Heavy nuclei (?) in astrophysical environments

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GSSI, L'Aquila, 13-14 June 2024

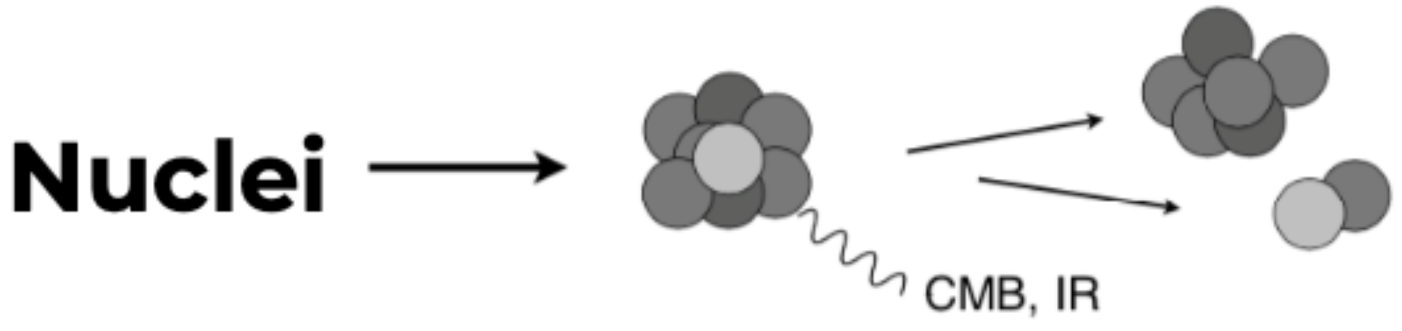
MOTIVATIONS

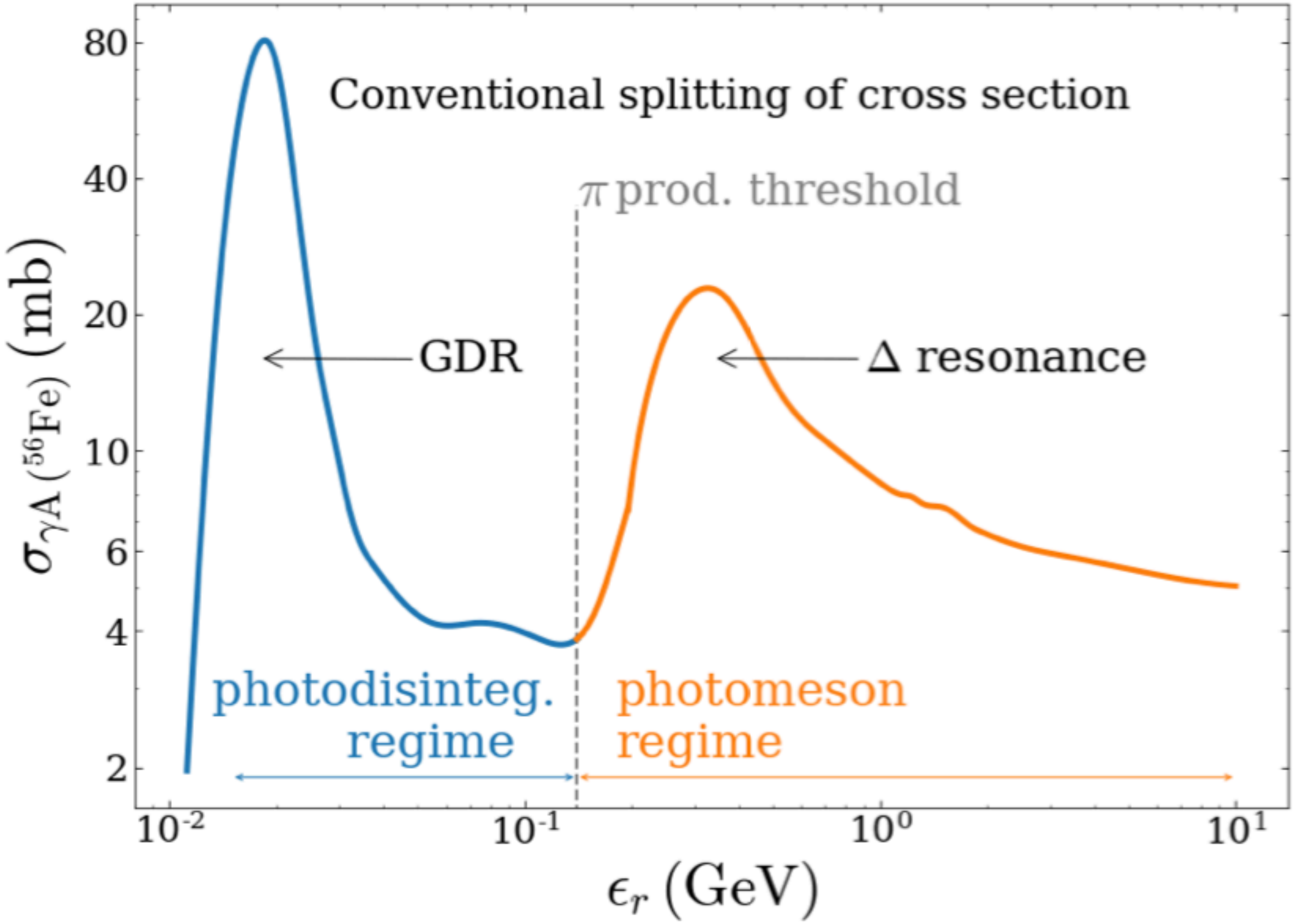
- Def: a heavy nucleus (HN) has A>56
- Heavy nuclei are synthesized due to the r-processes inside neutron-rich environments (compact binary mergers, including binary neutron star and neutron-star–black-hole mergers; collapsars including GRBs supernovae).

- To be considered as UHECRs they have to:
  - Be accelerated (advantage: large Z)
  - Escape
  - Propagate through extragalactic space

- Considering the highest-energy UHECR events, the heavier is the (assumed) nuclear species, the more distant can be its source

PHOTO-DISINTEGRATION





- Regimes
  - Giant Dipole Resonance (GDR): protons and neutrons can be considered as penetrating fluids; absorption of photons determines vibrations; ejection of one/two nucleons is dominant
  - Quasi-Deuteron (QD), 20-150 MeV: the photon wavelength becomes comparable with the nuclear dimensions; photon interacts with nucleon pair; ejection of pair + possibly other nucleons
- Conservation of Lorentz factor

$$\frac{1}{E}\frac{dE}{dt} = \frac{1}{\Gamma}\frac{d\Gamma}{dt} + \frac{1}{A}\frac{dA}{dt}$$

- **I will mainly consider the GDR in the following**

PHYSICS OF PHOTODISINTEGRATION

$E_{\text{GDR}} \approx 60\,\text{MeV}\,A^{-1/3}$ Typical GDR energy: mainly connected to the volume term in the SMF

A more refined model describes how protons an neutrons vibrate as incompressible fluids bound together by a flexible surface $E_{\text{GDR}} \propto A^{-1/6}$

From fits of available data on GDR maximum energies

$$E_{\text{GDR}}(A) = \hat{E}_{\text{GDR}} A^{-1/6},\ \hat{E}_{\text{GDR}} = 35.3\,\text{MeV}$$

$$\Gamma_{\text{GDR}}(A) = \hat{\Gamma}_{\text{GDR}} A^{-1/6},\ \hat{\Gamma}_{\text{GDR}} = 15.1\,\text{MeV}$$

- The photoabsorption cross section of the GDR is assumed to have a Lorentzian shape
- For the normalization,
  - the integrated cross section is used $\Sigma = 1.38\,\sigma_0\,\Gamma_{\text{GDR}}$
  - the one-nucleon emission is assumed as the main disintegration process
  - Parametrization from available data $\sigma_0(A) = \hat{\sigma}_0 A^{7/6},\ \hat{\sigma}_0 = 0.72\,\text{mbarn}$

CROSS SECTIONS

Models taken from:

TENDL-2021 Nuclear data library

Gamma sub-library for Pt (Z=78) and A=175: Tabular production and total cross sections

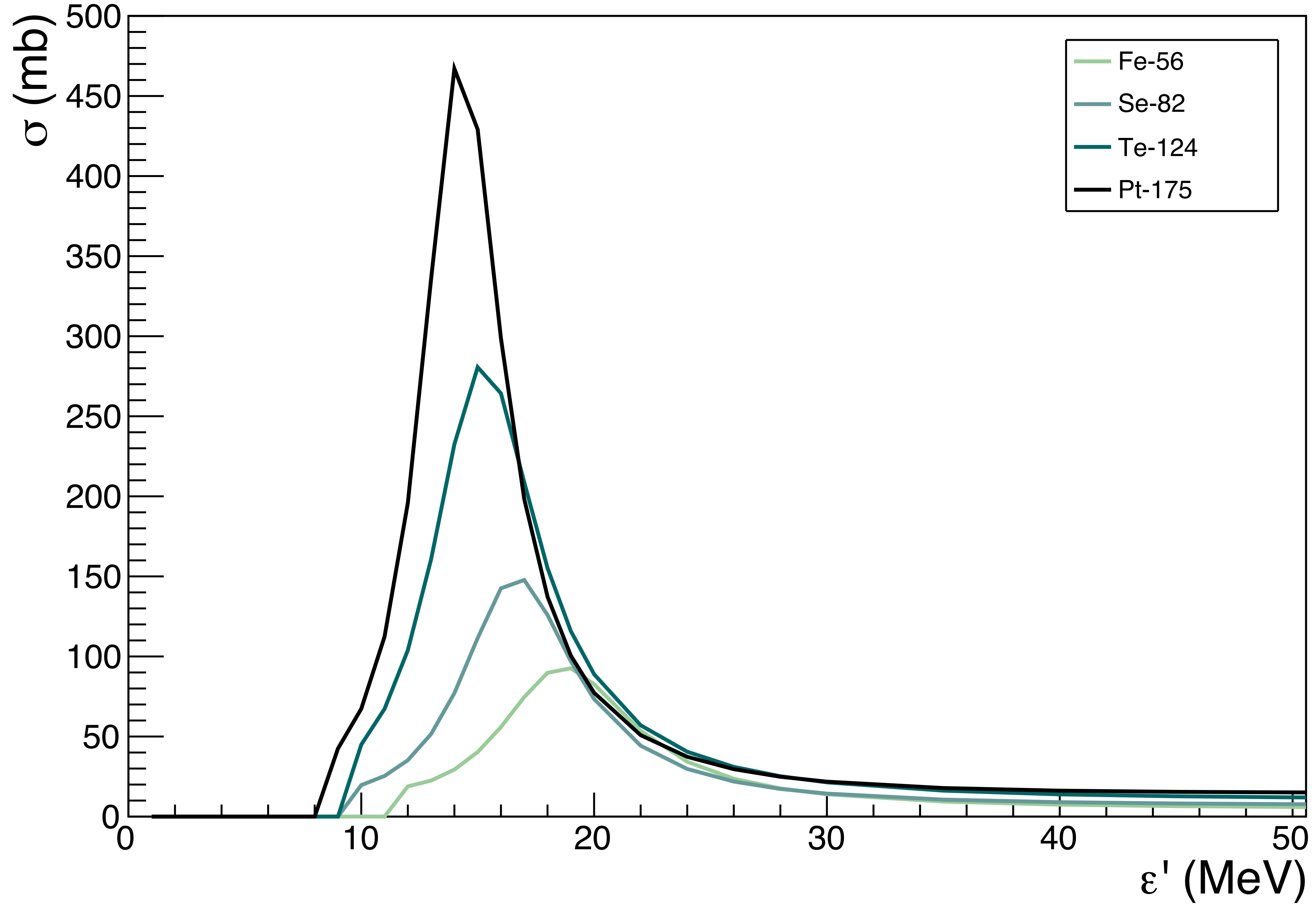
Production and total cross sections									
Reaction #	^{78}Pt(g,x)a	^{78}Pt(g,x)d	^{78}Pt(g,x)g	^{78}Pt(g,x)he3	^{78}Pt(g,non)	^{78}Pt(g,x)n	^{78}Pt(g,x)p	^{78}Pt(g,tot)	^{78}Pt(g,x)t
Reaction #									

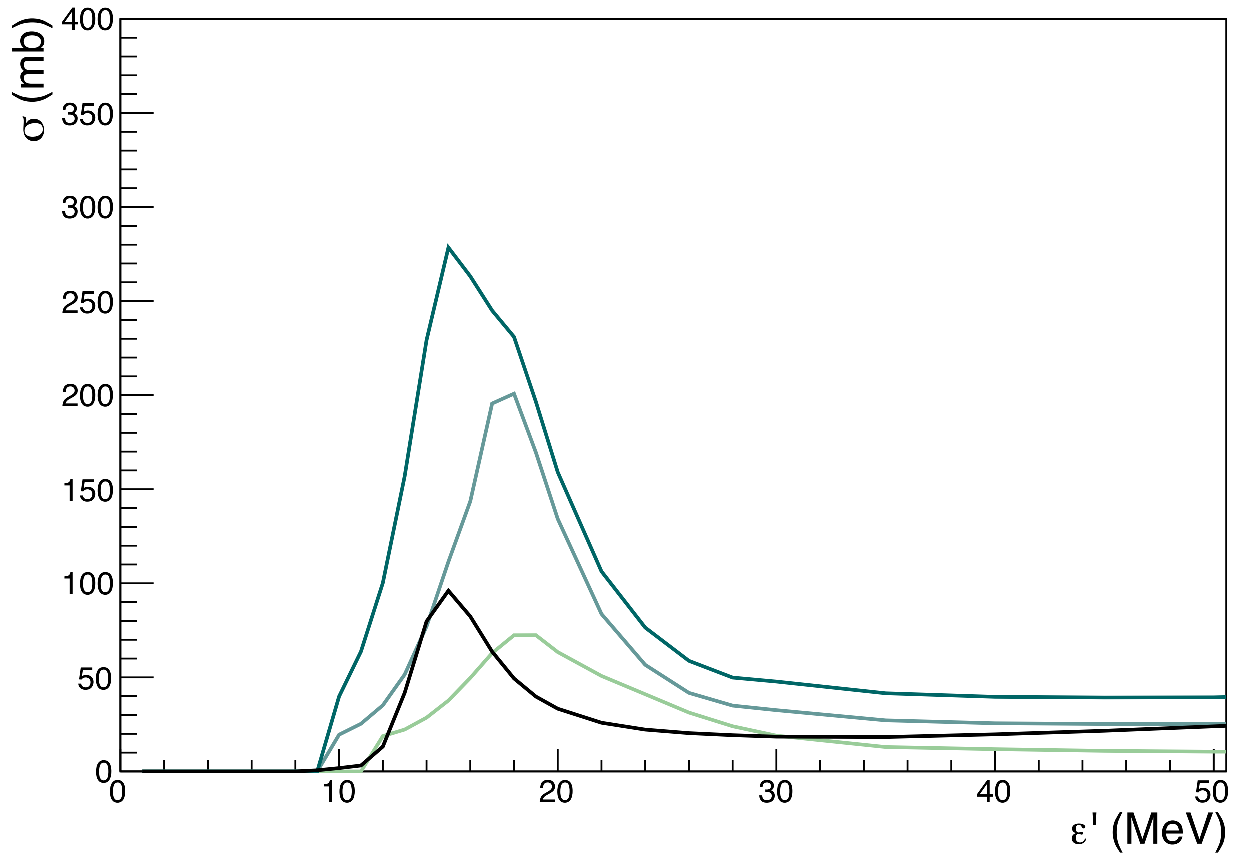
Partial cross sections				
Reaction #	^{78}Pt(g,g)	^{78}Pt(g,a)	^{78}Pt(g,2a)	^{78}Pt(g,3a)
Reaction #	^{78}Pt(g,He3)	^{78}Pt(g,He3+a)	^{78}Pt(g,He3+2a)	^{78}Pt(g,t)
Reaction #	^{78}Pt(g,t+a)	^{78}Pt(g,t+2a)	^{78}Pt(g,t+He3)	^{78}Pt(g,t+He3+a)
Reaction #	^{78}Pt(g,d)	^{78}Pt(g,d+a)	^{78}Pt(g,d+2a)	^{78}Pt(g,d+He3)
Reaction #	^{78}Pt(g,d+He3+a)	^{78}Pt(g,d+t)	^{78}Pt(g,d+t+a)	^{78}Pt(g,2d)
Reaction #	^{78}Pt(g,2d+a)	^{78}Pt(g,2d+2a)	^{78}Pt(g,2d+He3)	^{78}Pt(g,p)

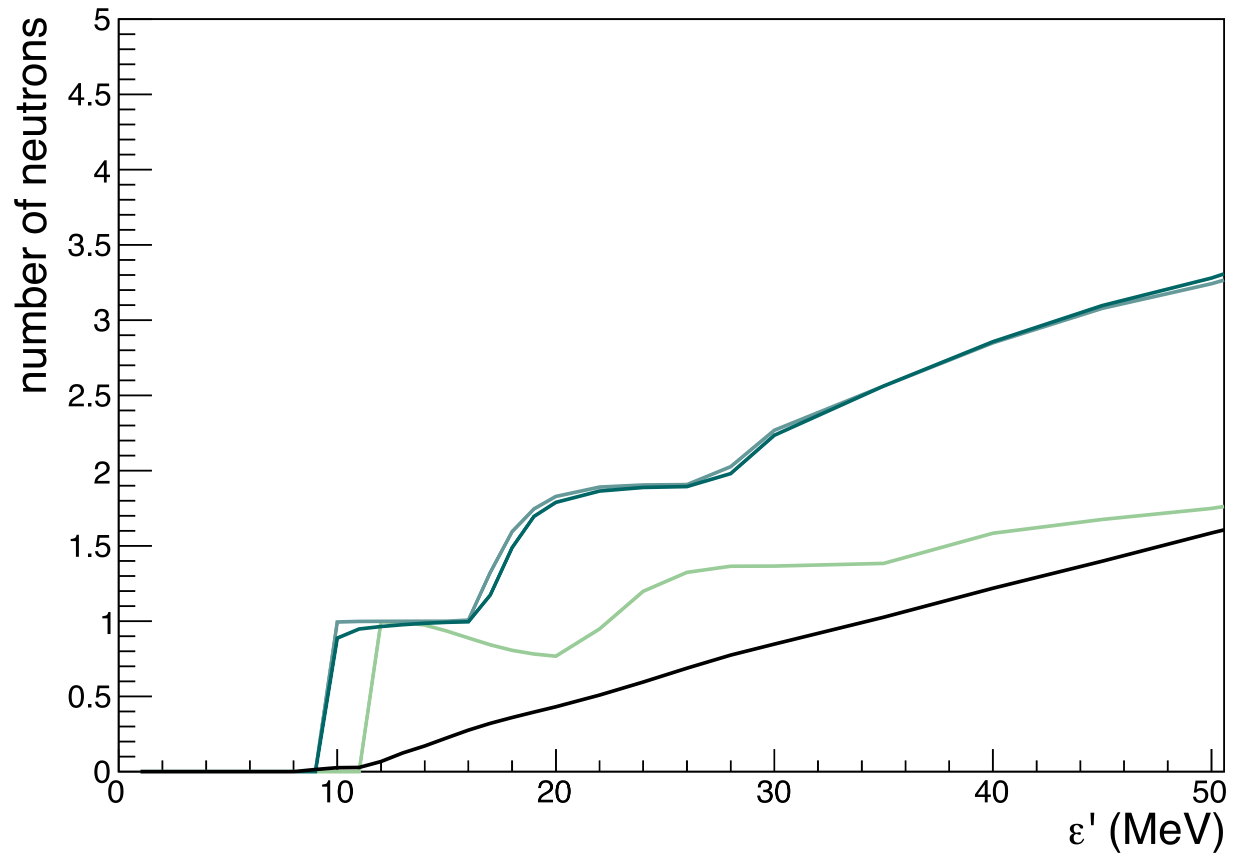
TENDL is a nuclear data library which provides the output of the **TALYS** nuclear model code system

TALYS is a nuclear reaction program with the objective to provide a complete and accurate simulation of nuclear reactions up to energies of 200 MeV, through an optimal combination of reliable nuclear models, flexibility and user-friendliness. TALYS can be used for the analysis of basic nuclear reaction experiments or to generate nuclear data for applications.

CROSS SECTIONS







Absorption cross section; can be obtained:

- From the inclusive cross section (production cross section)
- From the partial cross section

$$\sigma_j = \frac{\sigma_{incl,j\to i}}{M_{j\to i}}$$

Example (for the case of Fe):

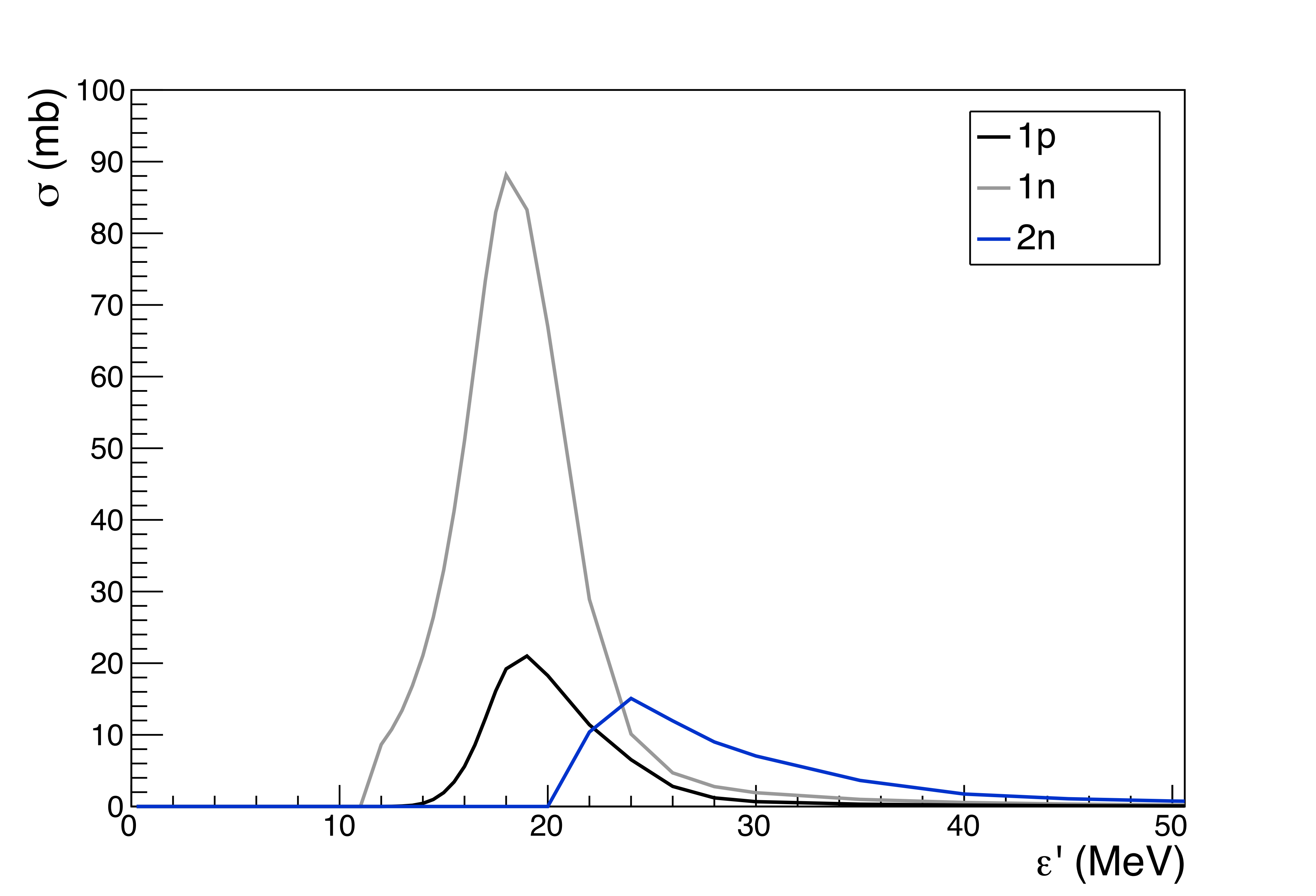
- Production cross section of protons: every time a proton is produced together with X in the final state
- Partial cross section: every time in which one proton is produced together with X in the final state

$$\mathrm{Fe}(g,X)p,\ \ \mathrm{Fe}+\gamma\to X+n_p p$$

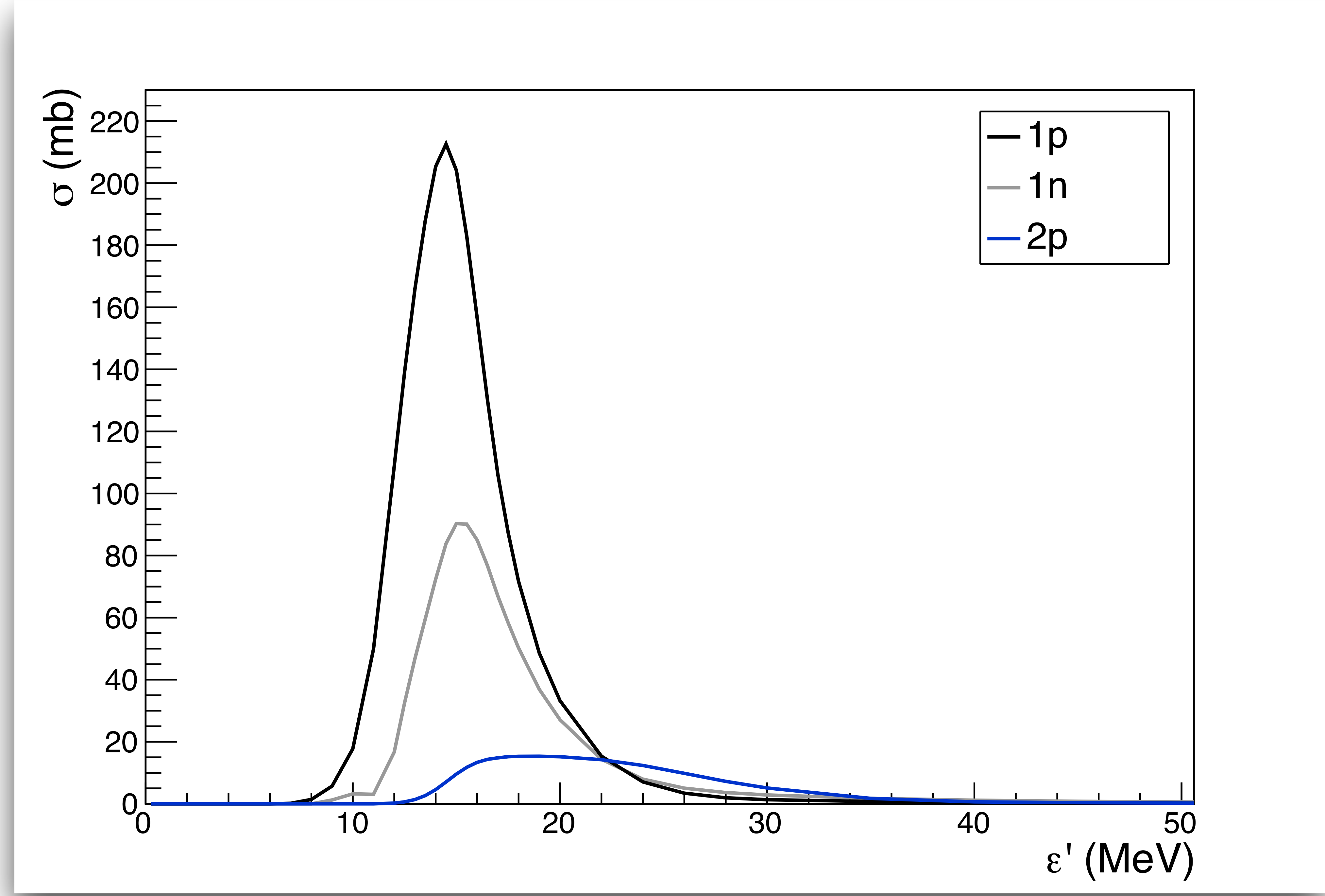
$$\mathrm{Fe}(g,X),\ \ \mathrm{Fe}+\gamma\to X+p$$

CROSS SECTIONS

Fe-56 (A=56, Z=26)



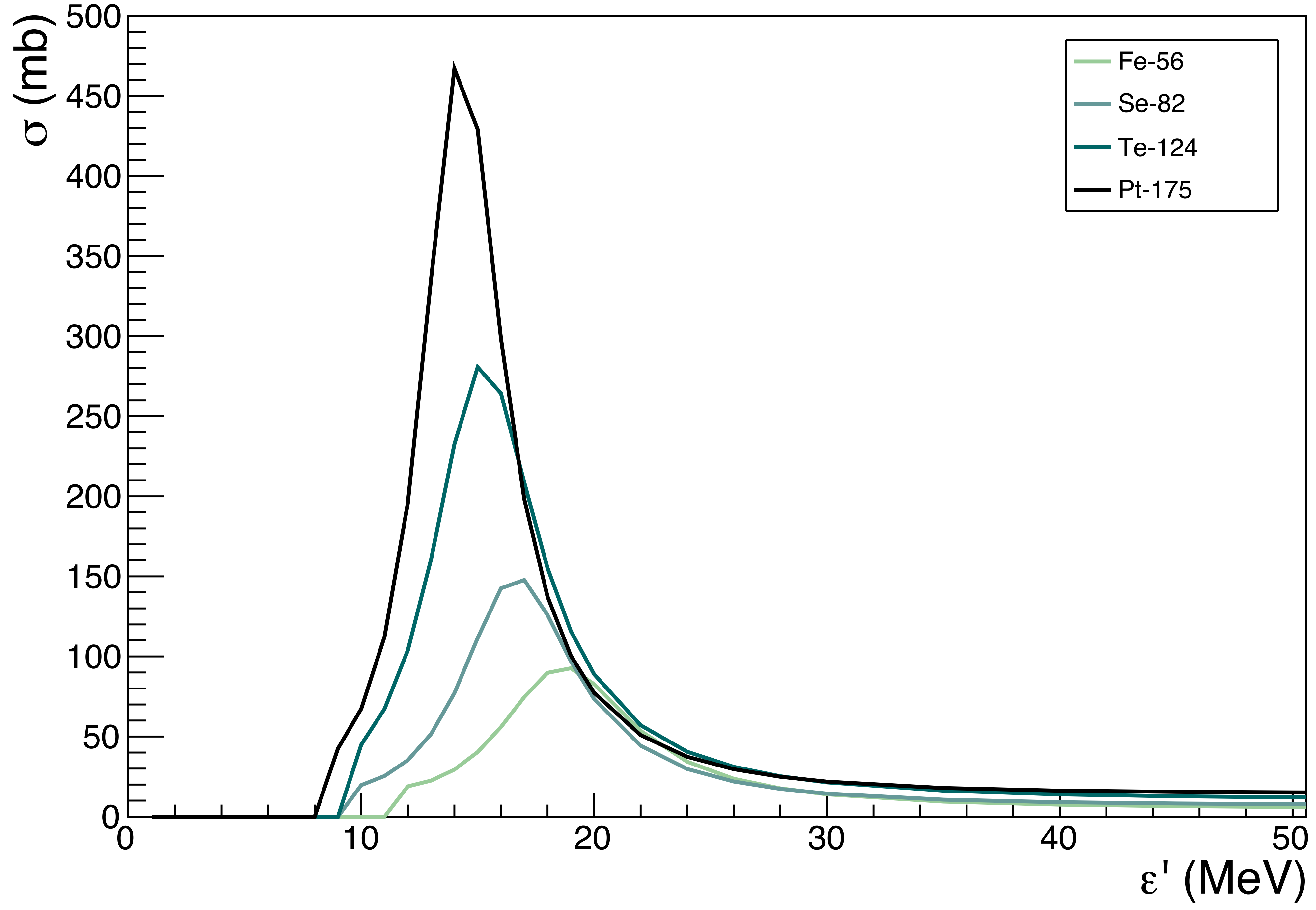
Pt-175 (A=175, Z=78)



One-nucleon emission dominates the GDR:

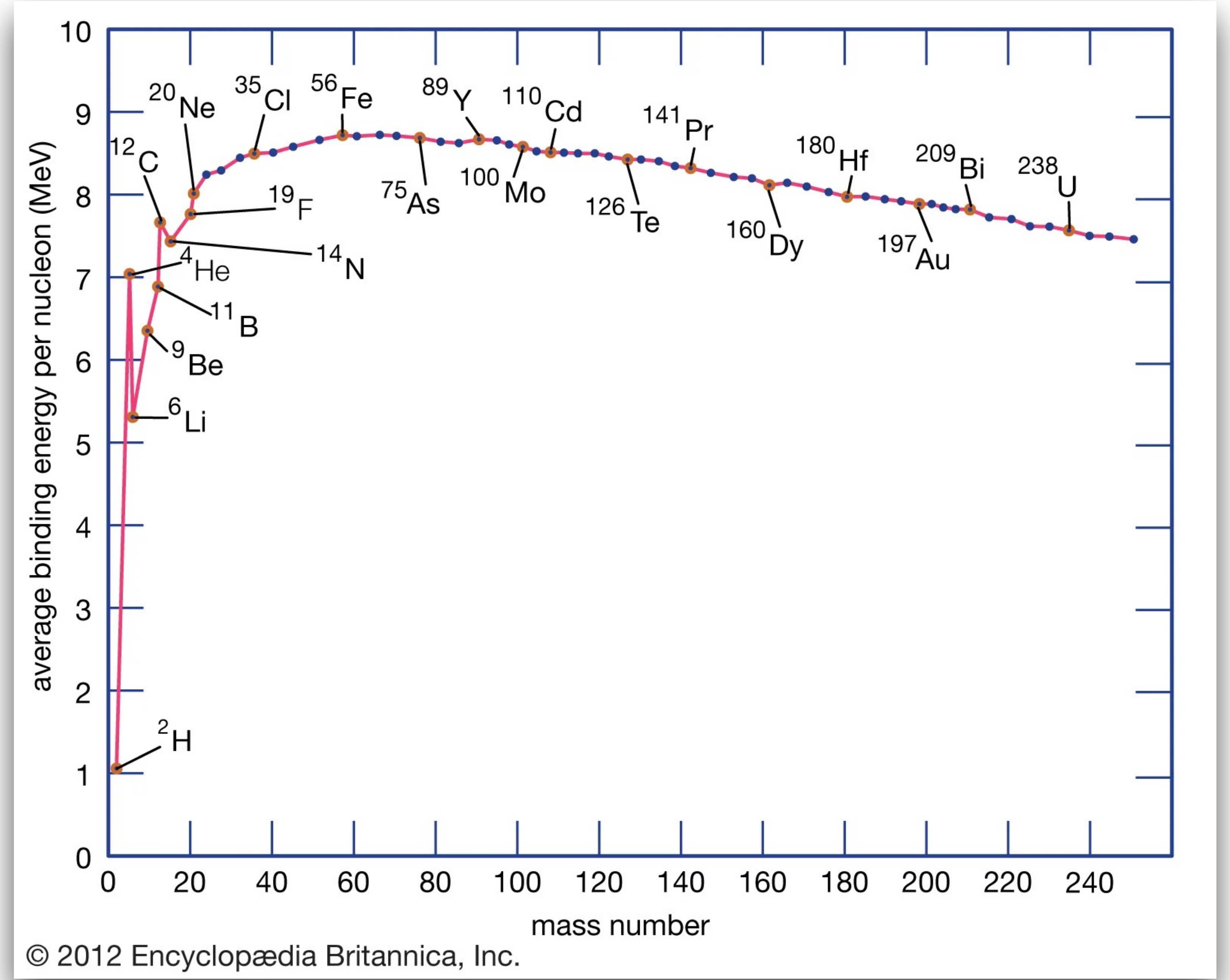
- Low threshold
- Highest contribution to cross section at maximum

CROSS SECTIONS



$$A + \gamma \rightarrow (A-1) + (n,p)$$

$$\varepsilon' = \varepsilon\Gamma(1-\cos\theta)$$



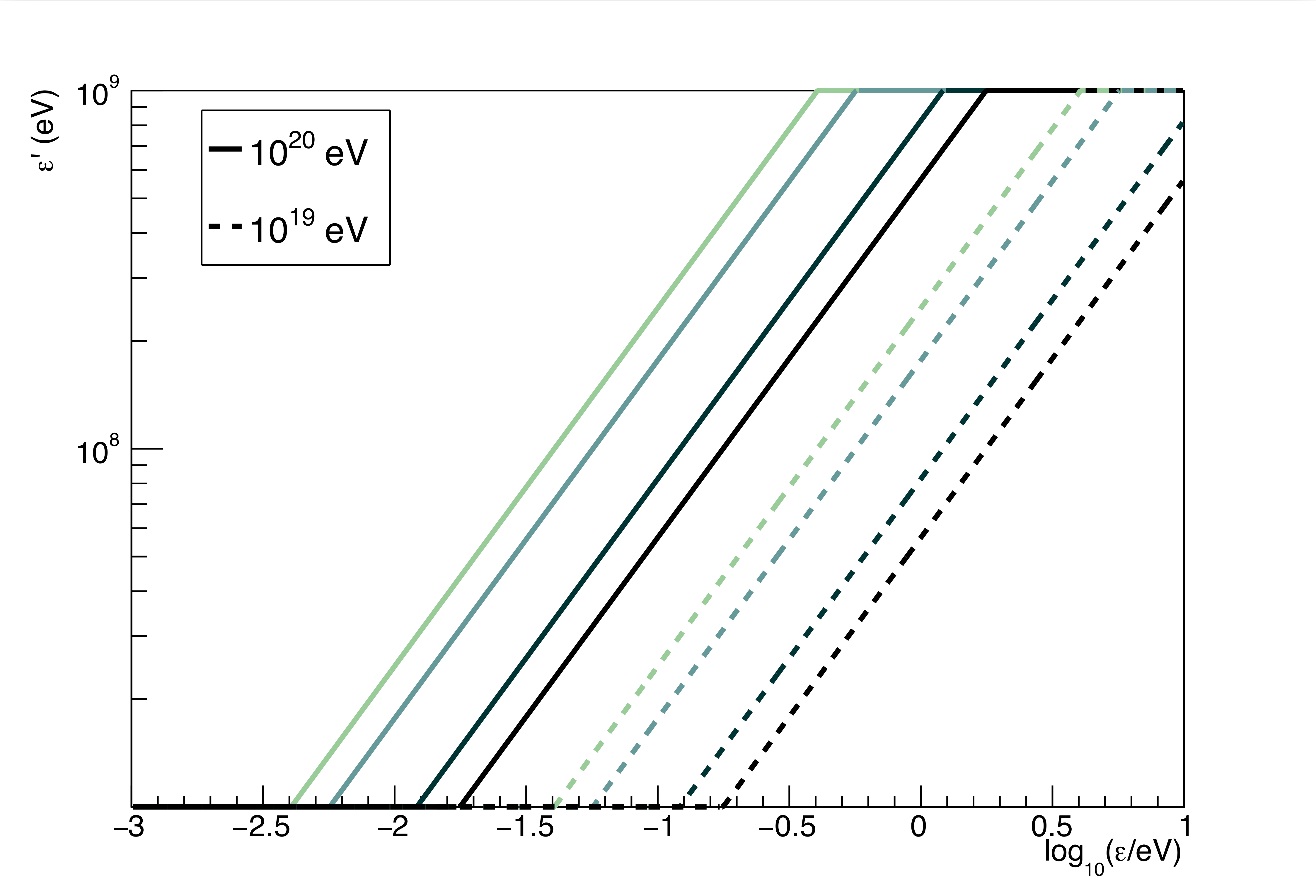
$$E_{\text{th}} = \frac{m_{n,p} A \Delta B}{2\varepsilon} \qquad \Gamma_{\text{th}} = \frac{\Delta B}{2\varepsilon}$$

- The threshold only depends on the difference of the binding energy for the emission of one proton or one neutron
- Weak dependence on A (the difference of the binding energy is O(MeV)

ENERGY THRESHOLD

$$\varepsilon' = \Gamma \epsilon$$

$$\Gamma_{\rm th} = \frac{\Delta B}{2\varepsilon}$$



- The highest energy events are cosmic rays which mainly interacted with the EBL

- Estimate of energy loss length

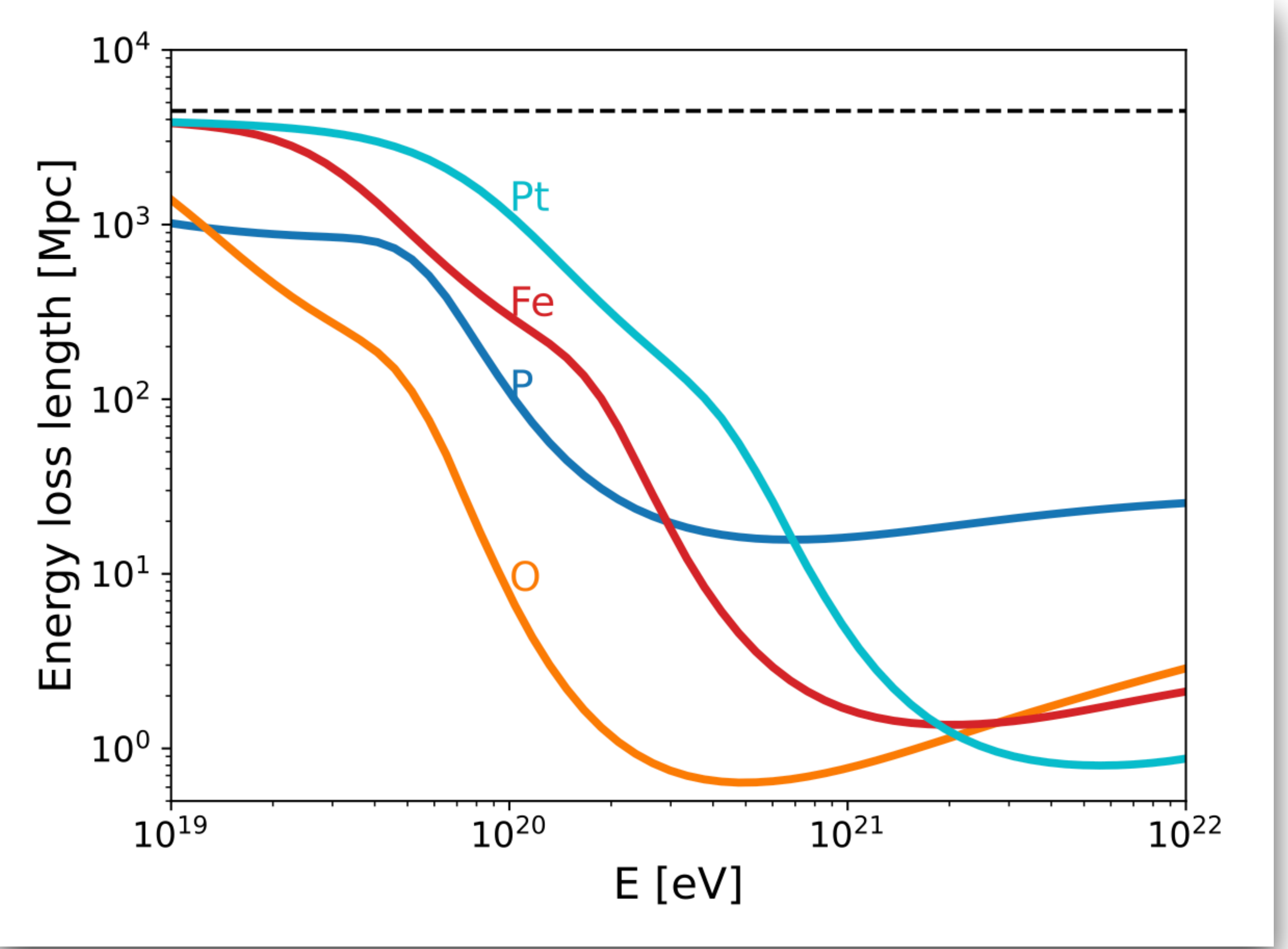
$$\mathrm{ELL} = \frac{1}{\sigma_{\rm abs} A\, n}$$

ENERGY LOSS LENGTH

$$\frac{1}{E}\frac{dE}{dt} = -\frac{c}{2\Gamma^2}\int_{\varepsilon'_{\rm th}}^{\infty}\varepsilon' f(\varepsilon')\sigma(\varepsilon')\int_{\varepsilon'/2\Gamma}^{\infty}\frac{n_\gamma(\varepsilon)}{\varepsilon^2}d\varepsilon d\varepsilon'$$

- At the minimum, the ELL are similar to each other
  - The increase in the maximum of the cross section is roughly compensated by the multiplicity
- If the ELL as a function of the Lorentz factor is taken into account,
  - The rapid decrease of the ELL has similar behaviours for each nucleus, due to the weak dependence of the threshold on the mass

Zhang et al, arxiv:2405.17409v1



- At a fixed energy, the ELL increases with A
  - A larger portion of the Universe is available if nuclei with large A are considered

WHAT CAN WE LEARN FROM THE HIGHEST ENERGY EVENTS?

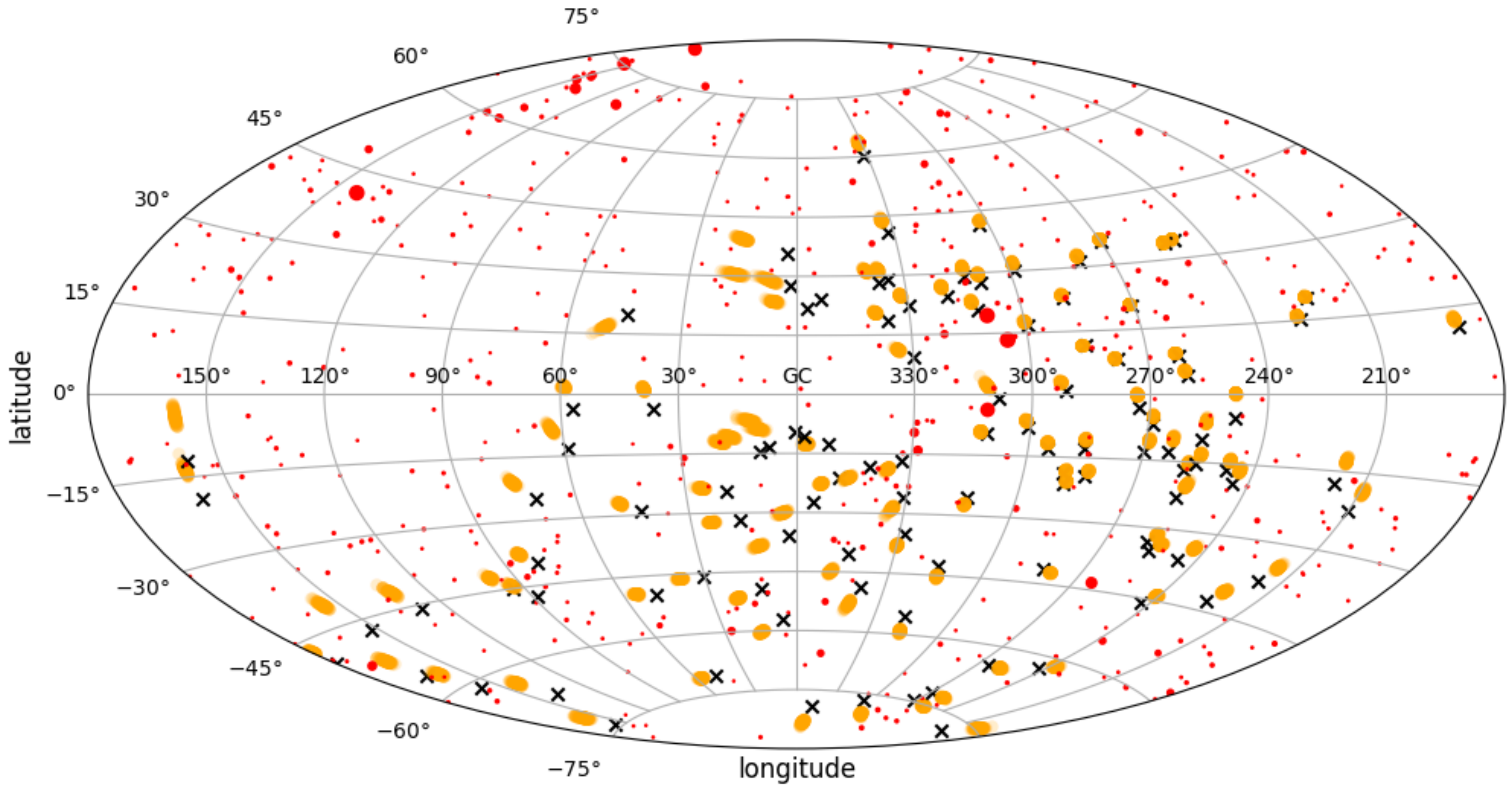
- **Inspired by the TA paper on the Amaterasu particle**; similar to what presented already in Unger&Farrar ApJL 2024, GAP2024_011, but **it is extended to the 100 highest-energy events**.

- Take into account the highest-energy events
- Identify the maximum distance of the possible source responsible for the cosmic-ray particle
  - Assigning a nuclear species to the detected event;
  - Taking into account the effect of extragalactic propagation;
  - Taking into account the effect of the Galactic magnetic field
- Assign a weight based on propagation effects and on the assumed nuclear species at Earth, to those backtracked events (at the border of the Galaxy) which are found within a chosen angular distance from a source
- Reject or accept sources based on the assigned weight

Backtracking of the highest-energy events

A=1

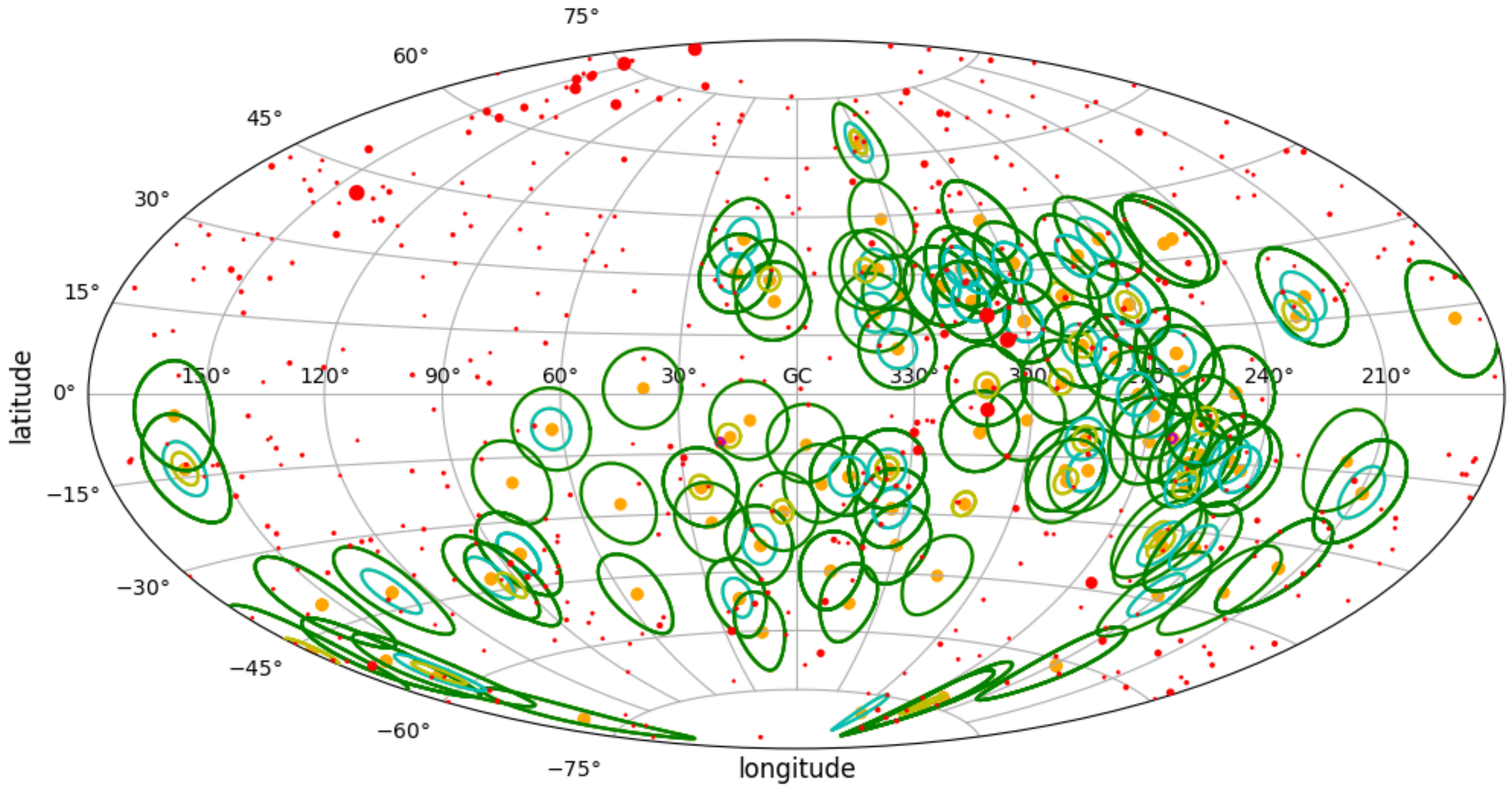
- CRPropa is used for the **backtracking** with JF12 (Jansson & Farrar ApJ 2012) model for the Galactic magnetic field (note that here and in the following plots, only the regular component is taken into account), including the uncertainty in energy



- Catalog (sources indicated as red dots; the size of the dots depends on the distance of the source): **Swift-BAT 70-month catalog of AGNs**, as used in the **AD paper of Phase1**

Association of the highest-energy events to source positions

A=1



- Case for **protons**: search for sources within chosen angular distances with respect to the backtracked event (in this case, no uncertainty in the energy is used)

Examples

- Assign a nuclear species
  - Compute the maximum distance
- Backtrack the arrival direction
  - Check the sources within some angular distances
- Check if the source distance is larger than the maximum distance

ID = PAO191110 - E = 166 EeV, , longitude = 269.08, latitude = -6.82

Element	Position	d_{max} [Mpc]	Source name	Source position	a_{GZK}
p	lon=269.11 lat=-4.90	39.74	2MASXJ09023729-4813339	lon=268.87 lat=-1.07 d=163.7 Mpc	1.92e-09
			ESO209-G012	lon=264.26 lat=-10.04 d=173.0 Mpc	5.53e-10
Fe	lon=282.89 lat=26.77	14.76	NGC3783	lon=287.46 lat=22.95 d=40.0 Mpc	2.91e-06
			ESO439-G009	lon=281.72 lat=30.16 d=100.9 Mpc	1.11e-16
			HE1136-2304	lon=282.06 lat=36.56 d=116.4 Mpc	∼ 0.0
			2MASXJ10483385-3902375	lon=278.31 lat=17.90 d=194.1 Mpc	∼ 0.0
N	lon=270.27 lat=6.03	8.10	ESO315-G020	lon=269.45 lat=8.45 d=67.0 Mpc	∼ 0.0
			ESO263-G013	lon=273.98 lat=10.80 d=143.9 Mpc	∼ 0.00
			2MASXJ09023729-4813339	lon=268.87 lat=-1.07 d=163.7 Mpc	∼ 0.00
He	lon=269.20 lat=-2.94	26.85	2MASXJ09023729-4813339	lon=268.87 lat=-1.07 d=163.7 Mpc	3.41e-12
			ESO209-G012	lon=264.26 lat=-10.04 d=173.0 Mpc	7.30e-13
Si	lon=271.53 lat=5.10	4.03	ESO315-G020	lon=269.45 lat=8.45 d=67.0 Mpc	∼ 0.0
			ESO263-G013	lon=273.98 lat=10.80 d=143.9 Mpc	∼ 0.0
			2MASXJ09023729-4813339	lon=268.87 lat=-1.07 d=163.7 Mpc	∼ 0.0

Examples

ID = PAO170528 - E = 95 EeV, , longitude = 255.49, latitude = -35.14

Element	Position	d_{max} [Mpc]	Source name	Source position	a_{GZK}
p	lon=253.7 lat=-33.29	84.88	PICTORA	lon=251.60 lat=-34.64 d=148.6 Mpc	6.72e-04
			ESO205-IG003NED01	lon=254.61 lat=-30.03 d=217.8 Mpc	8.39e-06
			2MASXJ04372814-4711298	lon=253.33 lat=-41.90 d=224.9 Mpc	5.35e-06
Fe	lon= 249.02 lat=33.61	81.02	NGC2992	lon=249.70 lat=28.77 d=31.8 Mpc	0.64
			NGC3035	lon=244.28 lat=34.92 d=61.7 Mpc	0.24
			ARK241	lon=247.30 lat=42.67 d=178.6 Mpc	3.96e-04
			2MASXJ10171680-0404558	lon=246.86 lat=41.45 d=178.6 Mpc	3.96e-04

- If iron is taken into account, two sources are found within 10 degrees AND within the maximum distance of the event

- If heavier nuclei are taken into account, their maximum distance can be larger and more sources can be considered

HEAVY NUCLEI IN SIMPROP

- With the current technology of SimProp, using **model 4** for the disintegration would allow to include also heavy nuclei, if the corresponding parameters are collected
  - See https://arxiv.org/pdf/1804.04445
  - See SimProp documentation

- First step:
  - Collect parameters
- Second step:
  - Compute cross section in nucleons and in alpha

$$\sigma_i(\epsilon') = \begin{cases} h_i^1 \exp\left(-\frac{(\epsilon'-x_i^1)^2}{w_i^1}\right), & t_i < \epsilon' < \epsilon_1, \quad i = N, \alpha; \\ c_i, & \epsilon_1 < \epsilon' < \epsilon_{\max}, \quad i = N, \alpha. \end{cases}$$

In `xsect_BreitWigner2_TALYS-1.6.txt` and `xsect_Gauss2_TALYS-restored.txt`, the cross sections for nucleon and alpha-particle ejection σ_N andσ_α were fitted to

$$\sigma_N = \sum_{\text{channels}} n_N \sigma_{n_n n_p n_d n_t n_h n_\alpha} = \langle n_N \rangle \sigma_{\text{tot}}, \text{ where } n_N = n_n + n_p + 2n_d + 3n_t + 3n_h; \quad (4.1)$$

$$\sigma_\alpha = \sum_{\text{channels}} n_\alpha \sigma_{n_n n_p n_d n_t n_h n_\alpha} = \langle n_\alpha \rangle \sigma_{\text{tot}}. \quad (4.2)$$

HEAVY NUCLEI IN SIMPROP

To-do list - open issues (not ordered)

- List of stable nuclei with A>56
- Estimate of interaction length of heavy nuclei in dense regions
- Check the beta-decay time
- Collection of parameters for emission of one nucleon and alpha