Constraining Sterile Neutrinos with pGRAMS and Future Detectors

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What is pGRAMS?

NASA

- pGRAMS: Prototype Gamma-Ray and AntiMatter Survey*
- Balloon experiment flying 30,000 m over Sweden/New Zealand, and uses a Liquid Argon Time Projection Chamber (LArTPC),
- Goal: study cosmic gamma rays in the MeV range

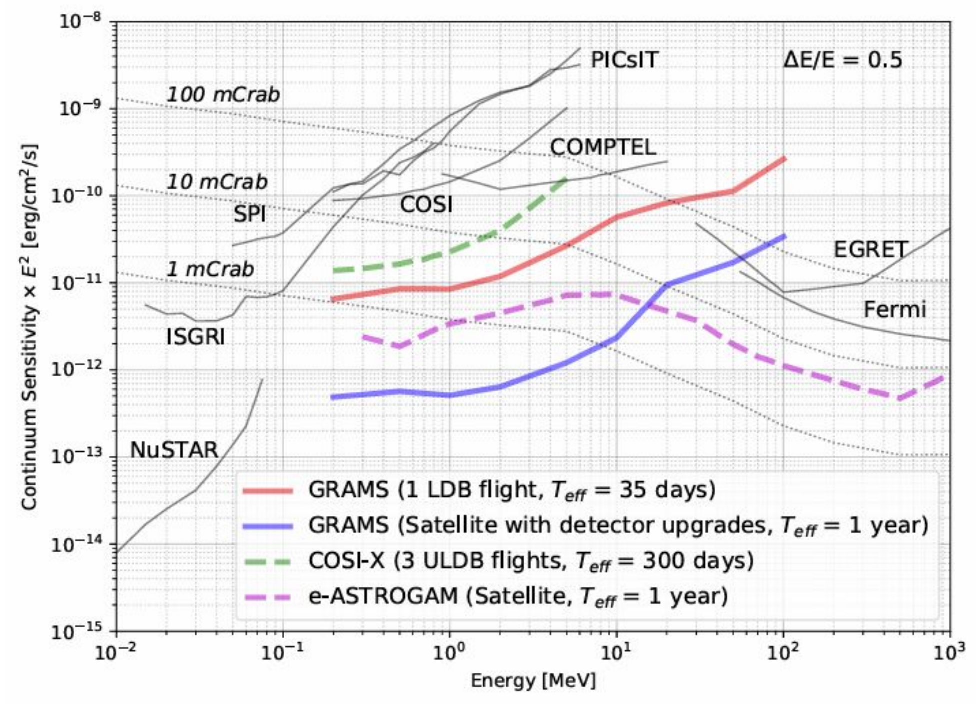
*This talk focuses on gamma rays, although the antimatter survey is very interesting for detecting antideuterons produced in dark matter self-interactions.

GRAMS

pGRAMS test flight
2026

First pGRAMS LDB
Science flight
~ 2028

First GRAMS LDB
Science flight
~ 2030



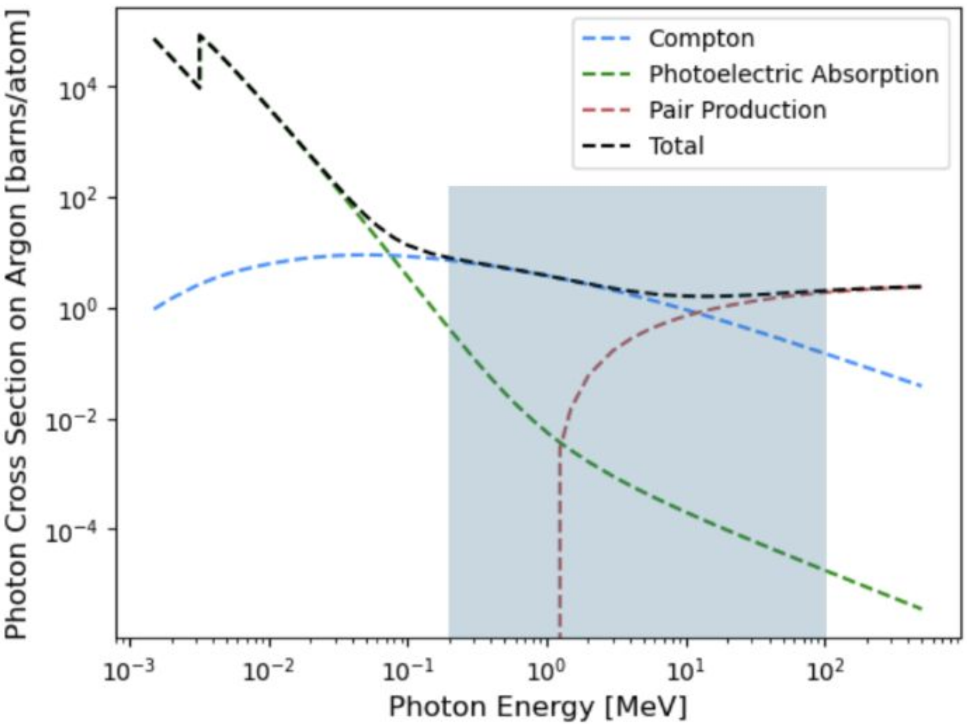
arXiv:1901.03430v3

- GRAMS is the successor to pGRAMS: LDB/satellite mission to take more detailed data of the gamma-ray sky.
- Advantages of future detectors:
  - Larger argon volume, allows for more reconstruction of high energy events
  - Longer runtime
  - Satellite mission has far less background flux

Motivation: The MeV Gap

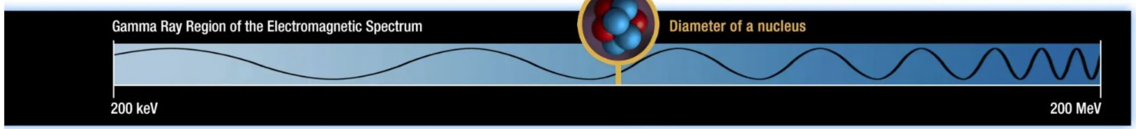
- Due to the **variety of processes** that occur in the .1 - 100 MeV range, these gamma rays are particularly difficult to study.
- Leads to **decreased sensitivity** in this energy band.

NIST XCOM

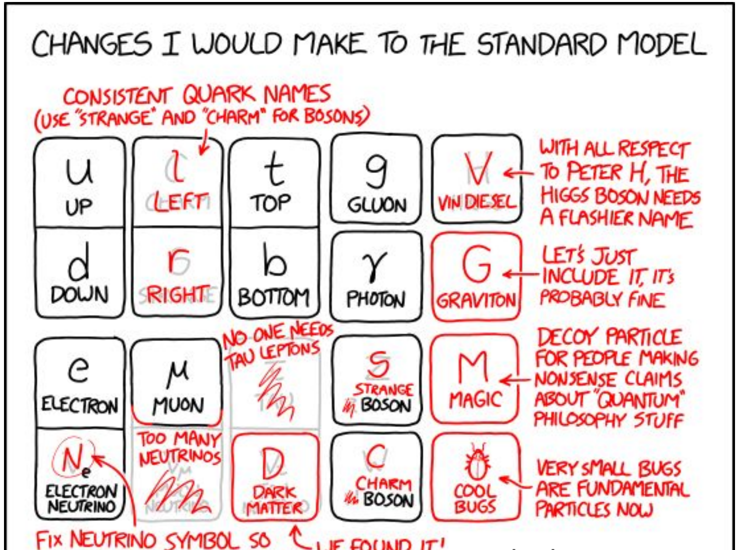


Why Gamma Rays?

Gamma Rays - NASA Science

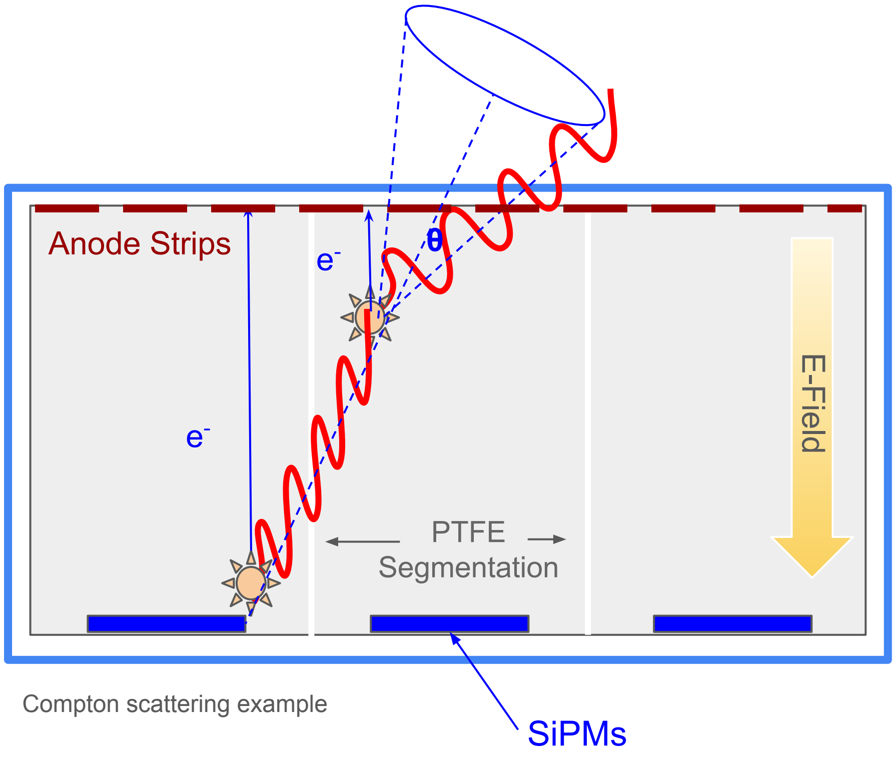


- Produced in the highest energy processes in the universe
  - AGN, Neutron star mergers, **supernovae**
- Excellent messengers because they travel almost entirely unimpeded through the universe due to nucleus-scale wavelength
- Potential new gateway into **neutrino physics** and **dark matter**



xkcd

How does the GRAMS TPC Work?



Compton scattering example

1. Primary gamma ray **Compton scatters** off an Argon-bound electron, changing direction at an angle governed by the Compton equation. The interaction creates **scintillation light** and **ionization electrons**.
2. Scintillation light triggers the SiPMs (photon detectors). This **sets the time** of the event. PTFE (Teflon) sheets helps to prevent scintillation light from different interactions being confused.
3. Ionization charge drifts agai the anode strips. These rec charge deposited and the **x** Compton scatter. Time difference between light trigger and charge detection sets **z location**.

$$E_{\gamma'} = \frac{E_\gamma}{1+(E_\gamma/m_e c^2)(1 -}$$

Energy Reconstruction

- Full energy reconstruction requires **two Compton scatters** and a **third interaction**.
  - These three points determine the scattering angles of the photon
- We also need the **energies** of the Compton scattered electrons to determine the amount of deposited energy.

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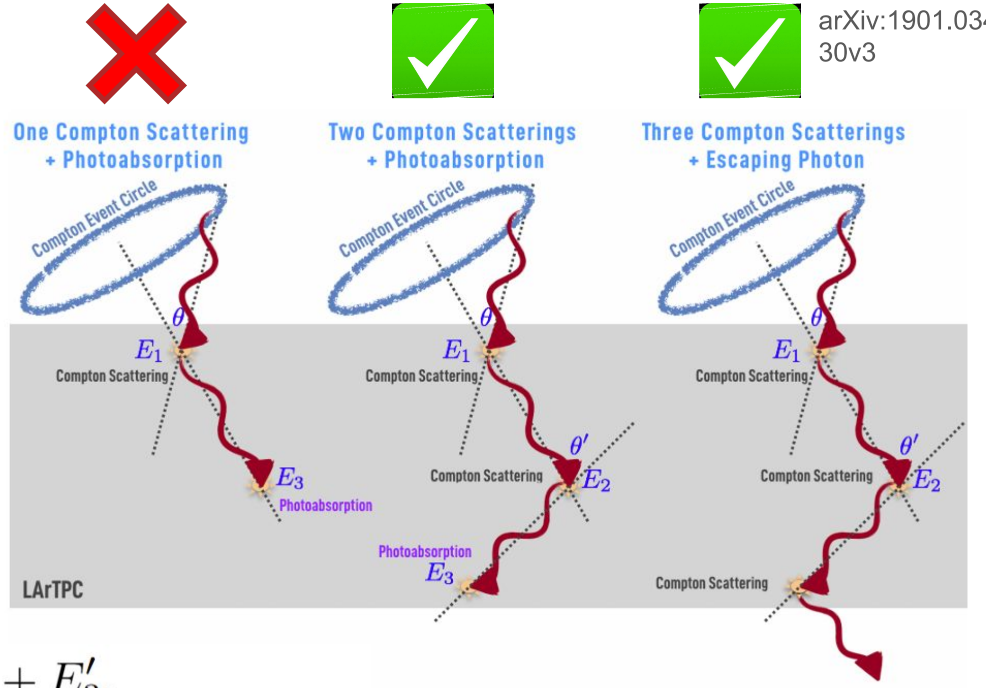
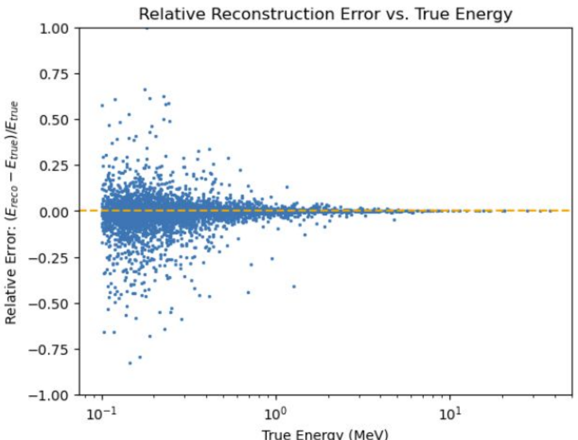


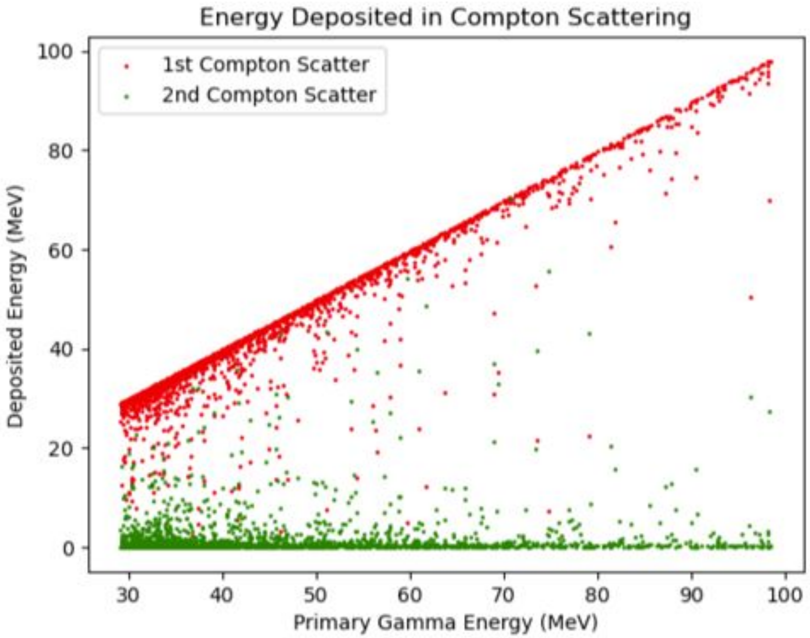
$$E = E_1 + E_2 + E_3',$$

$$E_3' = -\frac{E_2}{2} + \sqrt{\frac{E_2^2}{4} + \frac{E_2 m_e c^2}{1 - \cos\theta'}}$$

Challenges with Compton Energy Reconstruction

- Low Energies
  - Doppler Broadening
- High Energies
  - Close Compton Scatters
  - Pair Production
  - Bremsstrahlung Photons

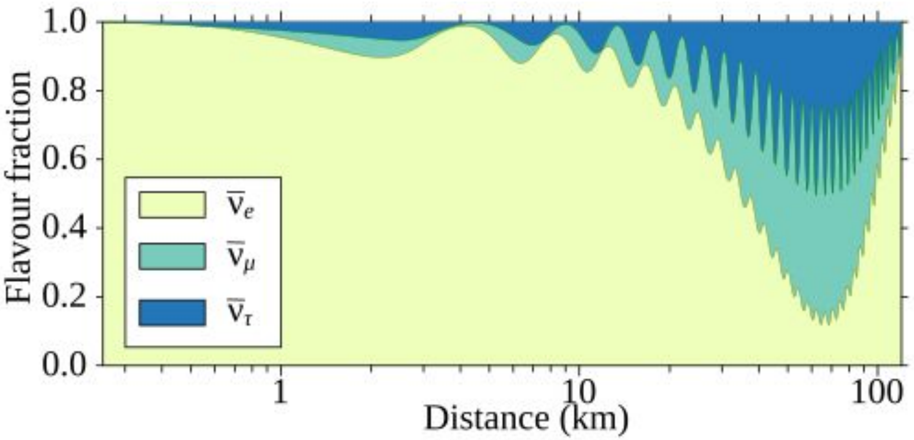




Active Neutrinos

DOI: 10.1038/ncomms7935

- Very weakly interacting particles of the Standard model, only interact via the weak force and gravity.
- Neutrino oscillations observed in multiple experiments (Super-Kamiokande, SNO).
    - Implies that neutrino flavor eigenstates and mass eigenstates are not equivalent, relationship defined by the PMNS matrix.



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

U = mixing angle

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Sterile Neutrinos

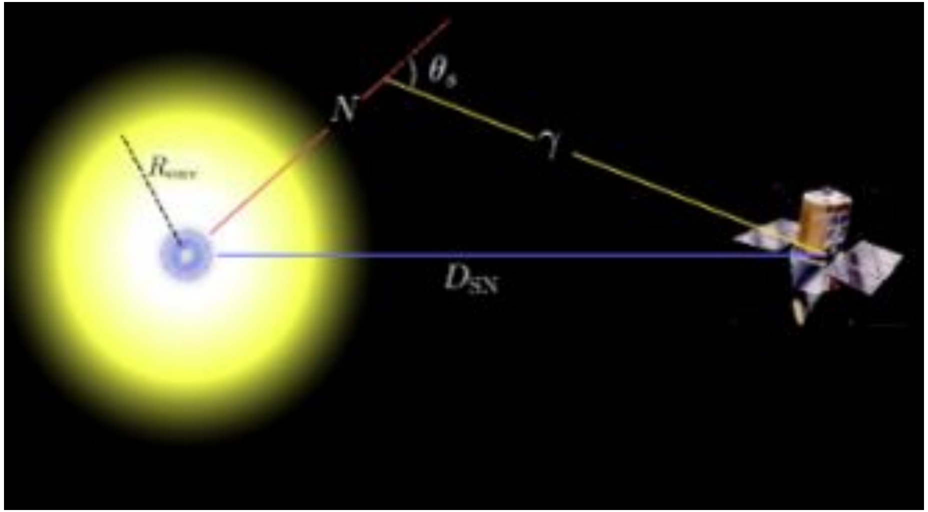
- Right handed neutrinos, only interact via gravity*.
- Assuming that the flavor and mass eigenstates of the sterile neutrino are not identical, the sterile neutrino wave function would have a non-zero left-handed component (i.e., $\mathbf{v}_e$, $\mathbf{v}_\mu$, or $\mathbf{v}_\tau$) allowing for suppressed weak force interactions.
- In contrast to the active neutrino masses, sterile neutrinos would have mass on the order of MeV.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_N \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{N1} & U_{N2} & U_{N3} & U_{N4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

For small sterile mixing angles, take $M_N \cong M_4$

*weak force only affects left-handed particles

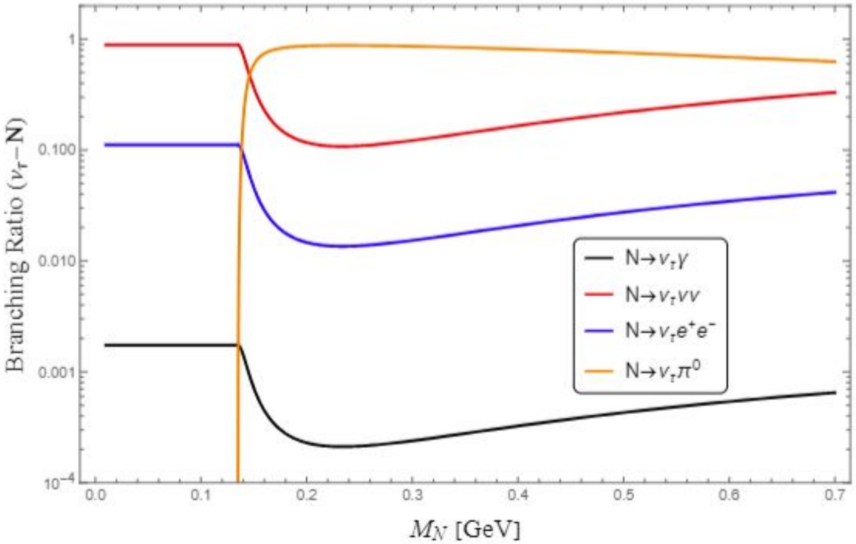
Sterile Neutrino Production in Supernovae



arXiv:2503.13607v1

- If right-handed sterile neutrinos exist, they would be generated in core-collapse supernovae.
  - Assume production at the center
- Due to the massive neutron density in the proto-neutron star, production via $\mathbf{v}_l + n \rightarrow \mathbf{v}_N + n$ dominates
- The sterile neutrinos travel radially outwards and decay.
  - Occurs long before the full light-emitting supernova, avoiding the additional gamma ray background

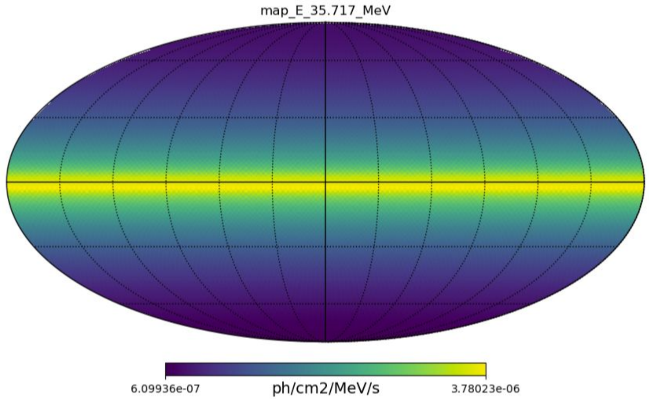
Sterile Neutrino Decay

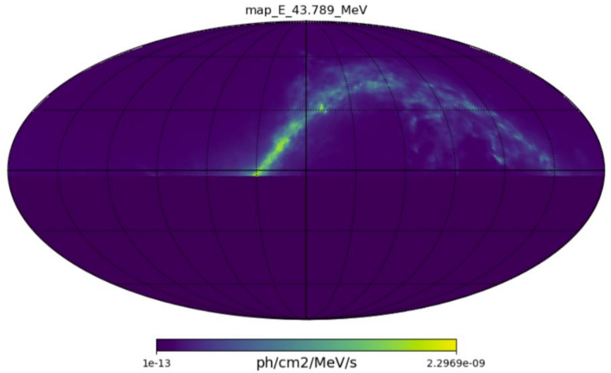


- Decay products depend on the mass of the sterile neutrino.
- Below the pion threshold (~135 MeV), the only process that produces gamma rays is decay to **lepton neutrino and photon**.
- Above 135 MeV, **production from pion decay** becomes accessible.
- Production and decay both increase with larger squared mixing angle
- These are the gamma rays we hope to see in (p)GRAMS in the event of a supernova

Gamma Ray Background

- Before we can find sensitivity to new flux, we must consider background fluxes.
  - Predominantly from atmospheric cosmic ray showers
  - Negligible contributions from cosmic diffuse emission (< .1%), but will be important for a GRAMS satellite
- For simplicity, assumed high efficiency in rejecting charged particles and nuclear recoils, so we only consider photons.
- Additionally, we also assume for simplicity that the supernova occurs directly above the detector.
  - (Yes, this particular choice is optimistic)

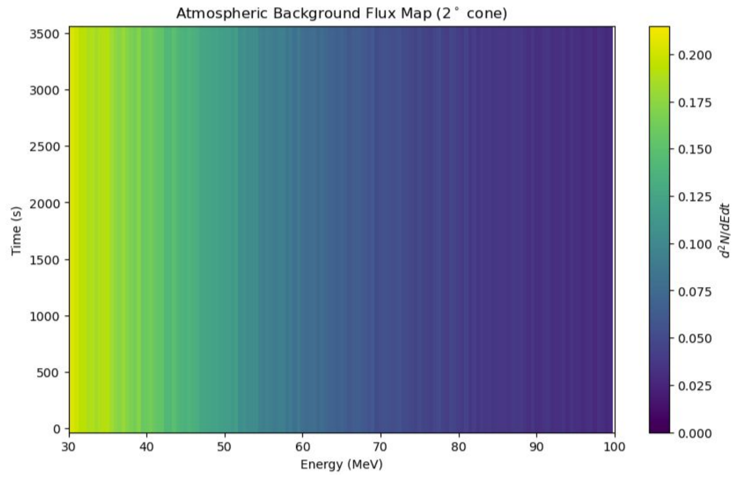


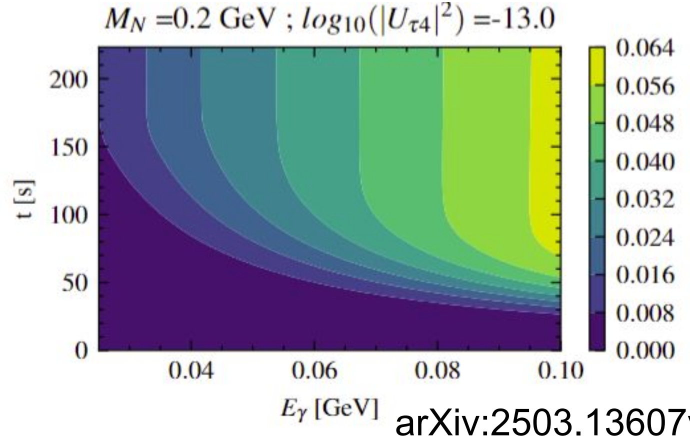


Top: Secondary photons from cosmic rays.
Bottom: Photons from the cosmic diffuse gamma-ray background

Signal/Background Flux Maps

- Twice-differential flux maps in energy and time are created for gamma ray fluxes on Earth
  - Distance to supernova = 10 kpc
- Assume that the atmospheric background flux is time independent over the span of 1 hour (sampling time).
  - Time = 0 is for the first detected neutrino event (not by pGRAMS, by a separate neutrino detector)
- Our sensitivity will depend on how well we can differentiate between the background-only distribution and the signal-plus-background distribution





arXiv:2503.13607v1

Significance Level Calculation Preparation

- Simulate particle generation and LAr interactions of primary gamma rays. The GRAMS simulation software does not include time dependence, so simulations were run for individual time bins
- To reconstruct the energy and position of primary gamma rays, we only accept events that undergo two Compton scatters and a third Compton scatter/absorption. Reject events that do not fit this criteria.
    - Leads to a different distribution than initially sampled
- Event amounts in each bin are scaled to reflect the physical flux, rather than the number of events that GramsSim generates.
- Sterile neutrino decay signal is multiplied by an attenuation factor (.83 for a 30 km balloon) to account for scattering in the upper atmosphere.

Likelihood Testing

- Now that the counts in each energy/time bin are more physically accurate, we run a likelihood test over all 50x140 = 7,000 bins
- Simulate Poisson noise* over each energy/time bin calculate test statistic of that distribution against the original background distribution.
  - Repeated O(10,000) times
- Calculate p-value by finding the number of “noised” events that have higher test statistic than the signal+background test statistic.

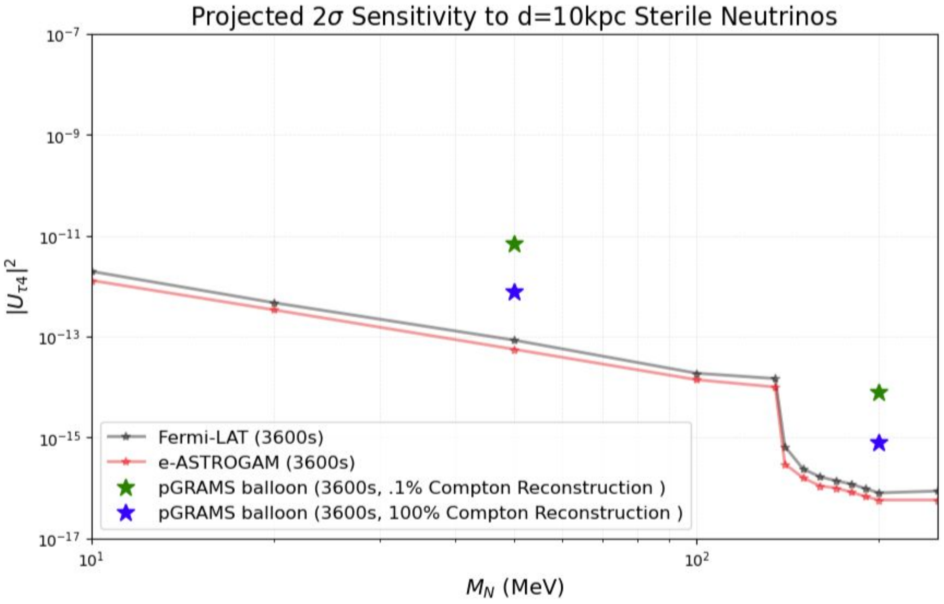
$$\ln \lambda = -\sum_i \left(n_i \ln \frac{n_i}{v_i} + v_i - n_i \right)$$

n = background only, v = background and signal. Sum over all energy bins to calculate the log test statistic.

*A chi-squared test is often used to determine the significance level from a likelihood ratio, but low counts make this invalid

Preliminary Result!

- Probing of squared mixing angles to 10^-12.1 and 10^-15.1 for 50 MeV and 200 MeV sterile neutrino masses, respectively.
- Significance largely depends on our ability to reconstruct high-energy events.
- Running on GRAMS-size detector is slightly better (more area, better reconstruction ability), but atmospheric background is still the primary constraint.



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Summary and Next Steps

- The (p)GRAMS LAr TPC technology allows for reconstruction of energy and position of astrophysical signals from MeV gamma ray sources
- Using detector simulations, we've created a workflow to study the sensitivity of (p)GRAMS to these cosmic signals.
- In the case of sterile neutrino decay, we have demonstrated initial capabilities of pGRAMS to limit mass/mixing angle parameter space, suggesting optimism for a future GRAMS detector

- Run on finalized pGRAMS geometry and future detector geometries.
- Develop reconstruction algorithms to better understand our effective area for 30 - 100 MeV gamma rays.
- Testing of ability to reject charged particles and neutrons.
- Developing a deeper understanding of how sterile neutrino production and decay depend on mixing angle and mass to test more points in parameter space.

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Image Citations

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Thank you! Questions?