IS OUR WORLD AN ALP FACTORY?

PROBING AXION-LIKE PARTICLES FROM THE EARTH IN NEUTRINO DETECTORS

Anirudh Chandra Shekar
Texas A&M University
anirudhcs@tamu.edu

260x.xxxxx : **ACS**, Bhaskar Dutta, Baishan Hu, Austin Schneider, Louis Strigari

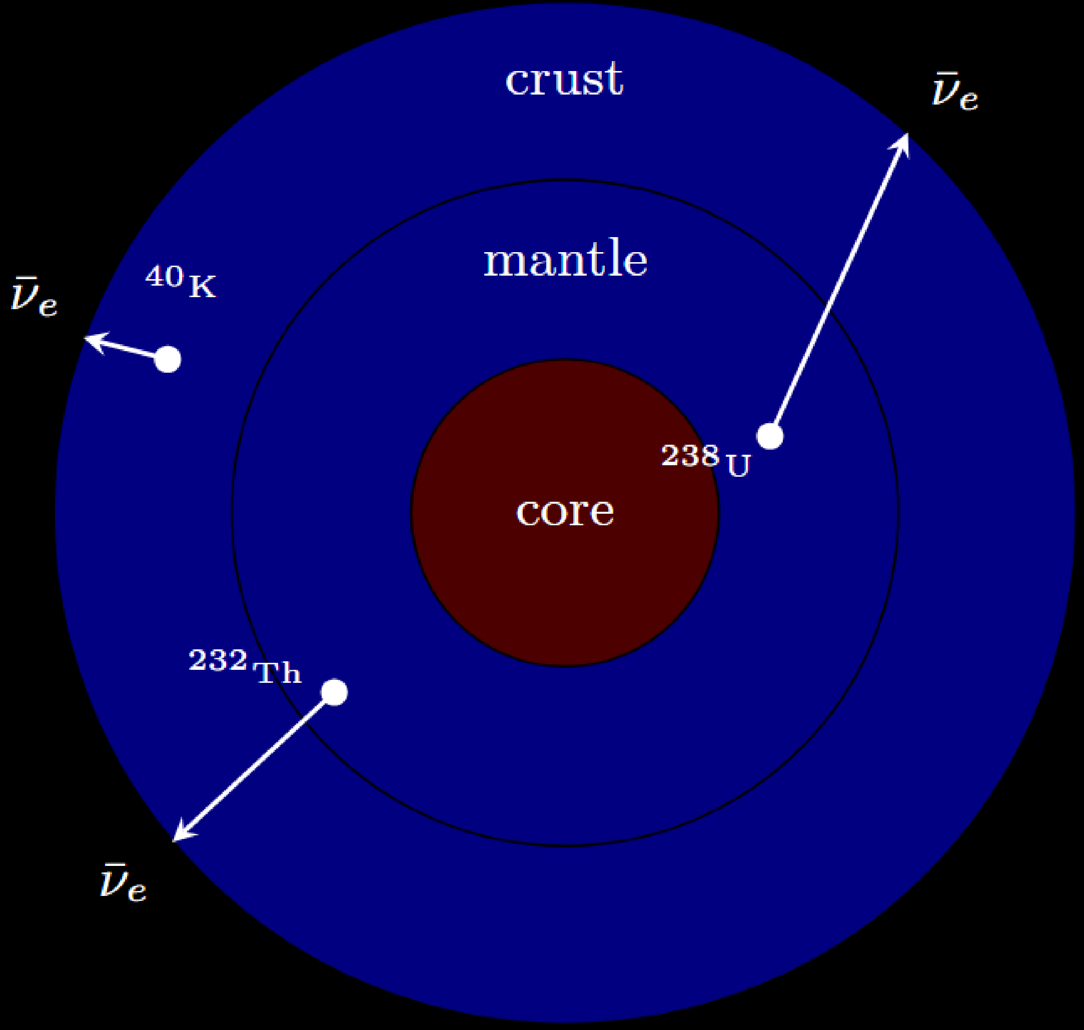
Axions and ALPs

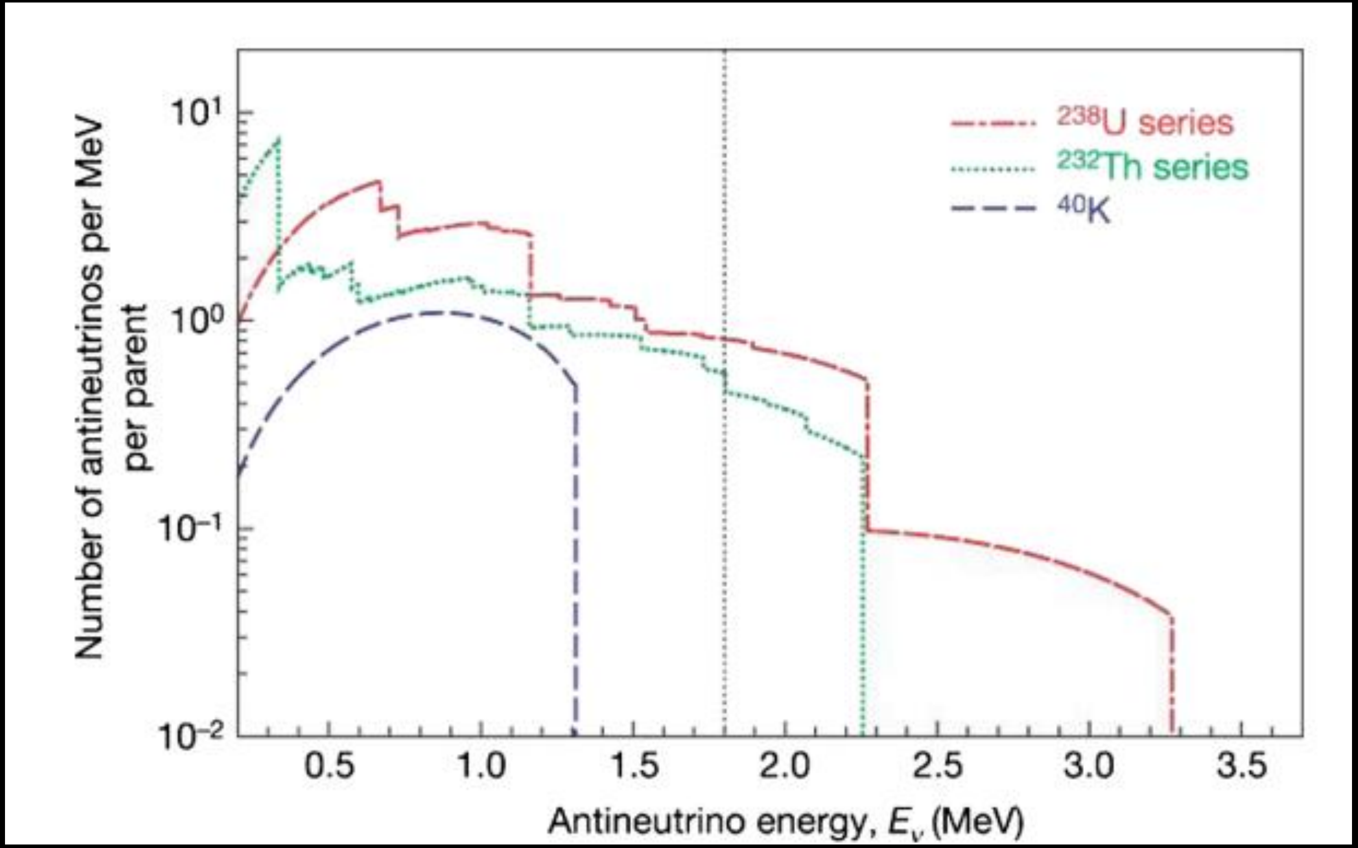
- Strong CP problem- theoretically CP violation is allowed but no experimental observation
- A possible solution in 1977- the Peccei-Quinn symmetry $U(1)_{PQ}$.
- 1978- Independently, Weinberg and Wilczek proposed the QCD "axion"- a pseudo-Nambu-Goldstone boson obtained from the spontaneous symmetry breaking of $U(1)_{PQ}$ symmetry.
- QCD Axion- neutral, pseudoscalar, spin 0 particle.
- Mass and coupling to SM particles are correlated and fixed by the Peccei-Quinn scale f_a.
- ALPs- the mass-coupling correlation is relaxed

Anirudh Chandra Shekar anirudhcs@tamu.edu

GEO-NEUTRINOS

Production





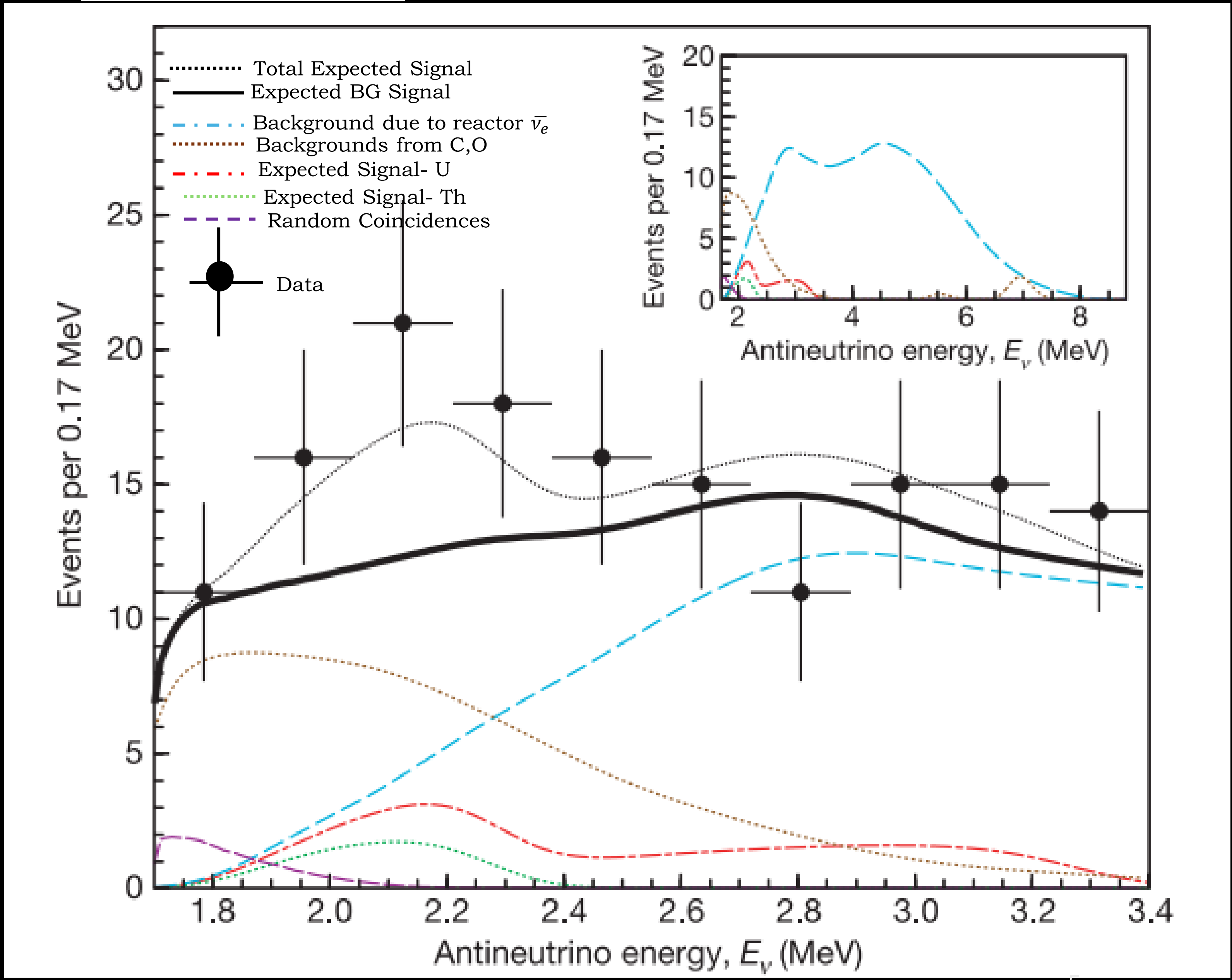
Plot Credit: Gelmini et al.(2019)
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.093009

Anirudh Chandra Shekar anirudhcs@tamu.edu

Detection

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

KamLAND detection



Plot Credit: Araki et al. KamLAND Collaboration (2005)
https://www.nature.com/articles/nature03980

Anirudh Chandra Shekar anirudhcs@tamu.edu

GEO-AXIONS

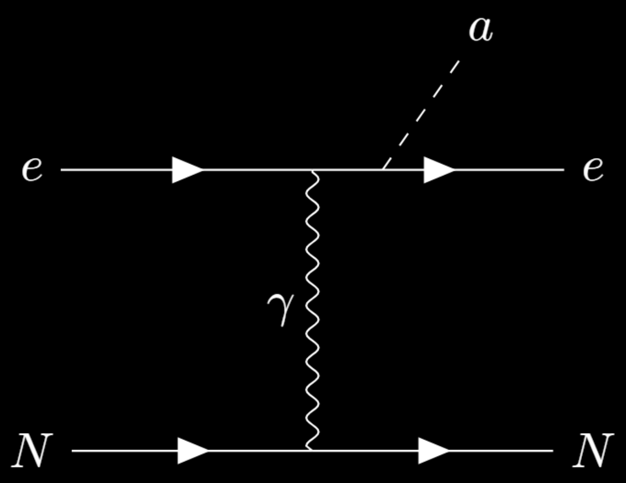
Anirudh Chandra Shekar anirudhcs@tamu.edu

AXION PRODUCTION CHANNELS

I

$$\mathcal{L}_{ae} \supset i g_{ae} a \bar{\psi}_e \gamma^5 \psi$$

Axion electron coupling



Electron Bremsstrahlung

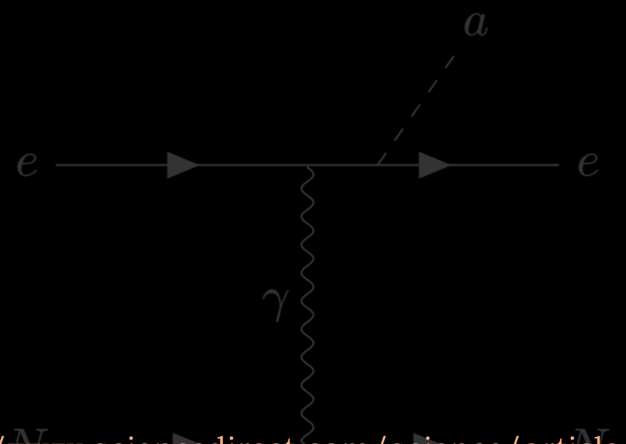
Davoudiasl, Huber (2009)-
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.79.095024

Anirudh Chandra Shekar anirudhcs@tamu.edu

AXION PRODUCTION CHANNELS

I

$$\mathcal{L}_{ae} \supset i g_{ae} a \bar{\psi}_e \gamma^5 \psi$$

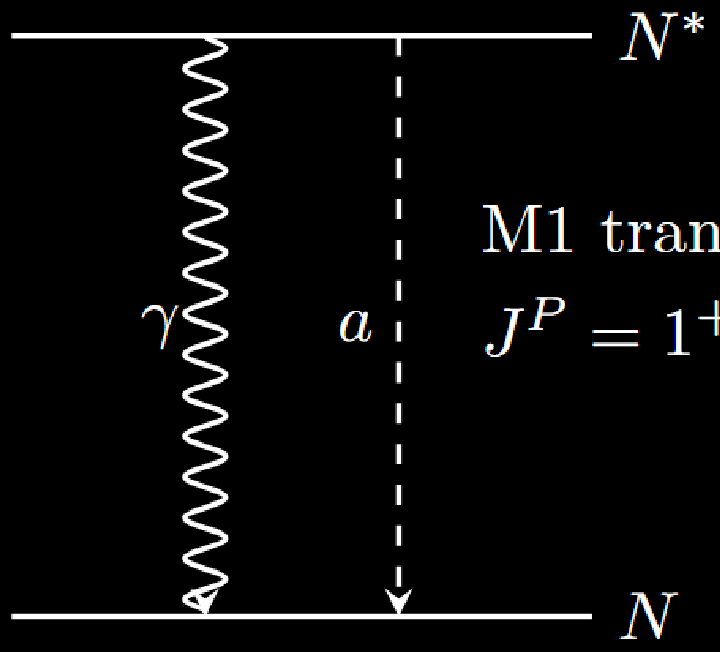


Liolios(2007)- https://www.sciencedirect.com/science/article/abs/pii/S0370269306015620

II

$$\mathcal{L} = ia\bar{\psi}_N \gamma_5 \left(g^0_{aNN} + g^1_{aNN}\tau_3\right)\psi_N$$
$$= ia\left(g_{app}\bar{p}\gamma_5 p + g_{ann}\bar{n}\gamma_5 n\right)$$

Axion nucleon coupling



Primakoff Production of Axion

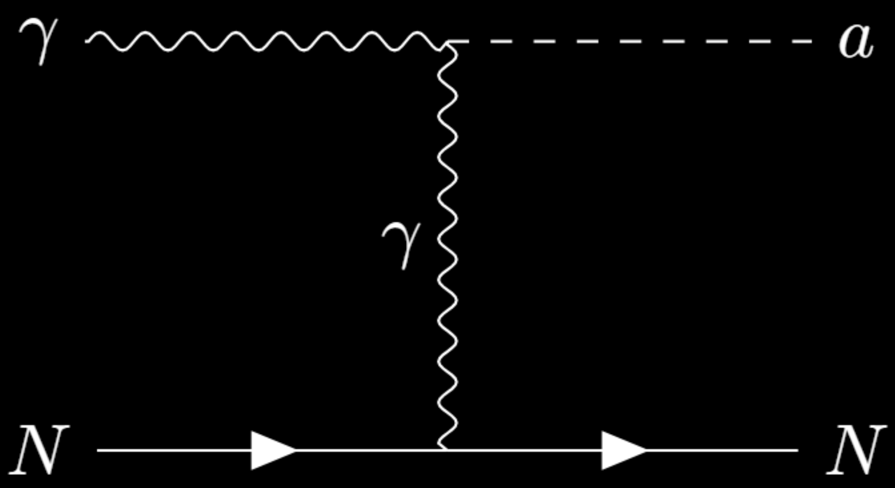
Anirudh Chandra Shekar anirudhcs@tamu.edu

AXION PRODUCTION

III

$$\mathcal{L}_{a\gamma\gamma} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}_{\mu\nu}$$

Axion di-photon coupling



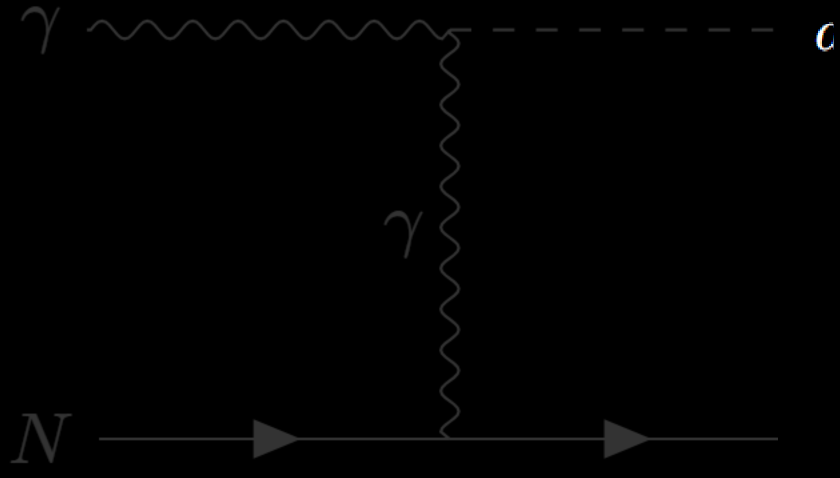
Primakoff Production of Axion

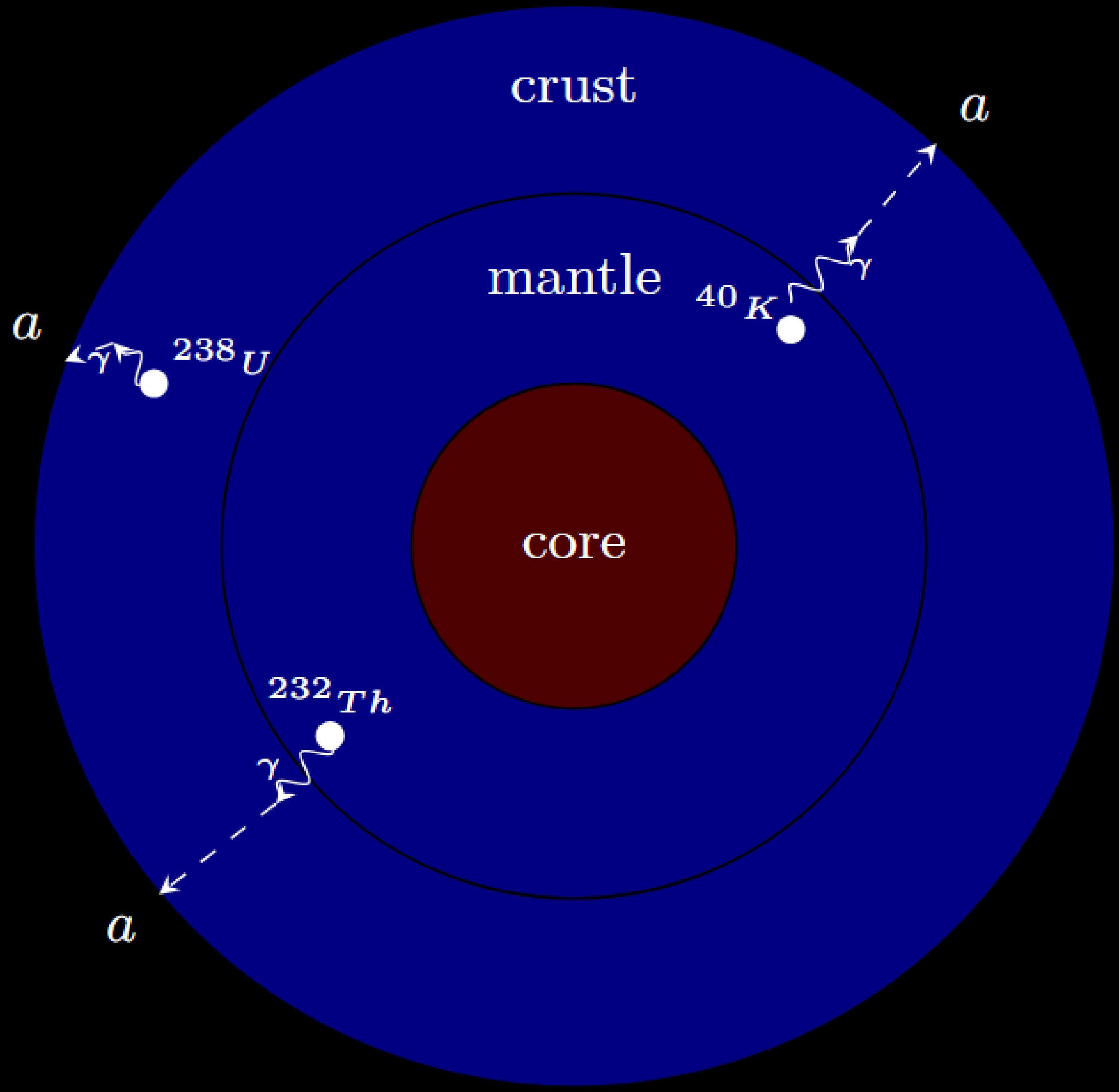
Anirudh Chandra Shekar anirudhcs@tamu.edu

AXION PRODUCTION

III

$$\mathcal{L}_{a\gamma\gamma} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}$$





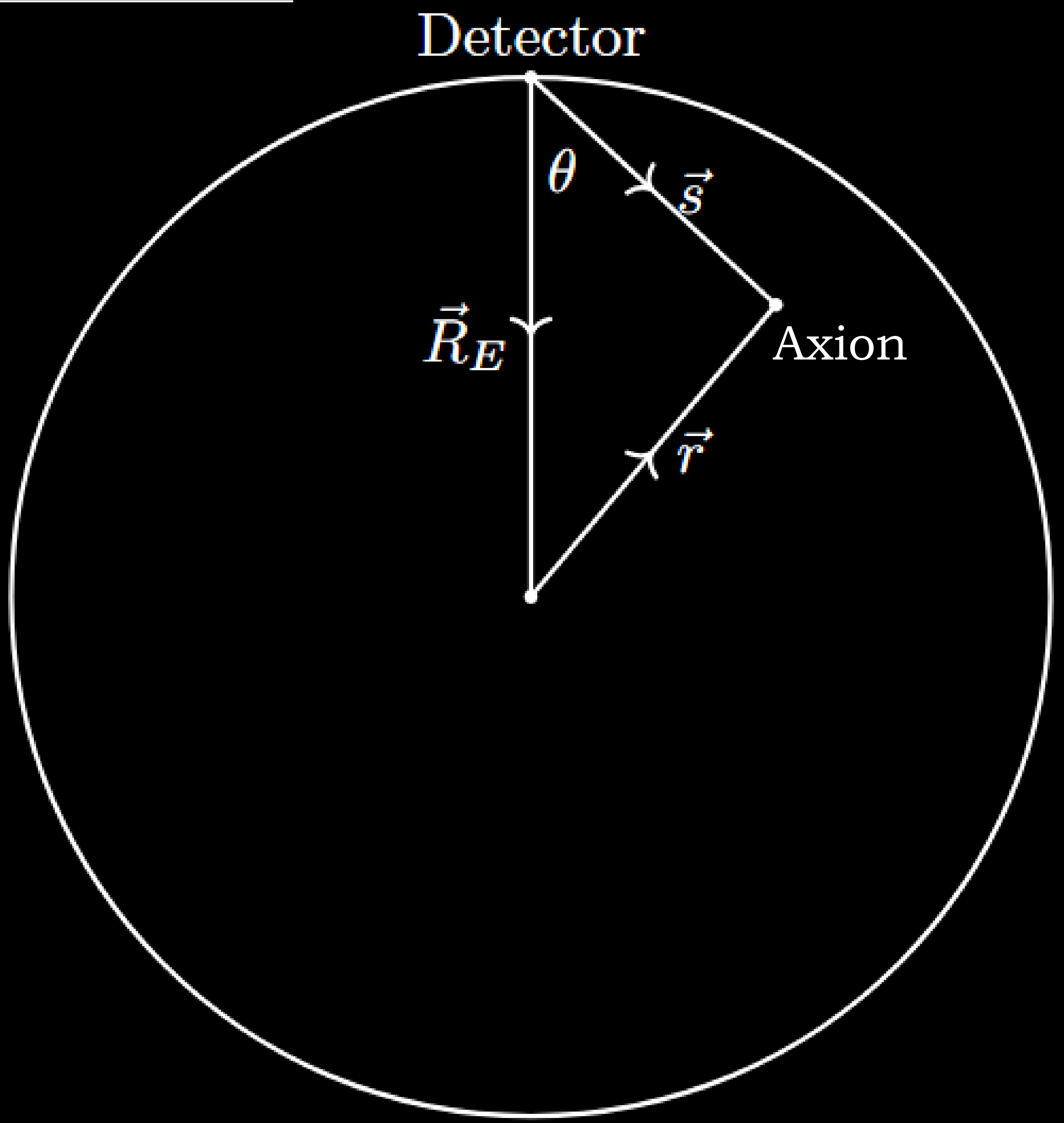
Photons produced in the radioactive decay chains of U, Th and K convert to axions by Primakoff scattering off nucleus

Anirudh Chandra Shekar anirudhcs@tamu.edu

EARTH MODELLING

Anirudh Chandra Shekar anirudhcs@tamu.edu

Geometric Factors

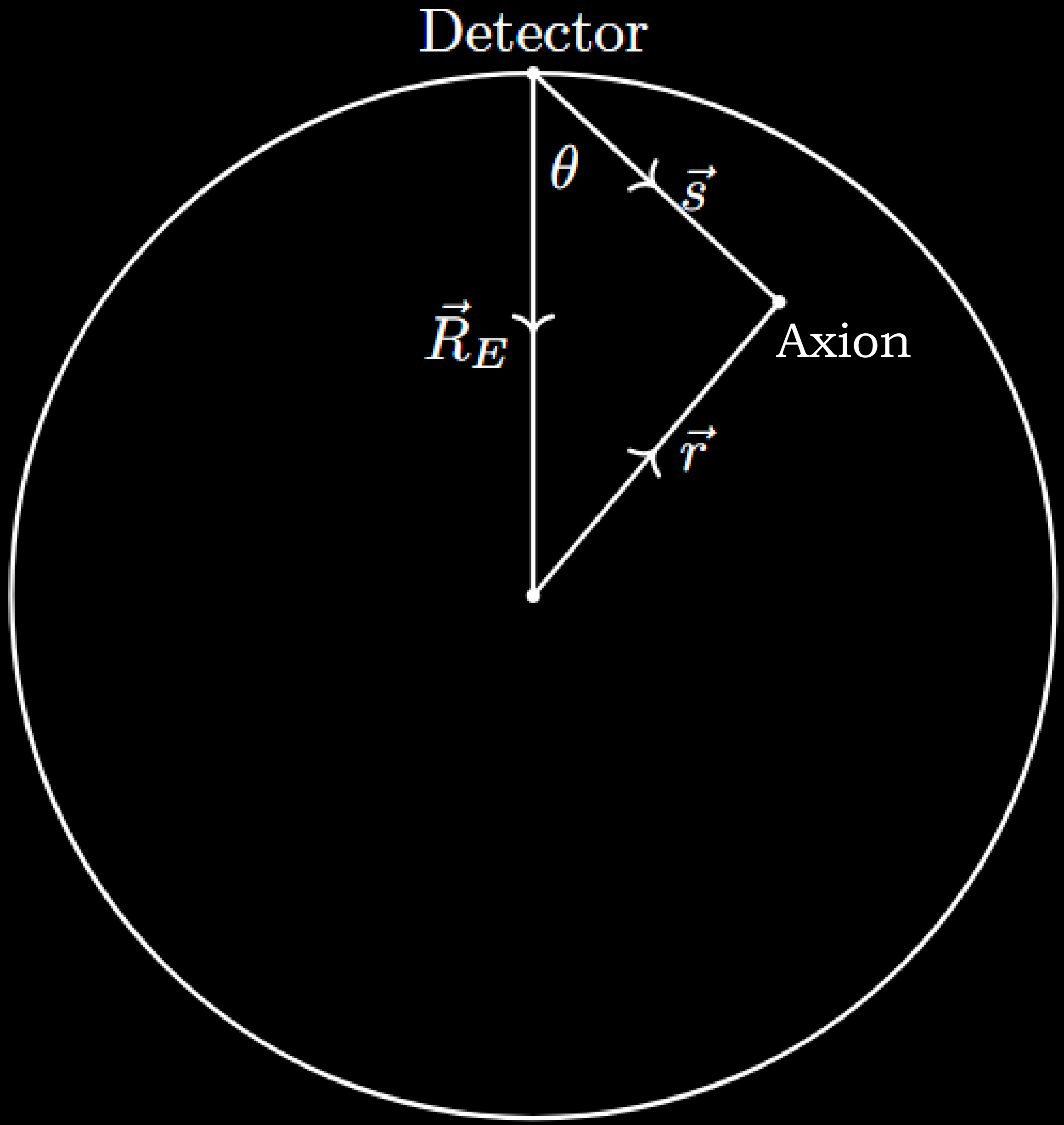


Anirudh Chandra Shekar anirudhcs@tamu.edu

Geometric Factors

Calculate the distribution of
axion flux v/s solid angle
along a line of sight

$$I(\theta, \phi) = \frac{dF}{d\Omega}$$



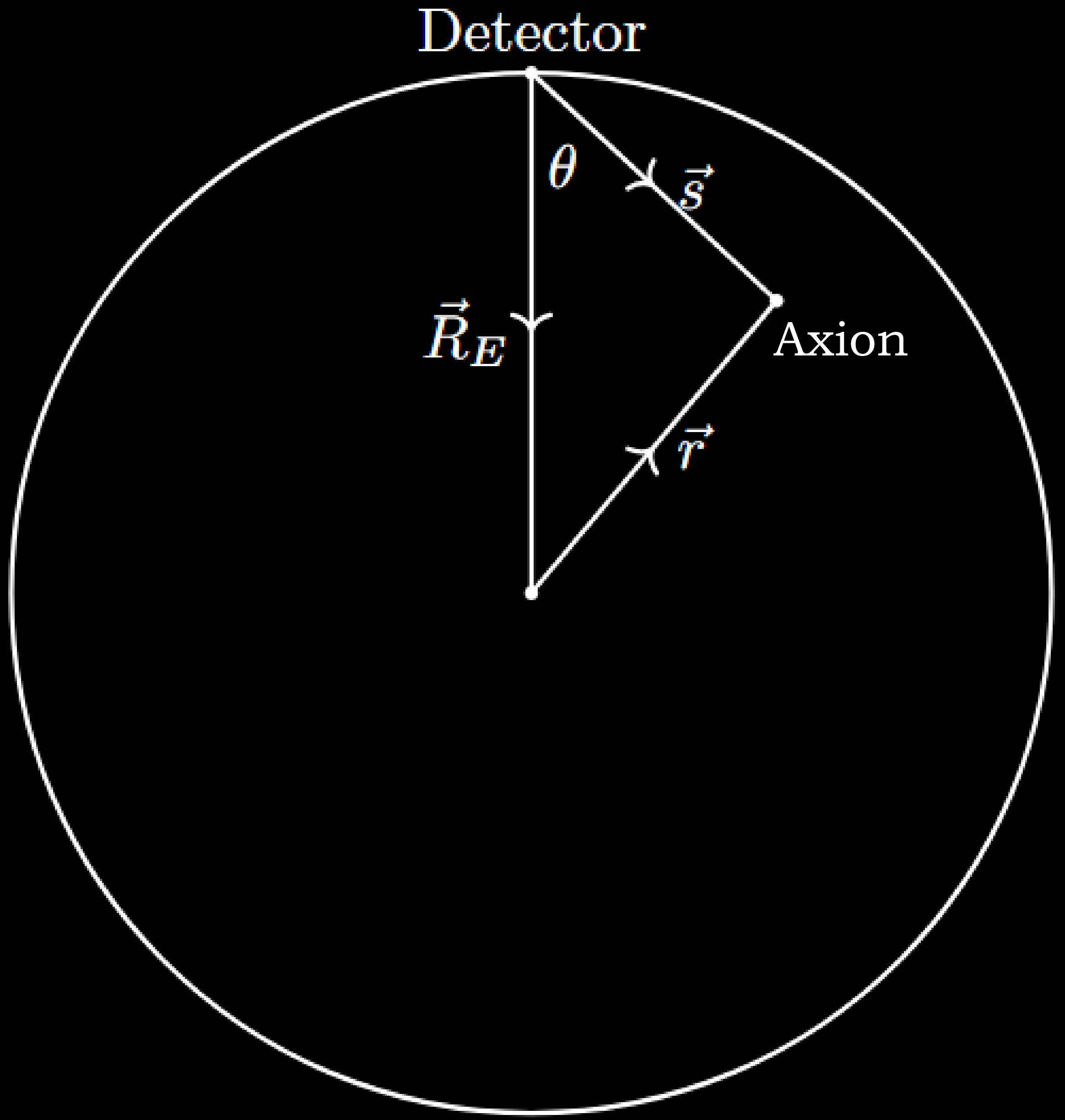
Anirudh Chandra Shekar anirudhcs@tamu.edu

Geometric Factors

Calculate the distribution of axion flux v/s solid angle along a line of sight

$$I(\theta, \phi) = \frac{dF}{d\Omega}$$

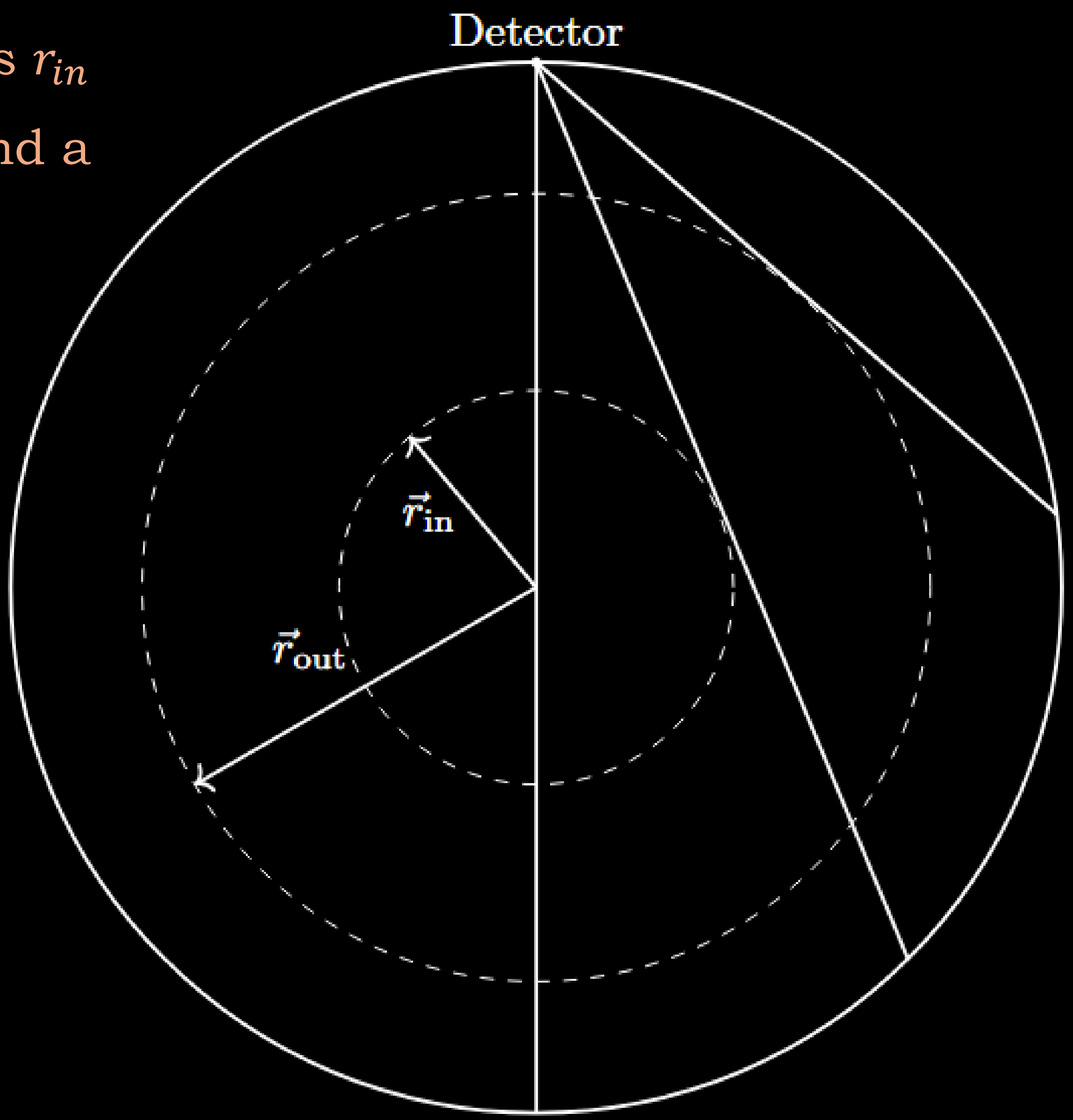
Integrate over line of sight and then integrate over the solid angle to get the full axion flux from the Earth



Anirudh Chandra Shekar anirudhcs@tamu.edu

Uniform Shell Model

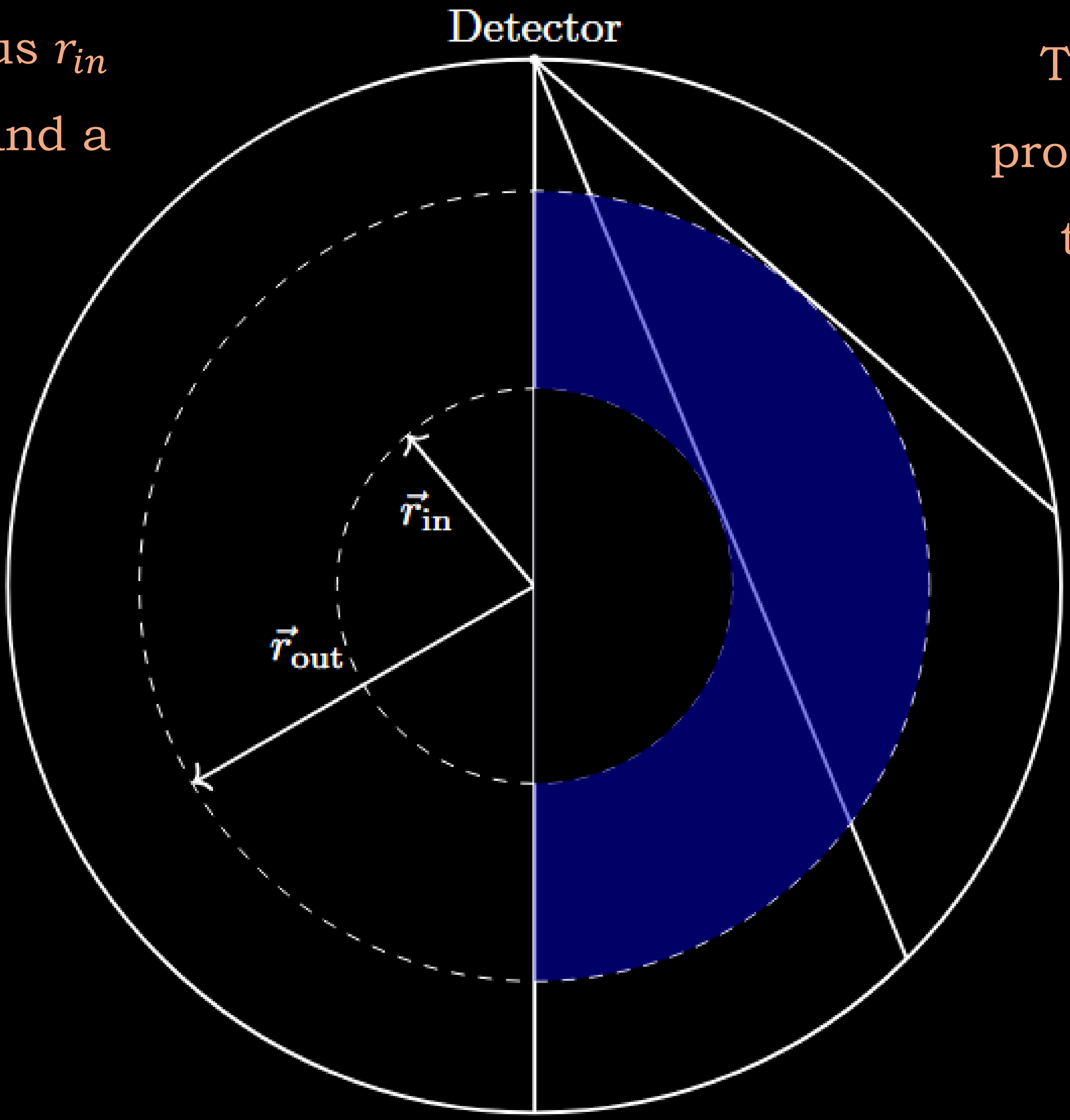
A shell with inner radius r_{in} and outer radius r_{out} and a fixed density



Anirudh Chandra Shekar anirudhcs@tamu.edu

Uniform Shell Model

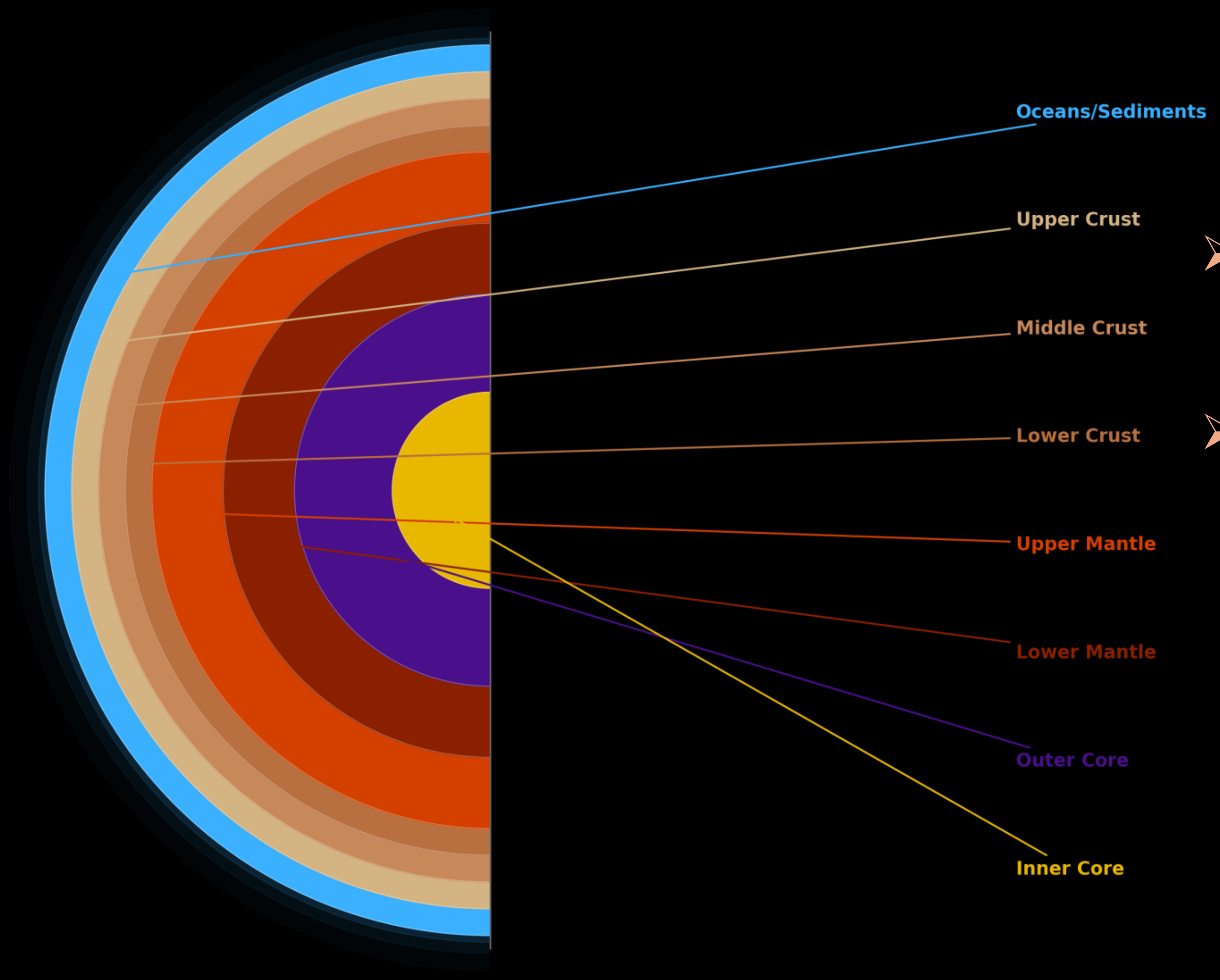
A shell with inner radius r_{in} and outer radius r_{out} and a fixed density



The gamma and axion production rate is uniform throughout the shell

Anirudh Chandra Shekar anirudhcs@tamu.edu

Preliminary Reference Earth Model (PREM)

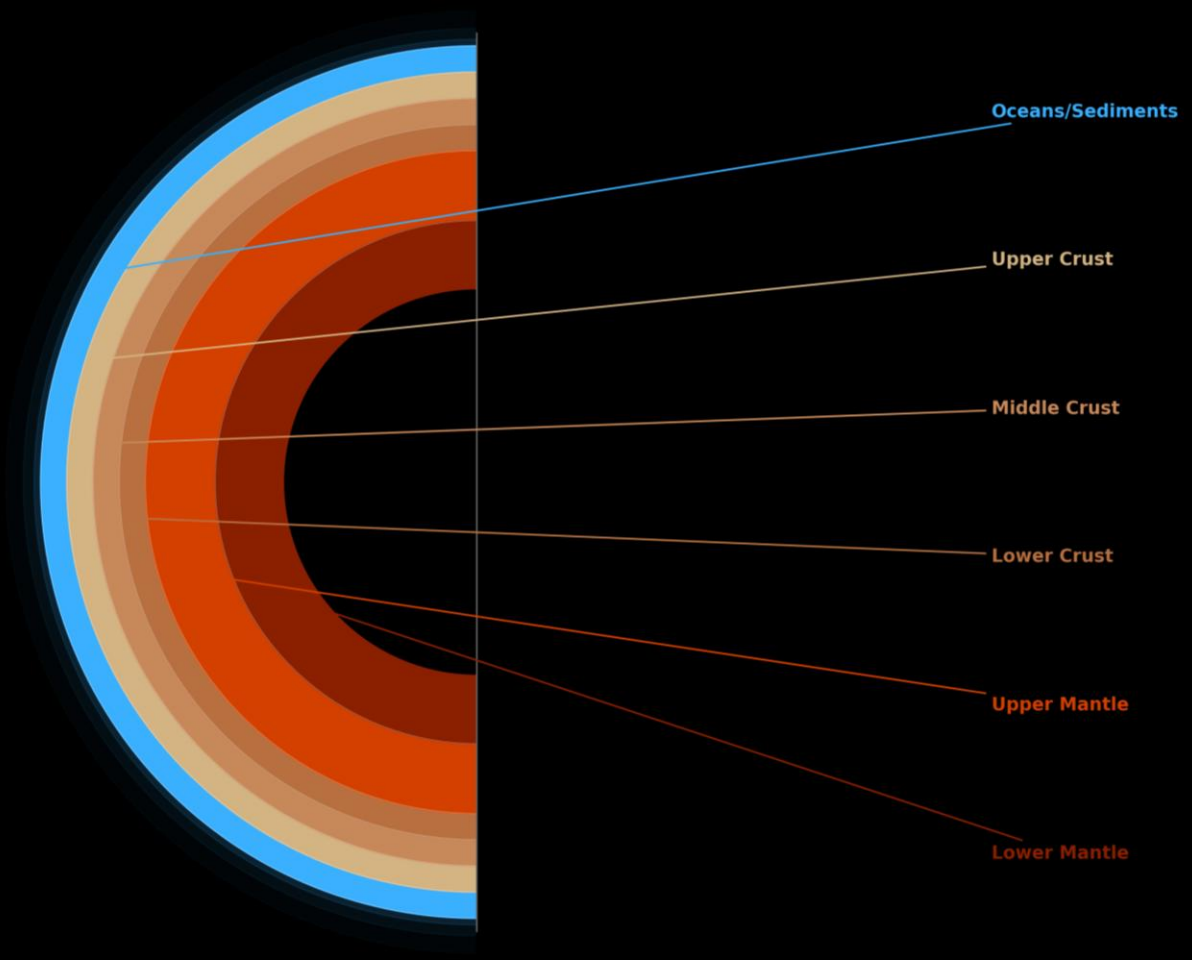


- Divide Earth into several spherical shells
- Each shell has a fixed density

Picture Credit: Perplexity (running on Claude 4.6 Model)

Anirudh Chandra Shekar anirudhcs@tamu.edu

Preliminary Reference Earth Model (PREM)



Picture Credit: Perplexity (running on Claude 4.6 Model)

- PREM gives abundances of radionuclides U,Th and K in each shell
- Calculate gamma spectrum from each radionuclide in each shell
- Convert the gammas into axions via Primakoff scattering

Anirudh Chandra Shekar anirudhcs@tamu.edu

AXION FLUX

Anirudh Chandra Shekar anirudhcs@tamu.edu

Primakoff Production

$$\Phi = \sigma_{\gamma \to a} \frac{n_\gamma(SR) R_E}{2} \sum_{\text{Shells}} \frac{M_{\text{shell}} L_\gamma N_n}{V_{\text{shell}}} f(r_{\text{in}}, r_{\text{out}}, R_E)$$

$$\propto Z^2 g_{a\gamma\gamma}^2$$

Photon absorption cross-section

Geometric Factor

Anirudh Chandra Shekar anirudhcs@tamu.edu

Primakoff Production

$$\Phi = \sigma_{\gamma \to a} \frac{n_\gamma (SR) R_E}{2} \sum_{\text{Shells}} \frac{M_{\text{shell}} L_\gamma N_n}{V_{\text{shell}}} f(r_{\text{in}}, r_{\text{out}}, R_E)$$

$$n_\gamma = \begin{cases} 1.2 & \text{U} \\ 0.65 & \text{Th} \\ 0.12 & \text{K} \end{cases}$$

Number of gamma produced by a single atom of radionuclide (Geant4 Simulation)

Anirudh Chandra Shekar anirudhcs@tamu.edu

Primakoff Production

$$\Phi = \sigma_{\gamma\to a}\frac{n_\gamma(SR)R_E}{2}\sum_{\text{Shells}}\frac{M_{\text{shell}}L_\gamma N_n}{V_{\text{shell}}}f(r_{\text{in}},r_{\text{out}},R_E)$$

$$n_\gamma = \begin{cases}1.2 & \text{U}\\ 0.65 & \text{Th}\\ 0.12 & \text{K}\end{cases}$$

Isotope	SR (/kg/s)
^{238}U	1.248×10^7
^{232}Th	4.07×10^6
^{40}K	2.66×10^8

Specific Activity

Anirudh Chandra Shekar anirudhcs@tamu.edu

Primakoff Production

$$\Phi = \sigma_{\gamma\to a}\frac{n_\gamma(SR)R_E}{2}\sum_{\text{Shells}}\frac{M_{\text{shell}}L_\gamma N_n}{V_{\text{shell}}}f(r_{\text{in}}, r_{\text{out}}, R_E)$$

$\propto a$

Mass Abundance

$$n_\gamma = \begin{cases} 1.2 & \text{U} \\ 0.65 & \text{Th} \\ 0.12 & \text{K} \end{cases}$$

Isotope	SR (/kg/s)
^{238}U	1.248×10^7
^{232}Th	4.07×10^6
^{40}K	2.66×10^8

$$\frac{a_{\text{K}}}{a_{\text{U}}} = \frac{a_{\text{K}}}{a_{\text{Th}}} \approx 10^{4-5}$$

Anirudh Chandra Shekar anirudhcs@tamu.edu

Primakoff Production

$$n_\gamma = \begin{cases} 1.2 & \text{U} \\ 0.65 & \text{Th} \\ 0.12 & \text{K} \end{cases}$$

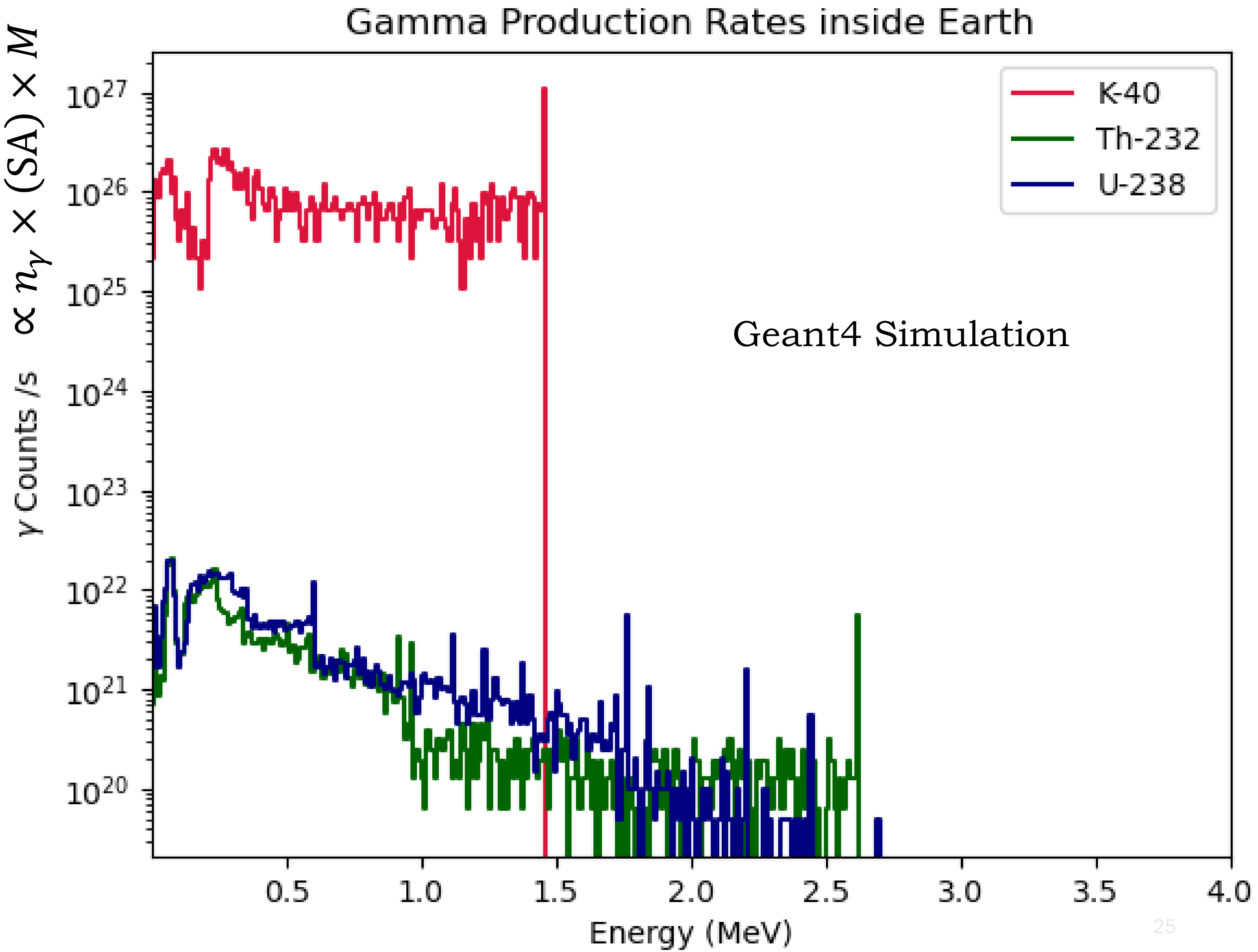
Isotope	SR (/kg/s)
^{238}U	1.248×10^7
^{232}Th	4.07×10^6
^{40}K	2.66×10^8

$$\frac{a_\text{K}}{a_\text{U}} = \frac{a_\text{K}}{a_\text{Th}} \approx 10^{4-5}$$

$$\Phi_\text{K} : \Phi_\text{Th} : \Phi_\text{U} \approx 10^{4-5} : 1 : 1$$

Anirudh Chandra Shekar anirudhcs@tamu.edu

The photon production rate in a region of fixed density



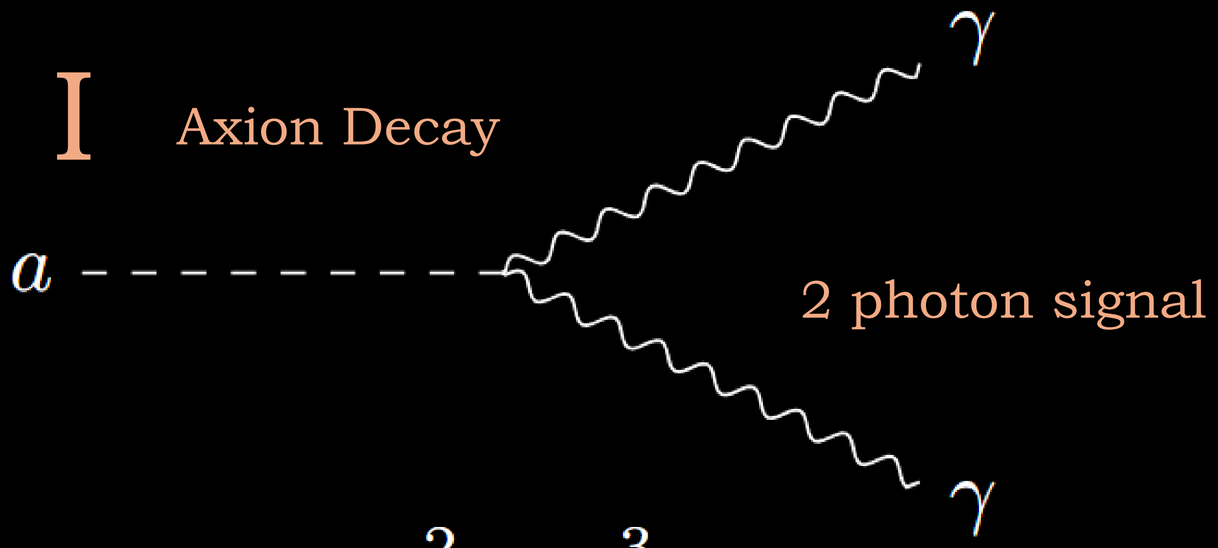
Anirudh Chandra Shekar anirudhcs@tamu.e

DETECTION

Anirudh Chandra Shekar anirudhcs@tamu.edu

Axion Detection Channels

I Axion Decay

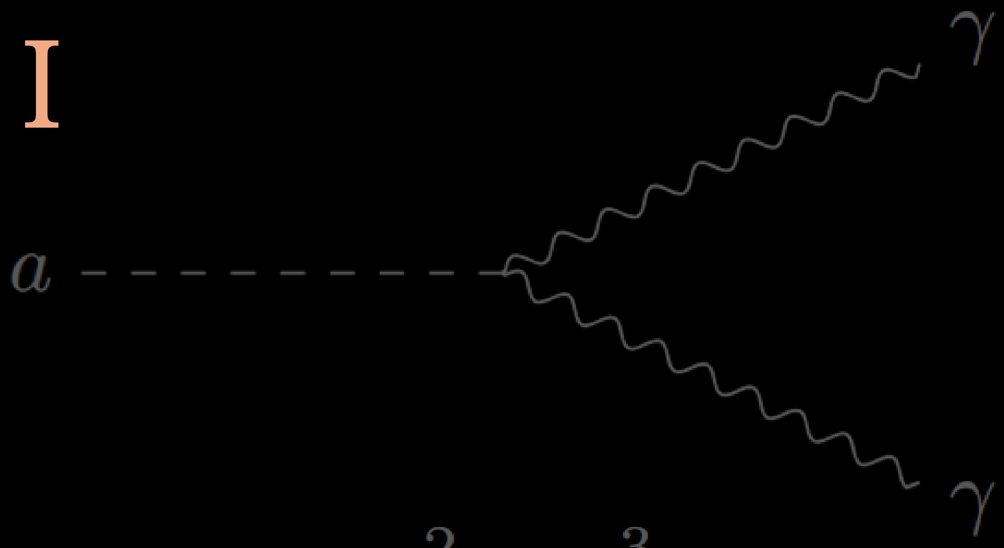


$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

Anirudh Chandra Shekar anirudhcs@tamu.edu

Axion Detection Channels

I



$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

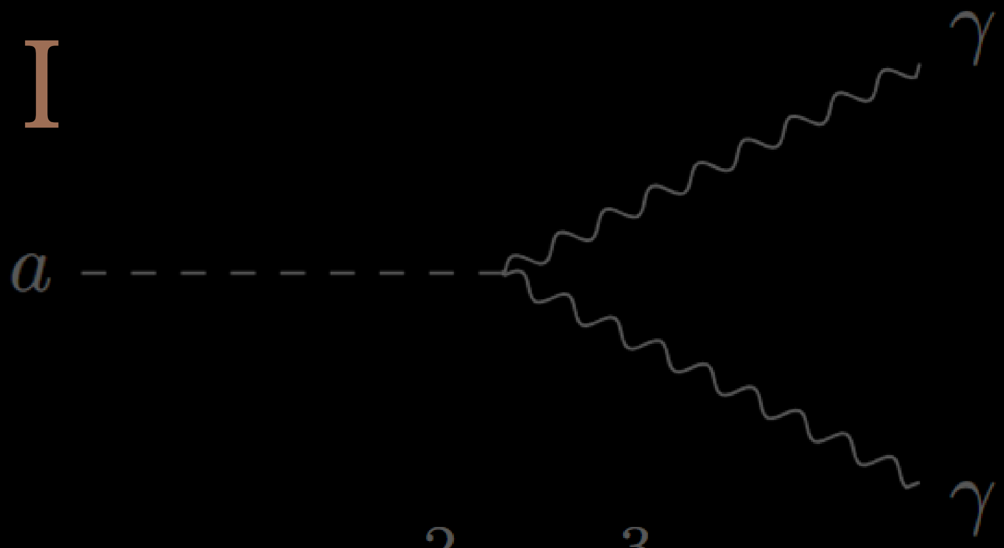
Detector

$$\text{Signal}_{\text{decay}} = \Phi_a \times (\text{T} \times \text{Area} \times \text{L}) \times \frac{1}{\lambda_a}$$

Anirudh Chandra Shekar anirudhcs@tamu.edu

Axion Detection Channels

I



$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

For L<<λ_a

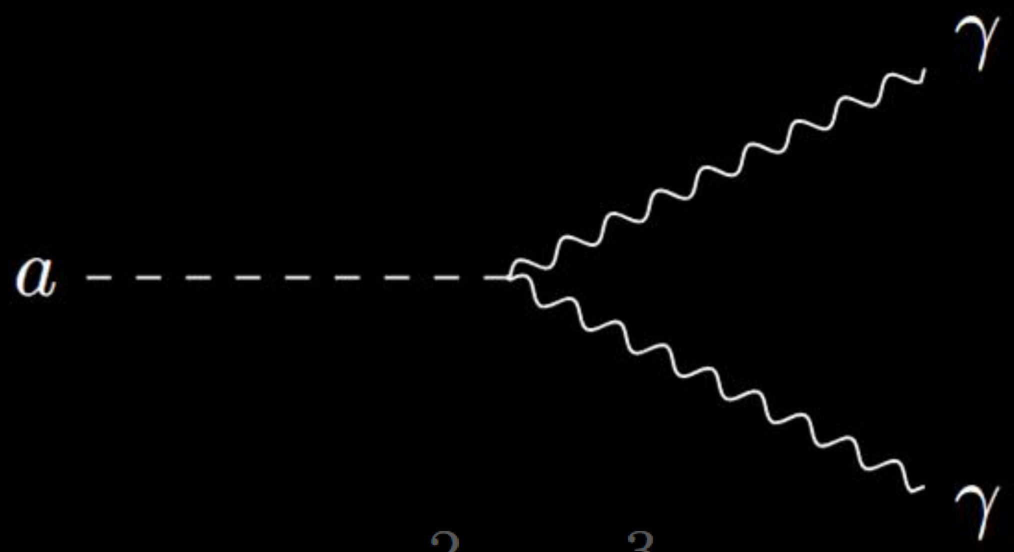
$$\text{Signal}_{\text{decay}} = \Phi_a \times (\text{T} \times \text{Area} \times \text{L}) \times \frac{1}{\lambda_a}$$

$$\propto g_{a\gamma\gamma}^2$$

$$\propto g_{a\gamma\gamma}^2 m_a^4$$

Anirudh Chandra Shekar   anirudhcs@tamu.edu

Axion Detection Channels



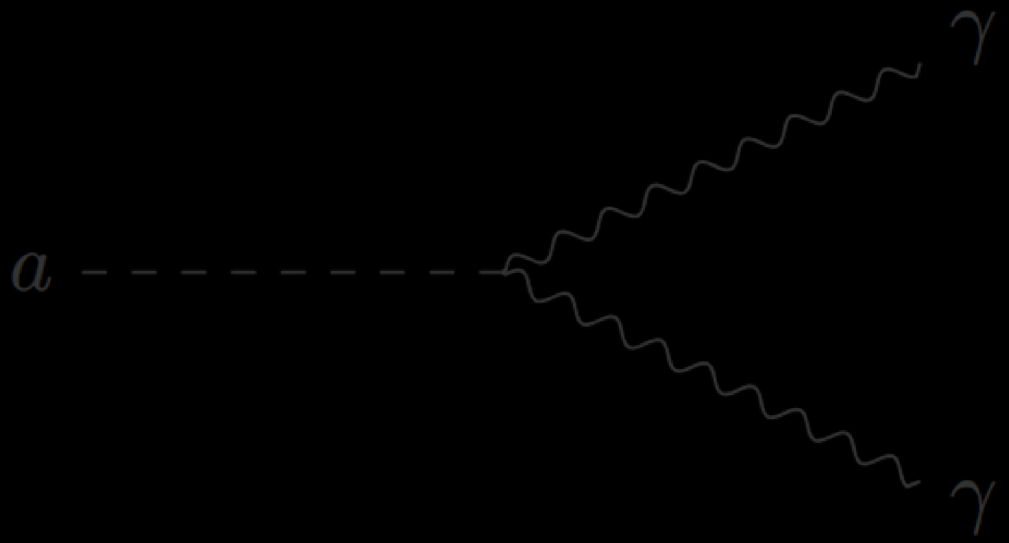
$$\text{Signal}_{\text{decay}} = \Phi_a \times (\text{T} \times \text{Area} \times \text{L}) \times \frac{1}{\lambda_a}$$

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

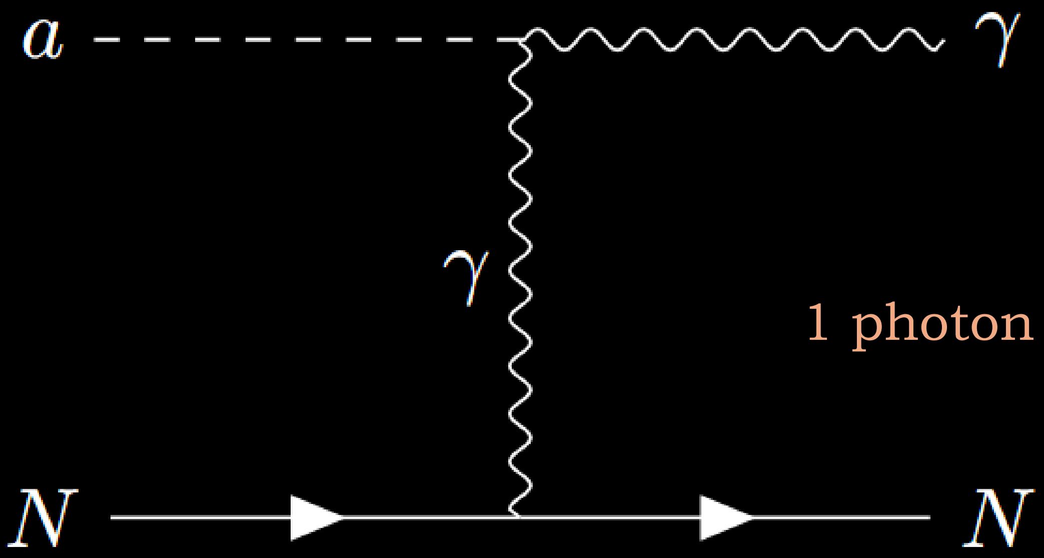
$$\text{Signal}_{\text{decay}} \propto g_{a\gamma\gamma}^4 m_a^4$$

Anirudh Chandra Shekar anirudhcs@tamu.edu

Axion Detection Channels



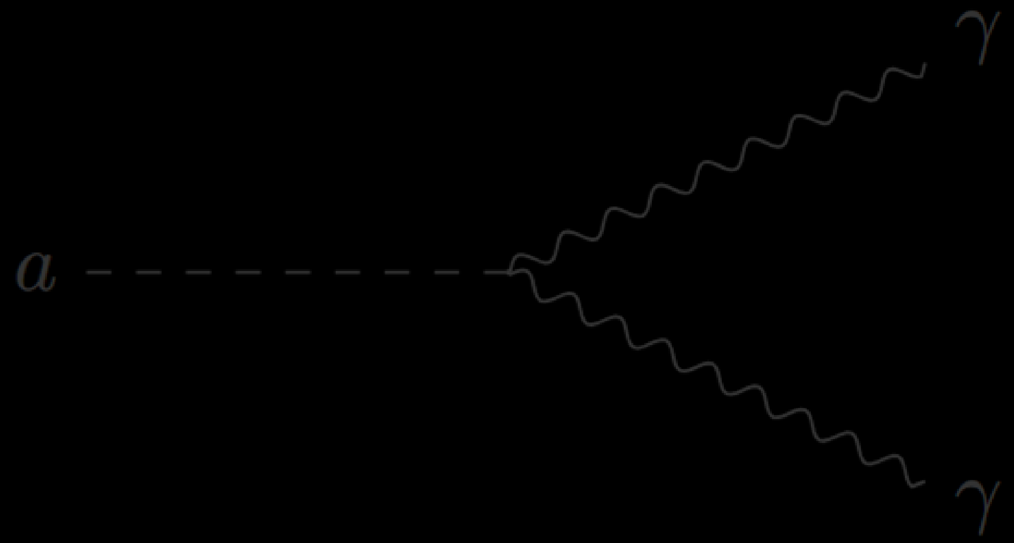
II Inverse Primakoff



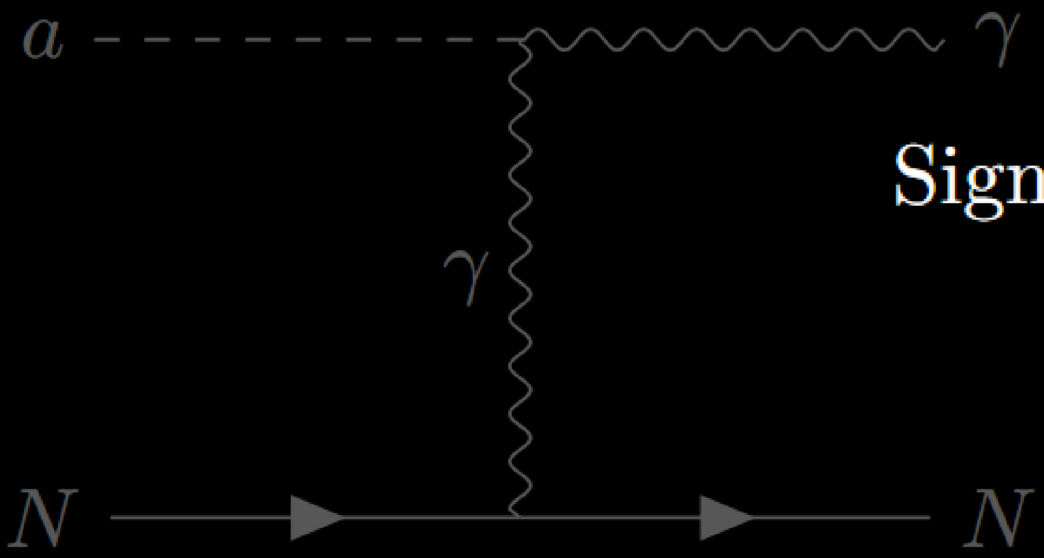
1 photon signal

Anirudh Chandra Shekar anirudhcs@tamu.edu

Axion Detection Channels



II

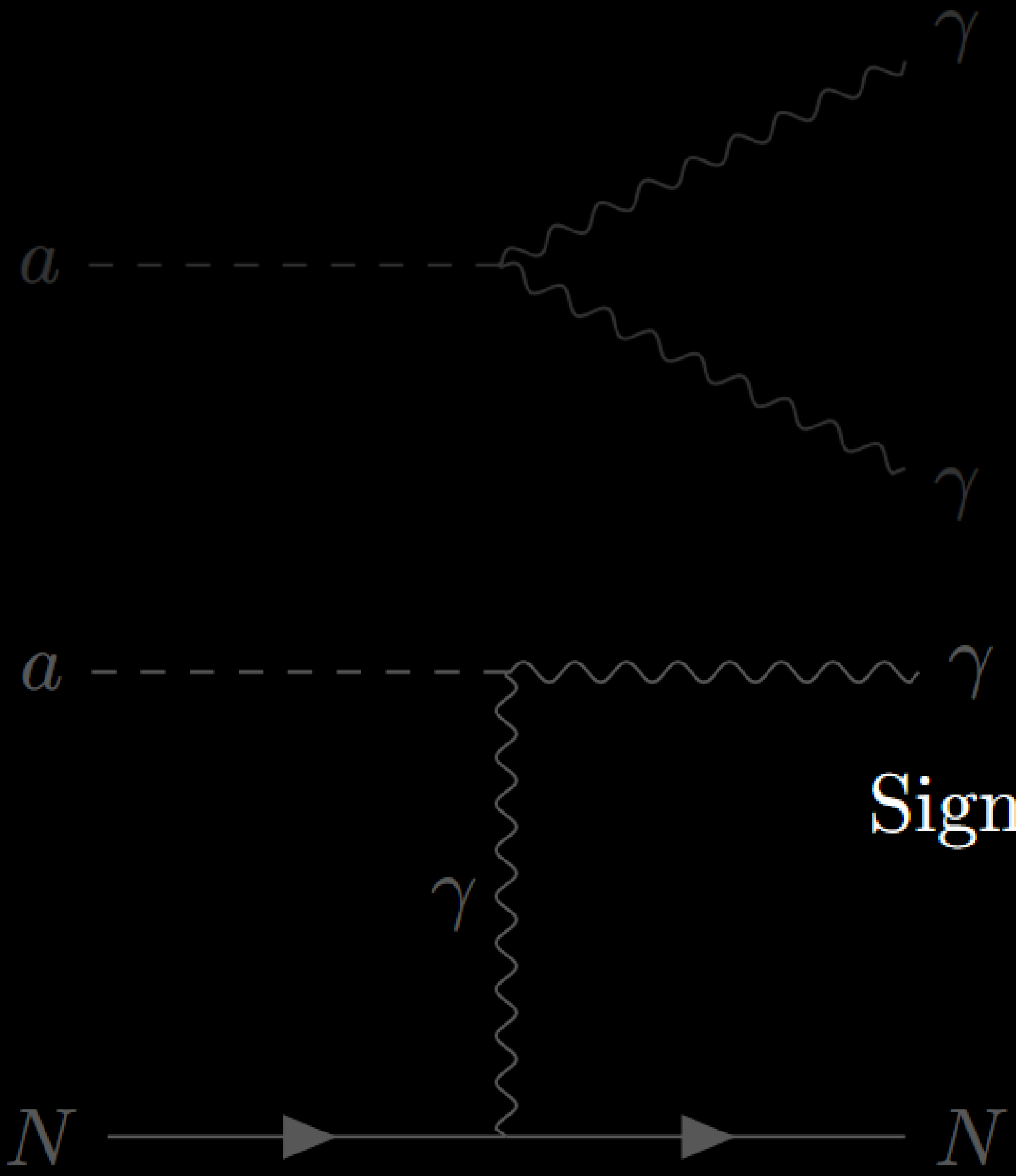


Detector

$$\text{Signal}_{\text{Prim.}} = \Phi_a \times \sigma_{a\to\gamma} \times (N_T \times T)$$

Anirudh Chandra Shekar anirudhcs@tamu.edu

Axion Detection Channels



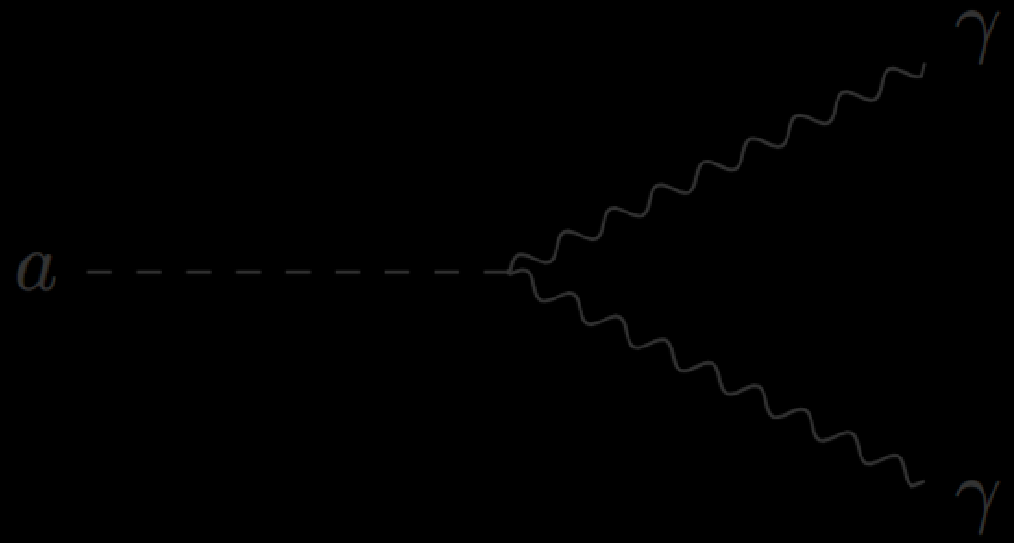
II

$\propto g^2_{a\gamma\gamma}$ $\propto g^2_{a\gamma\gamma}$

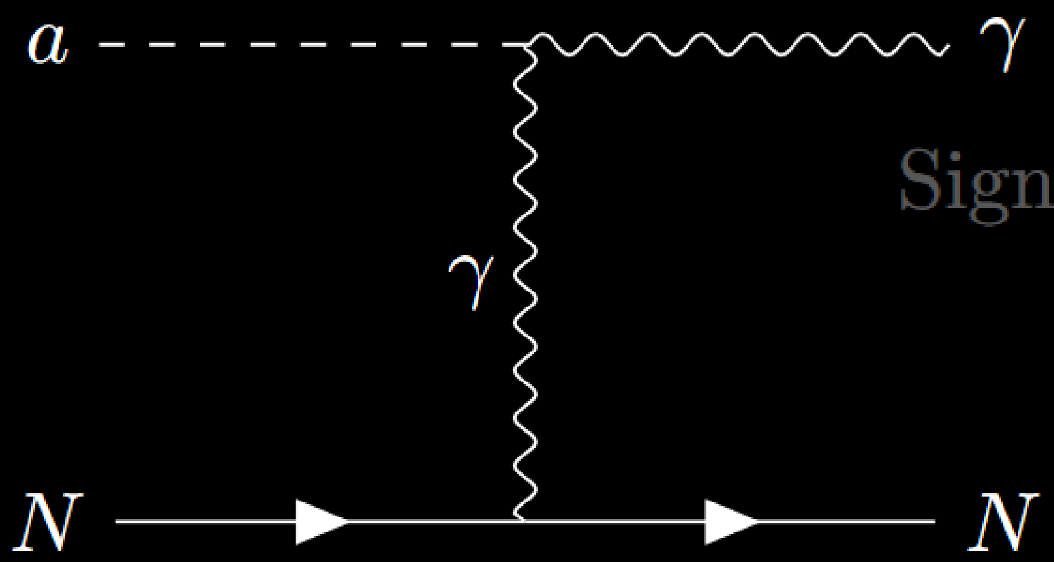
$$\text{Signal}_{\text{Prim.}} = \Phi_a \times \sigma_{a\to\gamma} \times (N_T \times T)$$

Anirudh Chandra Shekar anirudhcs@tamu.edu

Axion Detection Channels



II



$$\text{Signal}_{\text{Prim.}} \propto g_{a\gamma\gamma}^4$$

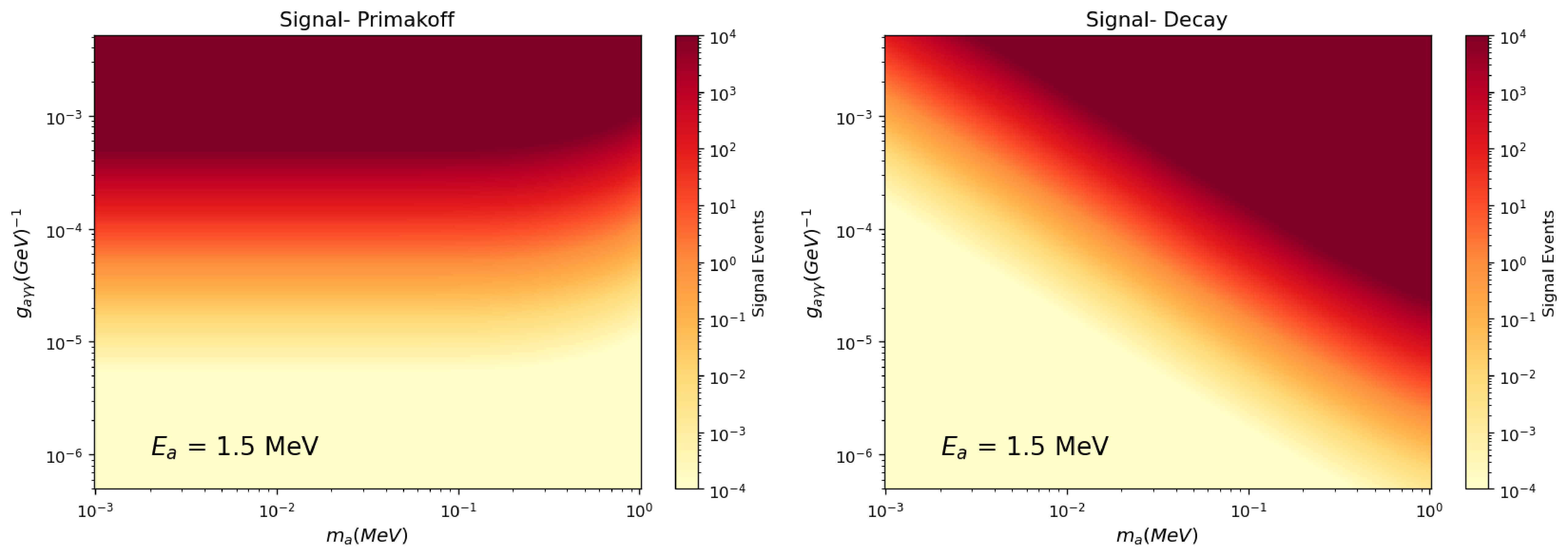
$$\text{Signal}_{\text{Prim.}} = \Phi_a \times \sigma_{a\to\gamma} \times (N_T \times T)$$

Anirudh Chandra Shekar anirudhcs@tamu.edu

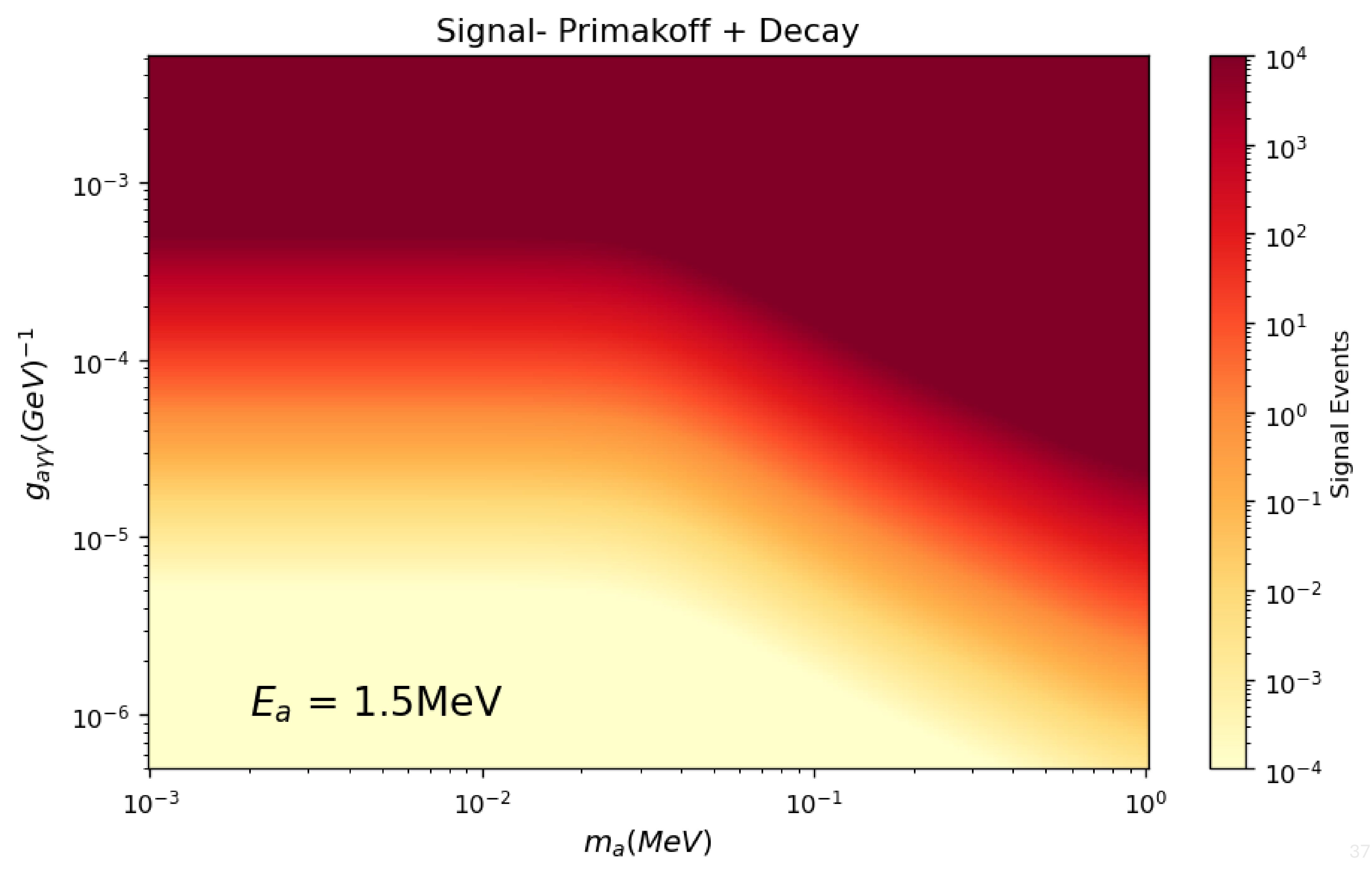
PRELIMINARY SENSITIVITIES

Anirudh Chandra Shekar anirudhcs@tamu.edu

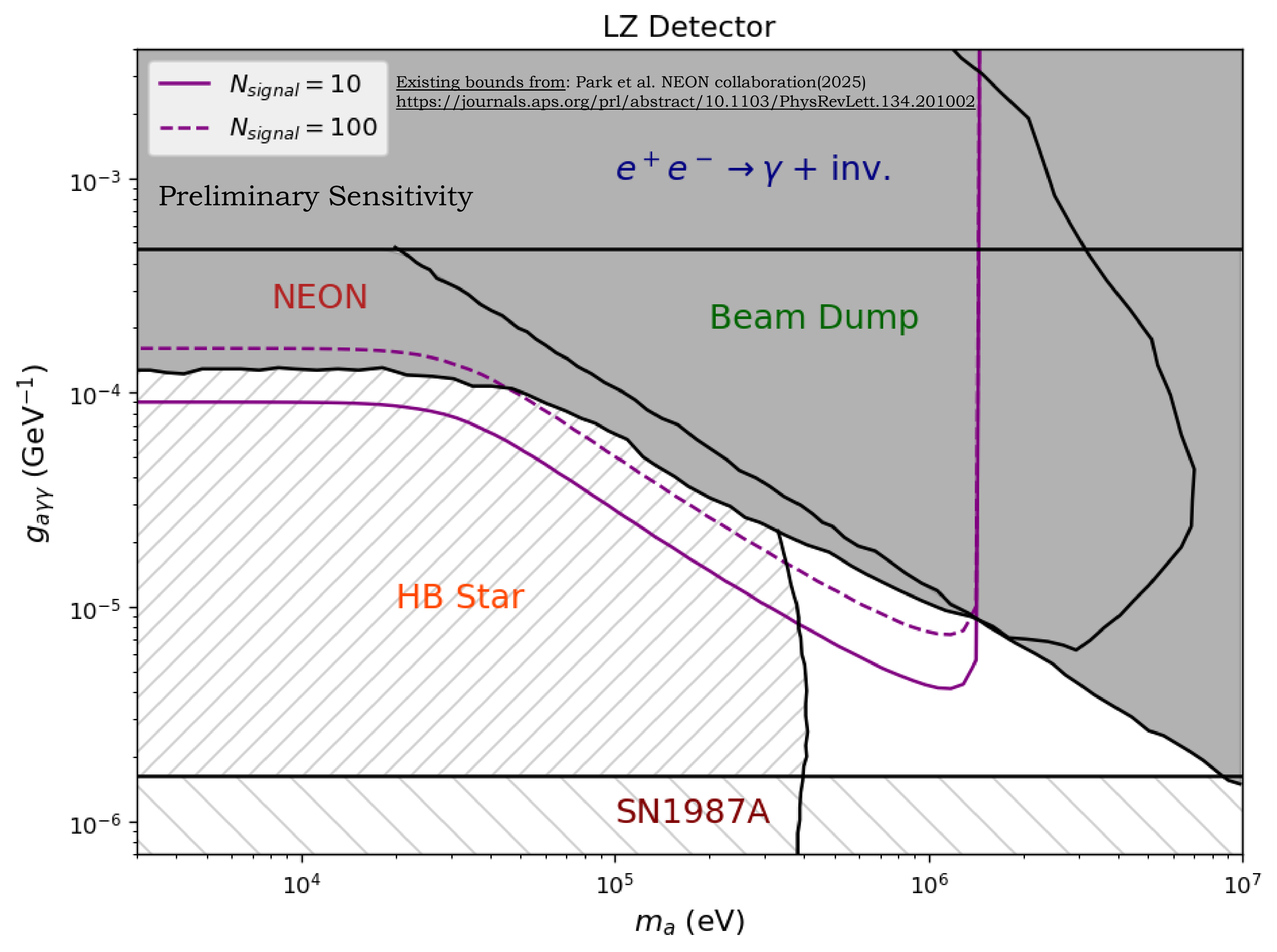
Signal Events from Primakoff and Decay



Anirudh Chandra Shekar anirudhcs@tamu.edu



Anirudh Chandra Shekar anirudhcs@tamu.edu



LZ Detector-

Fiducial Mass = 5 tonne

T = 10 years

Radius = 75 cm

Length = 150 cm

h Chandra Shekar anirudhcs@tamu.edu

Future Directions

I. Implementing a detailed detector background analysis into current work.

II. Currently investigating probing the axion-nucleon coupling $g_{a\mathrm{NN}}$.

- $g_{a\mathrm{NN}}$ production is via nuclear M1 transitions in the Earth's crust and mantle.

III. Working on probing the axion-electron coupling g_{ae}.

- The Earth's core can be a potential source for axion production via electron Bremsstrahlung process.

Conclusions

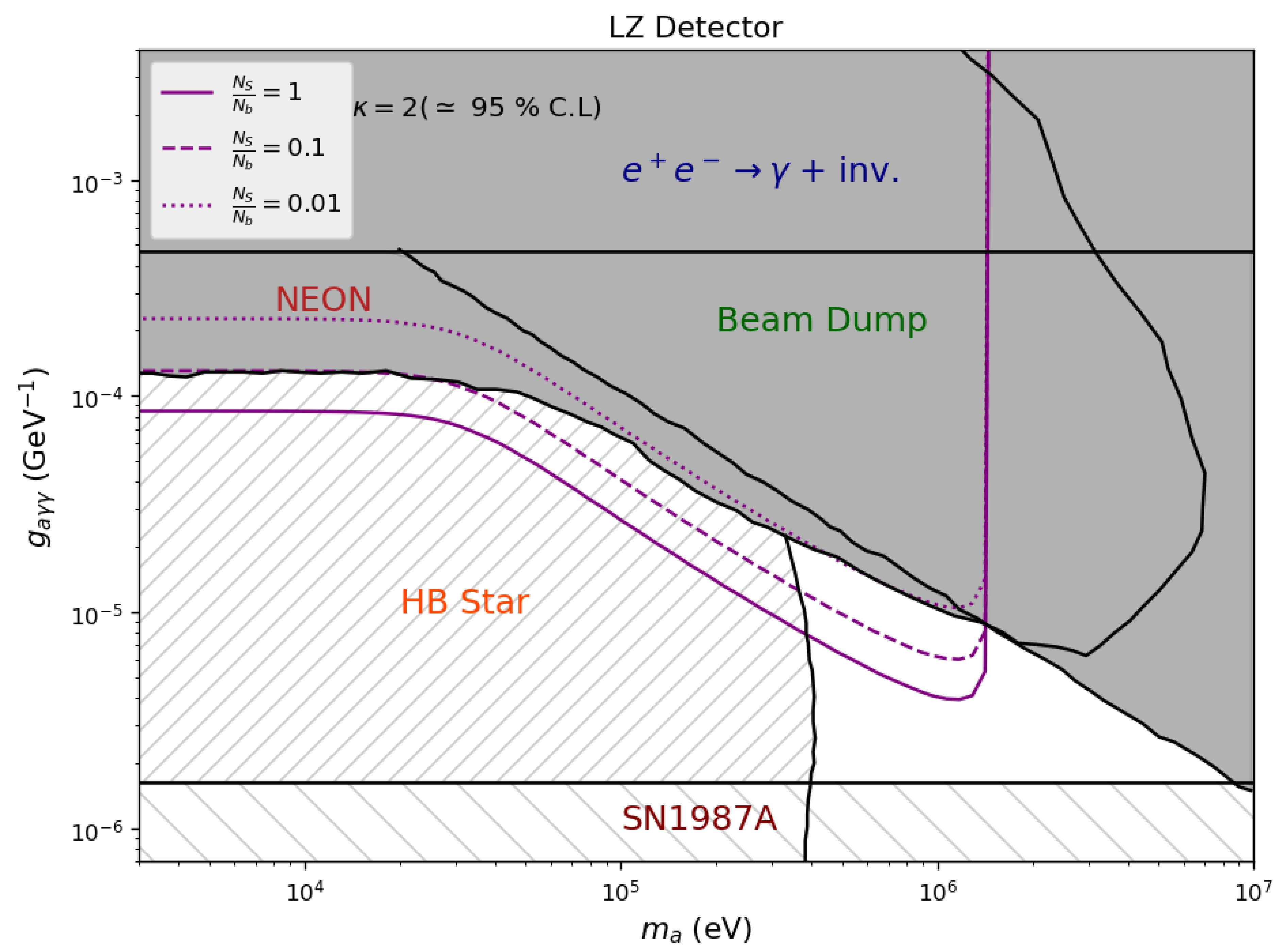
I. The Earth could be an important playground for probing axion sensitivities in previously unexplored regions.

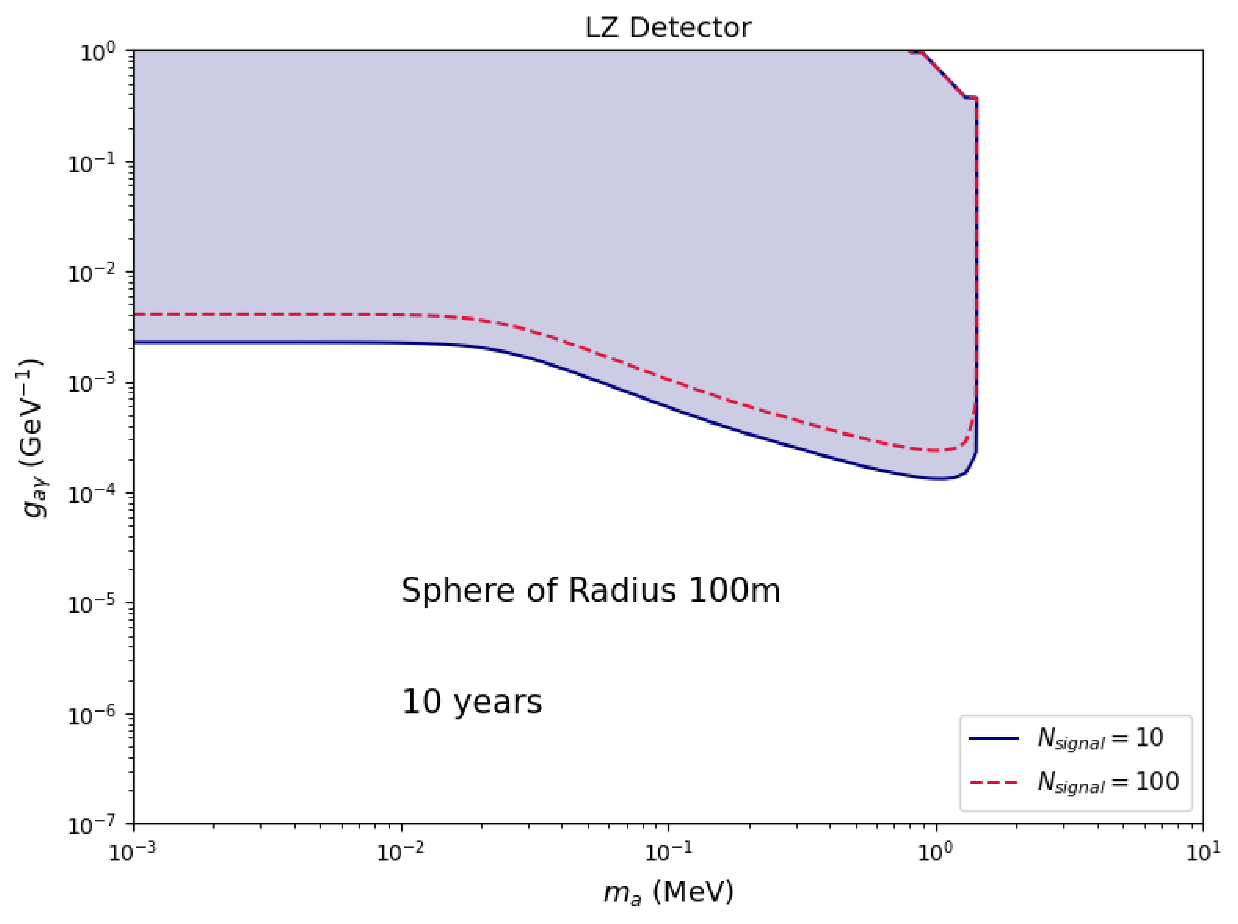
II. Opportunity to place laboratory-based constraints from an ALP factory which is right beneath us.

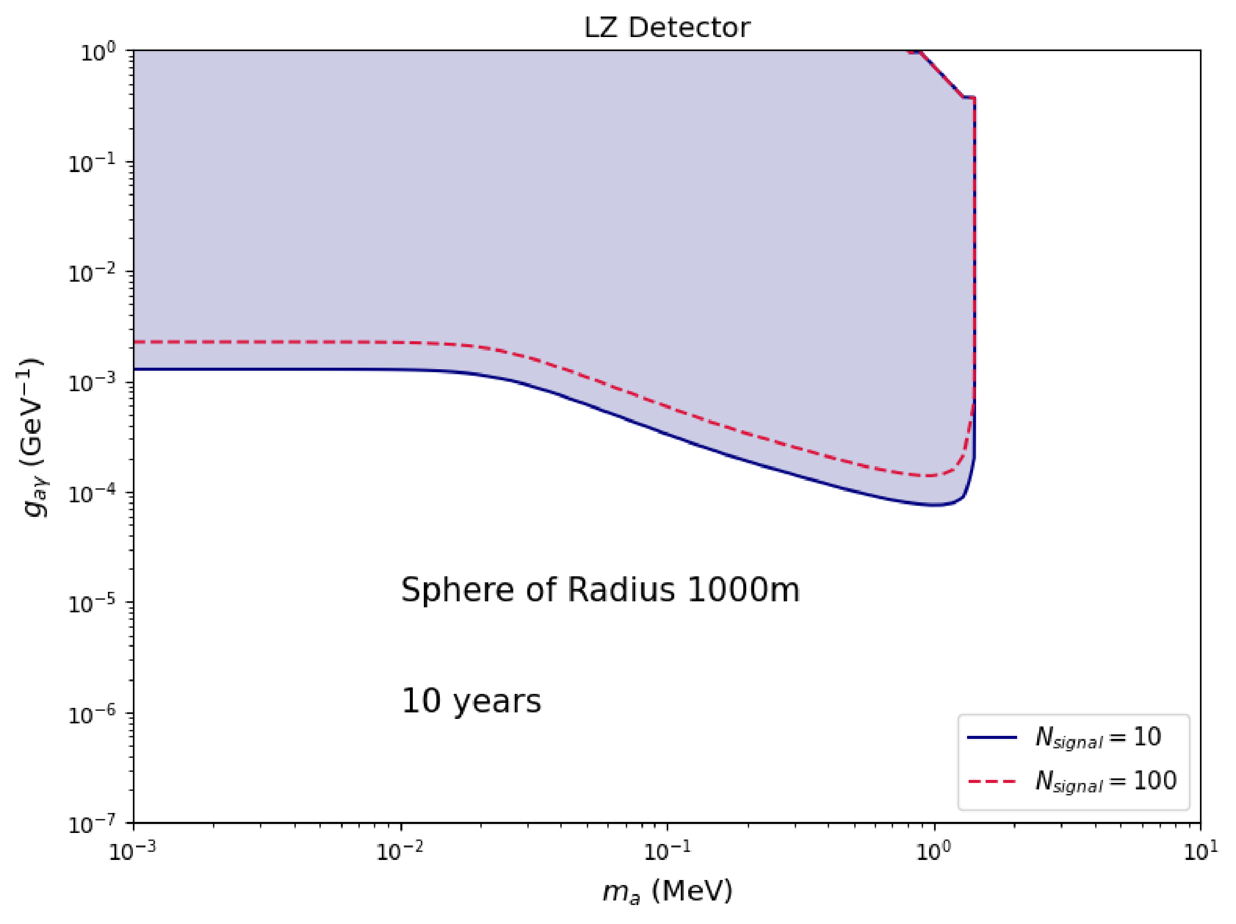
Anirudh Chandra Shekar anirudhcs@tamu.edu

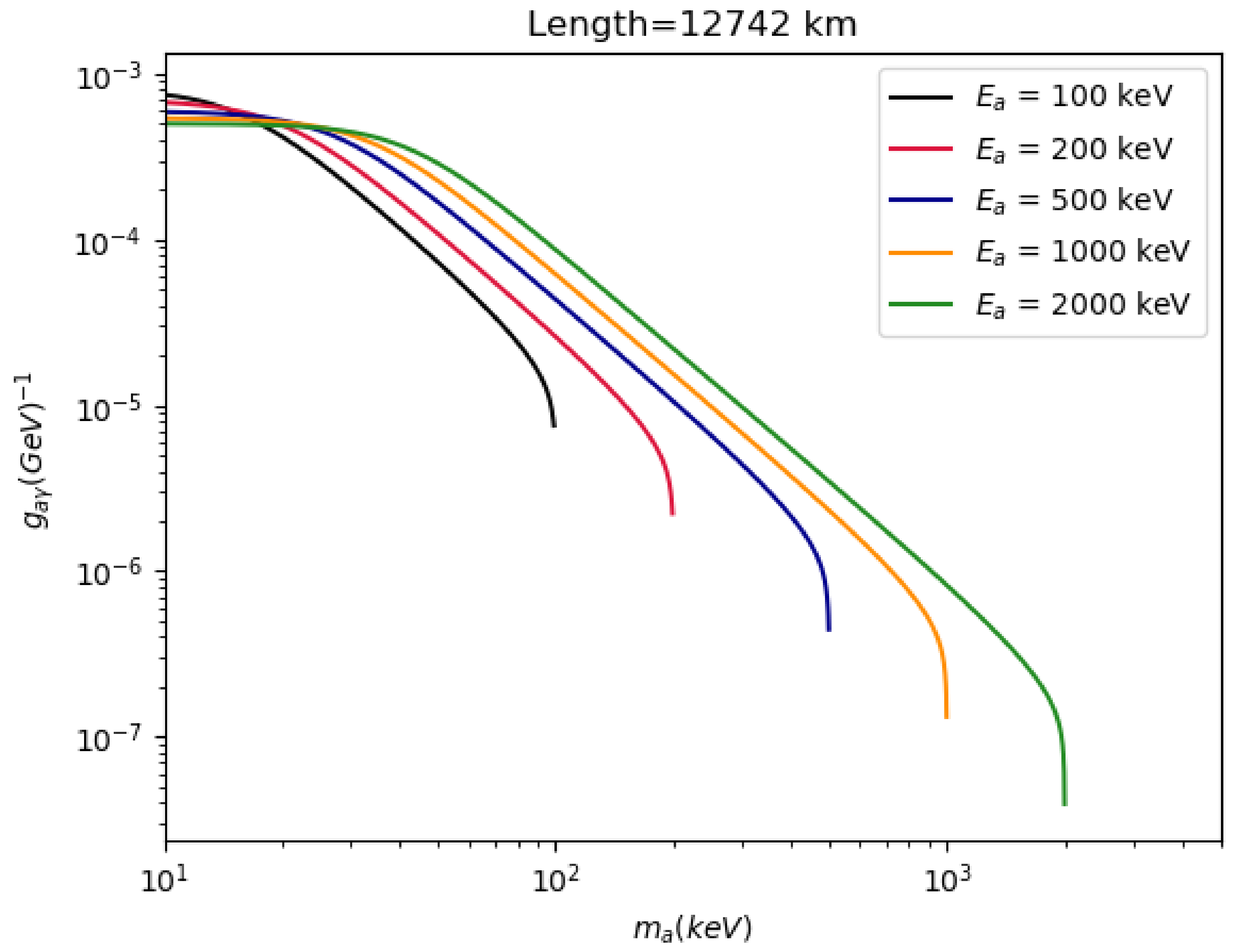
THANK YOU

SUPPLEMENTAL


LZ Detector
$\frac{N_S}{N_b} = 1$
$\frac{N_S}{N_b} = 0.1$
$\frac{N_S}{N_b} = 0.01$
$\kappa = 2(\simeq$ 95 % C.L)
$e^+e^- \to \gamma$ + inv.
NEON
Beam Dump
HB Star
SN1987A
$g_{a\gamma\gamma}$ (GeV^{-1})
m_a (eV)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{4}
10^{5}
10^{6}
10^{7}


LZ Detector
$g_{a\gamma}$ (GeV^{-1})
m_a (MeV)
Sphere of Radius 100m
10 years
$N_{signal} = 10$
$N_{signal} = 100$


LZ Detector
$g_{a\gamma}$ (GeV^{-1})
m_a (MeV)
Sphere of Radius 1000m
10 years
$N_{signal} = 10$
$N_{signal} = 100$


Length=12742 km
E_a = 100 keV
E_a = 200 keV
E_a = 500 keV
E_a = 1000 keV
E_a = 2000 keV
$g_{a\gamma}(GeV)^{-1}$
$m_a(keV)$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{1}
10^{2}
10^{3}

M1 Transition

$$\Phi = \frac{\Gamma_a}{\Gamma_\gamma} \frac{n_{M1}(SR) R_E}{2} \sum_{\text{Shells}} \frac{M}{V_{\text{shell}}} f(r_{\text{in}}, r_{\text{out}}, R_E)$$

M1 Transition

$$\Phi = \frac{\Gamma_a}{\Gamma_\gamma} \frac{n_{M1}(SR)R_E}{2} \sum_{\text{Shells}} \frac{M}{V_{\text{shell}}} f(r_{\text{in}}, r_{\text{out}}, R_E)$$

Number of M1 transition per parent decay

$$(n_{M1})_{\text{U}} = (n_{M1})_{\text{Th}} \approx 1$$

M1 Transition

$$\Phi = \frac{\Gamma_a}{\Gamma_\gamma} \frac{n_{M1}(SR)R_E}{2} \sum_{\text{Shells}} \frac{M}{V_{\text{shell}}} f(r_{\text{in}}, r_{\text{out}}, R_E)$$

Branching Ratio for M1 transitions

$$\frac{\Gamma_a}{\Gamma_\gamma} = \frac{1}{2\pi\alpha} \left(\frac{k_a}{k_\gamma}\right)^3 \frac{1}{1+\delta^2} \left(\frac{g^0_{aNN}\beta + g^1_{aNN}}{(\mu_0 - \frac{1}{2})\beta + \mu_1 - \eta}\right)^2$$

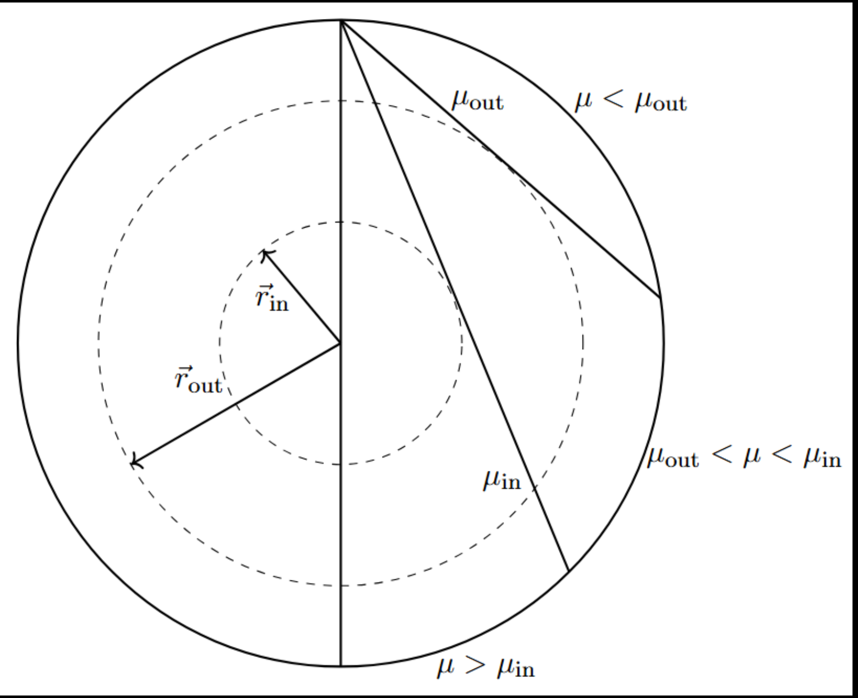
Ratio of E2 to M1 transitions

Nuclear structure parameters

$$\mu_0 = \mu_p + \mu_n$$
$$\mu_1 = \mu_p - \mu_n$$

Isoscalar and Isovector Magnetic Moments

Uniform Shell Approximation



$$f(r_{\text{in}}, r_{\text{out}}, R_E) = \frac{r_{\text{out}} - r_{\text{in}}}{R_E} - \frac{1}{2}\frac{R_E^2 - r_{\text{out}}^2}{R_E^2}\ln\left(\frac{R_E + r_{\text{out}}}{R_E - r_{\text{out}}}\right) + \frac{1}{2}\frac{R_E^2 - r_{\text{in}}^2}{R_E^2}\ln\left(\frac{R_E + r_{\text{in}}}{R_E - r_{\text{in}}}\right)$$

Geometric Factor