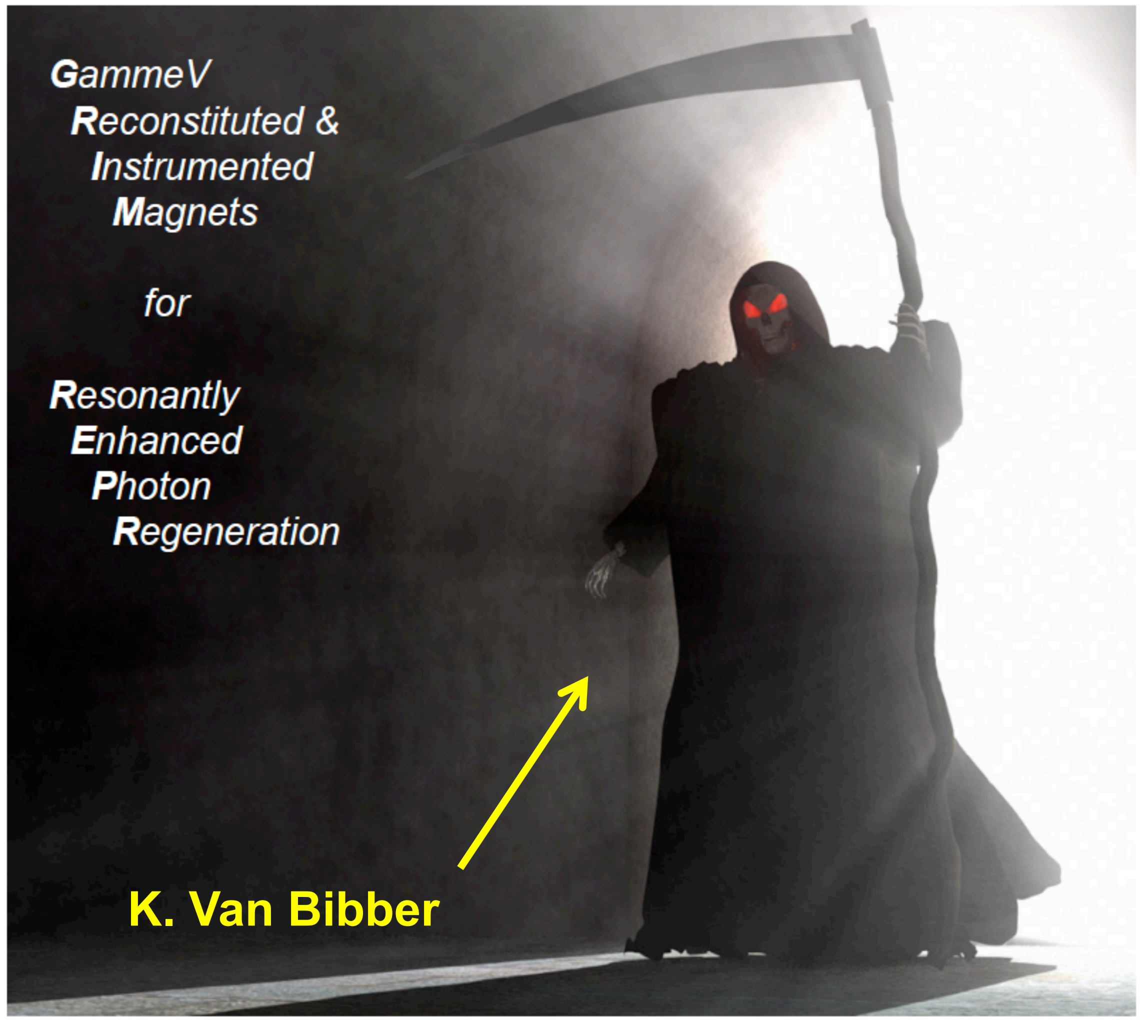
Search for axions via resonant photon regeneration

Aaron Chou
Wilson Fellow, FNAL

"This time we mow the axion down for good"



The Resonant Regeneration Collaboration

FNAL:

Aaron Chou (Wilson Fellow, co-spokesperson GammeV),
William Wester (co-spokesperson GammeV),
Jason Steffen (Brinson Fellow)
Peter Mazur,
Ray Tomlin,
Al Baumbaugh

Lawrence Livermore National Lab:

Karl van Bibber (Chief Scientist, spokesperson ADMX)

Univ. of Florida:

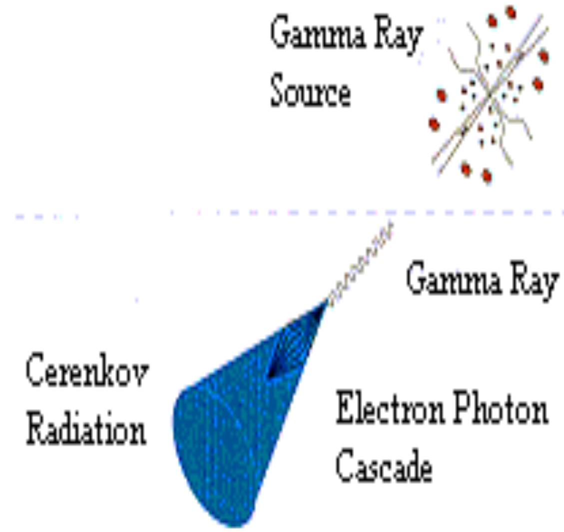
David Tanner (ADMX, LIGO)
Guido Muller (Chair of Interferometer working group, LISA)

Univ. of Michigan:

Dick Gustafson (LIGO)

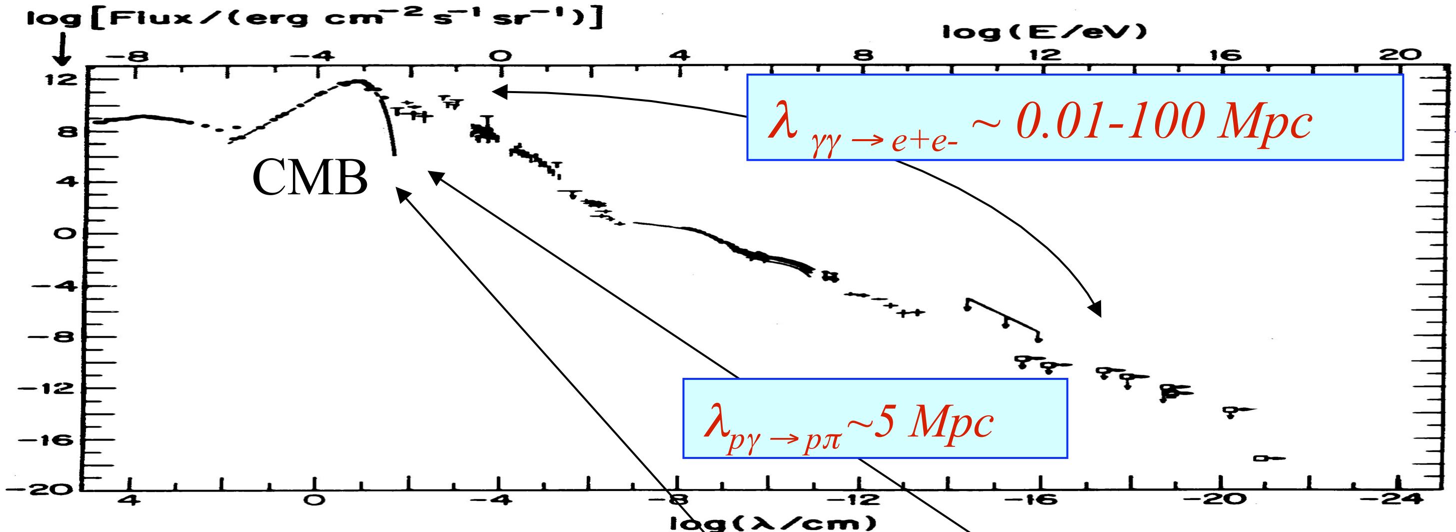
Motivation for axion-like particles from Particle Astrophysics observations

Air Cherenkov Telescopes detect TeV gamma rays



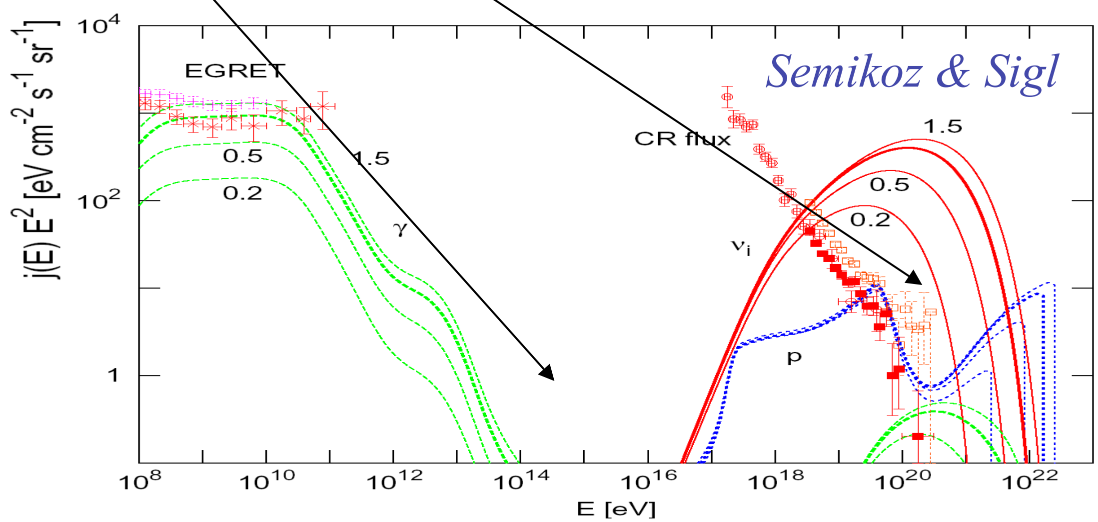
The extragalactic background light (EBL) makes the universe opaque to **E>100 GeV photons**

Observed background photon spectral density



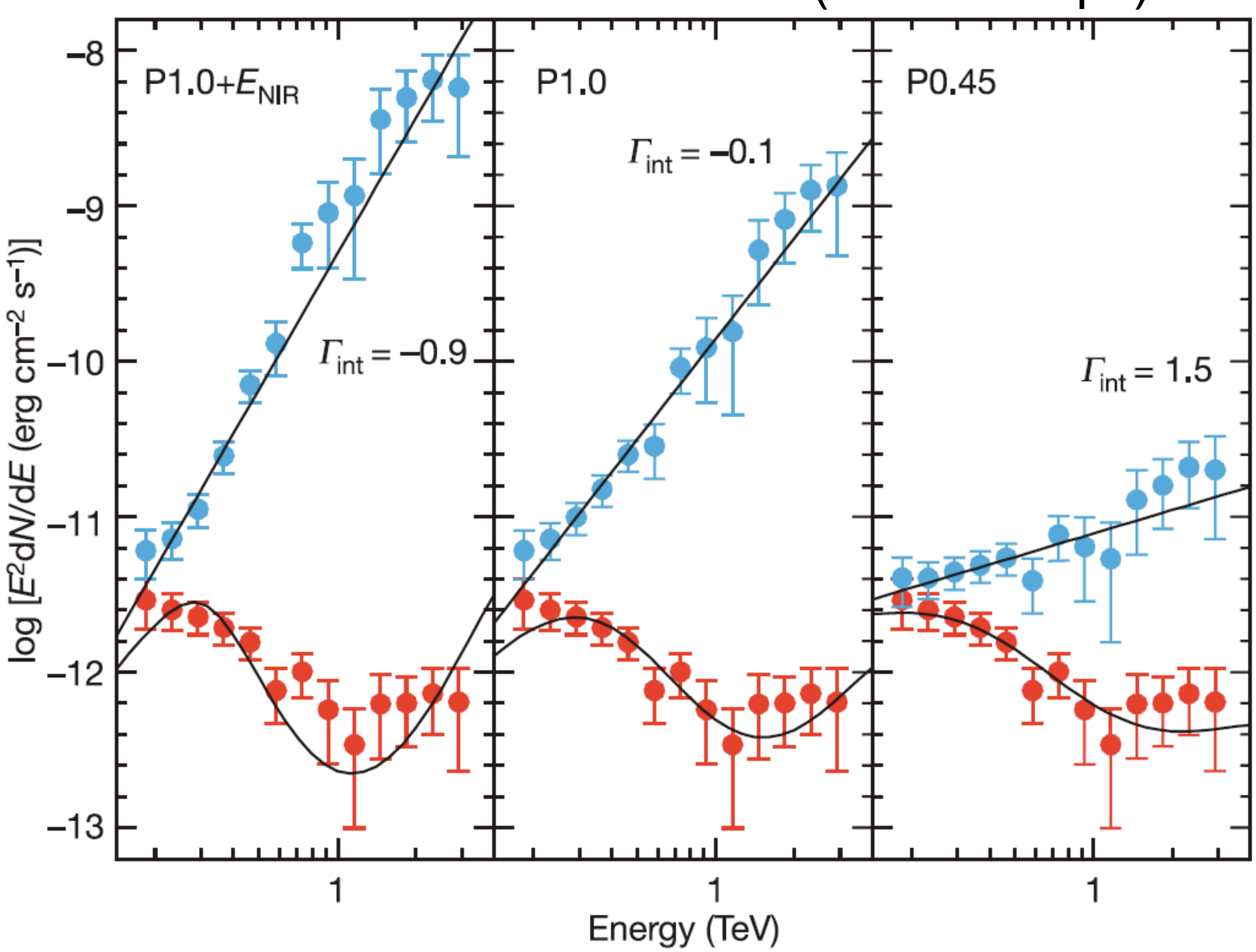
Halzen, Ressell & Turner

Large optical depth predicts severe attenuation of photons



Anomalous transparency at TeV energies

1ES 1101-232 (D ~ 750 Mpc)



H.E.S.S.,
Nature, Vol.440, 1018-1021, 20 April, 2006.

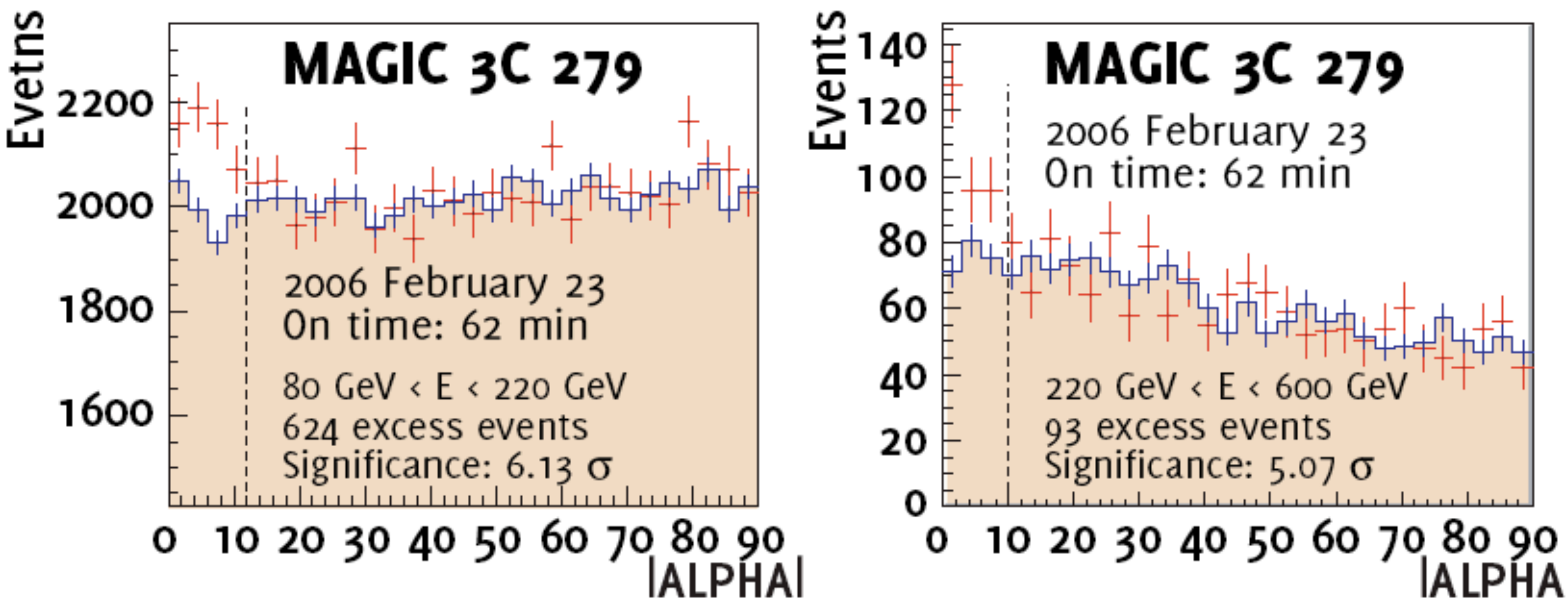
Corrected spectrum with 3 different models of EBL.

Observed raw spectrum

HESS measured blazar spectrum flattens at large E instead of dropping exponentially. Either the source spectrum is extremely hard, or the extragalactic background light density 0.45*expected. Or new physics….

3C 279 Blazar at z=0.538 detected by MAGIC Cherenkov telescope

Science, 320 (2008)



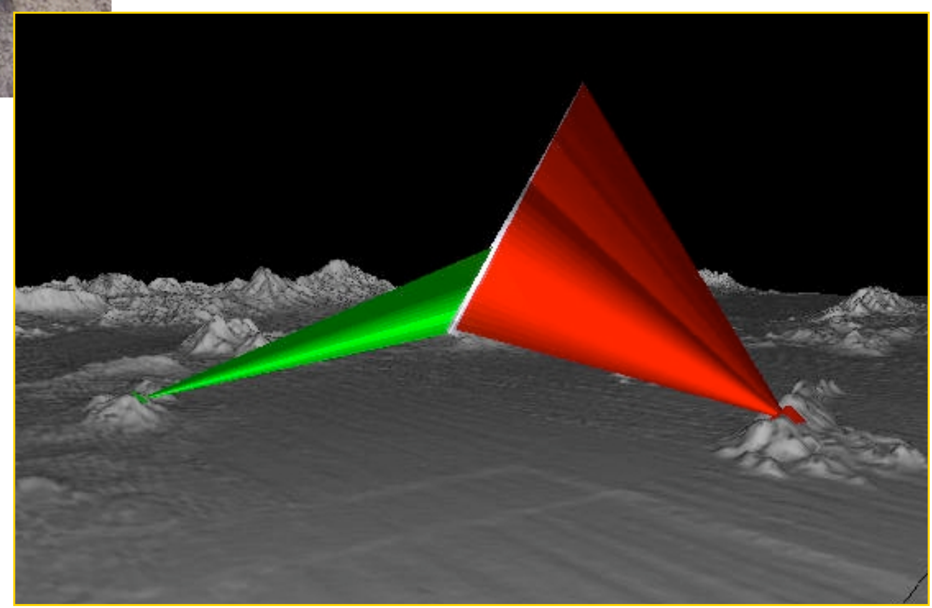
ALPHA = angle from source.

Z=0.538 --> **this source should not be visible even with reduced EBL**, but MAGIC has a 5-6σ detection in both low and high energy bins.

Need low EBL **and** an extremely hard spectrum with spectral index ~1.5 to explain the detection of this object. Fermi acceleration predicts index=2.0.

HiRes Fluorescence telescope for Ultra-high-energy cosmic rays (E>1e18 eV)

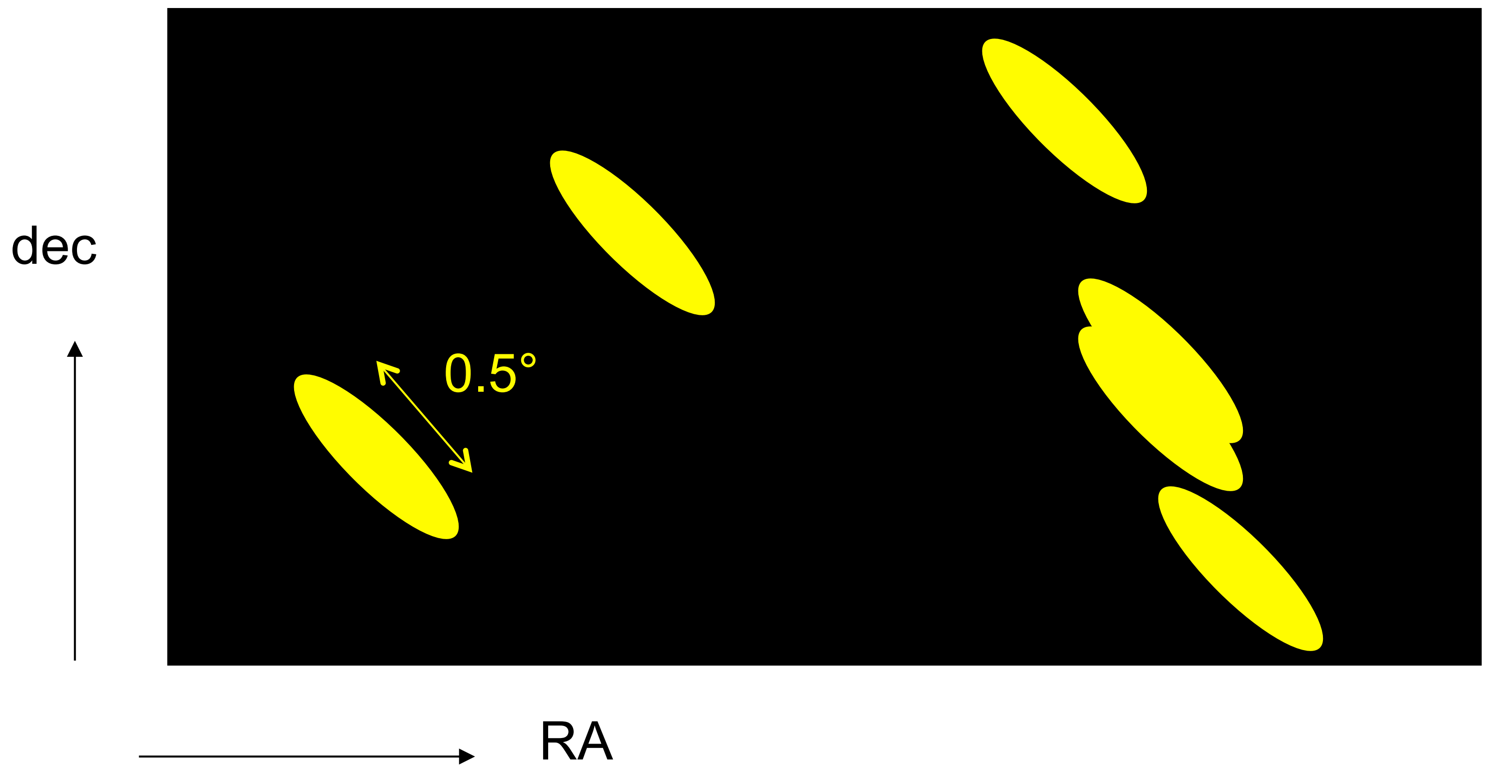
Identity of UHECRs is unknown, could be photons.



Stereo viewing of the fluorescence emission track gives 0.5° angular resolution

HiRes correlation with (m<18) BLLacs

- Stereo cosmic ray data from 12/99-1/04
  - 4495 events, 271 with $E>10^{19}$ eV
  - Using event angular errors, derive probability functions f_i for 157 equal probability BLLac "sources" from the VC catalog by drawing gaussian ellipses around each position.



HiRes correlation with (m<18) BLLacs

Astrophys. J. 636 (2006)

- **8 of the 271 events (3%) at $E>10^{19}$ eV appear to come from the source catalog within angular errors.**
  - The chance probability of getting a stronger signal from an isotropic flux is F=2e-4.

- The particles appear to be neutral since magnetic deflection of charged particles by galactic magnetic fields would give a much larger angular scale of correlation.

- They cannot be neutrons because the neutron decay length at these energies is 1 Mpc while the sources are 100's Mpc away.

- On the other hand, they can't be photons because of the large optical depth. Or can they?

Axions

(Peccei, Quinn, 1977: explains vanishing neutron electric dipole moment)

- Defining characteristic: kinetic coupling to two gauge bosons

$$\mathcal{L} \equiv \frac{1}{4} g\phi F\tilde{F} = g\phi \vec{E}\cdot\vec{B}$$

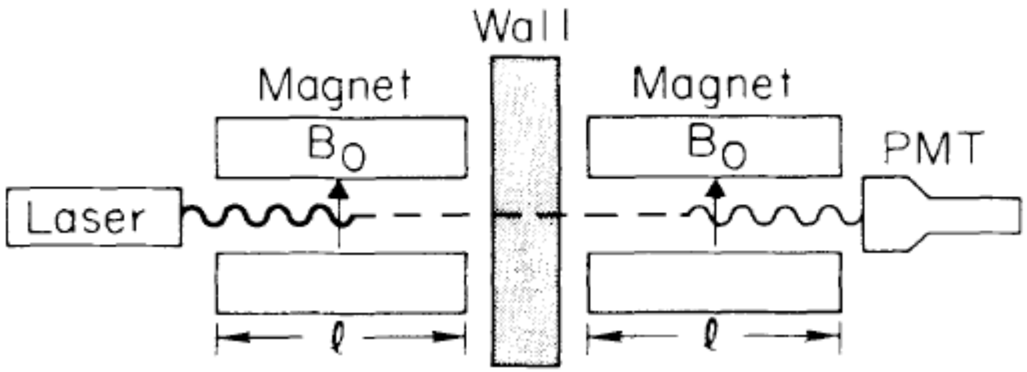
- Coherent interactions of a photon with energy ω with a background magnetic field B lead to oscillations between one photon polarization component and the axion

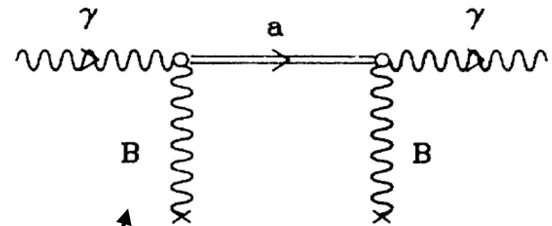
$$\left[\begin{pmatrix} E_\gamma^2+\partial_z^2 & 0 & 0 \\ 0 & E_\gamma^2+\partial_z^2 & 0 \\ 0 & 0 & E_\gamma^2+\partial_z^2 \end{pmatrix} - \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & igBE_\gamma \\ 0 & -igBE_\gamma & m^2 \end{pmatrix}\right]\begin{pmatrix} A_\perp \\ A_\| \\ \phi \end{pmatrix} = 0$$

$$\text{Prob}_{\gamma\to\phi} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\gamma}\right)$$

Depending on photon energy E_γ , either diagonal or off-diagonal terms can dominate Δm^2.

In laboratory experiments, $gBE_\gamma \ll m^2$ so $\Delta m^2 \approx m^2$





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

$$\mathcal{L} \equiv \frac{1}{4} g\phi F\tilde{F} = g\phi \vec{E} \cdot \vec{B}$$

$$P_{\text{regen}} = \frac{16 g^4 B_1^2 B_2^2 E_\gamma^4}{m^8} \sin^2\left(\frac{m^2 L_1}{4E_\gamma}\right) \cdot \sin^2\left(\frac{m^2 L_2}{4E_\gamma}\right)$$

Astrophysical transparency can be caused by photon-axion oscillations in a similar way, but in the limit of large B, E_γ .

At large E_γ: $\Delta m^2 \approx 2gBE_\gamma$ and mixing is maximal

$$P_{\rm osc} = \sin^2(2\theta)\sin^2\left[\frac{gBL}{2}\sqrt{1+\left(\frac{\mathcal{E}}{E_\gamma}\right)^2}\right]$$

E_γ = photon energy
L=magnetic baseline

Above a threshold energy: $\mathcal{E} \equiv \frac{m^2}{2gB}$

the mixing angle θ, defined by:

$$\sin^2(2\theta) = \frac{1}{1+(\mathcal{E}/E_\gamma)^2}$$

goes to θ=45 --> **maximal mixing!**

•100% of photons with the correct polarization get converted into axions **if the baseline is tuned to the oscillation length**: L ~ 1/(g*B).

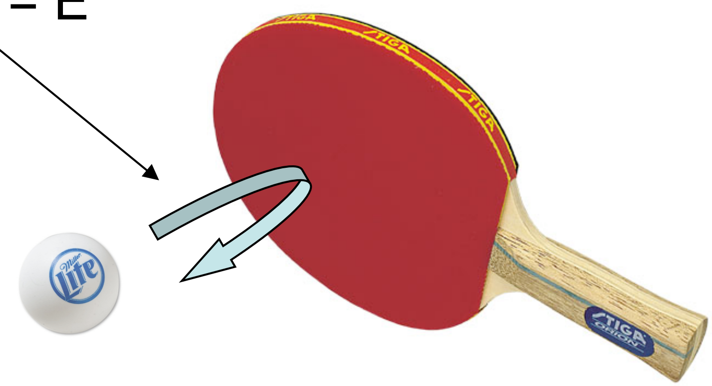
•If B field is along z, then photons travelling in x, y directions with linear polarization in xz and yz planes get converted. These are 2 out of the 6 possible direction+polarization combinations, so 1/3 of all photons above threshold are converted.

Auger Observatory sees correlation of UHECR ($E \sim 10^{20}$ eV) with nearby AGN

Angular scale consistent with magnetic deflection of protons.

AGN are proton accelerators!

To hit a ball with energy E and unit charge, a magnetic paddle must have B*L = E



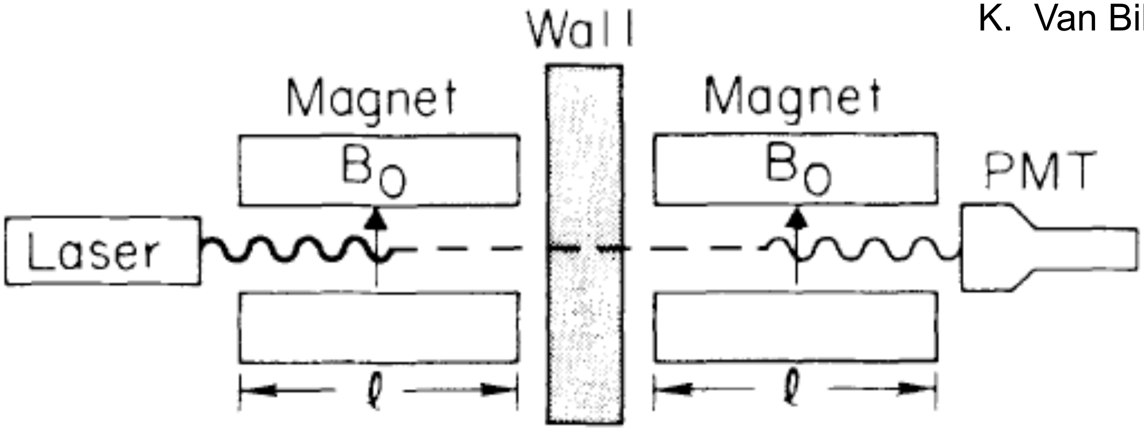
Secondary photons from decays of pions produced at the sources can be efficiently converted to axions if:

$g \sim 1/(B*L) = 10^{-11}\ \mathrm{GeV}^{-1}$,

one order of magnitude beyond the sensitivity of any previous axion experiment.

Light shining through a wall

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

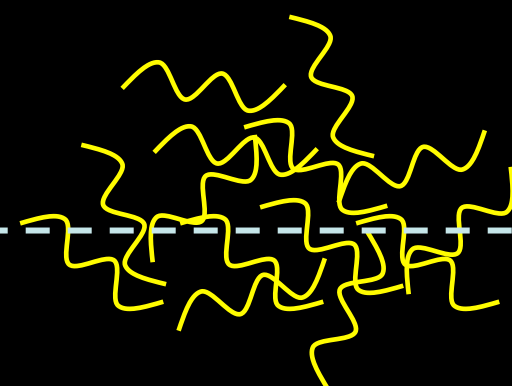


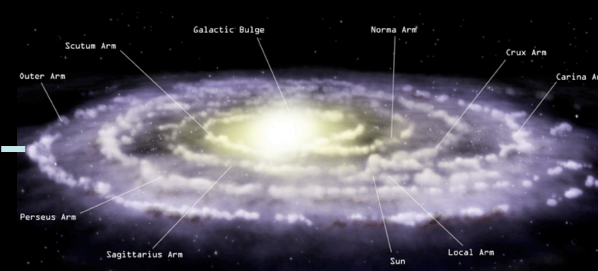
BFRT, GammeV, BMV, LIPSS, ALPS

BL=10^{20} eV

BL= 6.4μG 4kpc

= 3 10^{19} eV

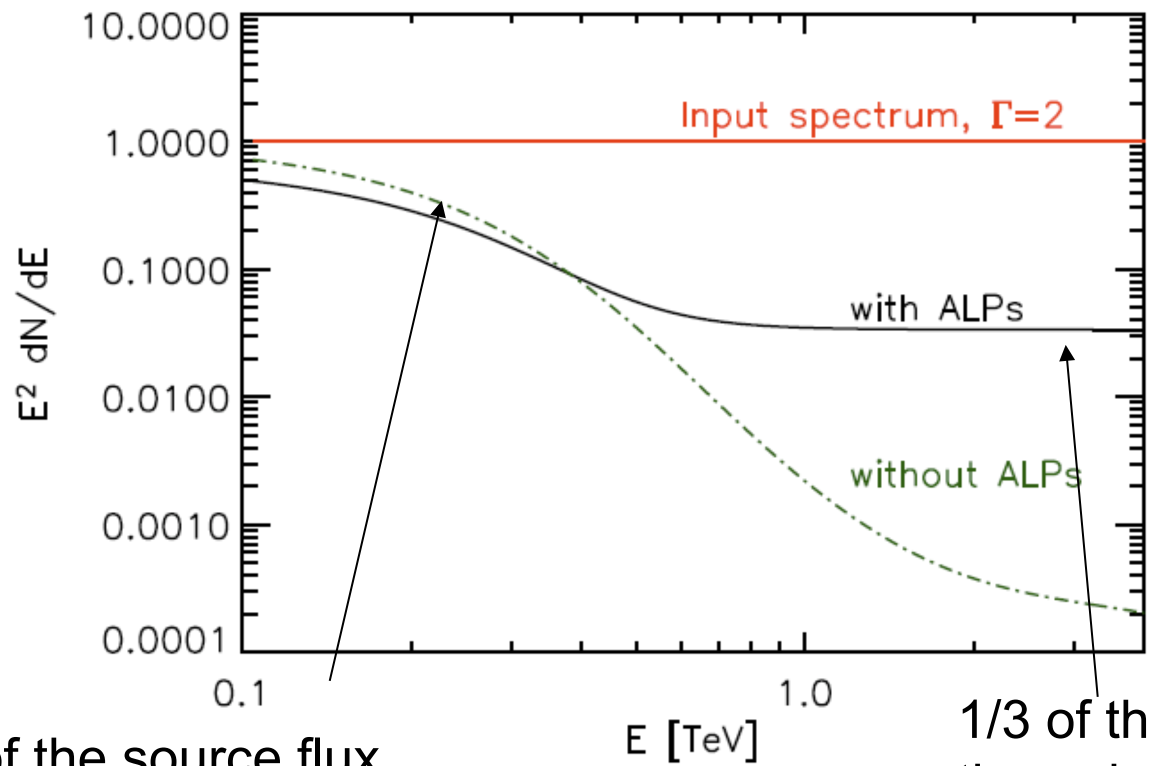




- High energy gamma rays can penetrate the opaque wall of background photons by converting into axions at the source, and then reconverting into photons in the galaxy.

Using axion-like particles to shine TeV photons through the “wall” of the extragalactic background light (EBL)

- 1/3 of the photons are converted to axions at the source.
- The Milky Way magnetic fields regenerate ~10% of the photons.



M.Simet, D.Hooper, P.Serpico, PRD77:063001, 2008

2/3 of the source flux attenuates normally with a “EBL cut-off” at ~200 GeV.

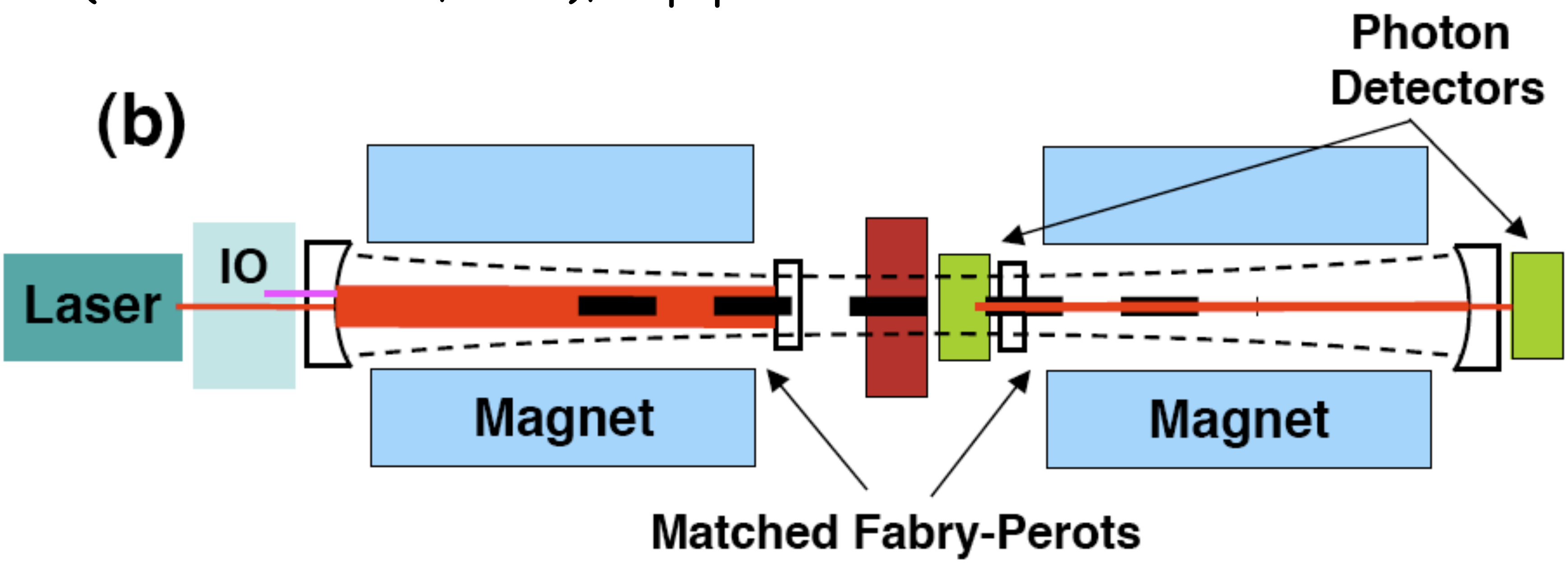
1/3 of the source flux passes through the “wall” with no spectral distortion, and 10% of that is regenerated into photons.

Predictions of axion-induced transparency

- **$g=1/(B^*L) > 10^{-11}$ GeV^{-1}** from Auger AGN corr. + Hillas criterion
  - best current limits $g<10^{-10}$ GeV^{-1} from solar axion search (CAST)
  - Maximal mixing: 1/3 of all source photon flux is converted above some energy threshold ~ 100 GeV
- **$m<10^{-8}$ eV**
  - Maximal mixing and hence efficient reconversion in the galaxy
- **Air showers are induced by undeflected, reconverted photons**
- Assuming Waxman-Bahcall secondary photon flux at the source,
  - **Observed photon fraction is <3%** due to 33% conversion rate at the source and <10% reconversion rate in the galaxy.
  - Consistent with Auger upper limits
  - Need lots of statistics to see this correlation signal.

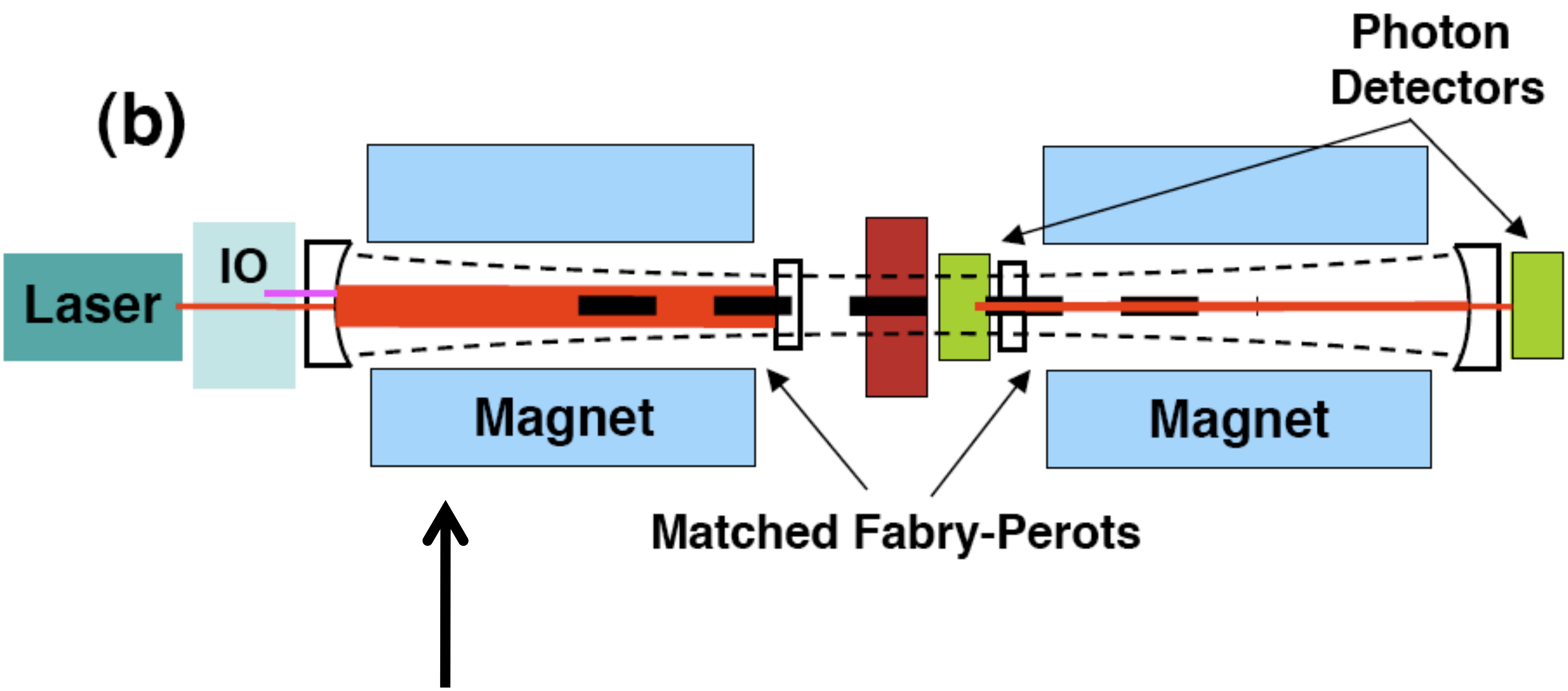
New FNAL experiment to probe the 10^{-11} GeV^{-1} coupling scale

- Sikivie/Tanner/van Bibber: resonantly-enhanced photon regeneration (PRL 98:172002,2007), hep-ph/0701198



Rate of photon-axion transitions is enhanced by a factor of the cavity finesse (F= ~10^5) on each side (resonant reconversion in the 2nd cavity)

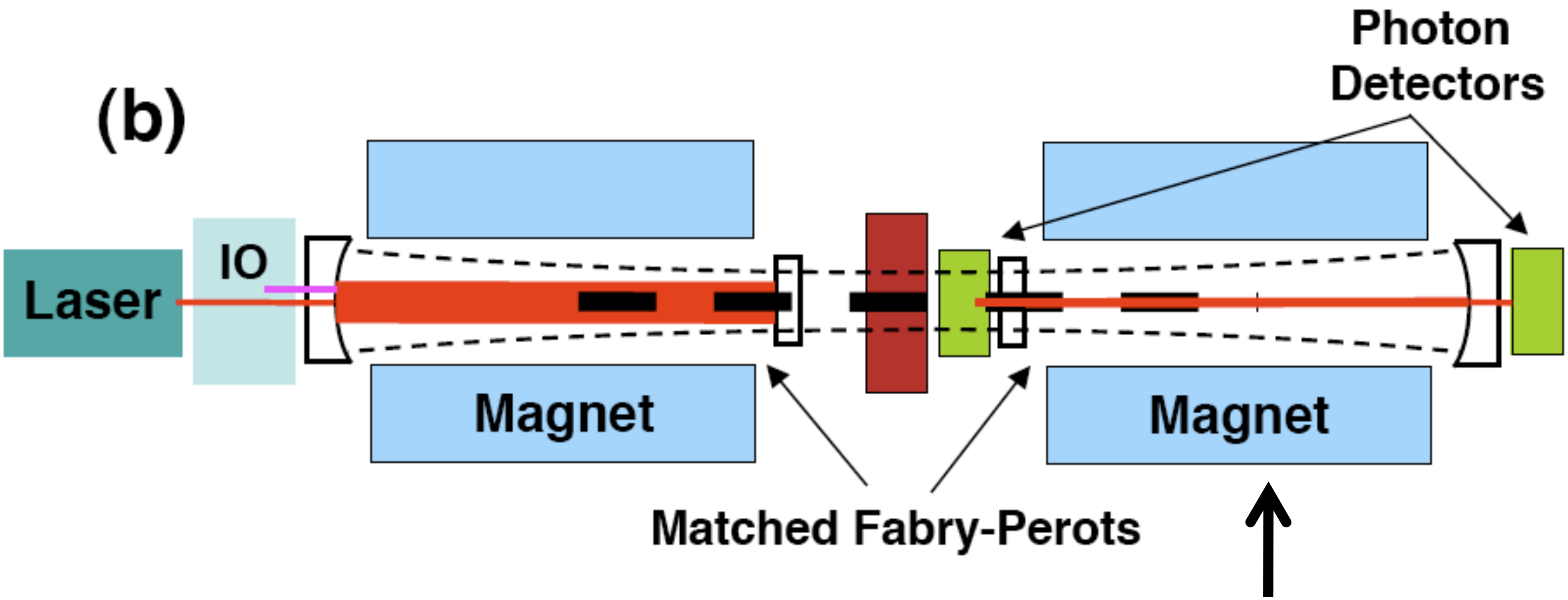
Resonant Regeneration



Cavity 1 recycles the laser beam. If the power transmission of the injection mirror is η, then the beam makes 1/η roundtrips on average.

The instantaneous power passing through the magnetic field is amplified by a factor of 1/η.

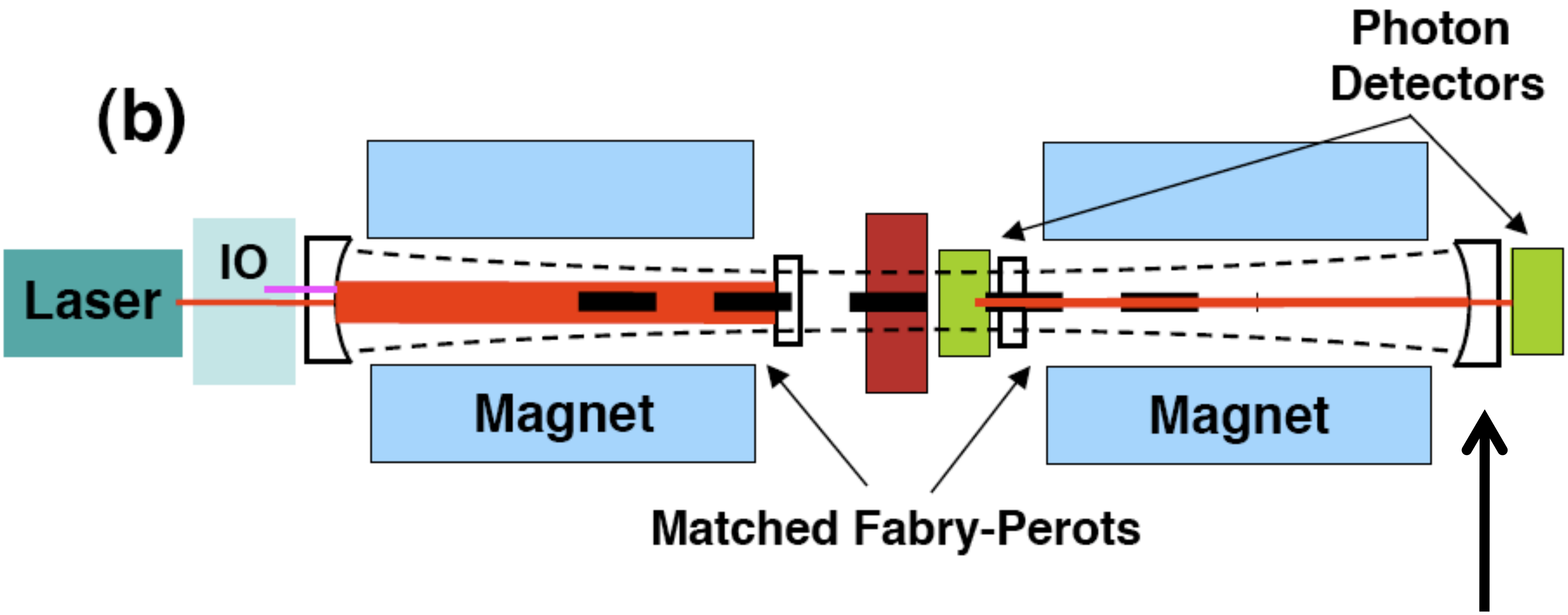
Resonant Regeneration



Cavity 2 captures the regenerated photon beam as a standing wave for $1/\eta$ roundtrips. If the two cavities are phase-locked, then the electric field of the standing wave builds up coherently over the cavity lifetime. The electric field is therefore enhanced by a factor of $1/\eta$ relative to that of a no-cavity configuration.

This coherent build-up gives a factor of $(1/\eta)^2$ in the regenerated photon population since $N \approx E^2$.

Resonant Regeneration



The regenerated standing wave is detected as it escapes the cavity through the far mirror. This escaping beam is attenuated by a factor of η relative to the photon flux bouncing around in the cavity.

The total enhancement in the event rate is:

$$(1/\eta)\times(1/\eta)^2\times\eta = (1/\eta)^2 = (F/\pi)^2$$

Resonant Regeneration baseline design

Regeneration rate:

$$\frac{dN_{\text{regen}}}{dt} = \frac{dN_{\text{laser}}}{dt} P^2_{\gamma\to\phi} \left(\frac{\mathcal{F}}{\pi}\right)^2 = \frac{dN_{\text{laser}}}{dt} \left(\frac{gBL}{4}\right)^4 \left(\frac{\mathcal{F}}{\pi}\right)^2$$

$$\frac{dN_{\text{regen}}}{dt} \approx (10^{-3}\ \text{Hz}) \times g_{10}^4 B_4^4 L_{54}^4 F_5^2 P_{10}$$

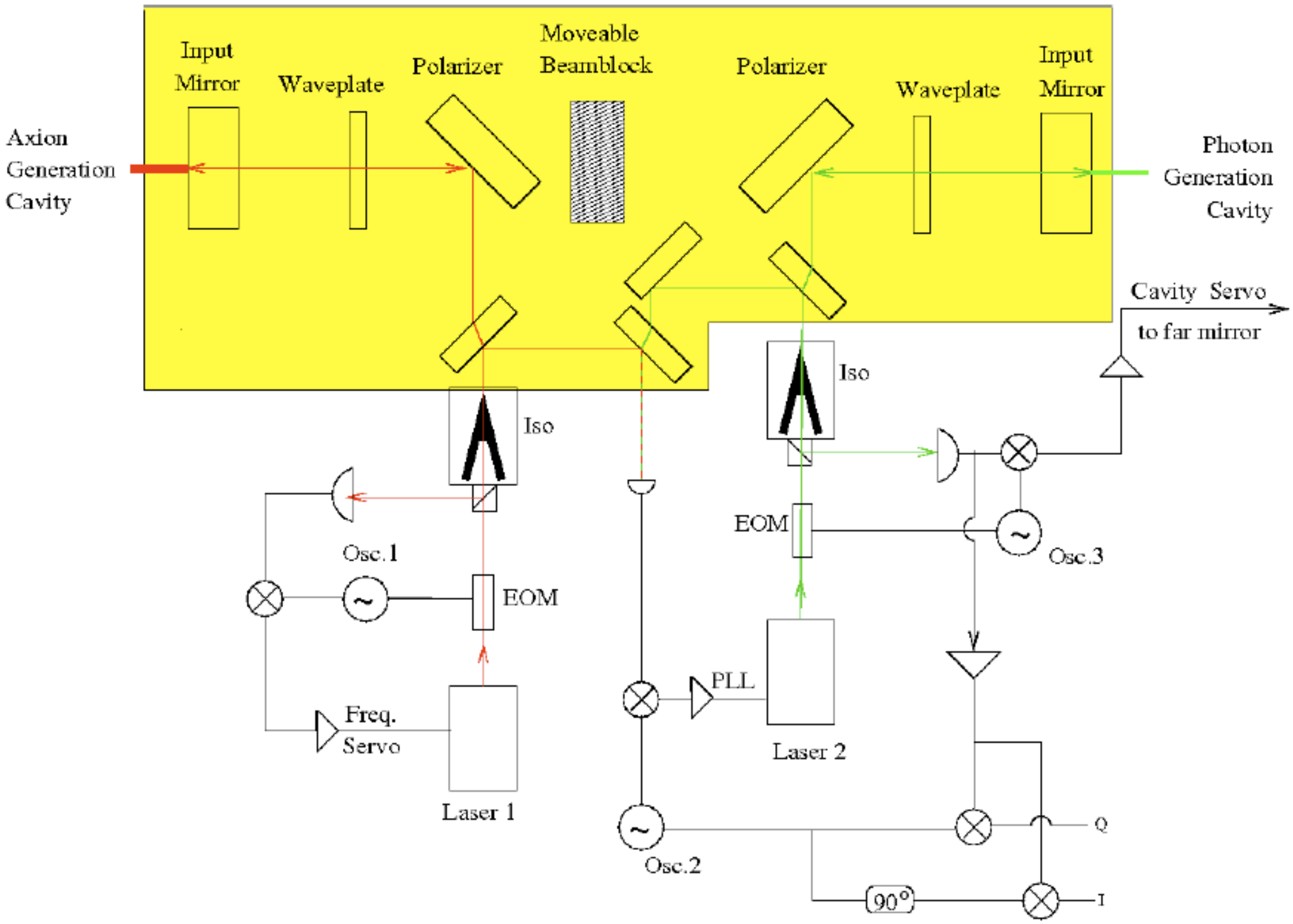
$g_{10} = g/(10^{-10}\ \text{GeV}^{-1})$, $B_4 = B/(4\ \text{T})$, $L_{54} = L/(54\ \text{m})$ (9 magnets),
$F_5 = F/10^5$, $P_{10} = P/(10\ \text{W})$

100% CL discovery at g_{10}=0.2 (3 events) in 30 days of continuous integration time if limited only by quantum zero-point background.

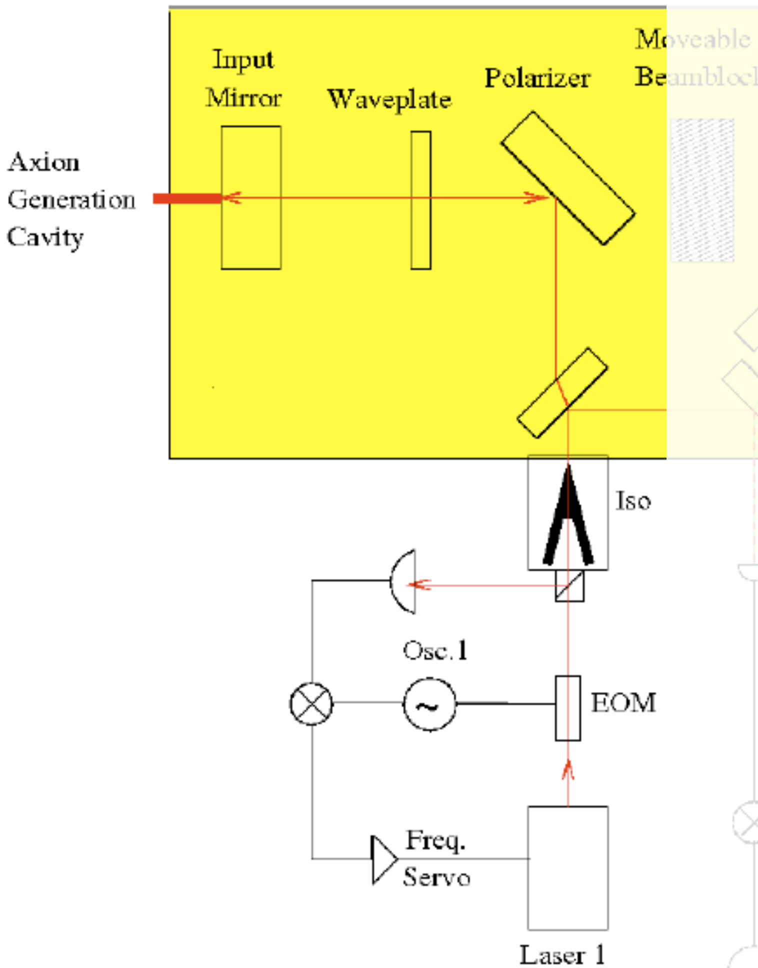
Sensitivity scaling:

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

Phase-locking and heterodyne detection



Pound-Drever-Hall Feedback:

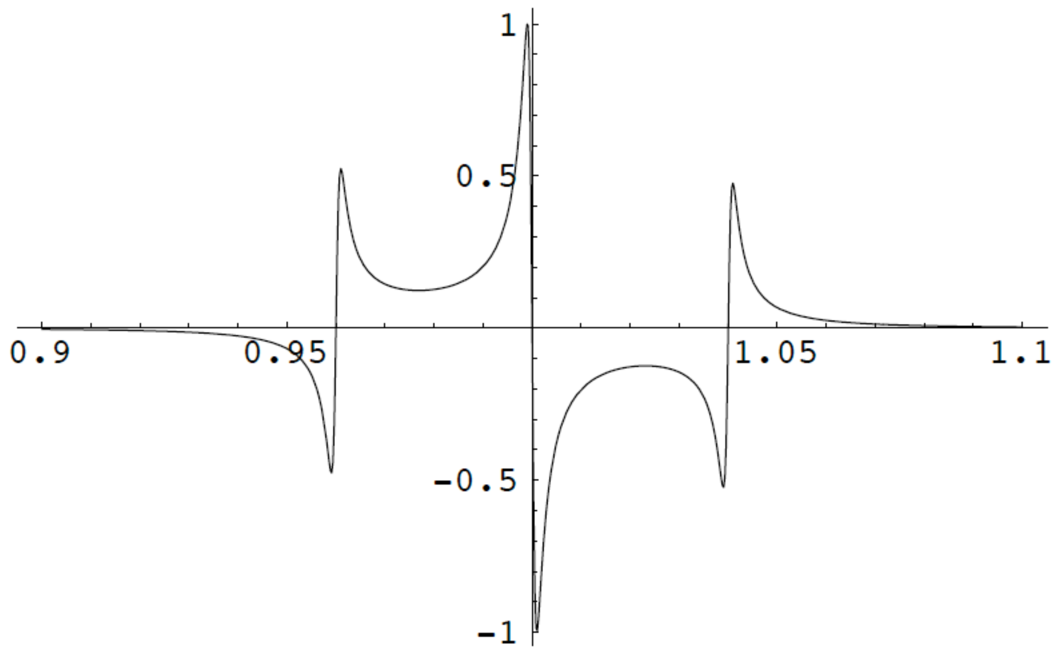


Cavity 1 is free-floating. Laser 1 is phase-modulated at some frequency which is non-resonant in cavity 1. The frequency sidebands bounce off the cavity, while the carrier frequency ω1 enters the cavity. If ω1 is resonant in the cavity then it undergoes no phase shift when it exits, and the total reflected wave is again purely phase-modulated.

If ω1 is off-resonance, then it undergoes a signed phase shift upon escaping. The initial pure phase-modulation now develops an amplitude-modulation component at the carrier-sideband beat frequency.

Pound-Drever-Hall error signal $\varepsilon = -16\sqrt{P_c P_s}\dfrac{\mathcal{F}}{\lambda}\delta L$

$\varepsilon / 2\sqrt{P_c P_s}$ (Signal at modulation frequency)

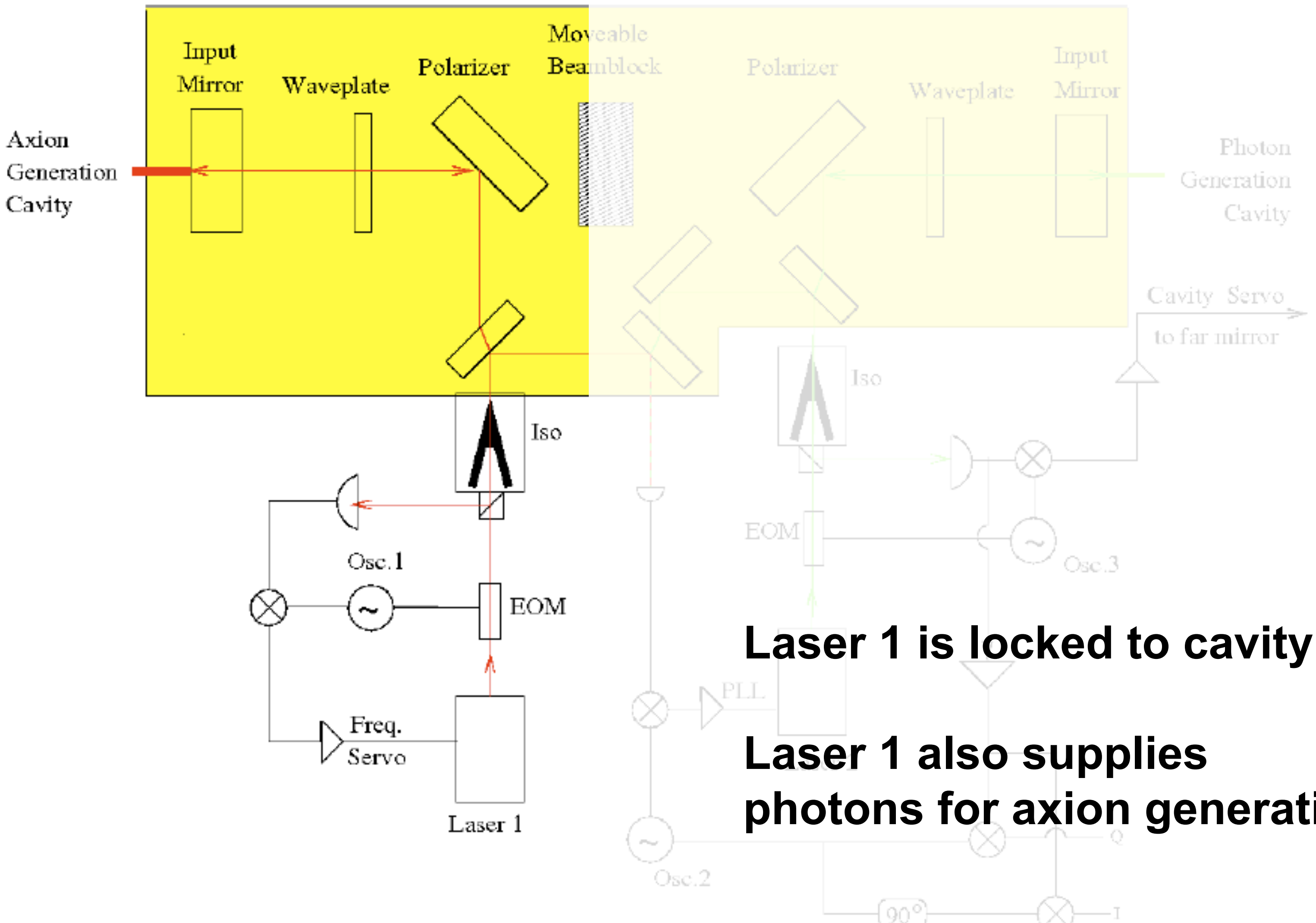


Φ (carrier phase)

This signal can be fed back into actuators which:

1) Change the laser frequency to match the instantaneous cavity length, or
2) Change the cavity length to match the instantaneous laser frequency.

Phase-locking



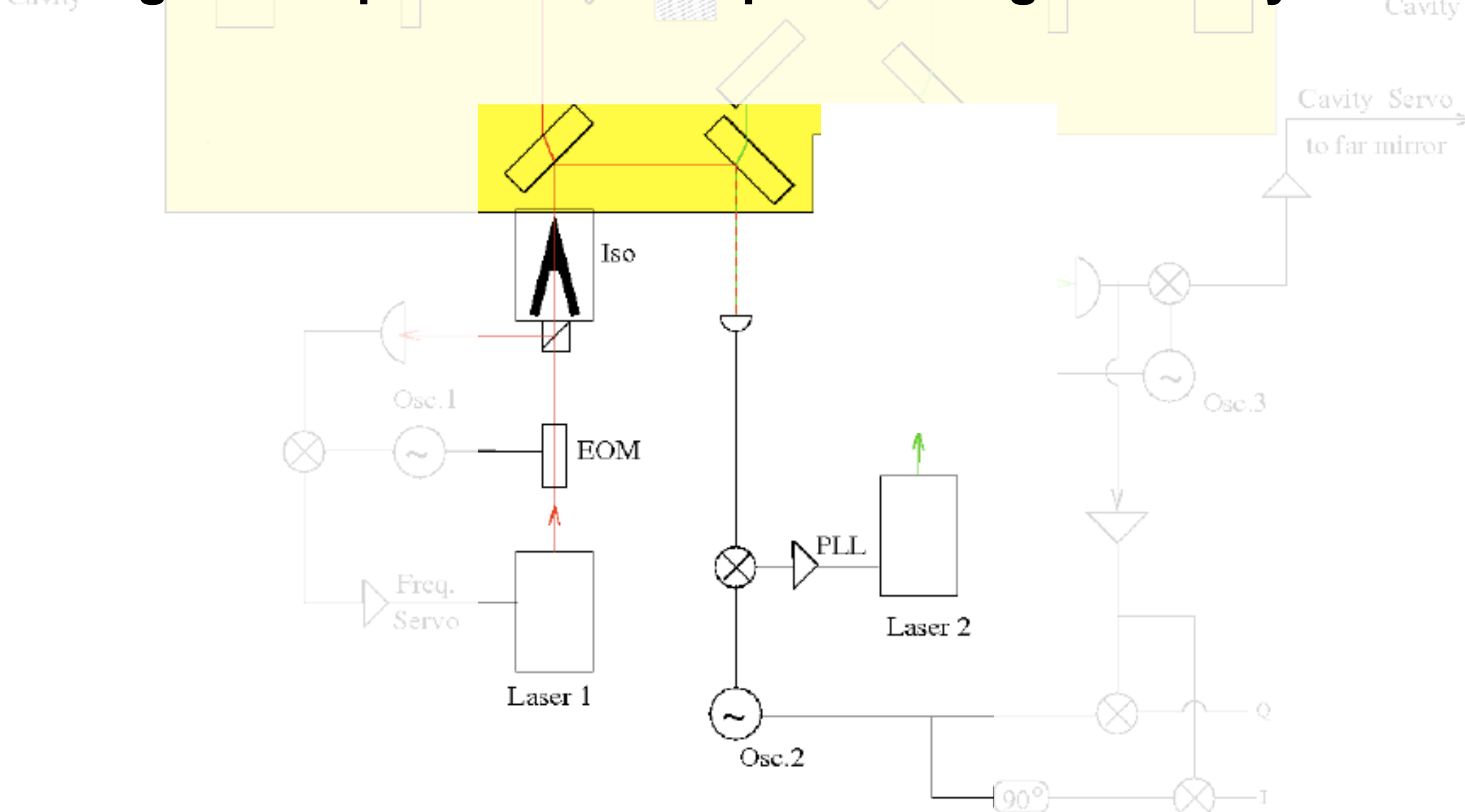
Laser 1 is locked to cavity 1.

Laser 1 also supplies photons for axion generation

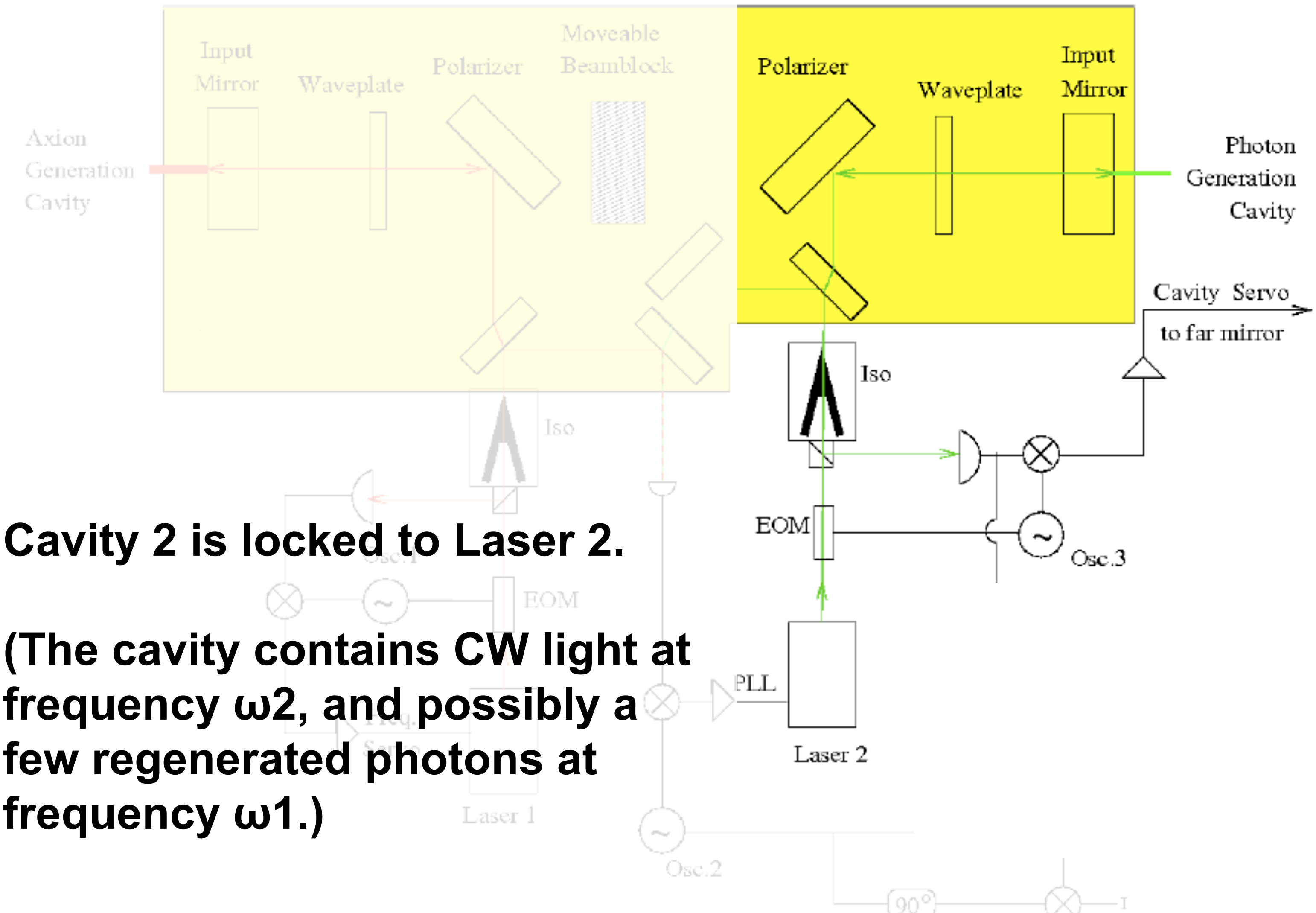
Phase-locking

Laser 2 is locked to laser 1 via a phase-locked loop.

The frequency is offset: $\omega 2=\omega 1+\Omega$ where Ω is an integer multiple of the free spectral range of cavity 1.



Phase-locking



Cavity 2 is locked to Laser 2.

(The cavity contains CW light at frequency ω2, and possibly a few regenerated photons at frequency ω1.)

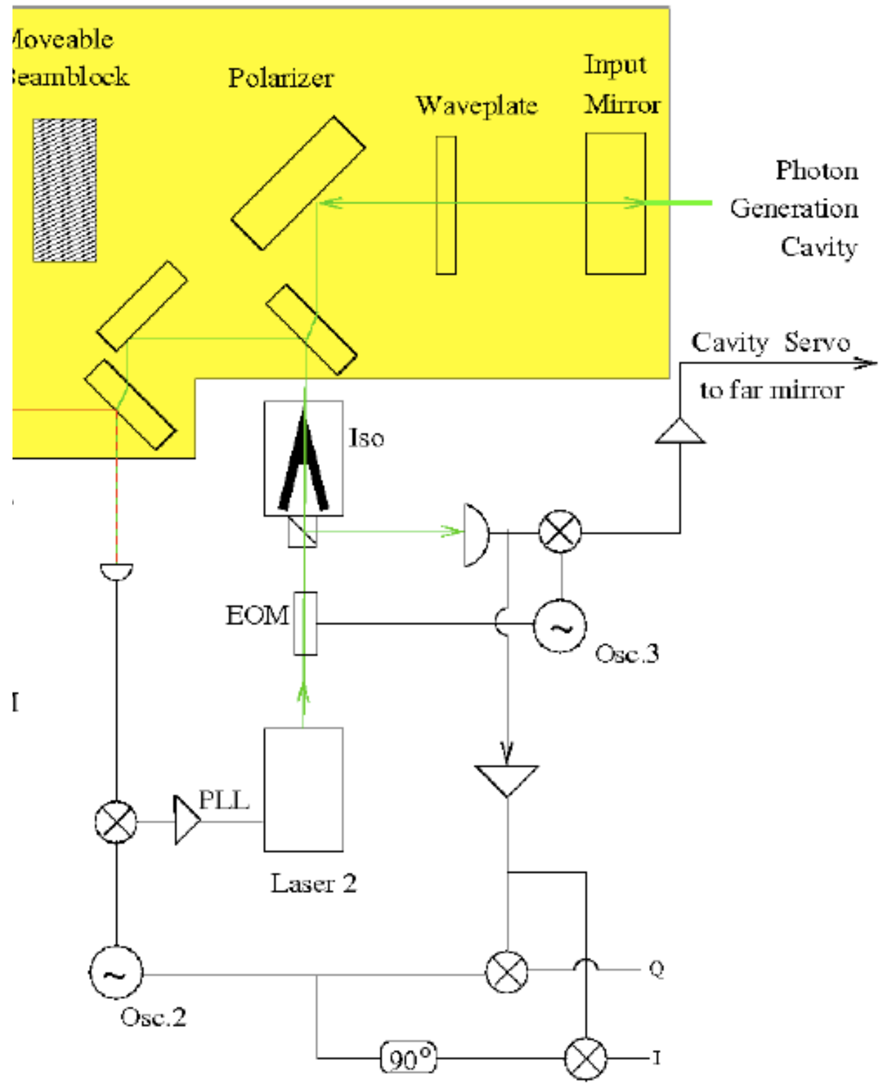
Optical heterodyne detection

Laser 2 also functions as the local oscillator (LO) for optical heterodyne detection.

The beat signal between the regenerated photons at ω1 and the local oscillator at ω2 is demodulated (or measured with an offline spectrum analysis).

The photocurrent at Ω is:

$$I_\Omega = 2\vec{E}_{\rm LO} \cdot \vec{E}_{\rm regen} \cos(\Omega t)$$
$$= 2\sqrt{\dot{N}_{\rm LO}\dot{N}_{regen}} \cos(\Omega t)$$



The signal is amplified by a huge factor by turning up the LO power!

Noise in heterodyne detection

The local oscillator power can be increased until the shot noise (intensity noise) from the LO becomes the dominant noise source.

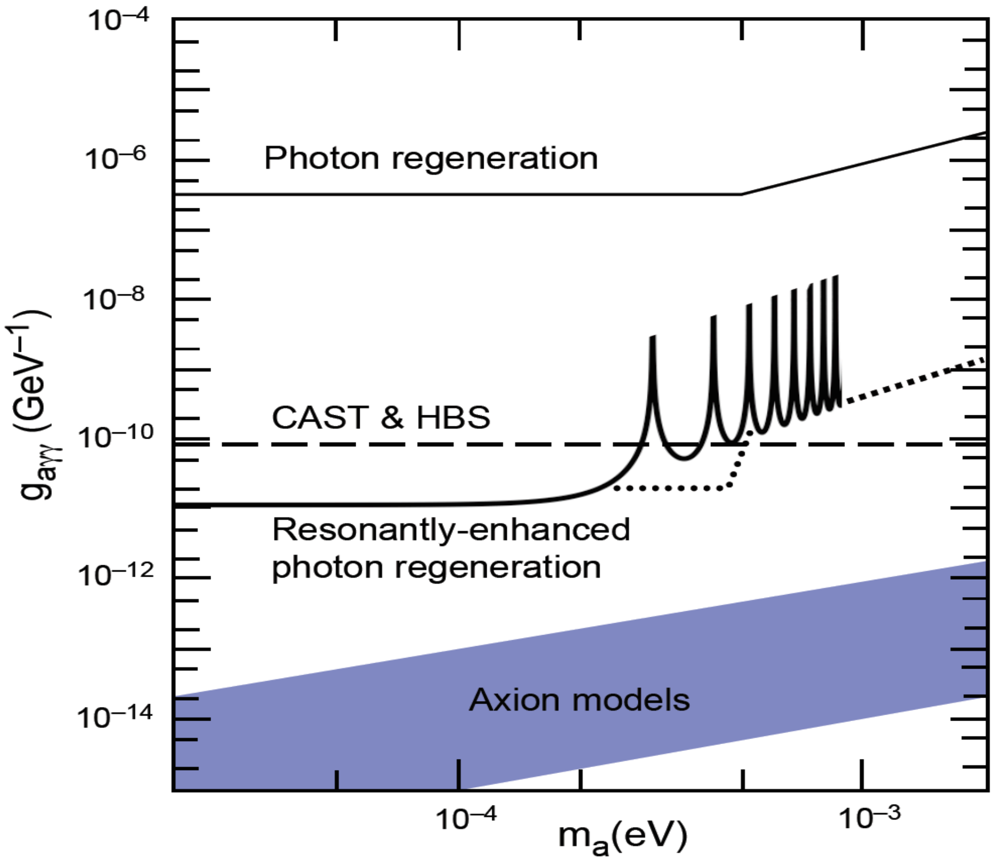
However, the heterodyne amplification factor is proportional to, and 100% correlated with the LO noise. So this dominant noise does not affect the detection of regenerated photons! A classical heterodyne system would therefore be noise-free.

However, there is also heterodyne amplification of the quantum zero-point noise. The incoming superposition of Fock states is:

$$\psi = |N_{\mathrm{LO}}\rangle_{\omega 2} + |N_{\mathrm{regen}}\rangle_{\omega 1} + |0\rangle_{\omega 2+\Omega} + |0\rangle_{\omega 2-\Omega} + \cdots$$

Each vacuum state contains ½ photon on average which are indistinguishable from the regenerated photon signal. However, the quadrature sum gives a strict upper bound of 2 zero-point photons per integration time, and **so measurement of 3 or more photons at the beat frequency Ω gives a 100%CL detection of axions.**

Potential sensitivity to photon coupling g



Baseline design with BL=180 Tesla-meters, with F=3 10^5 , P=10W, Integration time T=30 days.

Sensitivity g~10^{-11} GeV^{-1} or better with improved finesse.

Challenges:

1. Creating a clean vacuum system, 120m long
2. Operation of Tevatron magnets at a new site
3. Vibration isolation of mirrors, actuators
4. Relative alignment of dual cavities
5. Phase locking: cavity1 -> laser1 -> laser 2 -> cavity2
6. Climate control: relative phase stability of laser pathlengths
7. Controlling light leakage at the single photon level

Techniques:

1. Ultra high vacuum techniques--pumping, monitoring
2. State-of-the-art precision laser optics
3. Quantum optics: radiofrequency heterodyne detection at the quantum limit
4. Utilization of semi-classical coherent processes to probe mass scales far beyond the reach of collider experiments.

GammeV project schedule

FY2009:

1) Operate enhanced chameleon search at MTF with 1 magnet
2) Construct a tabletop prototype of the resonant regeneration optical system in order to test/validate data acquisition scheme, alignment procedure, shielding of light leakage, etc.
3) University colleagues apply for postdoc/student funding

FY2010:

1) Prepare infrastructure and run 1 magnet at E4R,
2) Construct full-scale optical system at E4R. Take paraphoton data.
3) Formal proposal of experiment.

FY2011:

Deploy full strings of magnets in E4R, commission optical system

FY2012-13:

Take axion data.

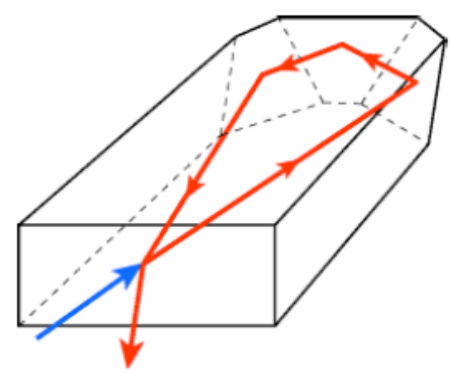
Technical issues

1064nm CW ND:YAG lasers

Lightwave NPRO 126, left over
from a previous FNAL experiment.

Innolight Mephisto ($25-50K)

Thermal tuning range: ~30 GHz
Piezo tuning range: ~100 MHz
Linewidth ~ kHz



FSR of a 50m cavity = 3 MHz
→ Choose LO frequency offset Ω=9 MHz, well within tuning range

The E4R Lab

This was the test area for SSC magnets. A satellite refrigerator + helium transfer lines already exist at one end of a 120m long tunnel. (Share cryogenics with Henryk Piekarz's rapid cycling SC magnet test?)

A large "clean," climate-controlled room in the central area was constructed for a previous light-on-light scattering experiment. This is connected to office space in a neighboring trailer.

The climate-controlled area will need to be extended to the ends of the tunnel in order to avoid day-night thermal contractions of the apparatus.

Safety issues:

The entire lab space will need to have a safety evaluation, including high voltage, cryogenic safety, and laser safety-interlocked entrances.

Operating Tevatron magnets at E4R

R. Hanft, May, 2008

Not Now Installed TB Dipoles
396 Installed in Tevatron in Collider Mode

Ready-to-Use Grades A,B,C	Ready-to-Use Grades D,M	Easy Repair Grades A,B,C	Easy Repair Grades D,M	Hard Repair Grade indicated
TB0701	TB0269	TB0373	TB1198	TB0841 (A)
TB0532	TB0413		TB0295	TB0207 (C)
TB1136				TB0378 (C)
TB1195				TB0334 (B)
TB1215				TB0332 (C)
TB0271				TB1107 (A)
TB1063				TB0324 (C)
TB0744				
TB0651				
9	2	1	2	7

Not Now Installed TC Dipoles
376 Installed in Tevatron in Collider Mode

Ready-to-Use Grades A,B,C	Ready-to-Use Grades D,M	Easy Repair Grades A,B,C	Easy Repair Grades D,M	Hard Repair Grade indicated
TC0777	TC0401	TC1146	TC1047	TC1052 (E)
TC0861	TC1070	TC1144	TC1077	TC0893 (B)
TC1130		TC1209	TC1022	TC0603 (C)
TC0710		TC1206		TC0496 (M)
TC0922		TC0464		
TC1207		TC0393		
TC1187		TC1222		
TC0535				
TC0525				
TC1061				
TC1184				
TC0604				
12	2	7	3	4

Many existing spare magnets in good condition.

AD has power spools which can be used as feed cans.

Existing spare components for quench protection.

The ramp rate can be arbitrarily slow to protect the magnets.

Afterwards, the goal is to continuously operate for the longest possible continuous integration time.

Number of magnets per string (2 strings total)

To reach the target 180 T-m per string, we can use:

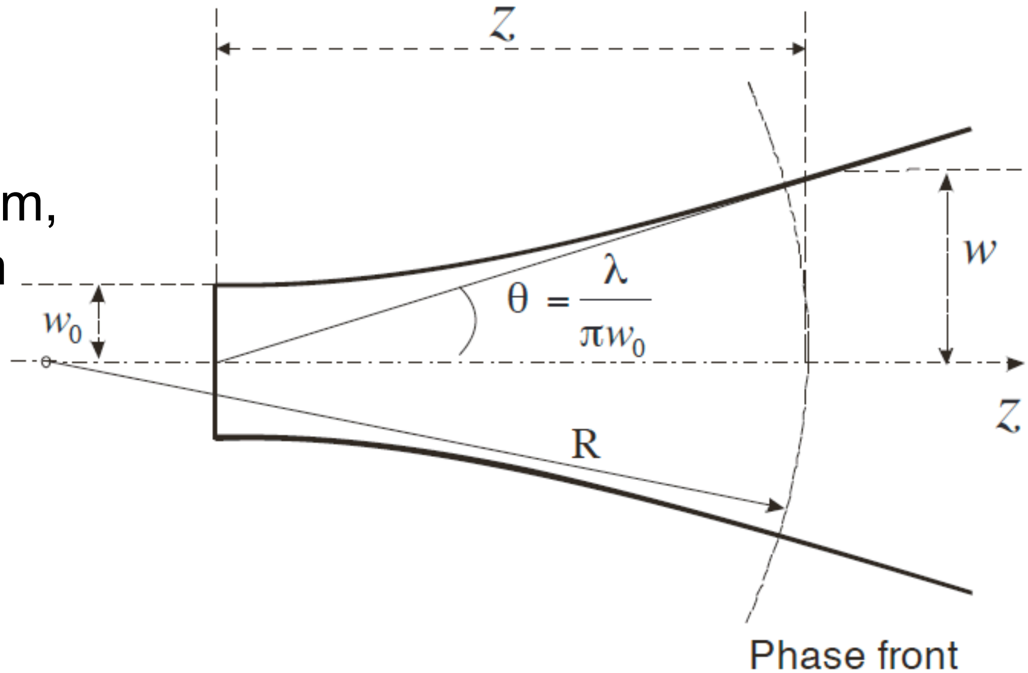
6 magnets at 5.0T or
7 magnets at 4.3T or
8 magnets at 3.75T

However we will run into aperture problems with longer strings, so running at higher field is preferable.

Gaussian optics in the cold bore

$$w_0 = \sqrt{\frac{L\lambda}{2\pi}}$$

For L=100m,
w_0=4.0mm



$$w(z) = w_0\left[1+\left(\frac{2z}{L}\right)^2\right]^{1/2}$$

w=5.6mm

Due to the transverse size of the cavity mode, the finite 5 cm inner diameter of the cold bore (+ the 0.22” sagitta) will limit the maximum cavity length.

By using the full aperture of the cold bore, we can minimize cavity losses due to beam clipping, and also take advantage of cryopumping.

Spool piece for intercavity optics

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.

Vacuum system

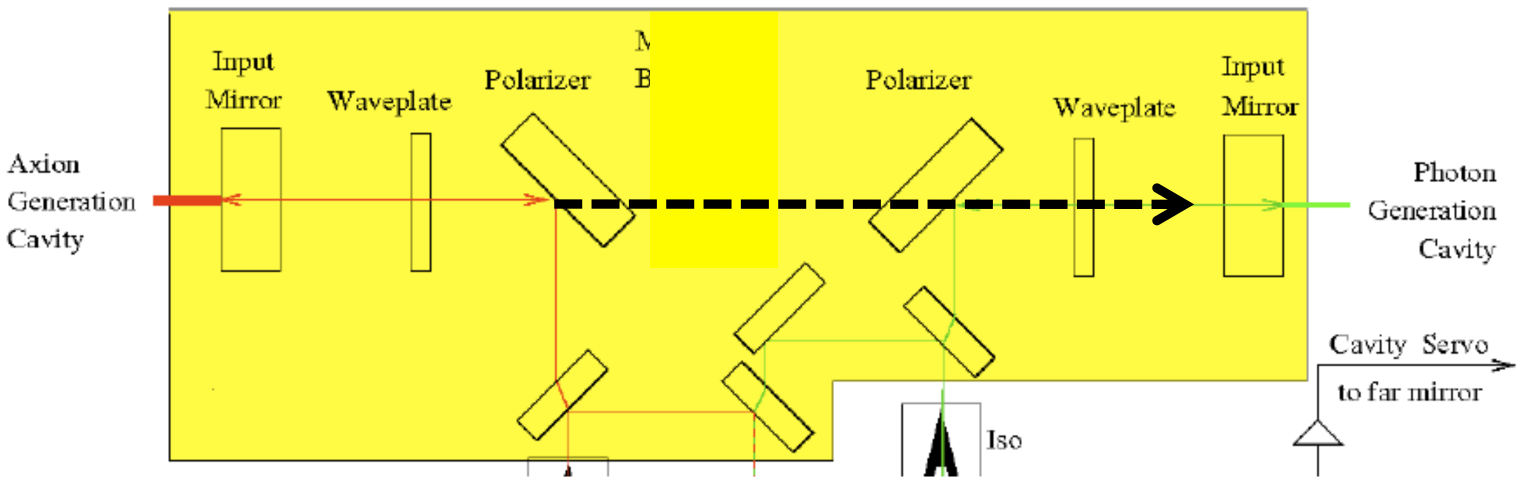
High finesse cavities should be operated at pressures $P<10^{-8}$ Torr to avoid index of refraction fluctuations in the optical path.

Backstreaming of pump oil onto the optics must be avoided due to high CW power ~ 10^5 W incident on each mirror.

Stage 1: Teflon-lubricated scroll pump + turbo pump
Stage 2: Ion pump (will this plate titanium on the optics?)
Stage 3: Ti sublimation pump + Cryopumping using the cold bore.

Small glow of photons from the ion pump and cold cathode pressure gauge is white noise, and be negligible in the frequency bins of interest. The ion pump can also be valved off after reaching its saturation pressure.

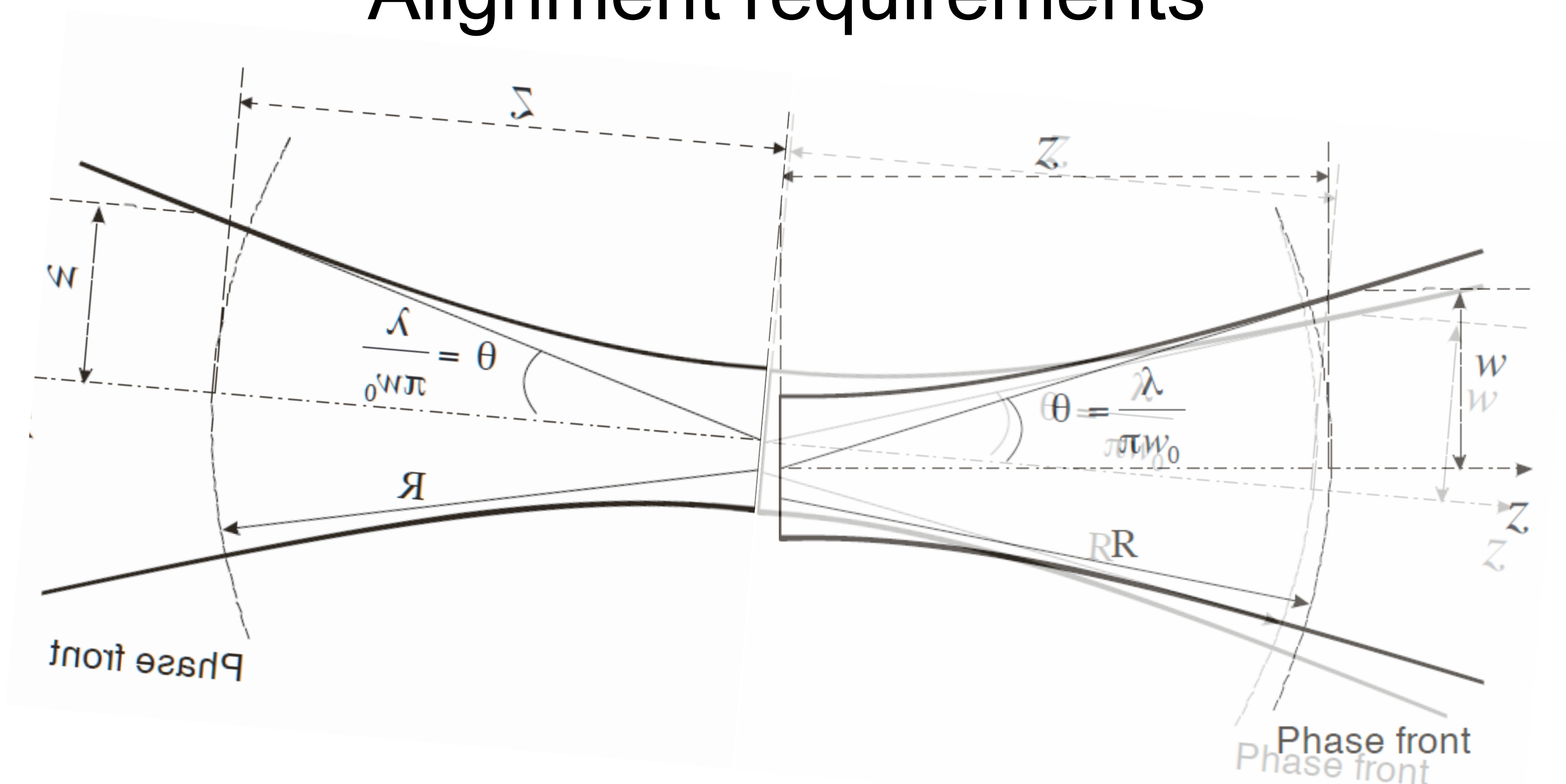
Alignment + DAQ test done by removing wall



The removal and re-insertion must not affect the optical alignment!

But the optical seal must also be tight enough that no photons at frequency ω1 leak through during the entire integration time when taking axion data. Also, no scattered light should get through via whatever circuitous path it may take.

Alignment requirements



For efficient population of the cavity 2 standing wave, the Hermite-Gauss transverse wavefunction of the axion beam must have significant overlap with the H-G profile of cavity 2. (H-G are orthogonal eigenfunctions.)

For a 5mm radius mode,
a 95% overlap requires transverse offset $dx<1.25$ mm
and misalignment angle $d\alpha<20$ μrad.