New Light Weakly-Coupled Particles

Subgroup of the Intensity Frontier and overlap with the Cosmic Frontier

Chapter 6: Fundamental Physics at the Intensity Frontier

arXiv:1205.2671

Community Planning Meeting

Fermilab, Oct 11-13, 2012

Convenors: Rouven Essiq, John Jaros, William Wester
(rouven.essiq@stonybrook.edu, john@slac.stanford.edu, wester@fnal.gov)

Bottom up Motivation

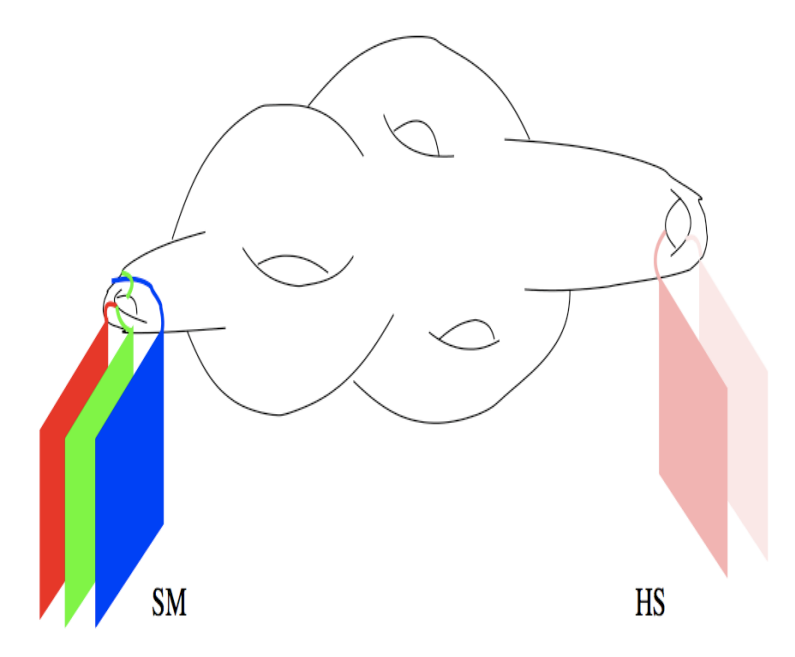
- Standard Model has mysteries
  - Strong-CP problem (axions in non-WIMP DM)
  - Neutrino masses
  - Physics at high scales
- Cosmology has mysteries
  - Dark matter
  - Dark energy
- Data and measurements have hints
- The origin of the New Physics is not known – many light weakly-coupled particle possibilities

Top down Motivation

- The axion arises naturally in the dynamical solution for the strong-CP problem
  - Supersymmetry with field-dependent gauge couplings imply axion type particles

- String compactification naturally has new scalars/pseudoscalars

- The possibility of hidden sectors can have new particles weakly coupled or weakly mixed with Standard Model particles



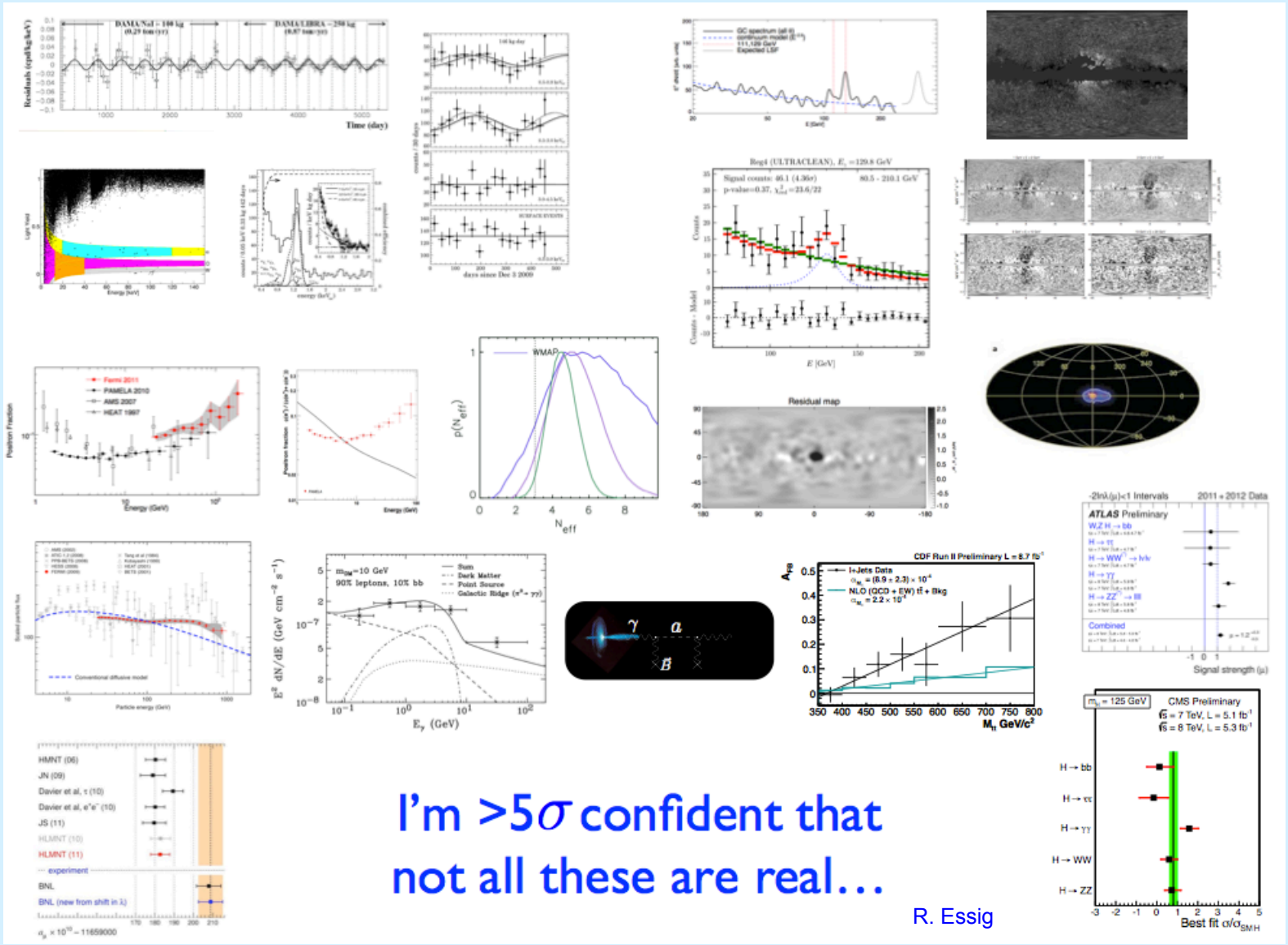
J. Jaeckel

Portals

Hidden particles	Portal
• Dark photons	$-\frac{\kappa}{2}B_{\mu\nu}V^{\mu\nu}$
• Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
• Sterile Neutrinos	LHN
• PNGBs	$\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$
• Dark Matter	$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q + \ldots,$
	$g_\chi\phi\bar{\chi}\chi + g_q\phi\bar{q}q + \ldots$

B. Batell

Observational Hints

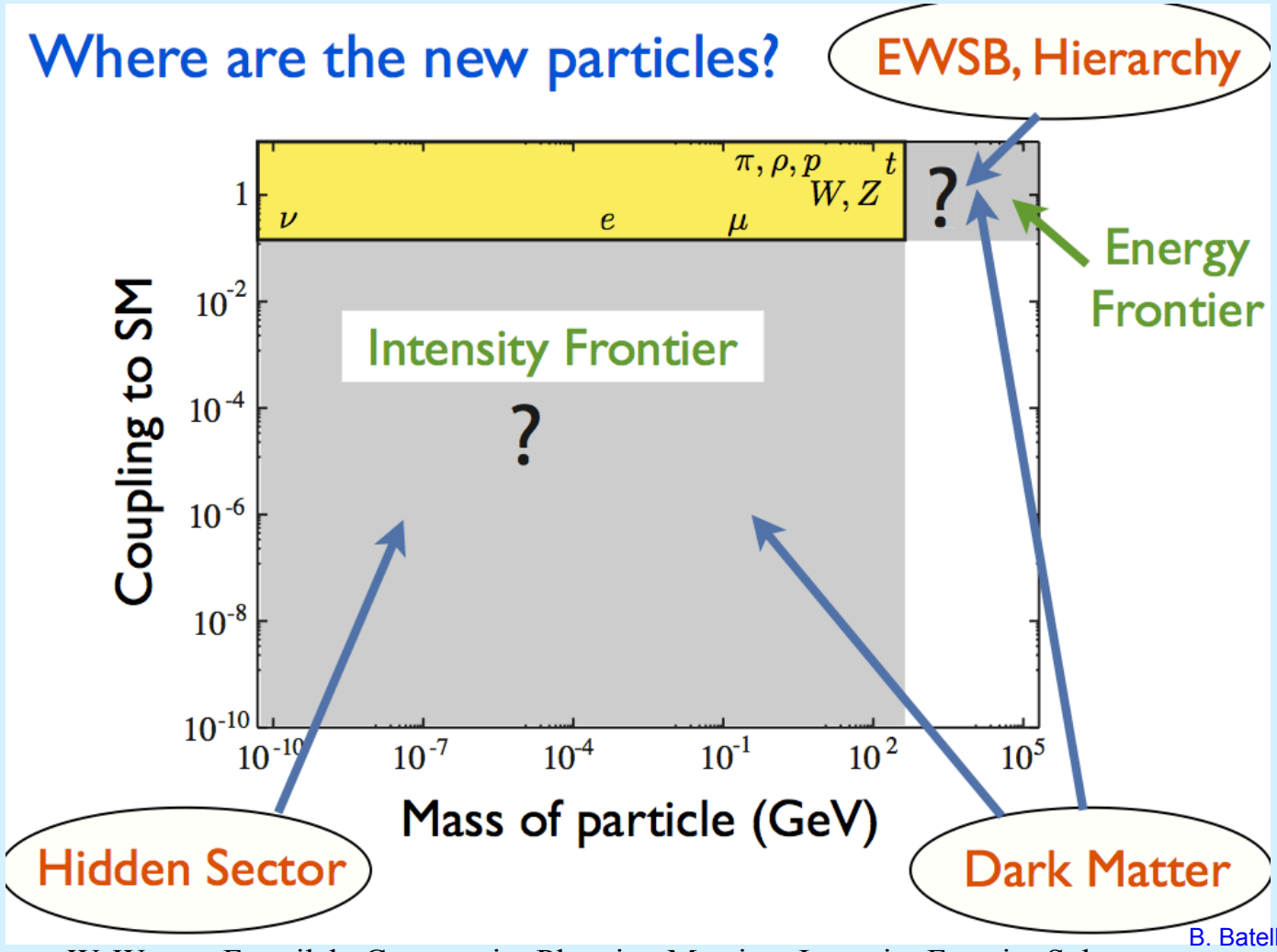


I'm >5σ confident that not all these are real…

R. Essig

WISPs

- Weakly-Interacting Slim (sub-eV) Particles

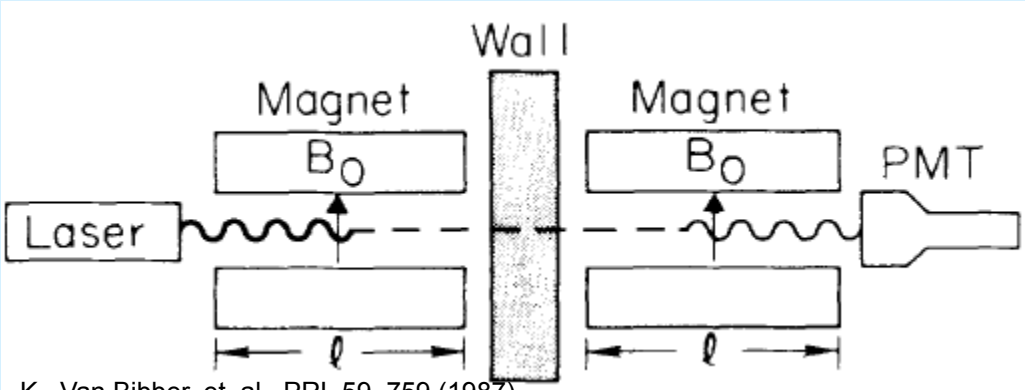


B. Batell

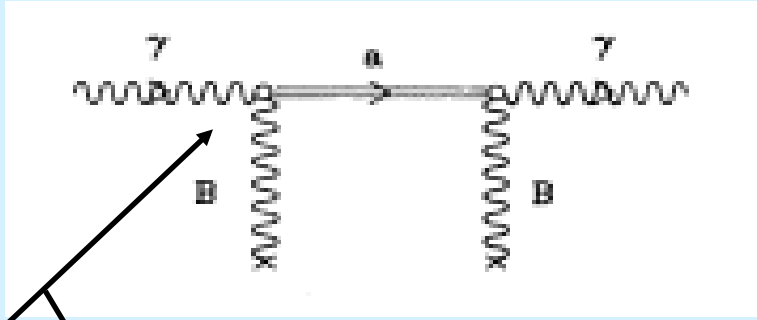
Axion-like particles

An axion-like particle is a (pseudo-) scalar that behaves similarly to the axion, but can have mass / couplings not constrained by QCD.

Light Shining Through a Wall



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

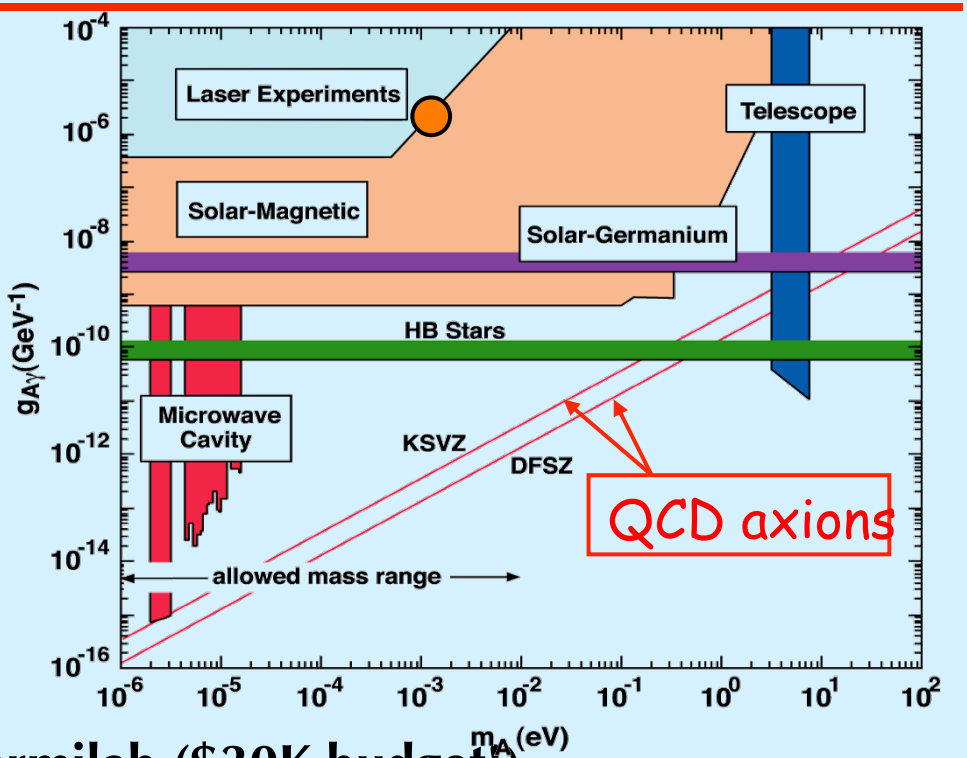


$$\mathcal{L}_{\rm int} = -\frac{1}{4}\frac{\phi}{M}F_{\mu\nu}F^{\mu\nu} = \frac{\phi}{M}(\vec{E}\cdot\vec{E} - \vec{B}\cdot\vec{B})$$

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

$$P_{regen} = \frac{16B_1^2B_2^2\omega^4}{M^4m_\phi^8}\sin^2\left(\frac{m_\phi^2L_1}{4\omega}\right)\cdot\sin^2\left(\frac{m_\phi^2L_2}{4\omega}\right)$$ ~10^{-21}

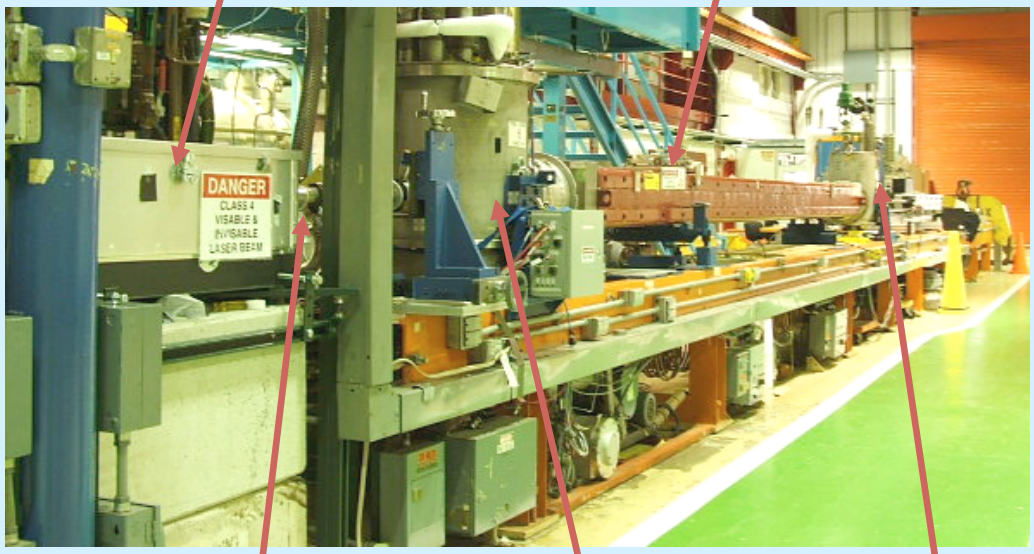
GammeV Collaboration

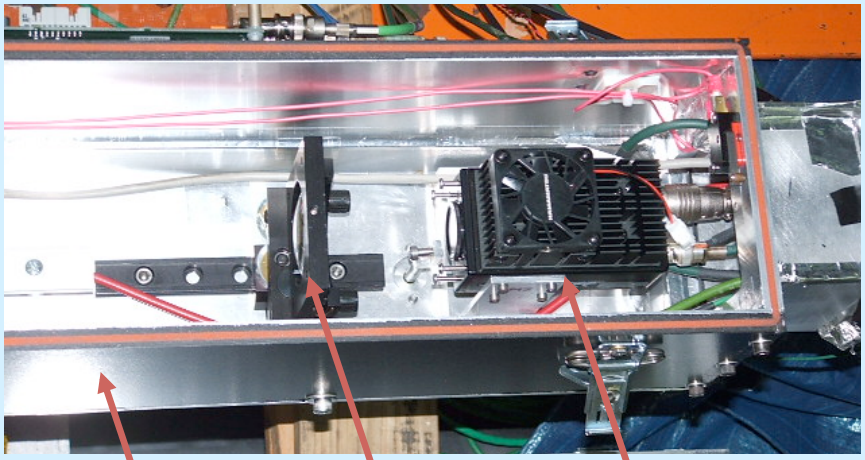


Nov : Initial discussion and design
Apr : Review and approval from Fermilab ($30K budget!)
May : Acquire and machine parts
Jun : Assemble parts, test electronics and PMT calibration
Jul : First data but magnet and laser problems
Aug : Start data taking in earnest
Sep : Complete data taking and analysis
Jan : PRL Accepted

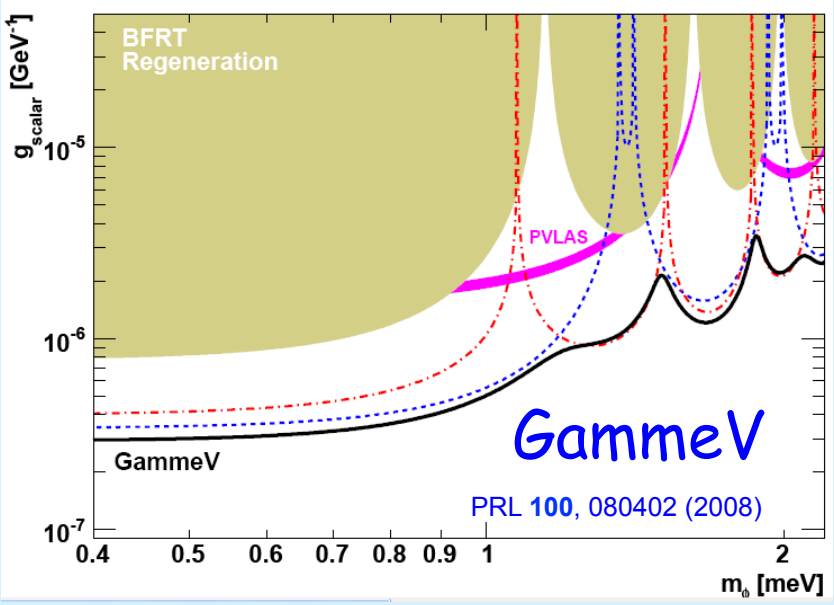
Apparatus

Gamme**V** was located on a test stand at Fermilab's Maget Test Facility. Two shifts/day of cryogenic operations were supported.



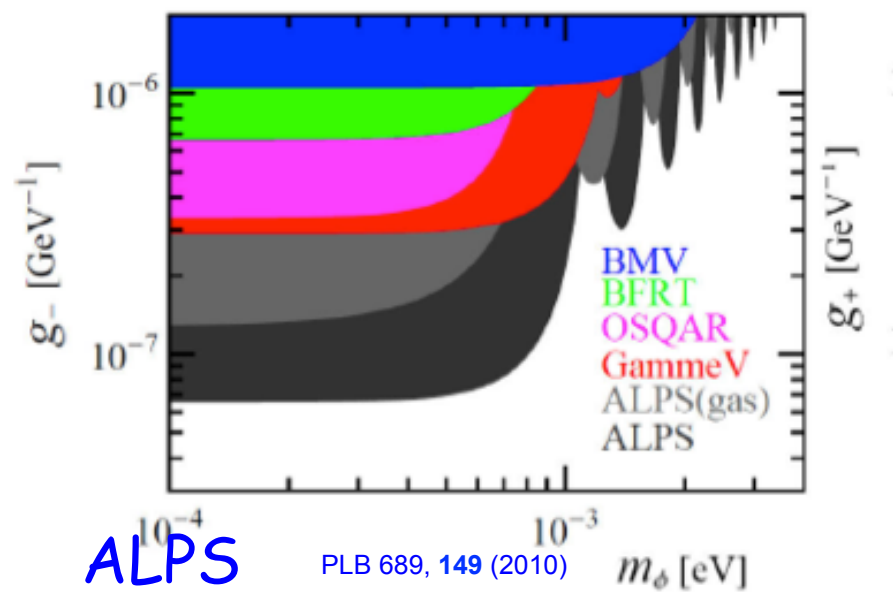


World-wide effort



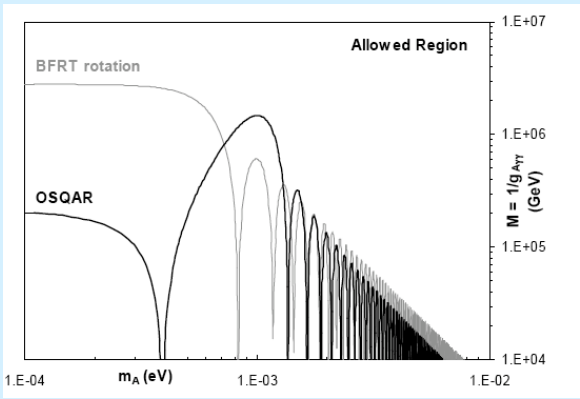
GammeV

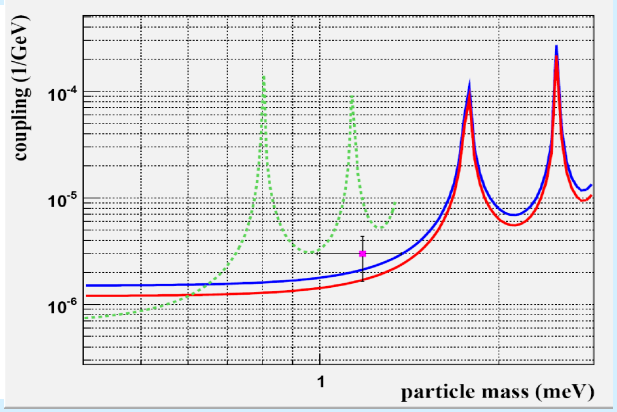
PRL **100**, 080402 (2008)

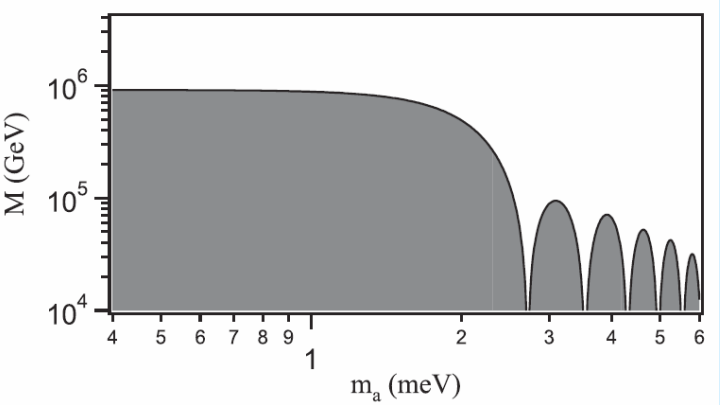


ALPS

PLB 689, **149** (2010)







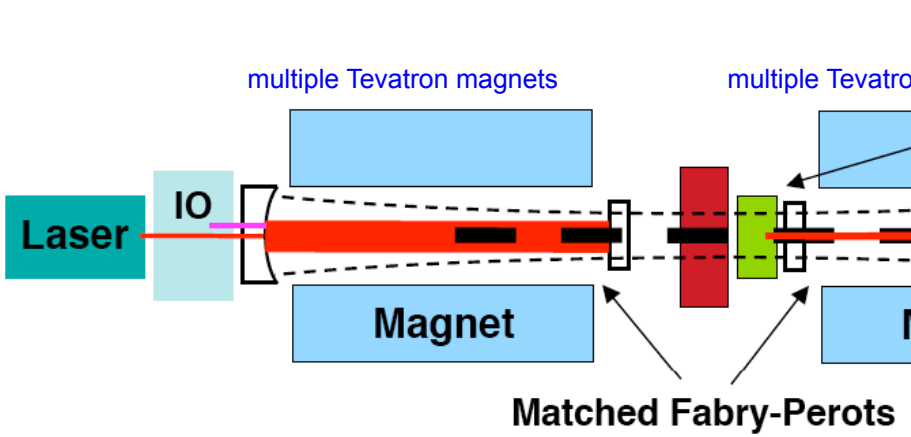
OSQAR PRD **78**, 092003 (2008)
Note: with N_2 gas

LIPSS scalar only
PRL **101**, 120401(2008)

BMV pseudoscalar only
1st results: PRL **99**, 190403 (2007)
Final results: PRD **78**, 032013 (2008)

Future LSW

Resonantly enhanced axion-photon regeneration

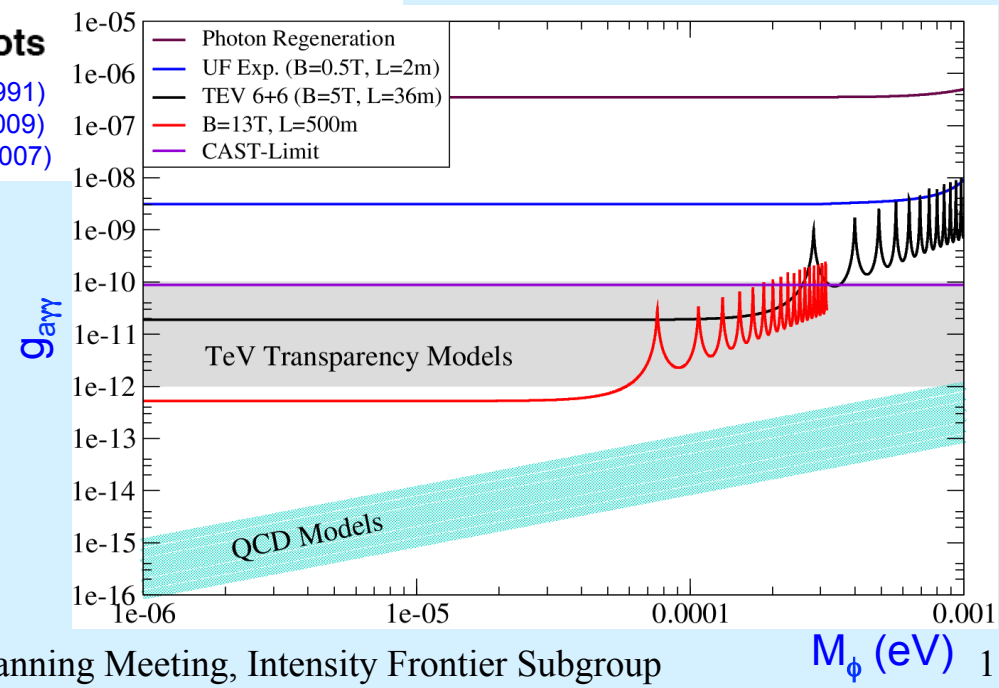


F. Hoogeveen and T. Ziegenhagen, Nucl. Phys. B **358**, 3 (1991)
Mueller, Sikivie, Tanner, van Bibber, Phys. Rev. D **80**, 072004 (2009)
Phys. Rev. Lett. **98**, 172002 (2007)

Probability of regeneration goes as the product of finesse's: $\mathcal{F}\mathcal{F}$

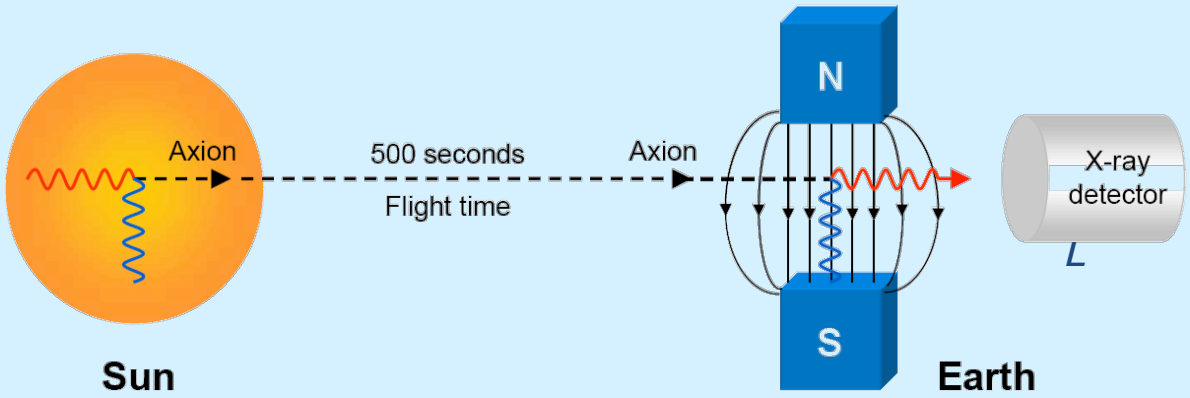
Possibility that this technique might exceed star / CAST limits.

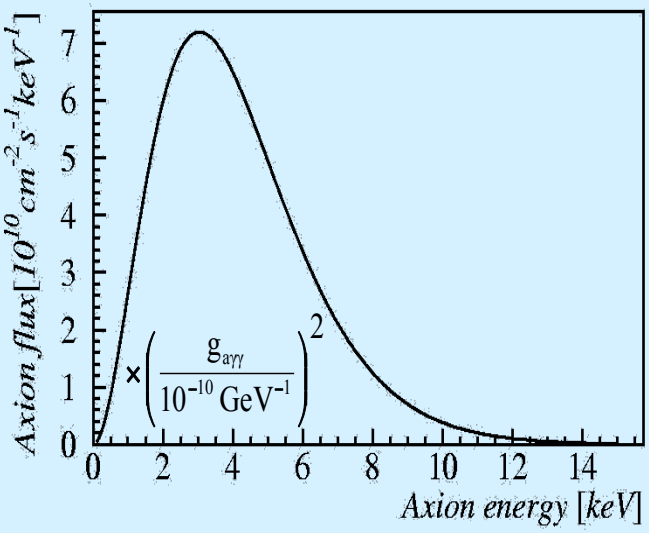
Hints that a coupling of 10^{-11} might be interesting from observations of unexpected high energy gamma rays that somehow propagate despite background IR photons.



CAST Experiment

- CERN Axion Solar Telescope



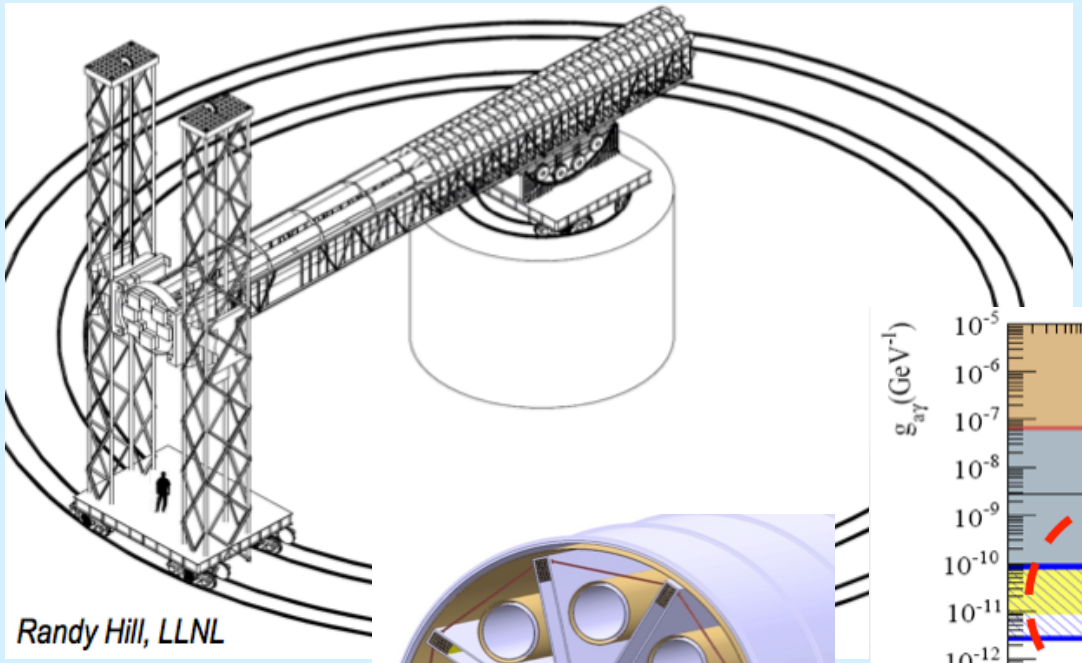


Point LHC dipole toward the sun. Detect possible X-rays from axion reconversion.

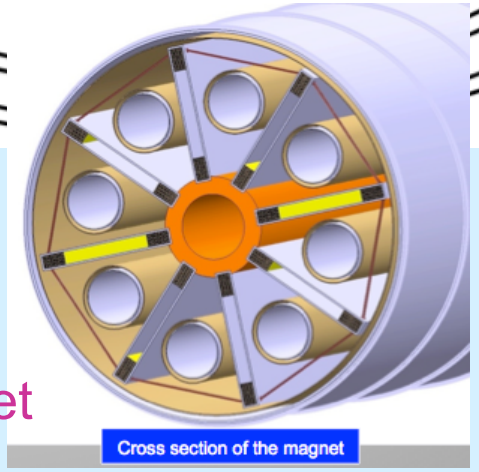
CAST

IAXO

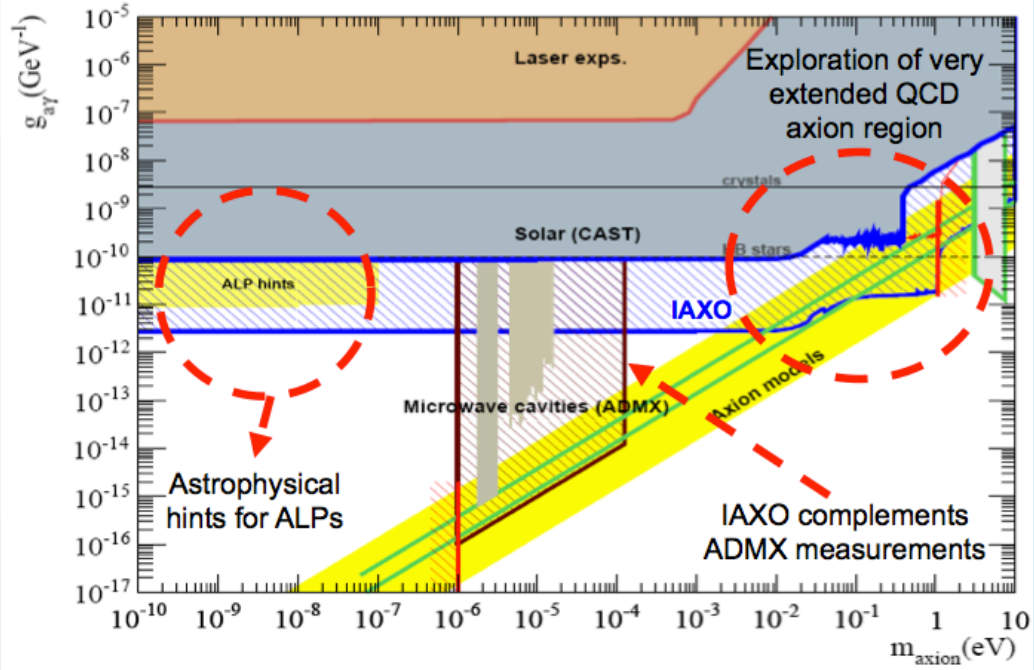
- International Axion X-ray Observatory



Broad sensitivity including "heavy" axions and a region with astrophysical hints



Large volume dedicated toroidal magnet



Chameleons

- A WISP with the property that its properties depend on its environment. In particular, a coupling to the stress energy tensor and a non-trivial potential result in unique properties such as a mass that depends on the ambient matter density: $m_{eff} \sim \rho^{\alpha}$.

$$\mathcal{L}_{\rm int} = -V(\phi) + \exp\left(\frac{\phi}{M_D}\right) g_{\mu\nu} T^{\mu\nu} - \frac{1}{4}\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$$

- Such a field might evade fifth force measurements and could explain how there could be an axion-like particle with a strong photon coupling which evades other bounds.

- The chameleon mechanism (Khoury and Weltman) was originally postulated as a mechanism to account for the cosmic expansion – "a dark energy particle".

Dedicated experiment

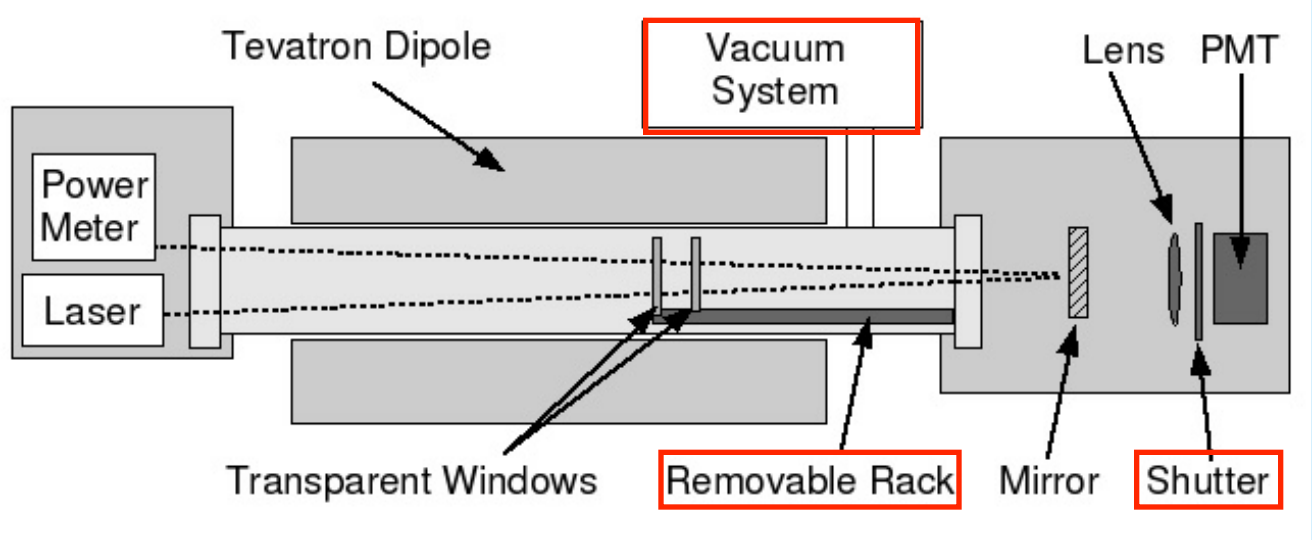
- GammeV – CHASE: Chameleon Afterglow Search

Improve vacuum (cryo pump) and monitoring.

Use a shutter to switch to PMT readout quickly.

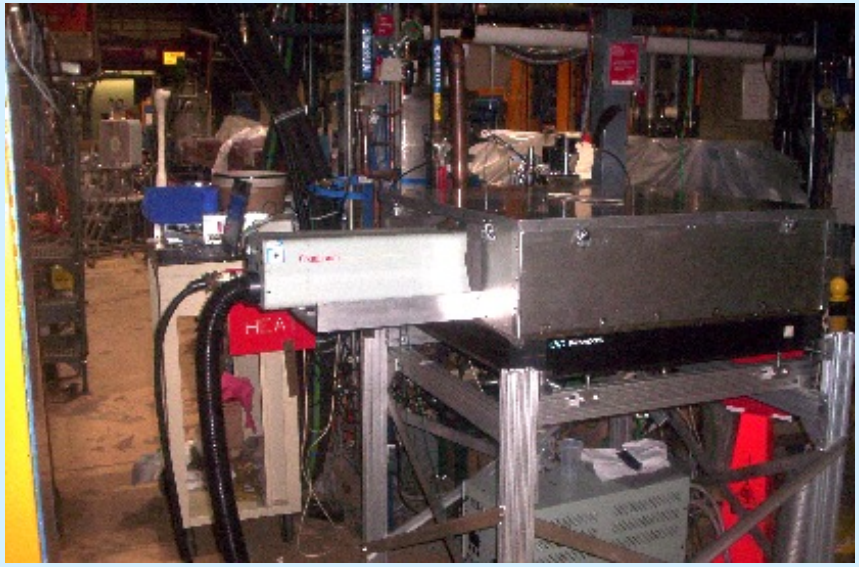
Use a run plan that with lower B fields in case the coupling is strong.

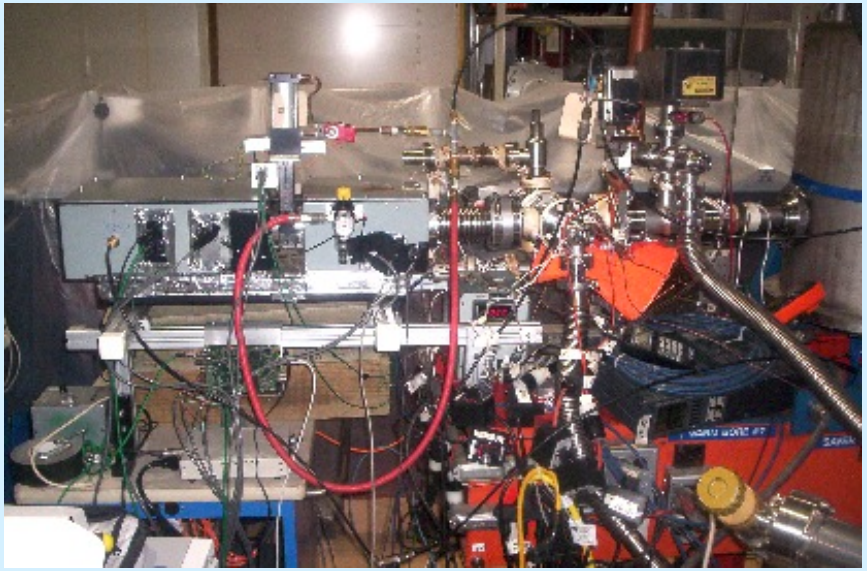
Use a lower noise PMT.



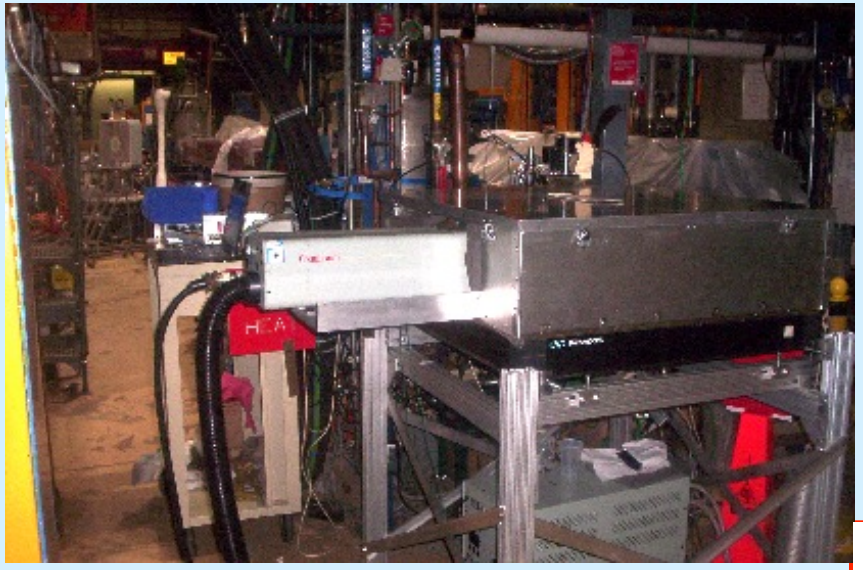
Employ the "dish rack" to effectively have 4.7m, 1m, 30cm magnetic field regions -a bit of cleverness similar to the plunger idea to be initially sensitive to a wider range of chameleon masses.

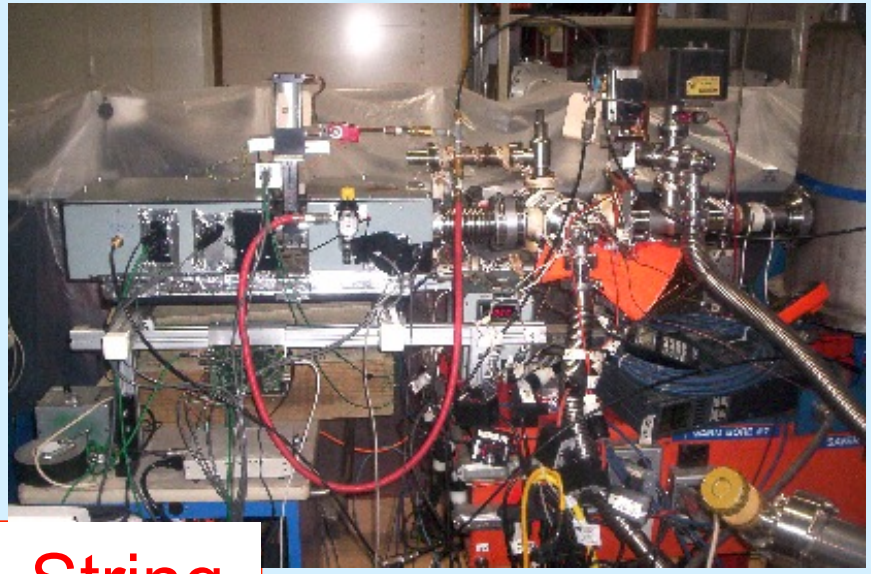
GammeV-CHASE





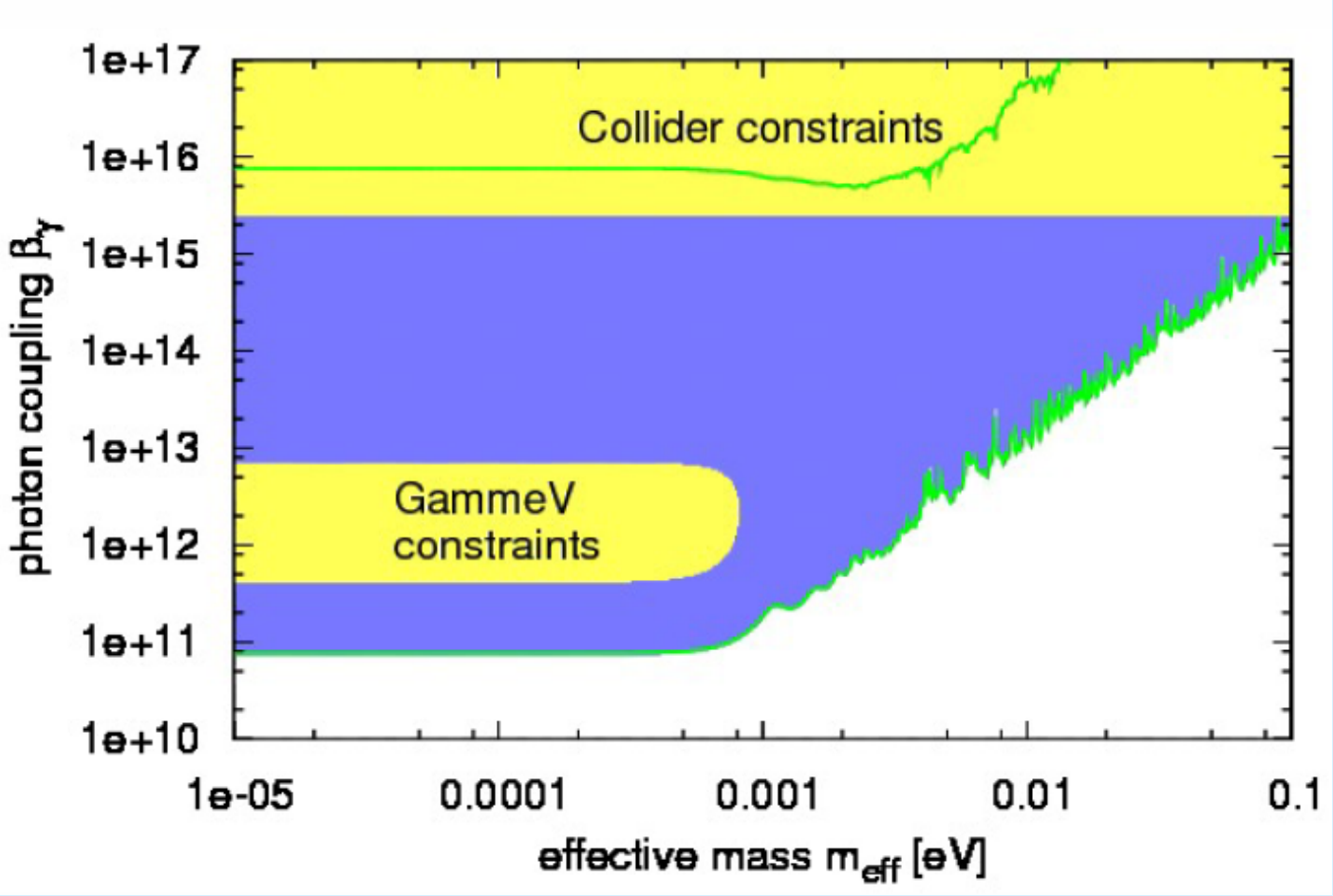
GammeV-CHASE

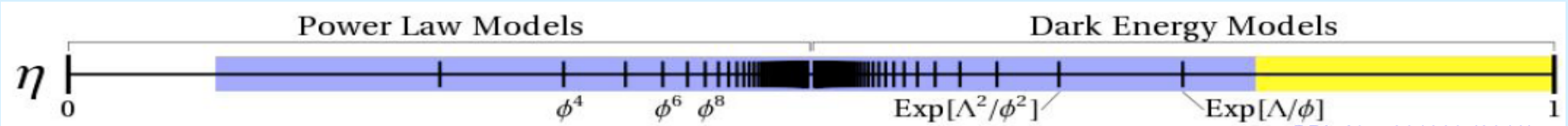




A String Theorist!

GammeV CHASE Results

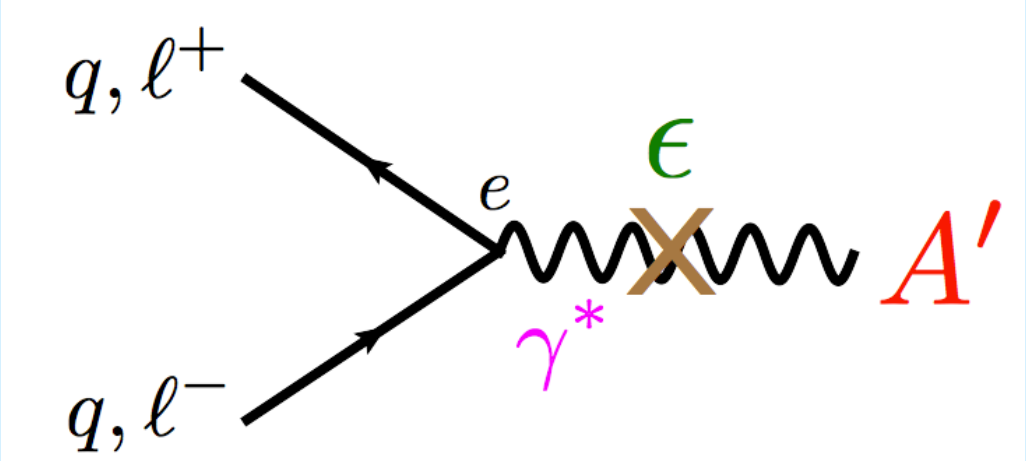




PRL **105**, 261803 (2010)

Hidden sector photons

New U(1) particles can kinematically mix with SM γ's

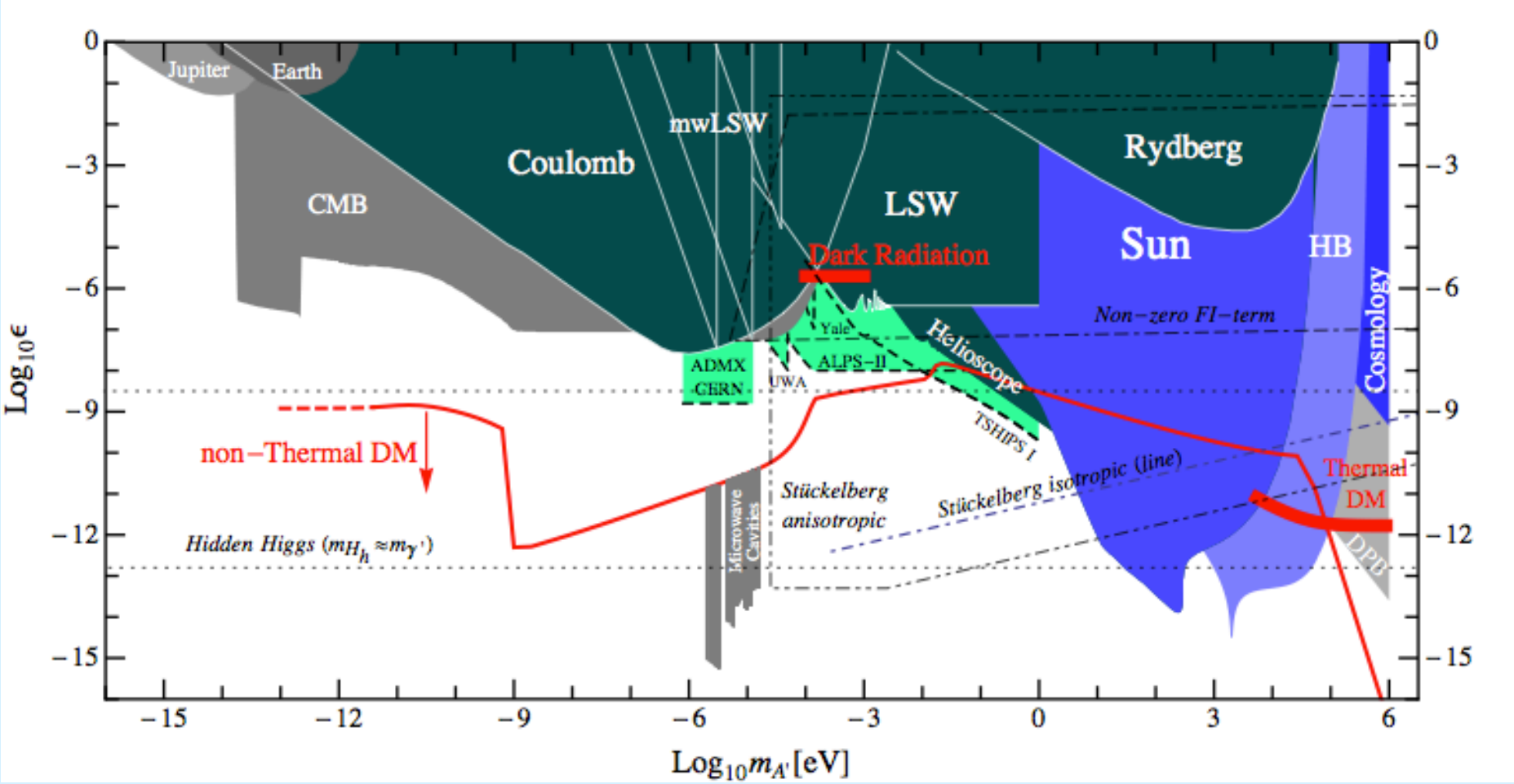


Light shining through a wall to search (no B field) just using mixing property

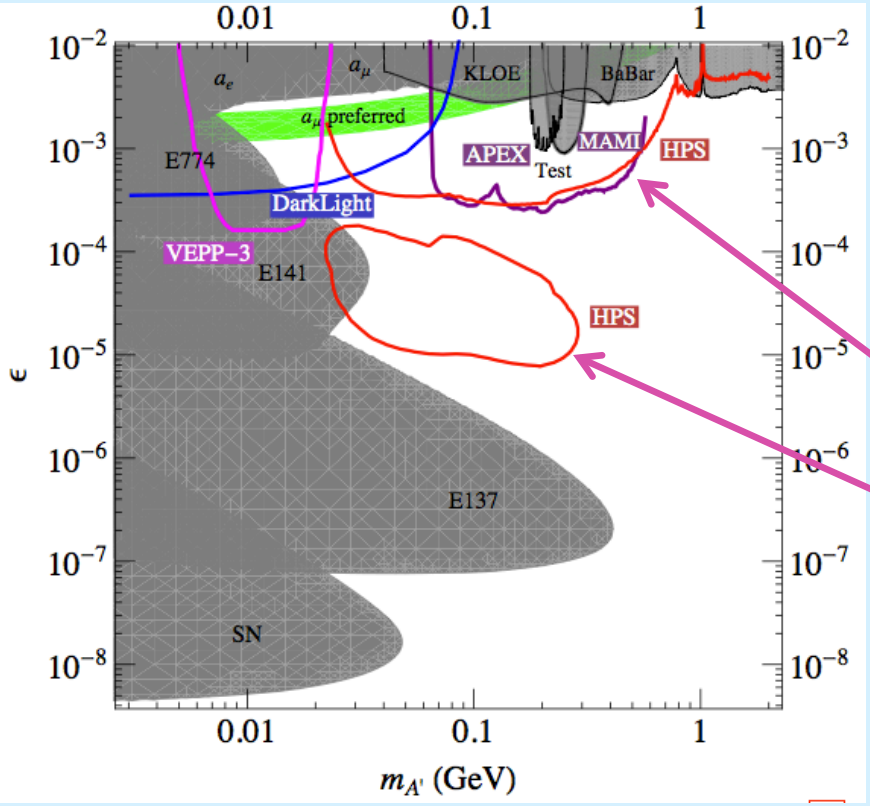
Beam experiments looking for $A' \to \ell^+ \ell^-$
(Jlab, Mainz, fixed target) + beam dump expt's

Current bounds

$M_{A'}$<1 MeV: Many bounds, but also much open parameter space



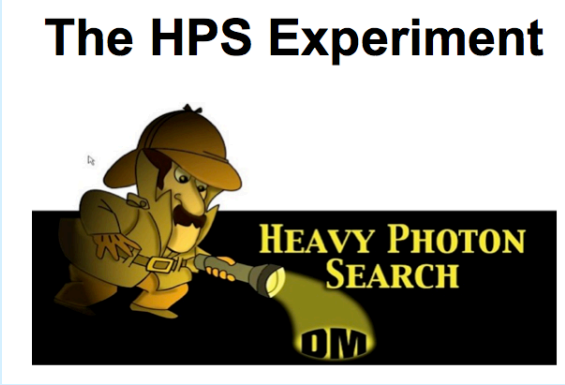
g-2 anomaly via $M_{A'}$ ~ MeV-GeV

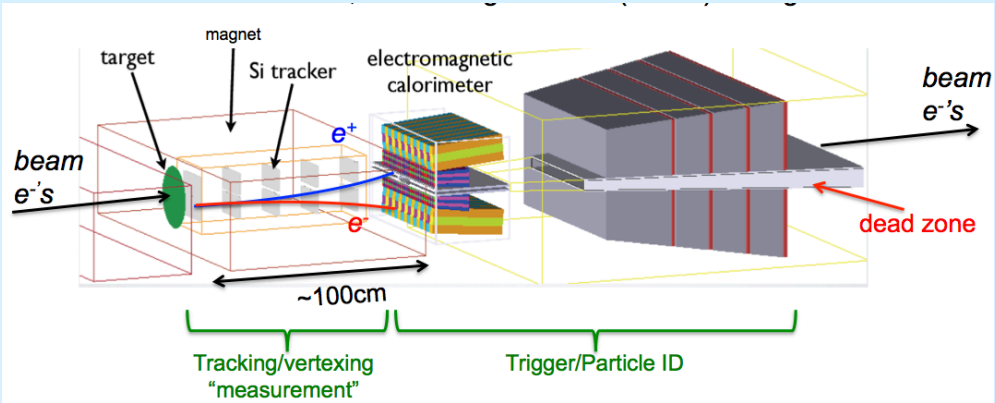


Programs at Jefferson Lab and Mainz along with proposals utilizing ν beams (beam dump-type) experiments

Bump hunt

Vertexing



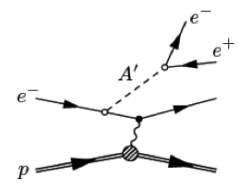


Intensity as a fixed target exp't
2012 Test run being analyzed
Hope to run after 12GeV upgrade

Jlab program (con't)

DARKLIGHT

Detecting **A** **R**esonance **K**inematically with
e**L**ectrons **I**ncident on a **G**aseous **H**ydrogen **T**arget



High Intensity, Low Energy Electron Beam
Using JLab's FEL on
Diffuse Hydrogen Gas Target

==> Luminosity: 1 ab^{-1}/month

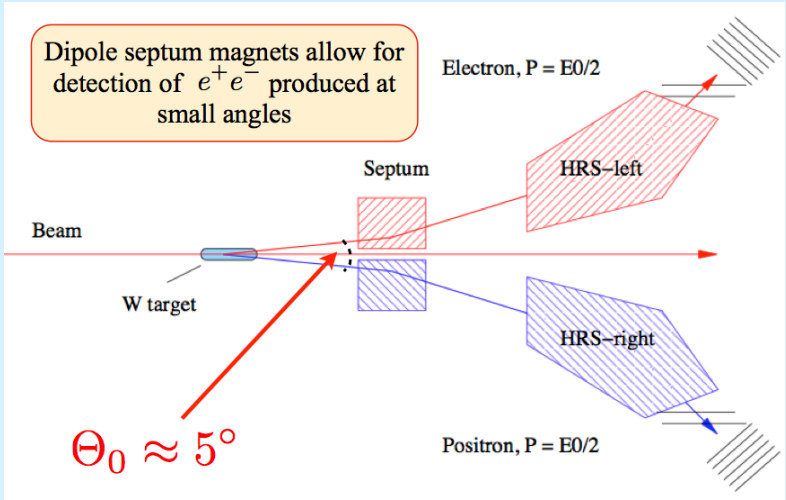
Use free electron beam and build a detector for the e+ e- pairs. Timescale: data taking ~2016

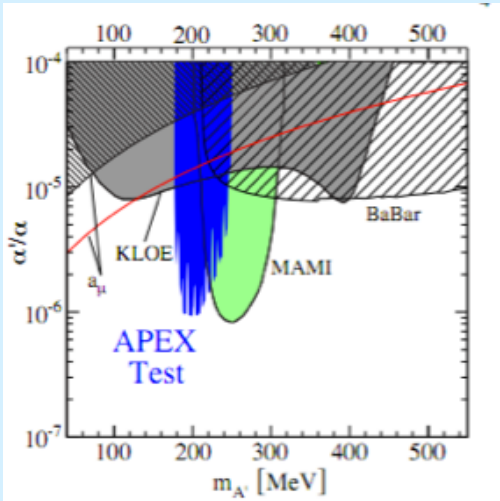
APEX

A' Experiment

Hall A high res spectrometer

Look for e+e- at an angle corresponding to A' mass



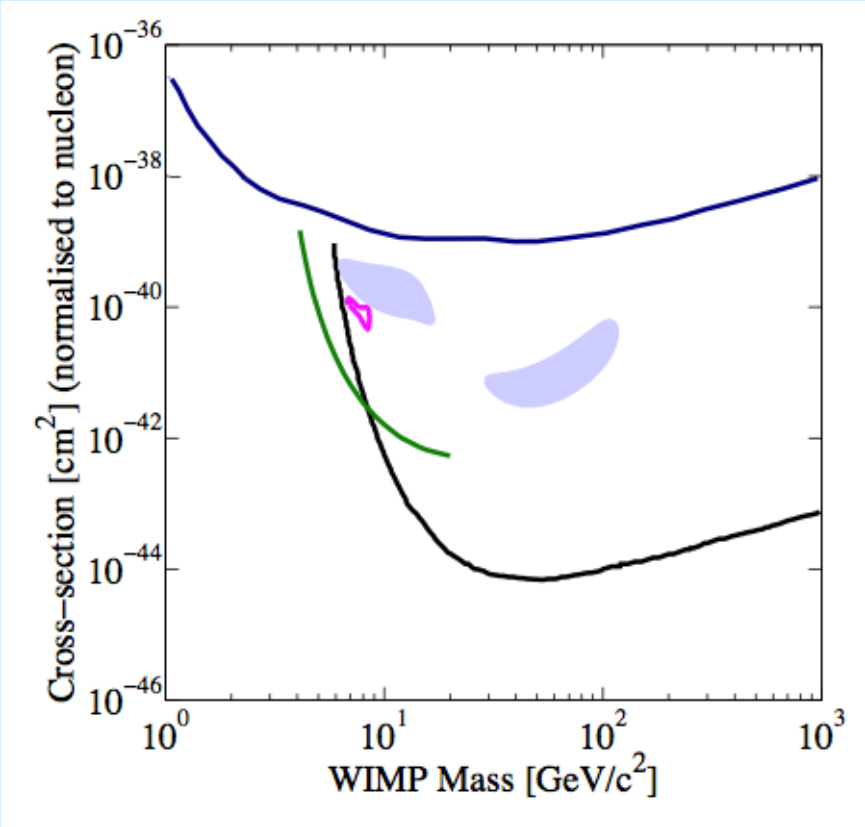


Results from test Exp't

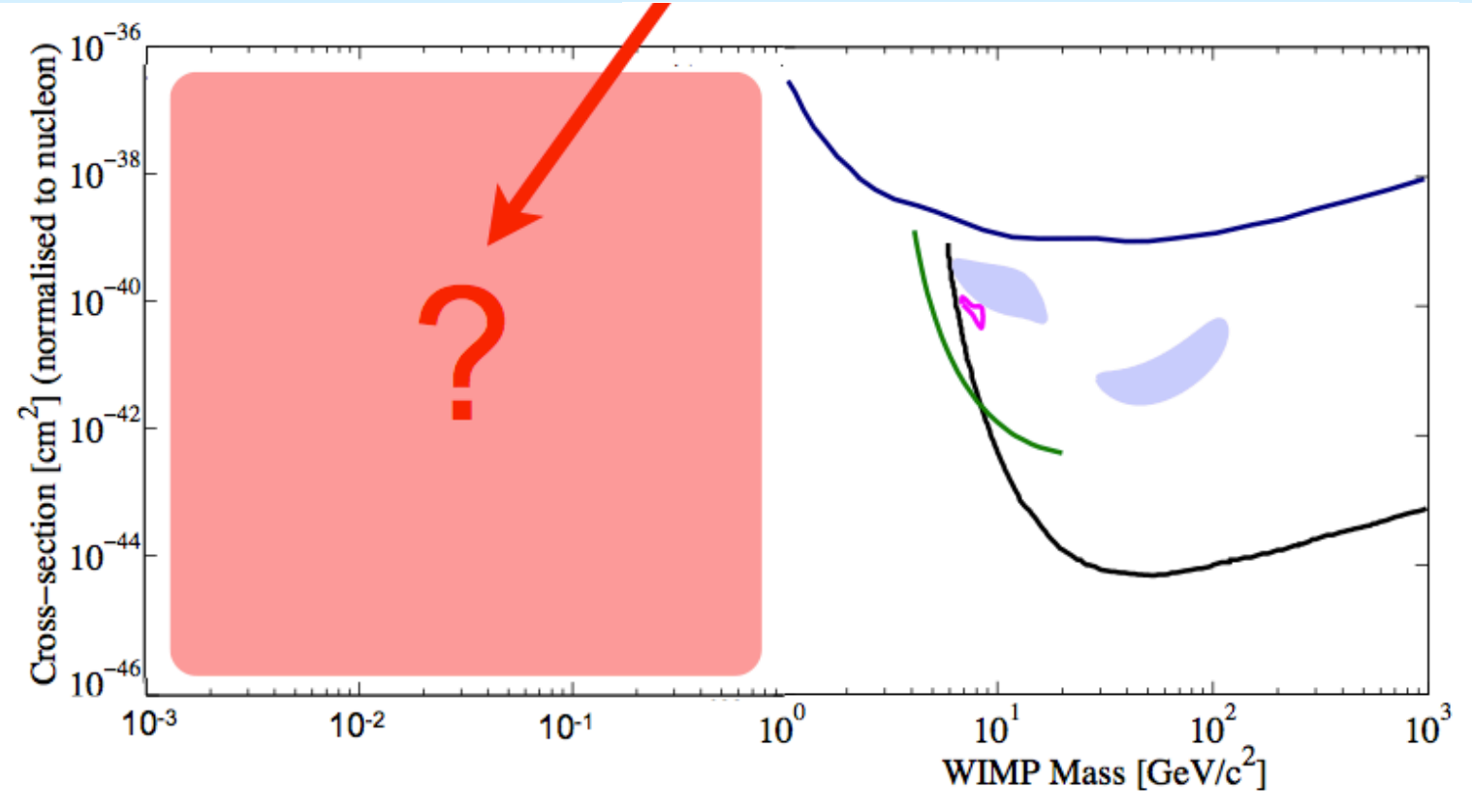
Plan to test entire g-2 motivated region of interest

Low mass dark matter

Usual exclusion limits for high mass WIMP dark matter



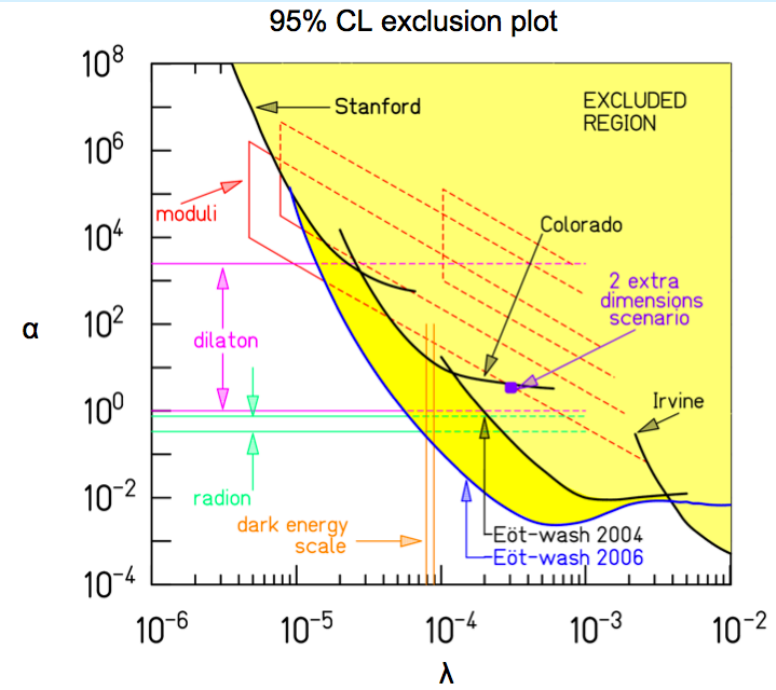
Low mass dark matter

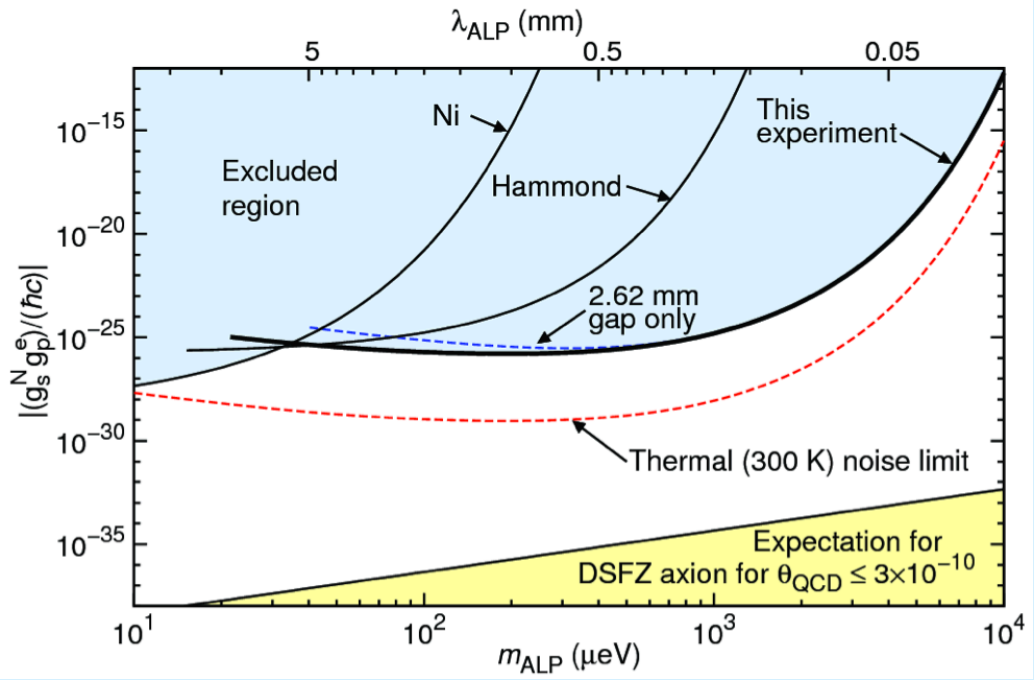


Experimental limits XENON 10 looking for DM scattering off of e^-'s
Low threshold devices (DAMIC low noise CCD's)
Many possibilities for future experiments (He, Xe, Ar, Ge)

Torsion balances

- Precision experiments testing the equivalence principle and searching for 5th forces also have strong sensitivities



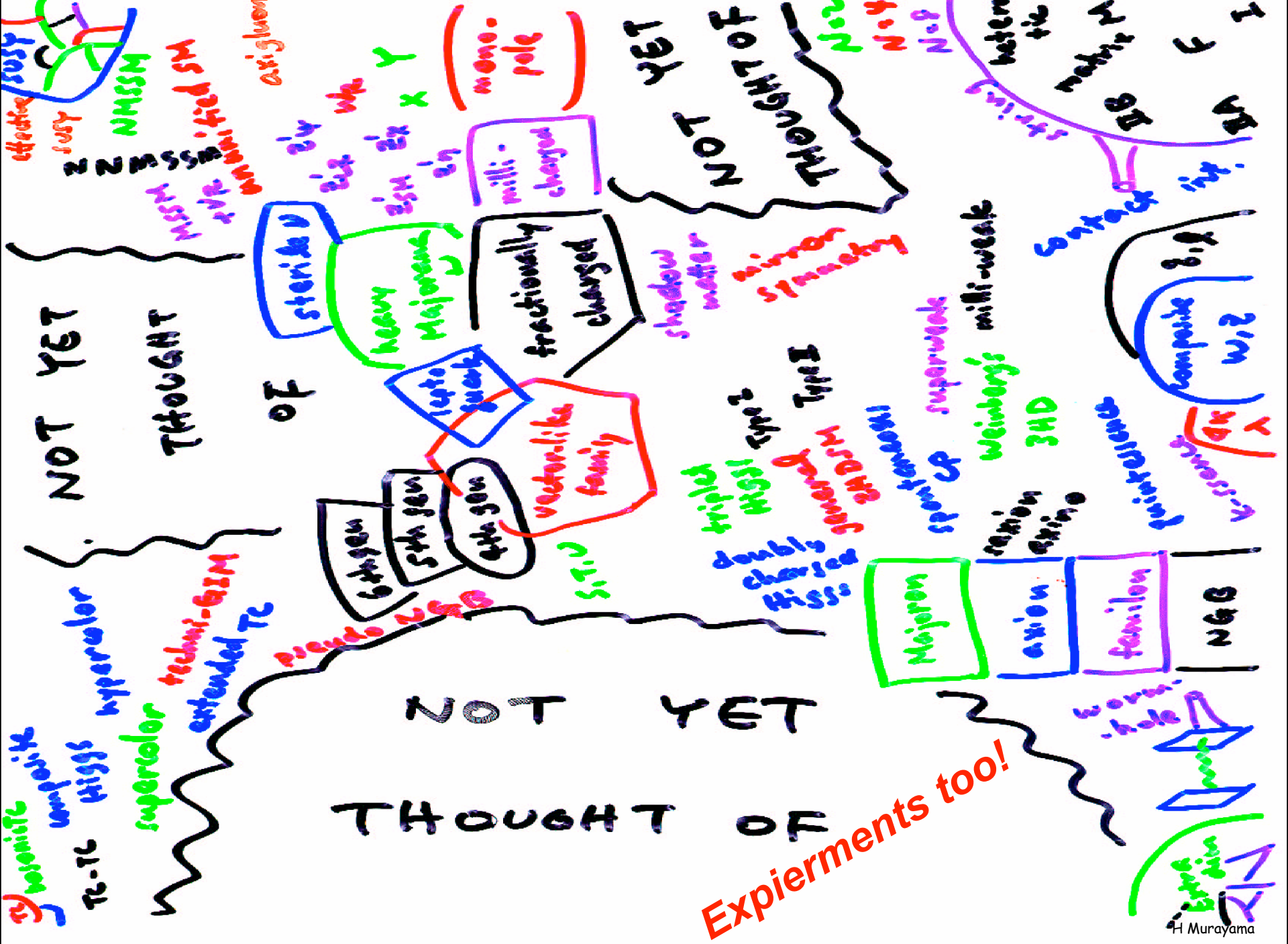


- Apologies to those efforts were not covered. This was not meant to be a review, but a highlight of the breath of the search for new light weakly coupled particles.

Conclusions

- New light weakly coupled particles are highly motivated theoretically in both bottom up and top down models
- The axion is a natural dark matter particle along with many other possibilities (ALPs, chameleons, hidden photons, etc.)
- There are large regions of phase space to be explored often with modest efforts
- Excellent training ground for students and much personal fun and satisfaction

NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NNMSSM
NMSSM
MSSM +VR
sterile ν
heavy Majorana ν
fractionally charged
milli-charged
mono-pole
shadow matter
mirror symmetry
vector-like family
6th gen
5th gen
4th gen
triplet Higgs
general 2HDSM
doubly charged Higgs
Type II
Type I
superweak
milli-weak
Weinberg's 3HD
spontaneous CP
axion
axino
Majoron
axion
familon
NGB
contact int.
composite W,Z
pseudo NGB
hypercolor
technicolor
extended TC
supercolor
composite Higgs
TC-TC
worm-hole
Extra dim
H Murayama


NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
Expierments too!
H Murayama
NMSSM
NNMSSM
MSSM
sterile ν
heavy Majorana ν
fractionally charged
milli-charged
mono-pole
shadow matter
mirror symmetry
vector-like family
6th gen
5th gen
4th gen
triplet Higgs
doubly charged Higgs
Majoron
axion
familon
NGB
Weinberg's 3HD
superweak
milli-weak
contact int.
composite W,Z
worm-hole
Extra dim
hypercolor
technicolor
extended TC
supercolor
composite Higgs
TC-TC
pseudo NGB
S,T,U
Type II
Type III
axion axino
spontaneous CP