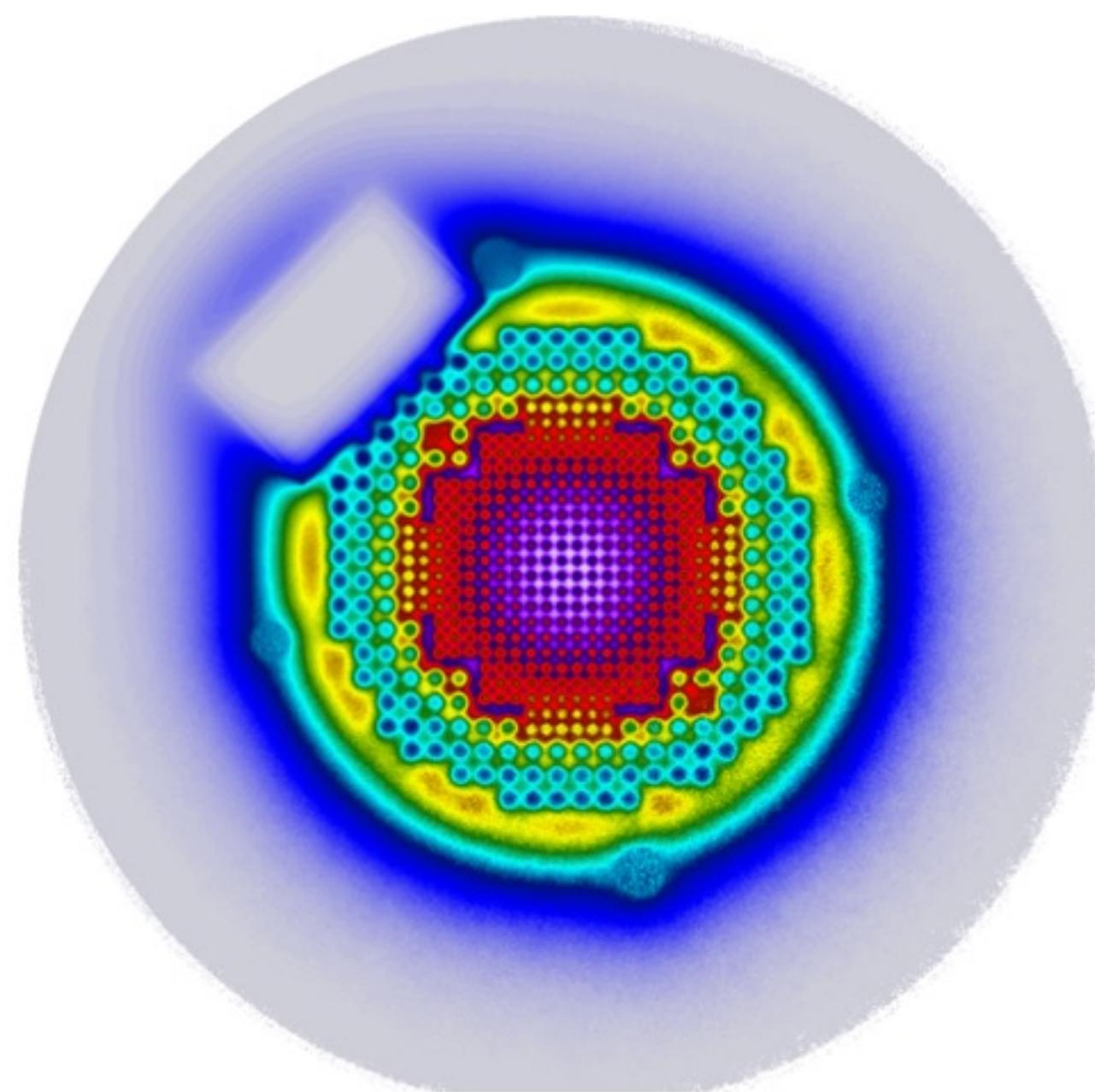


5TH INTERNATIONAL WORKSHOP ON NUCLEAR DATA EVALUATION FOR REACTOR APPLICATIONS



TOTAL MONTE CARLO ACCELERATION FOR THE PETALE EXPERIMENTAL PROGRAMME IN THE CROCUS REACTOR

Axel Laureau¹

Vincent Lamirand^{1,2}

Dimitri Rochman²

Andreas Pautz^{1,3}

*I: LRS/EPFL**

2: LRT/PSI

3: NES/PSI

*ECOLE POLYTECHNIQUE
FEDERALE DE LAUSANNE

Summary



I - Introduction

- Context: BMC for integral experiment
- PETALE exp & specific requirements

II - TMC-CS

- Correlated Sampling principle
- Correlated Sampling on Nuclear Data

III - Validation

- Reference and comparison
- k_{eff} uncertainty propagation
- Flux / dosimetry application
- Inter-dosimeter correlation

Bayesian Monte Carlo

Principle

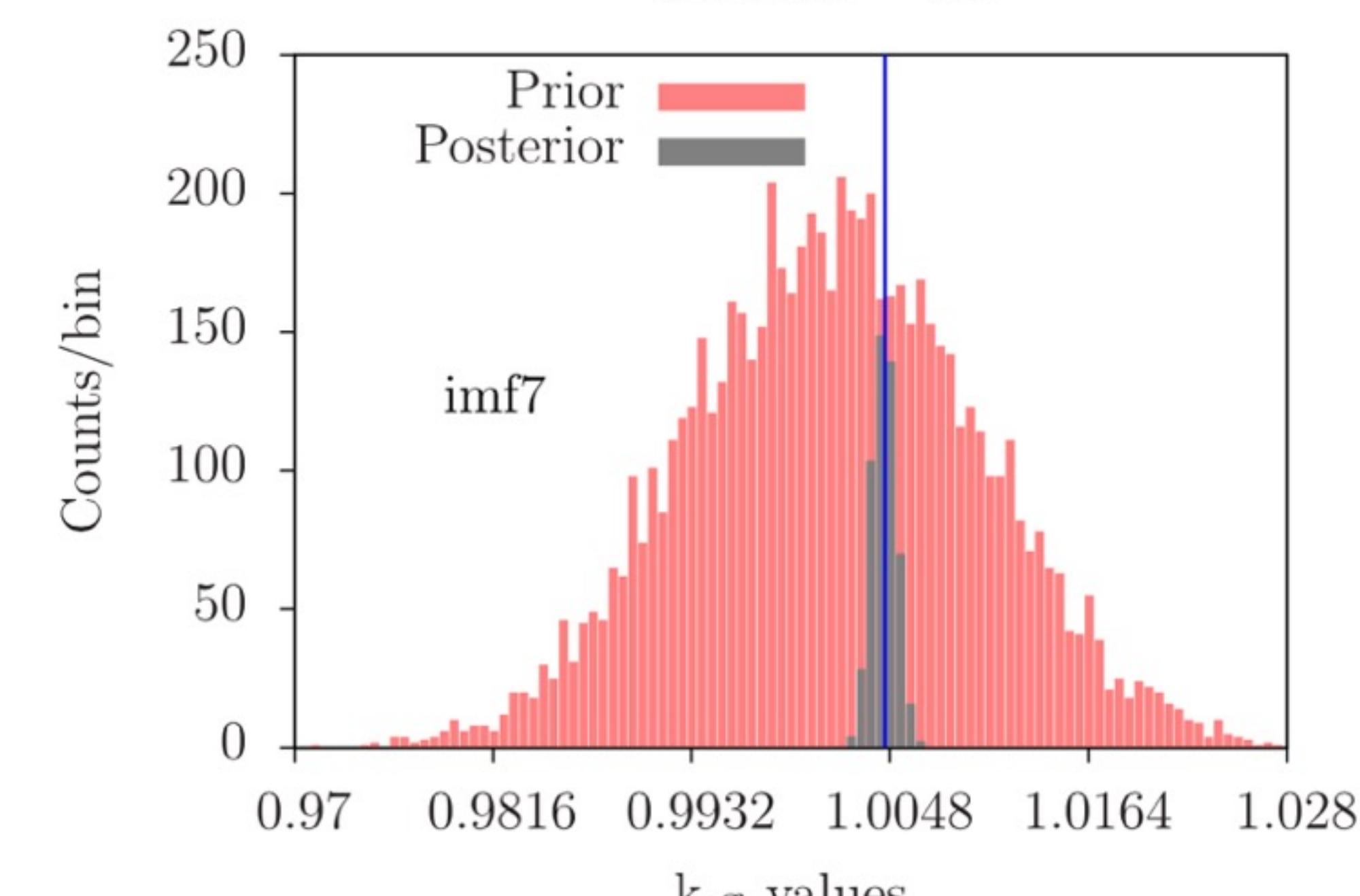
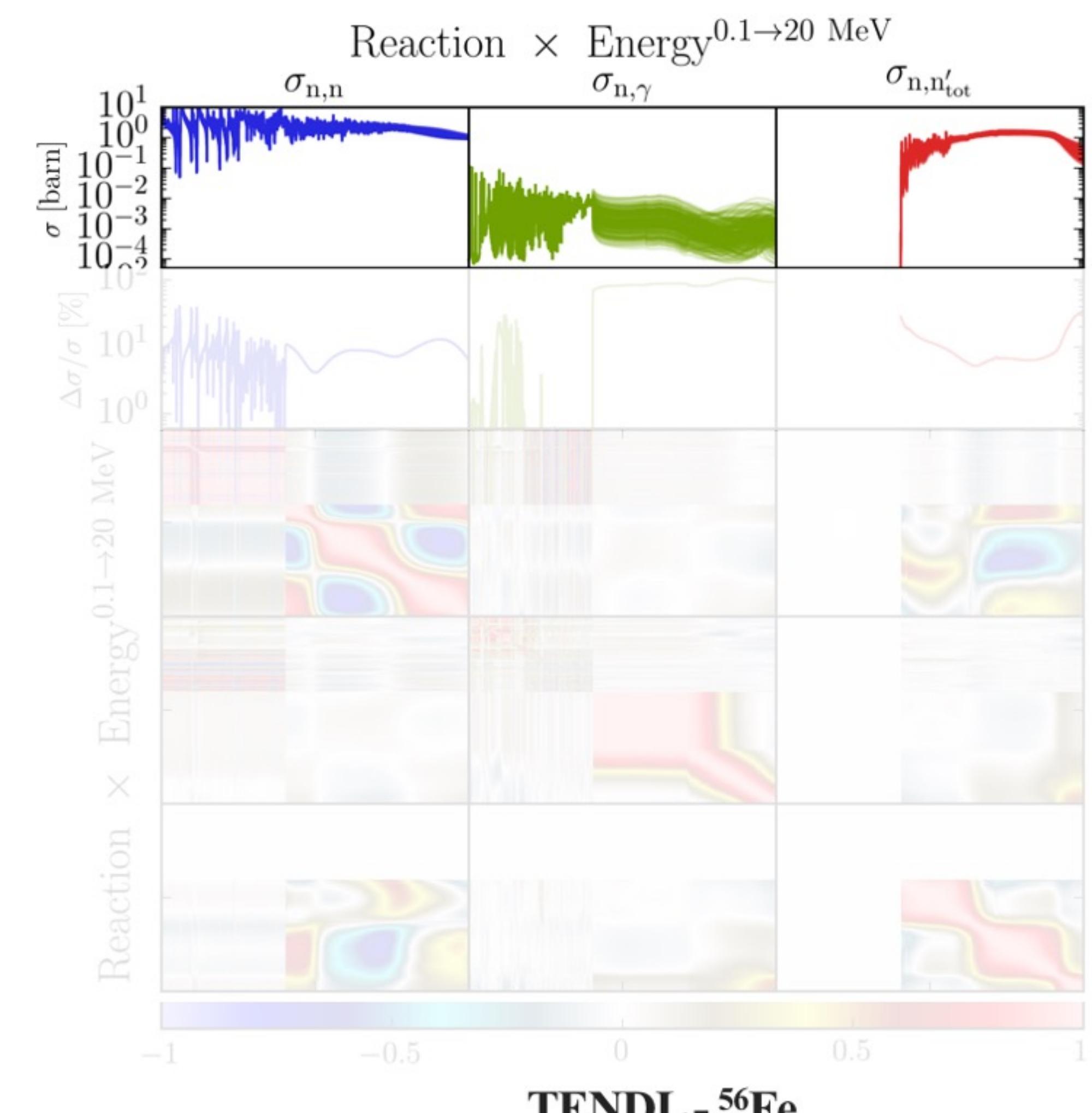
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 - *sampling on nuclear model parameters - TENDL*
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- Step 2: Total Monte Carlo (TMC) uncertainty propagation
 - *prior “C” value for each set of cross sections*
- Step 3: Comparison to experimental “E” results and XS-weighting in the BMC process
 - *reduced posterior uncertainty using* $w_x = \exp\left(-\frac{\chi^2}{2}\right)$

(some of the) Advantages

- No first order approximation
- Applicable to many kinds of observables...

(some of the) Drawbacks

- Requires one calculation per set of cross sections
- ... requires observables with a large dispersion



*[Rochman, D. A., Bauge, E., Vasiliev, A., Ferroukhi, H., & Perret, G. (2018). Nuclear data correlation between different isotopes via integral information. *EPJ Nuclear Sciences & Technologies*, 4, 7.]

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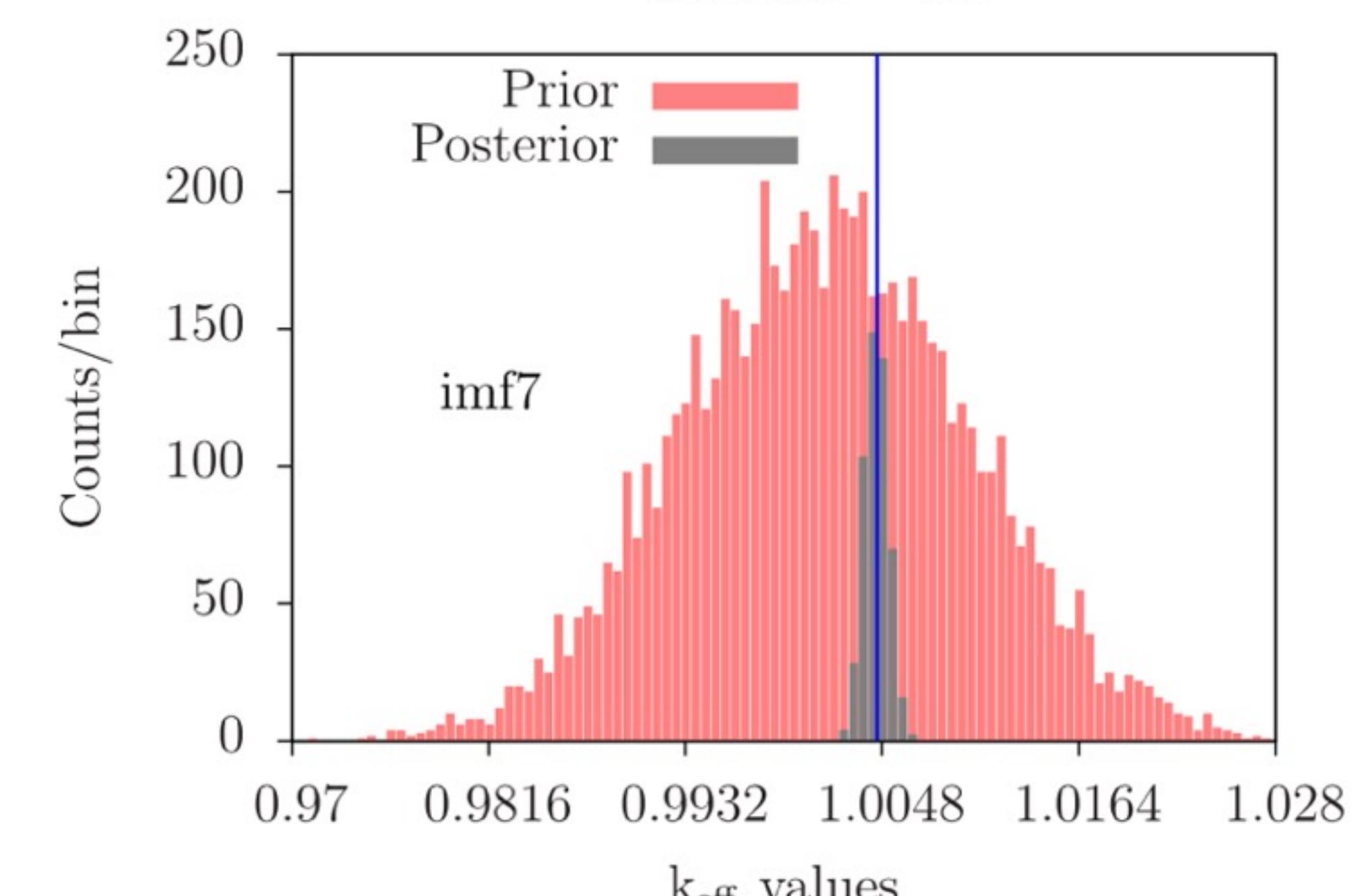
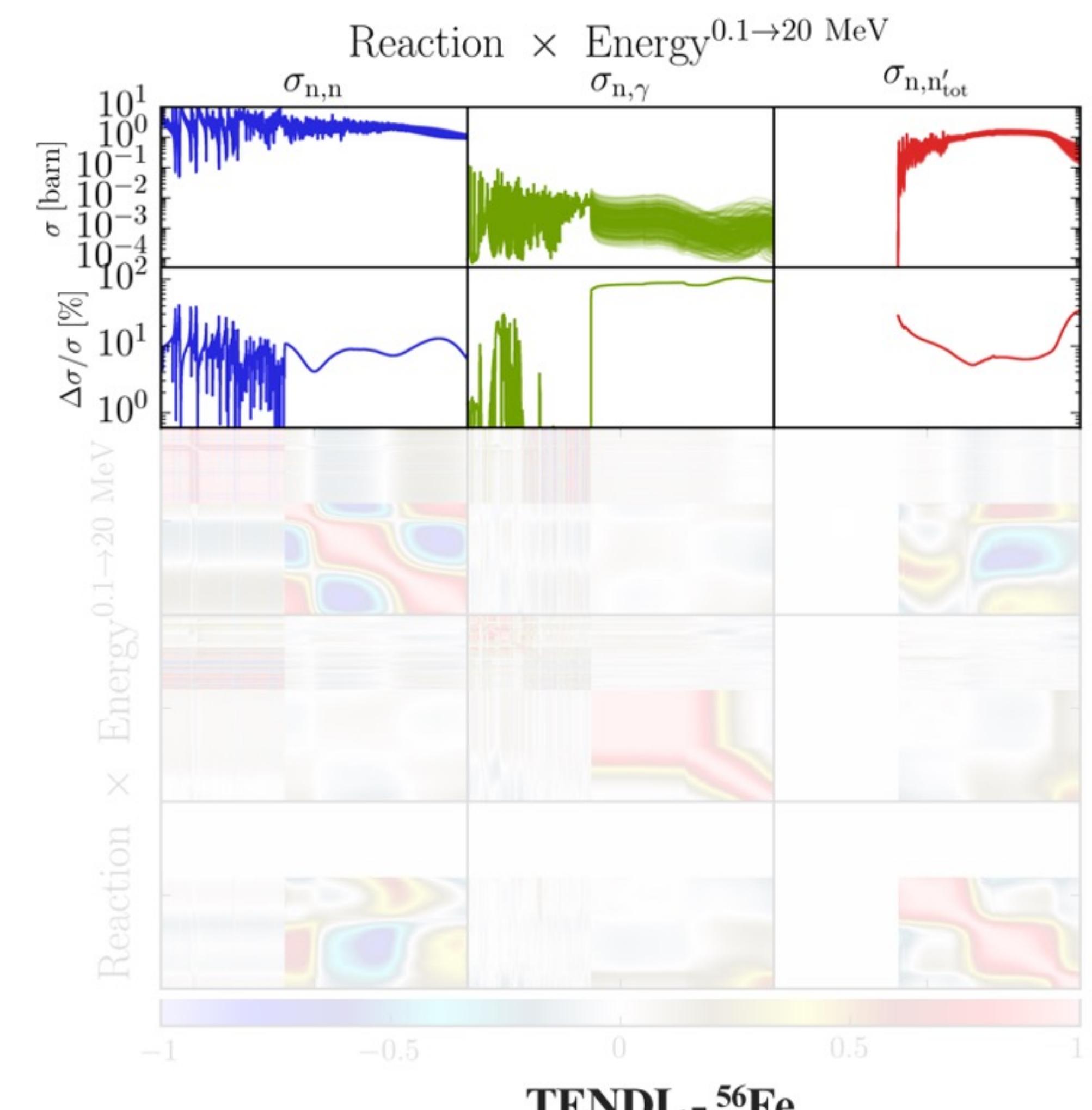
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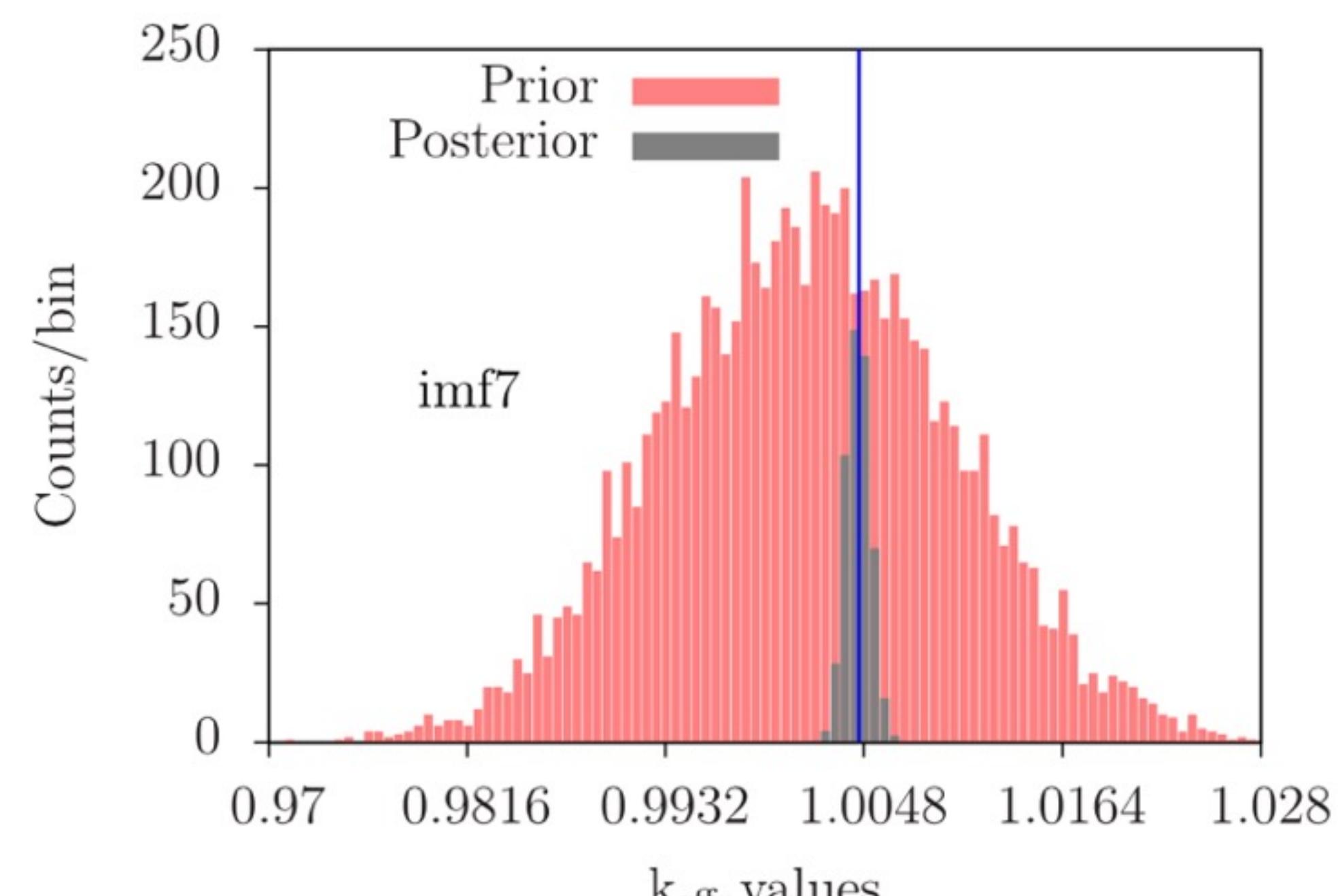
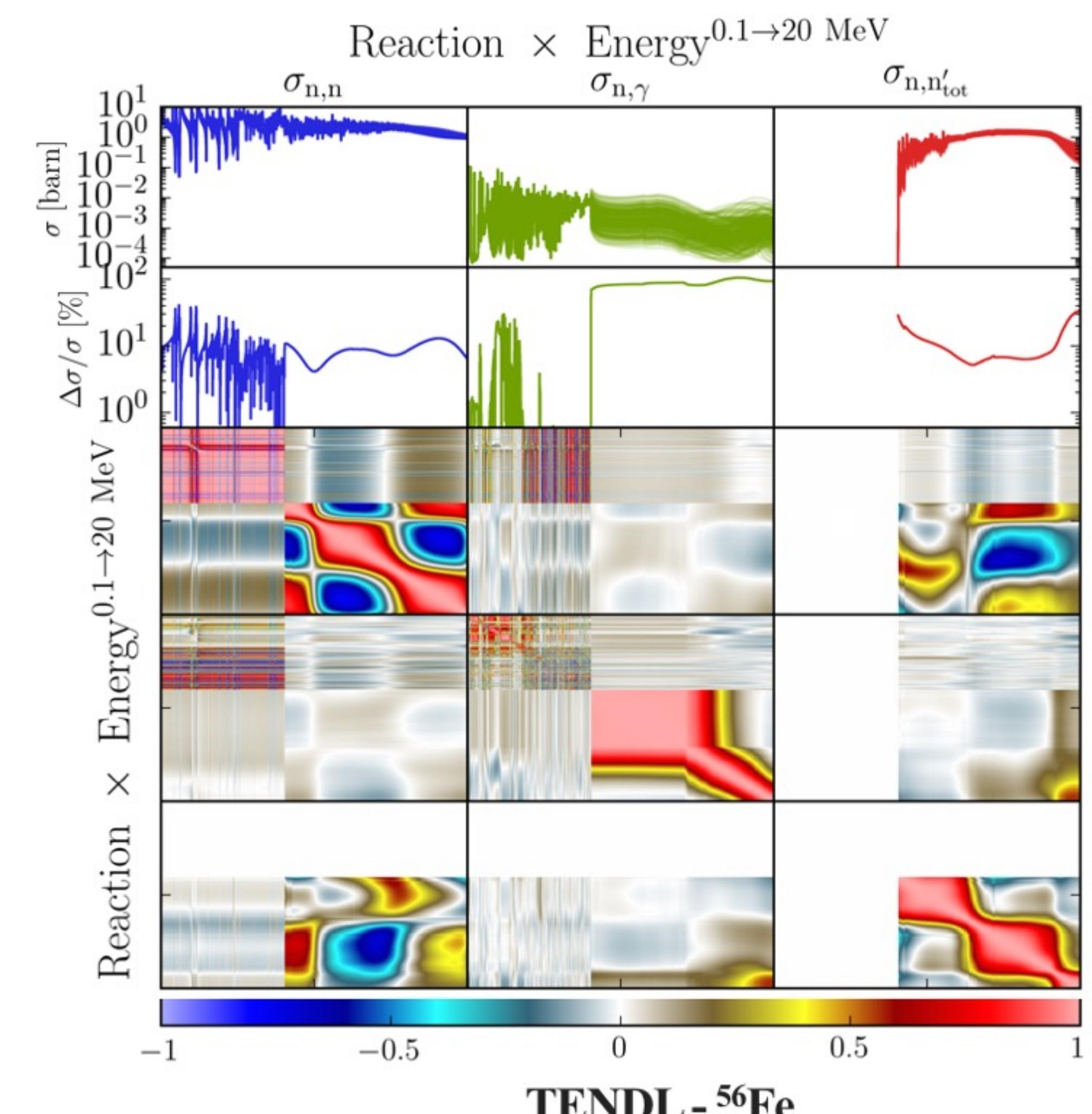
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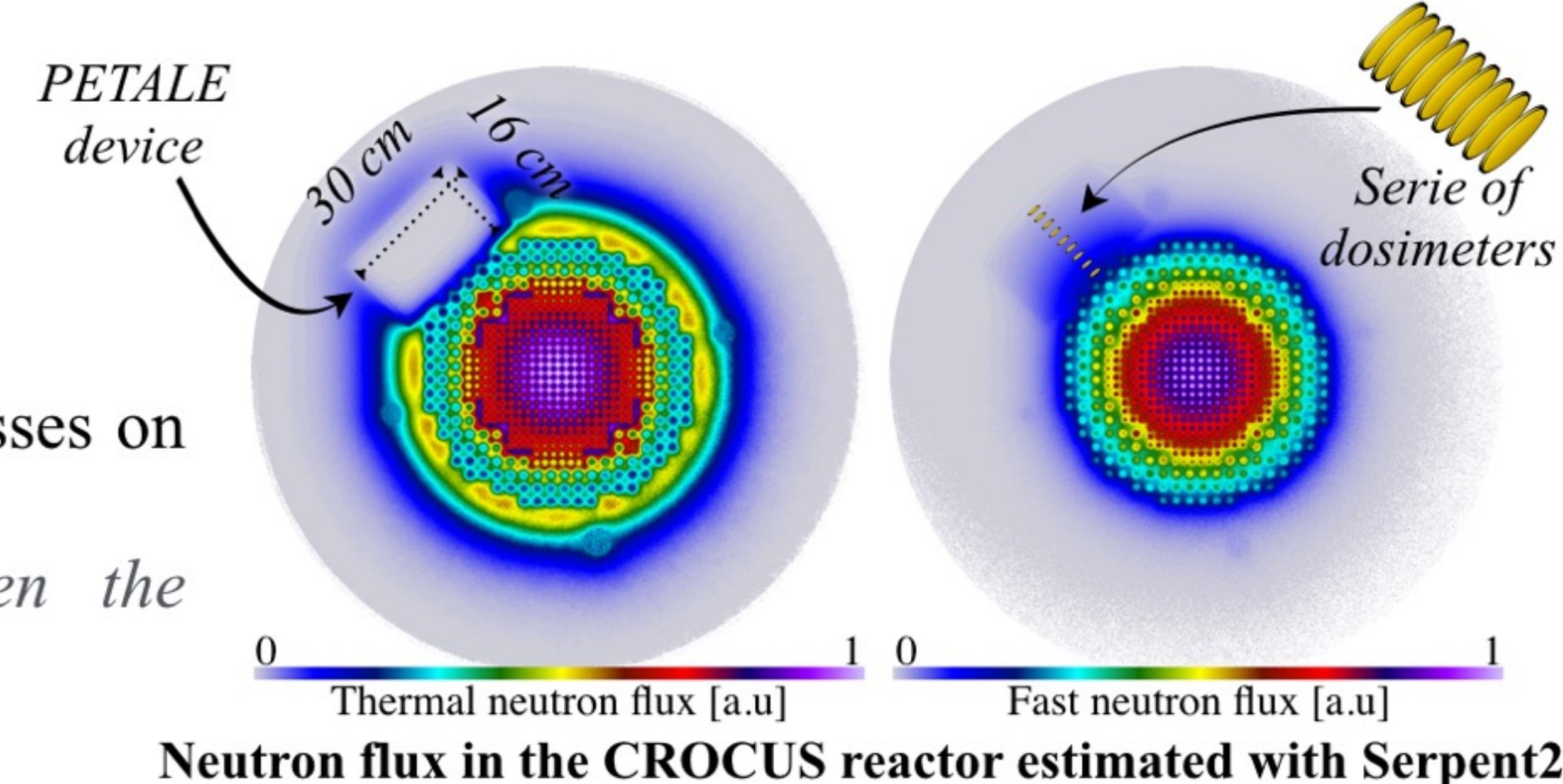
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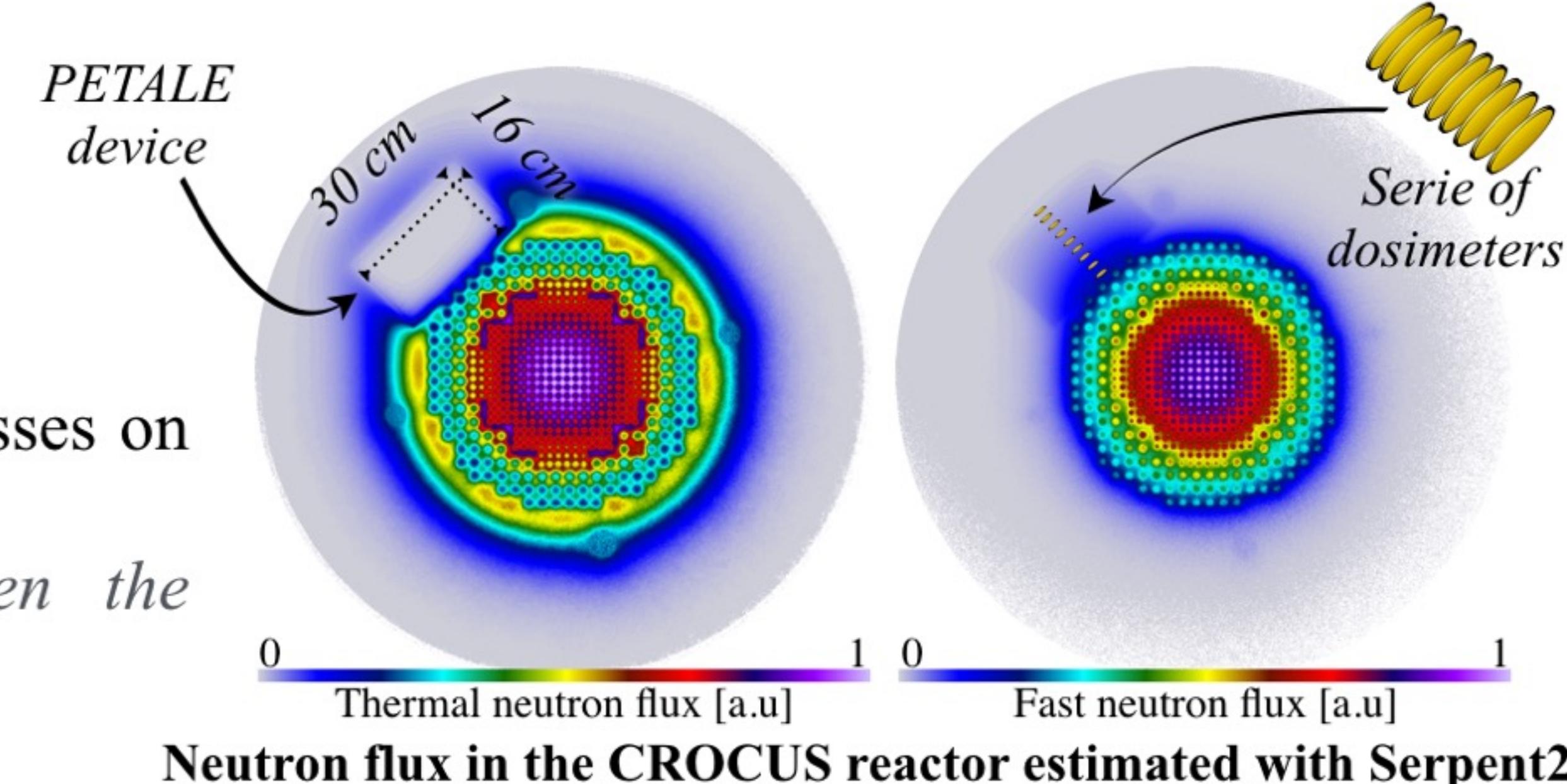
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- Heavy reflector near to the CROCUS reactor at EPFL
→ *all details in V. Lamirand's presentation!*
- Regular spacing of dosimeters in the reflector
→ $\sim \text{cm radius}$ and $\sim 0.1 \text{ mm thickness}$
- Apply a BMC (and other) nuclear data assimilation processes on the dosimeter activation
→ *progressive evolution of the reaction rate between the dosimeters*



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Challenges

- Monte Carlo modeling
Low flux (statistics) / streaming effect / dosimeter self-shielding
- Difficult classic TMC uncertainty propagation on reaction rates: $\sigma_{\text{Nuclear Data}} \sim \sigma_{\text{MC statistics}}$ and σ_{ND} estimated via Δ Monte Carlo with independent neutron histories...
- Classic CROCUS calculation: days
→ *one caculation required per random cross section!*

Additional objective of this work

- Use the TMC technics to optimise the experimental setup / organise the experimental programme
→ *several configurations have to be studied*

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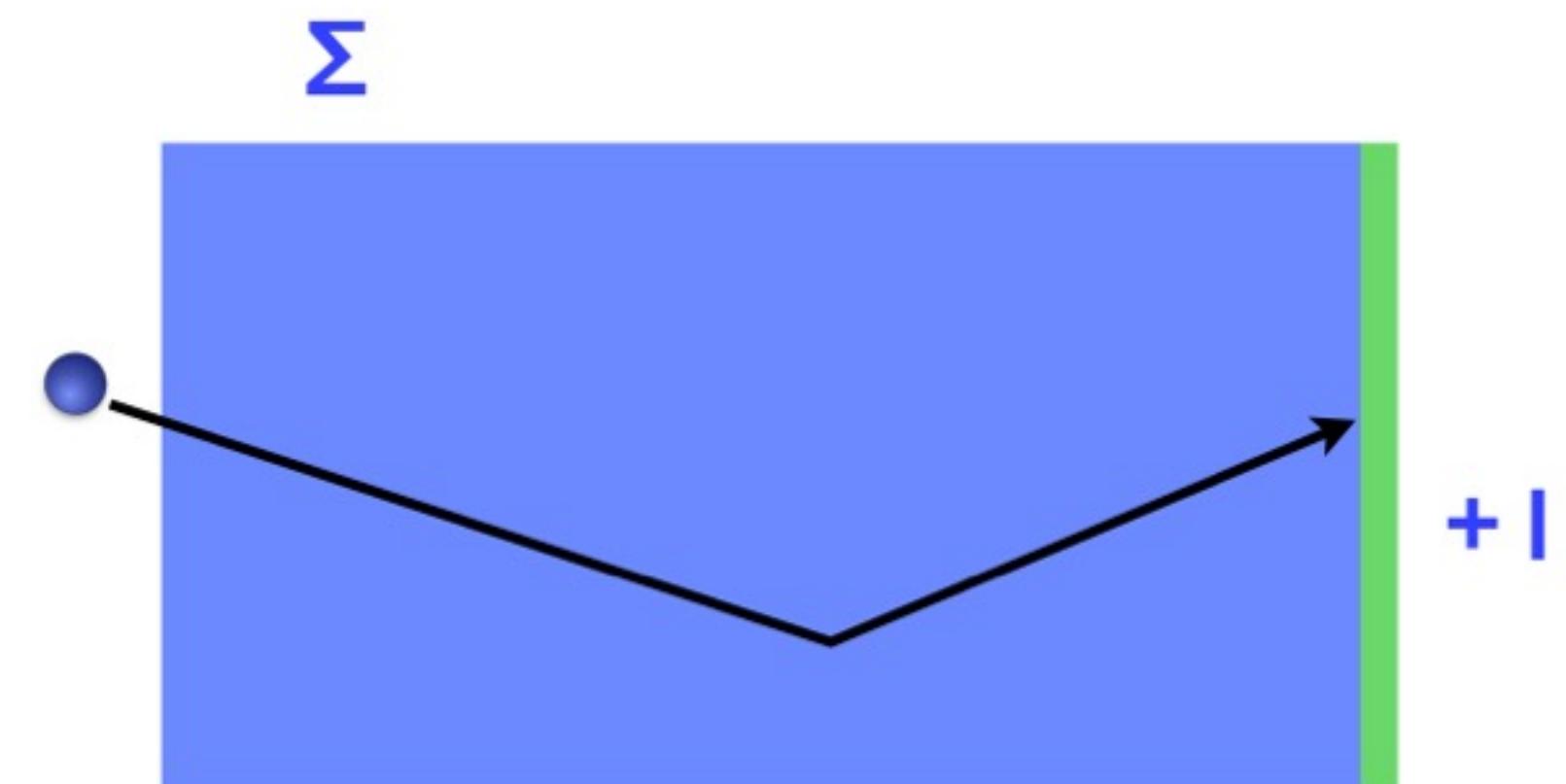
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Correlated Sampling technics?

Principle

- Objective: replace 2 “close” calculations by a single one
 - *calculation speed-up - only 1 run*
 - *variance reduction - same neutron path*
 - *no first order assumption*
- Neutron weight modification
 - *ratio of probabilities between the two systems*
- Different application fields
 - *surface displacement*
 - *element concentration / density modification*
 - *Doppler effect*
 - ... *nuclear data uncertainty*



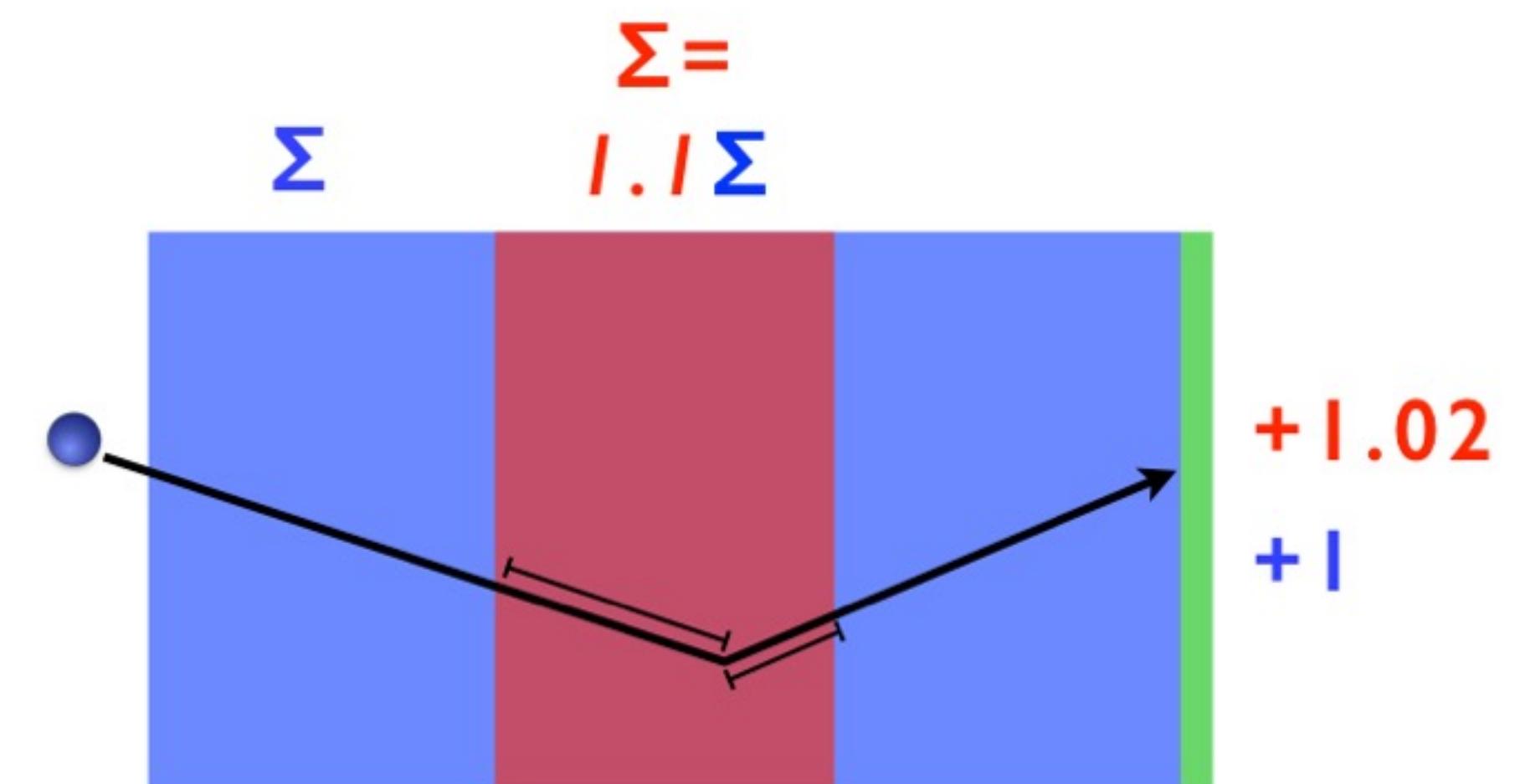
Ratio of probability for a distance d sampling:
$$\frac{\Sigma_{\text{tot}}^{\text{pert}} \exp(-d \cdot \Sigma_{\text{tot}}^{\text{pert}})}{\Sigma_{\text{tot}} \exp(-d \cdot \Sigma_{\text{tot}})}$$

Ratio of probability for the reaction sampling:
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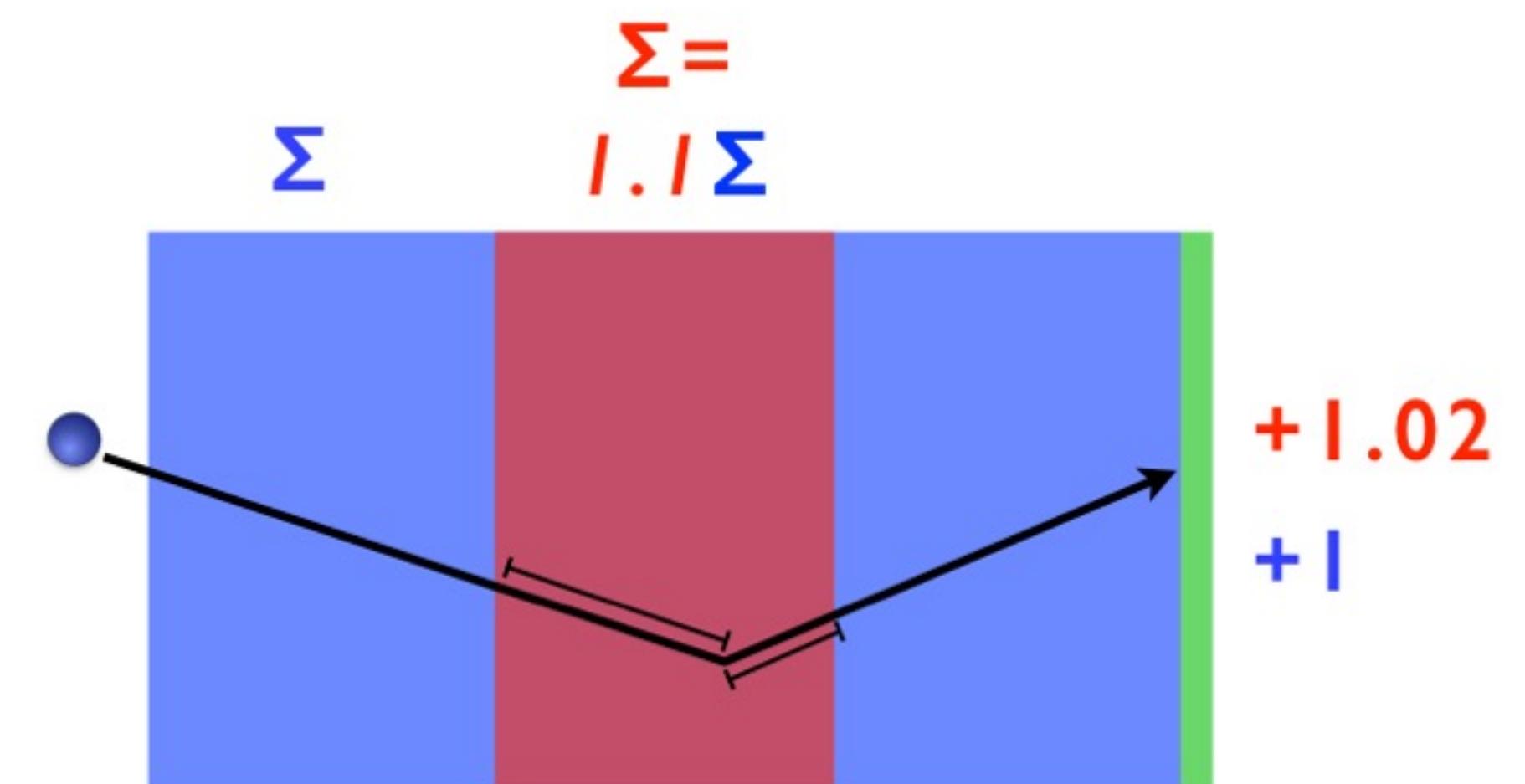
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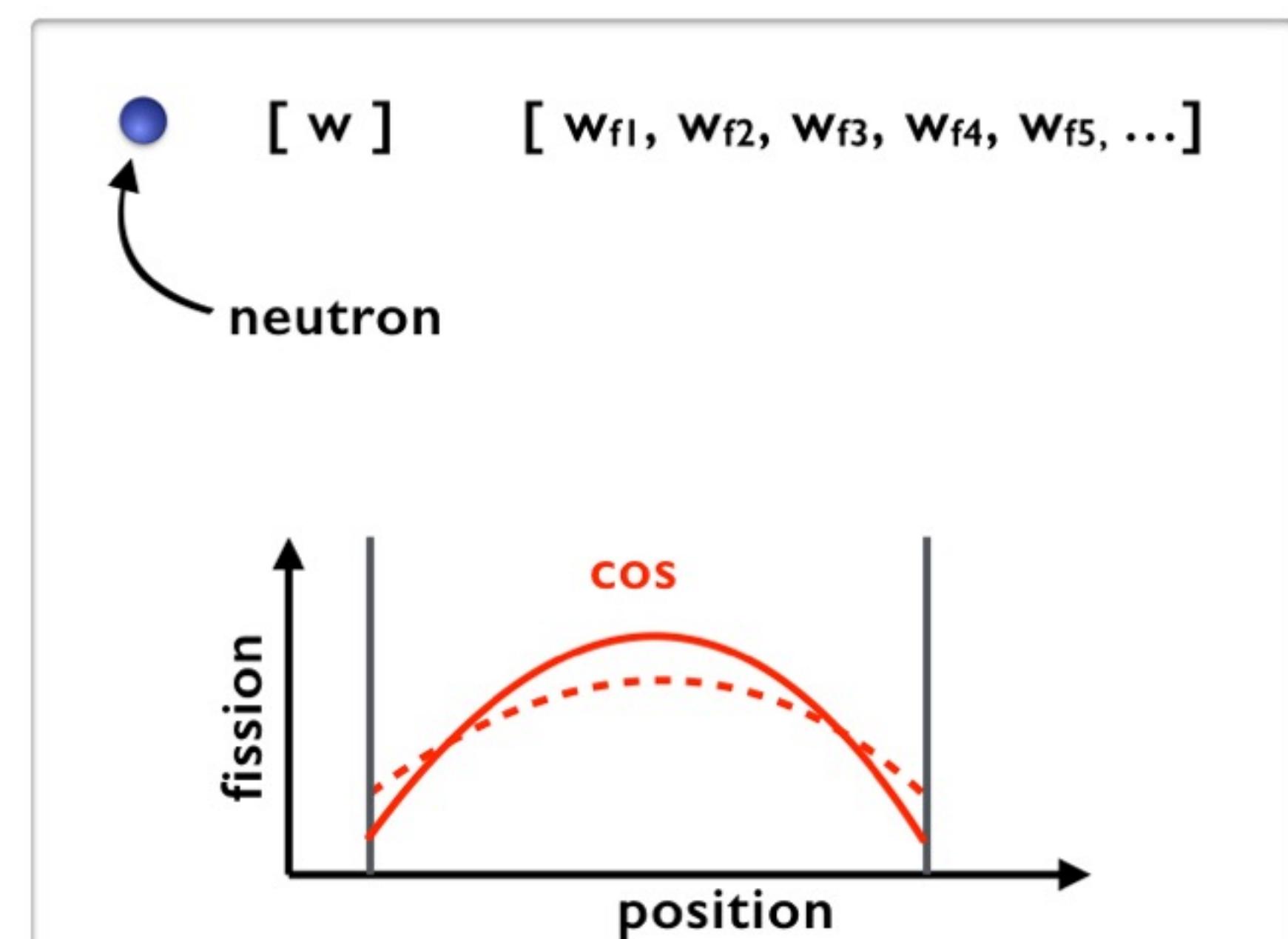
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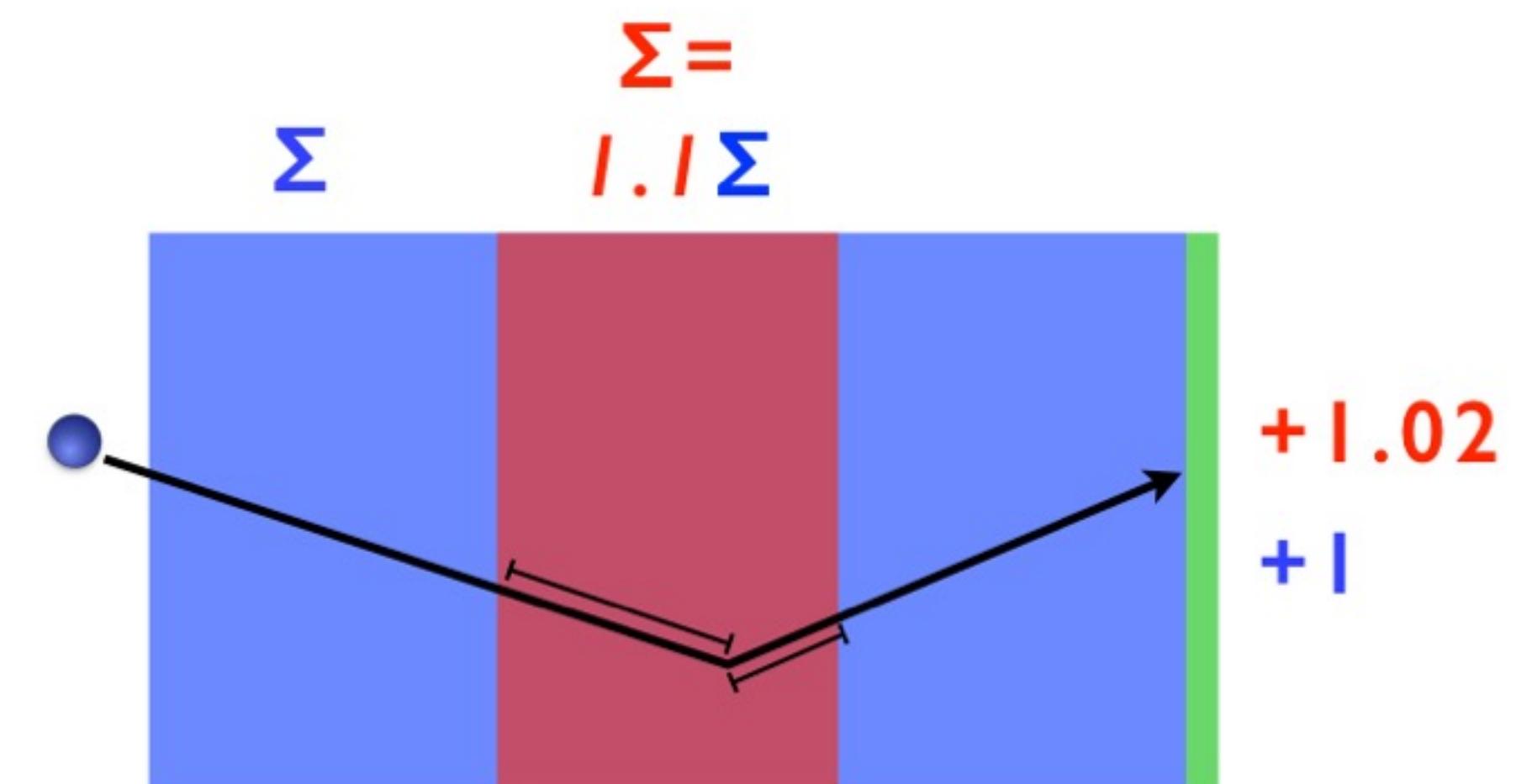
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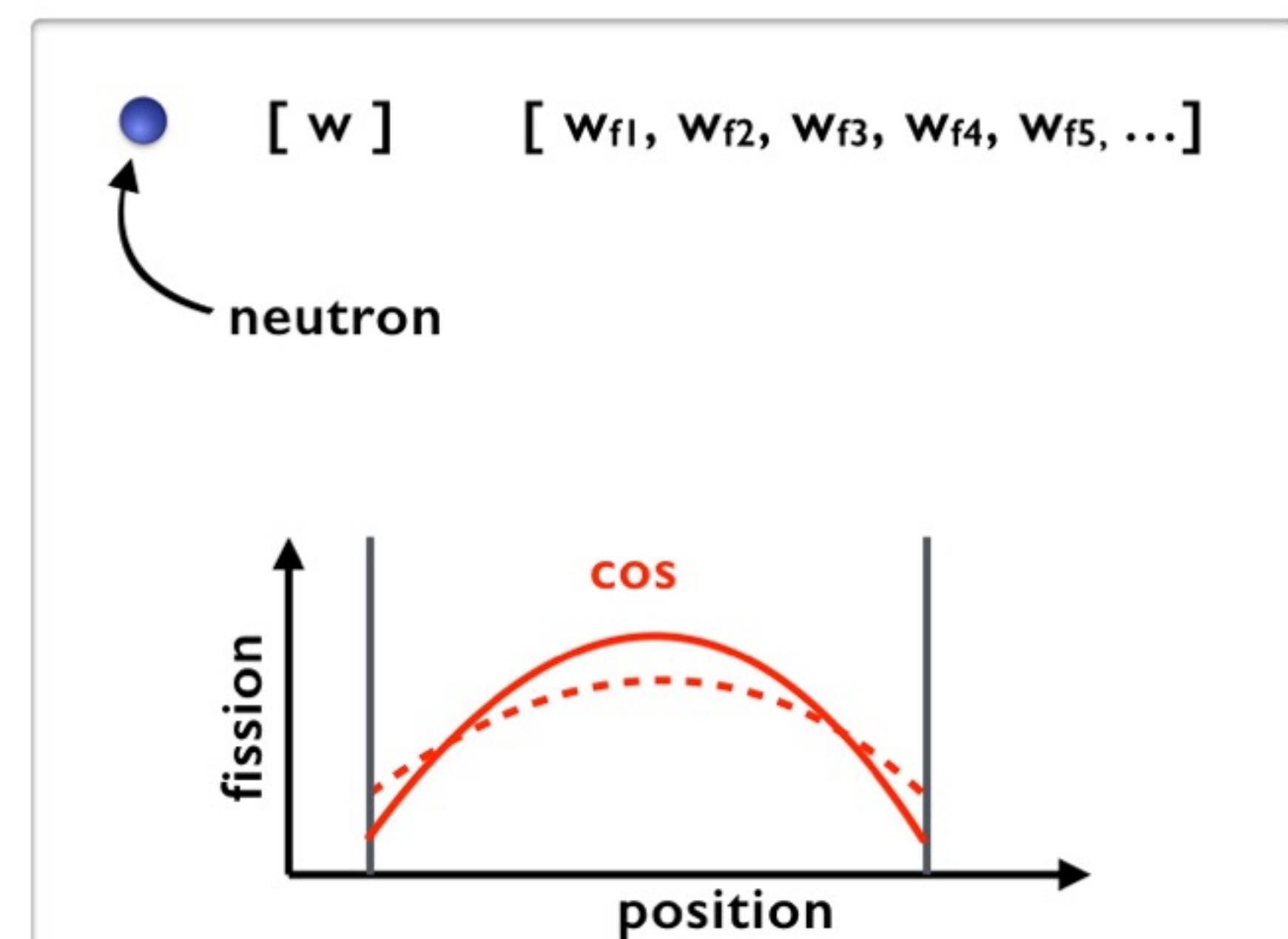


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Drawbacks

- Needs probabilities different from zero and infinity
 - *can not make isotope appears from scratch*
- If the systems are too different the neutron weight is too different
 - *bad convergence*



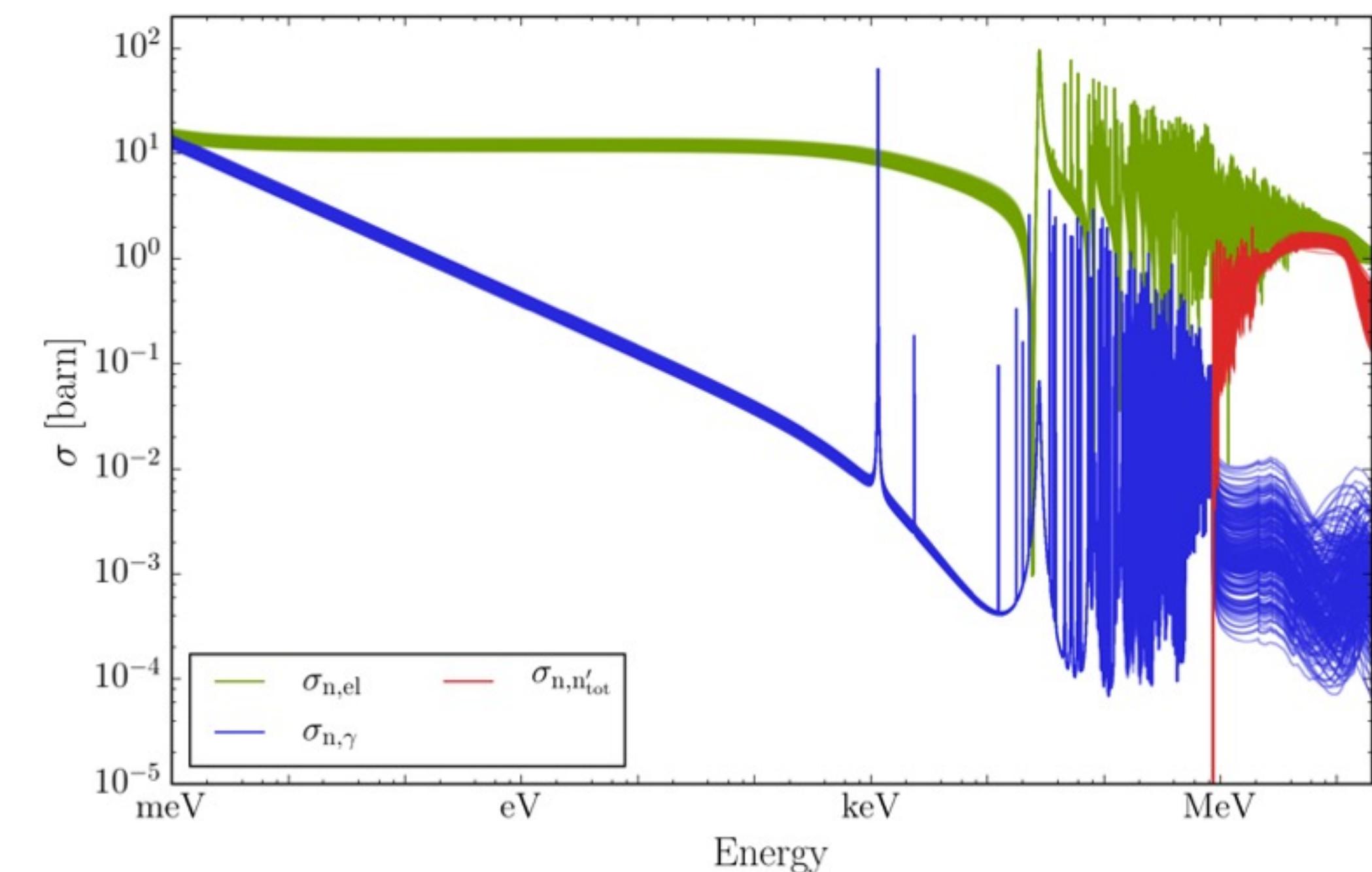
Correlated Sampling with multiple Cross Sections: TMC-CS

Principle

- Each set of cross sections corresponds to a different system
→ *different probabilities during the transport*
- Neutron weight modification for each XS set
- Multiple “isotopes” and “mt” all together
→ *ratio of probabilities between the two systems*

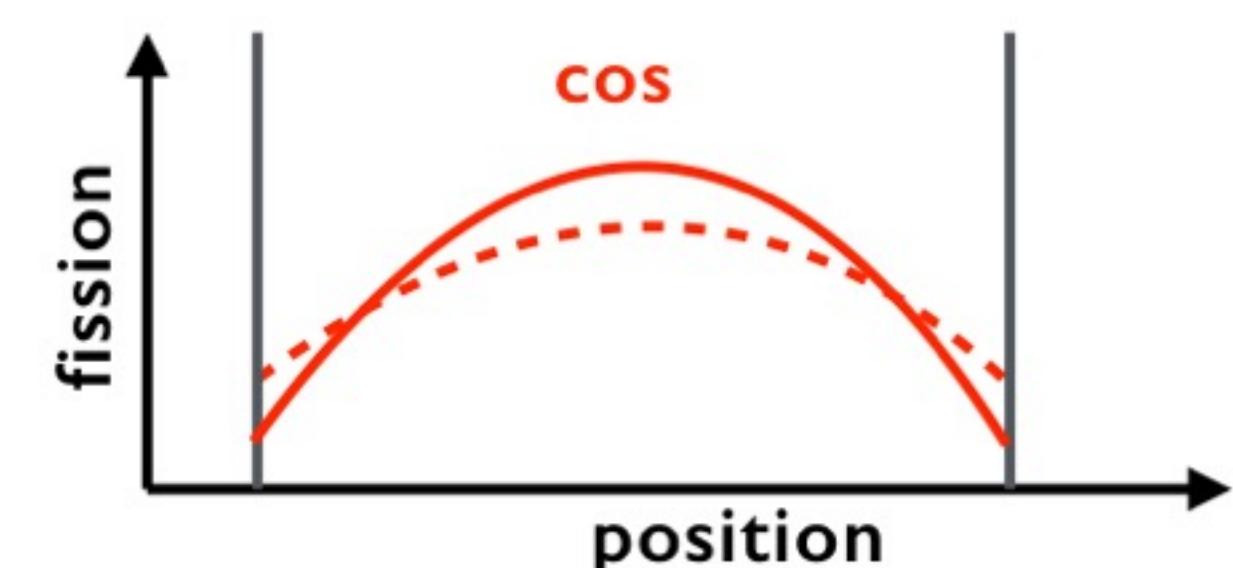
Nuclear Data cross sections

- “Classic” TENDL cross section
→ *sampling on the nuclear data parameters*
- “Extended” TENDL - EUROfusion (“to fill the gap”)
→ *sampling on the nuclear models themselves (more challenging)*



256 random TENDL ^{56}Fe cross sections

• $[^{xs1}w, ^{xs1}w_{f1}, ^{xs1}w_{f2}, ^{xs1}w_{f3}, \dots$
 $^{xs2}w, ^{xs2}w_{f1}, ^{xs2}w_{f2}, ^{xs2}w_{f3}, \dots$
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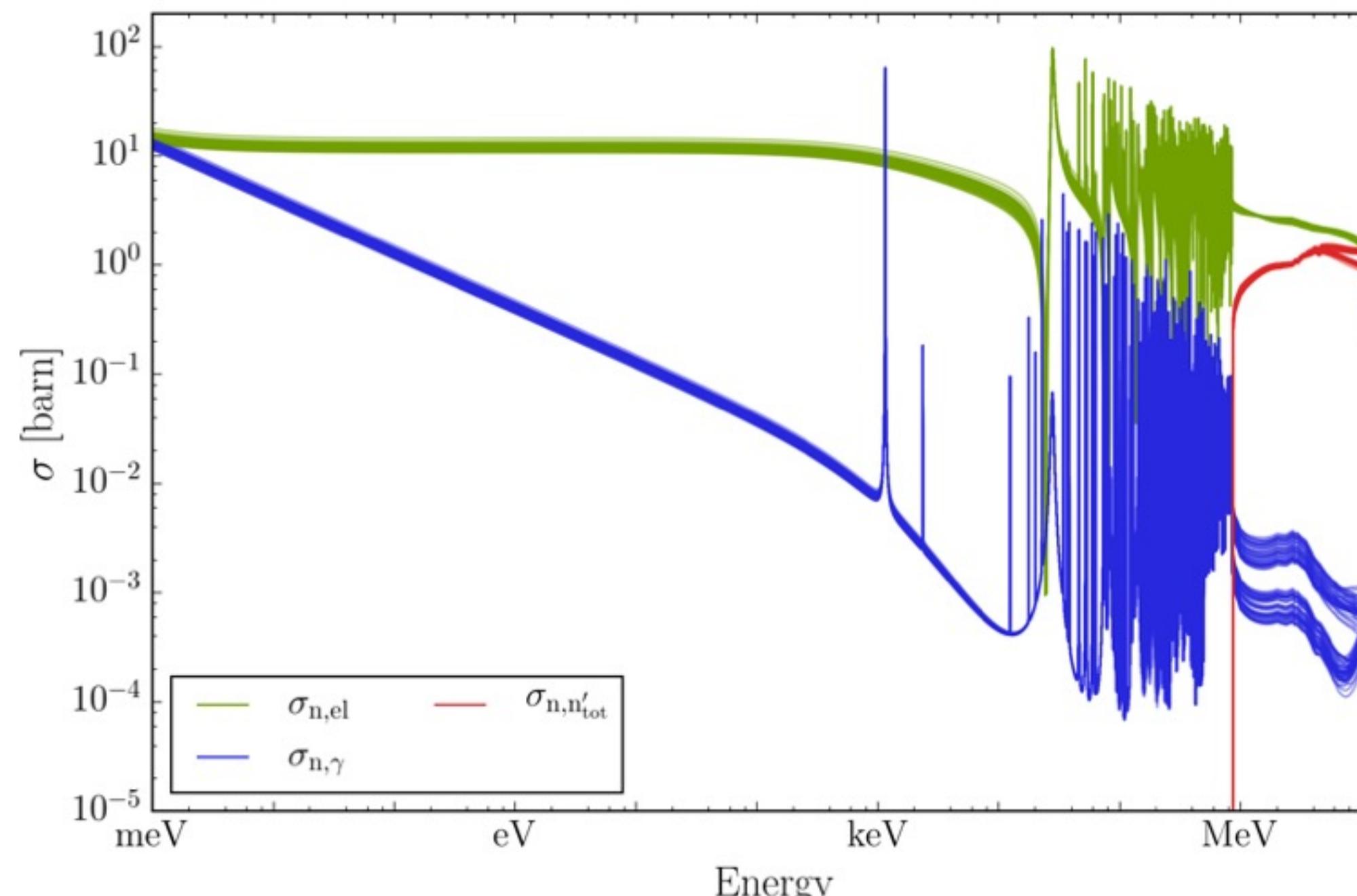
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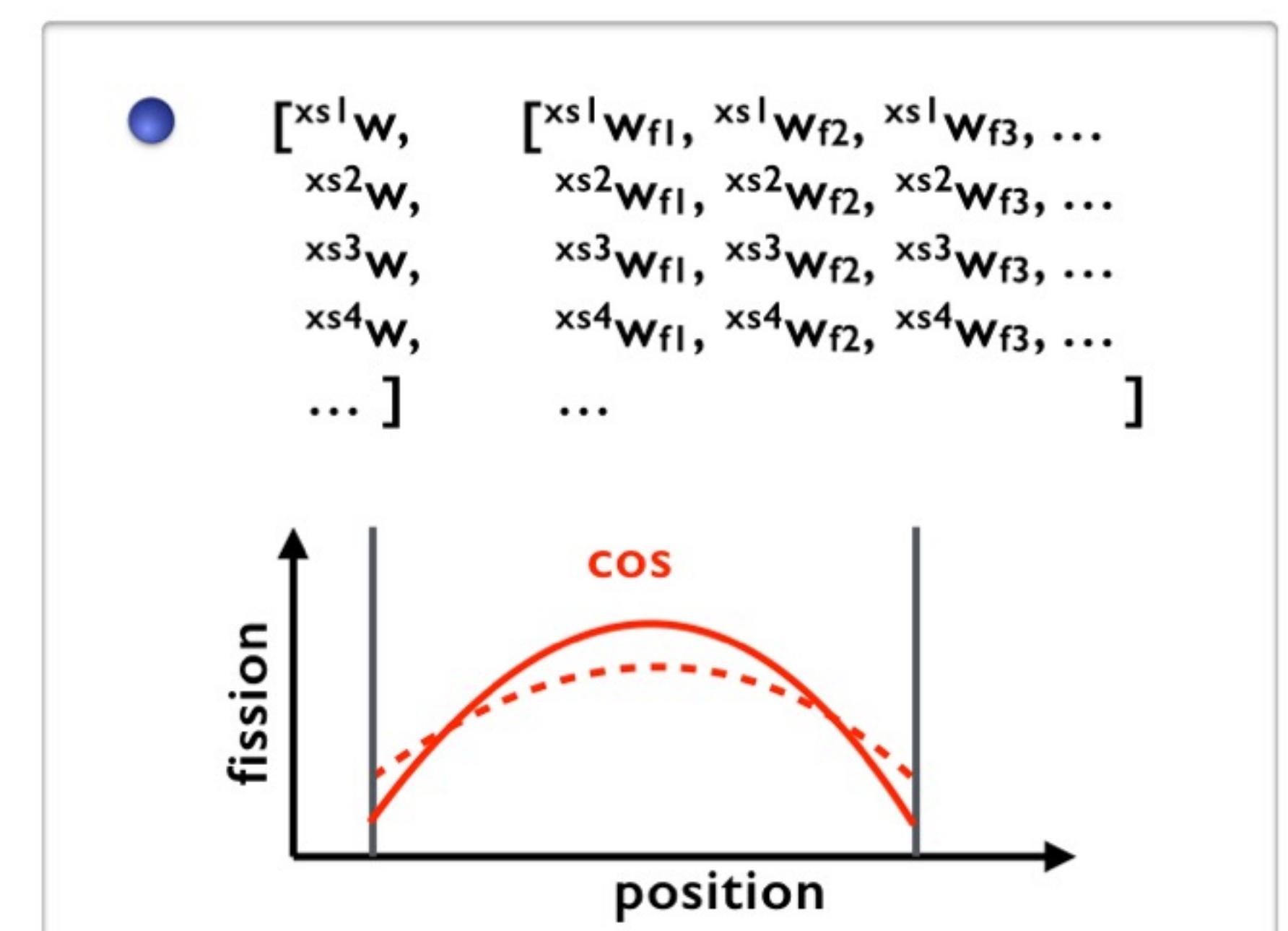
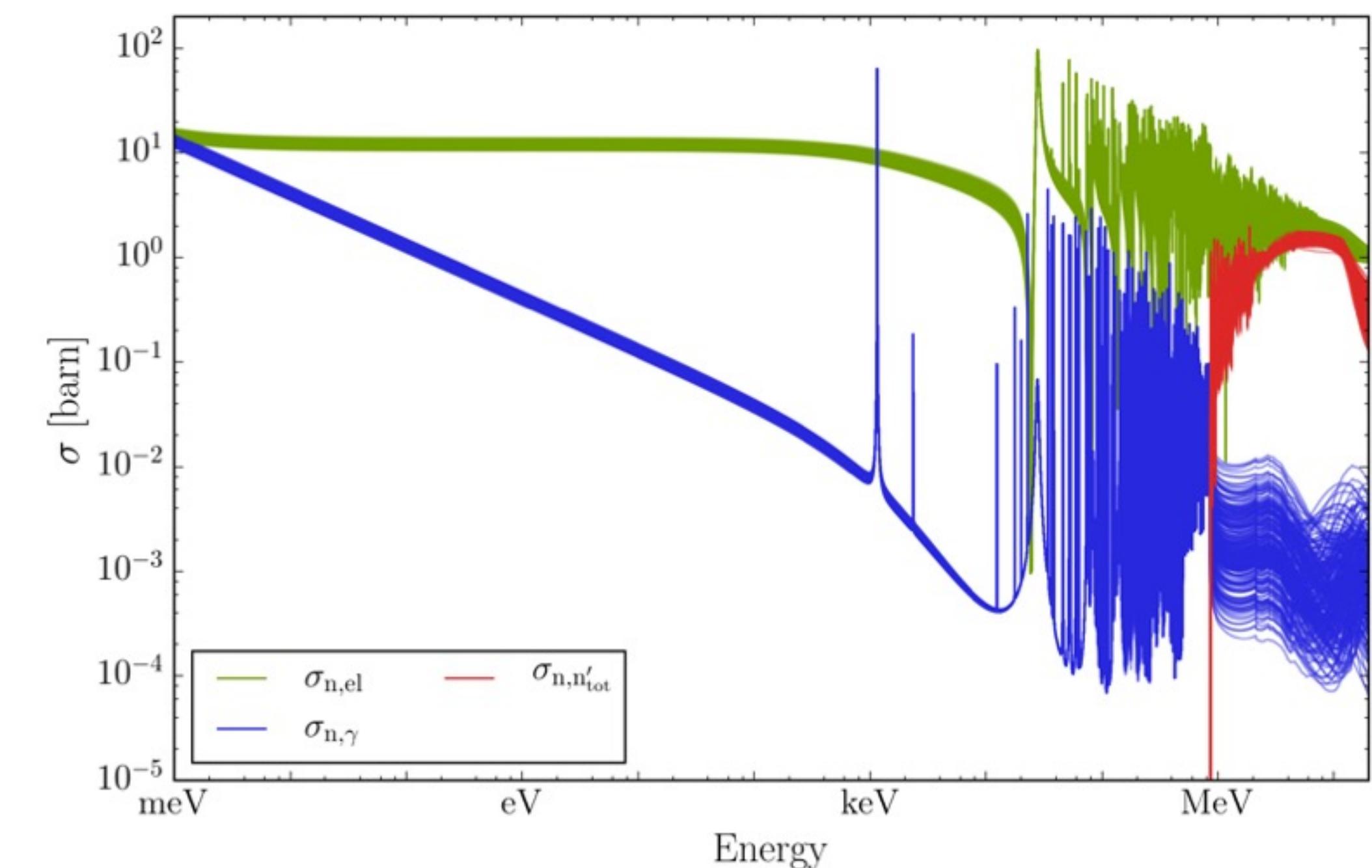
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→ discontinuities
→ non linearity?



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TMC-Ref

- Classic Total Monte Carlo uncertainty propagation (reference)
- N calculations for N cross section sets

TMC-CS

- Uncertainty propagation using the correlated sampling technics
- N / (~64) calculations for N cross section sets
memory limitation

TMC-sensi

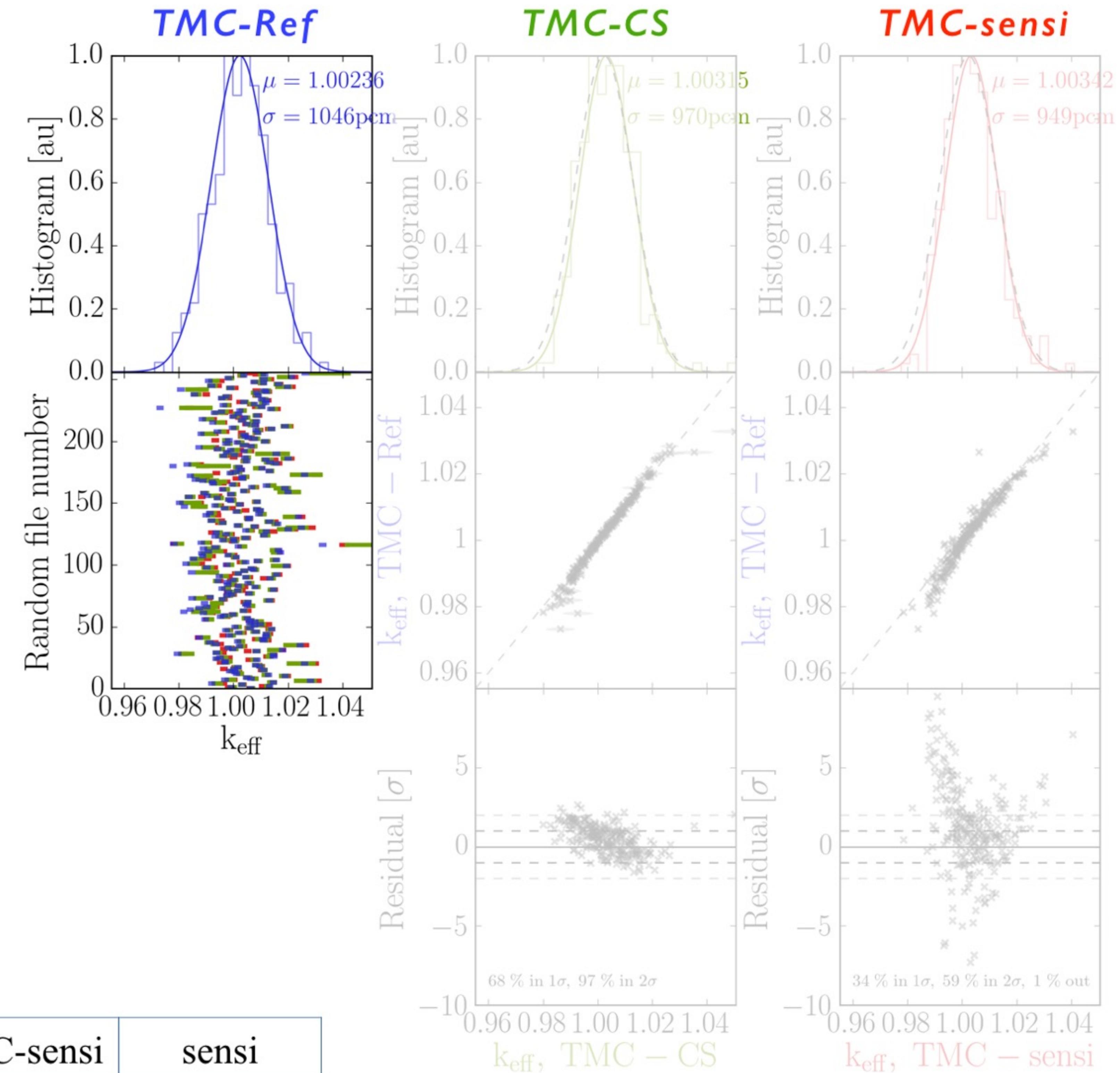
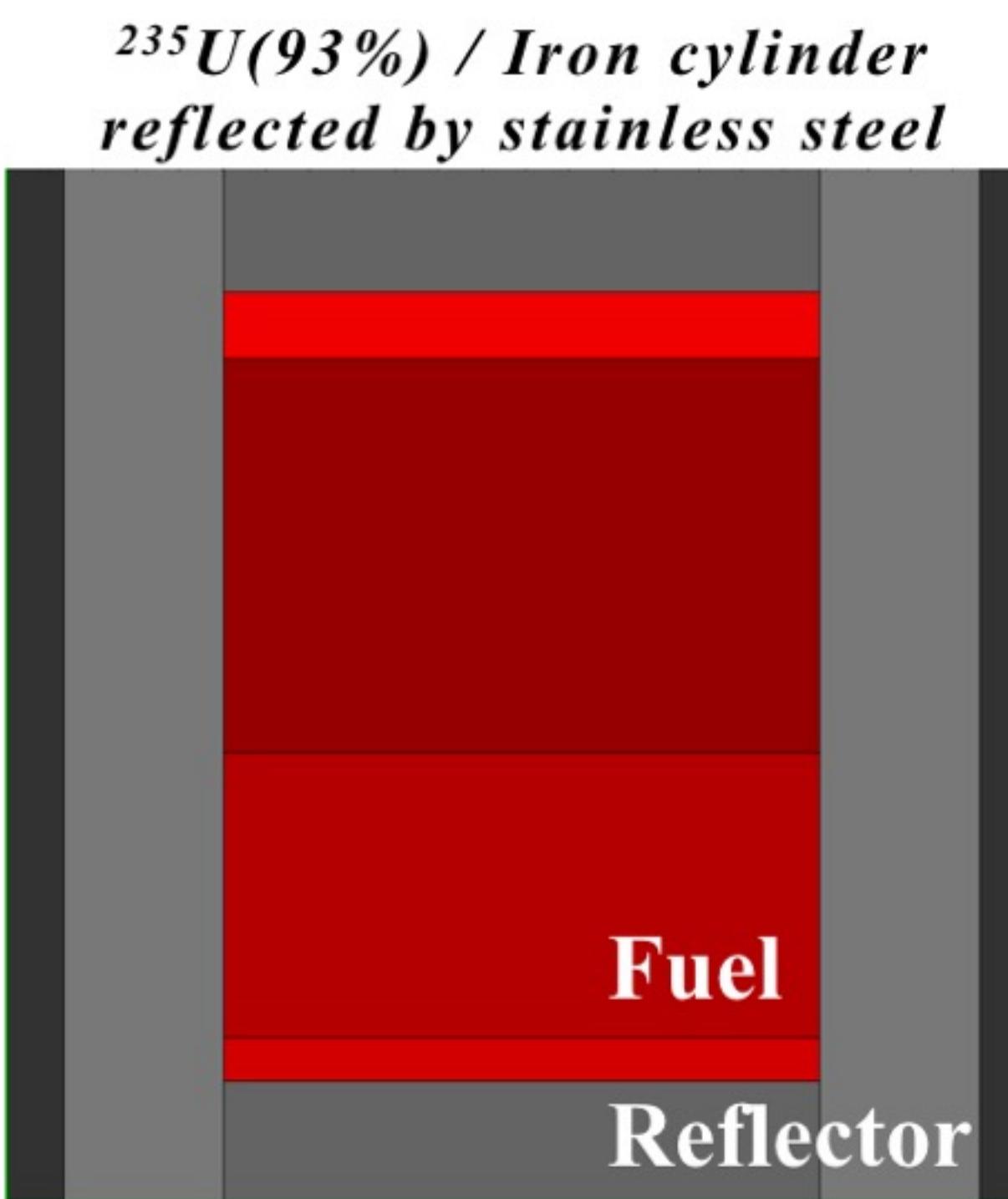
- Uncertainty propagation using the sensitivities (Serpent code)
- XS % variation between ACE files #x and #0
→ *uncertainty propagation for each XS file*

Sensi

- Uncertainty propagation using the sensitivities (Serpent code)
- Covariance matrix from all the random XS files
→ *one uncertainty propagation value*

HMI-001: ^{56}Fe

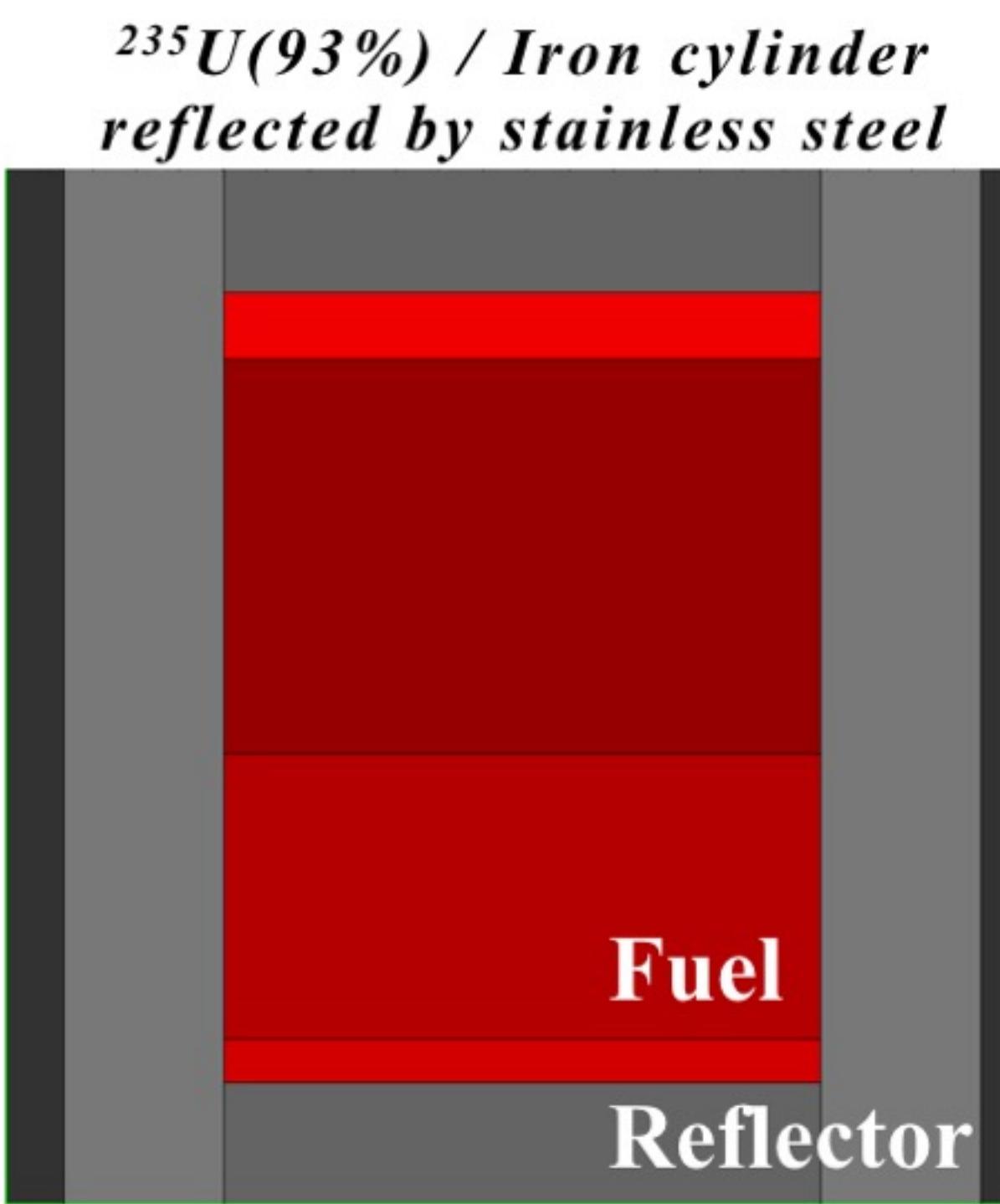
- Large uncertainty ~ 1000 pcm
- Same global distributions
- Good file to file agreement
- TMC-CS: difference appears after 2000 pcm
- TMC-sensi: good linearity with a comma trend



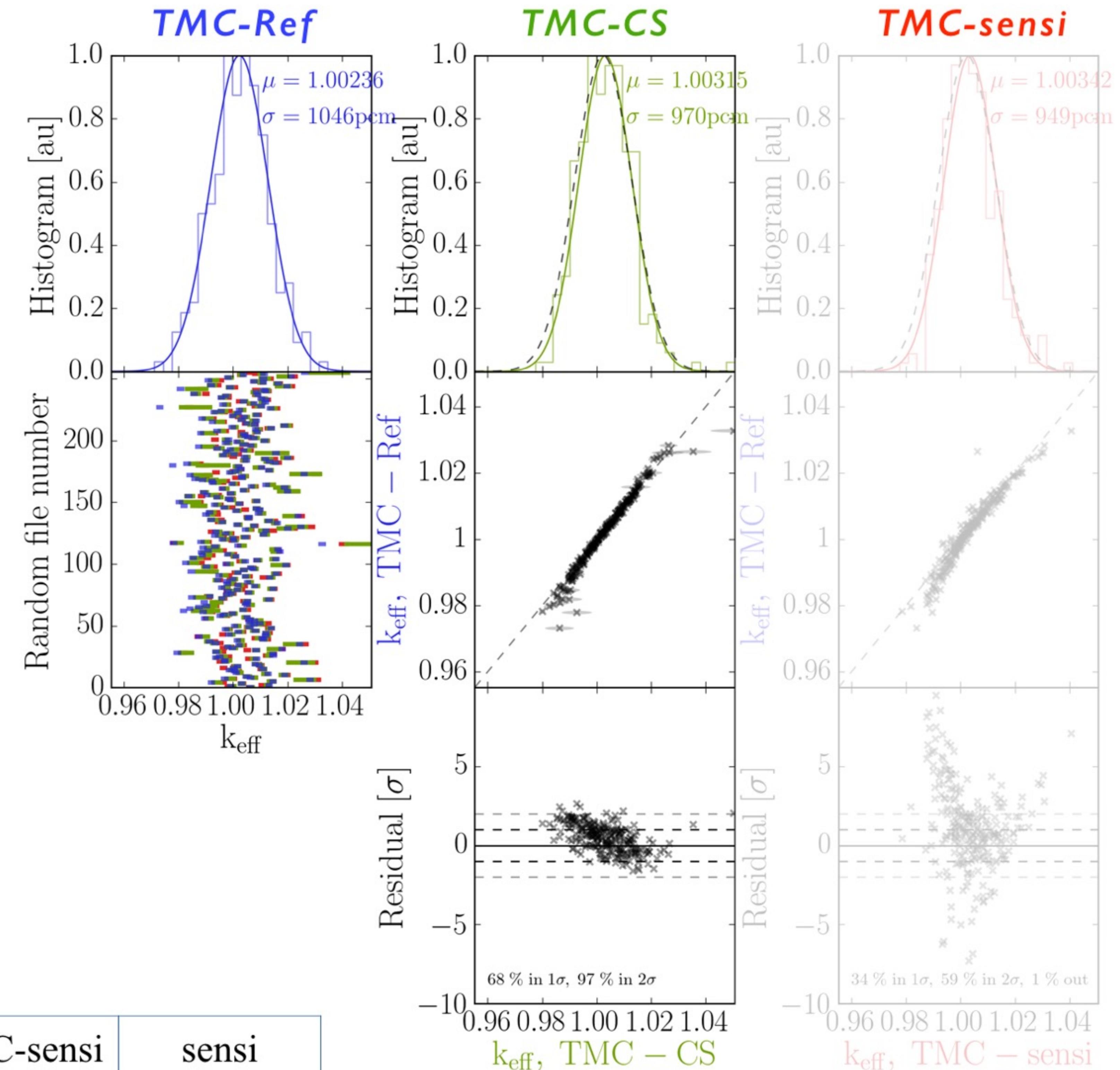
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$\sigma_{k_{\text{eff}}} [\text{pcm}]$	1046	970	949	1086

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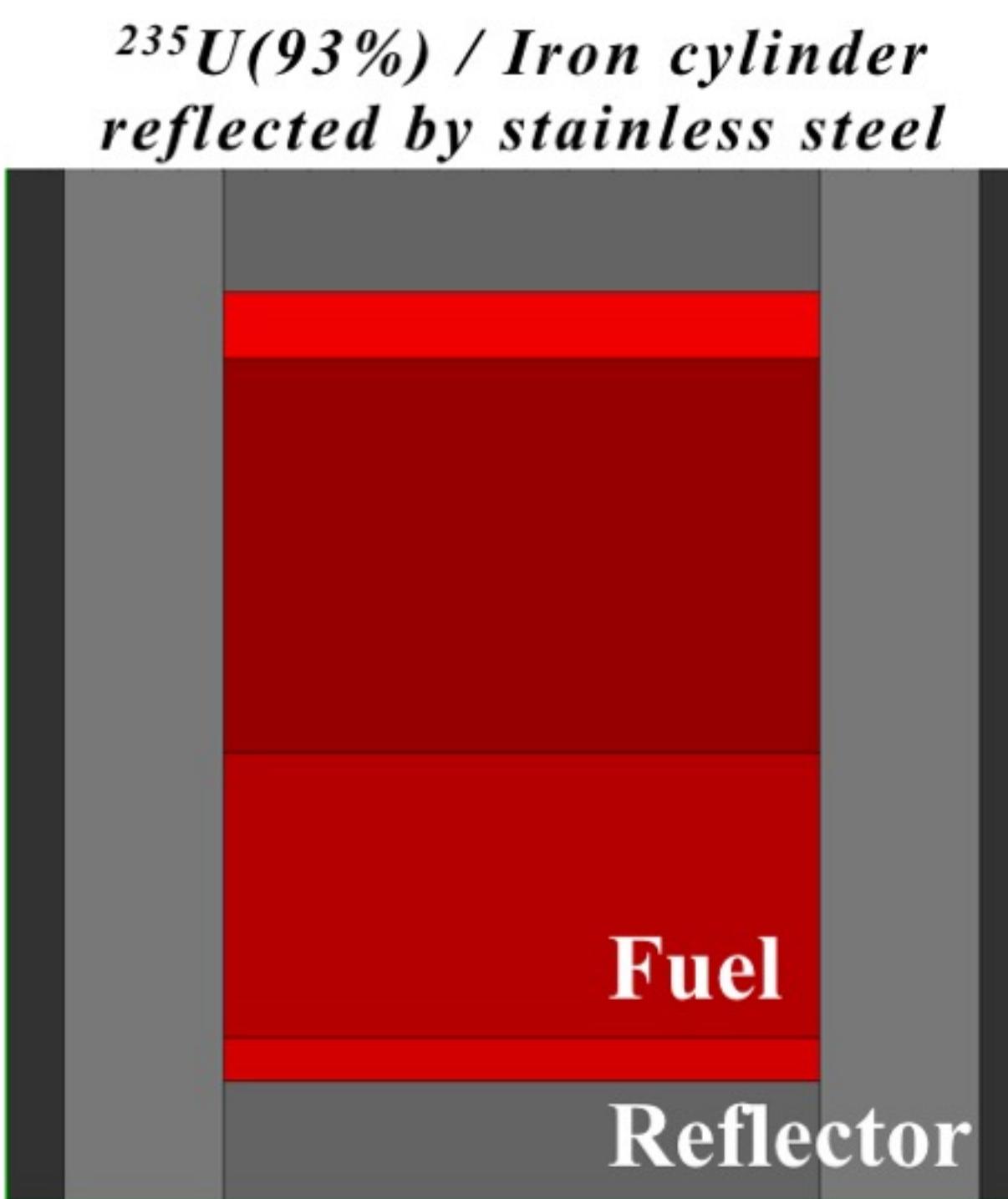


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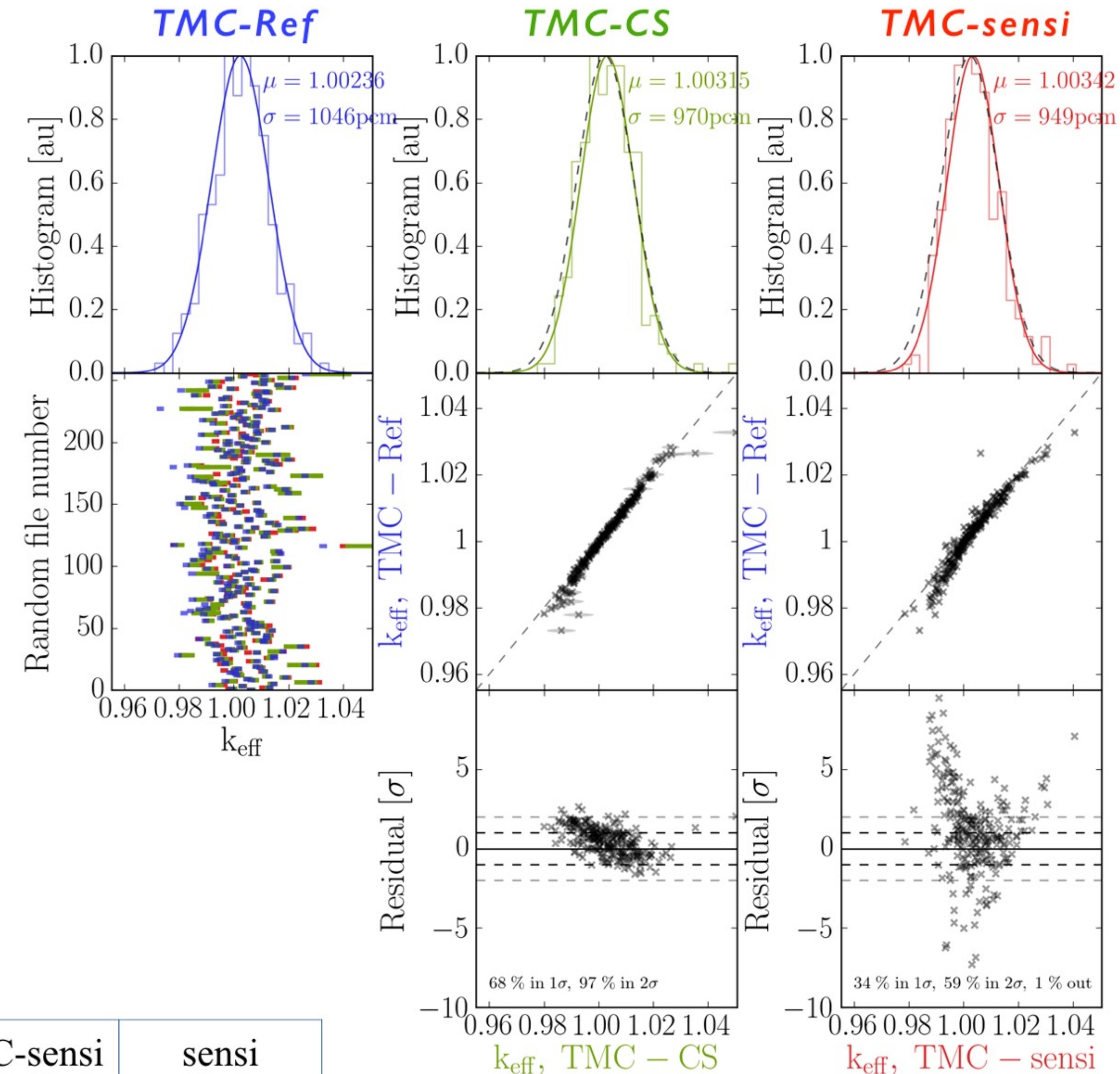


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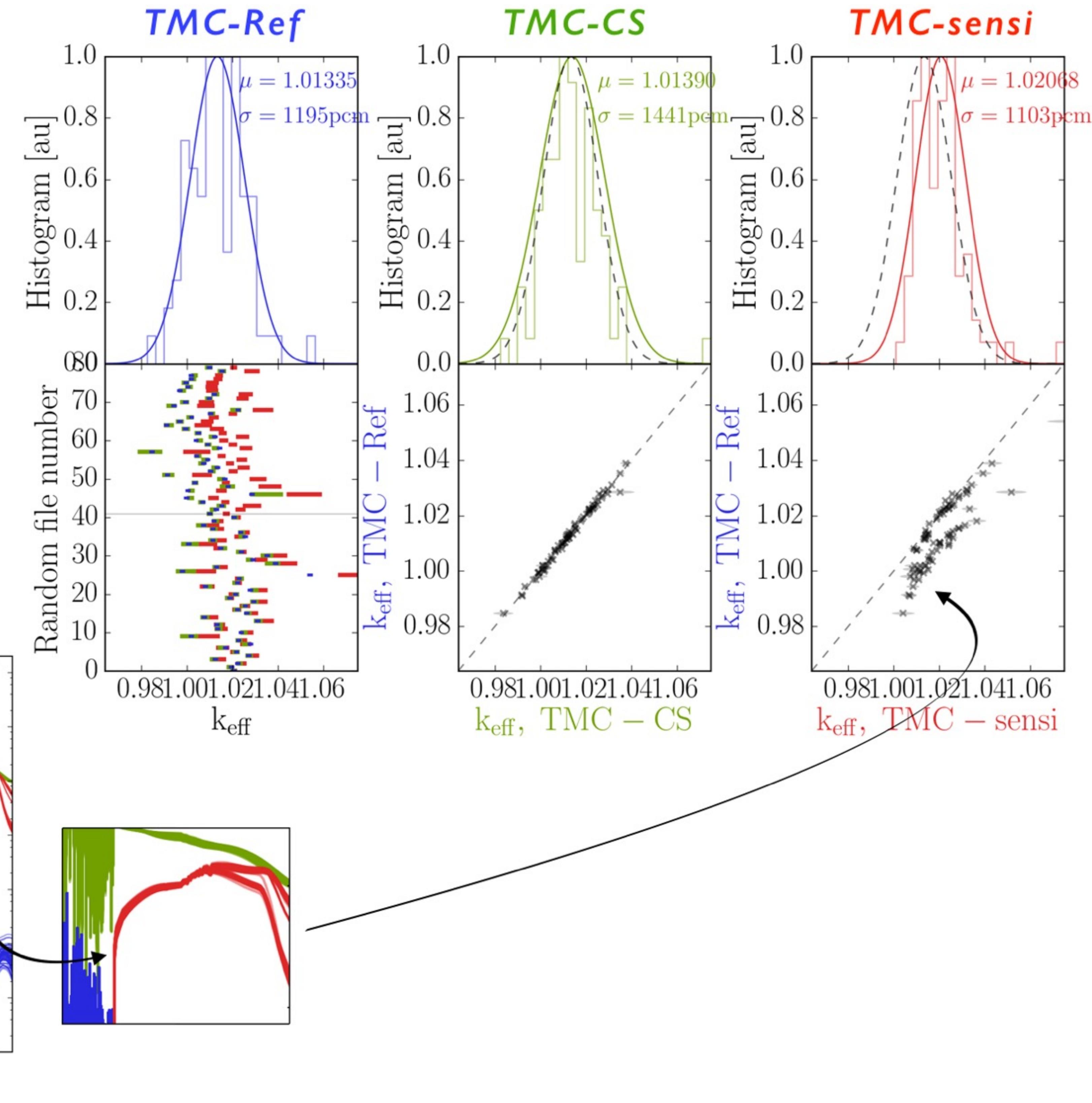
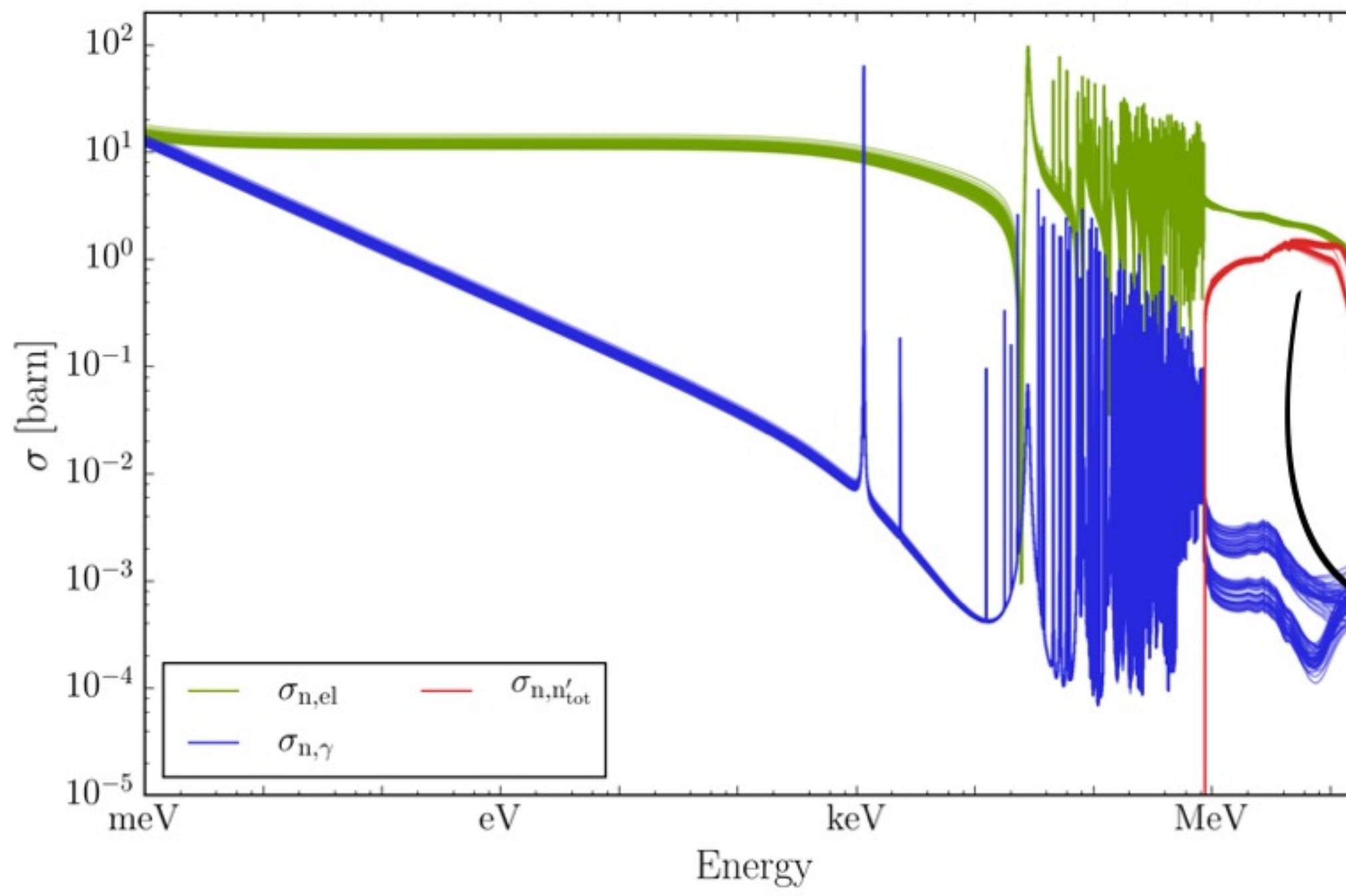


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HMI-001: ^{56}Fe & extended TENDL

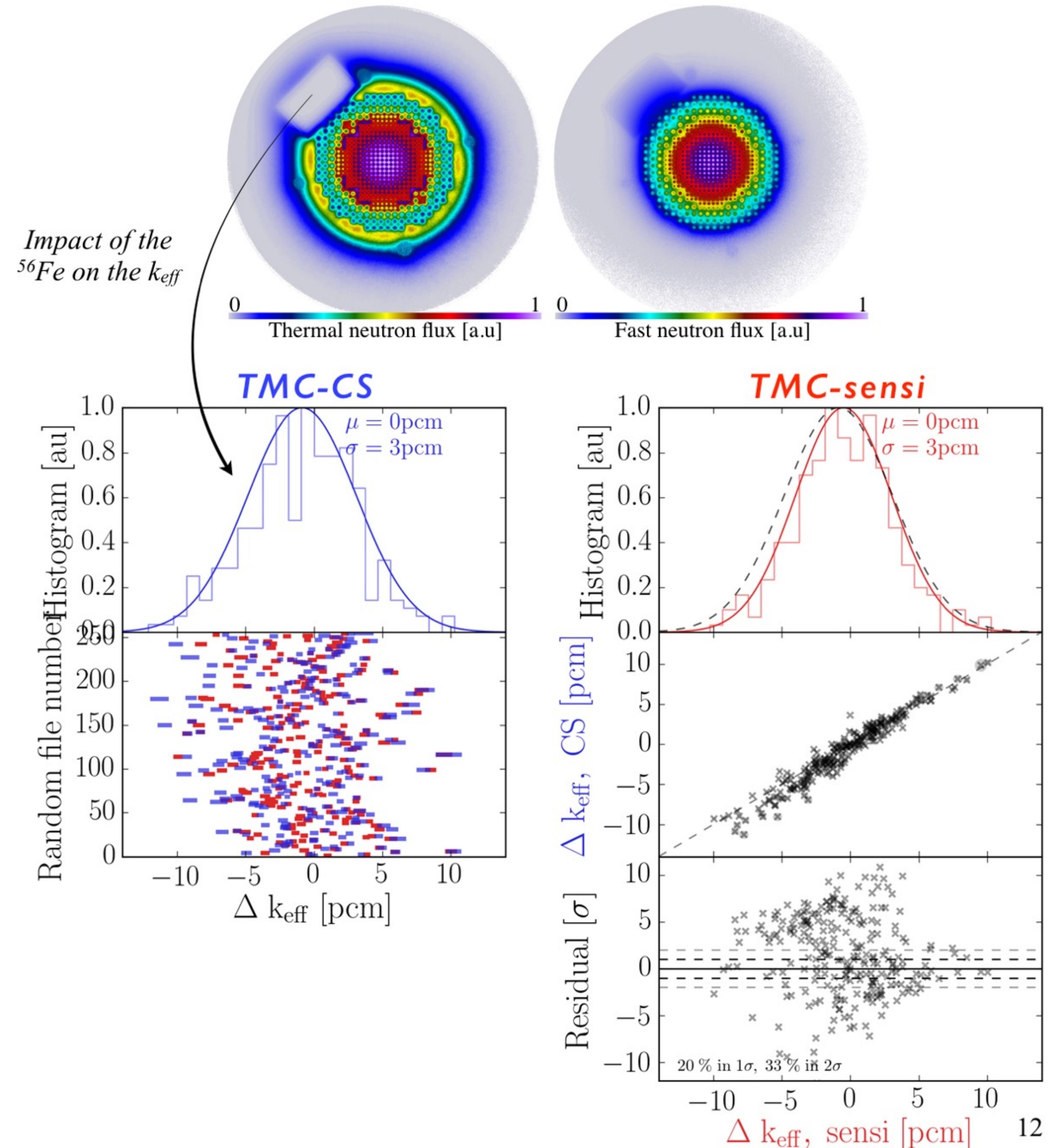
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- Good file to file agreement
- Non linearity appears on the sensitivity approach



CROCUS: ^{56}Fe

- Small uncertainty $\sim 3\text{pcm}$
- TMC-CS / TMC-sensi: good agreement! ...
- ... no TMC-Ref

$\sigma_{\text{MC stat}} \sim \sigma_{\text{ND}}$

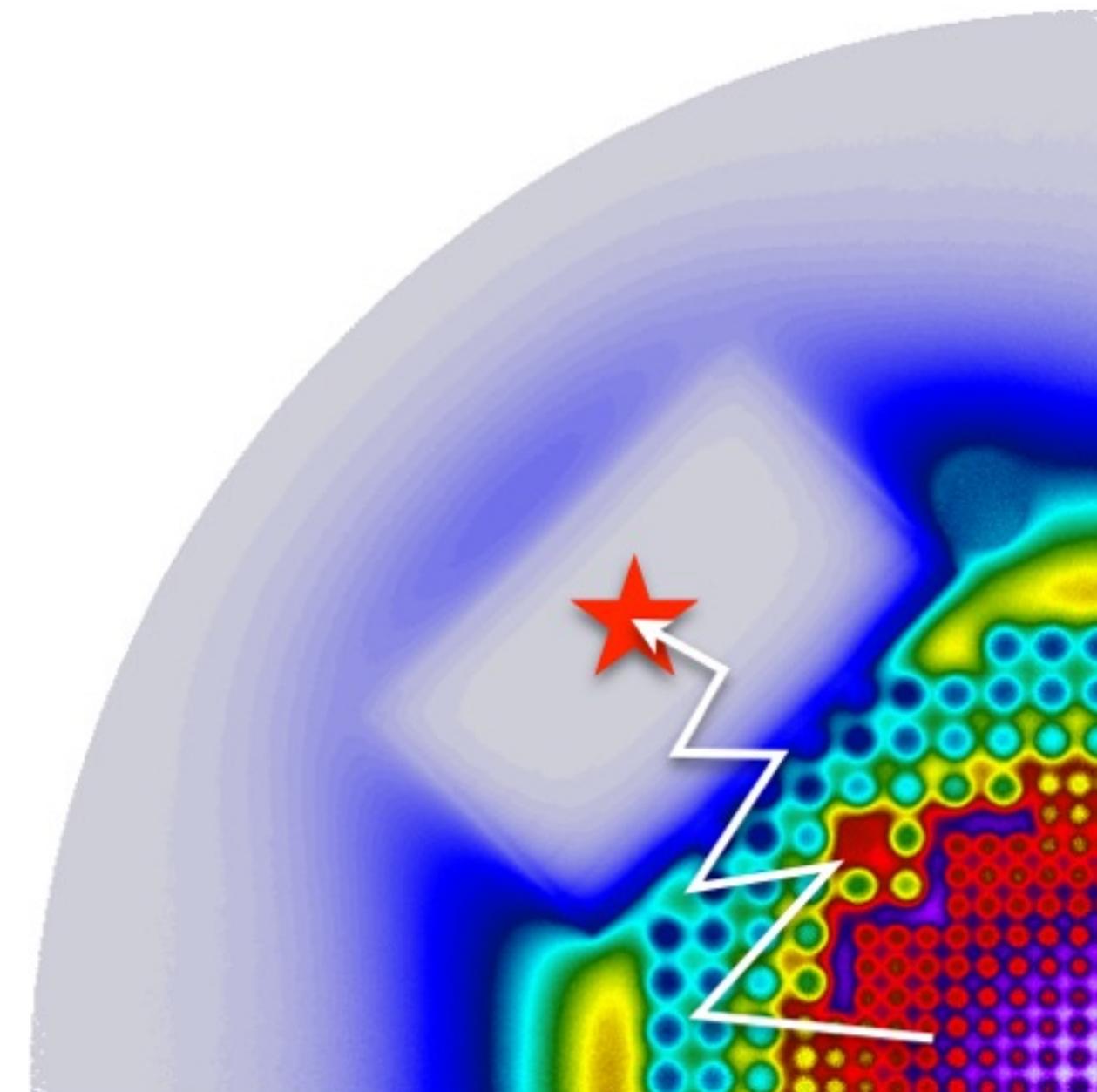


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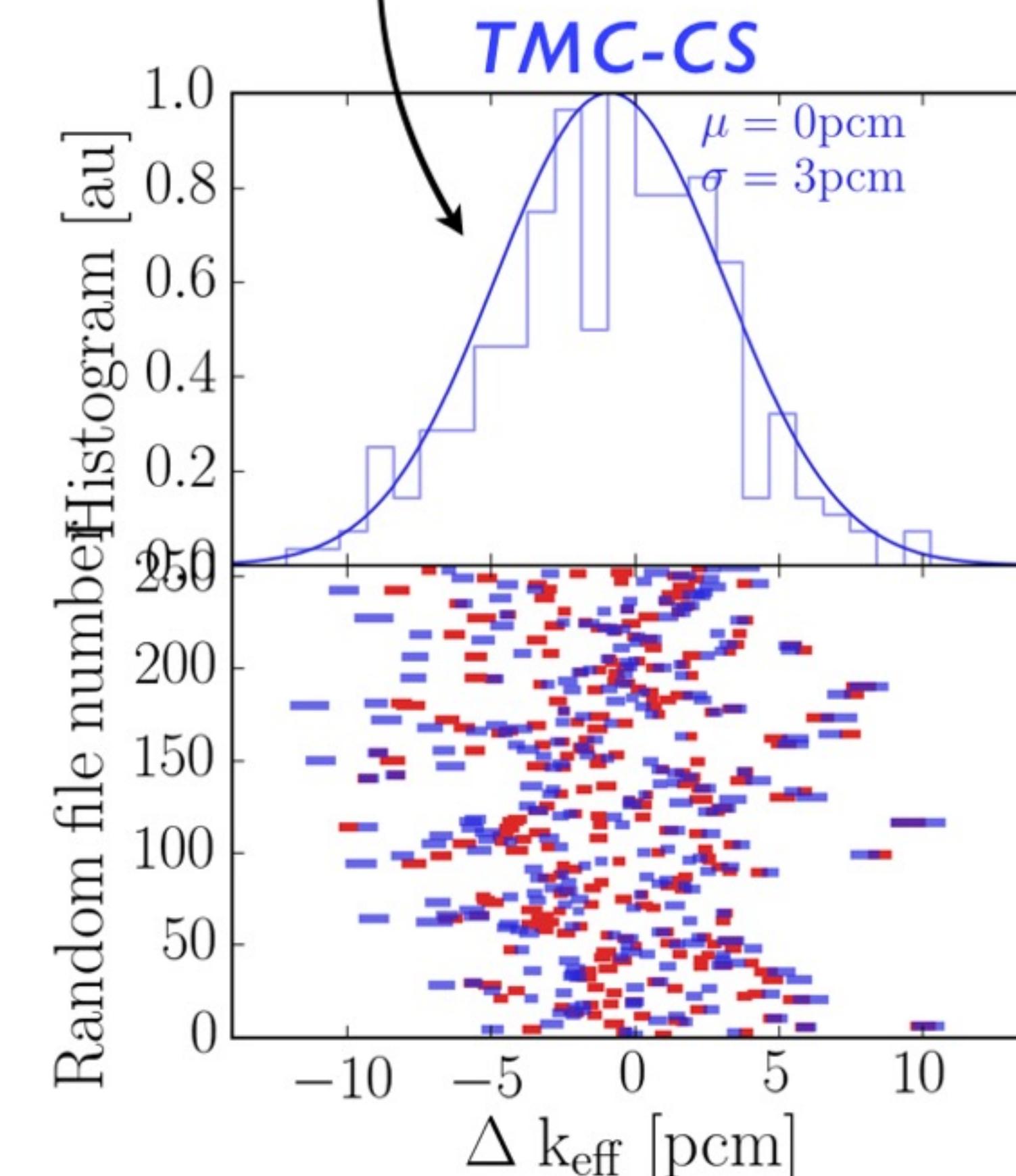
- Neutron flux / reaction rate in the dosimeters can be compared to TMC-Ref!
- But requires neutron biasing



*Impact of the
 ^{56}Fe on the k_{eff}*

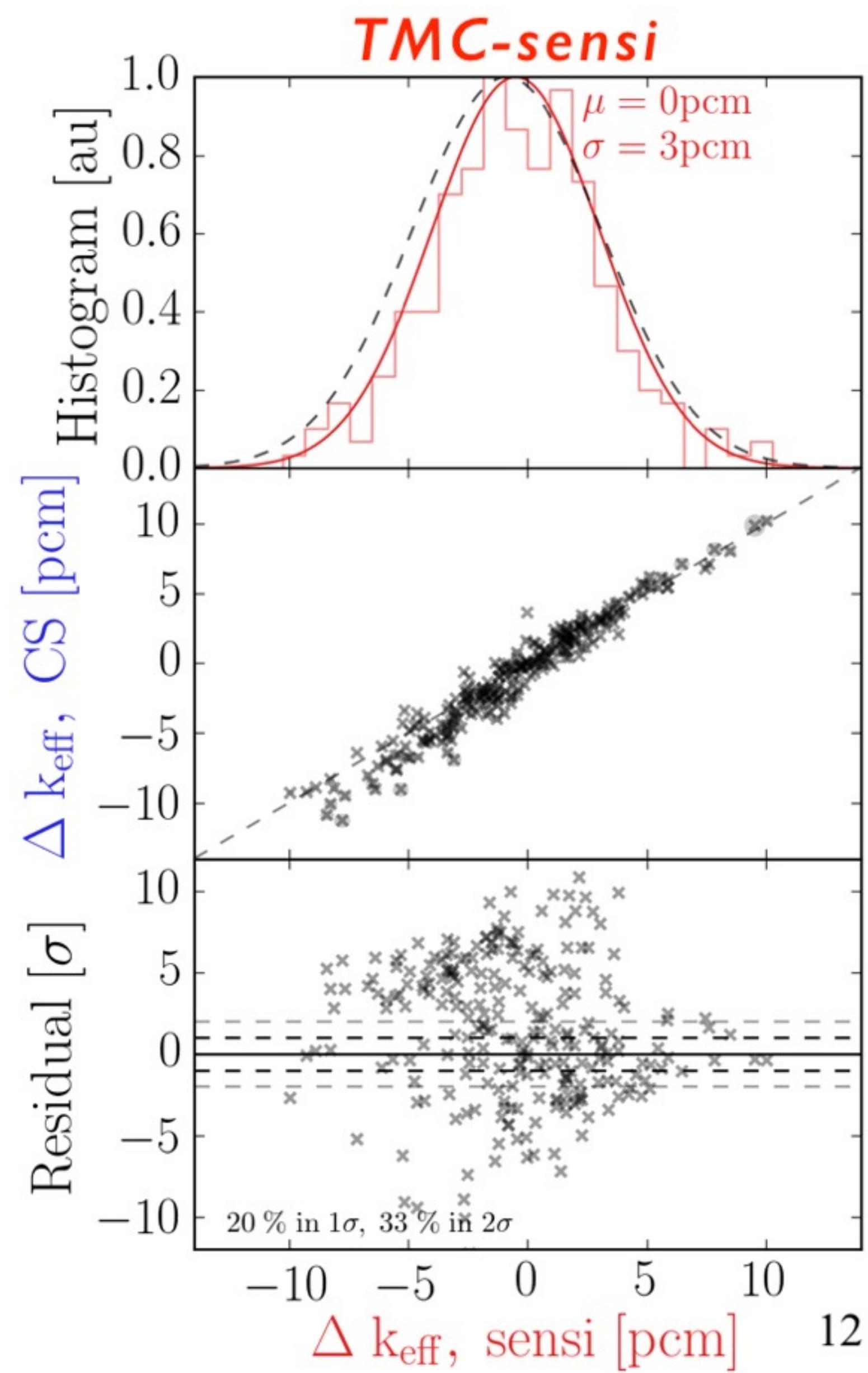
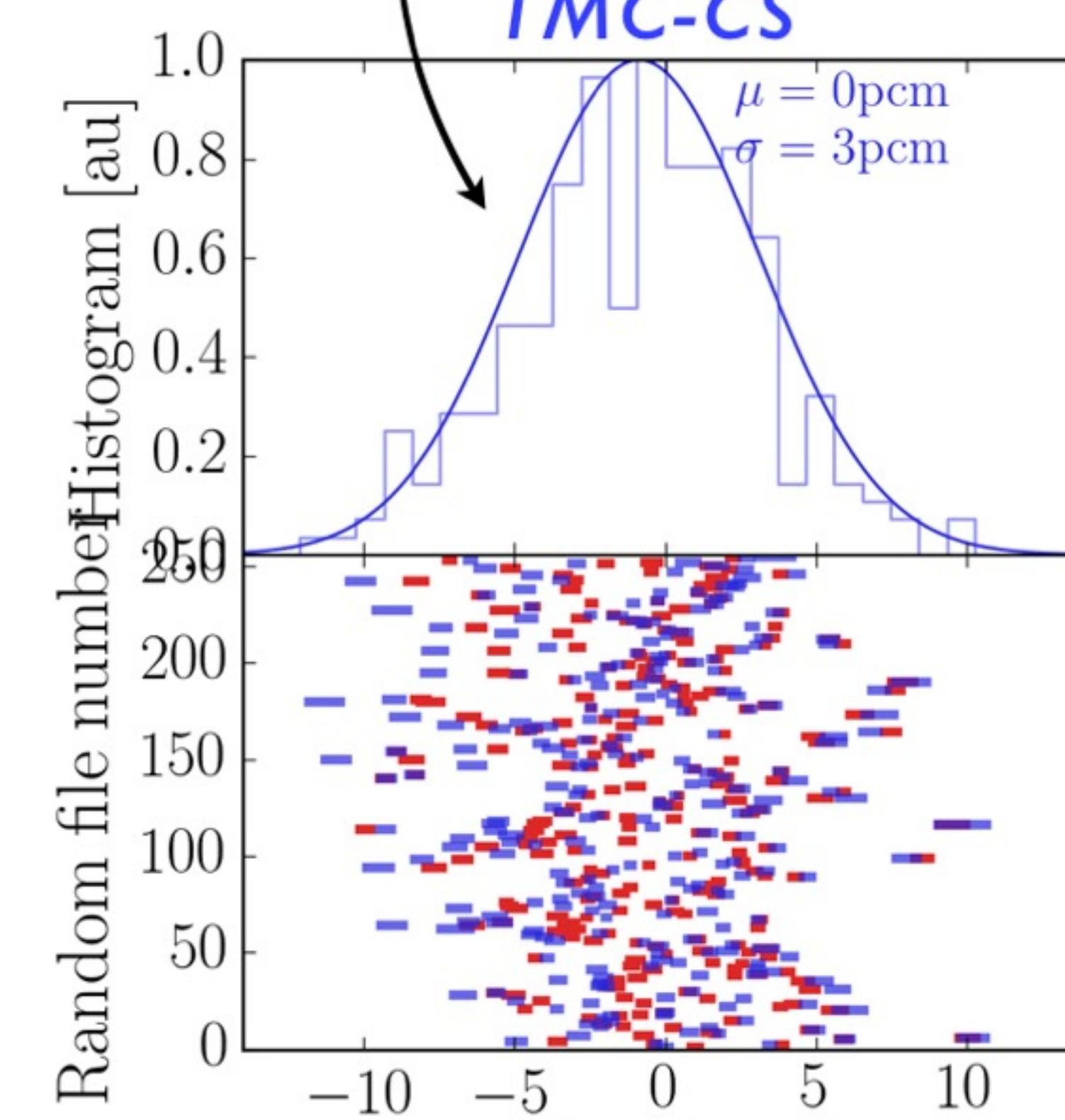
0 1
Thermal neutron flux [a.u]

0 1
Fast neutron flux [a.u]



TMC-CS

$\mu = 0\text{pcm}$
 $\sigma = 3\text{pcm}$





Thermal neutron with a weight of 1



Thermal neutron with a weight of 0.5

Principle

- On the fly learning of the “minimal number of displacements” required to reach the target
→ *Neutron splitting*
- Geometric X Energy grid (no angular grid yet)



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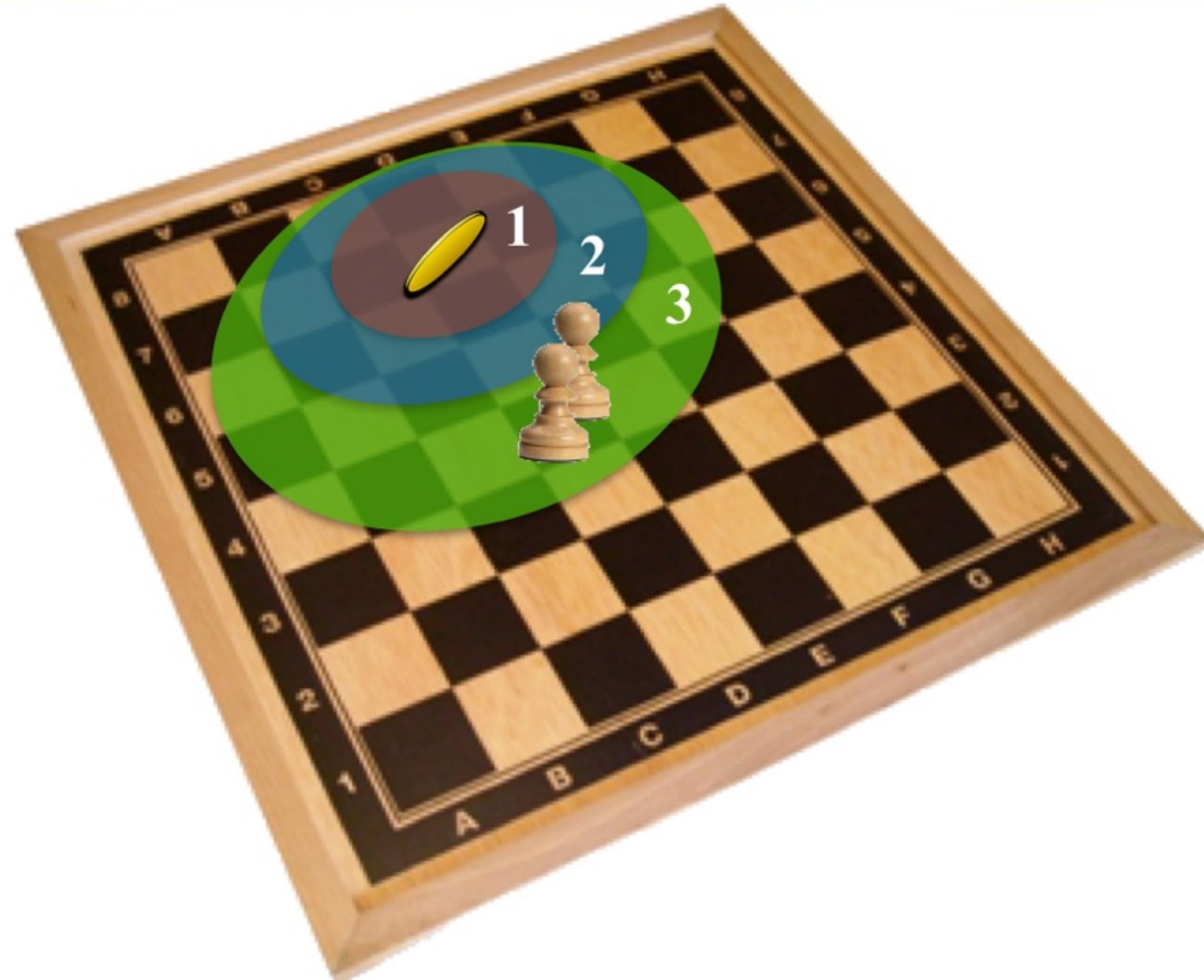
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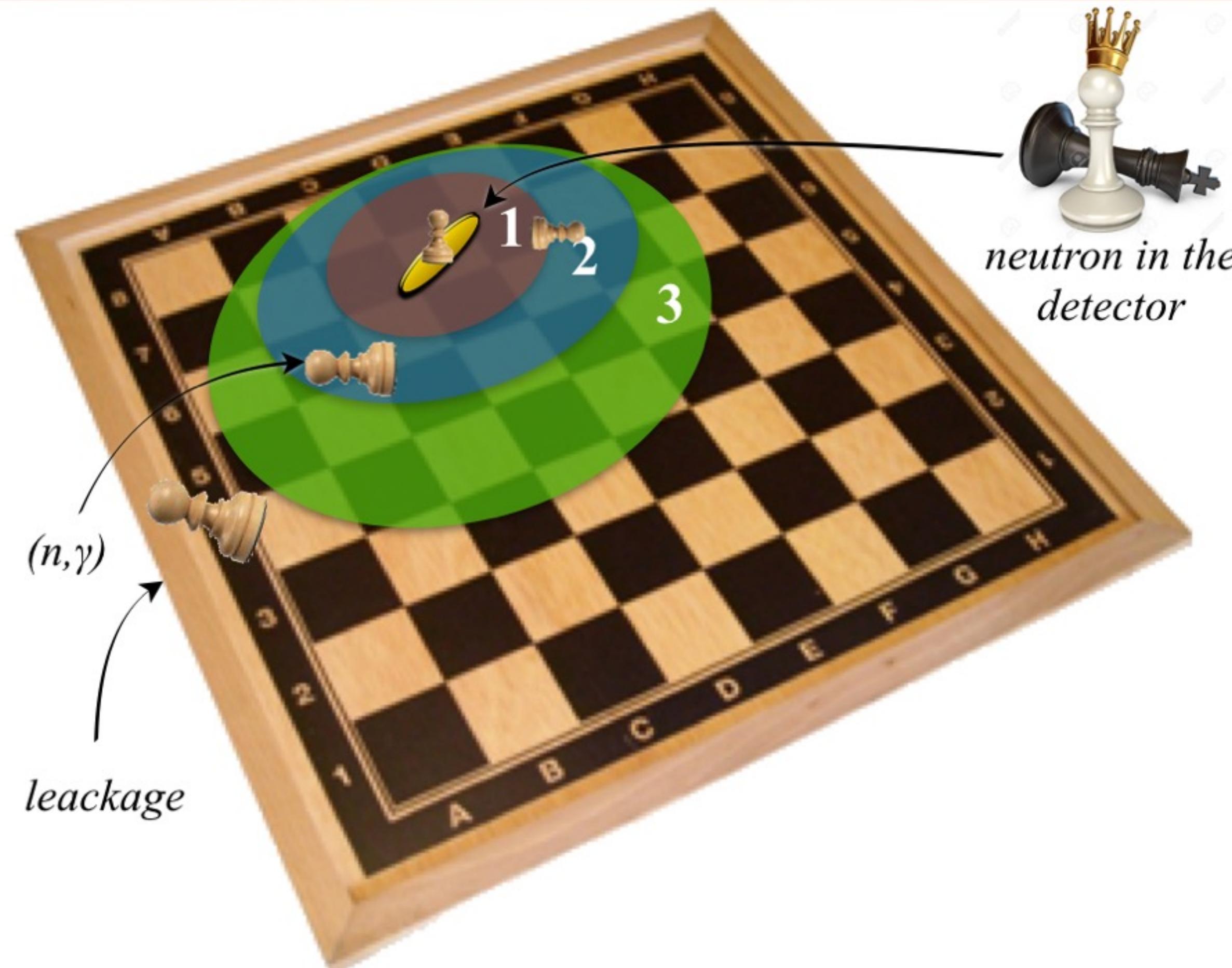
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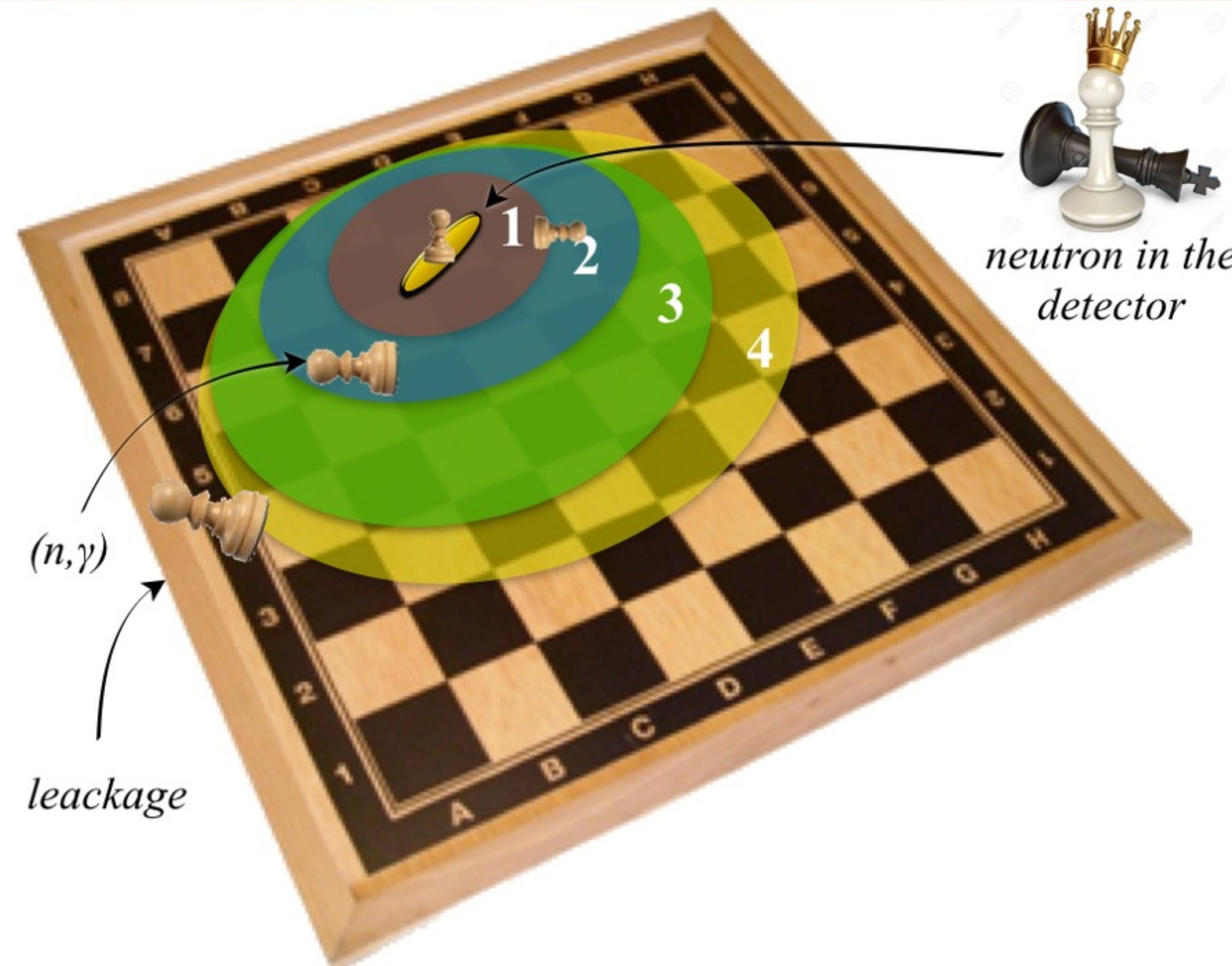
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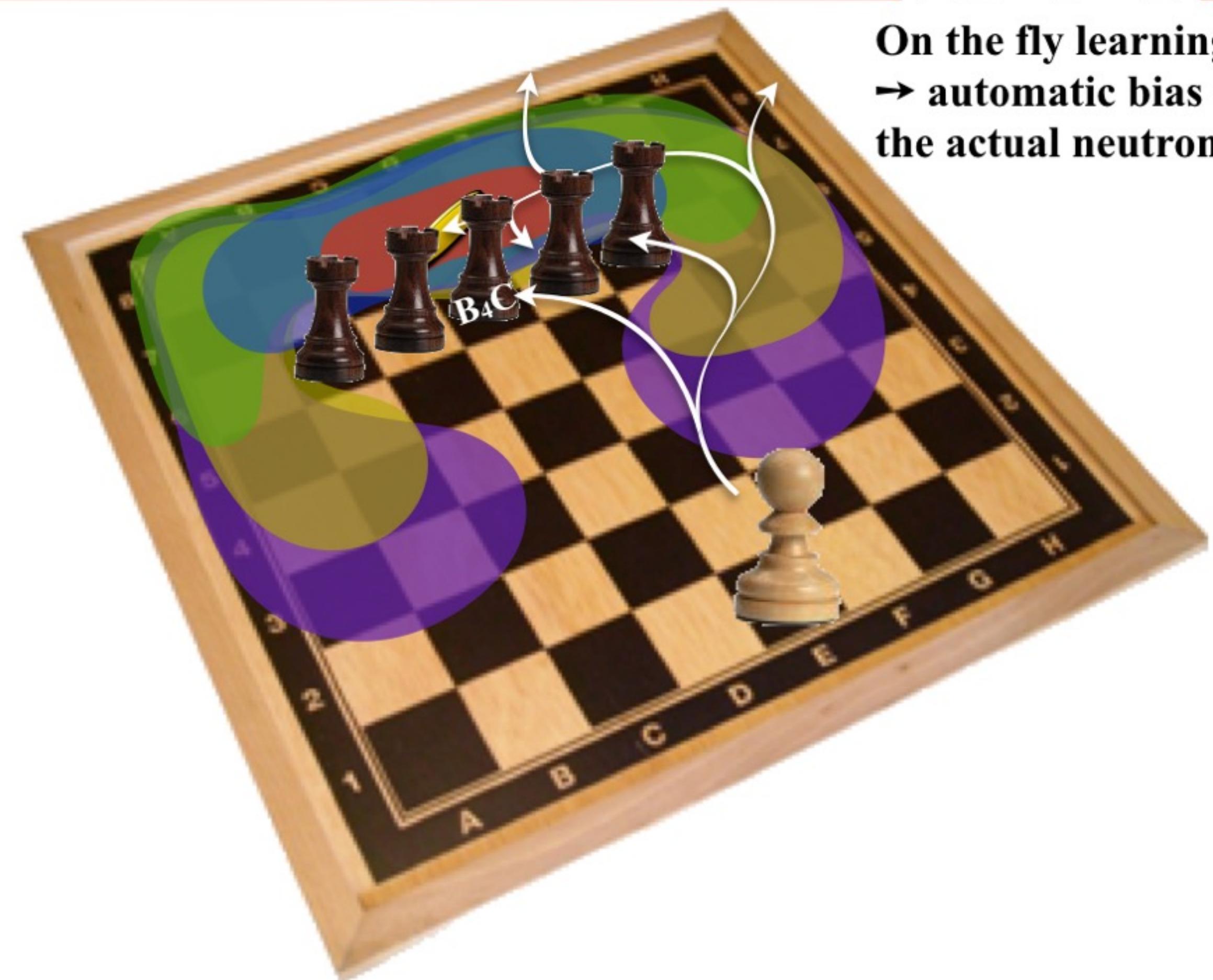
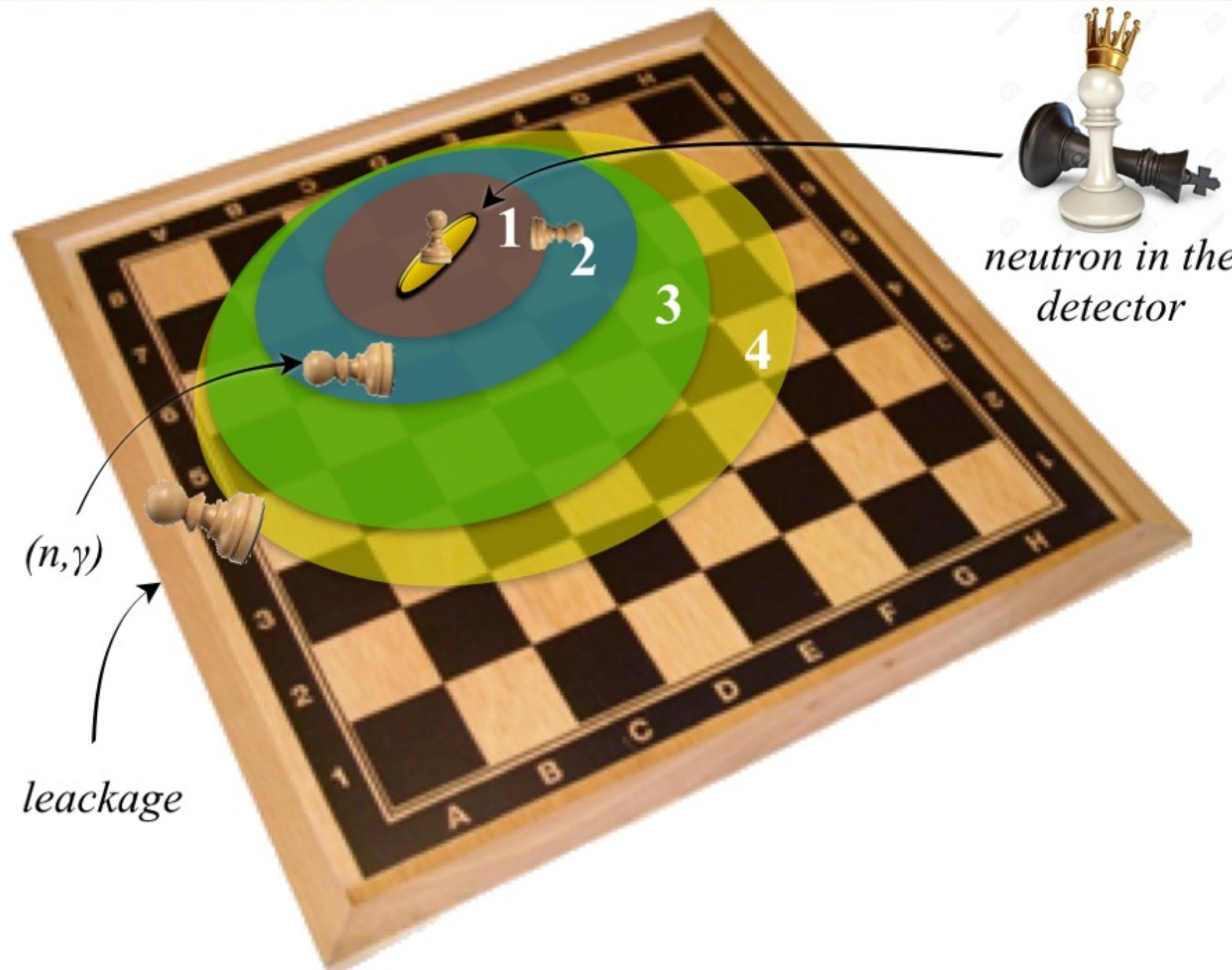
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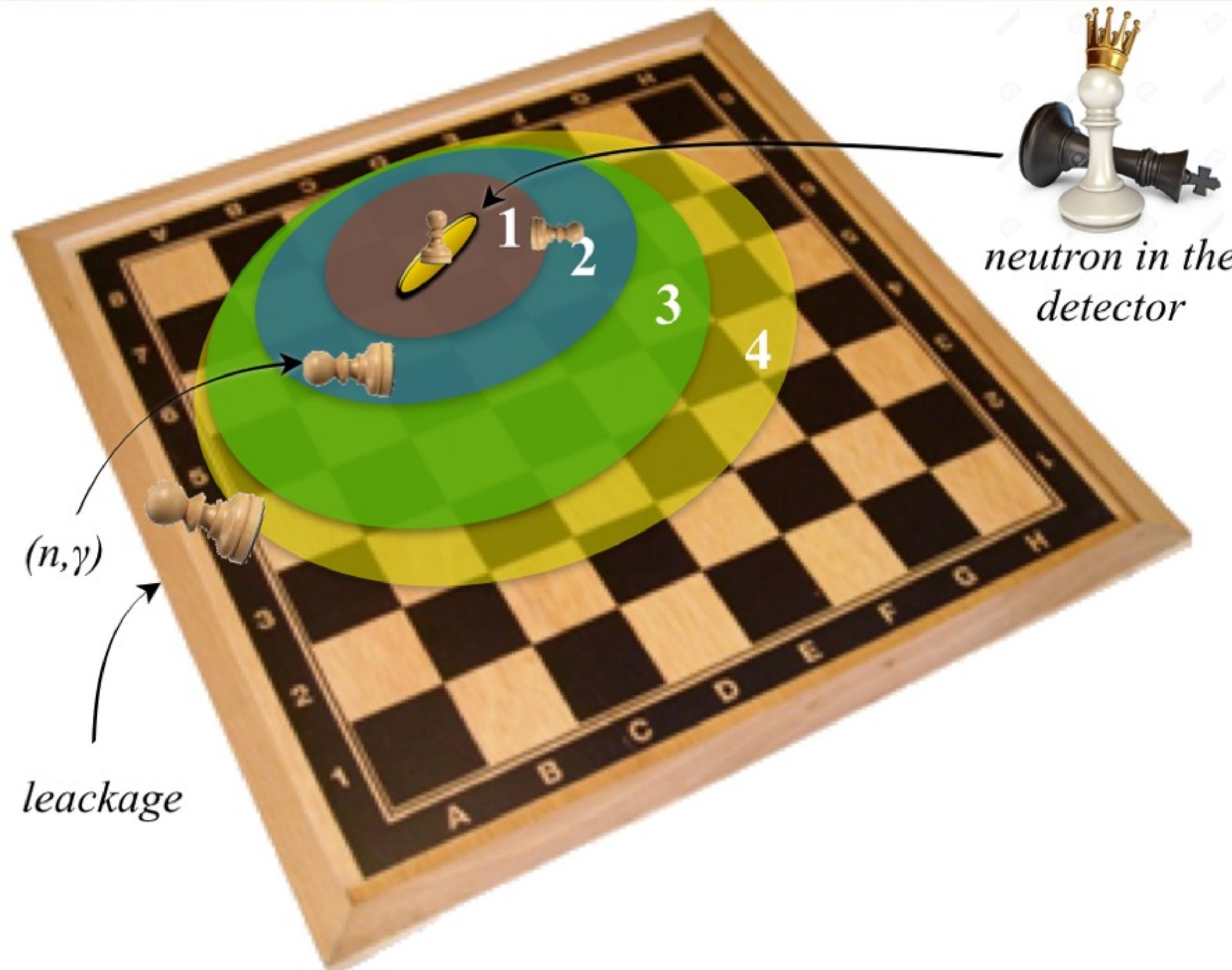
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Thermal neutron with a weight of 0.5

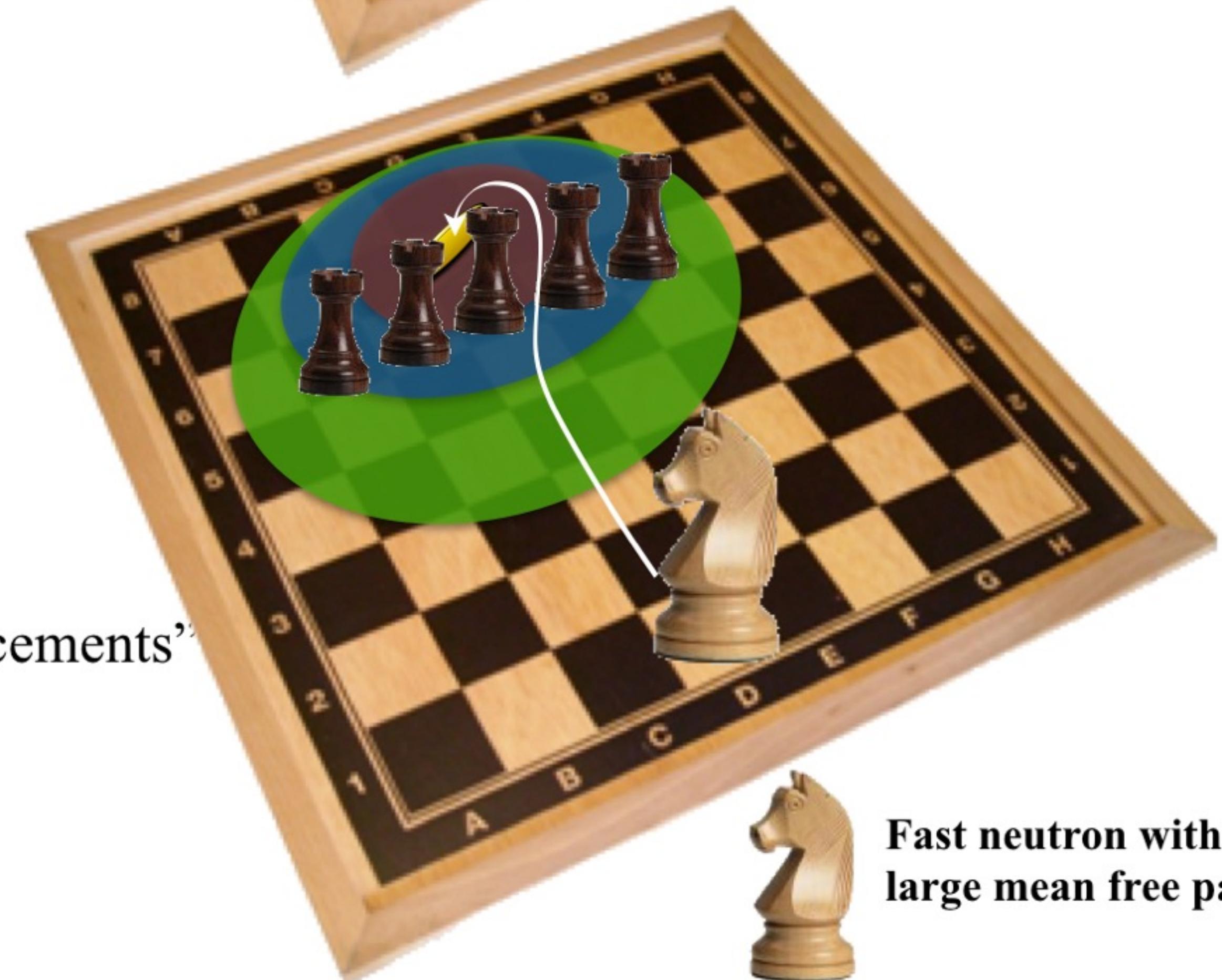
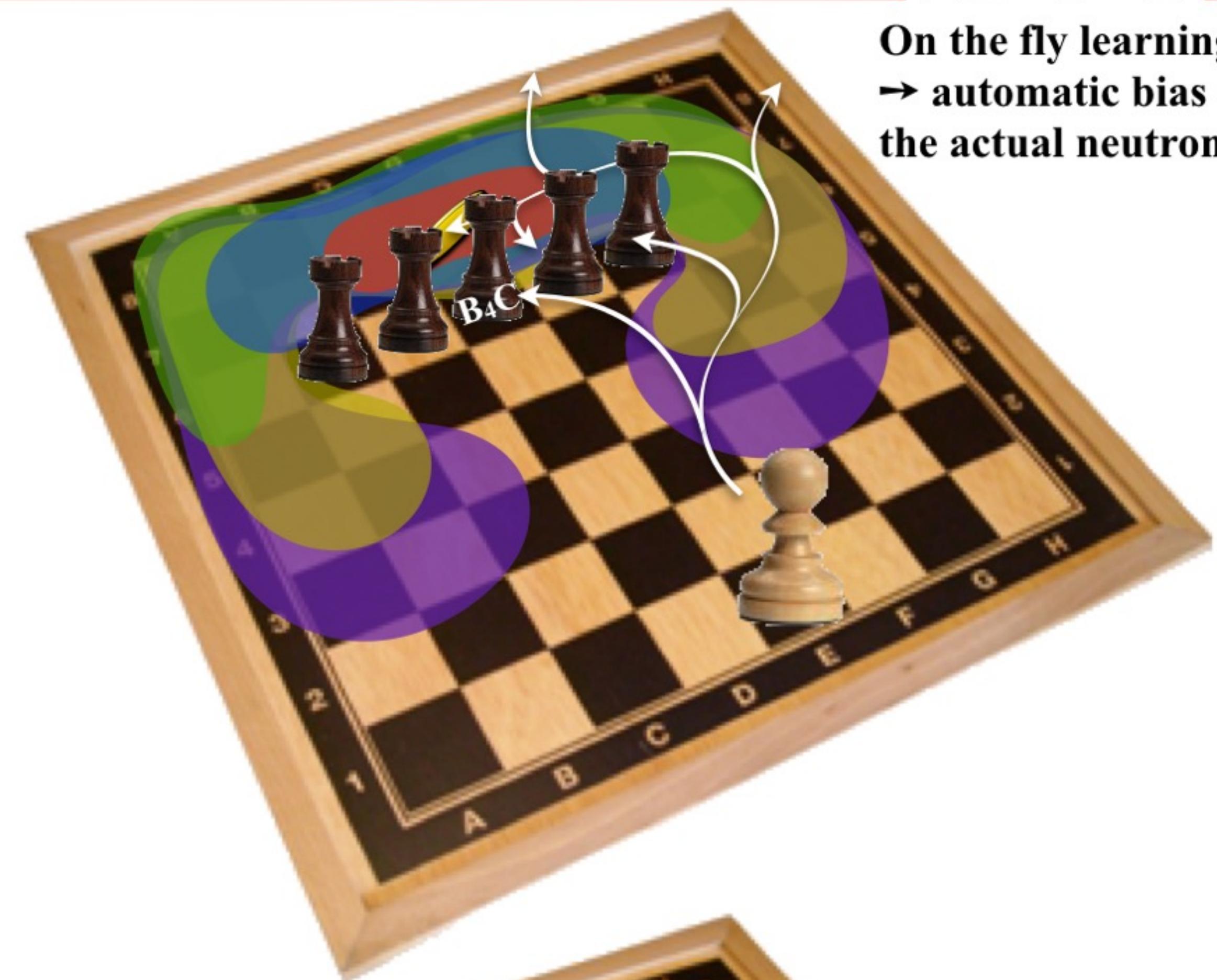
Principle

- On the fly learning of the “minimal number of displacements” required to reach the target
→ *Neutron splitting*
- Geometric X Energy grid (no angular grid yet)



Thermal neutron with a weight of 1

Thermal neutron with a weight of 0.5



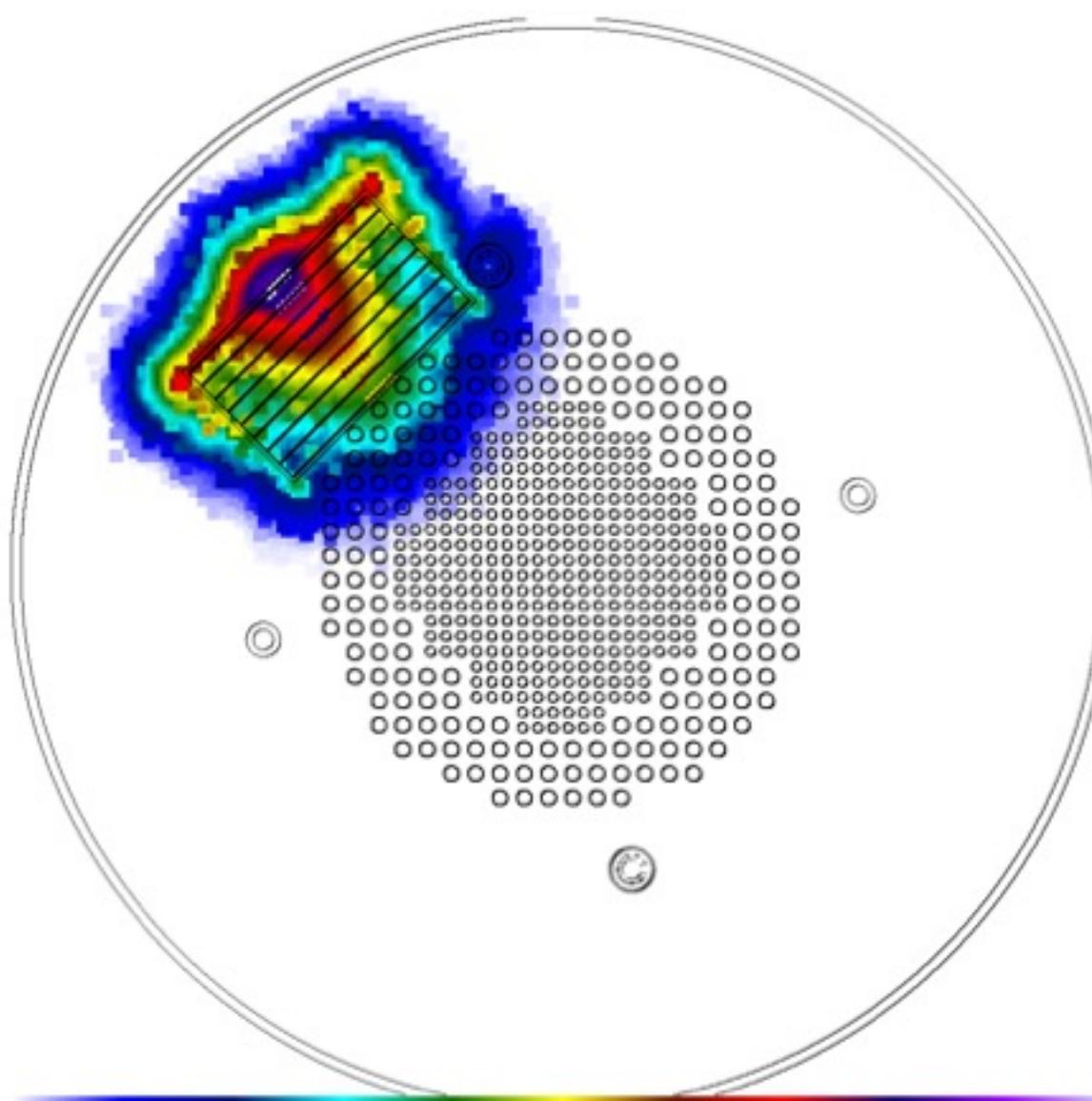
On the fly learning
→ automatic bias on
the actual neutron path

Principle

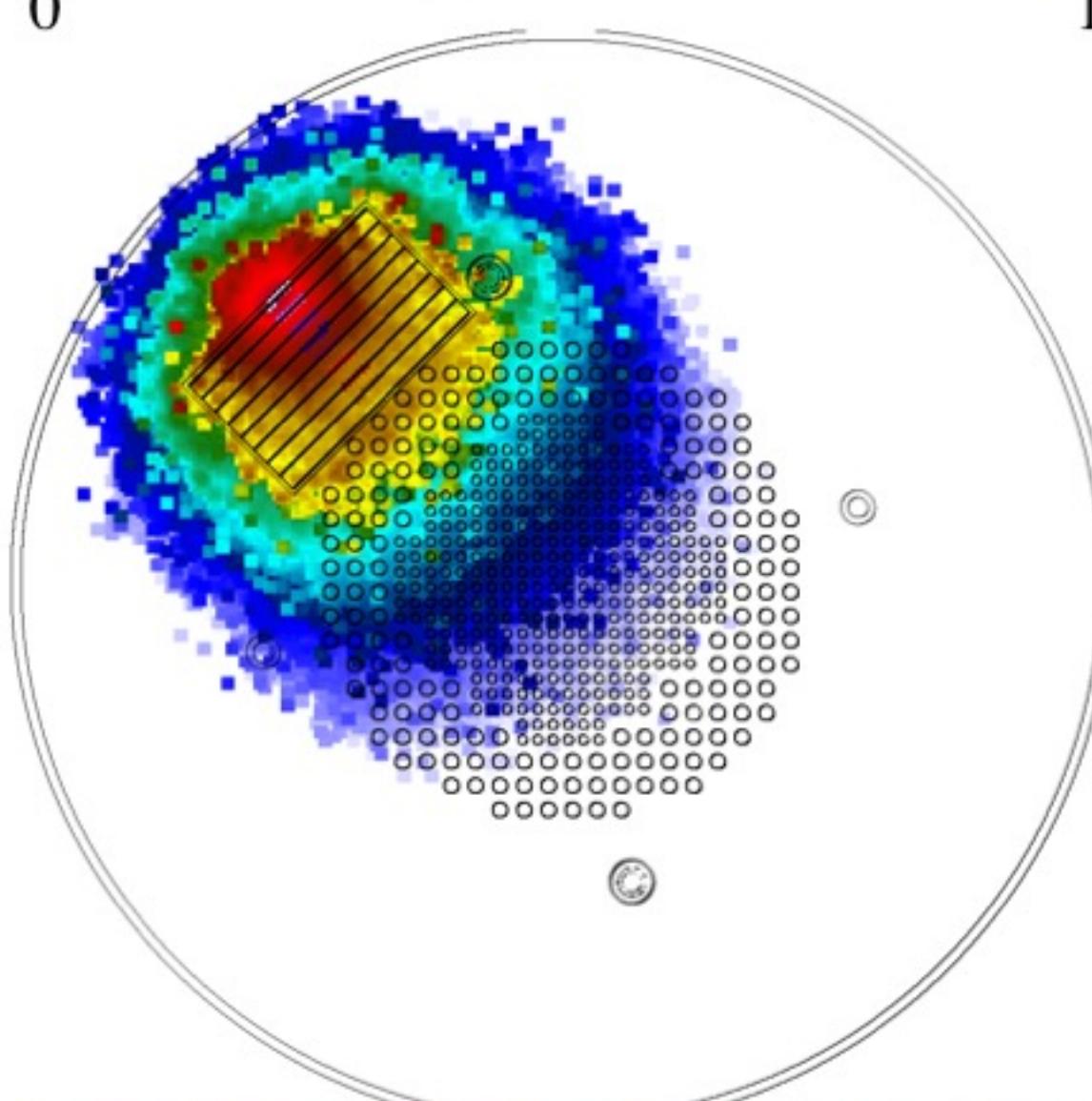
- On the fly learning of the “minimal number of displacements” required to reach the target
→ *Neutron splitting*
- Geometric X Energy grid (no angular grid yet)

Weight field

Thermal neutrons

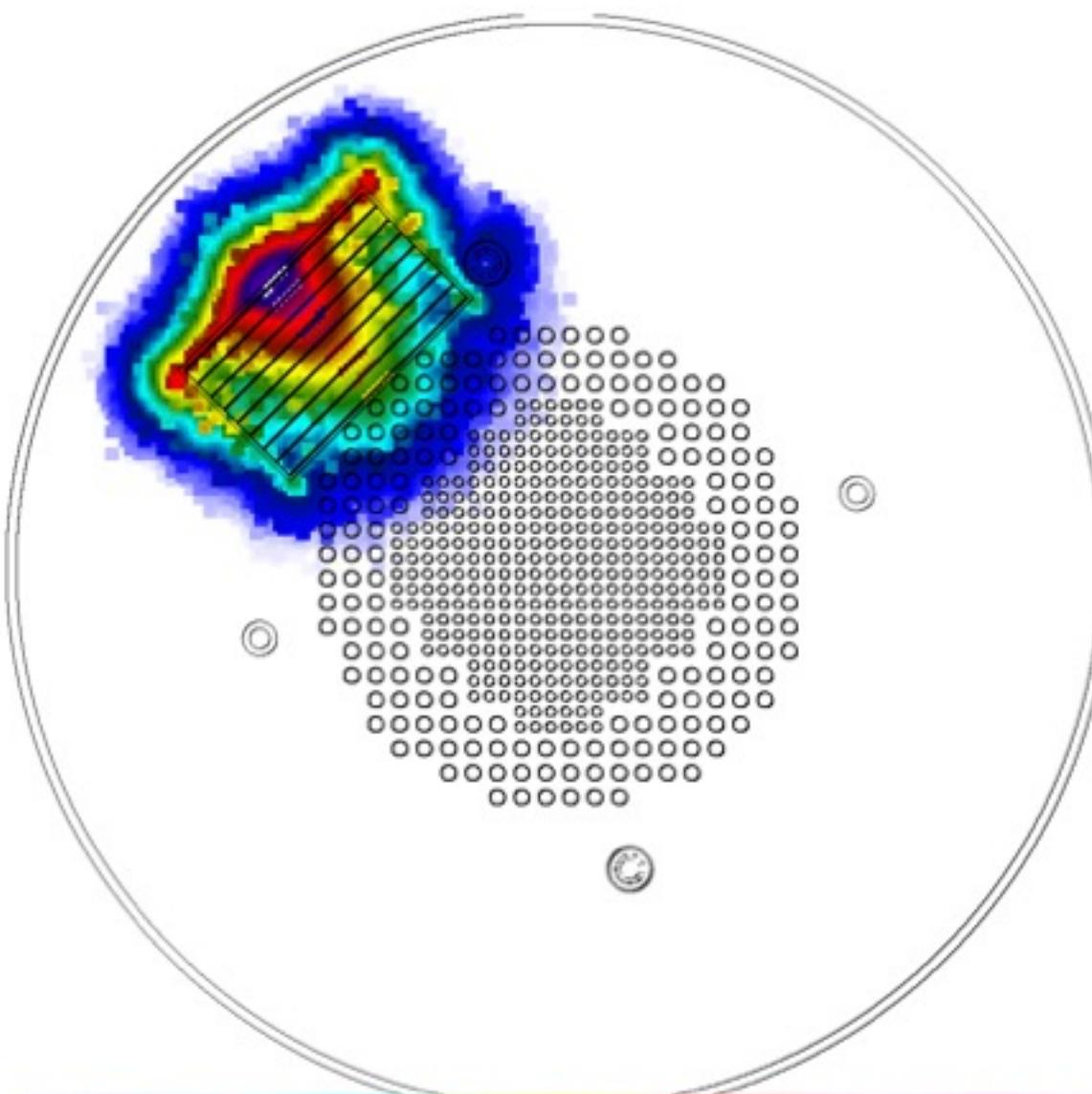


Fast neutrons

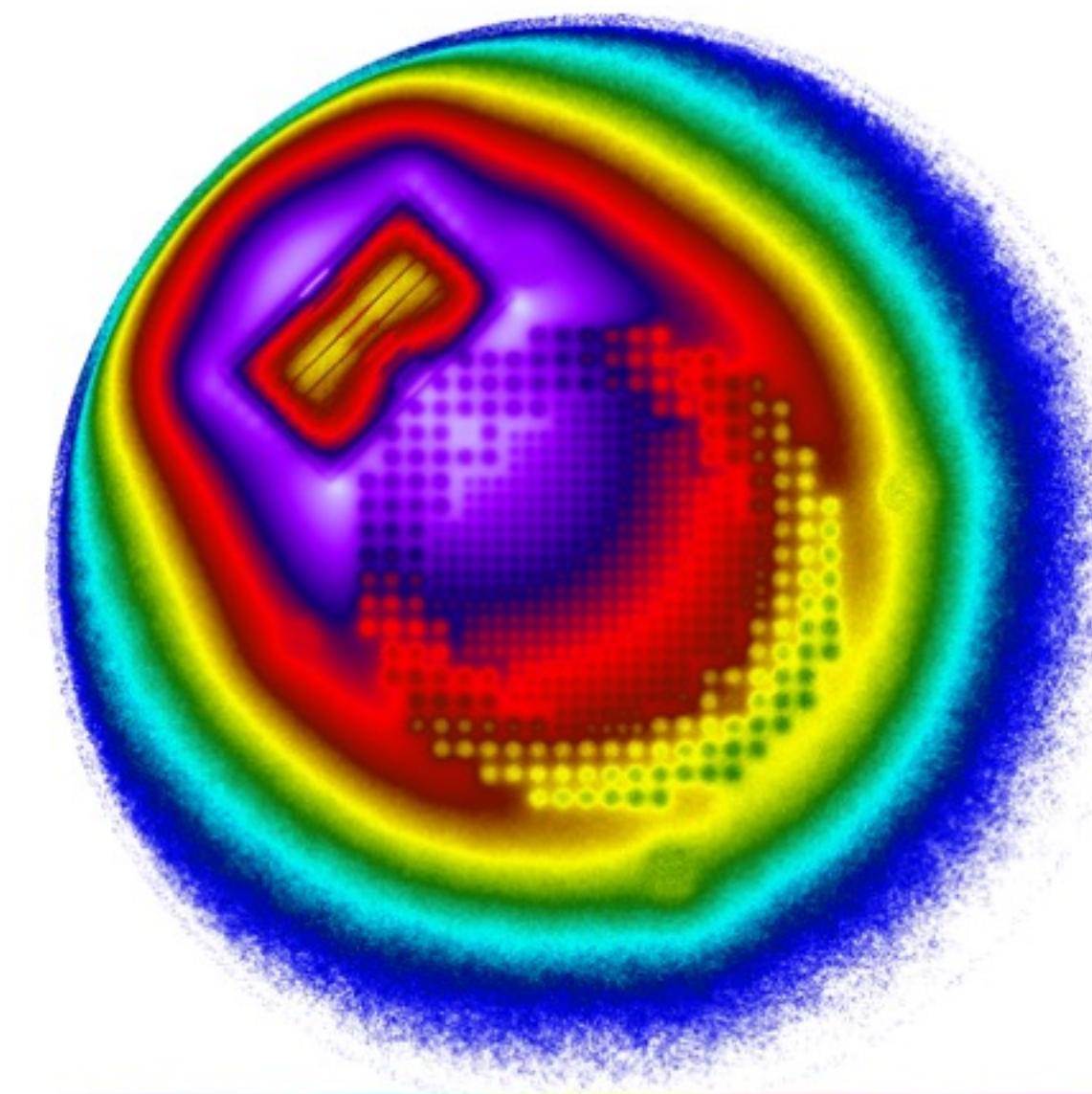


Thermal neutrons

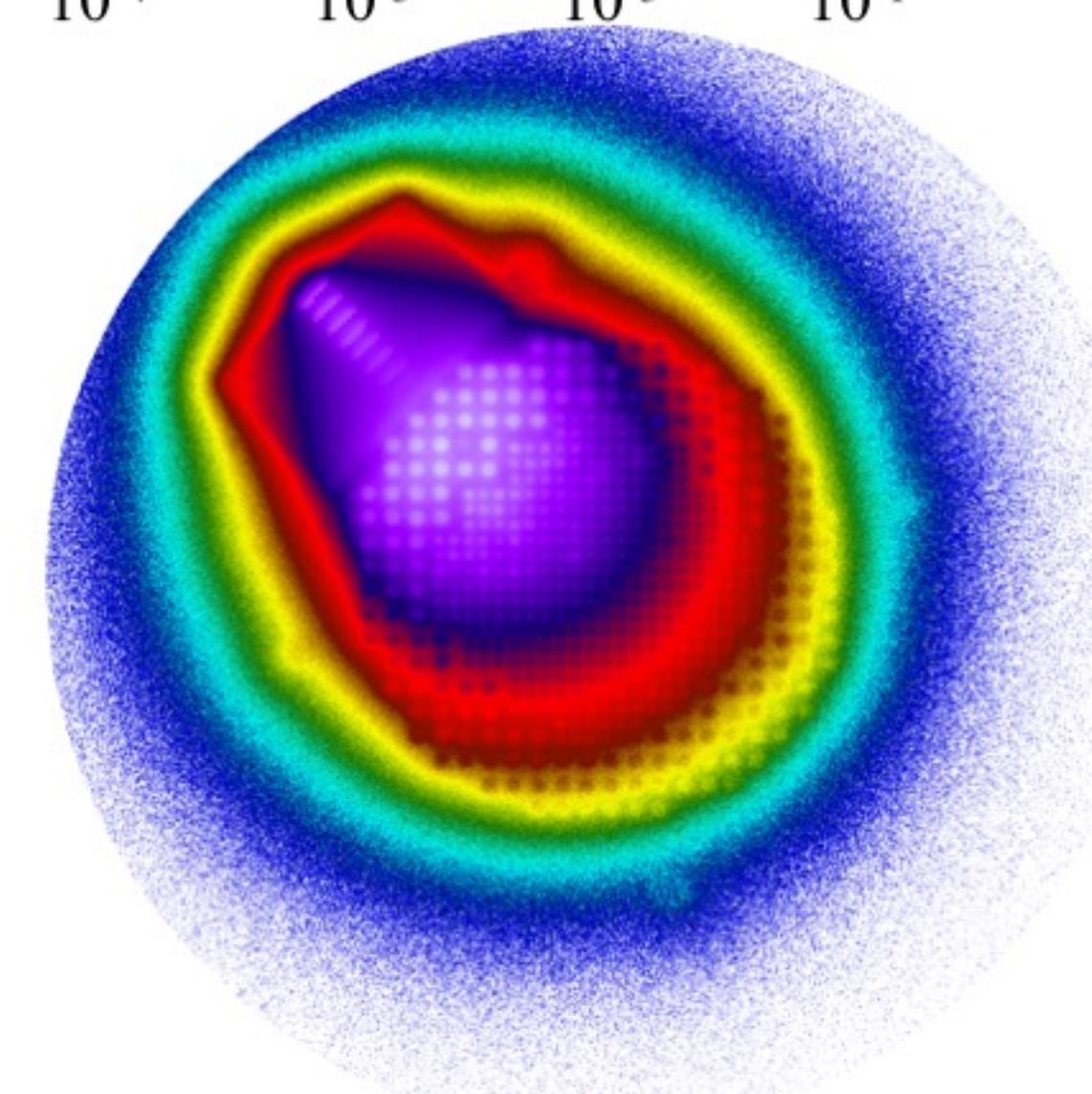
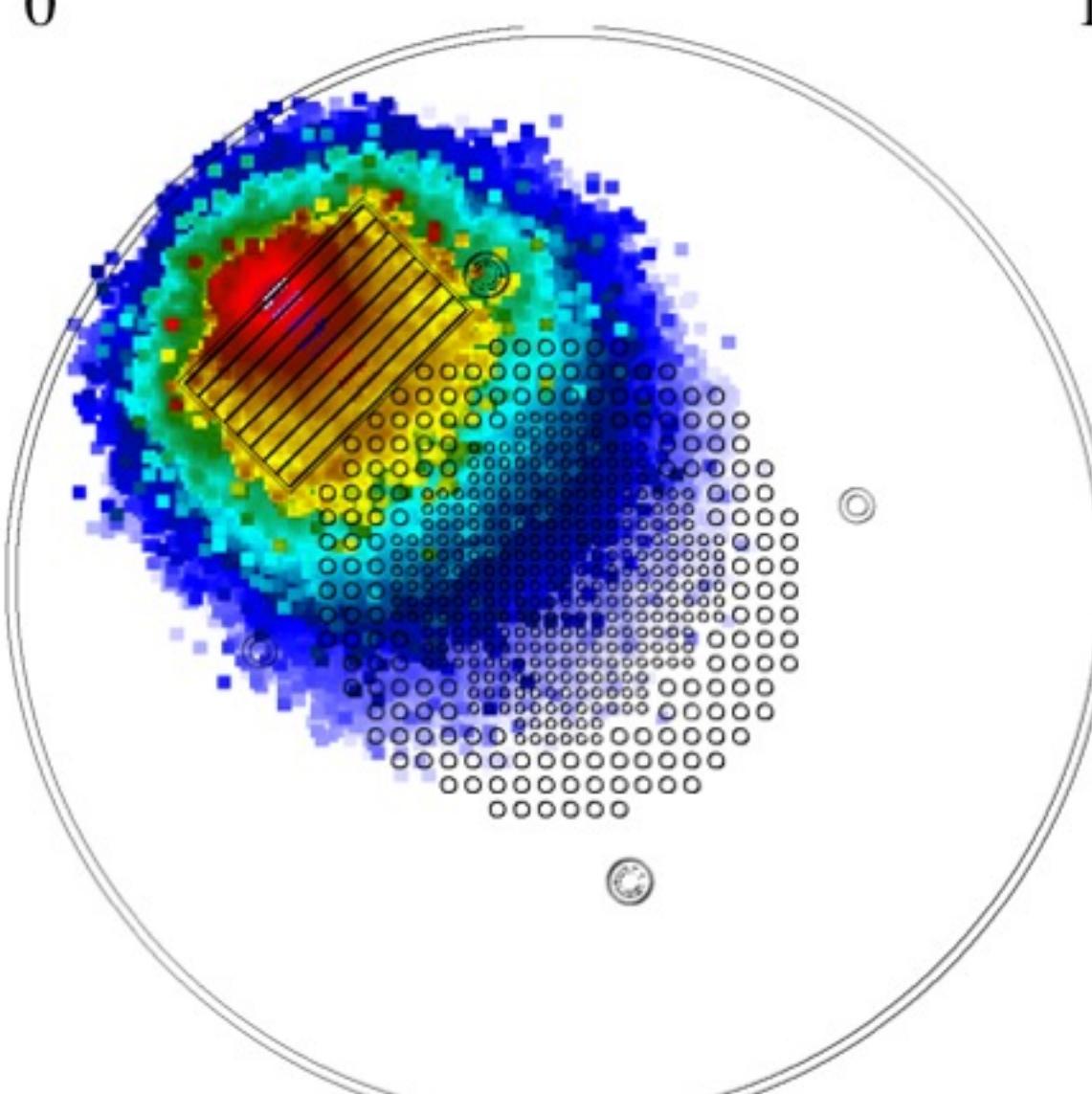
Weight field

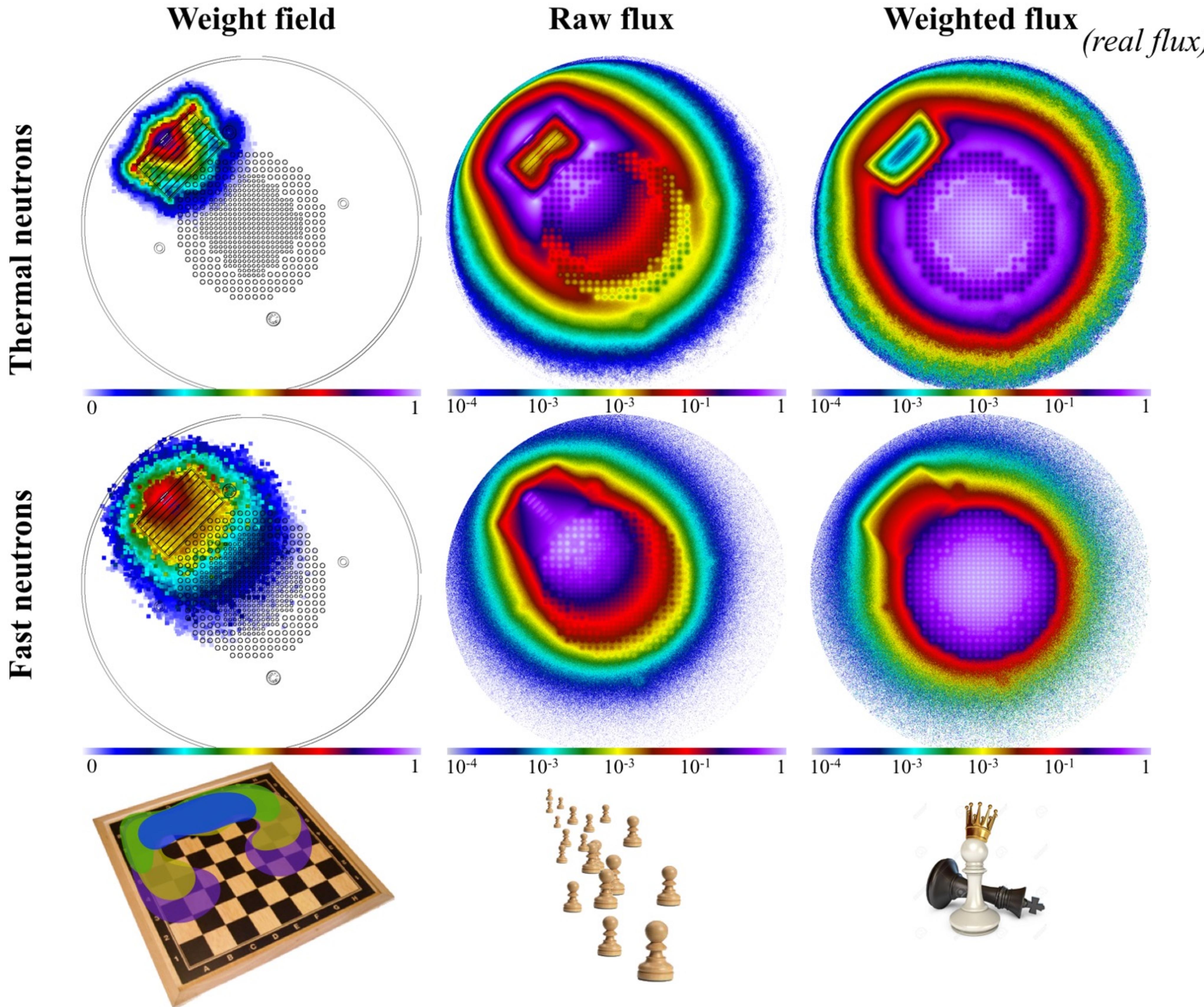


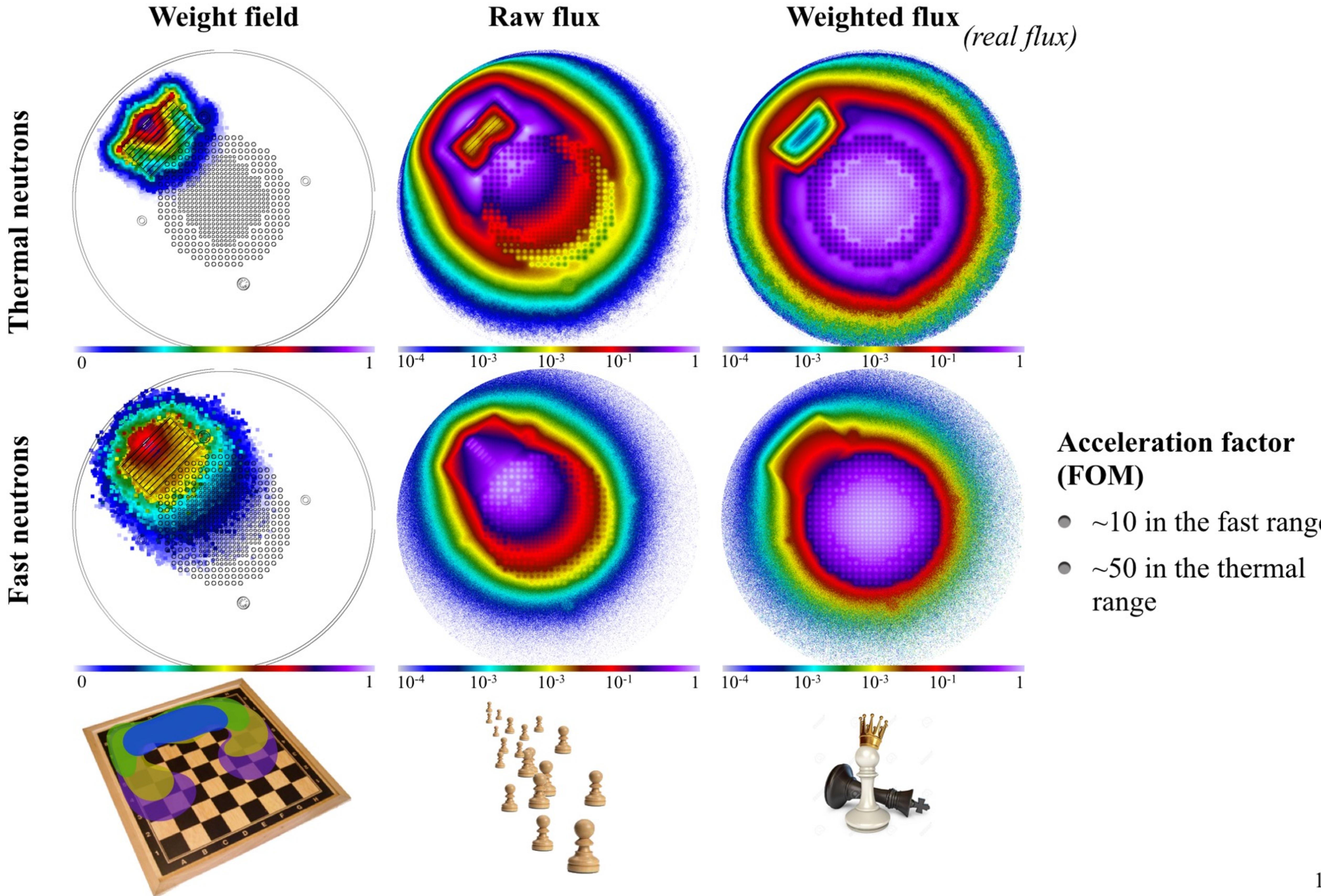
Raw flux



Fast neutrons



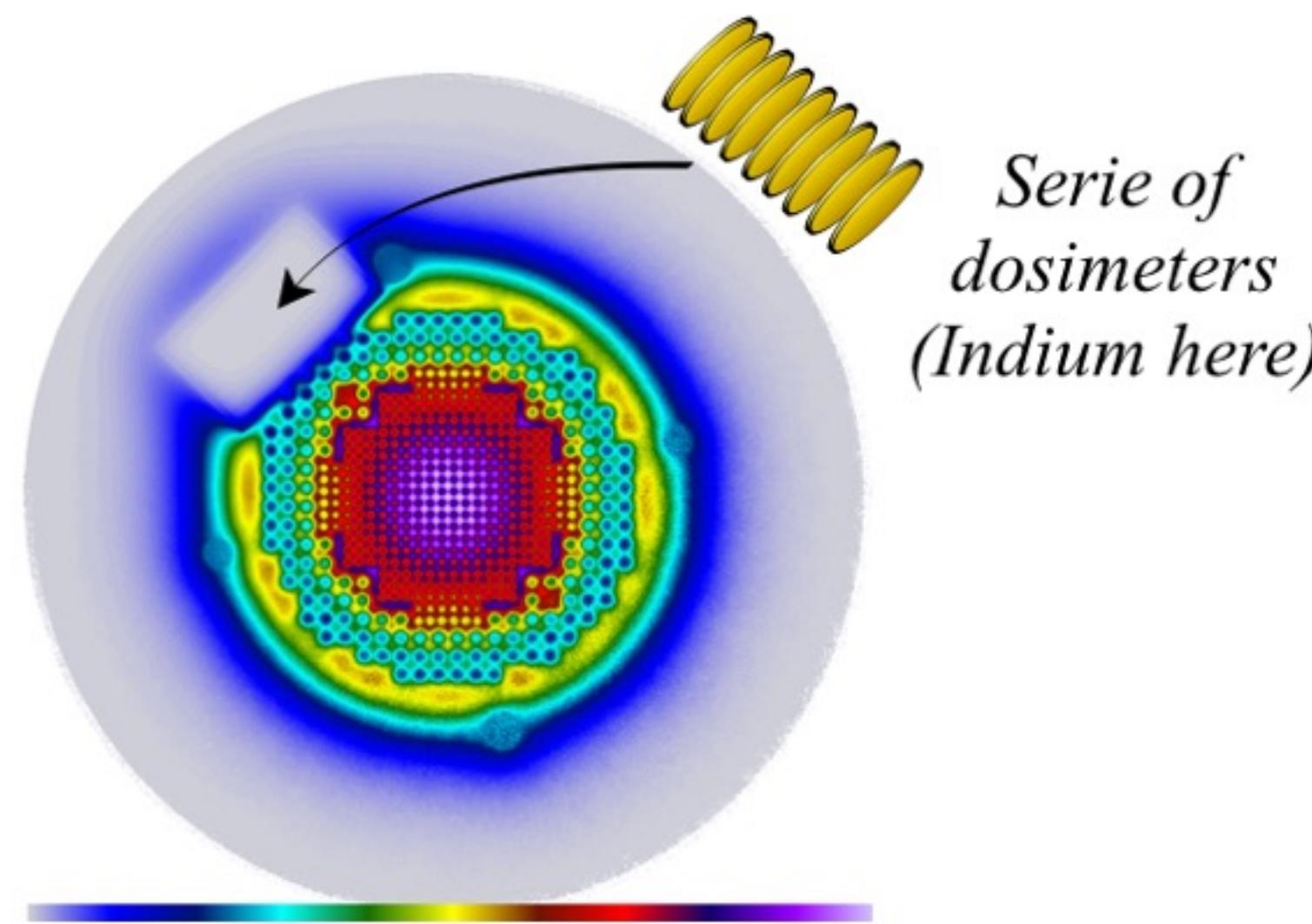




Flux / dosimetry application

CROCUS dosimetry: neutron flux

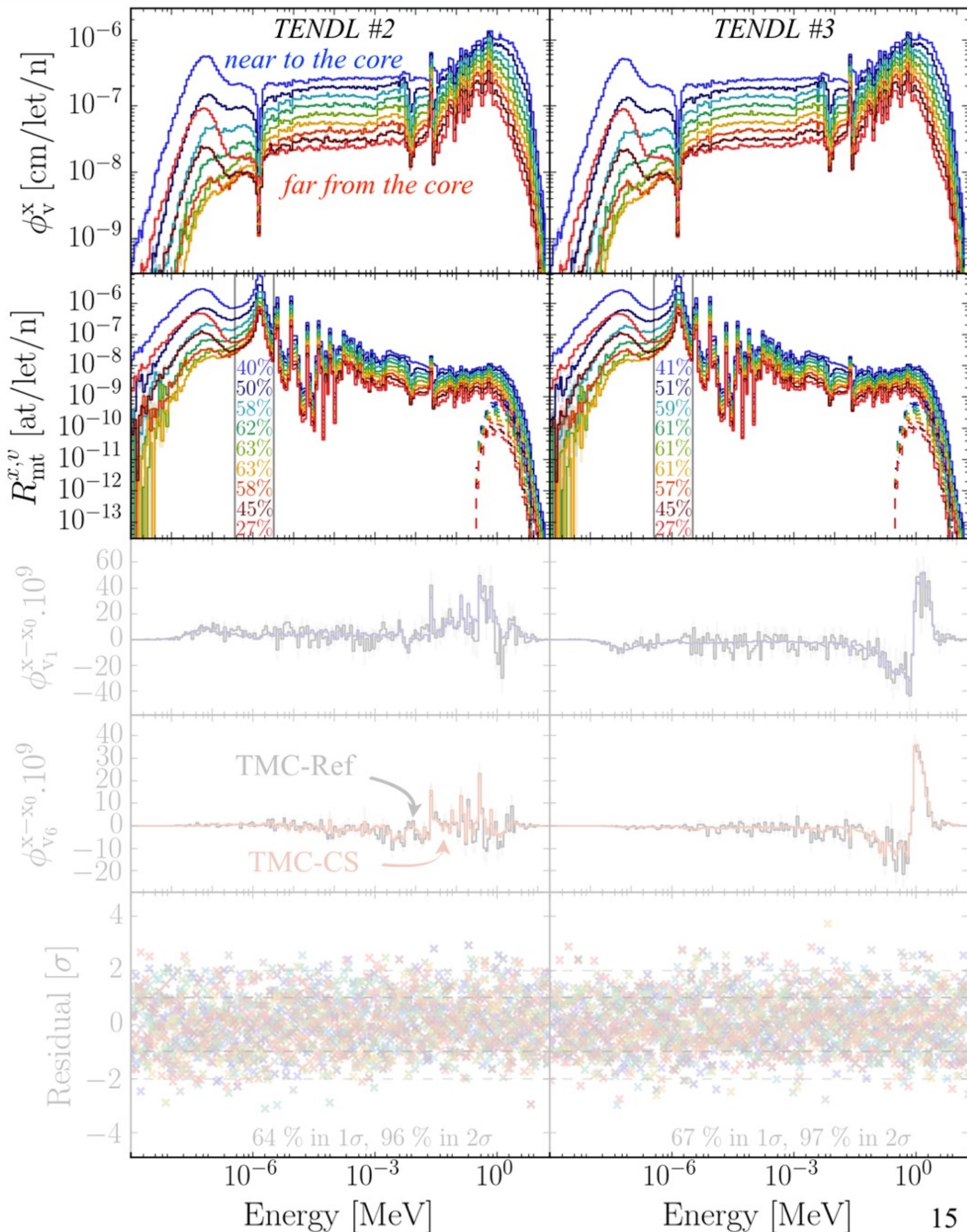
- Flux calculated in all the dosimeters



- Each flux is declined according to each TENDL cross section
→ *all Fe isotopes, all mt reactions*
- Spectrum distribution different according to the XS

Observation:

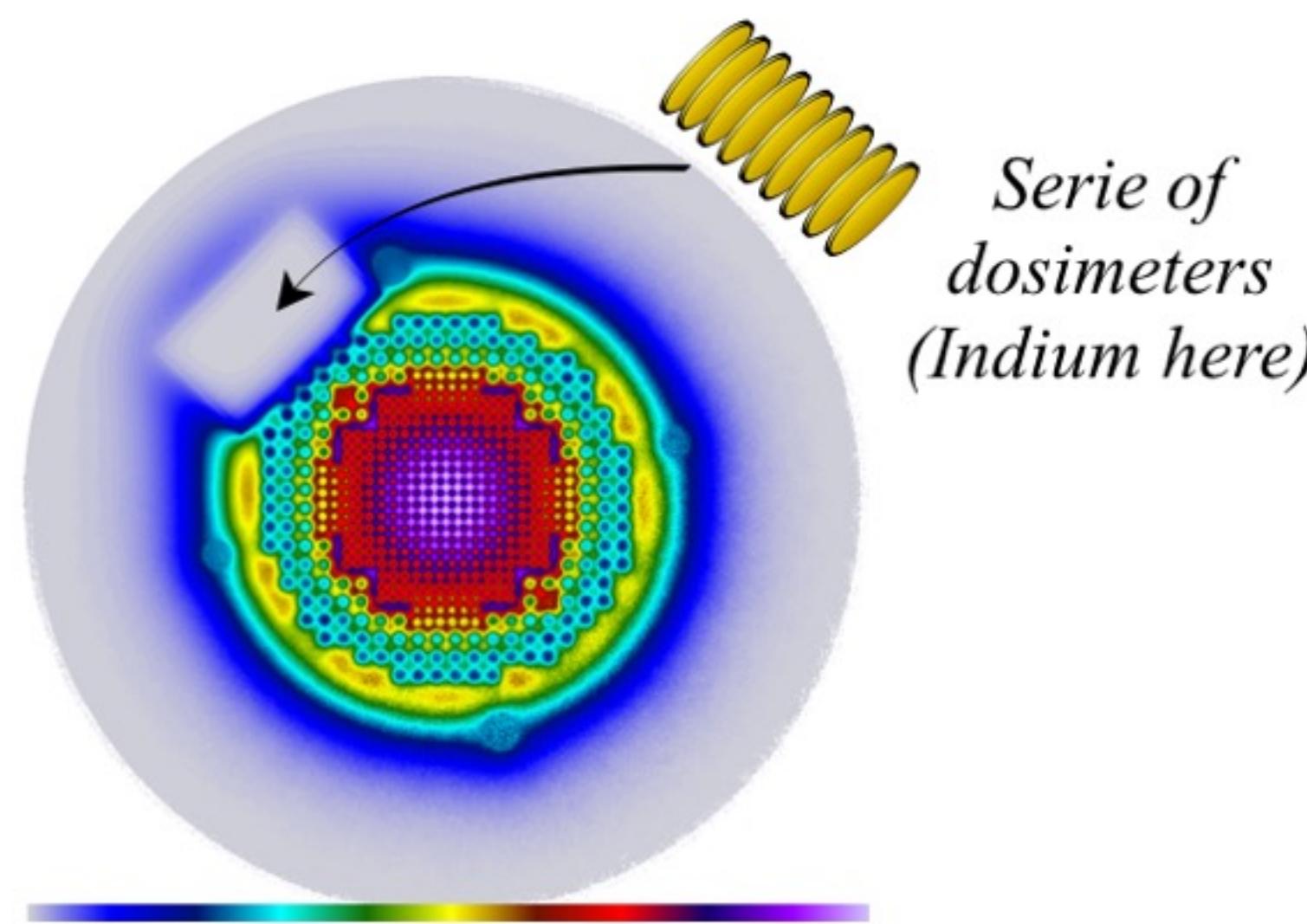
- Impact of ND uncertainty directly visible on the flux in the dosimeters
- Very close trend line between TMC-Ref and TMC-CS
- Reduced statistical uncertainty with TMC-CS



Flux / dosimetry application

CROCUS dosimetry: neutron flux

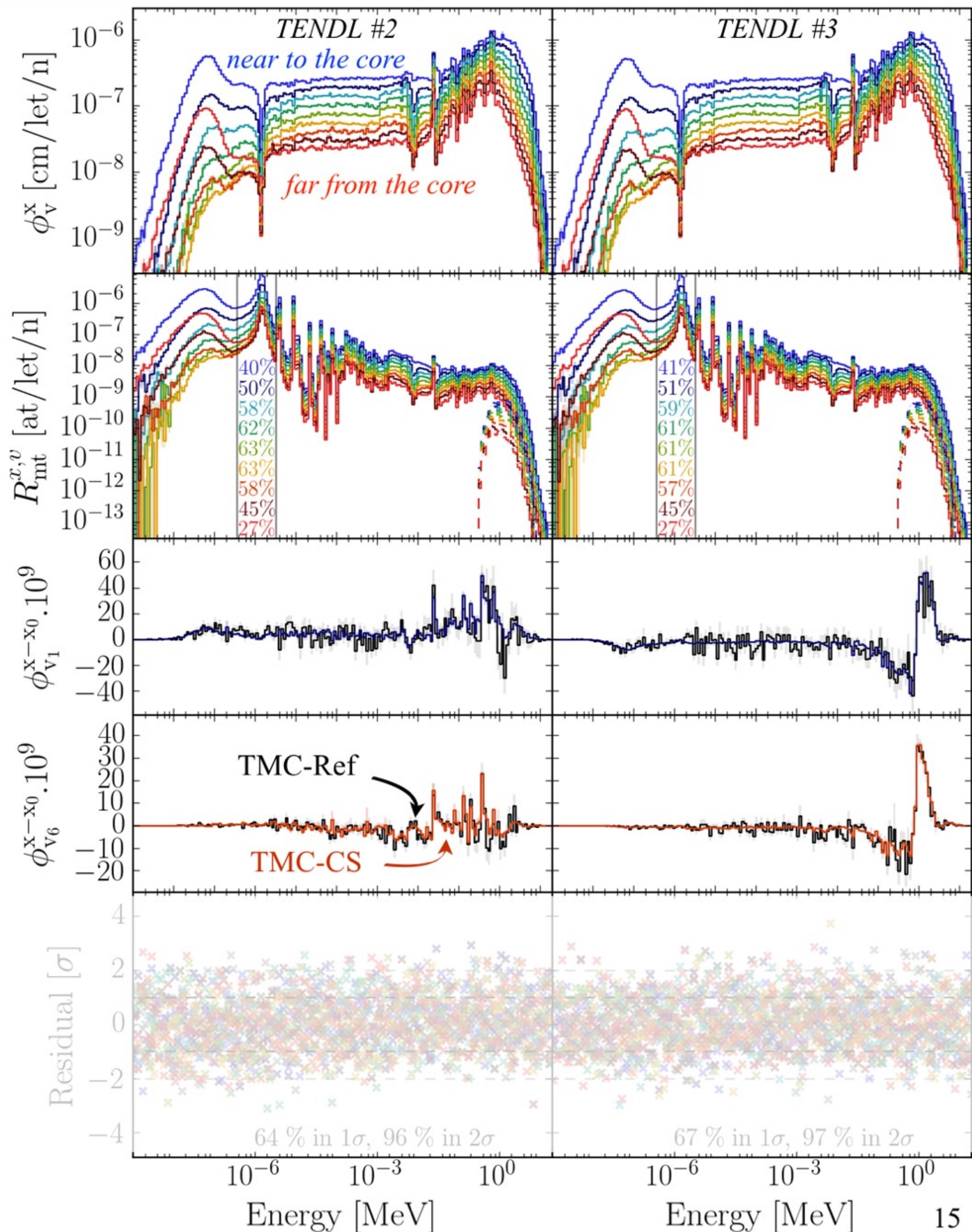
- Flux calculated in all the dosimeters



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Observation:

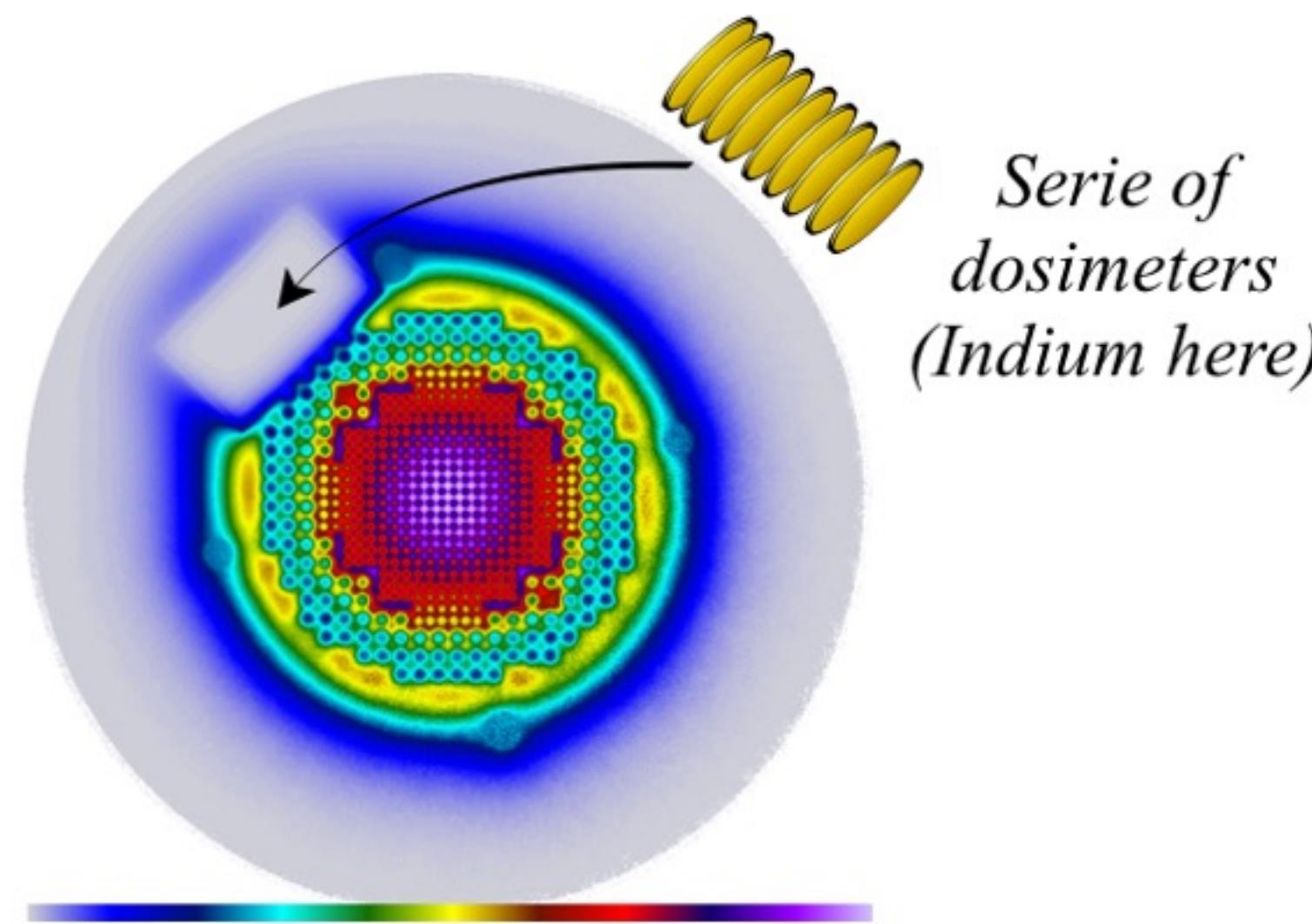
- Impact of ND uncertainty directly visible on the flux in the dosimeters
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- Reduced statistical uncertainty with TMC-CS



Flux / dosimetry application

CROCUS dosimetry: neutron flux

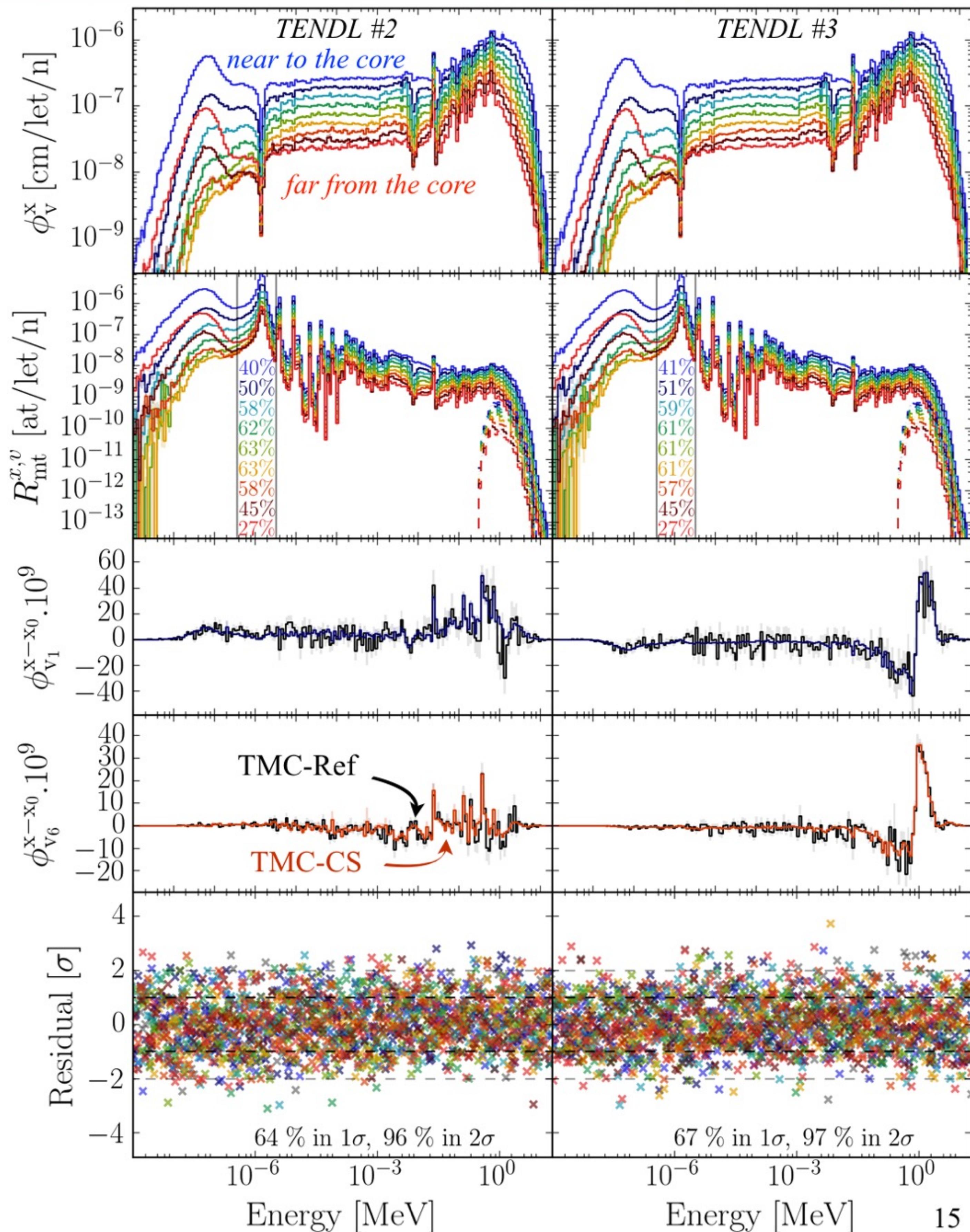
- Flux calculated in all the dosimeters



- Each flux is declined according to each TENDL cross section
→ *all Fe isotopes, all mt reactions*
- Spectrum distribution different according to the XS

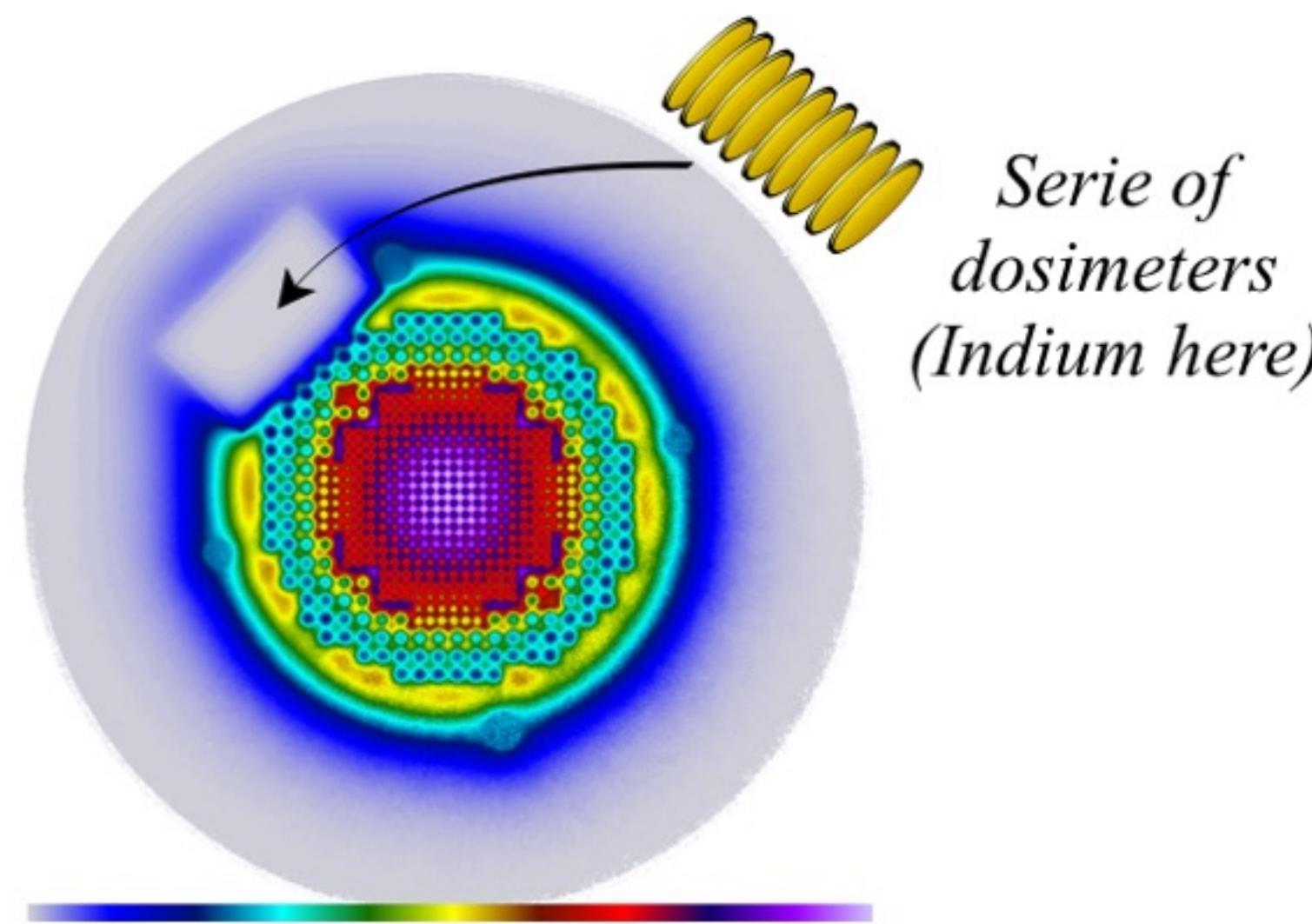
Observation:

- Impact of ND uncertainty directly visible on the flux in the dosimeters
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CROCUS dosimetry: reaction rate

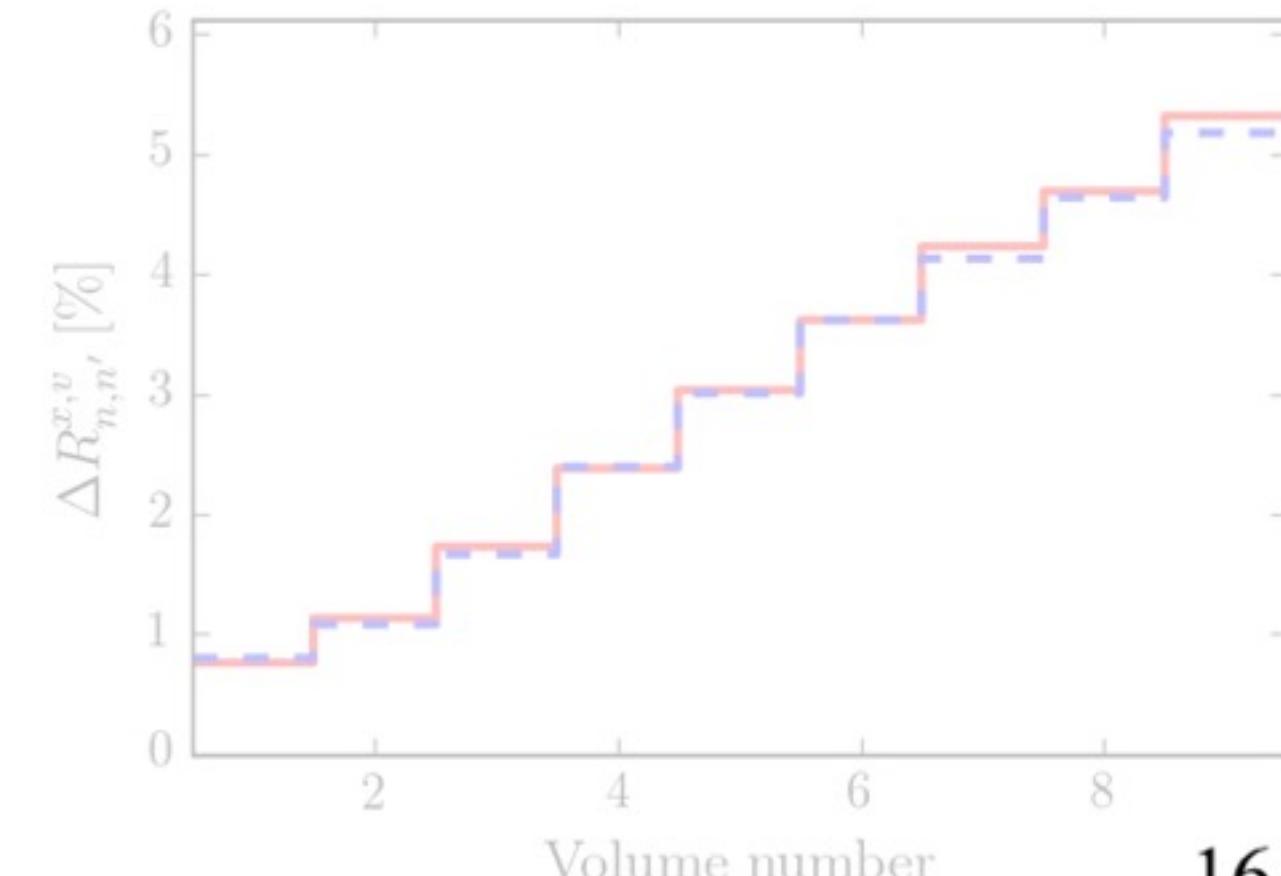
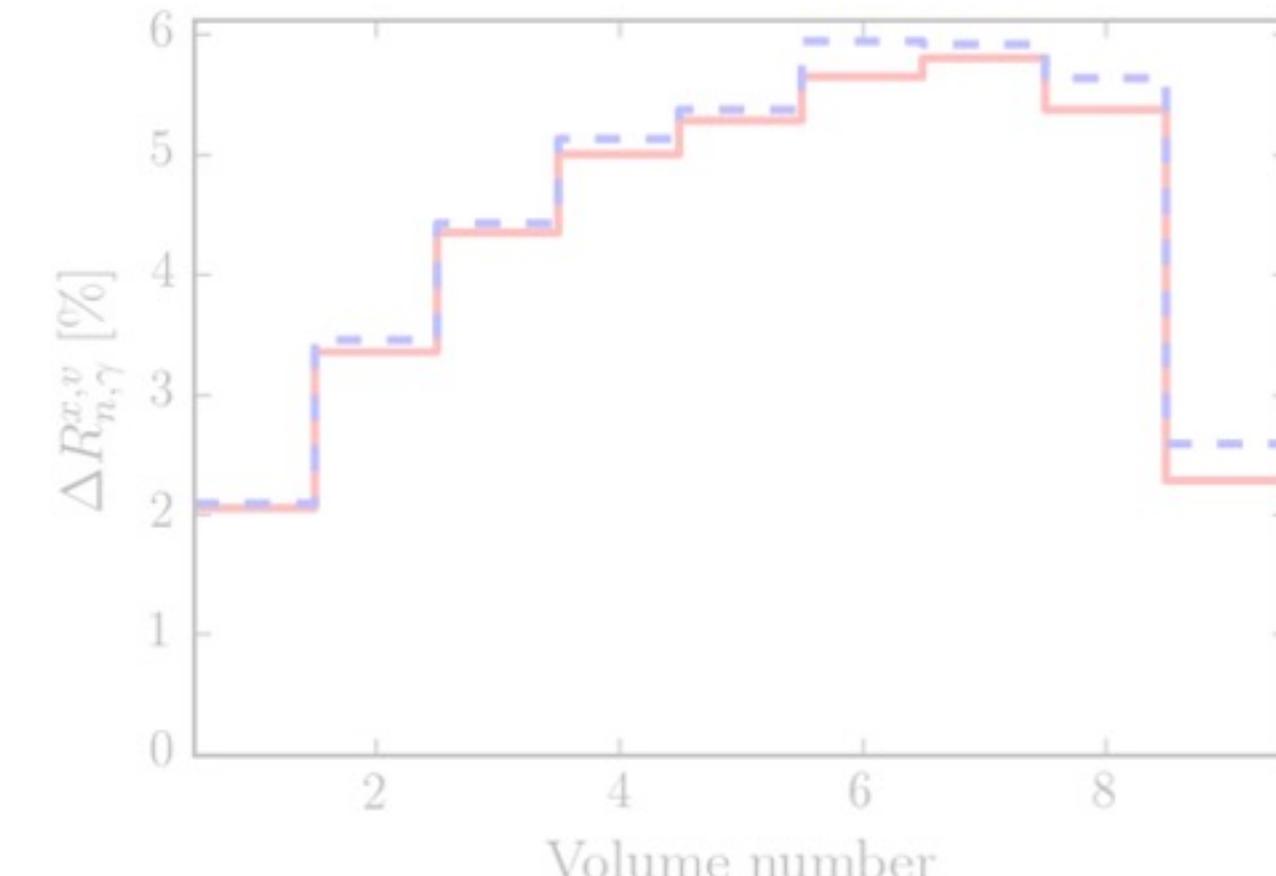
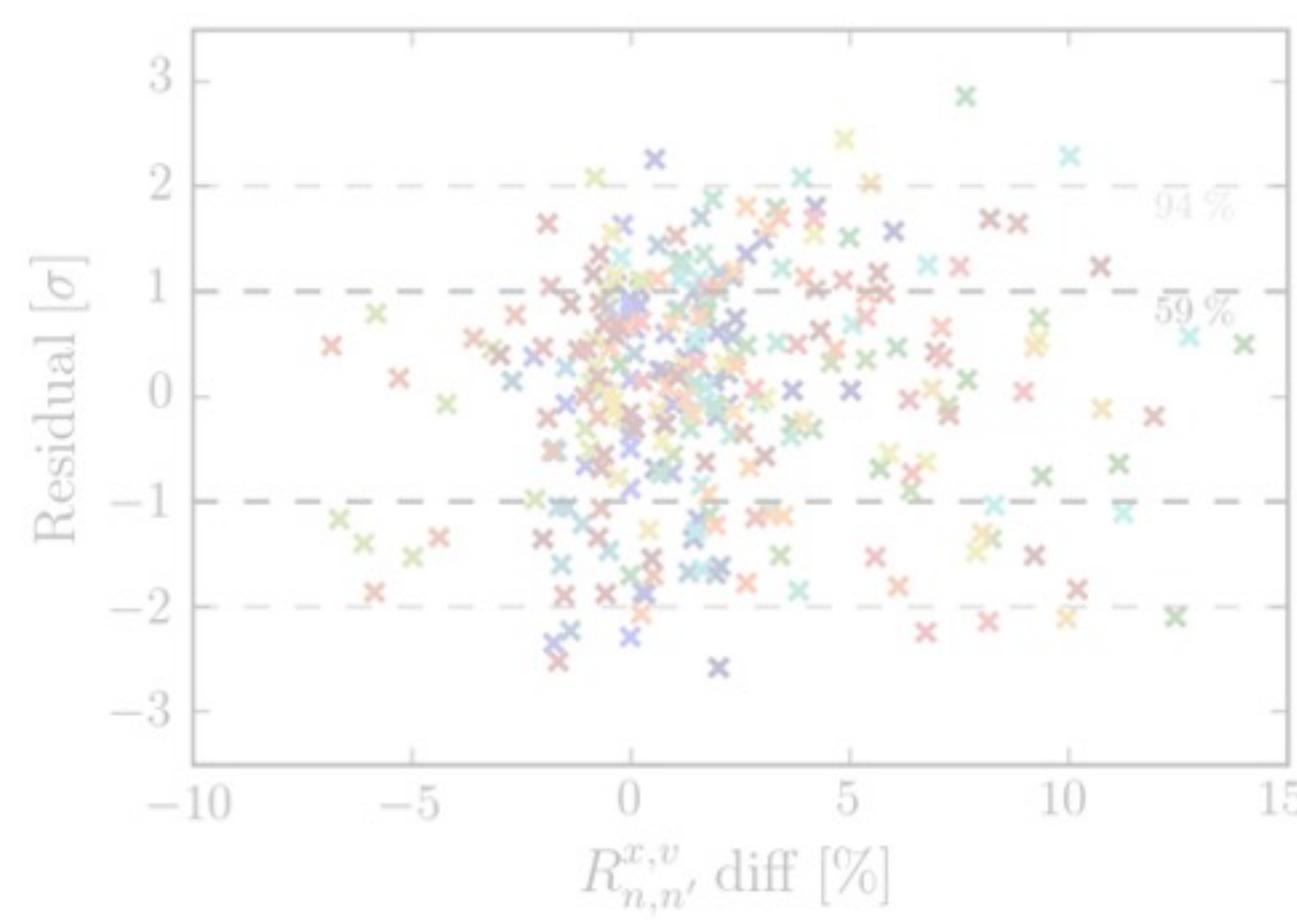
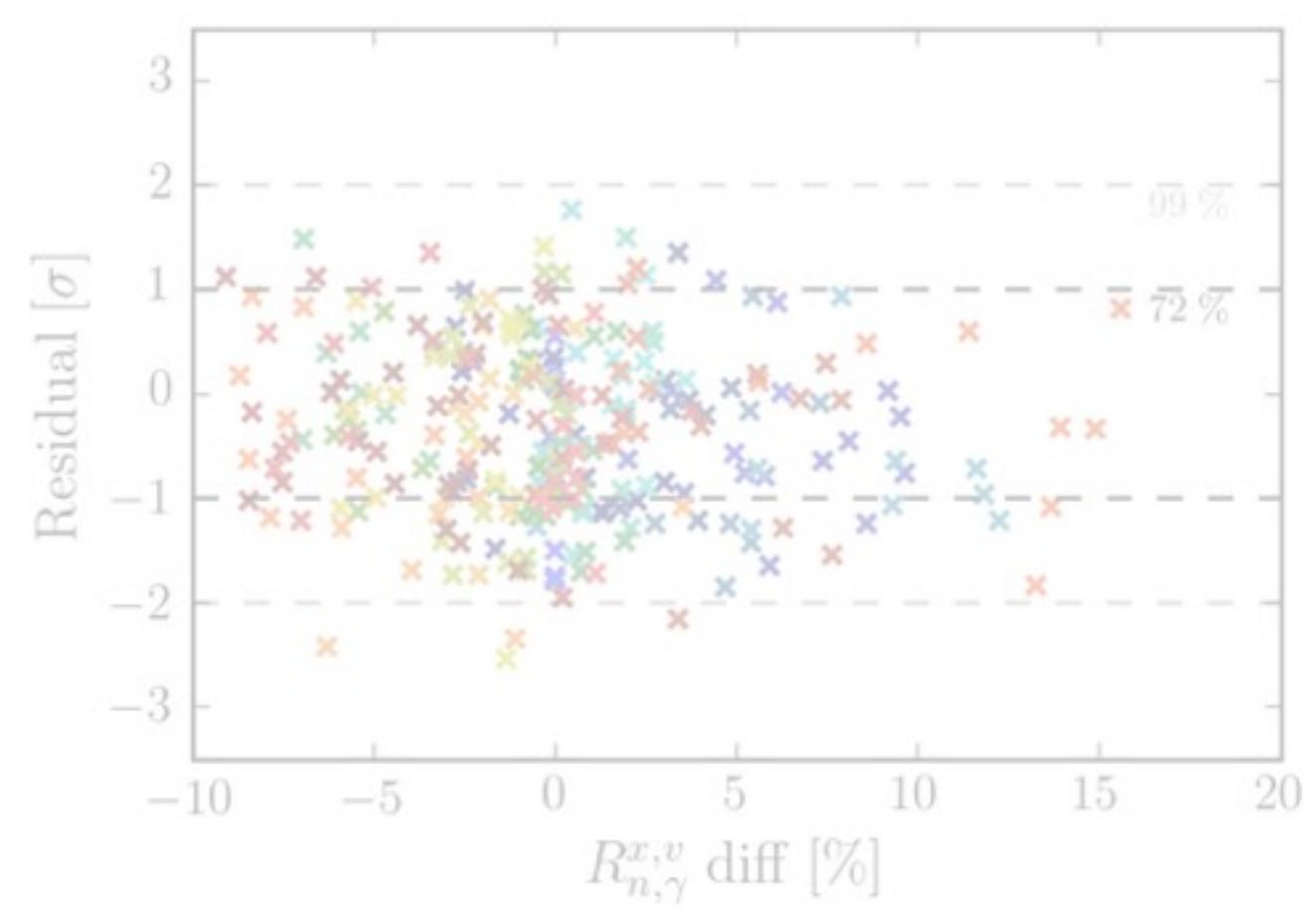
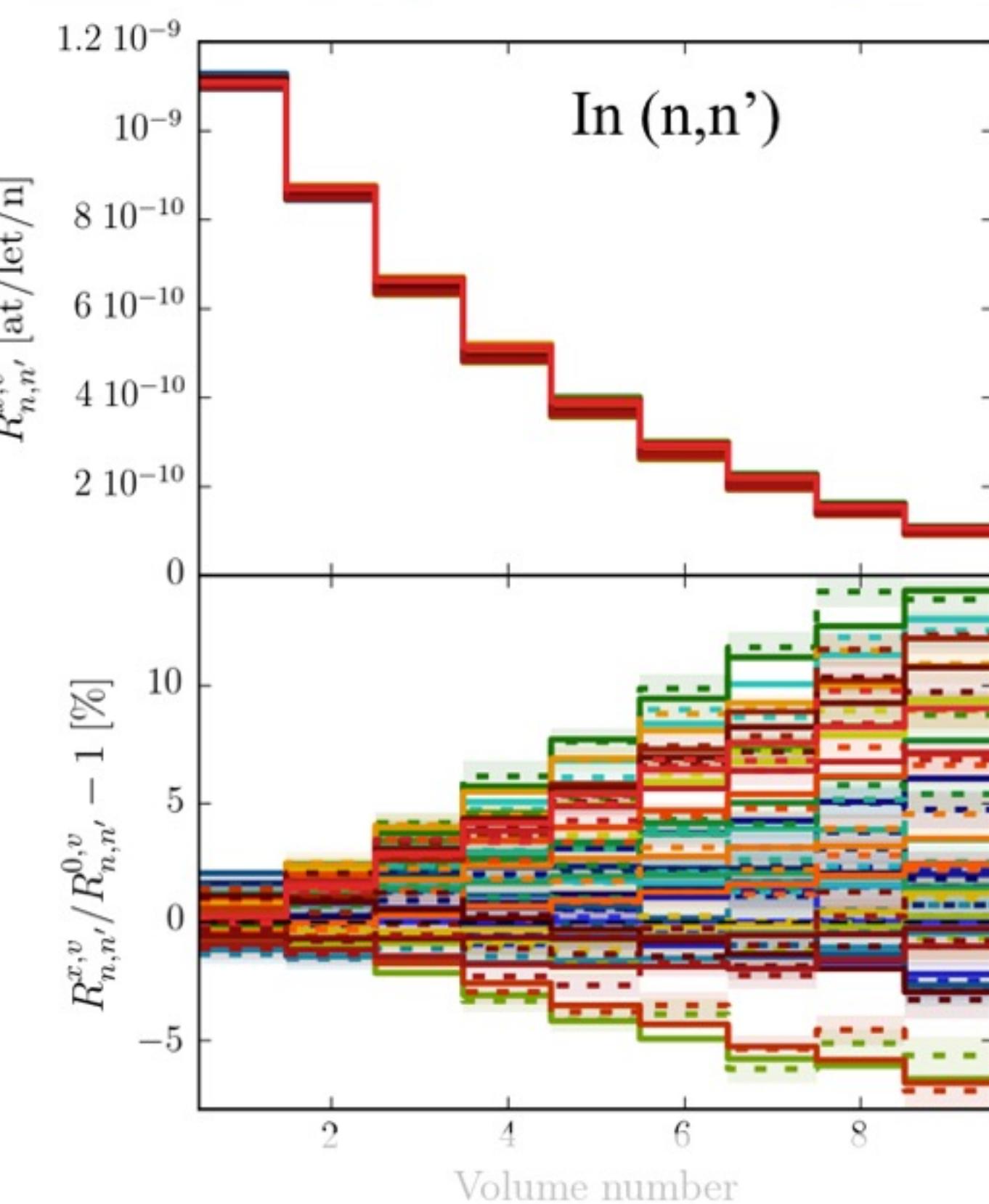
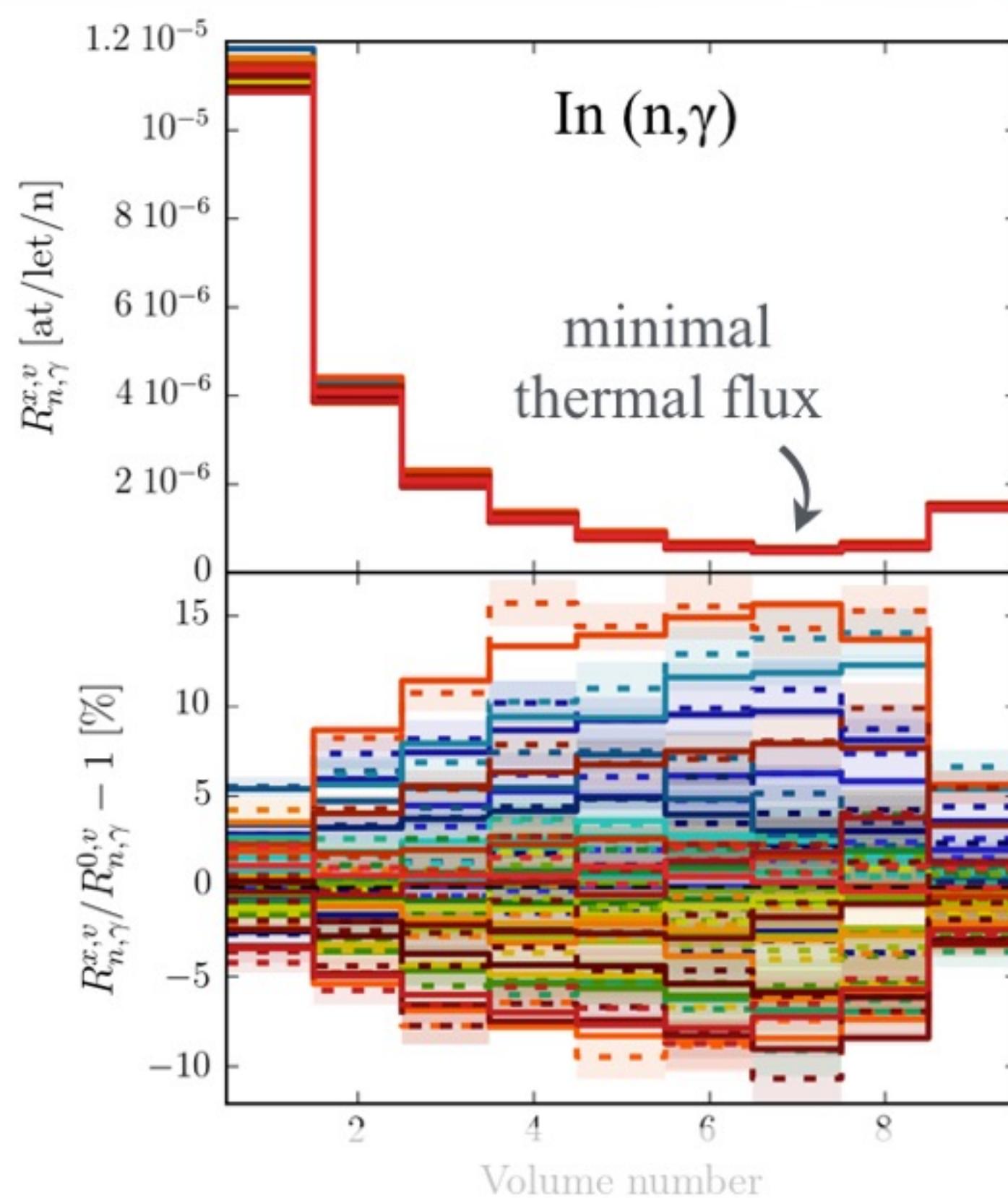
- Flux calculated in all the dosimeters



- Each reaction rate is declined according to each TENDL cross section
→ *all Fe isotopes, all mt reactions*

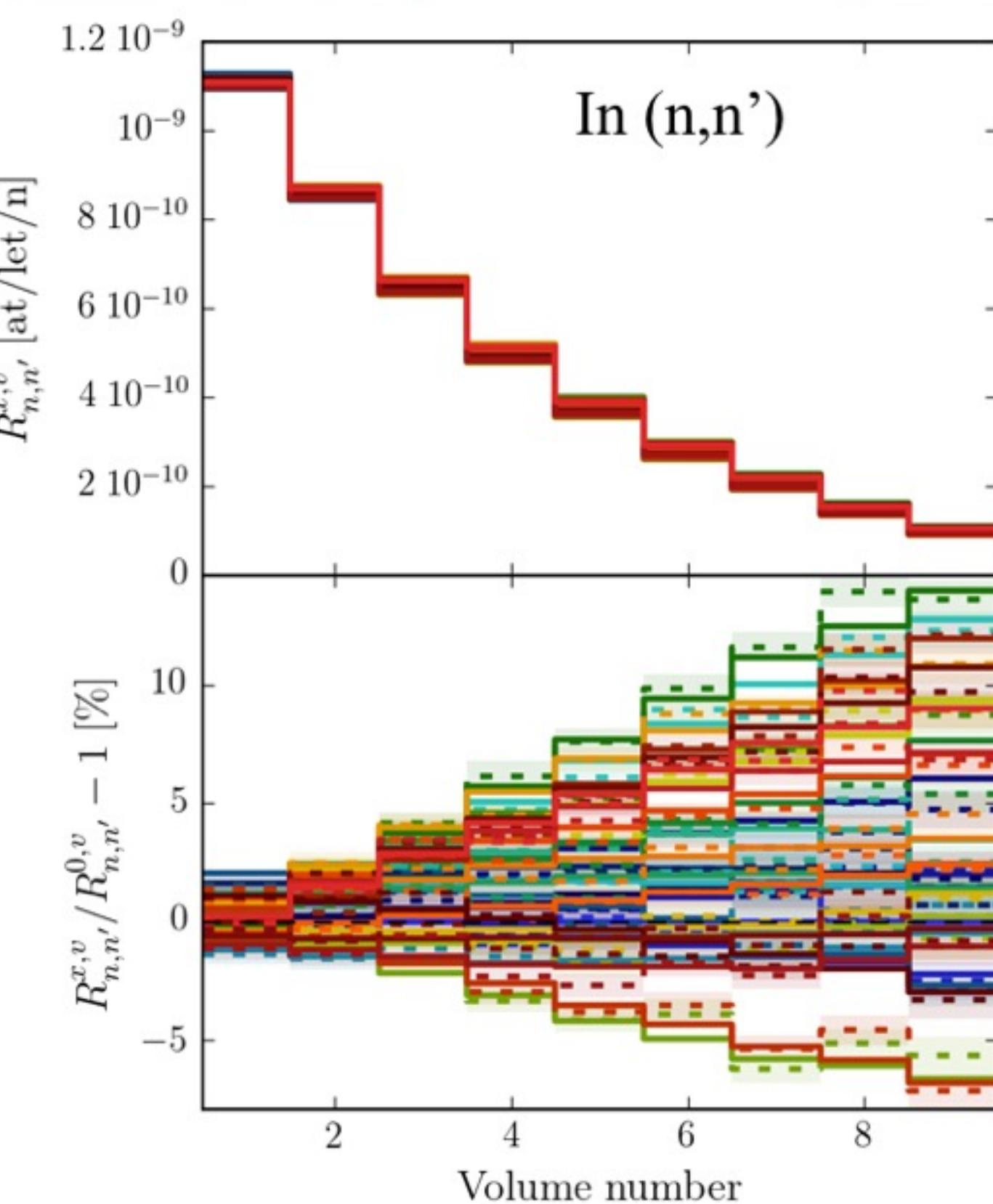
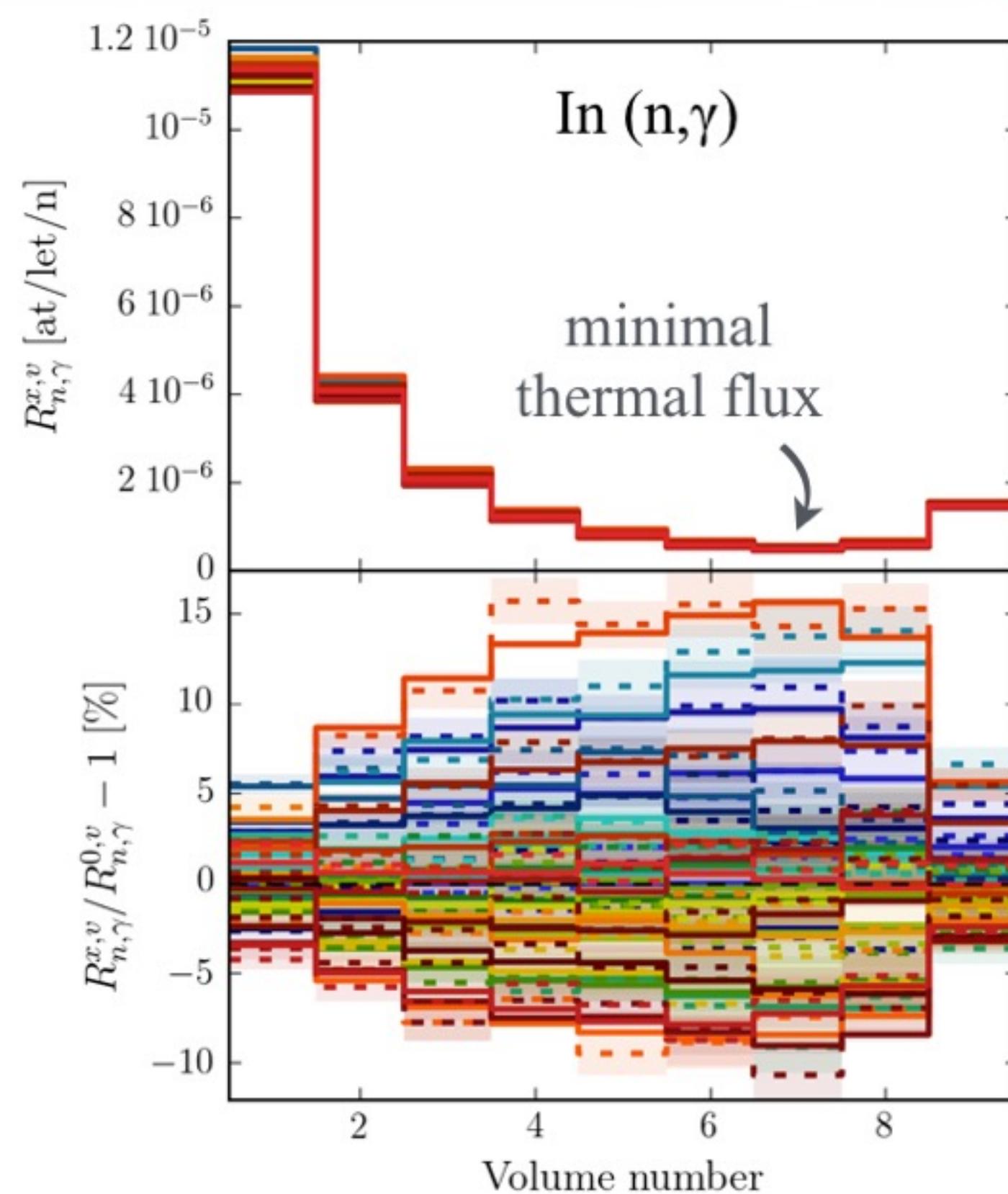
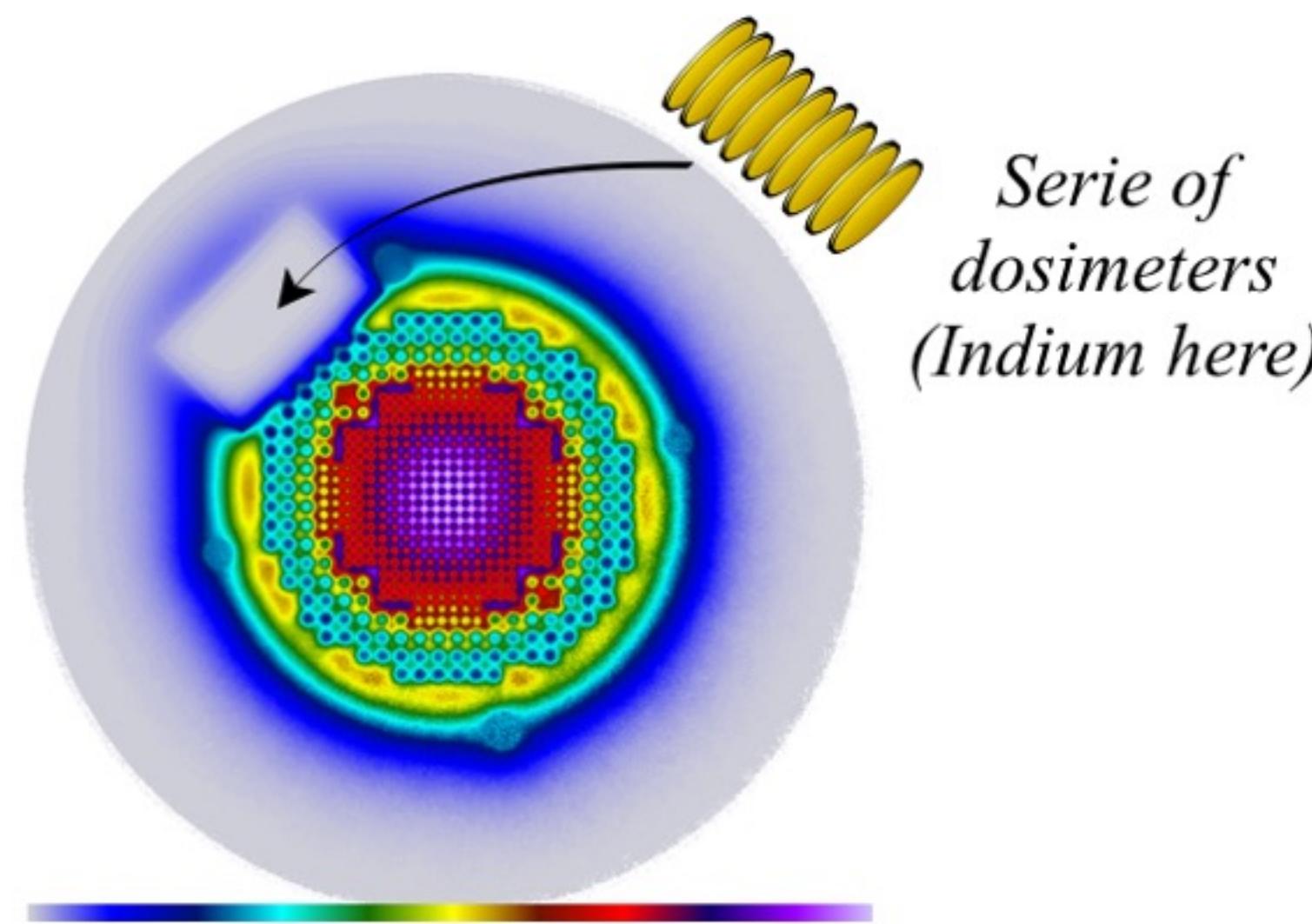
Observation:

- Very good prediction of the reaction rates difference between the TENDL cross sections (useful for BMC)



CROCUS dosimetry: reaction rate

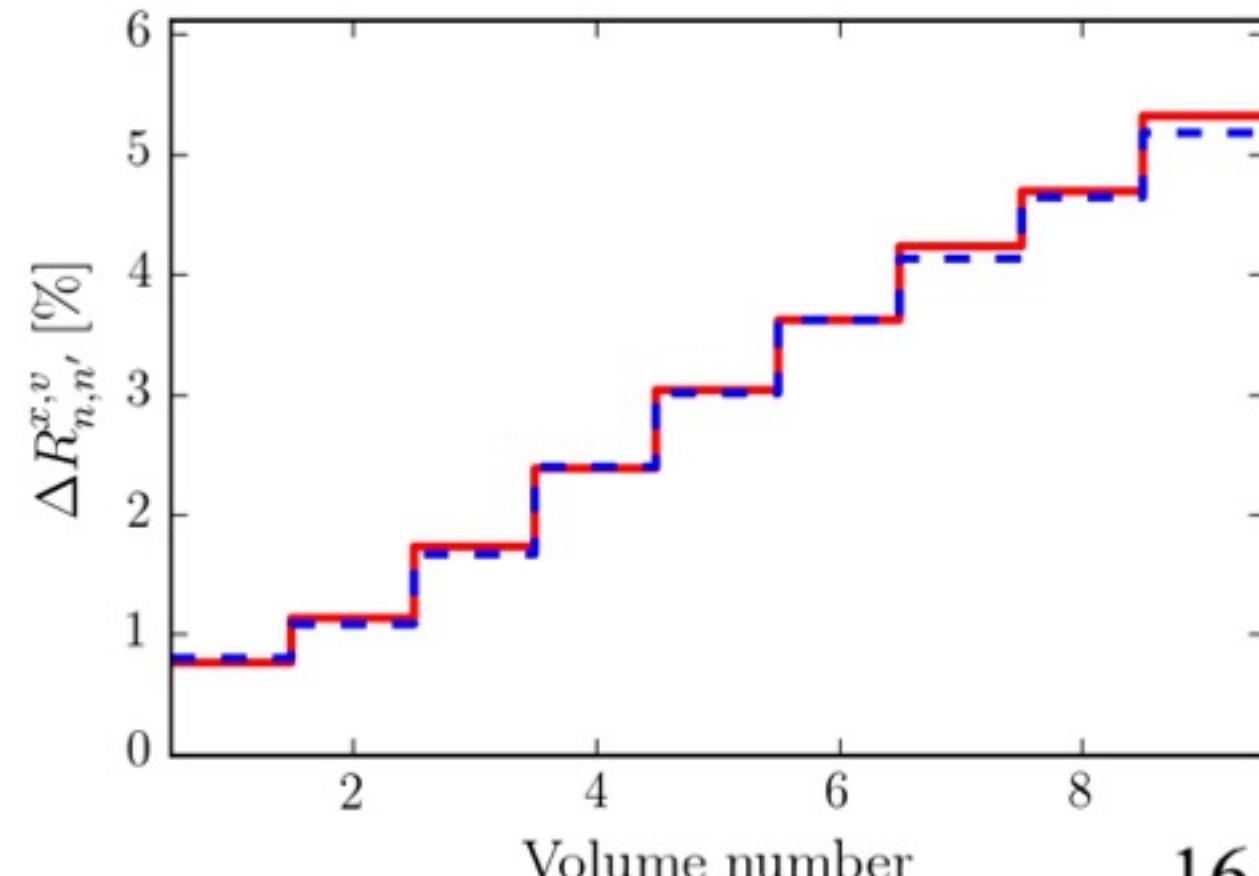
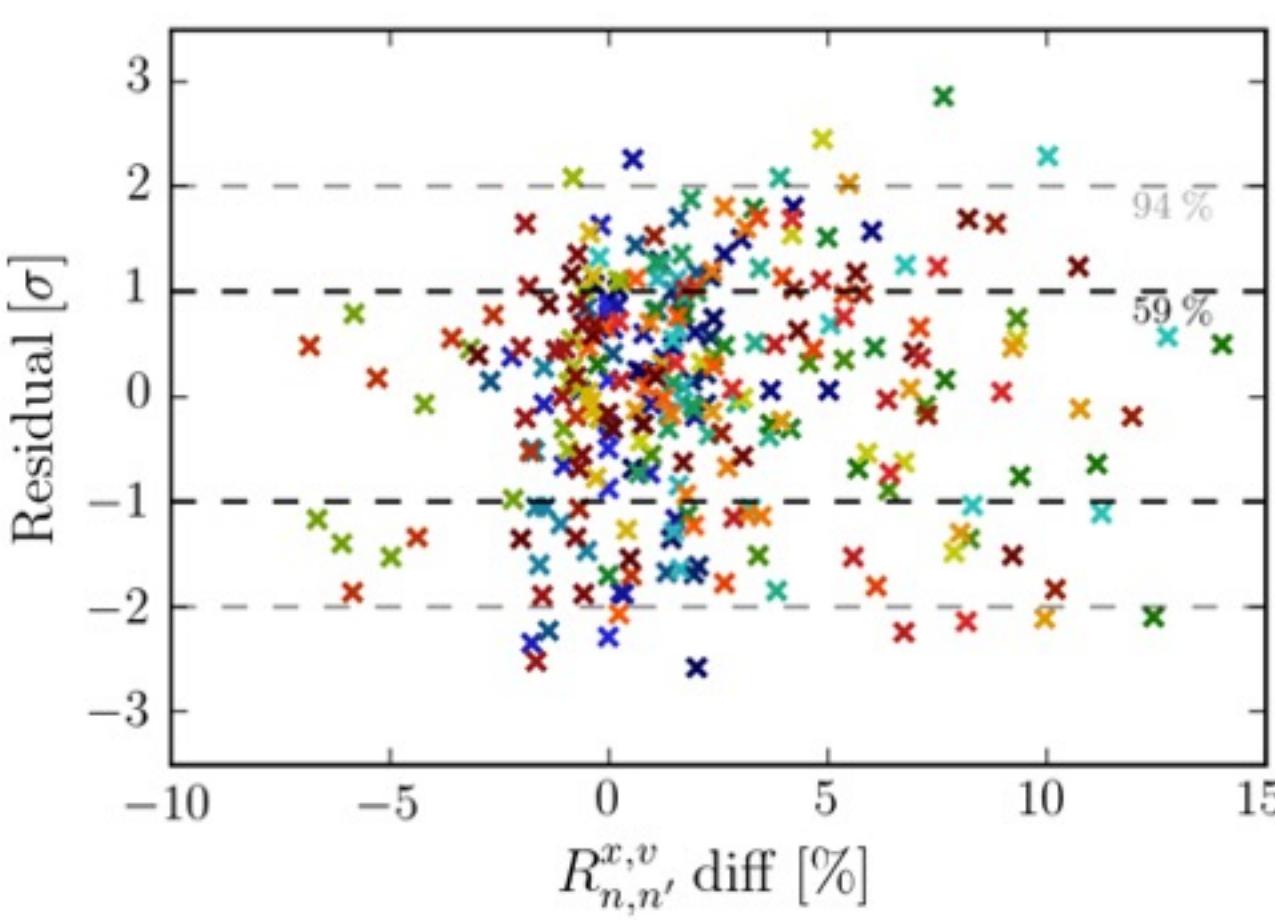
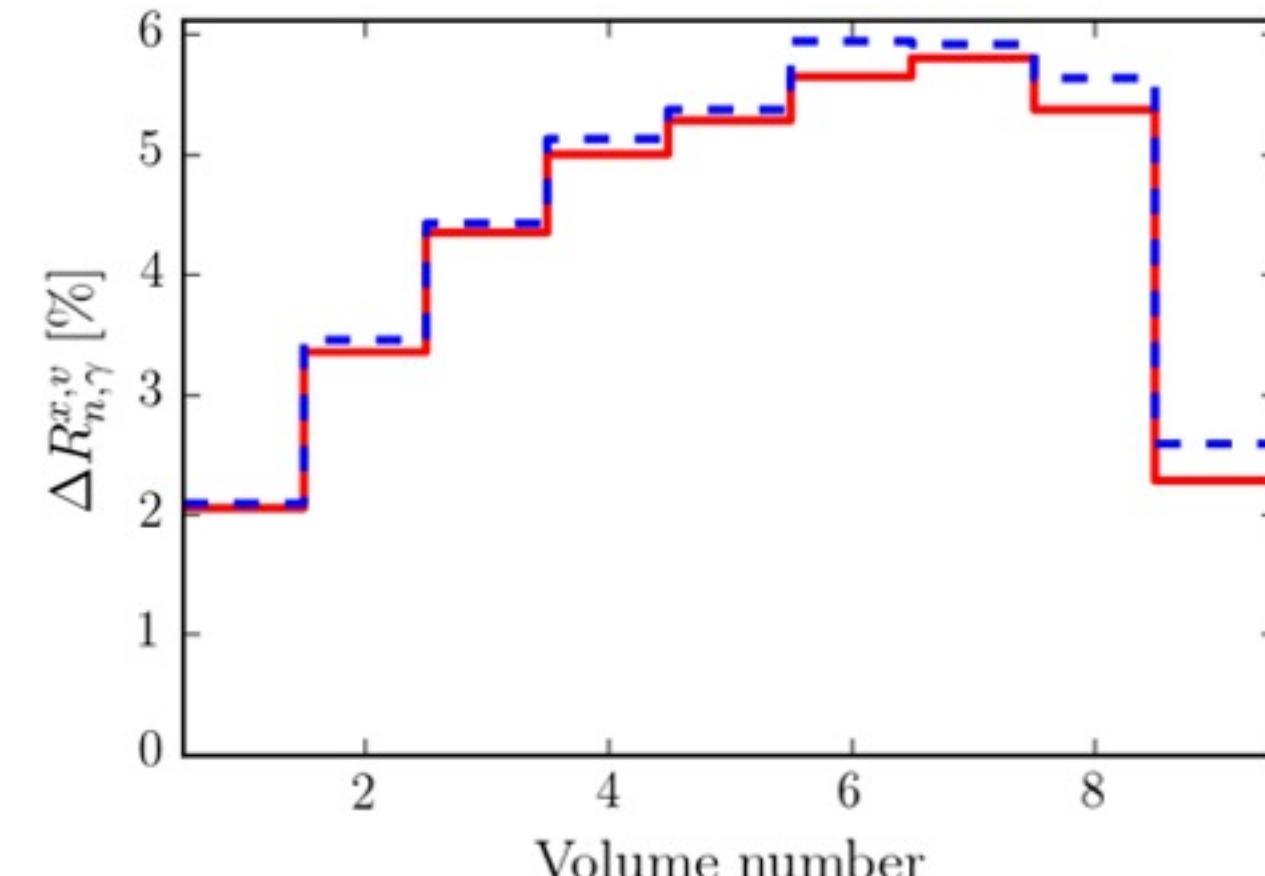
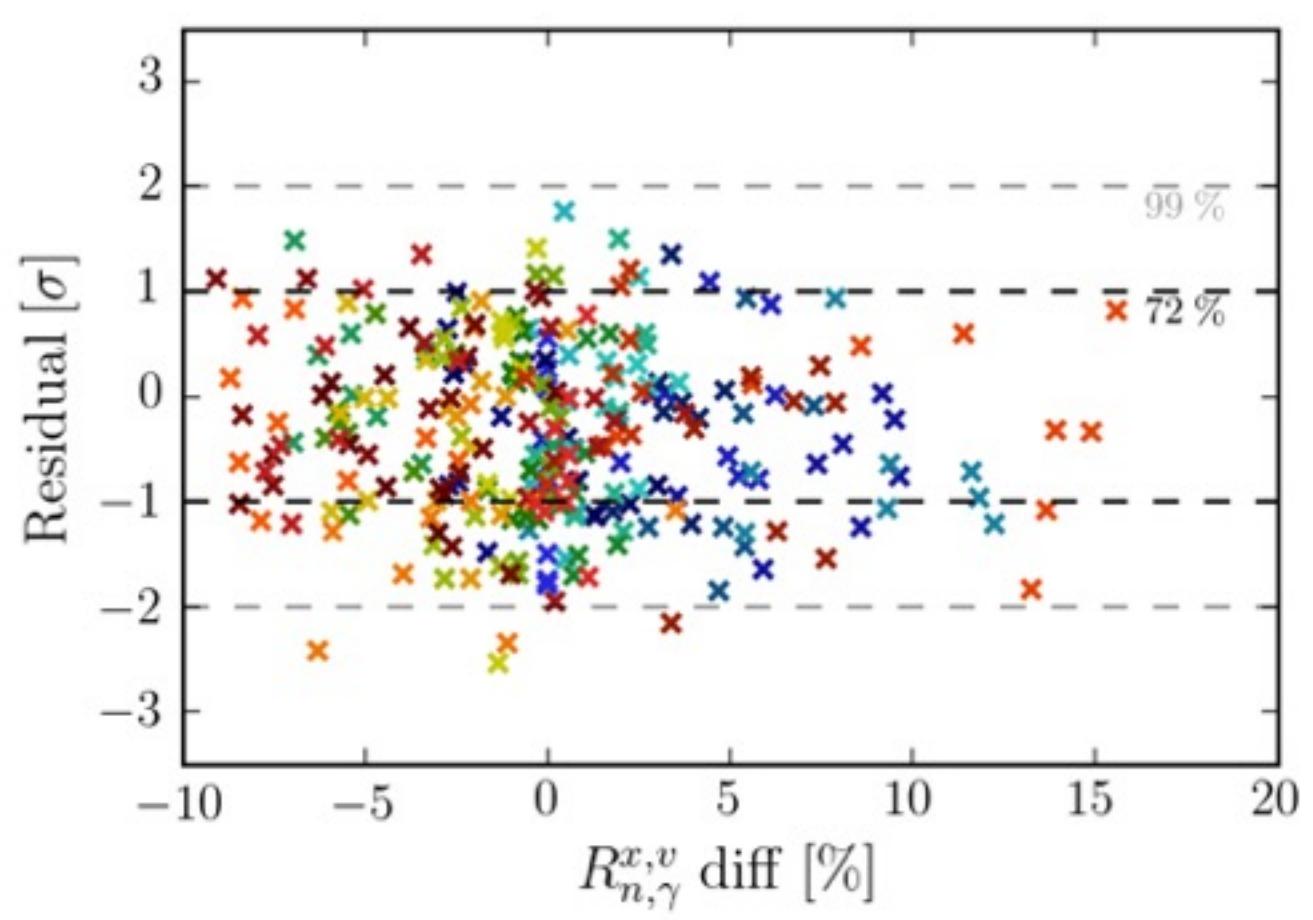
- Flux calculated in all the dosimeters



- Each reaction rate is declined according to each TENDL cross section
→ *all Fe isotopes, all mt reactions*

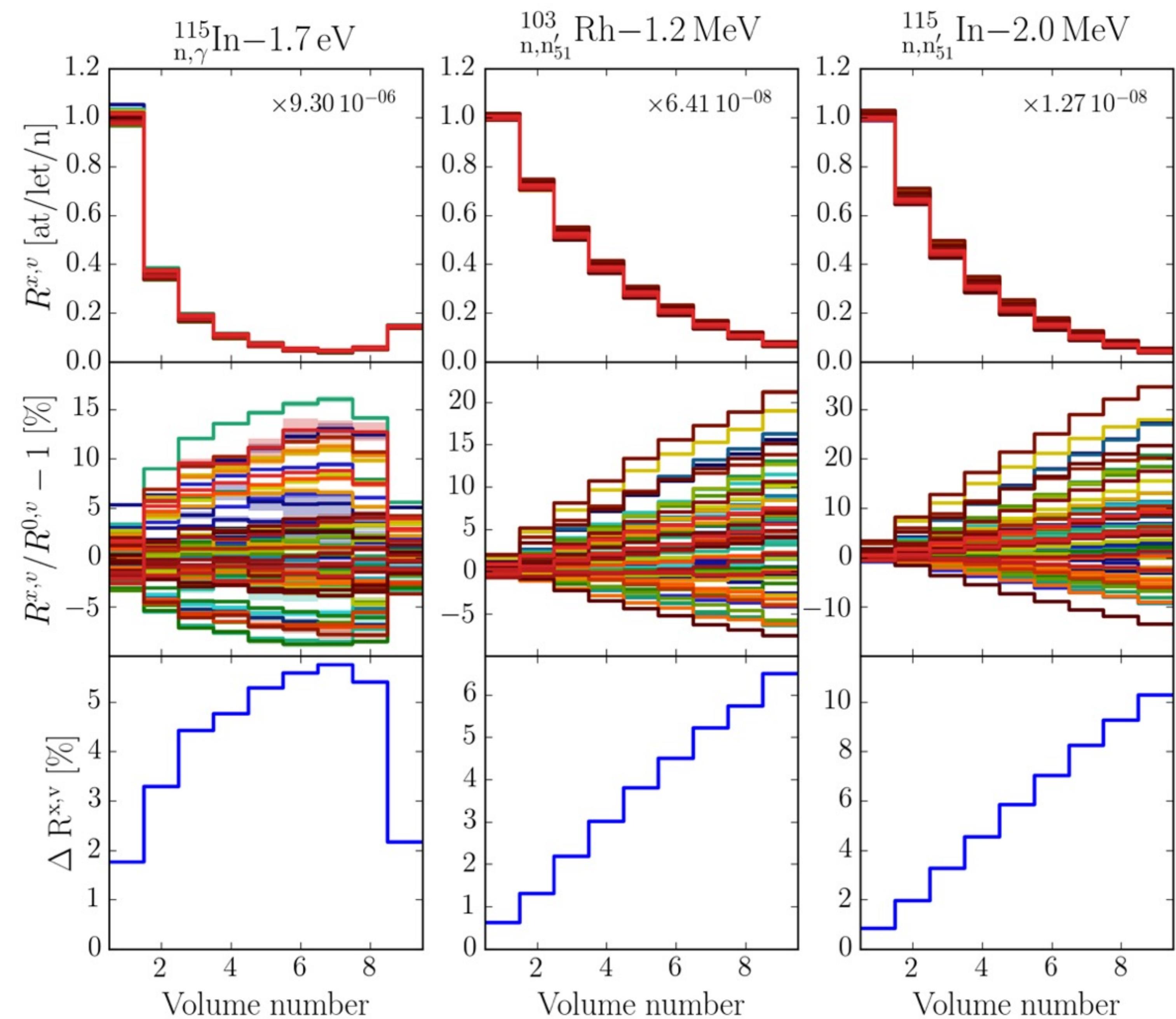
Observation:

- Very good prediction of the reaction rates difference between the TENDL cross sections (useful for BMC)



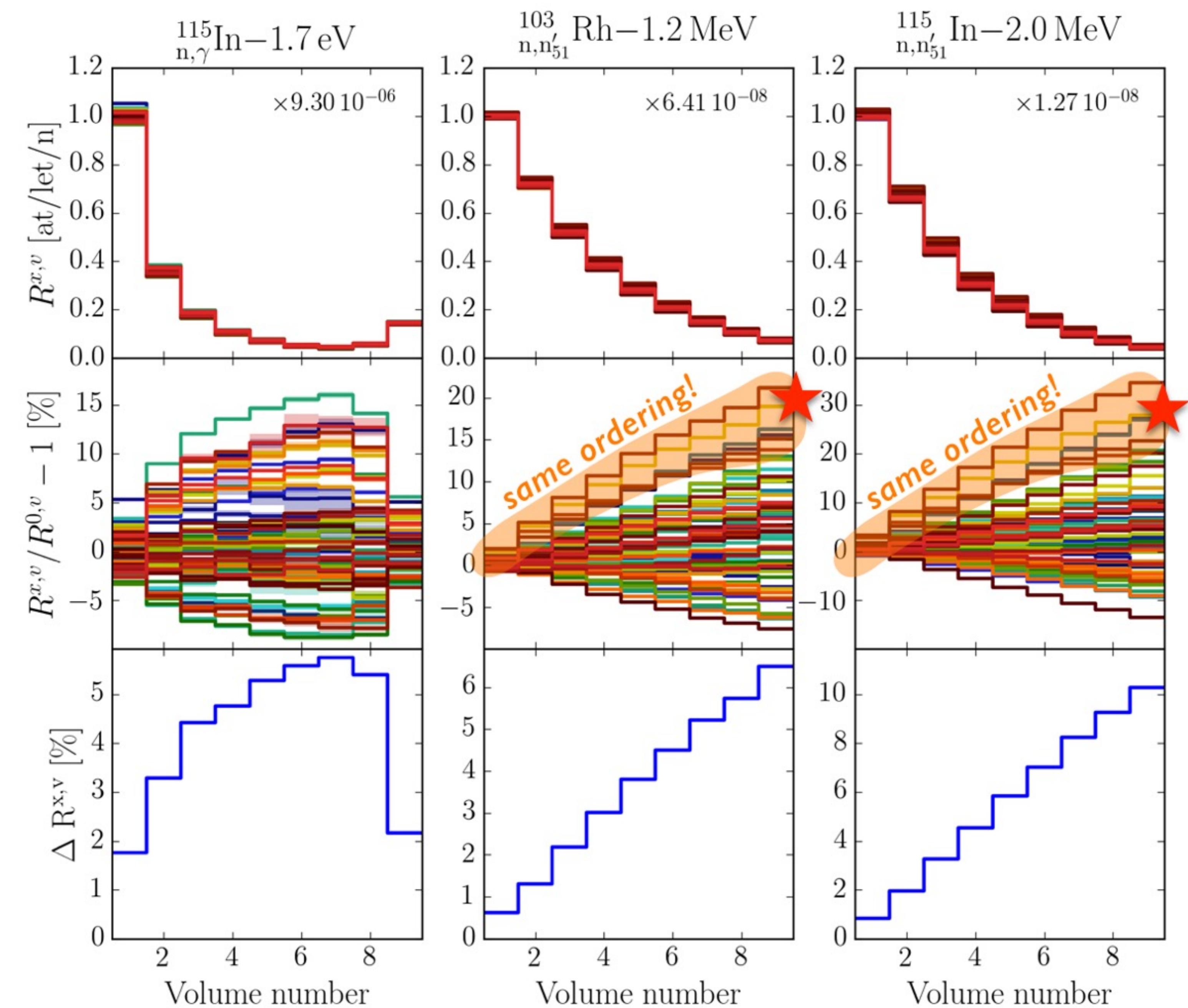
Separation power

- Multiple dosimeters... all independant ?
- Rhodium-Indium inelastic threshold reactions: similar ordering



Separation power

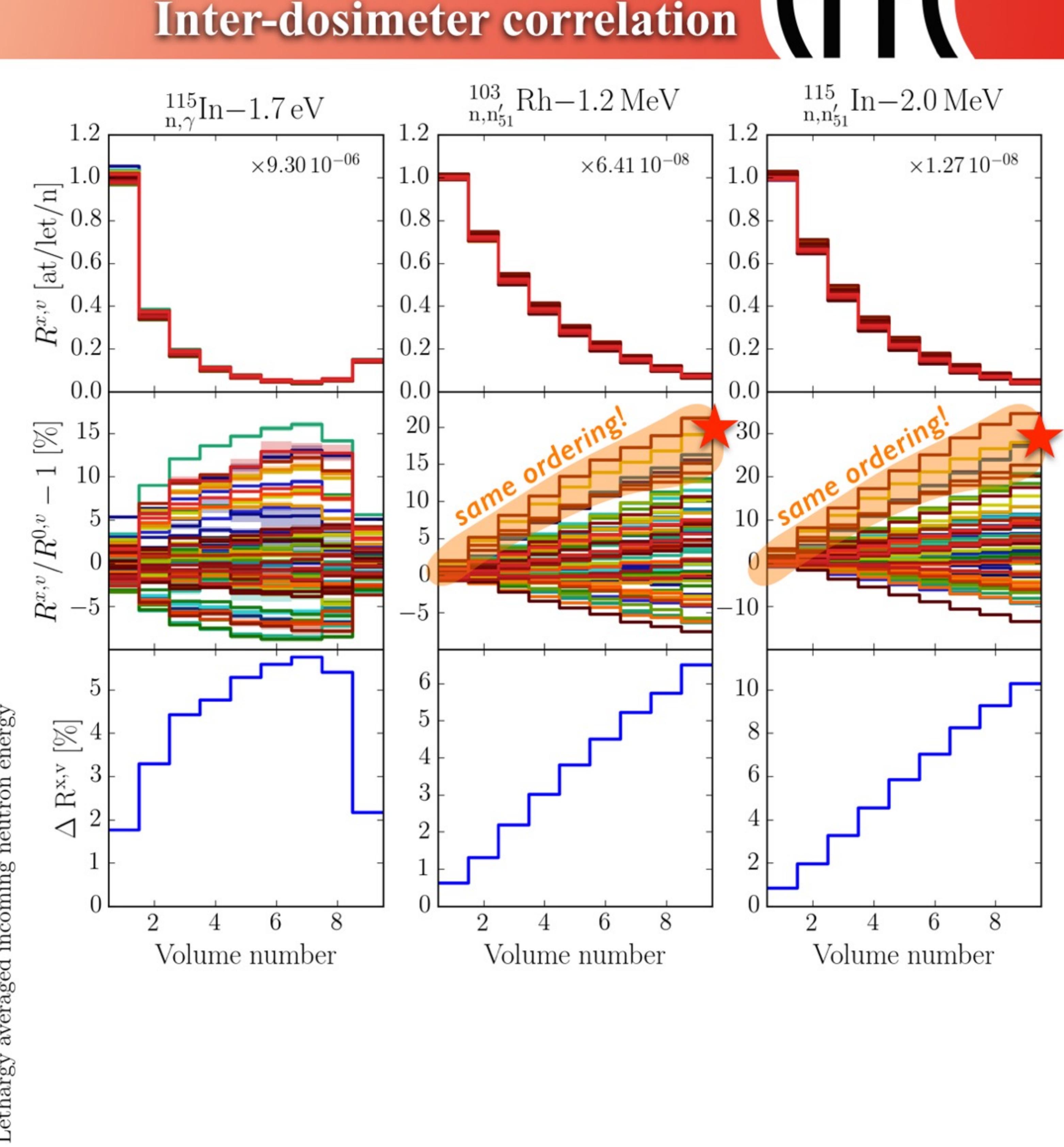
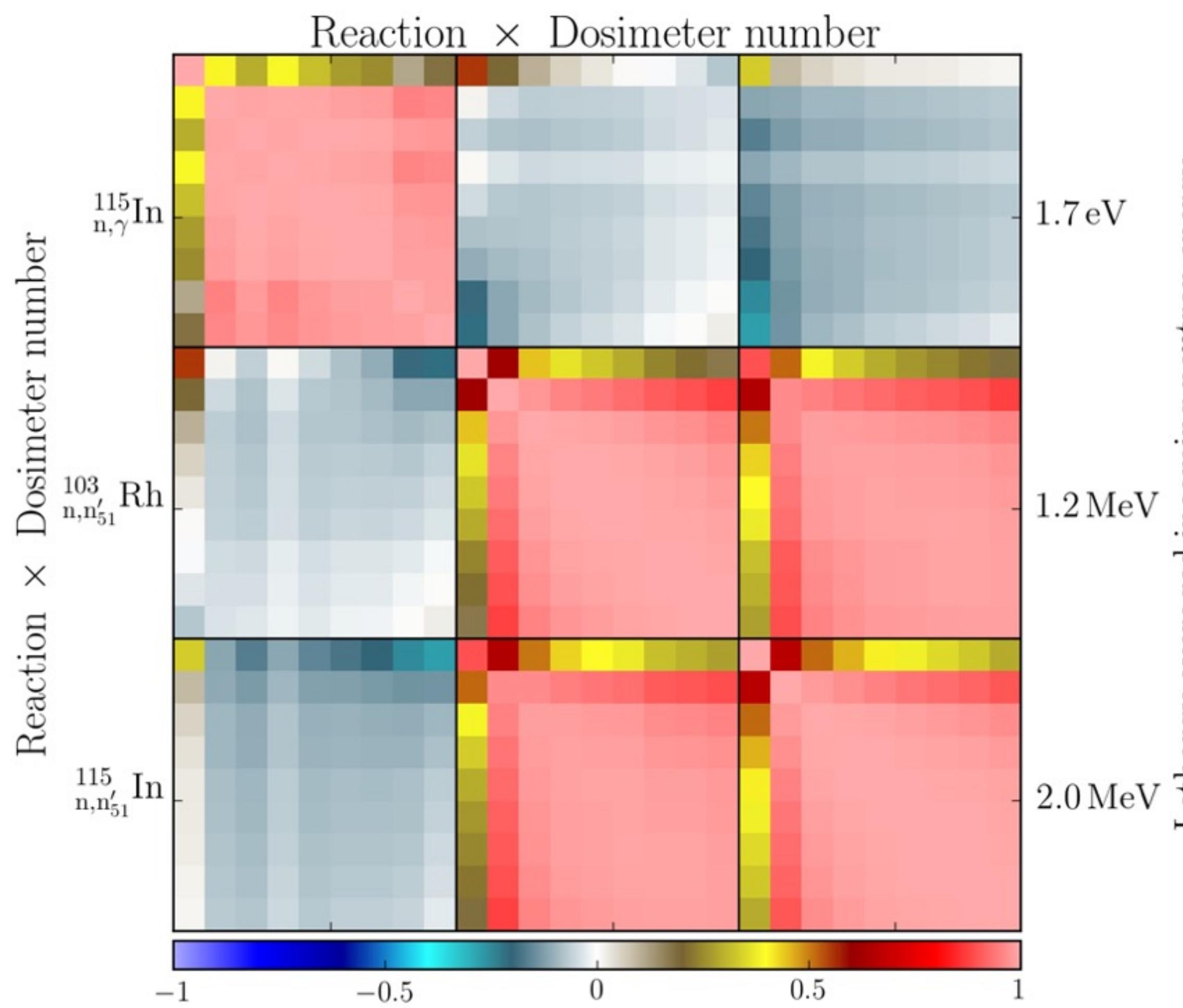
- Multiple dosimeters... all independant ?
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Separation power

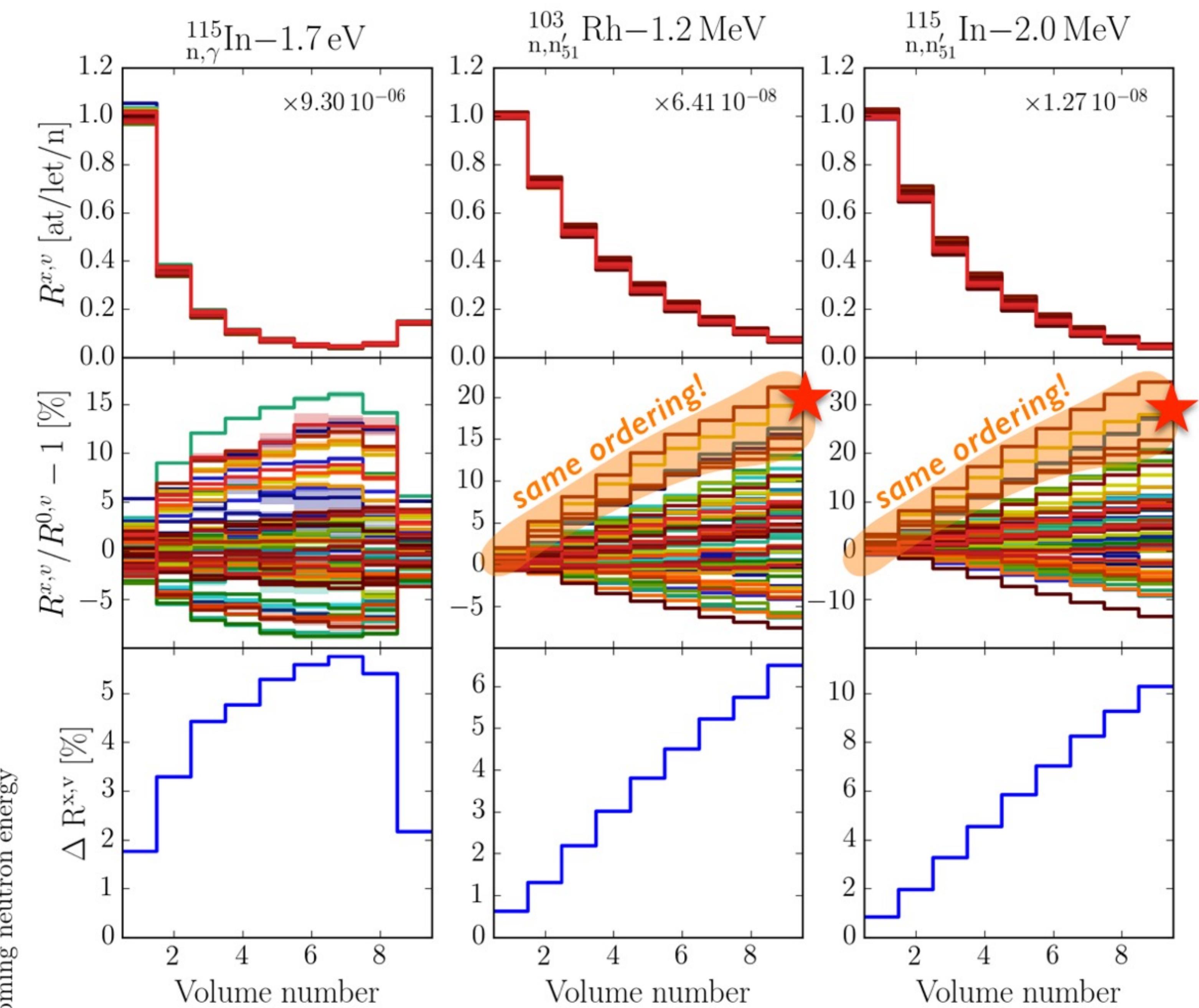
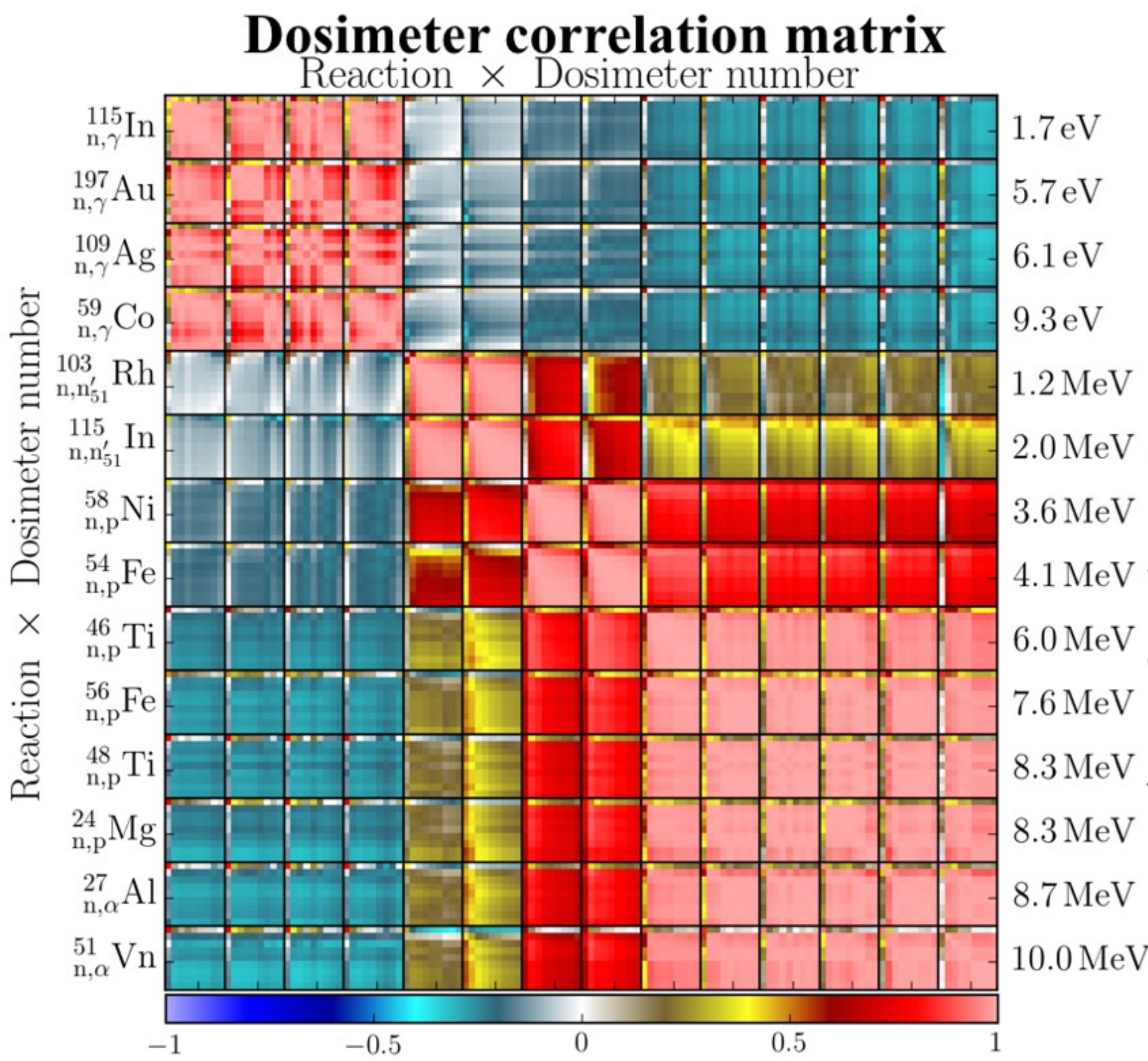
- Multiple dosimeters... all independant ?
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Dosimeter correlation matrix



Separation power

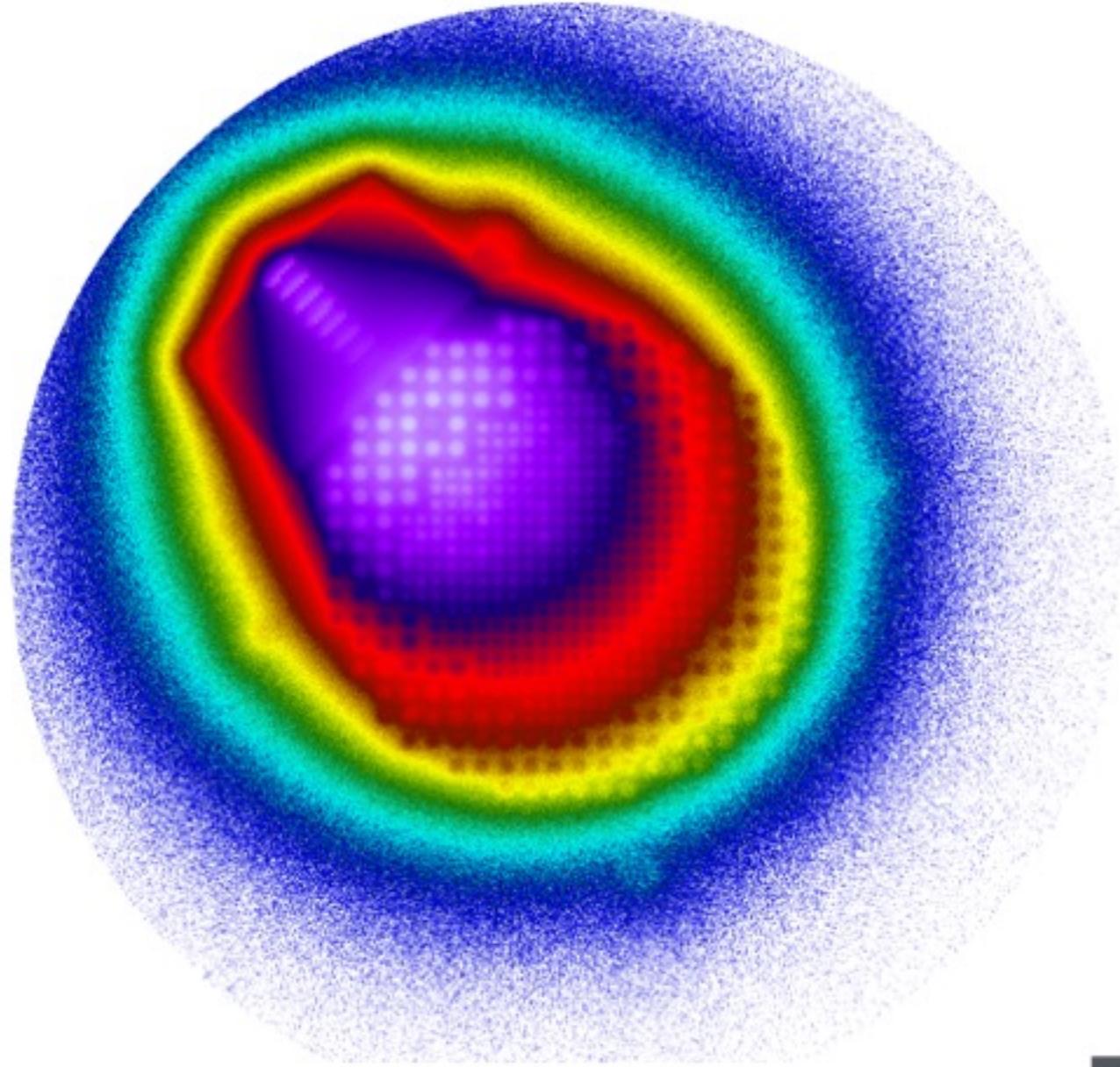
- Multiple dosimeters... all independant ?
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- Method generic for many dosimeters
- Important for dosimeter choice!
→ see V. Lamirand presentation

Conclusion

Methodology



Results

Perspectives

- The correlated sampling is nuclear data uncertainty propagation friendly
- Approach usable for different systems HMI-001, CROCUS, ...
- Helpful for observables with a small dispersion
- Apply BMC assimilation using TMC-CS
- Add v , X in the CS for fissionable isotopes & angular sampling
- Consider the angular dependance for the automatic biasing

Thank you for your attention!



Do you have some questions?



This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.