Nuclear challenges for astrophysics applications

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- Nuclear needs for astrophysics calculations
  - Nuclear versus Astrophysics modelling in nuclear astrophysics applications
- Experimental and theoretical nuclear challenges for an improved determination of reaction rates
  - with some illustrations: nuclear structure, NLD, Fission

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

Different types of astrophysics models

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

p-process in SNIa explosions

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

p- and s-processes in Massive Stars

– Parametrized (semi-realistic) 1D models

s-process in AGB Stars, r-process in NSM

– – Parametrized (unrealistic) 1D models

r-process in ν-driven wind

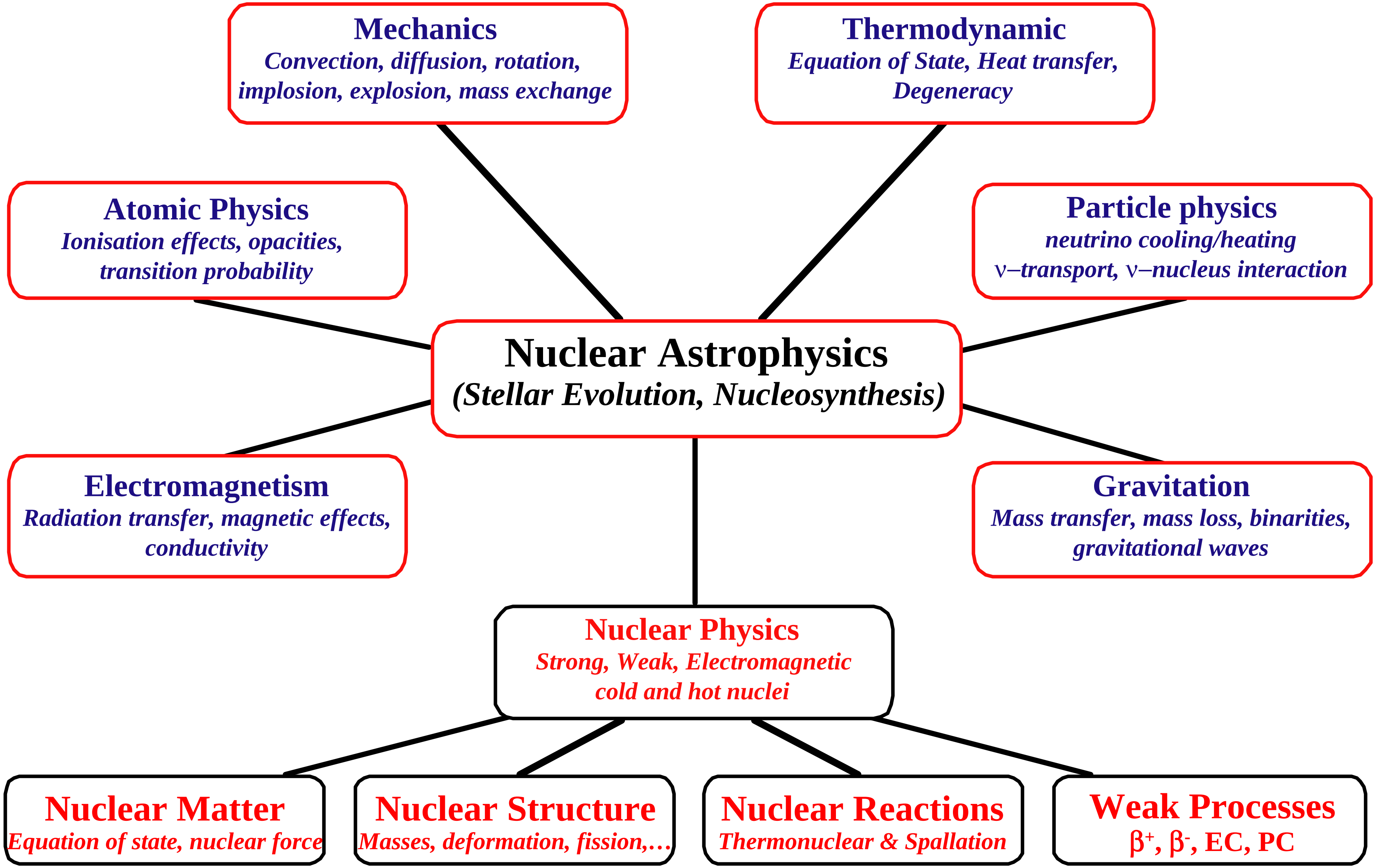
– – – Phenomenological parametrized site independent models

Canonical s- and r-processes

Remain critical about the astrophysics models
(even the 3D simulations are not free from astrophysics uncertainties!)

Obvious need for accurate and reliable nuclear data, … but the uncertainties in the astrophysics models most of the time prevail

Nuclear physics is a necessary but not sufficient condition for Nuclear Astrophysics



Mechanics
Convection, diffusion, rotation, implosion, explosion, mass exchange

Thermodynamic
Equation of State, Heat transfer, Degeneracy

Atomic Physics
Ionisation effects, opacities, transition probability

Particle physics
neutrino cooling/heating
ν–transport, ν–nucleus interaction

Nuclear Astrophysics
(Stellar Evolution, Nucleosynthesis)

Electromagnetism
Radiation transfer, magnetic effects, conductivity

Gravitation
Mass transfer, mass loss, binarities, gravitational waves

Nuclear Physics
Strong, Weak, Electromagnetic
cold and hot nuclei

Nuclear Matter
Equation of state, nuclear force

Nuclear Structure
Masses, deformation, fission,…

Nuclear Reactions
Thermonuclear & Spallation

Weak Processes
β^+, β^-, EC, PC

Astrophysics Modelling	Nuclear Physics Modelling
STELLAR EVOLUTION:	
low- & intermediate-M stars	pp,CNO,He-burning, e^--screening
massive stars	$^{12}C(\alpha,\gamma)^{16}O$, C+C,O+O
type-II supernovae, long γ-ray burst	NSE, EC, nuclear EOS, ν-interaction
neutron stars, short γ-ray burst	NM EOS, ν-interaction, picno-reaction…
novae, type-Ia supernovae	hot pp,CNO,NeNa-MgAl,α-chains
X-ray burst	hot CNO,NeNa-MgAl,(p,γ),(γ,p),(α,p),β^+
A<56 NUCLEOSYNTHESIS (in particular: ^{19}F, ^{23}Na, ^{26}Al...):	
low- & intermediate-M stars	pp,CNOF, NeNa, MgAl,He-burning
massive stars	He-burning, C+C,O+O,$^{12}C(\alpha,\gamma)^{16}O$
type-II supernovae	NSE, nuclear EOS, ν-interaction
novae, type-Ia supernovae	hot pp & CNO, NeNa-MgAl, α-chains

🟩 = + 🟧 = ± 🟥 = –

Astrophysics Modelling	Nuclear Physics Modelling
S-PROCESS:	
low- & intermediate-M AGB Stars	CNO,He-burning,(n,γ),β^-,EC,$^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$
Massive stars	(n,γ),β^-,EC, $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$
P-PROCESS:	
O/Ne layers of (pre)SNII / SNIa	(γ,n),(γ,p),(γ,α),β^+,(p,γ), $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$
He-detonation in Sub-Chandra WD	(α,γ),(α,p),(p,γ),(γ,n),(γ,p),(γ,α)
R-PROCESS:	
ν-driven wind of supernovae	n-,p-,α-captures,(γ,n),β^-,fission, ν-captures, ...
Decompression of neutron star matter	neutron matter EOS,β^-,fission, (n,γ),(γ,n)

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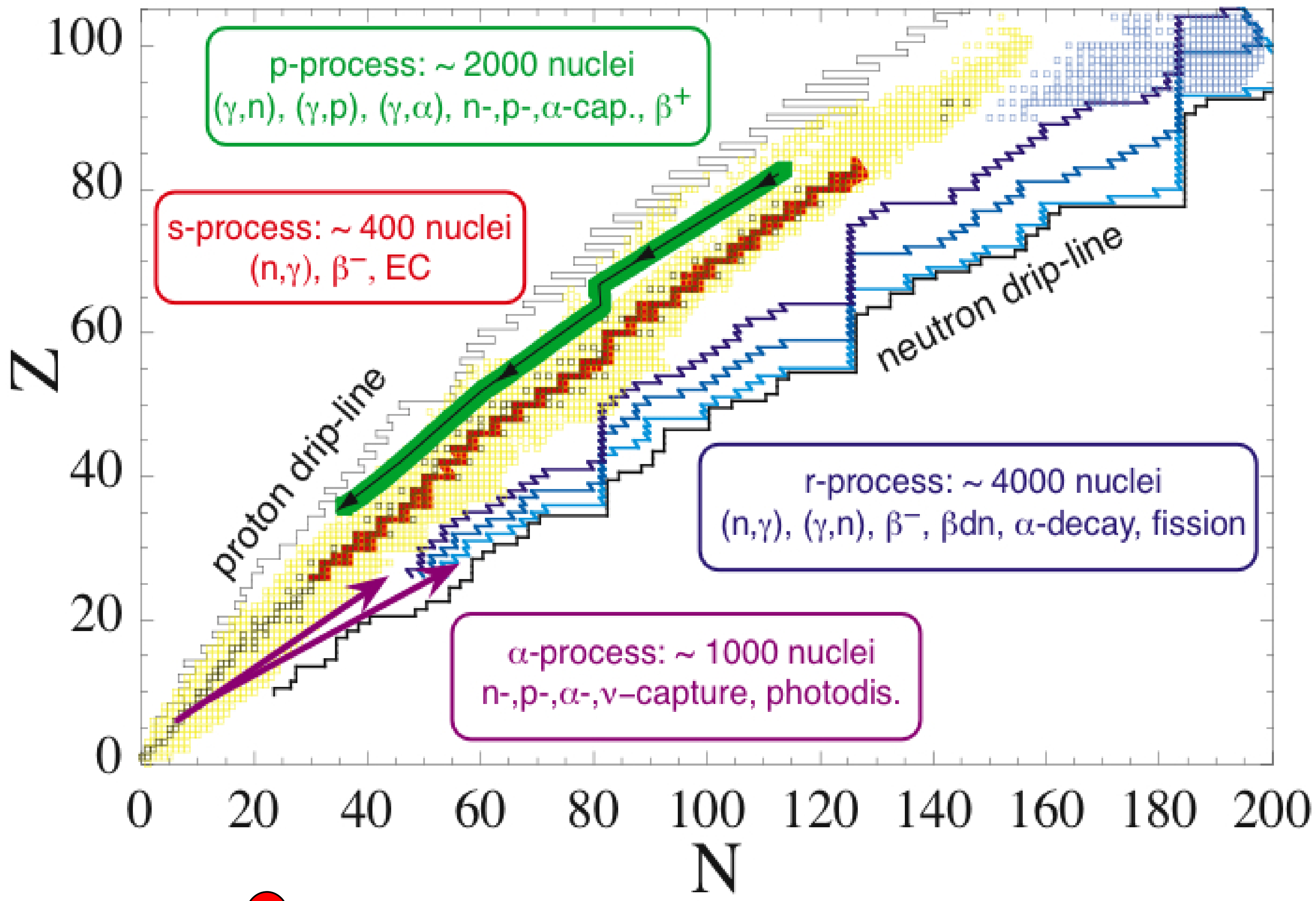
Nuclear needs for nucleosynthesis applications



p-process: ~ 2000 nuclei
(γ,n), (γ,p), (γ,α), n-,p-,α-cap., β^+

s-process: ~ 400 nuclei
(n,γ), β^-, EC

r-process: ~ 4000 nuclei
(n,γ), (γ,n), β^-, βdn, α-decay, fission

α-process: ~ 1000 nuclei
n-,p-,α-,ν-capture, photodis.

- ☹ Exotic species (no experimental data)
- ☹ Large number of nuclei and properties involved

From the lab to the astrophysics applications

Direct measurements of cross sections & β-decay half-lives

- Major burning phases (pp, CNO, He, …)
- S-process nucleosynthesis

Indirect information to estimate reaction & weak rates

Almost all nuclear astrophysics applications !

- Extrapolation of σ(E) to the energy range of relevance
- $<\sigma v>^*$ in a stellar plasma, T- and ρ-dependent weak rates
- many nuclei (radioactive, exotic)
- many properties (n-, p-, α-, γ-capture, fission)

In MOST cases, a direct measurement of the cross section is not enough !

Nuclear Ingredients required to estimate the stellar rate

1. Ground & Excited state properties

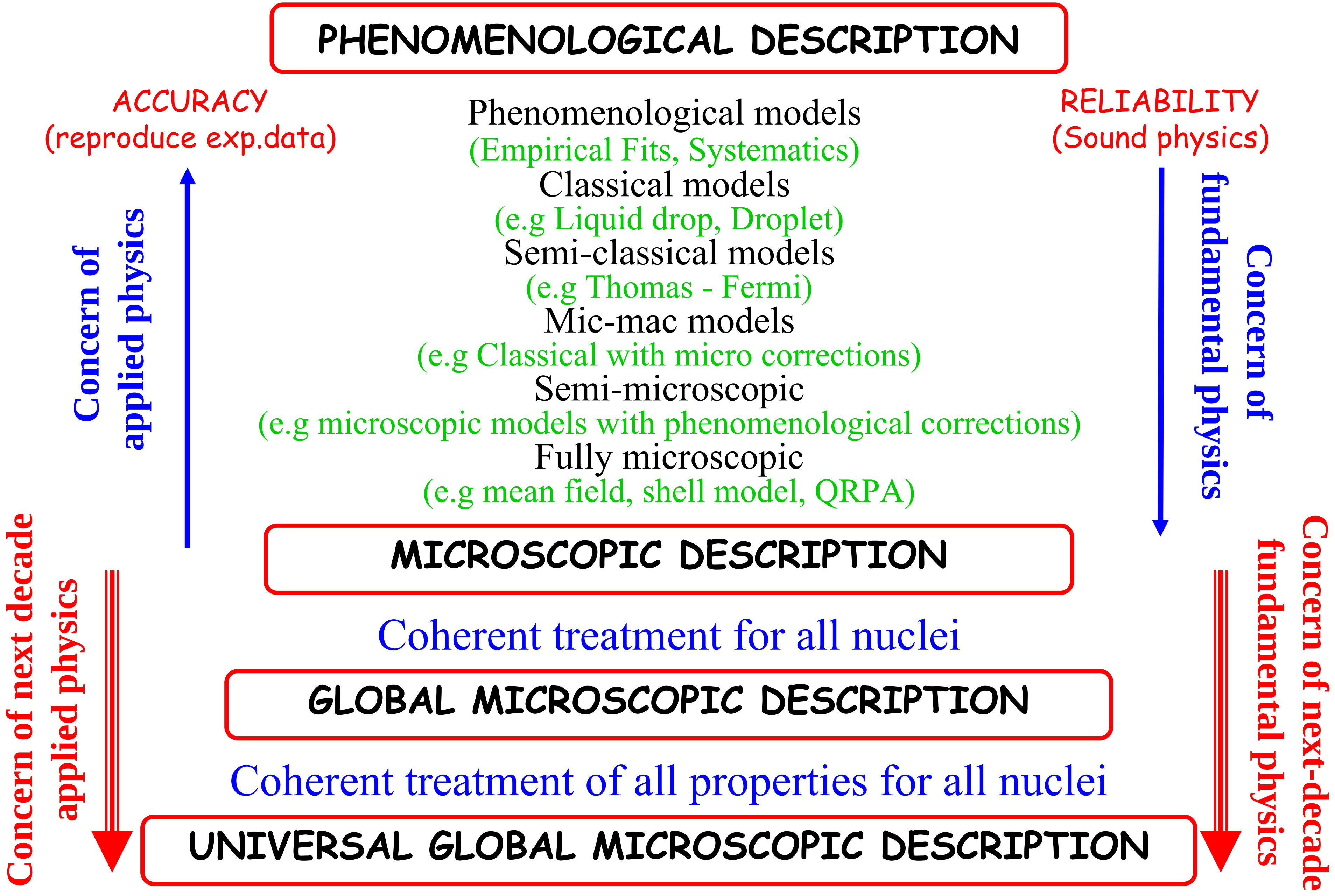
- Ground state mass, equilibrium deformation, density distribution, shell energy, pairing energy, spl scheme, etc...
- Excited spectrum (E,J,π) - Nuclear Level Densities ρ(E,J, π)
- Spectroscopic factors (E,J,π)
- Energy surfaces - Fission barrier, width

2. Interaction properties

- Nucleon-nucleus optical potential
- Alpha-nucleus interaction potential
- γ-strength function: Giant Resonance Properties
- Fission dynamics (neutron-induced, spontaneous fission)

Nuclear Ingredients from (1) direct experimental data
(2) indirect (model-dep) exp. data
(3) theoretical models

Challenges in *theoretical* physics



PHENOMENOLOGICAL DESCRIPTION

ACCURACY
(reproduce exp.data)

RELIABILITY
(Sound physics)

Phenomenological models
(Empirical Fits, Systematics)
Classical models
(e.g Liquid drop, Droplet)
Semi-classical models
(e.g Thomas - Fermi)
Mic-mac models
(e.g Classical with micro corrections)
Semi-microscopic
(e.g microscopic models with phenomenological corrections)
Fully microscopic
(e.g mean field, shell model, QRPA)

Concern of applied physics

Concern of fundamental physics

MICROSCOPIC DESCRIPTION

Coherent treatment for all nuclei

GLOBAL MICROSCOPIC DESCRIPTION

Coherent treatment of all properties for all nuclei

UNIVERSAL GLOBAL MICROSCOPIC DESCRIPTION

Concern of next decade applied physics

Concern of next-decade fundamental physics

Challenges in *experimental* nuclear physics

Three important components in experimental nuclear astrophysics

1) Cross section measurement for a given well-defined astrophysics scenario:

- stellar evolution:
  - hydrostatic burning phases (H-, He-, C-burning): $^{12}C(\alpha,\gamma)^{16}O$, $^{12}C+^{12}C$
  - explosive phases (SNIa): α-chains on ^{12}C and ^{14}C
- neutron source for nucleosynthesis: $^{22}Ne(\alpha,n)^{25}Mg$
- nucleosynthesis: (n,γ) cross sections for the s-process
- γ-astronomy: e.g $^{60}Fe(n,\gamma)^{61}Fe$

Relatively rare and difficult cases left over (though mainly stable targets)
Most has been done (“the feasible ones”)

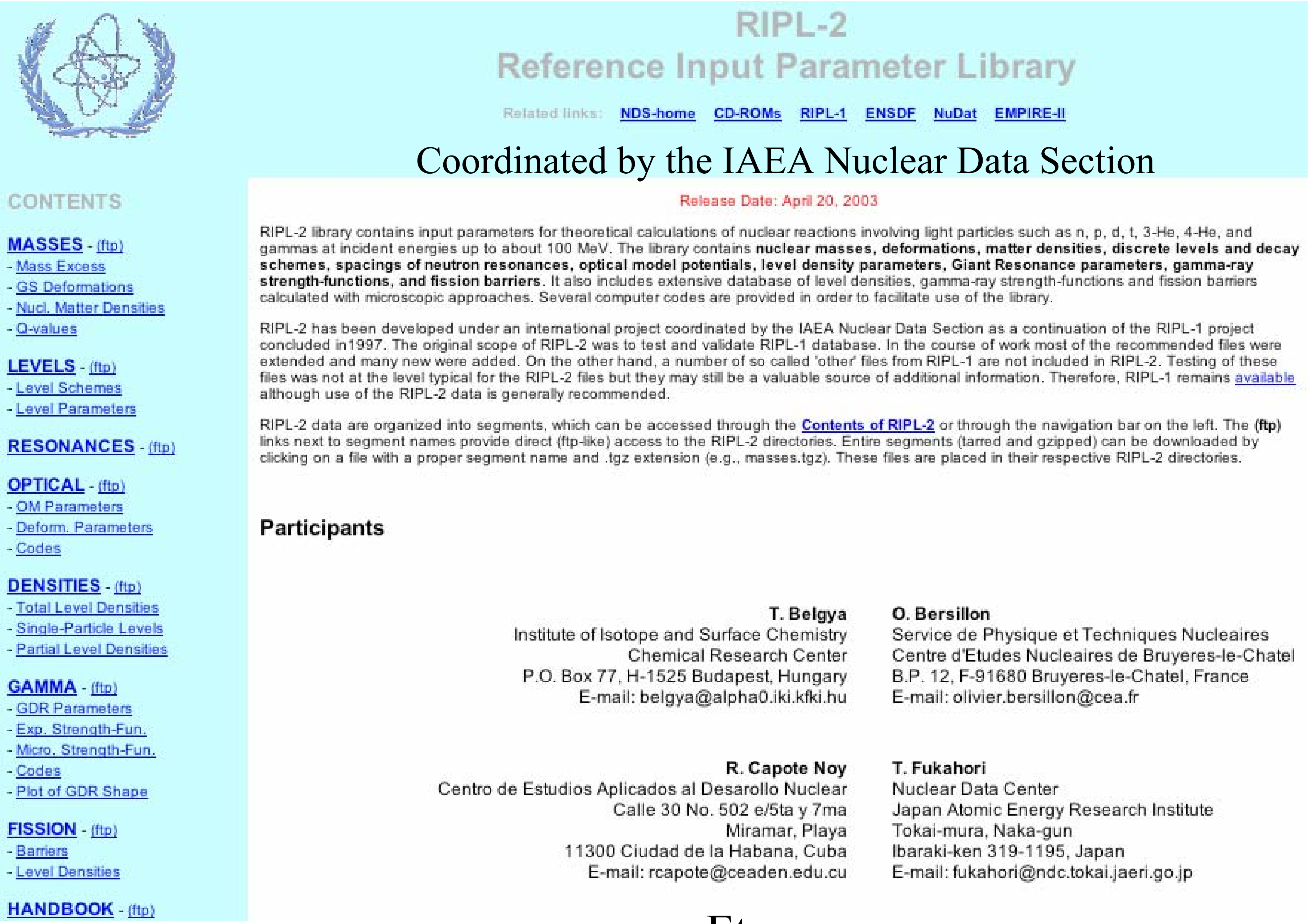
2) Measurement of given properties for a large set of nuclei:

- masses and structure properties of stable and exotic nuclei
- resonance spacings at S_n --> NLD $\rho(U,J,\pi)$
- photoabsorption data and $<\Gamma_\gamma>$ data --> $f_{E1}(U)$
- n, p and α elastic scattering and $<\Gamma_n>$ data --> OMP
- fission barriers
- reaction cross section (n,p,α-captures) --> Reaction model validation

Need for a regularly-updated library of evaluated input parameters:
Fundamental

- for accurate cross section (and rate) calculations
- to improve systematics of phenomelogical models
- to determine the best set of parameters of theoretical models
- to test physics input of *global microscopic* models

Extension of the systematics to unstable nuclei
but still many properties on stable nuclei are missing !!



RIPL-2
Reference Input Parameter Library

Coordinated by the IAEA Nuclear Data Section

Release Date: April 20, 2003

RIPL-2 library contains input parameters for theoretical calculations of nuclear reactions involving light particles such as n, p, d, t, 3-He, 4-He, and gammas at incident energies up to about 100 MeV. The library contains **nuclear masses, deformations, matter densities, discrete levels and decay schemes, spacings of neutron resonances, optical model potentials, level density parameters, Giant Resonance parameters, gamma-ray strength-functions, and fission barriers**. It also includes extensive database of level densities, gamma-ray strength-functions and fission barriers calculated with microscopic approaches. Several computer codes are provided in order to facilitate use of the library.

RIPL-2 has been developed under an international project coordinated by the IAEA Nuclear Data Section as a continuation of the RIPL-1 project concluded in1997. The original scope of RIPL-2 was to test and validate RIPL-1 database. In the course of work most of the recommended files were extended and many new were added. On the other hand, a number of so called 'other' files from RIPL-1 are not included in RIPL-2. Testing of these files was not at the level typical for the RIPL-2 files but they may still be a valuable source of additional information. Therefore, RIPL-1 remains available although use of the RIPL-2 data is generally recommended.

RIPL-2 data are organized into segments, which can be accessed through the **Contents of RIPL-2** or through the navigation bar on the left. The **(ftp)** links next to segment names provide direct (ftp-like) access to the RIPL-2 directories. Entire segments (tarred and gzipped) can be downloaded by clicking on a file with a proper segment name and .tgz extension (e.g., masses.tgz). These files are placed in their respective RIPL-2 directories.

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Etc ….

RIPL-2

MASSES - (ftp)
- Mass Excess
- GS Deformations
- Nucl. Matter Densities

LEVELS - (ftp)
- Level Schemes
- Level Parameters

RESONANCES - (ftp)

OPTICAL - (ftp)
- OM Parameters
- Deform. Parameters
- Codes

DENSITIES - (ftp)
- Total Level Densities
- Single-Particle Levels
- Partial Level Densities

GAMMA - (ftp)
- GDR Parameters
- Exp. Strength-Fun.
- Micro. Strength-Fun.
- Codes
- Plot of GDR Shape

FISSION - (ftp)
- Barriers
- Level Densities

Ground-state properties
- Audi-Wapstra mass compilation
- Mass formulas including deformation and matter densities

Discrete Level Scheme including J, π, γ-transition and branching
- 2546 nuclear decay schemes
- 115346 levels
- 12956 spins assigned
- 159323 γ-transitions

} ENSDF-II (1998)

Average Neutron Resonance Parameters
- average spacing of resonances ---> level density at U=S_n
- neutron strength function ---> optical model at low energy
- average radiative width ---> γ-ray strength function

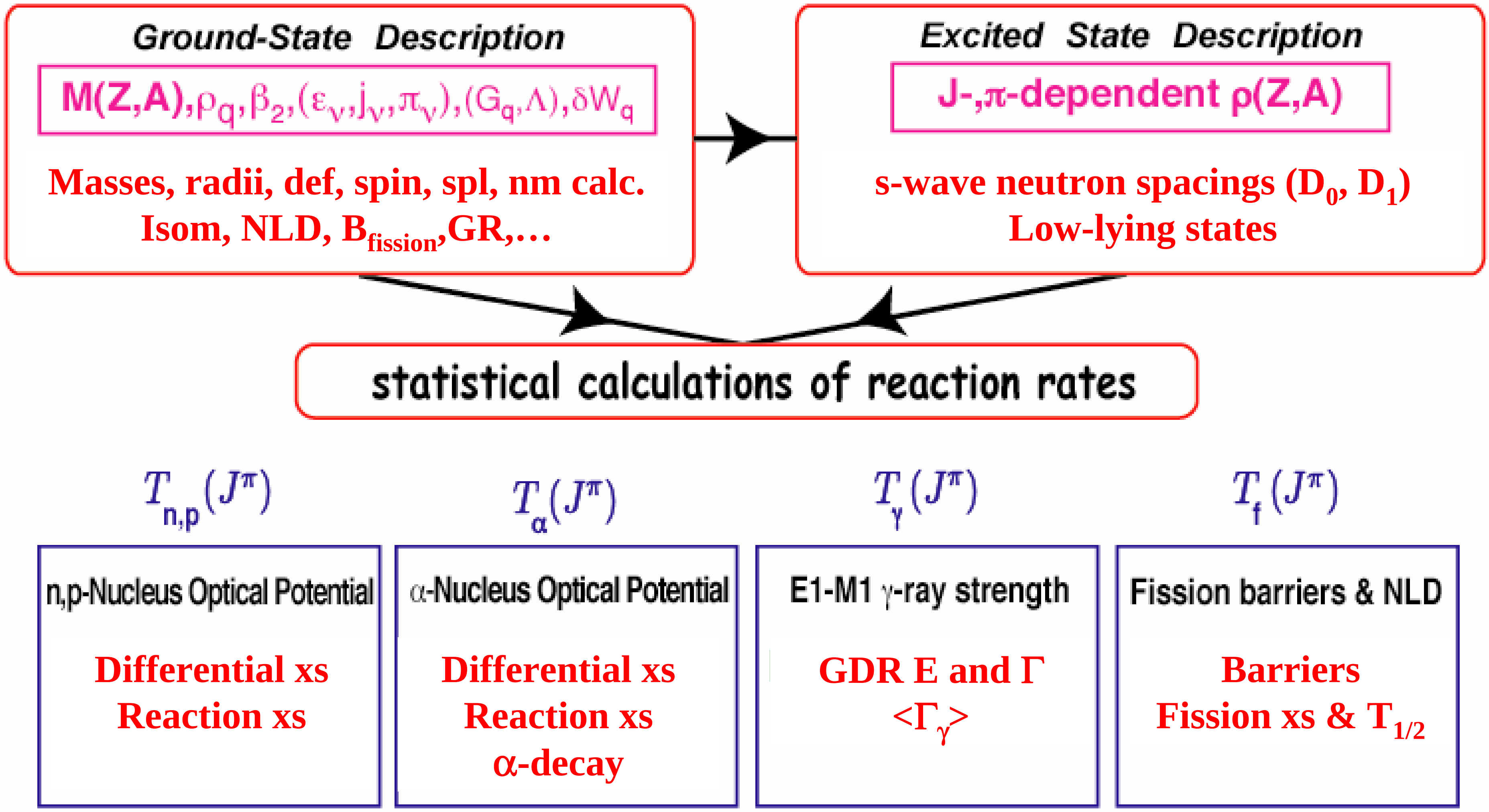
Optical Model Potentials (533) from neutron to ^{4}He
- Standard OMP parameters
- Deformation parameters
- E- and A-dependent global models (formulas and codes)

Nuclear Level Densities (formulas, tables and codes)
- Spin- and parity-dependent level density fitted to D_0
- Single-particle level schemes for NLD calculations
- Partial p-h level density

γ-strength function (E1)
- GDR parameters and low-energy E1 strength
- E1-strength function (formulas, tables and codes)

Fission parameters
- Fitted fission barriers and corresponding NLD
- Fission barriers (tables and codes)
- NLD at fission saddle points (tables)

Direct or Indirect Observables used to constrain nuclear models



Ground-State Description

$M(Z,A), \rho_q, \beta_2, (\varepsilon_\nu, j_\nu, \pi_\nu), (G_q, \Lambda), \delta W_q$

Masses, radii, def, spin, spl, nm calc.
Isom, NLD, $B_{fission}$, GR,…

Excited State Description

J-, π-dependent $\rho(Z,A)$

s-wave neutron spacings (D_0, D_1)
Low-lying states

statistical calculations of reaction rates

$T_{n,p}(J^\pi)$

n,p-Nucleus Optical Potential

Differential xs
Reaction xs

$T_\alpha(J^\pi)$

α-Nucleus Optical Potential

Differential xs
Reaction xs
α-decay

$T_\gamma(J^\pi)$

E1-M1 γ-ray strength

GDR E and Γ
$<\Gamma_\gamma>$

$T_f(J^\pi)$

Fission barriers & NLD

Barriers
Fission xs & $T_{1/2}$

3) Specific measurements to bring new insight on a given physical property (or parametrization) that could have a significant impact on the extrapolation of the predictions

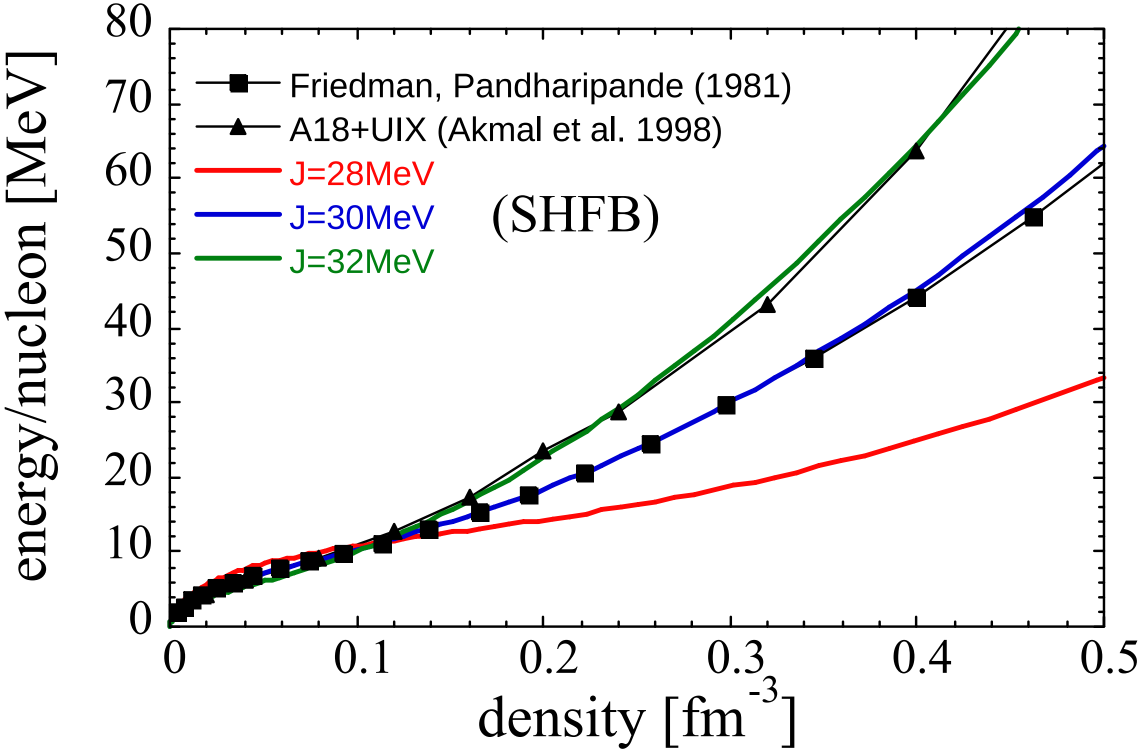
(in particular far away from the valley of stability)

For examples:

- Determination of specific nuclear structure properties
- Nuclear Level Densities at high energy and/or for exotic nuclei
- Dipole strength at low energies (pygmy resonance, zero-energy limit)
- Imaginary component of the neutron optical model potential for exotic n-rich nuclei
- α-nucleus optical model potential below the Coulomb barrier

Uncertainties in the symmetry energy

Energy per nucleon of pure neutron matter



J=30-32MeV also more compatible with ^{208}Pb neutron skin thickness: $\theta = R_n - R_p$

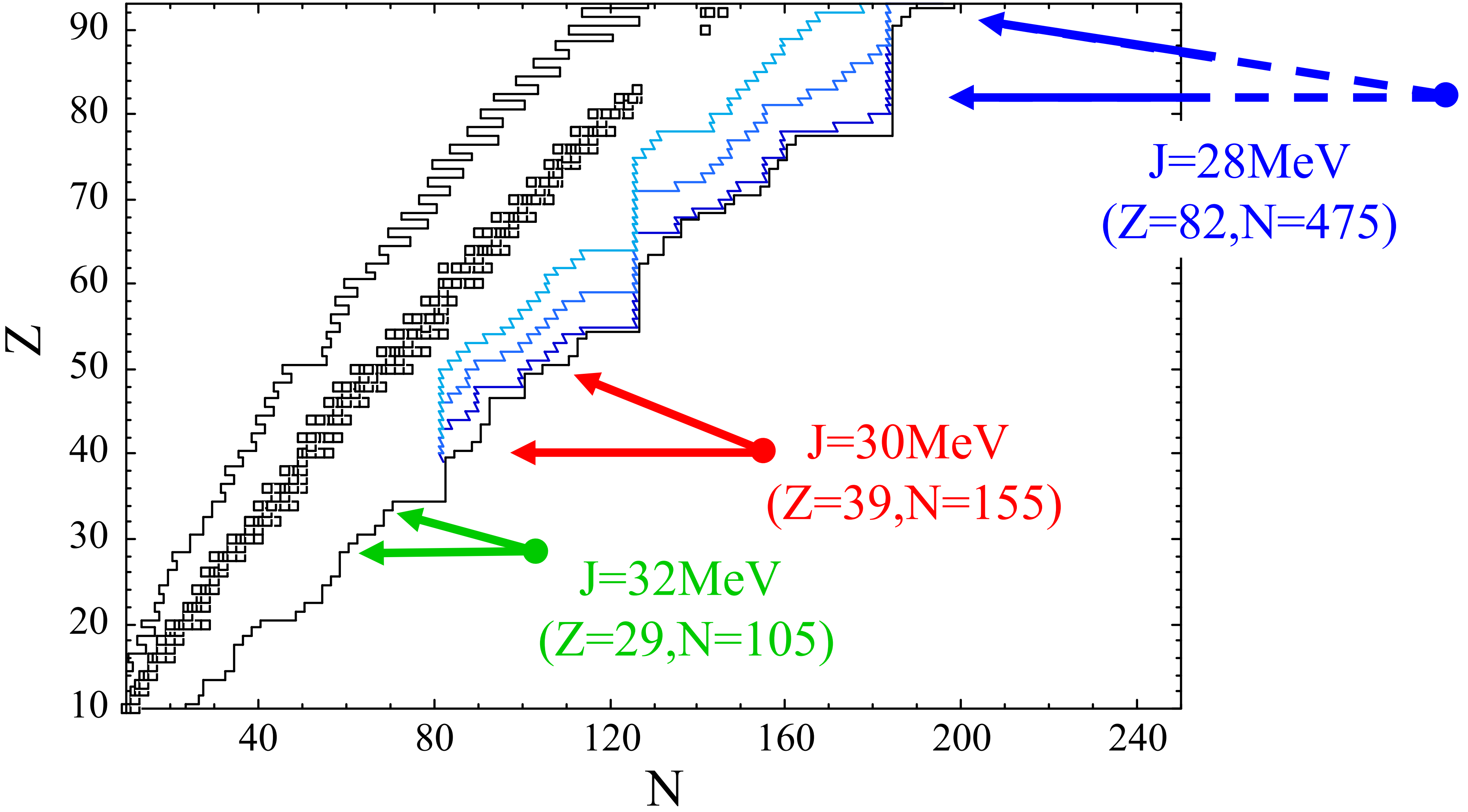
θ_{exp}= 0.14±0.04fm (Hoffman et al. 1980)
0.20±0.04fm (Starodubsky et al. 1994)

$\Rightarrow$ $\left\{ \begin{array}{l} \textbf{J=28MeV: } \theta_{th}\textbf{=0.12fm} \\ \textbf{J=30MeV: } \theta_{th}\textbf{=0.15fm} \\ \textbf{J=32MeV: } \theta_{th}\textbf{=0.19fm} \end{array} \right.$

nuclear matter at β-equilibrium
composition of the inner crust of neutron stars

($\rho_0=10^{14}$g/cm^3 - T = 0 MeV - Thomas-Fermi calculation)

Initial conditions for r-process in decompression of initially cold NS matter



J=28MeV
(Z=82,N=475)

J=30MeV
(Z=39,N=155)

J=32MeV
(Z=29,N=105)

Nuclear Level Densities

Fundamental ingredients for radiative neutron captures
(also define the relevance of the reaction model: resonance vs direct)

Models for practical applications:

- ***Phenomenological models (BSFG, Cst-T, …): highly parametrized***
- ***Two Microscopic Global models (statistical & combinatorial)***

(Extensive literature on microscopic models but nothing of practical use for nuclear applications)

ACCURACY:

- ~295 s-wave neutron spacing D_0 at $U=S_n$
- low-lying states for 1200 nuclei

Clear lack of exp. information, though many model-dependent data exist

particle–γ coincidence in the (^{3}He,$\alpha\gamma$) & (^{3}He,^{3}He'γ) reactions *(Oslo Group)*

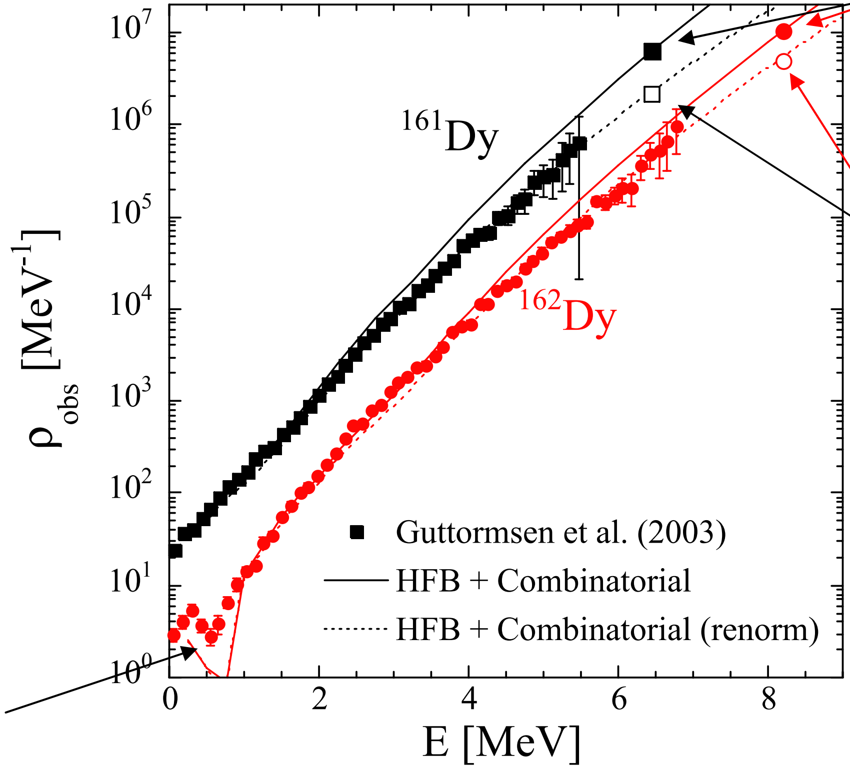
Difficulty to deal with model-dependent experimental data ….

$$D = \frac{1}{\rho(S_n, J_0 + 1/2, \pi_0) + \rho(S_n, J_0 - 1/2, \pi_0)} \qquad J_0 > 0$$

$$= \frac{1}{\rho(S_n, J_0 + 1/2, \pi_0)} \qquad J_0 = 0$$

$$\longleftrightarrow \qquad \rho_{obs}(U) = \sum_{J,\pi} \rho(U, J, \pi)$$

Different normalization at $\rho_{obs}(S_n)$ due to different spin and parity dependent NLD formula



Theoretical normalization based on the ***combinatorial*** predictions for spin and parity dependences

"experimental" normalization based on the ***BSFG*** formula with assumptions on the *a*, Δ_{pair} parameters, T(U) and σ^2(U)

BOTH combinatorial and BSFG reproduce exp. D_0 !!

Sensitive to π-dependence

Need for more experimental information on NLD

Compilation of 296 s-wave resonance spacings (RIPL-2):
strong constraint on NLD models at U=S_n at a given spin, parity

At U=S_n, strong shell, pairing, deformation dependence

$$D = \frac{1}{\rho(S_n, J_0+1/2, \pi_0) + \rho(S_n, J_0-1/2, \pi_0)} \qquad J_0>0$$

$$= \frac{1}{\rho(S_n, J_0+1/2, \pi_0)} \qquad J_0=0$$

What about isospin dependence ? High energy extrapolation ?

p-wave resonance spacings D_1 could further constrain NLD models
Compilation of 50 p-wave resonance spacings available (RIPL-2)

Need for more experimental information (as model-indep. as possible) !

Prediction of fission cross sections

Fundamental for the r-process & chronometry: no predictive power at the present time

$$T(E,J,\pi) = \int \rho(\mathrm{E},J,\pi) T_{HW}(\Delta,\hbar\omega) d\varepsilon \quad \begin{cases} T_{HW}(E,\hbar\omega) = \dfrac{1}{[1+\exp(-2\pi E/\hbar\omega)]} \\ \Delta = E - B_f - \varepsilon \end{cases}$$

Fundamental ingredients:

- Fission barrier heights
- Fission barrier widths

$\Big\}$ Fission path

- Nuclear Level Densities at saddle points

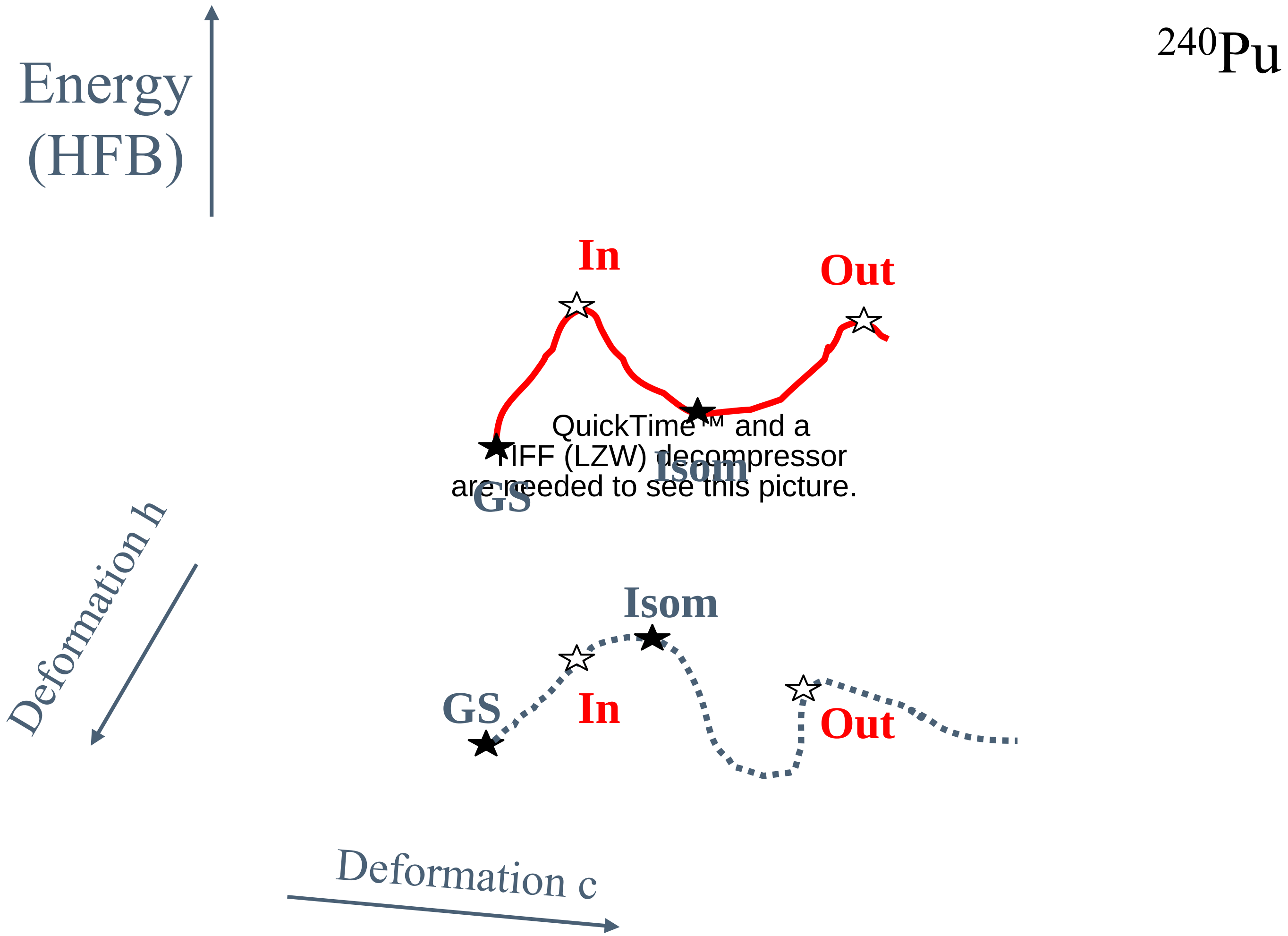
Only experimentally-based systematics or phenomenological models are used
Clear lack of a sound theory and direct experimental constraint to estimate in particular width and NLD for unknown nuclei

MAJOR CHALLENGES:

- coherent & microscopic predictions of all inputs
- significant experimental information to constrain & validate models

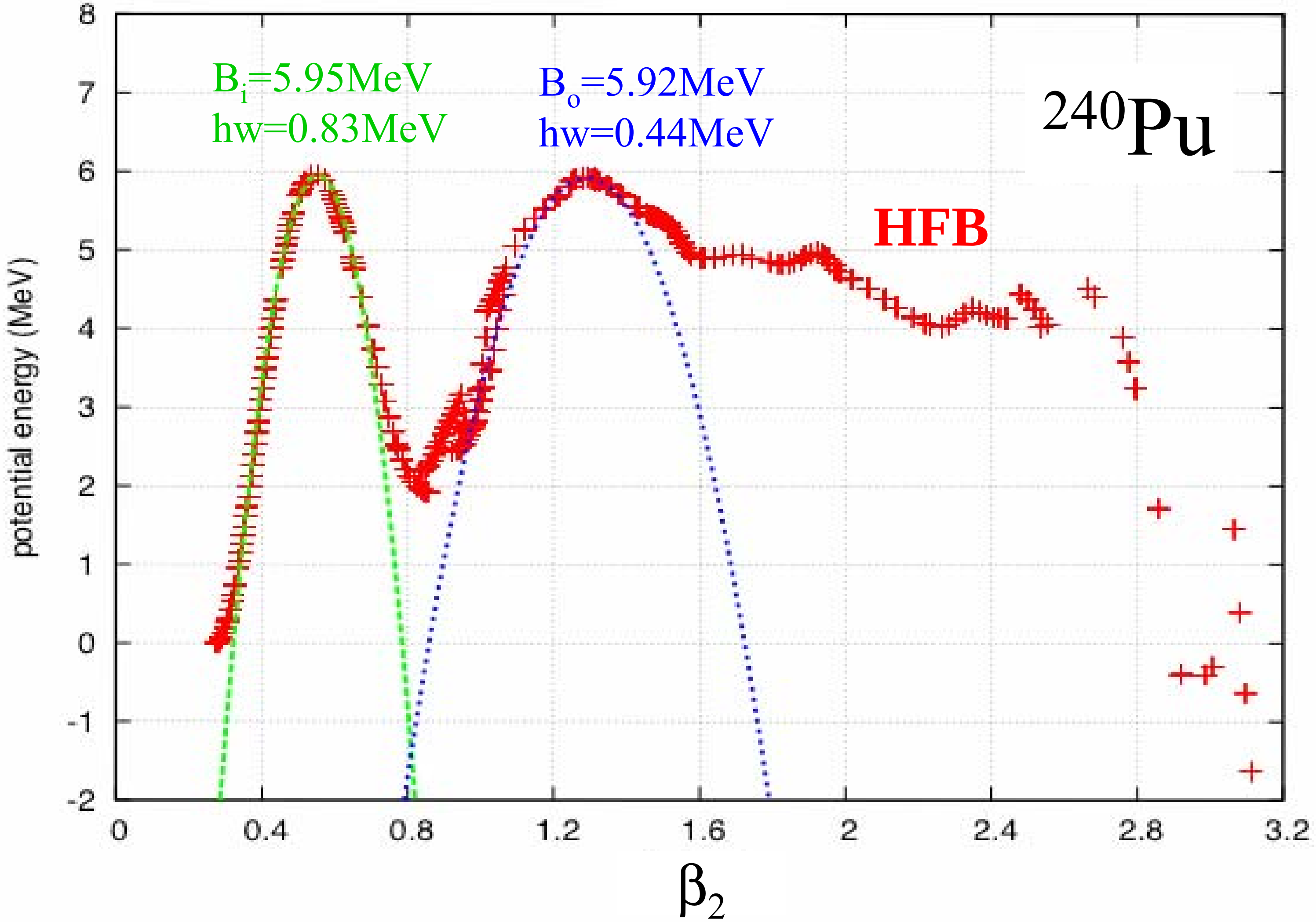
HFB calculation of the Fission Barriers

Full 3-D energy surface within the Constrained HFB model



Determination of the fission path

HFB path versus Inverted Parabola approximation

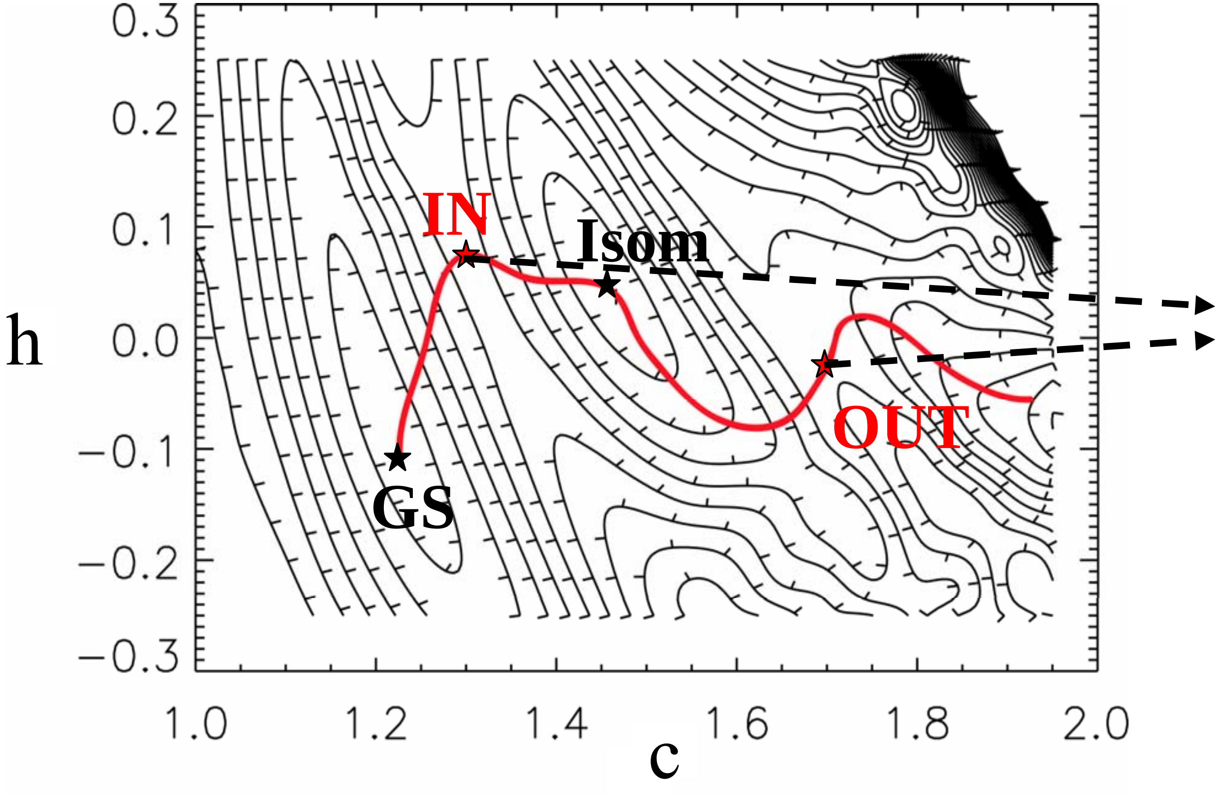


What about the impact of a large sub-barrier at high deformation ?

Nuclear level densities at the saddle points

HFB model constrained on Q,O,H moments provide at each deformation (and at saddle points) all nuclear properties needed to estimate the NLD

single-particle scheme
at saddle point deformation



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Determination of the n-induced fission cross section

Need for

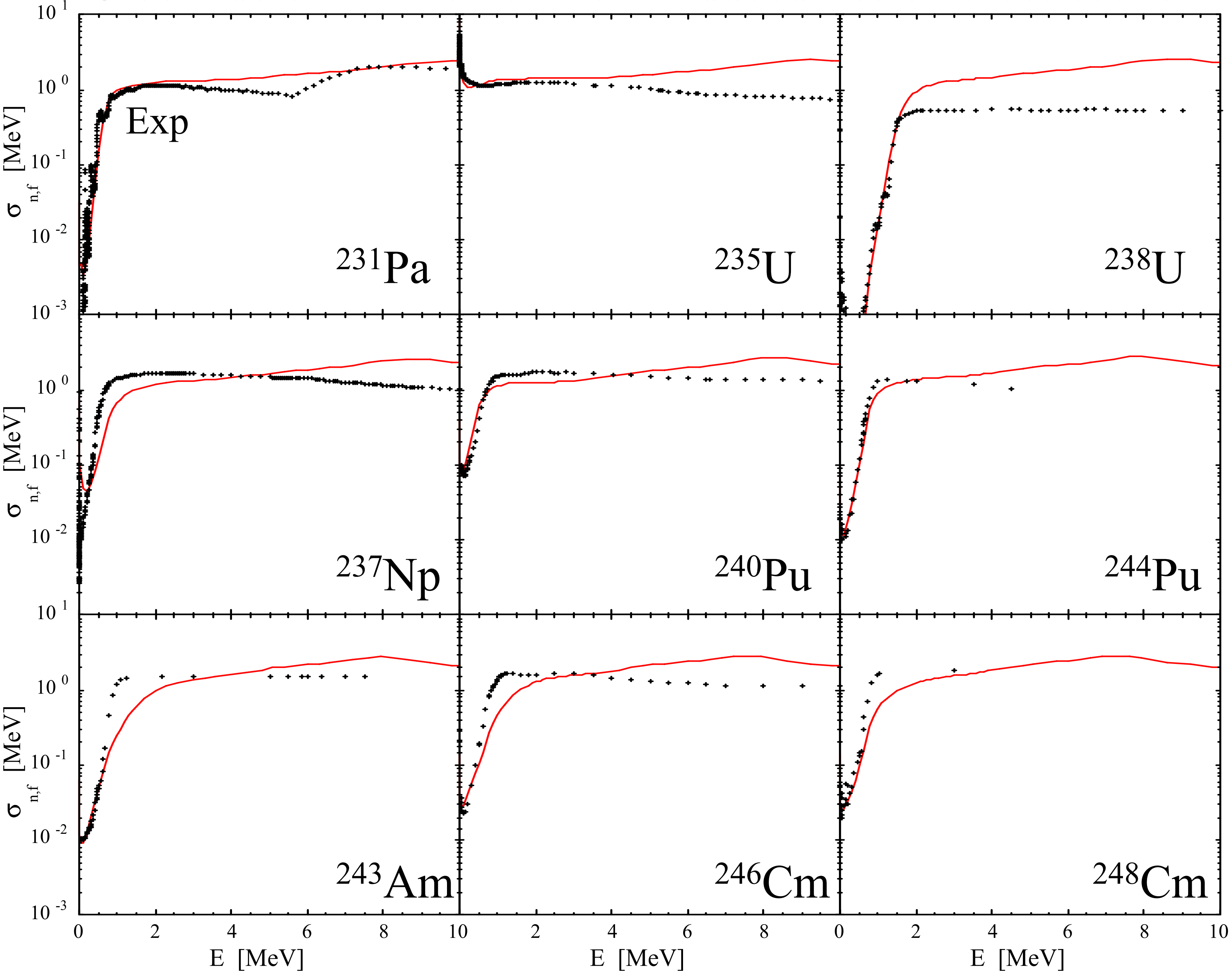
1) Microscopic predictions of the nuclear inputs

- Ground state properties (e.g from HFB models)
- Fission Barriers (to be adjusted in the comparison with exp. data)
- Fission width or full energy surface (e.g from HFB models)
- Nuclear Level Densities (e.g from combinatorial + HFB models)
- Microscopic n-OMP (e.g JLM-B)

  + *inclusion of dynamical effects (cf. H. Goutte)*

2) More experimental data, in particular (n,γ) and (n,f)
for validation of structure and reaction model

Global determination of the n-induced fission cross section



Conclusions

The exact role of nuclear physics in Astrophysics will remain unclear as long as the astrophysics site and the exact nuclear mechanisms of relevance are not fully under control

Evolution (+) P-process (±) S-process (±) R-process (—)

Emphasis in nuclear astrophysics should be put on a continued effort to provide the best nuclear physics**:**

- **Experimental data of relevance:**
  - **Direct measurements for specific reactions (level of accuracy is function of the astrophysics scenario)**
  - **Systematic measurements (masses, NLD, E1-strength, OMP, Fission,…)**
  - **Well-targeted experiments to highlight given properties**

with STABLE as well as UNSTABLE targets

- ***Universal Global Microscopic* models: Accuracy AND Reliability**

Observational information outside the solar system (mainly elemental spectroscopy)

Provide (in)direct information about the astrophysics site,
galactic history, nuclear mechanisms, …

S-process: intrinsic and extrinsic surface enrichments detected

++ Many observations that *can* be explained

– – Many observations that *cannot* be explained !!!!

R-process: only extrinsic surface enrichments detected

\+ Some still-debated observations in low-Z stars of interest

– – No information on possible astrophysics sites

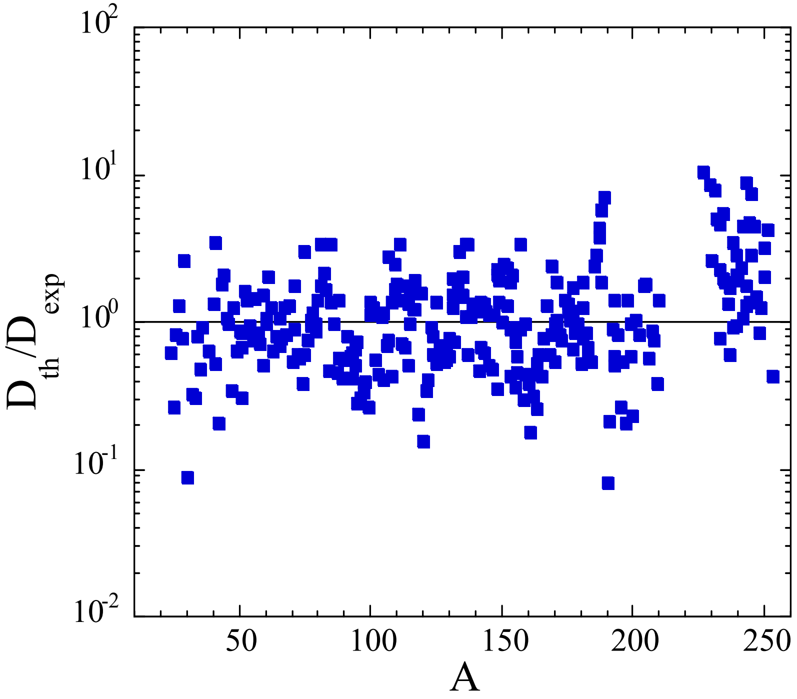
P-process: no p-process elements observable

– – No information of any kind outside the SoS

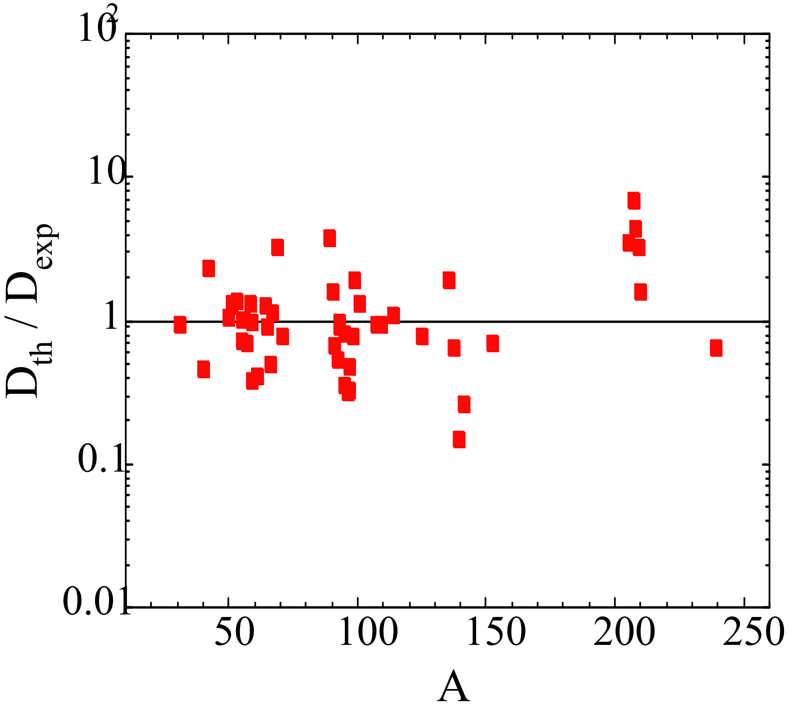
Combinatorial model based on HFB

S. Hilaire & S.G (2005)

s-wave spacings



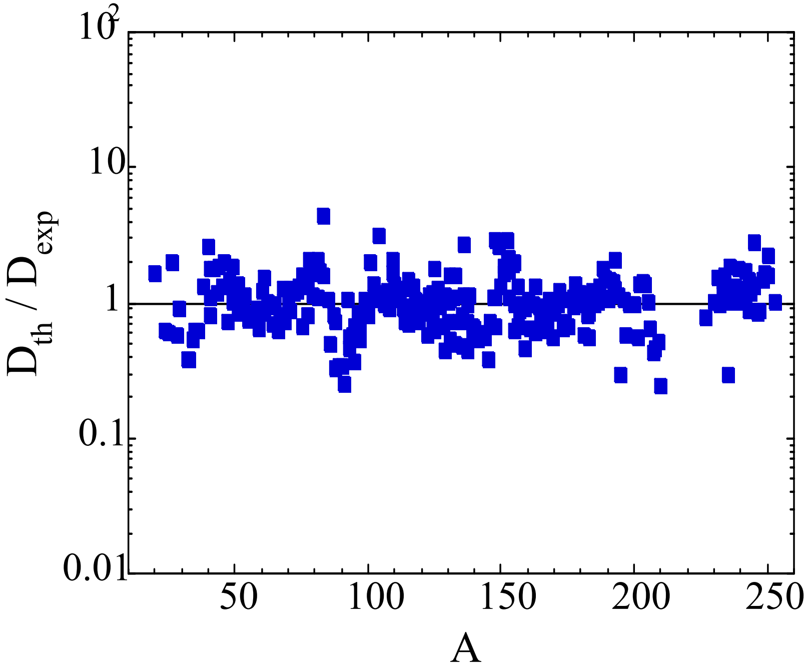
p-wave spacings



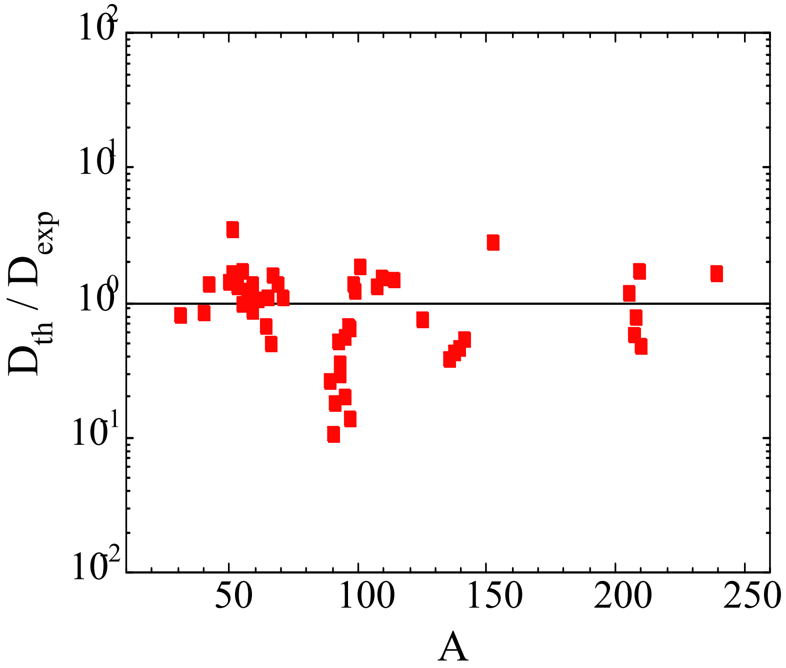
Shell-dependent BSFG model

Rauscher et al. (1997)

s-wave spacings



p-wave spacings



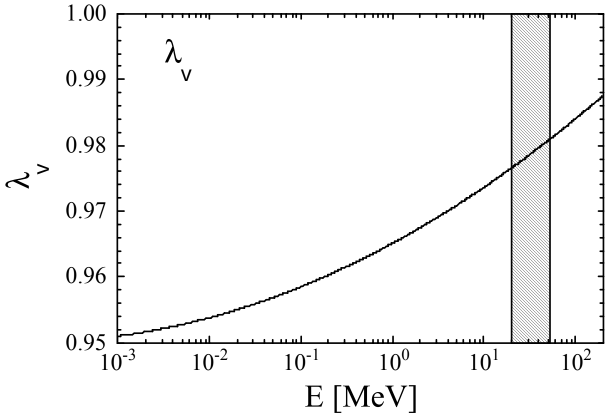
The isovector parametrization of JLMB (Bauge et al 2001)

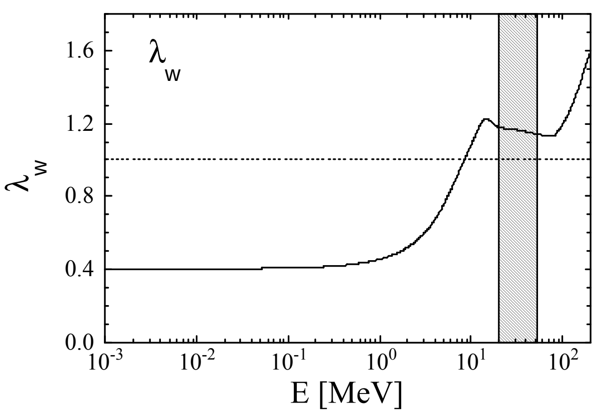
Renormalization of the JLM potential in a Lane-consistent potential (isospin symmetric)

- Real part: $V(r,E)= \lambda_v\,[V_0(r,E) \pm \lambda_{v1}\,(\rho_n-\rho_p)/(\rho_n+\rho_p)\,V_1(r,E)]$ + neutrons
- Imag. part: $W(r,E)= \lambda_w\,[W_0(r,E) \pm \boldsymbol{\lambda_{w1}}\,(\rho_n-\rho_p)/(\rho_n+\rho_p)\,W_1(r,E)]$ – protons

Renormalization on (n,n), (p,p) elastic scattering and (p,n) QE scattering from GS to IAS as well as reaction data ($40 \leq A \leq 209$; E=1keV - 200MeV) ⟶ JLM-Bruyere OMP

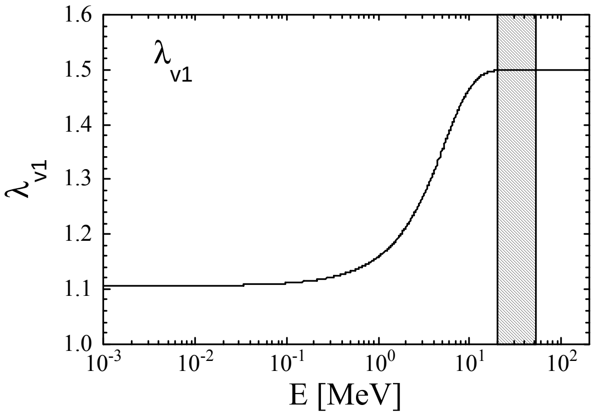
Isoscalar

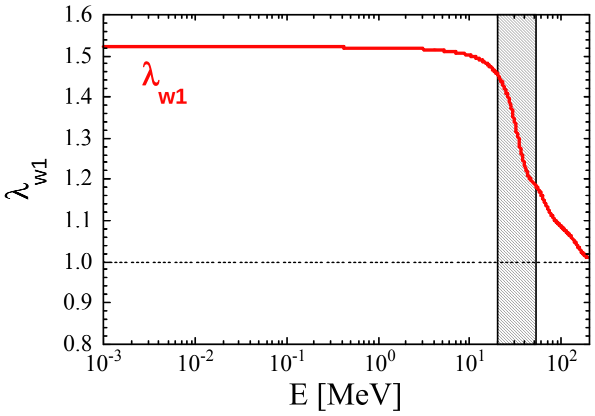




Energy region 20-50 MeV of highest confidence: uncertainties ~1.5% ▨

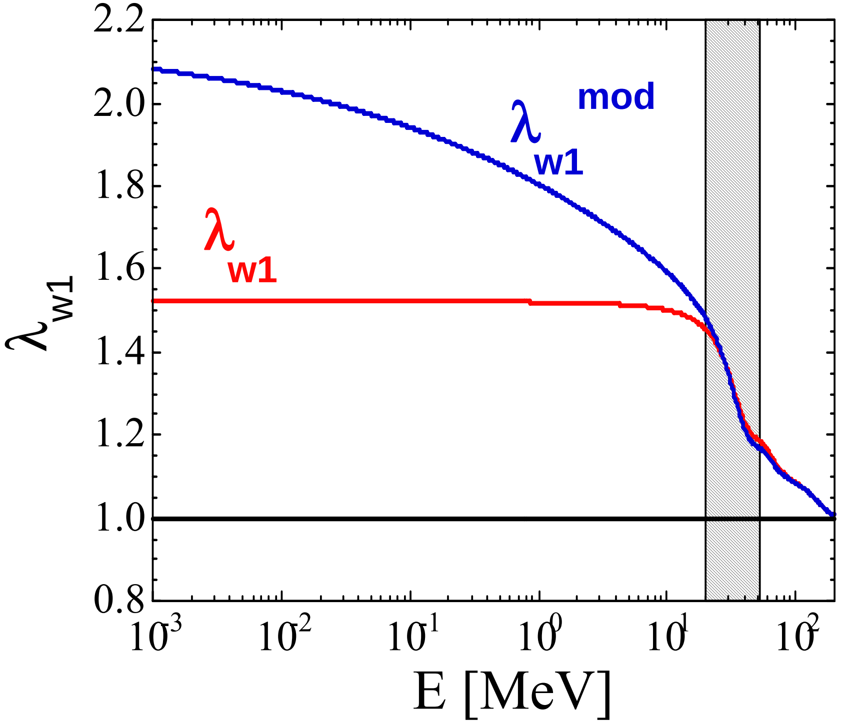
Isovector

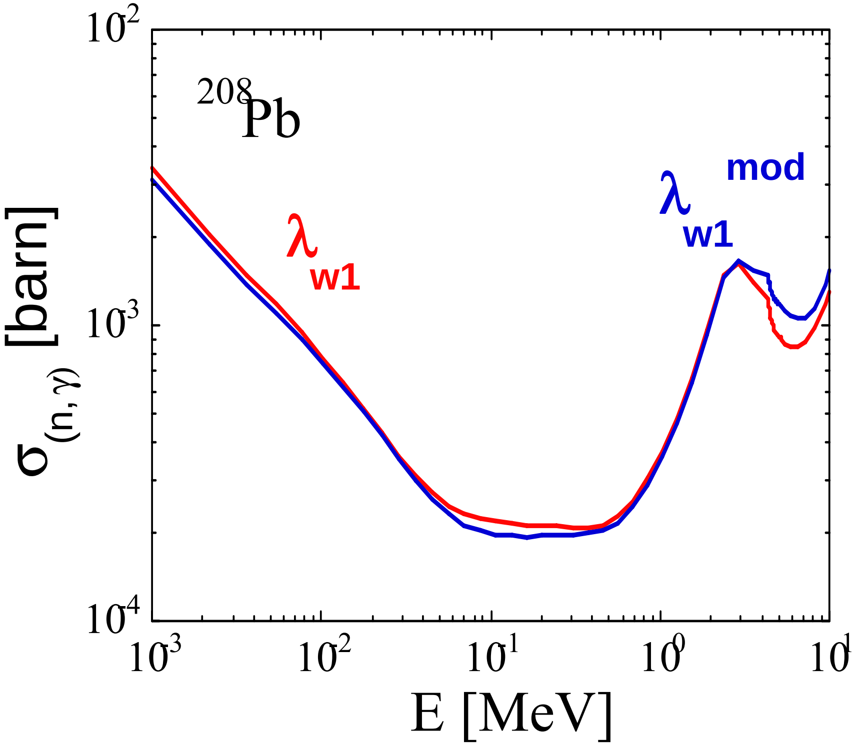




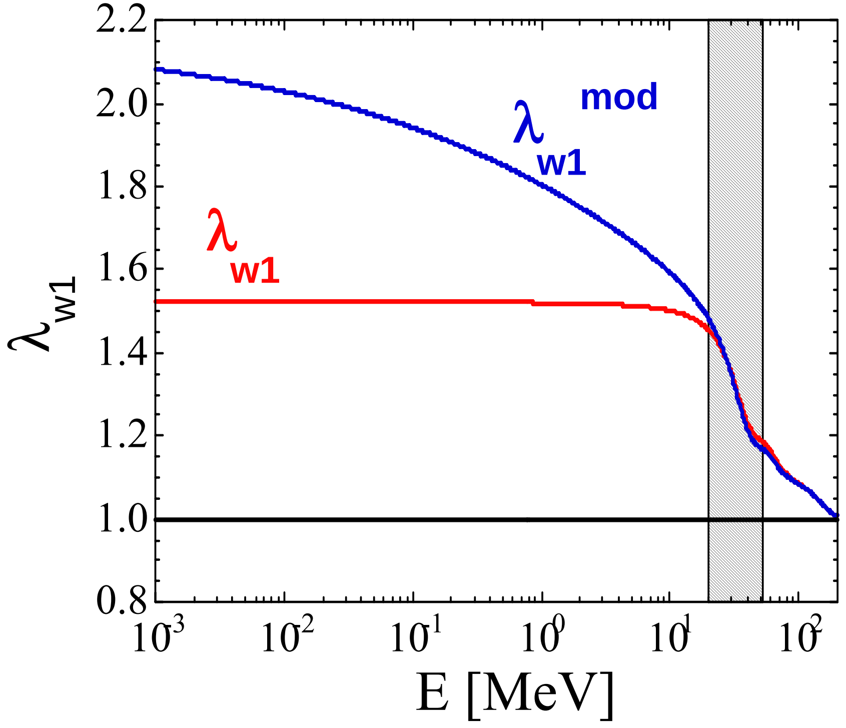
λ_{w1} = 1.52
at low energies
compared to
λ_{w1} = 1 for JLM

Impact of the isovector part of the imaginary potential close to the stability line

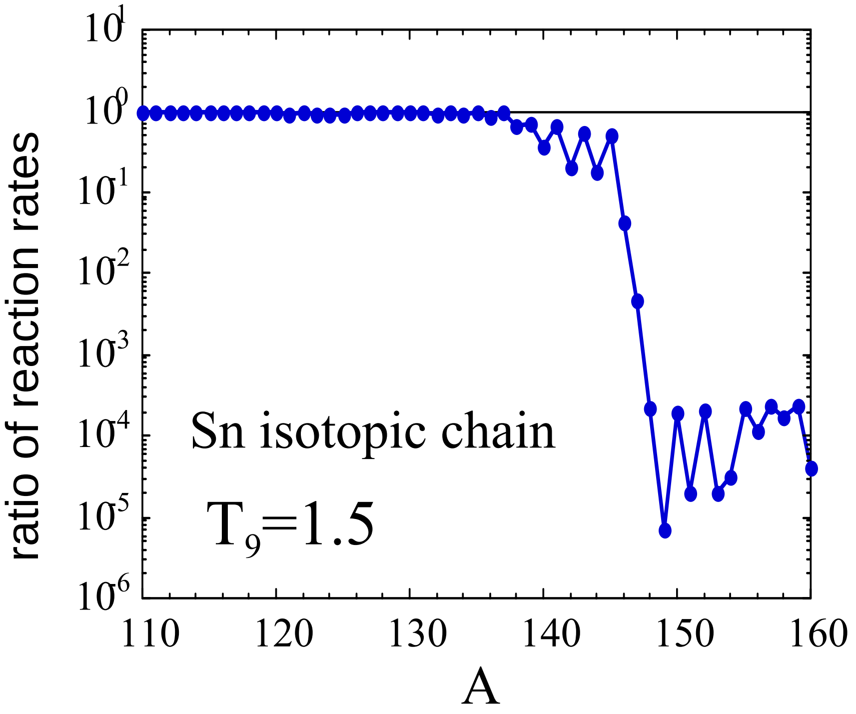




Impact of the isovector part of the imaginary potential far away from the stability line



$\langle\sigma v\rangle(\lambda_{w1}{}^{mod})$ / $\langle\sigma v\rangle(\lambda_{w1})$



Possible experimental information by (n,n) and (p,p) measurements on exotic n-rich nuclei at the same low energy

Also requires confirmation by extended BHF calculations in asymmetric NM