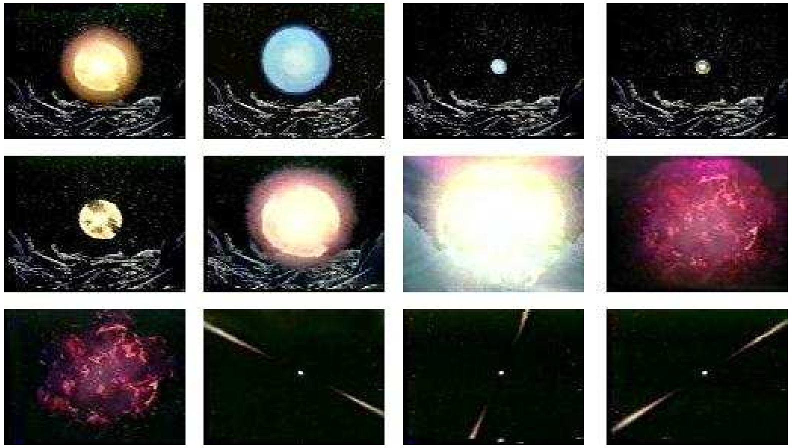
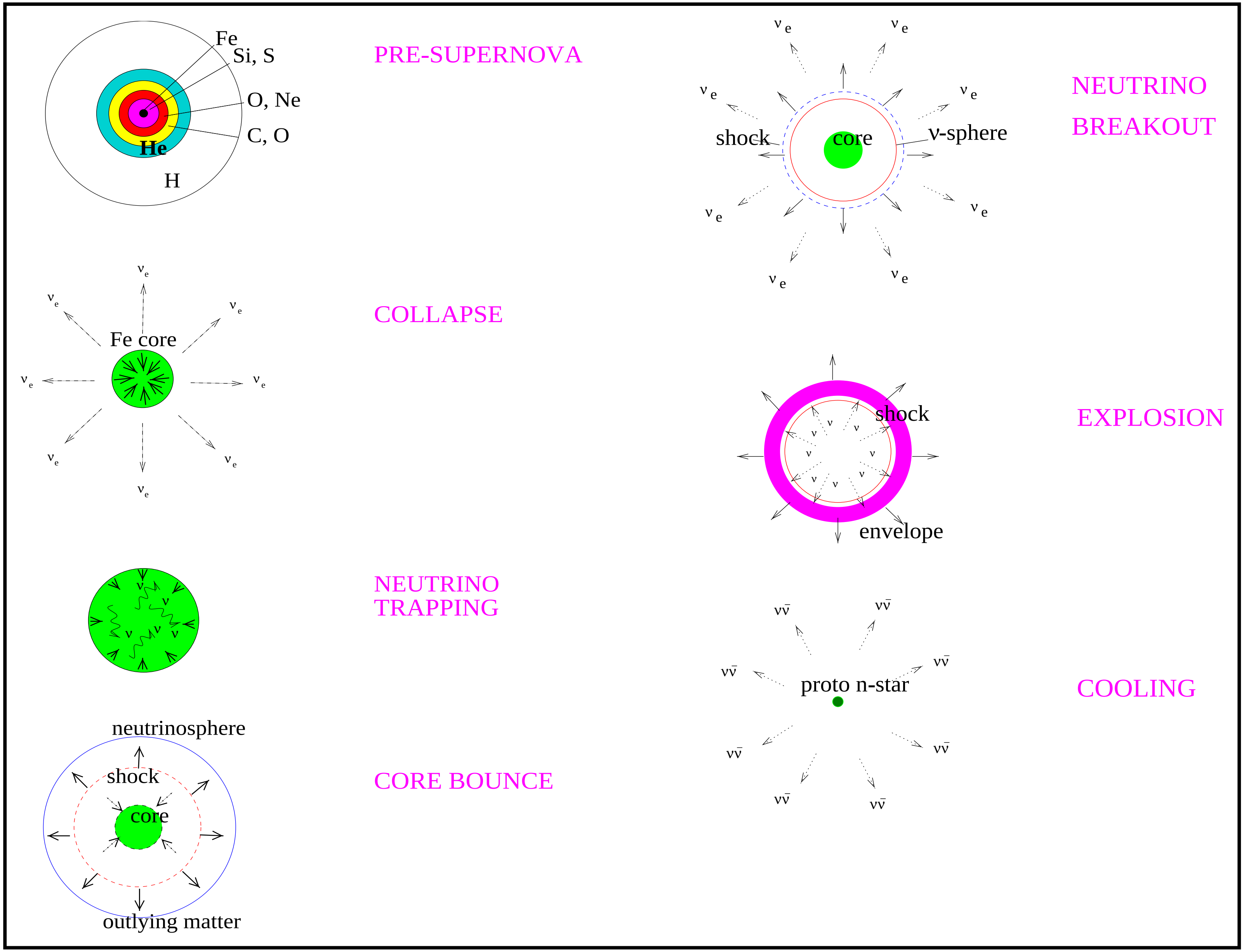
Neutrino reactions in astrophysics

Nuclear Physics aspects of core-collapse supernovae

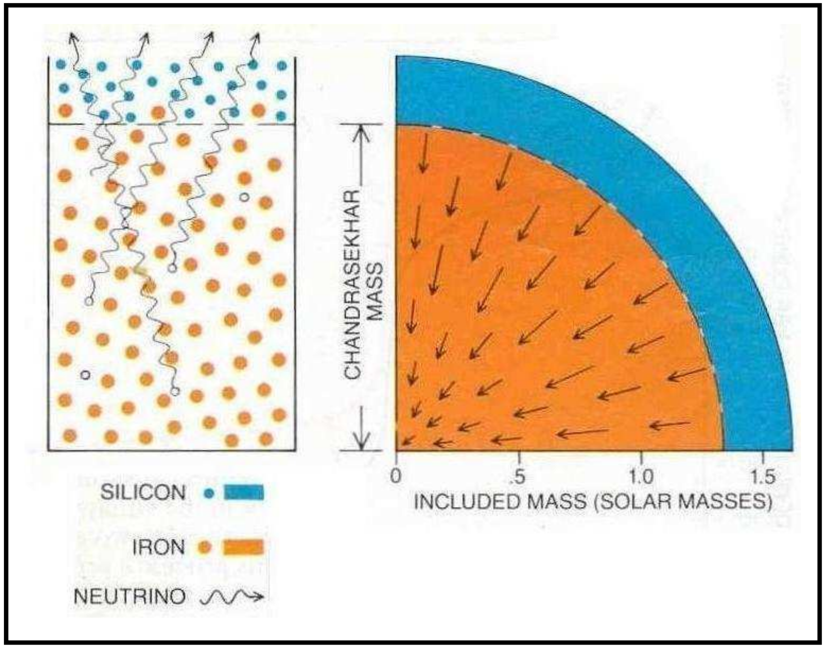
Gabriel Martínez Pinedo



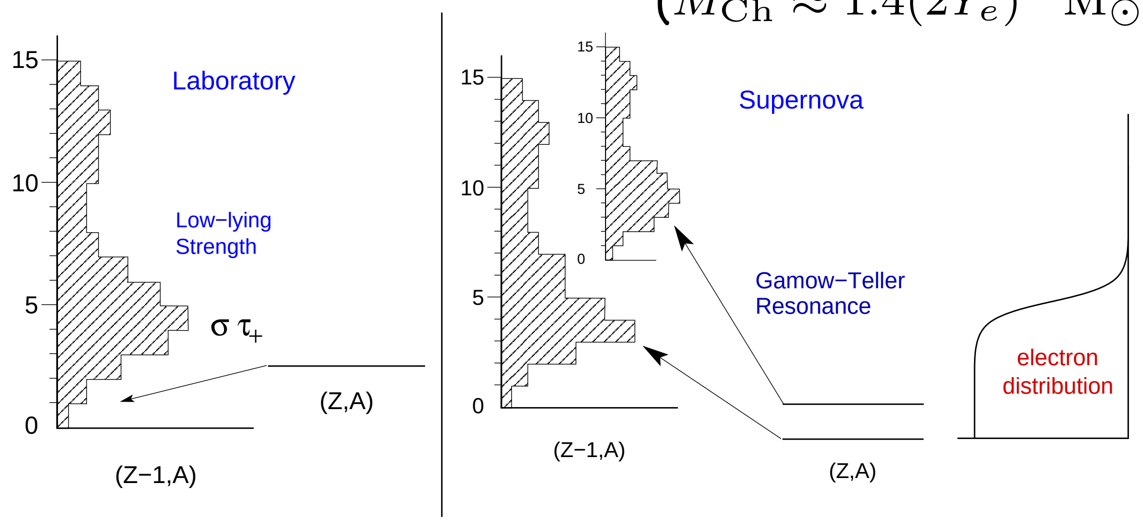
Core evolution (Outline)



Presupernova evolution

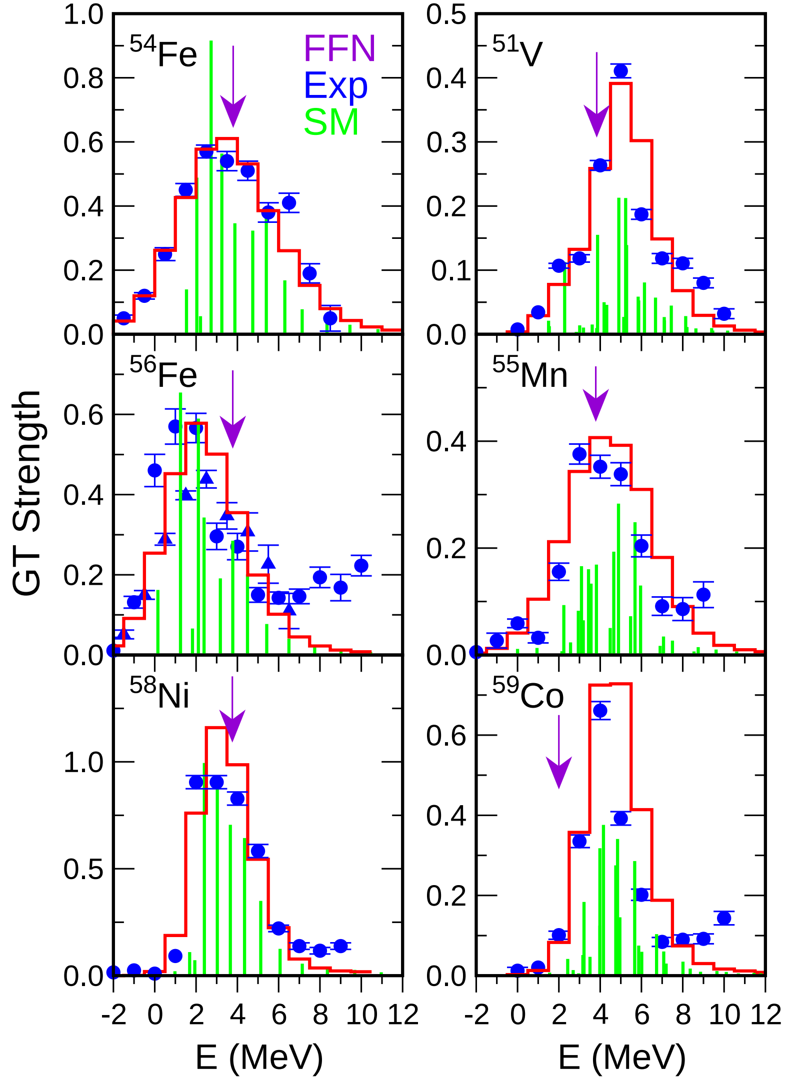


- $T = 0.1$–0.8 MeV, $\rho = 10^7$–10^{10} g cm^{-3}. Composition of iron group nuclei (A = 45–65)
- Important processes:
  - ➢ electron capture:
    $e^- + (N, Z) \rightarrow (N+1, Z-1) + \nu_e$
  - ➢ β^- decay:
    $(N, Z) \rightarrow (N-1, Z+1) + e^- + \bar{\nu}_e$
- Dominated by allowed transitions (Fermi and Gamow-Teller)
- Evolution decreases number of electrons (Y_e) and Chandrasekar mass ($M_{\rm Ch} \approx 1.4(2Y_e)^2$ M$_\odot$)



Gamow-Teller strength

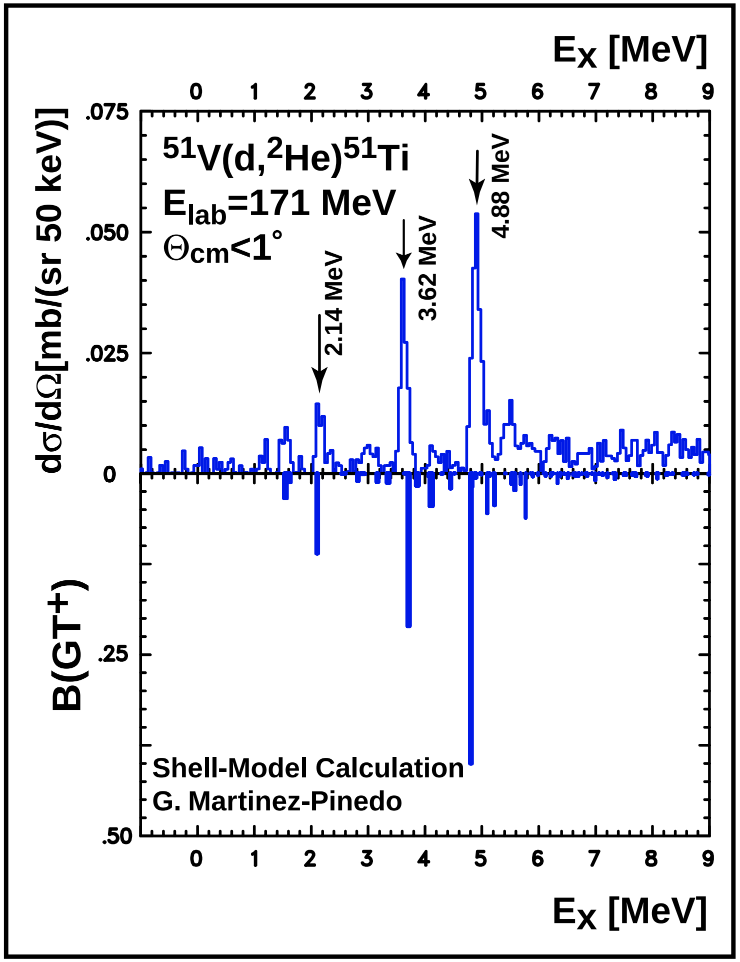
GT_+ strength measured in charge-exchange (n,p) experiments (TRIUMF).



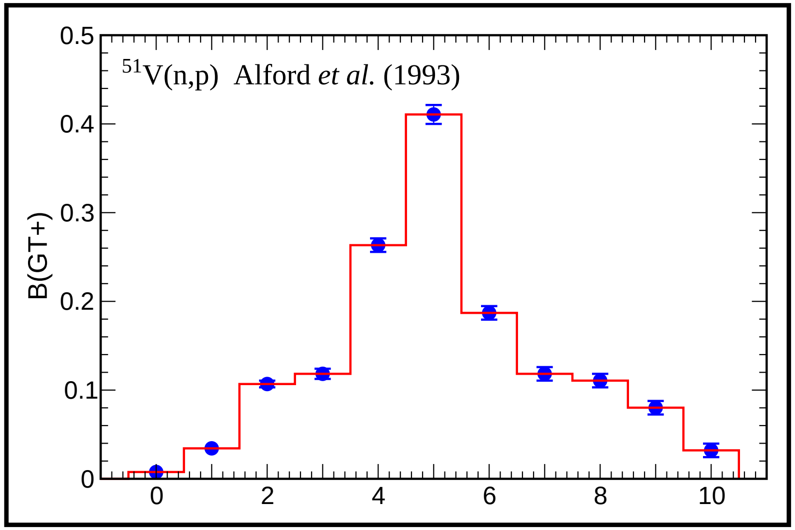
Radioactive-beams facility could provide:

- Improved energy resolution.
- Experimental data for unstable nuclei (no experimental information for odd-odd nuclei)
- New experimental techniques based on $(d, {}^2\mathrm{He})$ reaction

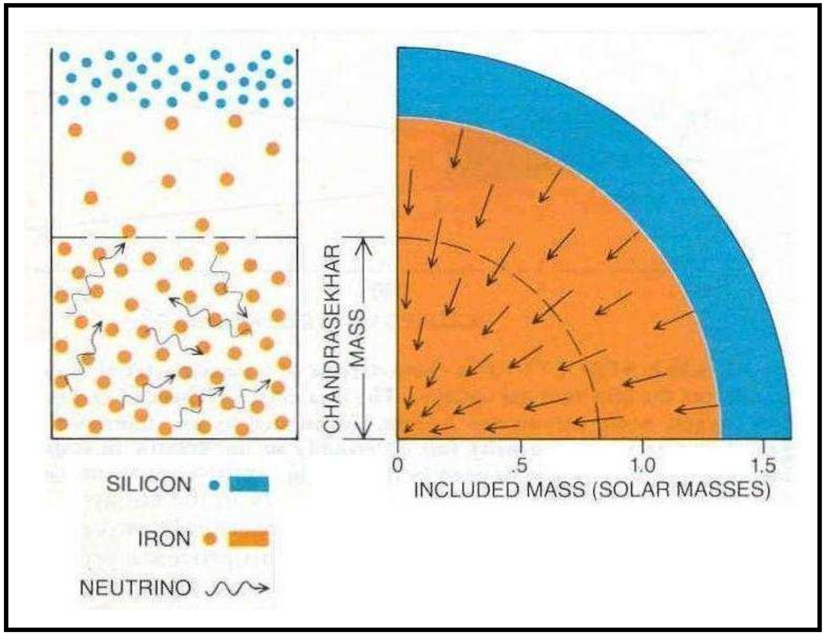
GT_+ *strength measured in* $(d,{}^2He)$



High resolution Gamow-Teller distributions on ^{51}V, ^{58}Ni (^{64}Ni,...) measured at KVI (Groningen) by EuroSupernova Collaboration.



Collapse phase



Important processes:

- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$
- Neutrino transport (Exact solution Boltzman equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

  cross sections $\sim E_\nu^2$

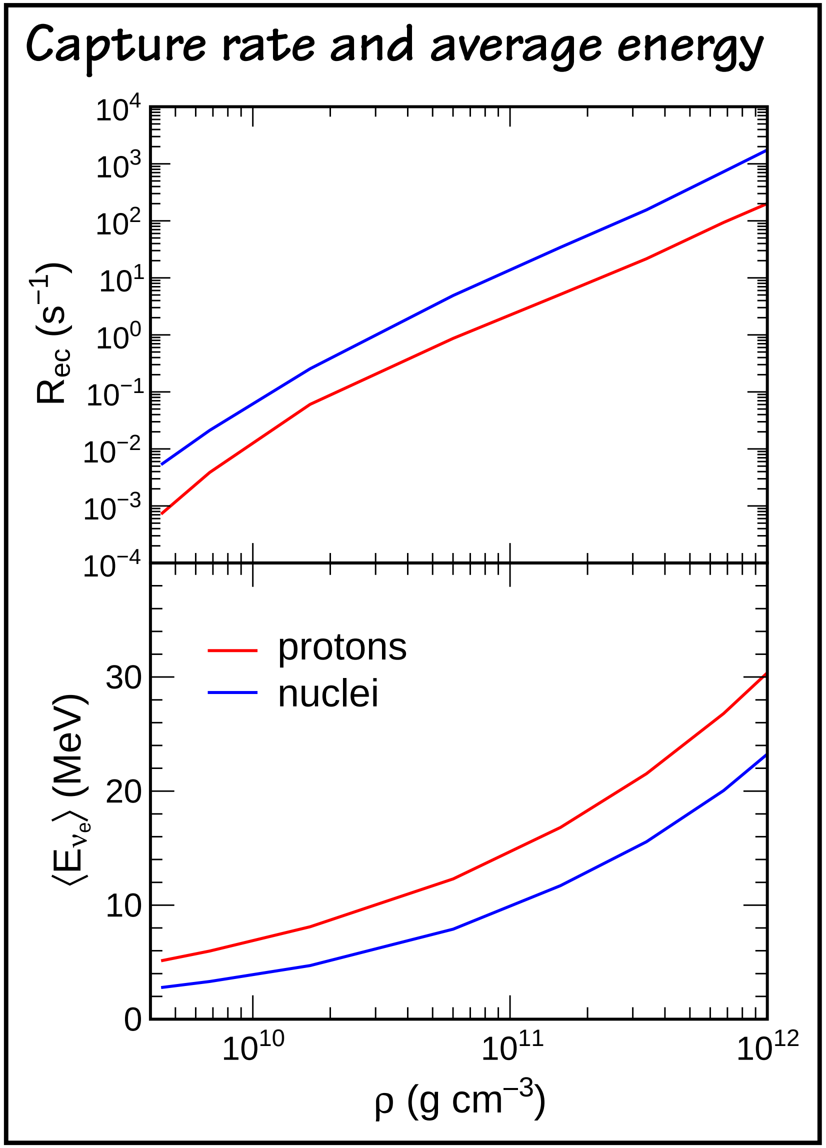
What is the role of electron capture on nuclei

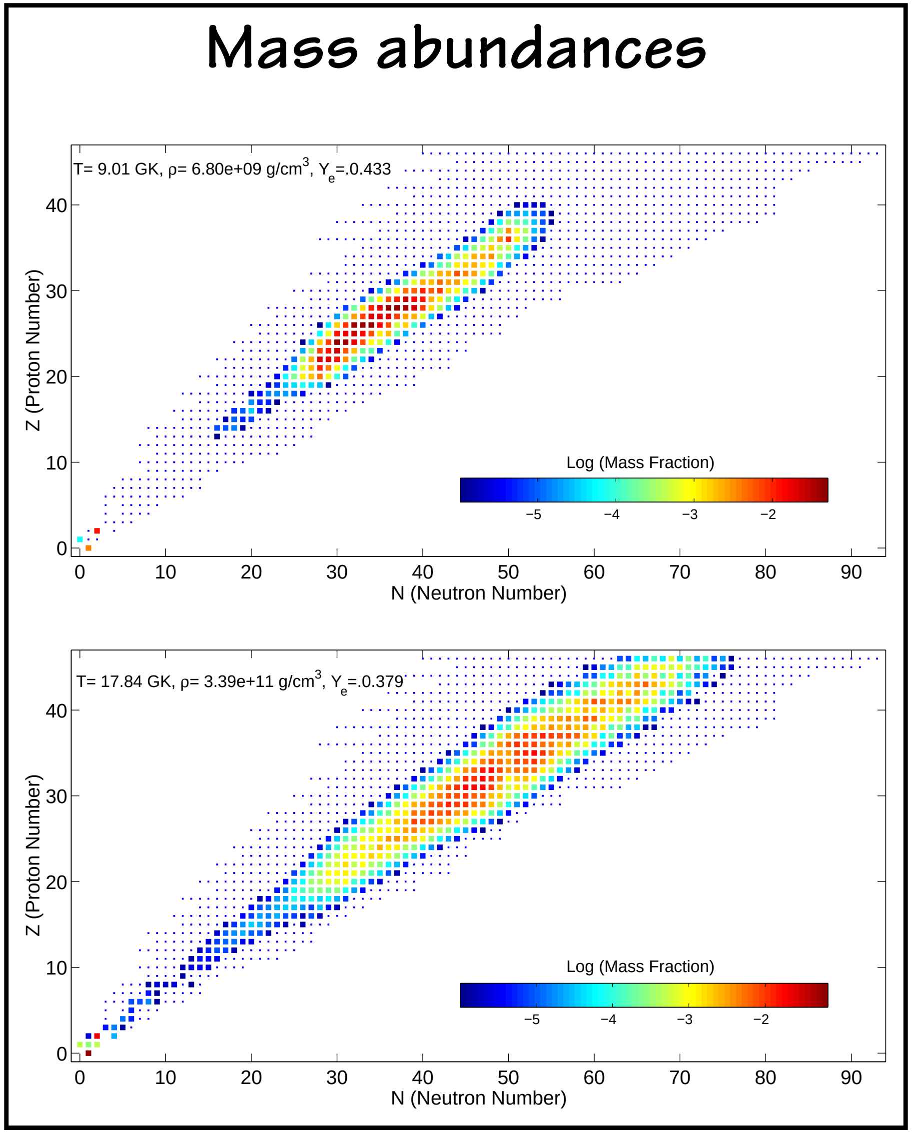
$$e^- + (N,Z) \rightarrow (N+1, Z-1) + \nu_e$$

Is inelastic neutrino-nucleus scattering comparable to neutrino-electron scattering?

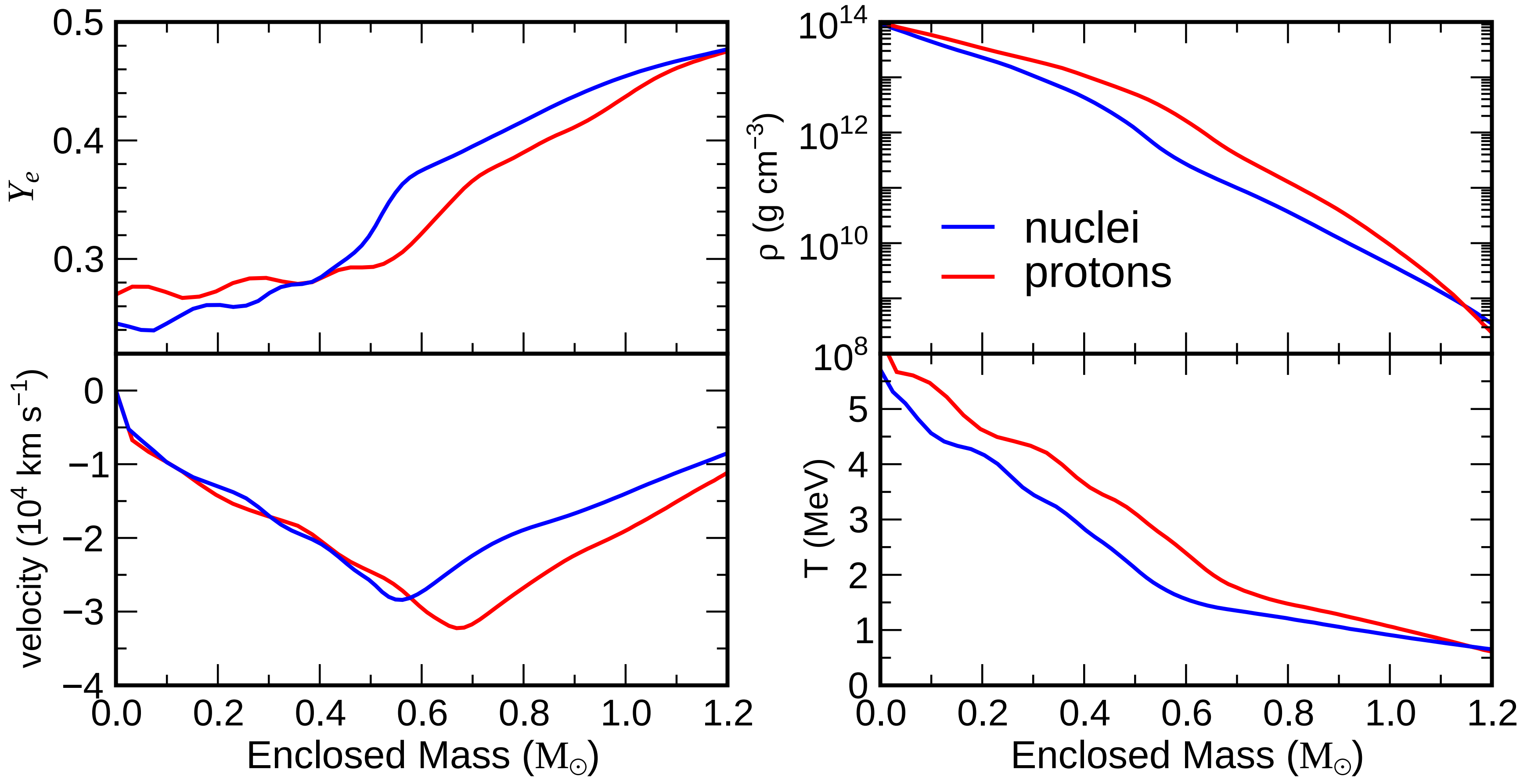
$$\nu + A \rightleftarrows \nu + A^*$$

Electron capture: nuclei vs protons





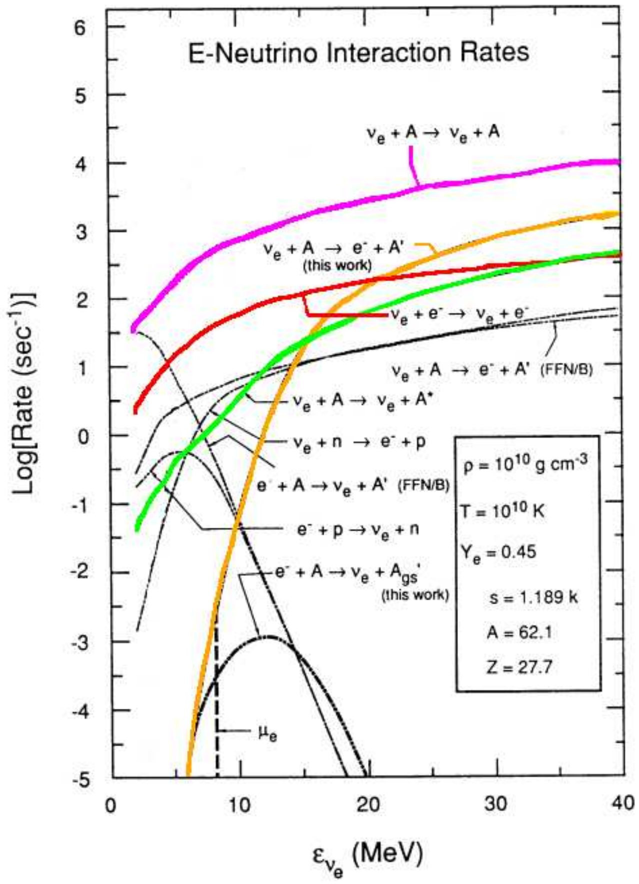
Consequences



Neutrino interactions in the collapse

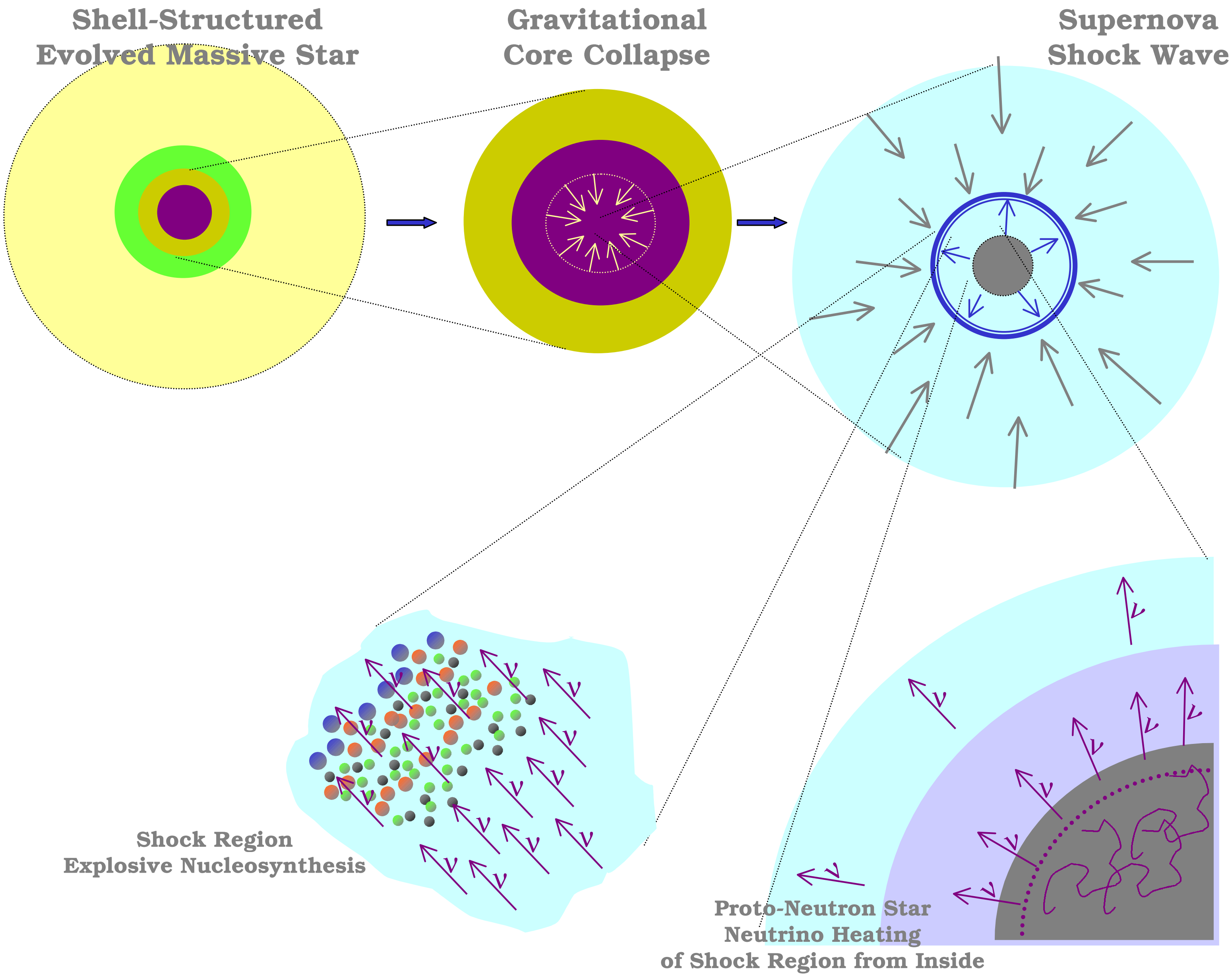
Bruenn and Haxton (1991)

Based on results for ^{56}Fe



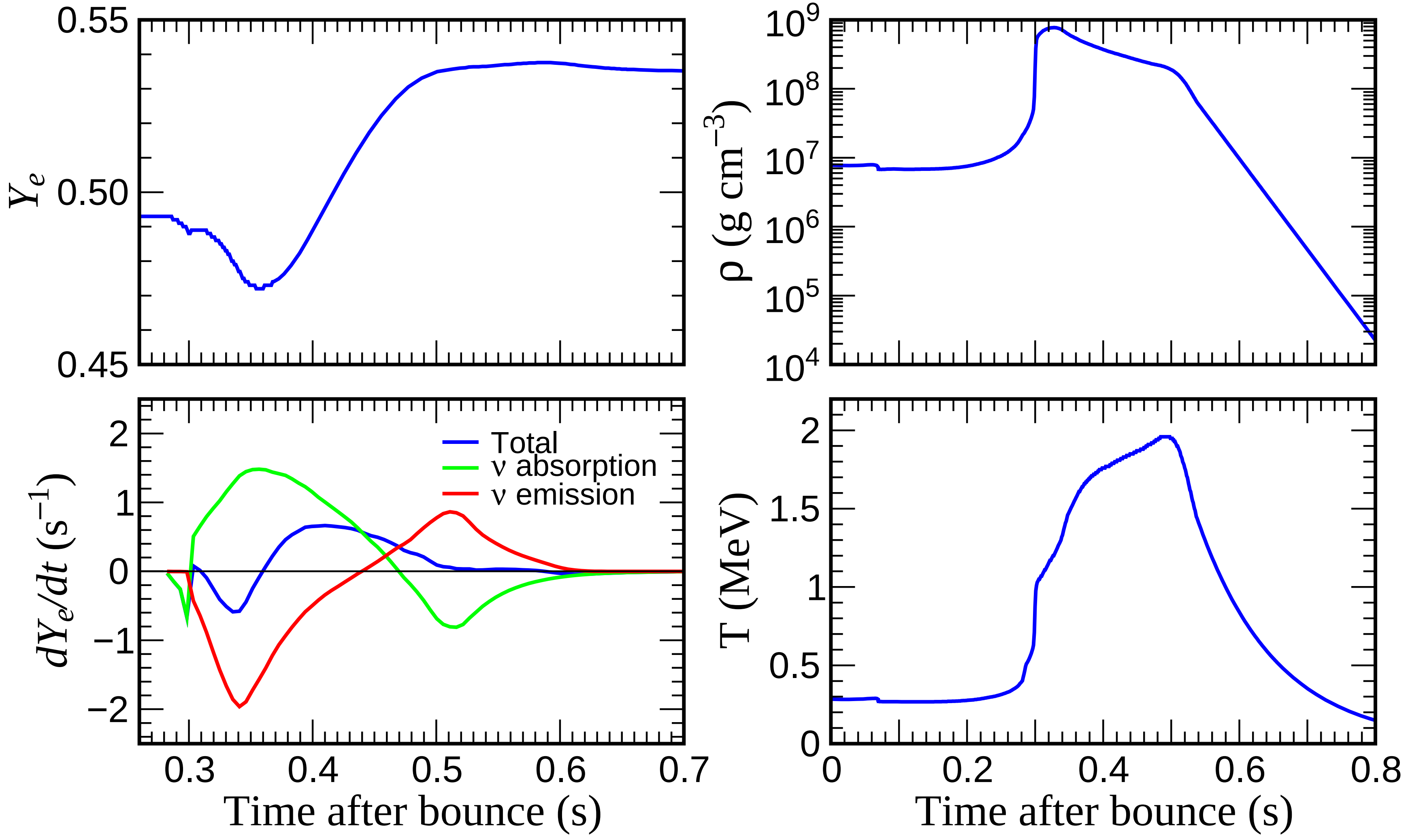
- **Elastic scattering:**
  $\nu + A \rightleftarrows \nu + A$ (trapping)
- **Absorption:**
  $\nu_e + (N,Z) \rightleftarrows e^- + (N-1, Z+1)$
- **ν-e scattering:**
  $\nu + e^- \rightleftarrows \nu + e^-$
- **Inelastic ν-nuclei scattering:**
  $\nu + A \rightleftarrows \nu + A^*$

Explosive nucleosynthesis

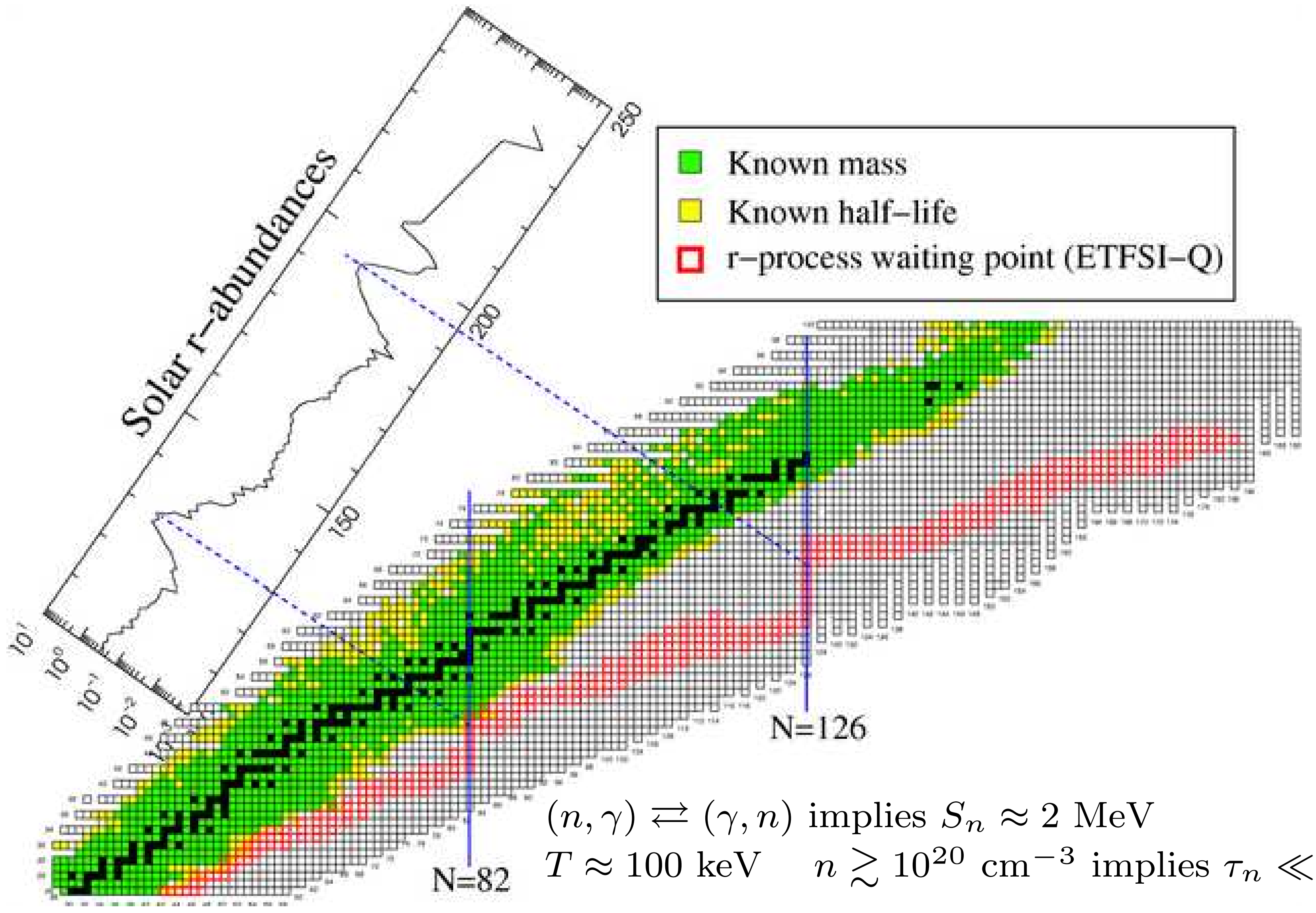


Neutrino interactions determine Y_e *value*

M. Liebendörfer *et al*



r-process

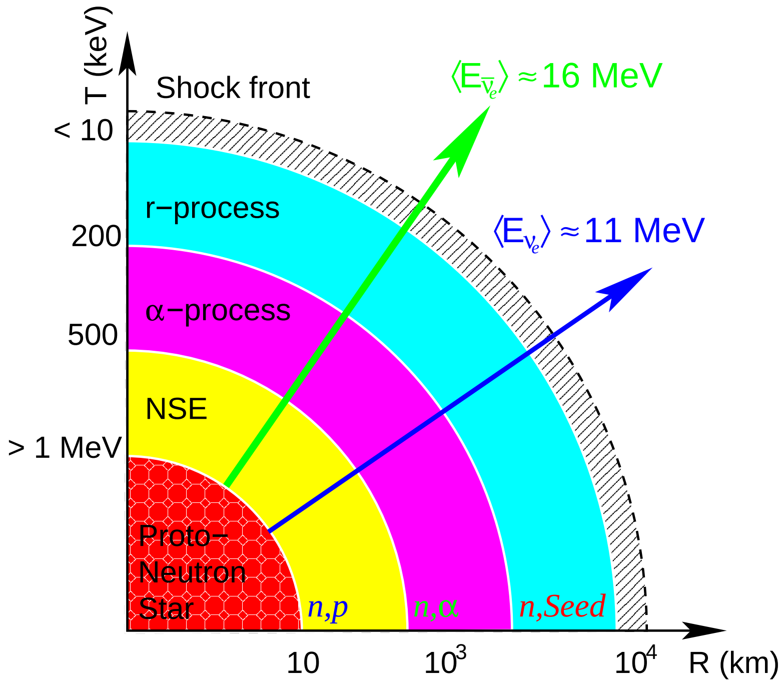


$(n, \gamma) \rightleftarrows (\gamma, n)$ implies $S_n \approx 2$ MeV

$T \approx 100$ keV $\quad n \gtrsim 10^{20}$ cm^{-3} implies $\tau_n \ll \tau_\beta$

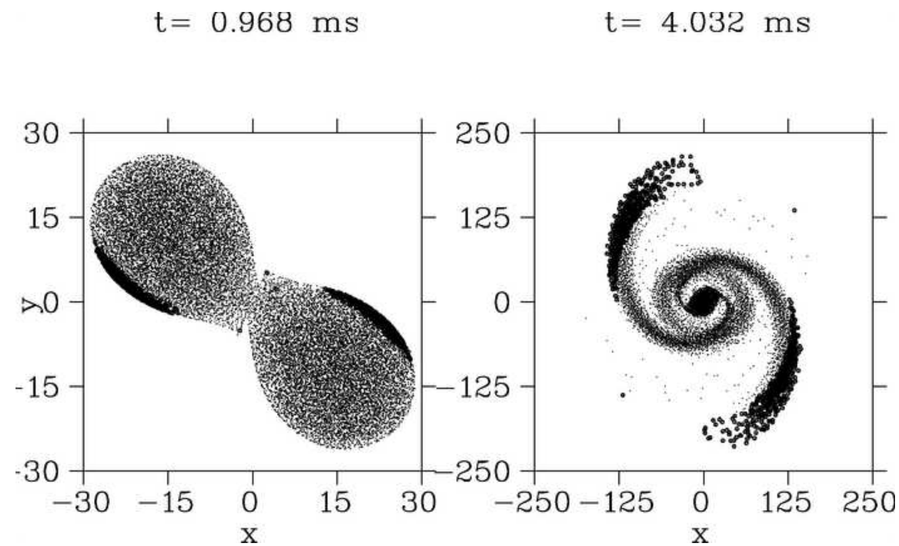
Astrophysical scenarios

Neutrino-driven wind



Neutron star mergers

(S. Rosswog et al)



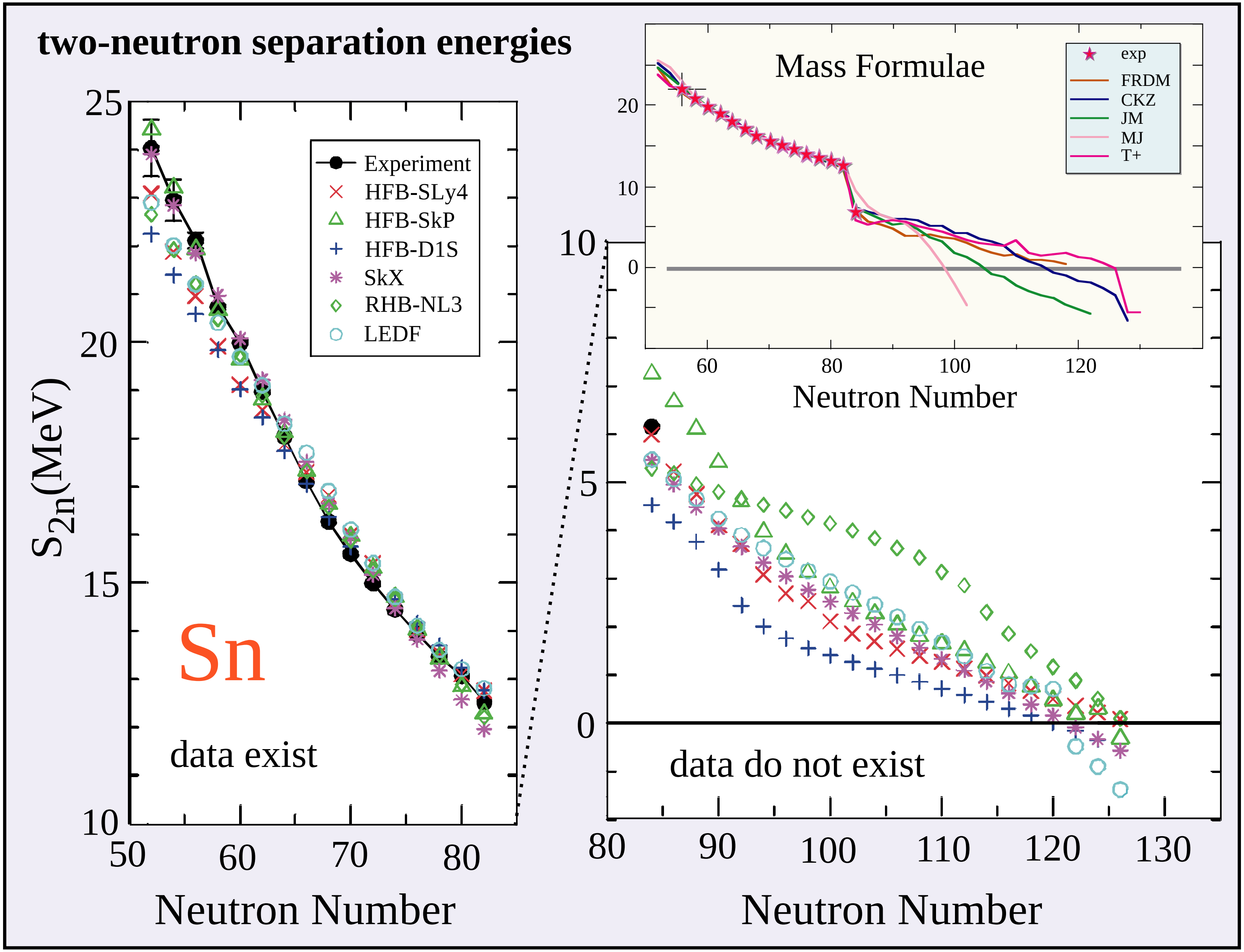
- Neutrino-wind from (cooling) NS

$$\nu_e + n \to e^- + p$$
$$\bar{\nu}_e + p \to e^+ + n$$

- α-process (formation seed nuclei)

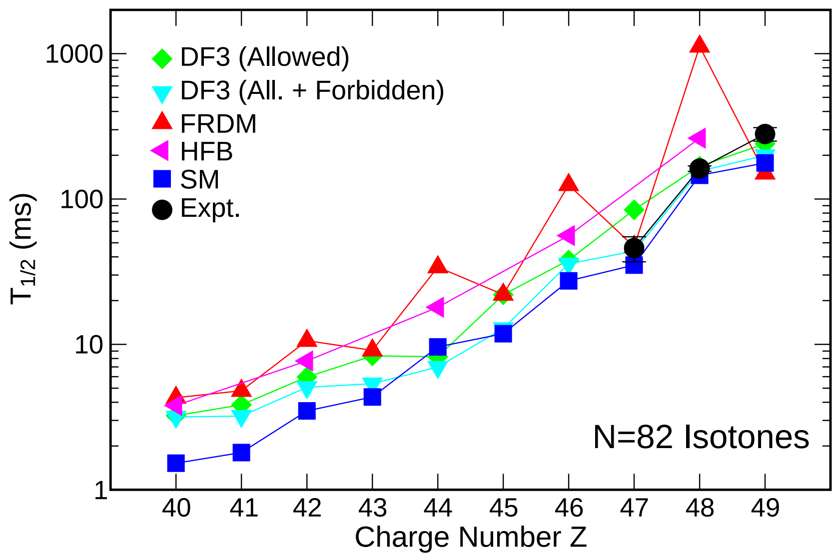
$$\alpha + \alpha + n \to {}^9\mathrm{Be} + \gamma$$
$$\alpha + {}^9\mathrm{Be} \to {}^{12}\mathrm{C} + n$$

Masses for r-process nuclei

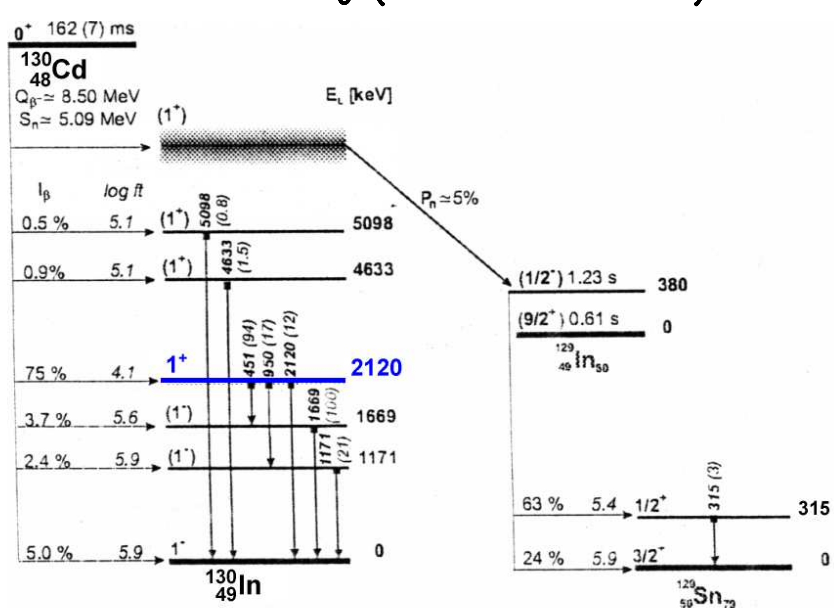


Half-lives for r-process nuclei

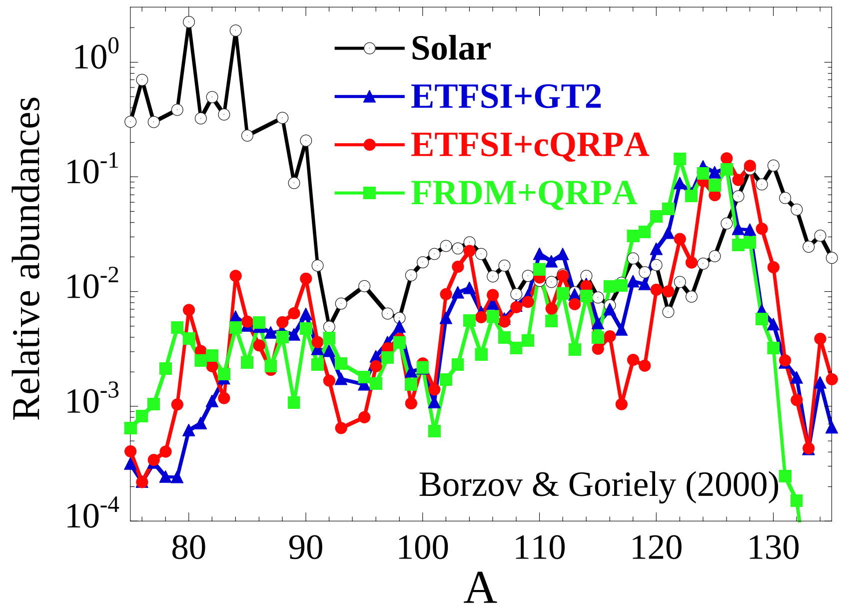
Half-lives N=82 isotones



^{130}Cd decay (K.-L. Kratz *et al*)



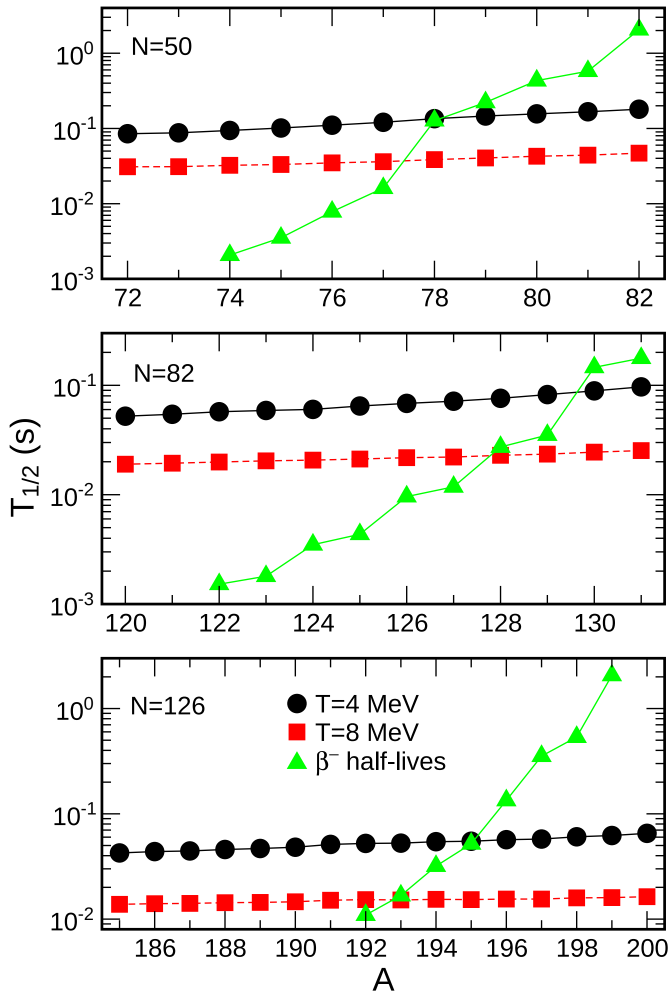
Effect of the half-lives

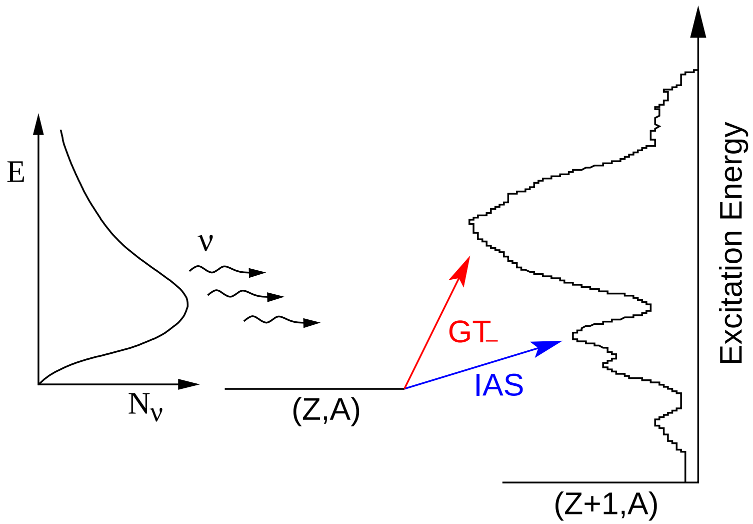


Peak position depends of the half-lives used

Neutrinos in the r-process

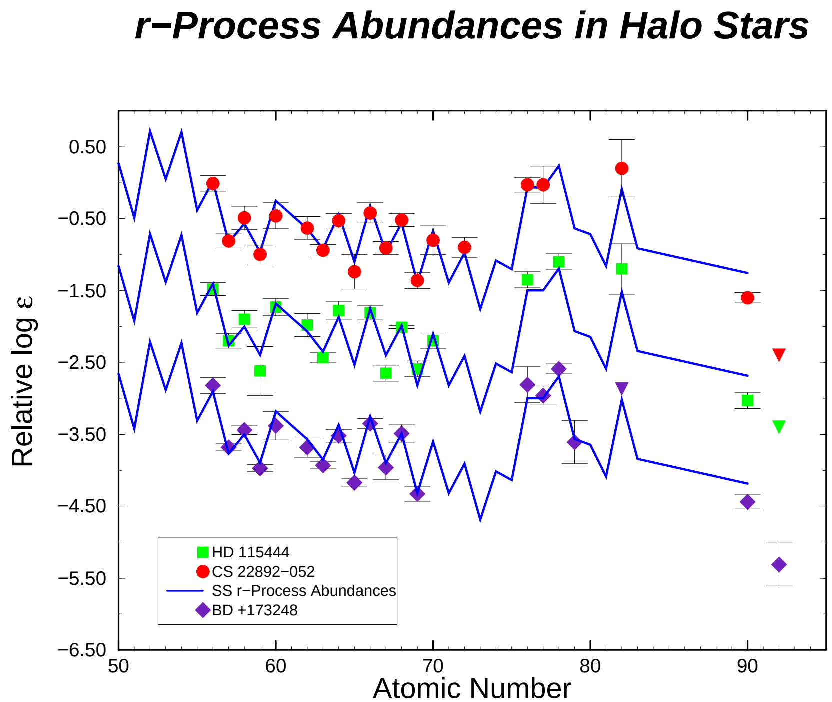
ν_e **charge-current interactions can accelerate the flow of matter** ($\lambda = \lambda_\beta + \lambda_{\nu_e}$)



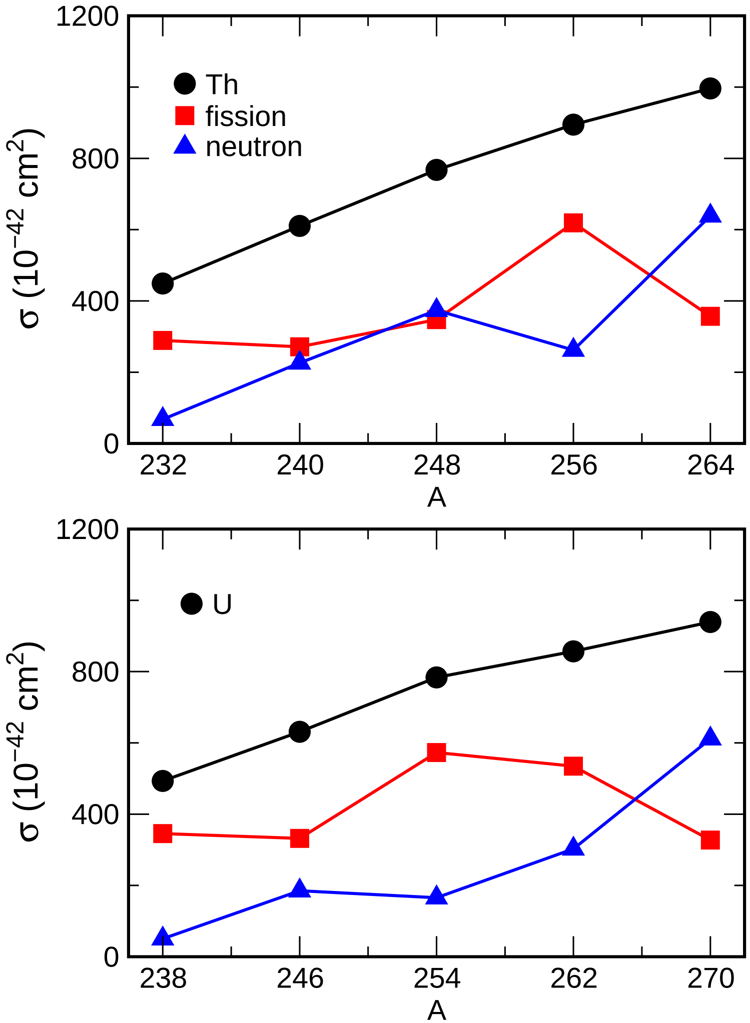


Neutrino rates are not sensitive to shell-effects

Abundances metal-poor stars



Abundance ration sensitive to fission: spontaneous, β-delayed, neutron-induced, neutrino-induced

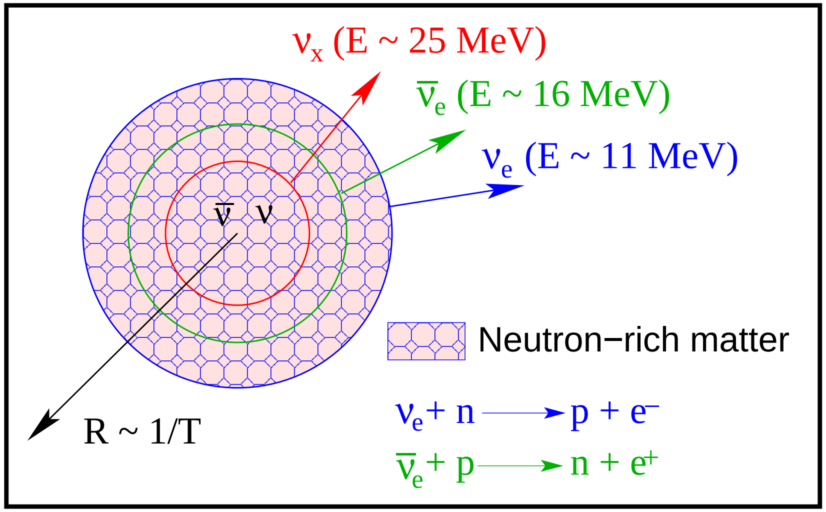


- ☞ Abundances for nuclei $Z \geq 56$ consistent with normalized solar distribution.
- ☞ U/Th ratio can be used to estimate age of the galaxy. (CS 22892-052, 15.6 ± 4.6 Gyr)

Neutrino nucleosynthesis

Neutrinos interact with abundant nuclear species

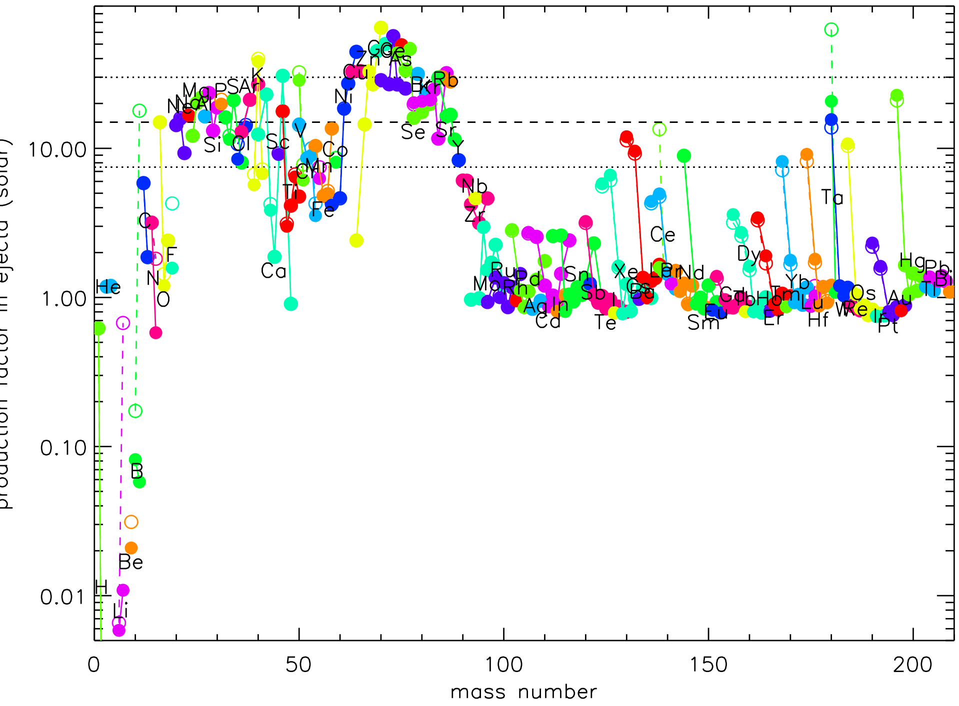
- Neutral current (ν, ν'): Nucleus excited to particle unbound states that decay by particle emission.
- Charged current (ν_e, e^-) and $(\bar{\nu}_e, e^+)$.

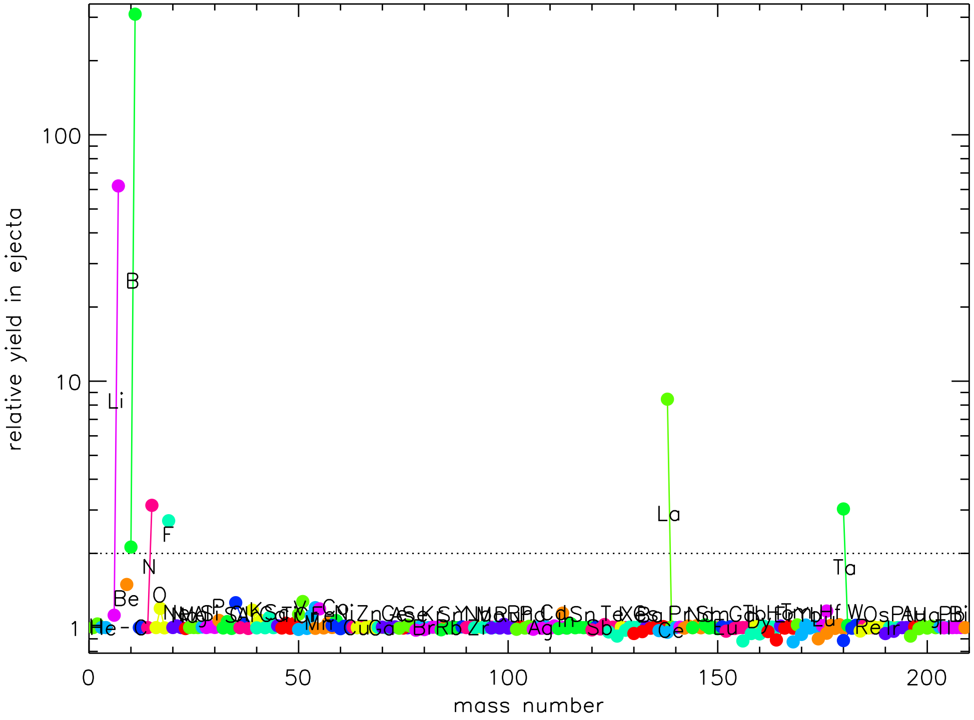


Product	Parent	Reaction
^{7}Li	^{4}He	$(\nu, \nu' n)^{3}\text{He}(\alpha, \gamma)^{7}\text{Be}(n, p)$
		$(\nu, \nu' p)^{3}\text{H}(\alpha, \gamma)$
^{11}B	^{12}C	$(\nu, \nu' n), (\nu, \nu' p)$
^{15}N	^{16}O	$(\nu, \nu' n), (\nu, \nu' p)$
^{19}F	^{20}Ne	$(\nu, \nu' n), (\nu, \nu' p)$
^{138}La	^{138}Ba	(ν, e^-)
	^{139}La	$(\nu, \nu' n)$
^{180}Ta	^{180}Hf	(ν, e^-)
	^{181}Ta	$(\nu, \nu' n)$

Nucleosynthesis with and without neutrinos

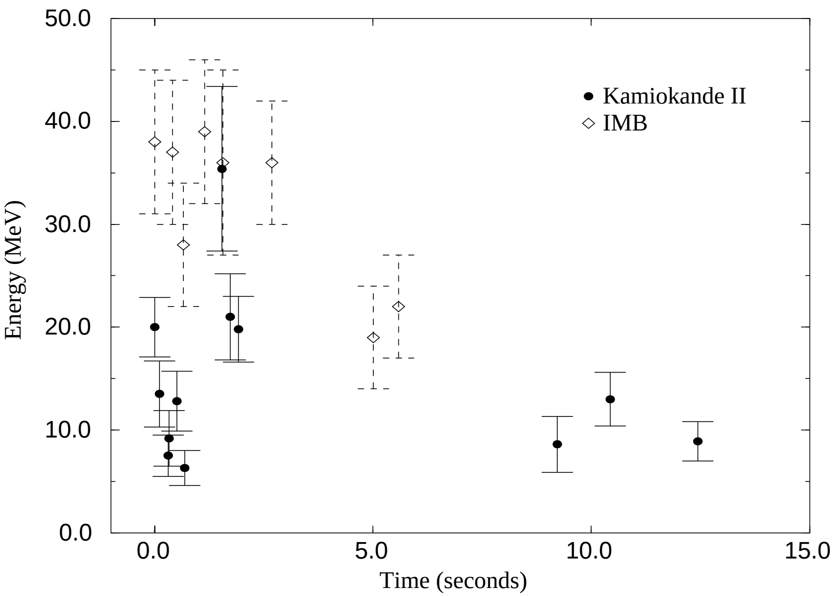
(A. Heger *et al*)





Neutrinos from SN1987A

Type II supernova in LMC ($\sim$ 55 kpc)

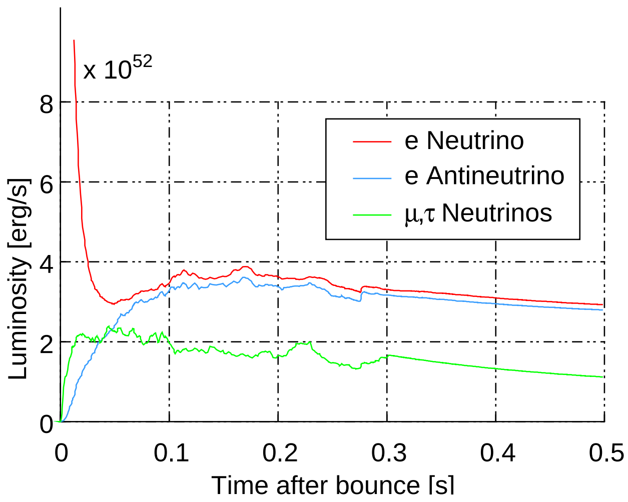


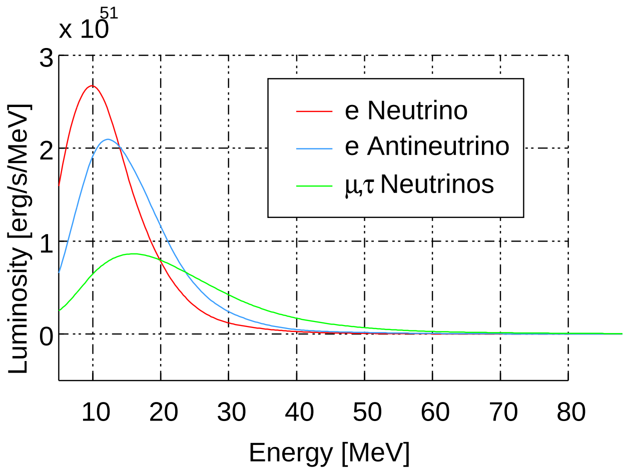
Confirmed core-collapse supernovae emit huge amounts of neutrinos ($\sim 10^{58}$)

Supernova rate: One each 30 years.

Supernova neutrino detection

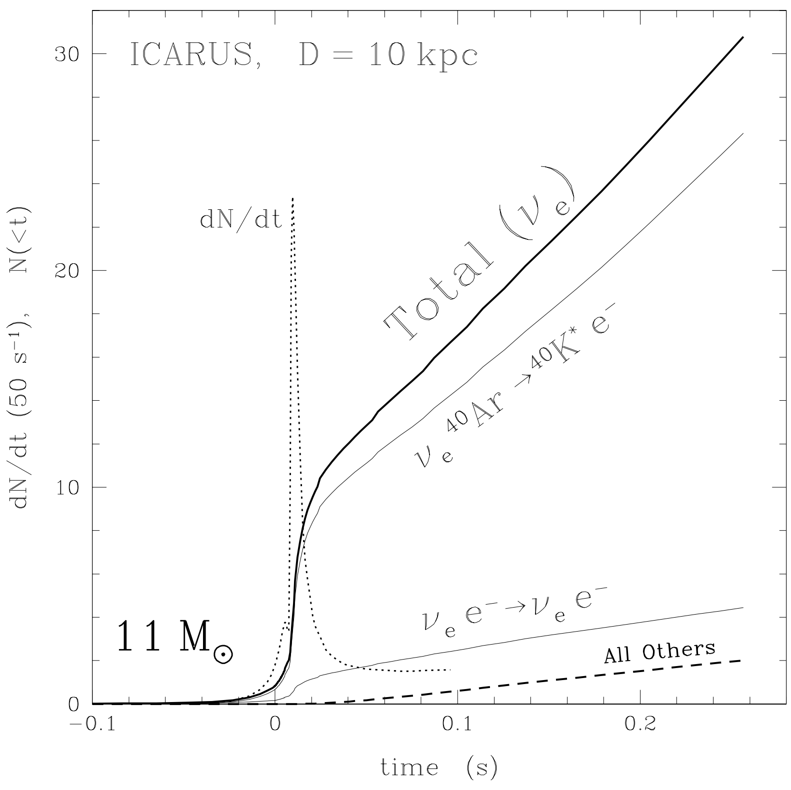
- Core-collapse physics.
  - Collapse and explosion dynamics.
  - Proto-neutron star cooling (EoS).
  - Black hole formation.
- Neutrino physics.
  - mass hierarchy.
  - mixing angle θ_{13}.
- SuperNova Early Warning System.
- Earth Core Tomography.



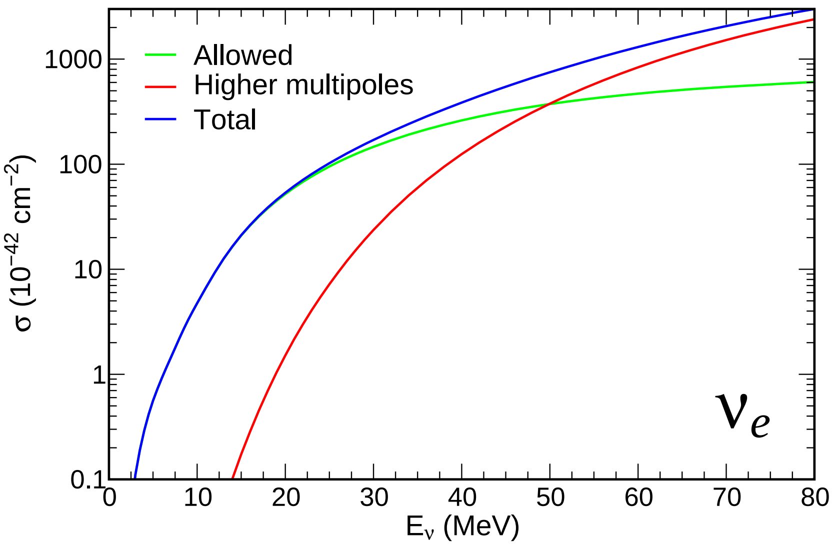


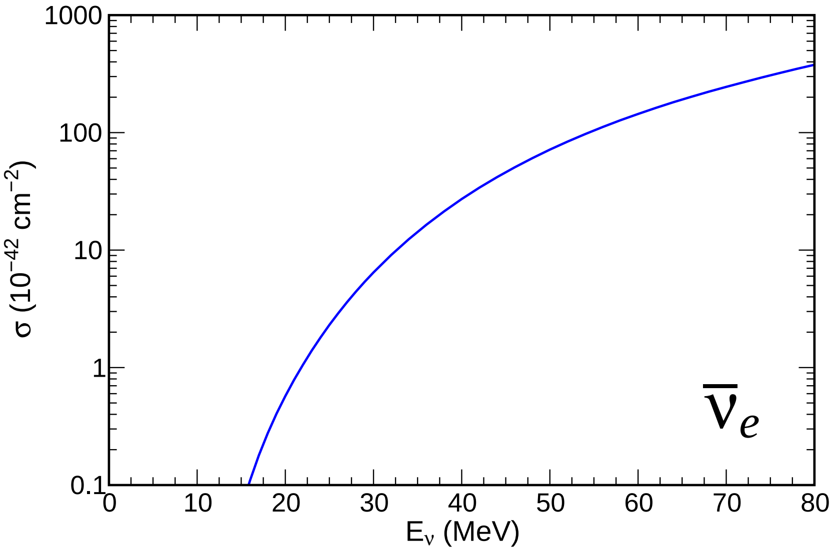
Supernova neutrino detection at ICARUS

T. A. Thompson *at al*, astro-ph/0211194



Allowed cross section well known from ^{40}Ti decay





Summary

- ☞ Radioactive beams offer the possibility of study the properties of exotic nuclei relevant for supernova evolution and nucleosynthesis
- ☞ Low energy neutrino beams are necessary to measure neutrino cross sections relevant for supernova dynamics, nucleosynthesis and neutrino detection.