Supernova Neutrino Physics with XENON1T and Beyond

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nuEclipse
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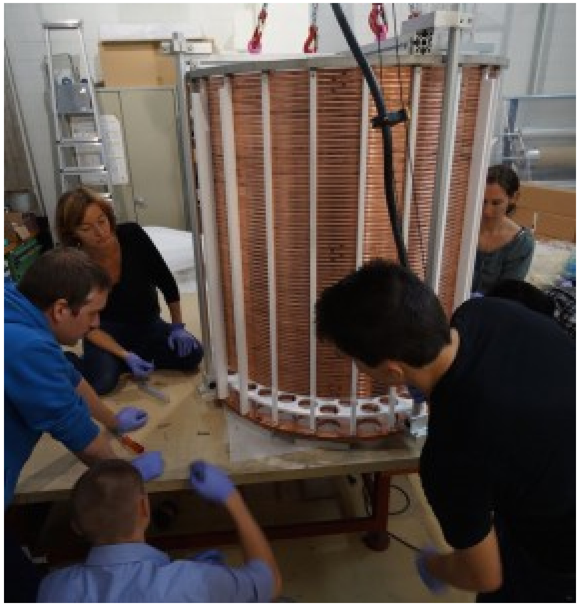
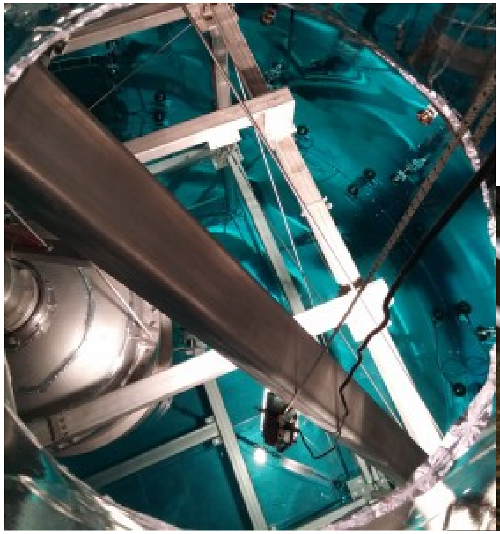
Phys. Rev. D94, arXiv:1606.09243

*Members of the XENON collaboration

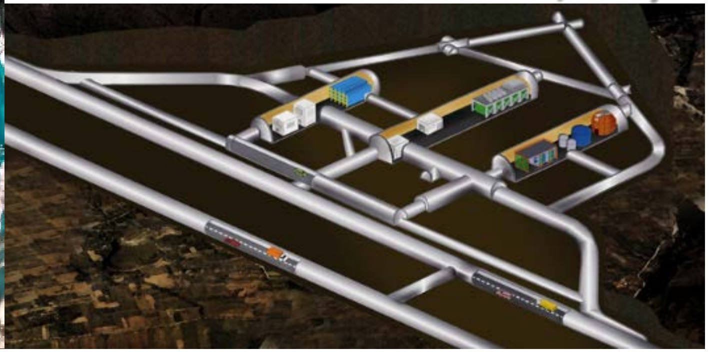
The XENON1T Experiment

- Liquid-Gas Time Projection Chamber
- Xenon Target
- Dark Matter (WIMPs)
- Nuclear Recoils
- **Acquiring data since November 2016**

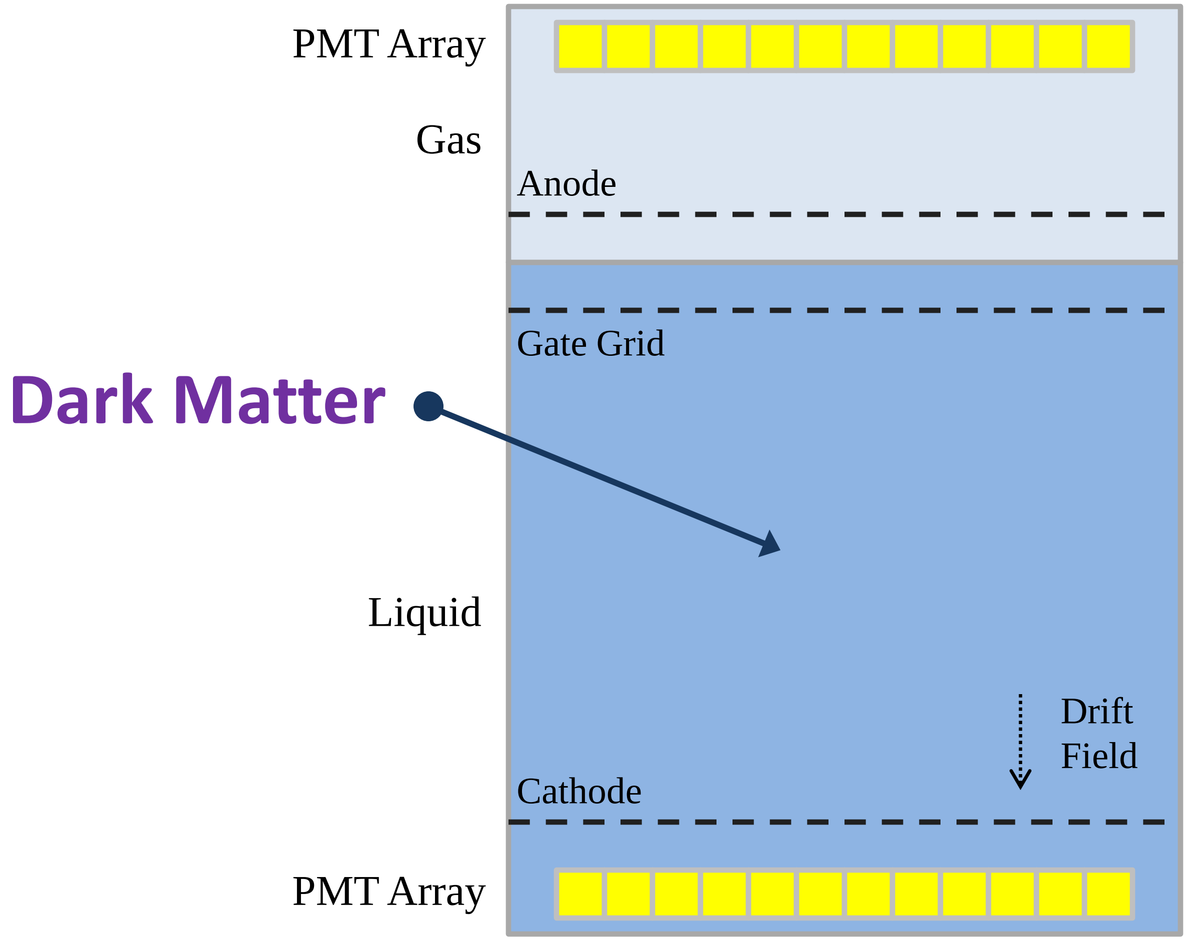




Laboratori Nazionali del Gran Sasso, Italy

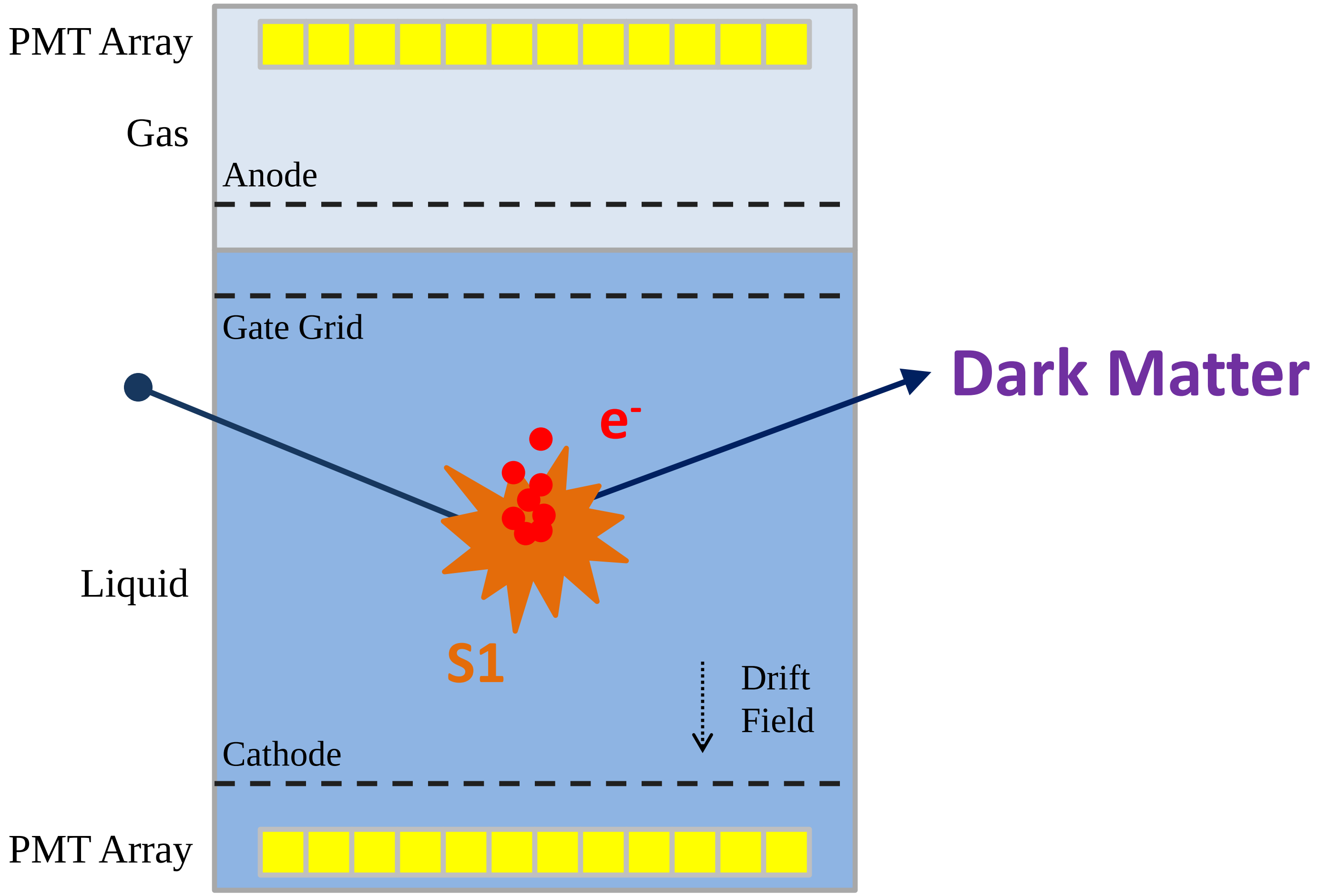


Detection Principle

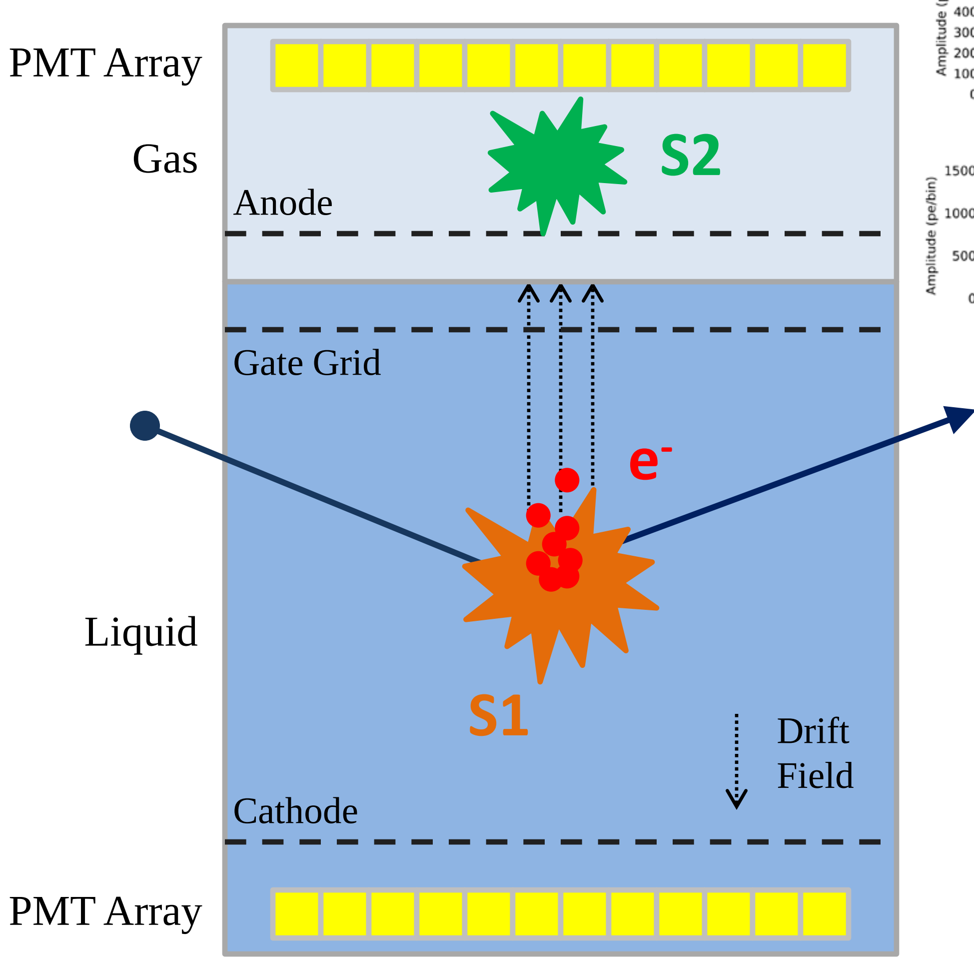


Detection Principle

Prompt Scintillation Signal

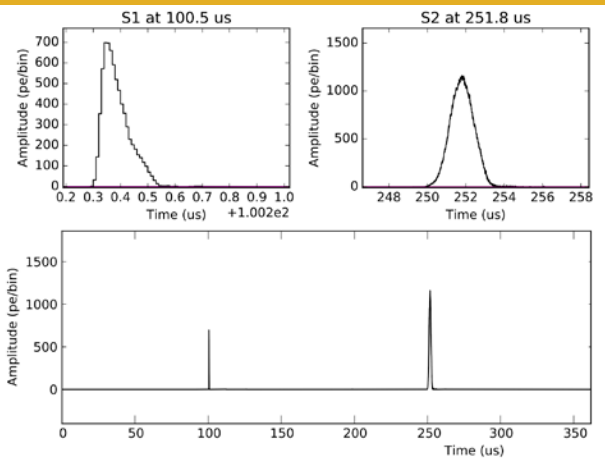


Detection Principle



Prompt Scintillation Signal

Proportional Scintillation Signal



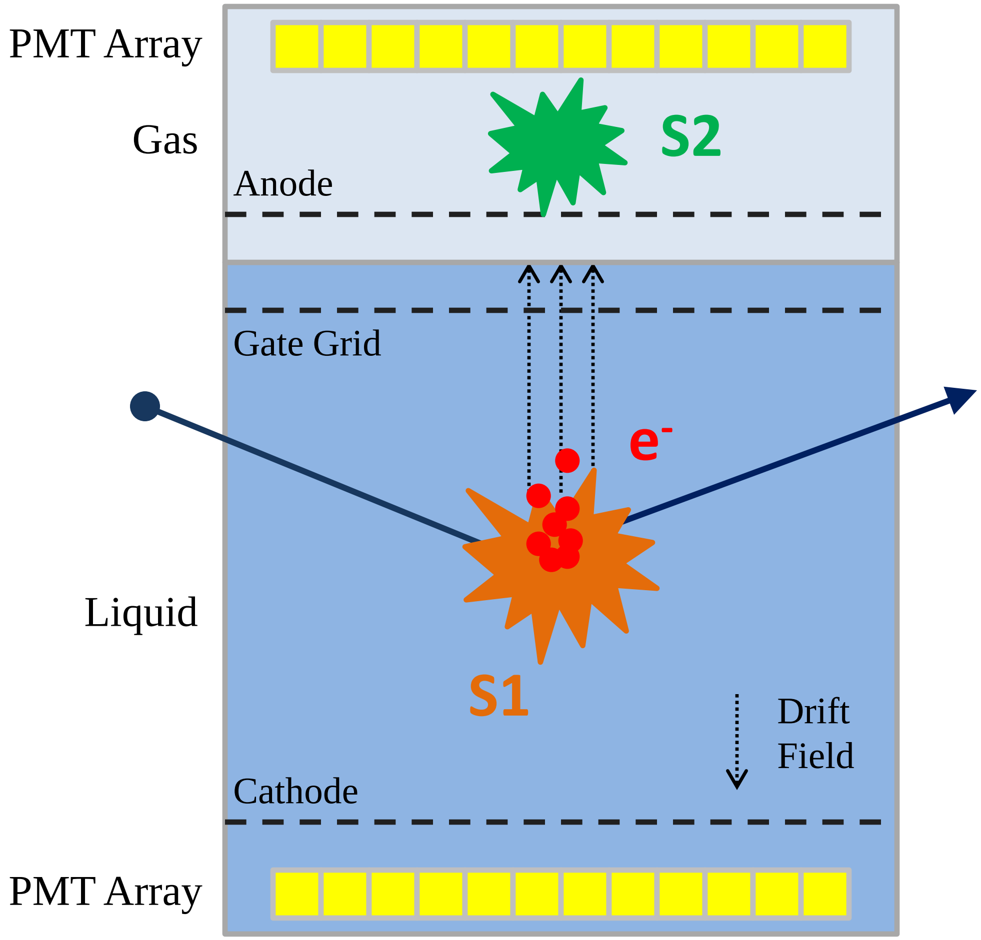
Dark Matter

Interaction: Unknown

Detection Principle

Prompt Scintillation Signal

Proportional Scintillation Signal



Similar to low-mass WIMP signal (require S2-only analysis)

SN neutrino

Interaction: Z-exchange (neutral current)

Old Idea...

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

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

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

- Benefit from coherence factor
- Equally sensitive to all flavors
- Known response to neutrinos

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

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

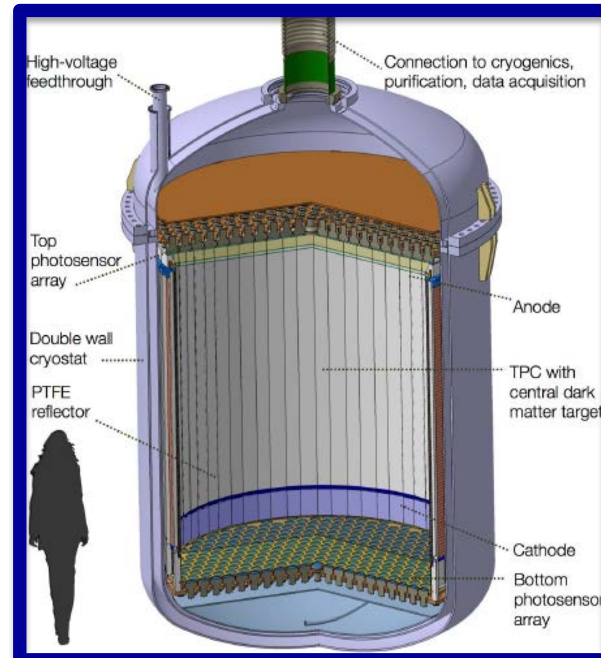
C. J. Horowitz K. J. Coakley D. N. McKinsey

- A few or more neutrino events per tonne (SN@10 kpc)

… New Relevance

The era of tonne-scale dark matter experiments:

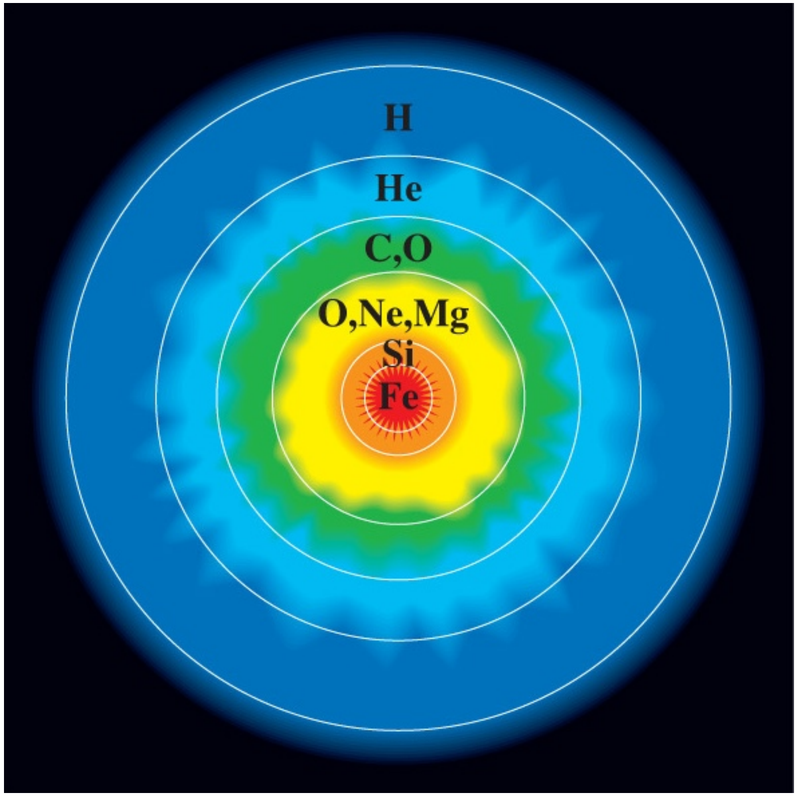
- XENON1T (~2t): operational since April 2016
- XENONnT & LZ (~7t): in design phase
- DARWIN (~40t): in R&D phase



What can we do with these experiments?

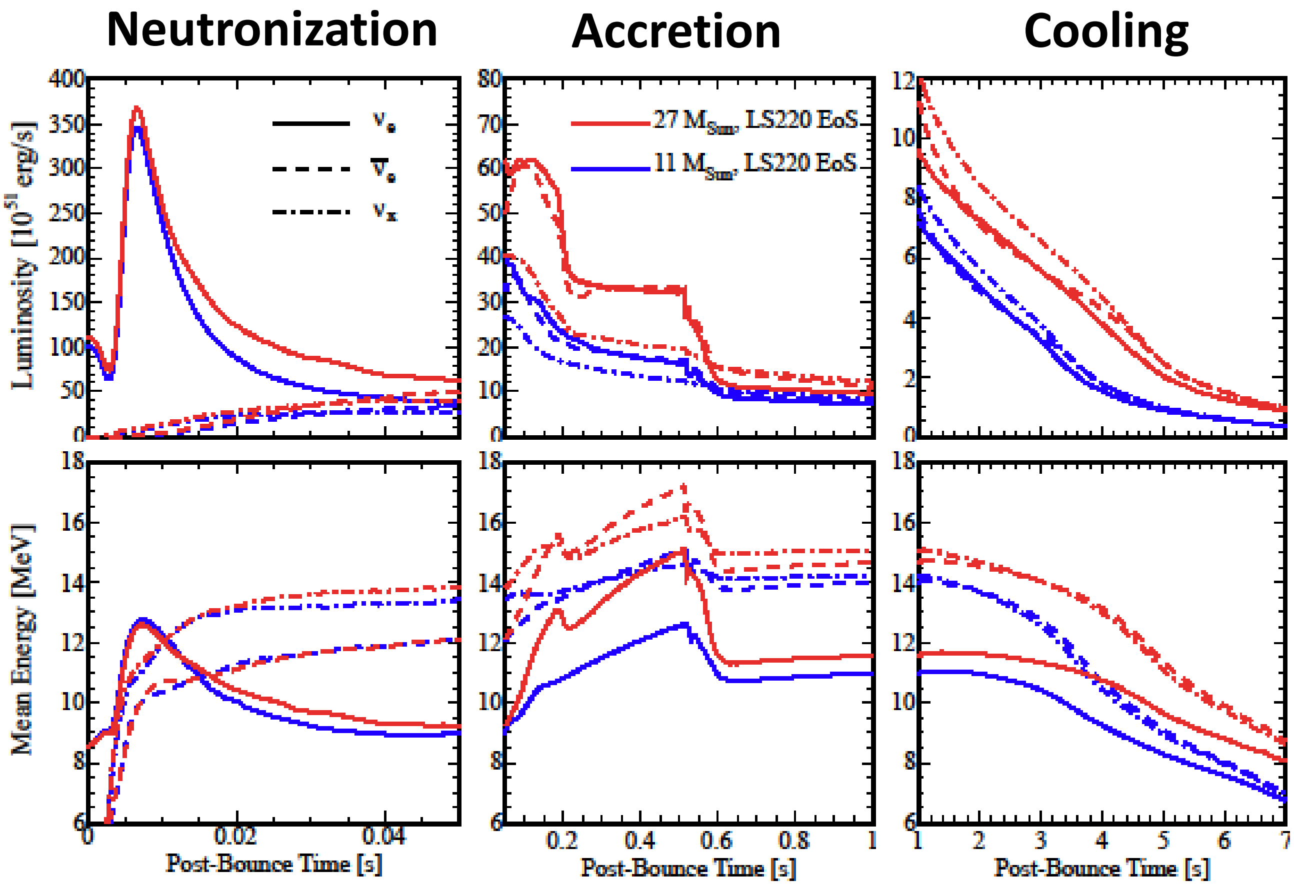
Supernova Burst

- Early detection
- Determine progenitor mass
- Identify equation of state
- Reconstruct the light curves
- Measure the total energy
- Measure the flux

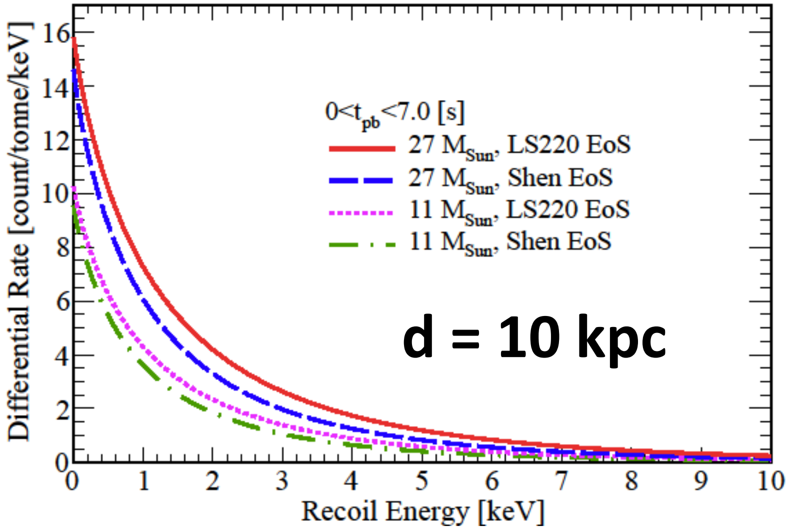


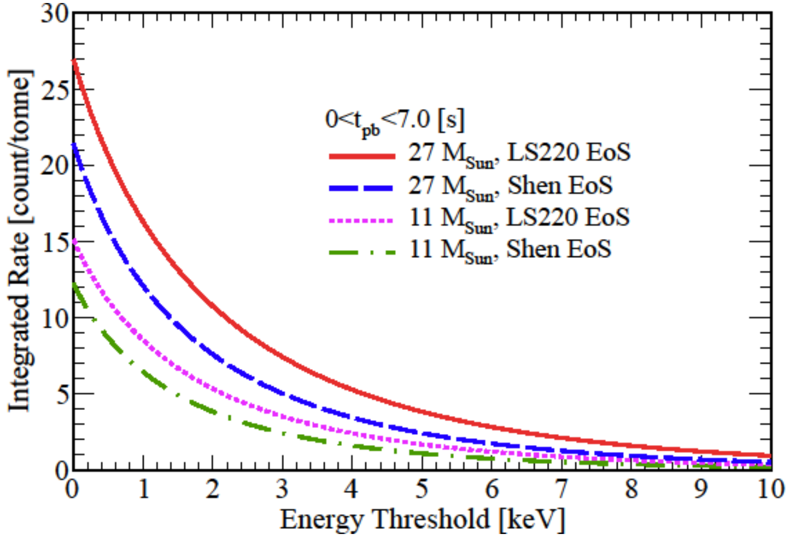
Supernova Progenitors

Two masses (11M, 27M); two equations of state (**LS220**, Shen)



Event Rates





- Coherent Elastic Neutrino-Nucleus Scattering* in LXe

$$\frac{dR}{dE_R} \propto \frac{d\sigma}{dE_R} \propto N^2$$

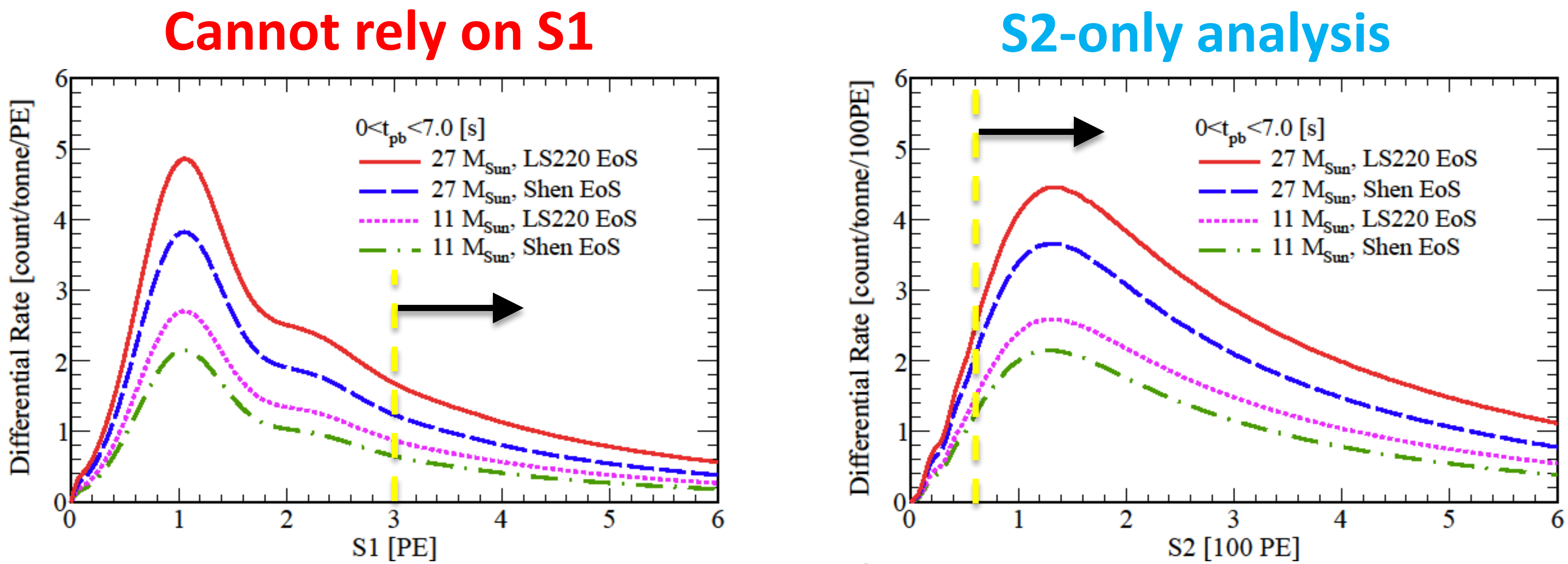
- Large rate at low energies

- Push energy threshold

*2 tonnes with coherence is like 100 tonnes without coherence

Observable Signals

- First realistic detailed simulation
- 0.7-keV cutoff for both light yield (L_y) and charge yield (Q_y)
- 60-PE threshold in S2 (**three** extracted electrons)



E_{th} = 0.7 keV

Results

	$27\ M_\odot$		$11\ M_\odot$	
	LS220 EoS	Shen EoS	LS220 EoS	Shen EoS
$S1_{th}$ [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
$S2_{th}$ [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

*Events/tonne for SN at **10 kpc** given S1 and S2 thresholds*

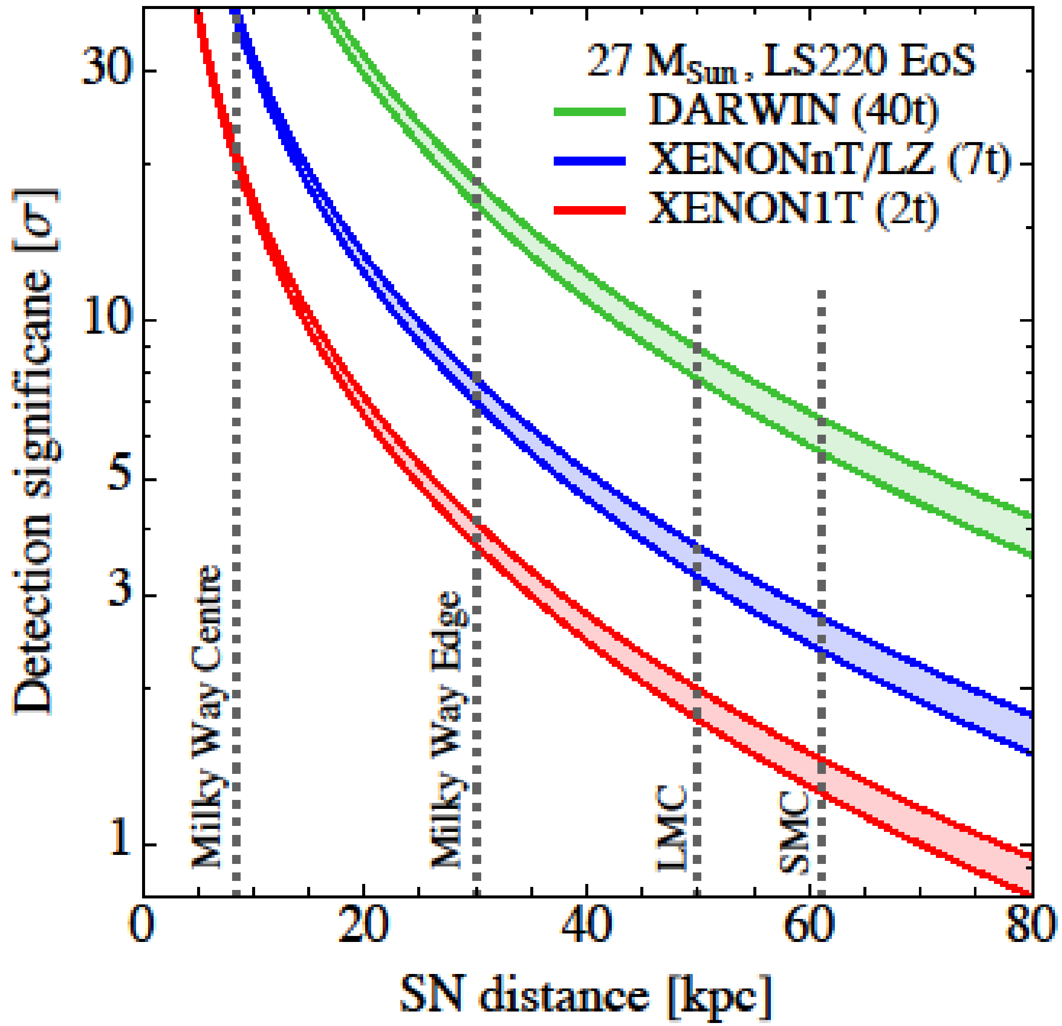
- **S2-only** analysis
- See 14-35 events in XENON1T, assuming…
  - 0.7-keV recoil threshold
  - 60-PE S2 threshold
  - 2-tonne target

Significance

- Background rate: 0.1-0.2 events/tonne

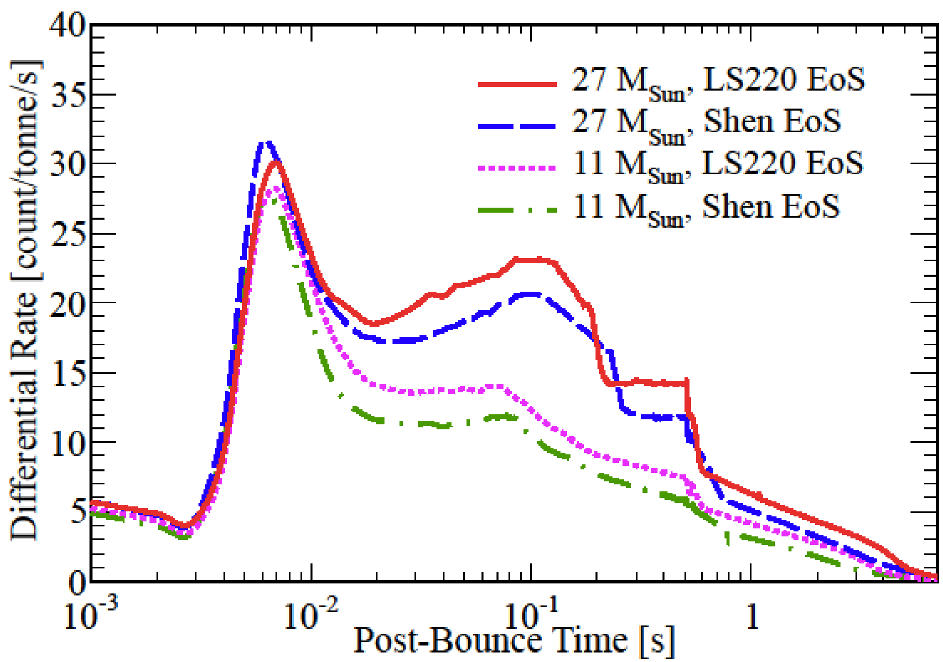
- XENON1T can observe the entire Milky Way at better than 3σ

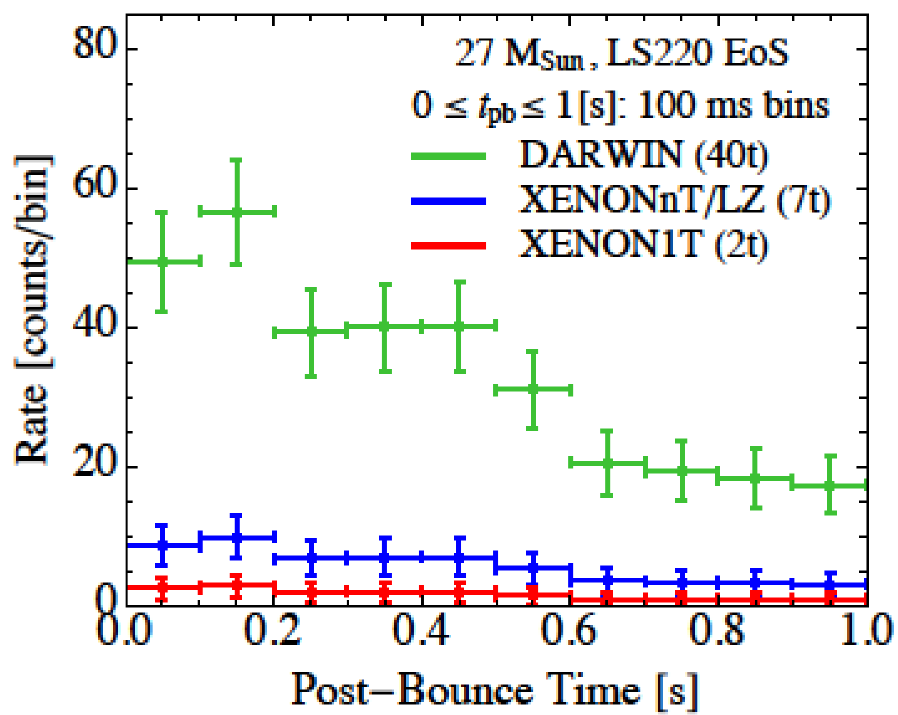
- DARWIN could see the Small Magellanic Cloud at better than 5σ



Light Curves

- Discern progenitor mass at 3.8σ, 7.1σ, and 16.9σ
- Need DARWIN to reconstruct SN light curves (and EoS)

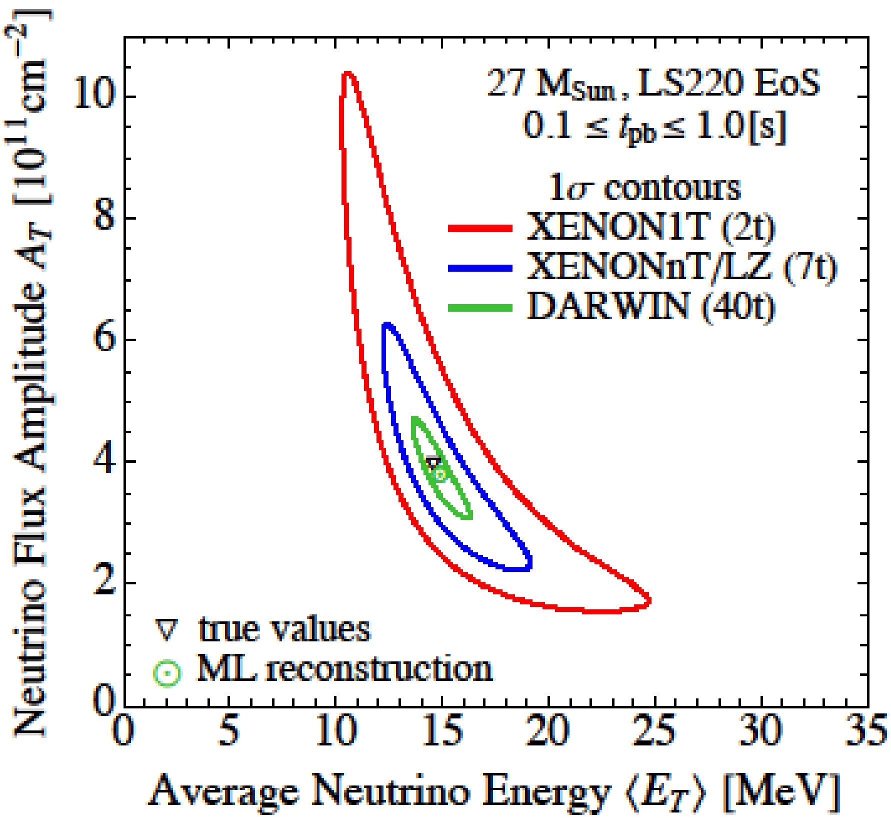




Reconstructing Neutrino Energy

$$F(E_\upsilon) = A_T \xi_T \left(\frac{E_\upsilon}{\langle E_T \rangle} \right)^{\alpha_T} \exp\left(\frac{-(1+\alpha_T) E_\upsilon}{\langle E_T \rangle} \right)$$

Use S2 spectral information



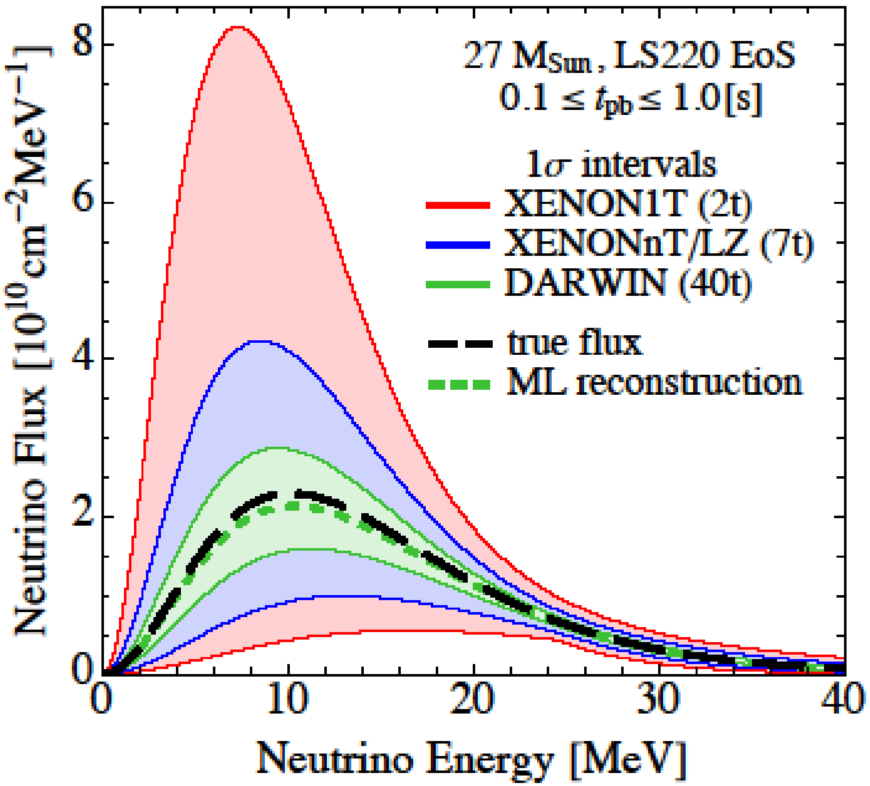
$\alpha_T = 2.3$

Fermi-Dirac distribution with zero chemical potential

Reconstructing the Flux

$$F(E_\upsilon) = A_T \xi_T \left(\frac{E_\upsilon}{\langle E_T \rangle} \right)^{\alpha_T} \exp\left(\frac{-(1+\alpha_T) E_\upsilon}{\langle E_T \rangle} \right)$$

Use S2 spectral information

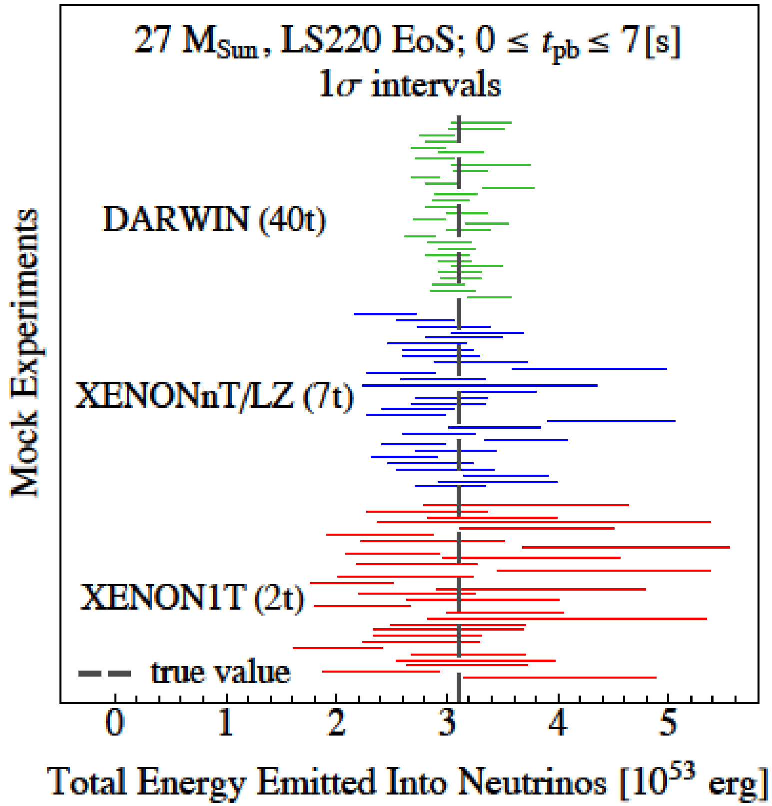


Propagate 1σ contours

Total Explosion Energy in Neutrinos

$$E_{tot} = 4\pi d^2 A_T \langle E_T \rangle$$

Uncertainties are propagated from flux amplitude and mean energy



XENON1T	**20-36%**
XENONnT/LZ	**11-20%**
DARWIN	**5-9%**

Summary

	High Detection Significance	Light Curve Reconstruction	Total Neutrino Energy Reconstruction	Neutrino Spectrum Reconstruction
XENON1T	✓	✗	~	~
XENONnT & LZ	✓	~	~	~
DARWIN	✓	✓	✓	✓

SuperNova Early Warning System

- Detectors that are sensitive to core-collapse supernovae
- Neutrinos precede photons by as much as several hours
- Alert astronomers to impending SN

Integrating XENON1T into SNEWS

- Negligible background
- Detection significance better than 3σ throughout Milky Way

- Equip XENON1T to receive SNEWS trigger
- Measure background (also during calibration campaigns) to establish that we can provide an alarm to SNEWS

Conclusions

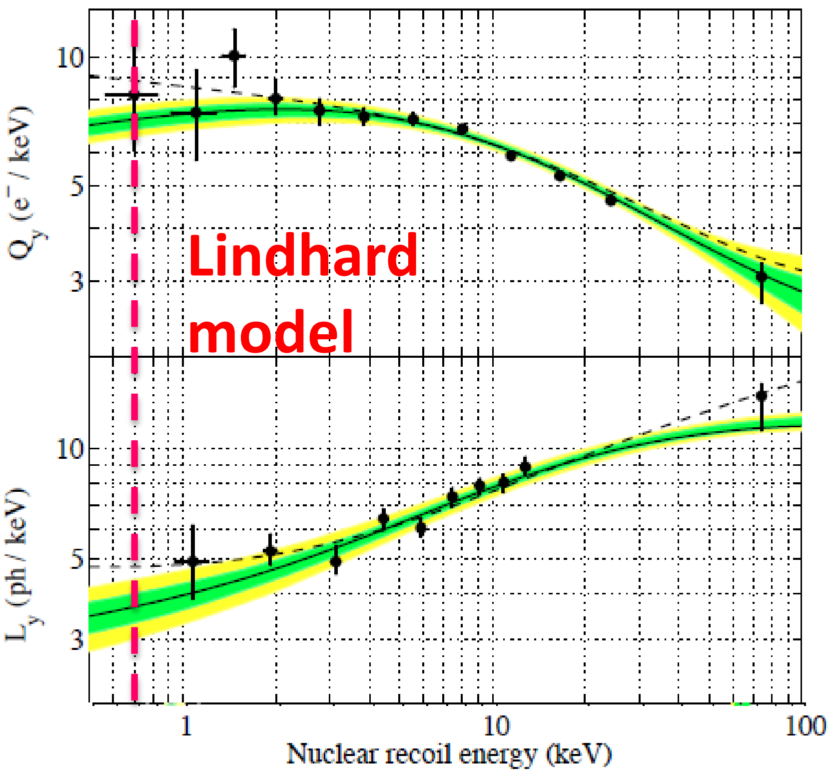
- XENON1T is operational with sensitivity to SN neutrinos
- First realistic detector simulation of S1 and S2 signals
  - Optimize the signal with S2-only analysis
  - High detection significance (>3σ across Milky Way)
- Integration of XENON1T into SNEWS
- Distinguishable SN phases
- High-precision measurements of energy and flux
- Complementarity: only completely flavor-insensitive experiment

R. F. Lang, C. McCabe, S. Reichard, M. Selvi, and I. Tamborra, Phys. Rev. D94 (2016), arXiv:1606.09243

Backup

Signal Generation

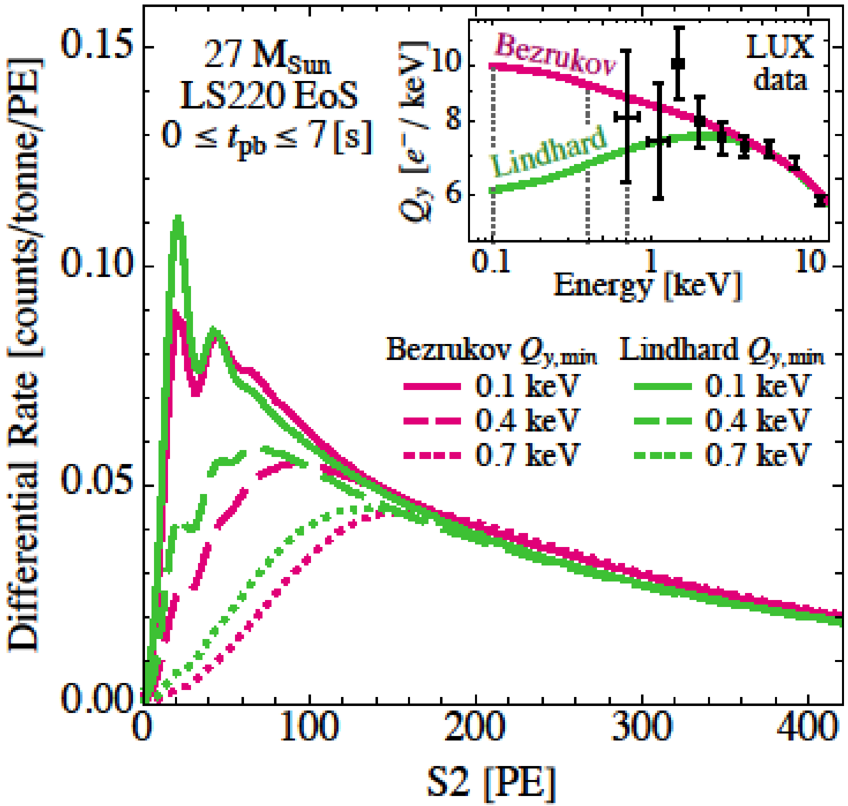
- **LUX** emission models
  - photons
  - electrons
- Statistical fluctuations
- Photon detection efficiency
- PMT response
- Electron loss from impurities
- Assume $\Delta z/\tau$ uniformly distributed on [0,2/3] mm/us



arXiv:1512.03506

Different Qy Models

o Variations in the cutoff of Q_y are larger than those of the chosen model



uncertainty from our choice of Q_y 5-13%