Optical Bifurcation in the Limit of Photon Statistics ICHEP2016

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Overview

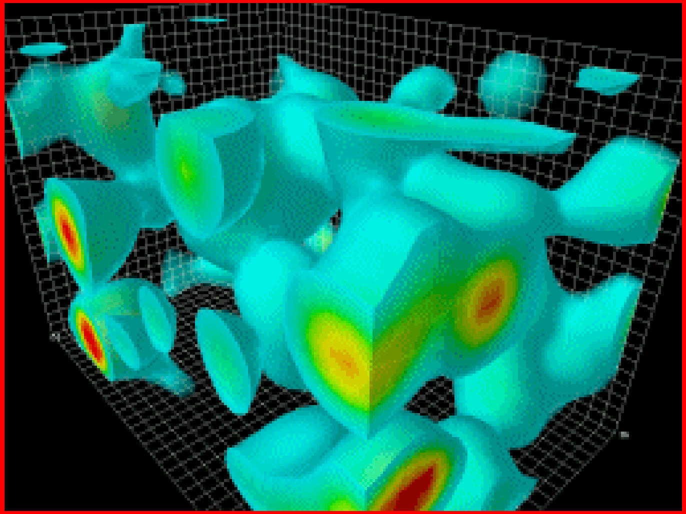
- Motivation for Axions and Axion Like Particles
- Methods to search for Axions
- Induced splitting creating Bifurcation
- Shifting in a cavity
- Limit of photon statistics – random walking starts
- Summary/Future

QCD Vacuum

- QCD Lagrangian contains CP Violating term. However strong interactions conserve CP symmetry:

$$L = \Theta \frac{\alpha_s}{8\pi} A^{uva} \tilde{A}^{a}_{uv}$$

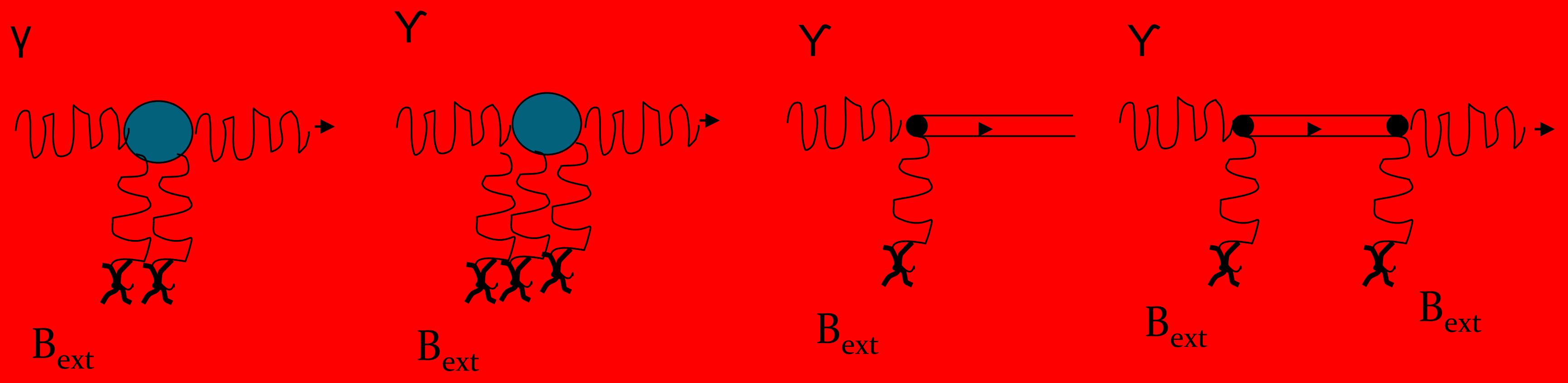
$$L = (\Theta - \frac{\phi_f}{f_A}) \frac{\alpha_s}{8\pi} A^{uva} \tilde{A}^{a}_{uv}$$



- Peccei & Quinn proposed an axion Field
- QCD ground state (A is the color field strength tensor and Ã is its dual)

The simulation shown is the work of:

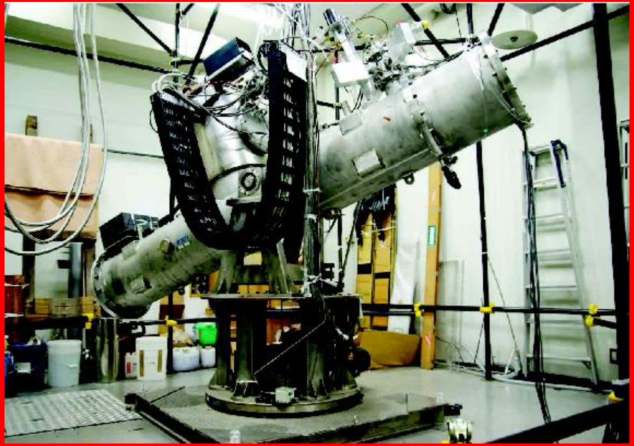
Photon Coupling to B_{ext}



- Previous searches focused on Primokoff Decays
- Diagrams: a) QED Vacuum Polarization b.) Photon Splitting c.) axion real production and d.) axion virtual production

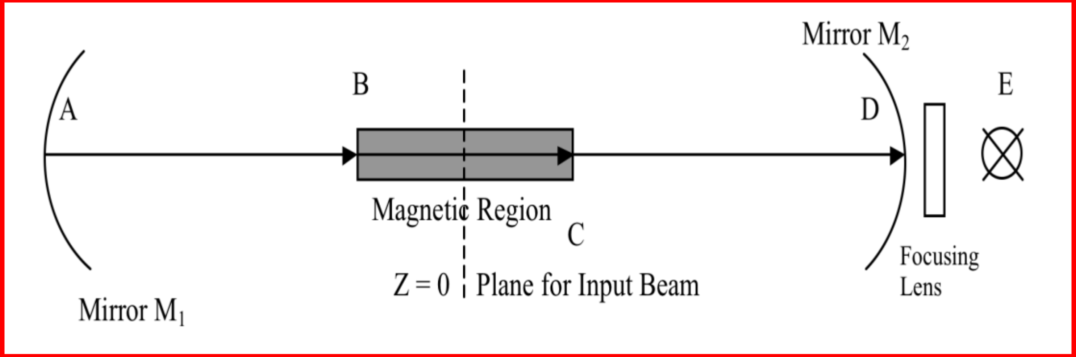
Searches To Date:

- Helioscope



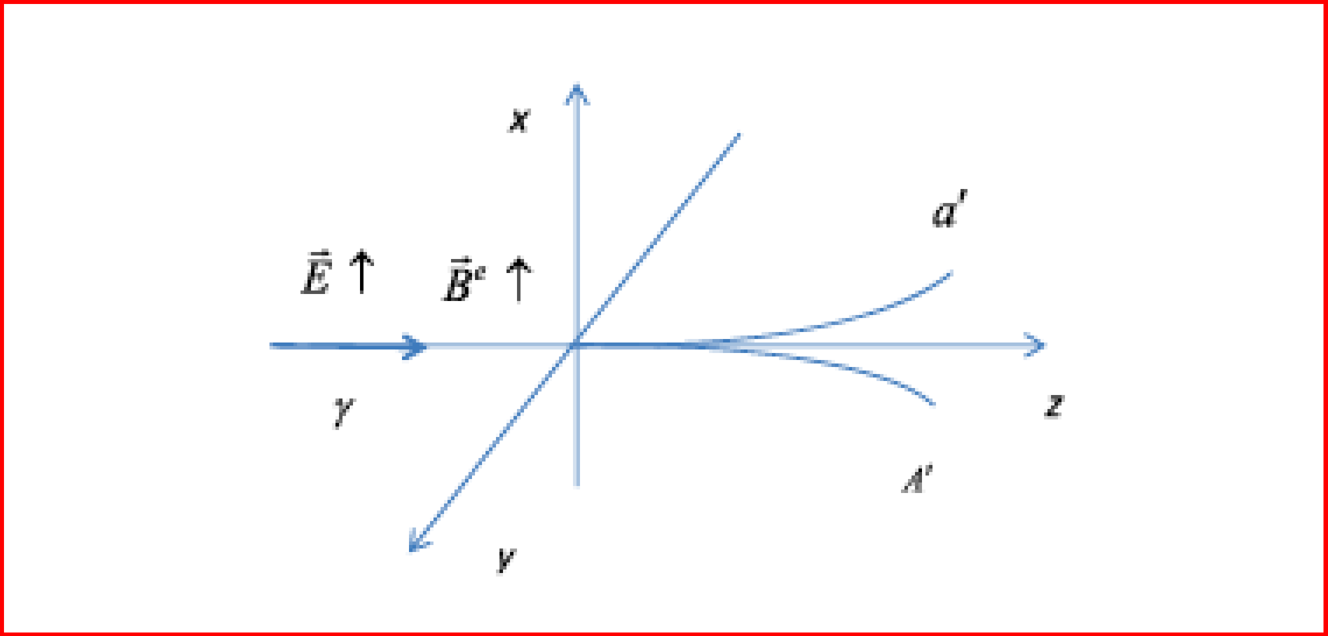
- Haloscope

- Cavity Regeneration & Vacuum Birefringence



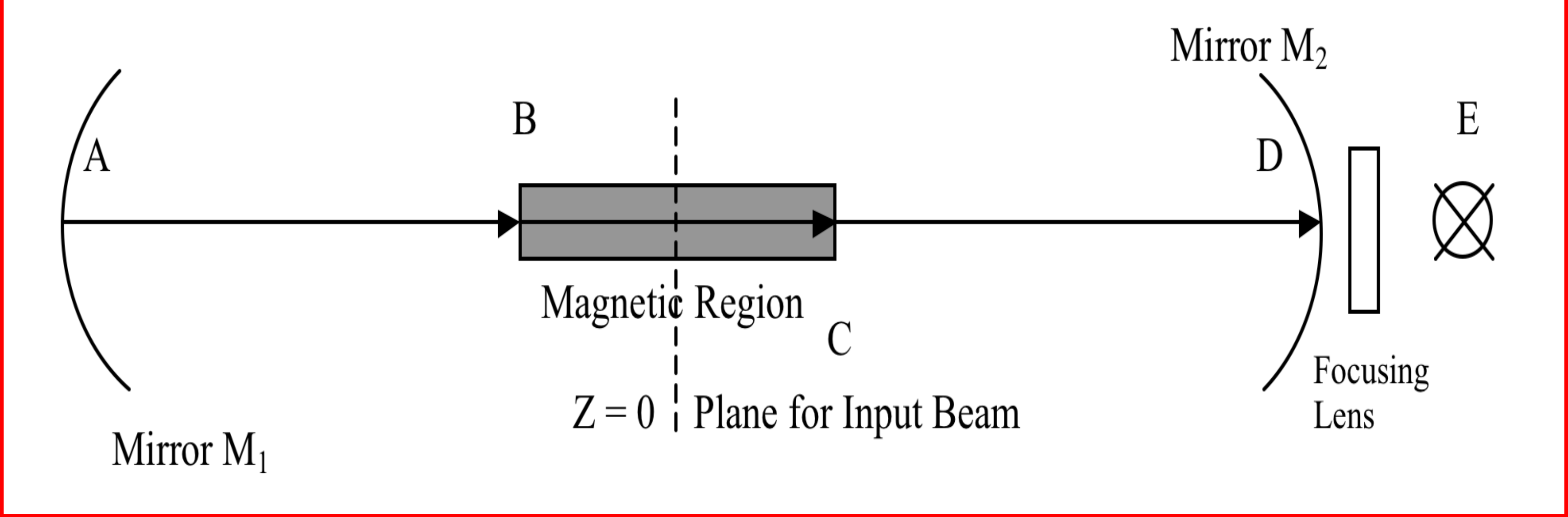
Axion Coupling to Photons

- In an inhomogeneous magnetic field axions-photon coupling leads to the formation of a particle/antiparticle state which causes the beam to split in two



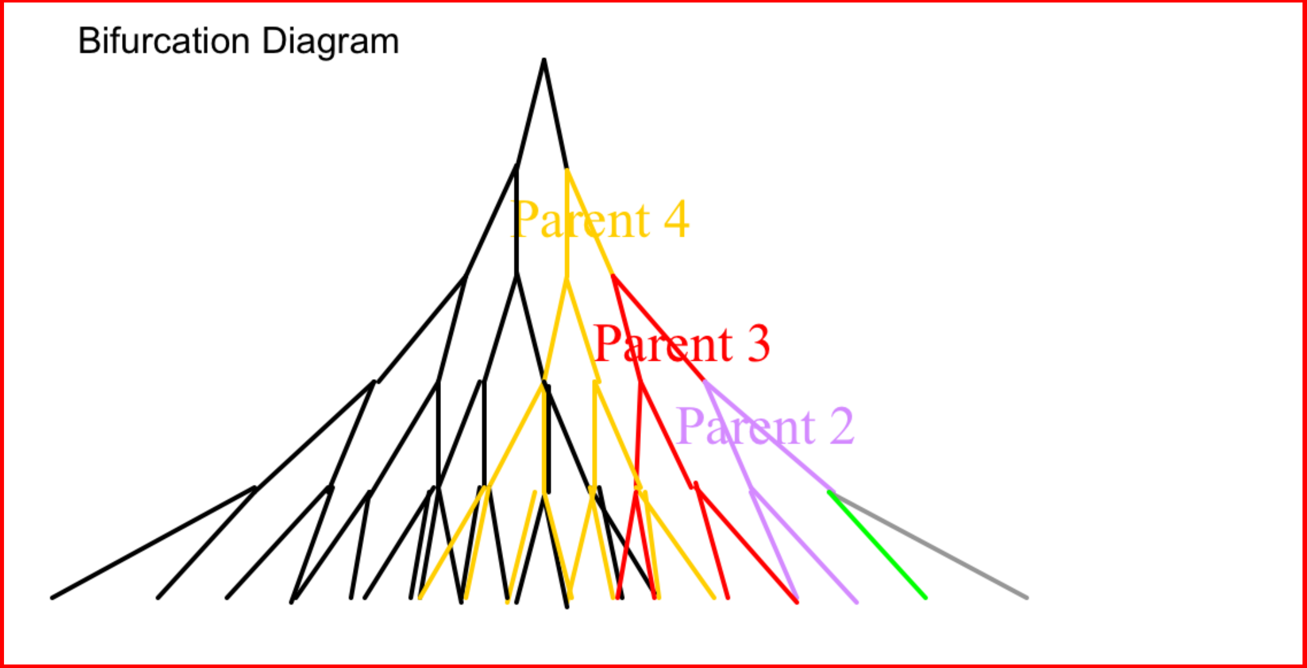
Mirror Cavity Experiments

- Consider the mirror cavity shown below
- To counter the natural divergence of the beam a stable cavity can be constructed using concave mirrors



In A Mirror Cavity

- In a mirror cavity reflection destroys the coupled state
- The returning beams re-couple to axions and continue to split with each entry into the field (each reflection)



Modeling Splitting

- Jones matrices were used to track the photons through the cavity they are defined as follows:

Focusing: $$\begin{bmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{bmatrix}$$

Propagating: $$\begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$$

Splitting: $$\begin{bmatrix} 1 & 0 \\ \frac{\pm \theta_{split}}{X_0} & 1 \end{bmatrix}$$

Intensity Changes

- Assuming an initial gaussian distribution, the changes in the beam profile due to splitting as a function of position relative to the center of the beam can be calculated:

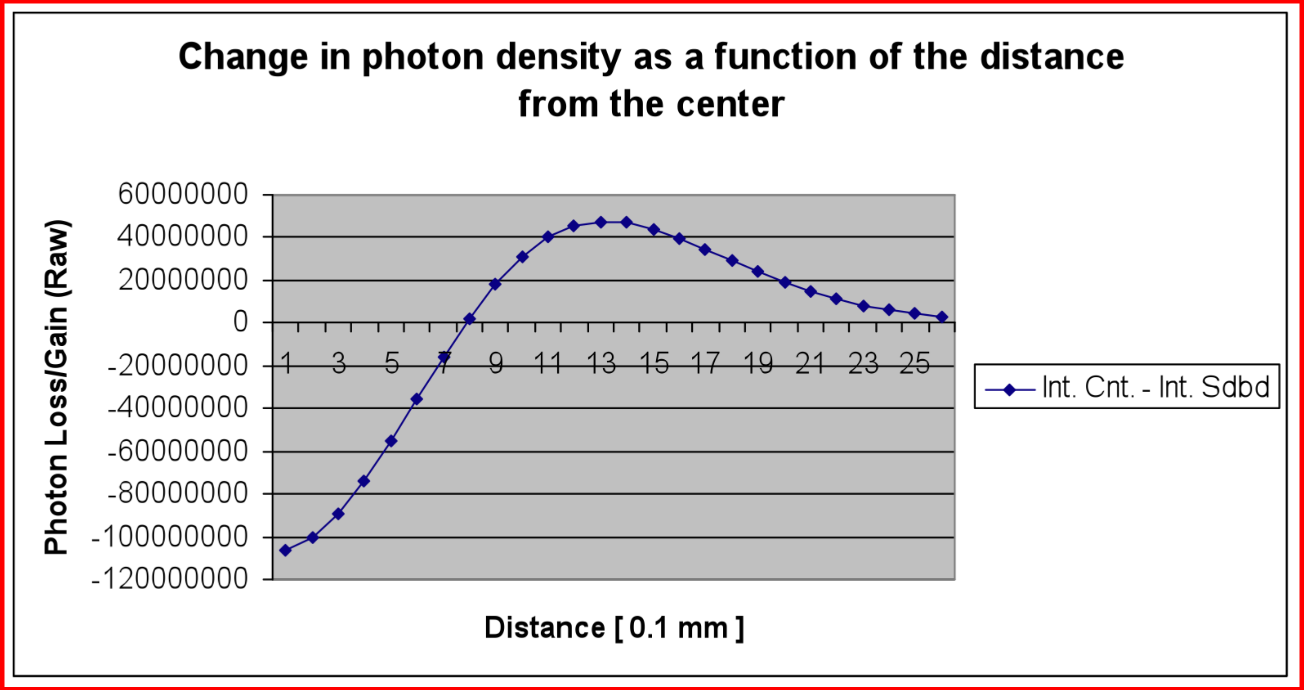
$$P_D = Ae^{-\frac{1}{2}\cdot\frac{x^2}{r^2}}$$

$$P_D'' + P_D' \approx A \cdot \frac{r-\varepsilon}{r} e^{-\frac{1}{2}\cdot\frac{x^2}{r^2}} \cdot e^{+\frac{x^2}{r^2}\cdot\frac{\varepsilon}{r}} \cdot e^{-\frac{\alpha^2}{r^2}} \cdot \cosh\left(\frac{x^2}{r^2}\cdot\frac{\alpha}{x}\right)$$

$$P_D - (P_D' + P_D'') \approx Ae^{-\frac{1}{2}\cdot\frac{x^2}{r^2}}\left[1 - \frac{r-\varepsilon}{r} \cdot e^{+\frac{x^2}{r^2}\cdot\frac{\varepsilon}{r}} \cdot e^{-\frac{\alpha^2}{r^2}} \cdot \cosh\left(\frac{x^2}{r^2}\cdot\frac{\alpha}{x}\right)\right]$$

Central Depletion

- The splitting leads to a drop in the central intensity accompanying an increase in the intensity of the sidebands



Real Parameters

- For actual experiments involving cavities there are stability condition

Cavity Type	Cavity Length	Magnetic Field Length	∇B Strength	Laser Wavelength	Laser Energy	Mirror Radius	Number of Bounces	$\theta_{split} \sim 10^{-10}$ ($g_a = 10^{-6}$)	Injection Angle
Confocal	14 m	10 m	200 T/m	1064 nm	1 W	25 m	$1.2 \cdot 10^4$	$4 \cdot 10^{-10}$	$1.5 \cdot 10^{-2}$ rad
Convex-Concaved	14 m	10 m	200 T/m	1064 nm	1 W	25 m, -11 m	$1.2 \cdot 10^4$	$4 \cdot 10^{-10}$	$1.5 \cdot 10^{-2}$ rad
Planear-Planear	14 m	10 m	200 T/m	1064 nm	1 W	∞	$1.2 \cdot 10^4$	$4 \cdot 10^{-10}$	$1.5 \cdot 10^{-2}$ rad

- As well there are limits on the strength of magnetic fields and gradients that subsequently limit the splitting angle for a given coupling of matter to axion particles

Each Traversal

- With each traversal the splitting occurs
- The simulations allow for a numerical solution to the intensity change as a function of traversal

$$\alpha = \theta_{split} \cdot d \cdot f(n)$$

- Where θsplit gives the angle of splitting
- Where d gives the length of the cavity
- Where f(n) must be extracted

60 Traversals for a 1Watt Beam

- A 1 Watt Beam has ~ 6.25 x 10^{-18} photons
- As the beam returns with the same polarization, with each pass splitting of a single beam into two beams of roughly the same intensity must occur
- After some 60 traversals (2^{+60} distributions) the limit of splitting is reached and no new distributions can be created
- Now when a photon gains transverse momentum and moves left there is no photon moving right from the same position – the intensity changes no longer scale as a sinh(~ $\theta_i \theta^2_{split}$) function

The End Of Splitting

- To capture what happens when splitting no longer occurs, a limit was imposed on the total number of rays tracked following splitting
- Some specific scenarios were considered first

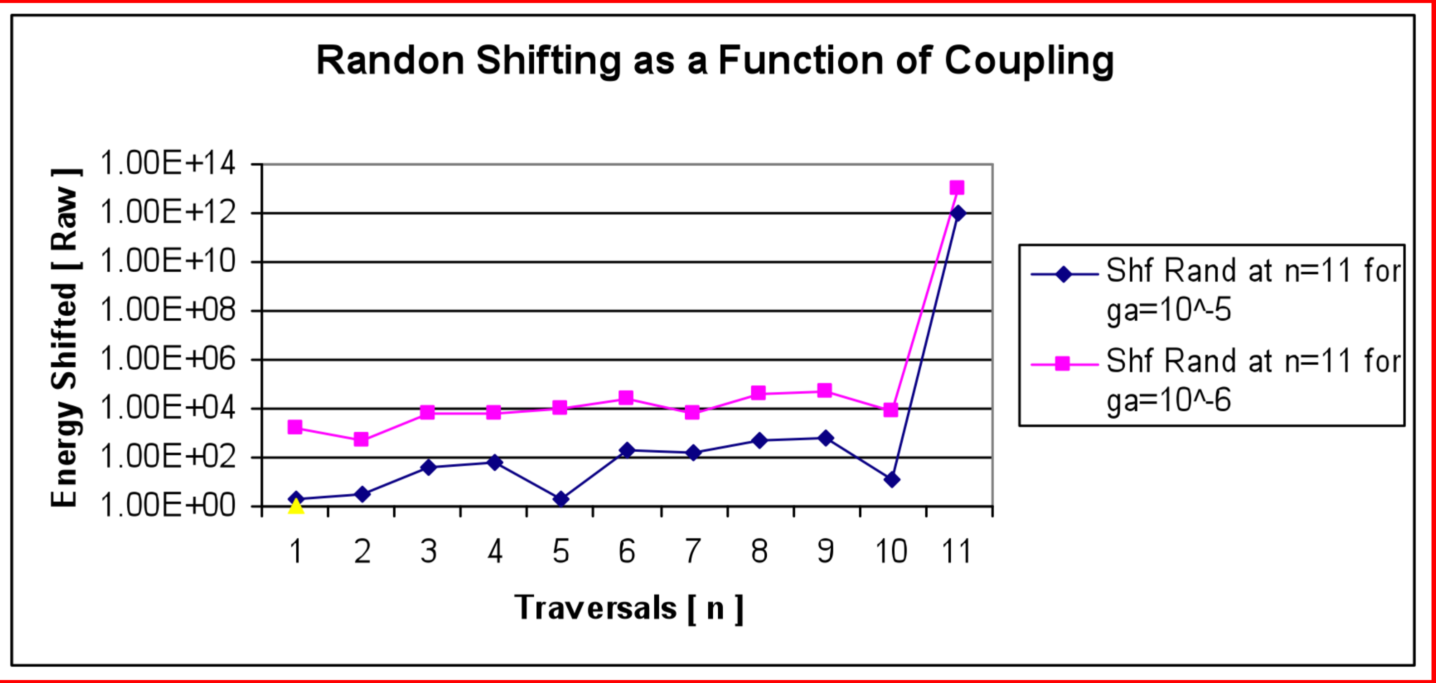
  +/- directed tracks loose/gain momentum

  Each track couples as a particle – shifts left

  Each track couples as an antiparticle – shifts right
- Each ray was given a random positive or negative shift
- Samples of 1000 randomly propagated sets of rays analyzed to understand behavior

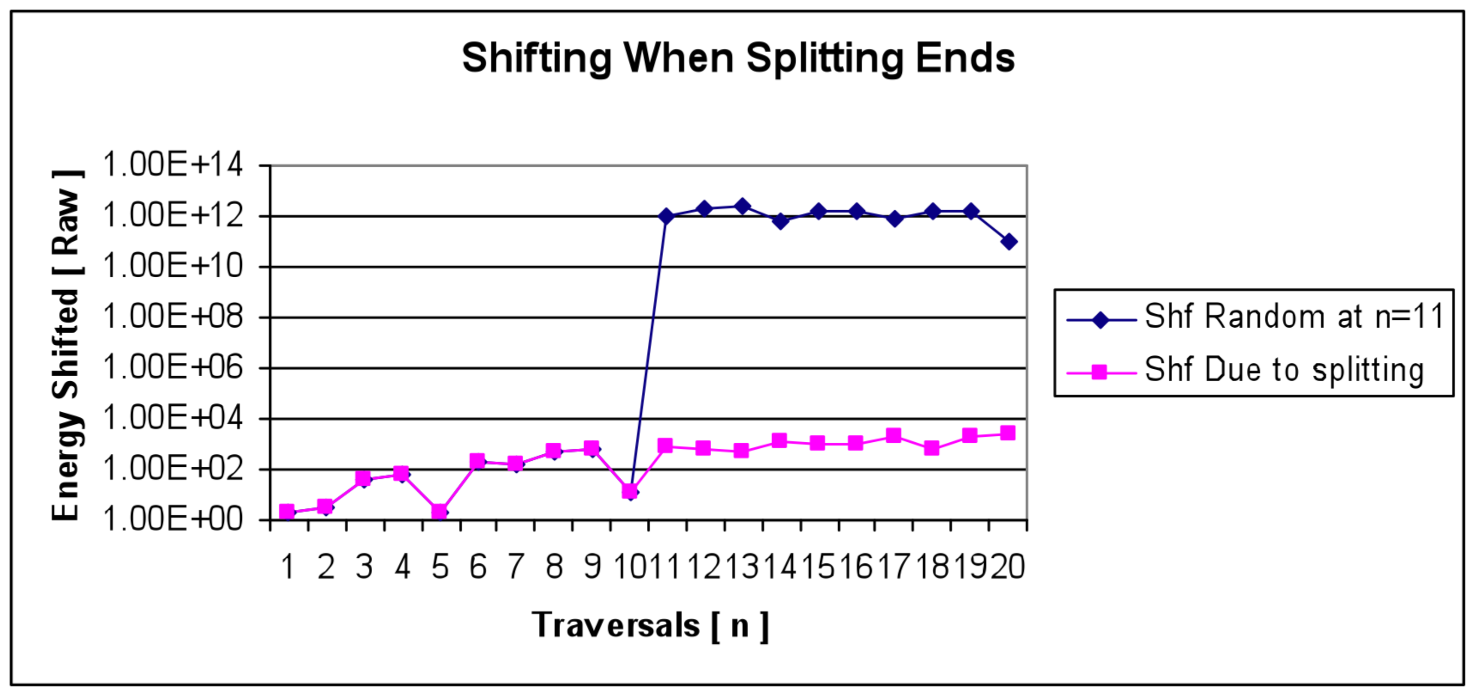
Random Change at n=11

- When the tracks are given randomly either + or – momentum at n=11



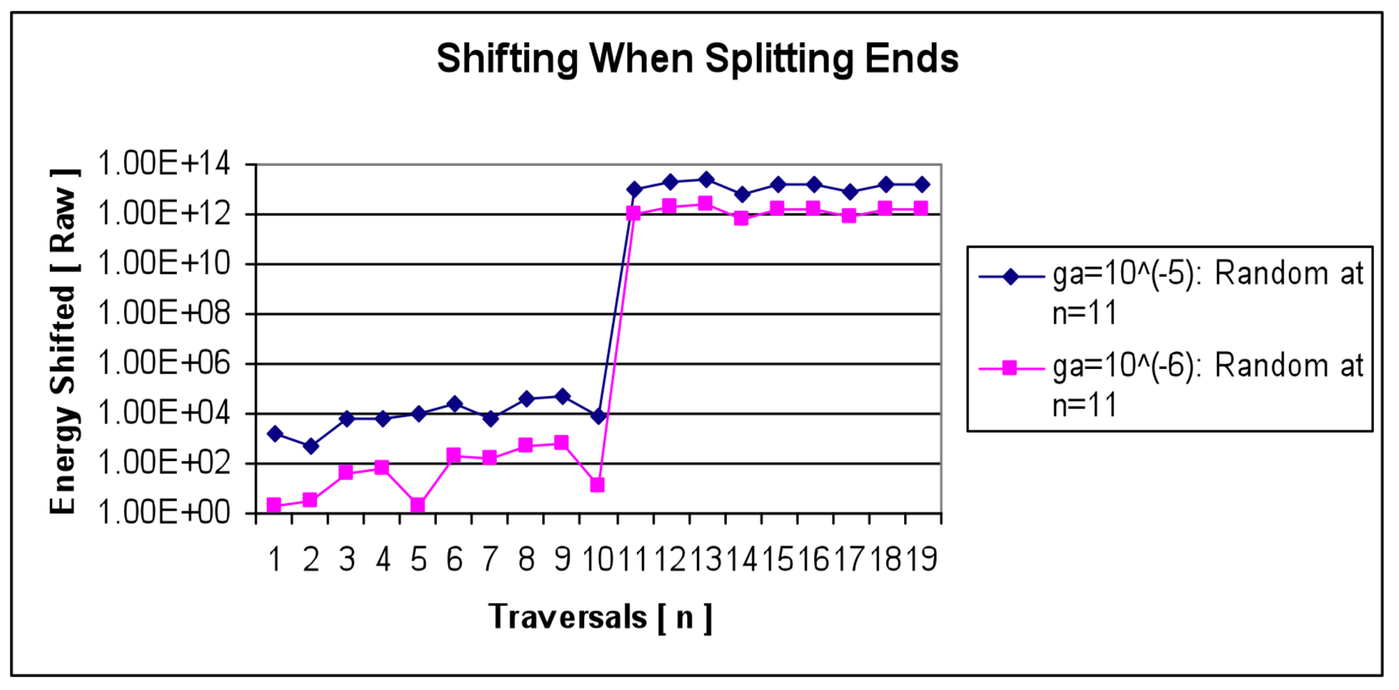
From Predicted To Random

- The continuous pattern is broken when the splitting behavior ends leading to rapidly changes



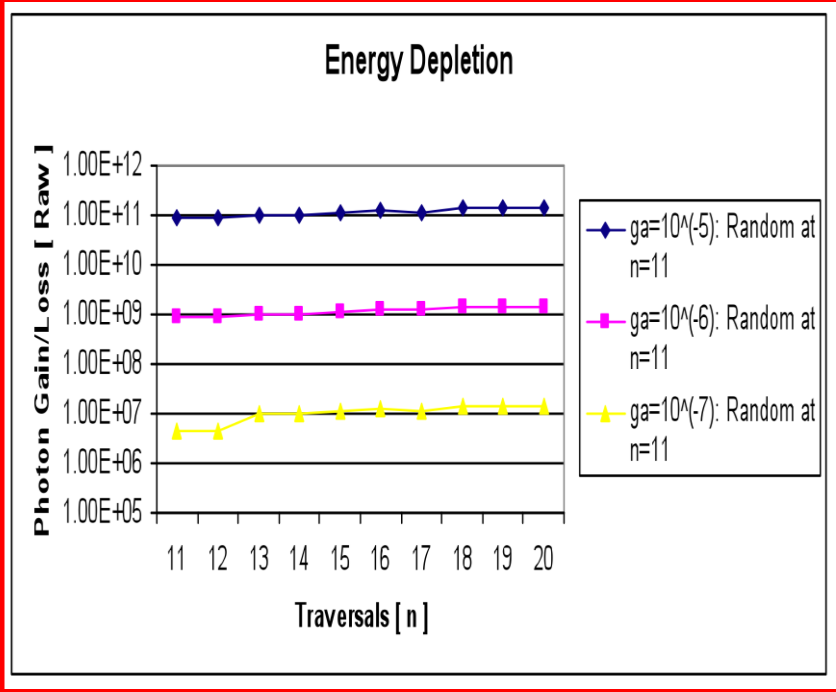
Varying Coupling

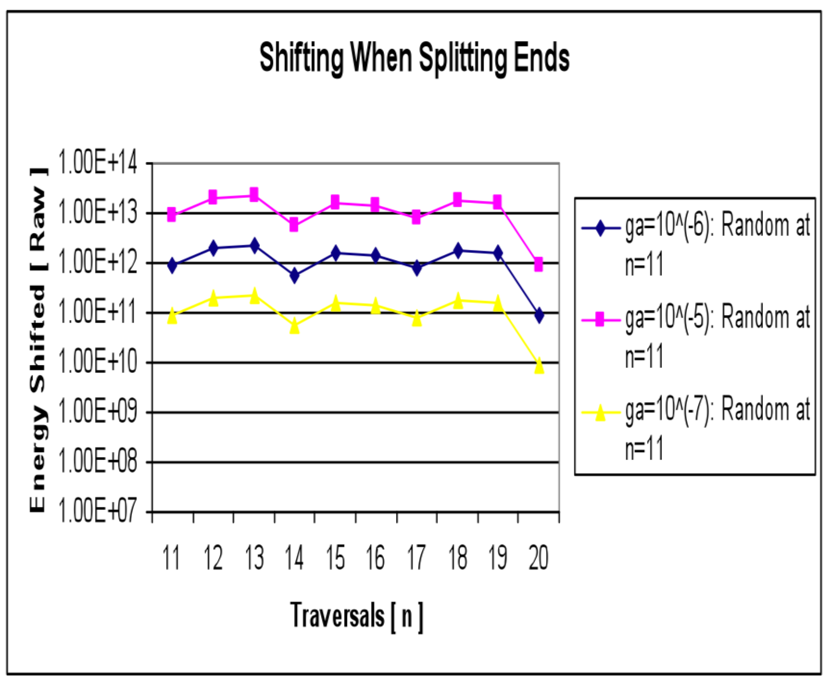
- The effect becomes linear once the limit of splitting is reached



Depletion vs Shifting

- Comparing Depletion to Shifting, when splitting stops, shows that shifting is more appropriate as coupling decreases

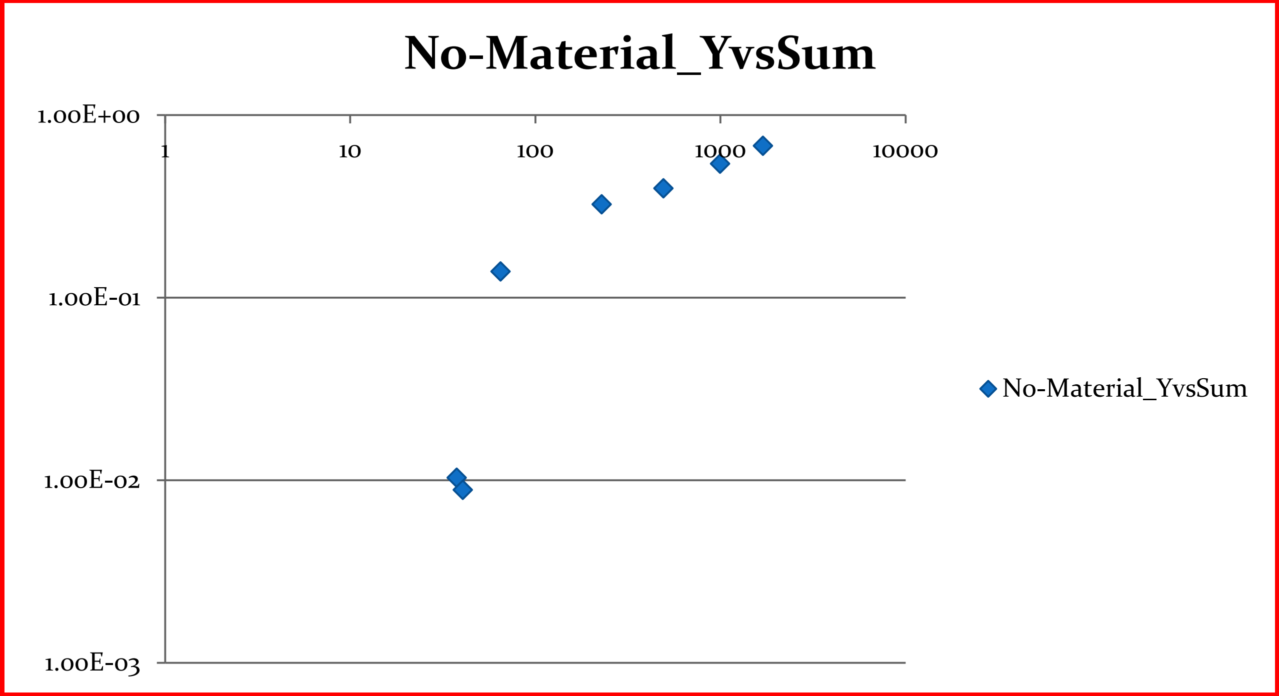




Numerical Observations

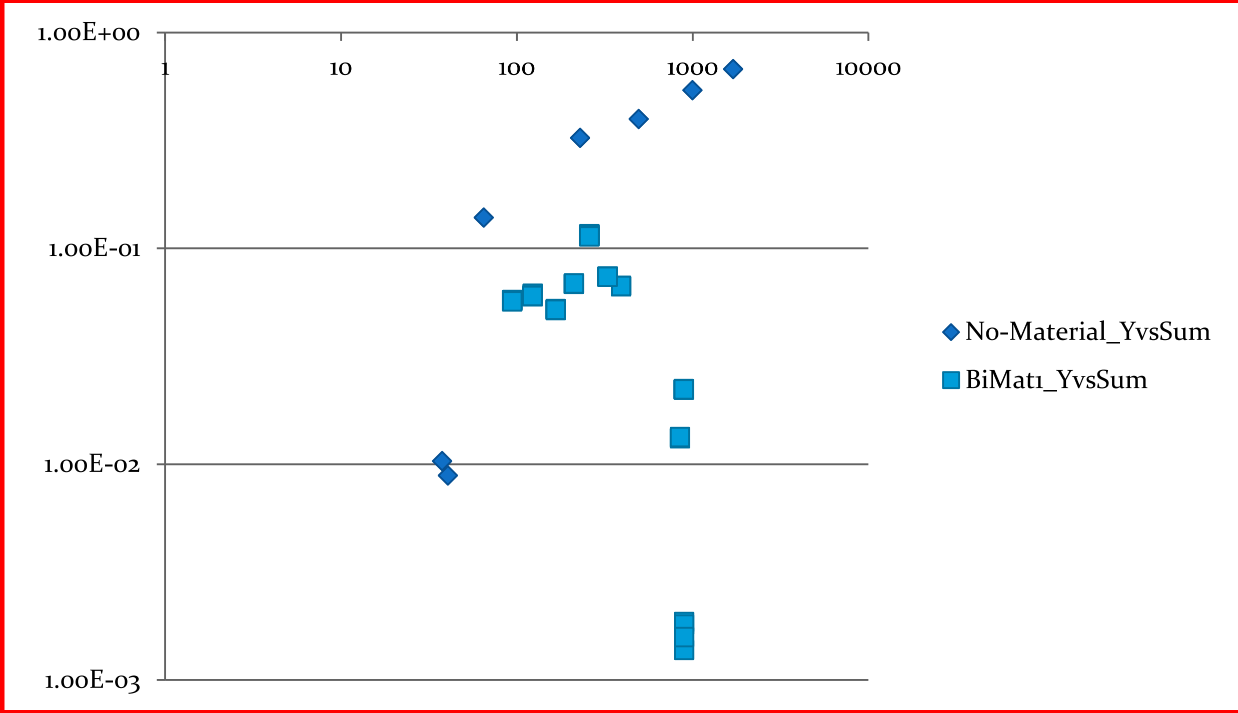
- For scenarios that shift tracks by one unit of momentum such that equal distributions of tracks gain (+) or loose (-) momentum, the overall effect is quadratic as with the splitting case
- For some random scenarios the energy shifting departs from the splitting case and gives a significant increase in left-right movement
- The large changes observed show linear behavior with respect to coupling strength

Birefringent Microscopy



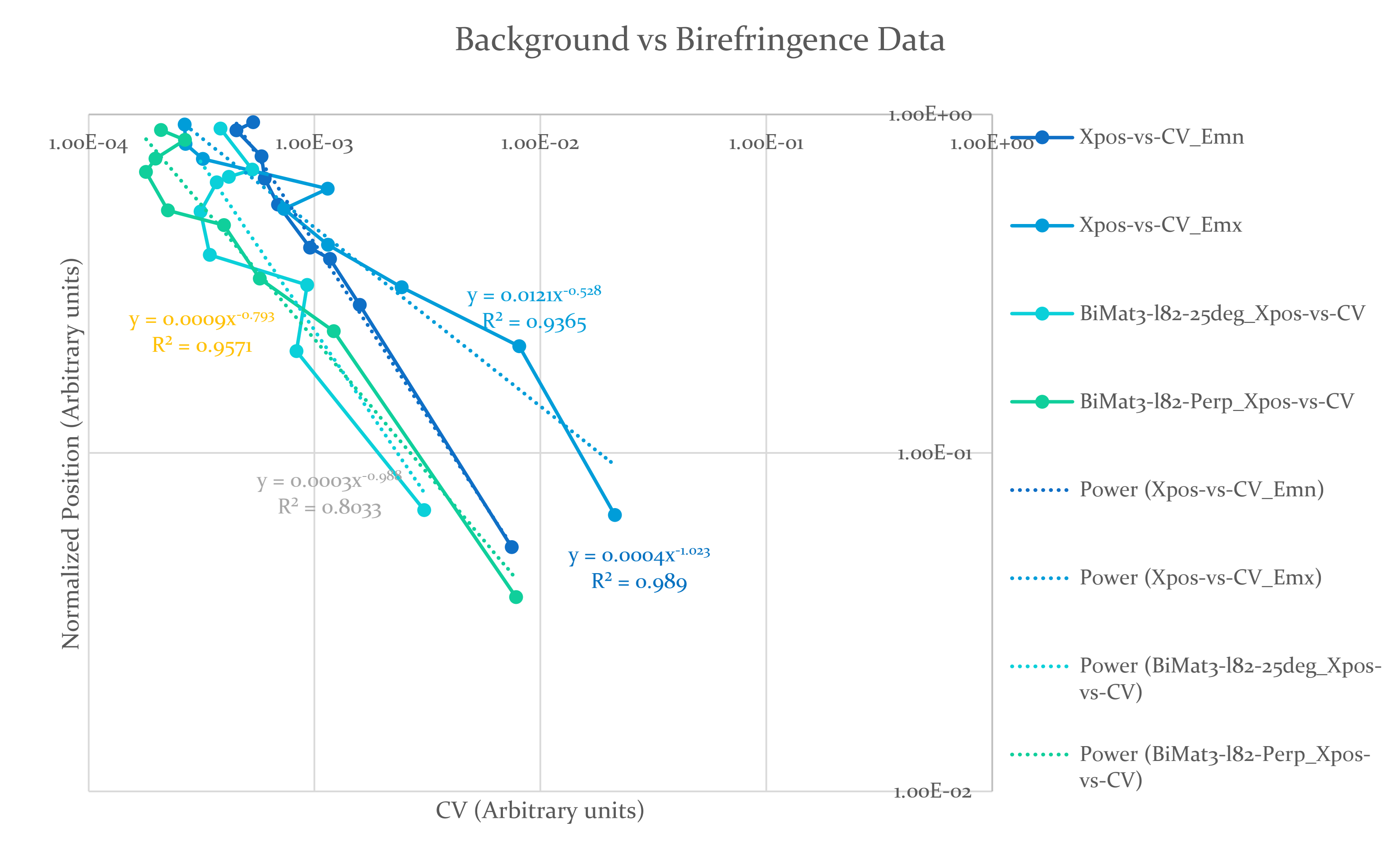
- BNL Summer 2016 – Detector Measurement
- Null measurement

Birefringent Microscopy



- Detector Measurement + Birefringent Sample 1
- Birefringent Samples – Stress induced effects

Birefringence & Noise



Summary

- Splitting leads to a quadratic depletion of the central intensity as well as a quadratic shifting of the beam's center
- The limit of photon statistics ends the process of splitting and gives rise to an energy shifting that has a better than 95.2% probability of behaving linearly
- The energy shifting grows chaotically
- Experiments seeking to observe exotic particles may benefit from such an enhancement in signal strength

Axion Mass

- The calculations for splitting assumed “maximum mixing” or an axion mass at the resonance condition ma = 0
- For non-resonance, there is a correction factor:

$$\tan(2\cdot\varphi)=\frac{2\cdot Q_M}{Q_\gamma - Q_a}$$

Where the parameters are defined :

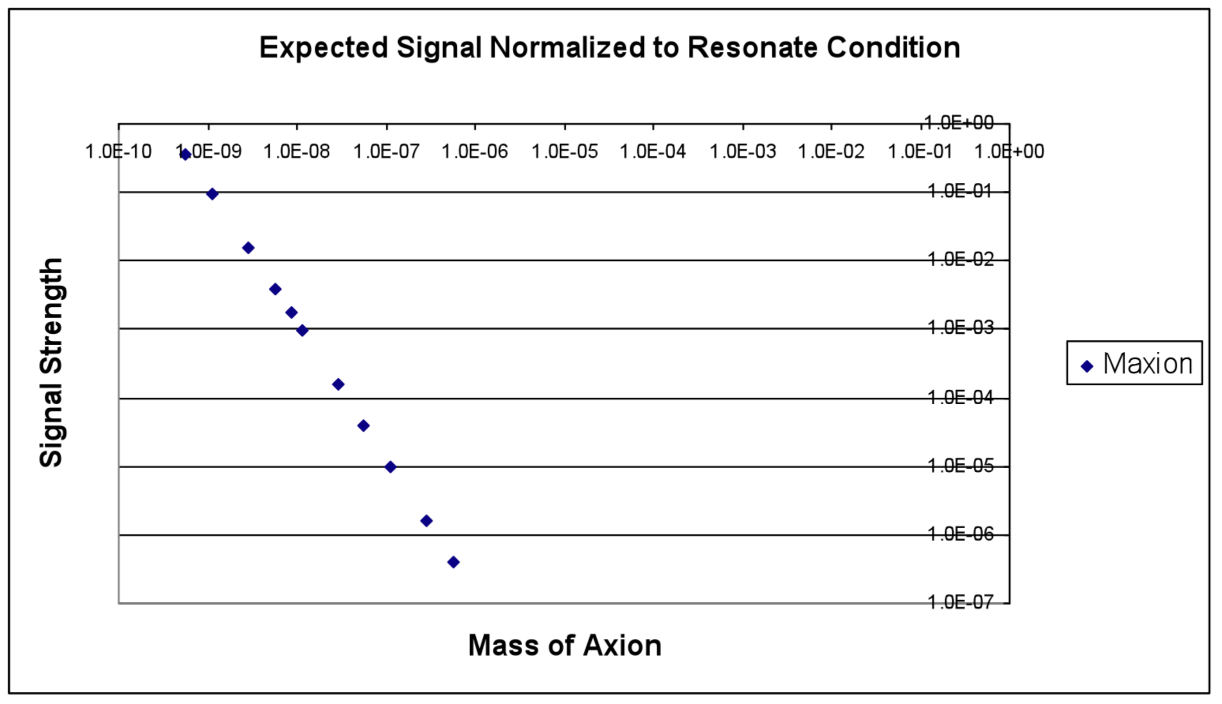
$$Q_M \approx \omega g_a B^e \approx 1ev\cdot 10^{-21}ev^{-1}\cdot 1T\cdot 195\frac{ev^2}{T}\approx 10^{-19}ev^2$$

$$Q_\gamma = \omega^2\frac{7\alpha}{45\pi}\left(\frac{B^e}{B_{crit}}\right)^2 \approx 3.19\cdot 10^{-23}ev^2$$

$$Q_a = -m_a^2$$

Non-resonance mass factor

- The resonance axion mass is just $m_a = 5.7\ 10^{-10}$
- Accounting for non-resonance, signal strength drops:



Non-resonance measurement

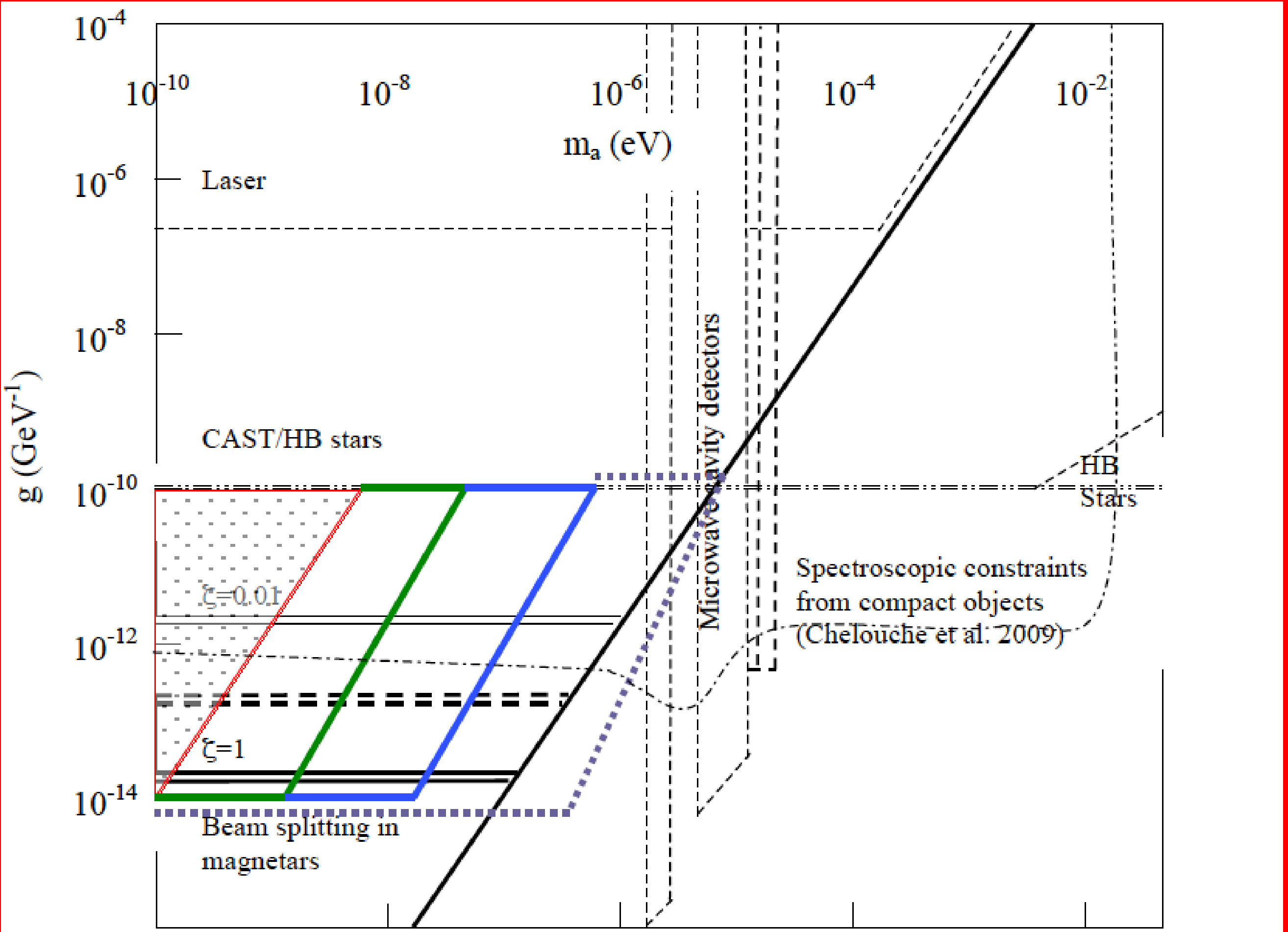


Figure 8: Axion space thus far explored by experimentation and astro-physical observation along with predictions (double solid and dashed lines) for magnetar observations.