RES-NOVA: Archaeological Pb observatory for astrophysical neutrino sources

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Which are the main challenges?
How do we detect SN neutrinos?
How does RN work?
What can we learn with RN?
Problem 1: SN rate too low

Galactic SN rate is $1.63\pm0.46$ SN/100y \cite{2021NewA...83101498N} 
Not uniform throughout the Galaxy

### Very Near

**Known past Galactic SNe**

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Common Name</th>
<th>Dist. (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1006 Apr 30</td>
<td>Lupus</td>
<td>SN 1006</td>
<td>1.56\textsuperscript{a}</td>
</tr>
<tr>
<td>1054 Jul 4</td>
<td>Taurus</td>
<td>Crab</td>
<td>2.0</td>
</tr>
<tr>
<td>1181 Aug 6</td>
<td>Cassiopeia</td>
<td>SN 1181</td>
<td>3.2</td>
</tr>
<tr>
<td>1572 Nov 6</td>
<td>Cassiopeia</td>
<td>Tycho</td>
<td>2.3</td>
</tr>
<tr>
<td>1604 Oct 9</td>
<td>Ophiuchus</td>
<td>Kepler</td>
<td>2.9</td>
</tr>
<tr>
<td>1671\textsuperscript{b}</td>
<td>Cassiopeia</td>
<td>Cas A</td>
<td>3.4</td>
</tr>
</tbody>
</table>


→ Need to survey D < 3 kpc  
→ High neutrino interaction rate

### Very Far

Probe more galaxies increases CC-SN rate

→ Need to survey D > 3 Mpc  
→ Highly sensitive neutrino detector
Problem II: SN composite neutrino signal

1D Hydro-dynamical simulation of a 27 M SN (LS220 EoS) occurring at 10 kpc

\[ \nu_x \text{ is the most } \textbf{intense} \text{ component of the flux} \]

\[ \bar{\nu}_x \text{ is the most } \textbf{energetic} \text{ component of the flux} \]

Current SN neutrino detectors are mostly sensitive to anti-\(\nu_e/\nu_e\).

Need for a \textbf{flavor independent} channel sensitive also to anti-\(\nu_x/\nu_x\).
Coherent elastic neutrino-Nucleus scattering

$$\sigma_{CE\nu NS} = \frac{G_F^2}{4\pi} F^2(q) Q_W^2(N) E_{\nu}^2$$

Neutral current process
- equally sensitive to all flavours

High cross-section
- $>10^4$ than NC

Threshold-less process
- sensitive to the entire $\nu$ emission

Pb as a target material

\[ \sigma_{CE\nu NS} = \frac{G_F^2}{4\pi} F^2(q) Q_W^2(N) E_{\nu}^2 \]

- Pb is the element with the highest CE\nu NS x-section
- Pb has with the highest nuclear stability
- Highly efficient target for SN neutrinos

Pb: ideal target for CE\nu NS
Pb as a target material

27 $\odot$ SN (LS220 EoS) occurring at 10 kpc

- Pb is the element with the highest CE$\nu$NS x-section
- Pb has with the highest nuclear stability
- Highly efficient target for SN neutrinos

Form factor

Electroweak-charge

Neutrino energy

Expected signal:

$\rightarrow$ low energy nuclear recoil $O(keV)$
RES-NOVA: Pb-based CRYO DETECTORS

Cryogenic detectors are a leading technology:
- Neutrinoless $\beta\beta$ decay: low background level
- Direct dark matter: low energy threshold

↑ Easily scalable technology (up to 1000 detectors)
↑ Excellent energy resolution from sub-keV to MeV
↑ Particle ID for scintillating cryogenic detectors
↓ Fully active detectors → low bkg
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PbWO$_4$
Mass: 500 g
Baseline resolution 600 eV
FWHM @ 2.6 MeV: 15 keV

Which Pb?

Low-background/Commercial Pb: high $^{210}\text{Pb}$ concentration ($Q_{\beta}$-value: 63 keV, $T_{1/2}=22.3$ y): 100 Bq/kg

Archaeological Pb is “old enough” (e.g. Roman Pb) to ensure a negligible $^{210}\text{Pb}$ concentration: < 1 mBq/kg

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Low background Pb (Boliden®) [1]</th>
<th>Archaeological Pb [2, 3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{Th}$</td>
<td>&lt;46 μBq/kg</td>
<td>&lt;45 μBq/kg</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>&lt;31 μBq/kg</td>
<td>&lt;46 μBq/kg</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>$(2.3\pm0.4) \cdot 10^7$ μBq/kg</td>
<td>&lt;715 μBq/kg</td>
</tr>
</tbody>
</table>


RES-NOVA design

Detector mass [ton]

<table>
<thead>
<tr>
<th>Detector</th>
<th>Mass (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-Gd (32 kt)</td>
<td>1.8 tons</td>
</tr>
<tr>
<td>LVD (1 kt) &amp; SNO+</td>
<td>(0.78 kt)</td>
</tr>
<tr>
<td>Borexino (0.3 kt)</td>
<td></td>
</tr>
<tr>
<td>Baksan (0.33 kt)</td>
<td></td>
</tr>
<tr>
<td>Halo (0.08 kt)</td>
<td></td>
</tr>
</tbody>
</table>

Counts above detector threshold

- Threshold 0.1 keV
- Threshold 1 keV
- Threshold 5 keV
- Threshold 10 keV

RN-1 small volume cryogenic facility
Detector mass: 1.8 tons
Array of 500 cryo-detectors
Energy threshold: 1 keV

RN-1 @ LNGS
Size: (60 cm)$^3$
Threshold: 1 keV
SN @ 10 kpc: ~50 counts
RES-NOVA energy response

![Graph showing energy response for different scenarios](image)

- **40 \( M_\odot \)** failed CC @ 10 kpc
- **27 \( M_\odot \)** CC @ 10 kpc

Rate [events ton\(^{-1}\) keV\(^{-1}\) s\(^{-1}\)]

Recoil energy [keV]

- Commercial low-background Pb bkg
- Archaeological Pb bkg
- Archaeological Pb bkg + Particle ID

Preliminary
RES-NOVA time response

- Detector time resolution: 100 μs
- High interaction rate in the detector
- Identification of SN models
- Study of the neutrino emission
RES-NOVA background model

MC simulation of the detector response to radioactive background sources (no veto included)

Background rate in ROI [1,30] keV vs Detector multiplicity

Different signal multiplicity → Different background rate
RES-NOVA-I sensitivity (medium-far distances)

- RN1 total active volume $\left(60 \text{ cm}\right)^3$ of PbWO$_4$
- Full investigation of the MW galaxy
- When particle ID is in place, RN1 reaches out to Magellanic Clouds
- Competitive with other CEvNS detectors techs, but with a smaller detector volume
• High interaction rate expected

• Conventional monolithic (giant) detectors have problems in handling:
  • data handling/storage
  • neutrino energy reconstruction/pile-up (e.g. slow neutron capture time \(\sim 200 \mu s\))
  • Only "bolometric" measurement \(\leq 5\) kpc

• Solution: high molularity detector
We parametrized the neutrino energy spectrum:

\[ f^0(E; \langle E \rangle, \alpha_T) = A_T \xi_T \left( \frac{E}{\langle E \rangle} \right)^{\alpha_T} \exp \left( - \frac{(1 + \alpha_T)E}{\langle E \rangle} \right) \]

\[ \langle \mathbf{E} \rangle \text{ and } A_T \text{ are inferred by a maximum likelihood analysis} \]

\[ \alpha_T \text{ is the time average over the relevant time interval} \]

\[ \mathcal{E}_{\text{tot}} = 4\pi d^2 A_T \langle E \rangle \]

Precision in total SN energy reconstruction

\[ v_x/\text{anti-}v_x \]

\begin{align*}
\text{RN-I} & \quad 30\% \\
\text{RN-2} & \quad 8\% \\
\text{RN-3} & \quad 4\%
\end{align*}

\[ v_{\text{all}}/\text{anti-}v_{\text{all}} \]

\begin{align*}
\text{SK - IBD only} & \quad 25\% \\
\text{SK - IBD+ES+NCR} & \quad 11% \\
\end{align*}

A. Gallo Rosso et al., JCAP 04 (2018) 040

LP et al., Phys. Rev. D 102, 063001 (2020)
Conclusions

- RES-NOVA is a newly proposed underground experiment @ LNGS:
  - CEvNS + Archeo-Pb + Cryo-detectors
  - cm-scale neutrino telescope

- The technology for the experiment realization is already established

- RES-NOVA (and CEvNS) can provide a complementary approach to the current SN neutrino observatories

- Archaeological Pb is an ideal material for CEvNS applications

L. Pattavina, N. Ferreiro Iachellini, I. Tamborra, Phys. Rev. D 102, 063001 (2020)
[ArXiv]
Our time machine works, but we're almost out of low-background metal. What's that?

Modern metal is contaminated by fallout from nuclear testing, and lead also has natural radioactivity that fades over time. To shield sensitive equipment, physicists use lead from sunken Roman ships. But shipwreck lead is hard to find.

How much do we have? Enough for one trip through time. Hmm...