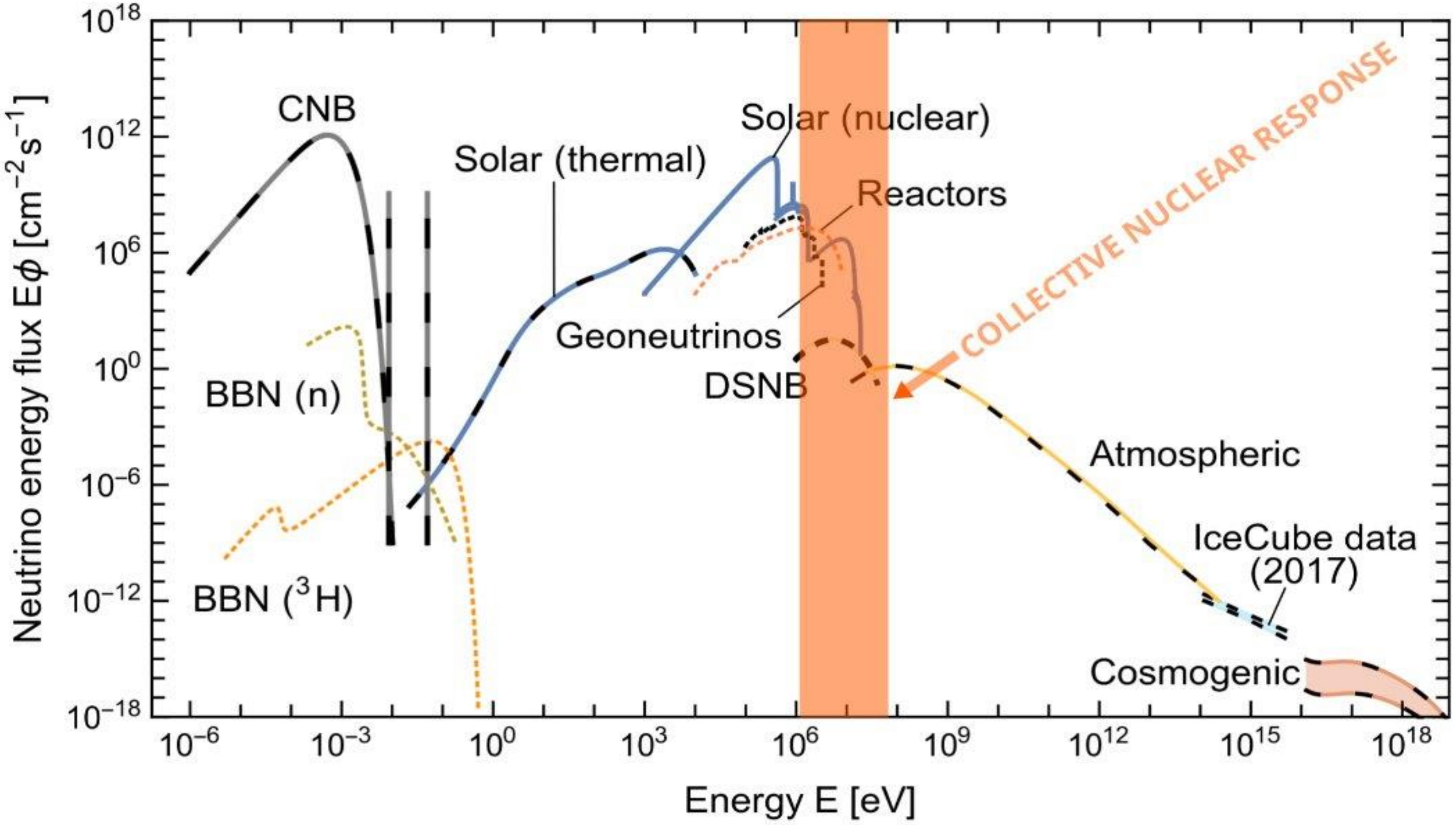
Low energy neutrino-nucleus interactions

with Relativistic Energy Density Functionals

Rade Smolović[1], Nils Paar[1], Ante Ravlić[1,2]

[1] Department of Physics, University of Zagreb, Croatia
[2] FRIB, Michigan State University, East Lansing, USA

"Low energy"



(Adapted from Vitagliano, Tamborra, and Raffelt, Rev. Mod. Phys. 045006, 2020)

Solar

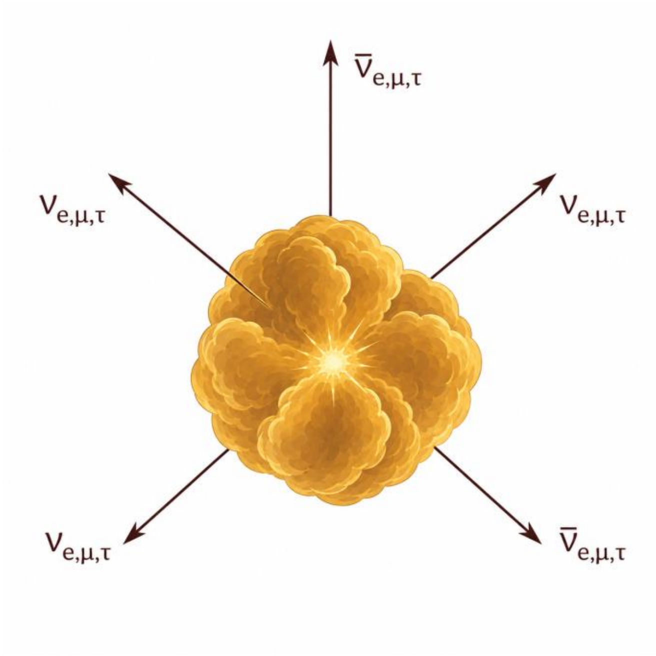
Supernova

Reactor

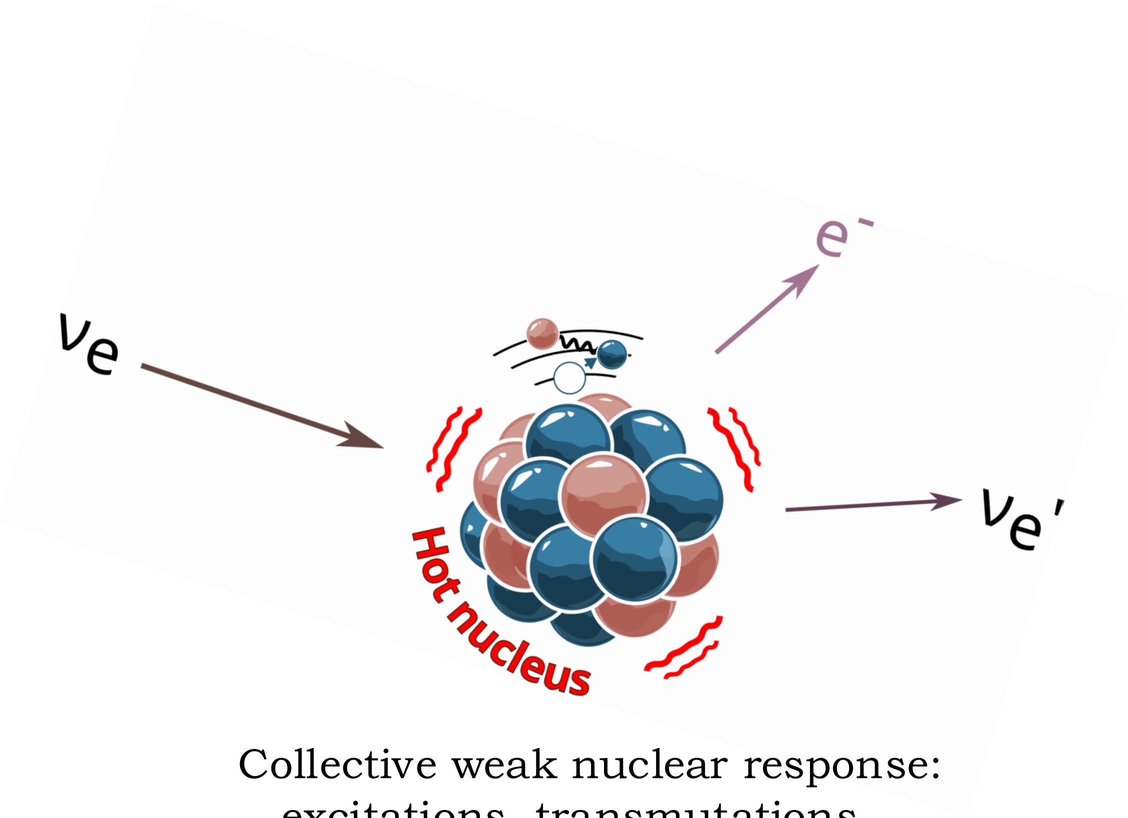
Stopped-pion sources

For tens-of-MeV neutrinos, the cross section is shaped by the **nuclear response**.

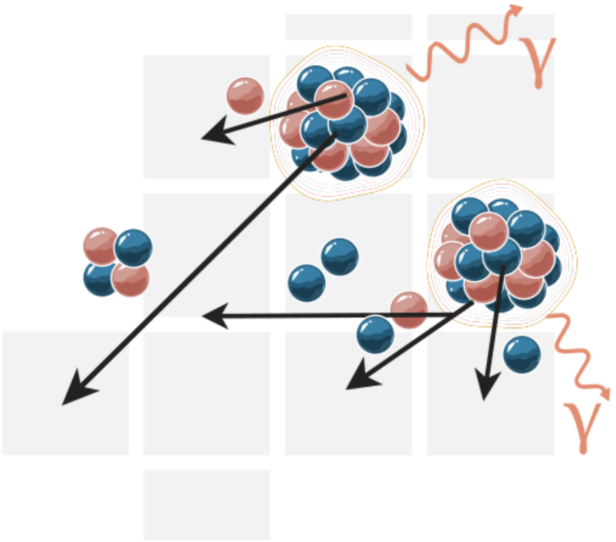
Neutrino nucleosynthesis



~10^{58} neutrinos released in a matter of seconds.

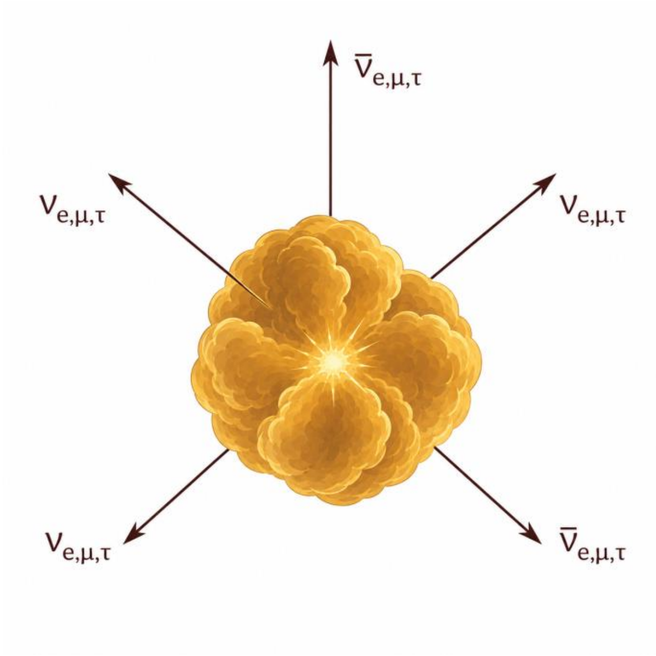


Collective weak nuclear response: excitations, transmutations...



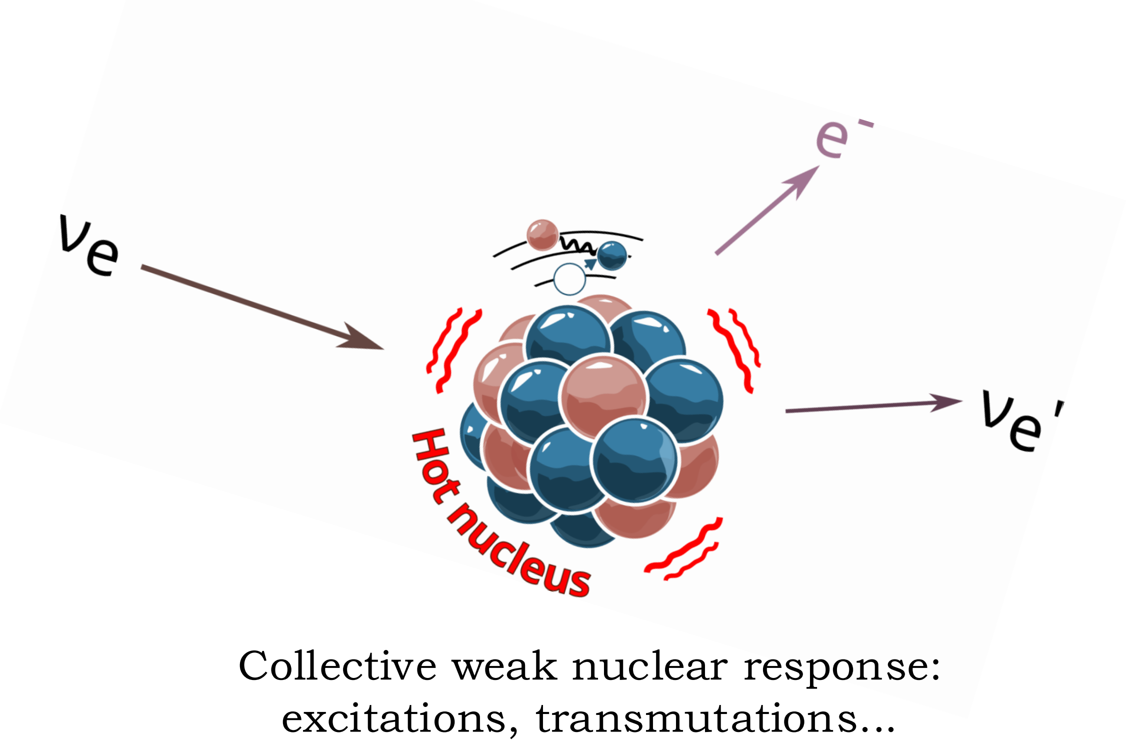
Affected nuclei enter the nucleosynthesis chain.

Neutrino nucleosynthesis

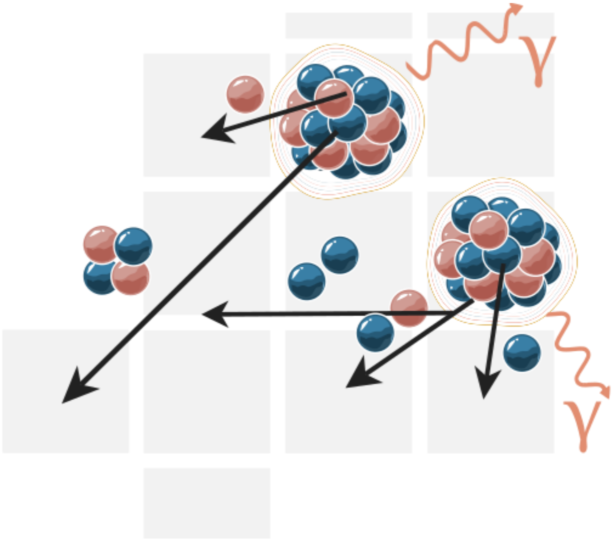


~10^{58} neutrinos released in a matter of seconds.

GOAL:
Global microscopic self-consistent estimates of the neutrino-nucleus cross sections .



Collective weak nuclear response: excitations, transmutations...



Affected nuclei enter the nucleosynthesis chain.

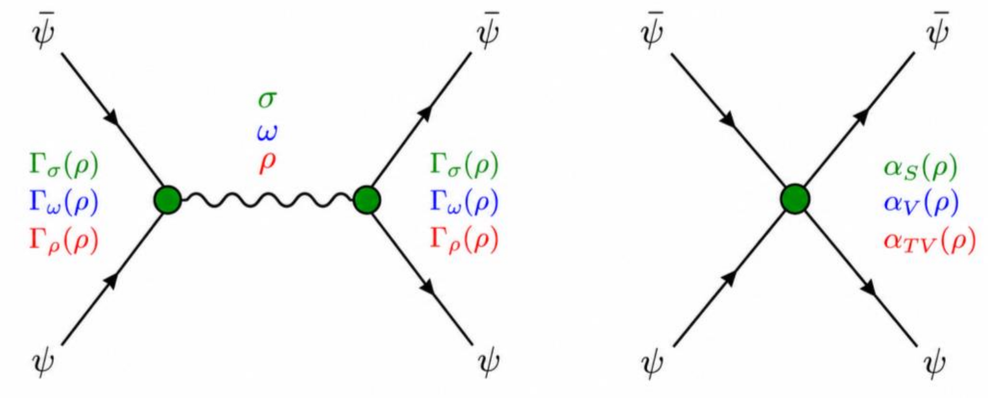
Relativistic QRPA

GROUND STATE

Relativistic energy density functional:

$$E[\rho,\kappa] = E_{\mathrm{RH}}[\rho] + E_{\mathrm{pair}}[\kappa], \qquad h_D = \frac{\delta E}{\delta \rho}, \qquad \Delta = \frac{\delta E}{\delta \kappa^*}.$$

Effective interaction through meson exchange:



Density-dependent couplings. Parameters fitted once and used for all nuclei.

Output: $\{\phi_k(\boldsymbol{r}), \epsilon_k, \Delta_k, \lambda_t, E_k, u_k, v_k\}$

EXCITED STATE

Relativistic QRPA:

$$\begin{pmatrix} A^J & B^J \\ -B^J & -A^J \end{pmatrix} \begin{pmatrix} X^J_\nu \\ Y^J_\nu \end{pmatrix} = \omega_\nu \begin{pmatrix} X^J_\nu \\ Y^J_\nu \end{pmatrix}.$$

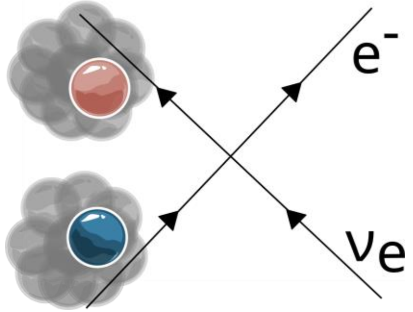
Residual interactions from the same EDF:

$$V^{ph}_{12,34} = \frac{\delta^2 E}{\delta\rho_{21}\,\delta\rho_{34}}, \qquad V^{pp}_{12,34} = \frac{\delta^2 E}{\delta\kappa^*_{12}\,\delta\kappa_{34}}.$$

Nuclear matrix elements from RQRPA:

$$\langle \nu J|\hat O_J|0\rangle = \sum_{pn} \left(X^{\nu J}_{pn} u_p v_n + Y^{\nu J}_{pn} v_p u_n \right) \langle p\|\hat O_J\|n\rangle$$

$$B_\nu(O_J) = \left| \langle \nu J|\hat O_J|0\rangle \right|^2.$$



Cross sections

TWO WAYS TO ESTIMATE THE CROSS SECTION

1| **FULL DECOMPOSITION**:

Lepton current: Plane waves – kinematics only.

Nuclear current: Many-body problem, nuclear response…

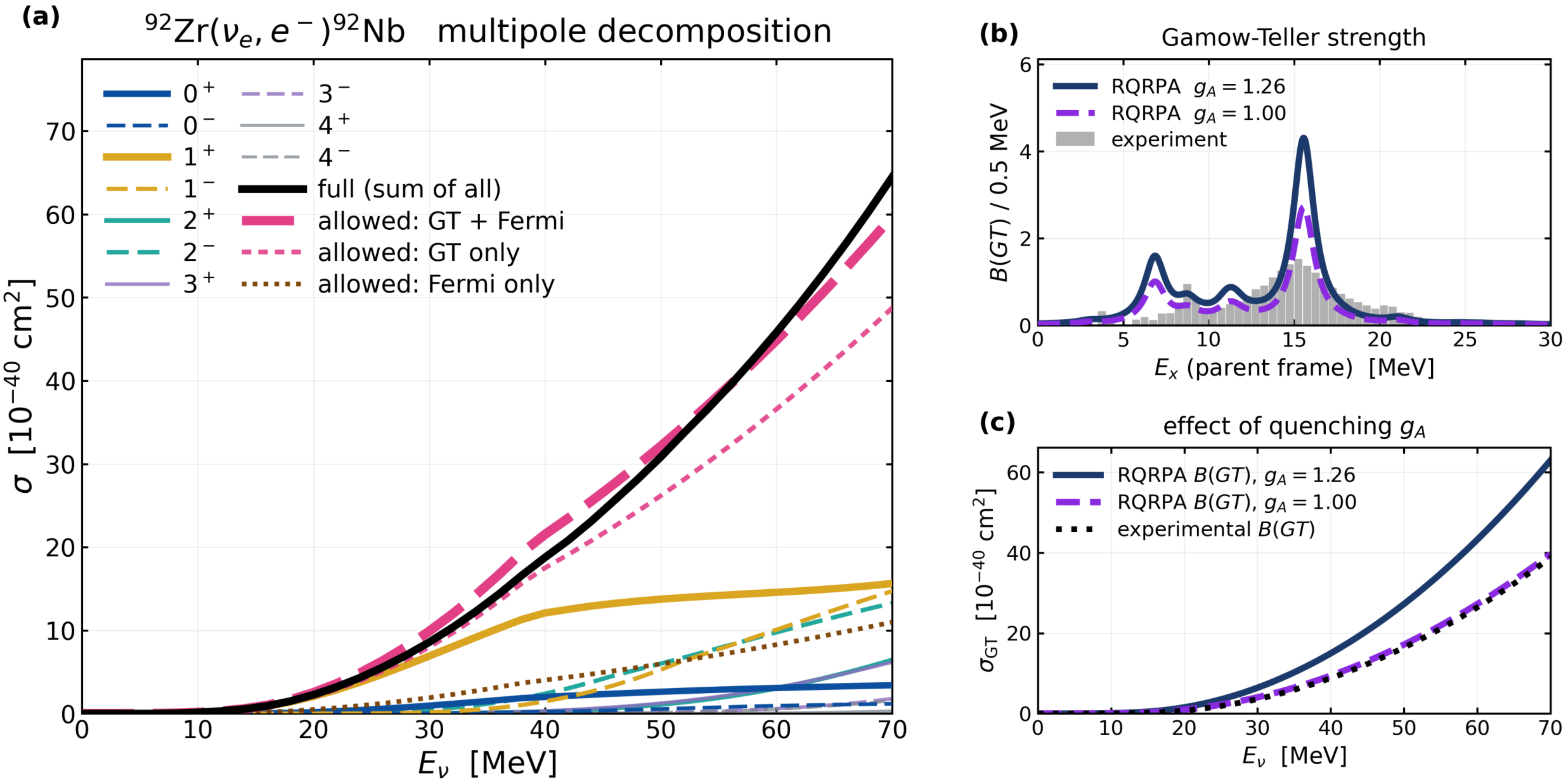
$$\left(\frac{d\sigma}{d\Omega}\right)_{\hat{\nu}} = \frac{G^2 k\epsilon}{\pi}\frac{1}{2J_i+1}\left\{\sum_{J=0}^{\infty}\left[(1+\hat{\nu}\cdot\vec{\beta})|\langle J_f\|\hat{\mathcal{M}}_J\|J_i\rangle|^2 + (1-\hat{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\hat{q}\cdot\vec{\beta}))|\langle J_f\|\hat{\mathcal{L}}_J\|J_i\rangle|^2 - [\hat{q}\cdot(\hat{\nu}+\vec{\beta})]\,2\,\mathrm{Re}\left(\langle J_f\|\hat{\mathcal{L}}_J\|J_i\rangle\langle J_f\|\hat{\mathcal{M}}_J\|J_i\rangle^*\right)\right] + \sum_{J\geq 1}\left[1-(\hat{\nu}\cdot\hat{q})(\hat{q}\cdot\vec{\beta})\right]\left(|\langle J_f\|\hat{\mathcal{J}}_J^{\mathrm{mag}}\|J_i\rangle|^2 + |\langle J_f\|\hat{\mathcal{J}}_J^{\mathrm{el}}\|J_i\rangle|^2\right) \pm [\hat{q}\cdot(\hat{\nu}-\vec{\beta})]\,2\,\mathrm{Re}\left(\langle J_f\|\hat{\mathcal{J}}_J^{\mathrm{mag}}\|J_i\rangle\langle J_f\|\hat{\mathcal{J}}_J^{\mathrm{el}}\|J_i\rangle^*\right)\right\}.$$

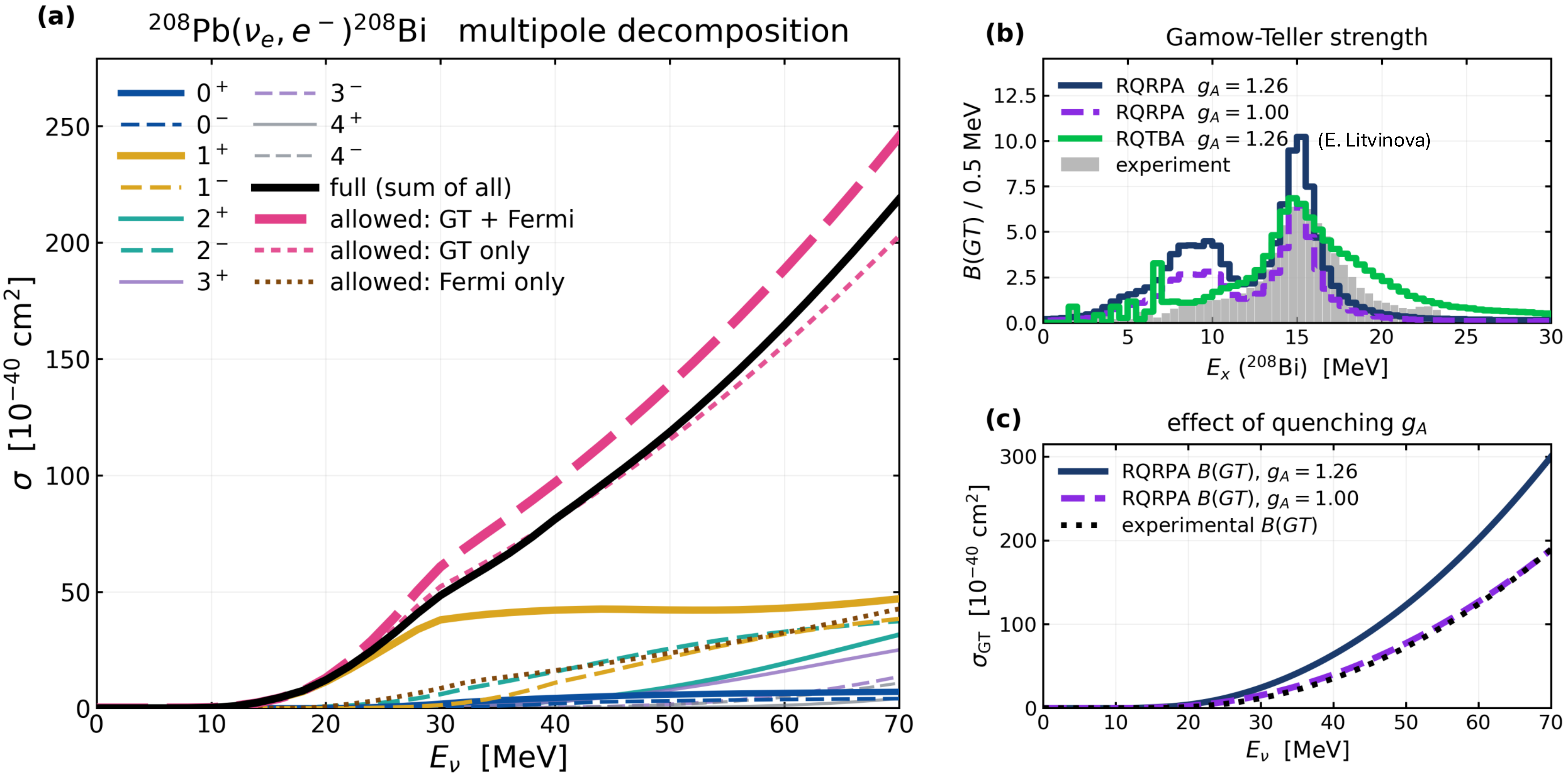
- More complex q-dependent matrix elements.
- Contains all J^π transitions.

2| **ALLOWED APPROXIMATION**: q ➞ 0

$$\sigma(E_\nu) = \frac{G^2 k\epsilon}{\pi}\frac{1}{2J_i+1}\sum_{J=0}^{1}[g_V^2|\langle J_f\|\hat{O}_{\mathrm{F}}\|J_i\rangle|^2 + g_A^2|\langle J_f\|\hat{O}_{\mathrm{GT}}\|J_i\rangle|^2]$$

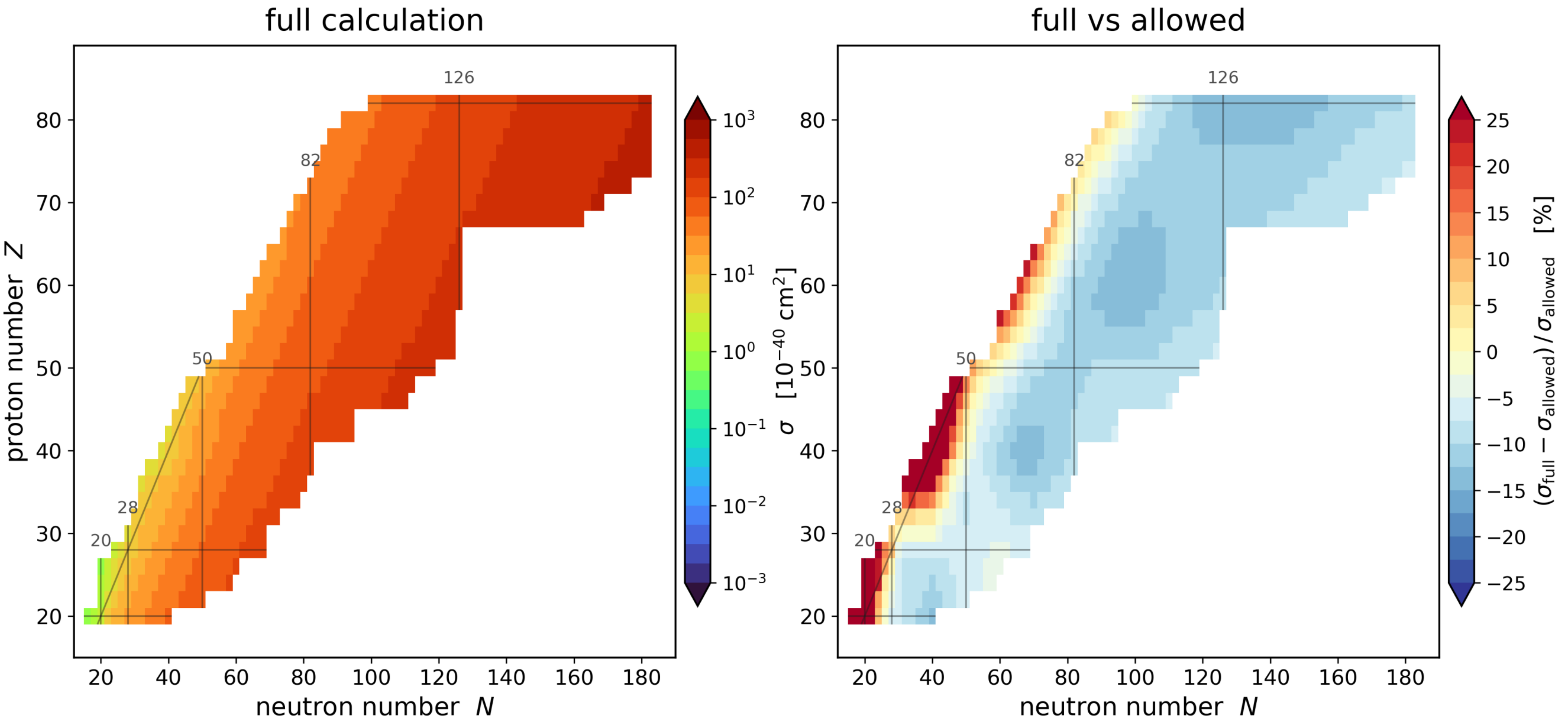
- Only two simple q-independent matrix elements.
- Only $J^\pi = 0^+, 1^+$ transitions survive.
- Connection to experiments through B(GT) ad B(F).


(a)
$^{92}Zr(\nu_e, e^-)^{92}Nb$ multipole decomposition
0^+
0^-
1^+
1^-
2^+
2^-
3^+
3^-
4^+
4^-
full (sum of all)
allowed: GT + Fermi
allowed: GT only
allowed: Fermi only
σ [10^{-40} cm^2]
E_ν [MeV]
(b)
Gamow-Teller strength
RQRPA $g_A = 1.26$
RQRPA $g_A = 1.00$
experiment
$B(GT)$ / 0.5 MeV
E_x (parent frame) [MeV]
(c)
effect of quenching g_A
RQRPA $B(GT)$, $g_A = 1.26$
RQRPA $B(GT)$, $g_A = 1.00$
experimental $B(GT)$
σ_{GT} [10^{-40} cm^2]
E_ν [MeV]

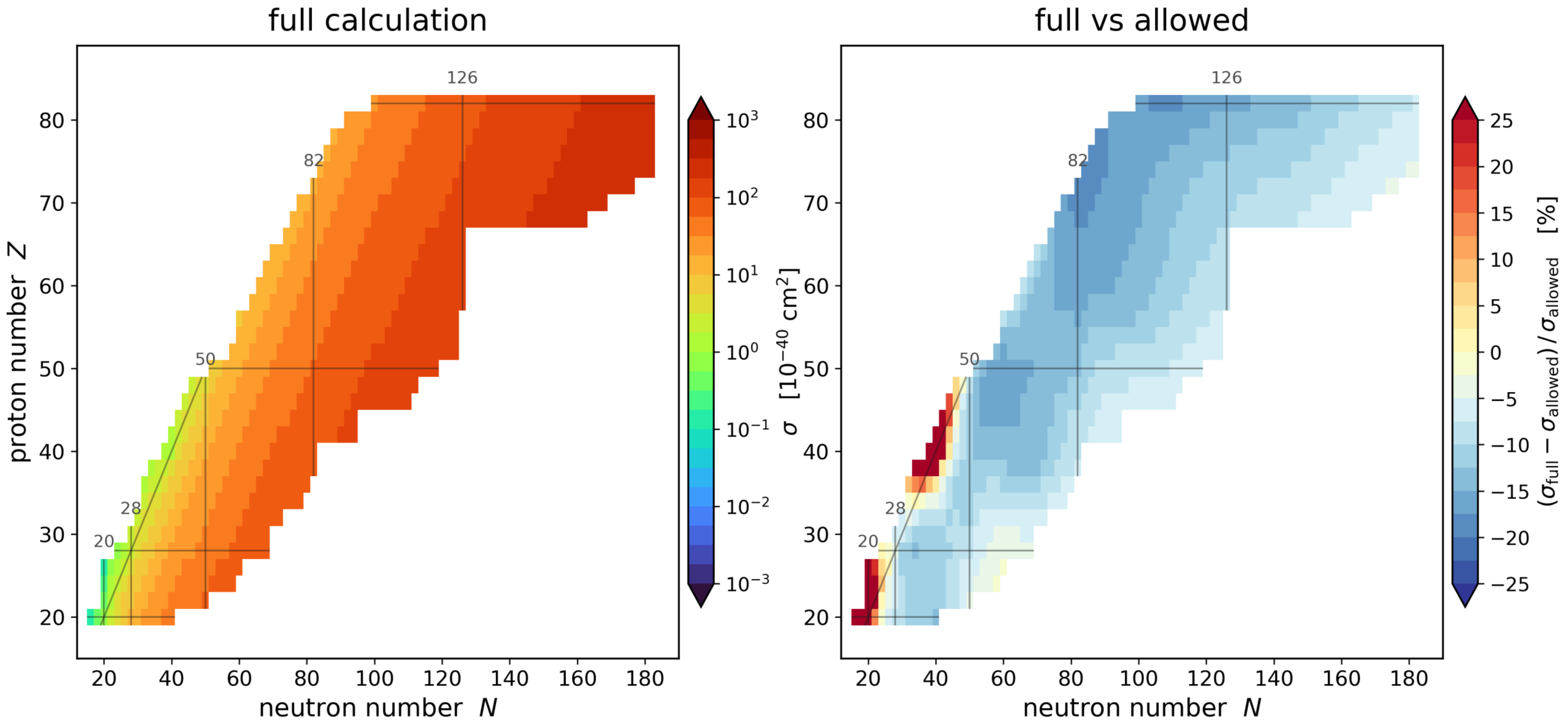


(a)
^{208}Pb(ν_e, e^-)^{208}Bi multipole decomposition
0^+
0^-
1^+
1^-
2^+
2^-
3^+
3^-
4^+
4^-
full (sum of all)
allowed: GT + Fermi
allowed: GT only
allowed: Fermi only
σ [10^{-40} cm^2]
E_ν [MeV]
(b)
Gamow-Teller strength
RQRPA $g_A = 1.26$
RQRPA $g_A = 1.00$
RQTBA $g_A = 1.26$
(E. Litvinova)
experiment
$B(GT)$ / 0.5 MeV
E_x (^{208}Bi) [MeV]
(c)
effect of quenching g_A
RQRPA $B(GT)$, $g_A = 1.26$
RQRPA $B(GT)$, $g_A = 1.00$
experimental $B(GT)$
σ_{GT} [10^{-40} cm^2]
E_ν [MeV]

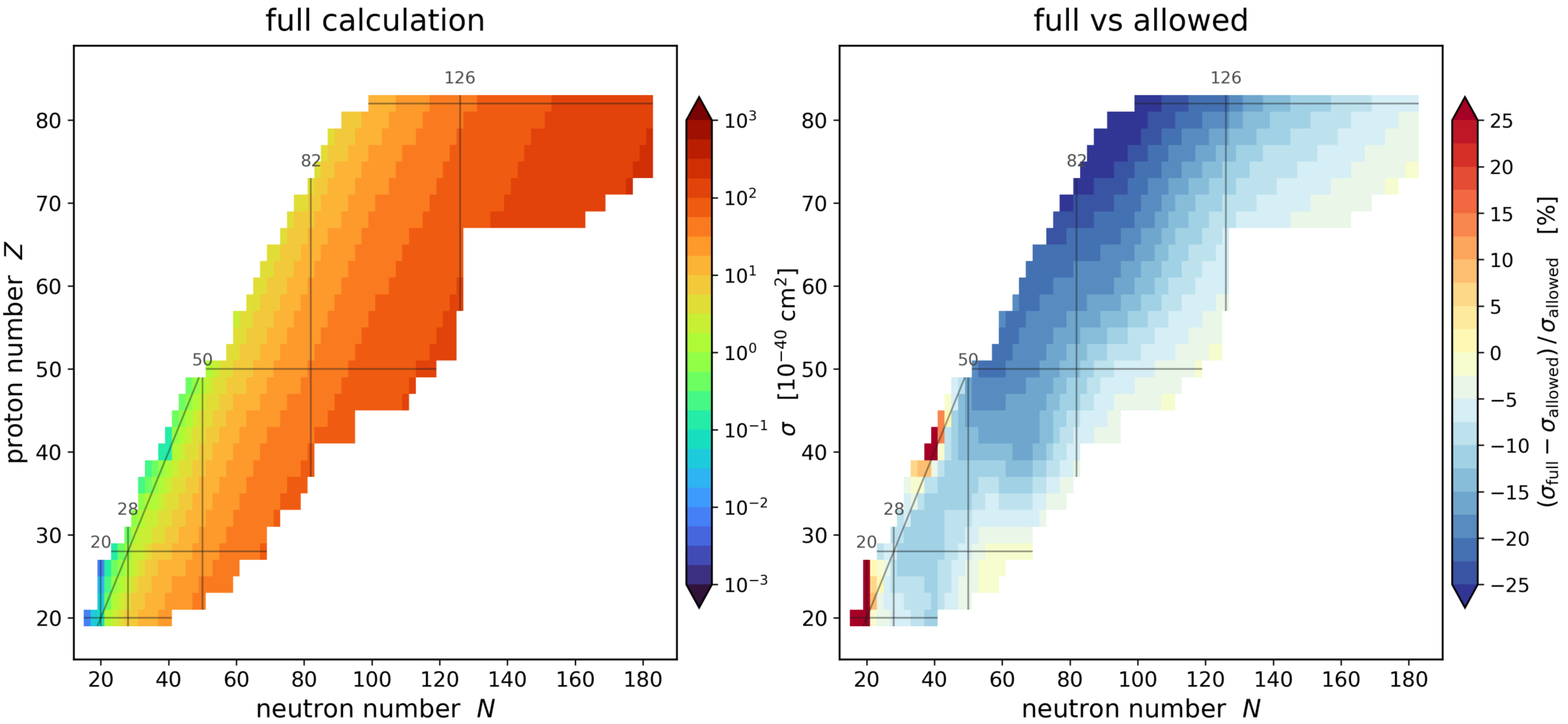
$E_\nu = 50$ MeV


full calculation
full vs allowed
proton number Z
neutron number N
σ [10^{-40} cm^2]
$(\sigma_{\text{full}} - \sigma_{\text{allowed}})/\sigma_{\text{allowed}}$ [%]
126
82
50
28
20

$E_\nu = 40$ MeV

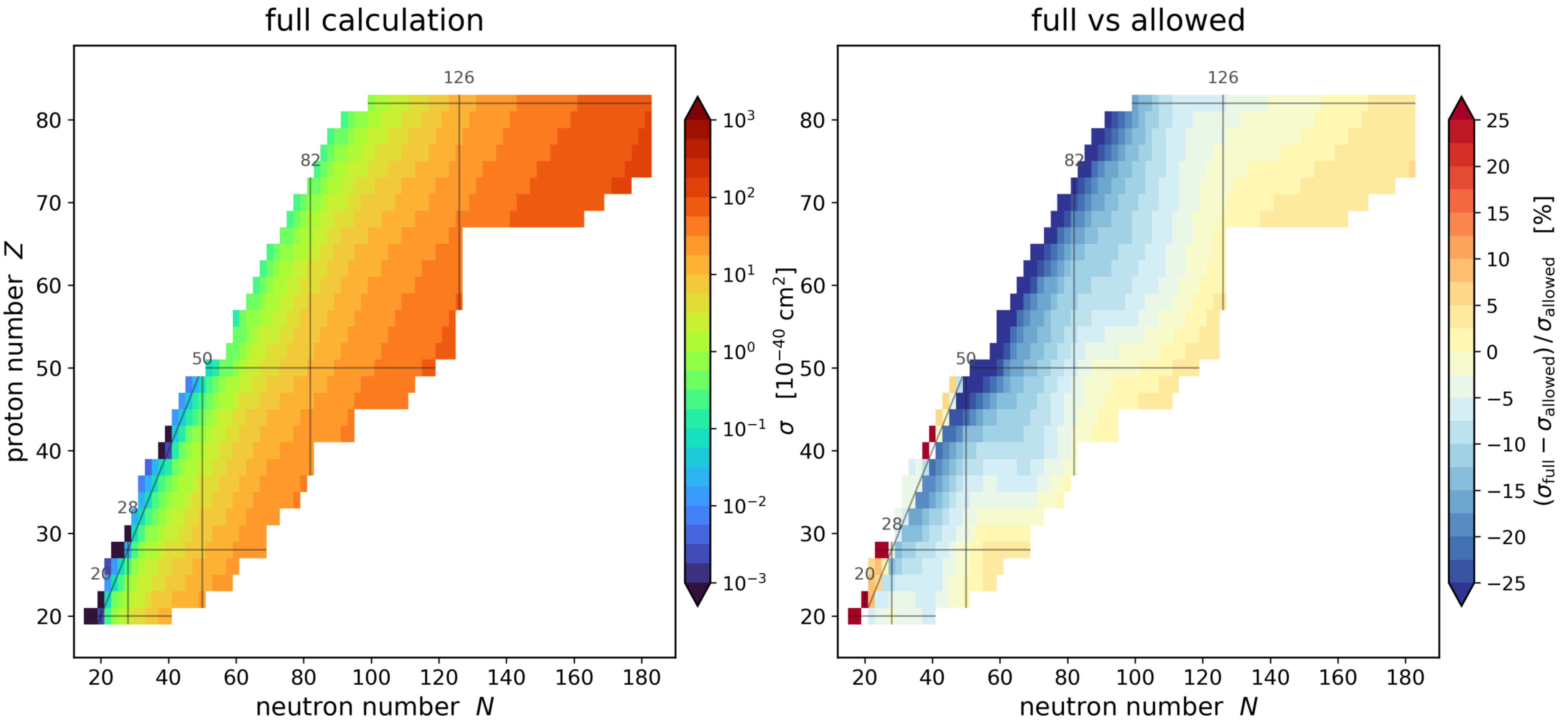

full calculation
full vs allowed
proton number Z
neutron number N
126
82
50
28
20
σ [10^{-40} cm^2]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$(\sigma_{\text{full}} - \sigma_{\text{allowed}}) / \sigma_{\text{allowed}}$ [%]
25
20
15
10
5
0
−5
−10
−15
−20
−25

$E_\nu = 30$ MeV

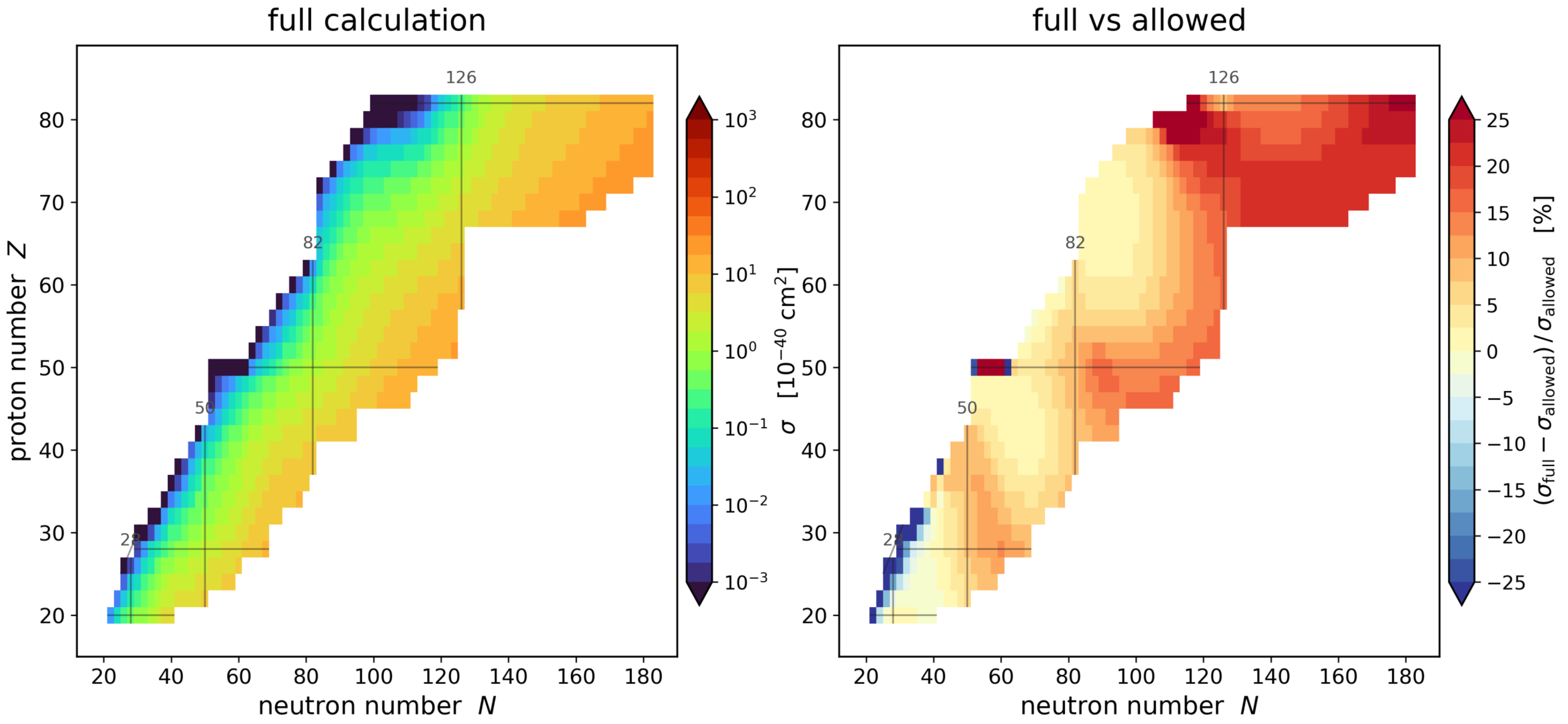


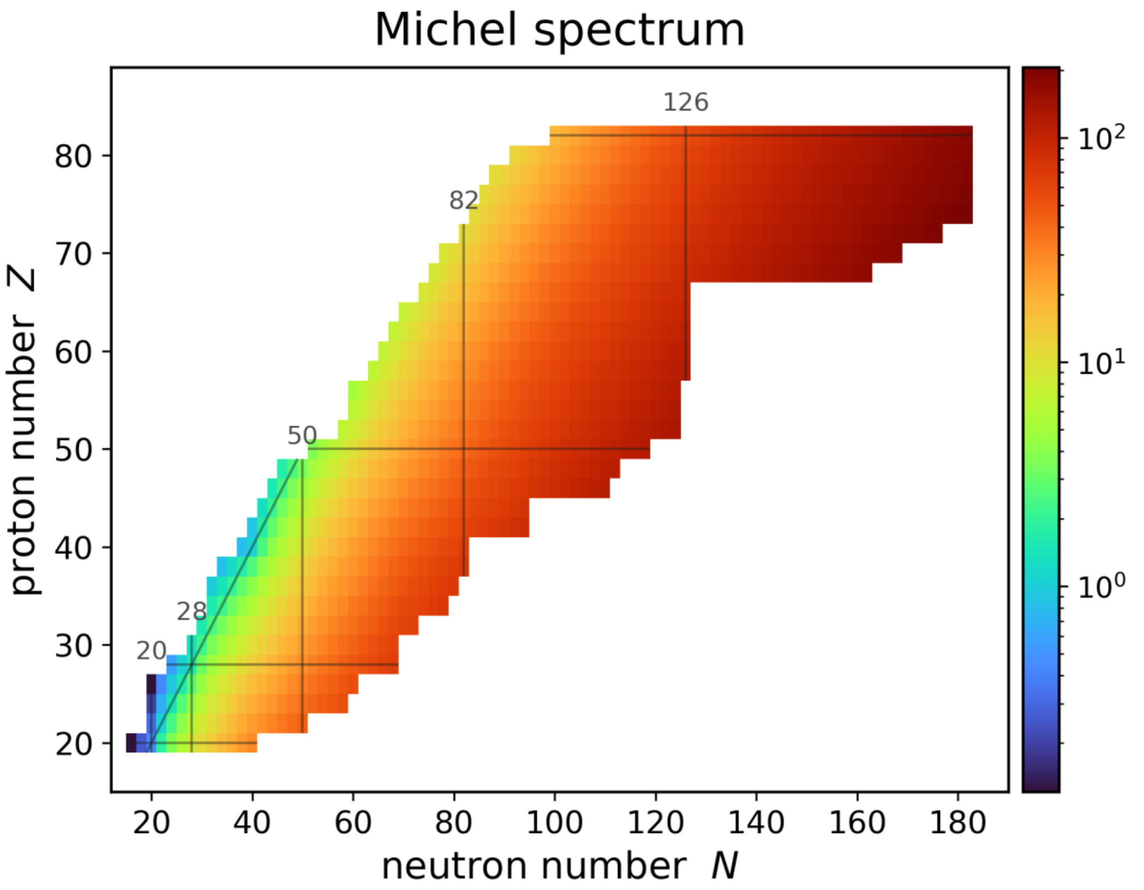
full calculation
full vs allowed
proton number Z
neutron number N
σ [10^−40 cm^2]
(σ_full − σ_allowed) / σ_allowed [%]
126
82
50
28
20

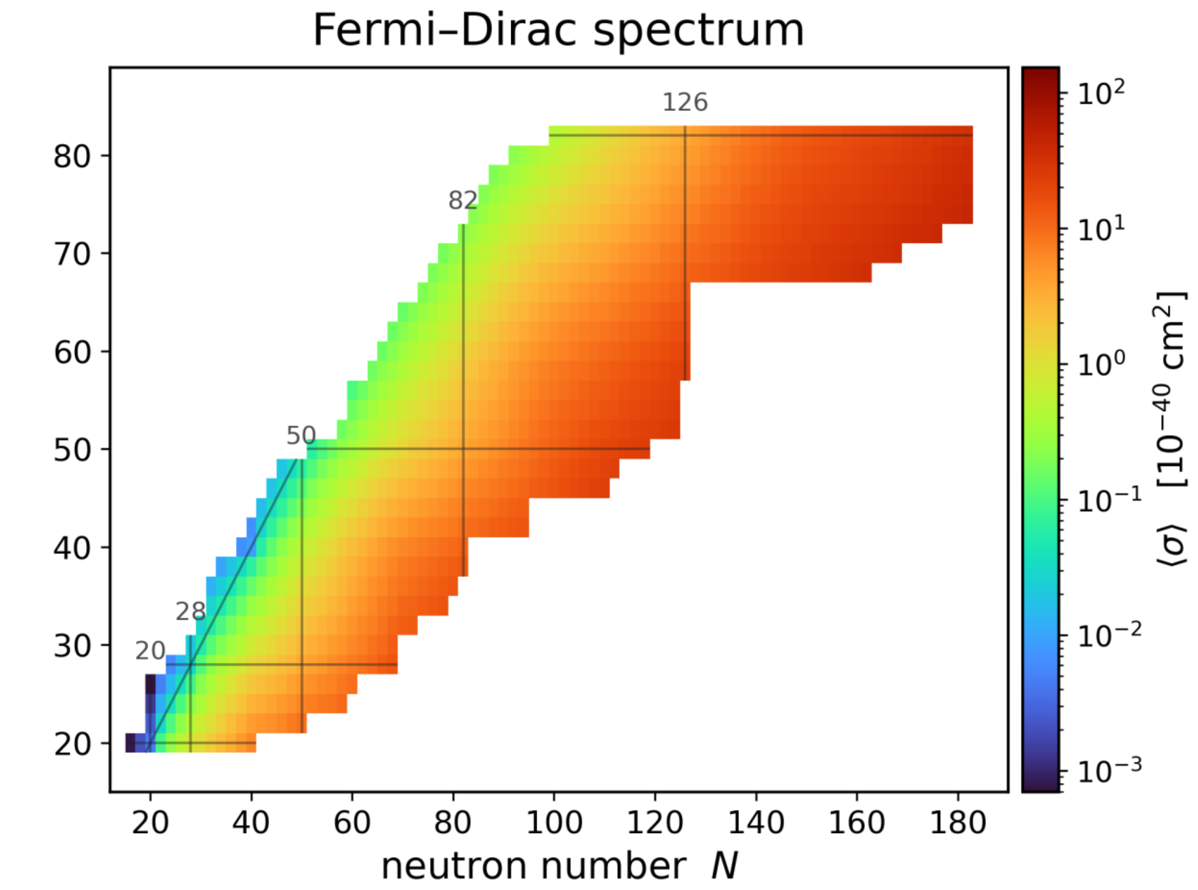
$E_\nu = 20$ MeV


full calculation
full vs allowed
proton number Z
neutron number N
σ [10^−40 cm^2]
(σ_full − σ_allowed) / σ_allowed [%]
20
28
50
82
126
20
40
60
80
100
120
140
160
180
30
70
10^3
10^2
10^1
10^0
10^−1
10^−2
10^−3
25
15
10
5
0
−5
−10
−15
−20
−25

$E_\nu = 10$ MeV

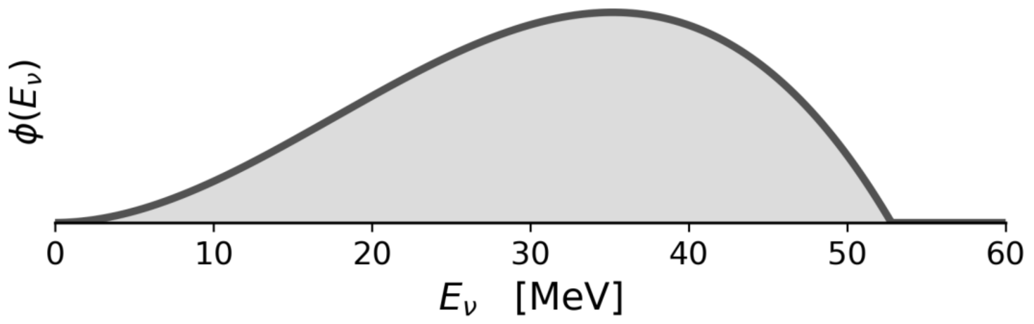

full calculation
full vs allowed
proton number Z
neutron number N
126
82
50
28
σ [10^−40 cm^2]
(σ_full − σ_allowed) / σ_allowed [%]

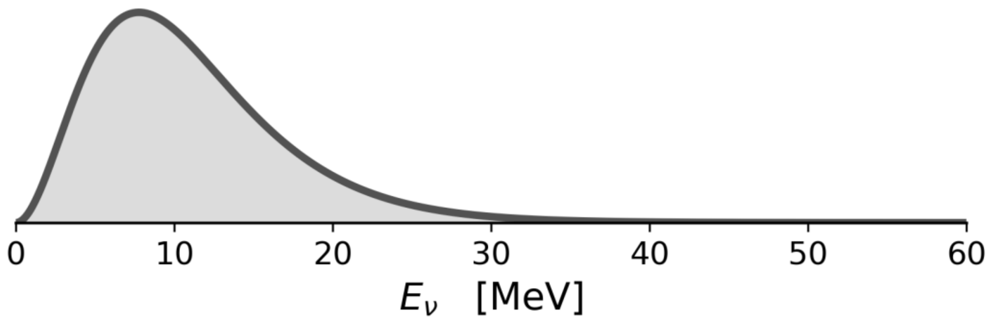




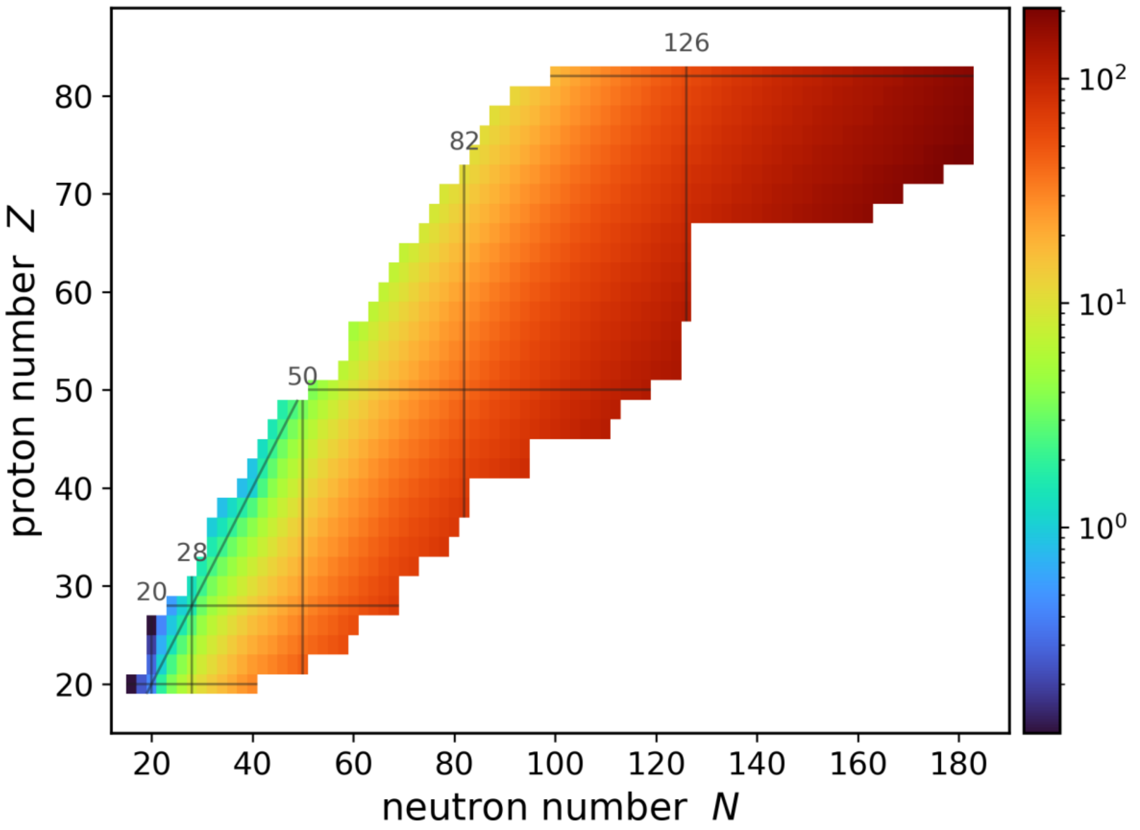
$\phi(E_\nu) = \frac{12}{E_0^4} E_\nu^2 (E_0 - E_\nu), \qquad E_0 = 52.8$ MeV

$\phi(E_\nu) \propto \frac{E_\nu^2}{e^{E_\nu/T}+1}, \qquad T = 3.5$ MeV

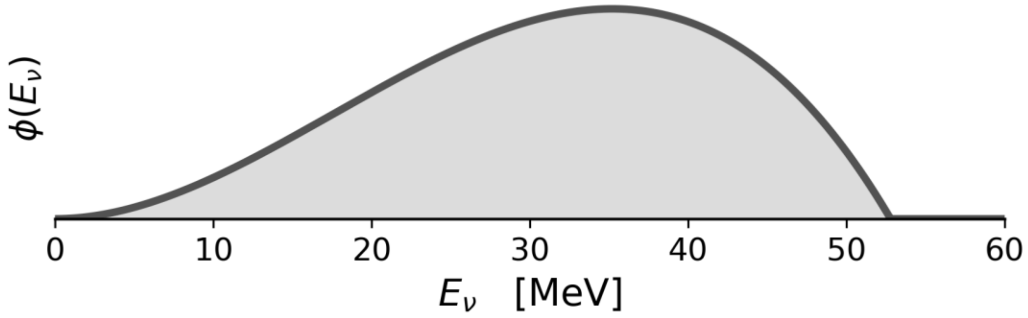




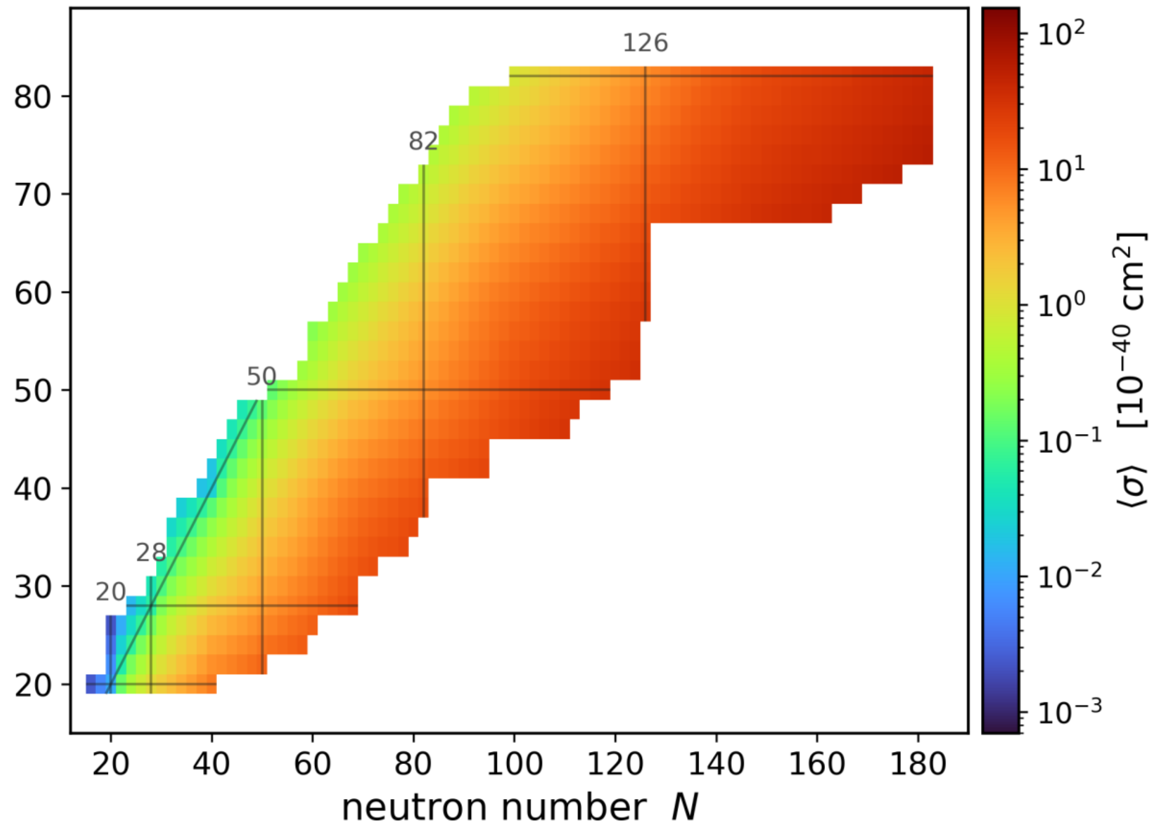
Michel spectrum



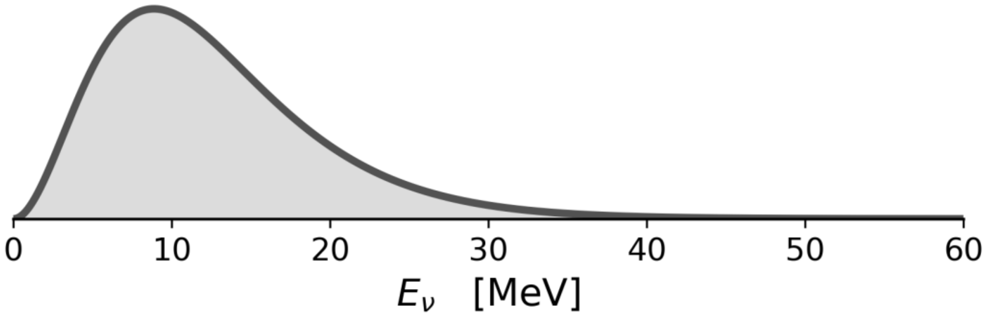
$$\phi(E_\nu) = \frac{12}{E_0^4} E_\nu^2 (E_0 - E_\nu), \qquad E_0 = 52.8\ \text{MeV}$$

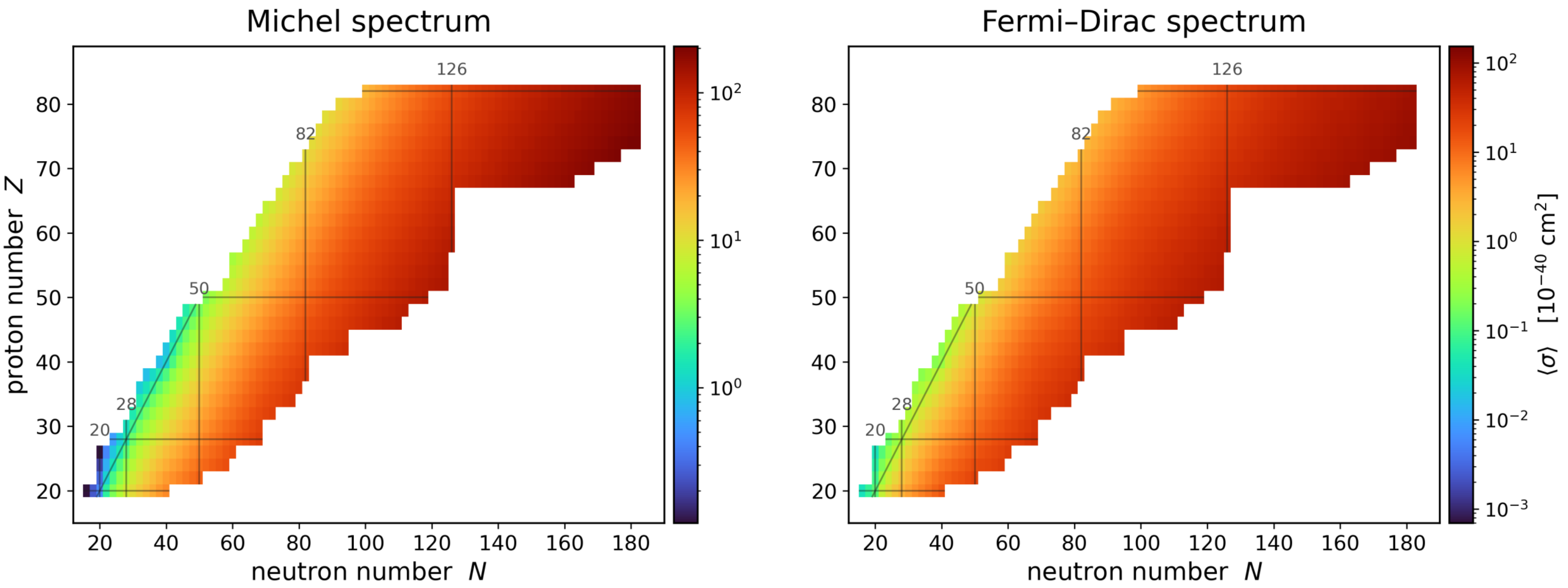


Fermi–Dirac spectrum



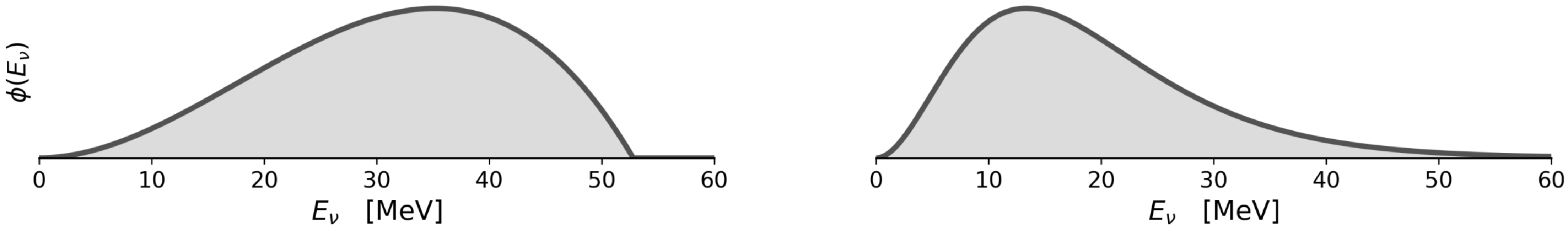
$$\phi(E_\nu) \propto \frac{E_\nu^2}{e^{E_\nu/T}+1}, \qquad T = 4\ \text{MeV}$$

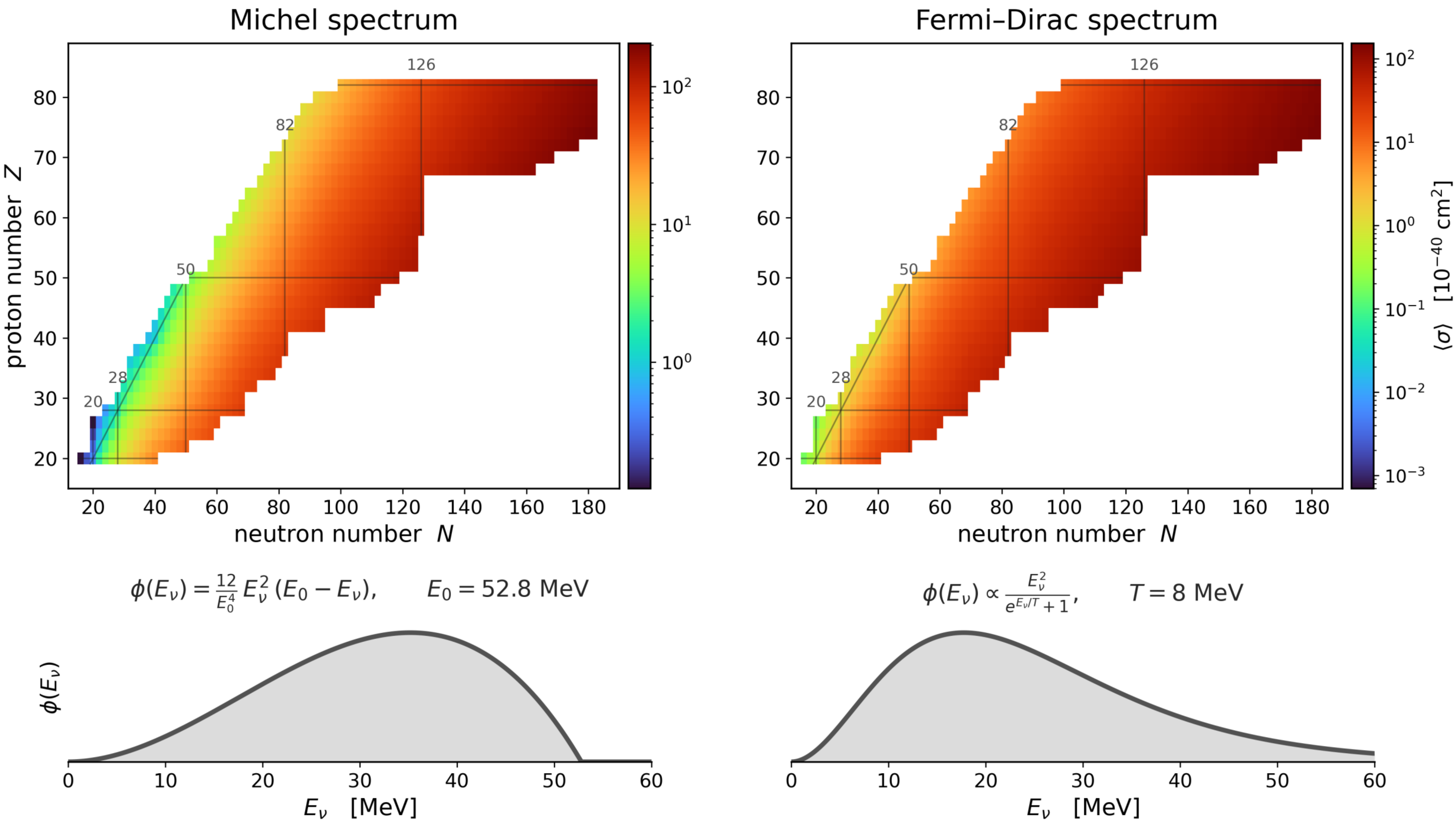




$\phi(E_\nu) = \frac{12}{E_0^4} E_\nu^2 (E_0 - E_\nu)$, $E_0 = 52.8$ MeV

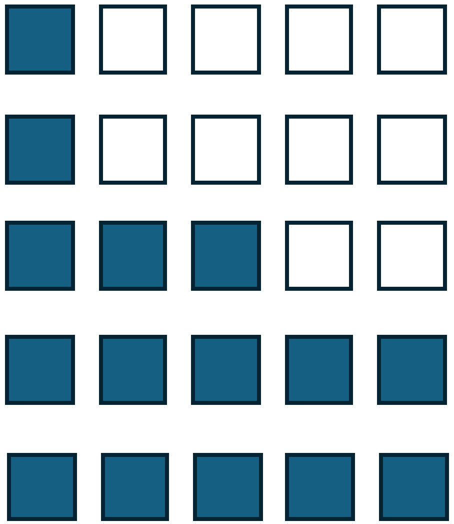
$\phi(E_\nu) \propto \frac{E_\nu^2}{e^{E_\nu/T}+1}$, $T = 6$ MeV




Michel spectrum
Fermi–Dirac spectrum
proton number Z
neutron number N
126
82
50
28
20
$\langle\sigma\rangle$ [10^{-40} cm^2]
$\phi(E_\nu) = \frac{12}{E_0^4} E_\nu^2 (E_0 - E_\nu)$, $E_0 = 52.8$ MeV
$\phi(E_\nu) \propto \frac{E_\nu^2}{e^{E_\nu/T}+1}$, $T = 8$ MeV
$\phi(E_\nu)$
E_ν [MeV]

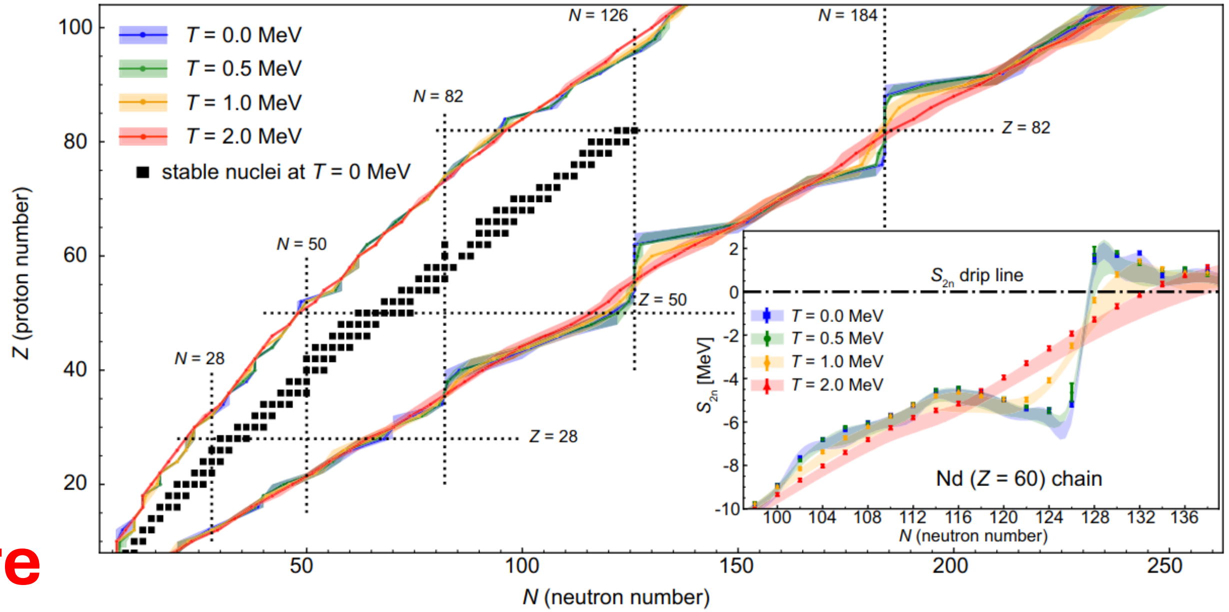
What is next:

- Develop neutral channel and include muon/tau leptons
- Odd nuclei
- Deformations, **nuclear temperature**
- Decay channels
- Higher order correlations



What is next:

- Deformations, **nuclear temperature**



nature communications

Article

https://doi.org/10.1038/s41467-023-40613-2

Expanding the limits of nuclear stability at finite temperature

Received: 29 November 2022

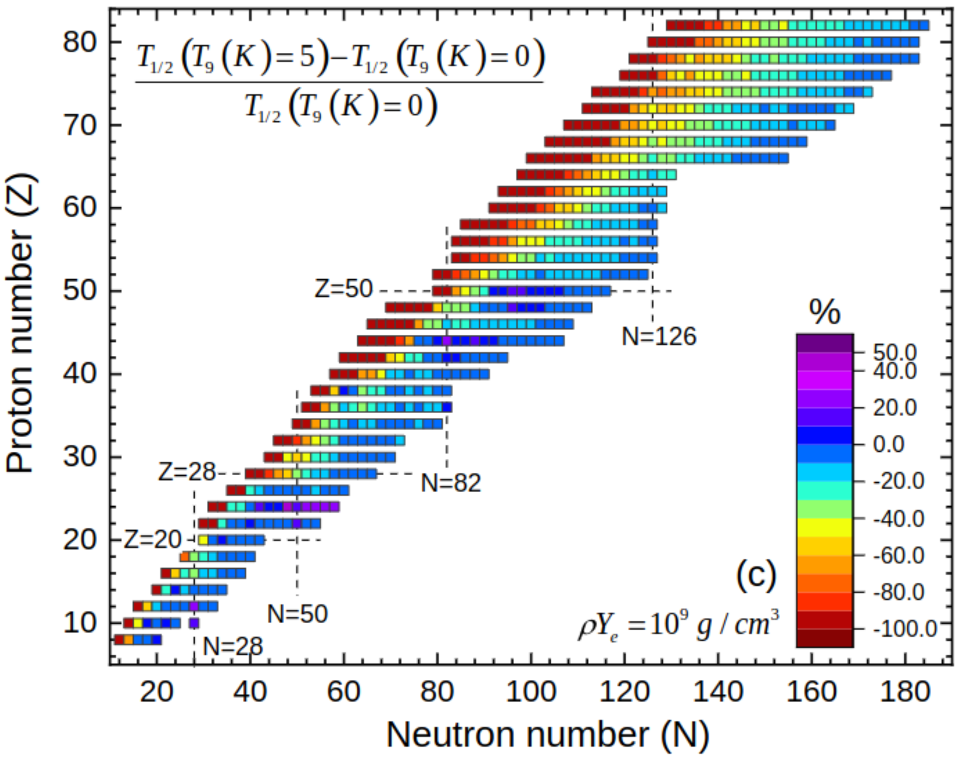
Accepted: 3 August 2023

Published online: 10 August 2023

Check for updates

Ante Ravlić[1], Esra Yüksel[2], Tamara Nikšić[1] & Nils Paar[1]

Properties of nuclei in hot stellar environments such as supernovae or neutron star mergers are largely unexplored. Since it is poorly understood how many protons and neutrons can be bound together in hot nuclei, we investigate the limits of nuclear existence (drip lines) at finite temperature. Here, we present



Thank you for your attention!

This work is supported by the Croatian Science Foundation under the project
Relativistic Nuclear Many-Body Theory in the Multimessenger Observation Era (HRZZ-IP-2022-10-7773).