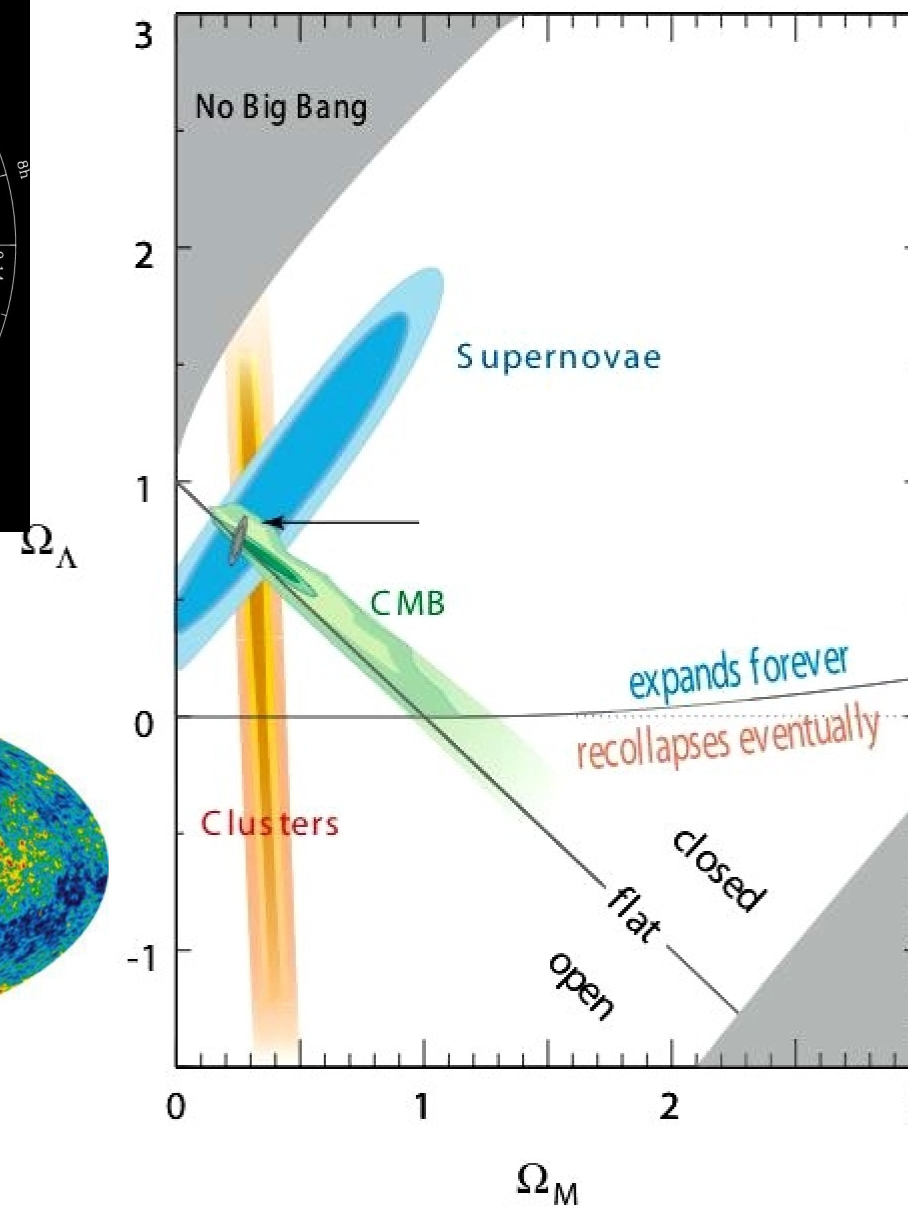
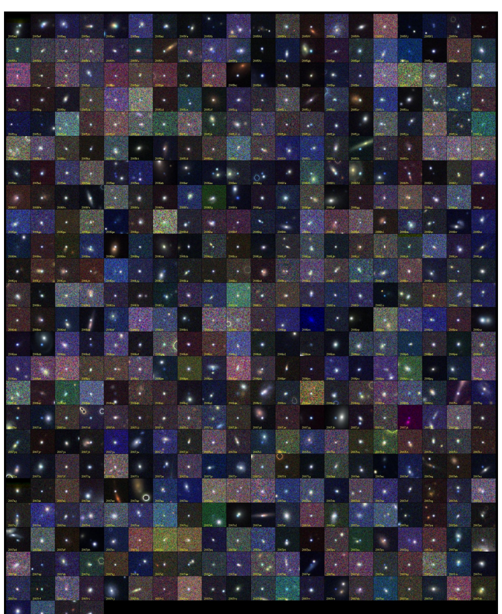
The Dark Sector

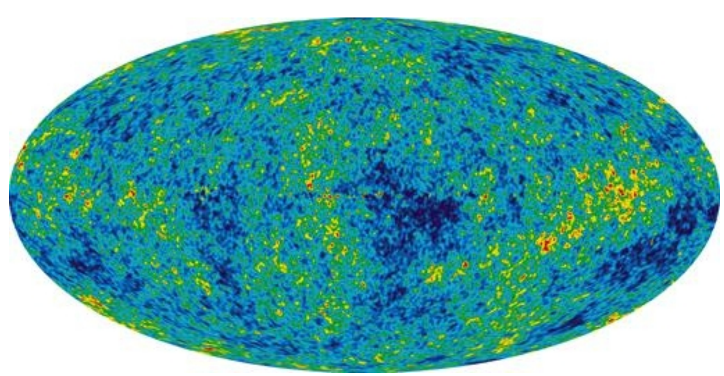
dark matter, dark energy, gravity











Dark Matter WIMPs

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

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Who is looking for WIMP dark matter?

Dark Matter WIMPs

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~~Who is looking for WIMP dark matter?~~

Who isn't looking for WIMP dark matter?

Axions, the other dark matter

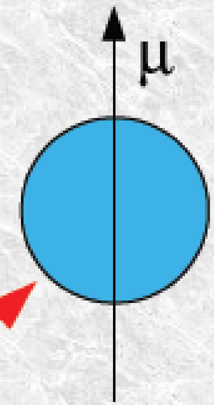
Axions, the other dark matter

The QCD Lagrangian has this

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

which should be of order unity.

This would give the neutron an electric dipole moment.

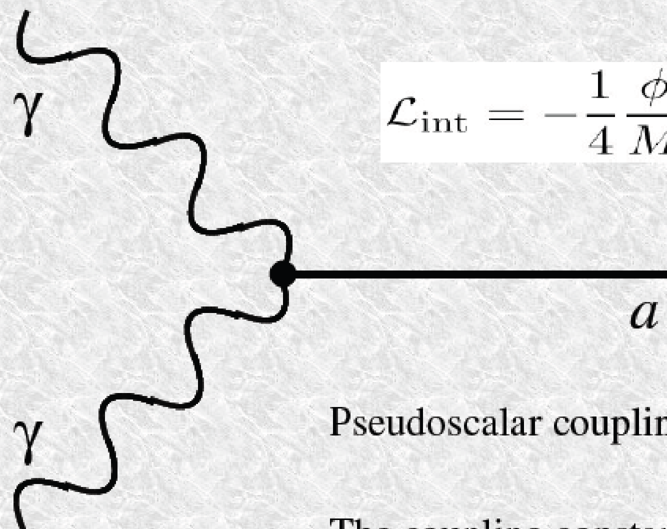


Measurements indicate that θ must be less than ~10^{-10}.

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

Axions, the other dark matter

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



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

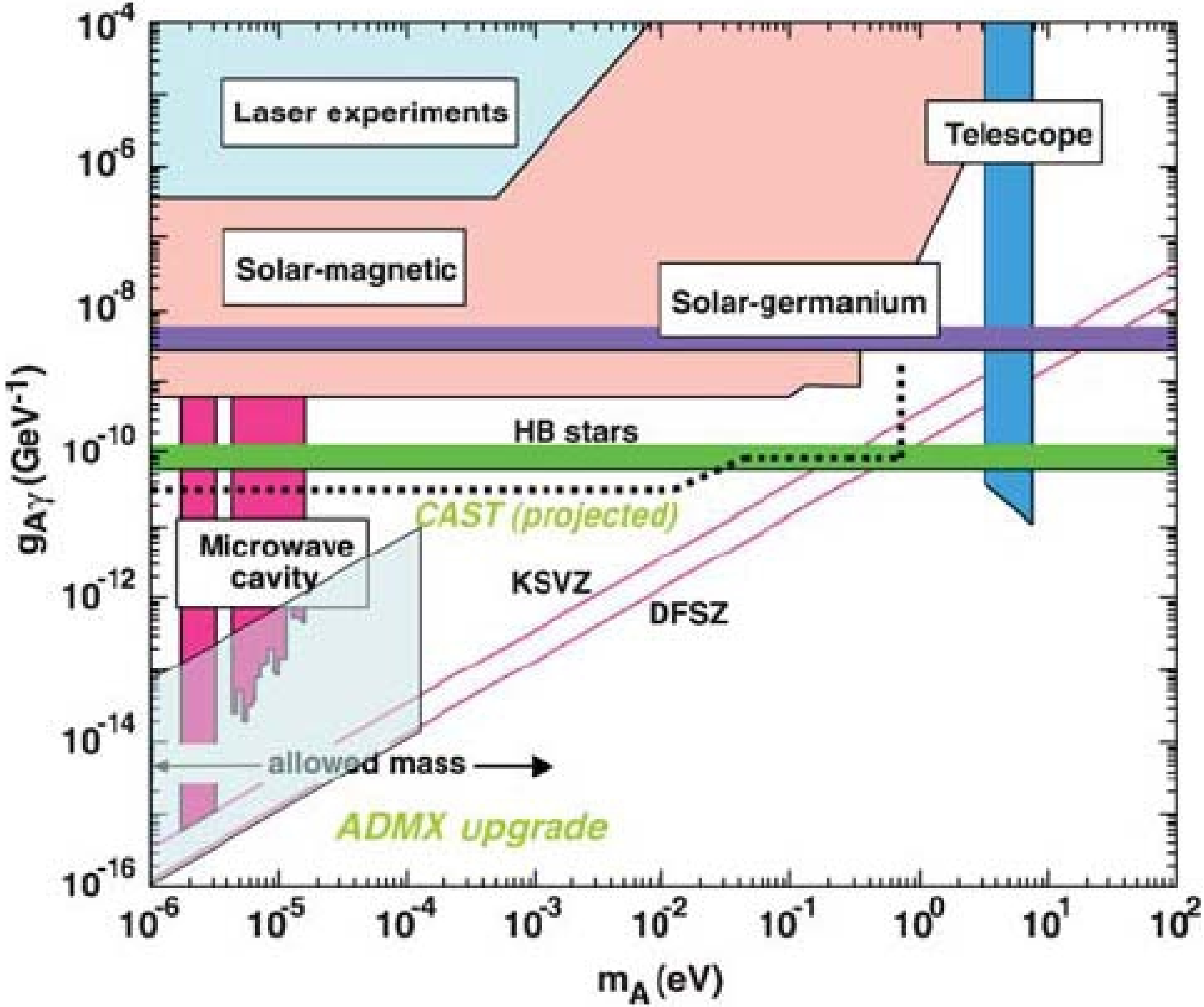
Pseudoscalar coupling to two photons.

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



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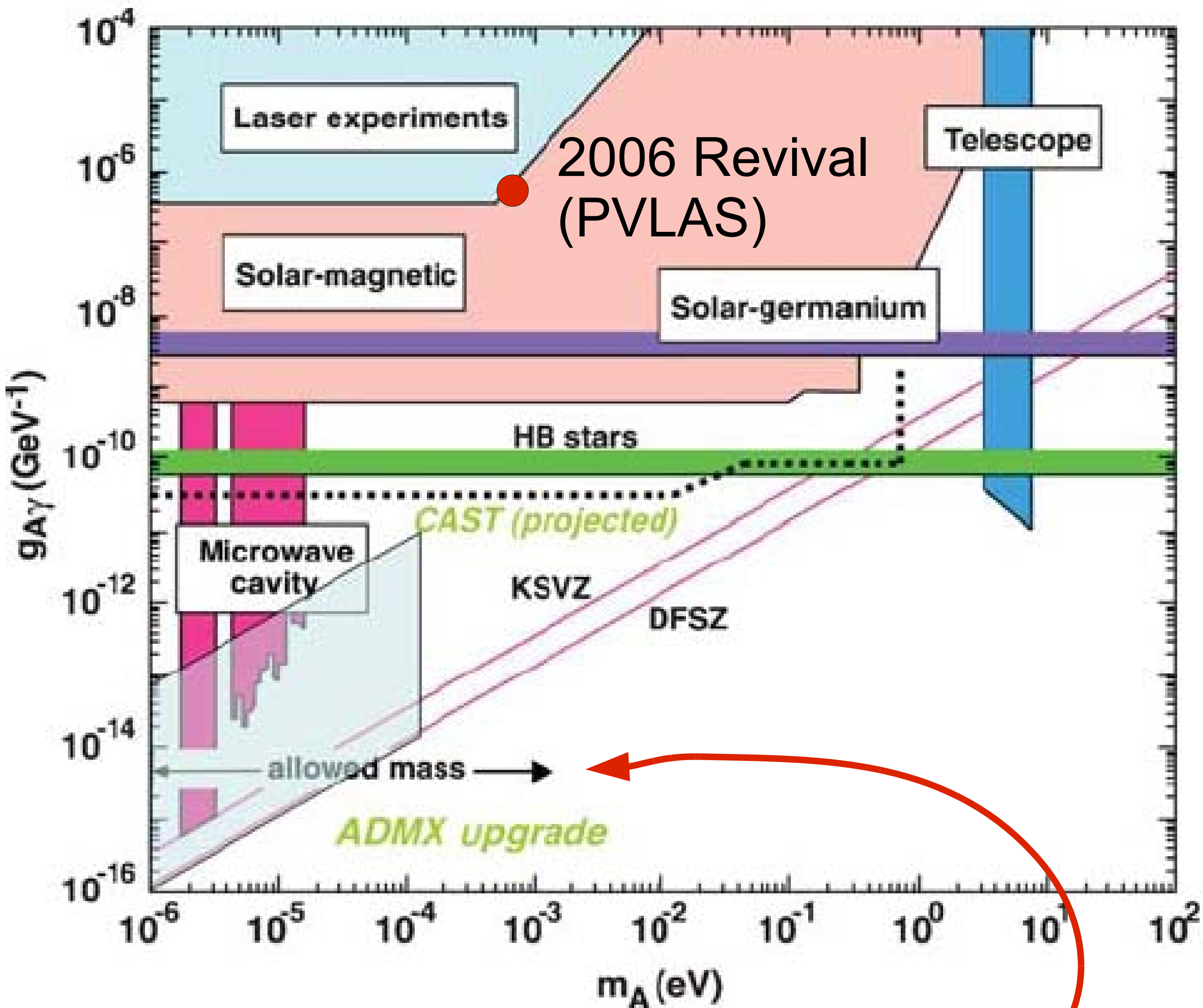
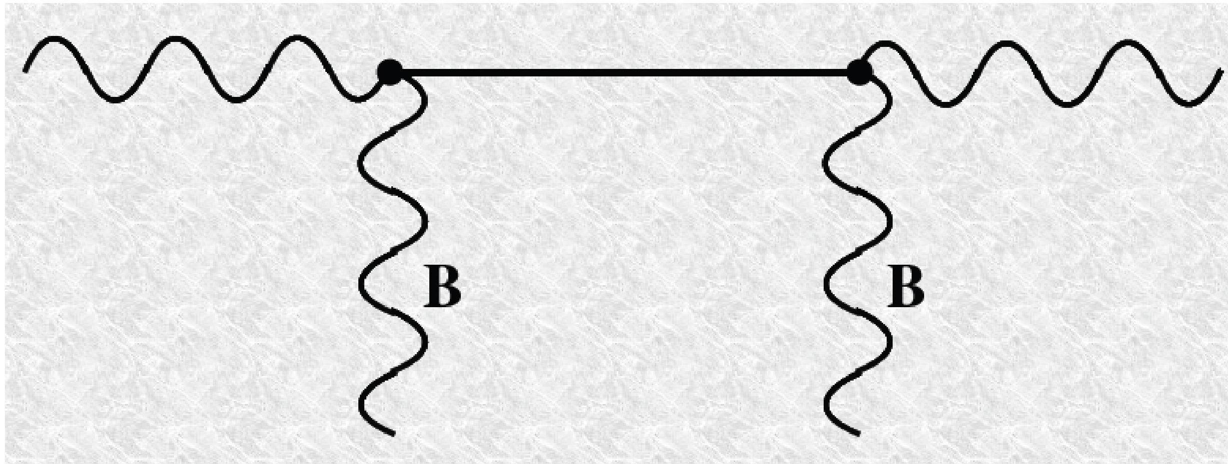
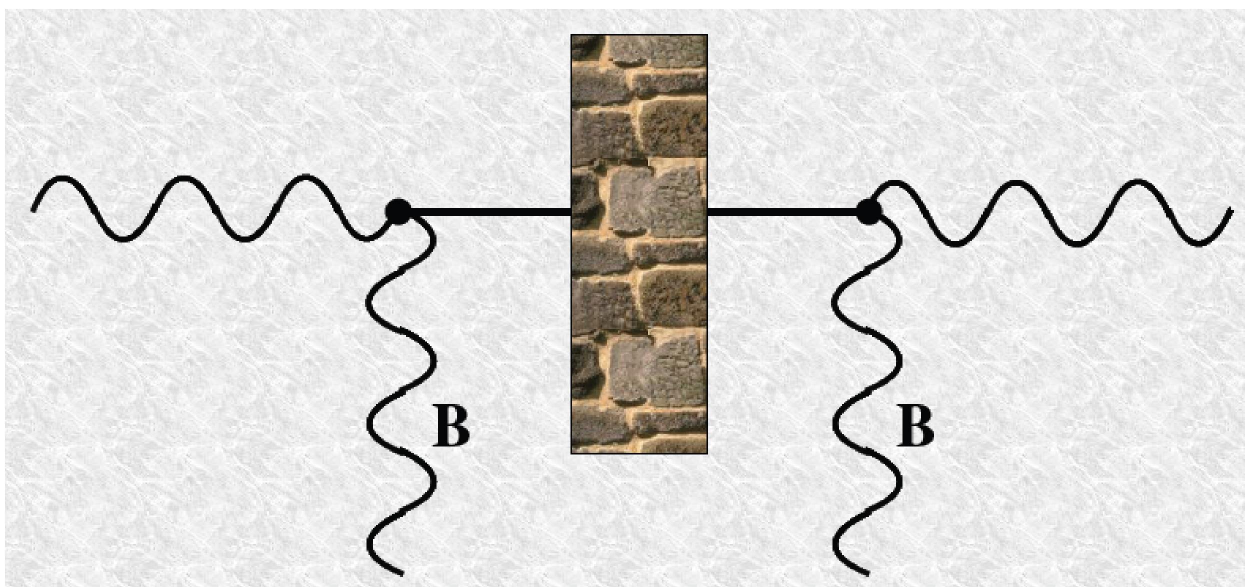


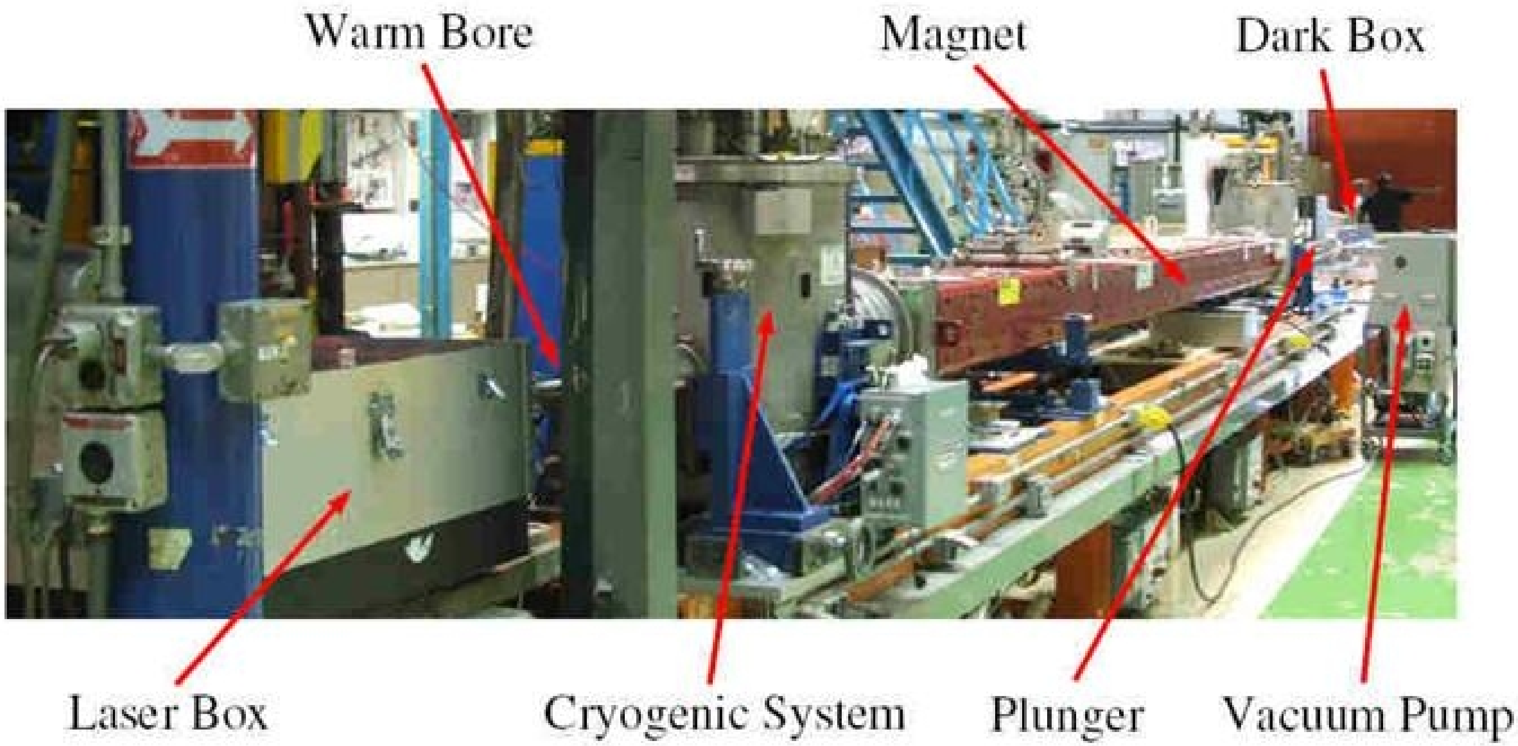
If axions are the dark matter, they would live here.

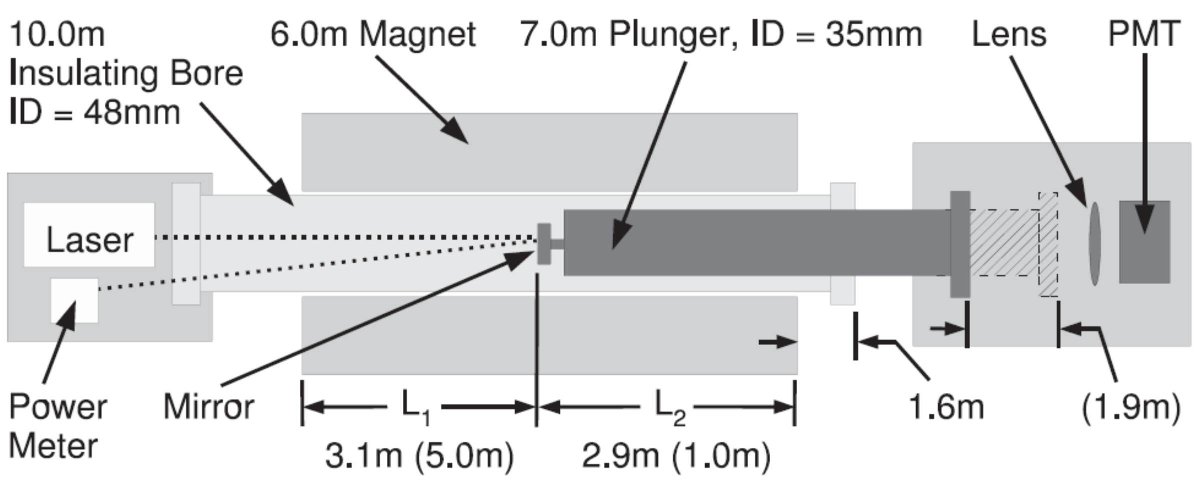
Laser searches for axion-like particles





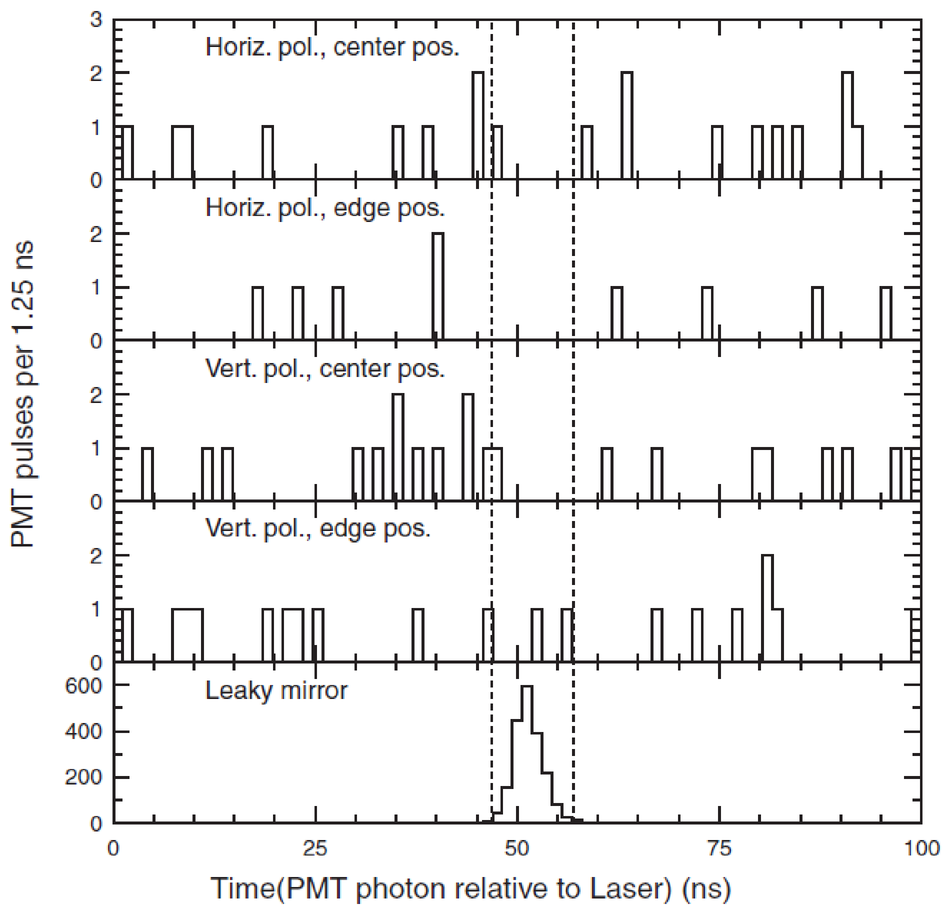
GammeV search for axion-like particles

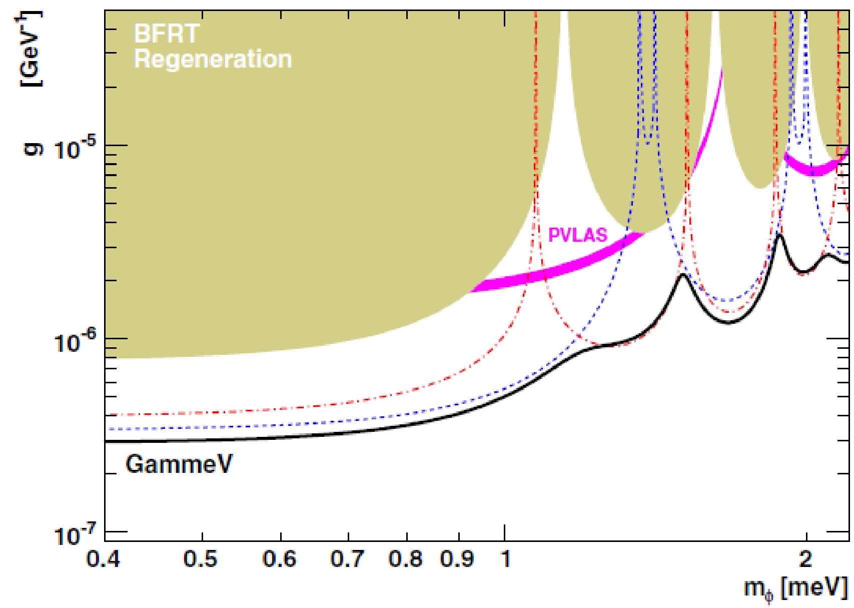


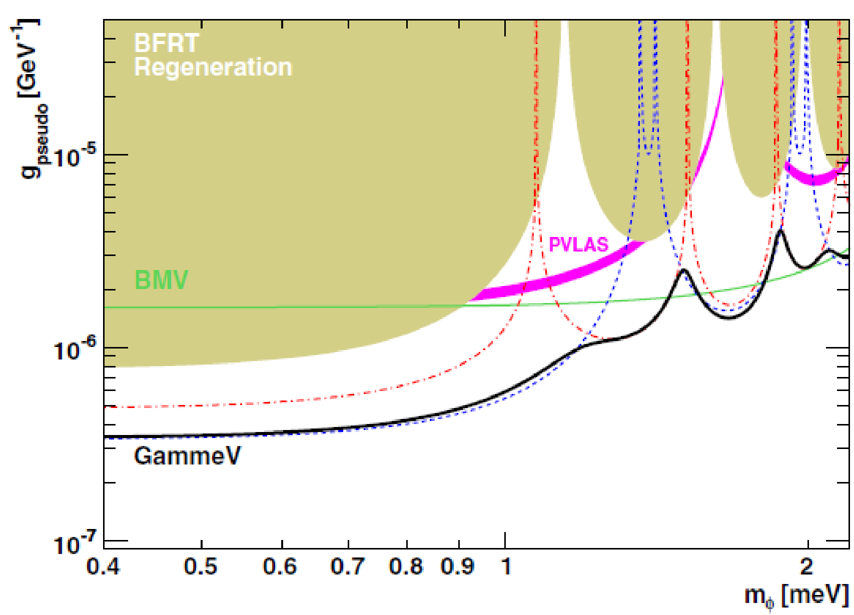


GammeV search for axion-like particles

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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hc ~ 1meV mm

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Optical Photons

Dark Energy

Situation somewhat similar to axions.

The vacuum should have some energy density,

$$E_{\mathrm{ground}} = \frac{1}{2}\hbar\omega$$ for each “smallest” box.

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Slight discrepancy

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Ask Santa Claus 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...

If something moves but it shouldn't...

Theorist

Physicists Toolkit

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

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Theorist

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

Physicists Toolkit

Experimentalist

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

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Theorist

$$\Phi$$

(scalar field)
If something should move but it doesn't...

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

Experimental Evidence for Scalar Fields

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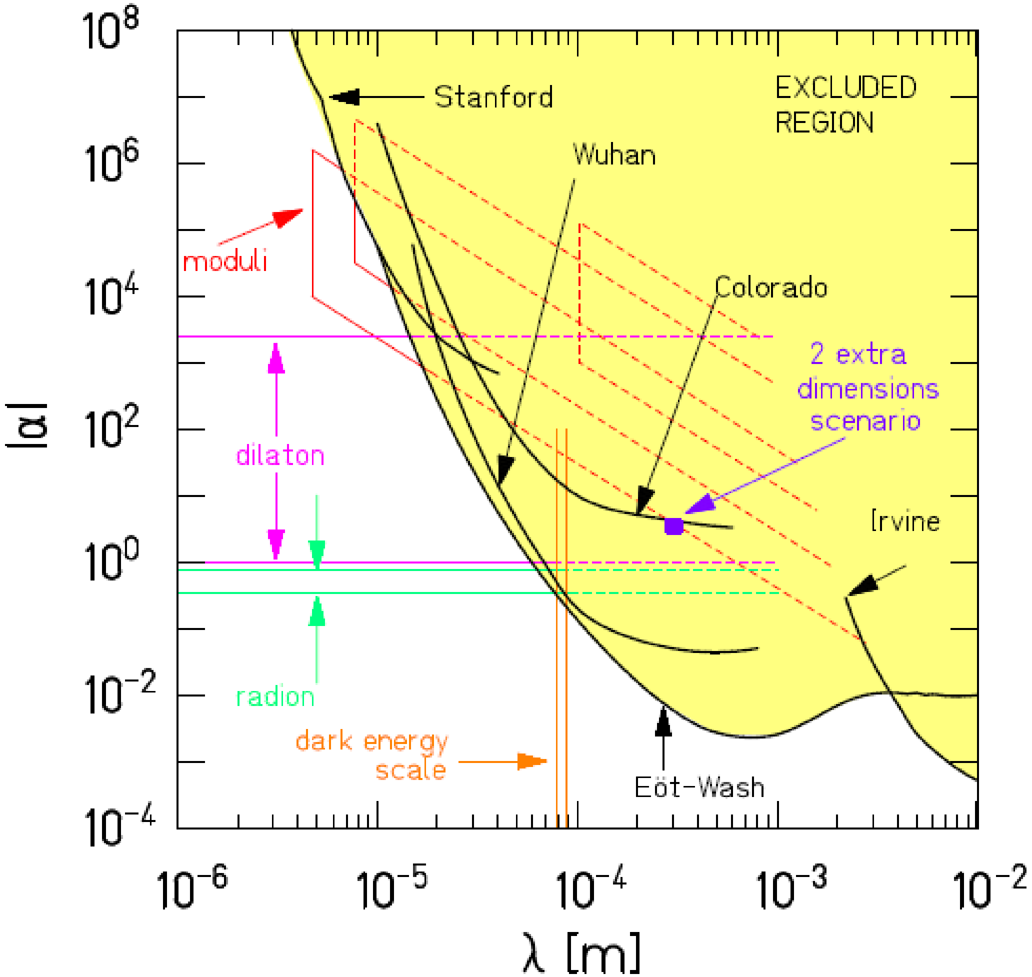
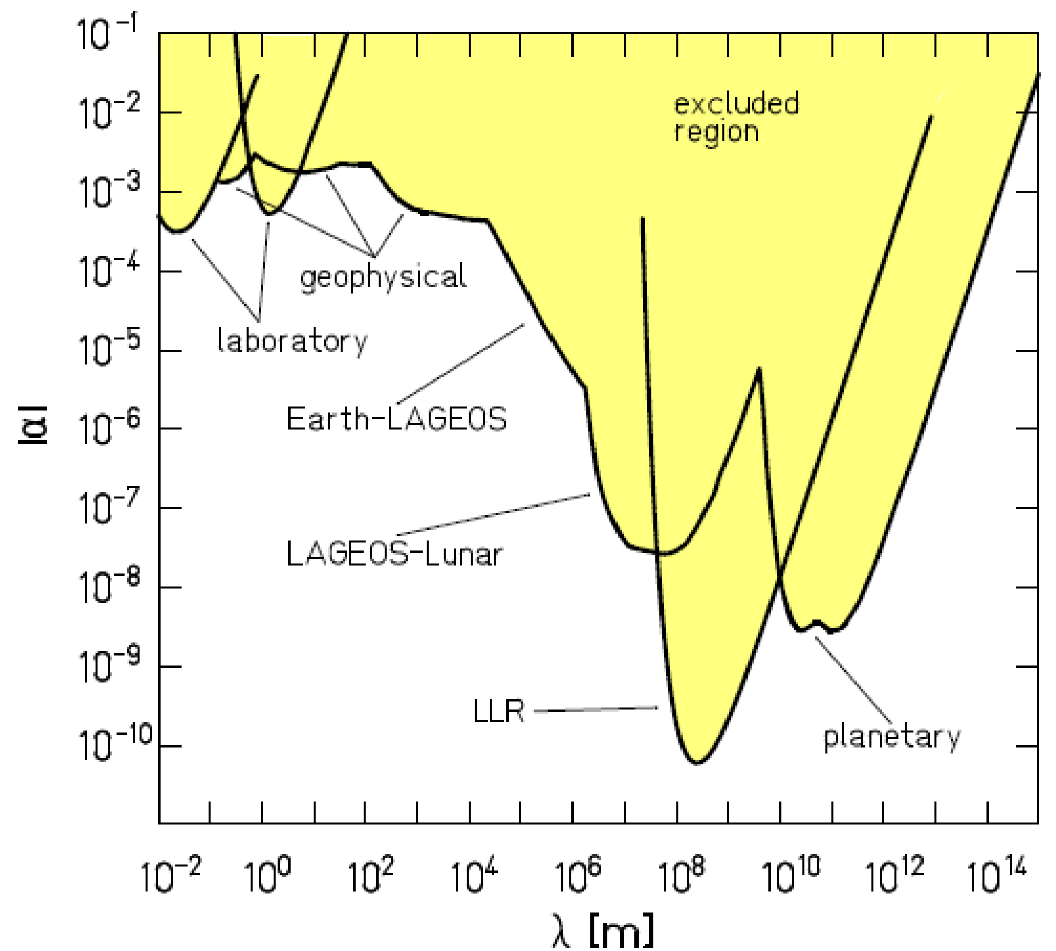
$$V = -\frac{GM}{r}\left(1 + \alpha \frac{e^{-r/\lambda}}{r}\right)$$





How do you hide a scalar field?

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

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

Vainshtein

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

symmetron

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

chameleon

Slides stolen from Justin Khoury

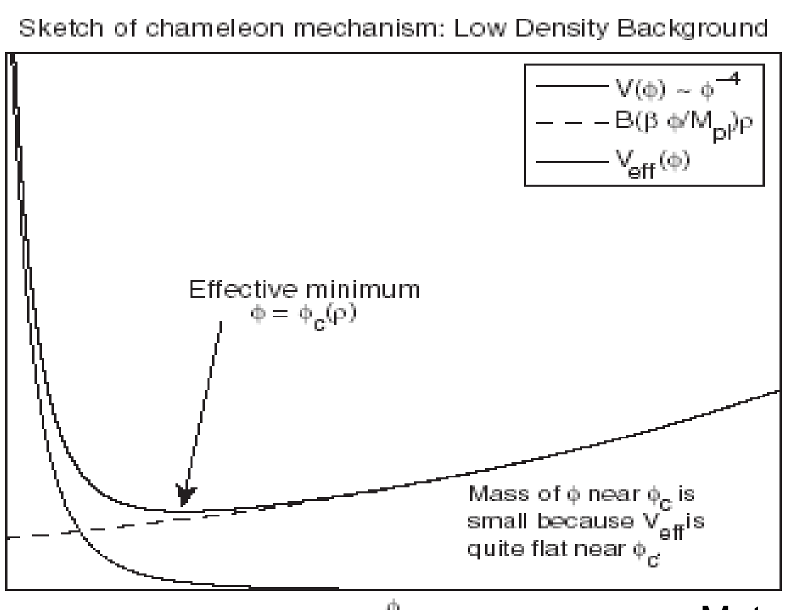
The Chameleon Effect

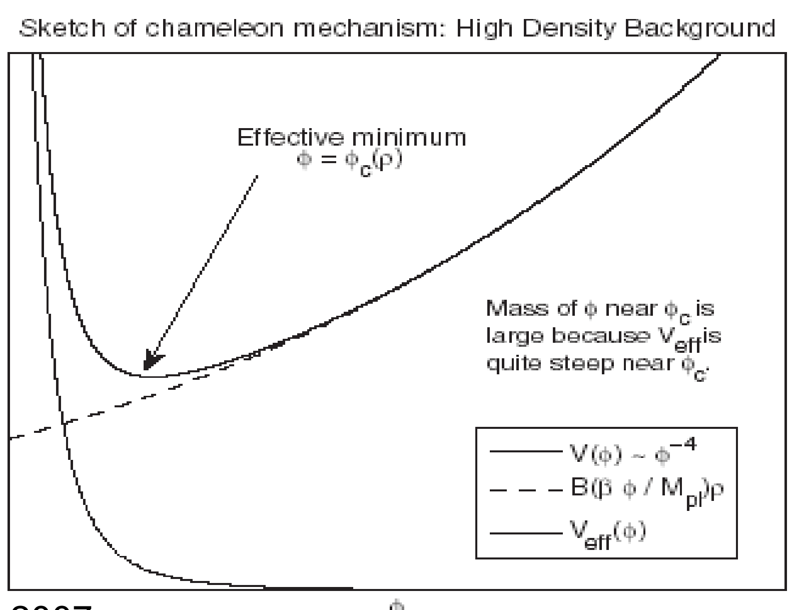
$$S = \int d^4x \sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}e^{\frac{\beta_\gamma\phi}{M_{\rm Pl}}}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_m(e^{\frac{2\beta_{\mathbf{m}}\phi}{M_{\rm Pl}}}g_{\mu\nu}, \psi_{\mathbf{m}}^{(i)})\right]$$

chameleon potential

photon coupling

matter coupling





Mota & Shaw 2007

Chameleon Dark Energy

We consider potentials of the form

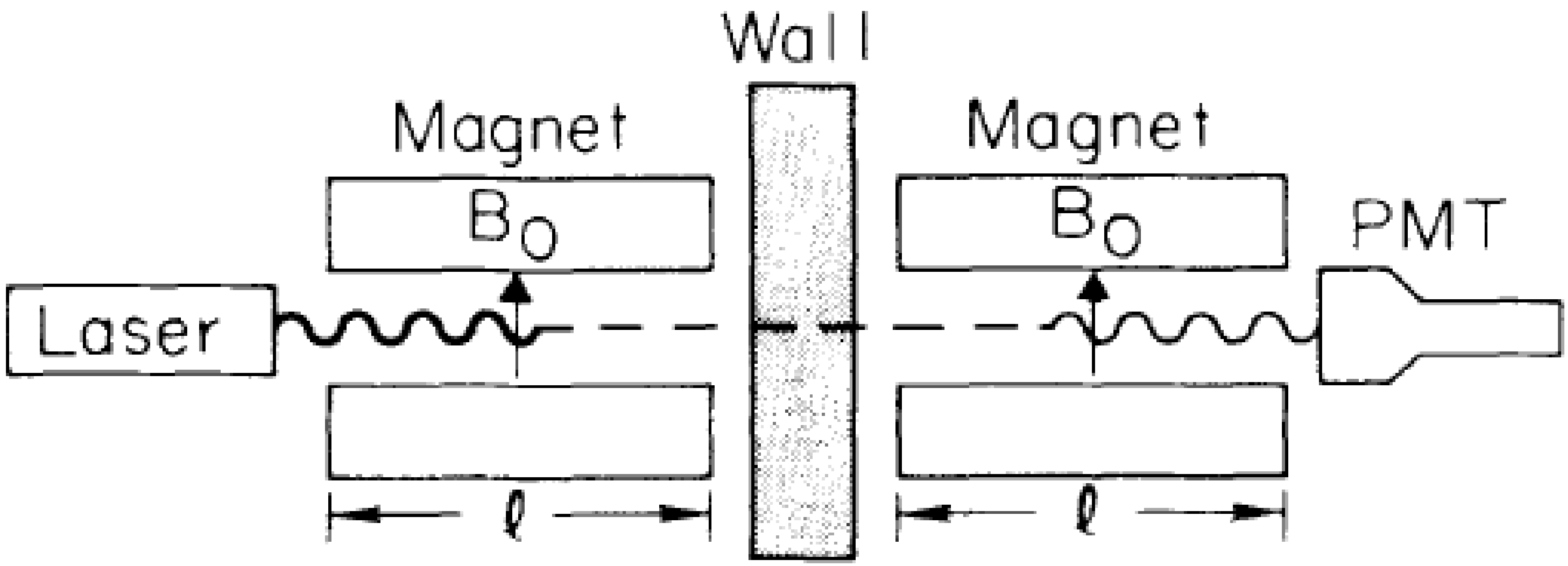
$$V(\phi) = M_\Lambda^4 \exp(\phi^N/M_\Lambda^N) \approx M_\Lambda^4 (1 + \phi^N/M_\Lambda^N)$$

- M_Λ is the dark energy scale, 2.4×10^{-3}eV

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

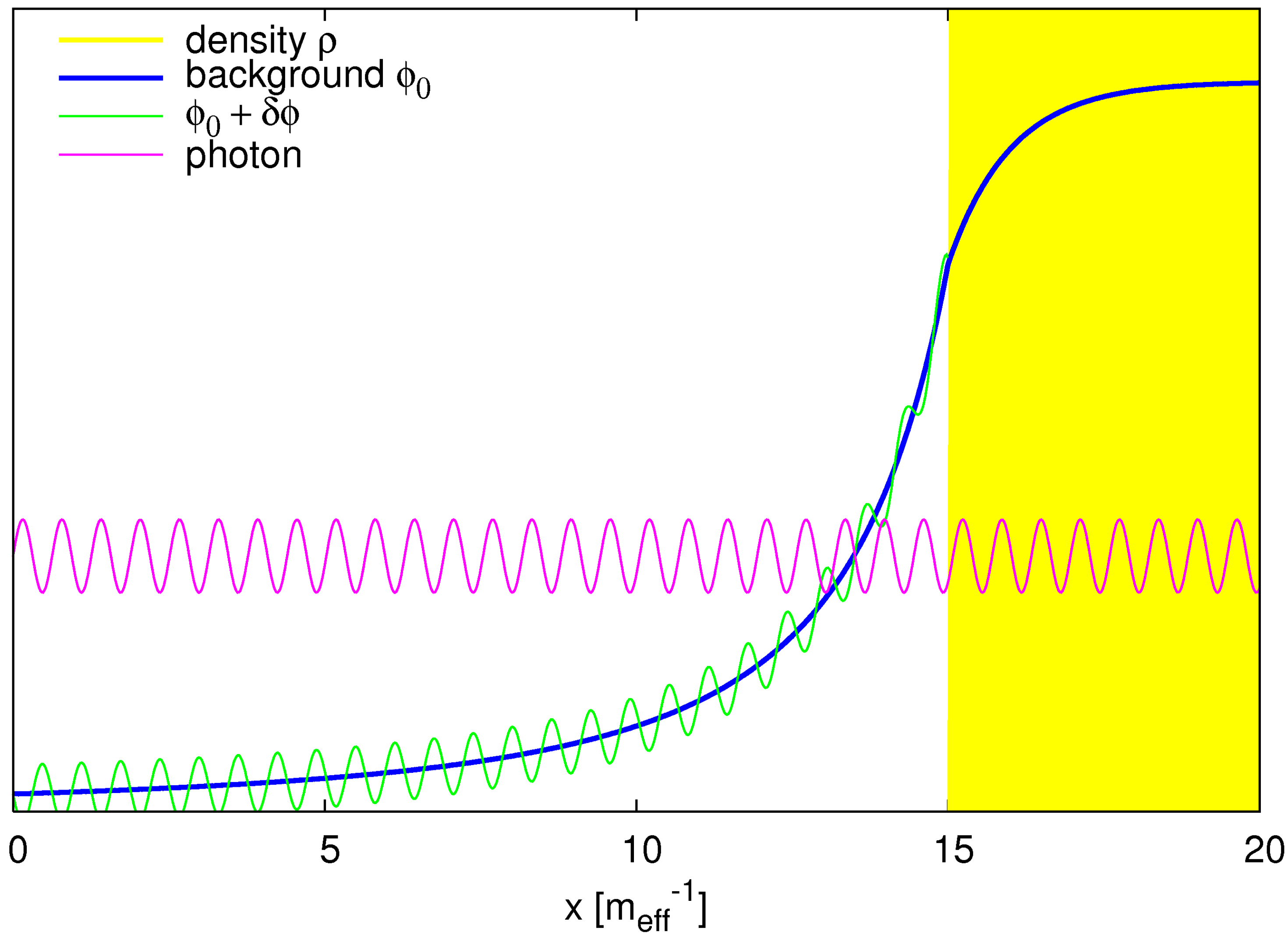
- $\eta=(N-2)/(2N-2)$
- $\eta=1/3$ for ϕ^4 theory, $\eta=3/4$ for $1/\phi$ model

Quantum Measurement: Walls



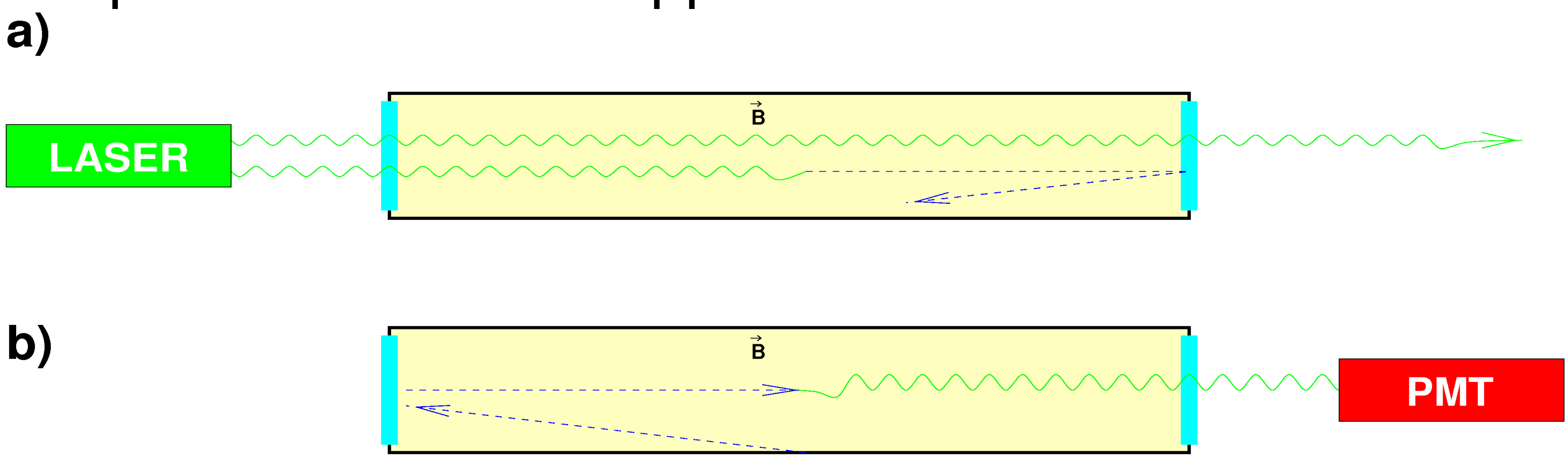
K. Van Bibber, et. al., PRL 59, 759 (1987)

Quantum Measurement: Windows



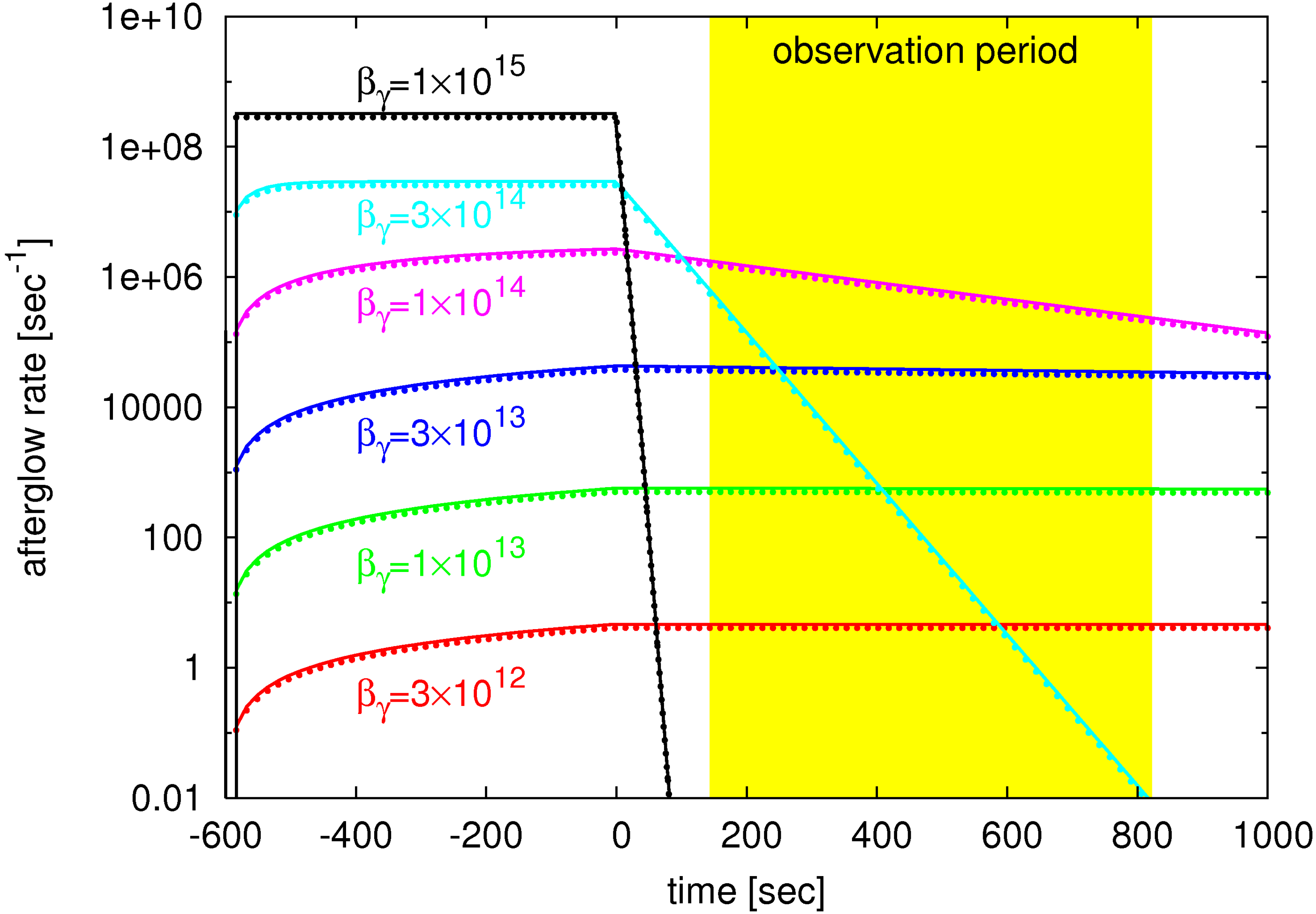
Afterglow Experiment

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



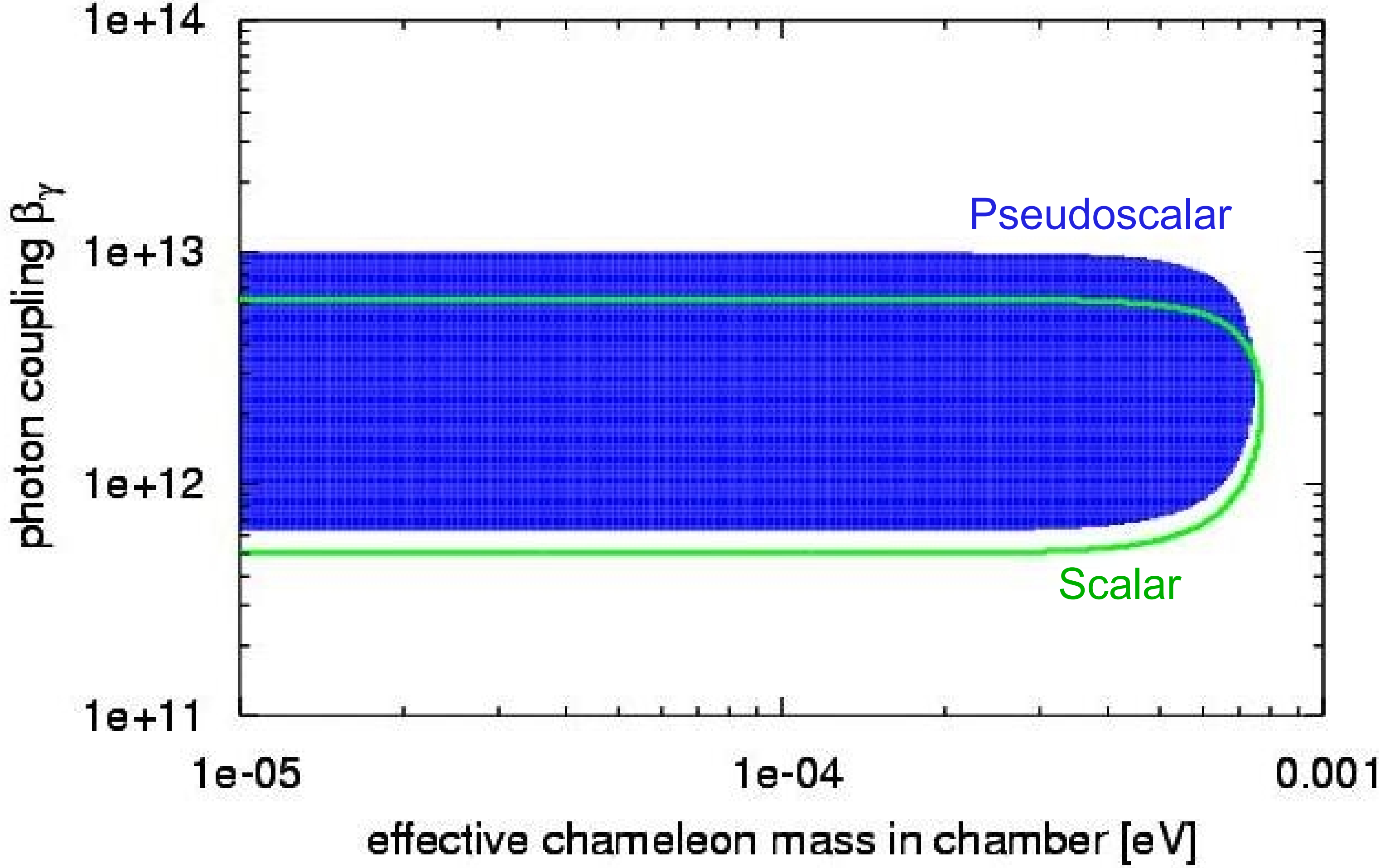
b) afterglow: Turn off the photon source, and wait for chameleon particles to convert back into detectable photons, which emerge through the windows.

Expected Signal



solid lines: $m_{eff}=1x10^{-4}eV$ dotted lines: $m_{eff}=5x10^{-4}eV$

Constraints from GammeV



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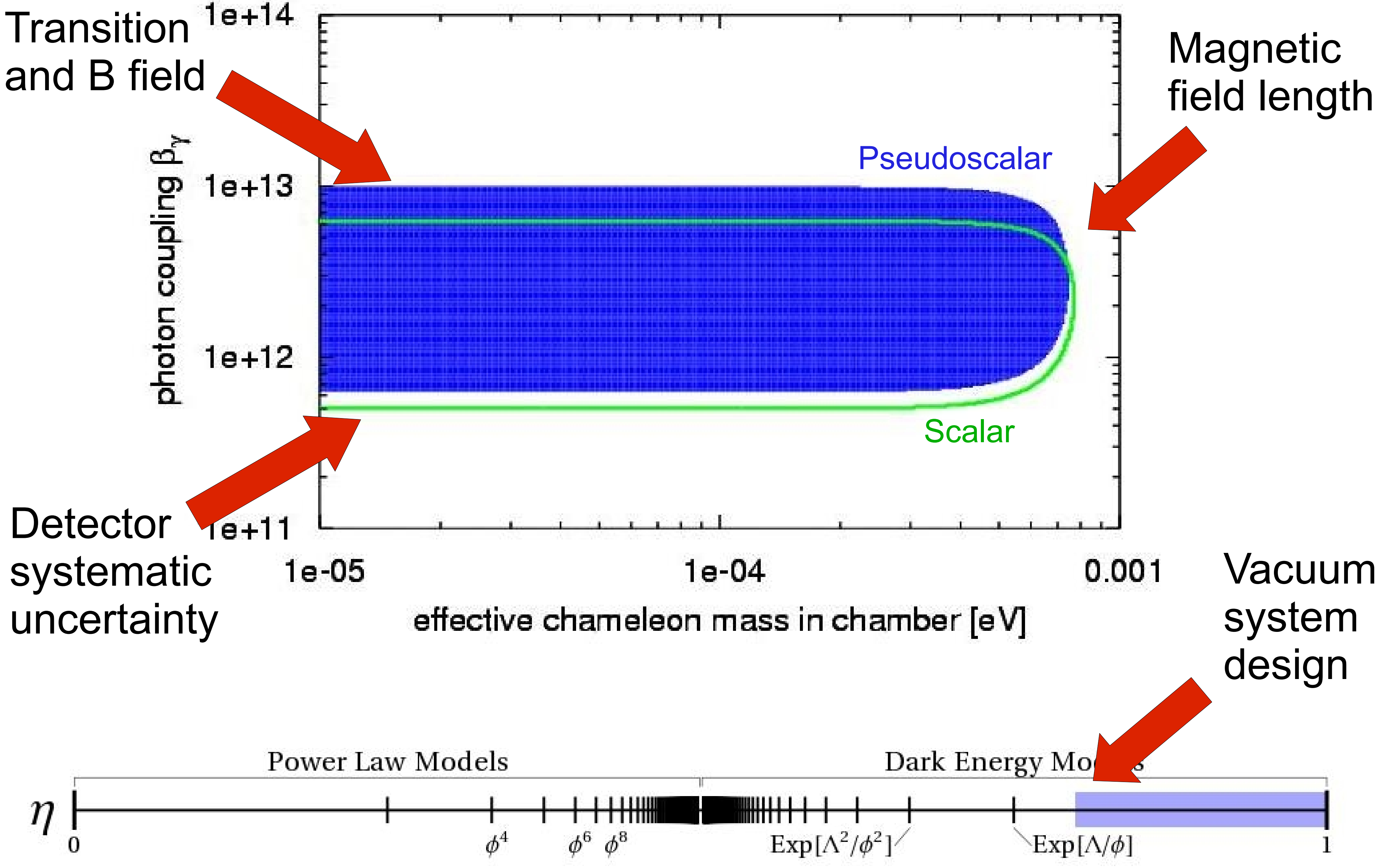
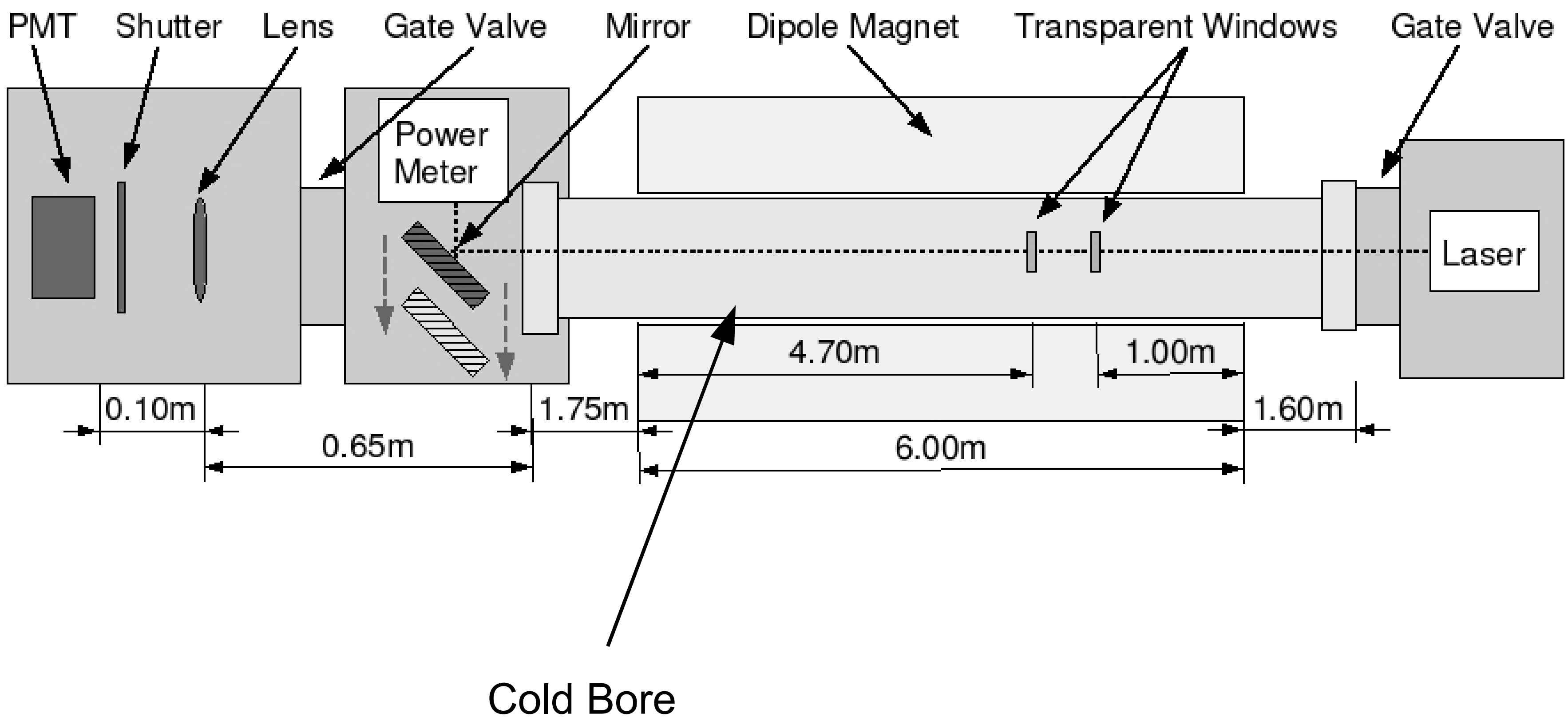


CHASE Schematic



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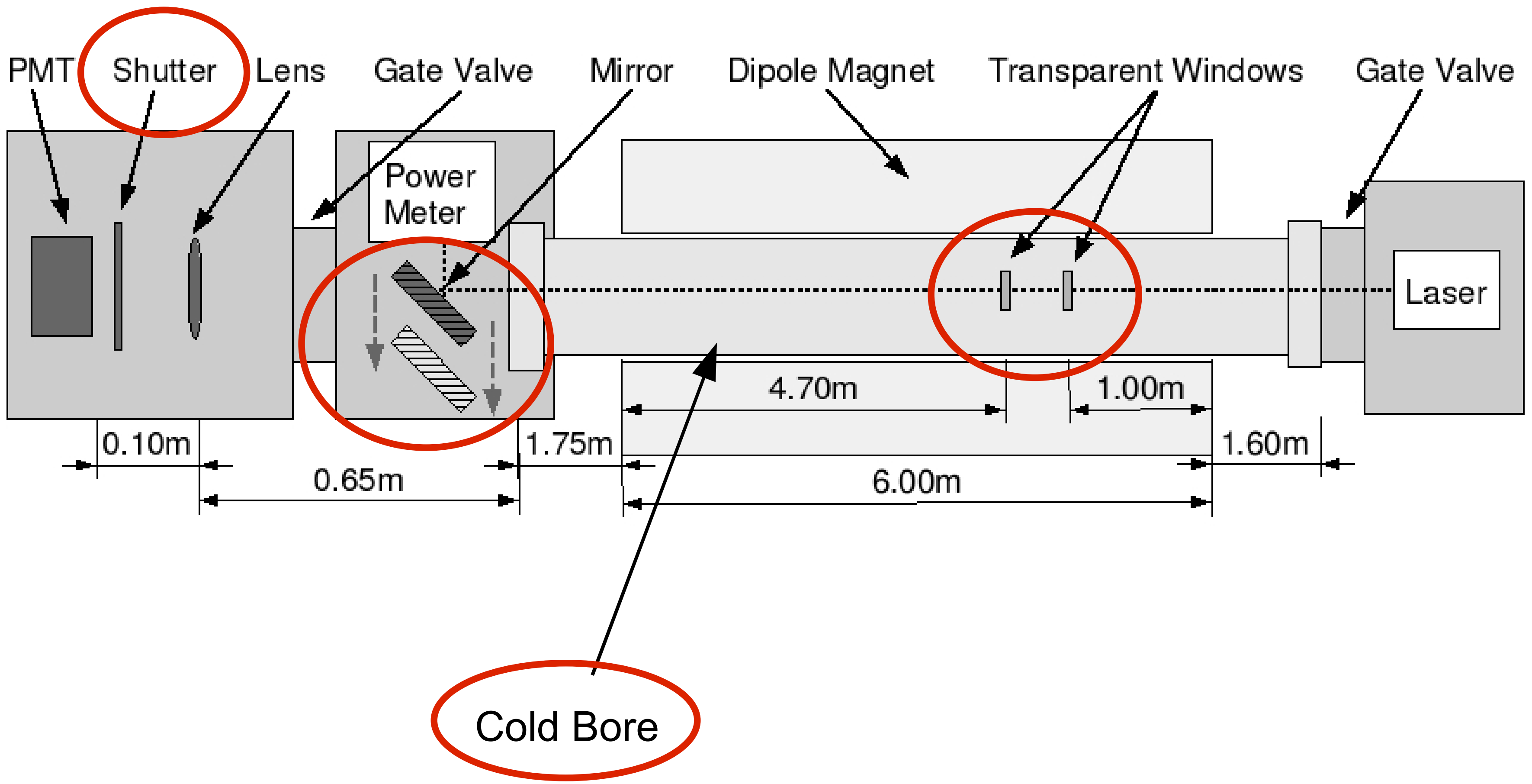
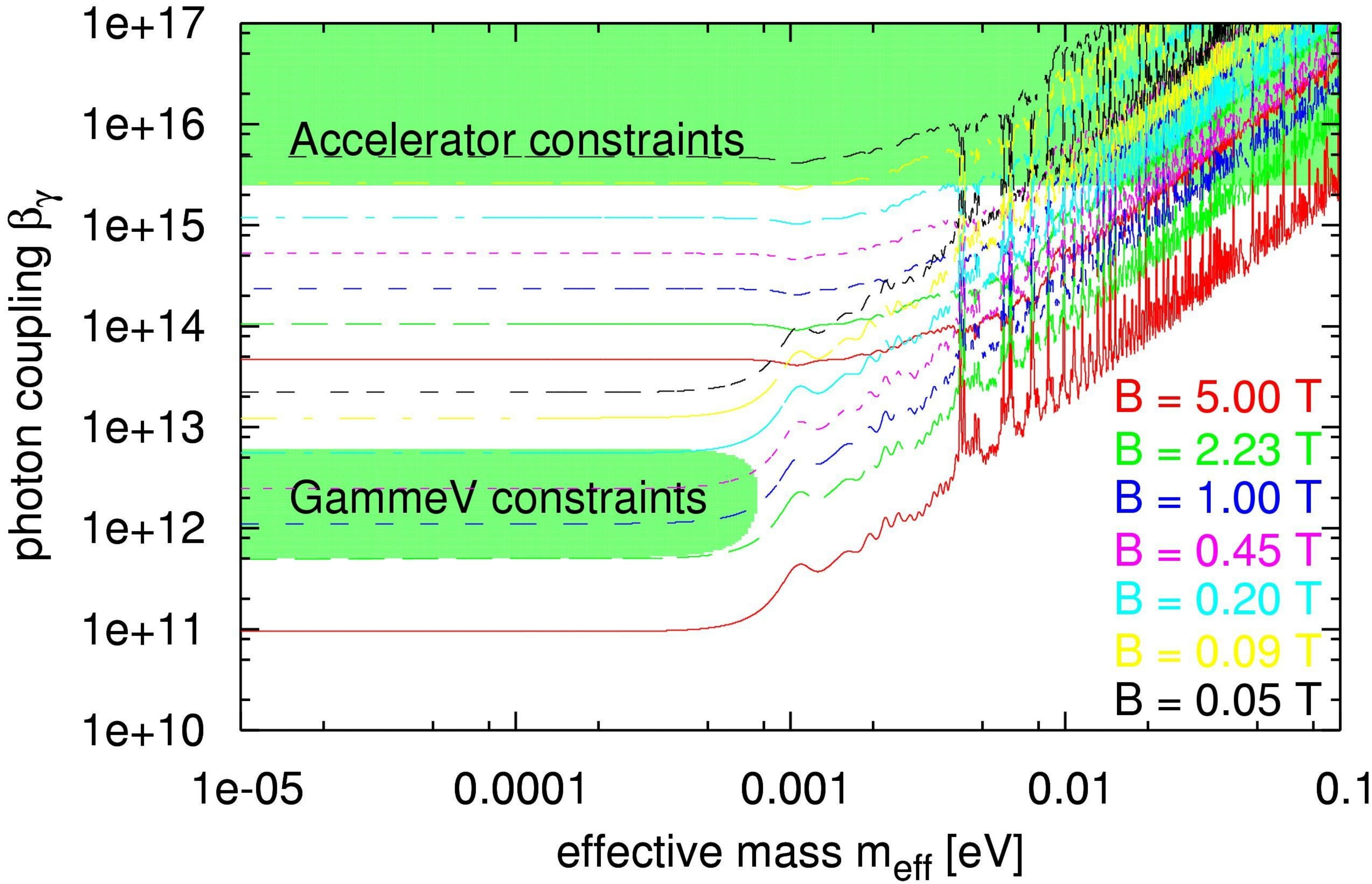
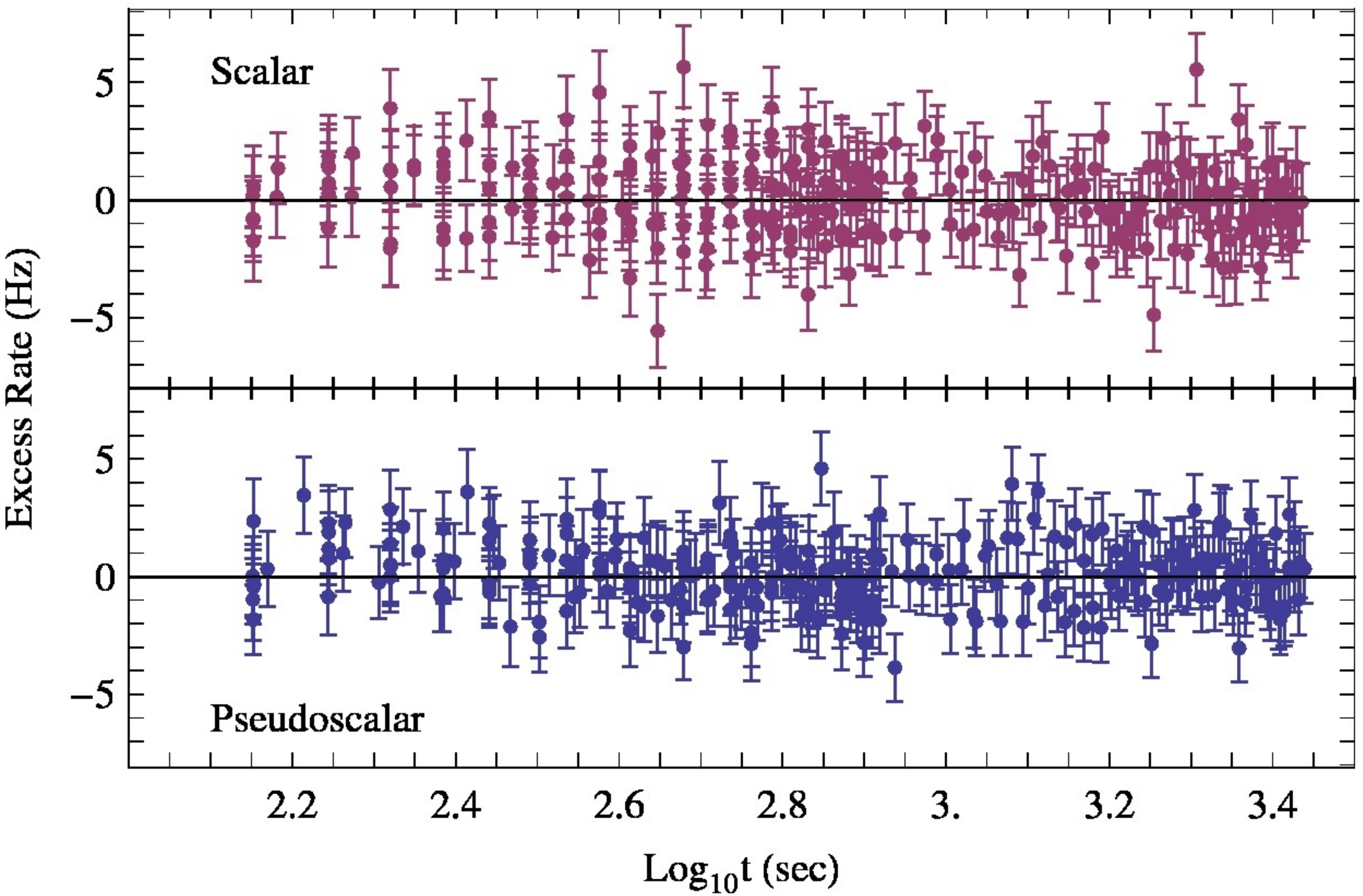


CHASE Experimental Approach



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

CHASE Science Data



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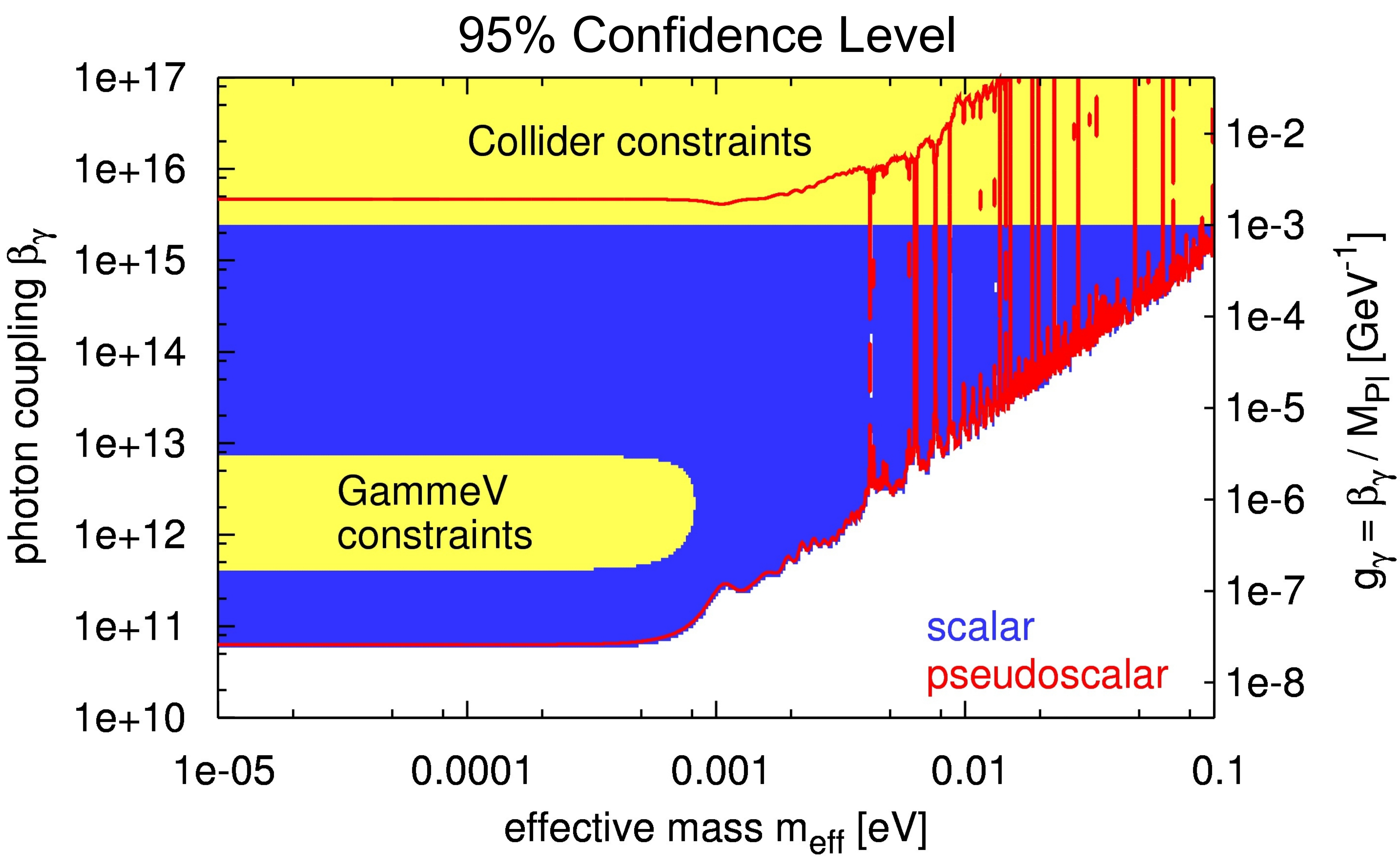

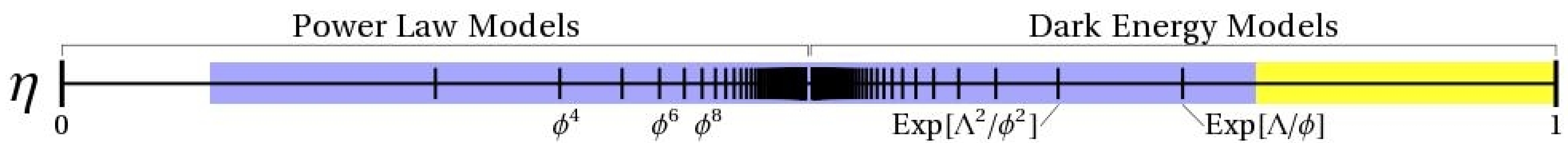

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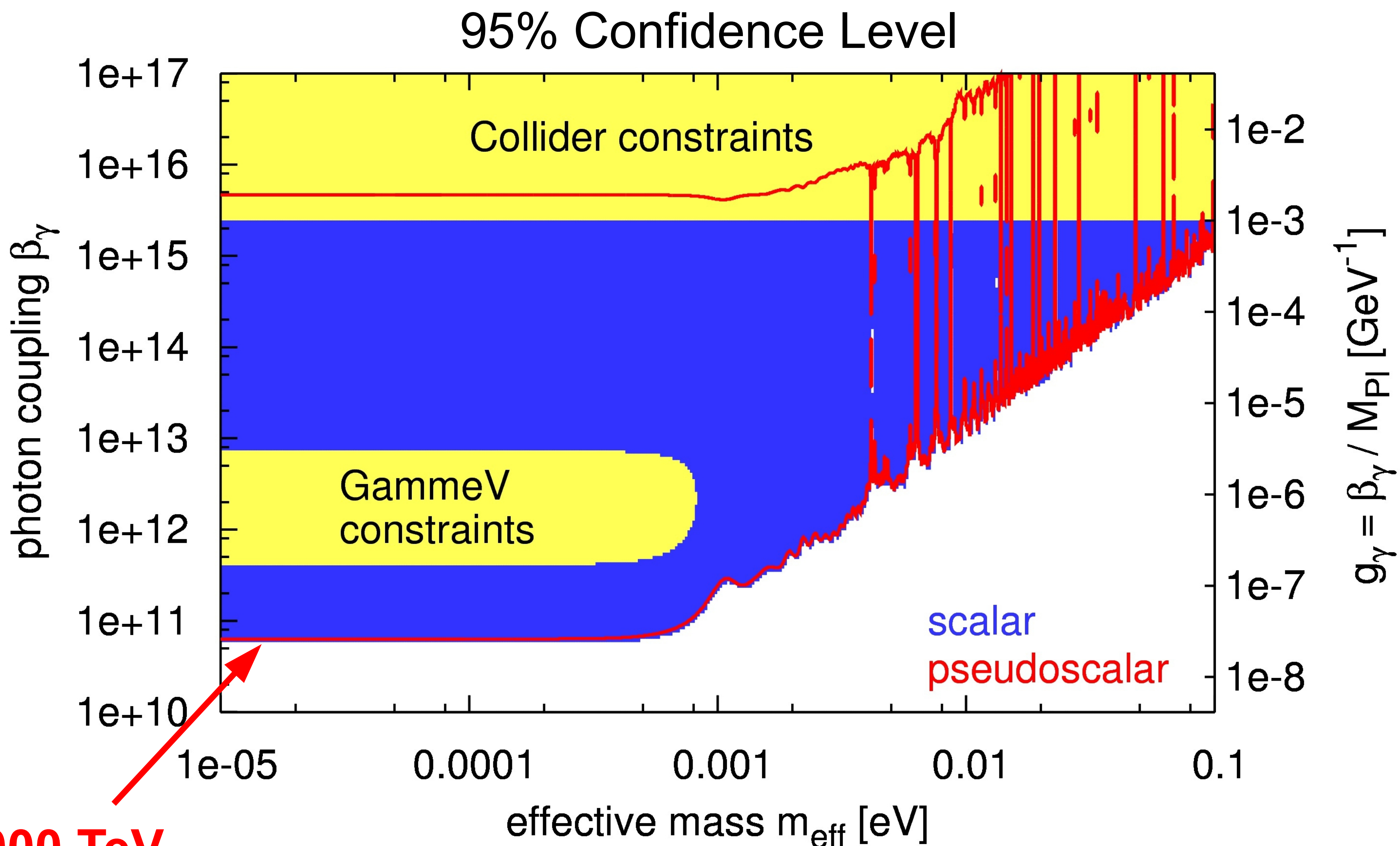
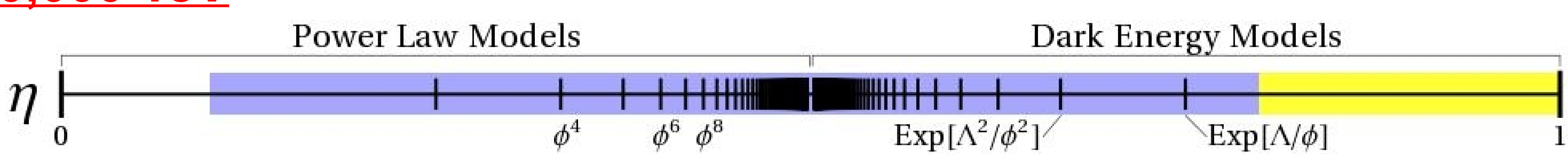
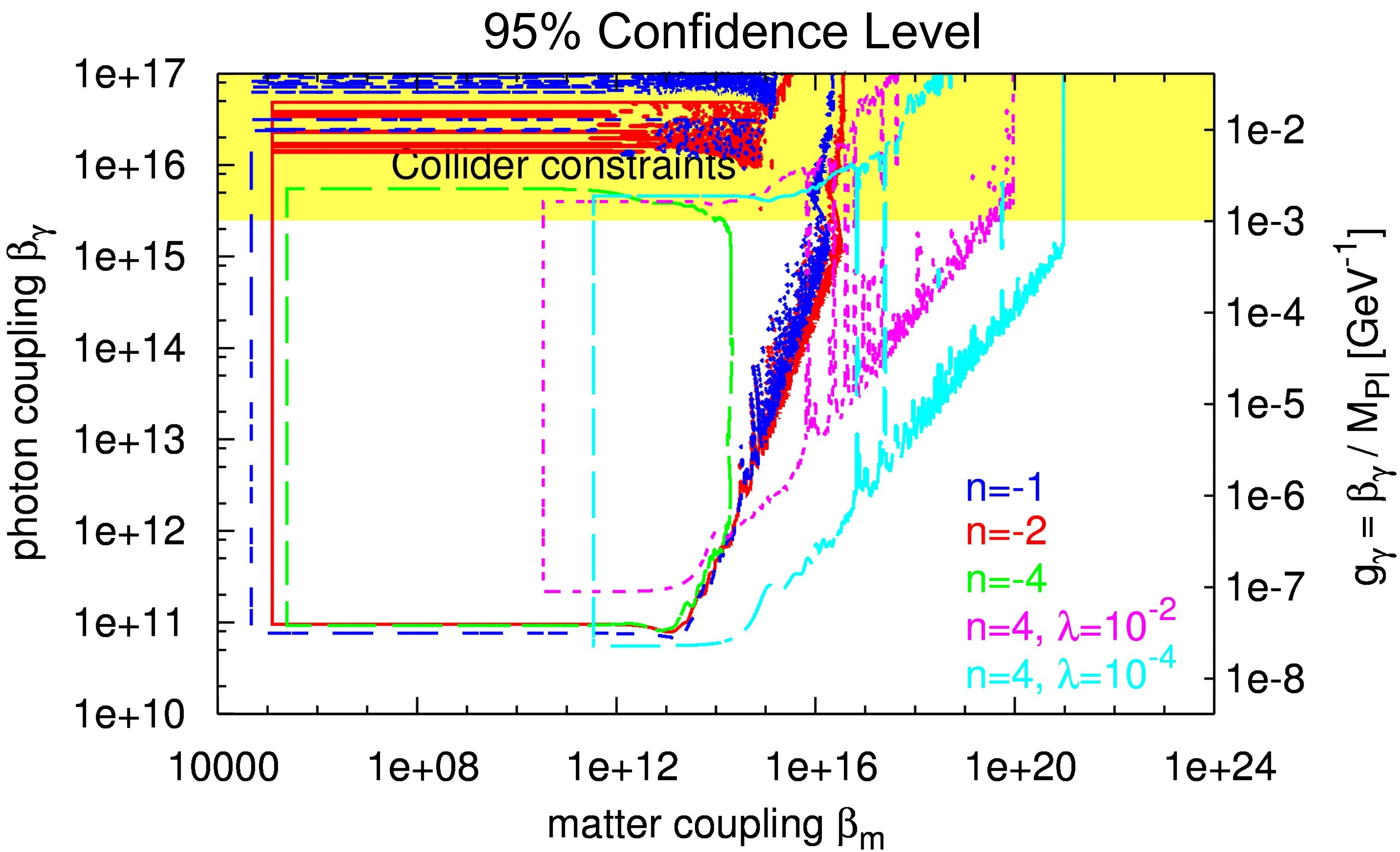
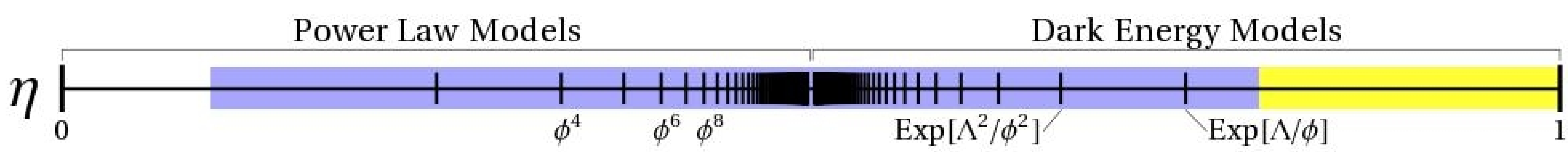


30,000 TeV



Model Dependent Results





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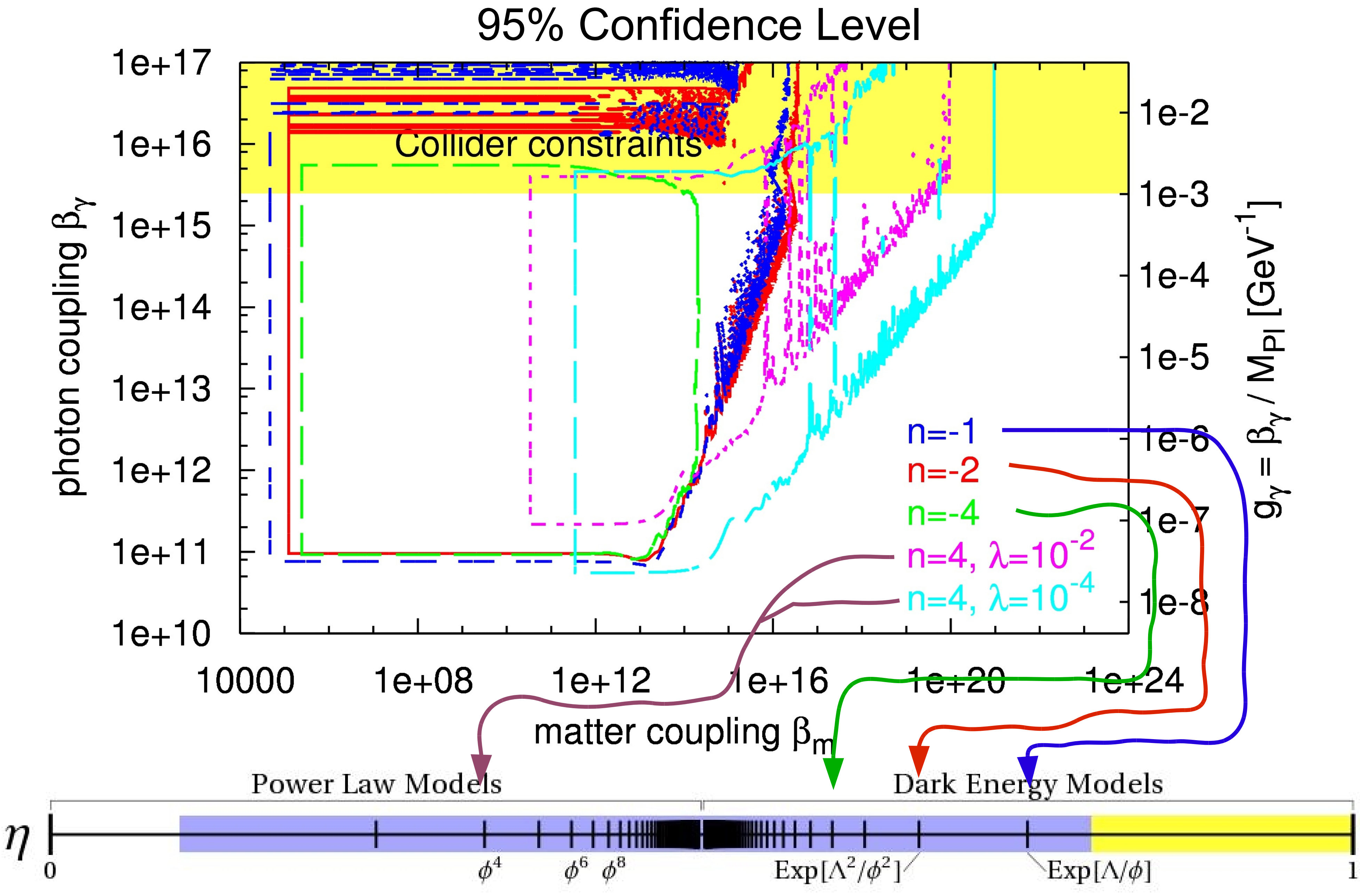

More Numerology

The Intensity Frontier:

1 Mega Watt 100 GeV proton beam ~ 10^{14} protons/second

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1 Watt eV photon beam ~ 10^{19} photons/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 ~ 10^{14} protons/second

1 Watt eV photon beam ~ 10^{19} photons/second

Add a resonating cavity...

Increase power by a factor of 100 to 100,000

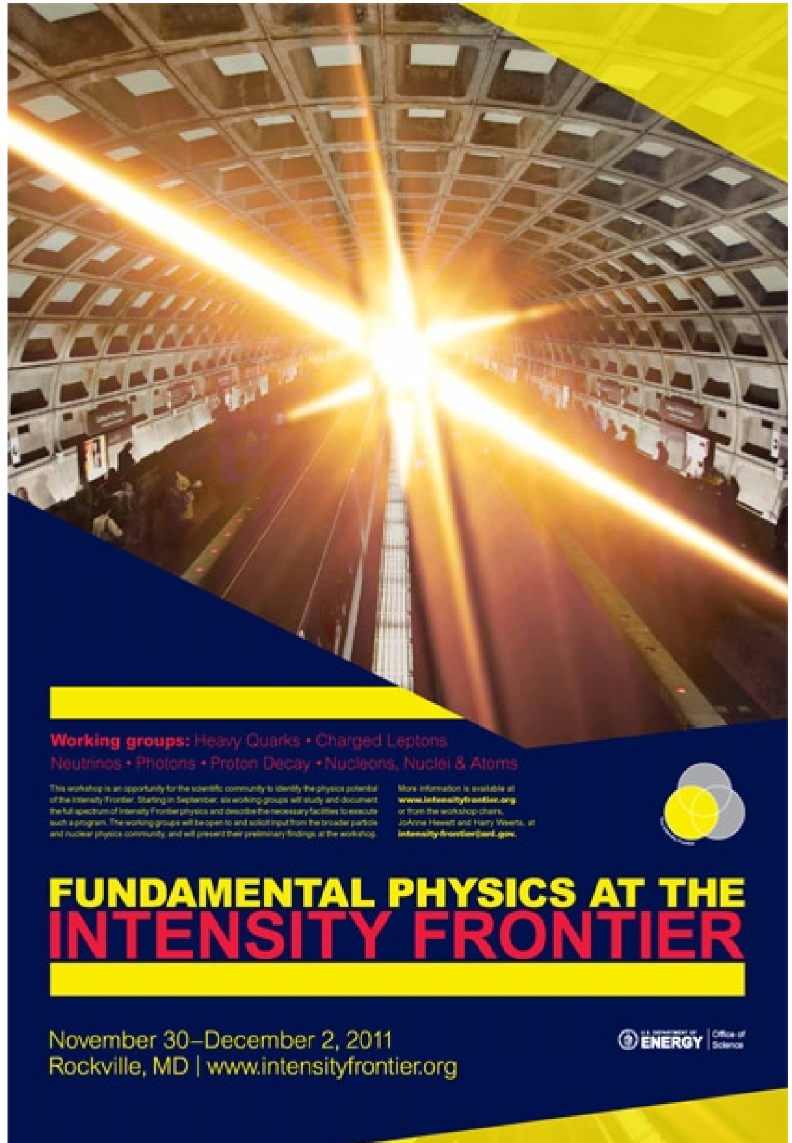
Power recycle for a factor of 10 to 100

Use an interferometer...

Angular sensitivity ~ 10^{-12} radians

Differential length sensitivity ~ 10^{-19} meters

The Intensity Frontier



Working group on
Hidden Sector Photons, Axions, and WISPs

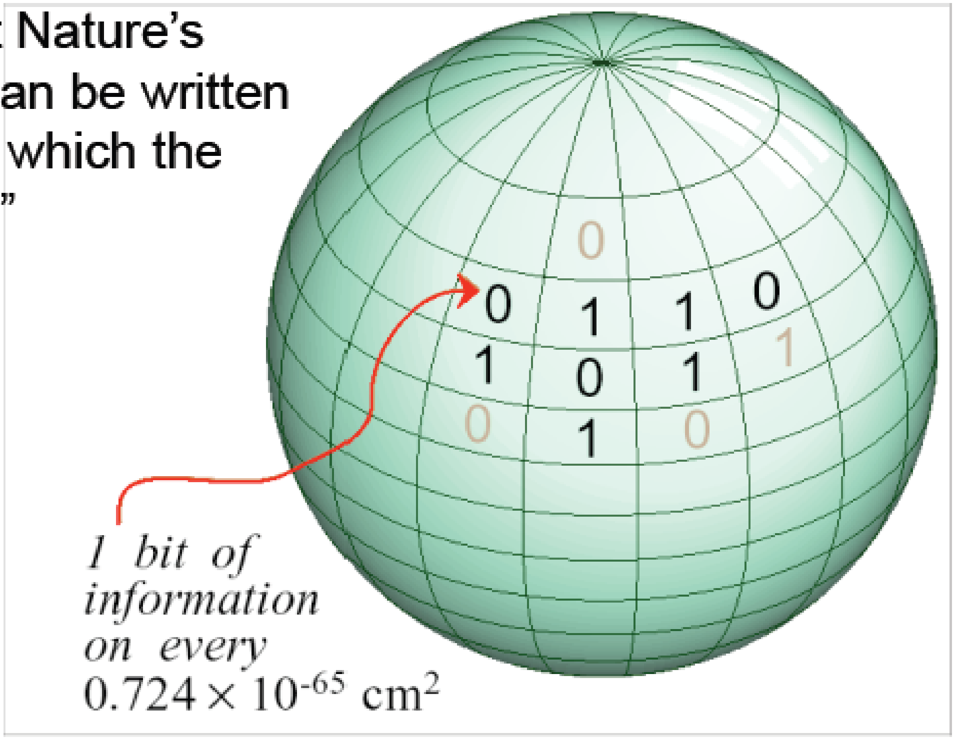
Laser Test of Gravity: The Holometer

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

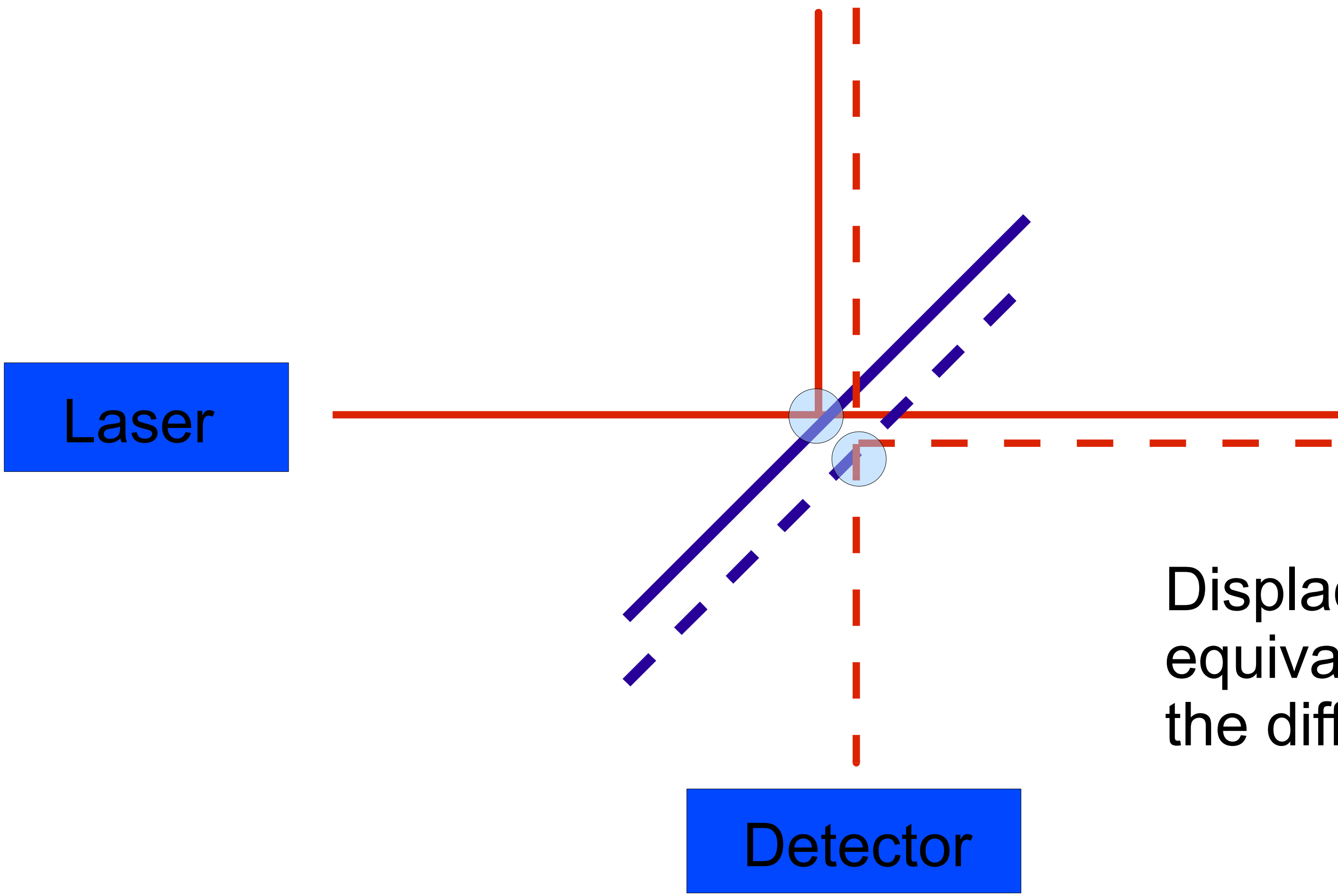
Everything is written on 2D surfaces moving at the speed of light



Are there experimental consequences of this idea?

Laser Test of Gravity: The Holometer

Suppose that there is an information bound at the Planck scale – Planck-sized bits on a null surface (light sheet).



Displacement noise is equivalent to the size of the diffraction spot:

$$\Delta x^2 = l_P L$$

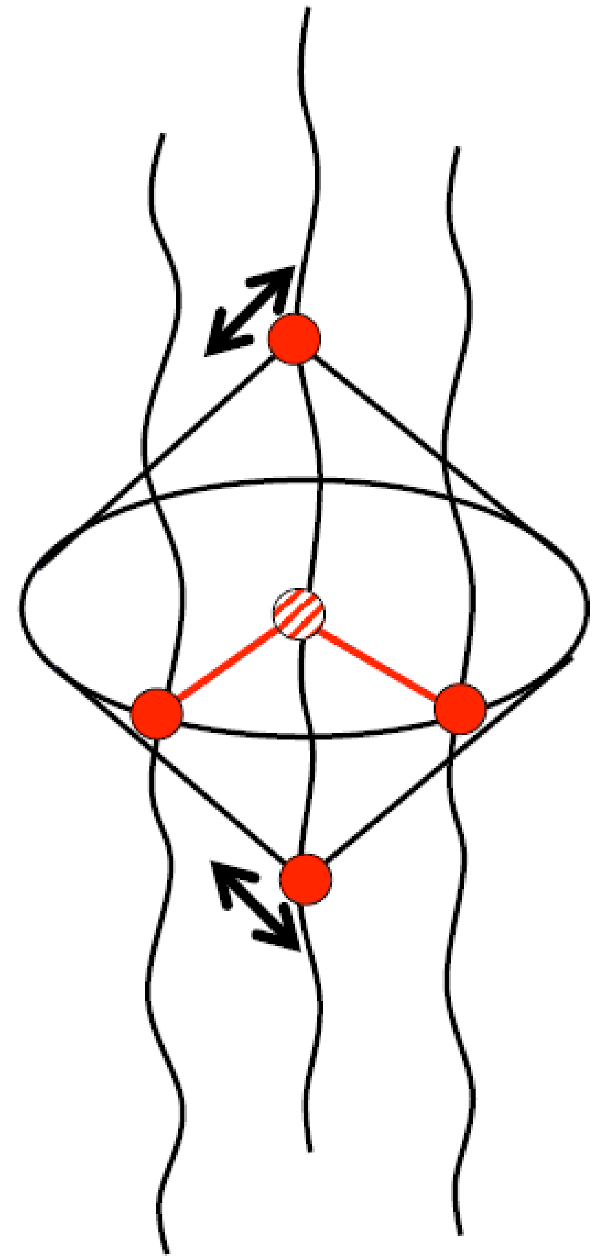
Laser Test of Gravity: The Holometer

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



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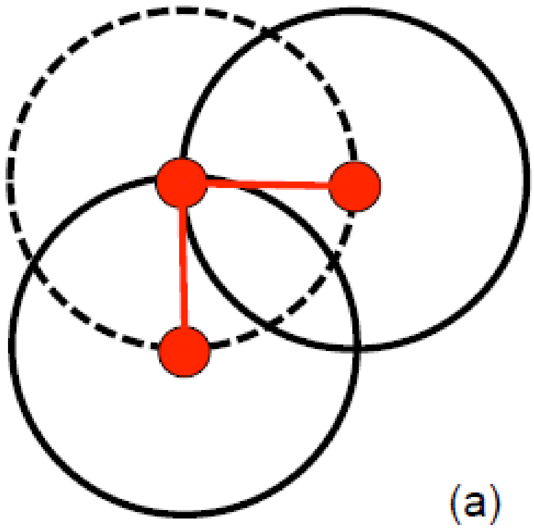
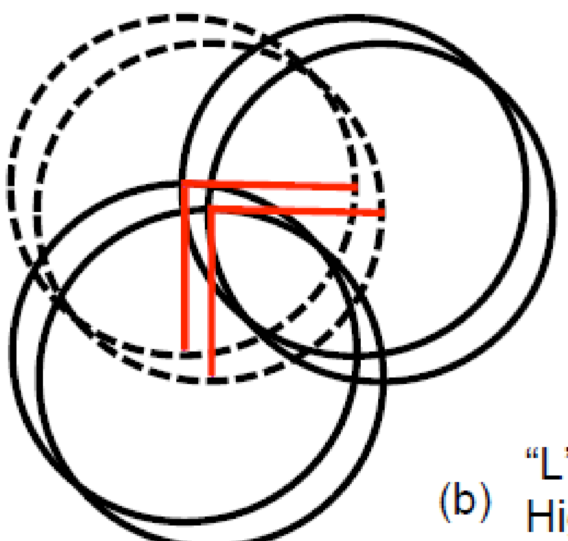
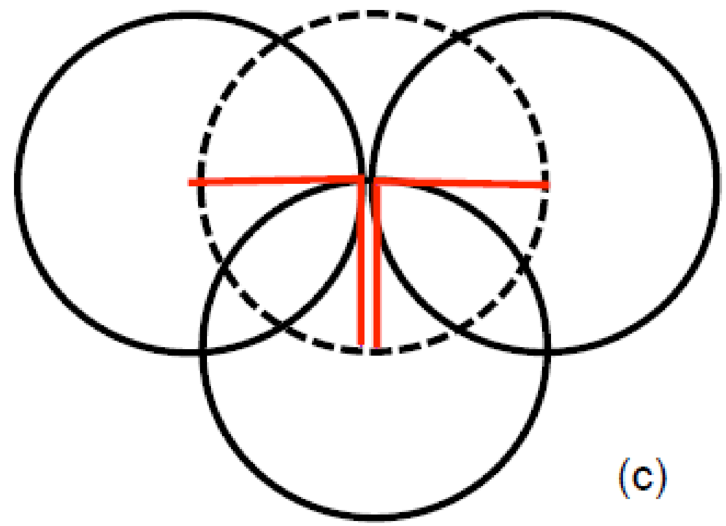


Top view of diamonds for one interferometer

(a)



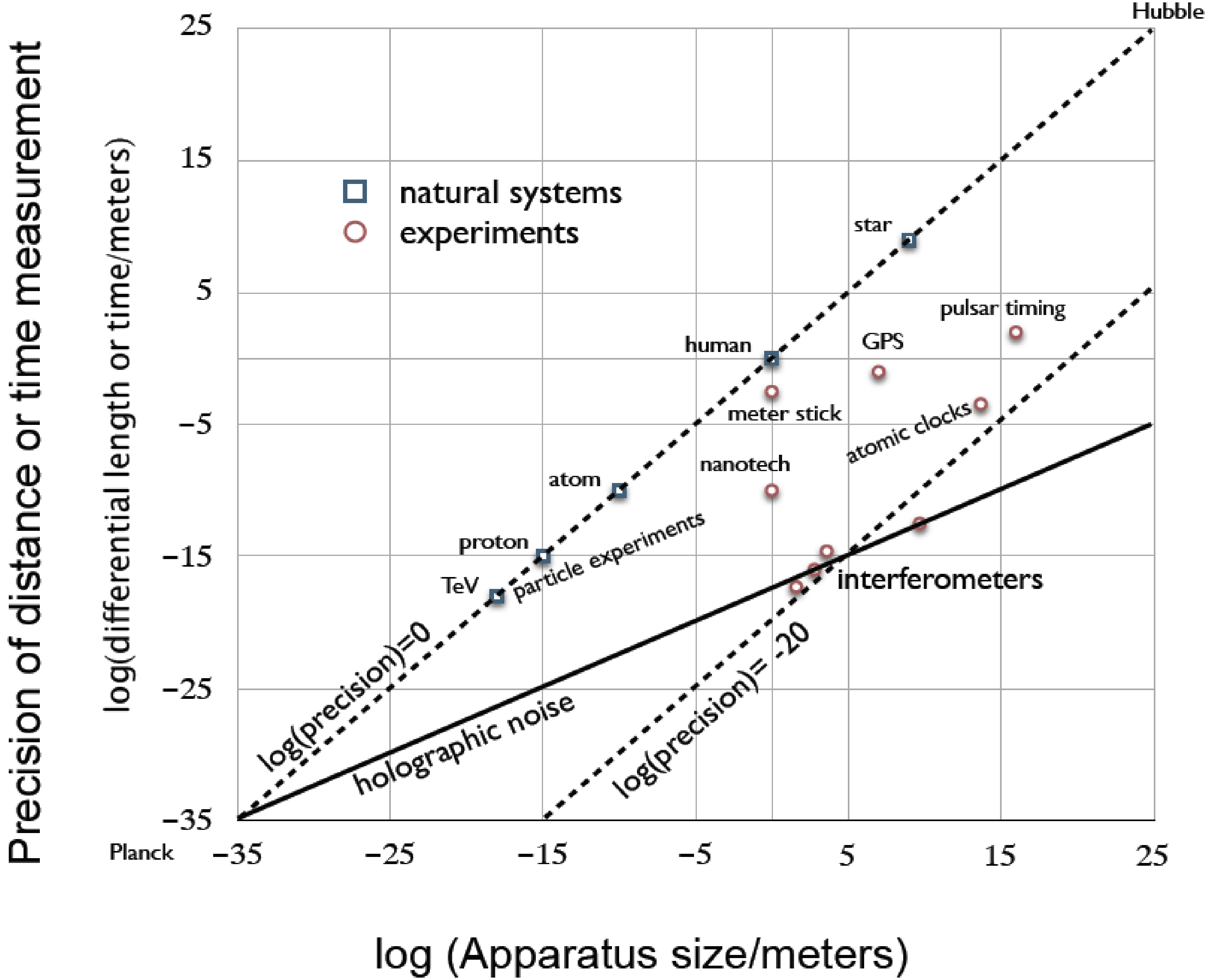
(b) “L” configuration
Highly entangled diamonds
Highly correlated signals



(c)

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

Laser Test of Gravity: The Holometer



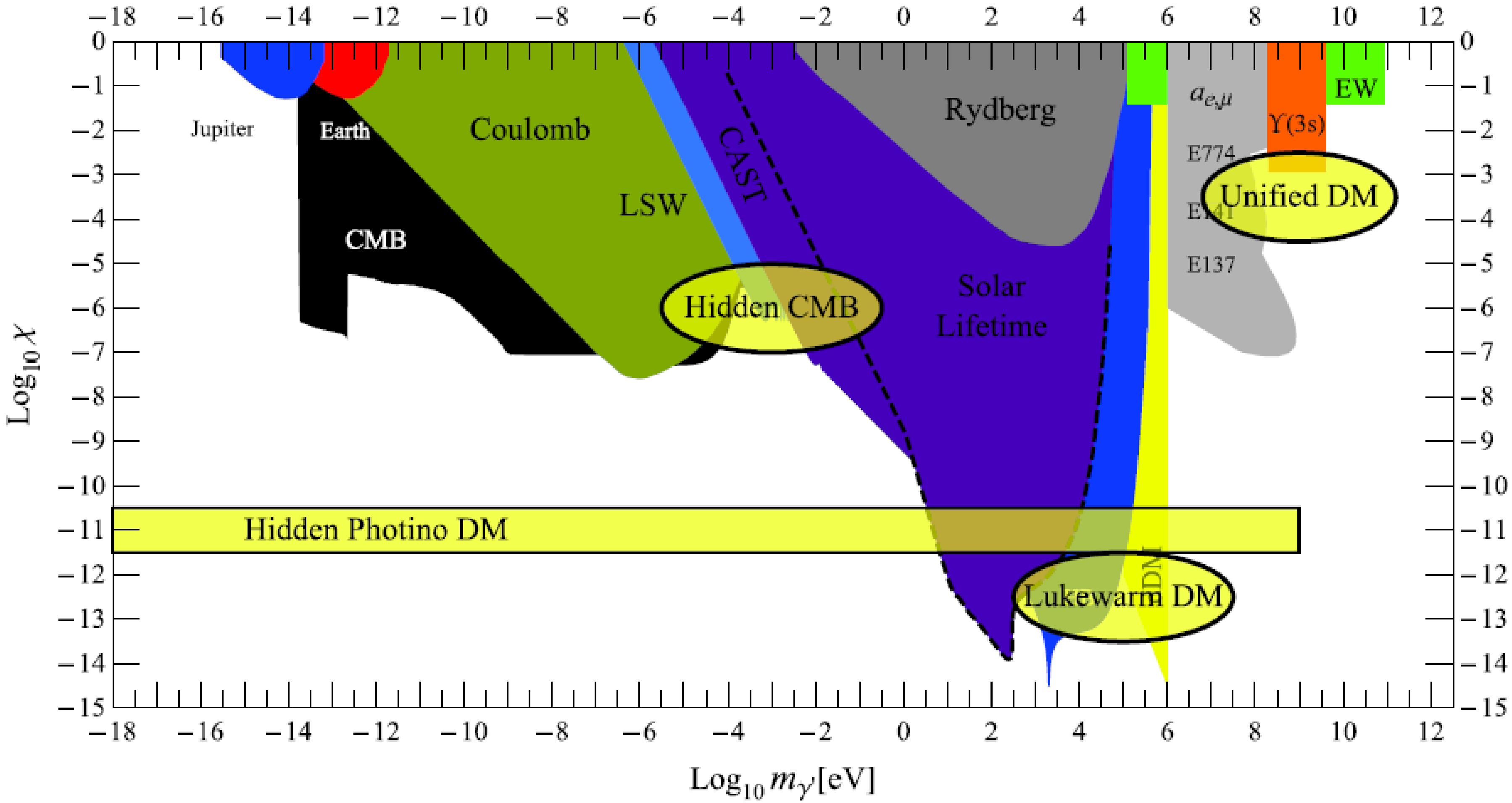
Laser Test of Gravity: The Holometer

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

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The Case for Dark Radiation

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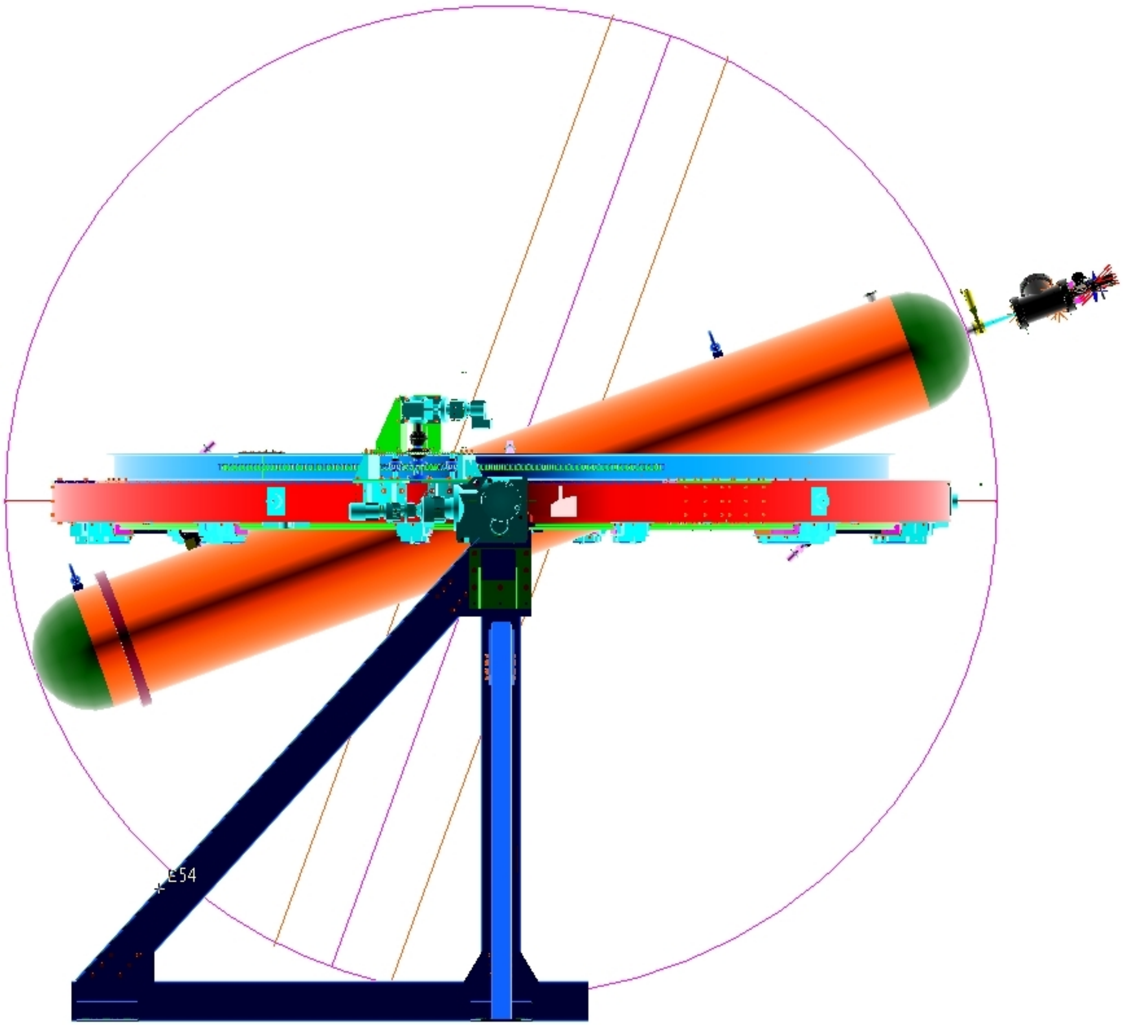
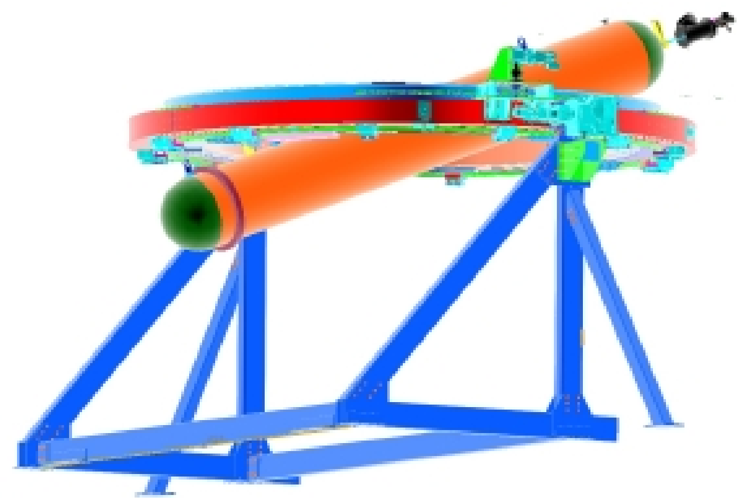
Where to go: Paraphoton Search





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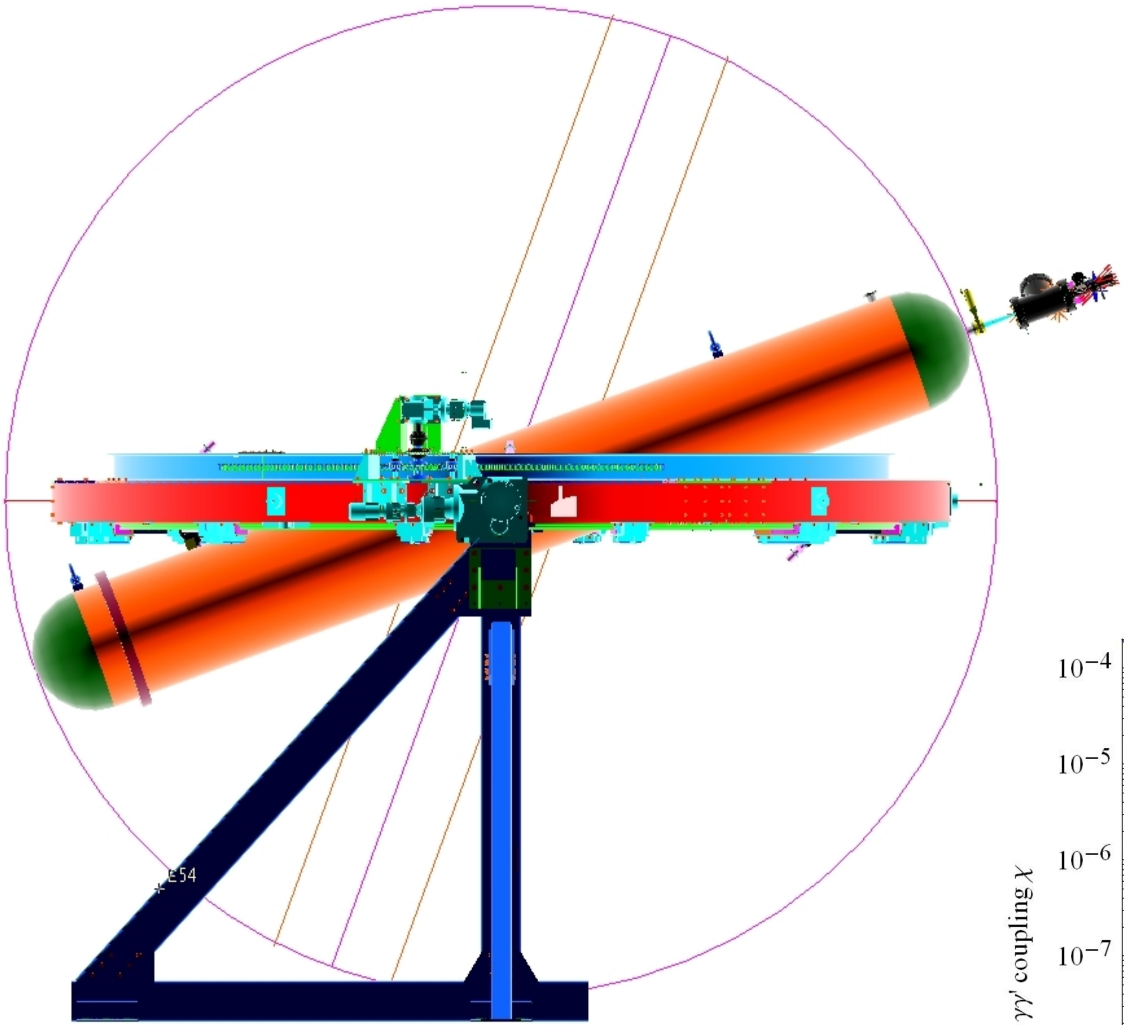
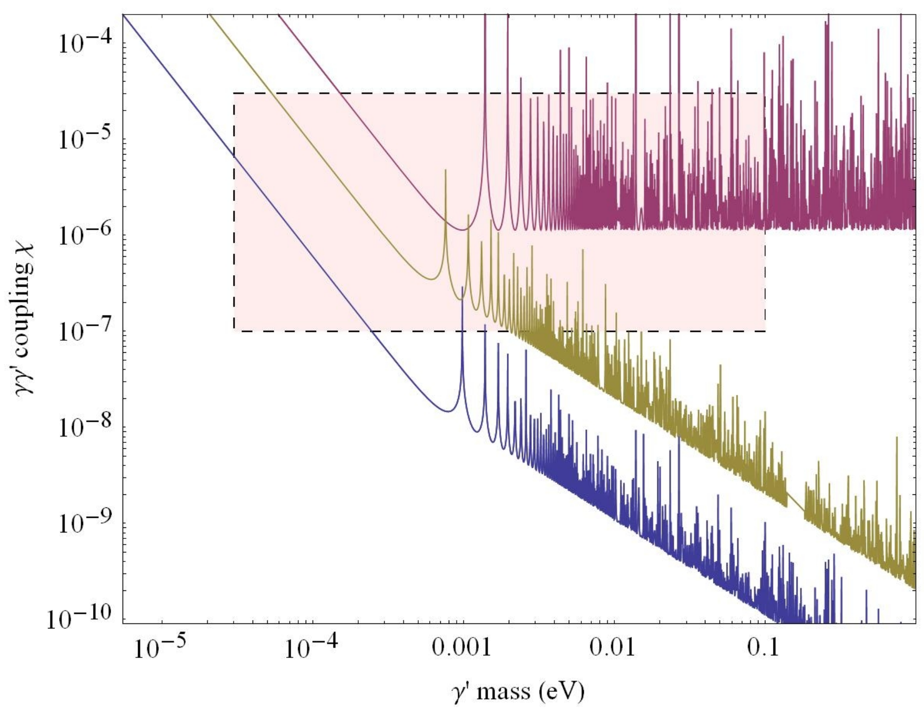
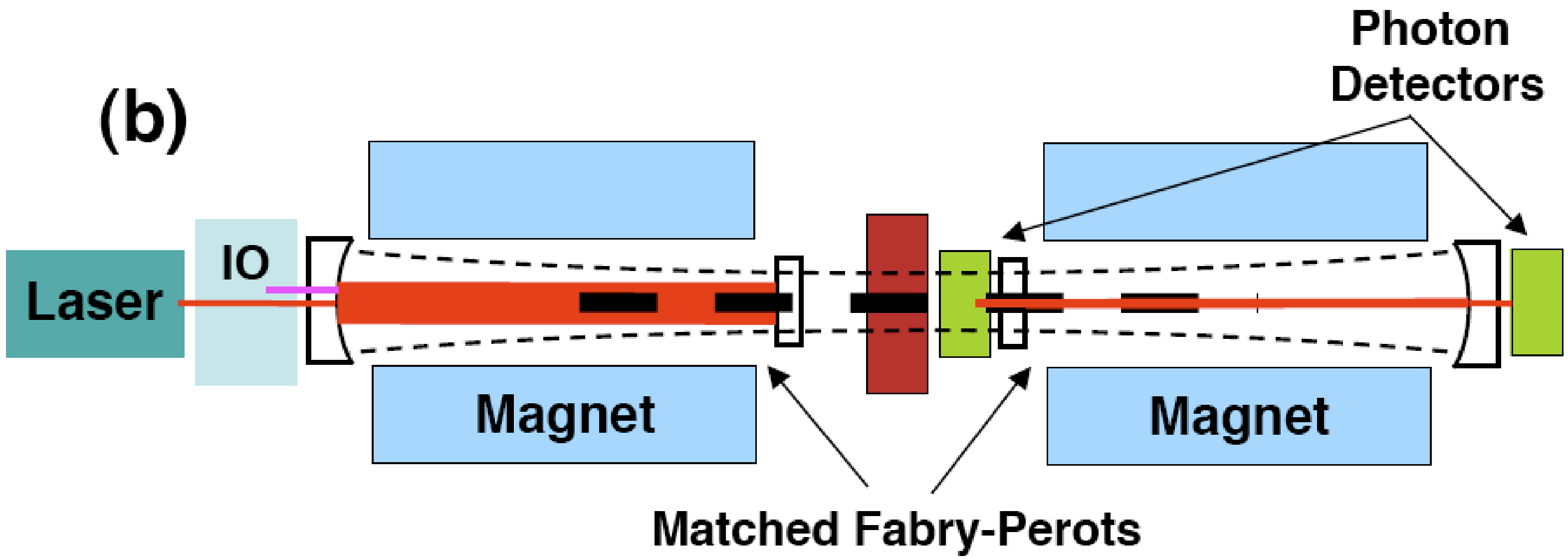
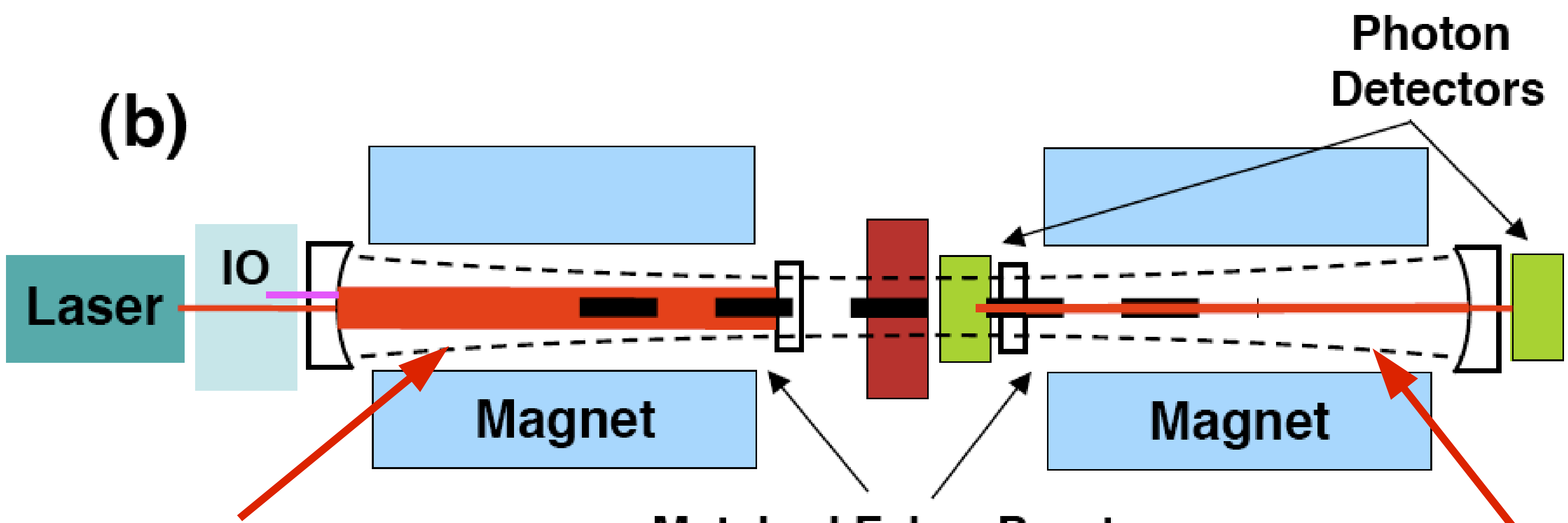




Where to go: Axion Search



Where to go: Axion Search

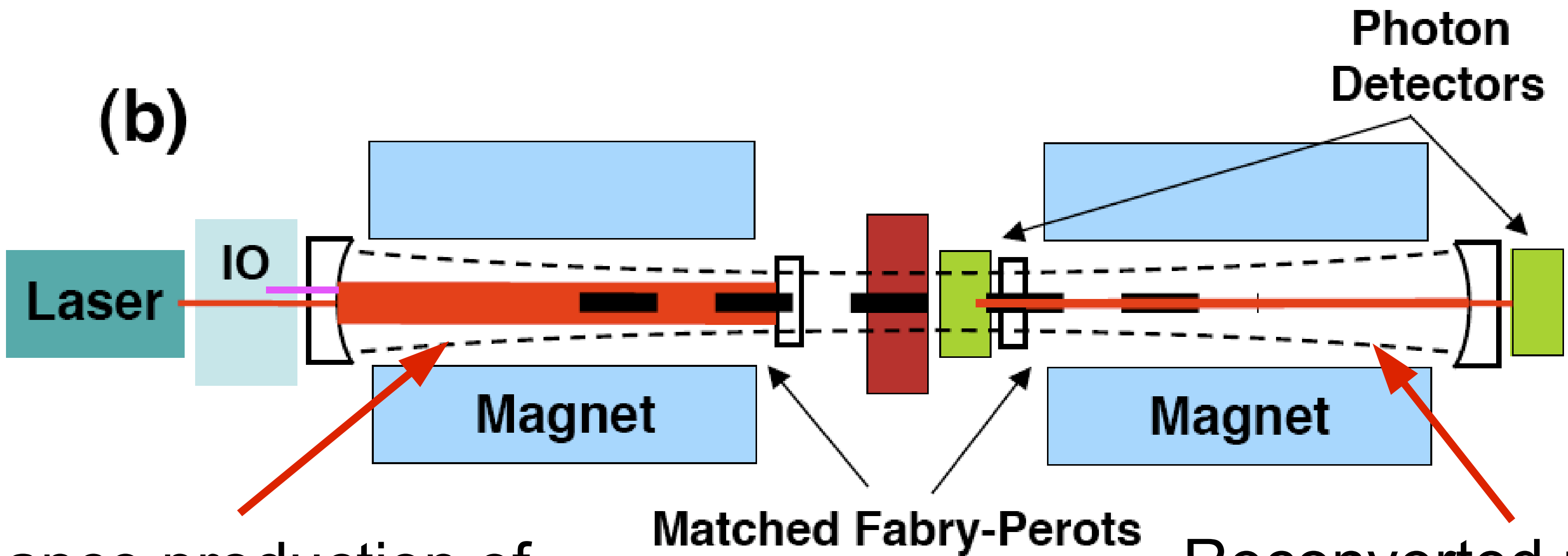


Enhance production of axions with this cavity

Reconverted photons resonantly drive this cavity

Where to go: Axion Search

(b)



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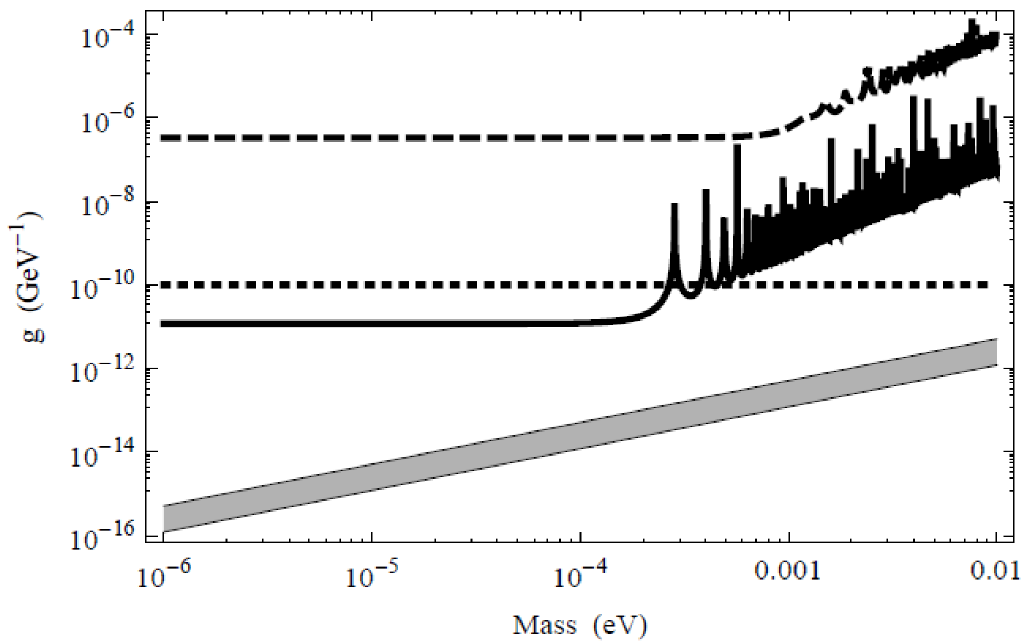
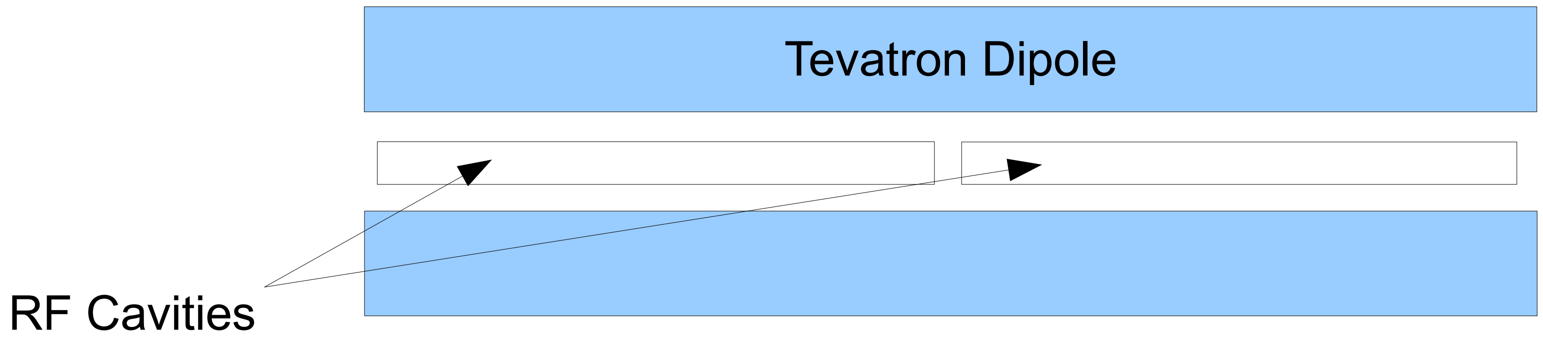
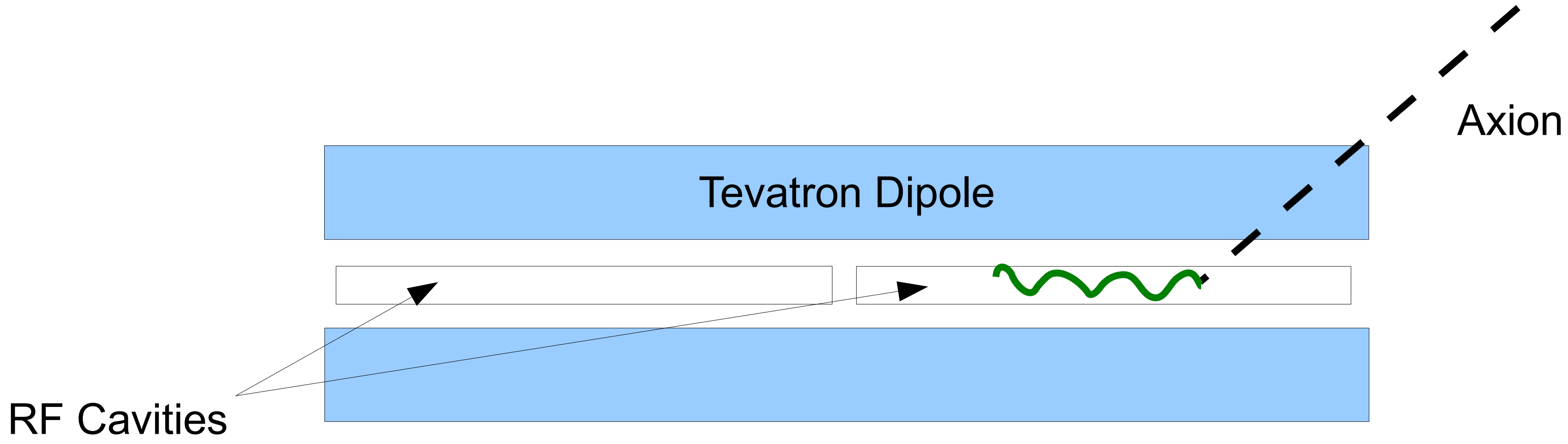
Reconverted photons resonantly drive this cavity



Where to go: Cavity Axion Search



Where to go: Cavity Axion Search



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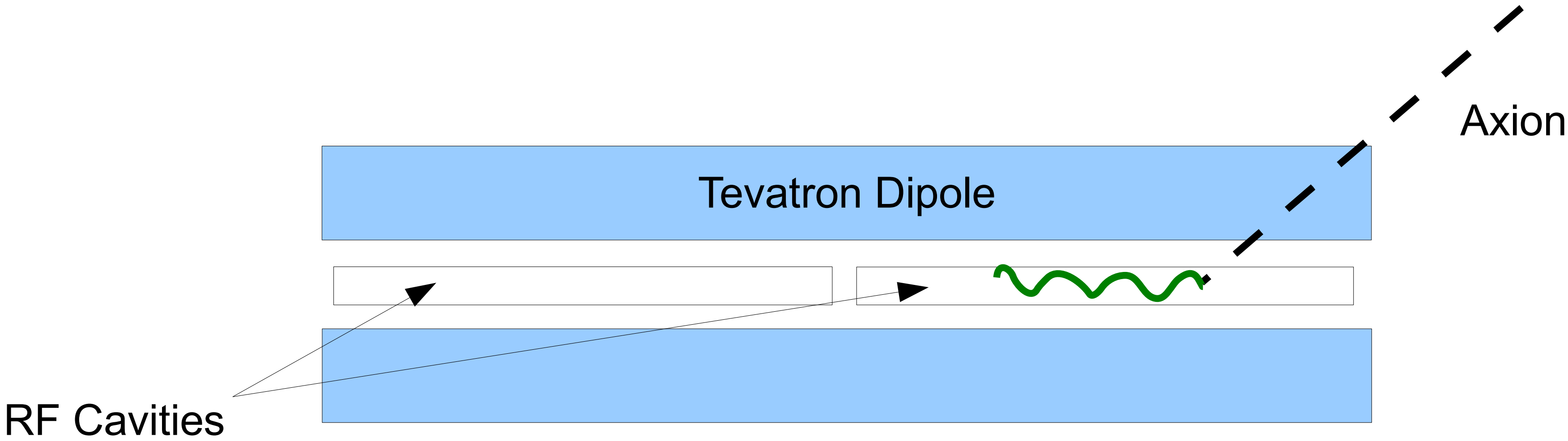
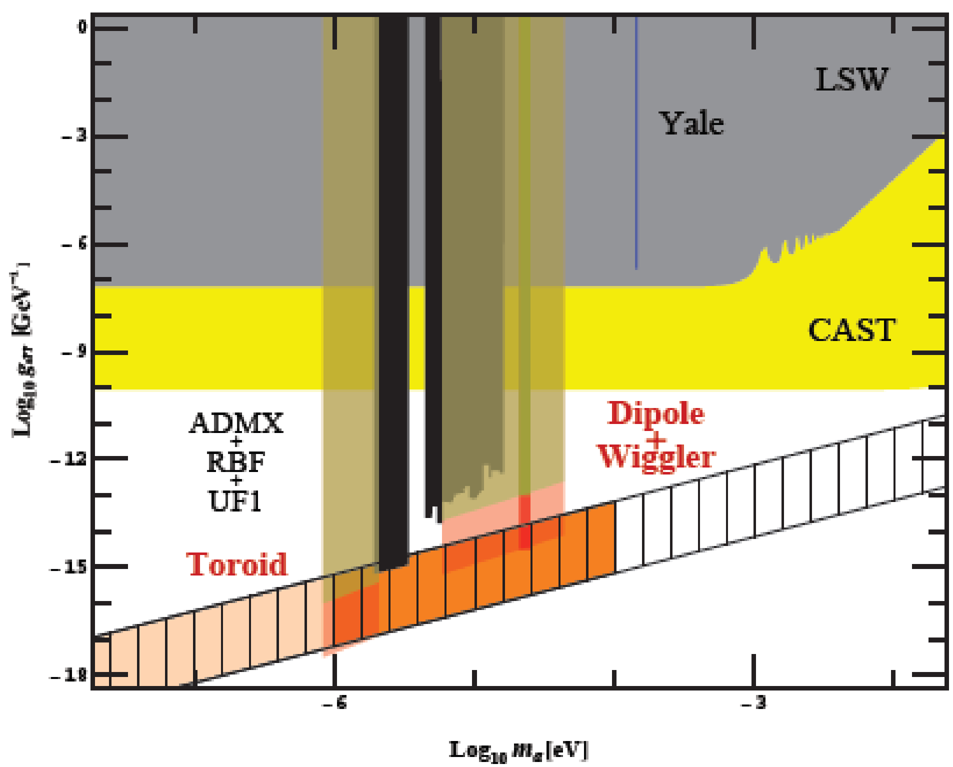




Conclusions

- 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

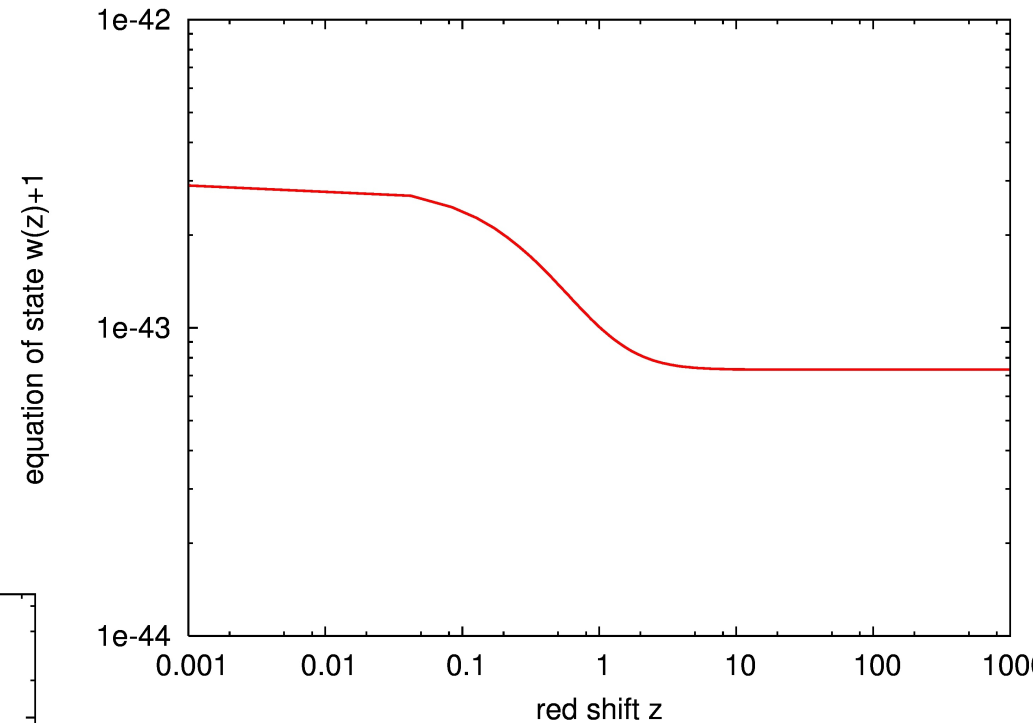
- A wide variety of future experiments are being conceived
  - The Holometer (now partly constructed)
  - Resonant regeneration axion search
  - Low-mass (meV) paraphotons from the Sun

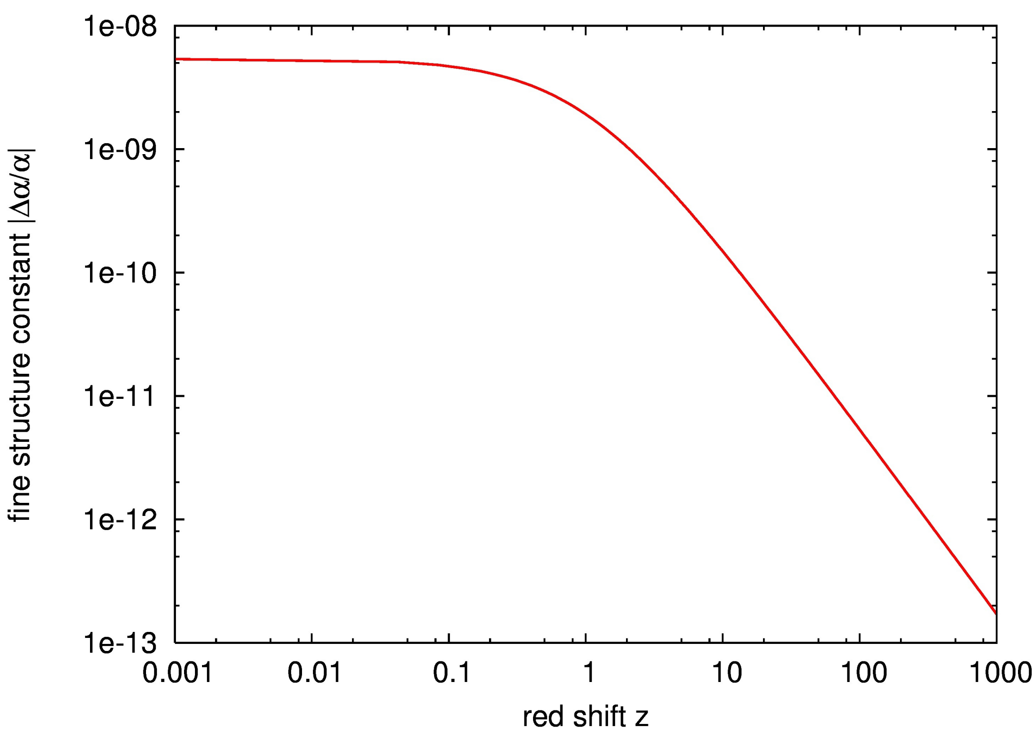
- Recent workshop on experimental tests of dark energy
  - Sizeable to-do list – perhaps reconvene in 18-24 months

- Pending workshop on the intensity frontier
  - Working group dedicated to topics discussed in this presentation

Chameleon Dark Energy

Equation of state parameter from chameleon dark energy (current limits ~0.1).



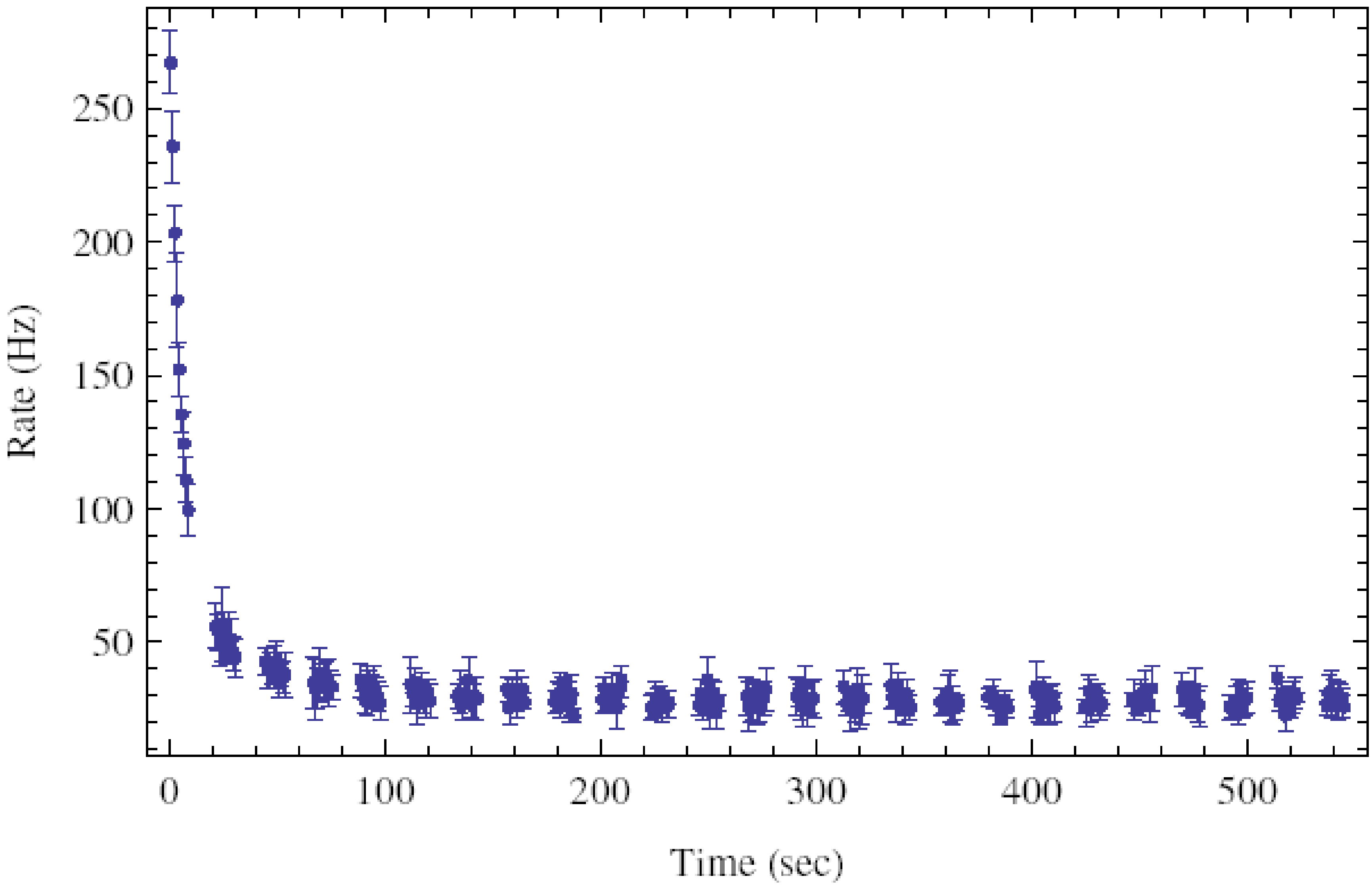


Variation in fine structure constant from chameleon dark energy (current limits 1e-6)

Conversion Rate

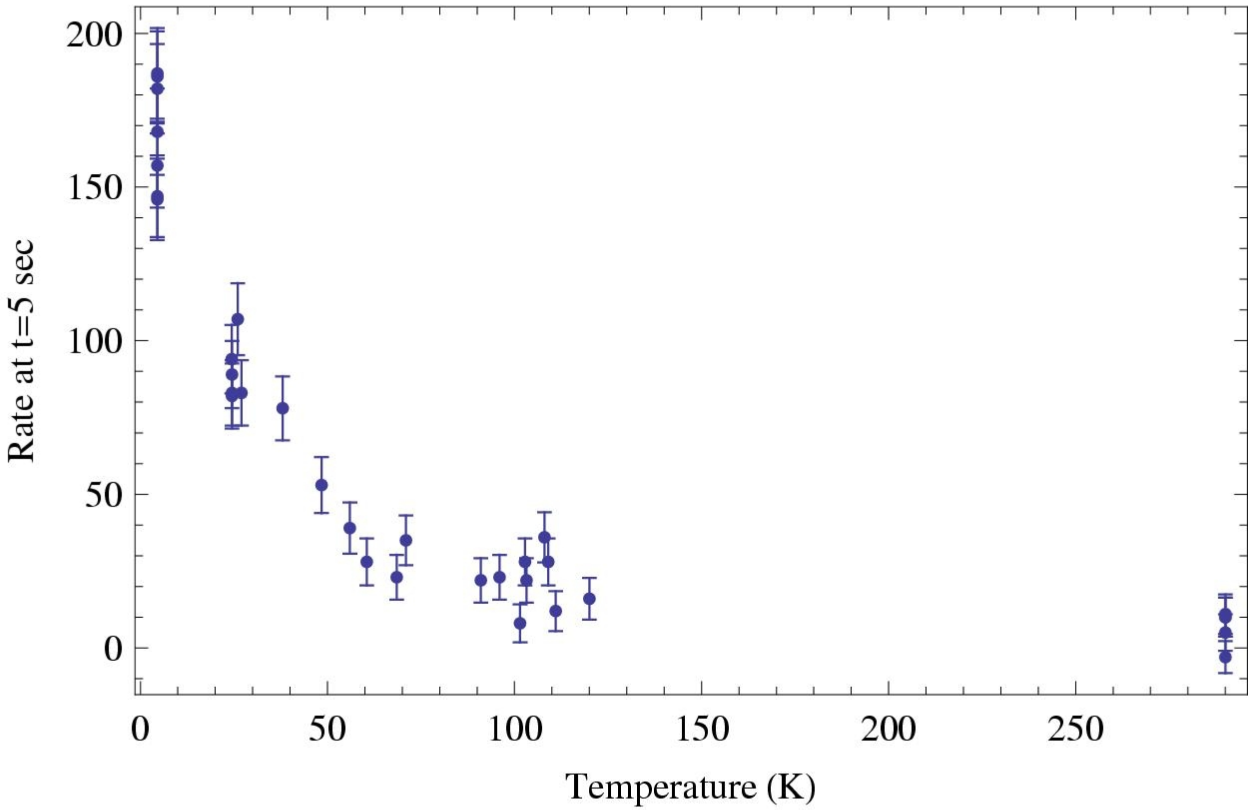
- The conversion process
  - chameleon measured at window
  - ϕ–γ superposition propagates in some direction k through magnetic field, with γ amplitude growing with time
  - particle bounces from walls, with partial reduction in photon amplitude due to nonzero absorption probability
  - particle measured again at opposite window
- Afterglow and decay rates
  - Afterglow: $\Gamma_{\mathrm{aft}} = \frac{1}{4\pi}\int d^2\hat{k}\frac{\mathcal{P}_{\gamma\leftrightarrow\phi}(\hat{k},t(\hat{k}))}{t(\hat{k})} \times \mathcal{P}(\mathrm{detection})$
  - Decay: $\Gamma_{\mathrm{dec},\gamma} = \frac{1}{4\pi}\int d^2\hat{k}\frac{\mathcal{P}_{\gamma\leftrightarrow\phi}(\hat{k},t(\hat{k})) + \mathcal{P}(\mathrm{absorption})}{t(\hat{k})}$

Orange Glow



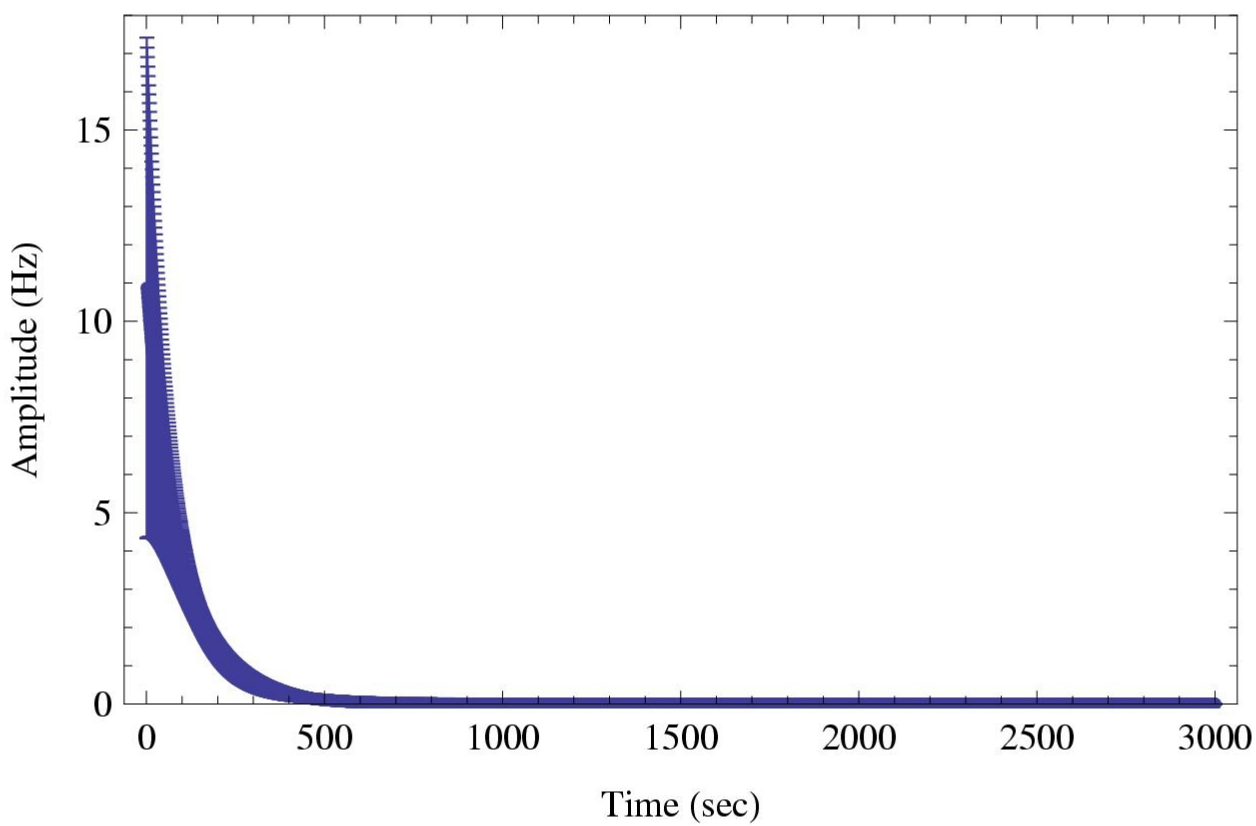
Orange Glow

- 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



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

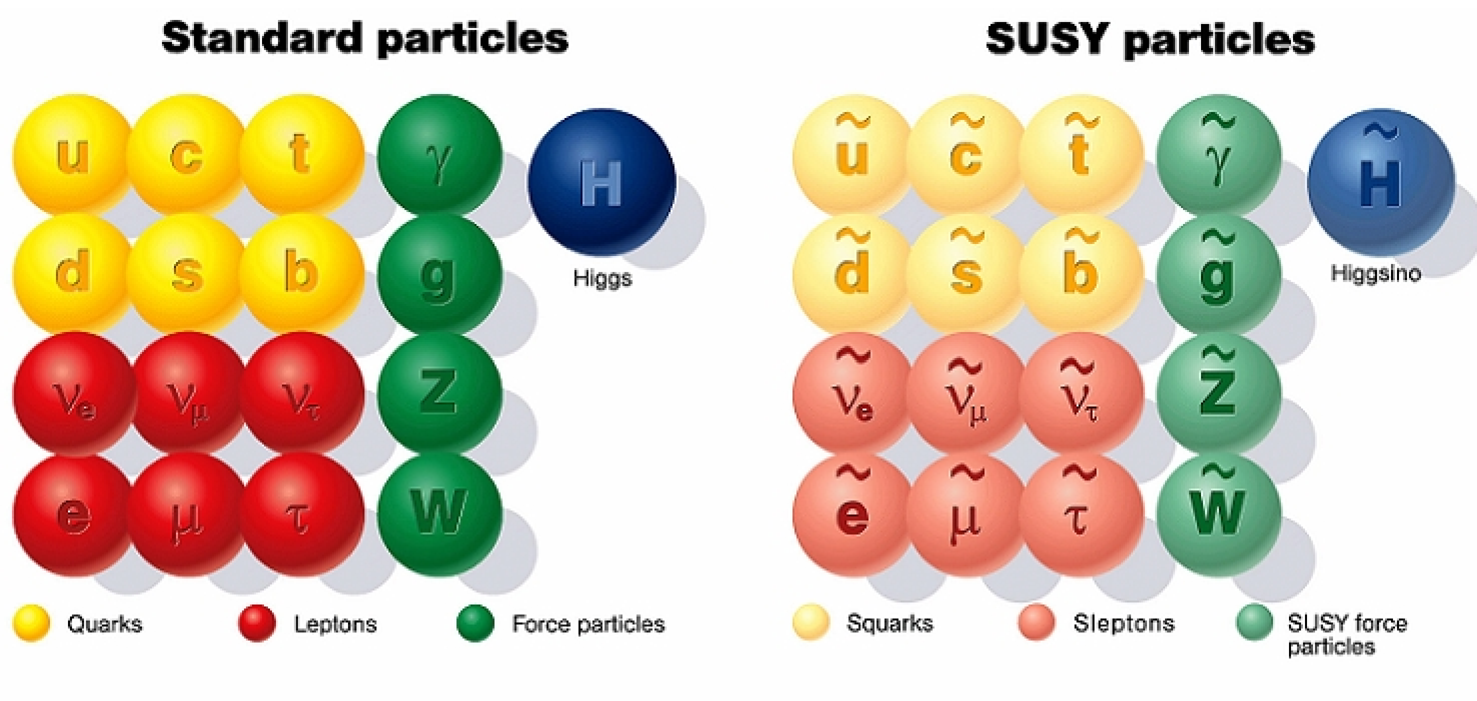
- Extended Run (for 5.0 Tesla magnetic field)
  - Fill cavity for 5 hours
  - Observe afterglow for 45 minutes
  - Repeat this measurement

- Shutter cycle is ~15 seconds on and ~15 seconds off

- 15 minute calibration run before and after each science run

Dark Matter WIMPs

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



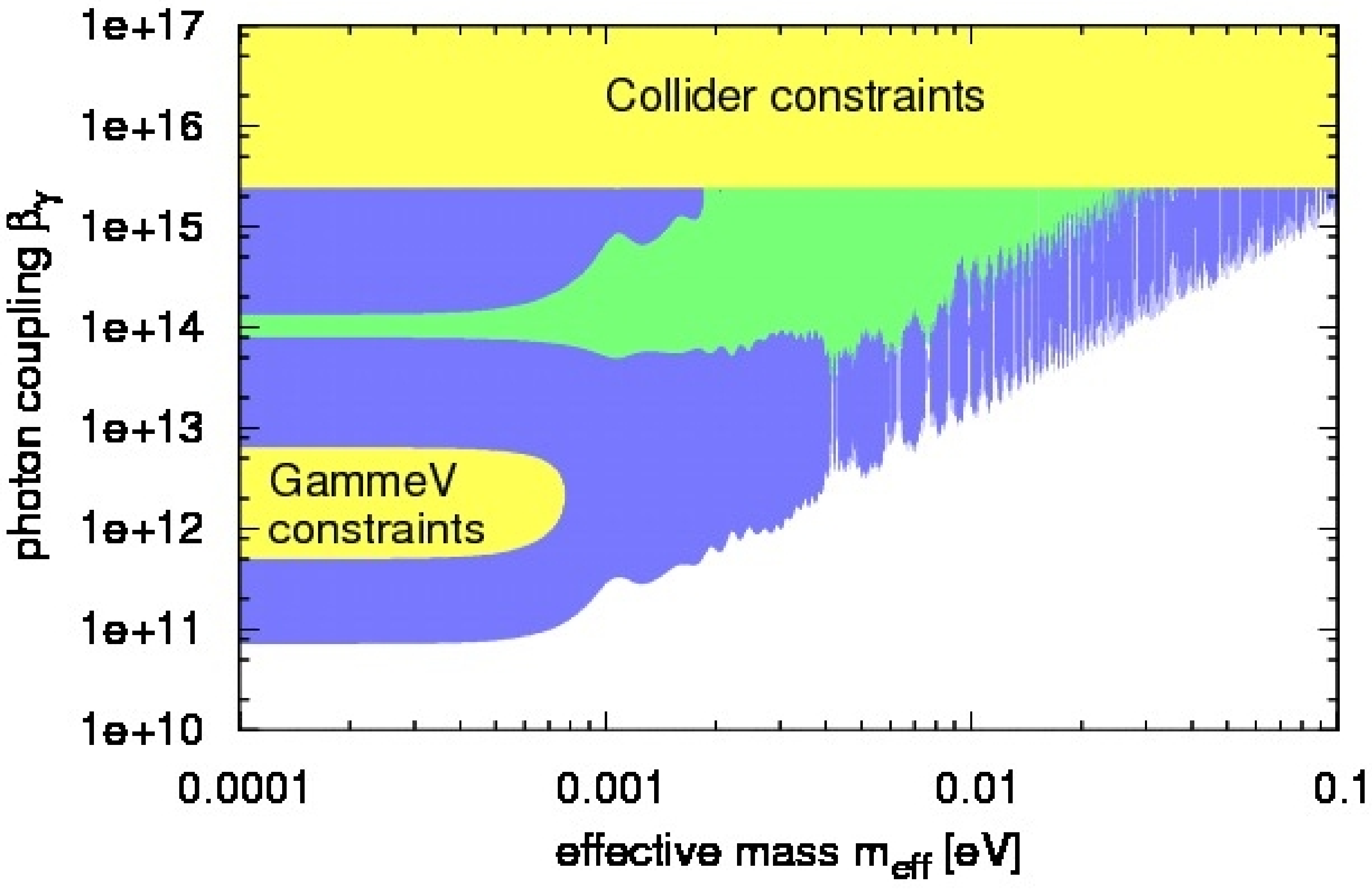
Among other things, supersymmetry:

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

Photons and Chameleon Dark Energy

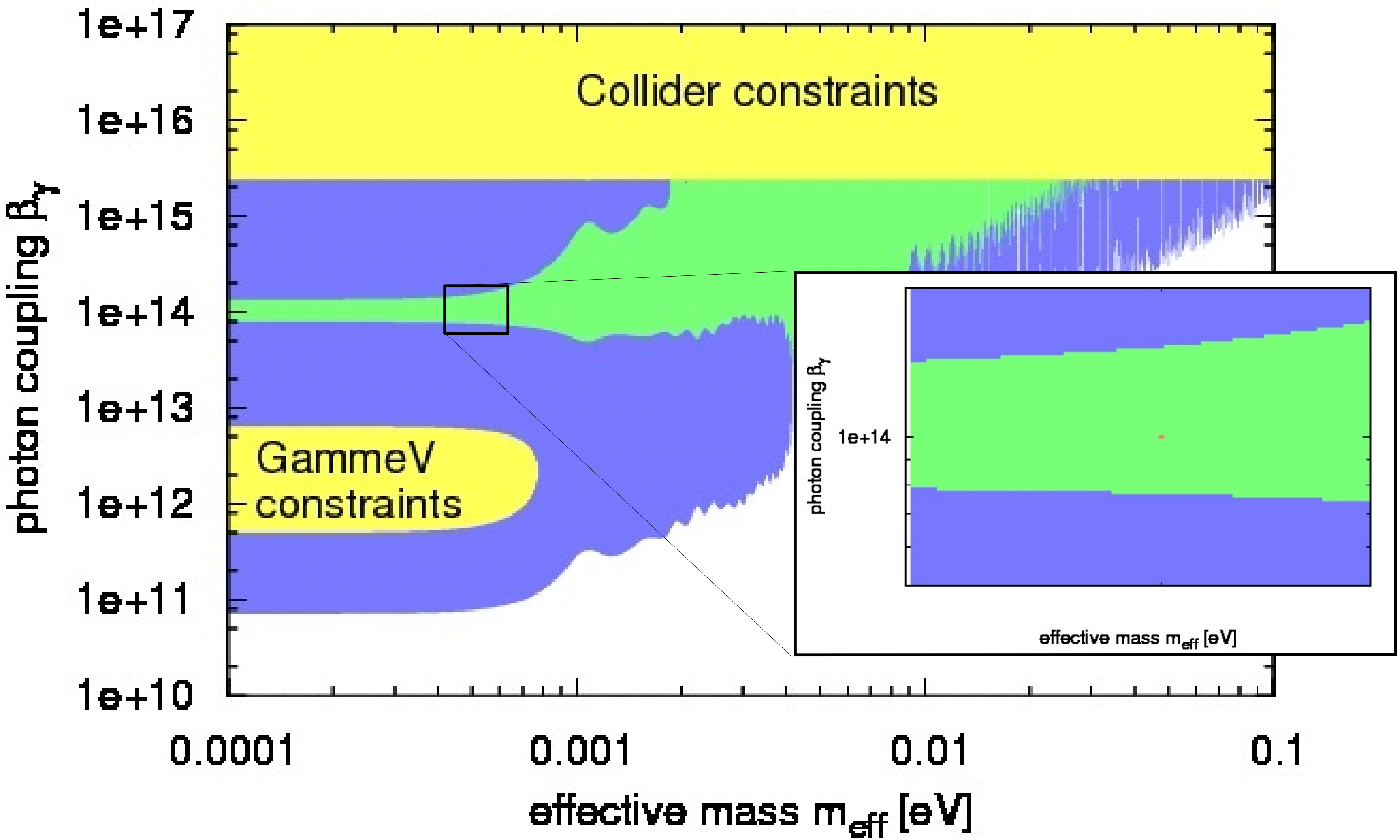
- equations of motion: $\partial_\mu \left(e^{\frac{\beta_\gamma \phi}{M_{\rm Pl}}} F^{\mu\nu} \right) = 0$
  - the other two of Maxwell's equations stay the same
- plane wave perturbations about background fields (assuming $\vec{B} = B_0 \hat{x}$)
  - $\left(-\frac{\partial^2}{\partial t^2} - \vec{k}^2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

What if...



Collider constraints
GammeV constraints
photon coupling β_γ
effective mass m_{eff} [eV]
1e+17
1e+16
1e+15
1e+14
1e+13
1e+12
1e+11
1e+10
0.0001
0.001
0.01
0.1

What if...



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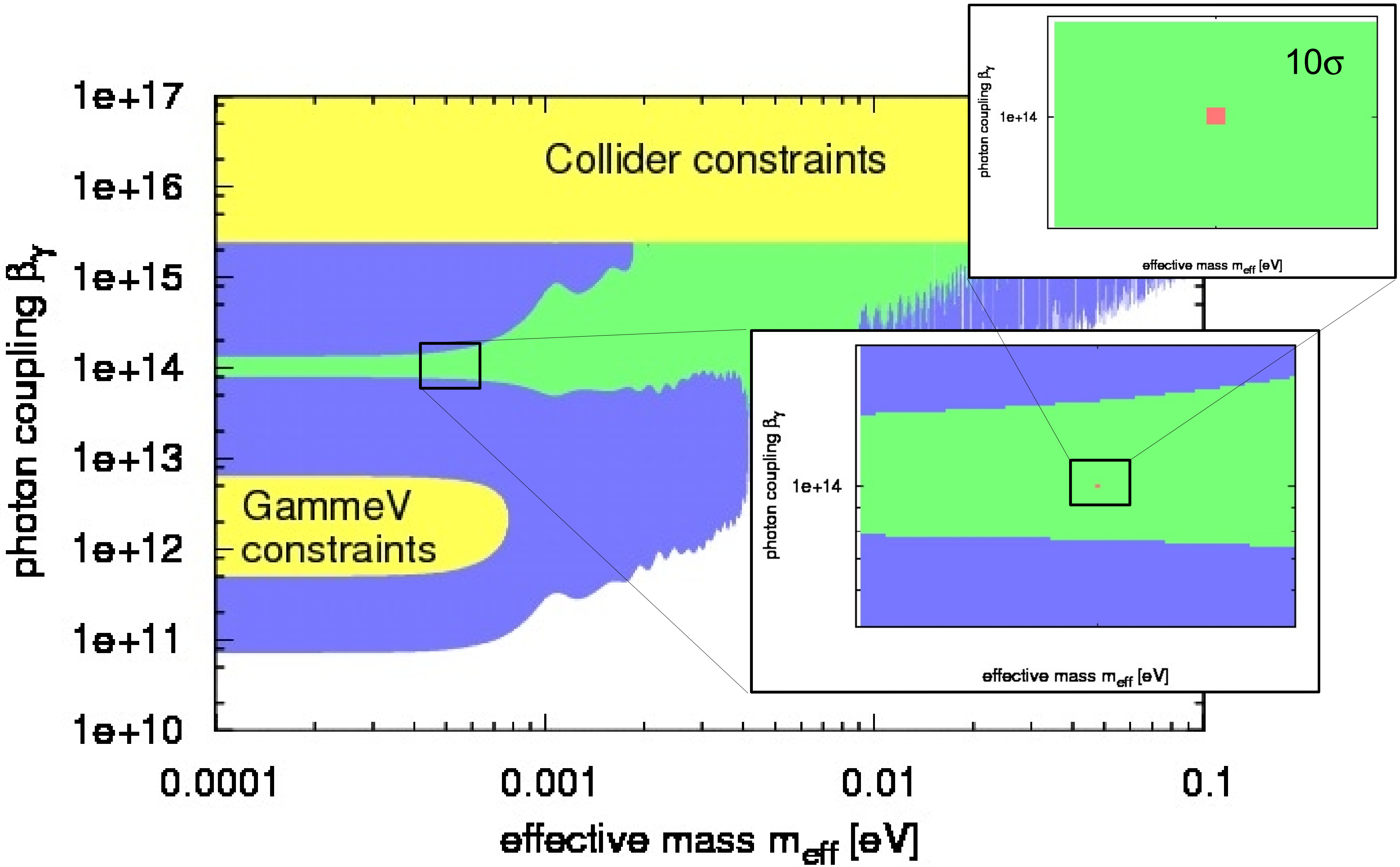
What if...



10σ
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effective mass m_{eff} [eV]
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GammeV constraints
1e+17
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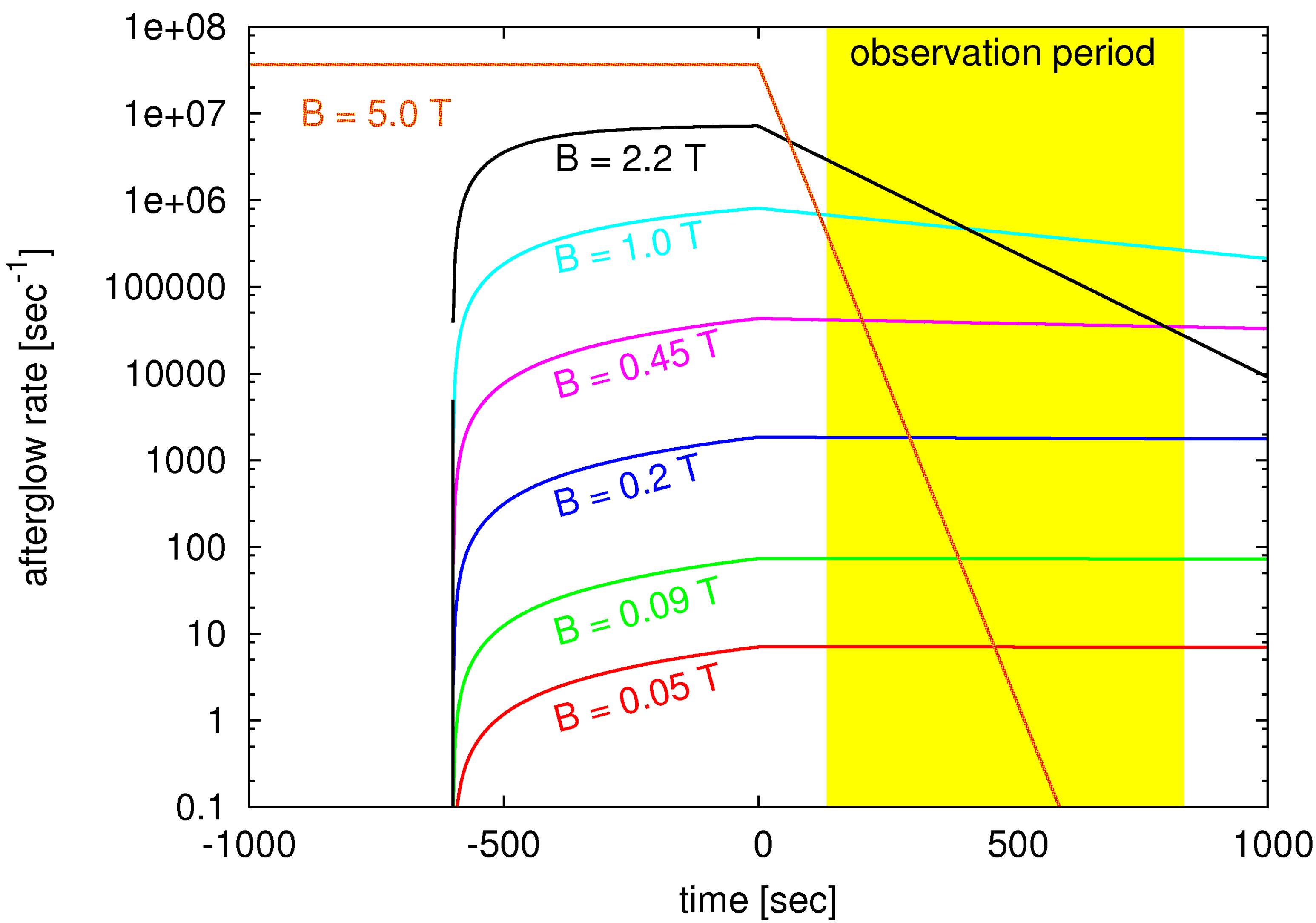
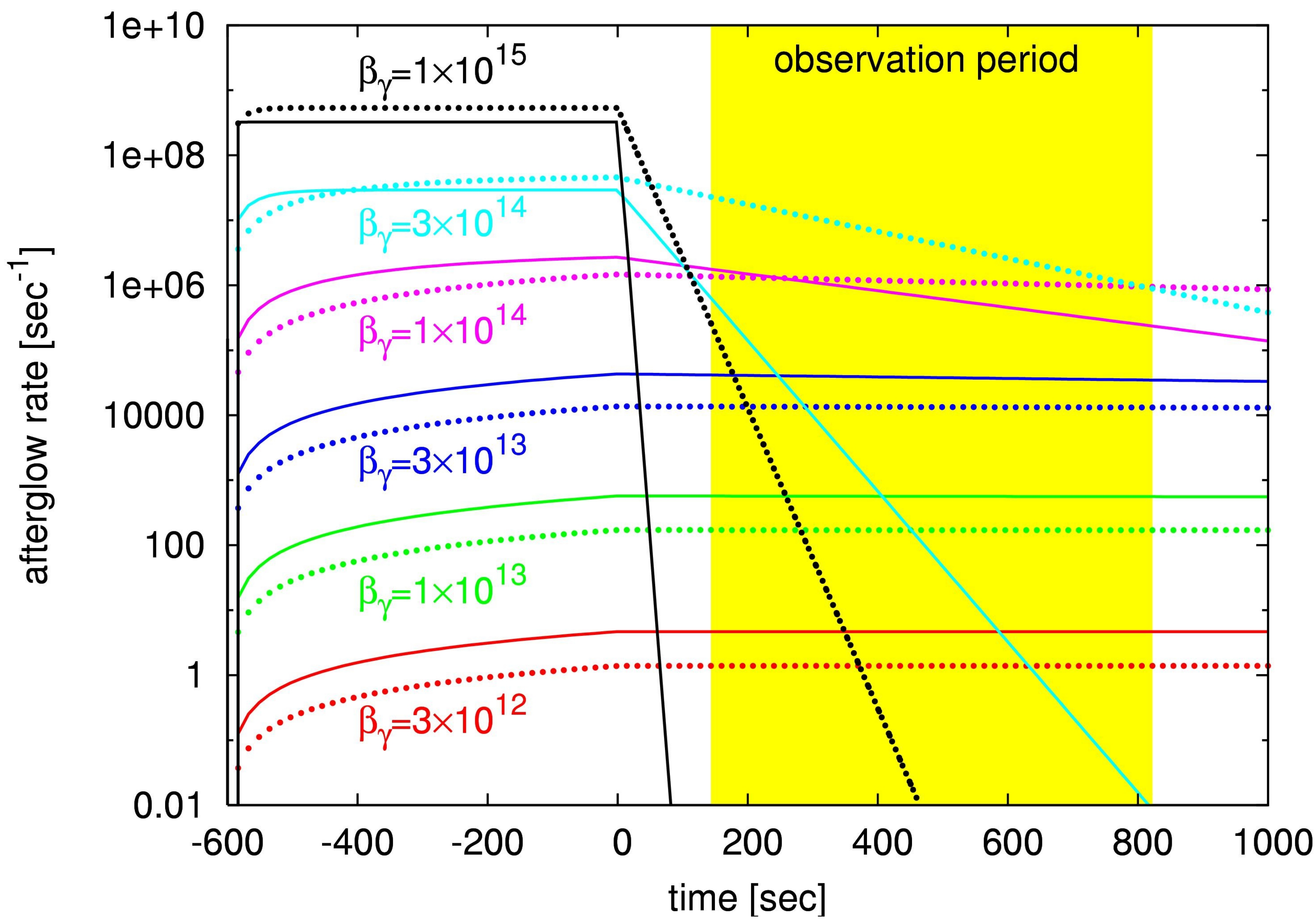
0.001
0.01
0.1

Expected Signal



Expected Signal

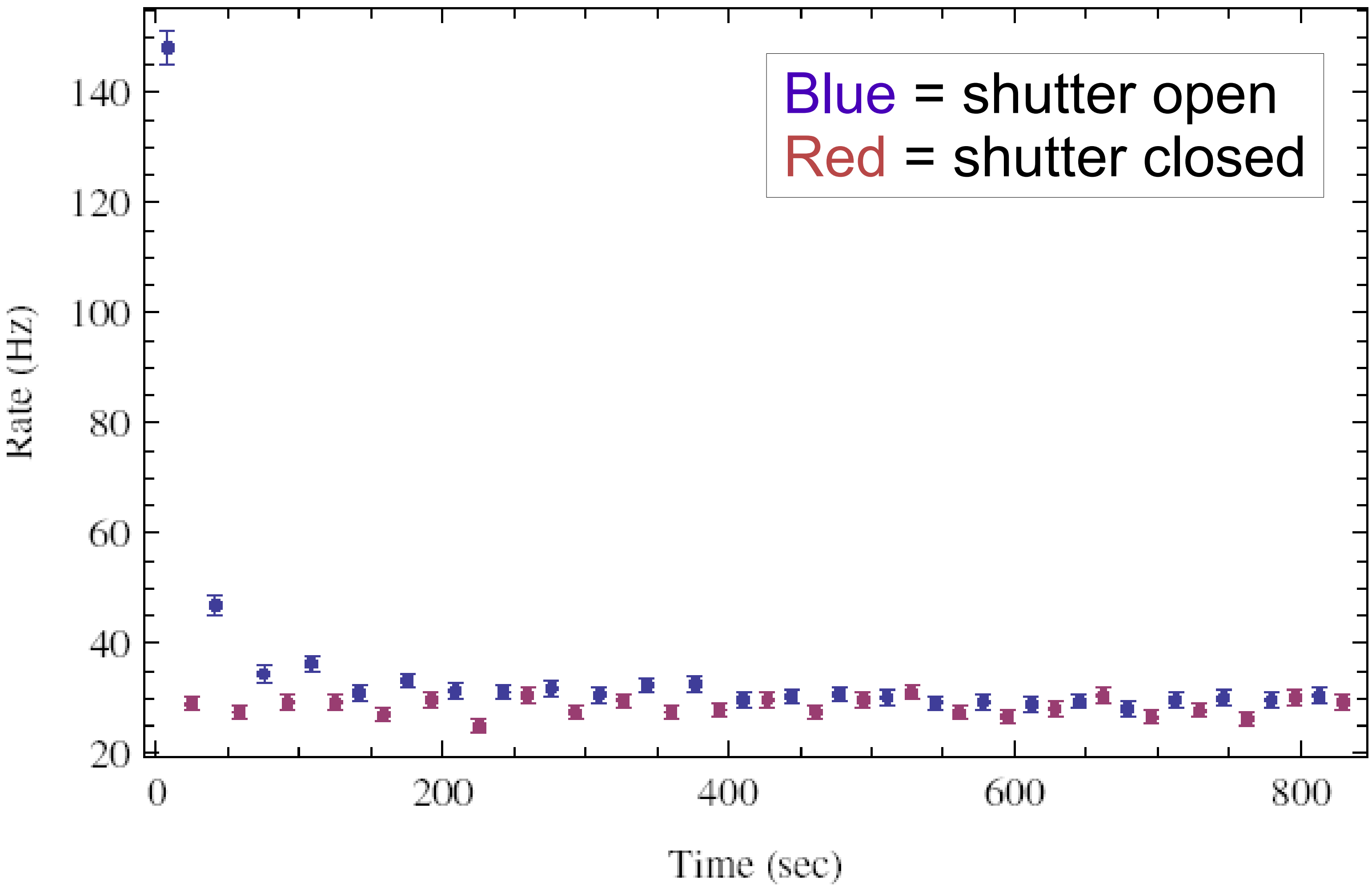


solid lines: $\xi_{ref}=0$ dotted lines: $\xi_{ref}=\pi/3$

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.

Laser Test of Gravity: The Holometer