Astrophysical implications of ISOL-type experimental measurements

(selected examples)

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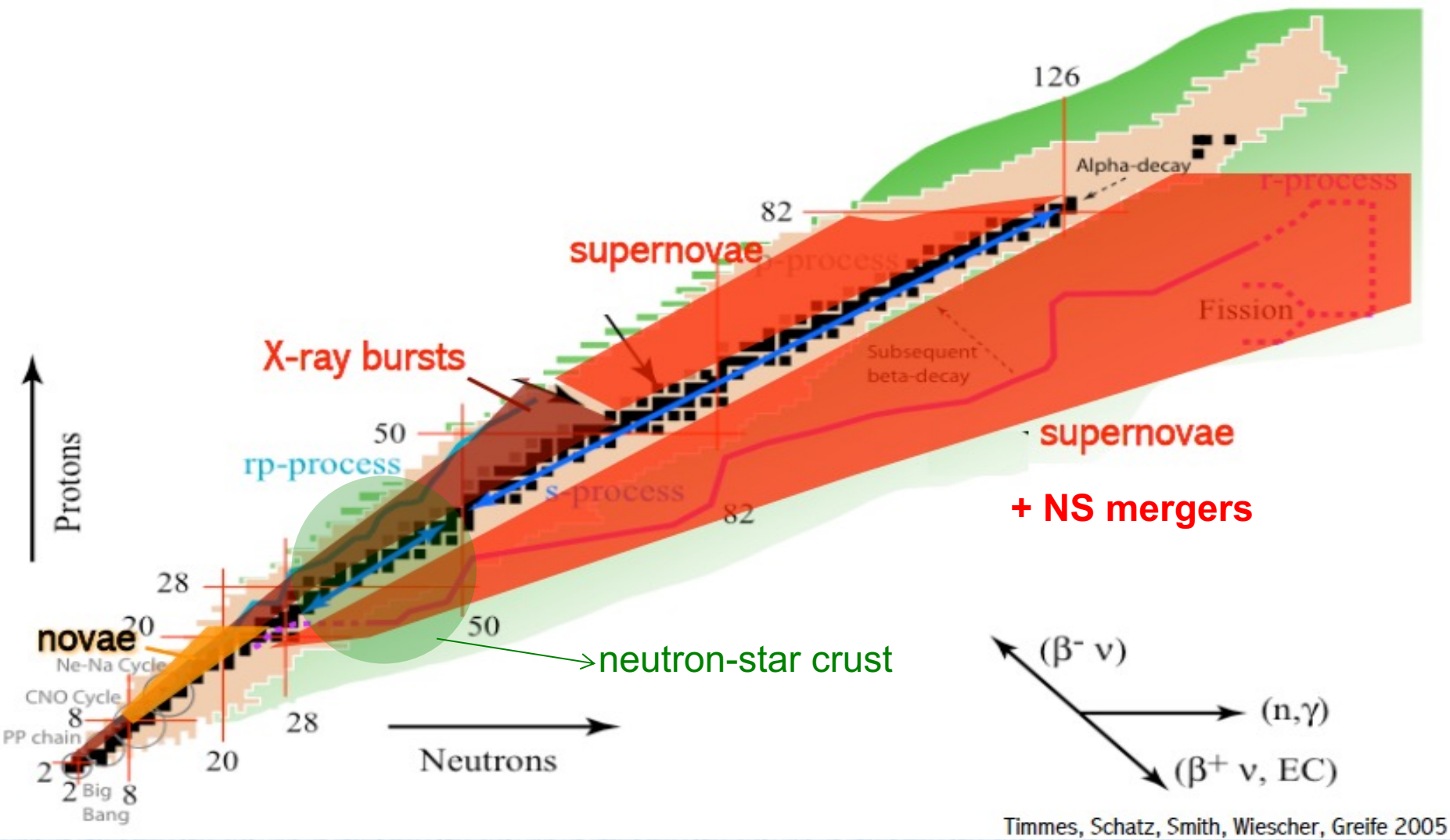
ISOL France workshop,
Caen (France), 09 – 11 March 2022

Outline

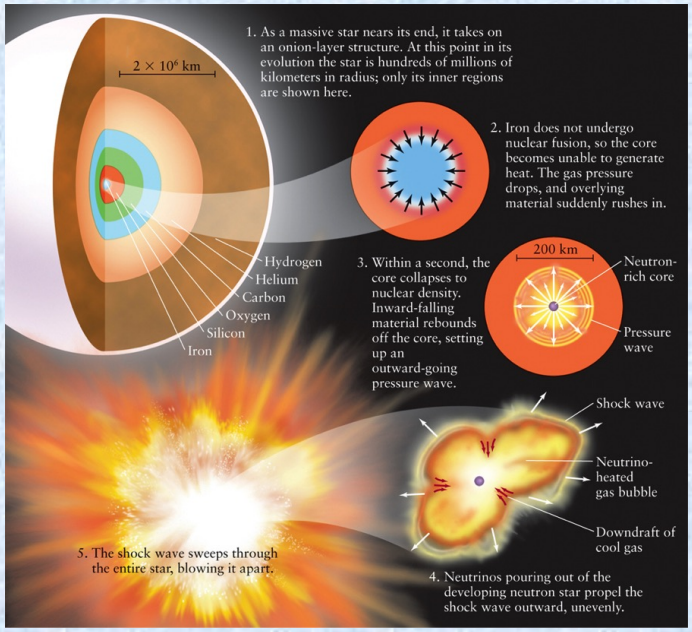
- Introduction
  - (Exotic) Nuclei in astrophysical context
- Role of nuclear data: (some) selected examples
  - Mass measurements
  - Beta-decays and electron captures (EC)
  - Beyond beta decays (Capture reactions)
- Conclusions & open questions

Origin of (exotic) nuclei

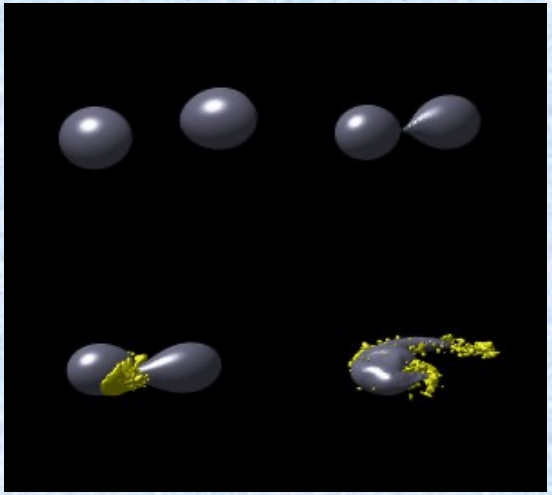


Compact-star scenarios

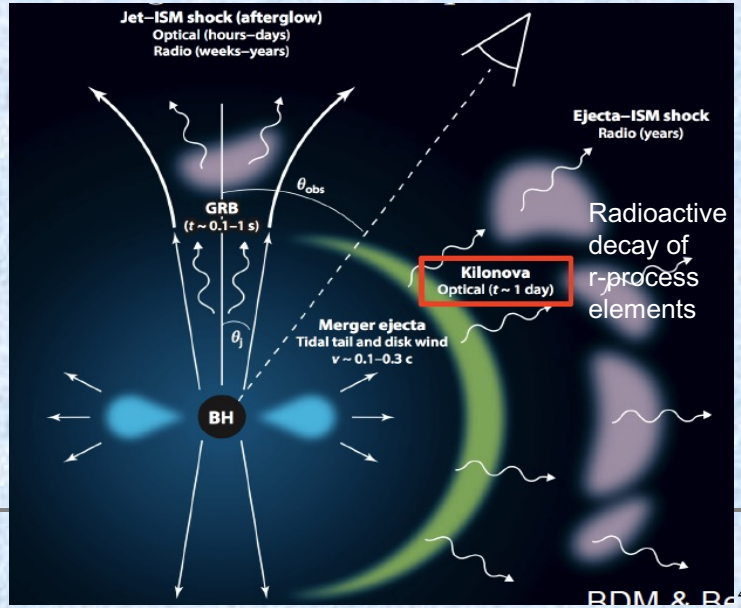
Core-collapse supernova (SN)



Binary NS mergers

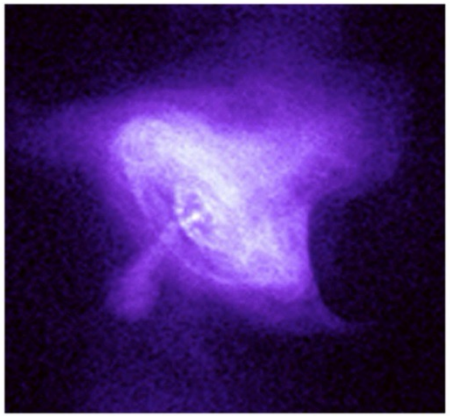


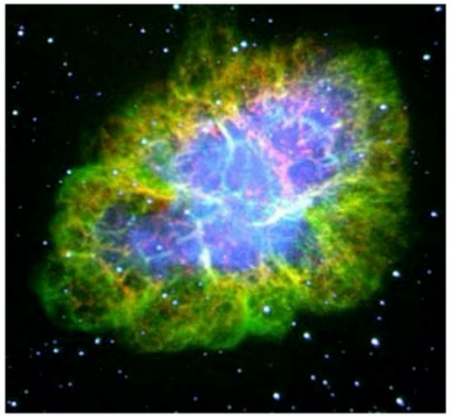
Simulation MPA Garching (Goriely, Bauswein,Janka, ApJ 738, 2011)



from B. Metzger's talk (2017)

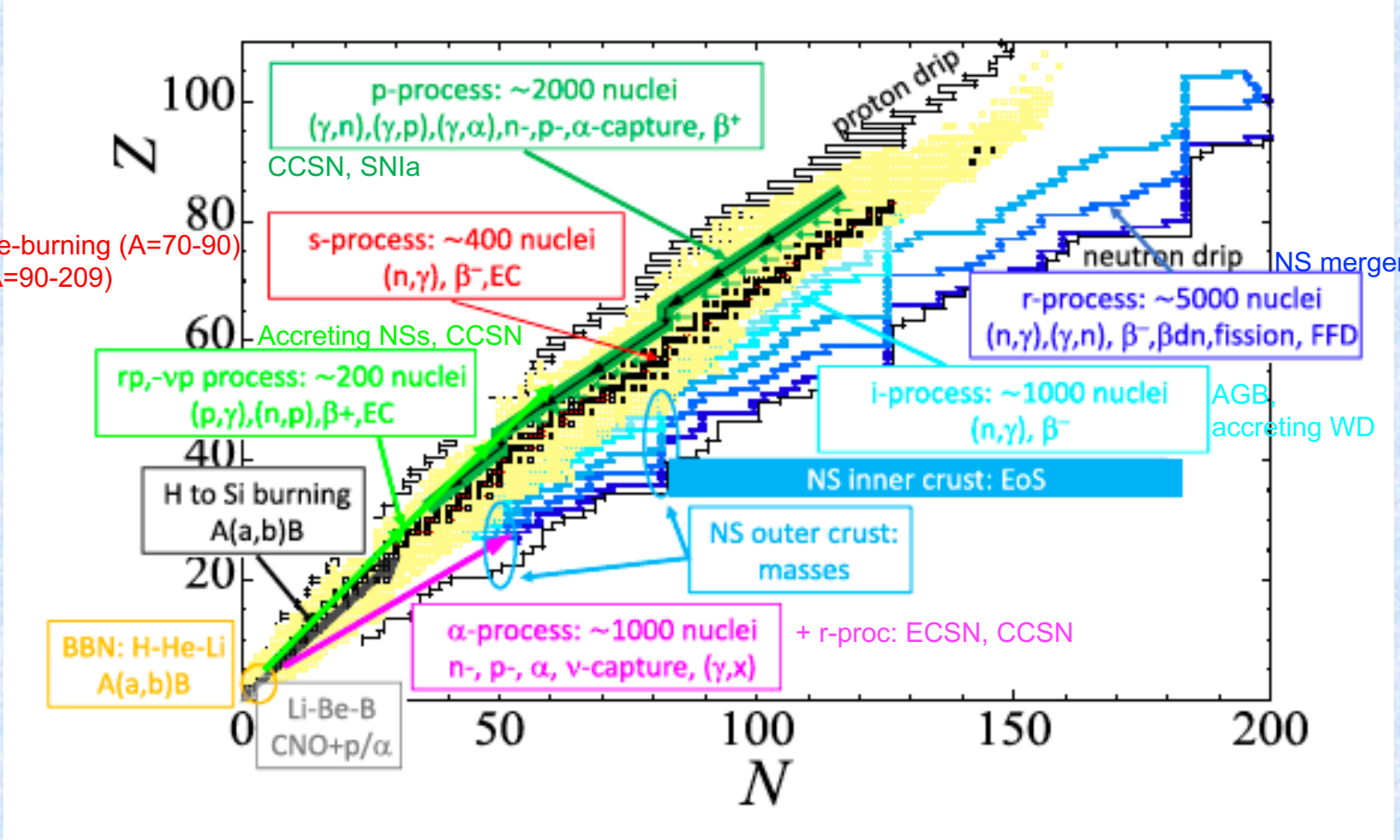
Neutron stars (NSs)





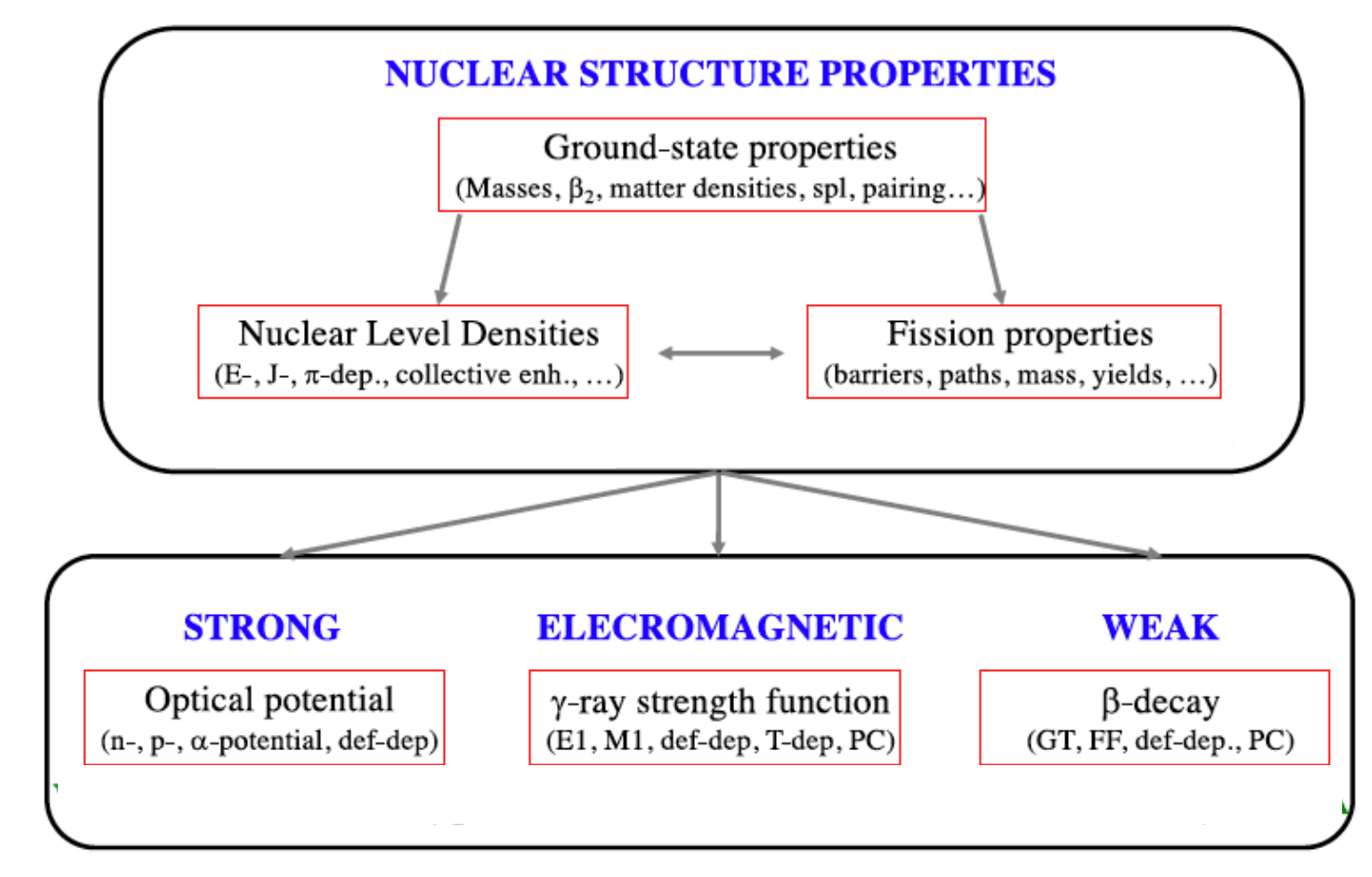
Credits: NASA/CXC/SAO (Crab, X ray), Palomar Observatory (Crab, visible)

Origin of nuclei and key data (1)



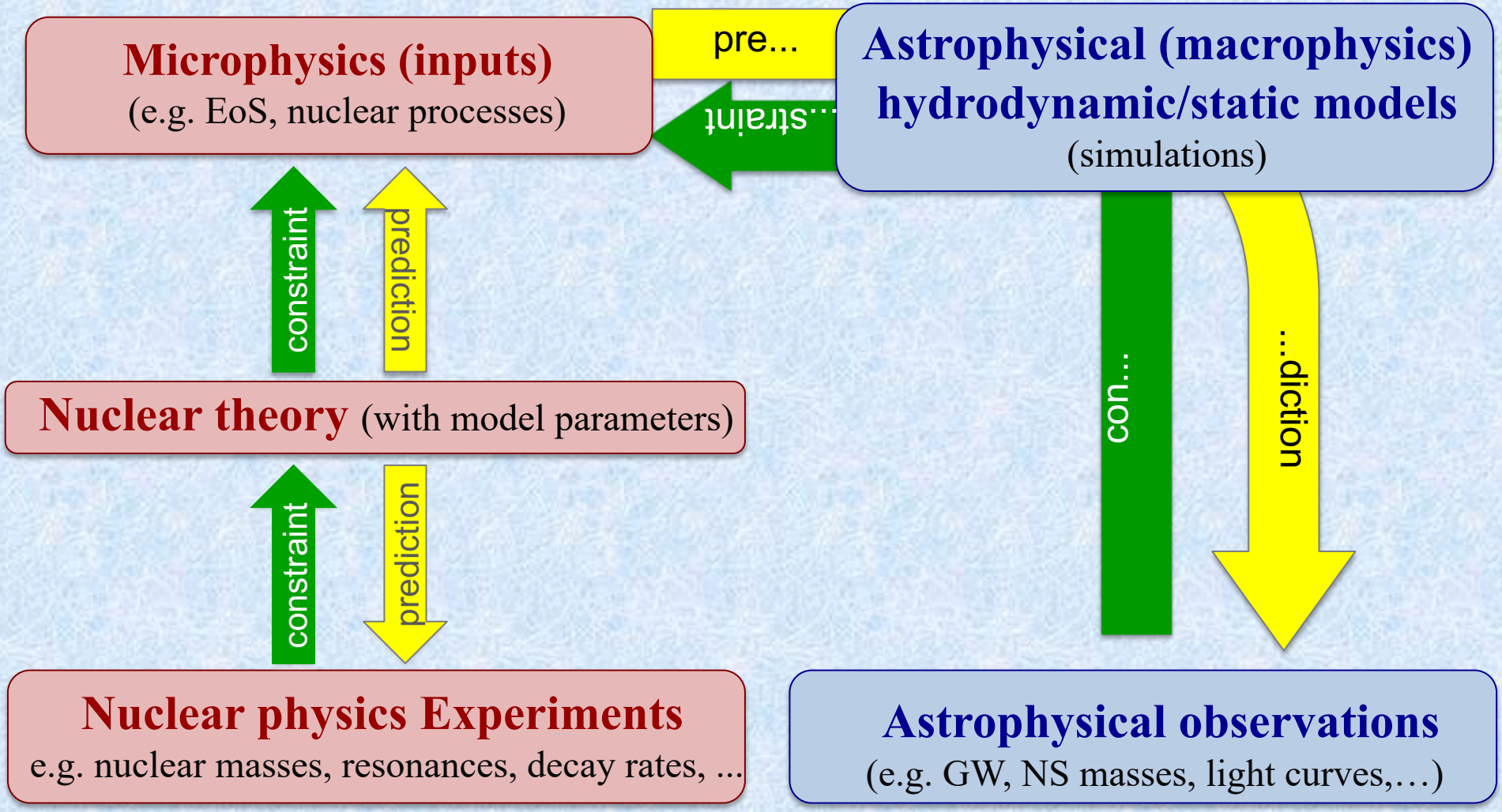
Arnould & Goriely, Prog. Part. Nucl. Phys. 112, 103766 (2020)

Origin of nuclei and key data (2)



Arnould & Goriely, Prog. Part. Nucl. Phys. 112, 103766 (2020)

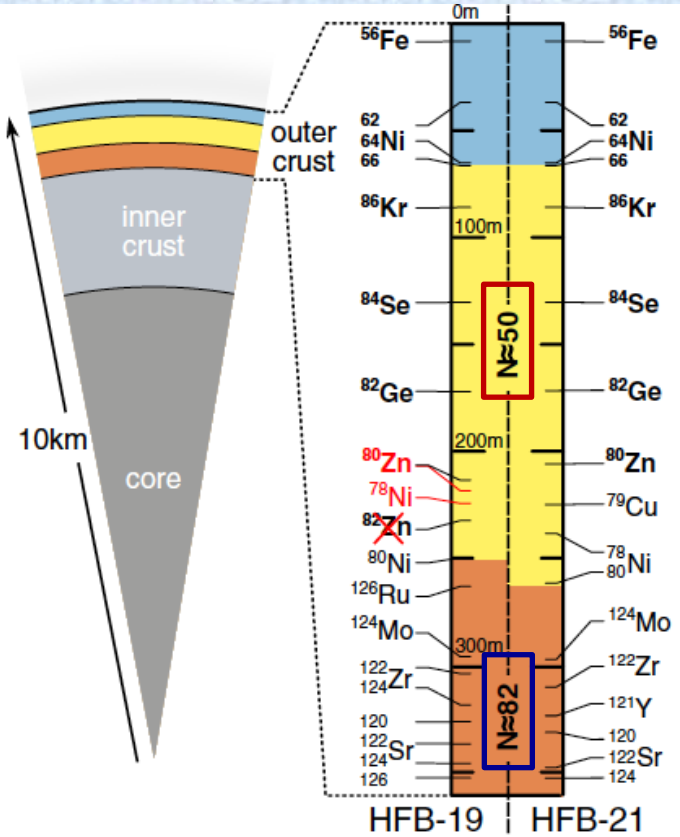
Micro to macro through modelling



Nuclear masses: NS outer crust (1)

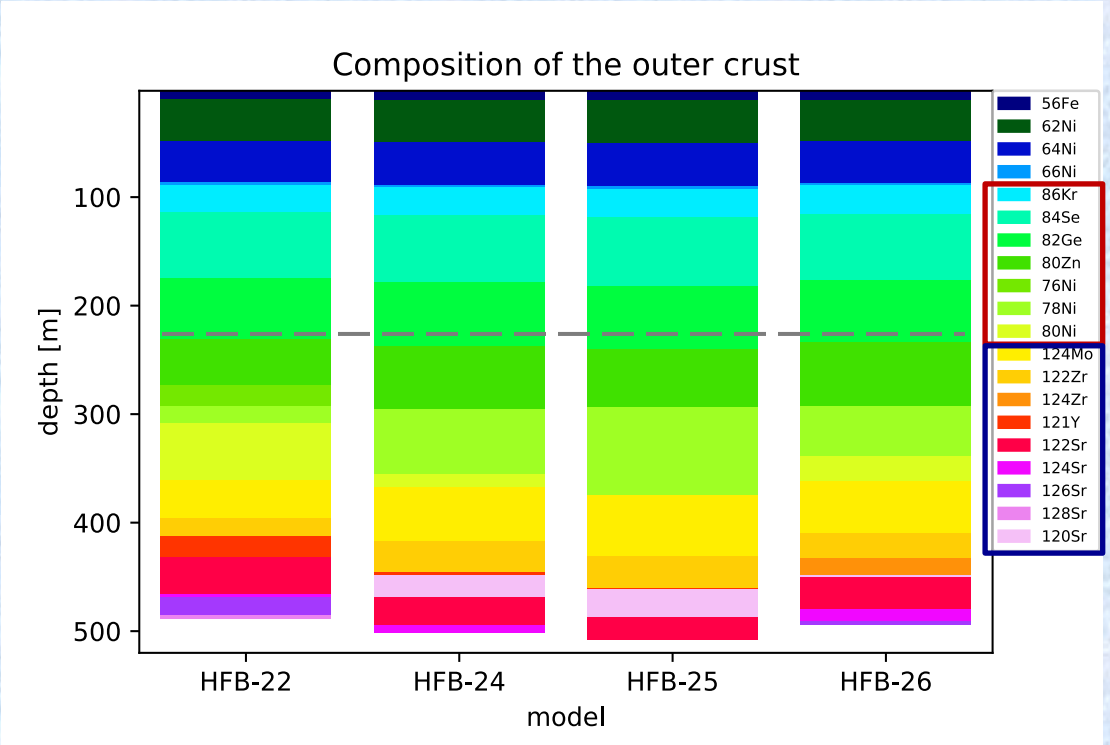
- ✓ Can be precisely measured (up to ~ 10 keV precision)
- ✓ Directly used to fit parameters of the models

➢ Enter in the determination of the EoS (energy) and the composition of matter for *outer crust* only nuclear input is nuclear masses



Wolf et al., PRL 110, 041101 (2013) - ISOLTRAP

see also Kreim et al. 2013



Pearson et al., MNRAS 481, 2994 (2018)

➡ Imprint of nuclear structure in composition of outer crust

Nuclear masses: NS outer crust (2)

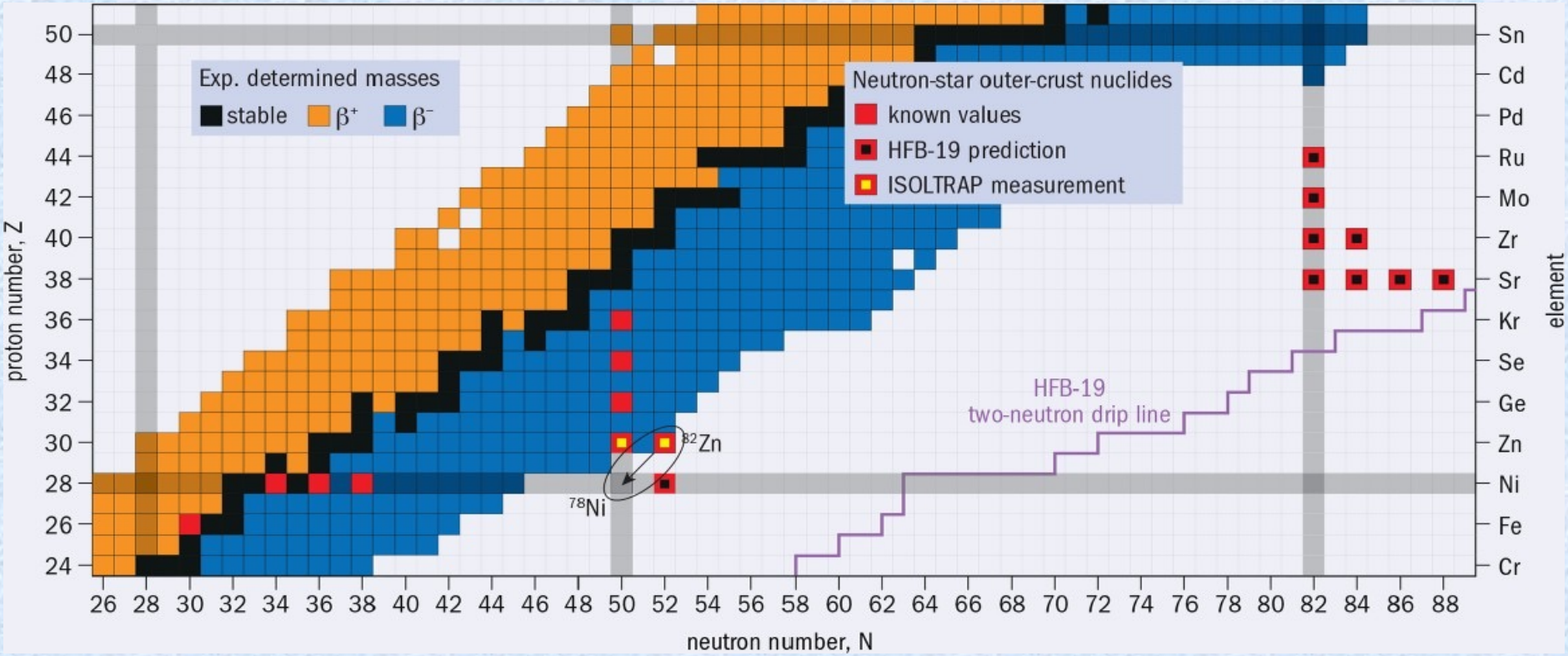


Image Credits: CERN Courrier (see also Wolf et al., PRL 110, 041101 (2013))

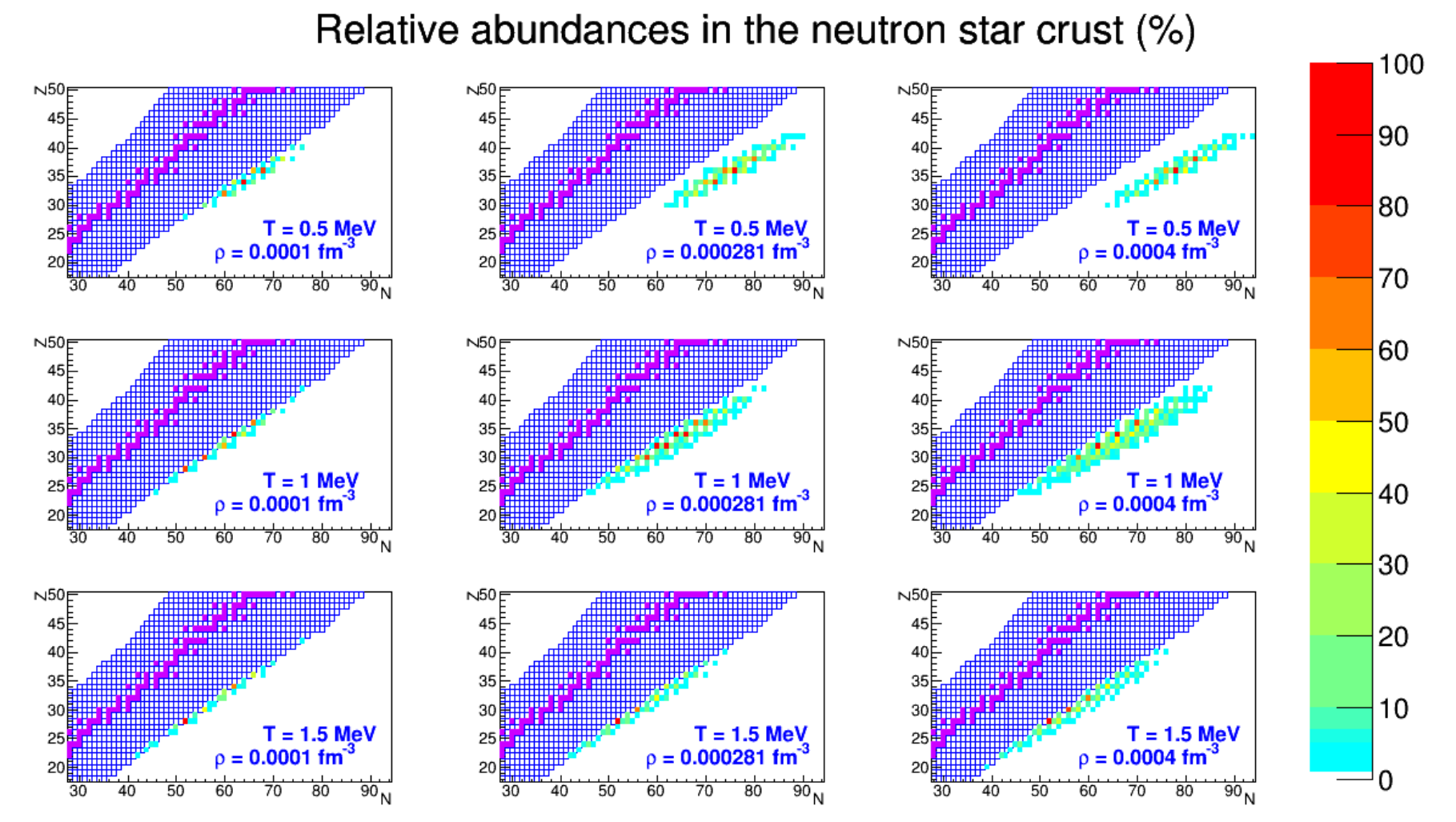
<u>but</u>: deep inside the NS outer crust → nuclei "too" n-rich and far from stability !

→ Could be measured ???

→ other measurements closer to valley of stability may be important in other environment (e.g. SN, r-process)

Nuclear masses: Proto-NS

Finite temperature (→ PNS) can populate broader range of (A,Z)



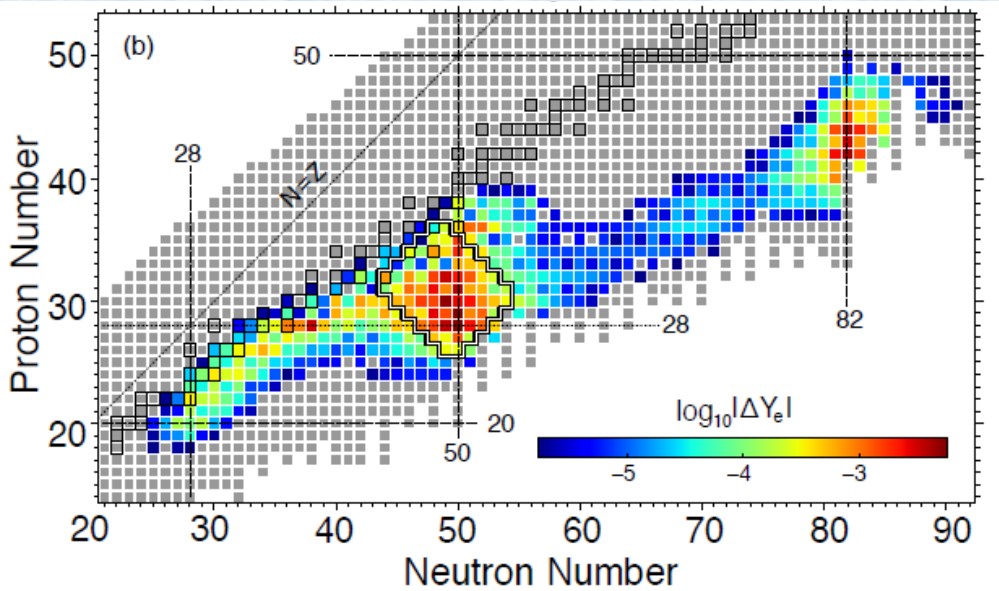
NSE calculations, Courtesy of F. Gulminelli, A. Raduta

Nuclear masses: SN (1)

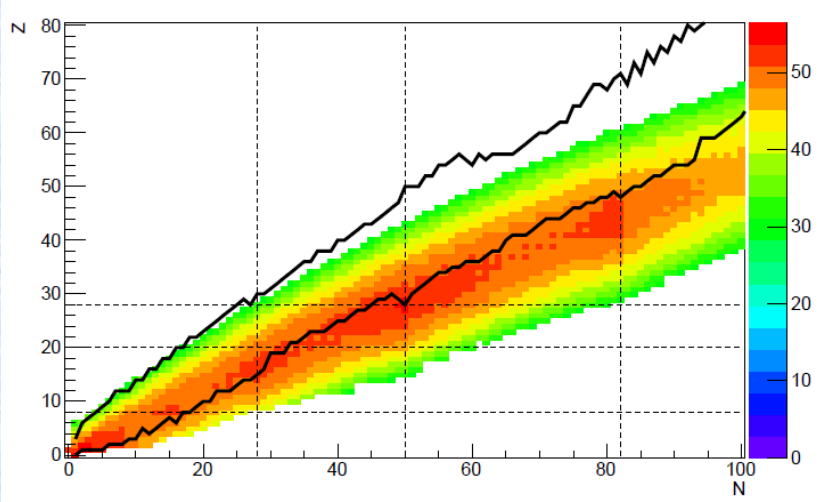
❖ (Precise) Mass measurements are necessary for the computation of :

- ✓ **Q value in EC** rates
- ✓ **EoS – composition of SN matter**

❖ Which nuclei matter ?



Sullivan et al., ApJ 816, 44 (2016);
see also Titus et al., J.Phys. G 45, 014004 (2018)



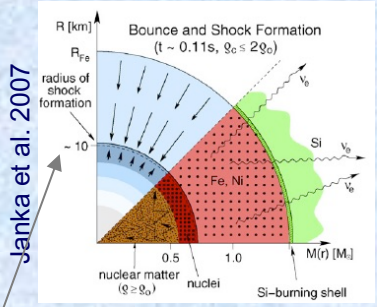
Raduta et al., PRC 93, 025803 (2016)

→ **Experiment I220@JYFL : mass measurements around ^{78}Ni** (run 11/2017)
B. Bastin, A. Kankainen, et al. (PhD thesis of S. Giraud @ GANIL, 2016-2019)

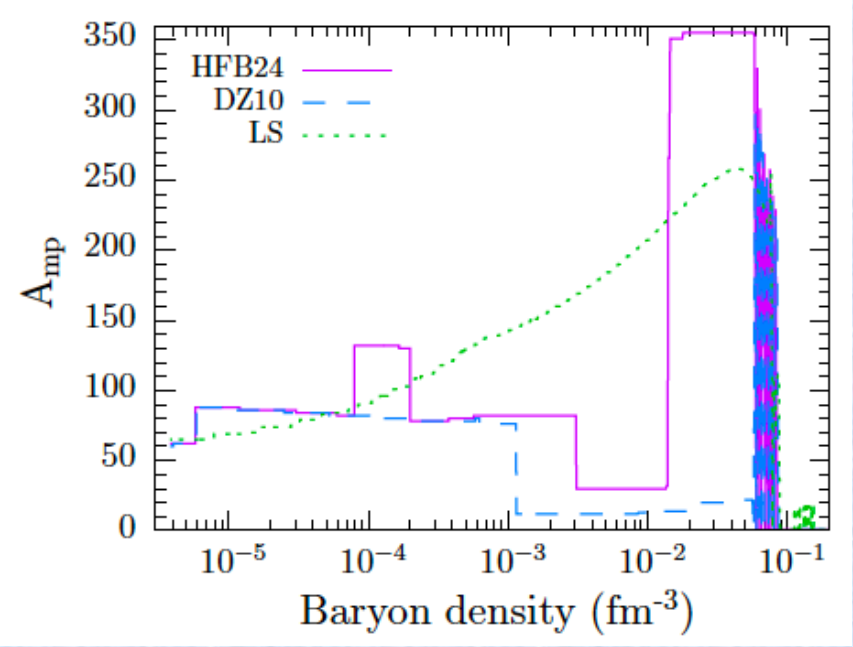
IGISOL technique + penning traps & MR-ToF-MS

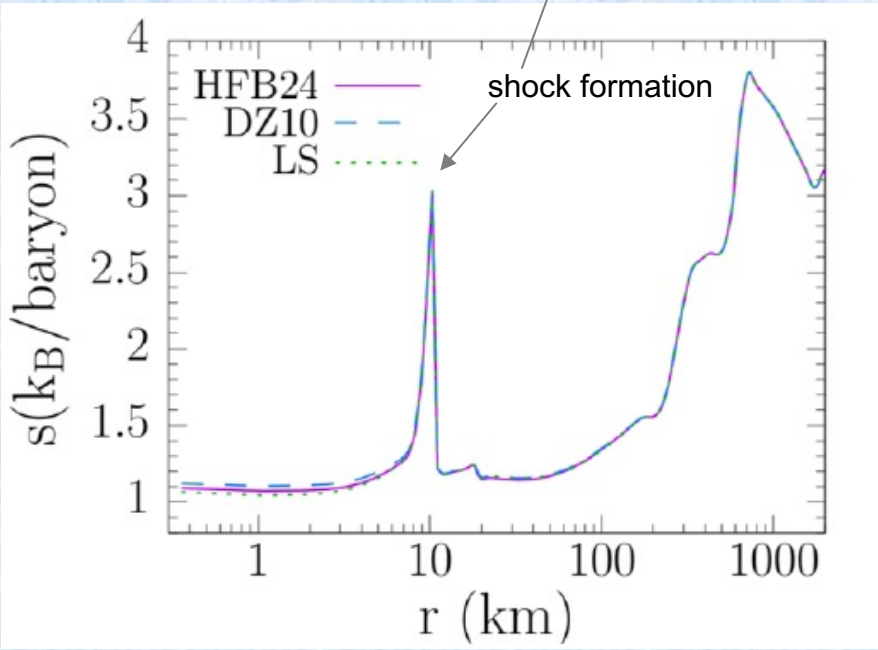
Nuclear masses: SN (2)

Impact on core-collapse dynamics
(1D core-collapse code in GR)



Janka et al. 2007





Pascal et al., PRC 101, 015803 (2020)

- Impact of masses non-negligible on composition (→ impact on rates?)
- Impact negligible on dynamics
  → strong feedback with hydrodynamics (Giraud et al., submitted)
- (Astro) Simulations needed to evaluate impact of nuclear data

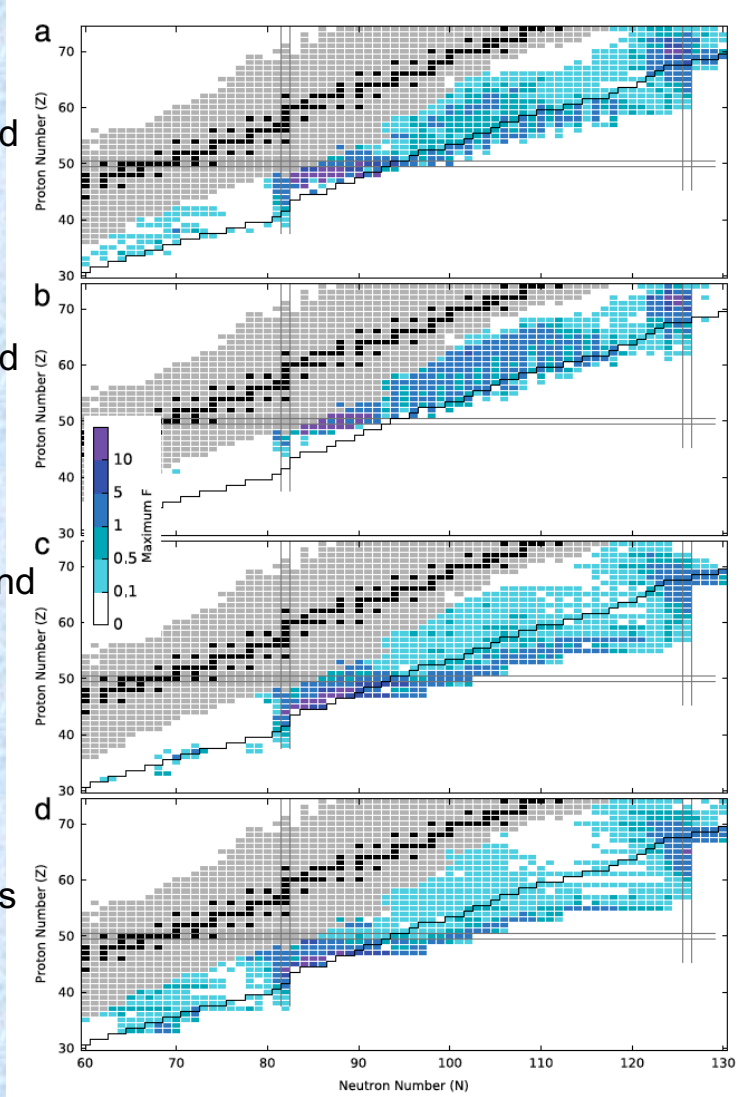
Nuclear masses: r-process

low S
hot wind

high S
hot wind

cold wind

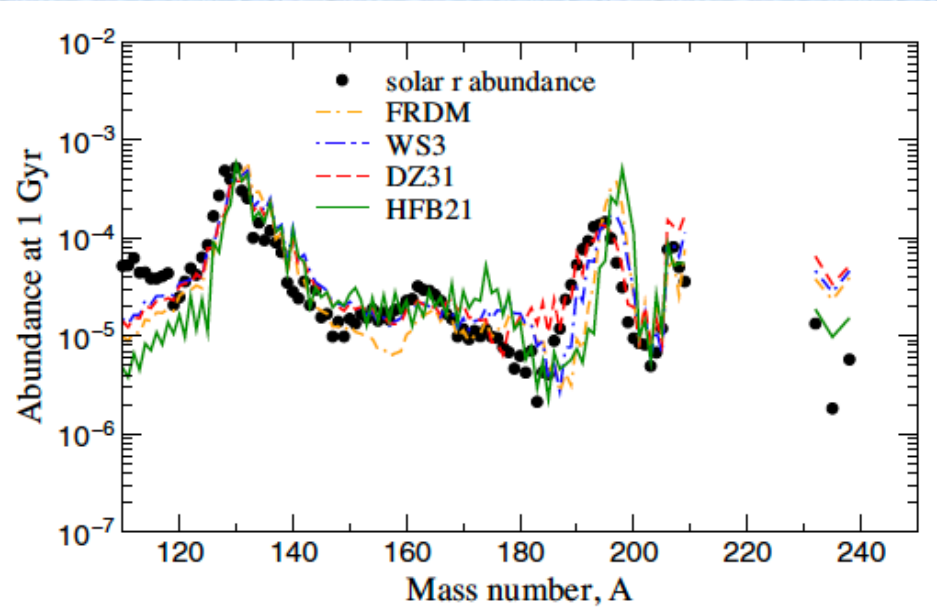
NS
mergers



Mumpower et al., Prog.Part.Nucl.Phys. 86, 86 (2016)

→ <u>dependence on astrophysical scenario</u>

→ most influential nuclei around
***N* = 82, *N* = 126**

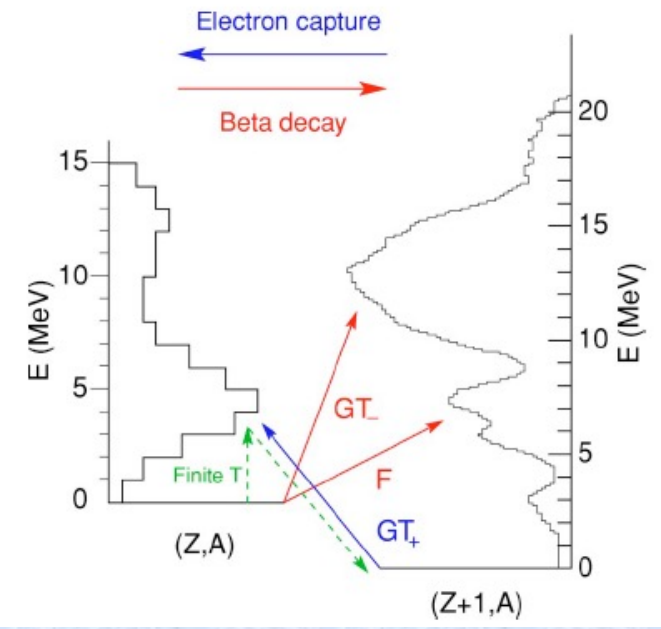


Cowan et al., Rev. Mod. Phys. 93, 015002 (2021)
Mendoza-Temis et al., PRC 92, 055805 (2015)

<u>but</u>: many other parameters enter !
(e.g. astro conditions, impact of ν,
fission barriers, decay rates, …)

Nuclear reactions: EC & β decays

- If **off-equilibrium** (chemical, τ_{nuc} not << τ_{dyn}) → full **reaction network**
- If τ_{nuc} << τ_{dyn} → **NSE** (T > 0.5 MeV)
  - Weak processes crucial all along the life of a star (burning chain)
  - **EC & β-decays**
    → late-stage evolutions (massive stars), NS cooling, nucleosynthesis (e.g. r-process)
  - In **SNe (core-collapse phase)**
    → NSE, but weak interactions off-equilibrium
    → **ELECTRON CAPTURES (EC)**
    (+ scattering of ν, bremsstrahlung, …)



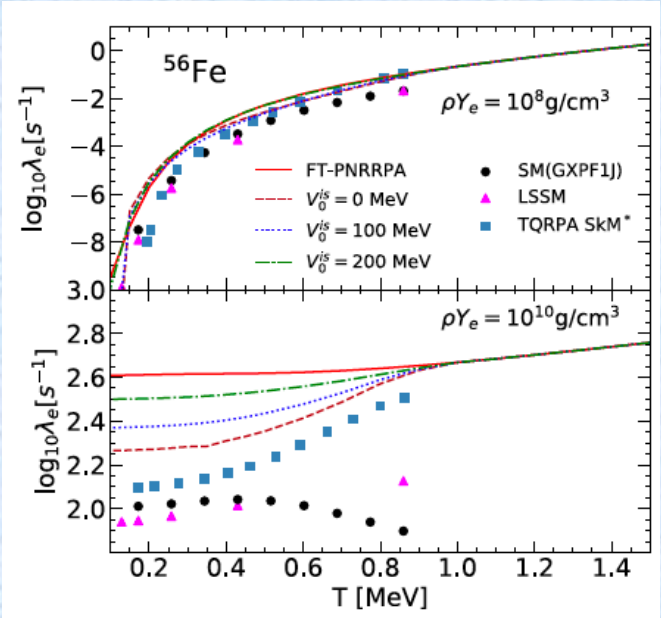
Langanke & Martínez-Pinedo, Rev. Mod. Phys. 75, 819 (2003)

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

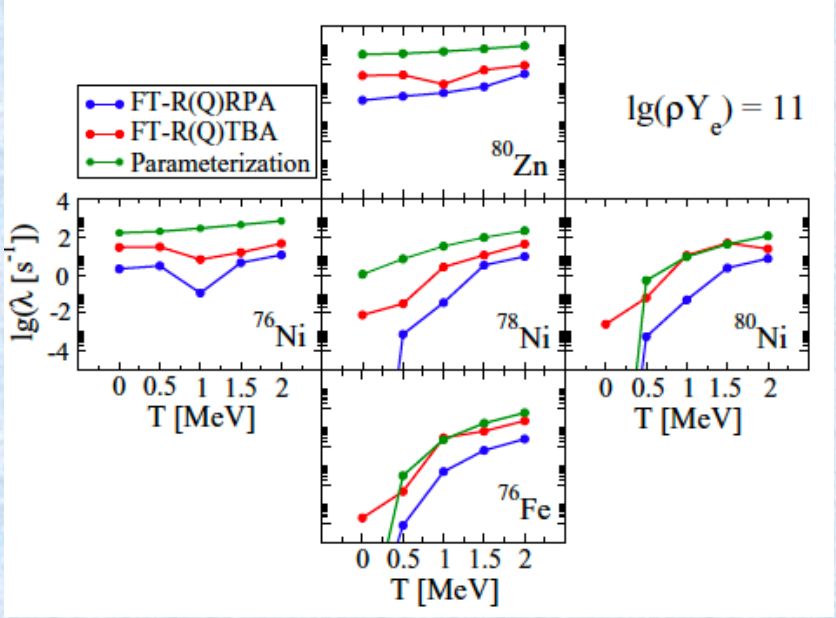
$$(Z, A) + e^- \rightarrow (Z - 1, A) + \nu_e$$ on nuclei

Electron captures (EC)

- Calculations of EC on nuclei (and β decays) exist in different frameworks:
  - *sp / independent particle model* (Fuller, Fowler, Newmann 1982, 1985, Pruet & Fuller 2003)
  - *shell model* (Oda et al. 1994, Langanke et al. 2000, 2001, …)
  - *MF / EDF + (Q)RPA / (R)RPA* (Paar et al. 2009, Dzhioev et al. 2010, Fantina et al. 2012, Sarriguren 2013, Niu et al. 2011, 2013, Ravlic et al. 2020, …)
  - *finite T relativistic nuclear field theory* (Litvinova et al. 2018, 2020, …)



Ravlic et al., PRC 102, 065804 (2020)

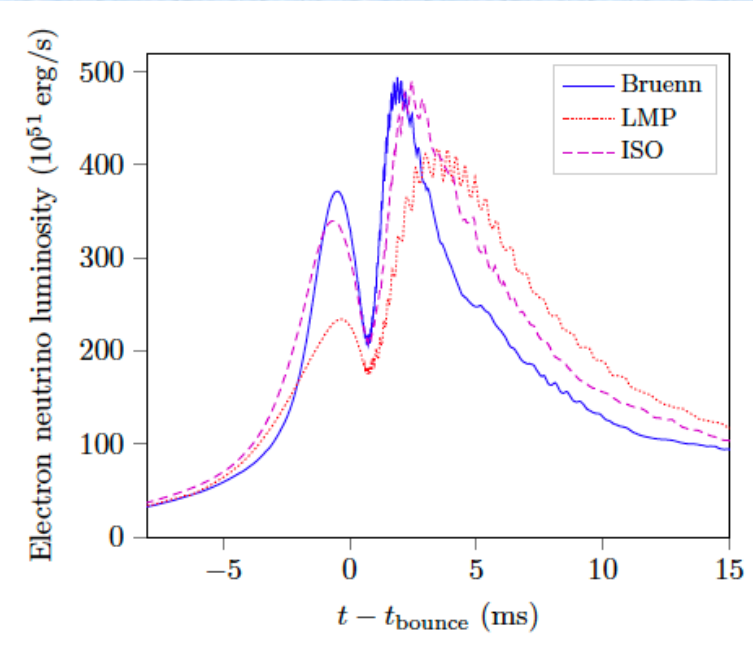


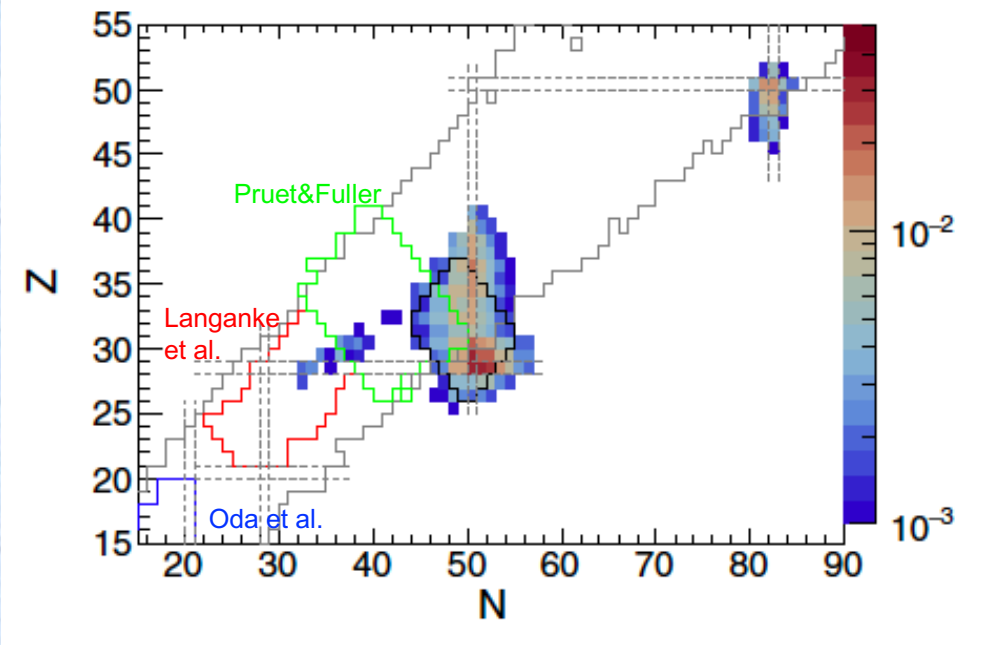
Litvinova & Robin, PRC 103, 024326 (2021)

✗ not for all "astro" nuclei → limited "large-scale" calculations!
✗ finite T needed for astro applications

EC: CCSN infall phase

- Individual EC rates on nuclei main source of uncertainties during CCSN infall

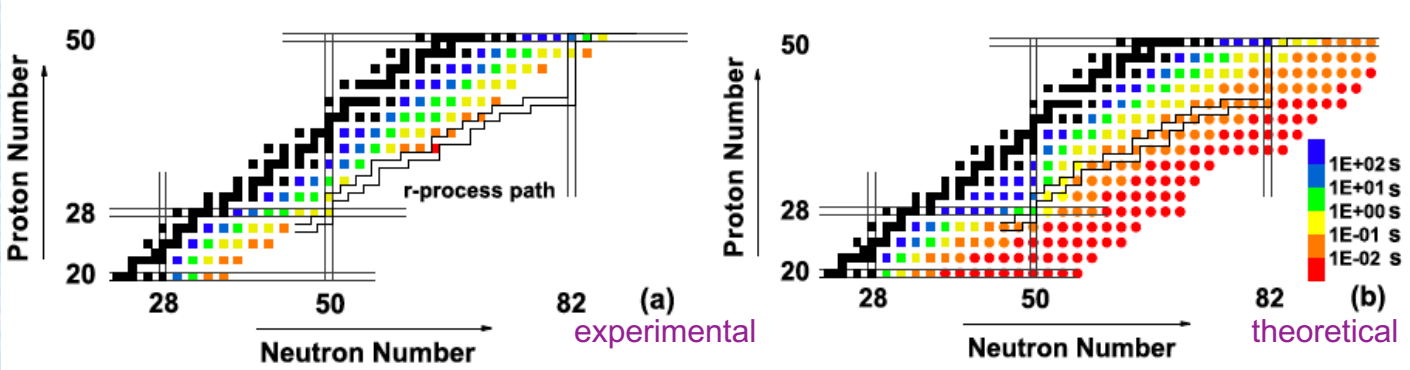




Pascal et al., PRC 101, 015803 (2020)
see also Sullivan et al., ApJ. 816, 44 (2016); Titus et al., J.Phys. G 45, 014004 (2018)

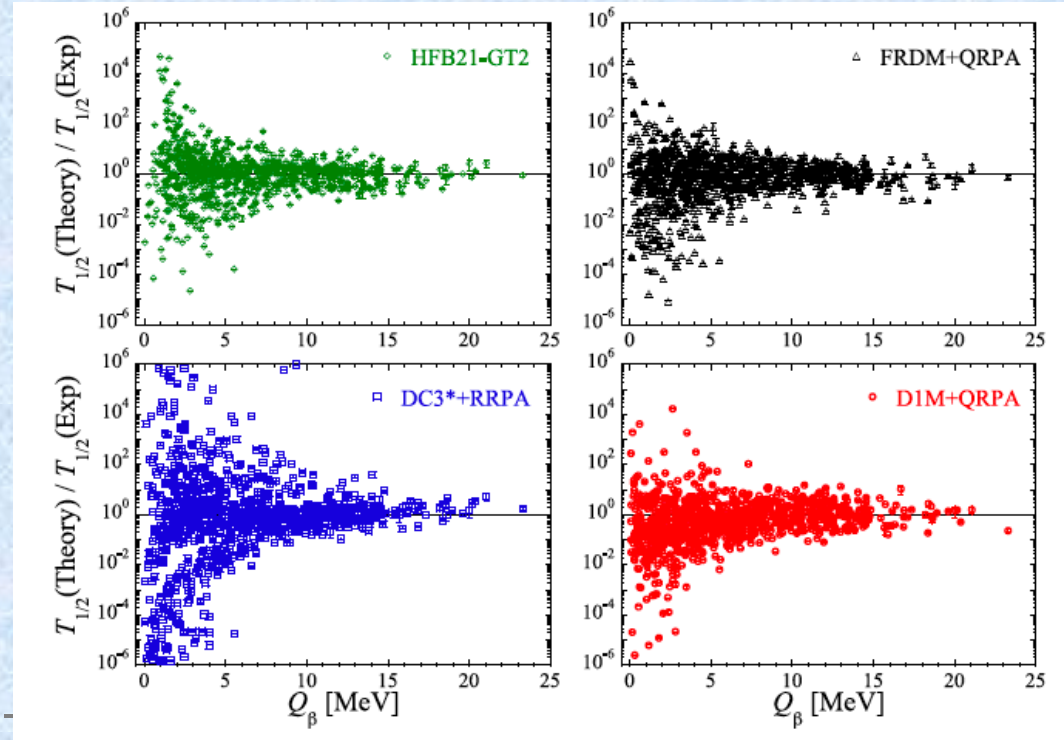
➡
- ✓ Different prescriptions of EC impact ν luminosity (and Y_e) at bounce (and shock formation)
- ✓ More influential nuclei located around $N = 50$ (and $N = 82$)
- ✗ For most of the ~170 nuclei represented no micro calculations exist!

β decays: r-process (1)



→ data scarce for (heavy) nuclei with $|Q_\beta| > 10$ MeV

Niu et al., PLB 723, 172 (2013)

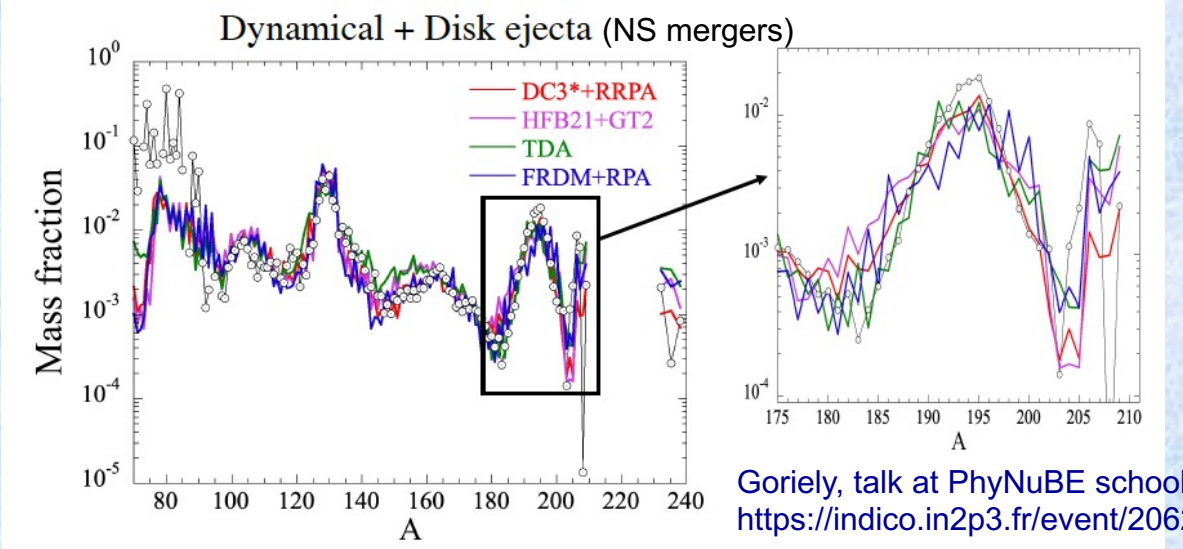


✗ limited number of available "large-scale" calculations!

N.B.: rates in astro ≠ lab ones! (e.g., due to e^- degeneracy, contribution of exc. states, …)

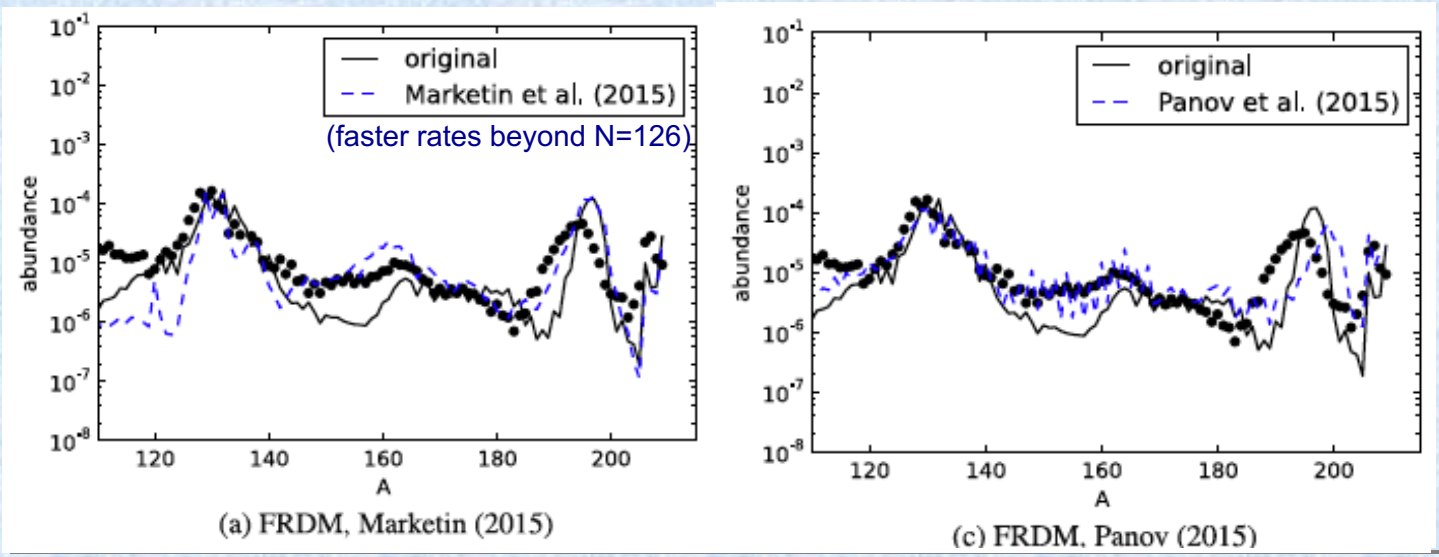
Arnould & Goriely, Prog. Part. Nucl. Phys. 112, 103766 (2020)

β decays: r-process (2)



Goriely, talk at PhyNuBE school, Dec. 2021
https://indico.in2p3.fr/event/20625/

- Large impact of β decay → rates set synthesis timescale !
- Dependence of final abundance on astro scenario



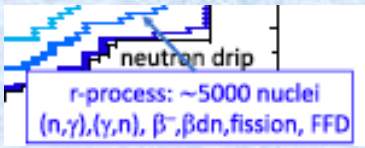
Eichler et al., ApJ 808, 30 (2015)

Nuclear reactions: beyond β decays

- If **off-equilibrium** (chemical, τ_{nuc} not << τ_{dyn}) → full **reaction network**
  e.g. *stellar evolution, explosive nucleosynthesis, novae* → cross sections needed !

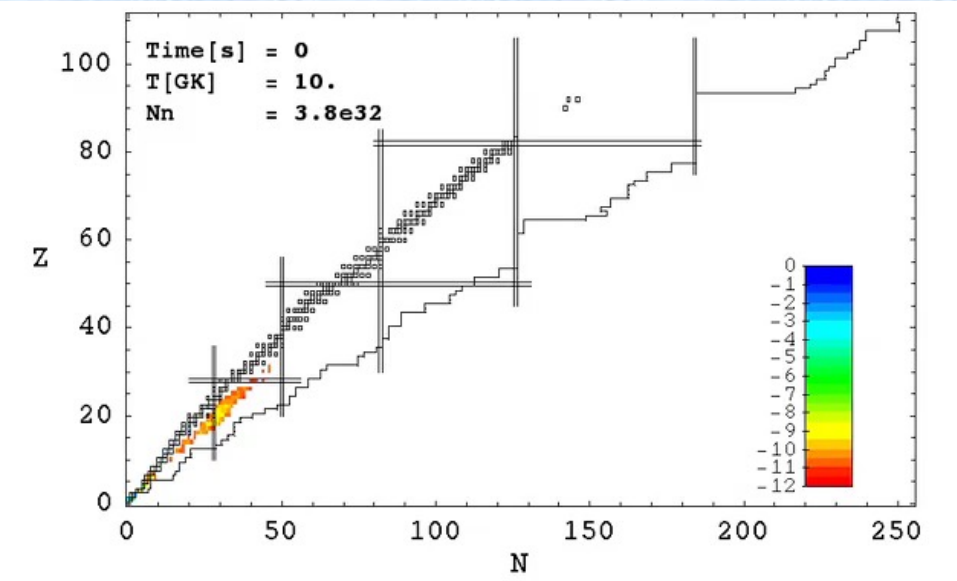
$$\dot{Y}(A,Z) = \pm \sum_{A',Z'} \lambda(A',Z')Y(A',Z') \pm \sum_{A',Z'} n_n \langle \sigma\nu \rangle Y(A',Z')$$

r-process: *β decay, photodisintegr., fission* *n capture*



If $\tau_{n,\gamma}$, $\tau_{\gamma,n}$ < τ_β → quasi-equilibrium or "*waiting point*" approx.
→ only "few" nuclei (*N* ~ 50, 82, 126, 184?)

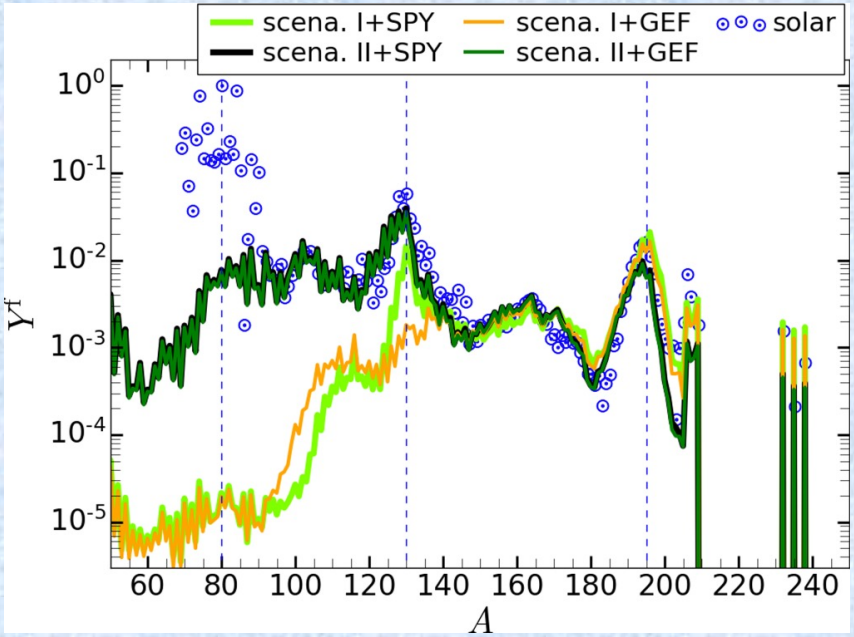
but: dynamical calculations show many nuclei involved (n_n is time dep.) !



Goriely, IAA ULB (2015)
r-process calculation

Fission and n capture reactions

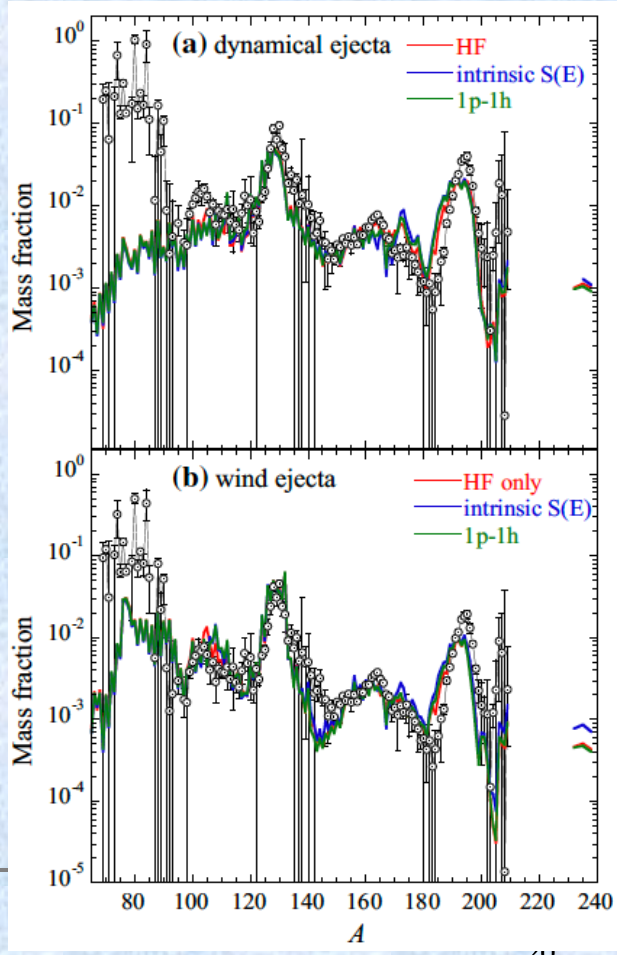
- Sensitivity of composition to *fission fragment distribution*, fission $T_{1/2}$, n release



Lemaître et al., PRC 103, 025806 (2021)

- Many different nuclear inputs required in r-process → consistency?
- Dependence on astro scenario

- Evaluation of direct n capture rates with detailed nuclear structure input (SM calculations)

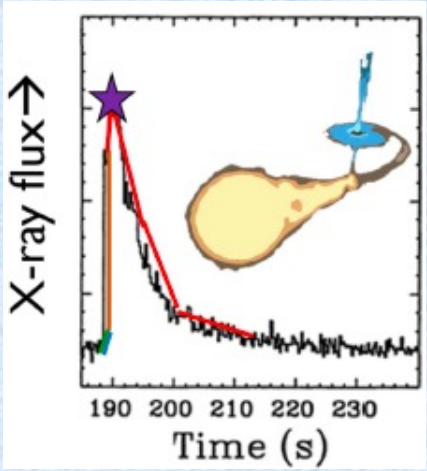


Sieja & Goriely, EPJA 57, 110 (2021)

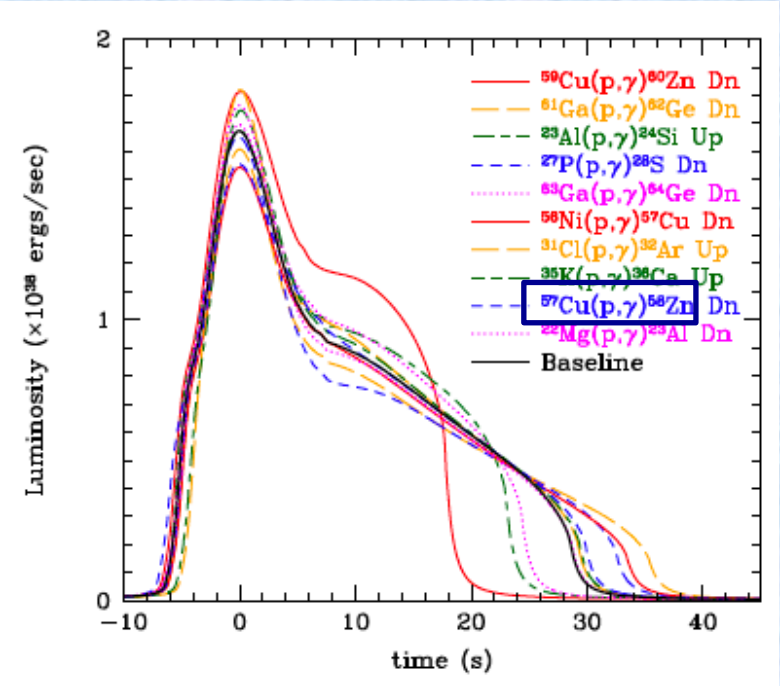
Capture reactions: p

- **X-ray burst / novae** : runaway nuclear fusion in accreting NSs/WDs → reaction network

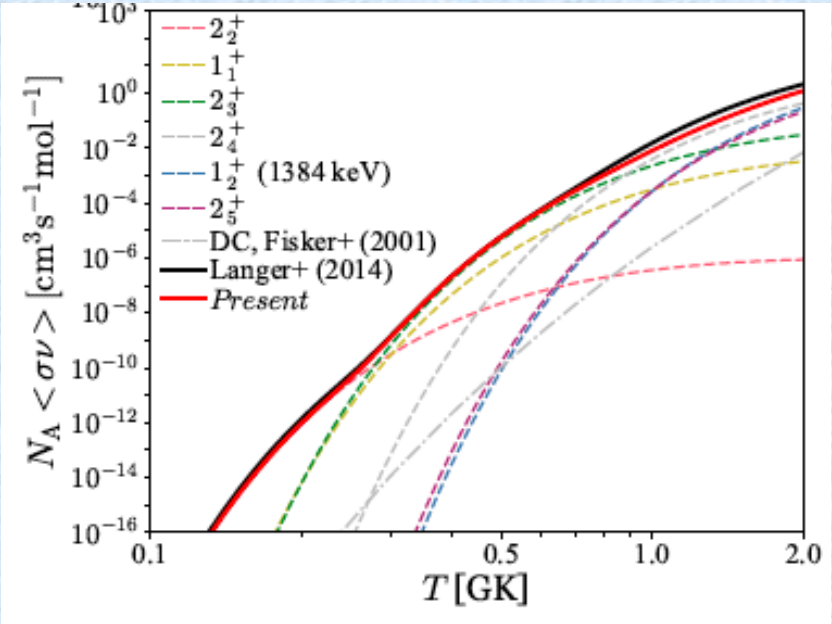
  (e.g. Galloway&Keek, ASSL Springer 2017 ; Cyburt et al., ApJ 830, 55 (2016))



Meisel et al.,
J.Phys. G 45, 093001 (2018)



Cyburt et al., ApJ 830, 55 (2016) – sensitivity study



Lam, [Smirnova] et al., arXiv:2107.11552v2

- Evaluation of (resonant) p capture with detailed nuclear structure input
- Calculation of pf-shell nuclei (update existing reaction database)

Conclusions & open questions

- Nuclear inputs needed for many astro environments (bursts, nucleos., SN/NS,…) → extrapolations of data & theoretical models needed

- Effort to produce more "realistic" inputs

- Uncertainties in nuclear data → impact astro observables

  ✓ need of (microscopic) reliable theoretical model when no data
  ✓ need of experimental data to calibrate the models
  + *astrophysical observations*

- Extrapolation from raw data → **model dependence of the constraints**

- In laboratory experiments mostly "low" density (~ saturation density) and low *T* probed; matter in astro sites different from lab → **extrapolation to astro conditions (high *T* and density, asymmetry, charge neutral) ?**

- Astro simulations vs microphysics inputs → **uncertainties in nuclear / astro**, **consistency of inputs** and relative **effects of microphysics inputs in astro simulations** ? → systematic studies needed


Thank you