SN 1987A and the Higgs Portal Dark Matter

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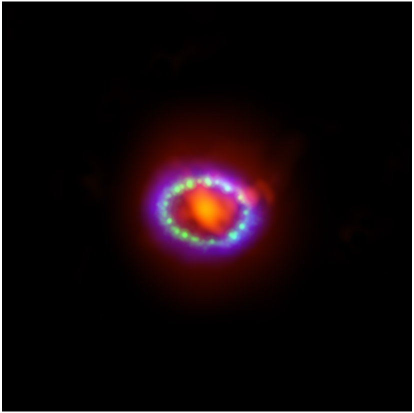
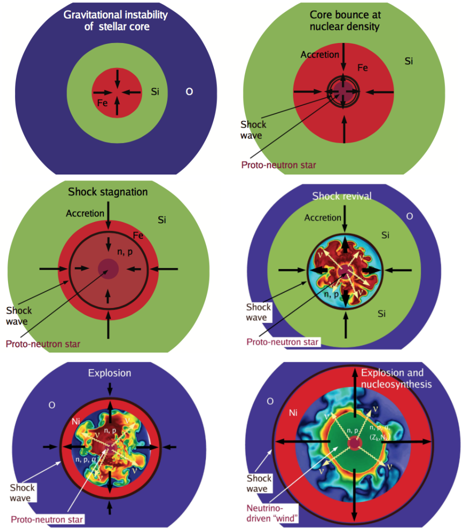
December 29, 2016

SN 1987A



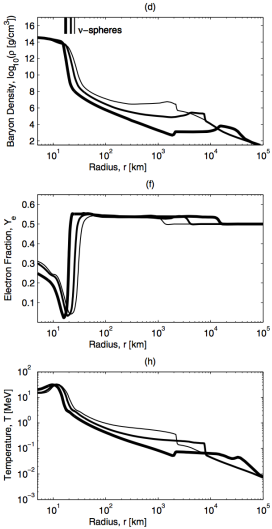
[By ALMA (ESO/NAOJ/NRAO)/A. Angelich. Visible light image: the NASA/ESA Hubble Space Telescope. X-Ray image: The NASA Chandra X-Ray Observatory - http://www.eso.org/public/images/eso1401a/, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=30512379]

Core-Collapse Supernovae



[Janka, Hanke, Huedepohl, Marek, Mueller, Obergaulinger 2012]

Post-Collapse Proto-Neutron Star (PNS)

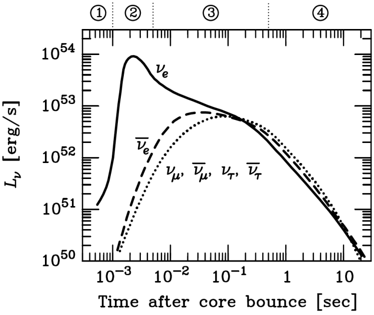


[Fischer, Whitehouse, Mezzacapp, Thielemann, Liebendoerfer 2010]

Supernova Neutrino Emission

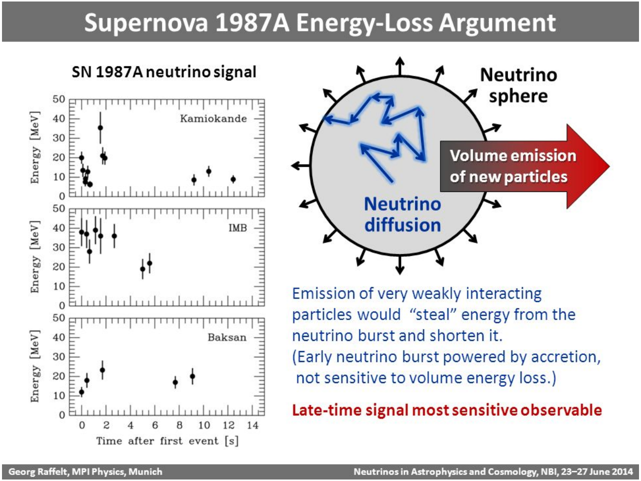
Four main phases:

- 1. Collapse
- 2. Prompt shock propagation, release of ν_e burst
- 3. Matter accretion and mantle cooling
- 4. Kelvin-Helmholtz cooling of PNS star



[Janka 1993; Raffelt 1996]

Supernova Cooling and Energy Loss Argument



[Raffelt @ Neutrinos in Astrophysics and Cosmology, NBI, 2014]

SN 1987A and Axions

Probing axions with the neutrino signal from the next galactic supernova

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(Dated: September 27, 2016)

We study the impact of axion emission in simulations of massive star explosions, as an additional source of energy loss complementary to the standard neutrino emission. The inclusion of this channel shortens the cooling time of the nascent protoneutron star and hence the duration of the neutrino signal. We treat the axion-matter coupling strength as a free parameter to study its impact on the protoneutron star evolution as well as on the neutrino signal. We furthermore analyze the observability of the enhanced cooling in current and next-generation underground neutrino detectors, showing that values of the axion mass $m_a \gtrsim 8 \times 10^{-3}$ eV can be probed. Therefore a galactic supernova neutrino observation would provide a valuable possibility to probe axion masses in a range within reach of the planned helioscope experiment, the International Axion Observatory (IAXO).

Weinberg's Higgs Portal Model for Dark Radiation

- Lagrangian

$$\mathcal{L} = \left(\partial_\mu S^\dagger\right)(\partial^\mu S) + \mu^2 S^\dagger S - \lambda(S^\dagger S)^2 - g(S^\dagger S)(\Phi^\dagger \Phi) + \mathcal{L}_{\rm SM}$$

where Φ is the SM Higgs doublet.

- Define

$$S(x) = \frac{1}{\sqrt{2}}\left(\langle r \rangle + r(x)\right) e^{2i\alpha(x)}$$

- Mixing angle between the radial field and the SM Higgs field

$$\tan 2\theta = \frac{2g\,\langle \varphi \rangle\,\langle r \rangle}{m_\varphi^2 - m_r^2}$$

- Model parameters: g, m_r and $\langle r \rangle$

Weinberg's Higgs Portal Model for Dark Radiation and Dark Matter

- Add one Dirac field

$$\mathcal{L}_\psi = i\bar{\psi}\gamma \cdot \partial\psi - m_\psi \bar{\psi}\psi - \frac{f_\chi}{\sqrt{2}}\bar{\psi}^c \psi S^\dagger - \frac{f^*}{\sqrt{2}}\bar{\psi}\psi^c S$$

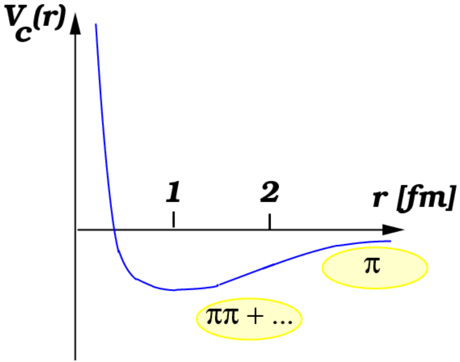
  and assign a charge $U(1)_W = 1$

- Splits into two Majorana fermions, the lighter one is DM

$$\mathcal{L}_\psi = \frac{i}{2}\bar{\psi}_\pm \gamma \cdot \partial\psi_\pm - \frac{1}{2} m_\pm \bar{\psi}_\pm \psi_\pm - \frac{i}{4\langle r\rangle}\left(\bar{\psi}_+ \gamma\psi_- - \psi\psi_- \gamma\psi_+\right) \cdot \partial\alpha$$
$$- \frac{f_\chi}{2} r \left(\bar{\psi}_+ \psi_+ - \bar{\psi}_- \psi_-\right)$$

- Model parameters now include: m_χ, f_χ, g, m_r, and $\langle r \rangle$
- Relic density set by $\chi\chi \leftrightarrow rr$, $\alpha\alpha$, $\bar{f}f$

Nucleon-Nucleon Interactions



[Epelbaum, Hammer, Meissner 2009]

Goldstone Boson Production in Proto-Neutron Star Core

- Amplitude for nuclear bremsstrahlung process in one-pion exchange (OPE) approximation

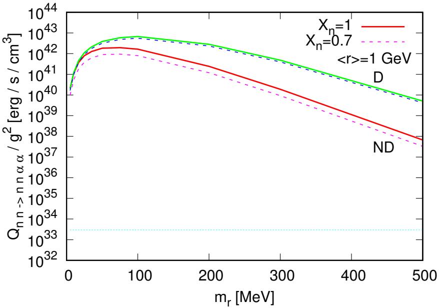
$$\sum_{\text{spins}} |\mathcal{M}_{NN\to NN\alpha\alpha}|^2 \approx 64 \left(\frac{f_N\, g\, m_N}{m_\varphi^2}\right)^2 \left(\frac{2m_N f_\pi}{m_\pi}\right)^4 \frac{(q_1\cdot q_2)^2}{(q^2-m_r^2)^2+m_r^2\Gamma_r^2}$$
$$\cdot \frac{(-2q^2)^2\, m_N^2}{(2p\cdot q)^4} \left\{ \frac{|\vec{k}|^4}{(|\vec{k}|^2+m_\pi^2)^2} + \frac{|\vec{l}|^4}{(|\vec{l}|^2+m_\pi^2)^2} + \frac{|\vec{k}|^2|\vec{l}|^2-2|\vec{k}\cdot\vec{l}|^2}{(|\vec{k}|^2+m_\pi^2)(|\vec{l}|^2+m_\pi^2)} + \ldots \right\}$$

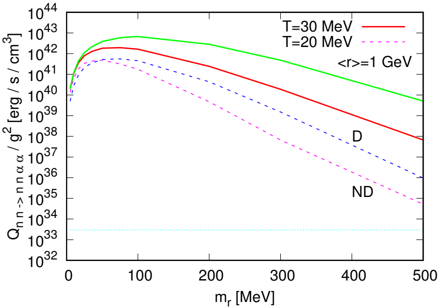
- Energy loss rate

$$Q_{NN\to NN\alpha\alpha} = \frac{\mathcal{S}}{2!}\int \frac{d^3\vec{q_1}}{2\omega_1\,(2\pi)^3}\frac{d^3\vec{q_2}}{2\omega_2\,(2\pi)^3}\int \prod_{i=1}^4 \frac{d^3\vec{p_j}}{2E_j\,(2\pi)^3}\, f_1 f_2 (1-f_3)(1-f_4)$$
$$\times \sum_{\text{spins}} |\mathcal{M}_{NN\to NN\alpha\alpha}|^2\,(2\pi)^4\delta^4(p_1+p_2-p_3-p_4-q_1-q_2)\,(\omega_1+\omega_2)$$

Energy Loss Rate due to Goldstone Boson Emission

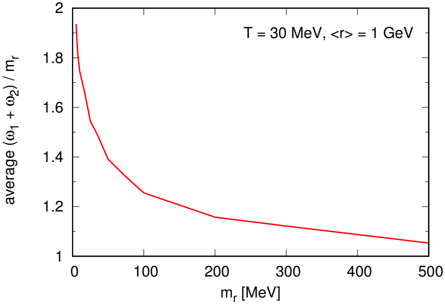
- Nuclear bremsstrahlung processes calculated in non-degenerate (ND) and degenerate (D) limit
- Dependence on neutron fraction X_n
- Dependence on PNS core temperature T

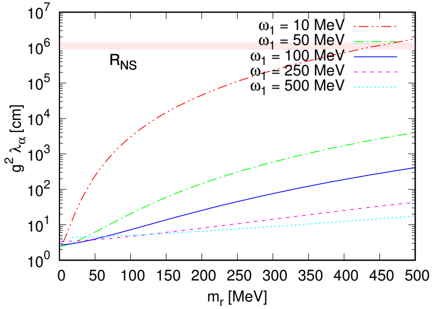




Goldstone Boson Average Emission Energy and Mean Free Path

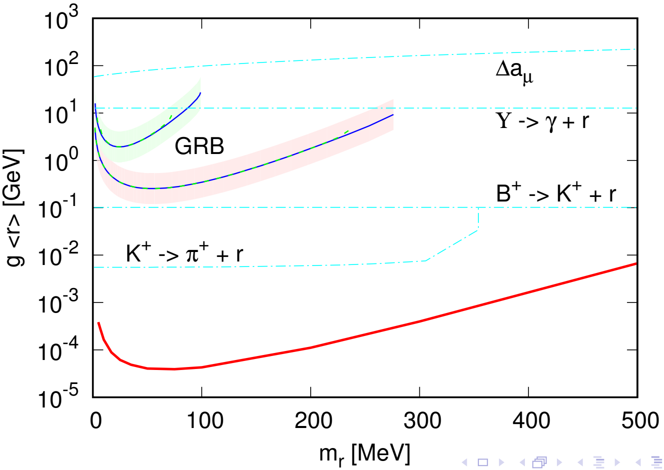
- Free-streaming ($\alpha N \to \alpha N$) and trapping ($\alpha\alpha NN \to \alpha\alpha$) regime
- Collider bound: $g < 0.011$



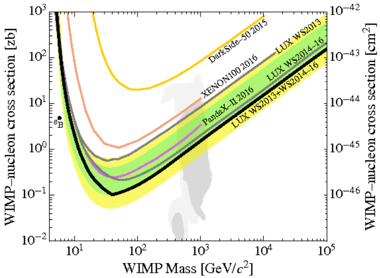


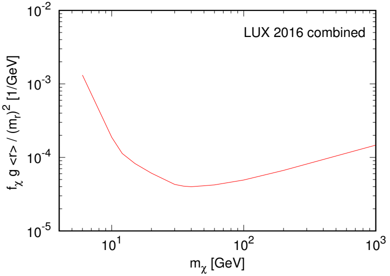
SN 1987A Constraint on Weinberg's Higgs Portal Model

- Consider free-streaming regime
- Apply Raffelt's criterion at $T = 30\ \mathrm{MeV}$, $\rho = 3 \cdot 10^{14}\ \mathrm{g/cm^3}$



Constraints from Dark Matter Direct Search Experiments





SN 1987A Constraint on Higgs Portal Model Dark Matter

- Dark matter coupling f_χ fixed by $\Omega_\chi h^2 = 0.11$ [Anchordoqui, Denton, Goldberg, Paul, da Silva, Vlcek, Weiler 2014]