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# Stellar electron-capture rates on nuclei
# ( based on Skyrme functional )

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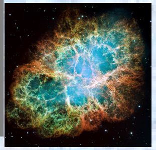
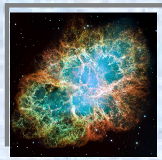


# Outline

- Astrophysical framework and motivation
- Introduction
  - Electron-capture in Type II SN and in hydro simulations
- The model we use
- Results
  - Electron-capture cross sections
  - Electron-capture rates
- Conclusions & Outlook



# Astro framework: SN theory

**MICROPHYSICS** ⟷ **MACROPHYSICS**

**Weak-processes**

ν interactions
**capture rates**

**Equation of State**

low density
high density

Neutrino transport

**SN Simulations**

Hydrodynamics

# Motivations

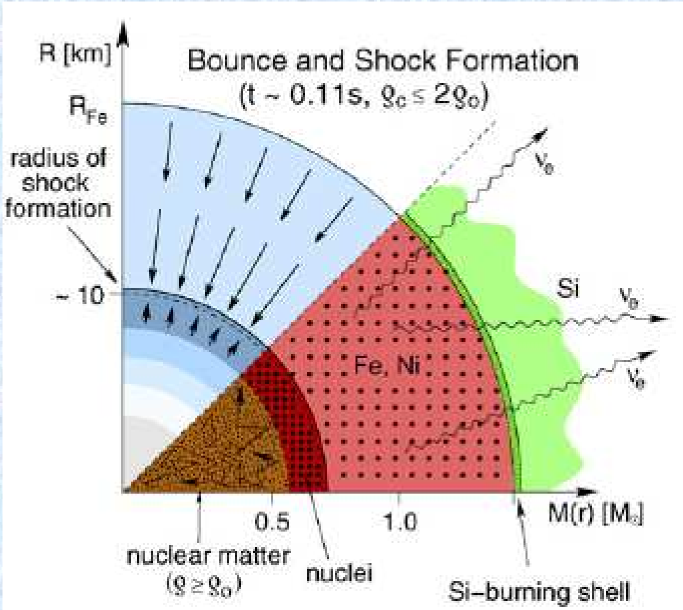
- Weak processes crucial all along the life of a star

- Electron-capture and beta decays crucial in pre-supernova phase
  - ⟶ determines $Y_e$ and $s$ in the core
  - ⟶ formation of neutron-rich nuclei

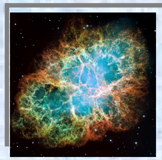
- Electron-capture governes the deleptonization phase
  - ⟶ $Y_e$ at trapping
  - ⟶ shock wave formation

$$M_{ch} = 5.8\ Y_{lept}^2$$

- In this work: calculations on **Fe** and **Ge** isotopes




Janka et al., Phys.Rep. 442, 38 (2007)



# Introduction: electron-capture

$$p + e^- \to n + \nu_e$$ on free protons

$$(Z, A) + e^- \to (Z-1, A) + \nu_e$$ on nuclei

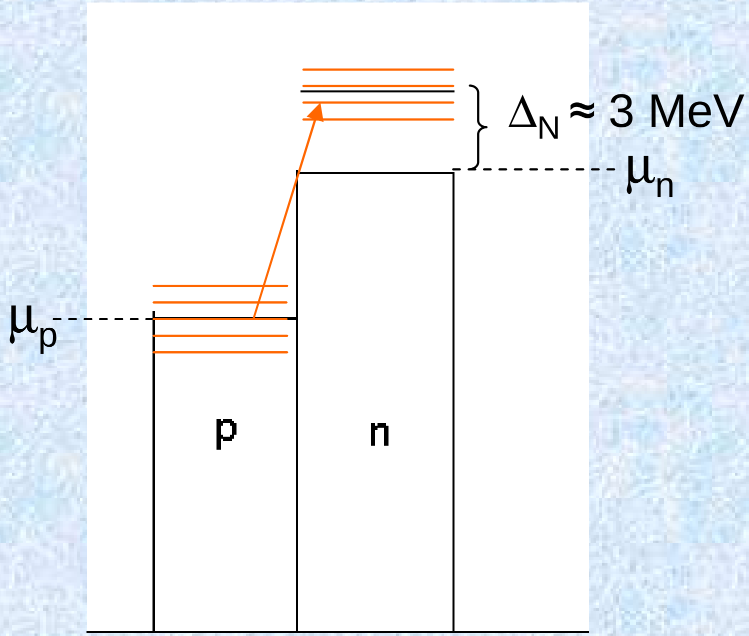
Condition during SN collapse:

$$\rho \in [10^5 - 10^{15}] \text{ g cm}^3$$

$$T \in [0.1 - 100] \text{ MeV}$$

$$Y_e \in [0.05 - 0.5]$$

⟶ capture allowed!




✧ *Electron capture on free protons*: known!

✧ *Electron capture on nuclei*: requires knowledge of nuclear structure → difficult!

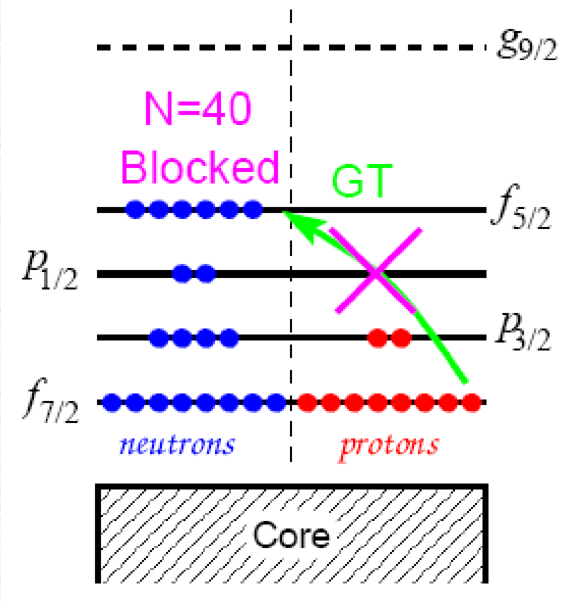
# Electron-capture rates in hydro codes (1)

- **<u>Fuller *et al.*</u>** 1982, 1985

  Fuller, ApJ 252, 741 (1982)
  Fuller, Fowler, and Newmann, ApJ 293, 1 (1982) ;
  ApJ Suppl. 48, 279 (1982); ApJ 252, 715 (1982);
  ApJ 293, 1 (1985)

  - Two-level transition at T ≠ 0 - IPM
  - GT transition on nuclei suppressed for Z < 20, N ≥ 40

  → *Capture on **free protons** dominates*




- **<u>Bruenn</u> 1985** parameterization in hydro codes

  Bruenn, ApJSS 58, 771 (1985)

But: - thermal excitations
- configuration mixing

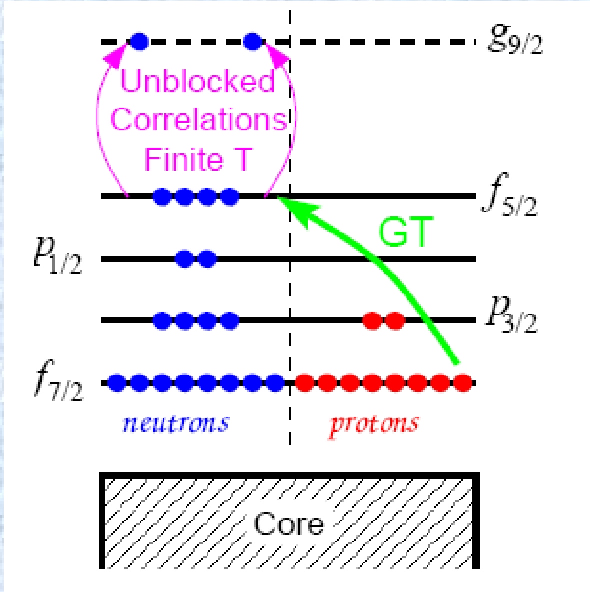
for a review, e.g. Langanke and Martinez-Pinedo, Rev. Mod. Phys. 75, 819 (2003)

# Electron-capture rates in hydro codes (2)

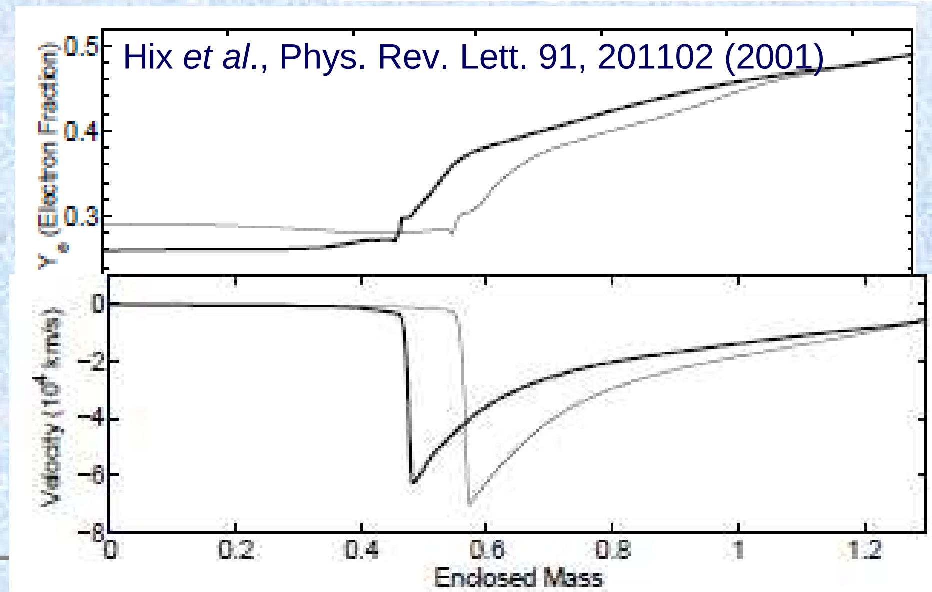
- **Langanke *et al.*** 2000, 2001
  Langanke and Martinez-Pinedo, ADTNDT **79**, 1 (2001)
  Martinez-Pinedo, Langanke, and Dean, ApJ SS **126** ,493 (2000)
  Langanke, Kolbe, and Dean, Phys. Rev. **C66**, 32801 (2001)

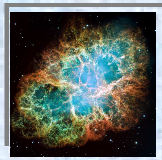
  - Shell Model Monte Carlo (SMMC)
  - Hybrid model (SMMC + RPA)

  → *Capture on **nuclei** dominates*




- new pre-supernova model
  (Heger et al. 2001)
- new "hybrid" rates in hydro codes
  results in smaller homologous core

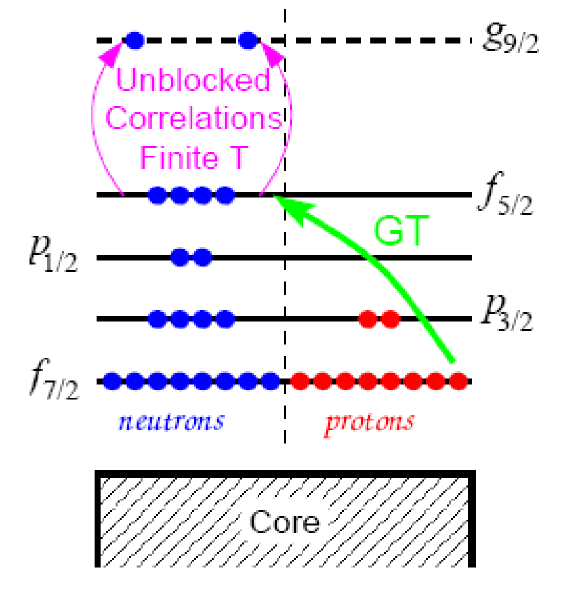




# and other calculations, among which:

- ➢ BBAL ( Bethe H.A. et al., Nucl. Phys. A324, 487 (1979) )
  Low free proton abundance → *Capture on **nuclei** dominates* (A = 60 – 80 )
  Statistical model at T = 0

- ➢ Cooperstein J. and Wambach J., Nucl. Phys. A420, 591 (1984)
  Capture on nuclei with N ≥ 40 can compete with capture on free protons
  RPA calculations at finite T ( T ~ 1.5 MeV ) → unblocking




<u>*More recently …*</u>

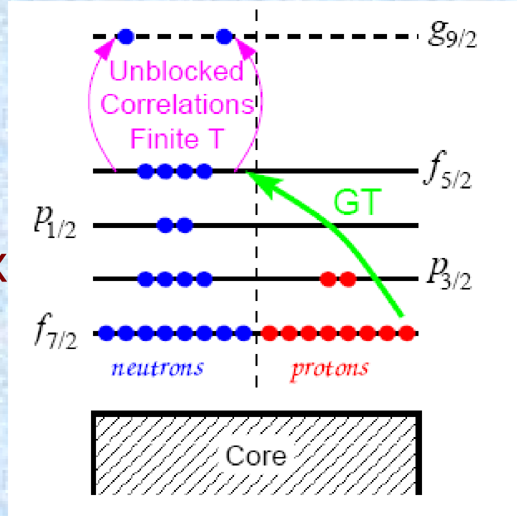
**Mean field based models:** (not implemented in codes)

- Paar et al., Phys. Rev. C 80, 055801 (2009)
- Niu et al., Phys. Rev. C 045807 (2011) : FTRRPA
- Dzhioev et al., Phys. Rev. C 81, 015804 (2010) : TQRPA

# The FTHF + FTRPA model (1)

• **FTHF** → single nucleon basis and occupation factors

• **FTRPA** (charge-exchange) → charge-exchange transitions
( Paar et al., PRC 80, 055801 (2009) )



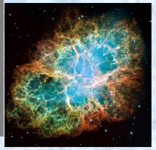

N.B.: The model is self-consistent: both HF eqs. and RPA matrix based on the *same* Skyrme functional

➢ Cross-section for electron-capture in 0.5 < $T$ < 2 MeV:

$$\sigma(E_e,T)=\frac{G_F^2}{2\pi}\sum_i F(Z,E_e)\frac{(2J_i+1)e^{-E_i/K_BT}}{G(Z,A,T)}\sum_{f,J}(E_e-Q+E_i-E_f)^2\frac{|<i|\hat{O}_J|f>|^2}{(2J_i+1)}$$

⇓ Brink hp.!

$$\sigma(E_e,T)=\frac{G_F^2}{2\pi}F(Z,E_e)\sum_f(E_e-Q+\omega_f)^2\sum_J S_j(\omega_f,T)$$



# The FTHF + FTRPA model (2)

- Electron-capture rates:

$$\lambda^{ec}(T)[\mathrm{s}^{-1}] = \frac{V_{ud}^2 g_V^2 c}{\pi^2(\hbar c)^3} \int_{E_{min}}^{\infty} \sigma(E_e, T)\; E_e\; p_e c\; f_e(E_e)\; \mathrm{d}E_e$$

Fermi Dirac $f_e = \dfrac{1}{1 + e^{\frac{E_e - \mu_e}{k_B T}}}$

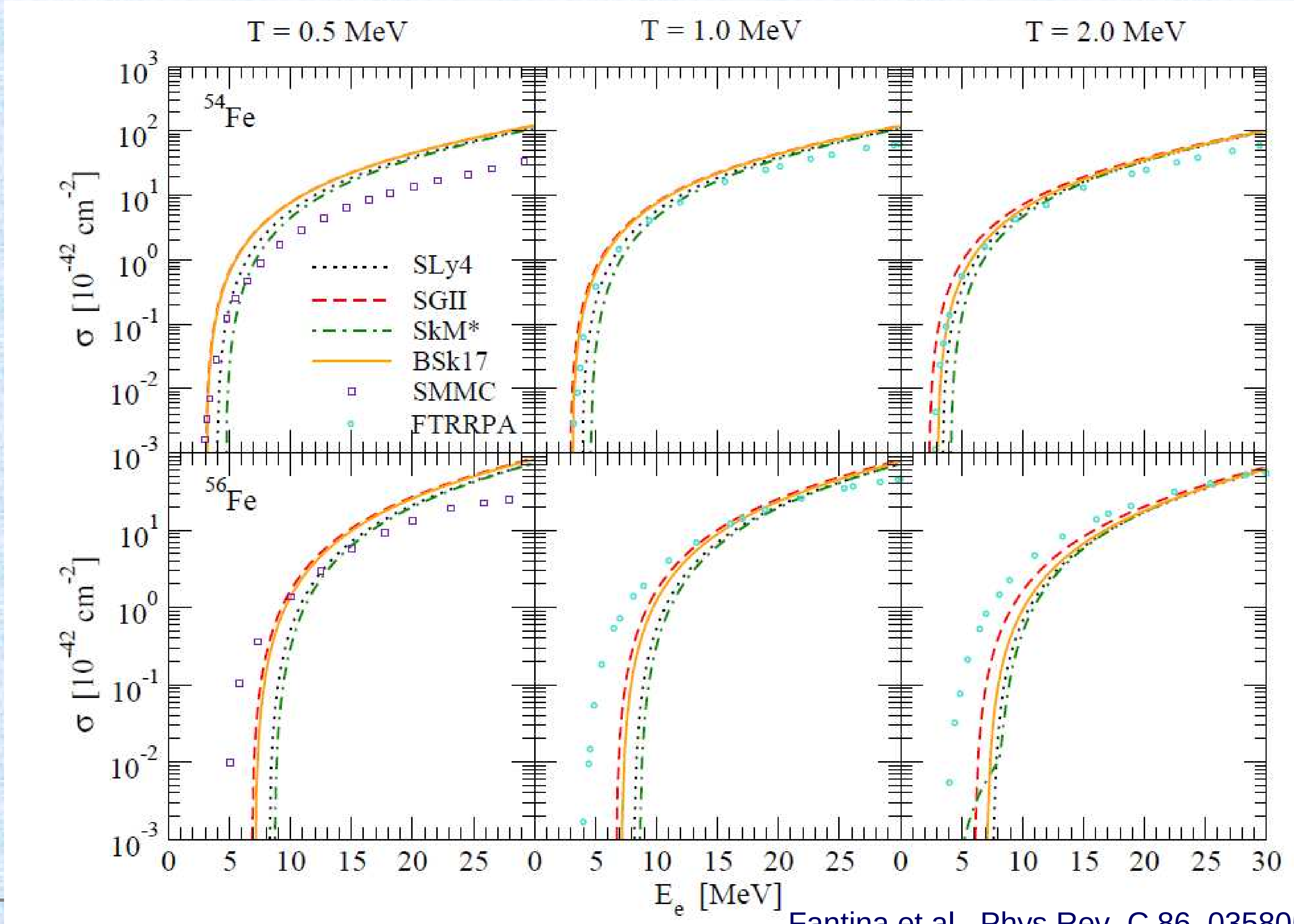
chemical potential calculated from electron density:

$$\rho Y_e = \frac{1}{\pi^2 N_A} \frac{1}{(\hbar c)^3} \int_0^{\infty} [f_e(E_e) - f_{e^+}(E_e)]\; (p_e c)^2\; \mathrm{d}(p_e c)$$

$$f_{e^+} = \frac{1}{1 + e^{\frac{E_e + \mu_e}{k_B T}}}$$

$$f_\nu = 0$$

# Electron-capture cross sections




Fantina et al., Phys.Rev. C 86, 035805 (2012)

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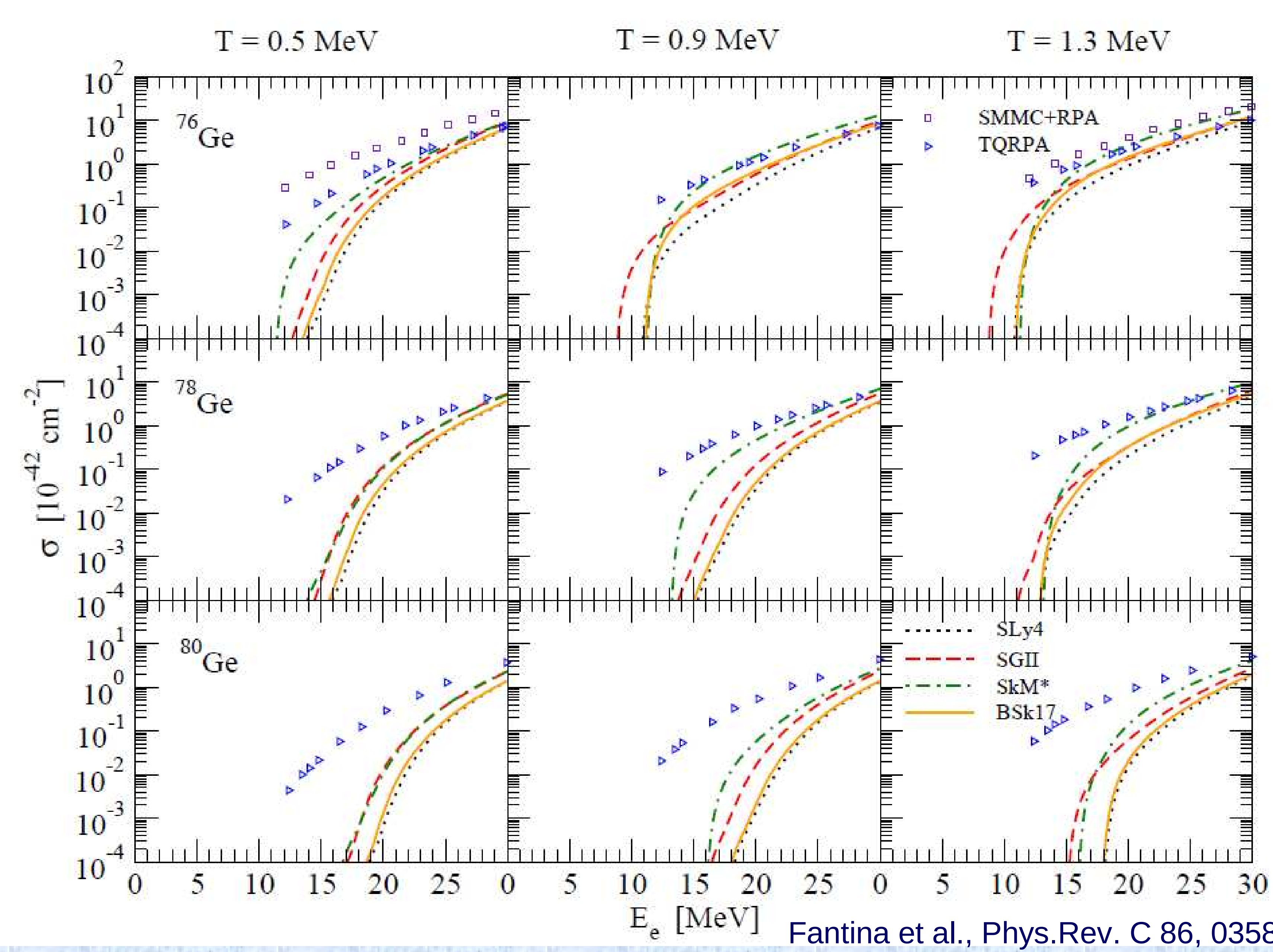


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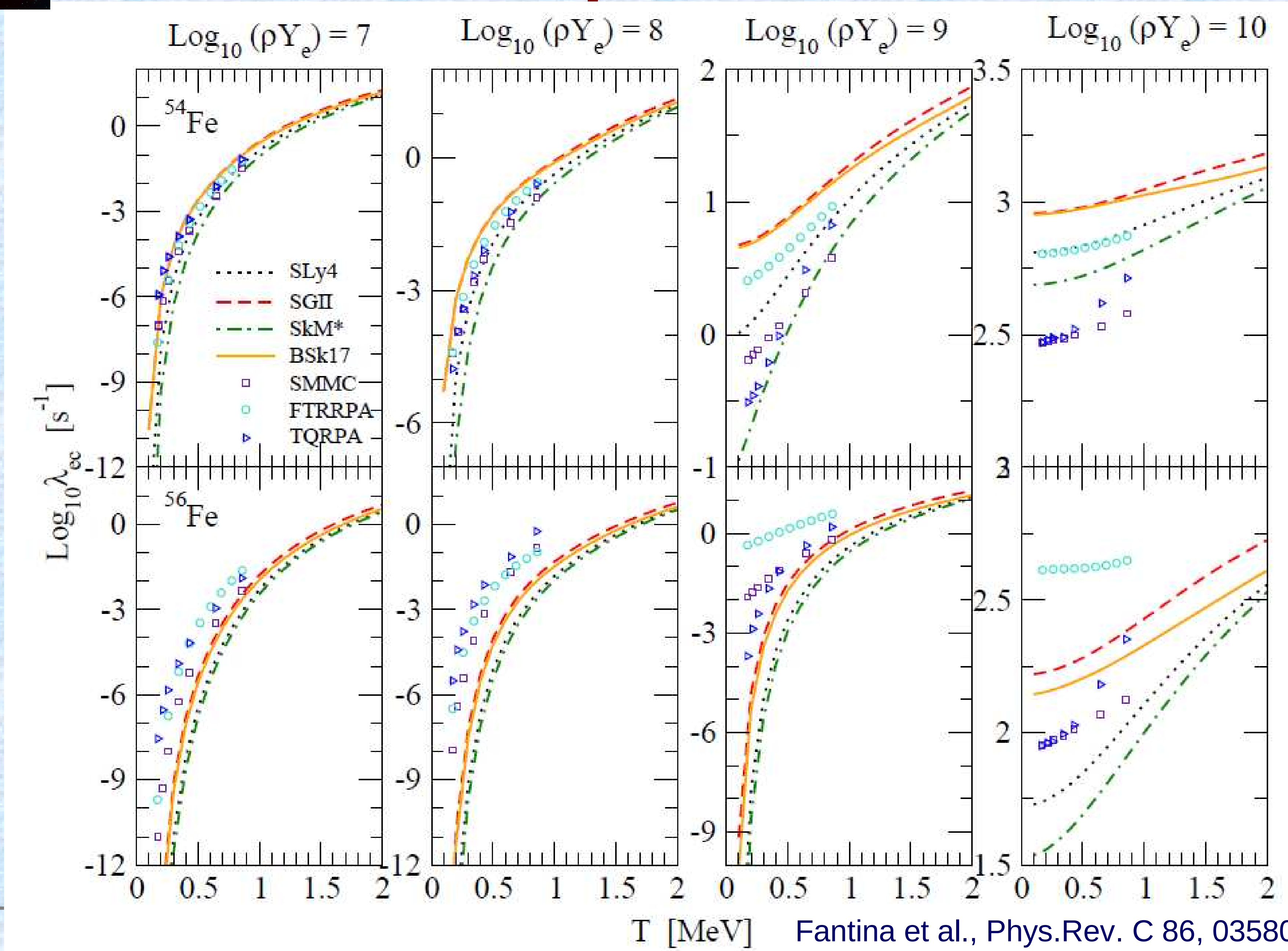


Fantina et al., Phys.Rev. C 86, 035805 (2012)

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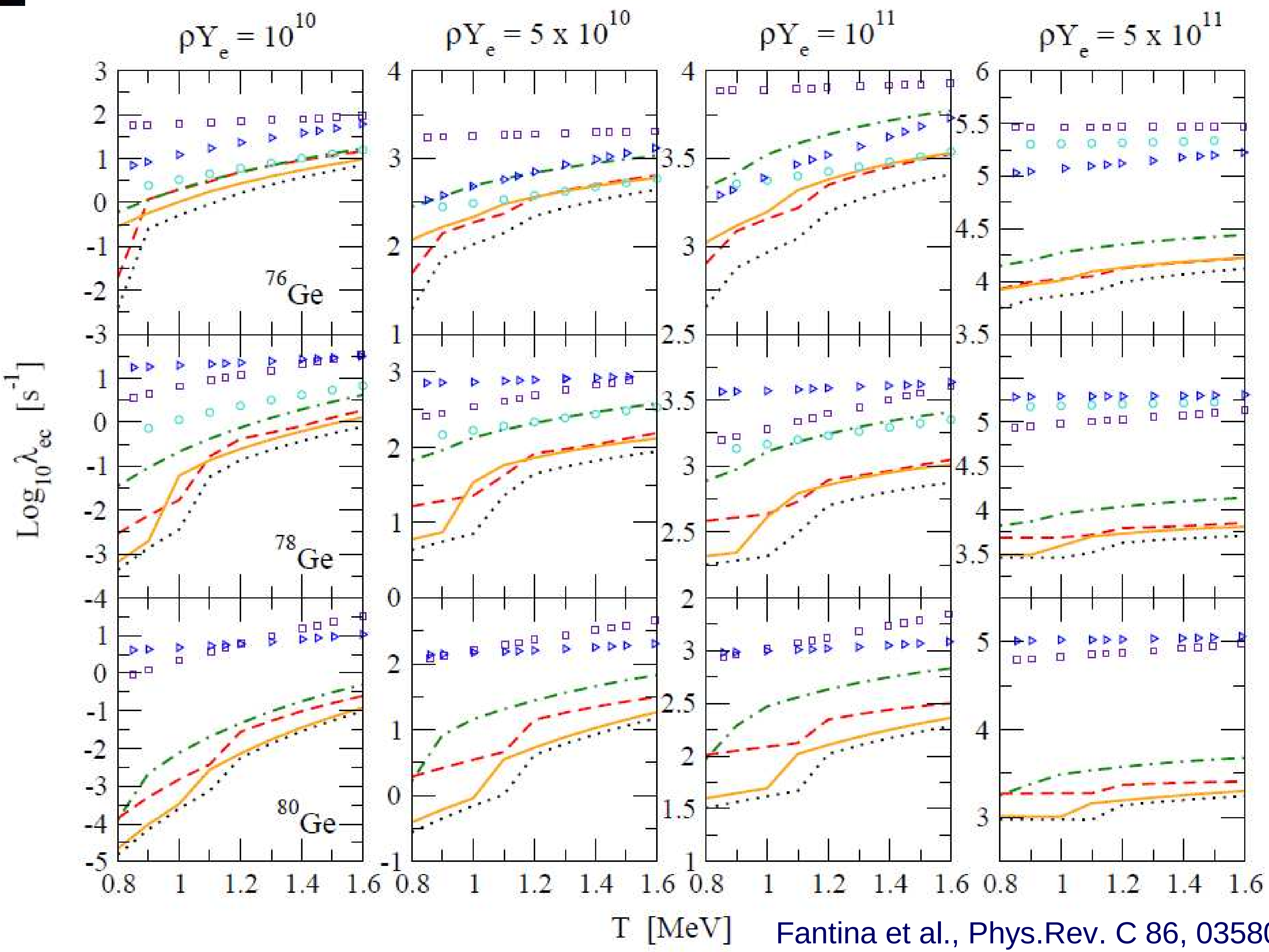


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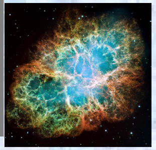

# Conclusions & Outlooks

- ❖ First calculation of electron-capture rates for stellar conditions within fully self-consistent approach
- ❖ Calculations on $^{54,56}$**Fe** and **Ge** isotopes
- ❖ Total spread evaluated at about 2 orders of magnitude

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- ➢ More systematic calculations → TABLES
- ➢ Implementation in stellar codes → CORE-COLLAPSE SN (e.g. CoCoNuT)


Thank you