Non-uniform (warm) matter and cluster distribution in core-collapse supernovae

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S. Giraud (GANIL)

Supernova Remnant 1987A in the Large Magellanic Cloud. HUBBLESITE.org

Open questions

- Treatment of non-uniform matter ?
  1. cluster formation & interactions
  2. SNA vs NSE

  → formalism to include cluster distribution in EoS
  & application in CCSNe

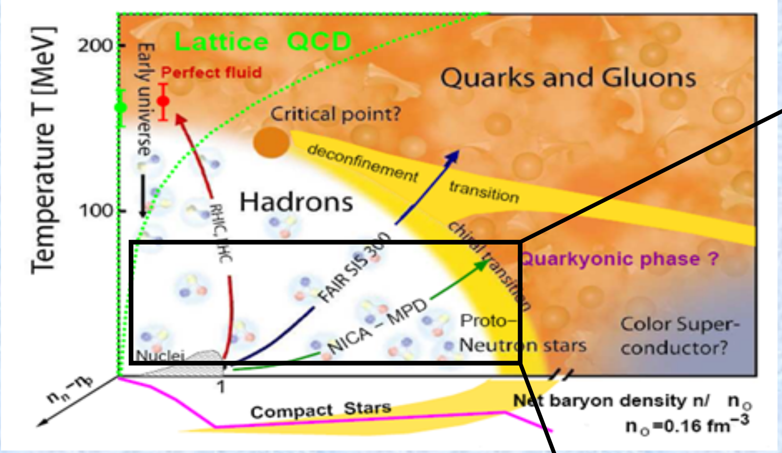
- Relevance of specific nuclear physics inputs / parameters ?

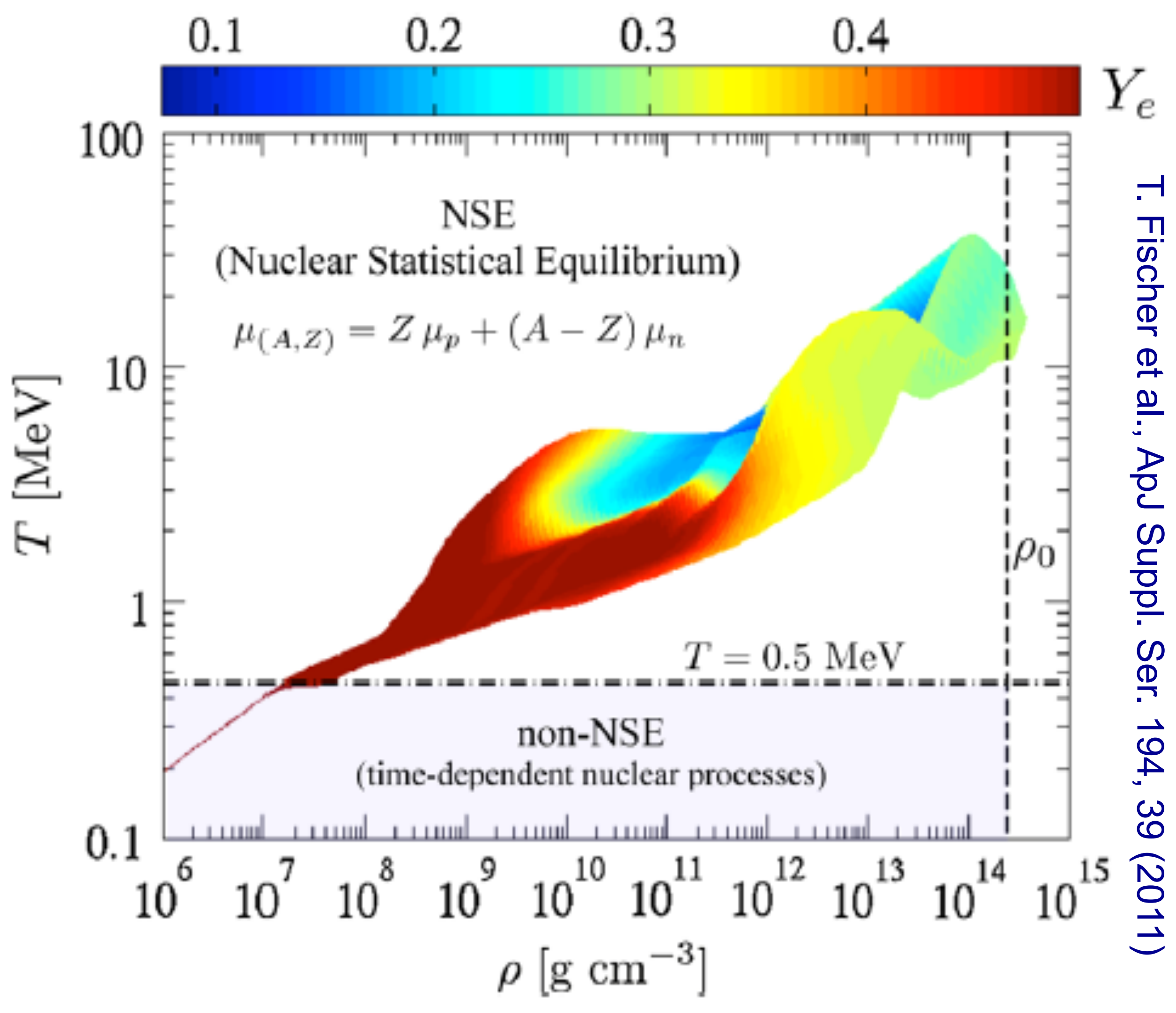
  → nuclear masses (experimental and reliable theoretical models)
  & CCSNe

Outline

- ❖ Introduction : EoS and treatment of non-uniform matter
- ❖ Nuclear distribution in CCSNe:
  - ▪ formalism for cluster distribution in a SNA EoS
  - ▪ impact of nuclear masses
- ❖ Conclusions

Probing extreme conditions in SNe





T. Fischer et al., ApJ Suppl. Ser. 194, 39 (2011)

Condition in the core
during collapse
and NS formation :

$$\begin{aligned} \rho &\in [10^5 - 10^{15}]\ \mathrm{g\ cm^{-3}} \\ T &\in [0.1 - 100]\ \mathrm{MeV} \\ Y_e &\in [0.05 - 0.5] \end{aligned}$$

At present, best 3D hydro simulations do not reproduce satisfactory CCSN explosions !

see e.g., for a review, Oertel *et al.*, Rev. Mod. Phys. 89, 015007 (2017)
Burgio & Fantina, Chap. 6 white book COST/NewCompStar, to be published

Probing extreme conditions in CC

We focus on **infall phase**

- mostly at sub-saturation
- mostly *T* up to a few MeV

→ nuclei

$$\begin{aligned} \rho &\approx [10^9 - \text{few } 10^{14}]\ \text{g cm}^{-3} \\ T &\approx [0.6 - 20]\ \text{MeV} \\ Y_e &\approx [0.2 - 0.5] \end{aligned}$$

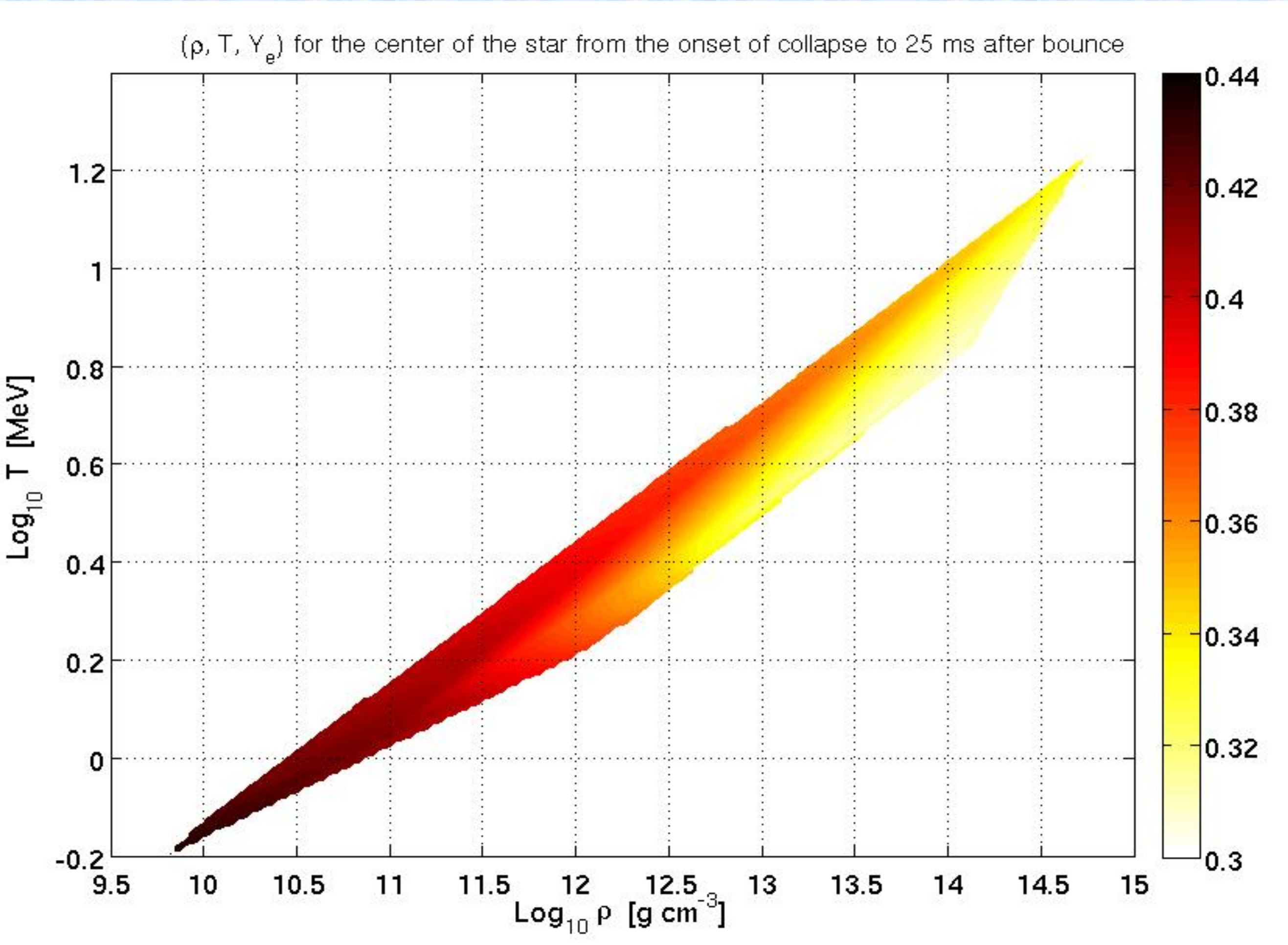
For CC key nuclear data are:

- ➢ **EoS ←→ Nuclear masses, level densities,...**
- ➢ **EC ←→ *Q*-val, GT response**
- ➢ **neutrino interactions**

⇒ All possible nuclear species

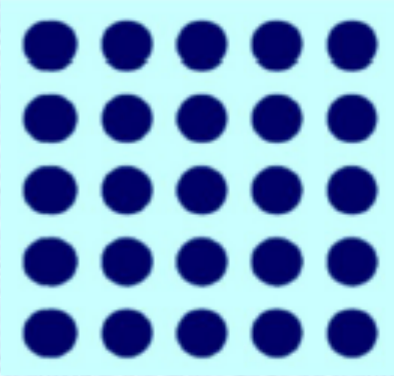
⇒ *What is the relevance of a specific nuclear physics input* ?

Simulation in 1D, GR (Fantina, PhD thesis (2010))



EoS in SN : SNA vs NSE

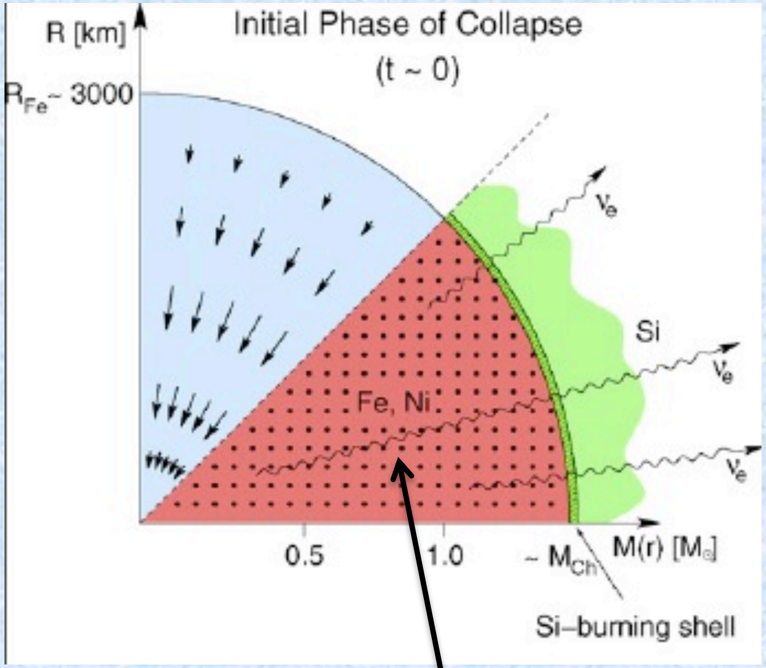
Single Nucleus Approximation (SNA)



- One “heavy” *(A,Z)* + gas *n, p,* e^- (+ alpha) for each thermo condition (n_B, T, Y_e)
- Used in most of EoSs in SN simulations

✓ OK for thermodynamic quantities
✓ Faster computationally

<u>BUT</u>:
➢ at finite T more microstates are populated
➢ reaction (EC) rates ?



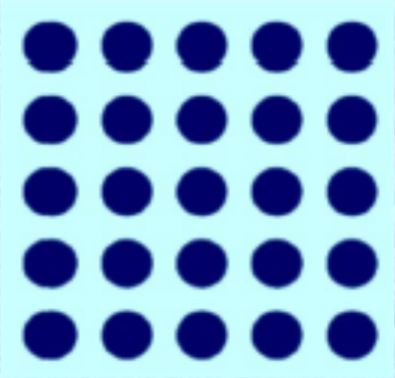
Nuclei + gas of nucleons and leptons

We focus on **infall phase**

- mostly at sub-saturation density
- mostly *T* up to a few MeV

EoS in SN : SNA vs NSE

Single Nucleus Approximation (SNA)



- One “heavy” *(A,Z)* + gas *n, p, e*$^-$ (+ alpha) for each thermo condition (n_B, T, Y_e)
- Used in most of EoSs in SN simulations

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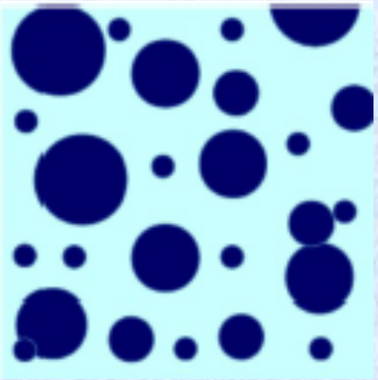
Nuclear Statistical Equilibrium (NSE)



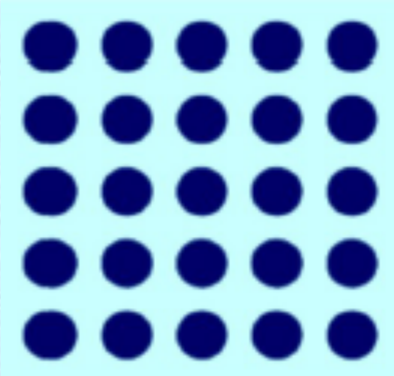
- Ensemble of nuclei (A_i, Z_i) + gas *n, p, e*$^-$ for each (n_B, T, Y_e)
- Some NSE EoSs implemented in simulations

✓ Distribution of nuclei

<u>BUT</u>:
➢ implemented as tables → no flexibility
➢ computationally expensive
→ difficult to perform systematic calculations

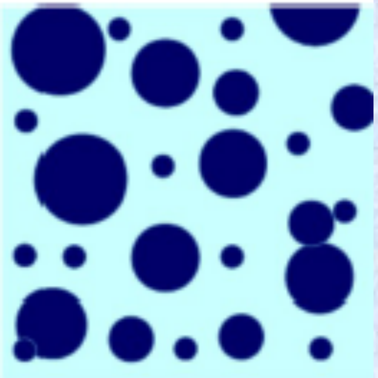
EoS in SN : SNA vs NSE

Single Nucleus Approximation (SNA)



- Compressible Liquid-drop models
  e.g. Baym et al. 1971, Lattimer & Swesty 1991,...
- (Extended) Thomas-Fermi
  e.g. Shen et al. 1998, Onsi et al. 2008, Shen et al. 2011,...
- Self-consistent mean field models
  e.g. Negele & Vautherin 1973, Baldo et al. 2007, Grill et al. 2011, Pais et al. 2014,...

Nuclear Statistical Equilibrium (NSE)



- (Extended) NSE
  e.g. Hillebrandt & Wolff 1985, Hempel & Schaffner-Bielich 2010, Raduta & Gulminelli 2010, Gulminelli & Raduta 2014, Furusawa et al. 2013, 2017
- + in-medium effects:
  Virial EoS, models with in-medium mass shifts; e.g. Horowitz & Schwenk 2006, Ropke et al. 2011,2013,2015, Typel et al. 2010, 2014, ...

e.g., for a review, Oertel *et al.*, Rev. Mod. Phys. 89, 015007 (2017) ; Burgio & Fantina, Chap. 6 white book COST/NewCompStar

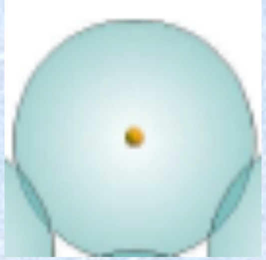
N.B. either using non-relativistic functional or RMF models

→ **Start from (any) EoS model based on the SNA and add NSE perturbatively**

Method in a nutshell (1)

Start from an EoS model with SNA and add NSE perturbatively

1. Start from the free energy density in a WS cell for an arbitrary EoS using SNA



$$F_{\rm WS} = \underbrace{F_{\rm nuc} + F_g}_{F_{bar}} + F_{\rm lept} + F_\gamma$$

$$\text{e.g. } F^{(j)}_{\rm nuc} = F^{(j)}_{\rm nuc}(A, Z, n_g, V_C)$$

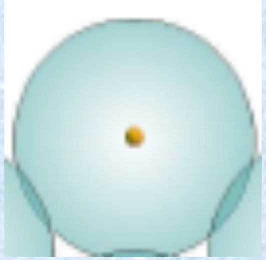
the total free energy of the system being

$$F_{\rm tot} = \sum_j N_j(k) F^{(j)}_{\rm WS} \qquad \langle N_j \rangle_k \longleftrightarrow \langle p_j \rangle_k \equiv p_j$$

Grams, Giraud, Fantina, Gulminelli, PRC 97, 035807 (2018)
Gulminelli & Raduta, PRC 92, 055803 (2015)

Method in a nutshell (2)

Start from an EoS model with SNA and add NSE perturbatively



1. Start from the free energy density in a WS cell for an arbitrary EoS using SNA

$$F_{\rm WS} = \underbrace{F_{\rm nuc} + F_g}_{F_{bar}} + F_{\rm lept} + F_\gamma$$

$$\text{e.g. } F^{(j)}_{\rm nuc} = F^{(j)}_{\rm nuc}(A, Z, n_g, V_C)$$

the total free energy of the system being

$$F_{\rm tot} = \sum_j N_j(k) F^{(j)}_{\rm WS} \qquad \langle N_j \rangle_k \longleftrightarrow \langle p_j \rangle_k \equiv p_j$$

2. Calculate the Gibbs free energy (Legendre transformation) working in a grand-canonical ensemble

$$G^{(j)}_{\rm nuc} = F^{(j)}_{\rm nuc} - \mu_n N^{(j)} - \mu_p Z^{(j)}$$

N.B. : *F* depends on the particular model employed

1. If F_{nuc} depends on the density (as in CLDM or EDF) → *rearrangement term* must be added !
2. In-medium effects (e.g. excluded volume) have to be accounted for !
3. the gas is kept as in the original model → only "non-uniform" part is changed

Grams, Giraud, Fantina, Gulminelli, PRC 97, 035807 (2018)
Gulminelli & Raduta, PRC 92, 055803 (2015)

Method in a nutshell (3)

Start from an EoS model with SNA and add NSE perturbatively

1. Start from the free energy density in a WS cell for an arbitrary EoS using SNA

2. Calculate the Gibbs free energy (Legendre transformation) working in a grand-canonical ensemble

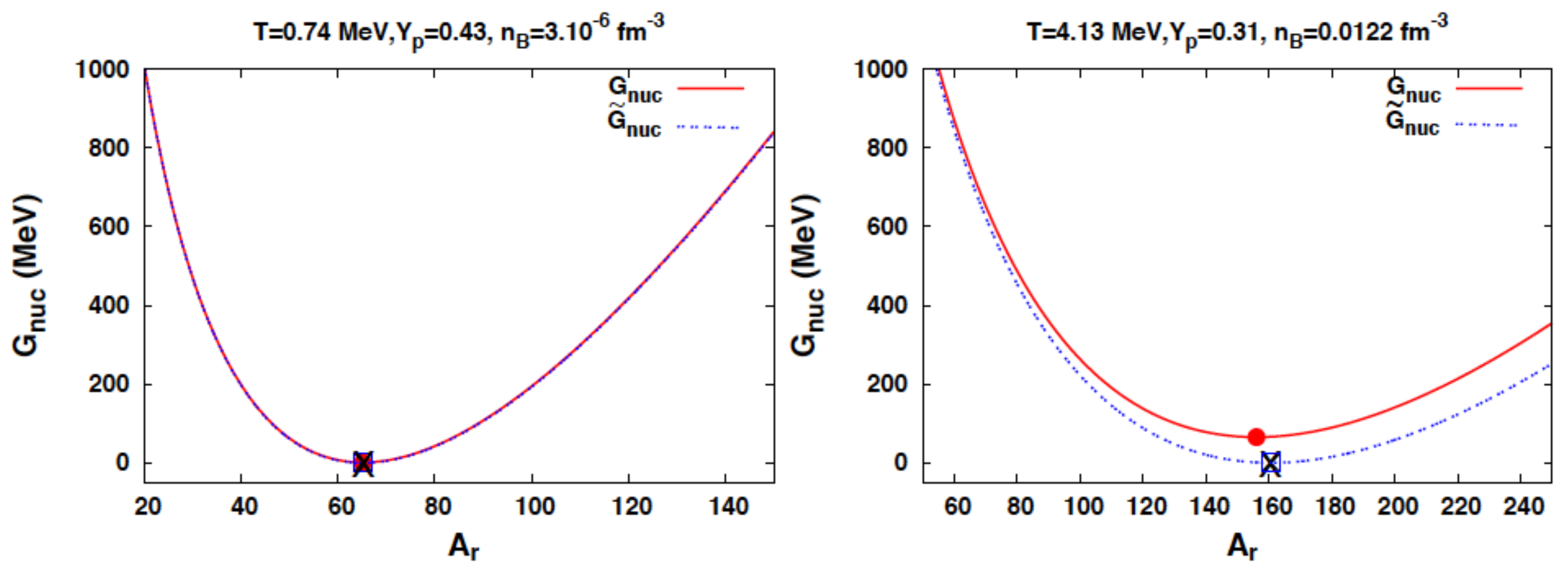
3. Construct the probability associated to a nucleus (*A,Z*) :

$$p_j = \frac{\langle N_j \rangle_k}{\sum_j \langle N_j \rangle_k} = \frac{\exp(-\tilde{G}^{(j)}_{\rm nuc}/k_B T)}{\sum_j \exp(-\tilde{G}^{(j)}_{\rm nuc}/k_B T)} \propto \exp(-\tilde{G}^{(j)}_{\rm nuc}/k_B T) \rightarrow p(A,Z)$$

- ✓ method is general
- ✓ masses are input in the model → can be changed
- ✓ we apply it to the Lattimer & Swesty (LS) EoS (based on CLDM) widely used in SN simulations (Lattimer & Swesty, Nucl. Phys. A 535, 331 (1991))

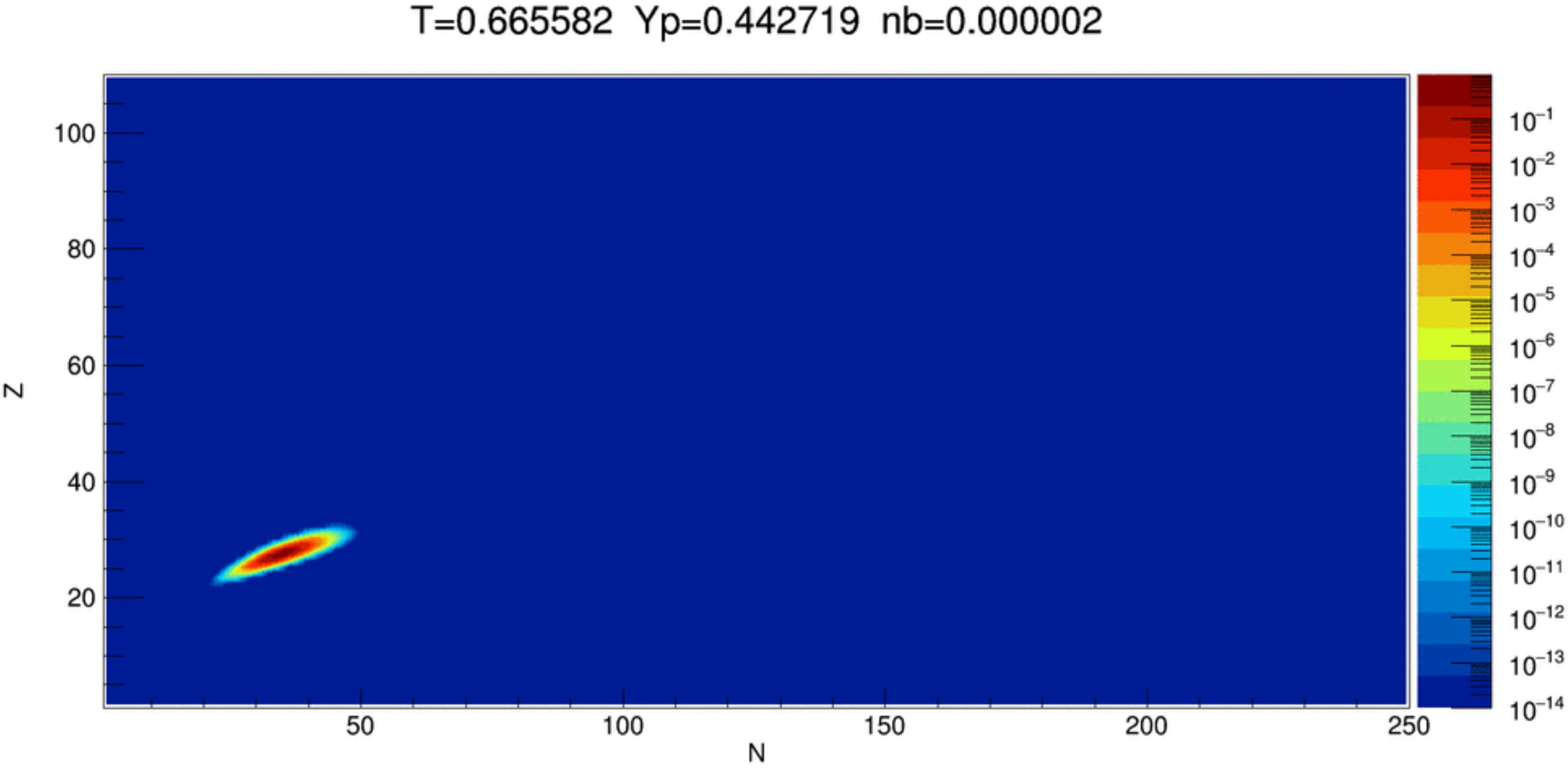
Grams, Giraud, Fantina, Gulminelli, submitted
Gulminelli & Raduta, PRC 92, 055803 (2015)

Application to the LS EoS (1)



→ only including the rearrangement term allows to correctly reproduce the SNA result insuring thermodynamic consistency

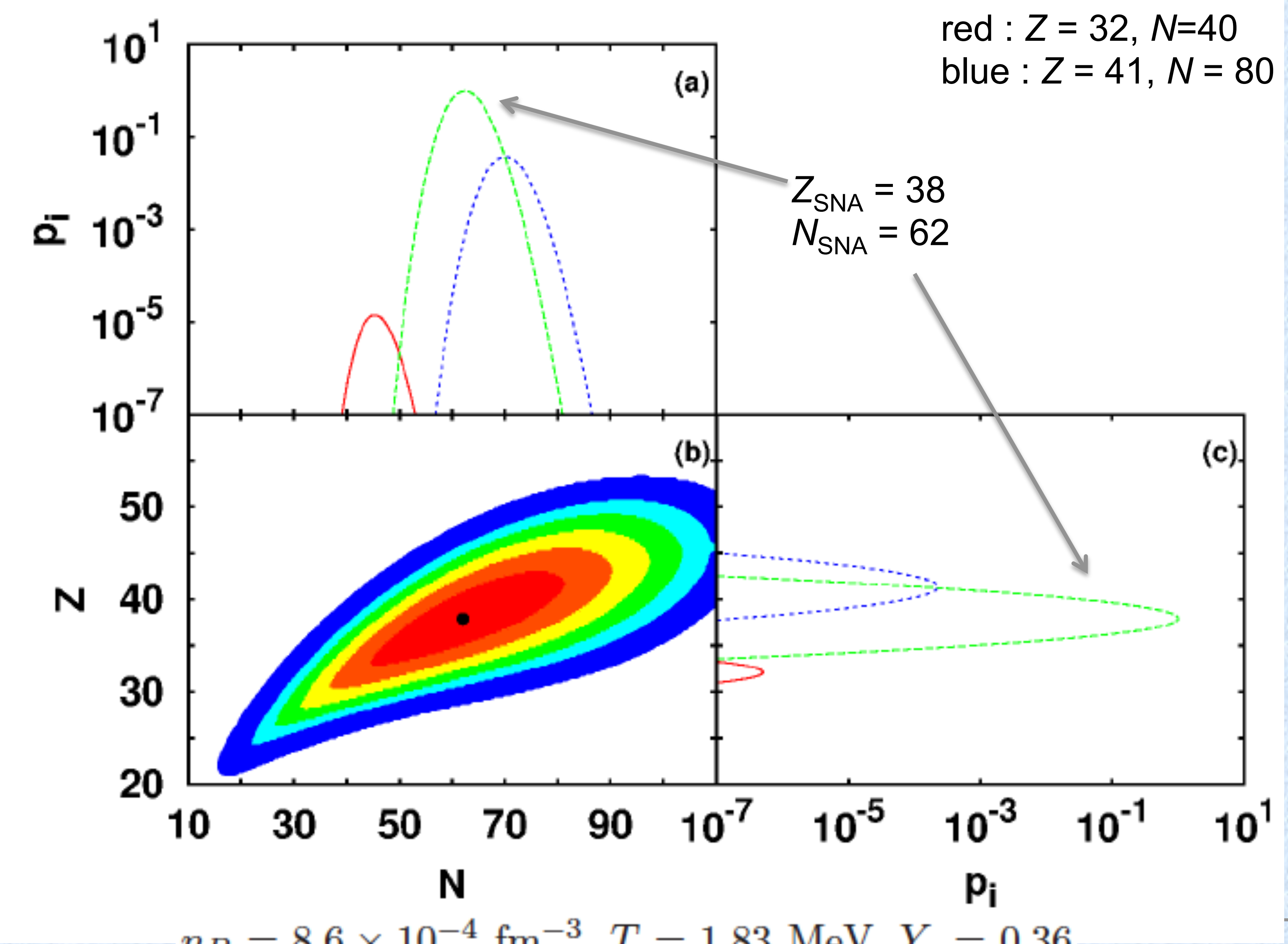
Application to the LS EoS (2)



Thermo conditions fixed from a CCSN trajectory − 40 solar mass progenitor (A. Fantina, PhD thesis 2010)

Movie by S. Giraud (PhD, GANIL)

Application to the LS EoS (3)



red : Z = 32, N=40
blue : Z = 41, N = 80

Z_{SNA} = 38
N_{SNA} = 62

Grams, Giraud, Fantina, Gulminelli, PRC 97, 035807 (2018)

$$n_B = 8.6 \times 10^{-4}\ \mathrm{fm}^{-3},\ T = 1.83\ \mathrm{MeV},\ Y_e = 0.36.$$

➡ most probable nucleus coincides with SNA

Application to the LS EoS (4)

- ✓ Nuclear distribution centred on the most probable which coincides with the SNA → consistency
- ✓ Nuclei bigger and distribution larger as n_B, T increase
- ✓ but : No shell or pairing effects
  → original LS model is simplified !
  (compressible liquid drop with simplified density-dependent nucleon-nucleon interaction)

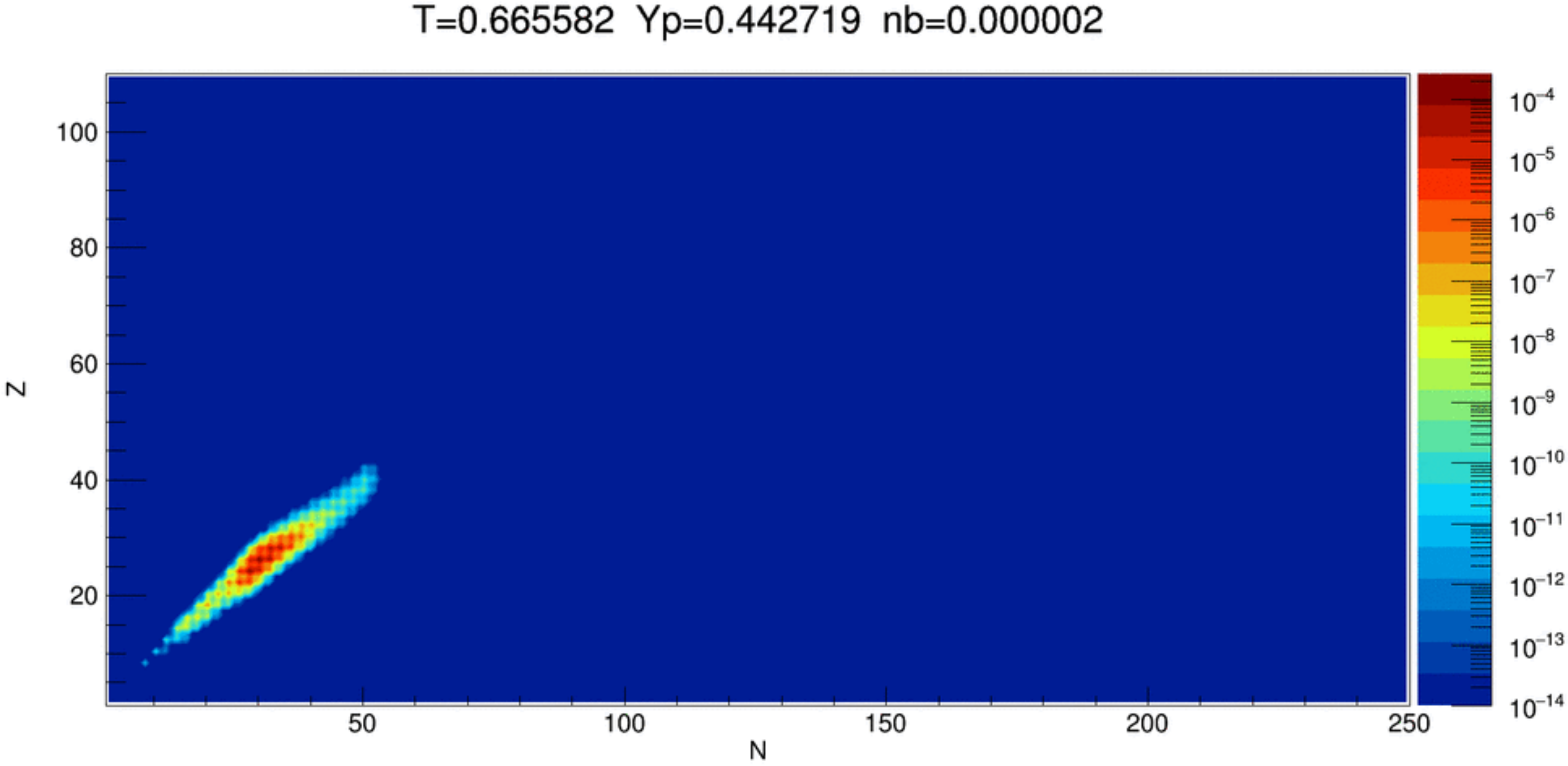
⬇

need of experimental masses or theoretical mass models !

➢ **More microscopic realistic mass models** → we use HFB-24 (Goriely *et al*. 2013, PRC88, 024308)

- HFB calculations with 16-parameter generalised Skyrme NN interaction with realistic pairing force
- fit the 2353 experimental masses in AME2012 with $Z,N > 8$ with a rms of about 0.5 MeV

Application to the LS EoS (5)

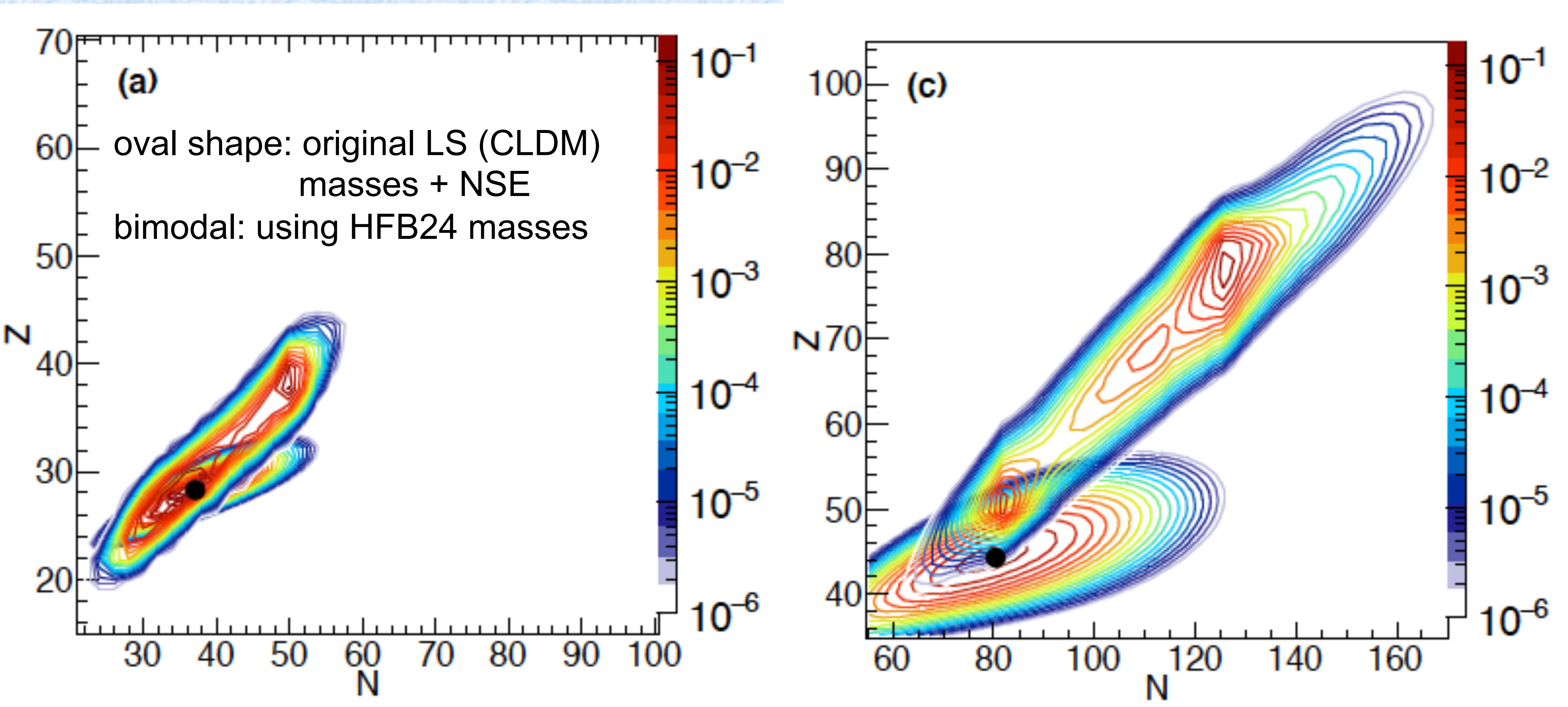


Thermo conditions fixed from a CCSN trajectory − 40 solar mass progenitor (A. Fantina, PhD thesis 2010)

Movie by S. Giraud (PhD, GANIL)

Application to the LS EoS (6)

$n_B = 3.86 \times 10^{-6}$ fm^{-3}, $T = 0.79$ MeV, $Y_e = 0.43$ $n_B = 3.01 \times 10^{-3}$ fm^{-3}, $T = 2.68$ MeV, $Y_e = 0.33$



oval shape: original LS (CLDM) masses + NSE

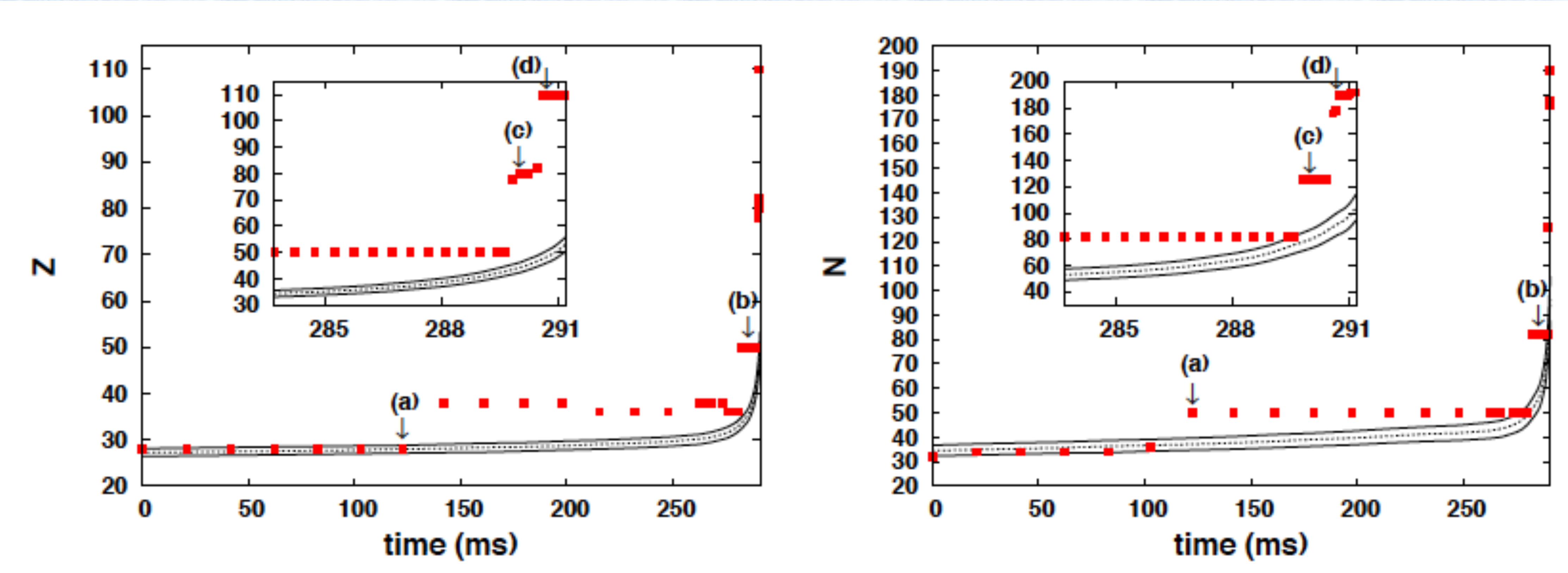
bimodal: using HFB24 masses

- ➢ **Bimodal distribution around magic nuclei**
- ➢ **in late stage of CC predictions for the distribution differ considerably**
  (*G* and μ_ι should be calculated with same model)

Grams, Giraud, Fantina, Gulminelli, PRC 97, 035807 (2018)

Application to the LS EoS (7)

Solid lines : original Lattimer & Swesty EoS model (compressible liquid drop model, no shell effects)
Dots : original masses replaced by HFB-24 mass model (shell and pairing included)



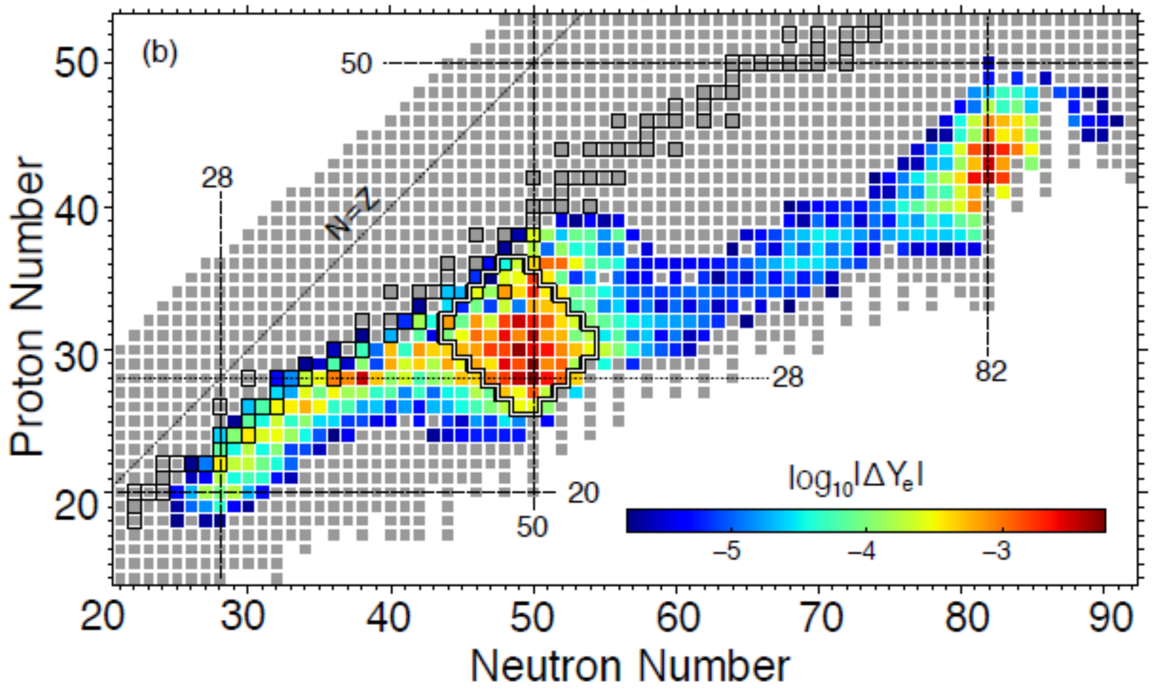
Magic nuclei dominate trajectory when realistic mass model employed
→ might impact electron-capture rates thus the collapse dynamics

Grams, Giraud, Fantina, Gulminelli, PRC 97, 035807 (2018)

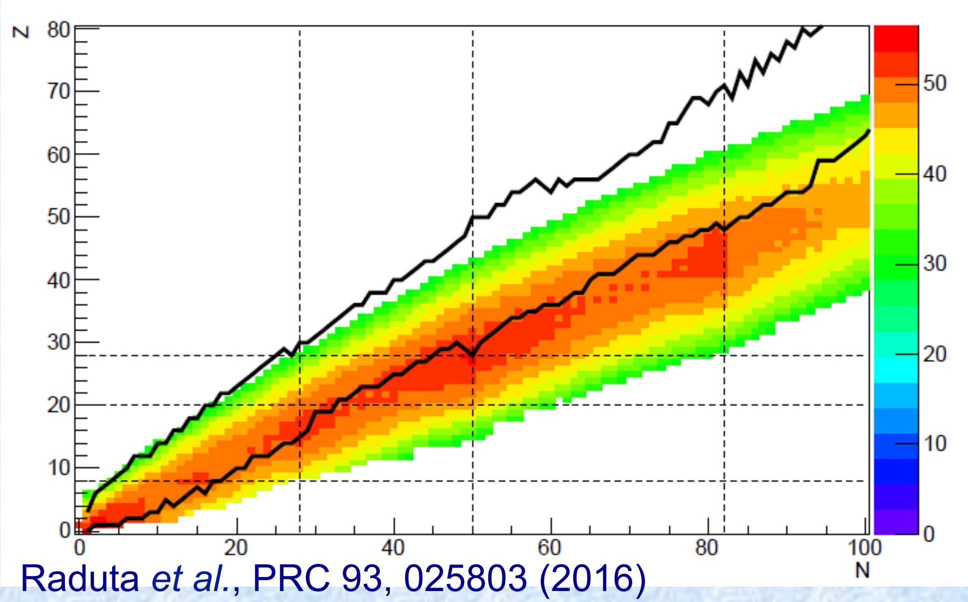
Mass measurements & SN (1)

- ❖ Very **precise mass measurements** (within ~100 KeV) are necessary for the computation of :
  - ✓ **Q value in EC** rates
  - ✓ **EoS – composition of SN matter**

- ❖ Which nuclei matter ?

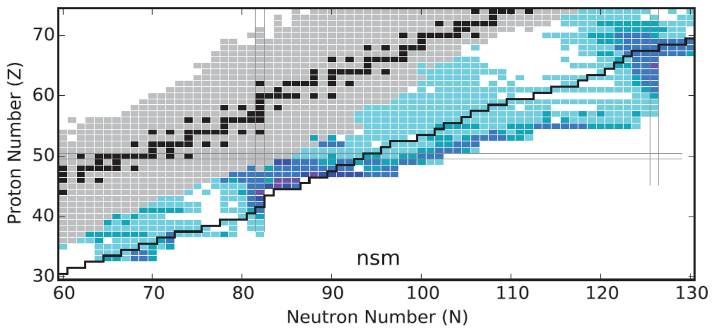


Sullivan *et al.*, ApJ 816, 44 (2016)



Raduta *et al.*, PRC 93, 025803 (2016)

NOTE : the **N=82** closed shell nuclei are **relevant for both core collapse and for r-process**.



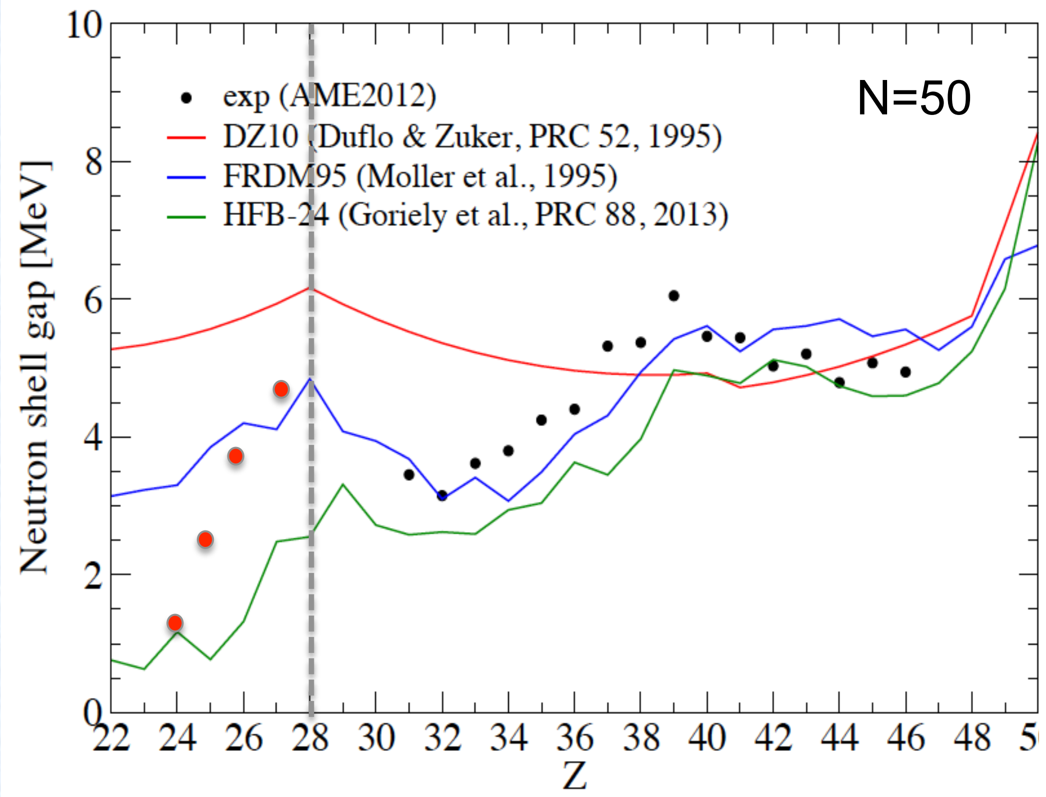
Mumpower *et al* 2015
Aprahamian 2015

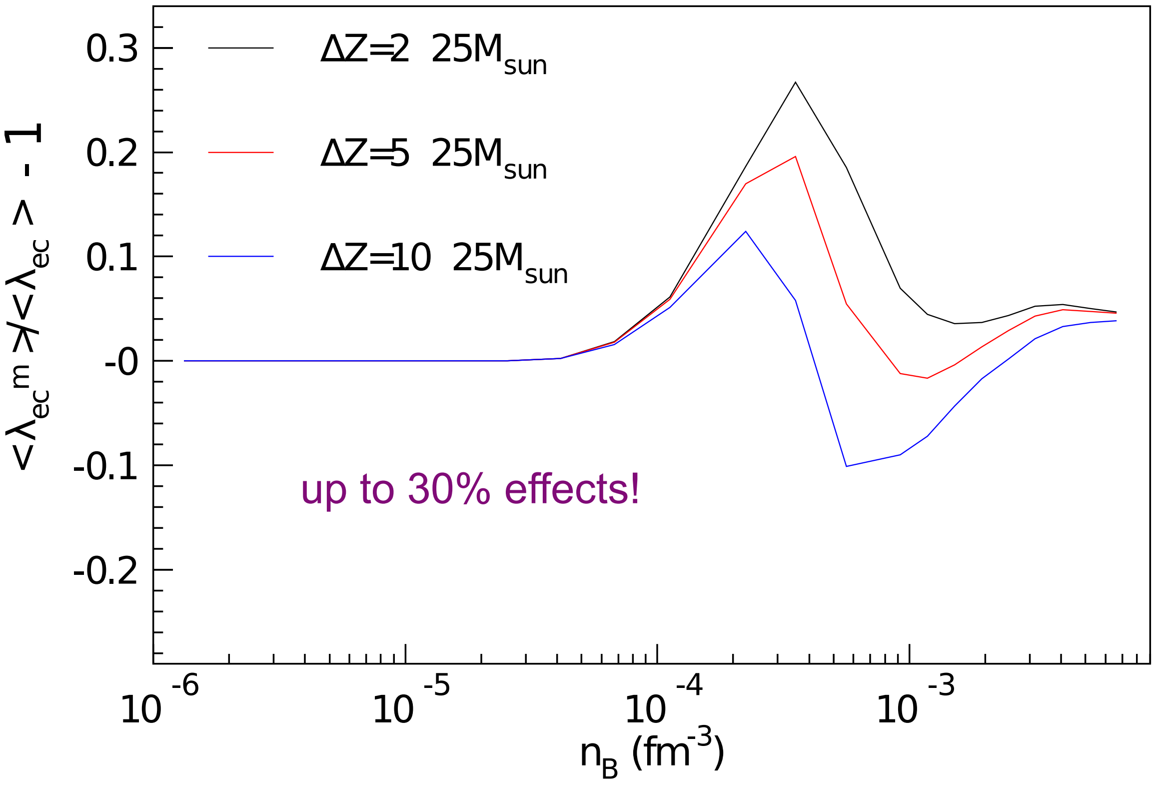
From the contributions of : F. Gulminelli, F. Aymard, D. Chatterjee, J. B. Briand (LPC Caen);
A.F. Fantina, B. Bastin, P. Delahaye, F. de Oliveira (GANIL); A. Raduta (IFIN-HH), J. Margueron (IPNL)

Mass measurements & SN (2)

❖ Exotic nuclei around N=50 (^{78}**Ni**) and N=82 (^{128}**Pd**) dominate because predicted to be magic.

→ What about more exotic nuclei ?!
e.g. ***N* = 50** gap far from stability → model predictions differ !





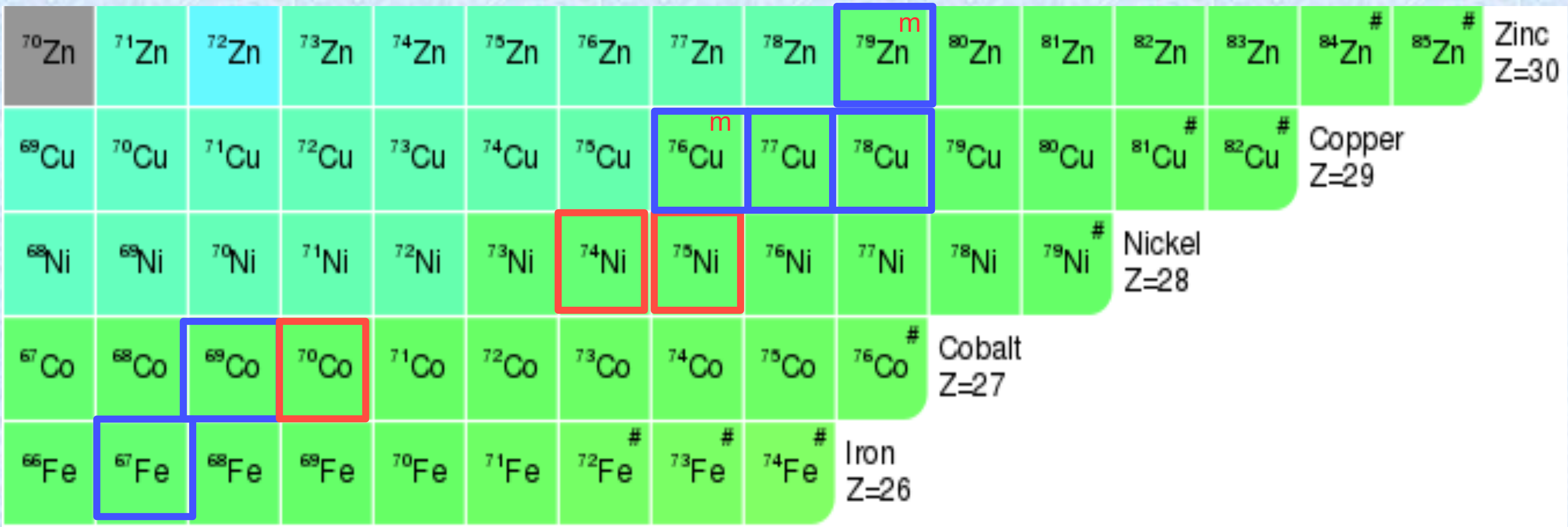
Raduta, Gulminelli, Oertel, PRC 93, 025803 (2016), using DZ10 with quenching function for exotic nuclei

→ in turn, impact on CCSN dynamics, neutrino luminosity, ...

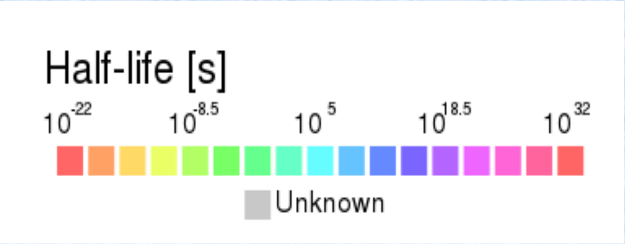
Mass measurements & SN (3)

experimental proposal @JYFL : mass measurements around ^{78}Ni (run 11/2017, under analysis)
Spokespersons : B. Bastin, A. Kankainen (exp) ; A. F. Fantina, F. Gulminelli (theo)
Collaboration : GANIL, JYFL, LPC Caen, IFIN-HH, LUTh, IPNL, CENBG, IPNO, KU Leuven
(PhD thesis of S. Giraud, 2016-2019)

IGISOL technique + penning traps & MR-ToF-MS



Courtesy of B. Bastin, S. Giraud (GANIL)



This work

🟦 Improved the precision

🟥 New masses

m New isomer masses

Conclusions & Outlook

- ❖ **Formalism to include cluster distribution in a SNA EoS**

- ❖ **CCSN** dynamics sensitive to microphysics (EoS & EC rates)

  → **Masses** of n-rich nuclei (^{78}Ni, ^{128}Pd → $N = 50, 82$)

  → **Magic nuclei dominate trajectory when realistic mass model employed**

    → might impact electron-capture rates thus the collapse dynamics

✓ need of (microscopic & reliable) theoretical model when no data
✓ need of experimental data to calibrate the models

- ➢ Implementation of new formalism in CCSN simulation (in progress)
- ➢ Check impact on EC (in progress)
- ➢ Impact of new results of **I220** experiment → test impact of new masses

Obrigada!

Supernova Remnant 1987A in the Large Magellanic Cloud. HUBBLESITE.org