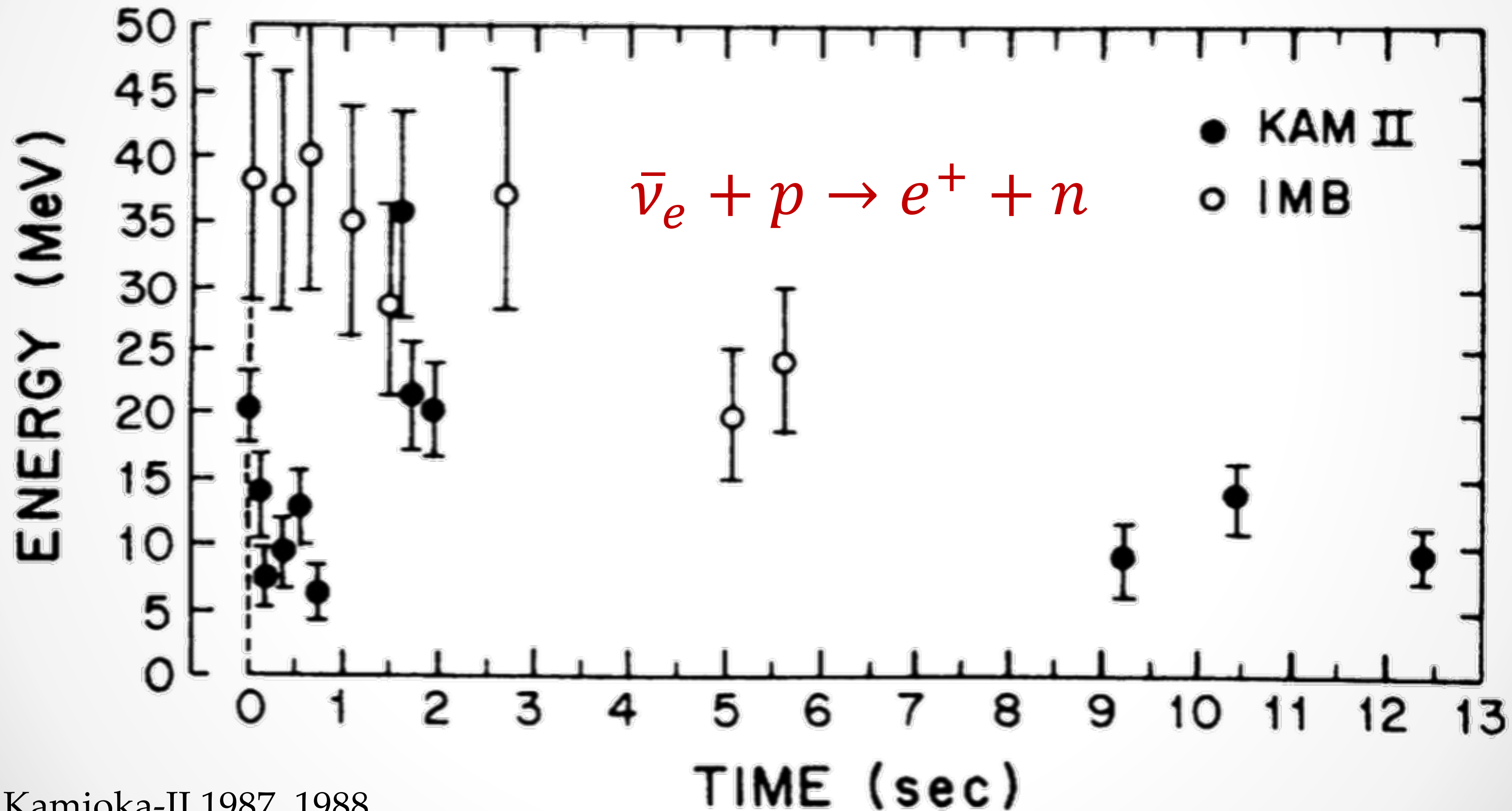
Physics Constraints From SN 1987A Detection

Shirley Li, UC Irvine

Workshop on Ghost Particle Hunting:
Neutrino Physics and its Applications to World Peace

Detection of SN 1987A!

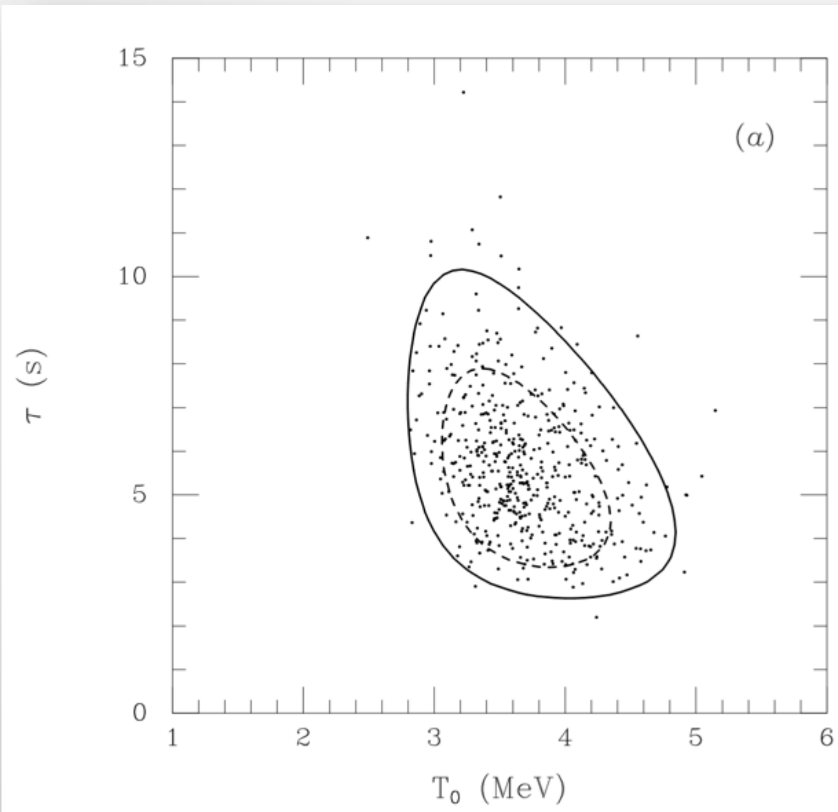
Large Magellanic Cloud, 50 kpc Away



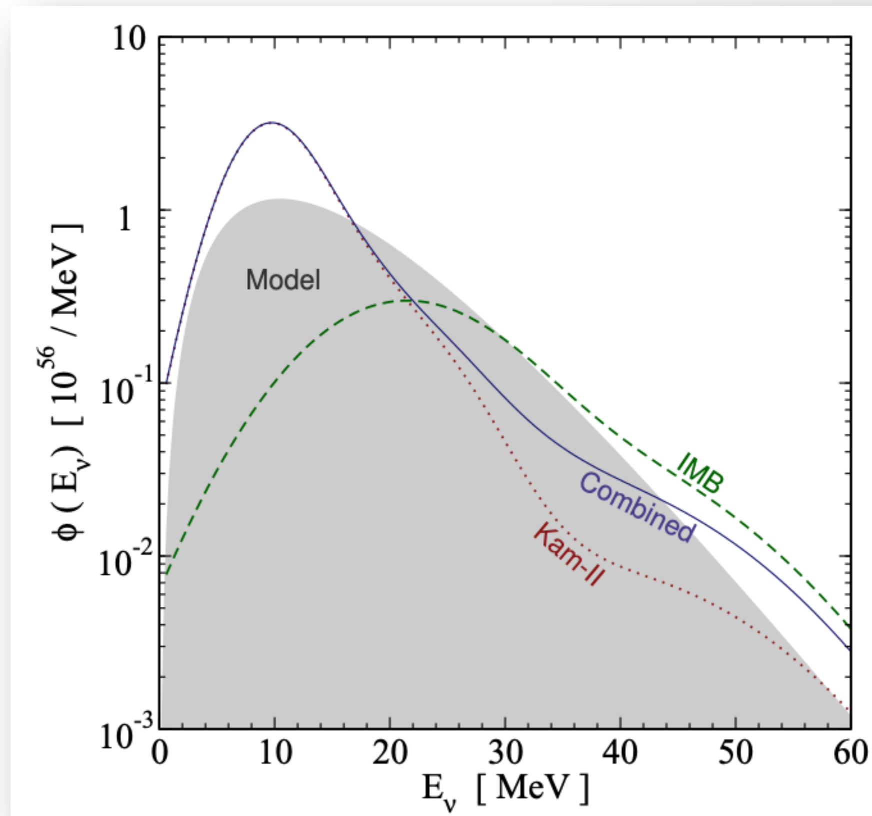
Kamioka-II 1987, 1988
IMB 1987, 1988

Big Picture Consistent

Total energy, average energy, thermal-like spectrum, time scale, all consistent with theoretical expectations



Loredo & Lamb, 2001

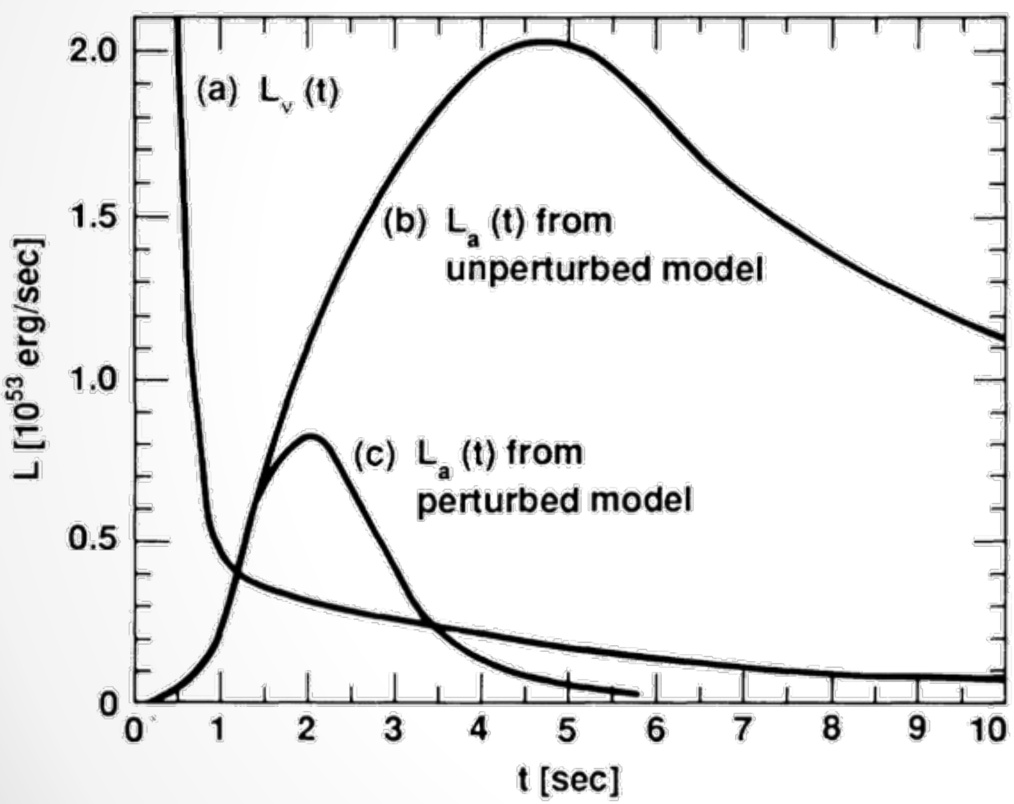


Yuksel & Beacom, 2008

Powerful Probe of New Physics

L_χ would shorten neutrino signal duration

Raffelt, Seckel, 1988



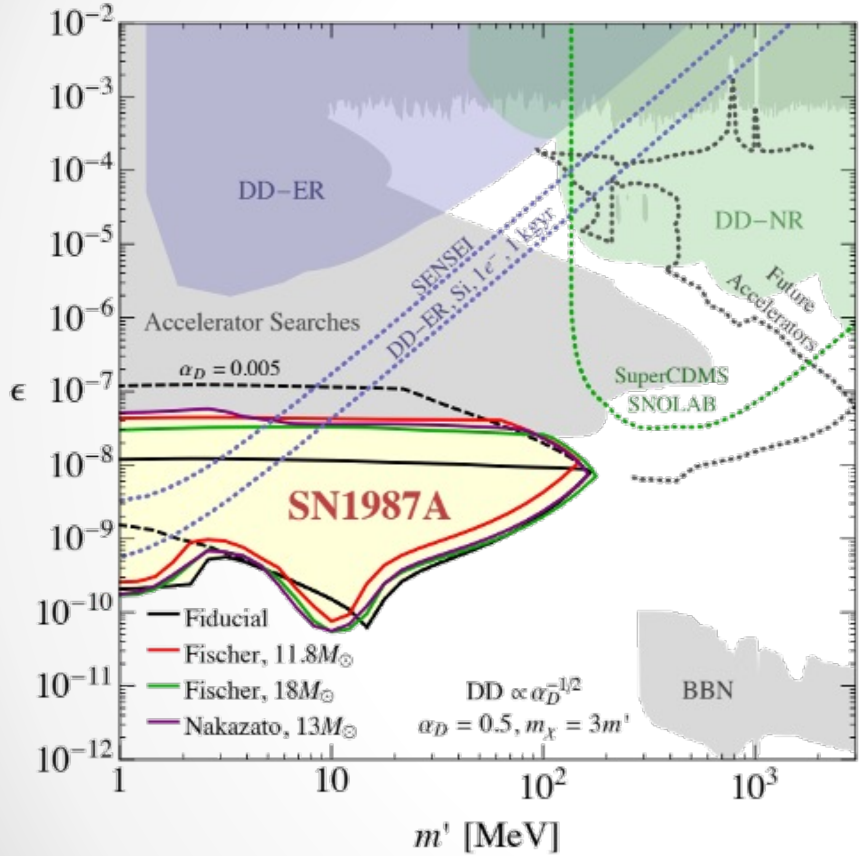
L_χ lowers the star temperature, which then lowers neutrino signal

The ~10 s timescale of neutrino flux can constrain new physics

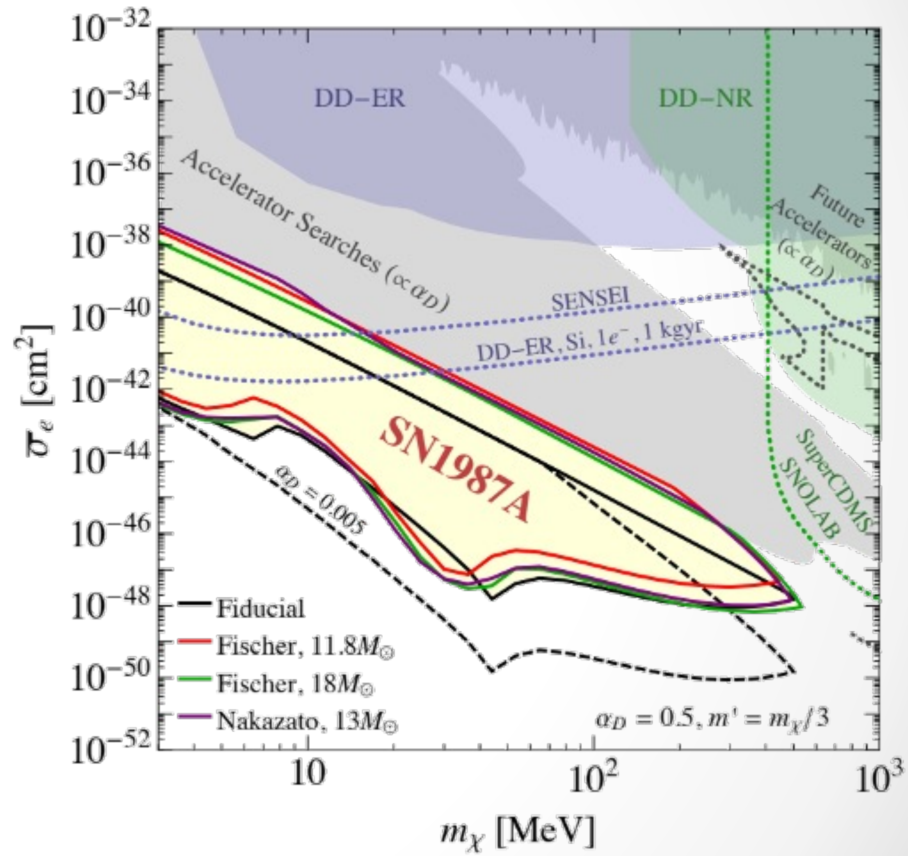
Dark Matter Example

Chang, Essig, McDermott, 2018

Dark photon



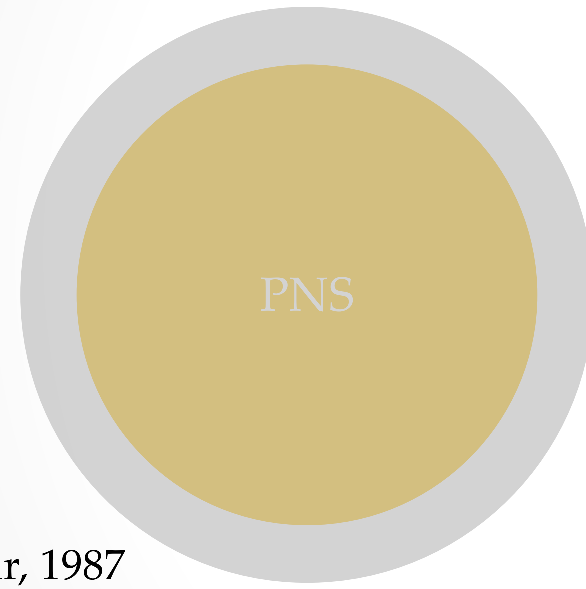
Dark matter

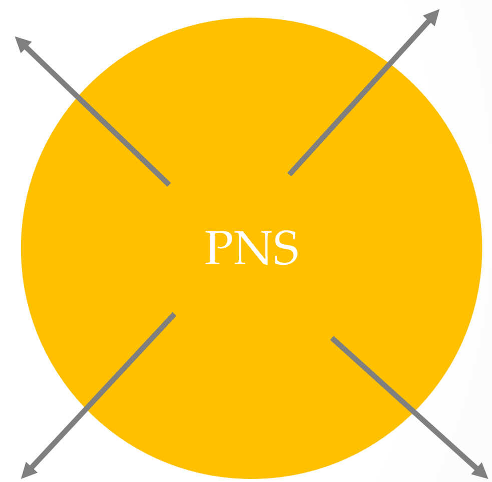


Complementary parameter spaces to other probes

Questions Remain

What happens when the light particles have self-interaction?





Manohar, 1987
Sung, Guo, Wu, 2021
…

Dicus, Nussinov, Pal, Teplitz, 1989
Chang, Essig, McDermott, 2018
…

Ongoing debate in the literature

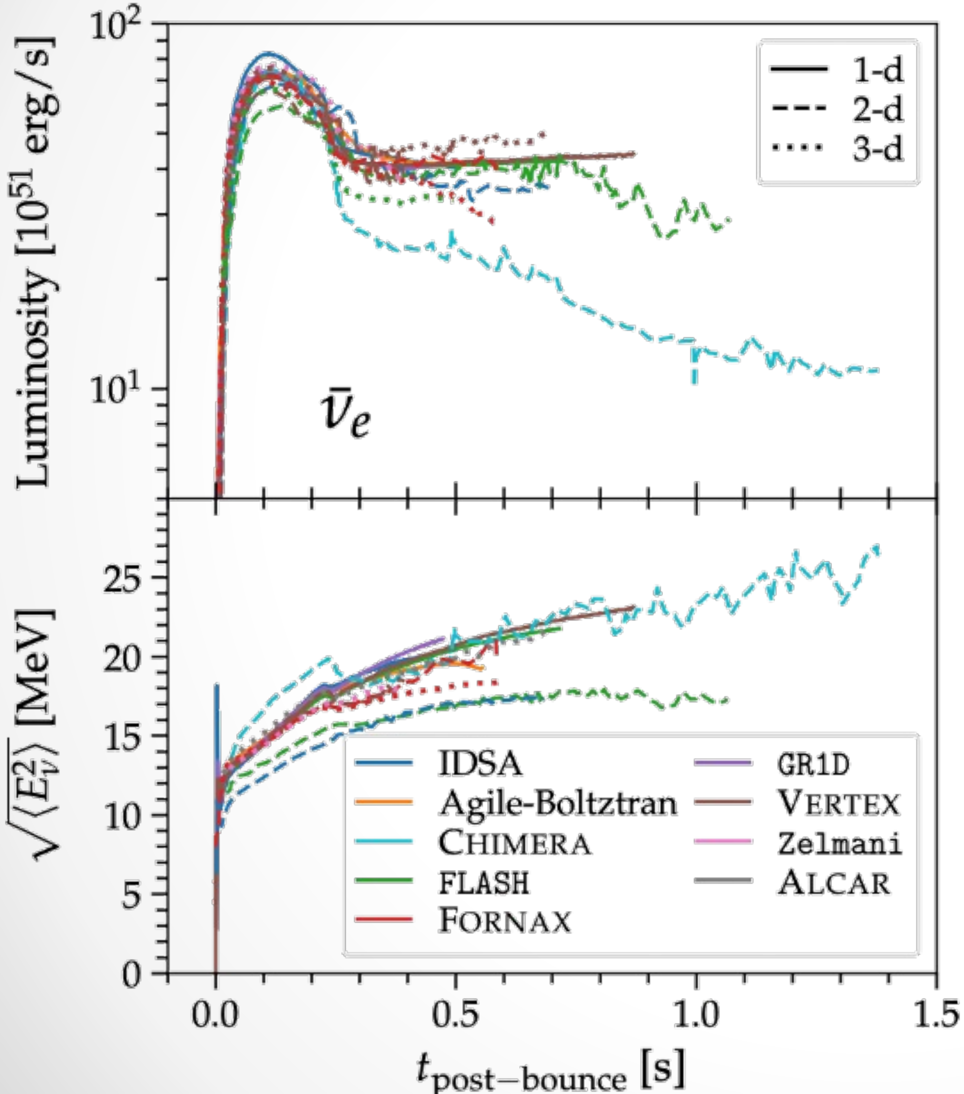
Results in orders of magnitude difference in bounds

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

Is this true??

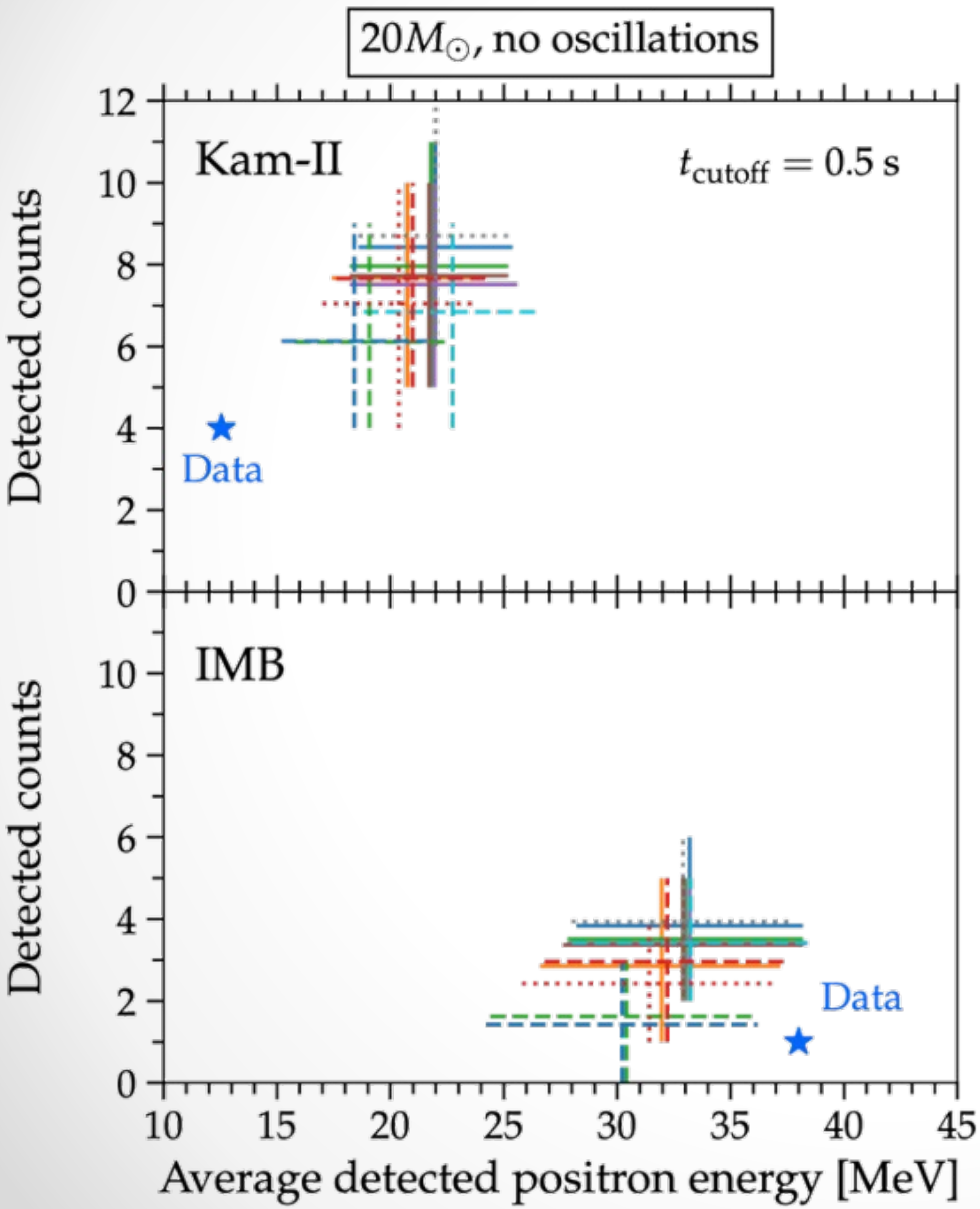
Let's Compare!



- ➢ Straight out of simulation, no oscillation
- ➢ $\bar{\nu}_e$ only
- ➢ 20 $M_\odot$
- ➢ All models in the last 10 years

SL, Beacom, Roberts, Capozzi, 2023

First Look at the Results



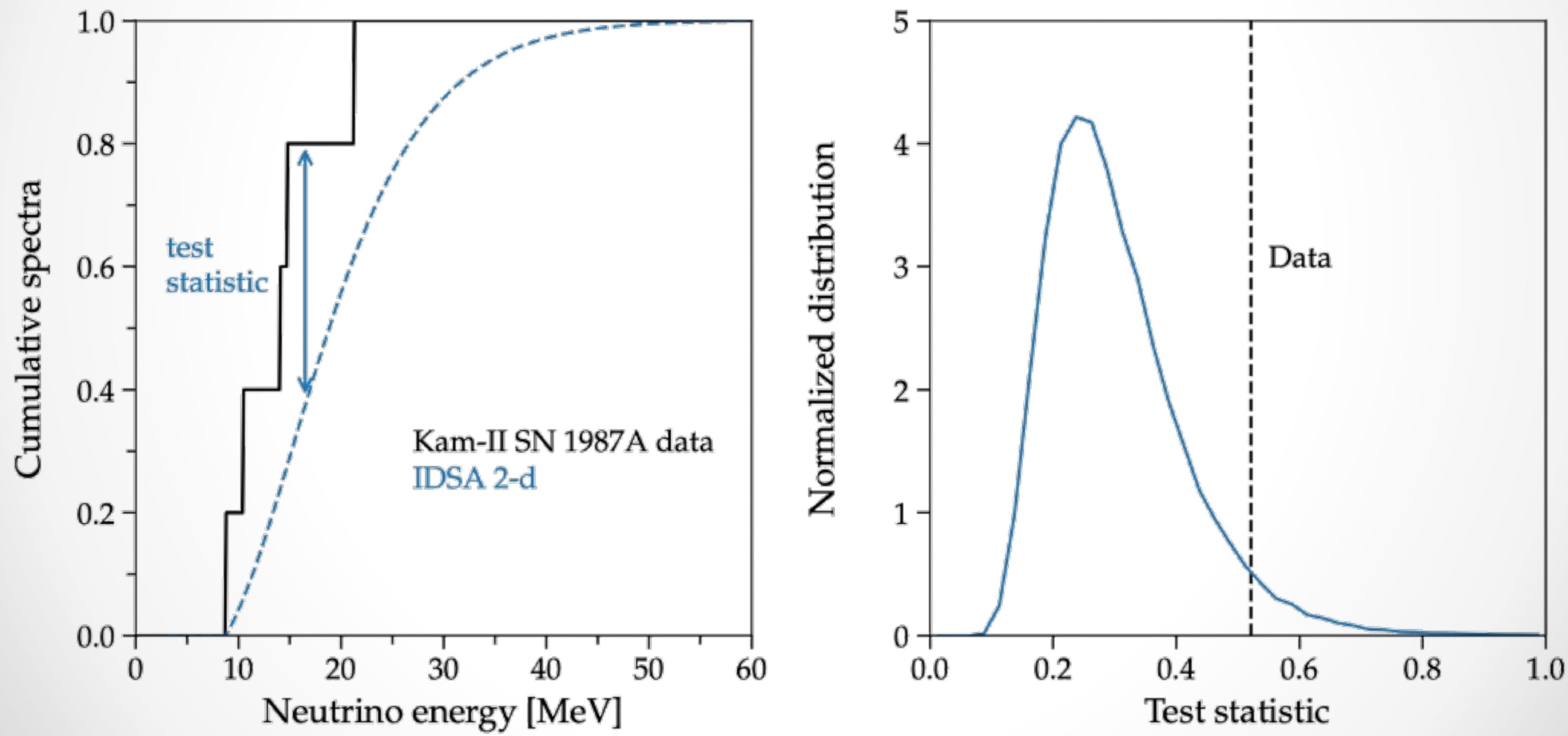
- Model simulation vs. 87A data
- Cut off all predictions and data at 0.5 s
- Forward modeling
- Error bars 1σ

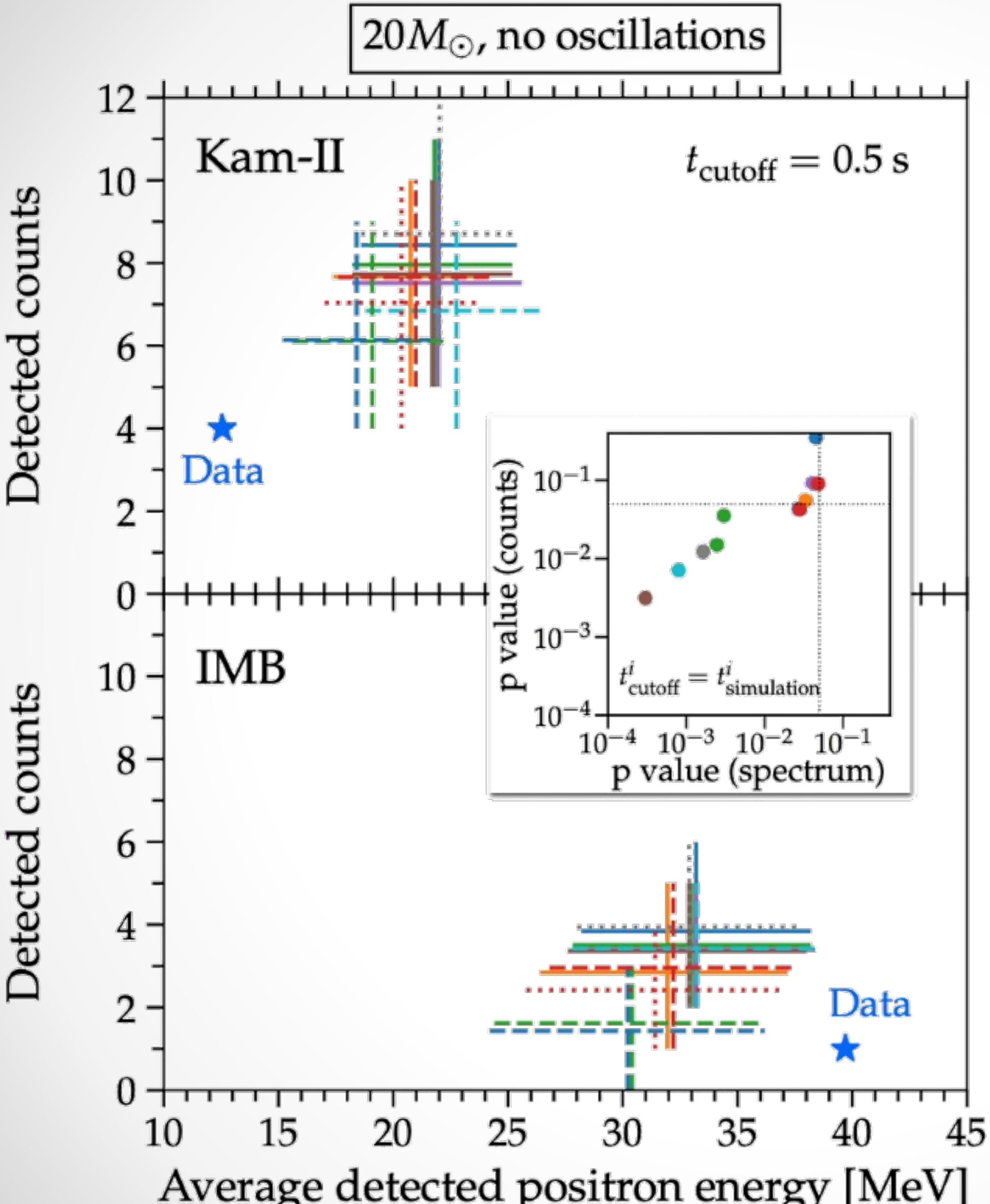
SL, Beacom, Roberts, Capozzi, 2023

Quantifying the Statistics

SL, Beacom, Roberts, Capozzi, 2023

KS test on spectrum

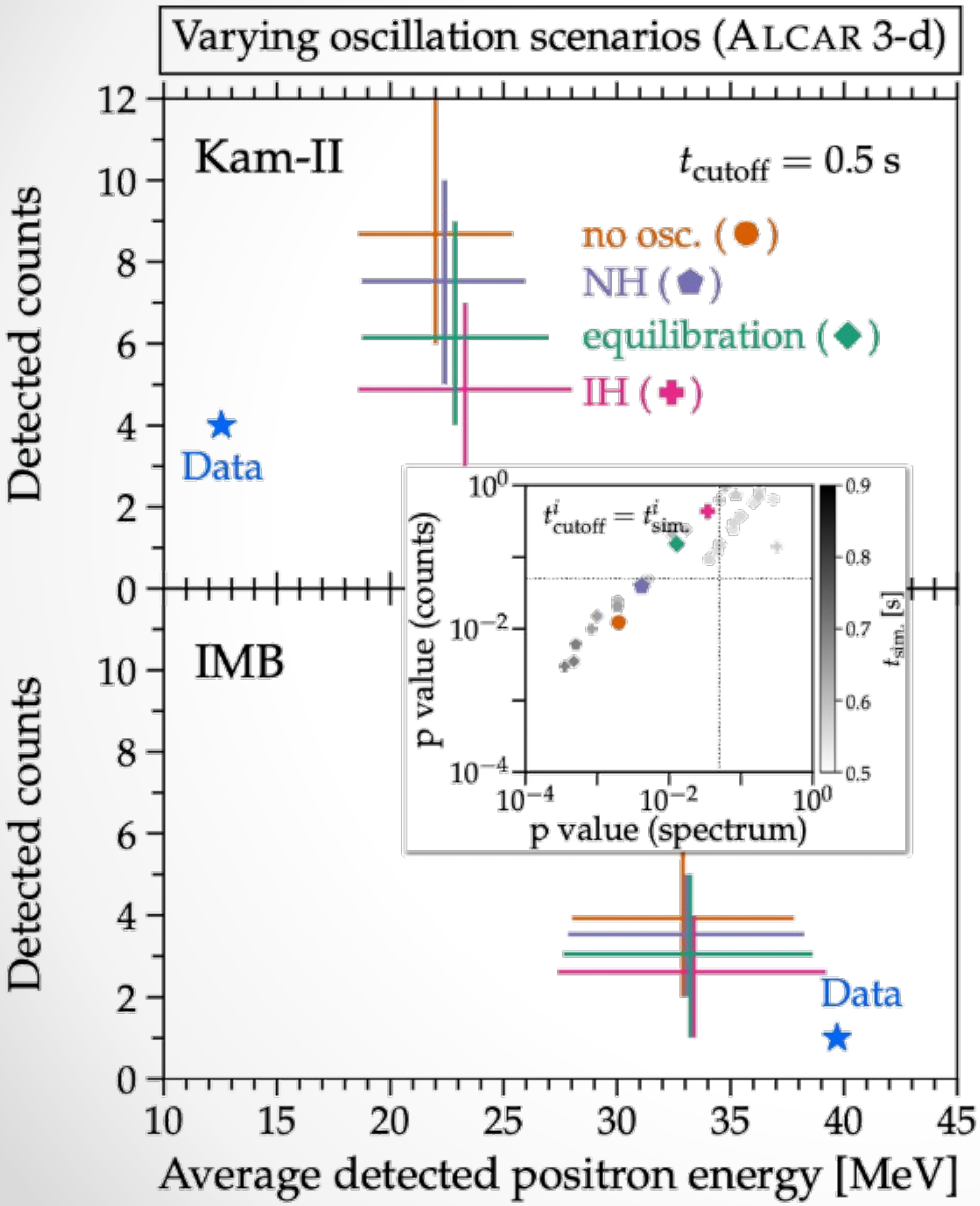




SL, Beacom, Roberts, Capozzi, 2023

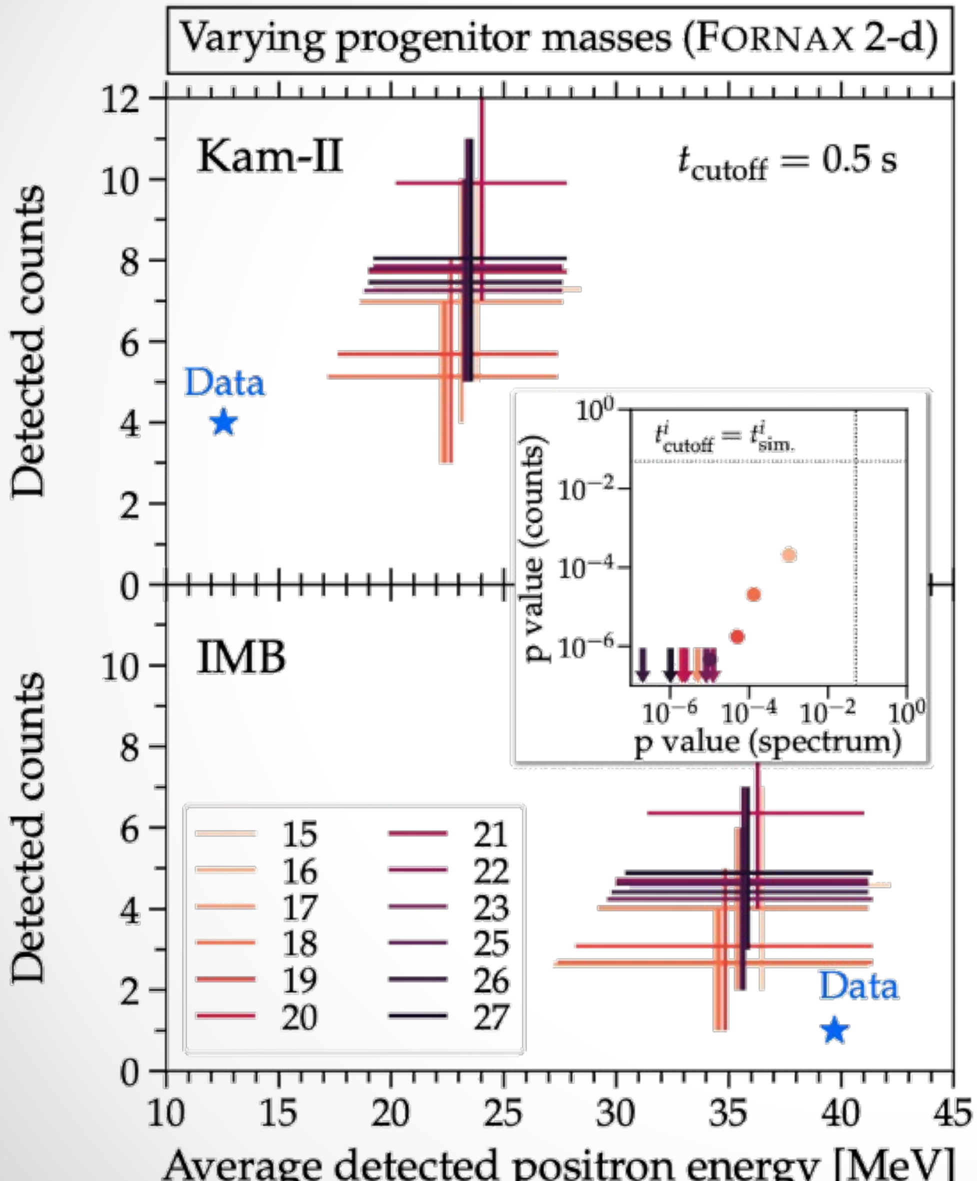
No model is compatible with data

Could Oscillation Fix This?



- ➢ How supernova ν oscillate is an unsolved problem
- ➢ Lowers the count, increases the temperature
- ➢ Not likely to be a solution

Could It Be Different Progenitors?



- We do not know the progenitor mass for 87A
- Probably roughly between 15-30M$_\odot$
- Not likely to be a solution

What Does This Mean?

- Flux seems high, temperature seems high
- Not definitive, simulation runtime too short
- Need further studies
  - Longer runtime
  - More progenitors
  - Neutrino oscillation implemented into simulation

The Plot Thickens

Supernova Simulations Confront SN 1987A Neutrinos

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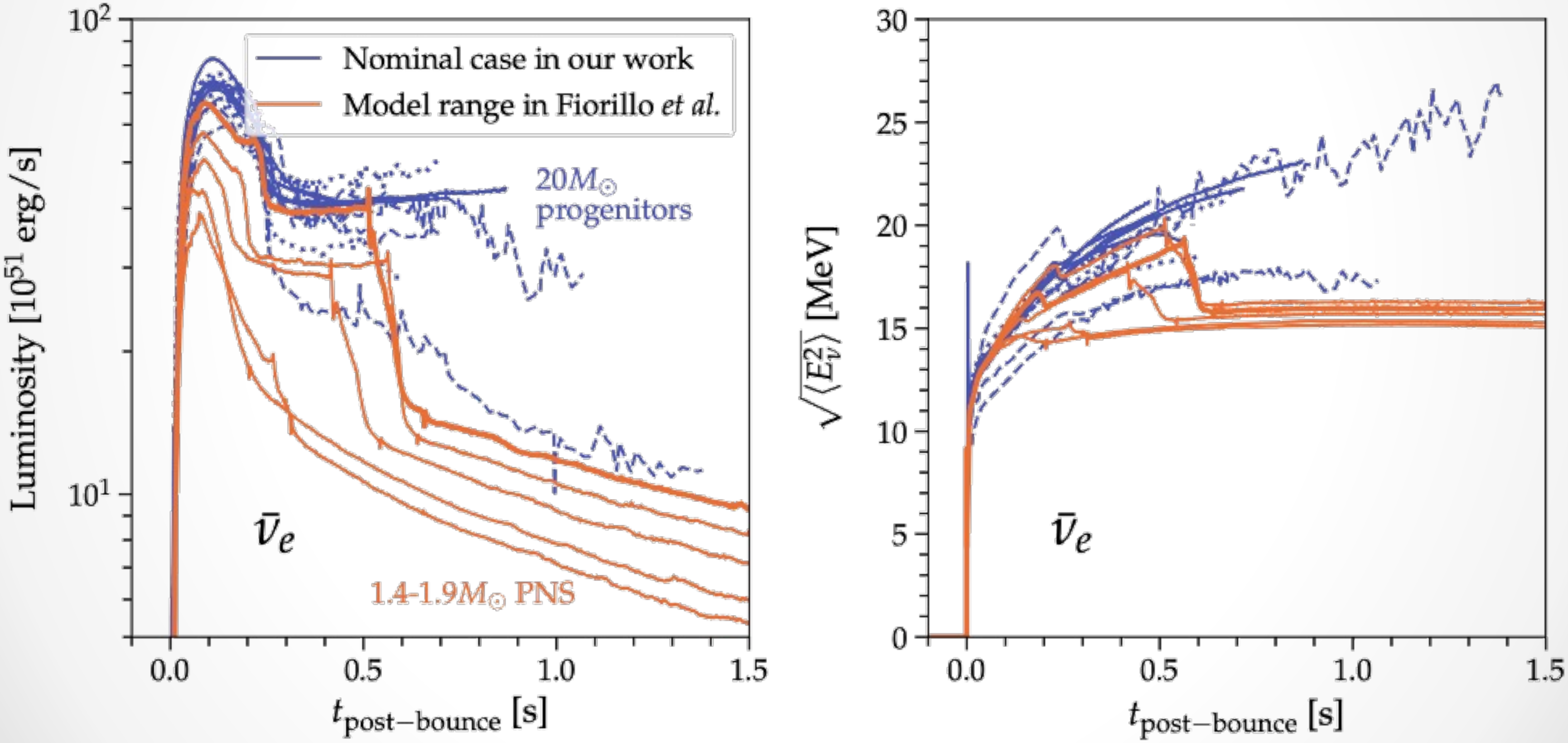
(Dated: August 4, 2023)

We return to interpreting the historical SN 1987A neutrino data from a modern perspective. To this end, we construct a suite of spherically symmetric supernova models with the PROMETHEUS-VERTEX code, using four different equations of state and five choices of final baryonic neutron-star (NS) mass in the 1.36–$1.93\,M_\odot$ range. Our models include muons and proto-neutron star (PNS) convection by a mixing-length approximation. The time-integrated signals of our $1.44\,M_\odot$ models agree reasonably well with the combined data of the four relevant experiments, IMB, Kam-II, BUST, and LSD, but the high-threshold IMB detector alone favors a NS mass of 1.7–$1.8\,M_\odot$, whereas Kam-II alone prefers a mass around $1.4\,M_\odot$. The cumulative energy distributions in these two detectors are well matched by models for such NS masses, and the previous tension between predicted mean neutrino energies and the combined measurements is gone, with and without flavor swap. Generally, our predicted signals do not strongly depend on assumptions about flavor mixing, because the PNS flux spectra depend only weakly on antineutrino flavor. While our models show compatibility with the events detected during the first seconds, PNS convection and nucleon correlations in the neutrino opacities lead to short PNS cooling times of 5–9 s, in conflict with the late event bunches in Kam-II and BUST after 8–9 s, which are also difficult to explain by background. Speculative interpretations include the onset of fallback of transiently ejected material onto the NS, a late phase transition in the nuclear medium, e.g. from hadronic to quark matter, or other effects that add to the standard PNS cooling emission and either stretch the signal or provide a late source of energy. More research, including systematic 3D simulations, is needed to assess these open issues.

Opposite conclusions for the first second signal?

Not Really

1-d simulations with explosion shouldn't be used in the first second



Even then, data still favors very light progenitors

Conclusions

- 87A data agree with theory at OoM level
- Incredibly useful probe for BSM physics
- Detailed comparison reveals discrepancy between modern simulation and 87A data
- Oscillations and different progenitors are likely not the solution

Backup

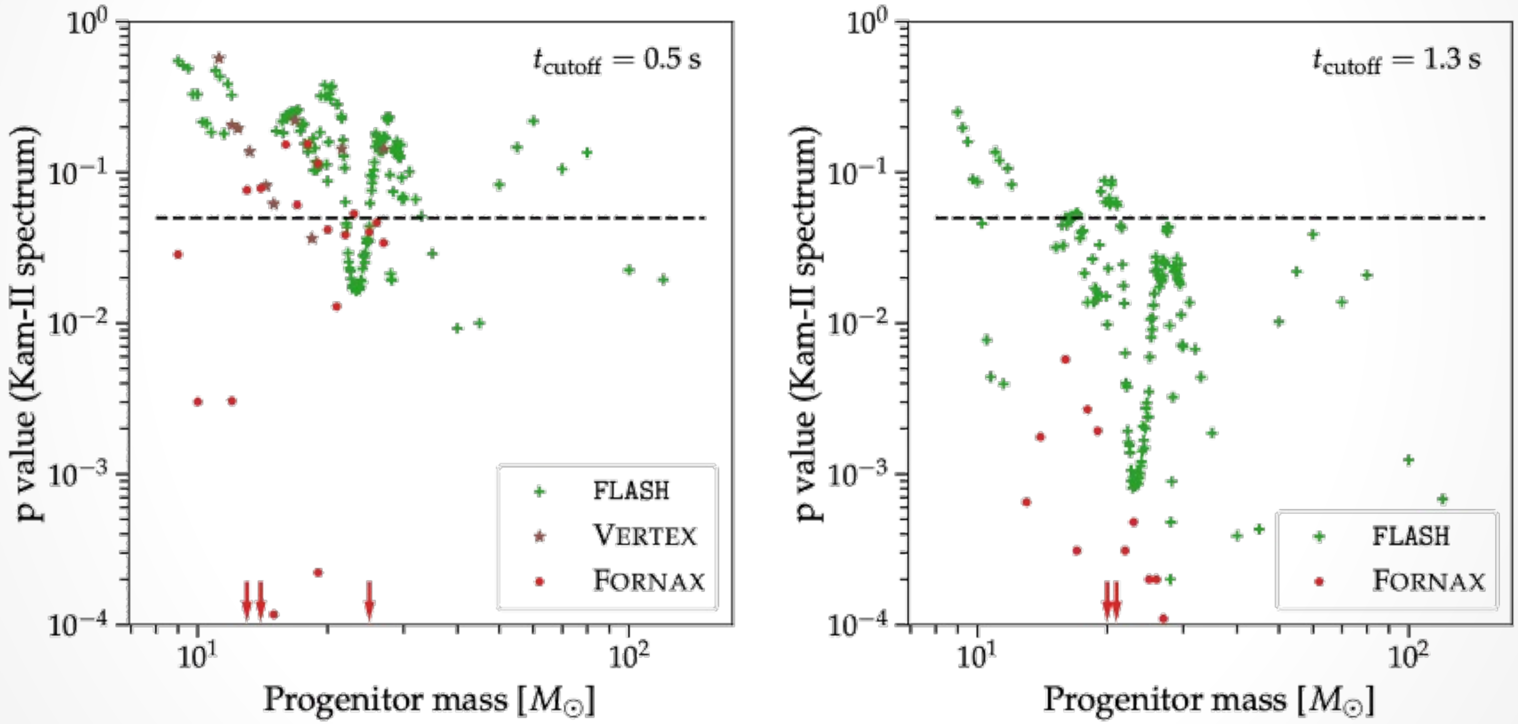
Models Considered

SL, Beacom, Roberts, Capozzi, 2023

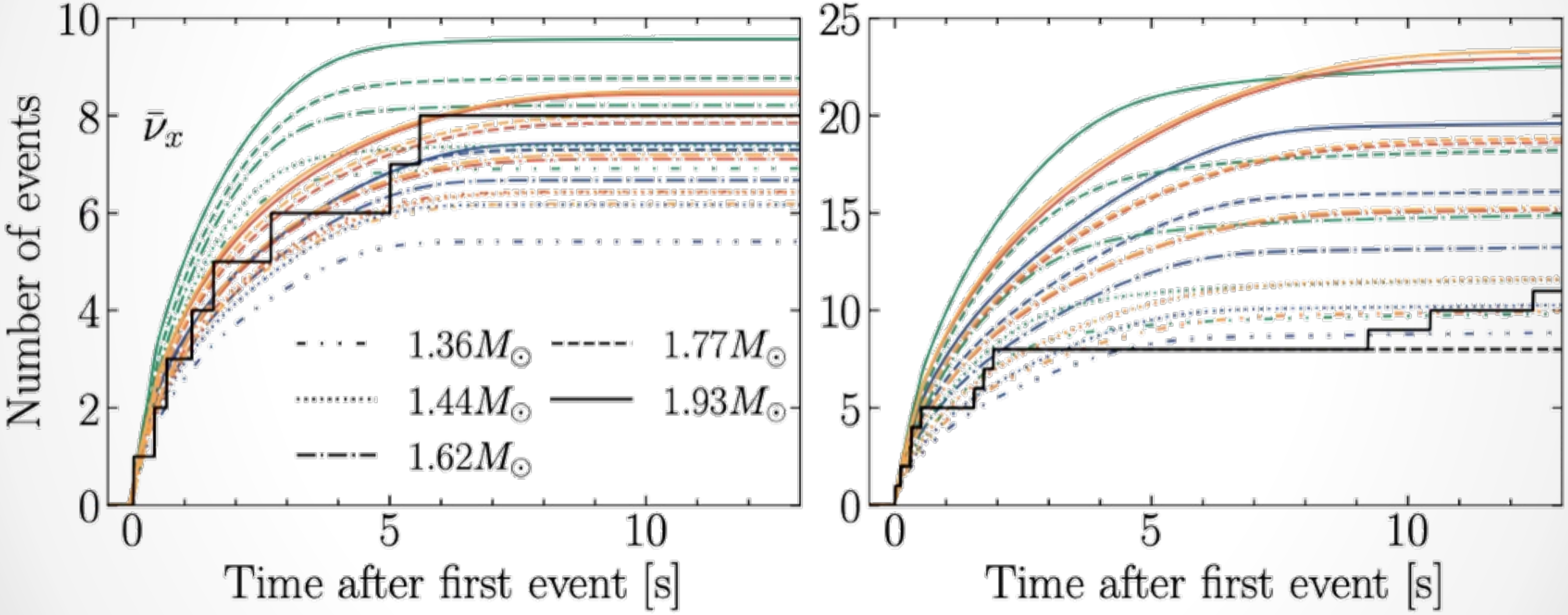
Code	Dimension	Progenitor Mass [$M_\odot$]	Explosion	$t_{\rm exp}$ [s]	$t_{\rm sim}$ [s]	p-value (counts)	p-value (spectra)	Reference
3DnSNe-IDSA	1-d	20 [53]	N/A	N/A	0.50	0.043	0.027	O'Connor et al. [18]
AGILE-BOLTZTRAN					0.55	0.055	0.034	
FLASH-M1					0.71	0.015	0.002	
FORNAX					1.10	–	–	
GR1D					0.47	0.092	0.043	
PROMETHEUS-VERTEX					0.87	0.003	3×10^{-4}	
CHIMERA	2-d	20 [53]	Yes	0.21	1.37	0.007	7×10^{-4}	Bruenn et al. [19, 20]
FLASH	2-d	20 [53]	Yes	0.82	1.06	0.035	0.003	O'Connor et al. [21]
PROMETHEUS-VERTEX	2-d	20 [53]	Yes	0.36	0.38	–	–	Summa et al. [22]
IDSA	2-d	20 [53]	Yes/No	0.4–0.6	0.68	0.35	0.047	Kotake et al. [23]
FORNAX	2-d	20 [53]	No	N/A	0.58	0.042	0.029	Vartanyan et al. [24]
Zelmani	3-d	20 [53]	Yes	0.38	0.38	–	–	Ott et al. [25]
FLASH	3-d	20 [84]	No	N/A	0.50	–	–	O'Connor et al. [26]
ALCAR	3-d	20 [53]	No	N/A	0.68	0.012	0.002	Glas et al. [27]
FORNAX	3-d	20 [85]	Yes	0.45	0.59	0.091	0.047	Burrows et al. [28]

Simulation Time

SL, Beacom, Roberts, Capozzi, 2023



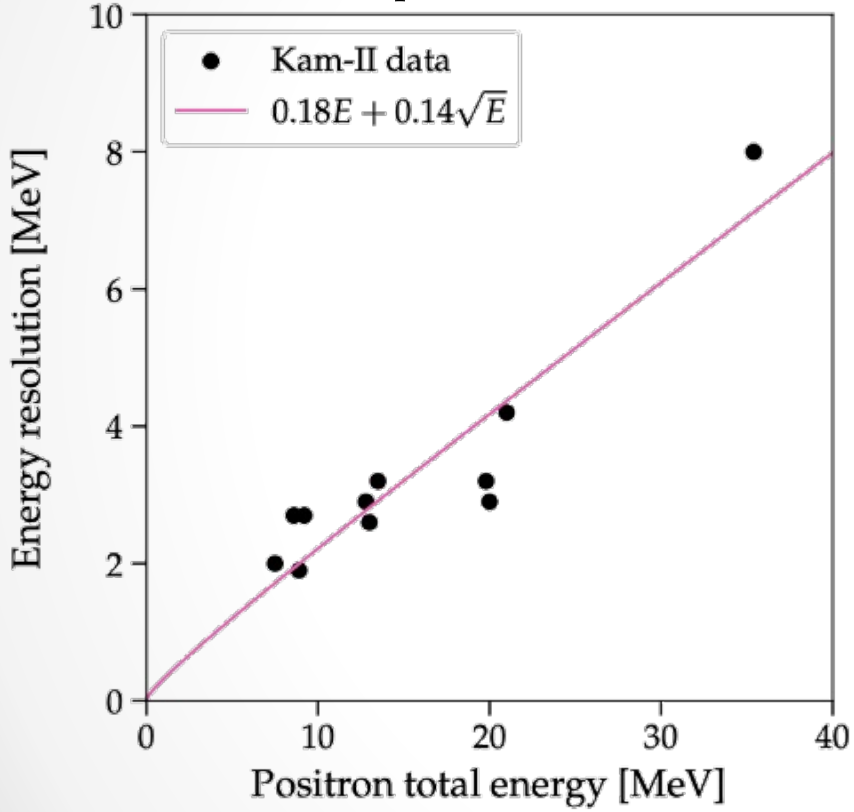
Fiorillo et al. Results

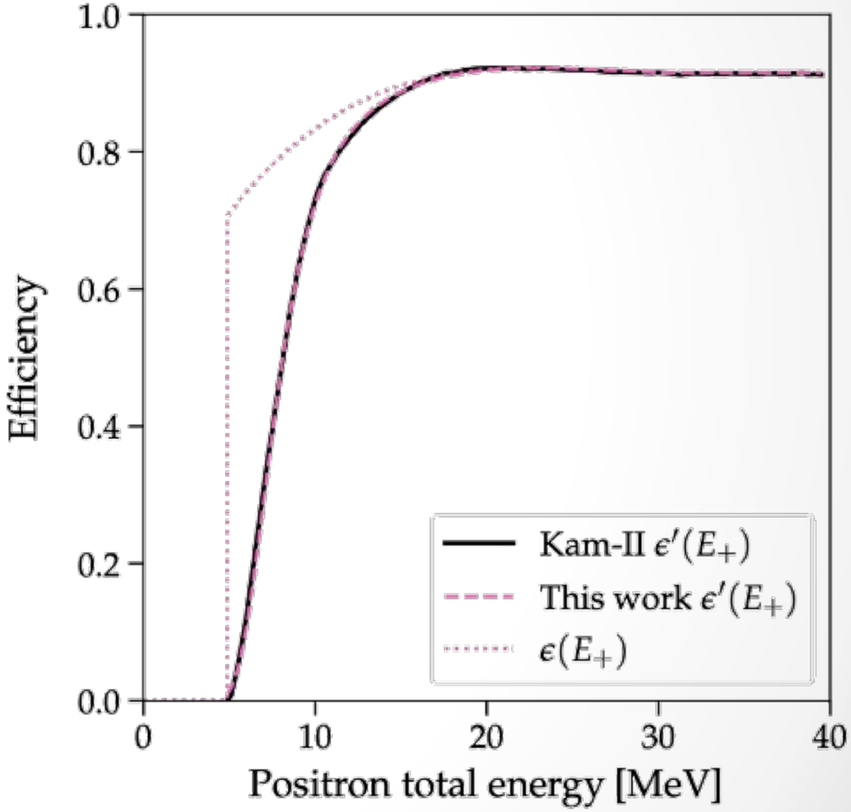


Predicting Signal in Kam-II

Need to interpolate resolution & efficiency

SL, Beacom, Roberts, Capozzi, 2023





Extrapolation uncertainty does not affect the final results significantly

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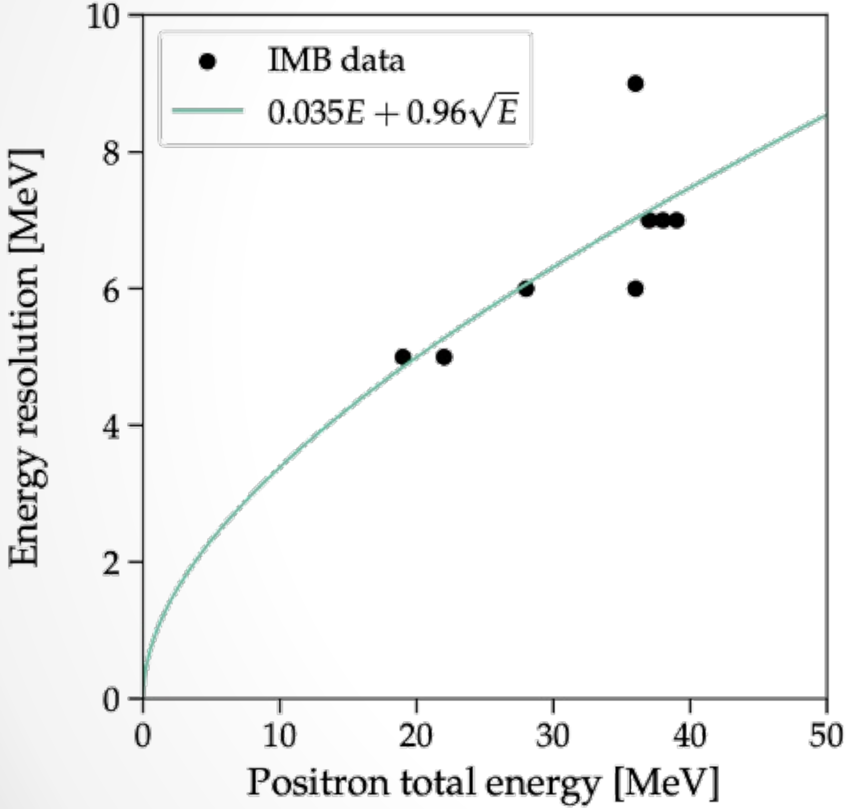
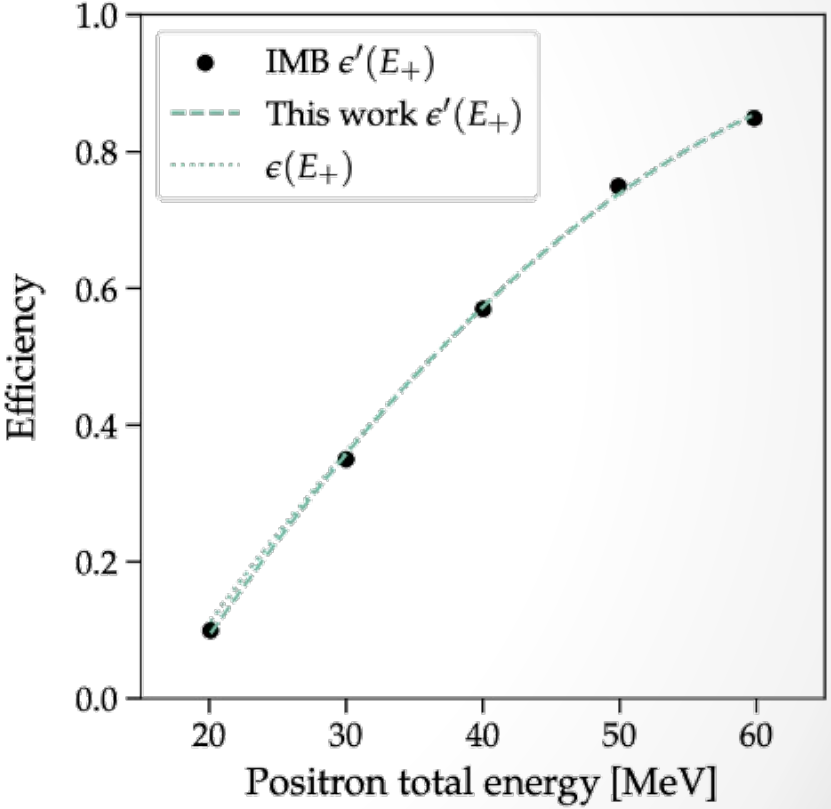
Predicting Signal in IMB

Need to interpolate resolution & efficiency

SL, Beacom, Roberts, Capozzi, 2023





Extrapolation uncertainty does not affect the final results significantly

Detector Efficiencies

How we computed the event rate:

$$N(E_{\mathrm{det}}) \propto \int dE_+ g(E_+)\epsilon(E_+)R(E_{\mathrm{det}}, E_+)\theta(E_{\mathrm{det}} - 7.5)$$

What we match to the experimental publications:

$$\epsilon'(E_+) = \epsilon(E_+) \int dE_{\mathrm{det}} R(E_{\mathrm{dec}}, E_+)\theta(E_{\mathrm{det}} - 7.5)$$