PRESUPERNOVA NEUTRINOS: REALISTIC EMISSIVITIES AND DETECTION POSSIBILITIES

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Neutrinos in Cosmology and Astrophysics
TRIUMF - March 6-8 2024

EVOLUTION OF A MASSIVE STAR

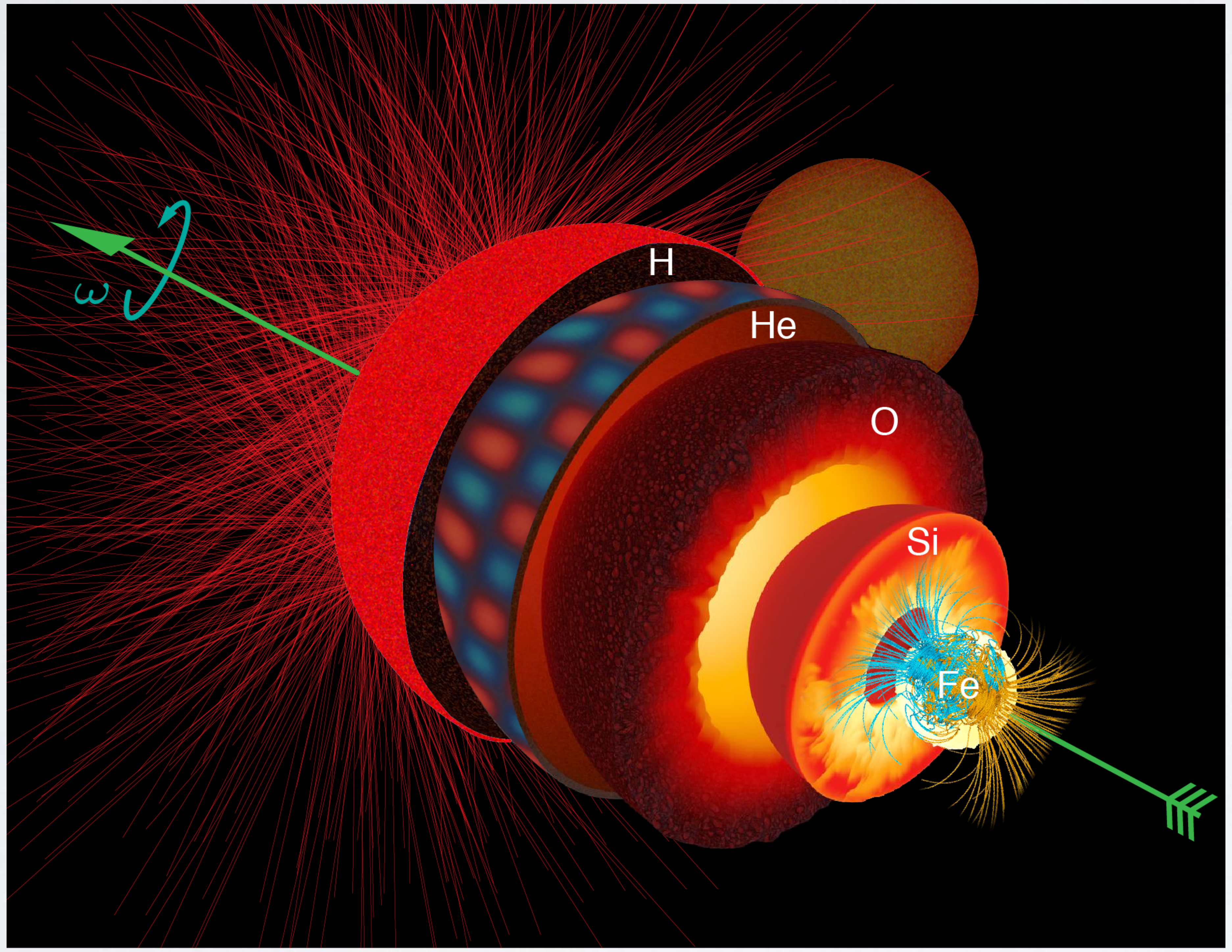
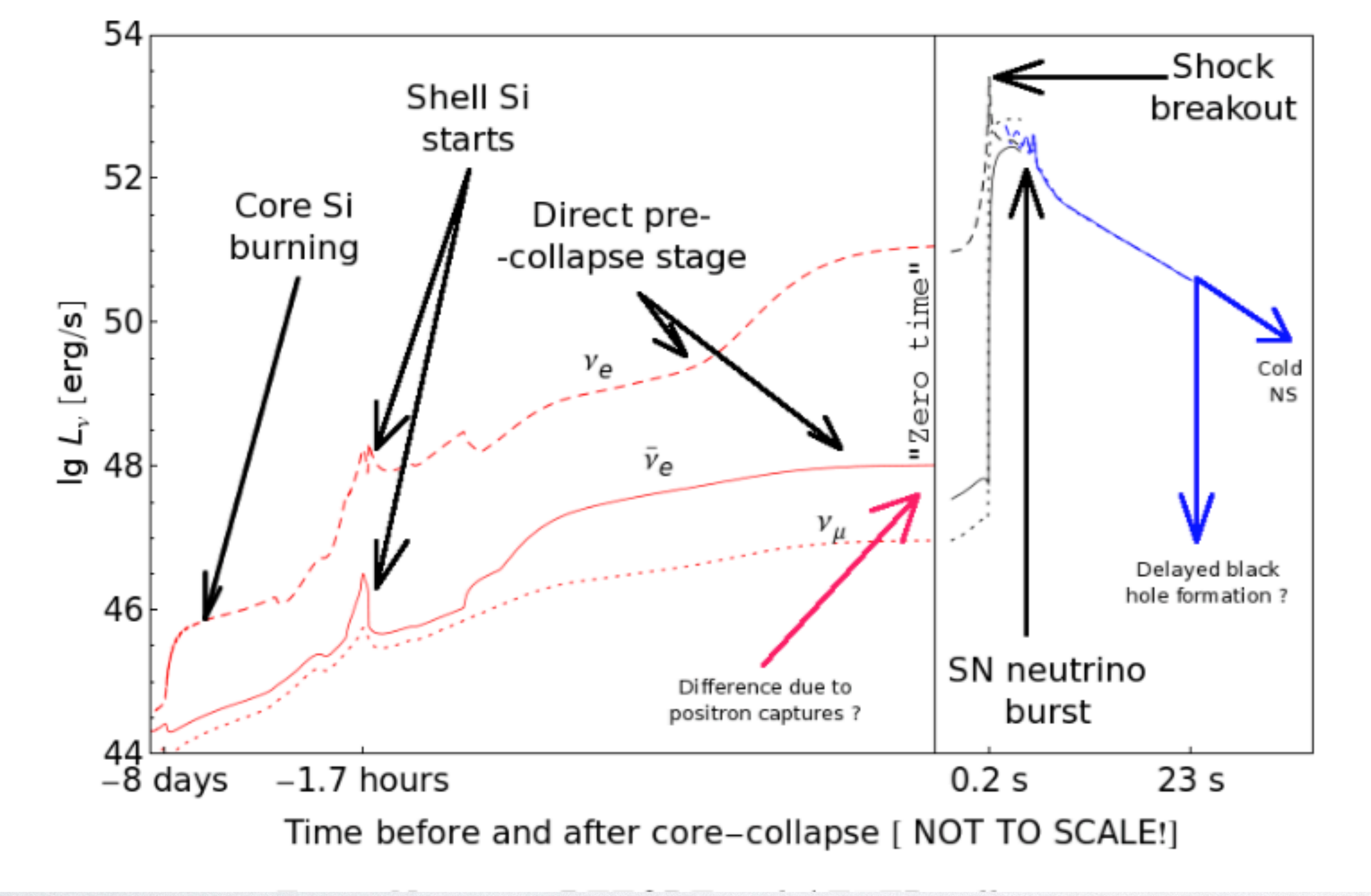


Image provided by F.X. Timmes

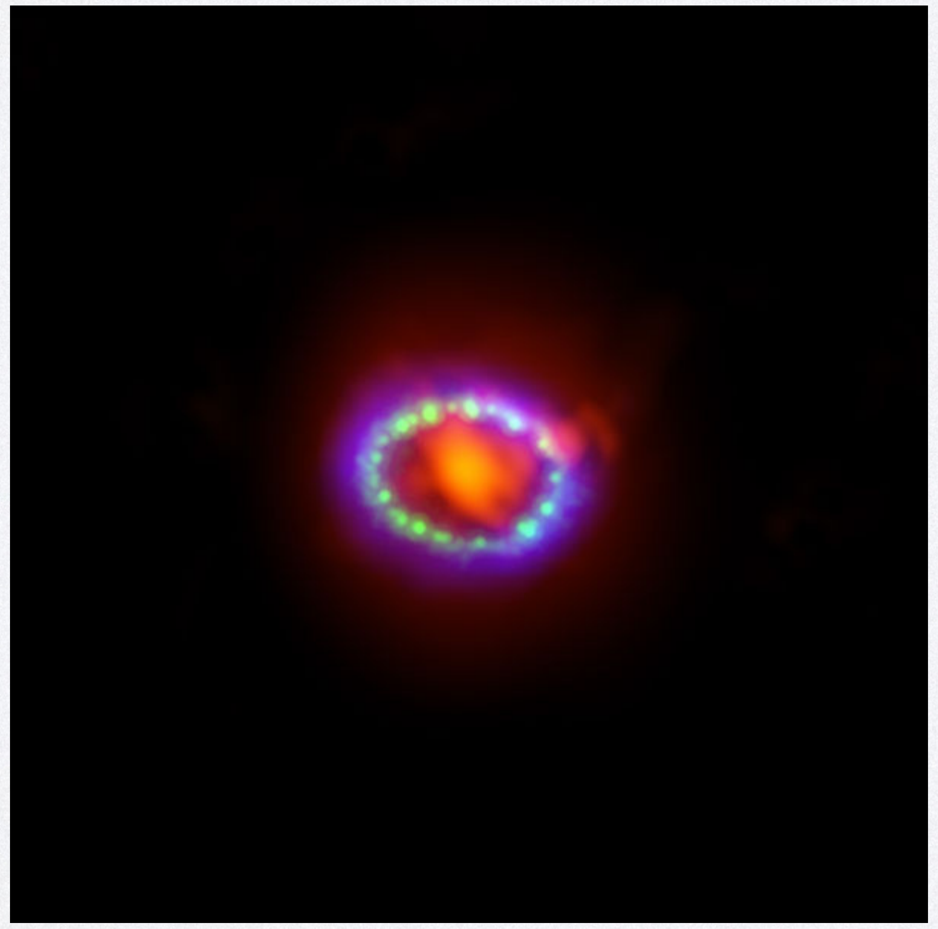
- Stars are born burning H in He in the core
- When H is exhausted, the star will burn He into O
- And so on, until an Fe core is created
- This leaves an onion structure behind, and the shells continue burning

PRESUPERNOVA NEUTRINOS



Odrzywolek and Heger *Acta Physica Polonica* B **41**, 1611 (2010)

- As the star gets hotter and denser, neutrino production ramps up
- After collapse we have a huge "burst" of neutrinos
- Notice that the pre-collapse luminosity is only a couple orders of magnitude below the "burst"
- We know we can see the burst (SN1987A), so the question is, can we see the presupernova?



SN1987A Image from https://chandra.harvard.edu/photo/2017/sn1987a/

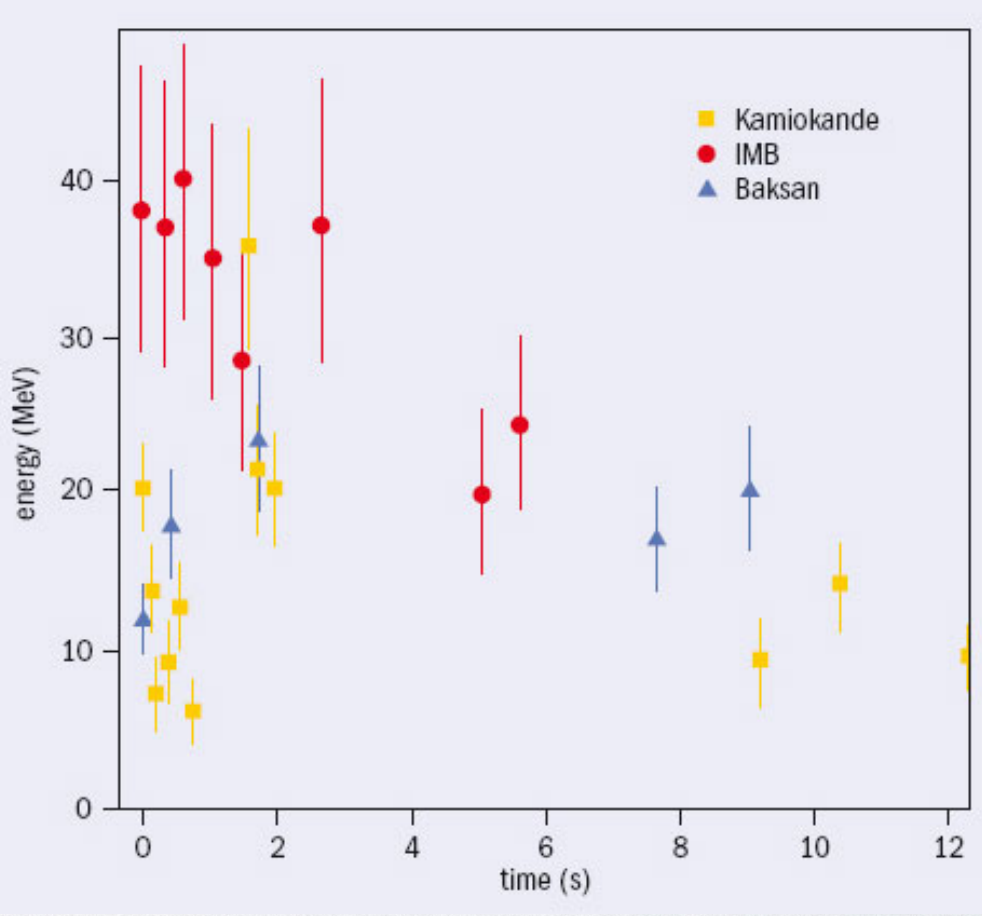
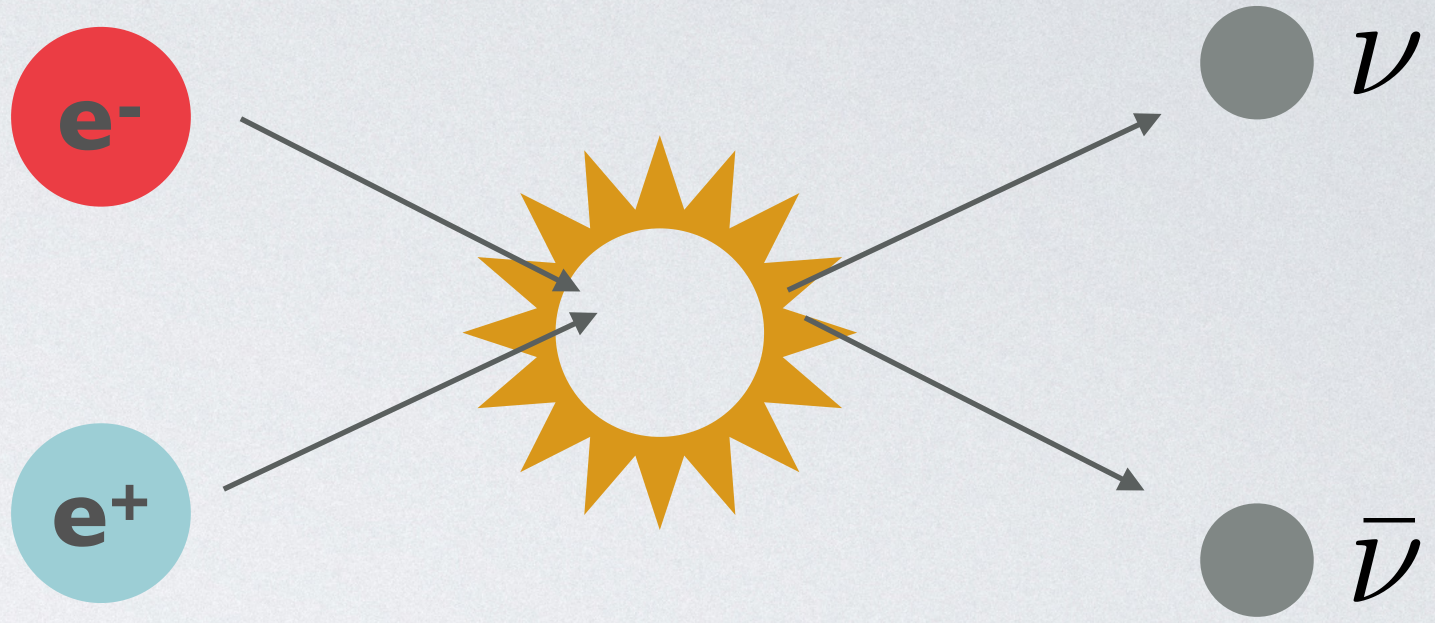


Figure from https://cerncourier.com/a/sn1987a-heralds-the-start-of-neutrino-astronomy/

PRESUPERNOVA NEUTRINOS

- The hot dense environment is a neutrino producing factory
- Two methods:
  - Thermal processes governed by T, ρ, and Ye
    - Dominated by pair annihilation
  - Nuclear processes governed by T, ρ, Ye , and isotopic composition



Pair Annihilation

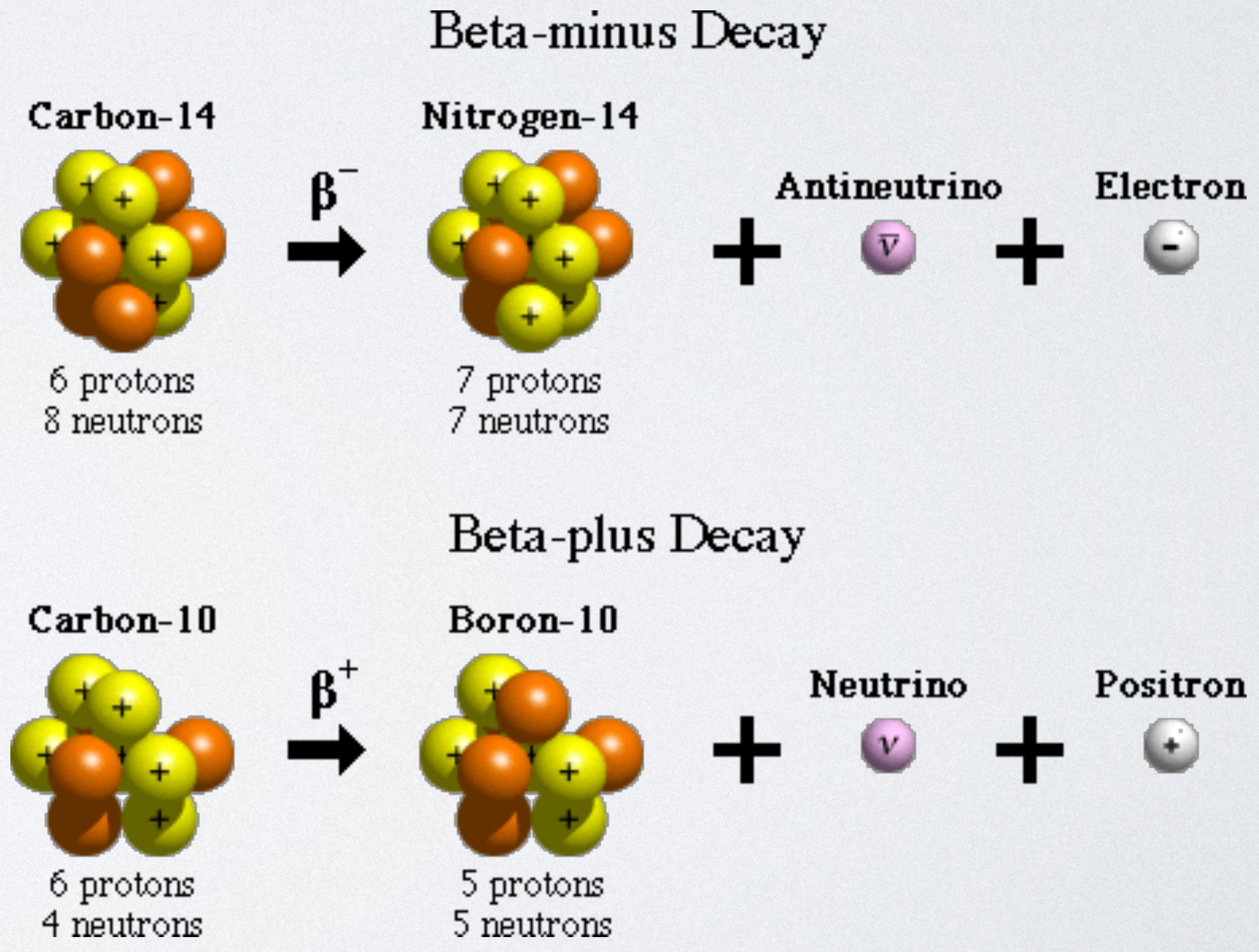
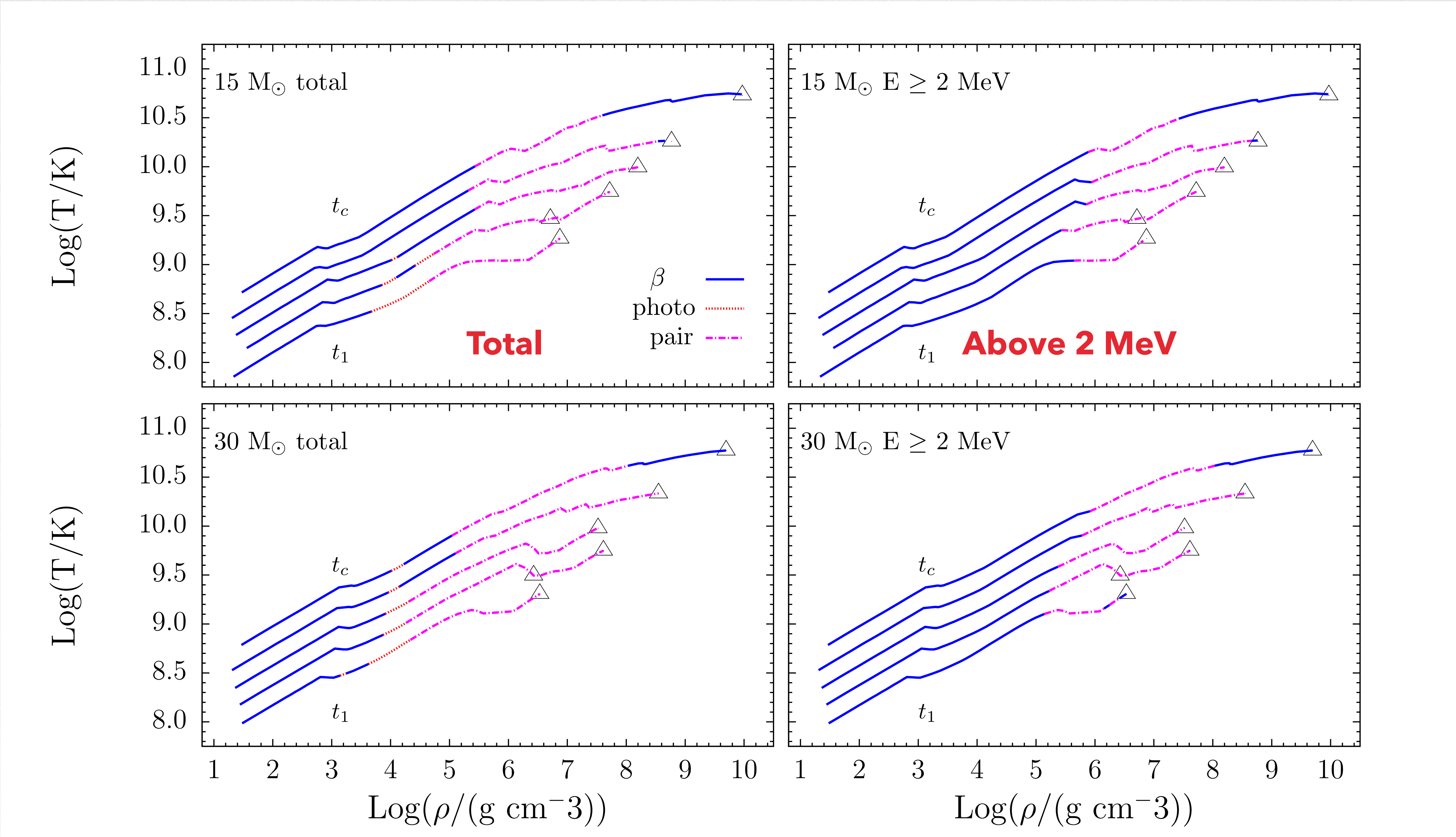


Figure from https://education.jlab.org/glossary/betadecay.html

PRESUPERNOVA NEUTRINOS: DOMINANT PROCESSES

▬ Beta
▬ Pair



Curve shifted upward by 0.2*(n-1) for n = 2 - 5

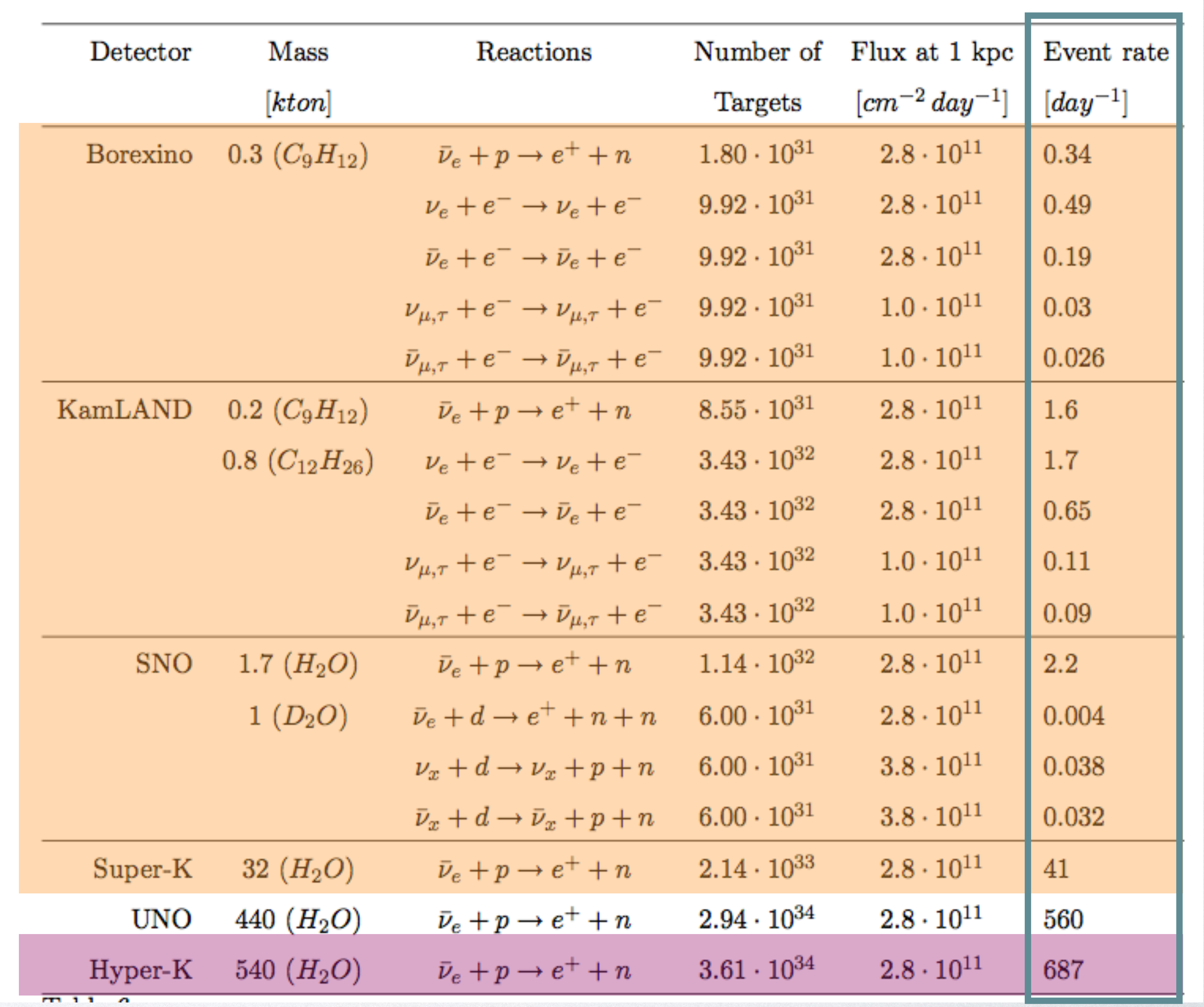
- Mainly pair or beta, with a few islands of photoneutrino dominance in total emissivity
- For detectable energies (E > 2 MeV), beta dominance is extended
- Beta very important in the core at t_c

Figure Adapted from KMP, C. Lunardini and R. J. Farmer ApJ 840, 2 (2017)

PRESUPERNOVA NEUTRINOS: PAIR ANNIHILATION

- Odryzwolek et al. in 2004
- Looked at core Si burning stage
- Assumed neutrinos only from pair annihilation
- Calculated the number of events in different detectors
- ~10s of events in current detectors
- ~100s of events in future detectors

20 $M_\odot$ star at D=1 kpc ~ 3200 lyr



Detector	Mass [$kton$]	Reactions	Number of Targets	Flux at 1 kpc [$cm^{-2}\,day^{-1}$]	Event rate [day^{-1}]
Borexino	0.3 (C_9H_{12})	$\bar{\nu}_e + p \to e^+ + n$	$1.80 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	0.34
		$\nu_e + e^- \to \nu_e + e^-$	$9.92 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	0.49
		$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	$9.92 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	0.19
		$\nu_{\mu,\tau} + e^- \to \nu_{\mu,\tau} + e^-$	$9.92 \cdot 10^{31}$	$1.0 \cdot 10^{11}$	0.03
		$\bar{\nu}_{\mu,\tau} + e^- \to \bar{\nu}_{\mu,\tau} + e^-$	$9.92 \cdot 10^{31}$	$1.0 \cdot 10^{11}$	0.026
KamLAND	0.2 (C_9H_{12})	$\bar{\nu}_e + p \to e^+ + n$	$8.55 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	1.6
	0.8 ($C_{12}H_{26}$)	$\nu_e + e^- \to \nu_e + e^-$	$3.43 \cdot 10^{32}$	$2.8 \cdot 10^{11}$	1.7
		$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	$3.43 \cdot 10^{32}$	$2.8 \cdot 10^{11}$	0.65
		$\nu_{\mu,\tau} + e^- \to \nu_{\mu,\tau} + e^-$	$3.43 \cdot 10^{32}$	$1.0 \cdot 10^{11}$	0.11
		$\bar{\nu}_{\mu,\tau} + e^- \to \bar{\nu}_{\mu,\tau} + e^-$	$3.43 \cdot 10^{32}$	$1.0 \cdot 10^{11}$	0.09
SNO	1.7 (H_2O)	$\bar{\nu}_e + p \to e^+ + n$	$1.14 \cdot 10^{32}$	$2.8 \cdot 10^{11}$	2.2
	1 (D_2O)	$\bar{\nu}_e + d \to e^+ + n + n$	$6.00 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	0.004
		$\nu_x + d \to \nu_x + p + n$	$6.00 \cdot 10^{31}$	$3.8 \cdot 10^{11}$	0.038
		$\bar{\nu}_x + d \to \bar{\nu}_x + p + n$	$6.00 \cdot 10^{31}$	$3.8 \cdot 10^{11}$	0.032
Super-K	32 (H_2O)	$\bar{\nu}_e + p \to e^+ + n$	$2.14 \cdot 10^{33}$	$2.8 \cdot 10^{11}$	41
UNO	440 (H_2O)	$\bar{\nu}_e + p \to e^+ + n$	$2.94 \cdot 10^{34}$	$2.8 \cdot 10^{11}$	560
Hyper-K	540 (H_2O)	$\bar{\nu}_e + p \to e^+ + n$	$3.61 \cdot 10^{34}$	$2.8 \cdot 10^{11}$	687

Odrzywolek, Misiaszek, and Kutschera *Astropart. Phy.* **21**, 303 (2004)

PRESUPERNOVA NEUTRINOS: BETA PROCESSES

- Beta processes are also needed
- Many isotopes are present in the late stage of the stellar evolution
- All of these can undergo beta decay or electron/positron capture
- These processes produce only electron flavor neutrinos or antineutrinos

β^-/β^+ Decay

$$A(N,Z) \rightarrow A(N-1,Z+1) + e^- + \bar{\nu}_e$$

$$A(N,Z) \rightarrow A(N+1,Z-1) + e^+ + \nu_e$$

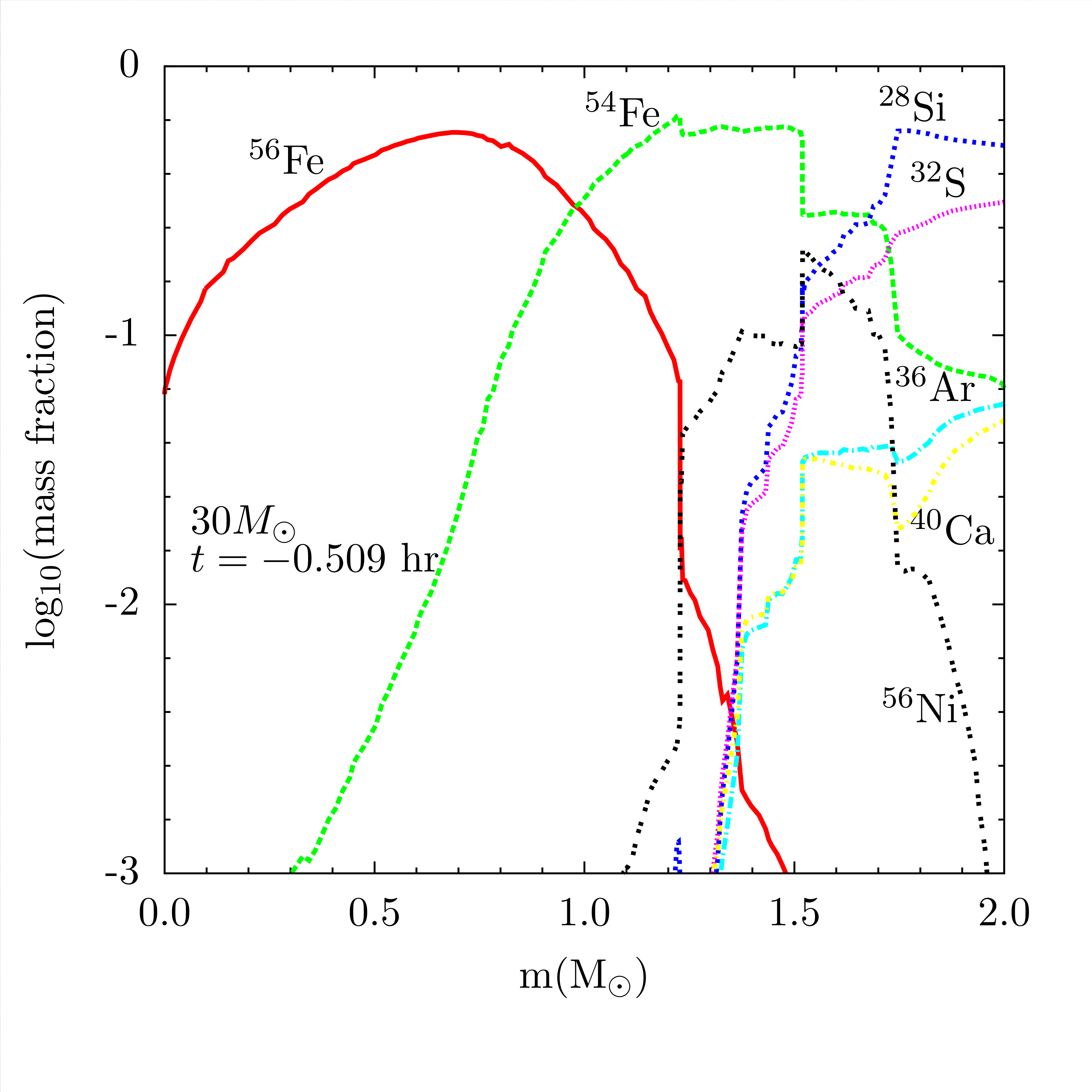
e^-/e^+ Capture

$$A(N,Z) + e^- \rightarrow A(N+1,Z-1) + \nu_e$$

$$A(N,Z) + e^+ \rightarrow A(N-1,Z+1) + \bar{\nu}_e$$

N = neutron number
Z = proton number
A = atomic number = N + Z

PRESUPERNOVA NEUTRINOS: BETA PROCESSES



Mass fractions for 10 most abundant isotopes

- Since nuclear processes depend so much on which isotopes are present, we have to decide how to calculate the abundances
- We chose to use the stellar evolution code

MESA

  - Tracks the abundance of 204 isotopes over the entire lifetime of the star
  - Evolves the abundances and nuclear reactions in situ, completely coupled to the hydrodynamics
  - Also tracks temperature, density, and electron fraction
  - See Farmer et al. arXiv:1611.01207 for details

BETA SPECTRUM

- Shape of spectrum completely determined by phase space of electrons involved
- Depends on chemical potential μ_e, and temperature T, which we get from MESA
- $N_{EC,PC}$ and N_β are normalization factors so our rates match tabulated rates

$$\phi_{EC,PC} = N_{EC,PC}\frac{E_\nu^2(E_\nu - Q)^2}{1+\exp\left((E_\nu - Q - \mu_e)/kT\right)}\Theta(E_\nu - Q - m_e)$$

$$\phi_\beta = N_\beta\frac{E_\nu^2(Q - E_\nu)^2}{1+\exp\left((E_\nu - Q + \mu_e)/kT\right)}\Theta(Q - m_e - E_\nu)$$

$$Q_{ij} = M_p - M_d + E_i - E_j$$

- Define "effective Q-value" as the one that reproduces tabulated rates
  - Langanke and Martinez-Pinedo, ADNDT **79**, 1 (2001)
  - Oda et al., ADNDT **56**, 231 (1994)
  - Fuller, Fowler, and Newman, ApJ **252**, 715 (1982)

PRESUPERNOVA NEUTRINOS: BETA PROCESSES

- The total spectrum is found from a weighted sum of all our isotopes

$$\Phi_{\nu,\bar{\nu}} = \sum_k \phi_k n_k = \sum_k X_k \phi_k \frac{\rho}{m_p A_k}$$

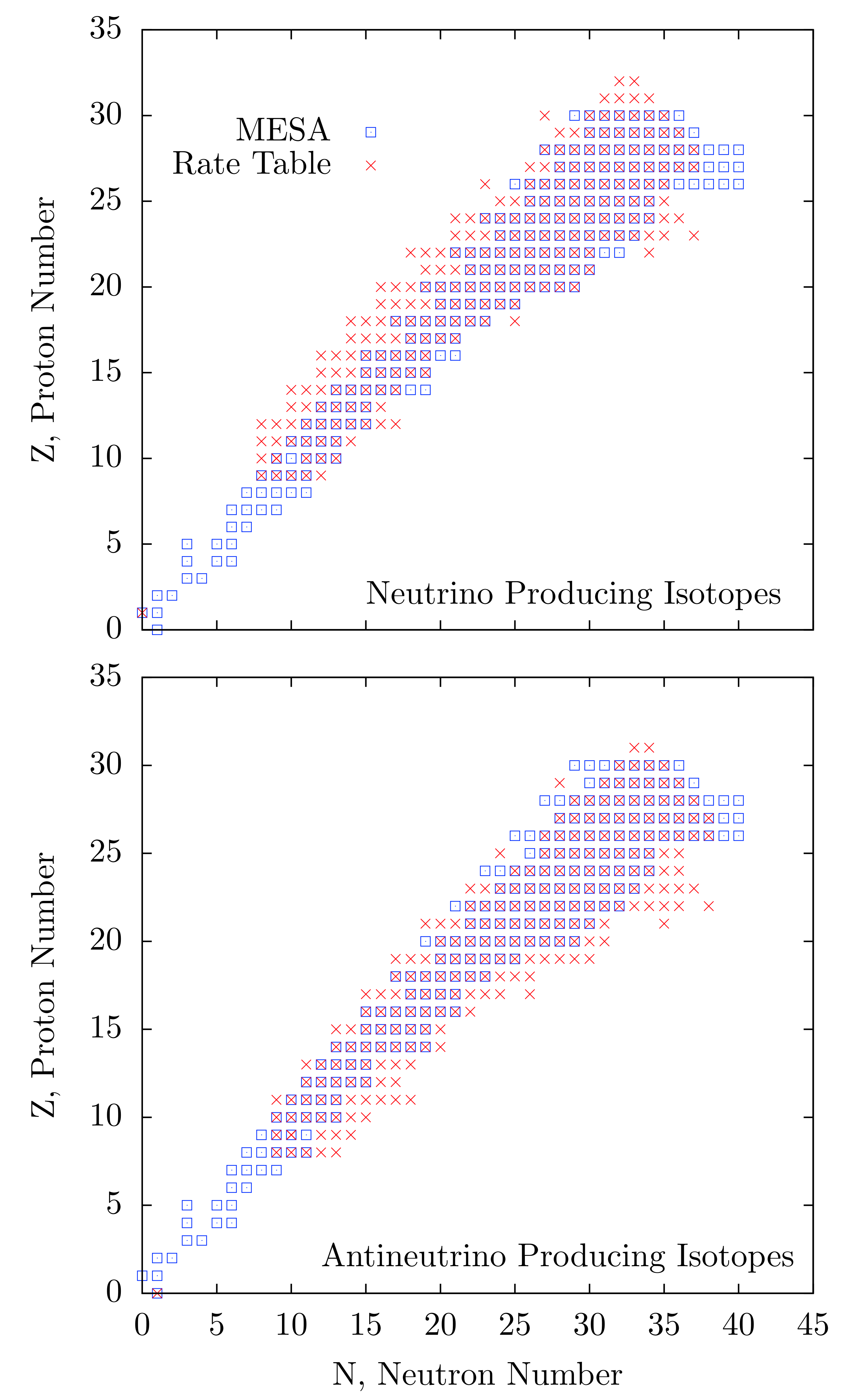
ϕ_k = single isotope spectrum, isotope k

X_k = mass fraction, isotope k

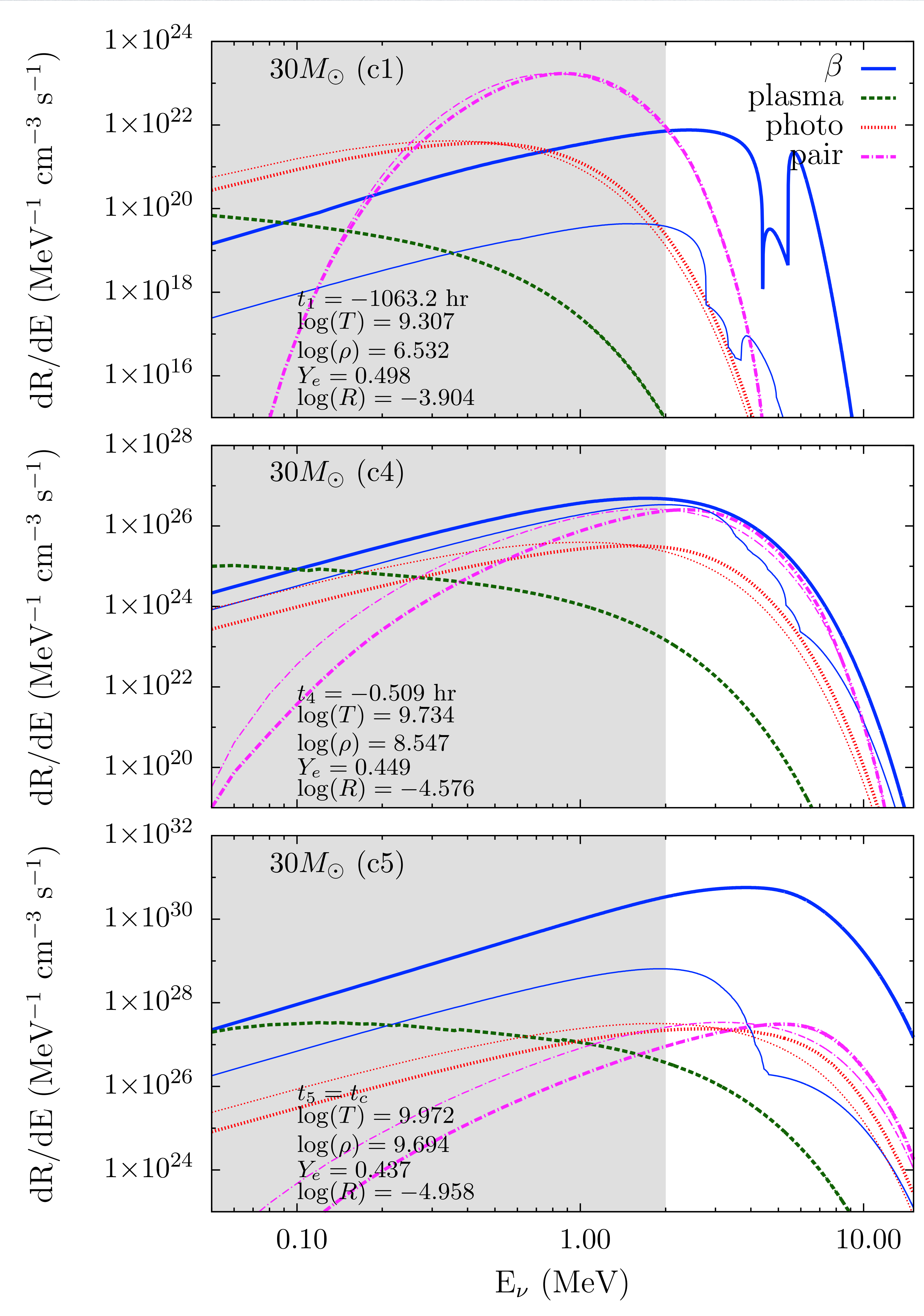
ρ = mass density

m_p = proton mass

A_k = atomic number, isotope k



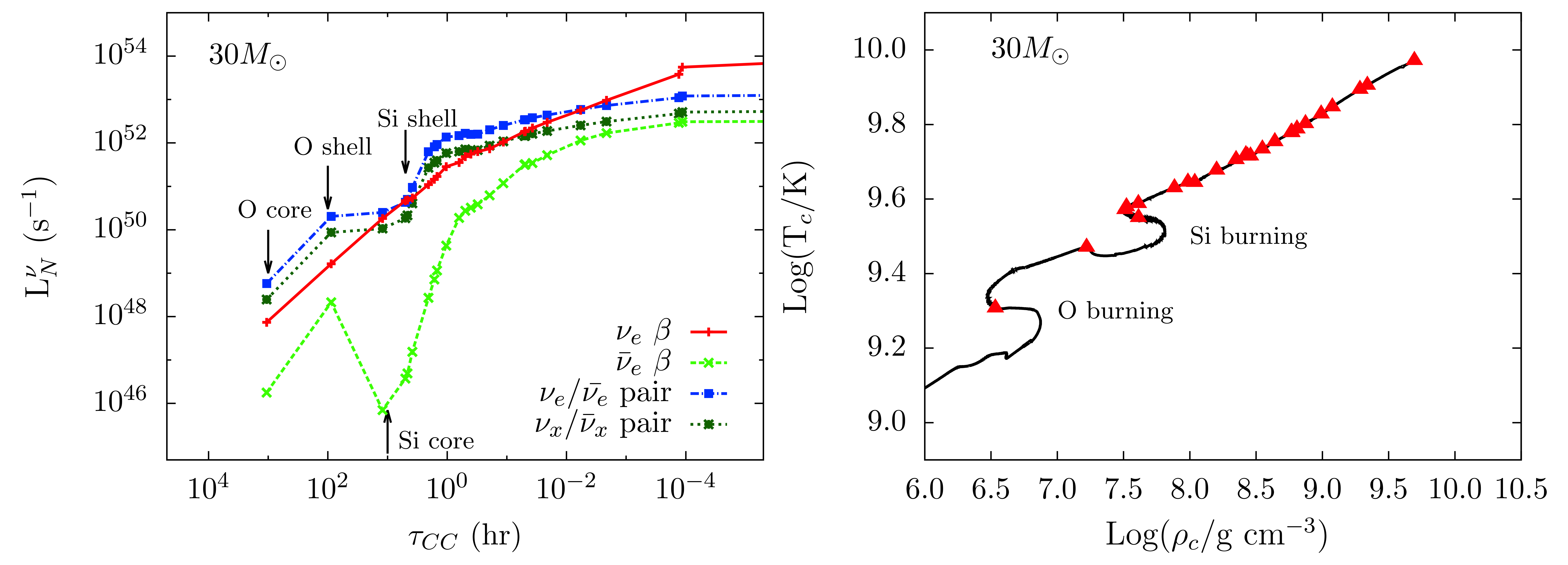
PRESUPERNOVA NEUTRINOS: 30 $M_\odot$



- Thick lines = ν_e, thin lines = $\bar{\nu}_e$
- Blue = beta, magenta = pair
- Early times, beta spectrum shows a lot of structure and dominates at high (detectable) energies
- Late times, beta spectrum smooths out and dominates overall for neutrinos
  - Pair is dominant at high energy for antineutrinos
  - Highest contributions from Fe, Co, Mn, and Cr isotopes

Figure Adapted from KMP, C. Lunardini and R. J. Farmer *ApJ* **840**, 2 (2017)

PRESUPERNOVA NEUTRINOS: IMPORTANCE OF BETA PROCESSES



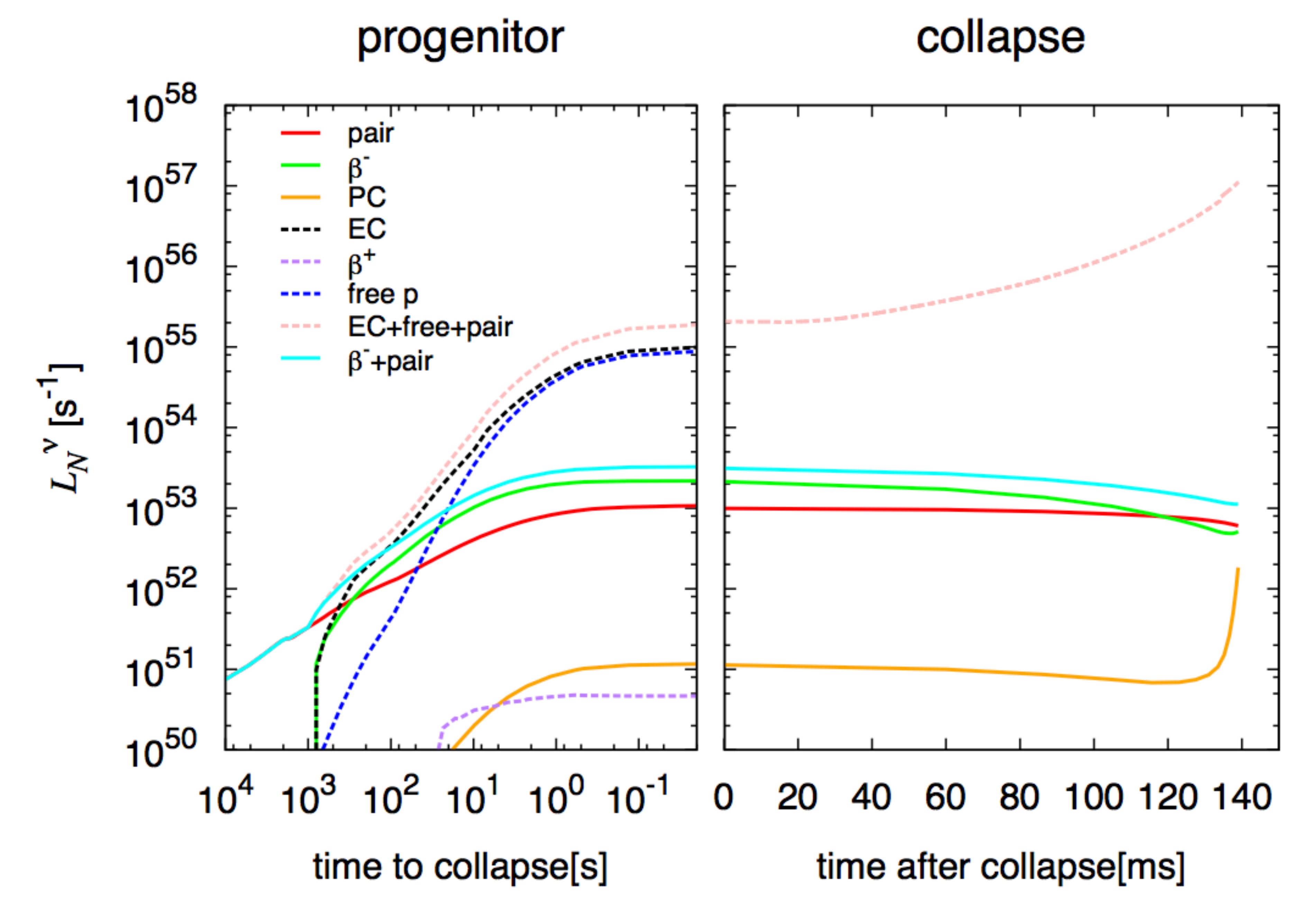
- At early times, pair process dominates

- Later on, in the neutrino channel beta processes rule

- Beta processes for antineutrinos are always subdominant

Figure from from KMP, C. Lunardini, R. J. Farmer, and F. X. Timmes *ApJ* **851**, 6 (2017)

COMPARISON TO KATO ET AL. (2017)



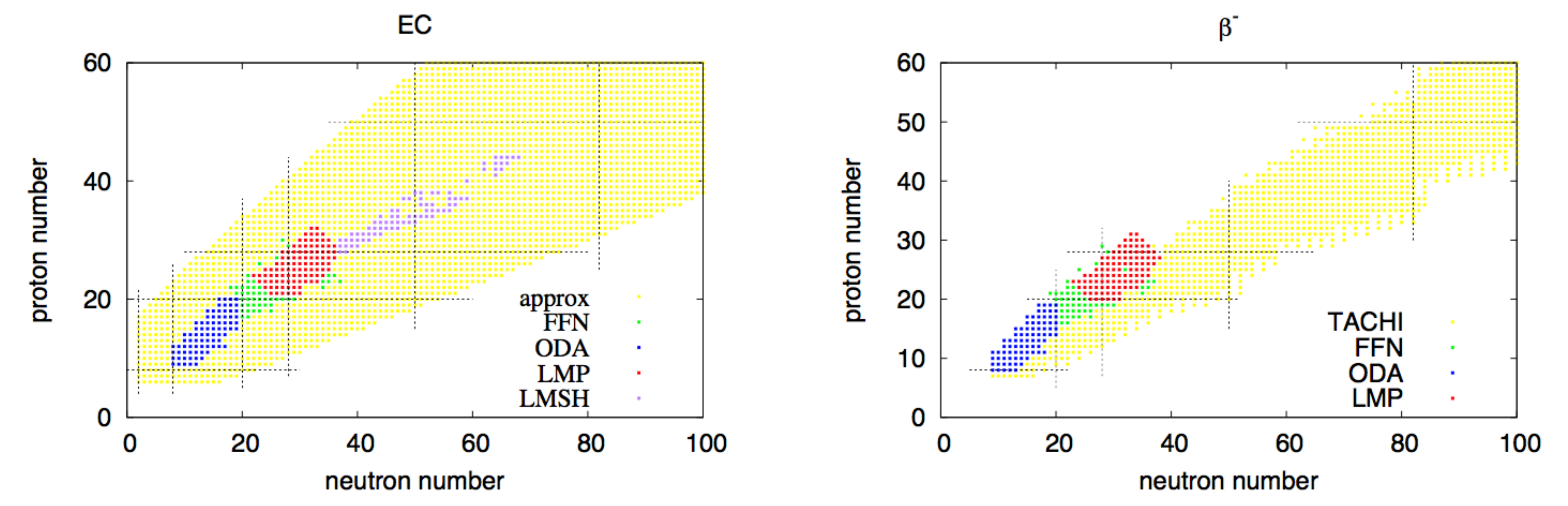
Kato et al. arXiv:1704:05480 (2017)

🟥 pair
🟪 β^+
🟩 β^-
⬛ e- capture

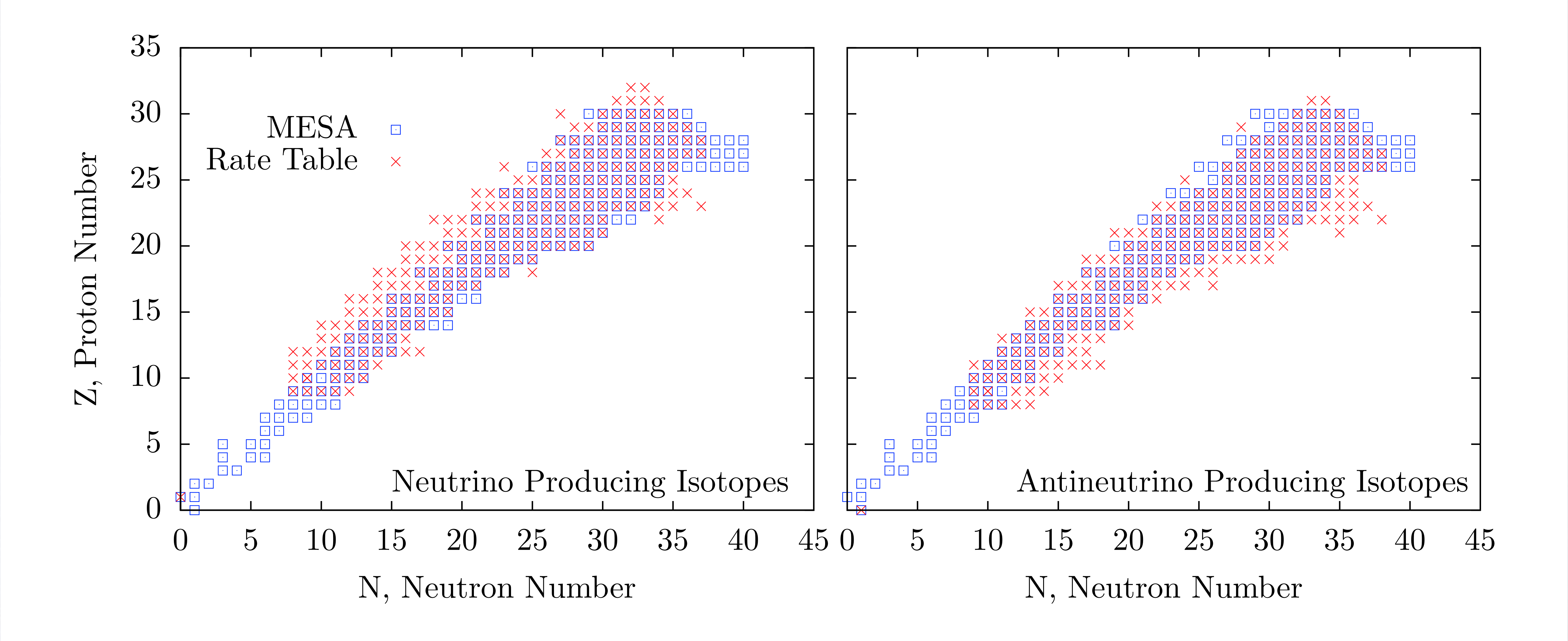
- Kato et al. looked at a $15M_\odot$ star
- They found a similar pattern with pair annihilation dominating until shortly before collapse
- One difference: antineutrinos from β^- decay overtake pair neutrinos

COMPARISON TO KATO ET AL. (2017)

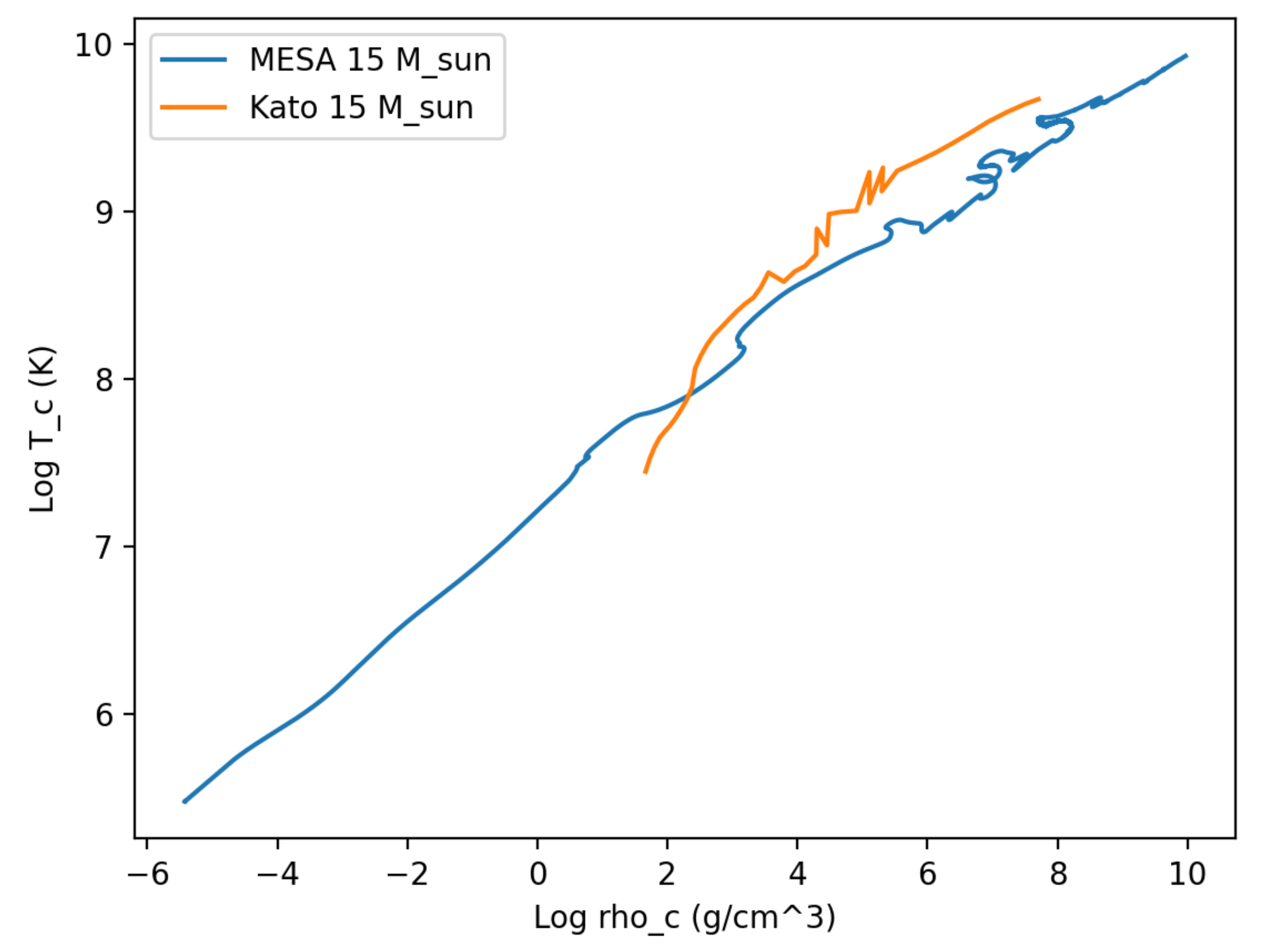
- Expanded isotope table
  - Yellow isotopes have terrestrial rates that are incorporated using a suppression factor $1 - f_e(\langle E_e \rangle)$
  - More neutron rich isotopes = more electron antineutrinos



Kato et al. arXiv:1704:05480 (2017)



COMPARISON TO KATO ET AL. (2017)



- Comparison of the central temperature and density to collapse also shows differences

- The star used by Kato et al. is generally hotter for a given density

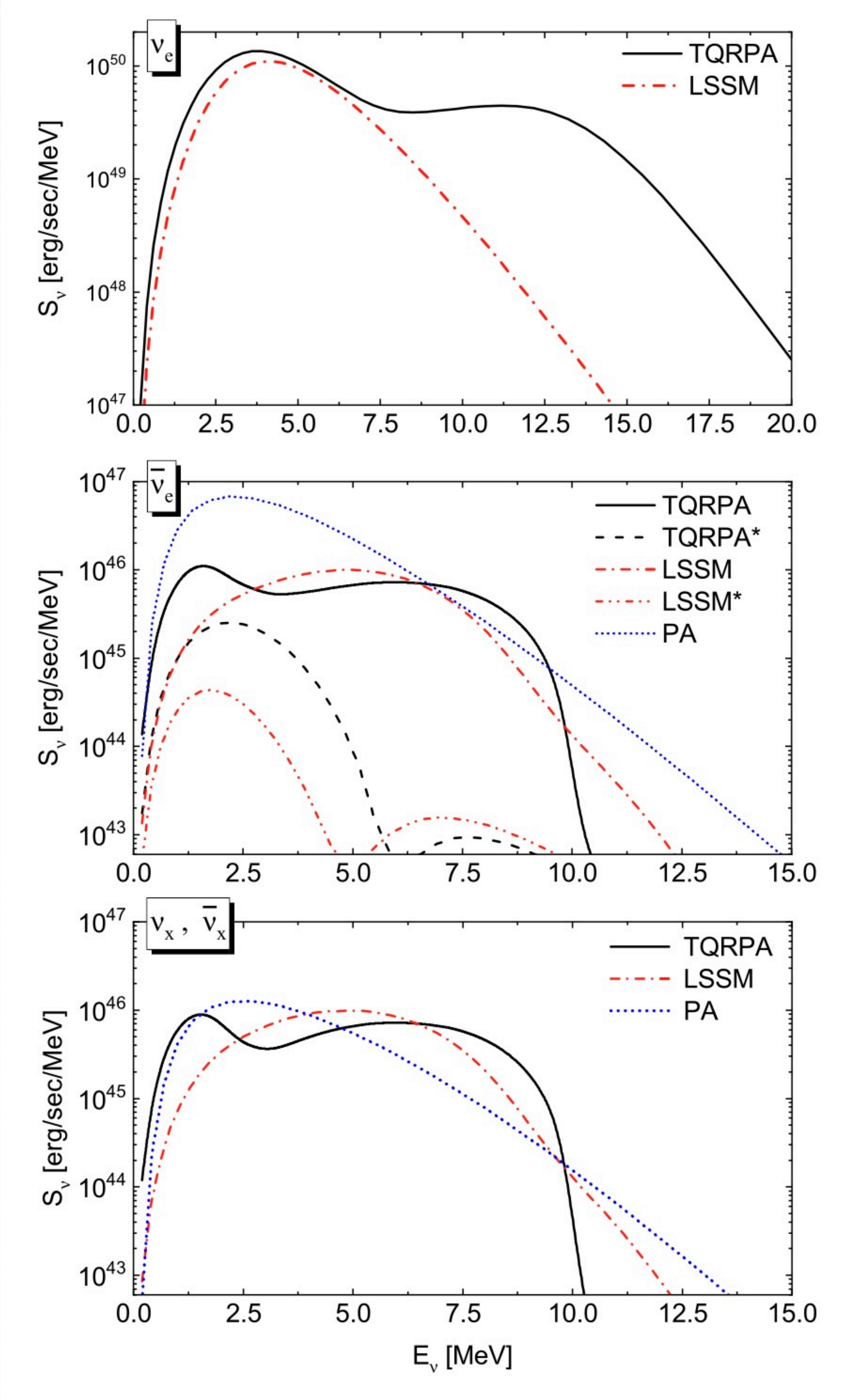
- The MESA model stretches to a higher temperature and density before collapse

ANOTHER METHOD AND ANOTHER PROCESS: TQRPA AND NEUTRAL CURRENT DE-EXCITATION

- The “effective q-value” method used here could miss important features in the spectrum

- Nuclei could emit neutrino pairs by a neutral current de-excitation process
  - Expect these neutrino pairs to be higher energy than from beta processes

- Could we be missing potentially detectable neutrinos?



Dzhioev et al. MNRAS **527**, 7701-7712 (2024)

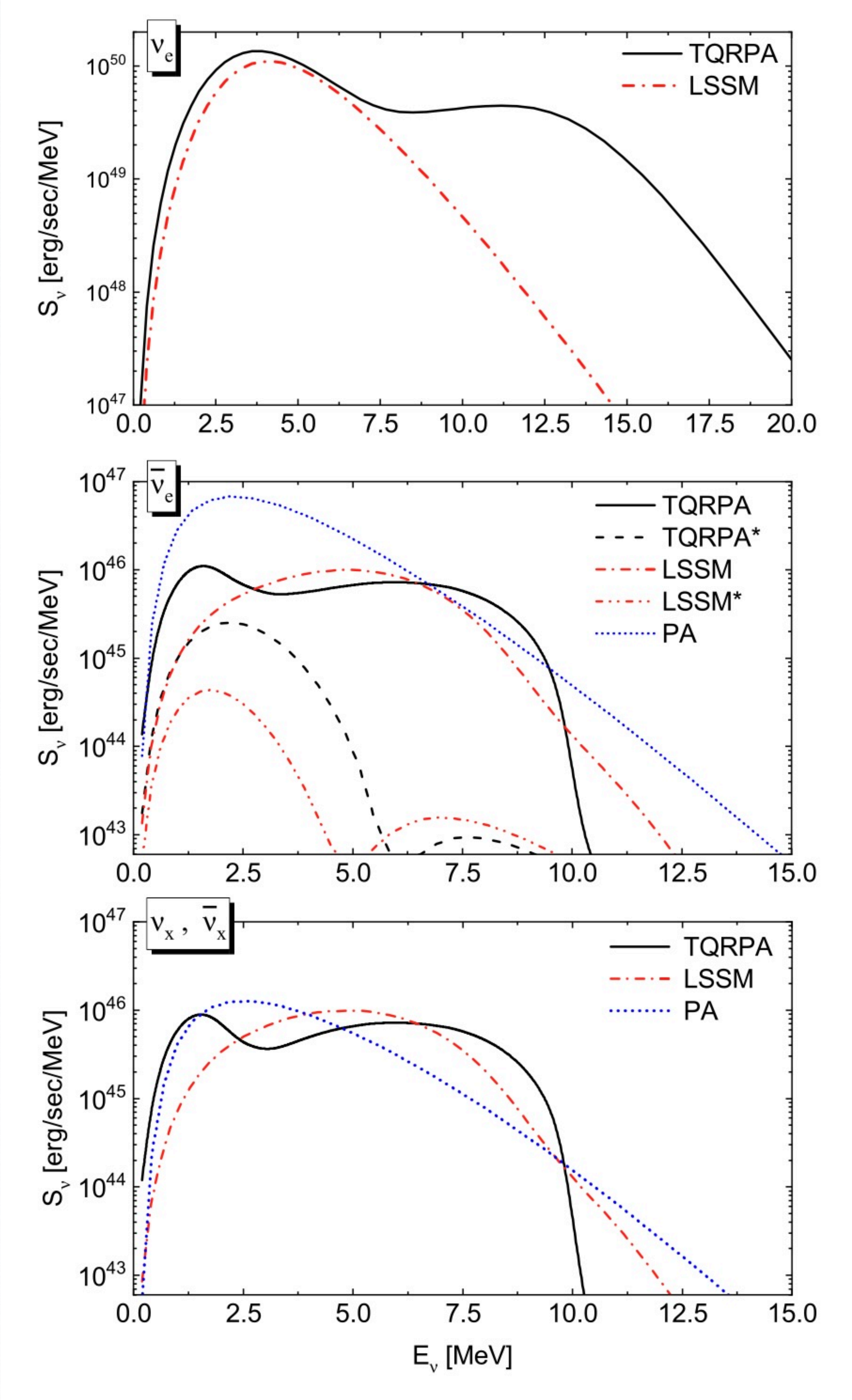
ANOTHER METHOD AND ANOTHER PROCESS: TQRPA AND NEUTRAL CURRENT DE-EXCITATION

- TQRPA - Thermal Quasiparticle Random Phase Approximation - is another way to compute the beta spectra

- Tends to produce higher energy peaks and sometimes double peaks where "effective q-value" (LSSM) produces one

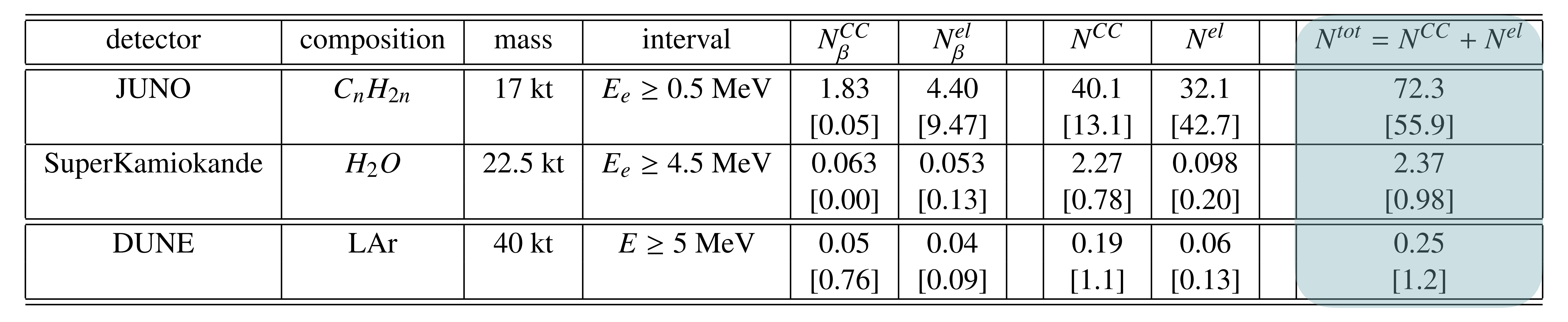
- Neutral current de-excitation also produces high energy neutrinos

- Shown here only for ^{56}Fe immediately pre-collapse, but an important process to add in!



Dzhioev et al. MNRAS **527**, 7701-7712 (2024)

DETECTION OF PRESUPERNOVAE



detector	composition	mass	interval	N_β^{CC}	N_β^{el}		N^{CC}	N^{el}		$N^{tot} = N^{CC} + N^{el}$
JUNO	C_nH_{2n}	17 kt	$E_e \geq 0.5$ MeV	1.83 [0.05]	4.40 [9.47]		40.1 [13.1]	32.1 [42.7]		72.3 [55.9]
SuperKamiokande	H_2O	22.5 kt	$E_e \geq 4.5$ MeV	0.063 [0.00]	0.053 [0.13]		2.27 [0.78]	0.098 [0.20]		2.37 [0.98]
DUNE	LAr	40 kt	$E \geq 5$ MeV	0.05 [0.76]	0.04 [0.09]		0.19 [1.1]	0.06 [0.13]		0.25 [1.2]

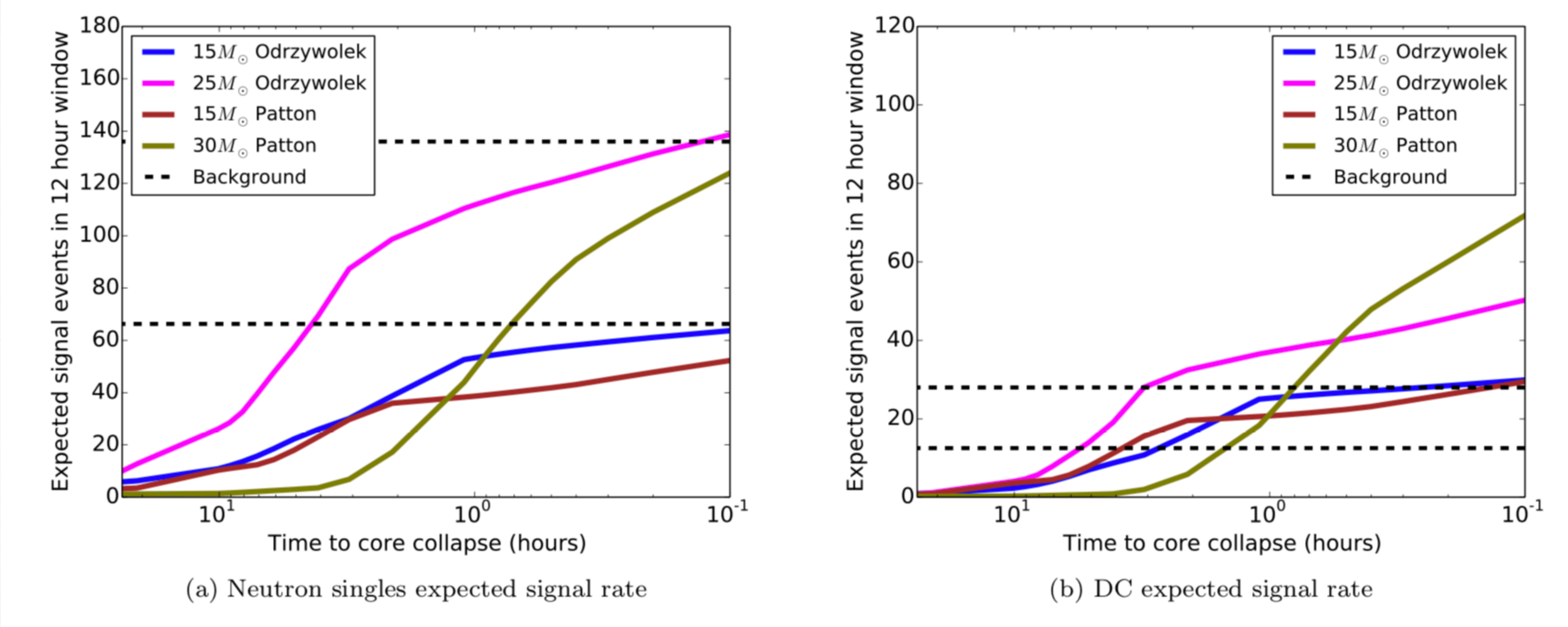
- Consider our 30 $M_\odot$ star at a distance of D = 1 kpc, over the last 2 hours before collapse
- JUNO has the best chance with around 70 events
- If we consider Betelgeuse (D = 200 pc), event numbers increase by a factor of 25

Table from from KMP, C. Lunardini, R. J. Farmer, and F. X. Timmes *ApJ* **851**, 6 (2017)

DETECTION: SUPER-K WITH GADOLINIUM

- SK-Gd increases detection efficiency because of Gd high neutron capture rate
  - Detection coincidence of IBD e$^+$ and γ-ray cascade after neutron capture on Gd
  - Also single neutron events (no IBD e$^+$): higher background but lower threshold

200 pc
Normal Hierarchy



(a) Neutron singles expected signal rate

(b) DC expected signal rate

Simpson et al. arXiv:1908.07551 (2019)

FUTURE

- More stars!
  - Kato et al. have shown that different mass progenitors have different neutrino spectra
  - Currently a work in progress
- Add in neutral current de-excitation
- Further comparison with TQRPA and/or update beta calculations with more detailed methods

THANK YOU!

- Thanks to the organizers for the invite
- Thanks to my collaborators: Cecilia Lunardini, Rob Farmer, Frank Timmes
- Thanks to ASU, INT/UW, Colby College, and Trinity College
- Thanks to you for listening!