Phenomenology of Axion-Like Particle Emission from Type Ia Supernovae

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20th Patras Workshop on Axions, WIMPs and WISPs

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):

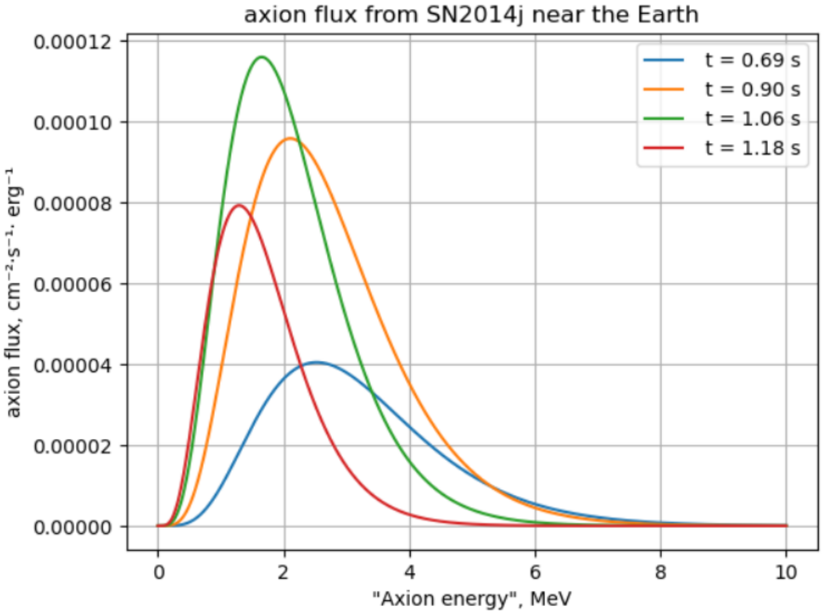
$$I(t) = \frac{dQ}{d\omega}(t) = \int_0^R \frac{dQ}{d\omega}\left(\frac{M_r}{M}, t\right) 4\pi r^2 dr$$

Key assumption

The star contains electron-nuclear plasma with hydrogen and helium nuclei:

$$\left(Y_e + \sum_j Z_j^2 Y_j\right) = 2.625 \tag{8}$$

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

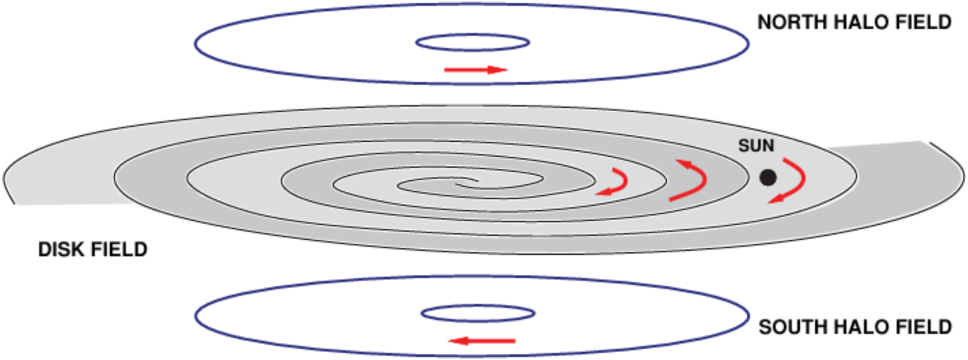
Sum of diagonal photon state elements gives probability to observe unpolarized photon at distance y from source.

- 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



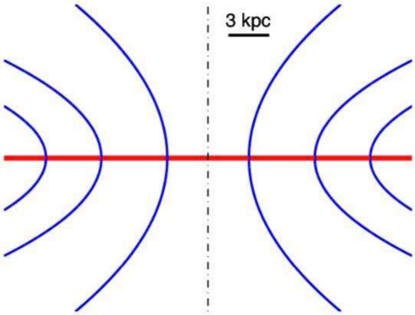
X-shaped Magnetic Field Component

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

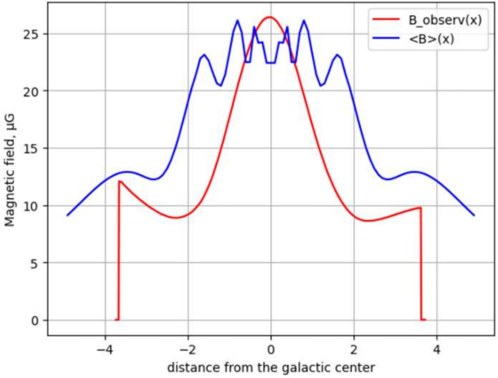
Магнитное поле M82

STEP 2

1.) Для сшивки модели и наблюдений мы определяем(при z = 0):

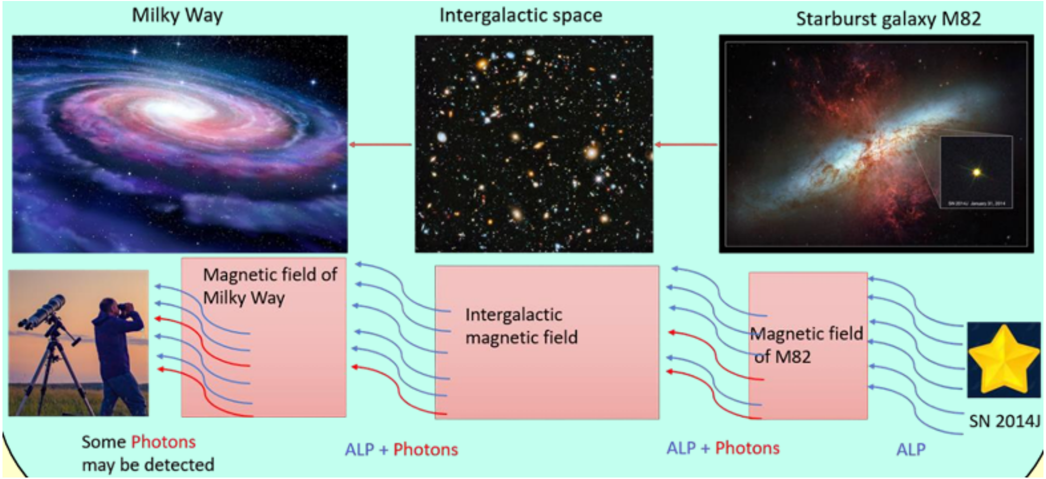
$$< B > (x) = \frac{\int_{-y(x)}^{y(x)} B_{model}(x, y')\rho(y')dy'}{\int_{-y(x)}^{y(x)} \rho(y')dy'}$$

2.) Then we plot both magnetic fields to obtain the best fit between them:

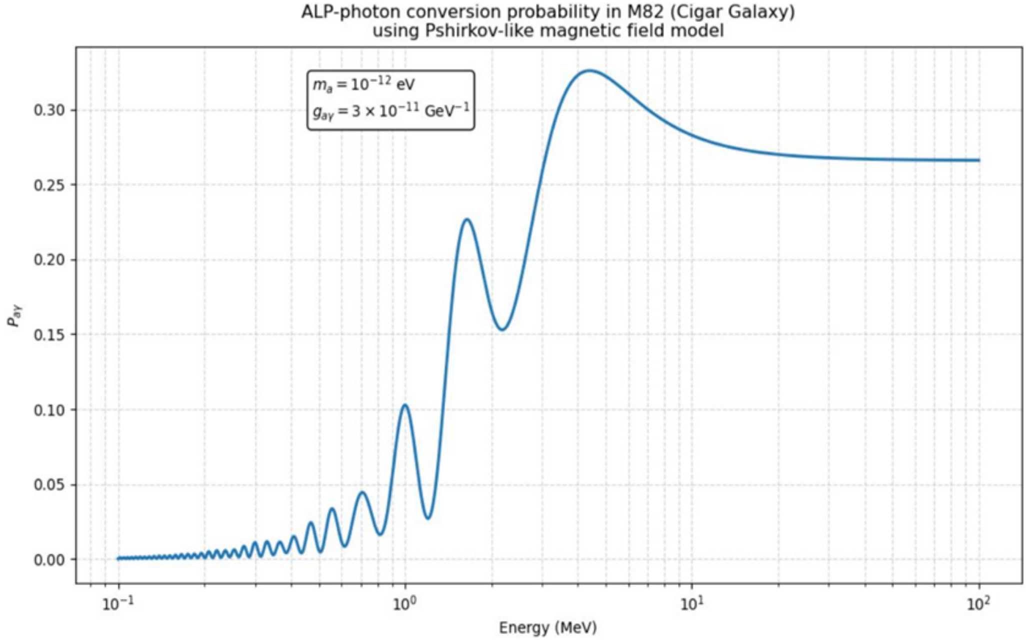


2.) В результате, мы определяем нормировку для параметров B_0 (для поля диска)и B_x (для X-shape).

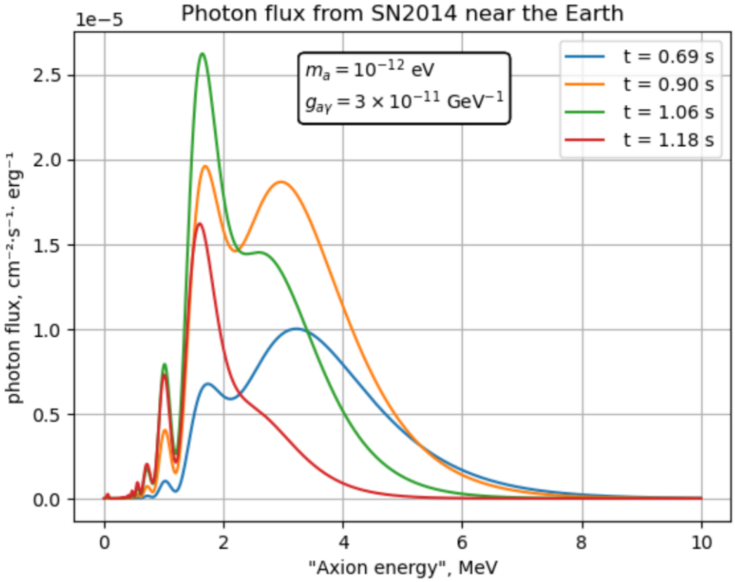
Main idea



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


ALP-photon conversion probability in M82 (Cigar Galaxy)
using Pshirkov-like magnetic field model
$m_a = 10^{-12}$ eV
$g_{a\gamma} = 3 \times 10^{-11}$ GeV^{-1}
$P_{a\gamma}$
0.00
0.05
0.10
0.15
0.20
0.25
0.30
10^{-1}
10^{0}
10^{1}
10^{2}
Energy (MeV)

Photon Flux Near the Earth



Comparison with instruments

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

$$\mathcal{F}luence = 1.52 \times 10^{-11}\ \text{erg cm}^{-2}$$

We recommend expanding the scope of research to include not only Type II supernovae, but also Type Ia supernovae.

Instrument	Energy range	Sensitivity
AMEGO-X	100 keV- 1 GeV	3 * 10^-11 erg $\cdot$cm$^{-2}\cdot$s^{-1}
E-Astrogram	0.3 MeV- 3 GeV	6 * 10^-12 erg$\cdot$ cm$^{-2}\cdot$s^{-1}

clearly detectable signal!

Thank You for Attention!

The study of axion spectrum and photon flux and numerically solving the density matrix equation is supported by Russian Science Foundation, grant 22–12–00215 (DD). Further analysis is supported by the BASIS Foundation, grant 24-2-1-127-1 (DD)