Modica,

$14^{\rm th}$ July 2023

Supernovae as factories of neutrinos and other feebly interacting particles

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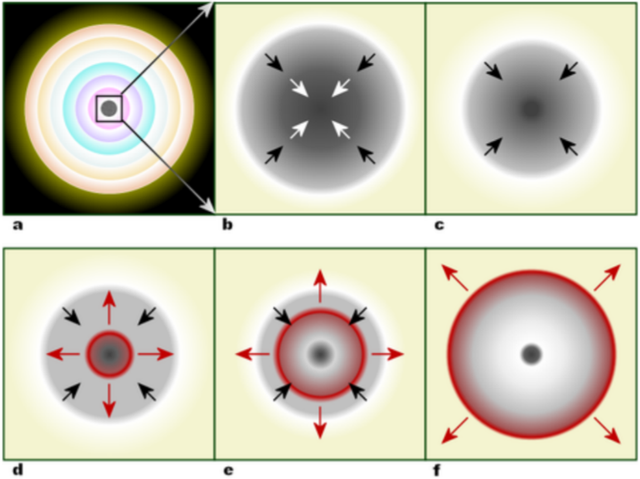
Core-Collapse Supernovae

For massive stars ($M > 8 M_\odot$) the nuclear fusion produces heavy elements in an onion structure and a degenerate iron core

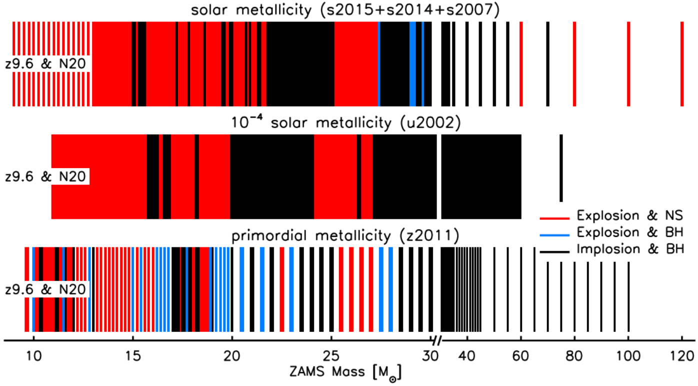


Iron in the core cannot be burnt and the star starts to collapse

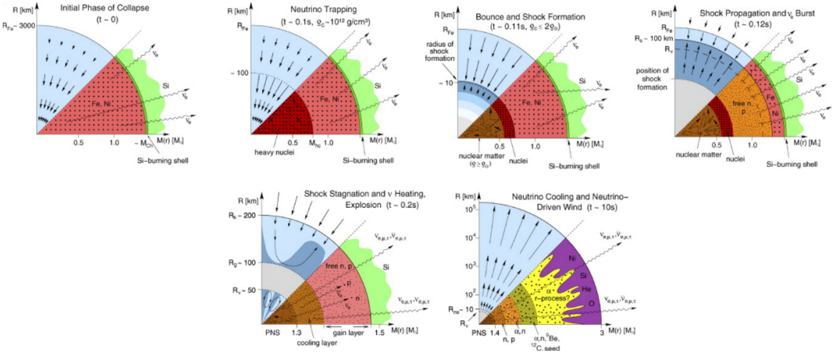
How many successfull SNe?

H. T. Janka, [arXiv:1702.08825 [astro-ph.HE]].

Very non-trivial to predict if a SN explodes or not, see how much it depends on metallicity



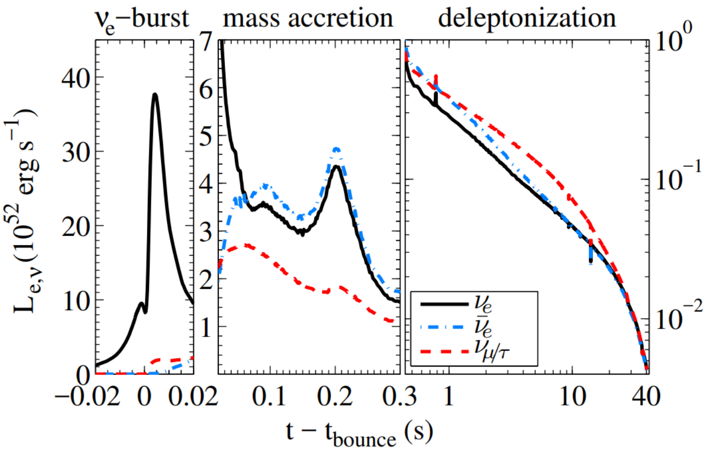
Phases of neutrino emission



Each phase is strongly characterized by a different neutrino signal

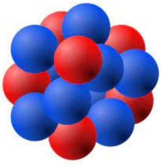
SN neutrino emission

T. Fischer *et al.*, Phys. Rev. D **94** (2016) no.8, 085012

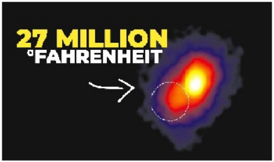


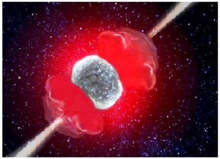
Orders of magnitude for SNe

The SN core is an extreme environment



1000x

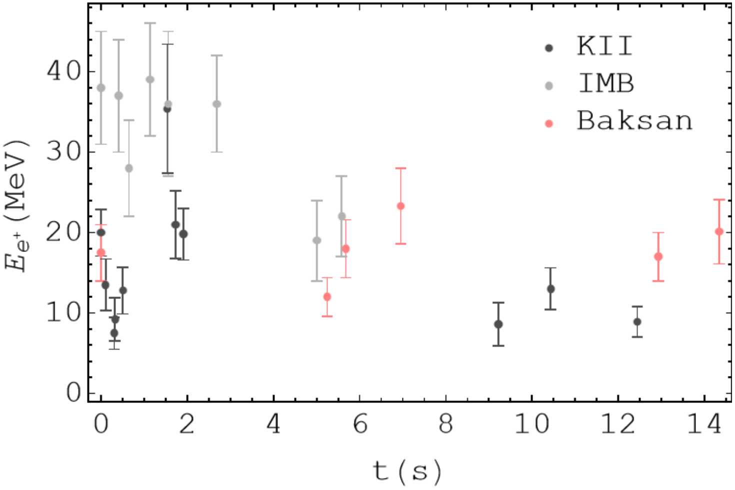




density	temperature	magnetic field
10^{14}g cm^{-3}	30 MeV	10^{15} G

SN1987A: neutrino signal

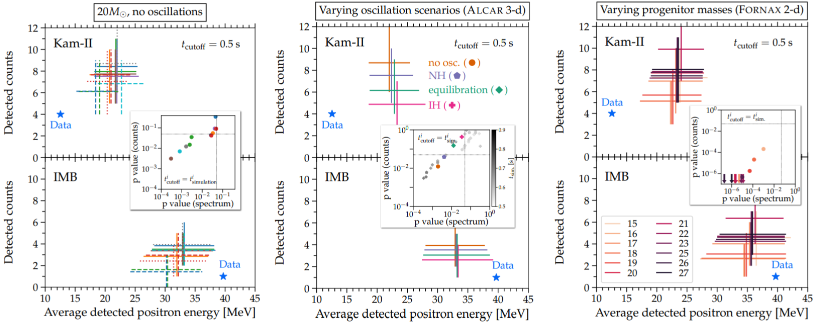
From the few $\bar{\nu}_e p \to n e^+$ events of SN 1987A we know that...



$\sim 10^{53}$ erg emitted as neutrinos with energy $\sim O(15\,\mathrm{MeV})$ in $\sim 10\,\mathrm{s}$

SN1987A: we don't understand the neutrino signal (?)

S. W. Li *et al.*, [arXiv:2306.08024 [astro-ph.HE]].



SN models generally agree with each other and disagree with data

Fundamental physics with SNe

G. G. Raffelt, 1996, ISBN 978-0-226-70272-8

Constraint on neutrino mass:

$$\Delta t_\nu = 2.57\,\mathrm{s}\left(\frac{d_{SN}}{50\ \mathrm{kpc}}\right)\left(\frac{E_\nu}{10\ \mathrm{MeV}}\right)^{-2}\left(\frac{m_\nu}{10\ \mathrm{eV}}\right)^{2} \rightarrow m_\nu \lesssim 23\ \mathrm{eV}$$

Constraint on neutrino lifetime:

$$\tau / m_\nu \gtrsim 6 \times 10^5\ \mathrm{s}\,/\,\mathrm{eV}$$

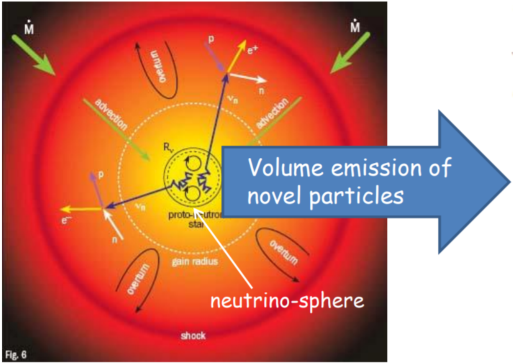
Secret interactions with $D\nu B$, speed of neutrinos/light, neutrino charge

Axions: Why? What?

The energy-loss argument

G. Raffelt, Lect. Notes Phys. **741** (2008)

Stars produce feebly interacting particles which escape, draining energy from the core



They strongly affect the SN neutrino burst if

$$L_{\mathrm{FIP}} > L_\nu = 3 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

The strong CP problem

The QCD Lagrangian includes a CP-odd term

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \bar{\theta}_{\rm QCD} \frac{g^2}{32\pi^2} \, \mathrm{tr} \, \tilde{G}_{\mu\nu} G^{\mu\nu}$$

where $\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} G^{\alpha\beta}$ and $\bar{\theta}_{\rm QCD} = \theta_{\rm QCD} + \arg\det M_{\rm quark}$

Prediction of neutron electric dipole moment
$\mathcal{L} \sim \mathrm{d}_n \cdot \mathrm{E} \quad \rightarrow \quad \mathrm{d}_n \approx |\bar{\theta}_{\rm QCD}| \times 10^{-15} \, e \, \mathrm{cm}$
Experimental bound: $|\bar{\theta}_{\rm QCD}| < 10^{-10}$
Naturalness problem, why $\bar{\theta}_{\rm QCD}$ *is so small?*

The Peccei-Quinn mechanism

R. D. Peccei *et al.*, Phys. Rev. Lett. **38** (1977)

PQ symmetry
$U(1)_{PQ}$ is a chiral global symmetry that drives dynamically $\bar{\theta}_{PQ} \to 0$

$U(1)_{PQ}$ is broken at a scale f_a, the **Peccei-Quinn scale**, and the Goldstone boson is the **axion**

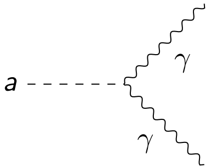
$$\begin{aligned}\mathcal{L}_{\rm ax} =& \frac{1}{2}\partial_\mu a \partial^\mu a - \xi \frac{a}{f_a}\frac{g^2}{32\pi^2}\tilde{G}^a_{\mu\nu}G^{\mu\nu a} + \\ &+ \frac{g_a}{2m}\bar{\Psi}\gamma^\mu\gamma^5\Psi\partial_\mu a - \frac{g_{a\gamma}}{4}a\tilde{F}^{\mu\nu}F_{\mu\nu}\end{aligned}$$

The minimum condition removes the CP-odd term: $\bar{\theta}_{\rm QCD} = 0$

Axion-SM interactions

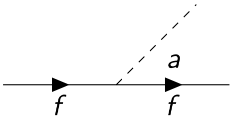
Axion-photon vertex

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} a \, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma} a \, \mathrm{E} \cdot \mathrm{B} \quad g_{a\gamma} = C_\gamma \frac{\alpha}{2\pi f_a}$$



Axion-fermion vertex

$$\mathcal{L}_{af} = \frac{g_{af}}{2m_f} \bar{\Psi}\gamma^\mu\gamma^5\Psi \, \partial_\mu a \quad g_{af} = C_f \frac{m_f}{f_a}$$



Axions and Axion-Like Particles

In any axion model

$$m_a \sim \frac{1}{f_a} \quad g_{a\gamma} \sim \frac{1}{f_a} \quad f_a \gg 246\,\text{GeV}$$

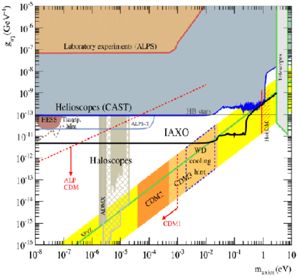
The typical QCD axion is **light** and **weakly interacting**

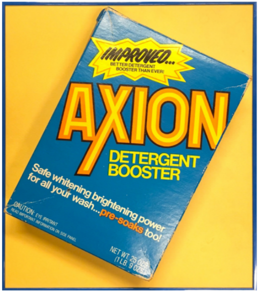
Axion-Like Particles (ALPs) are a generalization:

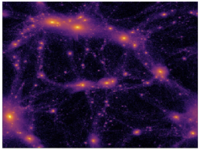
- Heavy ALP searches at collider
- Superlight ALPs as fuzzy Dark Matter
- Some ALPs could be the inflaton
- ALPs in flavor-violating processes...

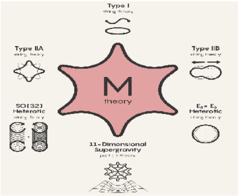
Motivations to study axions and ALPs

Axions and ALPs are a window on high-energy physics









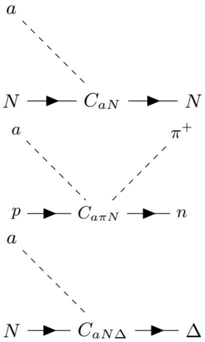
This hot topic is a motivation for interdisciplinary searches

Axion production in nuclear processes

Axion Lagrangian

L. Di Luzio *et al.*, Phys. Rept. **870** (2020), 1-117

$$\mathcal{L}_{\text{int}} = g_a \frac{\partial_\mu a}{2m_N}\Big[C_{ap}\bar{p}\gamma^\mu\gamma_5 p + C_{an}\bar{n}\gamma^\mu\gamma_5 n + \frac{C_{a\pi N}}{f_\pi}(i\pi^+\bar{p}\gamma^\mu n - i\pi^-\bar{n}\gamma^\mu p) + C_{aN\Delta}\left(\bar{p}\,\Delta^+_\mu + \overline{\Delta^+_\mu}\,p + \bar{n}\,\Delta^0_\mu + \overline{\Delta^0_\mu}\,n\right)\Big]$$

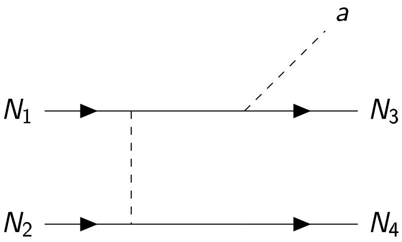


Axion-nucleon bremsstrahlung in SNe

M. S. Turner, Phys. Rev. Lett. **60** (1988)

PC, T. Fischer *et al.*, JCAP **10** (2019) no.10, 016

SN axions are produced by nucleon-axion bremsstrahlung

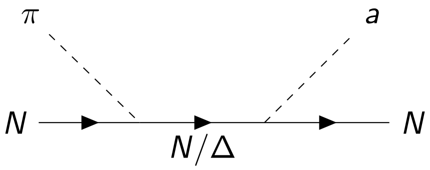


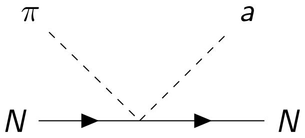
where we have to include detailed nuclear physics and many body effects

Pion-axion conversion in SNe

PC, B. Fore *et al.*, Phys. Rev. Lett. **126** (2021) no.7, 071102

SN axions are produced by pion-axion conversion



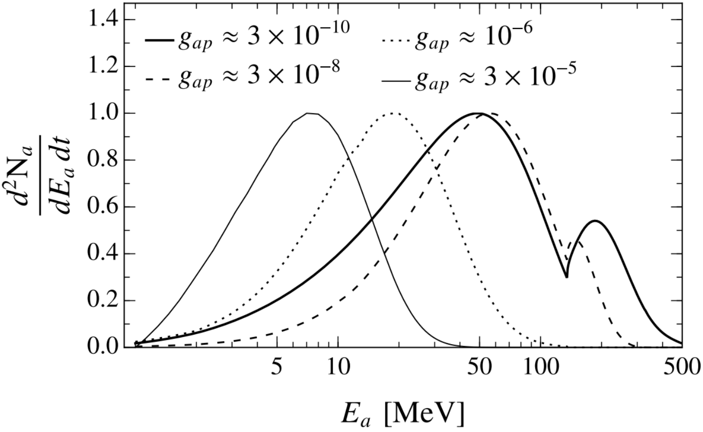


This is the leading axion production process in a SN despite the small density of pions ($\mathcal{O}(1\%)$)!!

Flux from pion-axion conversion

A. Lella *et al.*, [arXiv:2306.01048 [hep-ph]].

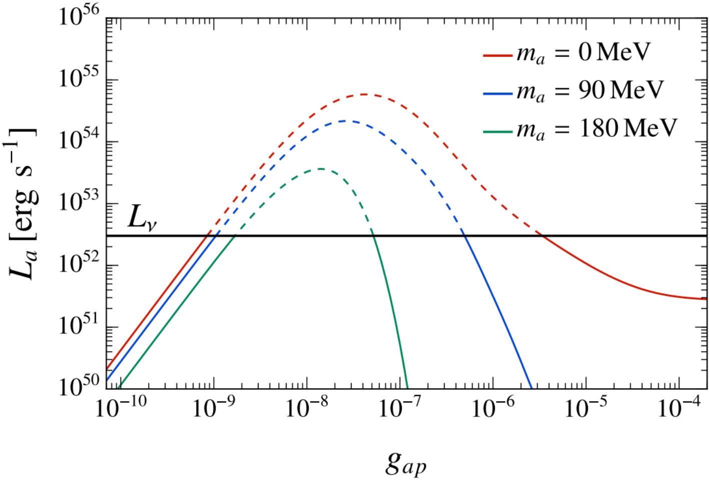
The harder spectrum is due to the pion rest mass



Notice the lower energies as axions become trapped

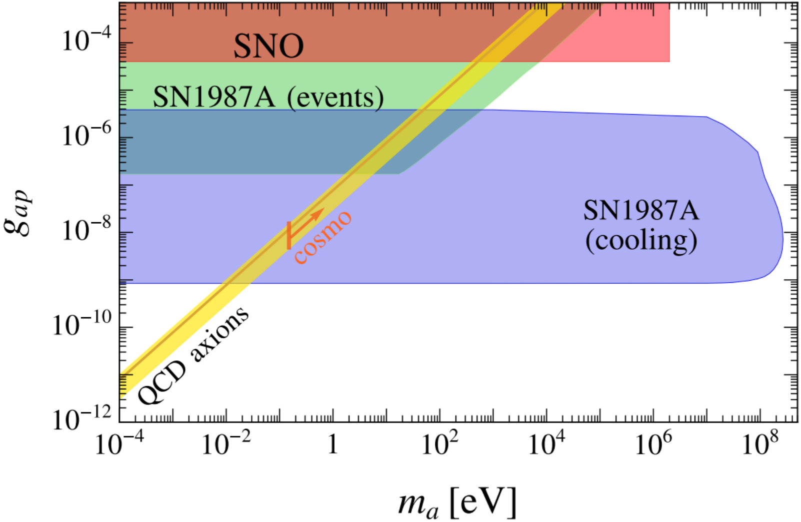
Consequences on the SN cooling

Clear behavior of free-streaming/trapping regime



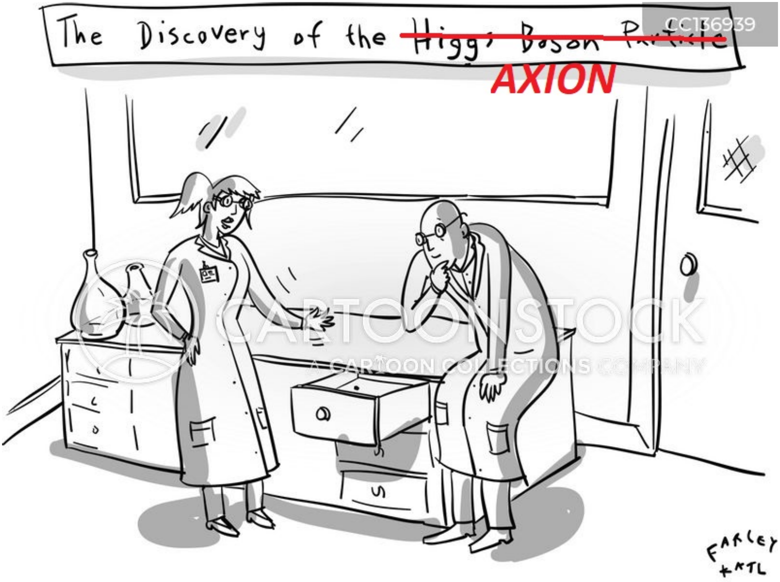
SN axion bounds

PC *et al.*, [arXiv:2306.17055 [astro-ph.HE]].



SN axion bound from KII (green): $a + {}^{16}O \rightarrow {}^{16}O^*$

Conclusions



"Always the last place you look!"