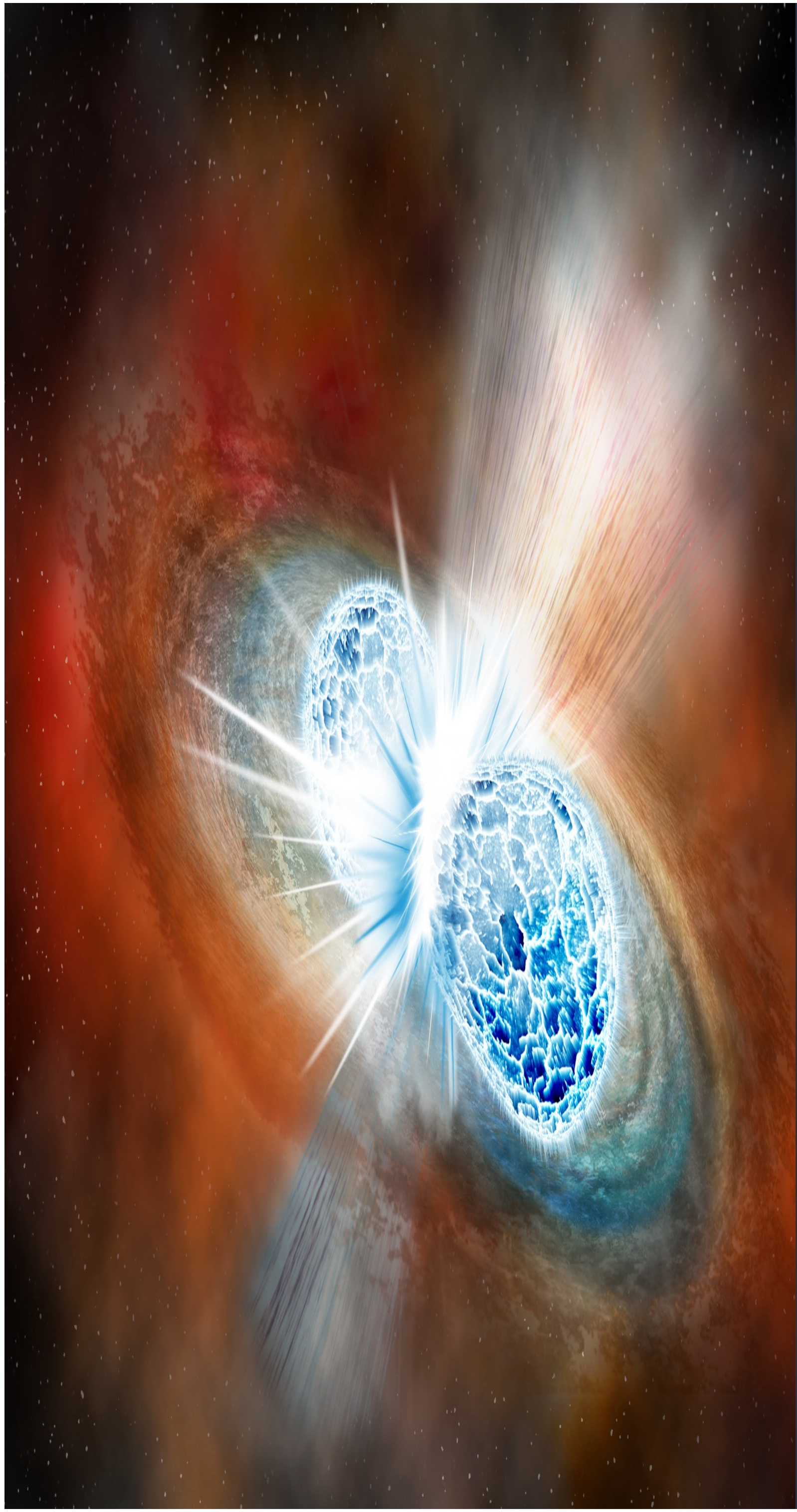


Nuclear and astrophysical aspects of the r-process nucleosynthesis

S. Goriely (IAA-ULB)

ULB UNIVERSITÉ LIBRE DE BRUXELLES

IAA bruxelles

The r-process nucleosynthesis

Part I:

The rapid neutron-capture process

- r-process in SNII, NSM, Collapsars
- Nuclear physics aspects

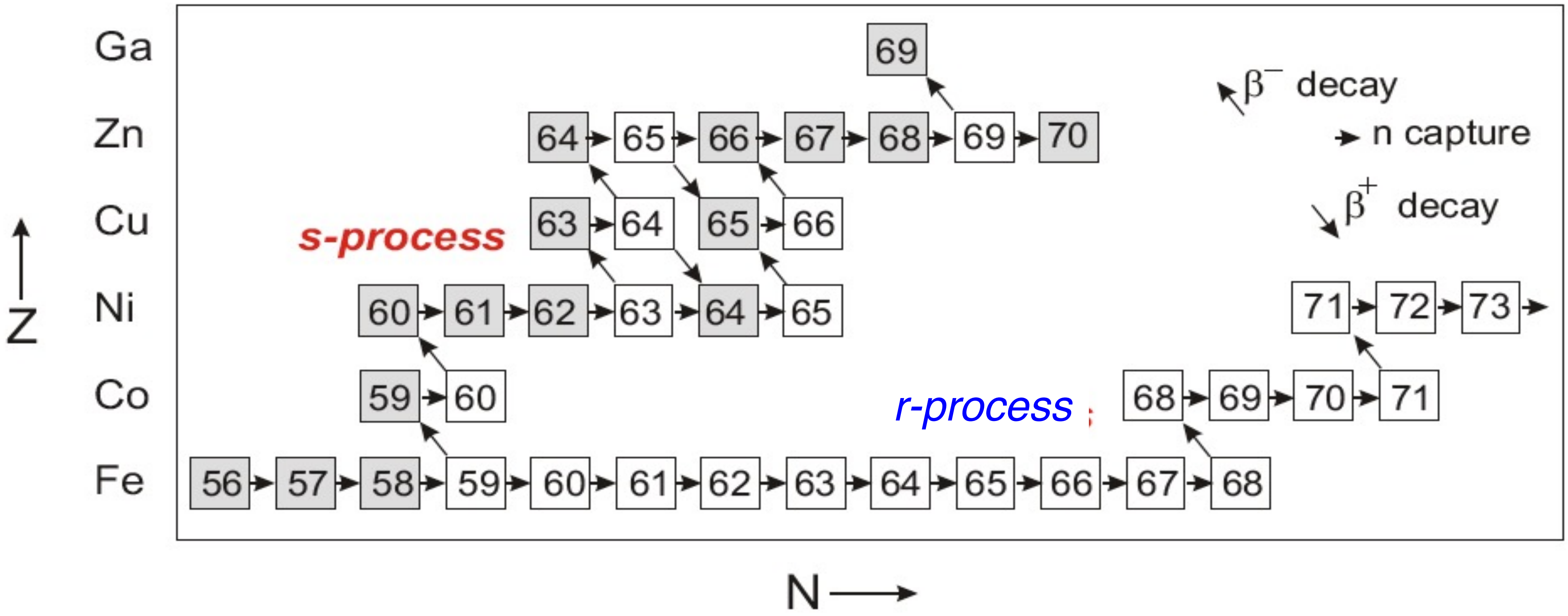
A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta \ll \tau_n$

Rapid neutron-capture process: $\tau_\beta \gg \tau_n$

τ_n = lifetime against neutron capture

τ_β = lifetime against β⁻ decay



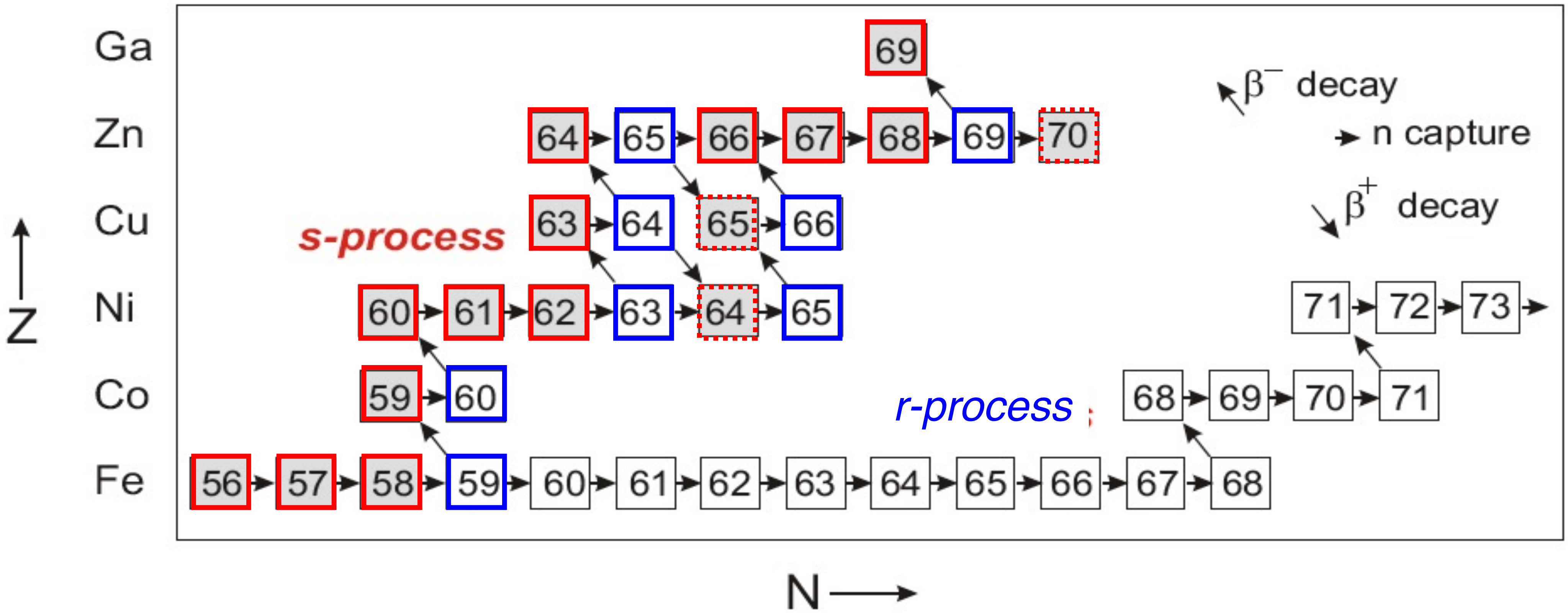
A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta \ll \tau_n$

$N_n \sim 10^7 - 10^{11}$ cm^{-3} $T \sim 1\text{-}3\ 10^8$K $t_{irr} \sim 10\text{-}10^4$yr

τ_n = lifetime against neutron capture

τ_β = lifetime against β^- decay



A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta << \tau_n$

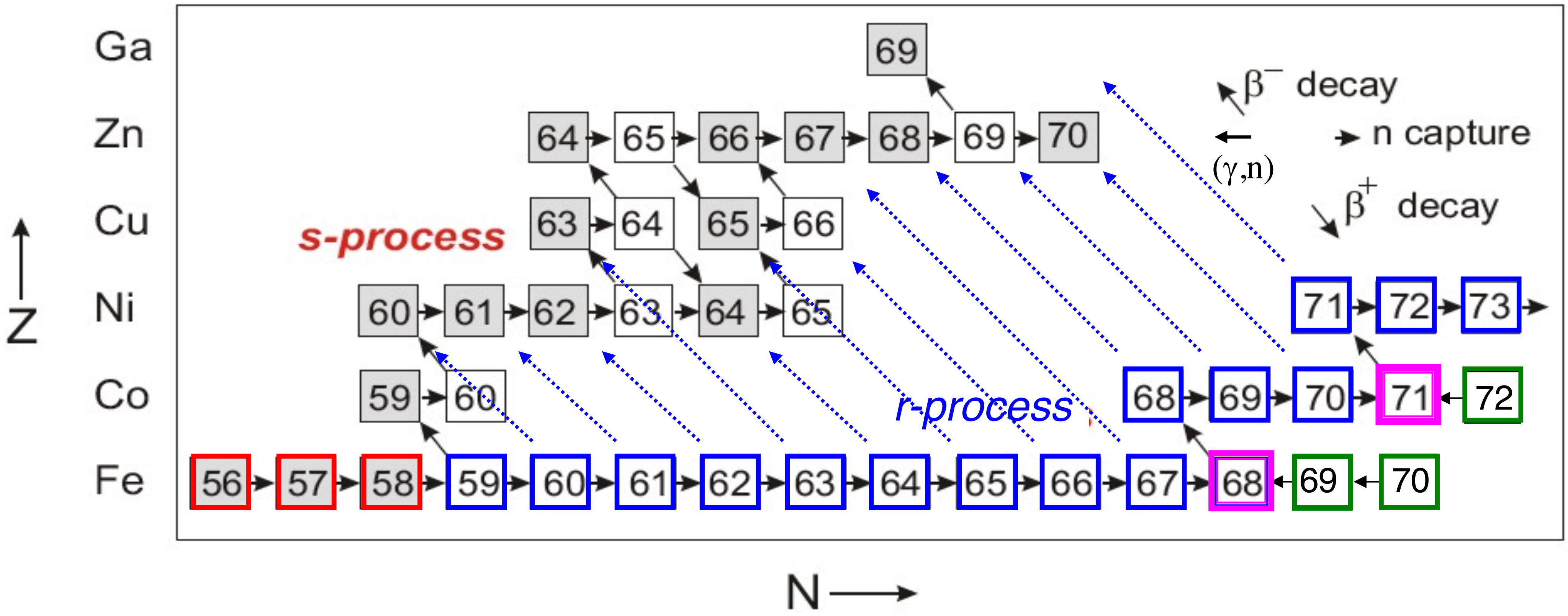
N_n~10^7-10^{11} cm^{-3} T~1-3 10^8K t_{irr}~ 10-10^4yr

Rapid neutron-capture process: $\tau_\beta >> \tau_n$

N_n>>10^{20} cm^{-3} T~1-2 10^9K t_{irr}~ 1s

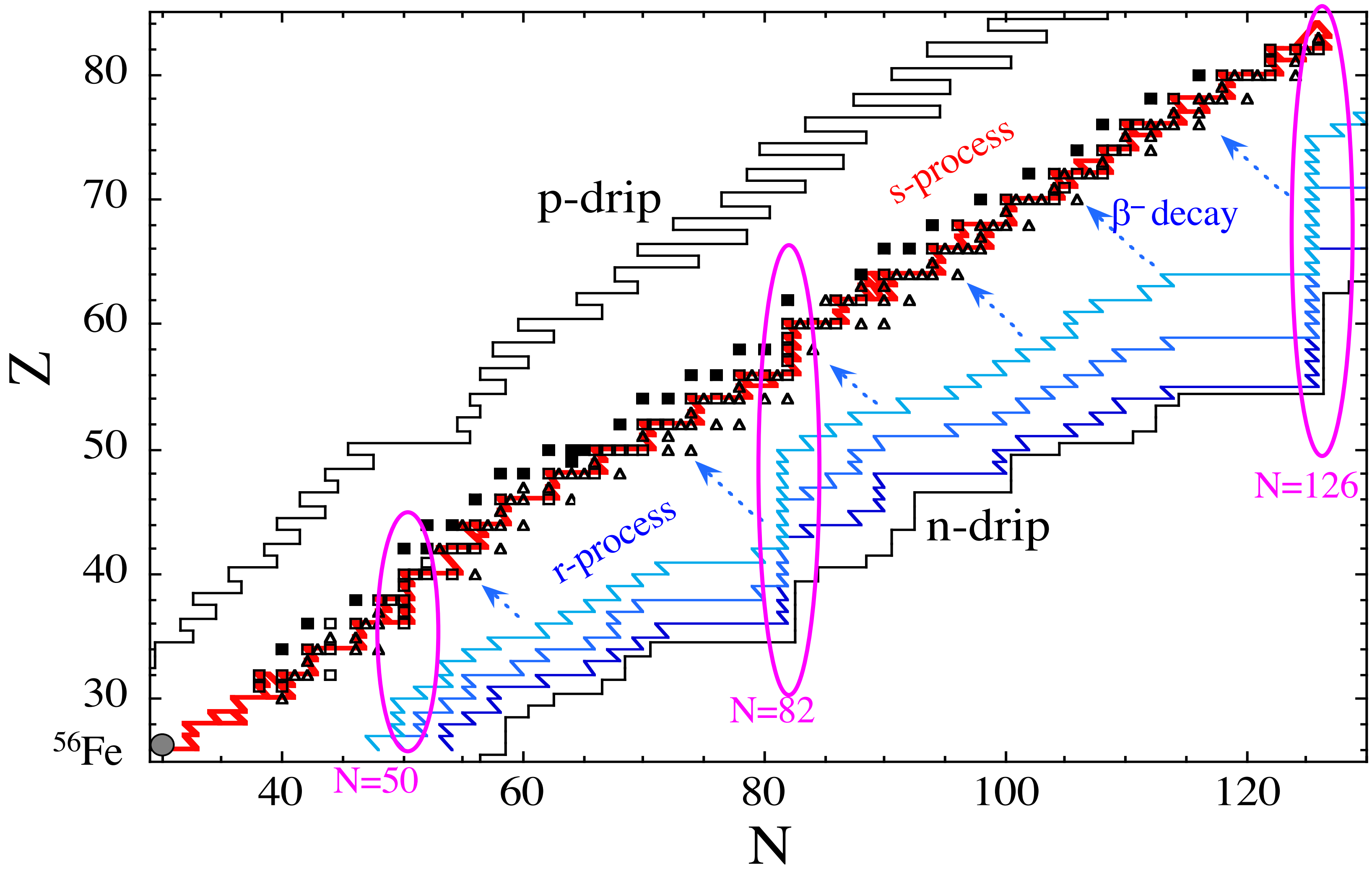
τ_n = lifetime against neutron capture

τ_β = lifetime against β^- decay

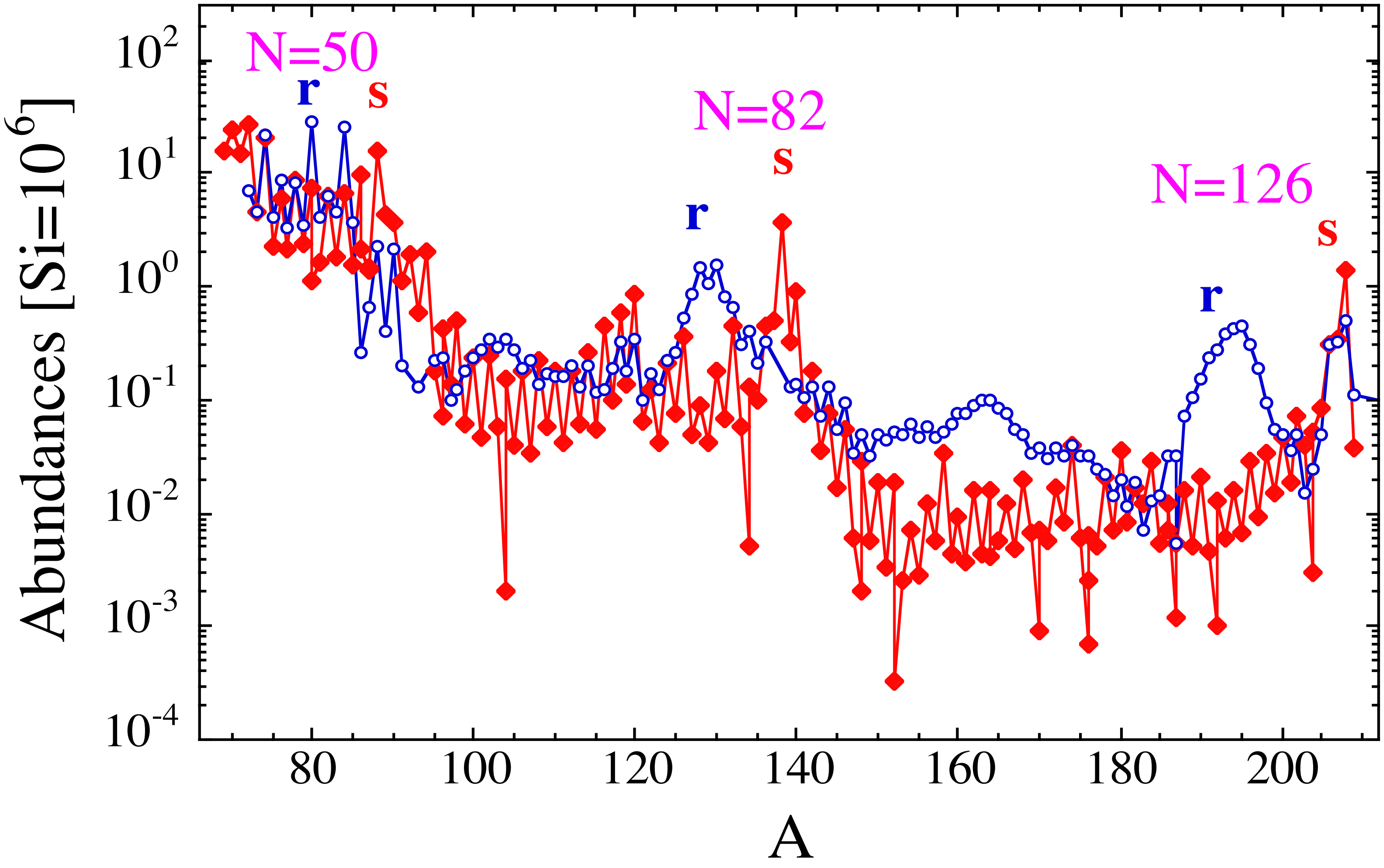


A schematic representation of the s- and r-processes

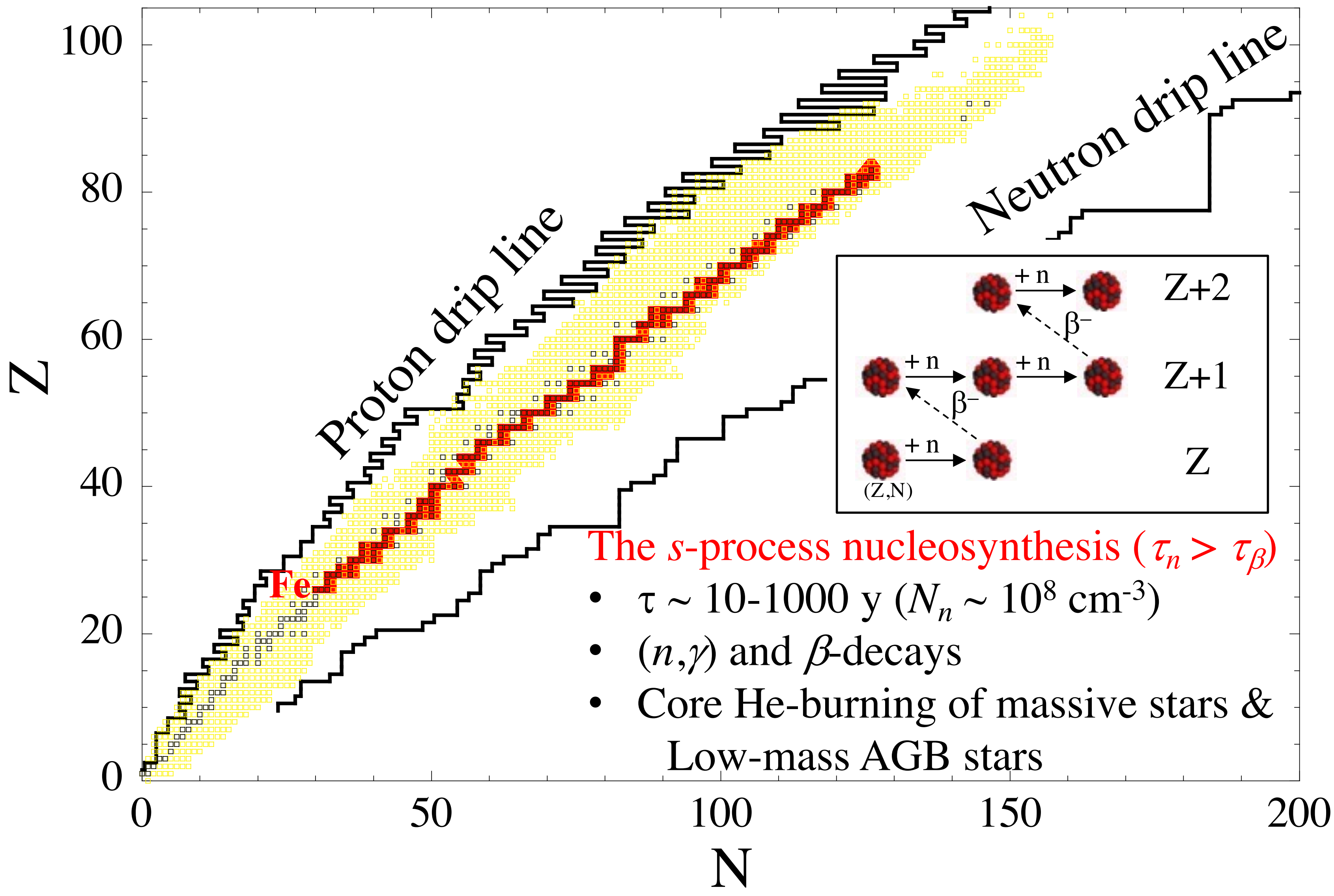
Closed shells at magic numbers N=50, 82, 126 --> slow n-capture



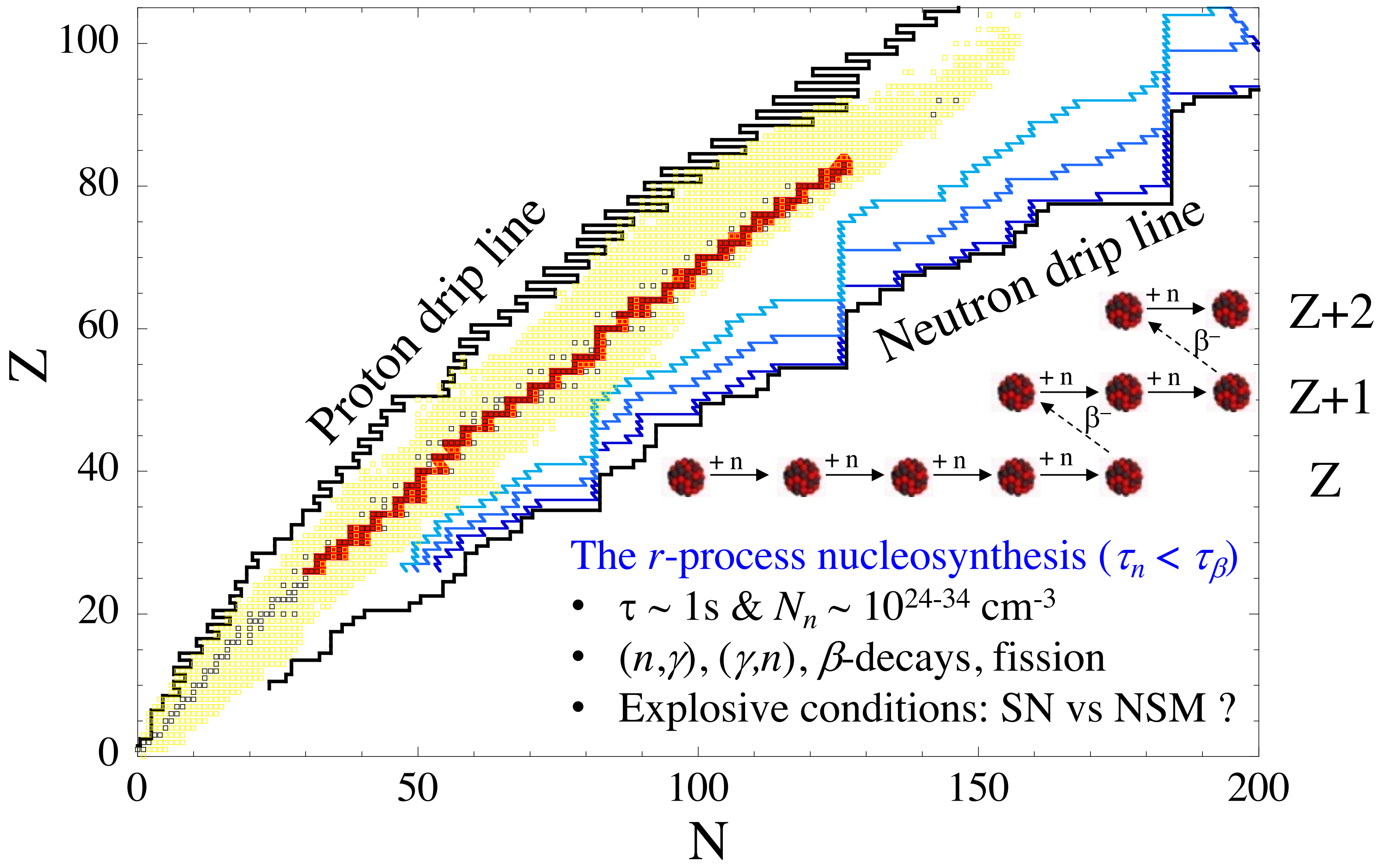
The signature of nuclear properties in the double-peak pattern of the solar abundance distribution



The *s*-process nucleosynthesis

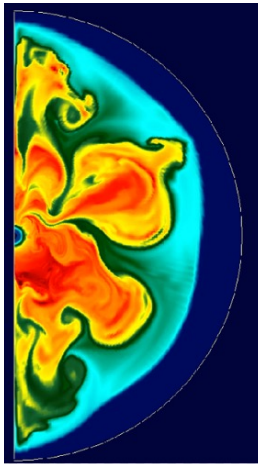


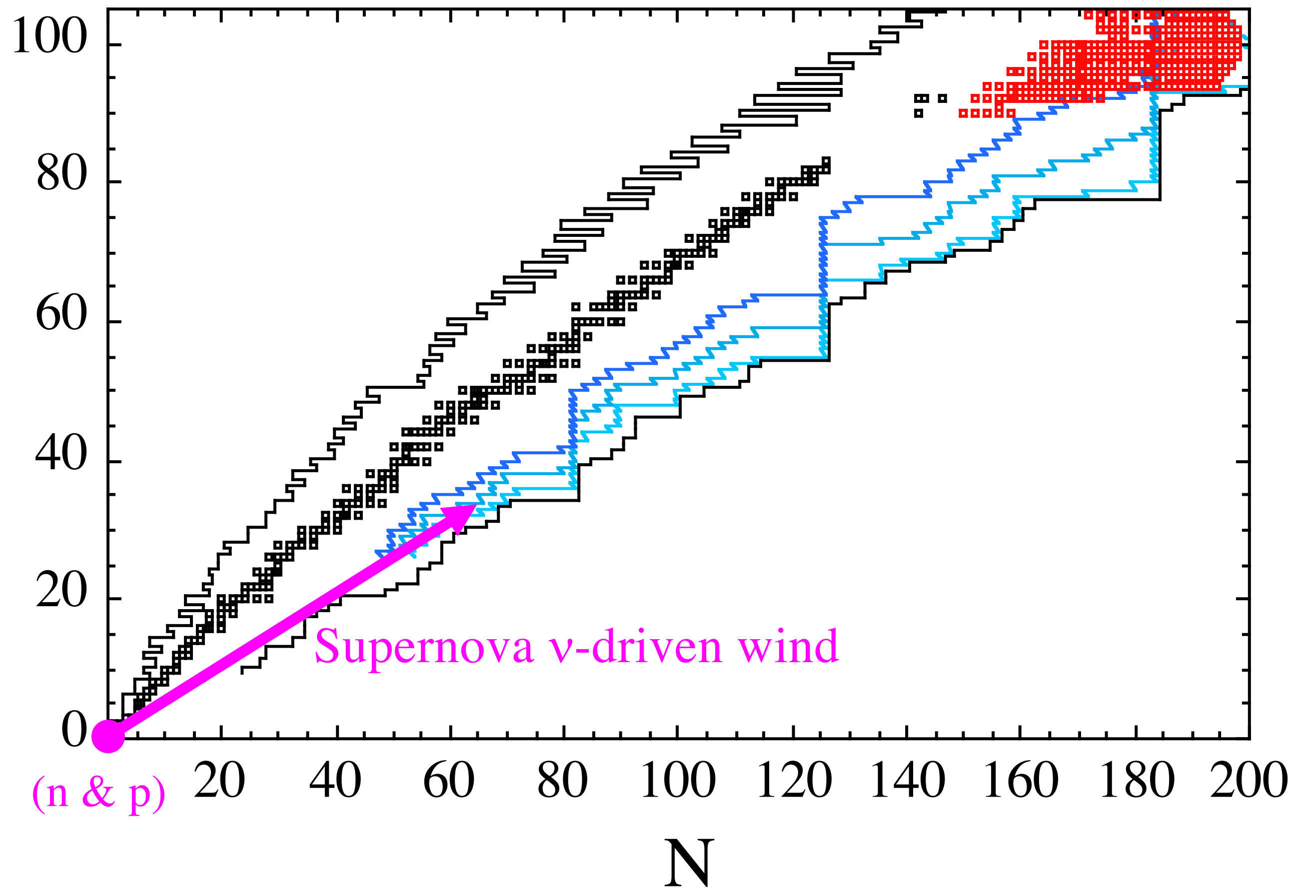
The *r*-process nucleosynthesis



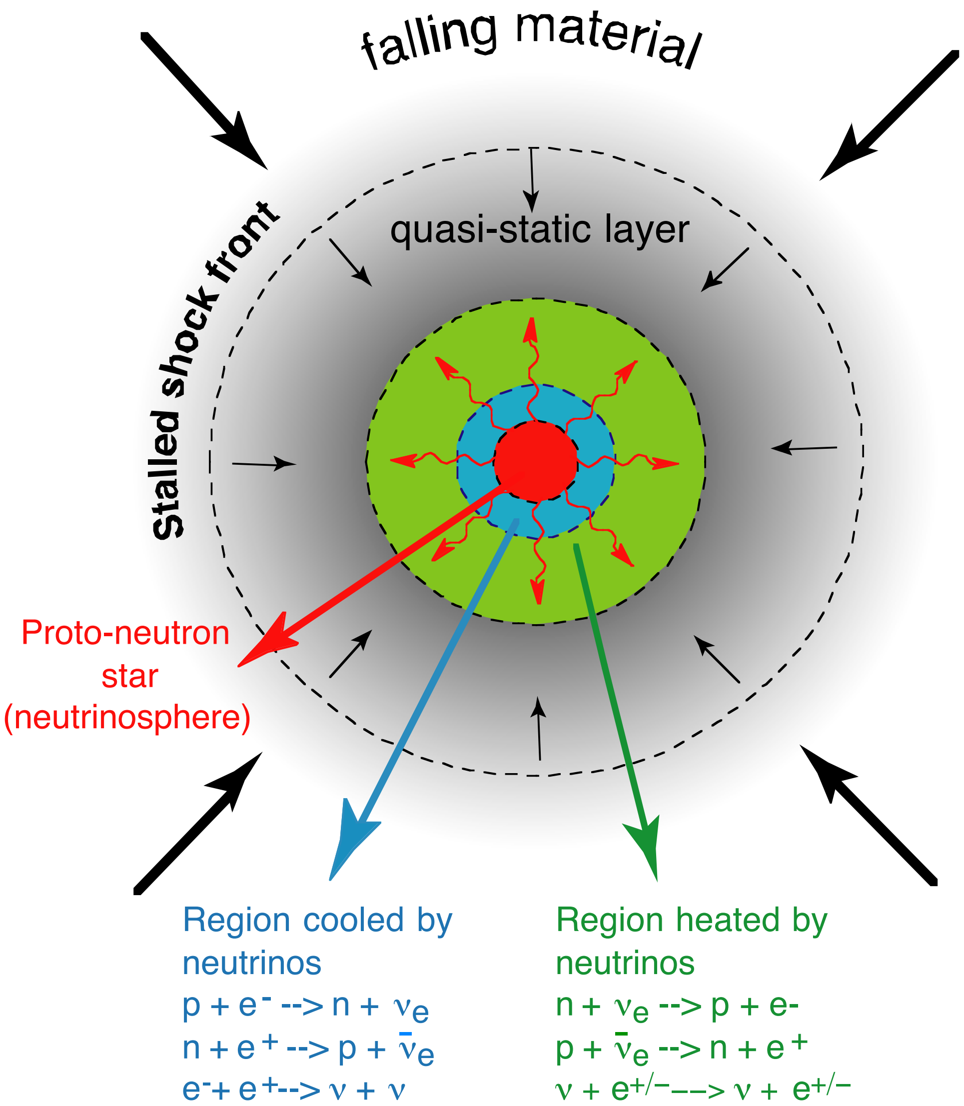
The *r*-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

one of the still unsolved puzzles in nuclear astrophysics





Nucleosynthesis in the ν-driven wind



Decompression of hot material

n,p at $T_9 \approx 10$ $\rho \sim 10^6$g/cm^3

↓ NSE

^{4}He recombination

↓ $\alpha\alpha$n-^{9}Be(α,n)

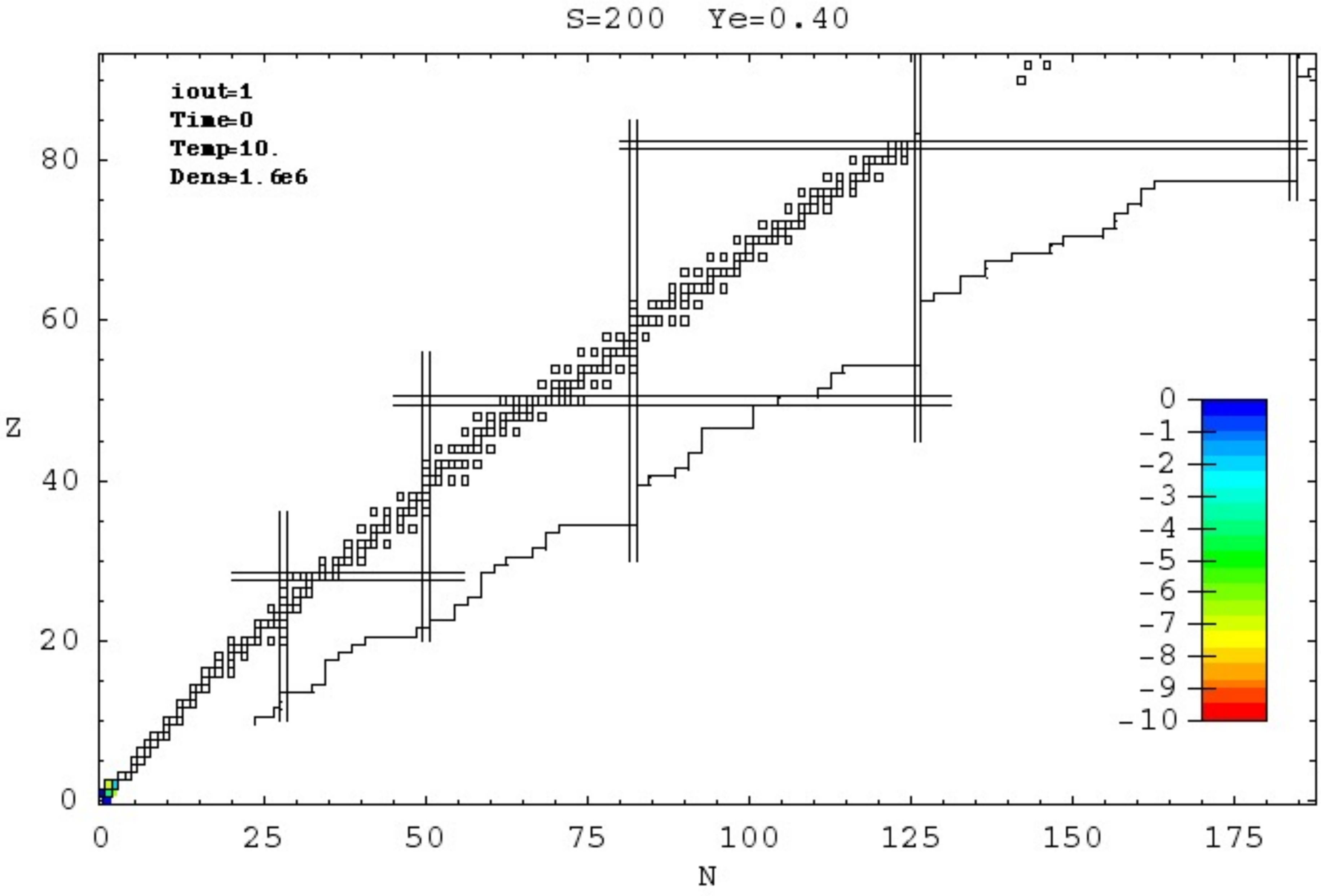
^{12}C bottleneck

↓ (α,γ) & (α,n)

$60 \leq A \leq 100$ seed

↓ (n,γ) & (γ,n) + β-decays

r-process


S=200 Ye=0.40
iout=1
Time=0
Temp=10.
Dens=1.6e6
Z
N
0
20
40
60
80
0
25
50
75
100
125
150
175
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

the r-process yields highly sensitive to

- the entropy $S \propto T^3 / \rho$
- the electron fraction $Y_e = Y_p/(Y_p + Y_n)$
- the expansion timescales τ_{dyn}

Typical conditions in the ν-driven wind

$$S \propto \frac{T^3}{\rho} \leq 100$$

$$Y_e = \frac{Y_p}{Y_p + Y_n} \approx 0.47$$

$$\tau_{dyn} = 100\text{ms}$$

No r-process in realistic hydrodynamical simulations:

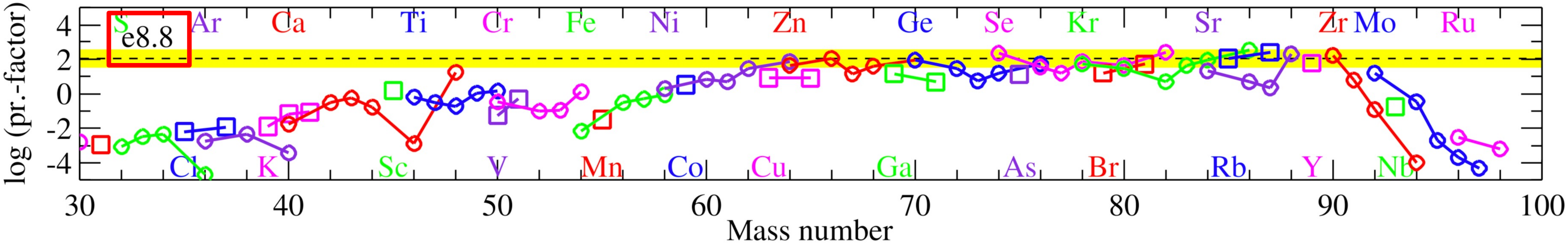
conditions for a successful r-process (high N_n/N_{seed})

- High entropy wind (hight-T, low-ρ) → Increase S — $S \sim 500$
- Low-Y_e wind (n-rich matter) → Lower Y_e — $Y_e \sim 0.3$
- Fast expanding wind → Lower τ_{dyn} — $\tau_{dyn} \sim 10\text{ms}$

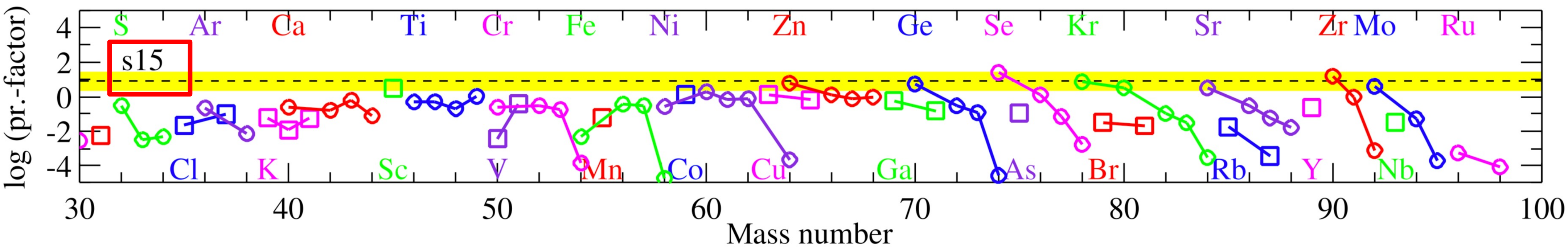
Self-consistent 2D hydrodynamical (successful) explosions

(Wanajo, Müller, Janka, Heger, 2018)

- Electron-Capture Supernova ($M_i \sim 8.8 M_o$) → production of n-rich up to ~Zr



- Core-Collapse Supernovae ($M_i = 11\text{-}15\text{-}27 M_o$) → production of p-rich up to ~Mo



2D/3D MHD jet-like explosion of magnetically driven core-collapse supernovae

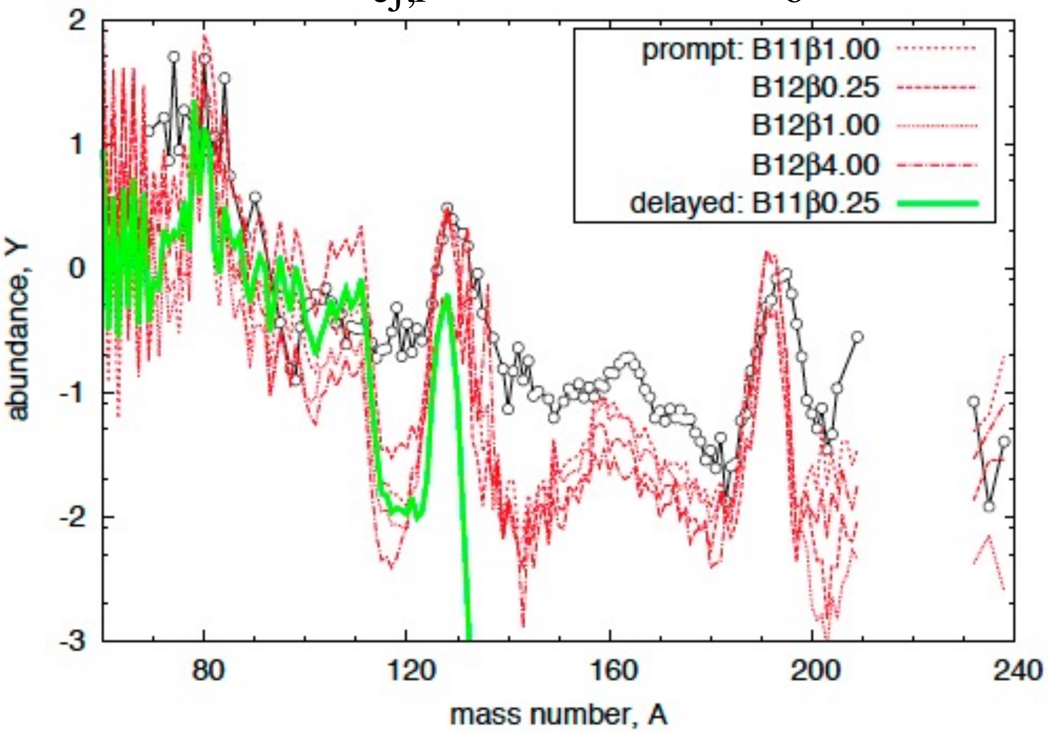
(Winteler et al. 2012; Mösta et al. 2014; Nishimura et al. 2015)

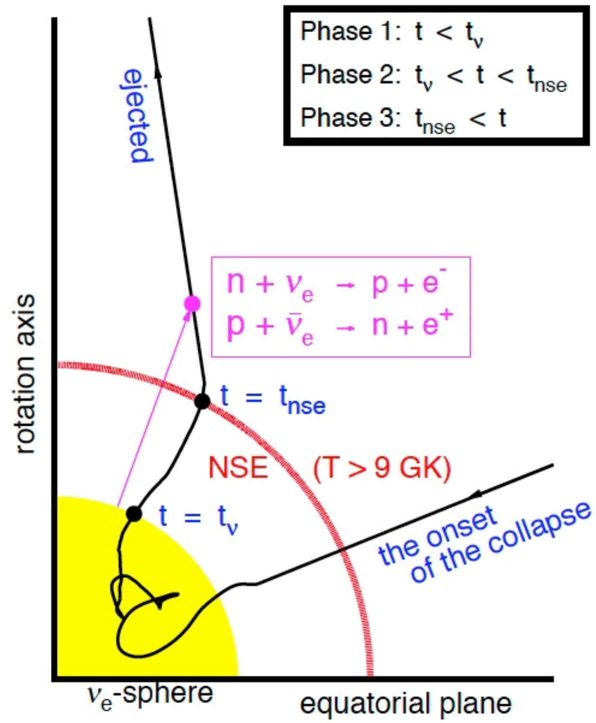
Pre-collapse core with **strong** initial magnetic fields and rapid rotation → highly magnetized NS with $B \sim 10^{15}$ G
Rare events $P \sim 0.01$–0.1% of all SNe

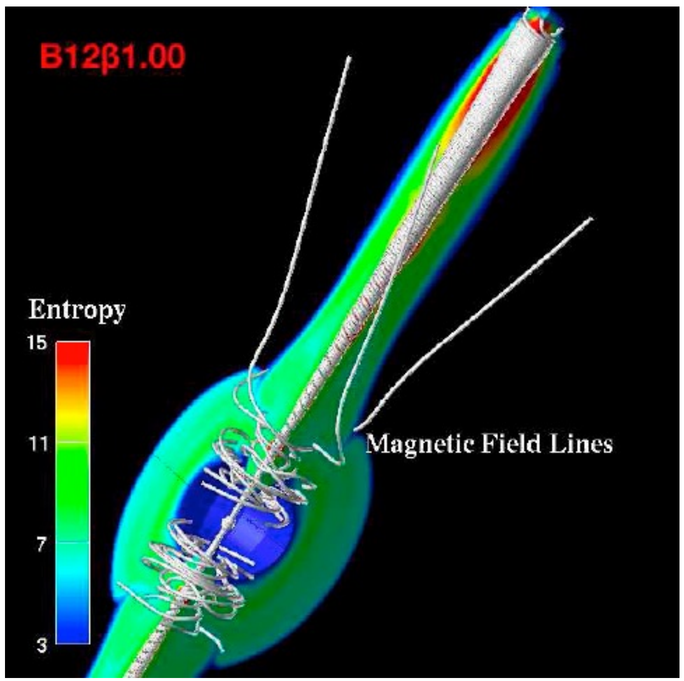
$B_0 = 10^{11}$ G → Synthesis up to $A \sim 130$

$B_0 = 10^{12}$ G → Synthesis up to Th/U

$M_{ej,r} \sim$ 1-2 $10^{-2}\ M_o$

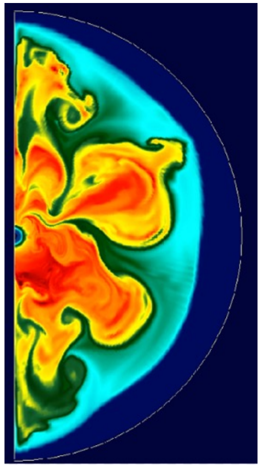


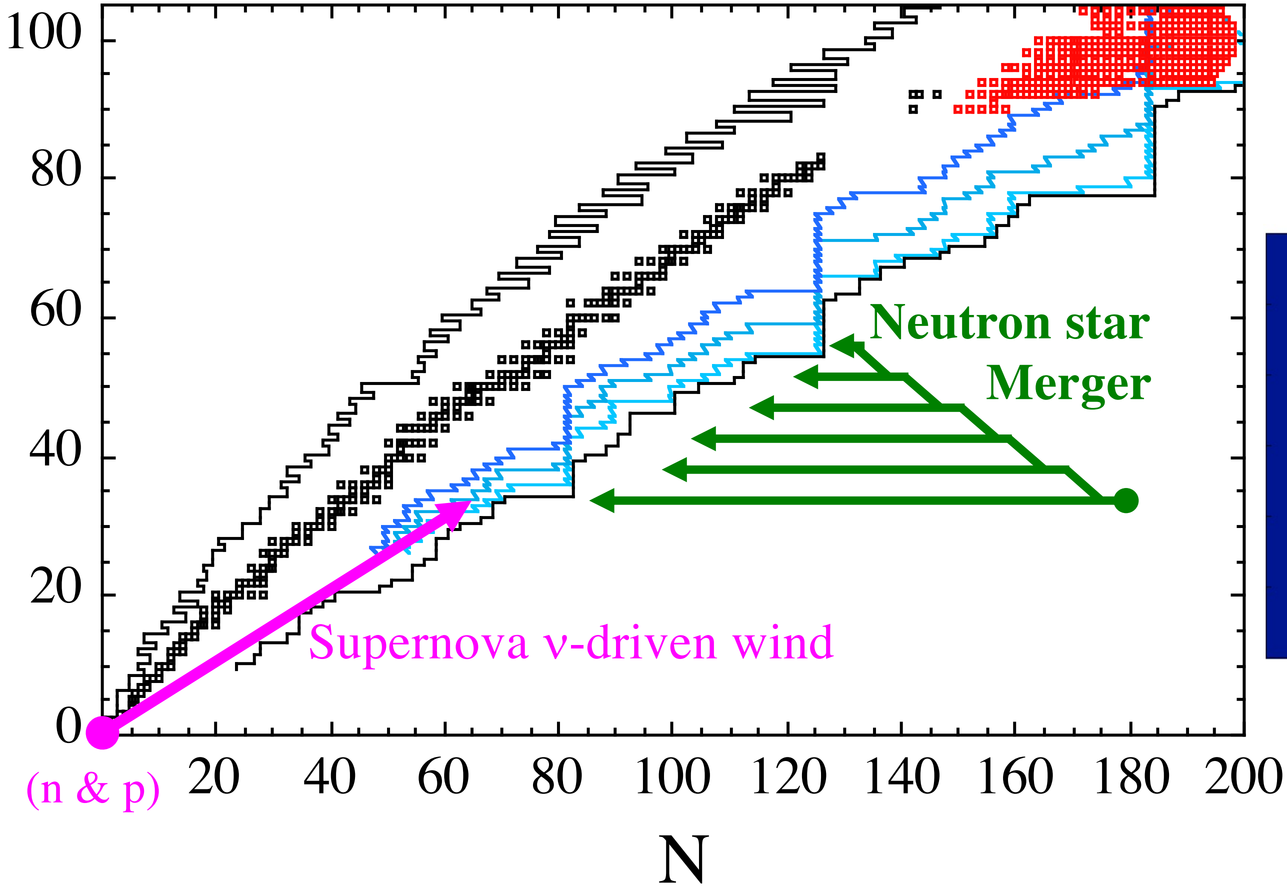


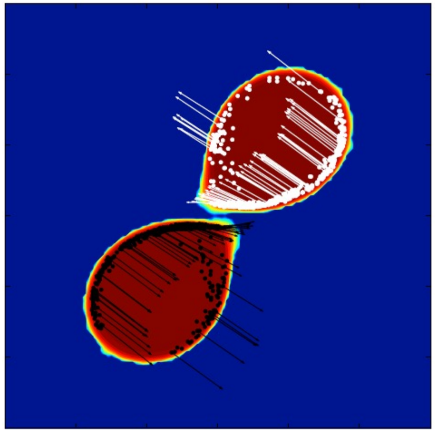


The *r*-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

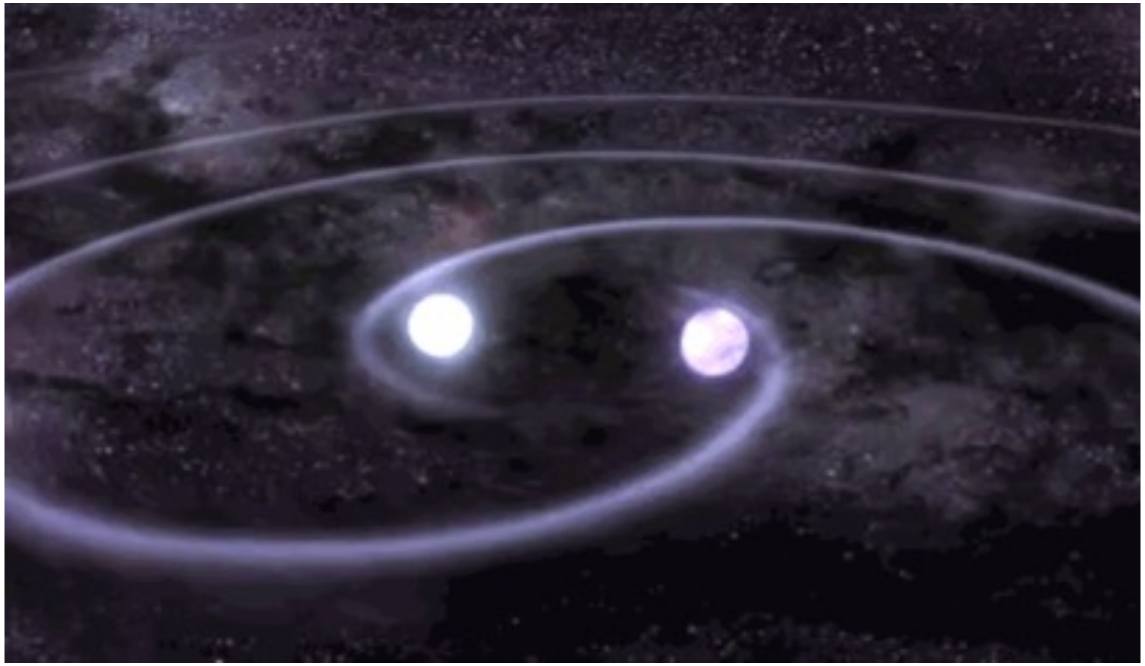
one of the still unsolved puzzles in nuclear astrophysics





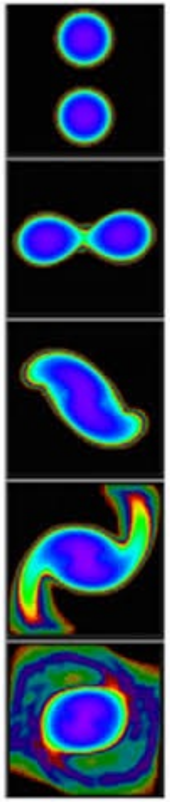


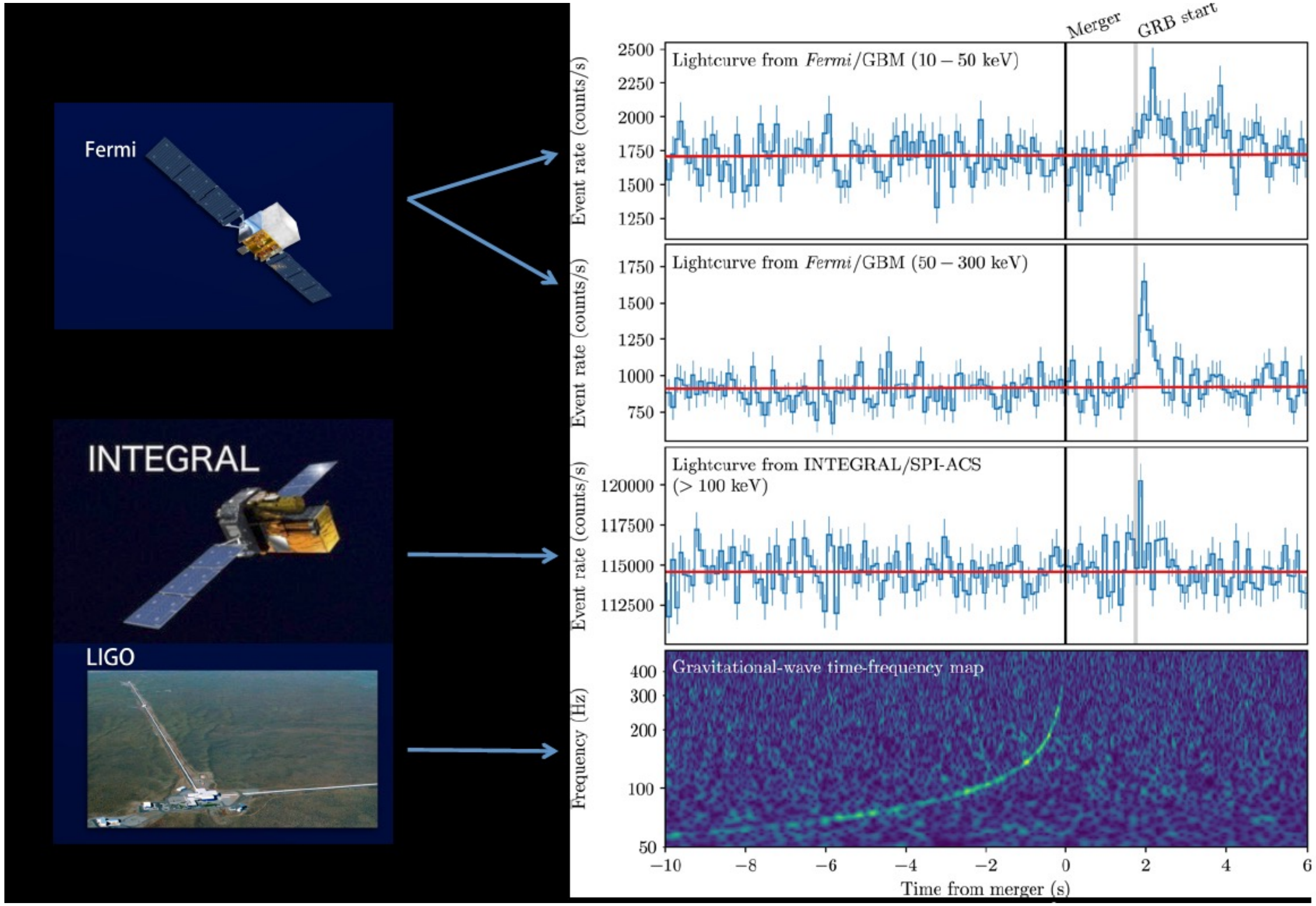
New observational insight thanks to the observation of GW170817 binary NS merger and its optical counterpart AT2017gfo



On August 17, 2017

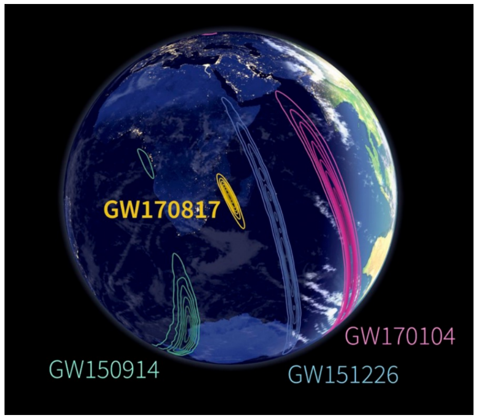
First detection of binary NS merger

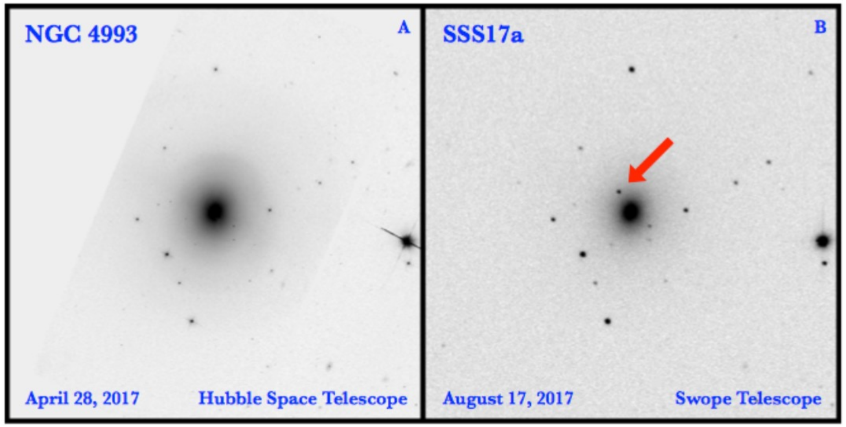




11h after

OPTICAL



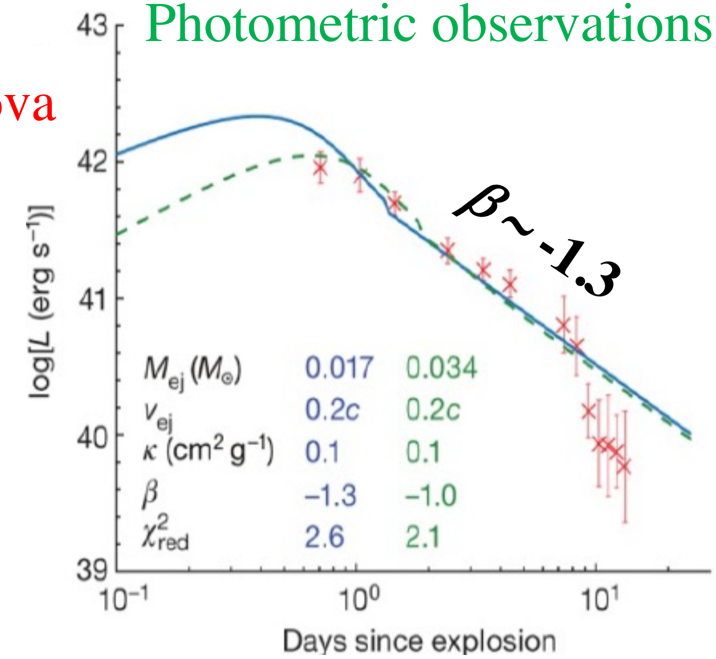


The analysis of the GW170817 light curve

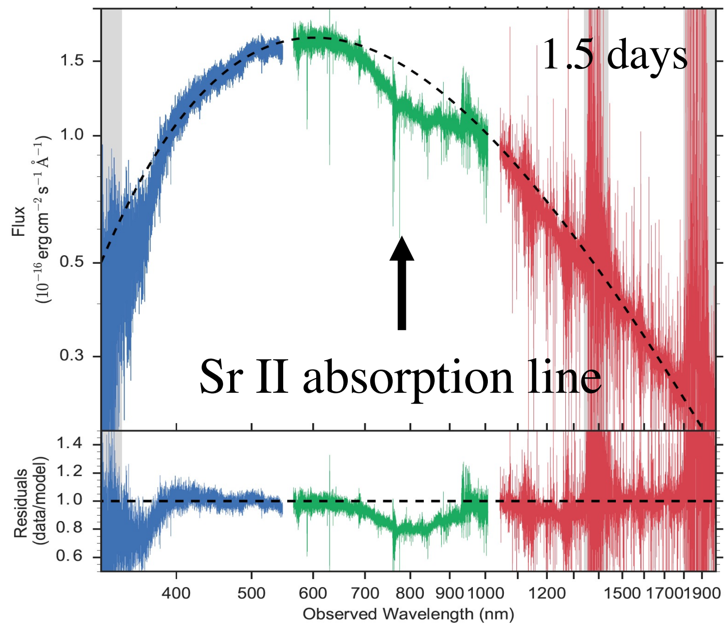
- The kilonova light curve is compatible with an ejecta mass ($M_{ej} \approx 0.03$-$0.06\ M_\odot$)
  - "Blue" $A<140$ component with $M_{ej} \approx 0.01$-$0.02\ M_\odot$ and $v_{ej} \approx 0.26c$
  - "Red" $A>140$ component with $M_{ej} \approx 0.02$-$0.05\ M_\odot$ and $v_{ej} \approx 0.15c$

Kilonova

Photometric observations

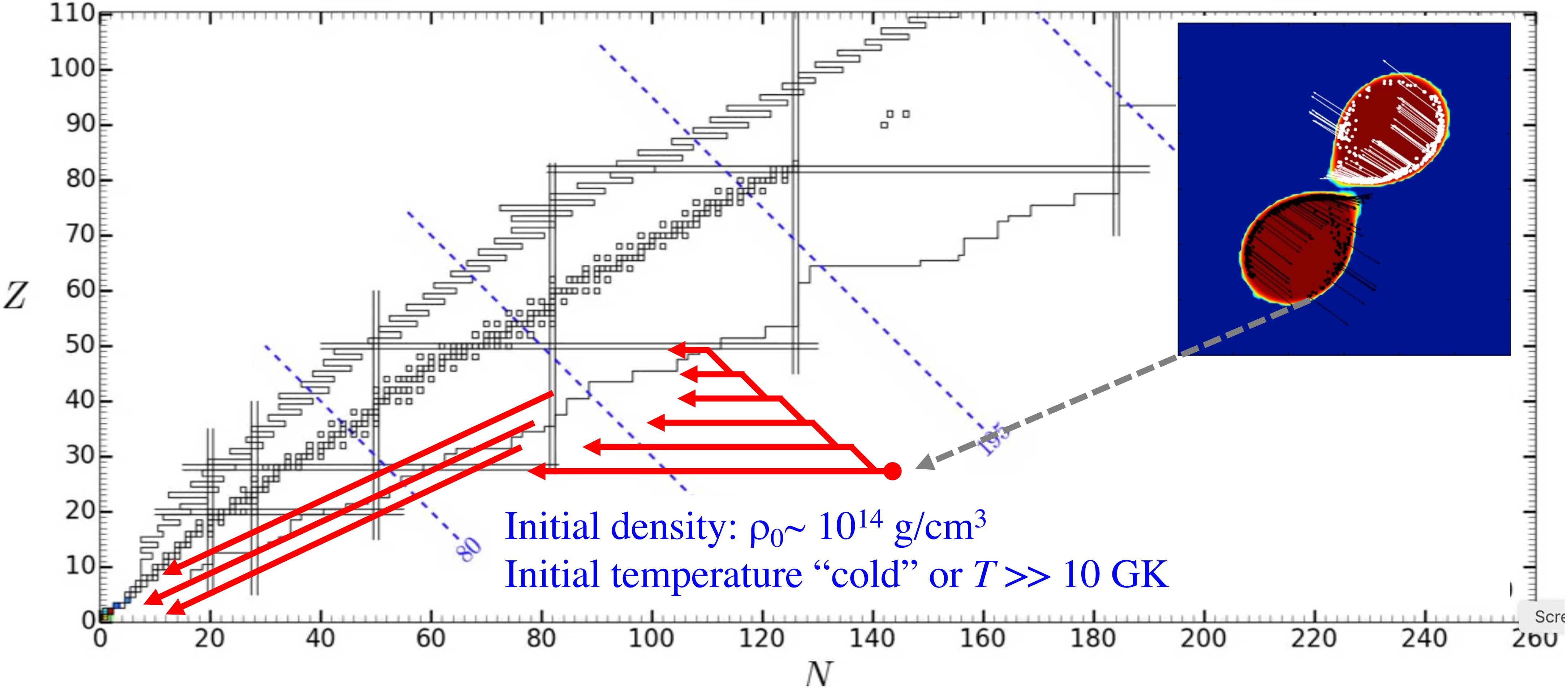


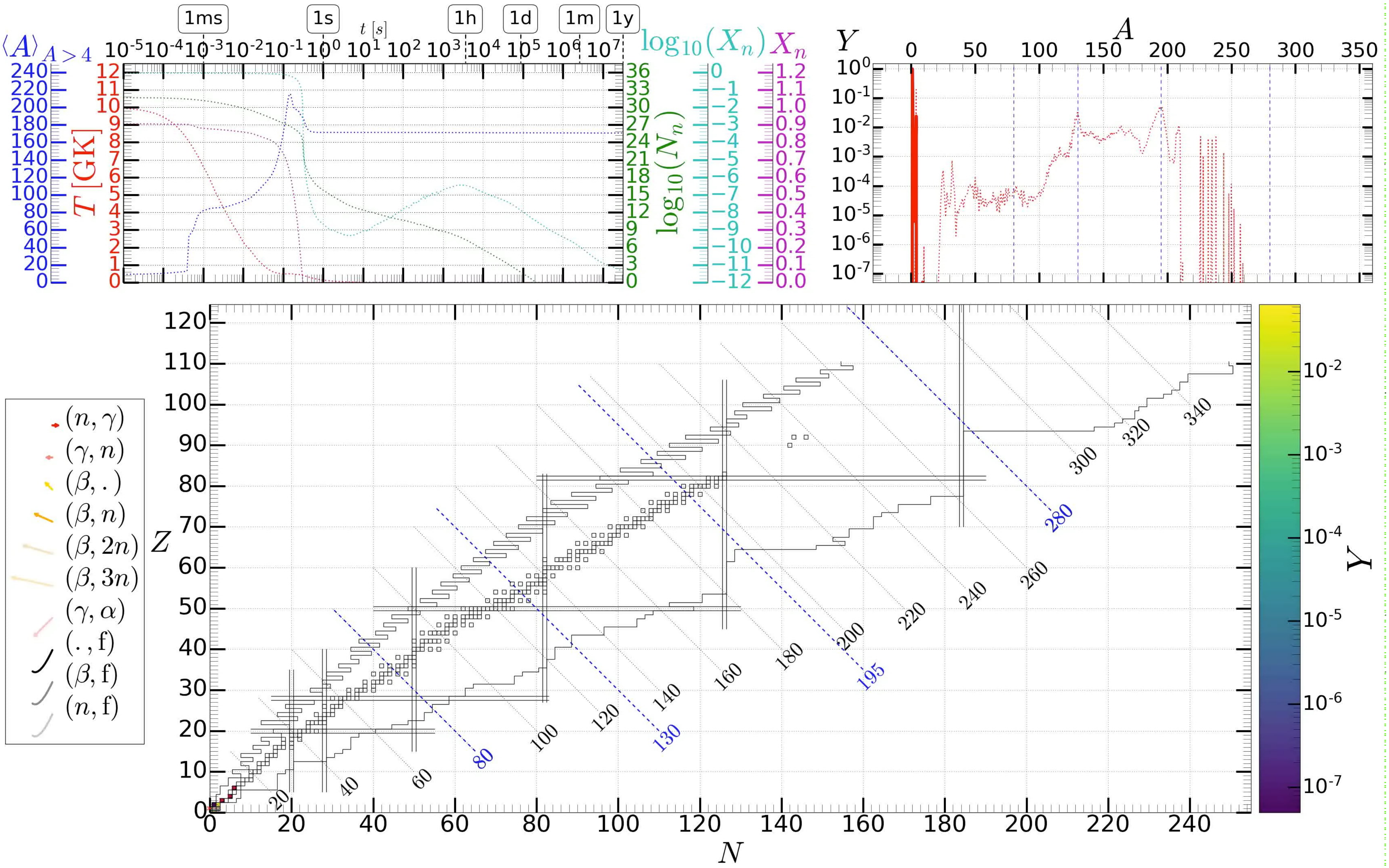
Spectroscopic observations



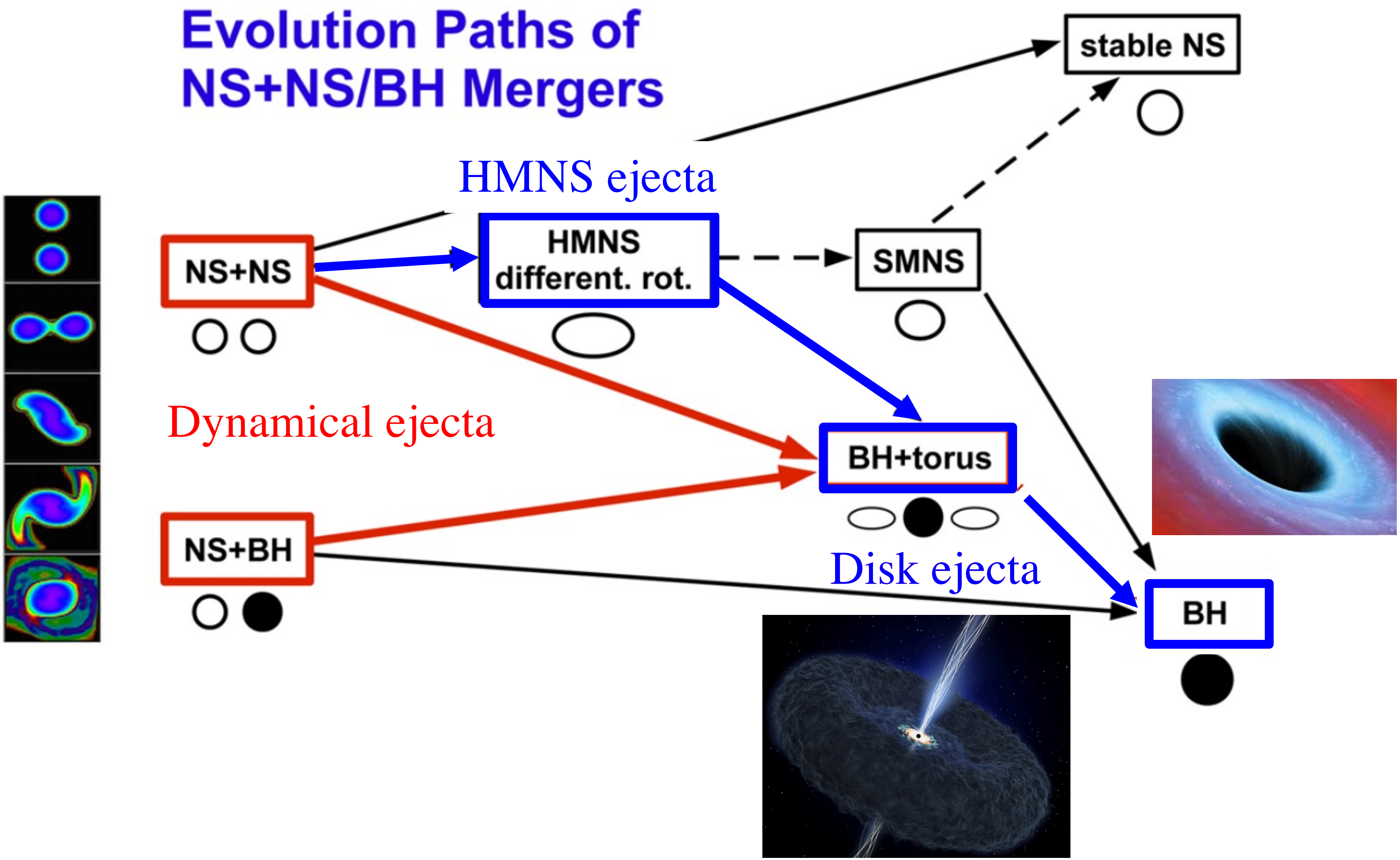
Watson et al. (2019)

- The ejected mass and new merger rate inferred from GW170817 imply that NS mergers are a dominant source of *r*-process production in the Universe.


Initial density: ρ0~ 10^14 g/cm^3
Initial temperature "cold" or T >> 10 GK
Z
N
80
135

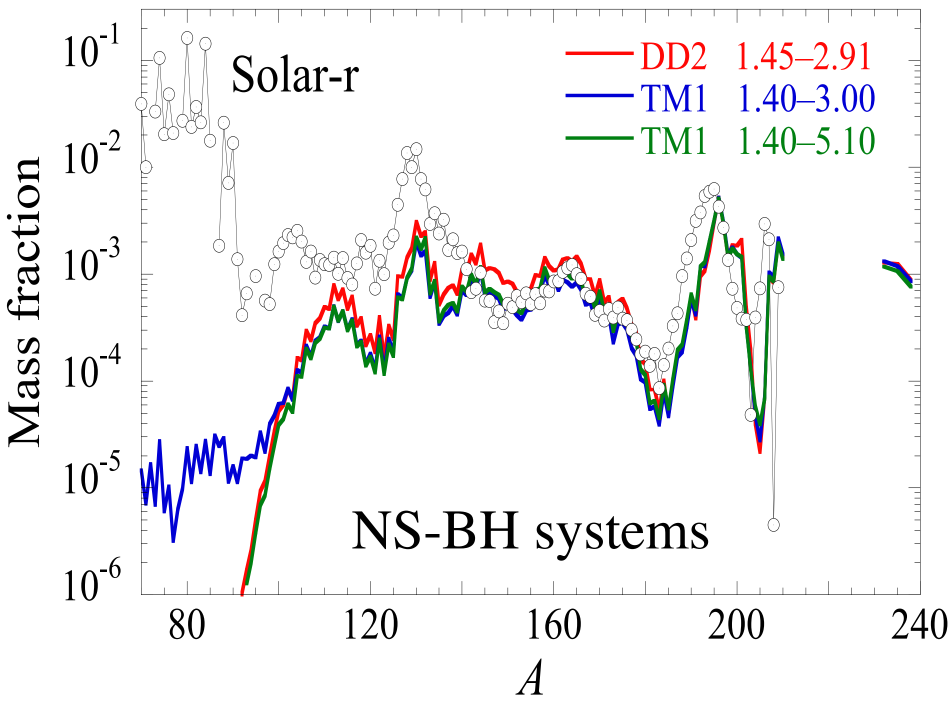


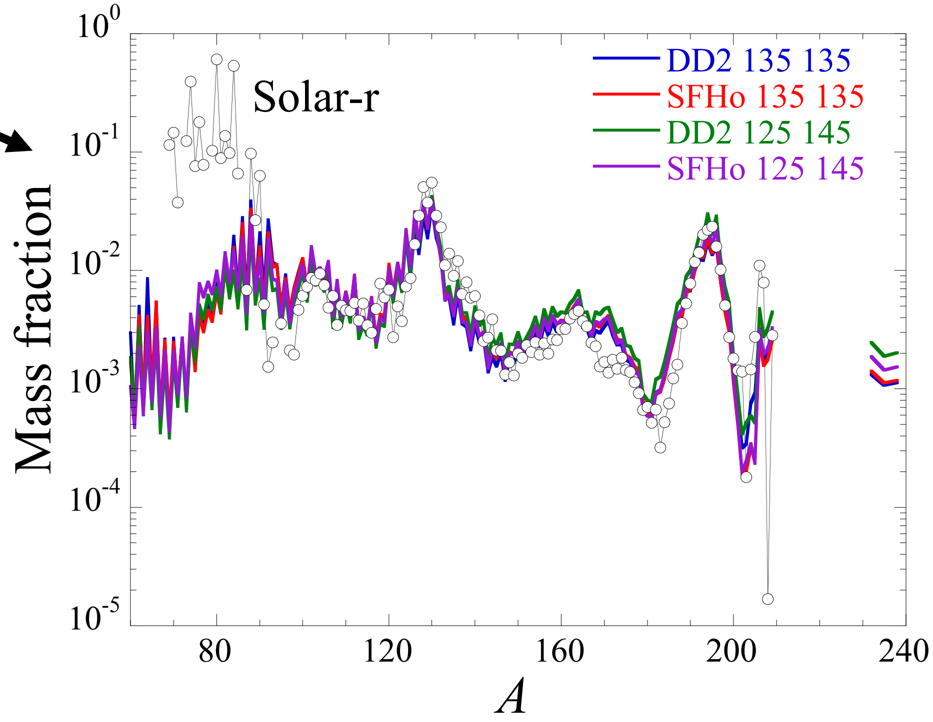
1ms
1s
1h
1d
1m
1y
t [s]
⟨A⟩_{A>4}
T [GK]
log10(N_n)
log10(X_n)
X_n
Y
A
Z
N
(n, γ)
(γ, n)
(β, .)
(β, n)
(β, 2n)
(β, 3n)
(γ, α)
(., f)
(β, f)
(n, f)


Evolution Paths of
NS+NS/BH Mergers
stable NS
HMNS ejecta
HMNS
different. rot.
SMNS
NS+NS
Dynamical ejecta
BH+torus
NS+BH
Disk ejecta
BH

Dynamical ejecta: very much dependent on the impact of neutrinos

- a delayed collapse of NS-NS
- a NS-BH system





Major impact of ν-interactions

$$\nu_e + n \rightleftharpoons p + e^-$$

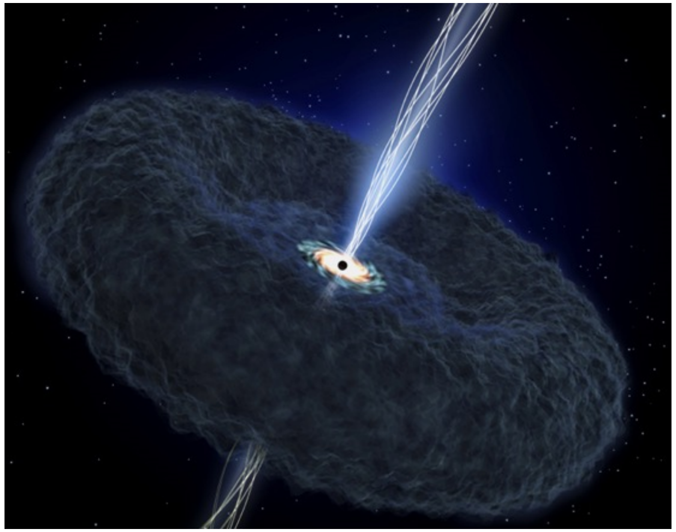
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

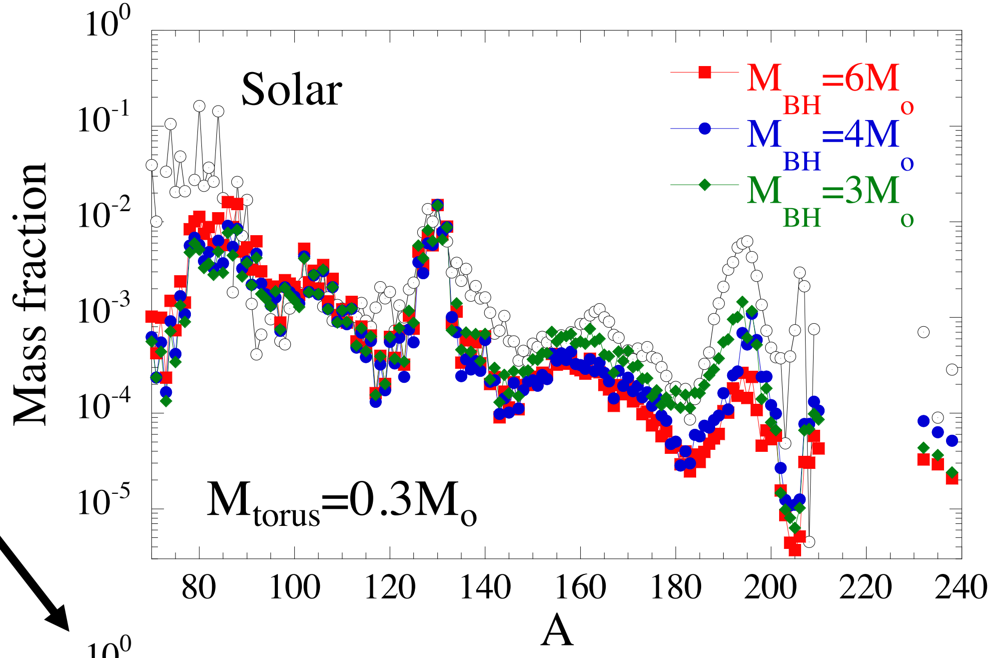
Disk ejecta of the BH-Torus system

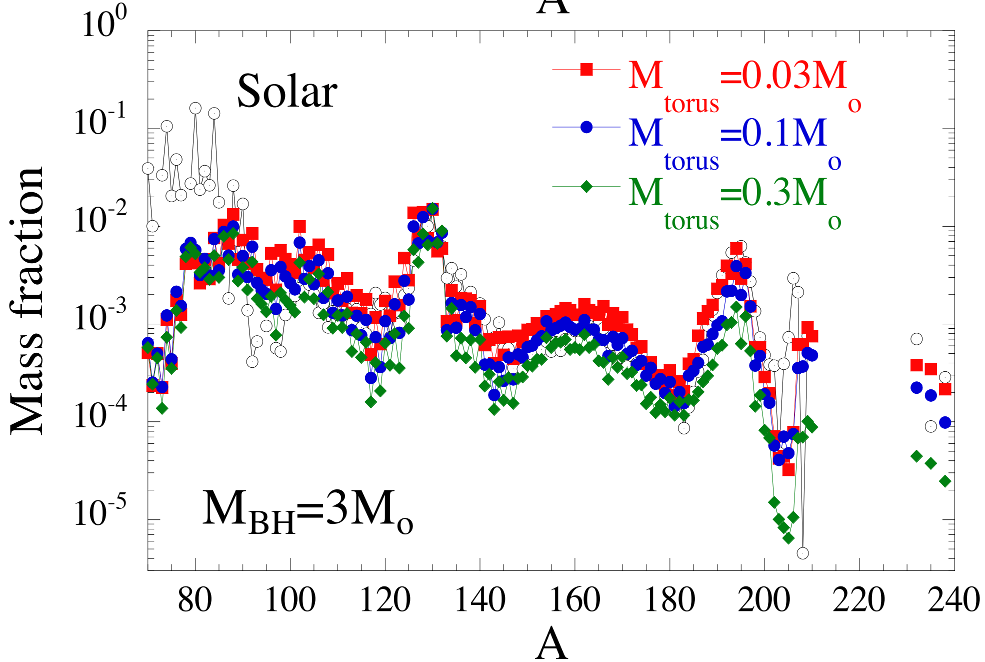
Different hydrodynamical simulations
(Just, et al. 2015; Wu et al. 2016)

Abundance predictions sensitive to

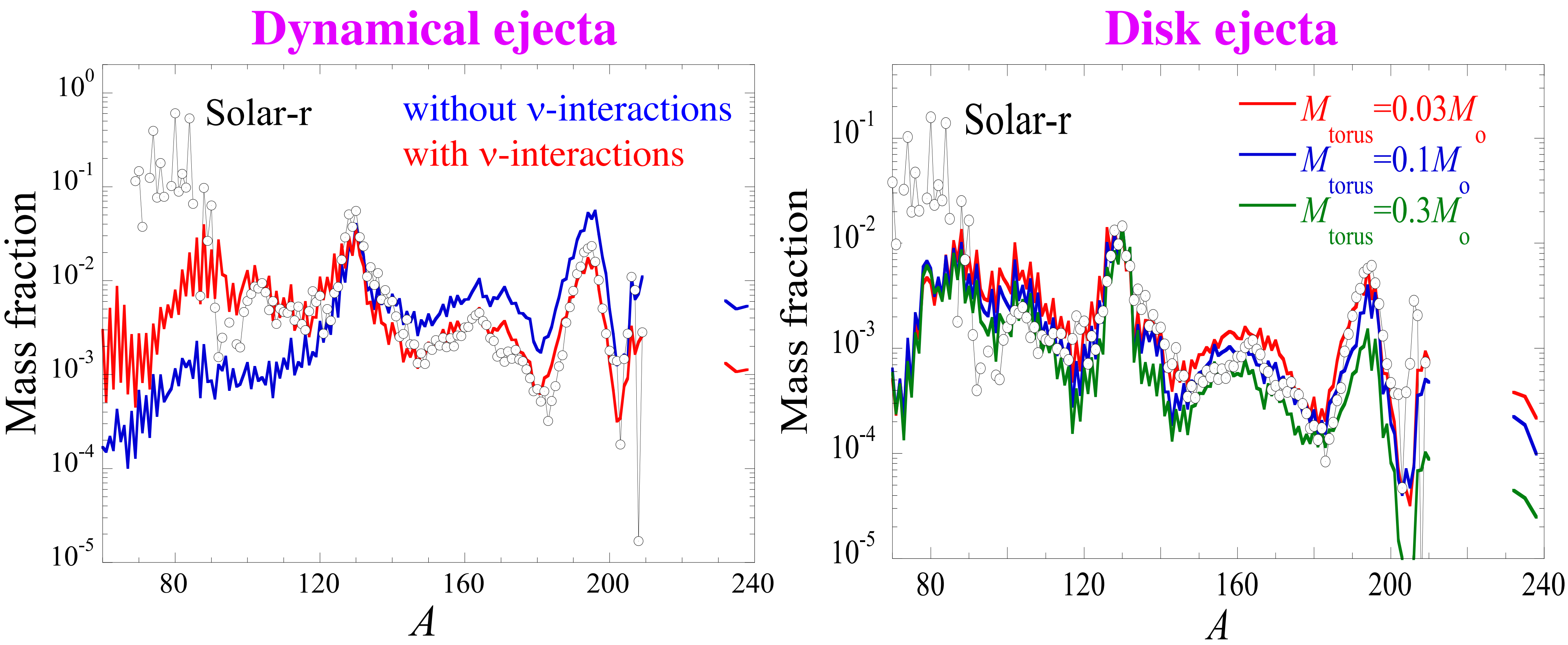
- Mass of the BH (same M_{torus})
- Mass of the torus (same M_{BH})







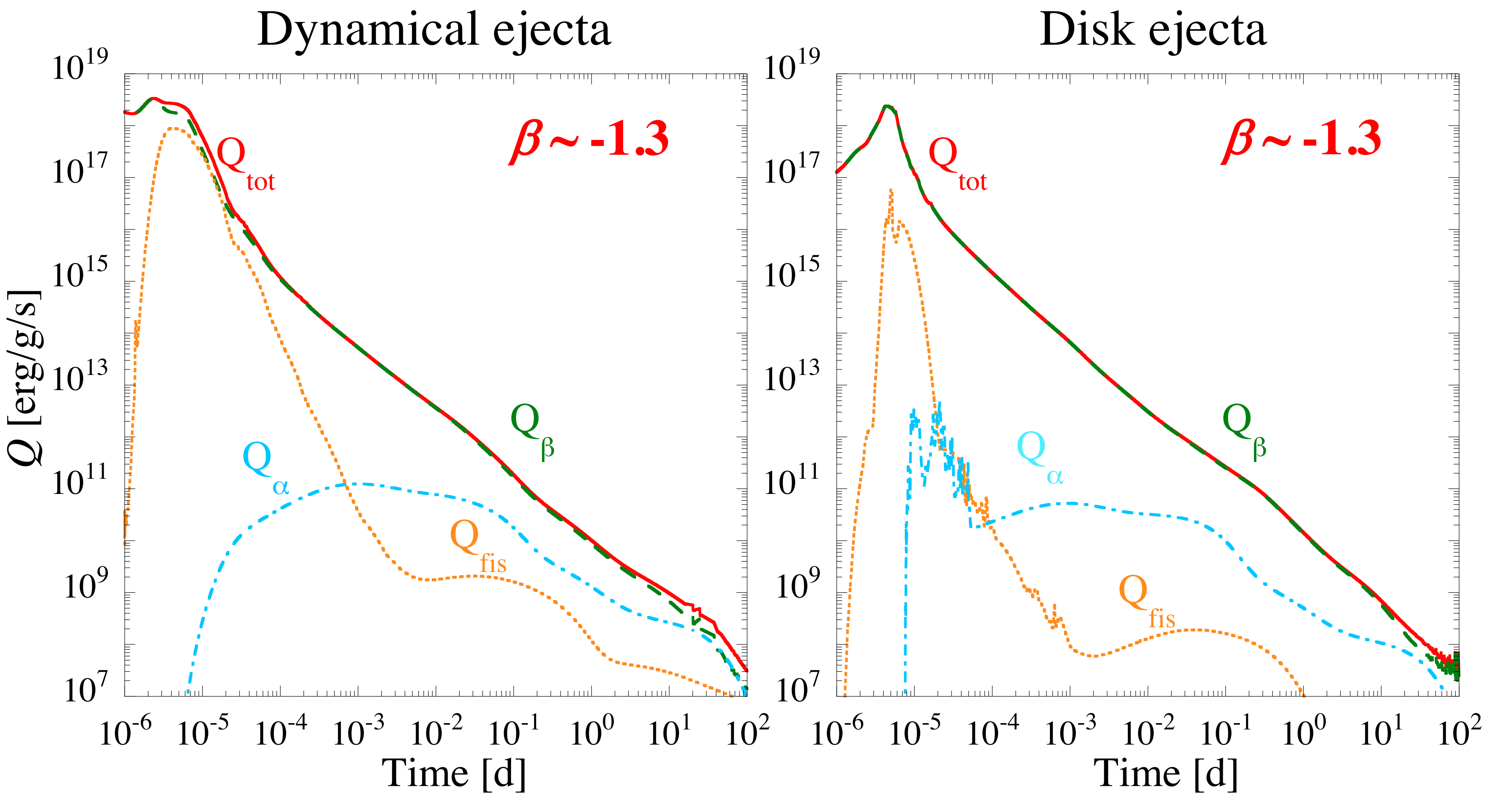
Composition of matter ejected during neutron star merger



Ejected masses: $M_{\mathrm{disk}} \gtrsim M_{\mathrm{dyn}}$

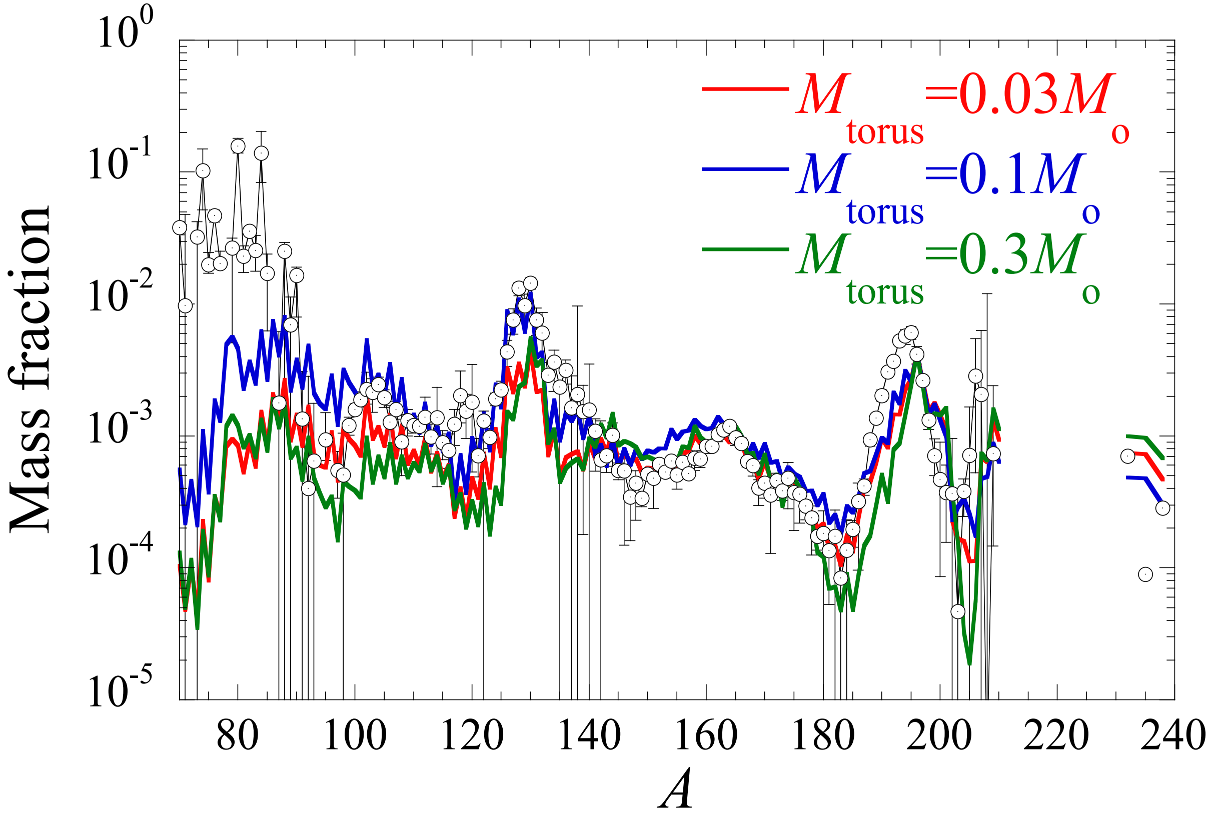
Total radioactive heating rate of the resulting Kilonova at late times

$$Q_{tot}=Q_{\beta}+Q_{fis}+Q_{\alpha}$$

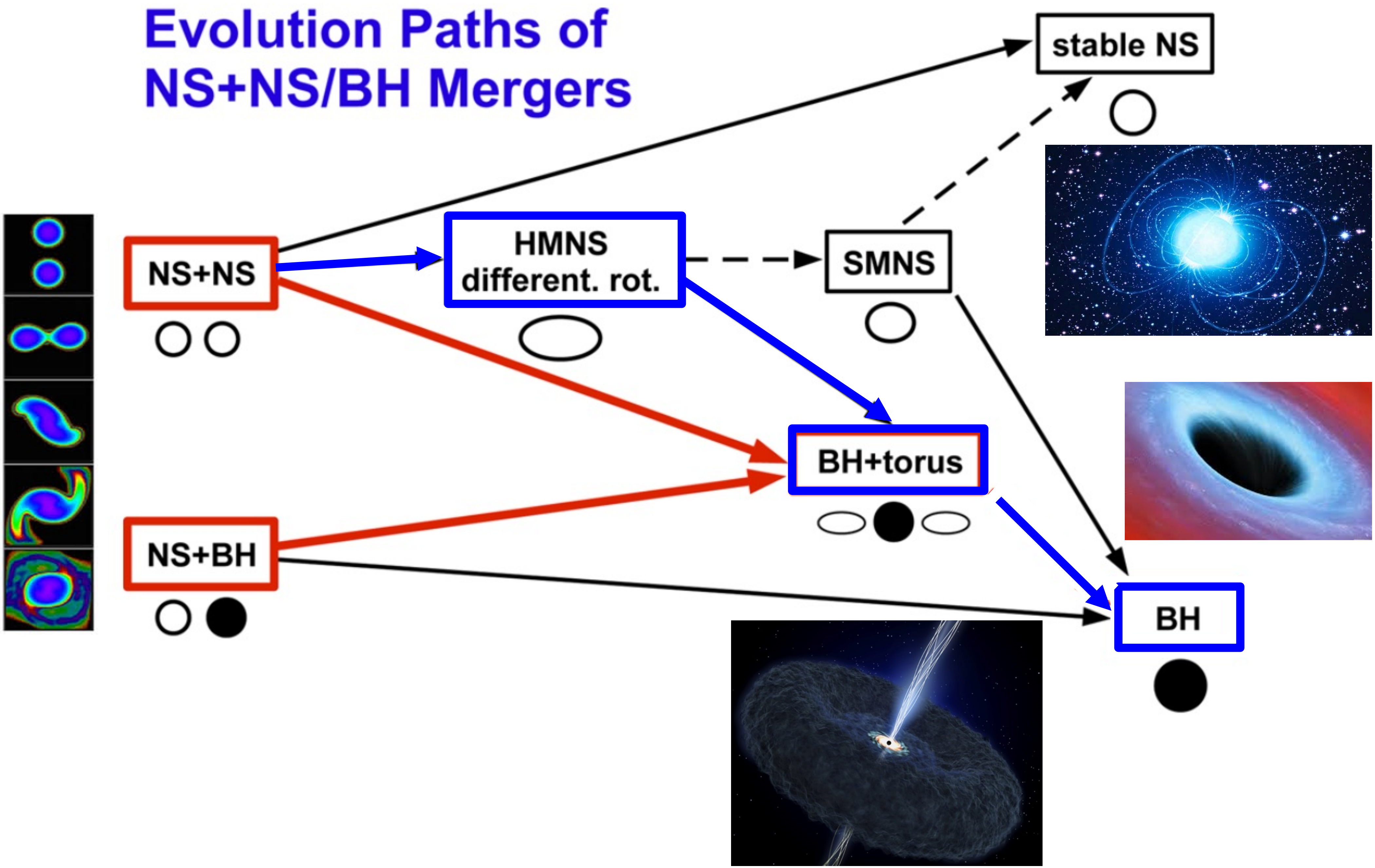


Composition of matter ejected during neutron star merger

Dynamical + BH-Torus system

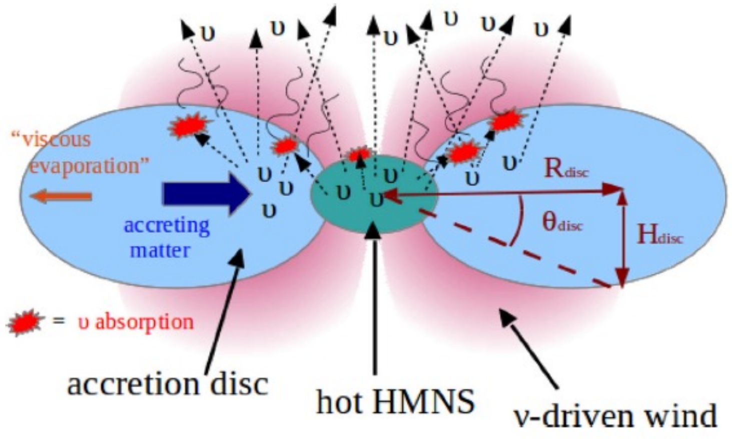


Robust production of all $A \geq 90$ r-nuclei with a rather solar distribution

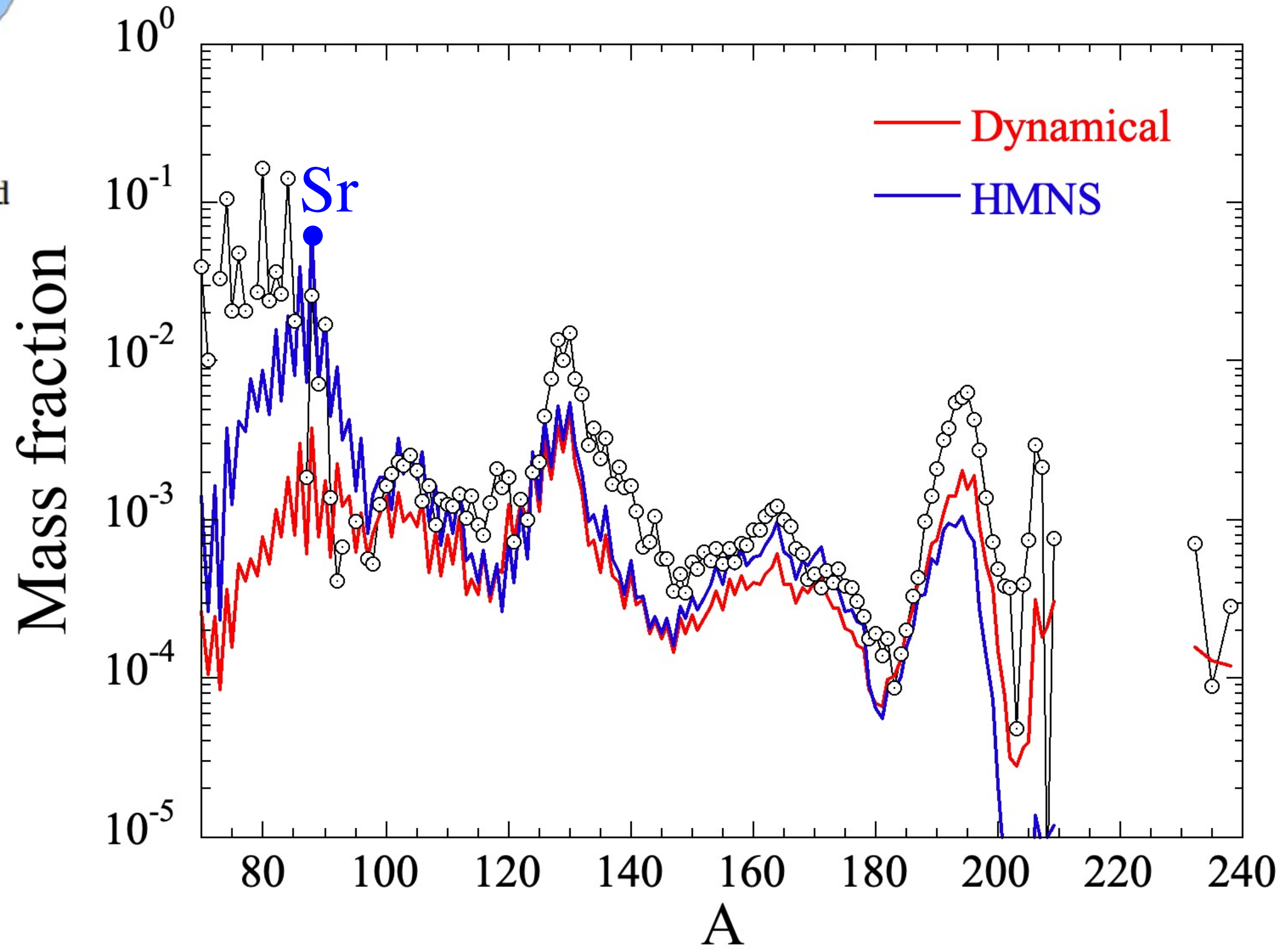

Evolution Paths of
NS+NS/BH Mergers
stable NS
NS+NS
HMNS
different. rot.
SMNS
BH+torus
NS+BH
BH

Composition of the matter ejected from a HMNS

((Perego et al. 2014; Martin et al. 2015, Wu et al. 2016, Lippuner et al. 2017; Just et al. 2022)



Contribution from both dynamical and HMNS
1.35 – 1.35 M_o

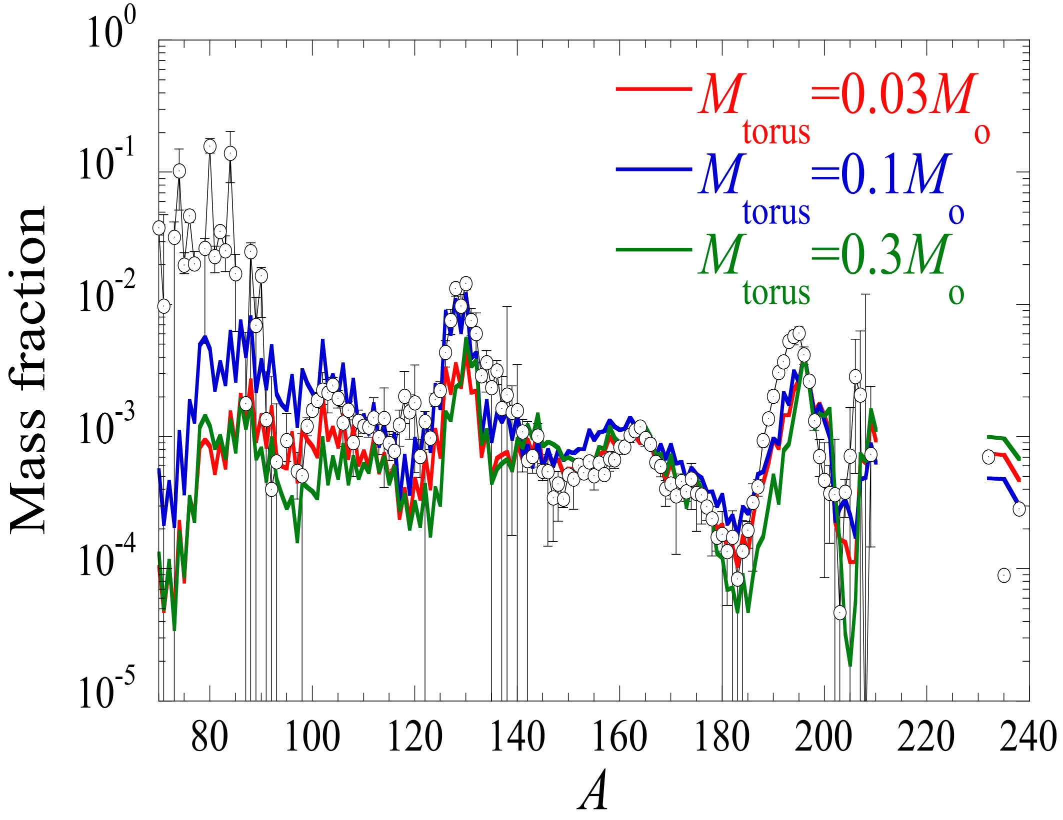


Significant production of A~90 nuclei including Sr

Final abundance distributions from Binary Neutron Star Mergers

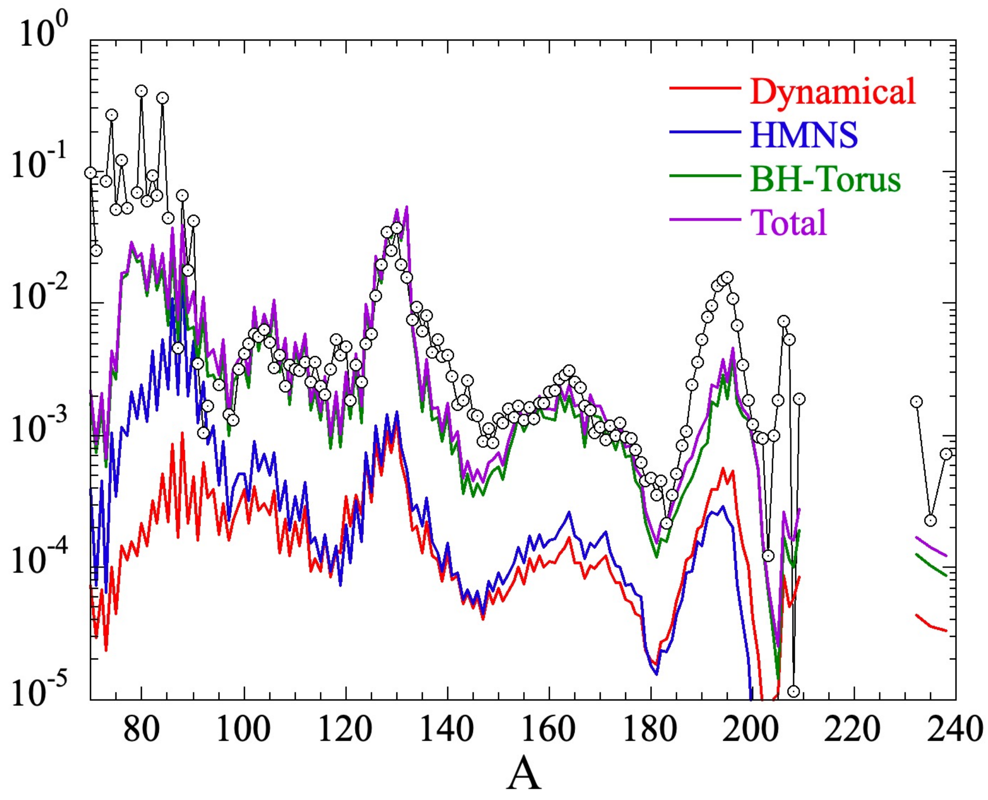
Dynamical + BH-Torus system

Just et al. (2015)



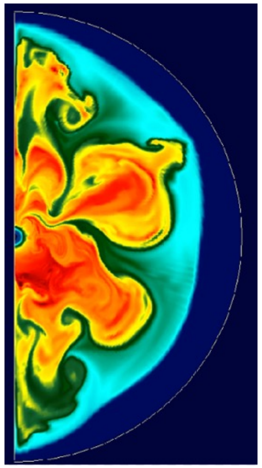
Dyn + HMNS +BH Torus system

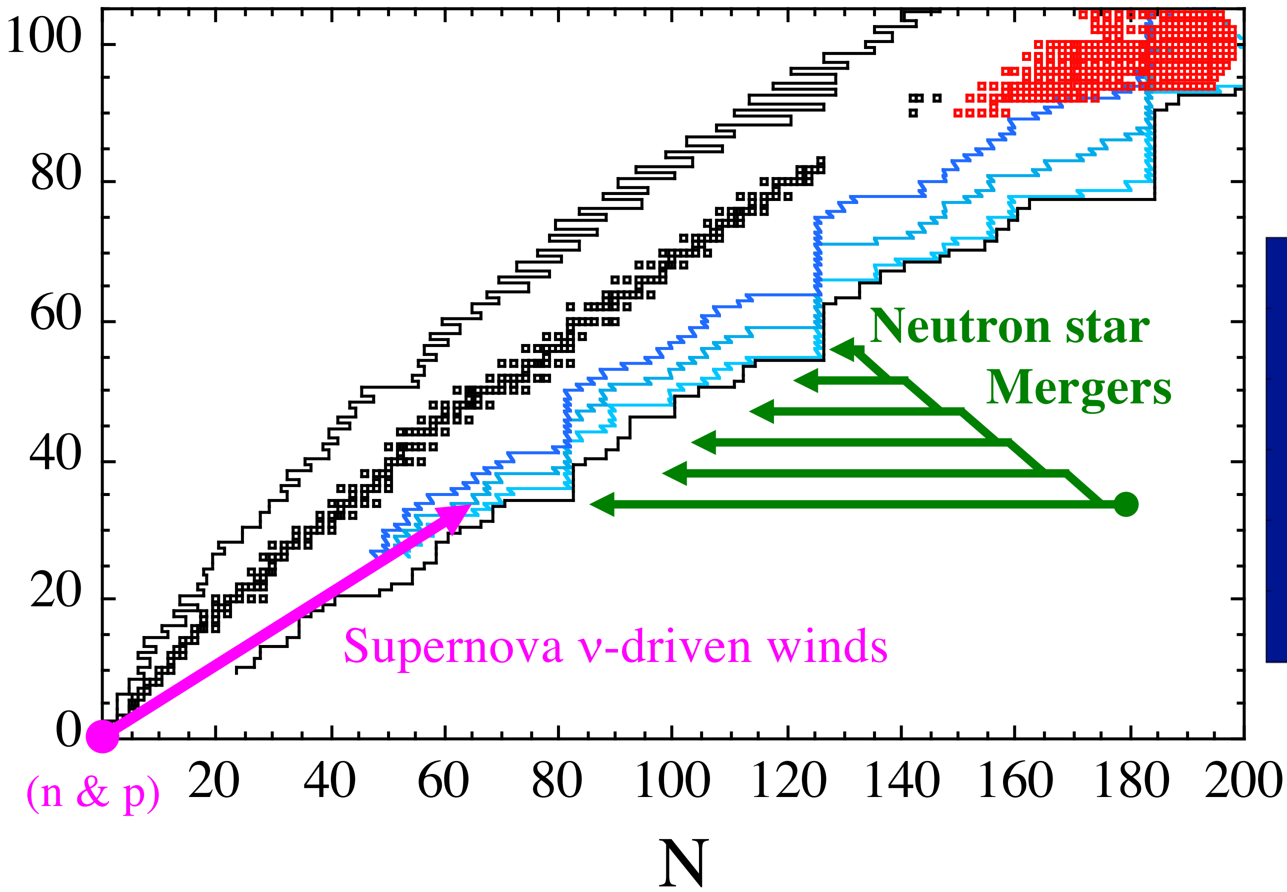
Just et al. (2022)

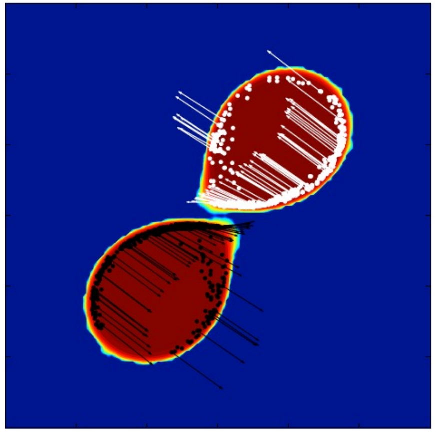


Robust production of all $A \geq 90$ r-nuclei with a rather solar distribution

What about other astrophysical sites for the *r*-process ??







Collapsar = Collapse of rapidly rotating massive stars (M>20M_o)

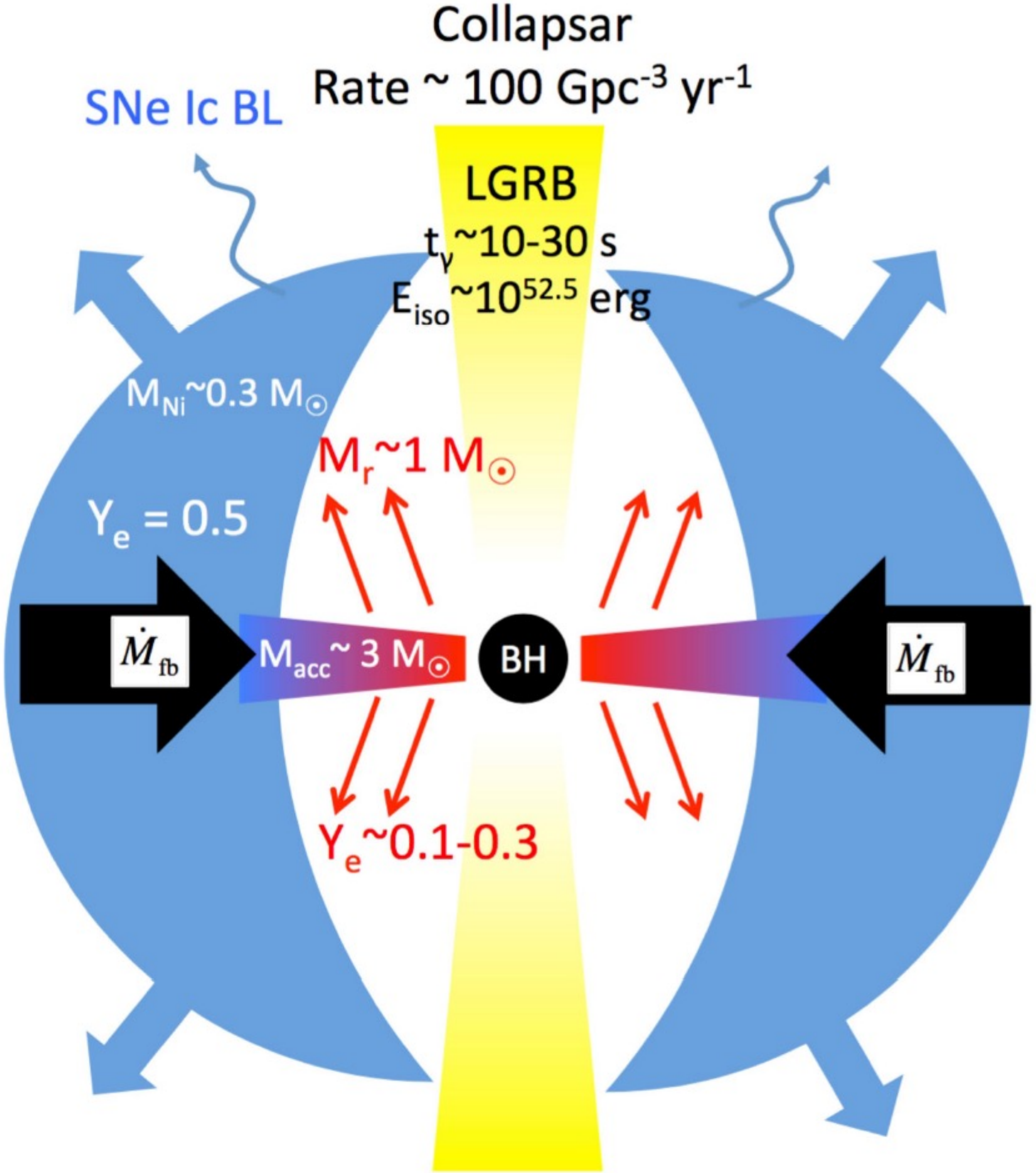
- Failed explosion with direct collapse to a BH
- Weak explosion with the proto-NS collapsing due to fallback material

↓

Rapid rotation of the infalling material leading to the formation of a massive accretion disk around the BH

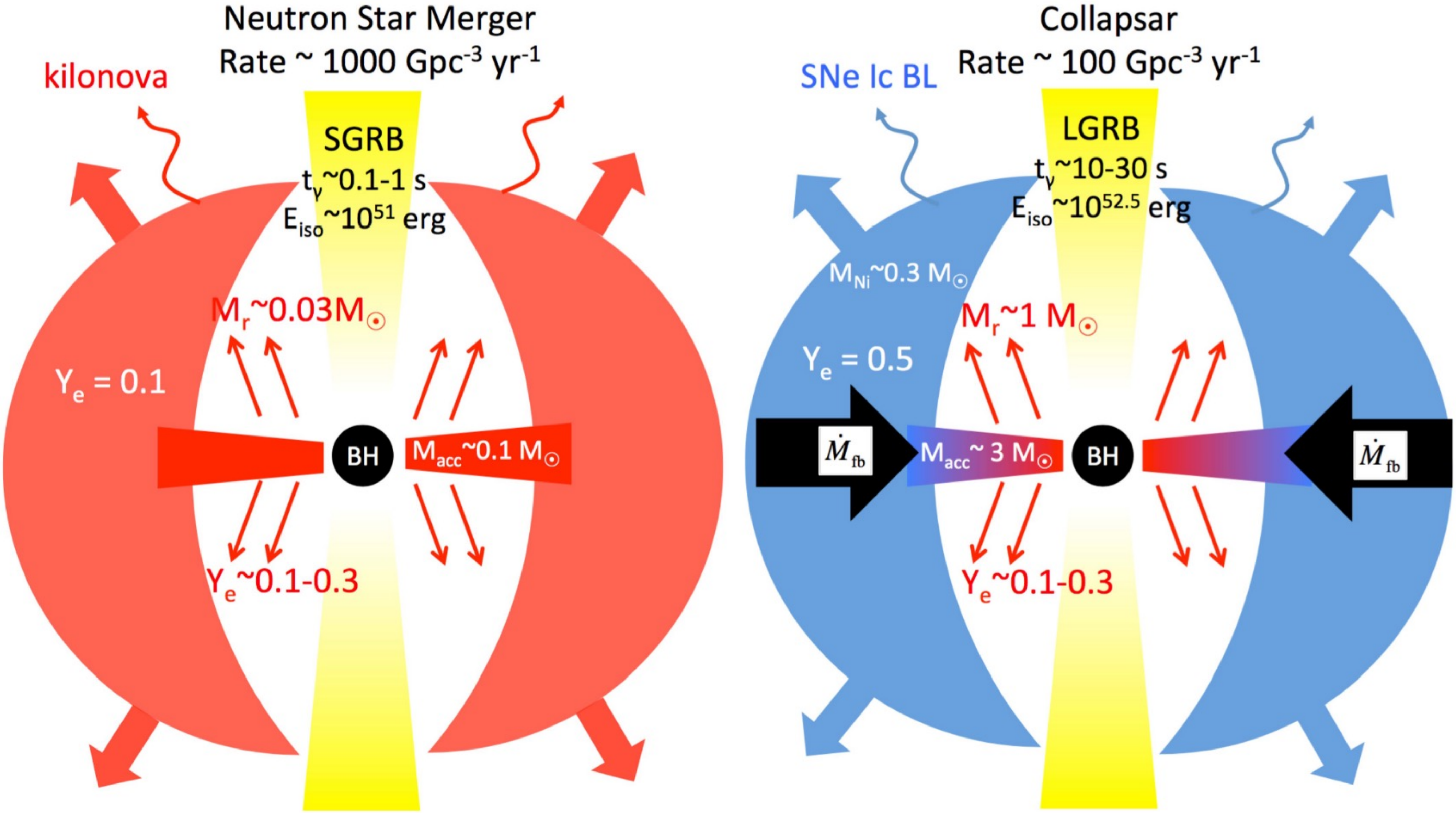
↓

Generation of long GRB & SN Ic



Long γ-ray bursts

Siegel et al. (2019)



Short γ-ray bursts

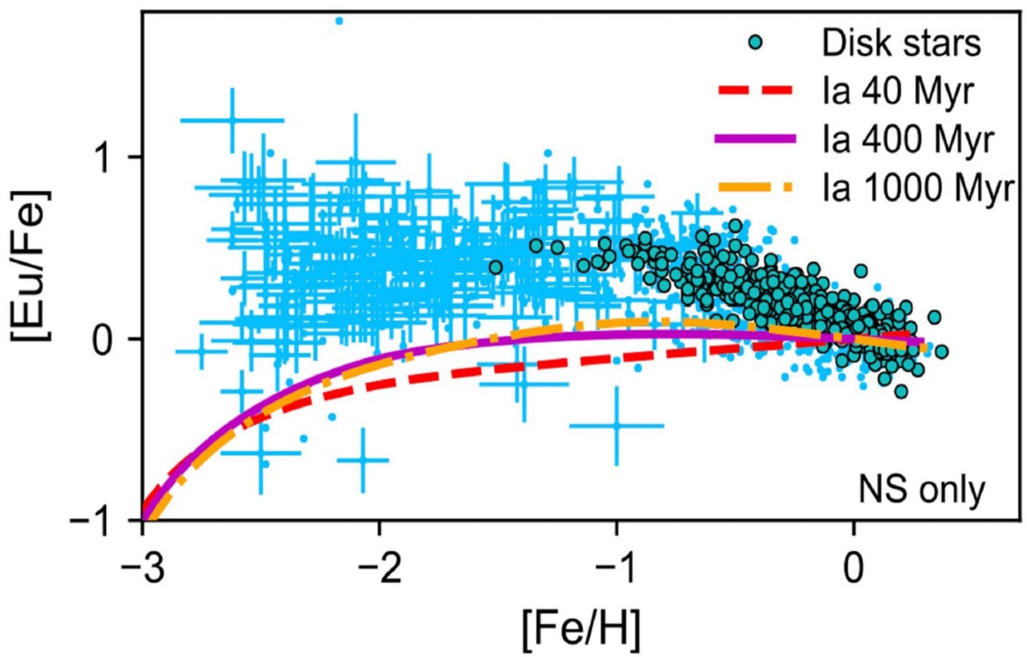
Long γ-ray bursts

Siegel et al. (2019)

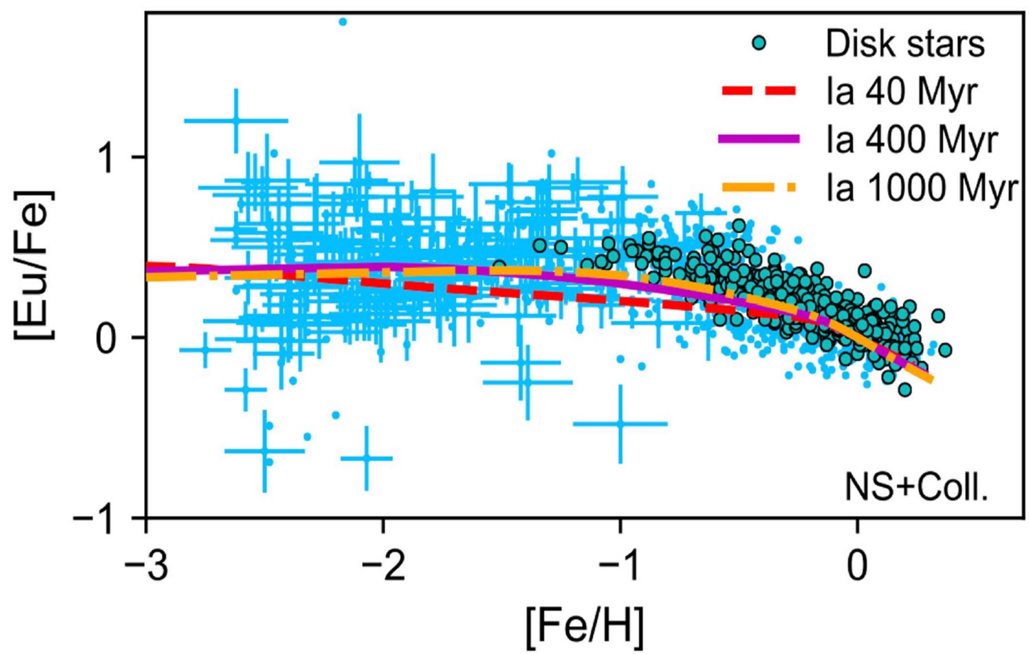
Contribution of collapsars vs NSM to the Galactic enrichment

Total ejected mass: ~1M_o ~ 10-30 x NSM
Frequency of events: ~ NSM / 10
→ Could produce the Galactic *r*-content
→ No time delay as in binary systems

r-process vs Fe evolution
NSM only



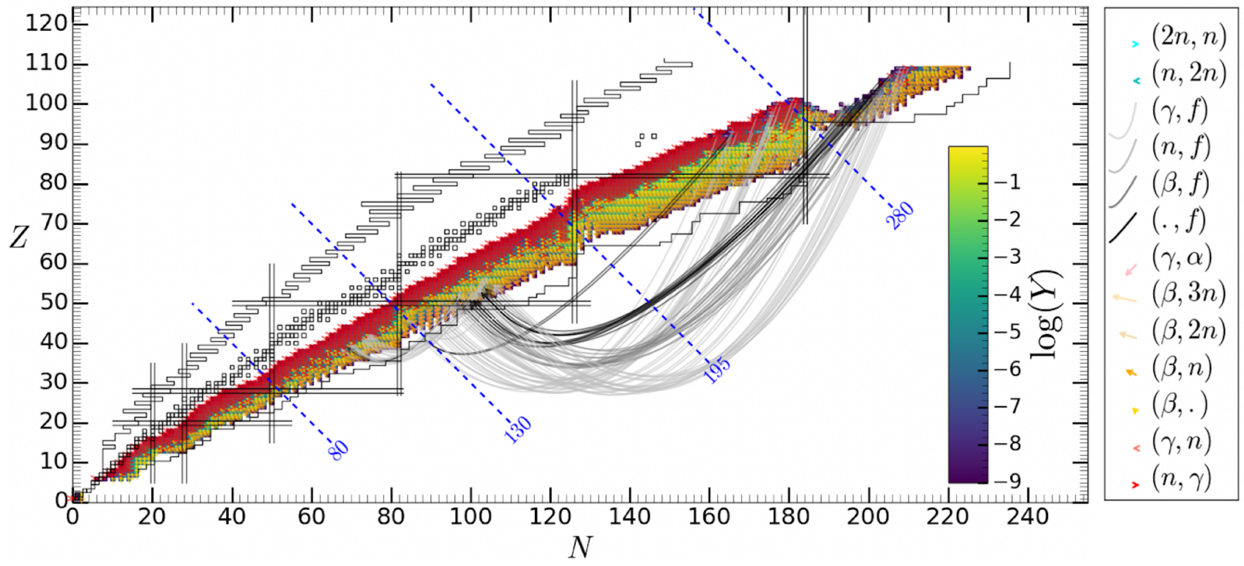
r-process vs Fe evolution
NSM + Collapsars



Siegel et al. (2019)

Many still open questions on the r-process remain …

- Dominant site(s) of the r-process: NSM ? MR-SNe ? Collapsars ? Others ?
- Frequency and properties of different sites (in particular, mass and velocity of the ejecta, coalescence time for binary systems) ?
- Impact of neutrino interactions during NSM and collapsar ejection ?
- Angular and velocity distribution of the ejecta ?
- Comparison with spectroscopic observations, in particular with *r*-enrichment in old low-Z stars (not as universal as often claimed), ultra-faint dwarf galaxies, … ?
- Chemical evolution of the Galaxy ?
- NUCLEAR PHYSICS ?



The r-process nucleosynthesis

Part II:

The rapid neutron-capture process

- r-process in SNII, NSM, Collapsars
- Nuclear physics aspects

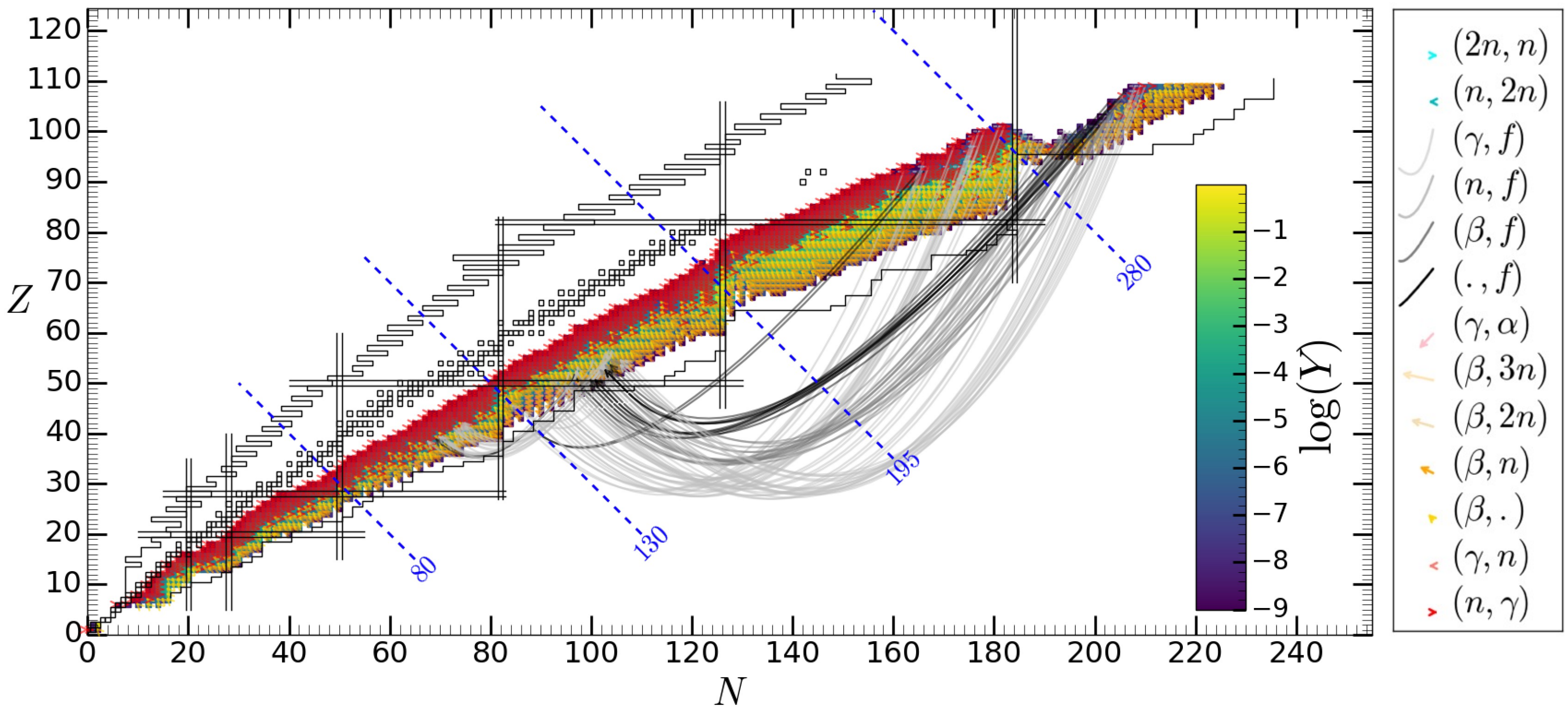
Another uncertainty: nuclear physics input

(n,γ) – (γ,n) – β competition & Fission

- β-decay rates
- (n,γ) and (γ,n) rates
- Fission (nif, sf, βdf) rates
- Fission Fragments Distributions

Still many open questions

some 5000 nuclei with $Z \leq 110$ involved on the n-rich side



Another uncertainty: nuclear physics input

(n,γ) – (γ,n) – β competition & Fission

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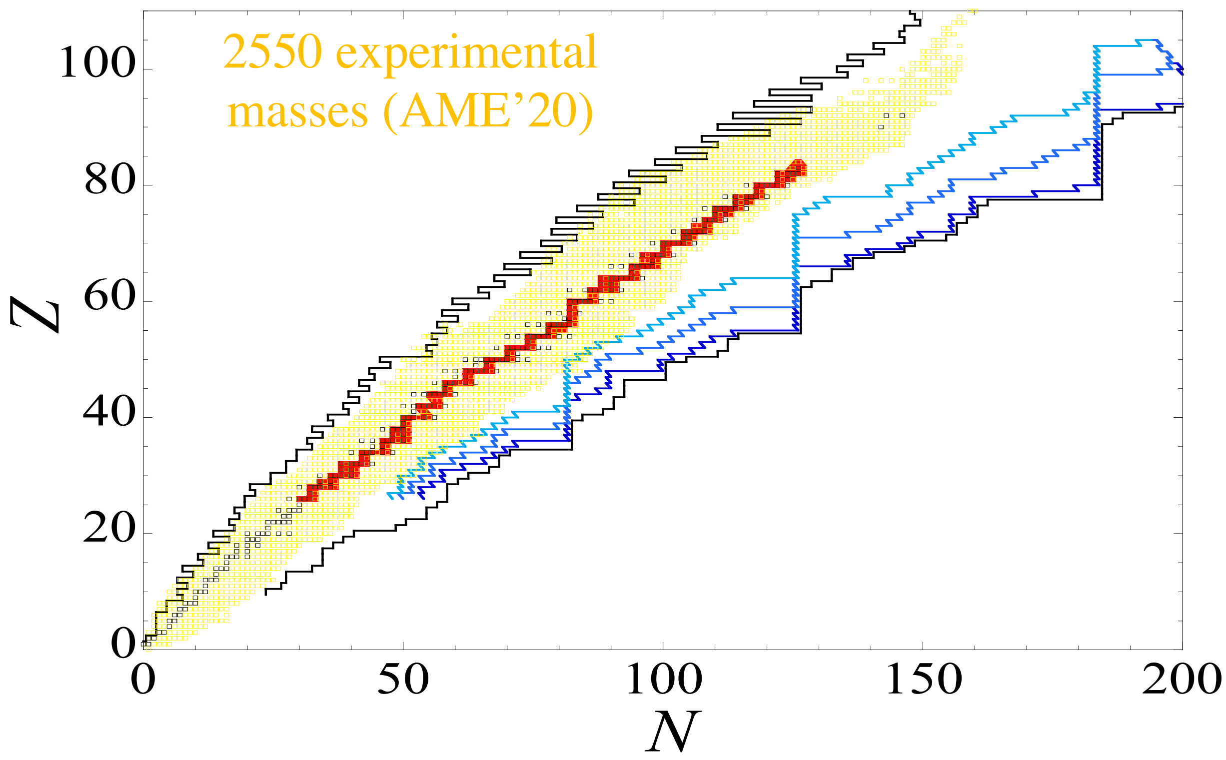

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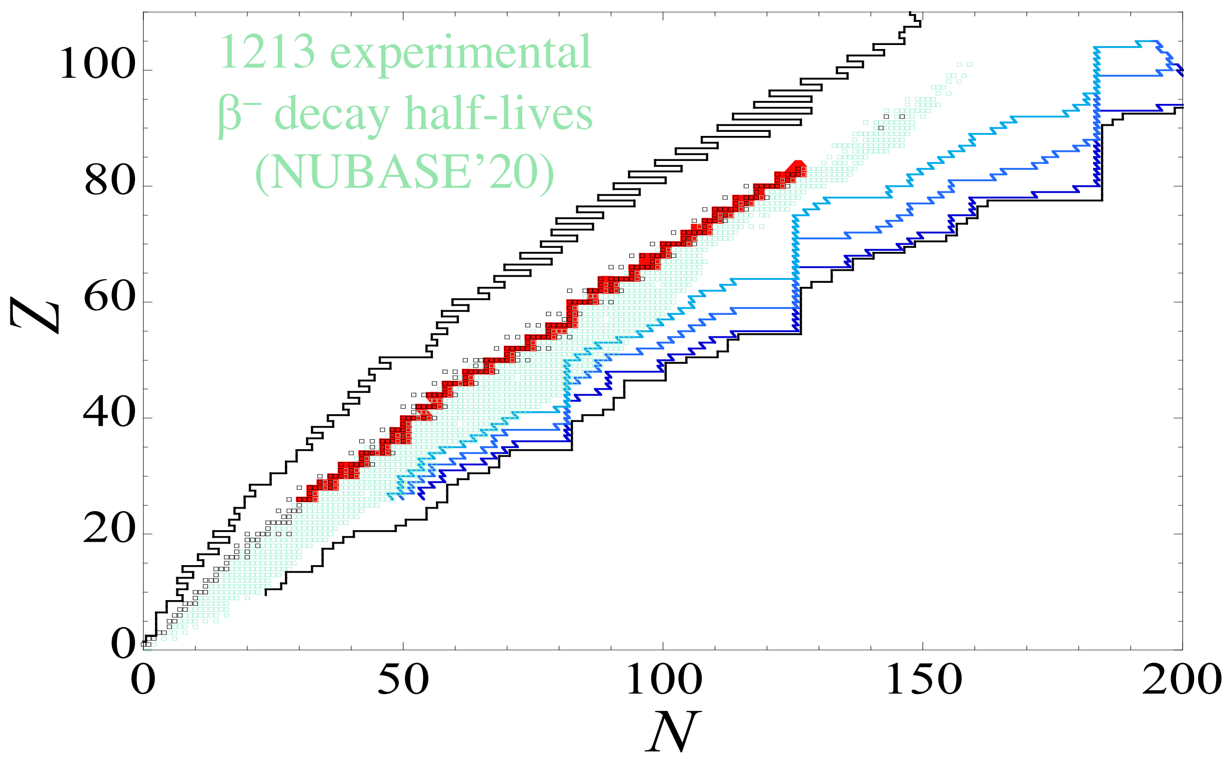
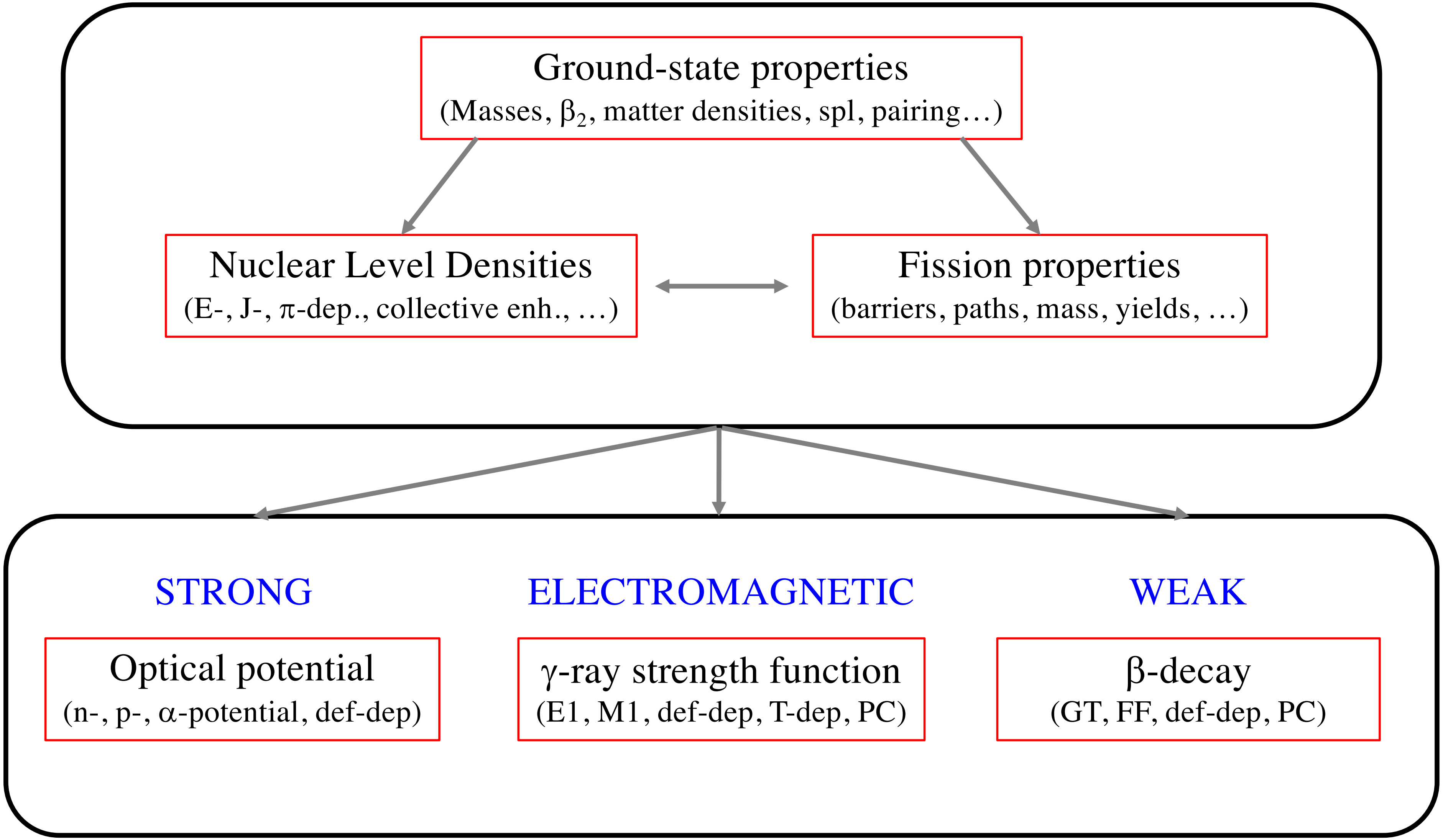
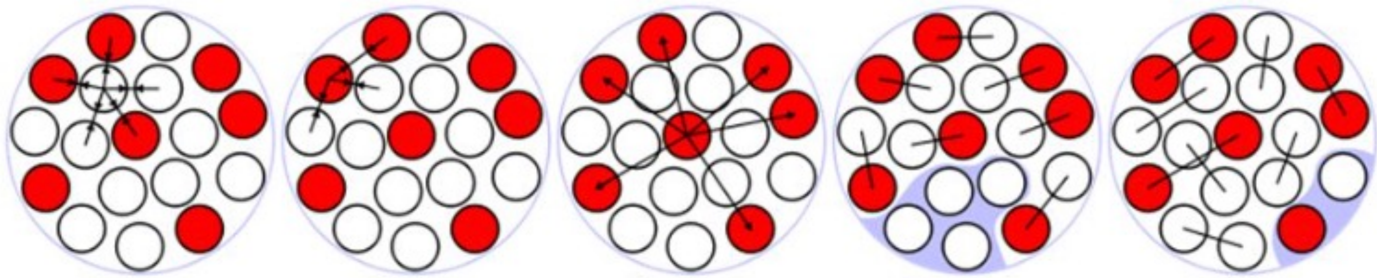


Nuclear inputs to nuclear reaction & decay calculations



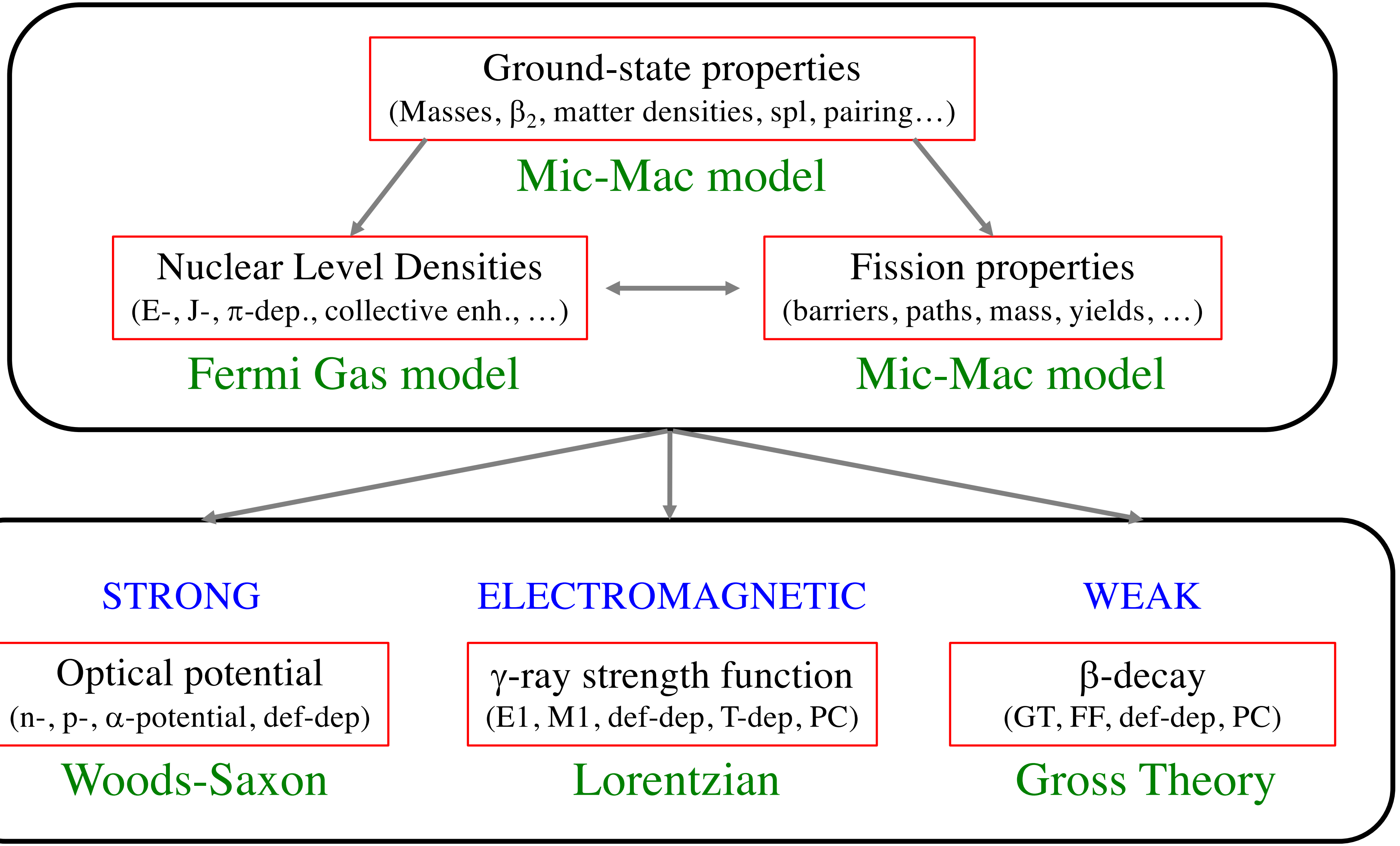
The macroscopic liquid-drop description of the nucleus



$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \Delta(Z,N)$$

Phenomenological description at the level of integrated properties (Volume, Surface, …) with quantum "microscopic" corrections added in a way or another (shell effects, pairing, etc...)

Nuclear inputs to nuclear reaction & decay calculations

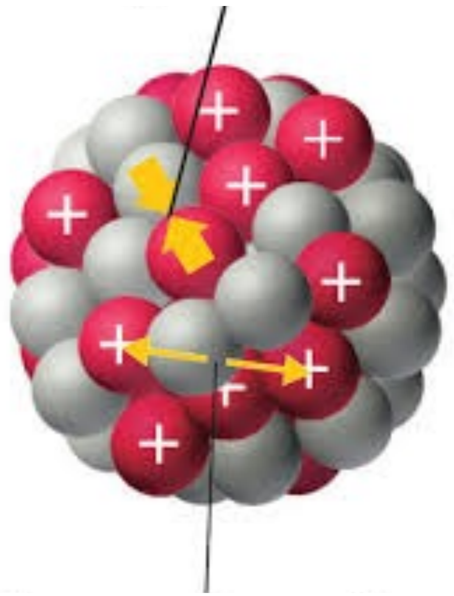


A more « microscopic » description of the nucleus

e.g. Mean-Field

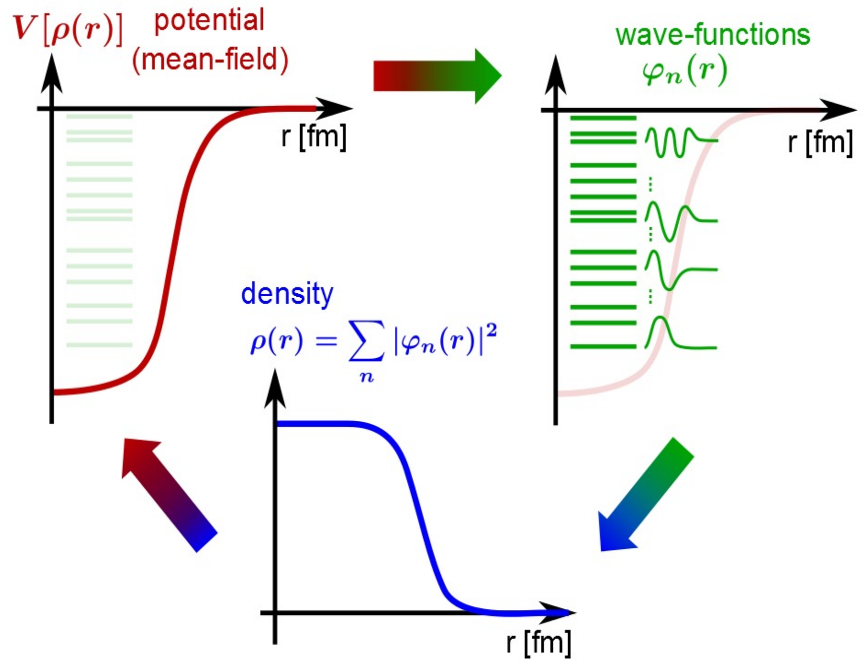
$$E_{MF} = \int \mathcal{E}_{nuc}(\mathbf{r}) d^3\mathbf{r} + \int \mathcal{E}_{coul}(\mathbf{r}) d^3\mathbf{r}$$

Strong nuclear force



Electrostatic repulsion

obtained on the basis of an Energy Density Functional generated by an effective n-n interaction !



Self-consistent mean-field theory

A more « microscopic » description of the nucleus

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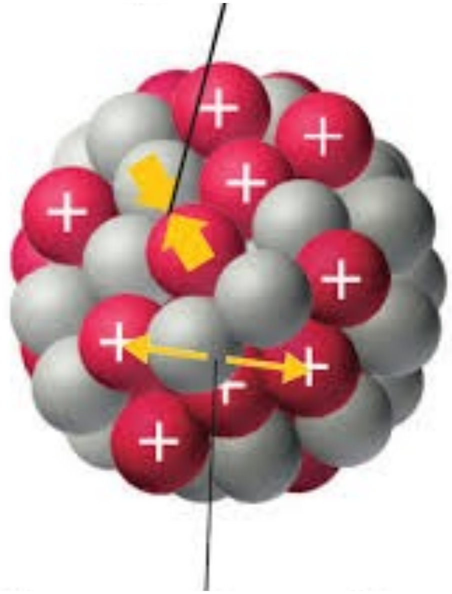


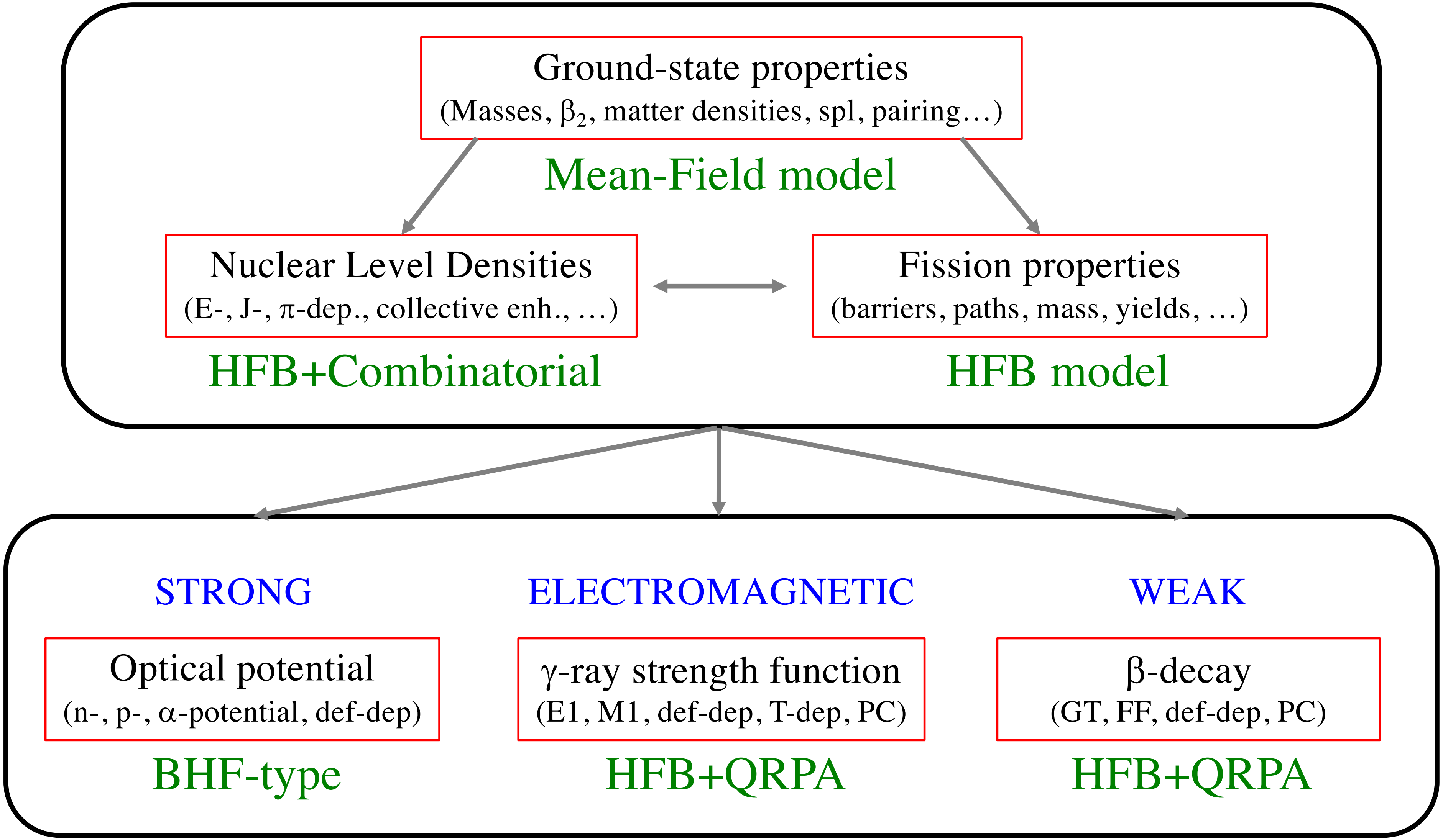
Electrostatic repulsion

obtained on the basis of an Energy Density Functional generated by an effective n-n interaction !

$$\begin{aligned}
\mathcal{E}_{\rm Sky} = &\sum_{q=n,p} \frac{\hbar^2}{2M_q}\tau_q + \frac{1}{2}t_0\left[\left(1+\frac{1}{2}x_0\right)\rho^2 - \left(\frac{1}{2}+x_0\right)\sum_{q=n,p}\rho_q^2\right] + \frac{1}{4}t_1\left\{\left(1+\frac{1}{2}x_1\right)\left[\rho\tau+\frac{3}{4}(\nabla\rho)^2\right]\right. \\
&\left. - \left(\frac{1}{2}+x_1\right)\sum_{q=n,p}\left[\rho_q\tau_q+\frac{3}{4}(\nabla\rho_q)^2\right]\right\} + \frac{1}{4}t_2\left\{\left(1+\frac{1}{2}x_2\right)\left[\rho\tau-\frac{1}{4}(\nabla\rho)^2\right] + \left(\frac{1}{2}+x_2\right)\right. \\
&\left. \times \sum_{q=n,p}\left[\rho_q\tau_q-\frac{1}{4}(\nabla\rho_q)^2\right]\right\} + \frac{1}{12}t_3\rho^\alpha\left[\left(1+\frac{1}{2}x_3\right)\rho^2 - \left(\frac{1}{2}+x_3\right)\sum_{q=n,p}\rho_q^2\right] \\
&+ \frac{1}{4}t_4\left\{\left(1+\frac{1}{2}x_4\right)\left[\rho\tau+\frac{3}{4}(\nabla\rho)^2\right] - \left(\frac{1}{2}+x_4\right)\sum_{q=n,p}\left[\rho_q\tau_q+\frac{3}{4}(\nabla\rho_q)^2\right]\right\}\rho^\beta \\
&+ \frac{\beta}{8}t_4\left[\left(1+\frac{1}{2}x_4\right)\rho(\nabla\rho)^2 - \left(\frac{1}{2}+x_4\right)\nabla\rho\cdot\sum_{q=n,p}\rho_q\nabla\rho_q\right]\rho^{\beta-1} + \frac{1}{4}t_5\left\{\left(1+\frac{1}{2}x_5\right)\left[\rho\tau-\frac{1}{4}(\nabla\rho)^2\right]\right. \\
&\left. + \left(\frac{1}{2}+x_5\right)\sum_{q=n,p}\left[\rho_q\tau_q-\frac{1}{4}(\nabla\rho_q)^2\right]\right\}\rho^\gamma - \frac{1}{16}(t_1x_1+t_2x_2)J^2 + \frac{1}{16}(t_1-t_2)\sum_{q=n,p}J_q^2 \\
&- \frac{1}{16}(t_4x_4\rho^\beta + t_5x_5\rho^\gamma)J^2 + \frac{1}{16}(t_4\rho^\beta - t_5\rho^\gamma)\sum_{q=n,p}J_q^2 + \frac{1}{2}W_0\left(J\cdot\nabla\rho + \sum_{q=n,p}J_q\cdot\nabla\rho_q\right).
\end{aligned}$$

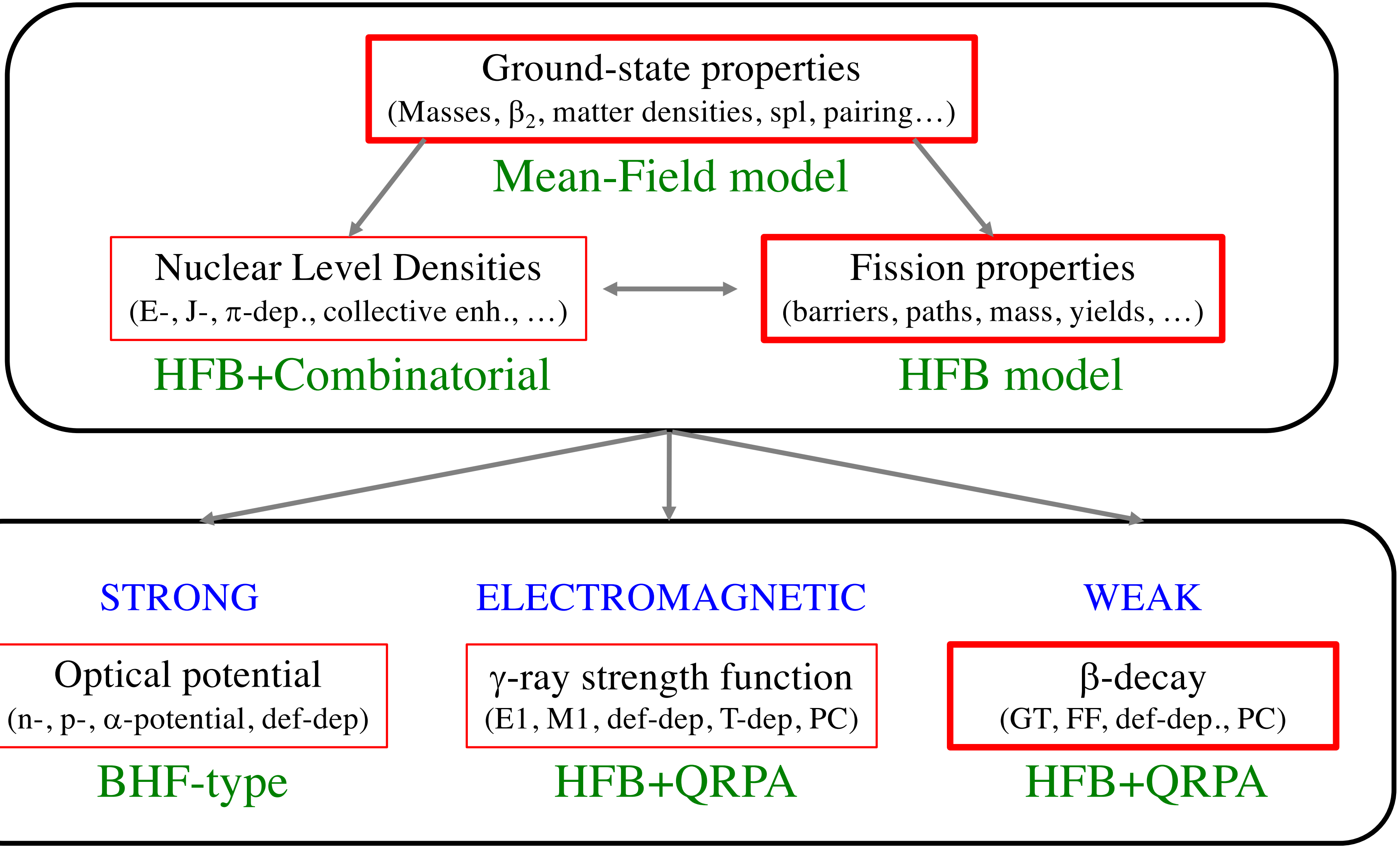
Still *phenomenological*, but at the level of the effective *n-n* interaction
Obviously more complex, but models have now reached stability and **accuracy** !

Nuclear inputs to nuclear reaction & decay calculations



"Microscopic" approach is a necessary but not a sufficient condition !
"(Semi-)Microscopic" models must be competitive in reproducing exp. data !

Nuclear inputs to nuclear reaction & decay calculations



"Microscopic" approach is a necessary but not a sufficient condition !

"(Semi-)Microscopic" models must be competitive in reproducing exp. data !

Nuclear mass models

Nuclear mass models provide all basic nuclear ingredients:

Mass excess (*Q*-values), deformation, GS spin and parity, radius, ...

but also the major nuclear structure properties

single-particle levels, pairing strength, density distributions, … in the GS as well as non-equilibrium (e.g fission path) configurations

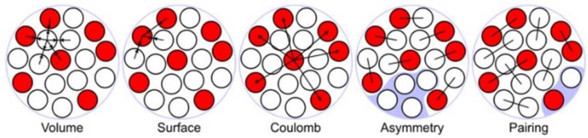
Building blocks for the prediction of ingredients of relevance in the determination of nuclear reaction cross sections and β-decay rates, such as

- nuclear level densities
- γ-ray strengths
- optical potentials
- fission probabilities
- etc …

The criteria to qualify a mass model should NOT be restricted to the rms deviation wrt to experimental masses (often now reduced by ML techniques), but also include
- the quality of the underlying physics (sound, coherent, "microscopic", …)
- all the observables of relevance in the specific applications of interest (e.g astro)

Recent Mic-Mac mass models

$$E = E_{LD} + E_{micro}$$



$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \Delta(Z,N)$$

- FRDM'12 : update from FRDM'95 (Möller 2012)
  - σ_{rms} = 0.60 MeV (2408 nuclei in AME'16)

- WS mass formula (Ning Wang et al. 2011 including RBF corr.)
  - WS3: σ_{rms} = 0.34 MeV (2408 nuclei in AME'16)
  - WS4: σ_{rms} = 0.30 MeV (2408 nuclei in AME'16)

Mean Field mass models

$$E = E_{MF} - E_{coll} - E_W$$

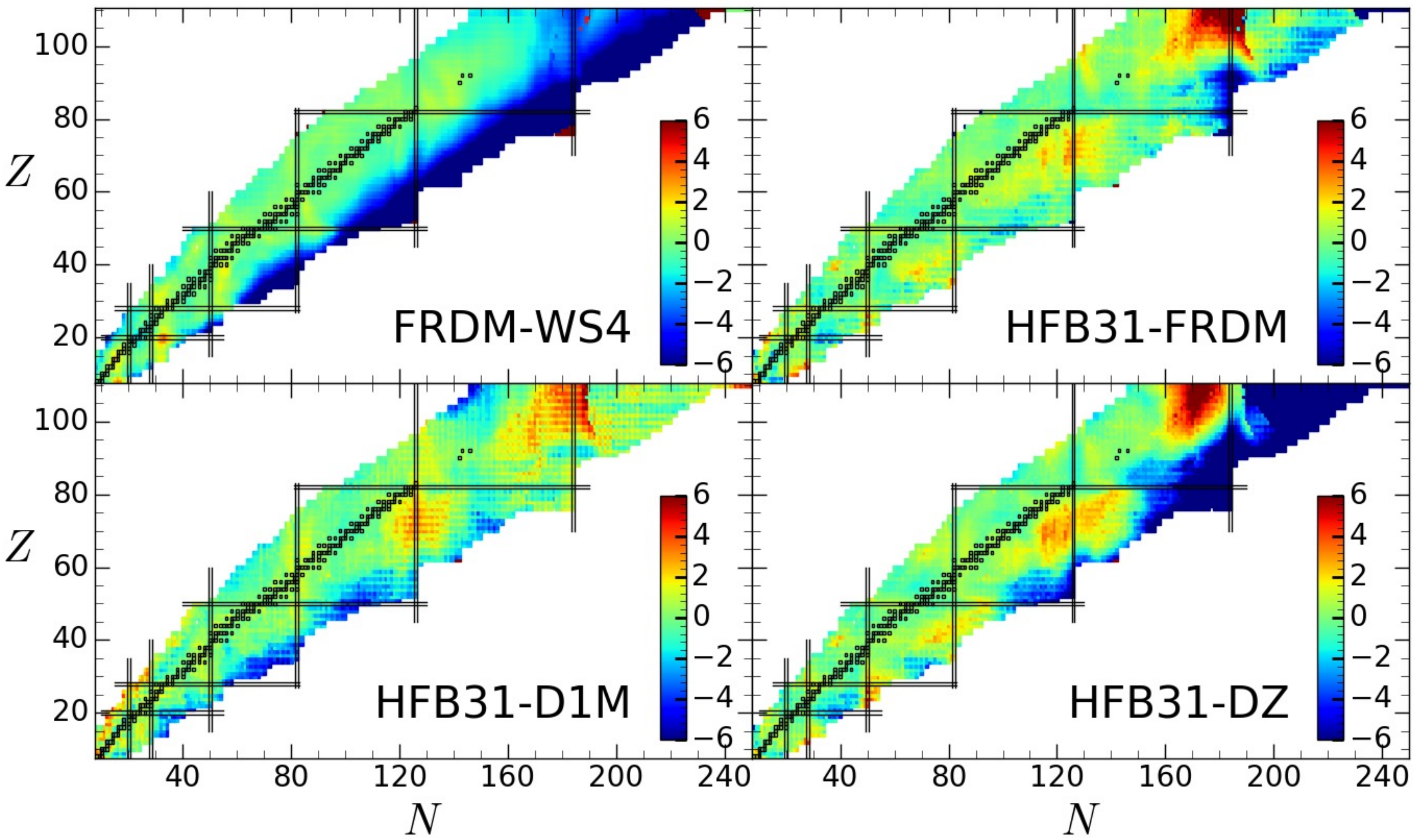
E_{MF} **:** HFB or HF-BCS (or HB) main Mean-Field contribution

E_{coll}**:** Quadrupole Correlation corrections to restore broken symmetries and include configuration mixing

E_W **:** *Wigner* correction contributes significantly only for nuclei along the $Z \sim N$ line (and in some cases for light nuclei)

Skyrme-HFB	Gogny-HFB	Relativistic MF
rms ~ 0.5-0.8MeV	rms ~ 0.8MeV	rms > 1.1MeV

Relative agreement/disagreement between mass models

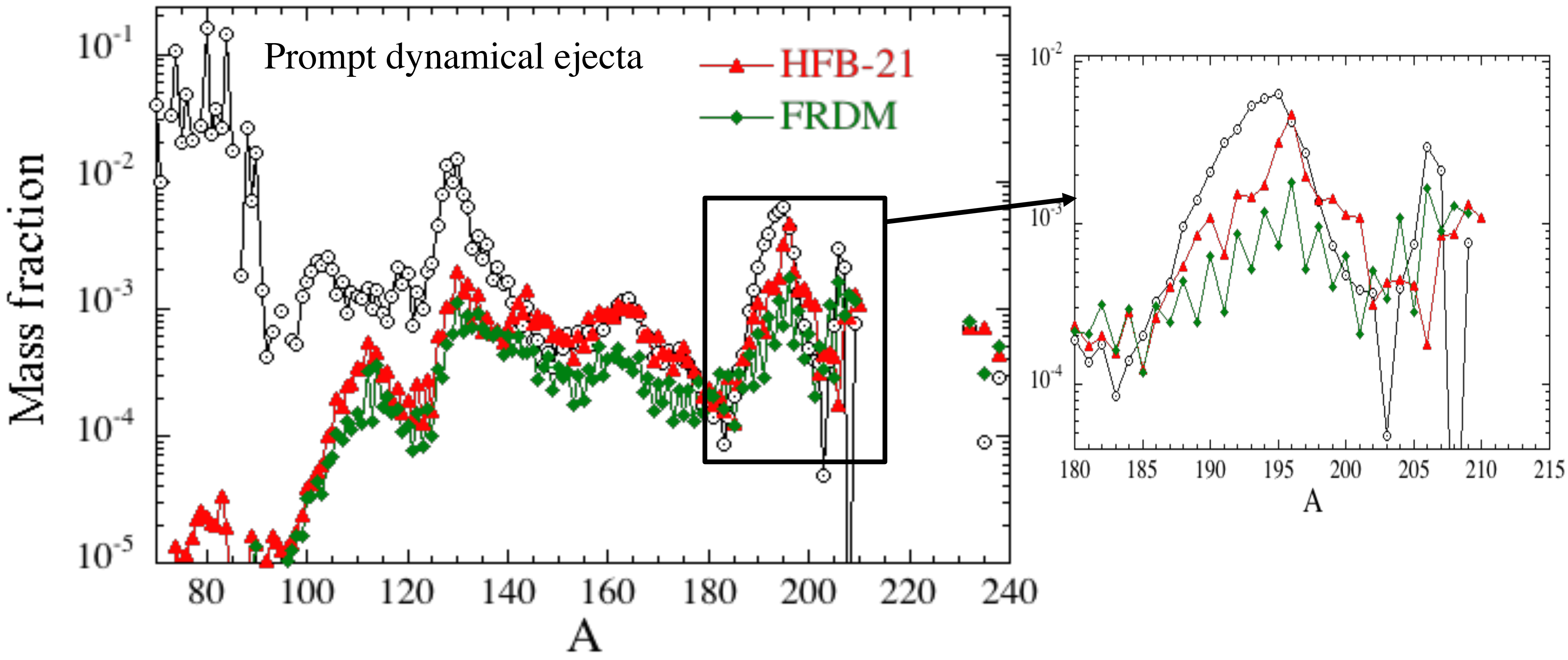


Major differences

- stiffness of the mass parabola
- around magic numbers *N*~126 and *N*~184
- heavy and super-heavy nuclei
- odd-even pairing effects

Impact of masses on the r-process nucleosynthesis in NS mergers

- β-decay rates calculated consistently with estimated Q_β
- n-capture rates calculated consistently with estimated S_n, β_2

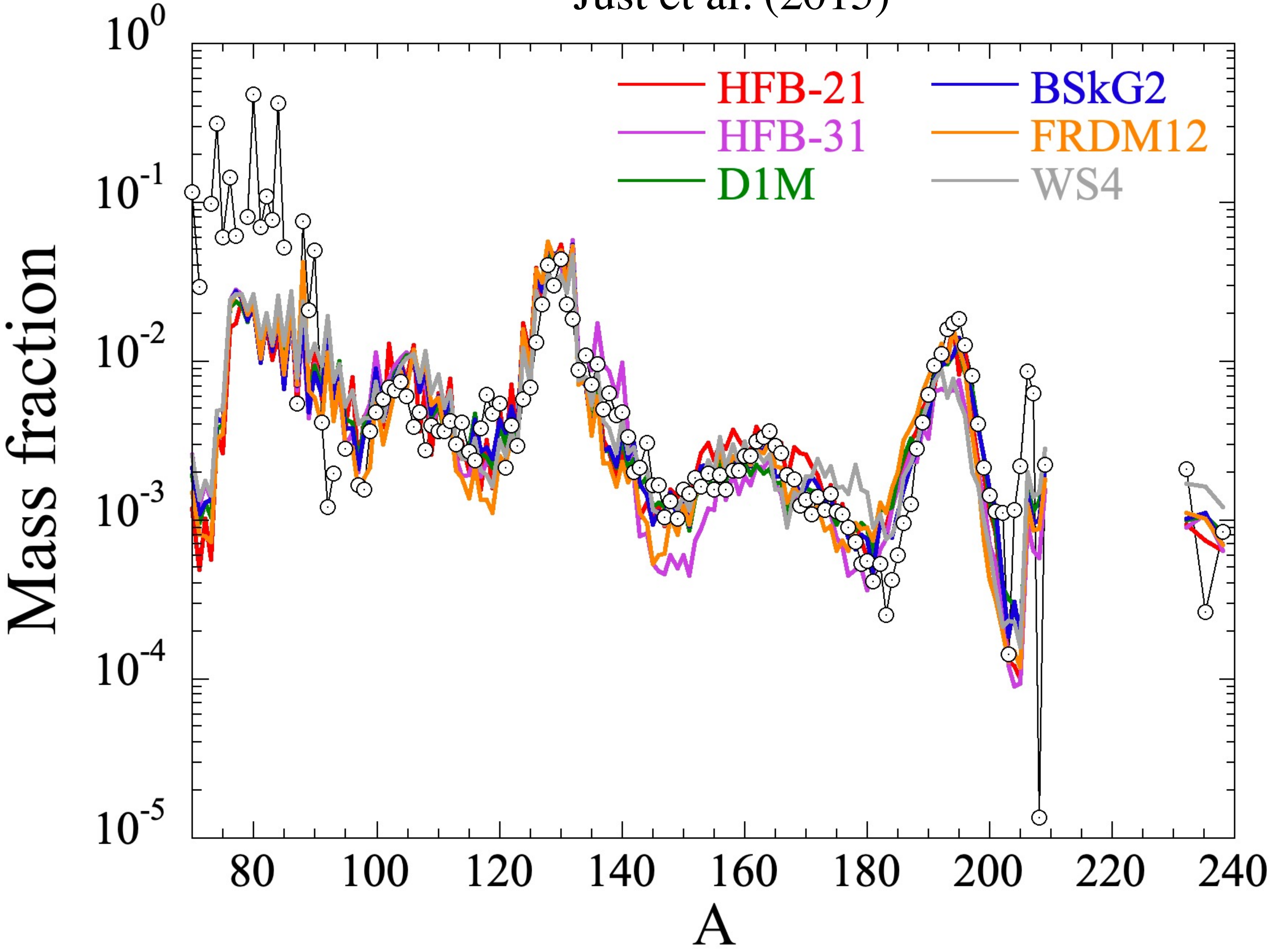


Attention: do not judge the quality of a mass model (or any nuclear input) from a comparison between r-process calculations and solar abundances !!

Impact of "relevant" mass models on the r-process in NS mergers

Dynamical + BH-Torus system

Just et al. (2015)

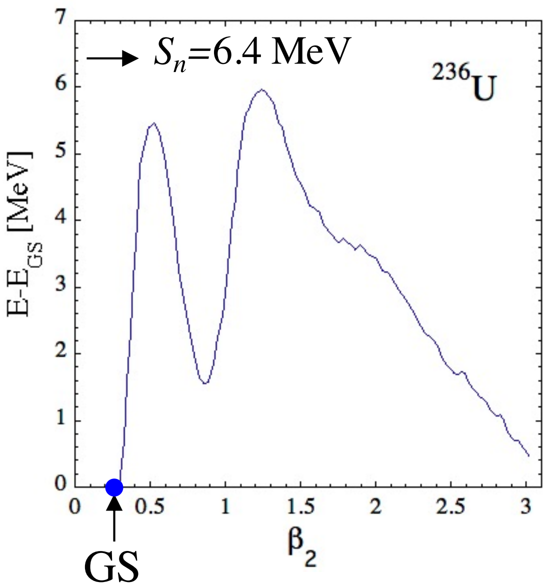


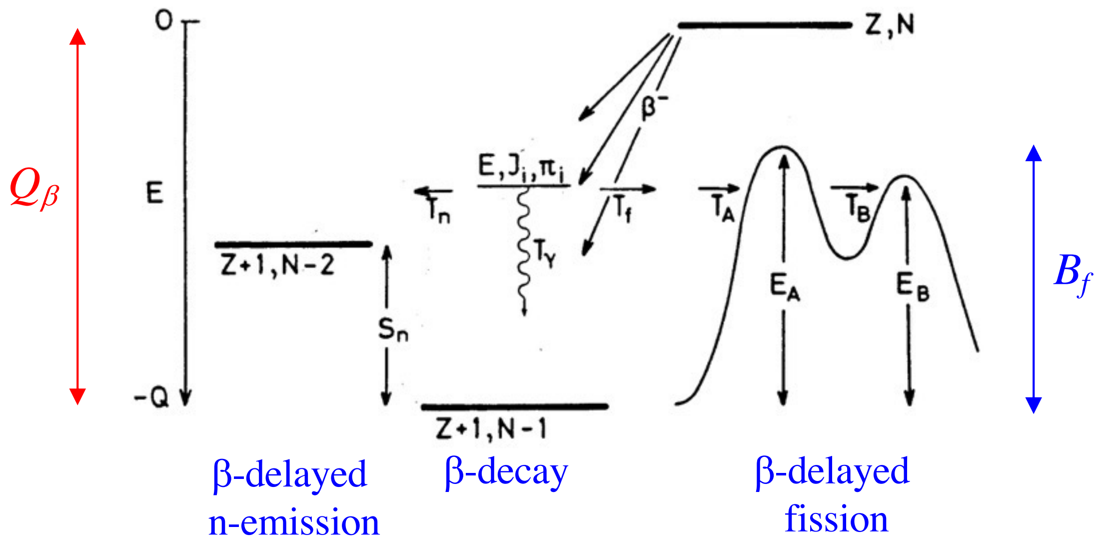
sfho135135+M3A8m1a5: Masses – TALYSxxx DC3*+RRPA SPY16

Nuclear fission

Three fission modes play an important role during the r-process nucleosynthesis:

- spontaneous fission: strongly depends on the fission barrier height
- neutron-induced fission: strongly depends on $S_n - B_f$ (for E_n~keV~kT)
- β-delayed fission, *i.e*. fission following a β-decay: strongly depends on $Q_\beta - B_f$



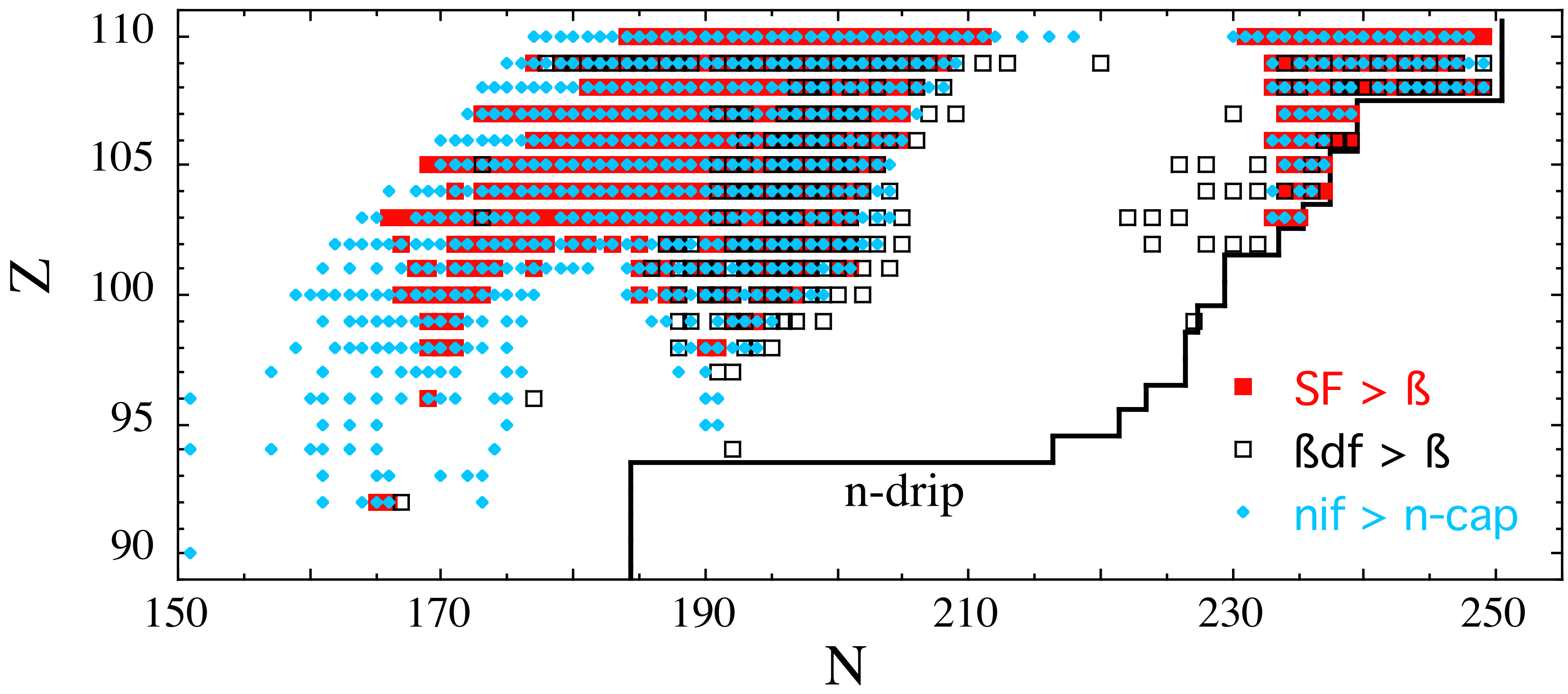


Fission and the production of actinides

Fission processes (spontaneous, β-delayed, neutron-induced) and fission fragment distribution of relevance for estimating the

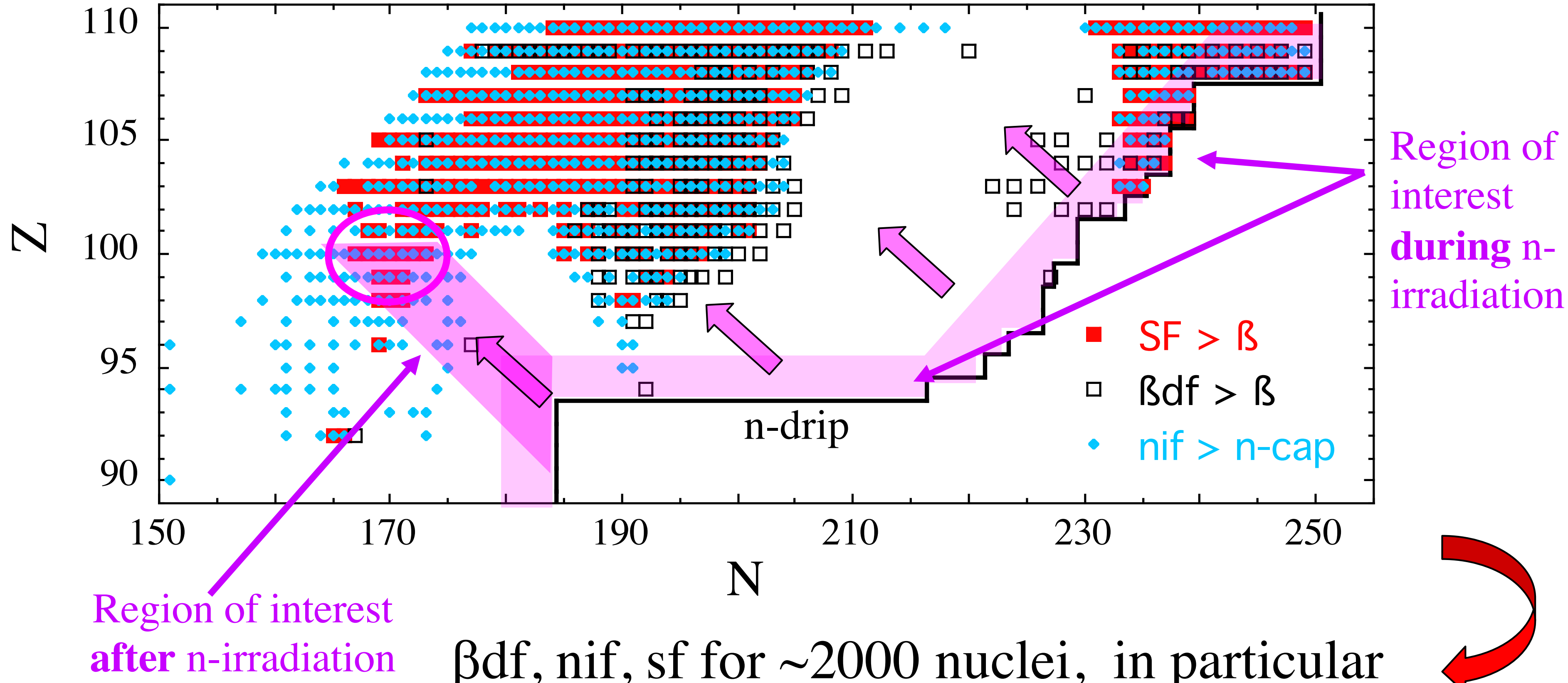
- termination point of the r-process (recycling, heating, prod of SH)
- production of Pb-peak elements
- production of radiocosmochronometers (U, Th)
- production of light species (*A*~110-160) by fission recycling

Detailed calculation of fission probabilities (sf, nif, βdf) for about 2000 nuclei



HFB-14 predictions

Fission properties and the r-process in NSM

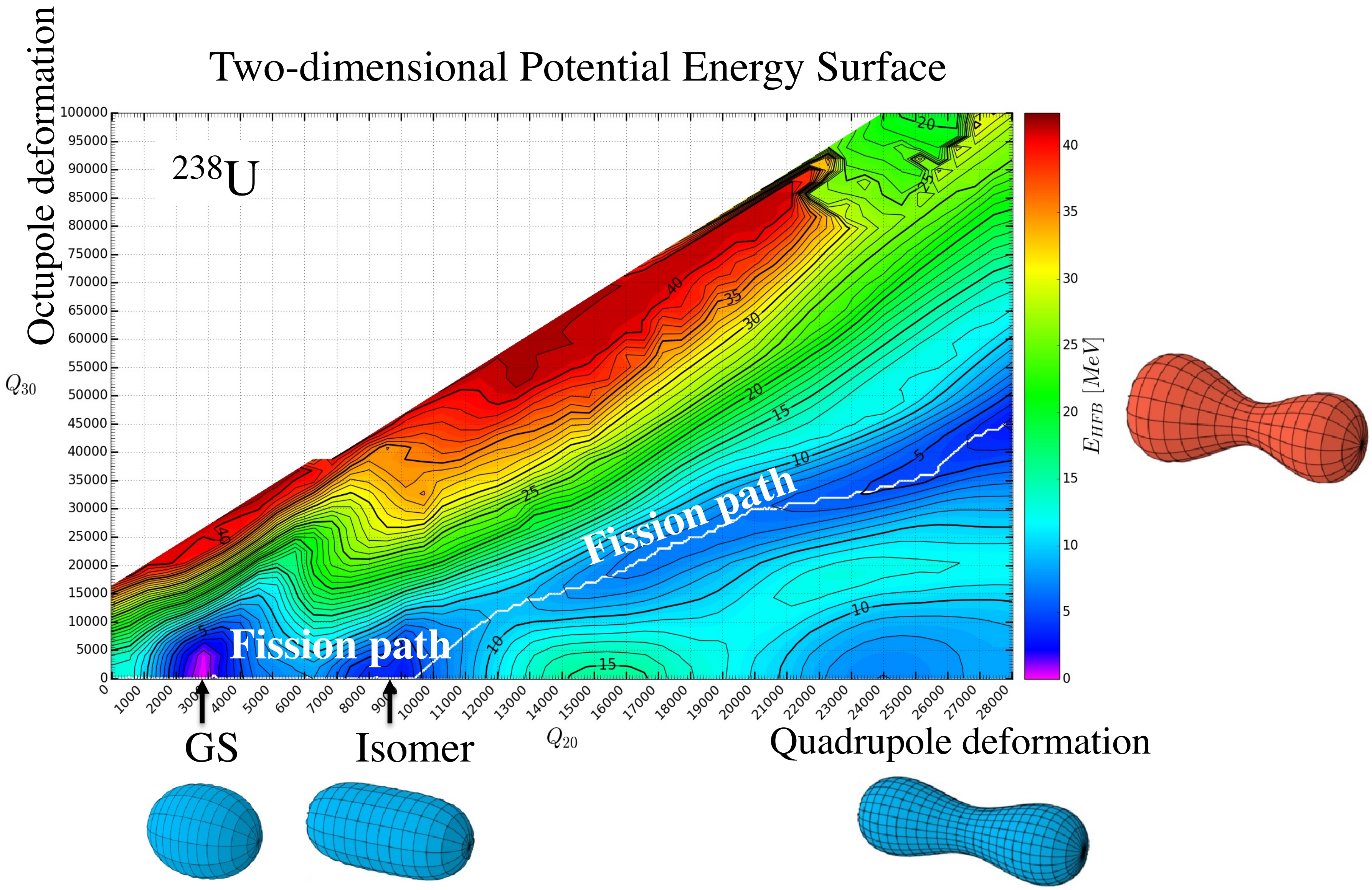


βdf, nif, sf for ~2000 nuclei, in particular along the n-drip line

Production of Super-Heavy nuclei ?

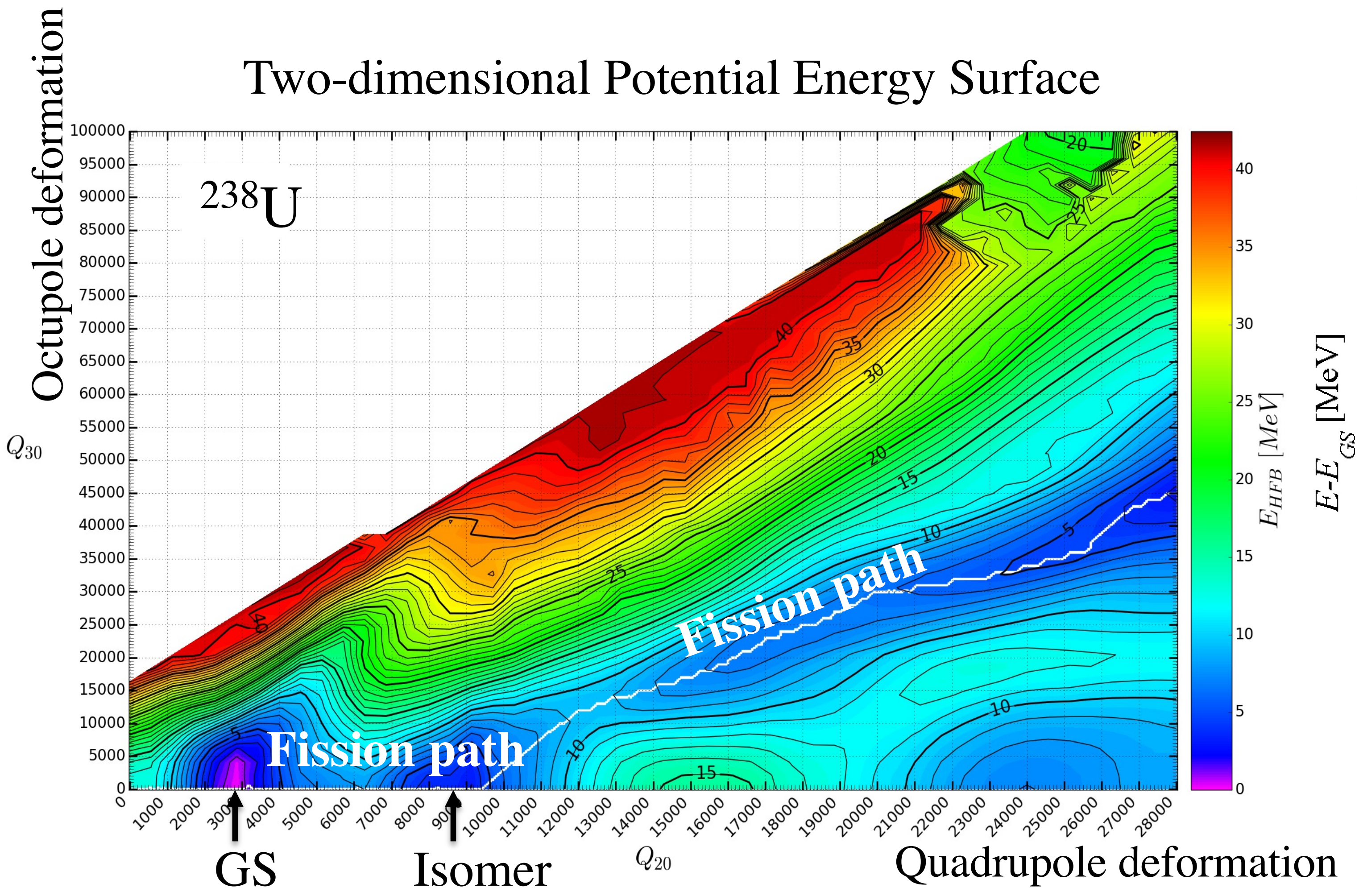
Special emphasis on Fission & FFD for *A*~278

Calculation of the fission path and barriers

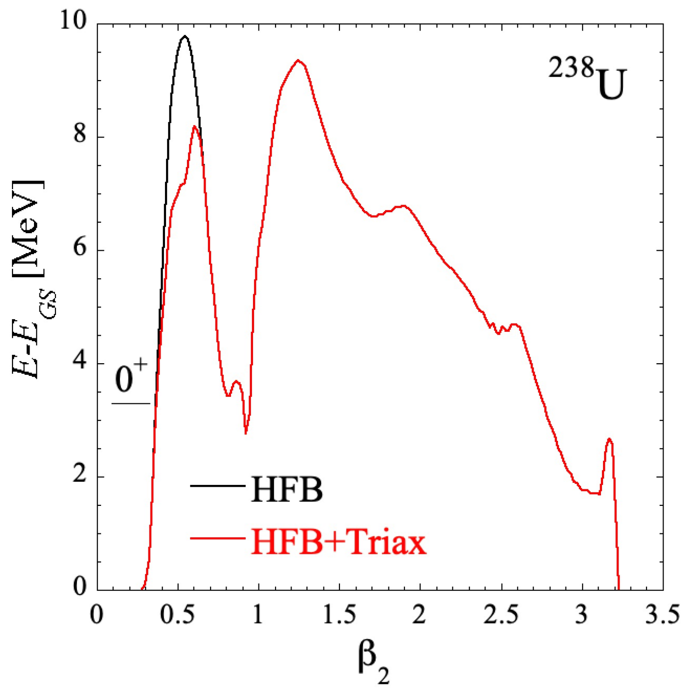


Calculation of the fission path and barriers

Two-dimensional Potential Energy Surface

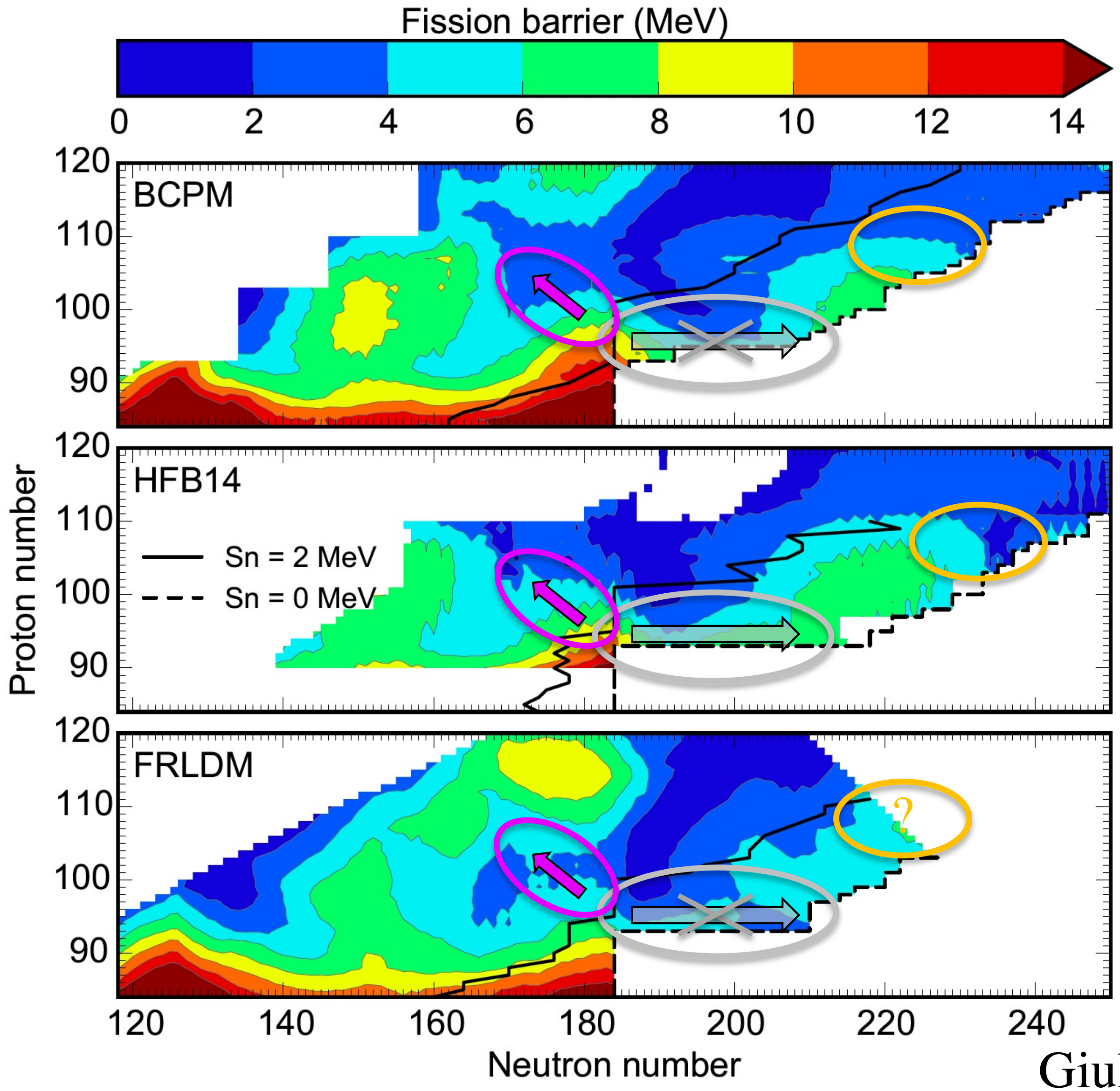


1D PES



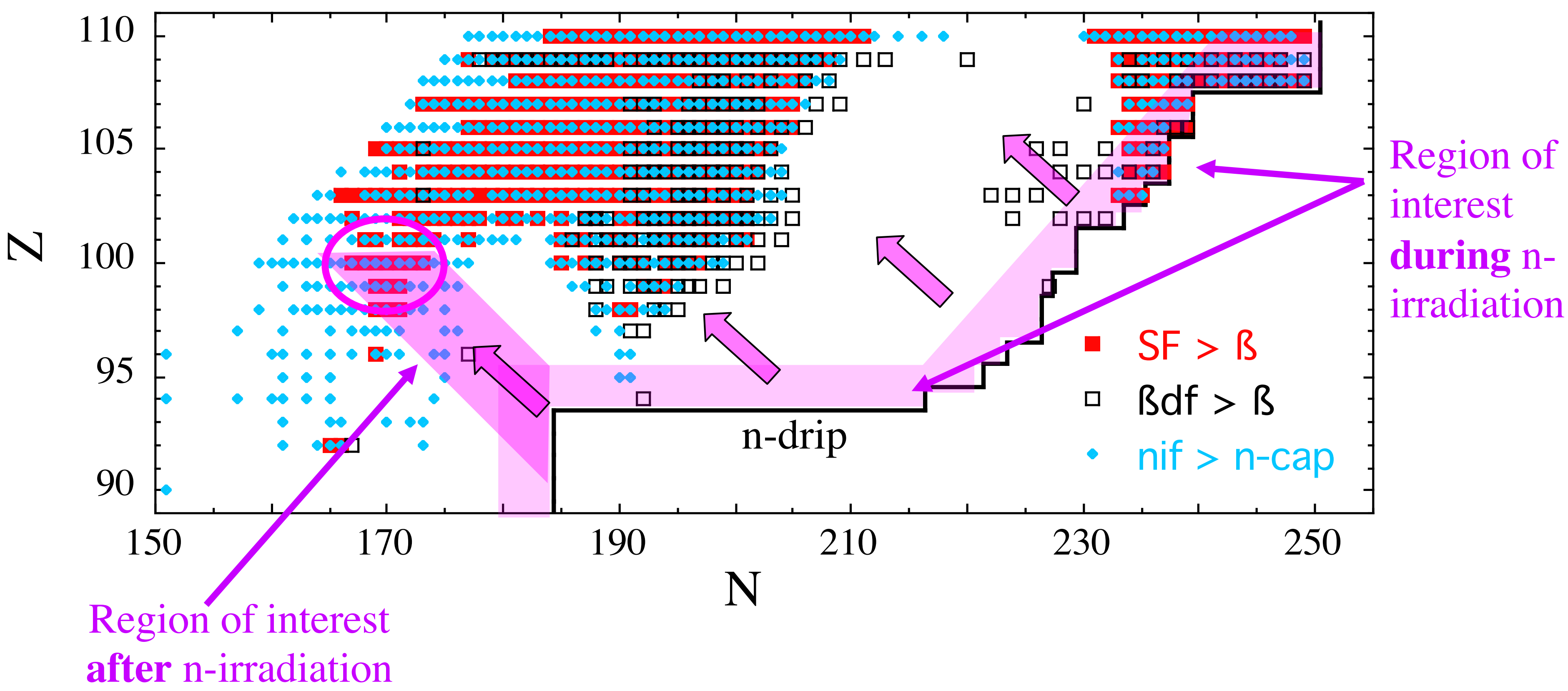
Fission properties mainly depend on the primary fission barriers

Fission barriers calculated for all nuclei with $90 \leq Z \leq 120$



Giuliani et al. (2018)

Fission properties and the r-process



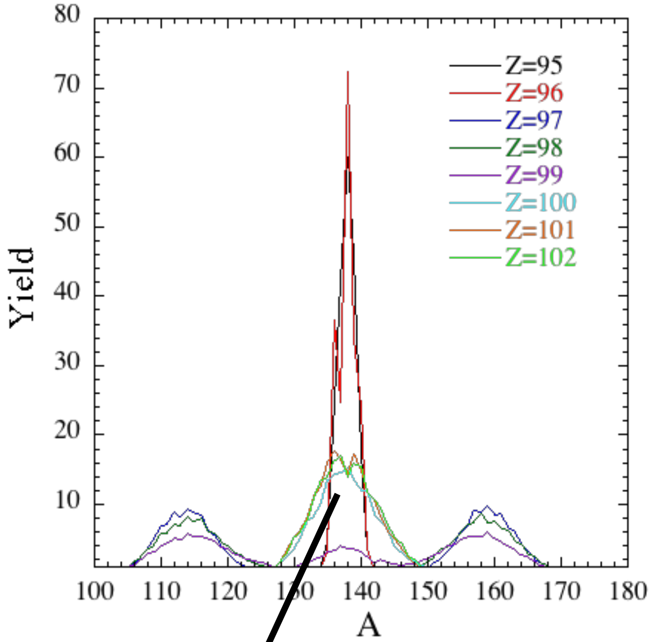
Special emphasis on the Fission Fragment Distribution for the *A*~278 isobars

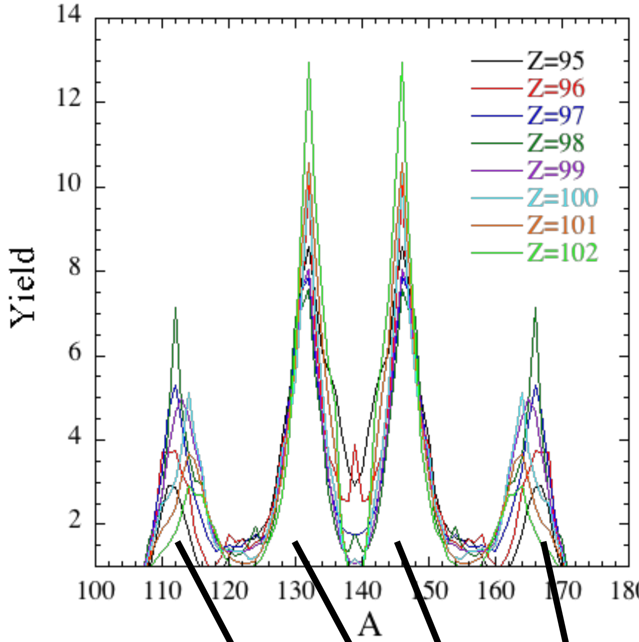
Sensitivity of dynamical composition to the fission fragment distribution

along the *A*=278 isobar (from the *N*=184 closed shell)

GEF v1.4
K. Schmidt et al. (2013)

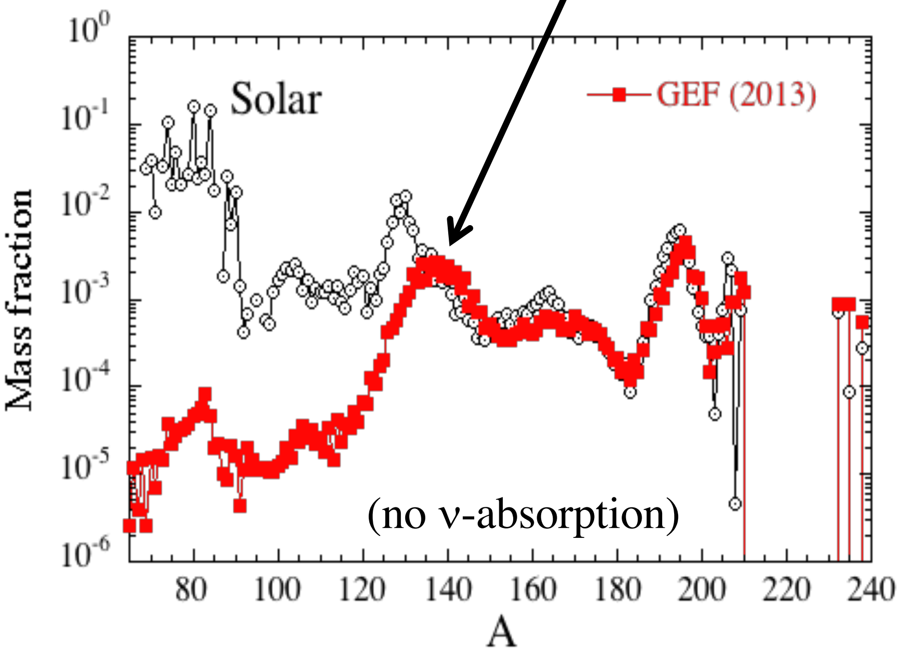
Semi-empirical mic-mac Scission Point model

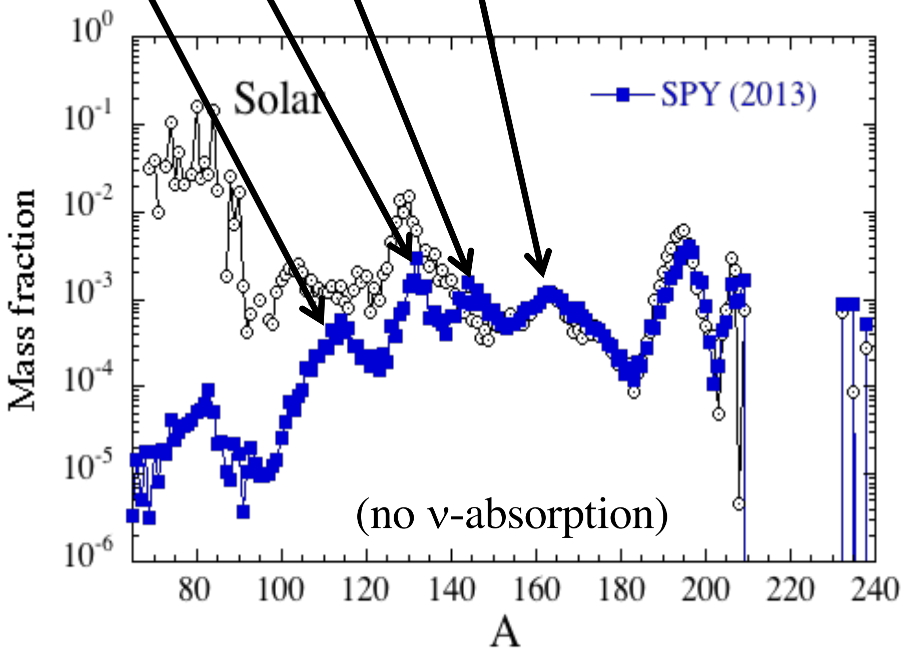




SPY:
S. Panebianco et al. (2013)

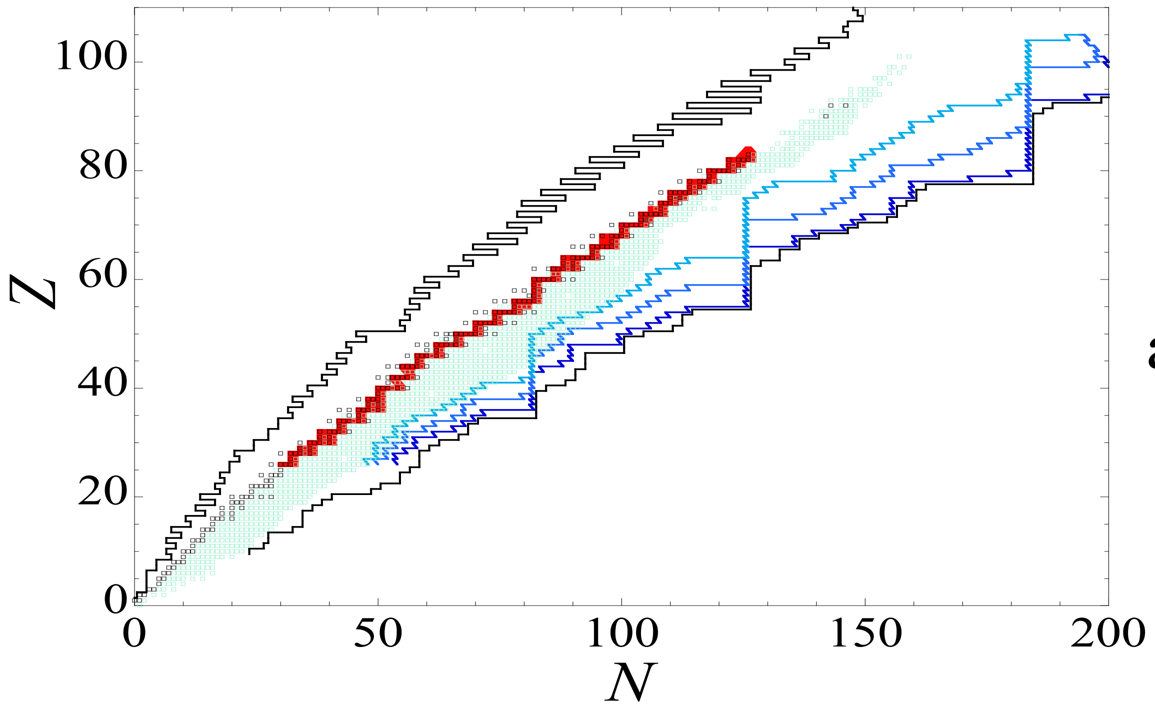
Parameter-free Scission Point model based on D1S potential energy surfaces





The fundamental role of β-decay rates

(including βdn & βdf)



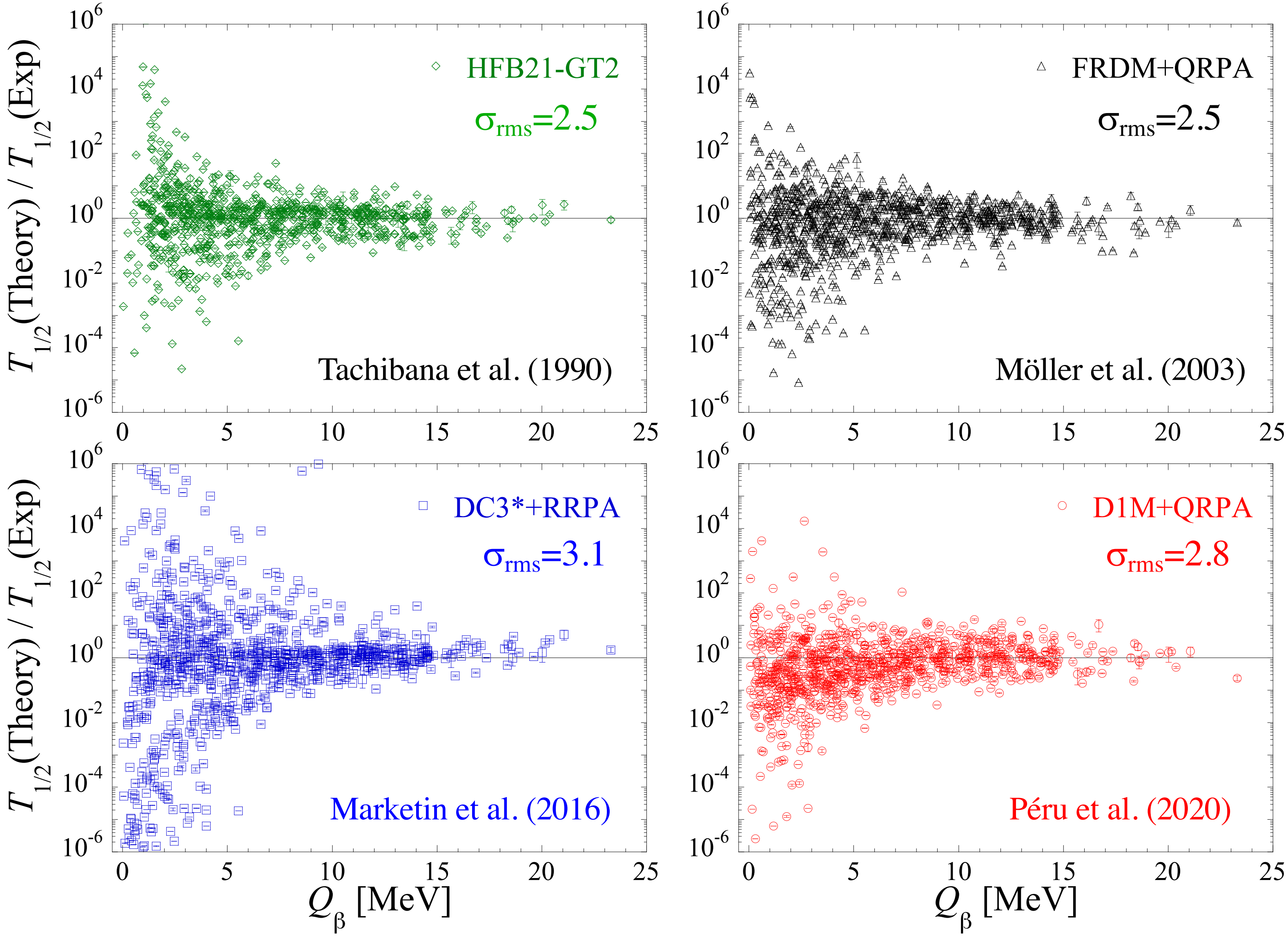
Experimental β⁻ half-lives available for some 1213 nuclei → some ~4000 missing

- Gross Theory :
  Description of the β-strength function in a statistical manner
- QRPA approach (Skyrme, Gogny, RMF)
  Description of the β-strength function through an effective n-n interaction

Impact of β-decay rates on the r-process nucleosynthesis in NS mergers

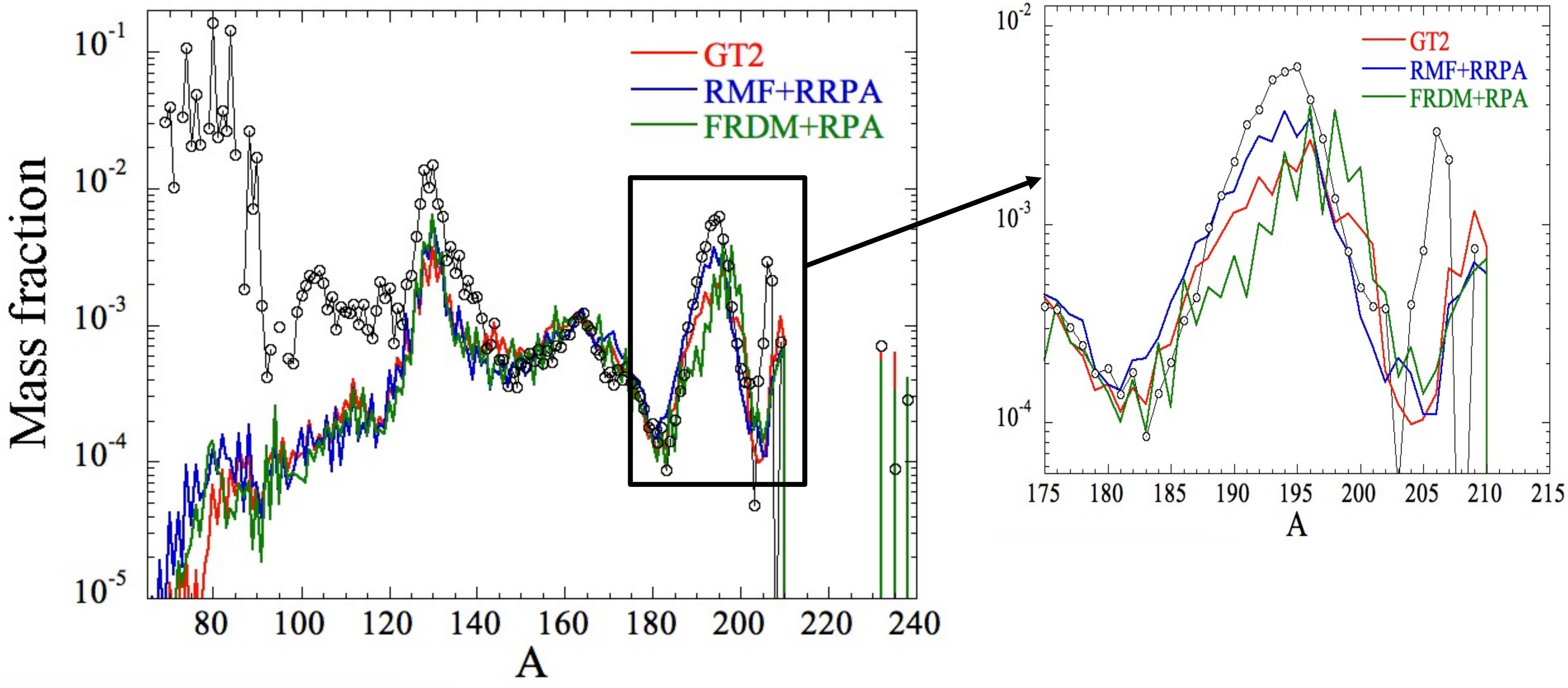
Limited number of available large-scale calculations

Comparison for all the 950 nuclei with $Z \geq 10$ – σ_{rms} on 312 $T_{1/2} \leq 1$ s



Impact of β-decay rates on the r-process nucleosynthesis in NS mergers

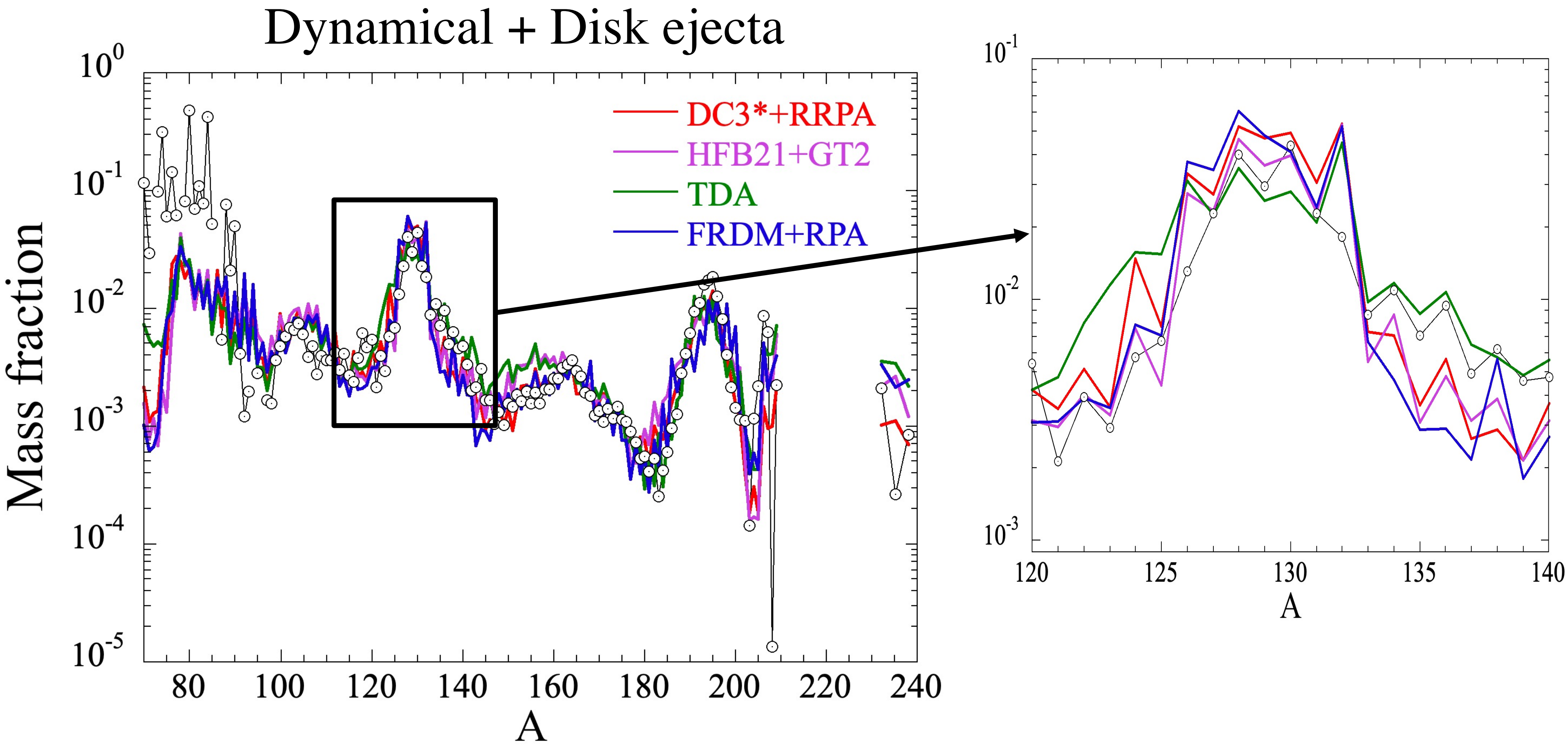
Dynamical ejecta



Large impact of the β-decay rates – set the synthesis timescales

→ Need *deformed* "microscopic" calculation (MF+QRPA) including GT+FF transitions, odd nuclei, PC, ….

Impact of β-decay rates on the r-process nucleosynthesis in NS mergers



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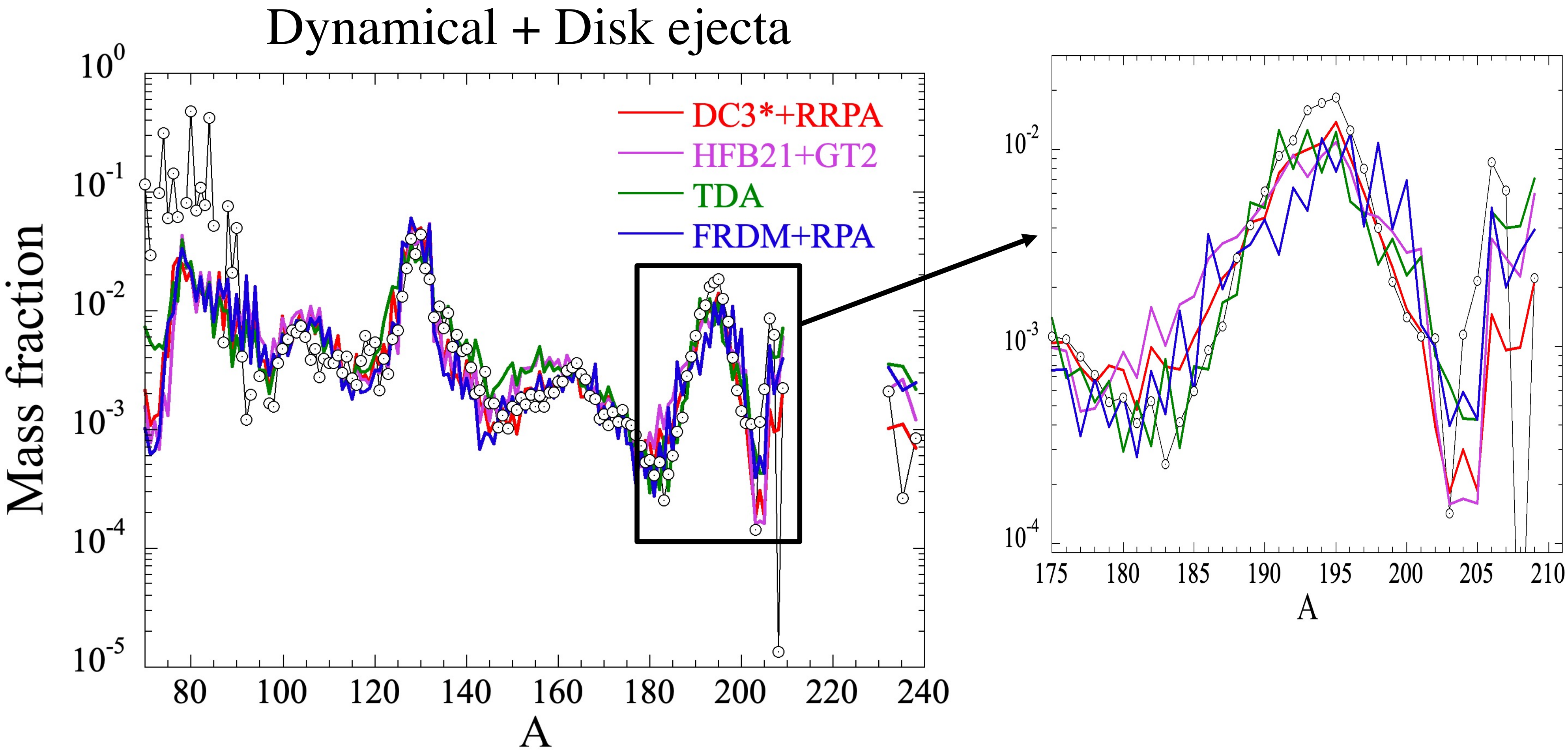

Large impact of the β-decay rates – set the synthesis timescales

→ Need *deformed* "microscopic" calculation (MF+QRPA) including GT+FF transitions, odd nuclei, PC, ….

Conclusions

The astrophysical site for the *r*-process remains puzzling !

Compact Object Mergers (NS-NS;NS-BH) :

- Analysis of GW170817 compatible with *r*-process
- Robust hydrodynamical simulations

  Successful solar-like *r*-process for $A \geq 90$ nuclei from Dynamical and Disk ejecta

But still some major open questions, in particular

- Neutrino effects in relativistic models
- Chemical evolution of the Galaxy
- Nuclear physics associated

and Supernovae/Collapsars have not said their last words

Conclusions : still many open Nuclear Physics questions

- **Fundamental role of experiments** (masses, β-decays, cross sections, nuclear ingredients, ...) though *mainly to adjust/guide models*
- **Nuclear inputs to the reaction model** (almost no exp. data !)
  - GS properties: masses (correlations - GCM, odd-nuclei)
  - Fission: fission paths, NLD at the saddle points, FFD
  - E1/M1-strength function: GDR tail, PR, ε_γ=0 limit, *T*-dep, PC
  - Nuclear level Densities: pairing, shell and collective effects
  - Optical potential: the low-*E* isovector imaginary component
- **The reaction model**
  - CN vs Direct capture for low-S_n nuclei
- **The β-decay rates**
  - Forbidden transitions, deformation effects, odd-nuclei, PC

We are still far from being capable of estimating ***reliably*** the neutron capture and β-decay of exotic n-rich nuclei