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PRESUPERNOVA NEUTRINOS: REALISTIC EMISSIVITIES FROM STELLAR EVOLUTION

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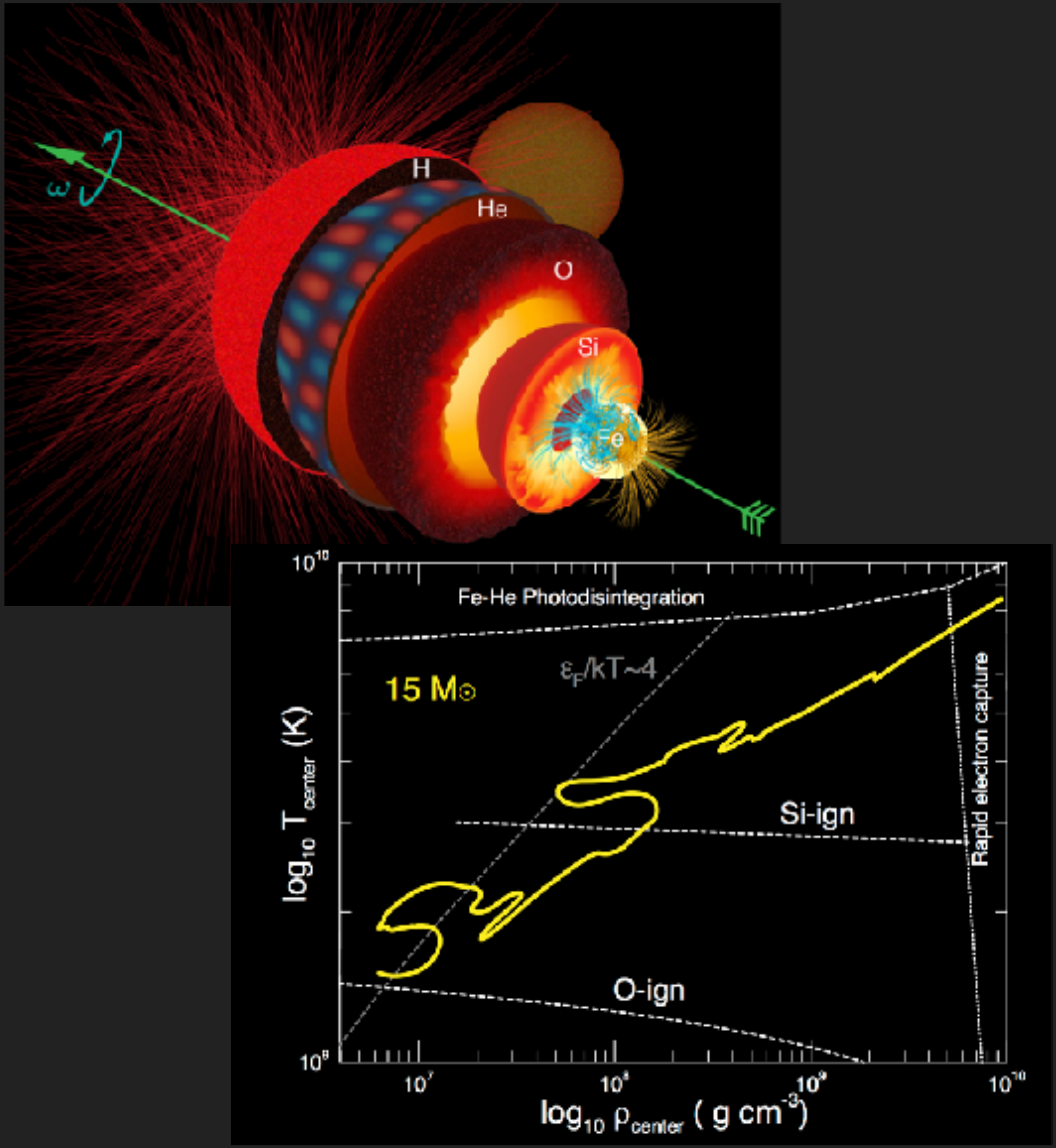
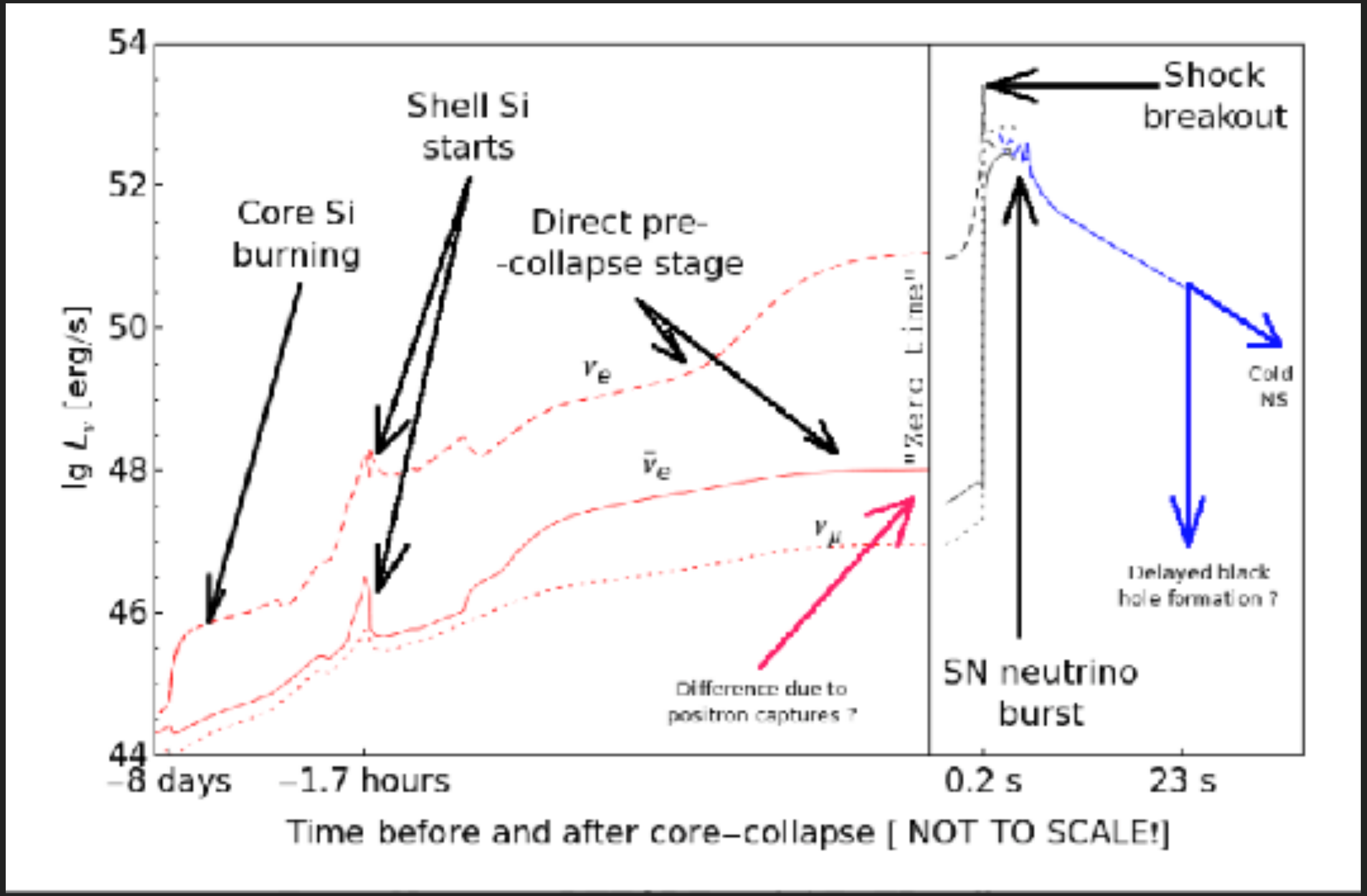
EVOLUTION OF MASSIVE STARS: CORE COLLAPSE



- As the star evolves, the core gets hotter and denser
- Successively heavier elements undergo burning, creating more heavy nuclei
- Iron core is formed, grows, then collapses

NEUTRINO EVOLUTION OF MASSIVE STARS

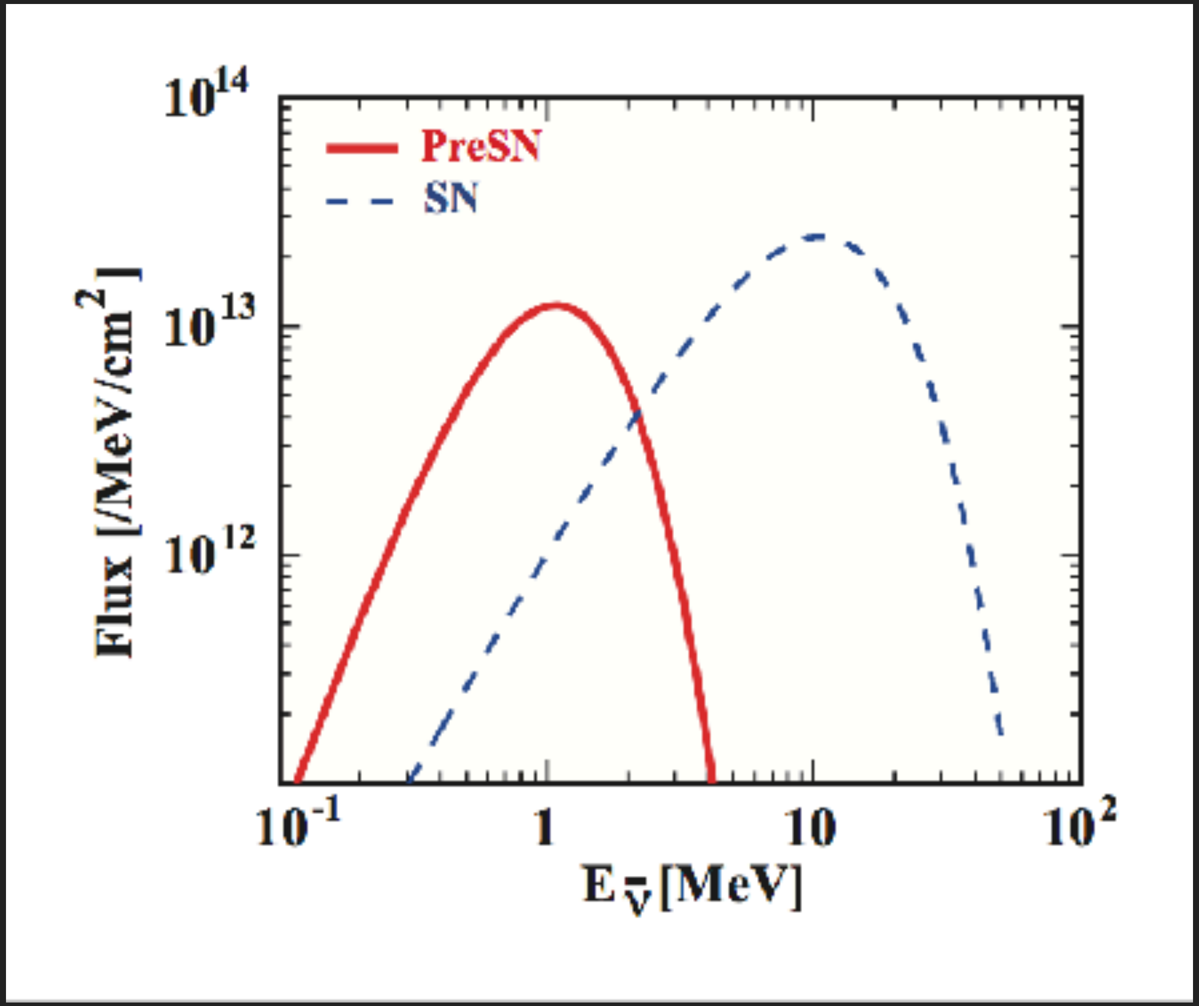


Odrzywolek and Heger *Acta Physica Polonica* B **41**, 1611 (2010)

- Neutrino luminosity grows by orders of magnitude in last hours/days before collapse
  - Thermal processes ramp up as (T, ρ) increase
  - β processes also increase depending on isotopic composition
- Pre-collapse luminosity is only ~2 orders of magnitude below that of burst

DETECTABLE?

- We know burst is detectable (SN1987A)
- Energy spectrum peaks lower than the SN burst
  - Lower energy means lower cross section in detectors
- Can we see the presupernova too?

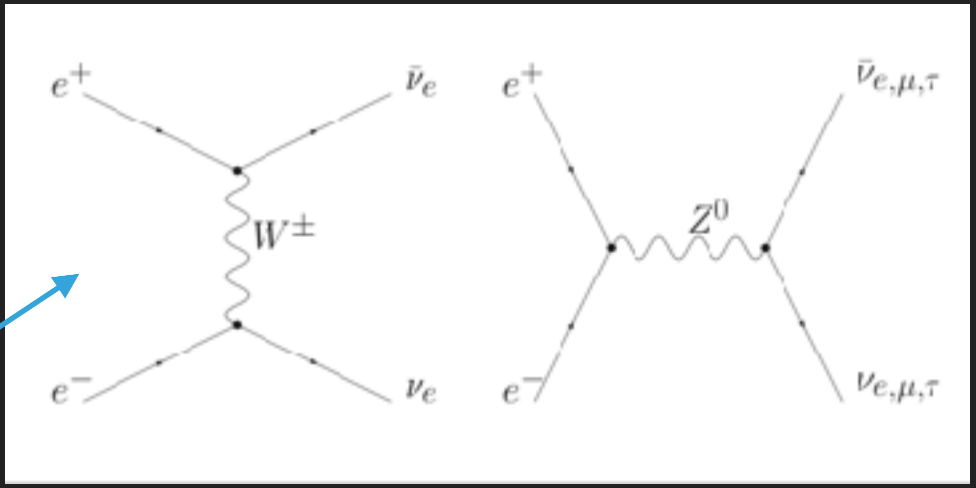


Asakura et al. (KamLAND) *ApJ* **818**, 91 (2016)

WHAT PRODUCES NEUTRINOS IN PRE-SN?

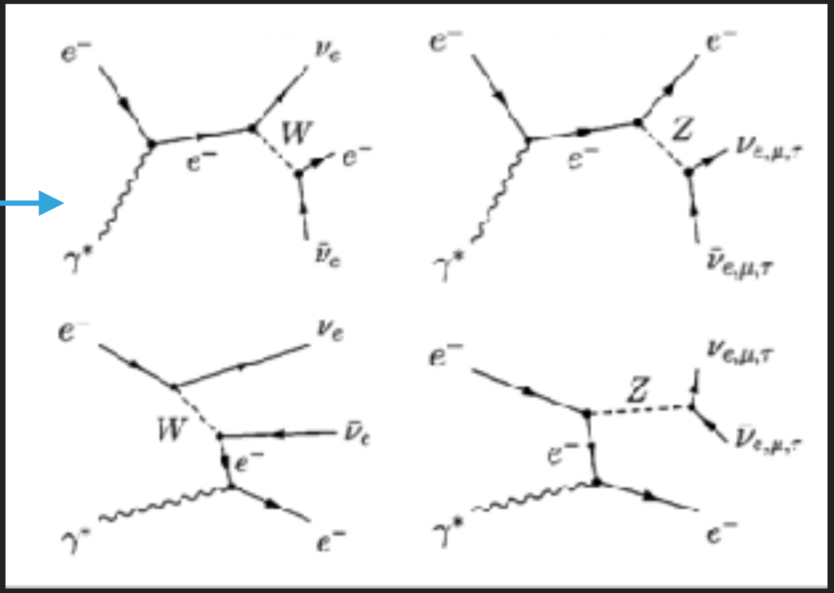
- Thermal processes
  - Pair annihilation

$$e^+ + e^- \rightarrow \nu_\alpha + \overline{\nu}_\alpha$$



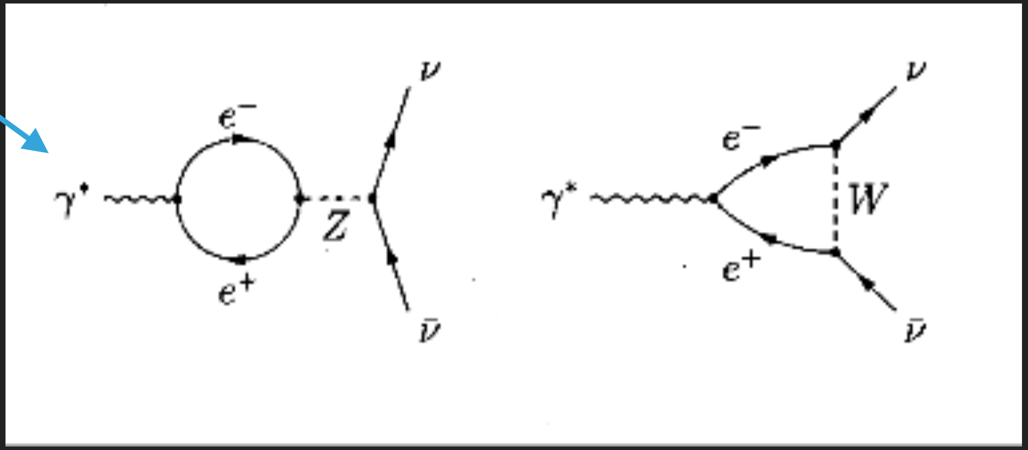
  - Photoneutrino process

$$e^\pm + \gamma \rightarrow e^\pm + \nu_\alpha + \overline{\nu}_\alpha$$



  - Plasmon decay

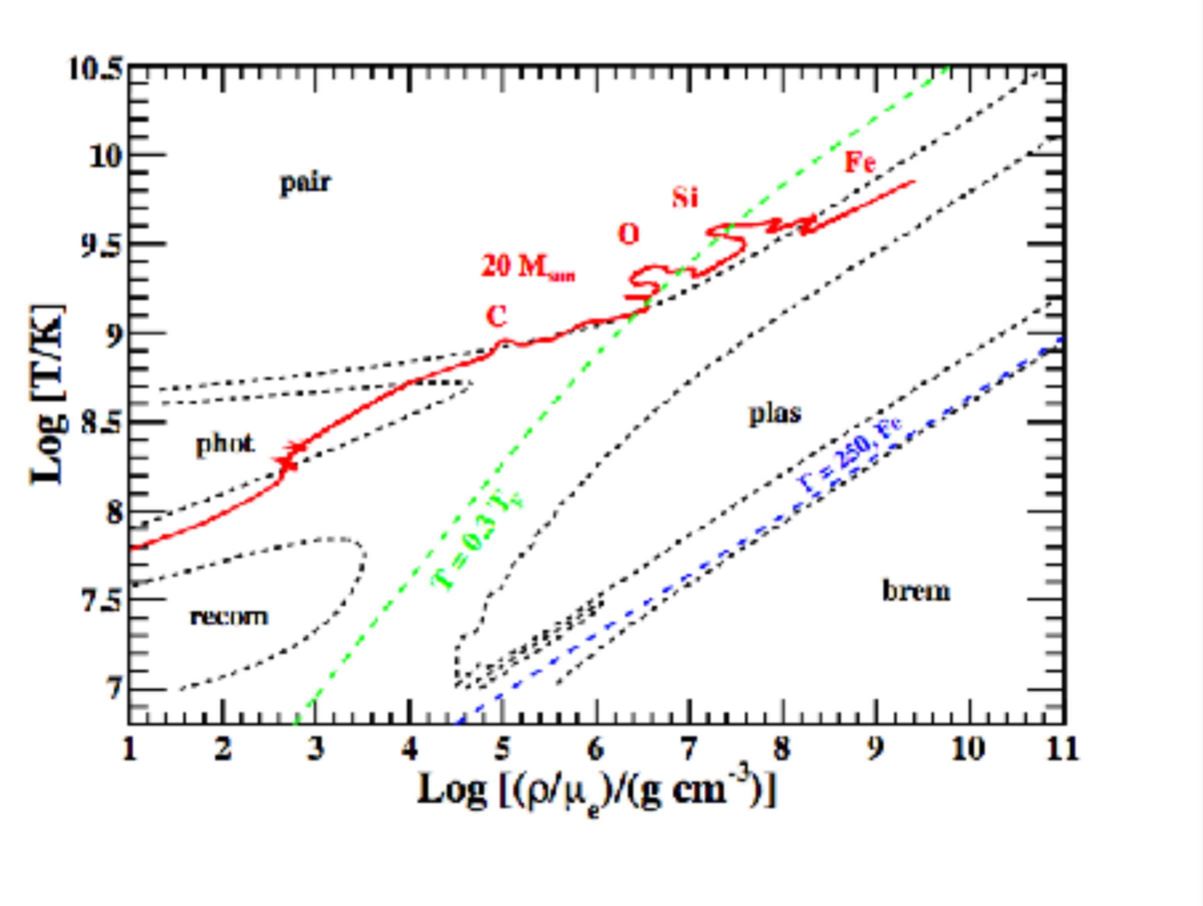
$$\gamma^* \rightarrow \nu_\alpha + \overline{\nu}_\alpha$$



  - (Bremsstrahlung)
  - (Recombination)
  - Itoh et al. (1996)

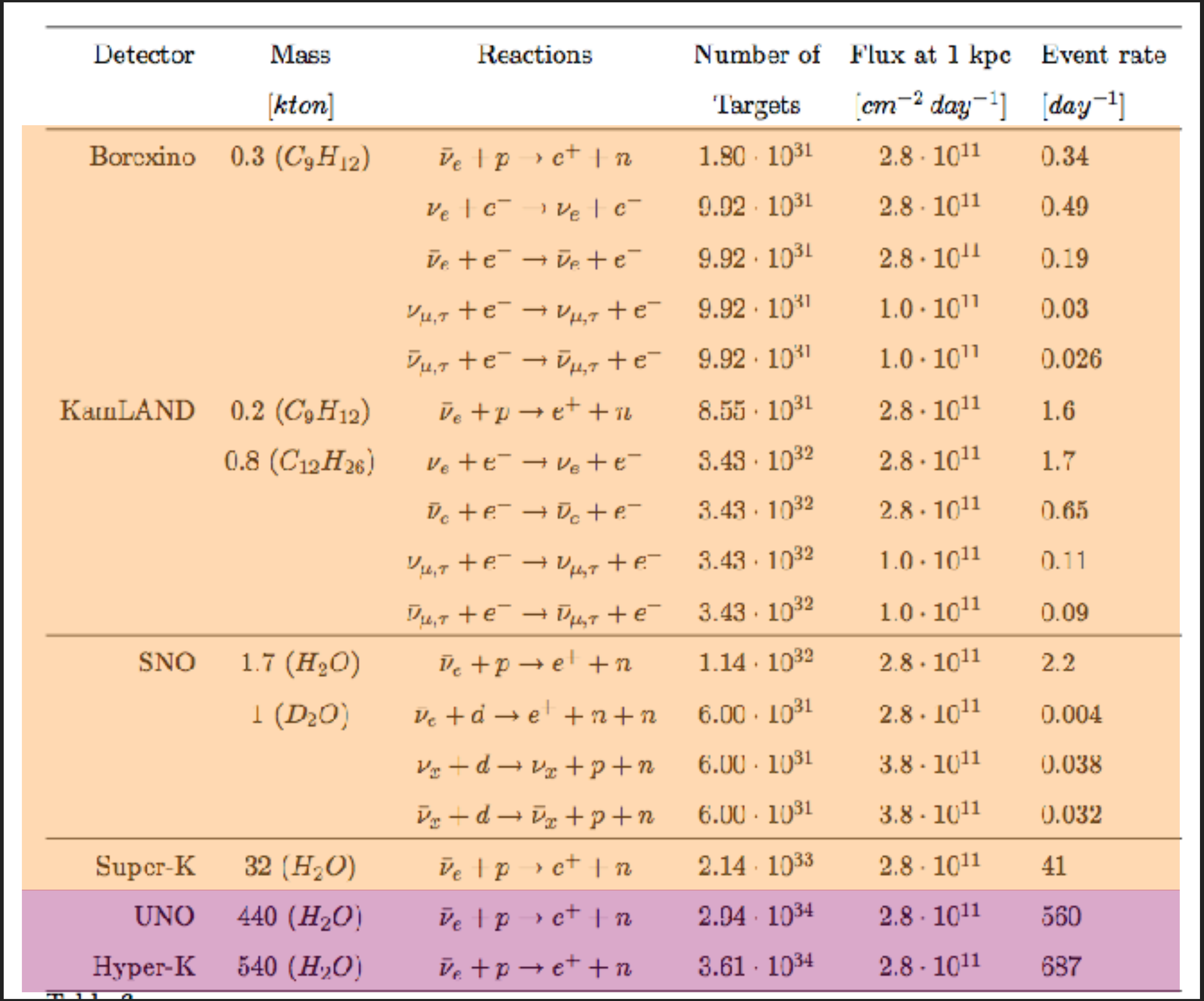
THERMAL PROCESSES

- Itoh et al. (1996) mapped out regions of dominance
- For the temperature and density during Si burning, pair annihilation dominates
- Assuming pair neutrinos only is a good first approximation



Guo and Qian arXiv:1608.02852

FIRST LOOK: ODRZYWOLEK ET AL. (2004)



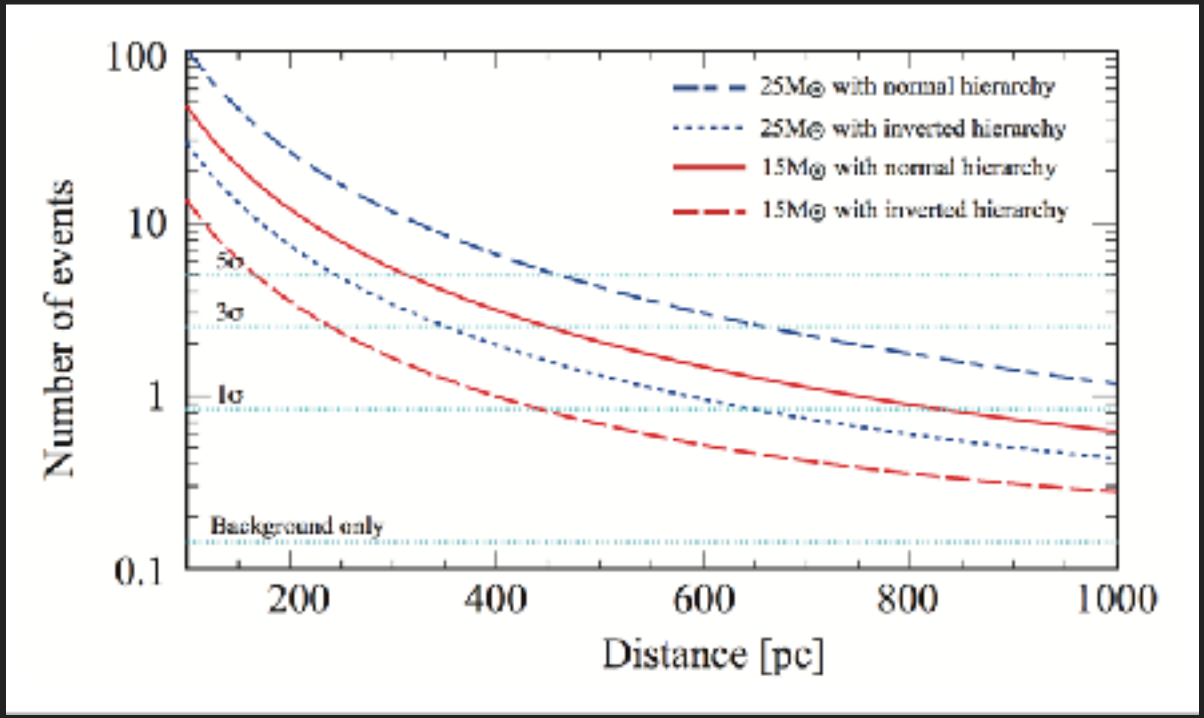
Detector	Mass [kton]	Reactions	Number of Targets	Flux at 1 kpc [$cm^{-2}\,day^{-1}$]	Event rate [day^{-1}]
Borexino	0.3 (C_9H_{12})	$\bar{\nu}_e + p \to e^+ + n$	$1.80 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	0.34
		$\nu_e + e^- \to \nu_e + e^-$	$9.92 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	0.49
		$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	$9.92 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	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)	$\nu_e + d \to e^+ + n + n$	$6.00 \cdot 10^{31}$	$2.8 \cdot 10^{11}$	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)

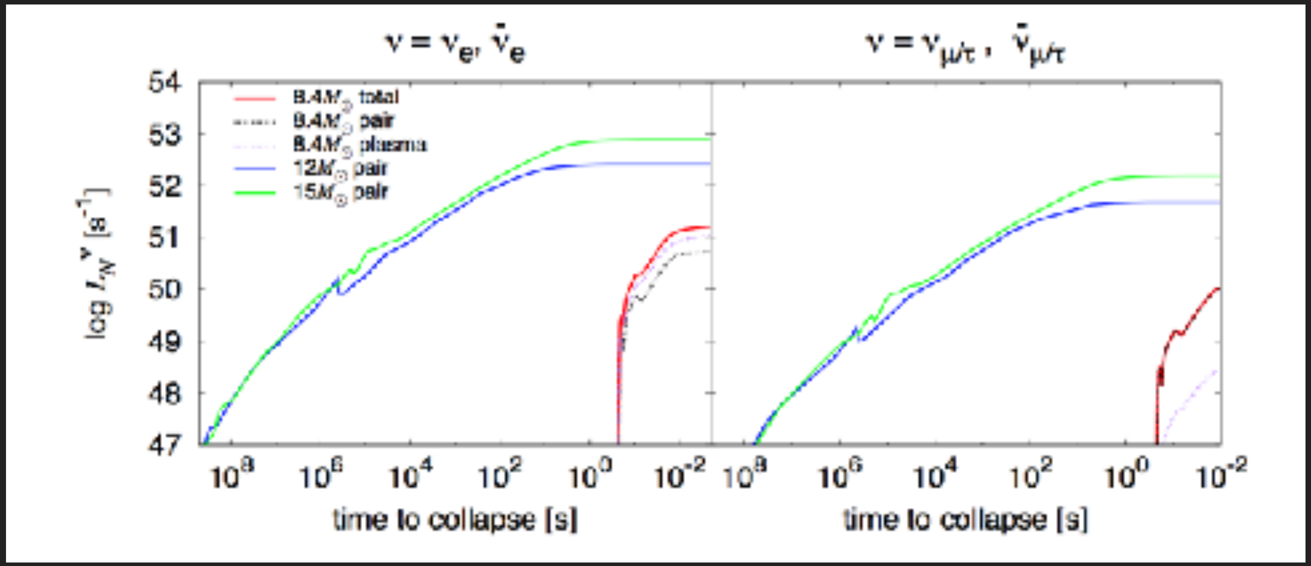
- Si burning stage, pair neutrinos only
- Tens of events in Super-K
- Hundreds in Hyper-K
- 20 $M_\odot$ star at D= 1 kpc

LOOK AGAIN

- KamLAND (2015): 48 hrs before collapse, pair neutrinos only
  - 3σ detection at 660 pc for 25 $M_\odot$
  - Same for 15 $M_\odot$ at 240 pc



Asakura et al. (KamLAND) *ApJ* **818**, 91 (2016)

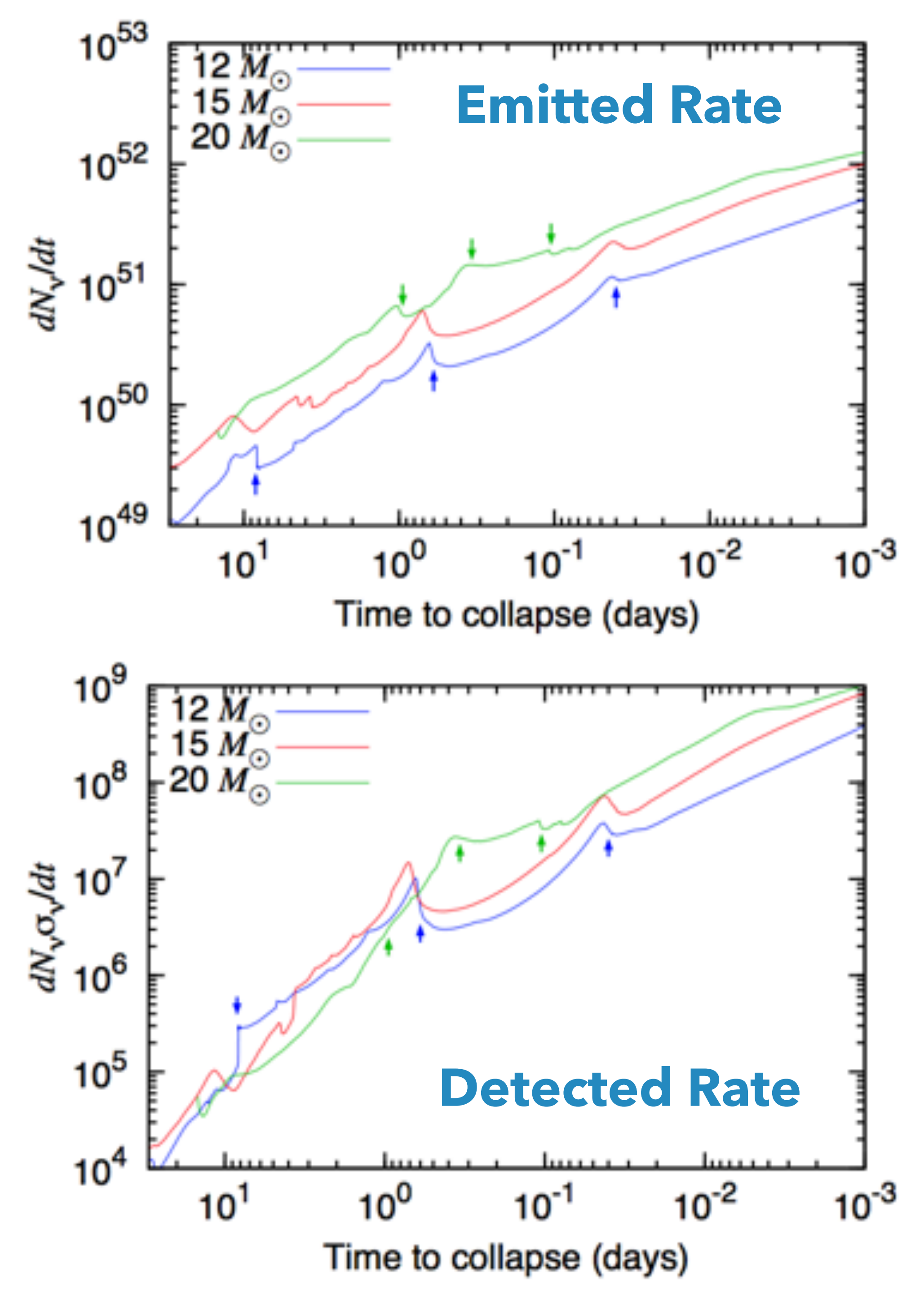


Kato et al. *ApJ* **808**, 168 (2015)

- Kato et al. (2015): pair and plasmon decay neutrinos
  - Discrimination between ONe core and Fe core progenitors

YOSHIDA ET AL. (2016):TIME EVOLUTION

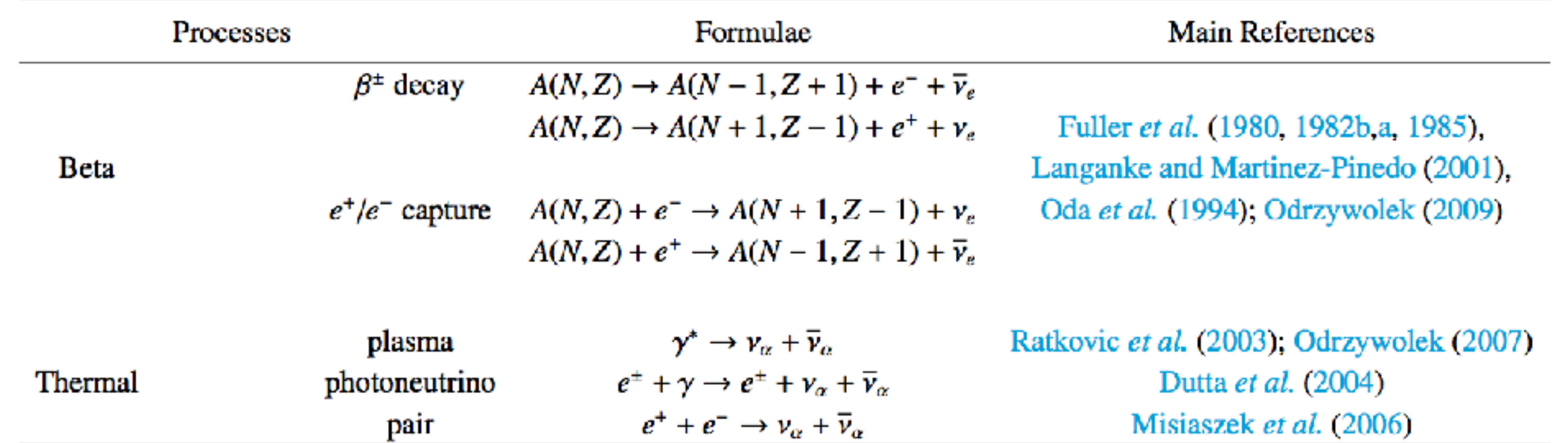
- Definite dips and spikes observed due to starting and stopping of different core burning phases
- Observation of time evolution could allow discrimination of stellar mass



Yoshida et al. *Phys. Rev. D* **93**, 123012 (2016)

ANOTHER PROCESS NEEDS TO BE INCLUDED…

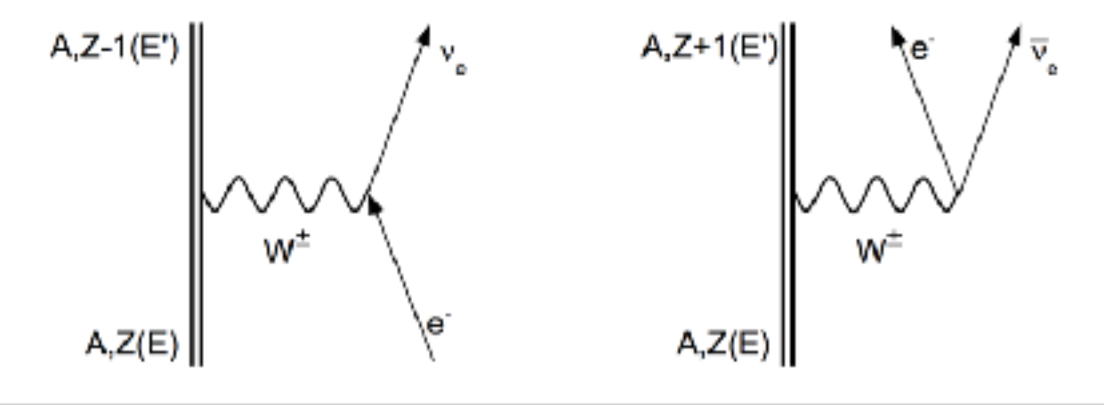
- To this point, all studies have been thermal neutrinos only
- But there’s a second type of process to consider



Processes		Formulae	Main References
Beta	$\beta^{\pm}$ decay	$A(N,Z) \rightarrow A(N-1,Z+1) + e^- + \overline{\nu}_e$ $A(N,Z) \rightarrow A(N+1,Z-1) + e^+ + \nu_e$	Fuller *et al.* (1980, 1982b,a, 1985), Langanke and Martinez-Pinedo (2001), Oda *et al.* (1994); Odrzywolek (2009)
	e^+/e^- capture	$A(N,Z) + e^- \rightarrow A(N+1,Z-1) + \nu_e$ $A(N,Z) + e^+ \rightarrow A(N-1,Z+1) + \overline{\nu}_e$	
Thermal	plasma	$\gamma^* \rightarrow \nu_\alpha + \overline{\nu}_\alpha$	Ratkovic *et al.* (2003); Odrzywolek (2007)
	photoneutrino	$e^{\pm} + \gamma \rightarrow e^{\pm} + \nu_\alpha + \overline{\nu}_\alpha$	Dutta *et al.* (2004)
	pair	$e^+ + e^- \rightarrow \nu_\alpha + \overline{\nu}_\alpha$	Misiaszek *et al.* (2006)

MISSING PIECE: BETA PROCESSES

- Beta processes
- Many isotopes present in core in late stages
- Electron neutrinos and antineutrinos produced through decay or capture reactions
- Importance of beta processes in late stages varies depending on stellar evolution model used



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

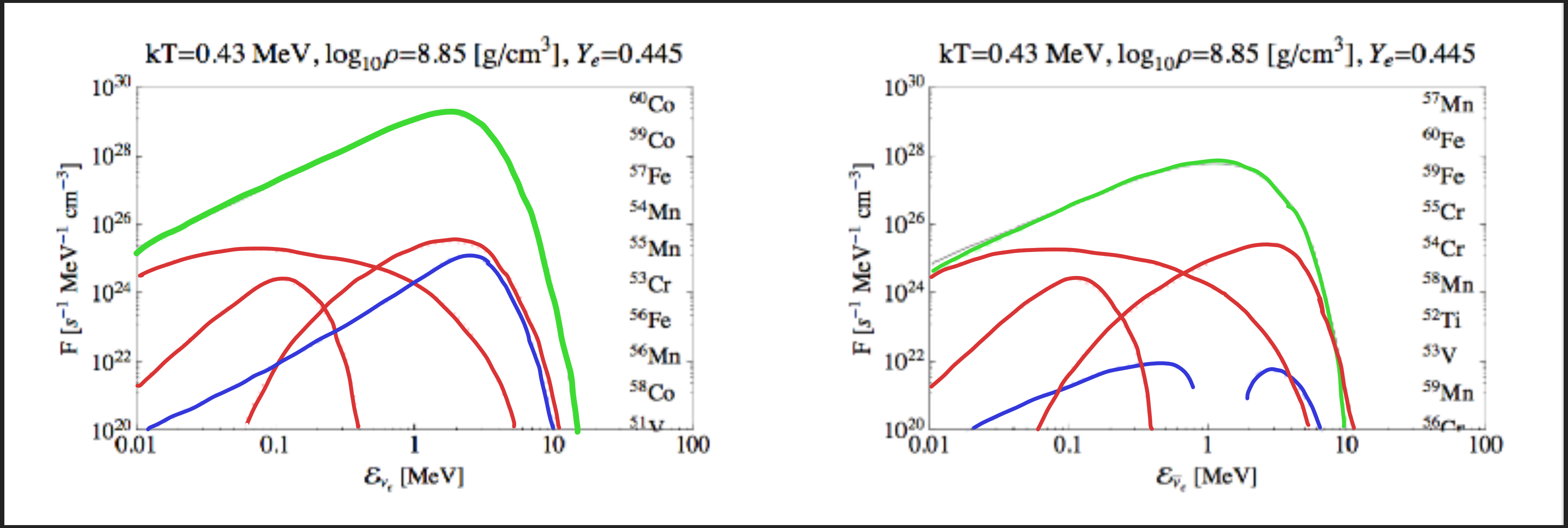
MISSING PIECE: BETA PROCESSES

- Odrzywolek PRC **80** 045801 (2009)
  - Assume nuclear statistical equilibrium
  - Single (T, ρ, Y_e) point typical for large star in Si burn phase
  - Majority of neutrinos produced via beta processes (green)

🟩 **Beta processes**

🟦 **Beta processes on n, p**

🟥 **Thermal processes**



Odrzywolek *PRC* **80,** 045801 (2009)

BETA SPECTRUM

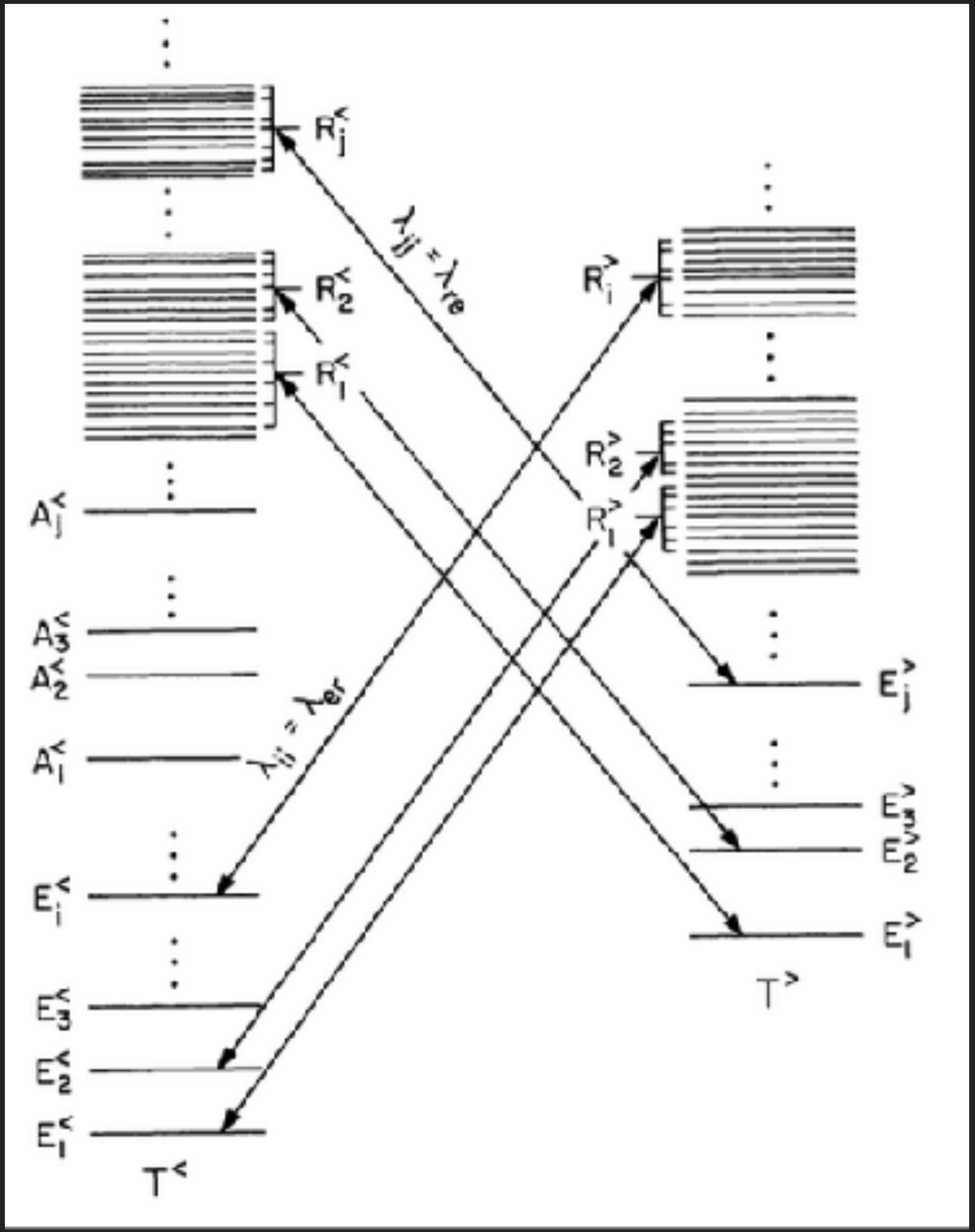
- Shape of spectrum completely determined by phase space of electrons involved
- Depends on chemical potential μ_e, temperature *T*, which we get from (see Farmer et al. arXiv:1611.01207)
- $N_{EC,PC}$ and N_β are normalization factors so our rates match tabulated rates

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

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

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

EFFECTIVE Q-VALUES



Fuller, Fowler, and Newman *ApJSS* **48,** 279 (1982)

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

- Q-value simple to calculate in theory
- In reality, initial and final states unknown
- Define "effective Q-value" as the value that reproduces tabulated average energy [1,2,3]
  - Calculate spectrum and average energy with any Q-value
  - Adjust Q-value until average energy matches

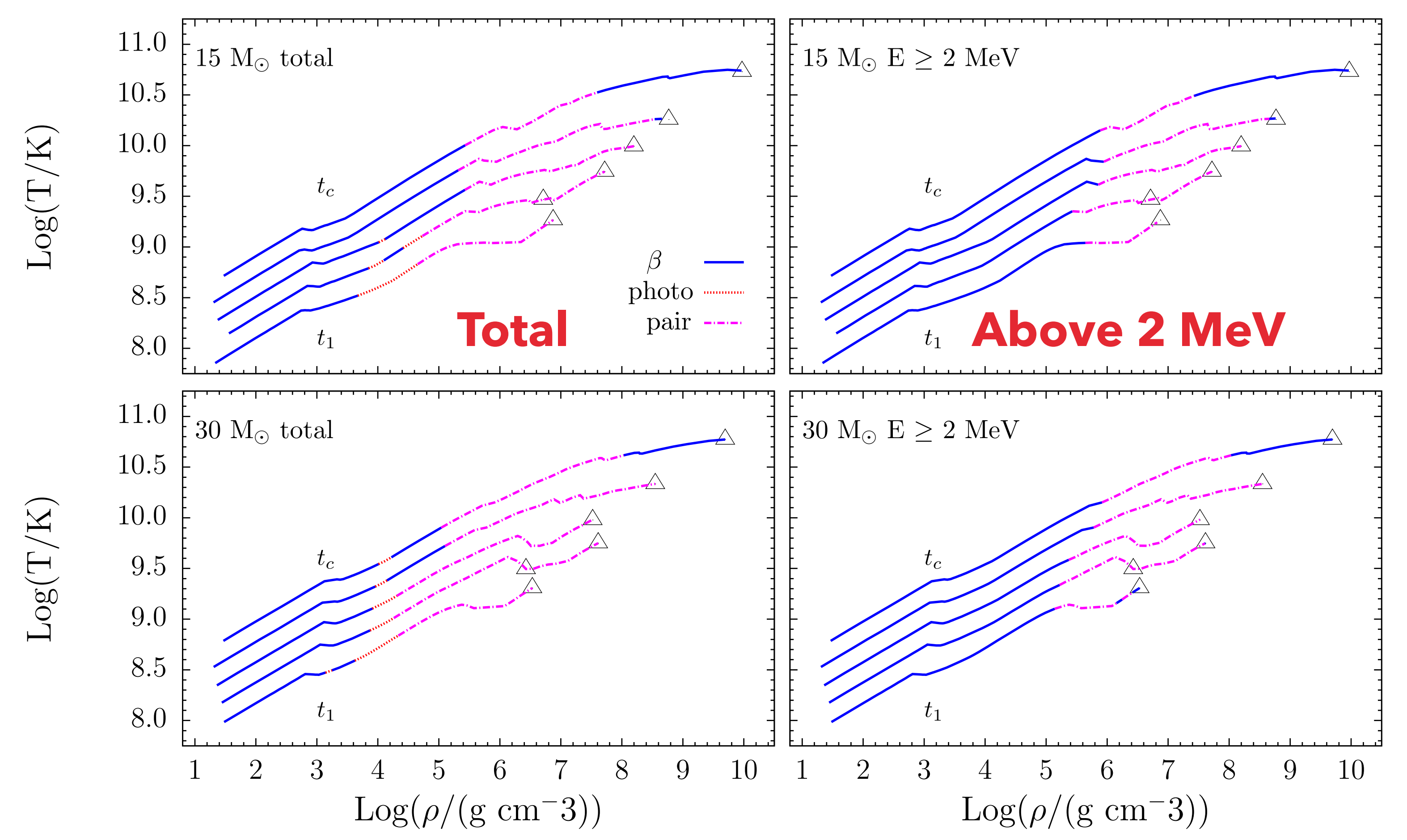
$$\Phi_{\nu,\overline{\nu}} = \sum_k \phi_k n_k = \sum_k X_k \phi_k \frac{\rho}{m_p A_k}$$

[1] Langanke and Martinez-Pinedo, ADNDT **79**, 1 (2001).
[2] Oda, Hino, Muto, Takahara, and Sato, ADNDT **56**, 231 (1994).
[3] Fuller, Fowler, and Newman ApJ **252**, 715 (1982).

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)

HOW MUCH DO BETA PROCESSES CONTRIBUTE OVER TIME?

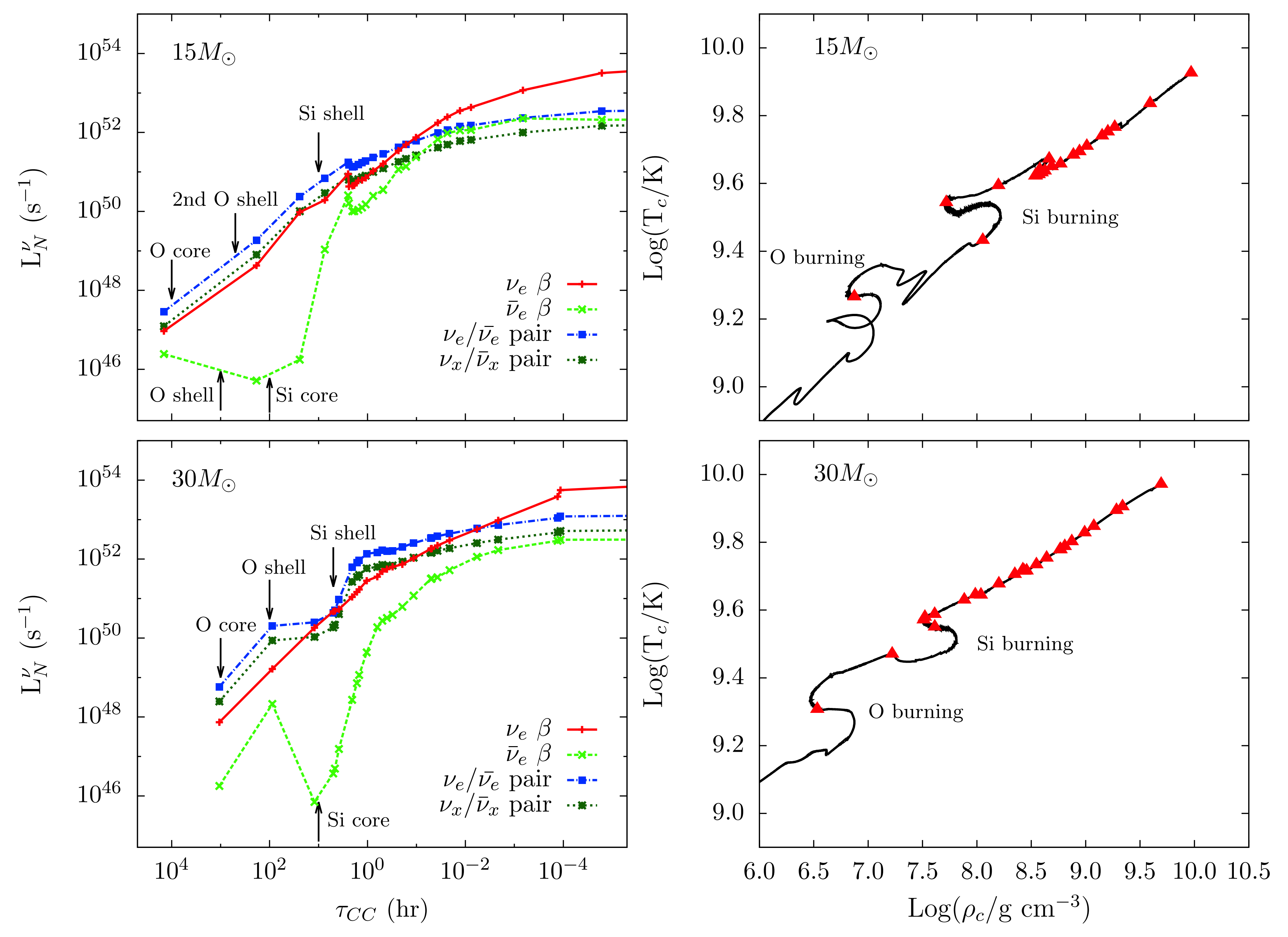
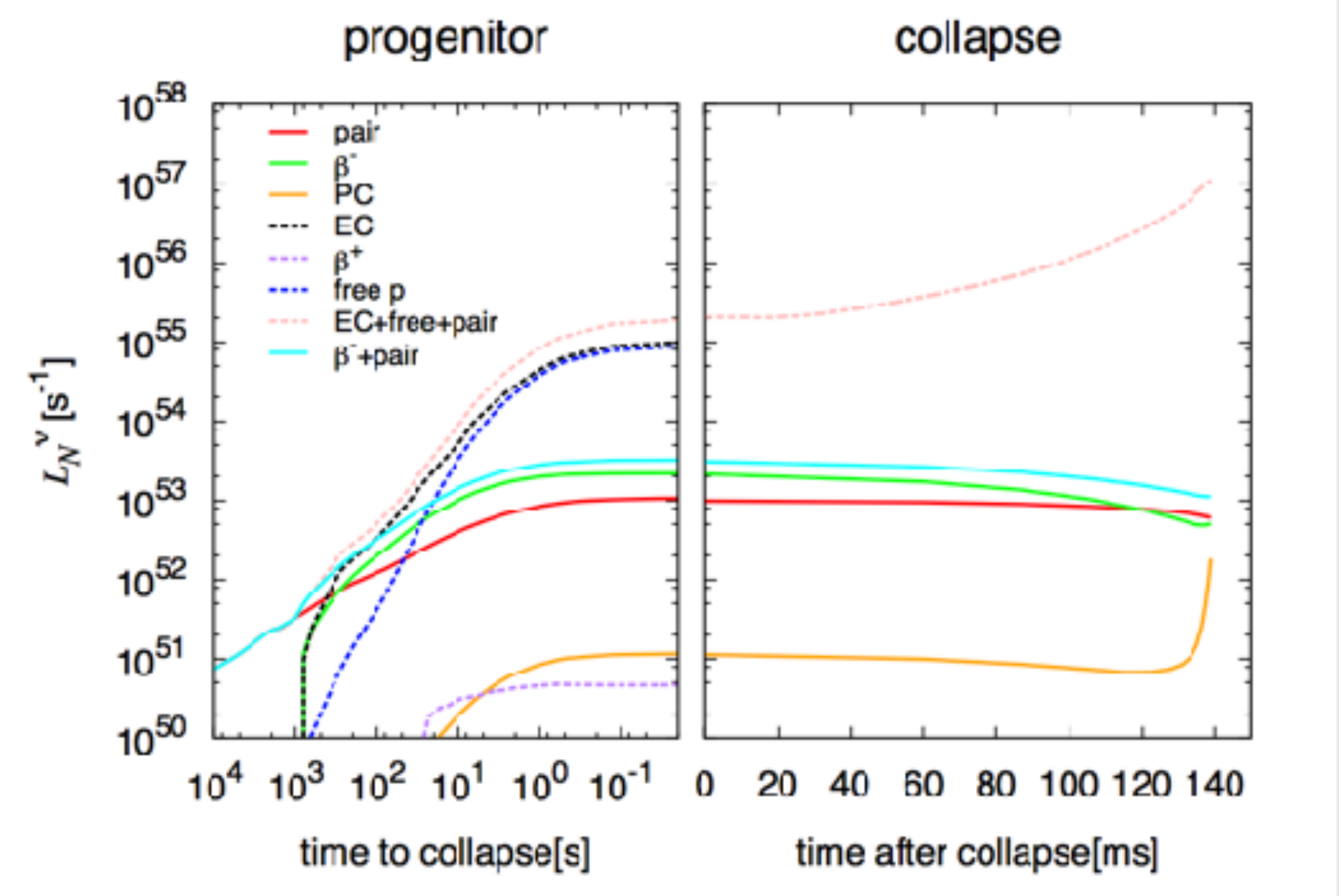


Figure from from KMP, C. Lunardini, R. J. Farmer, and F. X. Timmes *ApJ* **851**, 6 (2017)

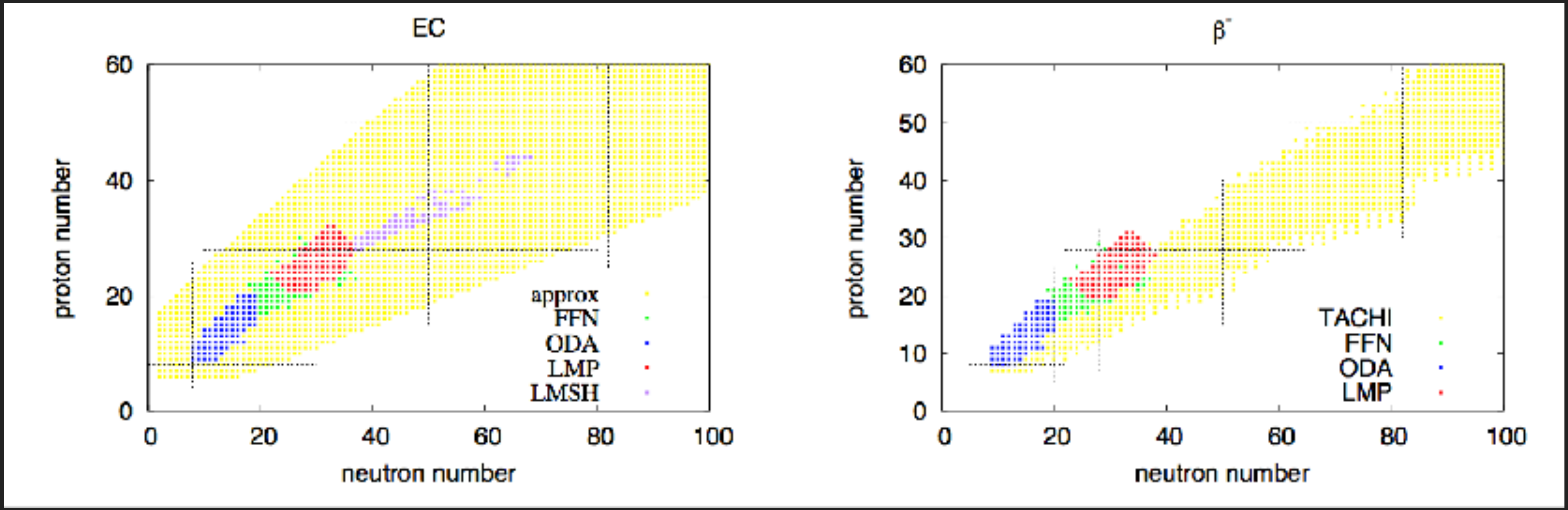
KATO ET AL. (2017)



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

- Included beta processes
- Found electron capture dominates ν_e emission in progenitor phase
- β⁻ decay dominates $\bar{\nu}_e$ emission at a few hundred seconds pre-collapse and after

KATO ET AL. (2017)



- Kato et al. find β processes dominate over pair annihilation for antineutrinos at late times
  - Use an expanded isotope list, with rates adapted from a terrestrial environment to a stellar one
  - More neutron-rich isotopes makes more antineutrinos

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

HOW MUCH DO BETA PROCESSES CONTRIBUTE?

- Dominate the luminosity at high energies ν_e
- Contribution increases over time, mostly electron captures
- Less contribution for $\bar{\nu}_e$
- Able to trace the highest contributing isotopes over time
- Large portion of β neutrinos come from just a handful of isotopes

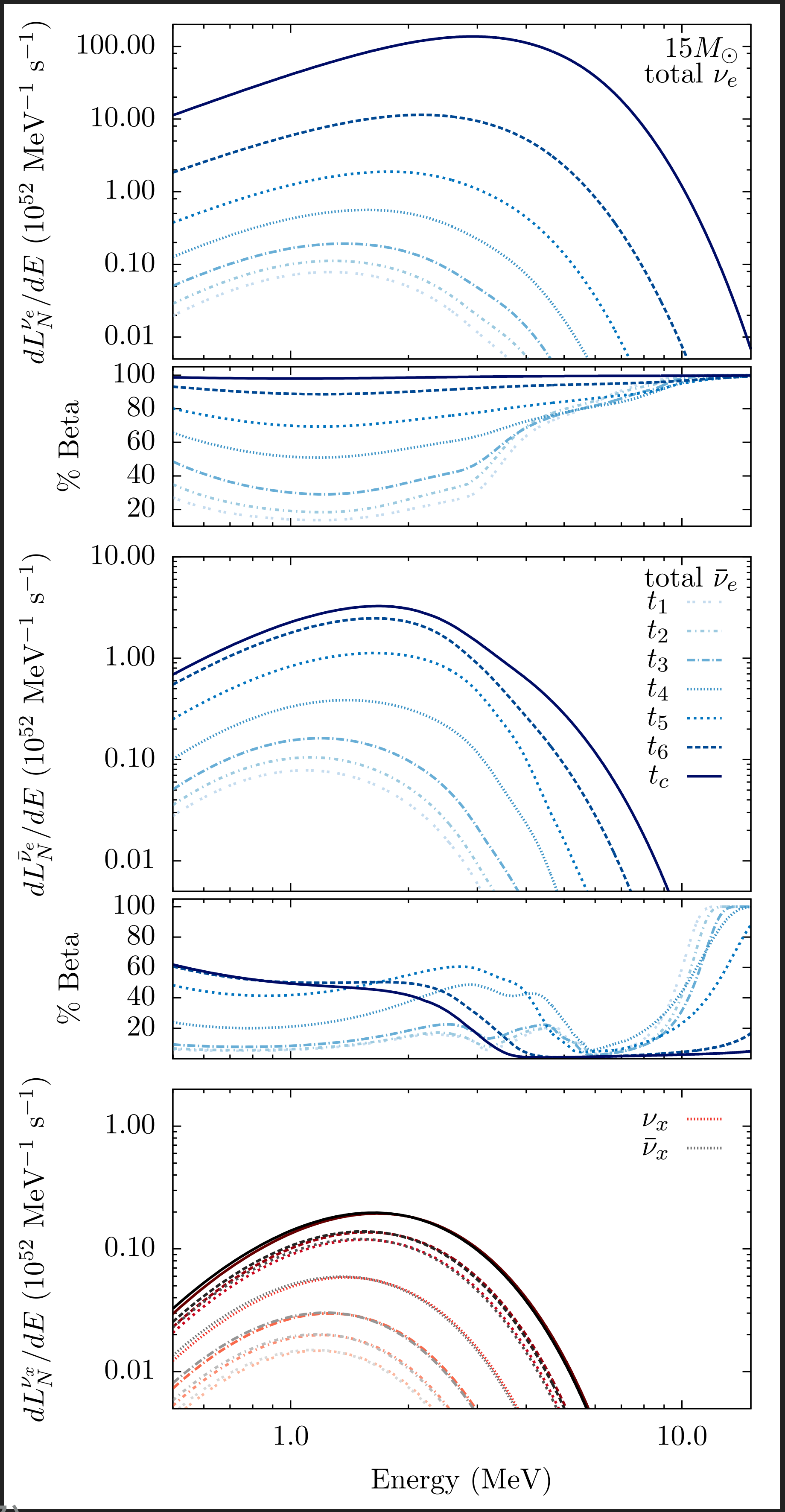


Figure from from KMP, C. Lunardini, R. J. Farmer, and F. X. Timmes *ApJ* **851**, 6 (2017)

DETECTION POSSIBILITIES: WINDOW OF OBSERVABILITY (15 $M_\odot$)

- 1 kpc - about 2 hrs pre-collapse for E ~ 0.5 - 20 MeV
- 200 pc - Could see as early as 10 hrs pre-collapse

NEUTRINOS

ANTINEUTRINOS

NH

IH

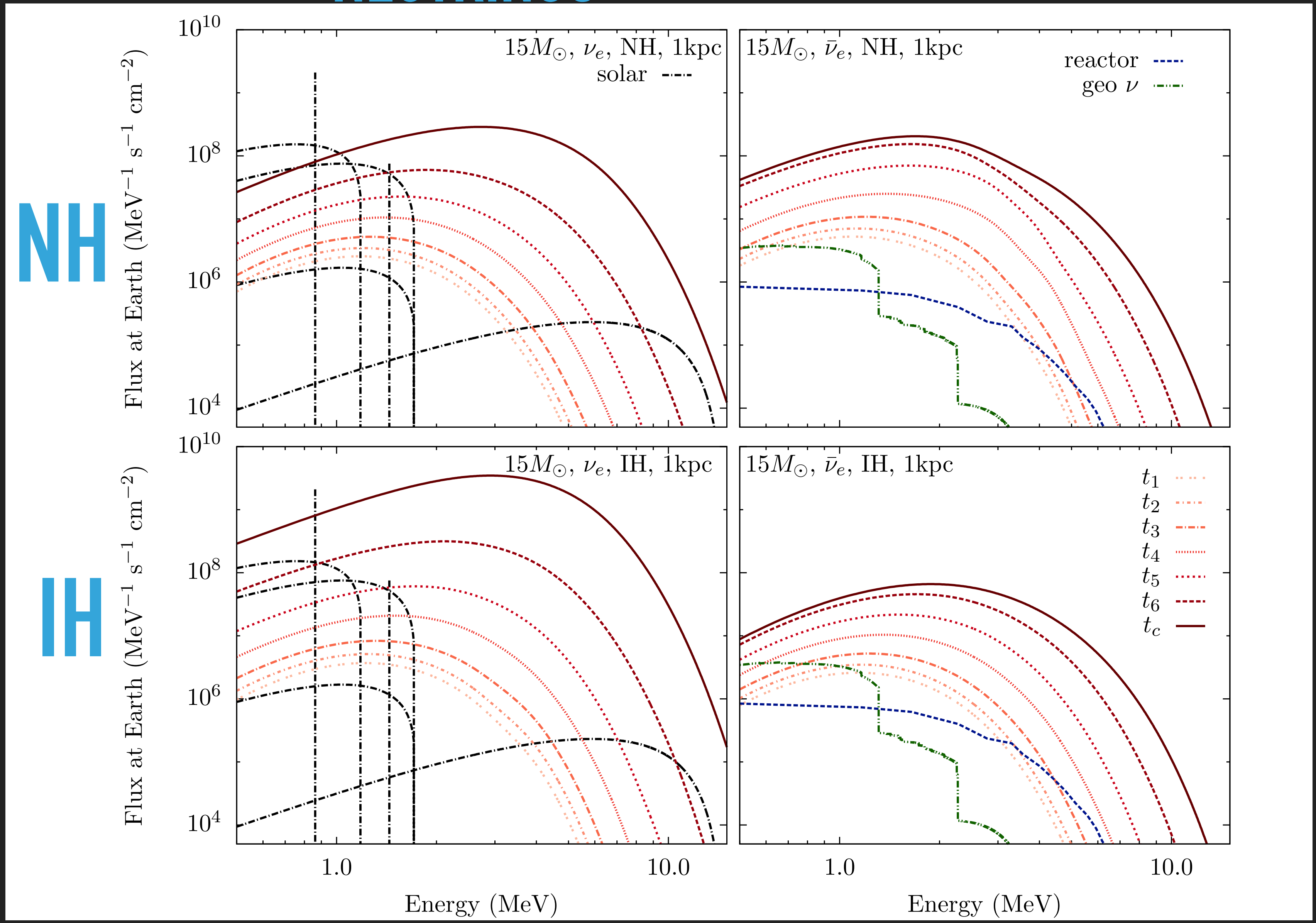
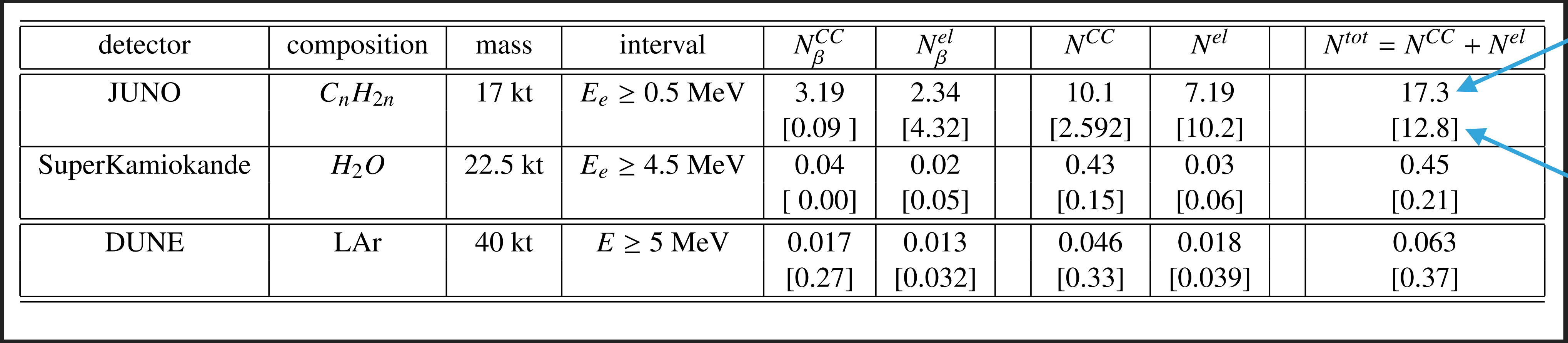


Figure from from KMP, C. Lunardini, R. J. Farmer, and F. X. Timmes *ApJ* **851**, 6 (2017)

DETECTION POSSIBILITIES: NUMBER OF EVENTS (D = 1 KPC)

$15M_\odot$

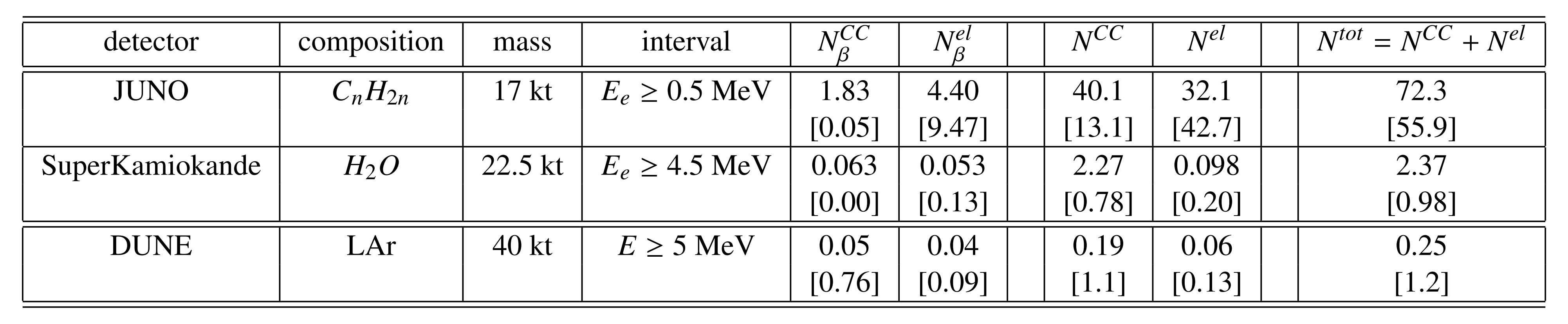


detector	composition	mass	interval	N_β^{CC}	N_β^{el}		N^{CC}	N^{el}		$N^{tot} = N^{CC} + N^{el}$
JUNO	C_nH_{2n}	17 kt	$E_e \geq 0.5$ MeV	3.19 [0.09]	2.34 [4.32]		10.1 [2.592]	7.19 [10.2]		17.3 [12.8]
SuperKamiokande	H_2O	22.5 kt	$E_e \geq 4.5$ MeV	0.04 [0.00]	0.02 [0.05]		0.43 [0.15]	0.03 [0.06]		0.45 [0.21]
DUNE	LAr	40 kt	$E \geq 5$ MeV	0.017 [0.27]	0.013 [0.032]		0.046 [0.33]	0.018 [0.039]		0.063 [0.37]

Normal

[Inverted]

$30M_\odot$



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]

- Large LS detector like JUNO is best chance due to low threshold
- DUNE has best chance for probing isotopic composition (for nearby star)

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

WHAT'S NEXT?

- Detectability
  - Include realistic detector response and backgrounds
- Nuclear physics
  - Effective-Q approximation could be improved
- More nuclear physics processes?
  - Neutral current de-excitations (see eg. Misch and Fuller arXiv: 1607.01448; Misch, Sun and Fuller *ApJ* **852** 43 (2018))
- Failed SN?

THANK YOU TO…

- My collaborators: Cecilia Lunardini, Rob Farmer, and Frank Timmes
- The CIPANP 2018 organizers

- Thanks for listening!