Axion-Like Particle Emission from Type Ia Supernovea

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Presentation Outline

-Primakoff process

-Axion spectrum from Type Ia Supernova

-Axion-photon propagation

-Magnetic field models

-Photon flux near the Earth

Objective

Evaluate the detection potential of photons originating from the conversion of axion-like particles produced in the Type Ia supernova SN2014J using next-generation gamma-ray telescopes.

Figure 1: SN 2014J in the M82 galaxy (HST

Primakoff Process

1951 — G. Primakoff's proposal:

- Original goal: study of $\pi^0 \to 2\gamma$ decay.
- Problem: difficulty measuring π^0-γ coupling in free decay.
- Solution: use of *external electromagnetic field* to amplify signal.

Process mechanism:

$$\pi^0 + \gamma_{\text{ext.}} \leftrightarrow \gamma + \gamma$$

Significance for astrophysics

- Became basis for ALP generation calculations in stars (e.g., Sun).
- Enabled connection between laboratory measurements and astrophysical observations.

Energy Release in SN Ia

Rewrite energy release per unit volume as:

$$Q = Q\left(\frac{M_r}{M}, t\right) = \int_0^{\infty} \frac{dQ}{d\omega}\left(\frac{M_r}{M}, t\right) d\omega$$

Type Ia supernova spectrum (7):

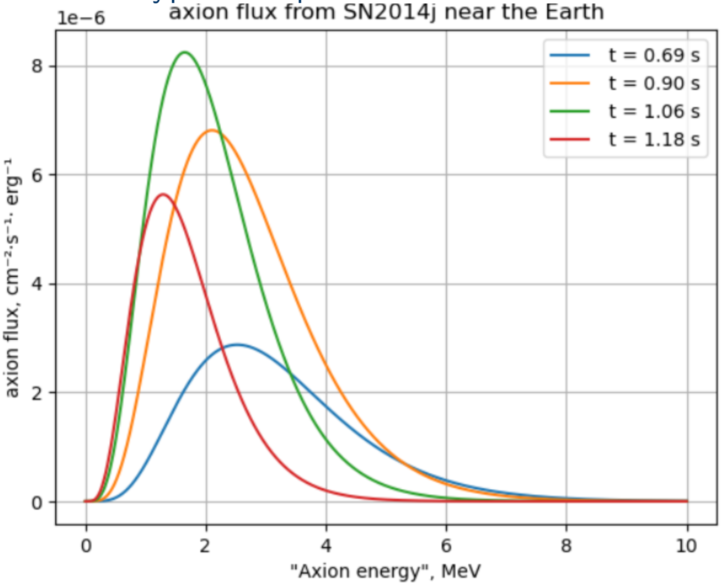
$$I(t) = \frac{dQ}{d\omega}(t) = \int_0^{R} \frac{dQ}{d\omega}\left(\frac{M_r}{M}, t\right) 4\pi r^2 dr$$

Core Composition

The star is modeled as a carbon-oxygen white dwarf consisting of an electron-nuclear plasma with ^{12}C and ^{16}O nuclei:

$$\left(Y_e + \sum_j Z_j^2 Y_j\right) \approx 4.0$$

Axion Spectrum from Type Ia Supernova



Von Neumann Formalism

Liouville equation for density matrix:

$$i\frac{d\rho(y)}{dy} = [\rho(y), M(\omega, y)] \tag{5.1}$$

Mixing matrix M:

$$M = \frac{1}{2}\begin{pmatrix} 0 & 0 & -ig_{a\gamma\gamma}B_1 \\ 0 & 0 & -ig_{a\gamma\gamma}B_2 \\ ig_{a\gamma\gamma}B_1 & ig_{a\gamma\gamma}B_2 & m_a^2/E \end{pmatrix} \tag{5.2}$$

Physical meaning

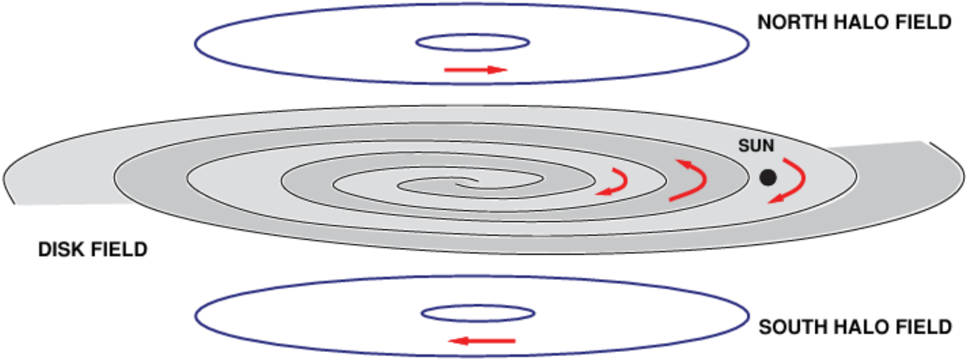
Sum of diagonal photon state elements gives probability to observe unpolarized photon at distance y from source.

- B_1, B_2 - magnetic field components along photon polarizations (requires inclusion of galactic MF models)

Galactic Magnetic Field Model (M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg, and K. J. Newton-McGee)

Two main components:

- Disk field
- Halo field



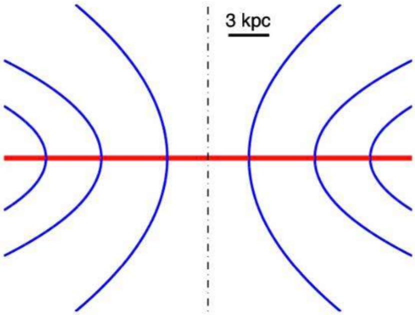
X-shaped Magnetic Field Component

Structure:

- Vertical symmetry resembling letter "X"
- Extent: up to 3 kpc from disk plane
- Observed near galactic center

Origin:

- Formed by:
  - Vertical gas flows
  - Central black hole activity
  - Galactic winds
- Related to turbulence and field line reconnection



X-shape magnetic field

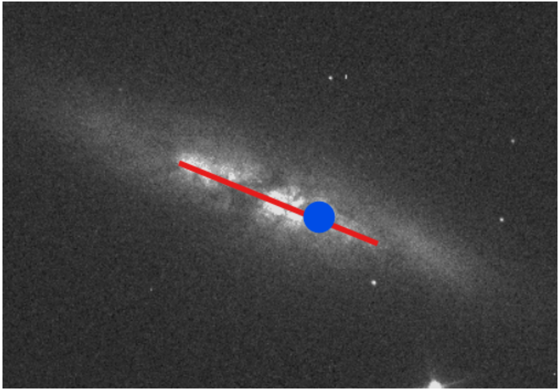
Significance

- Affects cosmic ray propagation
- Indicates active processes in galactic nucleus
- Differs from classical disk and halo fields

M82 Galaxy

Combined model with:

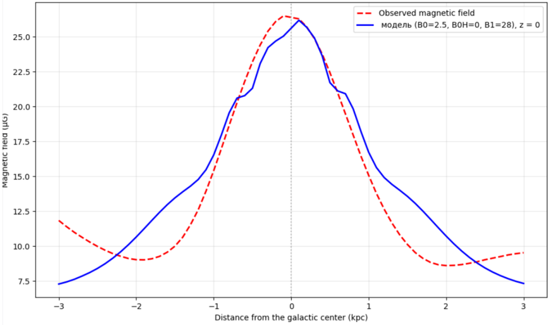
- Disk filed
- Halo filed
- X-shaped component



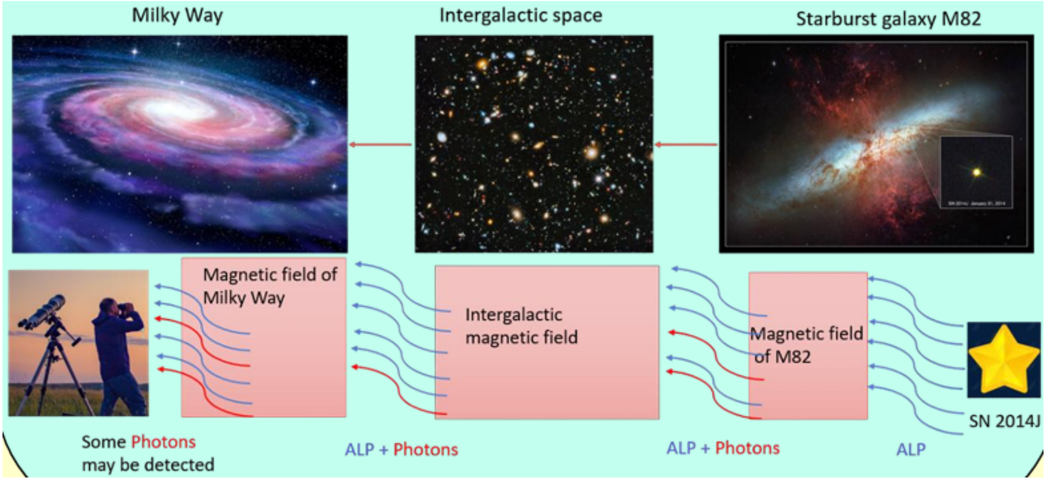
M82 Galaxy

- Fitting model with observations:

$$< B > (x) = \frac{\int_{-y(x)}^{y(x)} B_{model}(x, y')\rho(y')dy'}{\int_{-y(x)}^{y(x)} \rho(y')dy'}$$

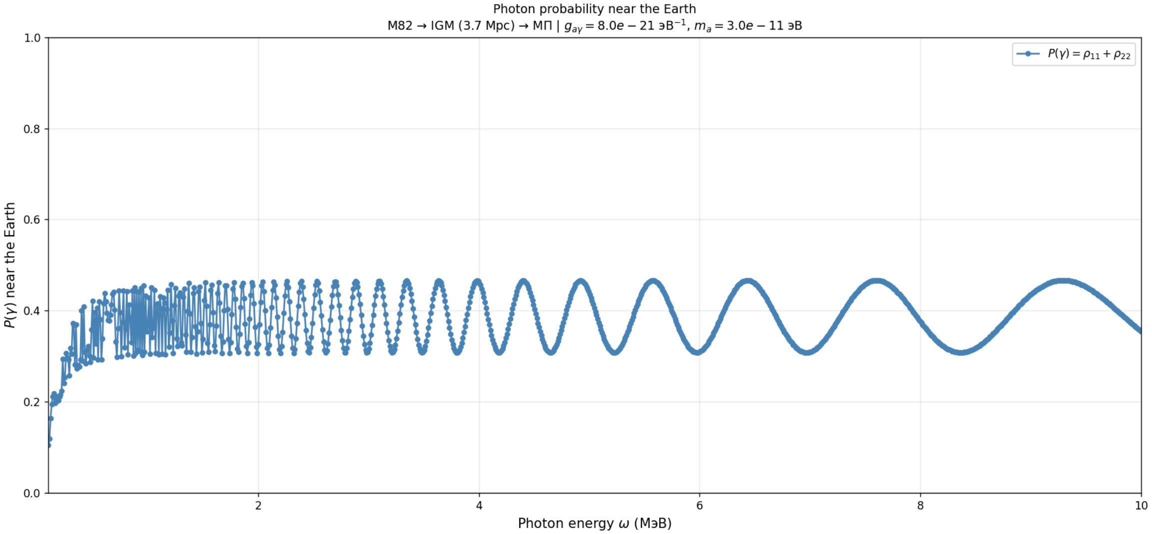


Main idea

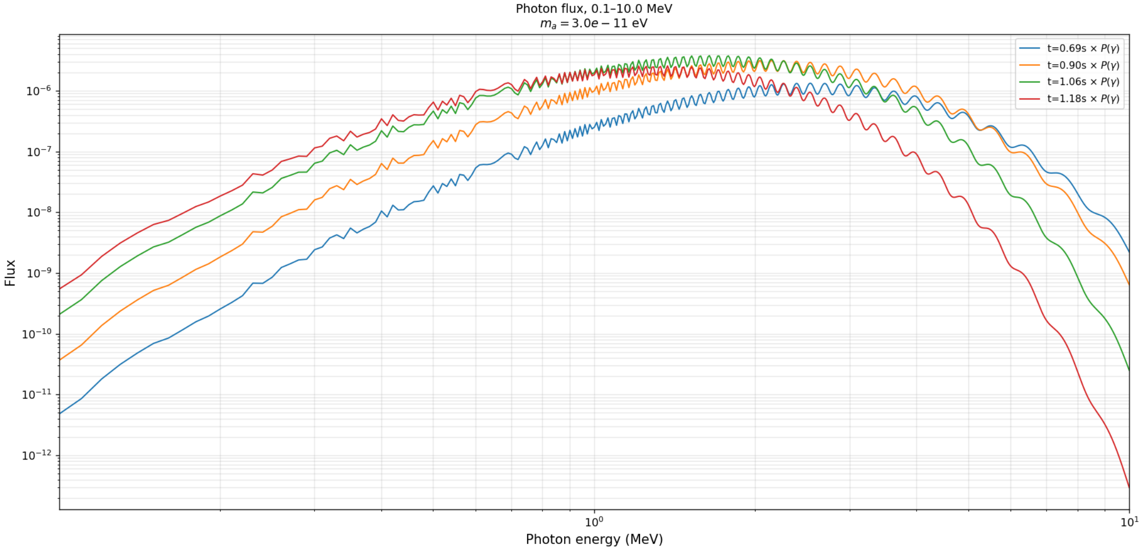


Milky Way
Intergalactic space
Starburst galaxy M82
Magnetic field of Milky Way
Intergalactic magnetic field
Magnetic field of M82
SN 2014J
Some Photons may be detected
ALP + Photons
ALP + Photons
ALP

Photon probability near the Earth



Photon Flux Near the Earth



Results and Comparison with Detectors

Photon Fluence:

$$\mathcal{F} = \int dt \int dE \, \mathrm{flux}(E, t)$$

$$\mathcal{F} \approx 5 \times 10^{-12} \ \mathrm{erg} \cdot \mathrm{cm}^{-2}$$

Detector	Range	Sensitivity
AMEGO-X	100 keV–1 GeV	3×10^{-11} erg/(cm^{2}s)
E-Astrogam	0.3 MeV–3 GeV	6×10^{-12} erg/(cm^{2}s)

Conclusion

The expected signal is **potentially detectable** by future gamma-ray telescopes.

Prospects

- Extend the analysis to other Type Ia supernovae
- Develop a framework to search for similar signals from Type Ia supernovae
- Search for signals in telescope data (Fermi LAT)

Signal search: two photons with small arrival intervals

Core Idea:

- Search for two photons with a short arrival interval Δt, instead of searching for a continuous flux.
- From the Poisson distribution, the probability of observing two photons with an interval greater than Δt is known:

$$P(\Delta t > 3\,\mathrm{s}) = e^{-3\frac{N}{t_{\mathrm{obs}}}}$$

where N — number of photons during observation time t_{obs}.

Observational data for SN2014J:

Energy (MeV)	Arrival Time (20.01.2014)
34	21:21:07
33	21:21:10
66	21:27:49
68	21:28:05

Conclusion

Main Results:

1. Calculated the spectrum of axions produced in SN2014J (M82 galaxy) via the Primakoff process.
2. Applied the von Neumann formalism to calculate the axion-to-photon conversion probability in the magnetic fields of M82 and the Milky Way.
3. Computed the expected photon fluence at Earth: $\mathcal{F} \approx 5 \times 10^{-12}\ \mathrm{erg\,cm^{-2}}$.
4. Demonstrated that the signal falls within the sensitivity range of the AMEGO-X and E-Astrogam detectors.

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Thank you for your attention!