Hunting neutrinos with ancient Pb

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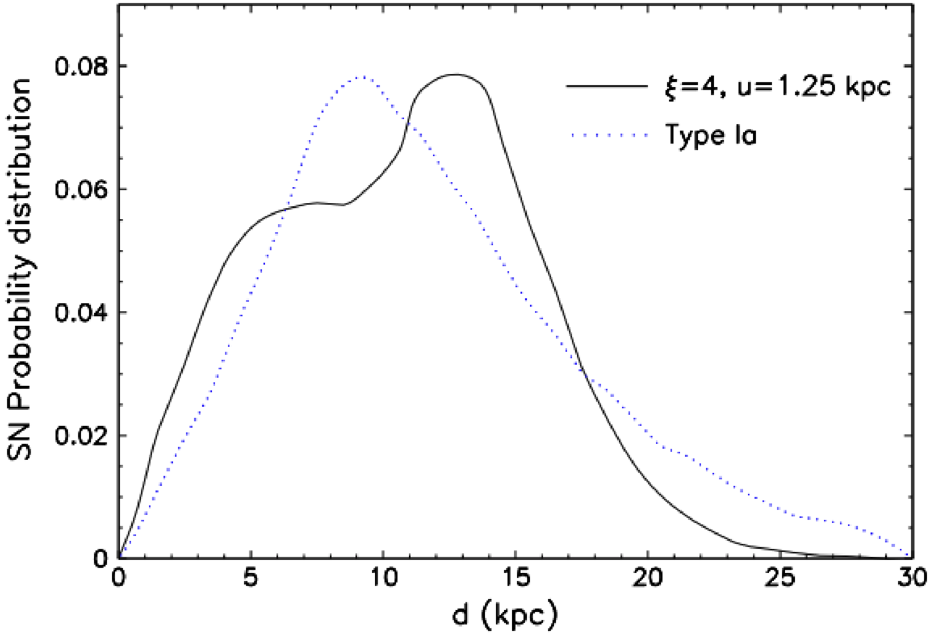
RES-NOVA

From latin -> “New thing”

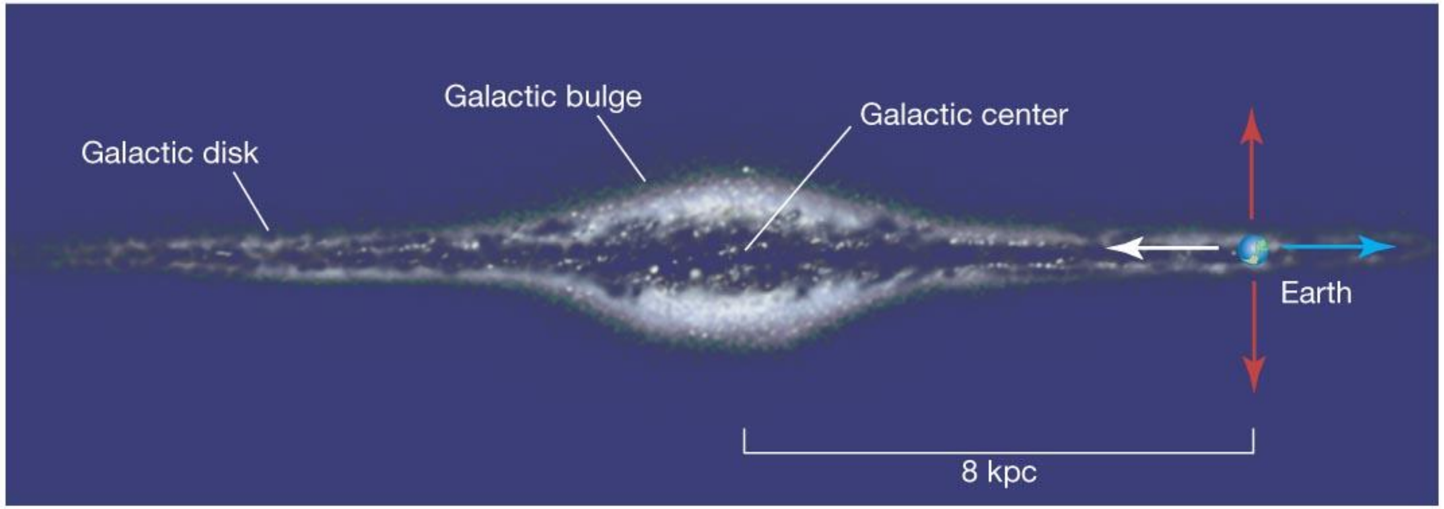
Latin -> Ancient lead from a Roman shipwereck

NOVA -> Supernovae

The next Galactic Supernova



Nuclear Physics B (Proc. Suppl.) 221 (2011)



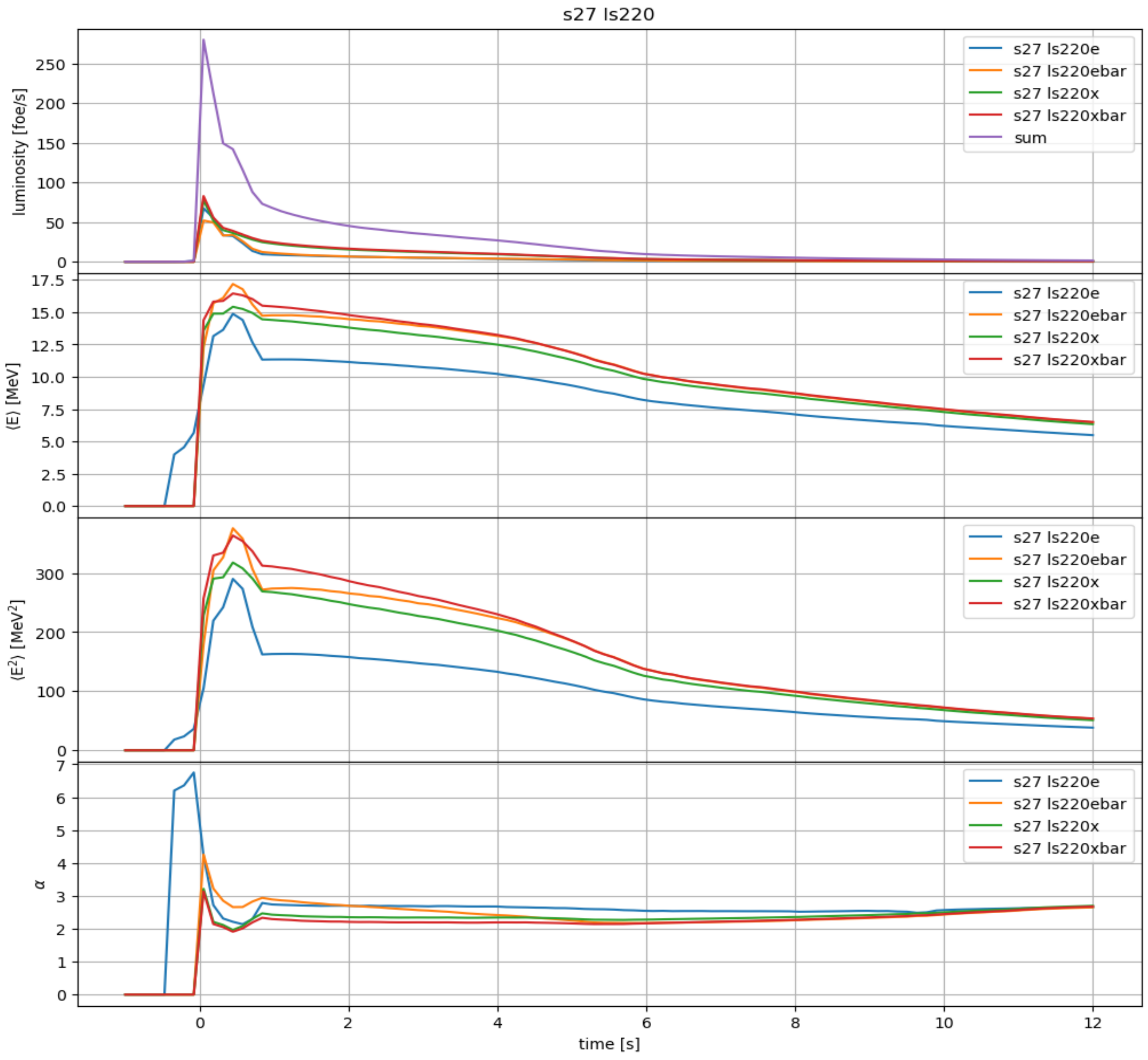
(a) Artist's view of Milky Way from afar

$$f^0_\beta(E,t) = \frac{L_\beta(t)}{4\pi d^2}\frac{\phi_\beta(E,t)}{\langle E_\beta(t)\rangle}$$

L_β ~ 100 foe/s

$\langle E_\beta \rangle$ ~ 10 MeV

$f^0_\beta \sim 10^{57}\ s^{-1}$



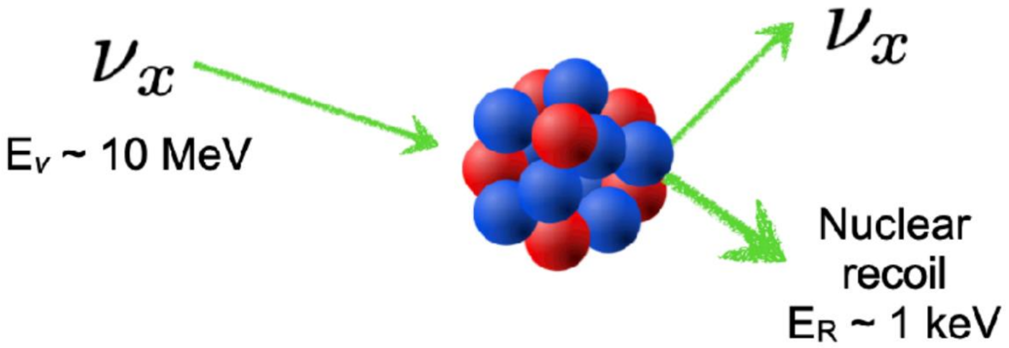
Our neutrino source

$$f^0_\beta(E,t) = \frac{L_\beta(t)}{4\pi d^2} \frac{\phi_\beta(E,t)}{\langle E_\beta(t)\rangle}$$

$$\phi_\beta(E,t) = \xi_\beta(t) \left(\frac{E}{\langle E_\beta(t)\rangle}\right)^{\alpha_\beta(t)} \exp\left(-\frac{(\alpha_\beta(t)+1)E}{\langle E_\beta(t)\rangle}\right)$$

Coherent Elastic ν Nucleus Scattering

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



> Equally sensitive to all ν-flavors

> High interaction cross-section

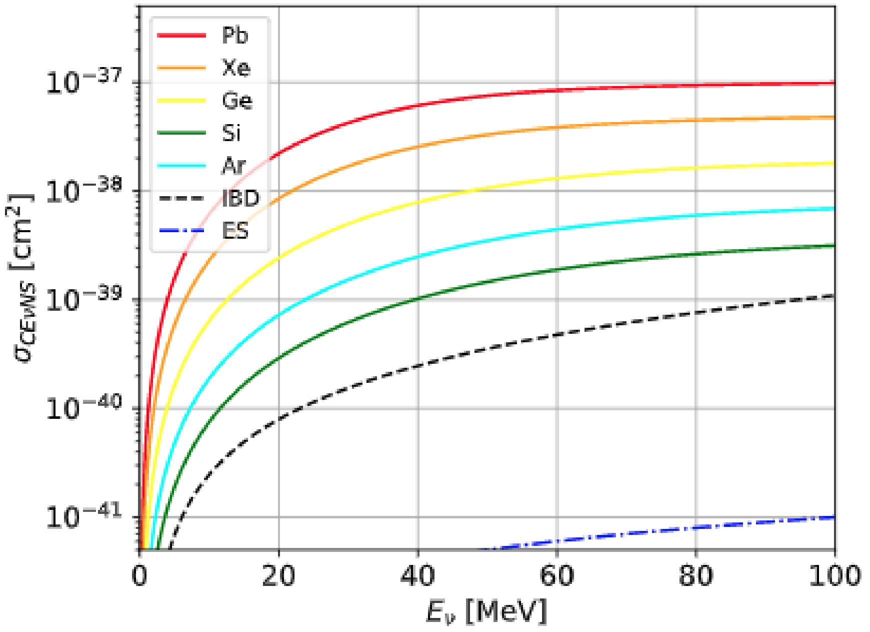
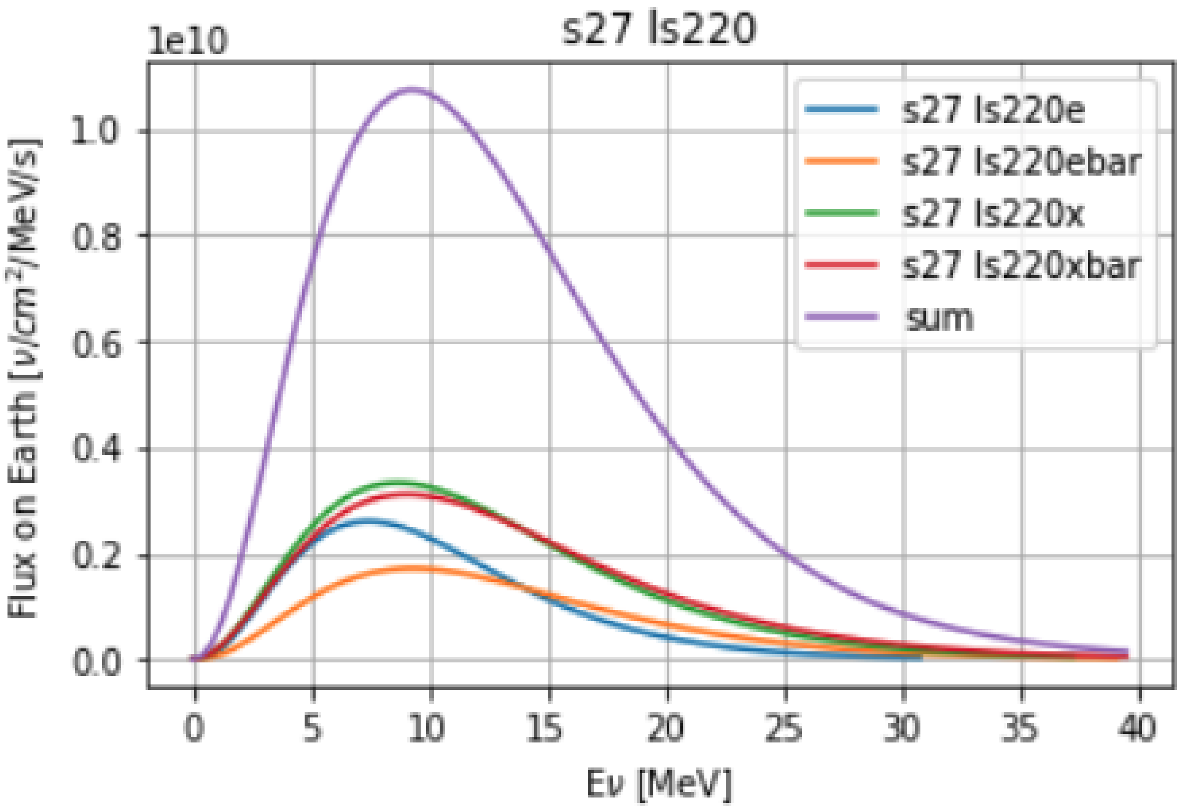


FIG. 2. Coherent elastic neutrino-nucleus scattering (CEνNS) cross sections as a function of the energy of the incoming neutrino for different target nuclei. The dashed lines show the inverse-beta decay (IBD) and neutrino elastic scattering on electrons (ES) cross-sections for comparison. Given the high cross-section, CEνNS has the potential to provide large statistics with small detector volumes.

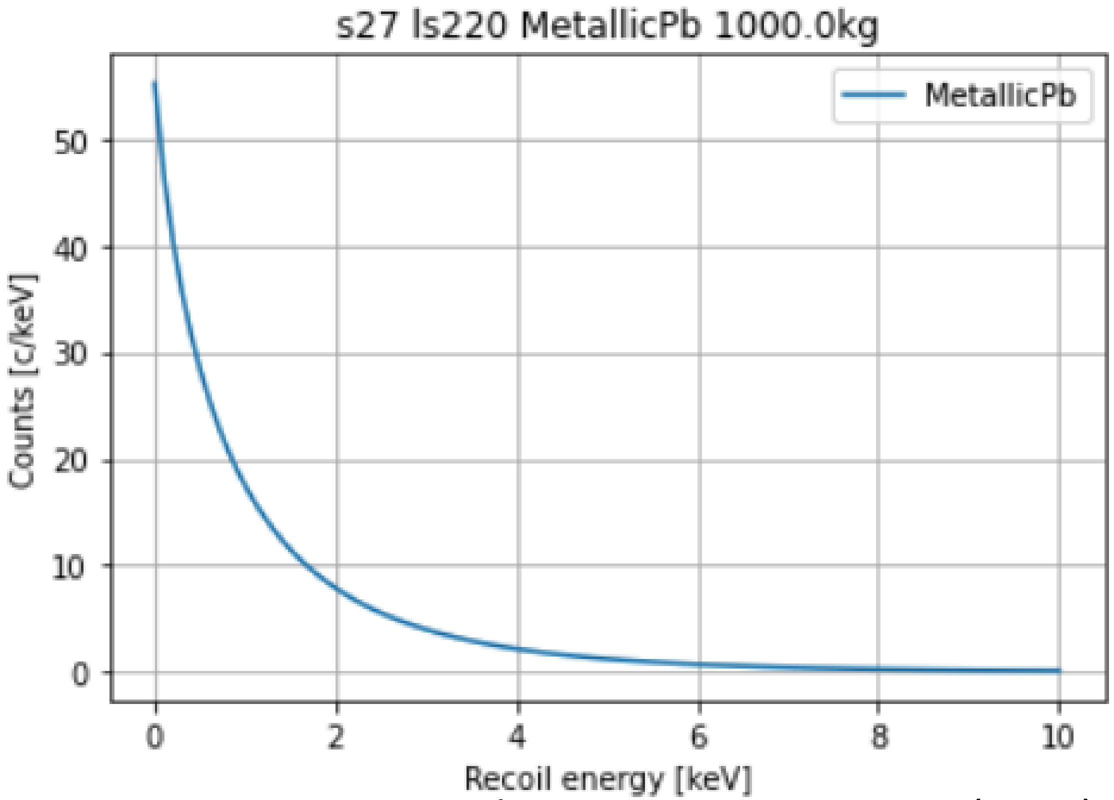
Phys. Rev. D 102, 063001 (2020)

SN CEνNS in Pb Target (on Earth)

The emitted neutrino spectrum is (almost) Maxwell-Boltzmann

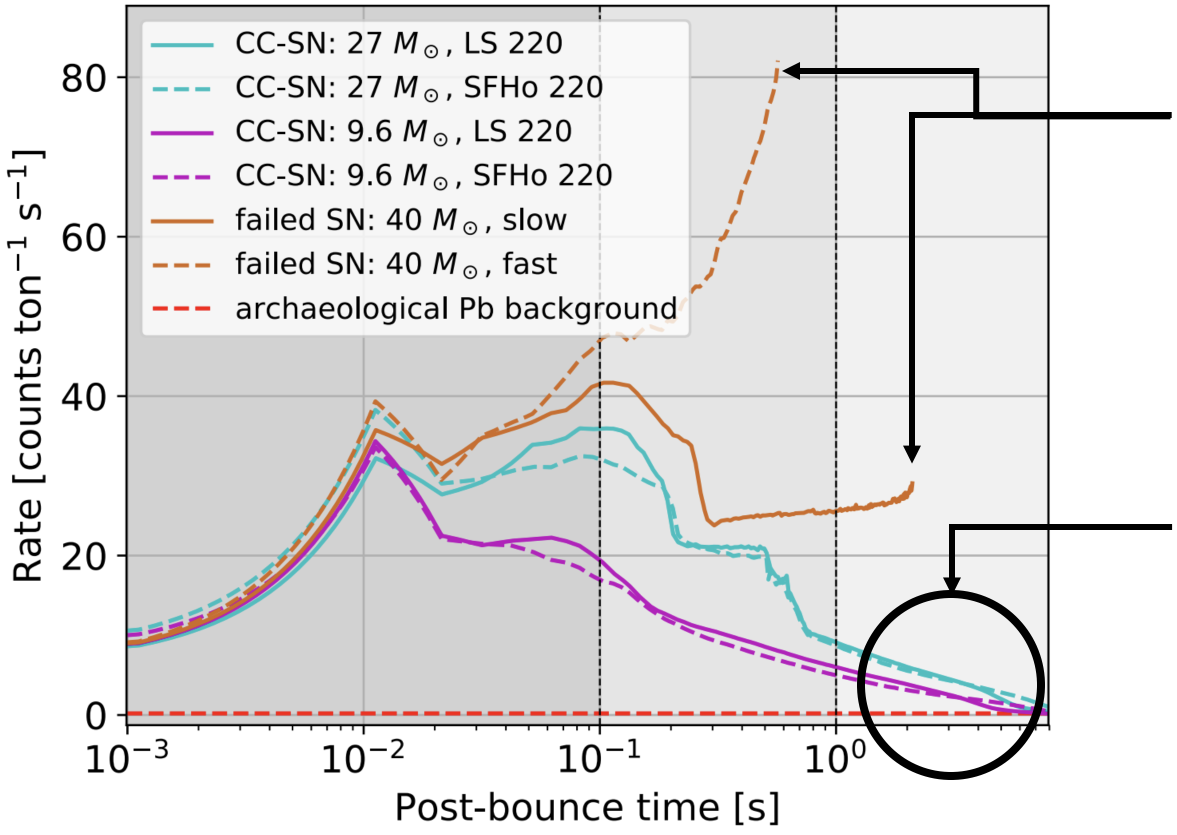


Observed nuclear recoil spectrum



Phys. Rev. D 102, 063001 (2020)

The light curve brings information!



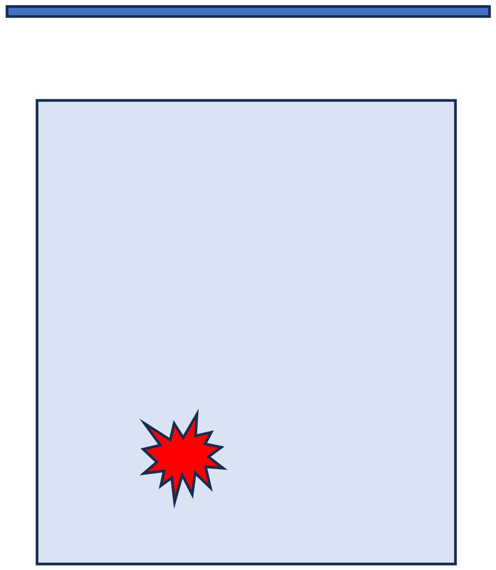
A sudden halt of the neutrino emission indicates a black hole formation

L. Pattavina et al., *JCAP* 10 (2021) 064

The cooling of the neutron star may be a gate to BSM physics

G. G. Raffelt, Phys. Rep. 198, 1 (1990)

The RES-NOVA detector



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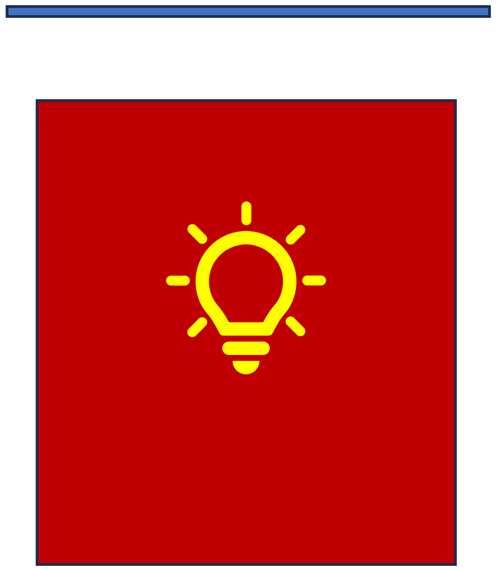
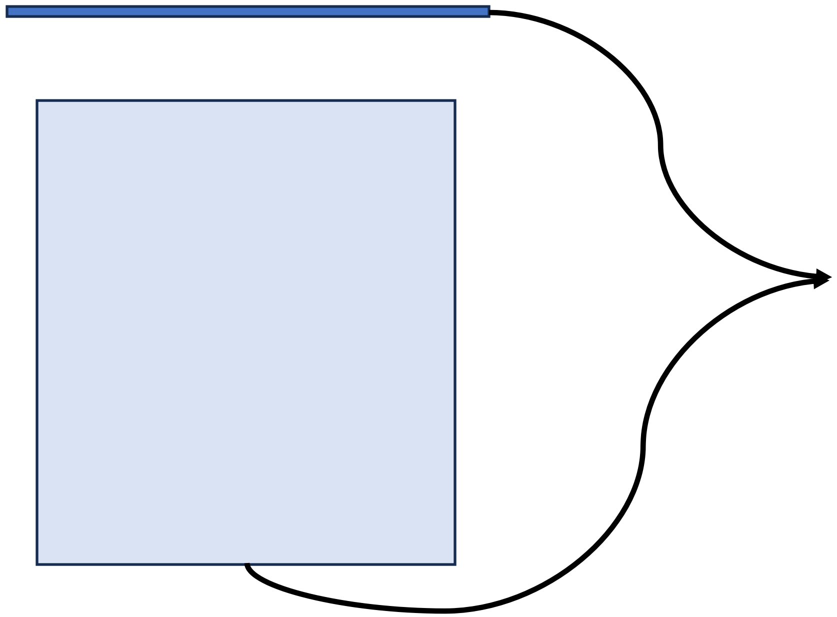
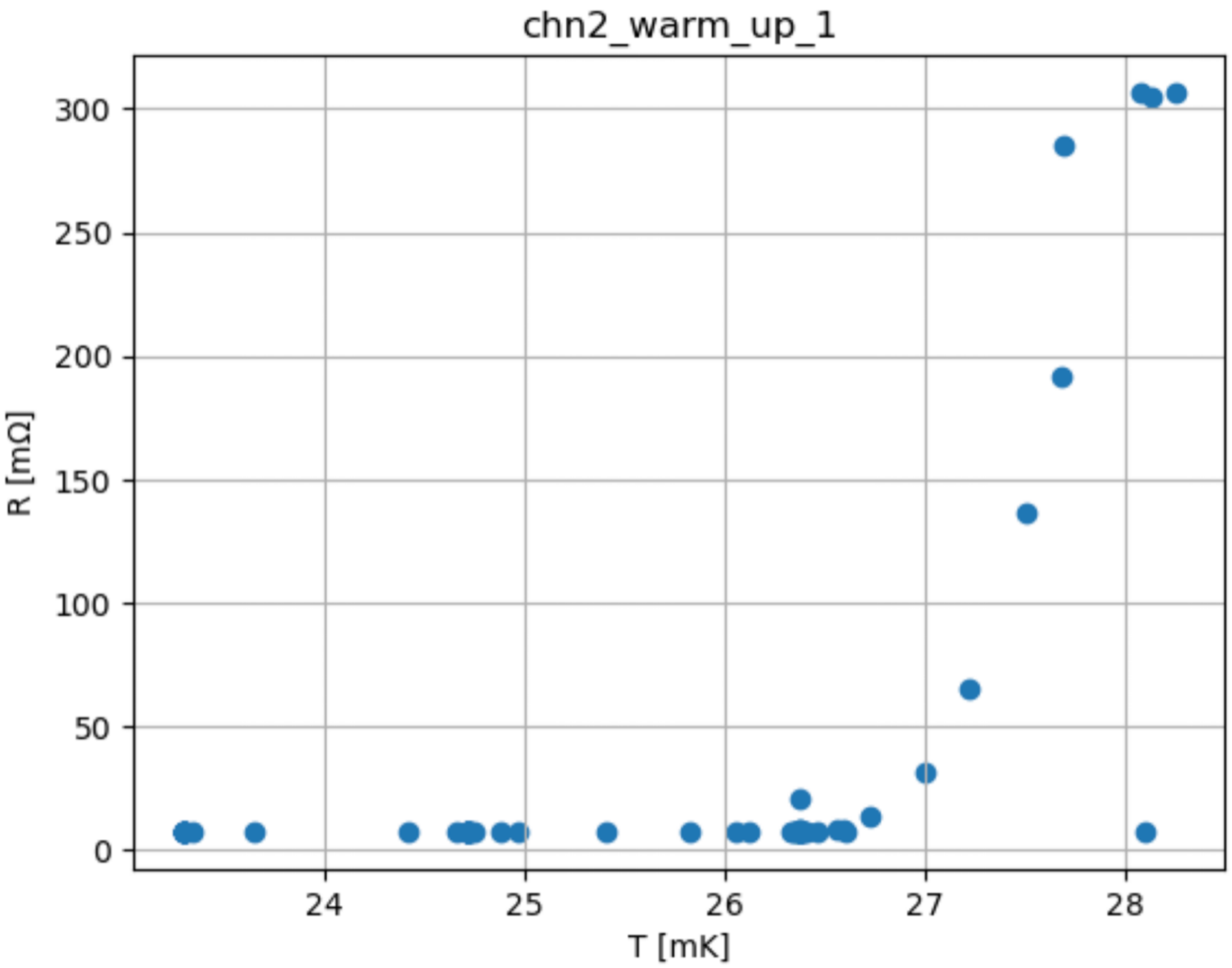


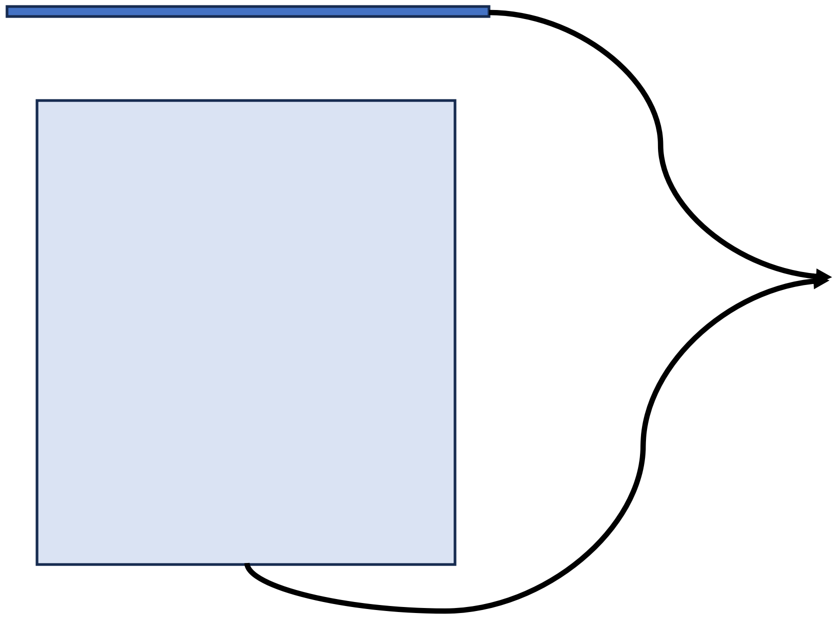
keV deposition -> μK temperature rise

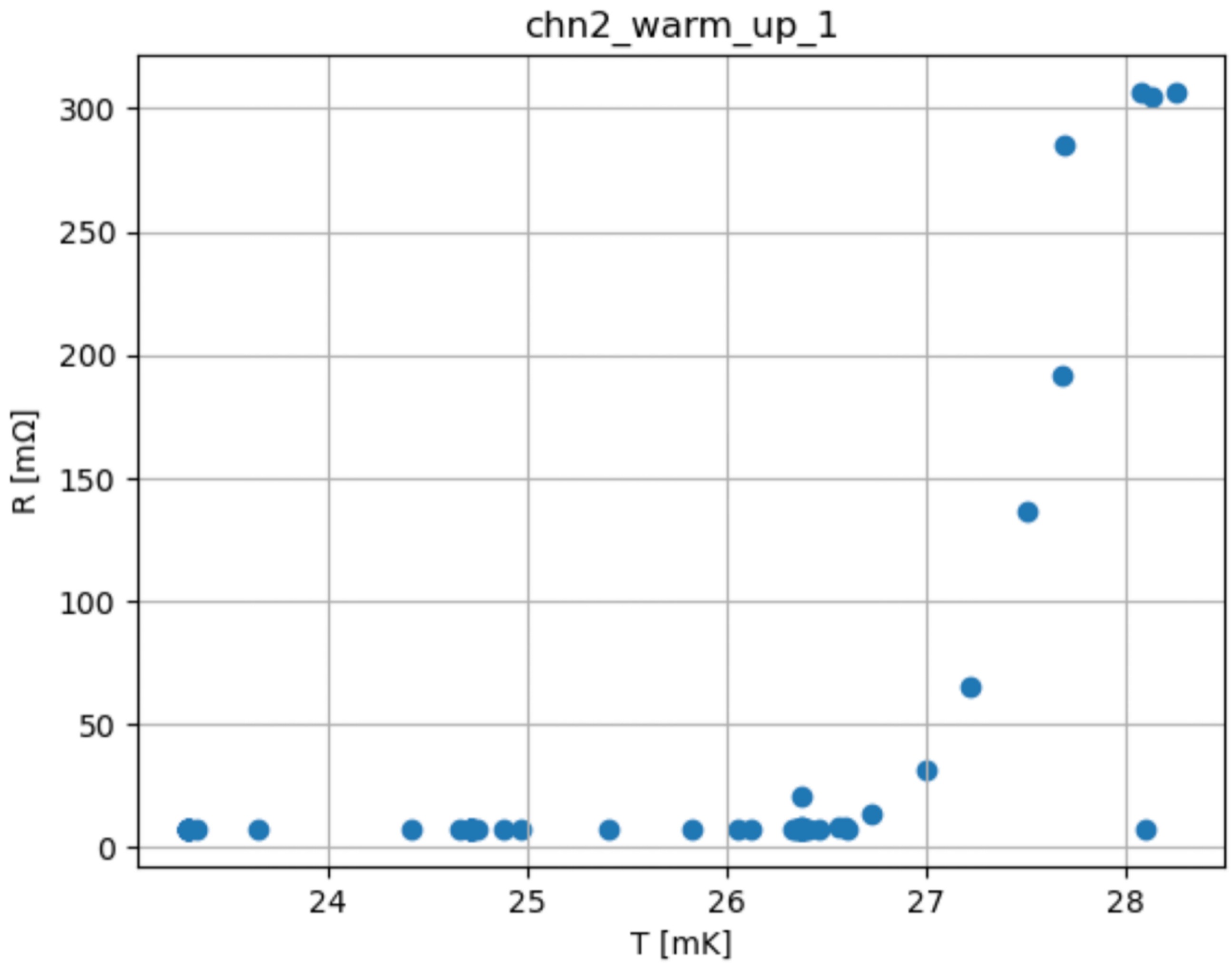
The RES-NOVA detector



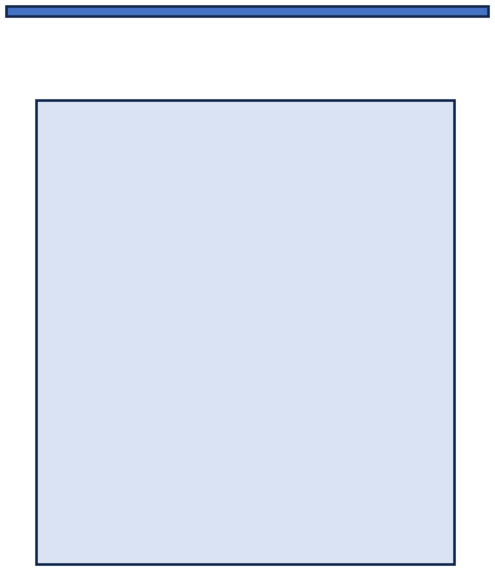


The RES-NOVA detector

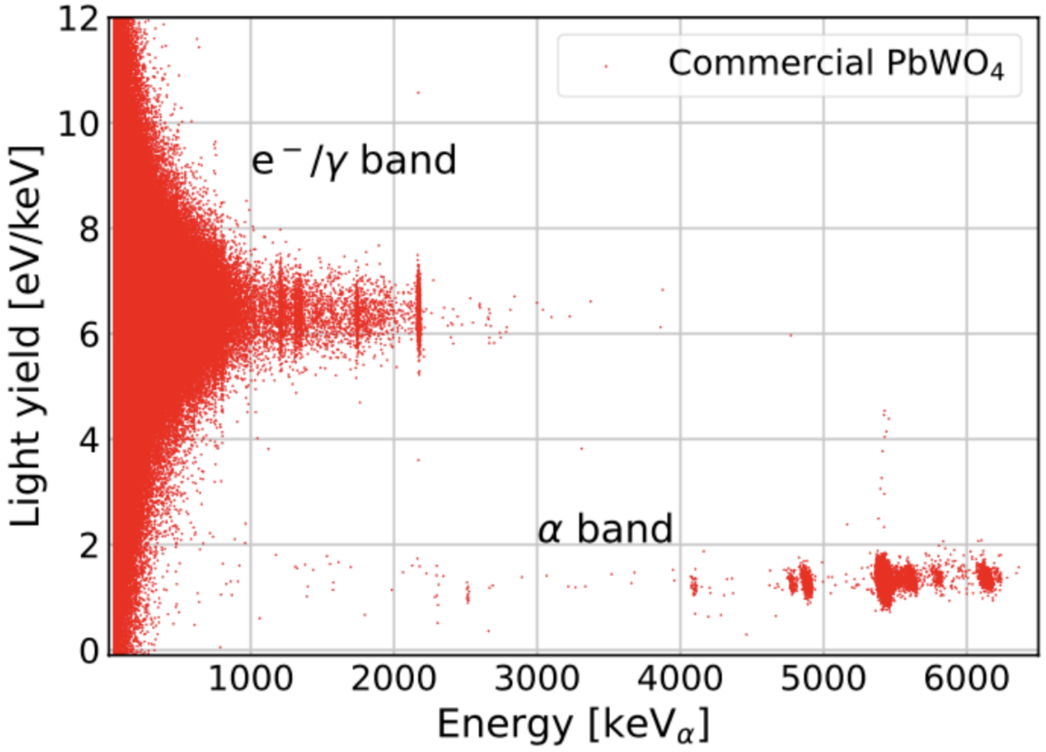




The RES-NOVA detector



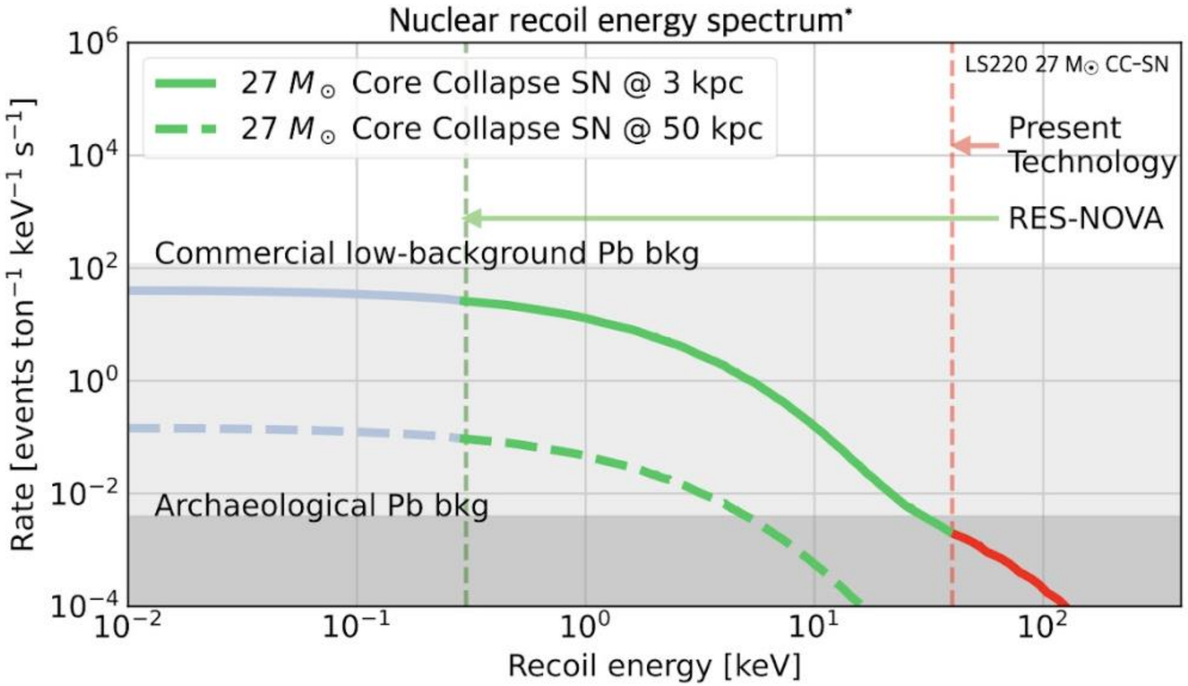
Detector energy spectrum of a cryo-$PbWO_4$



J.W. Beeman, **LP** et al., Eur. Phys. J. A 49, 50 (2013)

Why ancient Pb

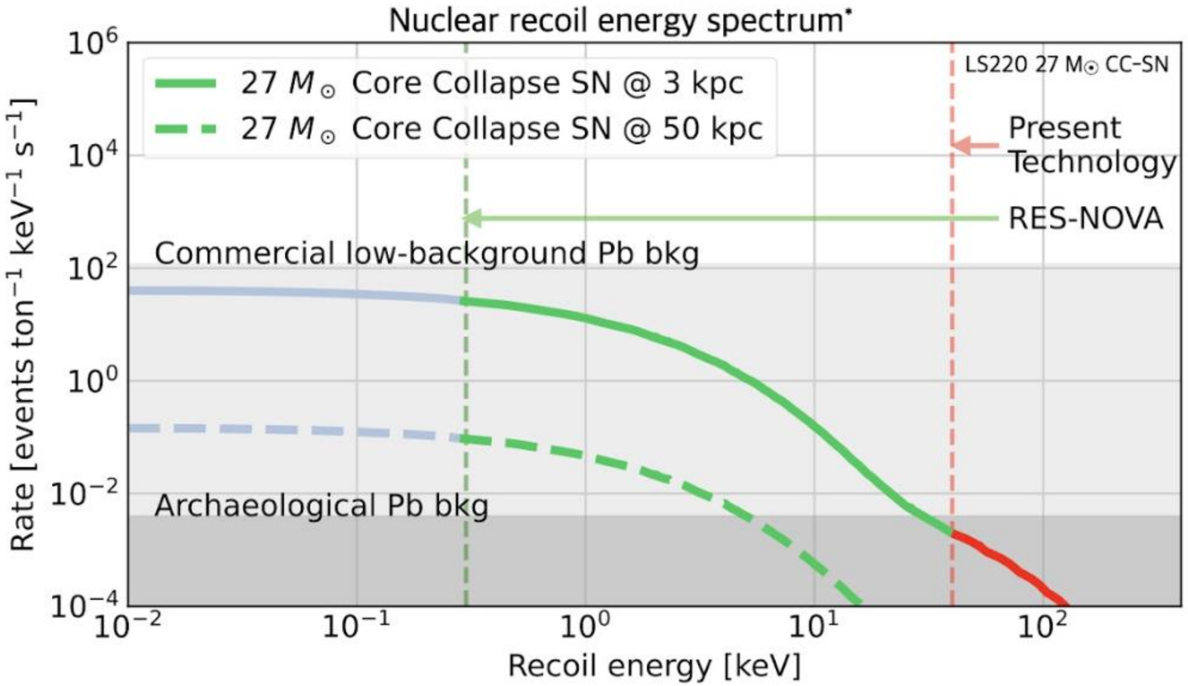
Commercial Pb has 10^4 Bq/ton of radioactive ^{210}Pb (Q-value 63 keV, $\tau_{1/2}$=22 y). That's bummer!



Why ancient Pb

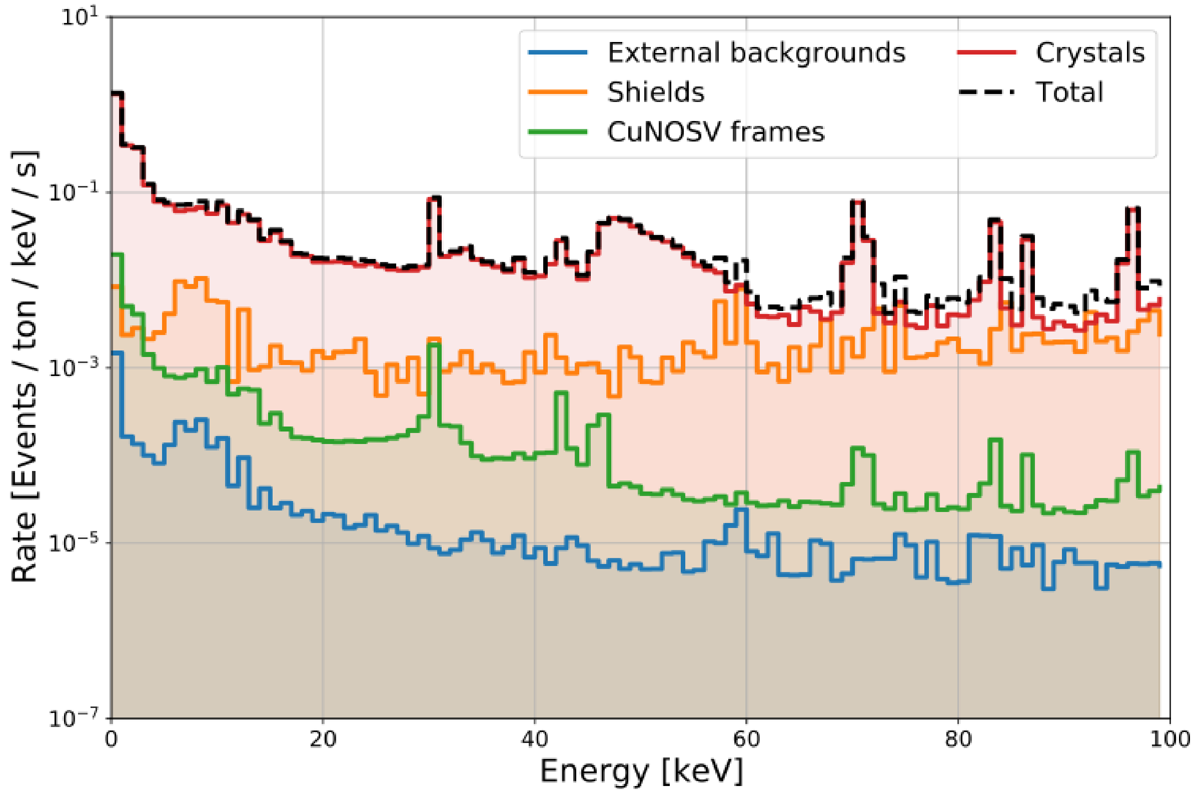
Commercial Pb has 10^4 Bq/ton of radioactive ^{210}Pb (Q-value 63 keV, $\tau_{1/2}$=22 y). That's bummer!

We will deploy $PbWO_4$ grown with 2000 years old archaeological lead ^{210}Pb is expected to be below 1mBq/kg

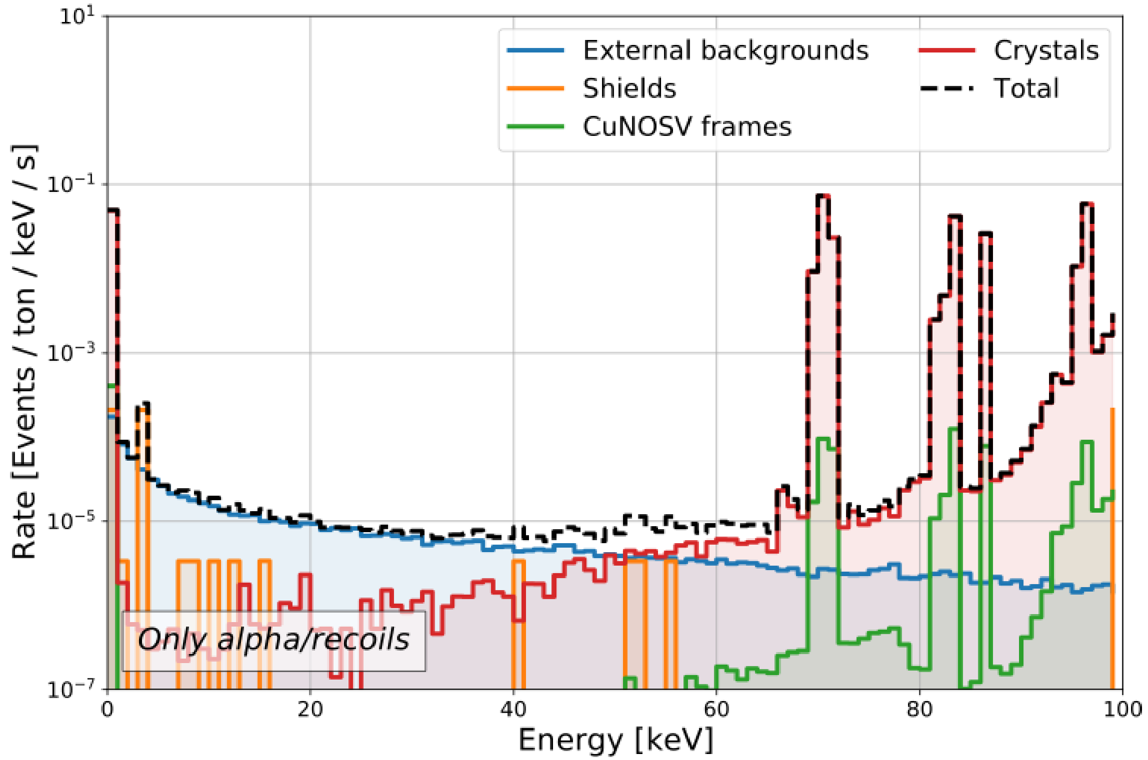


Our background model - complete

Electron/gamma

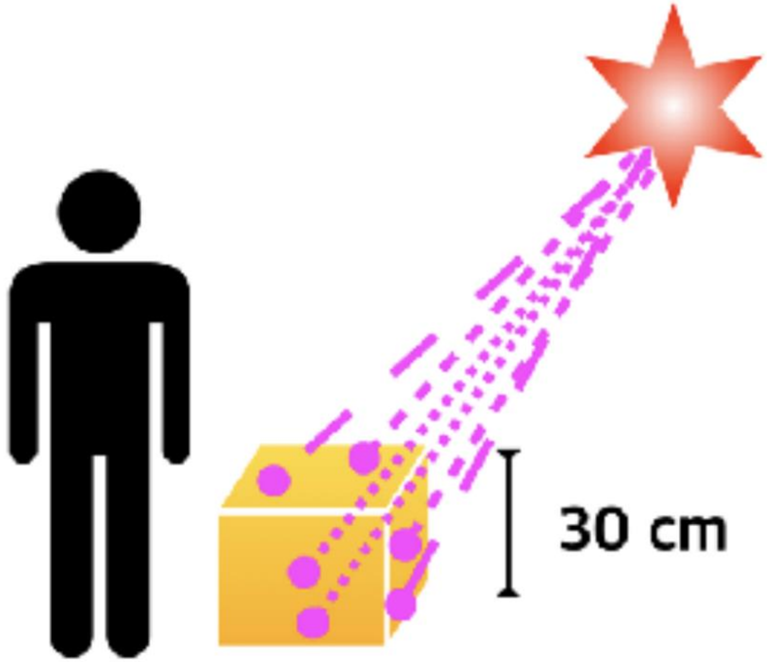


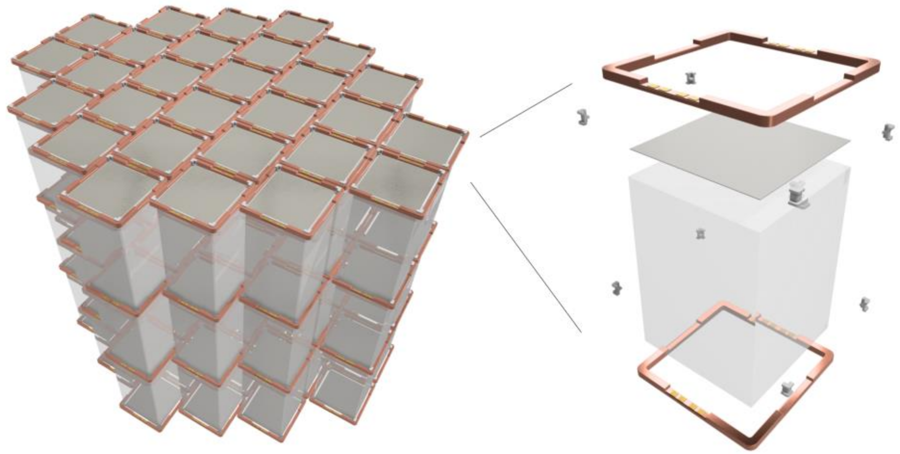
Nuclear recoils/alphas



The RES-NOVA detector

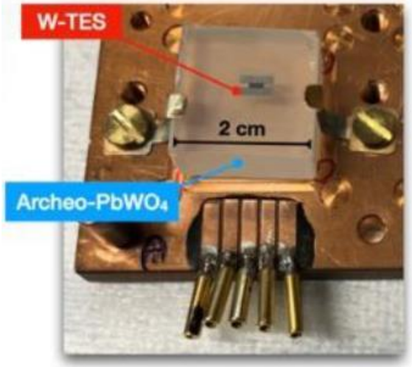
- Array of $PbWO_4$ crystals operated as (scintillating) cryogenic detectors (8.28 $g\cdot cm^{-3}$)
- Scintillating cryogenic detectors provide powerful background rejection thanks to the simulaneous read-out of phonon and light channels. Time coincident analysis of different detector modules allows for further background suppression
- Energy measured by means of sensitive Transition Edge Sensors (1sigma resolution: 200 eV)
- TESs have already demonstrated the capability of sub-keV nuclear recoil energy threshold





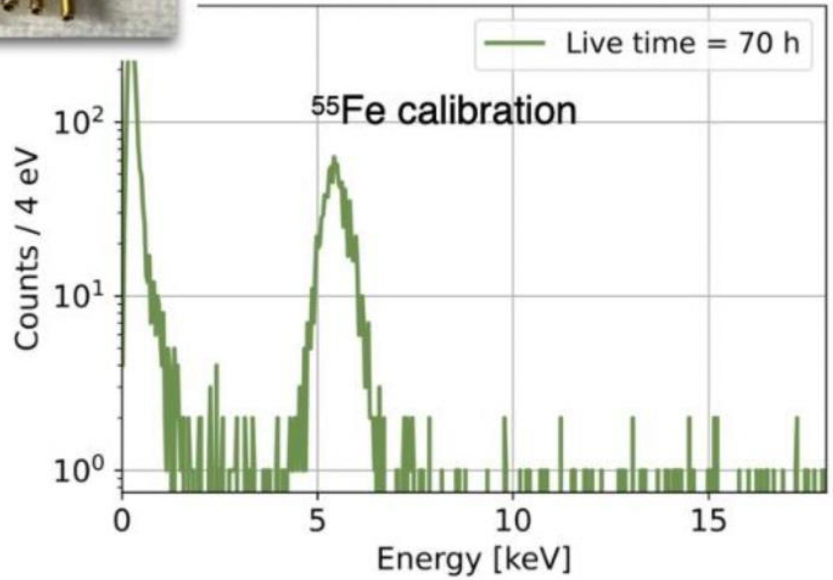
RES-NOVA PROOFS OF PRINCIPLE

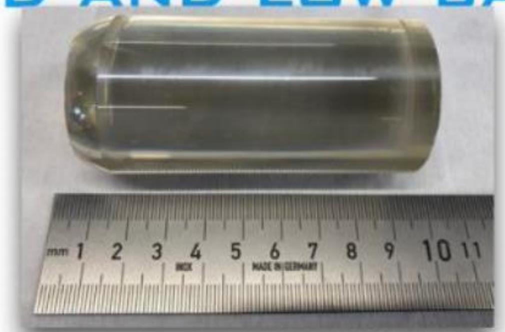
ACHIEVEMENT OF LOW THRESHOLD AND LOW BACKGROUND



N. Ferreiro Iachellini et al.,
J. Low Temp. Phys. 11, 184 (2022)

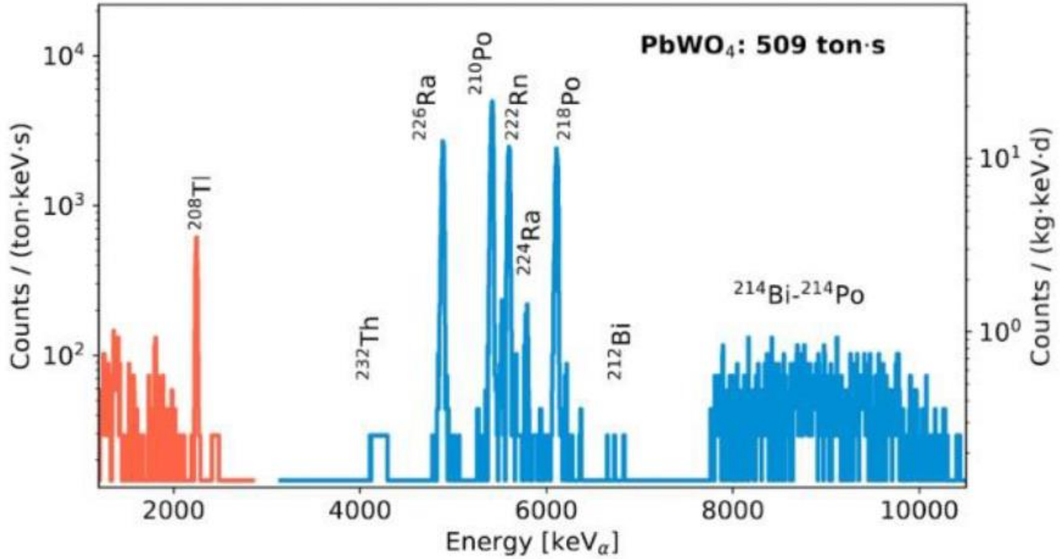
TOTAL ENERGY SPECTRUM





RES-NOVA group of interest
Eur. Phys. J. C 82, 692 (2022)

TOTAL ENERGY SPECTRUM



Above ground @ Max Planck Munich (DE)

Nuclear recoil threshold - 300 eV ($PbWO_4$ - 20 g)

Under ground @ LNGS (IT)

Radiopurity @ µBq/kg scale ($PbWO_4$ - 0.9 kg)

Why we can do SN (and DM) without spectroscopy

Sei V das gesamte Volumen des Gases, T die mittlere lebendige Kraft eines Gasmoleküls und N die Gesamtzahl aller Moleküle des Gases, endlich m die Masse eines Gasmoleküls, so ist für den Zustand des Wärmegleichgewichtes

$$f(x, y, z, u, v, w) = \frac{N}{V\left(\frac{4\pi T}{3m}\right)^{\frac{3}{2}}} \cdot e^{-\frac{3m}{4T}(u^2+v^2+w^2)}$$

Substituiert man diesen Wert in Gleichung (61), so erhält man

(62) $$\Omega = \frac{3N}{2} + N l \left[V\left(\frac{4\pi T}{3m}\right)^{\frac{3}{2}}\right] - N l N.$$

Versteht man nun unter dQ das dem Gase zugeführte Wärmedifferentiale, so ist

(63) $$dQ = N dT + p dV$$

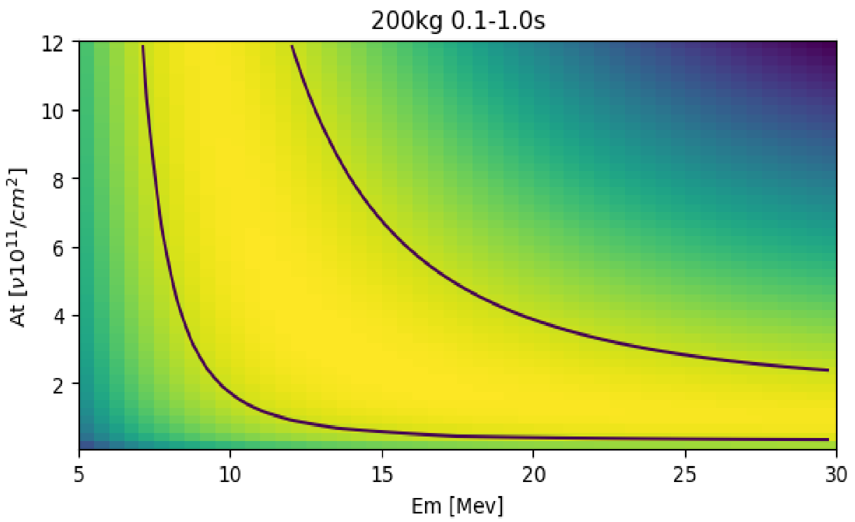
und

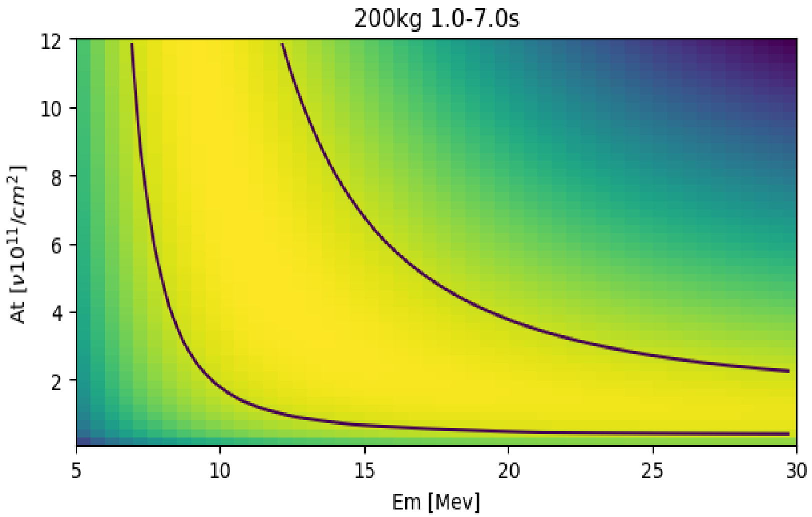
(64) $$pV = \frac{2N}{3} \cdot T.$$

p ist der Druck, bezogen auf die Flächeneinheit. Die Entropie des Gases ist dann:

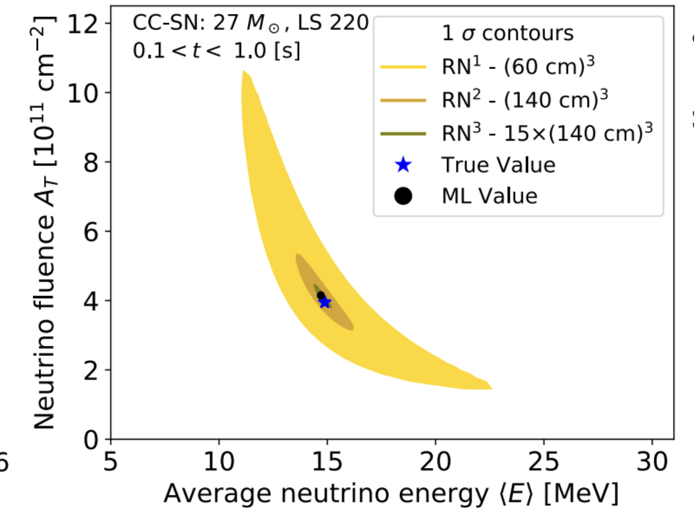
$$\int \frac{dQ}{T} = \frac{2}{3} N \cdot l(V \cdot T^{\frac{3}{2}}) + C.$$

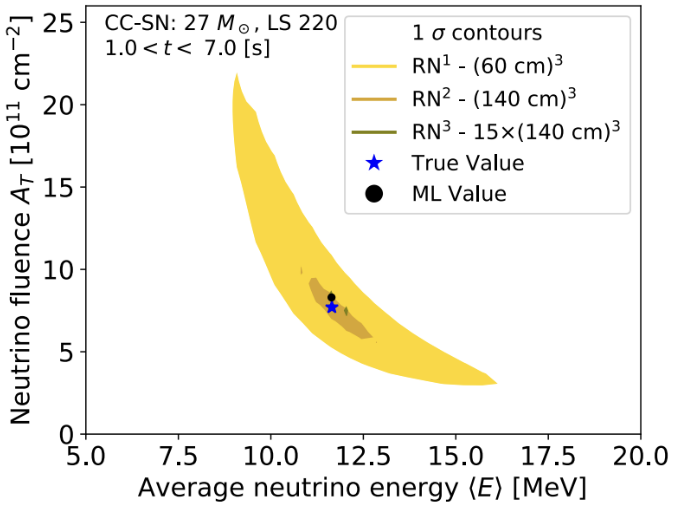
Constraining SN parameters (type II error)





~200kg coming in the next 2-4 years



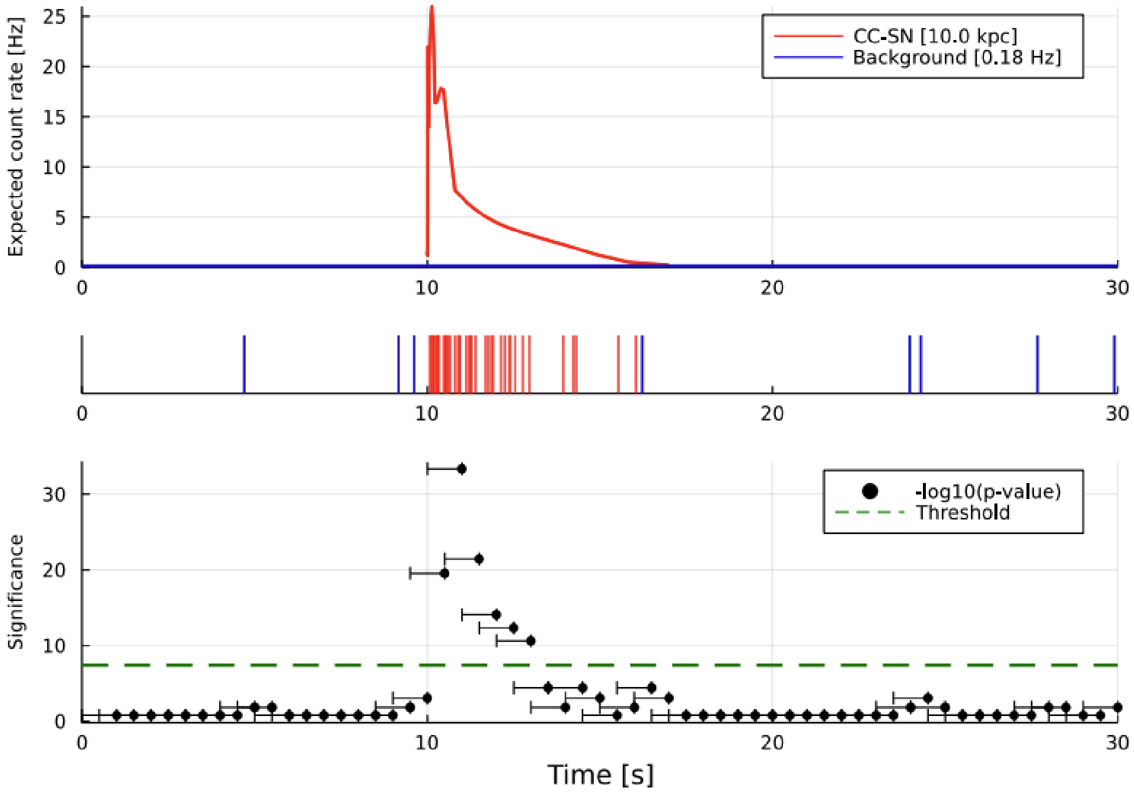


RN[1] 2.4t

RN[2] 31t

RN[3] 465t

Live detection of a SN event (type I error)



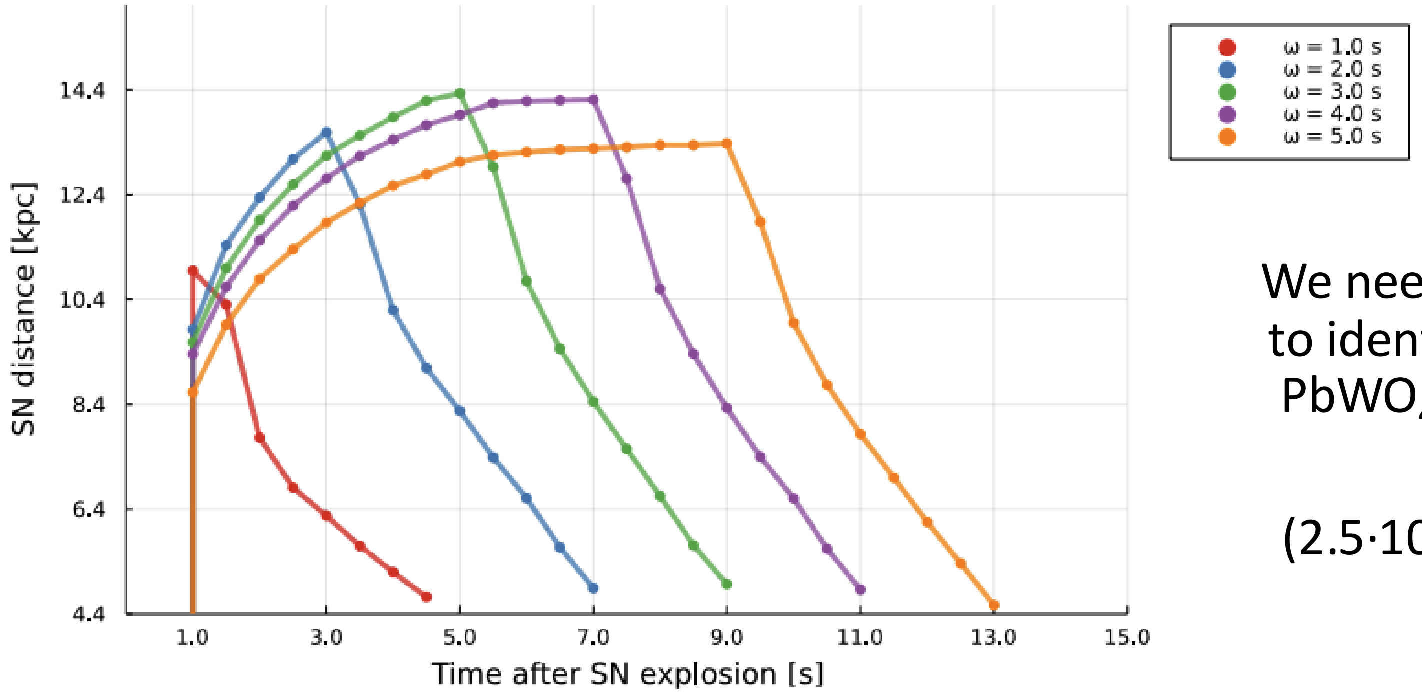
https://doi.org/10.1088/1475-7516/2022/10/024

The SN event appears as a sudden burst of nuclear recoils in the 1-10 keV energy range.

In the live trigger analysis we don't know when the SN occurs and we need enough recoils to distinguish it from Poissonian fluctuations of the background.

Type I error: we can fire 1 alarm at most every 15 days

Live detection of a SN event (type I error)

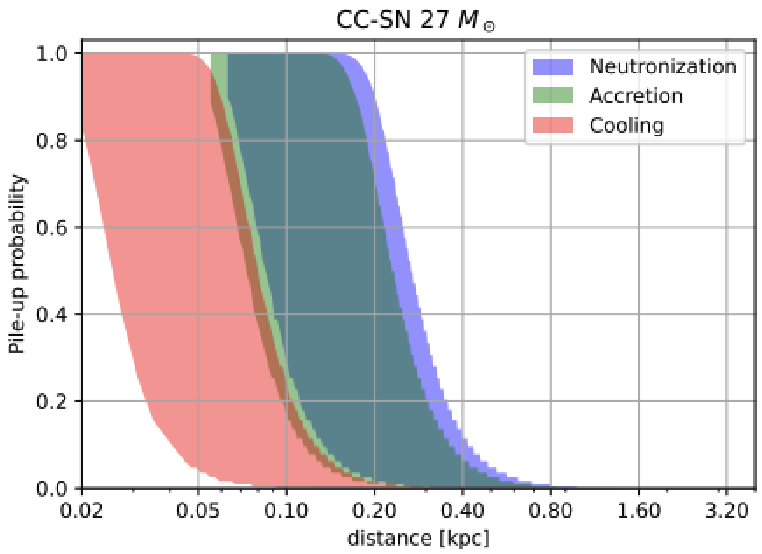


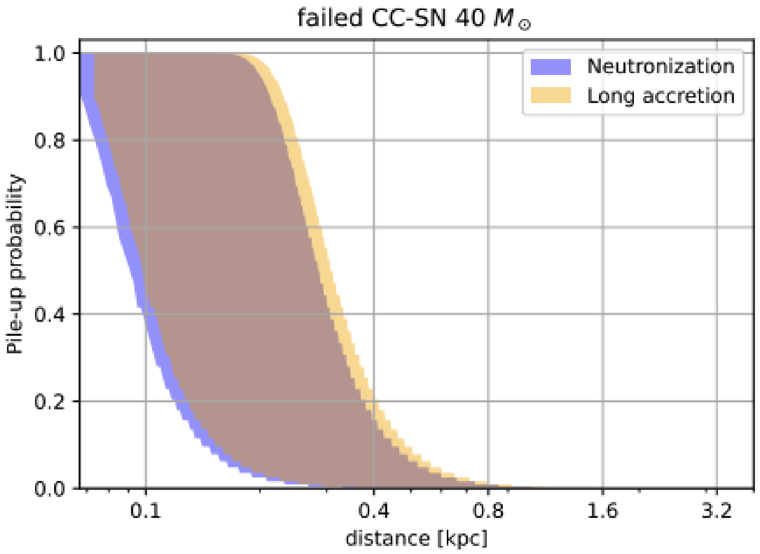
We need 1 s of data to collect enough events to identify an event @10kpc with 1750 kg of $PbWO_4$ and a background of 0.18 Hz in the ROI.

($2.5{\cdot}10^{-3}$ cts/ton/keV/s × 1.8 tons × 40 keV)

https://doi.org/10.1088/1475-7516/2022/10/024

The next Galactic Supernova: a close one

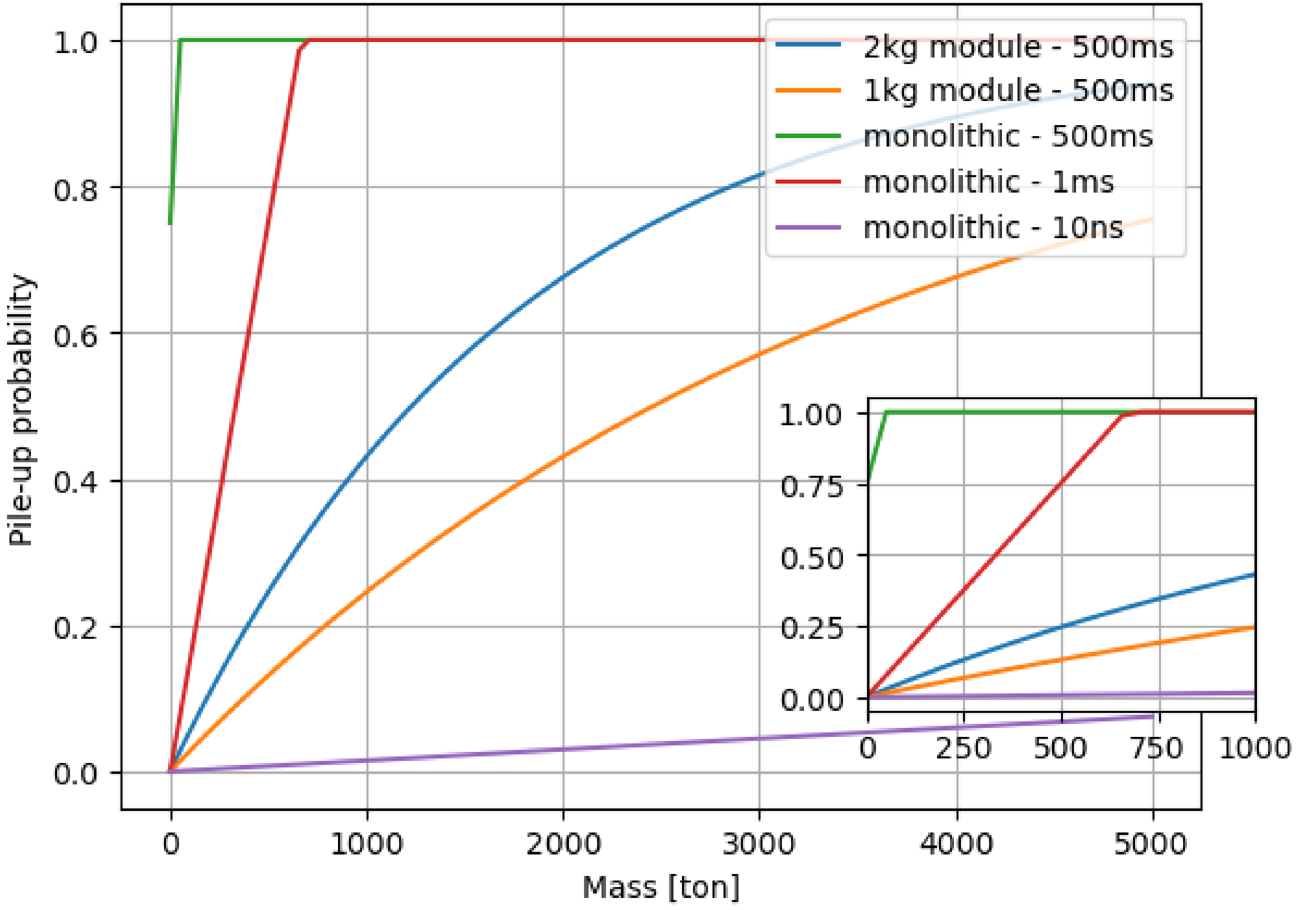




Due to the $1/d^2$ depency, nearby SN events may cause substantial pile-up in detectors designed for maximum sensitivity. We have quantified the efficiency loss in the case of RES-NOVA

JCAP 10 (2021) 064

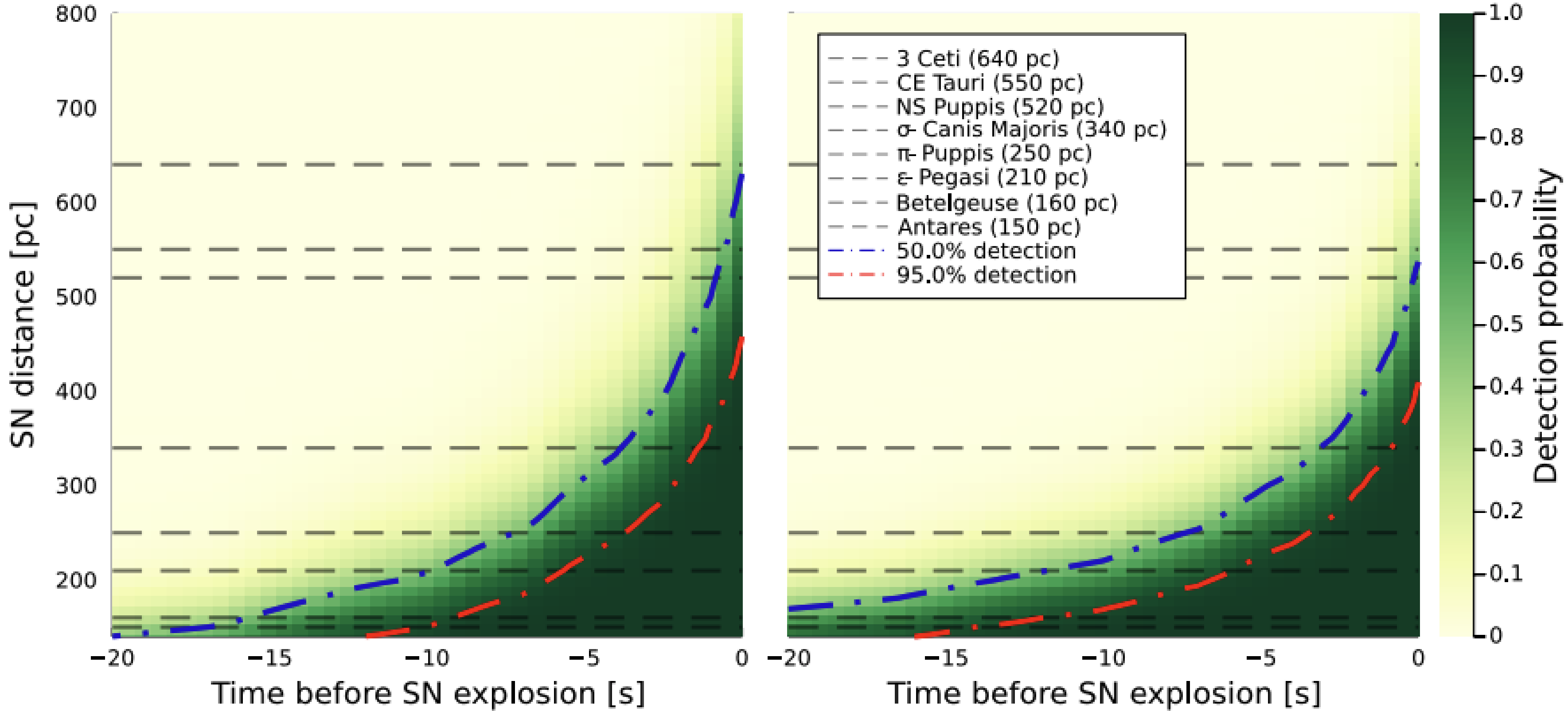
The next Galactic Supernova: a close one



Modularity withstand high interaction rates and it mitigates the effects.

In a detector array pile-up lowers the efficiency within the response time window, in a monolithic detector it blinds it completely

The next Galactic Supernova: a close one



Next phase of

RES-NOVA

1750kg of $PbWO_4$

Figure 10. Success rate of neutrinos detection prior to a SN explosion for three different window sizes: 15 s (left); 70 s (right).

https://doi.org/10.1088/1475-7516/2022/10/024

Conclusions

- The next galactic Supernova will trigger great excitement in the community
- The all-flavors sensitivity of CEνNS makes it ideal for a all-flavors source such a SN
- Archeo-Pb grown $PbWO_4$ crystals have been proven to be a fit in terms of cryogenic operation and radioactivity for this quest
- We don‘t know when and where the next one will occur, be ready for all scenarios

Thank you!