RES-NOVA

A revolutionary archaeological Pb observatory for astrophysical neutrino sources

Luca Pattavina
INFN - Laboratori Nazionali del Gran Sasso
Technical University of Munich

European Research Council
Established by the European Commission

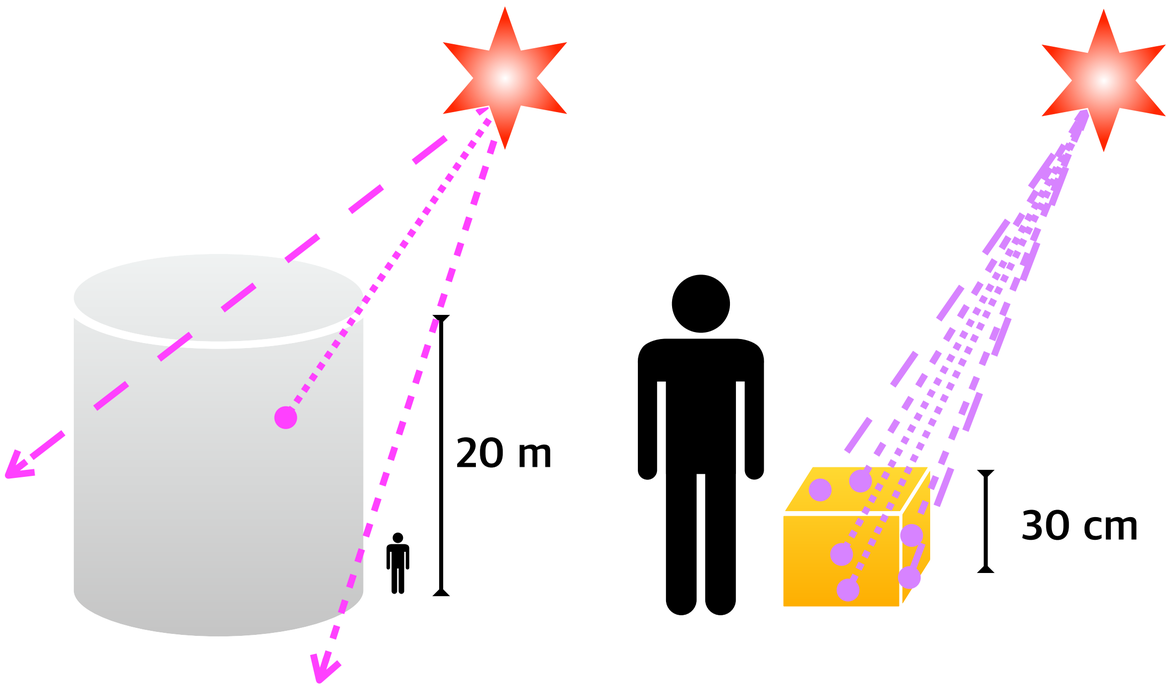
Technische Universität München

Modica - 13.07.2023 - Mayorana Workshop 2023

RES-NOVA IN ONE SLIDE

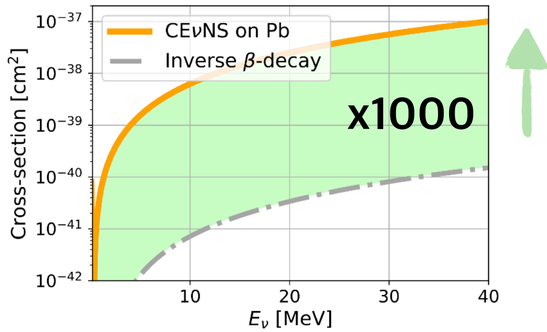
Detecting SuperNova neutrinos

1 SN / 50 years



using an innovative technology for high-statistic and flavor independent studies

Coherent neutrino-nucleus scattering on Pb



Archaeo-Pb-based neutrino telescope

Total detector volume (30 cm)³

Survey 90% of SN in Milky Way

Supernovae: cosmic fireworks

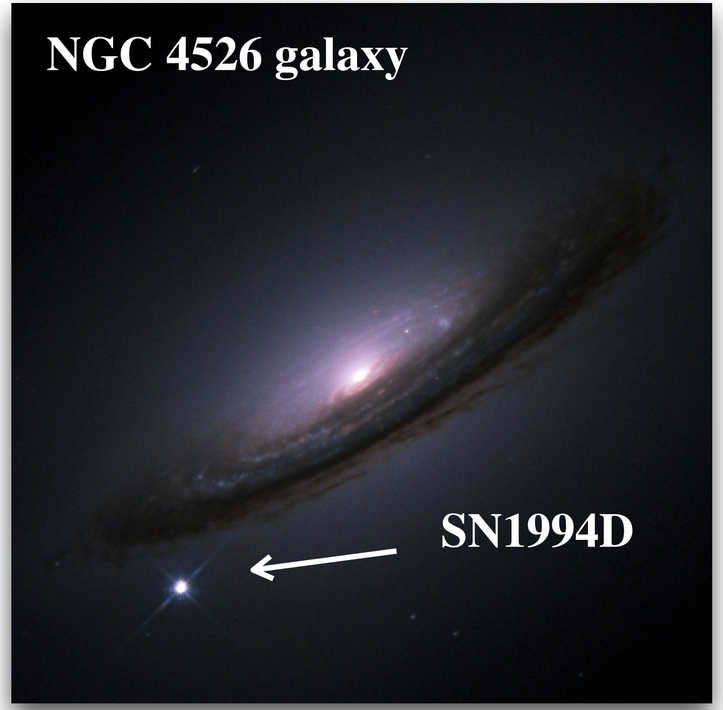
setting the stage

Supernovae (SN): high-energy **explosions of massive stars**

Almost total star binding energy converted into **all flavor-neutrinos**
but also **GW** and **EM** radiation

Neutrinos: direct **probes** and **messengers** of SNe hidden dynamics

Rare event: **1 observation** with underground instrumentation (1987)

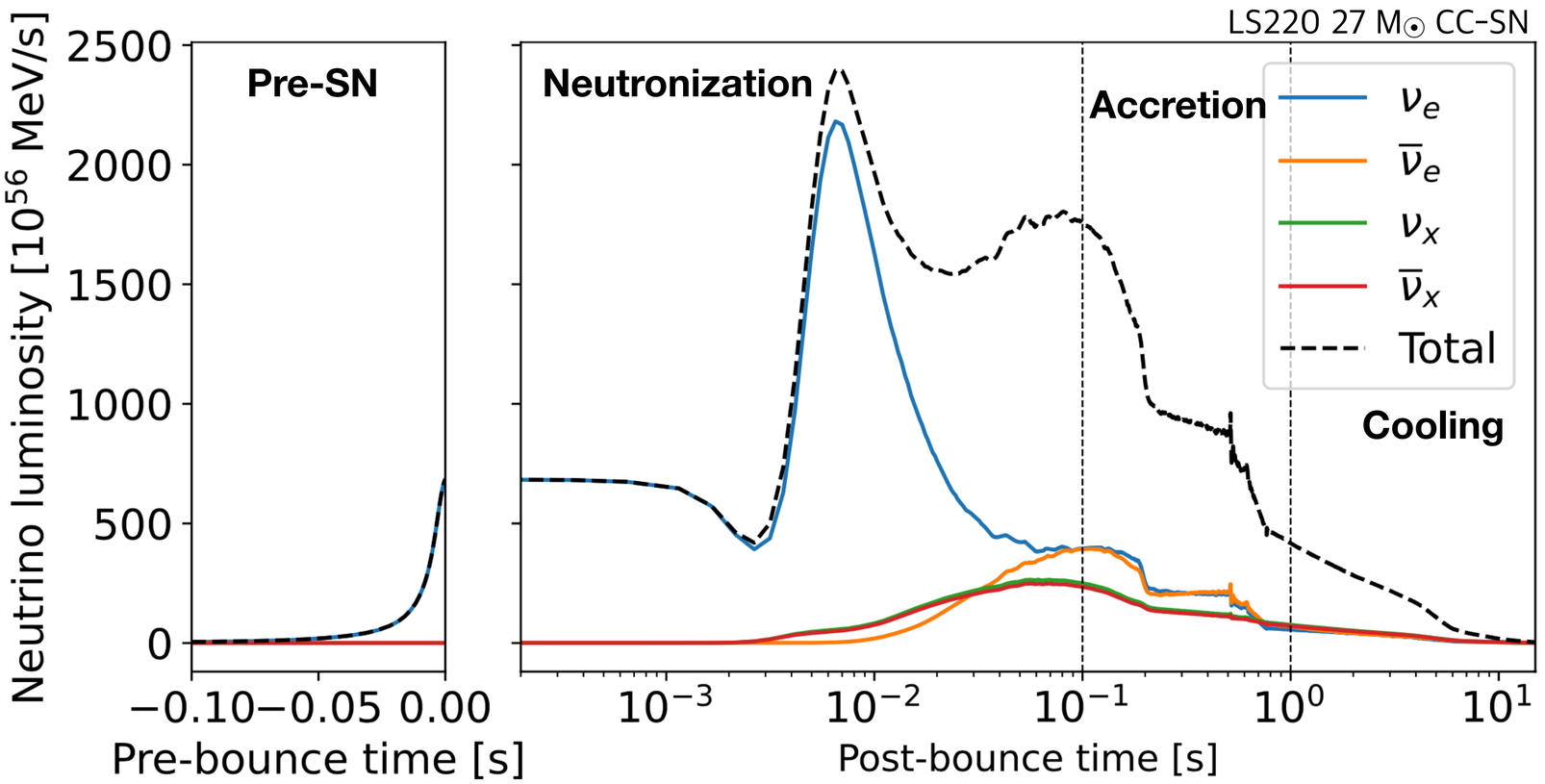


Credit: NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team

Neutrinos are emitted at all times

Unique neutrino signature

Neutrino transport simulation of a Core-Collapse SN



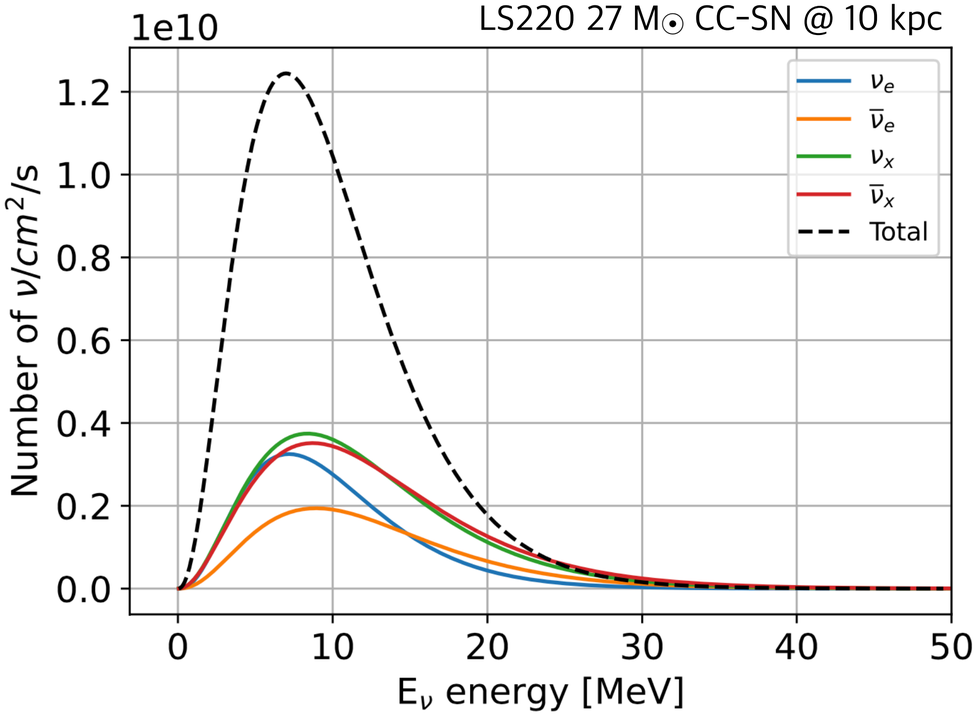
A. Mirizzi et al., Riv. Nuovo Cim.39, 1 (2016) [ArXiv:1508.00785]

Nota Bene: neutrino flavor oscillations not included

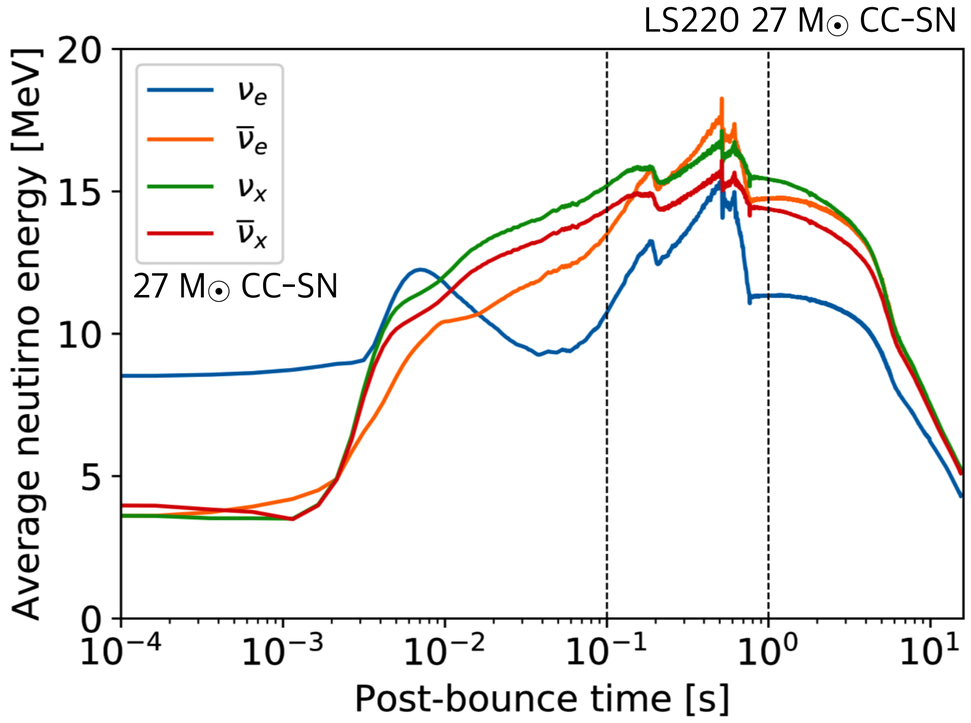
MPA Supernova Archive:
https://wwwmpa.mpa-garching.mpg.de/ccsnarchive

Supernova Neutrino signal

What is the average neutrino energy?



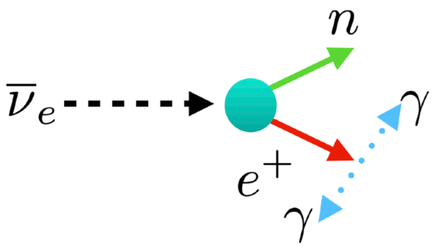
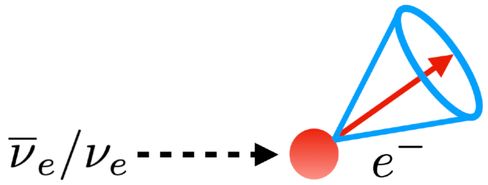
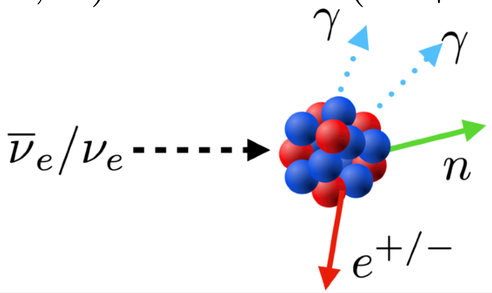
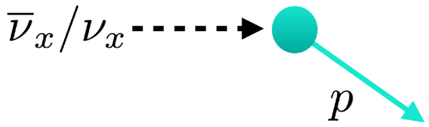
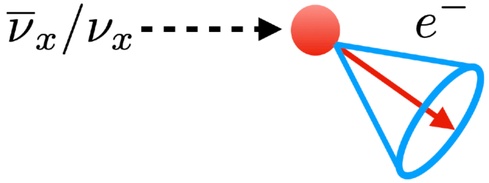
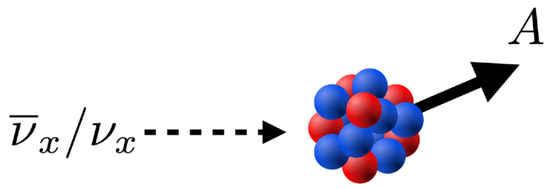
v_x is the most **intense** component of the flux



v_x is the most **energetic** component of the flux

Current SN neutrino detectors are mostly sensitive to anti-v_e/v_e

How do we detect SN neutrinos nowadays?

	PROTONS	ELECTRONS	NUCLEI
CHARGE CURRENT	**Inverse beta decay** $\overline{\nu}_e + p \rightarrow e^+ + n$ 	**Elastic scattering** $\nu + e^- \rightarrow \nu + e^-$ 	**Inelastic scattering** $\nu_e/\overline{\nu}_e + (N, Z) \rightarrow e^{-/+} + (N \mp 1, Z \pm 1)$ 
NEUTRAL CURRENT	**Elastic scattering** $\overline{\nu}_x/\nu_x + p \rightarrow \overline{\nu}_x/\nu_x + p$ 		**Coherent Elastic neutrino-nucleus scattering (CEvNS)** $\overline{\nu}_x/\nu_x + A \rightarrow \overline{\nu}_x/\nu_x + A$ 

From 1987 to nowadays

How do we detect SN neutrinos nowadays?

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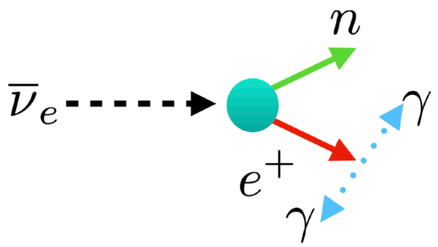
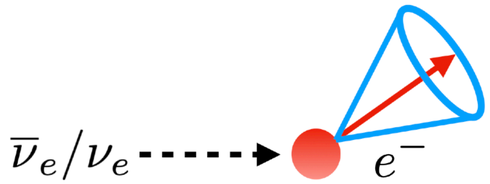
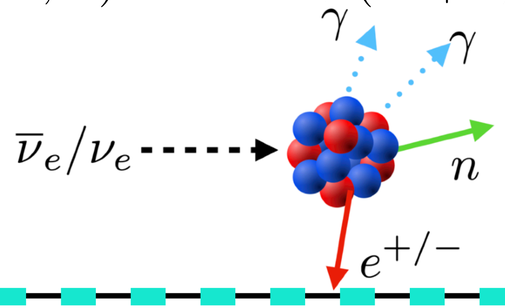
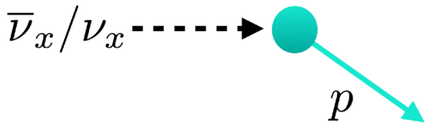
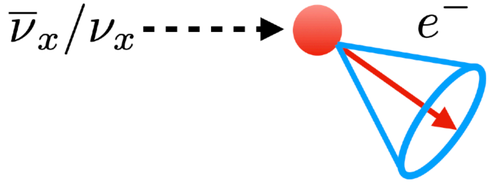
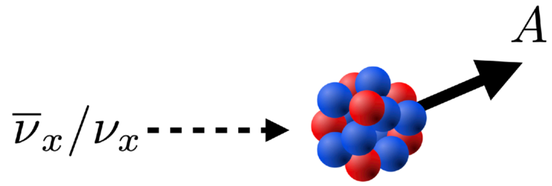
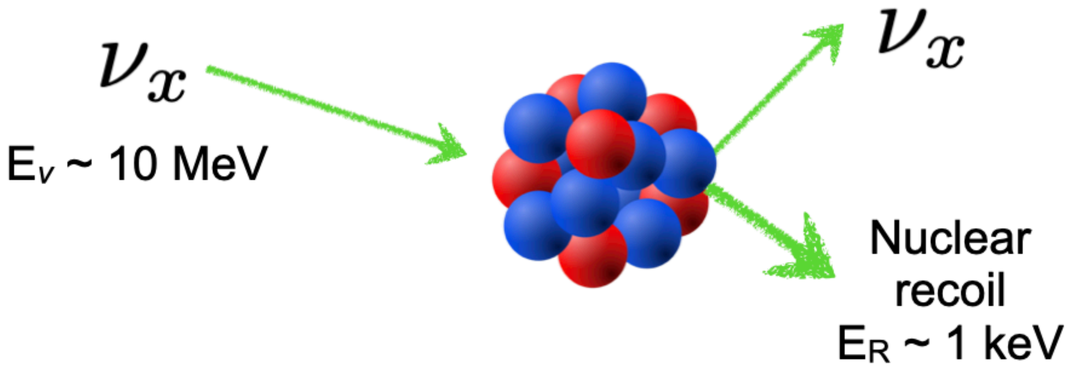
CHARGE CURRENT	**Inverse beta decay** $\overline{\nu}_e + p \rightarrow e^+ + n$ 	**Elastic scattering** $\nu + e^- \rightarrow \nu + e^-$ 	**Inelastic scattering** $\nu_e/\overline{\nu}_e + (N, Z) \rightarrow e^{-/+} + (N \mp 1, Z \pm 1)$ 
NEUTRAL CURRENT	**Elastic scattering** $\overline{\nu}_x/\nu_x + p \rightarrow \overline{\nu}_x/\nu_x + p$ 		**Coherent Elastic neutrino-nucleus scattering (CEvNS)** $\overline{\nu}_x/\nu_x + A \rightarrow \overline{\nu}_x/\nu_x + A$ 

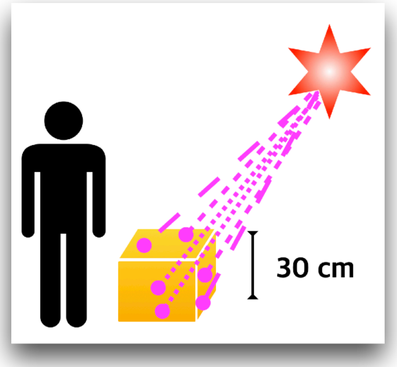
Since 2017

COHERENT Coll., *Science* 357 (2017) 6356, 1123

All neutrino flavors are detected

Coherent neutrino-nucleus scattering





> Equally sensitive to all ν-flavors

> High interaction cross-section

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

cross-section

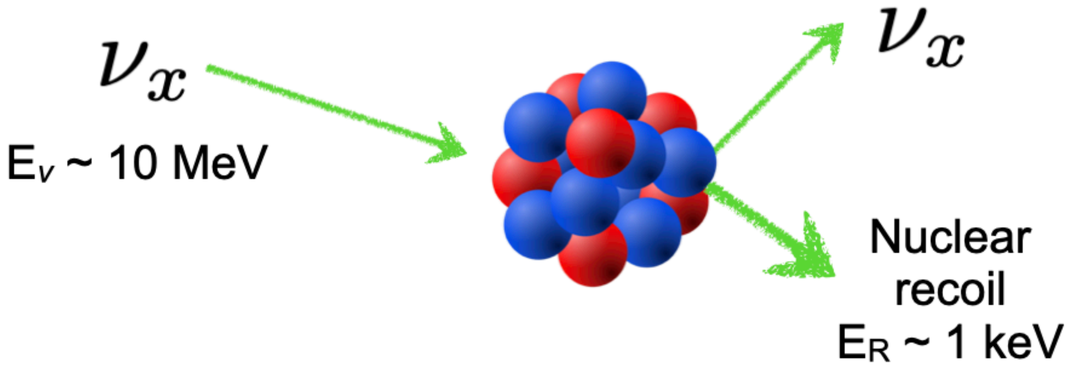
Nuclear Form factor

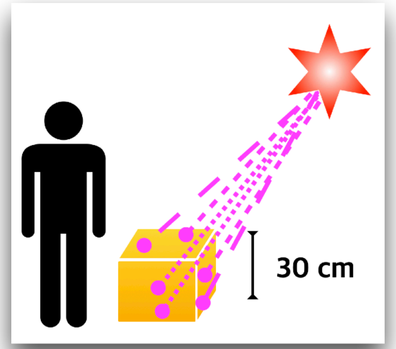
Neutrino energy

Weak nuclear charge

All neutrino flavors are detected

Coherent neutrino-nucleus scattering





> Equally sensitive to all ν-flavors

> High interaction cross-section

$$Q_W = N - Z(1 - 4\sin^2\theta_W)$$

~5%

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

cross-section

Nuclear Form factor

Neutrino energy

Weak nuclear charge

* Spin 0 interaction

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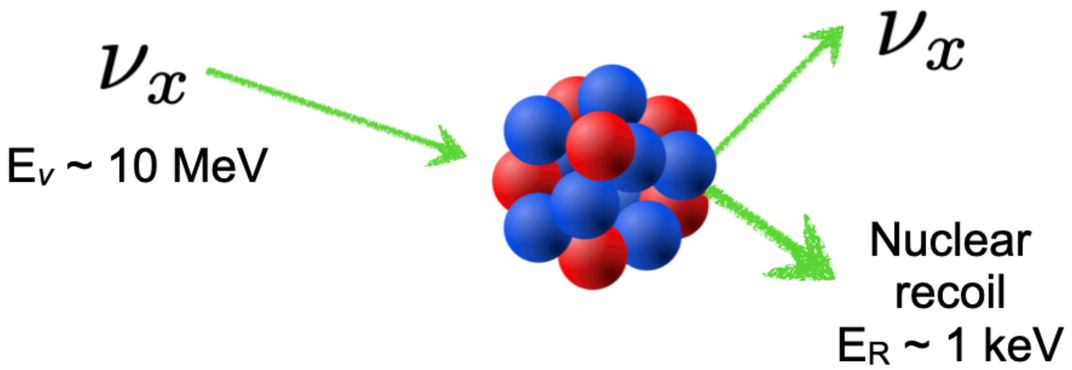

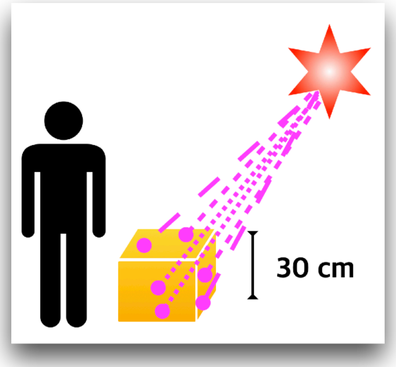

> Equally sensitive to all ν-flavors

> High interaction cross-section

$$\sigma_{CE\nu NS} \propto N^2$$

cross-section

Neutron number

All neutrino flavors are detected

Coherent neutrino-nucleus scattering

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cross-section

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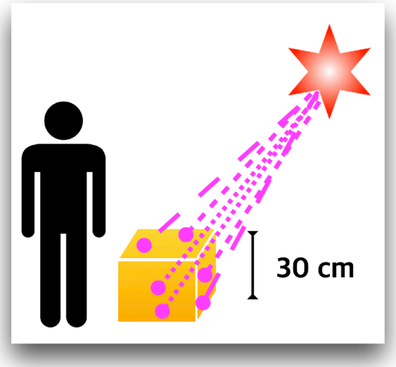

Pb ideal target

Highest neutron number

Highest nuclear stability

* Nuclear Weak Form Factor measured!

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cross-section

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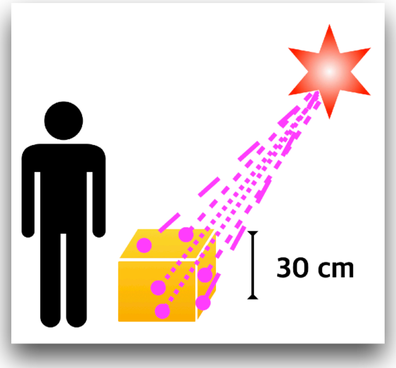

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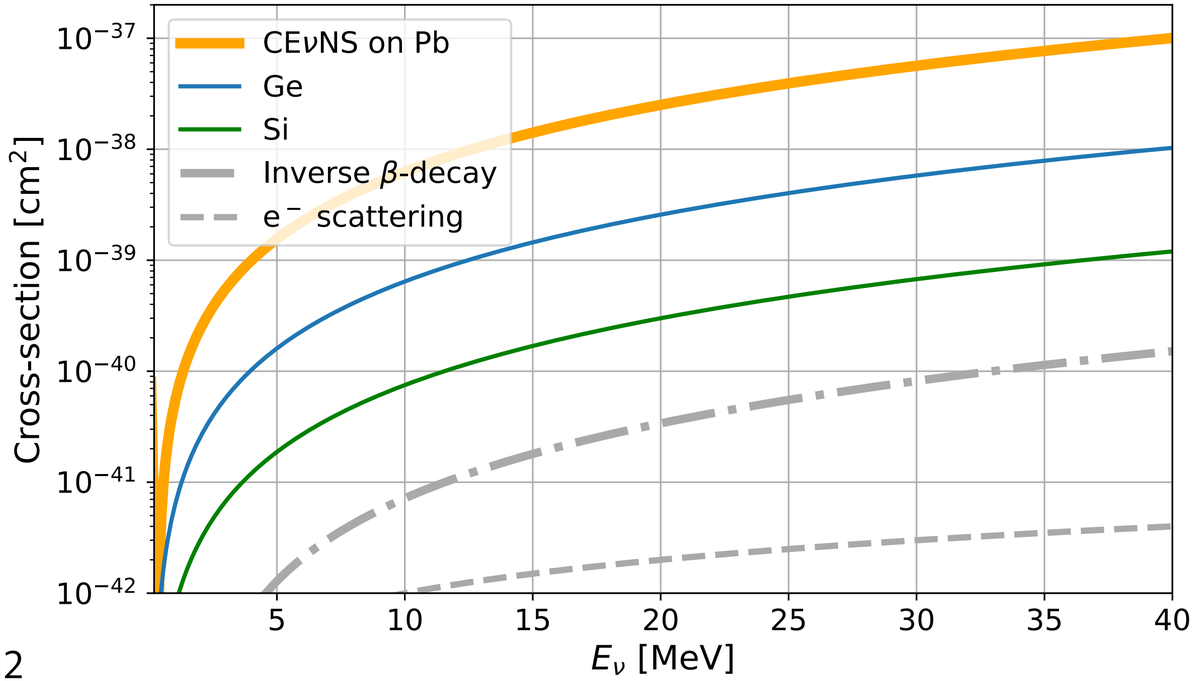

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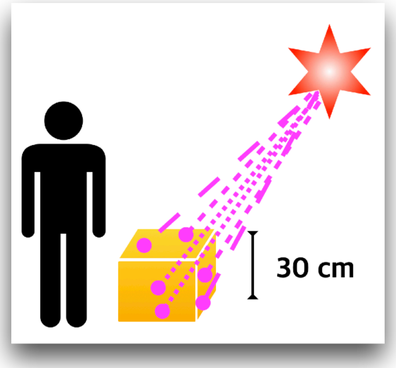

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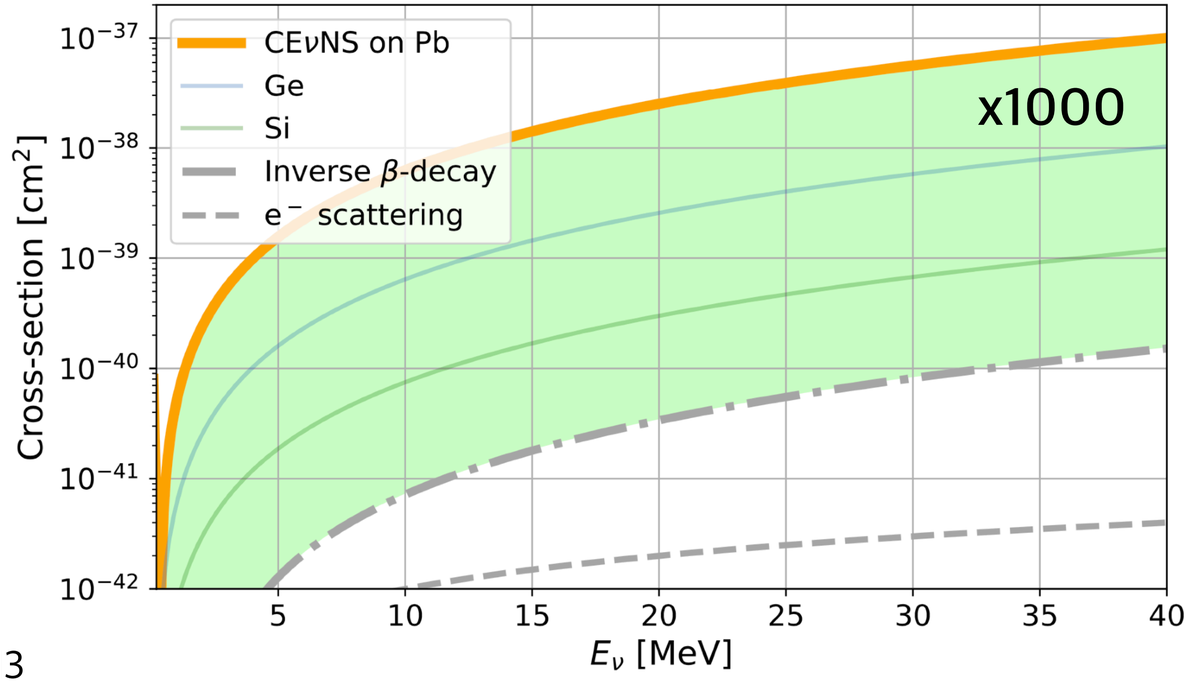

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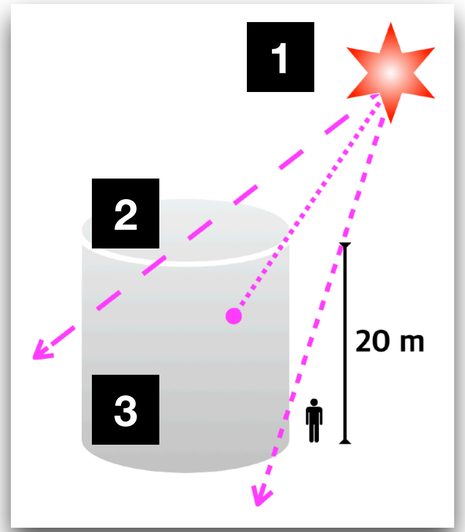
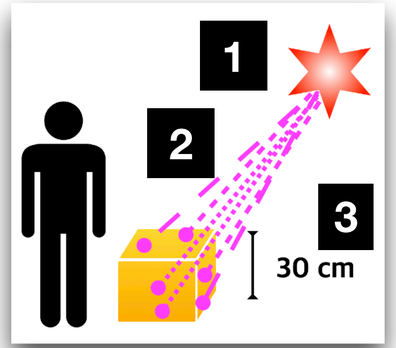


Status quo:

1. detection of ~1/6 SN flux
2. small cross-section
3. large volume detectors

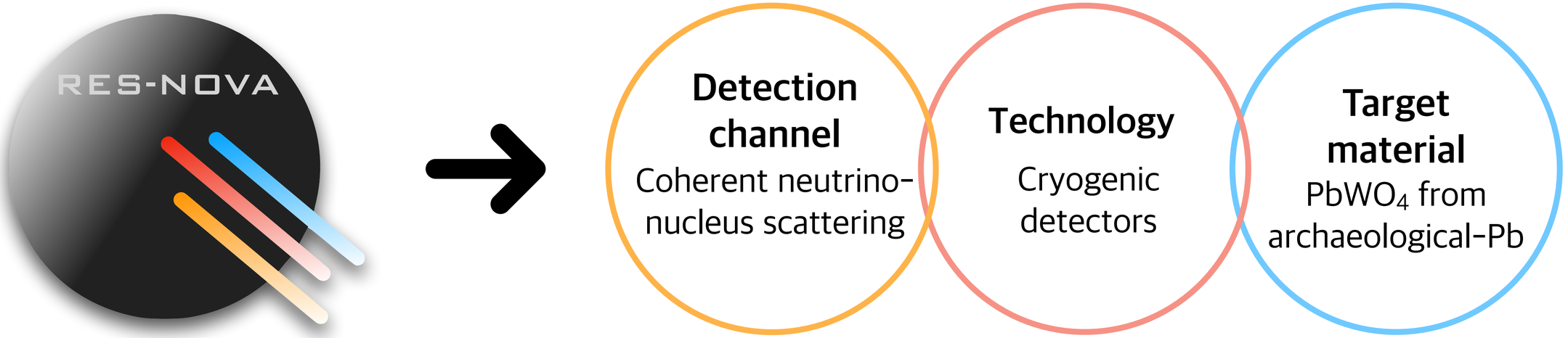


Opportunities:

1. detection of full SN ν flux
2. highest cross-section
3. cm-scale ν telescope

RES-NOVA gives unique insights into SNe

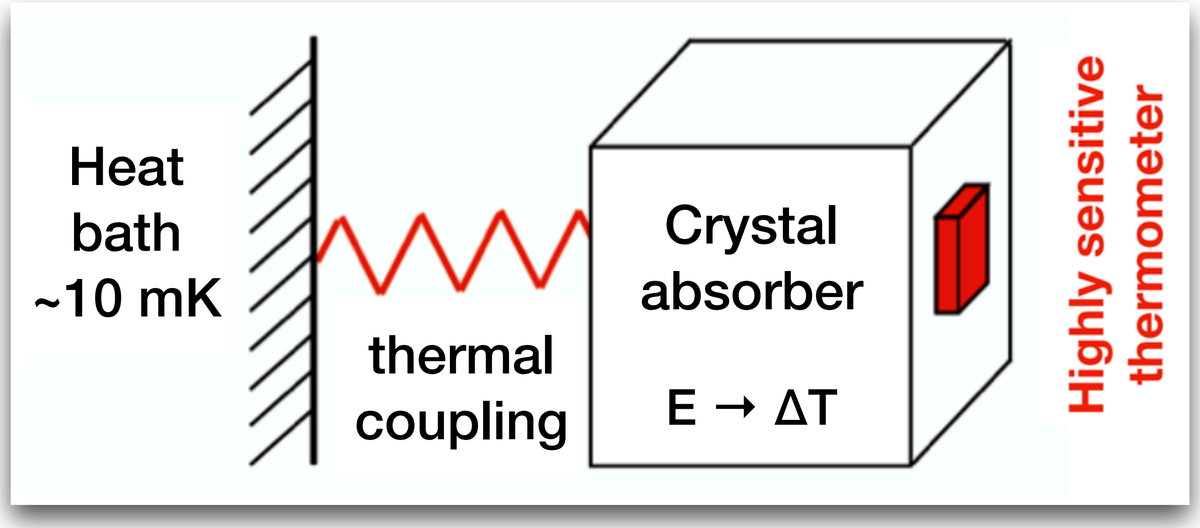
Innovative experimental approach



RES-NOVA detector technology

Advanced Cryogenic Detectors

Cryogenic detectors made from Pb



↑ Wide choice of compounds

↑ Easily scalable technology (modularity)

↑ Excellent energy resolution/threshold

⬇ Fully active detectors ➞ low background

⬇ slow signals ➞ underground installation

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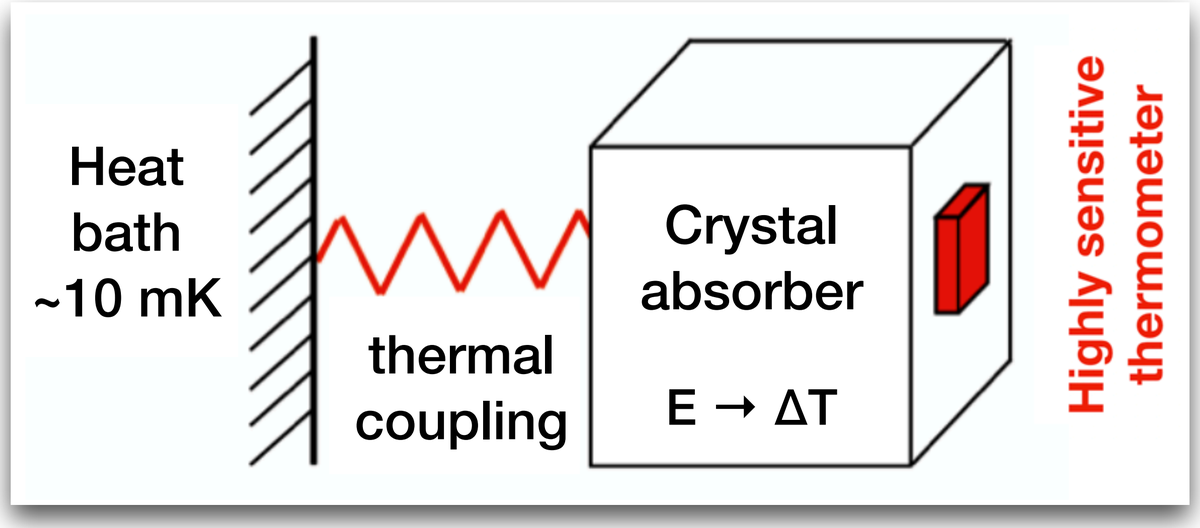

A bolometer is a highly sensitive calorimeter operated @ cryogenic temperature (~10 mK).

Energy deposits are measured as temperature variations of the absorber.

C ~ O(pJ/K) ~ O(keV/μK)

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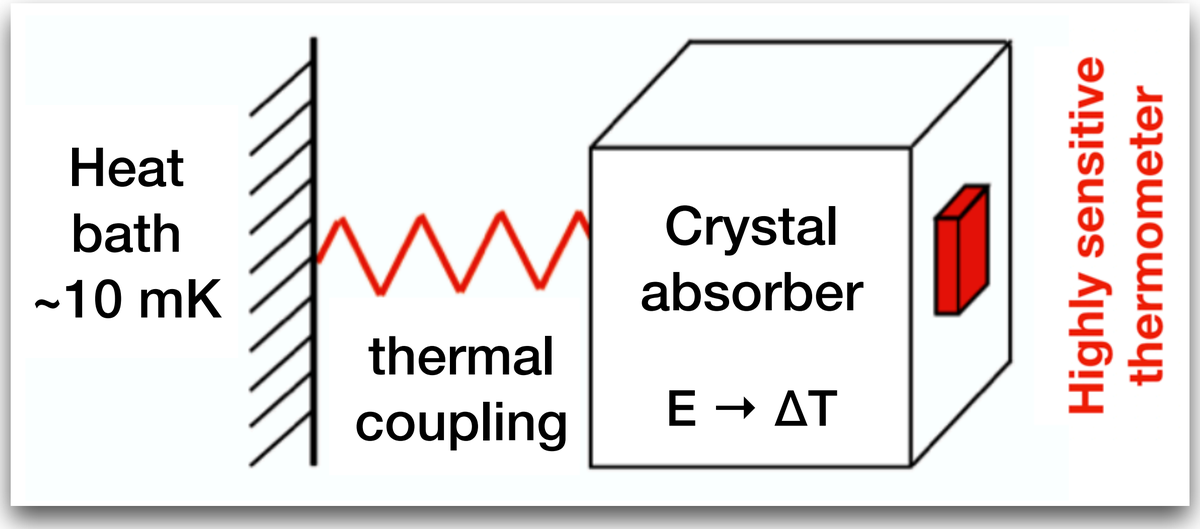
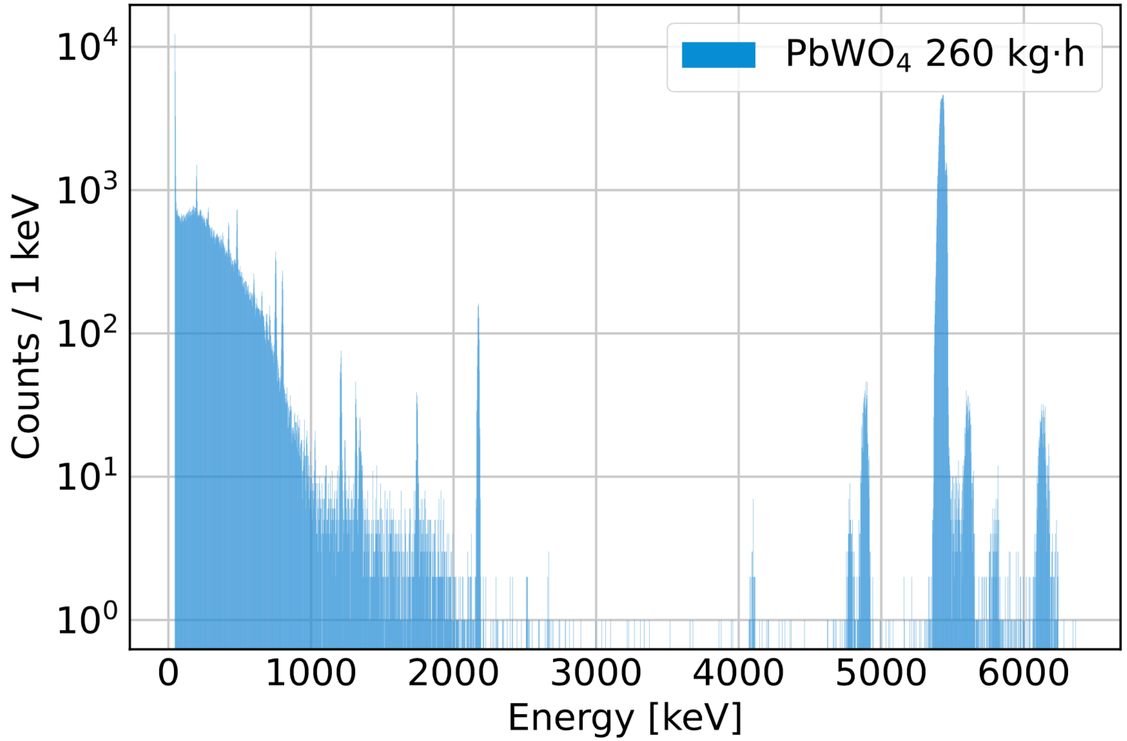


Cryogenic measurement of commercial $PbWO_4$



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

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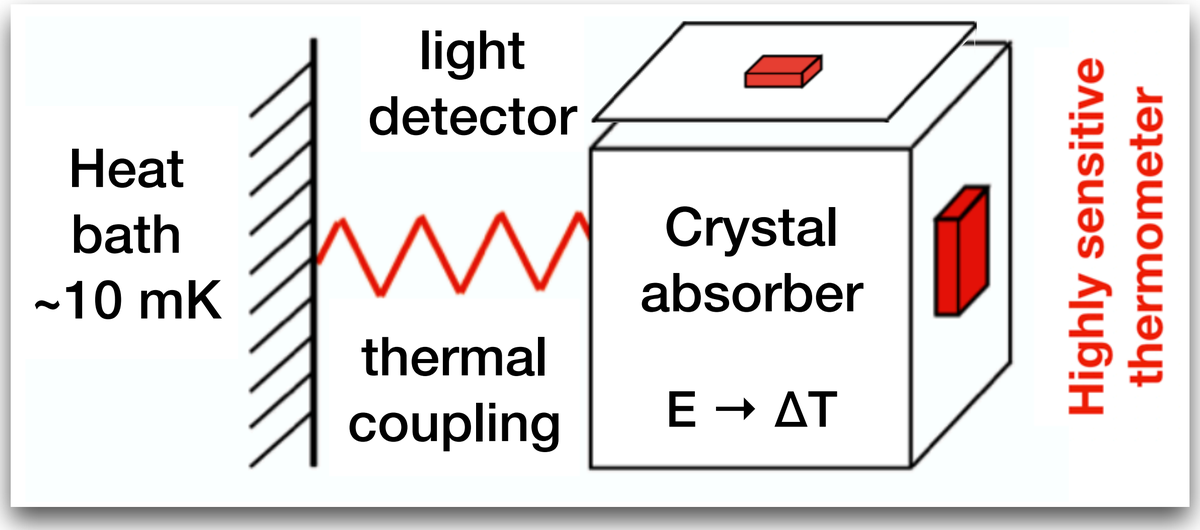

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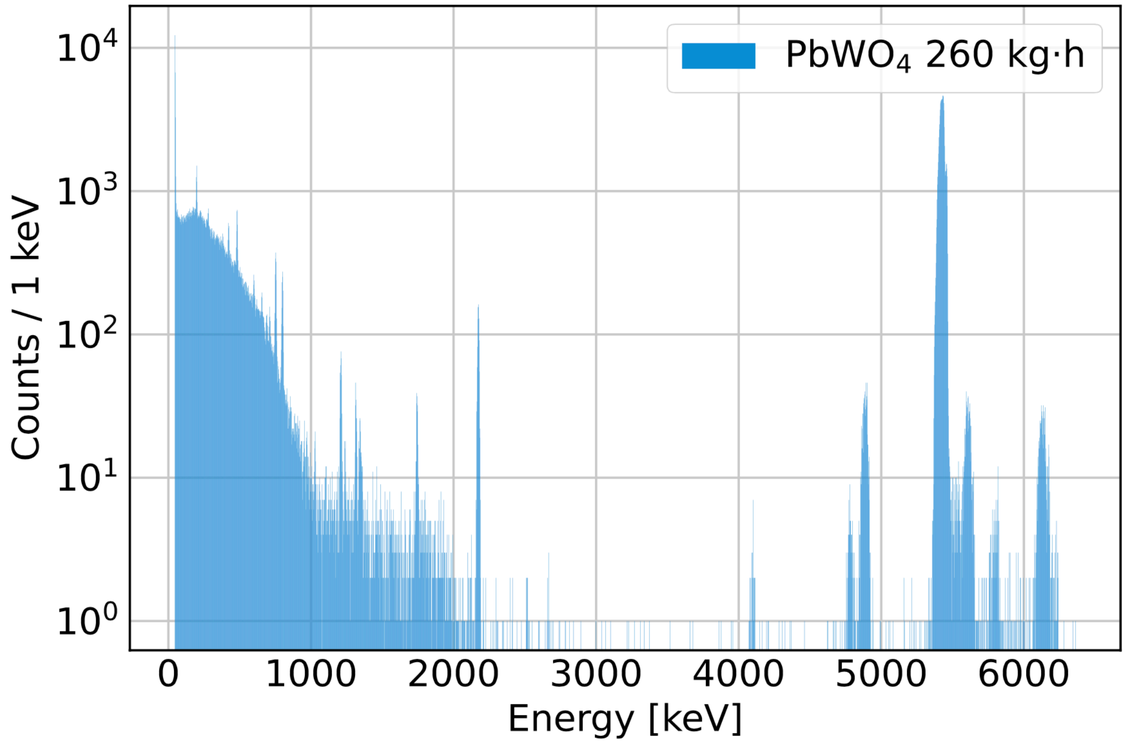

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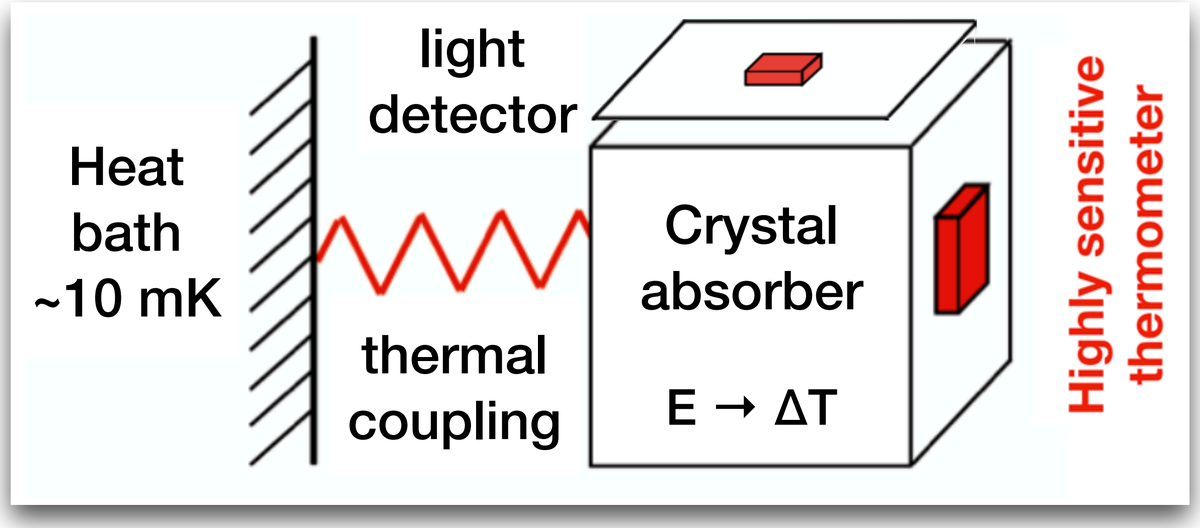

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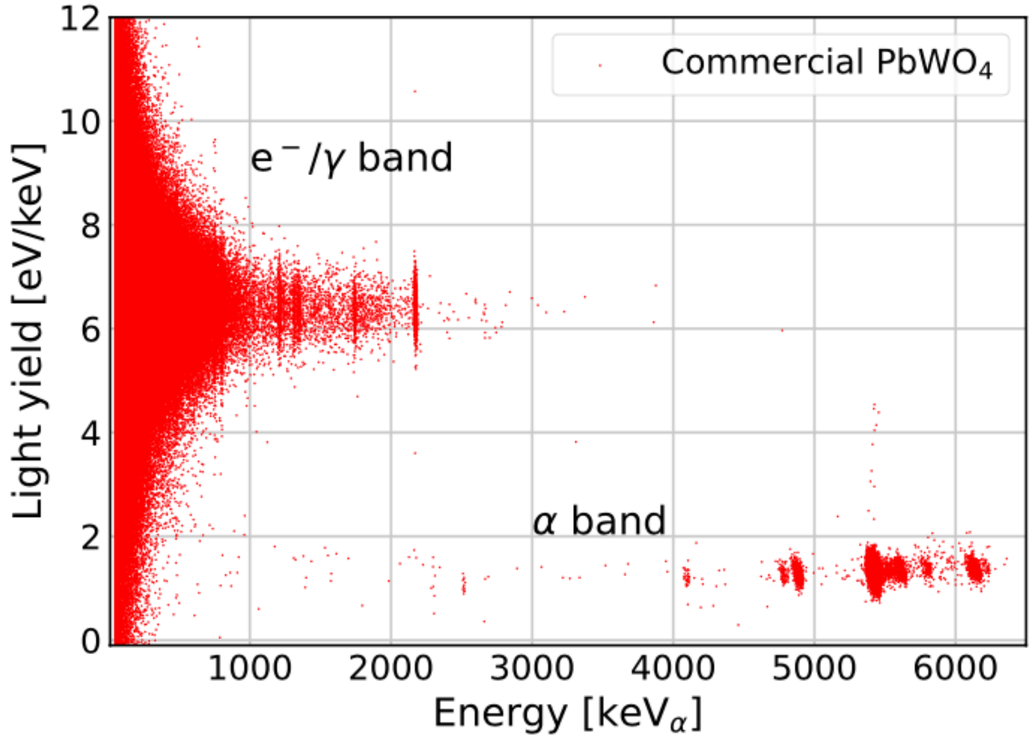

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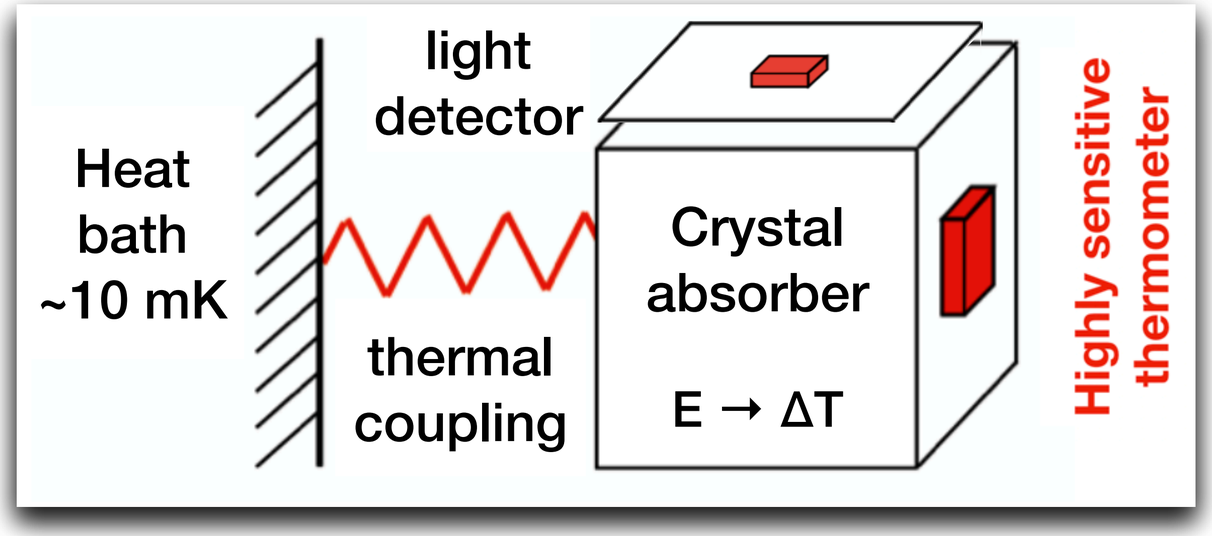

High-radiopurity crystal

$PbWO_4$ crystals

Low-background neutrinoless double-beta decay technology

Thermometer at mK

Transition Edge Sensor

Low-threshold Dark Matter technology

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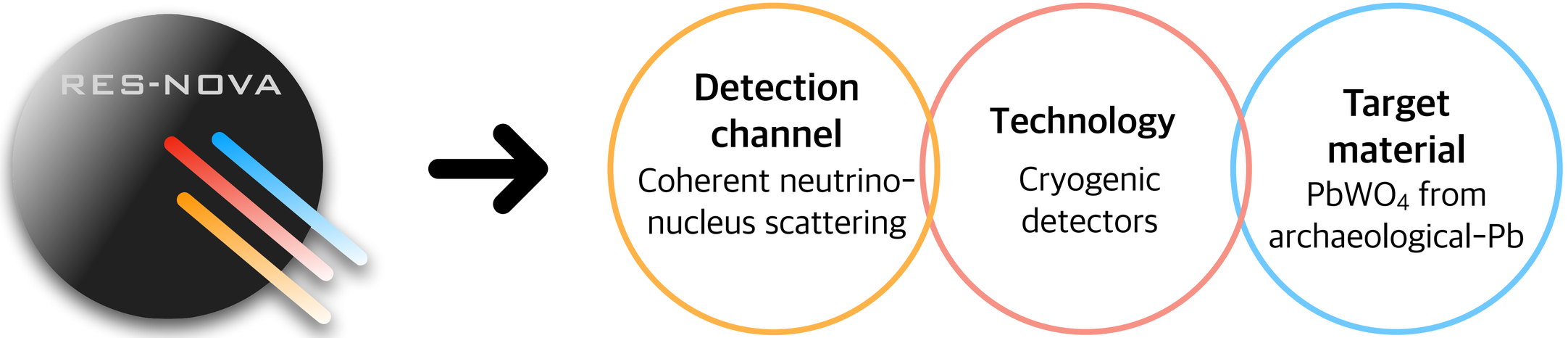
Innovative experimental approach



Why not Low-background Pb ?

Low-background/Commercial Pb: high **^{210}Pb** concentration (Q_{β^-}-value: 63 keV, $T_{1/2}$= 22.3 y)

Archaeological Pb is "old enough" (e.g. Roman Pb) to ensure a negligible ^{210}Pb concentration

Nuclide	Low background Pb (Boliden®) [1]	Archaeological Pb [2, 3]
^{232}Th	<46 μBq/kg	<45 μBq/kg
^{238}U	<31 μBq/kg	<46 μBq/kg
^{210}Pb	$(2.3\pm0.4)\cdot 10^7$ μBq/kg	<715 μBq/kg

from passive material to active detector component

Archaeological Pb-based detectors

[1] G. Heusser, Ann. Rev. Nucl. Part. Sci. 45 (1995) 543-590.
[2] L. Pattavina et al., Eur. Phys. J. A (2019) 55: 127.
[3] CUORE Coll., Eur. Phys. J. C (2017) 77: 543.

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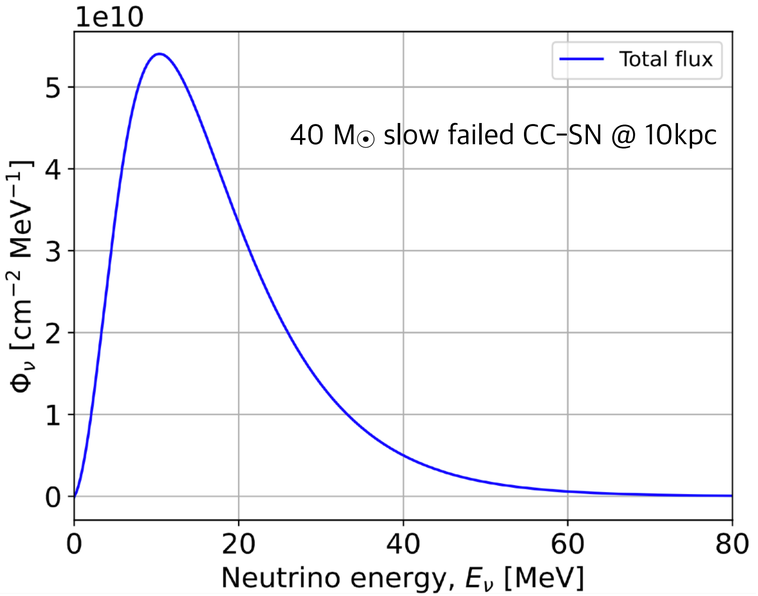
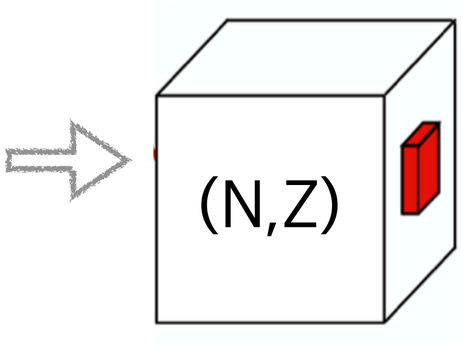
Is Pb the best target for SN neutrinos

let's have a look at the periodic table

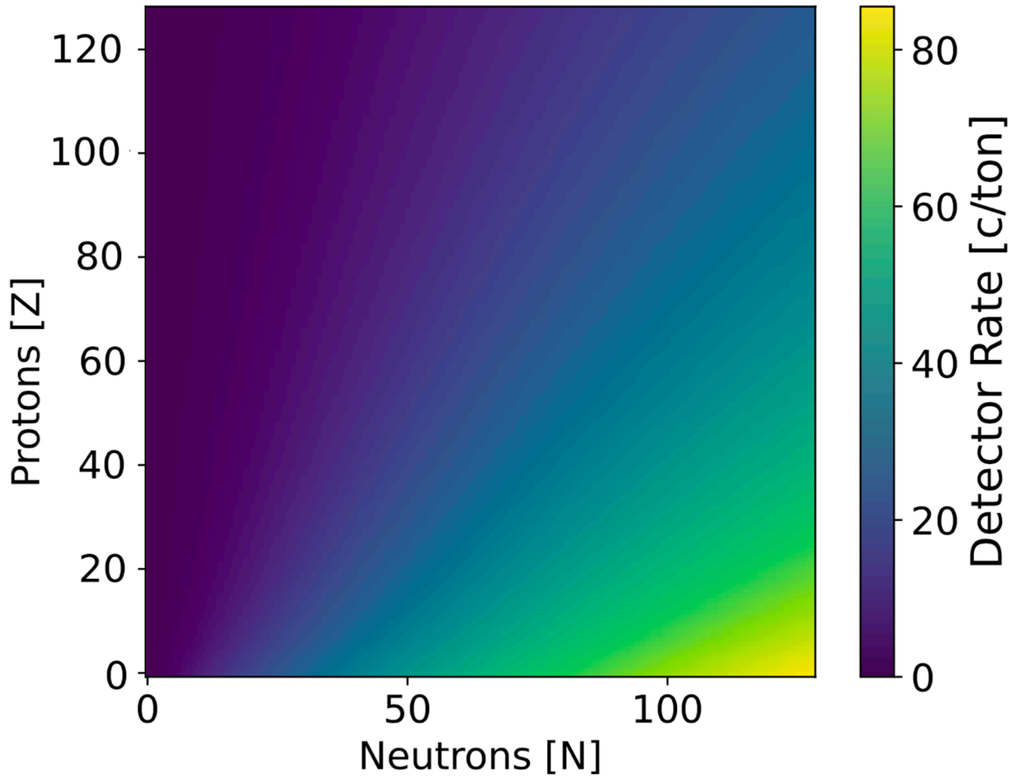
SN neutrino **source**



Cryogenic **detector**



Detector **counting rate** for E_{th} = 1 keV



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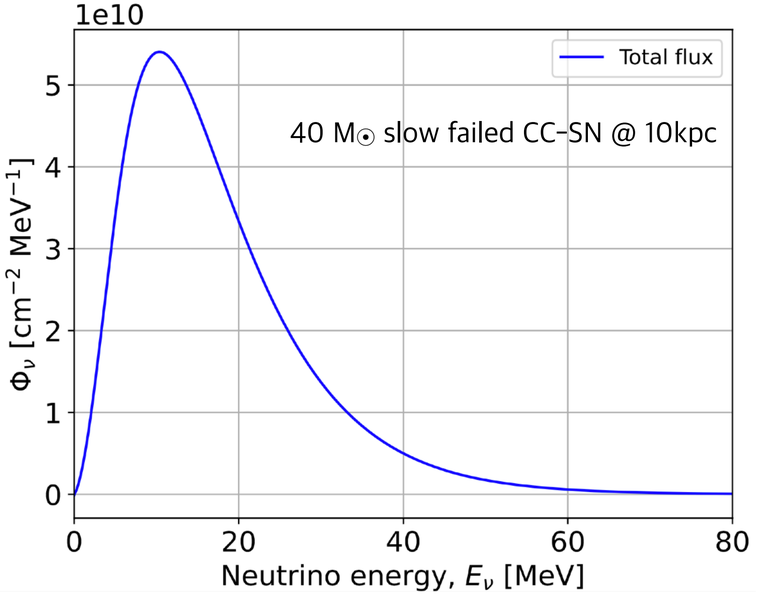
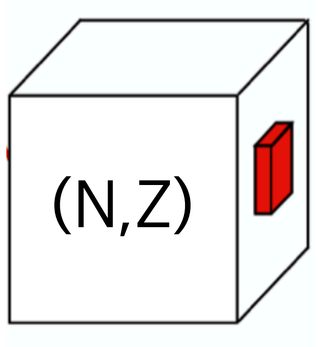
let's have a look at the periodic table

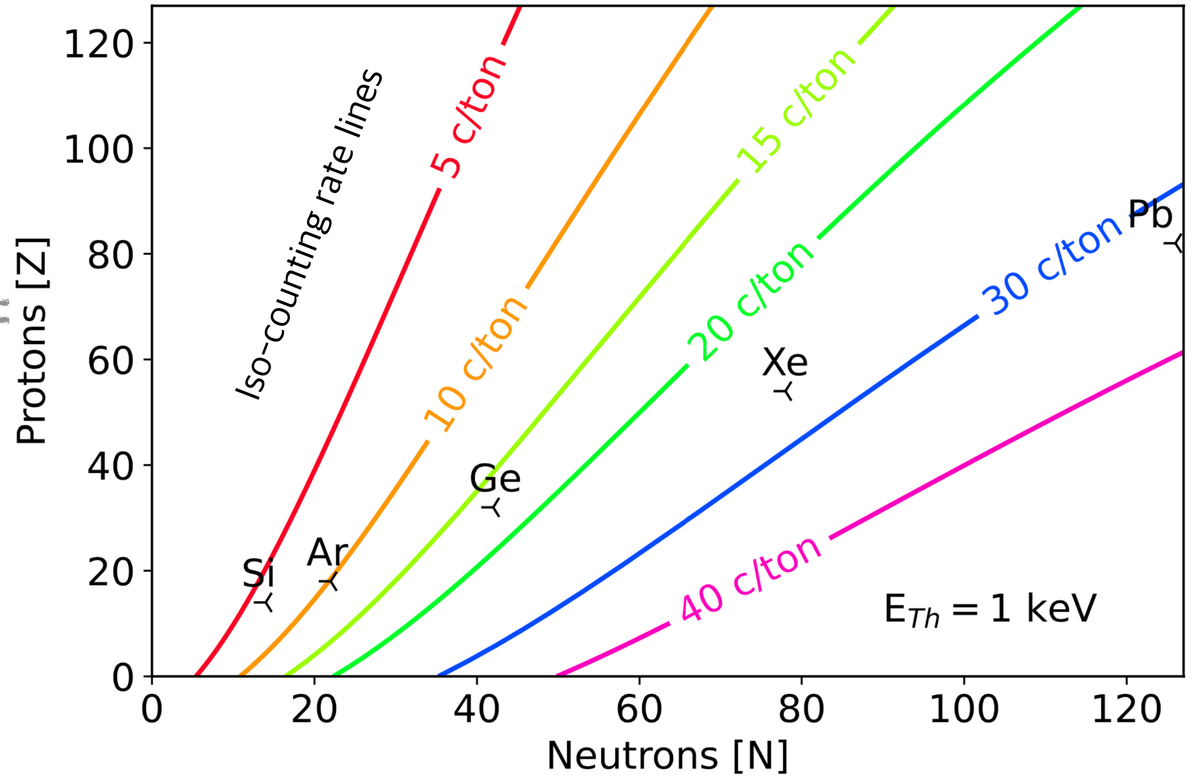
SN neutrino **source**



Cryogenic **detector**

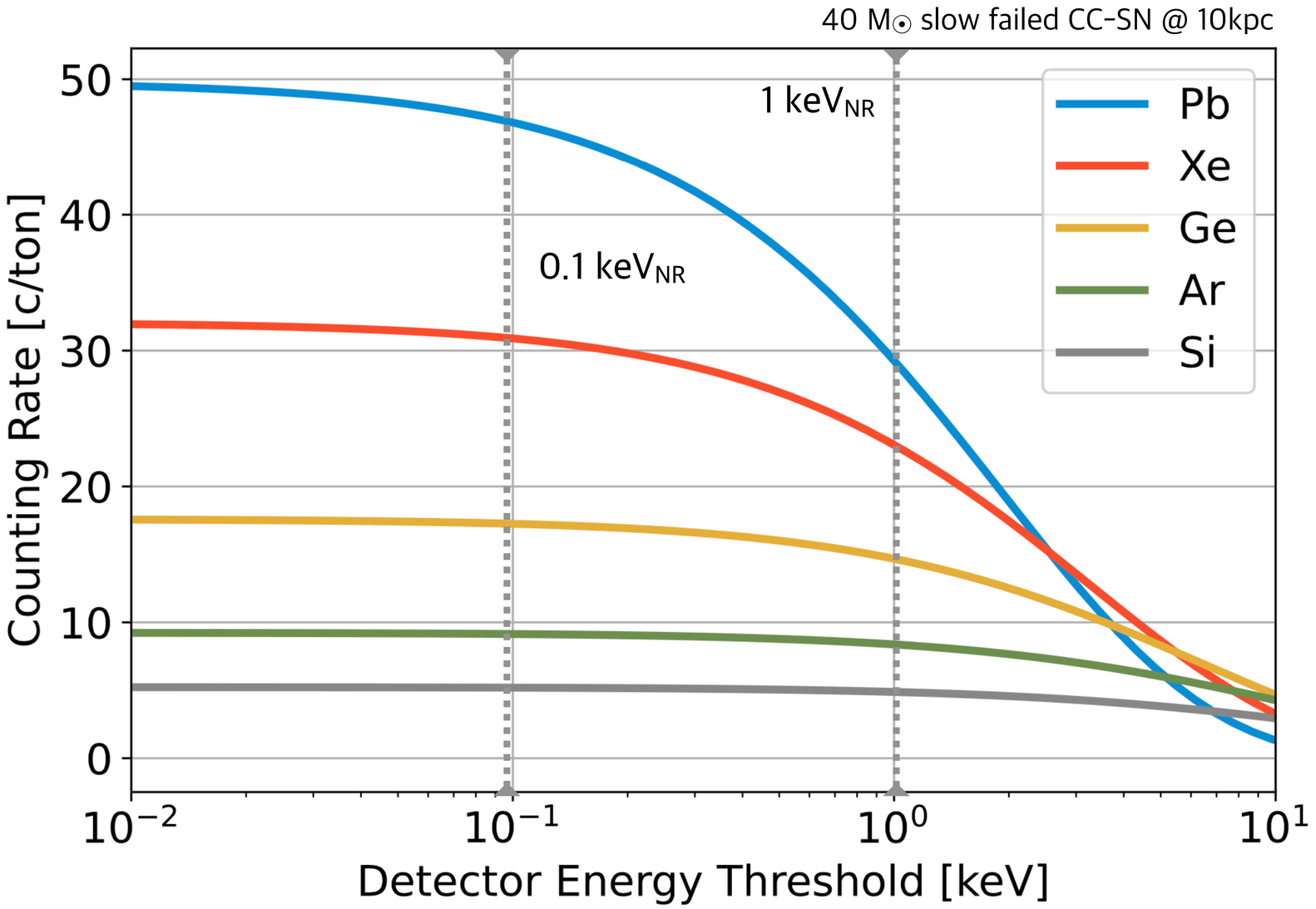


Detector **counting rate** for E_{th} = 1 keV



How low should the threshold be ?

ultra-low energy threshold are not needed



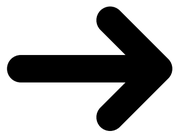
Lower threshold is beneficial

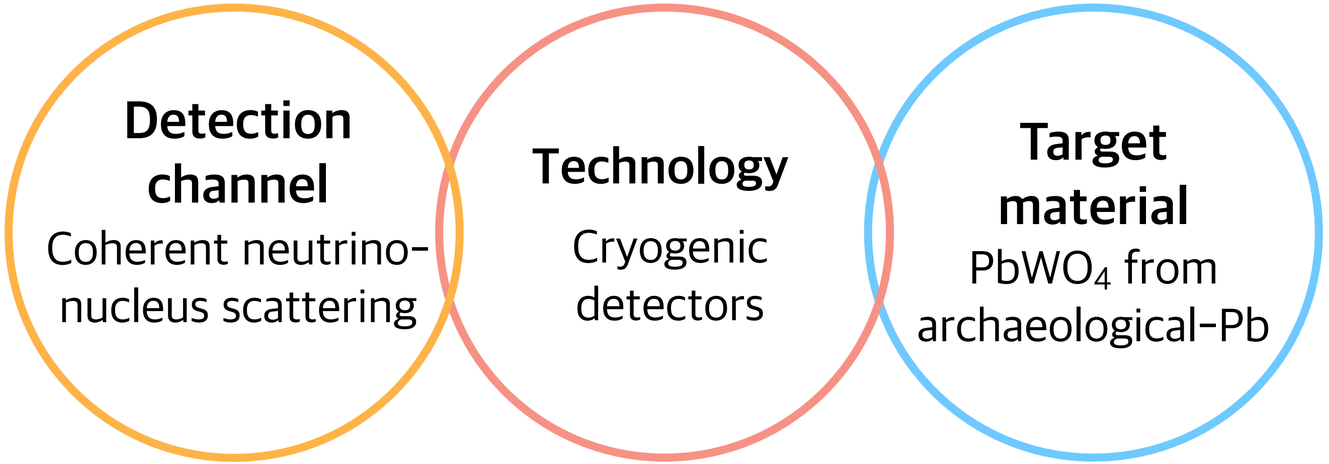
Lower threshold is not mandatory

The threshold is not limiting the statistics

RES-NOVA gives unique insights into SNe

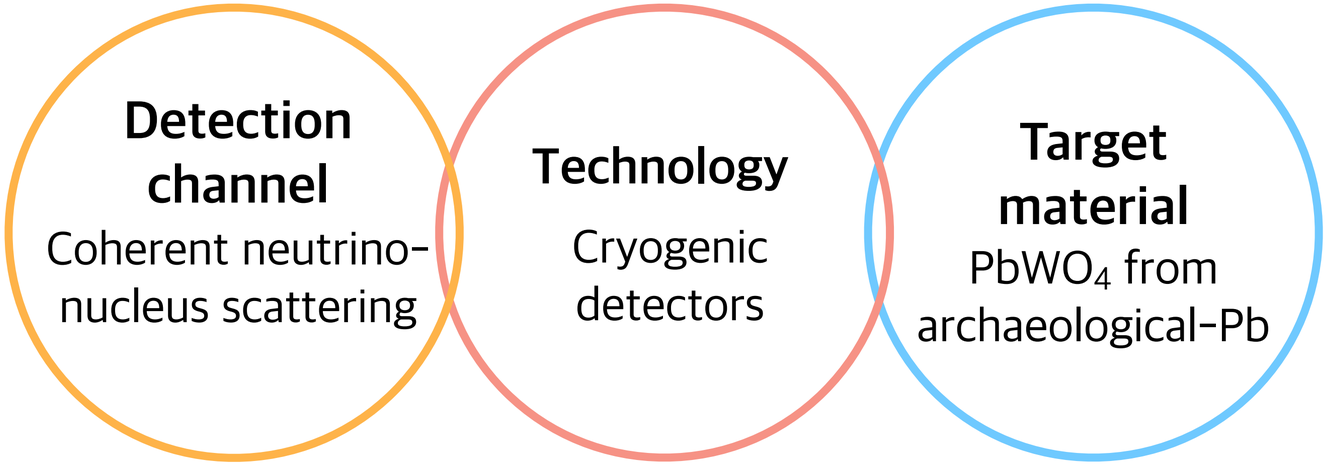
Innovative experimental approach





RES-NOVA gives unique insights into SNe

Innovative experimental approach



Galactic SN neutrino signal:

Water Cherenkov (SuperK): 0.2 ev./m^3

Liquid Scintillator (SNO+): 0.4 ev./m^3

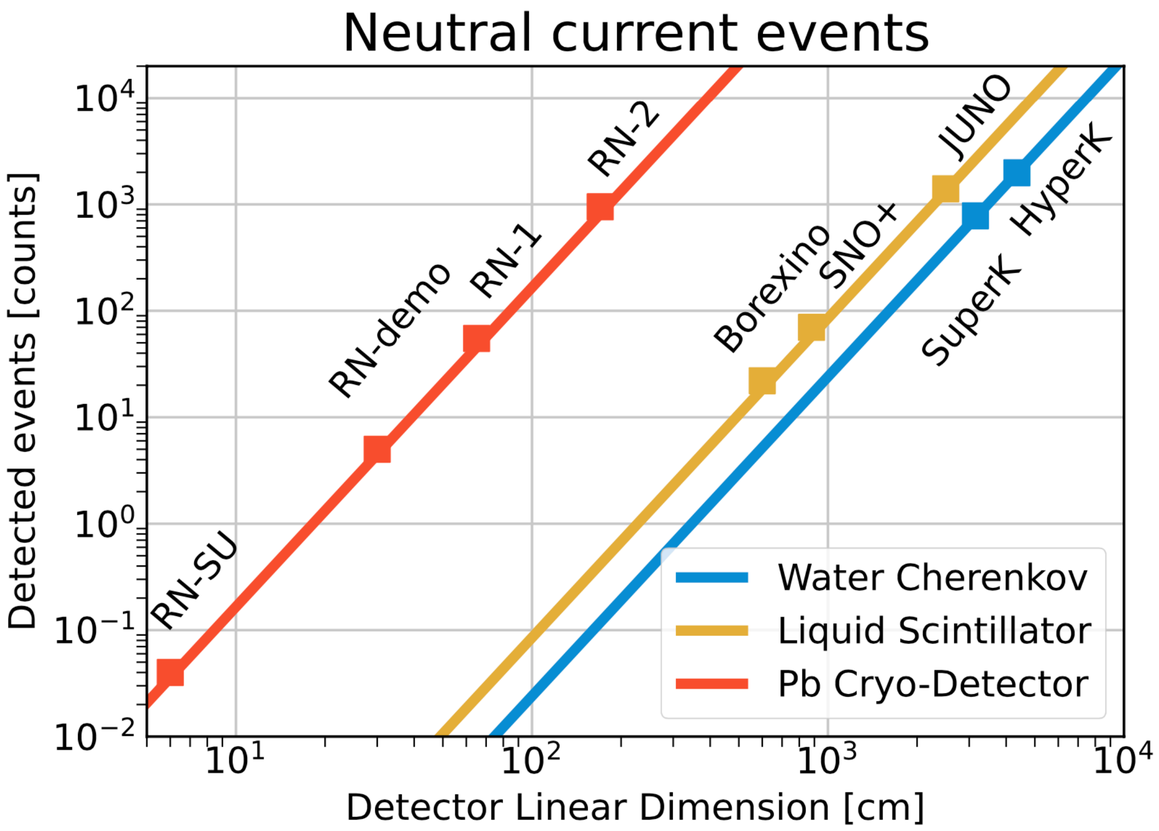
RES-NOVA: **~200 ev./m^3**

What can we learn?

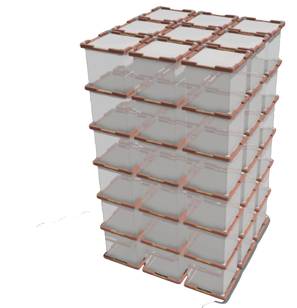
- Core-collapse physics studies
- Characterization of SN remnants
- Neutrino mass properties
- Multi-messenger Astronomy

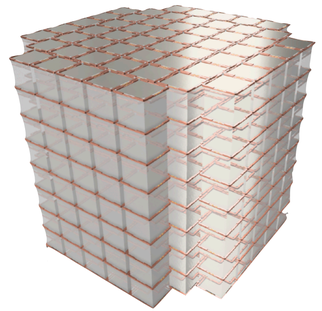
Neutrino observatory at the cm-scale

an array of $PbWO_4$ crystals



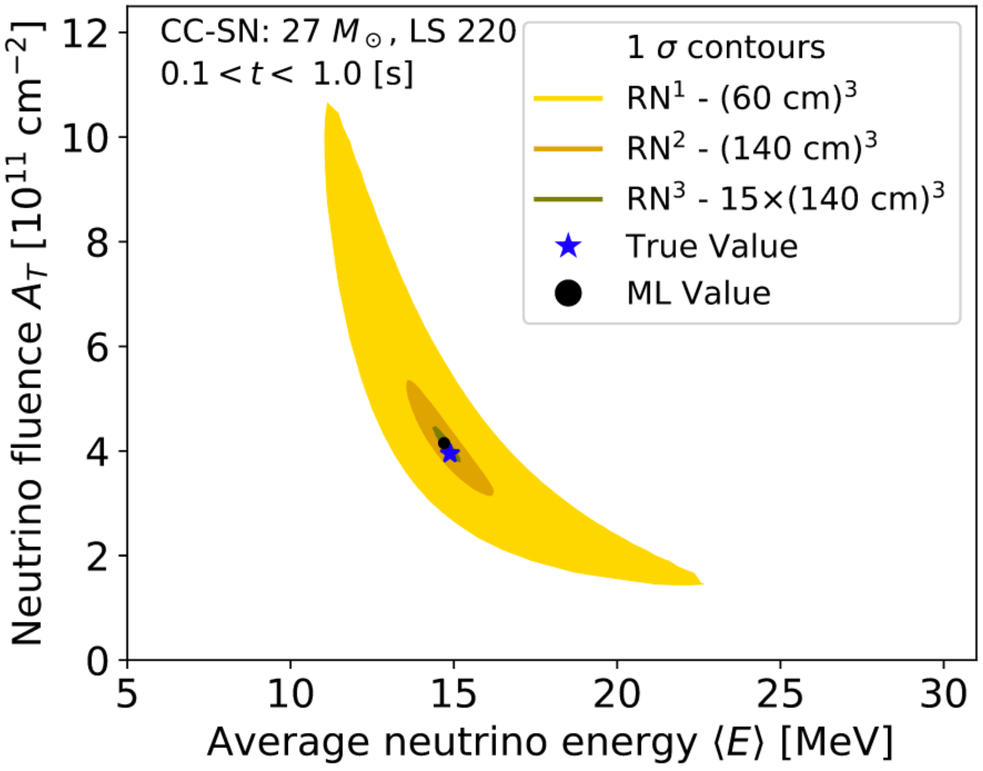
	RN-demo @ LNGS	RN-1	RN-2
Size:	$(30\ cm)^3$	$(60\ cm)^3$	$(140\ cm)^3$
Threshold:	1 keV	1 keV	1 keV
SN @ 10 kpc:	~10 counts	~50 counts	~900 counts





SN ENERGY RECONSTRUCTION IN RES-NOVA

Reconstruction of A_T and <E> by likelihood analysis



$$\mathcal{E}_{\rm tot} = 4\pi d^2 A_T \langle E \rangle$$

Neutrino fluence

Average neutrino energy

Precision in total SN energy reconstruction

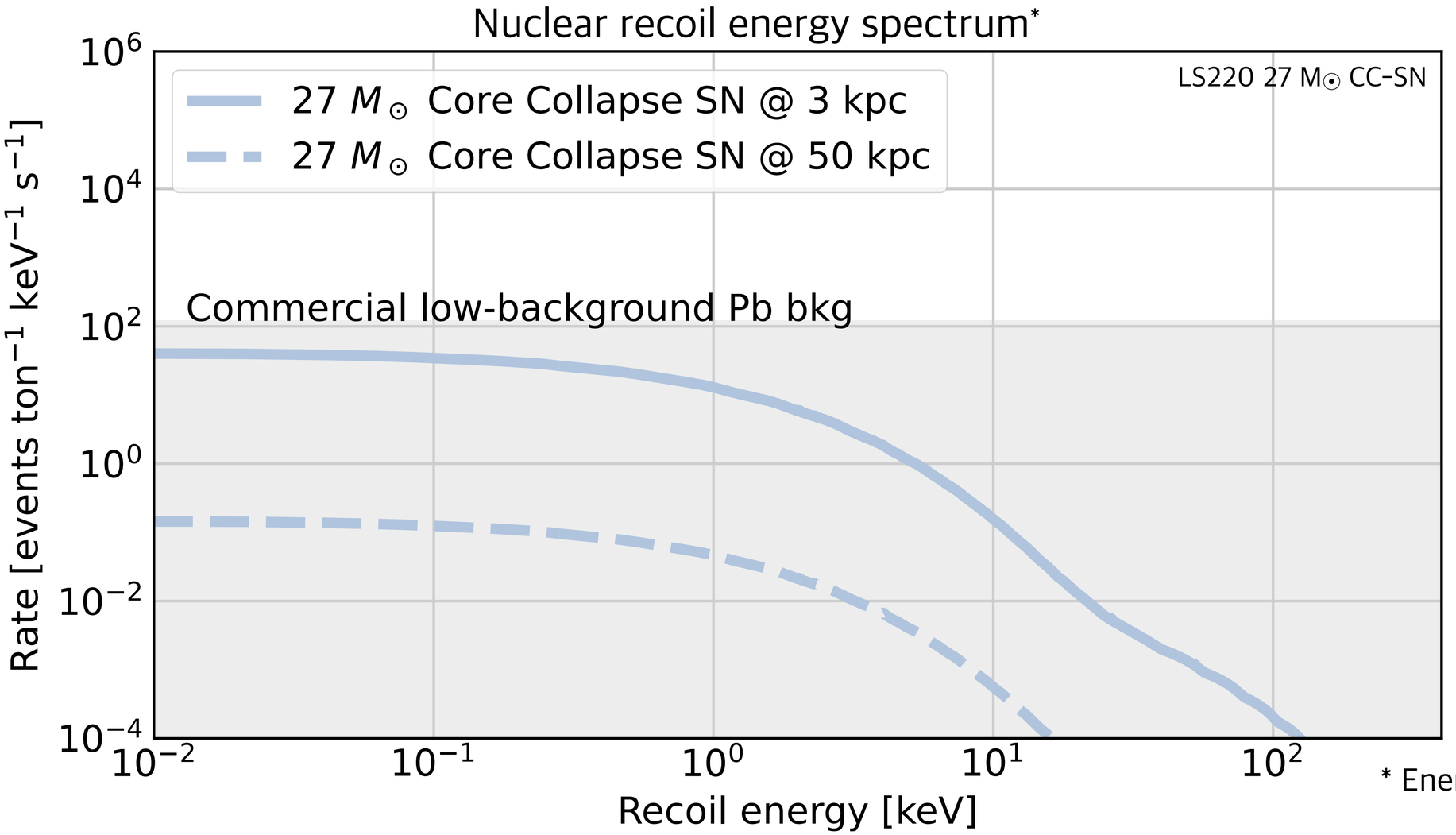
	ν_x/anti-ν_x	ν_e/anti-ν_e	
RN-I	30%		
RN-2	8%	SK-Gd* (IBD)	25%
RN-3	4%		

L. Pattavina et al., Phys. Rev. D 102, 063001 (2020)

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

* >90% Gd loading

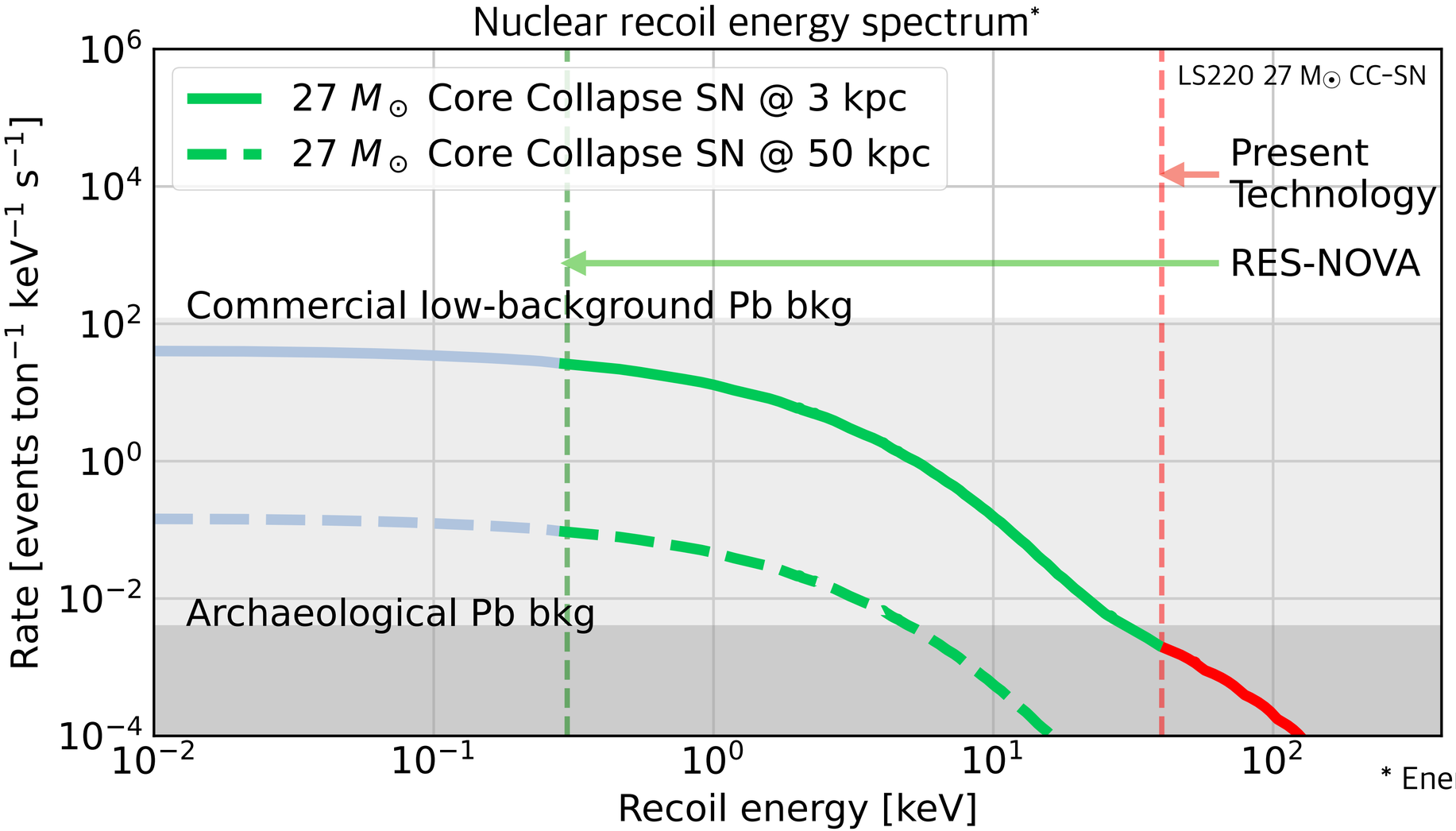
RES-NOVA DETECTS SN NEUTRINOS



* Energy resolution 0.2 keV

L. Pattavina et al., *Phys. Rev. D* 102, 063001 (2020)

RES-NOVA detects SN neutrinos



* Energy resolution 0.2 keV

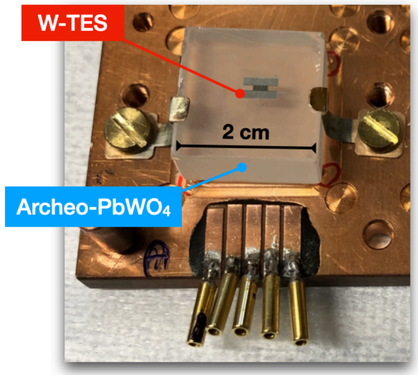
L. Pattavina et al., *Phys. Rev. D* 102, 063001 (2020)

RES-NOVA Group of Interest, *Eur. Phys. J. C* 82, 692 (2022)

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

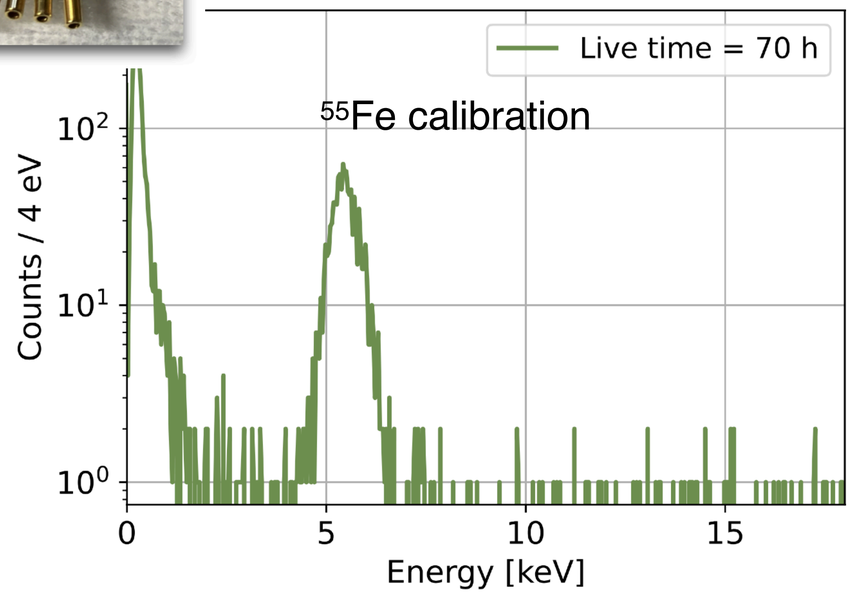
RES-NOVA PROOFS OF PRINCIPLE

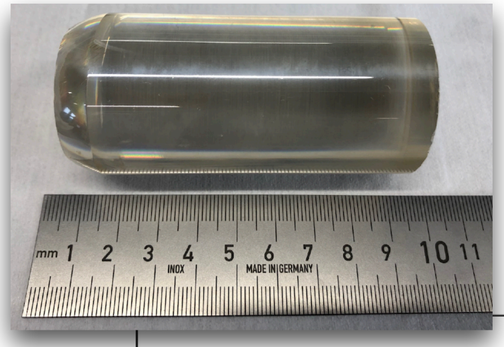
ACHIEVEMENT OF LOW THRESHOLD AND LOW BACKGROUND



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

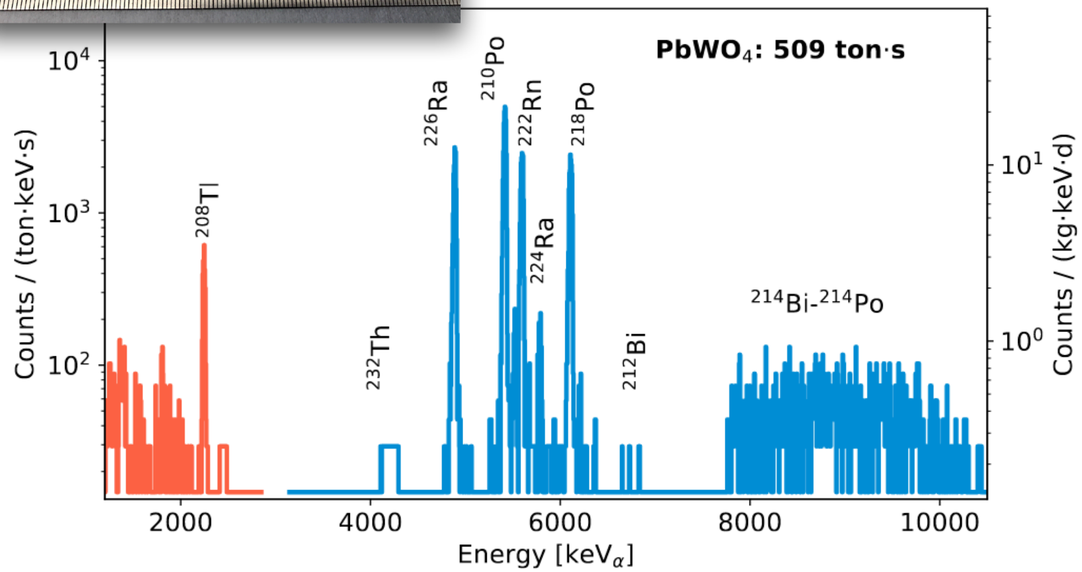
TOTAL ENERGY SPECTRUM





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)

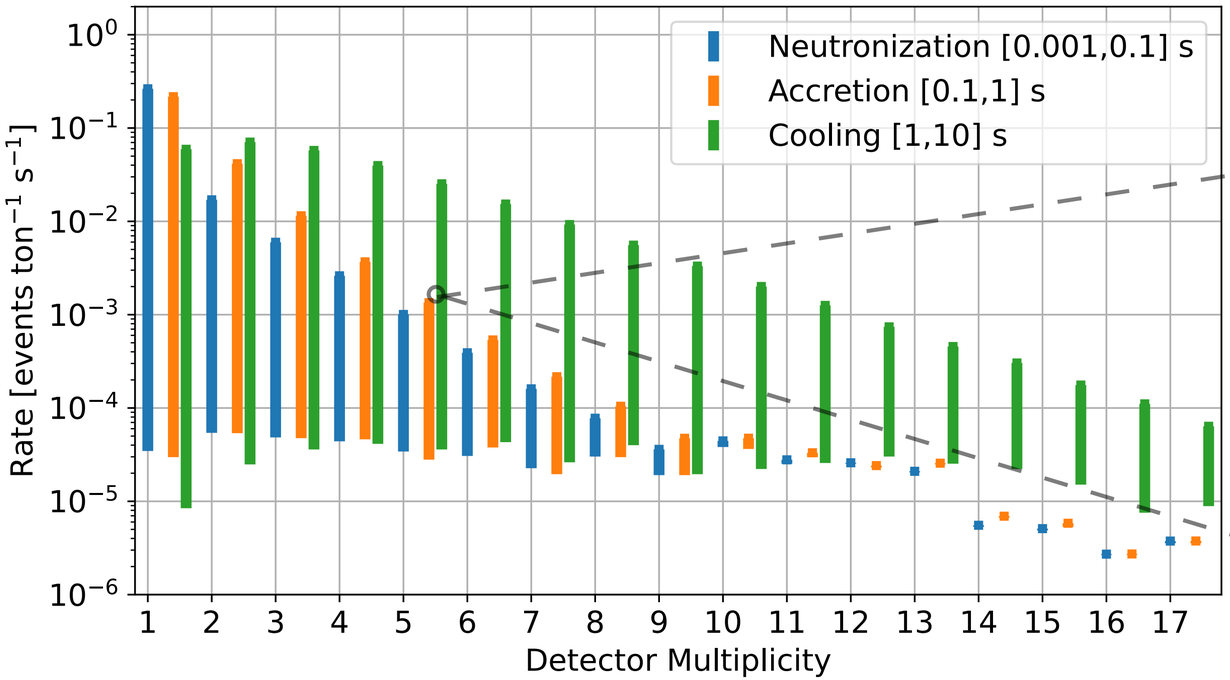
RES-NOVA BACKGROUND MODEL

High multiplicity SN signal → High multiplicity bkg → Low-background

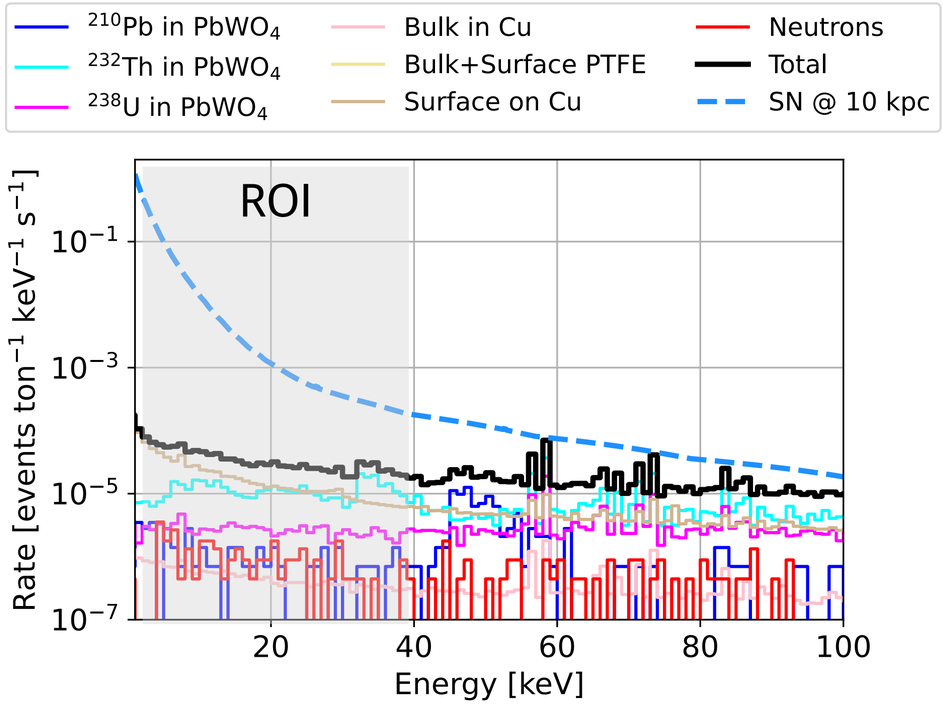
Bkg goal: <10^{-3} ev/ton/keV/s in coincidence mode (no particle ID)

<0.086 c/keV/kg/d

Background rate in the ROI

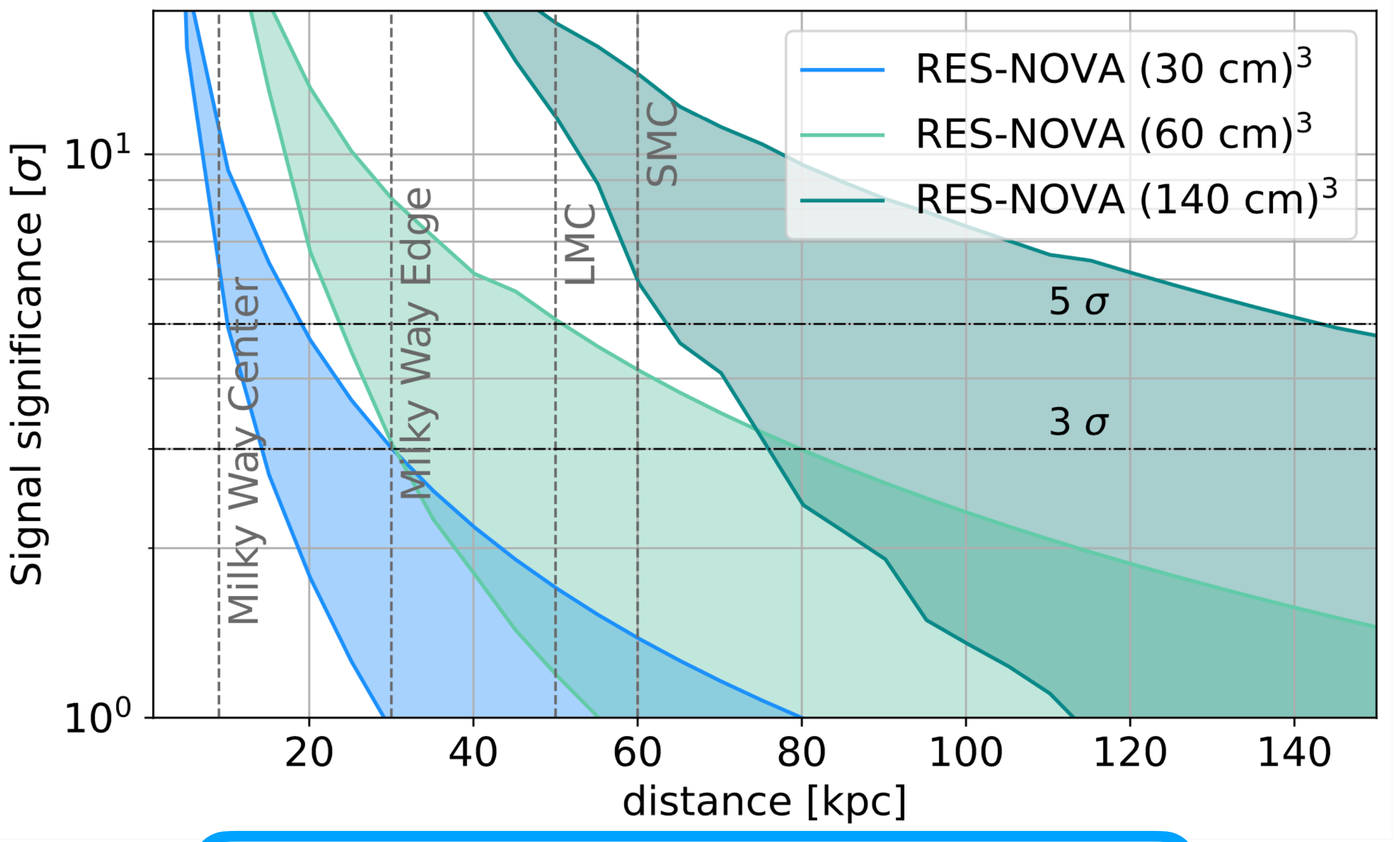


Detector energy spectrum for a SN @ 10 kpc

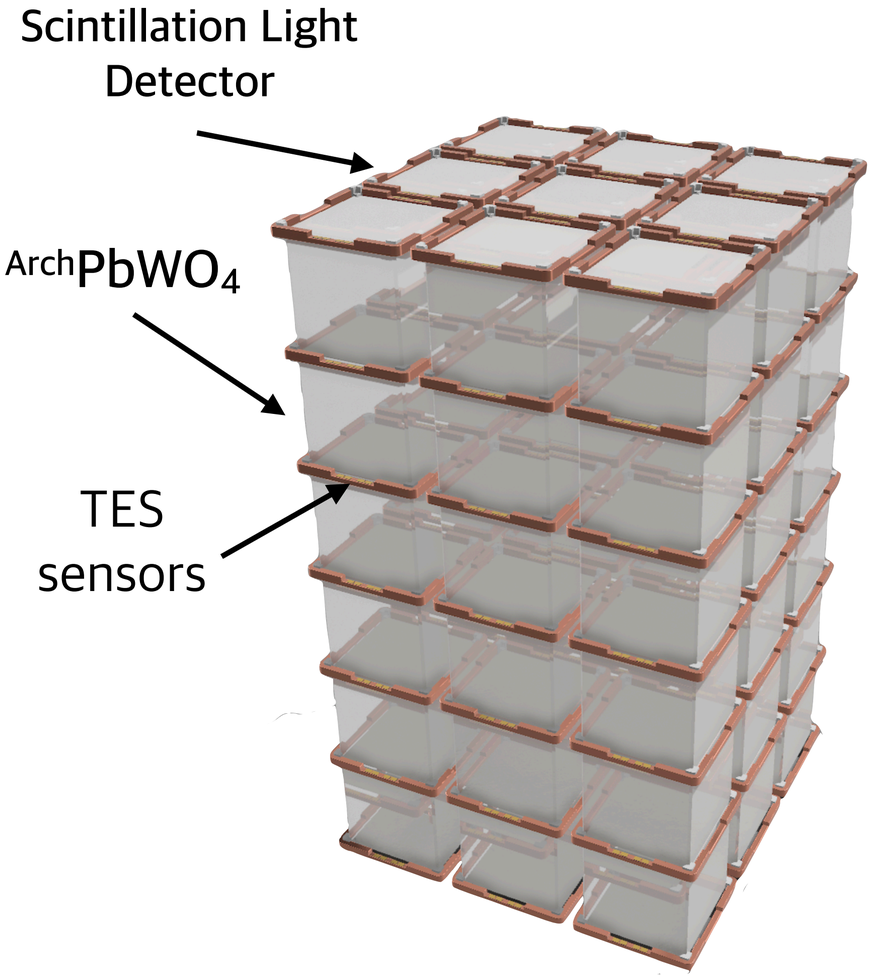


L. Pattavina et al., JCAP 10 (2021) 064

RESNOVA TECHNOLOGY DEMONSTRATOR



<15 kpc 90% of Galactic SNe are included



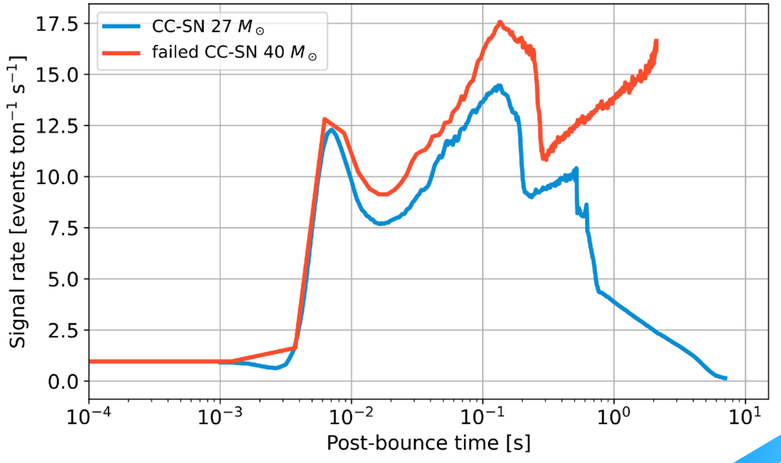
Transition Edge Sensors
Threshold 1 keV
Bkg in RoI 10^{-3} c/keV/ton/s

L. Pattavina et al., *JCAP* 10 (2021) 064
S. M. Adams et al., Astrophys. J. 778, 164 (2013)

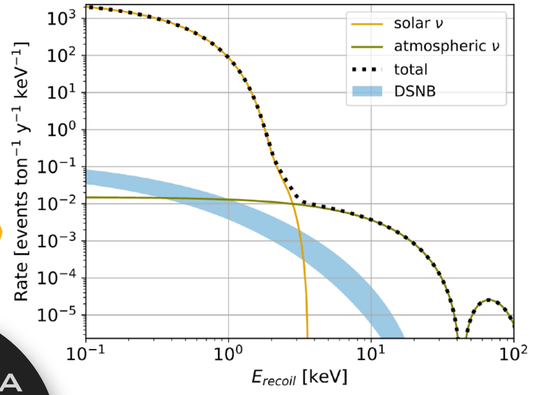
RES-NOVA Impact

MULTI-DISCIPLINARITY

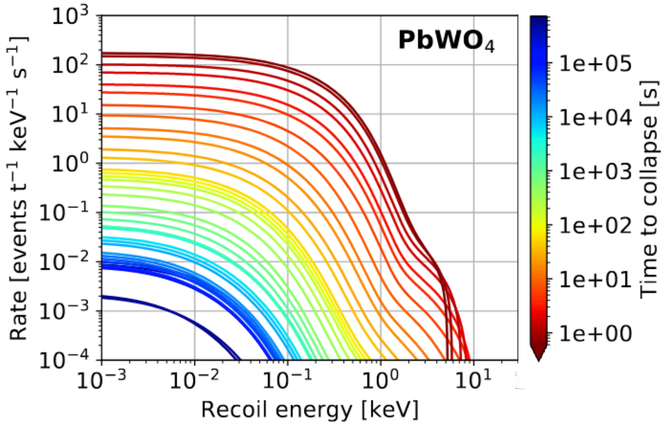
Core Collapse model discrimination



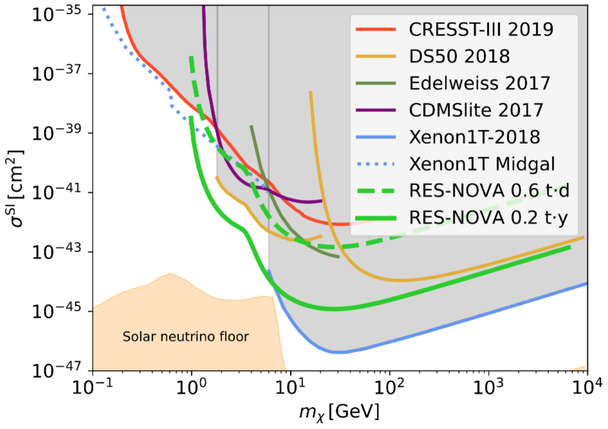
Diffuse SN neutrino Background



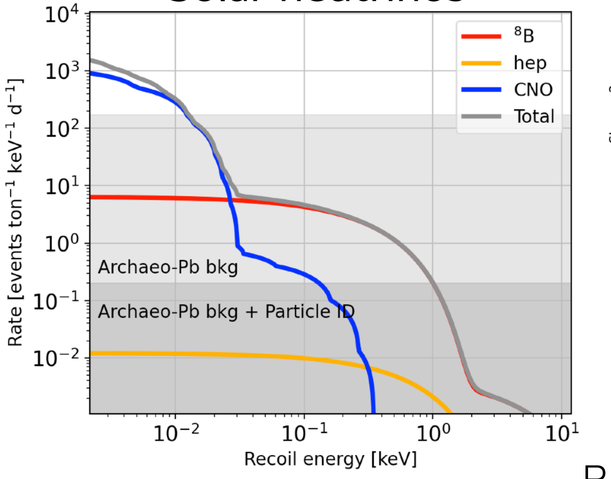
Pre-SN neutrino detection



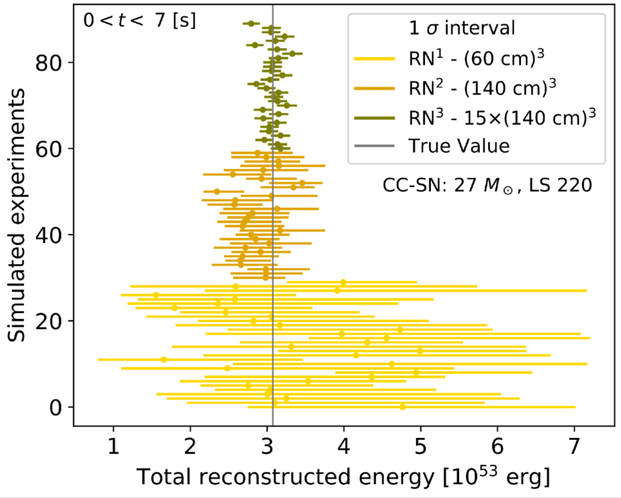
Direct DM searches



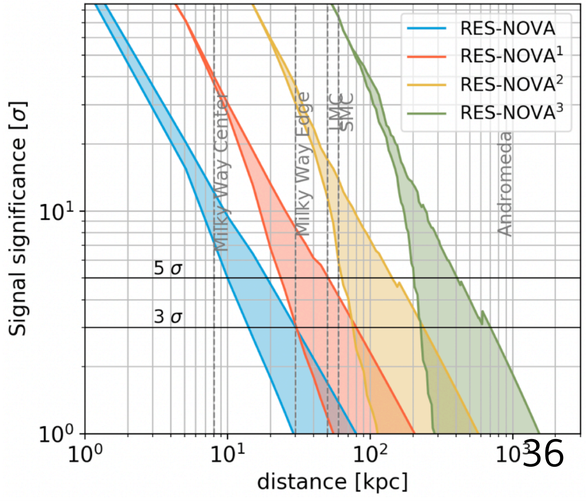
Solar neutrinos



Precise ε_{tot} reconstruction



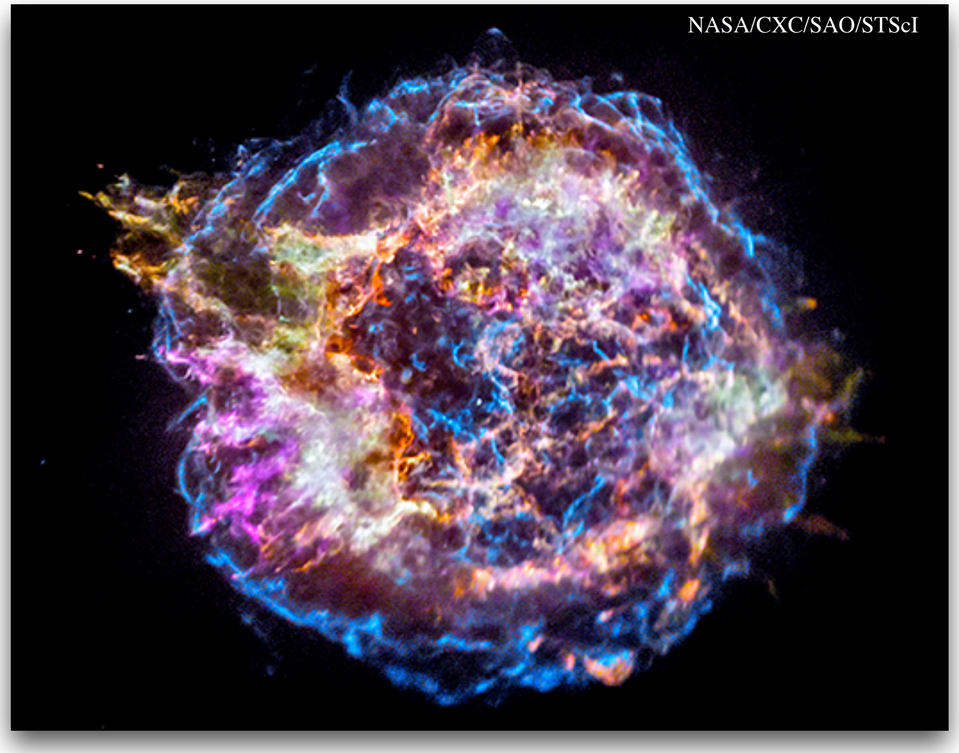
Deep space exploration



P. Eller, LP et al JCAP 10 (2022) 024
LP et al., JCAP 10 (2021) 064
LP et al., Phys. Rev. D 102, 063001 (2020)

Are we ready for the next SN ?

- SN1987A neutrinos took 160,000 y to reach our detectors
- In 2022 the most advanced EU neutrino detector went off-line



Are we ready for the next SN ?

Timeliness
A unique window of opportunity for a new technology

Innovative experimental approach
Multi-disciplinarity

Feasibility
Proof of principle detectors gave promising results

RES-NOVA demo is funded
Long-term science program on neutrino physics