DEGENERATE NEUTRON CAPTURE RATES IN NEUTRON STAR BINARY SYSTEMS

WE WILL INVESTIGATE NS-BH MERGERS AND X-RAY BINARIES

- Neutron star paired with low mass companion
- Large flux of proton rich matter interacts with NS atmosphere/crust
- Reactions produce X-Ray bursts and change the composition of the crust

- NS-BH system gradually lose energy due to gravitational wave emission
- During the last phase of coalescence, neutron rich matter is violently ejected
- Provides the requisite free neutron density and temperature for the R-process

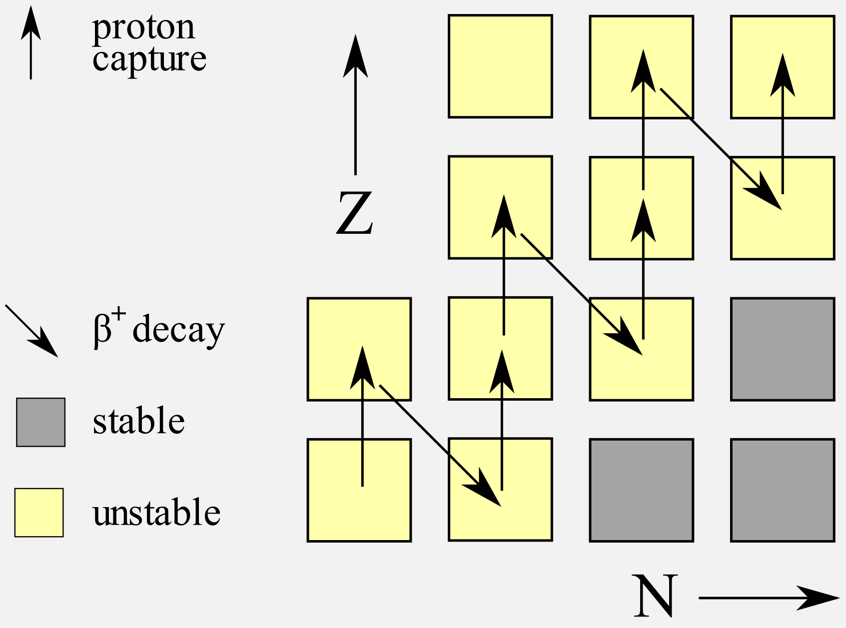
RP-PROCESS ASHES ACT AS INITIAL CONDITIONS FOR DEGENERATE NEUTRON CAPTURE CHAINS

- Neutron star is provided "fuel" via accretion from a companion star, kickstarting rp-process
- rp-process by-products (ashes) are relatively stable nuclei, dragged further down the crust[1]
- Ashes include ^{52}Fe, ^{56}Ni and ^{64}Ge

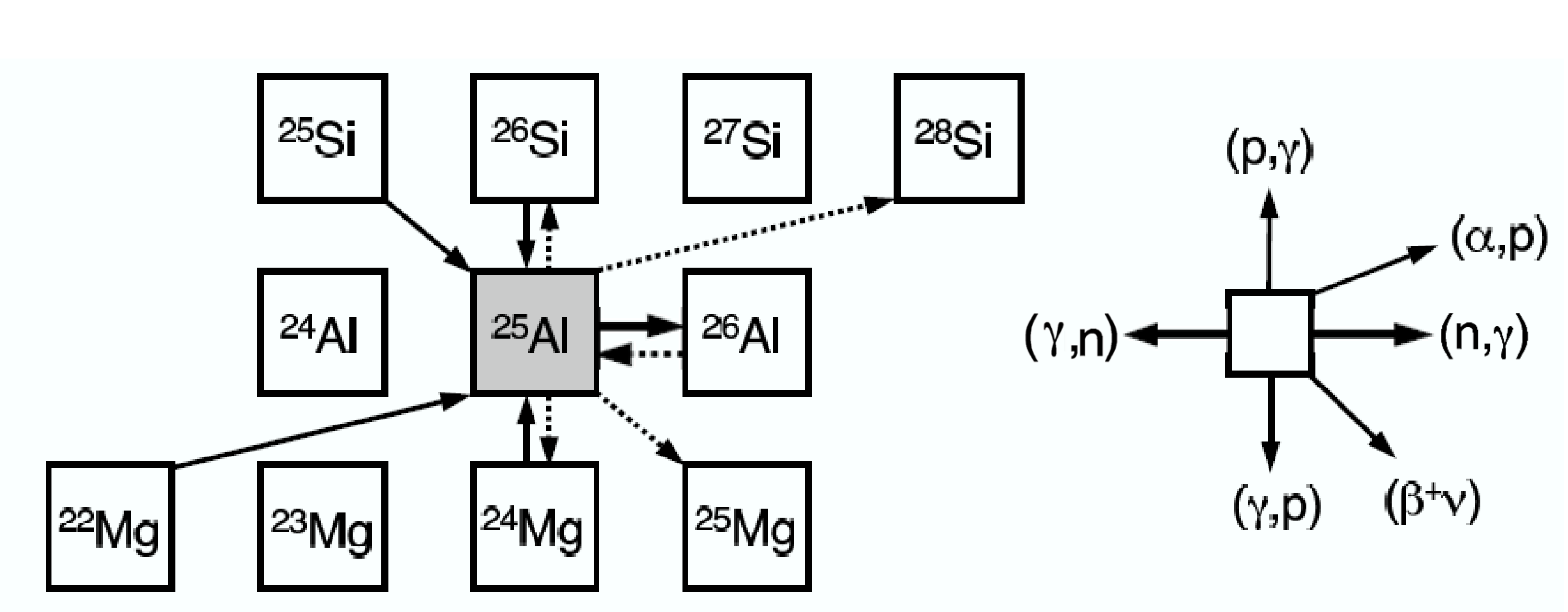
rp-process

rapid proton captures

$$X(p,\gamma)Y$$



1 - Hendrik Schatz *et al* 1999 *ApJ* **524** 1014



$$\frac{dN_{Al25}}{dt} = N_p N_{24\mathrm{Mg}}\langle\sigma v\rangle_{24\mathrm{Mg(p,}\gamma)} + N_n N_{24\mathrm{Al}}\underline{\langle\sigma v\rangle_{24\mathrm{Al(n,}\gamma)}} + \ldots$$
$$- \left[N_p N_{25\mathrm{Al}}\langle\sigma v\rangle_{25\mathrm{Al(p,}\gamma)} + N_{25\mathrm{Al}}\lambda_{25\mathrm{Al}(\gamma,\mathrm{n})} + \ldots\right]$$

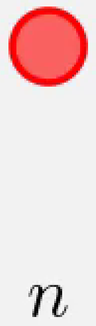
FREE NEUTRONS ARE DEGENERATE AT THERMODYNAMIC CONDITIONS RELEVANT TO OUR SYSTEMS

- Gas of neutrons are incredibly dense - we account for degenerate states

- Assuming T = 0.1 GK, neutron thermal wavelength ~160fm, while at a number density of $1 \times 10^{-4}\ fm^{-3}$ or ~ $2 \times 10^{12} g/cm^3$ neutron spacing ~ 20 fm.

- Readily available architecture assumes explosive conditions

What even is a neutron capture rate?



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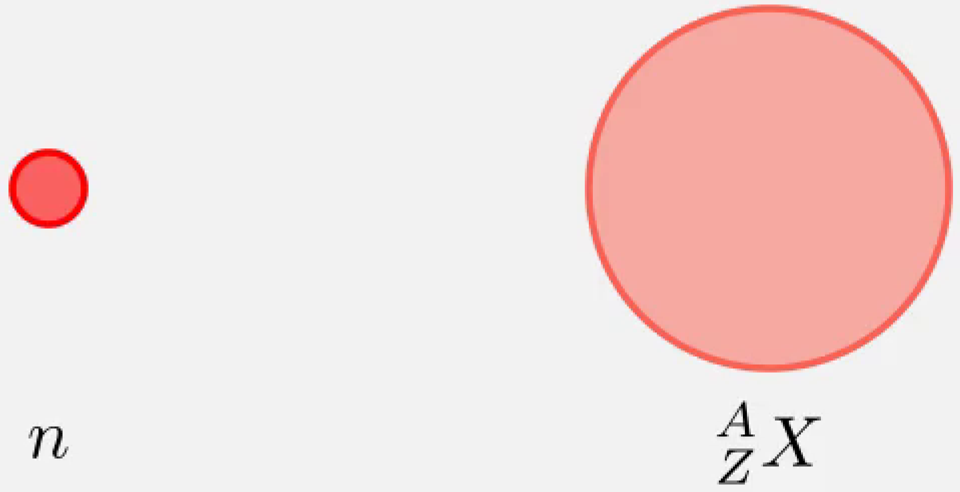
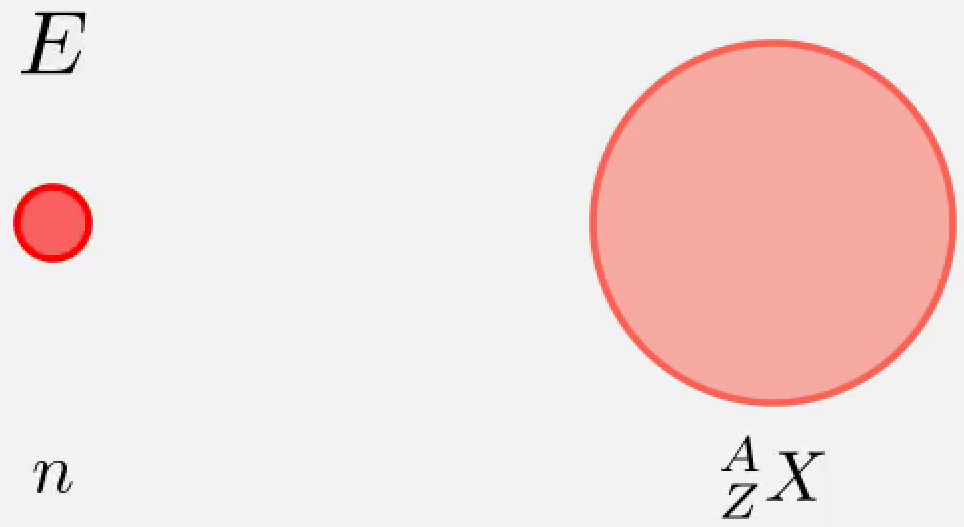


What even is a neutron capture rate?

$$\langle \sigma v \rangle =$$



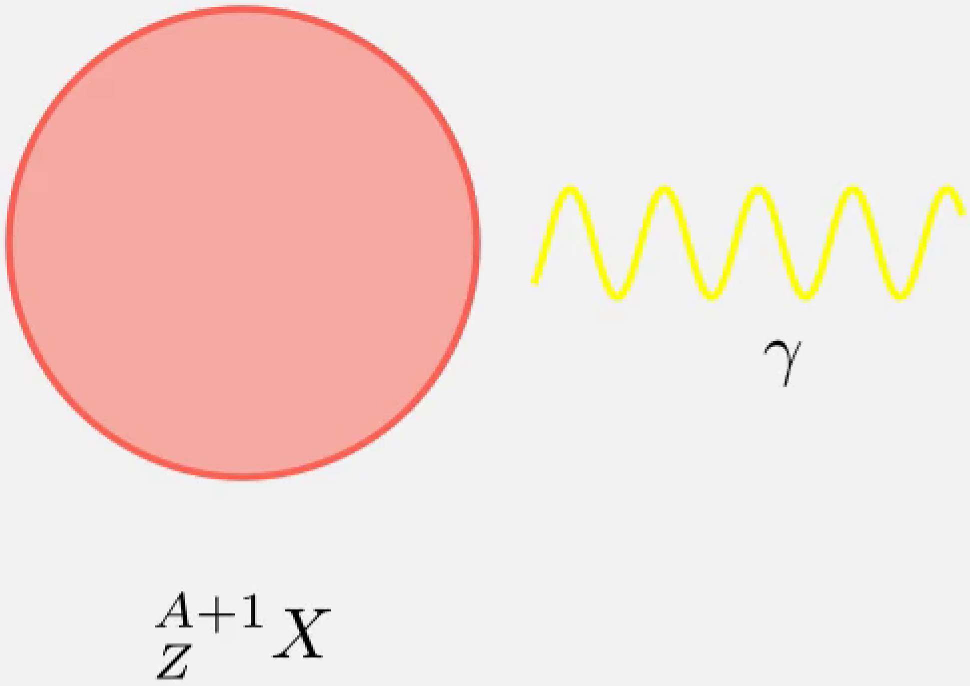
$$\langle \sigma v \rangle = E$$

$$n + {}^{A}_{Z}X$$

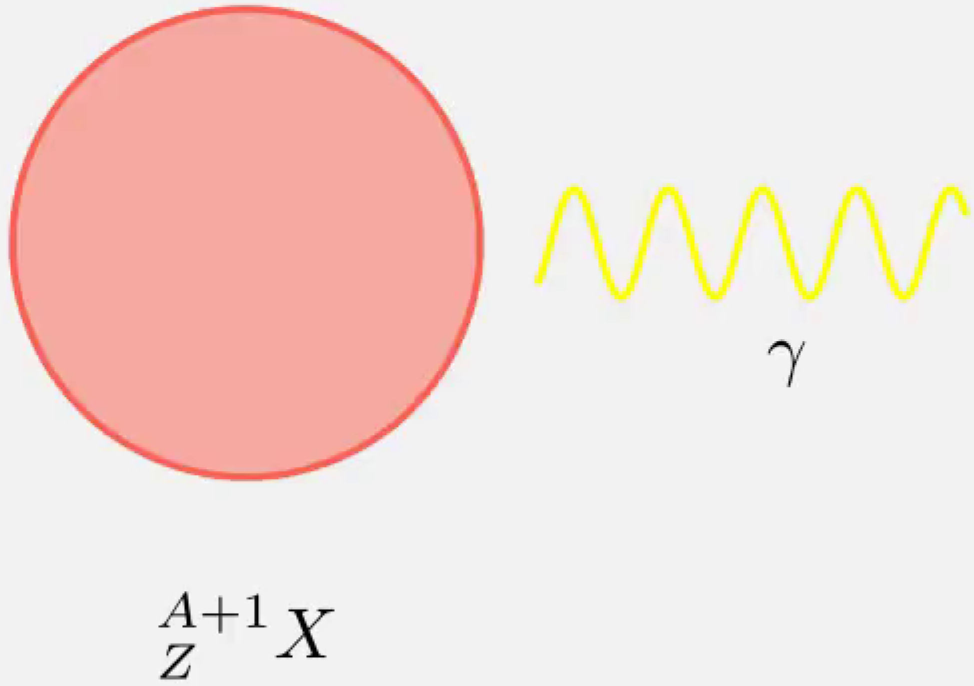
$$\langle \sigma v \rangle = E$$

$$^{A+1}_{Z}X^*$$

$$\langle \sigma v \rangle = E$$



$$\langle \sigma v \rangle = E\sigma(E)$$



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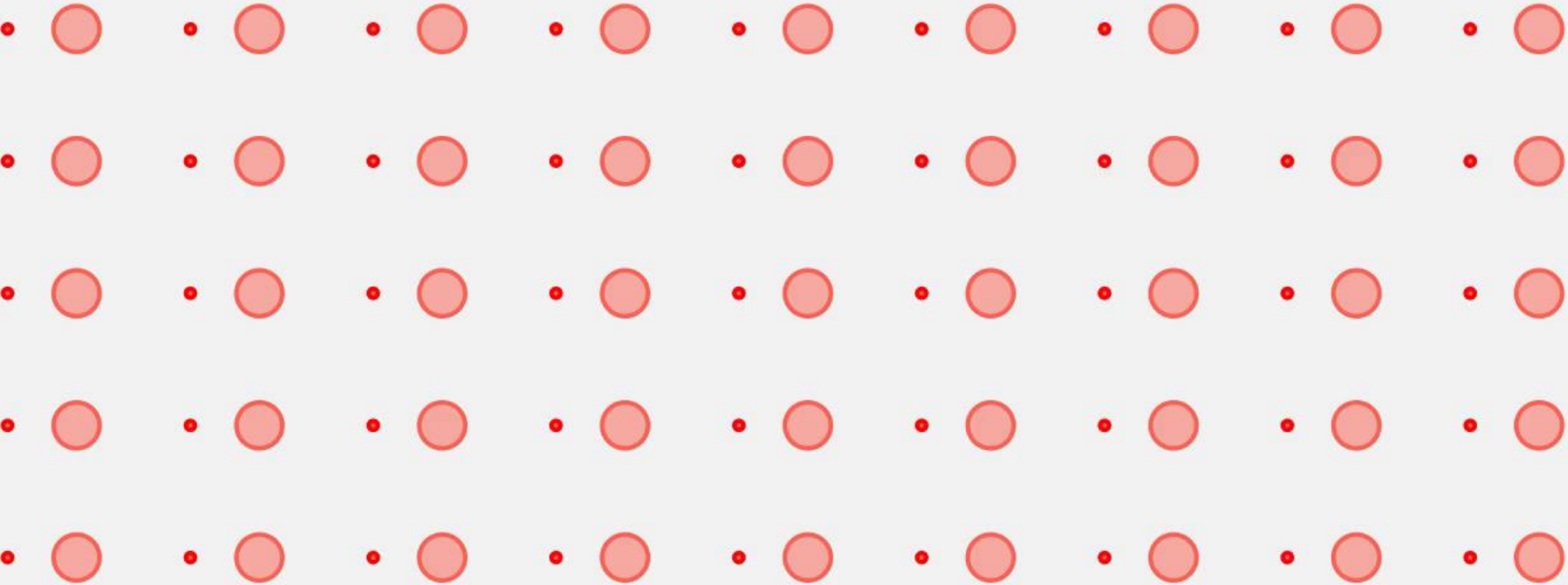

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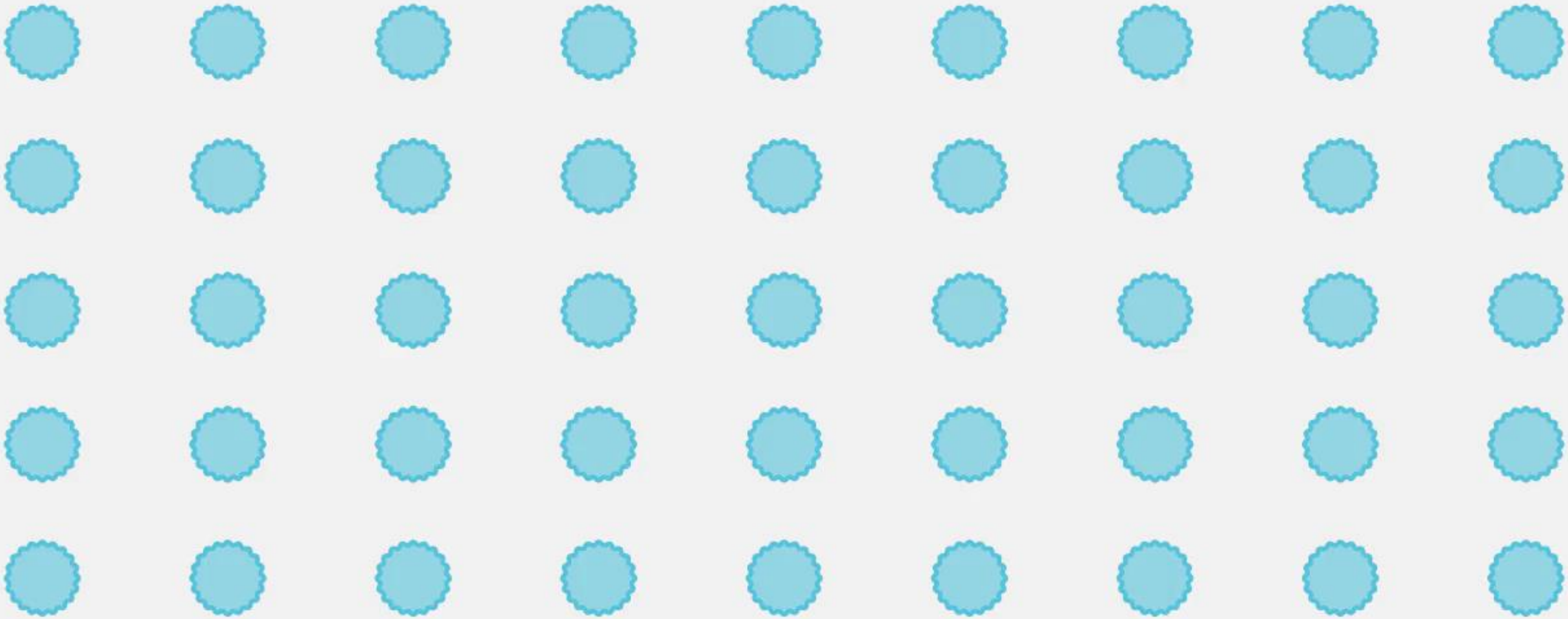

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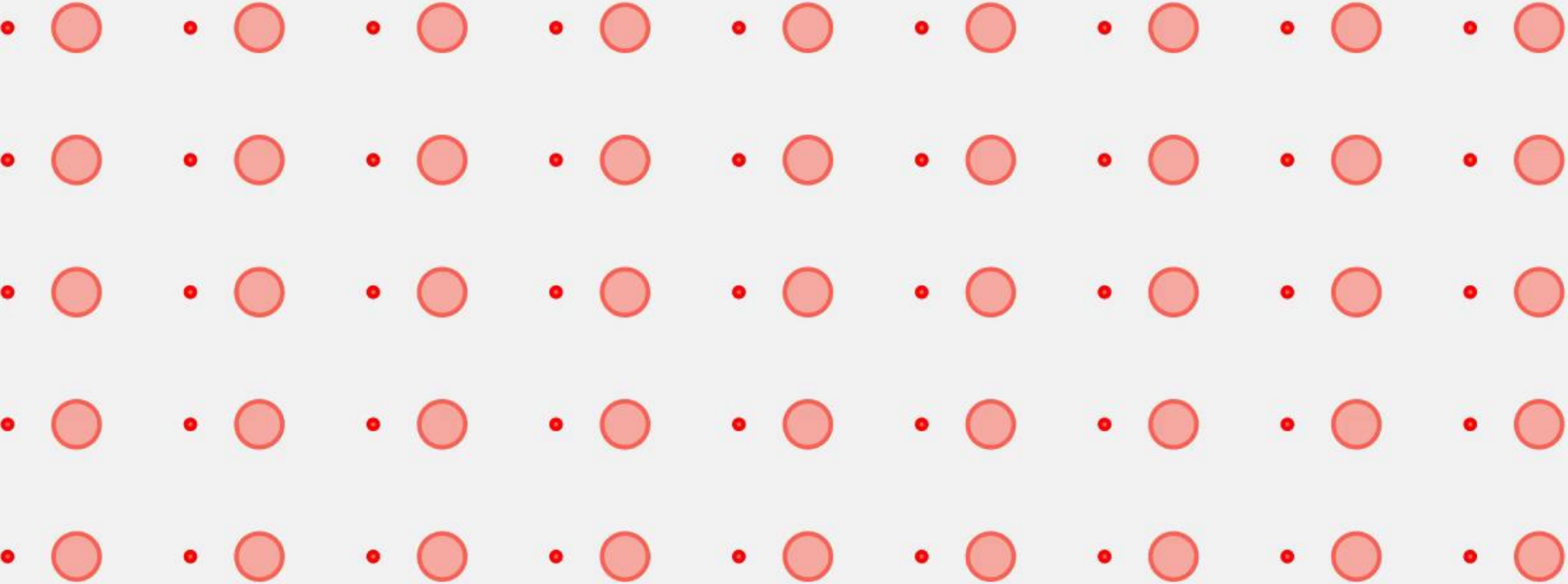

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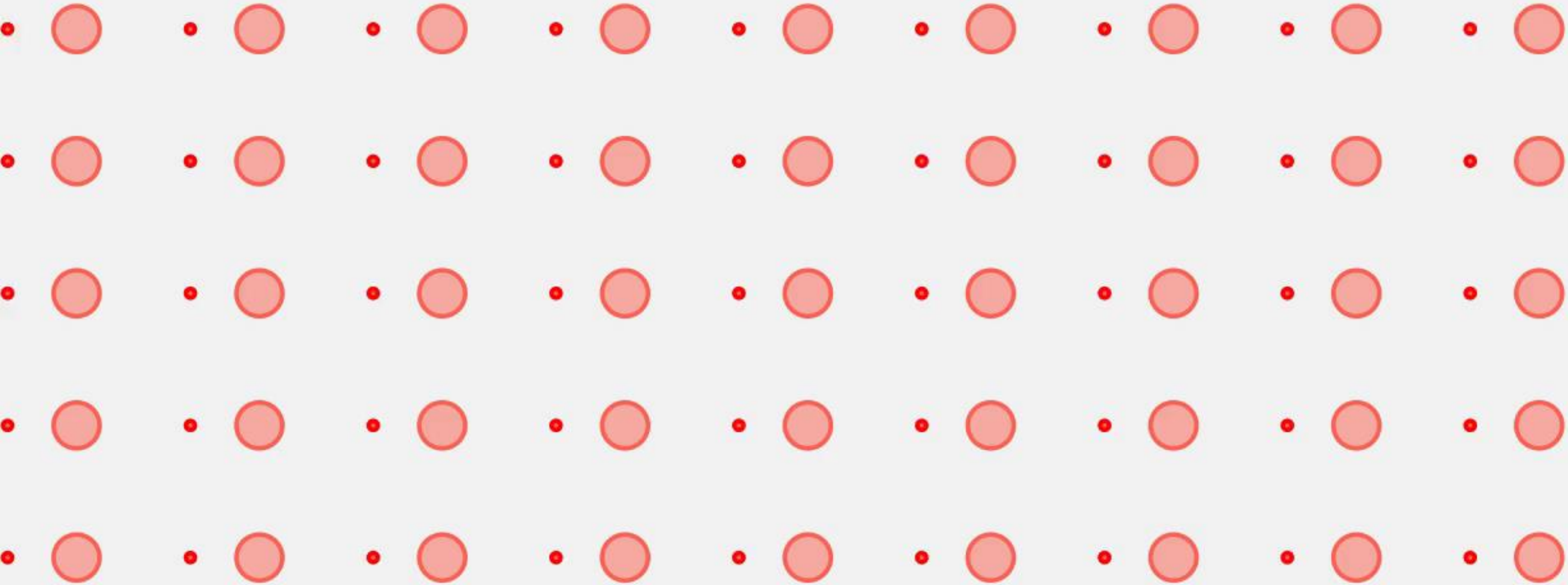

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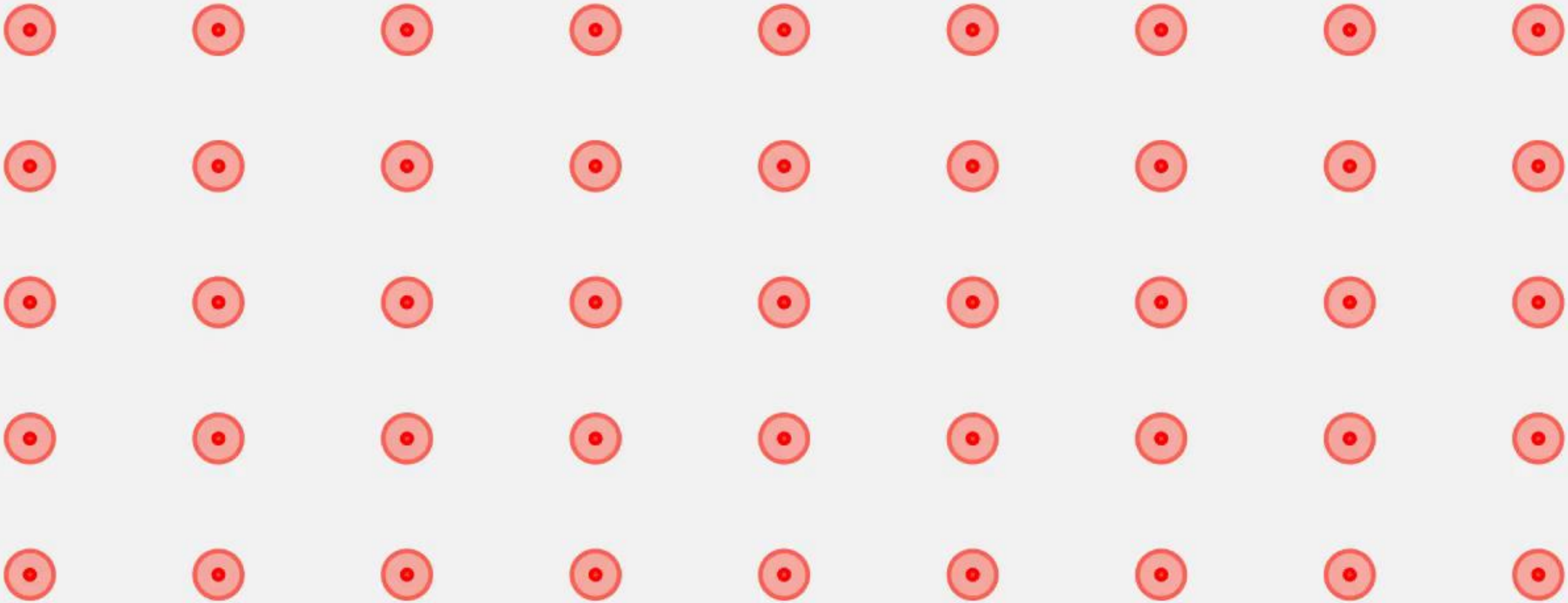

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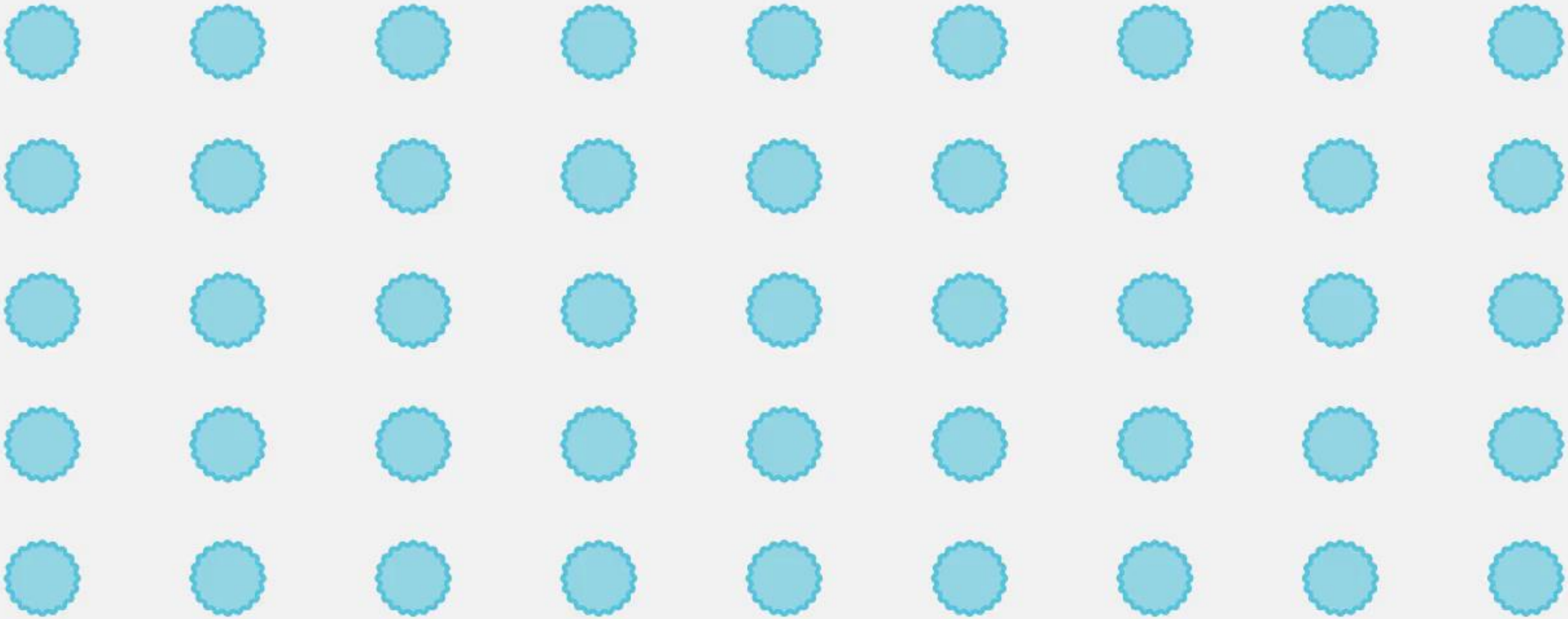

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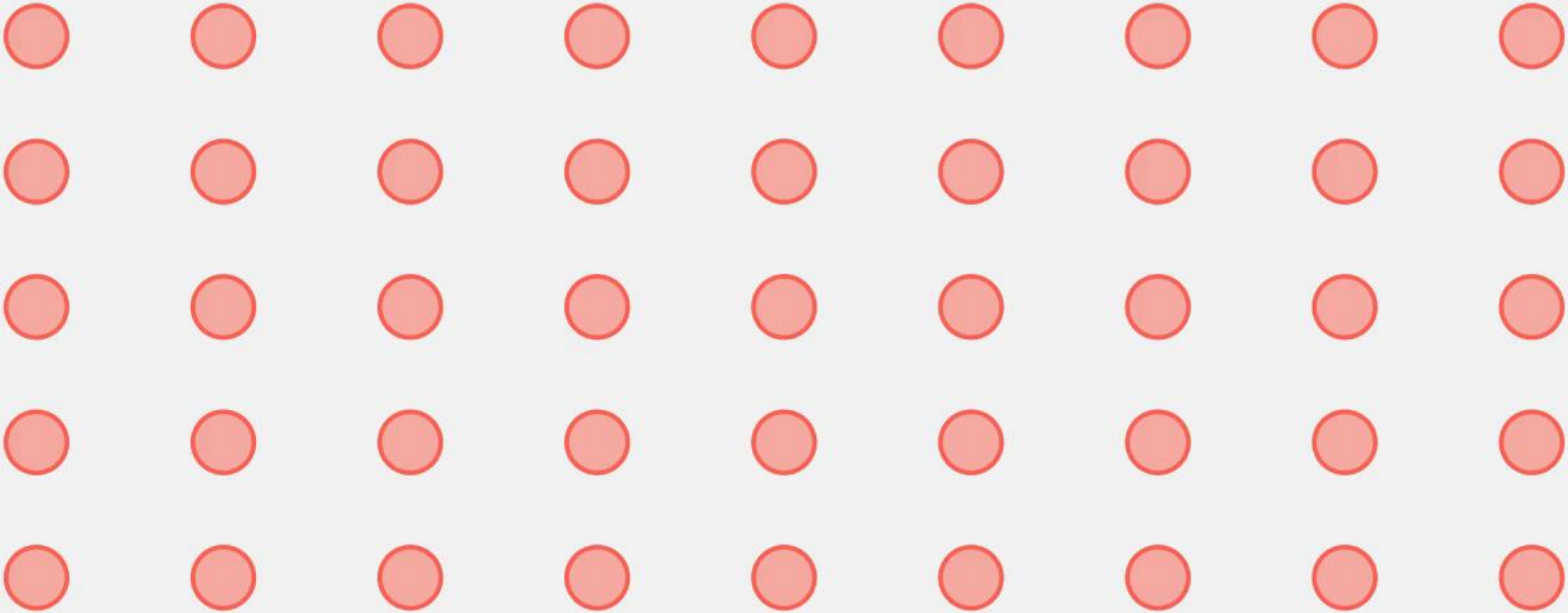
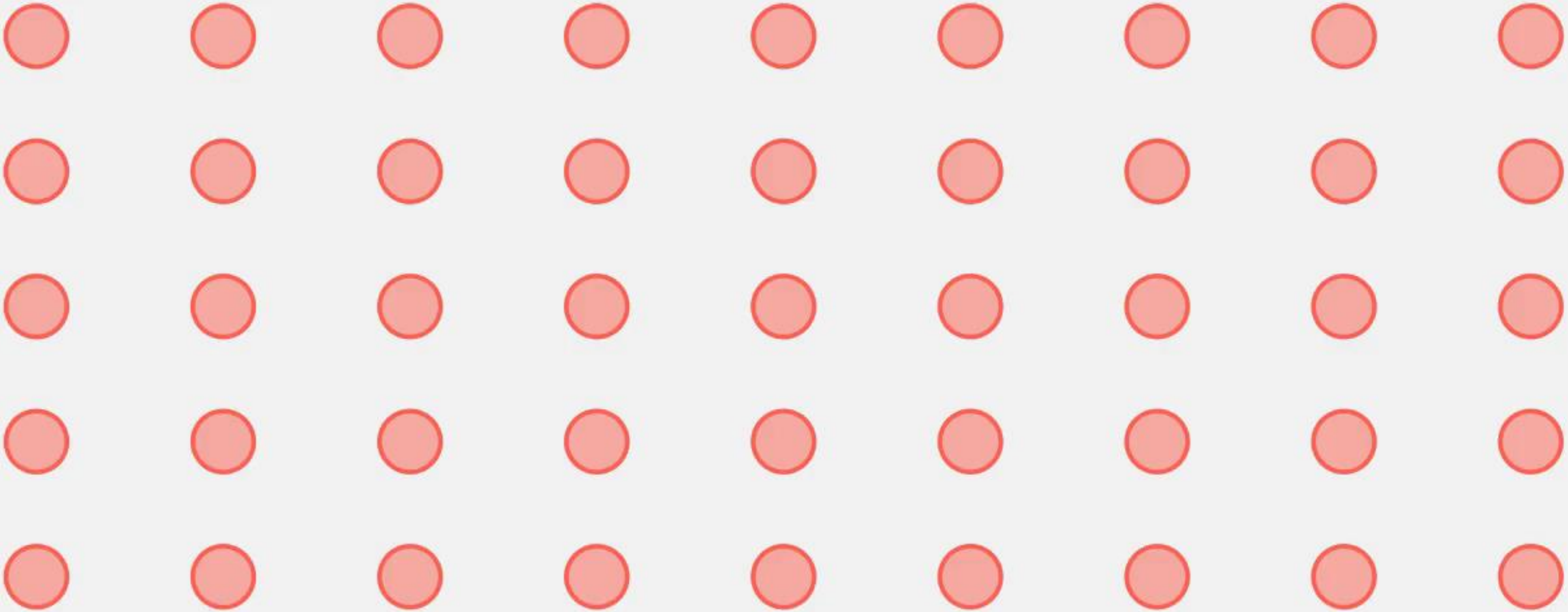


$$\langle \sigma v \rangle = E\sigma(E) f(E, T, \mu)$$



$$\langle \sigma v \rangle = E\sigma(E) f(E, T, \mu)$$

$$\langle \sigma v \rangle = \int_0^\infty E\sigma(E) f(E, T, \mu) dE$$

$$\langle \sigma v \rangle = \sqrt{\frac{2}{m}} \frac{1}{N} \int_0^\infty E\sigma(E) f(E, T, \mu) dE$$

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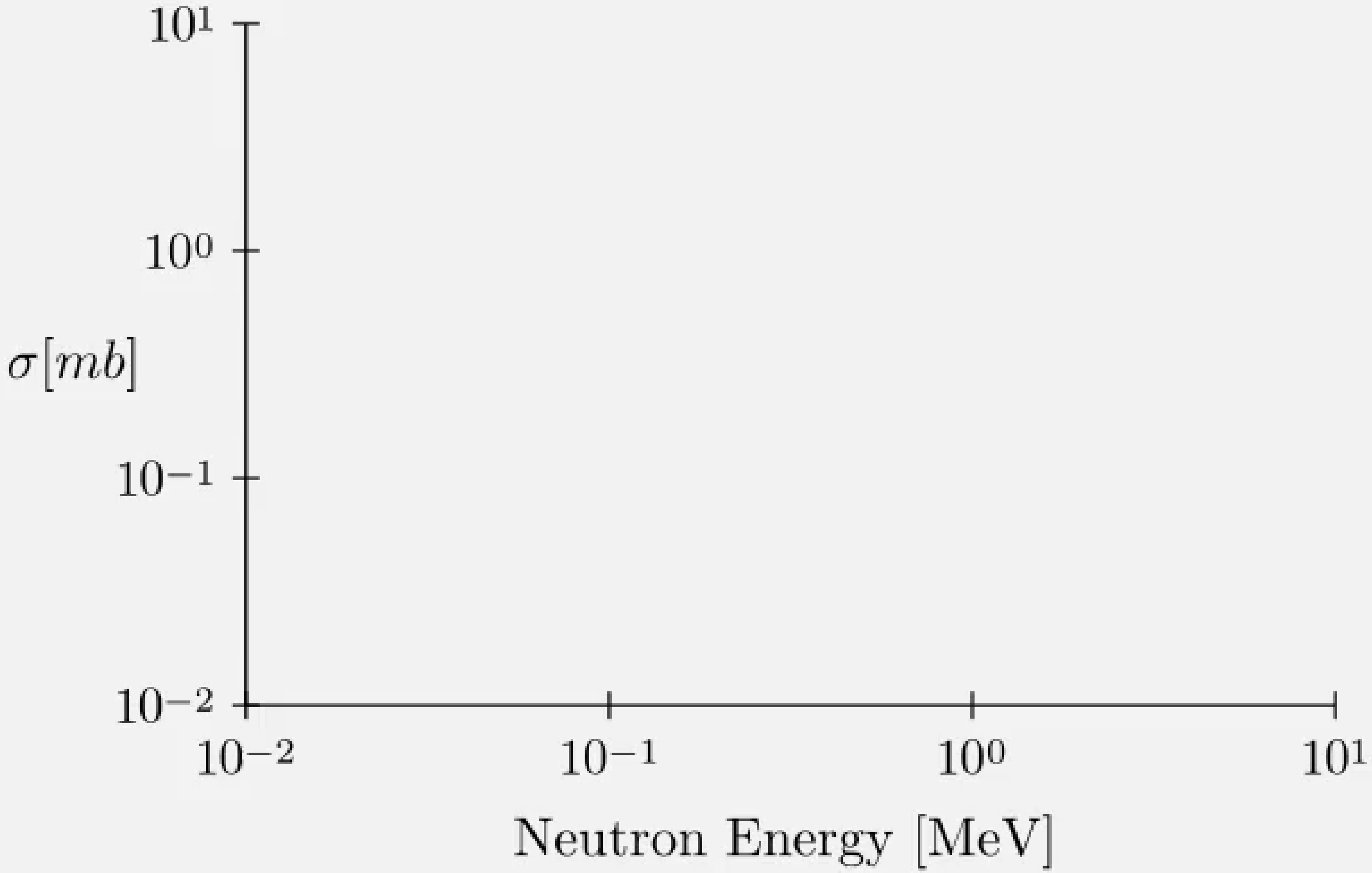

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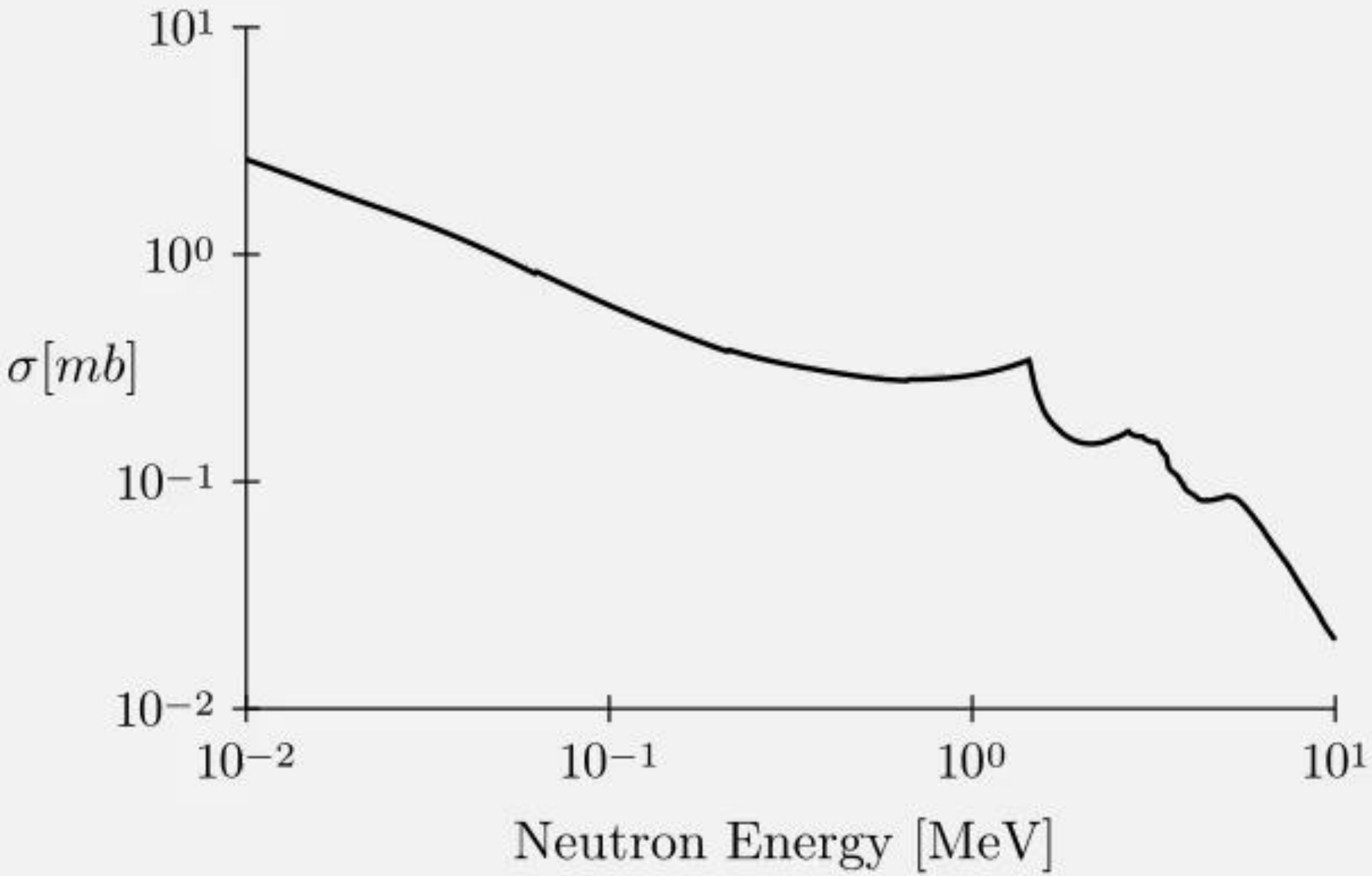

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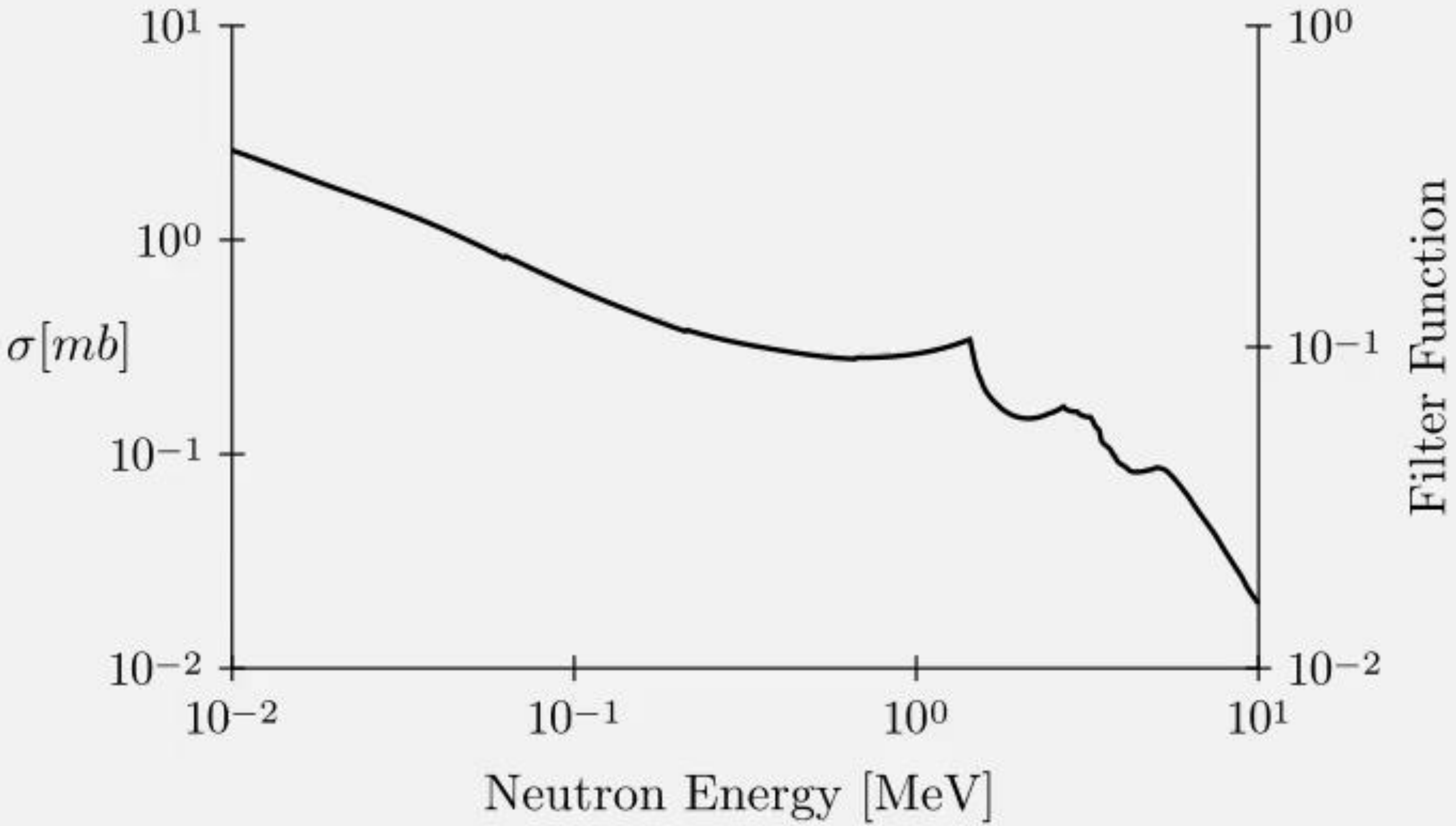
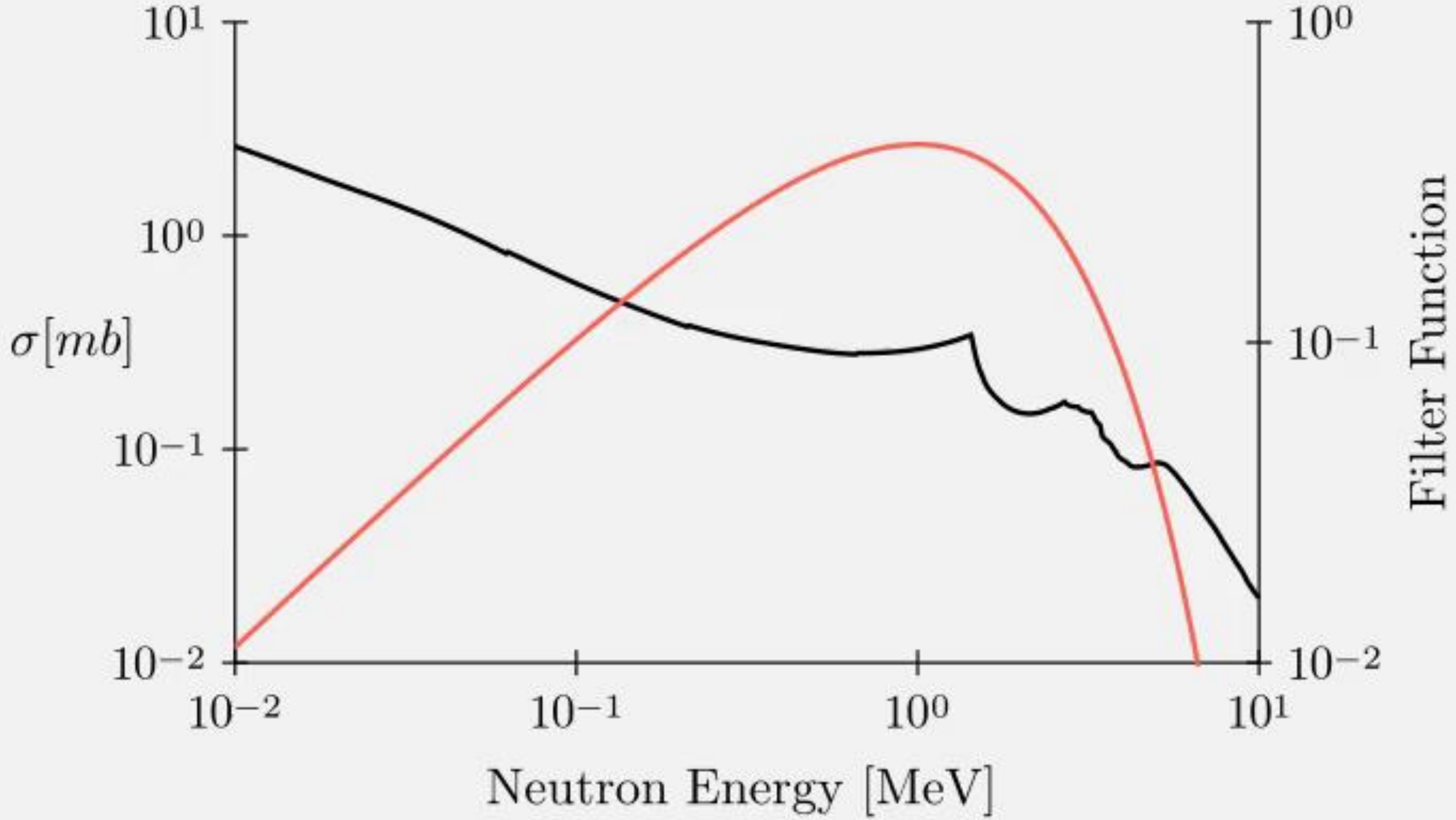


$$\langle \sigma v \rangle = \sqrt{\frac{2}{m}} \frac{1}{N} \int_0^\infty E\sigma(E) e^{\frac{-E}{T}} \, dE$$



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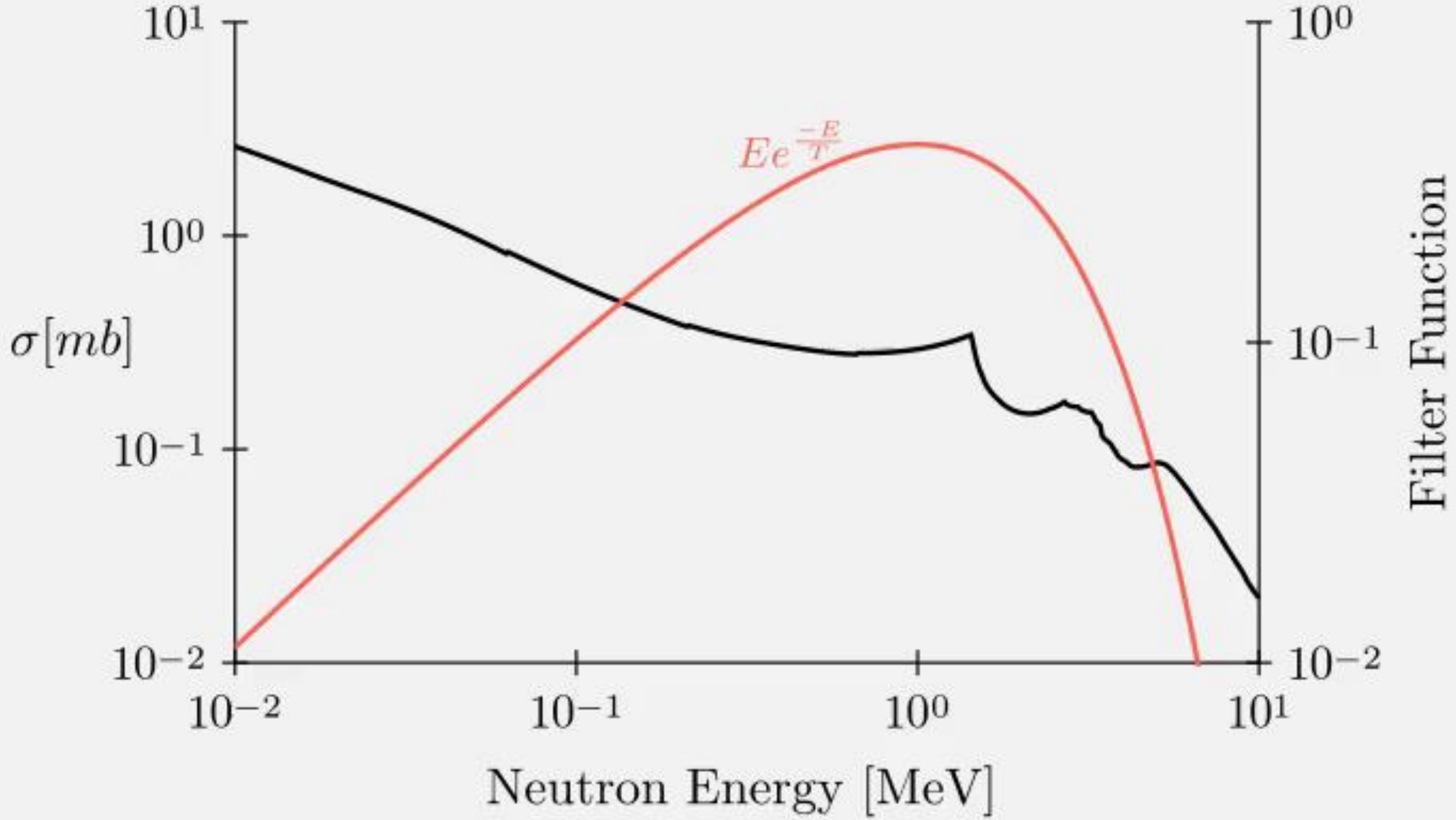
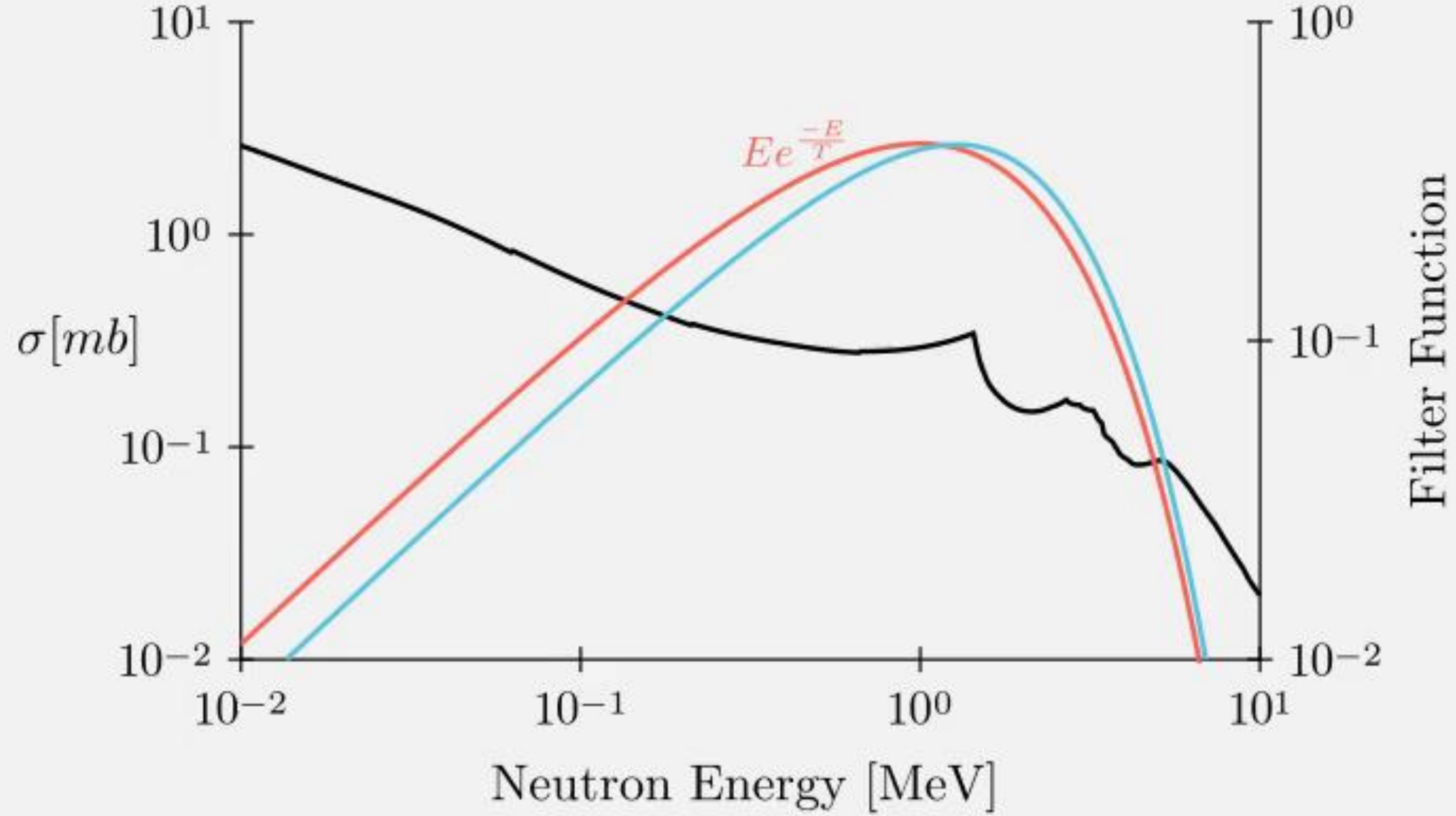


$$\langle \sigma v \rangle = \sqrt{\frac{2}{m}} \frac{1}{N} \int_0^\infty E \sigma(E) \frac{1}{1 + e^{\frac{E-\mu}{T}}} dE$$



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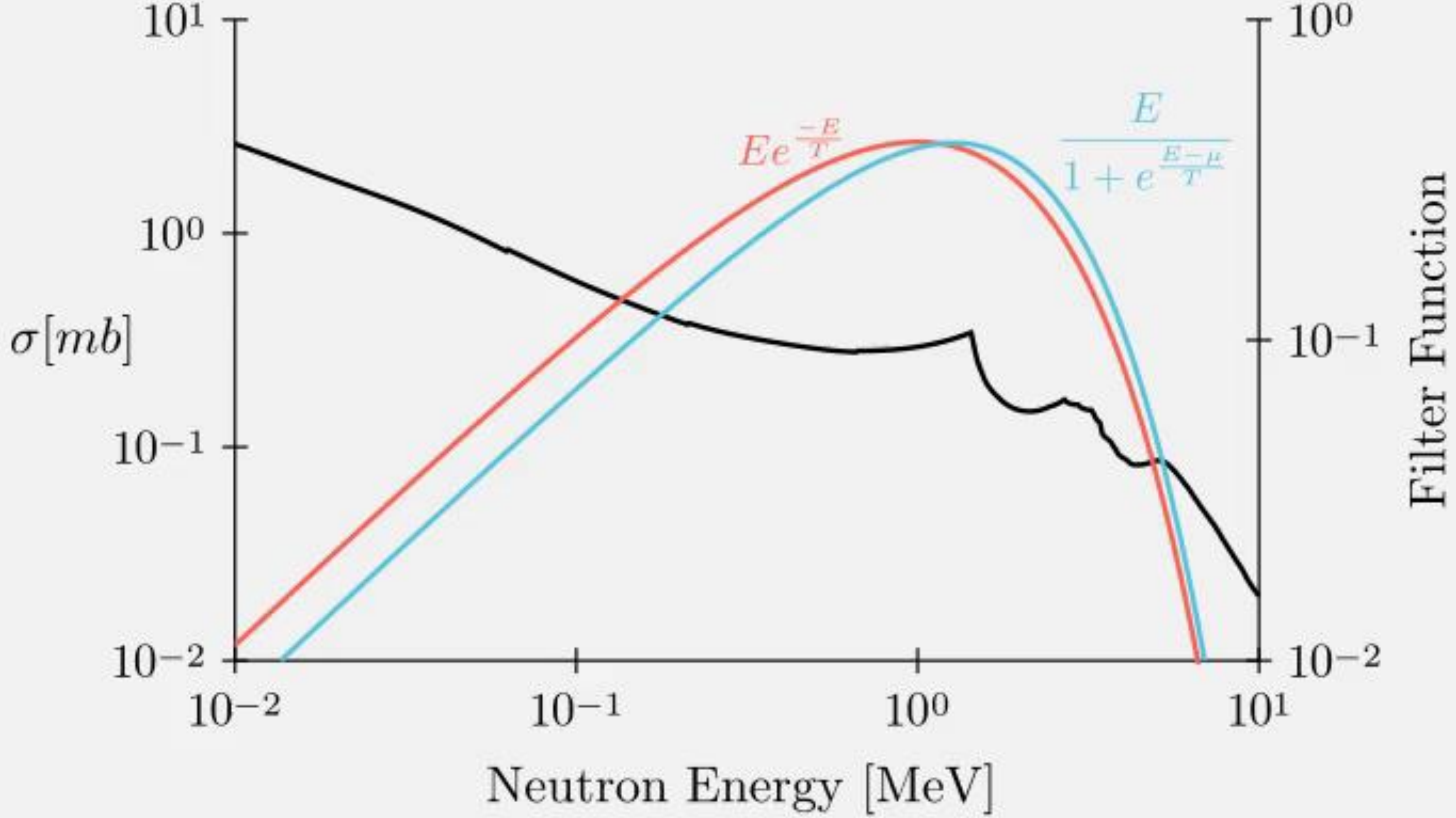

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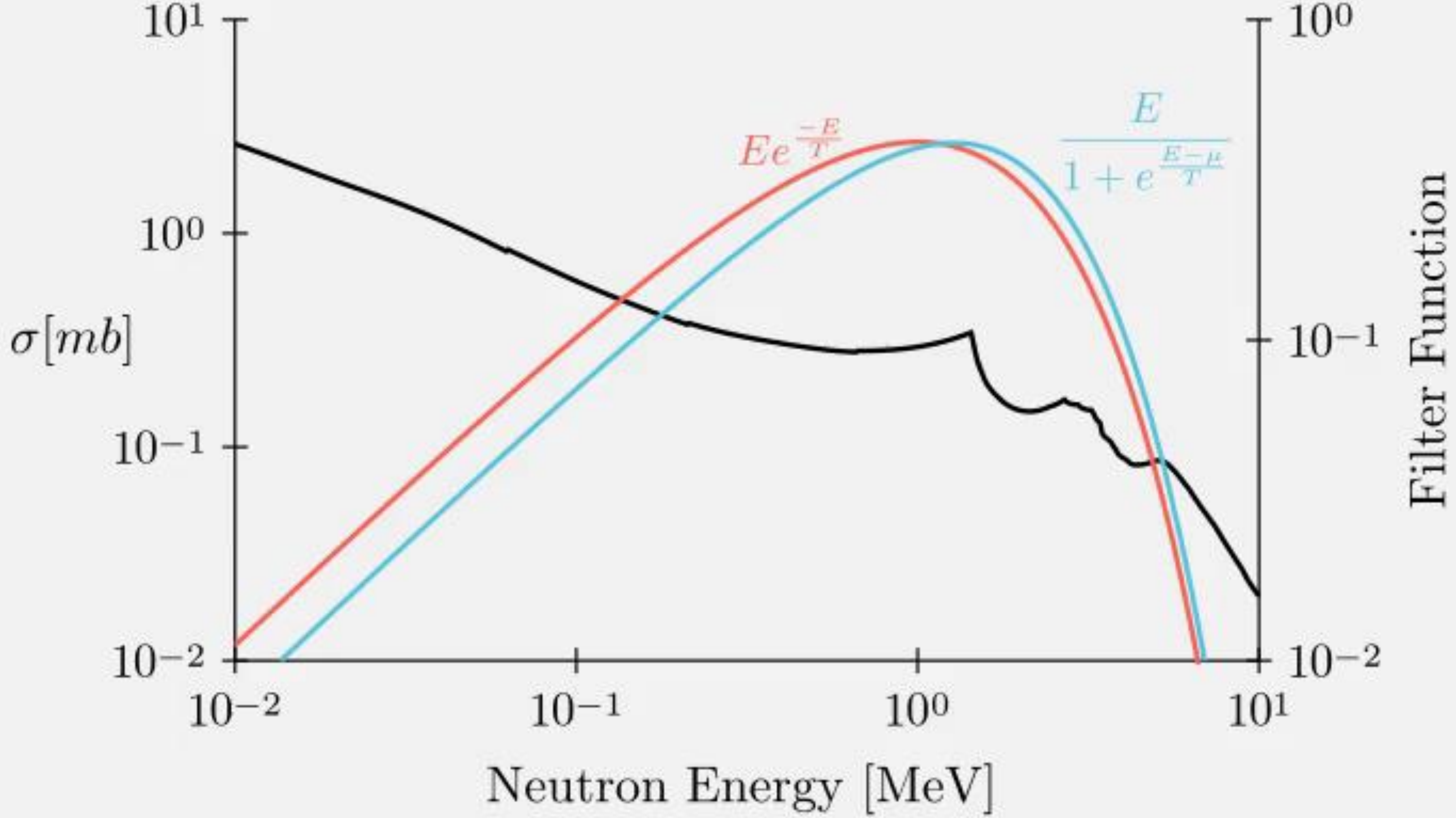

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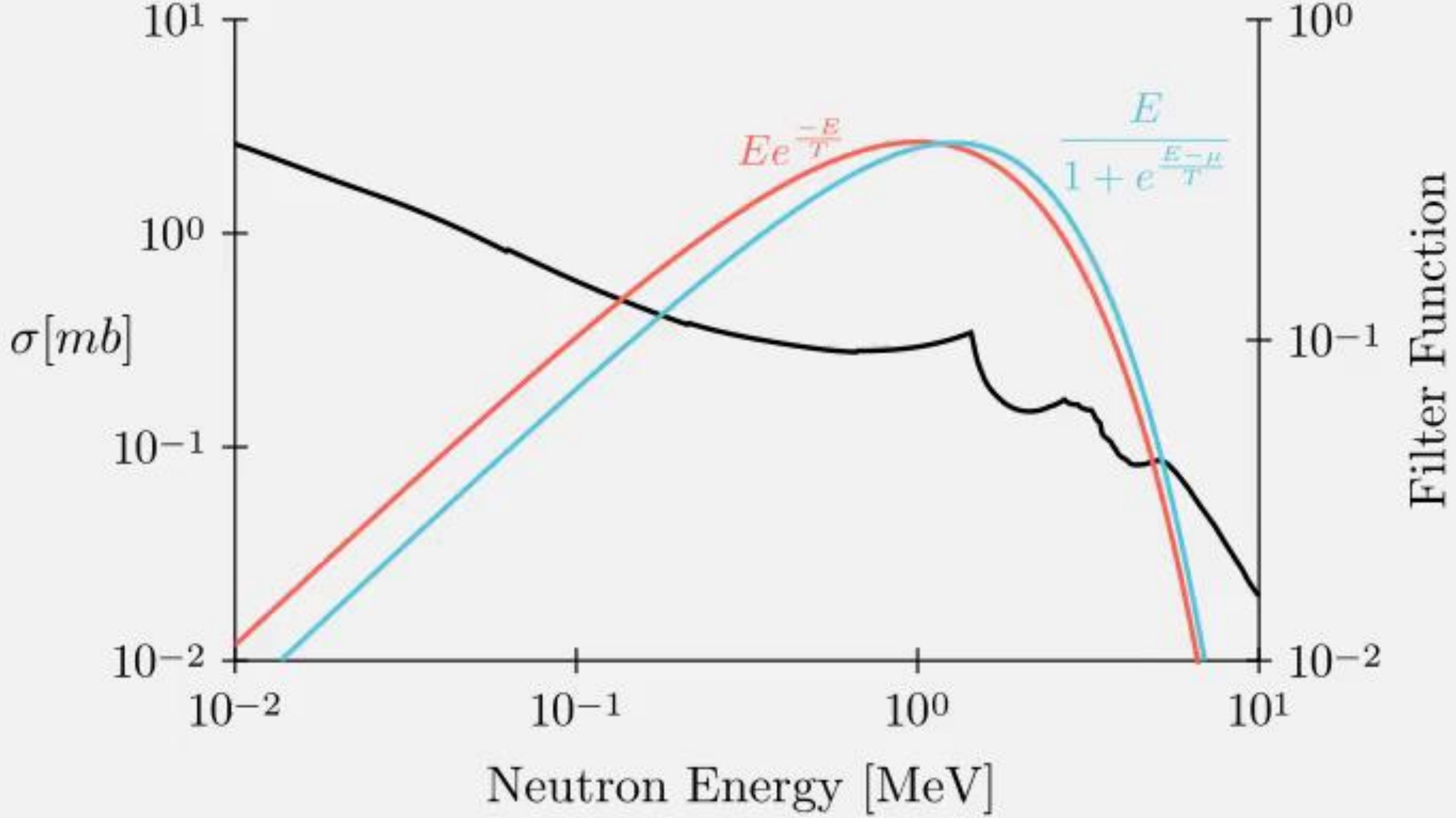
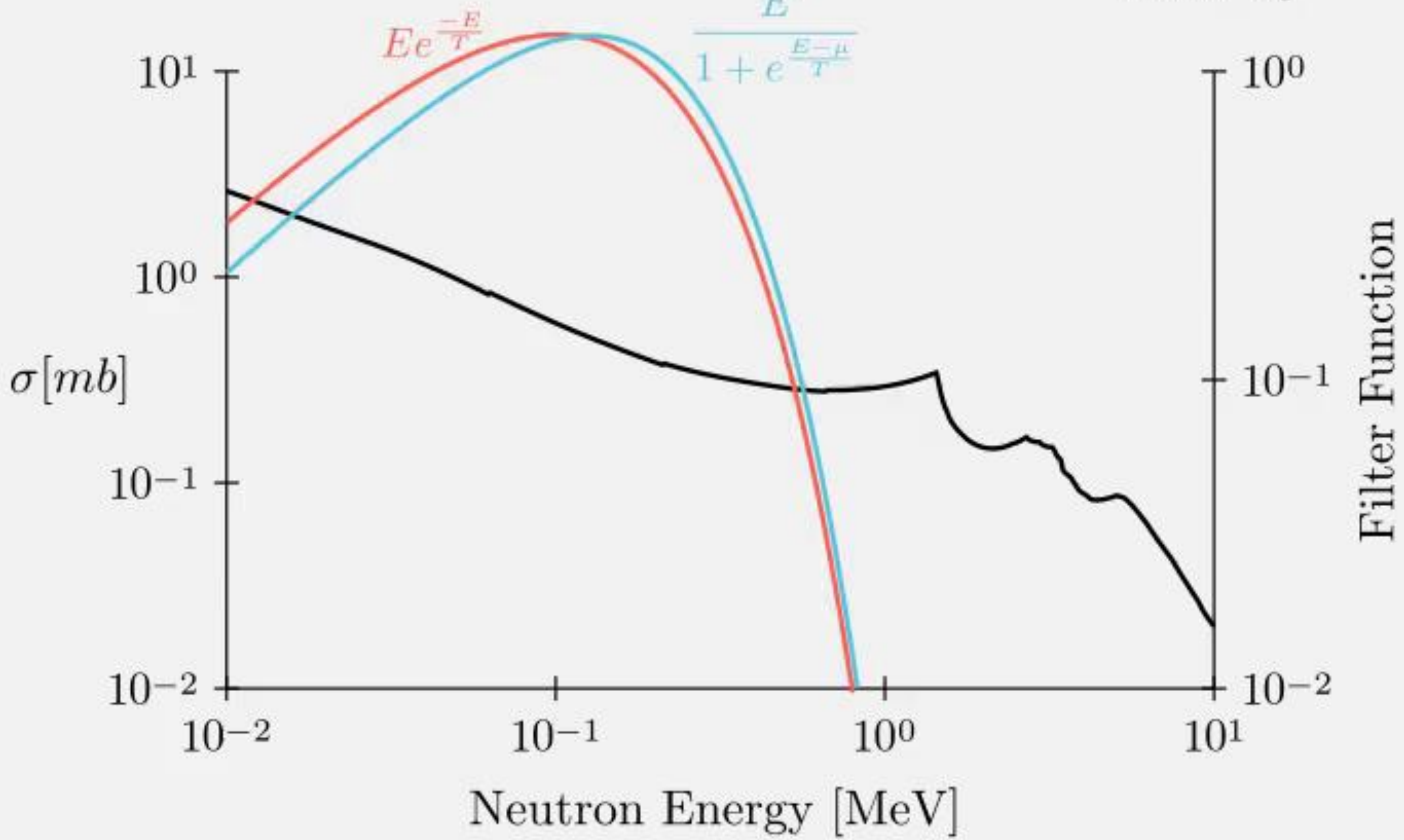


T [MeV]
1.000

μ [MeV]
0.000

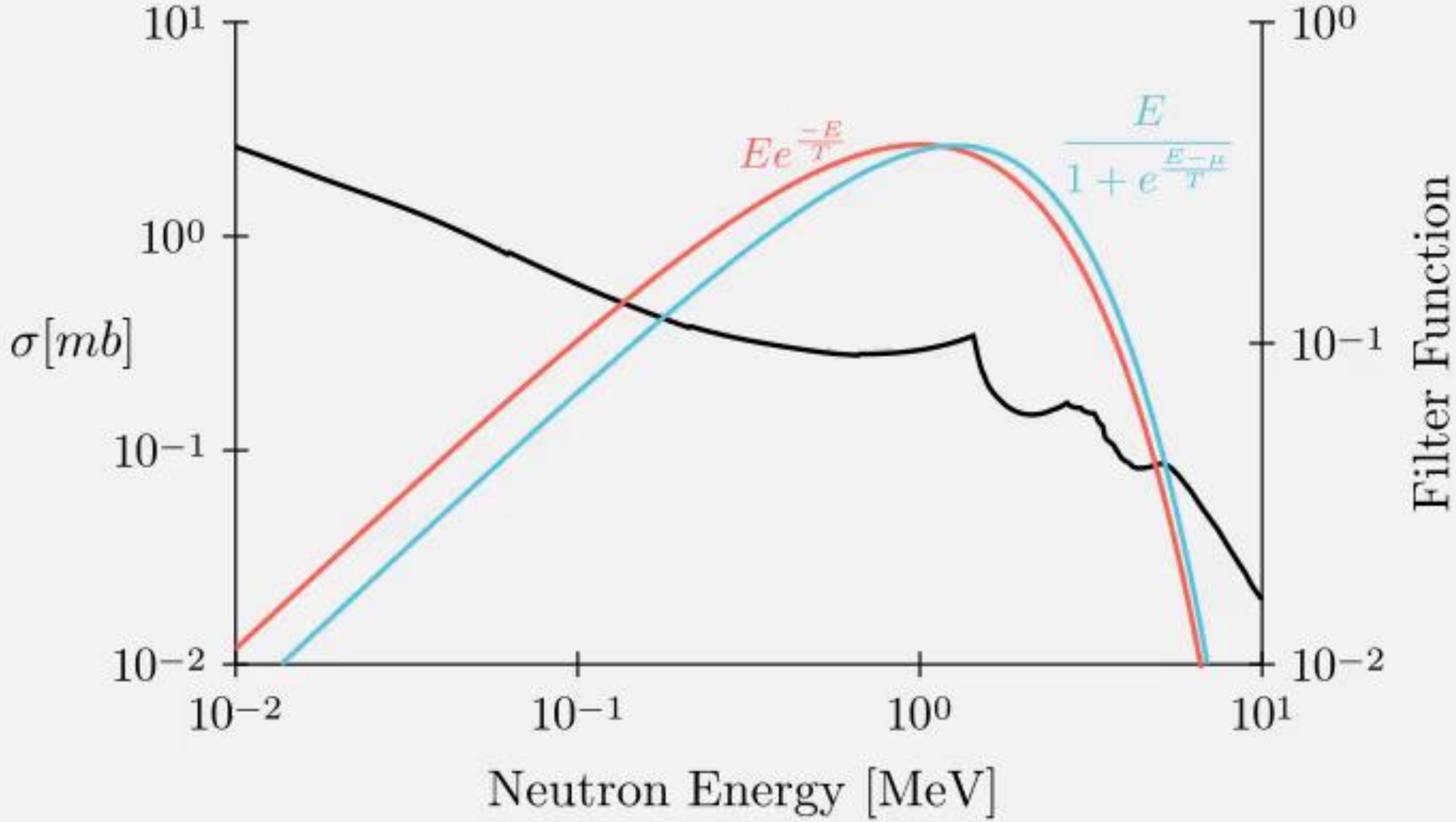
$$\langle \sigma v \rangle = \sqrt{\frac{2}{m}} \frac{1}{N} \int_0^\infty E\sigma(E) f(E, T, \mu) dE$$



T [MeV]
0.100

μ [MeV]
0.000

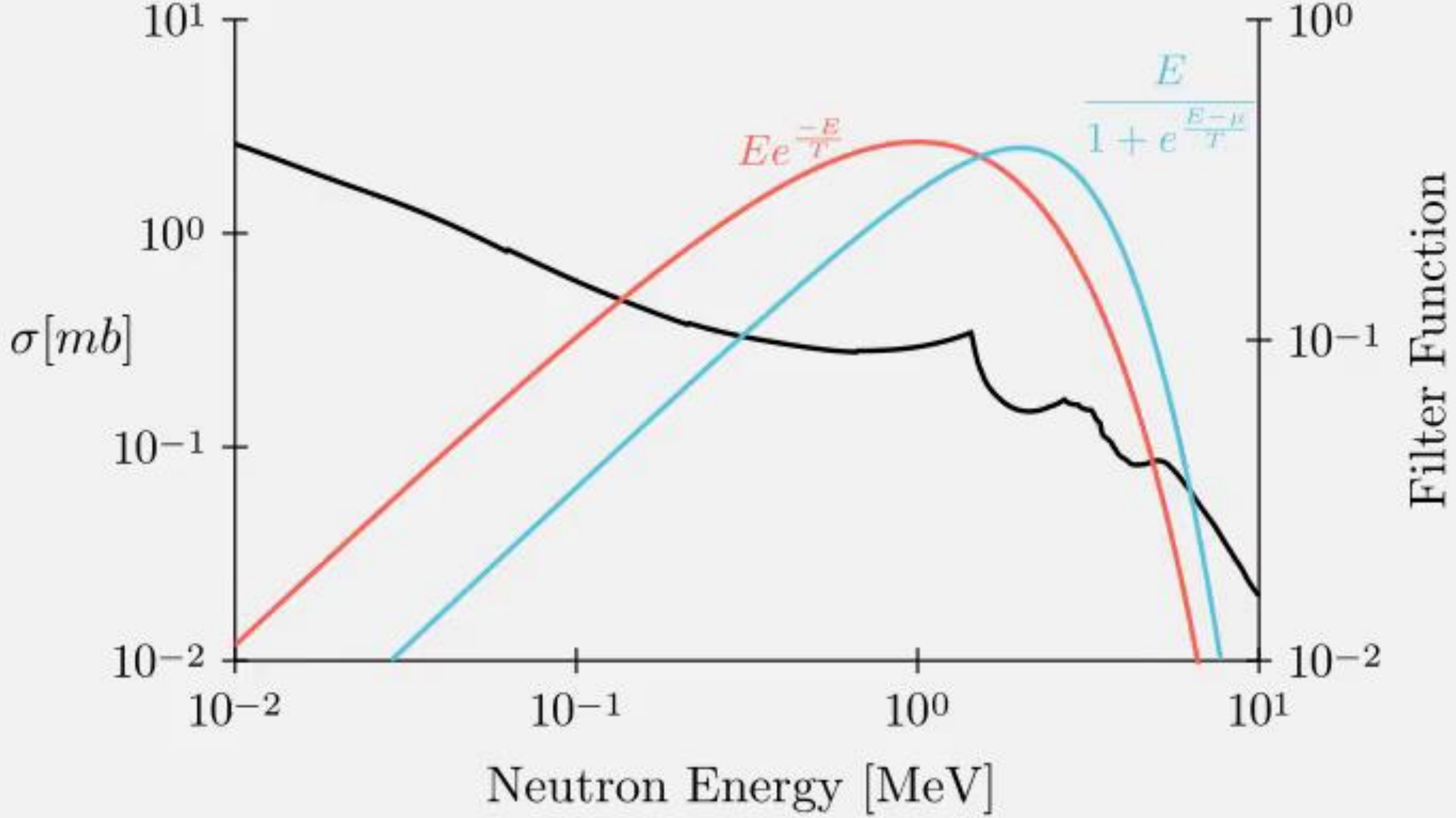
$$\langle \sigma v \rangle = \sqrt{\frac{2}{m}} \frac{1}{N} \int_0^\infty E\sigma(E) f(E, T, \mu) dE$$



T [MeV]
1.000

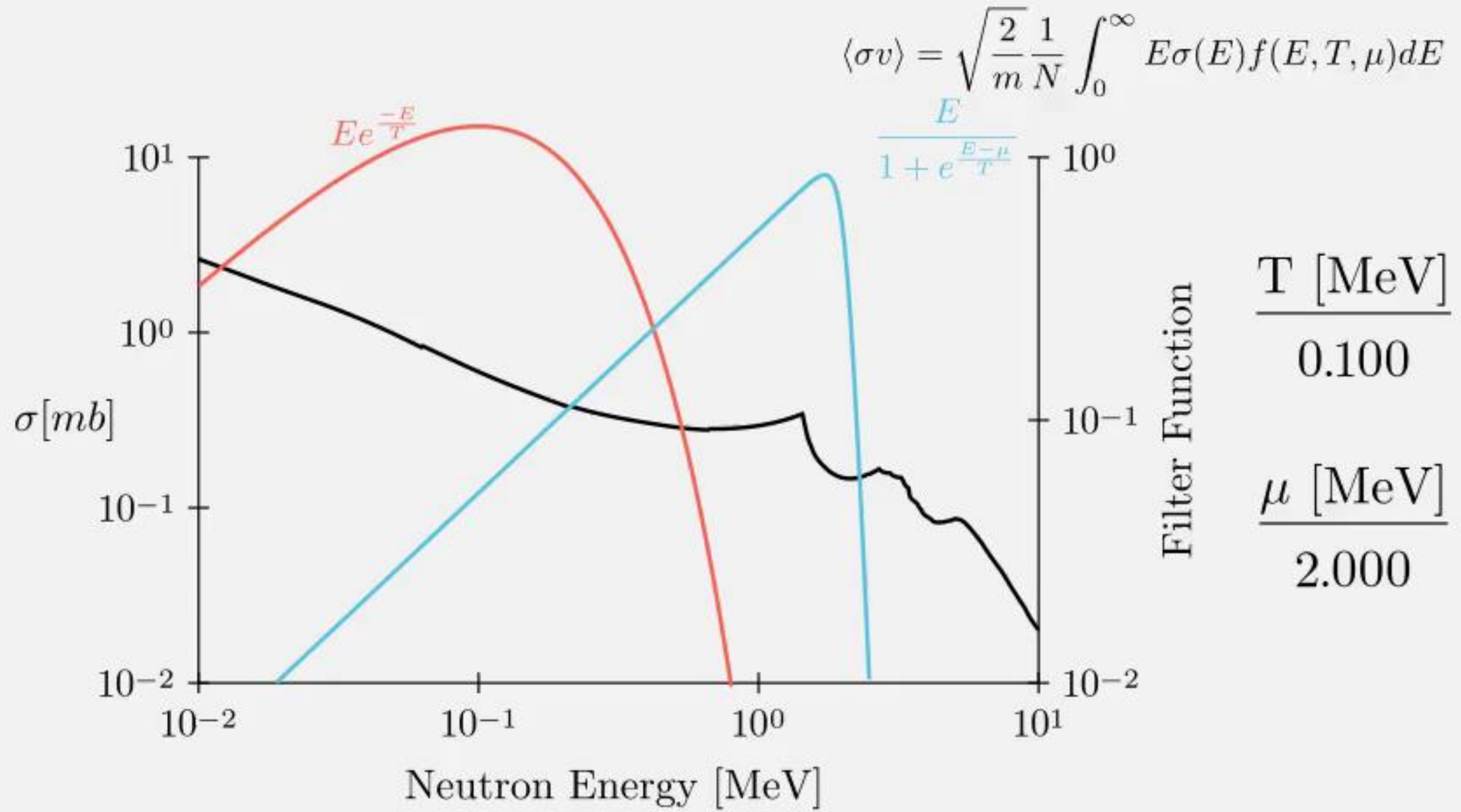
μ [MeV]
0.000

$$\langle \sigma v \rangle = \sqrt{\frac{2}{m}} \frac{1}{N} \int_0^\infty E\sigma(E) f(E, T, \mu) dE$$



T [MeV]
1.000

μ [MeV]
2.000



$\langle \sigma v \rangle = \sqrt{\frac{2}{m}} \frac{1}{N} \int_0^\infty E\sigma(E) f(E,T,\mu) dE$
$Ee^{\frac{-E}{T}}$
$\frac{E}{1+e^{\frac{E-\mu}{T}}}$
$\sigma[mb]$
Filter Function
Neutron Energy [MeV]
T [MeV]
0.100
μ [MeV]
2.000

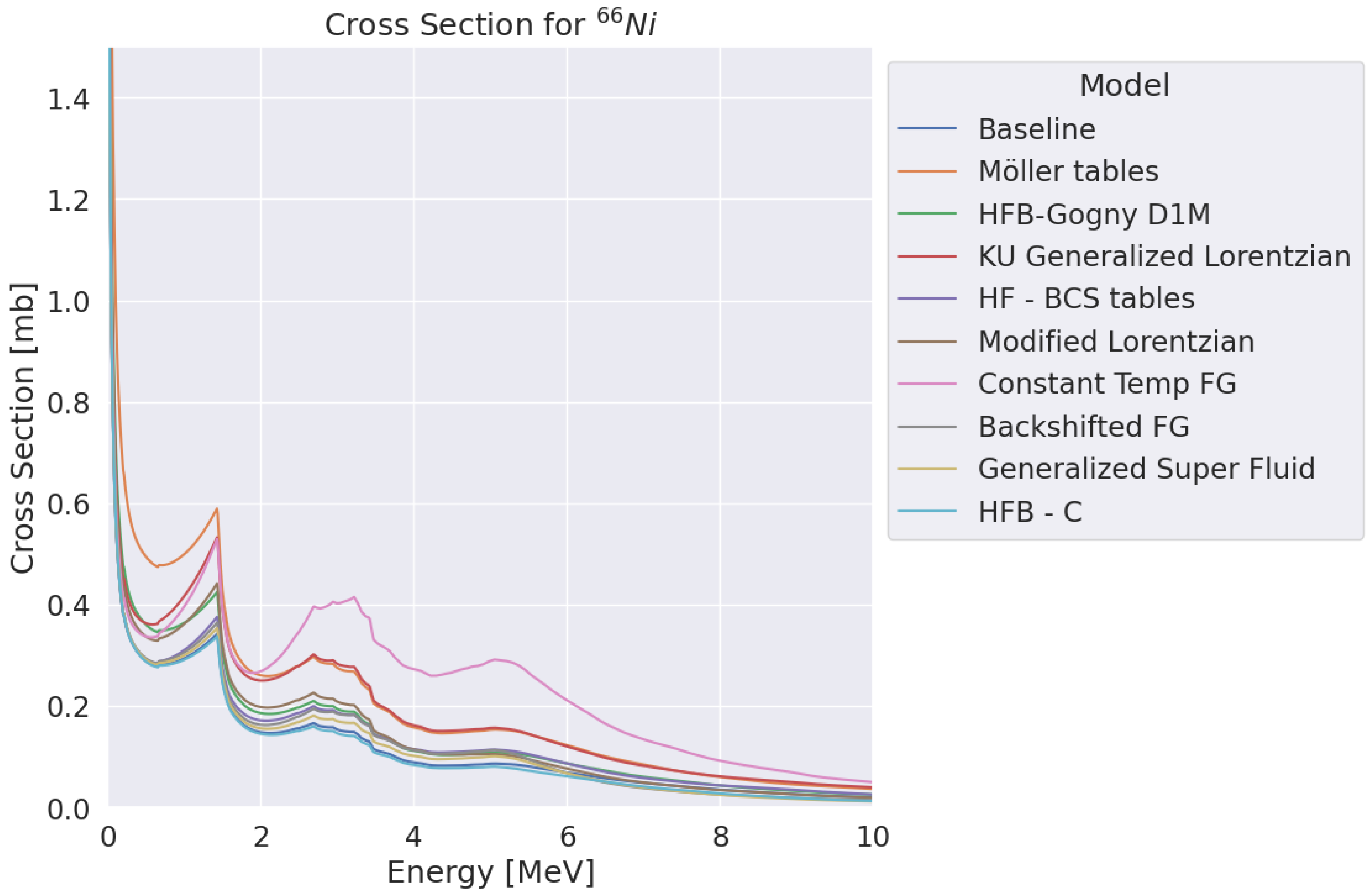
VARIATIONS IN THEORETICAL NUCLEAR INPUTS VIA TALYS

- For neutron rich nuclei, must rely on theoretical inputs
- TALYS[2] allows a multitude of models when calculating transmission coefficients for the cross section
- Determine the impact of mass model, level density, and gamma strength function on degenerate capture rates

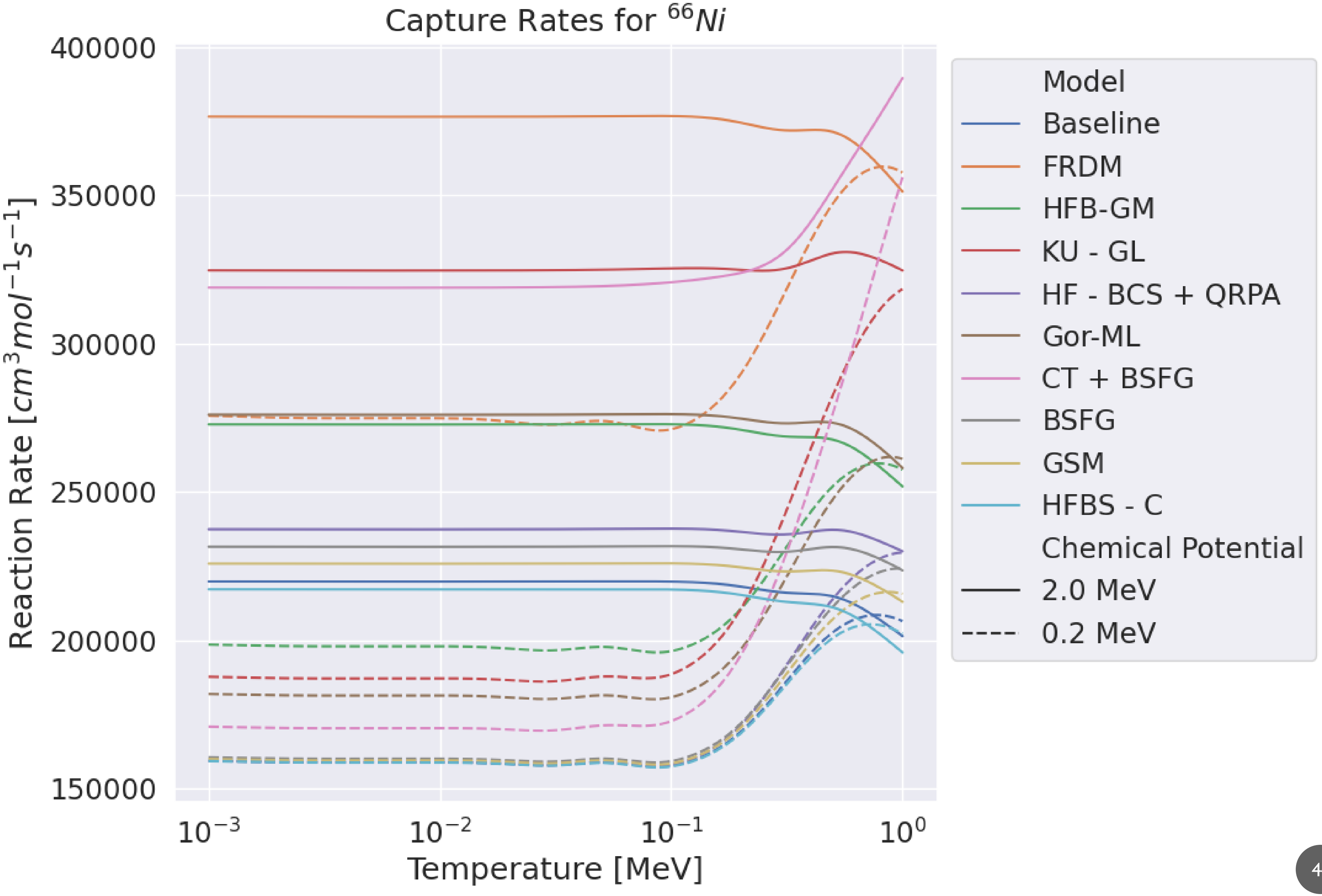
2 - Arjan Koning, Stephane Hilaire, Stephane Goriely
Eur. Phys. J. A 59 (6) 131 (2023)

TALYS INPUT VARIATIONS

γ-Strength Function	Level Density Model	Mass models
Kopecky-Uhl generalized Lorentzian	Constant temperature + Fermi gas model	Möller tables
Hartree-Fock BCS + QRPA	Back-shifted Fermi gas Model	Hartree-Fock-Bogolyubov using Skyrme Forces
Hartree-Fock-Bogolyubov + QRPA	Generalized super fluid model	Hartree-Fock-Bogolyubov using Gogny Forces
Goriely's Modified Lorentzian	Hartree-Fock Using Skyrme Force	
	Hartree-Fock-Bogolyubov (Skyrme Force) + Combinatorial method	



Cross Section for ^{66}Ni
Cross Section [mb]
Energy [MeV]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
2
4
6
8
10
Model
Baseline
Möller tables
HFB-Gogny D1M
KU Generalized Lorentzian
HF - BCS tables
Modified Lorentzian
Constant Temp FG
Backshifted FG
Generalized Super Fluid
HFB - C

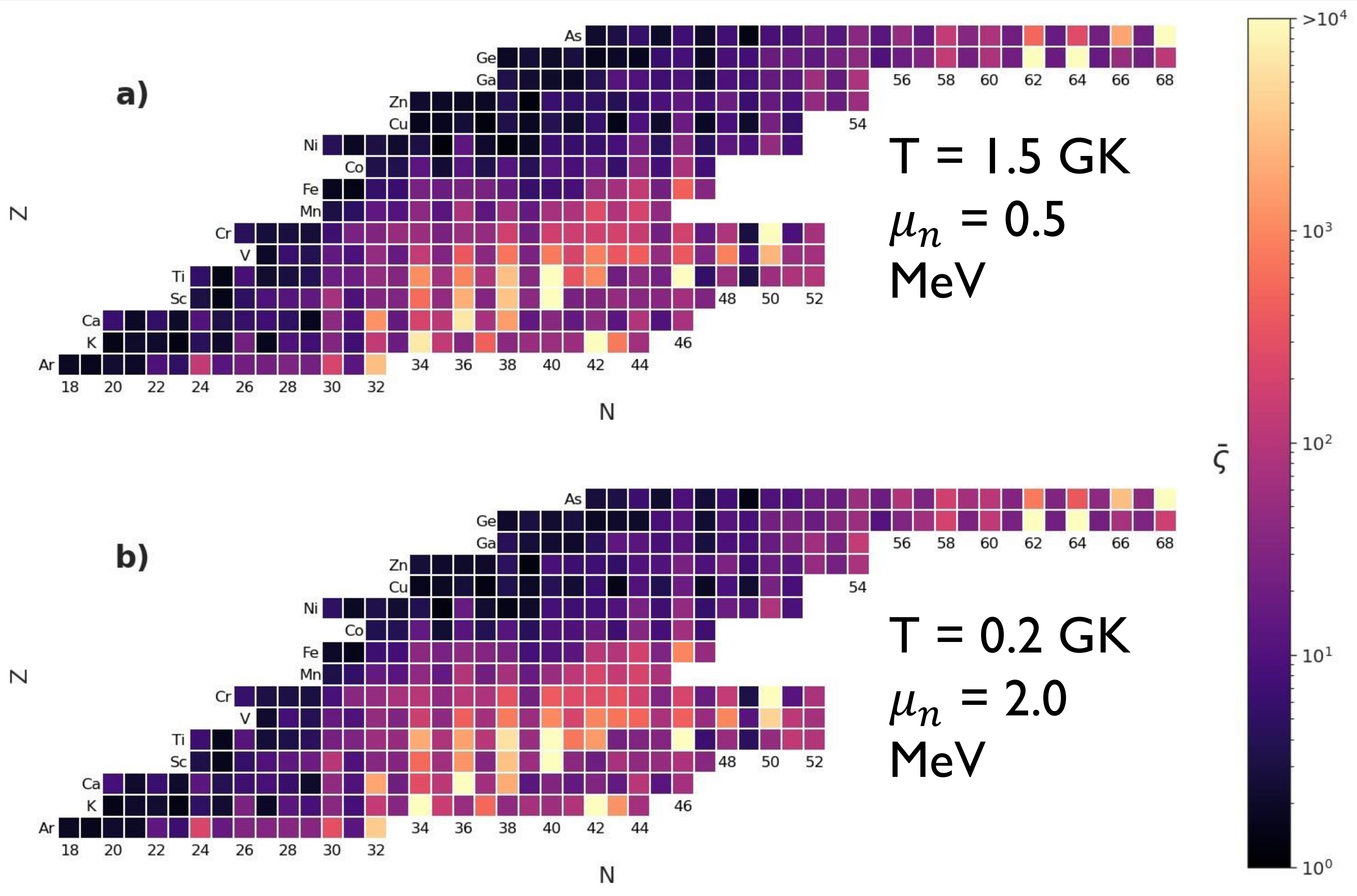


Capture Rates for ^{66}Ni
Reaction Rate $[cm^3 mol^{-1} s^{-1}]$
400000
350000
300000
250000
200000
150000
10^{-3}
10^{-2}
10^{-1}
10^{0}
Temperature [MeV]
Model
Baseline
FRDM
HFB-GM
KU - GL
HF - BCS + QRPA
Gor-ML
CT + BSFG
BSFG
GSM
HFBS - C
Chemical Potential
2.0 MeV
0.2 MeV

EVALUATE DEGENERACY IMPACT BY COMPARING MAX/MIN RATES

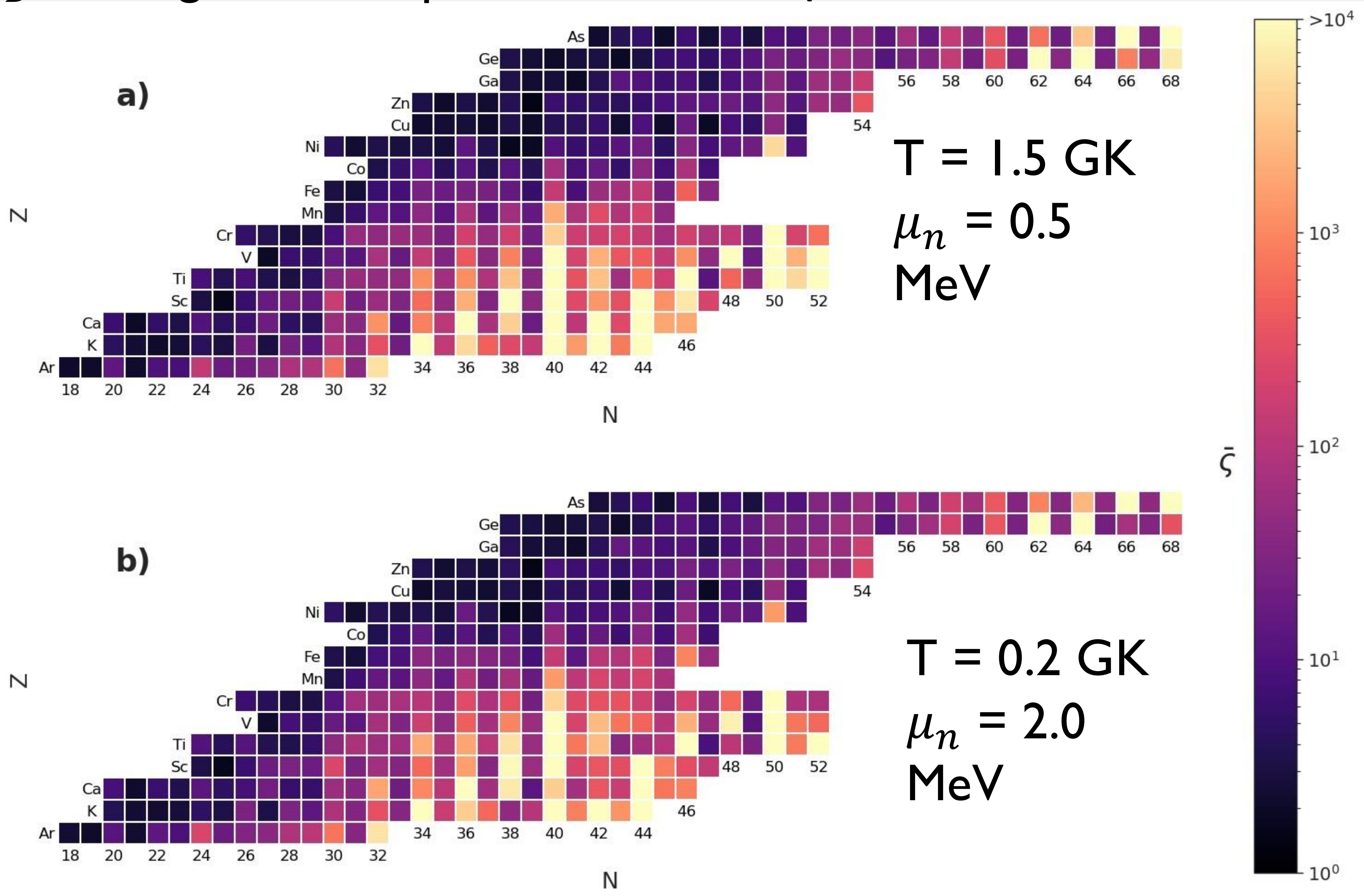
- For each nuclei, find the maximum and minimum rate for a given temperature, chemical potential
- $\bar{\varsigma} = \frac{MAX\langle\sigma v\rangle}{MIN\langle\sigma v\rangle}$
- From this, evaluate $\frac{\bar{\varsigma}_{FD}}{\bar{\varsigma}_{MB}}$ to investigate relative change due to degeneracy

$\bar{\varsigma}_{FD}$ for degenerate captures with γ-SF and LD model variations



B Knight, O L Caballero, H Schatz. 2024 *J. Phys. G: Nucl. Part. Phys.* **51** 095201

$\bar{\varsigma}_{FD}$ for degenerate captures with mass, γ-SF and LD model variations



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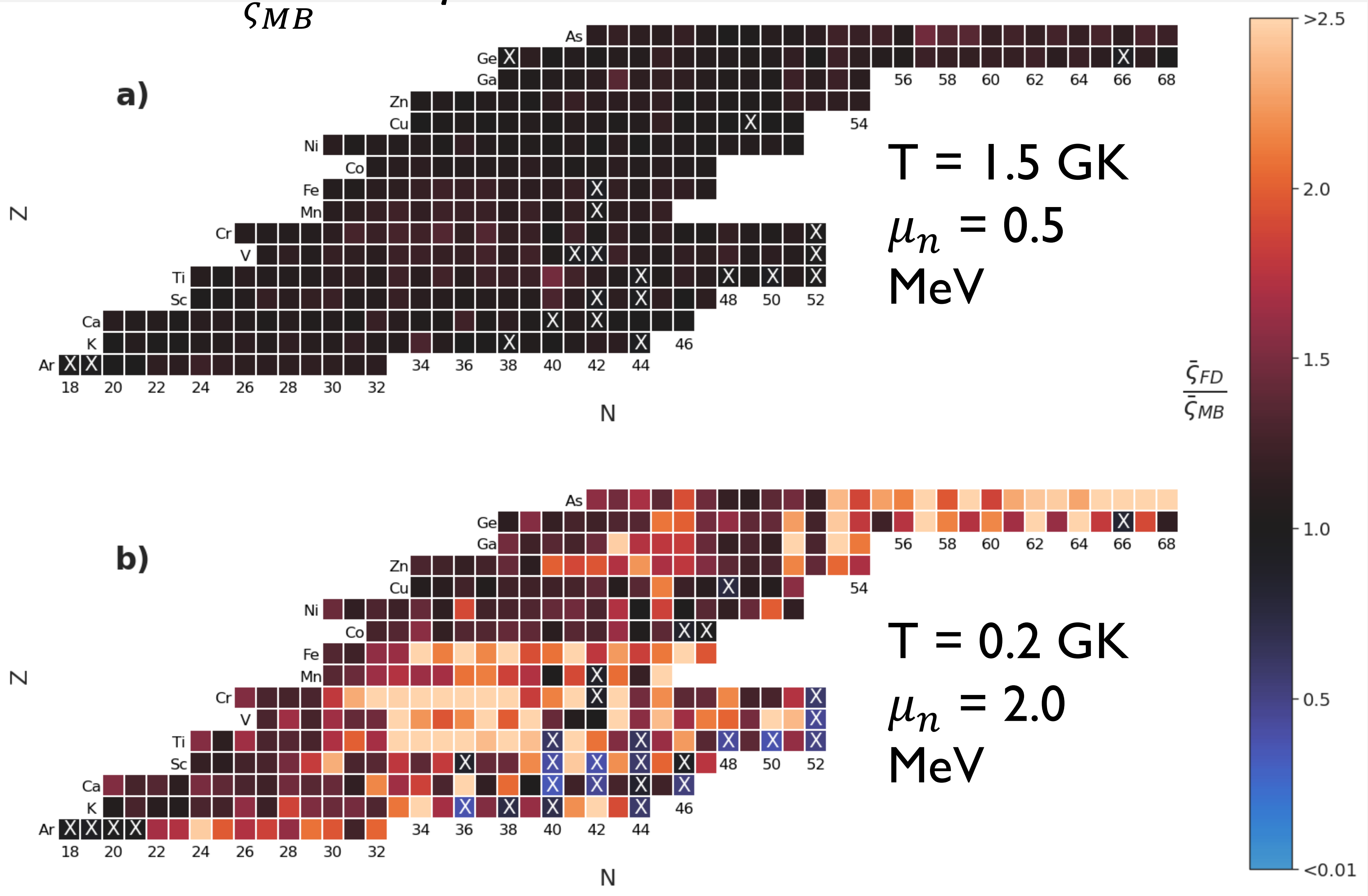
$\frac{\bar{\varsigma}_{FD}}{\bar{\varsigma}_{MB}}$ with γ-SF and LD model variations



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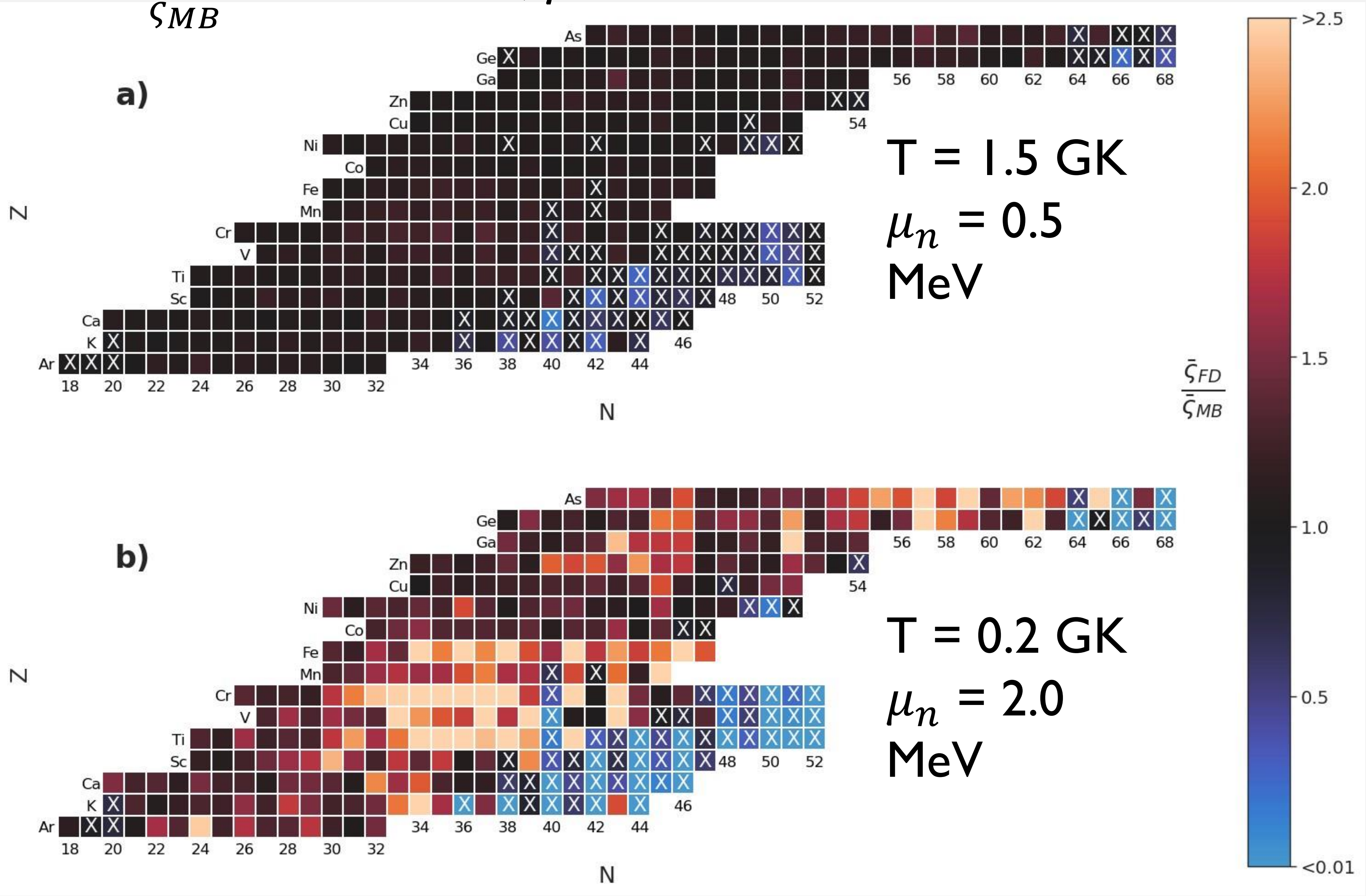
$\frac{\bar{\varsigma}_{FD}}{\bar{\varsigma}_{MB}}$ for with mass, γ-SF and LD model variations



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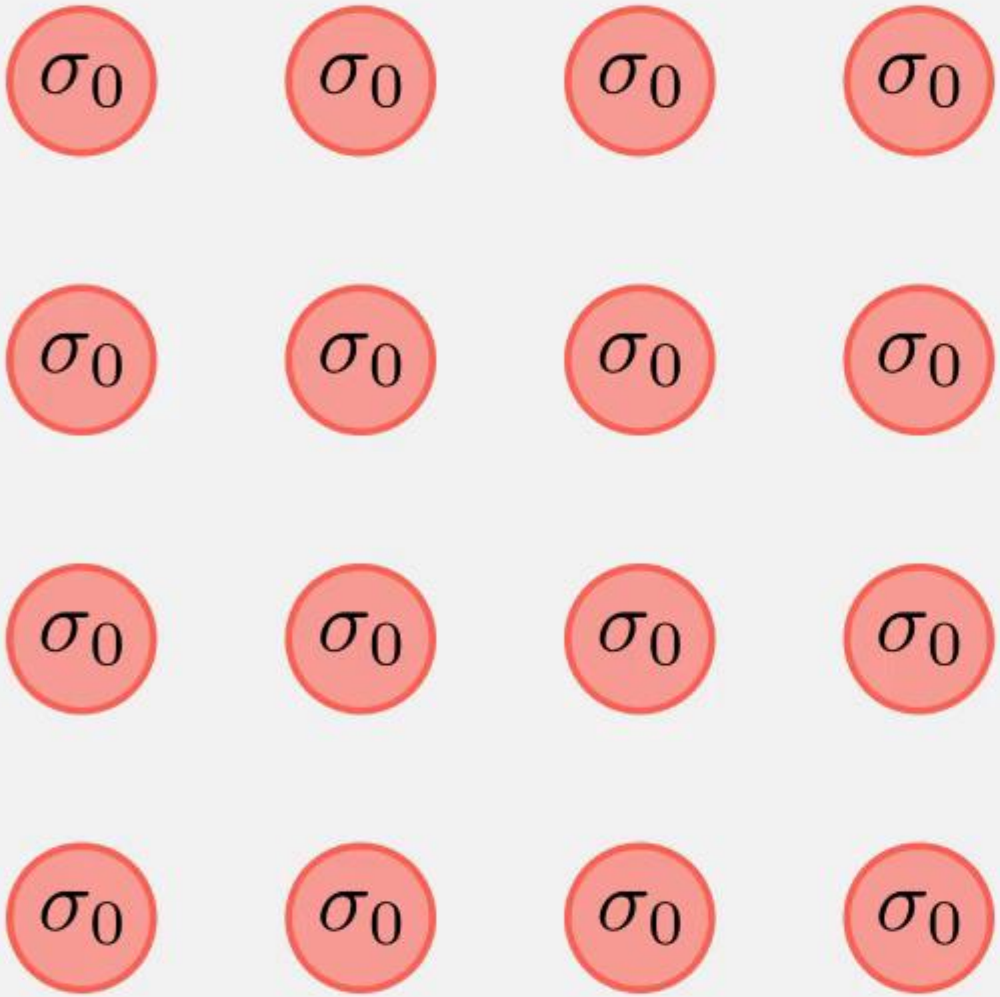
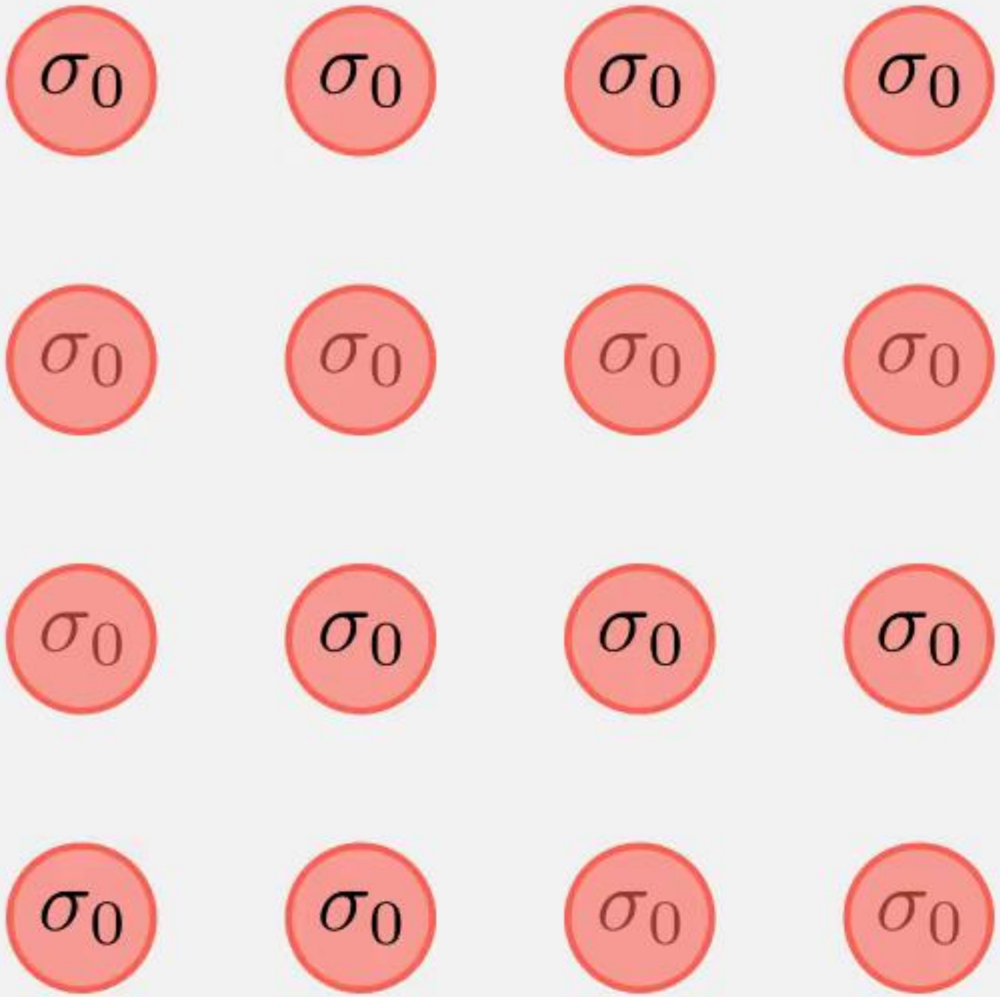
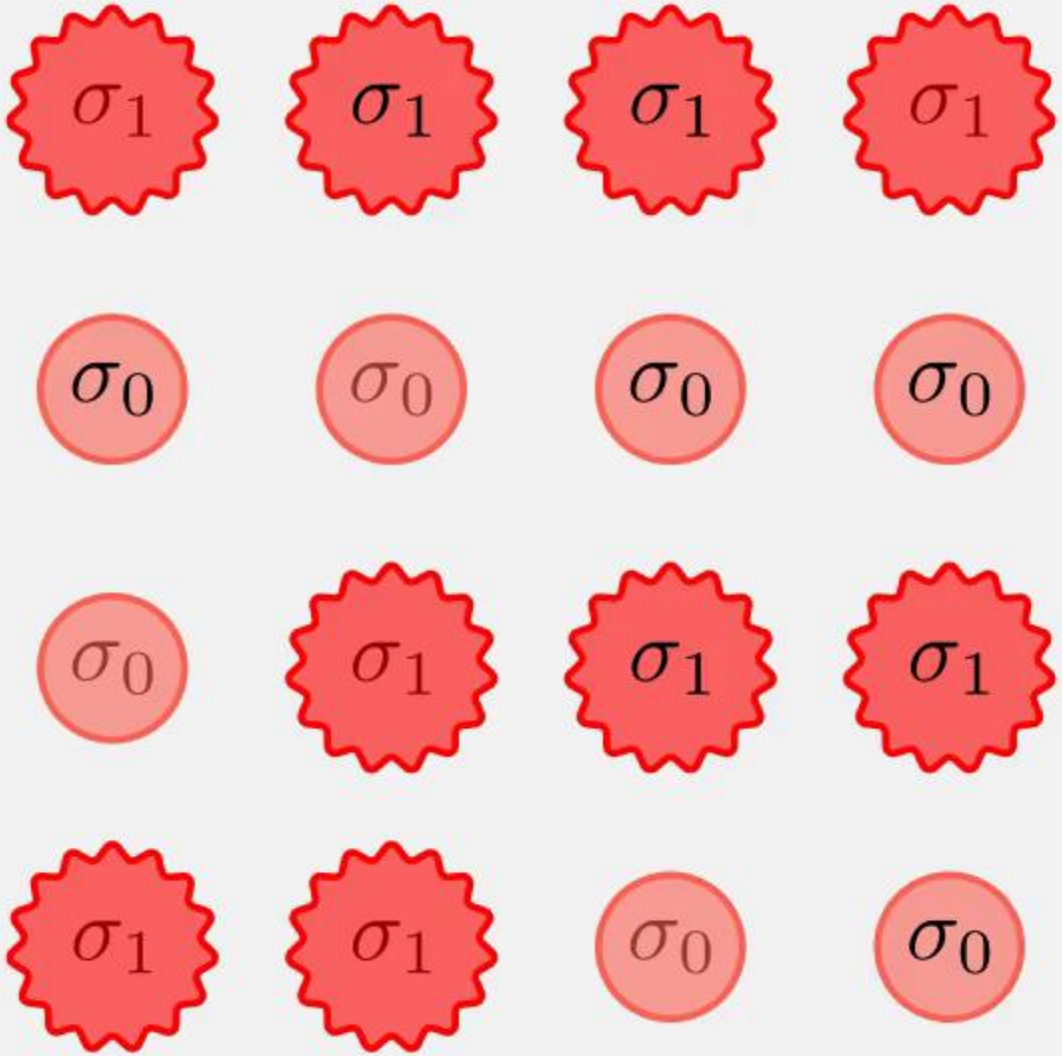
BH-NS MERGER CONDITIONS ARE MUCH HOTTER, DENSER

- Explosive ejecta have much higher temperatures
- There is enough thermal energy to excited target nuclei changing reaction properties
- Free neutron density is also much higher -> larger neutron chemical potential

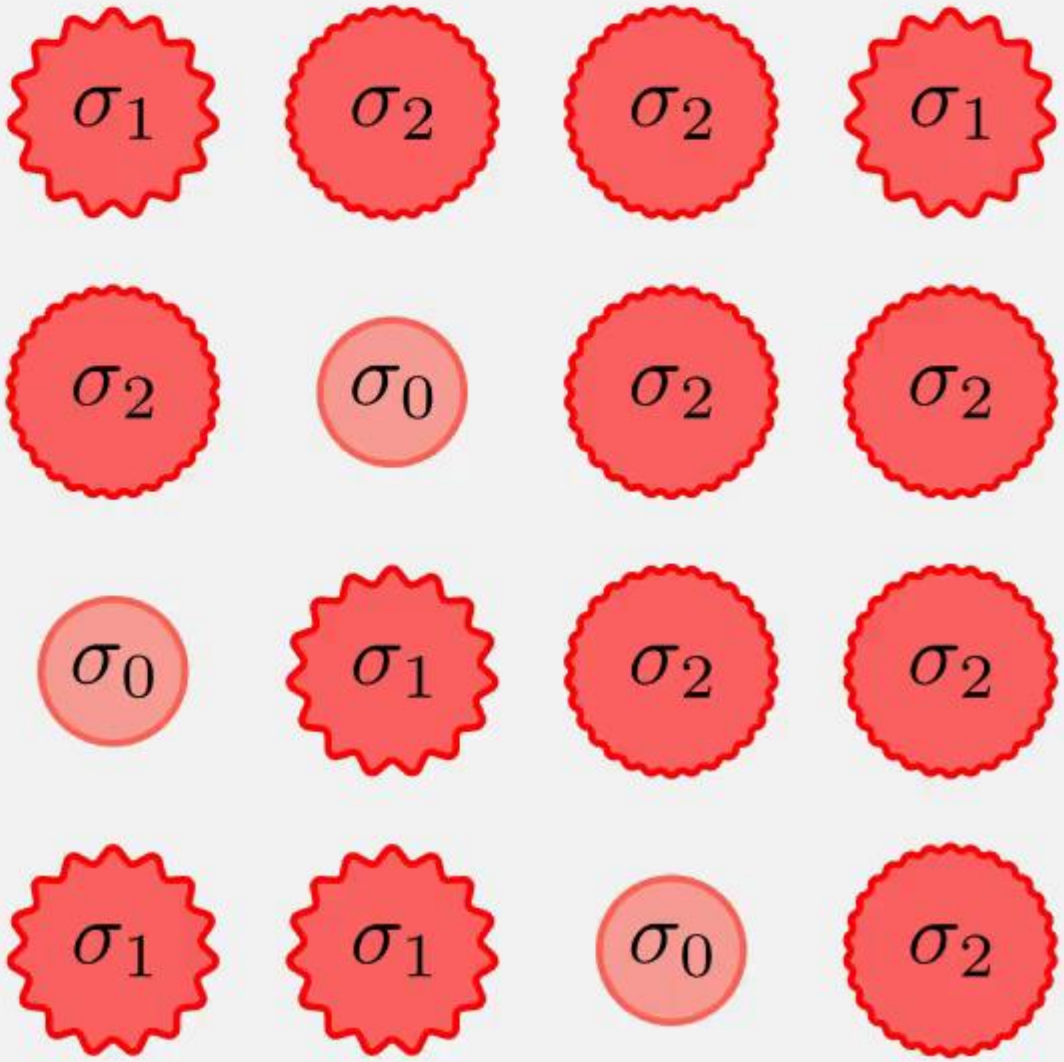

σ_0 σ_0 σ_0 σ_0
σ_0 σ_0 σ_0 σ_0
σ_0 σ_0 σ_0 σ_0
σ_0 σ_0 σ_0 σ_0


σ_0 σ_0 σ_0 σ_0
σ_0 σ_0 σ_0 σ_0
σ_0 σ_0 σ_0 σ_0
σ_0 σ_0 σ_0 σ_0

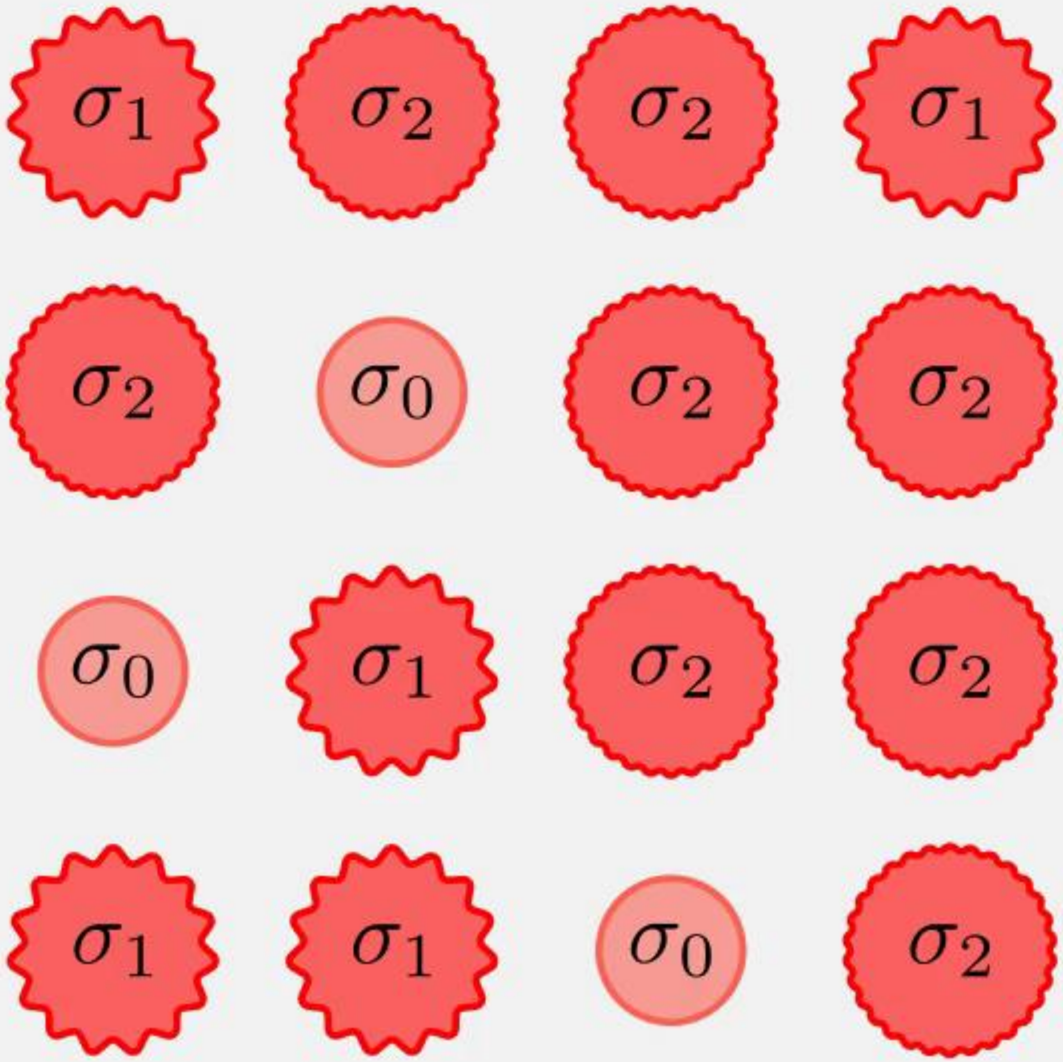
T [MeV]
0.001


σ_1 σ_1 σ_1 σ_1
σ_0 σ_0 σ_0 σ_0
σ_0 σ_1 σ_1 σ_1
σ_1 σ_1 σ_0 σ_0

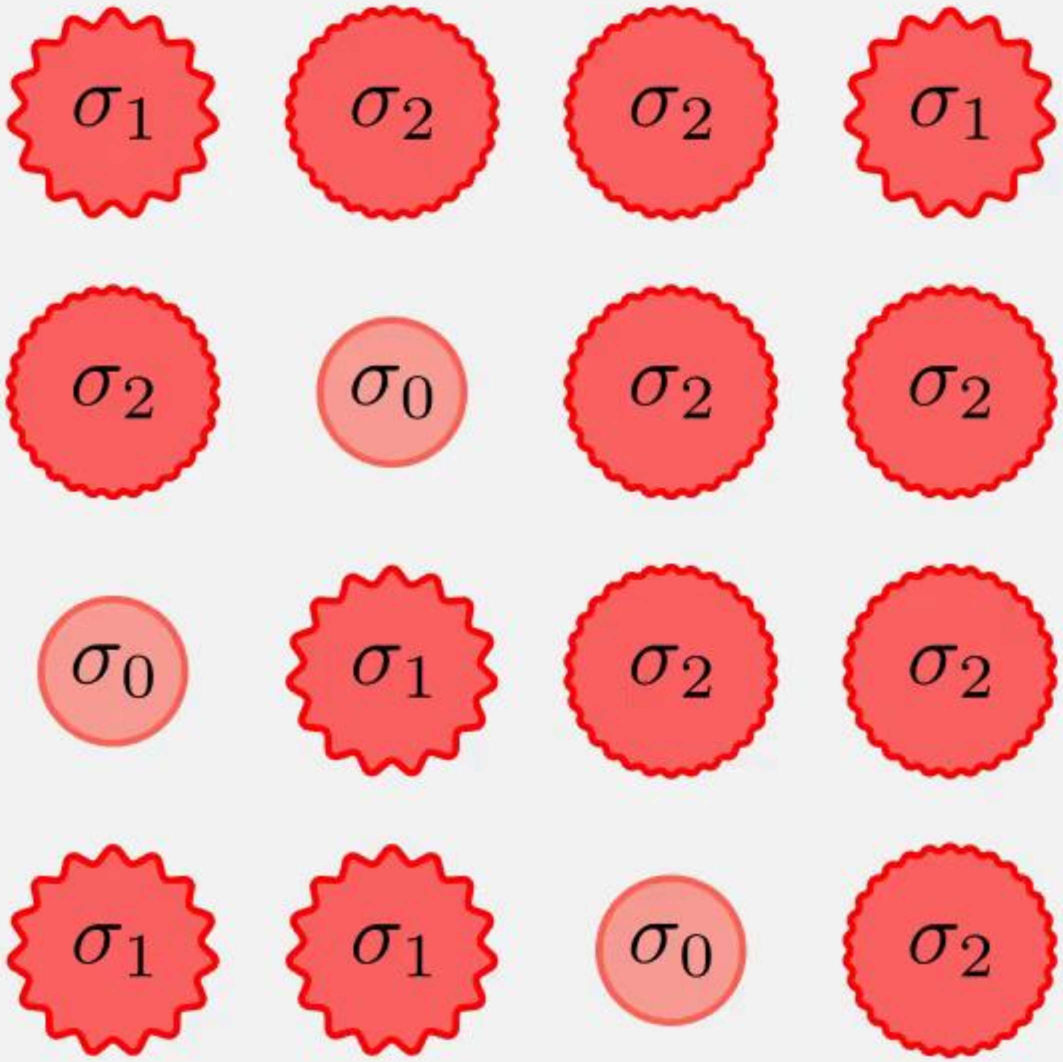
T [MeV]
0.100


σ_1 σ_2 σ_2 σ_1
σ_2 σ_0 σ_2 σ_2
σ_0 σ_1 σ_2 σ_2
σ_1 σ_1 σ_0 σ_2

T [MeV]
1.000



σ_1 σ_2 σ_2 σ_1
σ_2 σ_0 σ_2 σ_2
σ_0 σ_1 σ_2 σ_2
σ_1 σ_1 σ_0 σ_2



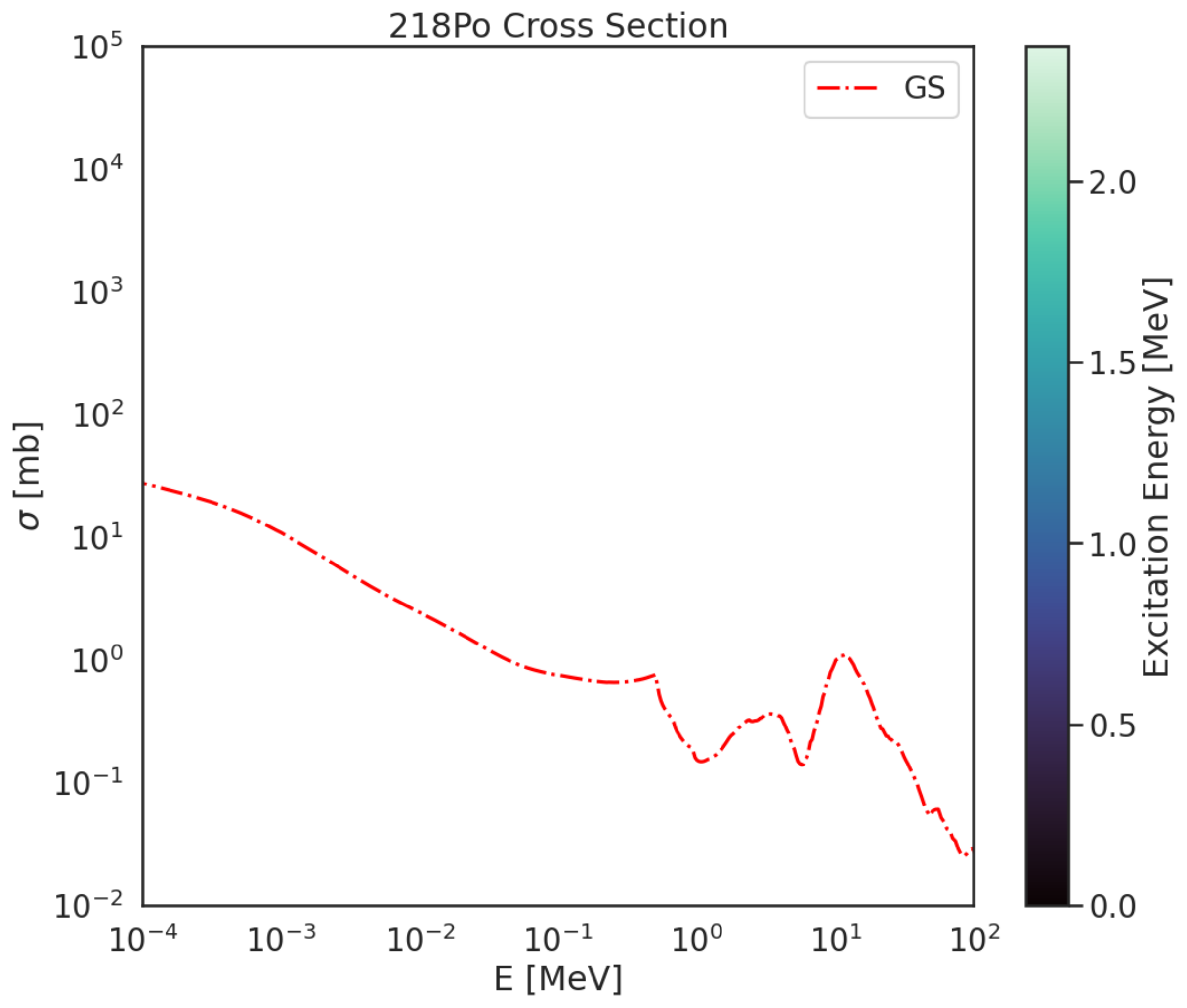
σ_1 σ_2 σ_2 σ_1
σ_2 σ_0 σ_2 σ_2
σ_0 σ_1 σ_2 σ_2
σ_1 σ_1 σ_0 σ_2

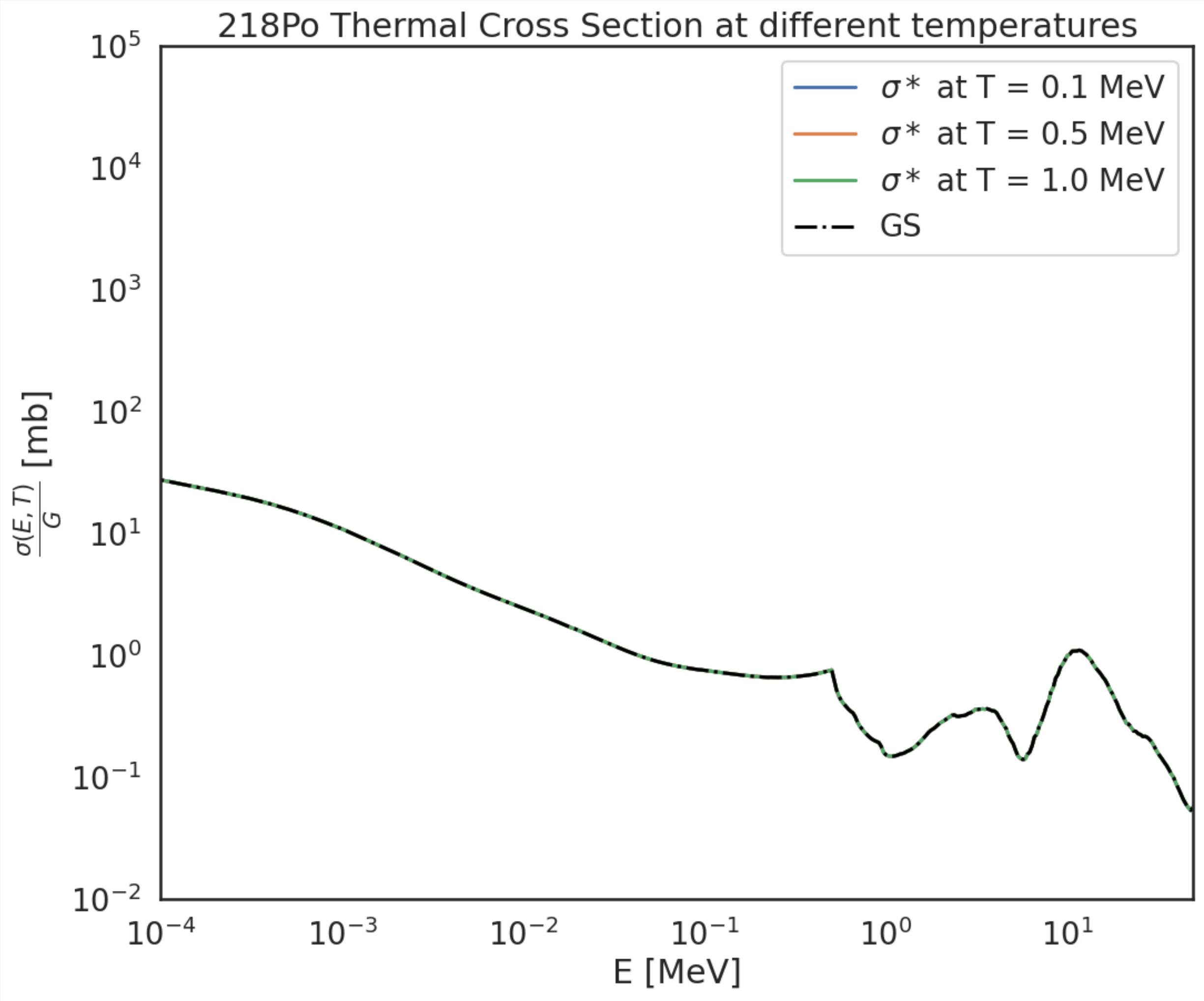
$$\sigma^*(E,T)$$

$$\sigma^*(E, T)$$

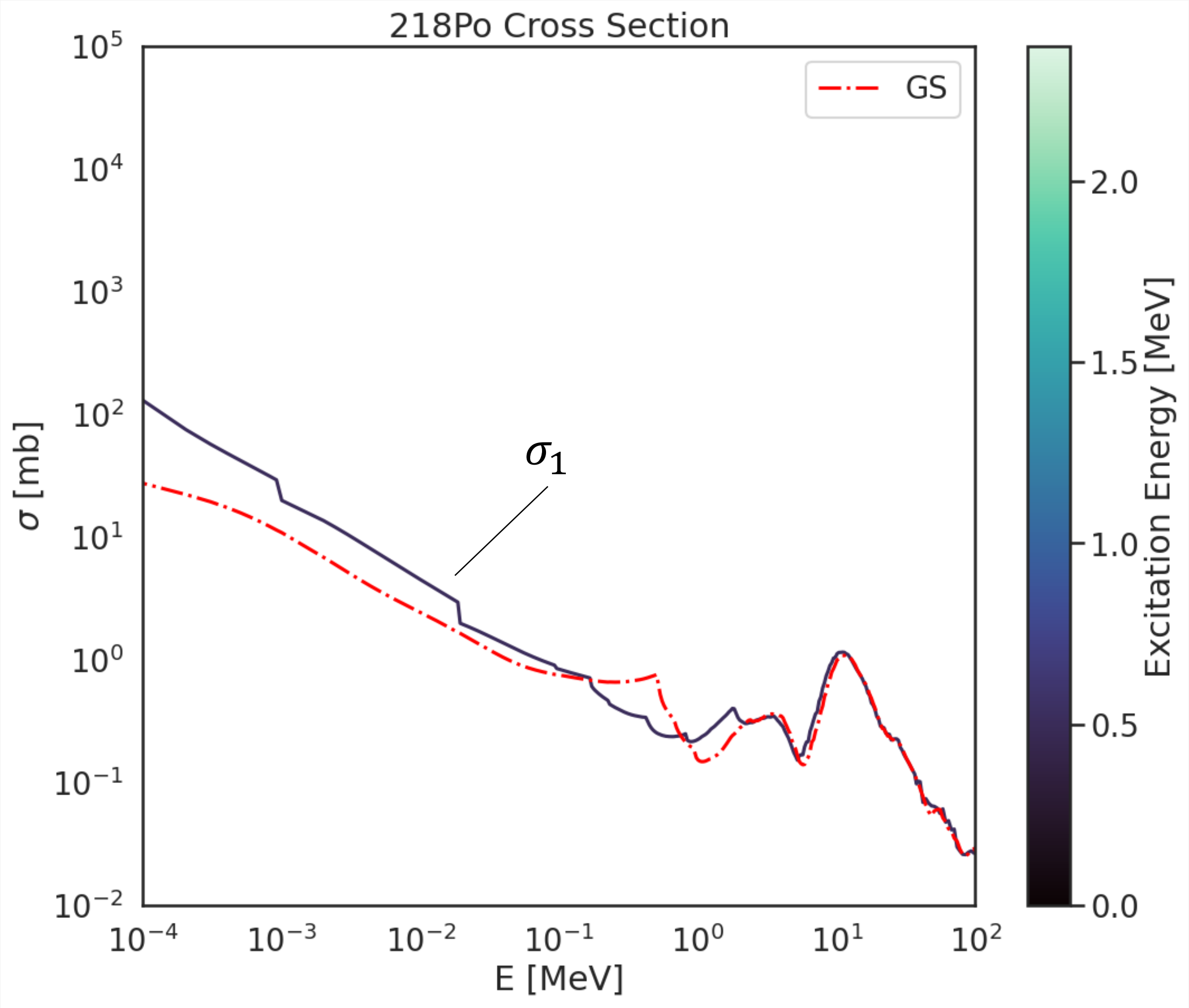
$$\sigma^*(E,T) = \sum_{\nu} P^{\nu} \sigma_{\nu}(E)$$

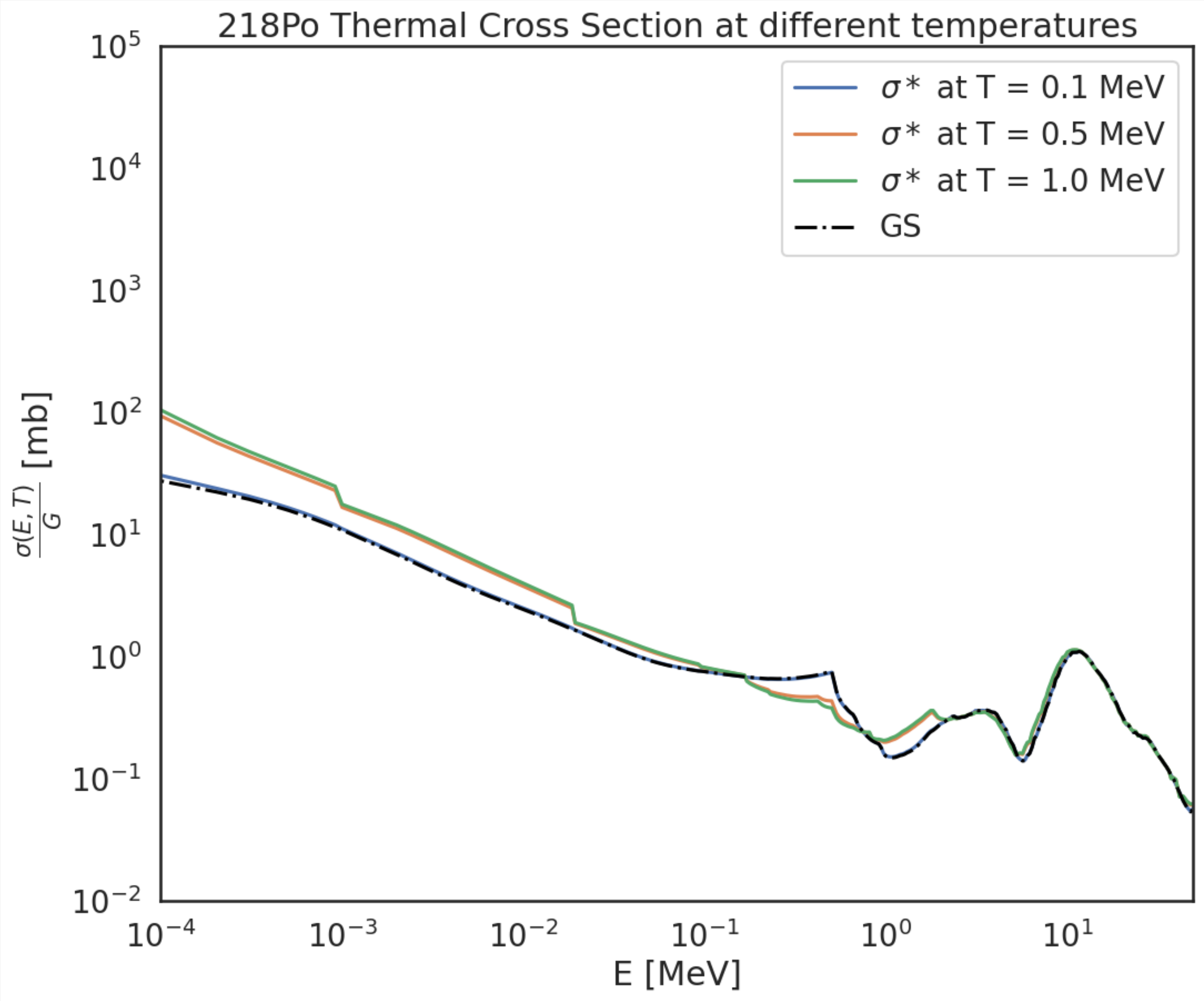
$$\sigma^*(E,T) = \sum_{\nu} \frac{(2I_\nu + 1)e^{-E_x^\nu/T}}{G(T)}\sigma_\nu(E)$$



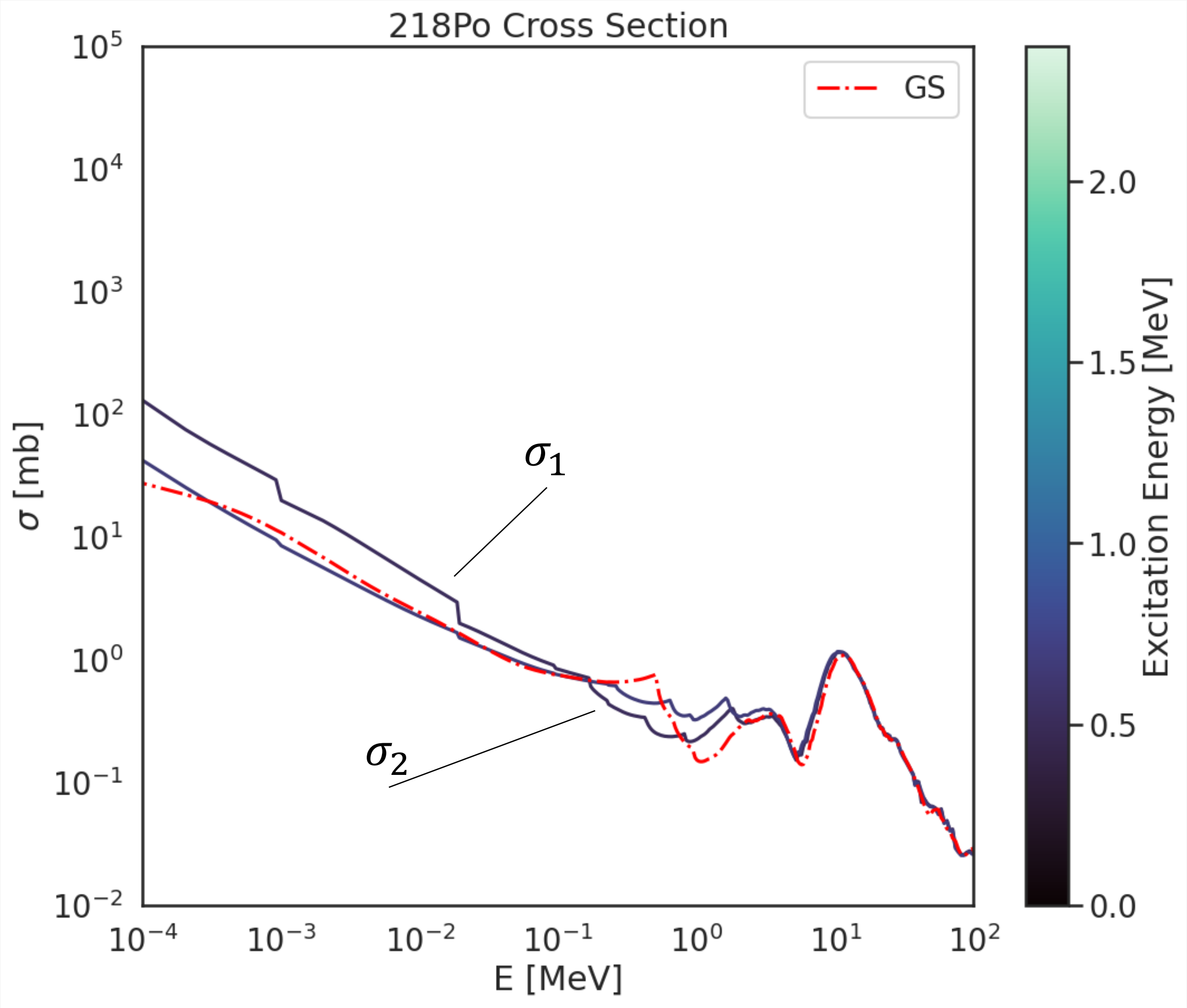


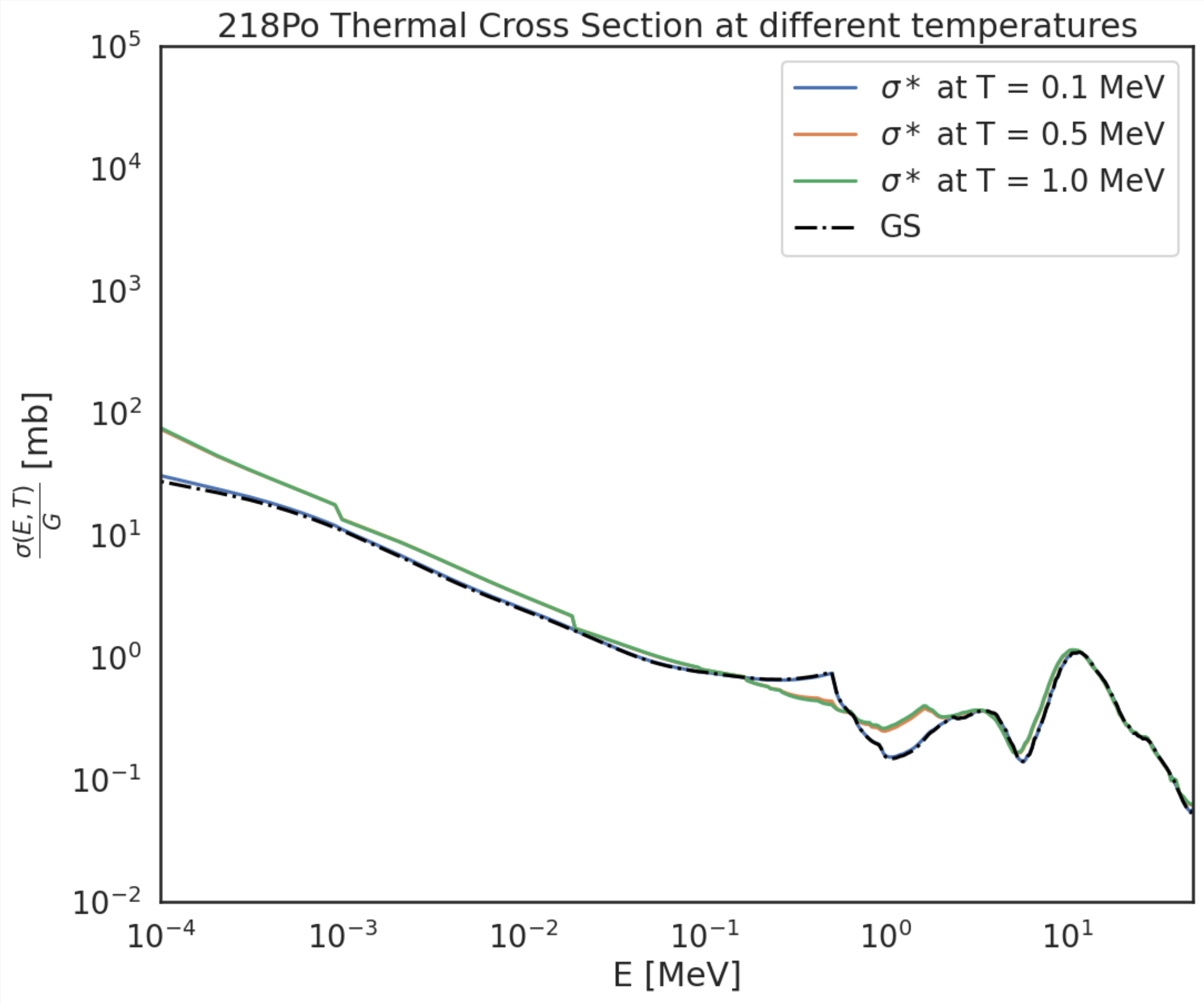
$$\sigma_0(E) = \sigma^*(E, T)$$



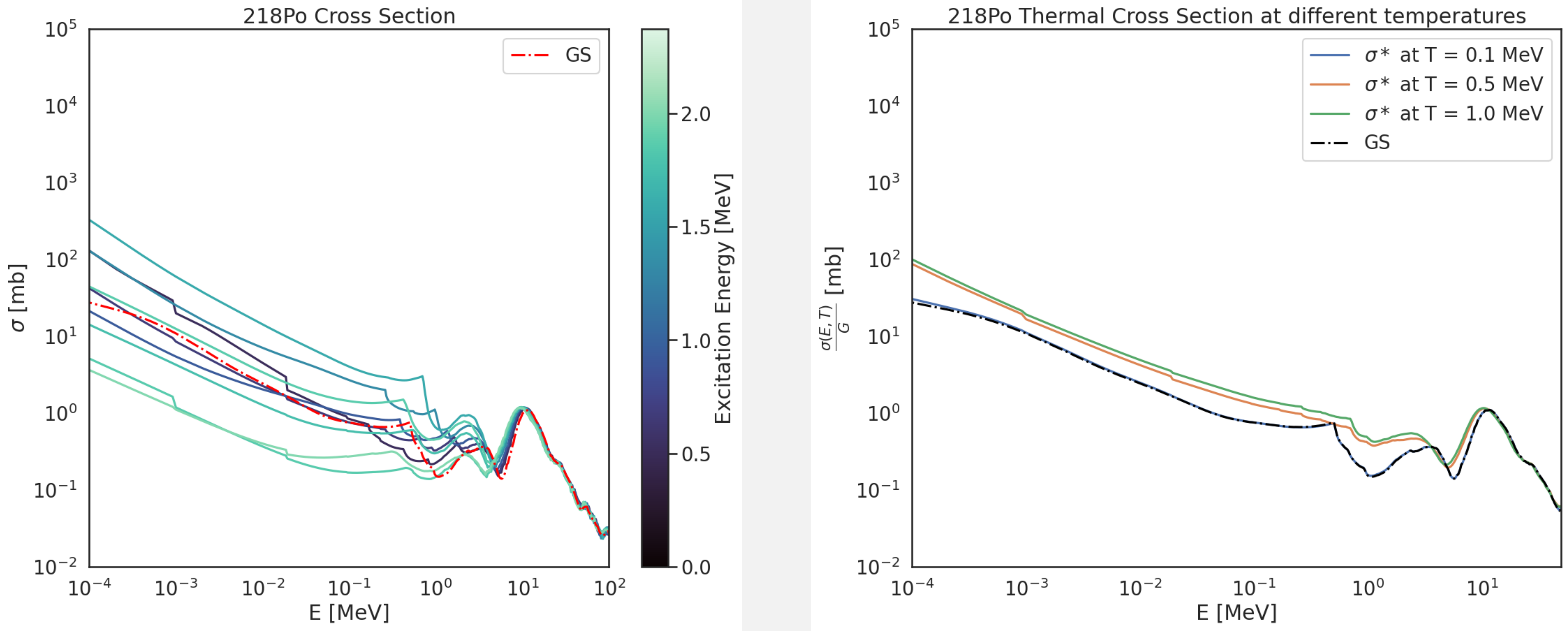


$$\frac{1}{G(T)}\left((2I_0+1)\sigma_0+(2I_1+1)\sigma_1 e^{\frac{-E_x^1}{T}}\right)=\sigma^*(E,T)$$

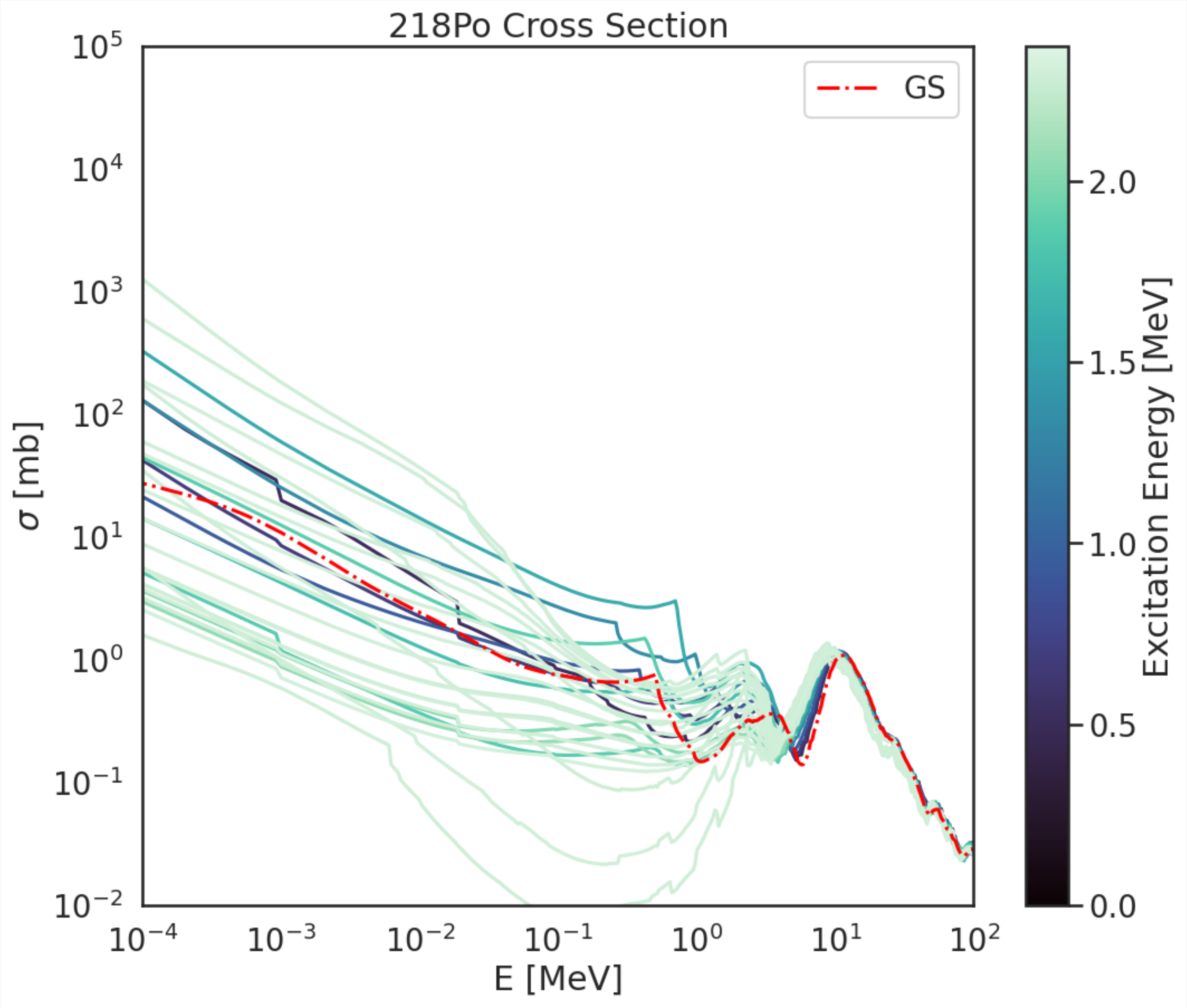


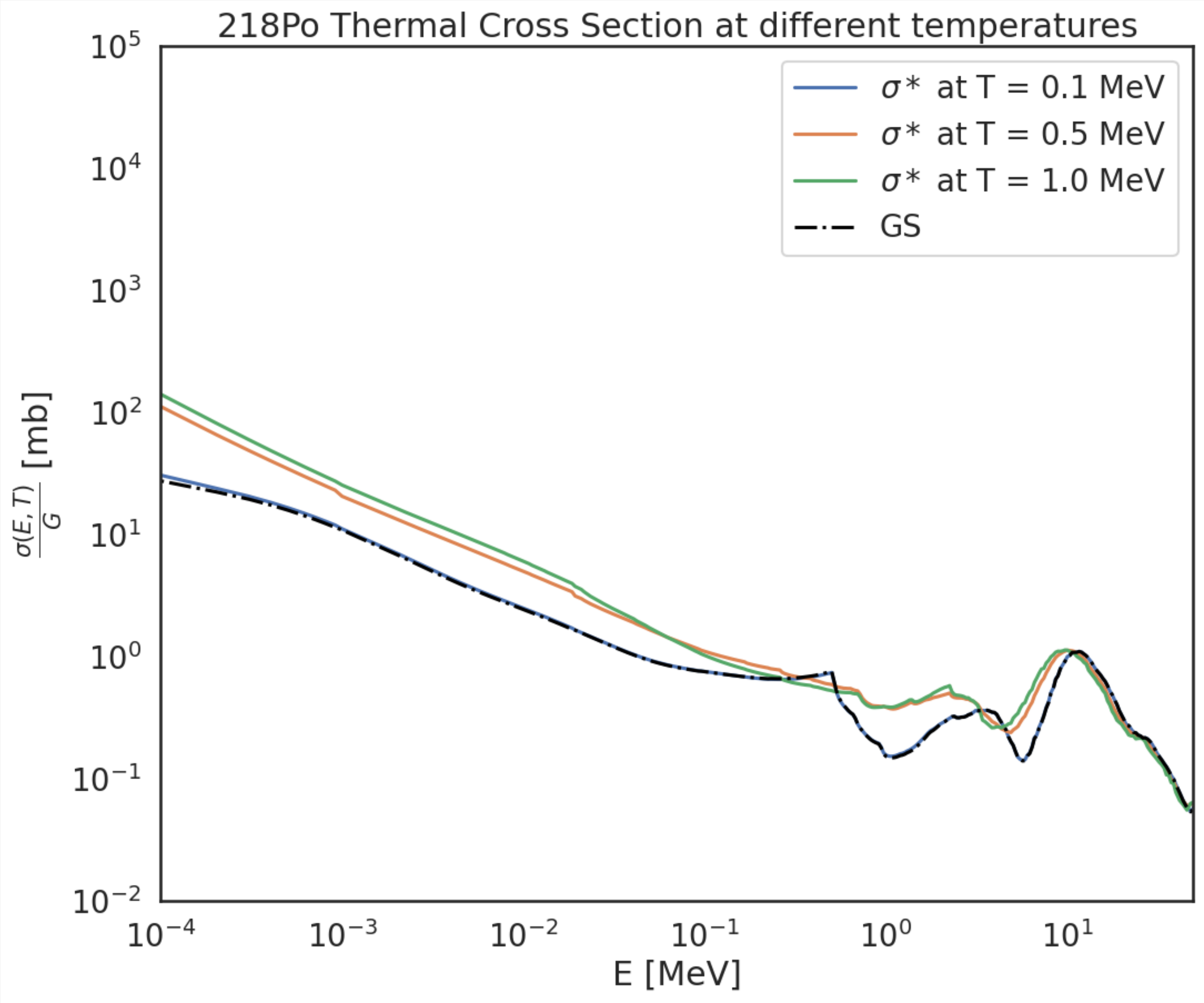


$$\frac{1}{G(T)}\left((2I_0+1)\sigma_0+(2I_1+1)\sigma_1 e^{\frac{-E_x^1}{T}}+(2I_2+1)\sigma_2 e^{\frac{-E_x^2}{T}}\right)=\sigma^*(E,T)$$

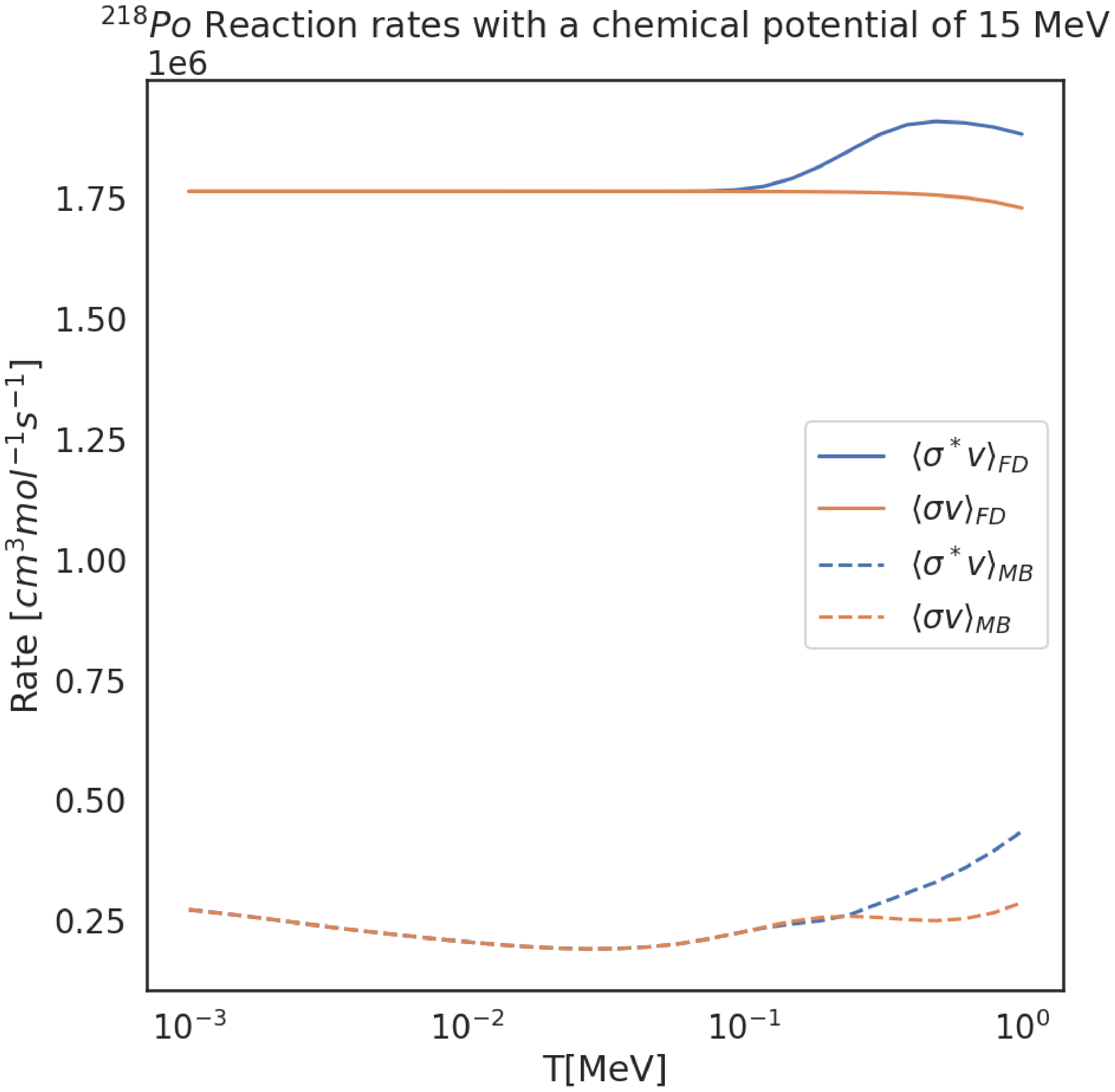


$$\frac{1}{G(T)}\left((2I_0+1)\sigma_0+(2I_1+1)\sigma_1 e^{\frac{-E_x^1}{T}}+(2I_2+1)\sigma_2 e^{\frac{-E_x^2}{T}}+\cdots\right)=\sigma^*(E,T)$$





$$\frac{1}{G(T)}\sum_{\nu=30}(2I_\nu+1)e^{\frac{-E_x^\nu}{T}}\sigma_\nu(E)=\sigma^*(E,T)$$



^{218}Po Reaction rates with a chemical potential of 15 MeV
1e6
1.75
1.50
1.25
1.00
0.75
0.50
0.25
Rate $[cm^3 mol^{-1} s^{-1}]$
$\langle \sigma^* v \rangle_{FD}$
$\langle \sigma v \rangle_{FD}$
$\langle \sigma^* v \rangle_{MB}$
$\langle \sigma v \rangle_{MB}$
10^{-3}
10^{-2}
10^{-1}
10^{0}
T[MeV]

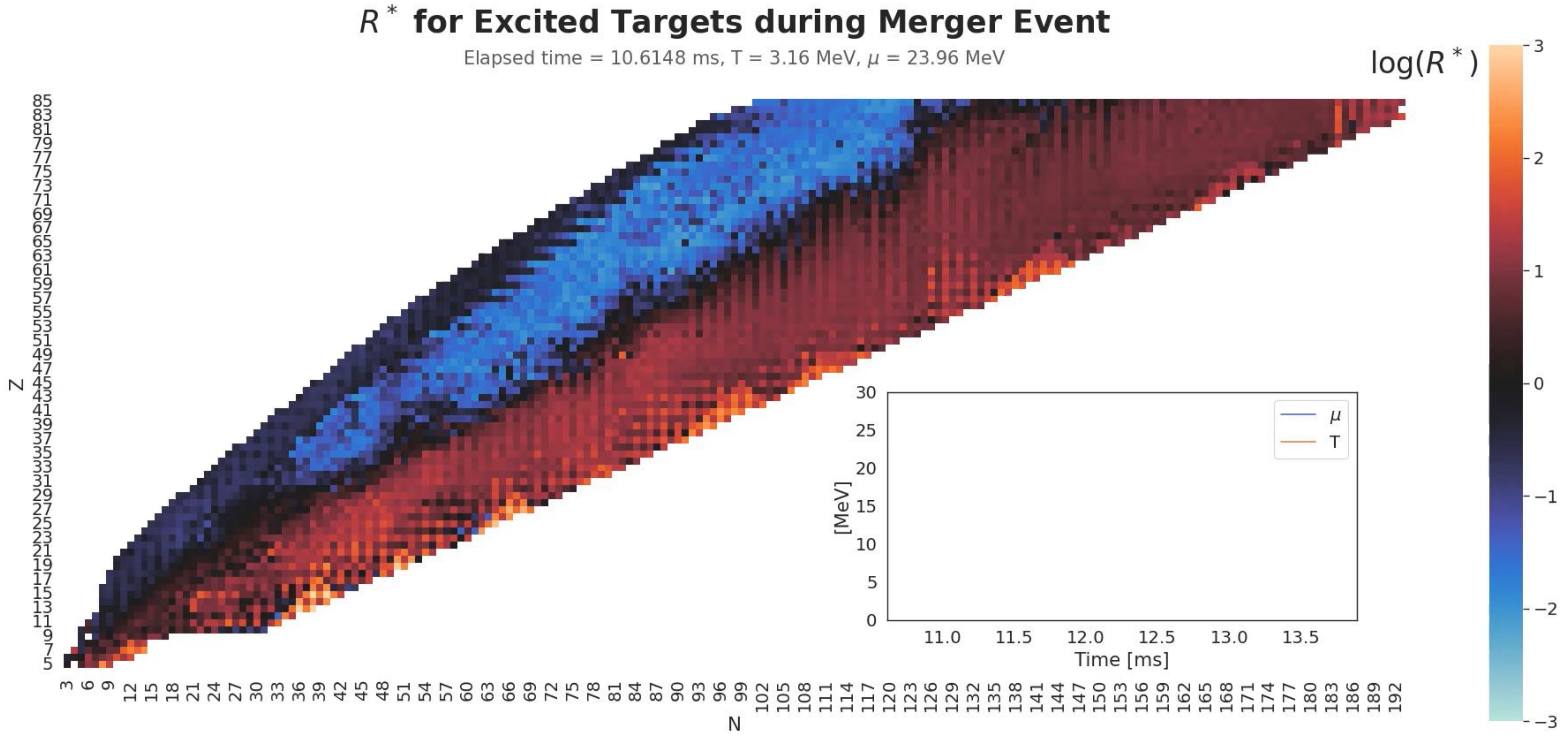
QUANTIFYING THE STELLAR REACTION RATE ENHANCEMENTS

- Compare the stellar reaction rates to the classical counterpart via $R^* = \frac{\langle \sigma^* v \rangle_{FD}}{\langle \sigma^* v \rangle_{MB}}$

- Check the impact the stellar cross section has on degenerate rates via $\frac{\langle \sigma^* v \rangle_{FD}}{\langle \sigma v \rangle_{FD}}$

- Thermodynamic conditions are based on a merger between a $10\ M_\odot$ BH and a $1.4\ M_\odot$ NS.[4]

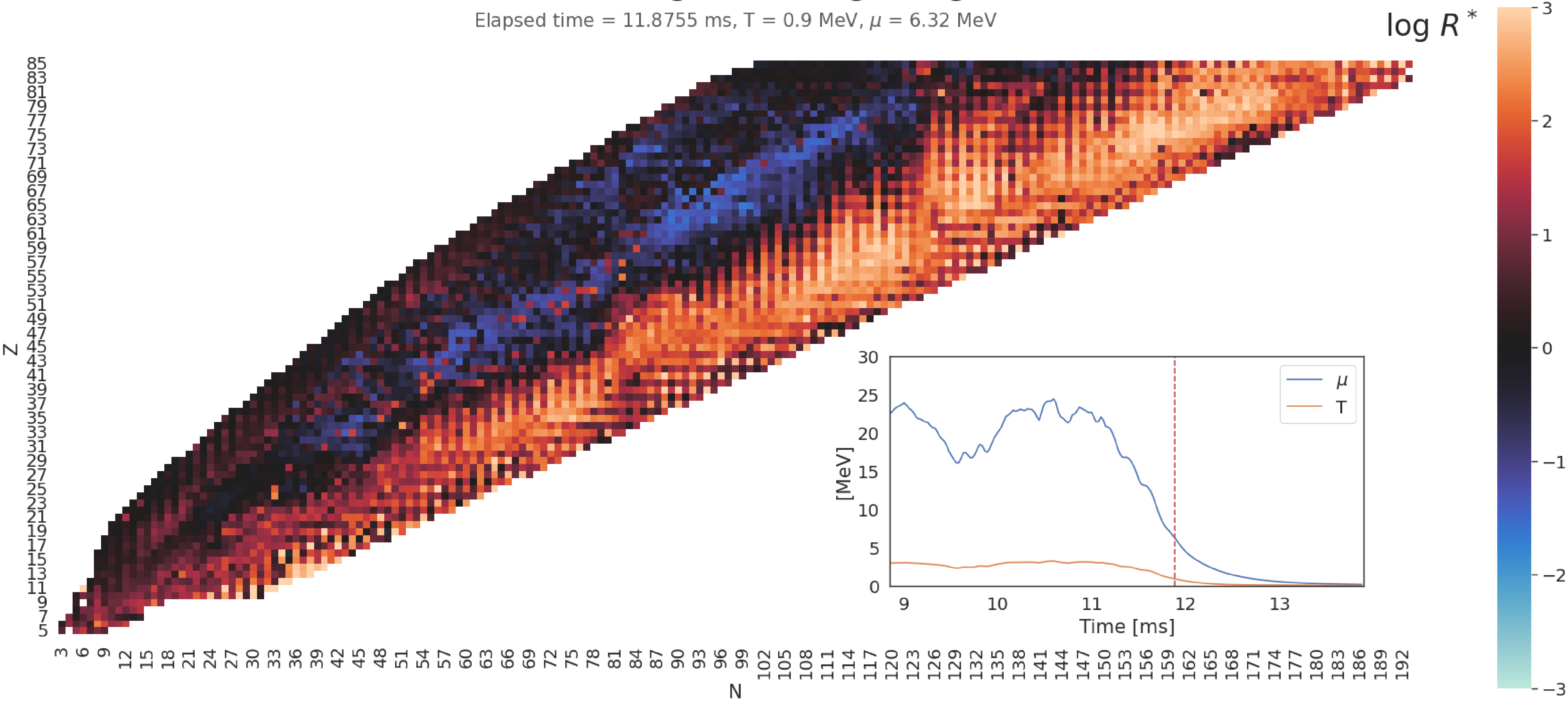
4 - S. Rosswog, T. Piran and E. Nakar, **MNRAS** 430 (4), pp.2585-2604 (2013)



R^* for Excited Targets during Merger Event
Elapsed time = 10.6148 ms, T = 3.16 MeV, μ = 23.96 MeV
log(R^*)
Z
N
μ
T
[MeV]
Time [ms]

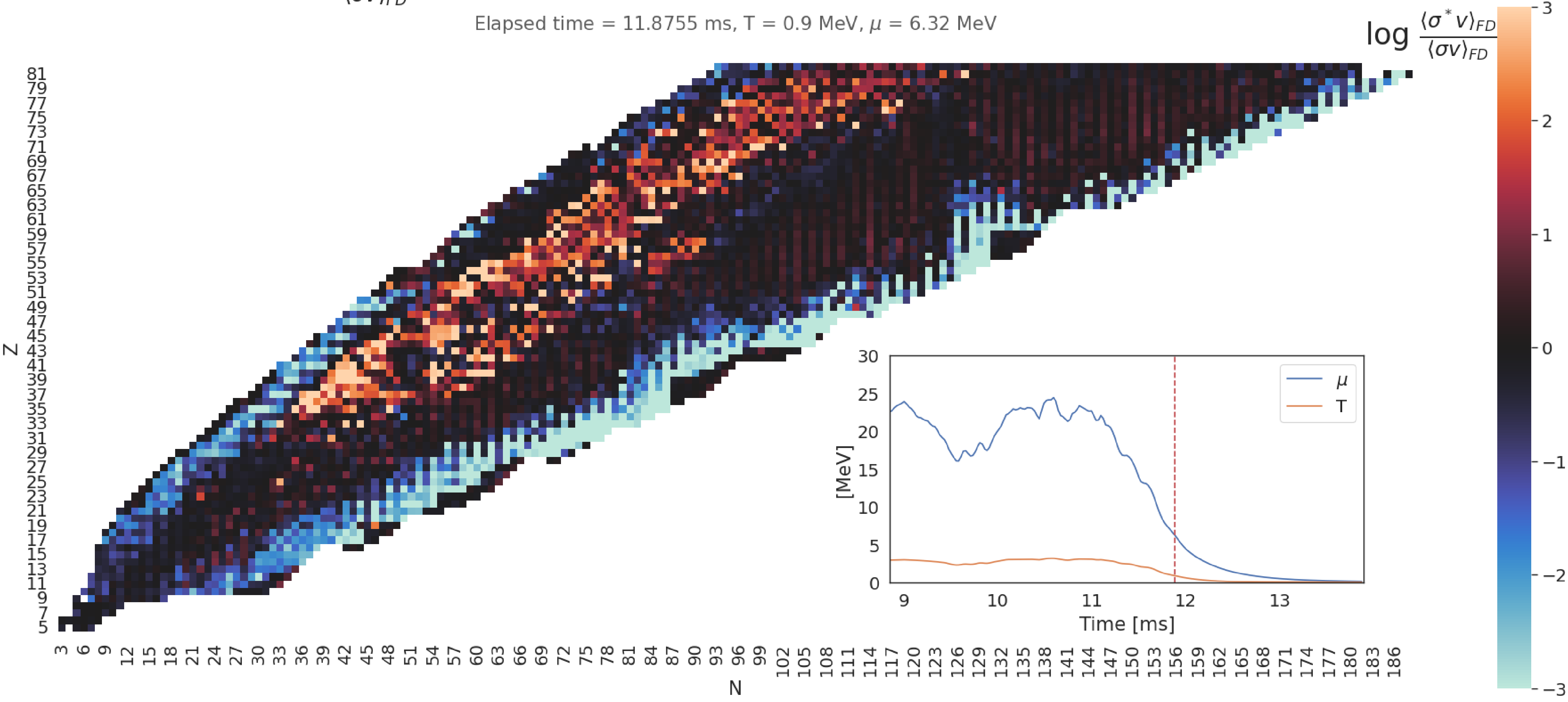
R^* for Excited Targets during Merger Event

Elapsed time = 11.8755 ms, T = 0.9 MeV, μ = 6.32 MeV



$\frac{\langle \sigma^* v \rangle_{FD}}{\langle \sigma v \rangle_{FD}}$ for Excited Targets during Merger Event

Elapsed time = 11.8755 ms, T = 0.9 MeV, μ = 6.32 MeV



SUMMARY

- Degeneracy effects can neutron capture rates by multiple orders of magnitude.

- Reaction rate uncertainty due to nuclear physics input is further enhanced with neutron degeneracy

- Neutron degeneracy could provide a significant change to R-Process abundances in NS-BH mergers.

THANK YOU!