Detecting supernova neutrinos with RES-NOVA archaeological Pb cryogenic detectors

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on behalf of the RES-NOVA group of interest

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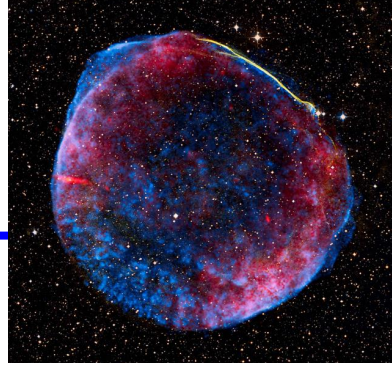
Supernova neutrinos



- Supernova (SN):
  - final stage of massive stars (heavier than $\sim 8\ M_{\odot}$);
  - gravitational core collapse (CC) → formation of neutron star (NS) / black hole (BH);
  - neutrino burst: $\sim 10^{58}$ ν emitted in ~ 10 s.

- SN-ν are direct probes of stellar core (not accessible through γ detection), providing insights into:
  - mechanism of gravitational collapse;
  - NS degenerate matter;
  - SN evolution and shockwave propagation;
  - acceleration mechanism of ultra-high energy cosmic rays.

- All ν/anti-ν flavours emitted (flavour equipartition often assumed).

- Current SN-ν observatories mostly sensitive to ν_e/anti-ν_e ($\sim$ ⅓ of total ν flux) through inverse-β decay (IBD)

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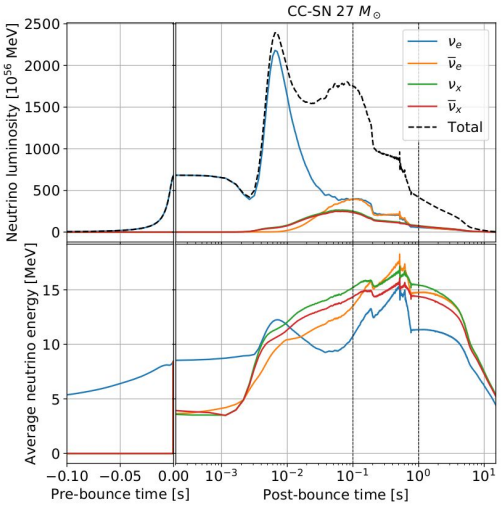
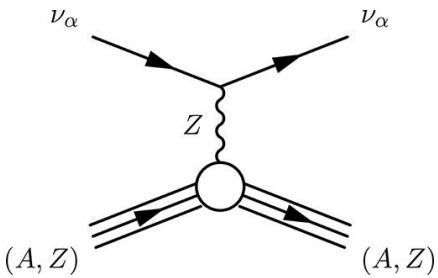
  need for a detection technique highly sensitive to all ν flavors.



Coherent elastic neutrino-nucleus scattering

- **Coherent elastic neutrino-nucleus scattering (CEνNS):**



  - ➢ ν-nucleus interaction via Z^0 exchange → nucleus recoils as a whole;
  - ➢ neutral-current weak process

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    equally sensitive to all ν/anti-ν flavours

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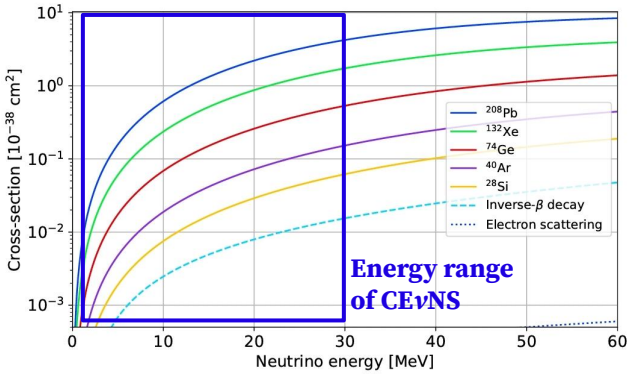
    no uncertainty due to ν-flavour oscillations in the extreme stellar environment;
  - ➢ CEνNS cross-section (spin-0 interaction):

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m_N}{8\pi(\hbar c)^4}\left[(4\sin^2\theta_W - 1)Z + N\right]^2\left(2 - \frac{E_R m_N}{E^2}\right)\cdot|F(q)|^2$$

    - cross-section $\propto$ (neutron number)^2 → enhanced in heavy nuclei (Pb);
    - **cross-section on Pb $\sim 10^{2\text{-}3}$ times higher w.r.t. IBD** → high statistics SN-ν detection.
  - ➢ CEνNS has zero energy threshold.



- Experimental signature of CEνNS: nuclear recoil (NR)

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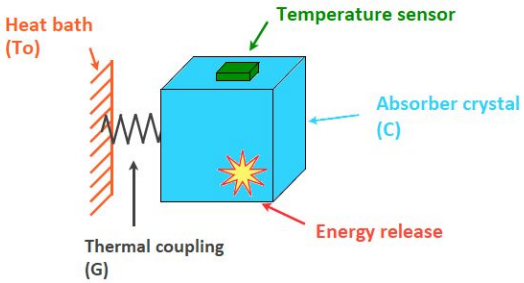
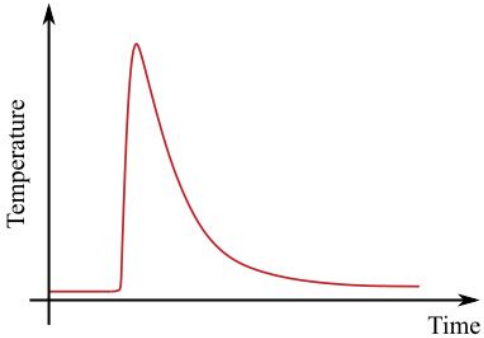
  detectors with low-energy threshold ($\sim$1 keV) required.

Low-temperature calorimeters

- Requirements for a SN-ν detector based on CEνNS:
  - Pb-based for high CEνNS cross-section;
  - ~1 keV low-energy threshold.

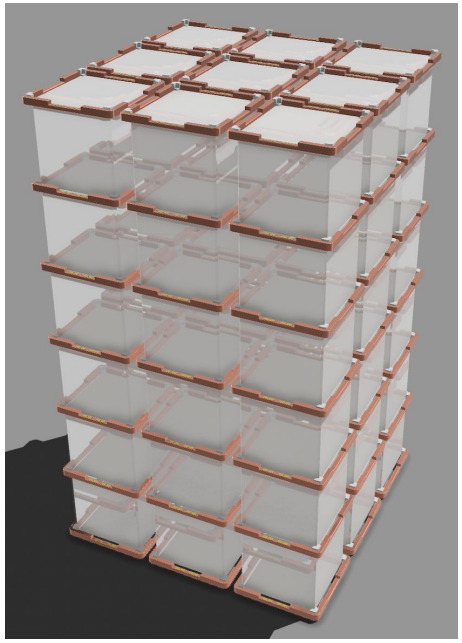
- Requirements can be addressed by low-temperature calorimeters:
  - operated at ~10 mK;
  - simplified model:
    - energy absorber: released energy is converted into phonons excitations → temperature increase ΔT;
    - thermal sensor: converts ΔT into an electric signal with amplitude proportional to the released energy;
    - thermal link to heat bath to restore initial temperature.
  - low energy threshold (~1 keV);
  - time resolution (~100 μs);
  - feasibility of ton-scale experiments already demonstrated.





RES-NOVA

Detector concept



- RES-NOVA demonstrator:
  - ➢ newly proposed observatory for SN-ν;
  - ➢ exploit CEνNS with low-temperature calorimeters;
  - ➢ array of 54 $^{arch}PbWO_4$ crystals:
    - 140 kg of $^{arch}PbWO_4$;
    - $(30\ cm)^3$ active volume → highly-compact detector;
  - ➢ Transition Edge Sensors (TES) as thermal sensors:
    - ~1 keV low-energy threshold;
    - ~100 μs time response.

- RES-NOVA next phases:
  - ➢ increase the active volume to increase sensitivity to farther SN events:
    - RES-NOVA^1: $(60\ cm)^3$ active volume → ~2 ton of $^{arch}PbWO_4$;
    - RES-NOVA^2: $(140\ cm)^3$ active volume → ~20 ton of $^{arch}PbWO_4$;
  - ➢ several tons of Roman ^{arch}Pb (2000 yr old) already stored at LNGS.

RES-NOVA

Background sources and archaeological lead

- RES-NOVA region of interest (ROI): $E_{NR} < 30$ keV.

- Background sources in ROI:
  - ➢ cosmic rays:
    - proposed underground installation at Laboratori Nazionali del Gran Sasso (LNGS): ~3600 m.w.e. overburden → μ flux suppressed by factor ~10^6 w.r.t. above ground;
  - ➢ ^{238}U - ^{232}Th natural decay chains;
  - ➢ ^{210}Pb (from ^{238}U decay chain):
    - β-decay: $Q = 63$ keV , $T_{1/2} \sim 22$ yr;
    - major background source from $PbWO_4$ crystals.

- Concentration of ^{210}Pb in modern low-bkg Pb is too high for SN-ν detection
  ↓
  ^{arch}Pb-based detectors for higher radiopurity:
  target background index in ROI **~10^{-3} counts/(keV · ton · s)**
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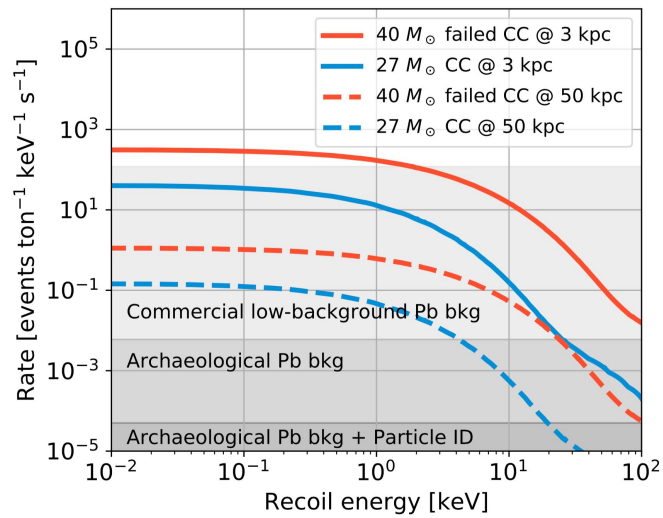
  RES-NOVA first-ever detector array of ^{arch}Pb-based crystals.



RES-NOVA

Topological background suppression

- Multiple detectors can be fired up by SN-ν interactions in a short time window

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  SN-ν signal features high multiplicity, while background rate decreases at higher multiplicities

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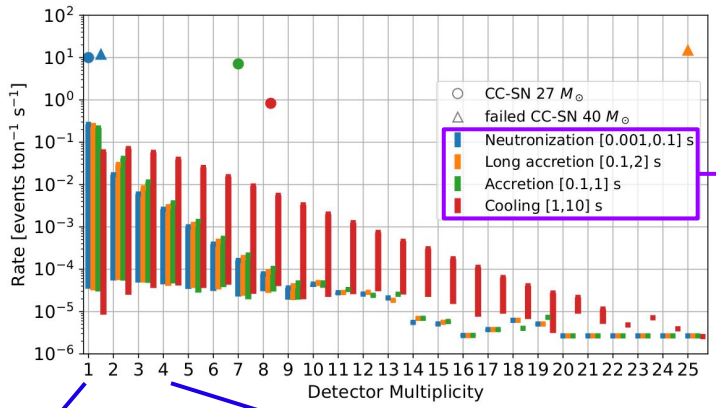
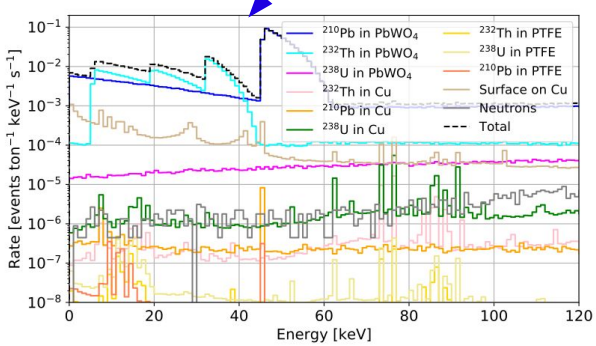
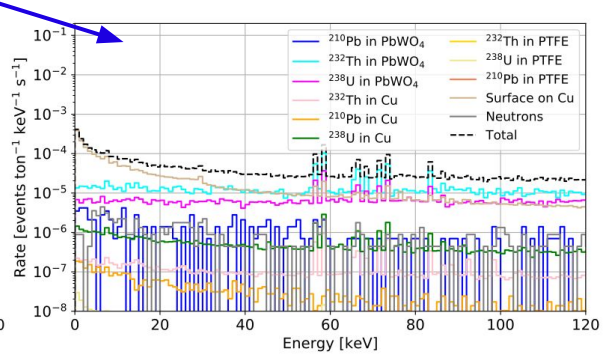
  Signal-to-background ratio is enhanced at higher multiplicity.



Background rates:
upper limit for 0% β/γ rejection;
lower limit for 100% β/γ rejection.



(a) Neutronization $[0.001, 0.1]$ s - $M = 1$



(b) Neutronization $[0.001, 0.1]$ s - $M = 4$

RES-NOVA

Sensitivity to SN-ν

- High CEνNS cross section on Pb + high radiopurity of ^{arch}Pb

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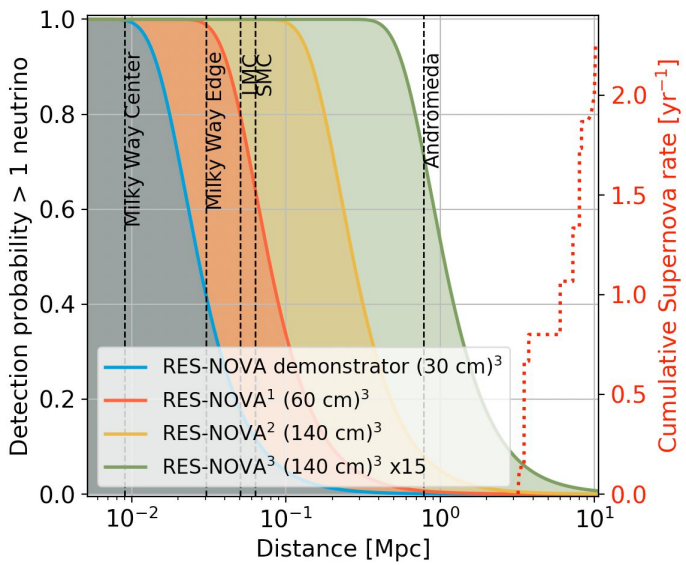
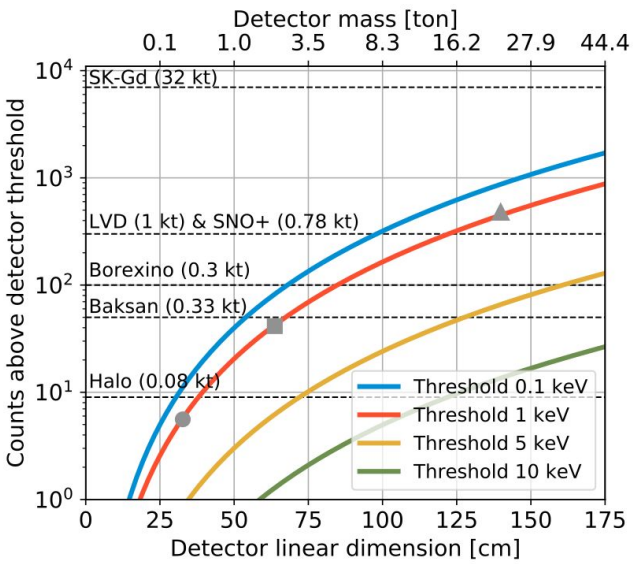
  - ➢ RES-NOVA demonstrator sensitive to ∼90% of galactic SN candidates (up to ∼20 kpc);
  - ➢ RES-NOVA cm-scale detector can collect statistics comparable to kton-scale experiments;
  - ➢ high sensitivity to total SN-ν flux.

- RES-NOVA next phases: increase the active volume to increase sensitivity to farther SN candidates.





27 $M_\odot$ progenitor at 10 kpc (galactic center at 8 kpc).

- ● RES-NOVA demonstrator (30 cm)^3
- ■ RES-NOVA^1 (60 cm)^3
- ▲ RES-NOVA^2 (140 cm)^3

RES-NOVA

Recent measurements

- Several ongoing activities to validate detector technology and crystals purification:

  - ➢ detailed studies on the intrinsic radiopurity of ^{arch}Pb
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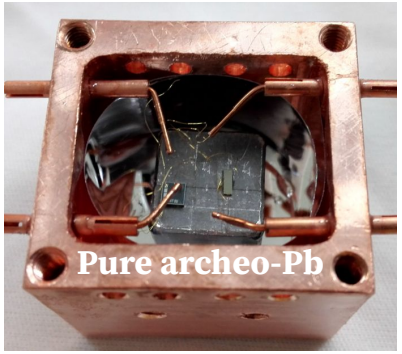
    ^{210}Pb concentration $< 2 \cdot 10^{-18}$ g/g → activity < 700 μBq/kg
    (10.1140/epja/i2019-12809-0);



  - ➢ operation of the first $^{arch}PbWO_4$ crystal read out by TES (CRESST technology)
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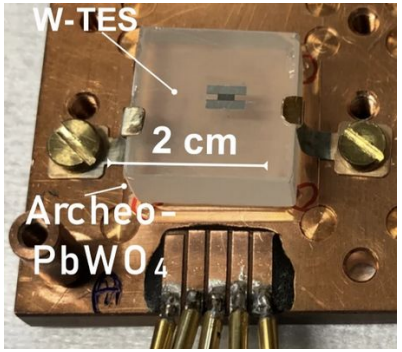
    300 eV energy threshold (10.1007/s10909-022-02823-8);



  - ➢ operation of the first kg-scale $^{arch}PbWO_4$ crystal
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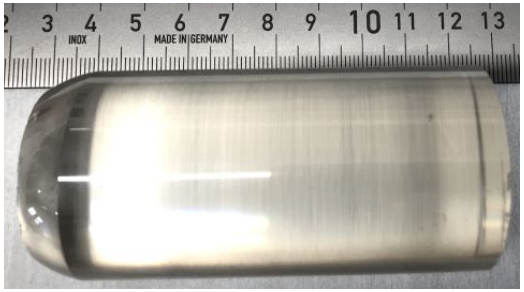
    test production of large-mass low-background $^{arch}PbWO_4$ crystals (10.1140/epjc/s10052-022-10656-8).



Conclusions

- RES-NOVA project:
  - ➢ newly proposed observatory for SN-ν exploiting CEνNS;
  - ➢ ^{arch}Pb-based low-temperature calorimeters for intrinsic radioactivity suppression;
  - ➢ highly-compact detector;
  - ➢ CEνNS neutral-current weak process → sensitive to the total SN-ν flux;
  - ➢ RES-NOVA demonstrator sensitive to galactic SN candidates.

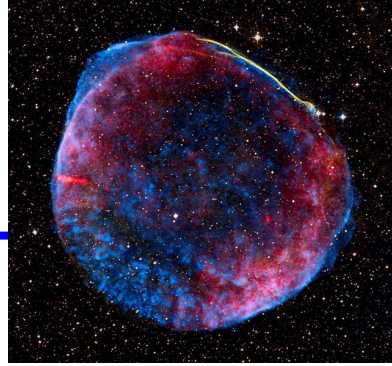
- RES-NOVA can contribute to the effort for the first multi-messenger SN detection involving gravitational waves, electromagnetic counterpart and neutrino burst.

Thanks for your attention!

Backup slides

Supernovae

Brief summary



- Stars heavier that 8 $M_\odot$ undergo core collapse (CC):
  - ➢ <u>Stellar nucleosynthesis</u>: after H in the stellar core is exhausted, new elements up to Fe are created by fusion reactions
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    Fe core is formed, sustained by the degeneracy pressure of electrons;
  - ➢ <u>Nuclear photodissociation</u>: photons in the core dissociate Fe nuclei: $\gamma + {}^{56}Fe \rightarrow 13\,{}^{4}He + 4n$
    $\gamma + {}^{4}He \rightarrow 2p + 2n$
  - ➢ <u>Neutronization</u>: protons undergo electron capture interactions: $e^- + p \rightarrow n + \nu_e$
    ↓
    - protons are converted into neutrons → burst of ν_e;
    - drop of electrons degeneracy pressure → <u>Core collapse (CC)</u> → neutron star formation;
  - ➢ <u>Shockwave propagation</u>: infalling matter bounces on NS → outgoing shockwave and SN;
    ↓
    All ν/anti-ν flavours emitted:
    - electron capture on protons: $e^- + p \rightarrow n + \nu_e$
    - positron capture on neutrons: $e^+ + n \rightarrow p + \bar{\nu}_e$
    - electron-positron pair annihilation: $e^- + e^+ \rightarrow \nu + \bar{\nu}$
    - nucleon bremsstrahlung → creation of ν/anti-ν pairs of all flavours.

Transition Edge Sensors (TES)

- Transition Edge sensors (TES):
  - ➢ thin film of superconductive material deposited on crystal;
  - ➢ operated at temperature just below the transition temperature T_C;
  - ➢ energy deposition in crystal → temperature increase ΔT

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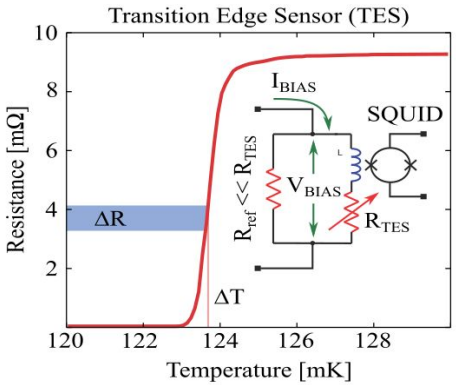
    resistance increases along the superconductive transition;



  - ➢ superconductive transition lies within ∼1 mK

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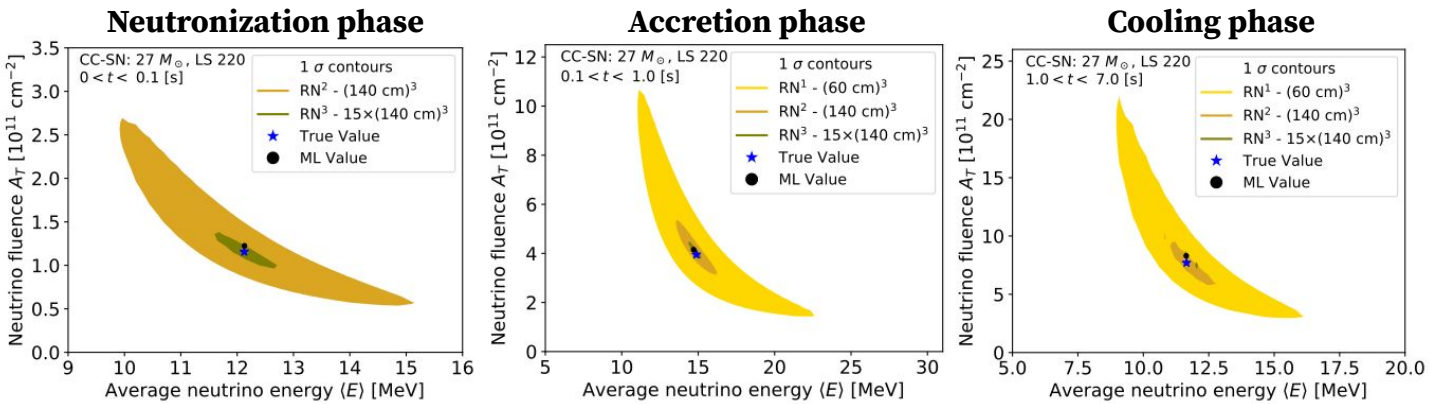
    high sensitivity to small energy deposition and very low energy threshold ($\lesssim$ 1 keV);
  - ➢ sensitive to athermal phonons → fast time response (∼100 μs).

Reconstruction of SN emitted energy

- Reconstruction of SN-ν average energy (<E>) and fluence (A_T):
  - ➢ parametrization of time-integrated ν flux: $$f^0(E;\langle E\rangle,\alpha_T) = A_T \xi_T \left(\frac{E}{\langle E\rangle}\right)^{\alpha_T} \exp\left(-\frac{(1+\alpha_T)E}{\langle E\rangle}\right)$$

    Normalization factor **Pinching factor**

  - ➢ maximum likelihood analysis (experimental data + SN model + f^0) → estimate <E>, A_T.



- Reconstruction of total energy ε_{tot} emitted as ν: $$\varepsilon_{tot} = 4\pi d^2 A_T \langle E\rangle$$

  ↓

  estimated precisions: 30% - 8% - 4% in RES-NOVA[1,2,3] .