Neutrinos from CCSN and the contribution of nuclear experiments

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With:

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Rémi Bougault (LPC, France)
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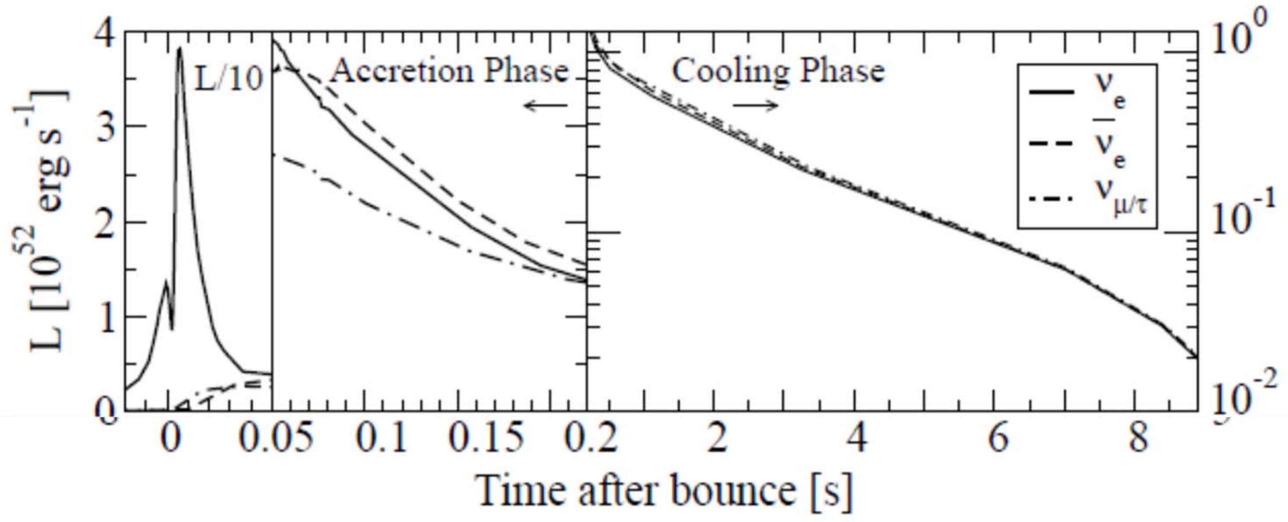
Neutrinos from CCSN

- Neutrinos are continuously emitted during SN evolution
- Three stages: infall and neutronization burst, accretion, and KH cooling.

1. **Prompt neutrinos: the role of e-capture**
   => charge exchange and β-decay
3. **Cooling phase: matter composition at the ν-sphere**
   => chemical constants



L.Hudepohl et al PRL 104 251101

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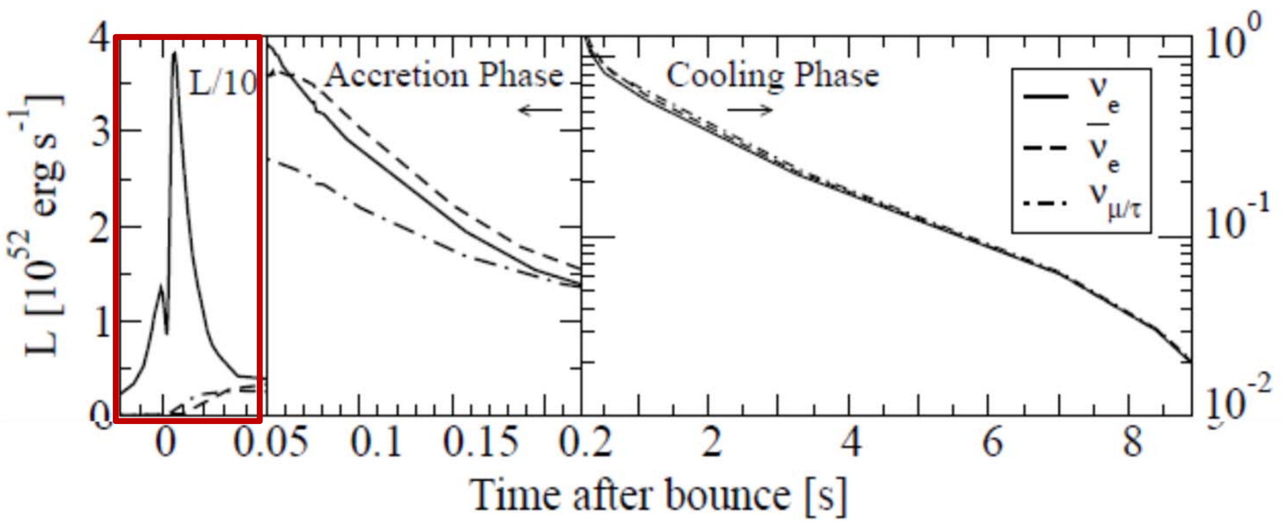

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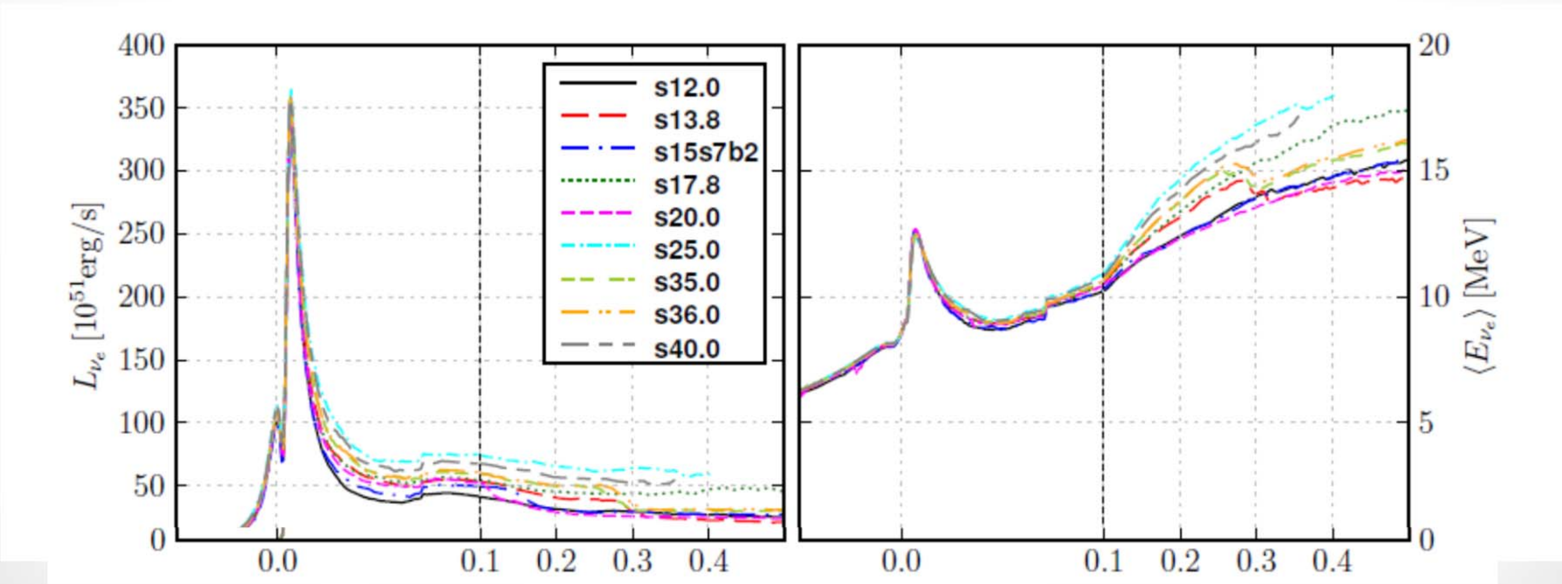
Prompt ν burst from collapse and early post-bounce

- t-t_b <100 ms : 1D dynamics, reduced progenitor dependence

=> A strong case for testing microphysics!



- L.Hudepohl et al, http://www.mpagarching.mpg.de/ccsnarchive
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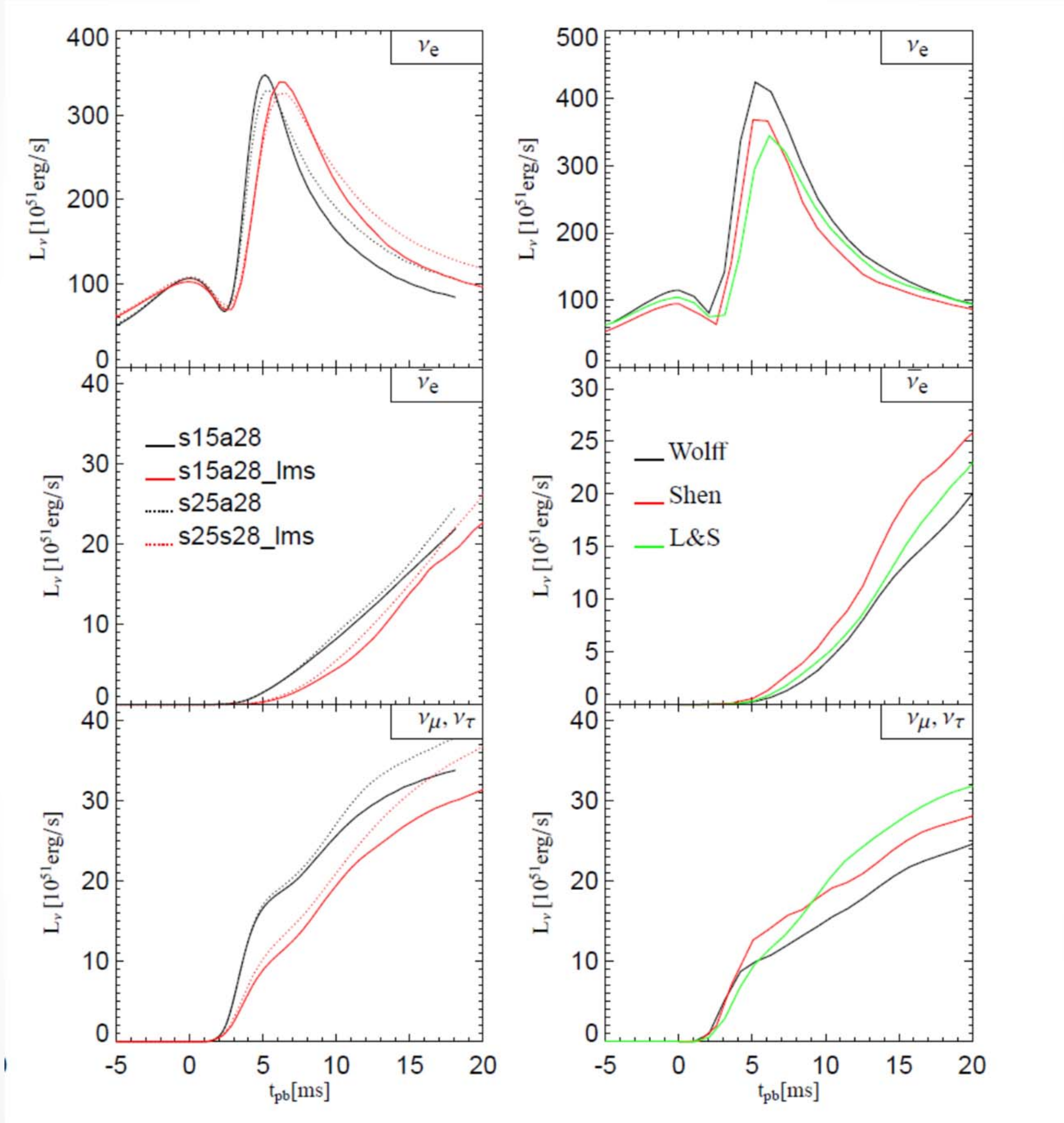
M.Kachelries et al. PRD71 063003 (2005)



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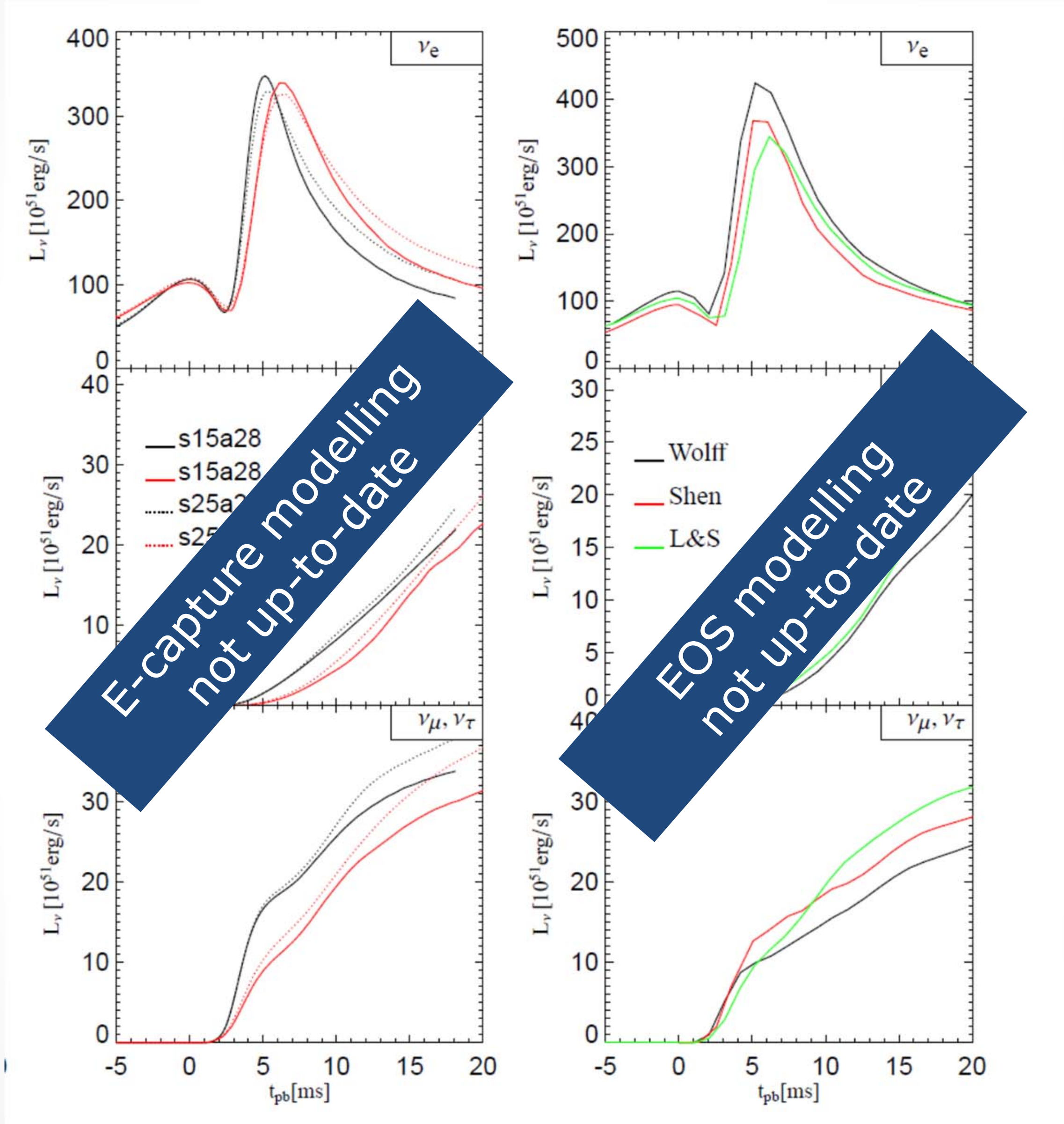


Simulations set-up

- CoCoNut hydro code in GR
    - o neutrino loss in FMT scheme

J.Novak ASCL 2012
B.Peres PRD 2013

- **Progenitors** from Woosely et al.

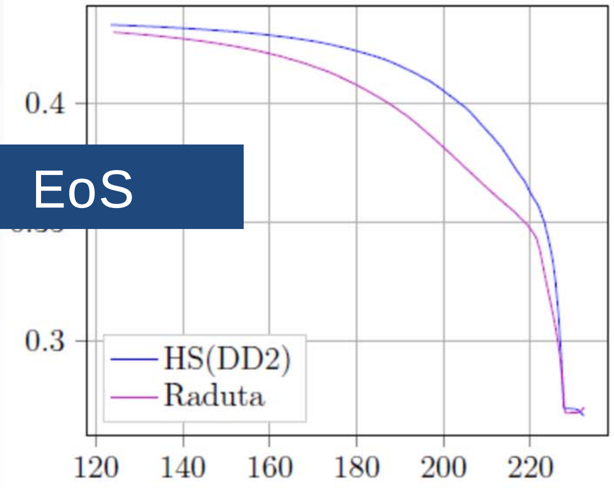
S.E.Woosley
Rev.Mod.Phys.2002

- **EoS** effect: realistic models with full nuclear distributions (HS-DD2 & Raduta-Gulminelli)
- **Mass effect**: HFB24 versus DZ10 and LDM
- **Electron-capture rates** : Bruenn versus LMP(0) and LMP(3)

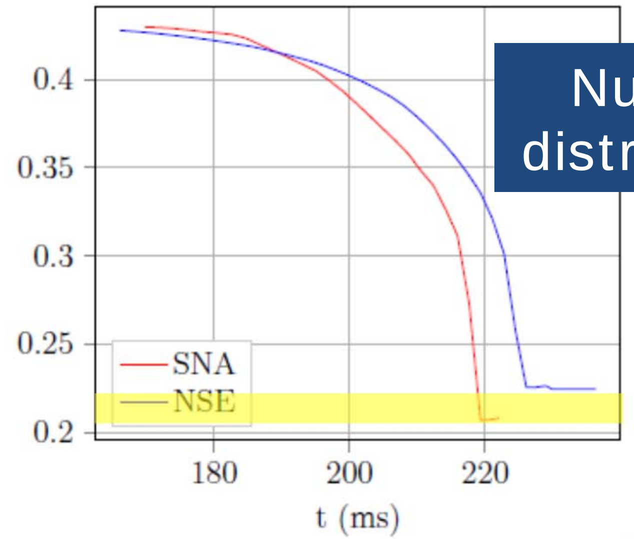
Results: $Y_e(t)$ in the central element

A.Pascal et al PRC 2020

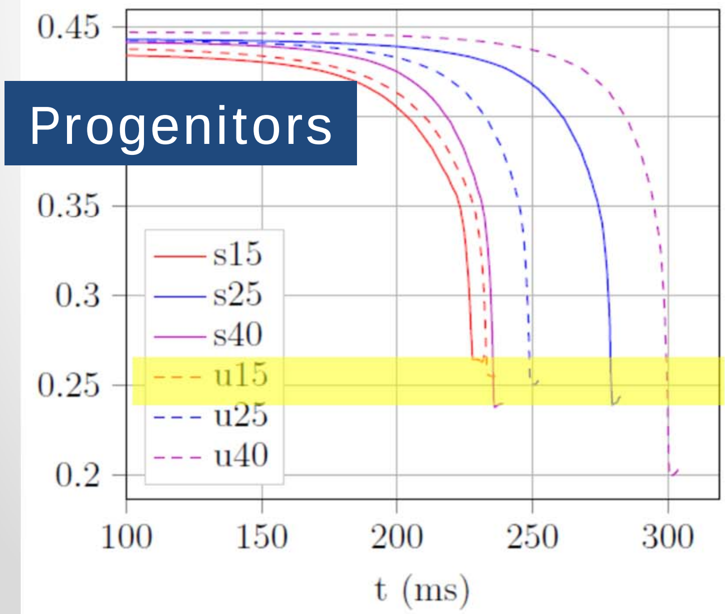
EoS



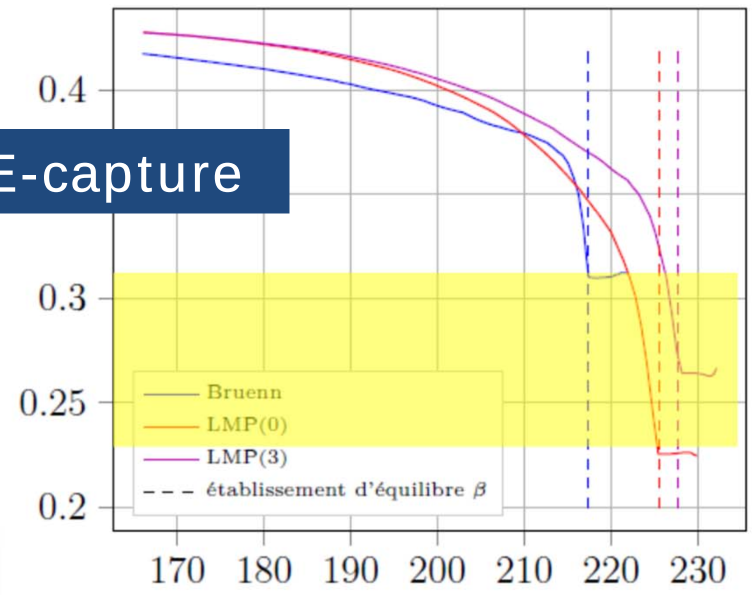
Nuclear distribution



Progenitors



E-capture



Simulations set-up

- CoCoNut hydro code in GR
  - neutrino loss in FMT scheme
  - full NSE from CompOse tables

J.Novak ASCL 2012
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- **EoS** effect: realistic models with full nuclear distributions (HS-DD2 & Raduta&Gulminelli)
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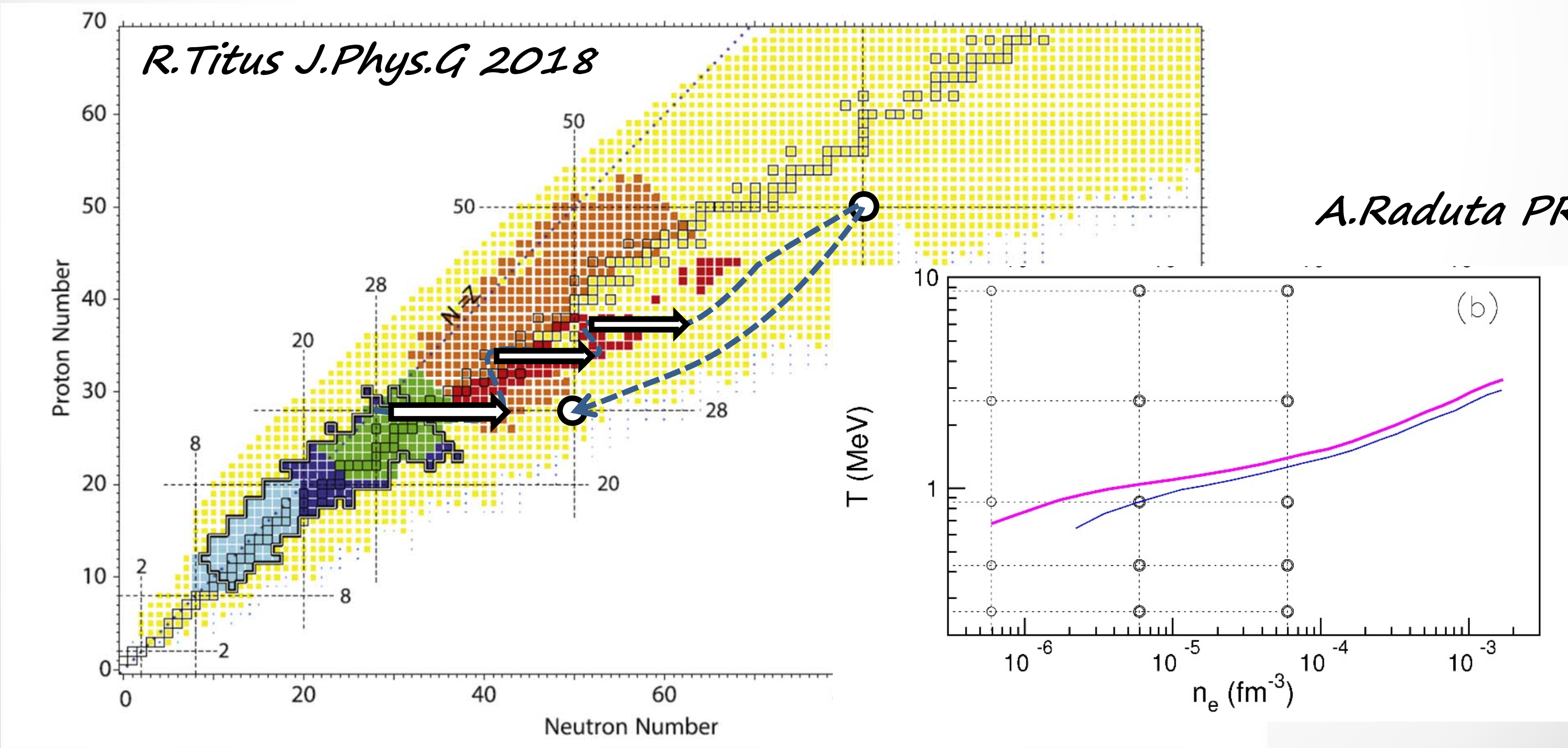
Electron capture rates

- $$\lambda^{EC}(A,Z) = \frac{ln2}{K}\sum_i \frac{(2J_i+1)e^{-\beta E_i}}{Z_\beta}\sum_j \int_{e_m}^{\infty} de\, f\left(e,Q,\Delta E_{ij}\right)B_{ij}$$

- Tabulated SM calculations of EC rates are only available for sd and fp nuclei at low ρ_e, while in the late stage of the collapse, exotic nuclei and high ρ_e dominate

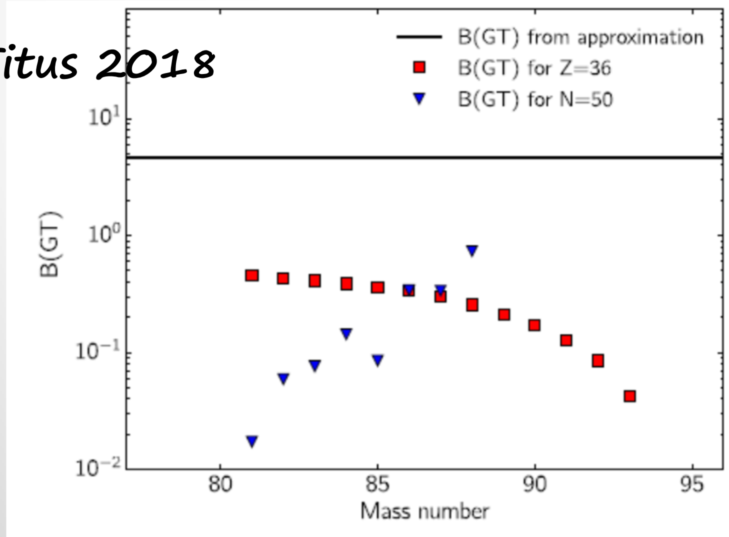


Approximations

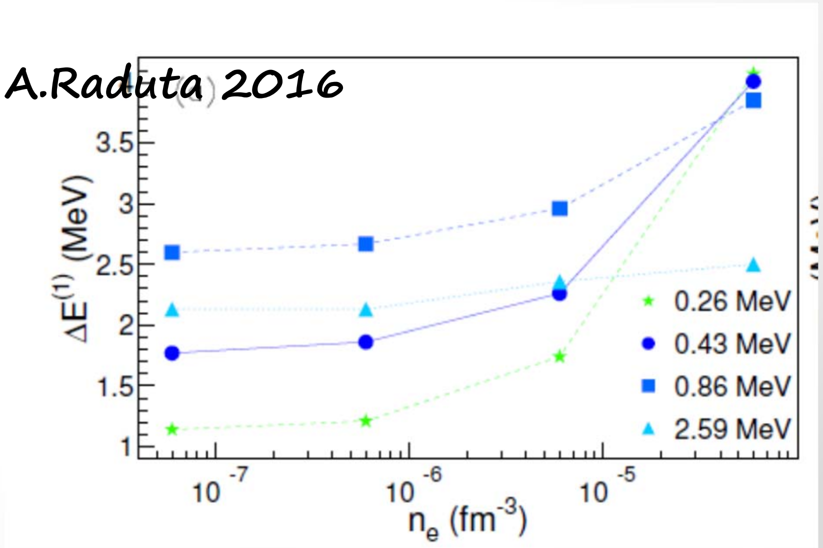
- $\boxed{\lambda^{EC}(A,Z) = \frac{ln2}{K} \cancel{\sum_i} \frac{(2J_i+1)e^{-\beta E_i}}{Z_\beta} \cancel{\sum_j} \int_{e_m}^{\infty} de\, f\left(e, Q, \Delta E_{ij}\right) B_{ij}}$

1. $\Delta E_{ij} = 3;\ Q = \mu_n - \mu_p; B_{ij} = \frac{2}{7} N_p(Z) N_h(N)$ => no capture beyond N=40 **BRUENN** **S.W.Bruenn ApJ 1985**
2. $\Delta E_{ij} = 2.5;\ B_{ij} = 3.6$ **LMP(0)** ***K.Langanke PRL 2003***
3. $\Delta E_{ij} = f(I, T, \rho_e);\ B_{ij} = 3.6$ **LMP(3)** ***A.Raduta PRC 2016***
   plus odd-even effects fitted from LSSM

R.Titus 2018

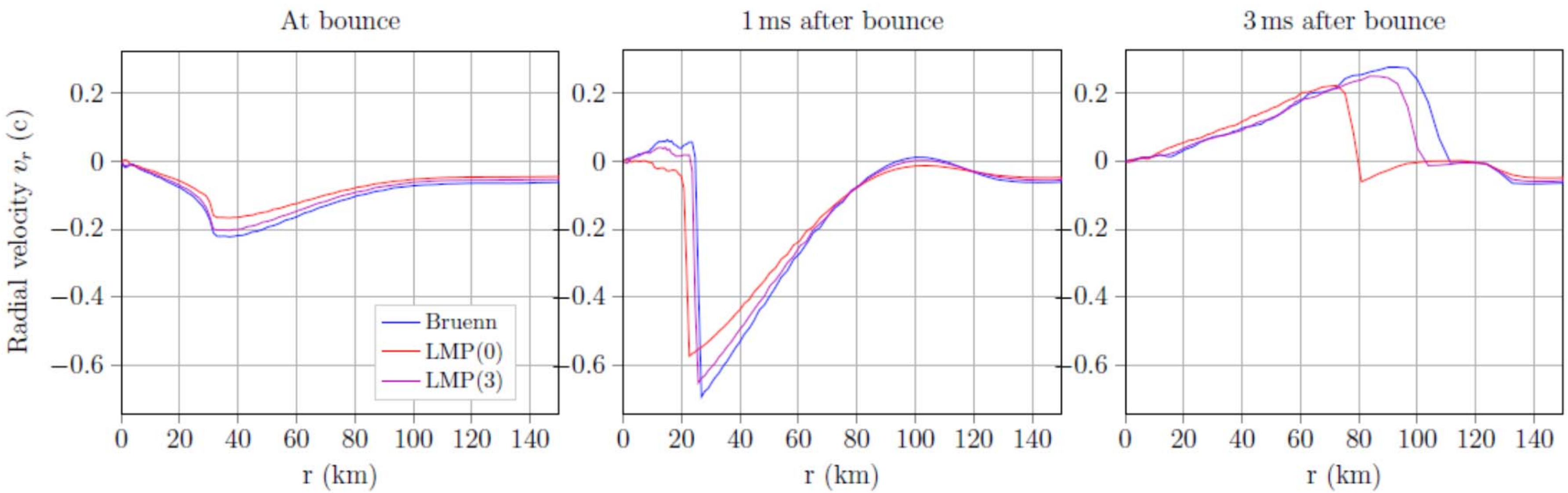


A.Raduta 2016



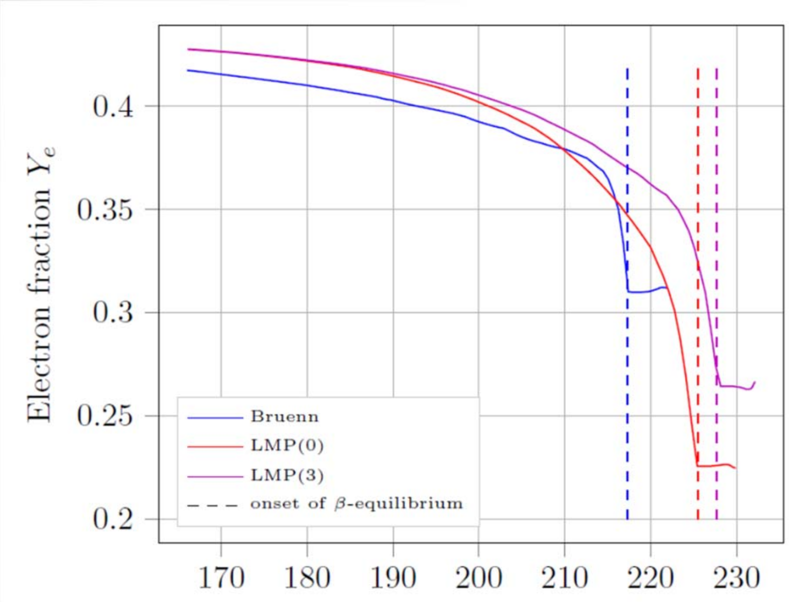
Results

A.Pascal et al PRC 2020



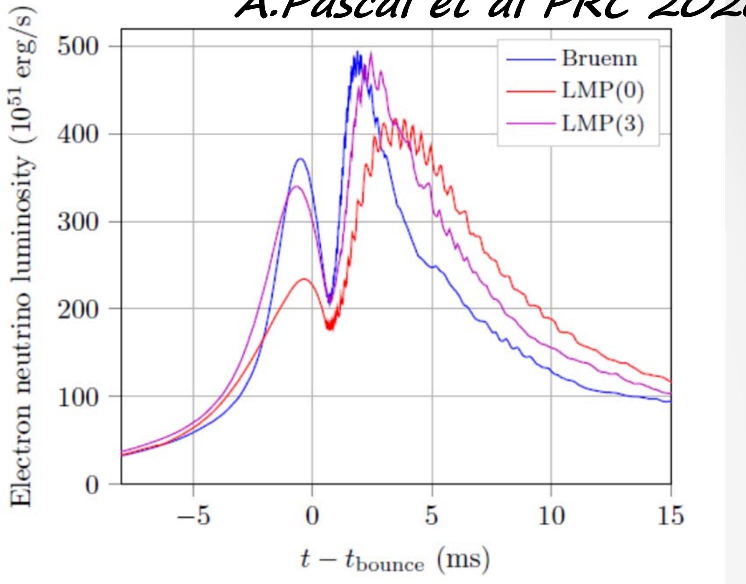
- Important effect of the different approx on the e-fraction dynamics
- Leads to a difference $\Delta Y_e/Y_e$=30% => $\Delta M_h/M_h$=30% in the enclosed mass at bounce
- Sizeable effect in the shock propagation after bounce

Results

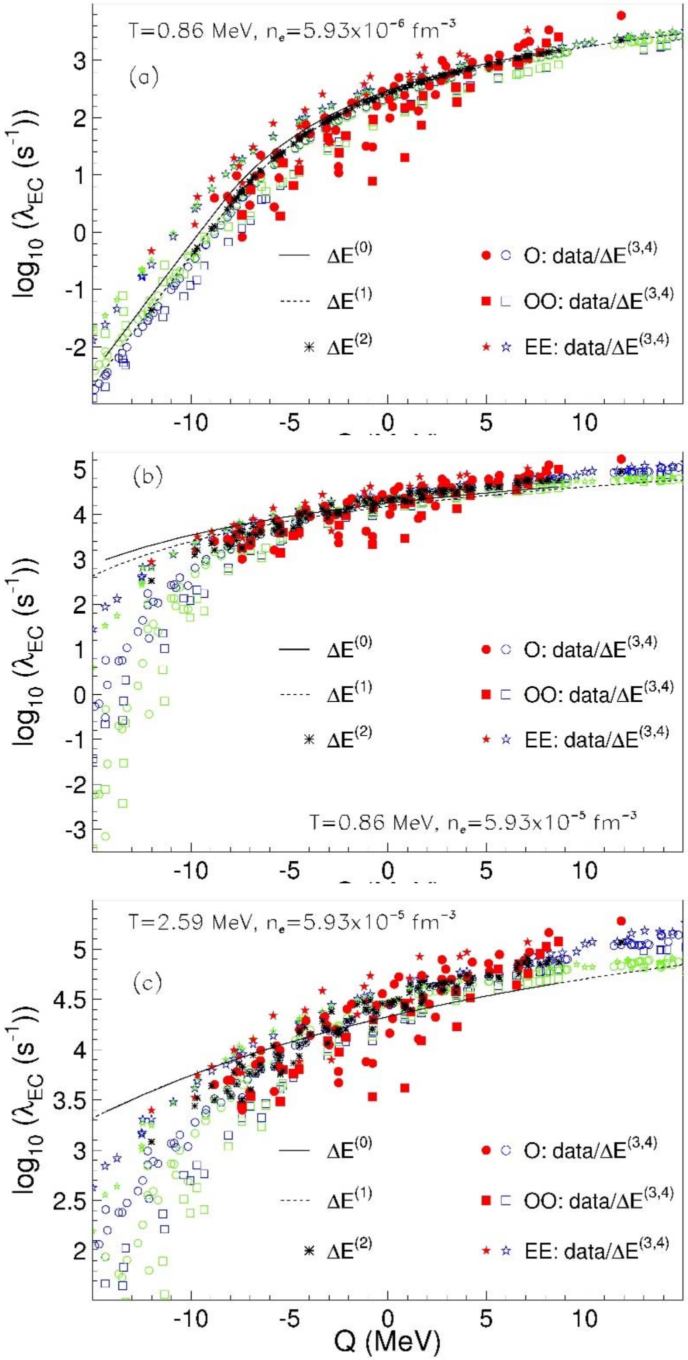


t(ms)

A.Pascal et al PRC 2020



- Important effect of the different approx on the e-fraction dynamics
- Leads to a difference $\Delta Y_e/Y_e$=30% => $\Delta M_h/M_h$=30% in the enclosed mass at bounce
- Reflects into the neutrino luminosity



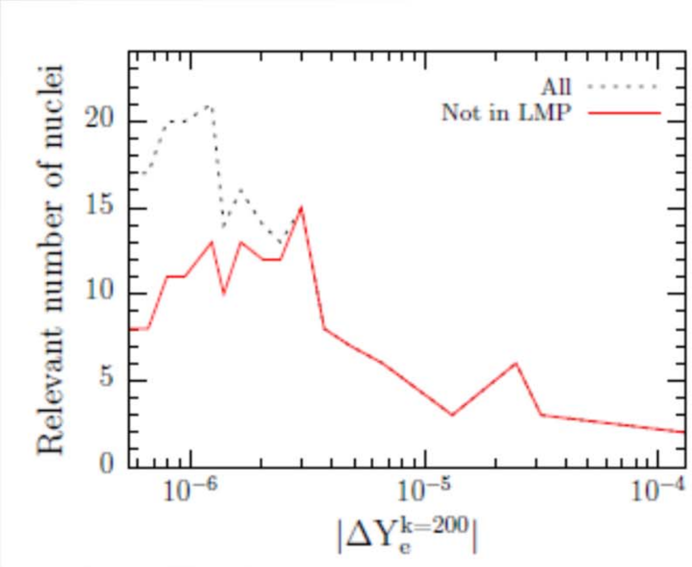
Which model is correct?

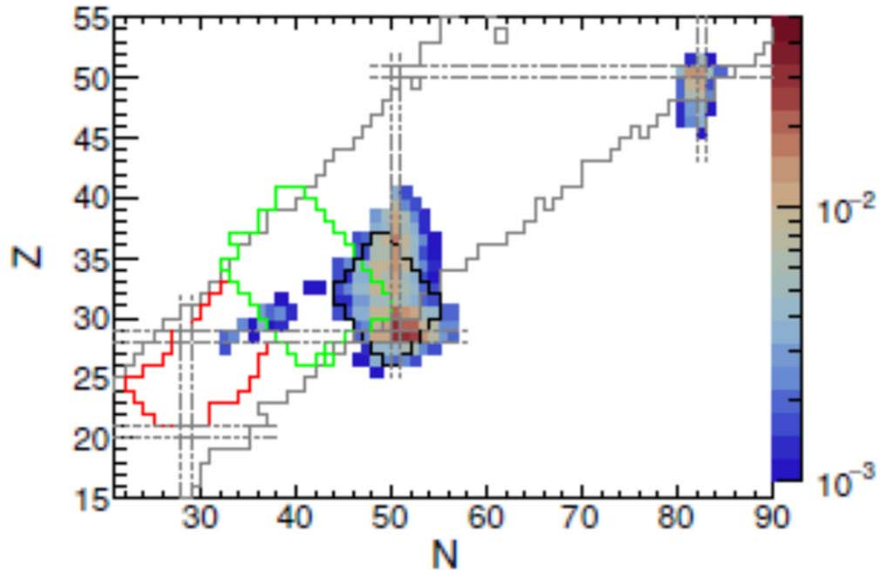
- LMP(3) contains more nuclear physics and leads to a better reproduction of microscopic rates
- Still the differences between LMP(0) and LMP(3) concern low Q-values where microscopic rates do not exist
- => Need to benchmark on exp data/microscopic calculations for some relevant nuclei

Tabulated SM calculations: K.Langanke
Fit: A.Raduta et al. PRC 2016

The most important nuclei for EC

A.Pascal et al PRC 2020



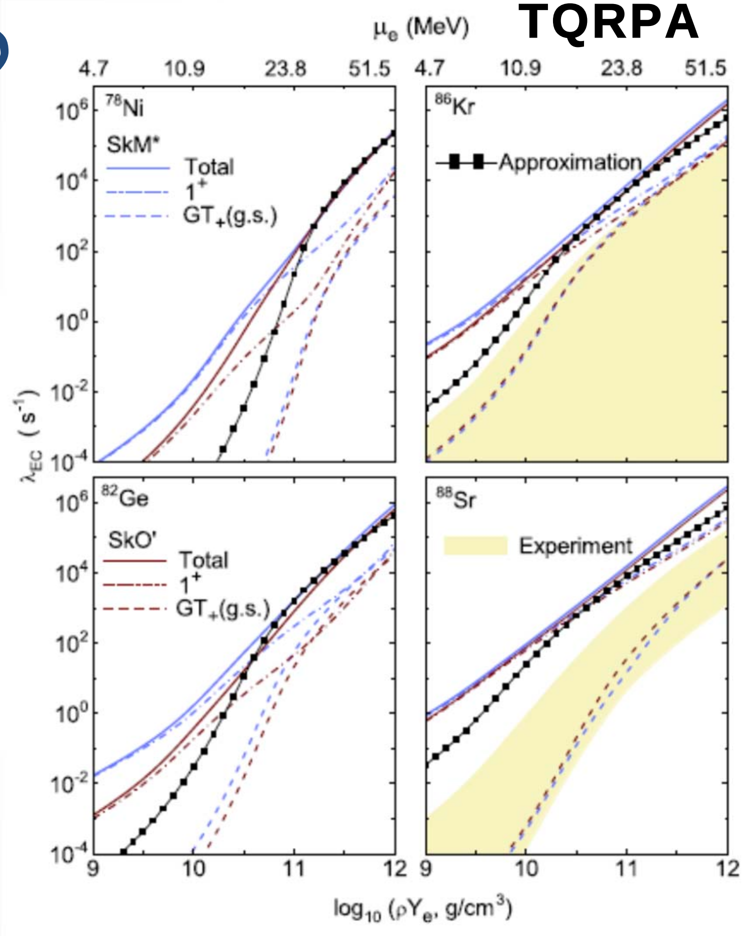


- In the advanced stage of the collapse, not more than 5 nuclei insure 50% of the total capture rate at each time
- 170 nuclei insure 90% of the total rate until neutrino trapping

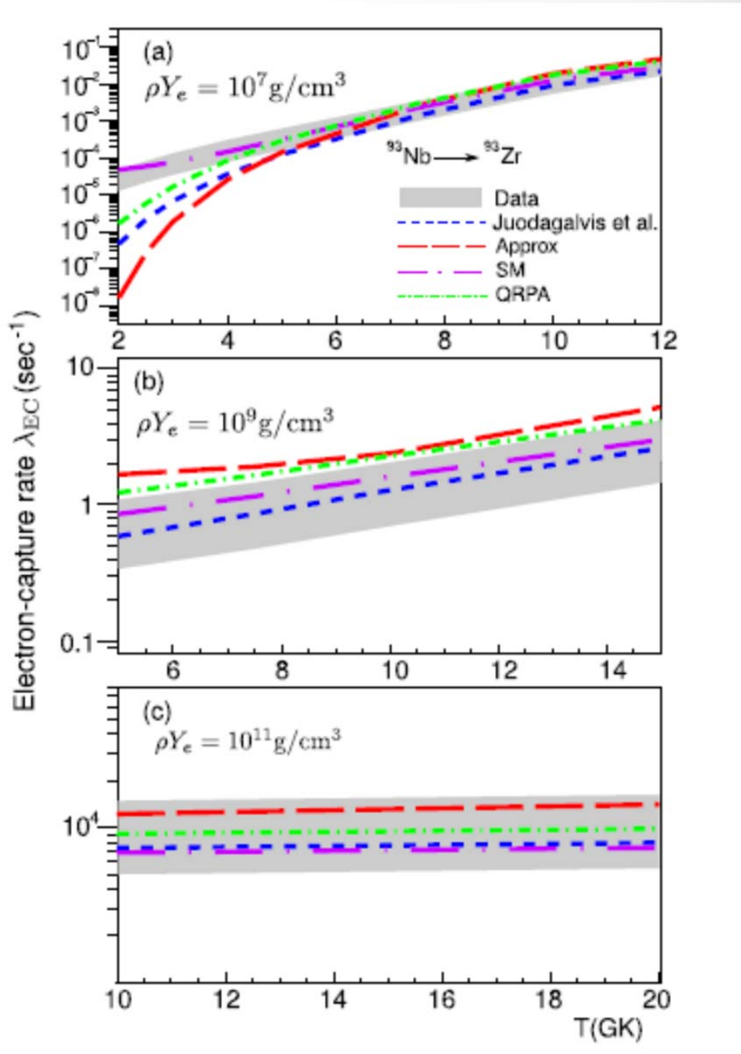
See also C.Sullivan ApJ 2016
R.Titus J.Phys.G 2018

New data and new calculations ~ N=50

TQRPA



^{93}Nb(t,^{3}He+γ)

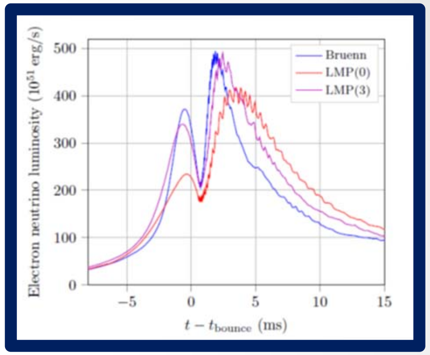


A.A.Dzhioev et al. PRC 101 (2020) 025805

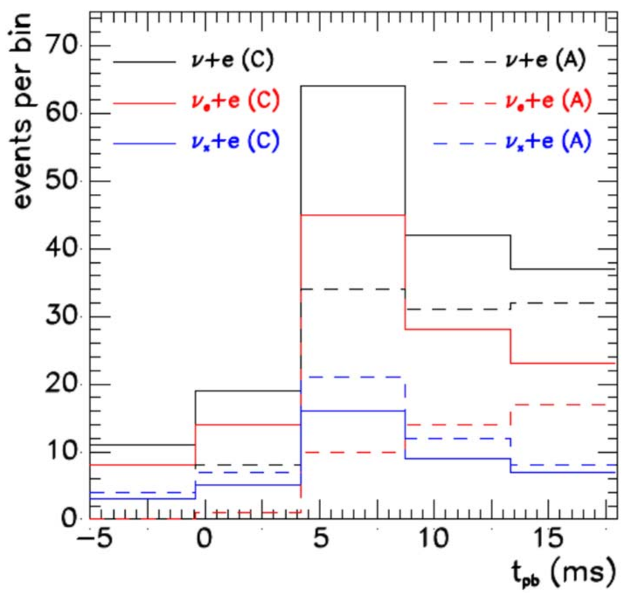
J.C.Zamora et al, PRC 100 (2019), 032801(R)

B.Gao et al. PRC 101 (2020) 014308

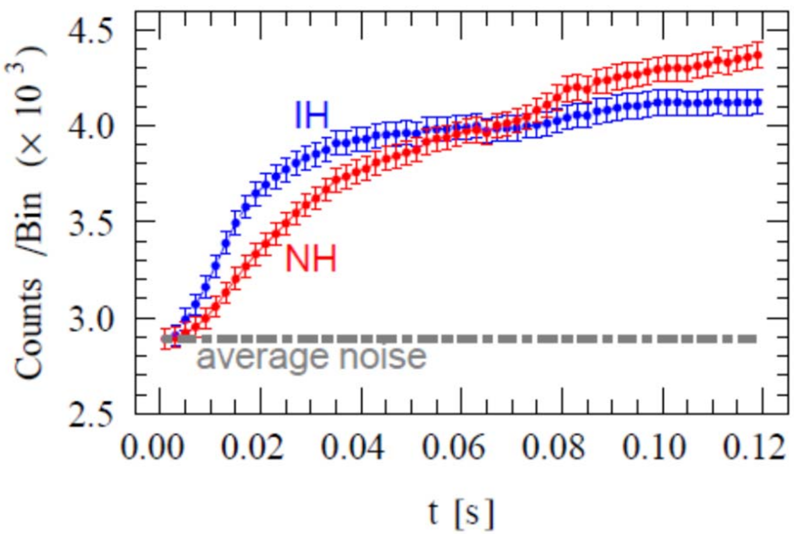
Nuclear physics constrained burst: Implications on the ν mass hierarchy



- NH (A): $\Delta m^2_{atm} = m^2_3 - m^2_{1,2} > 0$ & $\theta_{13} \gtrsim 10^{-3}$
- IH (B): $\Delta m^2_{atm} = m^2_3 - m^2_{1,2} < 0$ & $\theta_{13} \gtrsim 10^{-3}$
- (C) $\theta_{13} \lesssim 10^{-5}$



ICECUBE 10 kpc, 15 M⊙



M.Kachelries et al PRD71 063003

P. Serpico et al. PRD85 085031

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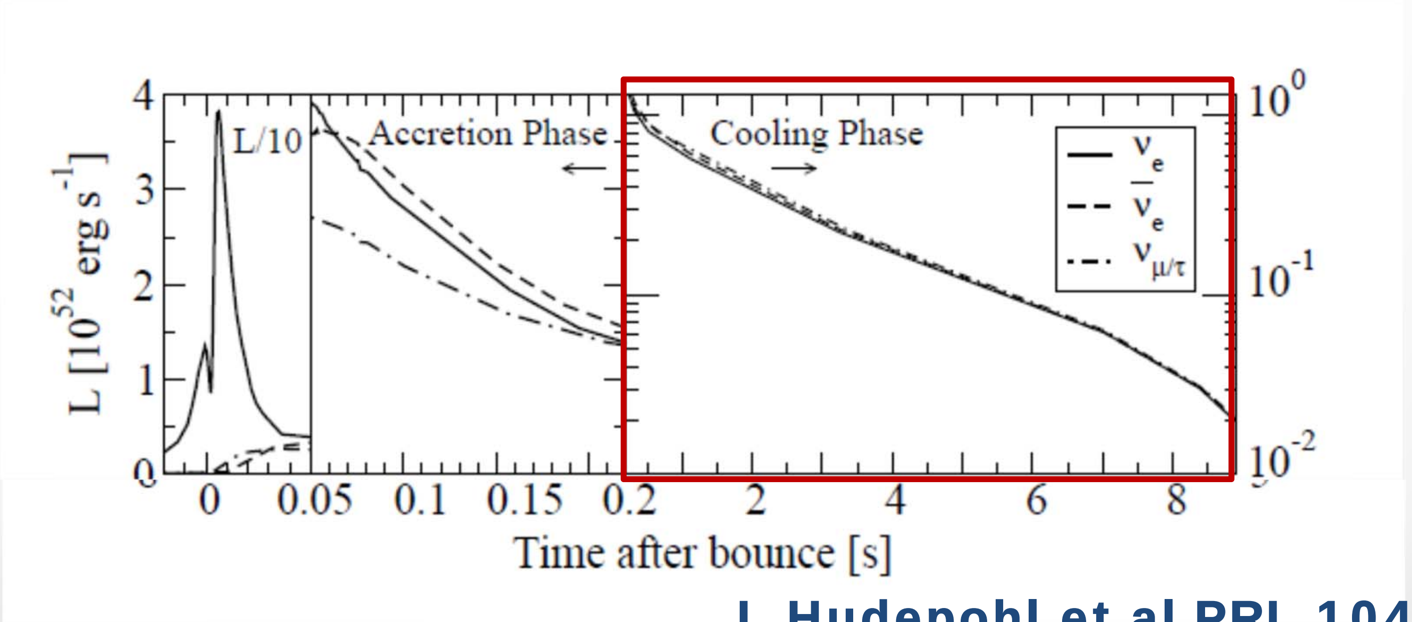

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PNS deleptonization and r-process seeds:

- Typical thermo conditions at the PNS surface ~5s after the explosion onset
- Deleptonization driven by ν interactions with light clusters => r-process seeds
- But com
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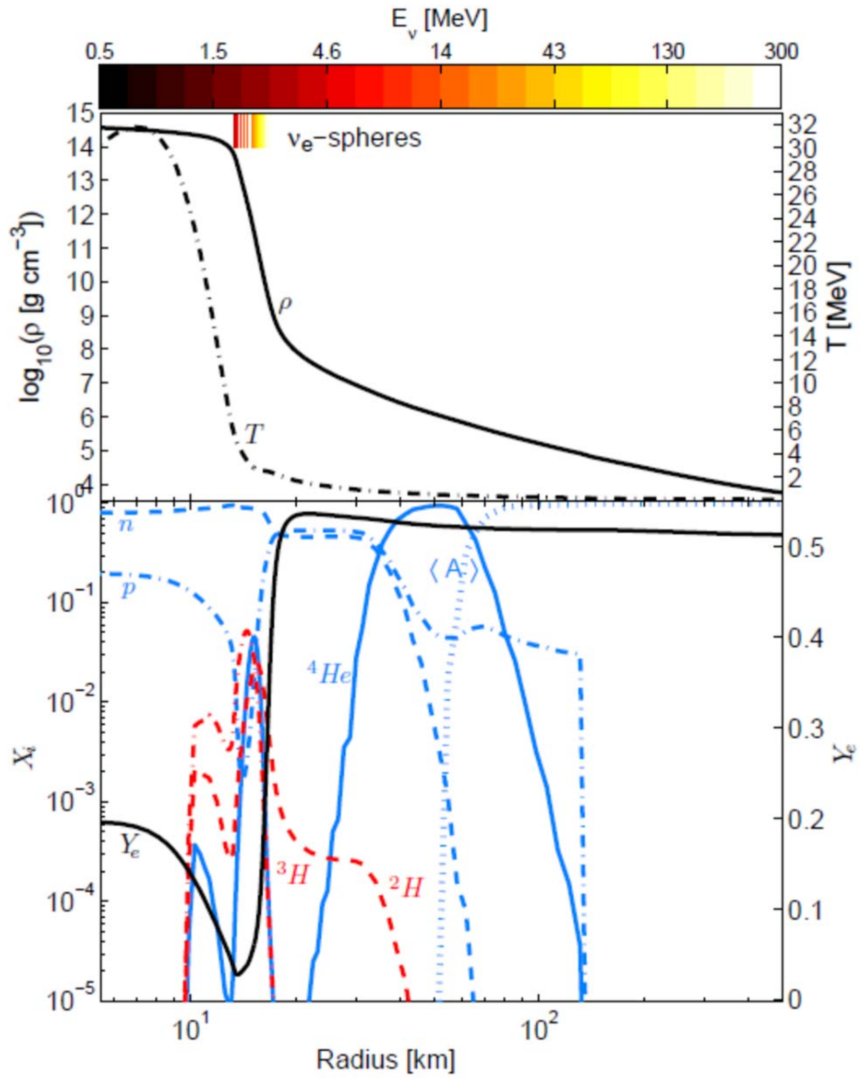
  energy



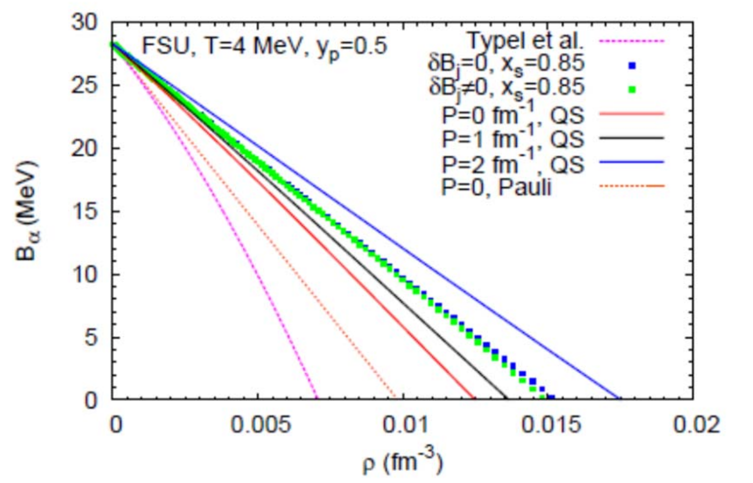
(b) PNS deleptonization phase.

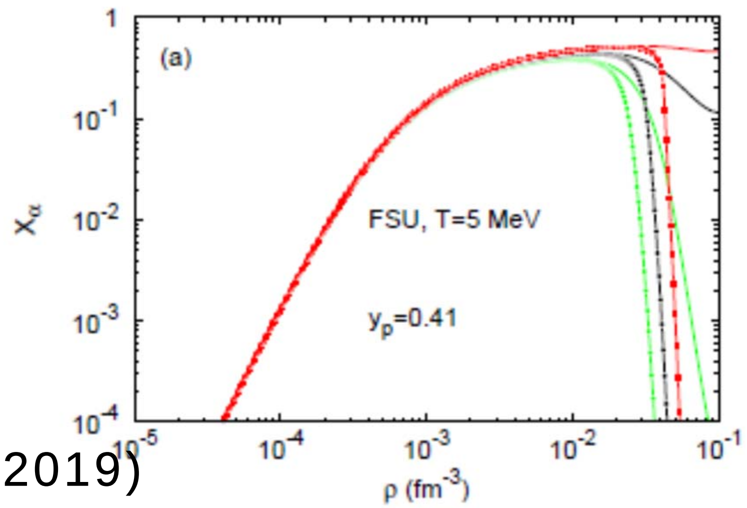
T.Fischer et al Eur. Phys. J. A50, 46

PNS deleptonization and r-process seeds:

$$n_i = \frac{1}{\pi^2}\int_0^\infty dp\,p^2 f_i(e_i^*) \quad e_i^* = \sqrt{p^2 + M_i^{*2}}$$

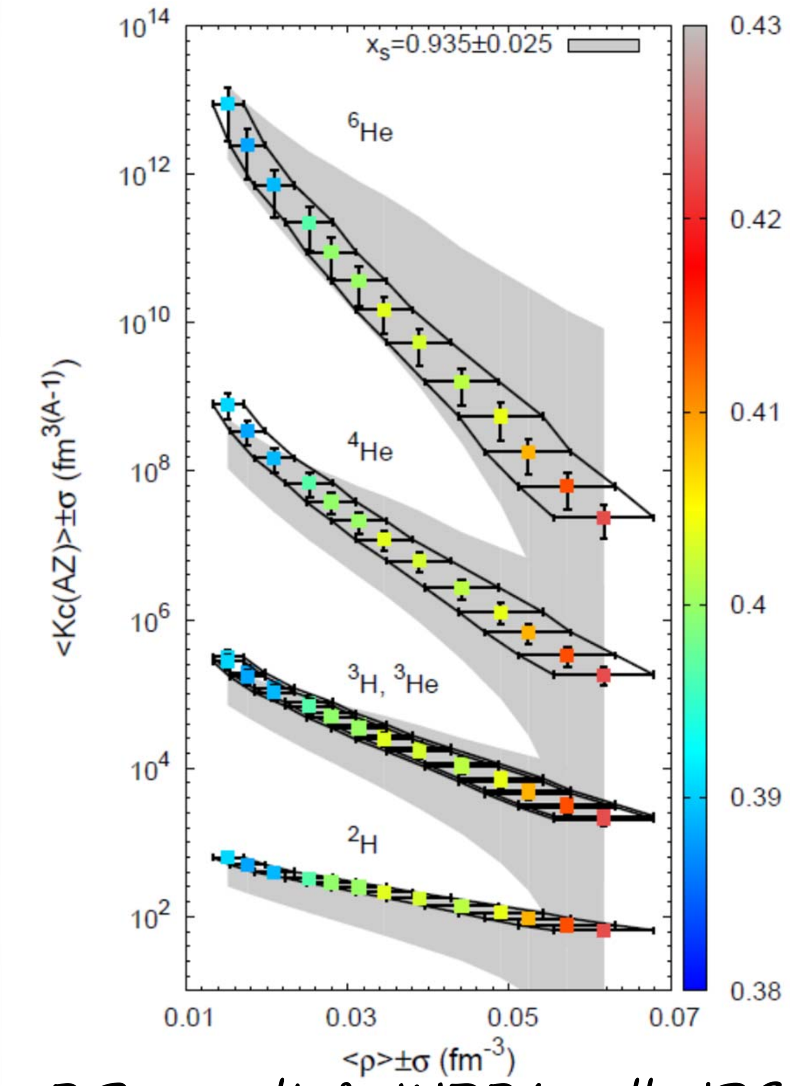
- Typical thermo conditions at the PNS surface ~5s after the explosion onset
- Deleptonization driven by ν interactions with light clusters => r-process seeds
- But composition depends on the in-medium modifications to the binding energy





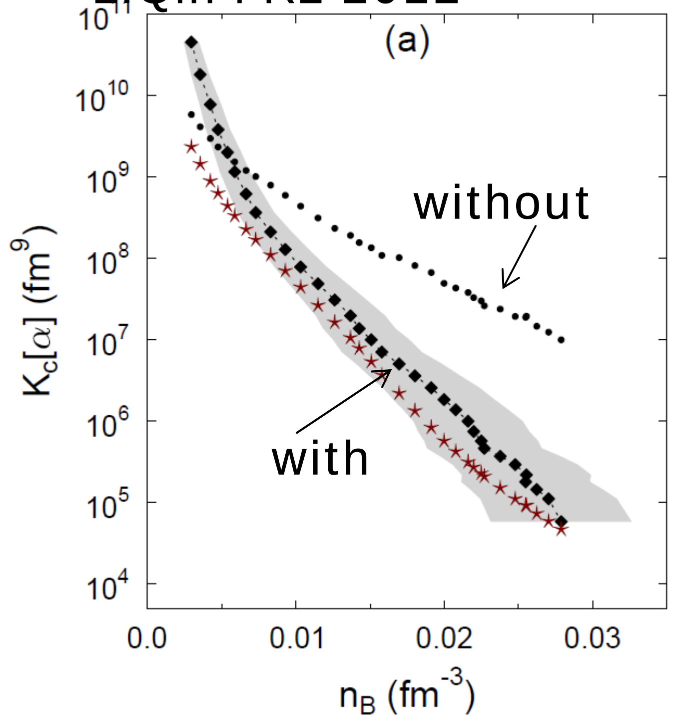
- H.Pais et al Phys. Rev. C 99 055806 (2019)

Chemical constants from multi-fragmentation



$$K_c(A,Z) = \frac{\rho_{pa}(A,Z)}{\rho_{pa}(1,1)^Z\ \rho_{pa}(1,0)^N}$$

L.Qin PRL 2012



R.Bougault & INDRA coll. JPG (2019)
H.Pais & INDRA coll. ArXiV 2020

Conclusions

- Contribution of nuclear physics experiments (**and theory!**) to the modelling of the neutrino signal in CCSN

1) Collapse and neutronization burst: essentially governed by e-capture rates

$\Rightarrow$ Residual model dependence to be benchmarked on experiments and calculations on sensitive nuclei

2) Early PNS cooling phase and initial conditions for r-process nucleosynthesis: need of a reliable modeling of the composition close to the neutrinosphere

=> cluster abundancies from HI collisions to settle the in-medium binding energy shifts

ERASMUS MUNDUS JOINT MASTER DEGREE IN NUCLEAR PHYSICS

Co-funded by the Erasmus+ Programme of the European Union

www.emm-nucphys.eu nucphysinfo@us.es

SPECIALIZATION PATHS

- Experimental / large accelerators
- Theoretical
- Applied / small accelerators

NUMBER OF ECTS CREDITS

- 120 (60 ECTS / year)

PUBLIC FEES

- 4500 euro / year Program Country Students

LANGUAGE OF INSTRUCTION

- English

HOST INSTITUTIONS

- University of Seville (Spain)
- University of Barcelona (Spain)
- University Complutense of Madrid (Spain)
- University Autonoma of Madrid (Spain)
- University of Catania (Italy)
- University of Padova (Italy)
- University of Caen (France)

DESCRIPTION AND OBJECTIVES

NucPhys is a 2-year Erasmus Mundus Master in Nuclear Physics (120 ECTS) and it is offered by a consortium of 7 partner universities in Spain, France and Italy, **with the participation of more than 30 research institutions/companies as associated partners worldwide**. Nuclear Physics is a broad matter of relevance from both the fundamental knowledge of Nature and the multiple applications to different fields of strategic economical relevance. Consequently, in this Master, fundamental theory and experiments as well as applications will be presented.

The main objective of the Master programme is to provide top-ranked students with an excellent background in Nuclear Physics so as to educate experts and foster their future career in this field. At the same time, NucPhys students carry out their master studies in least 3 countries, in a stimulating and scientifically excellent international environment, including Research internships (12 ECTS) carried out in companies or research institutions.

ADMISSION PROFILE

- NucPhys is aimed at all graduated in Physics, Chemistry, Engineering, Applied Mathematics or any other kind of scientist or engineer degree.
- Candidates from countries where English is not one of the official languages, must demonstrate their knowledge of English with a certified language level equivalent to B2 using the CEFR (Common European Framework of Reference for Languages).

15 ERASMUS+ SCHOLARSHIPS AVAILABLE

The Master scholarships from the ERASMUS + program include	Partner Country Up to 3 scholarships	Programme Country Up to 12 scholarships
Contribution to travel, installation and any other type of costs	up to € 3000 per year for costs for scholarship holder resident in a partner country. € 1000 for installation costs.	up to € 1000 per year per scholarship holder resident in a Programme Country for travel & installation costs
Contribution to subsistence costs (for both Programme and Partner Country scholarship holders)	€ 1000 / month for the entire duration of the EM study programme (24 months maximum)	
Contribution to participation costs	€ 18000 for the entire duration of the EM study programme (24 months) (this will cover mainly the inscription costs in the Master)	€ 9000 for the entire duration of the EM study programme (24 months) (this will cover mainly the inscription costs in the Master)

NUCPHYS WILL BE PARTICULARLY USEFUL FOR

- Research in the field of Fundamental Subatomic Physics
- Medical physics and hadrontherapy
- Radiology
- Environmental radioactivity
- Nuclear techniques for multi-elemental analysis
- Nuclear dating techniques
- Nuclear power plants and waste management