PPC 2021: XIV International Workshop on Interconnections between Particle Physics and Cosmology
University of Oklajoma, 17-21 May 2021

# ENHANCED SN AXION EMISSIVITY BY PIONIC PROCESSES

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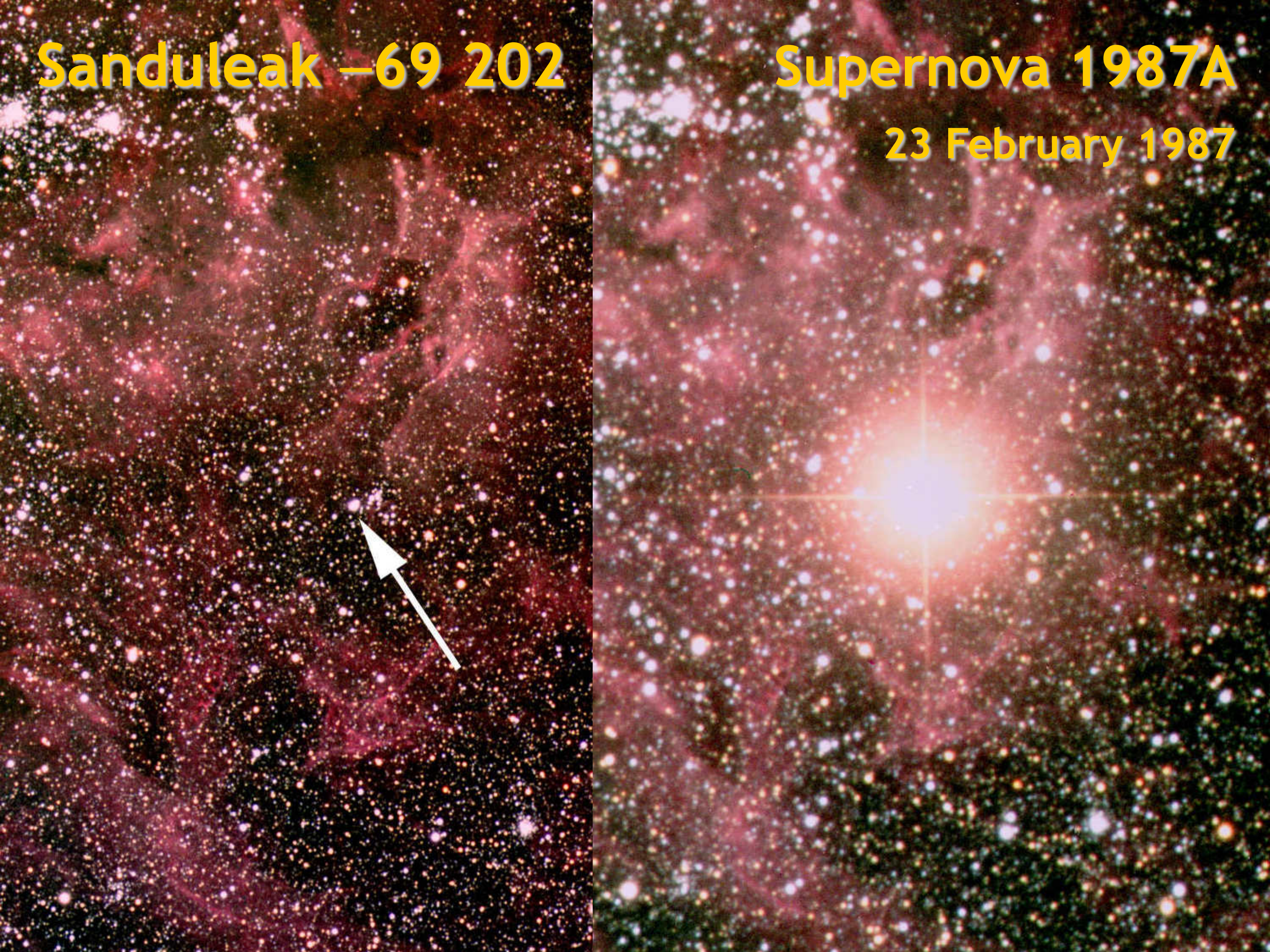
Based on a work in collaboration with Carenza, Fore, Giannotti and Reddy,
PRL 126 (2021)7, 071102, arXiv:2010.02943

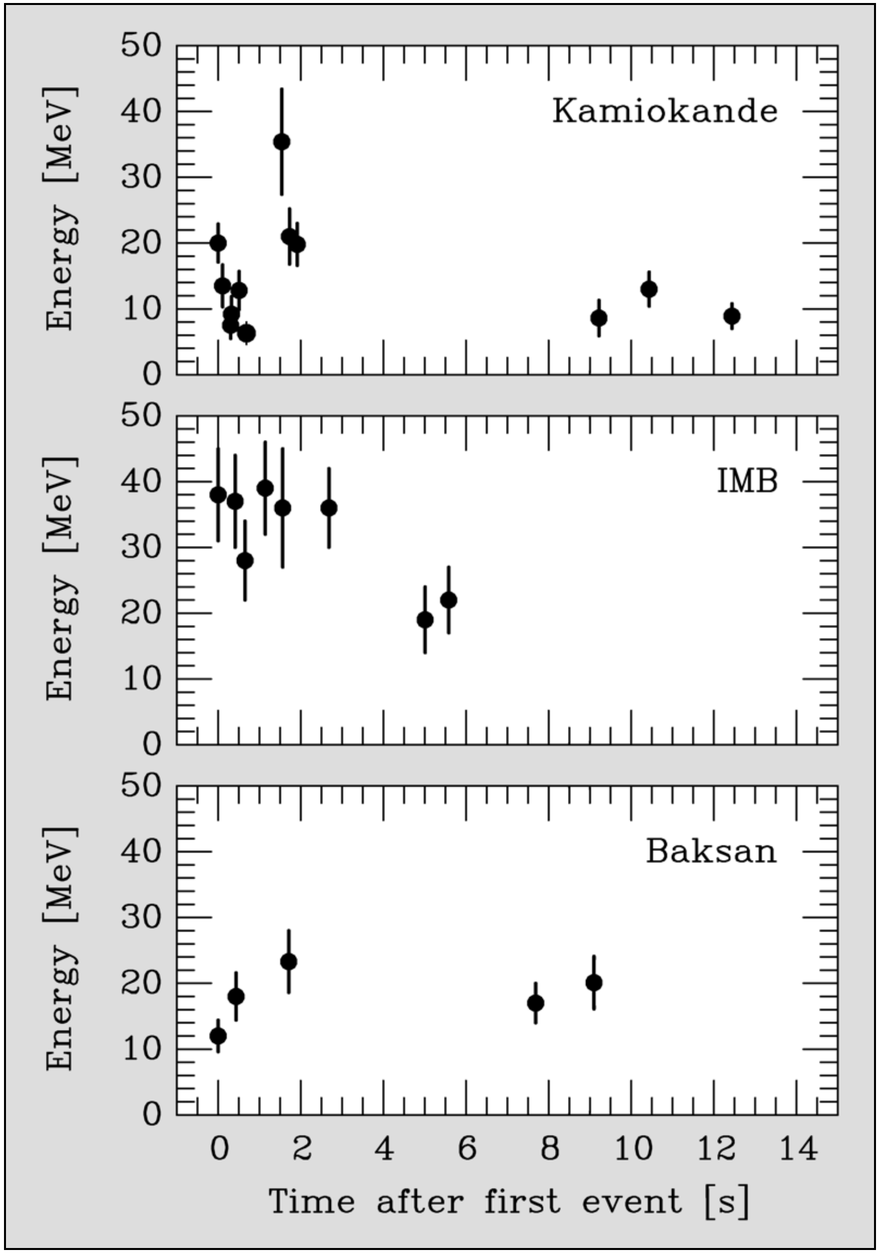
# SUPERNOVAE

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 $\nu$ 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 ≈ $\mathcal{O}$(10) kpc).


Sanduleak −69 202
Supernova 1987A
23 February 1987

# NEUTRINO SIGNAL OF SUPERNOVA 1987A



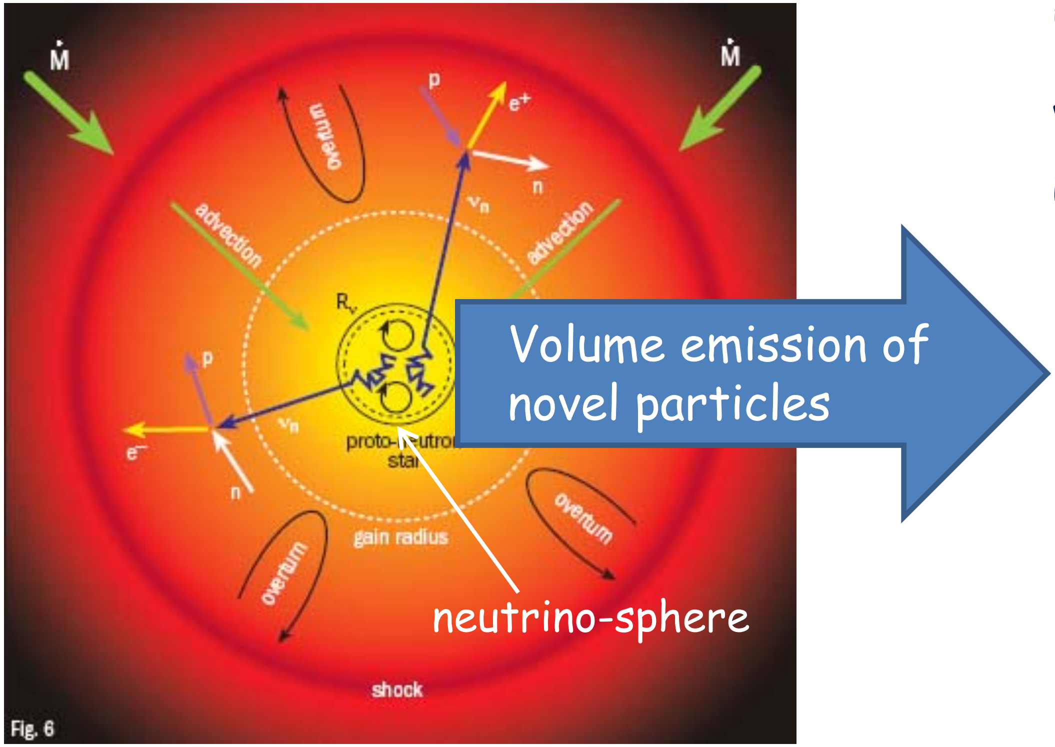

Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

# 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

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

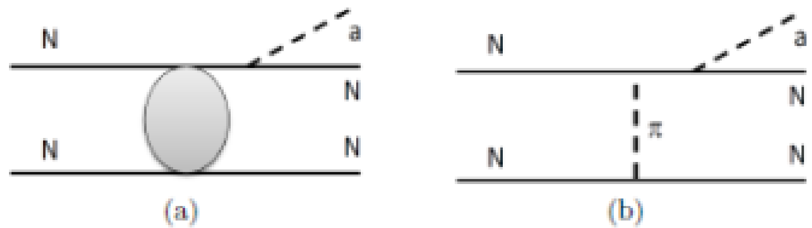
for $\rho \approx 3 \times 10^{14}$ g cm$^{-3}$ and $T \approx 30$ MeV

# AXION EMISSION FROM A NUCLEAR MEDIUM

[Burrows et al., PRD 39, 4 (1989), Brinkmann and Turner, PRD 34, 8 (1988), Keil, Janka et al, PRD 56, 4 (1997)…]

$$NN \to NNa$$

nucleon-nucleon bremsstrahlung




Bulk nuclear interaction    One pion exchange

$$L_{aN} = \frac{g_{aN}}{2m_N} \bar{N}\gamma_\mu\gamma_5 N \partial^\mu a$$

$$g_{aN} = C_N \frac{m}{f_a}$$

Non-degenerate energy-loss rate $\varepsilon_a = g_{aN}^2 \, 2\times10^{39}\,\mathrm{erg\,g^{-1}\,s^{-1}}\rho_{15}T_{30}^{3.5}$

$$\begin{pmatrix} T_{30} = T/30\,\mathrm{MeV} \\ \rho_{15} = \rho/10^{15}\,\mathrm{g\,cm^{-3}} \end{pmatrix} \quad \langle \rho_{15} \rangle \approx 0.4 \quad \langle T_{30}^{3.5} \rangle \approx 1.4$$

$$\Rightarrow \quad g_{aN} < 9\times10^{-10}$$

# SN 1987A AXION LIMITS FROM NU BURST DURATION

- Raffelt, Lect. Notes Phys. 741 (2008) 51 [hep-ph/0611350]
  Burst duration calibrated by early numerical studies
  "Generic" emission rates inspired by OPE rates
  $f_a > 4 \times 10^8$ GeV and $m_a < 16$ meV

- Chang, Essig & McDermott, JHEP 1809 (2018) 051 [1803.00993]
  Various correction factors to the emission rate, specific SN core models
  $f_a > 1 \times 10^8$ GeV and $m_a < 60$ meV [KSVZ, based on proton coupling]

- Bar, Blum & D'Amico, Is there a SN bound on axions?
  PRD 101 (2020) 12 [1907.05020]
  Alternative picture of SN explosion (thermonuclear event)
  Observed signal not PNS cooling.
  However the possible detection of NS 1987A in SN 1987A would disfavor alternative mechanisms [see Page et al., 2004.06078]
  (We will neglect this possibility hereafter)

# NEW CALCULATION OF SN AXION EMISSION RATE

*[Carenza, Giannotti,Gang,Fischer, Martinez-Pinedo,A.M., JCAP 10 (2019) 016, 1906.11844, v2]*

We performed an improved calculation of axion emissivity via NN process, including self-consistently different corrections on top of the naive OPE prescription

- Non-zero pion mass in the propagator → $\sqrt{3m_N T} \sim m_\pi$
  [Hannestad and Raffelt, astro-ph/9711132]
- Two-pions exchange → important around $2\, fm\ \approx 1.5\, m_\pi^{-1}$
  Mimicked by a rho-meson exchange with $m_\rho \approx 600\ MeV$
  [Ericson and Mathiot, PLB 219, 507 (1989)]
- Effective in-medium nucleon mass → $m_N^*(\rho)$
  [Hempel, 1410.6337]
- Multiple nucleon scatterings → Nucleon spin fluctuations
  [Raffelt and Seckel, PRL 67, 2605 (1991), Raffelt and Seckel, astro-ph/9312019]

# KVSZ AXION BOUND

| $C_{ap} = -0.47\,; C_{an} = 0$ | $g_{ap}\ (\times 10^{-10})$ | $m_a$ (meV) | $f_a (\times 10^8$ GeV) |
|---|---|---|---|
| OPE | 4 | 5 | 10.4 |
| OPE+MS | 5 | 6 | 9.7 |
| OPE+corr. (no MS) | 11 | 14 | 4.2 |
| OPE+corr.+MS | 12 | 15 | 4.0 |

- Our bound is (accidentaly) comparable with Raffelt (2006). However, this latter includes only OPE+MS in a schematic SN model, assuming medium composed by only protons.

- Our approach similar to Chang et al. (2018). However, their implementation of the corrections beyond OPE is more schematic than ours. Implemented as simple fudge factors without taking into account correlations among them (e.g. normalization conditions). Amplification of the relaxation of the mass bound

# THERMAL PIONS IN A SUPERNOVA CORE

- Neutron-rich dense stellar matter, electrically neutral and in beta-equilibrium ( $e\,p \leftrightarrow n\nu_e$ ) contains a high density of electrons. Beta equilibrium requires

$$\mu_e + \mu_p = \mu_n + \mu_{\nu_e}$$

$\hat{\mu} = \mu_n - \mu_p = \mu_e - \mu_{\nu_e}$ source for negatively charged particles

$\mu_{\mu}^{-} = \mu_{\pi}^{-} = \hat{\mu}$

($\pi^+, \pi^0$abundance suppressed wrt to $\pi^-$ by $Ae^{-\hat{\mu}/T}$)

- At high-temperature and low-density population of thermal pions (no Bose Einstein condensate)

# NEW CALCULATION OF PION ABUNDANCE

[Fore and Reddy, PRC 101 (2020) 035809, 1911.02632 [astro-ph.HE]]

- Pion density

$$n_{\pi^-} = z_\pi \left( I_\pi + \sum_{i=n,p} z_i \, b_2^{i\pi^-} + \mathcal{O}(z_i^2) \right) + \mathcal{O}(z_\pi^2) \,,$$

- Thermal contribution

$$I_\pi = \int \frac{d^3k}{(2\pi)^3} \exp\left[\beta(m_\pi - \sqrt{p^2 + m_\pi^2})\right]$$

- Attractive p-wave strong interactions between thermal pions and nucleons lowers the energy cost associated of introducing pions in dense matter
  - $b_2^{n\pi^-}$ and $b_2^{p\pi^-}$ the second virial coefficient including the contribution of $\pi^-$ interactions with neutrons and protons in terms of the measured pion-nucleon phase shifts
  - $z_\pi = \exp(\beta(\hat{\mu} - m_\pi)) \ll 1$ pion fugacity

# PION DENSITY

[Fore and Reddy, PRC 101 (2020) 035809, 1911.02632 [astro-ph.HE]]

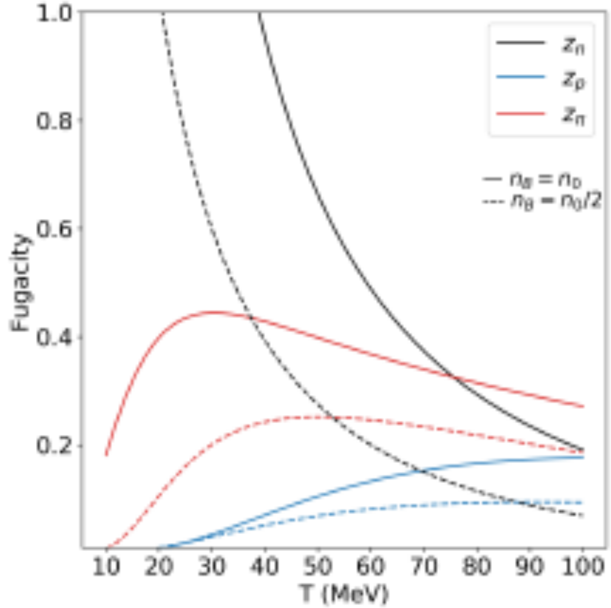



FIG. 3. Pion and nucleon fugacities in charge-neutral dense matter in $\beta$-equilibrium at $n_B = n_0$ (solid-curves) and $n_B = n_0/2$ (dashed-curves) are shown as function of temperature.

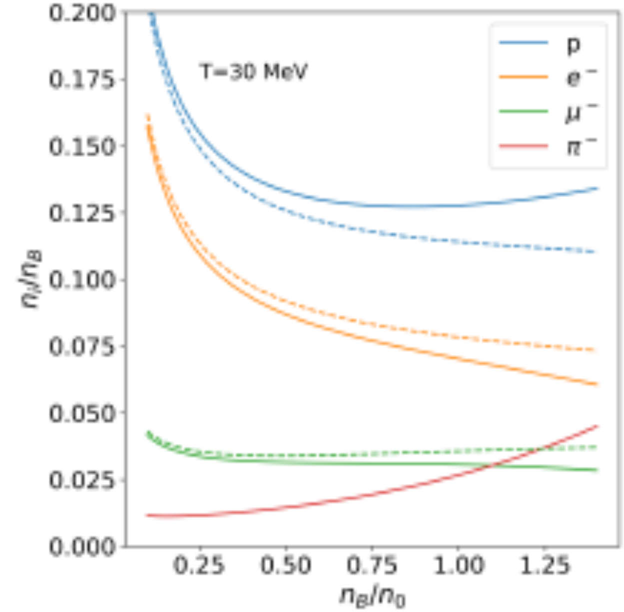
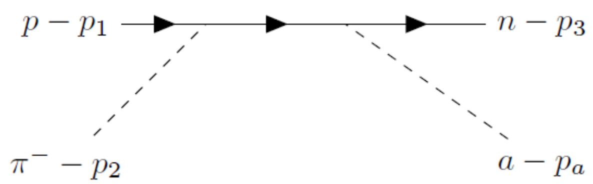


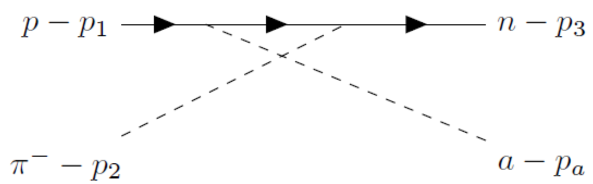

FIG. 2. Number fraction of charged particles at $T = 30$ MeV in $\beta$-equilibrium. Solid curves include pions and dashed curves only contain nucleons and leptons.

Around the saturation density $n_0 = 1.6\times10^{38} cm^{-3}$ the pion abundance can reach few % of the baryon one

# AXION EMISSIVITY VIA PIONIC PROCESS

A population of $\pi^-$ would lead to an additional channel of axions via Compton pionic process $\pi^- p \to n\, a$




Initial investigations suggested that that the thermal pion population was too small for the pionic reactions to be competitive wrt to the NN process.

- Turner, Phys. Rev. D 45, 1066 (1992)
- Raffelt and Seckel, Phys. Rev. D 52, 1780 (1995) [astro-ph/9312019]
- Keil, Janka, Schramm, Sigl, Turner and Ellis, Phys. Rev. D 56, 2419 (1997) [astro-ph/9612222]

# IMPACT ON AXION LUMINOSITY AND MASS BOUND

[Carenza, Fore, Giannotti, A.M., Reddy, 2010.02943]

- Axion emissivity

TABLE I: Axion emissivities $Q_a$ in units of $10^{32}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$ and luminosities $L_a$ in units $10^{51}\,\mathrm{erg\,s^{-1}}$ for KVSZ model ($C_{ap}=-0.47\,;C_{an}=0$) and $g_a=m_N/f_a=10^{-9}$, for different post-bounce times.

| $t_{pb}$ (s) | $\rho$ ($10^{14}$g/cm$^{-3}$) | T (MeV) | $Y_\pi$ | $Q_a^{NN}$ ($10^{32}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$) | $Q_a^{\pi}$ ($10^{32}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$) | $Q_a^{tot}/Q_a^{NN}$ | $L_a$ ($10^{51}\,\mathrm{erg\,s^{-1}}$) |
|---|---|---|---|---|---|---|---|
| 1 | 1.45 | 37.07 | 0.011 | 1.37 | 4.63 | 4.38 | 4.0 |
| 2 | 2.08 | 38.93 | 0.016 | 3.28 | 8.87 | 3.70 | 8.10 |
| 4 | 3.10 | 40.56 | 0.027 | 9.08 | 15.87 | 2.75 | 16.63 |
| 6 | 3.65 | 39.91 | 0.034 | 12.92 | 14.99 | 2.16 | 18.61 |

Axion emissivity increased by a factor 4 due to pionic processes at $t_{pb}$= 1 s

- Axion Mass bound

Schematic SN model. T= 30 MeV, $Y_p$=0.3, $\rho_{sat}$= 2.6 x $10^{14}$ g/cm$^3$

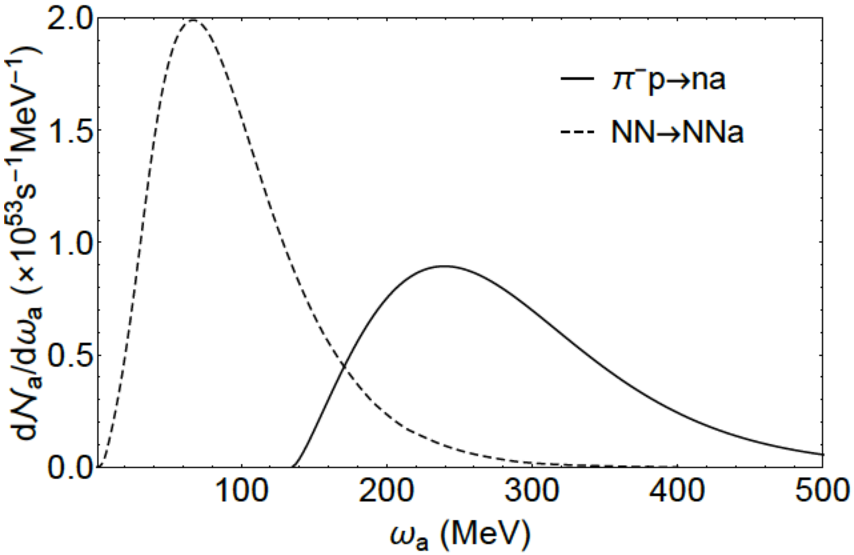
TABLE II: Bound on the effective axion-nucleon coupling $\bar{g}_{aN}$ obtained using Eq. (13). The corresponding bound on $m_a$ and $f_a$ for KVSZ model with $C_{ap}=-0.47\,,C_{an}=0$ are also shown.

| $\rho$ | | $\bar{g}_{aN}$ ($\times10^{-9}$) | $m_a$ (meV) | $f_a$ ($\times10^8$ GeV) |
|---|---|---|---|---|
| $\rho_0$ | only $NN$ | 0.81 | 21.02 | 2.71 |
| | $\pi N+NN$ | 0.46 | 11.99 | 4.75 |
| $\rho_0/2$ | only $NN$ | 0.93 | 24.11 | 2.36 |
| | $\pi N+NN$ | 0.42 | 10.96 | 5.20 |

Axion mass bound strengthened by a factor 2 when $\pi$N processes are included

# DETECTION PERSPECTIVES FOR SN AXION BURST

[Carenza, Fore, Giannotti, A.M., Reddy, 2010.02943]




- πN process produces a harder axion spectrum (E~ 200 MeV) with respect to the NN process
- High-energy axions would produce neutral and charged π in a water Cherenkov detector, due to processes a+ p → N + π
- For E~ 200-300 MeV resonant enhancement of the a-N cross section due to Δ intermediate state

Simple estimation of the axion events

$$\sigma_{aN} = (F_\pi \; / f_a \;)^2 \, \sigma_{\pi N}$$

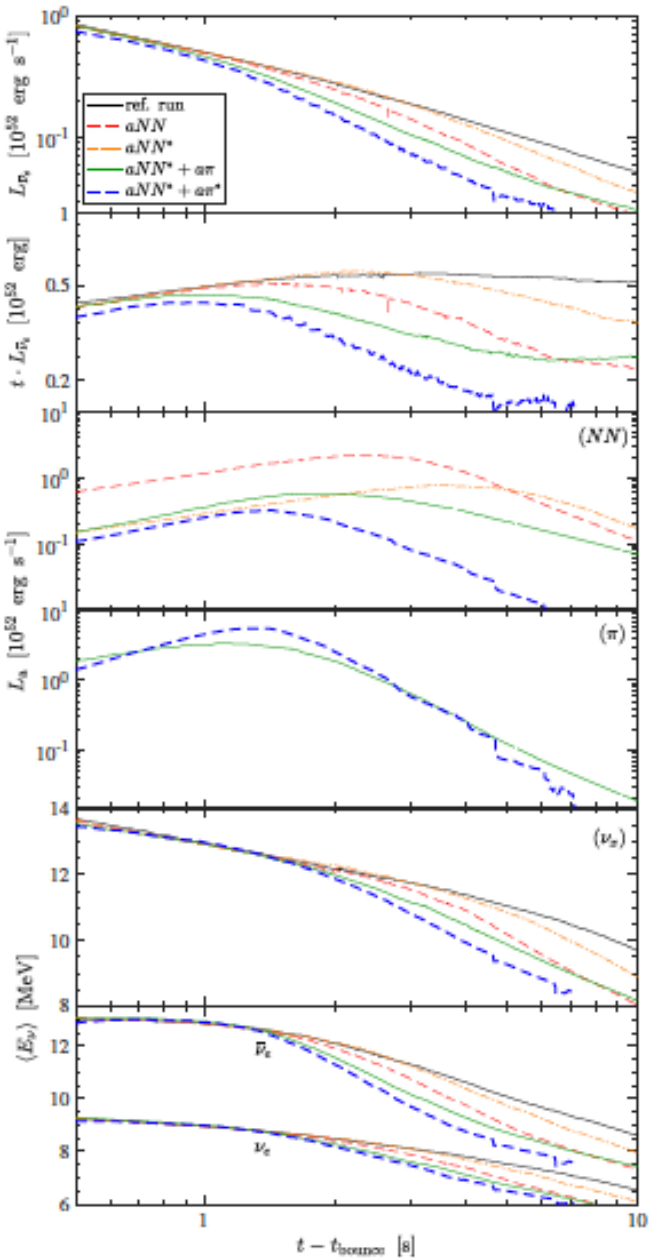
$$\sigma_{\pi N} \approx 100 \; mbarn$$

1000 pions !

@ $f_a = 10^9\; GeV$
($m_a$=5.7 meV)
$d_{SN}$= 1 kpc
1 Mton detector

Intriguing possibility to be investigated

# SN SIMULATIONS WITH PIONS




[Fischer, Fore, Reddy, Carenza, Giannotti, A.M. , work in progress]

$g_{ap}$=1.2 $\times 10^{-9}$ corresponding to bound from aNN*

- Remarkable differences wrt to reference case already at $t_{pb}$= 2 s
- Speed-up in SN neutrino cooling
- Pionic processes are the dominant channel of axion energy loss in SN

# CONCLUSIONS

Core-collapse SNe represent powerful laboratories to constrain axions

- We perfomed a reliable calculation of the NN axion emissivity including relevant corrections beyond OPE
- We pointed out that pionic processes might strongly enhance axion emissivity
- We included self-consistently these processes in a SN simulation to determine the feed-back on the neutrino signal
- It is mandatory to investigate impact of axion energy-loss on the observable SN neutrino signal.

A Galactic SN is a lifetime opportunity for axions !