Old Data, New Forensics: The First Second of SN 1987A Neutrino Emission

Shirley Li, UC Irvine

2306.08024

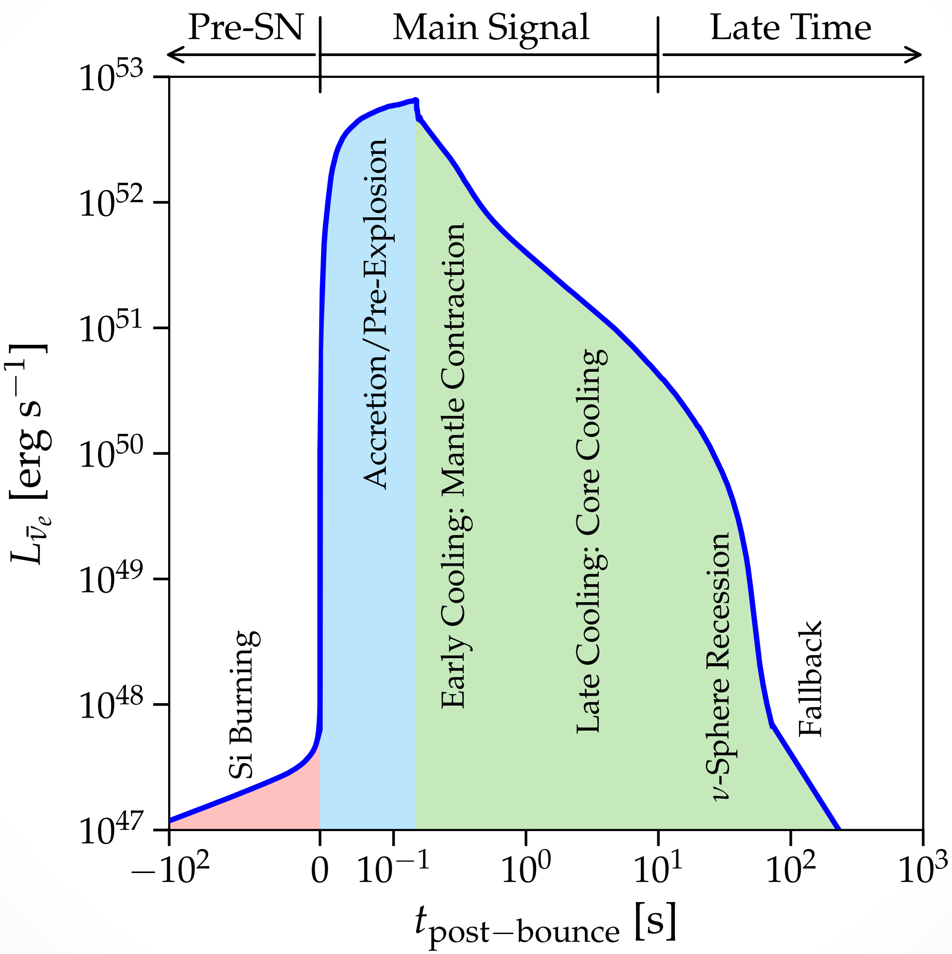
Neutrinos in Astrophysics and Cosmology

March 2024

SN 2030?

Are We Ready??

Basic Features of SN Neutrinos

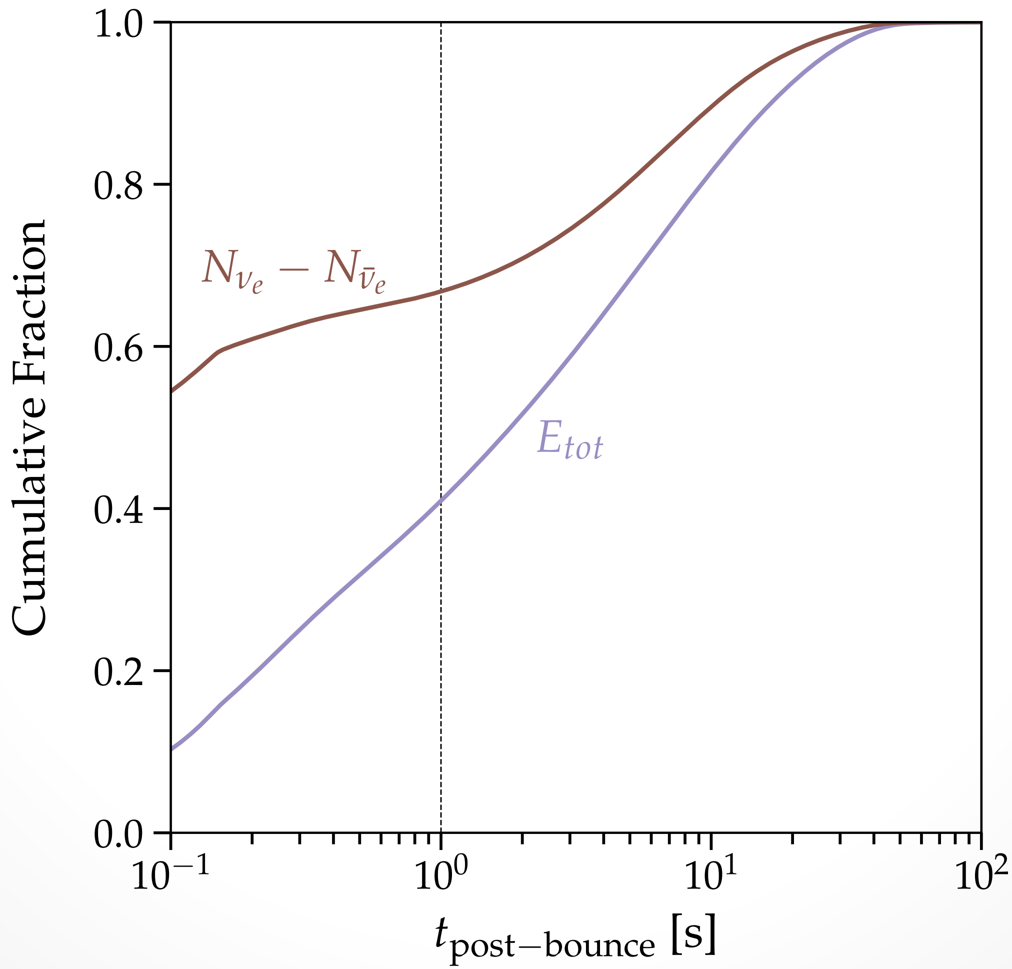


SL, Roberts & Beacom, 2020

Explosion Neutrinos

The First Second

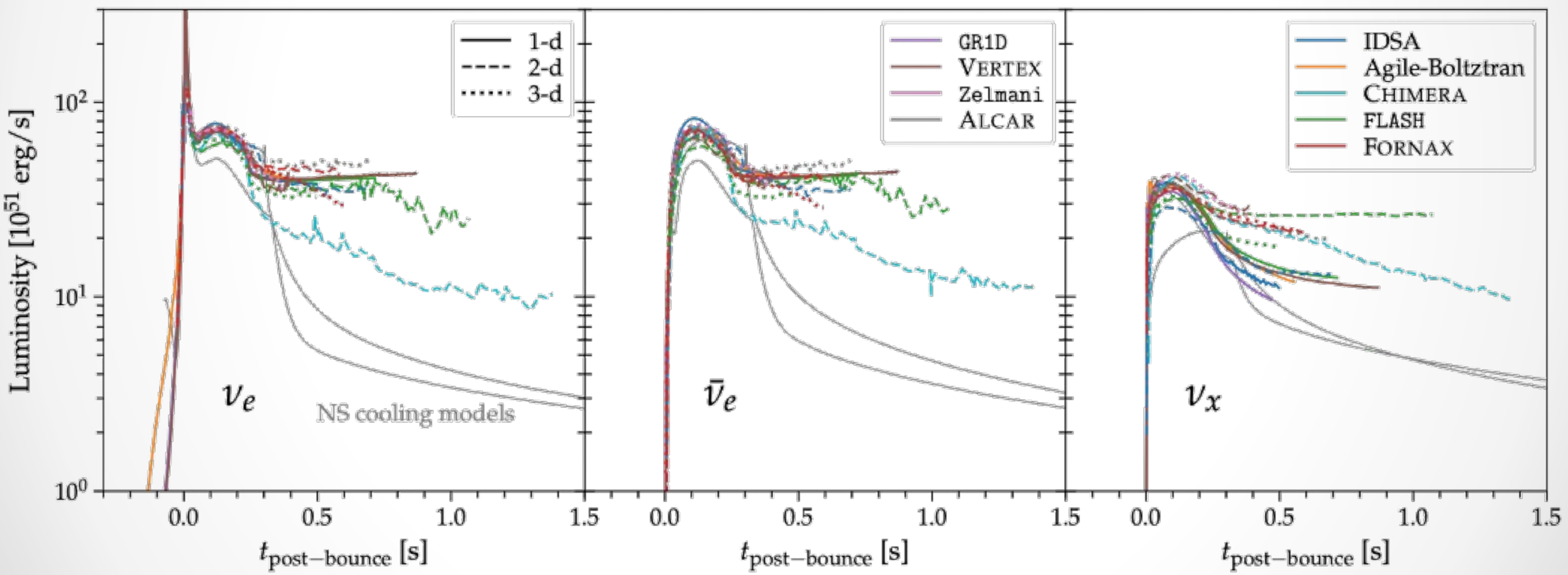
Significant energy and lepton number emission



Simulation Status

Intense efforts for decades, focus of multi-d studies

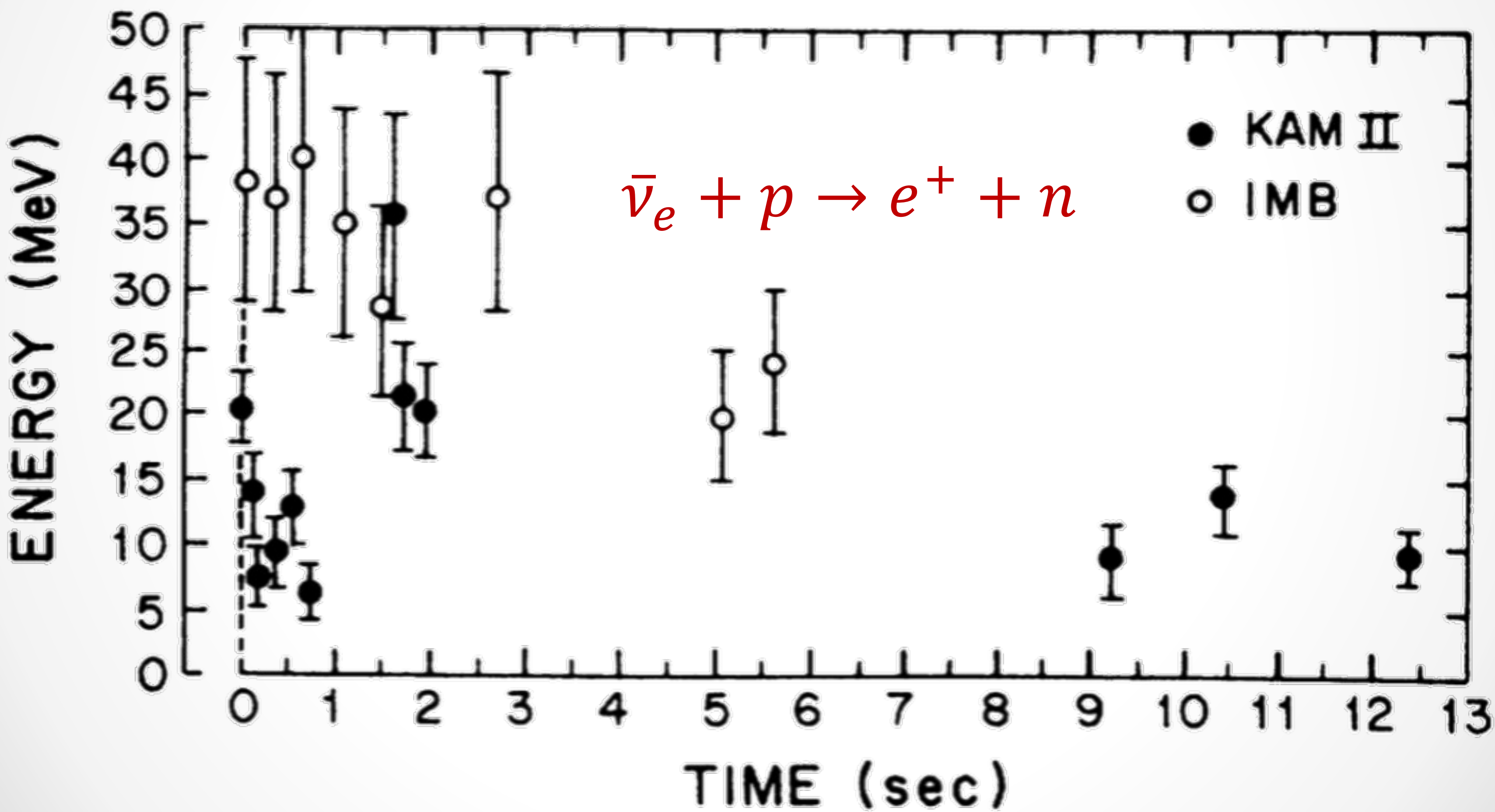
SL, Beacom, Roberts, Capozzi, 2023



$20M_\odot$ well studied, less so for other progenitors

We Have Data: SN 1987A!

Large Magellanic Cloud, 50 kpc Away



Kamioka-II 1988

Exciting New Development

The remnant of SN87A revealed to be a NS

Science

Current Issue | First release papers | Archive | About | Submit manuscript

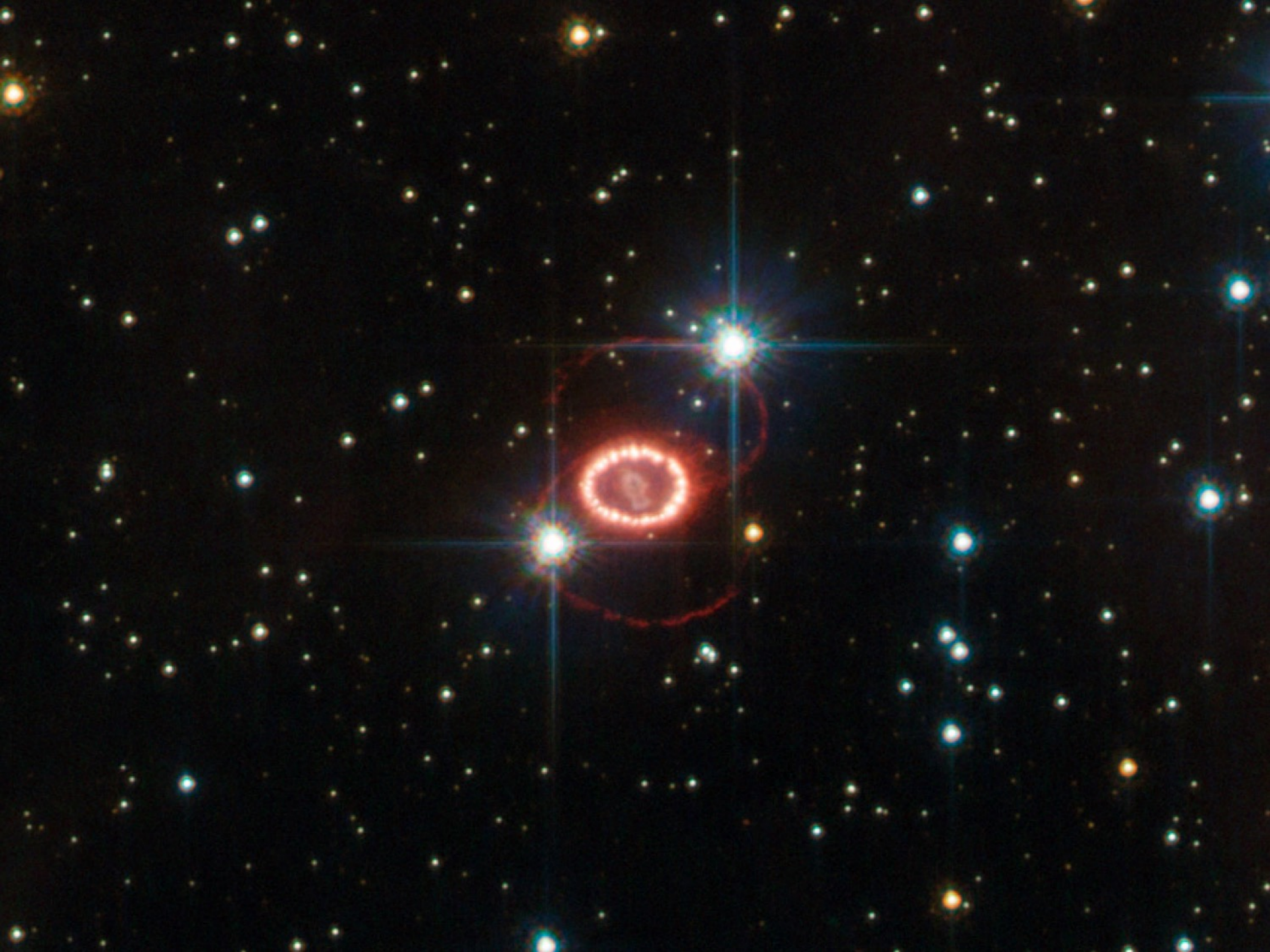
HOME > SCIENCE > VOL. 383, NO. 6685 > EMISSION LINES DUE TO IONIZING RADIATION FROM A COMPACT OBJECT IN THE REMNANT OF SUPERNOVA 1987A

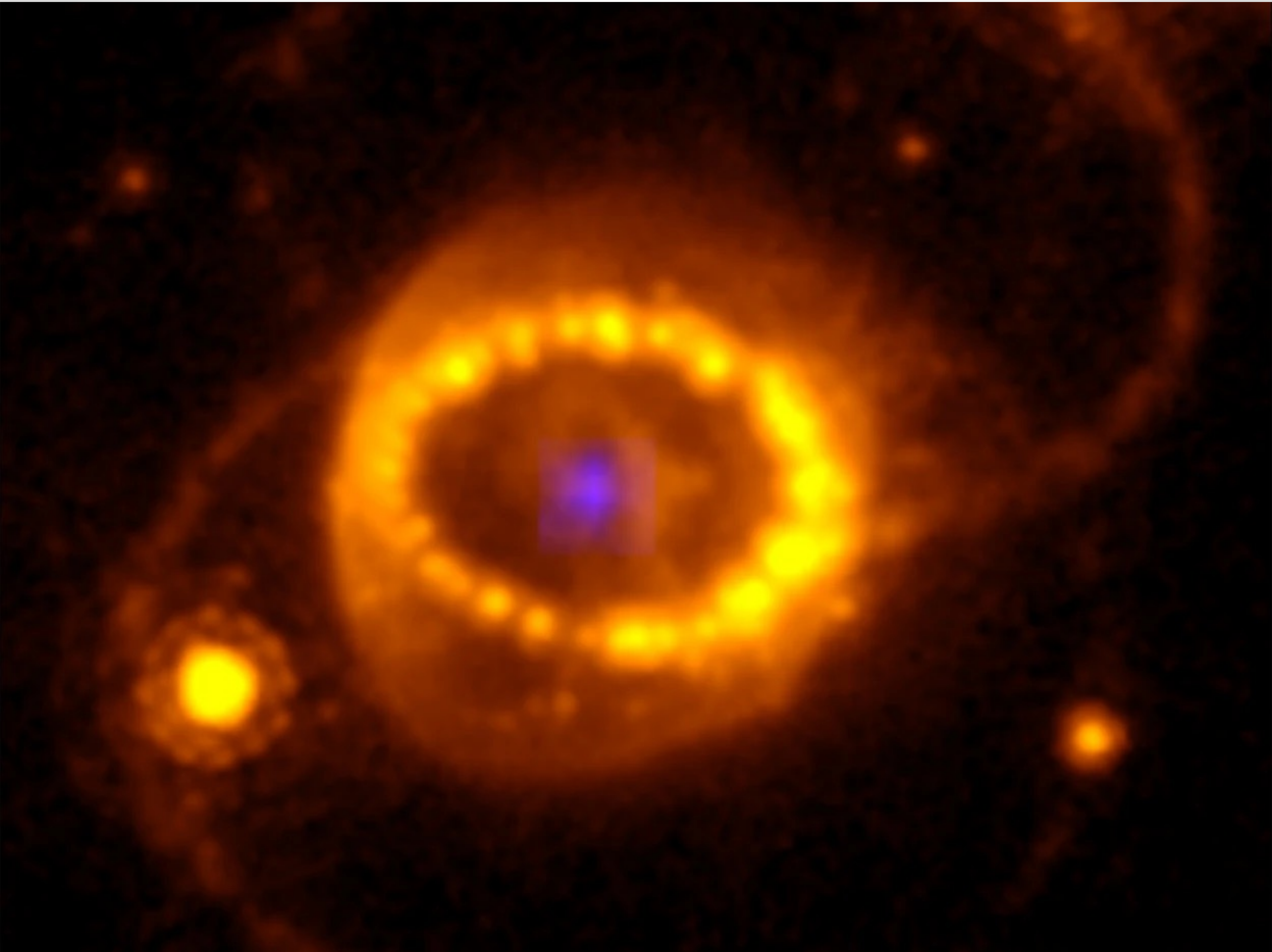
RESEARCH ARTICLE | SUPERNOVAE

Emission lines due to ionizing radiation from a compact object in the remnant of Supernova 1987A

C. FRANSSON, M. J. BARLOW, P. J. KAVANAGH, J. LARSSON, O. C. JONES, B. SARGENT, M. MEIXNER, P. BOUCHET, T. TEMIM, [...], AND B. VANDENBUSSCHE +24 authors Authors Info & Affiliations

SCIENCE · 22 Feb 2024 · Vol 383, Issue 6685 · pp. 898-903 · DOI: 10.1126/science.adj5796





Impact on BSM Searches

Exotic SN models ruled out

Is there a supernova bound on axions?

Nitsan Bar,[1,*] Kfir Blum,[1,2,†] and Guido D'Amico[3,‡]
[1]*Weizmann Institute of Science, Rehovot 7610001, Israel*
[2]*Theory department, CERN, CH-1211 Geneve 23, Switzerland*
[3]*Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94306, USA*

(Received 22 September 2019; accepted 11 June 2020; published 22 June 2020)

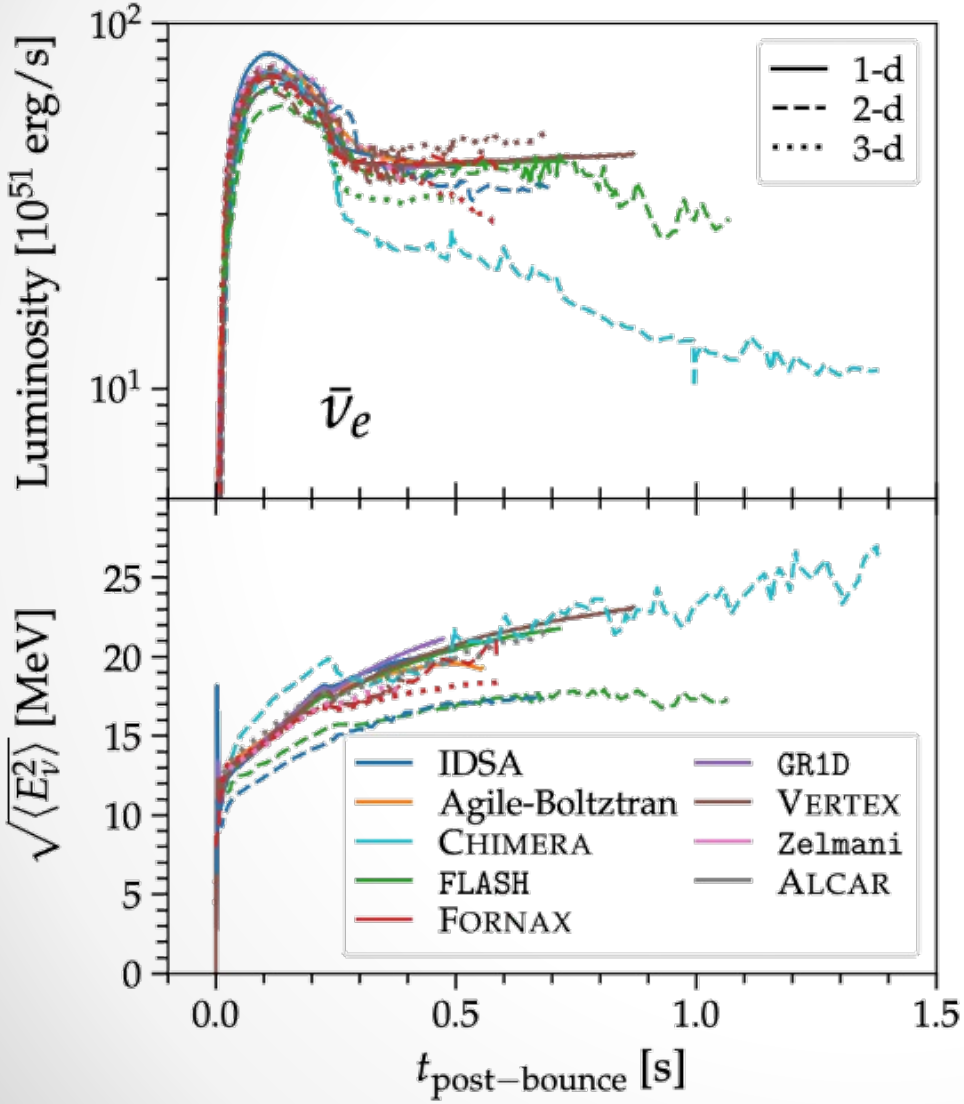
We present a critical assessment of the SN1987A supernova cooling bound on axions and other light particles. Core collapse simulations used in the literature to substantiate the bound omitted from the calculation the envelope exterior to the proto-neutron star (PNS). As a result, the only source of neutrinos in these simulations was, by construction, a cooling PNS. We show that if the canonical delayed neutrino mechanism failed to explode SN1987A, and if the precollapse star was rotating, then an accretion disk would form that could explain the late-time ($t \gtrsim 5$ sec) neutrino events. Such accretion disk would be a natural feature if SN1987A was a collapse-induced thermonuclear explosion. Axions do not cool the disk and do not affect its neutrino output, provided the disk is optically thin to neutrinos, as it naturally is. These considerations cast doubt on the supernova cooling bound.

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??

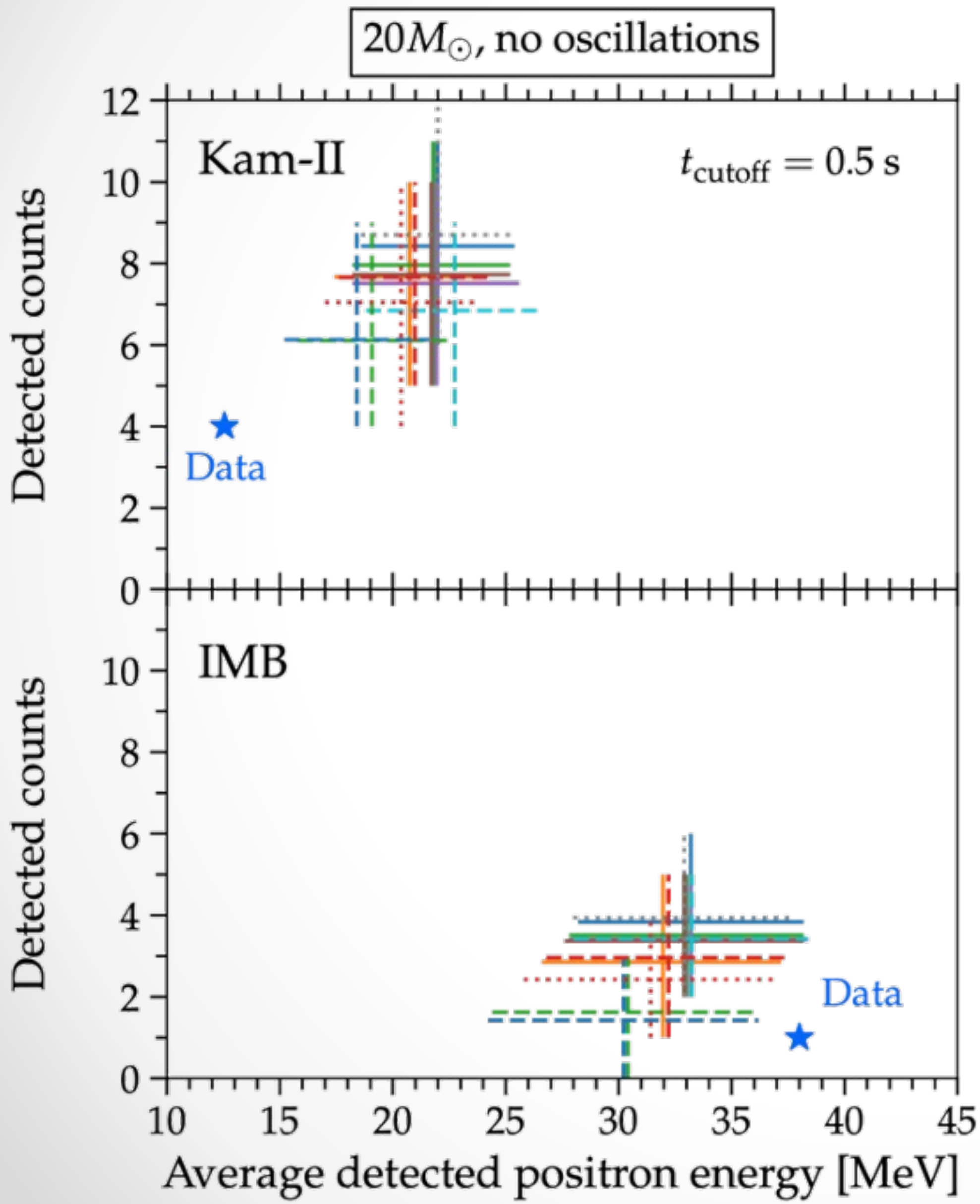
Let's Compare!



- 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



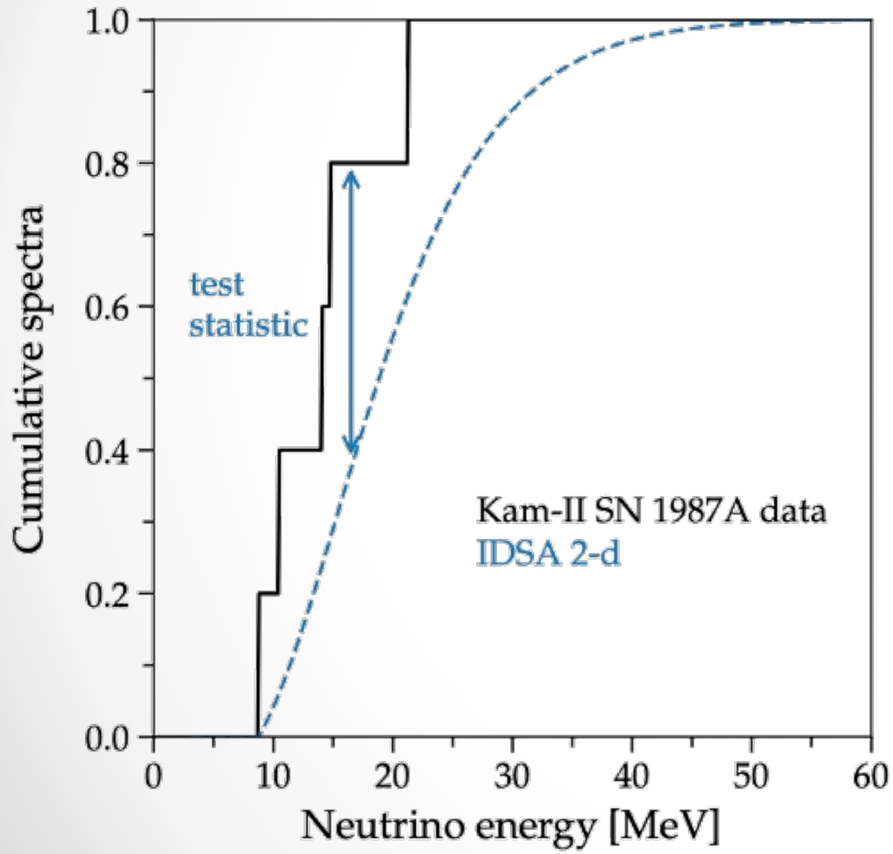
- Model simulation vs. 87A data
- Cut off all predictions and data at 0.5 s
- Forward modeling
- Error bars 1σ

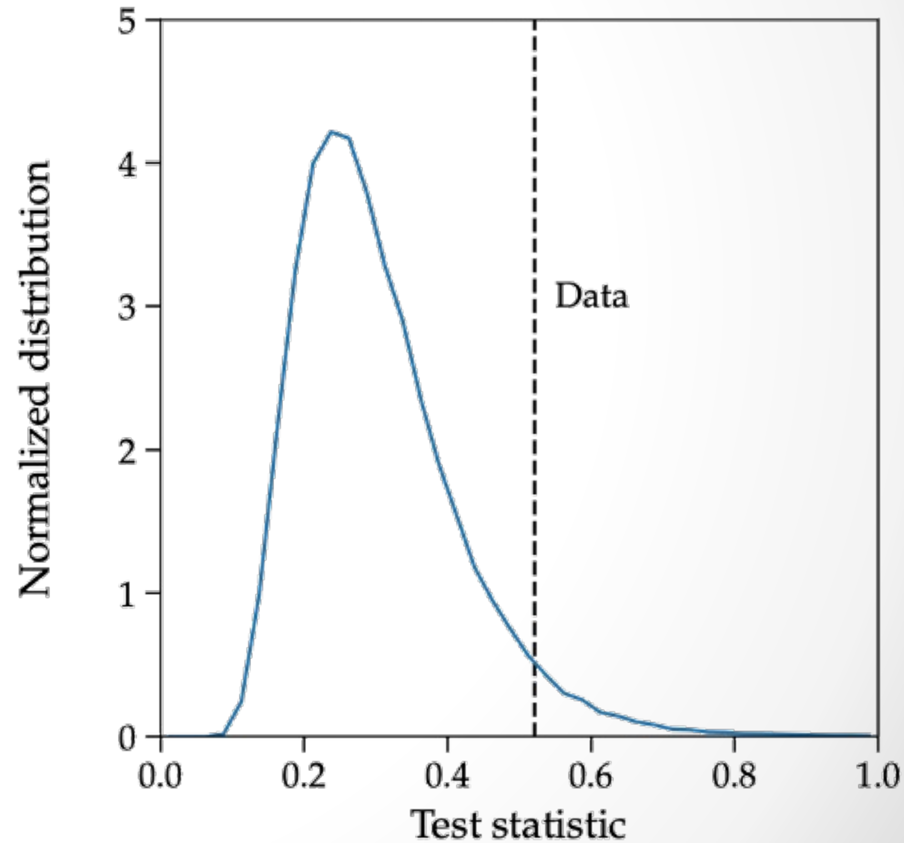
SL, Beacom, Roberts, Capozzi, 2023

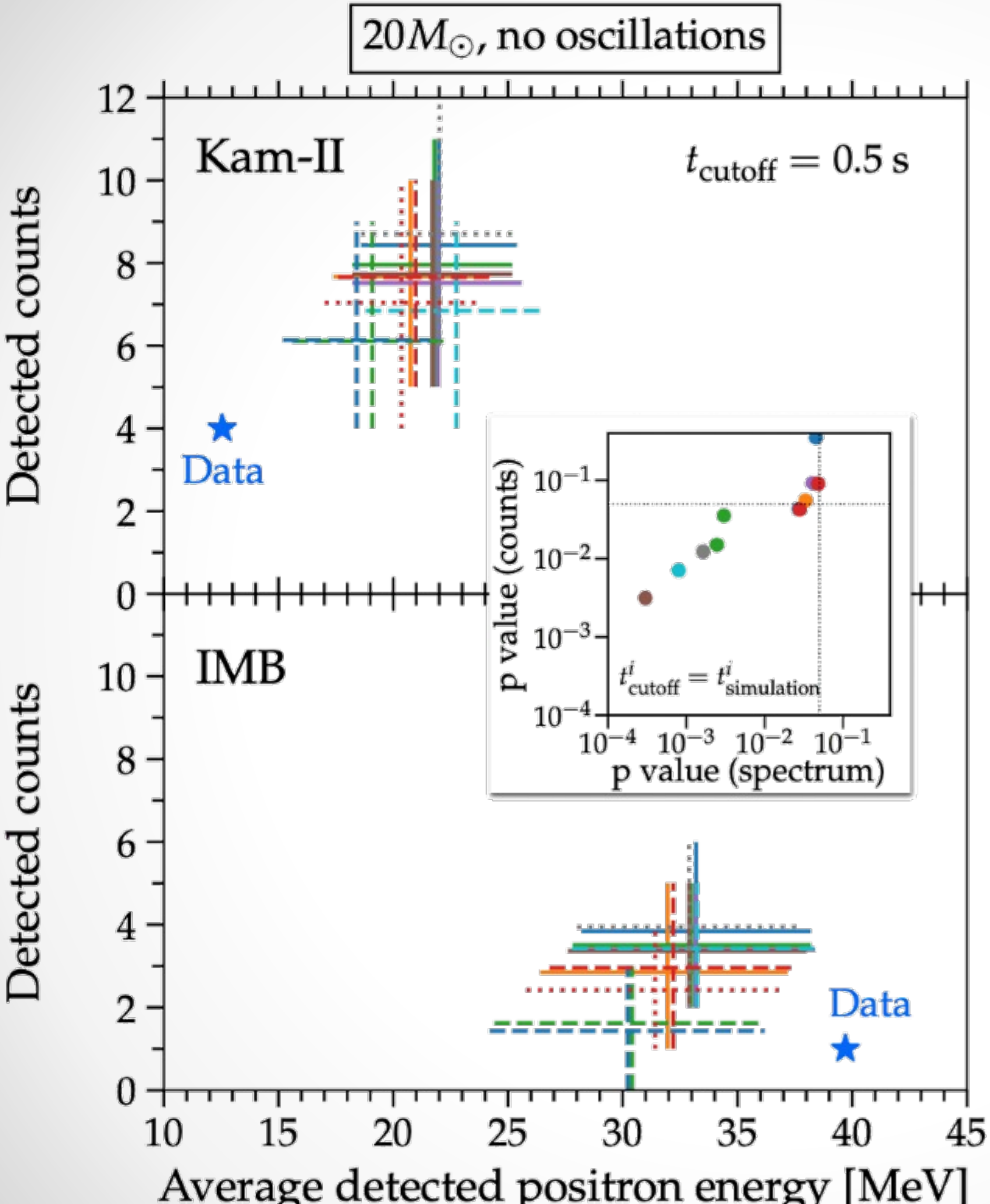
Quantifying the Statistics

SL, Beacom, Roberts, Capozzi, 2023

KS test on spectrum



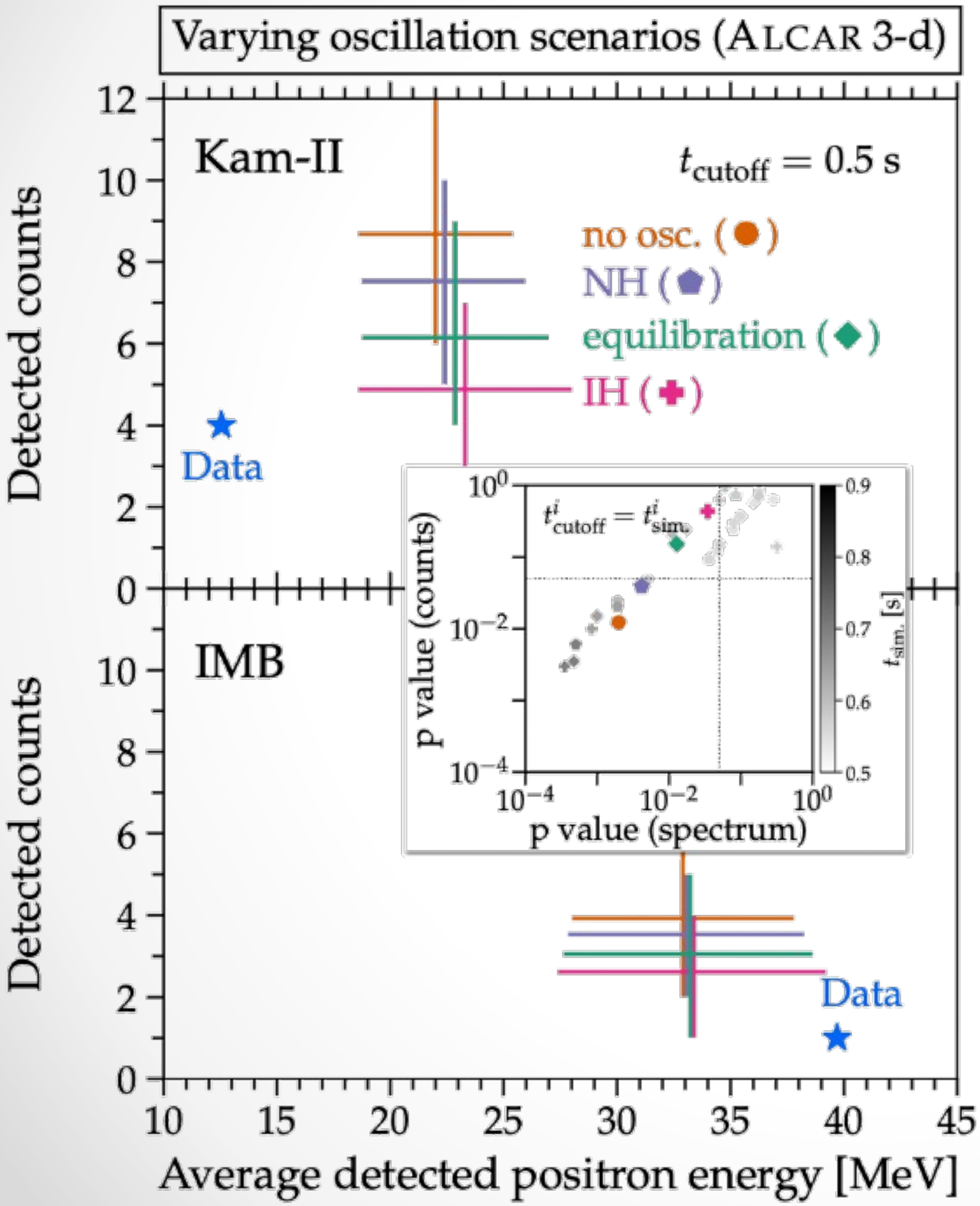




SL, Beacom, Roberts, Capozzi, 2023

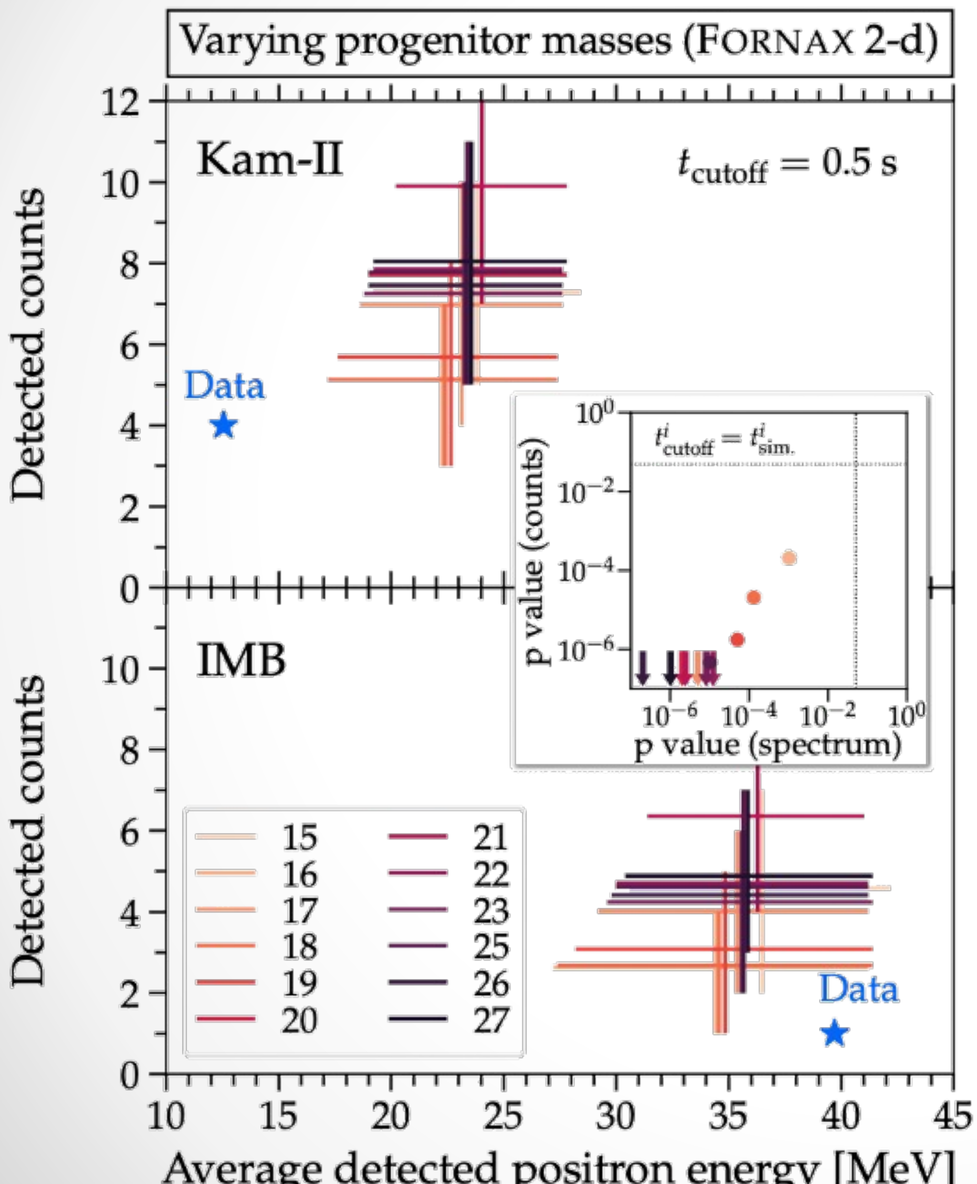
No model is compatible with data

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 15-30$M_\odot$
- 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

Damiano F. G. Fiorillo,[1] Malte Heinlein,[2,3] Hans-Thomas Janka,[2] Georg Raffelt,[4] and Edoardo Vitagliano[5]

[1] *Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany*
[3] *Technische Universität München, TUM School of Natural Sciences, Physics Department, James-Franck-Str. 1, 85748 Garching, Germany*
[4] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*
[5] *Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel*

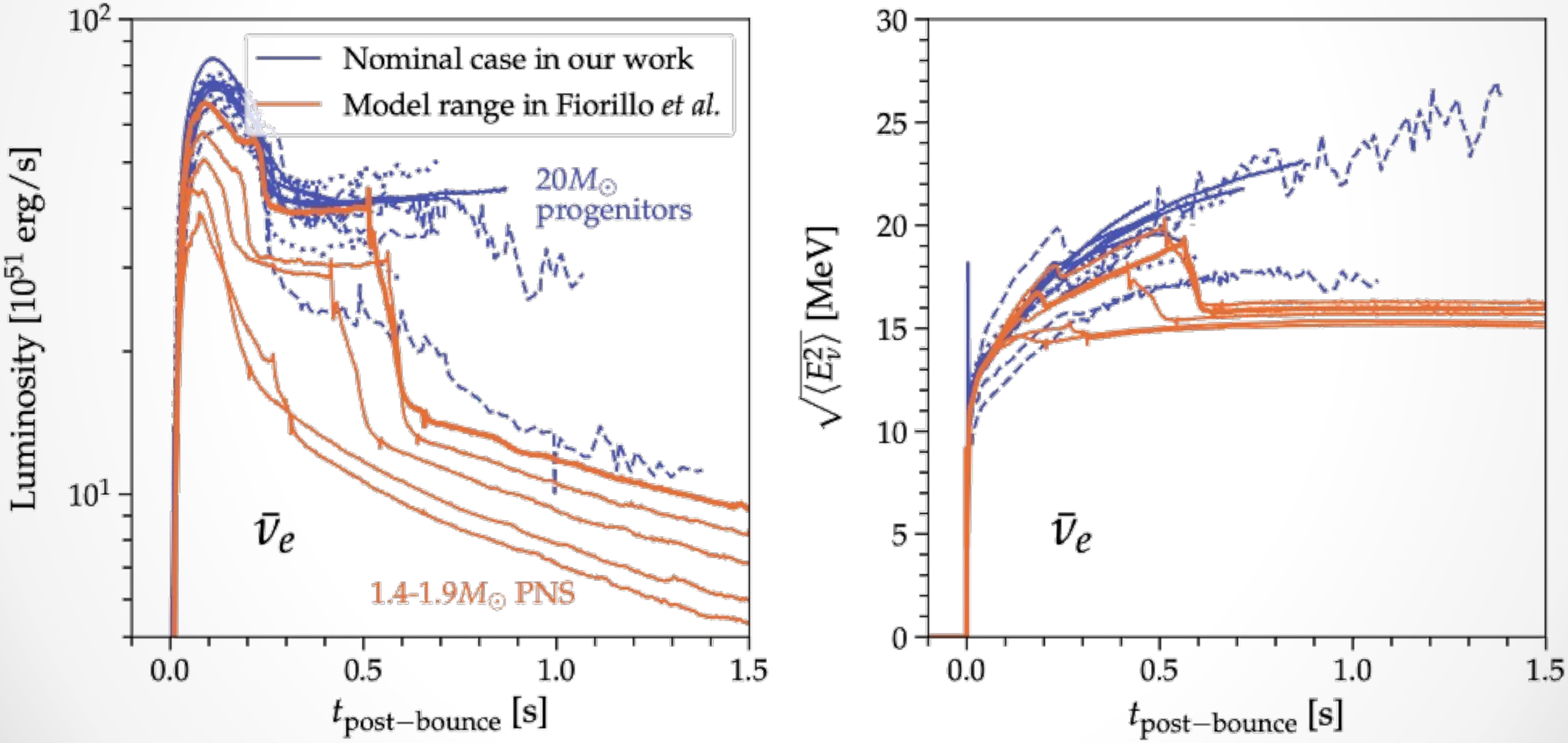
(Dated: August 4, 2023)

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

- The neutrino luminosities predicted by simulations show general agreement with each other in the first second
- They generally disagree with 87A data
- Oscillations and different progenitors are likely not the solution
- Hope to stimulate further work