Axion signatures from supernova explosions through the nucleon electric-dipole portal

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Based on G. Lucente, L. M,, P. Carenza, L. Di Luzio, M. Giannotti, A. Mirizzi, PRD 105 (2022) 12, 123020, ArXiv:2203.15812 [hep-ph]

OUTLINE

- Introduction
- Axions production in the Supernova explosion
- Bounds on axions parameter space
- Detection probability study
- Conclusions

WORK'S AIMS

- In this work we focused on obtaining:
  - a precise calculation of the axion production from SNe;
  - bounds on the axion parameters.
- The existence of ALPS emerges naturally in extensions of the Standard Model, like Peccei-Quinn theory or string theory [Peter Svrcek, Edward Witten *arXiv:hep-th/0605206*]

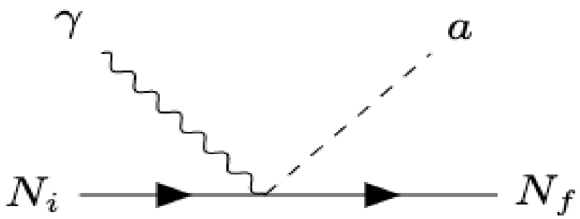
↓

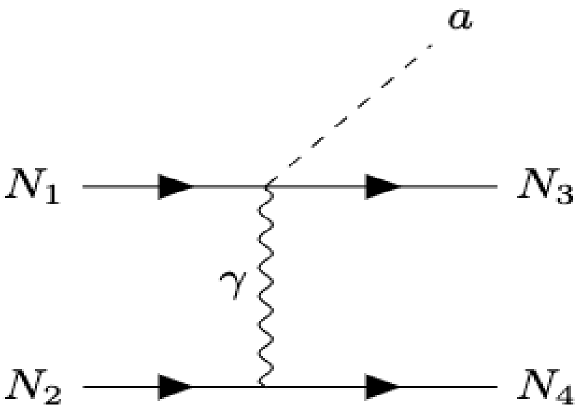
Interest in investigating their possible interactions

AXIONS INTERACTION

- Axion-like particles (ALPs) are pseudoscalar particles introduced in UV completions of the SM
- We consider only the EDM portal interaction [Graham & Rajendran (2013)]

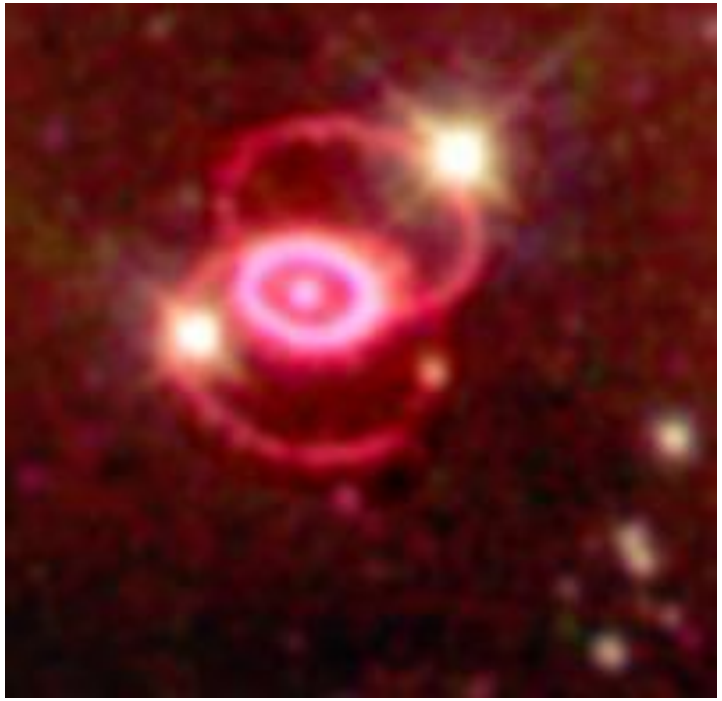
$$\mathcal{L}_a^{nEDM} = -\frac{i}{2} g_d \, a \, \bar{N} \gamma_5 \sigma_{\mu\nu} \, N \, F^{\mu\nu}$$





SUPERNOVA NEUTRINOS

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.



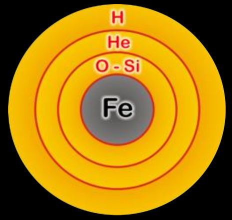
- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED: 1-3 SN/century** in our galaxy (d $\approx O$ (10) kpc).

Thermonuclear (Type Ia)

- Carbon-oxygen white dwarf (remnant of low-mass star)
- Accretes matter from companion

Core-Collapse Supernovae (Type II, Ib)

- Degenerate iron core of evolved massive star
- Accretes matter by nuclear burning at its surface



Chandrasekhar limit is reached – $M_{Ch} \approx 1.5\ M_{sun}\ (2Y_e)^2$

Nuclear burning of C and O ignites
→ Nuclear deflagration
("Fusion bomb" triggered by collapse)

Collapse to nuclear density
Bounce & shock
Implosion → Explosion

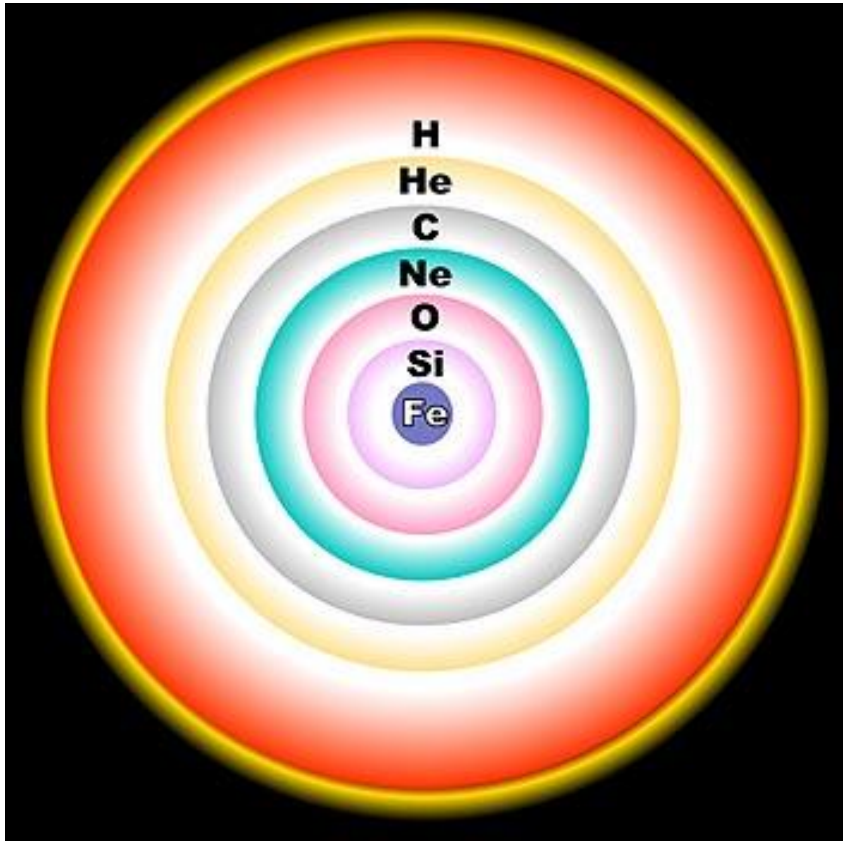
Powered by nuclear binding energy

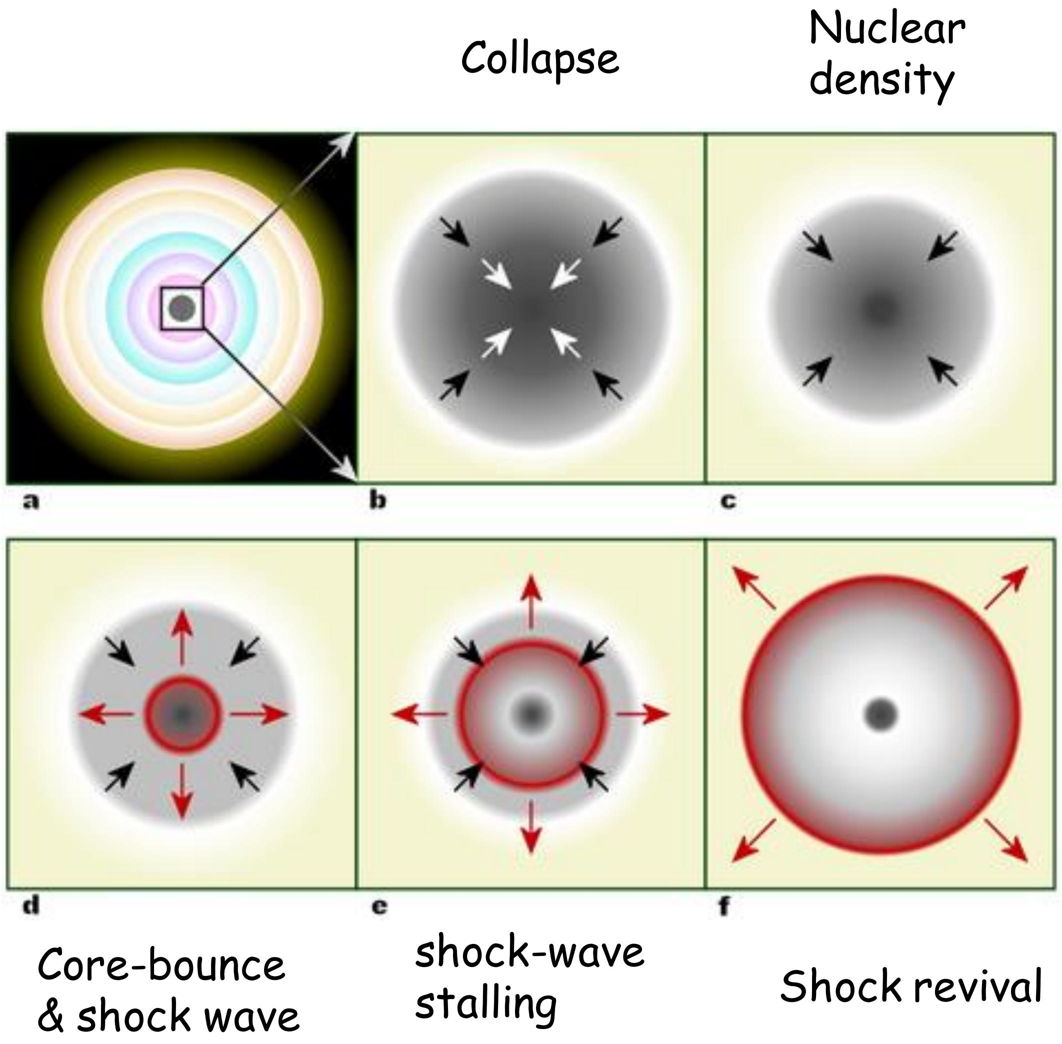
Powered by gravity

Comparable "visible" energy release of ~ 3×10^{51}erg

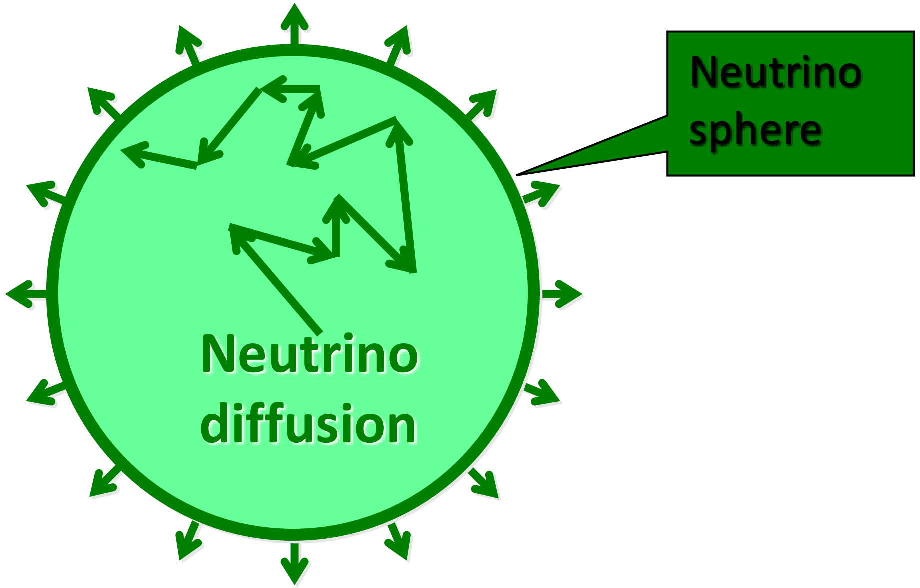
LIFE AND DEATH OF A MASSIVE STAR

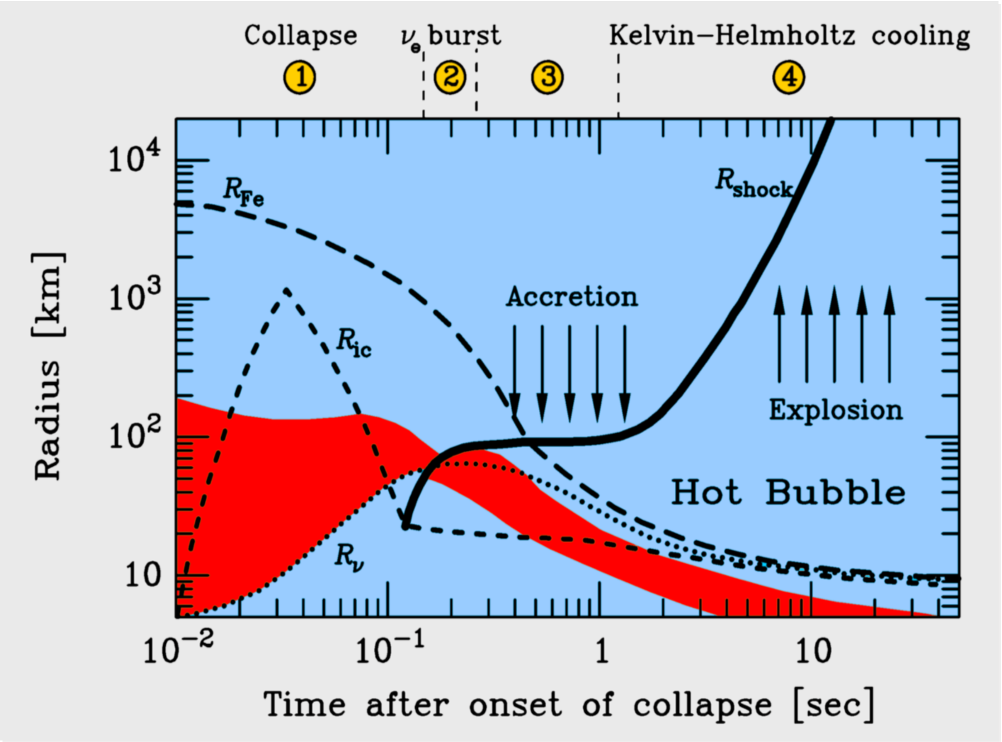
Onion-like layers of a massive, evolved star just before core collapse.





STELLAR COLLAPSE AND SUPERNOVAE EXPLOSION





Neutrino luminosity:

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

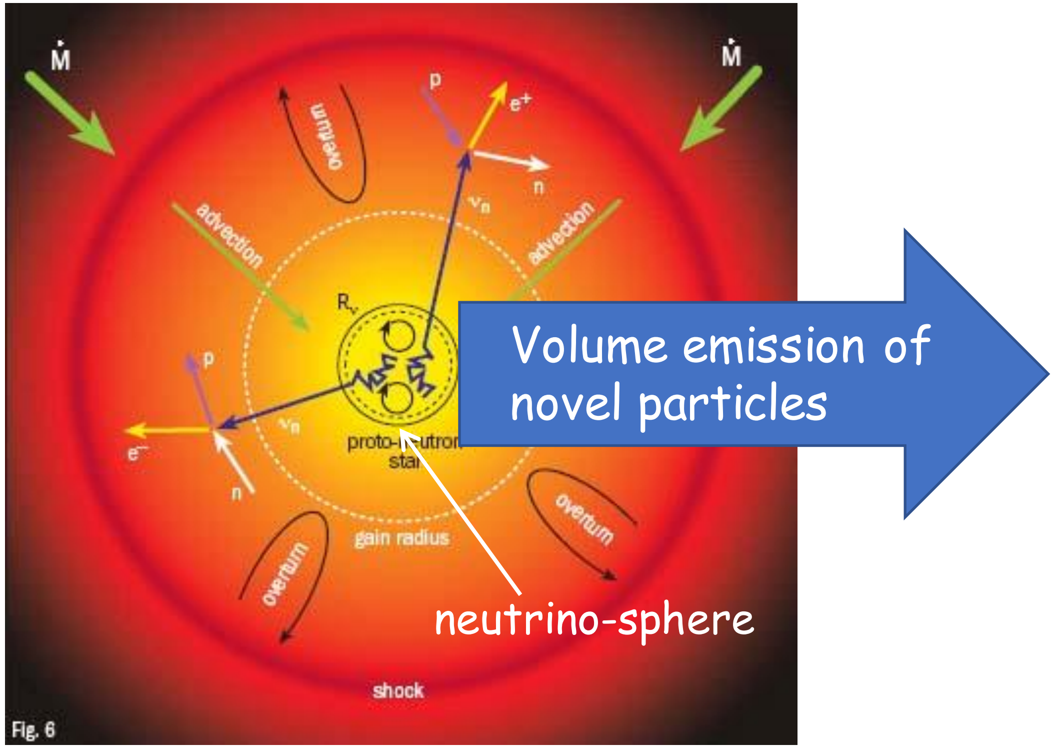
$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe!

Energy sharing:

99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

ENERGY-LOSS ARGUMENT



Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it.

Assuming that the SN 1987A neutrino burst was not shortened by more than ~½ leads to an approximate requirement on a novel energy-loss rate of

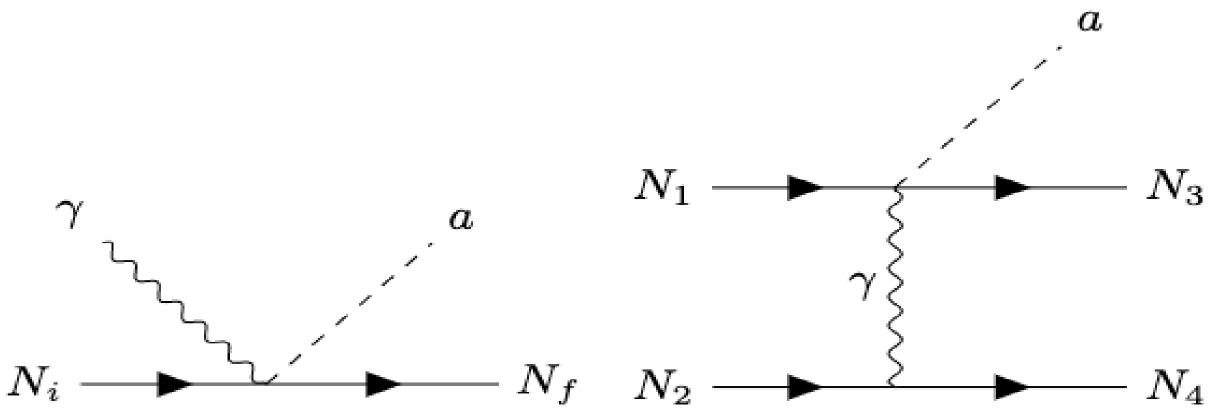
$$\varepsilon_x < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30$ MeV

HEAVY STERILE ν EMISSION FROM SNE

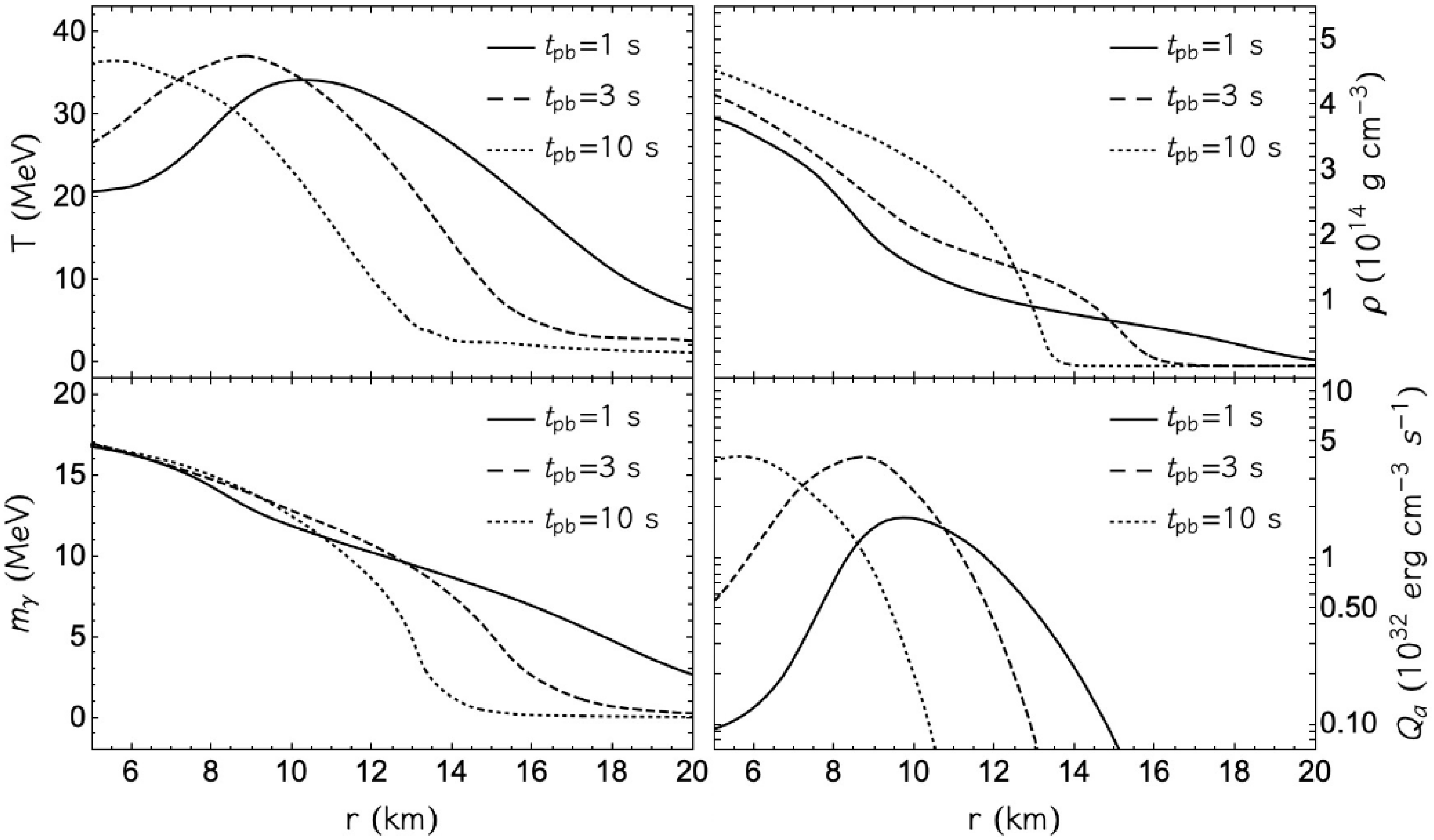
- We investigate the possibility that axions interacting via the EDM portal are produced in SNe [Fuller et al, arXiv: 0806.4273 [astro-ph]]
- In the hot core ν_e, e, p, n are degenerate. Thus, we obtain the chemical potential for p, n from Sne simulation
- We solved the Boltzmann equation for sterile neutrino population, following the technique developed by [Hannestad et al, arXiv: hep-ph/9506]

$$\frac{\partial f_s}{\partial t} = \frac{(2\pi)^4}{2E_1} \int d^3\widehat{p_2} d^3\widehat{p_3}\, d^3\widehat{p_4} \Lambda(f_s, f_2, f_3, f_4) S|M|^2 \delta^4(p_1 + p_2 - p_3 - p_4)$$



SNe RESULTS

- We report here the data obtained from the SNe



$$Q_a = \int dE_a E_a \frac{d\dot{n}_a}{dE_a}$$

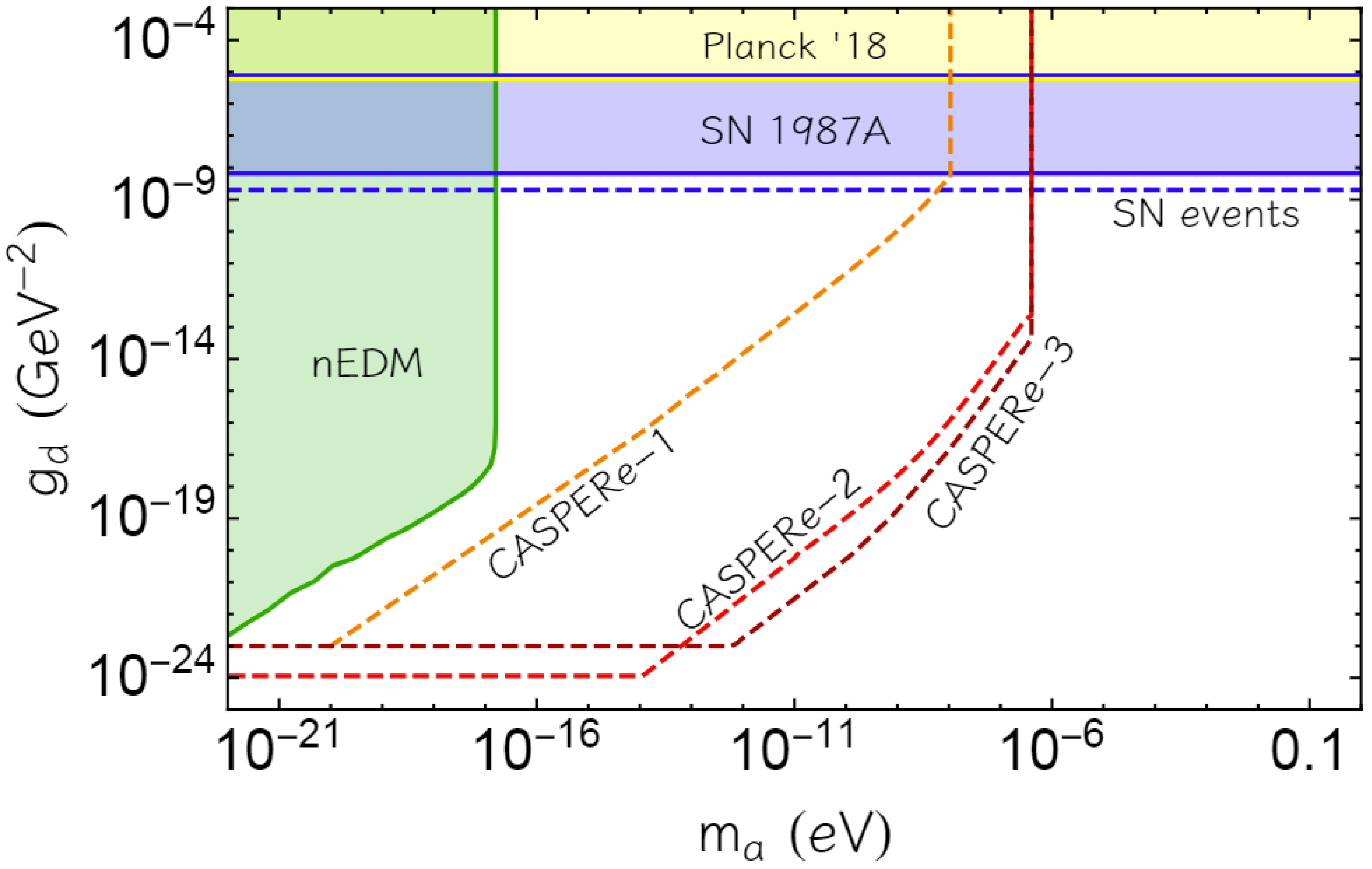
SN 1987A COOLING BOUND

- Axion emission must not shorten the duration of the neutrino burst. Bound on the axion luminosity:

$$L_a \lesssim 3 \times 10^{52} \text{ erg/s at 1 s after core bounce}$$

$$L_a = 4\pi \int_0^R dr r^2 \alpha^2 \int dE_a\, E_a \frac{d\dot{n}_a}{dE_a} \left\langle e^{-\tau(E'_a, r)} \right\rangle$$

- $\left\langle e^{-\tau(E'_a, r)} \right\rangle$ is a directional average of the axion emissivity
- α is the *lapse* factor
- E'_α is the redshifted energy



- Bounds obtained for ALPs EDM in green. Dashed lines for future experiment.

AXION SIGNAL

- We studied the possibility of axion detection on Earth.
- The detection channel is $a + p \to p + \gamma$

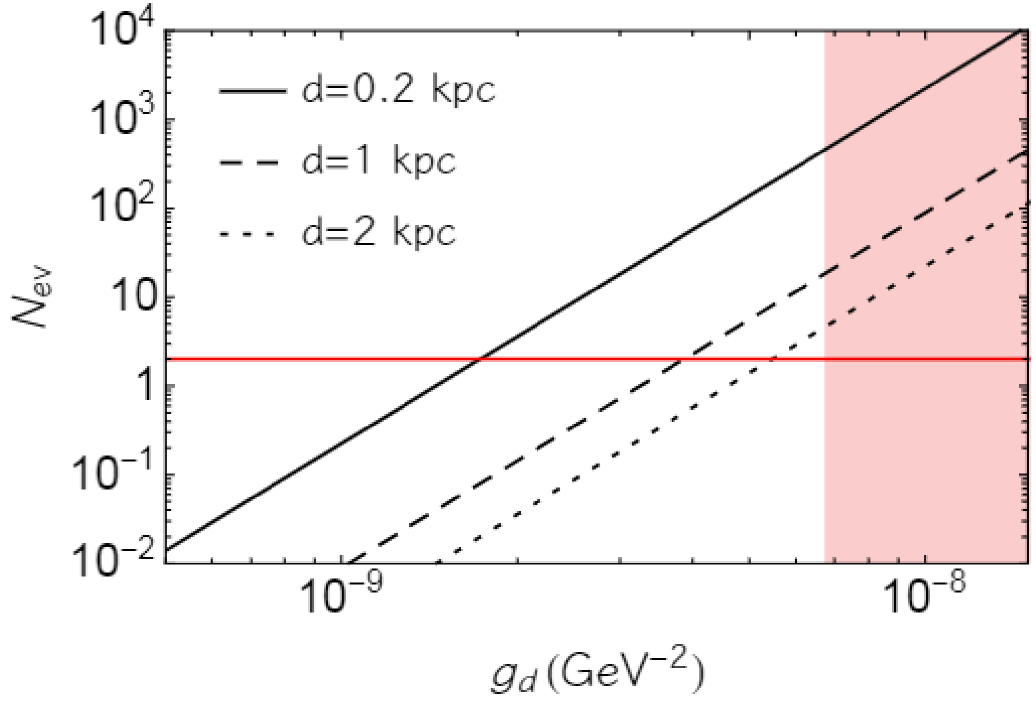
$$\sigma_a = \frac{g_d^2 E_a^2}{2\pi}$$

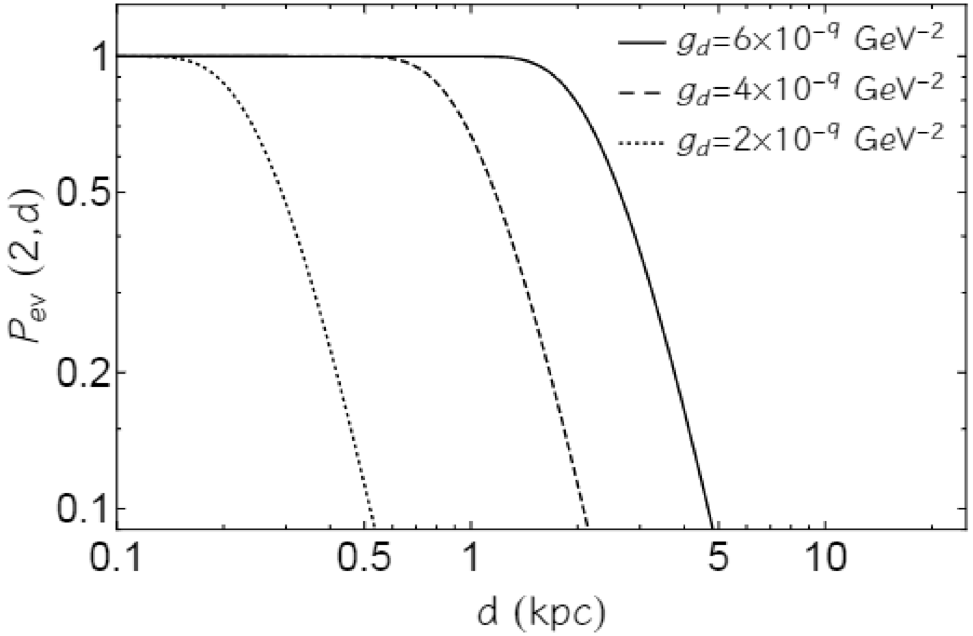
In the limit $m_a \to 0$ and $p_{n,p} \to 0$

- It is possible to analytically obtain the produced γ energy spectrum

$$\frac{dN_\gamma}{dE_\gamma} = \frac{N_t}{4\pi d^2} \frac{dN_a}{dE_a} \sigma_a$$

$$N_{ev} = 290\left(\frac{g_d}{6\times10^{-9}\mathrm{GeV}^{-2}}\right)^4 \frac{M_{dec}}{374\ \mathrm{kton}}\left(\frac{d}{0{,}2\ \mathrm{kpc}}\right)^{-2}$$





BBN BOUND

- To complete the oyr study, we have analysed the bound obtained from BBN with axions produced via EDM portal.

$$N_{eff} \sim 0.027\left(\frac{106.75}{g_*, s}\right)^{4/3}$$

- It is interest to forecast a bound for the future CMB-S4 experiments

$$N_{eff} < 0,027$$

$$\Downarrow$$

$$g_d > 1.3 \times 10^{-14} GeV^{-2}\left(\frac{T_{RH}}{10^{10}\ GeV}\right)^{-1/2}$$

CONCLUSIONS

- We analyzed the phenomenology of ALP produced in Supernovae explosion from the EDM portal
- We studied the Supernovae and BBN bound on this coupling
- We characterize axion production and detection on Earth.
- Considering the Super-K, we have obtained the detection probability, which is relevant up to a distance d $\sim$ 2 kpc

Thanks for the attention

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