

Fermilab

Detecting Late-Time Neutrinos from Core-Collapse Supernovae

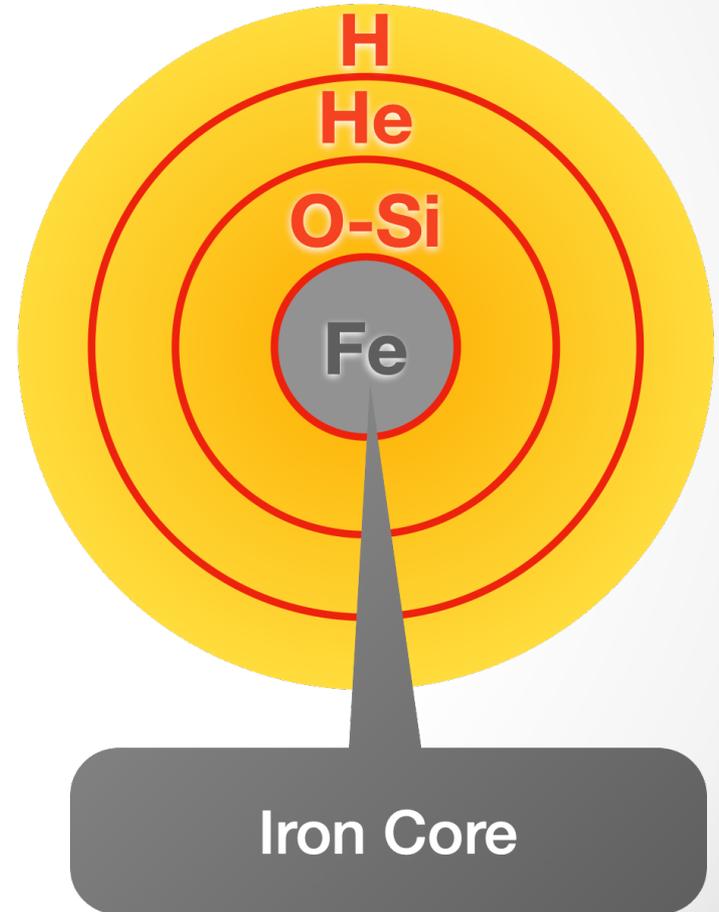
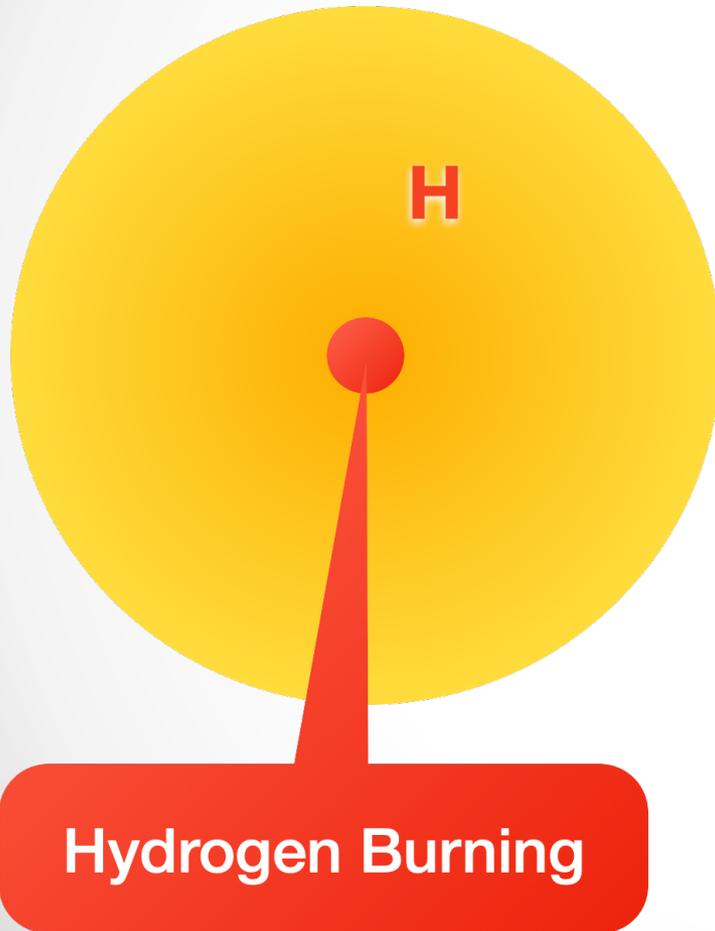
Shirley Li

2008.04340 w/ L. Roberts, J. Beacom

Fermilab, March 2021

Core-Collapse Supernovae

The End of Massive Stars ($> 8 M_{\odot}$)



Figures remade from Raffelt's talk

Core-Collapse Supernovae

The End of Massive Stars ($> 8 M_{\odot}$)



Figures remade from Raffelt's talk

WHY?

- How Do Massive Stars Die?
- Production Sites of Heavy Elements
- Supernova Remnants--Acceleration of Cosmic Rays
- Properties of Neutron Stars/Pulsars, Black Holes
- Possible Production Sites of Light Particles

Compute Theoretically, Confirm Experimentally

SN 2030?

...

Comparisons

SN 1987A

- $\bar{\nu}_e$ only
- 50 kpc
- ~ 20 events
- ~ 10 s

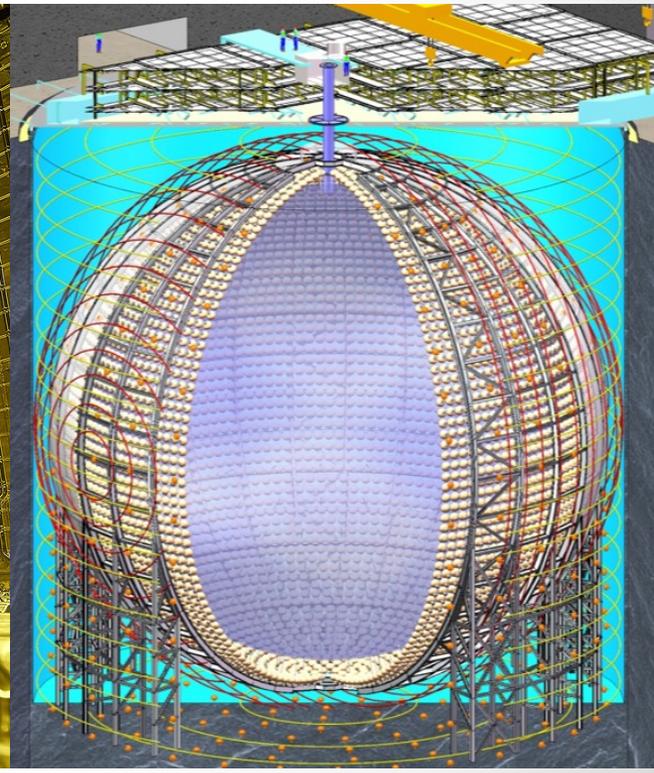
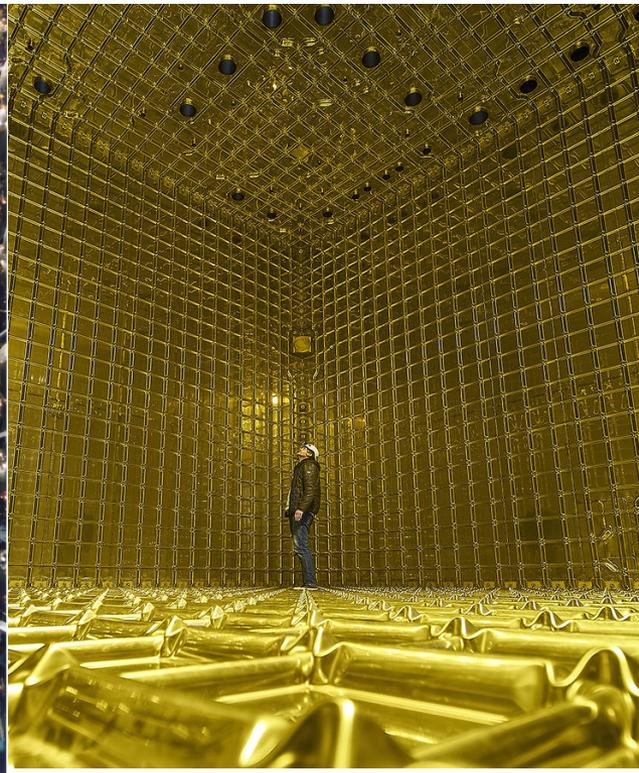
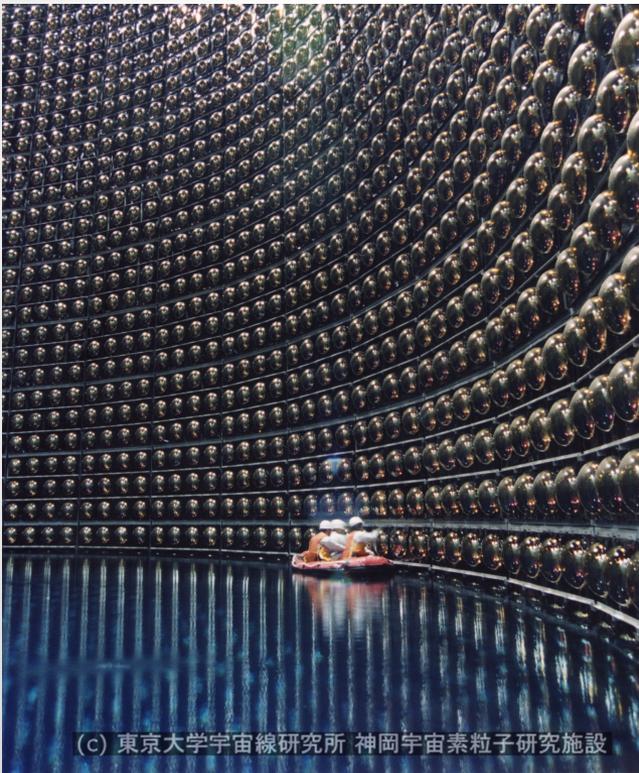
SN 2030?

- $\bar{\nu}_e$, ν_e , and ν_x
- ~ 10 kpc
- $\sim 10,000$ events
- ~ 1 min

Precision Measurements

ν_x means ν_μ , $\bar{\nu}_\mu$, ν_τ , $\bar{\nu}_\tau$

We May Have Only One Chance



(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

Not Clear Whether There Will Be Successors

Galactic CCSN

How Often?

$$3.2^{+7.3}_{-2.6}$$

Adams et al., 2013

$$2.8^{+0.6}_{-0.6}$$

(with a systematic
uncertainty of a
factor of ~ 2)

Li et al., 2011

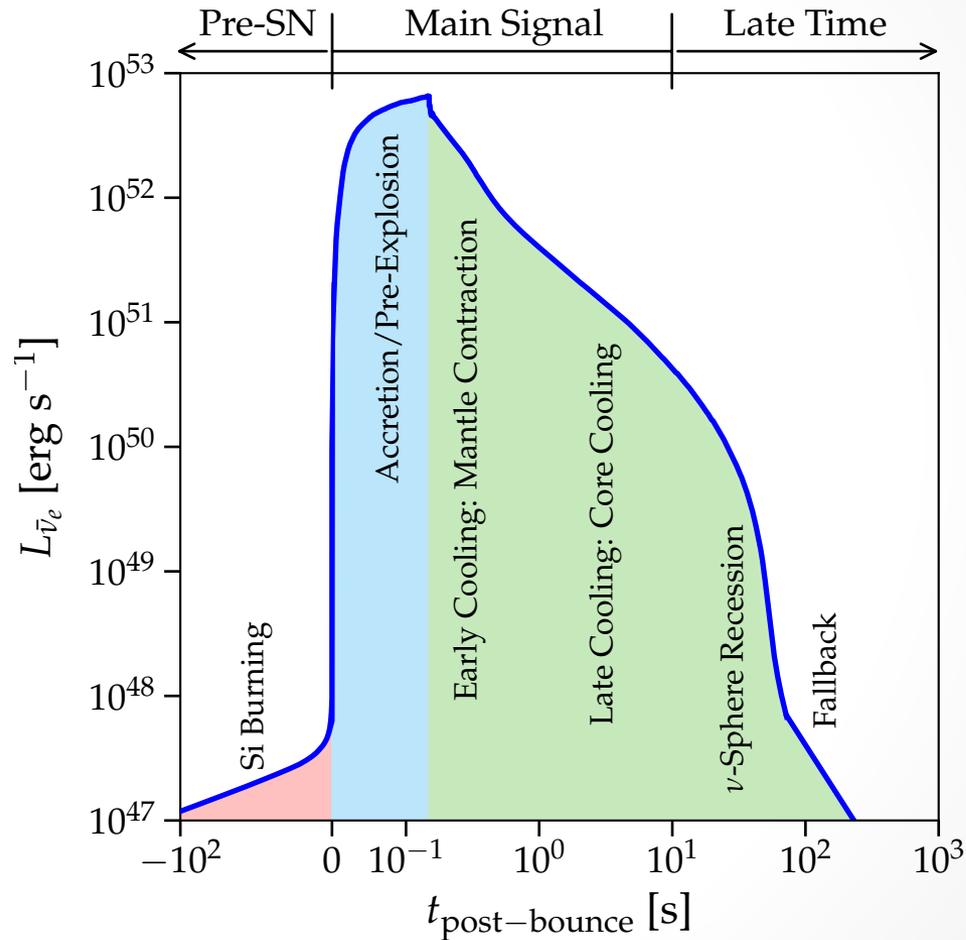
Per Century

How Can We Get Ready?

...

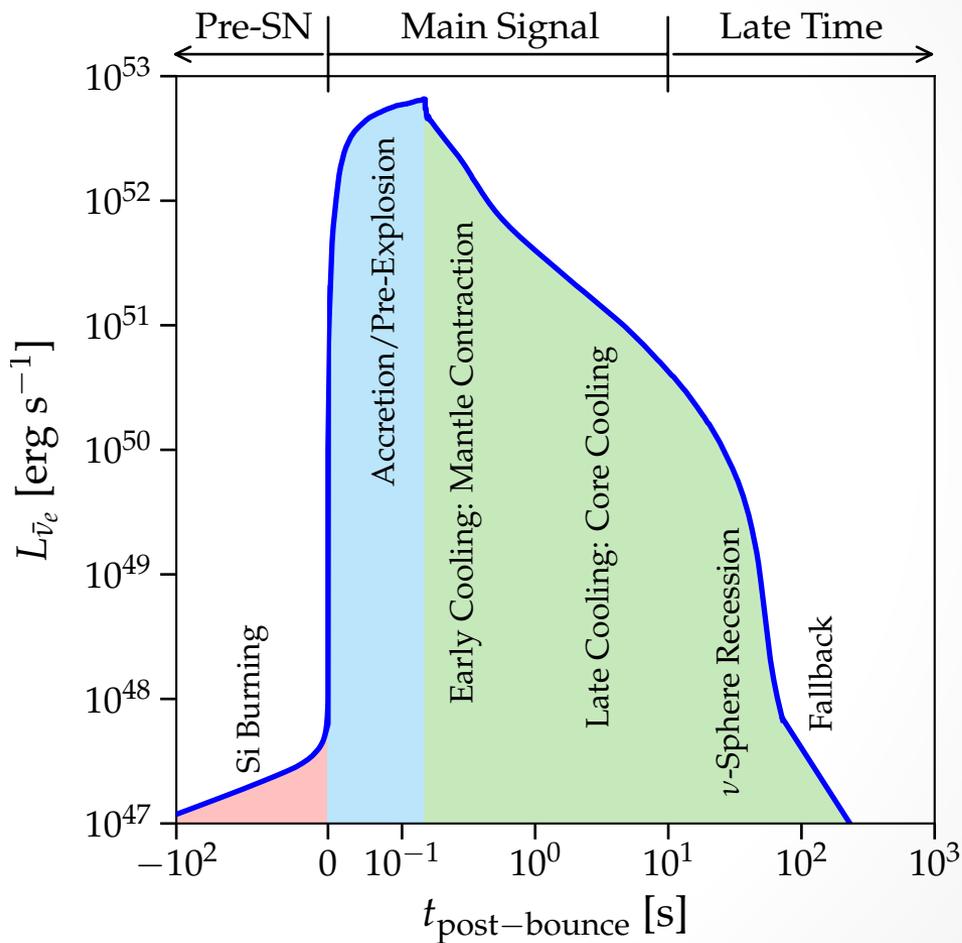
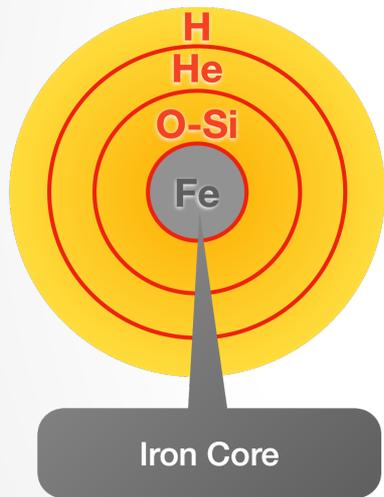
Can't We Just Wait?

Timescale of A SN



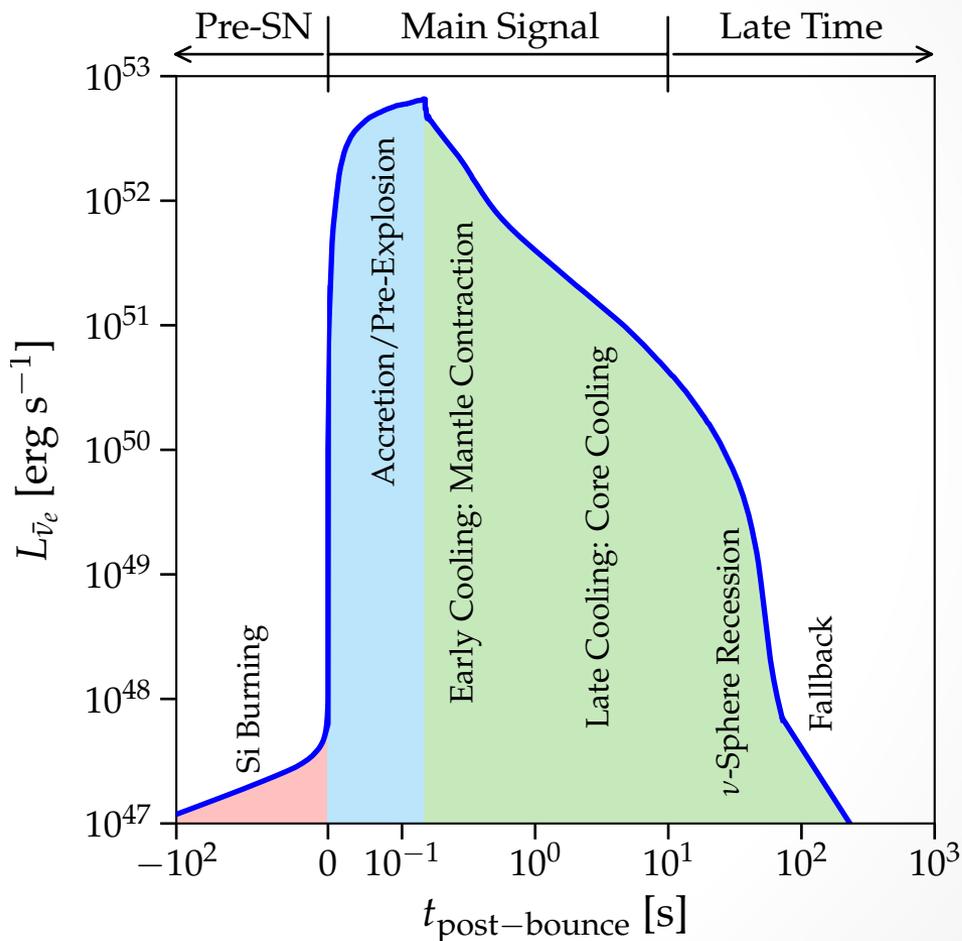
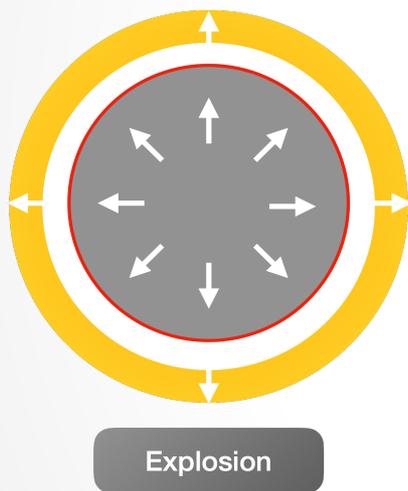
Li, Roberts &
Beacom, 2020

Timescale of A SN



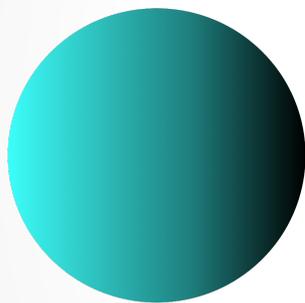
Li, Roberts &
Beacom, 2020

Timescale of A SN

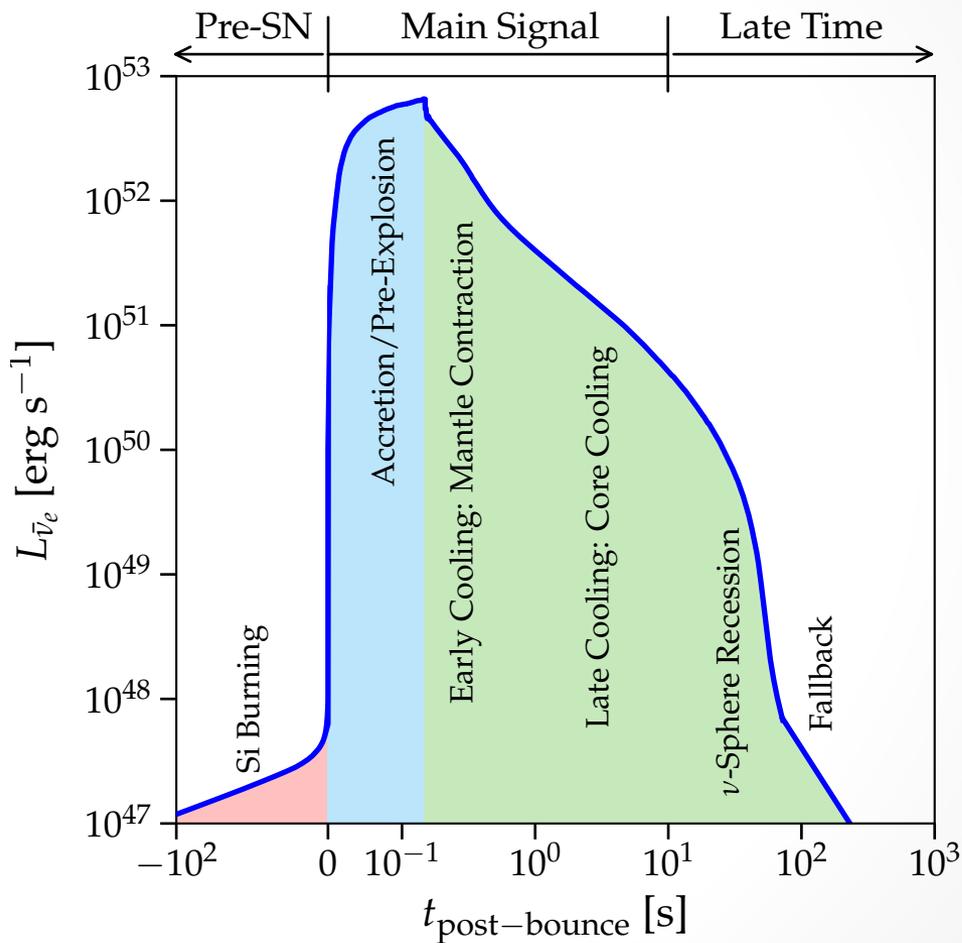


Li, Roberts &
Beacom, 2020

Timescale of A SN



Neutron Star
Or
Black Hole



Li, Roberts &
Beacom, 2020

Cooling

...

Input -- Simulation

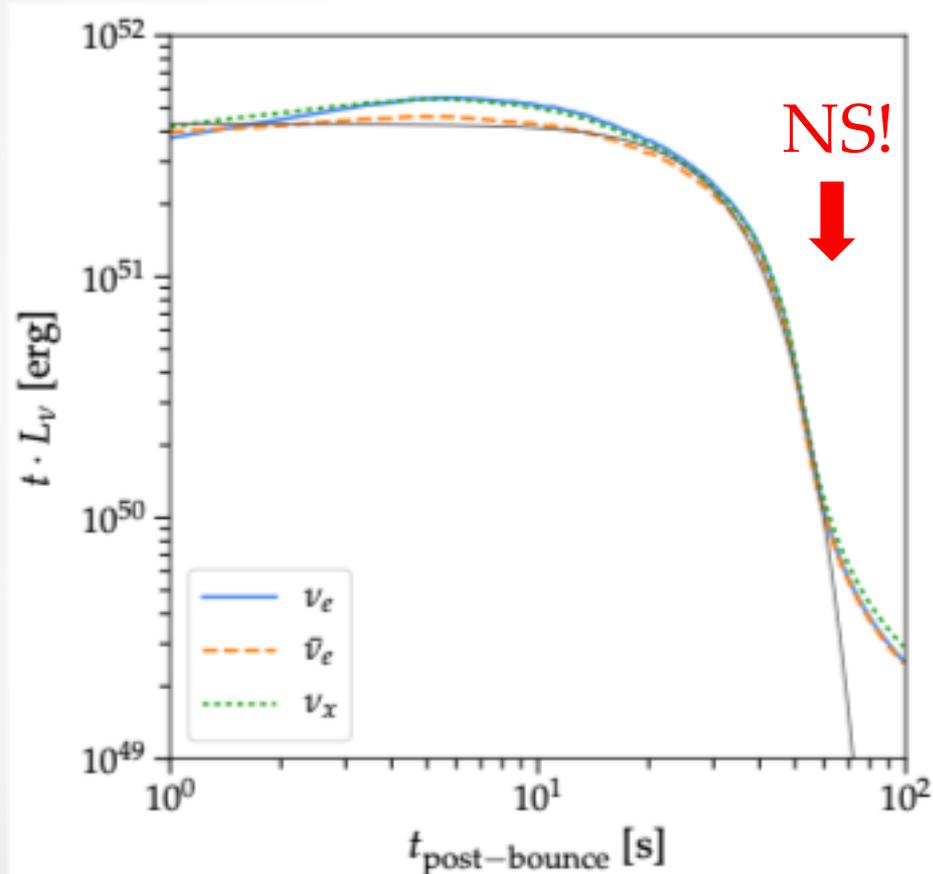


Luke Roberts

- 1D
- Goes Out to ~ 100 s
- No Convection
- 15 Solar Mass

Cooling Neutrinos

Neutrino Luminosity



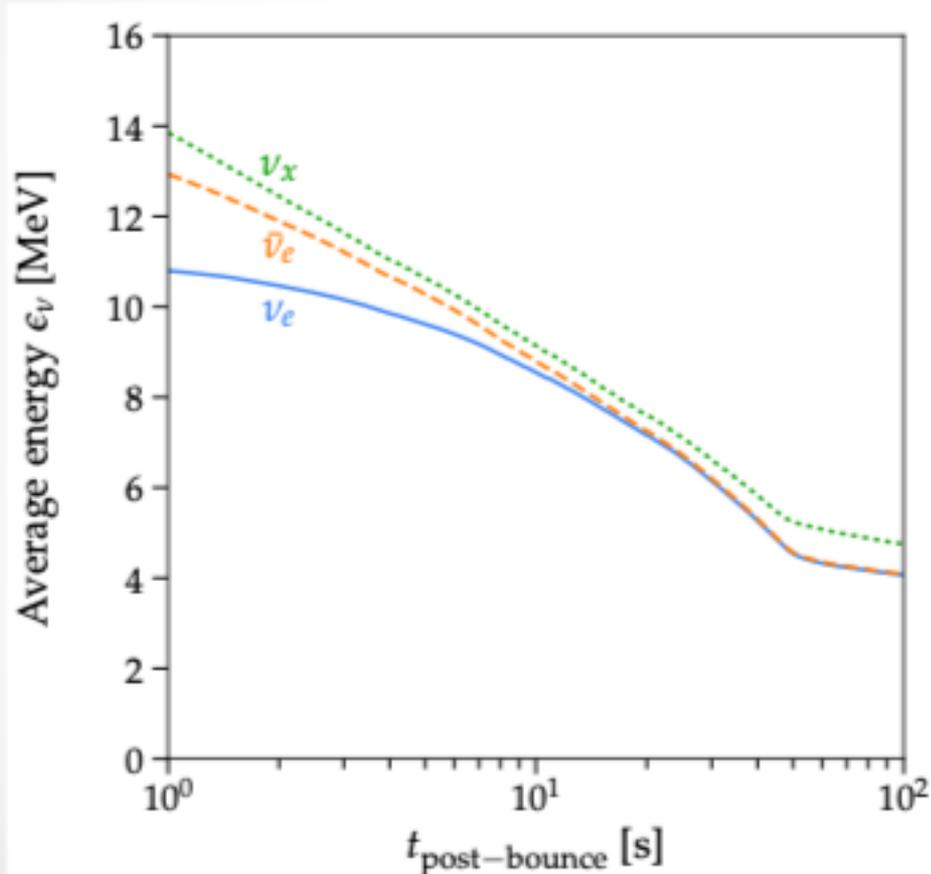
- $1/t$ Behavior Surprising
- Connects SN and NS
- Moderate Mixing Effect

Li, Roberts &
Beacom, 2020

Cooling Neutrinos Are Interesting & Robust!

Cooling Neutrinos

Neutrino Energy



- $1/t$ Behavior Surprising
- Connects SN and NS
- Moderate Mixing Effect

Li, Roberts &
Beacom, 2020

Cooling Neutrinos Are Interesting & Robust!

Supernova Neutrino Detection

Large Cross Sections

Multi-10 kton



Super-K

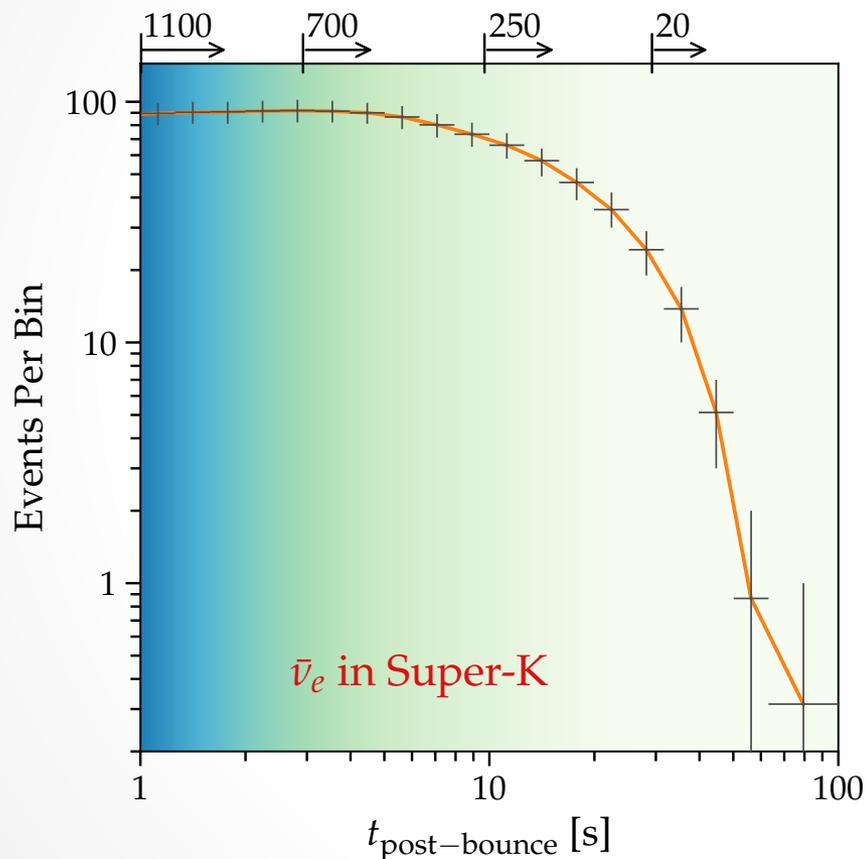


DUNE



JUNO

$\bar{\nu}_e$ Signal Rate



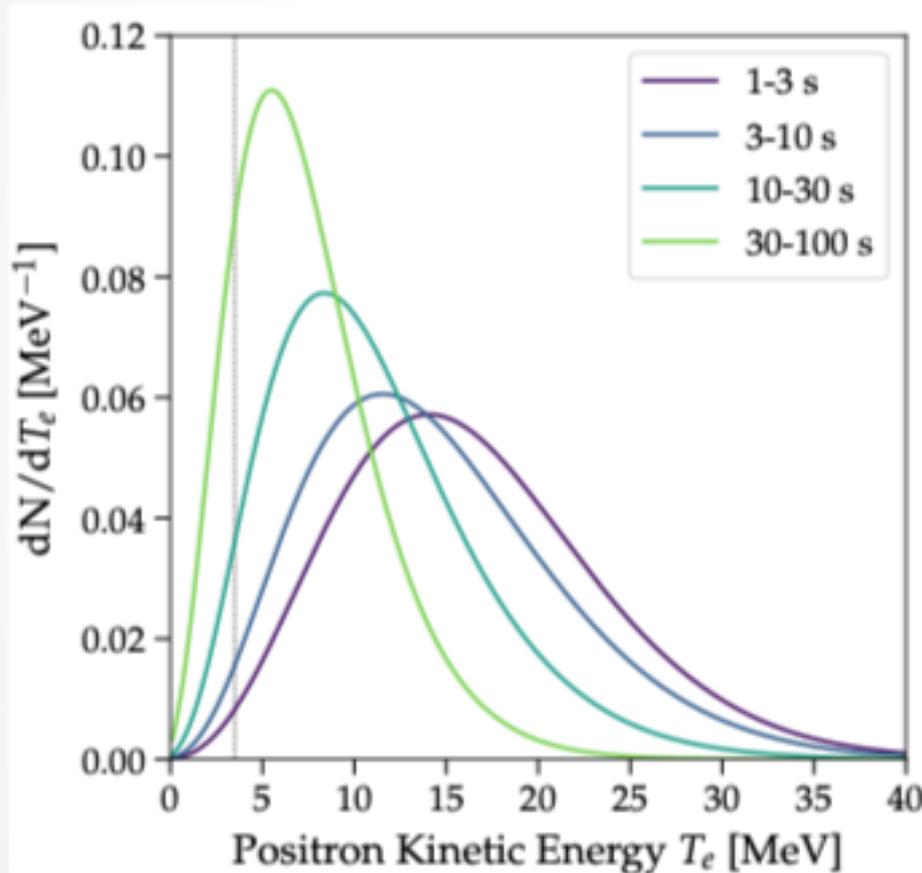
➤ Inputs:

- 10 kpc SN
- 22.5 kton
- 3.5 MeV Threshold

Li, Roberts &
Beacom, 2020

Plenty of Events in Super-K!

$\bar{\nu}_e$ Energy Spectrum



➤ $T_{e^+} = E_{\bar{\nu}_e} - 1.8 \text{ MeV}$

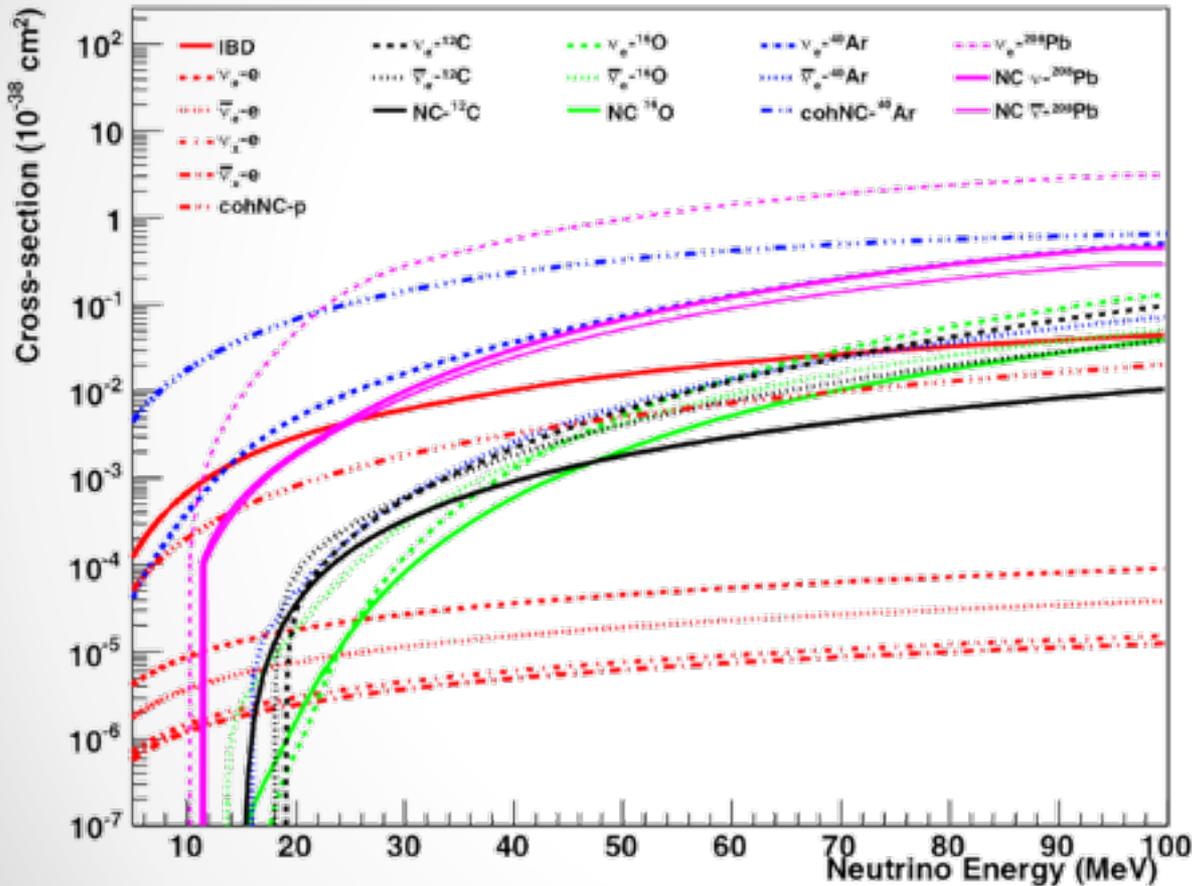
➤ --- Known Detection Threshold

Li, Roberts &
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Easily Reconstruct Neutrino Spectrum

Unique ν_e Detection Channel

K. Scholberg 2012



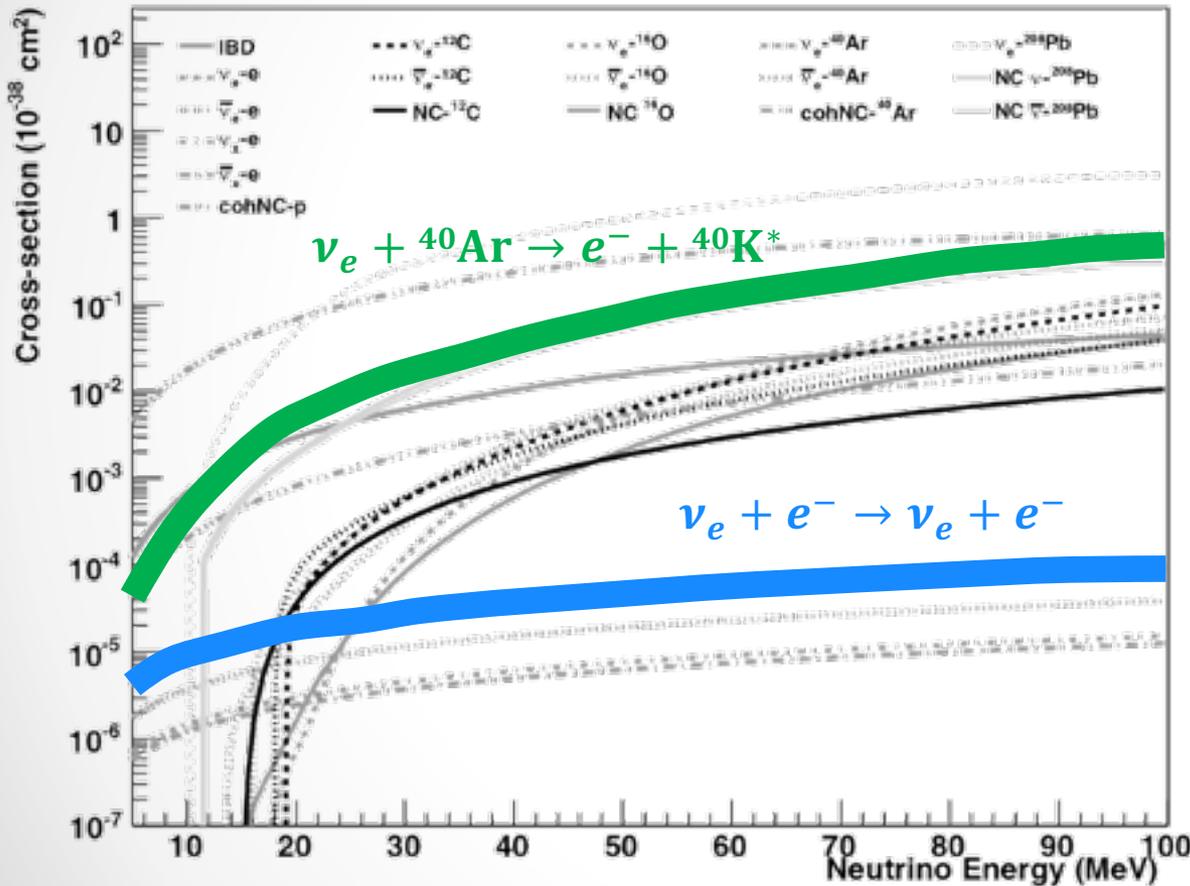
Clean Kinematics:

$$E_e = E_\nu - Q - \Delta E$$

Ideal Channel for ν_e

Unique ν_e Detection Channel

K. Scholberg 2012

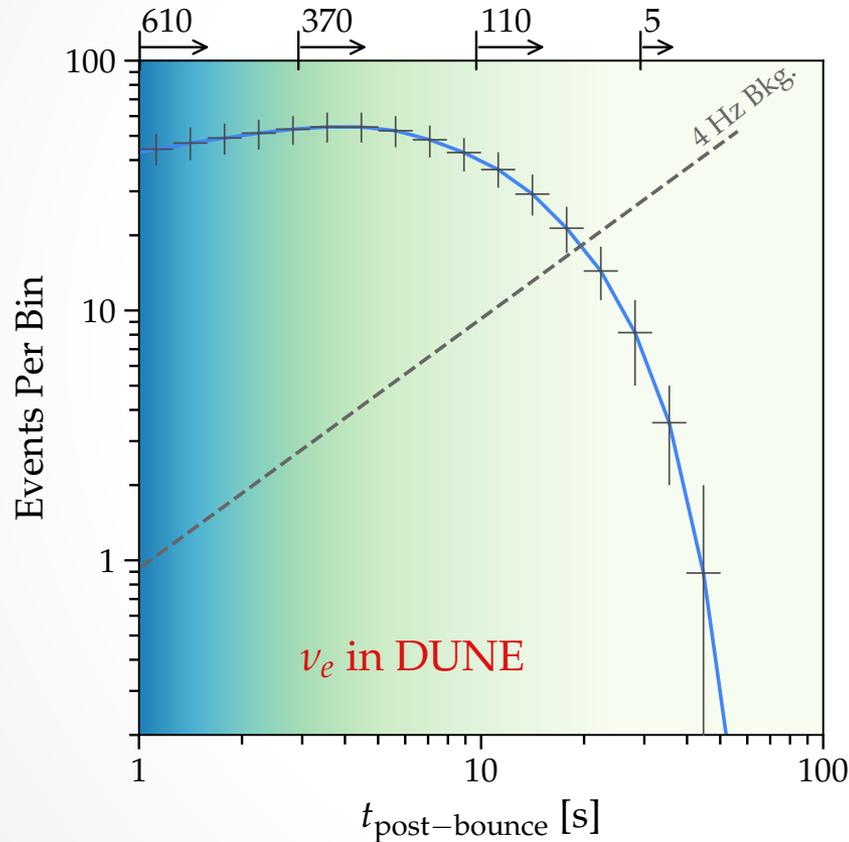


Clean Kinematics:

$$E_e = E_\nu - Q - \Delta E$$

Ideal Channel for ν_e

ν_e Signal Rate



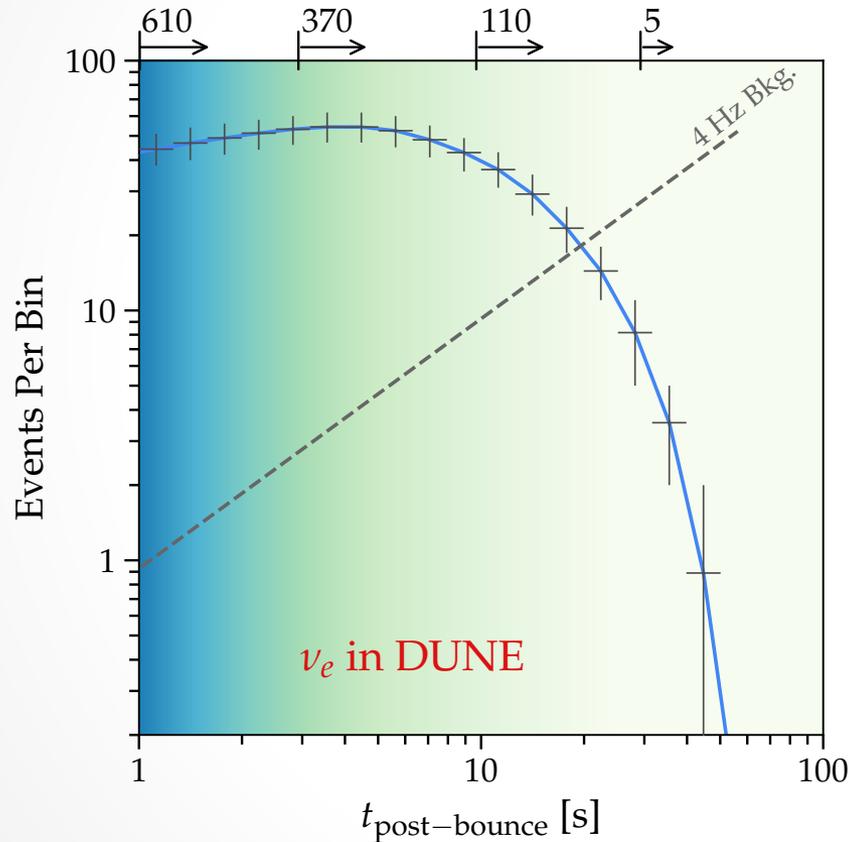
➤ Inputs:

- 10 kpc SN
- 40 kton
- 6 MeV Threshold

Li, Roberts &
Beacom, 2020

Plenty of Events to Late Times in DUNE!

ν_e Signal Rate

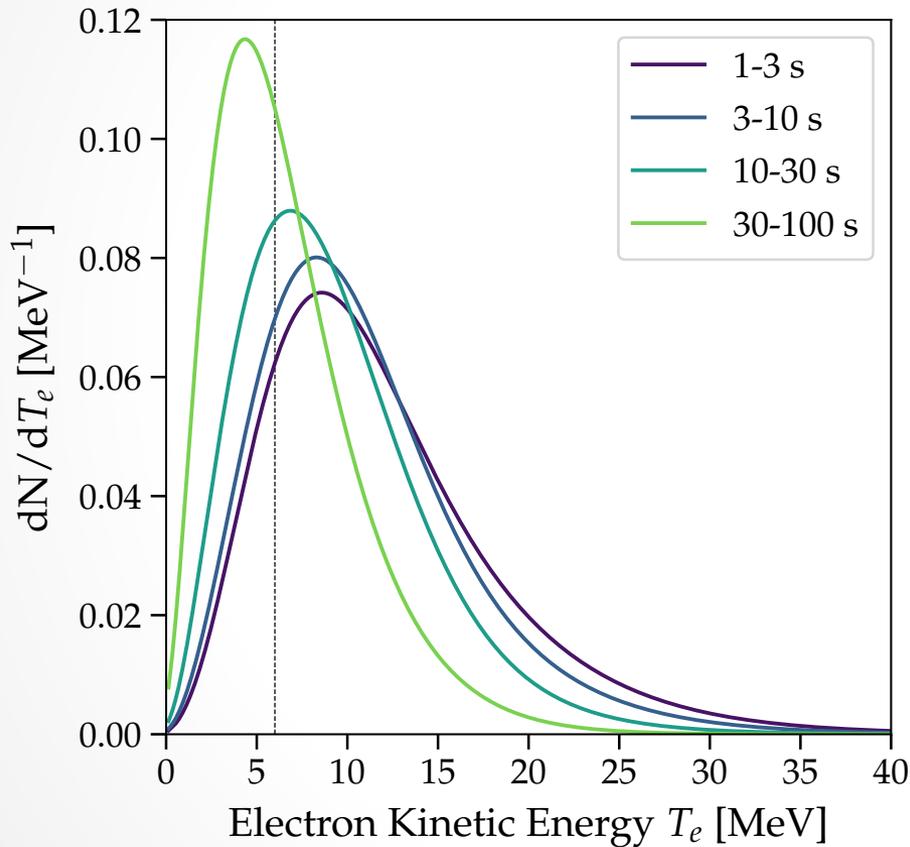


- We are the first to identify the leading MeV background
- First study to see how long the signal lasts, affecting DAQ

Li, Roberts &
Beacom, 2020

Plenty of Events to Late Times in DUNE!

ν_e Energy Spectrum



➤ $E_e = E_{\nu_e} - Q - \Delta E$

➤ --- Unknown

Detection Threshold

Li, Roberts &
Beacom, 2020

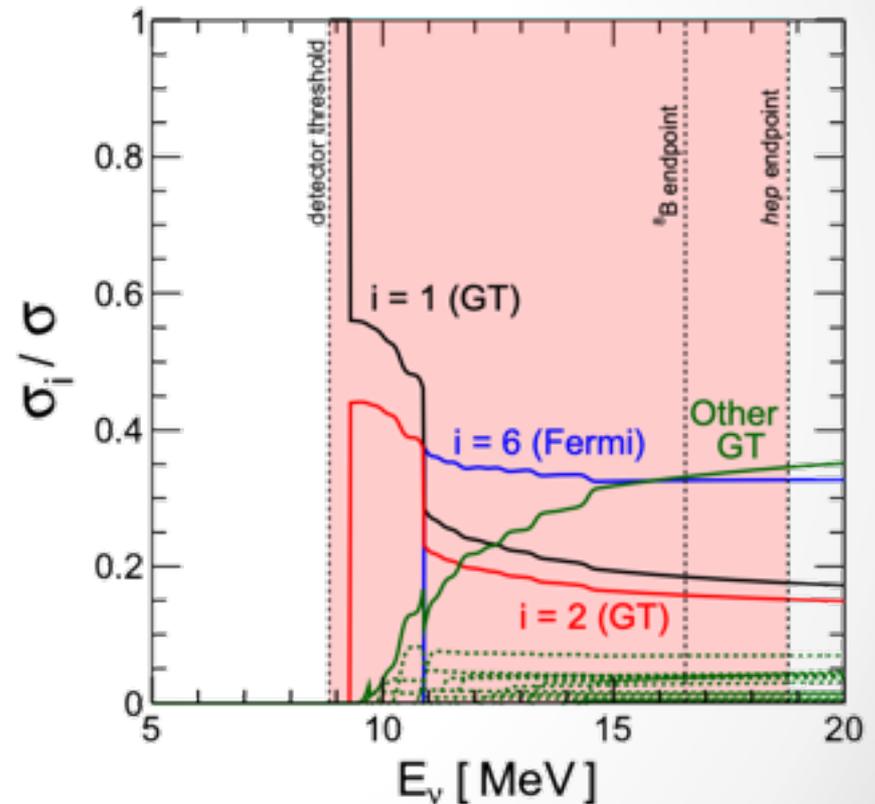
Detection Threshold Needs to Reach ~ 6 MeV

Cross Sections



Capozzi *et al.*, 2018

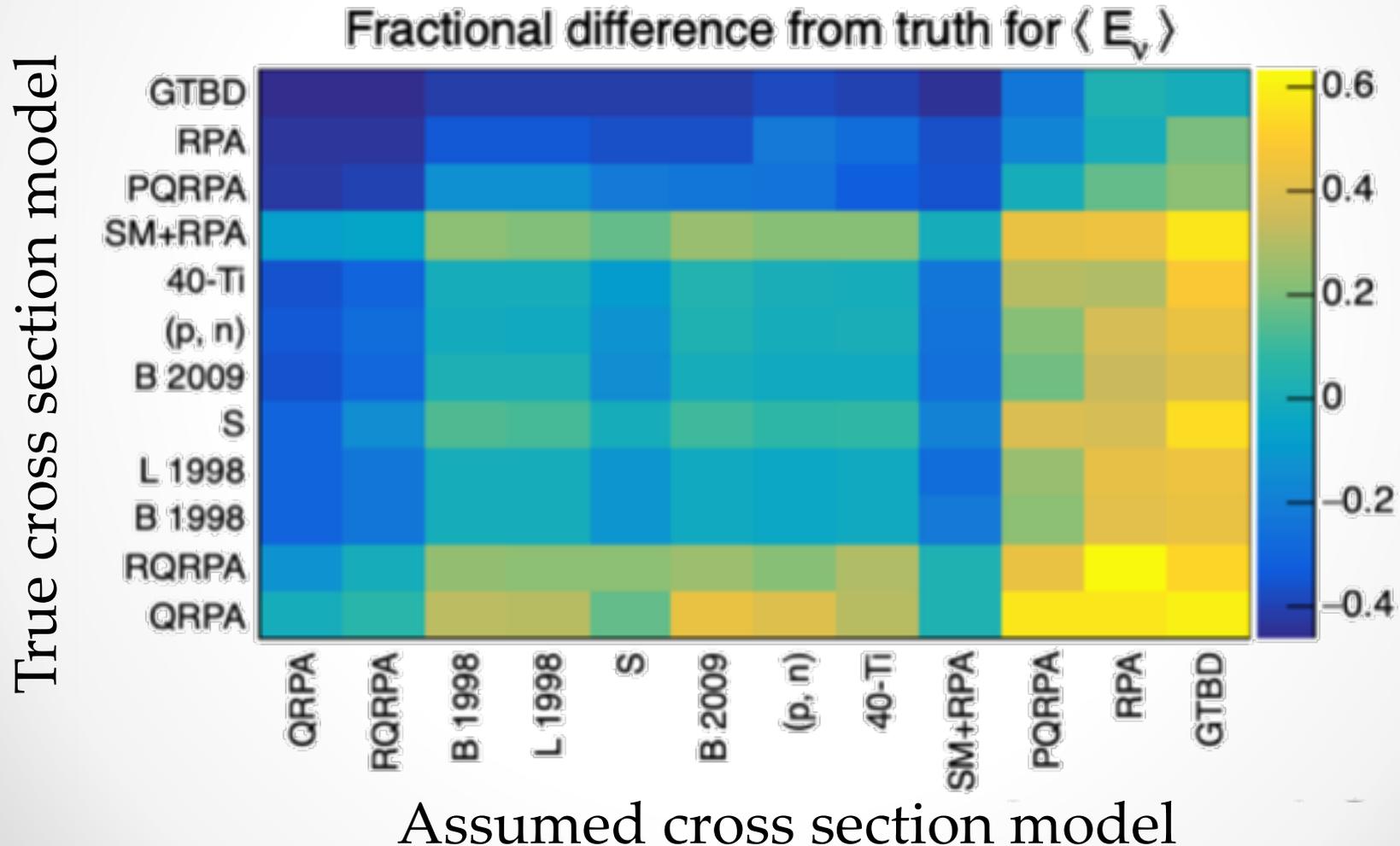
i	ΔE_i [MeV]	$B_i(\text{F})$	$B_i(\text{GT})$
1	2.333		1.64
2	2.775		1.49
3	3.204		0.06
4	3.503		0.16
5	3.870		0.44
6	4.384	4.00	
7	4.421		0.86
8	4.763		0.48
9	5.162		0.59
10	5.681		0.21
11	6.118		0.48
12	6.790		0.71
13	7.468		0.06
14	7.795		0.14
15	7.952		0.97
total		4.00	8.29



Difficult Theoretically and Experimentally

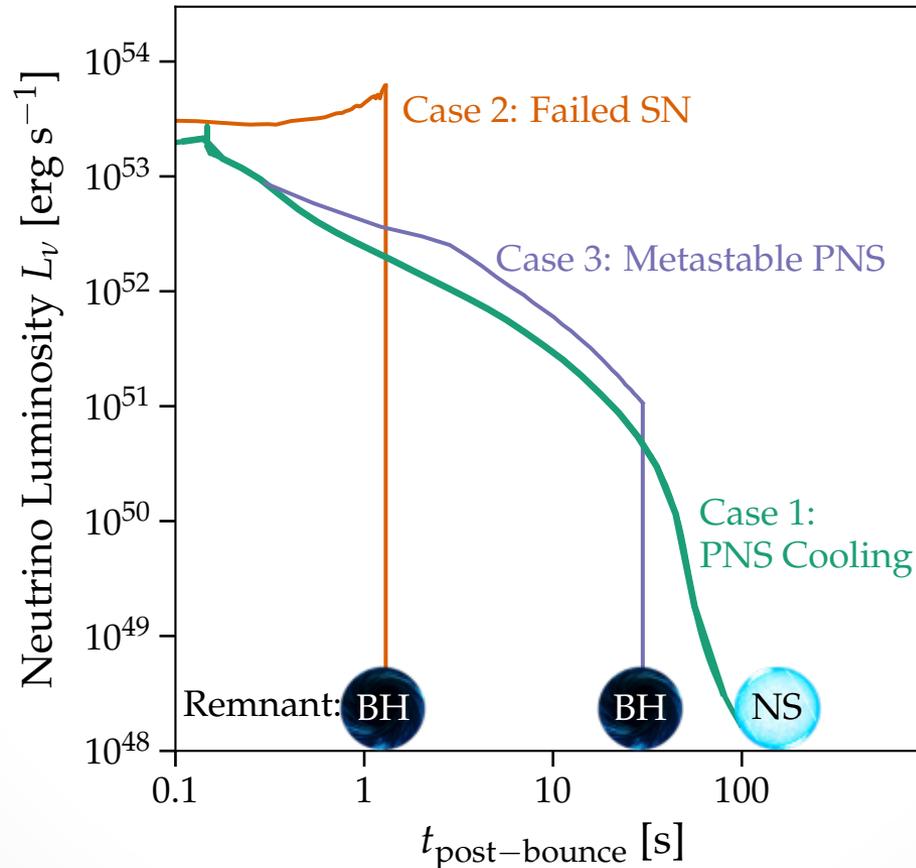
Large Impact on Supernova ν

E. Conley, DUNE-doc-14068



Alternative Outcome -- BH

Different Mechanisms for BH Formation



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BH May Form at Late Times

What Is the Fate of SN 87A?

We Still Don't Know!

Table 6. Literature Limits on SN 1987A

Frequency (Hz)	Flux Density ($\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$)	Epoch ([YYYY-]YYYY)	Instr. ^a	Resolution ^b	Conf. level ^c	Reference
0.076–8.642 $\times 10^9$	5.1–0.17 $\times 10^{-23}$	2013–2014	MWA, ATCA	U	...	Callingham et al. (2016)
1.7 $\times 10^9$	0.3 $\times 10^{-26}$	2008	VLBI	R	3- σ	Ng et al. (2011)
9 $\times 10^9$	0.3 $\times 10^{-26}$	1996 ^d	ATCA	S	3- σ	Ng et al. (2008)
36.2 $\times 10^9$	0.3 \pm 0.2 $\times 10^{-26}$	2008	ATCA	S	E	Potter et al. (2009)
44 $\times 10^9$	2.2 $\times 10^{-26}$	2011	ATCA	S	E	Zanarke et al. (2013)
94 $\times 10^9$	1 $\times 10^{-26}$	2011	ATCA	S	2- σ	Lakićević et al. (2012b)
0.6–4.3 $\times 10^{12}$	50–150 $\times 10^{-26}$	2012	SPIRE, PACS	U	...	Matsuura et al. (2015)
12–83 $\times 10^{12}$	1.0–76 $\times 10^{-26}$	2003–2015	MIPS, IRAC	U	...	Arendt et al. (2016)
26 $\times 10^{12}$	0.34 $\times 10^{-26}$	2003	T-ReCS	R	3- σ	Bouchet et al. (2006)
29 $\times 10^{12}$	0.32 $\times 10^{-26}$	2003	T-ReCS	R	E ^e	Bouchet et al. (2004)
0.5–1.5 $\times 10^{19}$	1.9–0.6 $\times 10^{-31}$	2010–2011	IBIS	U	...	Grebenev et al. (2012)
2.4–24.2 $\times 10^{20}$	2.2–0.22 $\times 10^{-36}$	2008–2014	LAT	U	...	Arkermann et al. (2016)
2.4–24.2 $\times 10^{28}$	2.8–0.04 $\times 10^{-46}$	2003–2012	HESS	U	...	H.E.S.S. Collaboration et al. (2015)

Alp et al., 2018

What Is the Fate of SN 87A?

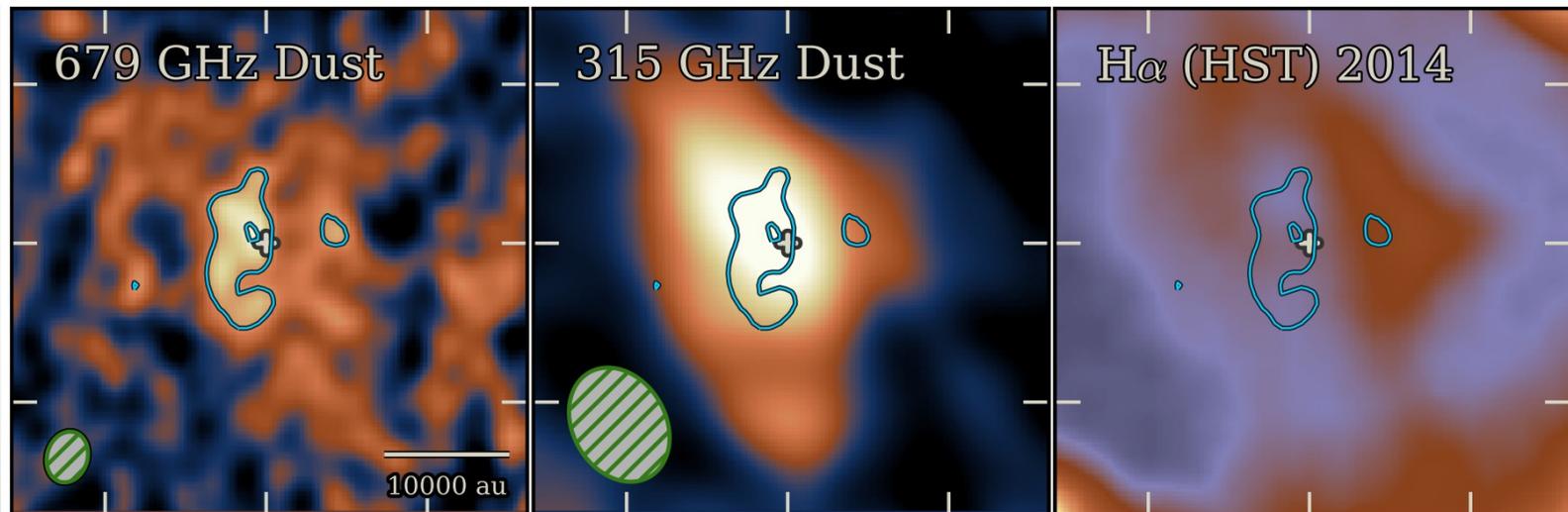
We Still Don't Know!

Cigan *et al.*, 2019

High angular resolution ALMA images of dust and molecules in the SN 1987A ejecta

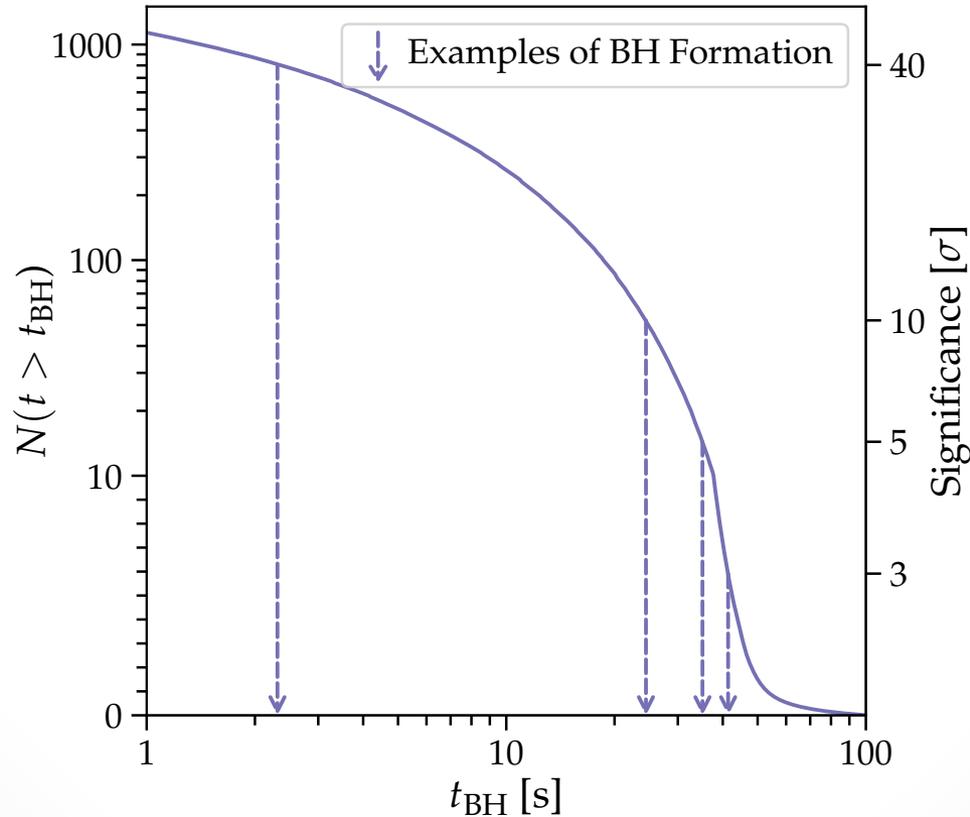
PHIL CIGAN,¹ MIKAKO MATSUURA,¹ HALEY L. GOMEZ,¹ REMY INDEBETOUW,² FRAN ABELLÁN,³ MICHAEL GABLER,⁴
ANITA RICHARDS,⁵ DENNIS ALP,⁶ TIM DAVIS,¹ HANS-THOMAS JANKA,⁴ JASON SPYROMILIO,⁷ M. J. BARLOW,⁸ DAVID BURROWS,⁹
ELI DWEK,¹⁰ CLAES FRANSSON,¹¹ BRYAN GAENSLER,¹² JOSEFIN LARSSON,⁶ P. BOUCHET,^{13,14} PETER LUNDQVIST,¹¹
J. M. MARCAIDE,³ C.-Y. NG,¹⁵ SANGWOOK PARK,¹⁶ PAT ROCHE,¹⁷ JACCO TH. VAN LOON,¹⁸ J. C. WHEELER,¹⁹ AND
GIOVANNA ZANARDO²⁰

images. That dust peak, combined with CO and SiO line spectra, suggests that the dust and gas could be at higher temperatures than the surrounding material, though higher density cannot be totally excluded. One of the possibilities is that a compact source provides additional heat at that location. Fits to the far-infrared–



The Next One Can Be Measured

Detection Significance of BH Formation

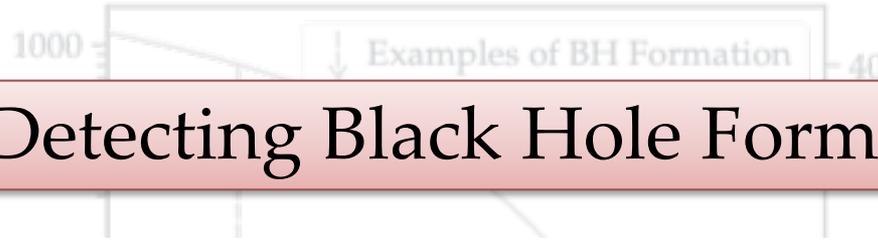


Li, Roberts &
Beacom, 2020

We Can Directly Detect BH Formation with Neutrinos

The Next One Can Be Measured

Detection Significance of BH Formation

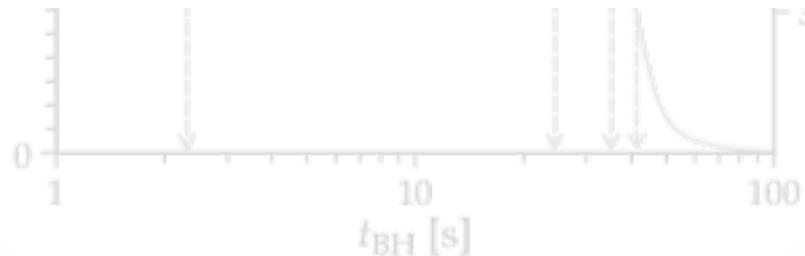


First to Study Detecting Black Hole Formation in DUNE



Black Hole Formation

DUNE's observation of thousands of neutrinos from a core-collapse supernova in the Milky Way would allow us to peer inside a newly-formed neutron star and potentially witness the birth of a black hole.



Li, Roberts &
Beacom, 2020

We Can Directly Detect BH Formation with Neutrinos

What Will We Learn?

- How Do Massive Stars Die?
- Production Sites of Heavy Elements
- Supernova Remnants--Acceleration of Cosmic Rays
- Properties of Neutron Stars/Pulsars, Black Holes
- Possible Production Sites of Light Particles

Almost zero effort



Compute Theoretically, Confirm Experimentally

Conclusions

SN 1987A

- $\bar{\nu}_e$ only
- 50 kpc
- ~ 20 events
- ~ 10 s

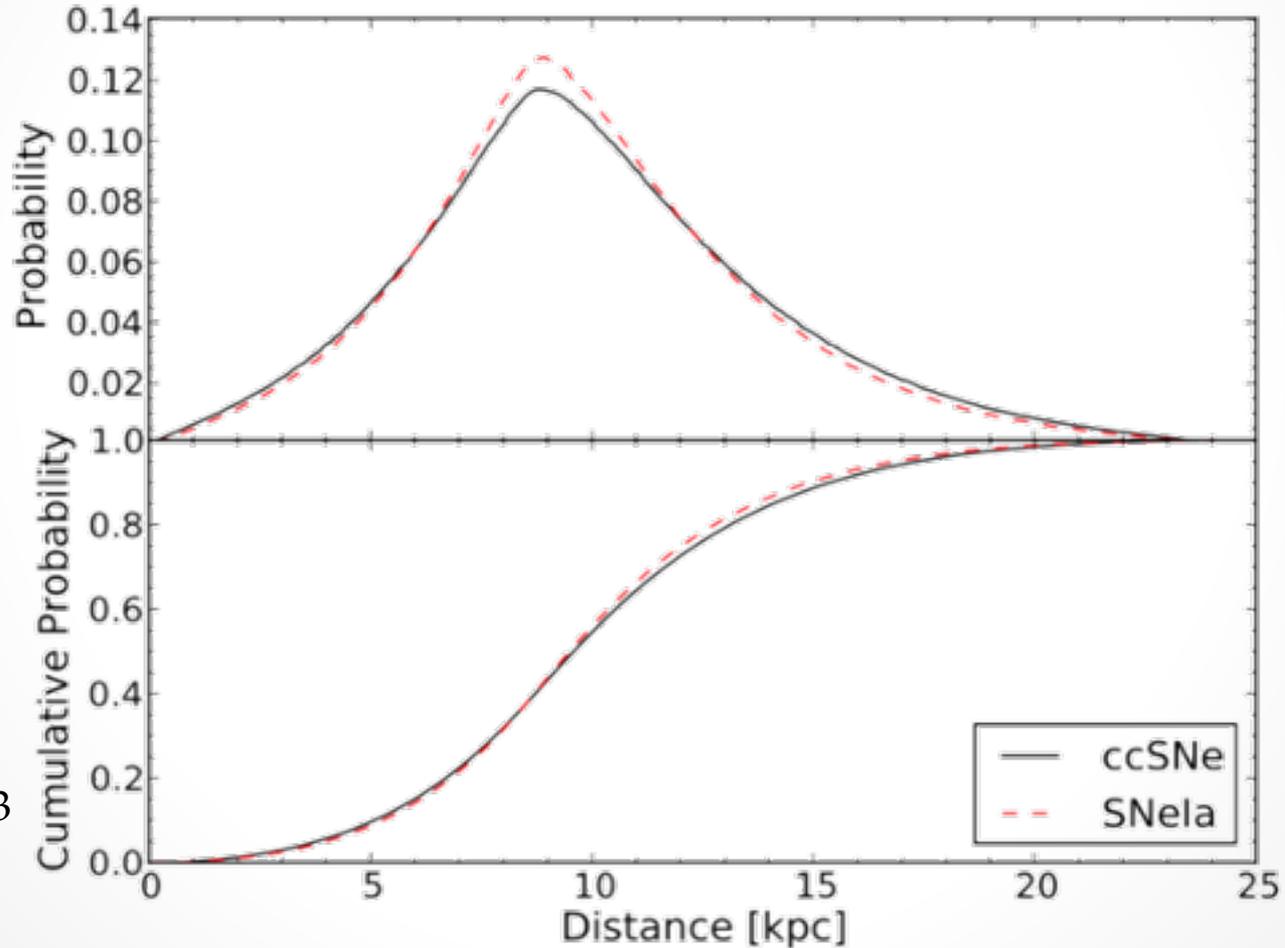
SN 2030?

- $\bar{\nu}_e$, ν_e , and ν_x
- ~ 10 kpc
- ~ 10,000 events
- ~ 1 min

Backup

Galactic Core-Collapse SN

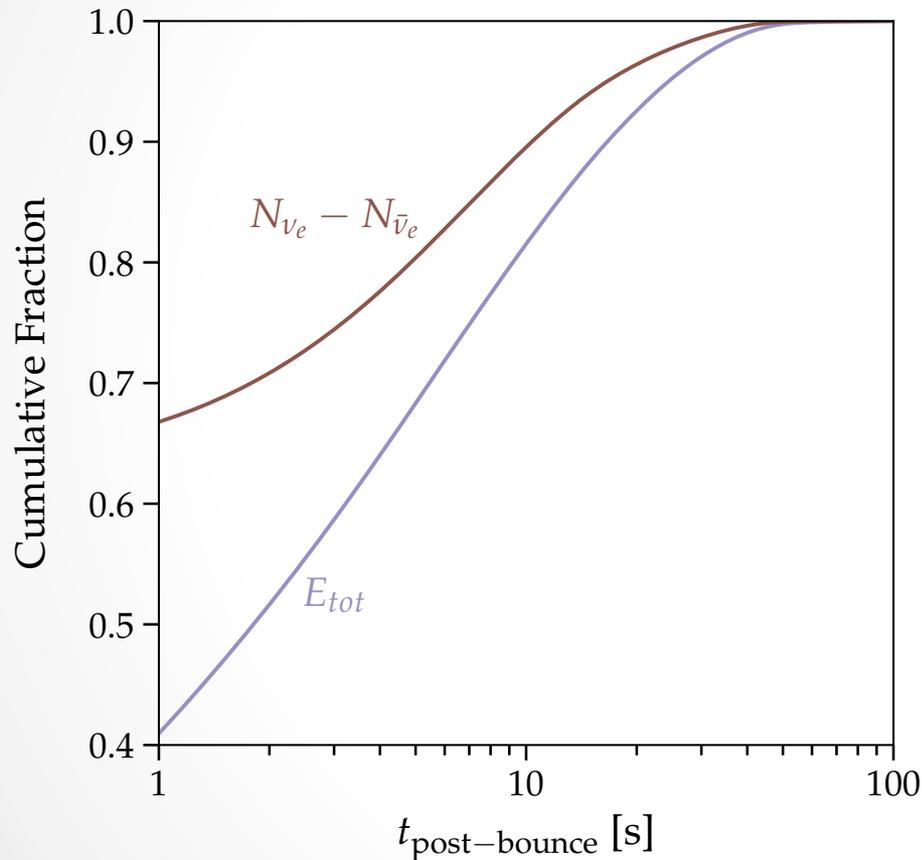
How Far Away?



Adams *et al.*, 2013

Cooling Neutrinos

Cumulative Quantities

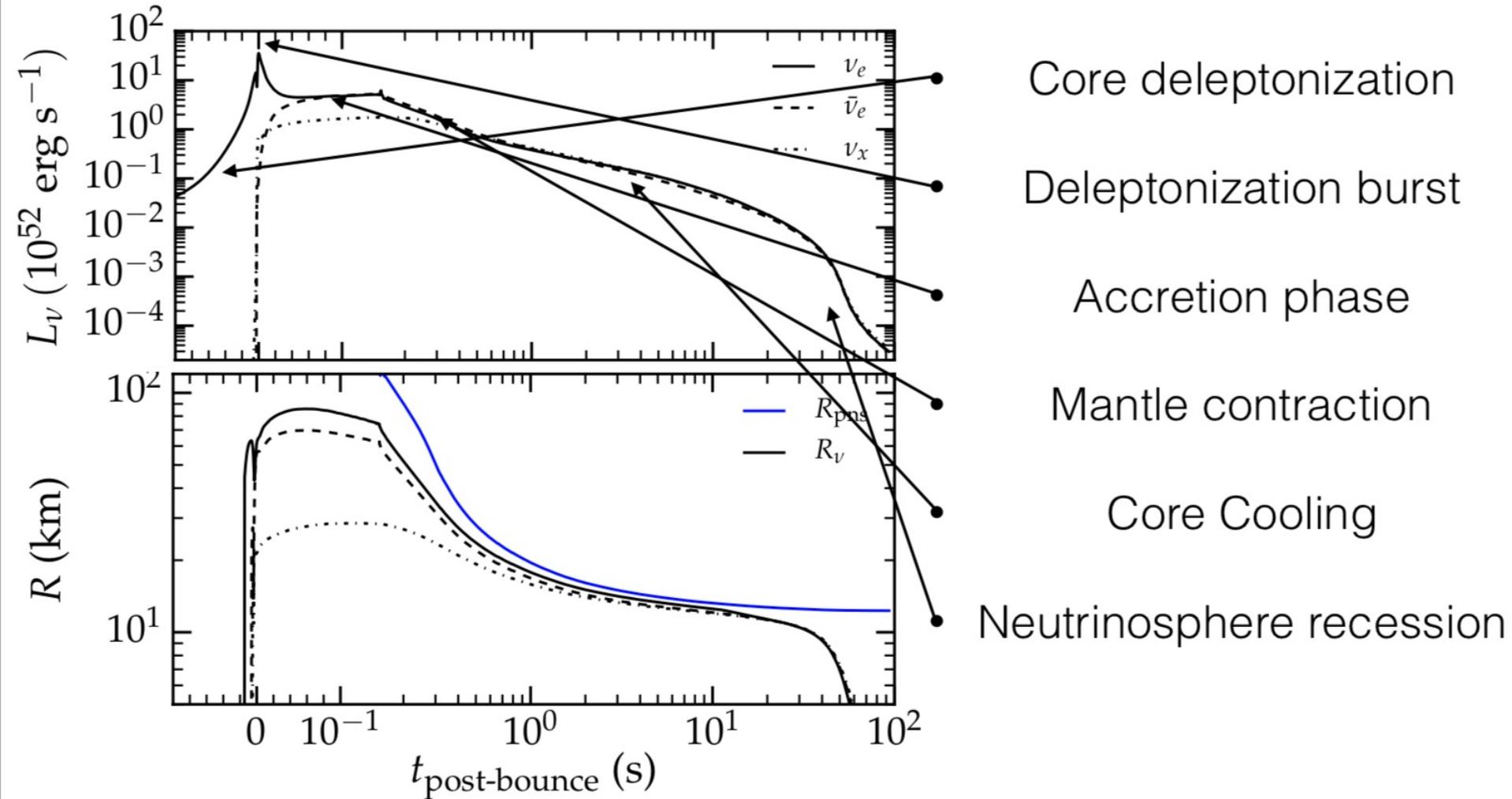


- ❖ $1/t$ Behavior Surprising
- ❖ Connects SN and NS
- ❖ Moderate Mixing Effect

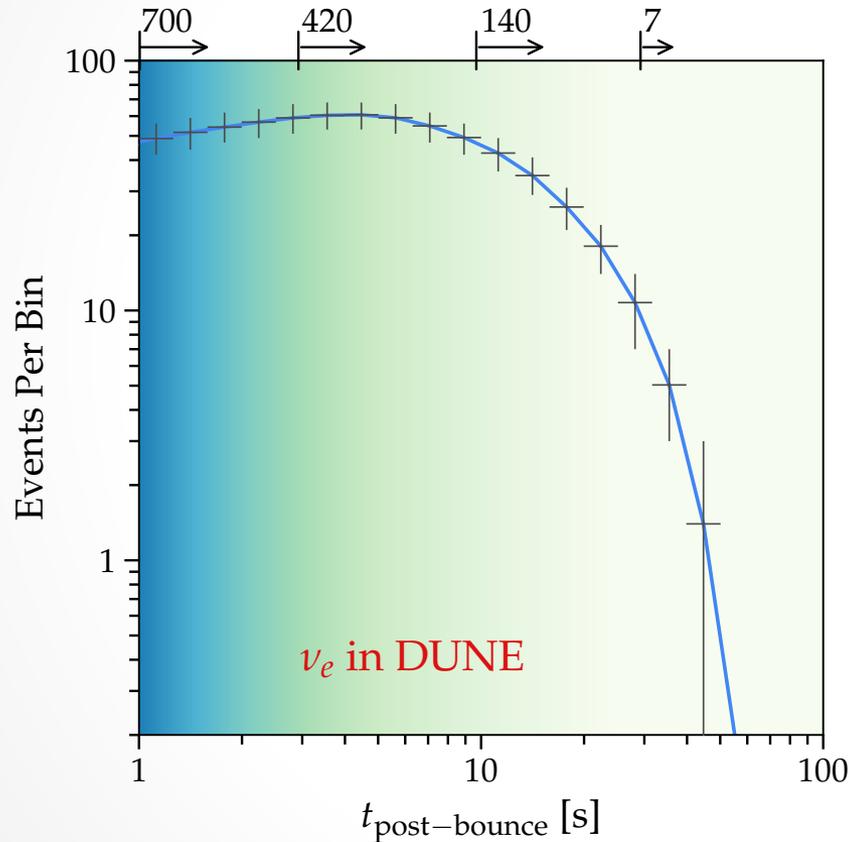
Li, Roberts &
Beacom, 2020

Cooling Neutrinos Are Interesting & Robust!

Anatomy of the Neutrino Signal



ν_e Signal Rate



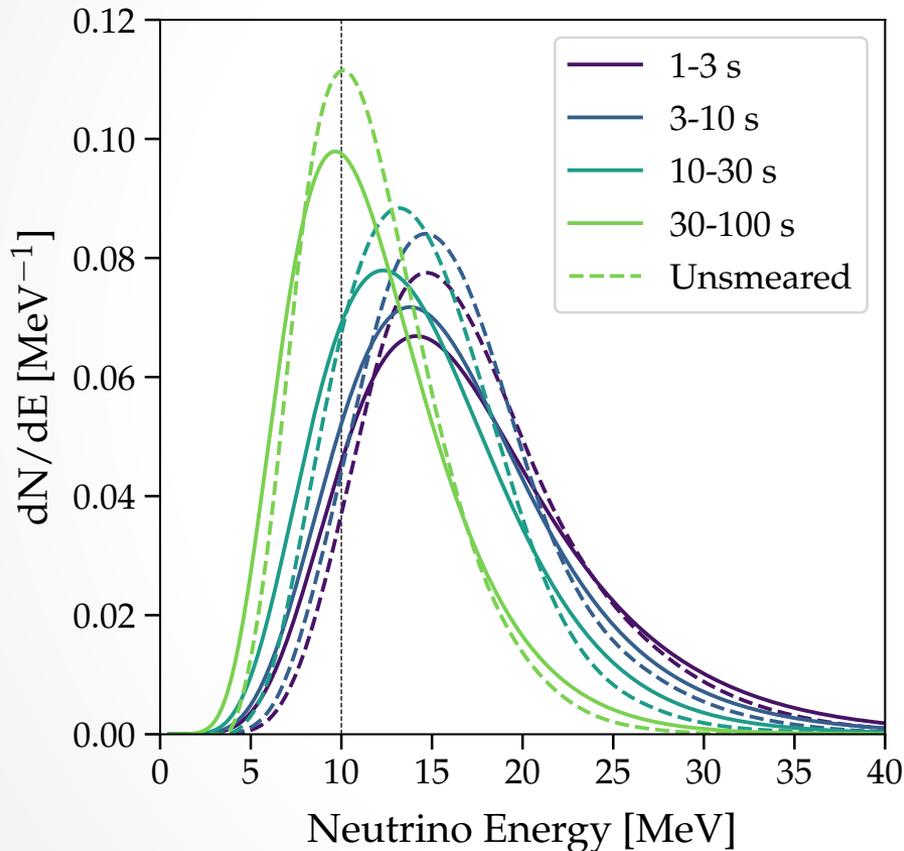
➤ Inputs:

- 10 kpc SN
- 40 kton
- 10 MeV Threshold

Li, Roberts &
Beacom, 2020

Plenty of Events to Late Time in DUNE!

ν_e Energy Spectrum



➤ $E_e = E_{\nu_e} - Q - \Delta E$

➤ --- Unknown

Detection Threshold

Li, Roberts &
Beacom, 2020

Detection Threshold Needs to Reach ~ 10 MeV

Cross Section Studies

PHYSICAL REVIEW C **80**, 055501 (2009)

Weak-interaction strength from charge-exchange reactions versus β decay in the $A = 40$ isoquintet

M. Bhattacharya,^{1,2,*} C. D. Goodman,² and A. García³

¹*Brookhaven National Laboratory, P.O. Box 5000, Upton, New York 11973-5000, USA*

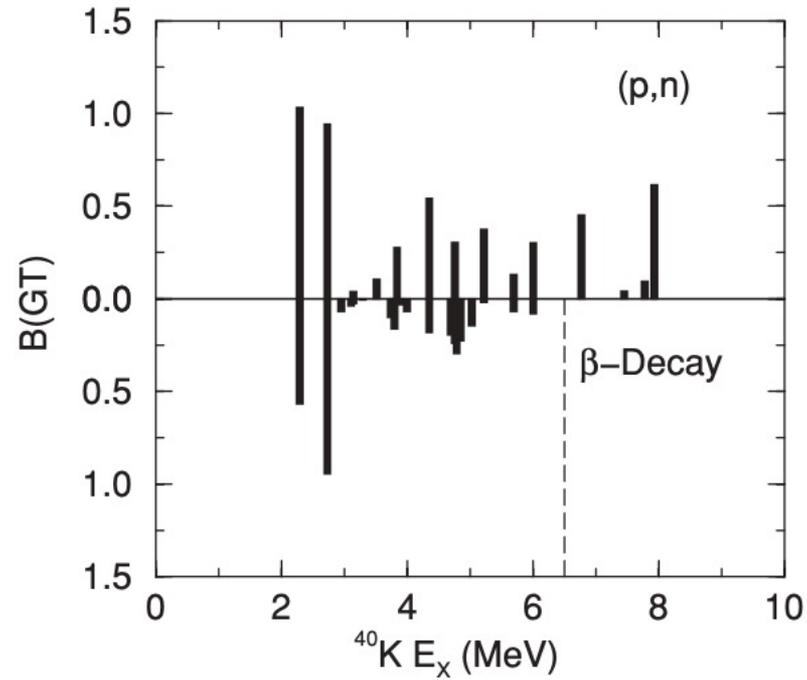
²*Indiana University Cyclotron Facility, 2401 Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*

³*Physics Department, University of Washington, Seattle, Washington 98195-1560, USA*

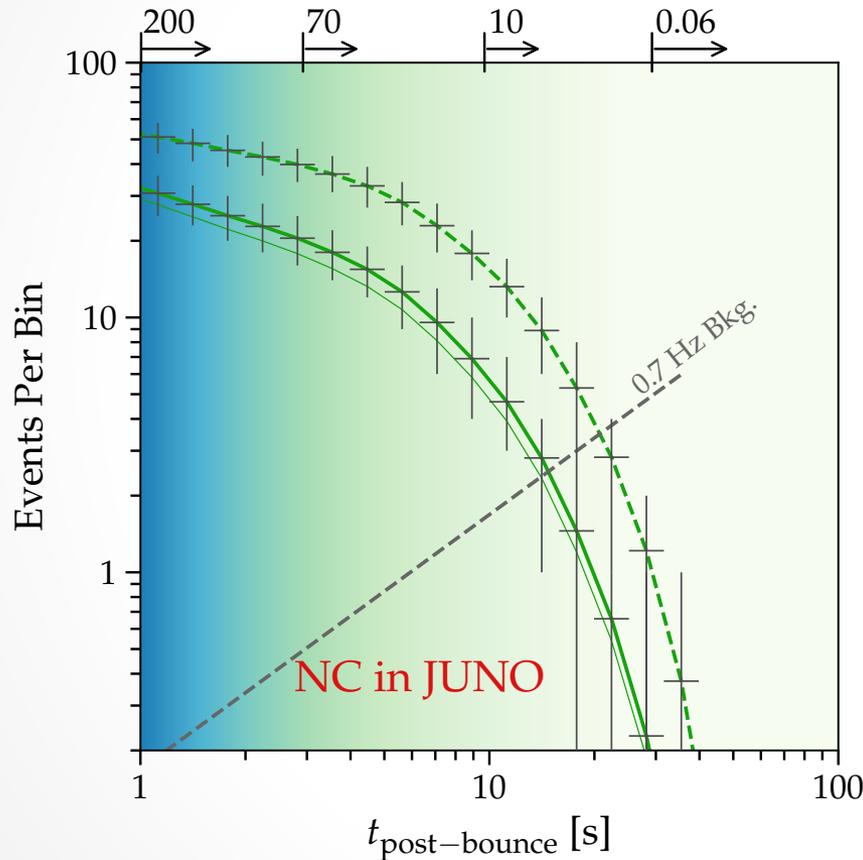
(Received 29 February 2008; revised manuscript received 1 July 2009; published 19 November 2009;
publisher error corrected 24 November 2009)

We report a measurement of the Gamow-Teller (GT) strength distribution for $^{40}\text{Ar} \rightarrow ^{40}\text{K}$ using the $0^\circ(p,n)$ reaction. The measurement extends observed GT strength distribution in the $A = 40$ system up to an excitation energy of ~ 8 MeV. In comparing our results with those from the β decay of the isospin mirror nucleus ^{40}Ti , we find that, within the excitation energy region probed by the β -decay experiment, we observe a total GT strength that is in fair agreement with the β -decay measurement. However, we find that the relative strength of the two strongest transitions differs by a factor of ~ 1.8 in comparing our results from (p,n) reactions with the β decay of ^{40}Ti . Using our results we present the neutrino-capture cross section for ^{40}Ar .

Cross Section Studies



ν_x Signal Rate



➤ Inputs:

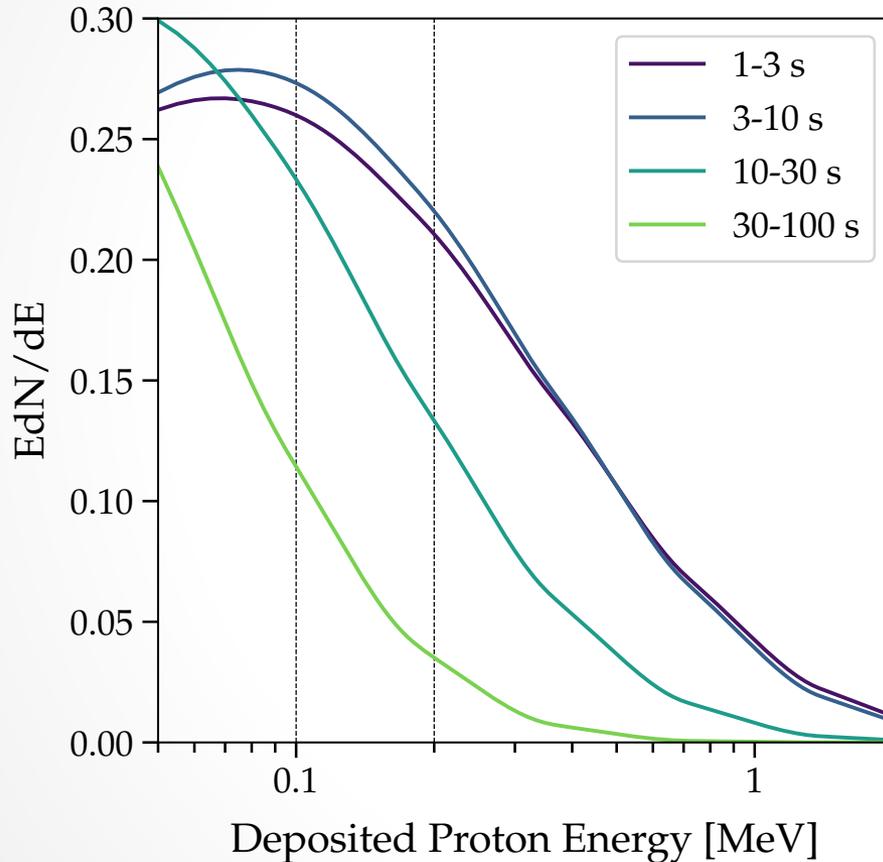
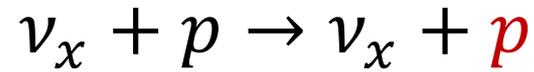
- 10 kpc SN
- 22.5 kton
- 0.1, 0.2 MeV

Threshold

Li, Roberts &
Beacom, 2020

Non-Negligible Events at Late Times

ν_x Energy Spectrum



➤ $E_{\text{det}} \ll E_{\nu_x}$

➤ --- Unknown

Detection Threshold

Li, Roberts &
Beacom, 2020

Detection Threshold Is Crucial