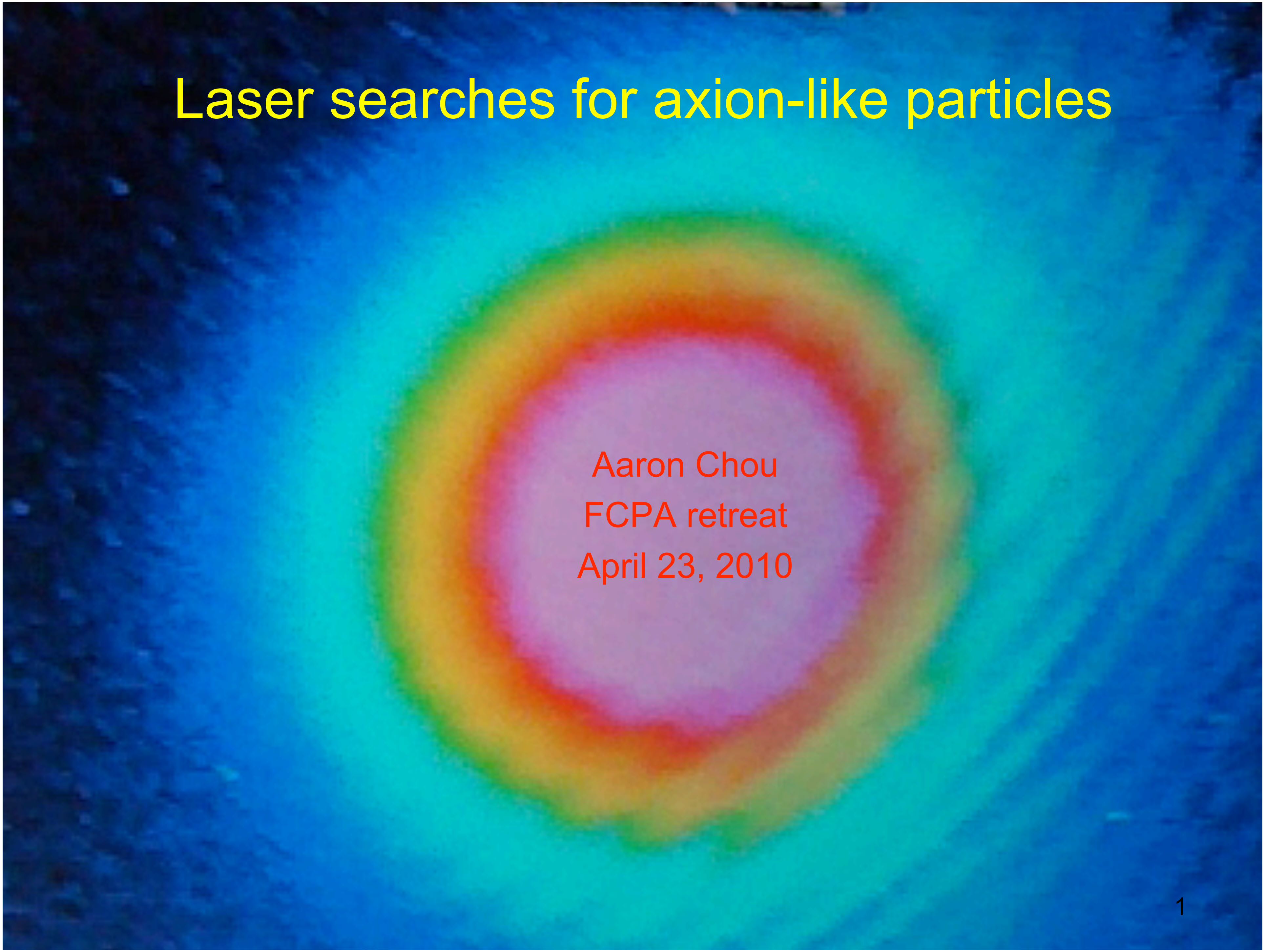
Laser searches for axion-like particles

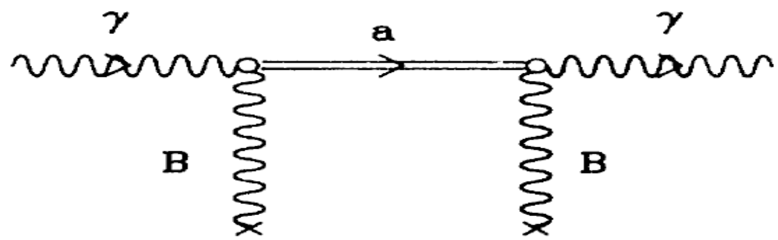


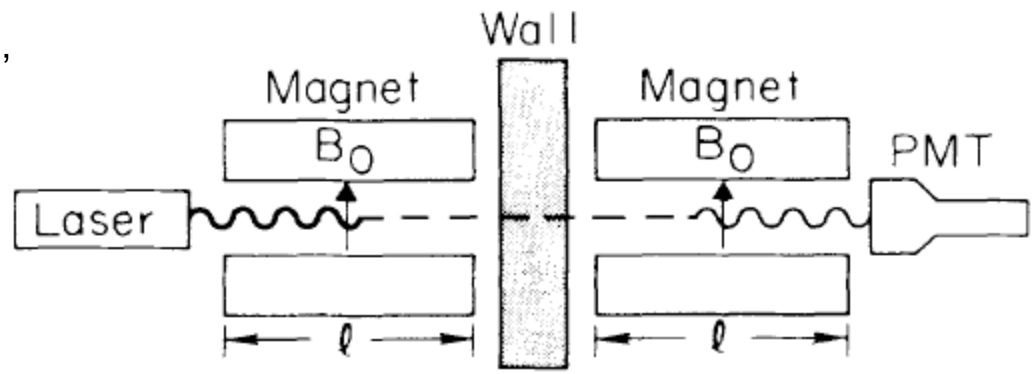
Aaron Chou
FCPA retreat
April 23, 2010

Axion search: Light shining though walls

Experimental configuration inspired by a Feynman diagram.

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





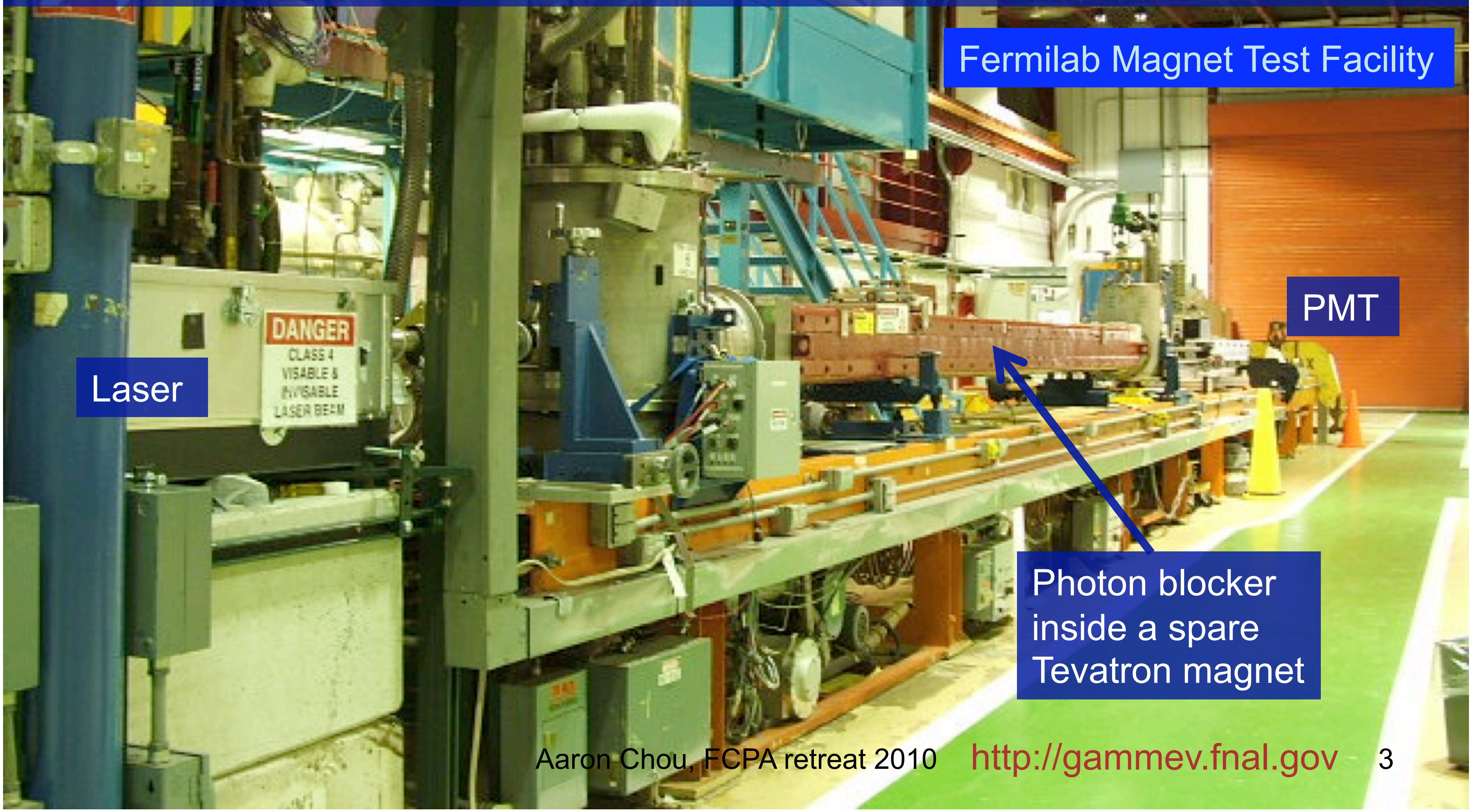
$$P_{\mathrm{regen}} \approx \left(\frac{1}{4} g^2 B^2 L^2\right)^2$$

g=coupling constant

Cost scales linearly with sensitivity.
How to achieve orders of magnitude improvement???

GammeV: Shining light through walls

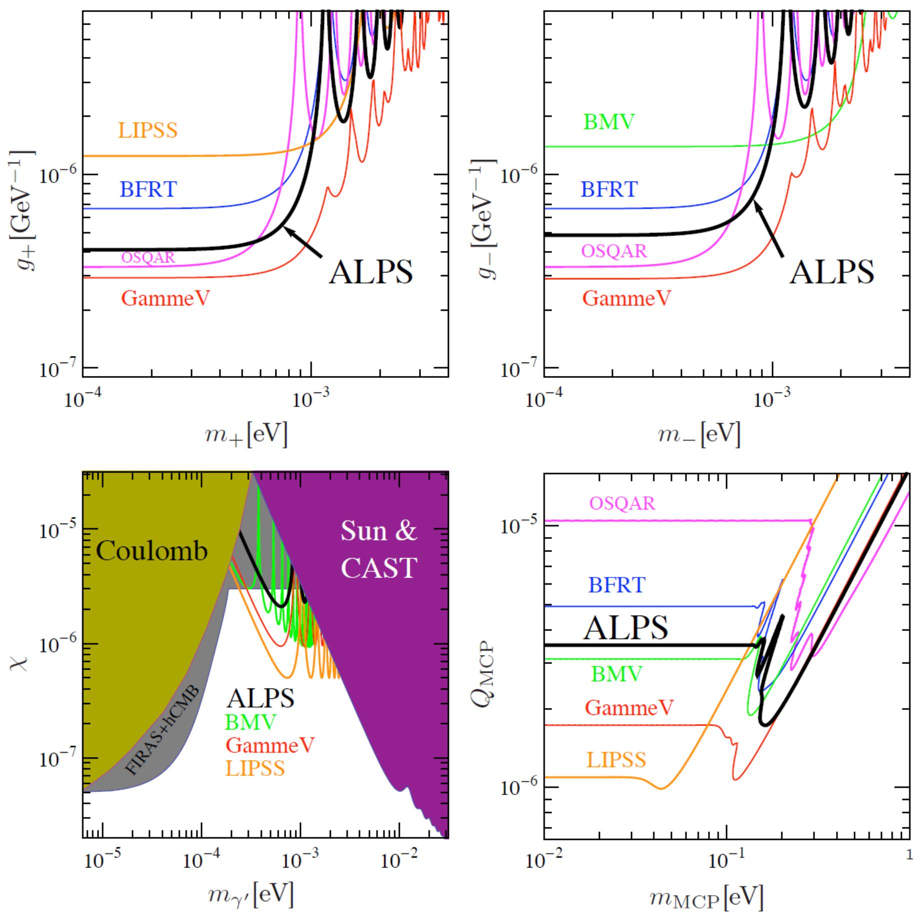
- Collaboration with U.Michigan, New York U., U.Chicago, Cambridge U.
- World’s best laboratory limit on axion-photon coupling, PRL 2008.
- World’s best limit on meV-mass hidden-sector vector bosons, PRD 2008 (Ahlers, et.al).
- Development of chameleon afterglow detection, first results published in PRL 2009.
- CHASE experiment currently running with improved sensitivity to dark energy models.

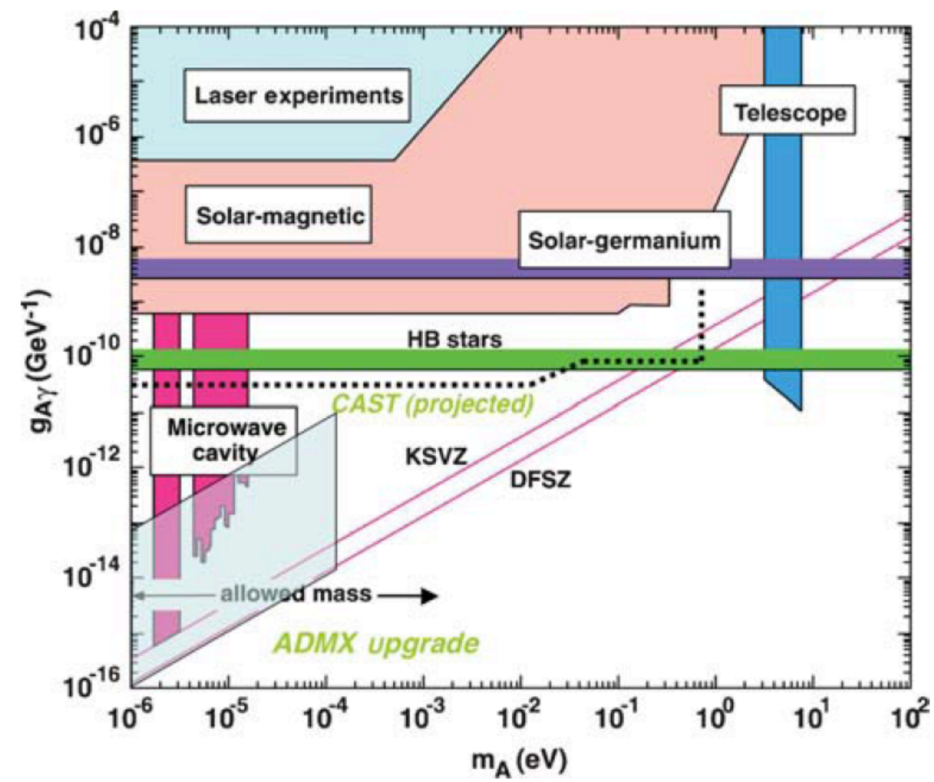


Axion limits

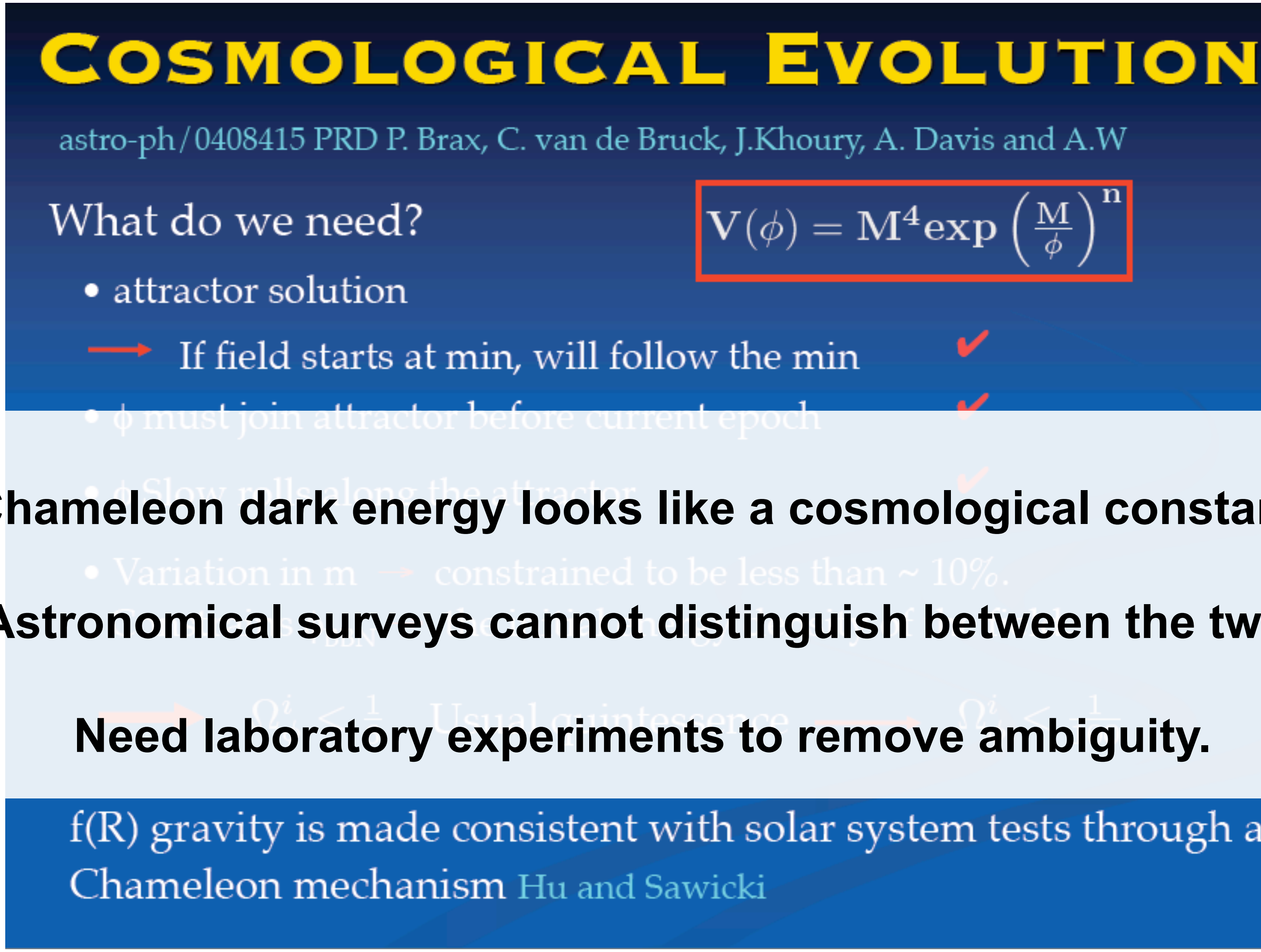
GammeV has world's best laboratory limit on the axion-photon coupling and achieved the project goal of testing (and excluding) the anomalous PVLAS results. But it is not competitive with astrophysical limits.

How do we do better?





Chameleon Dark Energy



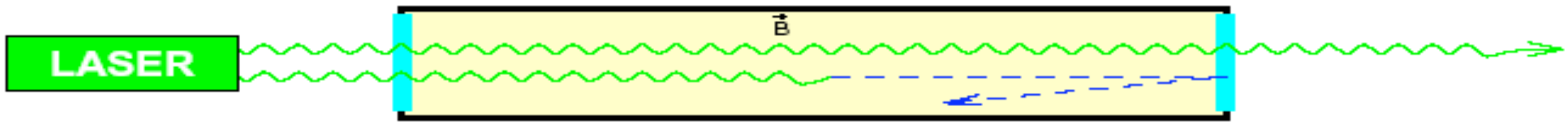
Chameleon dark energy looks like a cosmological constant.

Astronomical surveys cannot distinguish between the two.

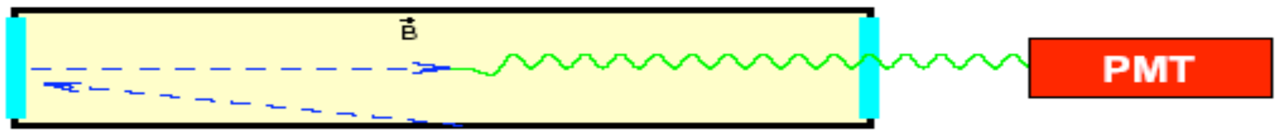
Need laboratory experiments to remove ambiguity.

Chameleon search: Particles trapped in a jar

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



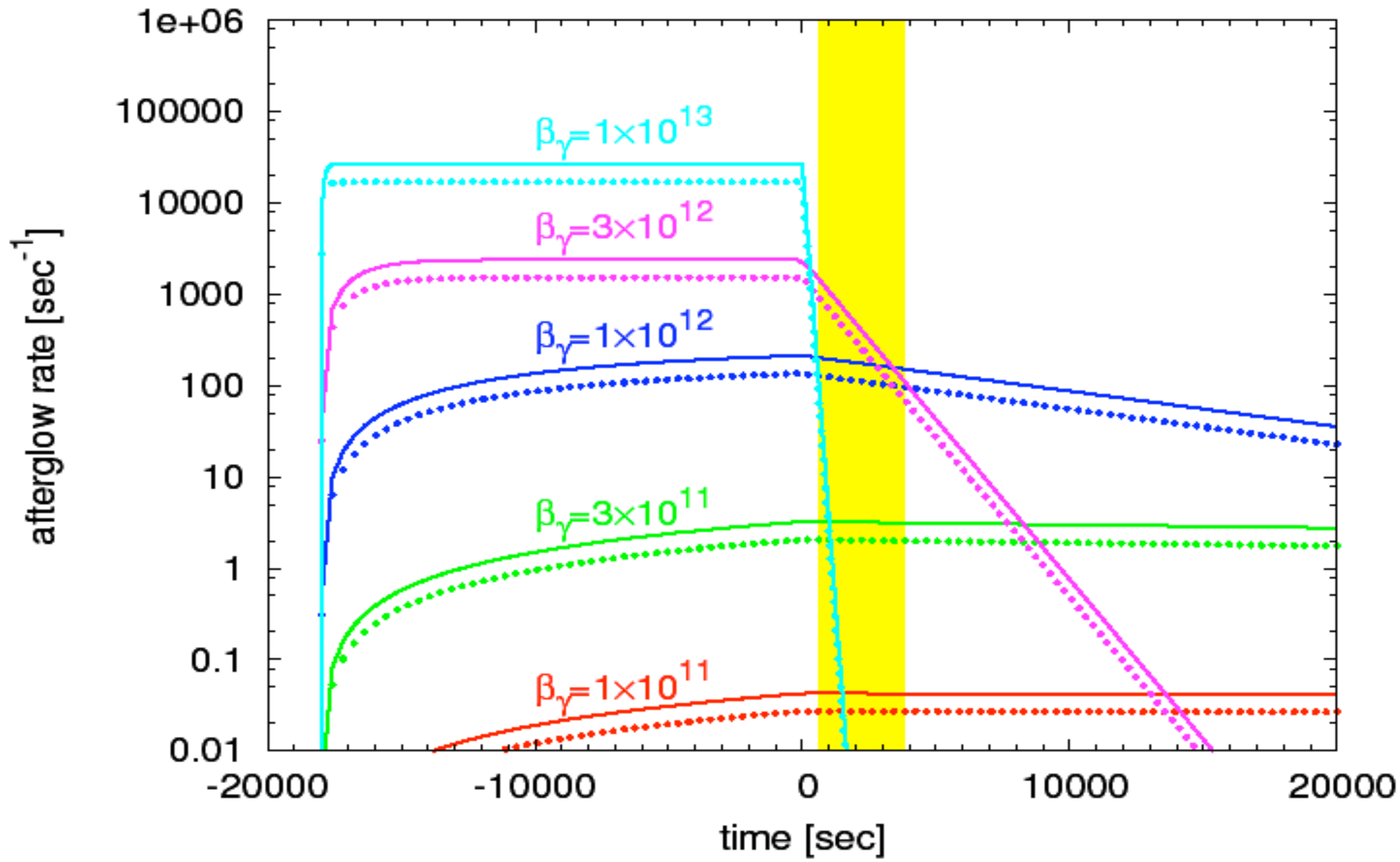
The laser shining into the cavity will fill the “jar” with chameleons.



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

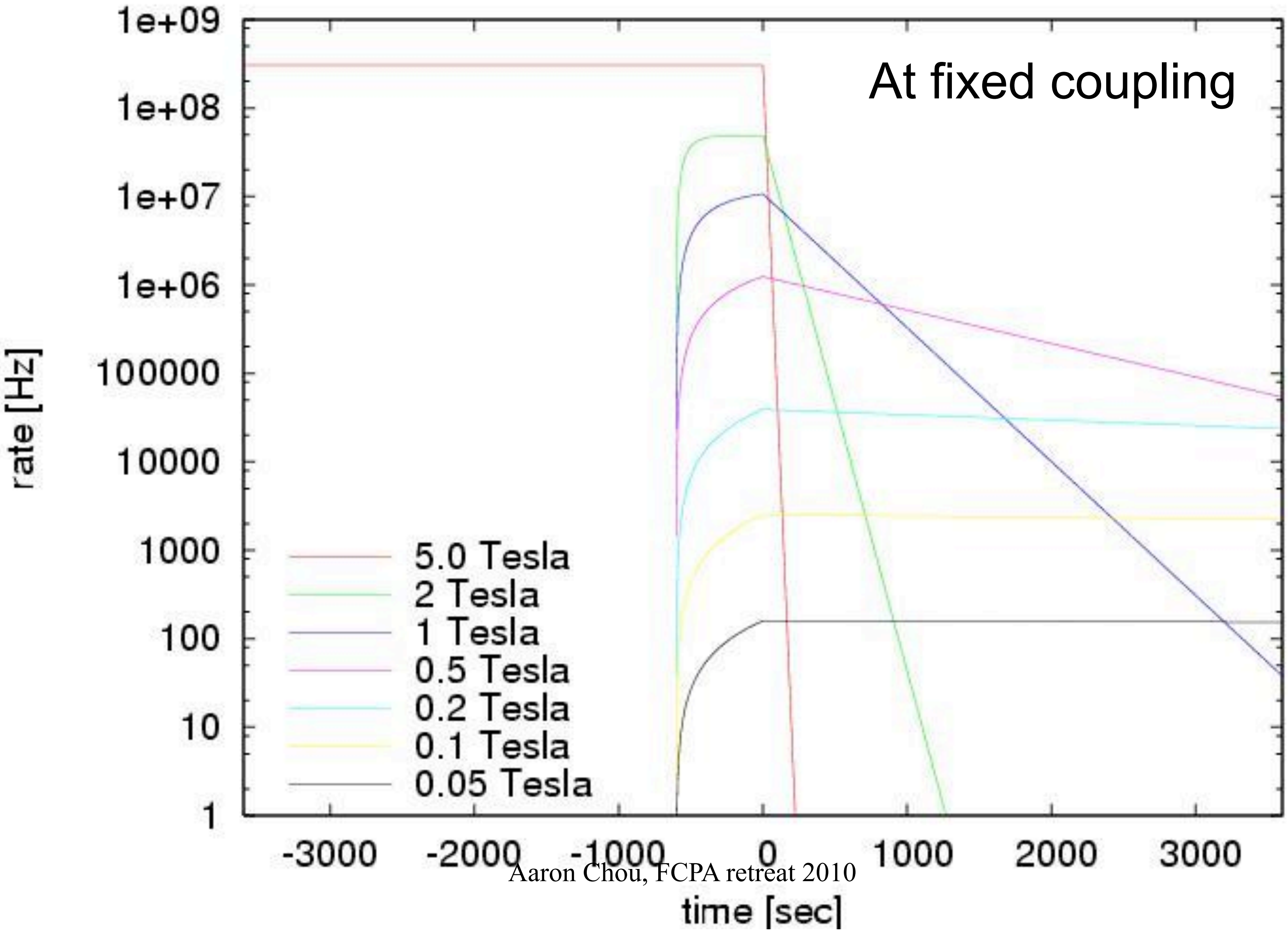
Note: This requires a photon coupling in addition to a matter coupling. However, matter couplings give effective photon couplings so this is generally satisfied.

Afterglow signal vs. photon coupling

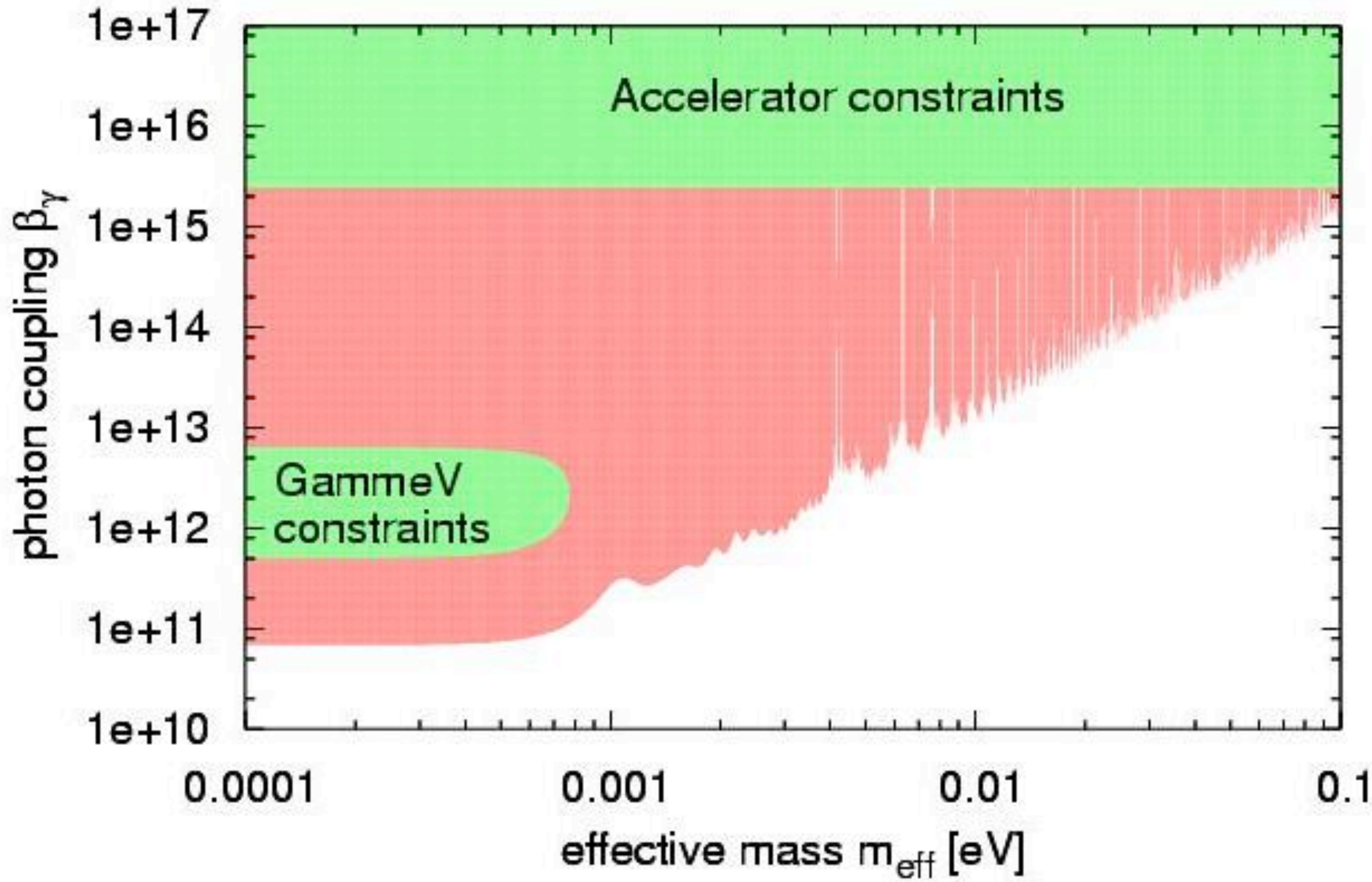


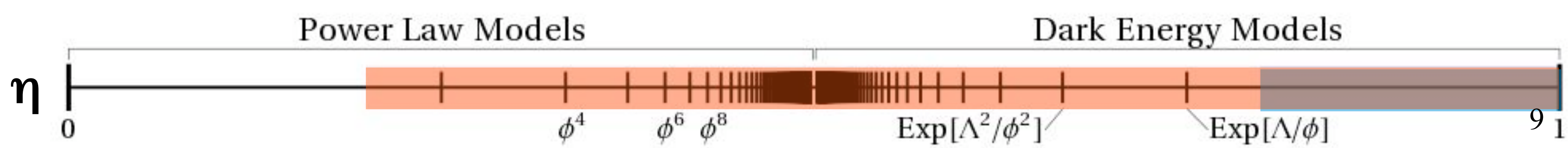
At fixed magnetic field

Afterglow signal vs. magnetic field



Expected CHASE Sensitivity





The Future: Search for axions via
Resonant Regeneration

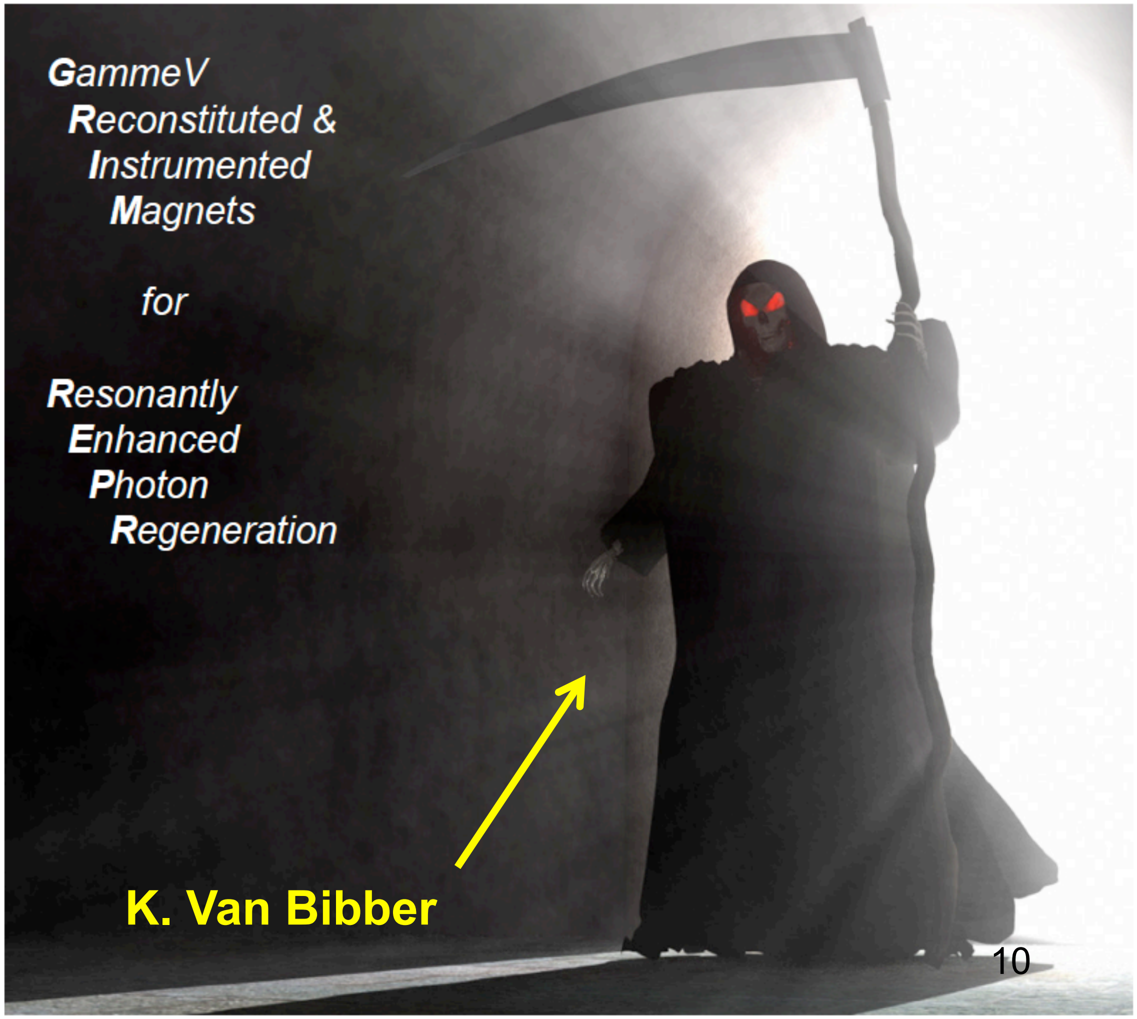
"This time we mow the axion down for good"

Hoogeveen, Ziegenhagan, Nucl. Phys. B (1990)

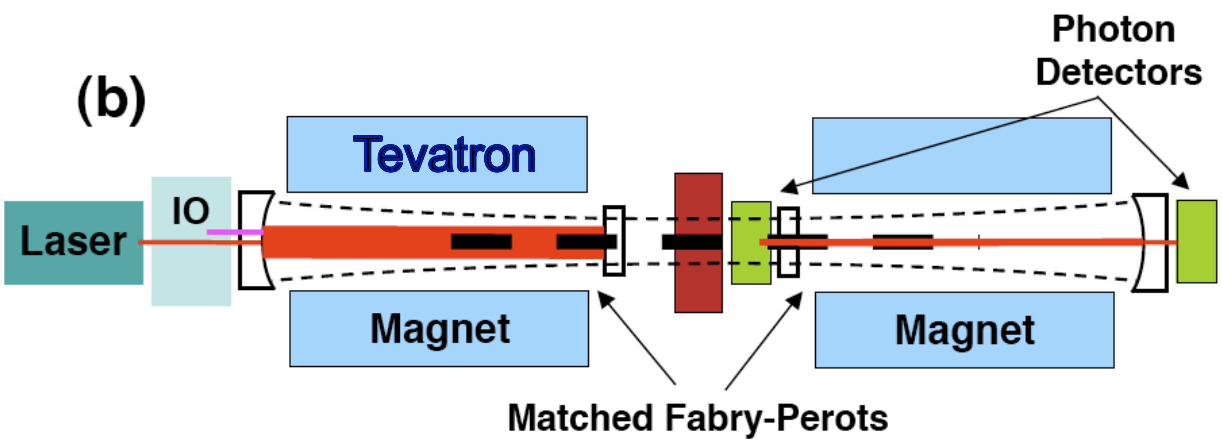
Sikivie, Tanner, van Bibber, PRL (2007)

Mueller, Sikivie, Tanner, PRD (2009)

Collaboration between FNAL, U.Florida, U.Michigan, Naval Postgraduate School



A game-changer: Cavity-enhanced photon-axion conversion



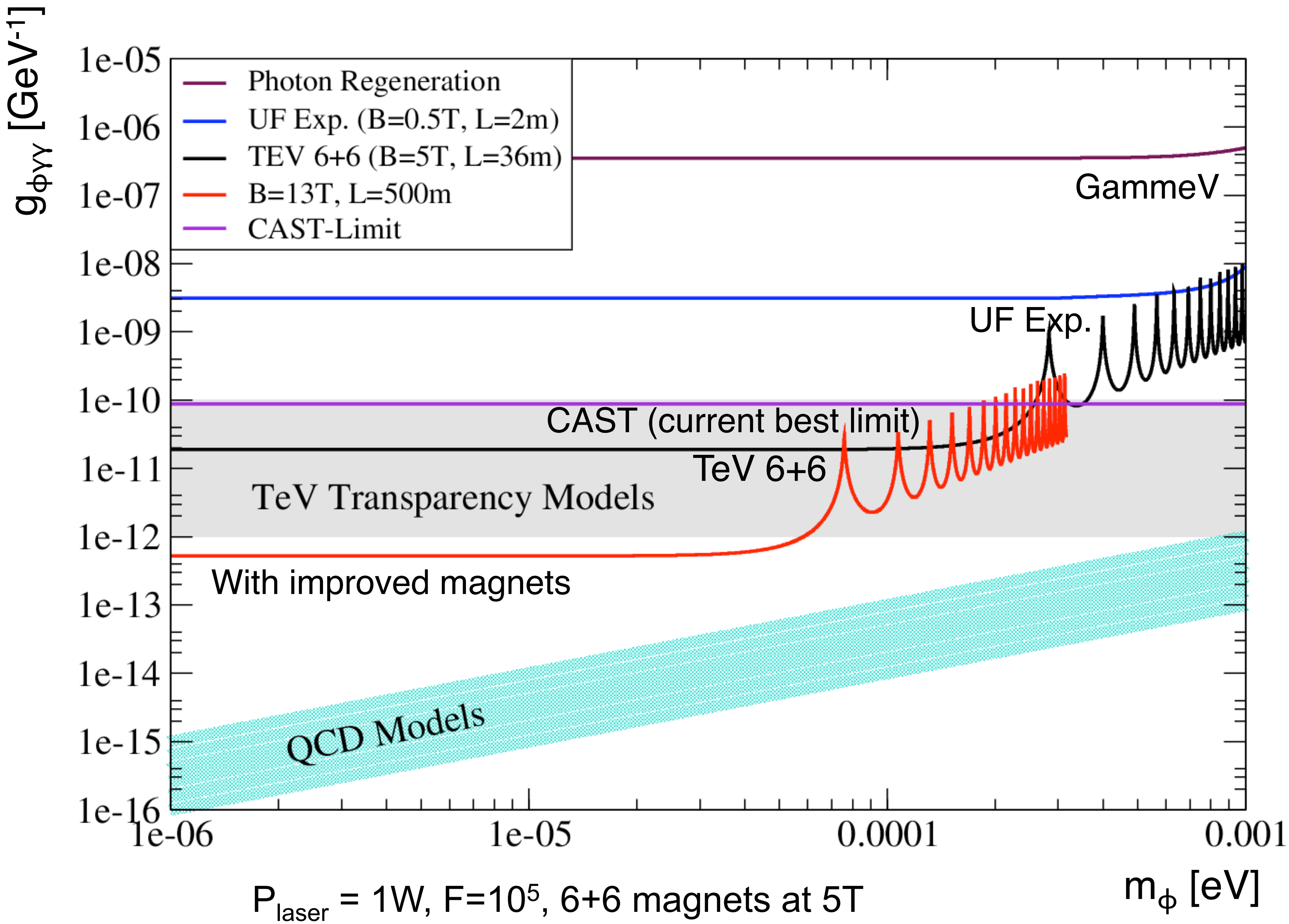
Matched Fabry-Perot cavities shape the axion beam and resonantly enhance the axion-photon transition probability. Light leaks coherently from the bright cavity into the dark cavity.

Signal rate increases as the square of cavity finesse: with 10^5 bounces, the rate increases by 10^{10} !!!

Possible to improve GammeV limit by 4 orders of magnitude using 40m strings of **existing spare Tevatron magnets (6+6 magnets)**.

Possible to improve by another factor of 4 by going to 160m strings, (24+24 magnets) before the finite magnet aperture starts to clip the beam.

Resonant regeneration discovery potential



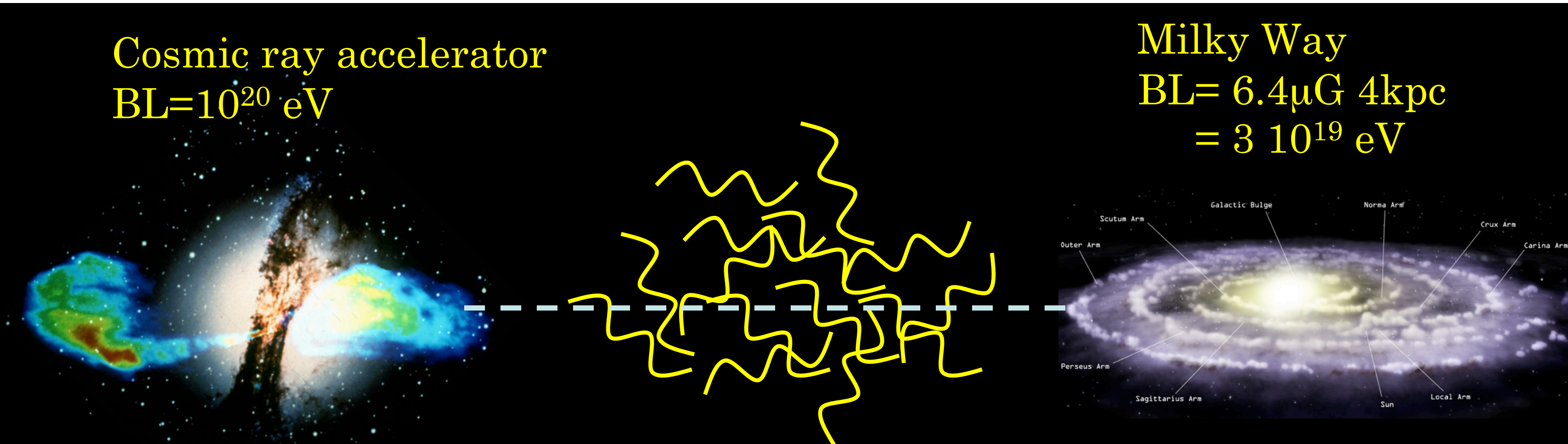
P_{laser} = 1W, F=10^5, 6+6 magnets at 5T

Light shining through the universe

Anomalous transparency of the universe to VHE and UHE gamma rays observed by HESS, VERITAS, MAGIC, Whipple, HiRes, can be explained by mixing of photons with axion-like particles

Hooper, Serpico, 2007
De Angelis, Mansutti, Roncadelli, 2007
Simet, Hooper, Serpico, 2008
Fairbairn, Rashba, Troitsky, 2009

$\text{Prob}(\gamma \leftrightarrow \phi) \approx (gBL/2)^2$



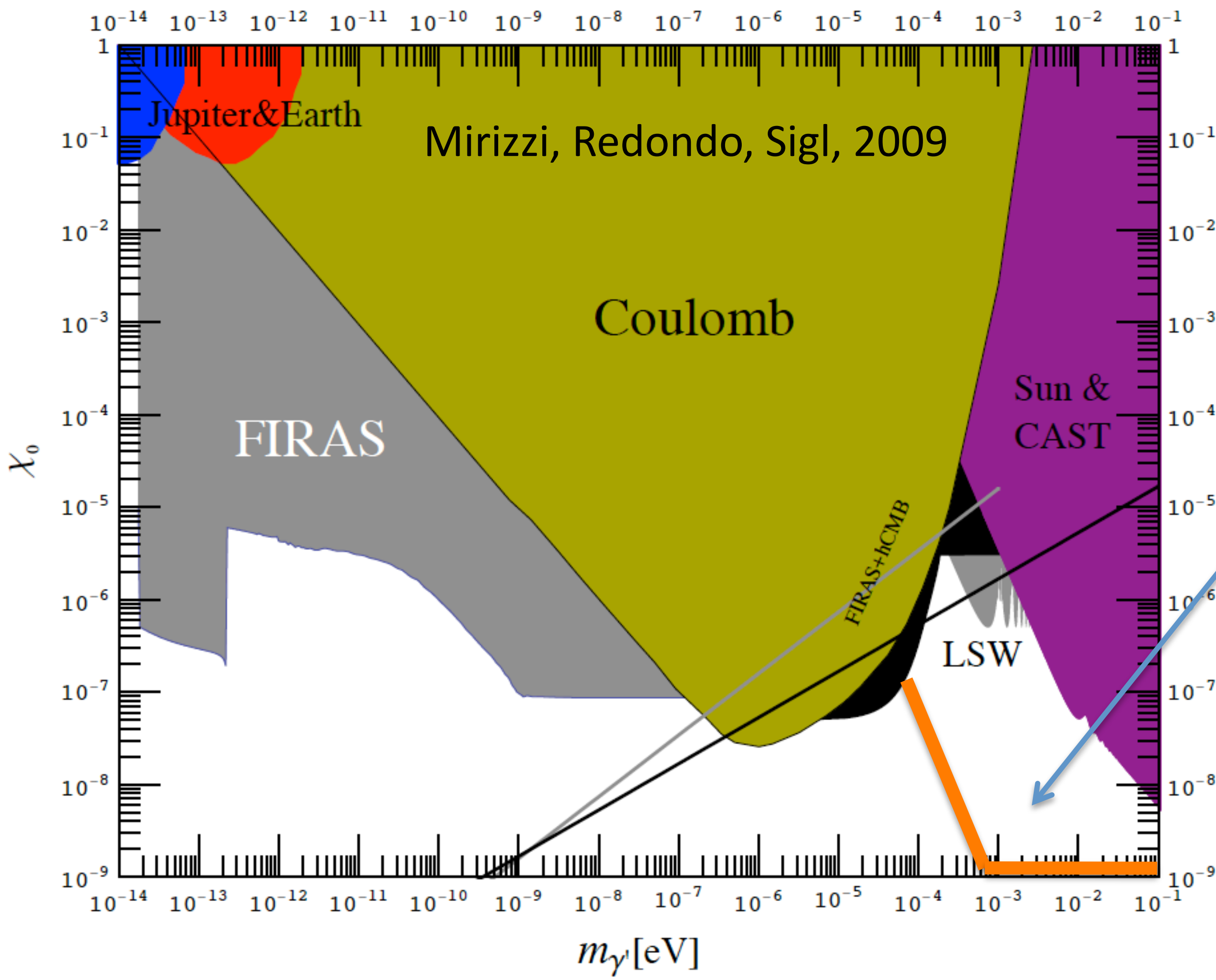
- If $g \approx 1/(BL) = 10^{-11}\ \text{GeV}^{-1}$, then high energy gamma rays can penetrate the opaque wall of background photons by efficiently converting into axions at the source, and then efficiently reconverting into photons in the galaxy.

Axion data can also be used for photon-paraphoton mixing

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

$$P_{\gamma\to\gamma'} = 4\chi^2 \sin^2(\Delta m^2 L/4E)$$

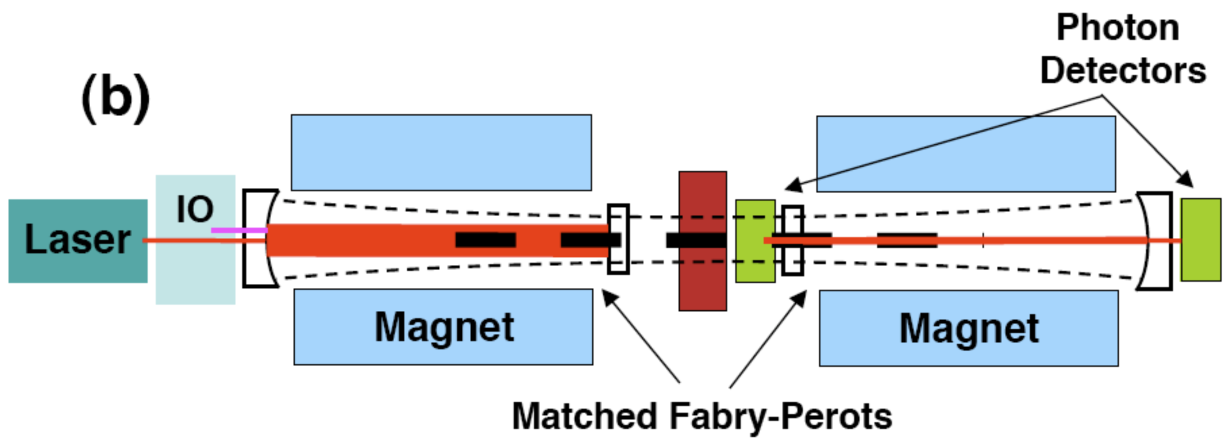
Rate does not depend on external B field anymore.



For a cavity-enhanced resonant regeneration experiment, F=10^5 gives a factor of 300 improvement previous LSW experiments.

This will probe whether free-streaming of paraphotons contributes to suppression of small-scale structure in the CMB.

Resonant Regeneration detection of chameleons



Chameleon mass changes in the blocker.
The resulting phase delay between the two cavities can be of order 1 if chameleon mass in 1 meter length blocker is 10^{-3} eV.

Need mass to scale linearly with density:
$m(rho_{lab}) = H_0 \, (rho_{lab}/rho_c)^1 = (10^{-33}\ \text{eV})\ (1\ \text{g/cm}^3/\ 10^{-30}\ \text{g/cm}^3) = 10^{-3}\ \text{eV}$.

Using dn*dphi =1, the O(1) phase change can be detected using just a few photons in each quadrature.

High cavity finesse is desirable but not absolutely necessary.

The effective intensity of the initial photon beam is really the intracavity power:

$$g_{\text{limit}} \propto \left(\frac{dN_{\text{laser}}}{dt} \cdot T_{\text{integration}} \right)^{-1/4} (BL)^{-1} \mathcal{F}^{-1/2}$$

$$g_{\text{limit}} \propto \left(\frac{dN_{\text{cavity}}}{dt} \cdot T_{\text{integration}} \right)^{-1/4} (BL)^{-1} \mathcal{F}^{-1/4}$$

So sensitivity really scales only as $(\text{Finesse})^{-1/4}$.

Intracavity power is limited only by thermal lensing of the mirrors, and LIGO uses up to 100s kW before extraordinary measures are called for.

Our initial spec of $P_{\text{cavity}} = P_{\text{laser}}$ * Finesse = 100 kW can be easily met using a MOPA laser amplifier and a lower finesse photon cavity.

The remaining scaling $(\text{Finesse})^{-1/4}$ can be compensated by longer integration time.

Why do this experiment at FNAL?

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The spool piece provides the cryo and power connection between the 2 strings of magnets while providing an open drift space in between. One of several existing optical tables can be placed here.

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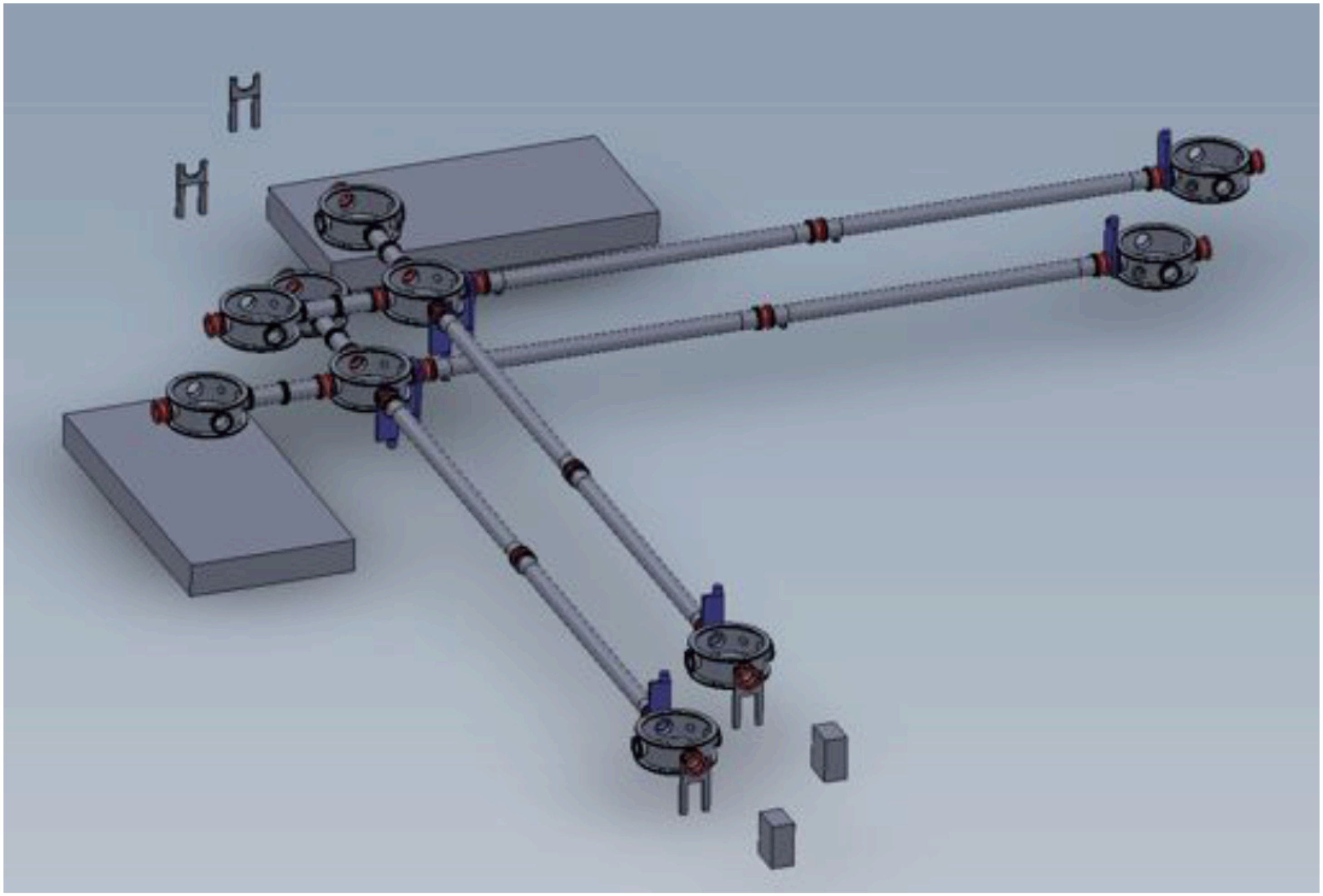
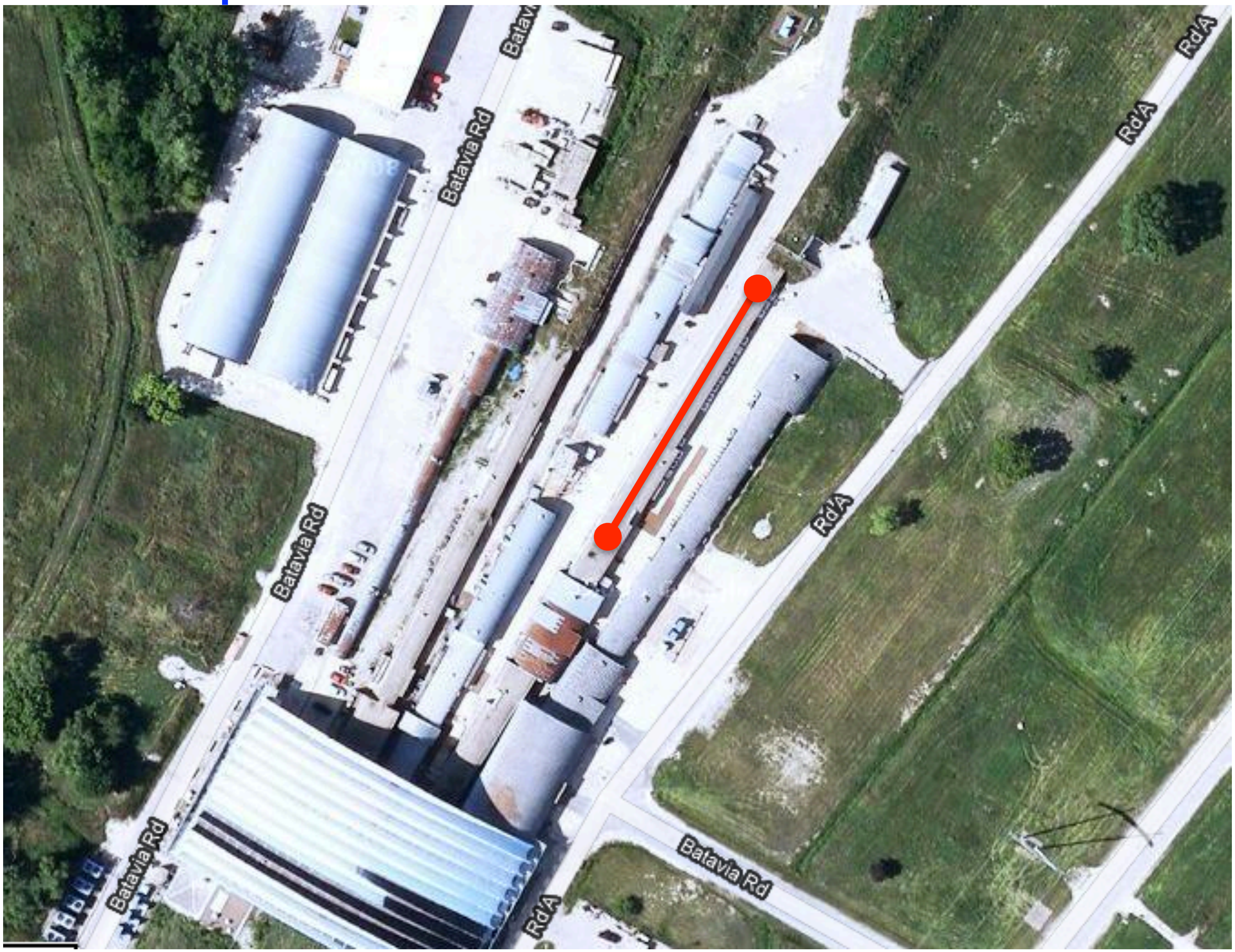


$$\Delta N \cdot \Delta\phi \geq 1$$

Holometer uses large photon flux to make precise phase measurement.
Axion uses large photon flux to search for rare transition processes.
Both need large intracavity photon population.

Currently building (with holometer project) a 40m optical testbench in the MP beamline



Dan's questions

- Science? Axions are in particle physics and particle astrophysics
- Leading the field? We have the best laser limits, and will beat the axion solar telescopes with the cavity-enhanced experiment. No one else has attempted a laser chameleon search.
- FNAL roles: Projects are initiated and managed at Fermilab.
- Future role: We plan to continue the leadership role in this FNAL-sited experiment
- Weaknesses: no FNAL graduate students. No innate optics expertise, but we have brought in LIGO collaborators
- Serving the community: Axion searches need humongous magnets. We can provide them, and the facilities to operate them.