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RES-NOVA: Archaeological Pb observatory for astrophysical neutrino sources

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OUTLINE

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±0.46 SN/100y [New Astron. 83 (2021) 101498]
Not uniform throughout the Galaxy

Very Near

Known past Galactic SNe

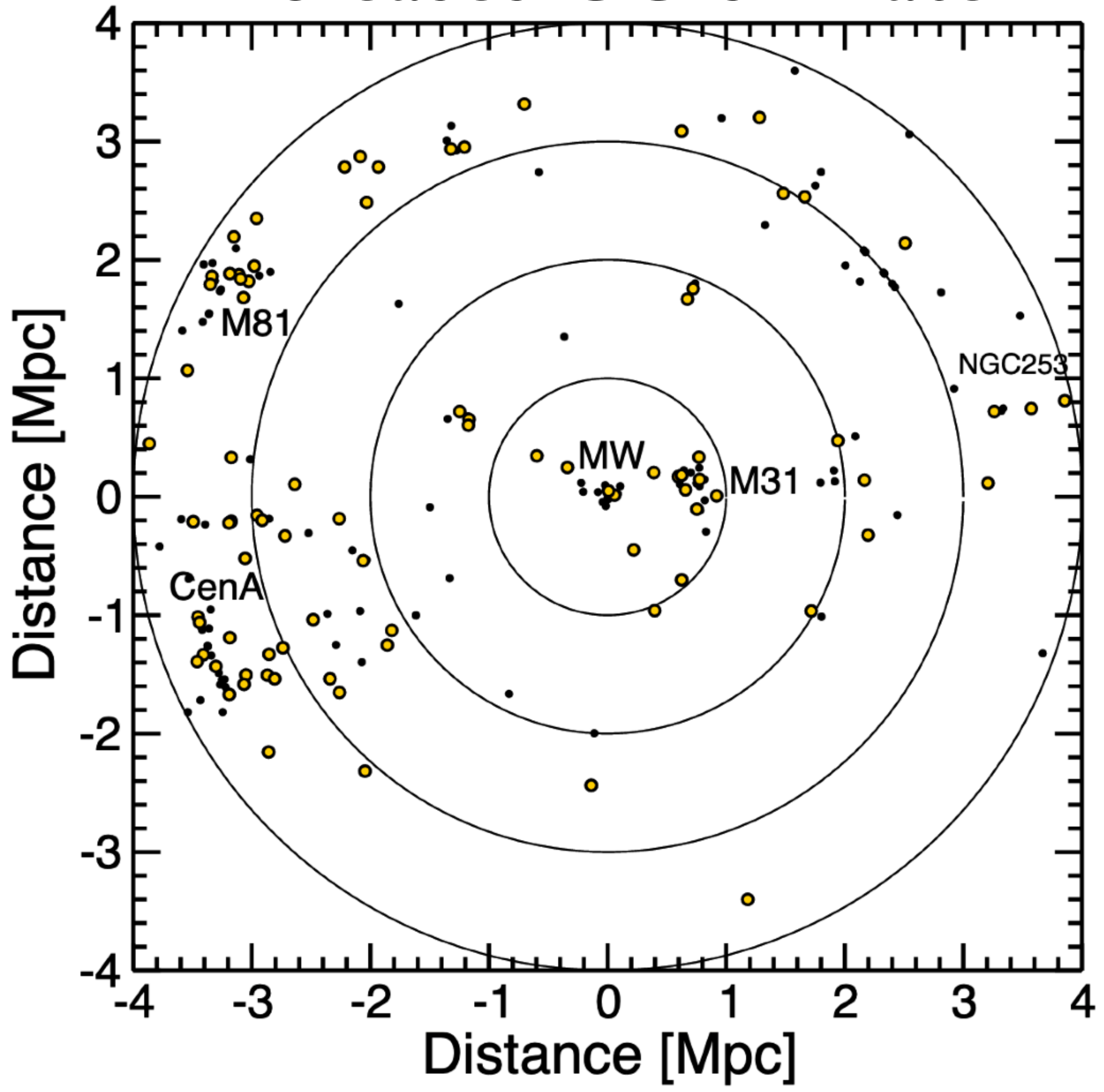
Date	Location	Common Name	Dist. (kpc)
1006 Apr 30	Lupus	SN 1006	1.56[a]
1054 Jul 4	Taurus	Crab	2.0
1181 Aug 6	Cassiopeia	SN 1181	3.2
1572 Nov 6	Cassiopeia	Tycho	2.3
1604 Oct 9	Ophiuchus	Kepler	2.9
1671[b]	Cassiopeia	Cas A	3.4

The, L.S., Clayton, D. D., Diehl, R., et al. 2006, A&A, 450, 1037

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

Very Far

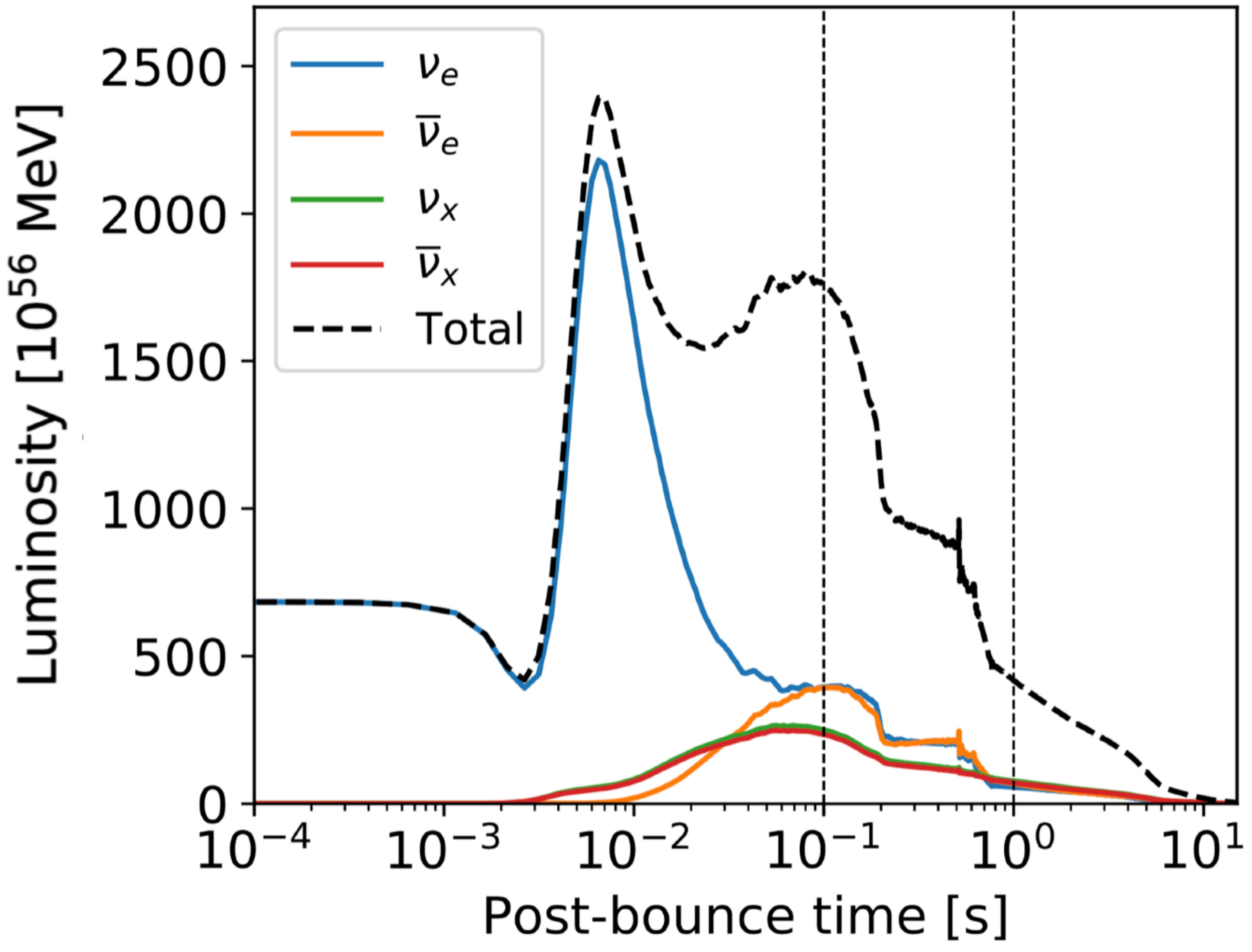
Probe more galaxies increases CC-SN rate



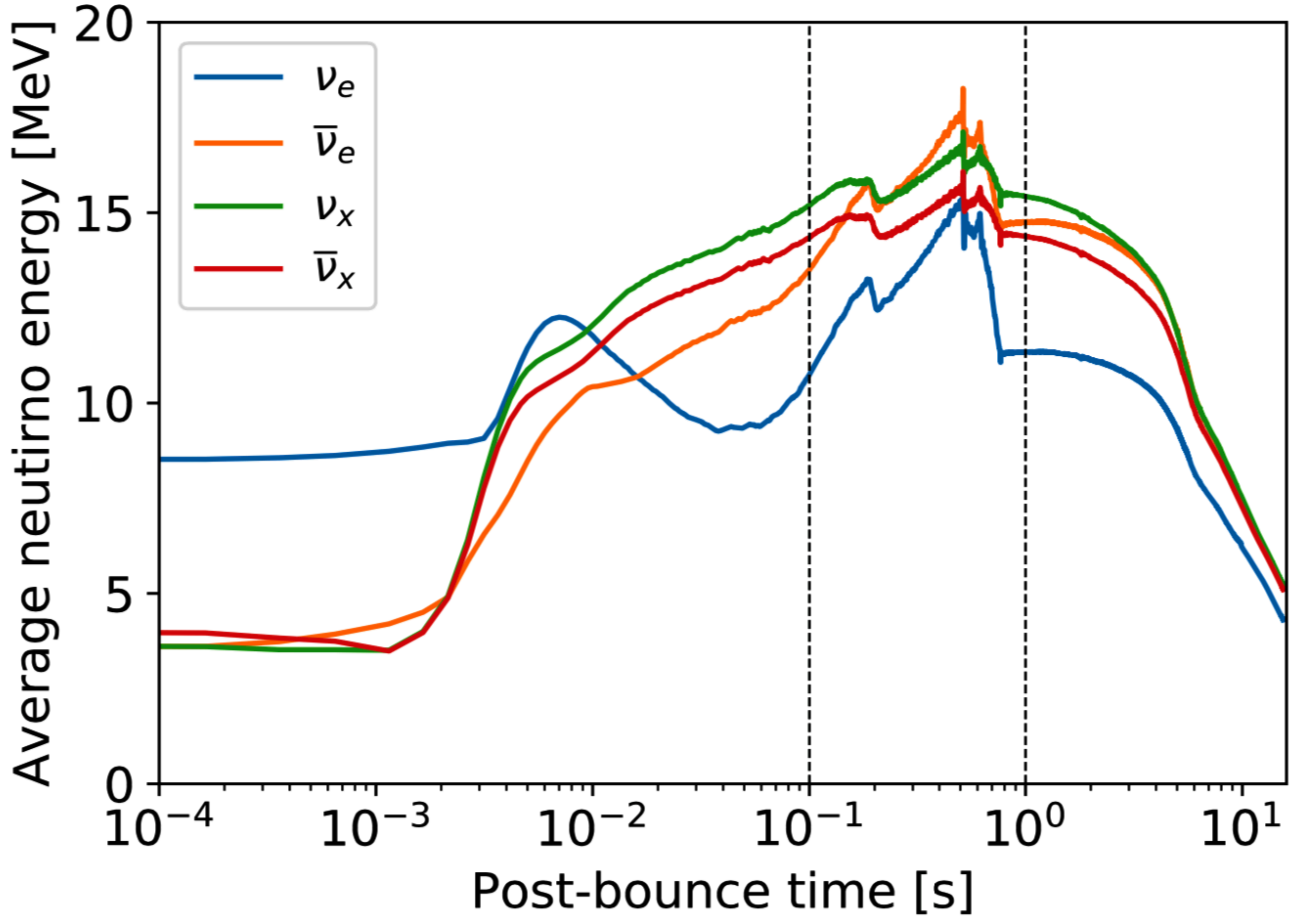
→ Need to survey D > 3 Mpc
→ Highly sensitive neutrino detector

Problem II: SN composite neutrino signal

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



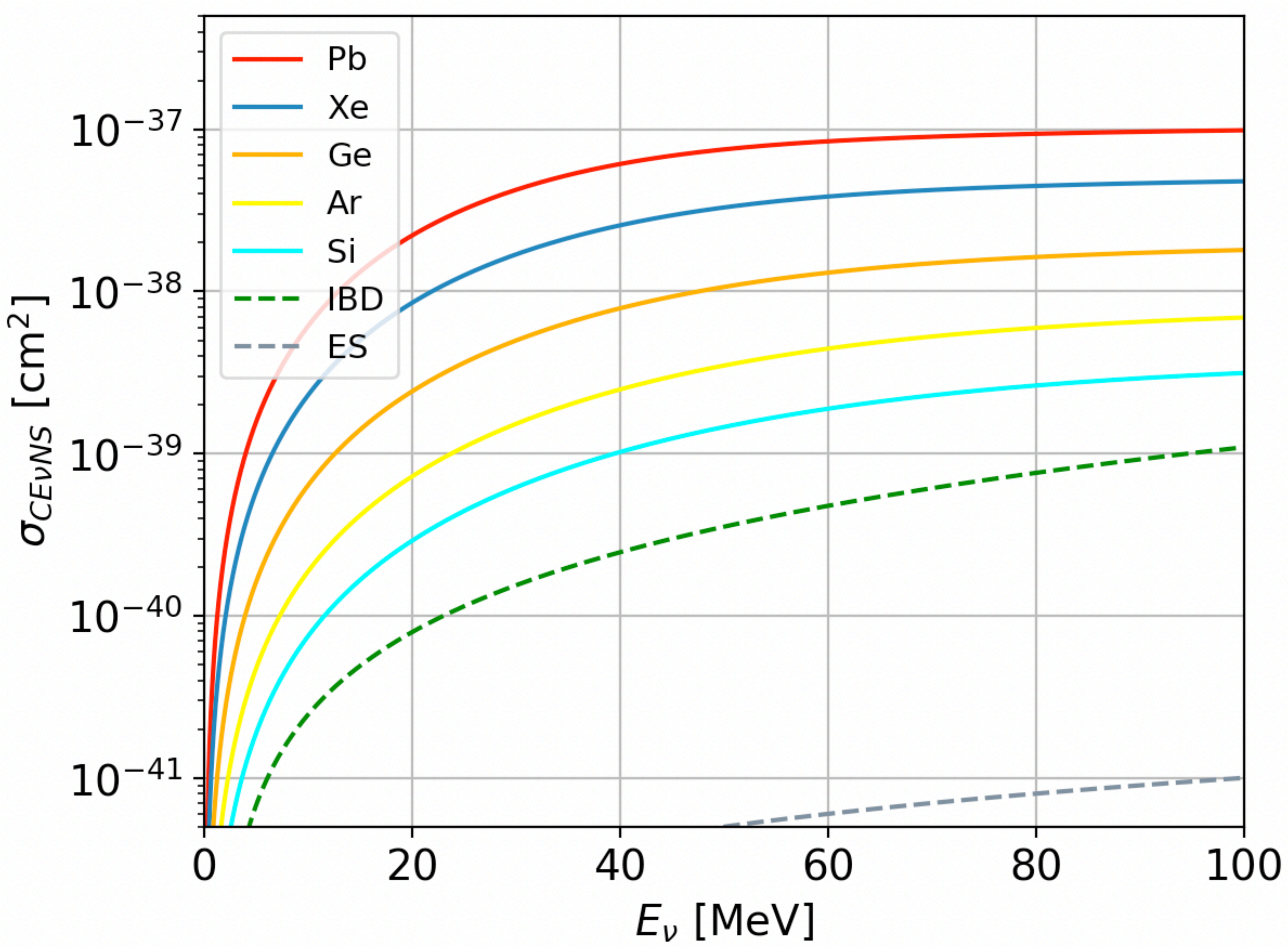
ν_x is the most **intense** component of the flux



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

Current SN neutrino detectors are mostly sensitive to anti-ν_e/ν_e
Need for a **flavor independent** channel sensitive also to anti-ν_x/ν_x

Coherent elastic neutrino-Nucleus scattering



Neutrino energy

Form factor

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

Electroweak-charge

Neutral current process

➜ equally sensitive to all flavours

High cross-section

➜ >10^4 than NC

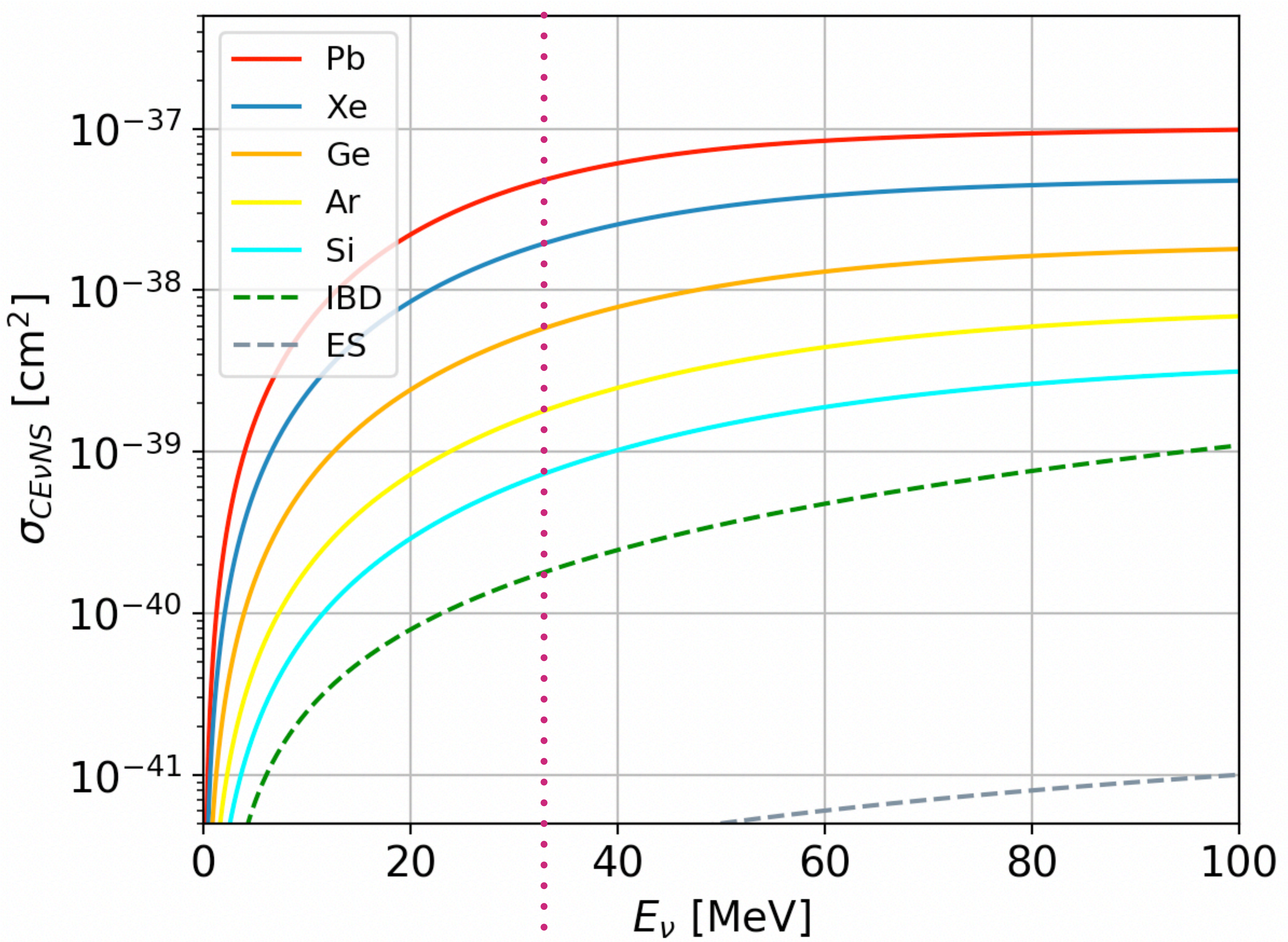
Threshold-less process

➜ sensitive to the entire ν emission

CEνNS ideal channel for SN **neutrino detection**

A. Drukier and L. Stodolsky, Phys. Rev. D 30, 2295 (1984)

Pb as a target material



"Pb coherence limit"

Neutrino energy

Form factor

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

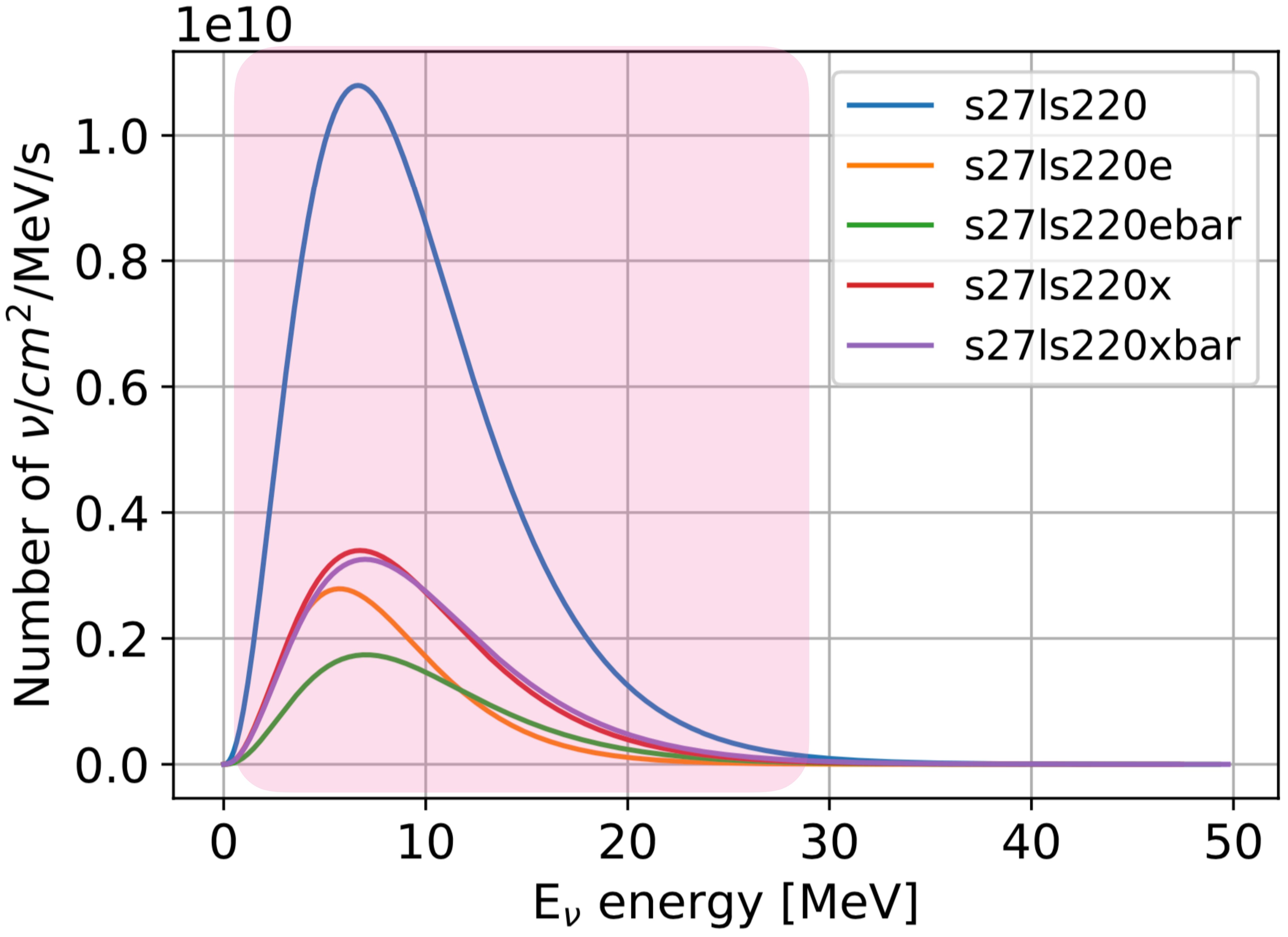
Electroweak-charge

- Pb is the element with the highest CEvNS x-section
- Pb has with the highest nuclear stability
- Highly efficient target for SN neutrinos

Pb: ideal target for CEvNS

Pb as a target material

27 M⊙ SN (LS220 EoS) occurring at 10 kpc



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Form factor

Neutrino energy

Electroweak-charge

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Pb: ideal target for CEvNS

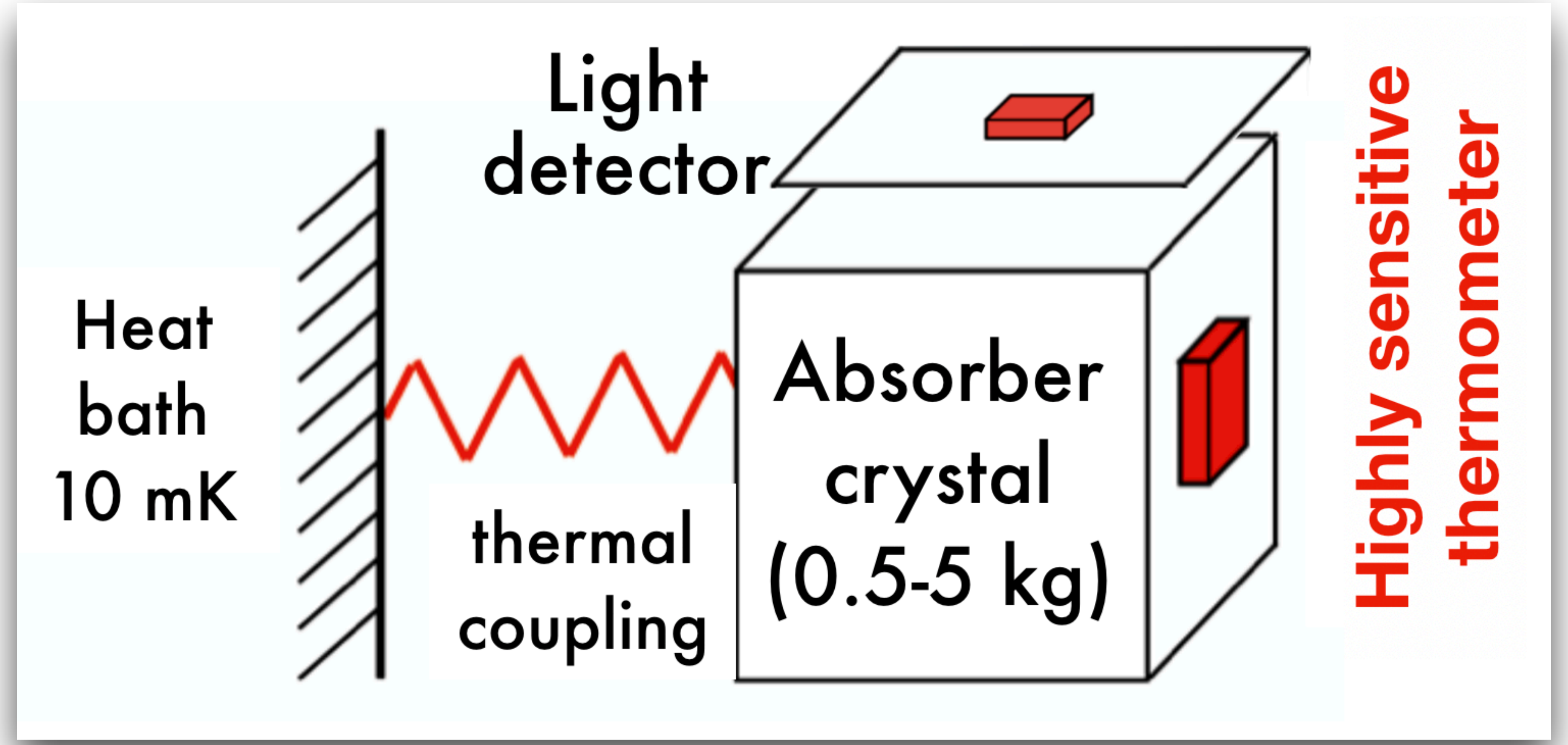
Expected signal:
→ low energy nuclear recoil O(keV)

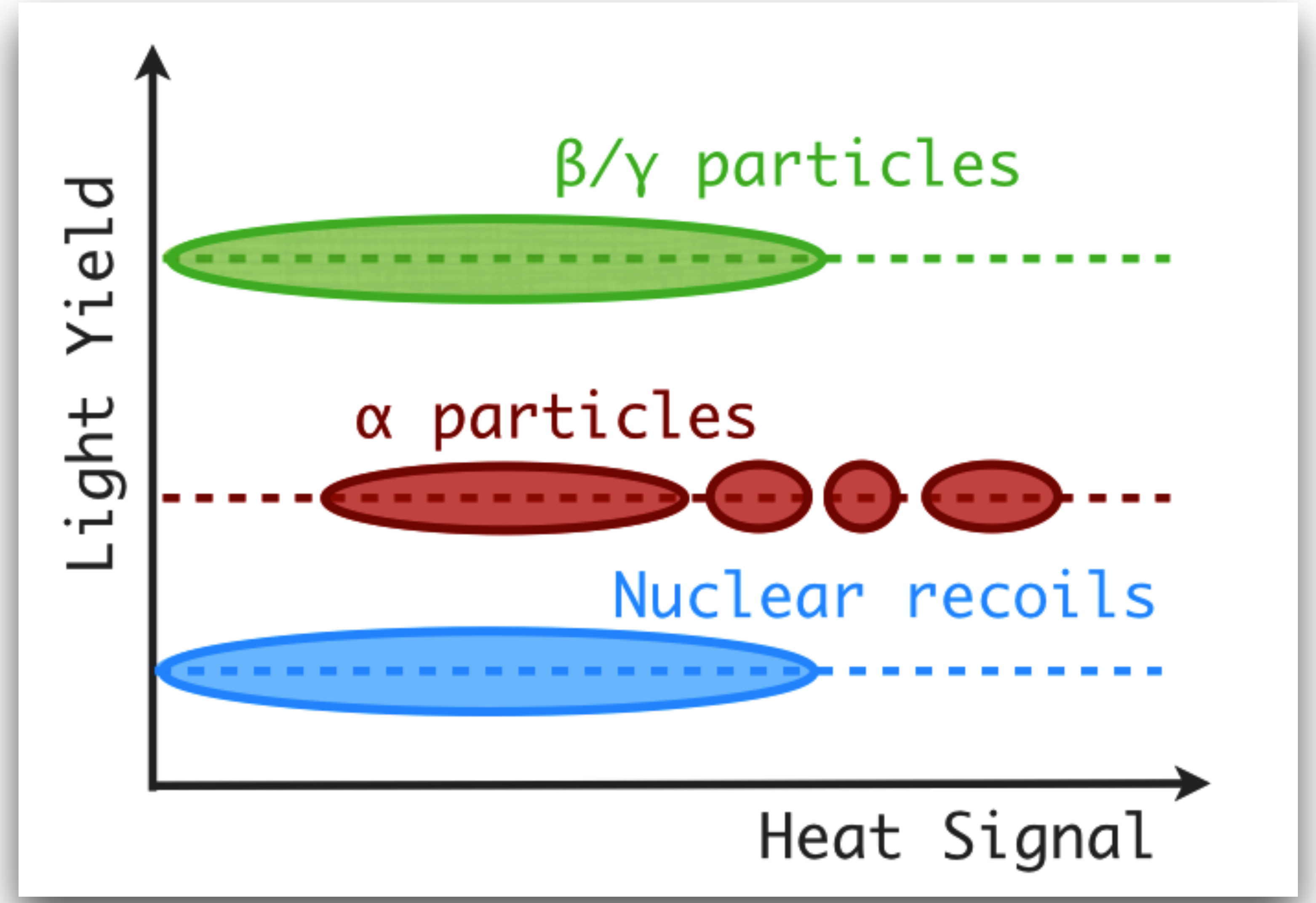
RES-NOVA: Pb-based CRYO DETECTORS

Cryogenic detectors are a leading technology:

Neutrinoless ββ 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

RES-NOVA: Pb-based CRYO DETECTORS

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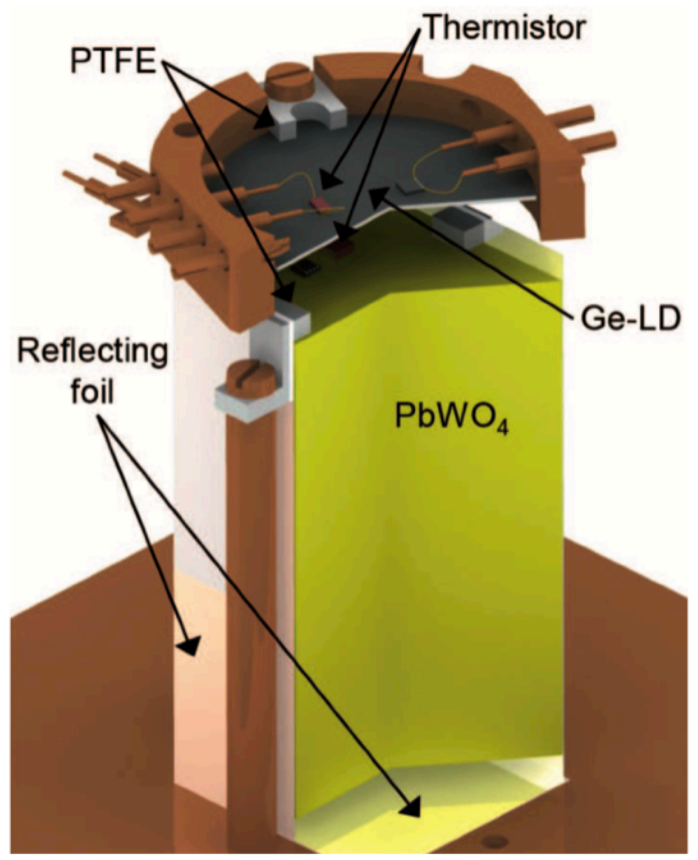
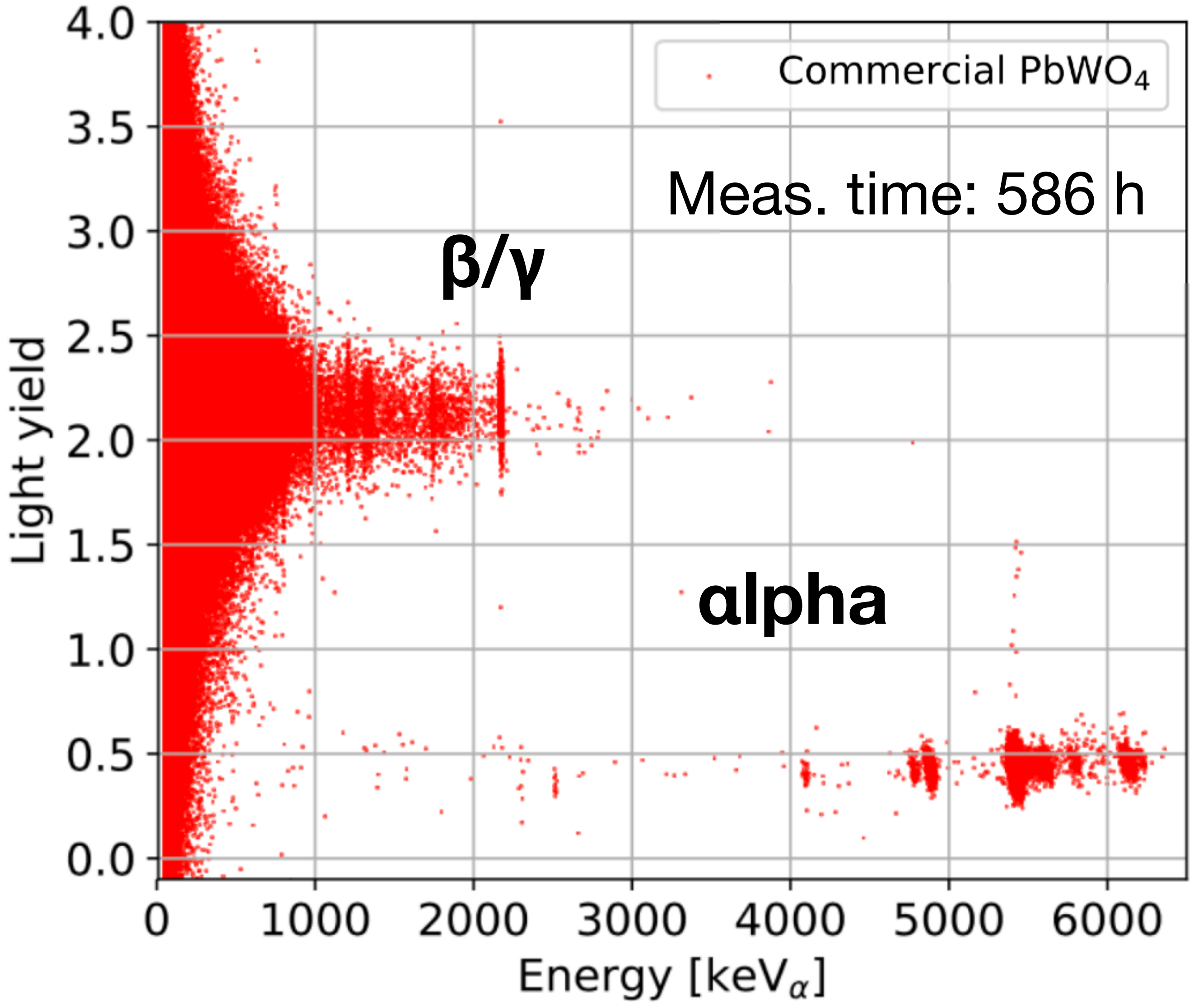


$PbWO_4$

Mass: 500 g

Baseline resolution 600 eV

FWHM @ 2.6 MeV: 15 keV



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

- ↑ 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

Which Pb?

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

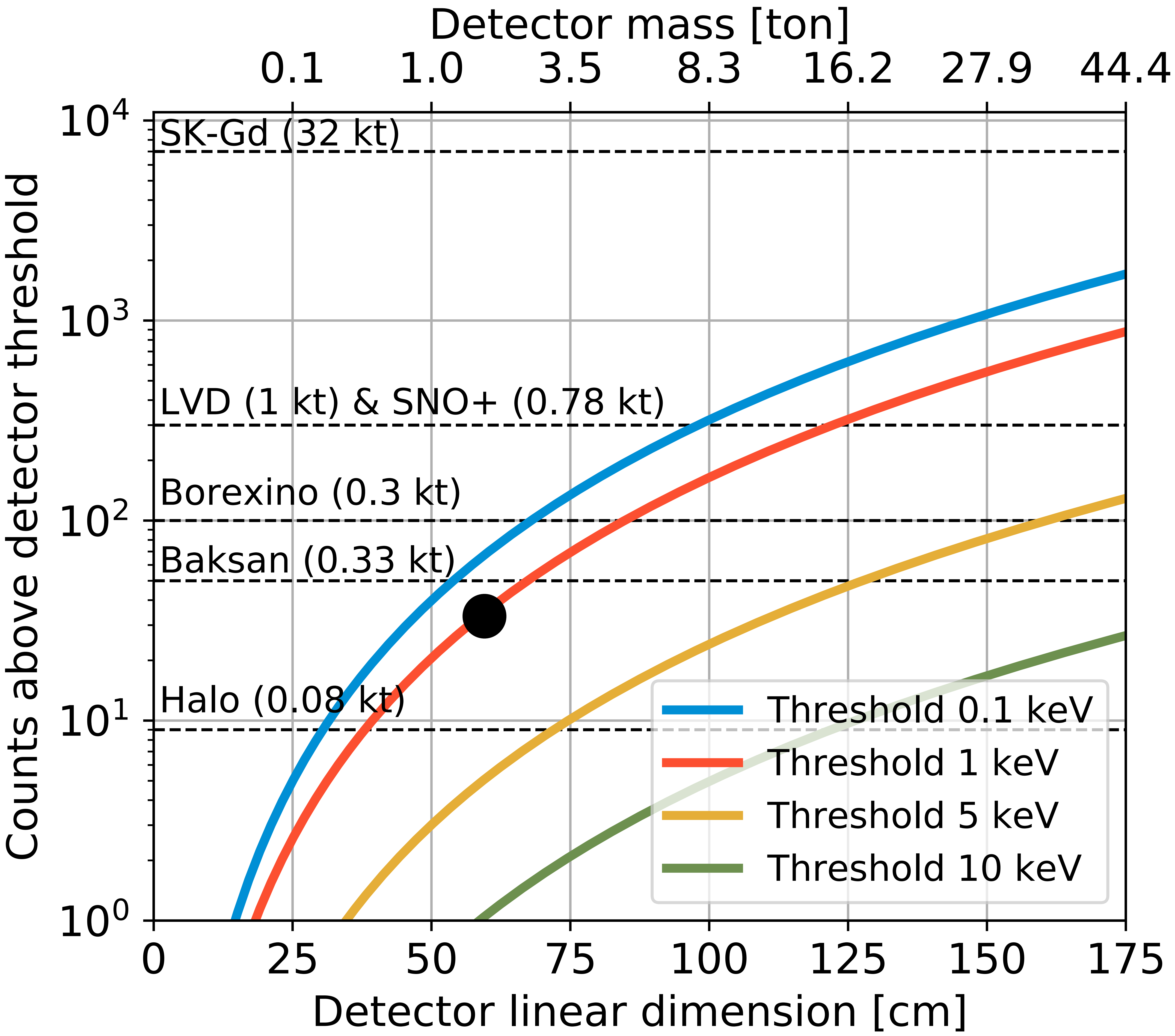
Archaeological Pb is "old enough" (e.g. Roman Pb) to ensure a negligible ^{210}Pb concentration: **< 1 mBq/kg**

N. Nosengo, Nature (2010), 10.1038/news.2010.186

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

[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.

RES-NOVA design



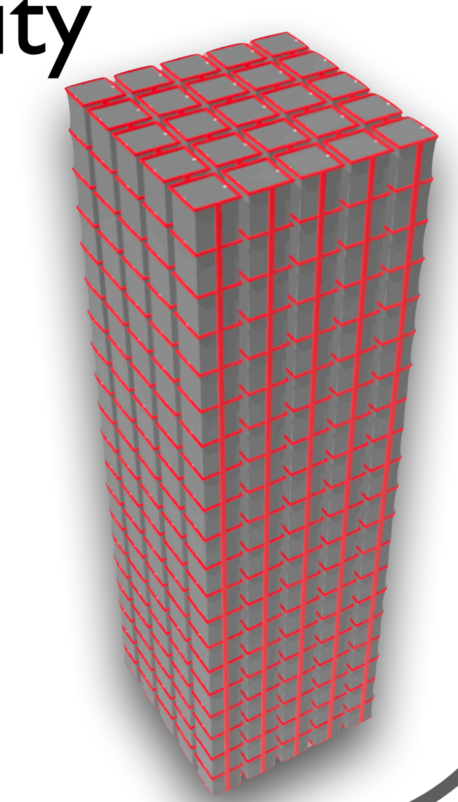
	RN-1 @ LNGS
Size:	$(60\ \text{cm})^3$
Threshold:	1 keV
SN @ 10 kpc:	~50 counts

RN-I small volume cryogenic facility

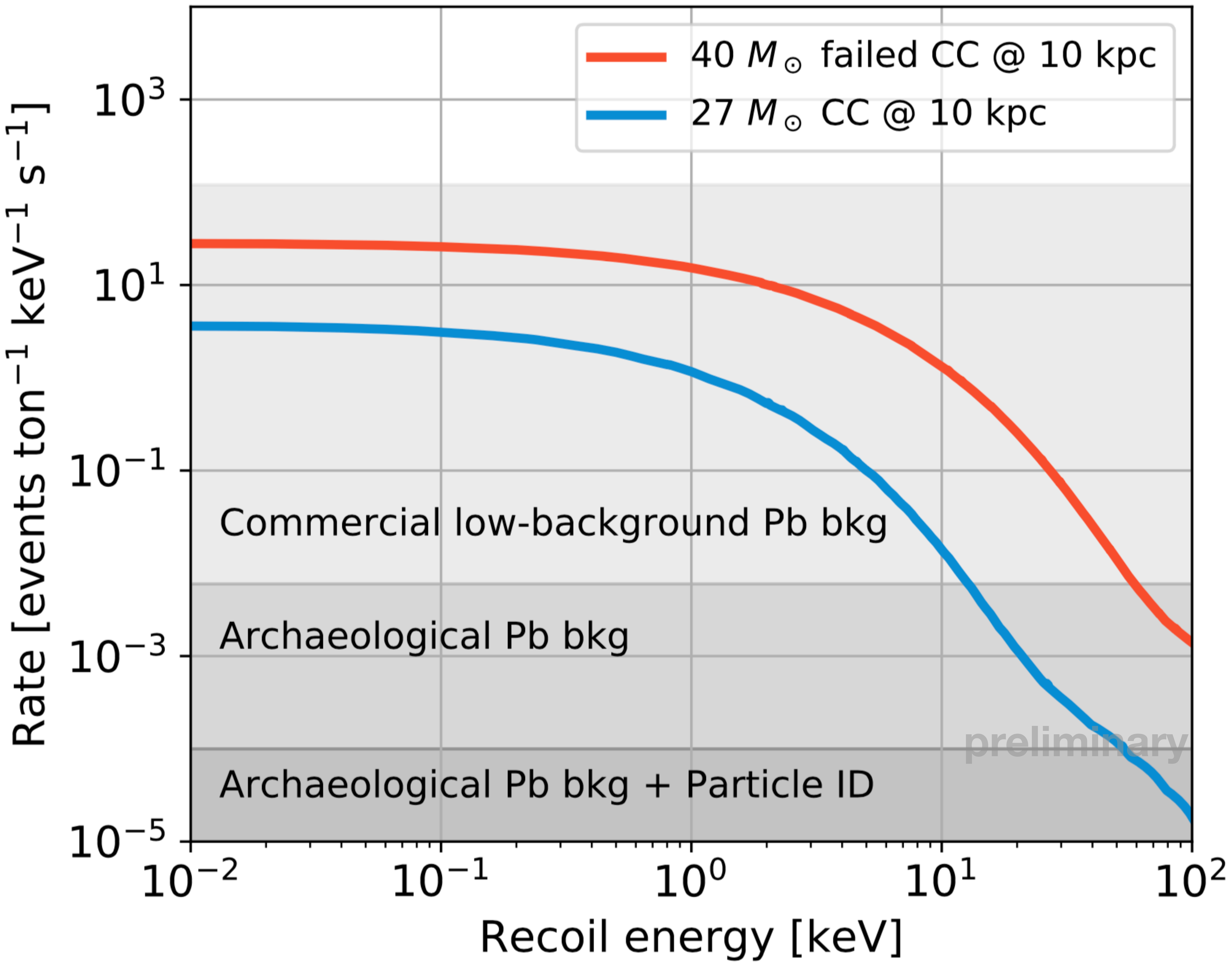
Detector mass: 1.8 tons

Array of 500 cryo-detectors

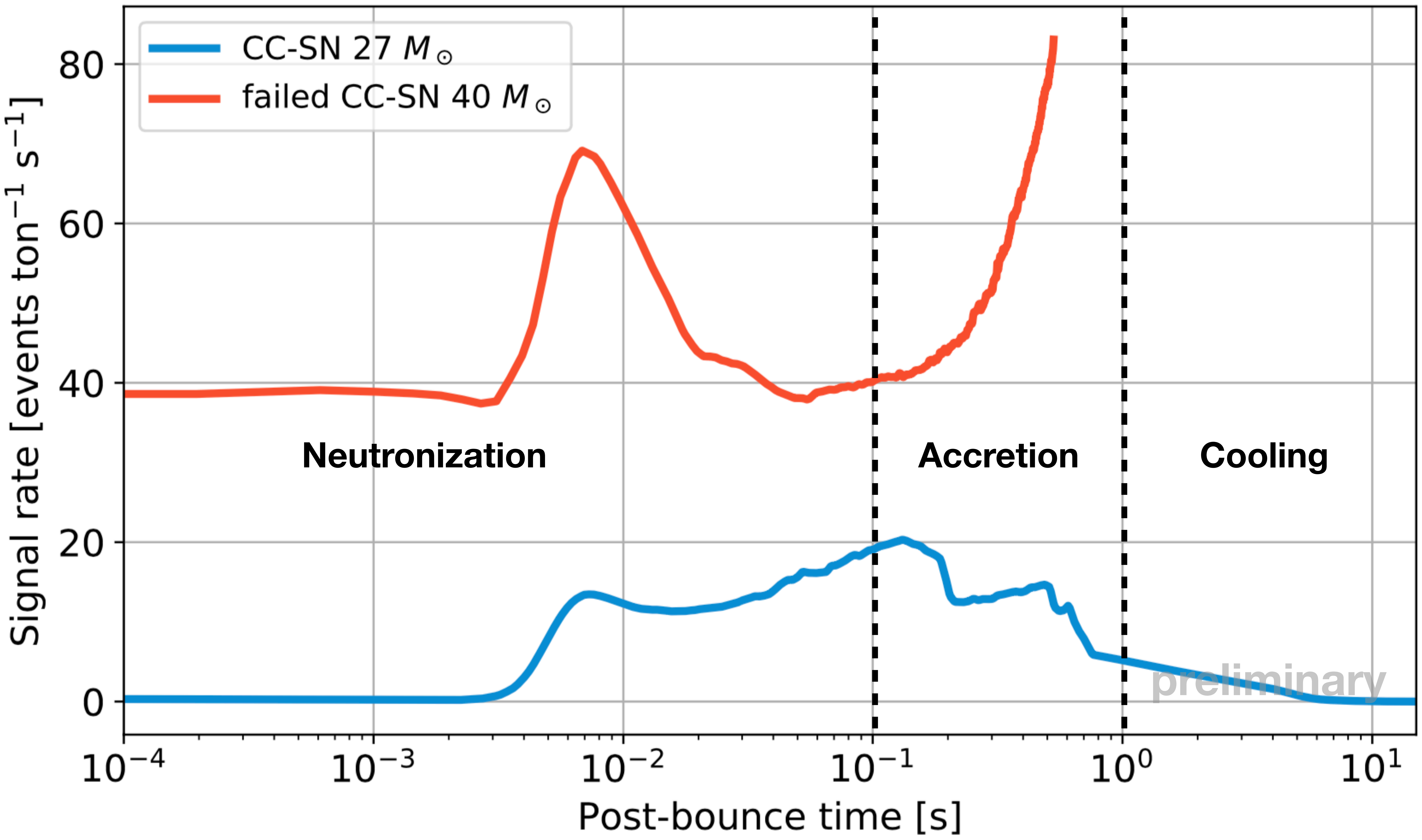
Energy threshold: 1keV



RES-NOVA energy response



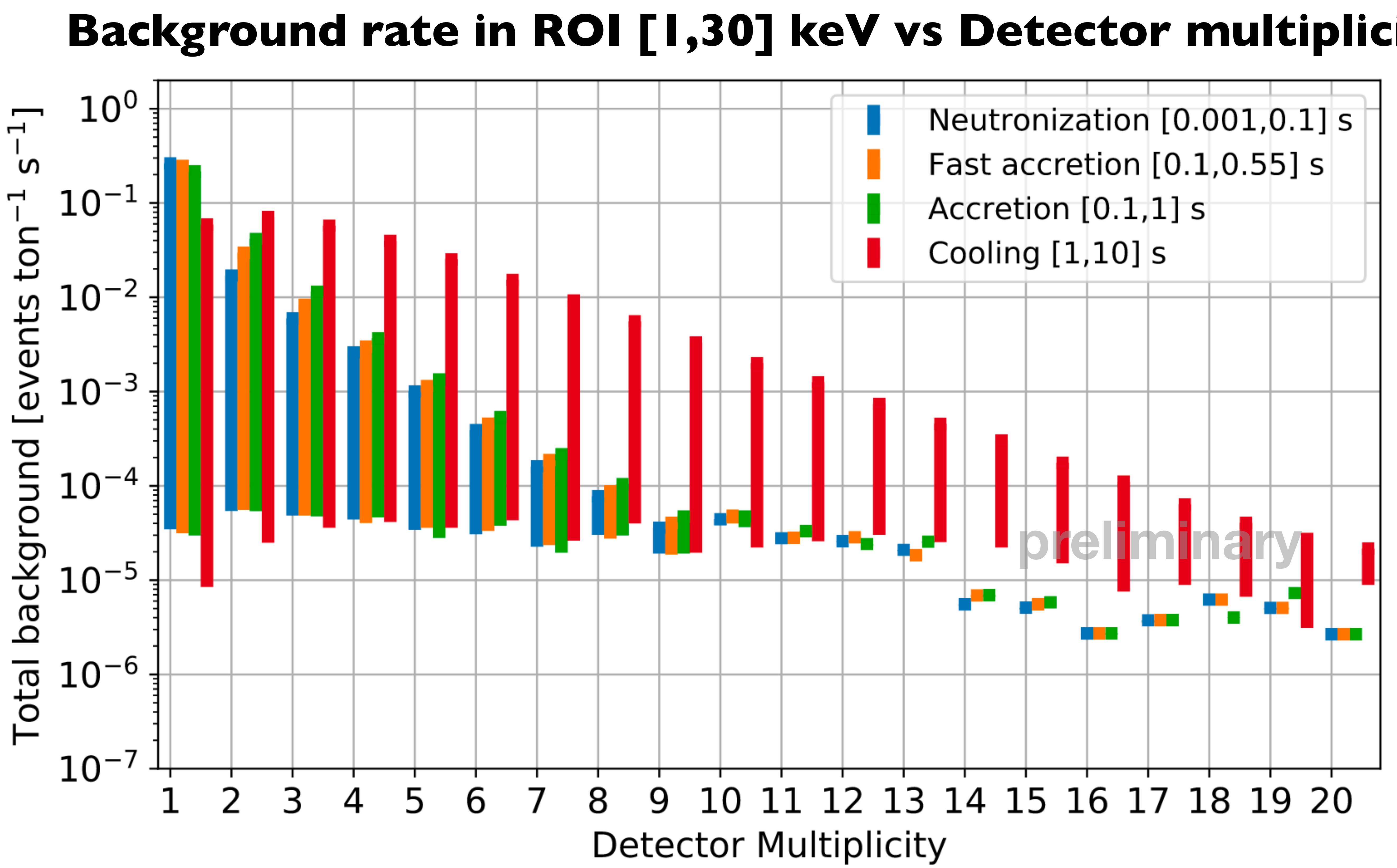
RES-NOVA time response



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

RES-NOVA background model

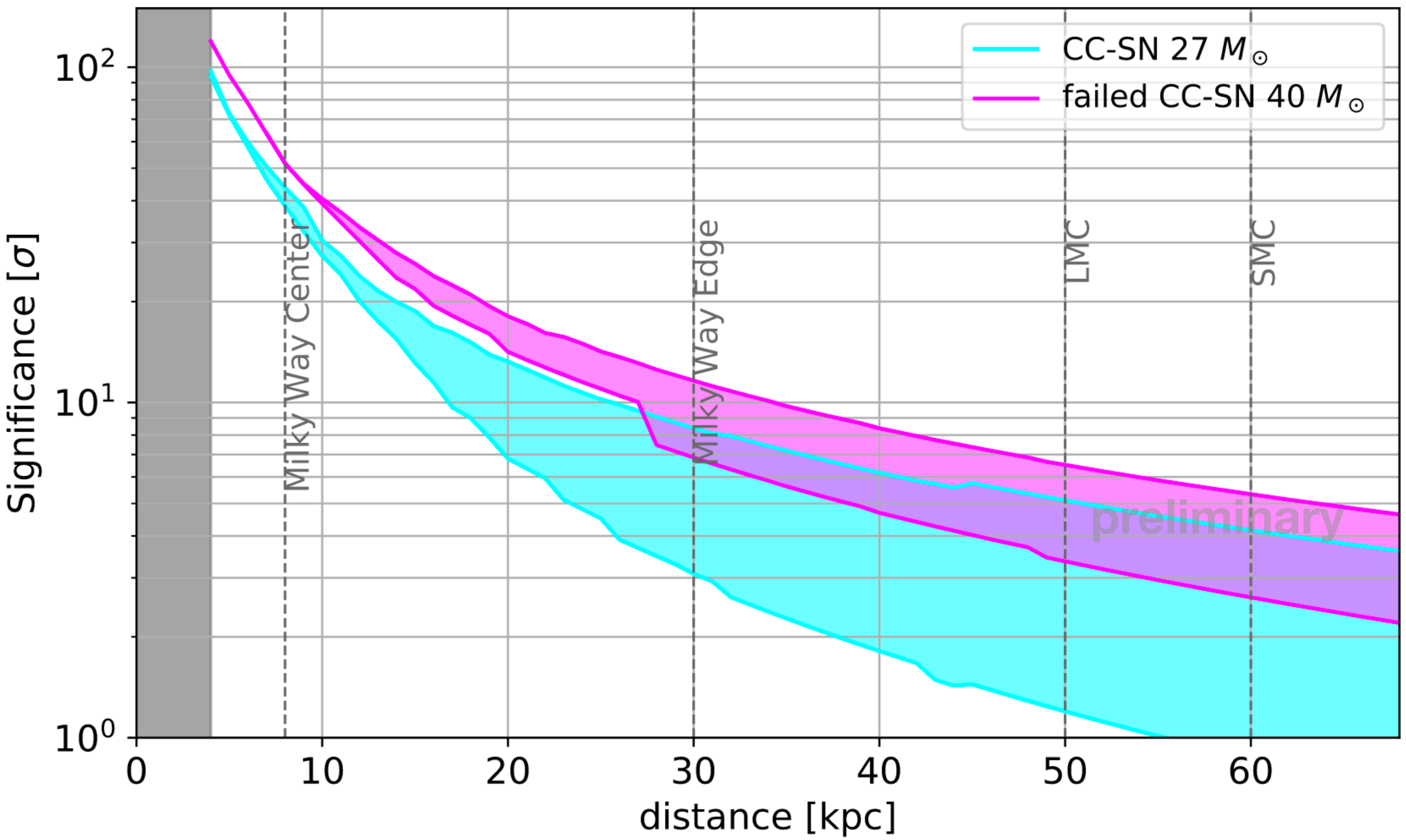
MC simulation of the detector response to radioactive background sources (no veto included)



Different signal multiplicity → Different background rate

RES-NOVA-1 sensitivity (medium-far distances)

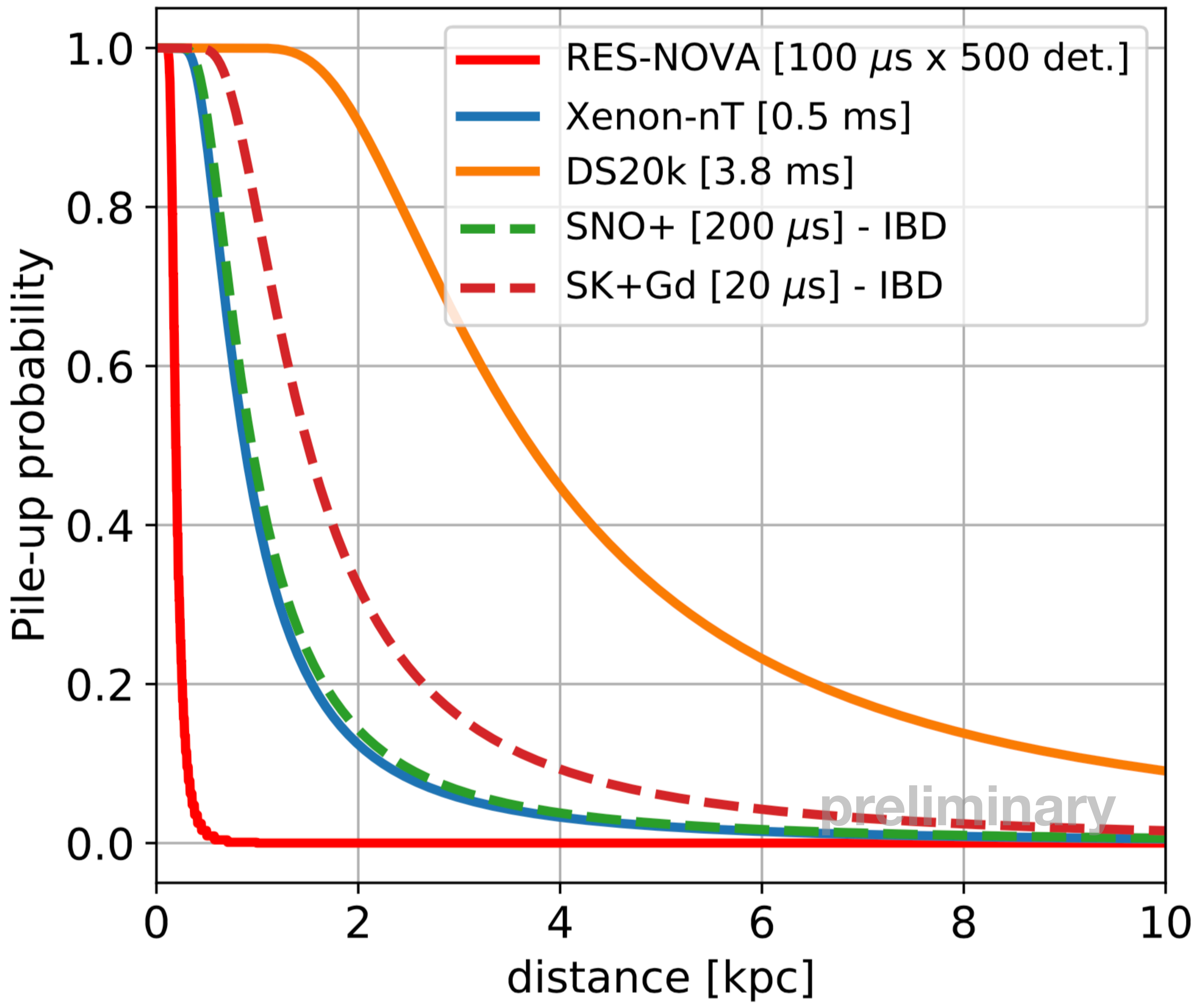
SN signal significance in RES-NOVA-1



- RN1 total active volume (60 cm)^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

RES-NOVA-1 sensitivity (near distances)

Signal (IBD) pile-up probability



- 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 ~200 μs)
  - Only "bolometric" measurement ≲ 5 kpc
- Solution: high molularity detector

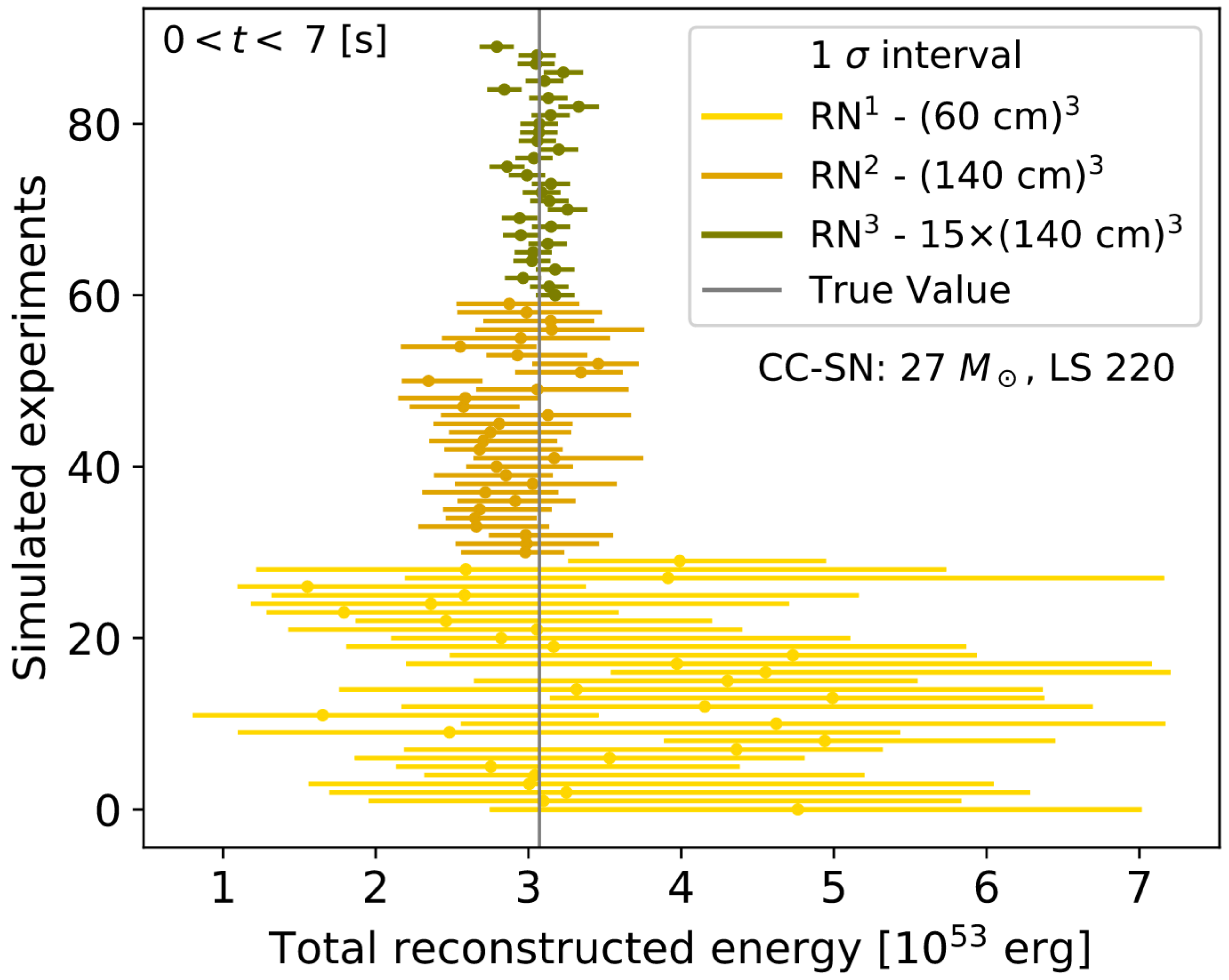
RN: CCSN total reconstructed energy

- We parametrized the neutrino energy spectrum:

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

Neutrino fluence (A_T), Normalization (ξ_T), Pinching parameter (α_T)

- $\langle \mathbf{E} \rangle$ and $\mathbf{A_T}$ are inferred by a maximum likelihood analysis
- $\boldsymbol{\alpha_T}$ 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

ν_x/anti-ν_x	
RN-1	30%
RN-2	8%
RN-3	4%

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

ν_{all}/anti-ν_{all}	
SK - IBD only	25%
SK - IBD+ES+NCR	11%

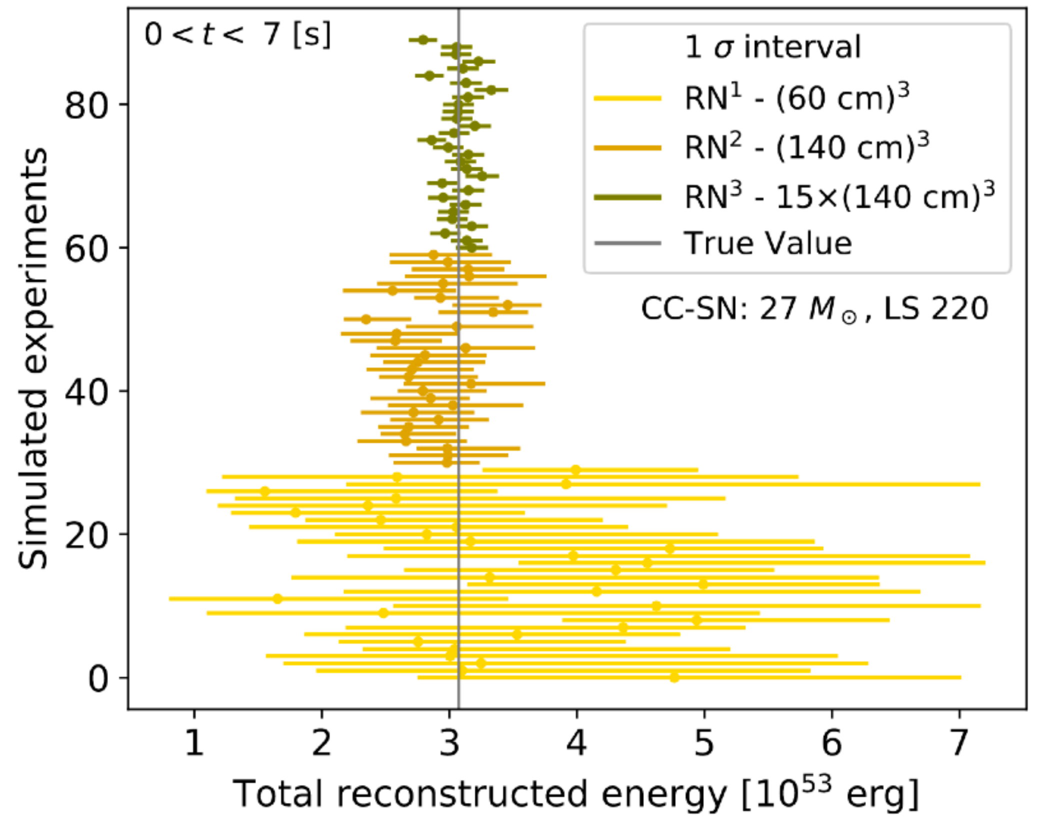
A. Gallo Rosso et al., JCAP 04 (2018) 040

Conclusions

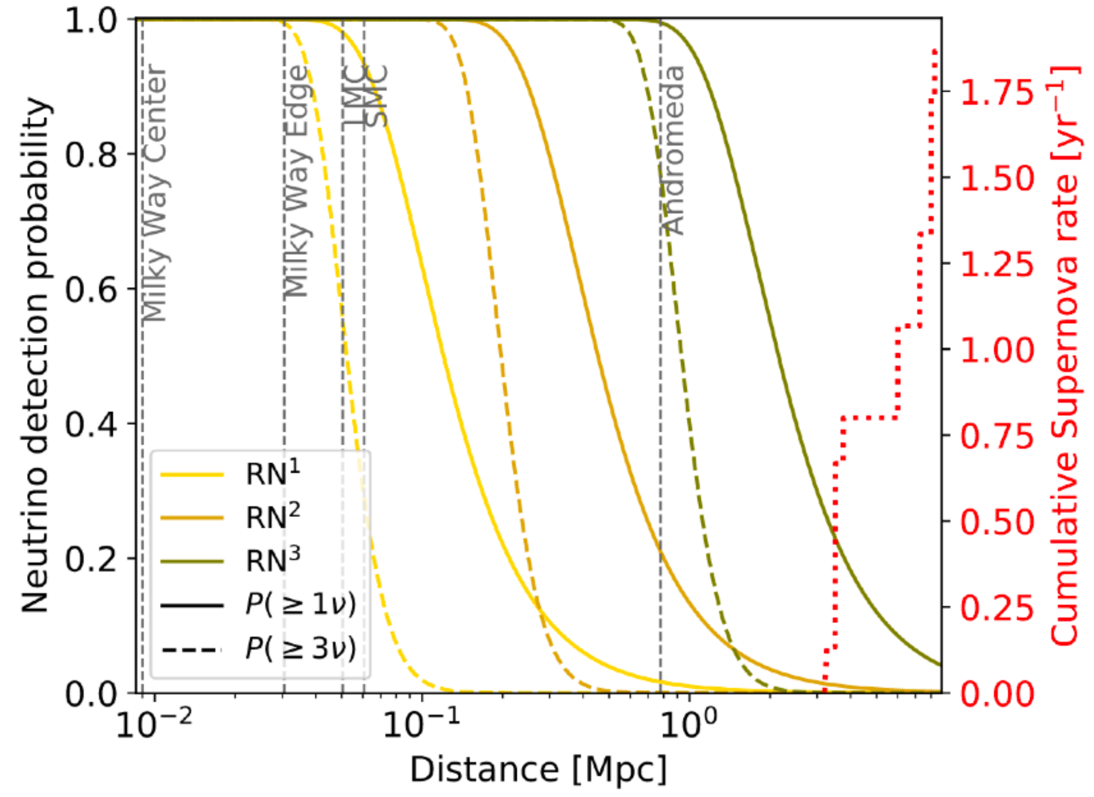
- RES-NOVA is a newly proposed underground experiment @ LNGS:
  - CEvNS + Archeo-Pb + Cryo-detectors
  - *cm-scale* neutrino telescope
- The technology for the experiment realization is already established
- RES-NOVA (and CEvNS) can provide a complementary approach to the current SN neutrino observatories
- Archaeological Pb is an ideal material for CEvNS applications

L. Pattavina, N. Ferreiro Iachellini, I. Tamborra, Phys. Rev. D 102, 063001 (2020) [ArXiv]

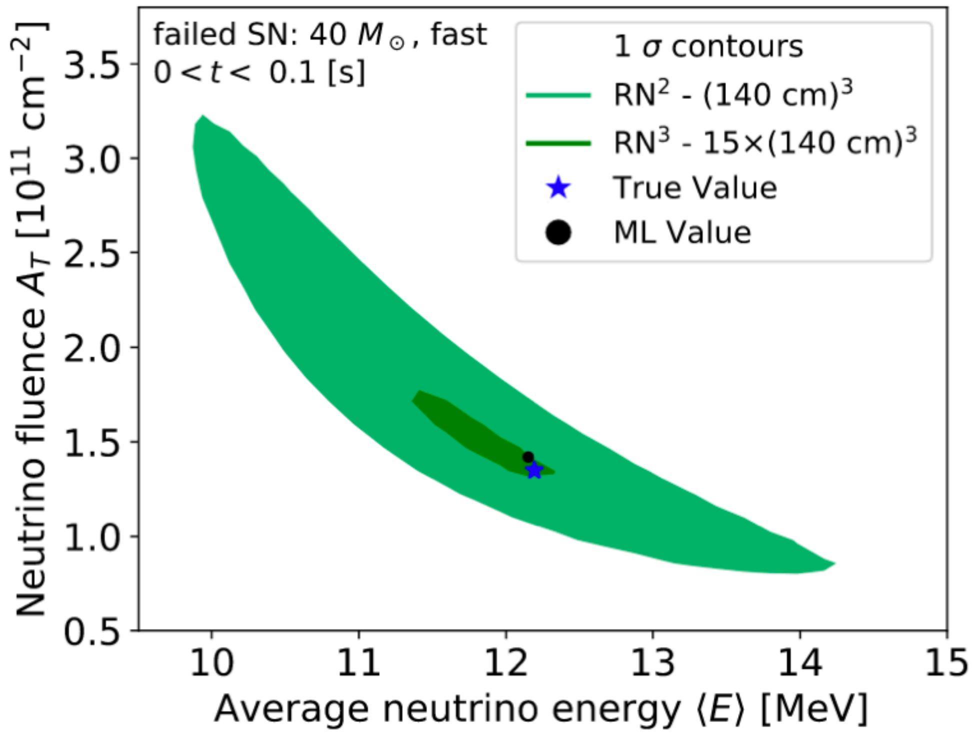
Total SN Energy



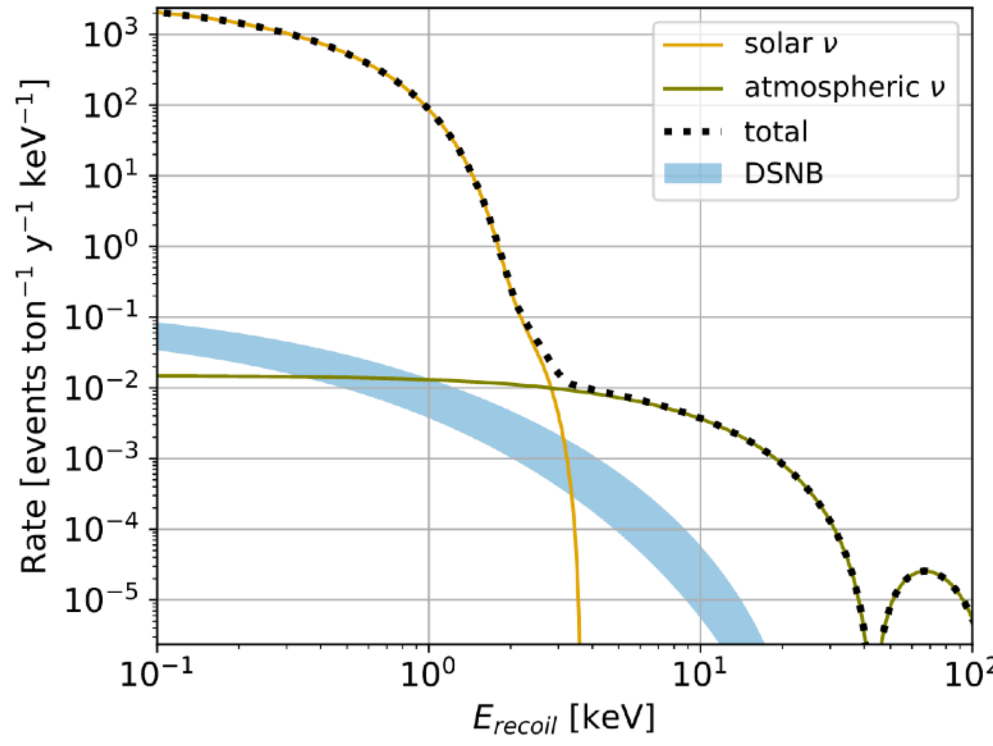
Deep space exploration



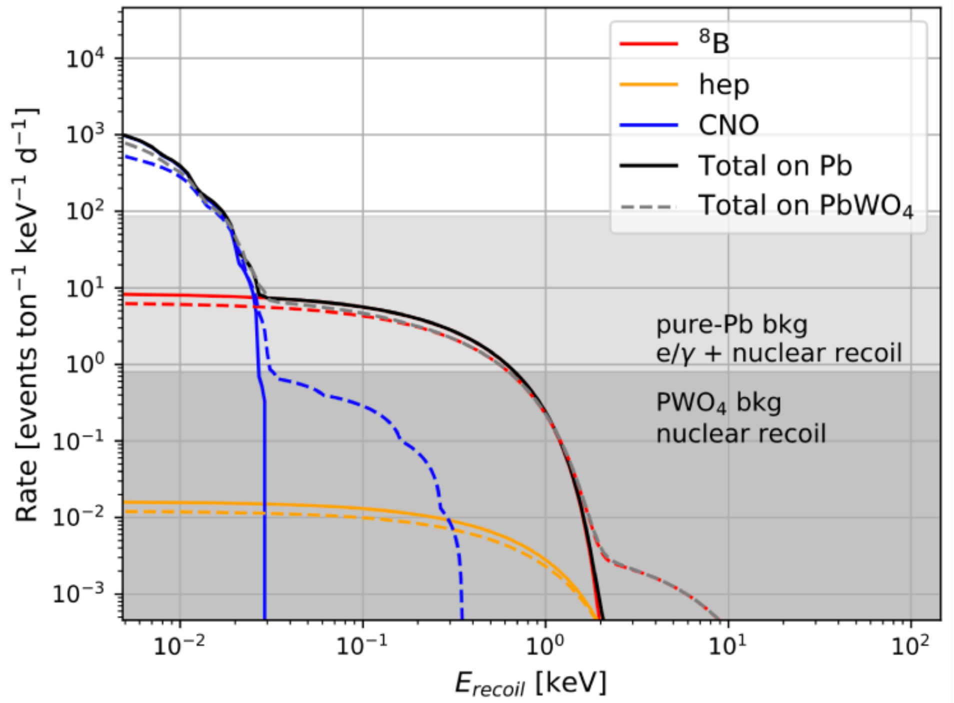
BH properties

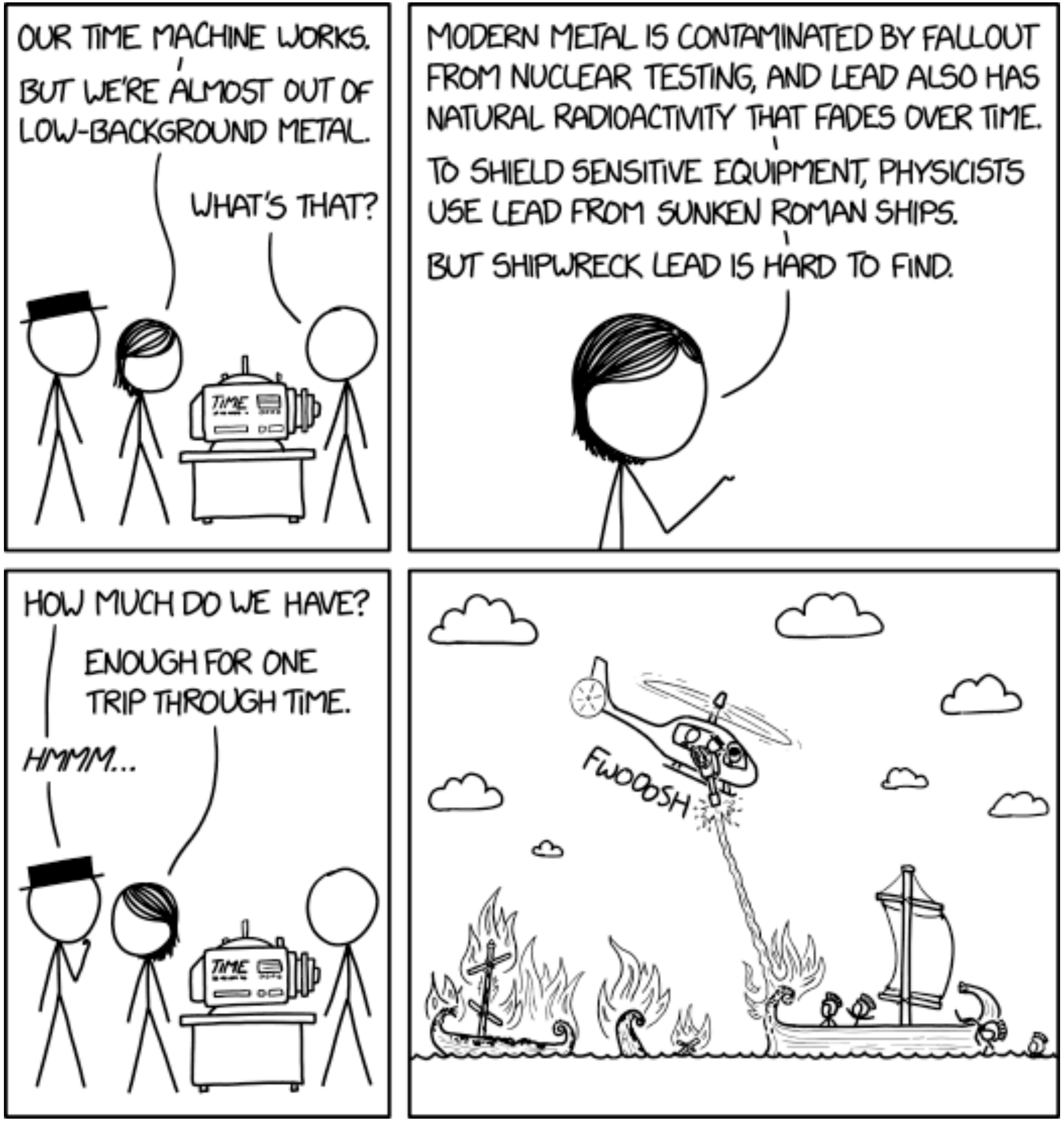


DSNB sensitivity



Solar neutrinos




OUR TIME MACHINE WORKS.
BUT WE'RE ALMOST OUT OF LOW-BACKGROUND METAL.
WHAT'S THAT?
TIME
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.
HMMM...
TIME
FWOOOSH