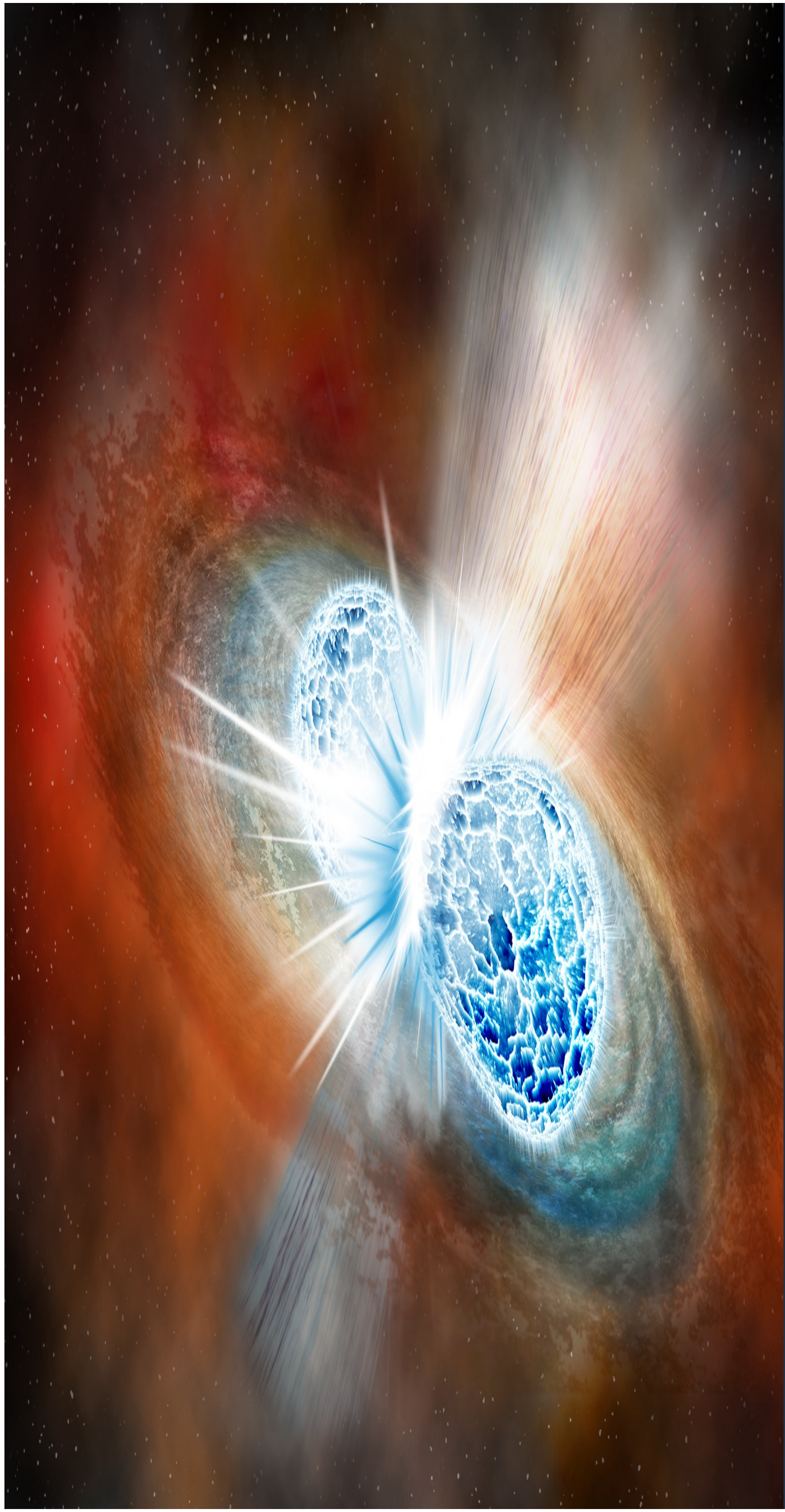
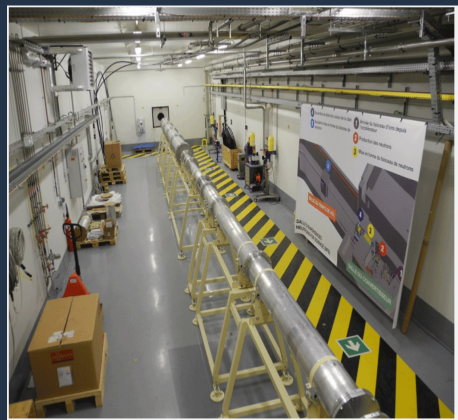
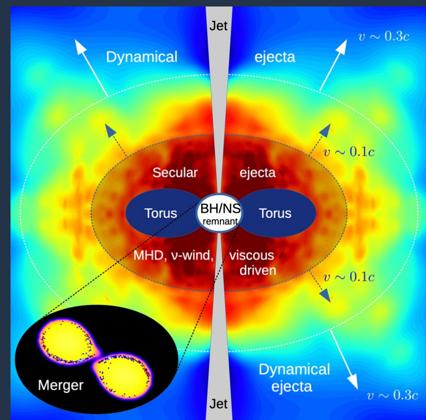


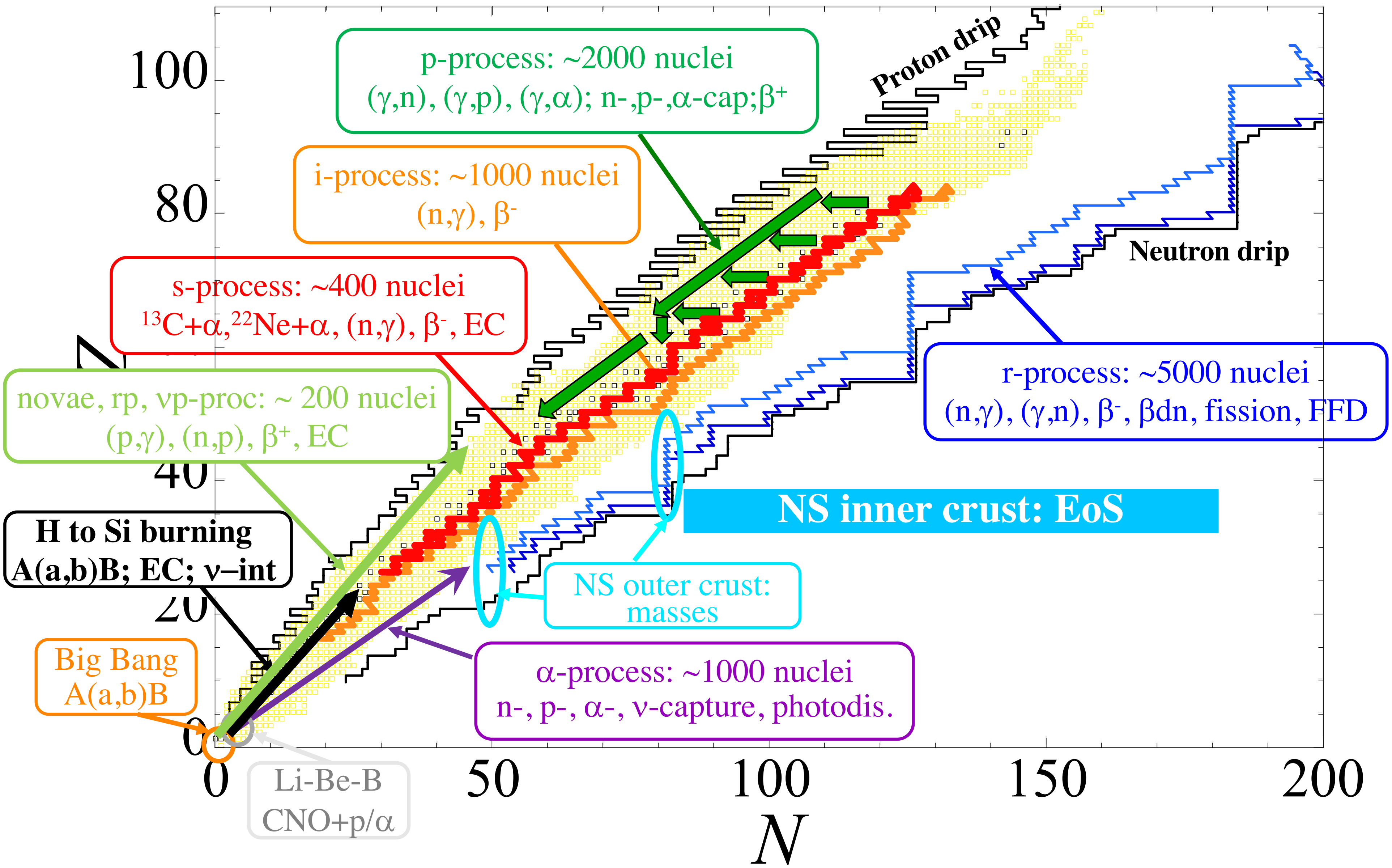
From Data to Theory, to Astrophysical applications



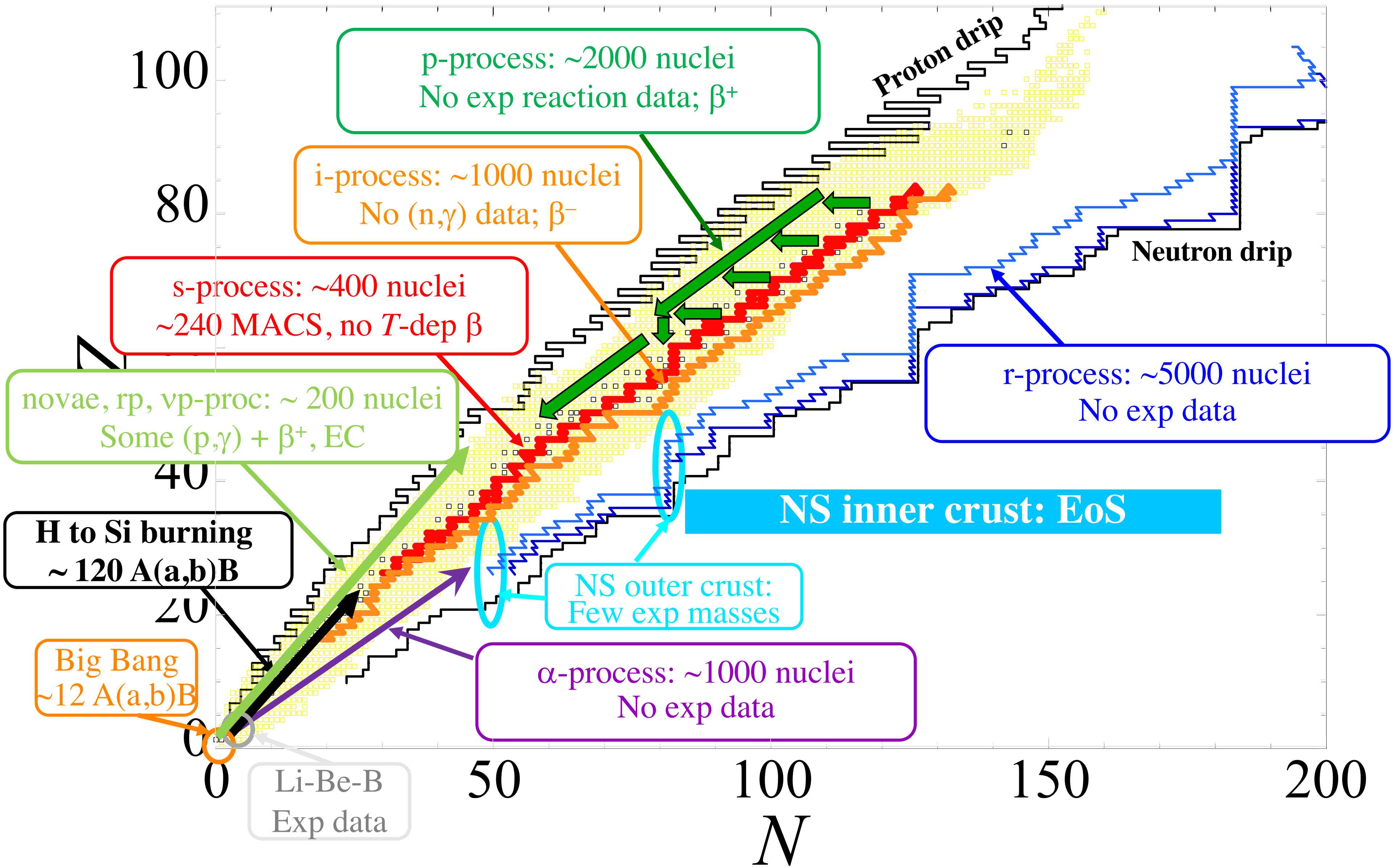


S. Goriely (IAA-ULB)

Nuclear Astrophysics: a field with high NP demands



Nuclear Astrophysics: a field with high NP demands



Relatively limited amount of direct experimental data → Theory needs to fill the gaps

BUT

Astrophysics needs for nuclear data are defined by the sensitivity of the astrophysics predictions to nuclear inputs

Different types of astrophysical models

+ + – State of the art: 3D (~ self-consistent) models

p-process in SNIa explosions, r-process in NSM

+ – Realistic 1D (~ self-consistent) models

s-process in Massive Stars

– Parametrized (semi-realistic) 1D models

s-process in AGB Stars

– – Parametrized (unrealistic) 1D models

r-process in ν-driven wind of SNII

– – – Phenomenological parametrized site-independent models

One-zone s-, i-, r-, or rp-processes

Obvious need for accurate and reliable nuclear data, …

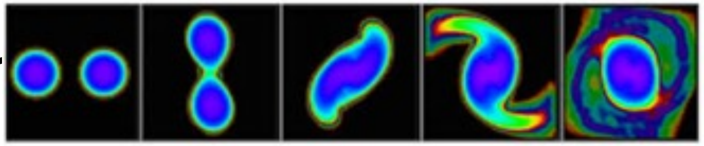
but

the uncertainties in the astrophysics models most of the time prevail

(even the 3D simulations are far from being free from astrophysical uncertainties)

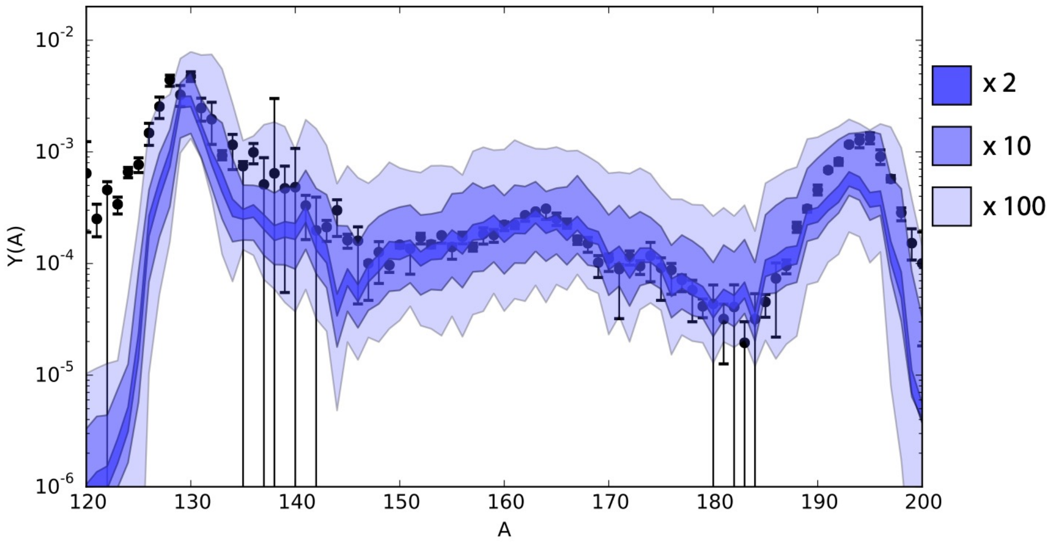
-- Not obvious to determine the sensitivity to Nuclear Physics --

And how to propagate NP uncertainties into astrophysics simulations ??



Uncorrelated MC approach

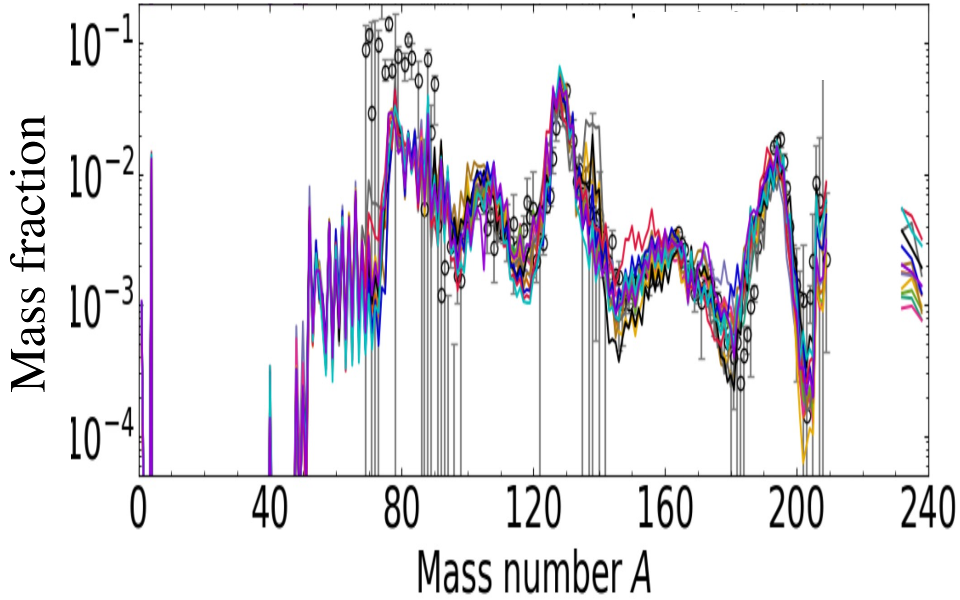
Mumpower et al. (2016); Nikas et al. (2020)



- Rates within an arbitray factor of 2, 10, 100
- Neglects correlations between uncertainties
- Overestimates impact

Model-correlated approach

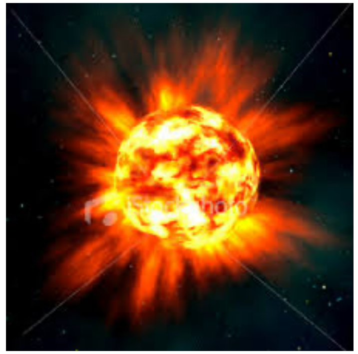
Sprouse et al. (2020); Kullmann et al. (2022)



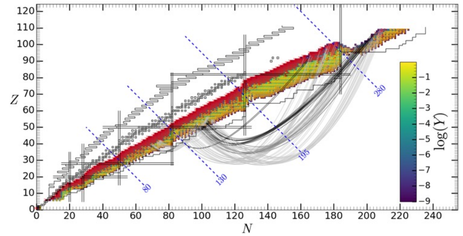
- Coherent model-correlated uncertainties
- Only statistical or systematic uncertainties
- Overestimates impact if not exp-constrained

In all cases, propagation must be applied to a statistically representative sample of astrophysical conditions

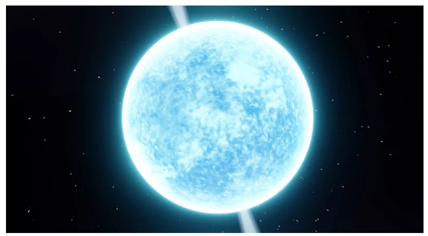
Some specificities of the astrophysical plasma



- Energy region of "almost no event" for charged-particle reactions:
  - low cross sections unreachable experimentally
- Unstable species involved:
  - limited experimental data are available
- Exotic species involved:
  - n-rich and n-deficient nuclei out of reach from experiment
- Large number of properties and nuclei involved
  - thousands of nuclei involved, tens of properties



- High-*T* environments:
  - thermalization effects of excited states by electron and photon interaction → Impact on reaction rates, β-decays
  - ionization effects → Impact on β-decays (bound state β-decay, continuum-$e^{-/+}$ capture) & reaction rates (e^-- screening effects)
- High-ρ environments (supernovae, neutron stars):
  nuclear binding understood in terms of a nuclear EoS



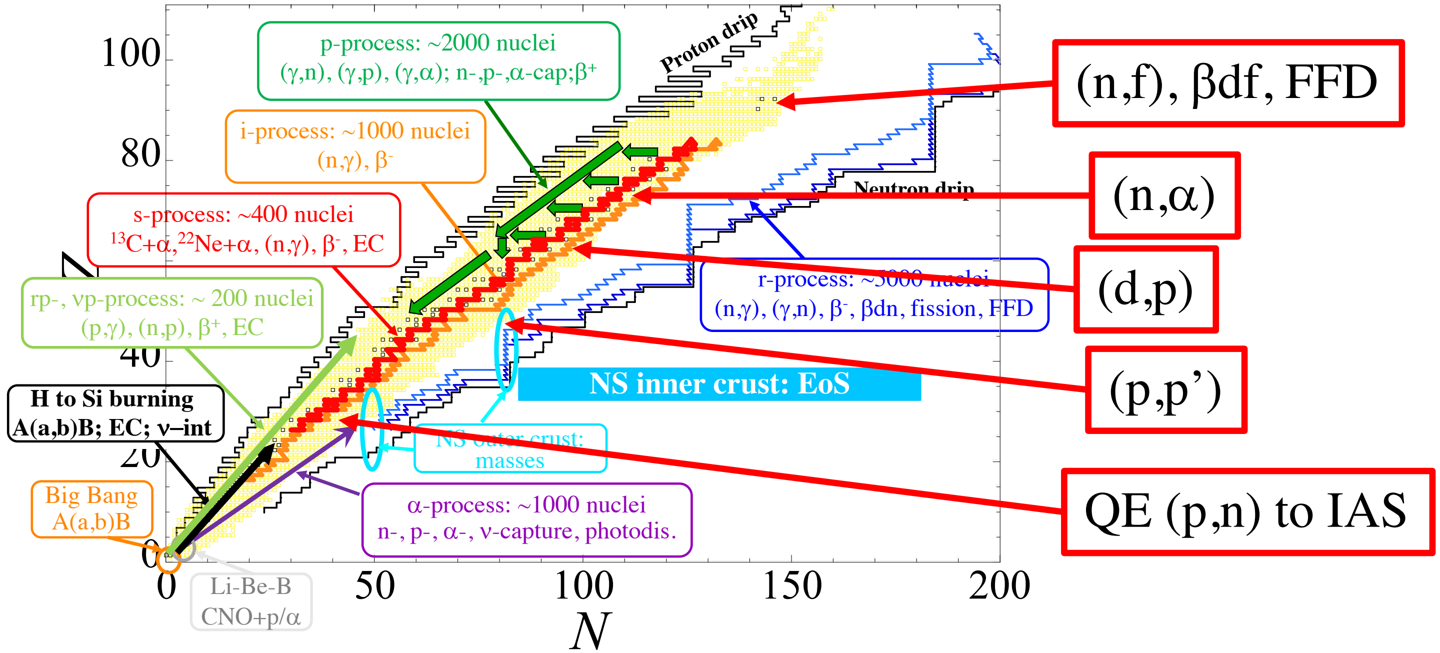
→ Use of theory is unavoidable

Still many open questions associated with predictions

- **Reaction model**
  - CN vs Pre-eq vs Direct capture & Isolated Resonance
- **Nuclear inputs to the reaction model**
  - GS properties: correlations (beyond MF), odd-*A*, triaxility
  - Fission: 3D fission paths, NLD at the saddle points, FFD
  - E1/M1-strength functions: PR, ε_γ=0 limit, *T*-dep, PC, J^π-dep
  - Nuclear level Densities: low-*E*, correlations, pairing, vib-rot
  - Optical potential: low-*E* isovector imaginary component, α-OMP
- **β-decay model (including βdn and βdf)**
  - Forbidden transitions, deformation effects, odd-Z/N, PC

We are still far from being able to estimate ***reliably***
the many reactions of astrophysical relevance, in particular
n-capture, β-decay, and even less, fission of exotic n-rich nuclei

What needs to be measured for astrophysics ?



Many Nuclear Physics needs but

- Not all is “crucial” for Astrophysics
- Many are unreachable (e.g. fission at the dripline)
- Astrophysical models evolve and are not necessary robust (what is important today may not be next year)
- May not have a direct, but rather an indirect impact

Challenges in experimental nuclear astrophysics

Three important components in experimental nuclear astrophysics

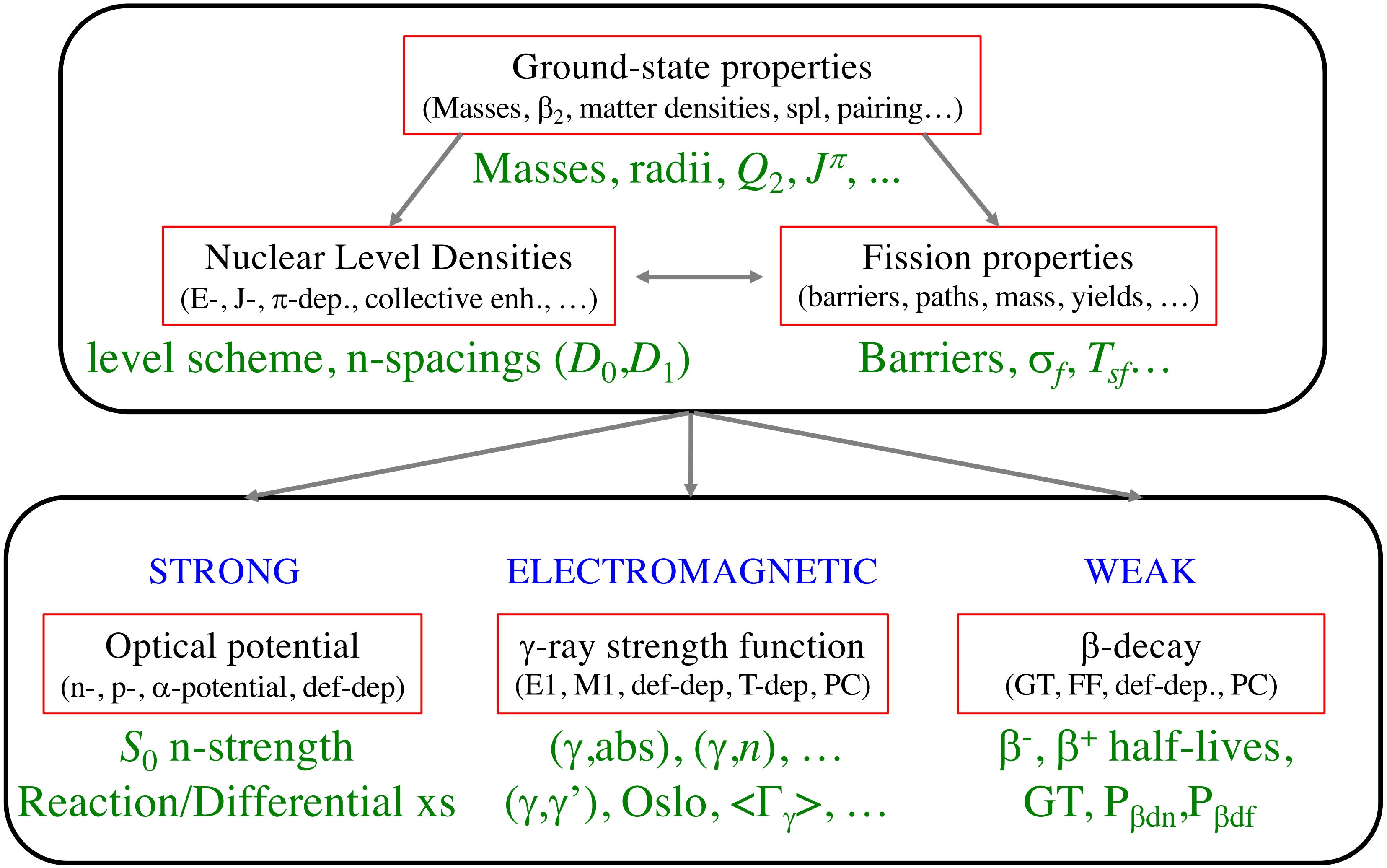
1) Cross section measurement with a direct impact for a given well-defined astrophysical scenario:

- stellar evolution:
  - hydrostatic burning (H-, He-, C-burning): 3α, $^{12}C(\alpha,\gamma)^{16}O$, $^{12}C+^{12}C$
  - explosive burning (SNIa): α-chains on ^{12}C and ^{14}C
- neutron source/poison for nucleosynthesis: $^{22}Ne(\alpha,n)^{25}Mg$ / $^{17}O(\alpha,\gamma)^{21}Ne$
- *s*/*i*-process nucleosynthesis: (n,γ) cross sections and *T*-dep β-decays
- more ... ??

Relatively rare and difficult cases left over
(the "easy/feasible" cases have been done)

2) Measurement of given properties for *a large set of nuclei*:

Need for a regularly-updated library of evaluated input parameters:
Fundamental for accurate cross section (and rate) calculations and extrapolations



3) Some specific measurements to bring new insights on a given physical property (or parametrization) that could have a significant impact on models/extrapolations

For example,

- Specific nuclear structure properties

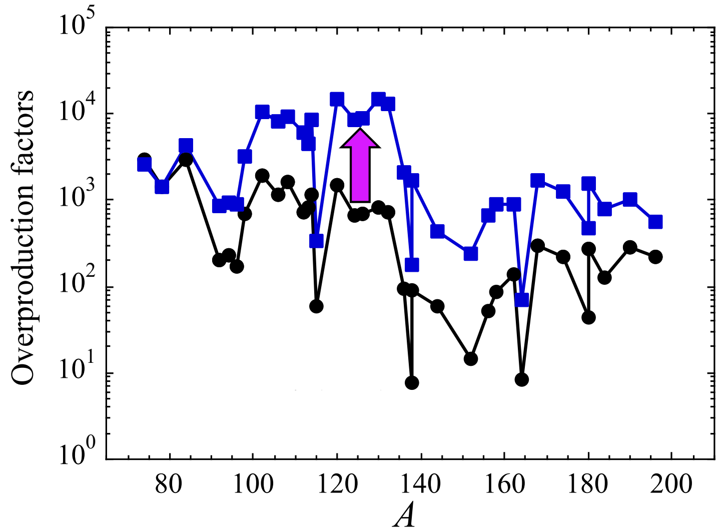
  e.g neutron skin, N=82 or 126 shell effects in n-rich region
- Dipole strength at low energies (pygmy resonance, ε_γ=0 limit)
- Nuclear Level Densities at fission saddle points
- Imaginary component of the neutron optical potential for n-rich nuclei
- α-optical potential far below the Coulomb barrier
- Pre-equilibrium contribution to the reaction for n-rich nuclei
- Etc...

Any property that can *potentially* have a global impact on the reaction or decay rates, hence *potentially* on the astrophysical observables …

From Data to Astrophysical Applications

Direct measurement
(e.g. xs, β-half-life)

Impact of a factor of 10 reduction of
$^{17}O(\alpha,\gamma)^{21}Ne$ on p-process



Application to astrophysics
with uncertainty propagation

From Data to Theory to Astrophysical Applications

Direct observables
(e.g. xs, β-half-life)

Compilation/Evaluation
(e.g. EXFOR / KADONIS / NUBASE)

Theoretical comparison (individual/global)
(e.g. TALYS for xs; QRPA for β-decay)

Indirect observables
(e.g. Mass, D_0, PSF, ...)

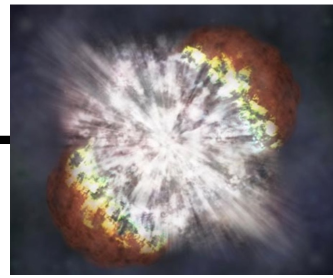
Compilation/Evaluation
(e.g. AME / RIPL-3 / PSF Library)

Theoretical comparison (individual/global)
(e.g. HFB masses, QRPA PSF, ...)

if accurate & reliable

Calculation of stellar rates
(e.g. TALYS for MACS)

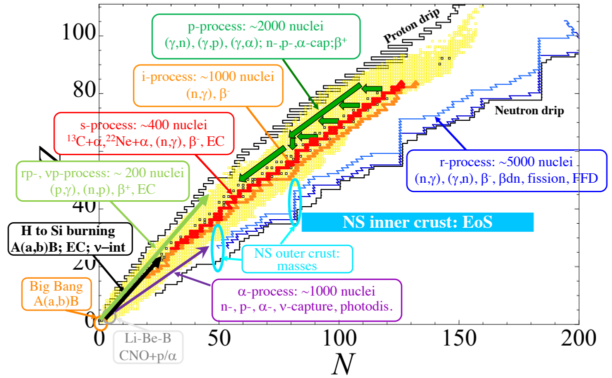
Application to astrophysics
with uncertainty propagation

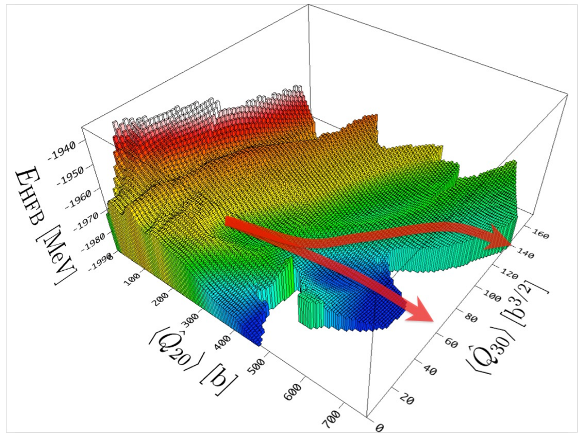


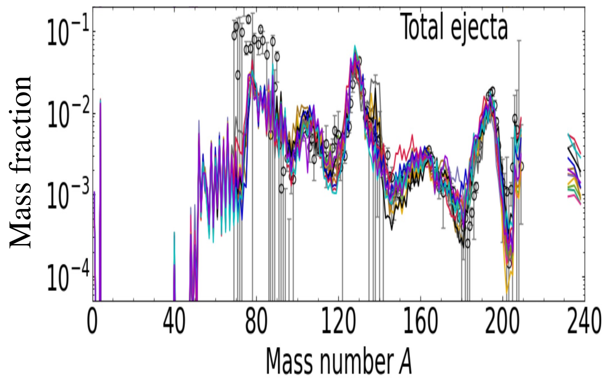
Conclusion: Progess in Nuclear Astrophysics

Despite impressive progress for the last years,
Nuclear Astrophysics still requires

- **Dedicated experimental work** on key reactions (^{12}C+α, ^{12}C+^{12}C, ^{22}Ne+α, ^{17}O+α, ...), key properties (M, R_c, B_f, NLD, PSF, OMP, ...) for stable as well as unstable nuclei
  - specific reactions for well-defined astrophysics scenarios
  - gross properties for a large set of nuclei
  - key properties from specific experiments
- **Dedicated theoretical work** based on as "microscopic" as possible models for experimentally unavailable nuclei
  (mean-field, shell model, ab-initio)
- **Detailed account of uncertainties** that need to be properly propagated into astrophysical observables.







THANK YOU
FOR
YOUR ATTENTION