PROBING NEUTRINOS (AND AXIONS) WITH NEXT GALACTIC SUPERNOVA

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OUTLINE

- Introduction to SN & neutrinos
- SN nu light curve in current and future detectors
- Signatures of neutrino flavor conversions
- Impact of axion emission on neutrino signal
- Conclusions
SUPERNova NeutrinoS

Core collapse SN corresponds to the terminal phase of a massive star \([M \geq 8 M_\odot]\) 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 (\(\sim 10^{53}\) erg) is emitted by \(\nu\) and \(\bar{\nu}\) of all flavors, with typical energies \(E \sim O(15\ MeV)\).

- **Time Scales:** Neutrino emission lasts \(\sim 10\ s\)

- **Expected:** 1-3 SN/century in our galaxy \((d \approx O(10)\ kpc)\).
THREE PHASES OF NEUTRINO EMISSION


27 M$_{\odot}$ progenitor mass
(spherically symmetric model)

Neutronization burst
- Shock breakout
- De-leptonization of outer core layers

Accretion
- Shock stalls ~ 150 km
- $\nu$ powered by infalling matter

Cooling
- Cooling on $\nu$ diffusion time scale
Sanduleak -69 202

Large Magellanic Cloud
Distance 50 kpc (160,000 light years)

Tarantula Nebula

Supernova 1987A
23 February 1987
Within clock uncertainties, signals are contemporaneous
Large Detectors for Supernova Neutrinos

In brackets events for a “fiducial SN” at distance 10 kpc

- HALO (tens)
- LVD (400)
- Super-Kamiokande (10⁴)
- Borexino (80)
- KamLAND (330)
- IceCube (10⁶)
High statistics reconstruction of the nu light curve. Possible to distinguish the different post-bounce phases.
NEXT-GENERATION DETECTORS

Mton scale water Cherenkov detectors
(10^5 events) \( (\bar{\nu}_e) \)

HYPER-KAMIOKANDE

40 kton Liquid Argon TPC
(3000 events) \( (\nu_e) \)

DUNE

Dark matter detectors

DARWIN
40 tons
(700 events)

(\nu_{e,x}, \bar{\nu}_{e,x})

JUNO

20 kton scintillator
(6000 events) \( (\bar{\nu}_e) \)
SN NU SIGNAL IN FUTURE DETECTORS

SN NU SIGNAL IN DM DETECTORS


DARWIN will be able to clearly reconstruct the neutrino light-curve and to differentiate among phases of neutrino signal. Partial sensitivity with XENONnT/LZ.
3ν FRAMEWORK

- **Mixing parameters:** \( U = U (\theta_{12}, \theta_{13}, \theta_{23}, \delta) \) as for CKM matrix

\[
\begin{pmatrix}
\nu_e \\ \nu_\mu \\ \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & \frac{c_{13}}{e^{-i\delta s_{13}}} & e^{-i\delta} s_{13} \\
c_{12} & s_{12} & c_{12} \\
-s_{12} & c_{12} & c_{12}
\end{pmatrix}
\begin{pmatrix}
c_{13} \\ e^{-i\delta} s_{13} \\ 1
\end{pmatrix}
\begin{pmatrix}
c_{12} \\ -s_{12} \\ c_{12}
\end{pmatrix}
\begin{pmatrix}
n_1 \\ n_2 \\ n_3
\end{pmatrix}
\]

\( c_{12} = \cos \theta_{12} \), etc., \( \delta \) CP phase

- **Mass-gap parameters:** \( \mathcal{M}^2 = \left\{ -\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm \Delta m^2 \right\} \)

   “solar” \hspace{1cm} “atmospheric”

SN neutrinos are sensitive to the unknown mass hierarchy
SNAPSHOT OF SN DENSITIES

- Matter bkg potential
  \[ \lambda = \sqrt{2G_F N_e} \sim R^{-3} \]
- \(\nu - \bar{\nu}\) interaction
  \[ \mu = \sqrt{2G_F n_\nu} \sim R^{-2} \]
- Vacuum oscillation frequencies
  \[ \omega = \frac{\Delta m^2}{2E} \]

When \(\mu \gg \lambda\), SN \(\nu\) oscillations dominated by \(\nu - \bar{\nu}\) interactions

Collective flavor transitions at low-radii [\(O(10^2 - 10^3 \text{ km})\)]

Far more complicated than expected
Spontaneous symmetry breaking in collective oscillations!
At the moment, predictions are more robust in the phases where collective effects are suppressed, i.e.:

- **Neutronization burst** ($t < 20 \text{ ms}$): large $\nu_e$ excess and $\nu_x$ deficit
  
  \cite{Hannestad:2006na}

- **Accretion phase** ($t < 500 \text{ ms}$): dense matter term dominates over $\nu$-$\nu$ interaction term
  

Large flux differences during the neutronization and accretion phase

Best cases for $\nu$ oscillation effects!
NEUTRONIZATION BURST

560 kton Water Cherenkov
40 kton LAr

Robust feature of SN simulations


At “large” $\theta_{13}$ (like recently measured!):
• The peak is not seen $\rightarrow$ The hierarchy is normal (if one could see it...)
• The peak is seen $\rightarrow$ The hierarchy is inverted (more robust)
3+1 scheme

- IH: disappearance of neutronization peak. Possible appearance of delayed peak due to the fraction of heavy $\nu_4$ component in $\nu_e$ (kinematical reason).
- Peculiar time-energy distribution in LAr TPC.
The production of $\bar{\nu}_e$ is more strongly suppressed than that of $\nu_x$ during the first tens of ms after bounce because of the high degeneracy of $e$ and $\nu_e$.

$\bar{\nu}_e$ are produced more gradually via cc processes ($e$ captures on free nucleons) in the accreting matter; $\nu_x$ come fastly from a deeper region

The lightcurves of the two species in the first $O(100)$ ms are quite different.
RISE TIME ANALYSIS: HIERARCHY DETERMINATION

[see Serpico, Chakraborty, Fischer, Hudepohl, Janka & A.M., 1111.4483]

In accretion phase one has

\[ F_{\nu_e}^D = \cos^2 \theta_{12} F_{\bar{\nu}_e} + \sin^2 \theta_{12} F_{\bar{\nu}_x} \quad \text{NH} \]

\[ F_{\nu_e}^D = F_{\bar{\nu}_x} \quad \text{IH} \]

A high-statistics measurement of the rise time shape may distinguish the two scenarios

- Are the rise time shapes enough robustly predicted to be useful?

Models with state-of-the-art treatment of weak physics (Garching simulations) suggest so: one could attribute a "shape" to NH and IH.

Given these promising early results, it would be mandatory in future to explore the robustness of the signature with other simulations. [see Ott et al., 1212.4250]
Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it.

Volume emission of novel particles

Assuming that the SN 1987A neutrino burst was not shortened by more than $\sim \frac{1}{2}$ leads to an approximate requirement on a novel energy-loss rate of

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

for $\rho \approx 3 \times 10^{14} \text{ g cm}^{-3}$ and $T \approx 30 \text{ MeV}$
**AXION EMISSION FROM A NUCLEAR MEDIUM**

\[ NN \rightarrow NNa \]

nucleon-nucleon bremsstrahlung

![Diagram showing nucleon-nucleon bremsstrahlung](image)

Bulk nuclear interaction  One pion exchange

\[ L_{aN} = \frac{g_{aN}}{2m_N} \overline{N} \gamma_\mu \gamma_5 N \partial^\mu a \]

\[ g_{aN} = C_N \frac{m}{f_a} \]

Non-degenerate energy-loss rate \( \varepsilon_a = g_{aN}^2 \times 10^{39} \text{ erg g}^{-1} \text{ s}^{-1} \rho_{15} T_{30}^{3.5} \)

\[
\begin{align*}
T_{30} &= T / 30 \text{ MeV} \\
\rho_{15} &= \rho / 10^{15} \text{ g cm}^{-3} \\
\langle \rho_{15} \rangle &\approx 0.4 \\
\langle T_{30}^{3.5} \rangle &\approx 1.4
\end{align*}
\]

\[ g_{aN} < 9 \times 10^{-10} \]
SN 1987A AXION LIMITS

Free streaming

Volume emission of axions

Trapping
[Burrows, Ressell & Turner, PRD 42:3297,1990]

Axion diffusion from an "axion-sphere"

Possible detection in a water Cherenkov detector via oxygen nuclei excitation

Hadronic axion ($m_a \sim 1$ eV, $f_a \sim 10^6$ GeV) not excluded by SN 1987A. Possible hot-dark matter candidate. The "hadronic axion window" is closed by cosmological mass bounds.
WHAT WE LEARNT FROM SN 1987A?

- General confirmation of core-collapse paradigm (total energy, spectra, time scale)

- No unexpected energy-loss channel: Restrictive limits on axions...but we a lot of uncertainties....

- Improving Energy-Loss Limits with Next Supernova?
  Sensitivity comparable to IAXO one. Important for hadronic axions where WD bounds are absent.
A REAPPRAISAL OF AXION EMISSION WITH STATE OF ART SIMULATIONS

[Fischer, Chakraborty, Giannotti A.M., Payez & Ringwald, 1605.08780]

18 $M_{\text{sun}}$ progenitor mass

(spherically symmetric with Boltzmann neutrino transport)

KSVZ hadronic axion model ($g_{\text{an}} = 0$)

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IMPACT ON NEUTRINO SIGNAL

@ Super-Kamiokande

(~ GC)

(Betelgeuse)

\[ m_a = 3 \times 10^{-2} \, eV, \quad f_a = 4.8 \times 10^8 \, GeV \]

\[ m_a = 8 \times 10^{-2} \, eV, \quad f_a = 7.3 \times 10^8 \, GeV \]
signal @ Icecube
@ 400 kton WC detector

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TeVPa

CERN, 15 September 2016
CONCLUSIONS

Observing SN neutrinos is the next frontier of low-energy neutrino astronomy

The physics potential of current and next-generation detectors in this context is enormous, both for particle physics and astrophysics.

Flavor conversions in SNe would provide valuable information on the neutrino mass hierarchy. Further investigations necessary on collective oscillations.

Neutrino signal duration provides most useful particle-physics information. Neutrino signal from next nearby SN would make this argument much more precise.
La Rivista del Nuovo Cimento
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Supernova neutrinos:
production, oscillations and detection

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