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Learning about Supernova Neutrinos with Xenon Dark Matter Detectors

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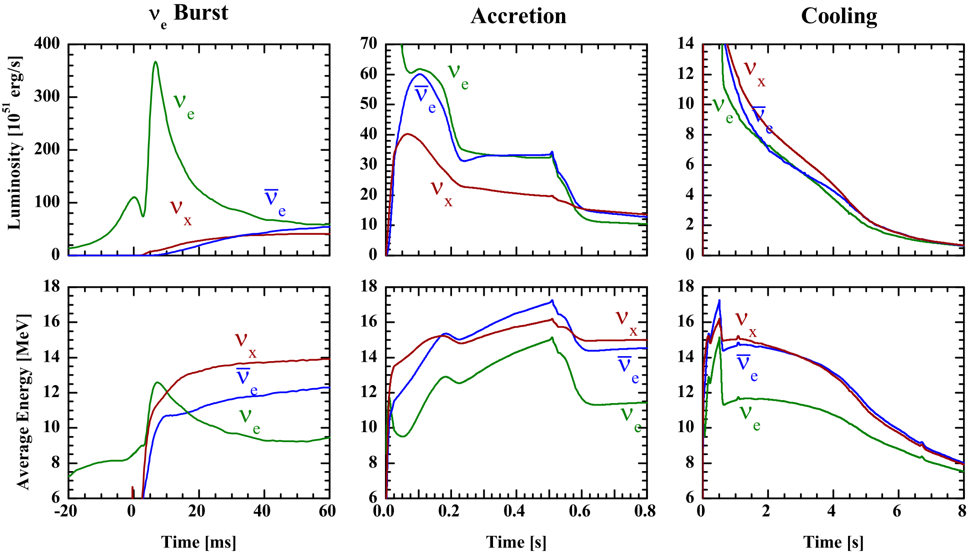
Outline

- Neutrinos from core-collapse supernovae.
- Dual phase xenon detectors.
- SN neutrino signal in a dual-phase xenon detector. What can we learn?
- Conclusions.

Based on work in collaboration with R. Lang, C. McCabe, S. Reichard and M. Selvi (arXiv: 1606.09243).

General Features of Neutrino Signal



Large ν_e luminosity peak

Large fluxes.

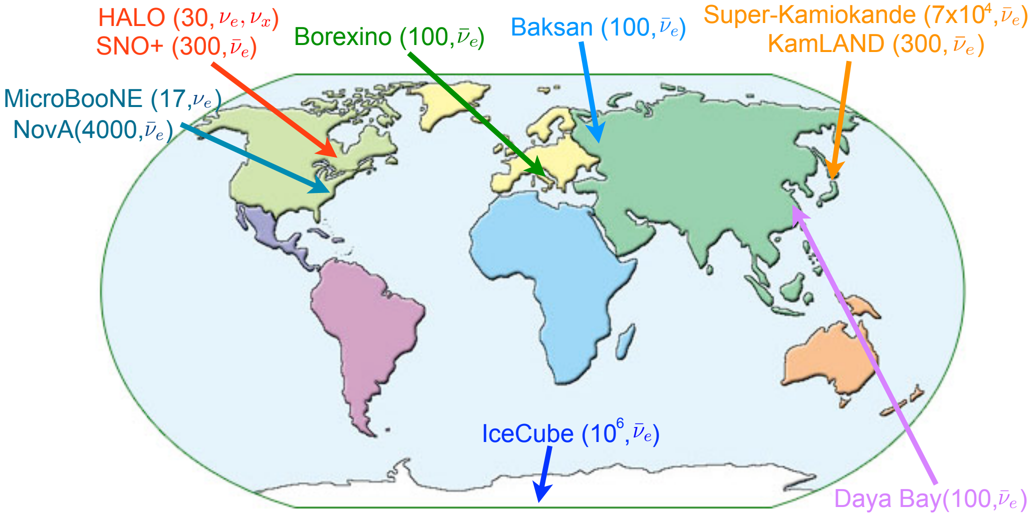
Large $\overset{(-)}{\nu}_e - \overset{(-)}{\nu}_x$ flux difference.

Smaller fluxes.

Small $\overset{(-)}{\nu}_e - \overset{(-)}{\nu}_x$ flux difference.

Figure: 1D spherically symmetric SN simulation (M=27 M_{sun}), Garching group.

Detectors Sensitive to SN Neutrinos



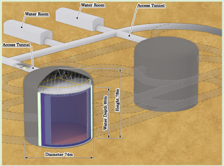
Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

Recent review papers: Scholberg (2012). Mirizzi, Tamborra, Janka, Scholberg et al. (2016).

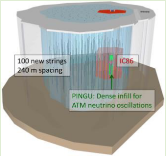
Next Generation Large Scale Detectors

Cherenkov telescopes ($\bar{\nu}_e$)

Hyper-Kamiokande (10^5)

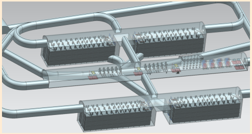


IceCube-Gen2 PINGU (10^6)



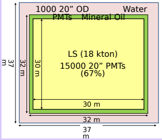
Liquid Argon detectors (ν_e)

DUNE (3000)

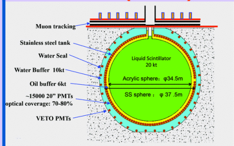


Scintillation detectors ($\bar{\nu}_e$)

RENO-50 (5400)



JUNO (6000)



Dark Matter Detectors ($\nu_{e,x}, \bar{\nu}_{e,x}$)

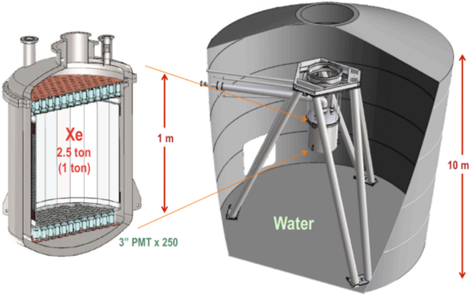
e.g., DARWIN (700)

Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

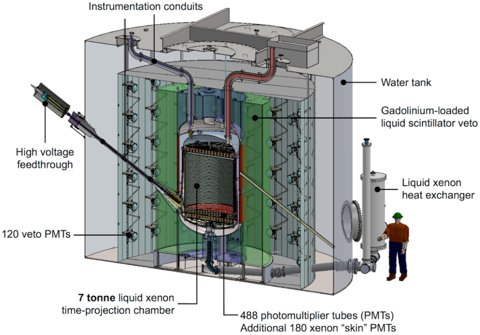
Recent review papers: Scholberg (2012). Mirizzi, Tamborra, Janka, Scholberg et al. (2016).

Dual-Phase Xenon Dark Matter Detectors

XENON1T (2 tons). Commissioning.



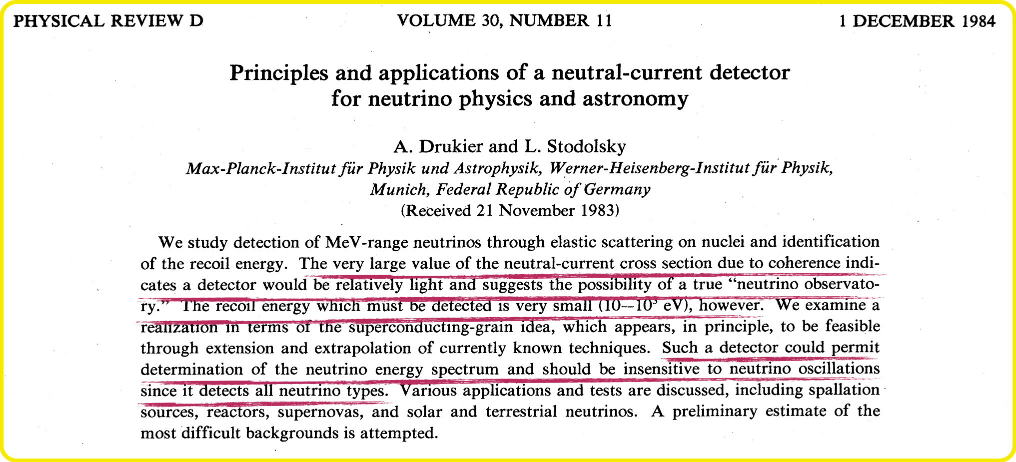
XENONnT & LZ (7 tons). In design.



DARWIN (40 tons). Early plans.

Are these detectors sensitive to SN neutrinos?

Neutrino-Nucleus Elastic Scattering



PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

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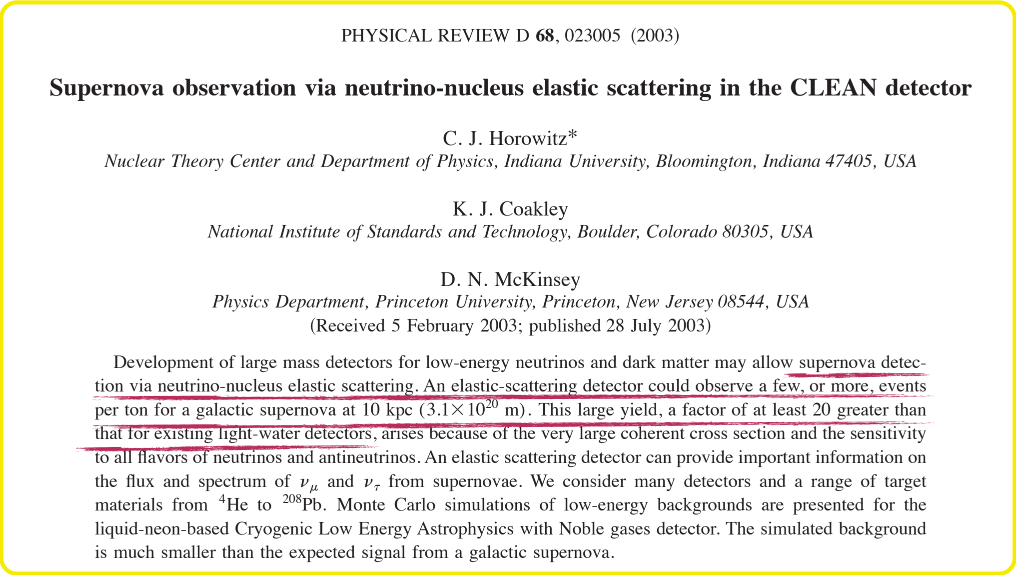
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10\text{—}10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Neutrino-Nucleus Elastic Scattering



PHYSICAL REVIEW D **68**, 023005 (2003)

Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

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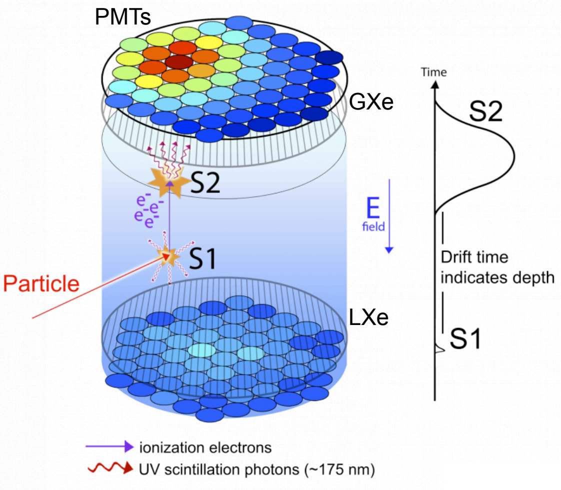
(Received 5 February 2003; published 28 July 2003)

Development of large mass detectors for low-energy neutrinos and dark matter may allow supernova detection via neutrino-nucleus elastic scattering. An elastic-scattering detector could observe a few, or more, events per ton for a galactic supernova at 10 kpc (3.1×10^{20} m). This large yield, a factor of at least 20 greater than that for existing light-water detectors, arises because of the very large coherent cross section and the sensitivity to all flavors of neutrinos and antineutrinos. An elastic scattering detector can provide important information on the flux and spectrum of ν_μ and ν_τ from supernovae. We consider many detectors and a range of target materials from ^{4}He to ^{208}Pb. Monte Carlo simulations of low-energy backgrounds are presented for the liquid-neon-based Cryogenic Low Energy Astrophysics with Noble gases detector. The simulated background is much smaller than the expected signal from a galactic supernova.

See also Beacom, Farr & Vogel, PRD (2002).

Dual-Phase Xenon Detectors



S1= Prompt scintillation light (in LXe).

S2= Ionization charge signal converted to scintillation signal (in GXe).

Recoil energy from a WIMP particle: $E_{\mathrm{R}} \sim 2.4\ \mathrm{keV} \left(\frac{m_{\mathrm{DM}}}{5\ \mathrm{GeV}}\right)^2$

Recoil energy from a SN neutrino: $E_{\mathrm{R}} \sim 2.4\ \mathrm{keV} \left(\frac{E_\nu}{12\ \mathrm{MeV}}\right)^2$

Comparable recoil energies.

Because of low background, all Xe instrumented volume can be used for SN neutrinos.

Supernova Neutrino Inputs

Four 1D simulations to gauge astrophysical uncertainty of the expected signal:

- Two progenitor masses (11 & 27 M_{sun})
- Two equations of state (LS220 & Shen EoS).

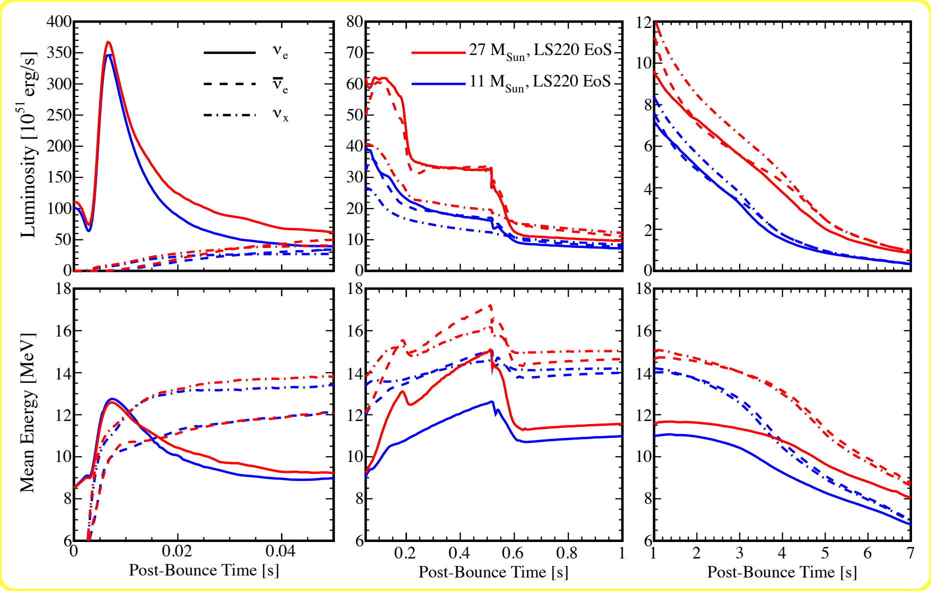


Figure: 1D spherically symmetric SN simulations, Garching group.

Scattering Rates

Recoil differential rate

$$\frac{d^2R}{dE_{\rm R}dt_{\rm pb}} = \sum_{\nu_\beta} N_{\rm Xe} \int_{E_\nu^{\rm min}} dE_\nu \, f^0_{\nu_\beta}(E_\nu, t_{\rm pb}) \frac{d\sigma}{dE_{\rm R}}$$

$$E_\nu^{\rm min} \simeq \sqrt{m_N E_R/2}$$

Coherent elastic neutrino-nucleus cross-section

$$\frac{d\sigma}{dE_{\rm R}} = \frac{G_F^2 m_{\rm N}}{4\pi} Q_W^2 \left(1 - \frac{m_{\rm N} E_{\rm R}}{2E_\nu^2}\right) F^2(E_{\rm R})$$

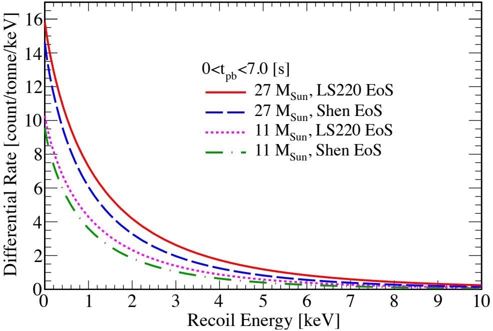
$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

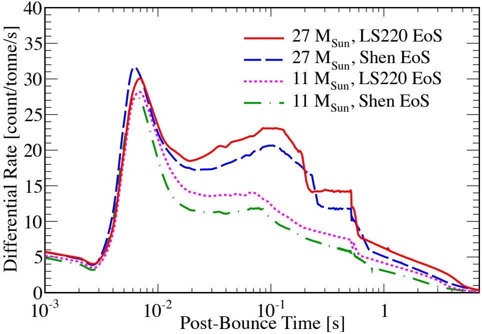
$$F(E_{\rm R}) = \frac{3j_1(qr_n)}{qr_n} \exp\left(-\frac{(qs)^2}{2}\right)$$

Differential rate as a function of the measured S1 and S2 signals

$$\frac{d^2R}{d{\rm S1}d{\rm S2}} = \int dt_{\rm pb} dE_{\rm R} \, {\rm pdf}\left({\rm S1}, {\rm S2}|E_{\rm R}\right) \frac{d^2R}{dE_{\rm R}dt_{\rm pb}}$$

Recoil Spectra

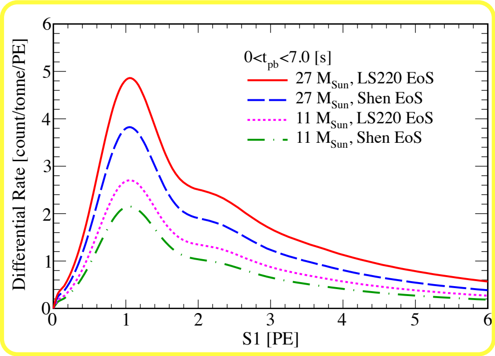


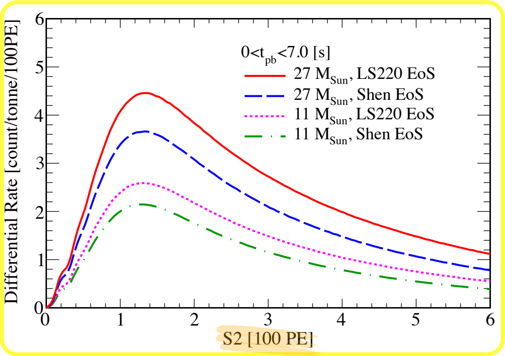


Different progenitors are distinguishable. Neutrino light-curve is reconstructable.

Observable Signals

The measured signal is the one in the S1 and S2 channels rather than the recoil spectrum.





An S2-only search is optimal for SN neutrinos. By combining S1&S2, event rate is ~ 2-3 times lower.

Observable Signals

Number of events/tonne for a SN at 10 kpc.

	27 $\mathrm{M}_\odot$		11 $\mathrm{M}_\odot$	
	LS220 EoS	Shen EoS	LS220 EoS	Shen EoS
$\mathrm{S1}_{\mathrm{th}}$ [PE]				
≥ 0	26.9	21.4	15.1	12.3
> 0	13.3	9.8	6.9	5.2
1	11.0	8.0	5.6	4.1
2	7.3	5.1	3.6	2.6
3 ($\star$)	5.2	3.5	2.4	1.7
$\mathrm{S2}_{\mathrm{th}}$ [PE]				
≥ 0	26.9	21.4	15.1	12.3
> 0	18.5	14.0	9.9	7.6
20	18.4	14.0	9.8	7.6
40	18.1	13.7	9.7	7.4
60 ($\star$)	17.6	13.3	9.4	7.2
80	17.0	12.8	9.0	6.9
100	16.3	12.2	8.6	6.5

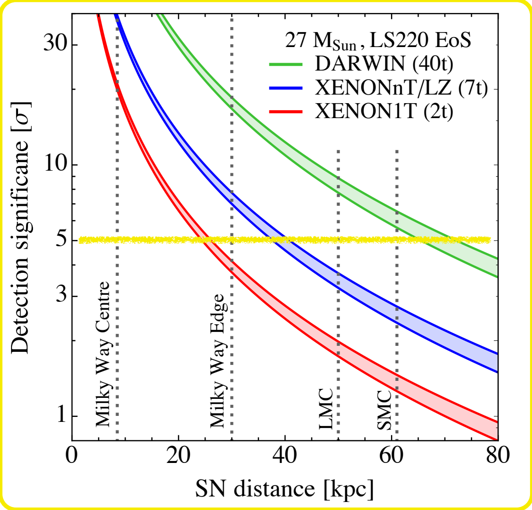
S2 background rate is small compared to signal.

Background (XENON10, XENON 100): $\mathcal{O}(10^{-2})$ events/tonne/s.

Signal: 1-2.5 events/tonne/s.

What Could We Learn?

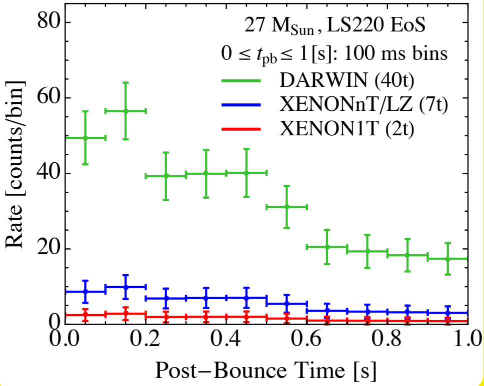
Detection Significance



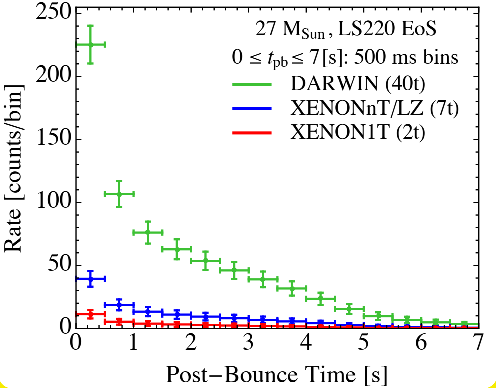
DARWIN will be sensitive to a SN burst up to the Small Magellanic Cloud.

Neutrino Light Curve

Accretion phase



Kelvin-Helmholtz cooling phase



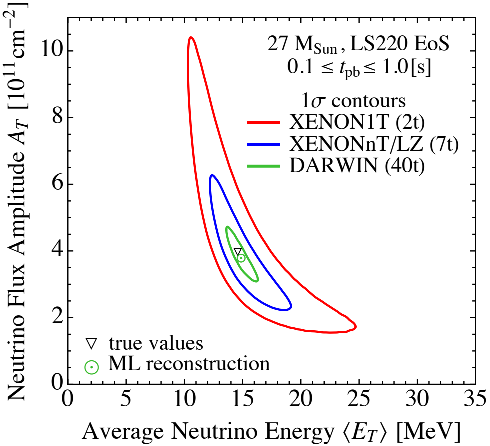
DARWIN will be able to clearly reconstruct the neutrino light-curve and to differentiate among phases of neutrino signal. Partial sensitivity with XENONnT/LZ.

Excellent timing resolution: $\mathcal{O}(100)\mu\mathrm{s}$.

Neutrino Spectral Information

Ansatz on flux parametrization for time-integrated flux:

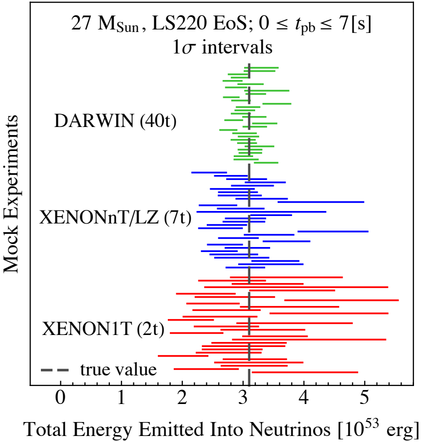
$$A_T \, \xi_T \left(\frac{E_\nu}{\langle E_T\rangle}\right)^{\alpha_T} \exp\left(\frac{-(1+\alpha_T)E_\nu}{\langle E_T\rangle}\right) \quad \text{with} \quad \alpha_T = 2.3$$



Excellent reconstruction of neutrino properties with DARWIN. Good prospects for XENON1T.

Supernova Explosion Energy

$$E_{\text{tot}} = \sum_{\nu_\beta} \int_{0\,s}^{7\,s} dt_{\text{pb}}\, L_{\nu_\beta}(t_{\text{pb}}) = 4\pi d^2 A_T \langle E_T \rangle$$



Precision

~ 5%

~ 10%

~ 20%

Excellent reconstruction of energy emitted into neutrinos with DARWIN. Good for XENON1T.

Summary of Physics Reach

For a SN at 10 kpc from Earth:

	High significance discovery	Light curve reconstruction	Total nu-energy reconstruction	nu-spectrum reconstruction
XENON1T (2t)	✔	✗	~	~
XENONnT/LZ (7t)	✔	~ ✗	~ ✔	~ ✔
DARWIN (40t)	✔	✔	✔	✔

Table: Courtesy of C. McCabe.

Conclusions

- First self-consistent modeling of the SN neutrino signal in dual-phase Xe detectors.

- SN neutrinos will be detectable through proportional scintillation signal (S2) with low-energy threshold and negligible background.

- Features in the neutrino light curve can be discriminated with next-generation Xe detectors.

- Neutrino emission properties can be reconstructed.

- Xenon detectors sensitive to all neutrino flavors. Complementary information wrt to dedicated flavor-sensitive detectors.

Thank you for your attention!