Key neutron capture rates for the r-process nucleosynthesis (in BNS mergers)

Diego Vescovi[1,2]

1. INAF – Osservatorio Astronomico d'Abruzzo, Teramo, Italy
2. INFN – Sezione di Perugia, Perugia, Italy

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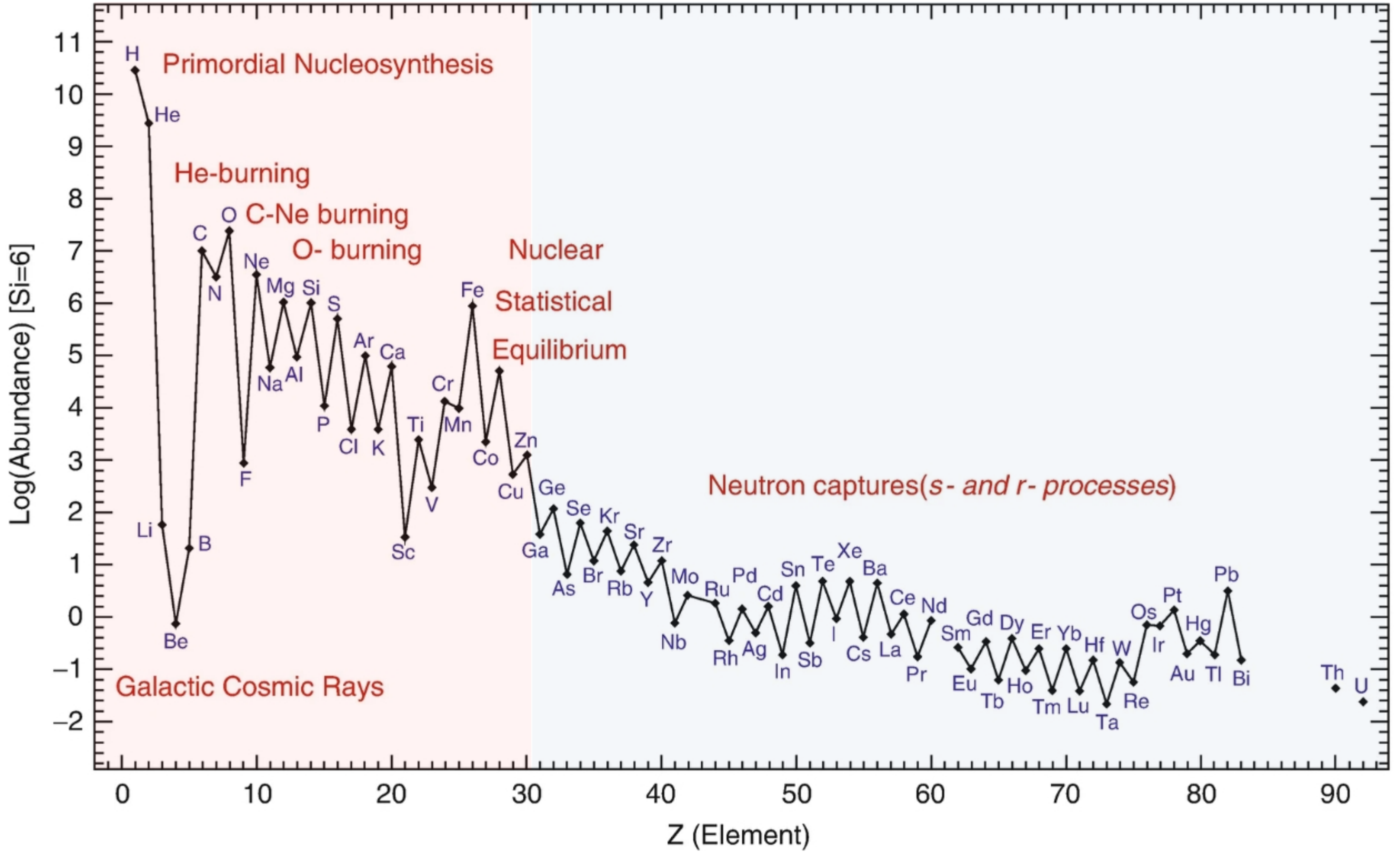
INFN Perugia Istituto Nazionale di Fisica Nucleare Sezione di Perugia

Nucleosynthesis of the heavy elements

- Fusion reactions between charged particles
- Neutron capture processes:
  - **s(low)-process**
  - **i(ntermediate)-process**
  - **r(apid)-process**

Prantzos+ 15, EnAs



Origin of the heavy elements

s(low) process

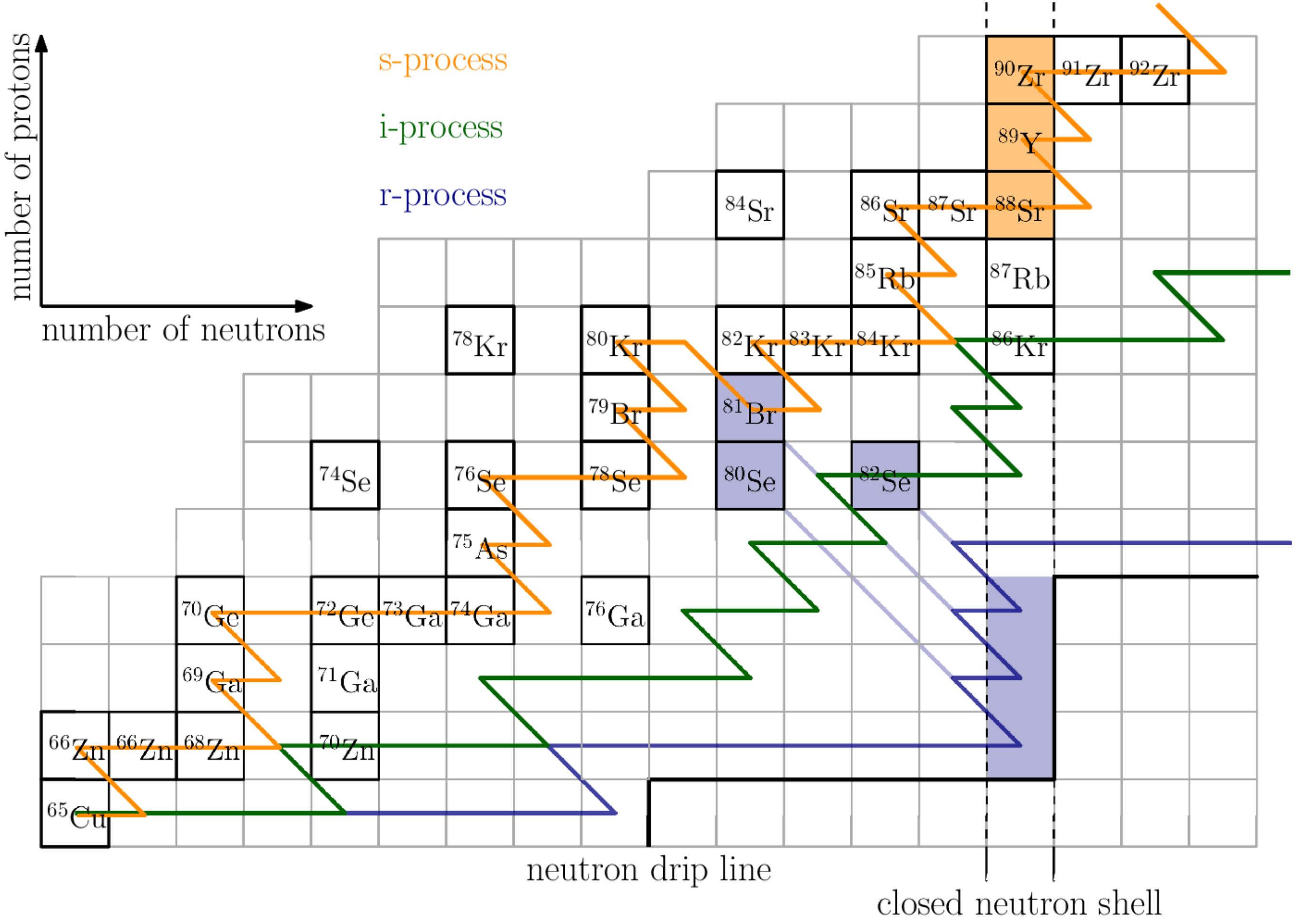
- Mild neutron density n_n~10^7
- Asymptotic giant branch (AGB) and massive stars

i(ntermediate) process

- Intemerdiate neutron density n_n~10^{15}
- AGB, rapidly accreting white dwarfs, massive stars, etc.

r(apid) process

- High neutron density $n_n \gtrsim 10^{21}$
- Supernovae and compact binary mergers



r-process: basic ideas

- key reactions:

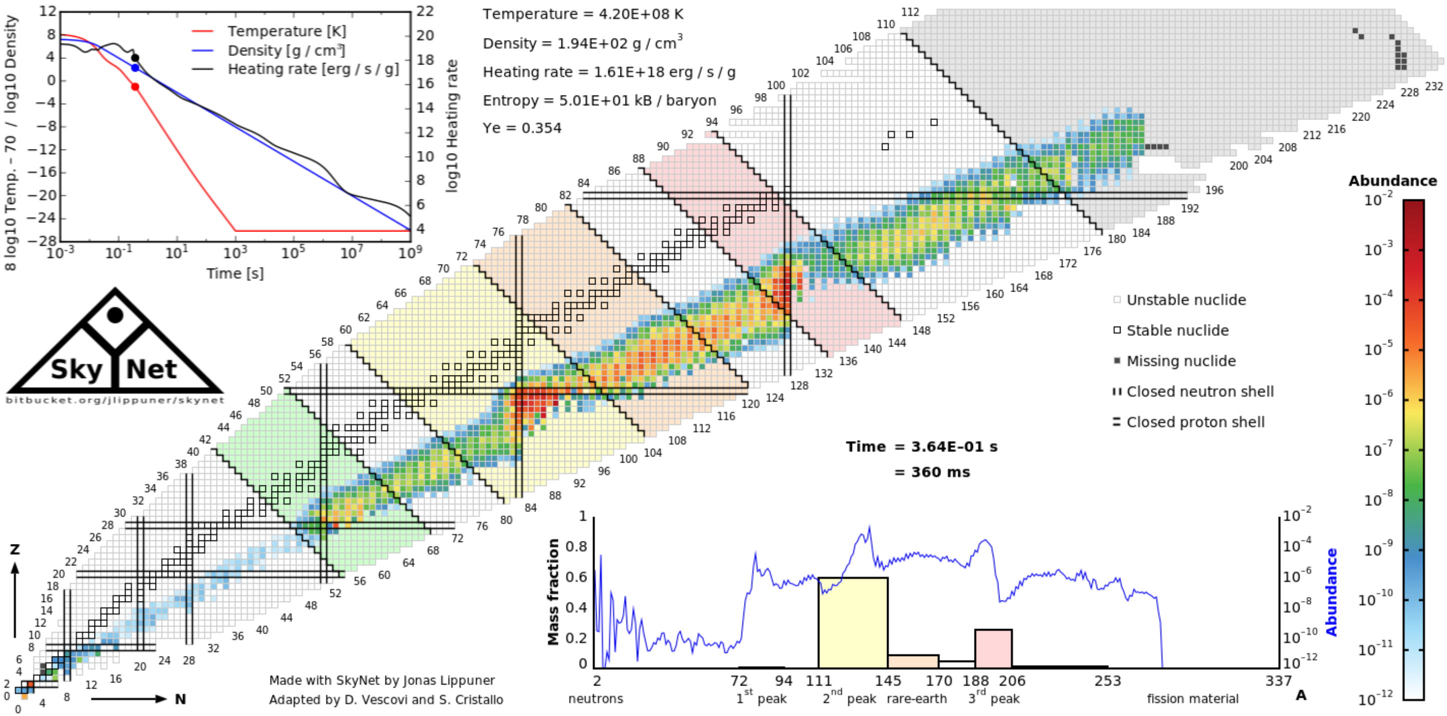
  $(A, Z) + n \leftrightarrow (A + 1, Z) + \gamma$

- *r*-process requires initial high n_n and T

  → high n_n : $\tau_{(n,\gamma)} << \tau_{\beta\text{-decay}}$

- equilibrium freeze-out:

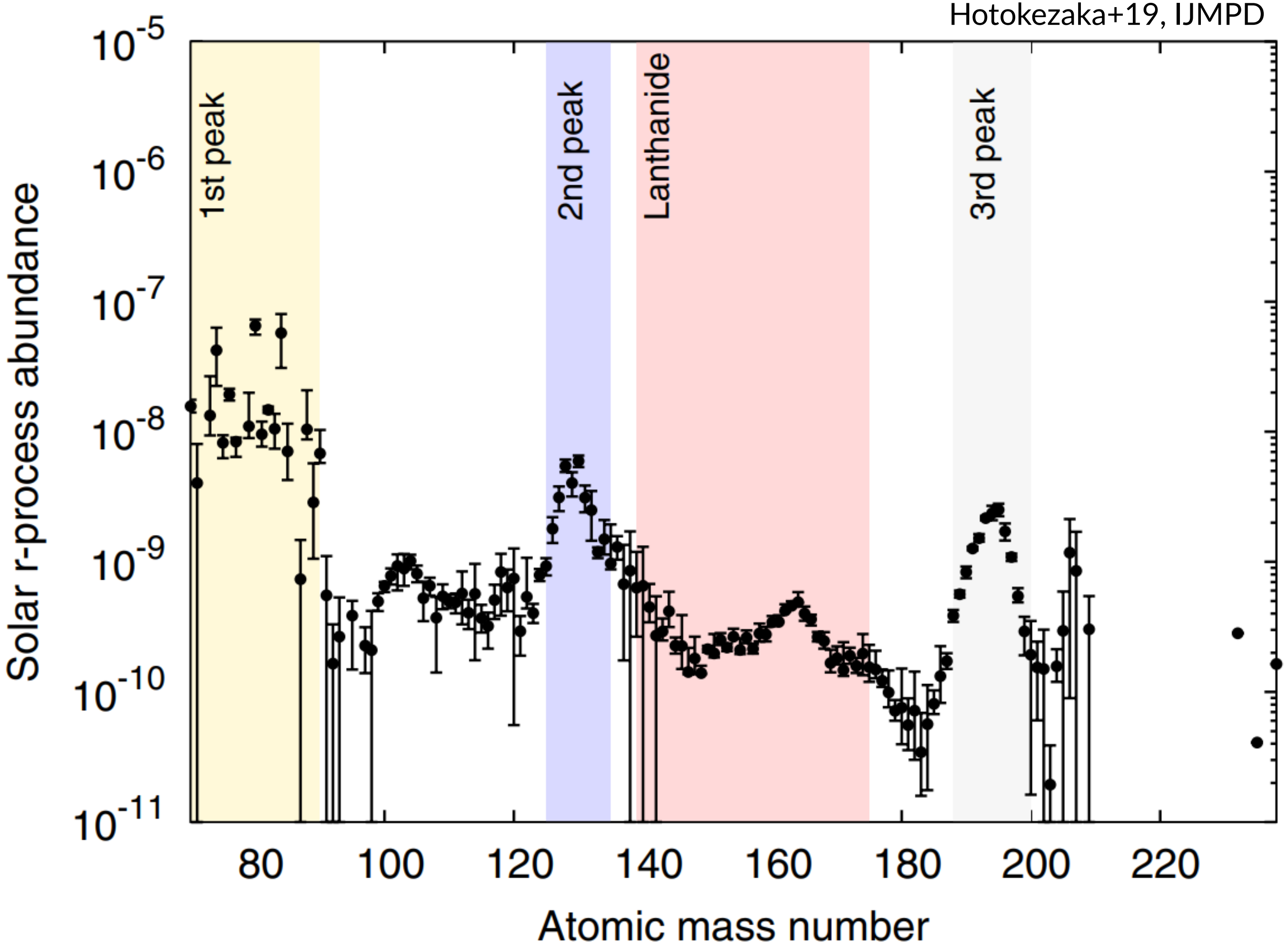
  n_n drops and β-decays take over



Modeling *r*-process abundances

- Astrophysical site
  - Sets thermodynamic conditions
- Nuclear physics
  - Shapes abundances distribution

Hotokezaka+19, IJMPD



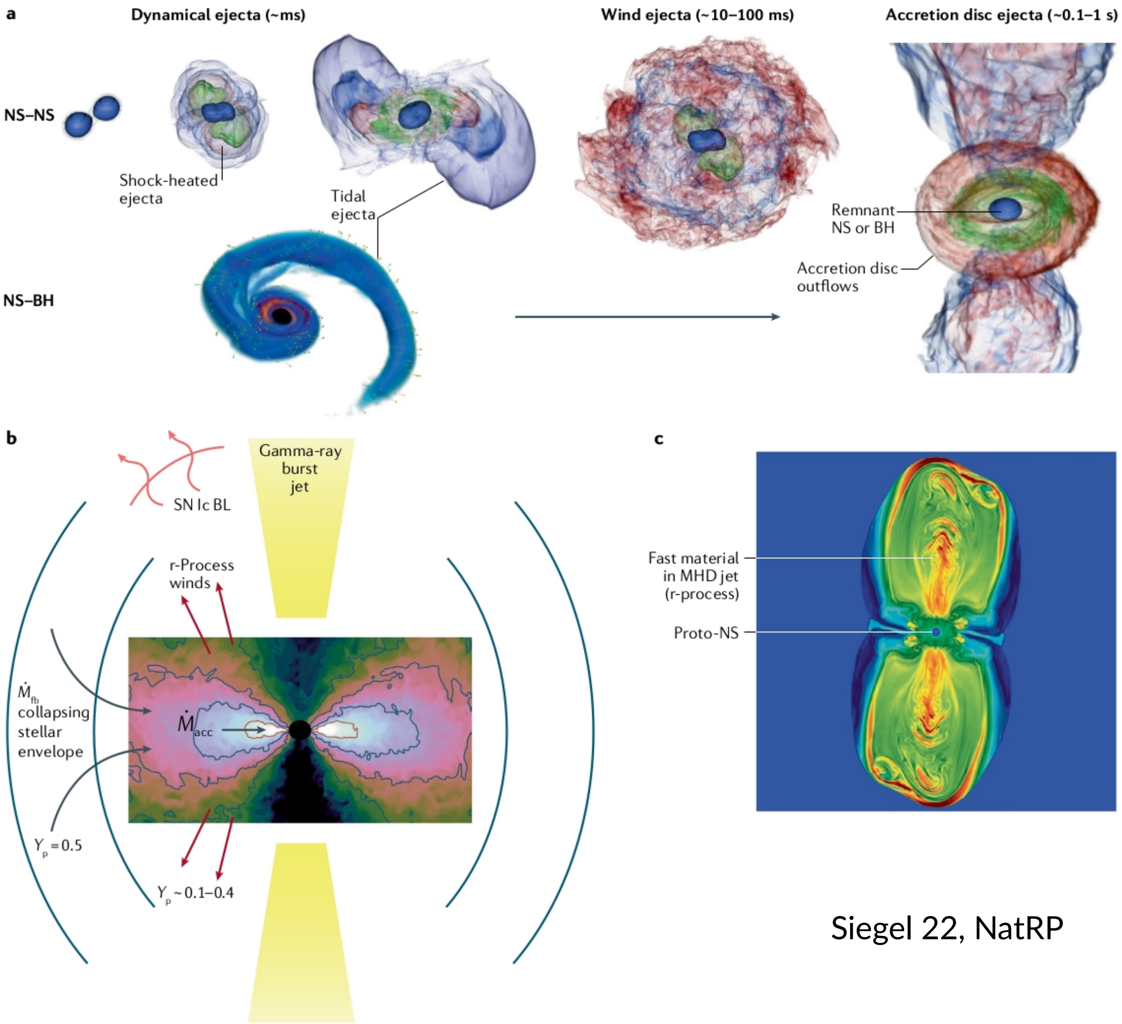
Astrophysical sites for r-process nucleosynthesis

a) Compact binary mergers:

- Binary neutron-star mergers (BNS)
- Neutron-star–black-hole mergers

b) Collapsar accretion discs

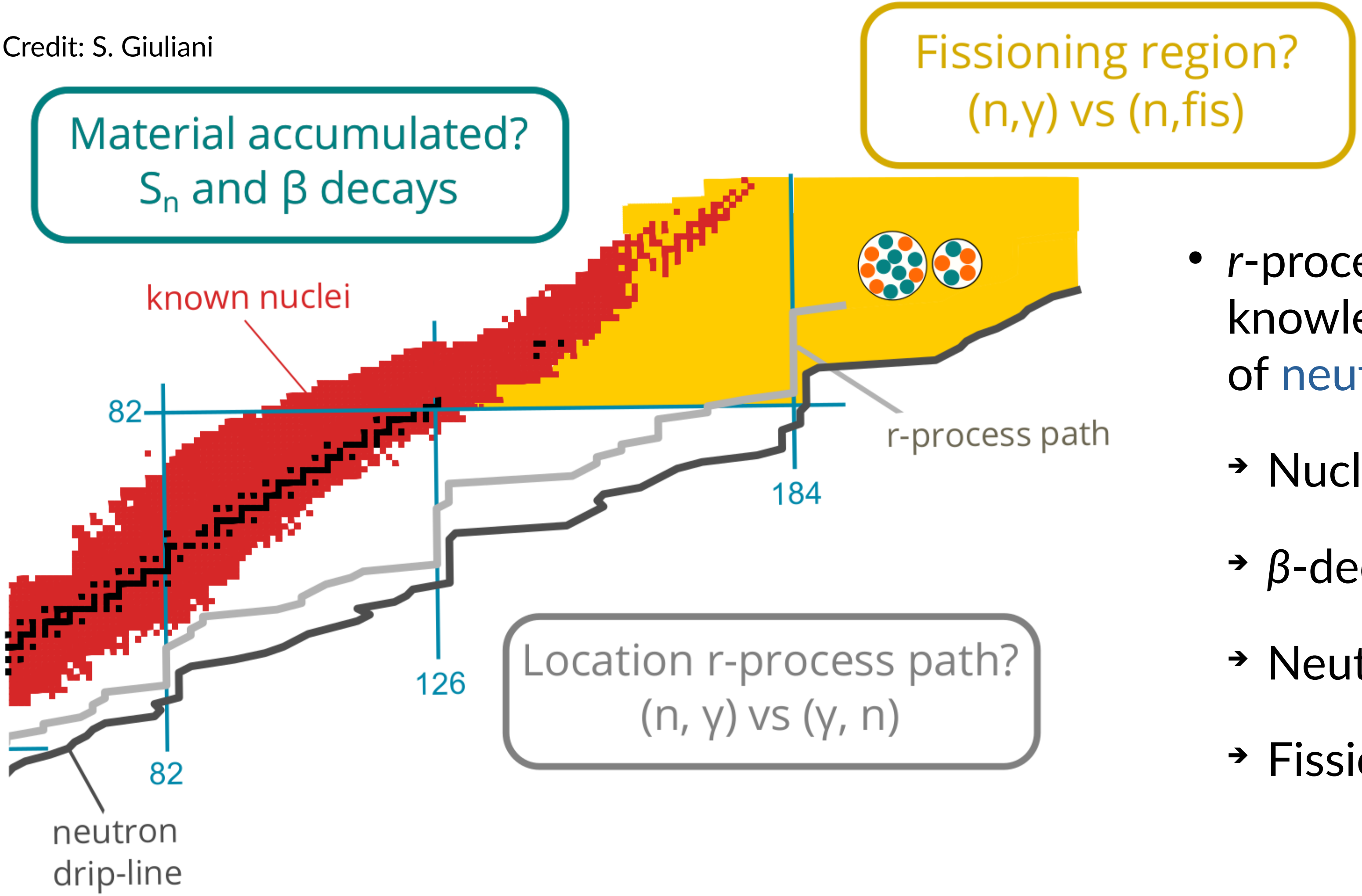
c) Fast outflows from magnetorotational supernovae



Siegel 22, NatRP

r-process: nuclear physics input

Credit: S. Giuliani



- *r*-process requires the knowledge of the properties of neutron-rich nuclei:
  - → Nuclear masses
  - → *β*-decay rates
  - → Neutron-capture rates
  - → Fission rates and yields

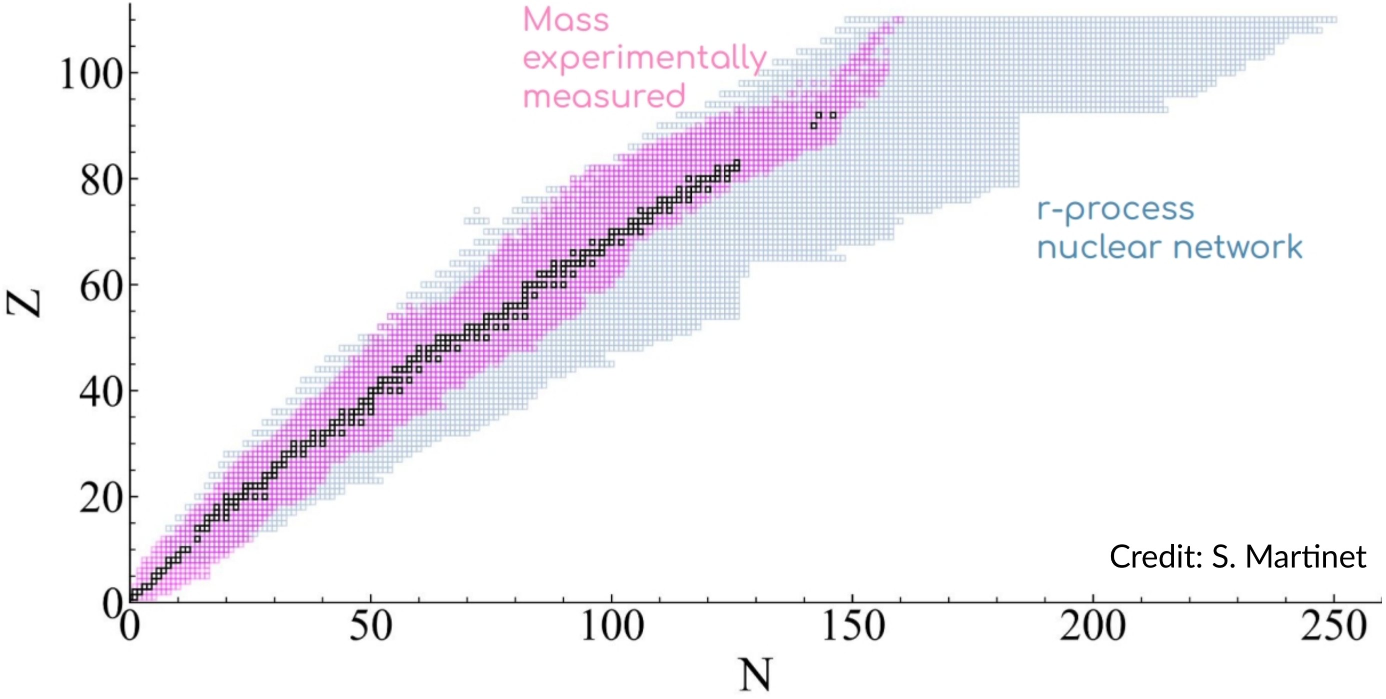
Impact of nuclear uncertainties for the r-process

- Masses and decay rates, radiative neutron capture rates and fission probabilities need to be estimated from nuclear models for almost all nuclei involved

- No reaction rates are known experimentally for unstable neutron-rich nuclei produced during the r-process

- Theoretical models are crucial to predict fundamental nuclear properties

- All enter into the r-process reaction network as input



Credit: S. Martinet

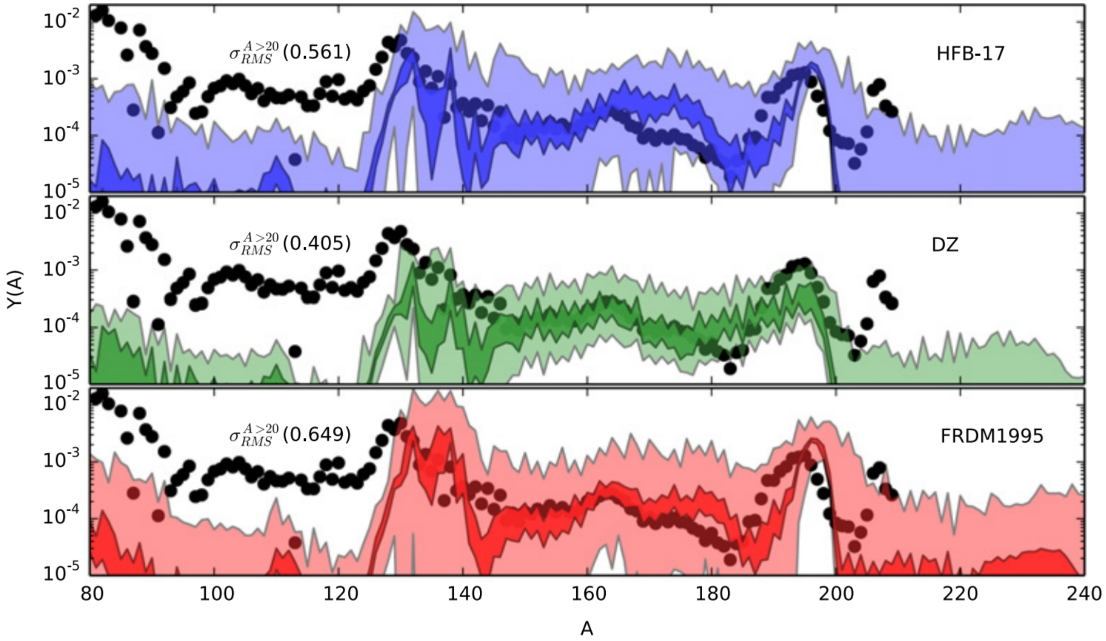
Impact of nuclear uncertainties for the r-process

- Estimating the sensitivity of the r-process nucleosynthesis yields to the nuclear input requires considering uncertainties

- **Monte Carlo variations of nuclear properties**

➔ Individual nuclear properties are varied throughout the nuclear chart using a probability distribution based on estimates of their theoretical uncertainties

Mumpower+ 16, PrPNP

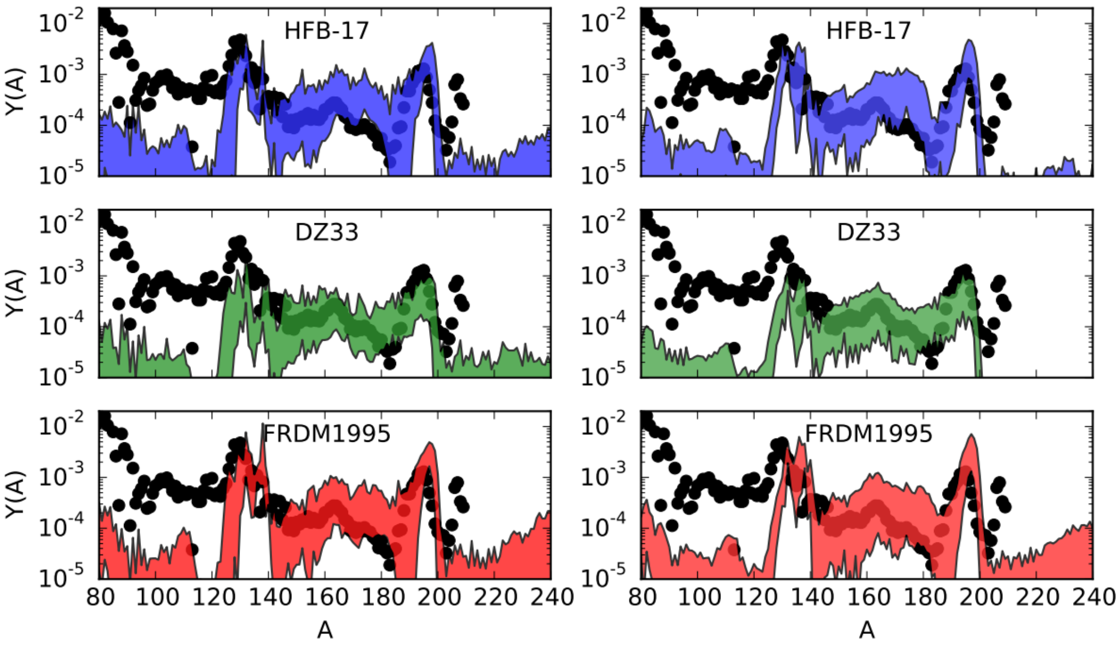


Nuclear masses

Impact of nuclear uncertainties for the r-process

- Modifying reaction or decay rates in a given range, independently of the changes of other reactions
  - Neglect correlations between uncertainties
  - May overestimates impact

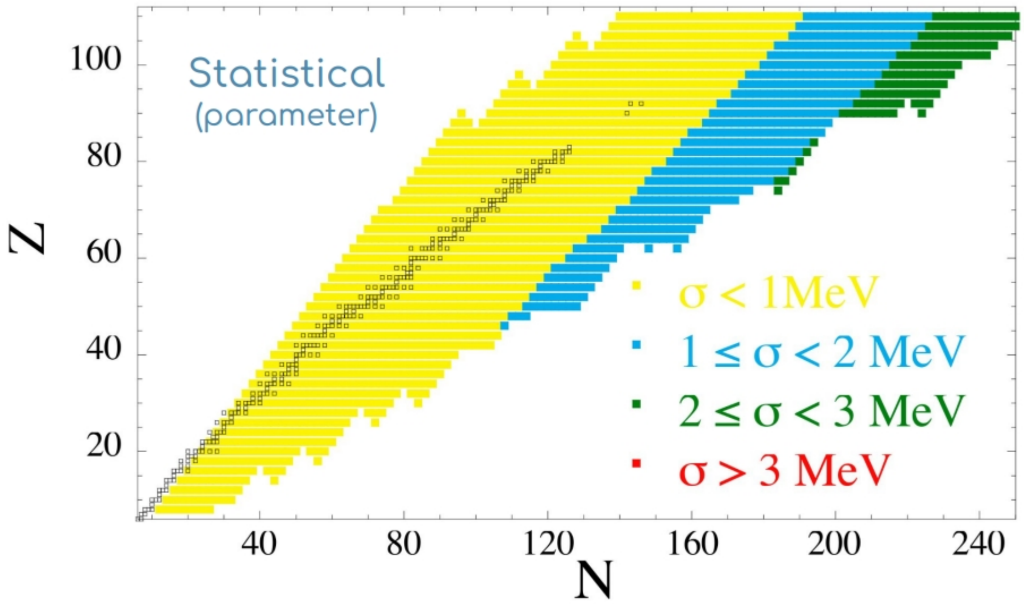
Mumpower+ 16, PrPNP

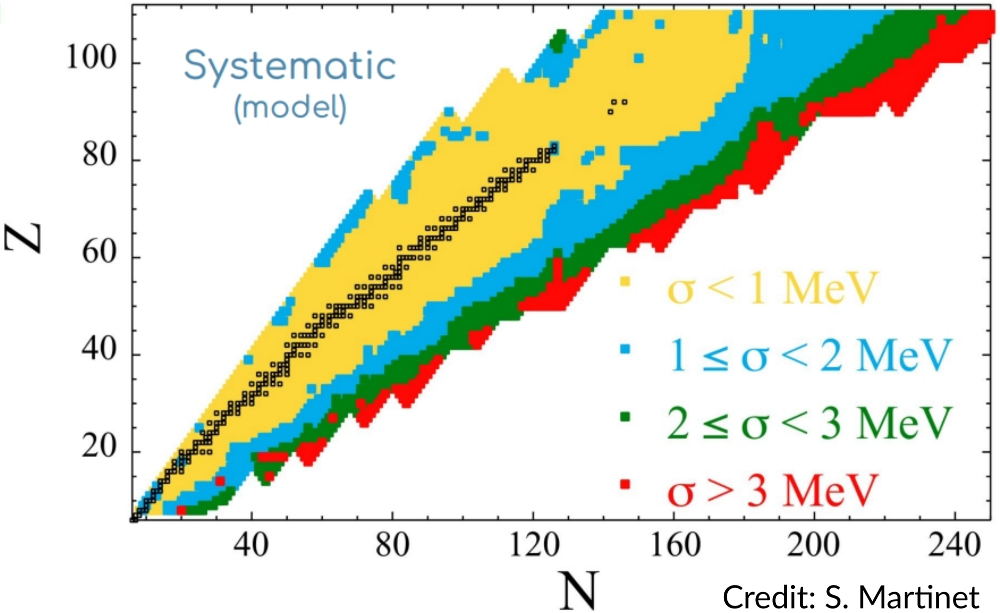


β-decay rates

n-capture rates

Impact of nuclear uncertainties for the r-process





Credit: S. Martinet

- Nuclear models = systematic uncertainties
- Nuclear parameters = statistical uncertainties
- Computationally expensive to consider coherent parameter uncertainties
- Few studies present in literature (e.g., Sprouse+ 20, Martinet+25)

Sensitivity studies for the r-process

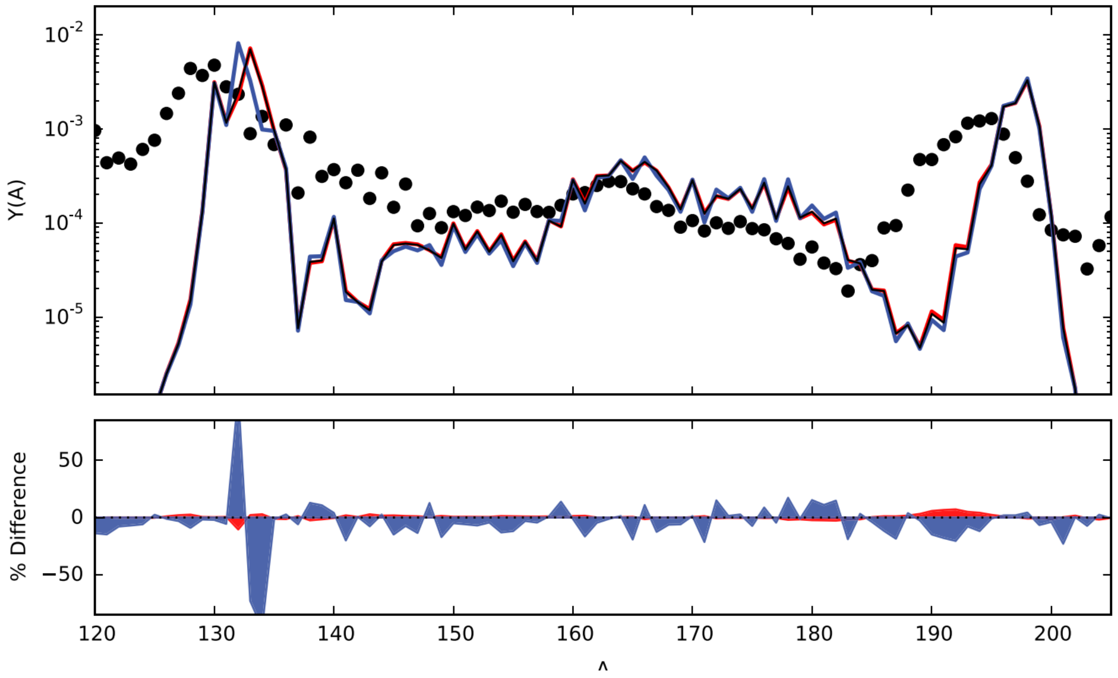
- A sensitivity study gauges the astrophysical response of a change in nuclear physics input(s)

→ It is useful in identifying **individual** nuclear data that should be the targets of new experimental campaigns

→ Baseline simulation defying astrophysical conditions and inputs from nuclear models.

→ Simulations are then performed with this fixed input, but allowing a subset of the nuclear input data to vary

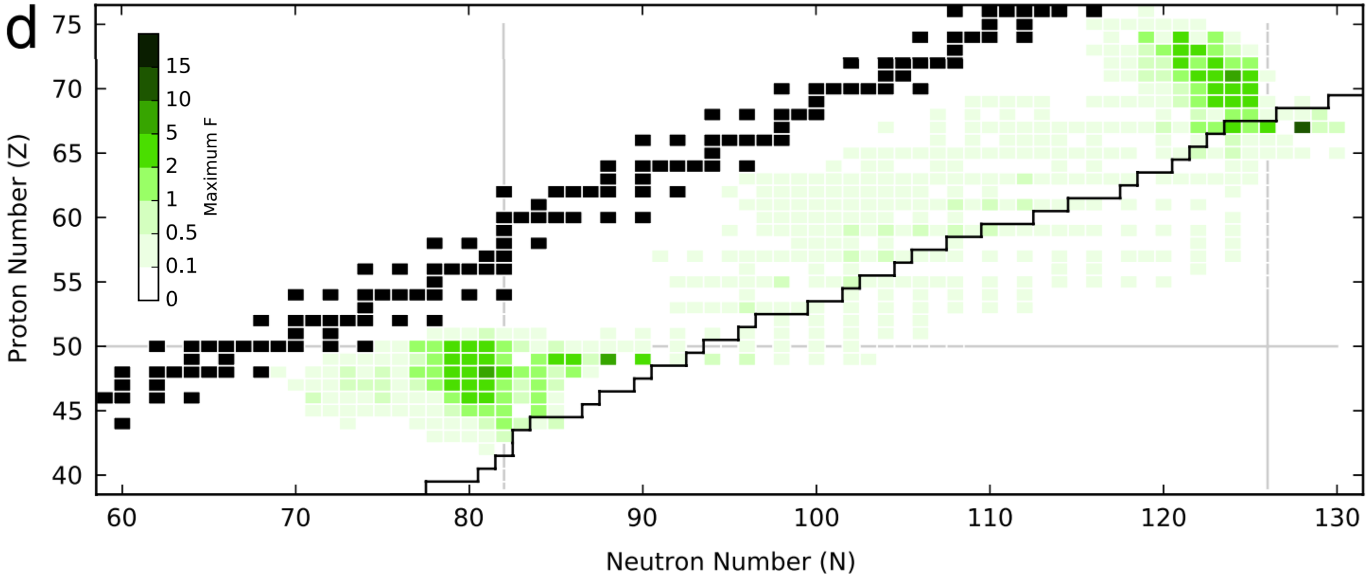
Mumpower+ 16, PrPNP



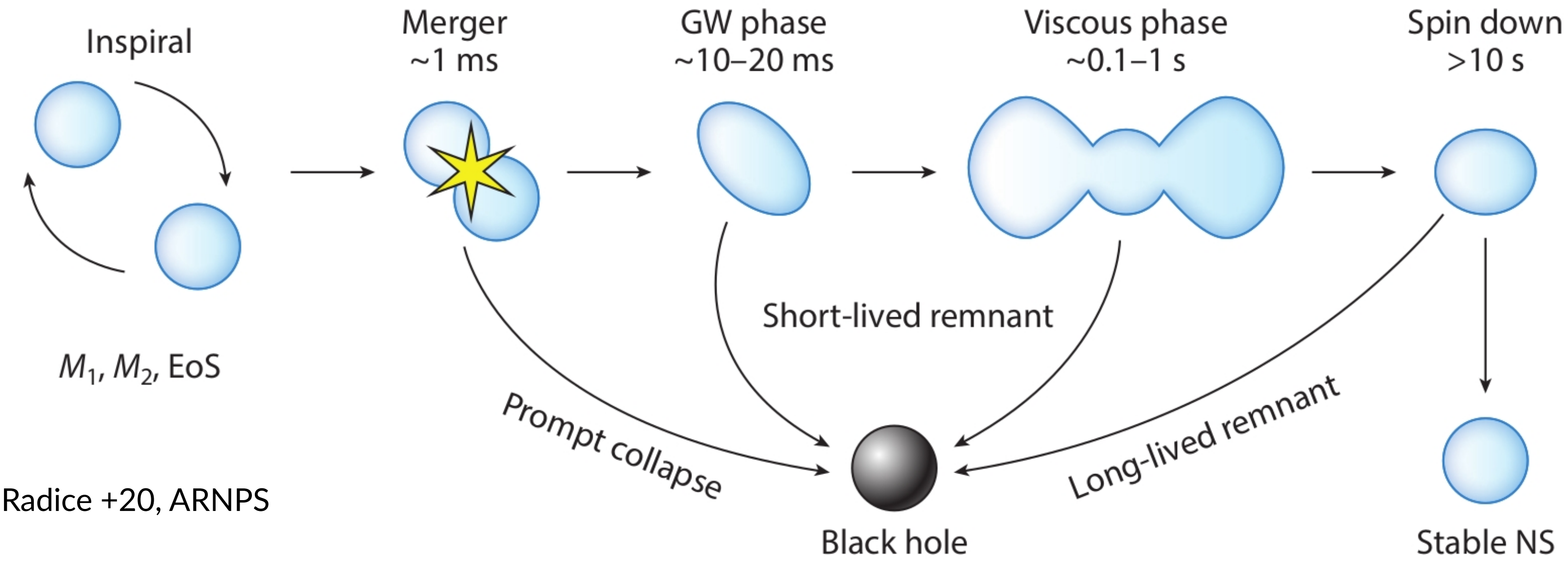
Sensitivity studies for the r-process

- All studies are for **main r-process** (*A* > 120)
- Astrophysical trajectories not representative of latest simulations of possible astrophysical sites
- Probe global changes in the abundance distribution
- Local changes often ignored

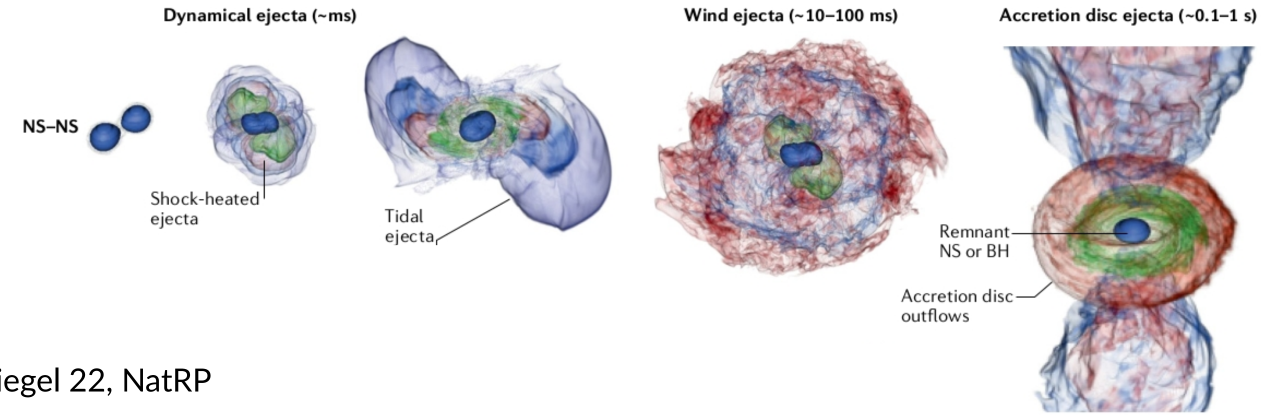
Mumpower+ 16, PrPNP



BNS merger

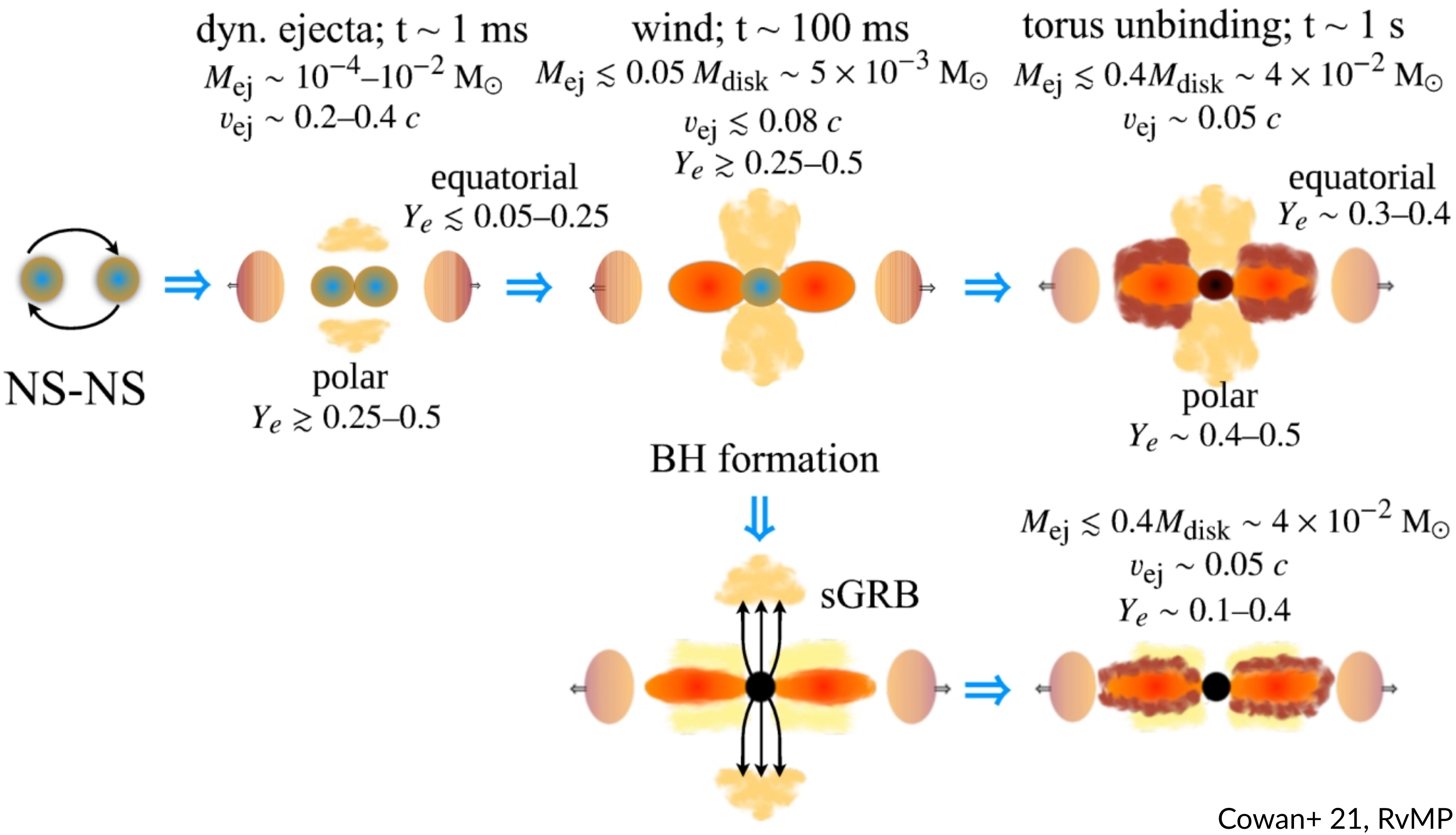


Radice +20, ARNPS



Siegel 22, NatRP

Merger channels and ejection mechanism

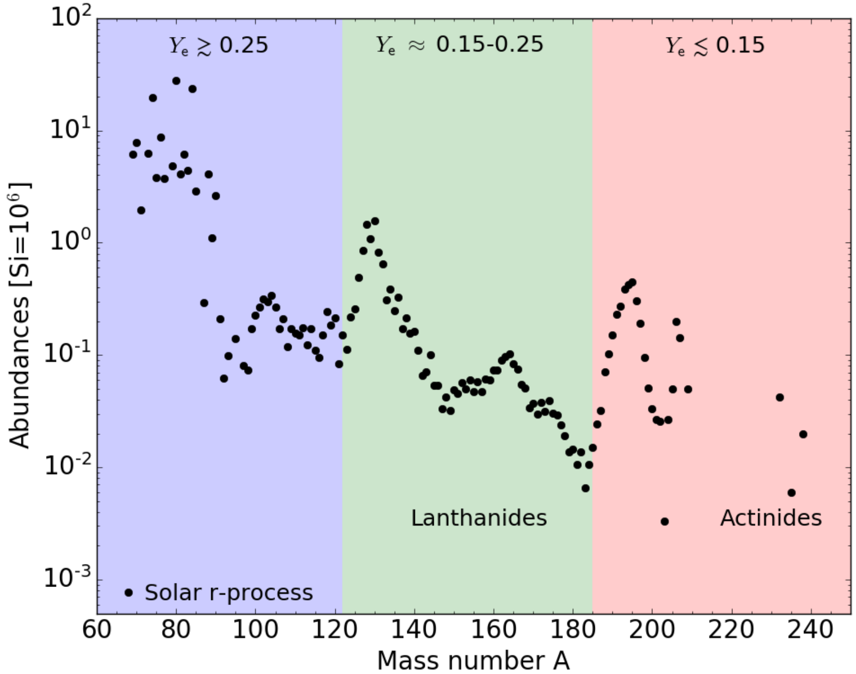


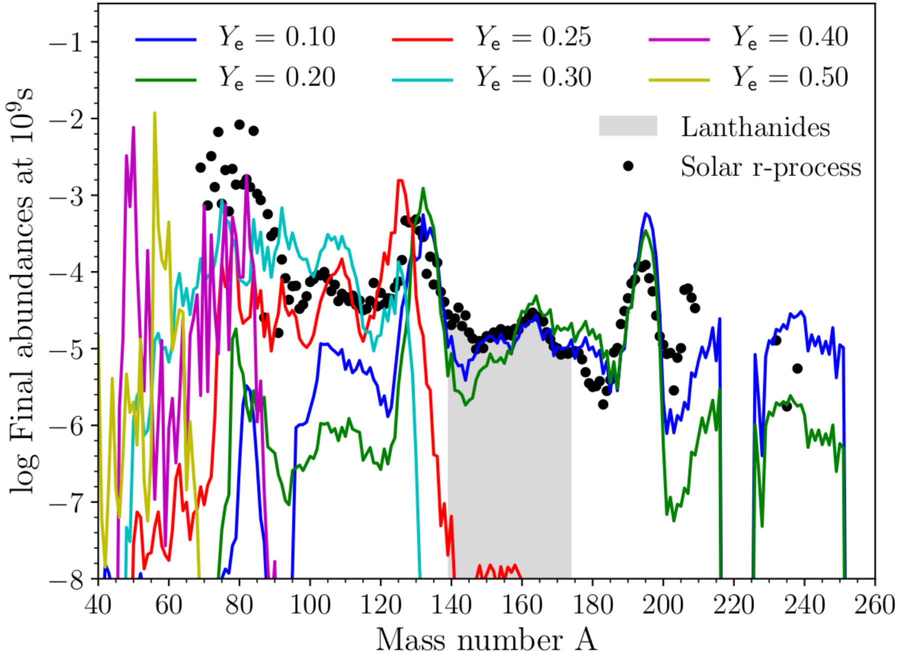
Cowan+ 21, RvMP

r-process nucleosynthesis in BNS mergers

$\mathbf{Y_e} \approx n_p/(n_n+n_p)$ is the **dominant parameter in low entropy environments**

- $Y_e < 0.15$: robust *r*-process, due to several fission cycles
- $Y_e \lesssim 0.25$: 2nd and 3rd *r*-process peaks, but no first
- $Y_e \gtrsim 0.25$: up to 2nd *r*-process peak





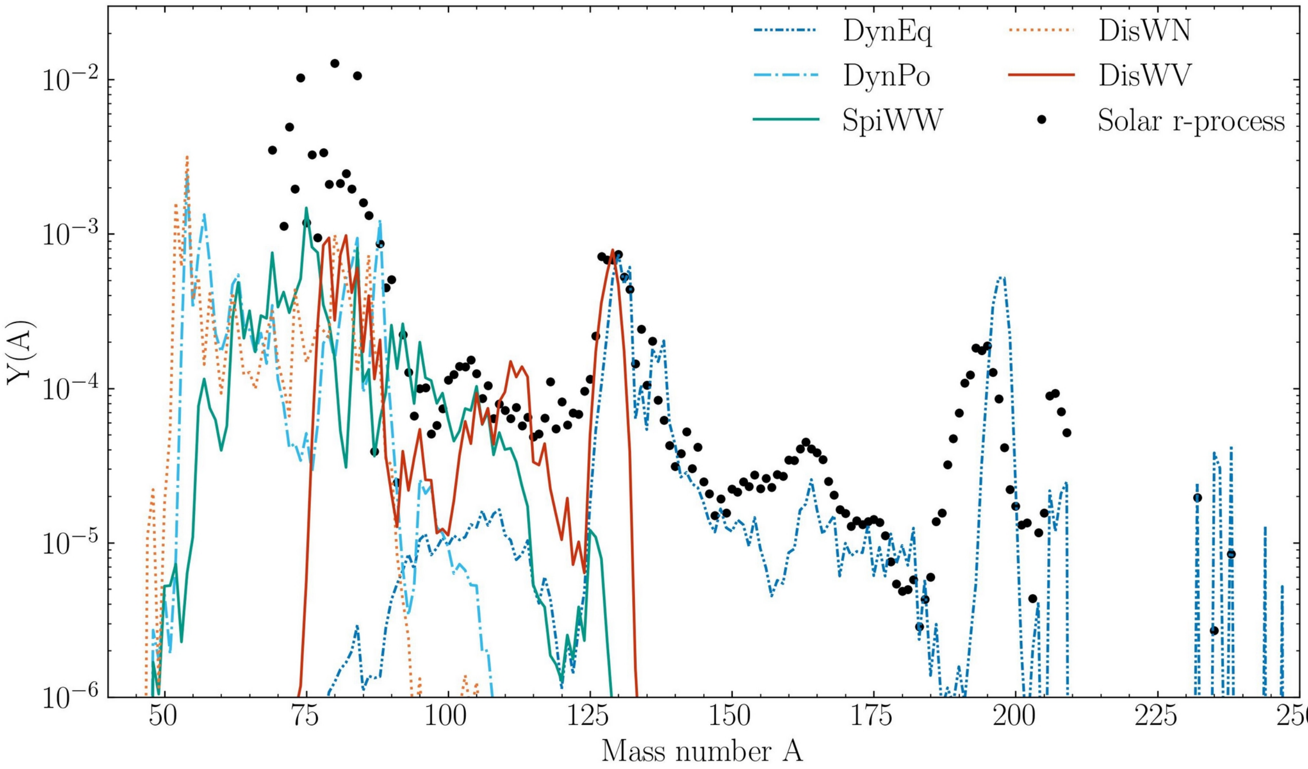
A sensitivity study for the r-process in BNS mergers

- *SkyNet* nuclear reaction network code (Lippuner+17)

- 5 parameterized trajectories representative of different ejecta from a BNS merger:

  1) Dynamical ejecta (polar angle)
  2) Dynamical ejecta (equatorial angle)
  3) Spiral-wave wind ejecta
  4) Neutrino-driven wind ejecta
  5) Viscous-driven wind ejecta

Vescovi+ 22, FrASS



Sensitivity to n-captures of the r-process in BNS mergers

🌟 AIMS

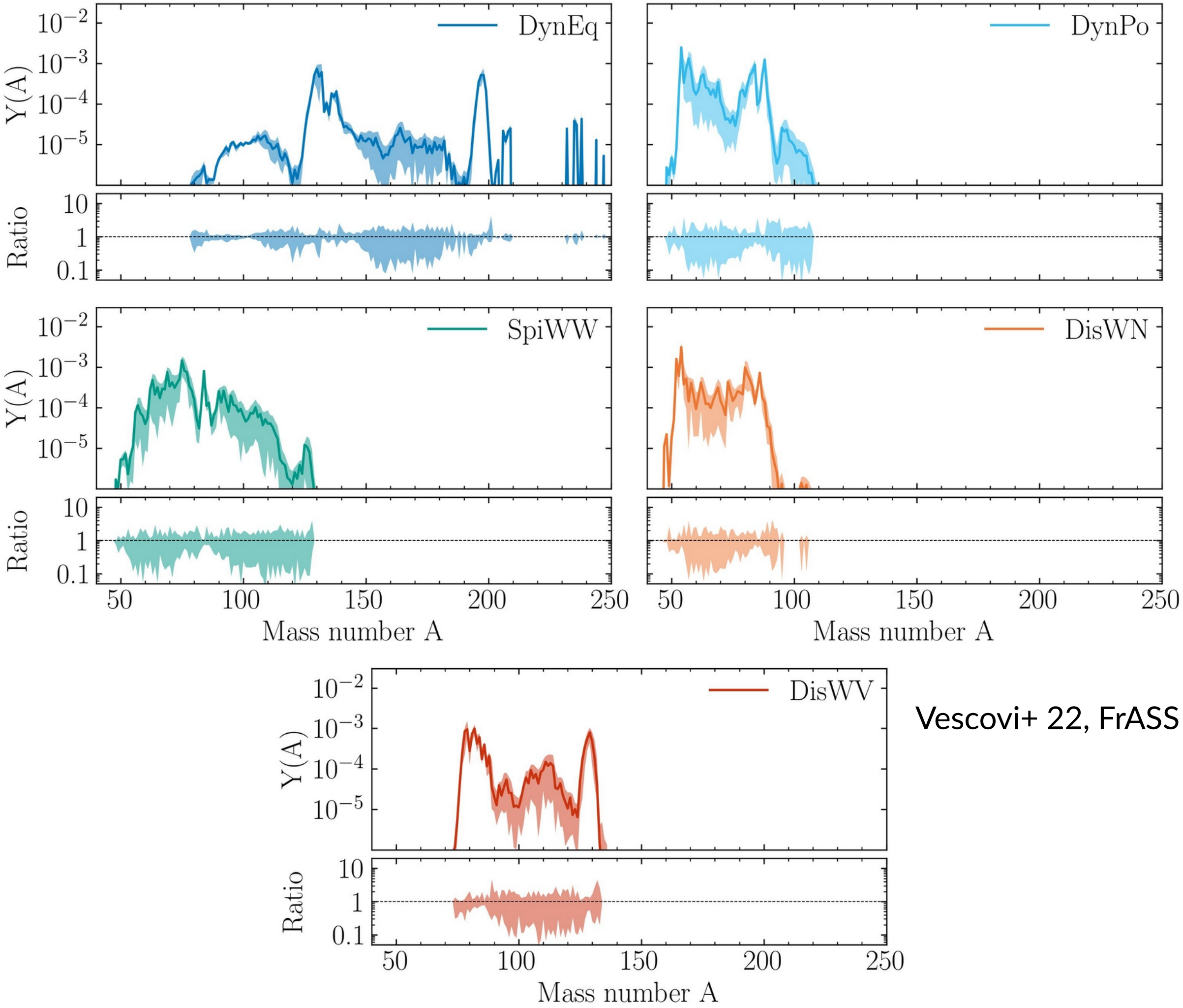
- Identify **key (n,γ) rates** affecting the **final r-process pattern**
- Target rates **accessible to future experiments**
- **Reduce** number of simulations

⚙️ METHOD

- Vary **one (n,γ) rate** → recompute abundances
- **Compare** with baseline simulation
- Scale each rate by **×100 / ÷100**
- Include only nuclei with:
  - **$Y \geq 10^{-10}$**
  - **$T_{1/2} > 1$ s**
  - **$Z \geq 20$** (lighter nuclei negligible, Perego+22)

Sensitivity to n-captures: isotopic abundances

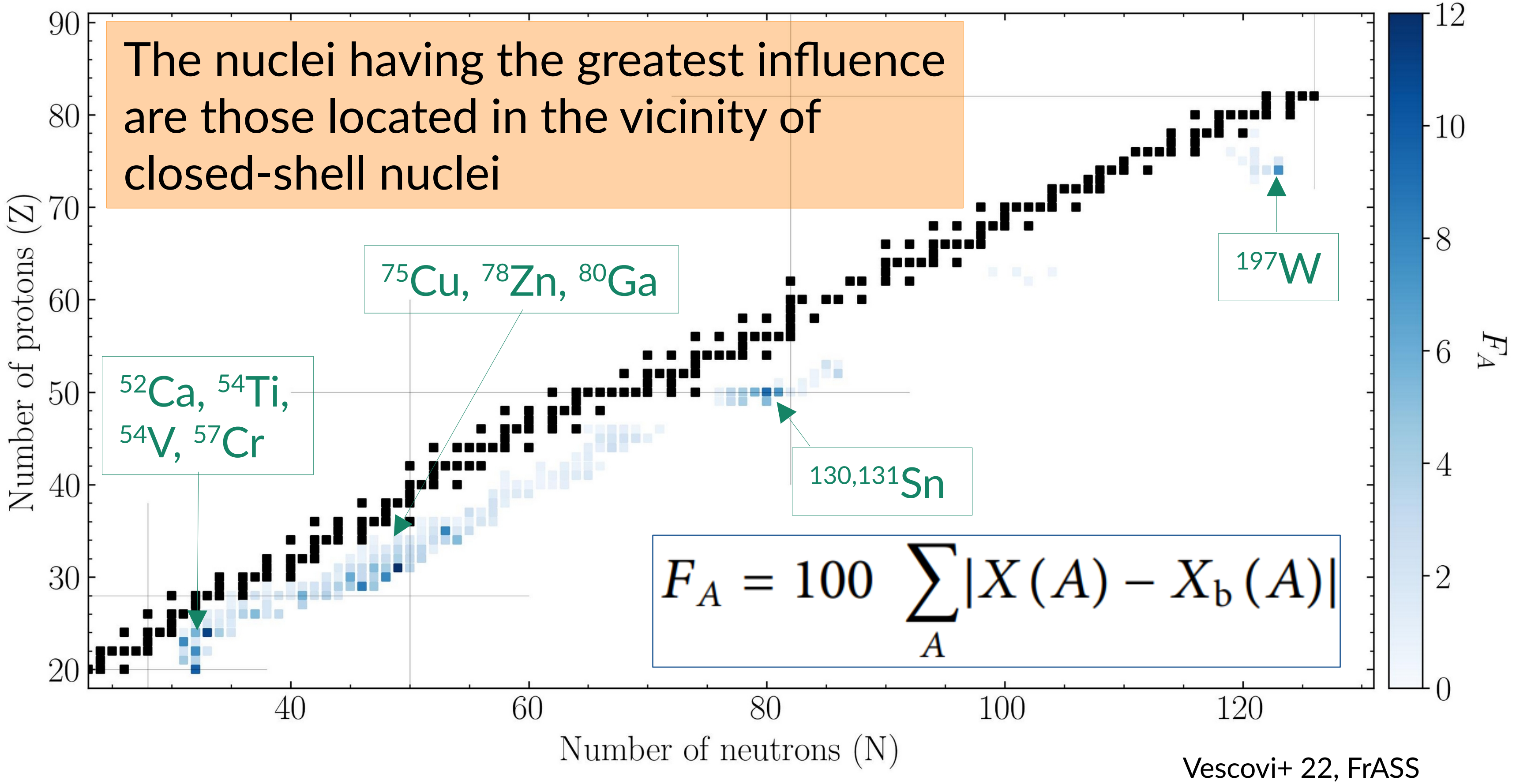
- Neutron capture rates cannot influence the abundance distribution throughout most of the r-process → (n,γ)-(γ,n) equilibrium
- n-captures become important at the freeze-out, when β-decays take over and the r-process path moves toward stability
- Final pattern is affected by both an early-freeze-out photodissociation effect and a late-freeze-out neutron capture effect [Surman+09]
- Variations up to one order of magnitude in the overall abundance pattern



Vescovi+ 22, FrASS

Sensitivity to n-captures: isotopic abundances

- Sensitivity measures estimating the **global chemical changes**



Vescovi+ 22, FrASS

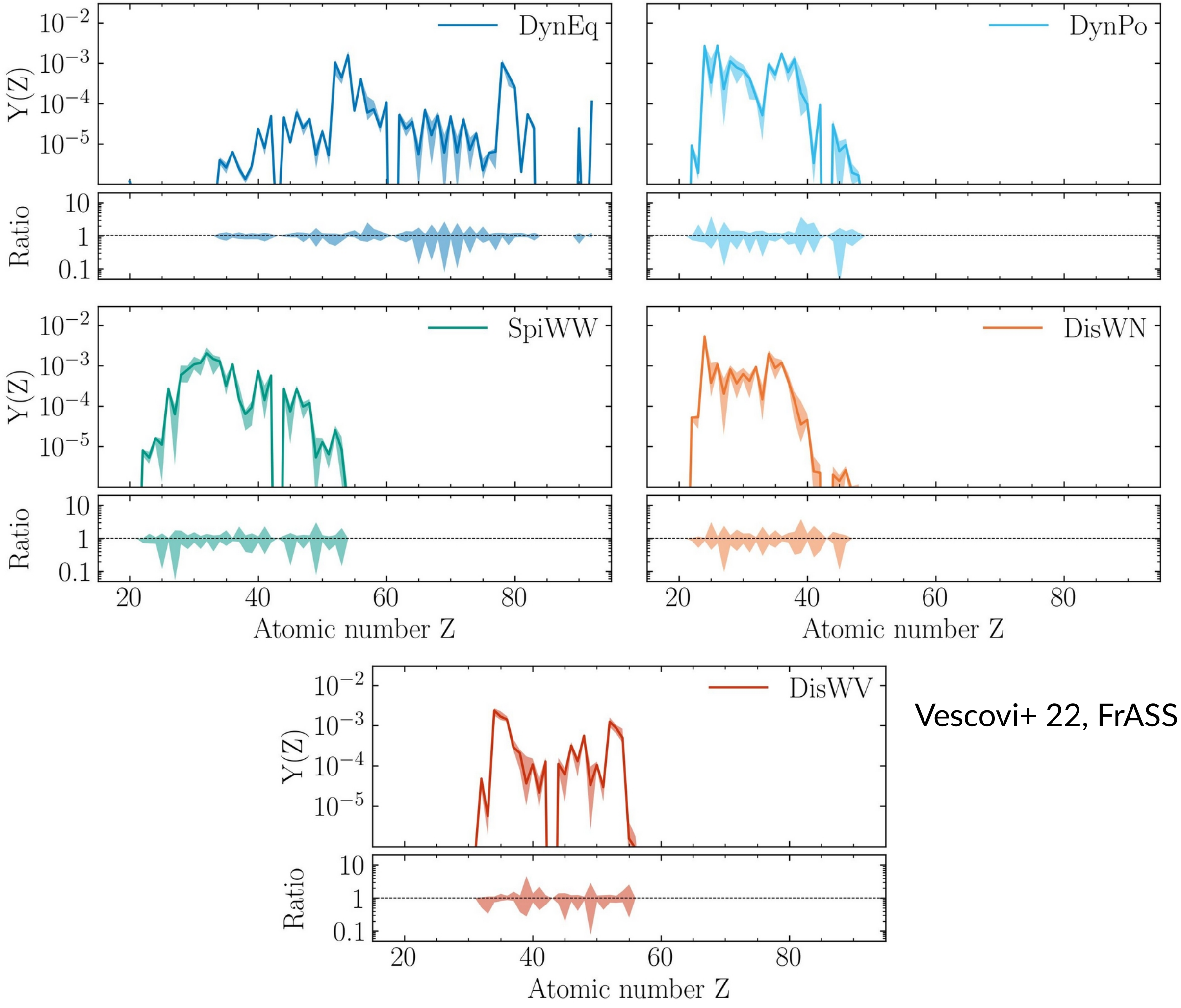
Sensitivity to n-captures: isotopic abundances

- Sensitivity measure estimating the **local isotopic abundance changes** → $F_{Z,A} = 100\,\frac{|Y(Z,A) - Y_b(Z,A)|}{Y_b(Z,A)}$

Z	A	Element	$F_{Z,A}^{max}$	^{A}X	$F_{Z,A}$	^{A}X	$F_{Z,A}$	^{A}X	$F_{Z,A}$	Ejecta
80	201	Hg	181.92	^{200}Ir	171.29	^{200}Os	24.70	^{201}Os	15.54	DynEq
39	89	Y	177.29	^{88}Br	177.29	^{88}Se	106.35	^{89}Br	36.22	DynPo
50	122	Sn	145.15	^{121}Cd	122.07	^{121}In	38.58	^{122}Cd	34.74	DisWV
49	115	In	140.55	^{114}Rh	107.53	^{114}Pd	99.10	^{115}Rh	92.42	DisWV
75	187	Re	138.45	^{186}Lu	111.44	^{187}Lu	51.34	^{186}Ta	47.35	DynEq
69	169	Tm	134.40	^{168}Tb	102.00	^{169}Tb	65.22	^{168}Gd	59.39	DynEq
25	55	Mn	133.15	^{54}V	113.65	^{54}Ti	110.27	^{55}Ti	35.05	DisWN
28	64	Ni	131.61	^{63}Fe	109.64	^{64}Fe	45.75	^{63}Co	32.43	DynPo
26	58	Fe	130.02	^{57}Cr	106.97	^{58}Cr	43.75	^{58}Mn	17.24	DynPo
30	70	Zn	130.01	^{69}Ni	95.19	^{70}Ni	43.38	^{70}Cu	24.47	SpiWW

- 10 most sensitive isotopes, with the top three relative rates having the greatest impact in their production

Sensitivity to n-captures: elemental abundances



- Changes in neutron-capture rates have an impact on **elemental abundances** as well
- Milder variations in the overall abundance pattern

Vescovi+ 22, FrASS

Sensitivity to n-captures: elemental abundances

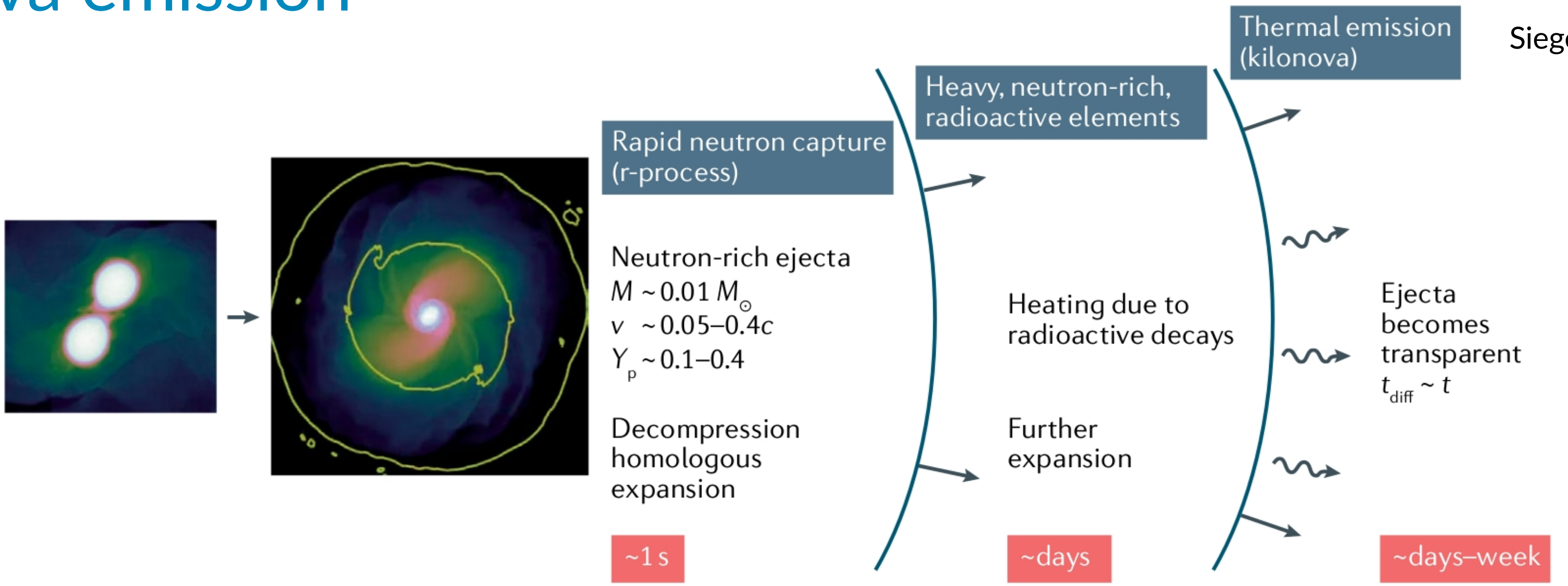
- Sensitivity measure estimating the **local elemental abundance changes** → $F_Z = 100 \dfrac{|Y(Z) - Y_b(Z)|}{Y_b(Z)}$

Z	Element	F_Z^{max}	^AX	F_Z	^AX	F_Z	^AX	F_Z	Ejecta
39	Y	177.29	^{88}Br	177.29	^{88}Se	106.35	^{89}Br	36.22	DynPo
49	In	140.55	^{114}Rh	107.53	^{114}Pd	99.10	^{115}Rh	92.42	DisWV
69	Tm	134.40	^{168}Tb	102.00	^{169}Tb	65.22	^{168}Gd	59.39	DynEq
25	Mn	133.15	^{54}V	113.65	^{54}Ti	110.27	^{55}Ti	35.05	DisWN
27	Co	128.21	^{58}Cr	89.84	^{59}Cr	58.98	^{58}Mn	43.58	DynPo
71	Lu	119.45	^{174}Ho	87.56	^{175}Er	49.12	^{174}Dy	46.23	DynEq
67	Ho	102.26	^{164}Eu	83.18	^{165}Eu	55.94	^{165}Gd	36.18	DynEq
41	Nb	99.96	^{92}Rb	77.88	^{92}Kr	47.73	^{93}Kr	45.61	SpiWW
57	La	95.30	^{138}I	95.30	^{138}Te	41.41	^{139}I	21.66	DynEq
73	Ta	86.21	^{180}Tm	59.38	^{181}Tm	41.54	^{180}Er	37.87	DynEq

- 10 most sensitive elements, with the top three relative rates having the greatest impact in their production

Kilonova emission

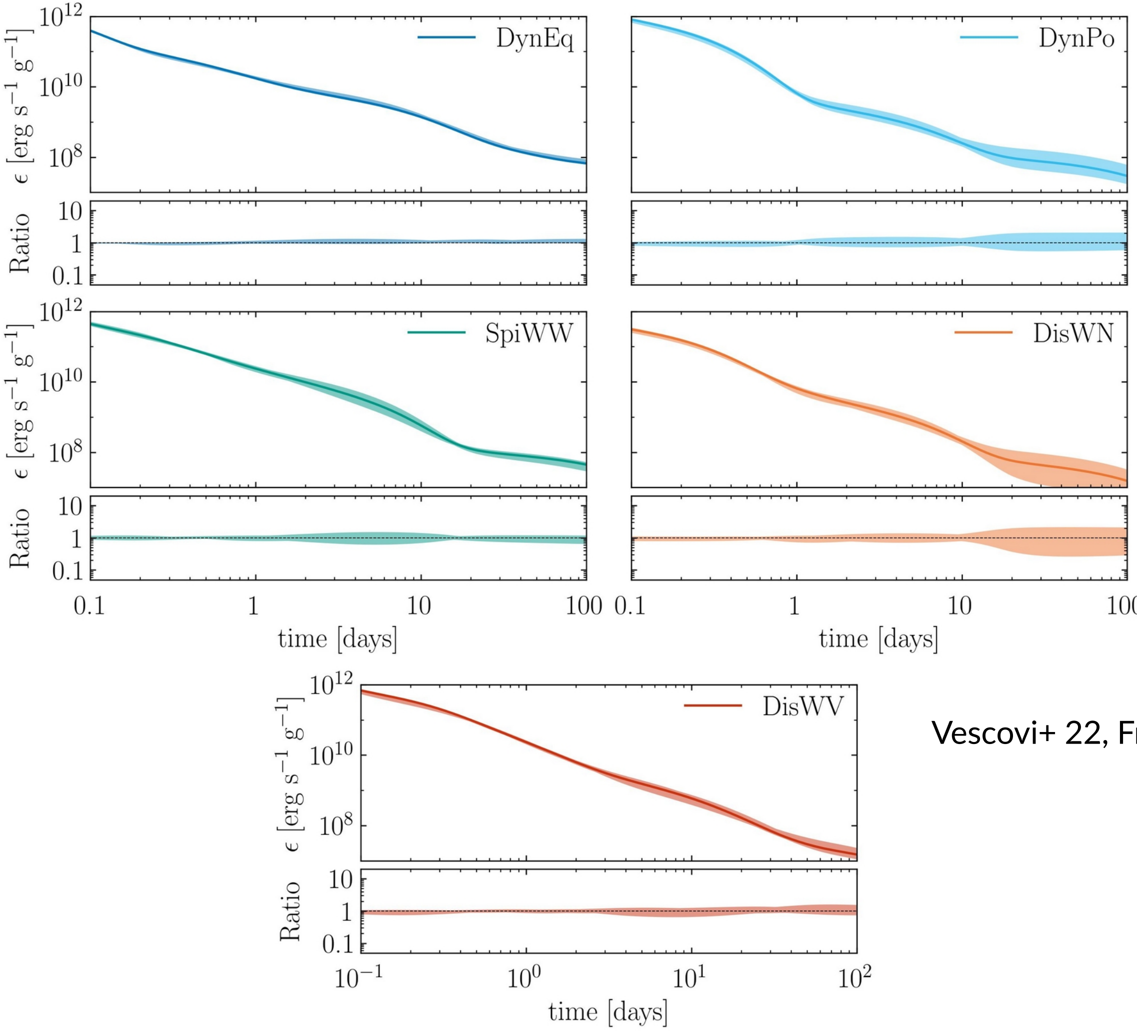
Siegel 22, NatRP



- Radioactive decay of *r*-process elements in ejecta → Release of nuclear energy
- Diffusion and emission of photons at photosphere → **Kilonova**
- Uncertainties from different mass models, fission rates, and fission fragment distribution on the heating rate and kilonova emission have been investigated [Zhu+21, Barnes+21]
- What about individual neutron-capture rates?

Sensitivity to n-captures: radioactive heating rate

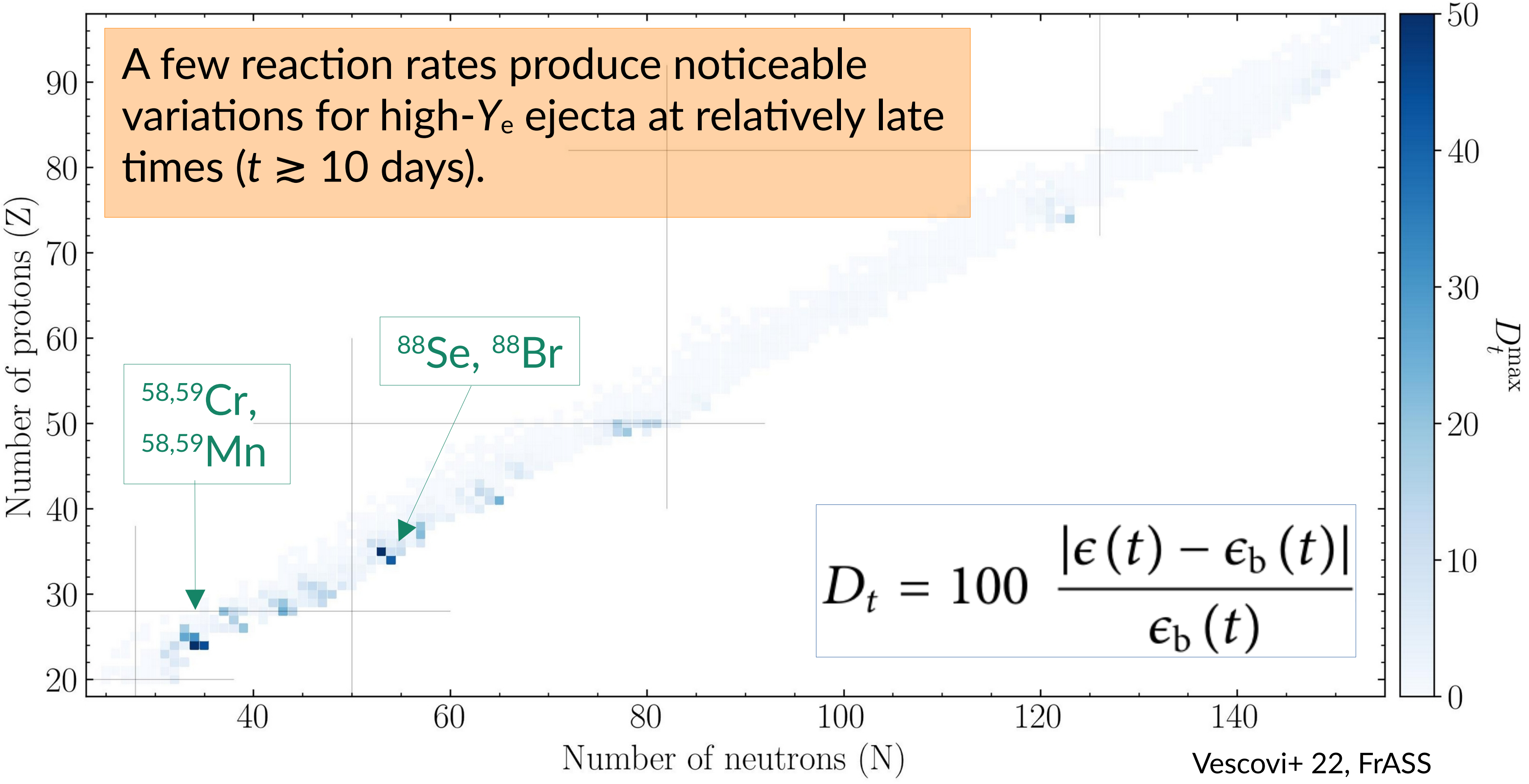
- Neutron-capture rates affects the **heating rate ϵ(*t*)**
- Larger variations for high-Ye ejecta cases
- Those produce a considerable amount of nuclei only in the limited range **50 ≲ A ≲ 90**
- Few isotopes have half-lives of 10–100 days may produce marked features in bolometric kilonova lightcurves [Wu+19]



Vescovi+ 22, FrASS

Sensitivity to n-captures: radioactive heating rate

- Sensitivity measure to describe the variations in the **nuclear heating rate ϵ(*t*)**
- t = 0.1, 1, 10, 100 days



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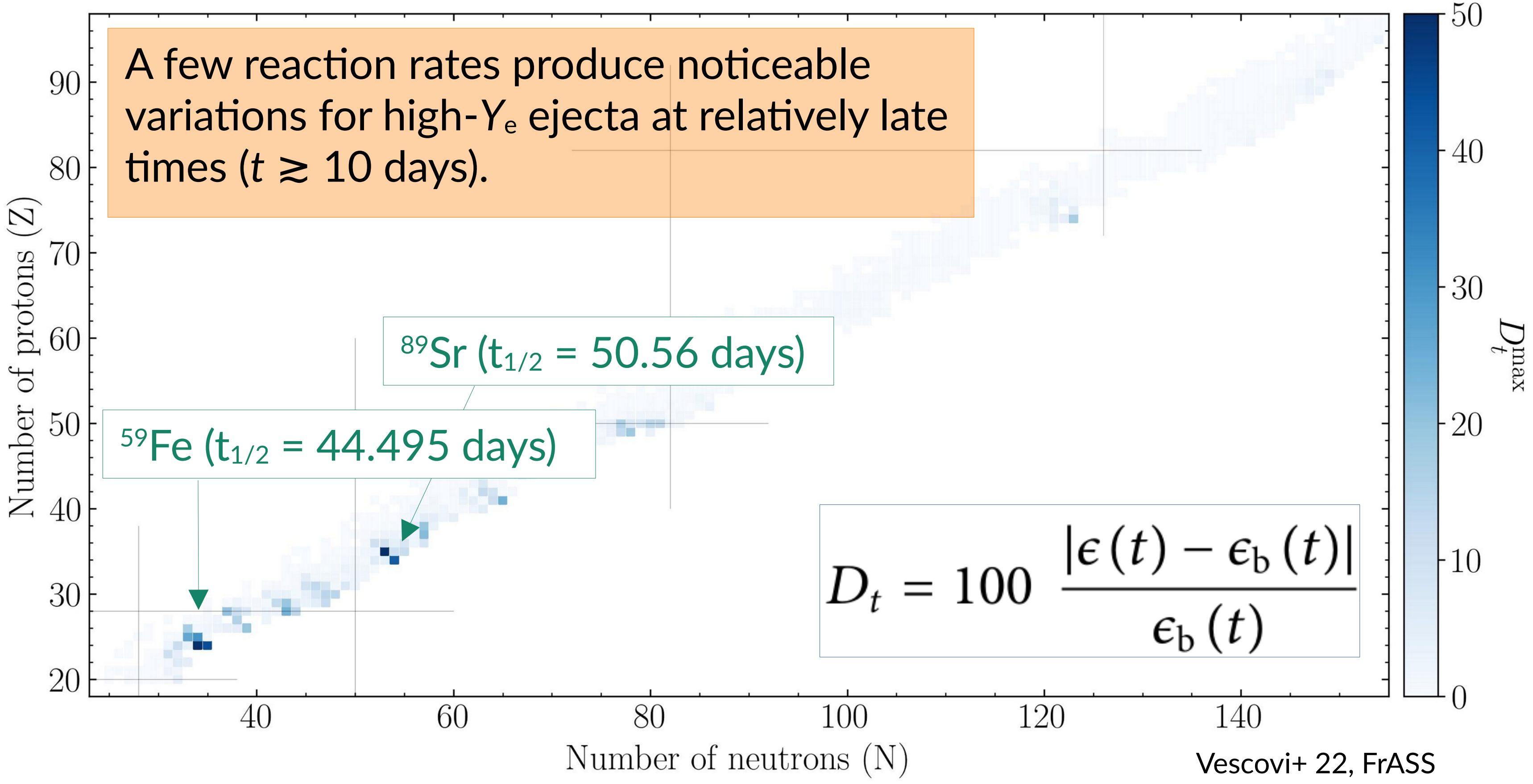
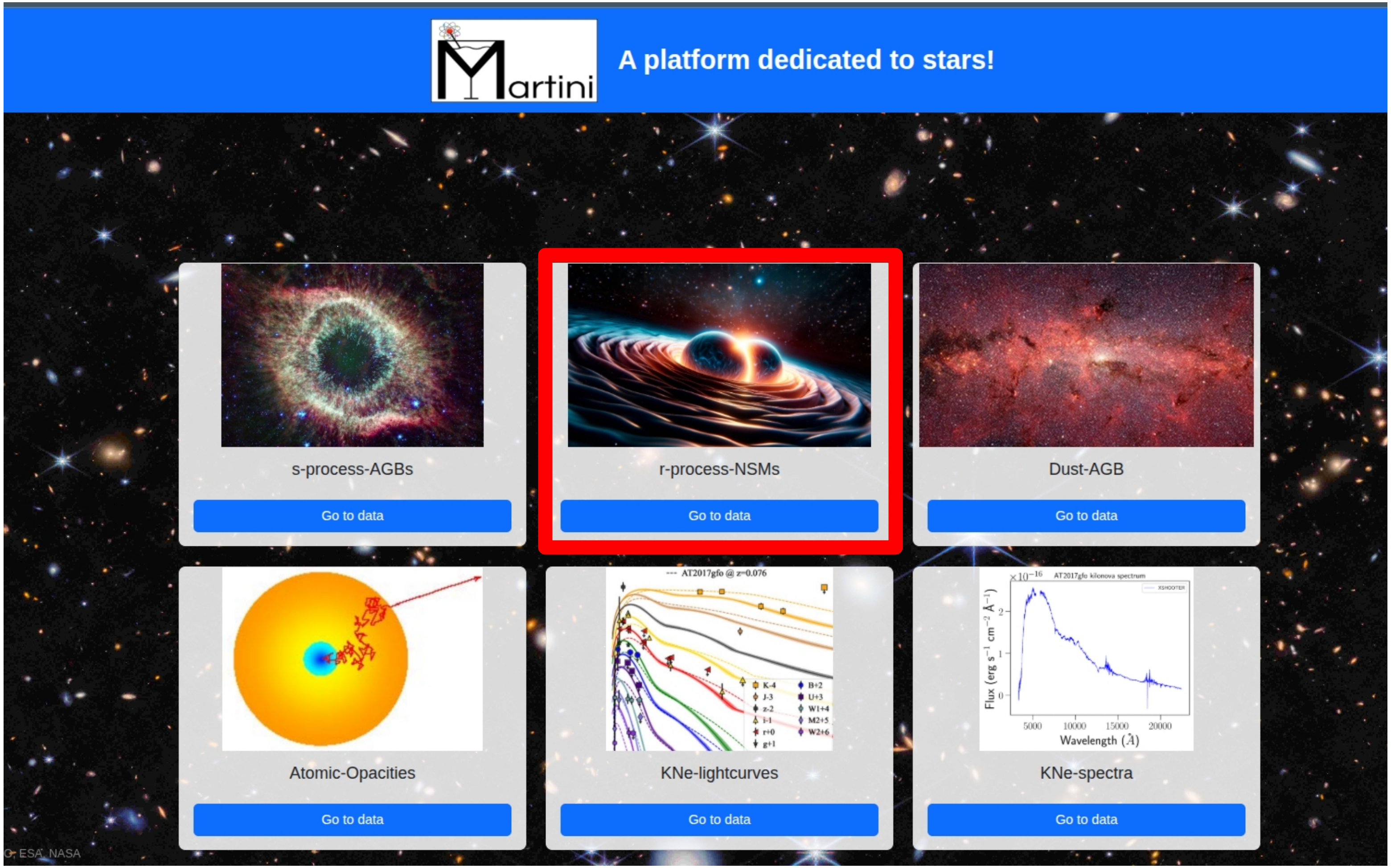


Vescovi+ 22, FrASS

MARTINI: a database for nuclear astrophysicists

Visit → https://martini.oa-abruzzo.inaf.it/



Tracing r-process nucleosynthesis in BNS mergers

🌟 AIMS

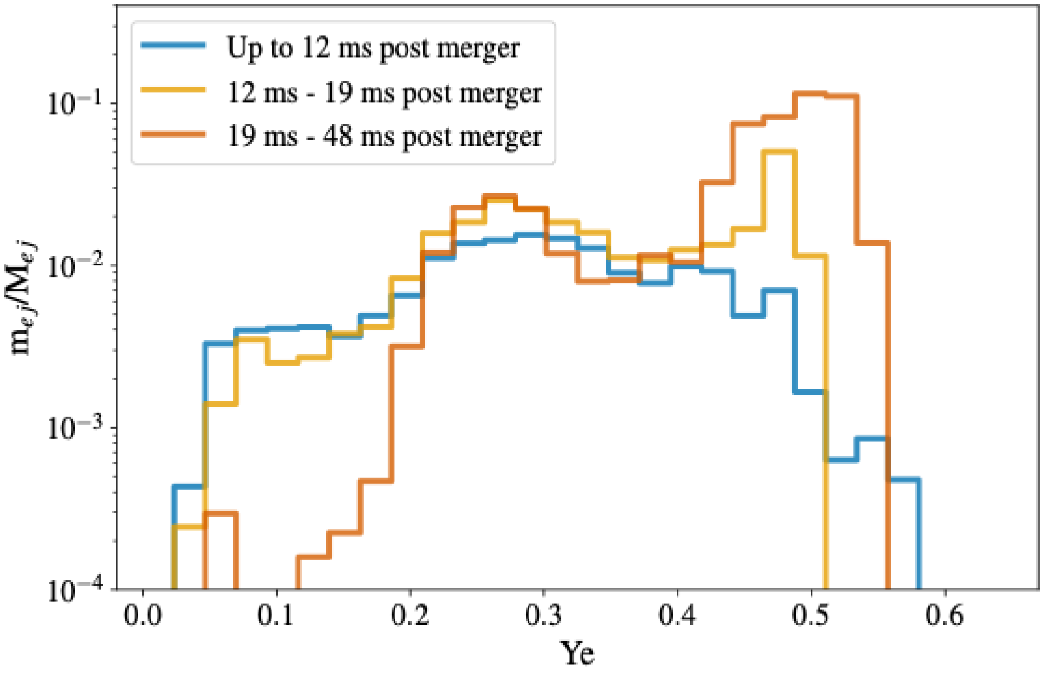
- Investigate impact of neutrino winds on the nucleosynthesis
- Produce publicly available database of r-process yields varying BNS mass ratio and EOS

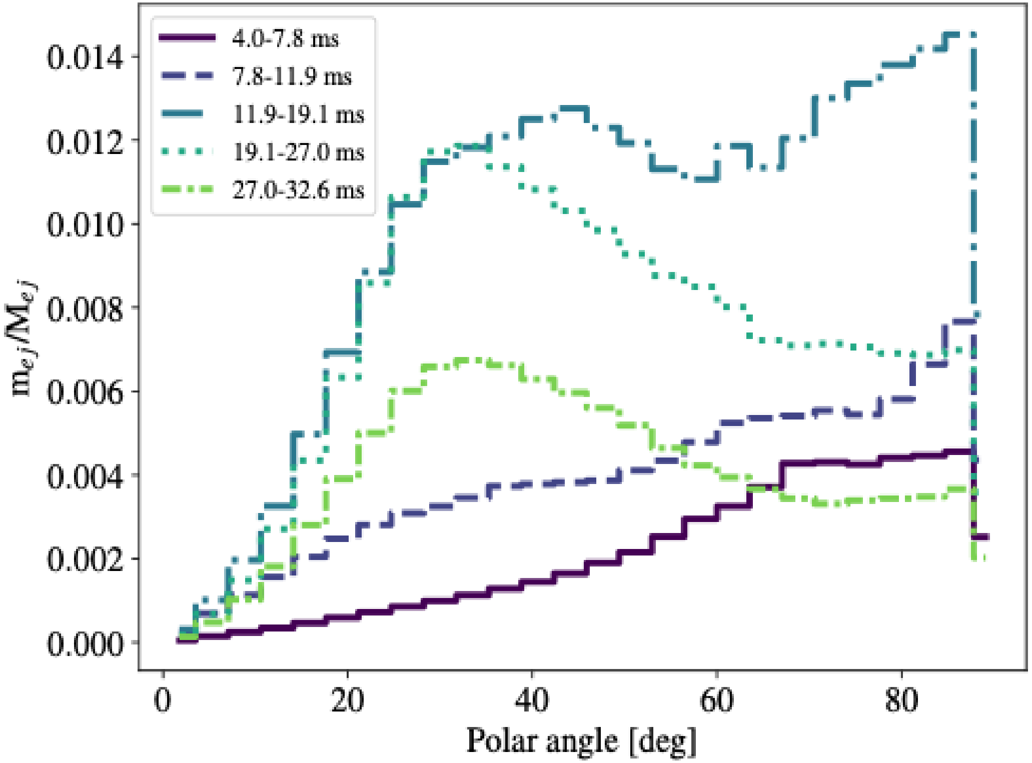
⚙️ METHOD

- Set of 8 BNS merger simulations with different masses, EOSs and mass ratios
- Neutrino treatment: M1 gray scheme [Radice+22]
- Extract tracer particles for ejecta and assign mass accordingly
- Compute nucleosynthesis with *WinNet* [Reichert+23]

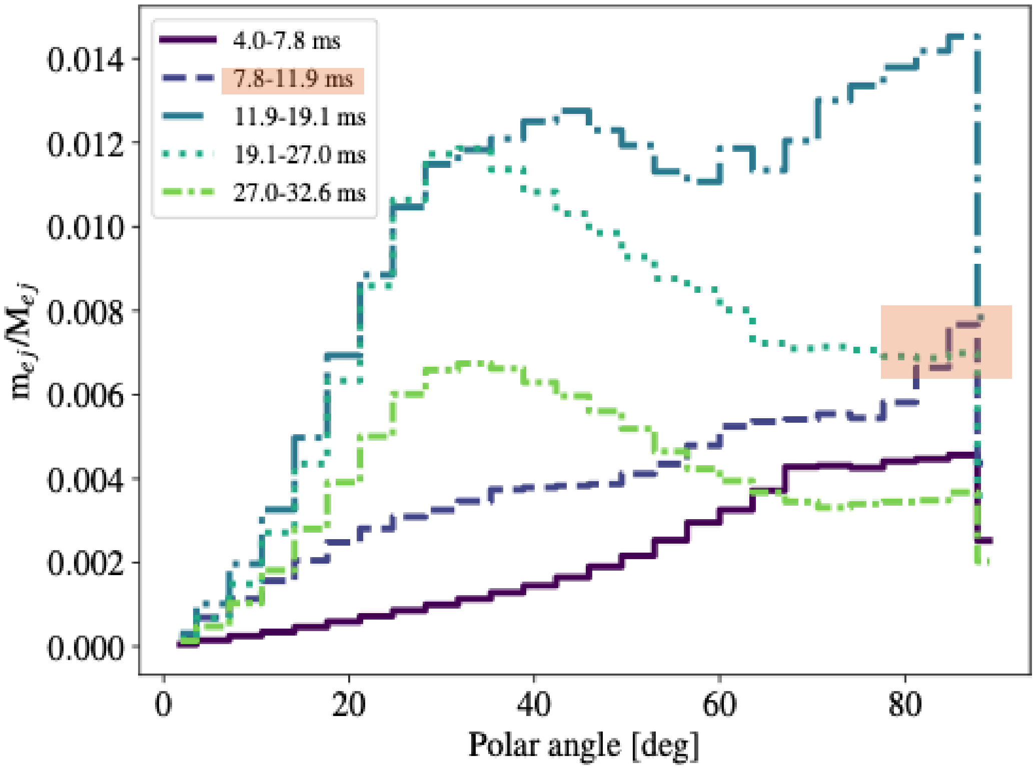
Ejecta analysis: Y_e and angular distribution

Credit: E. Loffredo



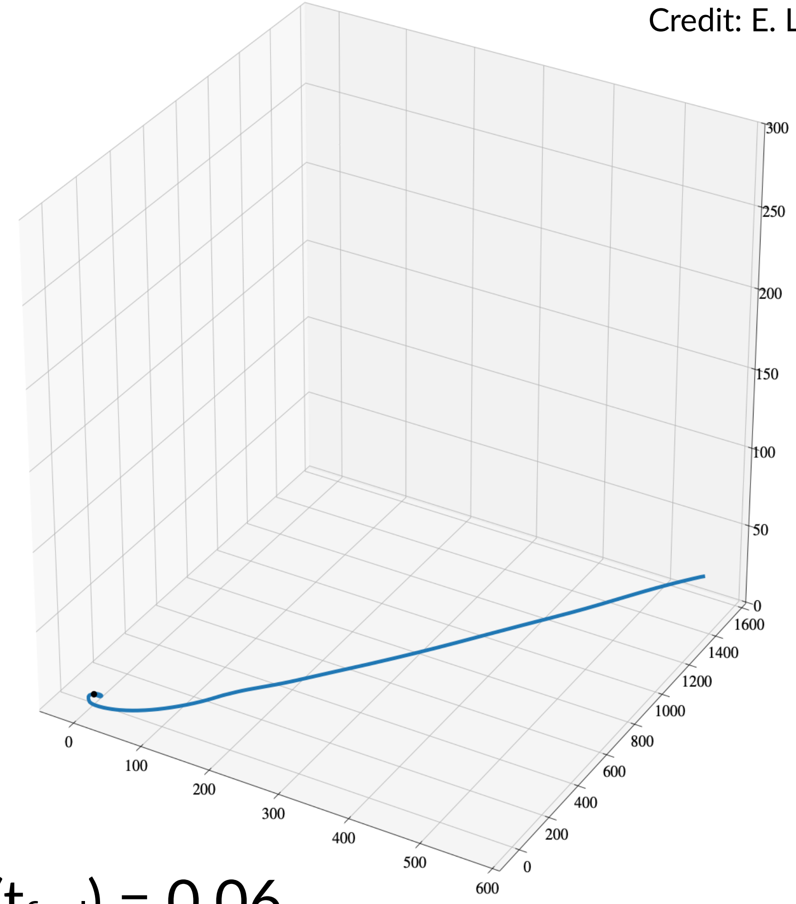


Ejecta analysis: Y_e and angular distribution



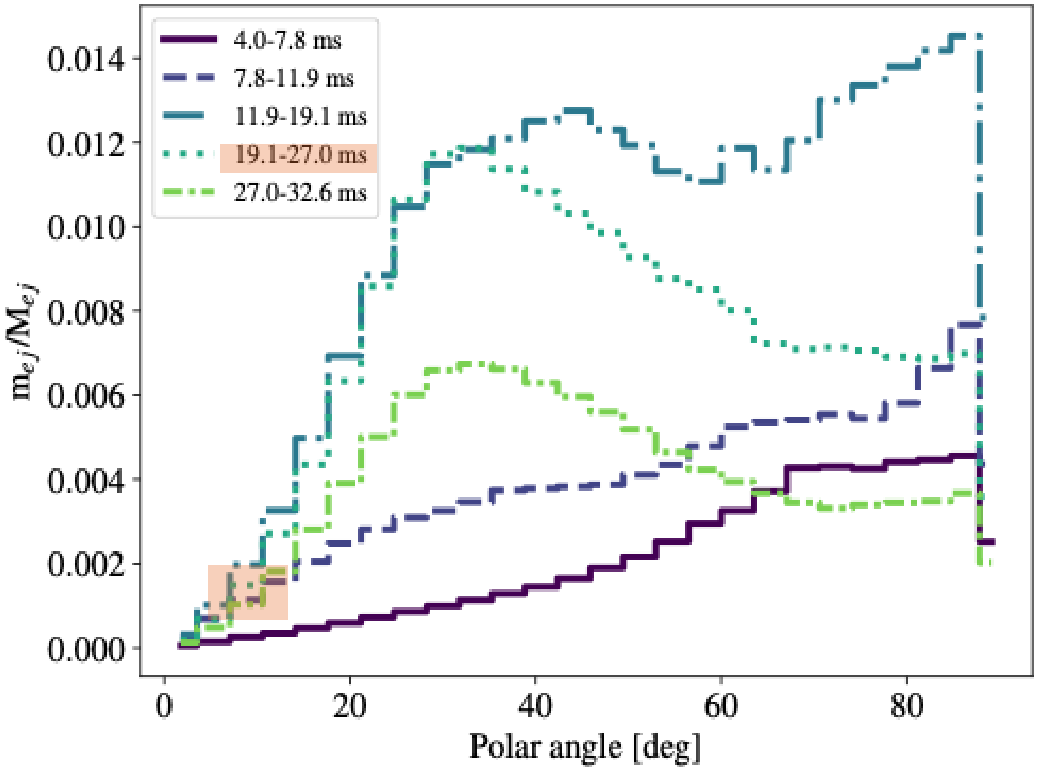
Y_e (t_{merger}) = 0.10

Credit: E. Loffredo



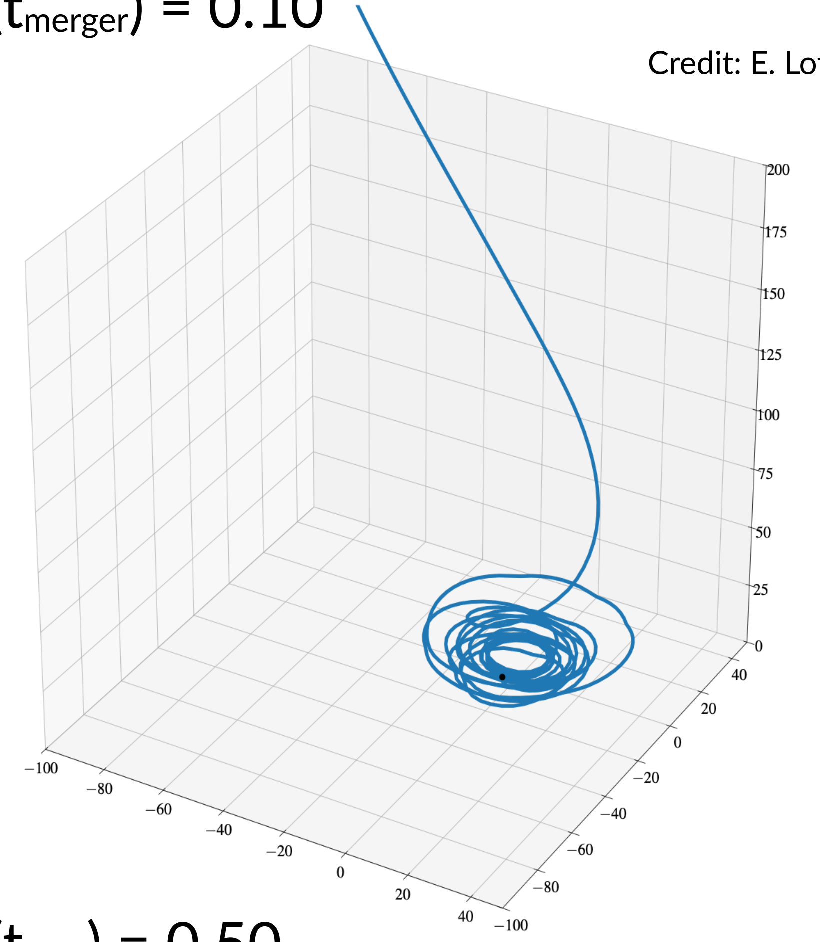
Y_e (t_{final}) = 0.06

Ejecta analysis: Y_e and angular distribution



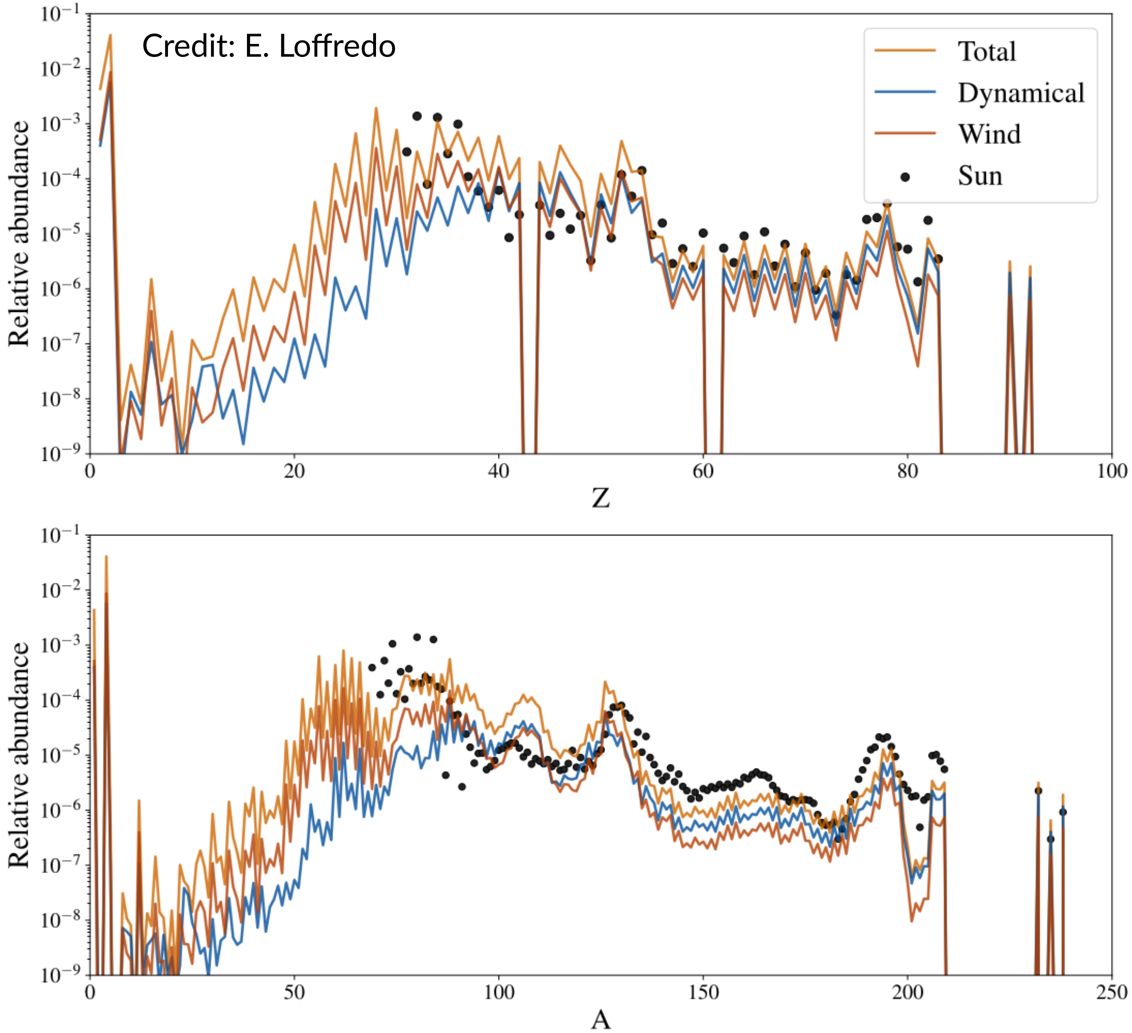
Y_e (t_{merger}) = 0.10

Credit: E. Loffredo



Y_e (t_{final}) = 0.50

Ejecta analysis: final abundance distribution



- <u>Dynamical ejecta</u>

  → Production of elements in 2nd and 3rd peak

- <u>Neutrino wind</u>

  → Production of lighter elements

- **Iron group elements** among the most abundant irrespective of the EOS

➔ Nuclear input physics?

➔ Asymmetric mass ratios?