Detecting neutrinos and dark matter with archaeological Pb-based cryogenic detectors

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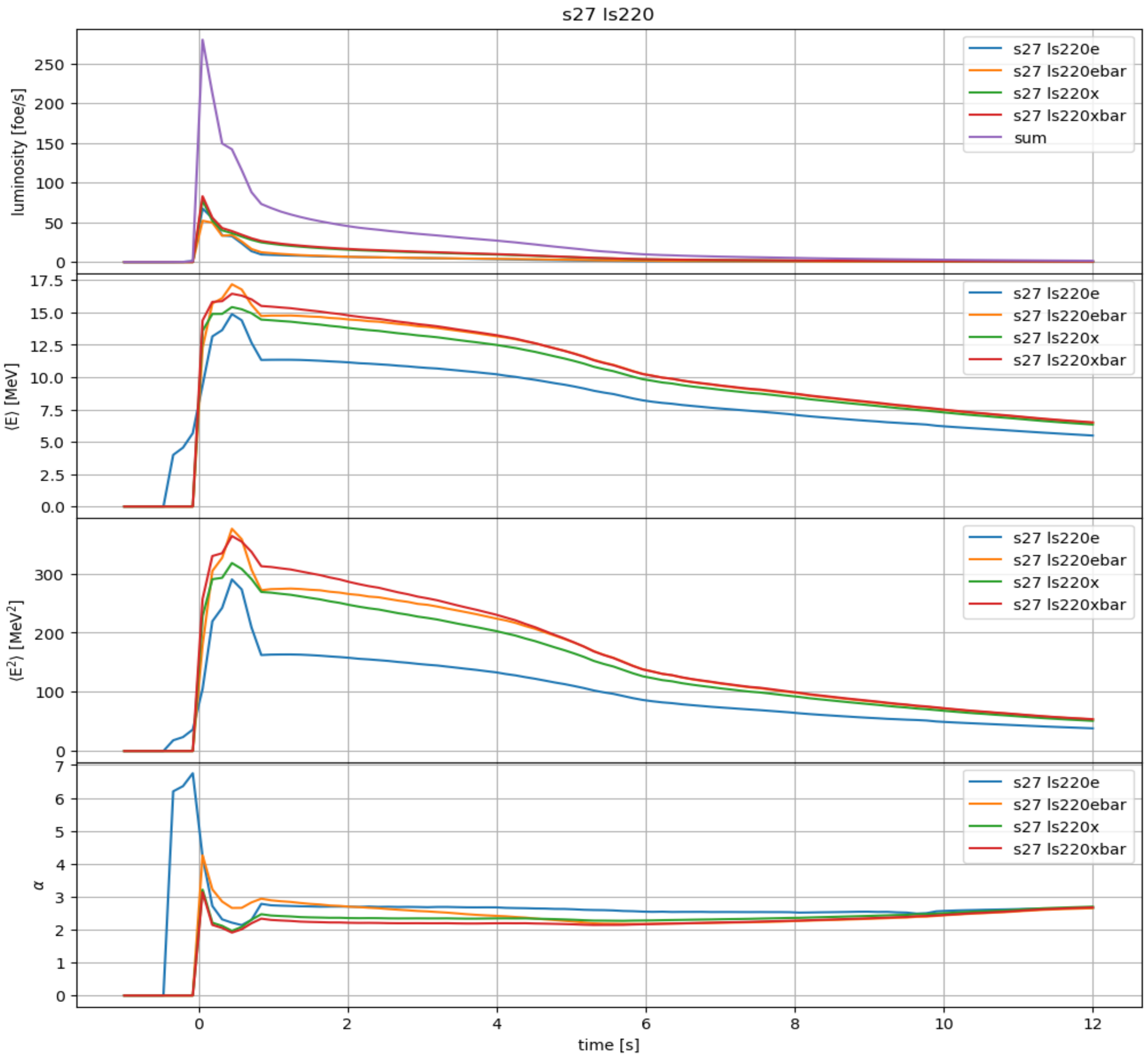
RES-NOVA

From latin -> “New thing”

Latin -> more on that later

NOVA reminds to Supernovae

The 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

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

- Neutrinos mainly scatter off neutrons
- Coherent enhancement
- Flavor-independent
- $\mathcal{O}$(10)MeV neutrinos deposit $\mathcal{O}$(1)keV energy
- SM process
- First observation:

Science 15 Sep 2017:
Vol. 357, Issue 6356, pp. 1123-1126
DOI: 10.1126/science.aao0990

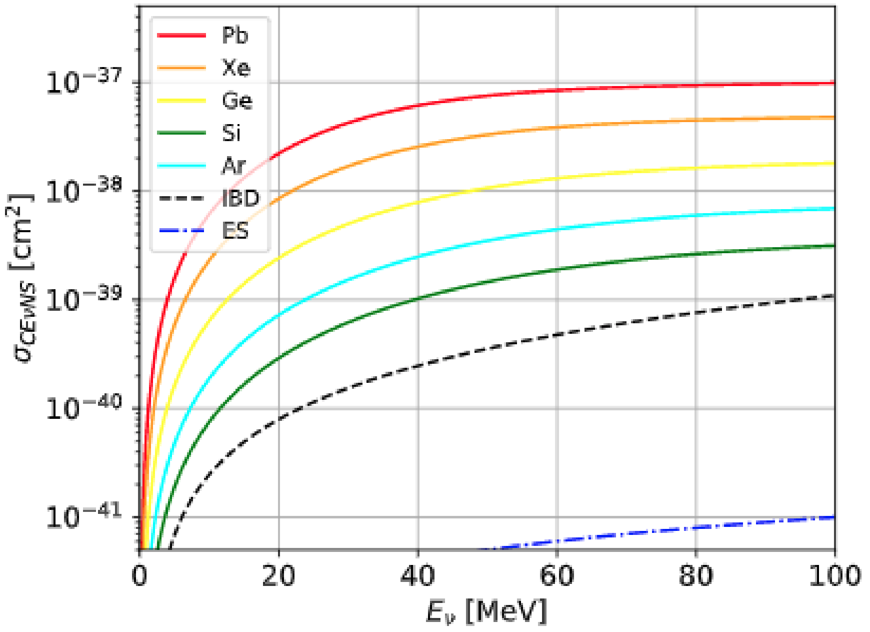
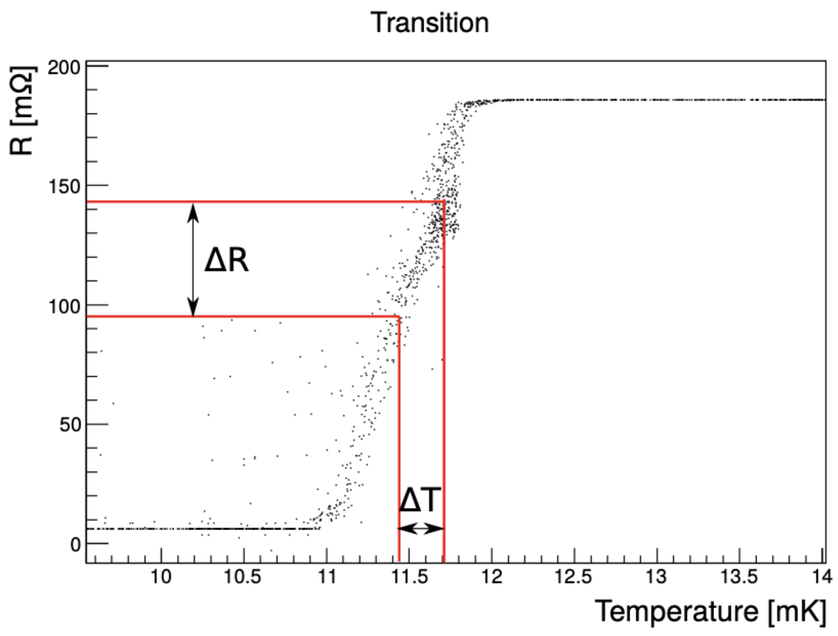


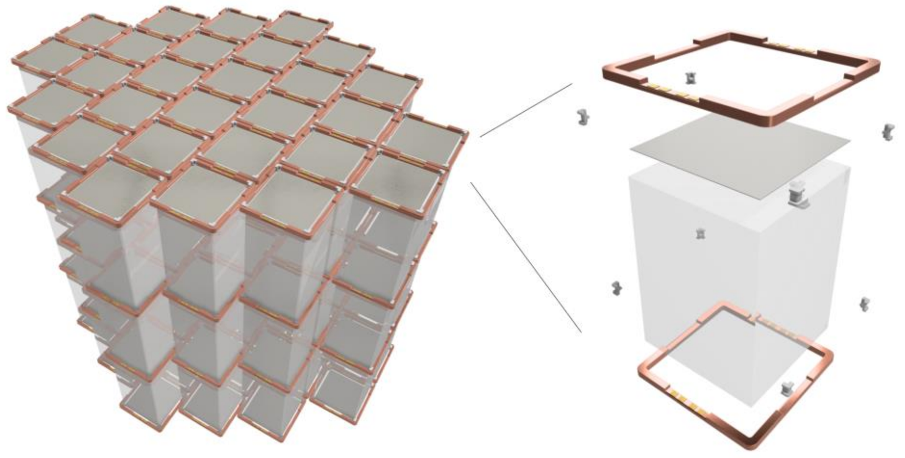
FIG. 2. Coherent elastic neutrino-nucleus scattering (CEνNS) cross sections as a function of the energy of the incoming neutrino for different target nuclei. The dashed lines show the inverse-beta decay (IBD) and neutrino elastic scattering on electrons (ES) cross-sections for comparison. Given the high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

Phys. Rev. D 102, 063001 (2020)

The RES-NOVA detector

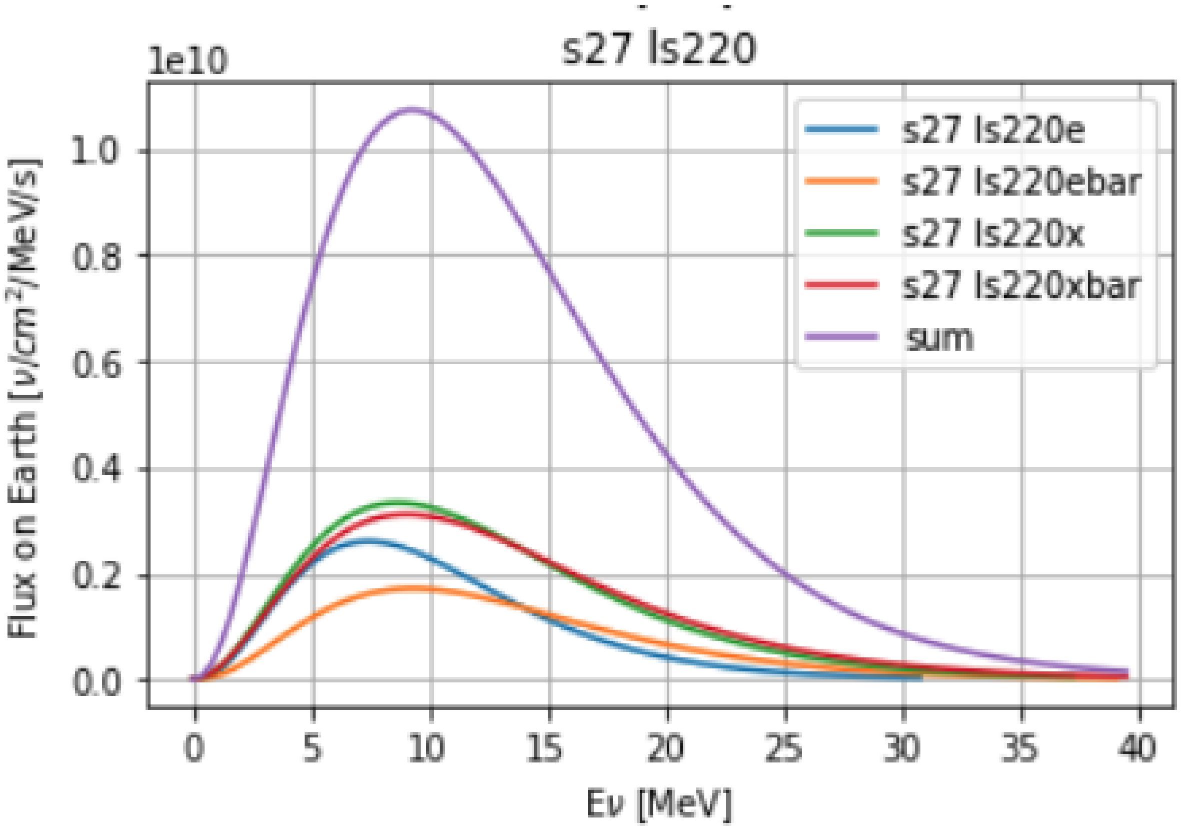
- Array of $PbWO_4$ crystals operated as (scintillating) cryogenic detectors ($8.28\ g \cdot cm^{-3}$)
- Scintillating cryogenic detectors provide powerful background rejection thanks to the simulaneous read-out of phonon and light channels. Time coincident analysis of different detector modules allows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



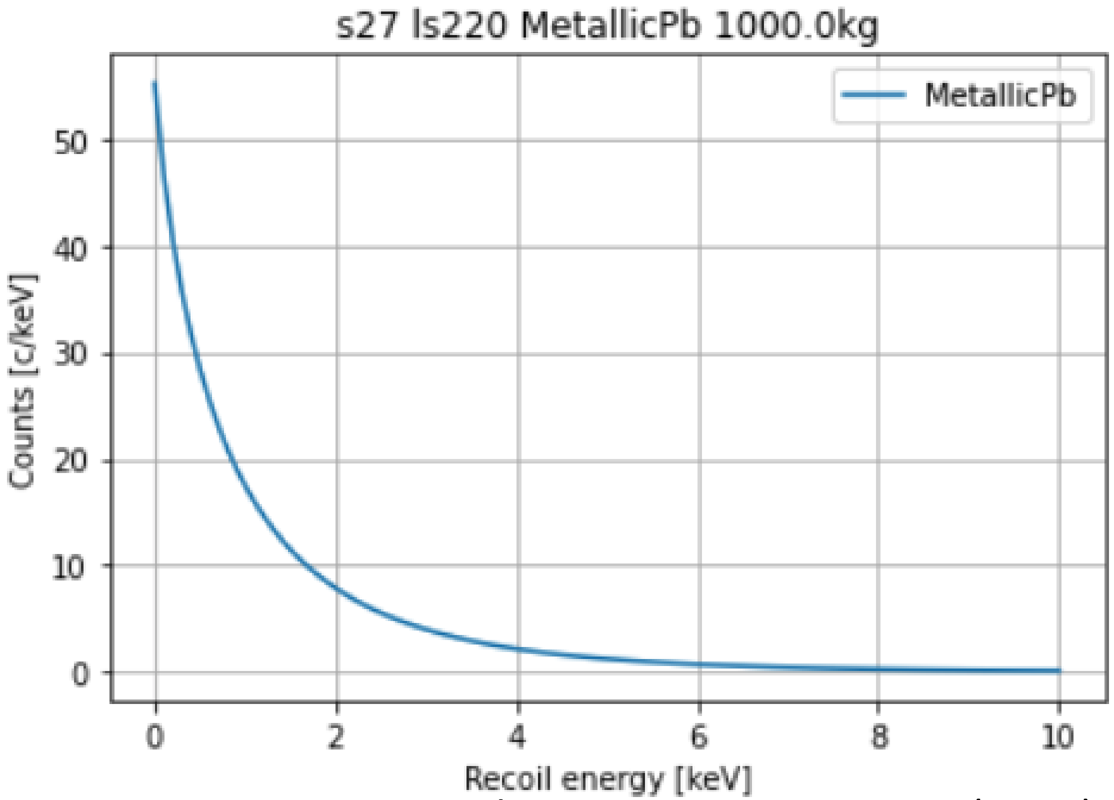


SN CEνNS in Pb Target (on Earth)

The emitted neutrino spectrum is (almost) Maxwell-Boltzmann

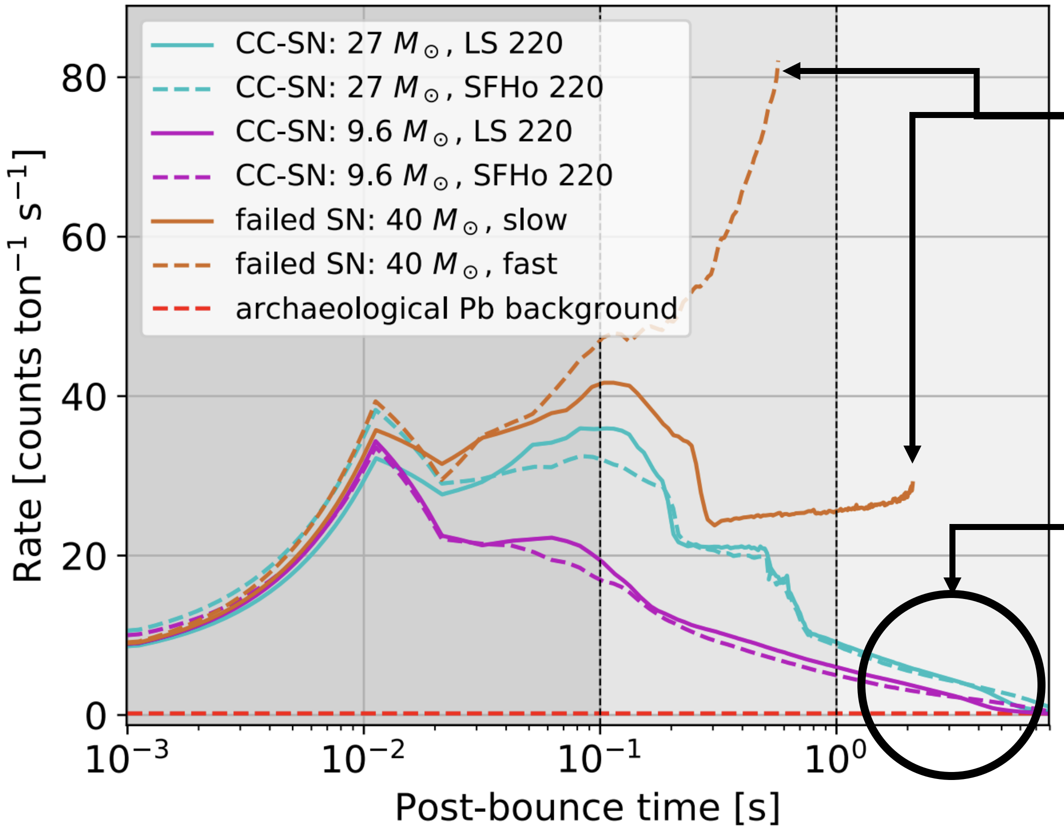


Observed nuclear recoil spectrum



Phys. Rev. D 102, 063001 (2020)

The light curve brings information!



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

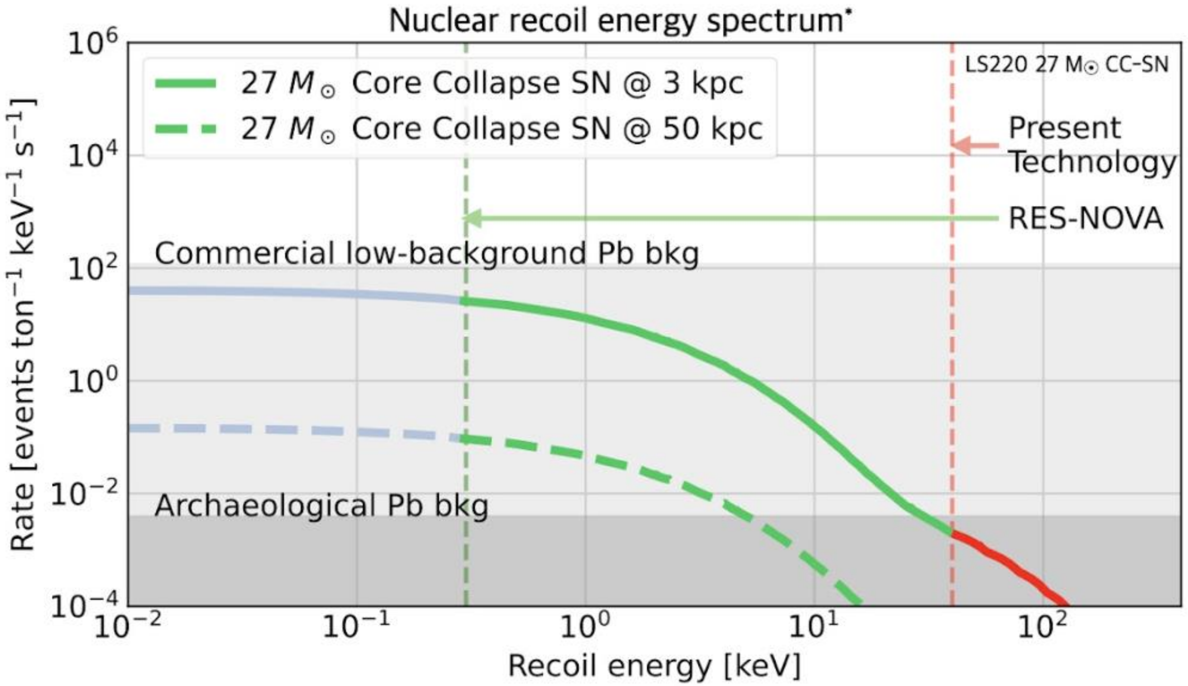
L. Pattavina et al., *JCAP* 10 (2021) 064

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

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

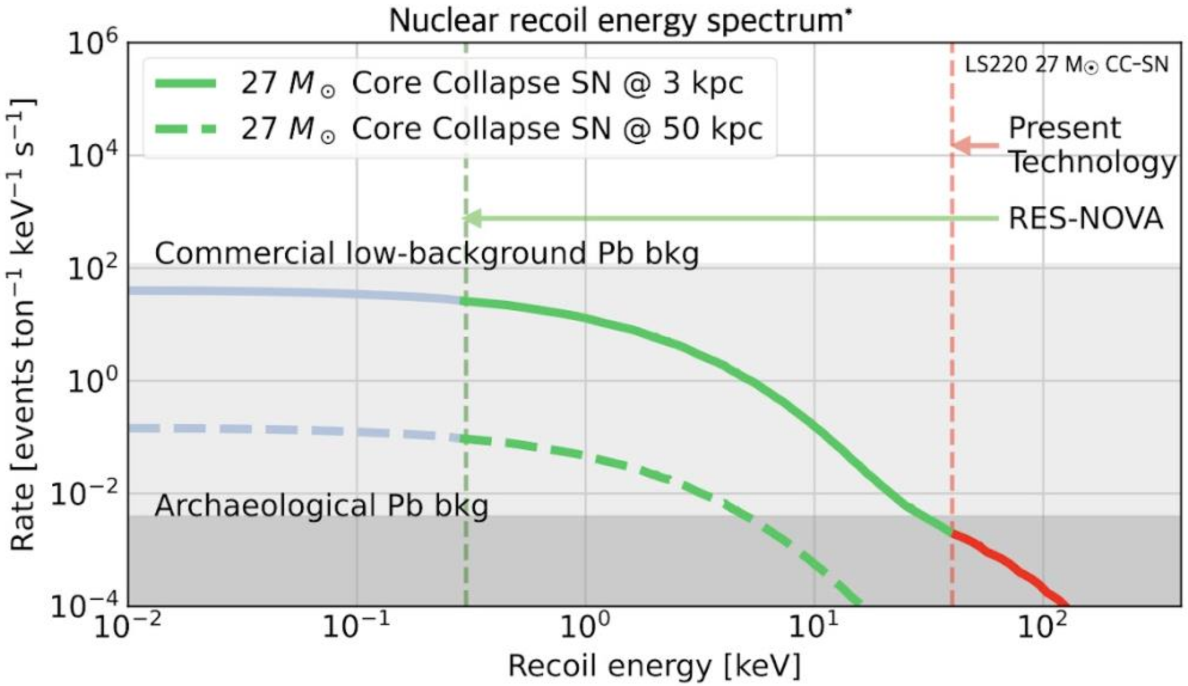
The downfall of Pb

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



And the solution

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 2000years old archaeological lead ^{210}Pb is expected to be below 1mBq/kg

From SN neutrinos to Dark Matter

- Pb can proble N^2 weak-scattering down to $10^{-38}/10^{-39}$cm^2
- (Spin-independent WIMPs) Dark matter couples to A^2 and obeys a Maxwell-Boltzmann distribution

$$\frac{d\Gamma}{dE_R} = \frac{\rho_\chi}{m_N m_\chi} \int_{v_{min}}^{\infty} d^3\overline{v} f(\overline{v}) v \frac{d\sigma(v, E_R)}{dE_R}$$

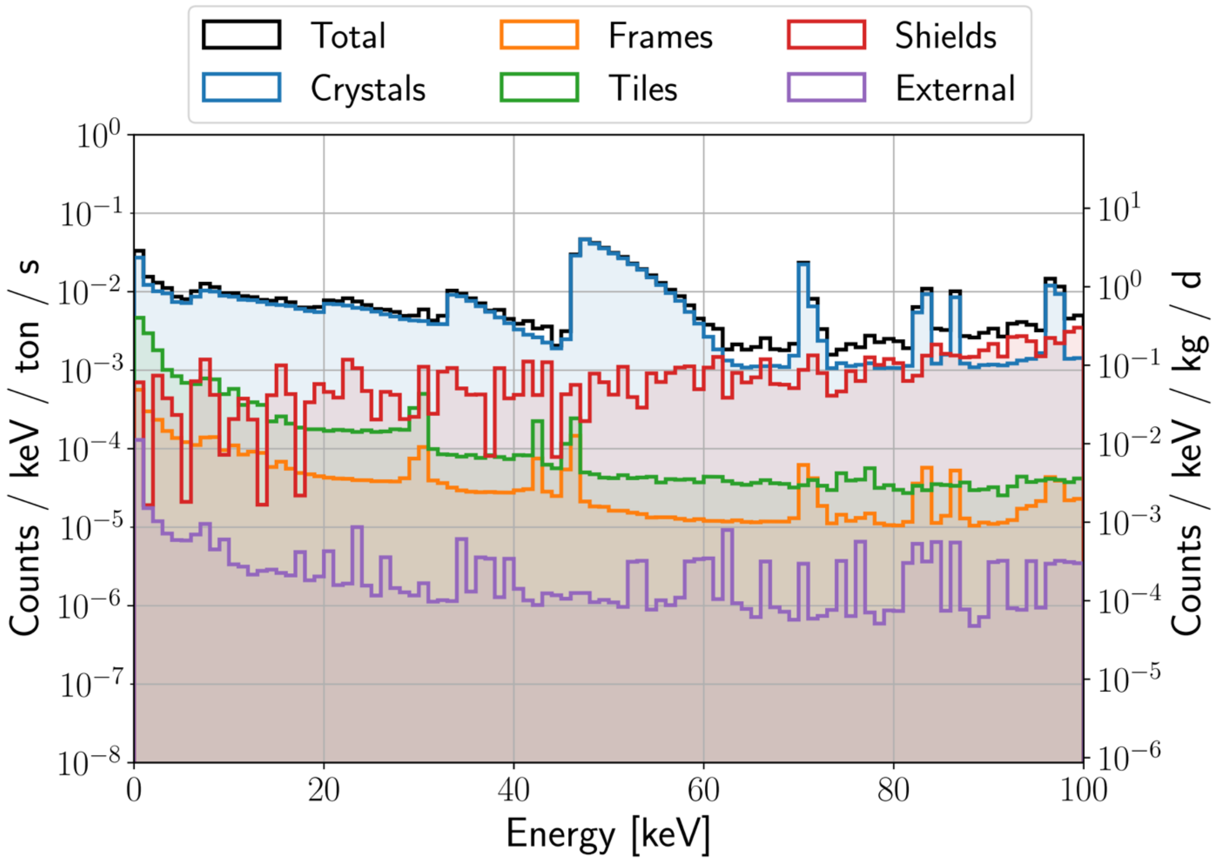
$$\left(\frac{d\sigma}{dE_R}\right)_{SI} = \frac{m_N \sigma_0}{2\mu^2 v^2} F^2(E_R)$$

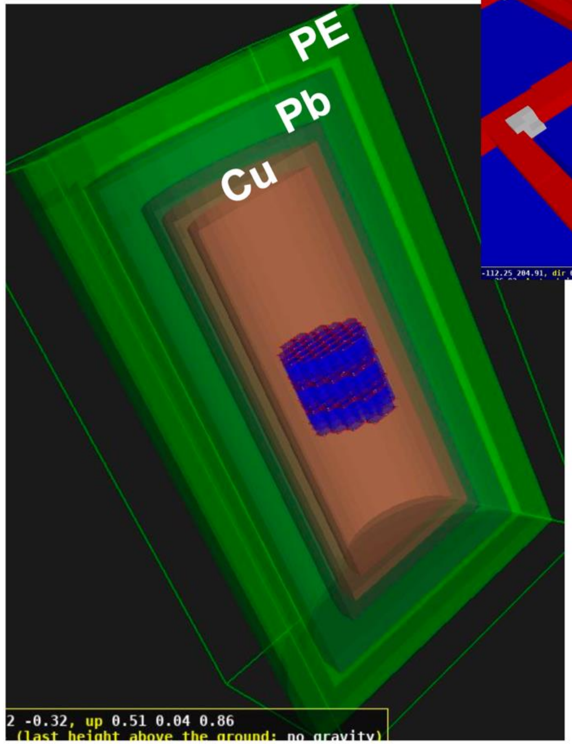
$$\sigma_0 = \frac{4}{\pi} A^2 f^2 \mu^2$$

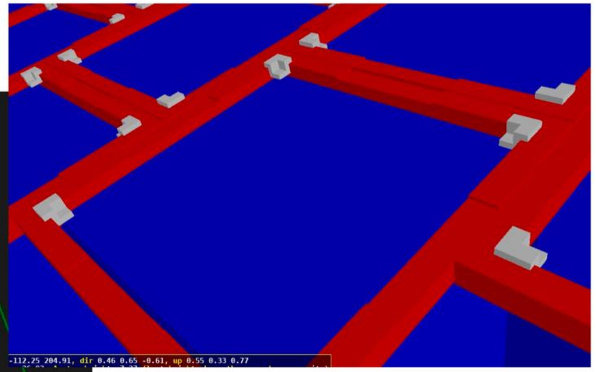
- Dark matter is a always-on source, making its flux 10^7 greater than SN neutrinos (for a 1y measurement).

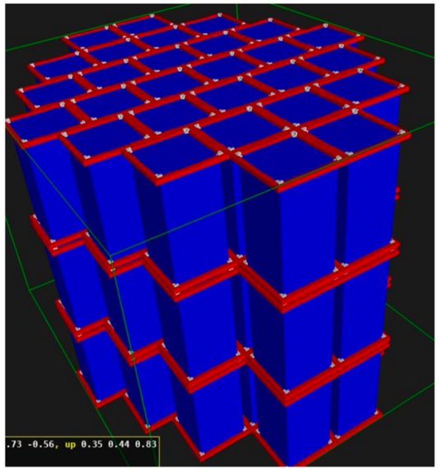
A detailed calculation yields that we can reach 10^{-43} cm^2 of sensitivity

Our background model - complete

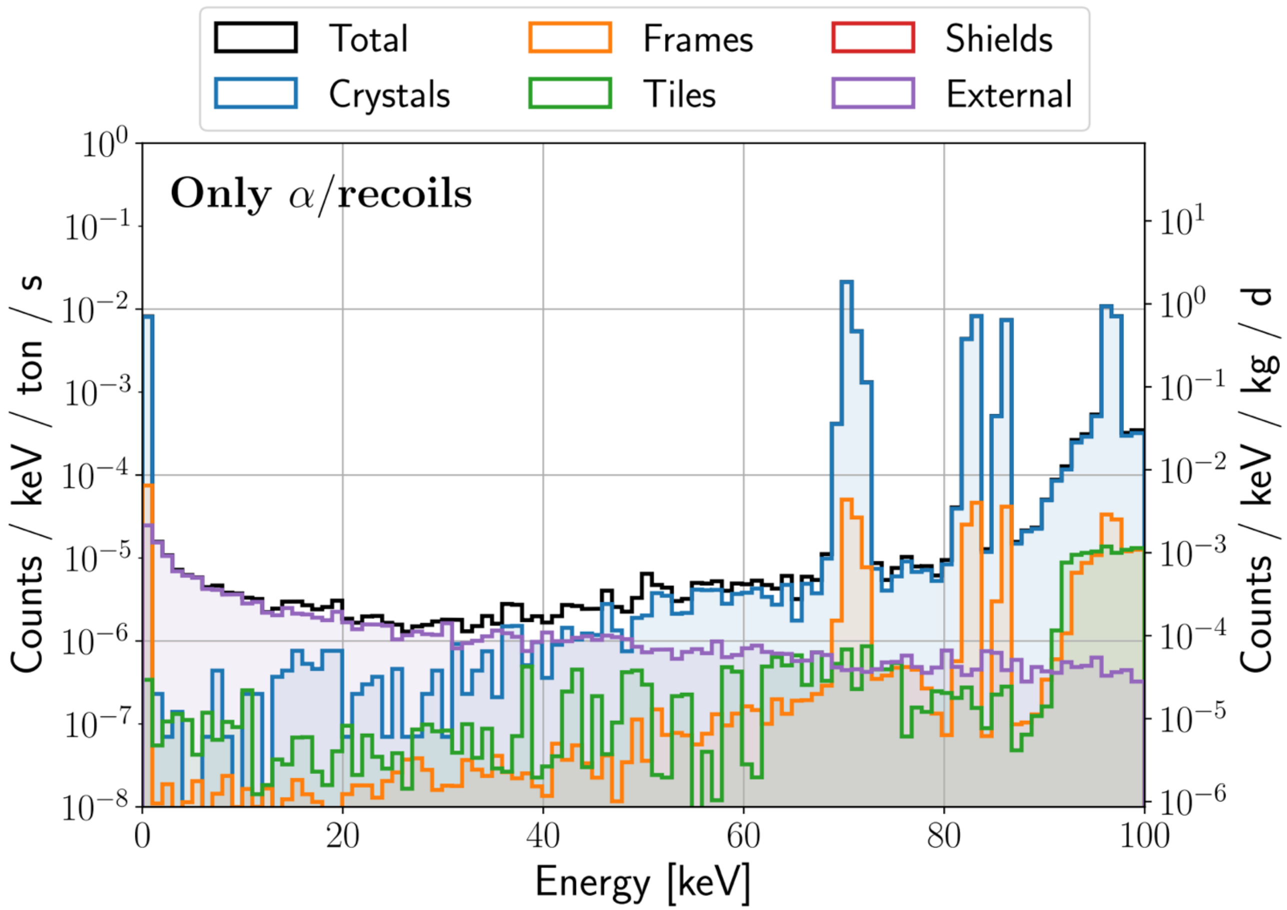


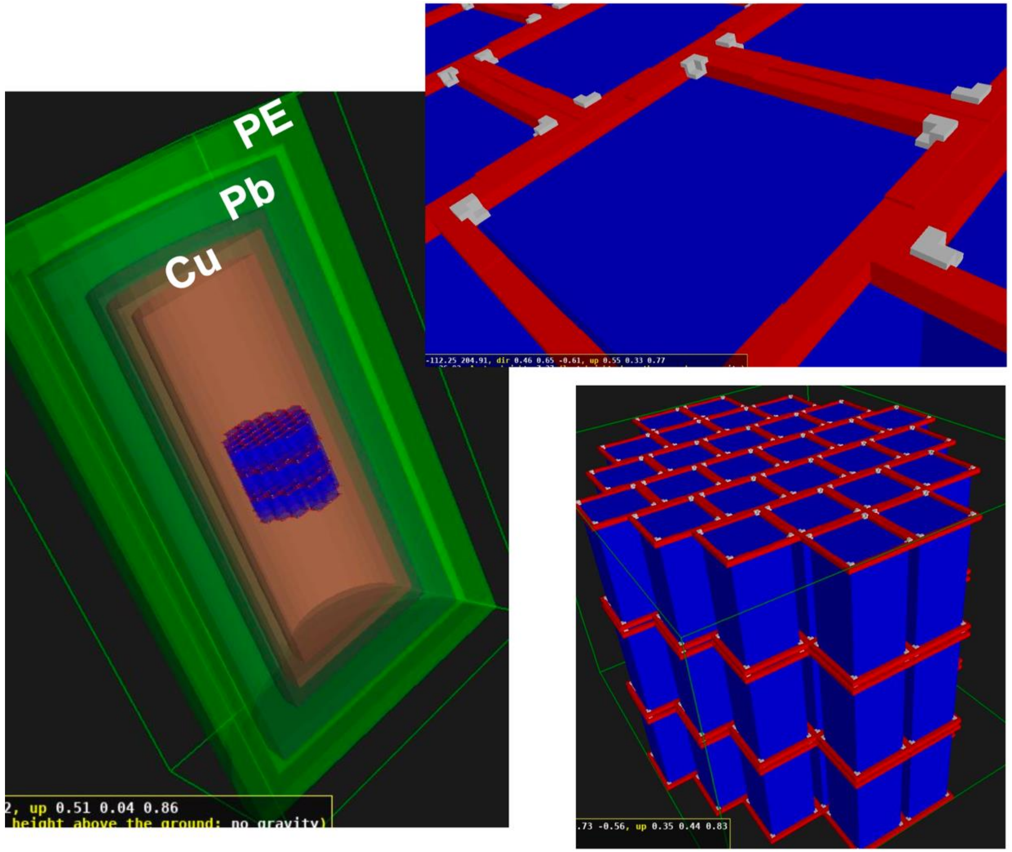






Our background model – nuclear recoils

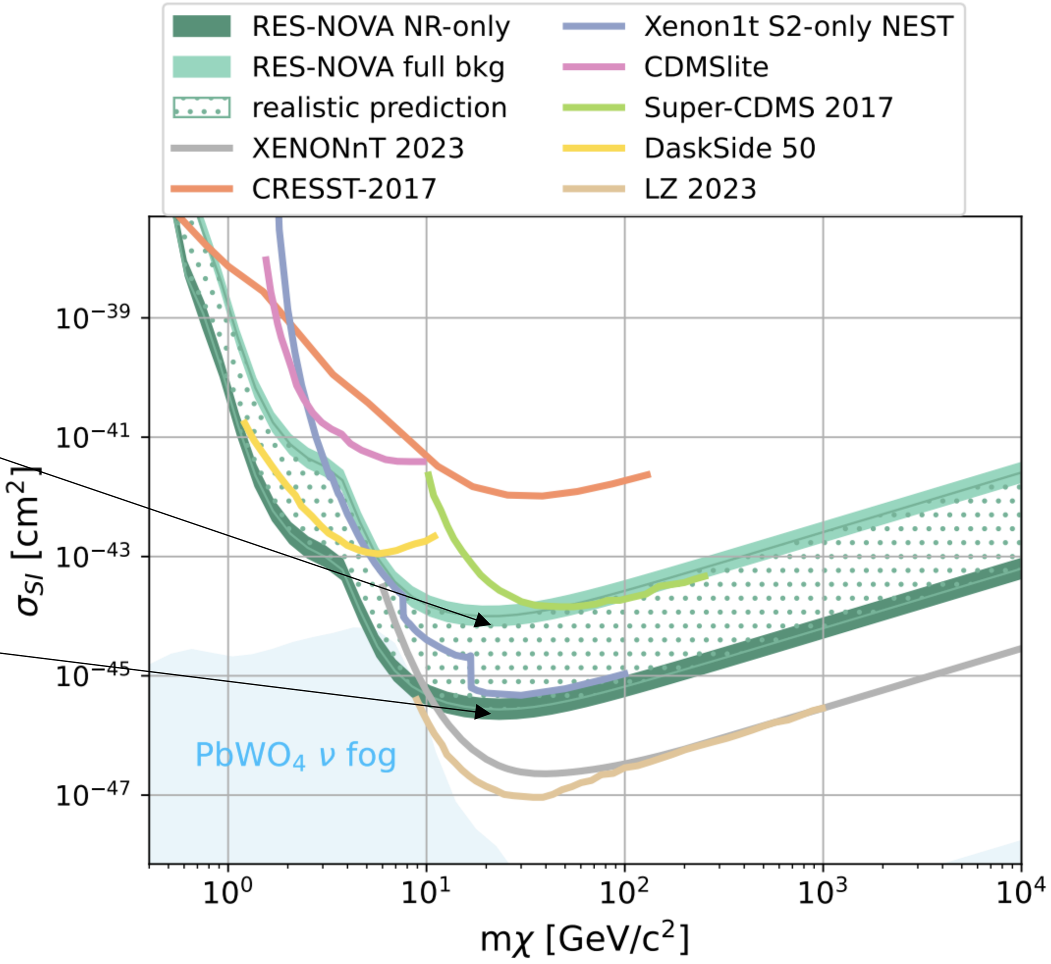




Projected sensitivity – spin independent

No bck rejection

Full e/gamma
bck rejection

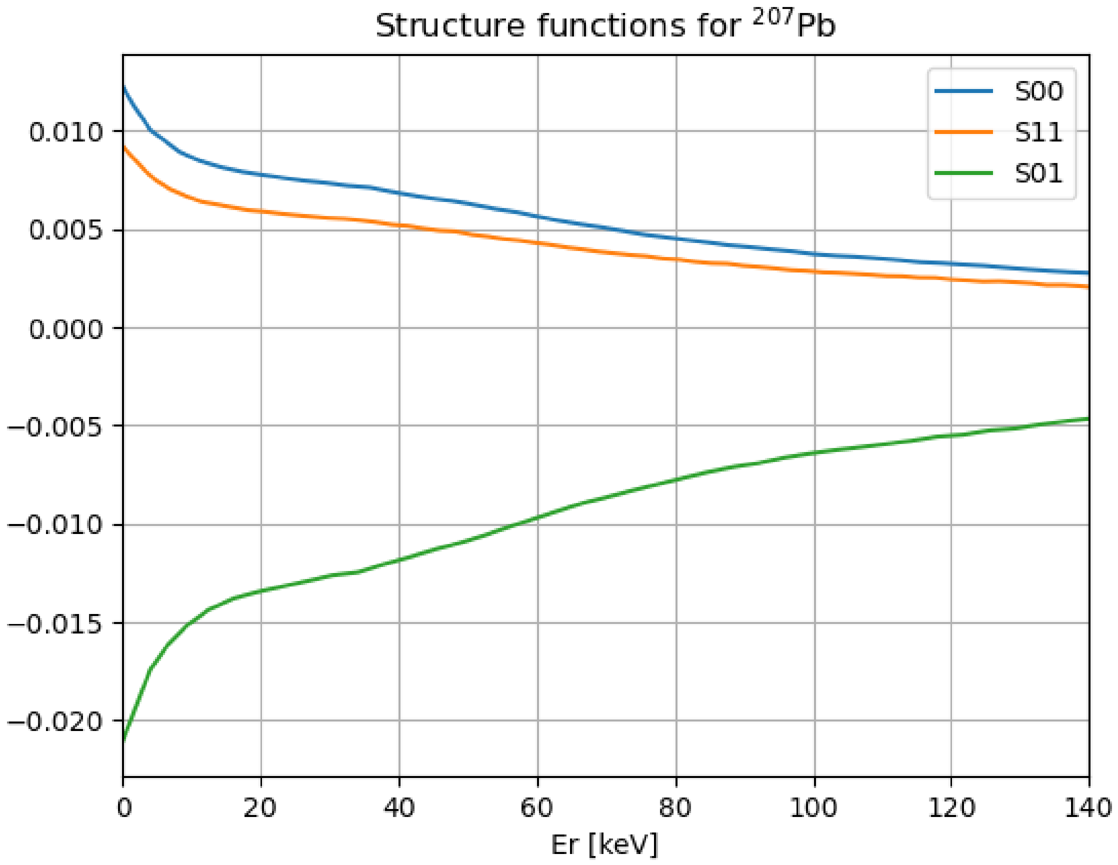


RES-NOVA Coll., *ArXiv:2501.12409*

Spin-dependent sensitivity

- ^{207}Pb has a natural abundance of 22.1% and it's a 2p1/2 neutron hole within the doubly magic ^{208}Pb
- It's heavy and has known SD structure function => good target for heavy DM

- ^{17}O has 0.037% of abundance
- It's light and no known SD structure fucntion => kinematically favored target for light DM

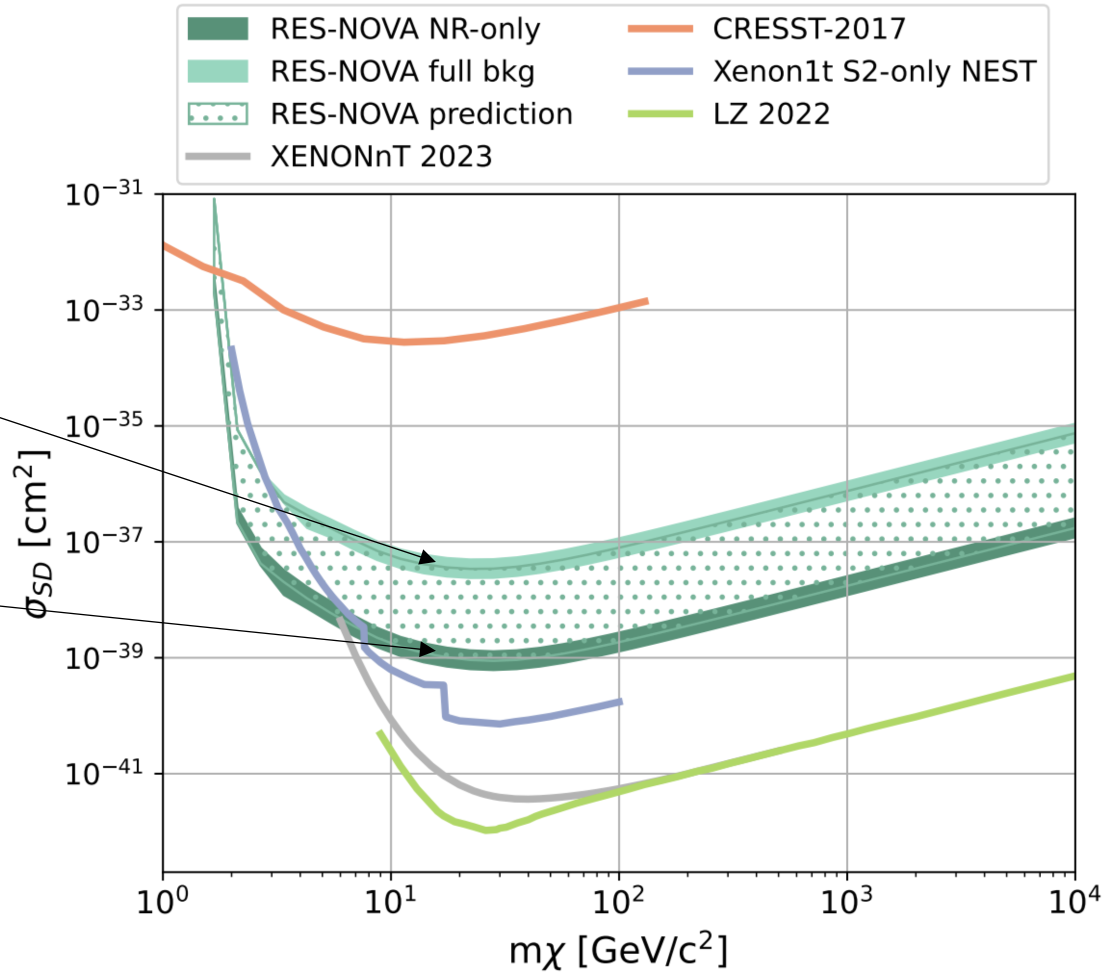


Kosmas, T. S. and Vergados, J. D. Cold dark matter in SUSY theories, 10.1103/PhysRevD.55.1752

Spin-dependent sensitivity

No bck rejection

Full e/gamma bck rejection



RES-NOVA Coll., *ArXiv:2501.12409*

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

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

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

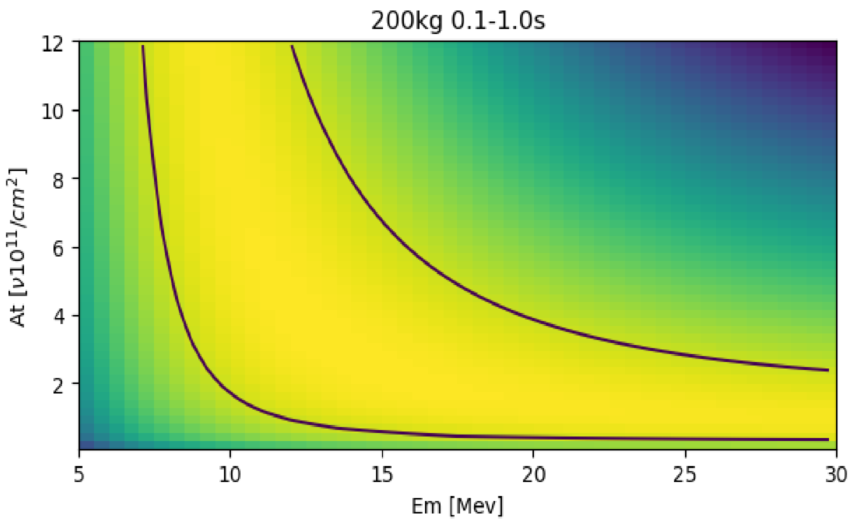
und

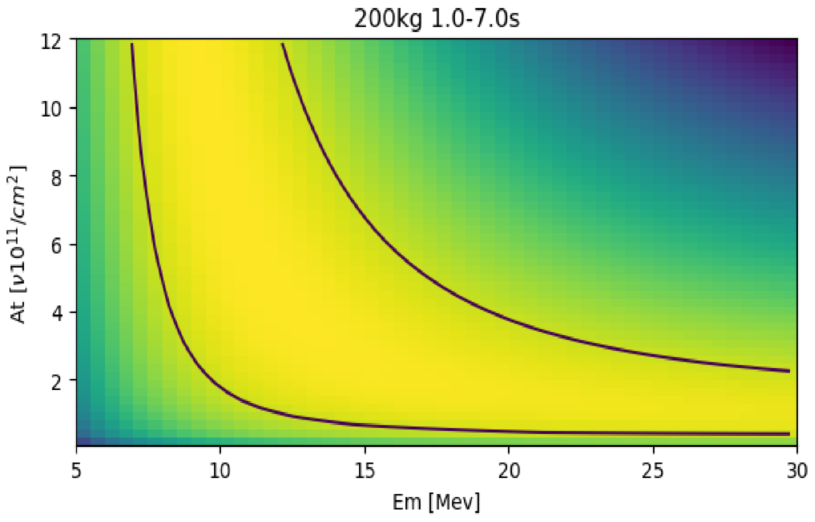
(64) $$pV = \frac{2N}{3} \cdot T.$$

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

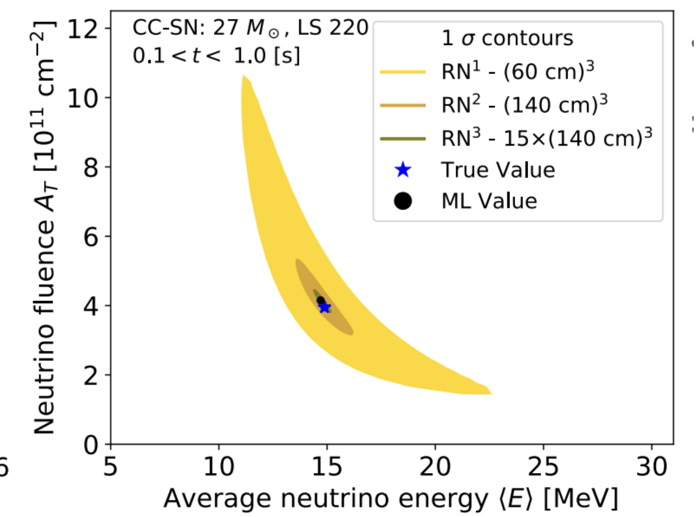
$$\int \frac{dQ}{T} = \frac{2}{3} N \cdot l(V \cdot T^{\frac{3}{2}}) + C.$$

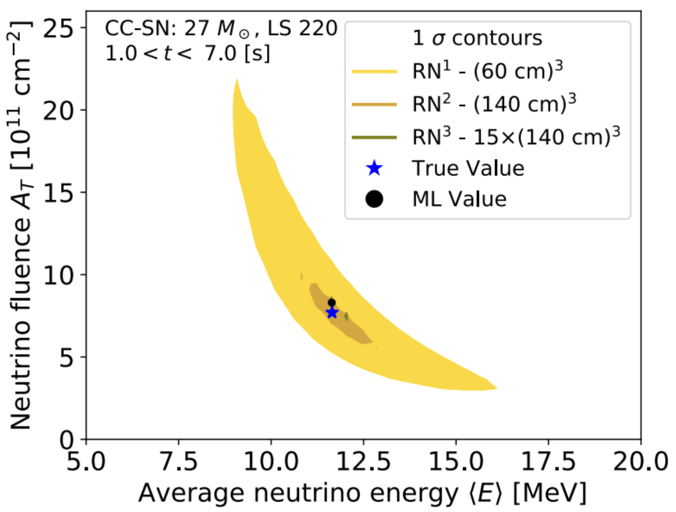
Constraining SN parameters





RN Demo
coming in the next
3-5 years



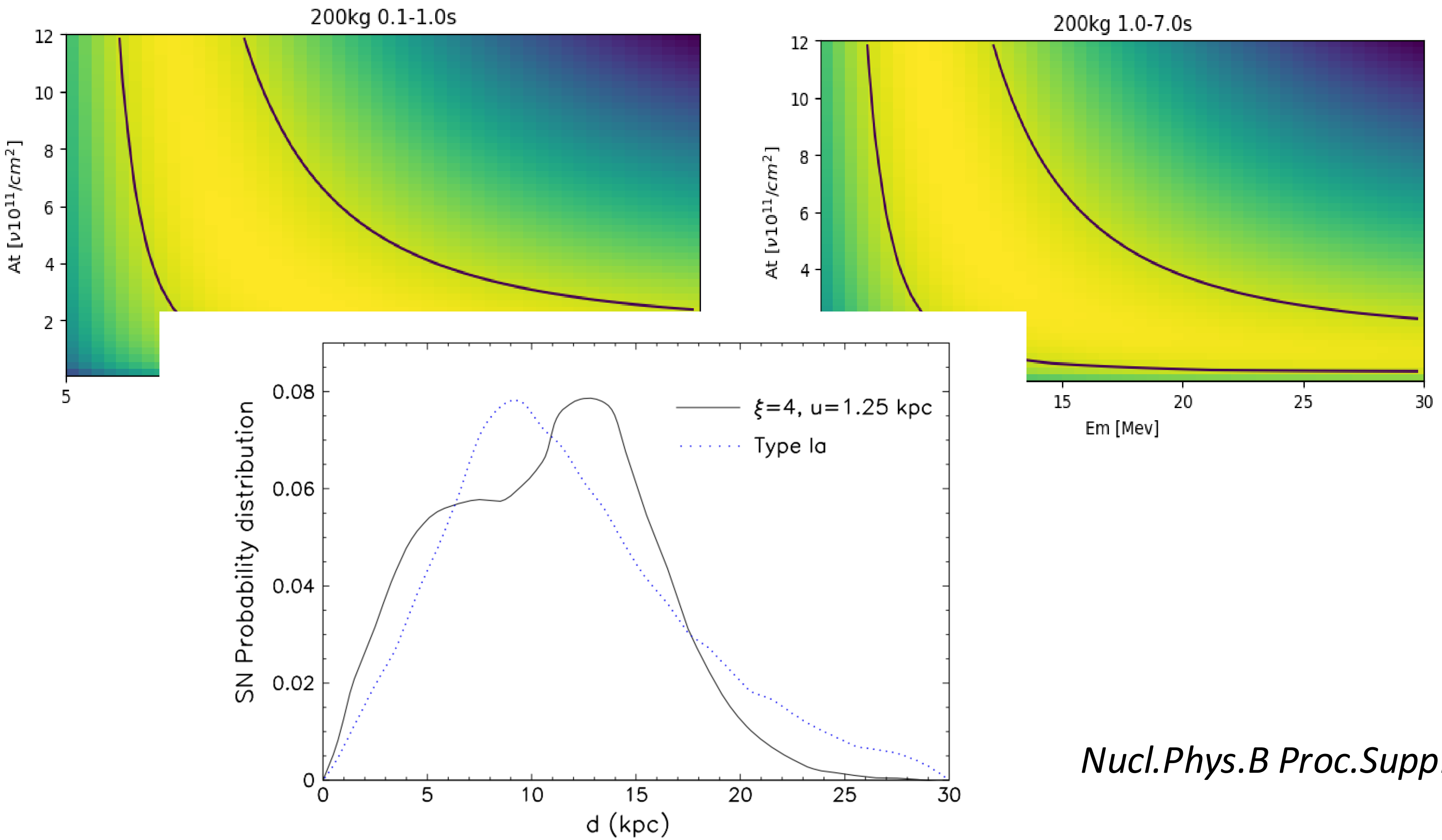


RN[1] 2.4t

RN[2] 31t

RN[3] 465t

Constraining SN parameters



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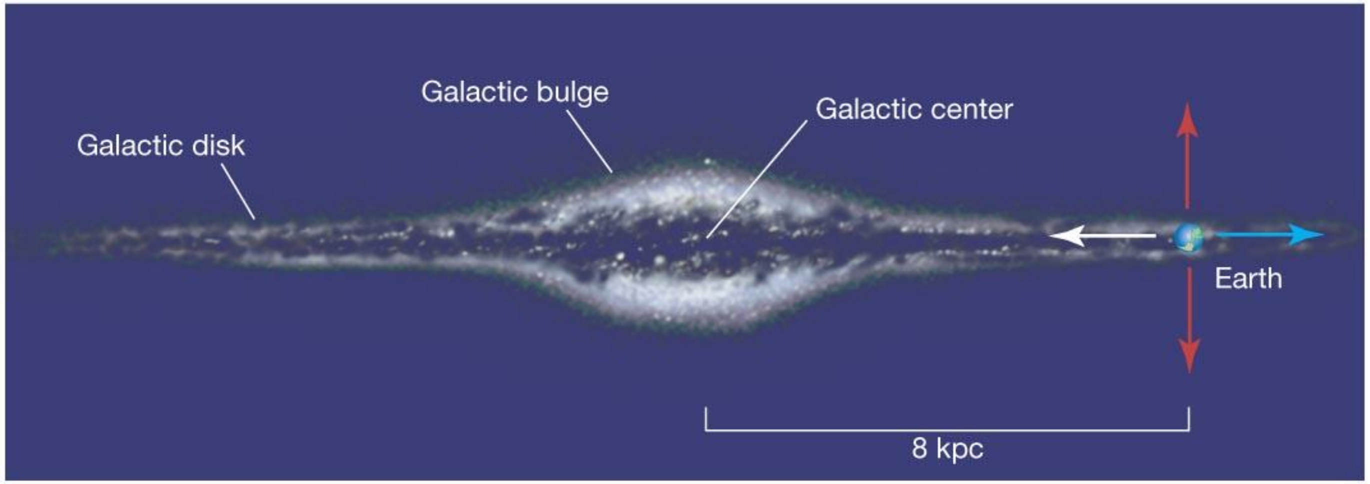
Nucl.Phys.B Proc.Suppl. 221 (2011) 218-229

Constraining SN parameters



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

RN Demo => probing 13 kpc

RN[1] 2.4t => probing more than 50 kpc

RN[2] 31t => more than 100kpc

RN[3] 465t => more than 1 Mpc

Conclusions

- The high sensitivity of cryogenic detectors opens the possibility to detect SN neutrinos with existing technologies
- Archaeo-Pb is a great candidate to detect SN neutrinos via CEνNS
- The cryogenic technology and the high density of Pb allows for a “miniaturized” detector
- RES-NOVA is pursuing a rich physics program and first exciting results are only a few years away

Thank you!