Axion-photon conversion in transient compact stars: Systematics, constraints, and opportunities

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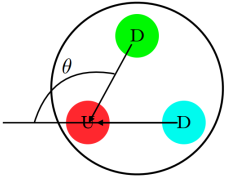
Based on: Fiorillo, AGM, Janka, Raffelt, Vitagliano [2509.XXXXX] (**This week!**)

Headline Slide

Hot, dense sources, as **supernovae and neutron star mergers, emit axions**. These axions **convert into photons** in the magnetic field outside these sources, which could be detected as gamma rays. We use this to place **bounds on the axion couplings**, specifically $g_{a\gamma}$ and $g_{ap} \times g_{a\gamma}$.

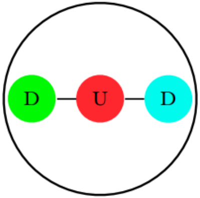
Strong CP Problem

Classical perspective: **Why is the electric dipole moment of the neutron so small?**



$$|\vec{d}| = |\sum q\vec{r}| = 10^{-13}\sqrt{1-\cos\theta}\ e\ \text{cm}$$

Experiments: $|\vec{d}| < 10^{-26}\ e\ \text{cm} \implies$



Drawings borrowed from TASI lectures notes by Anson Hook.

Strong CP Problem

Quantum field theory perspective of the problem: **Why does QCD preserve CP?**

$$\mathcal{L}_{QCD} \supset \boldsymbol{\theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}}; \quad G_{\mu\nu}\tilde{G}^{\mu\nu} \equiv \epsilon^{\mu\nu\alpha\beta} G_{\mu\nu} G_{\alpha\beta}$$

$G\tilde{G}$ term is **CP-odd**, so it contributes to EDM.

SM prediction: $d = 3 \cdot 10^{-16}\ \boldsymbol{\bar{\theta}}\ e$ cm; $\quad \boldsymbol{\bar{\theta} = \theta + \theta_{EW}}$

Experiments: $|d| < 10^{-26}\ e$ cm $\implies$ $\boldsymbol{|\bar{\theta}| < 10^{-10}}$ **???**

Solution: axion

Axion solution: we add a new pseudoscalar field a coupled with gluons.

$$\mathcal{L}_{QCD} \to \mathcal{L}_{QCD} + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{f_a}\frac{1}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} - V(a)$$

Now, the prediction for the electric dipole moment is

$$d = 3 \cdot 10^{-16} \left(\frac{\boldsymbol{a}}{\boldsymbol{f_a}} + \bar{\theta} \right) e \text{ cm}$$

The potential for the axion is

$$V(a) \approx 1 - \cos\left(\frac{a/f_a + \bar{\theta}}{2}\right) \implies \langle a \rangle = -f_a \bar{\theta}$$

The axion **dynamically** cancels the CP-breaking contribution.

Axion electrodynamics

The axion photon coupling modifies Maxwell's Equations:

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma}\ a\ F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\ a\ \vec{E}\cdot\vec{B}$$

$$\begin{cases} \vec{\nabla}\cdot\vec{B} = 0 \\ \partial_t\vec{B} + \vec{\nabla}\times\vec{E} = 0 \\ \vec{\nabla}\cdot\vec{E} = \rho \\ \vec{\nabla}\times\vec{B} - \partial_t\vec{E} = \vec{j} \\ -\partial_t^2 a + \nabla^2 a = m_a^2 a \end{cases}$$

Axion electrodynamics

The axion photon coupling modifies Maxwell's Equations:

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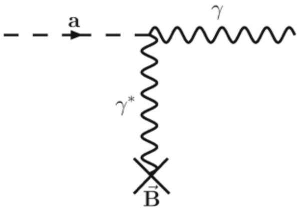
$$\begin{cases} \vec{\nabla} \cdot \vec{B} = 0 \\ \partial_t \vec{B} + \vec{\nabla} \times \vec{E} = 0 \\ \vec{\nabla} \cdot \vec{E} = \rho - \boldsymbol{g_{a\gamma} \vec{B} \cdot \vec{\nabla} a} \\ \vec{\nabla} \times \vec{B} - \partial_t \vec{E} = \vec{j} + \boldsymbol{g_{a\gamma} (\vec{B} \partial_t a - \vec{E} \times \vec{\nabla} a)} \\ -\partial_t^2 a + \nabla^2 a = m_a^2 a - \boldsymbol{g_{a\gamma} \vec{B} \cdot \vec{E}} \end{cases}$$

Axion electrodynamics

$g_{a\gamma}$ is very small. How could we measure $g_{a\gamma}\ a\ \vec{E} \cdot \vec{B}$?

Idea: Strong **external magnetic field**.



Axion-photon conversion

Possible **indirect detection** of axions!

Axion production

Where do these axions come from? They are a **good dark matter candidate!**

Axions are copiously produced in hot, dense environments: **stars**

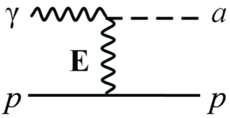
Stars also provide an **external magnetic field**, enhancing the axion-photon conversion.

We consider two cases: **Core-collapse Supernovae** and **Neutron Star mergers**.

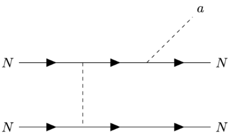
Axion production

We will consider axion production through **axion-photon coupling** $g_{a\gamma}$ and, separately, through **axion-nucleon coupling** g_{ap}.

Production through $g_{a\gamma}$ is dominated by **Primakoff** ($p\ \gamma \to p\ a$), and production through g_{ap} is dominated by **Bremsstrahlung** ($N\ p \to N\ p\ a$):



Primakoff



Bremsstrahlung

Axion-photon conversion within magnetic fields

Assuming ultrarelativistic axions, the **mixing system** can be reduced to a Schröndiger-like system:

$$i\frac{\partial}{\partial R}\begin{pmatrix} A \\ a \end{pmatrix} = -\mathcal{H}\begin{pmatrix} A \\ a \end{pmatrix}, \quad \text{with} \quad \mathcal{H} = \begin{pmatrix} \Delta_\gamma & \Delta_{a\gamma} \\ \Delta_{a\gamma} & \Delta_a \end{pmatrix}, \tag{1}$$

where

$$\Delta_a = \frac{-m_a^2}{2\omega} \qquad \Delta_{a\gamma} = \frac{g_{a\gamma}B_\perp}{2}$$

The kinetic term for the photon Δ_γ can include different contributions; here we consider only **vacuum birefringence**:

$$\Delta_\gamma = \Delta_\parallel = \frac{7\alpha\ \omega}{90\pi}\left(\frac{B_\perp}{m_e^2/e}\right)^2$$

Axion-photon conversion within magnetic fields

For $B_\perp$, we consider a **dipole magnetic field**:

$$B_\perp = B_0 \left(\frac{R_0}{R} \right)^3$$

In the **small-coupling regime**, we can solve the mixing system perturbatively; for a single initial axion:

$$P_{a\gamma} = |A|^2_{R\to\infty} = \left| \int_{R_0}^{\infty} ds' \Delta_{a\gamma}(s') \exp\left[i \int_0^{s'} ds'' \left(\Delta_\gamma(s'') - \Delta_a(s'') \right) \right] \right|^2$$

The **conversion probability** $P_{a\gamma}$ tells us how many axions convert into photons.

Axion-photon conversion within magnetic fields

$$P_{a\gamma} = |A|^2_{R\to\infty} = \left| \int_{R_0}^{\infty} ds' \Delta_{a\gamma}(s') \exp\left[i \int_0^{s'} ds'' \left(\Delta_\gamma(s'') - \Delta_a(s'')\right)\right] \right|^2$$

The conversion will be suppressed while the phase difference is large.

Massless-axion case ($\Delta_a = 0$): suppressed conversion until the accumulated phase is small enough, i.e. $\Delta_\gamma(R) \cdot R \sim 1$; this defines a **conversion radius** $R_{\rm conv}$. Then,

$$P_{a\gamma} \sim \left(\Delta_{a\gamma}(R_{\rm conv}) \cdot R_{\rm conv}\right)^2$$

This reasoning is **generic**. In our specific case, the factor is $\simeq 0.71$.

Axion-photon conversion: mass effect

(Not the classic videogame saga).

$$P_{a\gamma} = |A|^2_{R\to\infty} = \left| \int_{R_0}^{\infty} ds' \Delta_{a\gamma}(s') \exp\left[i \int_0^{s'} ds'' \left(\Delta_\gamma(s'') - \Delta_a(s'') \right) \right] \right|^2$$

Δ_a becomes relevant when $\Delta_a \gtrsim \Delta_\gamma(R_{\text{conv}})$: suppressed conversion because the accumulated phase is always $\gtrsim 1$.

The conversion will occur at R_a such that $\Delta_a = \Delta_\gamma(R_a)$, and then

$$P_{a\gamma} \sim \Delta_{a\gamma}(R_a)^2 \cdot \frac{R_a}{|\Delta_a|} \cdot e^{-k|\Delta_a|R_a}$$

$k \sim 1$. Again, **generic**.

Axion-photon conversion: irrelevant Δ_γ

$$P_{a\gamma} = |A|^2_{R\to\infty} = \left| \int_{R_0}^{\infty} ds' \Delta_{a\gamma}(s') \exp\left[i \int_0^{s'} ds'' \left(-\Delta_a(s'') \right) \right] \right|^2$$

Until now, we assumed that $R_0 < R_{\text{conv}}$. If $R_{\text{conv}} < R_0$, then Δ_γ can be neglected. In this case,

$$\text{Massless case: } P_{a\gamma} \sim (\Delta_{a\gamma}(R_0) \cdot R_0)^2 = (B_0 \cdot R_0)^2$$

Now Δ_a becomes relevant when $\Delta_a \cdot R_0 \gtrsim 1$. In this case,

$$\text{Massive case: } P_{a\gamma} \sim \left(\frac{\Delta_{a\gamma}(R_0)}{|\Delta_a|} \right)^2 = \left(\frac{B_0}{|\Delta_a|} \right)^2$$

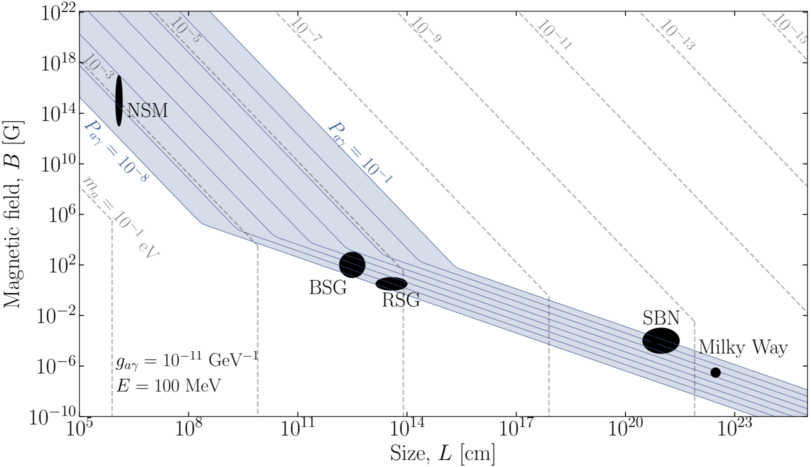
Axion-photon conversion: summary

These numbers can be computed exactly. In our specific case of a dipole magnetic field $\Delta_{a\gamma} \sim R^{-3}$, $\Delta_\gamma \sim R^{-6}$,

- Massless, $R_0 < R_{\rm conv}$: $P_{a\gamma} \simeq 0.71 \left(\Delta_{a\gamma}(R_{\rm conv}) \cdot R_{\rm conv}\right)^2$
- Massive, $R_0 < R_{\rm conv}$: $P_{a\gamma} \simeq \frac{\pi}{3}\Delta_{a\gamma}(R_a)^2 \cdot \frac{R_a}{|\Delta_a|} \cdot e^{-1.2|\Delta_a|R_a}$
- Massless, $R_0 > R_{\rm conv}$: $P_{a\gamma} \simeq 0.25 \left(B_0 \cdot R_0\right)^2$
- Massive, $R_0 > R_{\rm conv}$: $P_{a\gamma} \simeq \left(\frac{B_0}{|\Delta_a|}\right)^2$

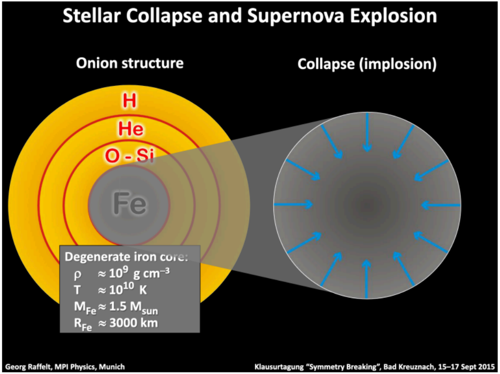
Once we know the axion energy ω, the surface magnetic field B_0, and the size R_0, we can classify our system.

Fiorillo-Hillas Plot



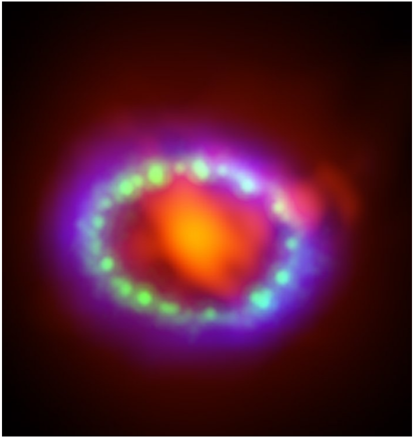
Core-collapse supernovae

During a type II supernovae, the core reaches temperatures of $\sim$ 30 MeV: efficient emission of axions, which convert in the magnetic field of the progenitor (Manzari et al., 2405.19393).



SN1987A

In February 1987, SN 1987A was detected, but no gamma-rays were observed by Solar Maximum Mission $\Longrightarrow$ **bounds on axions**.



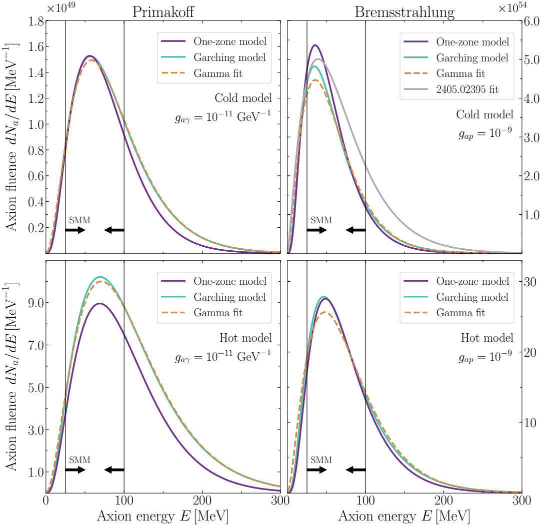
Supernova axion fluxes

We use several Garching models to build two informed one-zone models, using weighted averages of the relevant quantities.

Quantity	**Cold**	**Hot**
Density ρ $[10^{14}\ \mathrm{g/cm^3}]$	4.0	6.0
Temperature T [MeV]	30	45
Proton fraction Y_p	0.15	0.15
Lapse $(1+z)^{-1}$	0.75	0.65
Exposure of mass Mt $[M_\odot\ \mathrm{s}]$	5.0	10.0

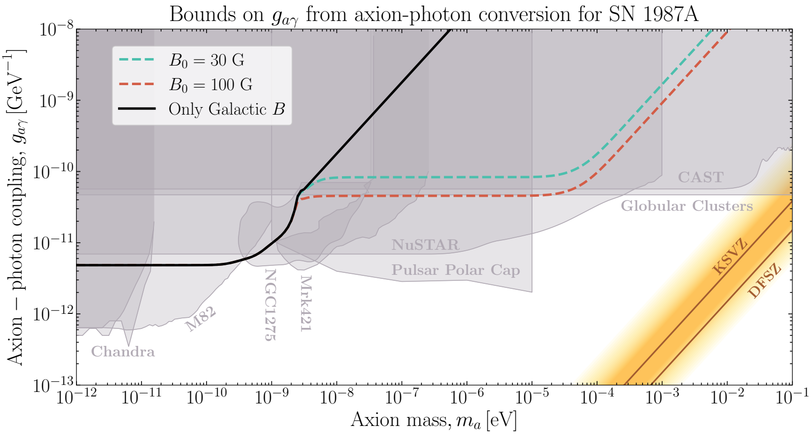
Supernova axion fluxes

Here we compare with two different Garching models: SFHo-18.8 (Cold) and LS220-20.0 (Hot).



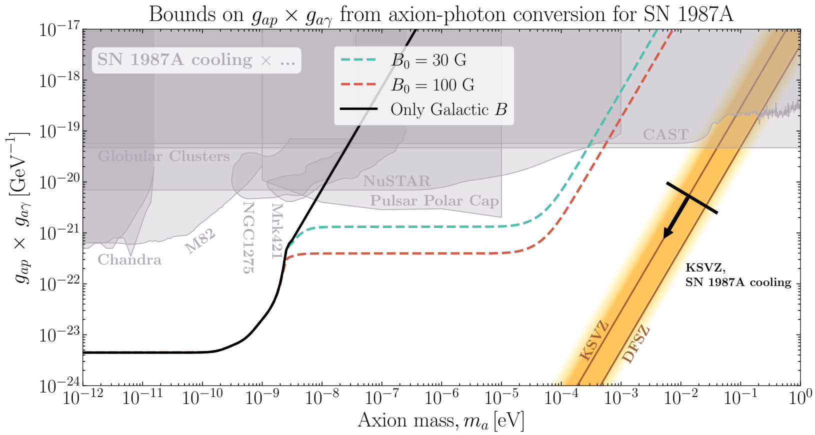
SN 1987A bounds on $g_{a\gamma}$

We also include the conversion within the galactic magnetic field (Unger and Farrar, 2311.12120). We use $R_0 = 30R_\odot$.



SN 1987A bounds on $g_{ap} \times g_{a\gamma}$

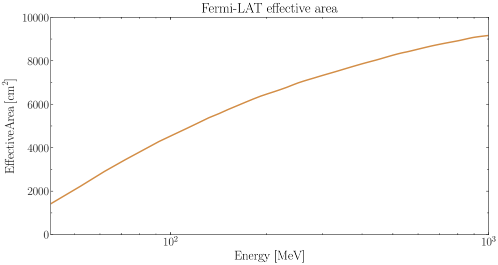
We also include the conversion within the galactic magnetic field (Unger and Farrar, 2311.12120). We use $R_0 = 30 R_\odot$.



Future Supernovae

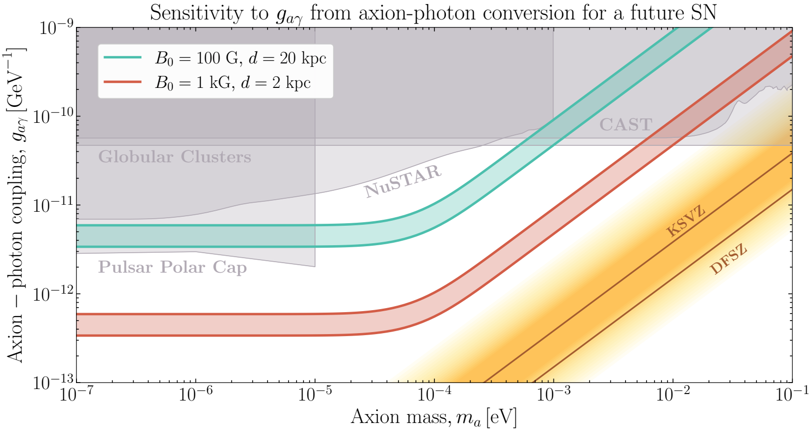
What if we detected a supernova nowadays? In the Milky Way, $1 \sim 2$ supernovae are expected per century.

Fermi-LAT is the current most sensitive telescope in the $10 - 100$ MeV range.



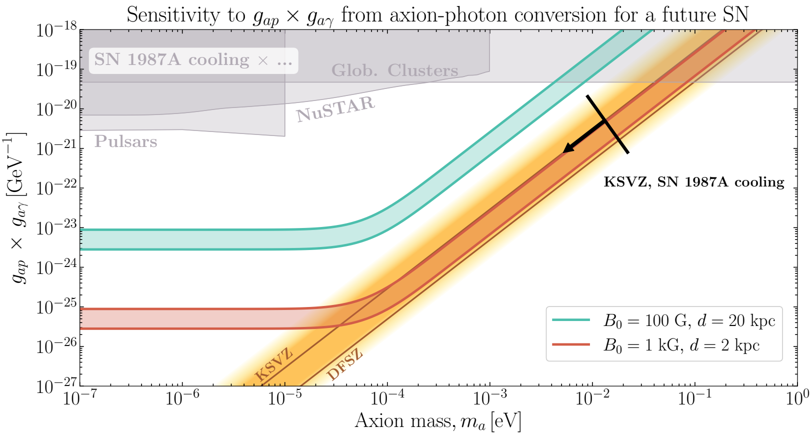
Sensitity from future supernova on $g_{a\gamma}$

We use $R_0 = 30 R_\odot$.



Sensitity from future supernova on $g_{ap} \times g_{a\gamma}$

We use $R_0 = 30 R_\odot$.



Neutron star mergers

When two neutron stars collide, a hypermassive neutron star (HMNS) might form.

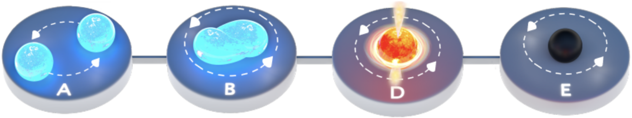


Imagen taken from 2012.08172

In August 2017, the first merging of two neutron stars was detected: GW17087 + GRB 170817A + AT 2017gfo. Two neutron stars with masses of $\sim 1.35 M_{\odot}$ collided in NGC 4993, a galaxy located 44 Mpc from Earth, and a HMNS formed.

Sadly, Fermi-LAT was crossing the south South Atlantic Anomaly, so we cannot set competing bounds :(

Kilonova: ejected material

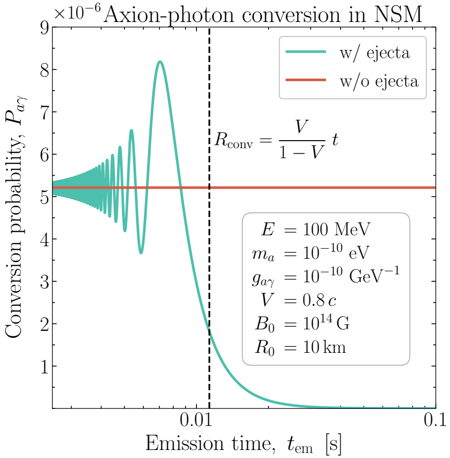
Large amounts of material are ejected after the collision!

$|\Delta_{\mathrm{pl}}| \cdot R_{\mathrm{conv}} \gg 1 \implies$ **Conversion is suppressed!**

Once the ejecta arrives to R_{conv}, the conversion is completely suppressed.

Conversion outside the Hypermassive neutron star

When the ejected material arrives to R_{conv}, the conversion is rapidly suppressed.



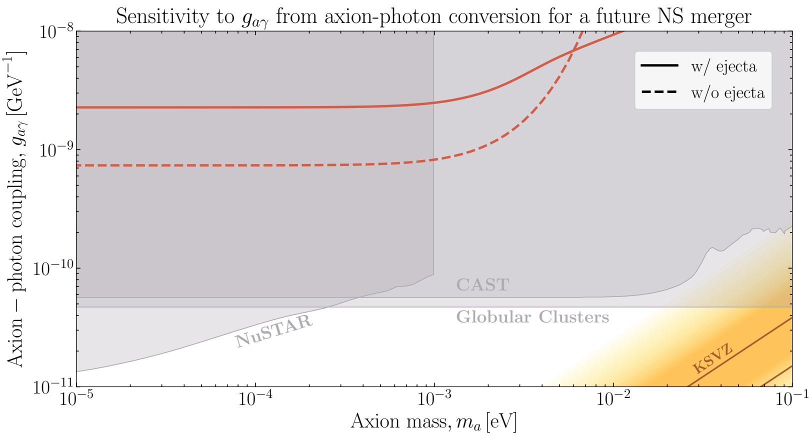
HMNS axion fluxes

We use four different (Garching) models (DD2 and SFHo, with symmetric masses and asymmetric masses) to build a representative one-zone HMNS model.

Quantity	**NSM**
Density ρ [10^{14} g/cm^3]	4.0
Temperature T [MeV]	25
Proton fraction Y_p	0.07
Lapse $(1+z)^{-1}$	0.85
Exposure of mass Mt [$M_\odot$ s]	6.0×10^{-3}

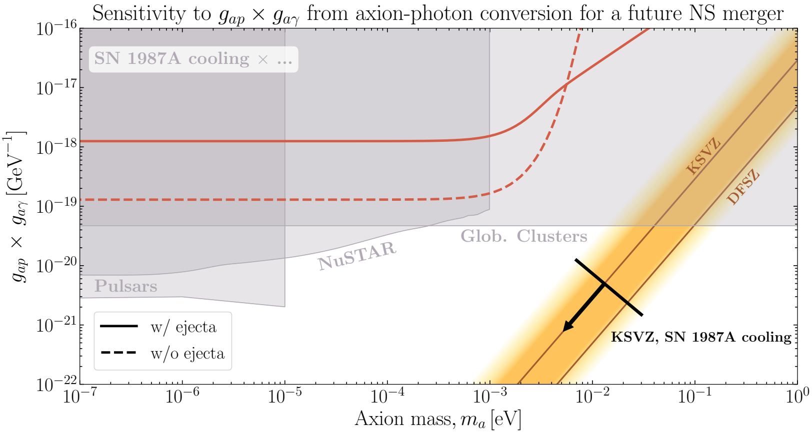
Sensitity from future NSM on $g_{a\gamma}$

We assume $B_0 = 10^{14}$ Gauss and $R_0 = 10$ km.



Sensitity from future NSM on $g_{ap} \times g_{a\gamma}$

We assume $B_0 = 10^{14}$ Gauss and $R_0 = 10$ km.



Conclusions

Conclusions

- We have derived simple expressions for the probability of (ultrarelativistic) axion-photon conversion within magnetic fields, including axion mass suppression.
- Strongest bounds to date on $g_{ap} \times g_{a\gamma}$ from the non-observation of gamma rays from SN 1987A.
- Fermi-LAT sensitivity could probe the QCD axion band for some optimistic cases.
- It is unlikely that Neutron Star Mergers will set stringent bounds on axion couplings, especially considering the presence of the ejected material.
- Main drawback: No information on the magnetic field of Sanduleak.

Backup slides

Axion potential

Vaffa-Witten theorem predicts that the energy will be minimized at $\theta = 0$.

To compute the axion potential, one starts from the QCD lagrangian before chiral symmetry breaking. We do a chiral rotation of the quark fields $q \to e^{i\frac{a}{f_a}Q\gamma_5} q$ to remove the $aG\tilde{G}$ term, so the axion is present in the quark mass matrices M. Then we break chiral symmetry and write the chiral lagrangian with the explicit symmetry-breaking term M, which now includes the axion. This leads to

$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a}\right)}\ ,$$

QCD axion vs. ALPs

From the potential one can get

$$m_a = \sqrt{V''(0)} = 5.7 \left(\frac{10^{12}\text{GeV}}{f_a} \right) \mu\text{eV}$$

Interaction with pions also yields an axion-photon coupling:

$$g_{a\gamma} = g^0_{a\gamma} - \frac{\alpha_{\text{EM}}}{2\pi f_a} \left(\frac{2}{3} \frac{4m_d + m_u}{m_d + m_u} \right) \equiv \frac{\alpha_{\text{EM}}}{2\pi f_a} c_\gamma$$

If we break these relations between m_a and f_a, we have **axion-like particles (ALPs)**.

Emission processes

Primakoff:

$$\frac{d\dot{N}_a}{dMdE} = \frac{E^2}{\pi^2(e^{E/T}-1)}\,\frac{g_{a\gamma}^2\alpha Y_p}{8}\left[\left(1+\frac{k_{\rm S}^2}{4E^2}\right)\log\left(1+\frac{4E^2}{k_{\rm S}^2}\right)-1\right].$$

Bremsstrahlung:

$$\frac{d\dot{N}_a}{dEdM} = \frac{g_{ap}^2}{8\pi^2 m_p^2}\,\frac{Y_p}{m_u}\,\frac{E}{e^{E/T}+1}\,\frac{\Gamma_\sigma}{1+(\Gamma_\sigma/2E)^2}.$$

$$\Gamma_\sigma = 40\,\mathrm{MeV}\,\frac{\rho}{4\times 10^{14}\,\mathrm{g/cm^3}}\sqrt{\frac{T}{30\,\mathrm{MeV}}}.$$

SN Averages

Weighted with T^3 (or $T^{5/2}$).

Model		SFHo–18.8		SFHo–18.6		LS220–20.0		SFHo–20.0	
Our name		Cold model		—		—		Hot model	
$M_{\rm NS}$ (baryon)	$M_\odot$	1.351		1.553		1.926		1.947	
$M_{\rm NS}$ (grav.)		1.241		1.406		1.707		1.712	
$E_{\rm bind}$	10^{53} erg	1.98		2.64		3.94		4.23	
Lapse $\langle(1+z)^{-1}\rangle$		0.77	(0.76)	0.77	(0.76)	0.67	(0.65)	0.66	(0.64)
$T_{\rm max}$	MeV	39.4		45.5		60.0		59.2	
$\langle T\rangle$		30.3	(29.4)	35.1	(34.1)	43.3	(41.1)	45.4	(44.4)
$\rho_{\rm max}$	10^{14} g/cm^3	7.82		8.70		10.2		10.9	
$\langle\rho\rangle$		4.08	(4.73)	4.53	(5.23)	5.45	(6.33)	5.71	(6.52)
$\langle Mt\rangle$	$M_\odot$s	5.28	(5.06)	6.76	(6.46)	8.45	(8.63)	10.5	(9.90)
Average abundances per baryon									
$\langle Y_p\rangle$		0.138	(0.132)	0.140	(0.137)	0.188	(0.189)	0.161	(0.154)
$\langle Y_n\rangle$		0.853	(0.865)	0.849	(0.861)	0.811	(0.811)	0.834	(0.845)
$\langle Y_e\rangle$		0.119	(0.111)	0.120	(0.114)	0.149	(0.149)	0.128	(0.122)
$\langle Y_\mu\rangle$		0.022	(0.022)	0.025	(0.024)	0.039	(0.040)	0.035	(0.033)
Nucleon degeneracy suppression factors									
$\langle F_{pp}\rangle$		0.80	(0.77)	0.72	(0.77)	0.85	(0.82)	0.76	(0.77)
$\langle F_{nn}\rangle$		0.48	(0.42)	0.42	(0.44)	0.61	(0.55)	0.49	(0.47)

NSM Averages

Weighted with T^3 (or $T^{5/2}$).

Model		DD2 Asym.		DD2 Sym.		SFHo Asym.		SFHo Sym.	
$M_{\rm NS} + M_{\rm NS}$ (baryon)	$M_\odot$	1.25 + 1.45		1.35 + 1.35		1.25 + 1.45		1.35 + 1.35	
Lapse $\langle (1+z)^{-1} \rangle$		0.85	(0.84)	0.82	(0.81)	0.88	(0.87)	0.82	(0.81)
$T_{\rm max}$	MeV	30.7		69.4		36.7		73.4	
$\langle T \rangle$		19.8	(20.6)	22.6	(22.9)	23.3	(24.2)	27.6	(27.8)
$\rho_{\rm max}$	10^{14} g/cm^3	5.63		6.43		6.40		9.74	
$\langle \rho \rangle$		2.58	(3.15)	3.78	(4.36)	2.70	(3.46)	5.46	(6.73)
$\langle Mt \rangle$	$10^{-3} M_\odot \rm s$	7.46	(5.47)	7.44	(6.26)	5.67	(3.99)	5.69	(4.59)
Average abundances per baryon									
$\langle Y_e \rangle$		0.071	(0.069)	0.069	(0.069)	0.073	(0.067)	0.065	(0.062)

Kilonova: ejected material

Large amounts of material are ejected after the collision! **Can it suppress the conversion?**

Conversion is suppressed if $|\Delta_{\text{pl}}| \cdot R_{\text{conv}} \gtrsim 1$

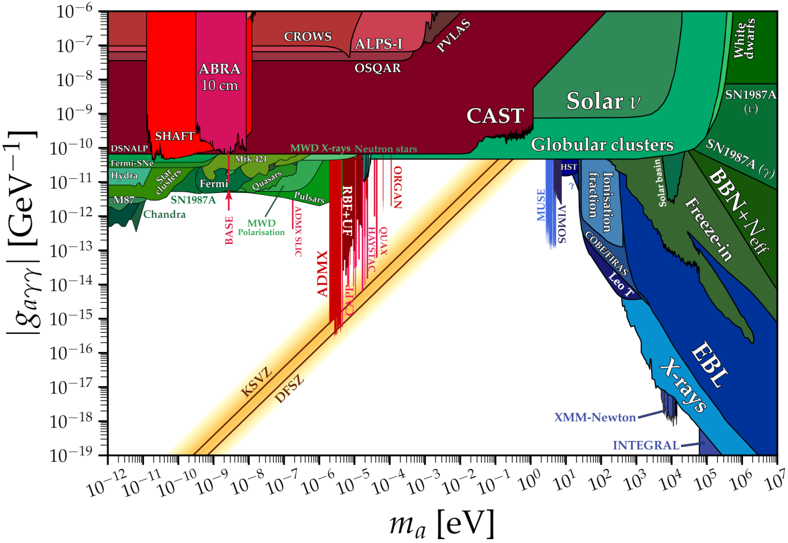
$$|\Delta_{\text{pl}}| \cdot R_{\text{conv}} = \frac{\omega_{\text{pl}}^2}{2\omega} R_{\text{conv}} = \frac{e^2 \rho}{2 m_e m_p \omega} R_{\text{conv}} \gtrsim 1 \implies \rho \gtrsim 10^{-9} \text{ g/cm}^3$$

$$\rho = \frac{M_{\text{ejected}}}{4\pi R_{\text{conv}}^2 \cdot V \delta t}$$

If we consider relativistic velocities, $V \sim 0.8c$, $\delta t \sim 100$ ms, then $M_{\text{ejected}} \gtrsim 10^{-14} M_{\odot}$ shuts down the conversion.

Typical ejected mass at relativistic velocities is $M_{\text{ejected}} \gtrsim 10^{-7} M_{\odot}$! **Once the ejecta arrives to R_{conv}, the conversion is completely suppressed.**

Axion-photon coupling constraints



https://github.com/cajohare

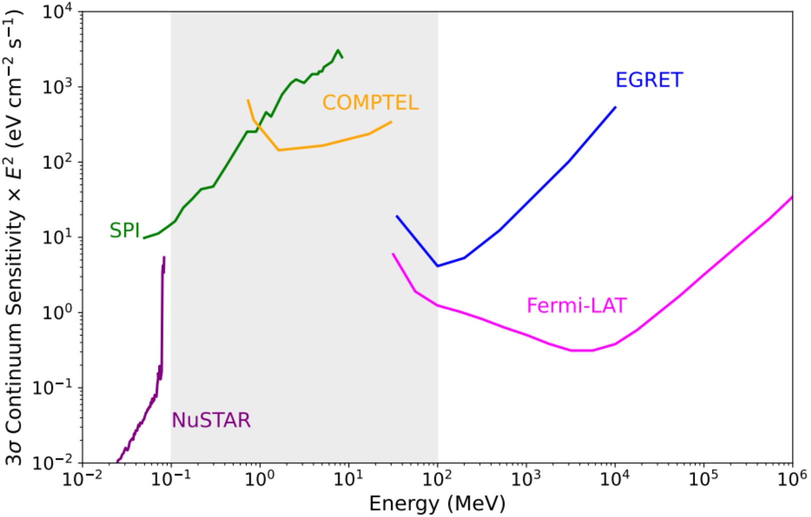


Imagen taken from 2111.10362