Detecting Late-Time Neutrinos from Core-Collapse Supernovae

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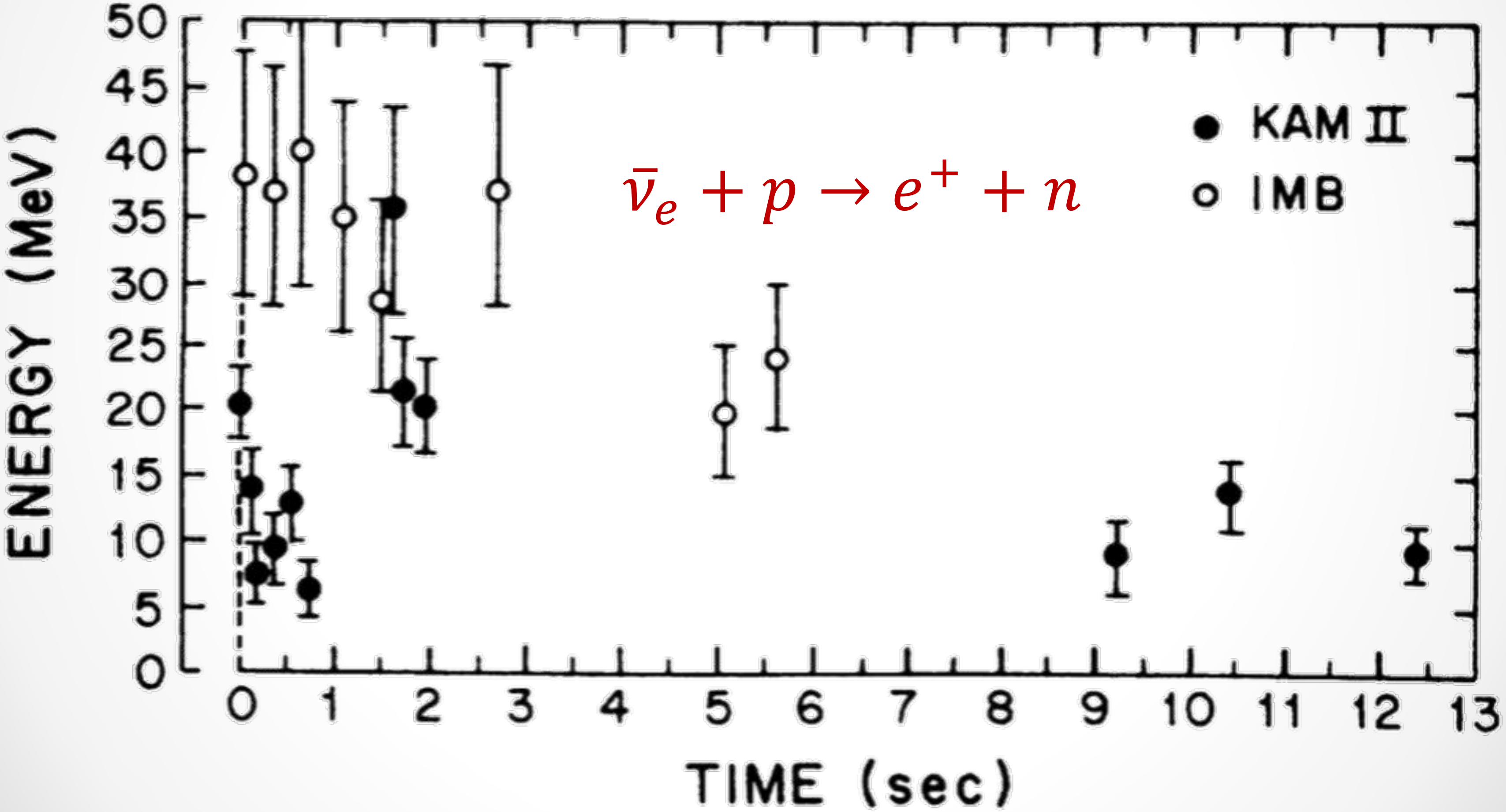
Collaborators: L. Roberts, J. Beacom

N3AS Seminar, July 2020

SN 1987A

LMC, 25 kpc Away



$\bar{\nu}_e + p \rightarrow e^+ + n$

Kamioka-II 1988

Supernova Neutrino Physics

What We Learned From SN 87A

Supernova 1987A by Arnett, Bahcall, Kirshner, Woosley

The results for the temperature, the cooling time scale, and the $\bar{\nu}_e$ flux are consistent with the standard picture of stellar collapse that is based upon detailed numerical models and on analytic arguments. The success of this simplified "standard" model suggests that it will be difficult to use the neutrino events observed from SN 1987A to establish more detailed models. The observations of SN 1987A have triumphantly confirmed the schematic picture of core collapse. The observational test of such a complex phenomenon is a great achievement. However, the data are not sufficient to discriminate between equations of state or to validate specific detailed models. There is no need to invoke new particle physics or complicated

Open Questions

- Is Neutrino Heating the Explosion Mechanism?
- How Do Neutrinos Oscillate In Dense Environment?
- What Are the Yields of Heavy Elements?
- What Remnant Forms From A SN Explosion?

Compute Theoretically, Confirm Experimentally

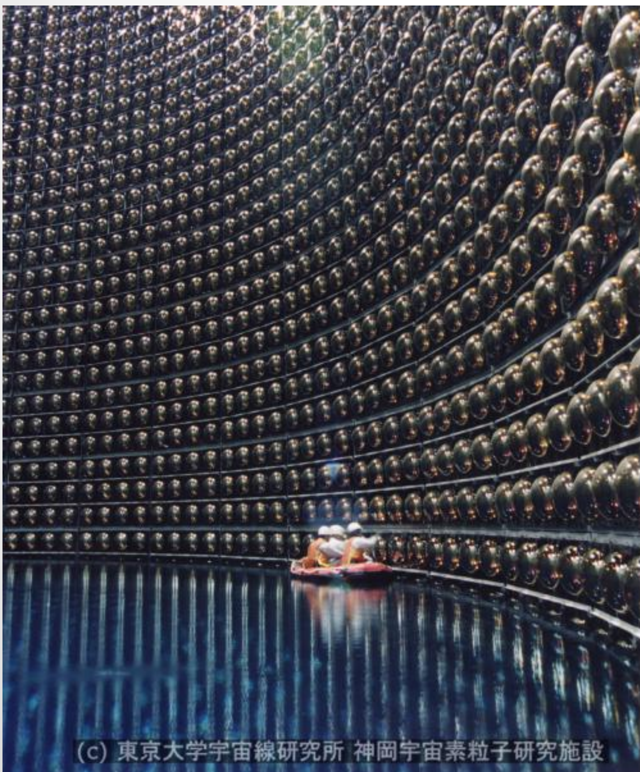
SN 2030?

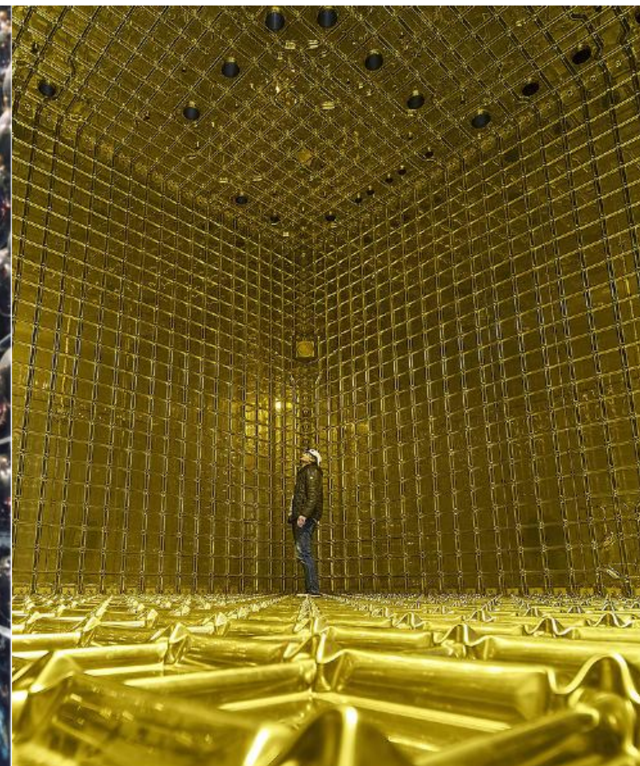
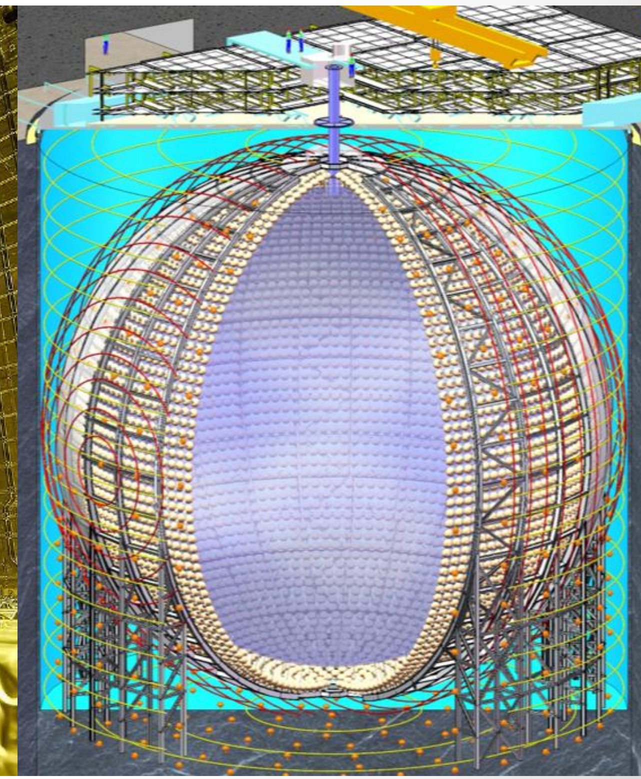
Comparisons

SN 1987A	SN 2030?
❖ $\bar{\nu}_e$ only	❖ $\bar{\nu}_e$, ν_e, and ν_x
❖ 50 kpc	❖ ~ 10 kpc
❖ ~ 20 events	❖ ~ 10,000 events
❖ ~ 10 s	❖ ~ 1 min

Precision Measurements

We May Have Only One Chance



Not Clear Whether There Will Be Successors

We May Have Only One Chance

- Physics:

  What's After Mass Hierarchy and CP Violation?

- Technology:

  Photon Attenuation in Water and Oil

Not Clear Whether There Will Be Successors

How Can We Get Ready?

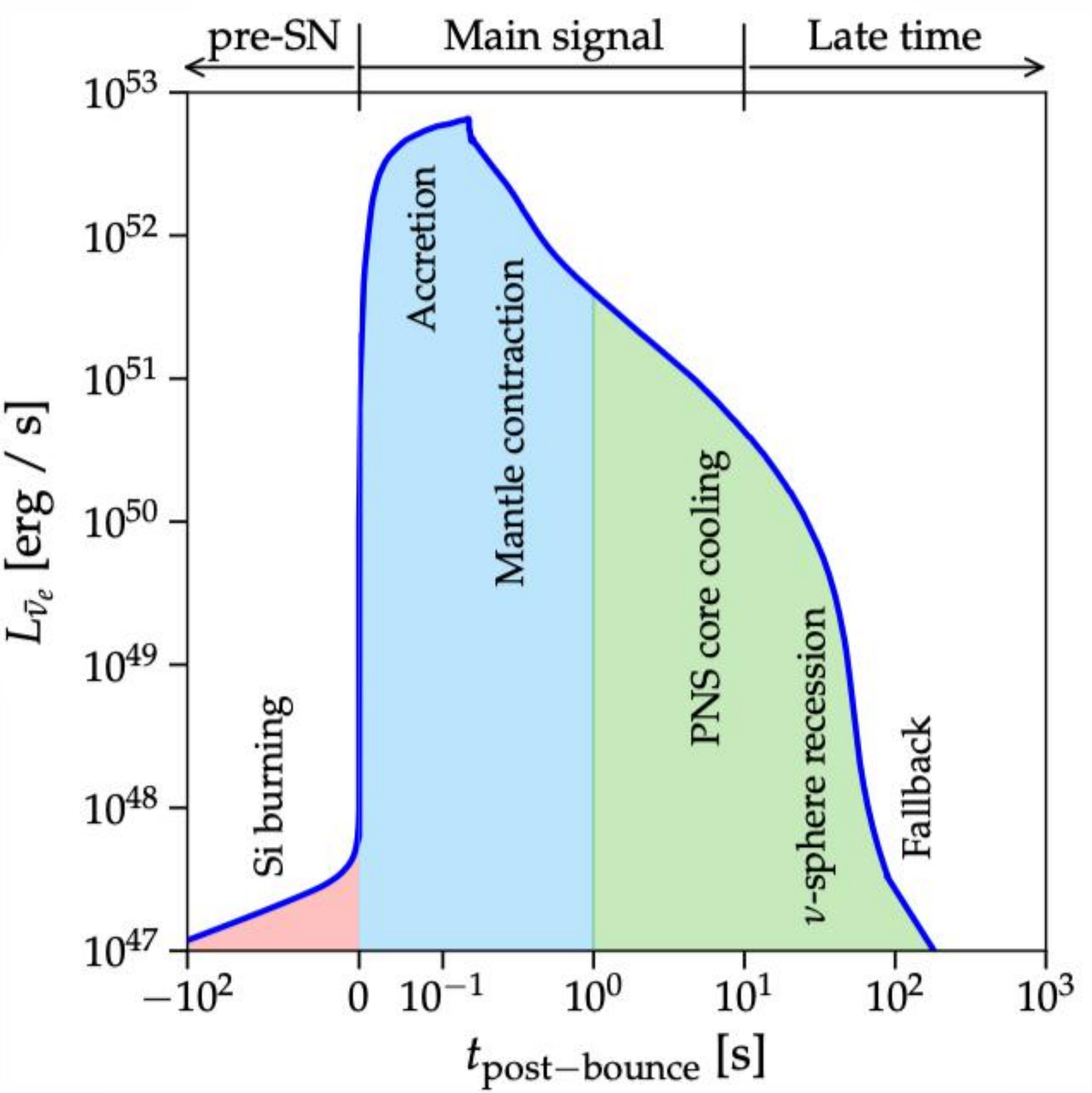
Clearly Show What We Can Learn

Pointing

Average Energy

Total Energy

Timescale of A SN



Cooling

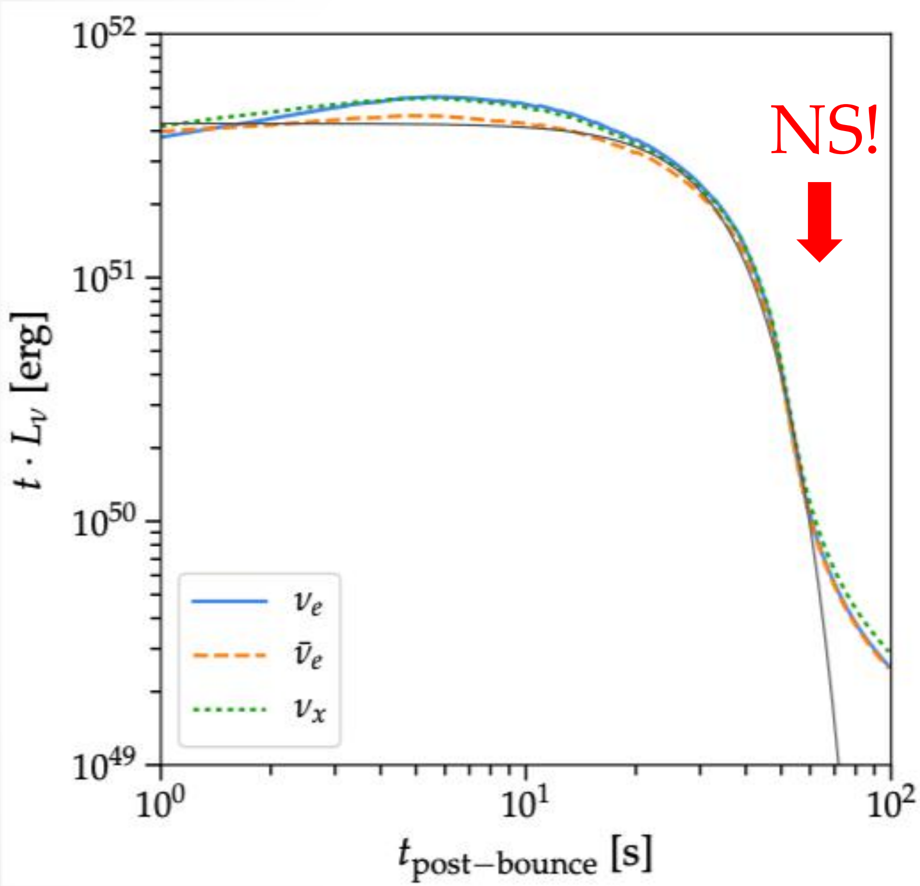
Input -- Simulation

Luke Roberts

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

Cooling Neutrinos

Neutrino Luminosity



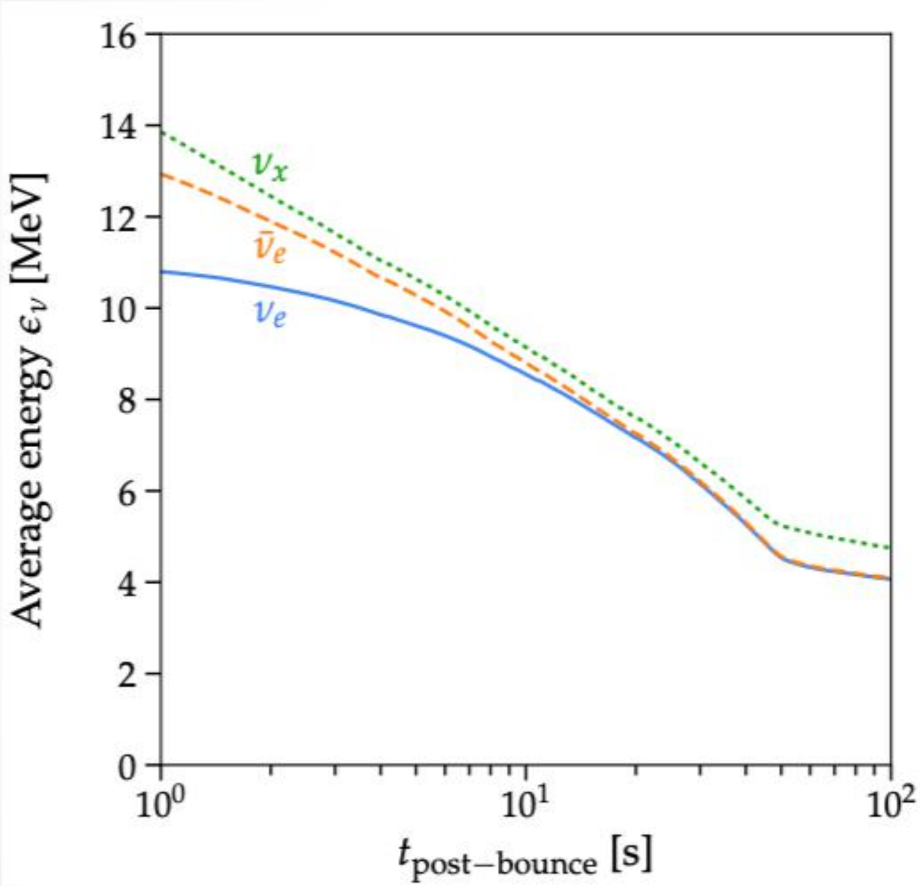
- 1/t Behavior Surprising
- Connects SN and NS
- Moderate Mixing Effect

Li, Roberts & Beacom, in prep

Cooling Neutrinos Are Interesting & Robust!

Cooling Neutrinos

Neutrino Energy



- 1/t Behavior Surprising
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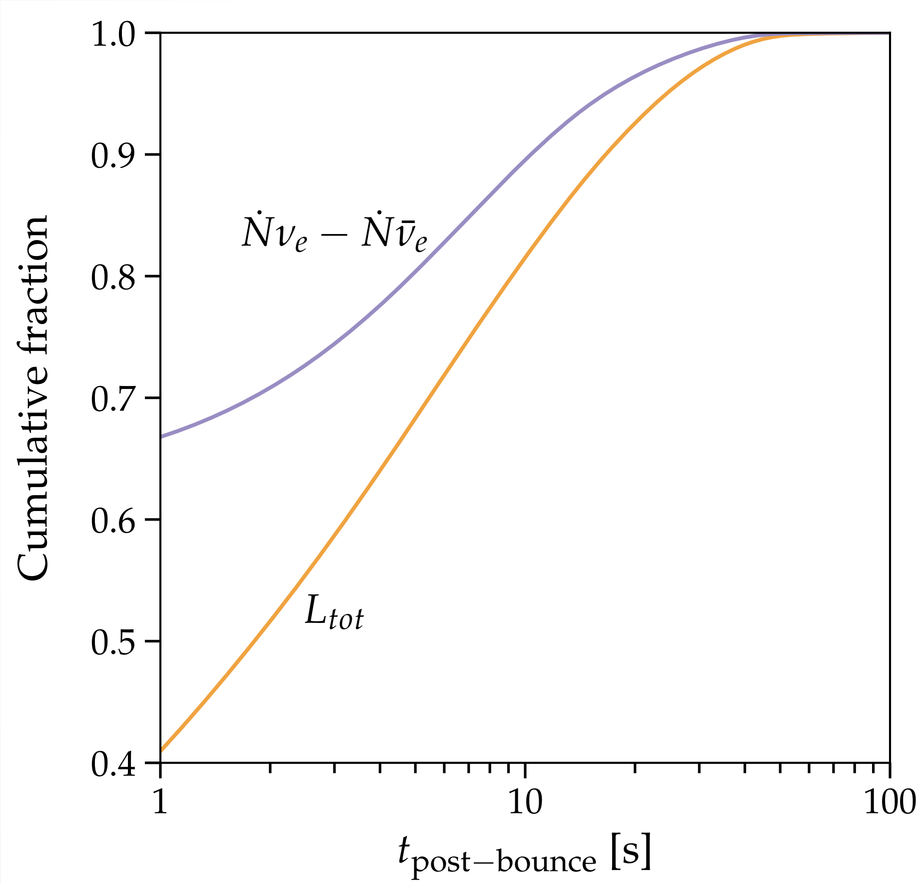
Li, Roberts & Beacom, in prep

Cooling Neutrinos Are Interesting & Robust!

Cooling Neutrinos

Cumulative Quantities



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

Li, Roberts & Beacom, in prep

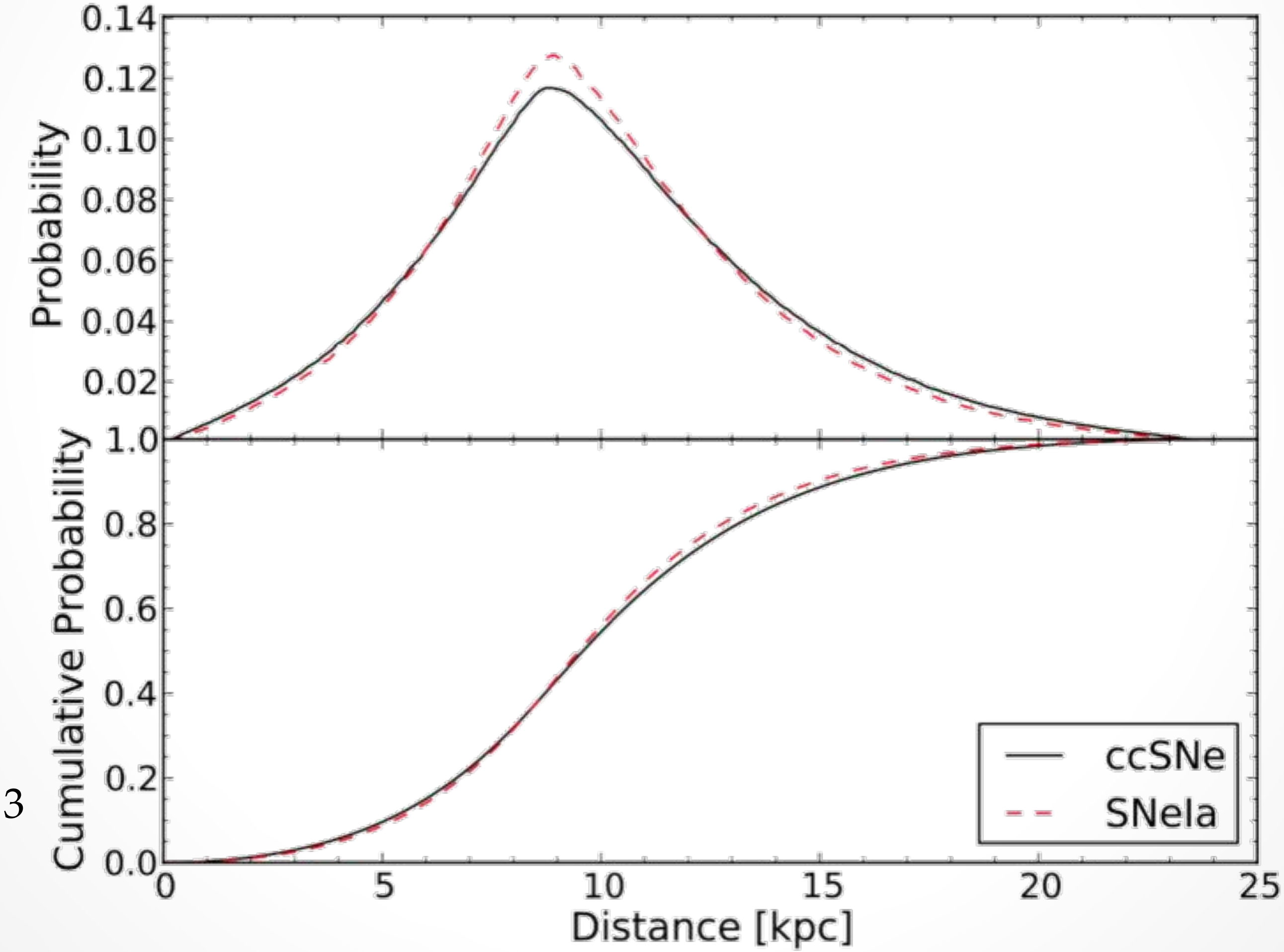
Cooling Neutrinos Are Interesting & Robust!

Supernova Neutrino Detection

Large Cross Sections	Multi-10 kton
$\bar{\nu}_e + p \rightarrow e^+ + n$	Super-K
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	DUNE
$\nu_x + p \rightarrow \nu_x + p$	JUNO

Galactic Core-Collapse SN

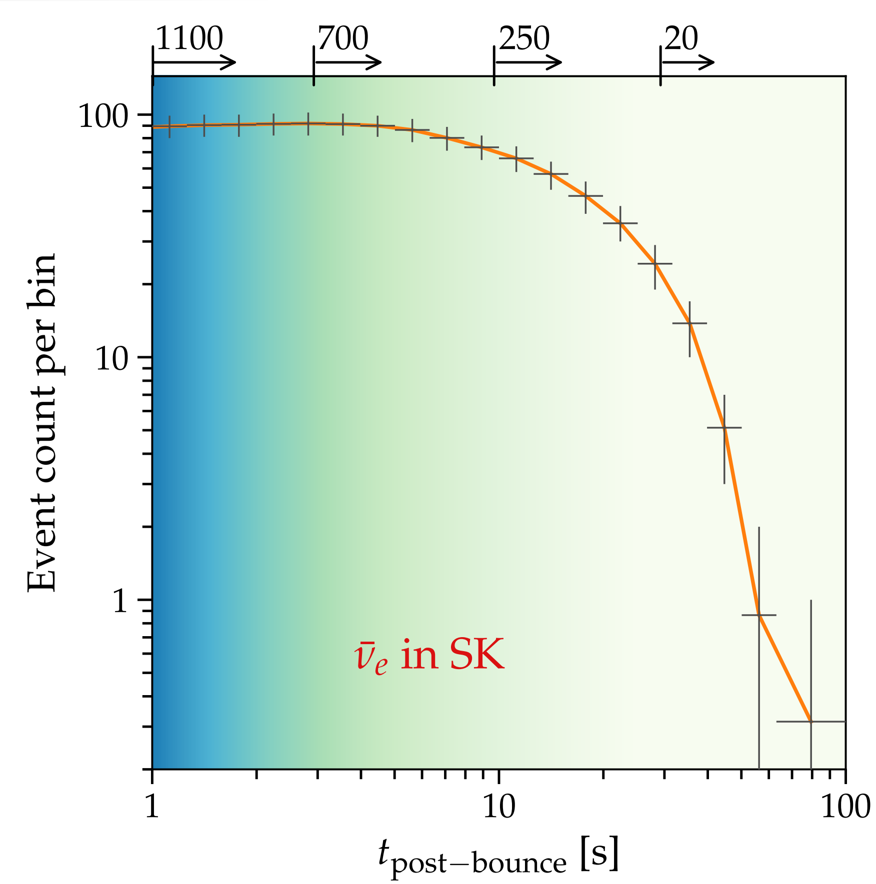
How Far Away?



Adams et al, 2013

$\overline{\nu}_e$ Signal Rate

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



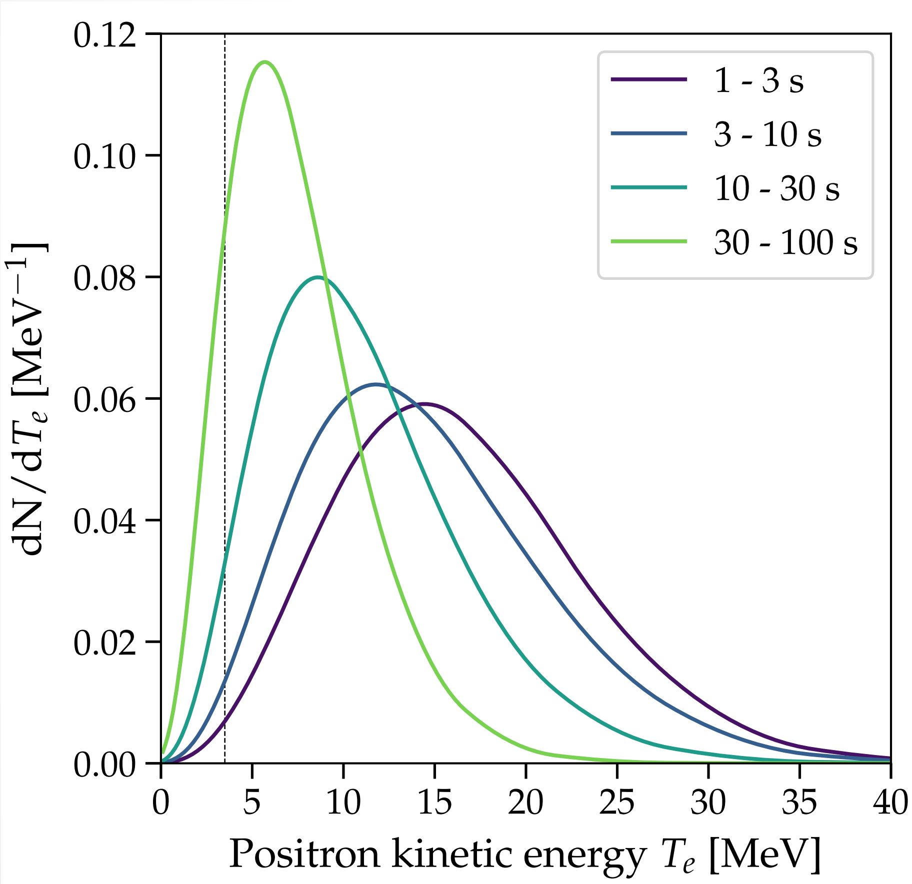
- Inputs:
  - 10 kpc SN
  - 22.5 kton
  - 3.5 MeV Threshold

Li, Roberts & Beacom, in prep

Plenty of Events in Super-K!

$\overline{\nu}_e$ Energy Spectrum

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



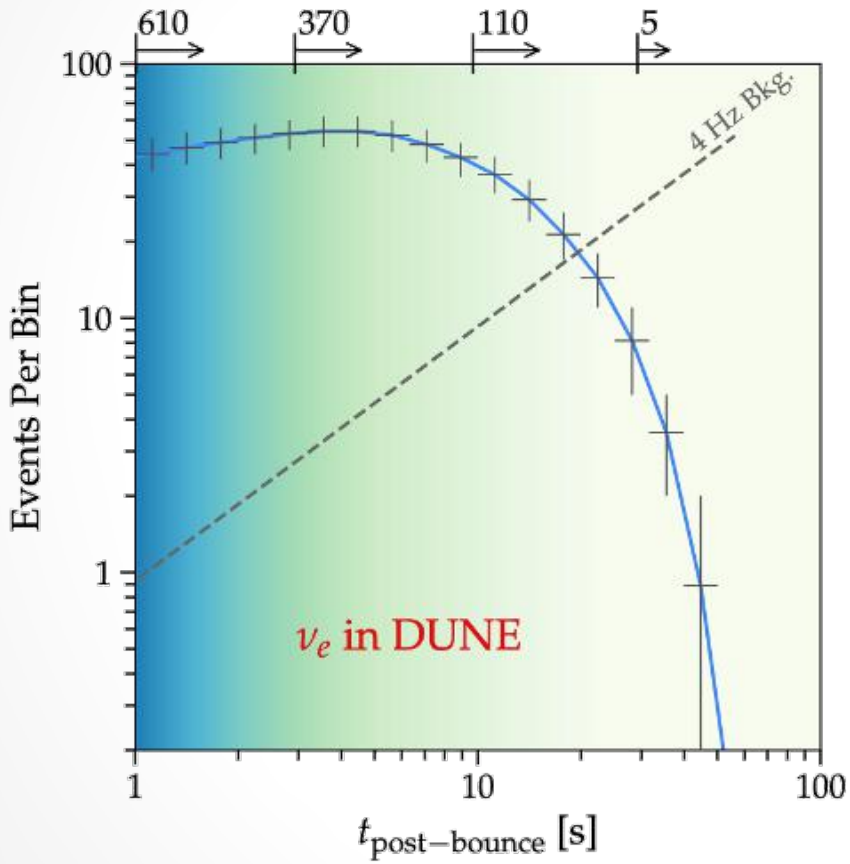
- $T_{e^+} = E_{\overline{\nu}_e} - 1.8$ MeV
- --- Known Detection Threshold

Li, Roberts & Beacom, in prep

Easily Reconstruct Neutrino Spectrum

ν_e Signal Rate

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



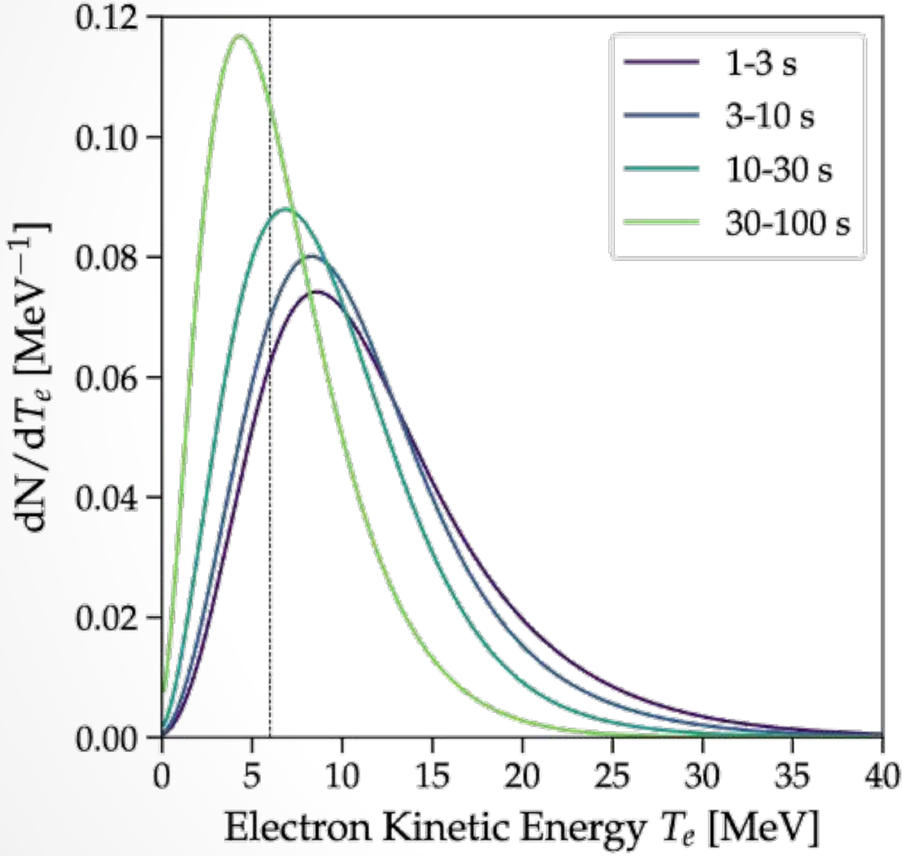
- Inputs:
  - 10 kpc SN
  - 40 kton
  - 6 MeV Threshold

Li, Roberts & Beacom, in prep

Plenty of Events to Late Time in DUNE!

ν_e Energy Spectrum

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



- $E_e = E_{\nu_e} - Q - \Delta E$
- --- Unknown

  Detection Threshold

Li, Roberts & Beacom, in prep

Detection Threshold Needs to Reach ~ 6 MeV

We Don’t Know the Cross Sections Well!

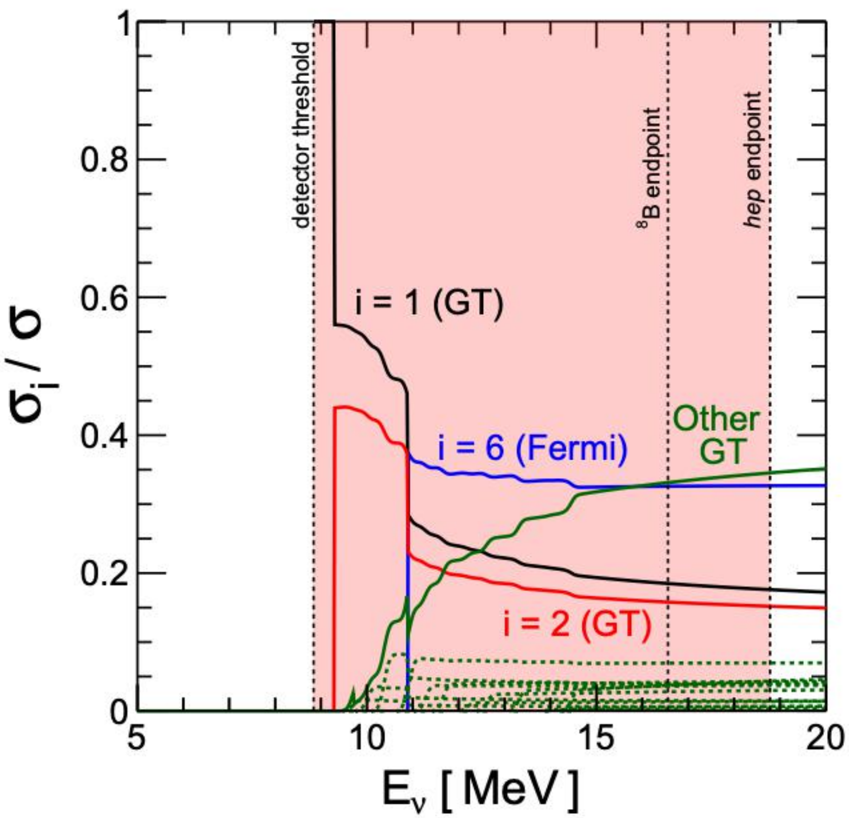
• • •

Cross Sections

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

Capozzi et al., 2018

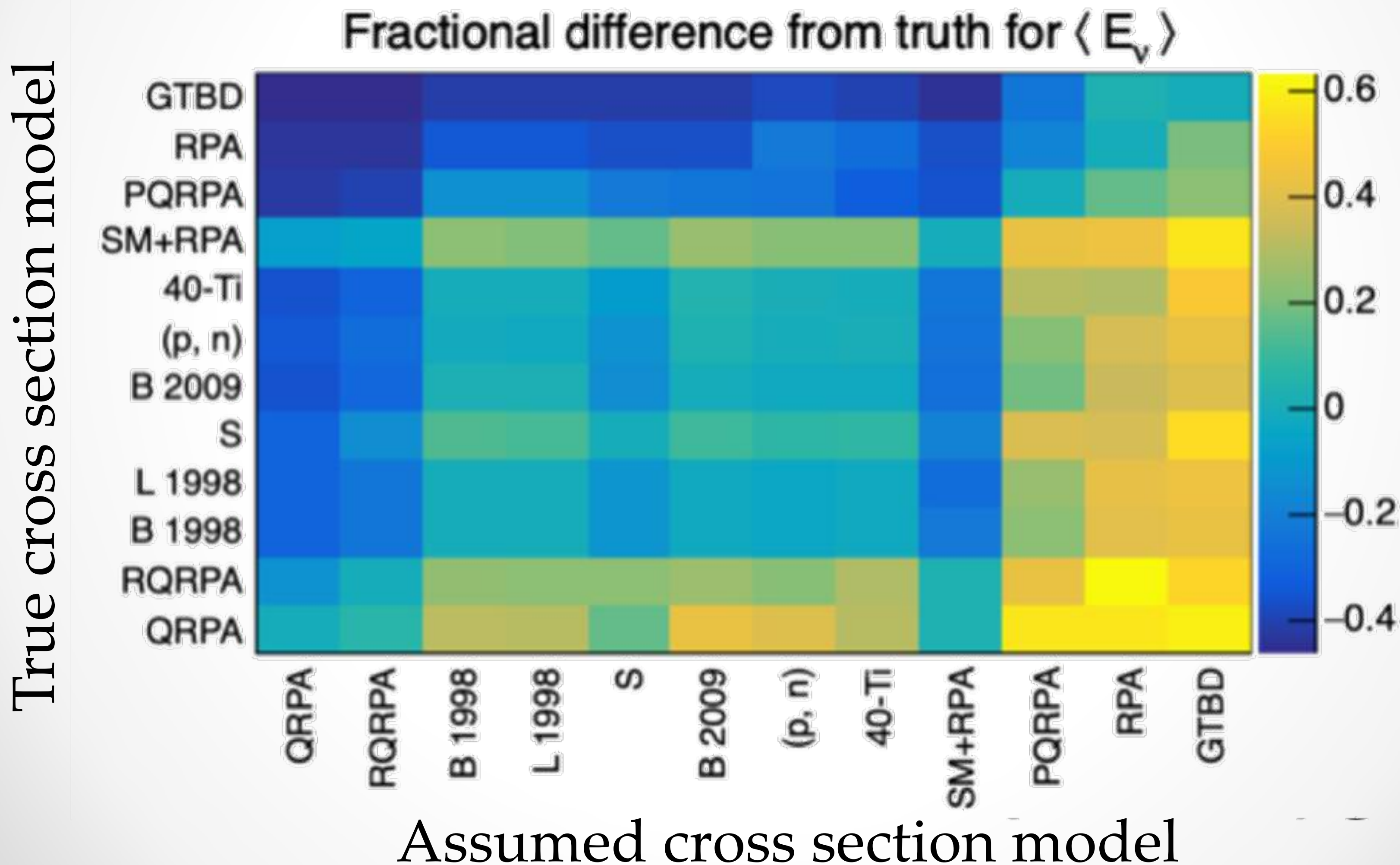
i	ΔE_i [MeV]	B_i(F)	B_i(GT)
1	2.333		1.64
2	2.775		1.49
3	3.204		0.06
4	3.503		0.16
5	3.870		0.44
6	4.384	4.00	
7	4.421		0.86
8	4.763		0.48
9	5.162		0.59
10	5.681		0.21
11	6.118		0.48
12	6.790		0.71
13	7.468		0.06
14	7.795		0.14
15	7.952		0.97
total		4.00	8.29



Difficult Theoretically and Experimentally

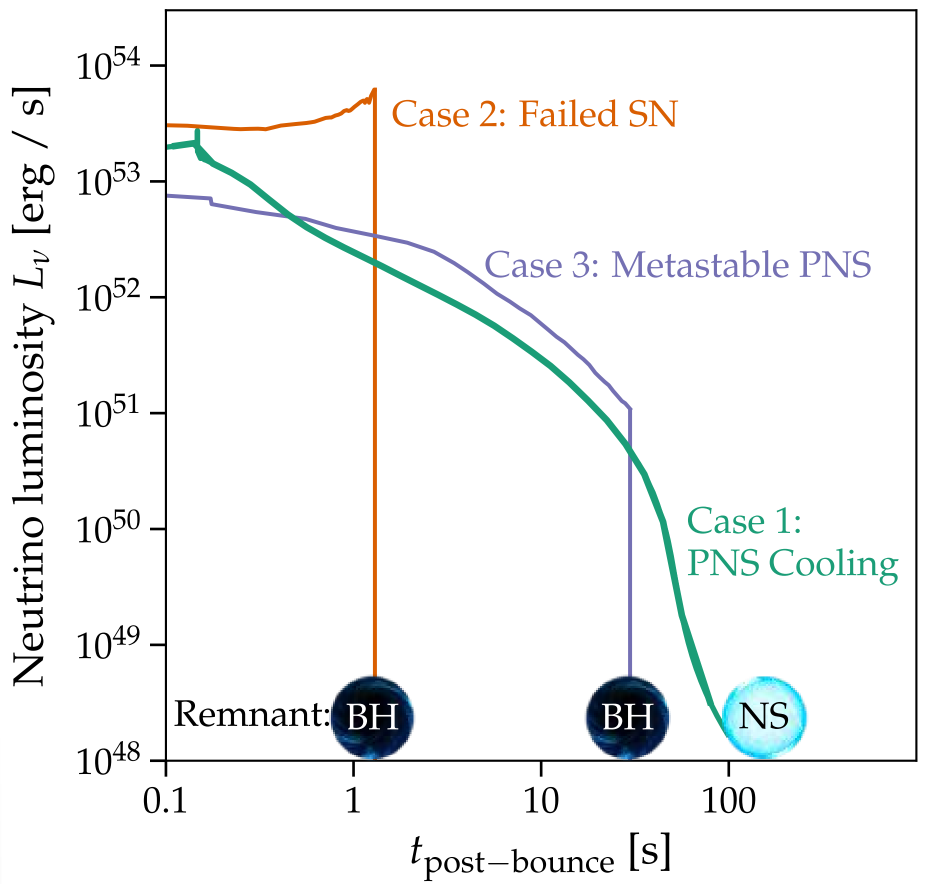
Large Impact on Supernova ν

E. Conley, DUNE-doc-14068



Alternative Outcome -- BH

Different Mechanisms for BH Formation

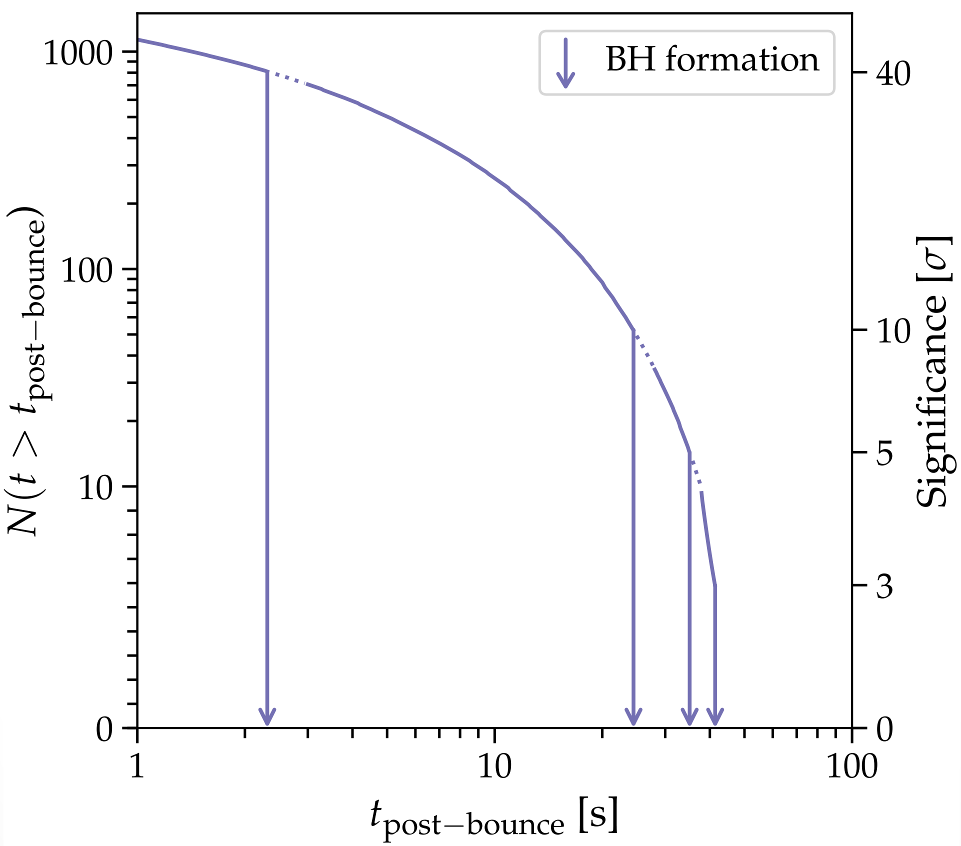


Li, Roberts & Beacom, in prep

BH May Form at Late Times

Detecting BH Formation

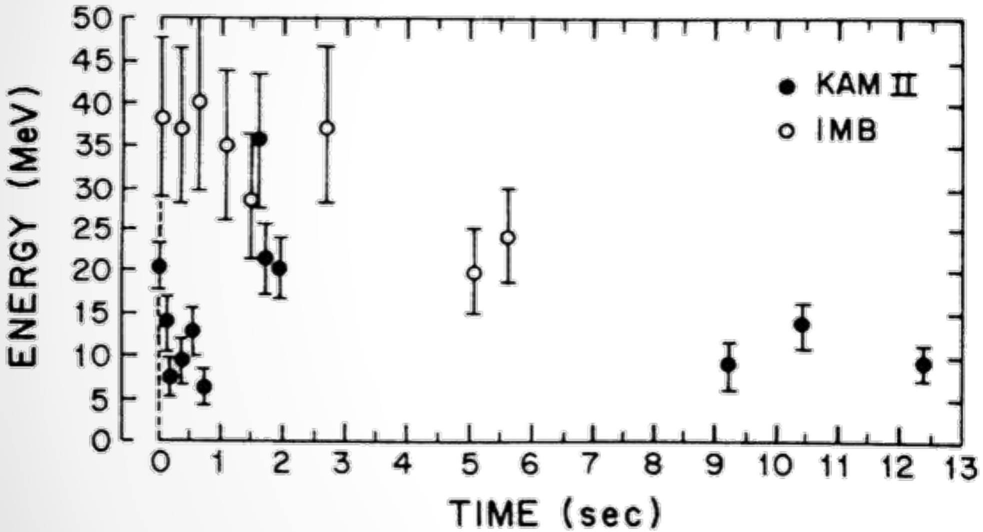
Detection Significance of BH Formation

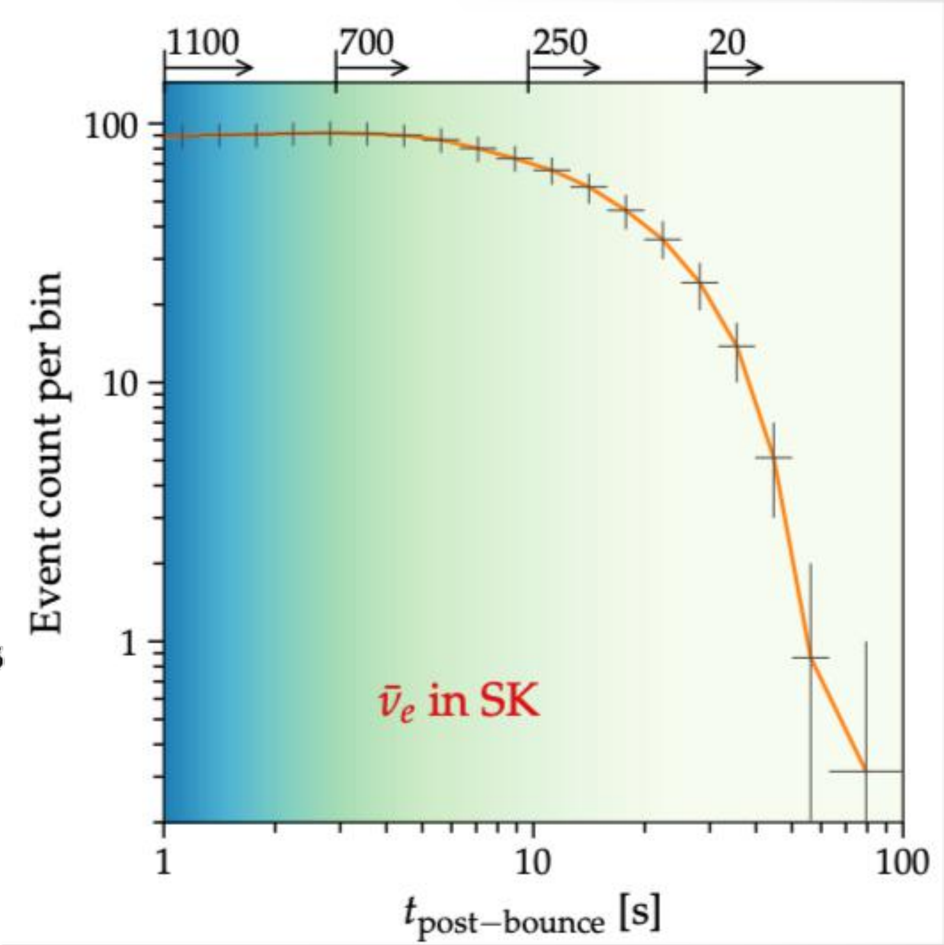


Li, Roberts & Beacom, in prep

We Can Detect BH Formation at Late Times

Conclusions





Backup

Galactic Core-Collapse SN

How Often?

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

Adams et al, 2013

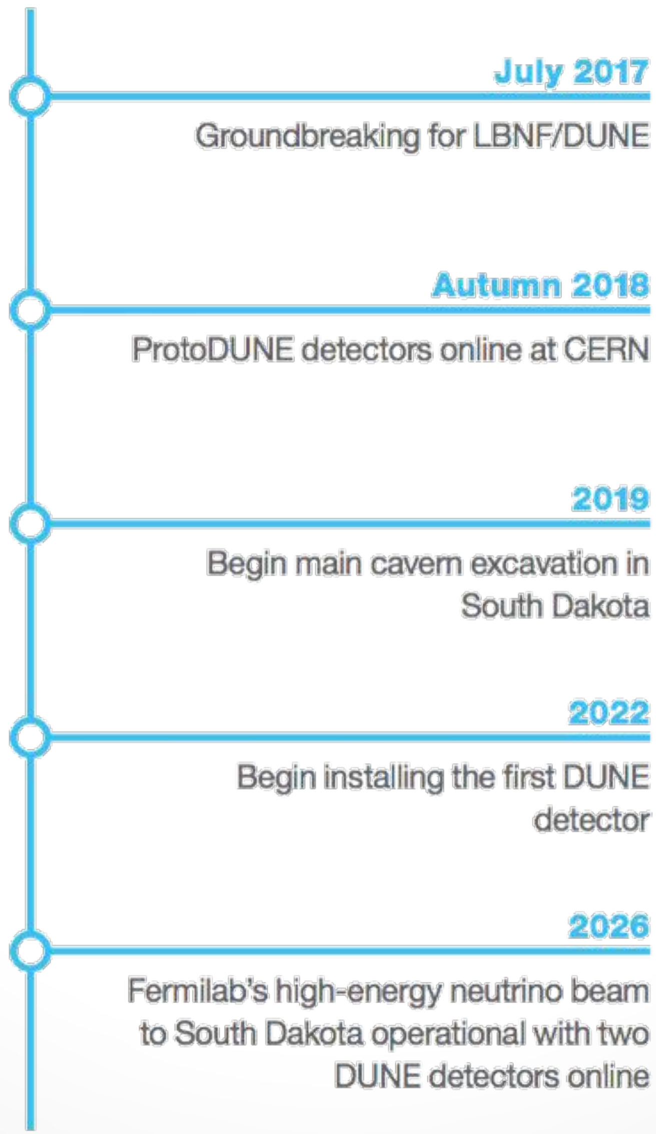
$2.8^{+0.6}_{-0.6}$

(With A Systematic Uncertainty of A Factor of ~2)

Li et al, 2011

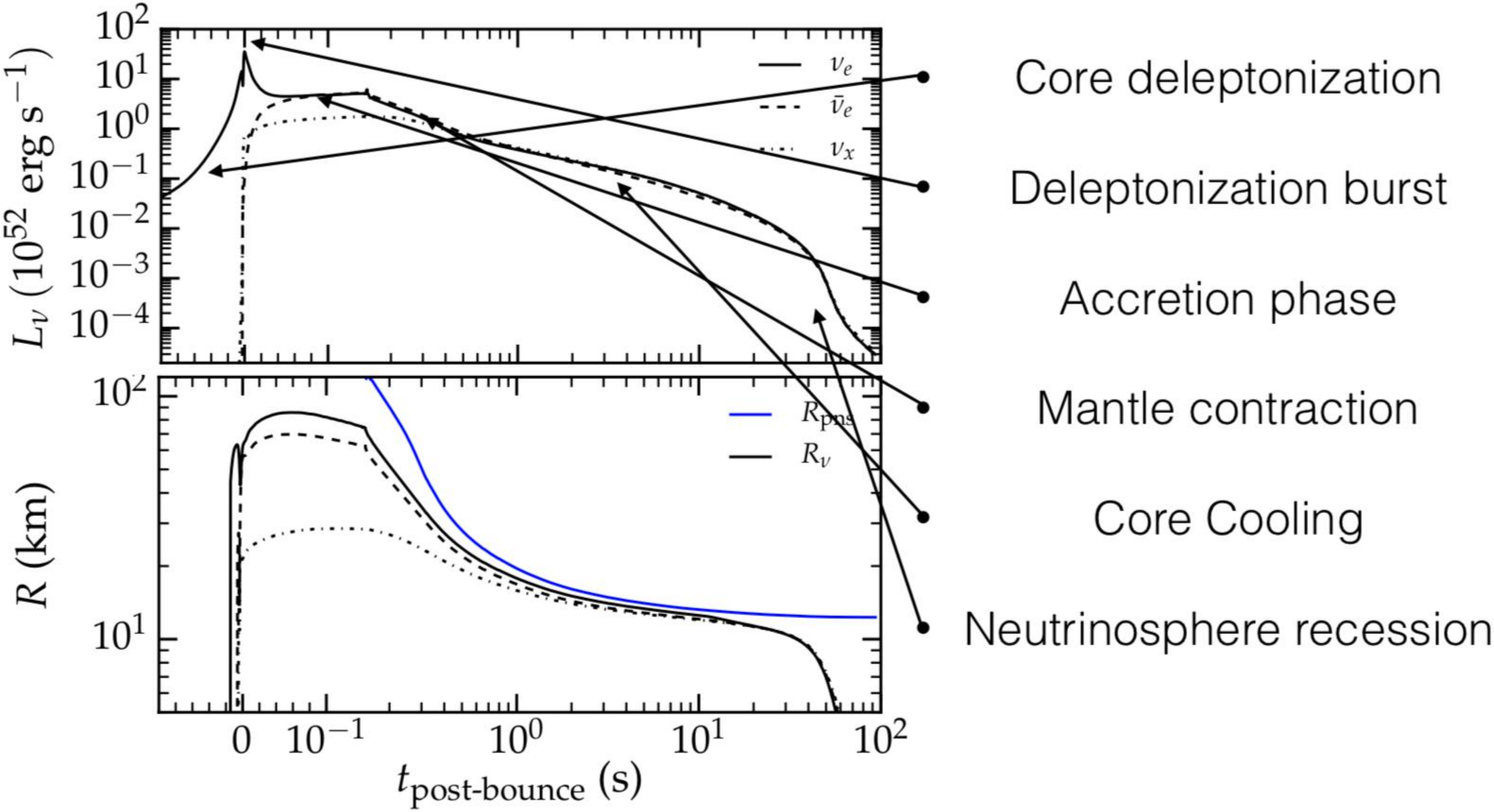
Per Century

DUNE Timeline



Fnal.gov

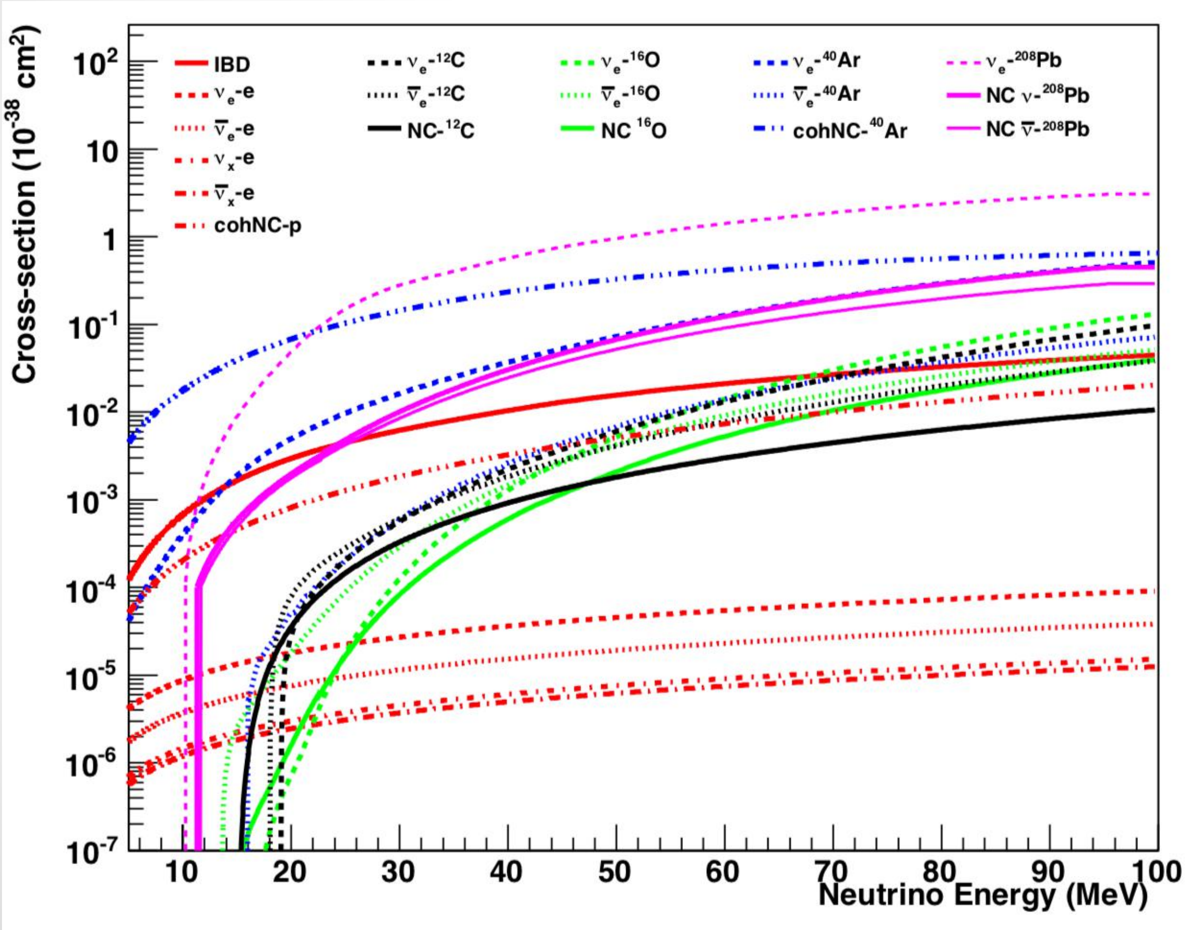
Anatomy of the Neutrino Signal



Unique ν_e Detection Channel

K. Scholberg 2012

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$



Clean Kinematics:

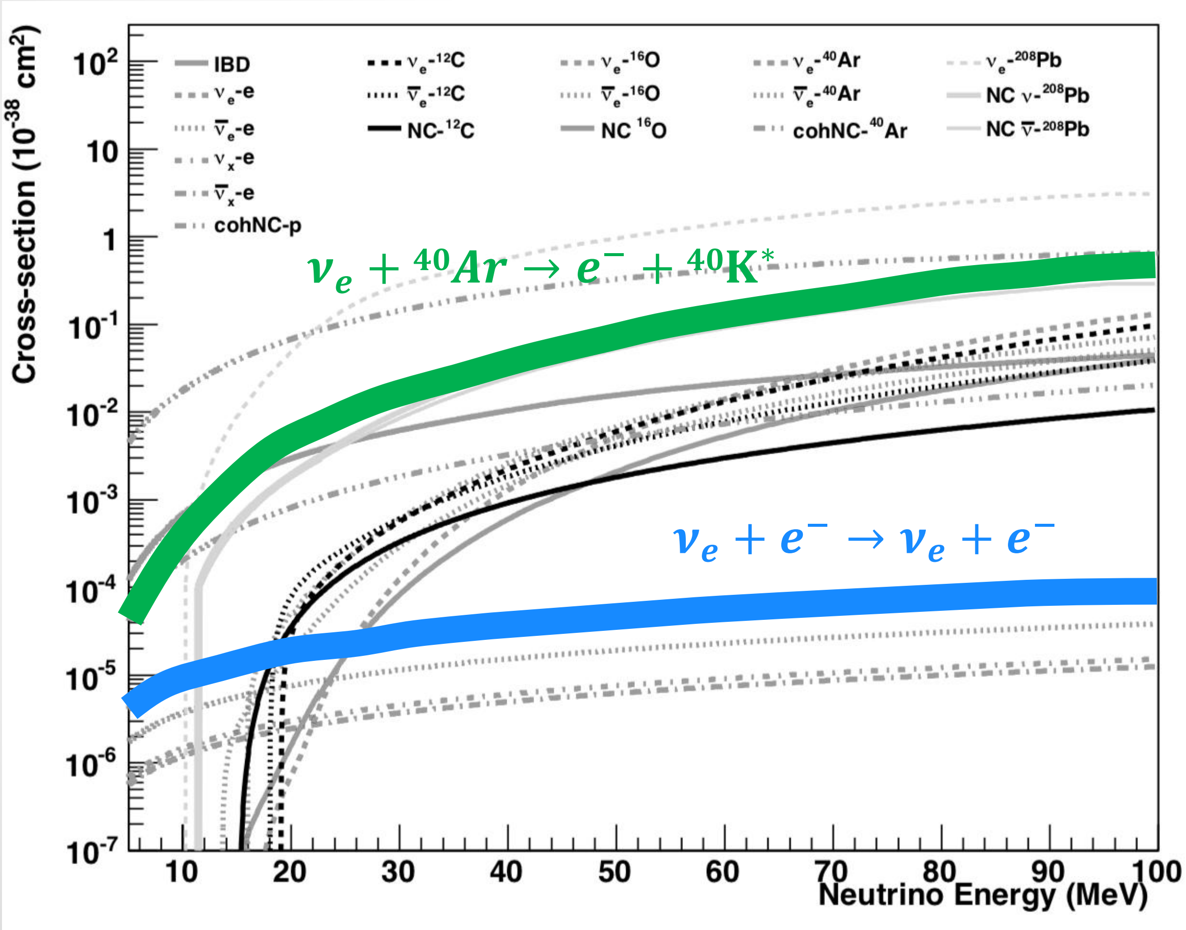
$$E_e = E_\nu - Q - \Delta E$$

Ideal Channel for ν_e

Unique ν_e Detection Channel

K. Scholberg 2012

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$



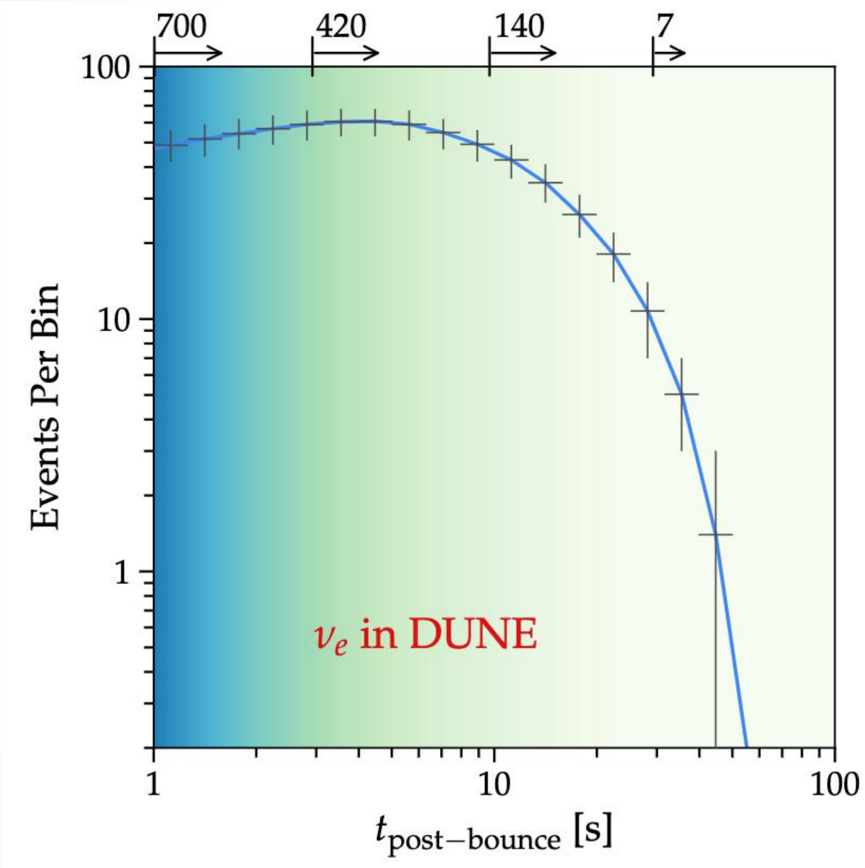
Clean Kinematics:

$$E_e = E_\nu - Q - \Delta\text{E}$$

Ideal Channel for ν_e

ν_e Signal Rate

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



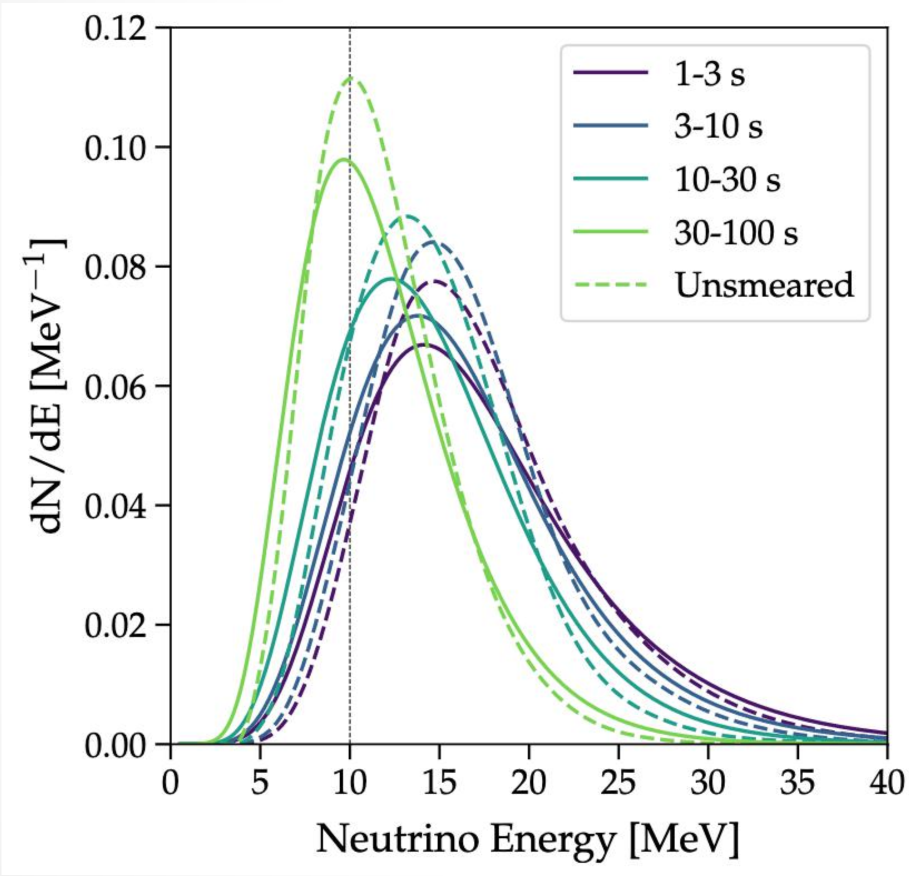
- Inputs:
  - 10 kpc SN
  - 40 kton
  - 10 MeV Threshold

Li, Roberts & Beacom, in prep

Plenty of Events to Late Time in DUNE!

ν_e Energy Spectrum

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$



- $E_e = E_{\nu_e} - Q - \Delta\text{E}$
- --- Unknown

  Detection Threshold

Li, Roberts & Beacom, in prep

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. García[3]

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

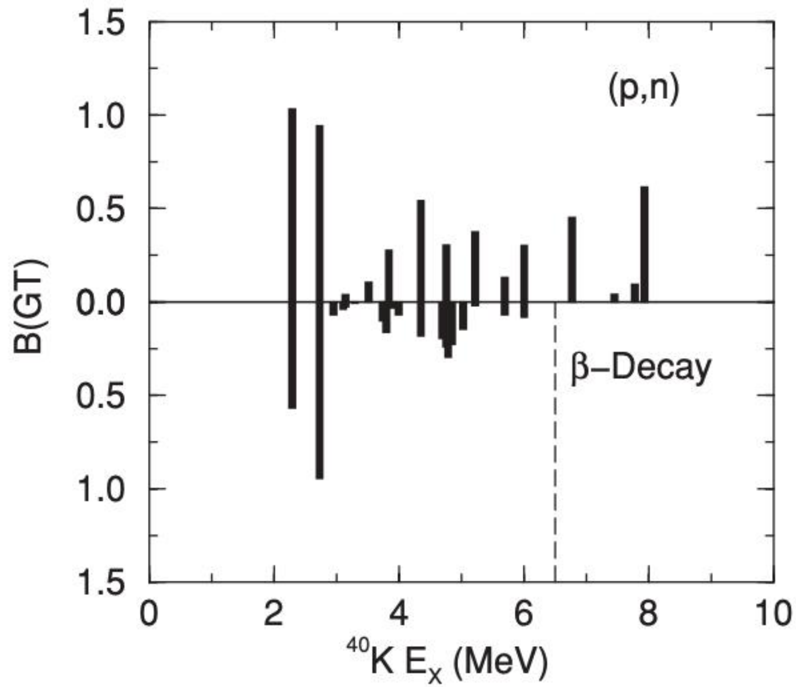
[2] *Indiana University Cyclotron Facility, 2401 Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*

[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)

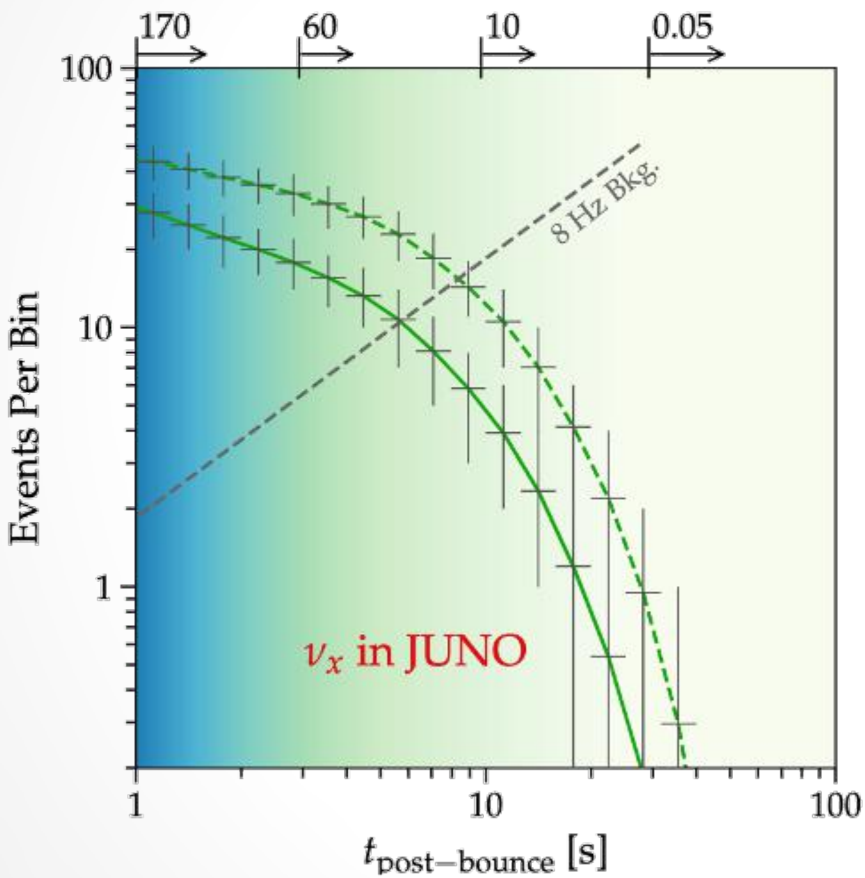
We report a measurement of the Gamow-Teller (GT) strength distribution for $^{40}Ar \rightarrow {}^{40}K$ using the $0^{\circ}(p,n)$ reaction. The measurement extends observed GT strength distribution in the $A = 40$ system up to an excitation energy of $\sim$8 MeV. In comparing our results with those 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 $\sim$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

$$\nu_x + p \rightarrow \nu_x + p$$



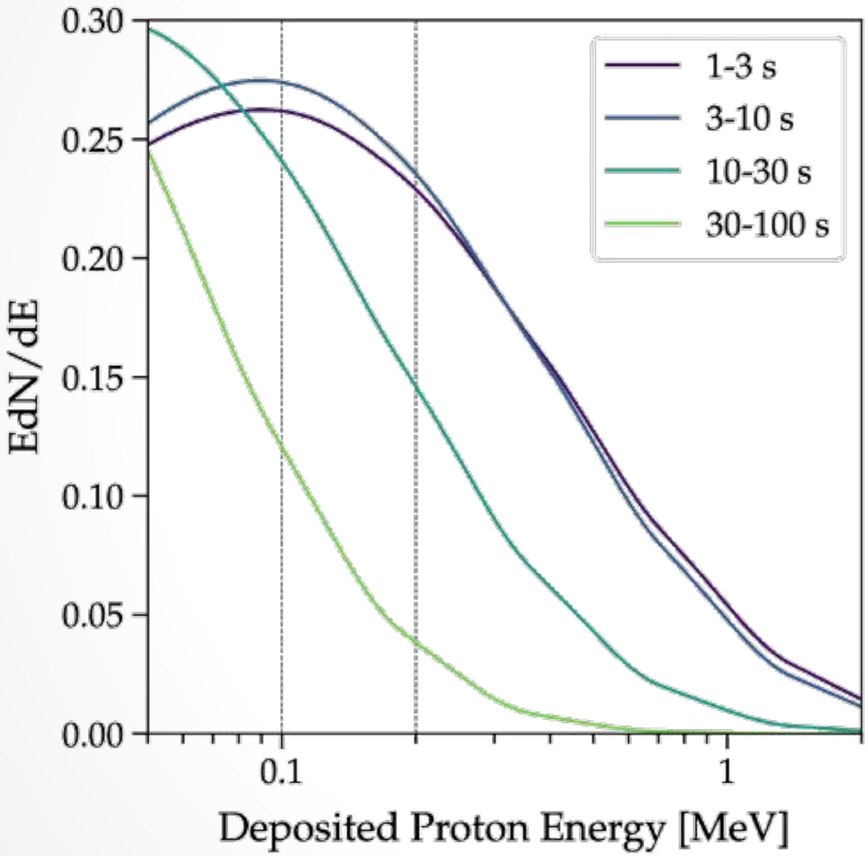
- Inputs:
  - 10 kpc SN
  - 20 kton
  - 0.1, 0.2 MeV Threshold

Li, Roberts & Beacom, in prep

Non-Negligible Events at Late Time

ν_x Energy Spectrum

$$\nu_x + p \rightarrow \nu_x + p$$



- $E_{\text{det}} \ll E_{\nu_x}$
- --- unknown
  Detection Threshold

Li, Roberts & Beacom, in prep

Detection Threshold is Crucial