Neutron invisible decay in rocks

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In collaboration with
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Presenter: Audrey Fung, APCTP

Neutron lifetime

Beam vs Bottle

- Pass cold neutron beams
- Trap and count proton from neutron decay
- $\tau_n^{\text{beam}} = 888.0 \pm 2.0\text{s}$

- Ultracold neutrons trapped in a specialised container
- Count remaining neutrons at set times
- $\tau_n^{\text{bottle}} = 878.4 \pm 0.5\text{s}$

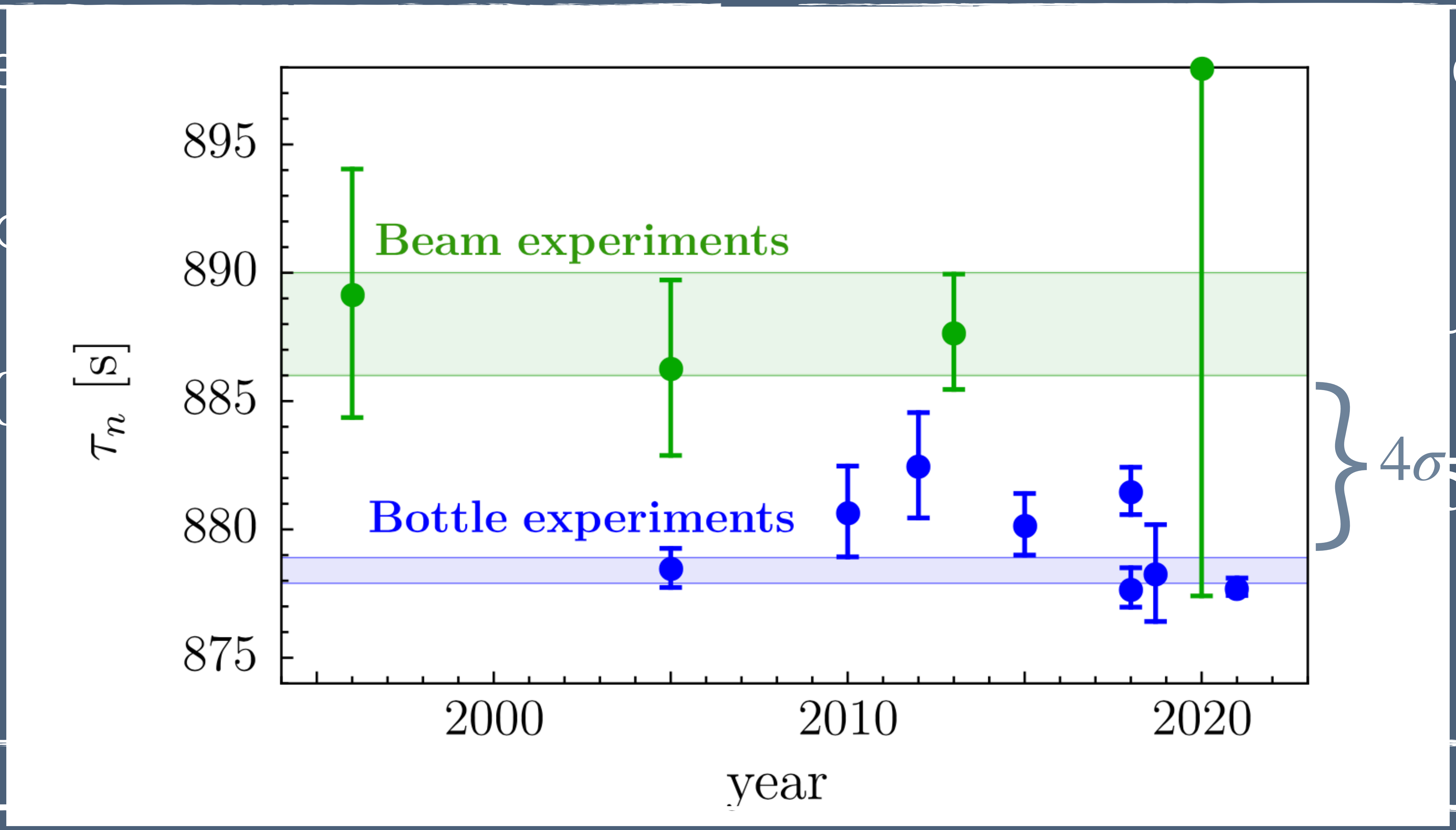
$$n \rightarrow p + e + \bar{\nu}_e$$

Source: J. S. Nico et al., "Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam," Physical review. C, Nuclear physics, vol. 71, no. 5, Art. no. 055502, May 2005, doi: 10.1103/PhysRevC.71.055502.

Neutron lifetime

Beam vs Bottle

- Pass cold neutron be… …apped in a specialised
- Trap and count proto… …utrons at set times
- $\tau_n^{\text{beam}} = 888.0 \pm 2.($ … 5s



4σ

$$n \rightarrow p + e + \bar{\nu}_e$$

Source: J. S. Nico et al., "Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam," Physical review. C, Nuclear physics, vol. 71, no. 5, Art. no. 055502, May 2005, doi: 10.1103/PhysRevC.71.055502.

Neutron lifetime

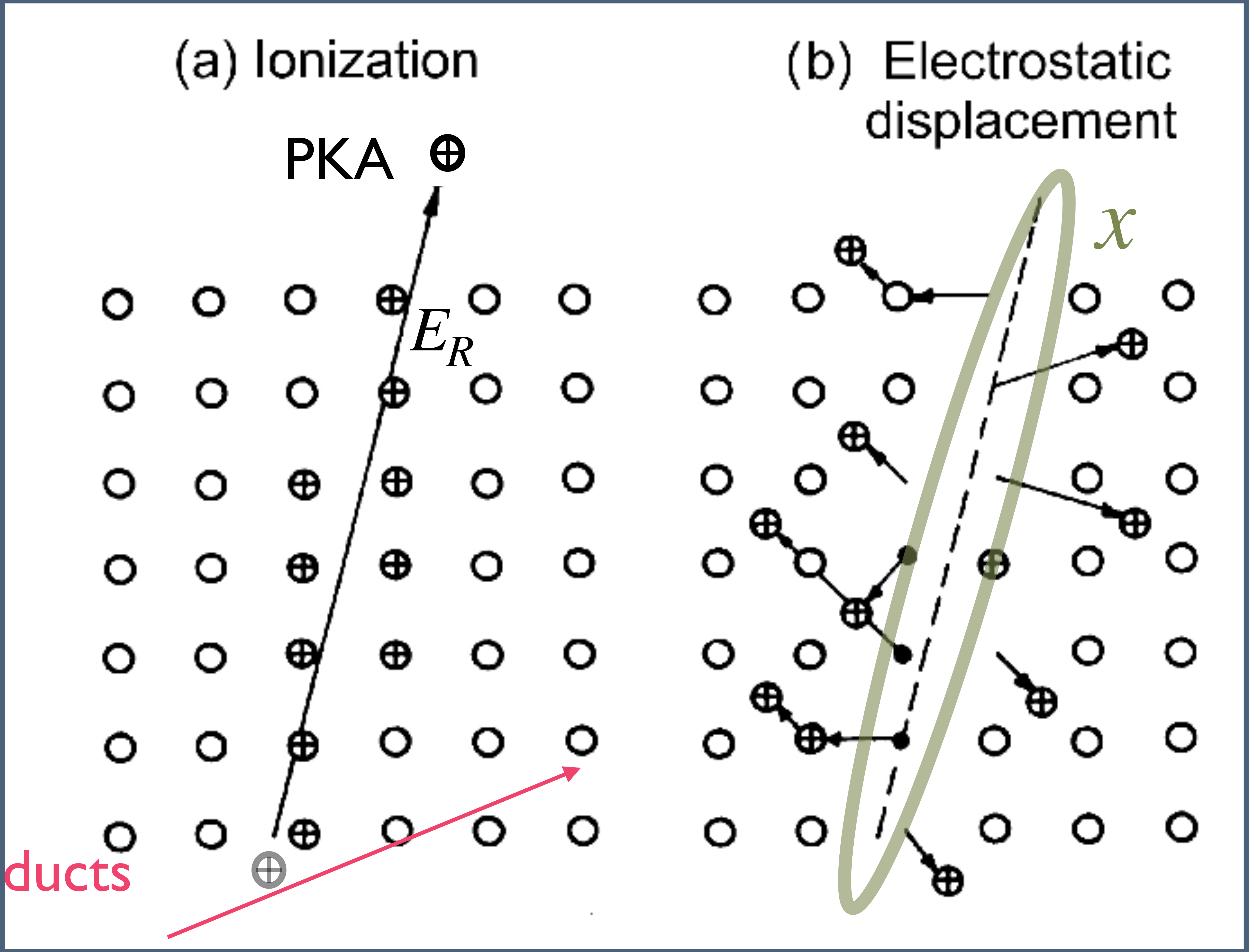
Invisible decay?

- $\tau_n^{\text{bottle}} = \tau_n^{\text{beam}} \times \text{Br}(n \to p + \text{anything}) \leq \tau_n^{\text{beam}}$
- $\text{Br}(n \to p + \text{anything}) \approx 99\,\%$
- $\text{Br}(n \to \text{anything} \neq p) \approx 1\,\%$
- $\tau(n \to inv) > 9.0 \times 10^{29}\text{years}$ (bound neutrons)
- $\tau(nn \to inv) > 1.5 \times 10^{28}\text{years}$ (bound neutrons)

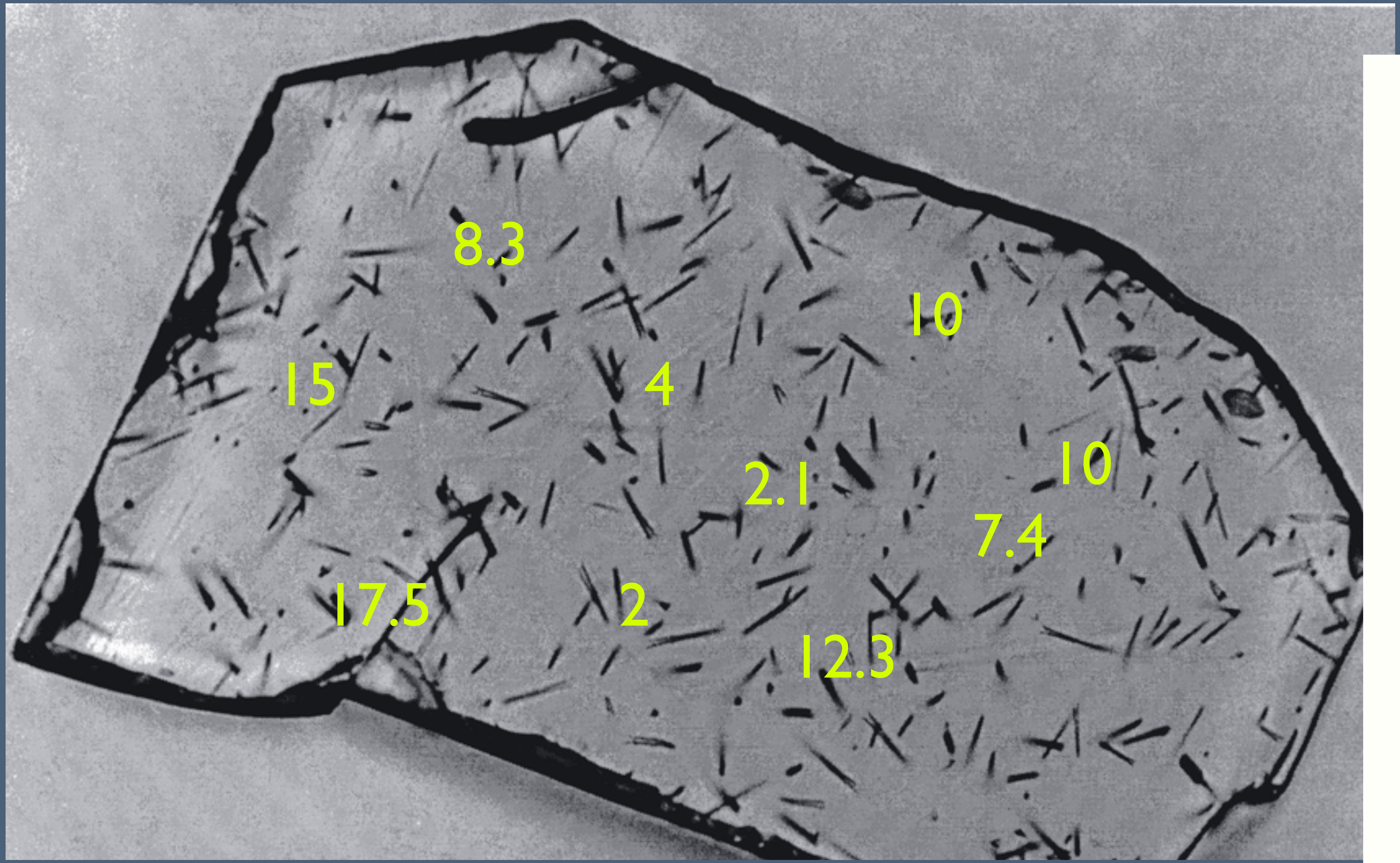
A. Allega et al., "Improved search for invisible modes of nucleon decay in water with the SNO + detector," Physical review. D, vol. 105, no. 11, Art. no. 112012, June 2022, doi: 10.1103/PhysRevD.105.112012.

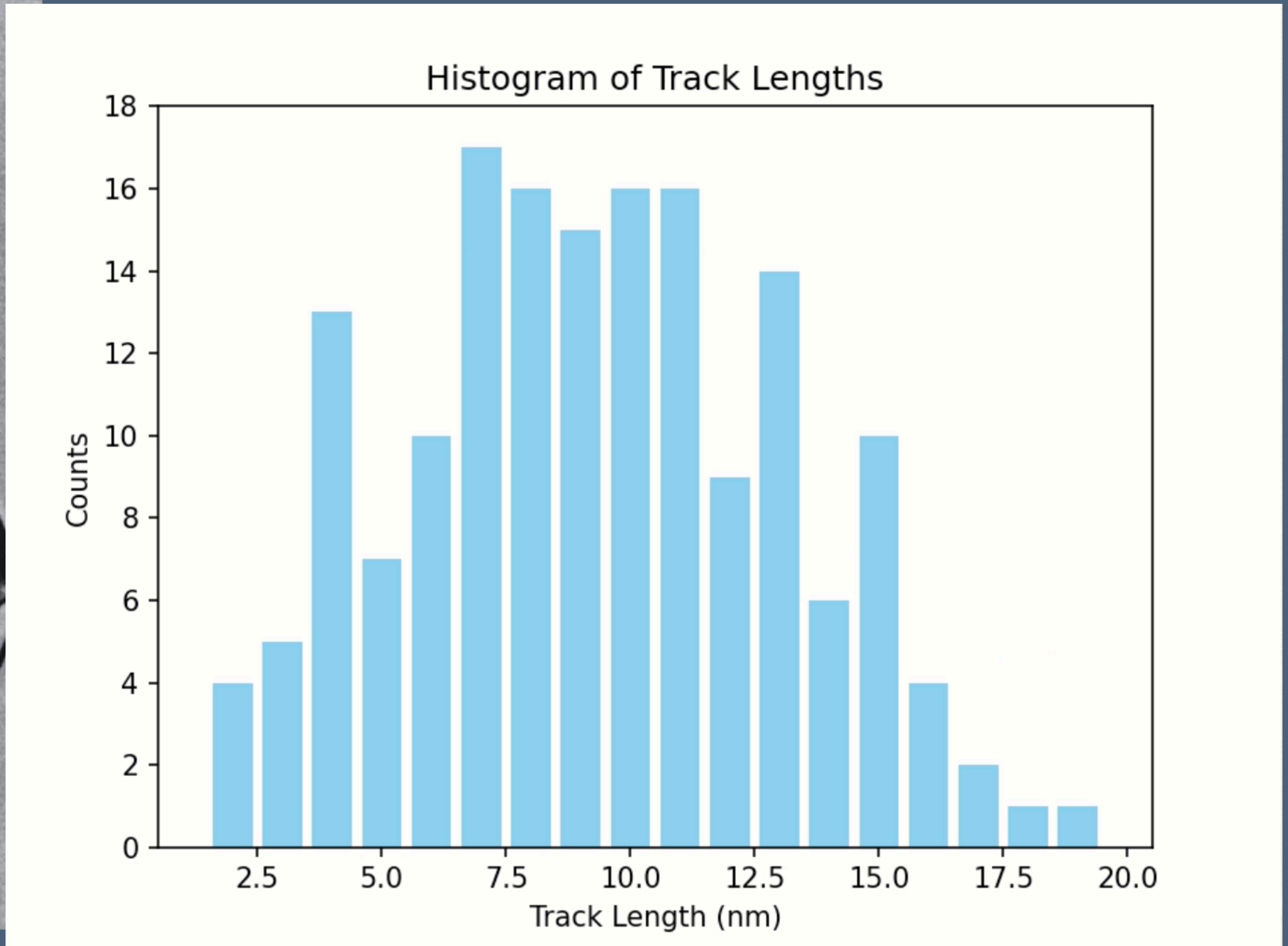
What is paleodetection?

- particles leave latent damage to crystal structure
- Preserved crystal damage over Gyr timescale
- Infer particle incident energy and flux from track length (and its distribution), track counts and vacancy defects



Dickin, A. P. (2005). *Radiogenic isotope geology* (2nd ed.). Cambridge University Press.


8.3
10
15
4
2.1
10
7.4
17.5
2
12.3


Histogram of Track Lengths
Counts
Track Length (nm)
0
2
4
6
8
10
12
14
16
18
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

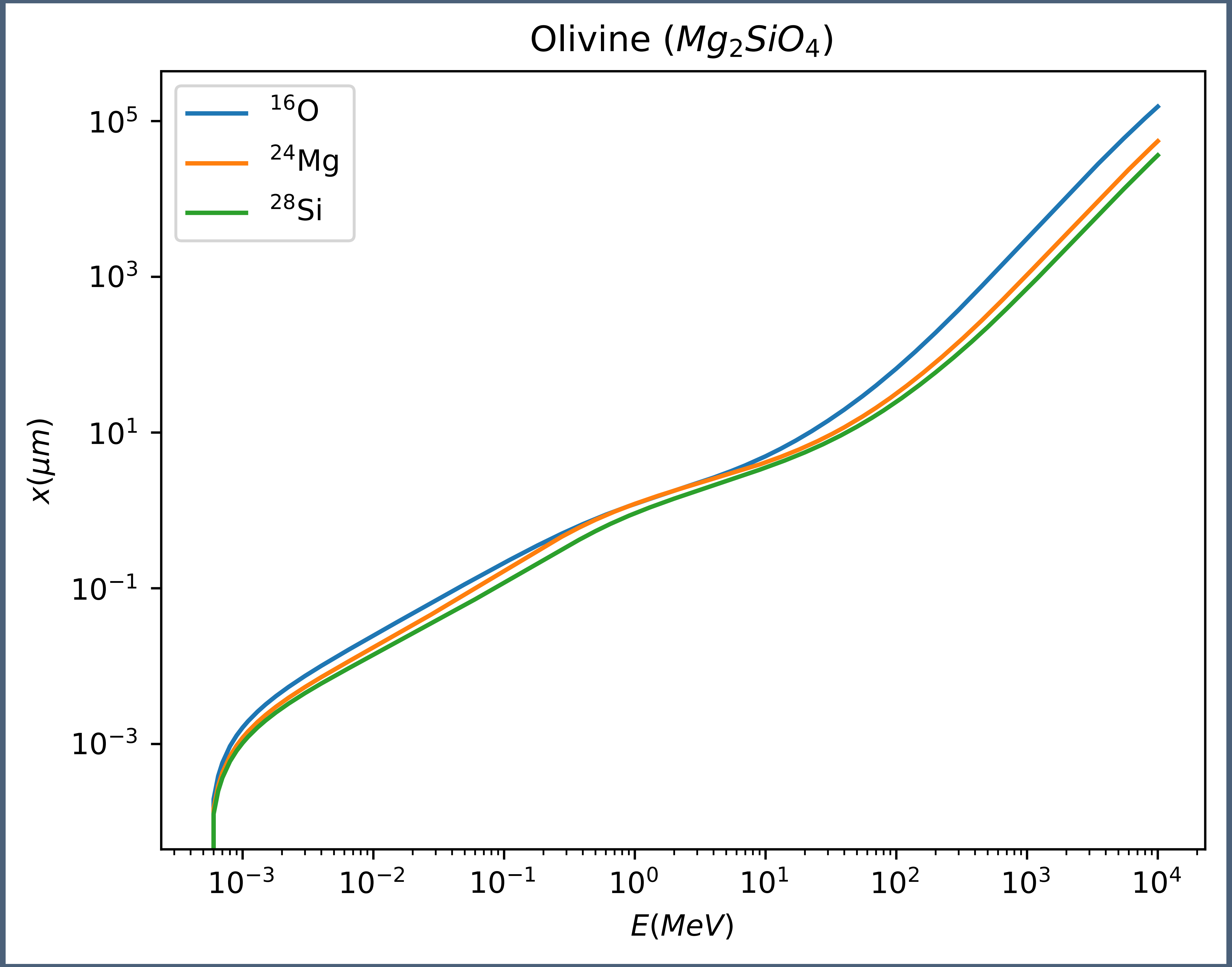
E_R - X_T relation

Stopping power

$$\boxed{\frac{dR}{dx} = \frac{dR}{dE} \times \left|\frac{dE}{dx}\right|}$$

Energy spectrum of the incoming particle

stopping power of the target



Backgrounds

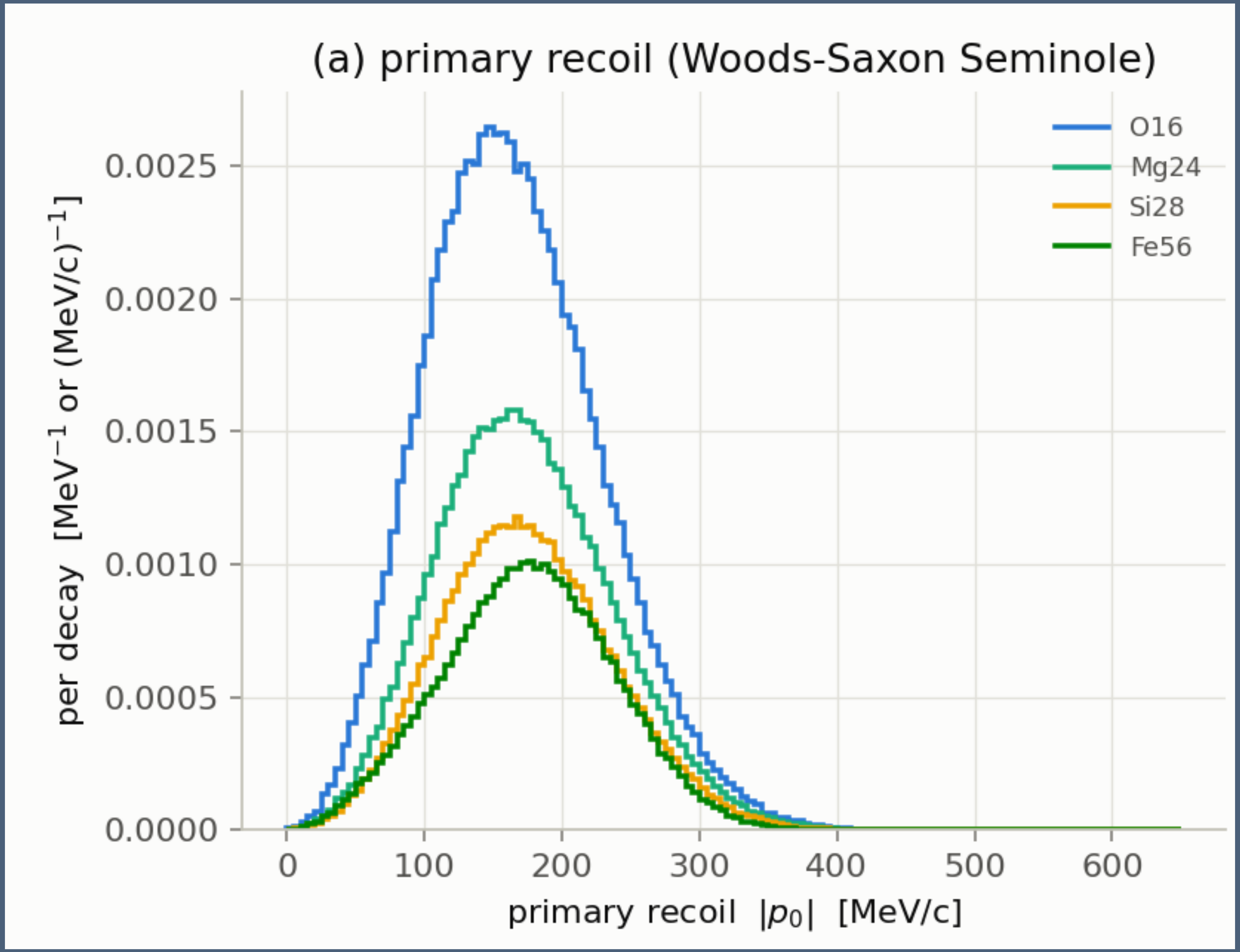
- ^{238}U decay : 8 alpha decays→8 alpha particles
- ^{238}U decay→neutrons
- ^{238}U spontaneous fission→neutrons + fission fragments
- Atmospheric neutrinos

Signals

- Neutron decay → remnant recoil → track
- Neutron decay → remnant at excited state de-excited →remnant recoil → track
- Neutron decay → remnant at excited state de-excited →secondary particles → track

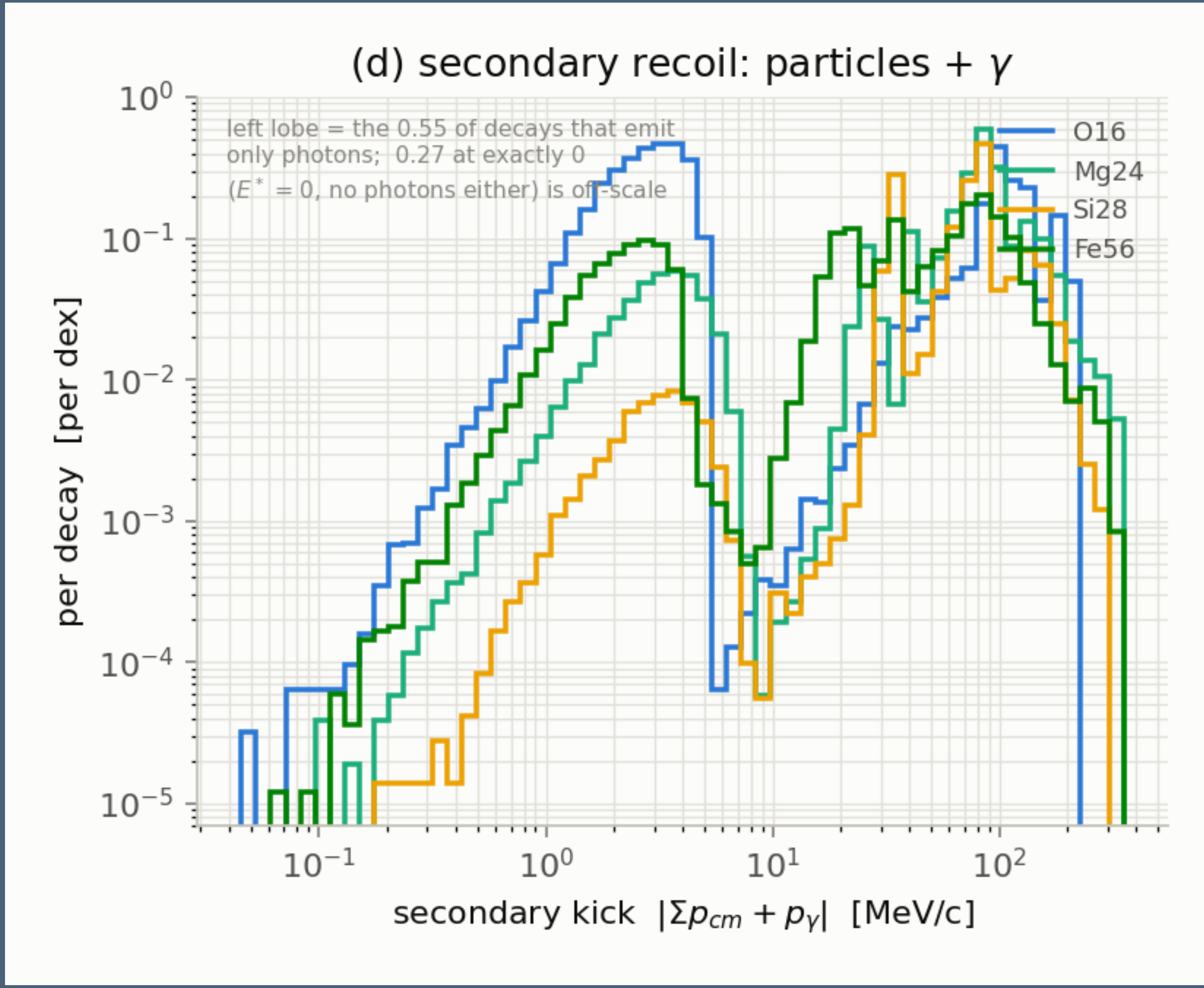
$n \to inv$

Primary recoil spectra



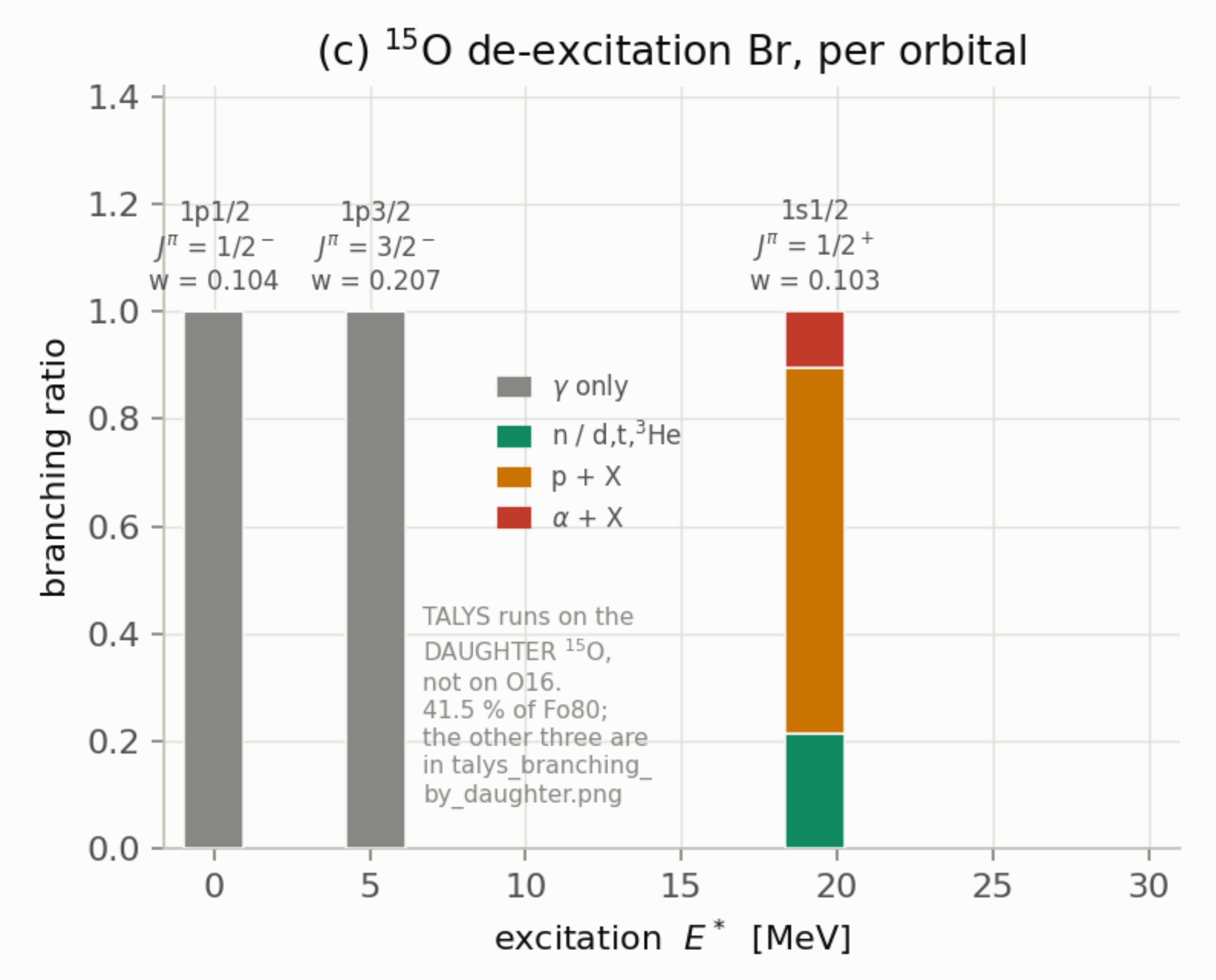
$n \to inv$

Secondary recoil spectra



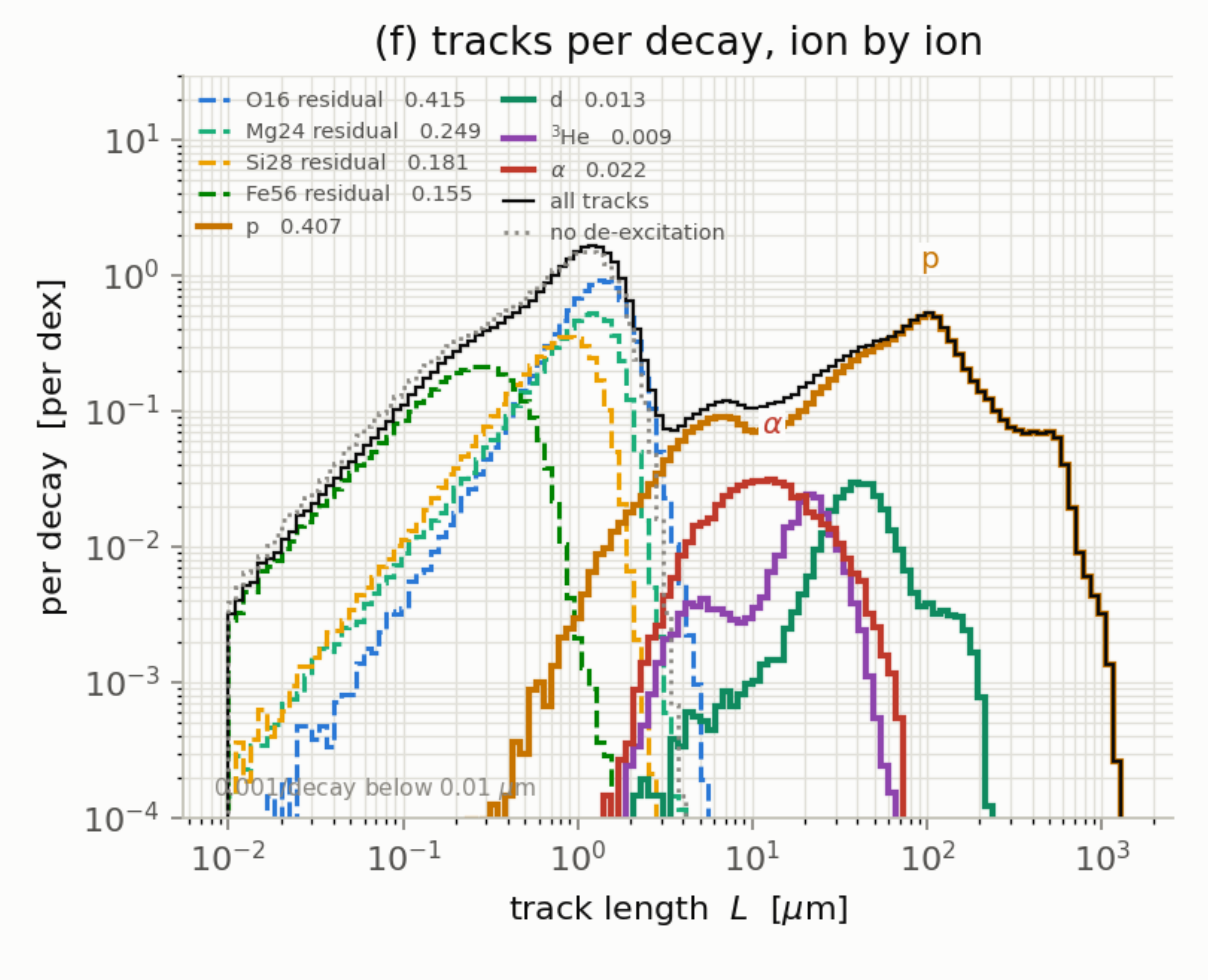
$n \to inv$

De-excitation channels per orbital

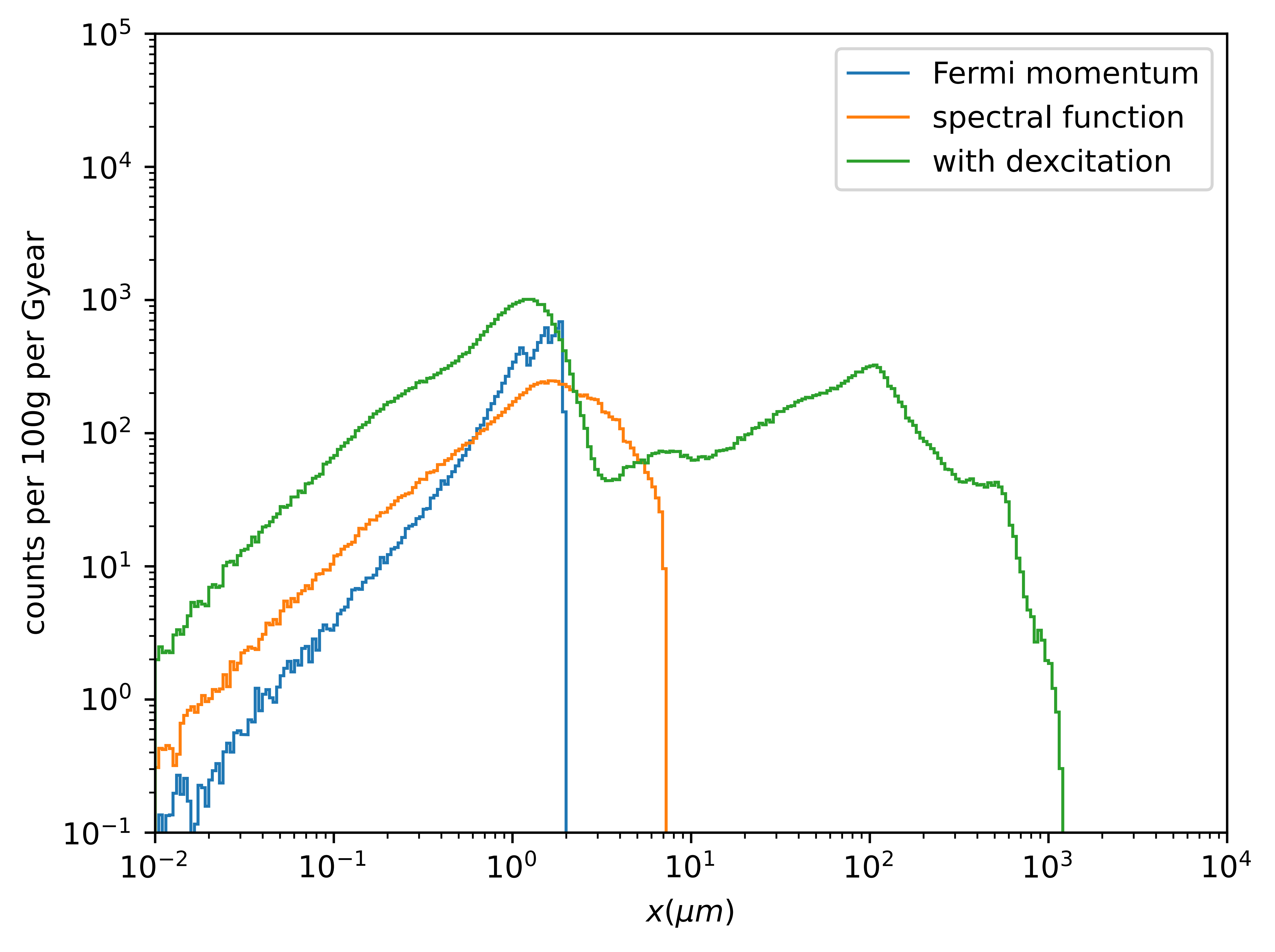


$n \to inv$

Track length distribution

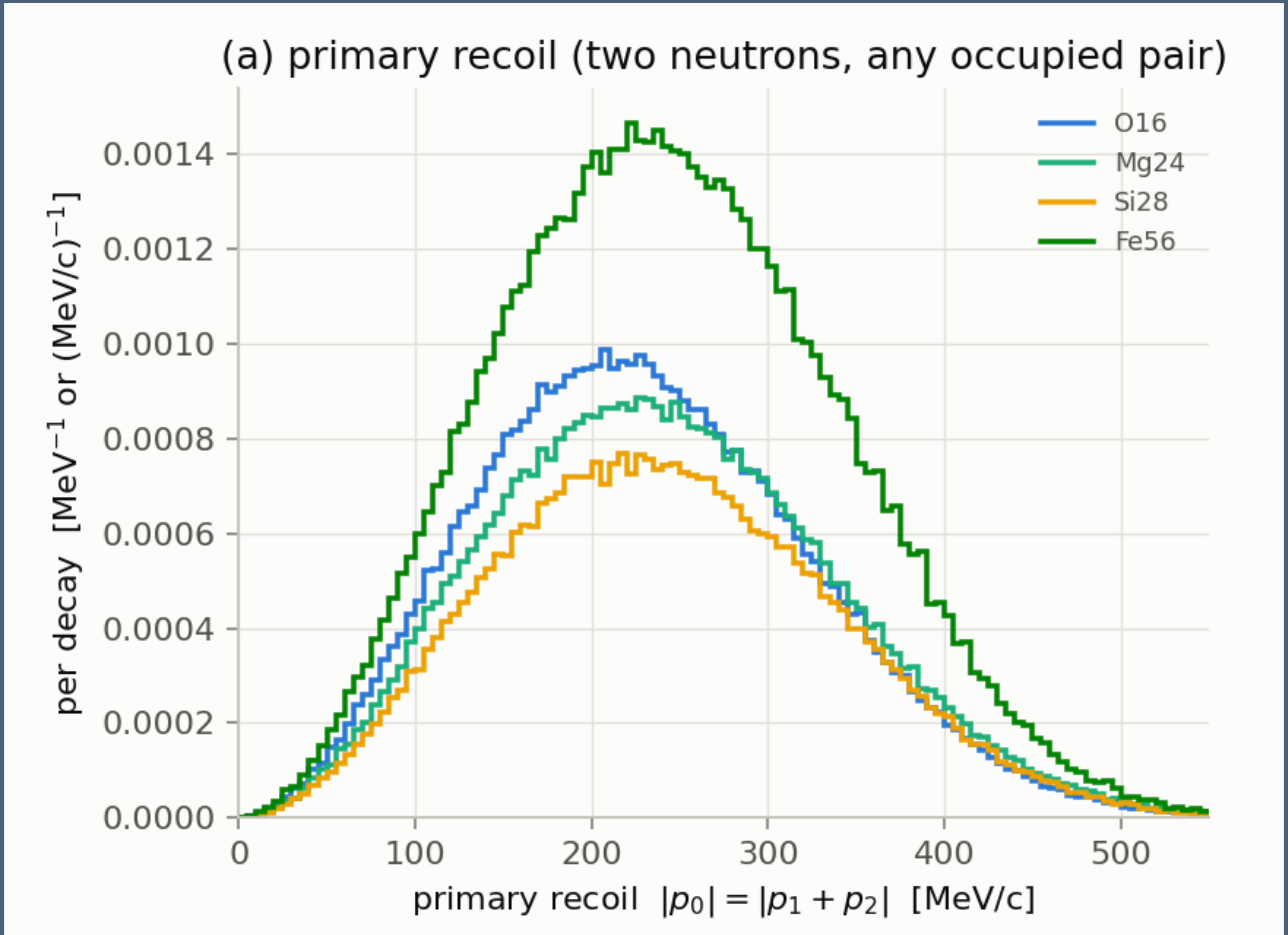


With vs. Without de-excitation



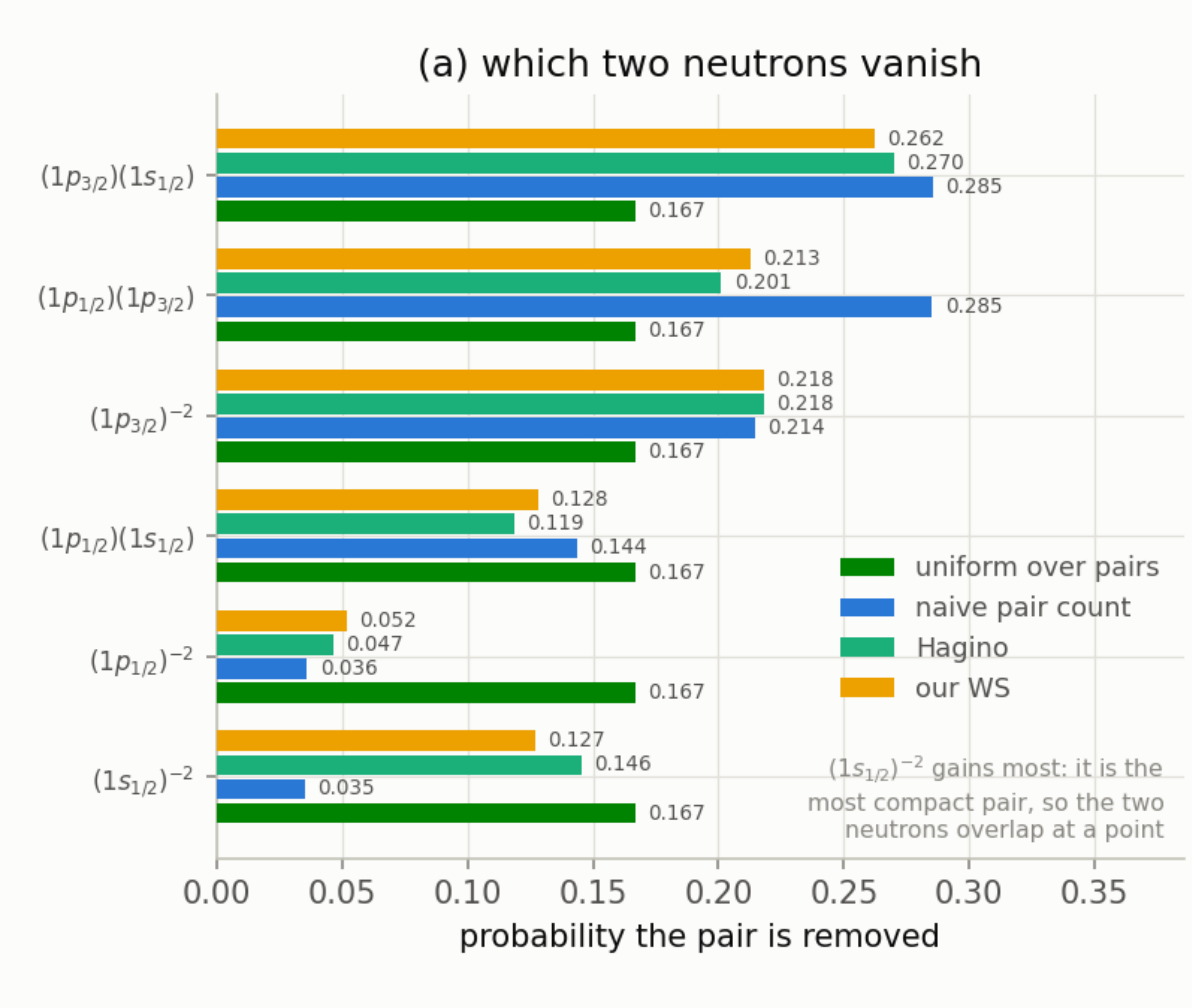
$nn \to inv$

Primary recoil spectra



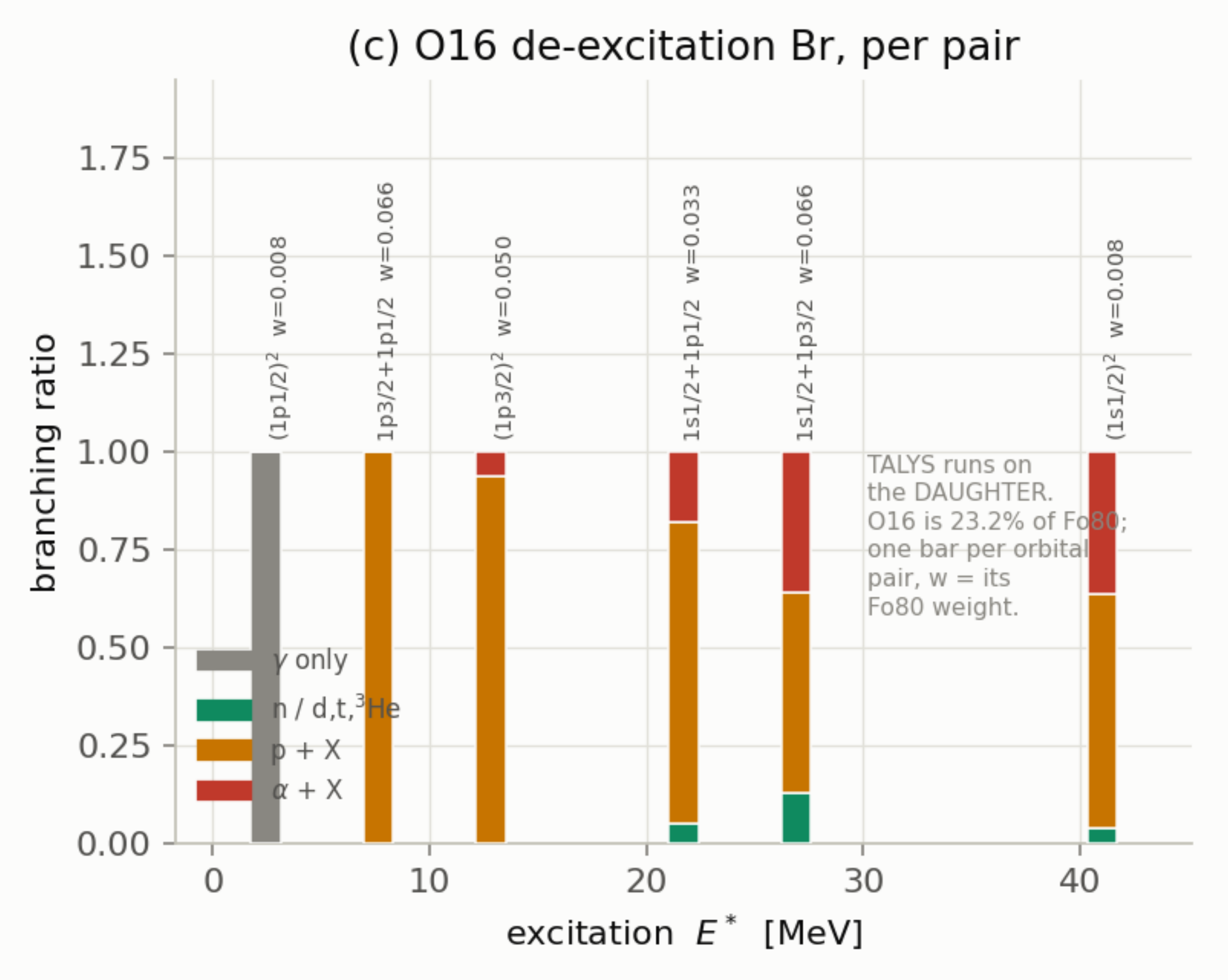
$nn \to inv$

Which two neutrons decay?



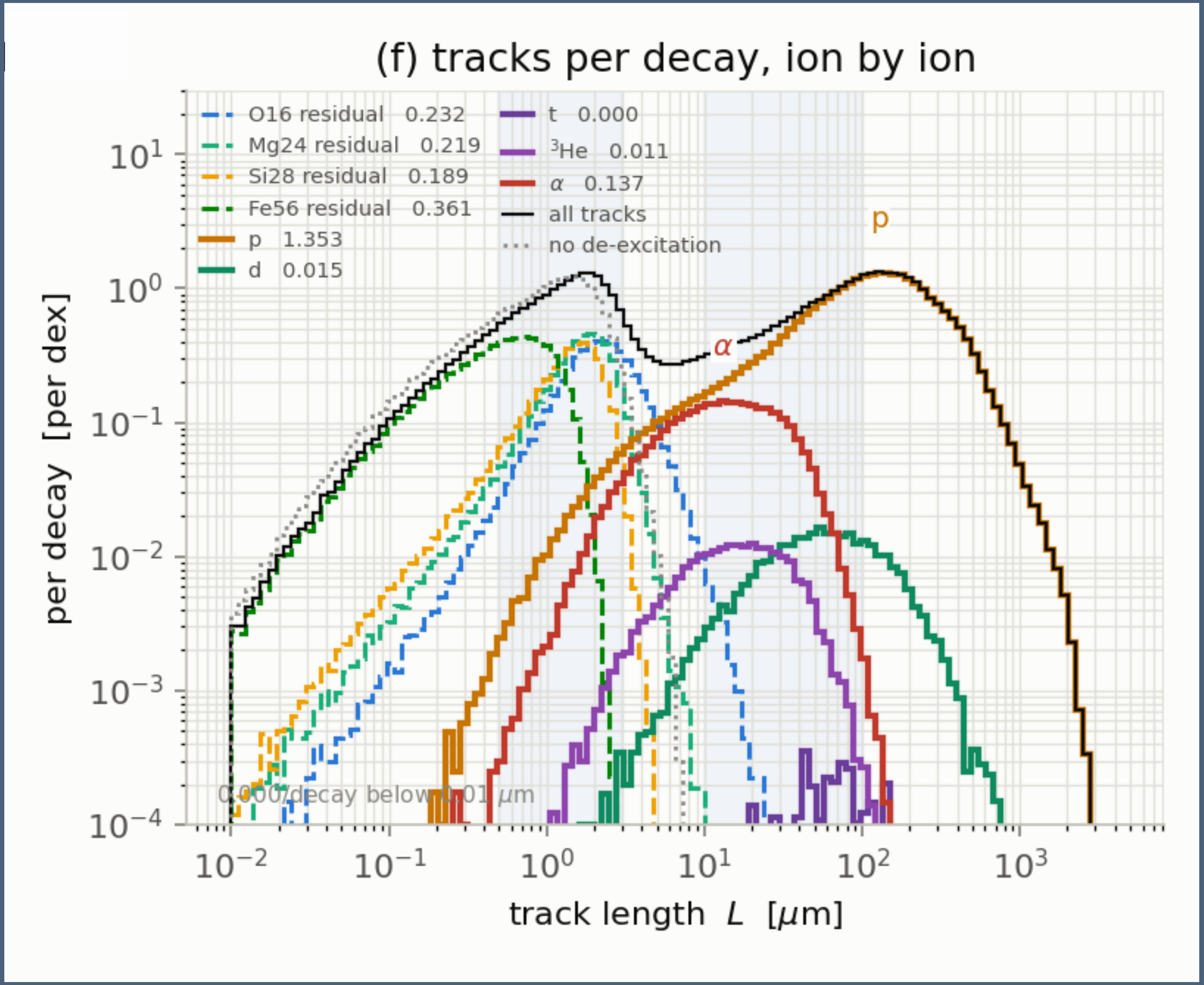
$nn \to inv$

De-excitation channels per orbital



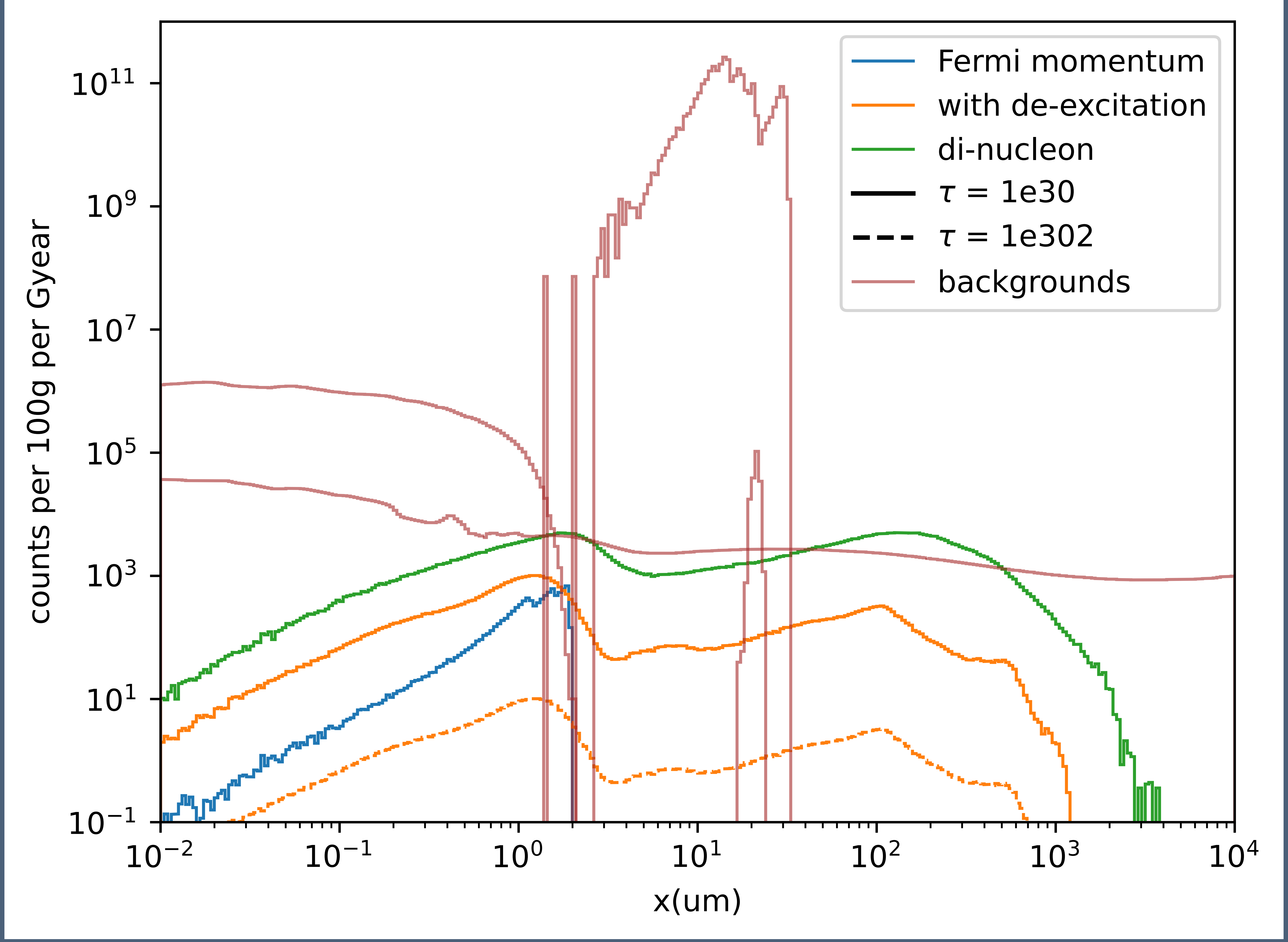
$nn \to inv$

Track length distribution

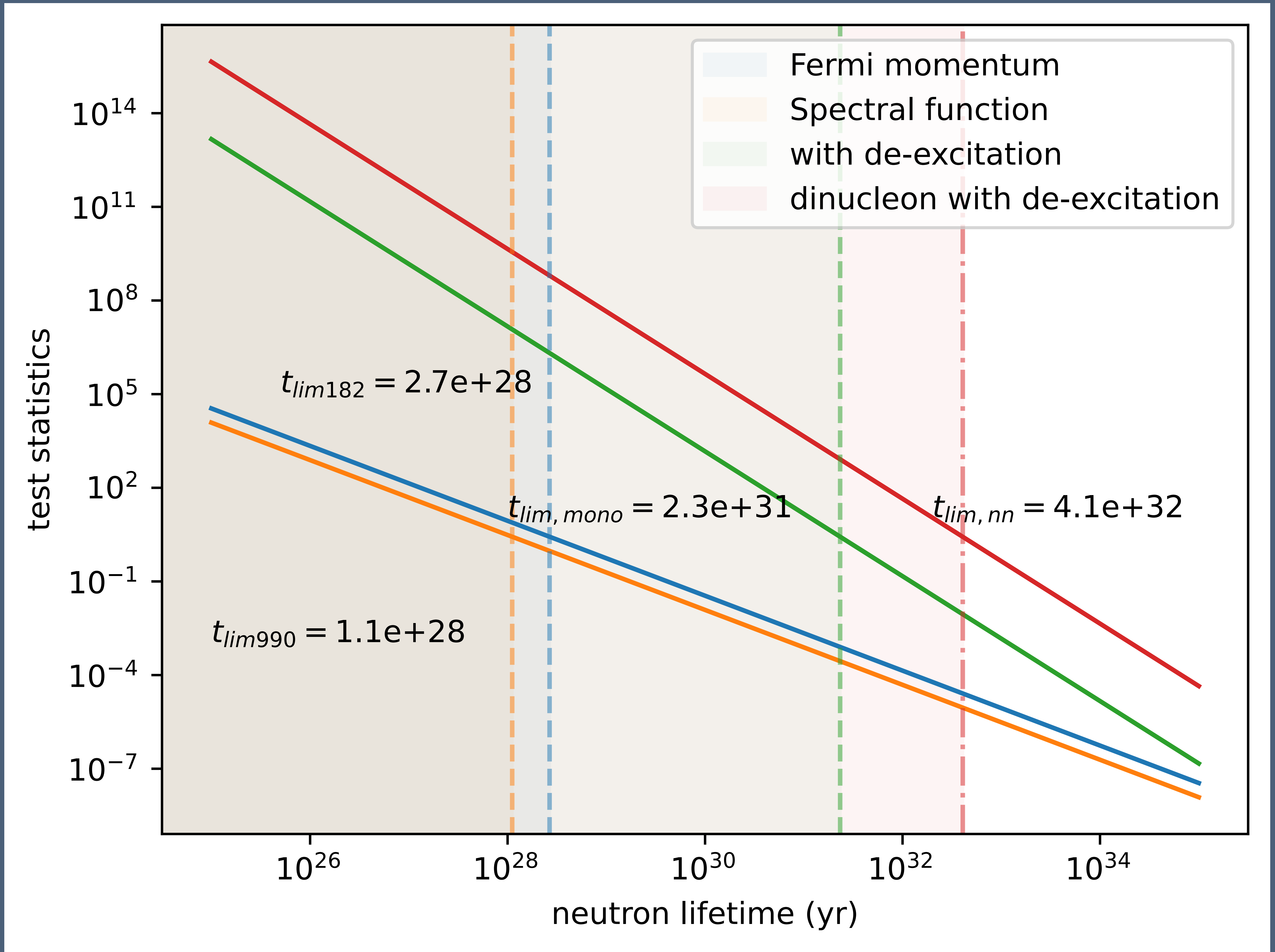


Signal + background

Track length distribution

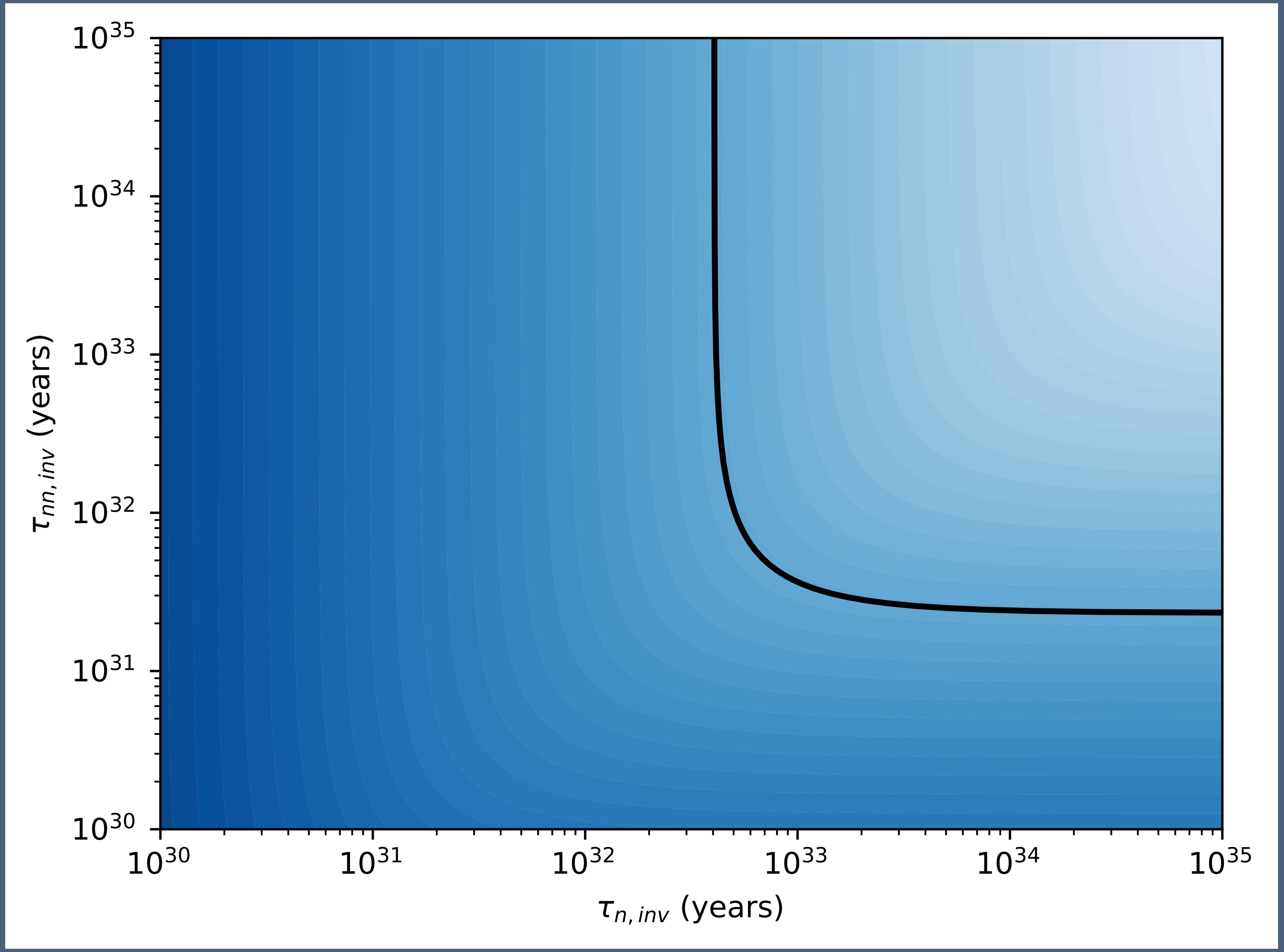


Projected sensitivity



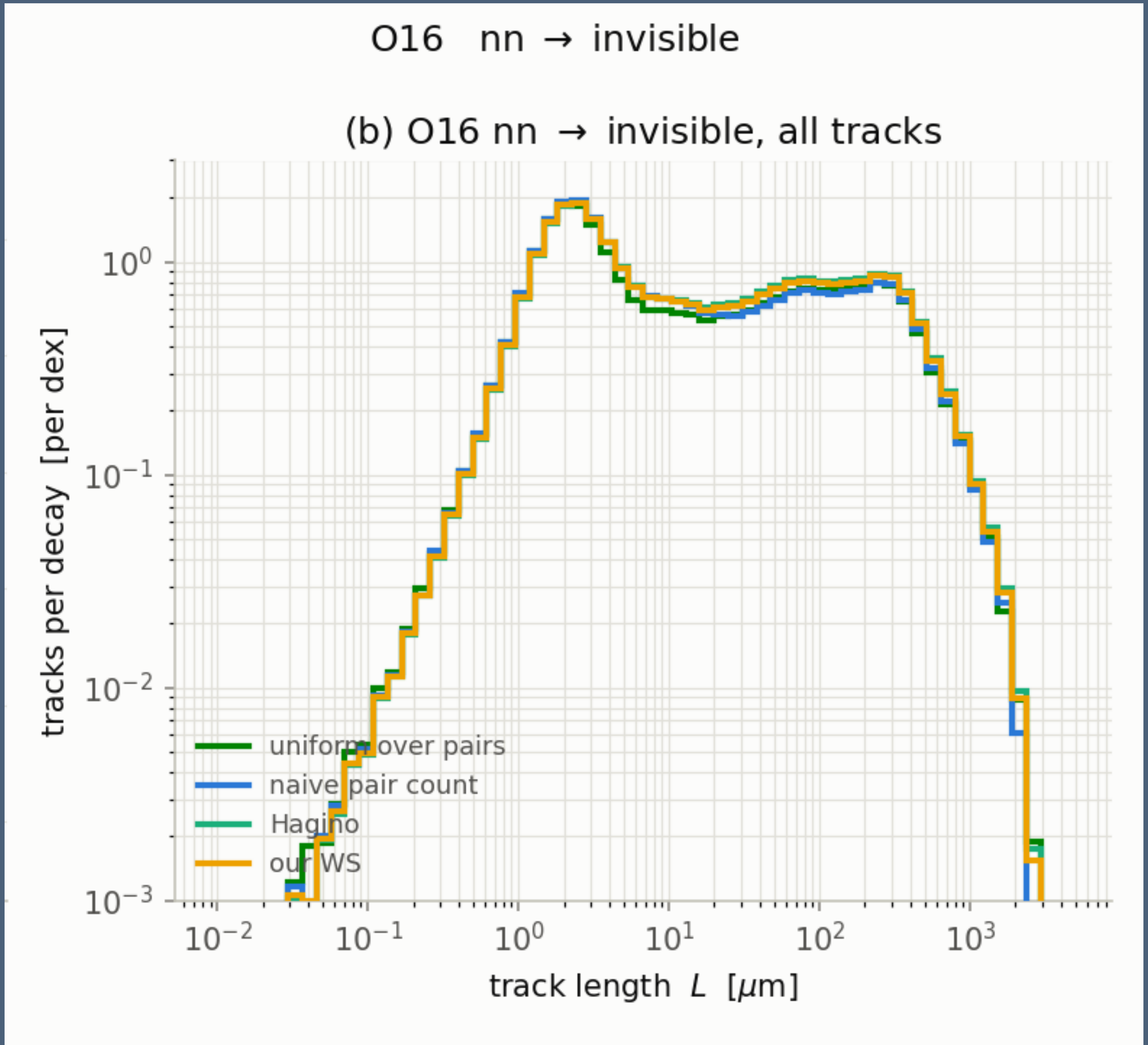
Projected sensitivity

- $\tau(n \to inv) > 2.3 \times 10^{31}$years
- $\tau(nn \to inv) > 4.1 \times 10^{32}$years



Theoretical uncertainties

Which two neutrons decay



Theoretical uncertainties

Discrepancies

Summary and closing remarks

- Including track from de-excitation greatly enhanced sensitivity
- $\tau(n \to inv) > 2.3 \times 10^{31}\text{years}$
- $\tau(nn \to inv) > 4.1 \times 10^{32}\text{years}$

- Signal tracks are long : don't need to constrain ourselves specific minerals
- Favour high neutron numbers
- Paper coming out soon, stay tuned!

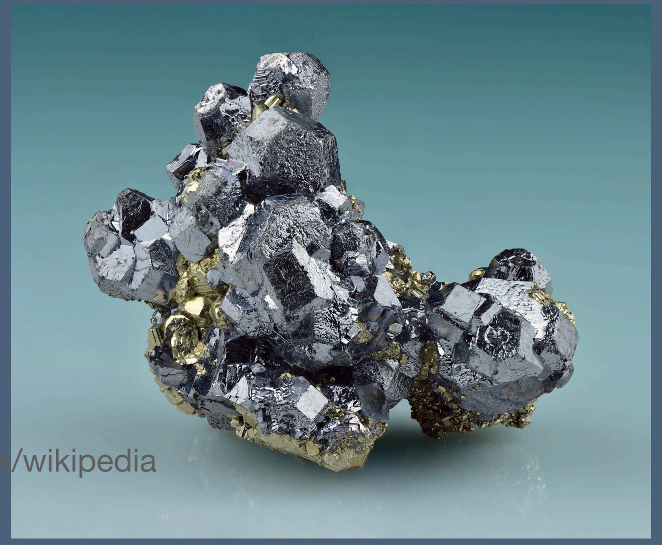
Backup slides

Mineral candidates

- be suitable for imaging
- be $5 \sim 10$ km underground for > 500 Myr
- be able to preserve tracks

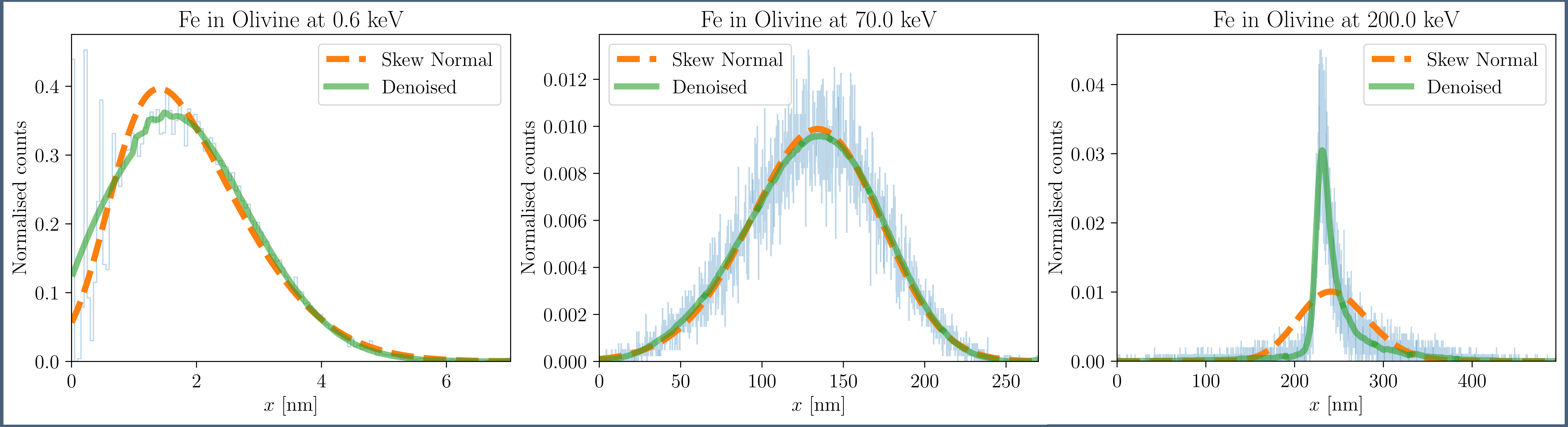
- Olivine $(Mg,Fe)_2SiO_4$
  - Has been suggested before (e.g. Drukier et al)
  - Not expected to take up much Uraniu
  - non-hydrous

- Galena (PbS)
  - Not used before (as far as we know)
  - Not expected to take up much uranium
  - non-hydrous

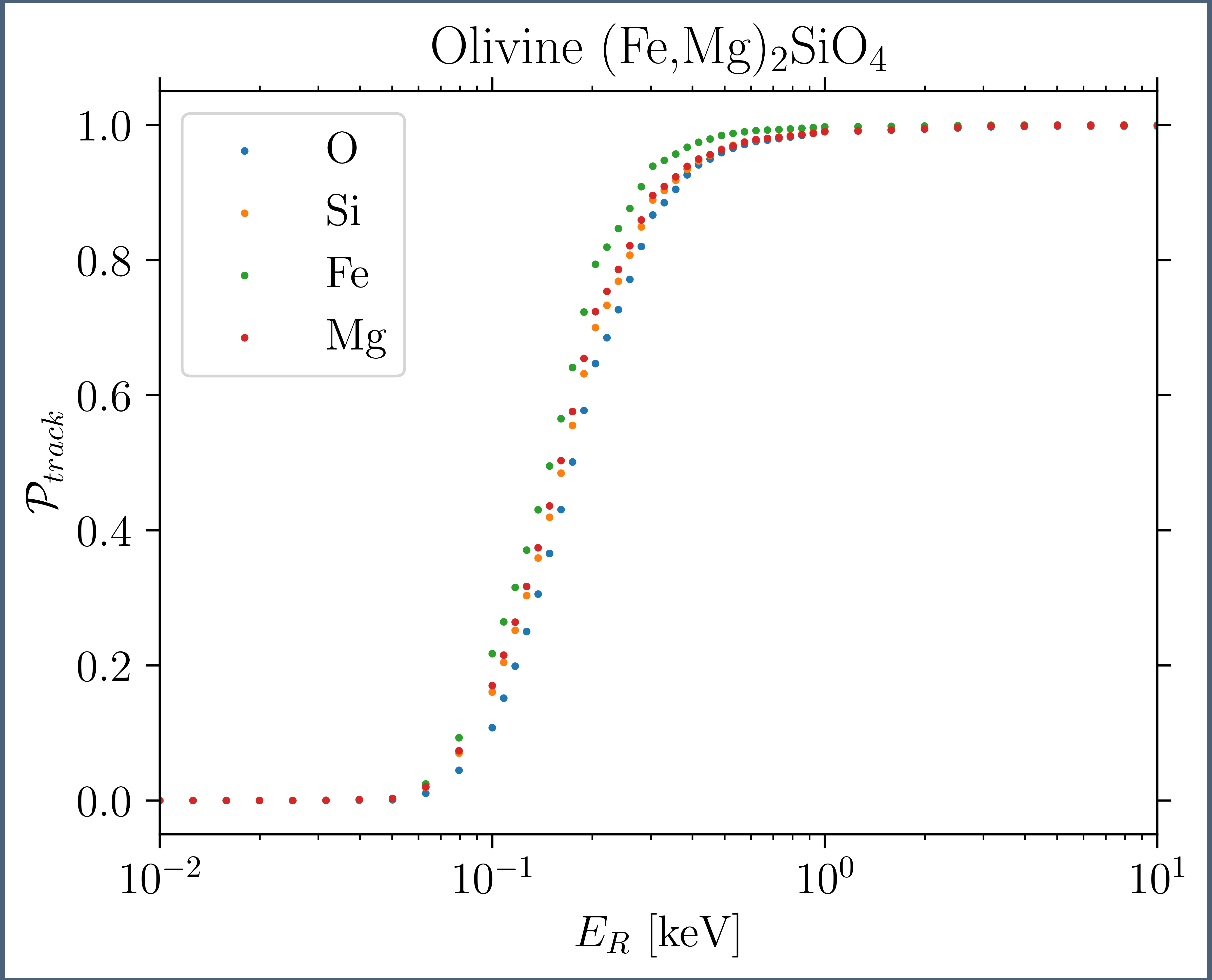


Track length distribution $\mathscr{P}_i(x \mid E_R)$

Fe in olivine $\mathbf{(Mg, Fe)_2\ SiO_4}$

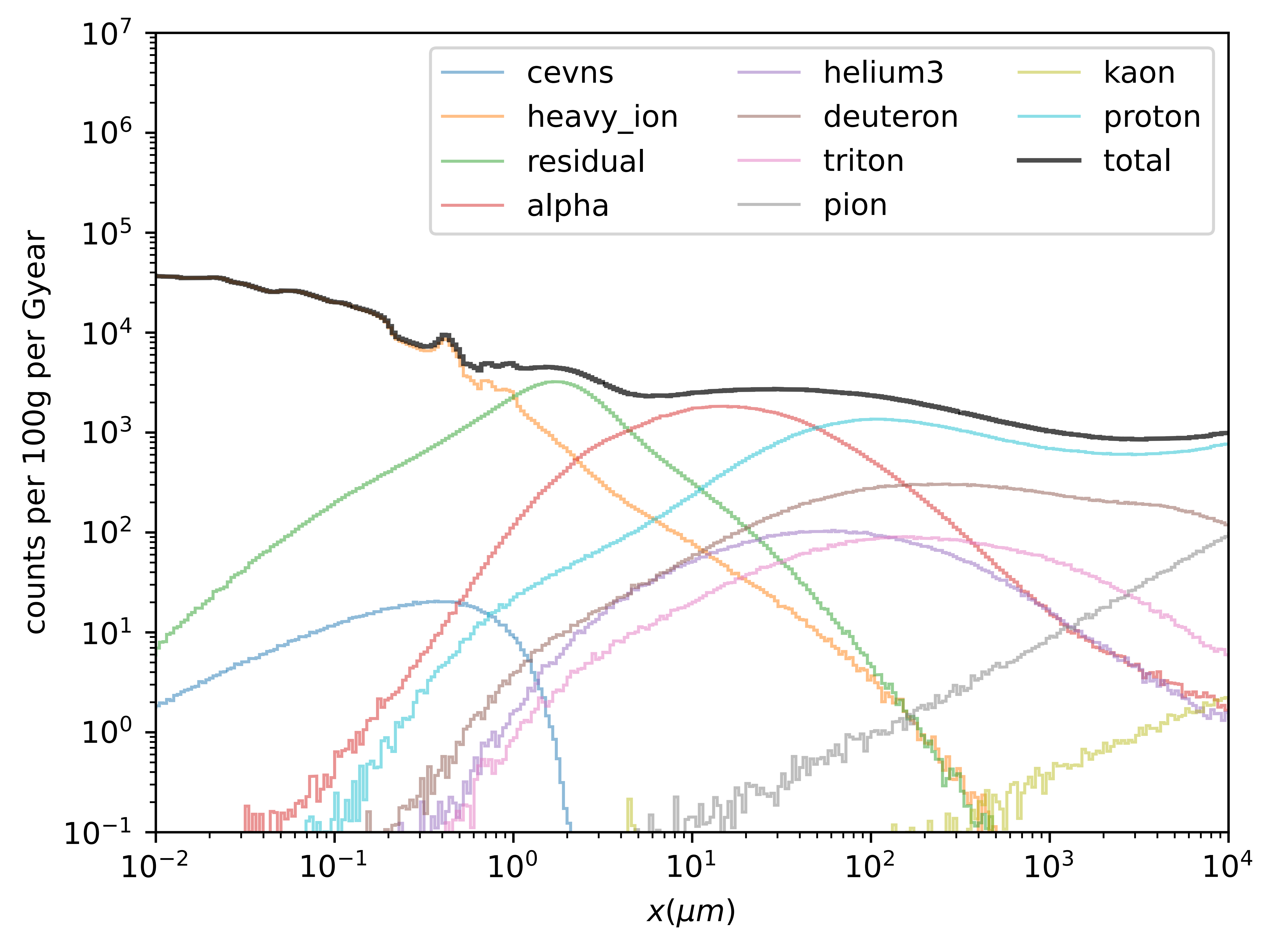


Probability of track formation $\mathscr{P}_{i,track}$



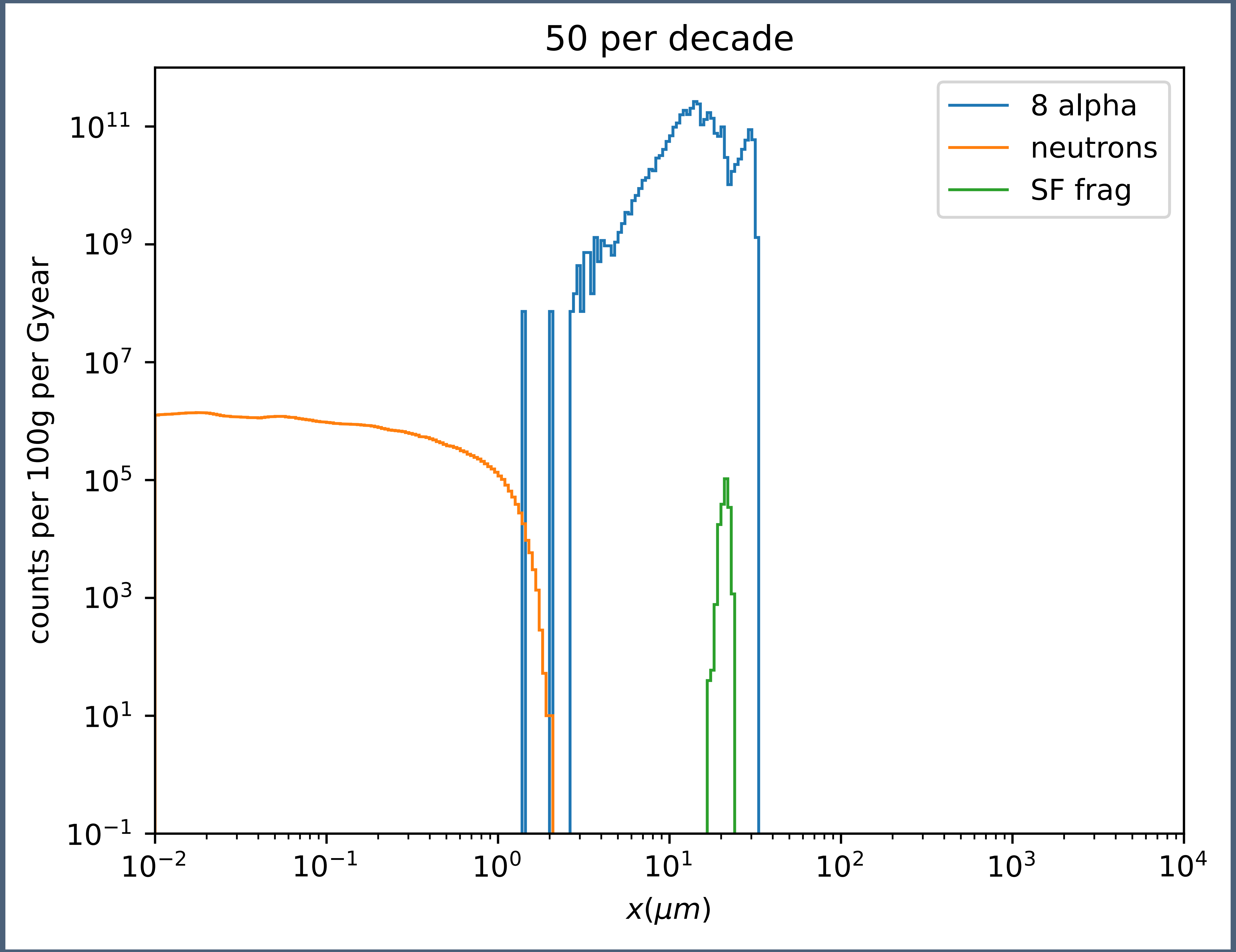
Atmospheric neutrino backgrounds

Track length distribution



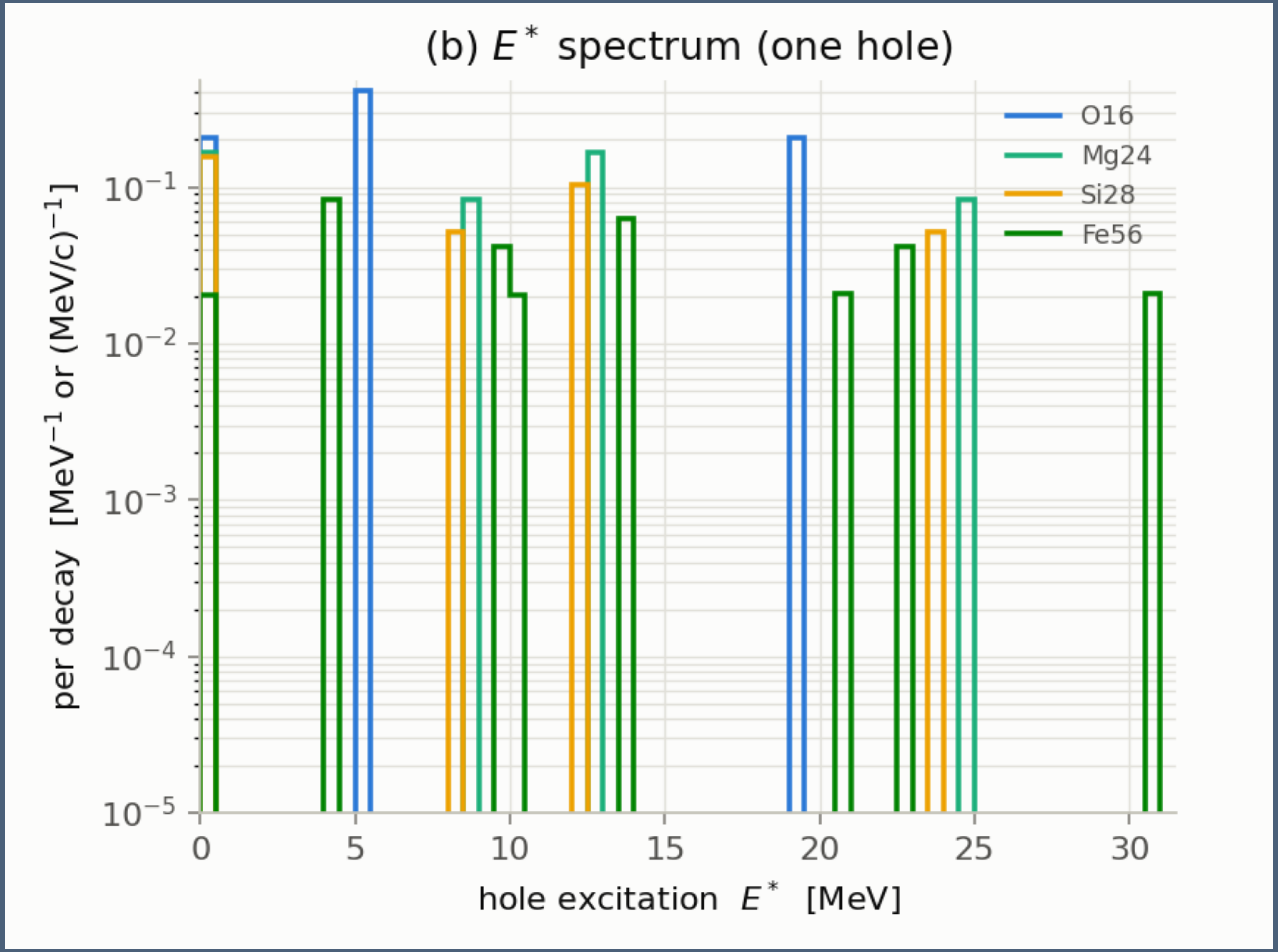
^{238}U backgrounds

Track length distribution



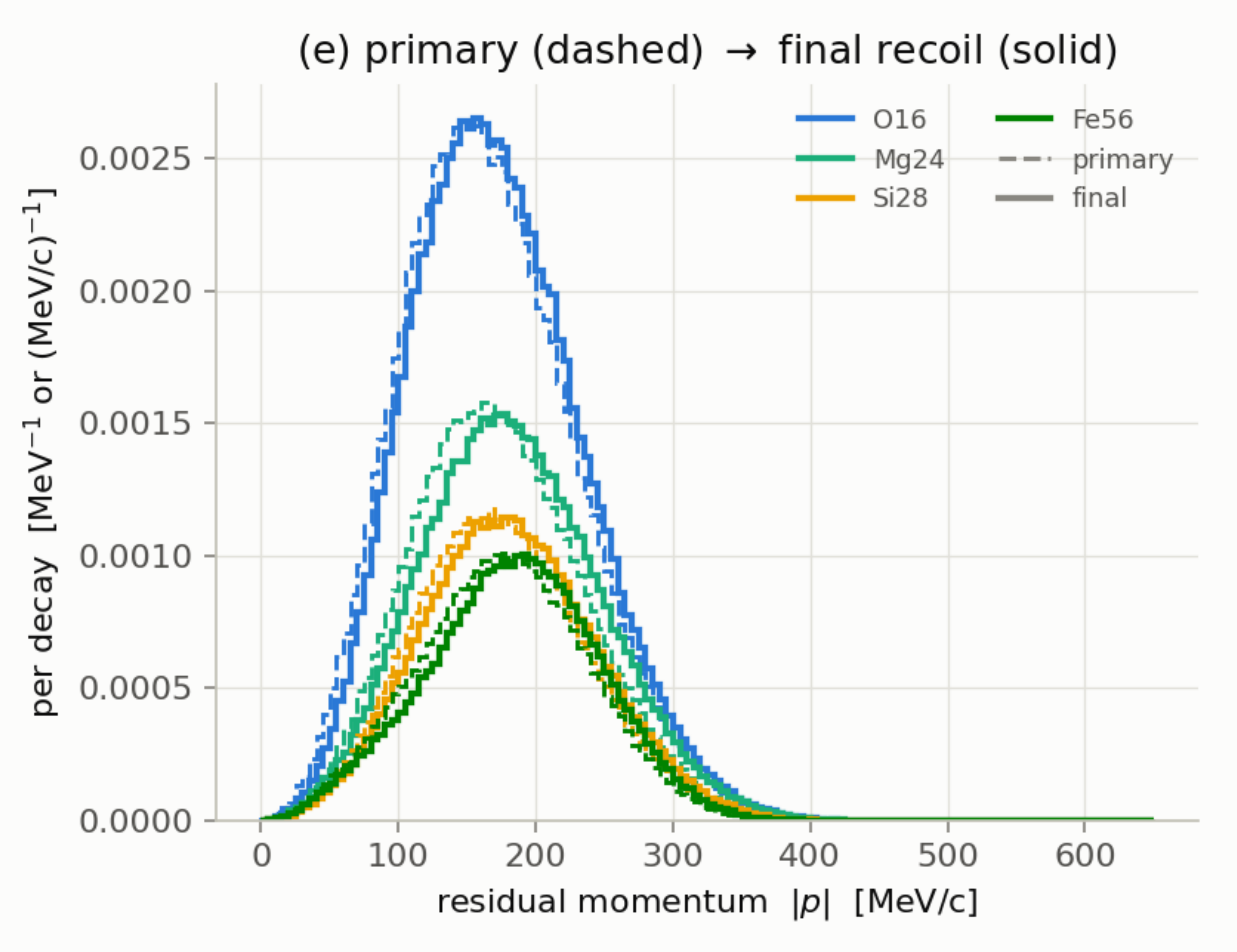
$n \to inv$

Hole excitation distribution



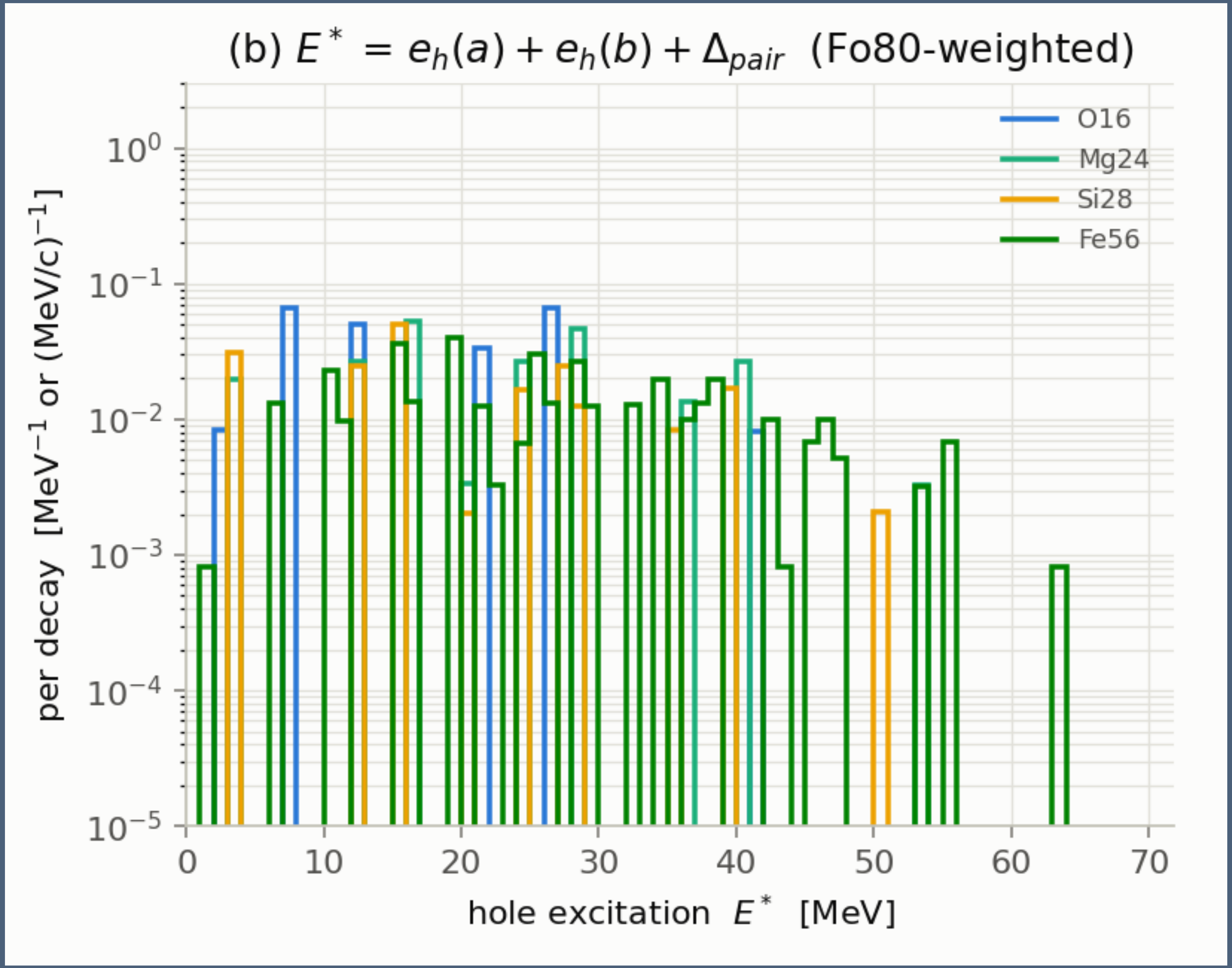
$n \to inv$

Total recoil spectra



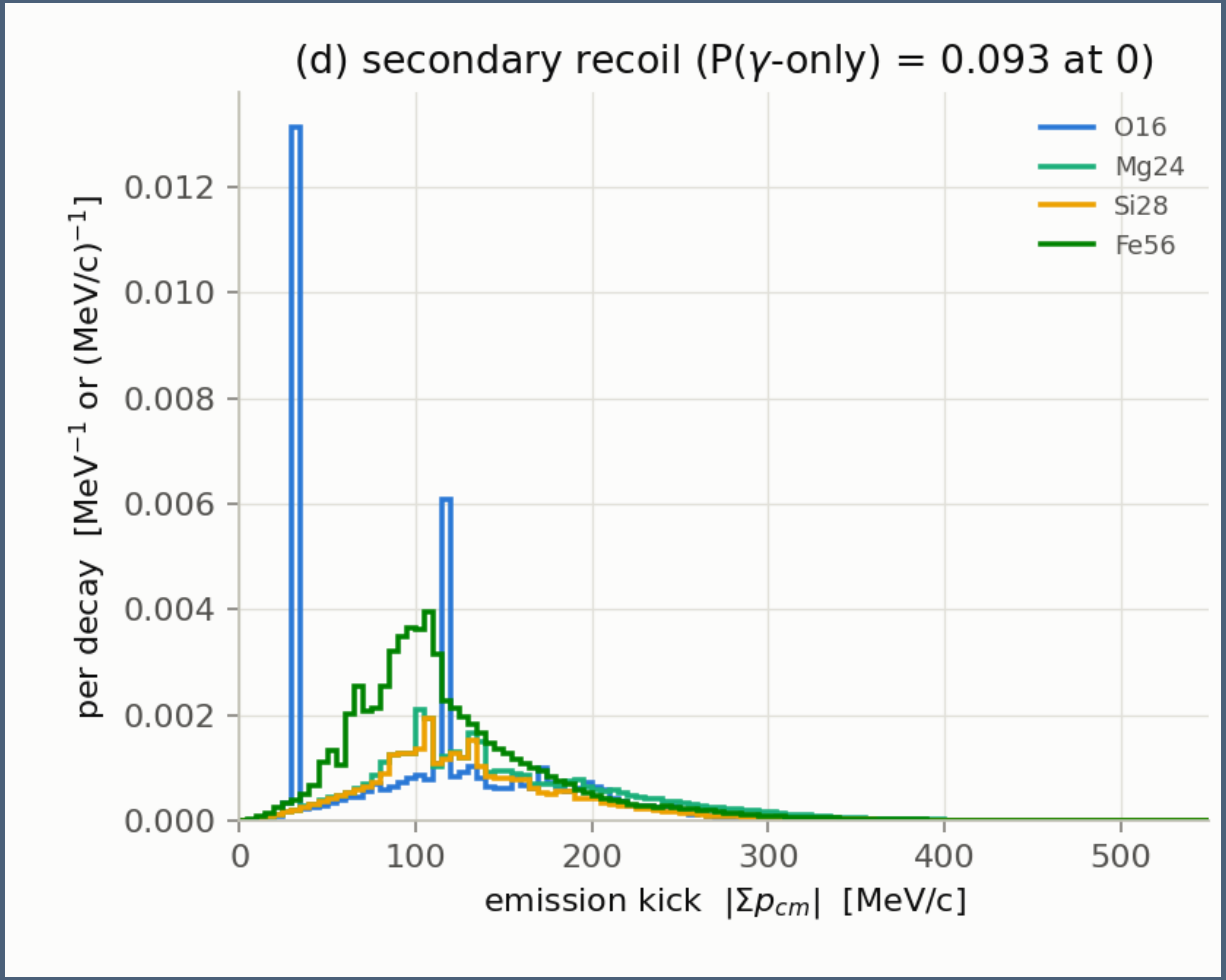
$nn \rightarrow inv$

Hole excitation distribution



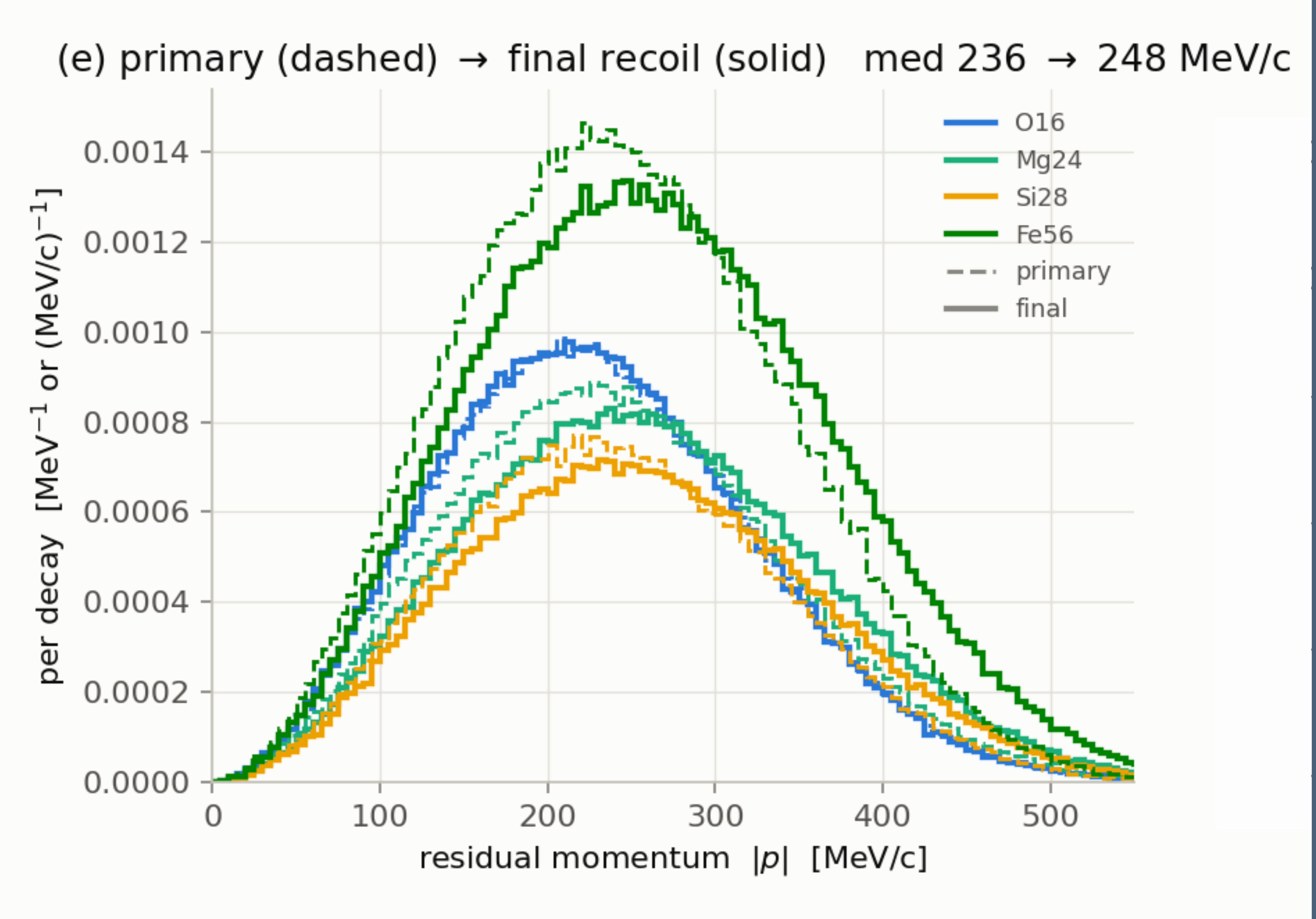
$nn \to inv$

Secondary recoil spectra



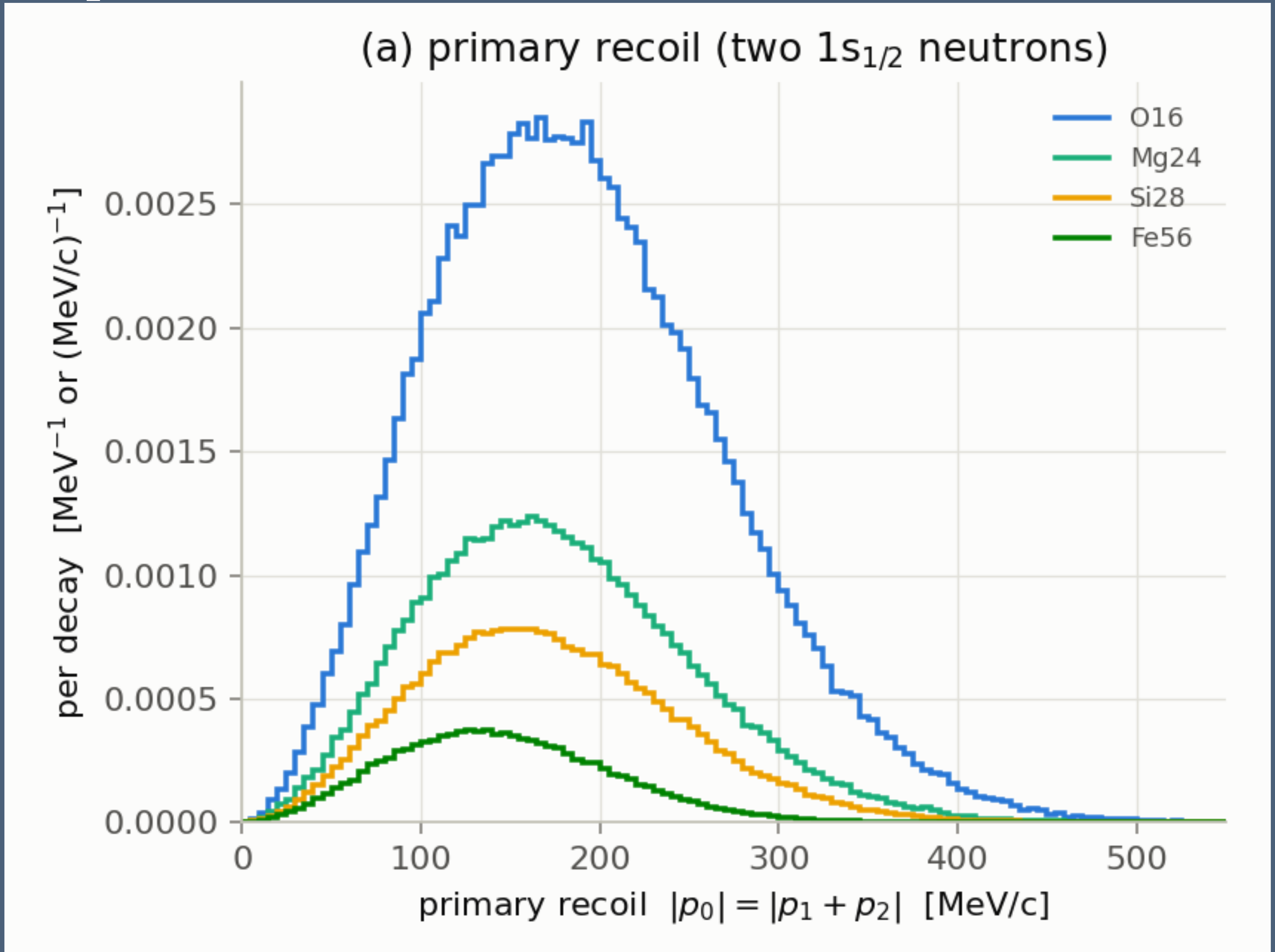
$nn \to inv$

Total recoil spectra



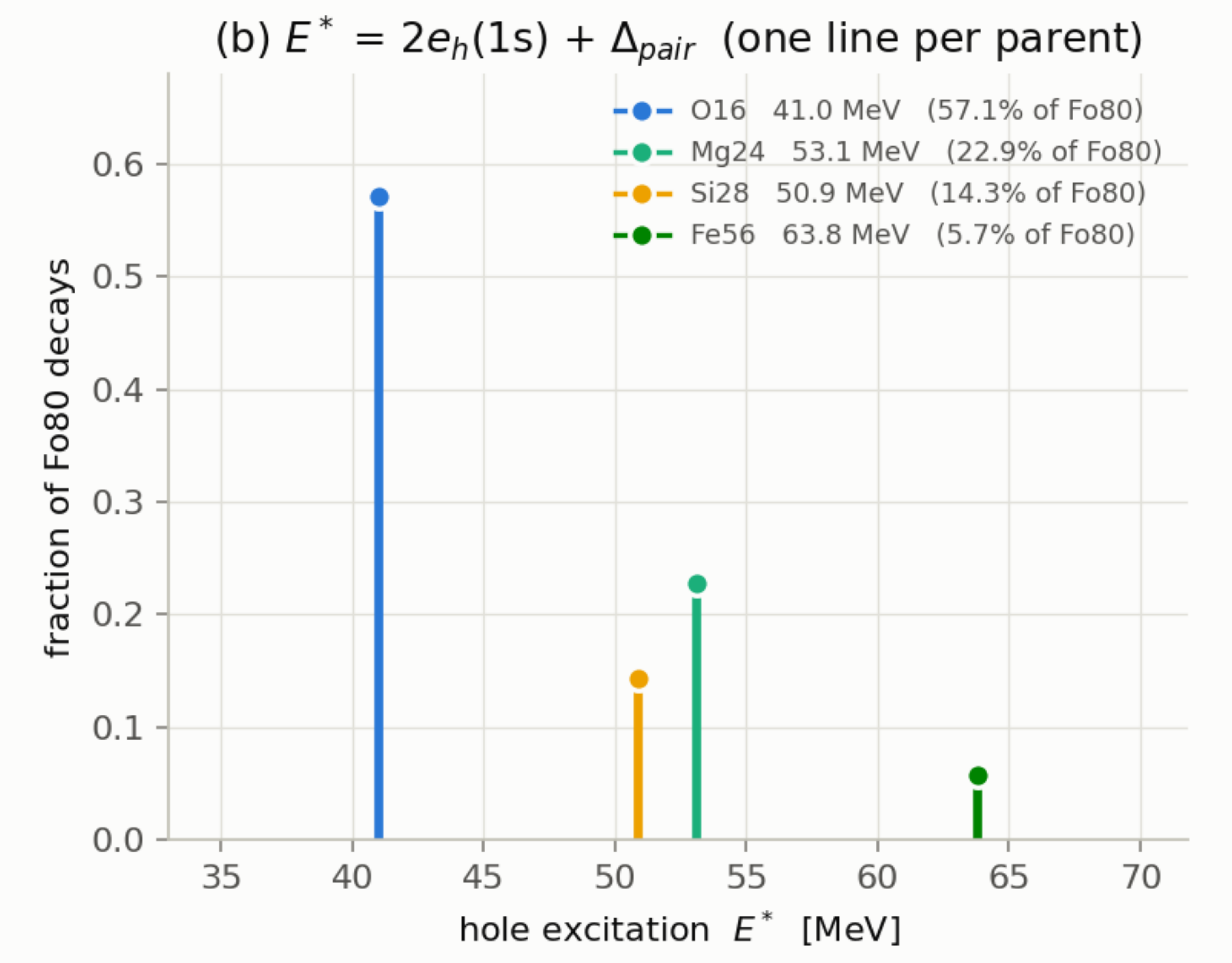
$nn \to inv$ (s-shell)

Primary recoil spectra



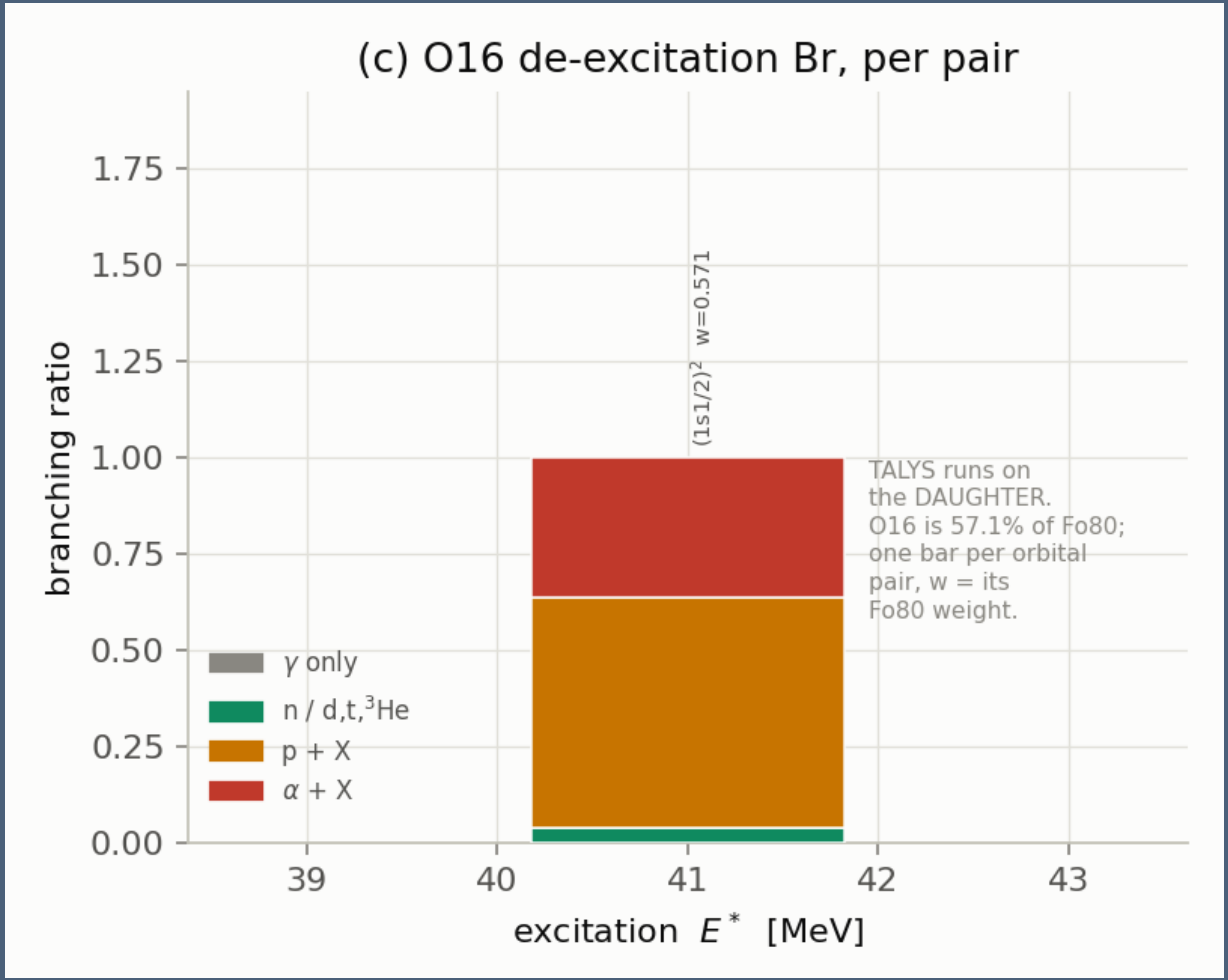
$nn \rightarrow inv$ (s-shell)

Hole excitation distribution



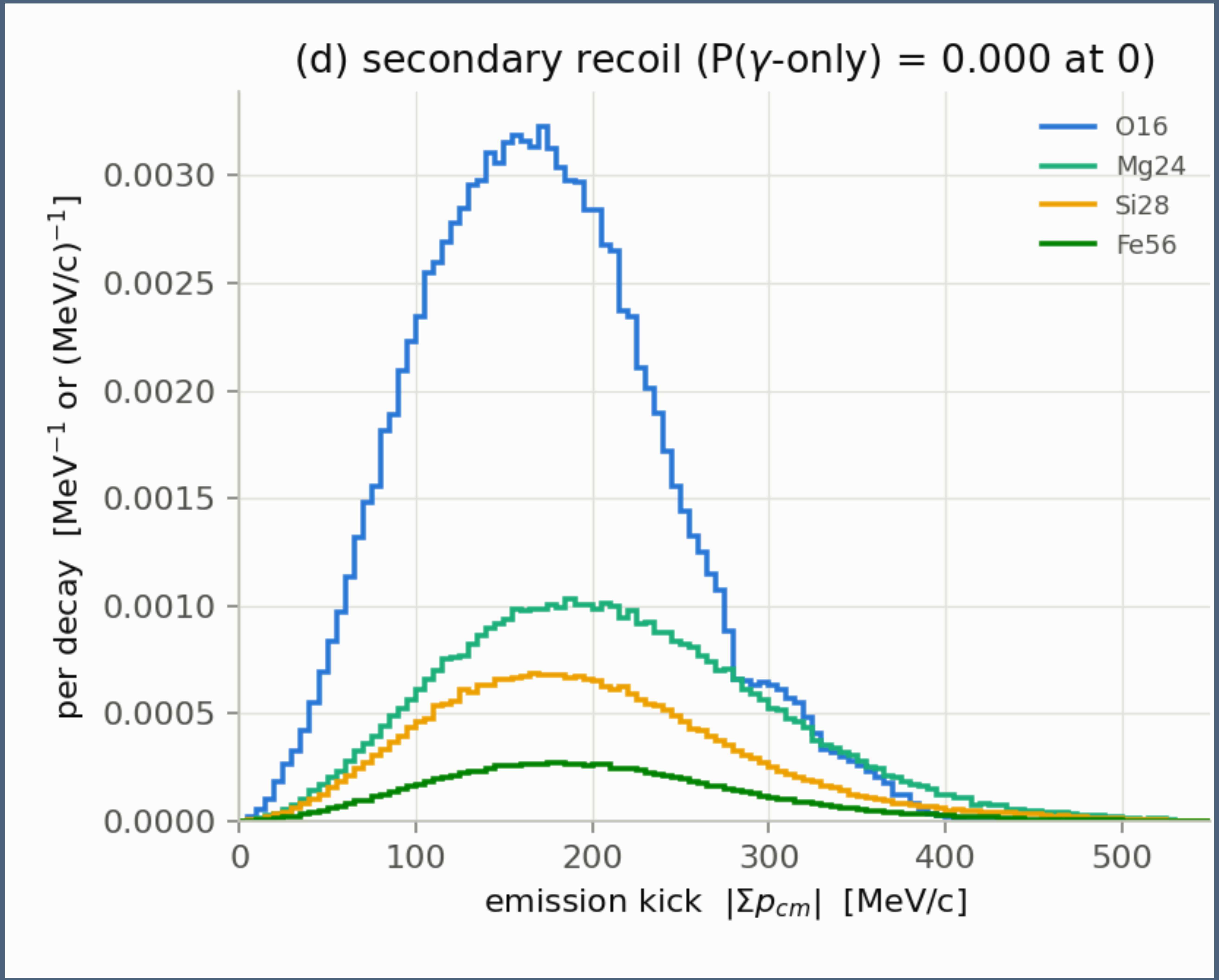
$nn \to inv$ (s-shell)

De-excitation channels



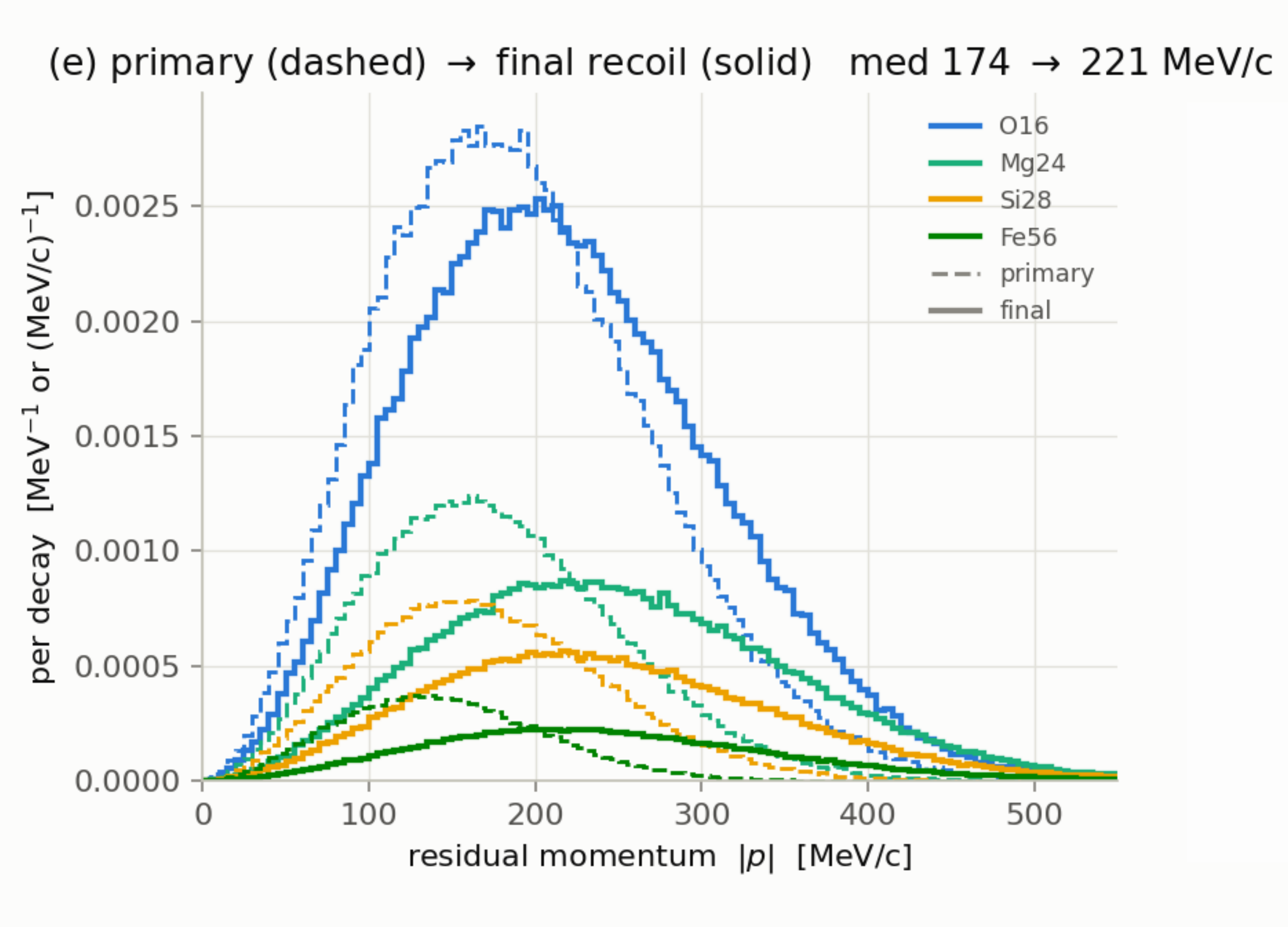
$nn \to inv$ (s-shell)

Secondary recoil spectra



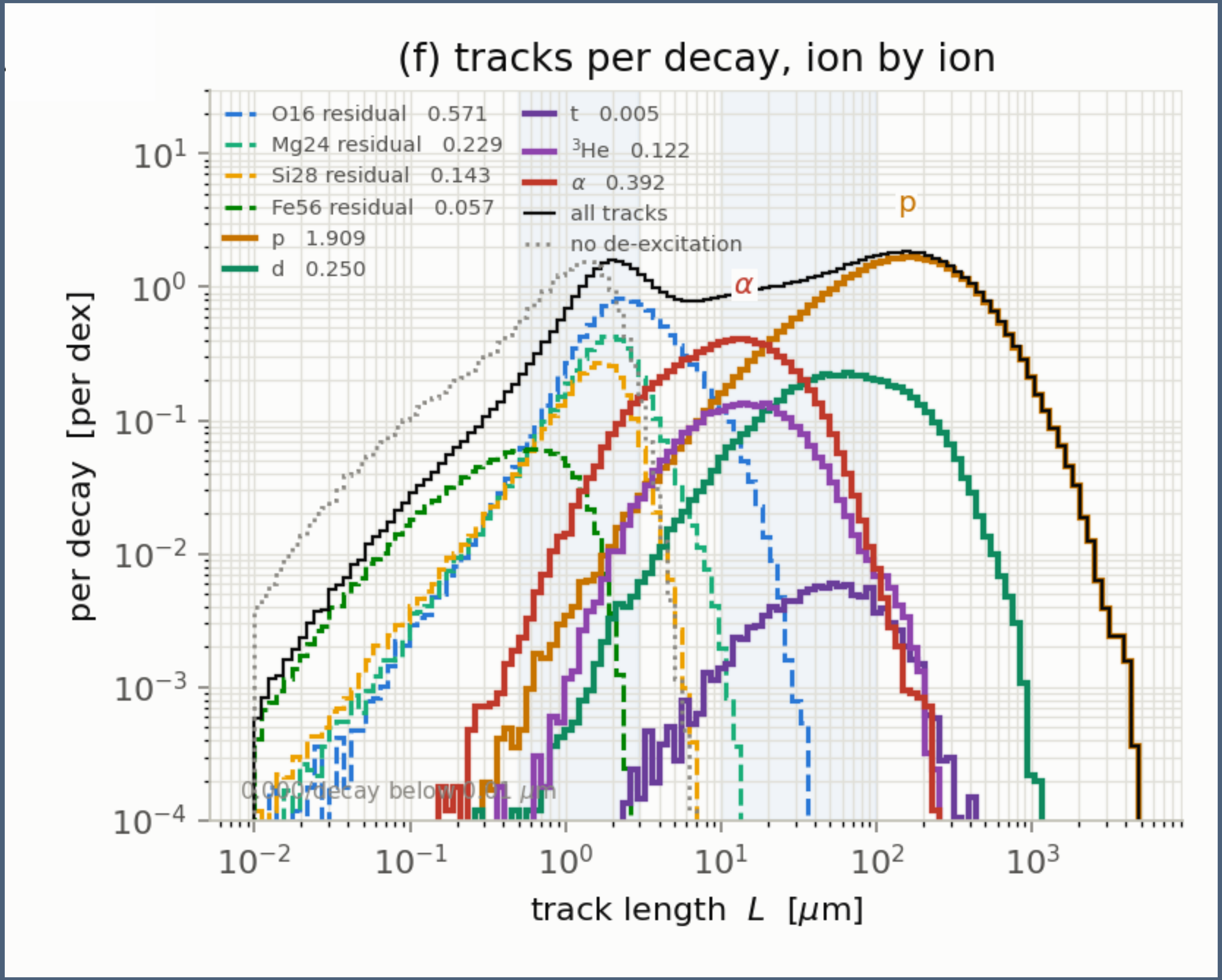
$nn \to inv$ (s-shell)

Total recoil spectra



$nn \to inv$ (s-shell)

Track length distribution



Population probabilities of hole states

Table 2. Ppop for ^{28}Si

T	I^π	**configuration**	E^* (MeV)	P_{pop}
1	0^+	$(1d_{5/2})^{-2}$	X	0.0479
1	2^+	$(1d_{5/2})^{-2}$	X	0.0547
1	4^+	$(1d_{5/2})^{-2}$	X	0.0410
1	0^+	$(1p_{1/2})^{-2}$	X	0.0250
1	0^+	$(1p_{3/2})^{-2}$	X	0.0487
1	2^+	$(1p_{1/2})^{-1}(1p_{3/2})^{-1}$	X	0.0985
1	2^+	$(1p_{3/2})^{-2}$	X	0.0487
1	1^-	$(1p_{1/2})^{-1}(1s_{1/2})^{-1}$	X	0.0587
1	1^-	$(1p_{3/2})^{-1}(1s_{1/2})^{-1}$	X	0.113
1	0^+	$(1s_{1/2})^{-2}$	X	0.0515
1	2^-	$(1d_{5/2})^{-1}(1p_{1/2})^{-1}$	X	0.0
1	3^-	$(1d_{5/2})^{-1}(1p_{1/2})^{-1}$	X	0.106
1	1^-	$(1d_{5/2})^{-1}(1p_{3/2})^{-1}$	X	0.128
1	2^-	$(1d_{5/2})^{-1}(1p_{3/2})^{-1}$	X	0.0
1	3^-	$(1d_{5/2})^{-1}(1p_{3/2})^{-1}$	X	0.0852
1	4^-	$(1d_{5/2})^{-1}(1p_{3/2})^{-1}$	X	0.0
1	2^+	$(1d_{5/2})^{-1}(1s_{1/2})^{-1}$	X	0.0932
1	3^+	$(1d_{5/2})^{-1}(1s_{1/2})^{-1}$	X	0.0

All invisible channels listed

Single neutron

Channel	$\|\Delta(B-L)\|$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$n \to e^- + \pi^+$	2	65 [51] (5300* [44])
$n \to e^- + \rho^+$	2	62 [51] (217* [46])
$n \to e^- + K^+$	2	32 [52]
$n \to e^- + K^{*,+}$	2	
$n \to e^+ + \pi^-$	0	5300 [44]
$n \to e^+ + \rho^-$	0	217 [46]
$n \to e^+ + K^-$	0	17 [46]
$n \to e^+ + K^{*,-}$	0	
$n \to \mu^- + \pi^+$	2	49 [51] (3500* [44])

Channel	$\|\Delta(B-L)\|$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$n \to \mu^- + \rho^+$	2	7 [51] (228* [46])
$n \to \mu^- + K^+$	2	57 [52]
$n \to \mu^+ + \pi^-$	0	3500 [44]
$n \to \mu^+ + \rho^-$	0	228 [46]
$n \to \mu^+ + K^-$	0	26 [46]
$n \to \nu + \gamma$	0,2	550 [28]
$n \to \nu + \pi^0$	0,2	1100 [48]
$n \to \nu + \eta$	0,2	158 [46]
$n \to \nu + \rho^0$	0,2	19 [51]
$n \to \nu + \omega$	0,2	108 [46]
$n \to \nu + K^0$	0,2	130 [45]
$n \to \nu + K^{*,0}$	0,2	78 [46]

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.101.015005

All invisible channels listed

Single neutron

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$n \to e^- + \pi^+$	2	65 [51] (5300* [44])
$n \to e^- + \rho^+$	2	62 [51] (217* [46])
$n \to e^- + K^+$	2	32 [52]
$n \to e^- + K^{*,+}$	2	
$n \to e^+ + \pi^-$	0	5300 [44]
$n \to e^+ + \rho^-$	0	217 [46]
$n \to e^+ + K^-$	0	17 [46]
$n \to e^+ + K^{*,-}$	0	

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$n \to \mu^- + \pi^+$	2	49 [51] (3500* [44])
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$n \to \nu + \omega$	0,2	108 [46]
$n \to \nu + K^0$	0,2	130 [45]
$n \to \nu + K^{*,0}$	0,2	78 [46]

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.101.015005

All invisible channels listed

Single neutron two-body decays

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$n \to e^- + \pi^+$	2	65 [51] (5300* [44])
$n \to e^- + \rho^+$	2	62 [51] (217* [46])
$n \to e^- + K^+$	2	32 [52]
$n \to e^- + K^{*,+}$	2	
$n \to e^+ + \pi^-$	0	5300 [44]
$n \to e^+ + \rho^-$	0	217 [46]
$n \to e^+ + K^-$	0	17 [46]
$n \to e^+ + K^{*,-}$	0	

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$n \to \mu^- + \pi^+$	2	49 [51] (3500* [44])
$n \to \mu^- + \rho^+$	2	7 [51] (228* [46])
$n \to \mu^- + K^+$	2	57 [52]
$n \to \mu^+ + \pi^-$	0	3500 [44]
$n \to \mu^+ + \rho^-$	0	228 [46]
$n \to \mu^+ + K^-$	0	26 [46]
$n \to \nu + \gamma$	0,2	550 [28]
$n \to \nu + \pi^0$	0,2	1100 [48]
$n \to \nu + \eta$	0,2	158 [46]
$n \to \nu + \rho^0$	0,2	19 [51]
$n \to \nu + \omega$	0,2	108 [46]
$n \to \nu + K^0$	0,2	130 [45]
$n \to \nu + K^{*,0}$	0,2	78 [46]

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.101.015005

All invisible channels listed

Single neutron three-body decays

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [46]
$n \to \nu + e^- + \mu^+$	0,2	83 [46]
$n \to \nu + e^+ + \mu^-$	0,2	83* [46]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [46]
$n \to 3\nu$	0,2,4	0.58 [83]
$n \to e^- + \pi^+ + \pi^0$	2	29 [52] (52* [46])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [46]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [82]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	

TABLE III. Same as Table II, but for neutron decays.

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [46]
$n \to \nu + e^- + \mu^+$	0,2	83 [46]
$n \to \nu + e^+ + \mu^-$	0,2	83* [46]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [46]
$n \to 3\nu$	0,2,4	0.58 [83]
$n \to e^- + \pi^+ + \pi^0$	2	29 [52] (52* [46])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [46]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [82]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	
$n \to \mu^- + \pi^+ + \pi^0$	2	34 [52] (74* [46])
$n \to \mu^- + \pi^+ + \eta$	2	
$n \to \mu^- + \pi^+ + K^0$	2	
$n \to \mu^- + K^+ + \pi^0$	2	
$n \to \mu^+ + \pi^- + \pi^0$	0	74 [46]
$n \to \mu^+ + \pi^- + \eta$	0	
$n \to \mu^+ + \pi^- + K^0$	0	
$n \to \mu^+ + K^- + \pi^0$	0	
$n \to \nu + 2\gamma$	0,2	219 [46]
$n \to \nu + \pi^- + \pi^+$	0,2	
$n \to \nu + \rho^- + \pi^+$	0,2	
$n \to \nu + K^- + \pi^+$	0,2	
$n \to \nu + \pi^- + \rho^+$	0,2	
$n \to \nu + \pi^- + K^+$	0,2	
$n \to \nu + 2\pi^0$	0,2	
$n \to \nu + \pi^0 + \eta$	0,2	
$n \to \nu + \pi^0 + \rho^0$	0,2	
$n \to \nu + \pi^0 + \omega$	0,2	
$n \to \nu + \pi^0 + K^0$	0,2	

Channel $\lvert\Delta(B-L)\rvert$ $\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
34 [52] (74* [46])
74 [46]
219 [46]

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.101.015005

All invisible channels listed

Di-neutron decay

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$nn \to e^+ + e^-$	2	4200 [43]
$nn \to e^+ + \mu^-$	2	4400 [43]
$nn \to \mu^+ + e^-$	2	4400 [43]
$nn \to \mu^+ + \mu^-$	2	4400 [43]
$nn \to e^+ + \tau^-$	2	
$nn \to \tau^+ + e^-$	2	
$nn \to 2\nu$	0,2,4	1.4 [83]
$nn \to 2\gamma$	2	4100 [43]
$nn \to \gamma + \pi^0$	2	
$nn \to \gamma + \eta$	2	
$nn \to \gamma + \rho^0$	2	
$nn \to \gamma + \omega$	2	
$nn \to \gamma + \eta'$	2	
$nn \to \gamma + K^0$	2	
$nn \to \gamma + K^{*,0}$	2	
$nn \to \gamma + D^0$	2	
$nn \to \gamma + \phi$	2	
$nn \to \pi^- + \pi^+$	2	0.7 [52] (72* [115])

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$nn \to \pi^+ + \rho^-$	2	
$nn \to K^- + \pi^+$	2	
$nn \to K^{*,-} + \pi^+$	2	
$nn \to \pi^- + \rho^+$	2	
$nn \to K^+ + \pi^-$	2	
$nn \to K^{*,+} + \pi^-$	2	
$nn \to 2\pi^0$	2	404 [115]
$nn \to \eta + \pi^0$	2	
$nn \to \pi^0 + \rho^0$	2	
$nn \to \pi^0 + \omega$	2	
$nn \to \eta' + \pi^0$	2	
$nn \to K^0 + \pi^0$	2	
$nn \to K^{*,0} + \pi^0$	2	

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.101.015005