Statistical Model Calculations for (n,γ) Reactions

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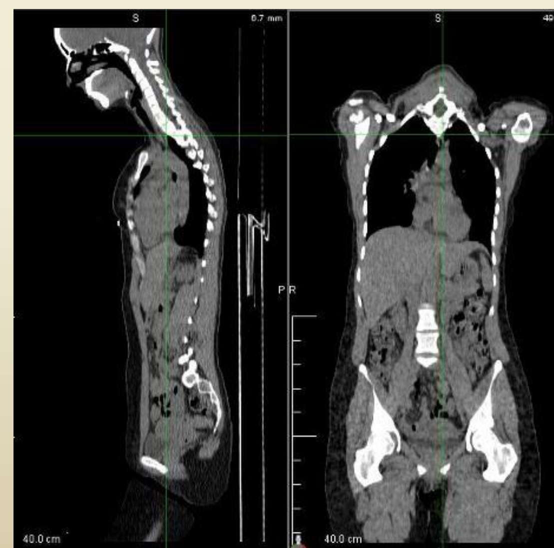
HELMHOLTZ ASSOCIATION
Alliance on Cosmic Matter in the Laboratory
National Science Foundation
WHERE DISCOVERIES BEGIN

Nuclear astrophysics

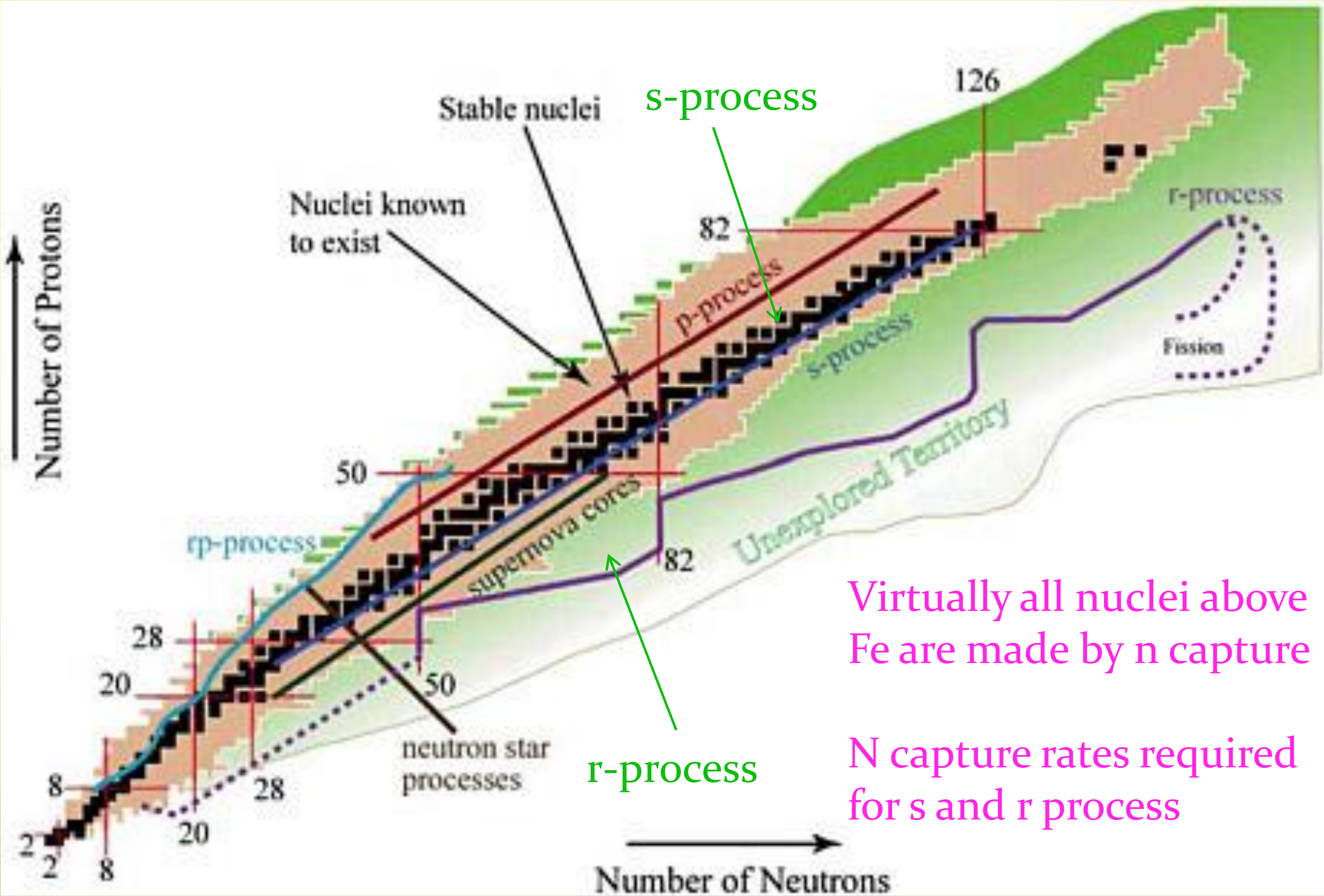
Waste transmutation

uses include

Reactor technologies



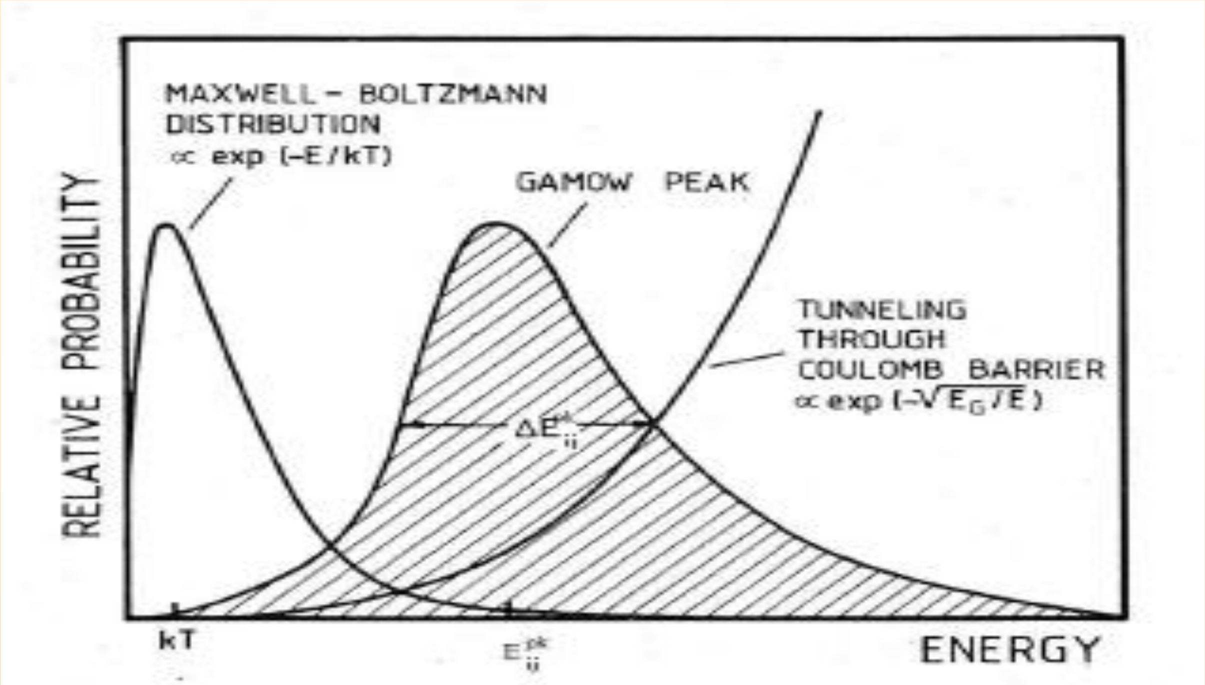
Medical applications



Virtually all nuclei above Fe are made by n capture

N capture rates required for s and r process

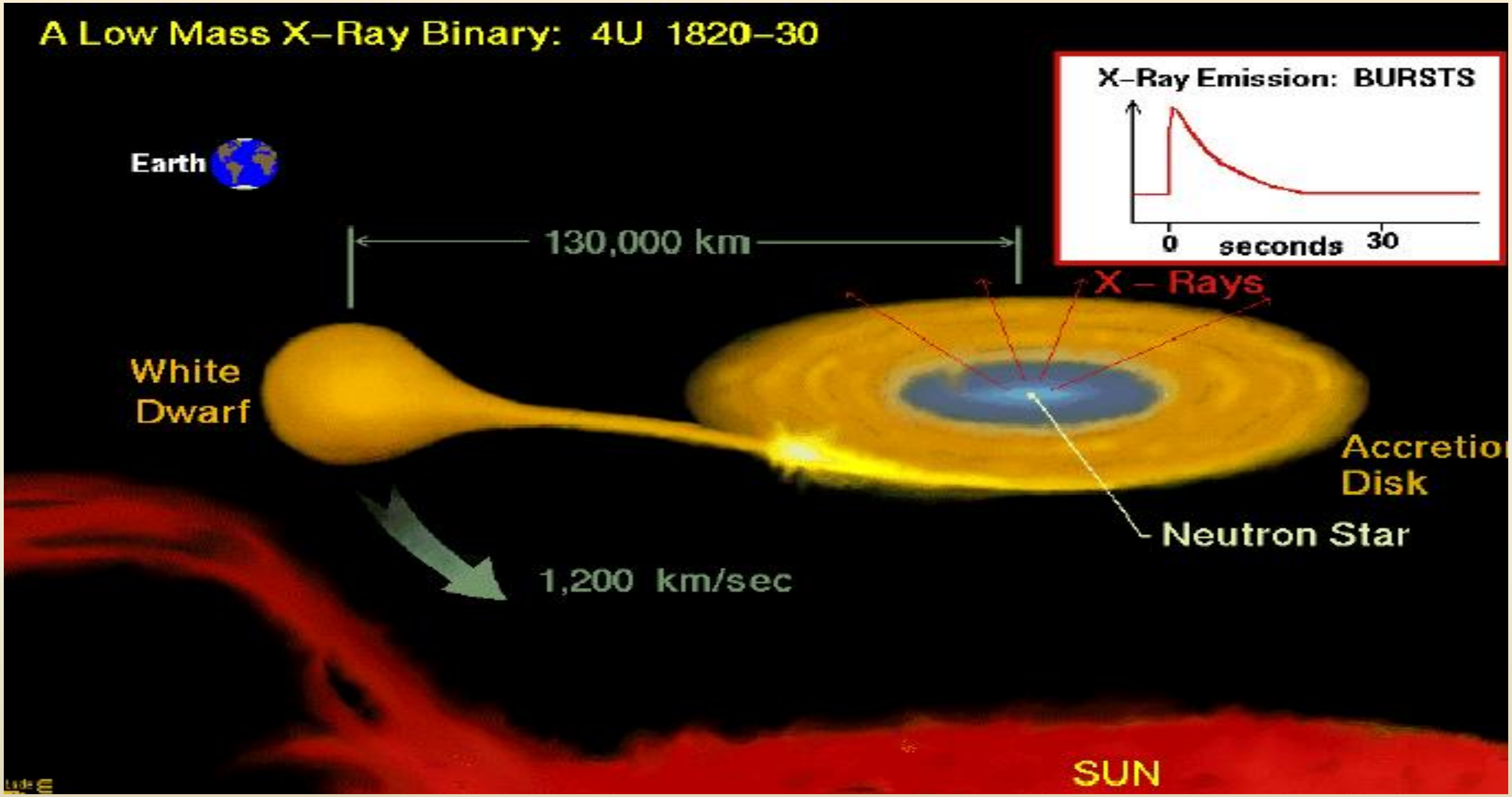
Most astrophysical sites need thermonuclear n capture rates

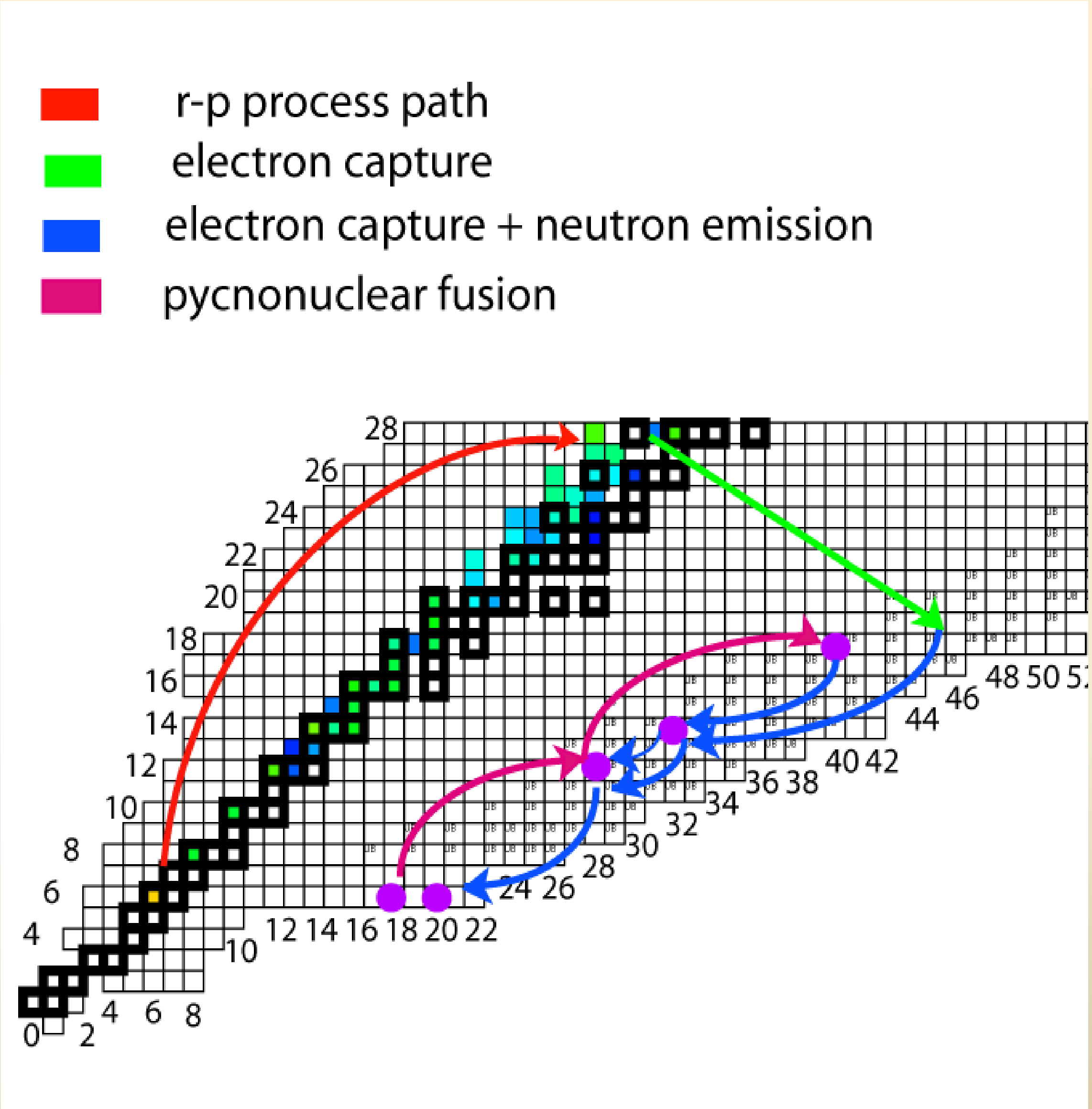


$$<\sigma v> = \left(\frac{8}{\pi\mu_{ij}}\right)^{1/2} \frac{1}{(k_B T)^{2/3}} \int_0^\infty \sigma(E) E \, exp\left(\frac{-E}{k_B T}\right) dE.$$

MACS: $<\sigma v>_T = \dfrac{<\sigma v>}{\sqrt{2k_B T / \hat{A}}}$ → KADoNiS

Neutron Star Crust

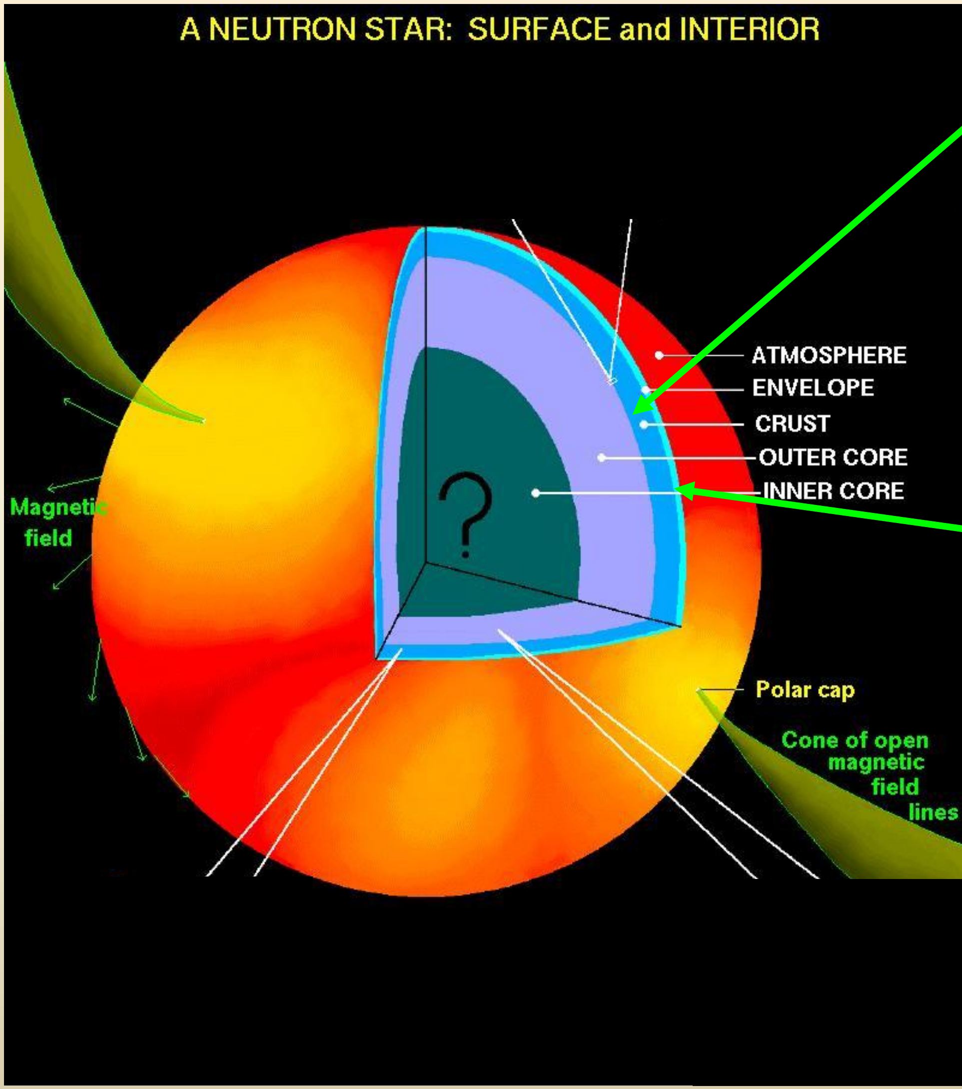


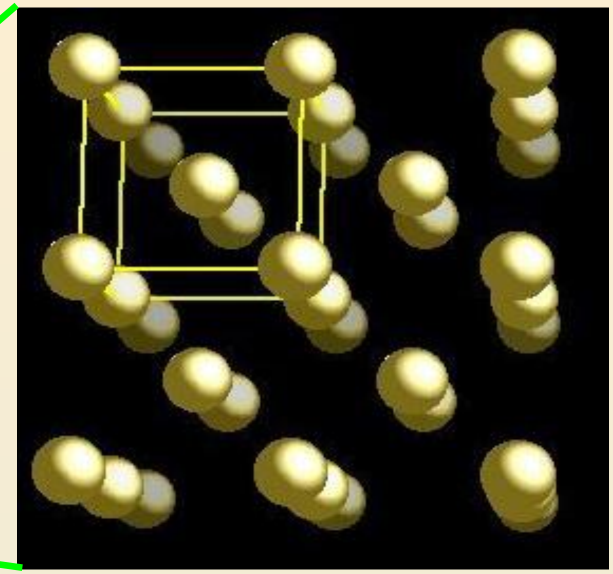


- Matter continually compressed – ignites via triple α and hot cno breakout
- Follows rp-process path
- ρ ~ 1.5 x 10^9 g/cm³ electron captures dominate
- At drip line neutron emissions process ashes into light material in the C to Mg range
- EC leads to high concentrations of free neutrons

- →degenerate neutron capture

Neutron Star Environment





Tightly bound lattice structure

BCC, FCC, Imperfections, dislocations……

Neutrons are confined in Coulomb crystal. → Not MB dist.

Degenerate N capture

$$N_A < \sigma v > = K \int_0^\infty E \sigma(E) f(E,T) dE$$

$$f_{FD} = \frac{1}{1 + e^{(E-\mu_N)/T}}$$

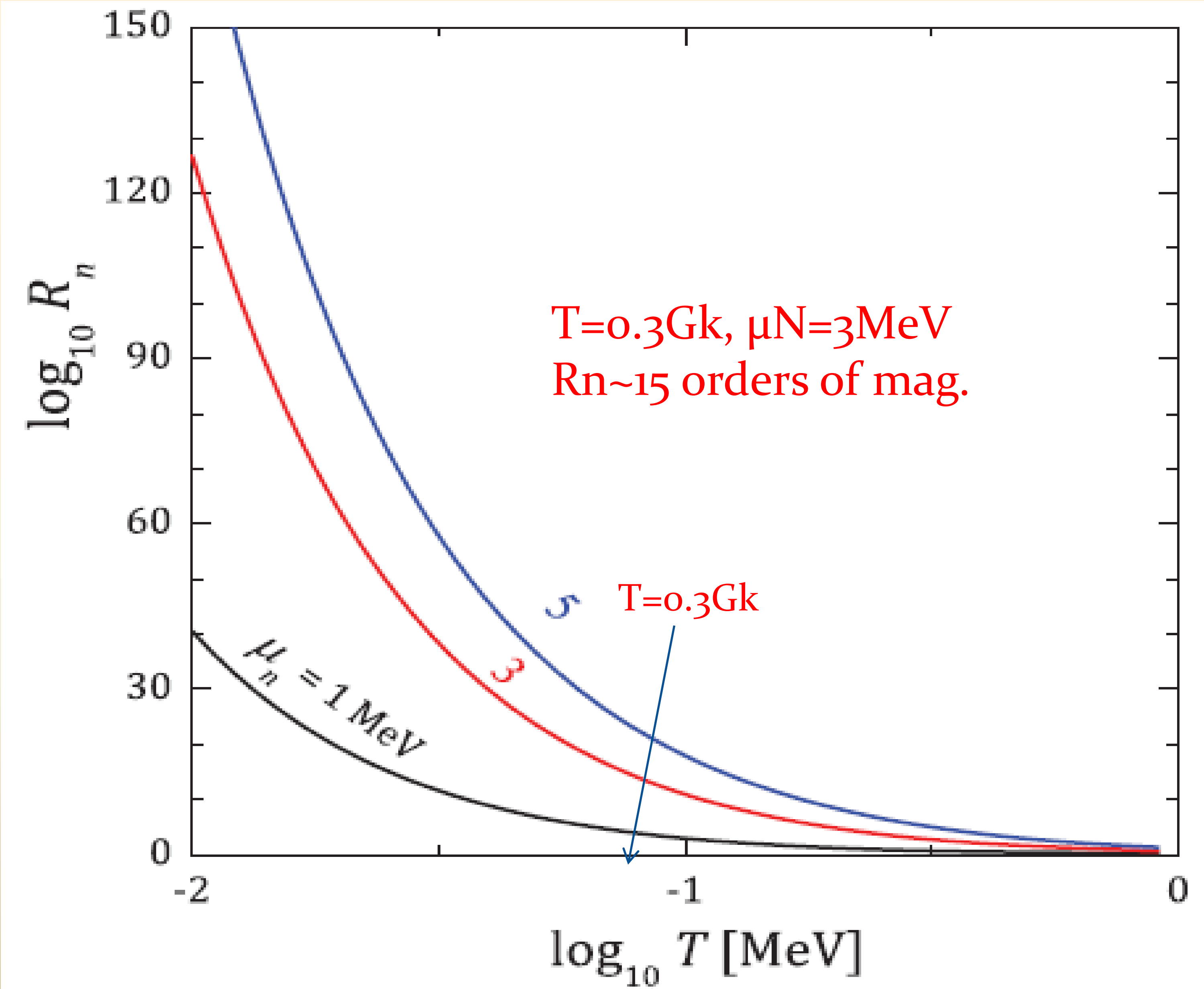
Introduce correction parameter Rn:

$$R_n = \frac{< \sigma v >_{FD}}{< \sigma v >_{MB}}$$

Measure of how applicable MB rates are

REACLIB, BRUSLIB....

Shternin et al PRC 86 015808 (2012)


T=0.3Gk, μN=3MeV
Rn~15 orders of mag.
T=0.3Gk
5
3
μ_n = 1 MeV
$\log_{10} R_n$
$\log_{10} T$ [MeV]
150
120
90
60
30
0
-2
-1
0

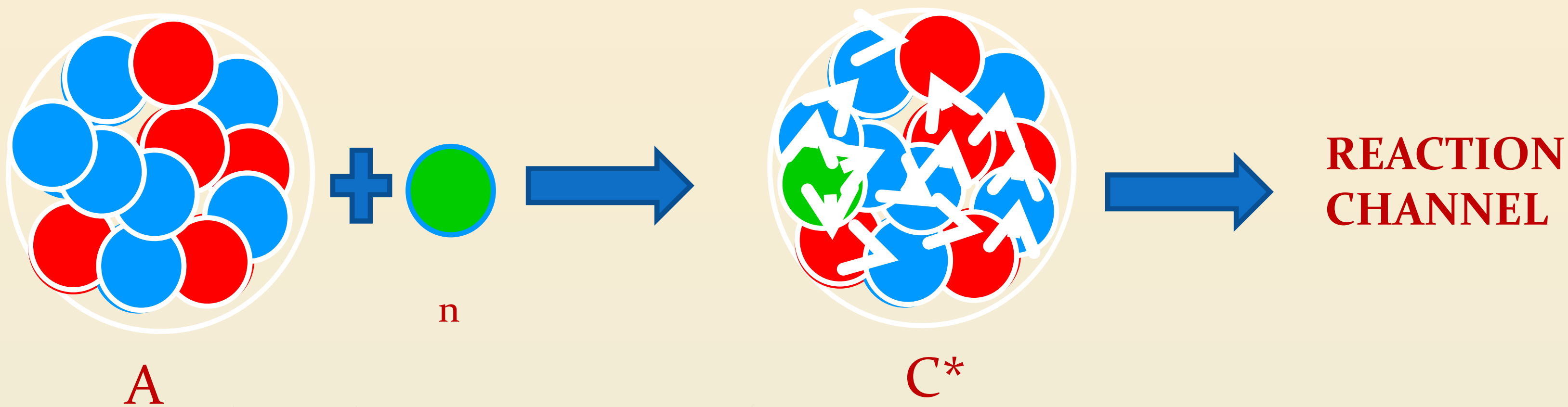
Astrophysical networks require 1000's of rates!

$$N_A < \sigma v > = K \int_0^\infty E \sigma(E) f(E,T) dE$$

$$f_{FD} = \frac{1}{1 + e^{(E-\mu_N)/T}} \qquad f_{MB} = \exp(-E/T)$$

σ(E) typically obtained from HF calculations

The Statistical Model: $N_A < \sigma v > = K \int_0^{\infty} E \sigma(E) f(E,T) dE$



Reaction takes place via intermediary C*
C* must reach a state of thermodynamic eq.

Statistical model normally valid if LD in C* is high, so that resonances overlap

HF Reaction σ

$$I^{\mu} + j \rightarrow J^{*} \rightarrow k + L$$

Reaction Cross Section needs

- transmission co-efficients →n, gamma

$$\sigma_{jk}^{\mu}(E) = \pi ƛ_{j}^{2} \frac{1}{(2J_{I}^{\mu}+1)(2J_{j}+1)} \sum_{J,\pi} (2J+1) \frac{T_{j}^{\mu}(J^{\pi}) T_{k}(J^{\pi})}{T_{tot}(J^{\pi})}$$

Spins :
tar., proj., & comp.

Transmission coefficient (make/destroy J^{π} from I^{μ} + j)

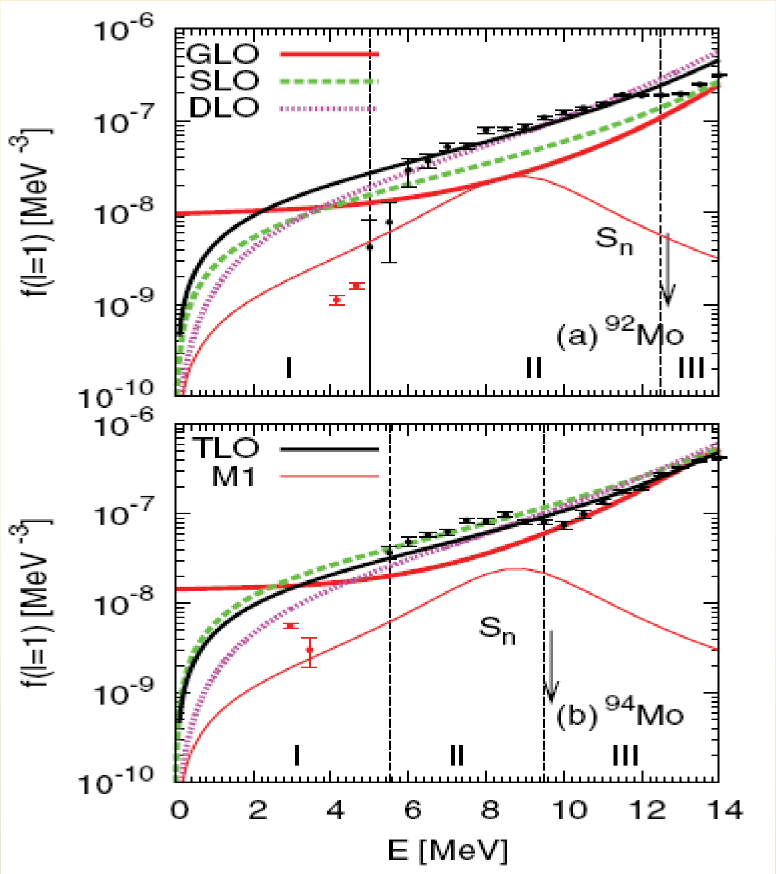
Transmission coefficient (make/destroy J^{π} from k + L)

Total decay transmission coefficient (any channel)

Transmission Functions

Particle – OMP, LD (often BSFG , CT)

Photon – GDR. Normally E1 dominates. See talk by S. Frauendorf



$$T_{E1}(E_\gamma) = 2\pi E_\gamma^3 f_{E1}(E_\gamma)$$

Parameterized Lorentzian(s)

Ingredients

data

- masses
- deformations
- Jπ, Ex

models

- level density
- γ-strength function
- optical model

Calculating Trans. requires nuclear inputs

→ HF calculations are sensitive to:
choice of models
quality/quantity of data

XS uncertainties

Is CN model applicable?
- Pre-equilibrium
- direct reactions

Model/data uncertainties
- Masses
- Deformation
- Jπ
- Level densities
- GSF
- OMP

3rd source:

- Code approximations
- Implementation details (matching E, GDR param, a, δ....)

To test the 3rd point, xs calculations have been performed with:

TALYS

SAPPHIRE
(Statistical Analysis forParticle and Photon capture and decay of HIgh energy REsonances)

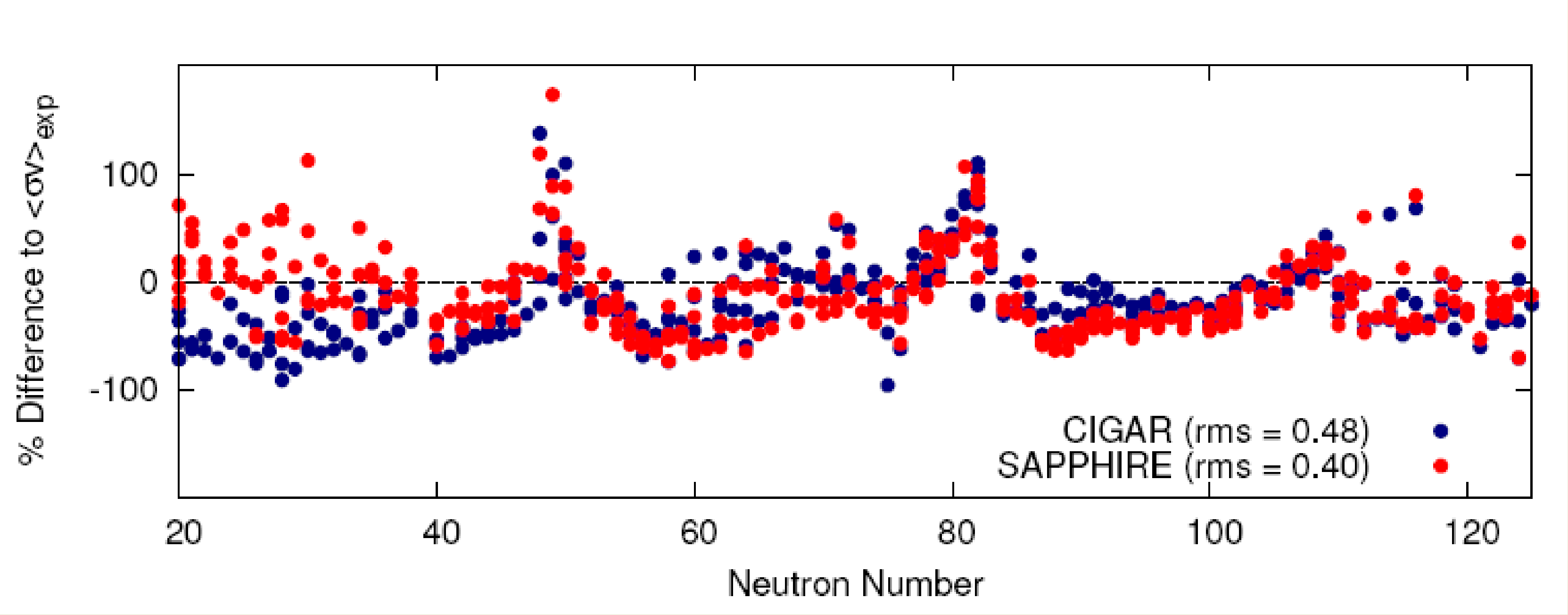
CIGAR **(Capture Induced Gamma-ray Reactions)**

Contain identically implemented nuclear models

Calculations performed for ~340 nuclei in KADoNiS database

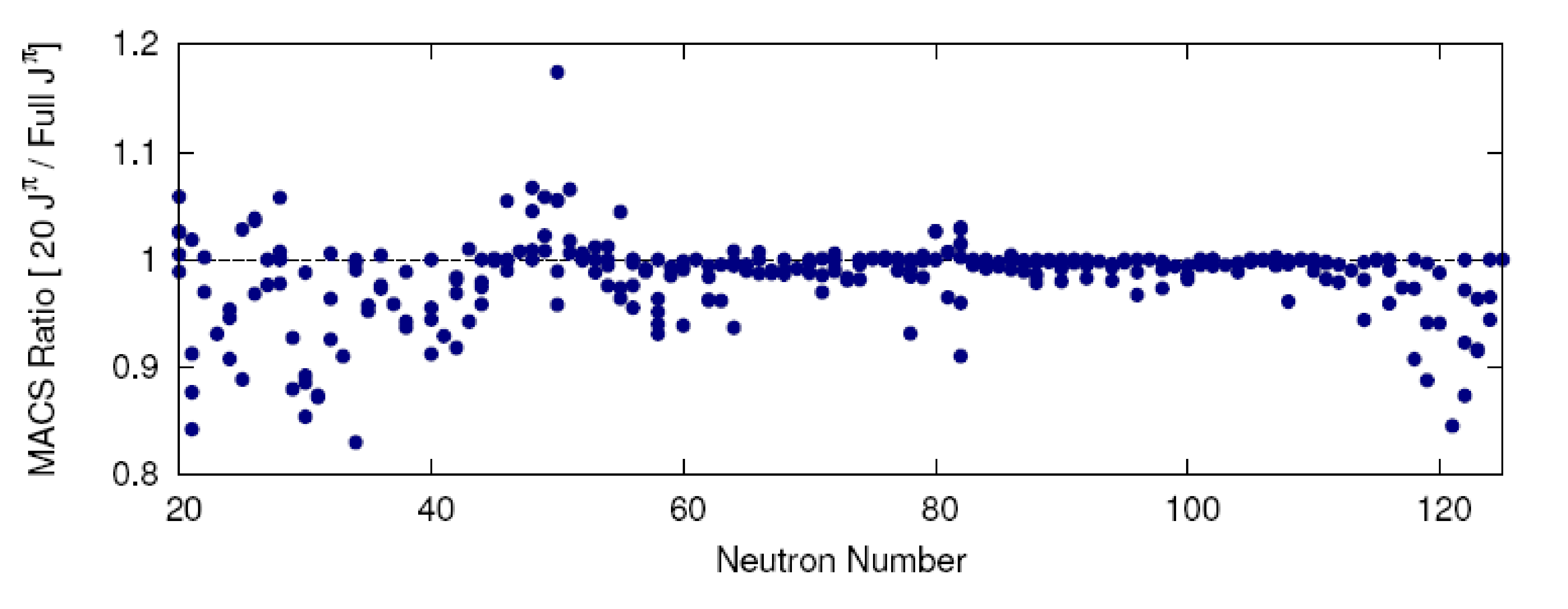
→calculated MACS @ 30keV compared to exp. MACS

CIGAR vs SAPPHIRE



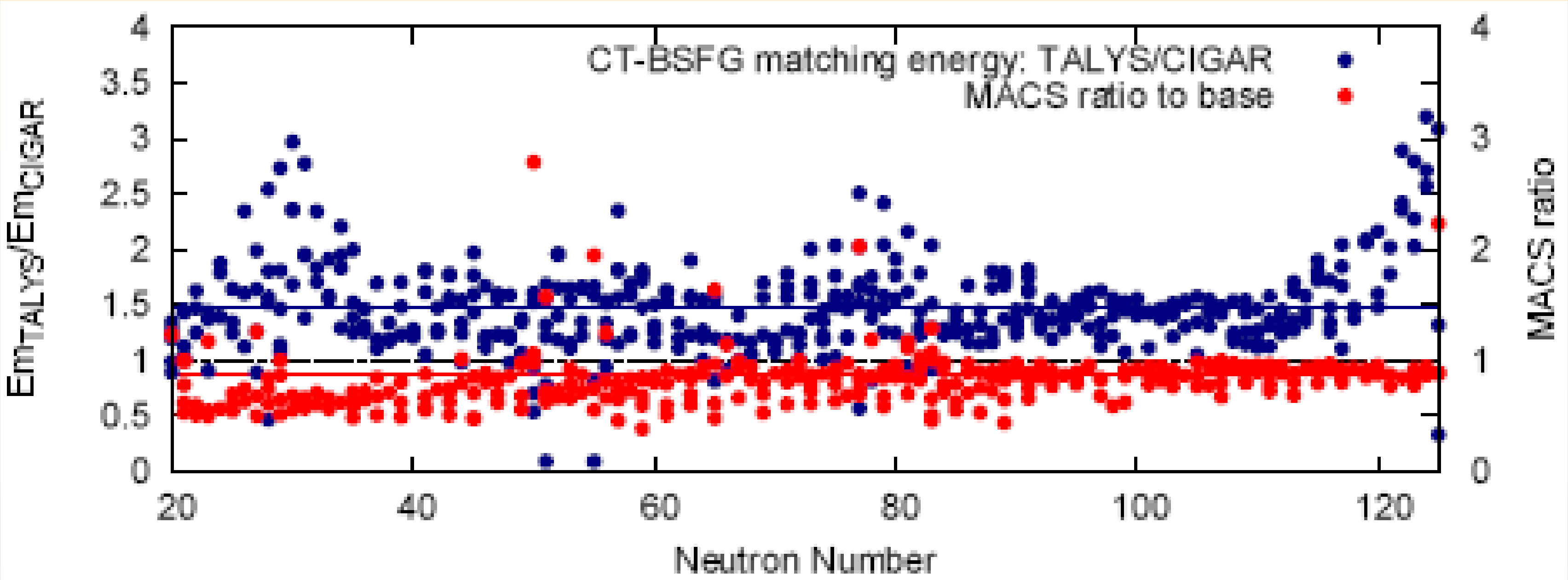
Identical nuclear models in both codes. Differences due to Jπ data truncation

Code approximation:
Jπ truncation



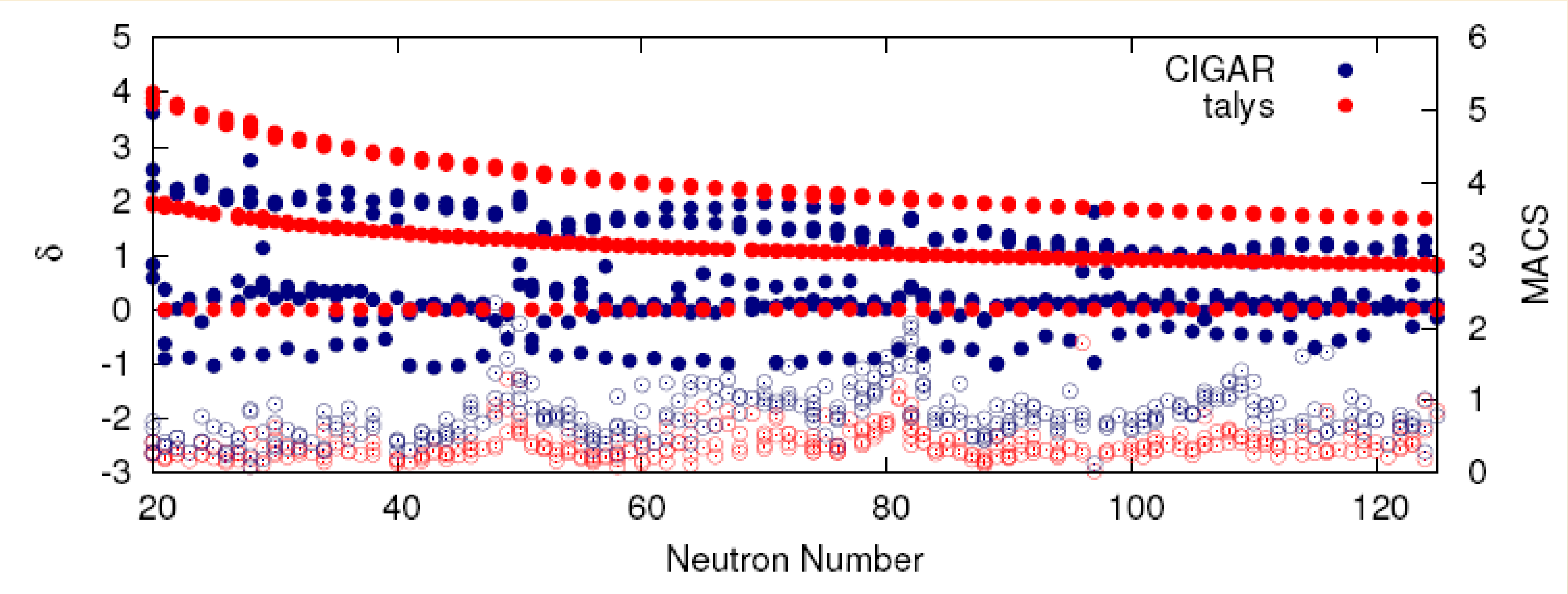
→ Truncating Jπ data use can impact calculations

Model Implementation:
CT – BSFG matching E



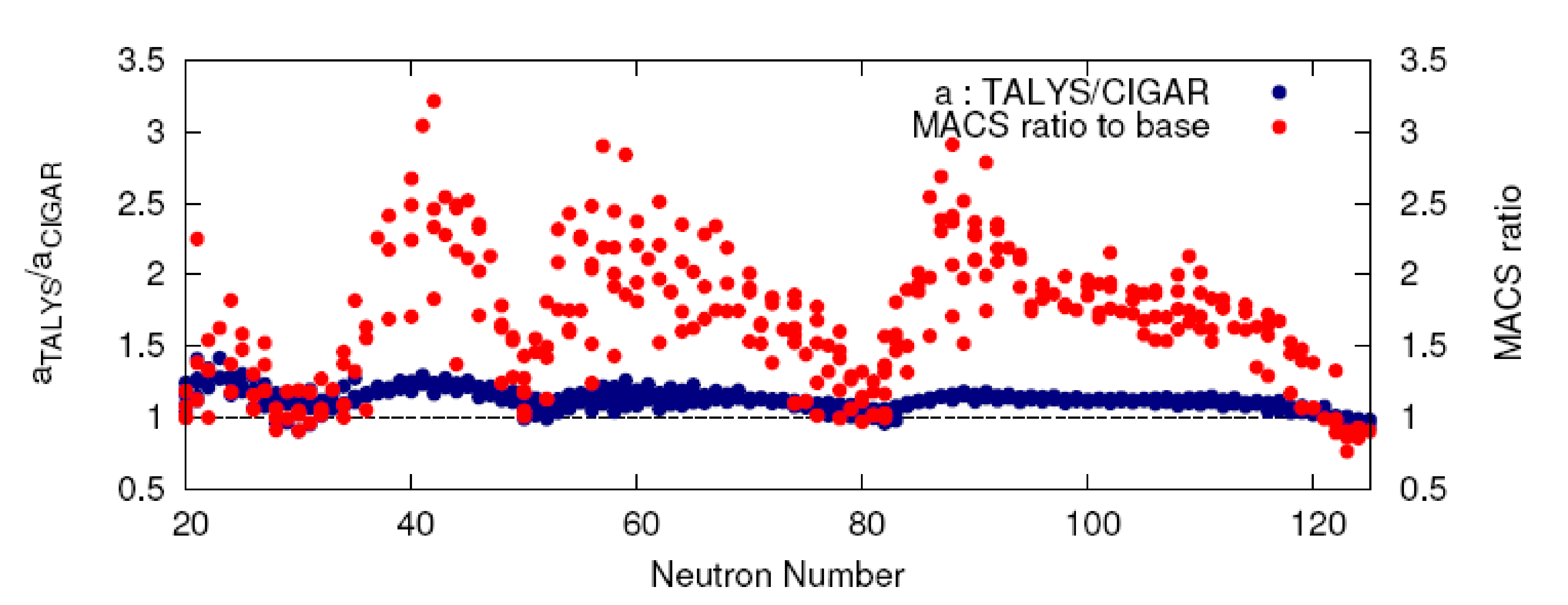
Larger Em leads to modest reduction of MACS

Model Implementation:
LD model BSGF δ



Both codes use BSFG, but different def. of back-shift
→ Reflected in MACS

Model Implementation:
LD parameter *a*



Conclusions

HF rates are integral to huge number of applications

Large number of different types of uncertainties, good to ~ factor 3….but that is not all models

- But also from code assumptions and implementation

Collaborators

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