Astrophysical Implications of Recent Photo-Absorption Cross Section Measurements

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Nucleosynthesis Overview

- Nuclear abundance data comes from:

  Meteorite analysis (primary source)
  Solar system observations (Sun, planetary rocks)
  Star light observations (galactic & extra-galactic)

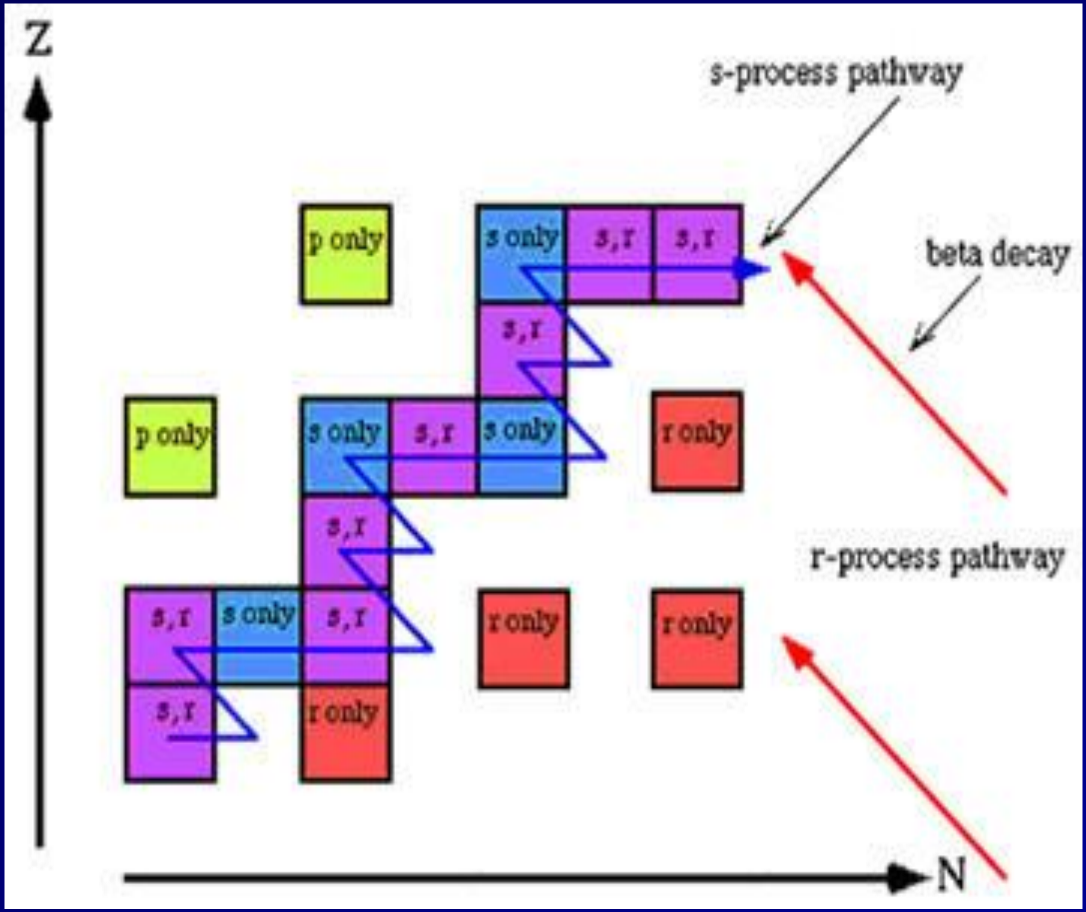
- Conclusion:

  no one process can explain abundance pattern

- Above Fe, nuclei are produced by the r, s and p process

  ($Z<26$ by thermonuclear stellar burning)

Nucleosynthesis Mechanisms

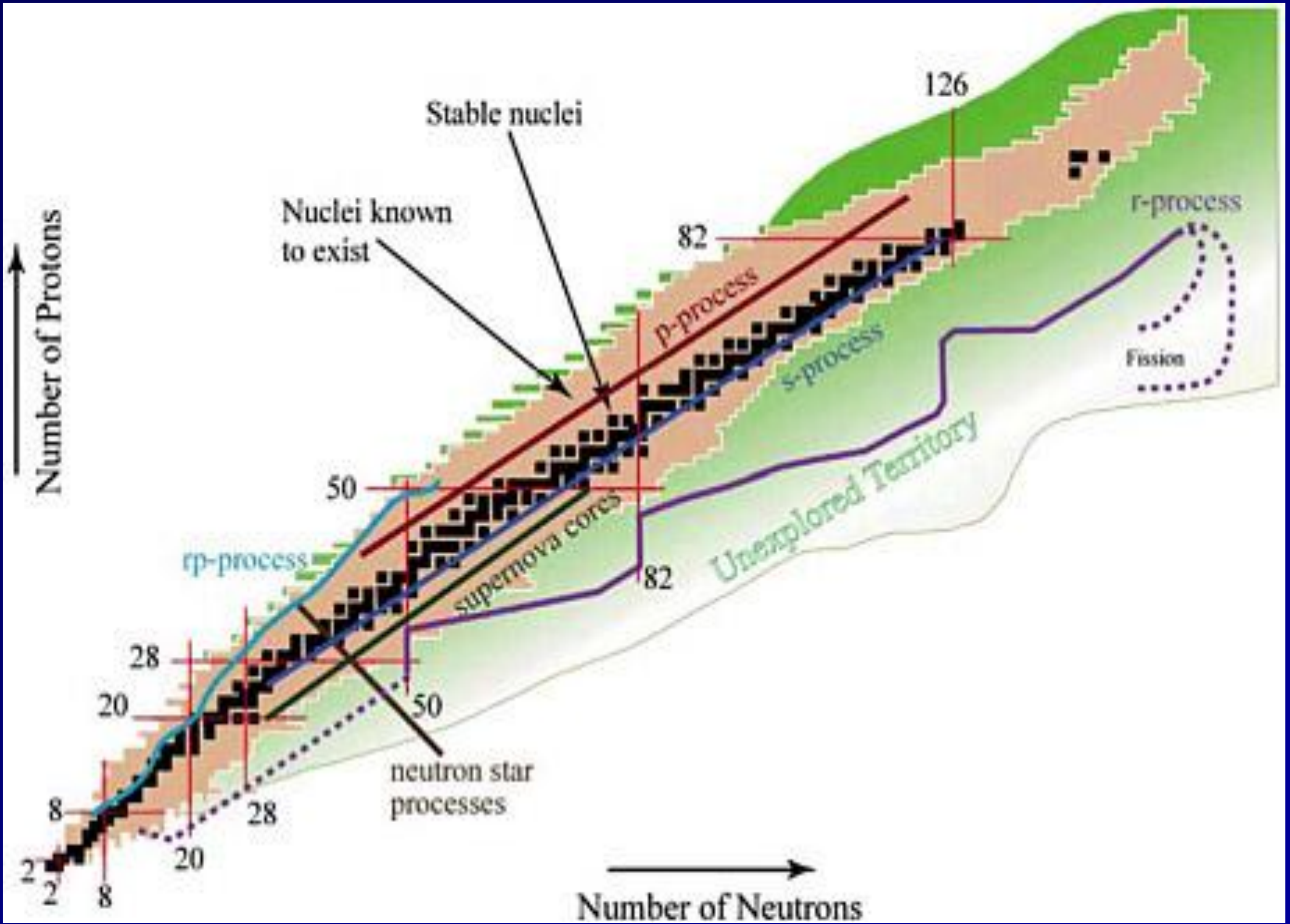


s-process:
(weak) Core He/shell C
(main) He shell AGB stars

β^- decay rates < n capture

r-process:
neutron star mergers
Type II SN

β^- decay rates > n capture

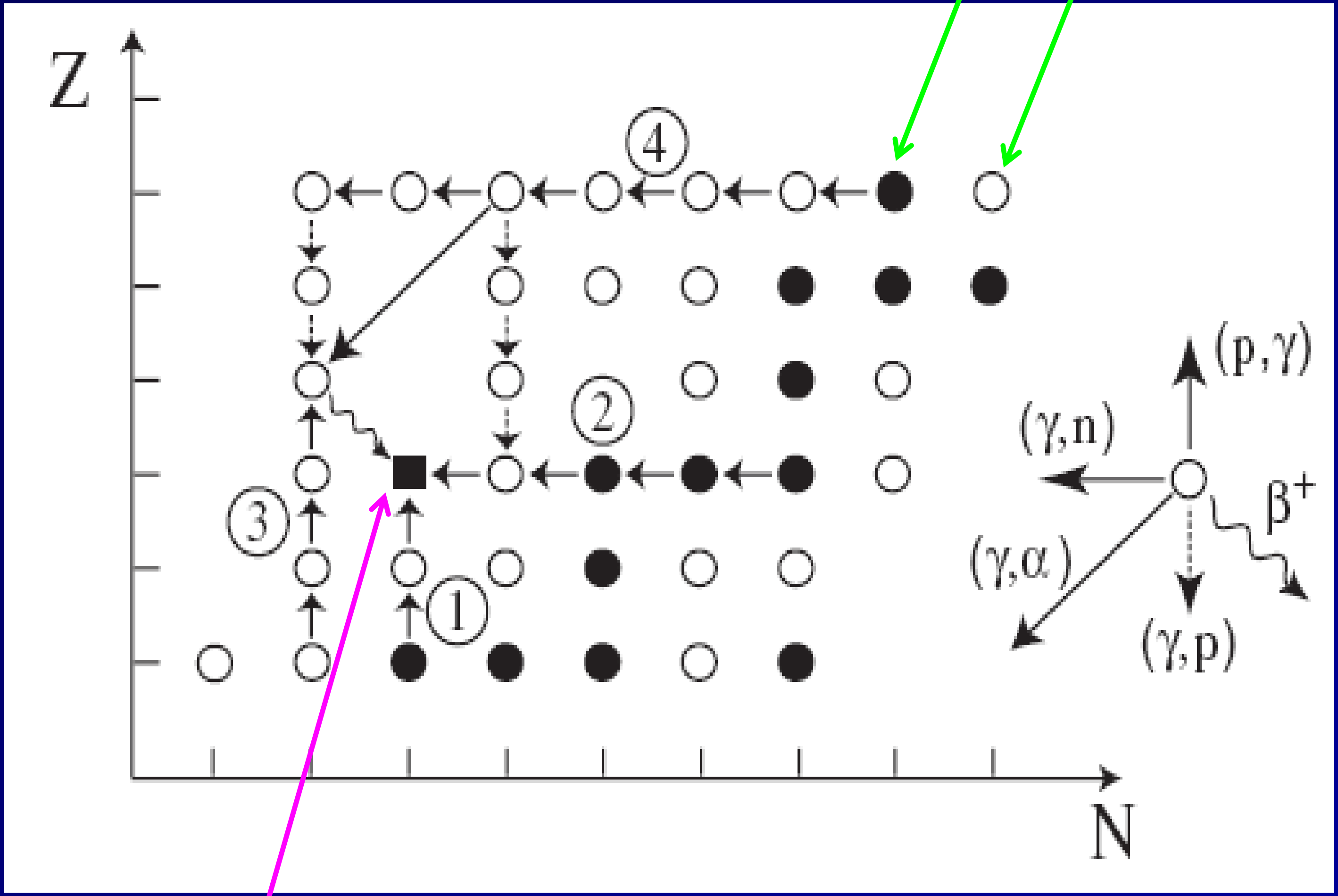

Stable nuclei
Nuclei known
to exist
126
82
50
28
20
8
2
p-process
s-process
r-process
Fission
rp-process
supernova cores
Unexplored Territory
neutron star
processes
Number of Protons
Number of Neutrons

The p - process

- Predominantly (γ,n), (γ,p), (γ,α) reactions
- Formed from s & r –process seeds
- Neutron deficient

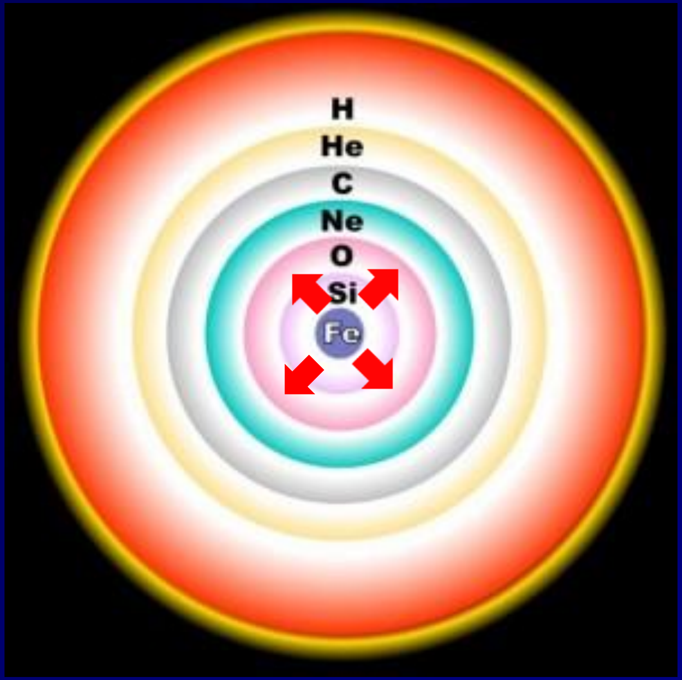
Scenario:

- T=2-3 GK
- Short time scale

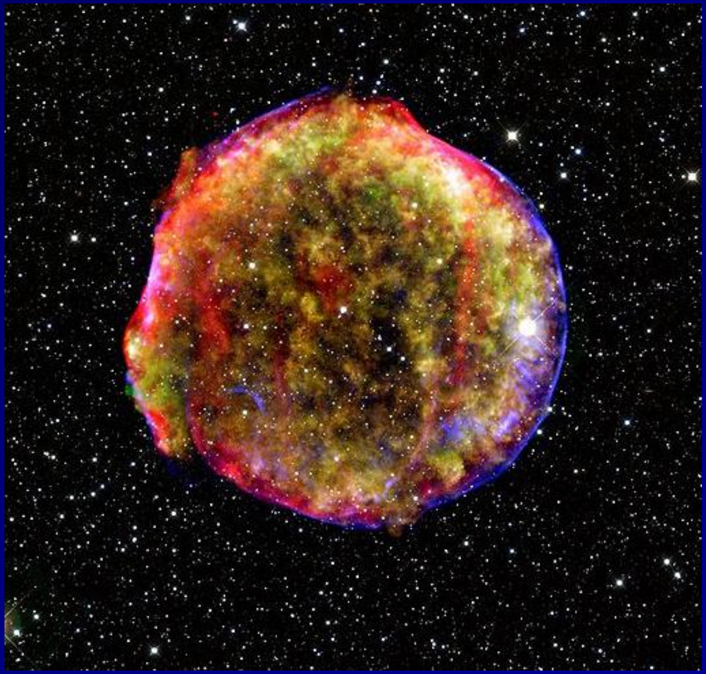


Specific paths are critically T dependent

Where?



Type II SN shock front passing through Ne/O layer

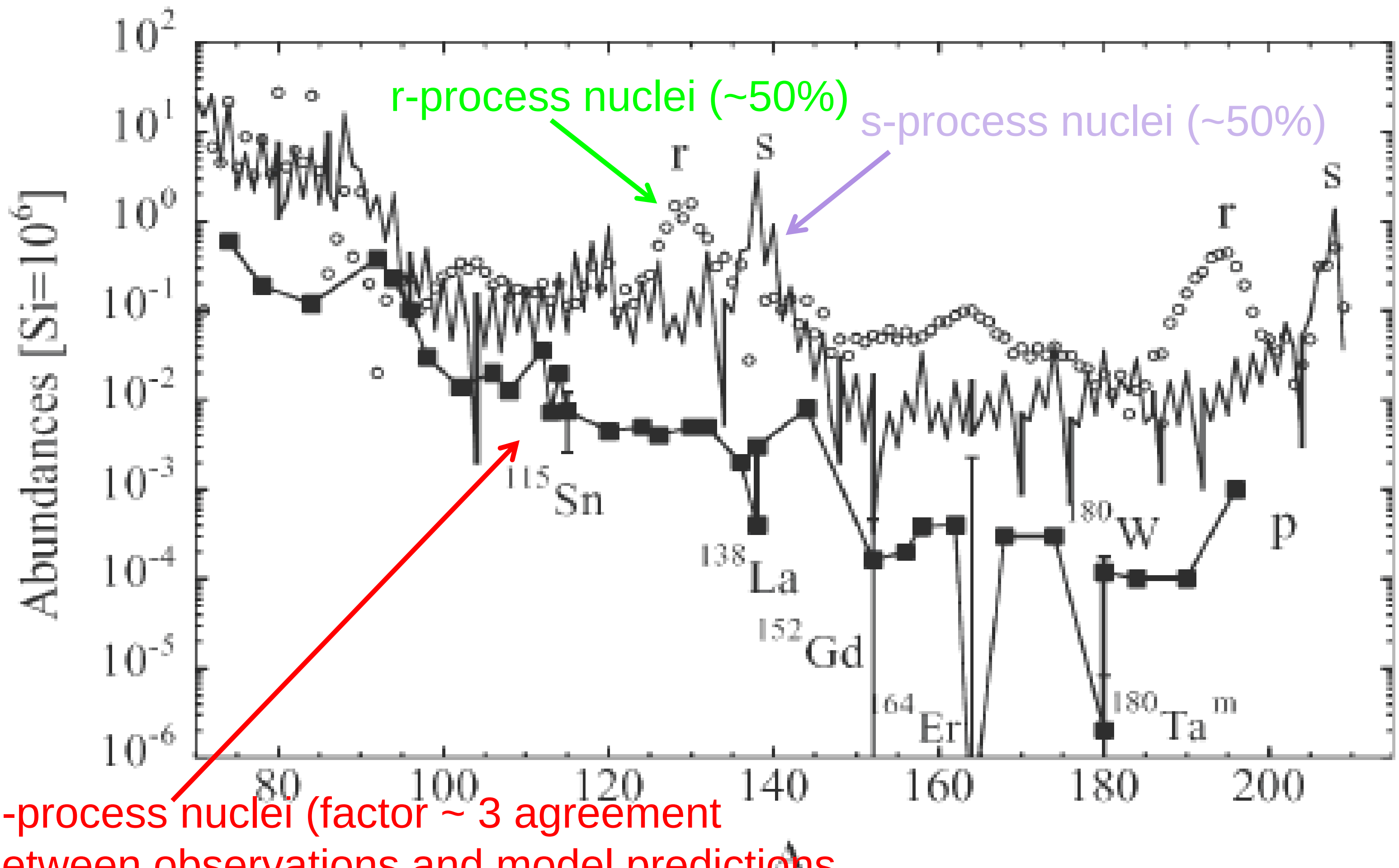


Type Ia supernova

Also suggested:

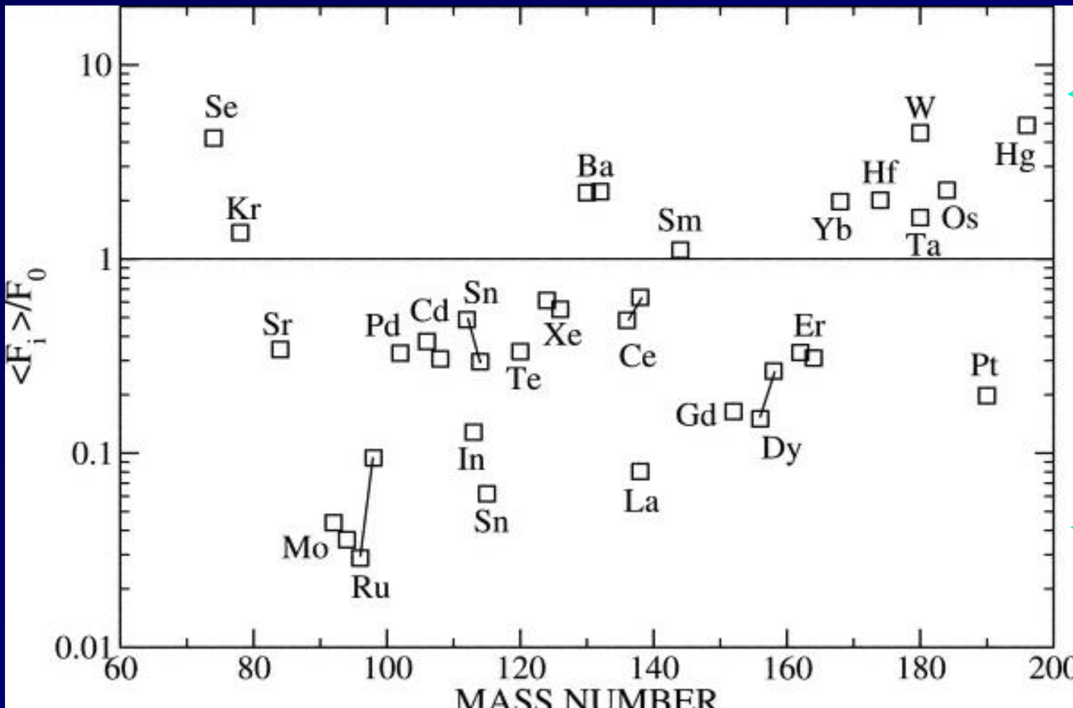
- Presupernova Ne/O layers
- Accretion discs

Solar system abundance contributions



p-process nuclei (factor ~ 3 agreement between observations and model predictions for most nuclei)

Anomalies



Over produced

Matched

Under produced

Possible causes :

→ Nuclear physics parameters (eg: α optical model)

→ New sites? (eg: rp-process in n.s layers)

→ Enhancement in γ absorption (eg: pygmy dipole)

Model Ingredients

p – process synthesis requires:

- 10,000 + reactions

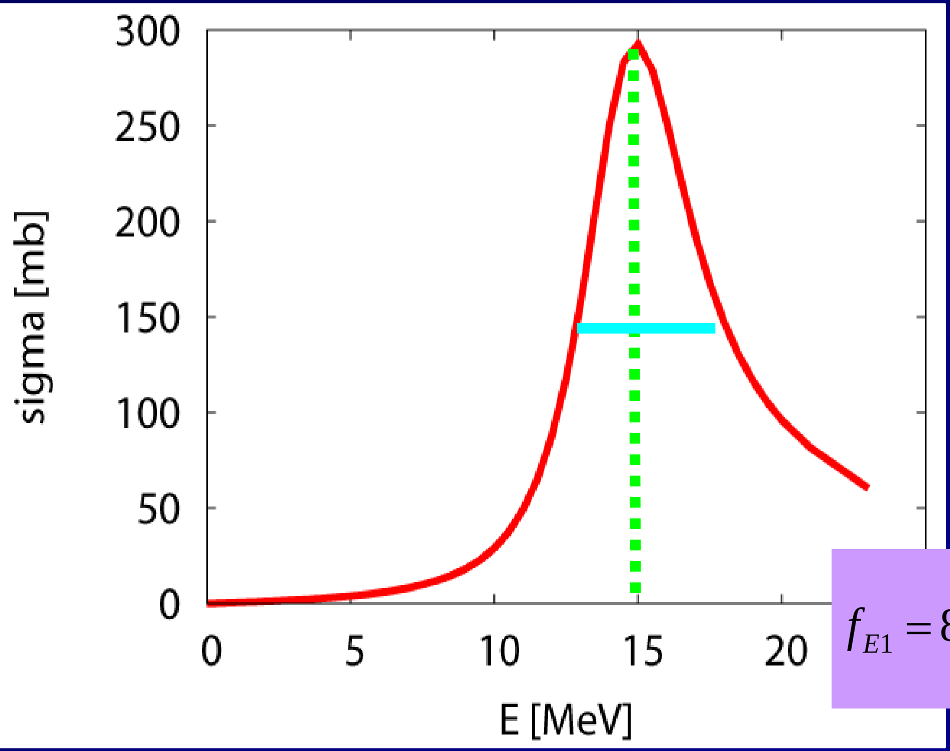
→ reliant on statistical model calculations (HF)

- Optical potentials
- Level densities
- Photon transmission function → dominated by the GDR
- Need x-sec data at astrophysically relevant energy

→ reaction network to model nucleosynthesis

Modeling the GDR

- Typically described by Γ, σ and E



Brink – Axel:

$$f_{E1} = 8.68x10^{-8} \frac{\sigma_0 E_\gamma \Gamma^2}{(E_\gamma^2 - E^2)^2 + E_\gamma^2 \Gamma^2}$$

Kopecky - Uhl:

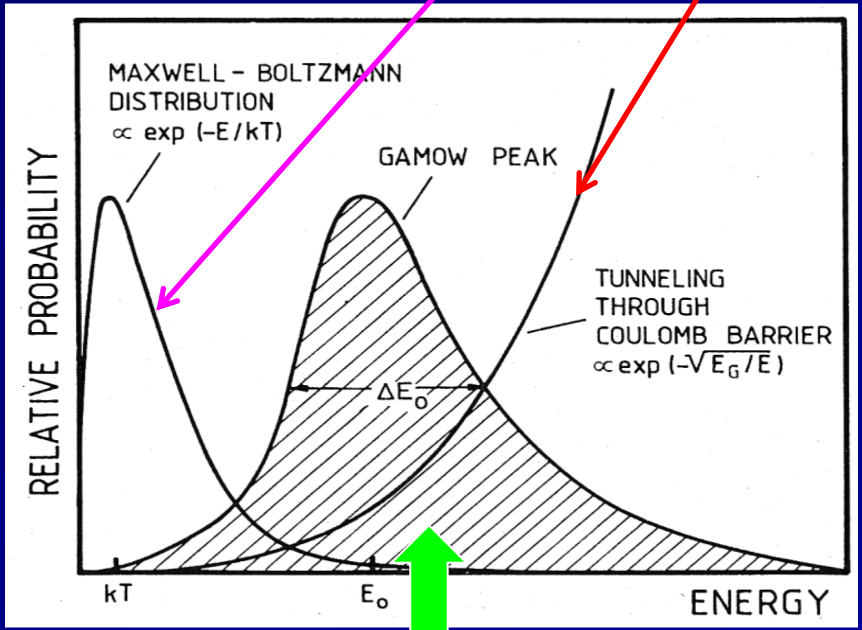
$$f_{E1} = 8.68x10^{-8} \left[\frac{E_\gamma \Gamma(E_\gamma)}{(E_\gamma^2 - E^2)^2 + E_\gamma^2 \Gamma(E_\gamma)^2} + \frac{0.7\Gamma 4\pi^2 T^2}{E^3} \right] \sigma_0 \Gamma$$

Energy dependent damping term

Astrophysically relevant energy

Charged particle :

$$N_A < \sigma v > \propto T^{-3/2} \int \exp\left(-\frac{E}{kT}\right) \sigma E dE$$

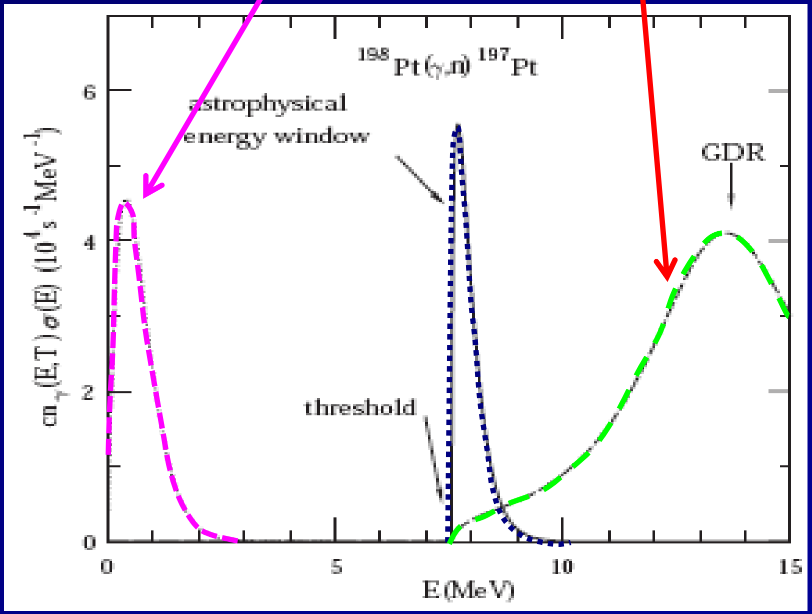


Gamow Window – effective stellar burning energy

Astrophysically relevant energy

Photodissociation :

$$\lambda_{(\gamma,j)} = \int_0^\infty c n_\gamma(E,T)\, \sigma_{(\gamma,j)}(E)\, dE$$



P. Mohr Phys Rev C 61 045802 (2000)

Impact of ELBE measurements

- Dipole strength function measurements performed for :

^{88}Sr, ^{90}Zr, ^{92}Mo, ^{94}Mo, ^{96}Mo, ^{98}Mo, ^{100}Mo, ^{139}La

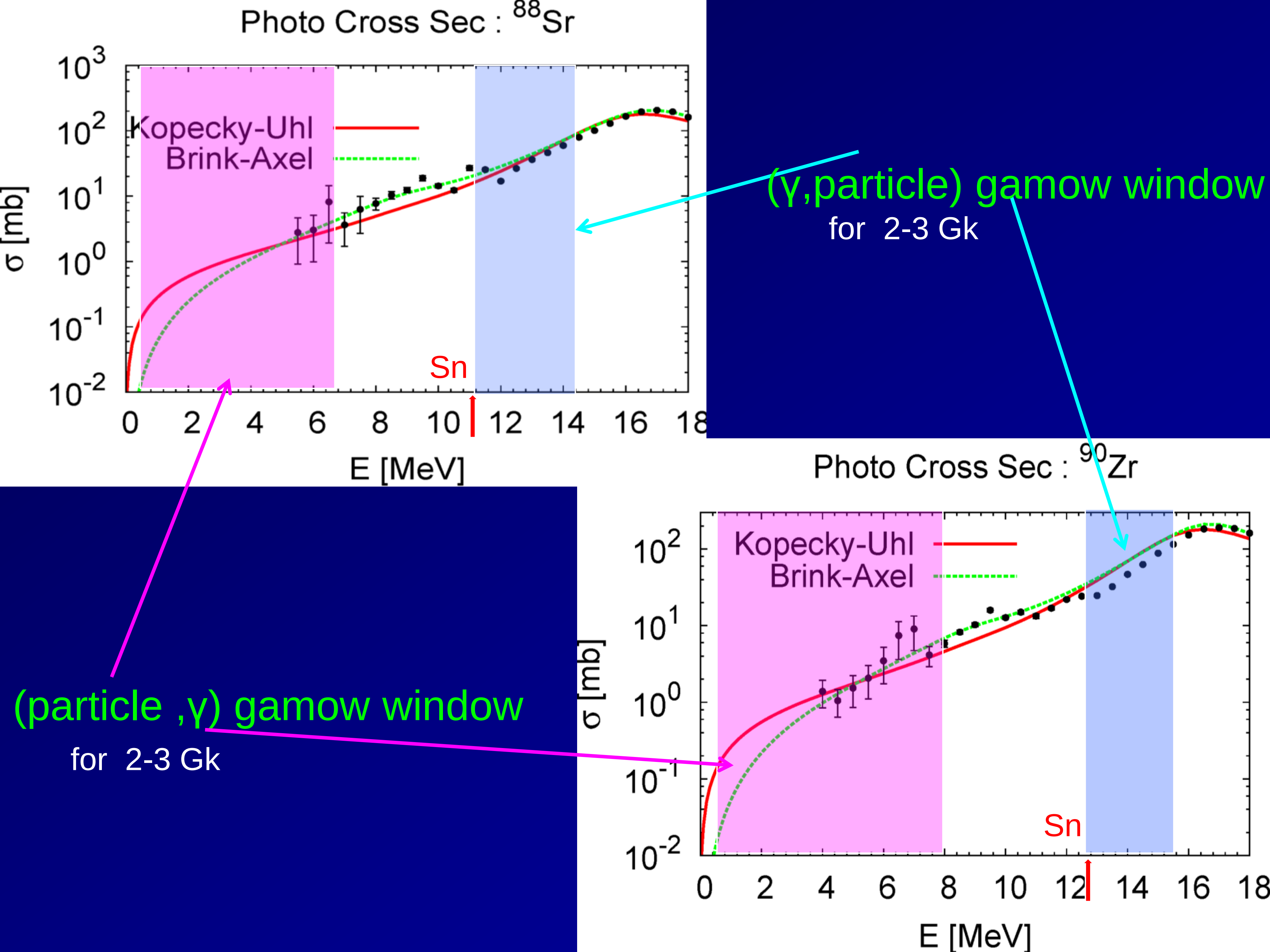


Photo Cross Sec : ^{88}Sr
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
σ [mb]
Kopecky-Uhl
Brink-Axel
Sn
0 2 4 6 8 10 12 14 16 18
E [MeV]
(γ,particle) gamow window
for 2-3 Gk
Photo Cross Sec : ^{90}Zr
10^2
10^1
10^0
10^{-1}
10^{-2}
σ [mb]
Kopecky-Uhl
Brink-Axel
Sn
0 2 4 6 8 10 12 14 16 18
E [MeV]
(particle ,γ) gamow window
for 2-3 Gk

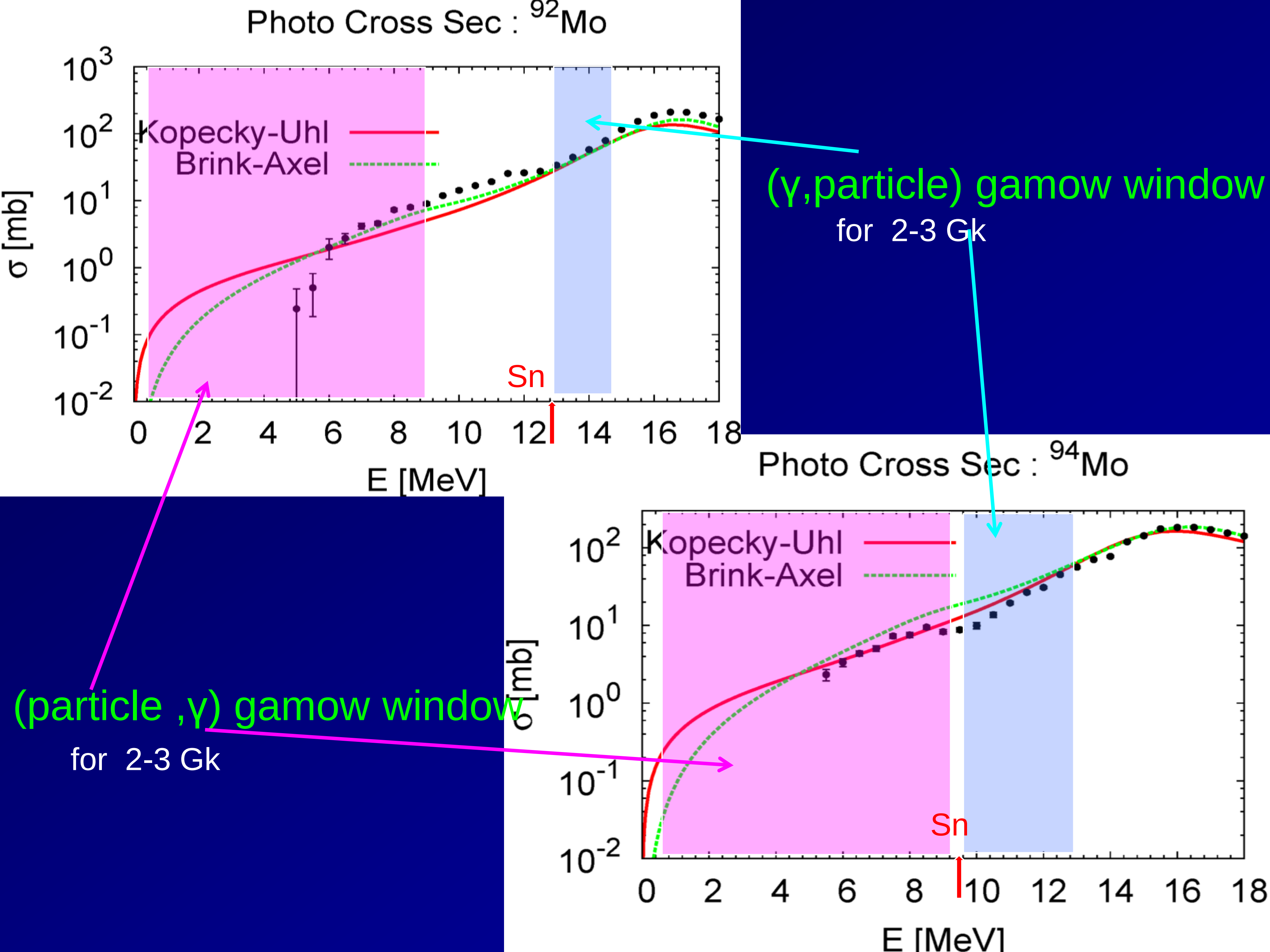


Photo Cross Sec : 92Mo
Kopecky-Uhl
Brink-Axel
σ [mb]
E [MeV]
Sn
(γ,particle) gamow window
for 2-3 Gk
Photo Cross Sec : 94Mo
Kopecky-Uhl
Brink-Axel
σ [mb]
E [MeV]
Sn
(particle ,γ) gamow window
for 2-3 Gk

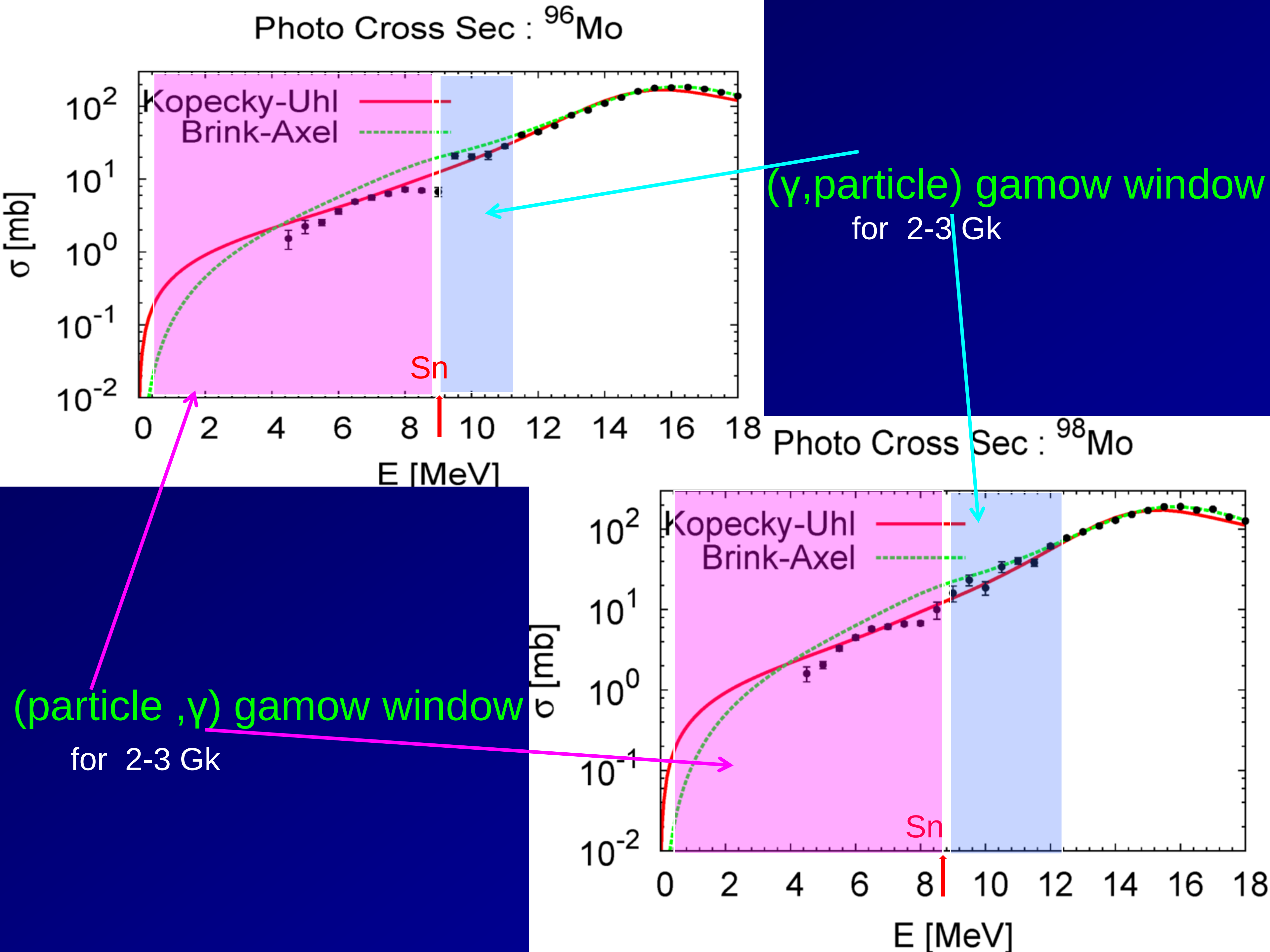
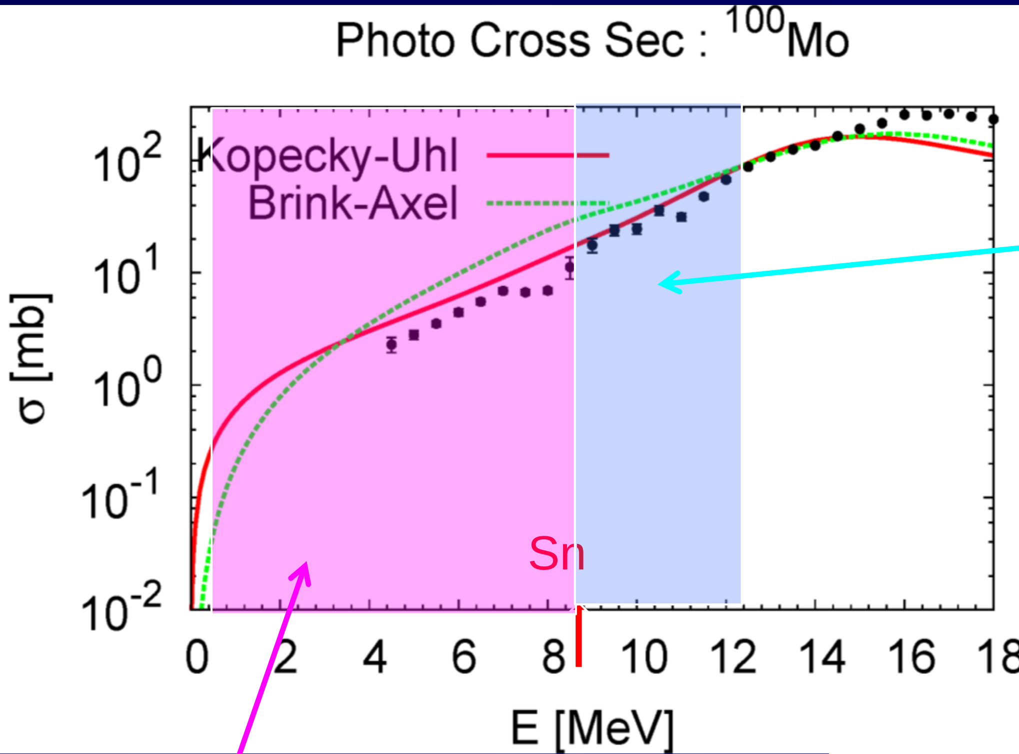


Photo Cross Sec : 96Mo
Kopecky-Uhl
Brink-Axel
σ [mb]
Sn
E [MeV]
(γ,particle) gamow window
for 2-3 Gk
Photo Cross Sec : 98Mo
Kopecky-Uhl
Brink-Axel
σ [mb]
Sn
E [MeV]
(particle ,γ) gamow window
for 2-3 Gk

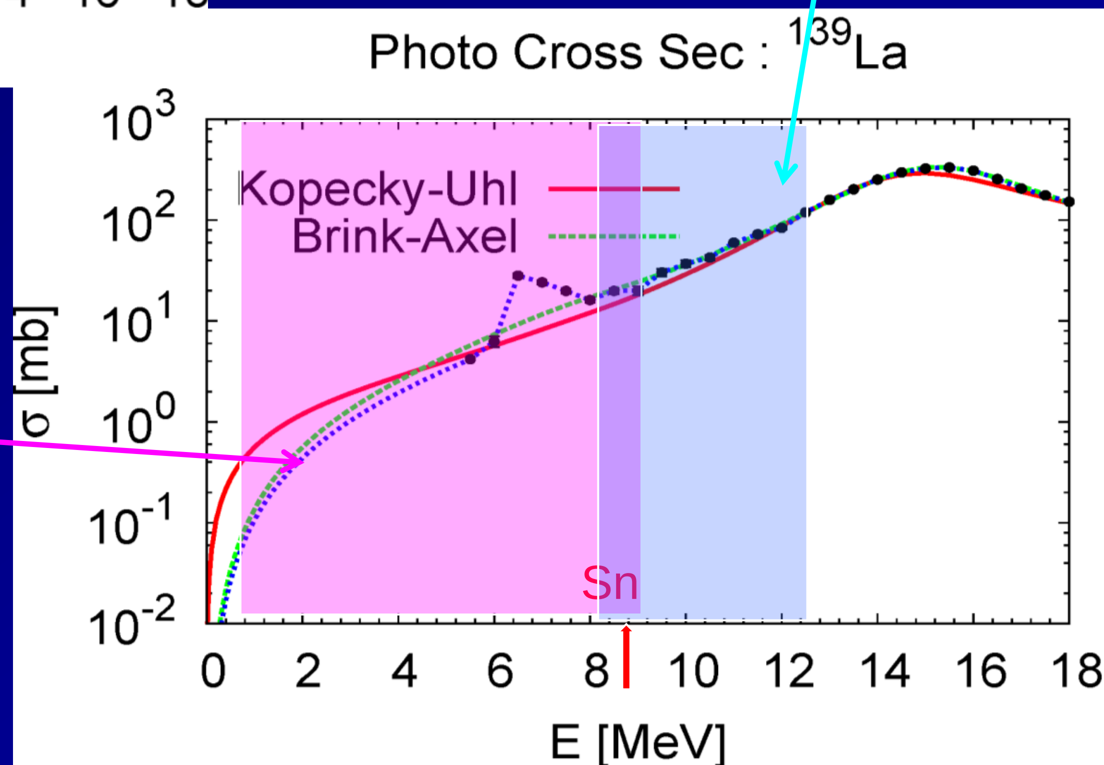


(γ,particle) gamow window

for 2-3 Gk

(particle ,γ) gamow window

for 2-3 Gk



Astrophysical Implications

Using HF code TALYS:

→ Replaced photo-strength calculation

(possible models: Kopecky-Uhl, Brink-Axel, microscopic models)

calculate (E1) strength function according to:

$$f_{E1}(E_\gamma) = \frac{\langle \sigma_\gamma (E_\gamma) \rangle}{3(\pi \hbar c)^2 E_\gamma}$$

obtain transmission co-efficient:

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

Reaction σ can then be obtained from:

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

M1 transmission co-efficient obtained from Brink-Axel

TALYS default OMP used (Nucl. Phys. A713, 231 2003)

Level density model: BSFG

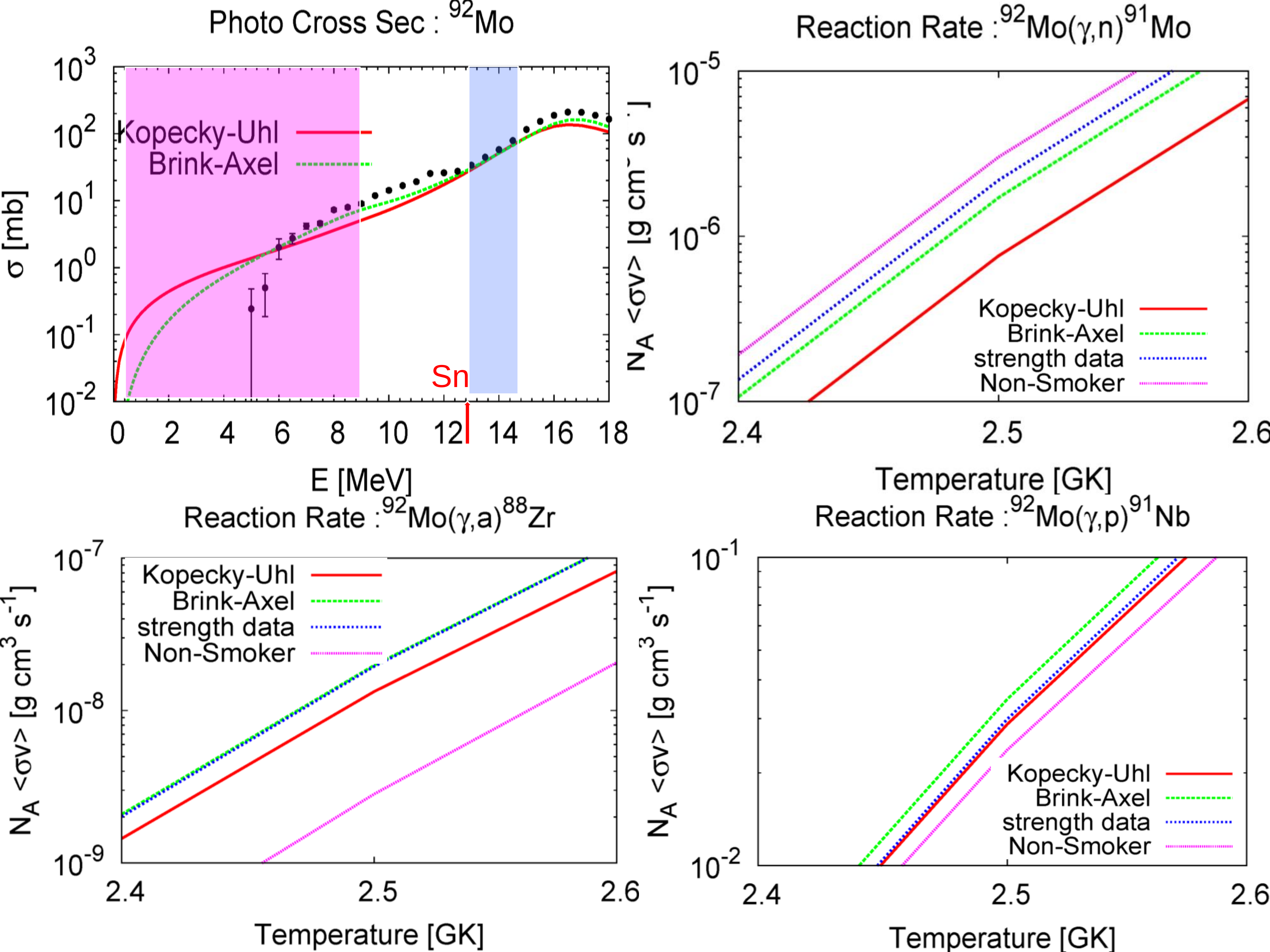


Photo Cross Sec : 92Mo
σ [mb]
E [MeV]
Kopecky-Uhl
Brink-Axel
Sn
10^3
10^2
10^1
10^0
10^-1
10^-2
0
2
4
6
8
10
12
14
16
18
Reaction Rate : 92Mo(γ,n)91Mo
NA <σv> [g cm3 s-1]
Temperature [GK]
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
10^-5
10^-6
10^-7
2.4
2.5
2.6
Reaction Rate : 92Mo(γ,a)88Zr
NA <σv> [g cm3 s-1]
Temperature [GK]
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
10^-7
10^-8
10^-9
2.4
2.5
2.6
Reaction Rate : 92Mo(γ,p)91Nb
NA <σv> [g cm3 s-1]
Temperature [GK]
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
10^-1
10^-2
2.4
2.5
2.6

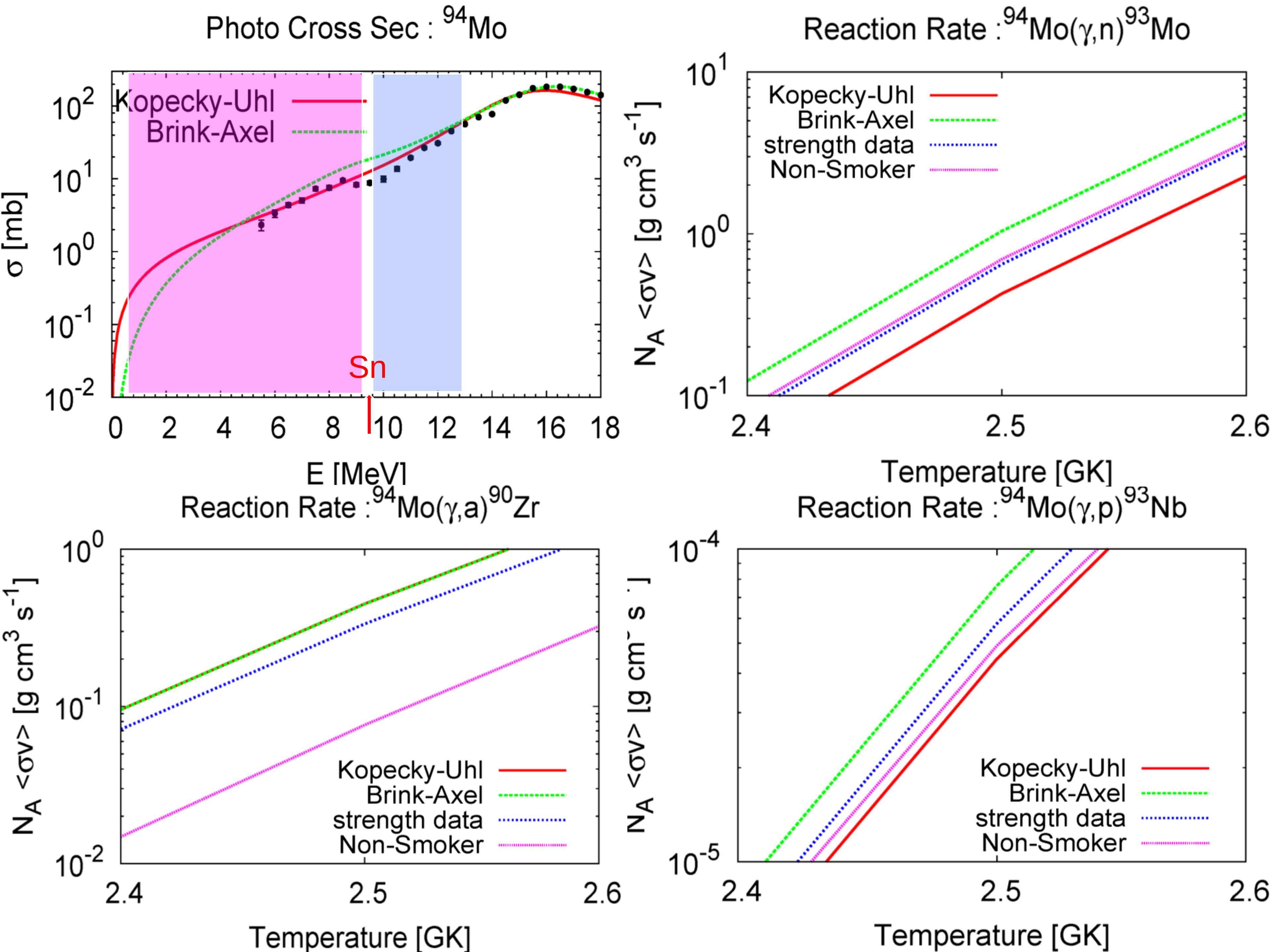


Photo Cross Sec : 94Mo
σ [mb]
E [MeV]
Kopecky-Uhl
Brink-Axel
Sn
Reaction Rate : 94Mo(γ,n)93Mo
NA <σv> [g cm3 s-1]
Temperature [GK]
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
Reaction Rate : 94Mo(γ,a)90Zr
NA <σv> [g cm3 s-1]
Temperature [GK]
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
Reaction Rate : 94Mo(γ,p)93Nb
NA <σv> [g cm s]
Temperature [GK]
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker

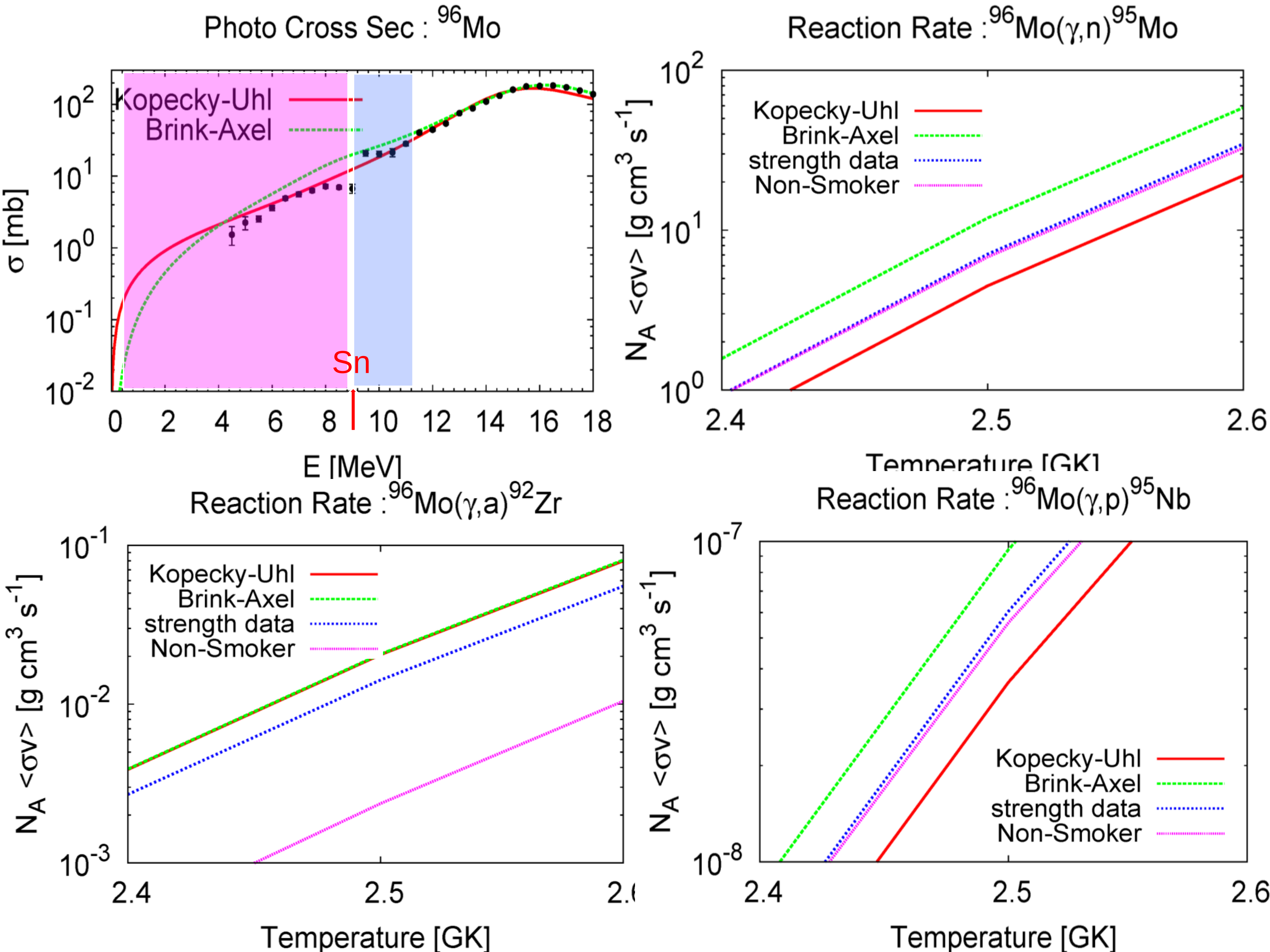


Photo Cross Sec : 96Mo
Kopecky-Uhl
Brink-Axel
σ [mb]
10^2
10^1
10^0
10^-1
10^-2
Sn
0 2 4 6 8 10 12 14 16 18
E [MeV]
Reaction Rate : 96Mo(γ,n)95Mo
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^-1]
10^2
10^1
10^0
2.4 2.5 2.6
Temperature [GK]
Reaction Rate : 96Mo(γ,a)92Zr
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^-1]
10^-1
10^-2
10^-3
2.4 2.5
Temperature [GK]
Reaction Rate : 96Mo(γ,p)95Nb
N_A <σv> [g cm^3 s^-1]
10^-7
10^-8
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
2.4 2.5 2.6
Temperature [GK]

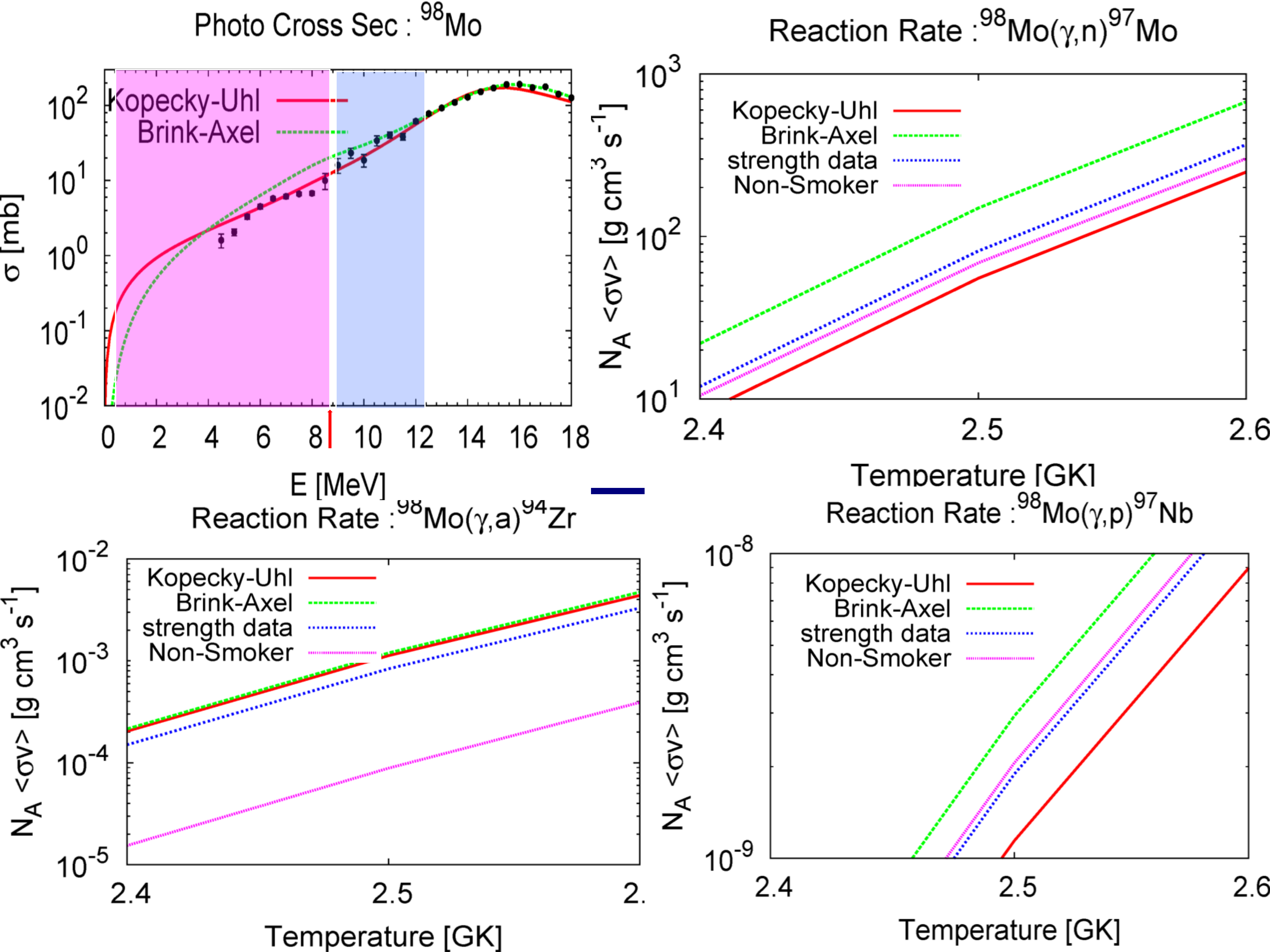


Photo Cross Sec : ^{98}Mo
Kopecky-Uhl
Brink-Axel
σ [mb]
E [MeV]
Reaction Rate : ^{98}Mo(γ,n)^{97}Mo
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^{-1}]
Temperature [GK]
Reaction Rate : ^{98}Mo(γ,a)^{94}Zr
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^{-1}]
Temperature [GK]
Reaction Rate : ^{98}Mo(γ,p)^{97}Nb
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^{-1}]
Temperature [GK]

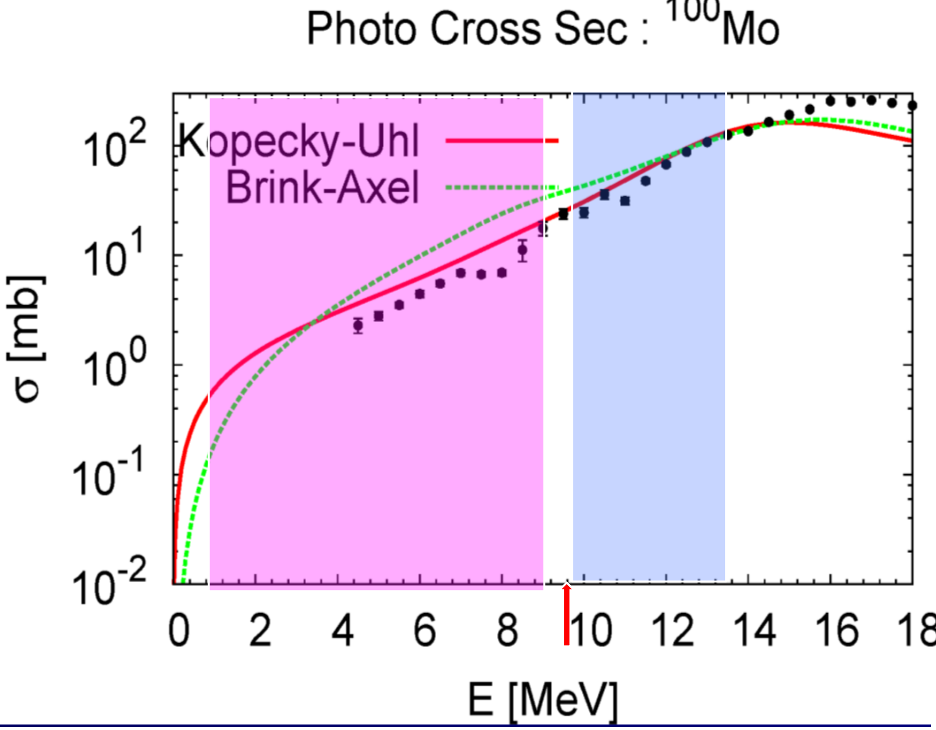
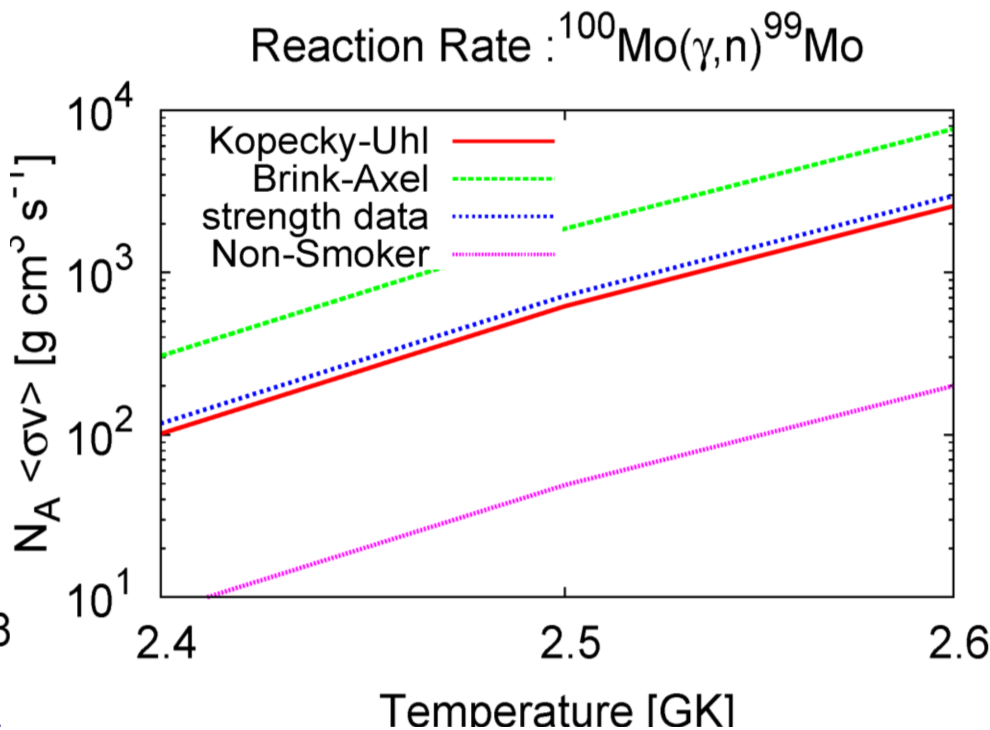
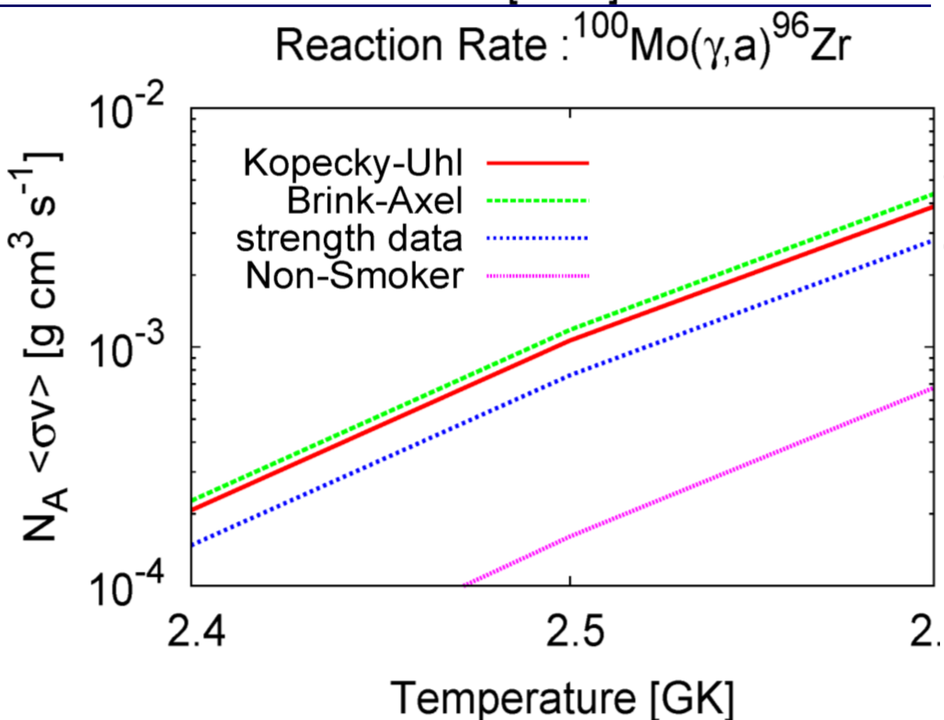
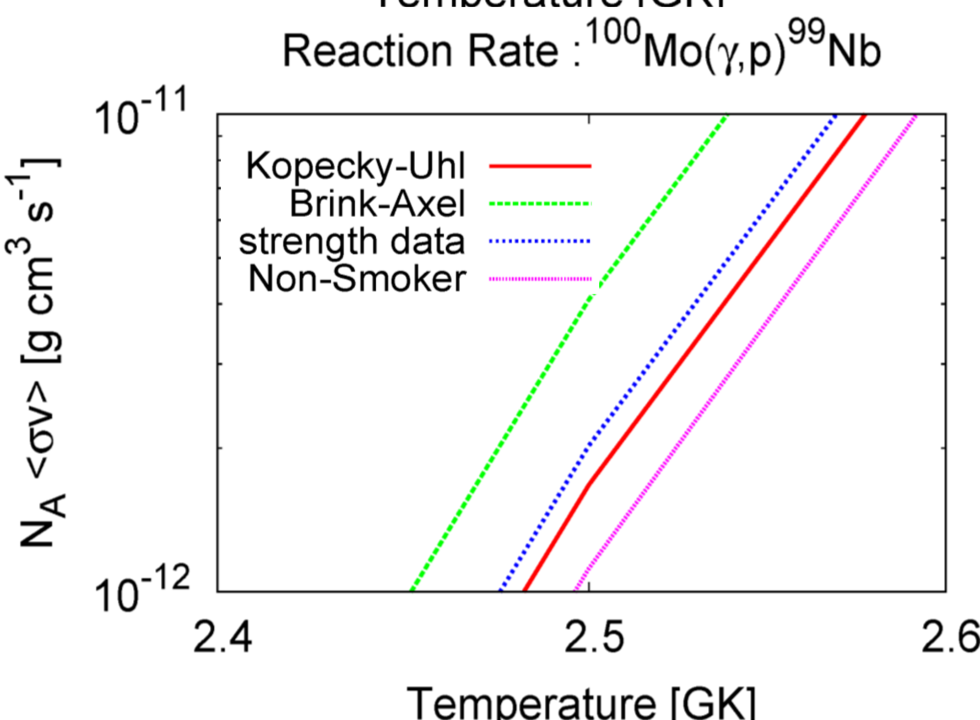


Photo Cross Sec : ^{100}Mo
Kopecky-Uhl
Brink-Axel
σ [mb]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
2
4
6
8
10
12
14
16
18
E [MeV]


Reaction Rate : ^{100}Mo(γ,n)^{99}Mo
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^{-1}]
10^{4}
10^{3}
10^{2}
10^{1}
2.4
2.5
2.6
Temperature [GK]


Reaction Rate : ^{100}Mo(γ,a)^{96}Zr
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^{-1}]
10^{-2}
10^{-3}
10^{-4}
2.4
2.5
2.
Temperature [GK]


Reaction Rate : ^{100}Mo(γ,p)^{99}Nb
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^{-1}]
10^{-11}
10^{-12}
2.4
2.5
2.6
Temperature [GK]

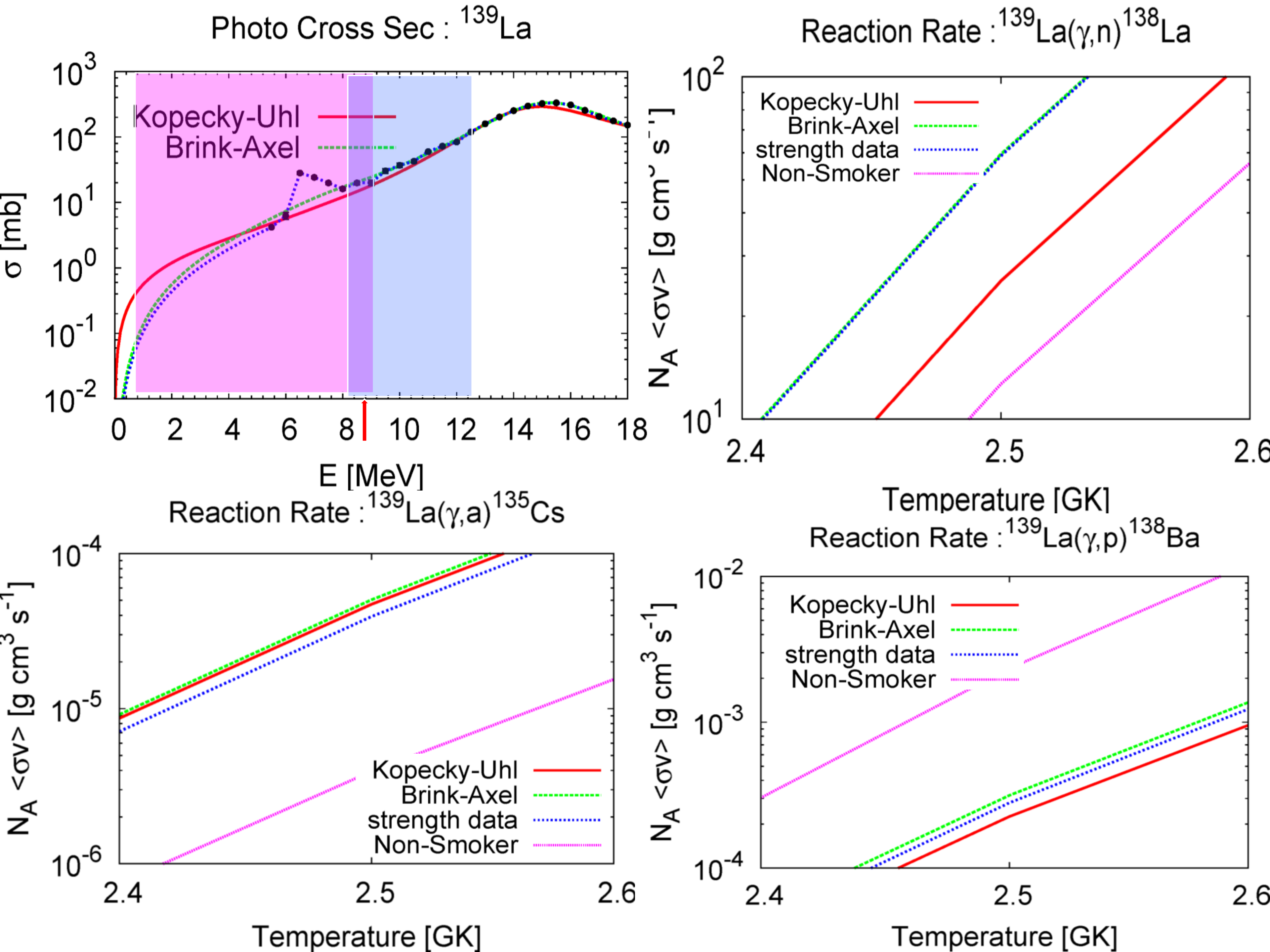


Photo Cross Sec : ^{139}La
Kopecky-Uhl
Brink-Axel
σ [mb]
E [MeV]
Reaction Rate : ^{139}La(γ,n)^{138}La
Reaction Rate : ^{139}La(γ,a)^{135}Cs
Reaction Rate : ^{139}La(γ,p)^{138}Ba
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker
N_A <σv> [g cm^3 s^{-1}]
Temperature [GK]

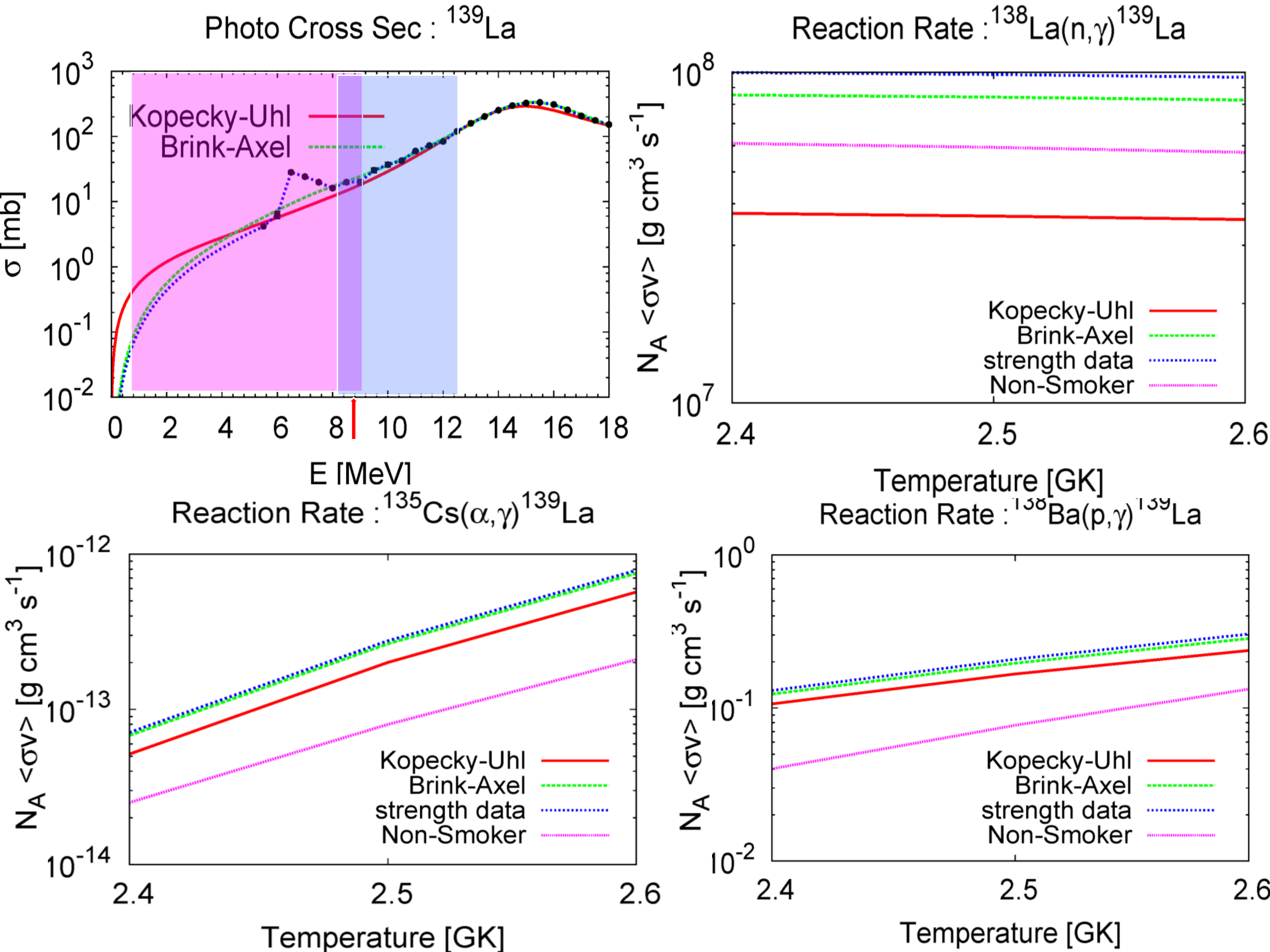


Photo Cross Sec : 139La
σ [mb]
E [MeV]
Kopecky-Uhl
Brink-Axel
Reaction Rate : 138La(n,γ)139La
Reaction Rate : 135Cs(α,γ)139La
Reaction Rate : 138Ba(p,γ)139La
N_A <σv> [g cm3 s-1]
Temperature [GK]
Kopecky-Uhl
Brink-Axel
strength data
Non-Smoker

Conclusions

- No definitive answers yet
- Data is reasonably well described by current models (disagreement with non-smoker calculations)
- Low energy pigmies do not appear to lead to large enhancements in reaction rate
- Probably does not solve the Mo underproduction problem (sensitivity study of Rapp, 2006, found reaction rate was not the cause)
- Potentially pygmy resonance near thresholds could impact reaction rates