Supernova Bounds on sub-GeV Particles

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1611.03864 & 1803.00993
with Rouven Essig and Jae Hyeok Chang
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Executive Summary

- Supernova 1987A reached extremely high temp ~ 30 MeV and density ~ $3 \times 10^{14}$ g/cm$^3$ and was necessarily “powered” by neutrinos
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- an axion with a large [small] $f_a$ would have not been produced [gotten trapped]

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• an axion with a large [small] f_a would have not been produced [gotten trapped]

• intermediate f_a would “defuse” neutrinos

*[~ m_N\times(110 \text{ MeV})^3 \sim m_N\times0.17\text{fm}^3]*
Axions in SN1987A

• $\lambda_{\text{mfp},v} \sim 1/(n_N G_F^2 T^2) \sim 1\text{m} \times (\text{radius}/10\text{km})^8 \implies$ neutrinos diffuse until radius $\sim 40\text{km}$

• At $r \sim 40\text{km}$ they are emitted with a blackbody spectrum of $L_v \sim 10^{52}\text{erg/s}$
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- $L_a \sim \text{Vol} Y_p C_p^2 n_N^2 \sigma_N T^3 / f_a^2 \sim L_\nu \times (f_a/10^9 \text{GeV})^2 \Rightarrow$ axions “compete” if their decay constant is $< 10^9 \text{GeV}$ (or $m_a > 10^{-11} \text{GeV} = 10^{-2} \text{eV}$)
Bounds: Expectation

Because the environment is so hot and extreme, but the criterion is so coarse, SN1987A bounds on a given model are generically entirely below the terrestrially accessible regions of parameter space.
How the bound works

\[ \varepsilon_{\text{pr}} \left( m' \right) \varepsilon_{\text{tr}} \left( m' \right) \]

\[ g_a \sim m_a \sim 1/f_a \]
How the bound works
Novelt(ies) in our work(s)

• Novel treatment of large mixing angles (blackbody emission underestimates the emission of bosons, not using optical depth ~ O(1) for fermions)
• Systematic uncertainties from progenitor profile
• Chiral effective theory results for nuclear matrix element to which axion couples
Novelt(ies) in our work(s)

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extends bounds by $\sim$ order of magnitude at large coupling
Novelties in our work(s)

- Novel treatment of large mixing angles (blackbody emission underestimates the emission of bosons, not using optical depth $\sim O(1)$ for fermions)
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Novelt(ies) in our work(s)

• Novel treatment of large mixing angles (blackbody emission underestimates the emission of bosons, not using optical depth \( \sim O(1) \) for fermions)

• Systematic uncertainties from progenitor profile

• Chiral effective theory results for nuclear matrix element to which axion couples

  weakens constraints \( \sim \) order of magnitude
Outline

I. Knowns and Unknowns of SN1987A

II. Calculating with the QCD Axion

III. Results and Future Directions
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Broad(est possible) Picture

Supernova 1987A:

~ 99% of the grav. binding energy of a collapsing blue supergiant radiated away in the form of neutrinos over the course of ~ 10s

spacetelescope.org
Why Supernova 1987A?

• Cooling phase is consistent with analytic expectation

• ...but wouldn’t be if a new “energy sink” competed with Standard Model processes

• Limited amount of luminosity may be diverted to novel particles ⇔ bounds on new coupling with SM
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Credit: Colin Legg
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Burrows and Lattimer, 1987
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Fischer et al. 1605.08780
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\[ L_{\text{new}} \leq L_{\nu} \]
Outline

I. Knowns and Unknowns of SN1987A

II. Calculating with the QCD Axion

III. Results and Future Directions
Basics of the QCD Axion

a particle that solves the strong CP problem can be produced coherently as dark matter

\[ \mathcal{L} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^a_{\mu\nu} \bar{G}^a_{\mu\nu} \]
Basics of the QCD Axion

a particle that solves the strong CP problem
necessarily couples to nucleons at low energy

\[ \mathcal{L} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \rightarrow \frac{C_N}{2f_a} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N \]
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\[ \mathcal{L} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G_{\mu\nu}^{\alpha} \bar{G}^{\alpha \mu \nu} \rightarrow \frac{C_N}{2f_a} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N \]

couple to:

\[ \mathcal{L} \sim G_F \bar{\nu} \gamma_\mu P_L \nu \bar{N} (C_V - C_A \gamma_5) \gamma^\mu N \]

helpfully, this is the same nucleon current that neutrinos (dominantly) couple to:

\[ \left| \mathcal{M} \right|_{\text{nonrel.}}^2 \propto C_A^2 G_F^2 \]
Basics of the QCD Axion

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from this, we can get an interaction rate (equivalently, a mean free path) for bremsstrahlung
Basics of the QCD Axion

a particle that solves the strong CP problem necessarily couples to nucleons at low energy

\[ \mathcal{L} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \rightarrow \frac{C_N}{2f_a} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N \]

calculate axion rates using this Lagrangian and the improved matrix element for the nuclear spin flip rate
Particle Luminosity

\[ dL = e^{-\tau} dP \]
Particle Luminosity

energy lost in a’s per unit time

\[ dL = e^{-\tau} dP \]
Particle Luminosity

energy lost in a’s per unit time = rate at which a’s are produced

\[ dL = e^{-\tau} dP \]
Particle Luminosity

\[ dL = e^{-\tau} dP \]

- energy lost in a’s per unit time
- rate at which a’s are produced
- odds of escaping
Power and Optical Depth

differential power is the integral of production rate:

\[
\frac{dP}{dV} = \int \frac{d^3 k}{(2\pi)^3} \omega \Gamma_{\text{prod}}
\]

not all power gets out because of a nonzero “optical” depth:

\[
\tau = \int_{r}^{R_{\text{far}}} \Gamma_{\text{abs}}(r') dr'
\]

by detailed balance, \( \Gamma_{\text{prod}} = e^{-\omega/\Gamma} \Gamma_{\text{abs}} \), so calculate \( \Gamma_{\text{abs}} \) only
Axion Bremsstrahlung Rate

\[
\Gamma_{ij}^a = \frac{C_i^2 Y_i Y_j}{4 f_a^2} \frac{\omega}{2} \frac{n_B^2 \sigma_{np\pi}}{\omega^2} \gamma_f \gamma_p \gamma_\chi
\]

\[
\sigma_{np\pi} = 4\alpha^2_\pi \sqrt{\pi T/m_N^5}
\]
Axion Bremsstrahlung Rate

\[ \Gamma_{ia}^{ij} = \frac{C_i^2 Y_i Y_j}{4 f_a^2} \omega \frac{n_B^2 \sigma_{n p \pi}}{\omega^2} \gamma_f \gamma_p \gamma_\chi \]

\[ \sigma_{n p \pi} = 4 \alpha^2 \pi \sqrt{\pi T / m_N^5} \]

in the free-streaming limit,

\[ \text{Vol} \times \int \frac{d^3 p_a}{(2\pi)^3} \omega \Gamma_a \simeq \frac{10^{56} \text{erg}}{\text{sec}} \frac{C^2}{C_{\text{KSVZ}}^2} \left( \frac{m_a}{\text{eV}} \right)^2 \gamma_f \gamma_p \gamma_\chi \]
Axion Bremsstrahlung Rate

\[ \Gamma_{a}^{ij} = \frac{C_{i}^{2} Y_{i} Y_{j} \omega n_{B}^{2} \sigma_{n p \pi}}{4 f_{a}^{2} \omega^{2}} \gamma_{f} \gamma_{p} \gamma_{\chi} \]

in the free-streaming limit,

\[ \sigma_{n p \pi} = 4 \alpha_{\pi}^{2} \sqrt{\pi T / m_{N}^{5}} \]

cuts off low-energy divergence

\[ \gamma_{f} \equiv 1 \frac{1}{1 + (n N \sigma_{n p \pi})^{2} / 4 \omega^{2}} \]
Axion Bremsstrahlung Rate

\[
\Gamma_{a}^{ij} = \frac{C_{i}^{2} Y_{i} Y_{j}}{4 f_{a}^{2}} \frac{\omega}{2} \frac{n_{B}^{2} \sigma_{np\pi}}{\omega^{2}} \gamma_{f} \gamma_{p} \gamma_{\chi}
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Axion Bremsstrahlung Rate

\[ \Gamma_{ij}^a = \frac{C_i^2 Y_i Y_j \omega n_B^2 \sigma_{np\pi}}{4 f_a^2} \frac{2}{\omega^2} \gamma_f \gamma_F \gamma_\chi \]

\[ \sigma_{np\pi} = 4 \alpha_\pi^2 \sqrt{\pi T/m_N^5} \]

in the free-streaming limit, corrects rate to agree with \( \text{N}^3\text{LO} \) \( \chi\text{EFT} \) calc.

series of papers by Schwenk, Pethick, and many collaborators:
0812.0102, 1112.5185, 1403.4114, 1608.05037
χEFT (& what is χx?)

- χx summarizes χEFT calculations
- calculations ca. 1988 were done for exchange of a single massless π
- this is LO in chiral effective theory

Machleidt and Entem, nucl-th/0503025; Epelbaum 1001.3229
χEFT (& what is γₓ?)

- γₓ summarizes χEFT calculations
- calculations ca. 1988 were done for exchange of a single massless π
- this is LO in chiral effective theory

Machleidt and Entem, nucl-th/0503025; Epelbaum 1001.3229
Cancellation in $\chi$EFT

Stable beyond NLO

Bacca, Hally, Pethick, Schwenk
0812.0102
Dependence on Density and $Y_p$

Nontrivial dependence on proton number (deuteron production resonance):
Ratio vs the LO result

![Graph showing ratio vs. LO result with various plots for different values of Ye]
Similar physics known for \( \sim O(20 \text{ years}) \)

**Identical nucleons**

- **Hanhart, Phillips, Reddy 2000**

**np scattering**

- **Sigl 1997**

\[ R_g \]

\[ \frac{\omega}{T} \]

axions

\[ \text{neutrinos} \]
Correction Factors

\[ \Gamma_{ij}^{\alpha} = \frac{C_i^2 Y_i Y_j}{4 f_a^2} \frac{\omega}{2} \frac{n_B^2 \sigma_{np \pi}}{\omega^2} \gamma_f \gamma_p \gamma_x \]
Supernova Thermo

“fiducial model” (Raffelt, 1995)

\[
\rho_c \approx m_N (100 \text{ MeV})^3, \quad T_c = 30 \text{ MeV}, \quad Y_p \approx 0.3
\]

\[
\rho(r) = \rho_c \times \begin{cases} 
1 + k_\rho (1 - r/R_c) & r < R_c \\
(r/R_c)^{-\nu} & r \geq R_c 
\end{cases}
\]

\[
T(r) = T_c \times \begin{cases} 
1 + k_T (1 - r/R_c) & r < R_c \\
(r/R_c)^{-\nu/3} & r \geq R_c 
\end{cases}
\]
Uncertainties

“fiducial model” differs from sims by ~O(few):

- value of $R_f$ (important for optical depth, $\tau(r) = \int_0^{R_f} \Gamma'(r') \, dr'$)

<table>
<thead>
<tr>
<th>Possible values for $R_{far}$</th>
<th>distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{gain}$</td>
<td>100 km</td>
</tr>
<tr>
<td>$R_{shock}$</td>
<td>1000 km</td>
</tr>
</tbody>
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Luminosity vs. Coupling

\[ f_a \cdot C_{\text{KSVZ}} / C \quad [\text{GeV}] \]

\[ \frac{L_a}{L_\nu} \]

\[ m_a \cdot C / C_{\text{KSVZ}} \quad [\text{eV}] \]

\[ f_a \cdot C_{\text{KSVZ}} / C \quad [\text{GeV}] \]

\[ \frac{L_a}{L_\nu} \]

\[ m_a \cdot C / C_{\text{KSVZ}} \quad [\text{eV}] \]
Constraints

\[ f_a \cdot \frac{C_{\text{KSVZ}}}{C} \quad \text{[GeV]} \]

\[ m_a \cdot \frac{C}{C_{\text{KSVZ}}} \quad \text{[eV]} \]

- PDG (2016)
- Fiducial
- Fischer, 11.8\,M_\odot
- Fischer, 18\,M_\odot
- Nakazato, 13\,M_\odot
"hadronic axion window" seems to be ruled out
Different Models
Lightning Round!
Axion-Like Particle

couples to all SM fermions ~ mass but $m_A f_A \neq m_\pi f_\pi$
Dark Photon

![Graph showing the relationship between $\varepsilon$ and $m'$, with regions labeled for SN1987A, stars, late decays, terrestrial, BaBar, and BBN. There are also color-coded regions for fiducial, systematic, and robustly excluded.](image)
Millicharged Particle

different bounds (or signals!) if it is the dark matter
Dark Photon + Dark Matter
Inelastic Dark Matter

\[ y = \epsilon^2 \alpha_D (m_1/m)^4 \]

Accelerator Searches

Belle II

Thermal Target

BDX Scatter

BDX Decay

LDMX

\[ \alpha_D = 0.1, m' = 3m_1, \Delta = 0.4m_1 \]

\[ m_1 \text{ [MeV]} \]

SN1987A
A note on (very) high mixing

Natalia Toro, KITP Particle Physics at the Sensitivity Frontier Conf., 2018
A note on (very) high mixing

\[ dL = dP \]

Efficiently Produced

\[ \epsilon_{pr}(m') \]

\[ \epsilon_{tr}(m') \]

\[ \nu \]

\[ g_a \sim m_a \sim 1/f_a \]

Luminosity [arb. units]

\[ dL < dP \]

No Trapping

Efficiently Trapped

Thermal Emission
A note on (very) high mixing

\[ T_{BSM} = T_{SM} \left( \frac{\sum_{i \in SM} g_i}{\sum_{i} g_i} \right)^{1/3} \approx T_{SM} \left( 1 - \frac{1}{3} \frac{\sum_{i \in BSM} g_i}{\sum_{i \in SM} g_i} \right) \]
A note on (very) high mixing

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axion: \( \sim 1 \)

\( \sim 20 \)
A note on (very) high mixing

\[ T_{BSM} = T_{SM} \left( \frac{\sum_{i \in SM} g_i}{\sum_i g_i} \right)^{1/3} \approx T_{SM} \left( 1 - \frac{1}{3} \frac{\sum_{i \in BSM} g_i}{\sum_{i \in SM} g_i} \right) \]

dark sector: \(~6.5\)

\(~20\)
Conclusions

• Supernova 1987A provides a unique and powerful probe of light and weakly coupled physics

• Provides strongest bounds for wide variety of modern models of BSM particle physics

• Exciting possibilities to combine cutting edge astrophysics, nuclear physics, and particle physics