Results of the GammeV Axion-like Particle Search

Jason H. Steffen
Brinson Postdoctoral Fellow
Fermilab Center for Particle Astrophysics

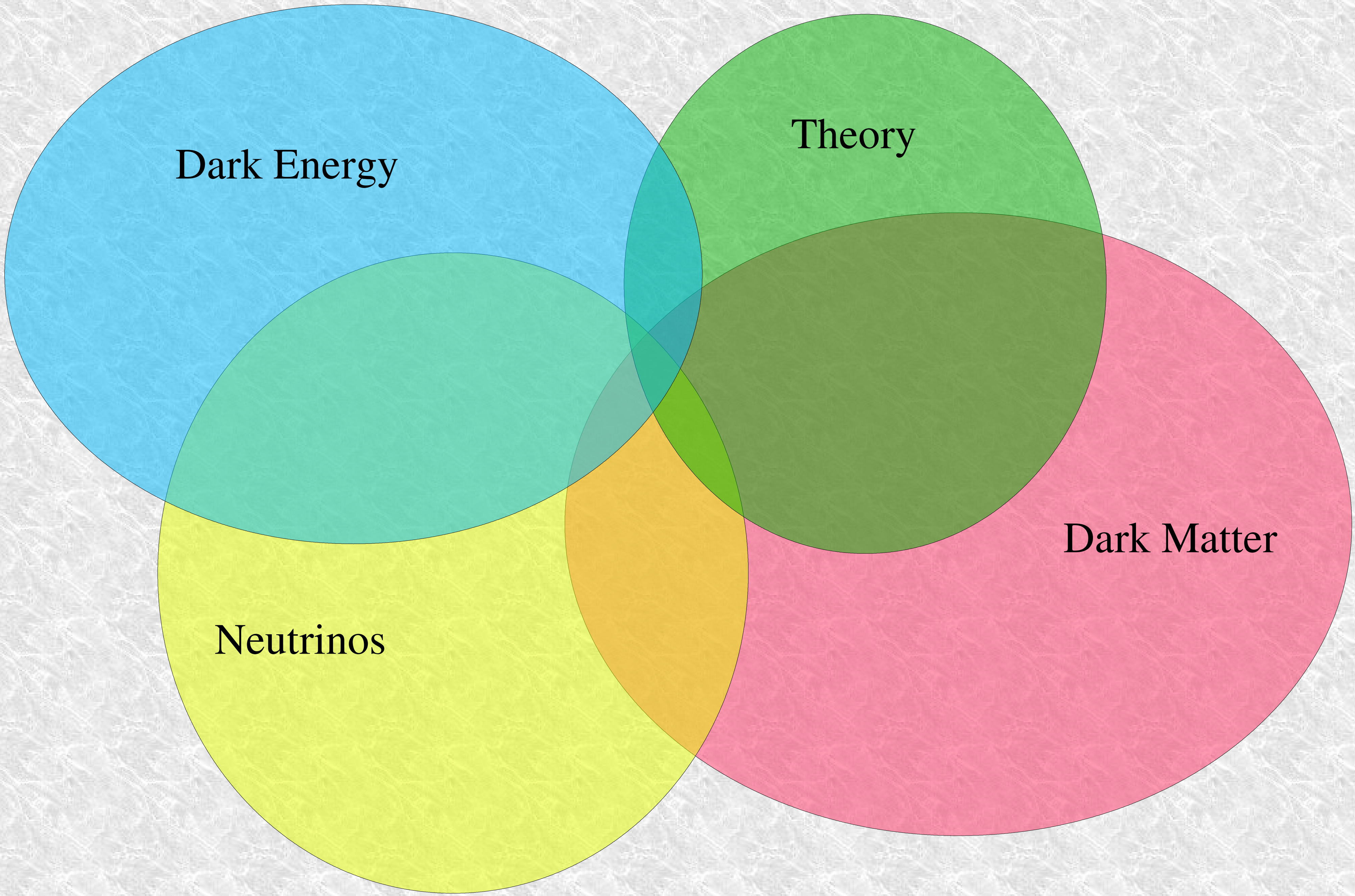
Harvard University
February 27, 2008

Aaron Chou
William Wester
Al Baumbaugh
Dick Gustafson
Yilda Irizarri-Valle
Peter Mazur
Jason Steffen
Ray Tomlin
Xi Yang
Jonghee Yoo

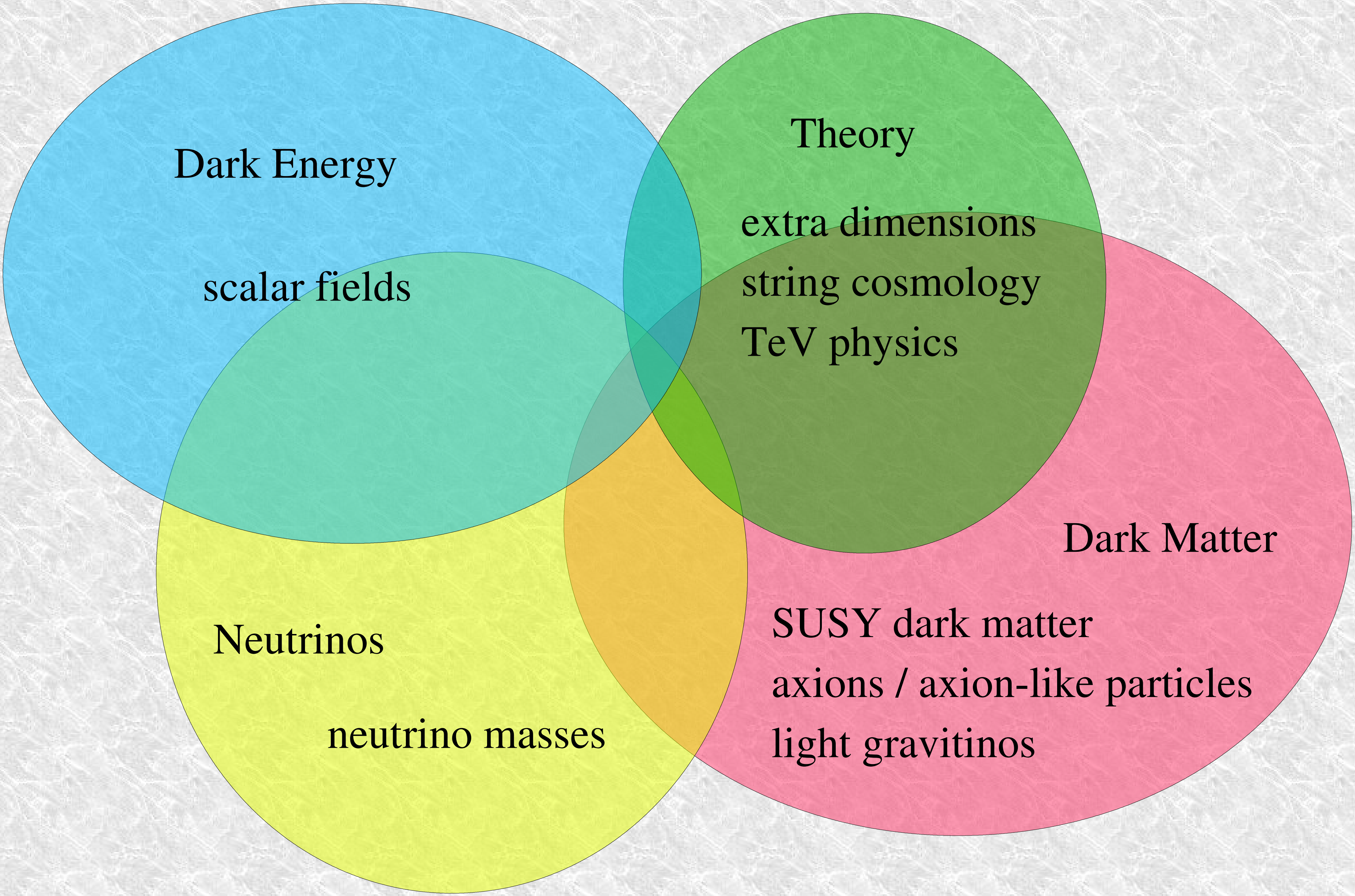
Outline

- Interesting physics
- The year 2006
- Digression: TEH parity
- GammeV – Axion
  - Axion background information
  - Concept
  - Realization
  - Results
- GammeV – Chameleon
  - Chameleon background information
  - Concept
  - Realization
  - Pseudo-results
- Future Axion searches

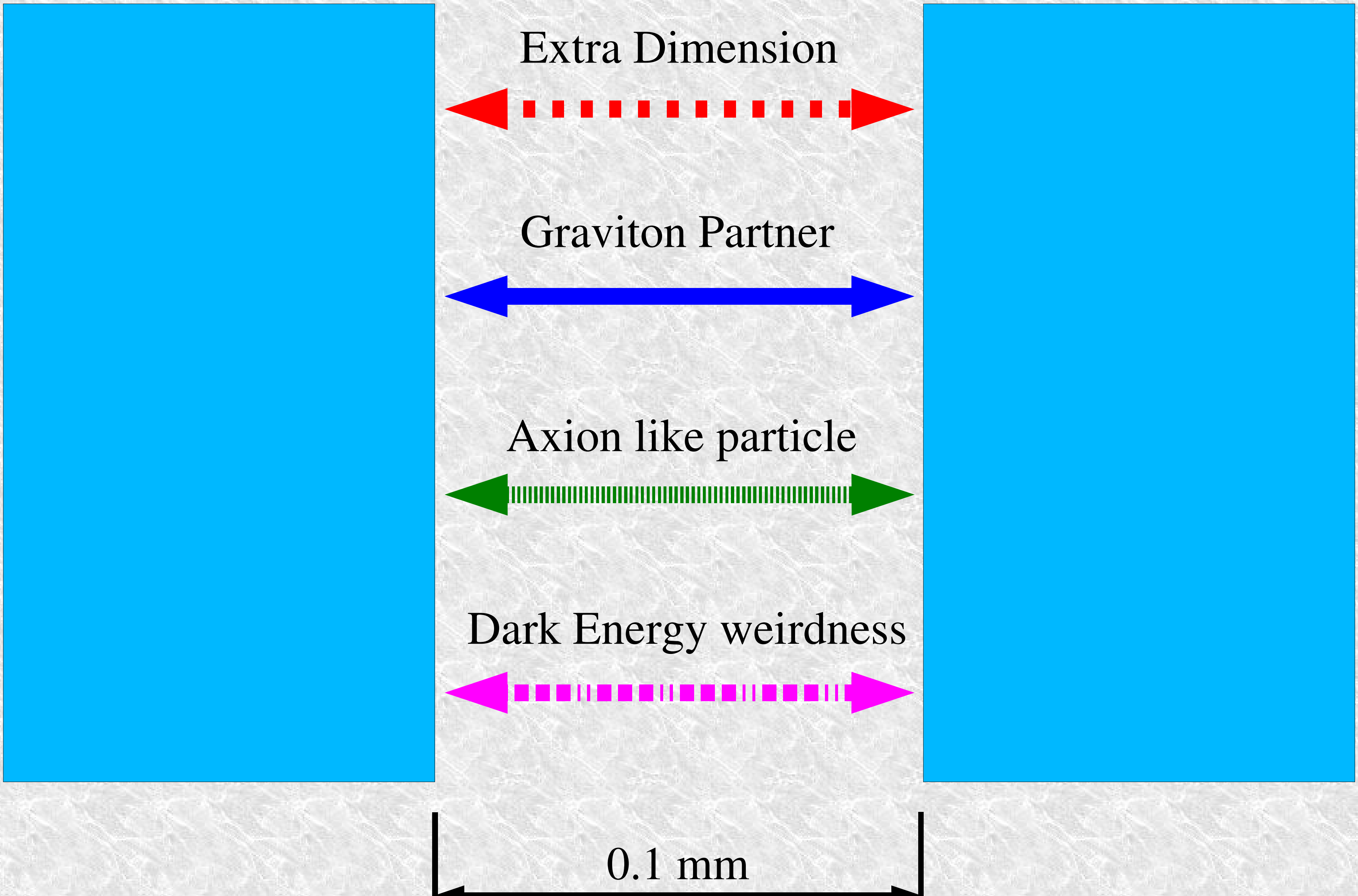
Interesting Physics



Interesting Physics

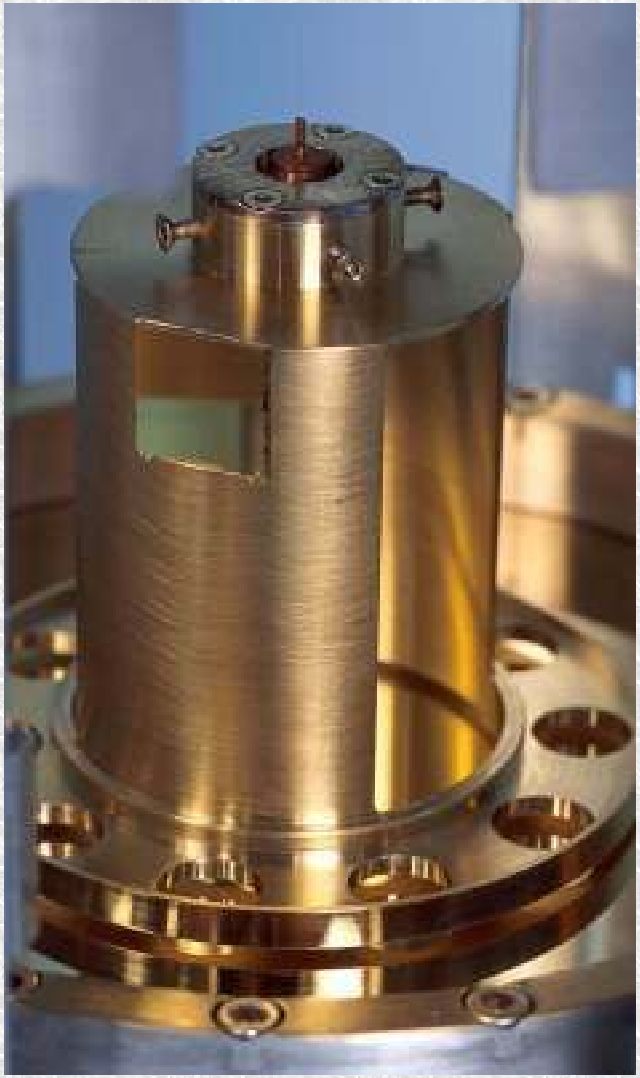


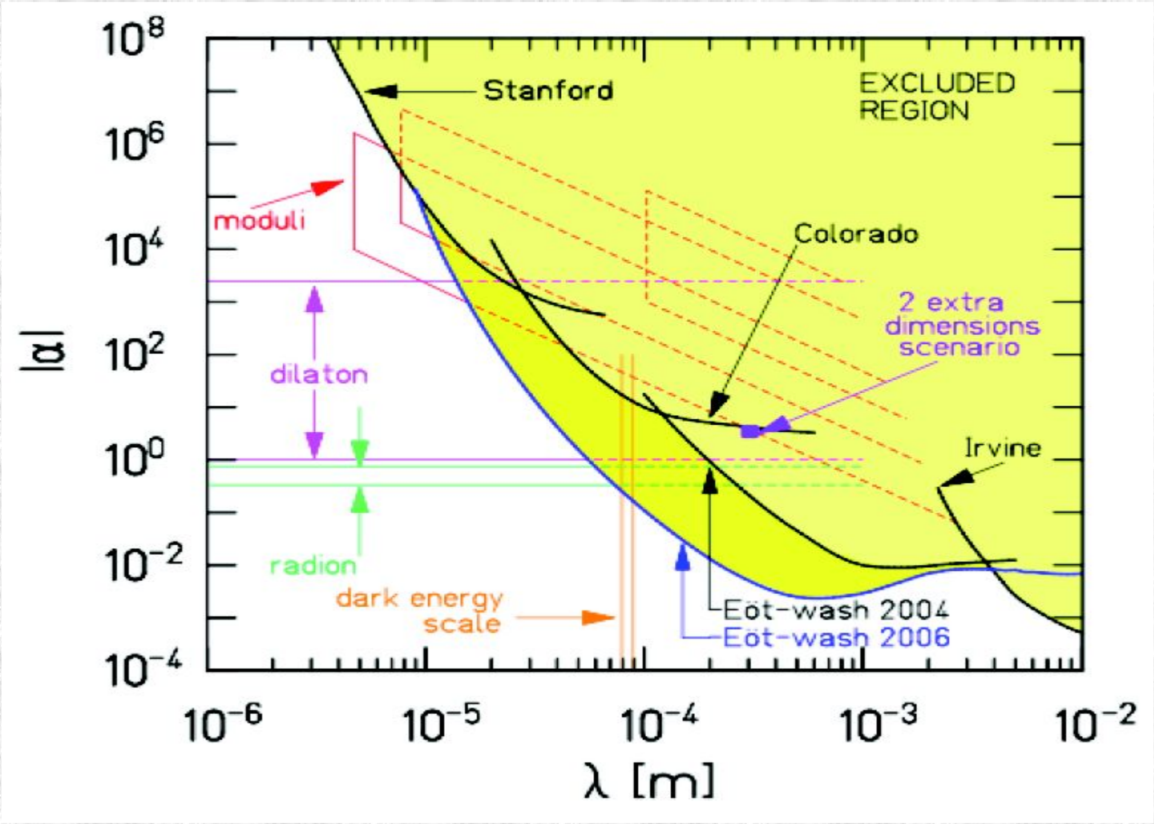
Physics Results of 2006



Physics Results of 2006

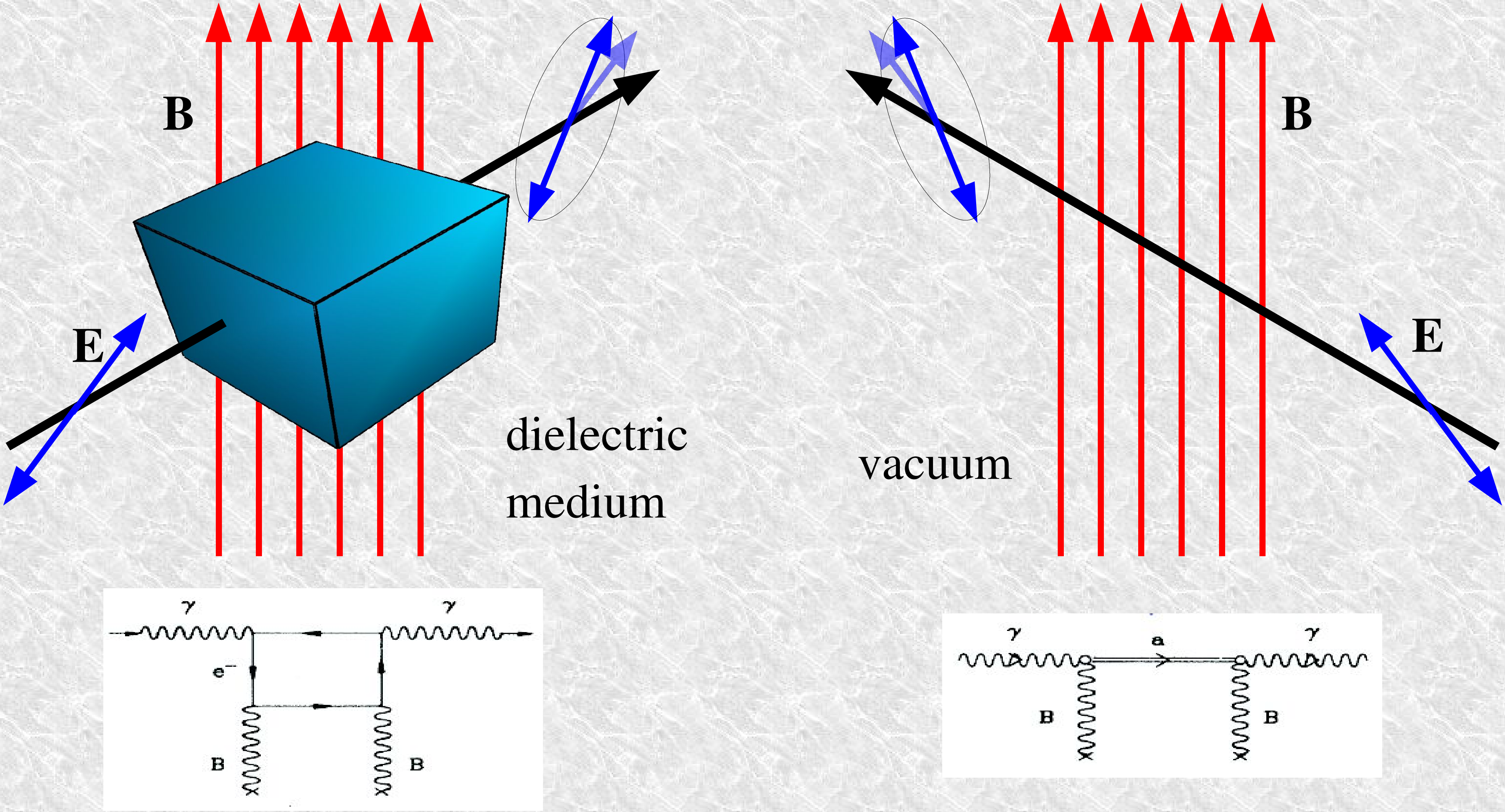
Eöt-Wash puts new limits on weird physics.





Newton is still right. No new physics here.

Physics Results of 2006

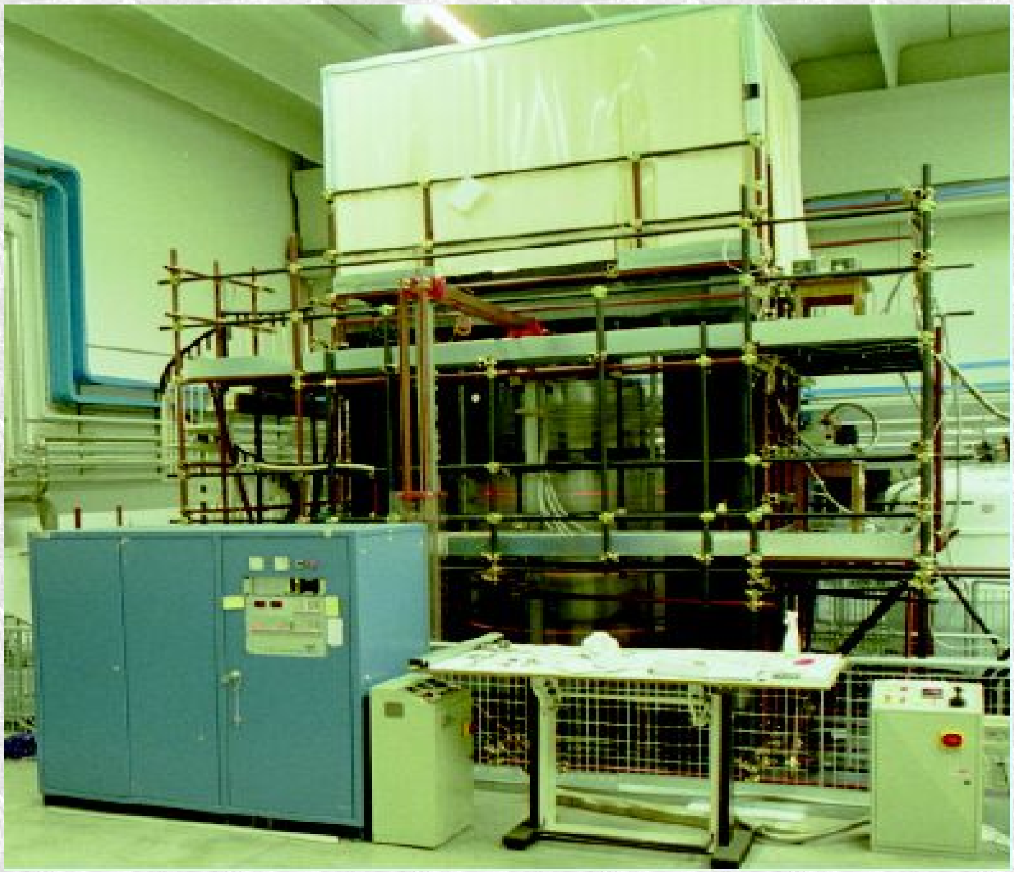


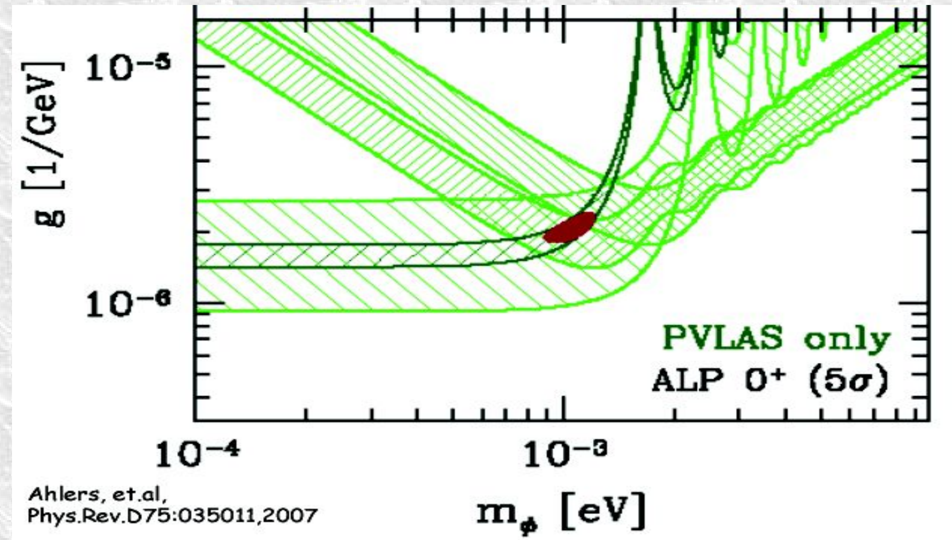
One component has a different phase velocity.

One component has different absorption properties.

Physics Results of 2006

PVLAS sees evidence for weird physics.





Four measurements of ellipticity and polarization for two different wavelengths give a consistent picture of a new meV-mass scalar particle.

Digression

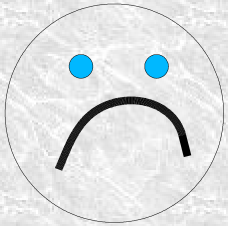
TEH conservation:
The product of the happiness of theorists and the happiness of experimentalists is constant.

Digression

TEH conservation:
The product of the happiness of theorists and
the happiness of experimentalists is constant.

Theorist

Experimentalist

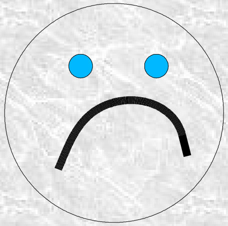


LHC finds standard model Higgs.

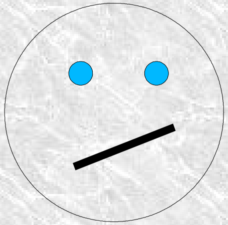
Digression

TEH conservation:
The product of the happiness of theorists and the happiness of experimentalists is constant.

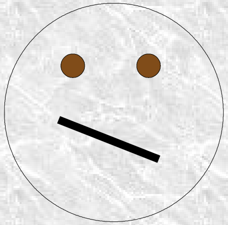
Theorist | Experimentalist



LHC finds standard model Higgs.



Britney Spears shaves her head.

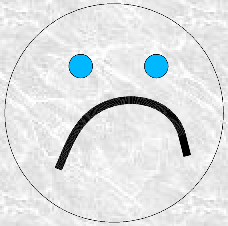


Digression

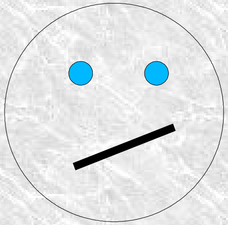
TEH conservation:

The product of the happiness of theorists and the happiness of experimentalists is constant.

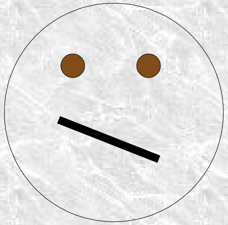
Theorist | Experimentalist

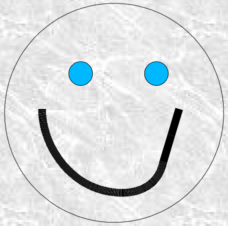


LHC finds standard model Higgs.



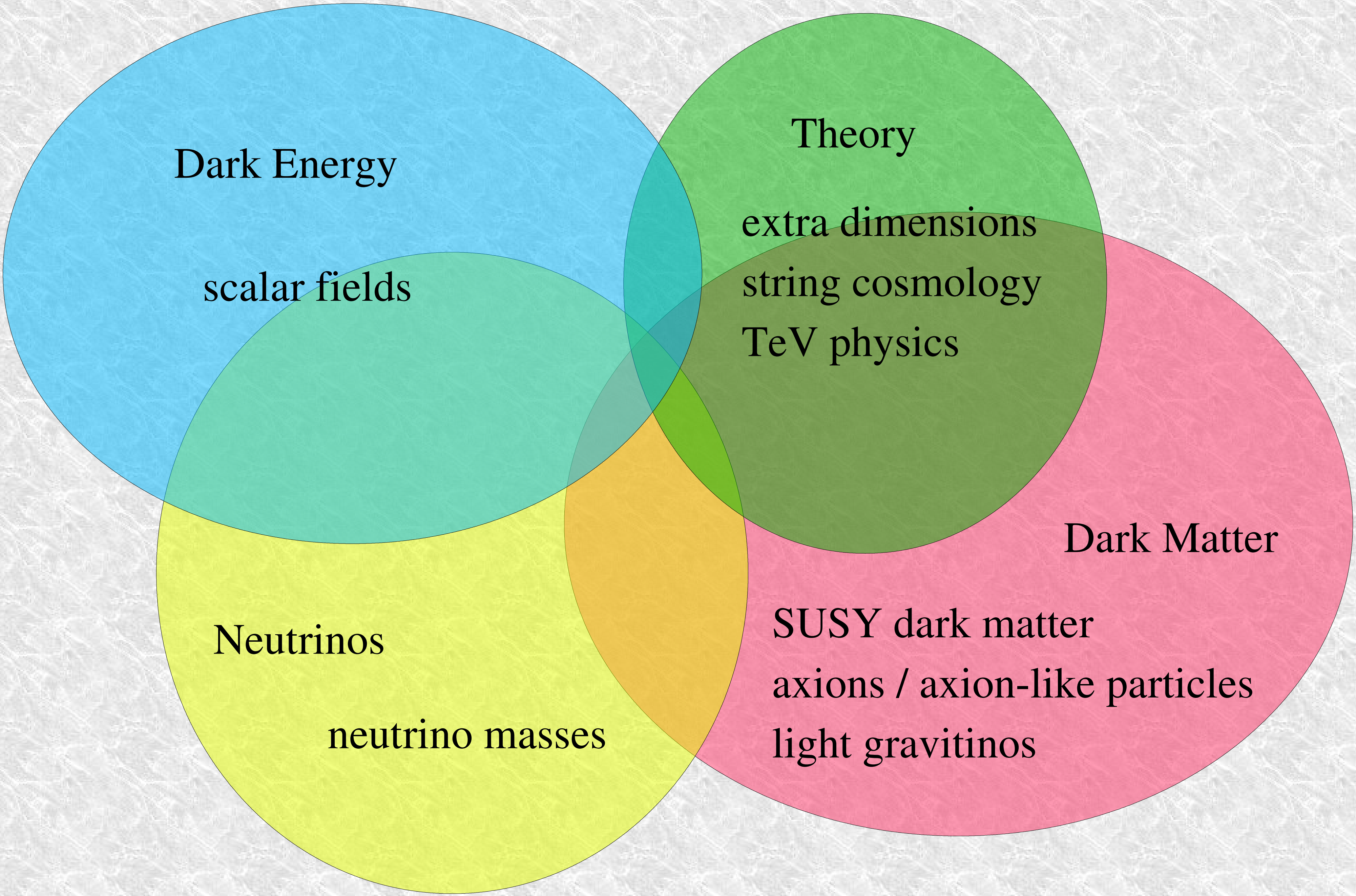
Britney Spears shaves her head.



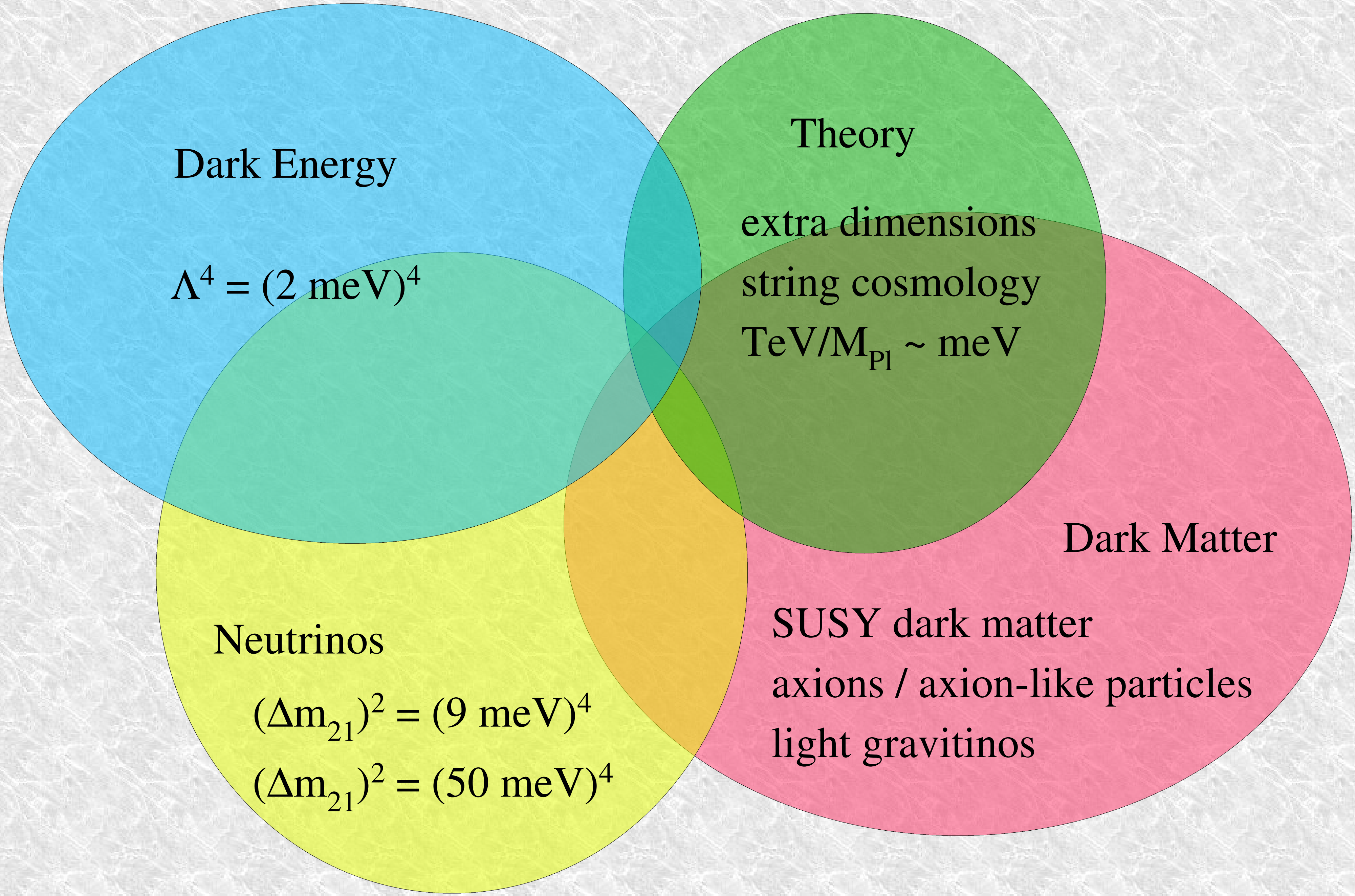


Two experiments give conflicting results.

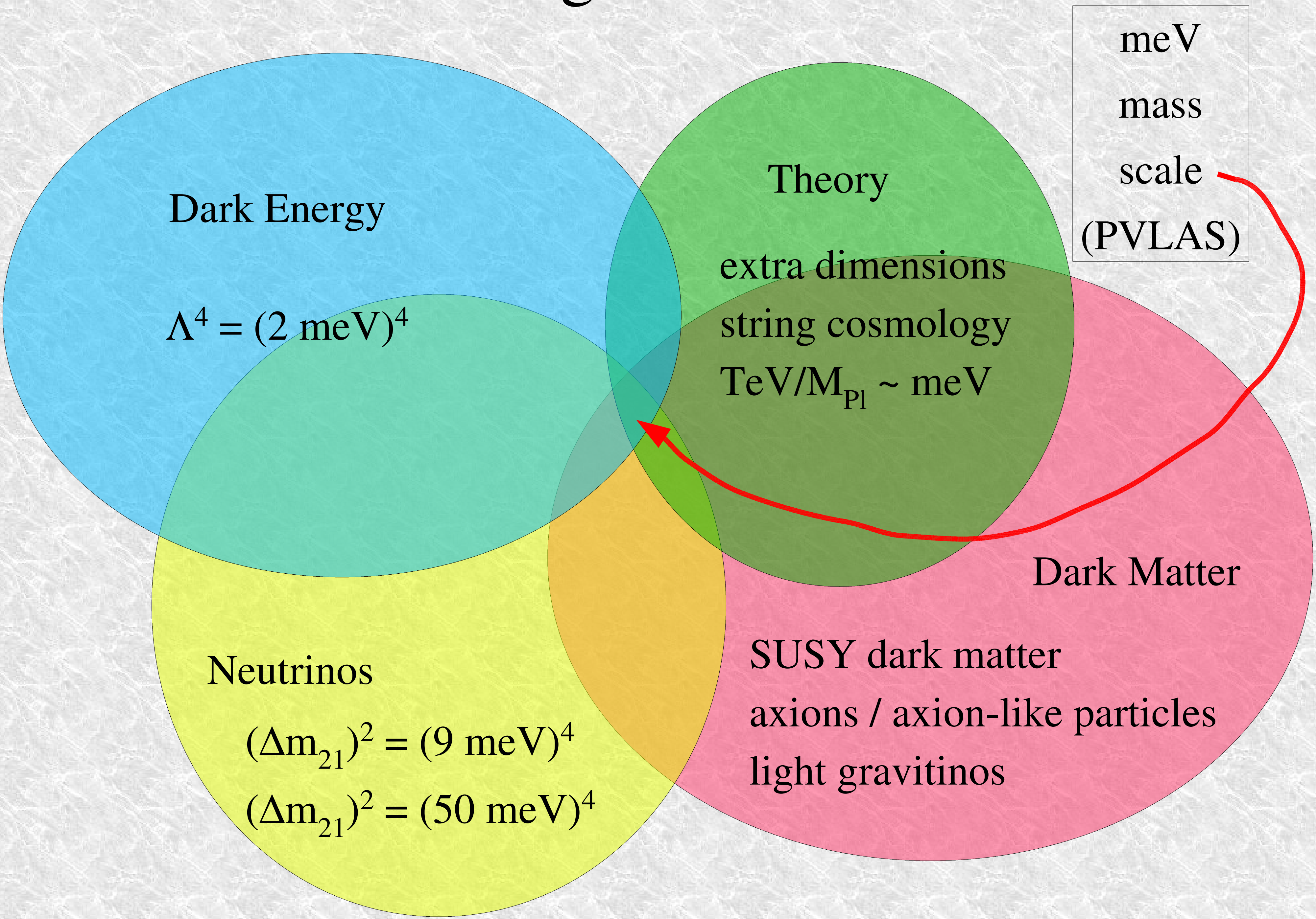
Digression


Dark Energy
scalar fields
Theory
extra dimensions
string cosmology
TeV physics
Dark Matter
SUSY dark matter
axions / axion-like particles
light gravitinos
Neutrinos
neutrino masses

Digression


Dark Energy
$\Lambda^4 = (2\ \text{meV})^4$
Theory
extra dimensions
string cosmology
$\text{TeV}/M_{Pl} \sim \text{meV}$
Dark Matter
SUSY dark matter
axions / axion-like particles
light gravitinos
Neutrinos
$(\Delta m_{21})^2 = (9\ \text{meV})^4$
$(\Delta m_{21})^2 = (50\ \text{meV})^4$

Digression

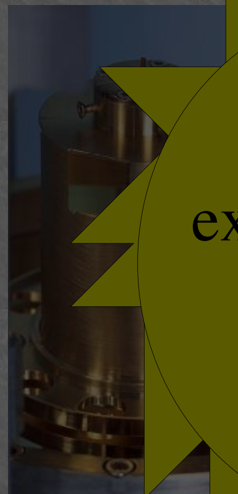

meV
mass
scale
(PVLAS)
Dark Energy
$\Lambda^4 = (2\ \mathrm{meV})^4$
Theory
extra dimensions
string cosmology
$\mathrm{TeV}/M_{Pl} \sim \mathrm{meV}$
Dark Matter
SUSY dark matter
axions / axion-like particles
light gravitinos
Neutrinos
$(\Delta m_{21})^2 = (9\ \mathrm{meV})^4$
$(\Delta m_{21})^2 = (50\ \mathrm{meV})^4$

Digression

A new scalar field could explain:

- The Eöt-Wash null result
- The PVLAS result
- The Dark Energy

Digression



experimentalist nightmare

A new scalar field could explain:

- The Eöt-Wash null result
- The PVLAS result
- The Dark Energy

More on this later.

GammeV

- GammeV – Axion
  - Axion background information
  - Concept
  - Realization
  - Results
- GammeV – Chameleon
  - Chameleon background information
  - Concept
  - Realization
  - Pseudo-results

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.

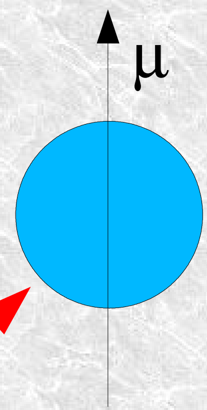
Axions, the Other Dark Matter

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}.

Axions, the Other Dark Matter

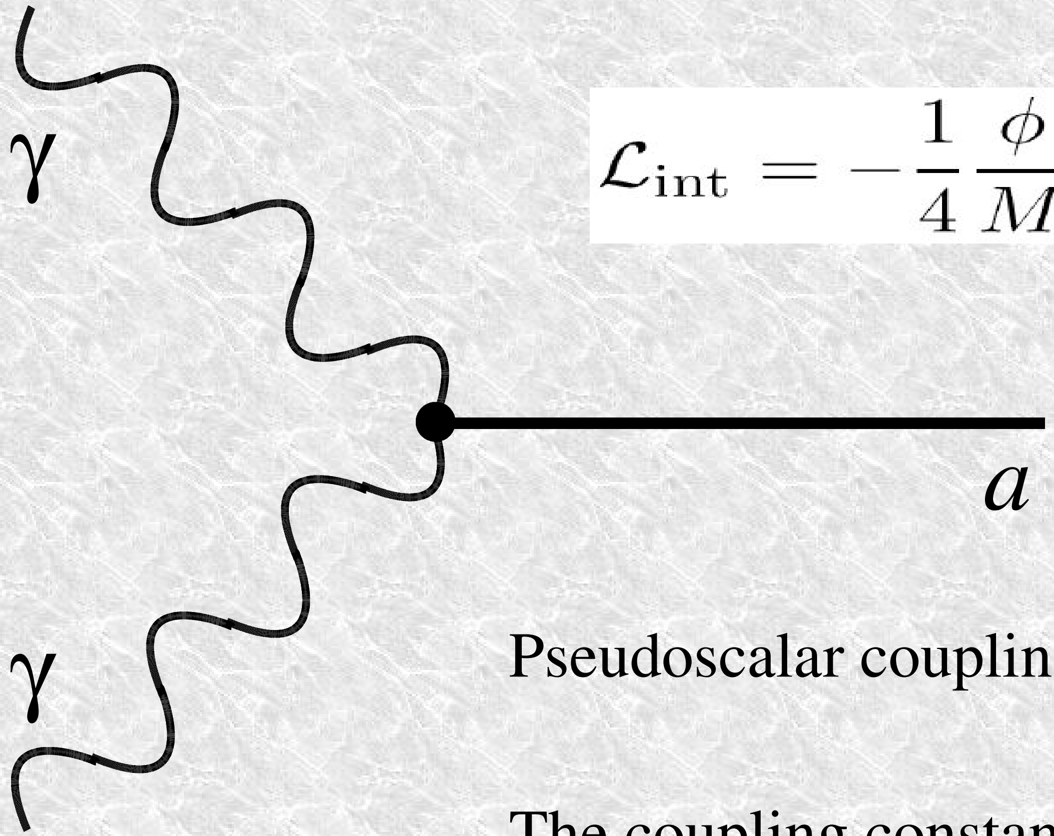
Peccei-Quinn ('77), Wilczek ('78), Weinberg ('78) proposed a solution:

Axions, the Other Dark Matter

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

- NEW! dynamical degree of freedom
- NEW! spontaneously broken U(1) symmetry
- NEW! pseudo Nambu-Goldstone boson (with mass)
- CLEANS! your CP problems
- SOLVES! the dark matter question

Axions, the Other Dark Matter



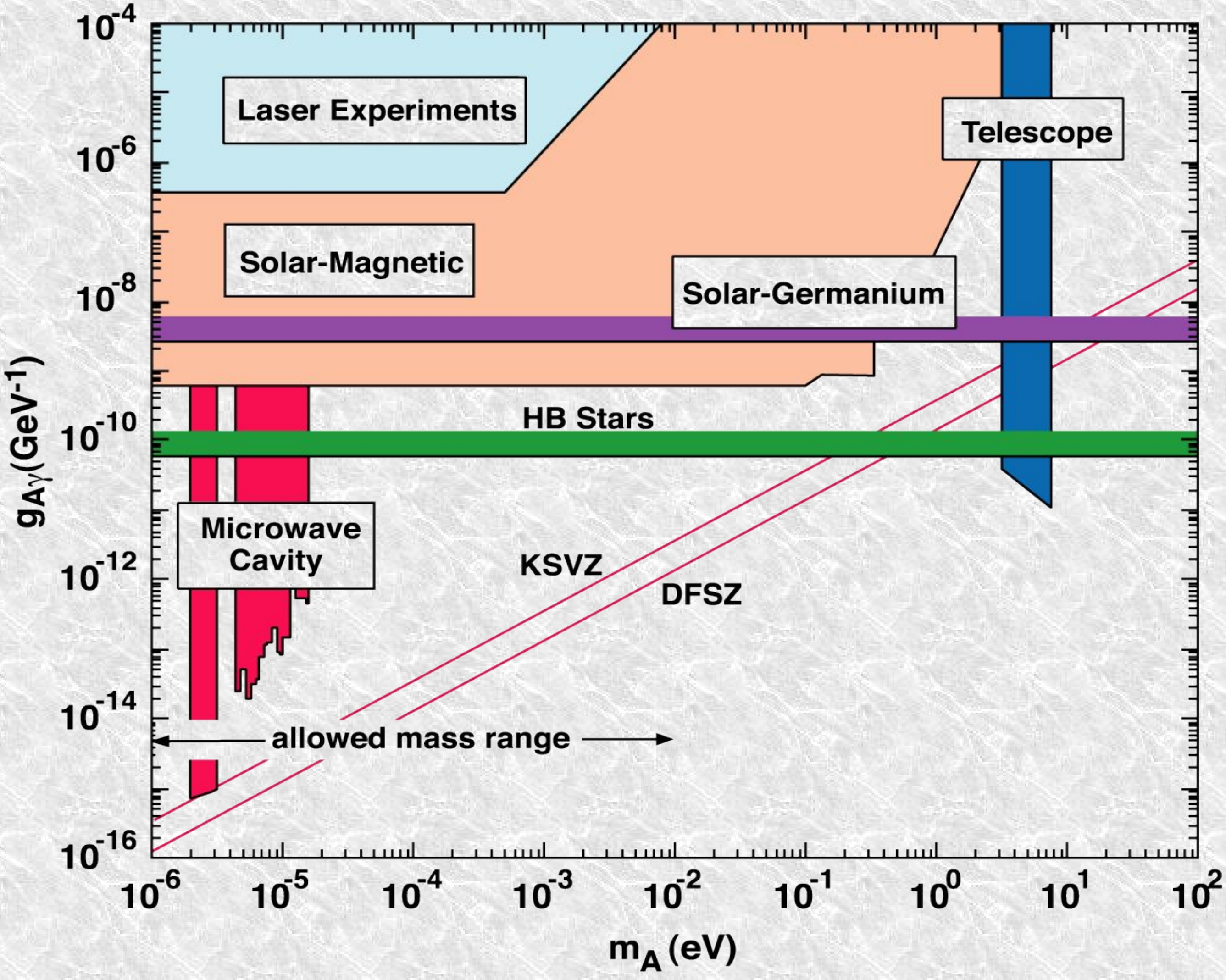
$$\mathcal{L}_{\rm int} = -\frac{1}{4}\frac{\phi}{M}F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{\phi}{M}(\vec{E}\cdot\vec{B})$$

Pseudoscalar coupling to two photons.

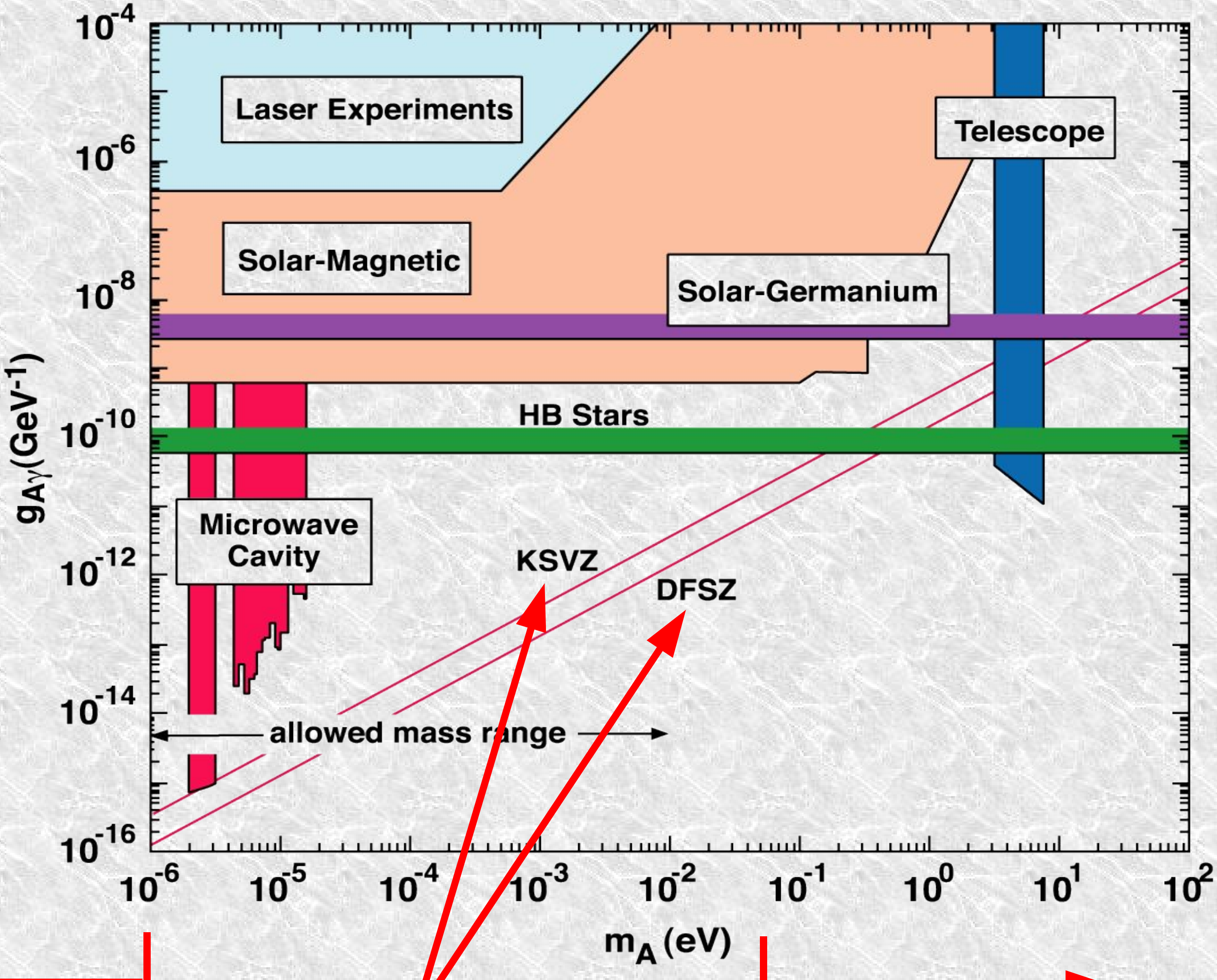
The coupling constant and mass depend upon the mass and coupling constant of the pion.

$(f_a m_a = f_\pi m_\pi)$

Axions, the Other Dark Matter



Axions, the Other Dark Matter

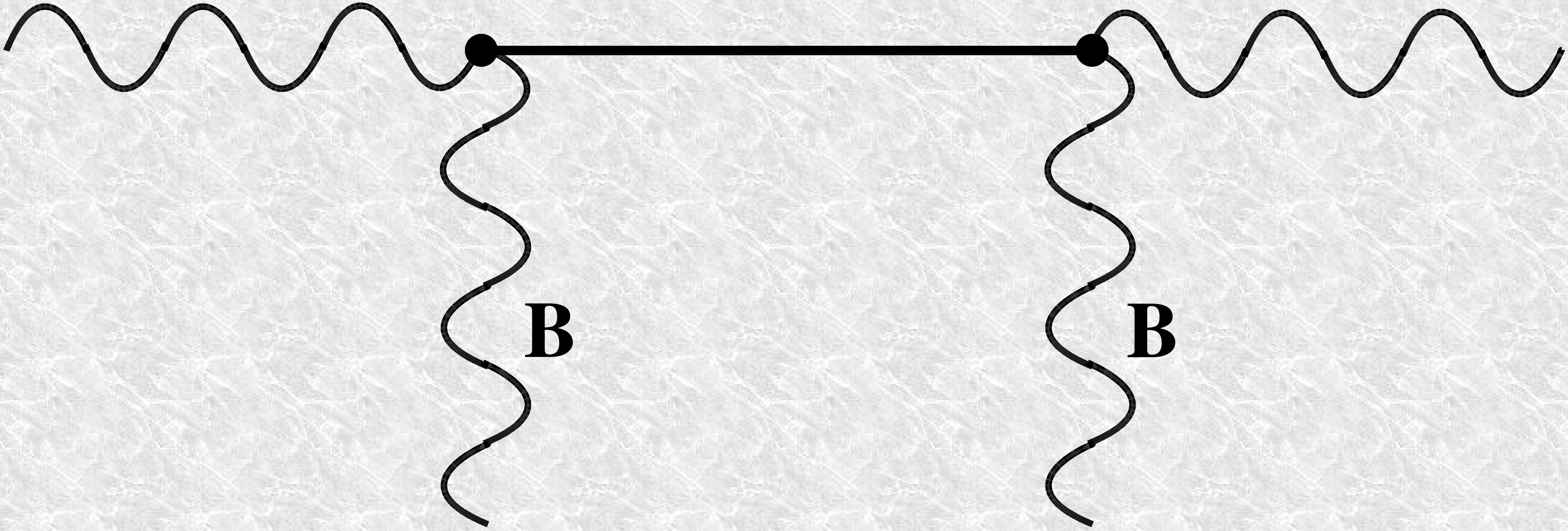


$\Omega_a > 1$

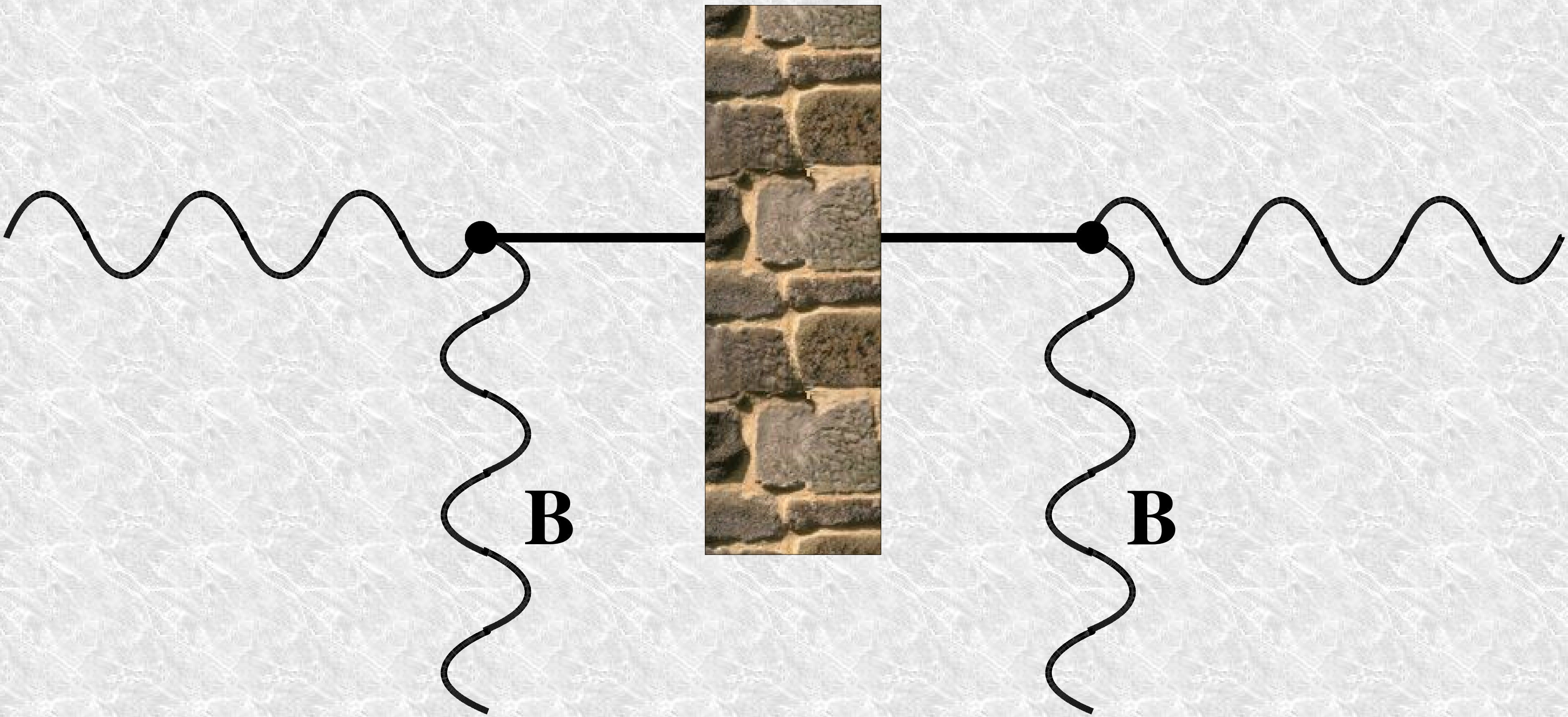
QCD axion models

SN 1987a

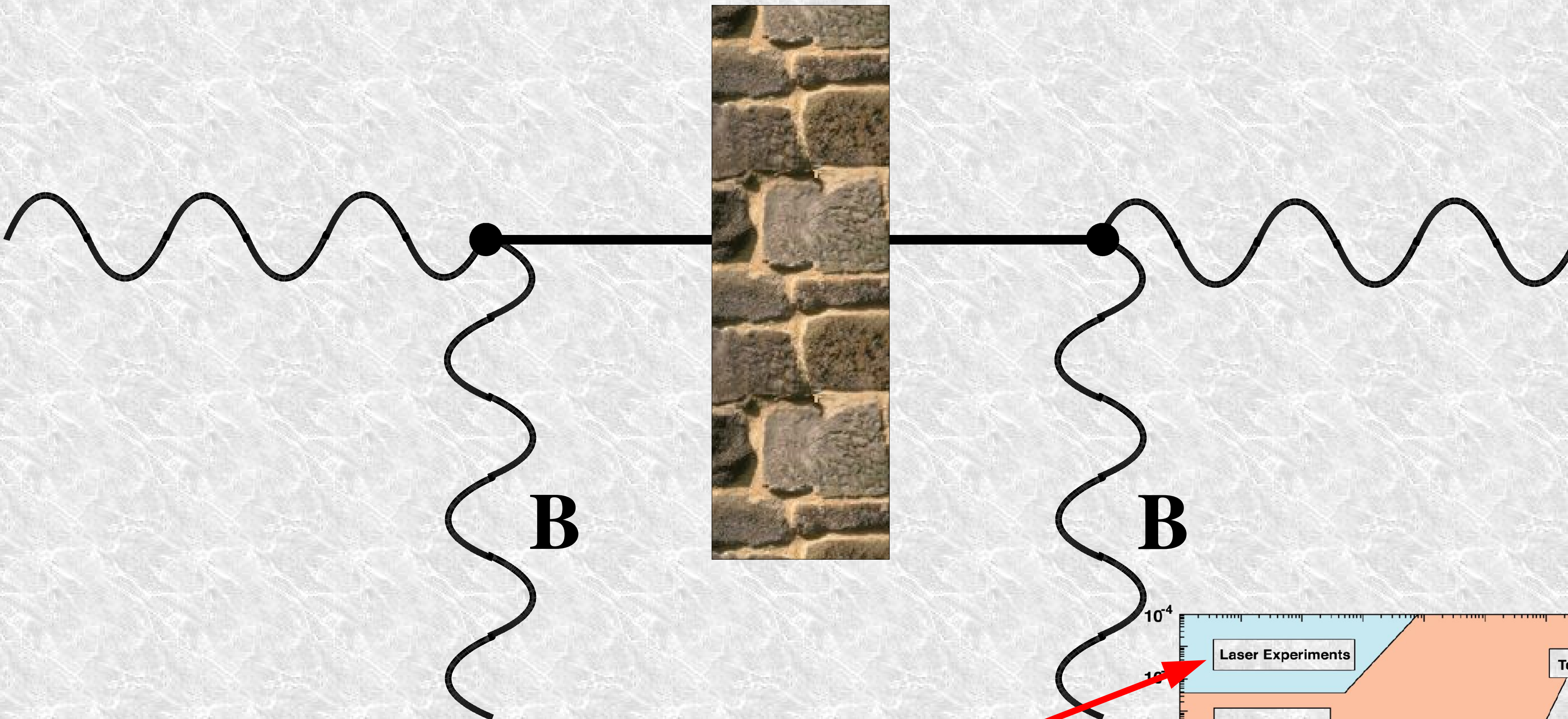
Axions, the Other Dark Matter



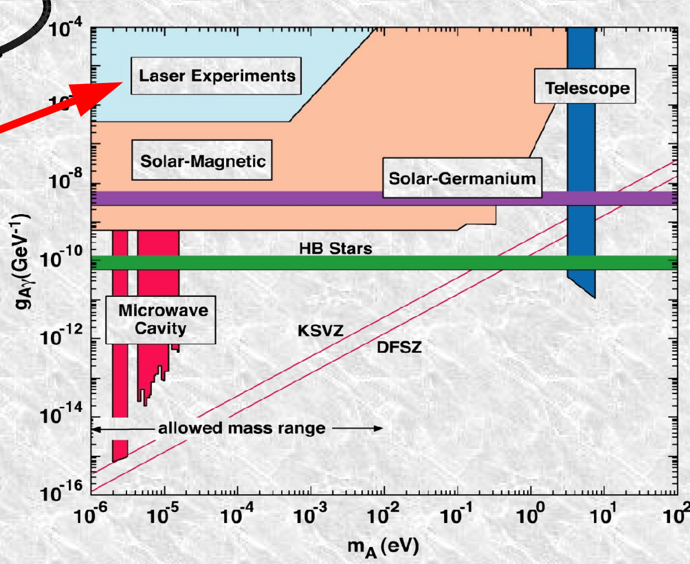
Axions, the Other Dark Matter



Axions, the Other Dark Matter

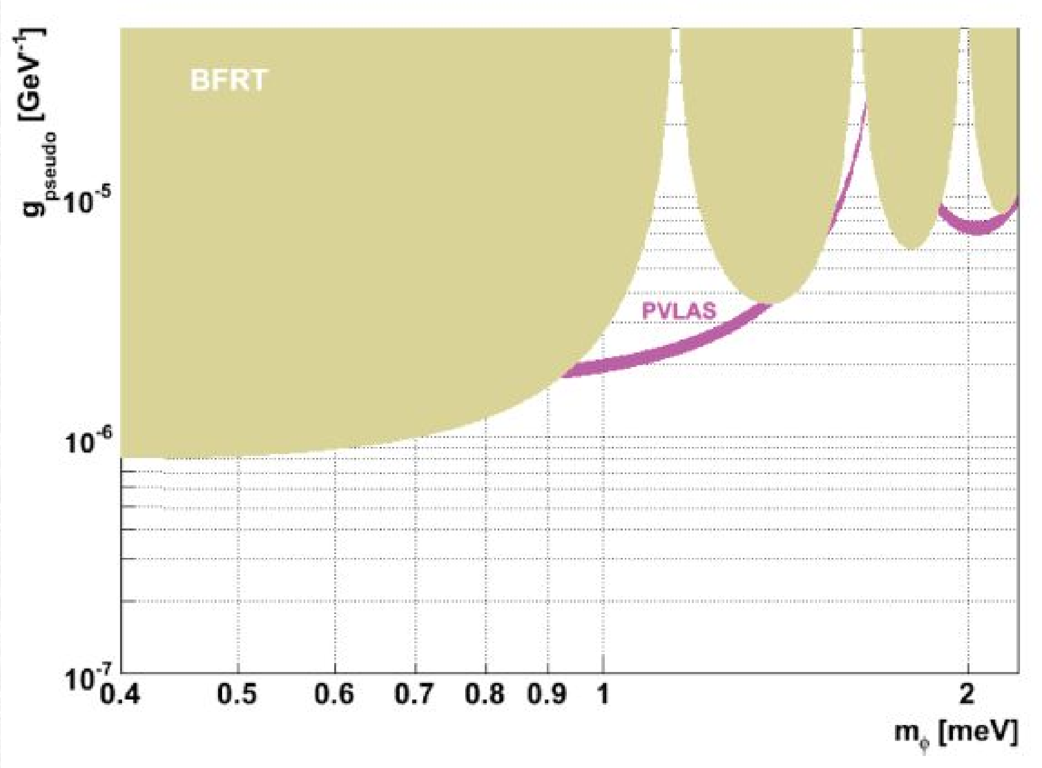


This process gives the "laser"
experimental results.
(BFRT Experiment)



Gamme**V** – Axion: Concept

- PVLAS parameters lie in a region of diminished BFRT sensitivity
- Tevatron dipole magnets are slightly larger and can cover this region
- Existing high-power, pulsed laser is sufficient to probe PVLAS parameters in hours

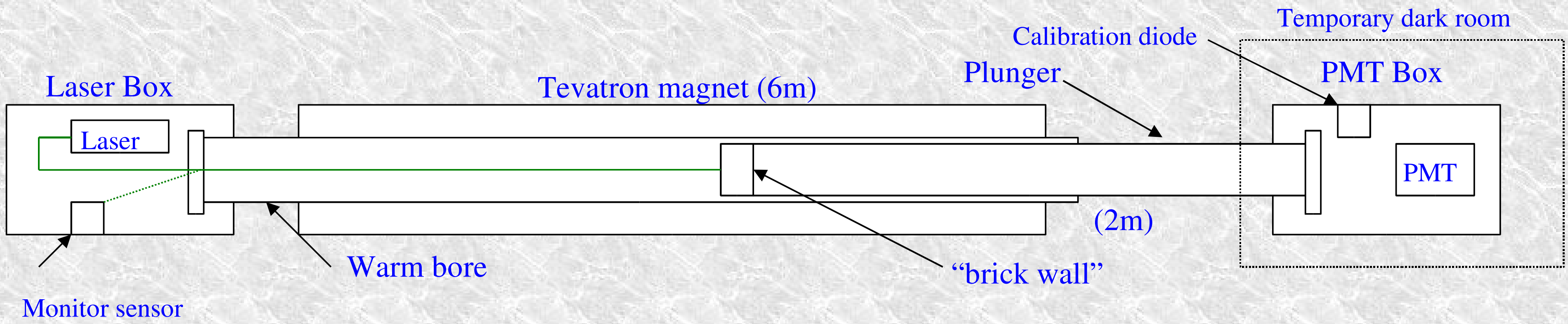


$$P_{regen} = \frac{16 B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8} \sin^2\left(\frac{m_\phi^2 L_1}{4\omega}\right) \cdot \sin^2\left(\frac{m_\phi^2 L_2}{4\omega}\right)$$

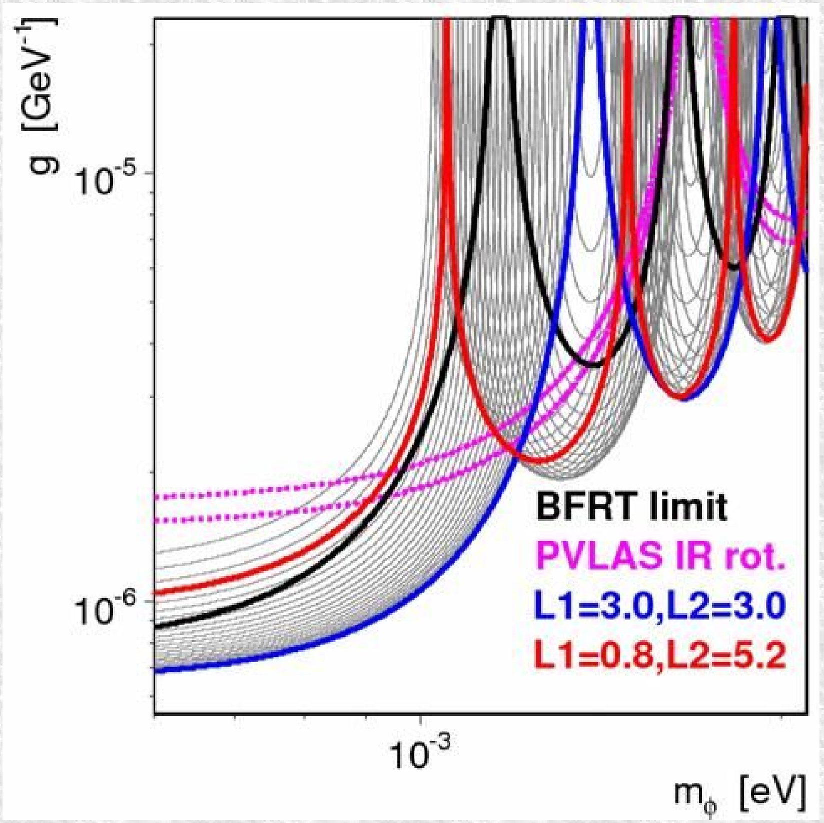
$$= (2.25 \times 10^{-22}) \times \frac{(B_1/\mathrm{Tesla})^2 (B_2/\mathrm{Tesla})^2 (\omega/\mathrm{eV})^4}{(M/10^5\ \mathrm{GeV})^4 (m_\phi/10^{-3}\ \mathrm{eV})^8}$$

$$\times \sin^2\left(1.267 \frac{(m_\phi/10^{-3}\ \mathrm{eV})^2 (L_1/\mathrm{m})}{(\omega/\mathrm{eV})}\right) \sin^2\left(1.267 \frac{(m_\phi/10^{-3}\ \mathrm{eV})^2 (L_2/\mathrm{m})}{(\omega/\mathrm{eV})}\right)$$

GammeV – Axion: Concept



- A movable plunger allows us to change the effective lengths of the magnetic field regions
- Off-the-shelf Quarknet boards can be used for control and data acquisition
- Optics, some materials, and detector are the only major purchases. Requested budget: $30,000
- Expected duration: 6 months



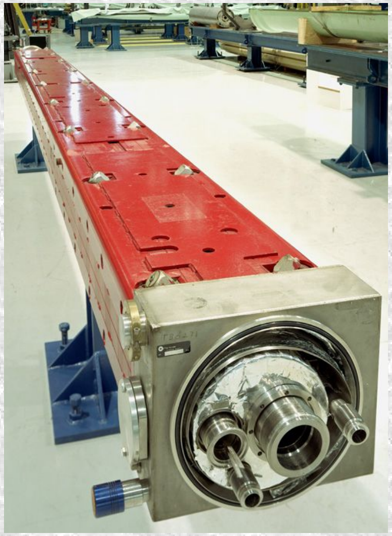
Limits after 5 hours

GammeV – Axion: Concept

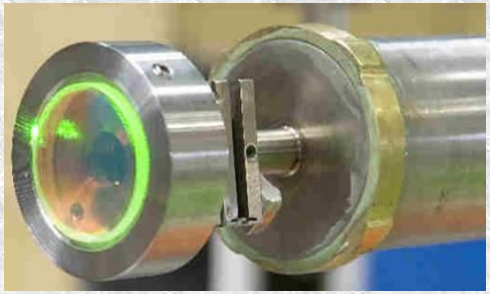
The time component is critical due to world-wide efforts.

name	place	magnet (field length)	laser wavelength power	P_{PVLAS}	photon flux at detector
ALPS	DESY	5 T 4.21 m	1064 nm 200 W CW	$= 10^{-19}$	10/s
BMV	LULI	11 T 0.25 m	1053 nm 500 W 4 pulses/day	$= 10^{-21}$	10/pulse
LIPSS	Jefferson Laboratory	1.7 T 1.0 m	900 nm 10 kW CW	$= 10^{-23.5}$	0.1/s
OSQAR (preliminary phase)	CERN	9.5 T 1.0 m 9.5 T 3.3 m	540 nm 1 kW CW	$= 10^{-20}$	10/s
PVLAS (regeneration)	INFN Legnaro	5 T 1 m 2.2 T 0.5 m	1064 nm 0.8 W CW Npass $= 5 \times 10^5$	$= 10^{-23}$	10/s

GammeV – Axion: Realization



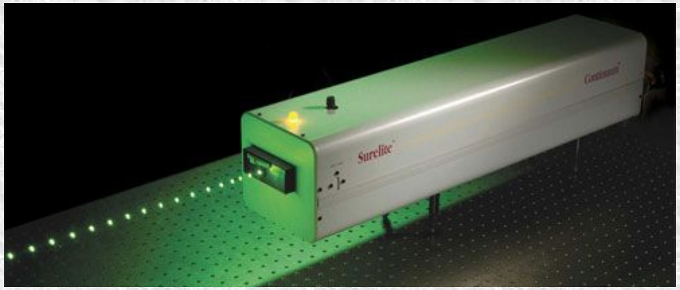
- Spare Tevatron dipole (TC 1206)
- 5T field over 6m length
- LHC insulating bore
- Support from Magnet Test Facility (real estate, cryogenics, and magnet operations)



- Welded cap with adjustable mirror mount
- Concave mirror with 10 m focal length
- Prevents heating the cryogenic system
- Keeps incoming and outgoing beams separate

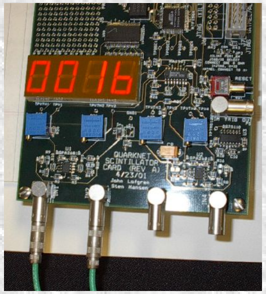
- 10 m stainless steel plunger
- 2 meters of travel
- Dark box houses the PMT
- 2 independent vacuum systems each pumped to $<10^{-4}$ torr.

GammeV – Axion: Realization



- Continuum Surelite Nd:YAG laser doubled to 532 nm light
- 160 mJ per pulse (~3 W)
- 5ns pulses at 20Hz
- Half-wave plate allows for testing both scalar and pseudoscalar couplings

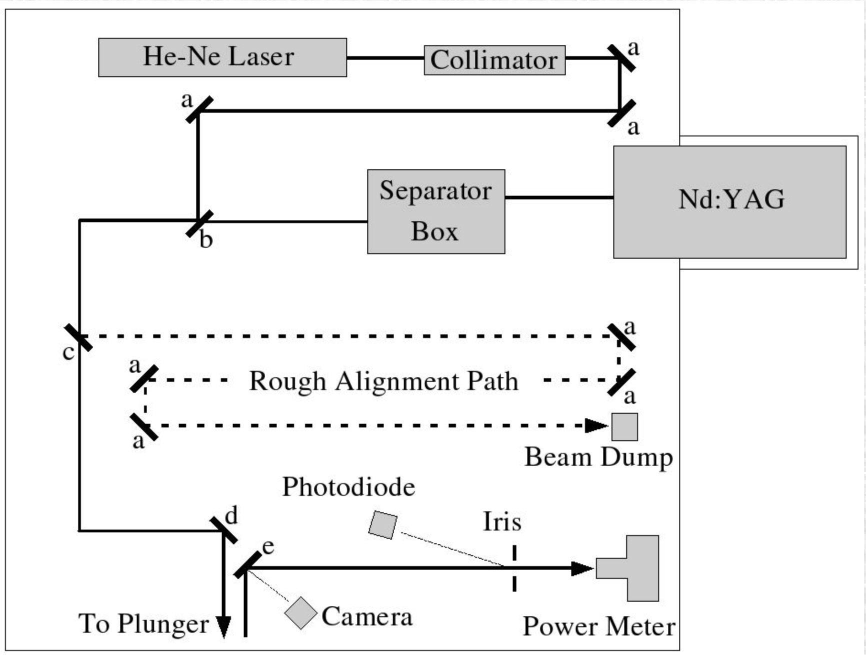
- Hamamatsu PMT
- 39% QE at 532 nm
- Built-in cooler (0^o C)
- Dark count rate ~100Hz gives expected signal-to-noise ratio of ~100



- QuarkNet timing board (used for EPO experiments)
- 4 inputs locked to GPS
- 100 MHz clock split into eight 1.25 ns divisions
- Controls laser and data acquisition

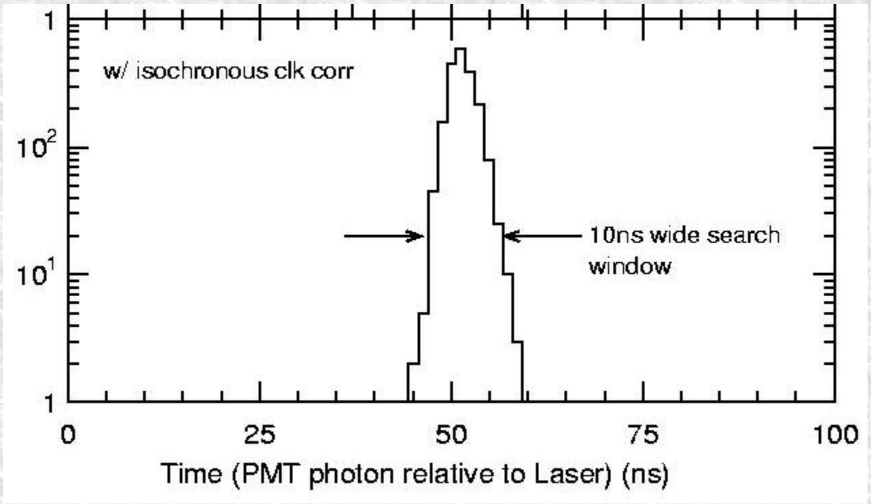
GammeV – Axion: Realization

Optical Alignment



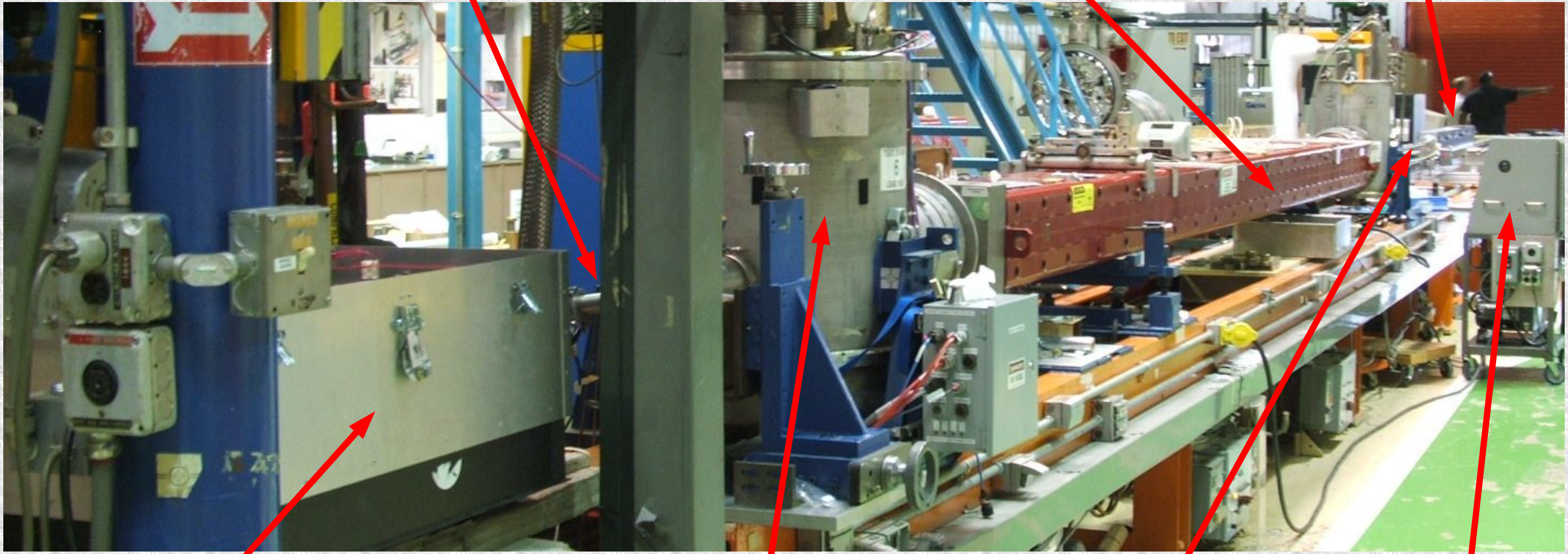
- HeNe alignment laser follows path of high power laser
- Open-ended plunger and mock target verify alignment at PMT
- Return beam monitored with solid state camera and photodiode

Timing Calibration



- High power laser light attenuated by a factor of ~10^{20} using mirrors, a pinhole, and filters
- Delay between laser firings and PMT hits identified
- 10 ns gate chosen as coincidence window

GammeV – Axion: Realization



Gamme**V** – Axion: Results

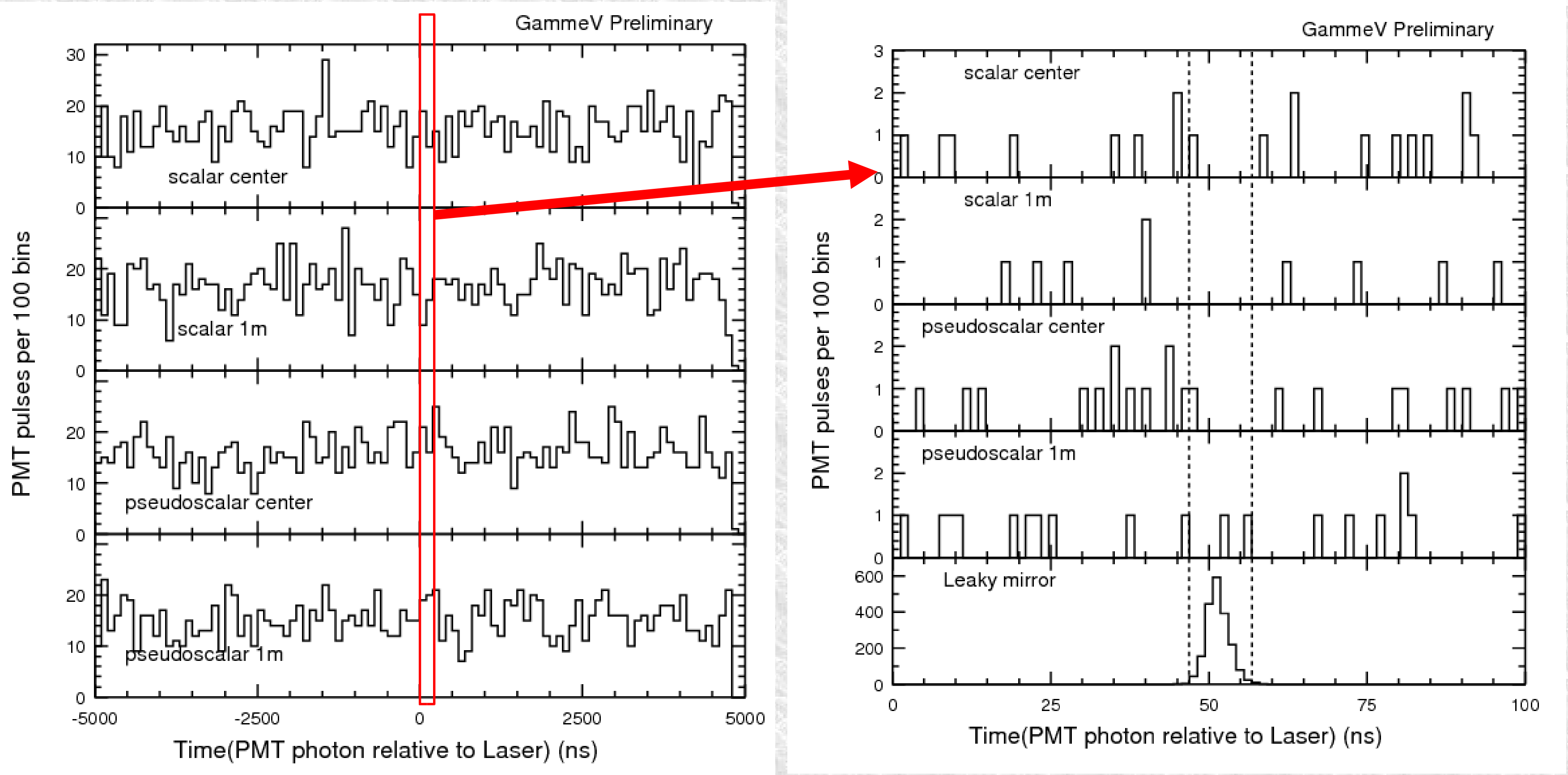
- Take data in four configurations
  - Two polarizations for scalar and pseudoscalar particles
  - Two plunger positions (L_1, L_2) = (3.1m, 2.9m) and (5.0m, 1.0m)

- Use 20 hours of magnet time in each configuration
  - Monitor laser power with calorimetric power meter
  - Expect roughly 1.5M pulses ~ Avogadro's number of photons

- Estimate detection efficiency of (25 +/- 3)%
  - 39% QE – factory measured
  - 70% CE – factory estimated
  - 92% Optical transport efficiency – empirically measured

- Estimate background using non-coincident windows

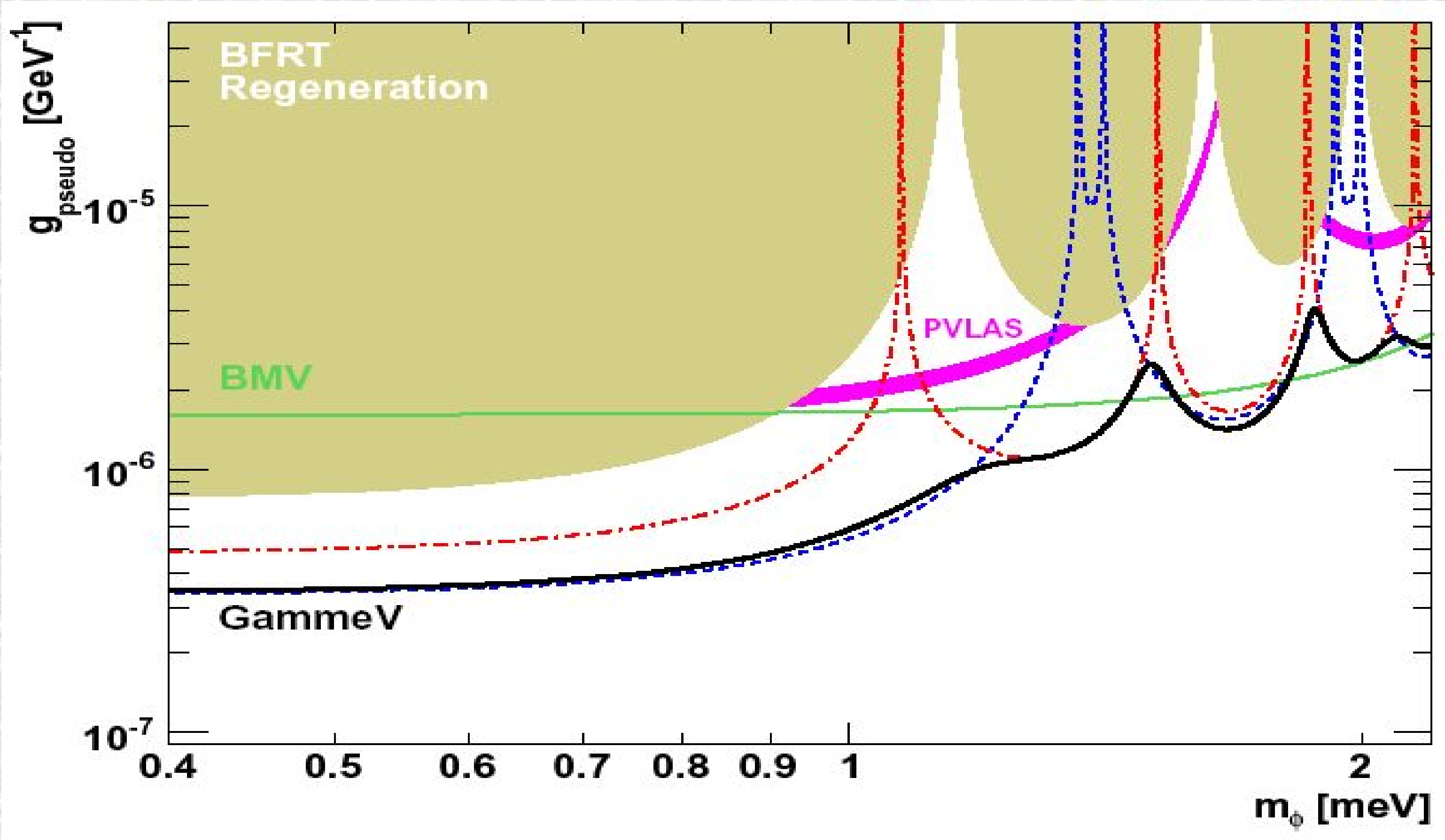
GammeV – Axion: Results



Spin	Position	# Laser pulse	# photons	Expected Background	Signal Candidates
Scalar	Center	1.34M	6.3e23	1.6	1
Scalar	1 m	1.47M	6.4e23	1.7	0
Pseudo	Center	1.43M	6.6e23	1.6	1
Pseudo	1m	1.47M	7.1e23	1.5	2

Gamme**V** – Axion: Results

Pseudoscalar Limits



Tan region: BFRT 3-sigma exclusion

Pink region: PVLAS 3-sigma detection

Green line: BMV 3-sigma exclusion

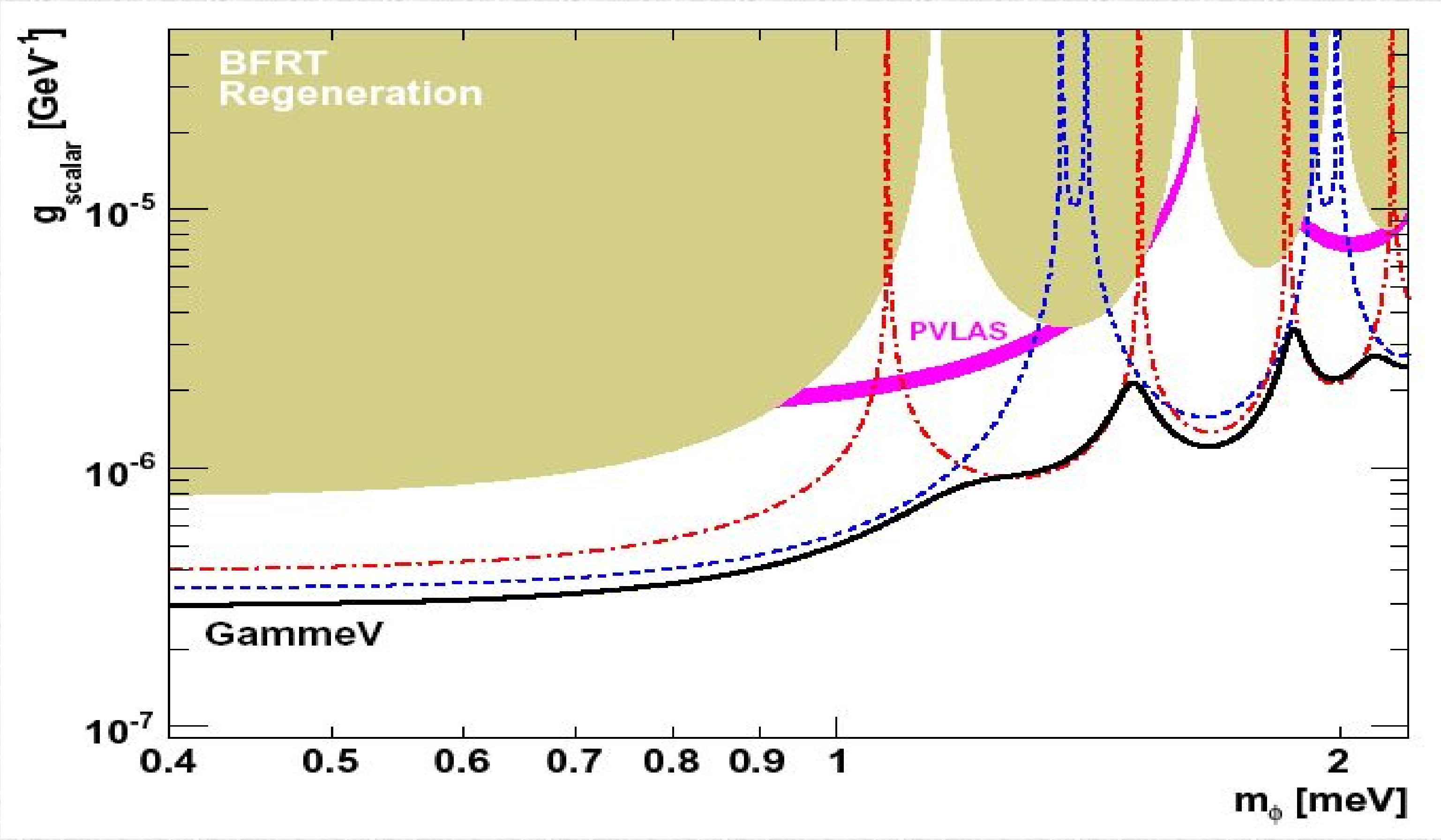
Red line: **G**amme**V** 3-sigma exclusion center position

Blue line: **G**amme**V** 3-sigma exclusion edge position

Black line: **G**amme**V** 3-sigma combined limit

Gamme**V** – Axion: Results

Scalar Limits



Tan region: BFRT 3-sigma exclusion

Pink region: PVLAS 3-sigma detection

Red line: **G**amme**V** 3-sigma exclusion center position

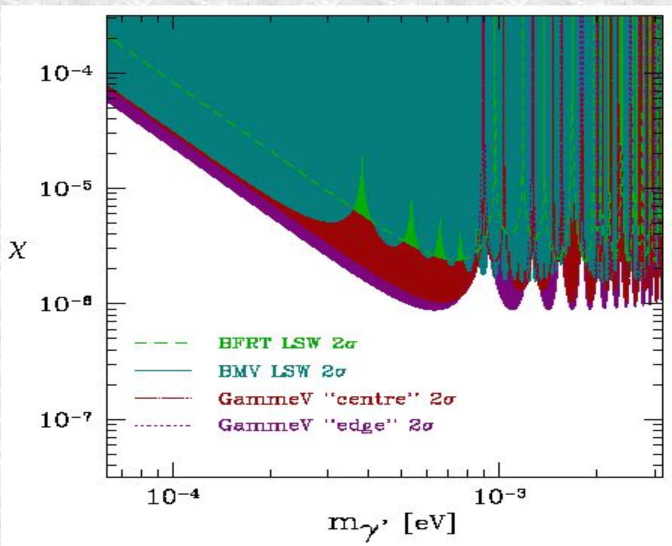
Blue line: **G**amme**V** 3-sigma exclusion edge position

Black line: **G**amme**V** 3-sigma combined limit

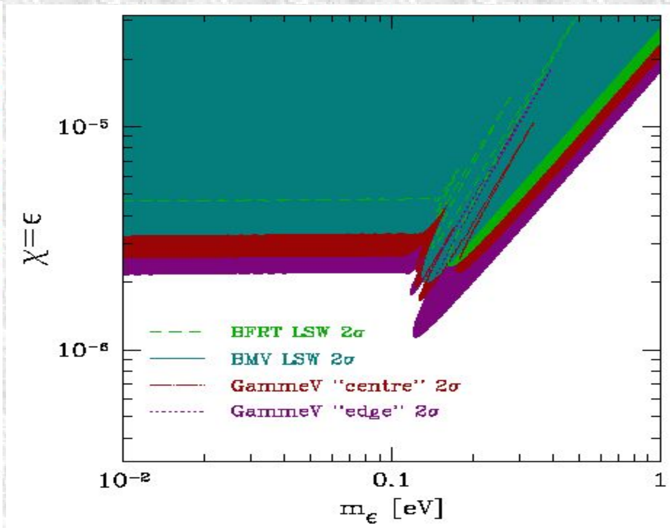
Gamme**V** – Axion: Results

Hidden sector photons:

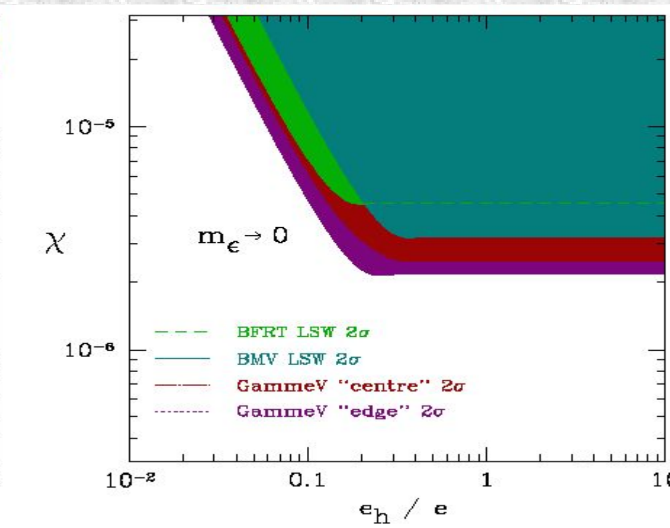
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 B_\mu B^\mu$$



Limits on hidden sector photons mixing with photons.



Limits on kinetic mixing of hidden sector photons with photons with a minicharged particle.



Limits on kinetic mixing parameter in a model with a massless minicharged particle with coupling e_h.

Results from Ahlers et al. arXiv:0711.4991

GammeV – Axion: Results

- **GammeV**'s variable baseline approach allows us to probe for particles of all masses in the region of interest

- Pulsed laser improves signal-to-noise ratio by coincidence counting

- Small budget, small team; conception to results in 11 months

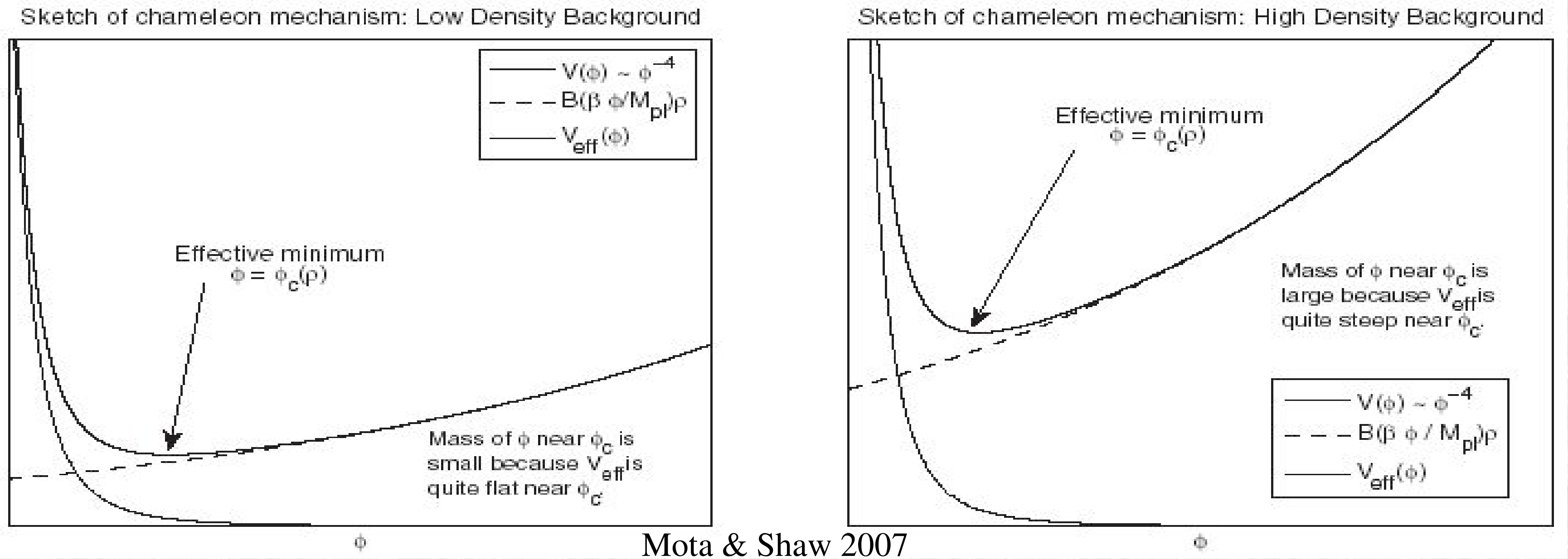
- Particle interpretation of the PVLAS signal excluded at more than 5-sigma for both scalars and pseudoscalars

- **GammeV** also places interesting limits on hidden sector photons

- Results published in PRL February 23, 2008 (arXiv:0710.3783) (see also Science June 27, 2008)

Chameleon Particles

- New scalar field with nontrivial potential and coupling to the energy–momentum tensor
- Mass is a strong function of the local energy density



Mota & Shaw 2007

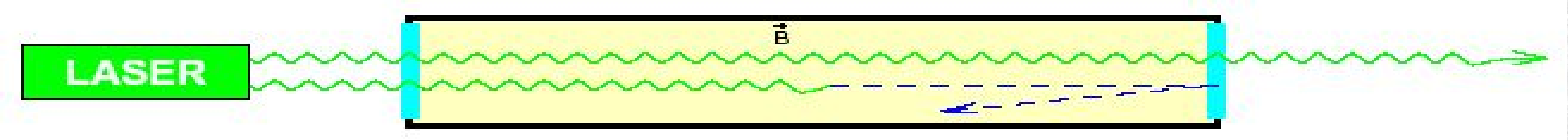
- Hides the axions of string theory (Khoury/Weltman)
- Evades short-range tests of gravity via “thin shell” mechanism
- Evades star cooling limits due to large mass in stellar environment

Gamme**V** – Chameleon: Concept

Strong matter effects cause the warm bore walls and vacuum windows to act like fully reflective mirrors.

GammeV – Chameleon: Concept

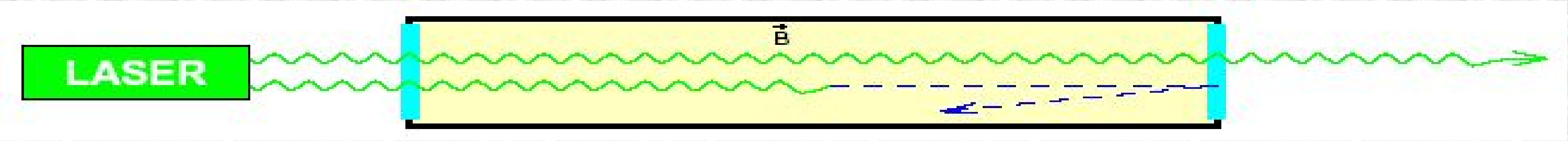
Strong matter effects cause the warm bore walls and vacuum windows to act like fully reflective mirrors.



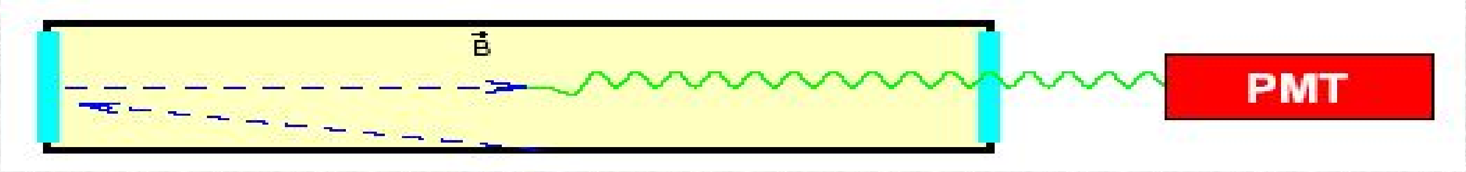
The laser shining into the cavity will fill the “jar” with chameleons.

GammeV – Chameleon: Concept

Strong matter effects cause the warm bore walls and vacuum windows to act like fully reflective mirrors.

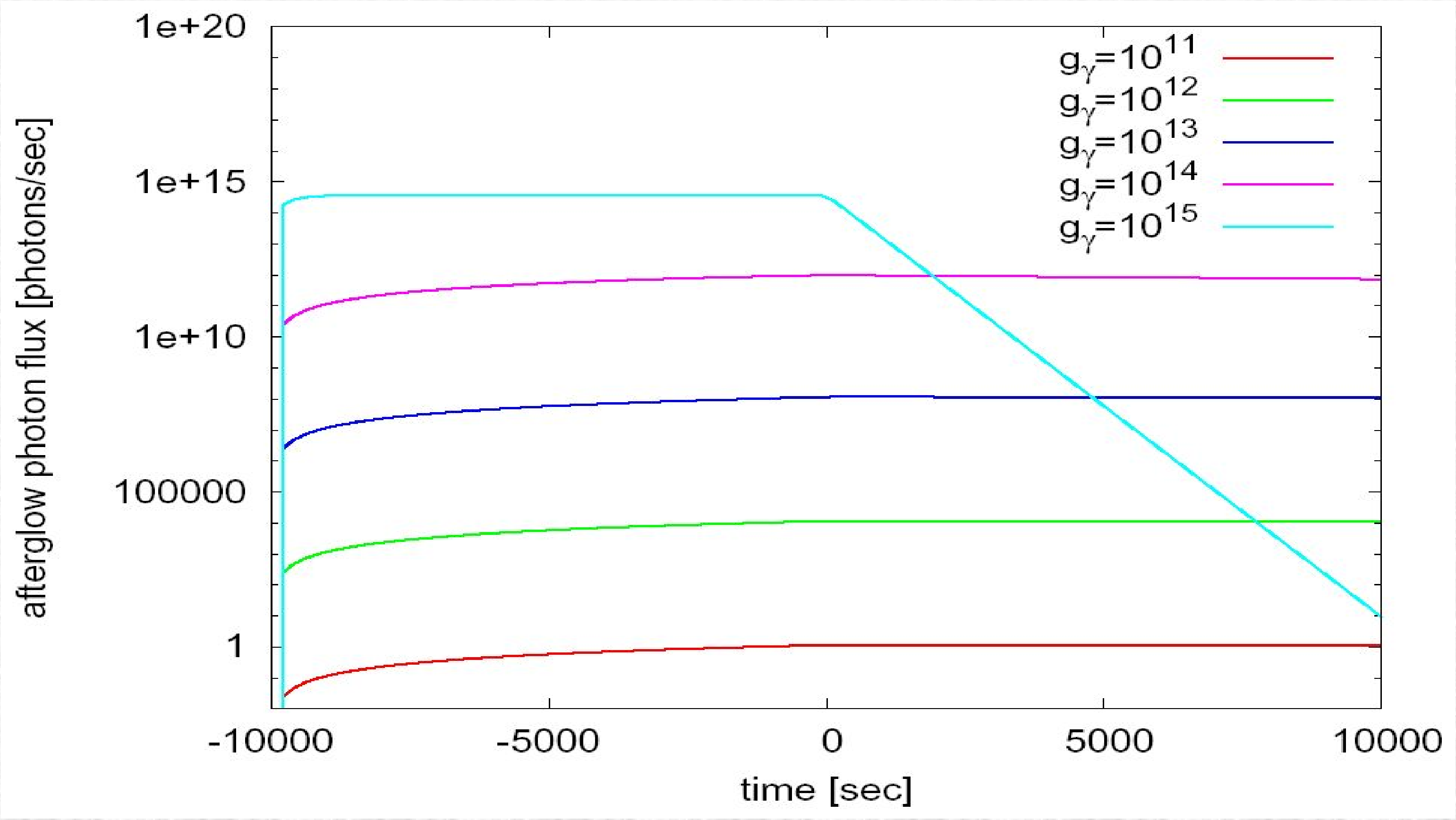


The laser shining into the cavity will fill the "jar" with chameleons.



After the jar is filled and the laser is turned off, you should see an afterglow as the chameleons reconvert to photons and escape.

GammeV – Chameleon: Concept

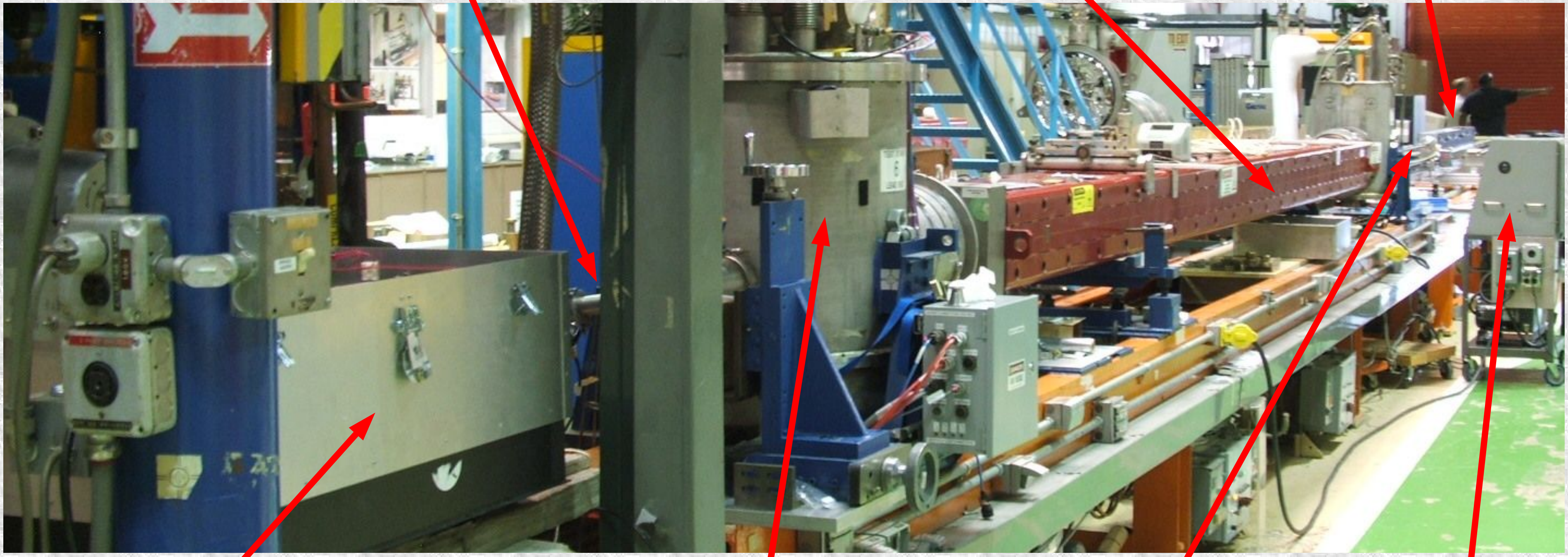


Gamme**V** – Chameleon: Concept

- Chameleon aspect was part of the original **G**amme**V** objectives
- Use existing equipment and experimental setup
- Fill the cavity for 5 hours in each of the two polarizations
- Collect data for 1 hour in each of the two polarizations

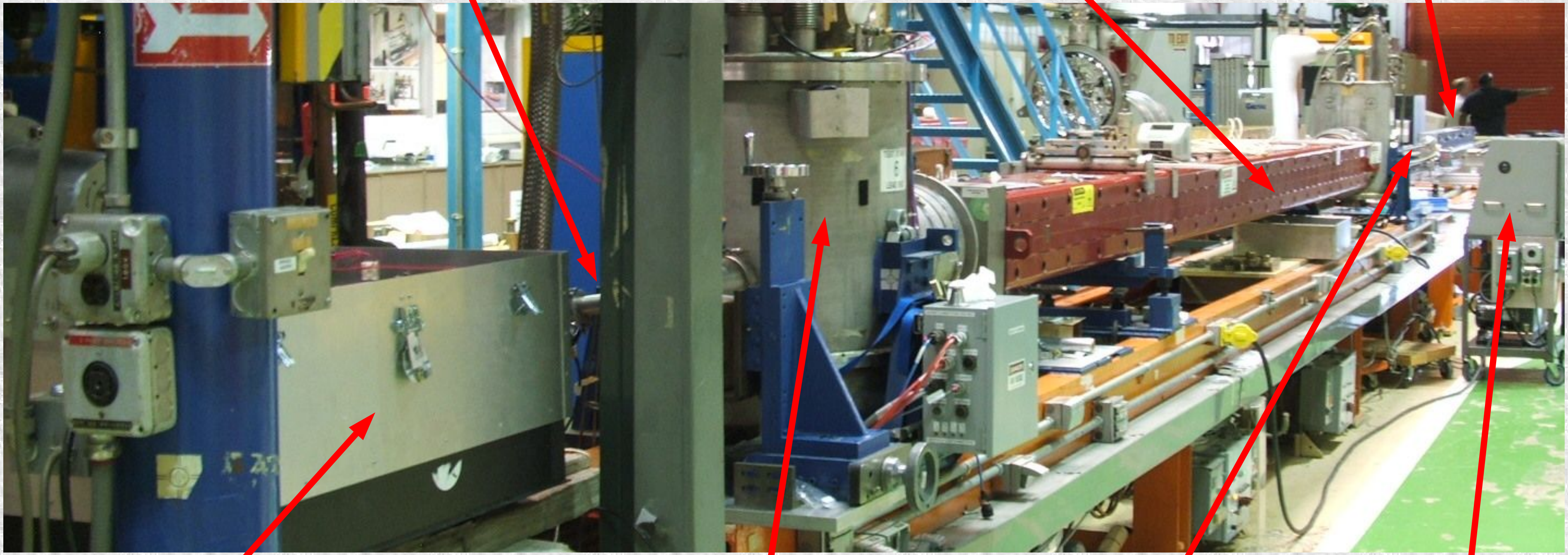
Gamme**V** should be able to constrain cosmologically interesting chameleon models near $g_\gamma \sim 10^{12}$.

GammeV – Chameleon: Realization



GammeV – Chameleon: Realization

(no new hardware)



Gamme**V** – Chameleon: Realization

(new human capital)

GammeV – Chameleon: Realization

(new human capital)

Amanda Weltman
(Cambridge)

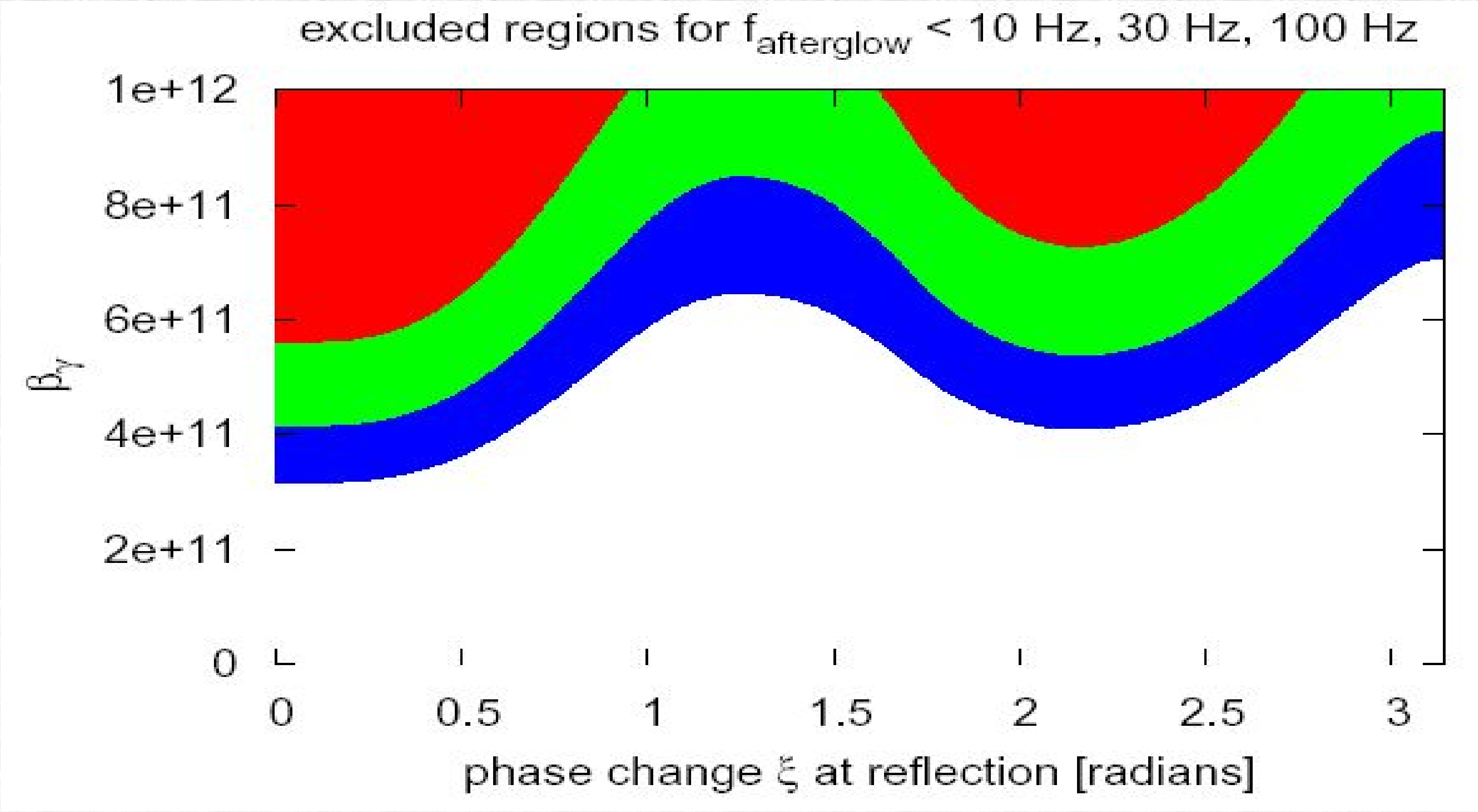
Amol Upadhye
(KICP)

Gamme**V** – Chameleon: Pseudo-results

- We have data
- We are currently analyzing that data
- We should have results shortly

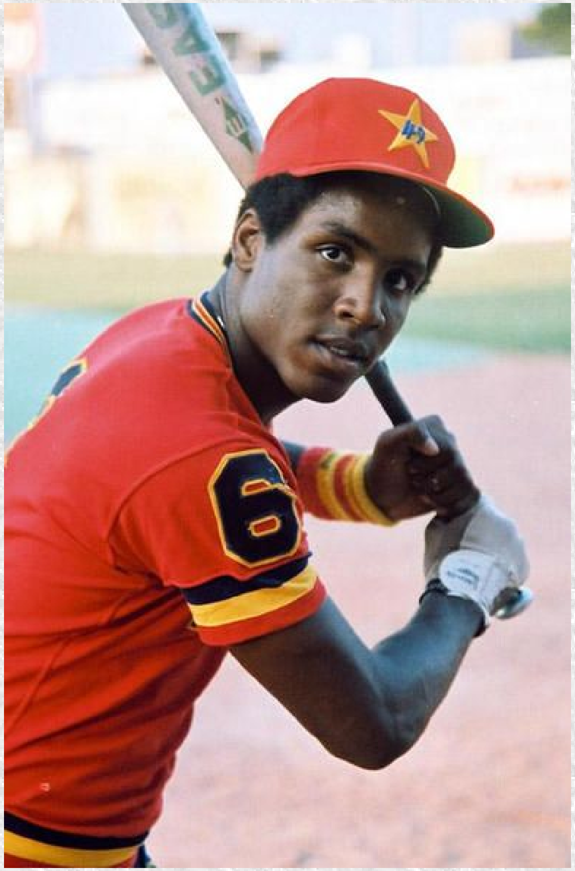
Gamme**V** – Chameleon: Pseudo-results

Our results will look something like this...



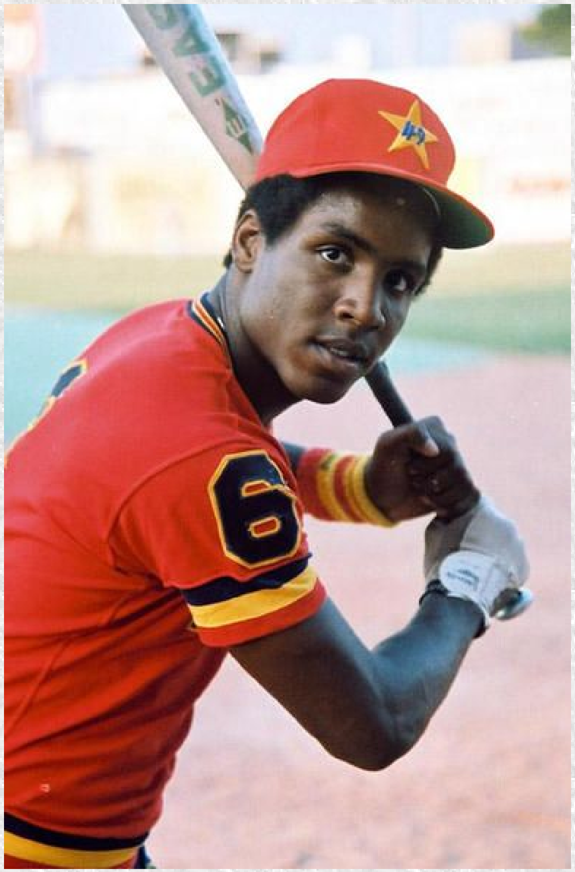
Where ξ is the relative phase change of the photon and chameleon portions of the wave upon reflection off the warm bore and β_γ is the something or other.

The Future of Axions



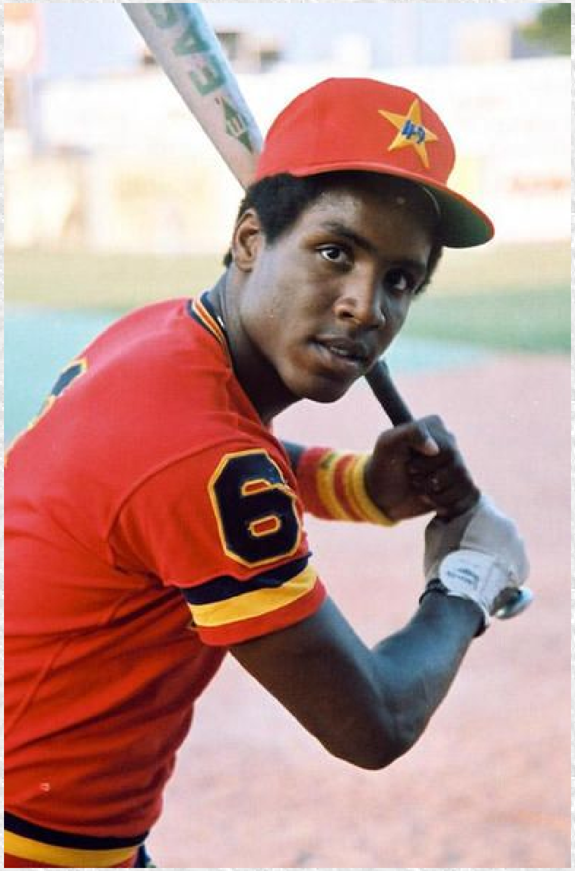
Regular Barry

The Future of Axions



Regular ~~Barry~~ GammeV

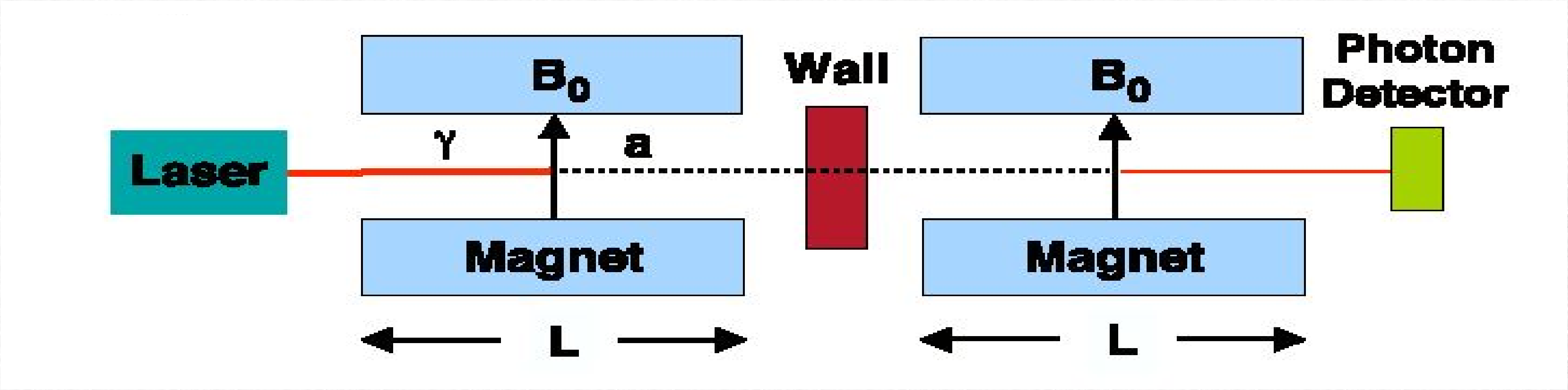
The Future of Axions



Regular ~~Barry~~ GammeV

Resonantly Enhanced ~~Barry~~ GammeV

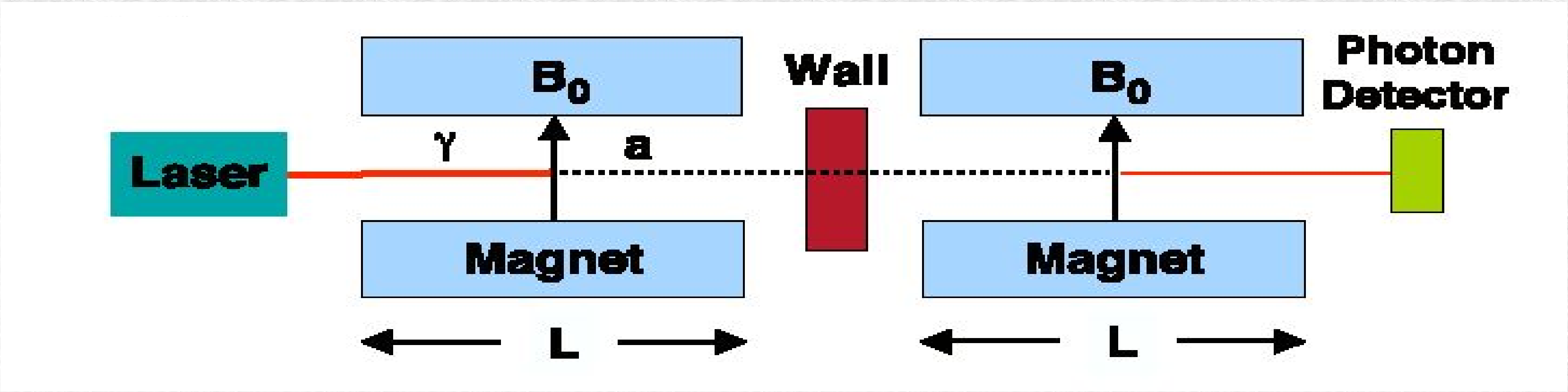
The Future of Axions



Standard photon regeneration suffers from two conspiratorial limitations.

$$P_{regeneration} = (P_{\phi\gamma})^2 \propto g^4 \times (\text{stuff})$$

The Future of Axions



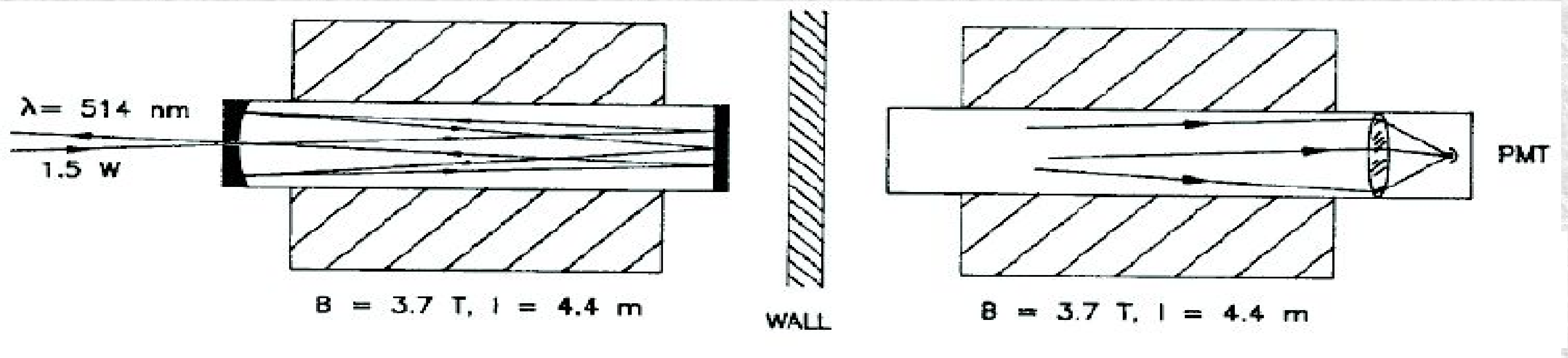
Standard photon regeneration suffers from two conspiratorial limitations.

$$P_{regeneration} = (P_{\phi\gamma})^2 \propto g^4 \times (\text{stuff})$$

A regenerated photon must convert twice.

Thus, you only gain as the fourth root of time.

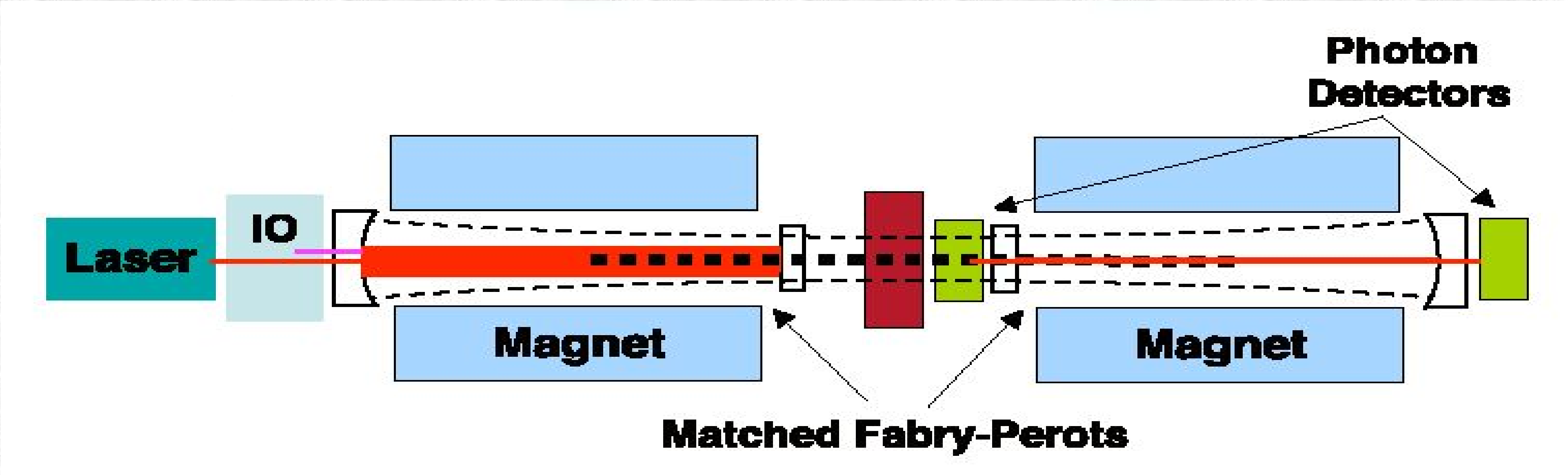
The Future of Axions



By having a Fabry-Perot optical cavity, one improves the conversion probability by a factor of the finesse. Thus, the signal is enhanced significantly since such cavities often have a finesse of order $\sim 10^4 - 10^5$.

This was employed by the BFRT experiment (shown) in 1992.

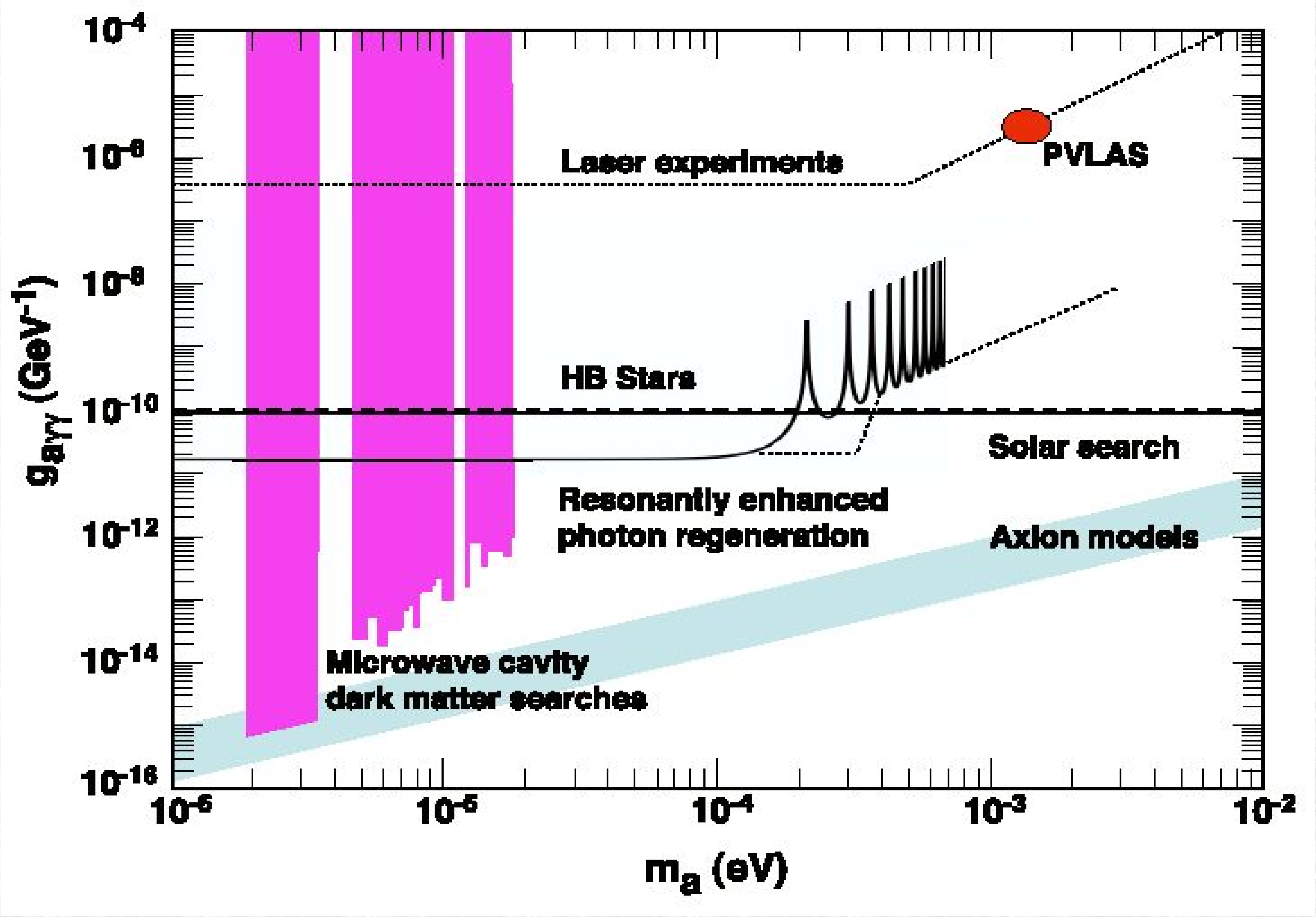
The Future of Axions



By having two *coupled* Fabry-Perot optical cavities, one improves both the conversion probability and the regeneration probability by a factor of the finesse. Thus, the reconversion probability gains as the square of the finesse, ~ $10^8 – 10^{10}$.

The Future of Axions

Expected limits would look something like...



K. van Bibber 2002

The Future of Axions

- This scenario is a probe for axions that is more sensitive than the current star cooling limits and more sensitive than the solar helioscope limits set by CAST.

- Its results are not model dependent and its interpretation would be unambiguous.

- Such an experiment provides an important verification of the CAST results.

- The **G**amme**V** collaboration is exploring possible involvement in an experiment of this type.

Conclusions

- **G**amme**V** wins.
- Chameleon results forthcoming.
- Axions are cool

October 2007:

The Competition

- <u>OSQAR</u>: null result for PVLAS scalar/pseudoscalar, but no limits set and they may use a residual gas (not vacuum)
- <u>LIPSS</u>: begin to cover PVLAS region of interest for scalar particle interpretation.
- <u>BMV</u>: Use 14 pulses (hep-ex/0707.1296) and cover PVLAS region of interest for pseudoscalar case. Only group with a current preprint.
- <u>ALPS</u>: Should also be taking data and have something to say soon?