PRESUPERNOVA NEUTRINOS

Cecilia Lunardini
Arizona State University

work in progress with Kelly Patton (ASU → INT), Robert Farmer and Francis Timmes (ASU)

Contents

- Introduction and motivations

- neutrinos from *beta processes* and numerical stellar evolution
  - state-of-the-art presupernova neutrino flavor spectra
  - flux at Earth, detectability

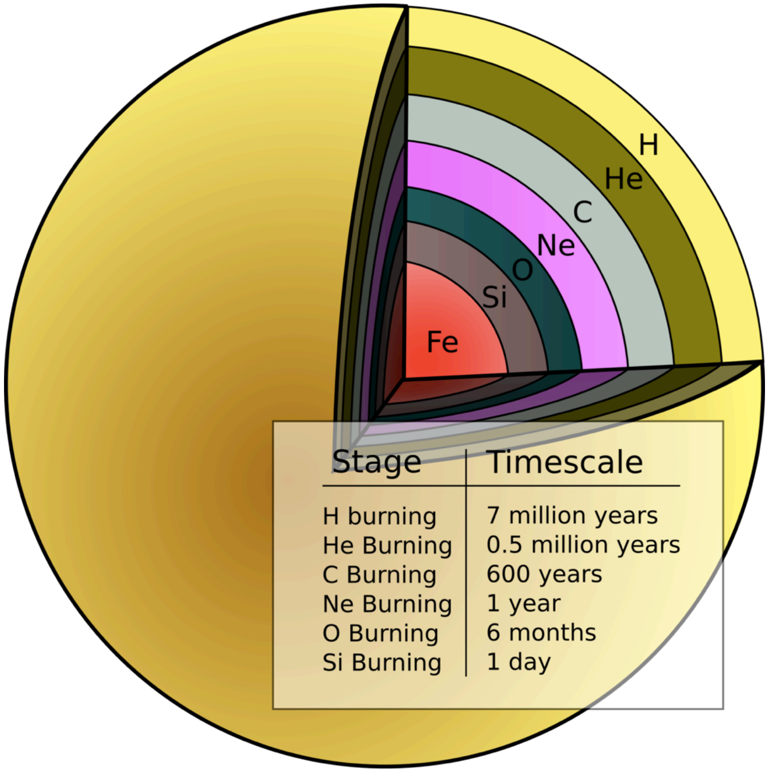
- summary, discussion

Introduction and motivation

The last months of stellar evolution

- Last stages of fusion chain
  - rapid evolution of isotopic composition
  - increase of core density, temperature
  - *increase of neutrino emission*
    - *detectable!*

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

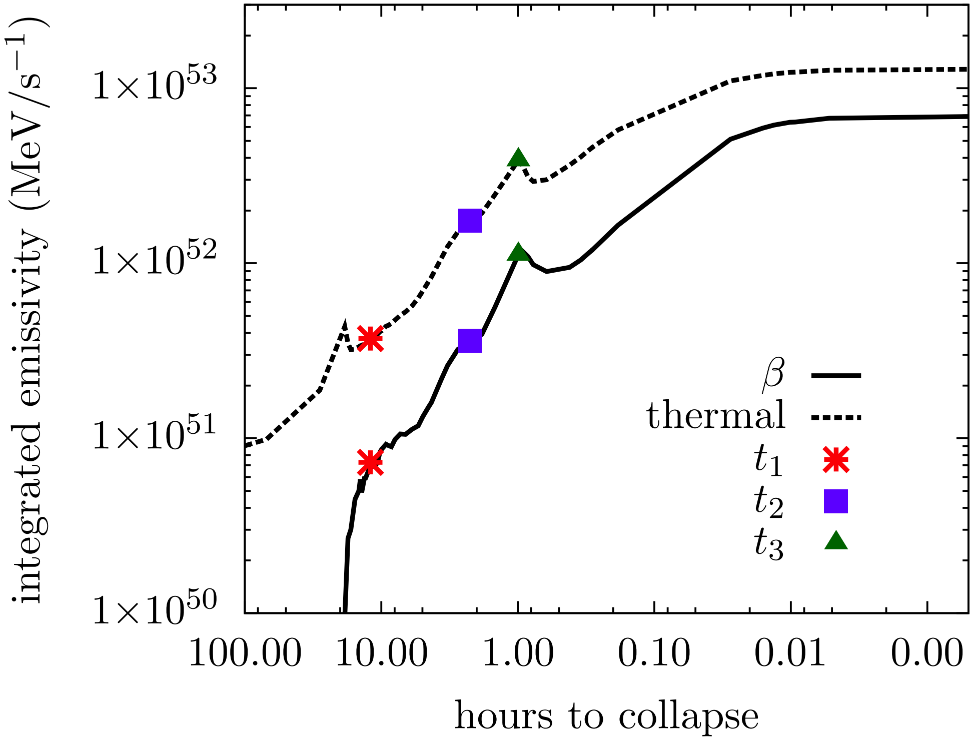


Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

A. C. Phillips, *The Physics of Stars, 2nd Edition* (Wiley, 1999)

A new neutrino signal!

- early alert of imminent collapse



K .M. Patton. C. Lunardini, R. Farmer and F. X. Timmes, in preparation

Direct probe of advanced stellar evolution

- *O(0.1 – 1) MeV thermal neutrinos*
  - test evolution of stellar temperature and density

- *O(0.1 – 1) MeV neutrinos from beta processes*
  - test evolution of isotopic composition, nuclear transitions in extreme conditions

A presupernova renaissance

- Thermal neutrino emission
  - seminal studies

A. Odrzywolek, M. Misiaszek, and M. Kutschera, Astropart. Phys. 21, 303 (2004)
A. Odrzywolek, M. Misiaszek, and M. Kutschera, Acta Physica Polonica B 35, 1981 (2004)
M. Kutschera, A. Odrzywolek, and M. Misiaszek, Acta Physica Polonica B 40, 3063 (2009)
A. Odrzywolek and A. Heger, Acta Physica Polonica B 41, 1611 (2010)

  - detectability

K. Asakura et al. (KamLAND), Astrophys. J. 818, 91 (2016)
T. Yoshida, K. Takahashi, H. Umeda, and K. Ishidoshiro, Phys. Rev. D93, 123012 (2016)

  - detailed neutrino spectra + numerical stellar evolution

C. Kato et al., Astrophys. J. (2015), arXiv:1506.02358
T. Yoshida, K. Takahashi, H. Umeda, and K. Ishidoshiro, Phys. Rev. D93, 123012 (2016)

New: focus on beta processes

- neutrinos from *beta processes (βp)* + numerical stellar evolution
  - *βp* neutrino spectra
  - MESA stellar evolution code: extended nuclear network!

K. M. Patton and C. Lunardini, arXiv:1511.02820
K .M. Patton. C. Lunardini, R. Farmer and F. X. Timmes, in preparation

For earlier, approximate predictions, see :
A. Odrzywolek, Phys. Rev. C 80, 045801 (2009)
A. Odrzywolek and A. Heger, Acta Physica Polonica B 41, 1611 (2010)

neutrino from *beta processes* and numerical stellar evolution

Modules for **E**xperiments in **S**tellar **A**strophysics
version r7624
Paxton, Bildsten, Dotter, Herwig, Lesaffre, and Timmes, ApJ. Suppl. 192, 3 (2011)

- Output for each radial zone (r) and time step (t):
  - temperature, mass density, electron fraction: T(r,t), ρ(r,t), Y(r,t)
  - isotopic abundances : $X_k(r,t)$
  - neutrino emissivity for each process: $Q_i(r,t)$
- For βp : *nuclear network,* 204 isotopes
  - rates from tables

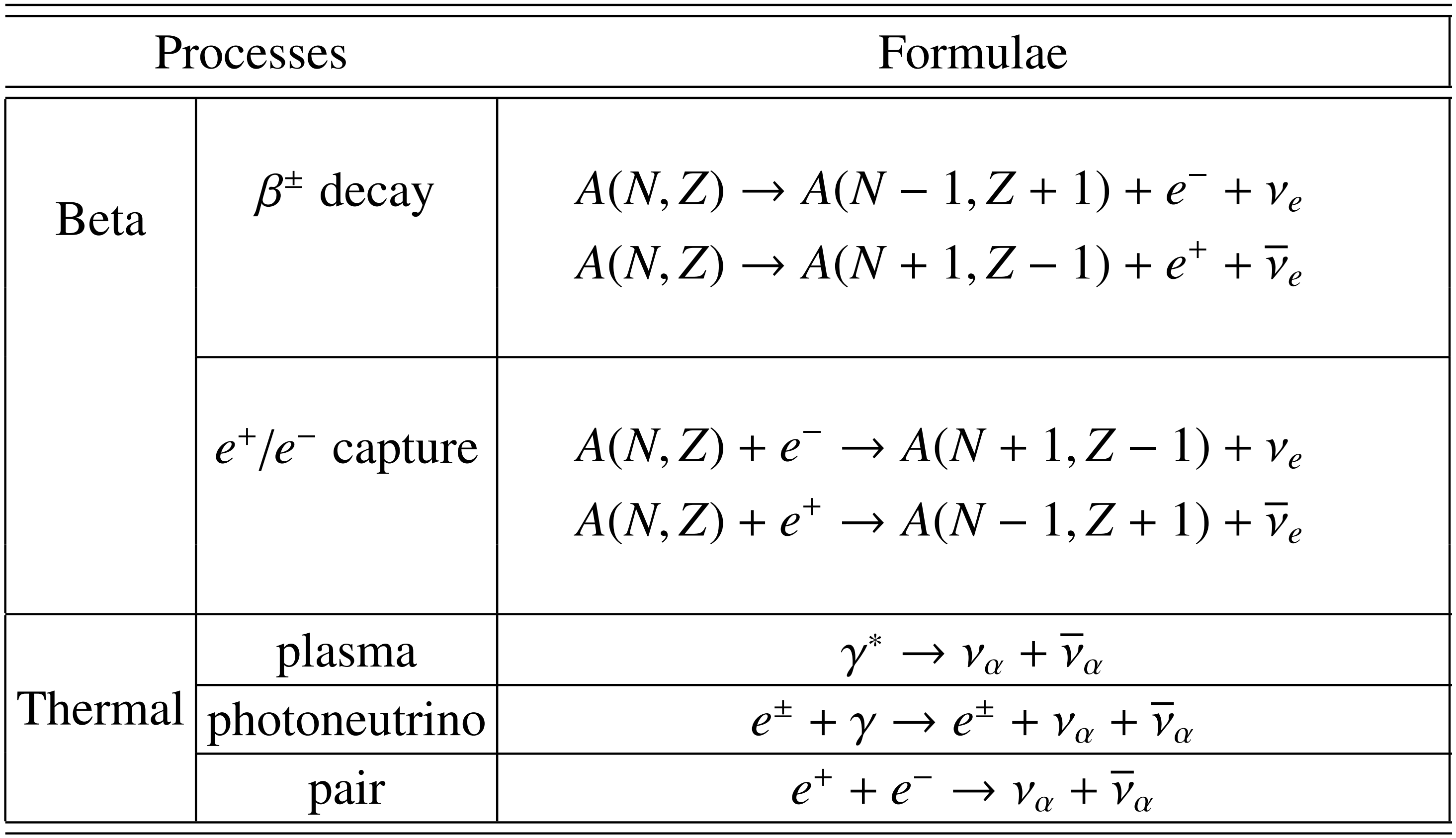
G. M. Fuller, W. A. Fowler and M. J. Newman, ApJ 293 1 (1985) K. Langanke and G. Martinez-Pinedo, Nucl. Phys. A, 673 481 (2000)
T. Oda et al., Atomic Data and Nuclear Data Tables 56 231 (1994)

- *Not included: neutrino spectra → need dedicated work*

K. M. Patton and C. Lunardini, arXiv:1511.02820

Calculating neutrino spectra…

K. M. Patton and C. Lunardini, arXiv:1511.02820



Processes		Formulae
Beta	$\beta^{\pm}$ decay	$A(N,Z) \rightarrow A(N-1,Z+1) + e^{-} + \nu_e$ $A(N,Z) \rightarrow A(N+1,Z-1) + e^{+} + \bar{\nu}_e$
	e^{+}/e^{-} capture	$A(N,Z) + e^{-} \rightarrow A(N+1,Z-1) + \nu_e$ $A(N,Z) + e^{+} \rightarrow A(N-1,Z+1) + \bar{\nu}_e$
Thermal	plasma	$\gamma^{*} \rightarrow \nu_\alpha + \bar{\nu}_\alpha$
	photoneutrino	$e^{\pm} + \gamma \rightarrow e^{\pm} + \nu_\alpha + \bar{\nu}_\alpha$
	pair	$e^{+} + e^{-} \rightarrow \nu_\alpha + \bar{\nu}_\alpha$

βp spectra: effective Q

- Depend on phase space factors, normalization, and Q-value:

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

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

$$Q = M_p - M_d + E_p - E_d$$

- *Single, effective Q-value and transition strength*
  - accounting for all transitions involving different excited states
  - fit to reproduce tabulated number- and energy-losses

Langanke, Martinez-Pinedo and Sampaio, PRC 64 055801 (2001)

- Individual spectra are normalized to tabulated rates

$$\lambda^{i} = \int_{0}^{\infty} \phi_{i} dE_{\nu} \quad i = EC, PC, \beta^{\pm}$$

- Total spectrum: sum over all nuclear species

$$\Phi = \sum_{k} X_{k} \phi_{k} \frac{\rho}{m_{p} A_{k}}$$

Thermal neutrino spectra

$$\begin{aligned} R = &\int (\mathit{incoming\ momenta}) * (\mathit{incoming\ distributions}) \\ &\times \int (\mathit{outgoing\ momenta}) * (\mathit{outgoing\ distributions}) \\ &\times |M|^2 \delta^4 (\mathit{energy\ conservation}) \end{aligned}$$

- Lengthy calculations, follow literature
  - involve, e.g., 7-dimensional Monte Carlo integral
- *first time application to MESA*

N. Itoh and Y. Kohyama, Astrophys. J. 275, 858 (1983).

N. Itoh, T. Adachi, M. Nakagawa, Y. Kohyama, and H. Munakata, Astrophys. J. 339, 354 (1989).

N. Itoh, H. Mutoh, A. Hikita, and Y. Kohyama, Astrophysical Journal 395, 622 (1992).

N. Itoh, H. Hayashi, A. Nishikawa, and Y. Kohyama, Astrophysical Journal Supplemental Series 102, 411 (1996).

N. Itoh, A. Nishikawa, and Y. Kohyama, Astrophysical Journal 470, 1015 (1996).

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993).

S. I. Dutta, S. Ratkovic, and M. Prakash, Phys. Rev. D 69, 023005 (2004).

S. Ratkovic´, S. I. Dutta, and M. Prakash, Phys. Rev. D **67** 123002 (2003)

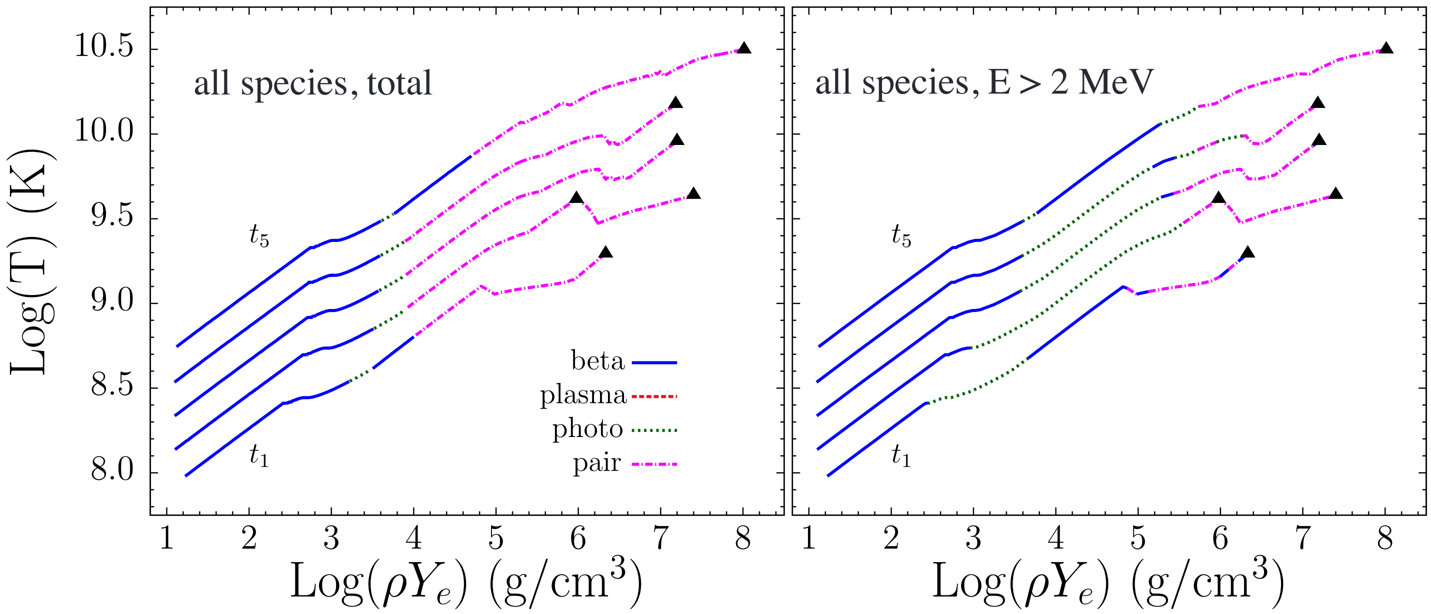
S. Hannestad and J. Madsen, Phys. Rev. D **52** 1764 (1995)

state-of-the-art presupernova neutrino flavor spectra

All results for 25 M_{sun} progenitor

Emissivities at sample r,t

- Temperature-density diagram: dominant processes
  - pair dominates near core
  - some regions of photo-neutrinos and *βp* dominance



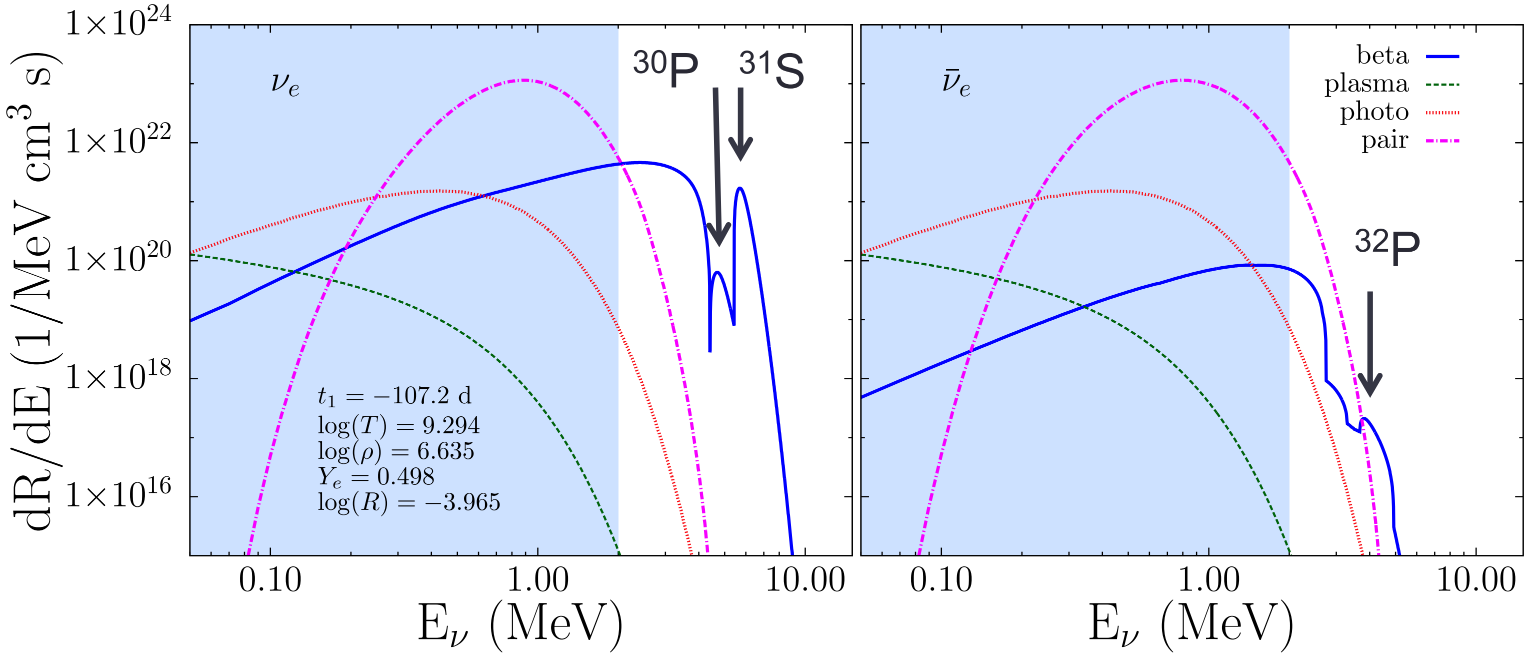
t
t_1 = −107.2 days
t_2 = −1.18 day
t_2 = −1.18 day
t_3 = −12.01 hrs
t_4 = −5.95 hrs
t_5 = −0.99 hr

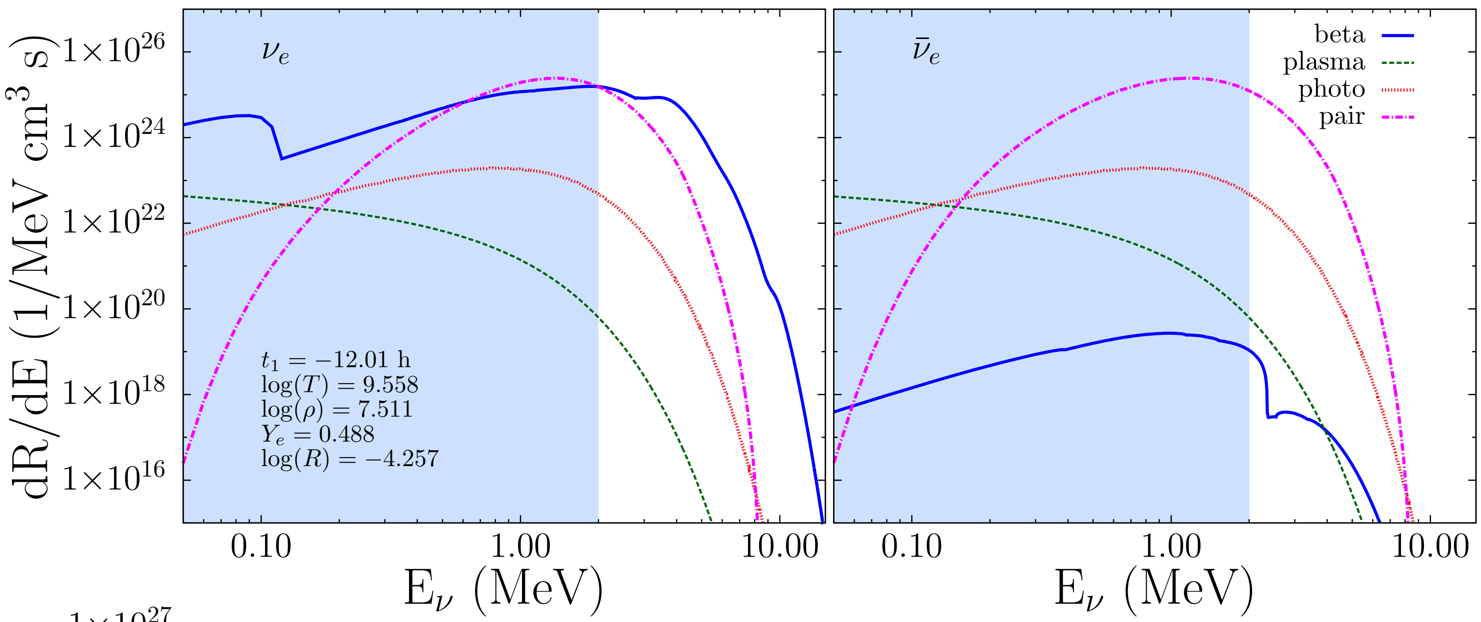
(curves shifted upwards for visibility)

Spectra at sample r,t

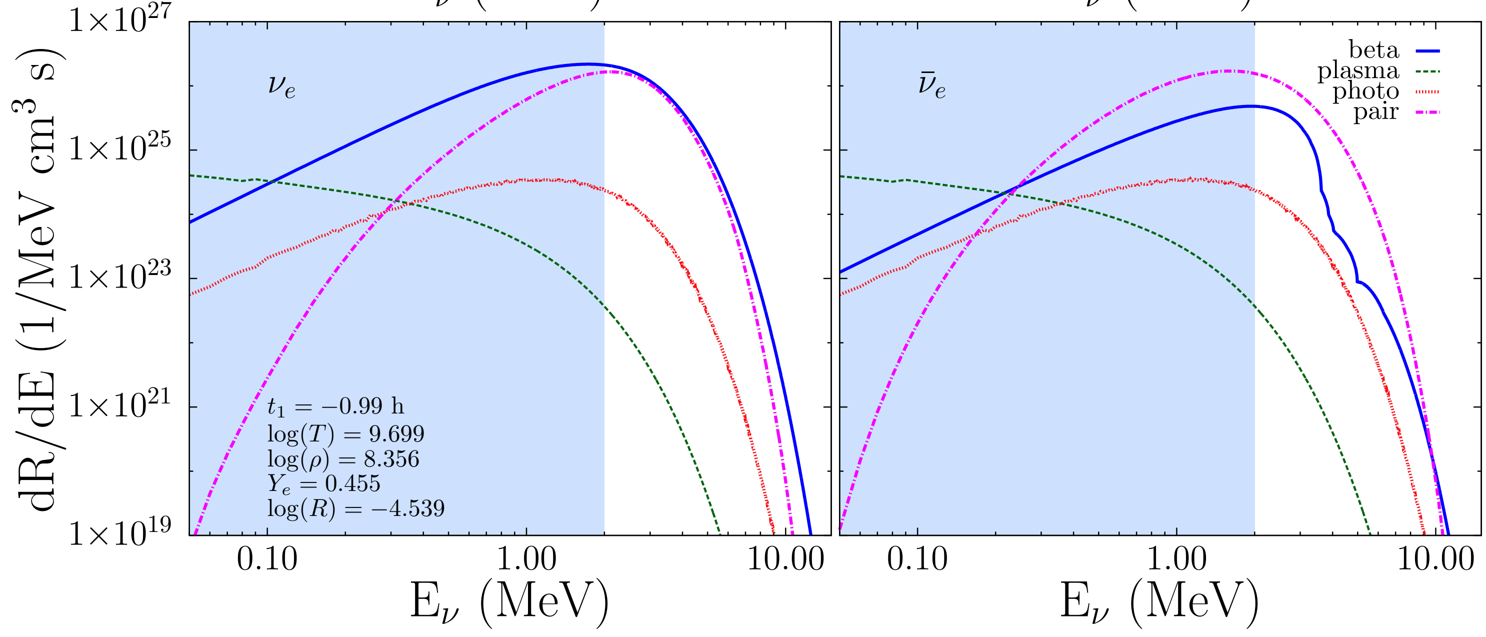
- *βp important in detectable window!*
- distinct spectrum peaks evolve into smooth spectrum as T increases

~ center of star, t=-107 d





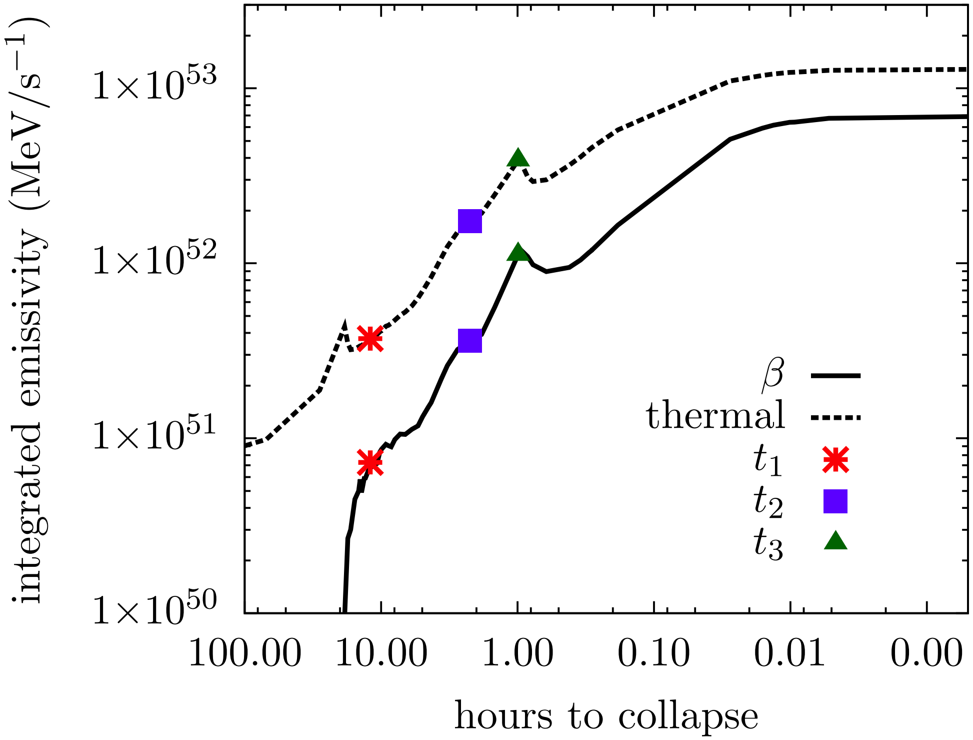
t=-12 hrs



t=-1 hrs

Total neutrino emissivity (r-integrated)

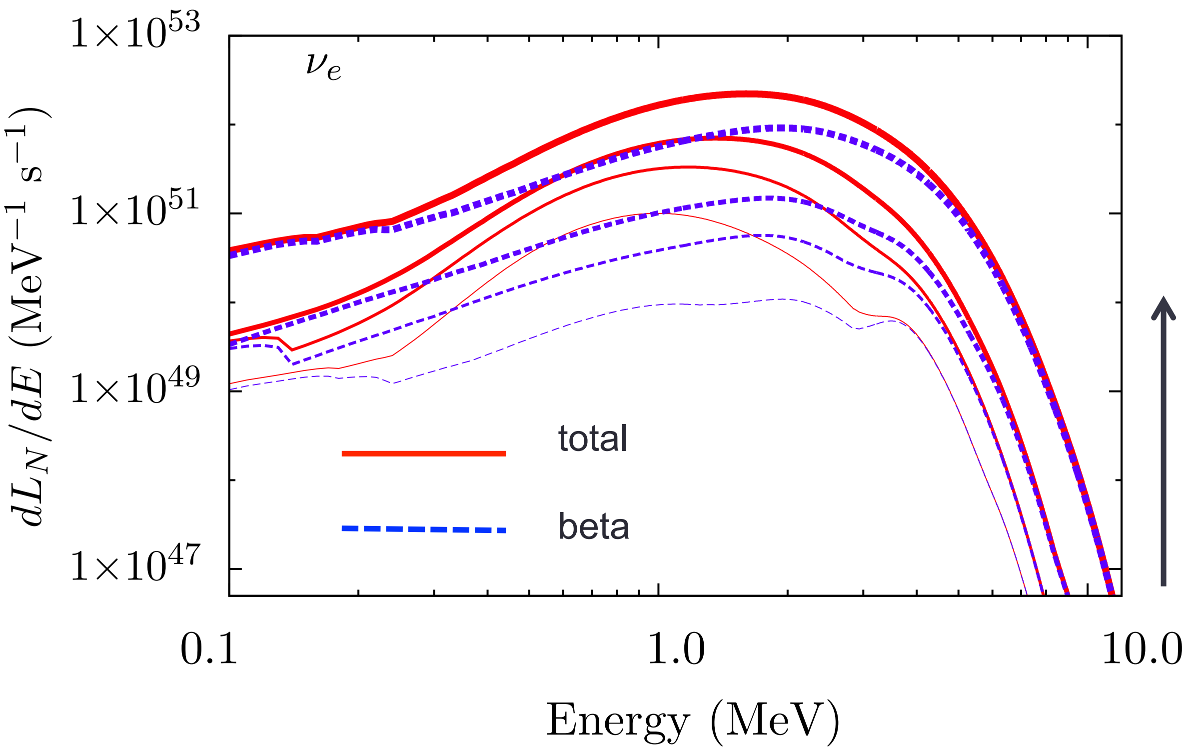
- significant *βp* component at late times



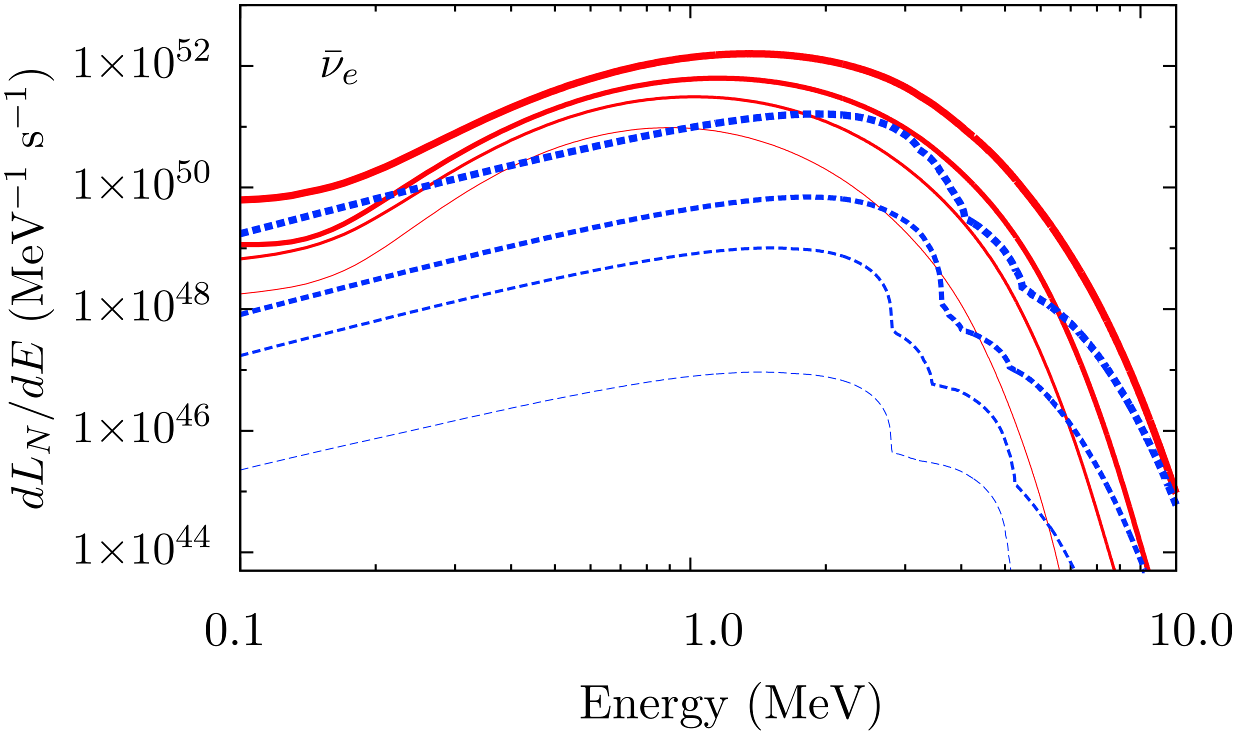
t4	0 hrs
t3	-1 hrs
t2	-2 hr
t1	-12 hrs

Total neutrino spectrum (r-integrated)

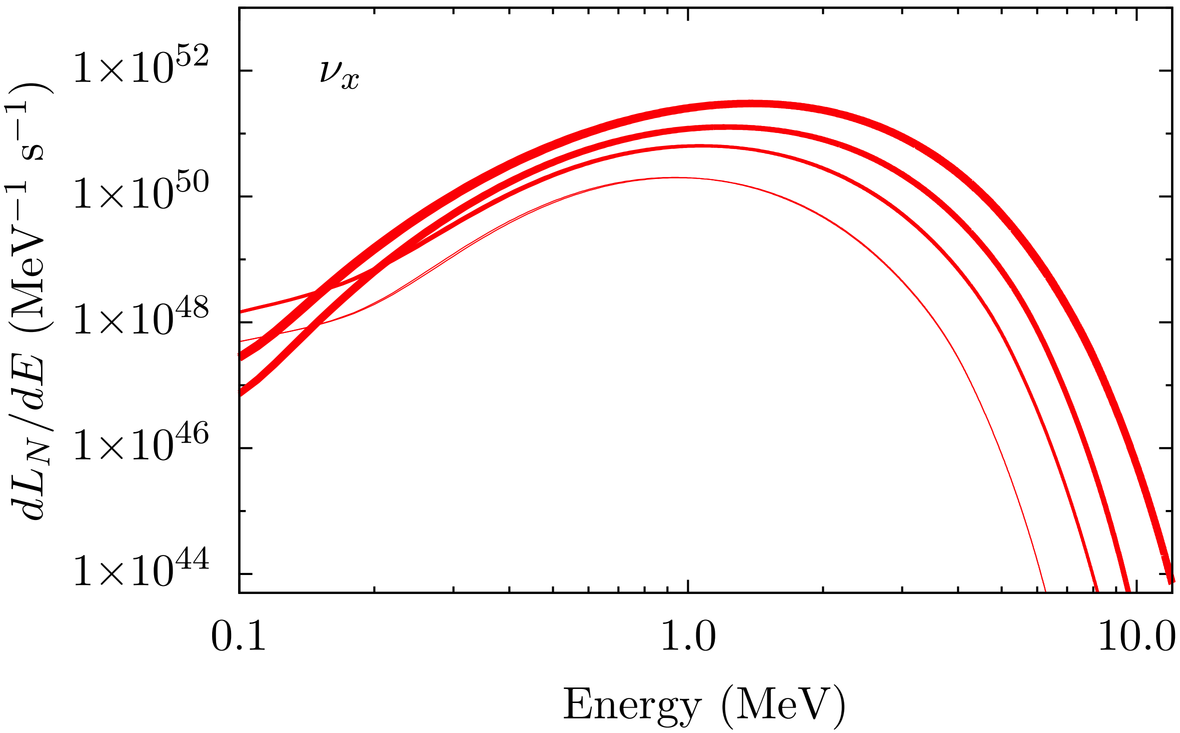
- ν_e : *βp dominate* at E > 4-5 MeV



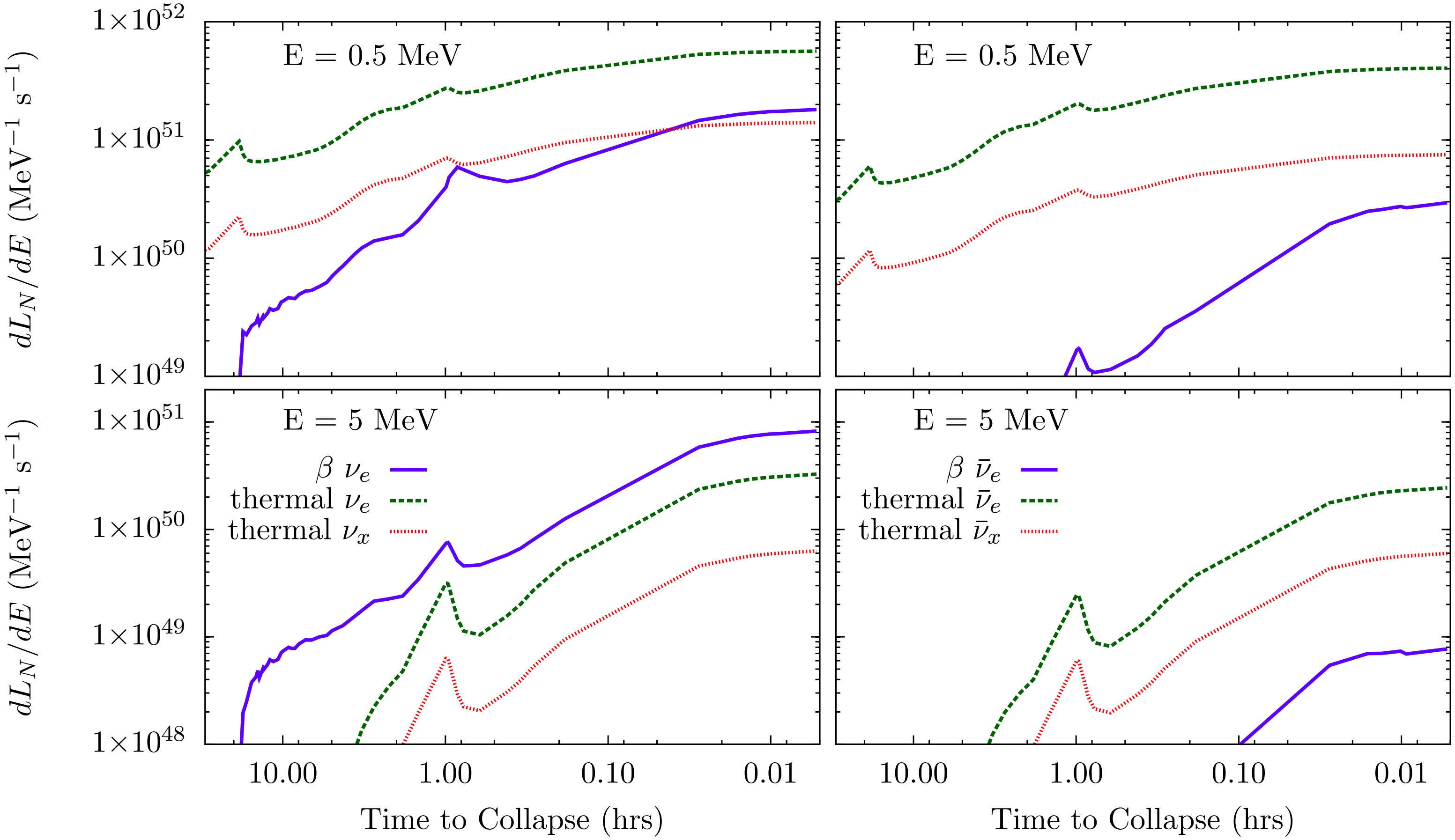
t4	0 hrs
t3	-1 hr
t2	-2 hrs
t1	-12 hrs


$\bar{\nu}_e$
dL_N/dE (MeV^{-1} s^{-1})
1×10^{52}
1×10^{50}
1×10^{48}
1×10^{46}
1×10^{44}
0.1
1.0
10.0
Energy (MeV)

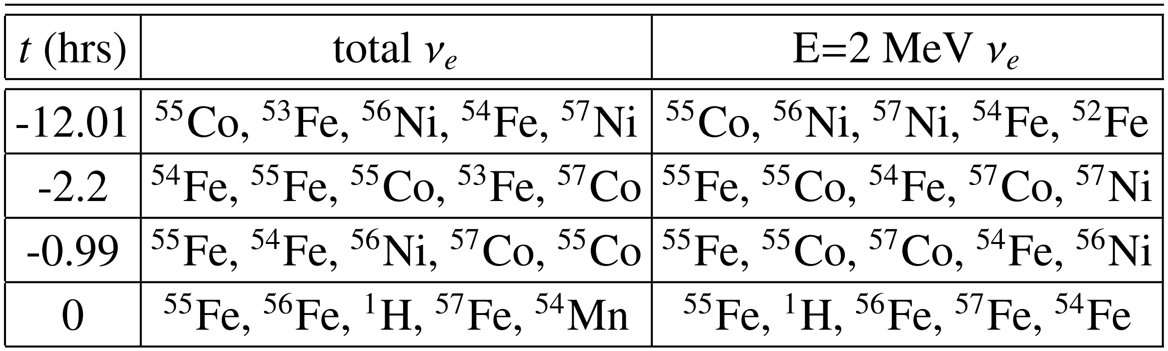
x=μ, τ


ν_x
1×10^{52}
1×10^{50}
1×10^{48}
1×10^{46}
1×10^{44}
dL_N/dE (MeV^{-1} s^{-1})
0.1
1.0
10.0
Energy (MeV)

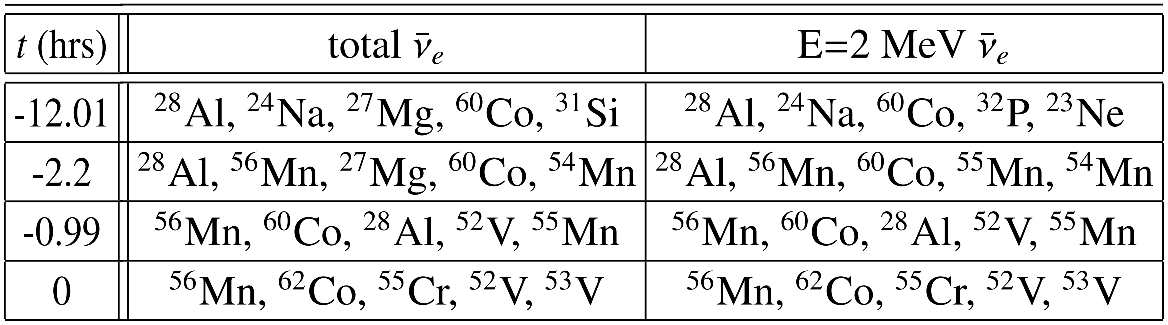
Time evolution



- Main contributing isotopes :



t (hrs)	total ν_e	E=2 MeV ν_e
-12.01	^{55}Co, ^{53}Fe, ^{56}Ni, ^{54}Fe, ^{57}Ni	^{55}Co, ^{56}Ni, ^{57}Ni, ^{54}Fe, ^{52}Fe
-2.2	^{54}Fe, ^{55}Fe, ^{55}Co, ^{53}Fe, ^{57}Co	^{55}Fe, ^{55}Co, ^{54}Fe, ^{57}Co, ^{57}Ni
-0.99	^{55}Fe, ^{54}Fe, ^{56}Ni, ^{57}Co, ^{55}Co	^{55}Fe, ^{55}Co, ^{57}Co, ^{54}Fe, ^{56}Ni
0	^{55}Fe, ^{56}Fe, ^{1}H, ^{57}Fe, ^{54}Mn	^{55}Fe, ^{1}H, ^{56}Fe, ^{57}Fe, ^{54}Fe



t (hrs)	total $\bar{\nu}_e$	E=2 MeV $\bar{\nu}_e$
-12.01	^{28}Al, ^{24}Na, ^{27}Mg, ^{60}Co, ^{31}Si	^{28}Al, ^{24}Na, ^{60}Co, ^{32}P, ^{23}Ne
-2.2	^{28}Al, ^{56}Mn, ^{27}Mg, ^{60}Co, ^{54}Mn	^{28}Al, ^{56}Mn, ^{60}Co, ^{55}Mn, ^{54}Mn
-0.99	^{56}Mn, ^{60}Co, ^{28}Al, ^{52}V, ^{55}Mn	^{56}Mn, ^{60}Co, ^{28}Al, ^{52}V, ^{55}Mn
0	^{56}Mn, ^{62}Co, ^{55}Cr, ^{52}V, ^{53}V	^{56}Mn, ^{62}Co, ^{55}Cr, ^{52}V, ^{53}V

flux at Earth, detectability

Oscillations

- Matter-driven flavor conversion inside the star
  - 2 adiabatic MSW resonances
  - depend on mass Hierarchy (Normal or Inverted)

$$F_e = pF_e^0+(1-p)F_x^0\,, \qquad 2F_x = (1-p)F_e^0+(1+p)F_x^0$$

$$p = \begin{cases} |U_{e3}|^2 \simeq 0.02 & \text{NH} \\ |U_{e2}|^2 \simeq 0.32 & \text{IH} \end{cases} \qquad \bar{p} = \begin{cases} |U_{e1}|^2 \simeq 0.68 & \text{NH} \\ |U_{e3}|^2 \simeq 0.02 & \text{IH} \end{cases}$$

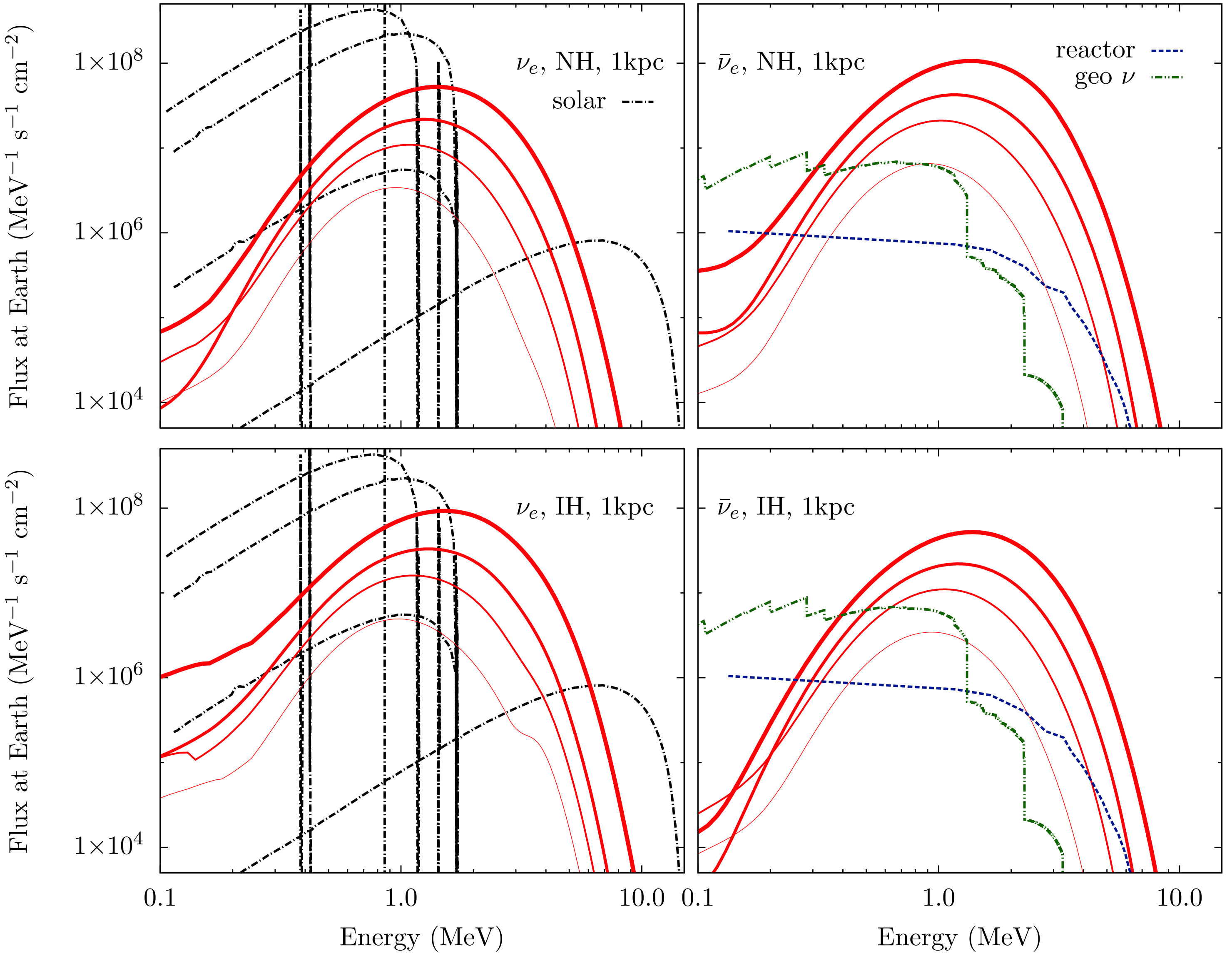
- negligible:
  - neutrino-neutrino refraction effects (low neutrino density)
  - oscillations inside the Earth

Flux at Earth: detectability window

- *Optimistic* window: S/B > 1
  - S=signal, time-dependent, scales like $1/D^2$

- B = competing neutrino fluxes (detector-independent)
  - solar neutrinos (for non-directional detectors)
  - reactor antineutrinos
  - geo-antineutrinos

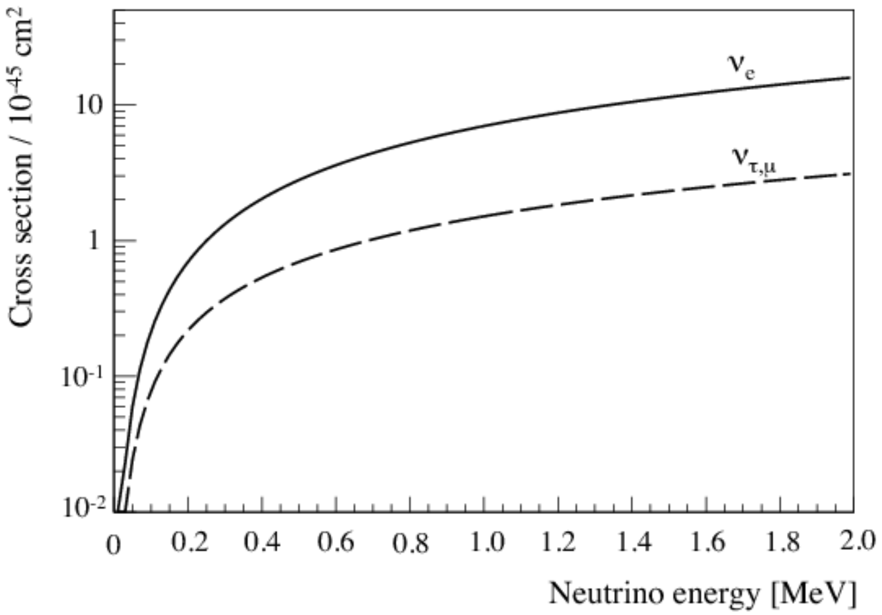
D=1 kpc



t4	0 hrs
t3	-1 hr
t2	-2 hrs
t1	-12 hrs

Detectability: energy threshold is key

- inverse beta decay: E > 1.8 MeV , anti-nue only
- ν + e , elastic scattering: threshold-less, directional, *sensitive to* ν_e



Number of events (preliminary)

2 hours pre-collapse, D = 1 kpc (for Betelgeuse : multiply by 25)

detector	composition	mass	interval	N^{el}_{β}	N^{el}	N^{CC}_{β}	N^{CC}	$N^{tot} = N^{el} + N^{CC}$
JUNO	C_nH_{2n}	17 kt	$E_e \geq 0.5$ MeV	9.3 [4.1]	39.0 [28.8]	0 [0]	12.3 [36.9]	51.3 [65.8]
SuperKamiokande	H_2O	22.5 kt	$E_e \geq 4.5$ MeV	0.11 [0.04]	0.17 [0.08]	0 [0]	0.65 [1.9]	0.82 [2.0]
DUNE	LAr	40 kt	$E \geq 5$ MeV	0.07 0.03	0.1 0.05	0.64 [0.04]	0.91 [0.17]	1.0 [0.22]

el = elastic scattering on electrons
CC = Charged Current on nuclei
β = contribution of neutrinos from beta processes

  ..   = results for IH
[..] = results for NH

- spectacular signal for Betelgeuse (D=200 pc), in ~6 hrs:
  - ~ 50 events at DUNE (> 25 from *βp)*
  - ~ 800 events at HyperK (E>4.5 MeV) (~ 100 from *βp)*
  - *> 2000 events at JUNO (> 400 from βp)*

Summary, discussion

A new signal!

- potentially detectable at JUNO, for D < 1-3 kpc
  - *interesting chance of detection*

- state-of-the-art neutrino flux prediction from MESA
  - time dependent, energy spectra, include thermal and beta processes

- ν_e from beta processes *are important!*
  - direct probe of advanced fusion chain, isotopic evolution
  - ~ few 10% of signal for sub-MeV thresholds (JUNO)
  - > 50% of signal for multi-MeV thresholds (DUNE, SuperK)

Towards more realistic predictions…

- beyond single Q, single strength approximation
  - detailed structure of excited states important in certain cases

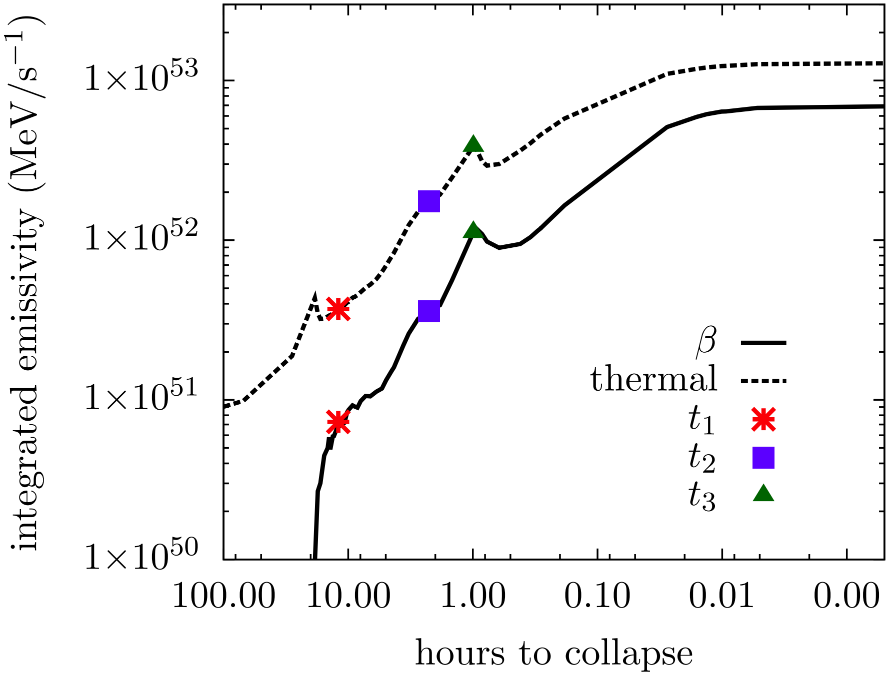
W. Misch and G. Fuller, arxiv:1607.01448

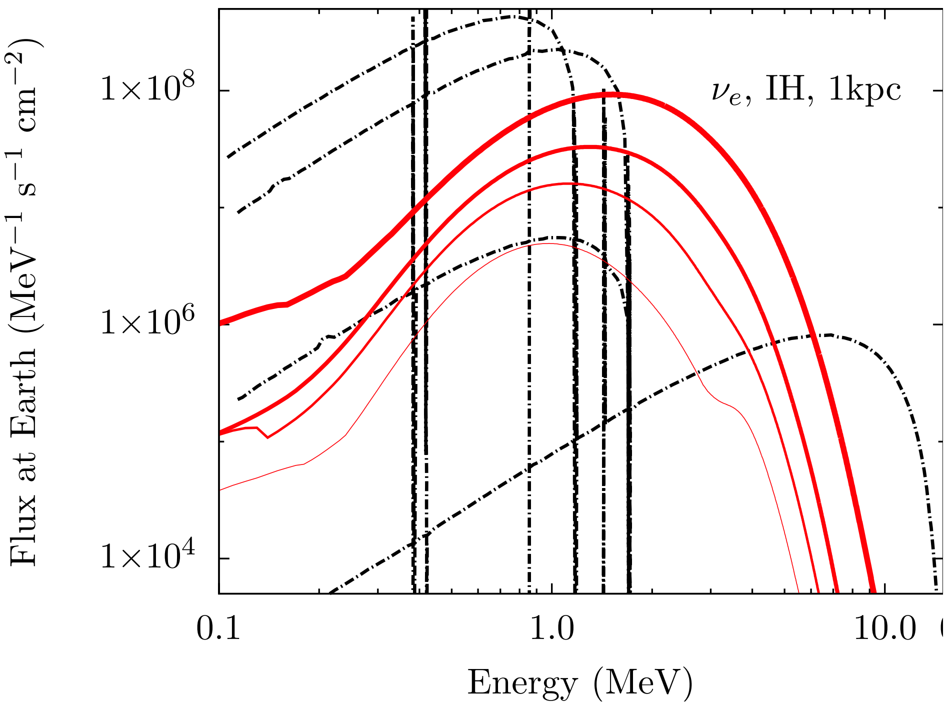
- include other neutrino production channels
  - electron nucleus bremsstrahlung, pairs from nuclear de-excitation

G. Guo and Y. Qian, Phys.Rev. D94 (2016)
W. Misch and G. Fuller, arxiv:1607.01448

- study progenitor dependence

- realistic detectability studies
  - detector-specific background, time-domain analysis, early alert methods


integrated emissivity (MeV/s^{-1})
1×10^{53}
1×10^{52}
1×10^{51}
1×10^{50}
100.00
10.00
1.00
0.10
0.01
0.00
hours to collapse
β
thermal
t_1
t_2
t_3


Flux at Earth (MeV^{-1} s^{-1} cm^{-2})
1×10^8
1×10^6
1×10^4
ν_e, IH, 1kpc
0.1
1.0
10.0
Energy (MeV)

thank you!