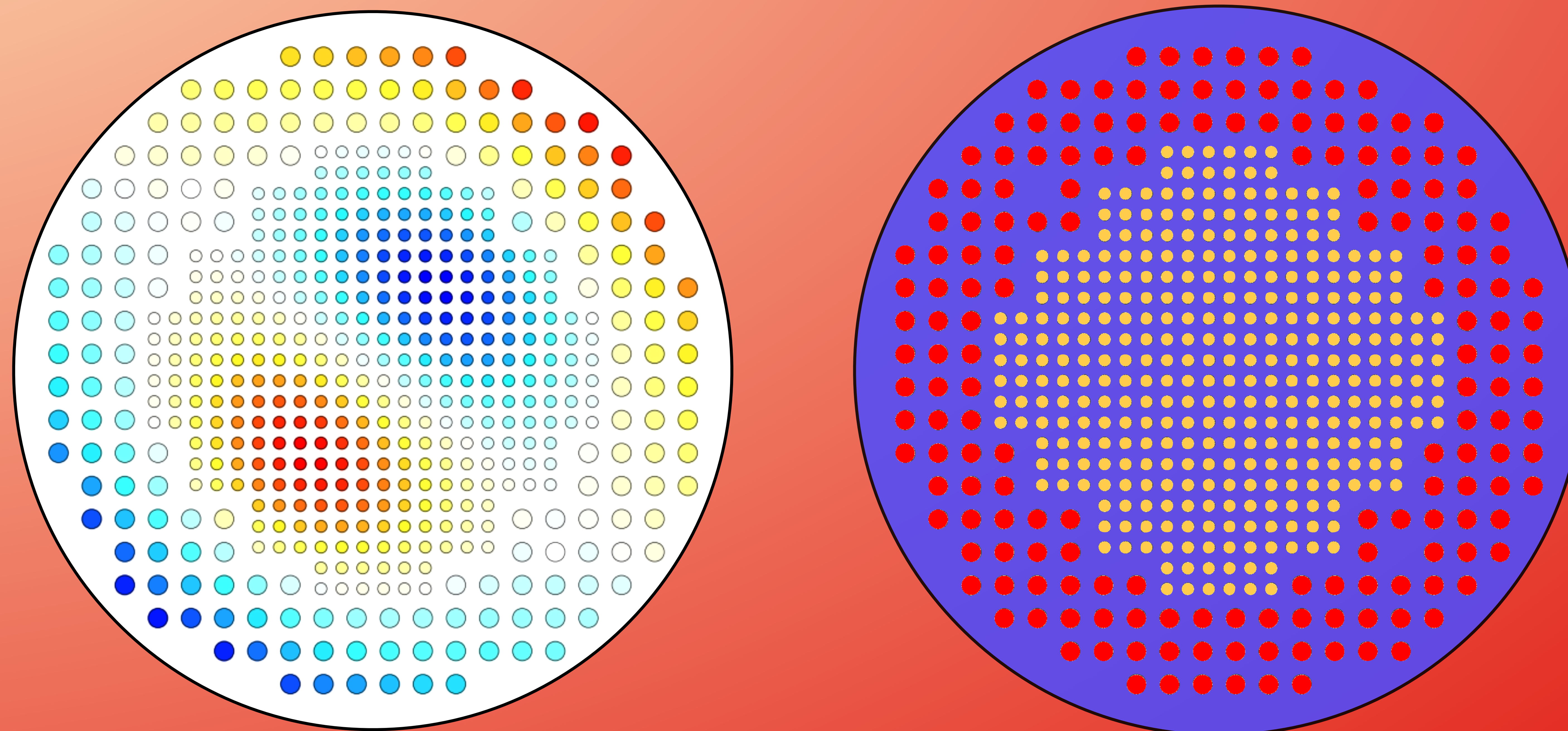


MODULATION NOISE CALCULATION: FROM MONTE-CARLO TO DETERMINISTIC APPROACHES AND BACK AGAIN



OUTLINE

I - Introduction

- Starting point: FM based coupled calculation
- Transient Fission Matrix in a nutshell
- CROCUS TFM operators

II - Modulation noise

- "Randomized" RTFM Algorithm
- Statistical uncertainty propagation
- Examples

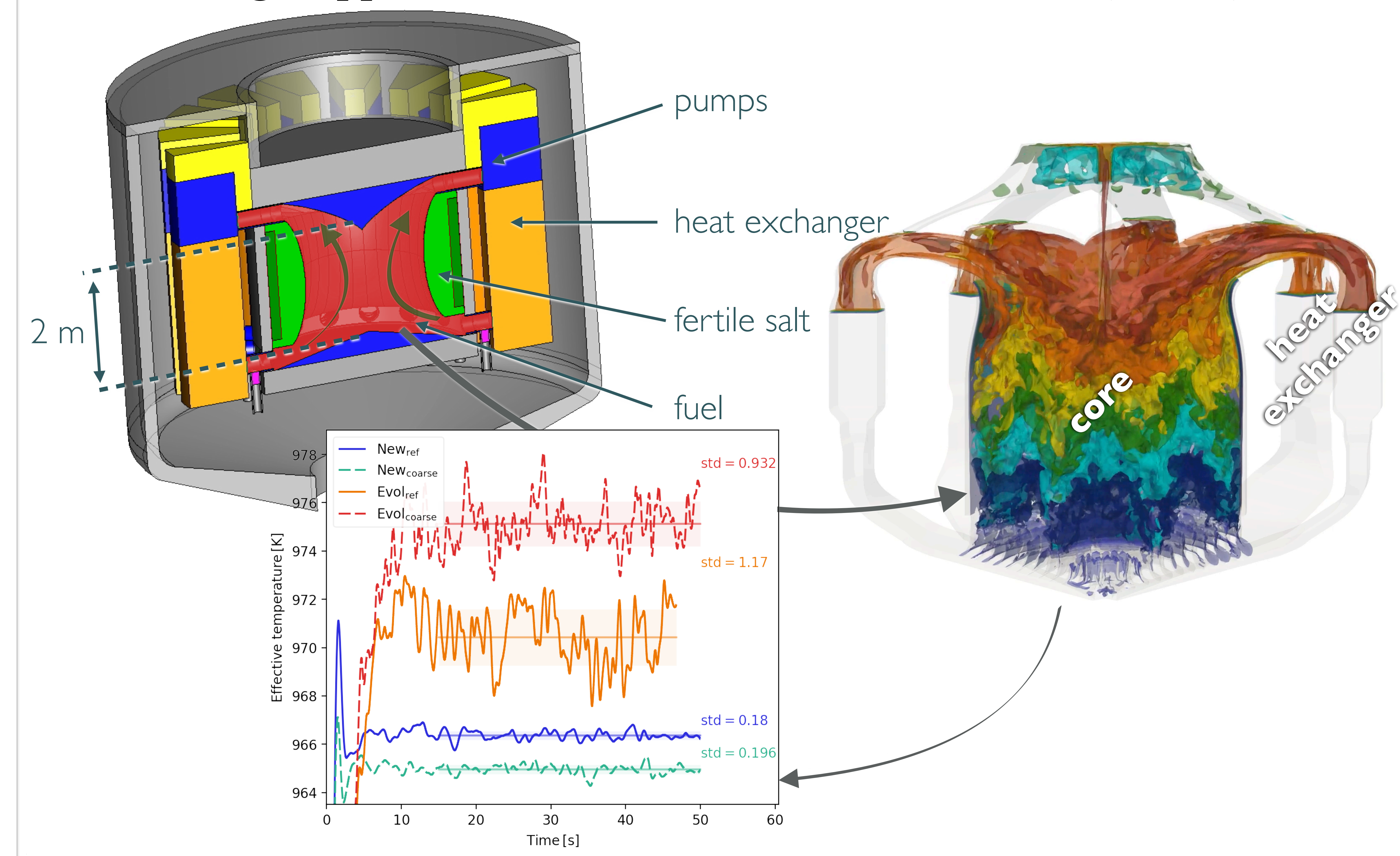
III - Noise simulator

- RTFM toymodel
- Teaching activities

Objectives

- Best estimate calculations
→ Monte Carlo, CFD
- Design and safety studies
→ not too slow calculations
- Gen IV Molten Salt Fast Reactor
→ Circulating liquid fuel and complex core flow pattern

Target application case: Molten Salt Fast Reactor (MSFR)



General approach

- Pre-calculation of the MC response: Transient Fission Matrix (TFM)
→ spatial prompt/delayed neutron propagation probability and time
- Time dependent deterministic approach with correlated sampling based matrix interpolation model, e.g:

Fission Matrix

Neutron source

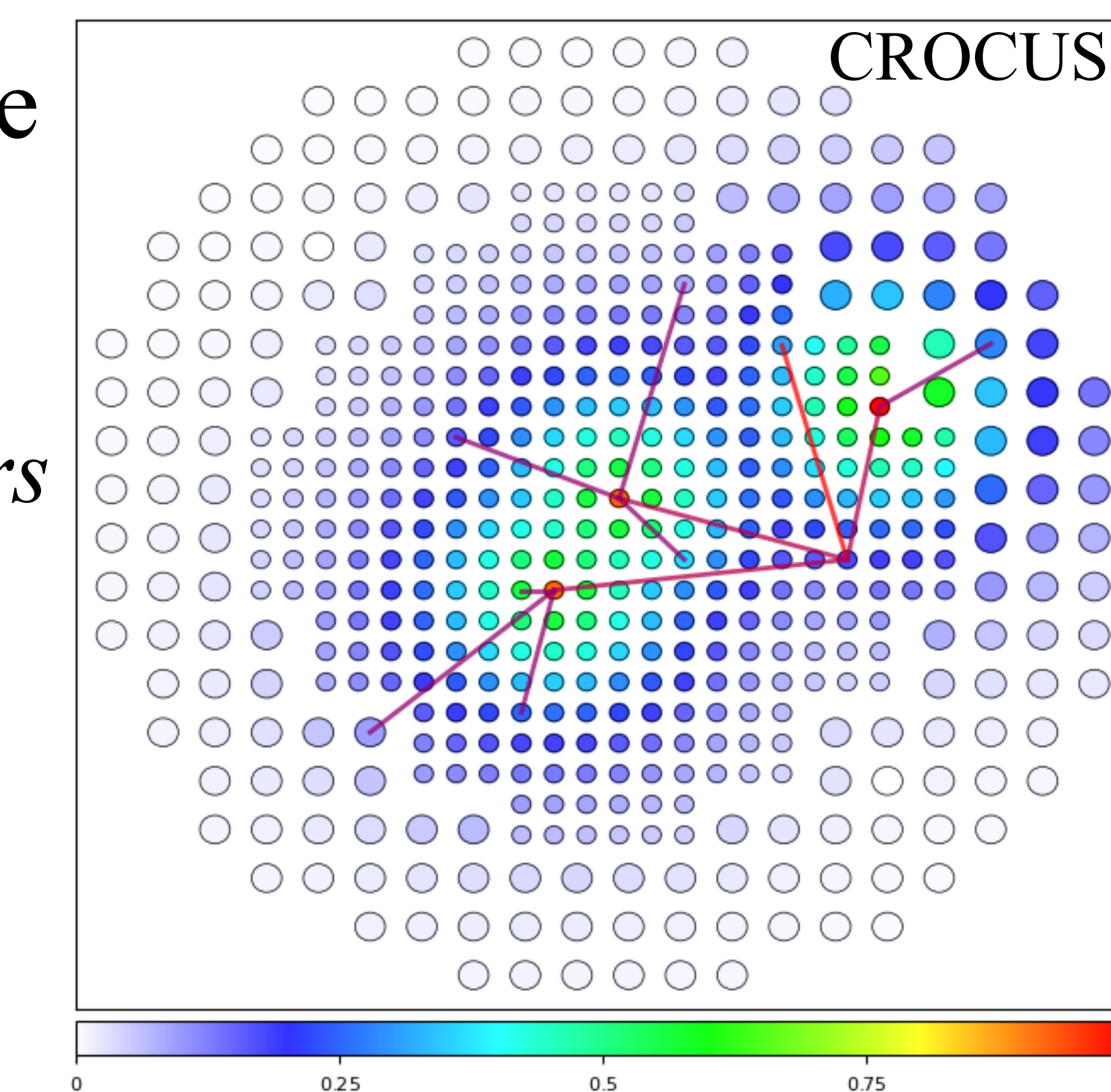
$$\frac{dV_p}{dt} = \left(\frac{K_{pp}}{l_{eff}} \frac{1}{V_p} + \frac{K_{dp}}{\sum_f \lambda_f P_f} \right) - \frac{1}{l_{eff}} V_p$$

Precursor concentration

$$\frac{dP_f}{dt} = \left(\frac{K_{pd}}{l_{eff}} \frac{1}{V_p} + \frac{K_{dd}}{\sum_g \lambda_g P_g} \right) \frac{\beta_f}{\beta_0} - \sum_f \lambda_f P_f$$

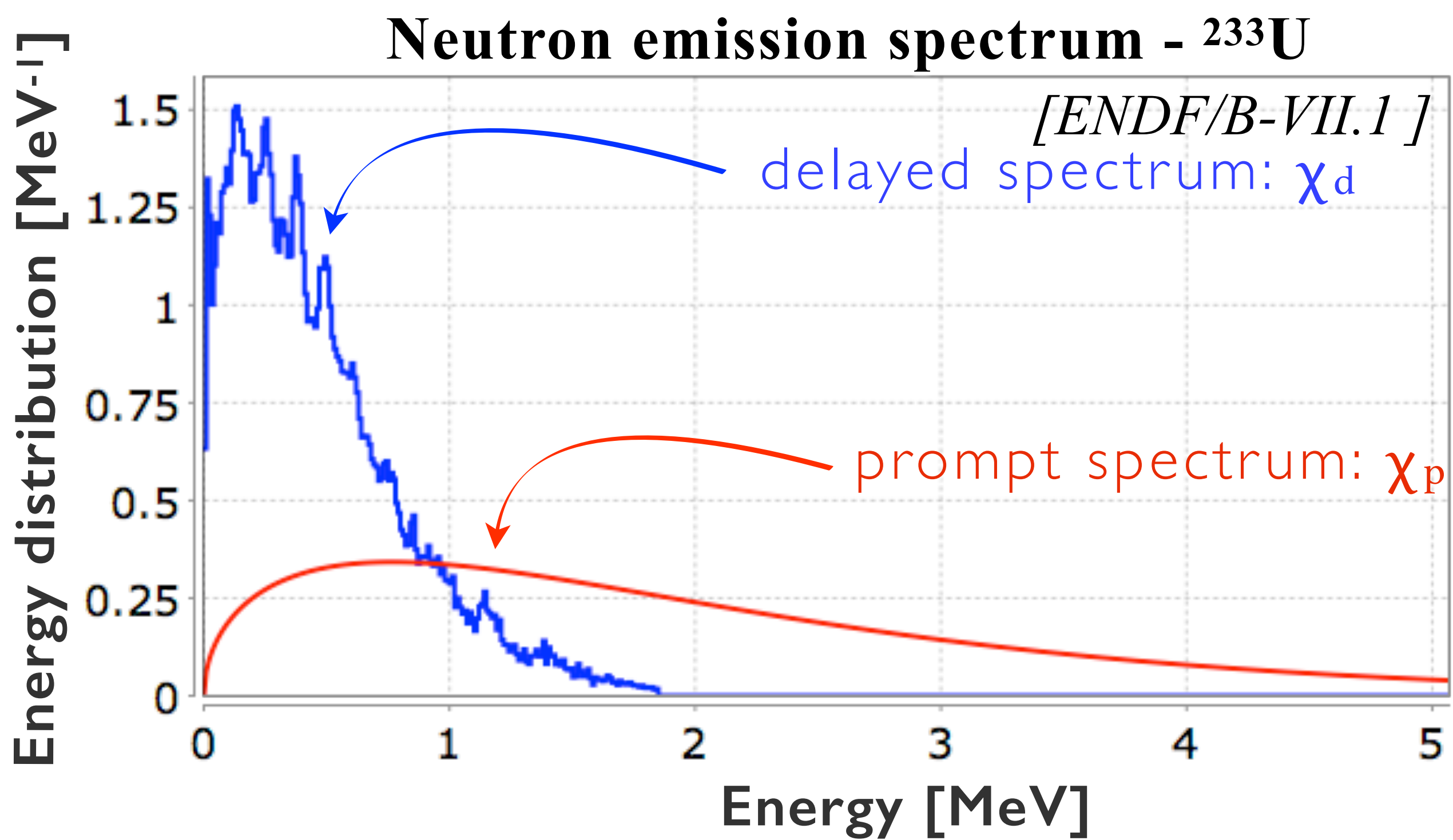
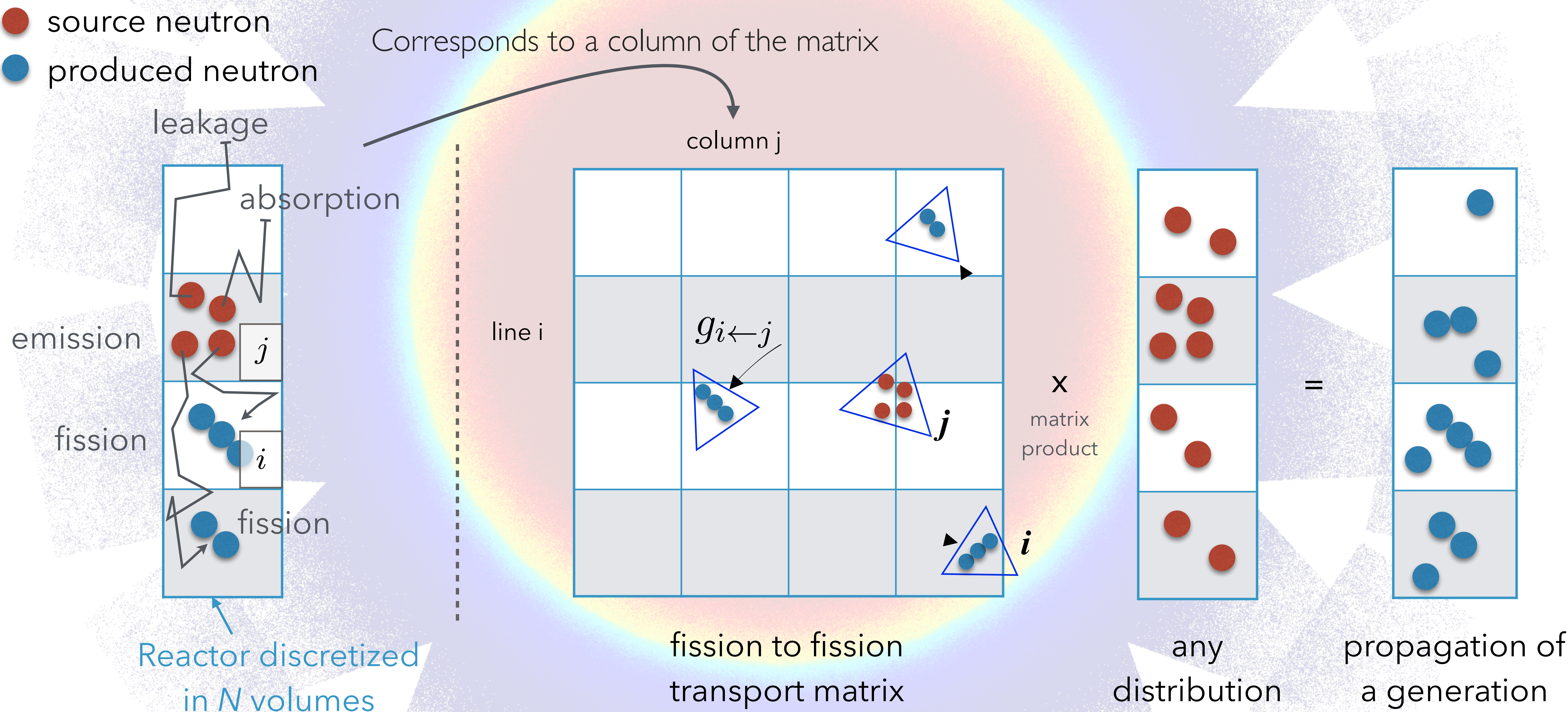
New open questions

- Neutron noise exists due to fuel turbulence
→ temperature fluctuations
→ decaying precursor position fluctuations
- *Is it possible to model this using the operators of the TFM approach?*

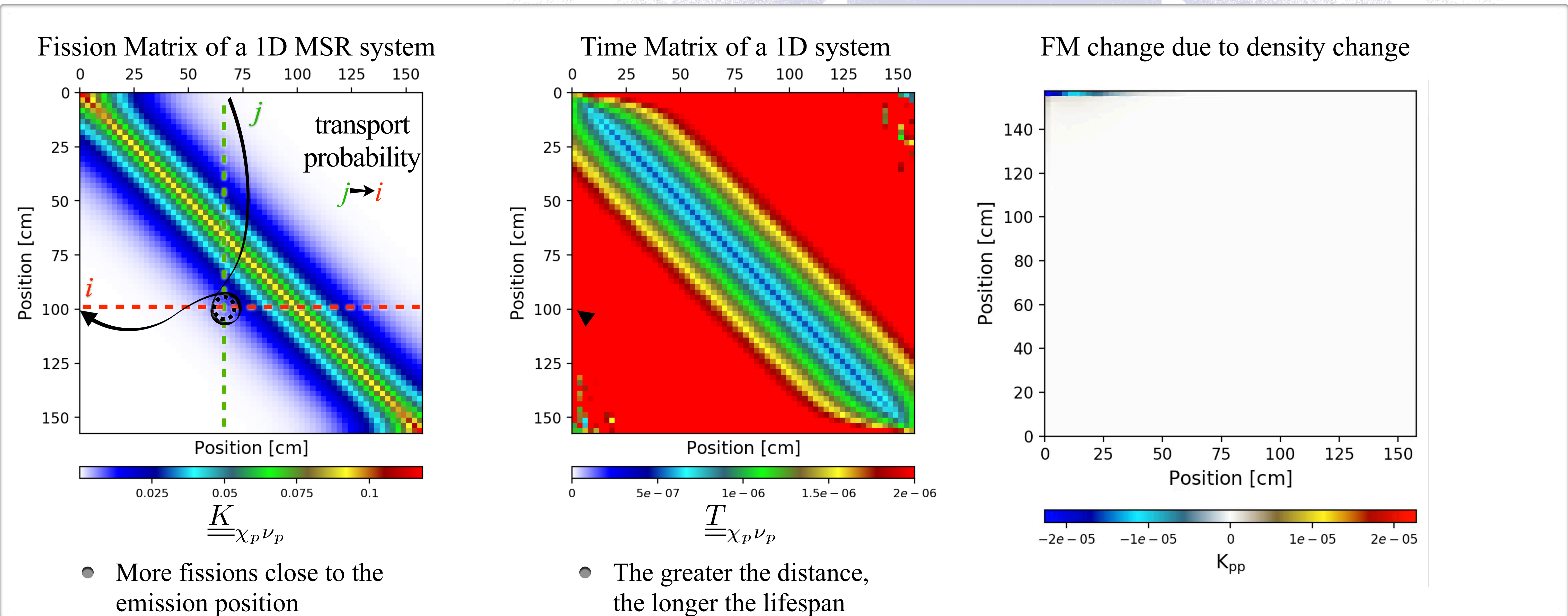


Principle: response function pre-calculation

- Green function
 - Reactor transfert function
- Different matrices
 - Prompt and delayed fission matrices (x4)
 - Absorption matrices (x2)
 - Time matrix (x1)
- Thermal feedback interpolation model exists
 - But not discussed today

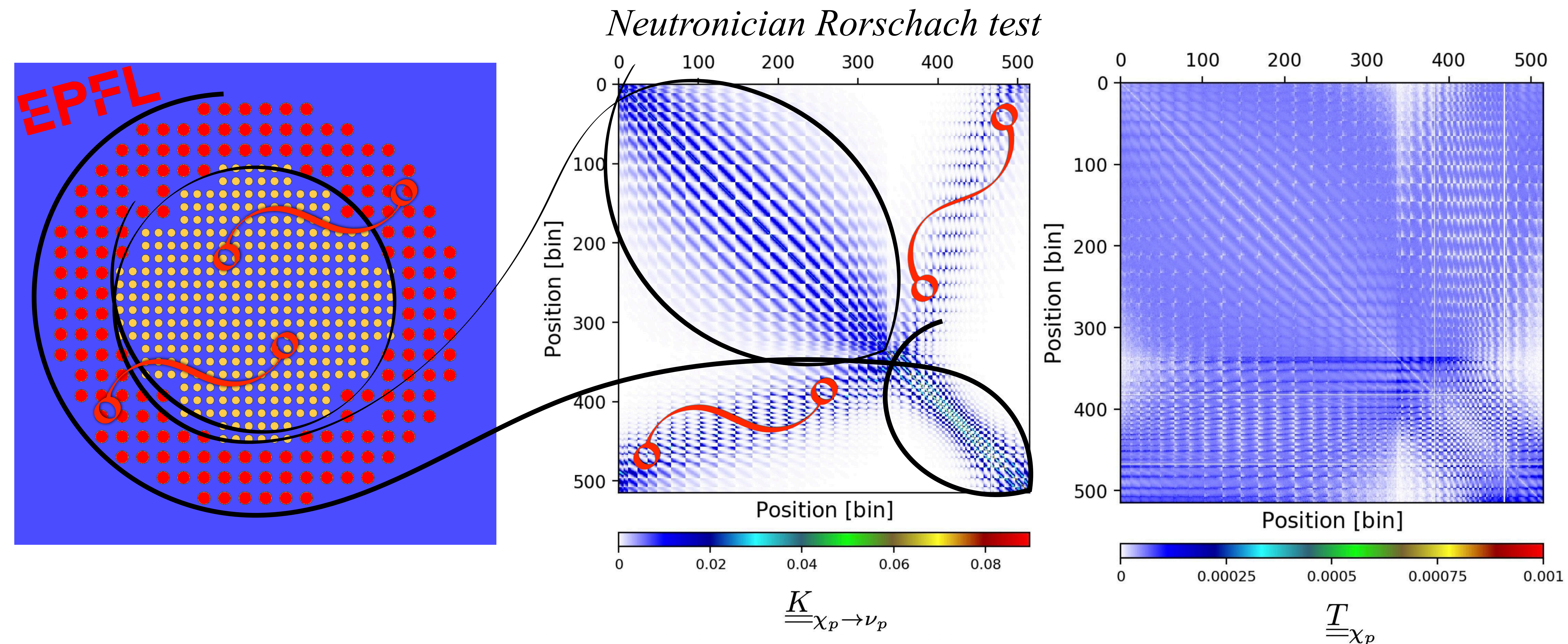


$\underline{\underline{K}}_{\chi_p \nu_p}$	$\underline{\underline{K}}_{\chi_p \nu_d}$	$\underline{\underline{A}}_{\chi_p}$	$\underline{\underline{T}}_{\chi_p \nu_p}$
$p \rightarrow p$	$p \rightarrow d$	$p \rightarrow \text{abs.}$	$p \text{ lifespan}$
$\underline{\underline{K}}_{\chi_d \nu_p}$	$\underline{\underline{K}}_{\chi_d \nu_d}$	$\underline{\underline{A}}_{\chi_d}$	
$d \rightarrow p$	$d \rightarrow d$	$d \rightarrow \text{abs.}$	



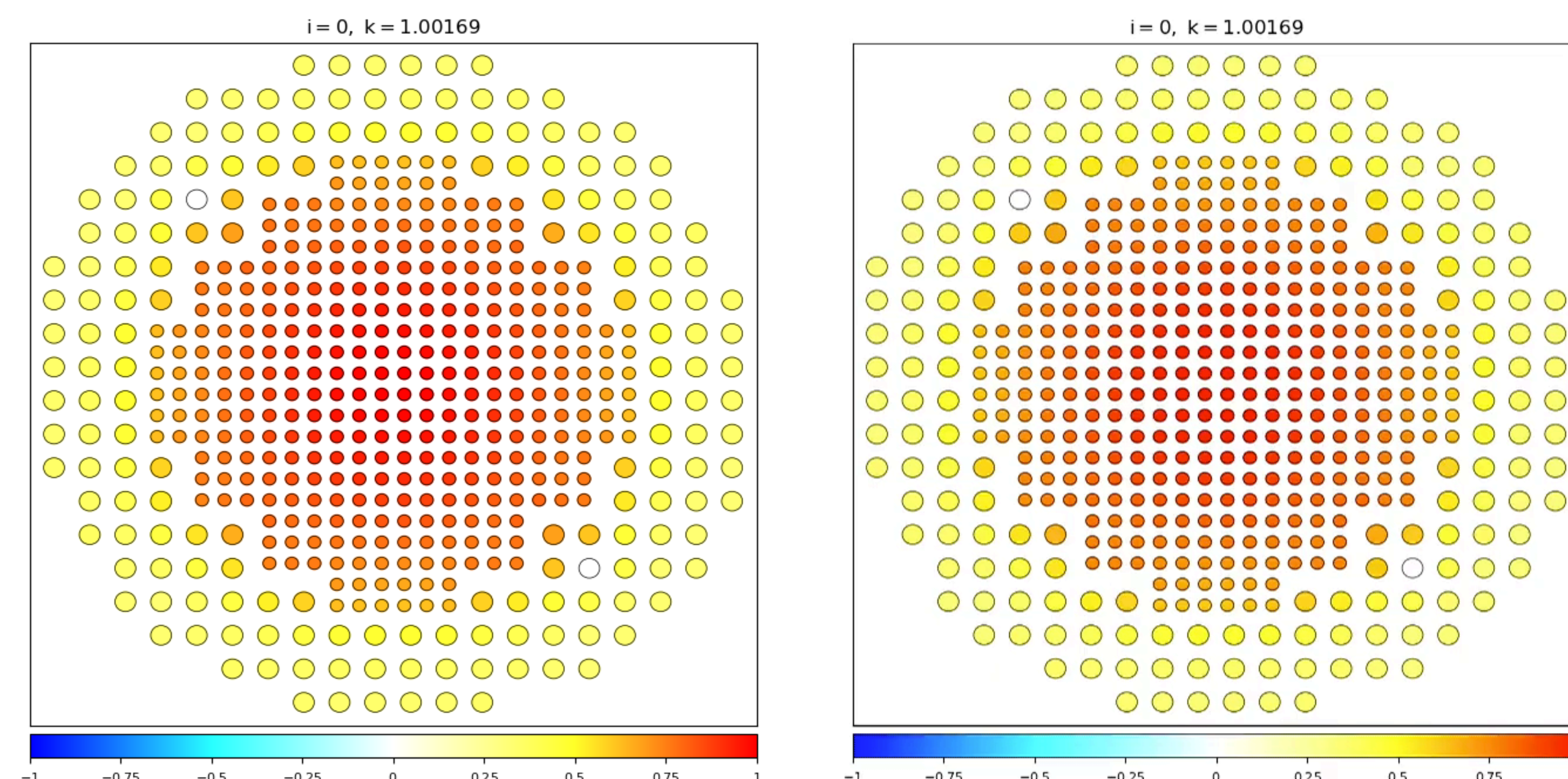
CROCUS zero power reactor

- Research & training reactor at EPFL (Switzerland)
- Oxide (center) / metal (periphery) enriched uranium + light water
- Maximal power: 100W
- Well-known reactor for neutron noise studies
 - intrinsic neutron noise
 - fuel oscillations
 - pile-oscillations (BLOOM)
- In this work: simplified OpenMC geometry 2Dx1D

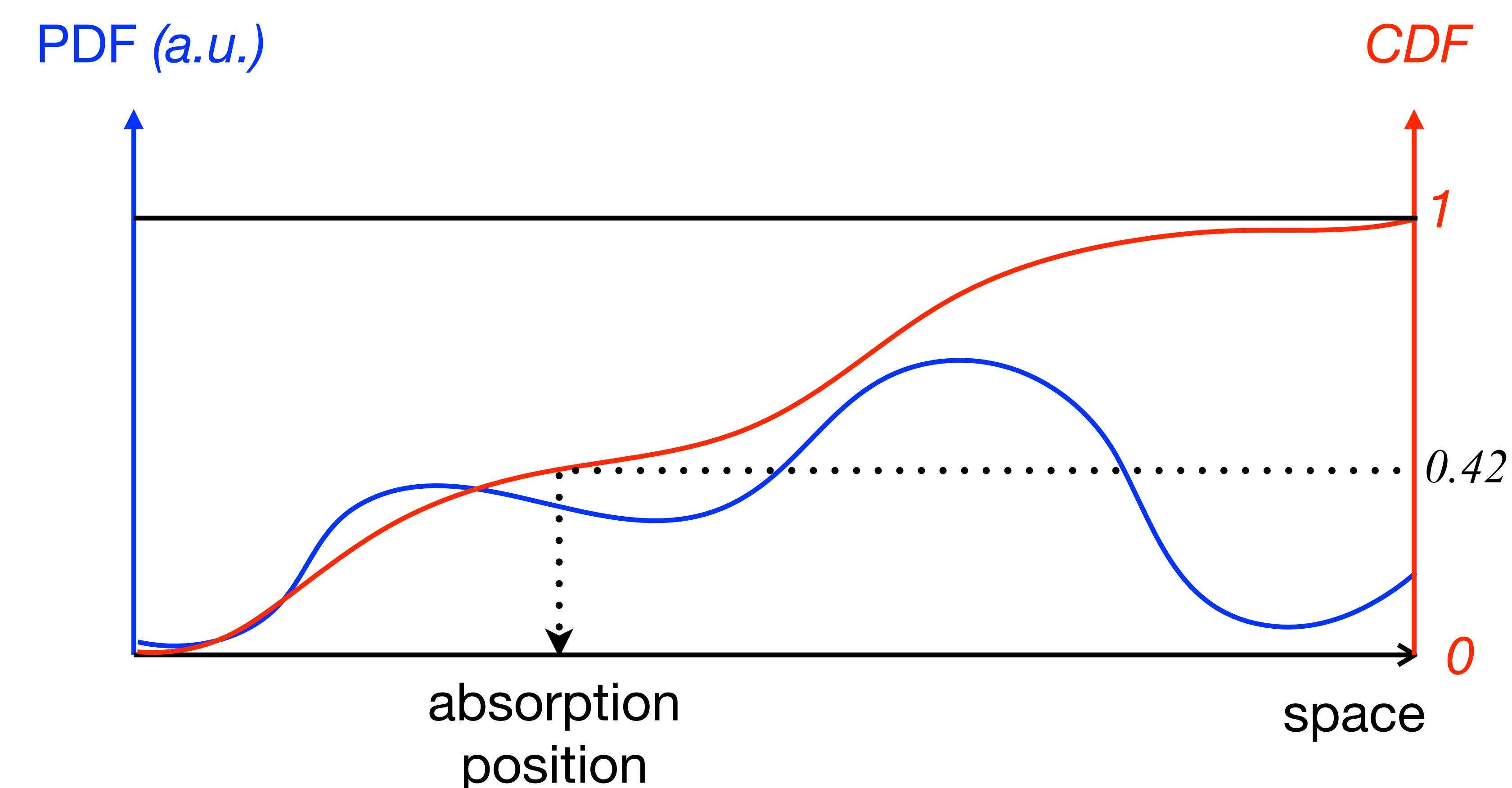


Extra information in fission matrices:

- Eigenvectors



- Probability Density Function (PDF)
 - column of the absorption matrices



*sampling a number in $[0,1]$
provides the position of the
neutron at the next generation*

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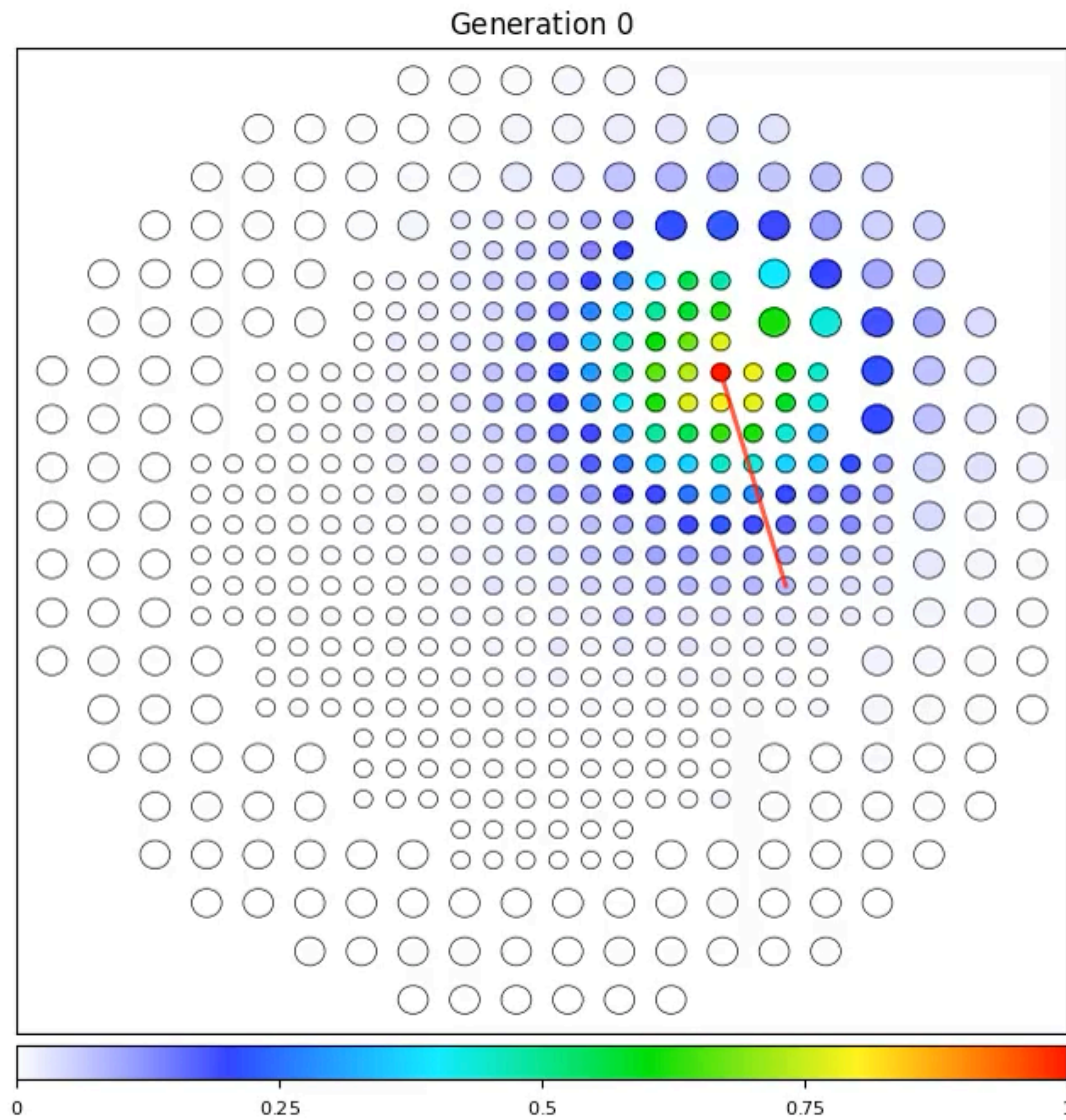
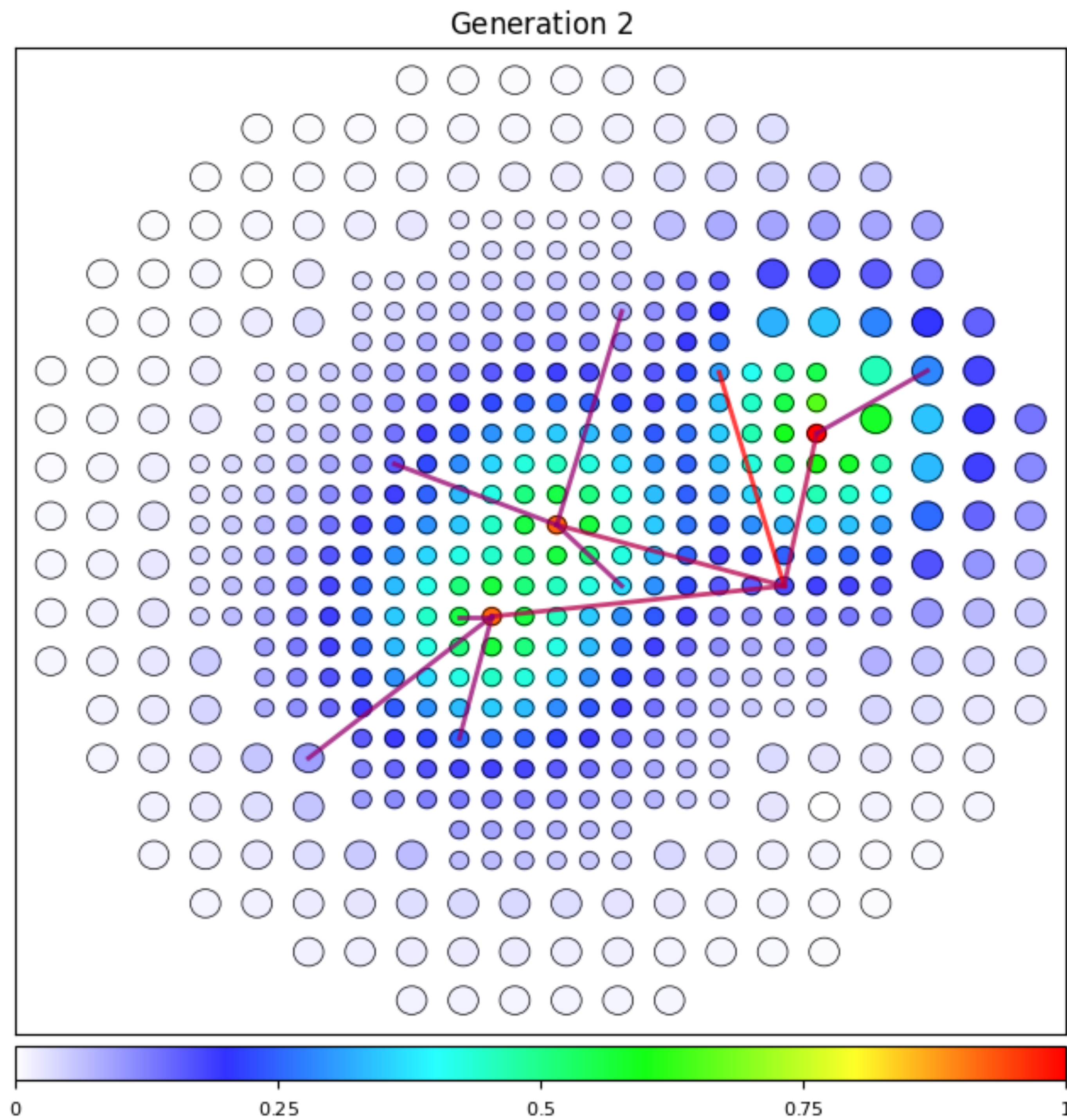
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The RTFM - Radomized TFM - generation procedure

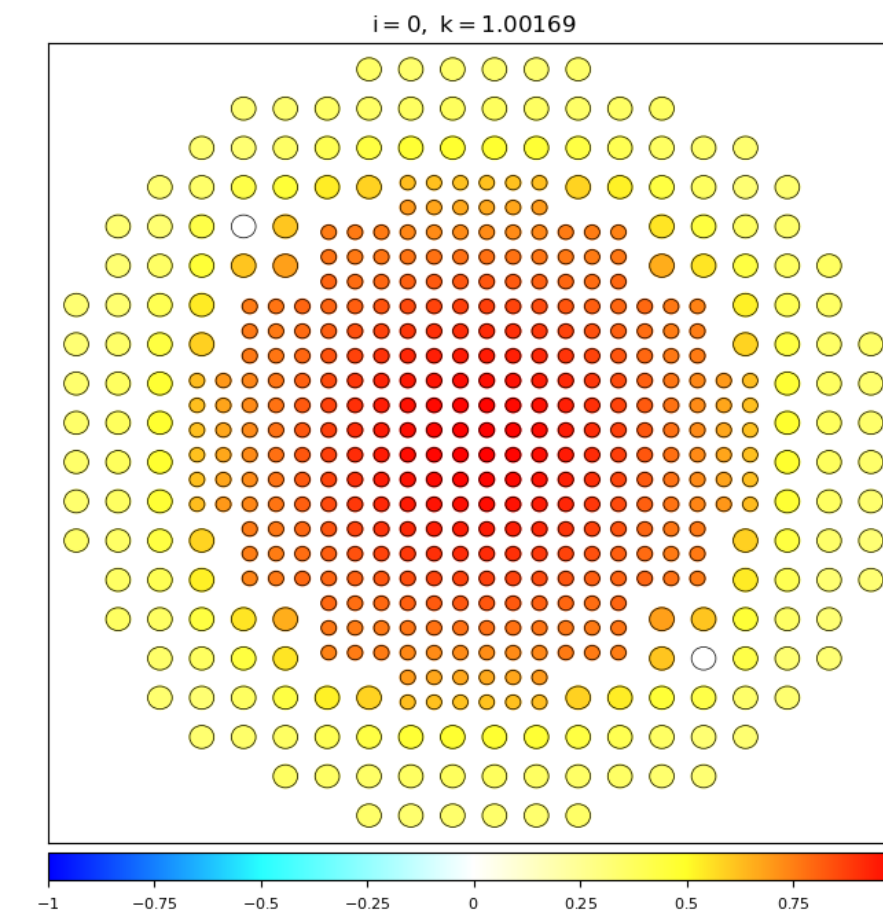
- **sample** a decaying delayed neutron precursor: j at time $t=0$ *fission matrix eigen vector*
- propagation over one generation: (adapt probabilities to delayed/prompt neutron)
 - **sample** target absorption cell i *absorption matrix column*
 - increase t by the lifespan $j \rightarrow i$ *value in time matrix*
 - **sample** if fission: *fission/abs. matrix ratio*
 - **sample** n neutrons form v_p *tally*
 - loop on the n neutrons

~1/β_{eff} times



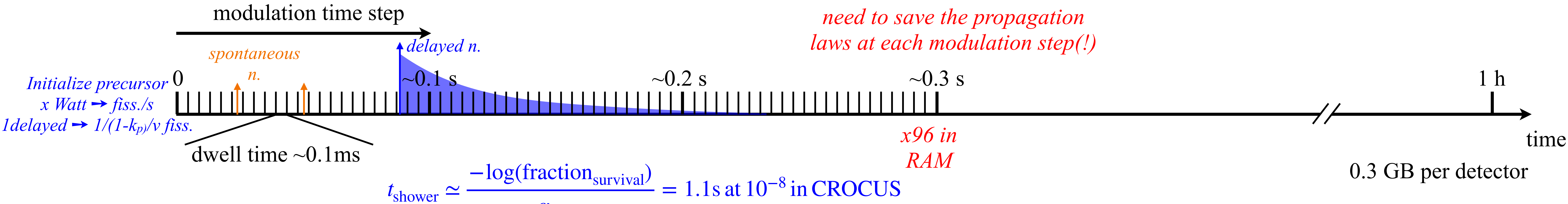
List of required distributions

- **Delayed neutron distribution**
PDF = fission matrix eigen vector or thermalhydraulics based $\Sigma_f \lambda_f P_f$
- **Absorption CDF $j \rightarrow i$**
PDF = abs. column matrix, prompt or delayed
- **Lifespan $j \rightarrow i$**
element i,j time matrix $\rightarrow$ new models @Max Begue thesis
- **Fission probability $j \rightarrow i$**
fission/ v_i /absorption matrices, prompt and delayed
- **Neutron prompt/delayed multiplicity in i**
sample based on a regular v_i tally $\rightarrow$ new models @Max Begue thesis



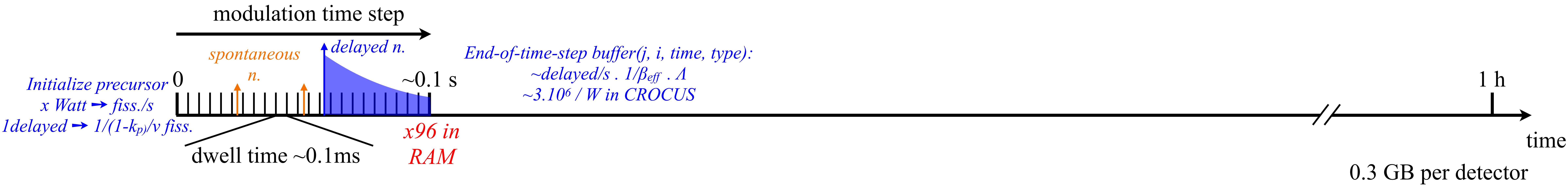
- $\rightarrow$ Transfert function ~260 000 k neutrons per second
- $\rightarrow$ Classic Monte Carlo ~ 160 k neutrons per second

First approach - cython 96 MPI (with shared memory for laws)



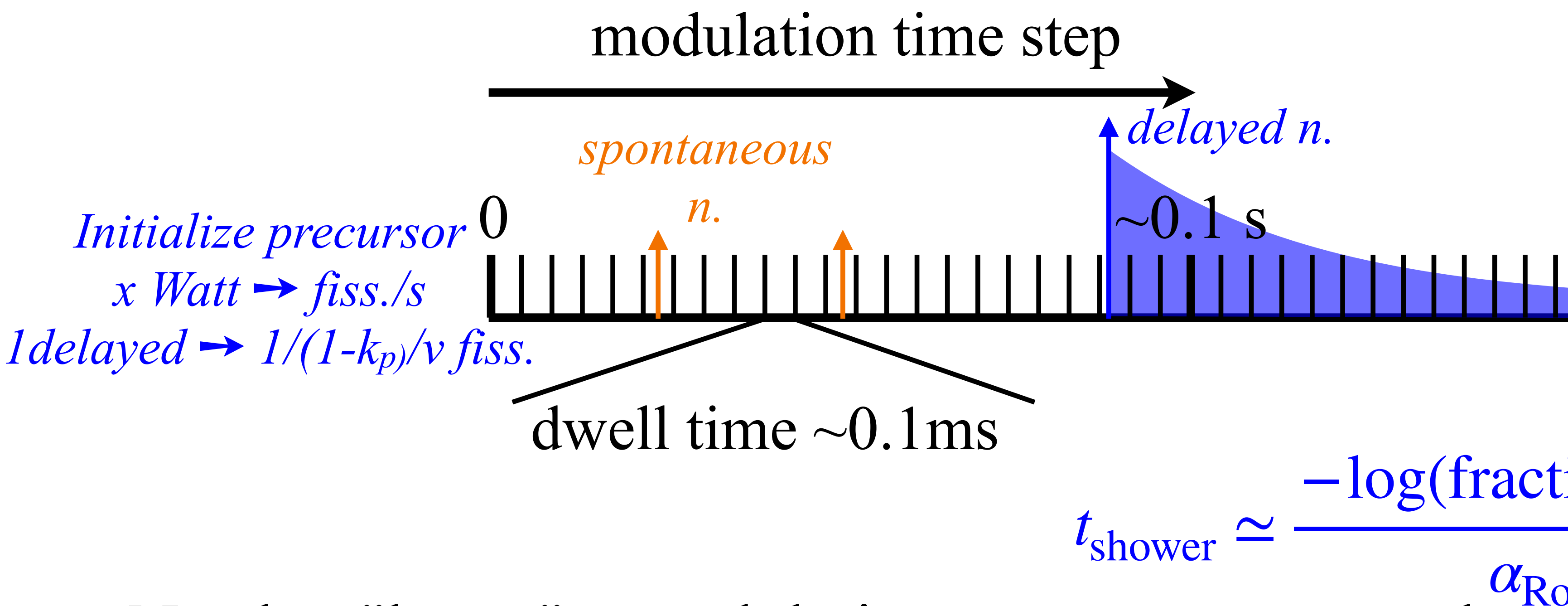
- Need to "know" n modulation states to generate the samples
- Memory requirement for the tallies
- Shared memory for the laws (read only)
 - cyclic memory management

Current approach - cython 8 MPI (with shared memory for laws) x 12 OMP



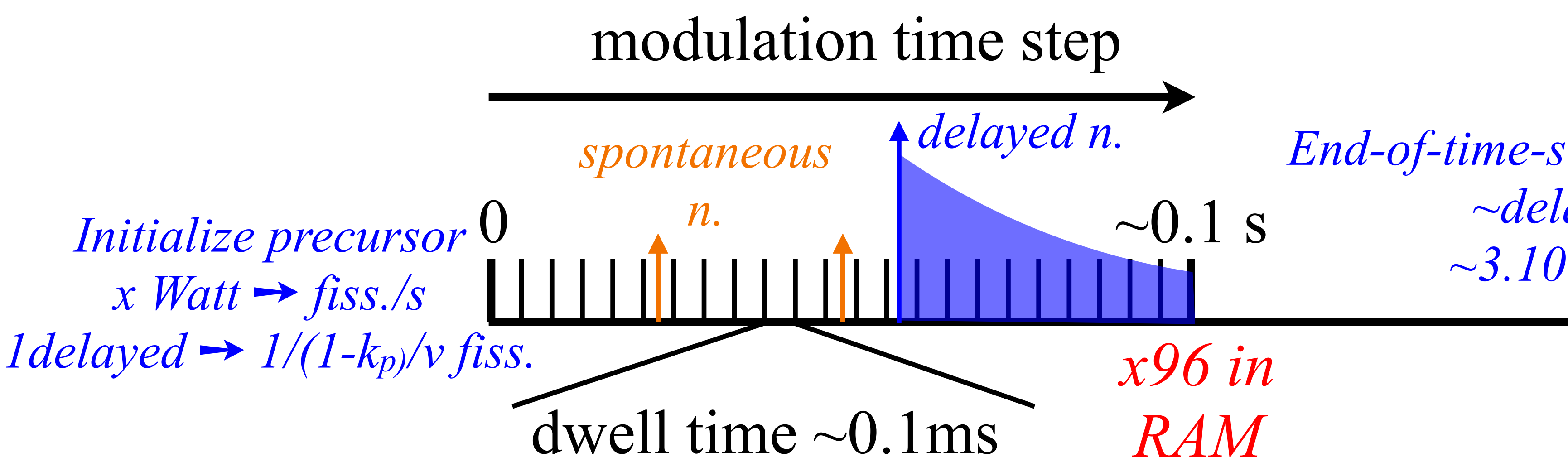
- Only two laws have to be generated at the same time
 - important for coupled noise generation - toward tracking of precursors by CFD
 - predictor-corrector algorithm is possible
- Two step generation
 - remaining cut showers of previous step
 - decaying precursors during the step (MPI-balanced)

First approach - cython 96 MPI (with shared memory for laws)



- Need to "know" n modulation states to generate the shower
- Memory requirement for the tallies
- Shared memory for the laws (read only)
→ cyclic memory management

Current approach - cython 8 MPI (with shared memory for laws)



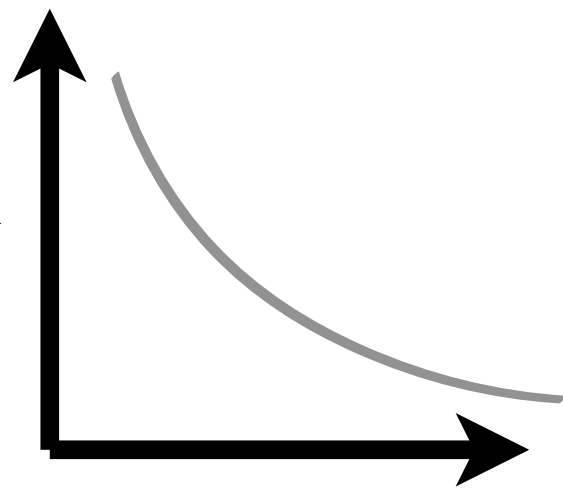
- Only two laws have to be generated at the same time
→ important for coupled noise generation - toward tracking of precursors by CFD
→ predictor-corrector algorithm is possible



time series with T values



autocorrelation

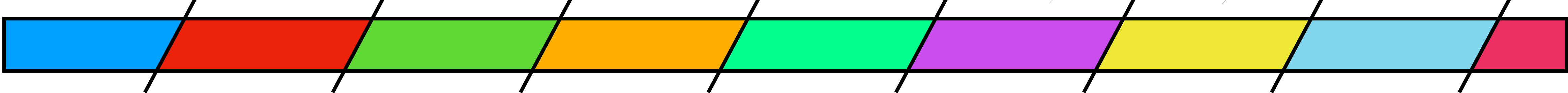


fit

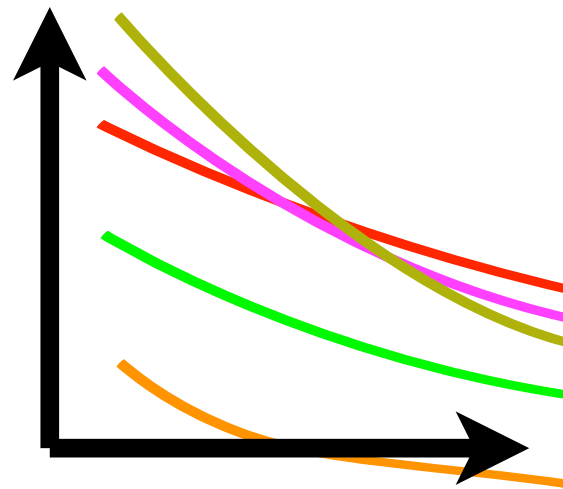
α

$\sigma(\alpha) = ???$

Naive approach: N sub time series of T/N values



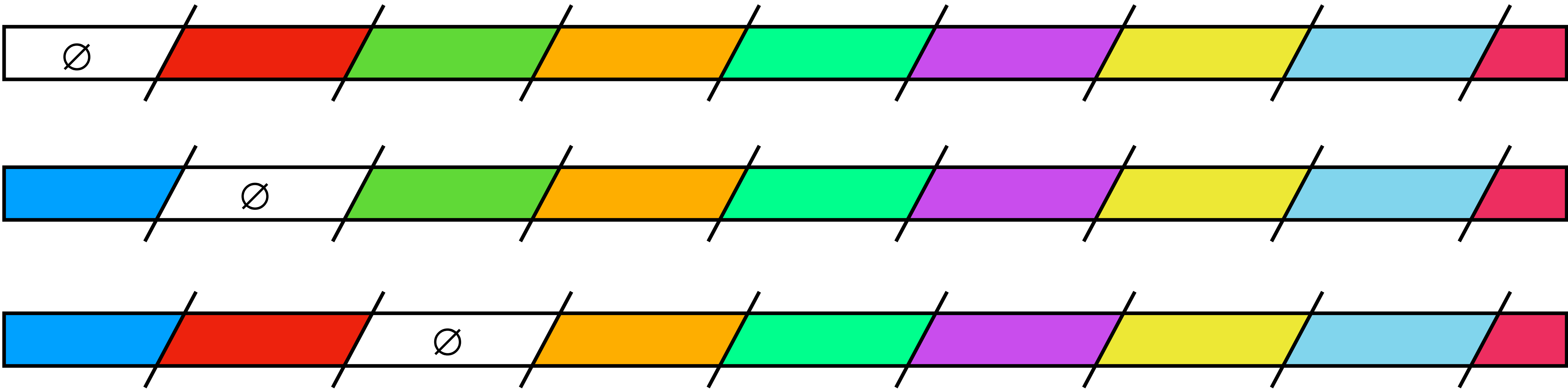
- Sensitive to statistical issues if the chunks are too small



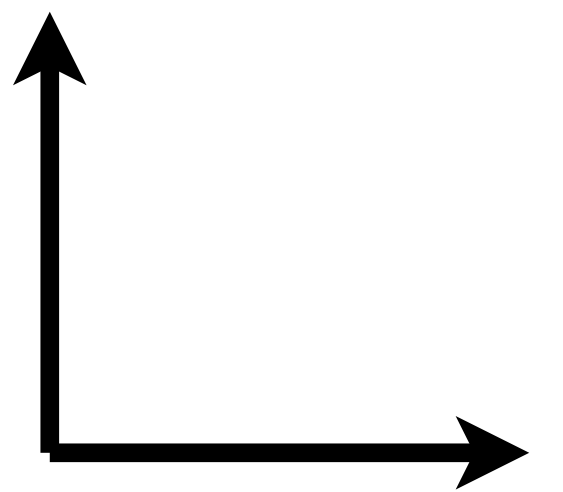
$\{\alpha_n \llbracket n \in 1, N \rrbracket\}$

$\vartriangleright \text{var}(\alpha) = \frac{1}{N(N-1)} \text{var}(\alpha_n)$

Jackknife resampling: N sub time series of T.(N-1)/N values



- Better estimation of the uncertainty

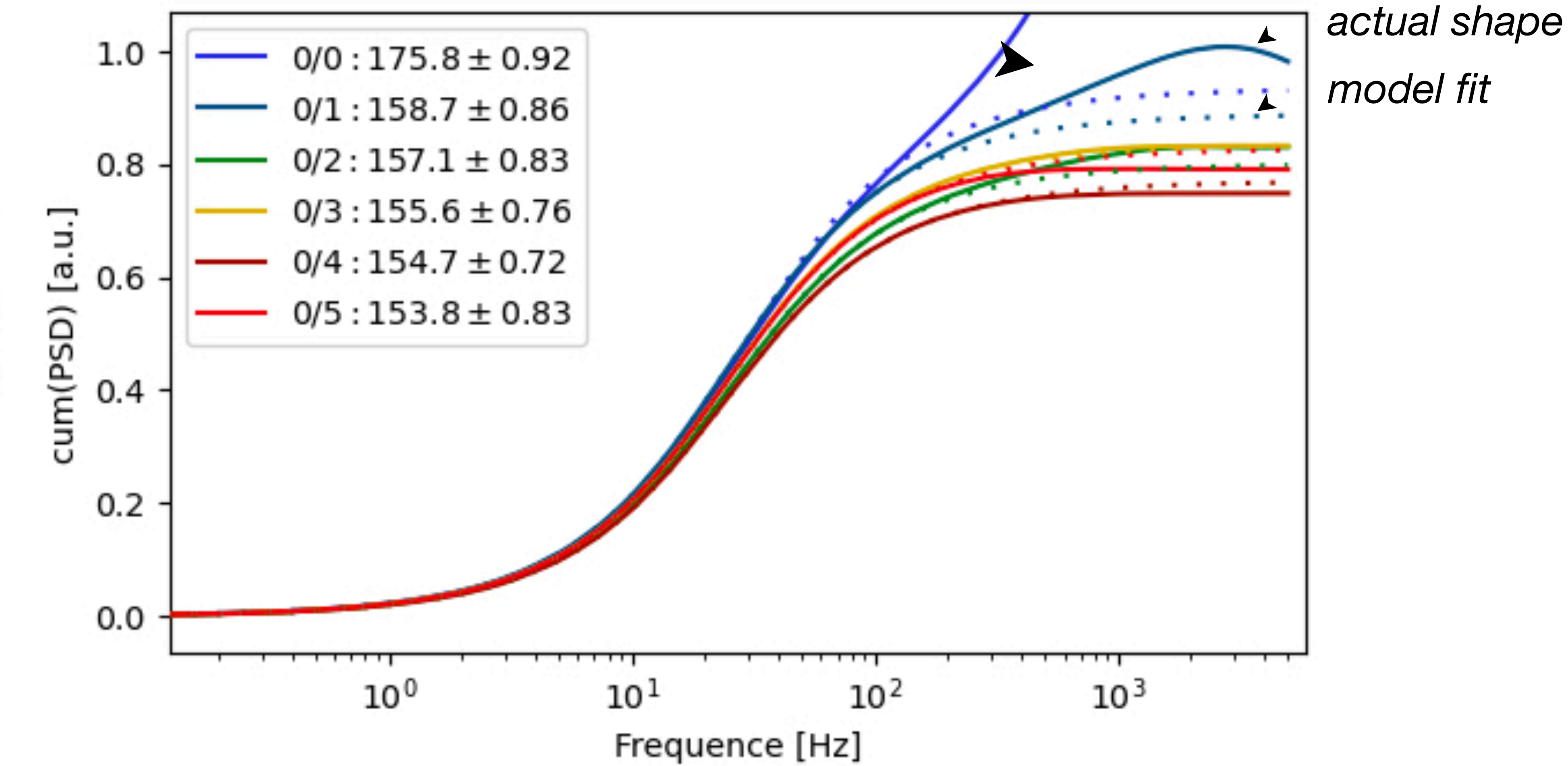
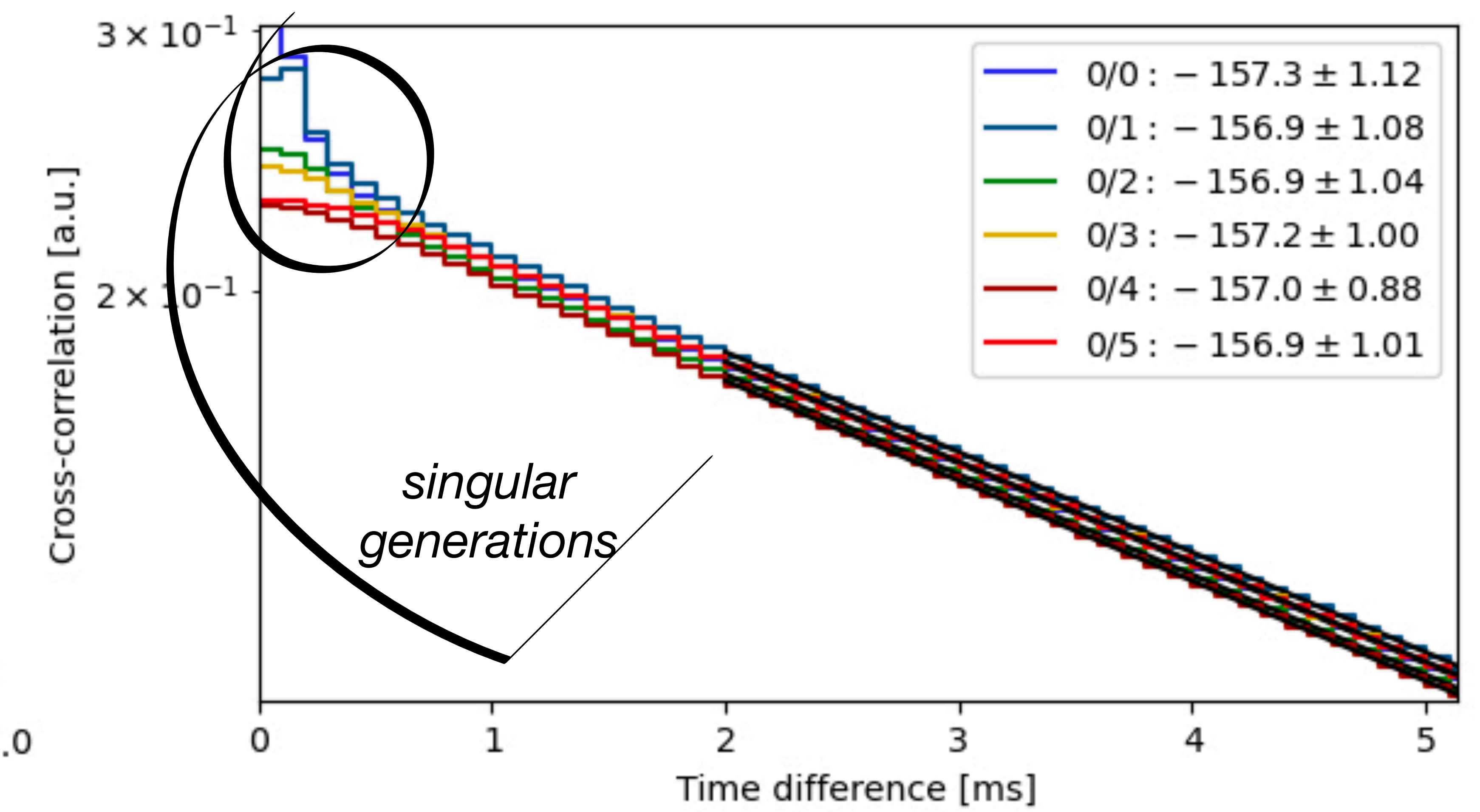
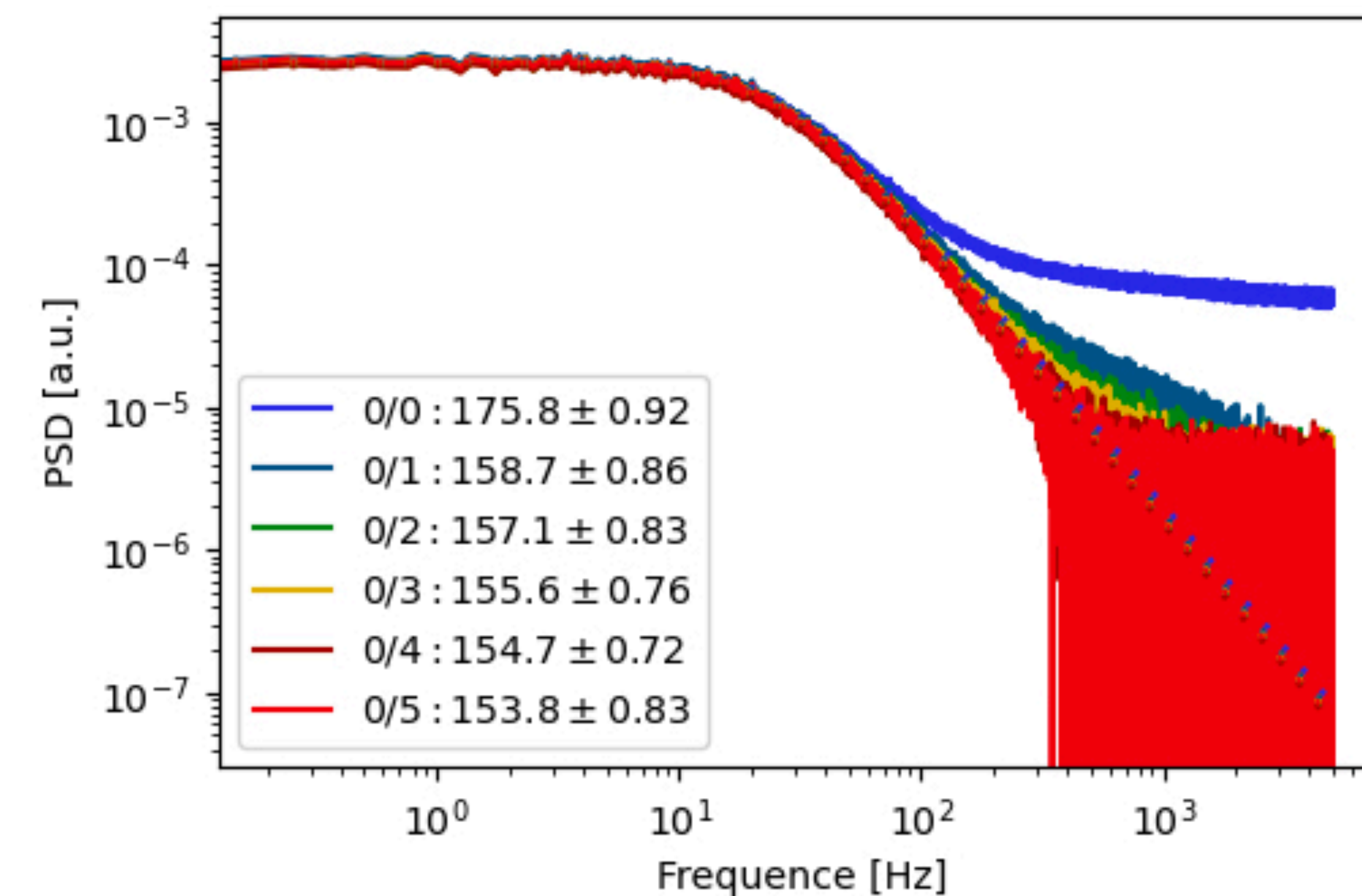
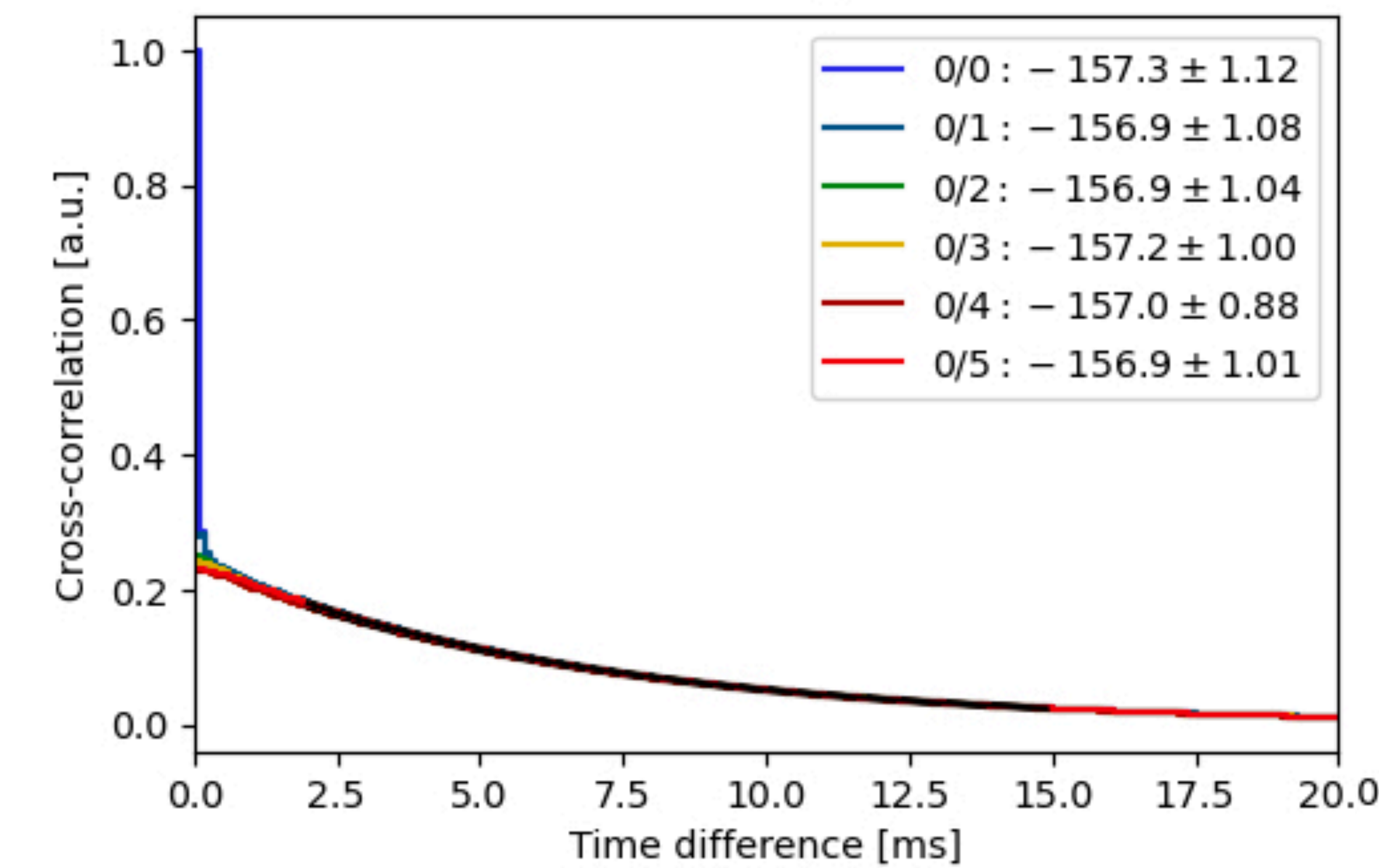
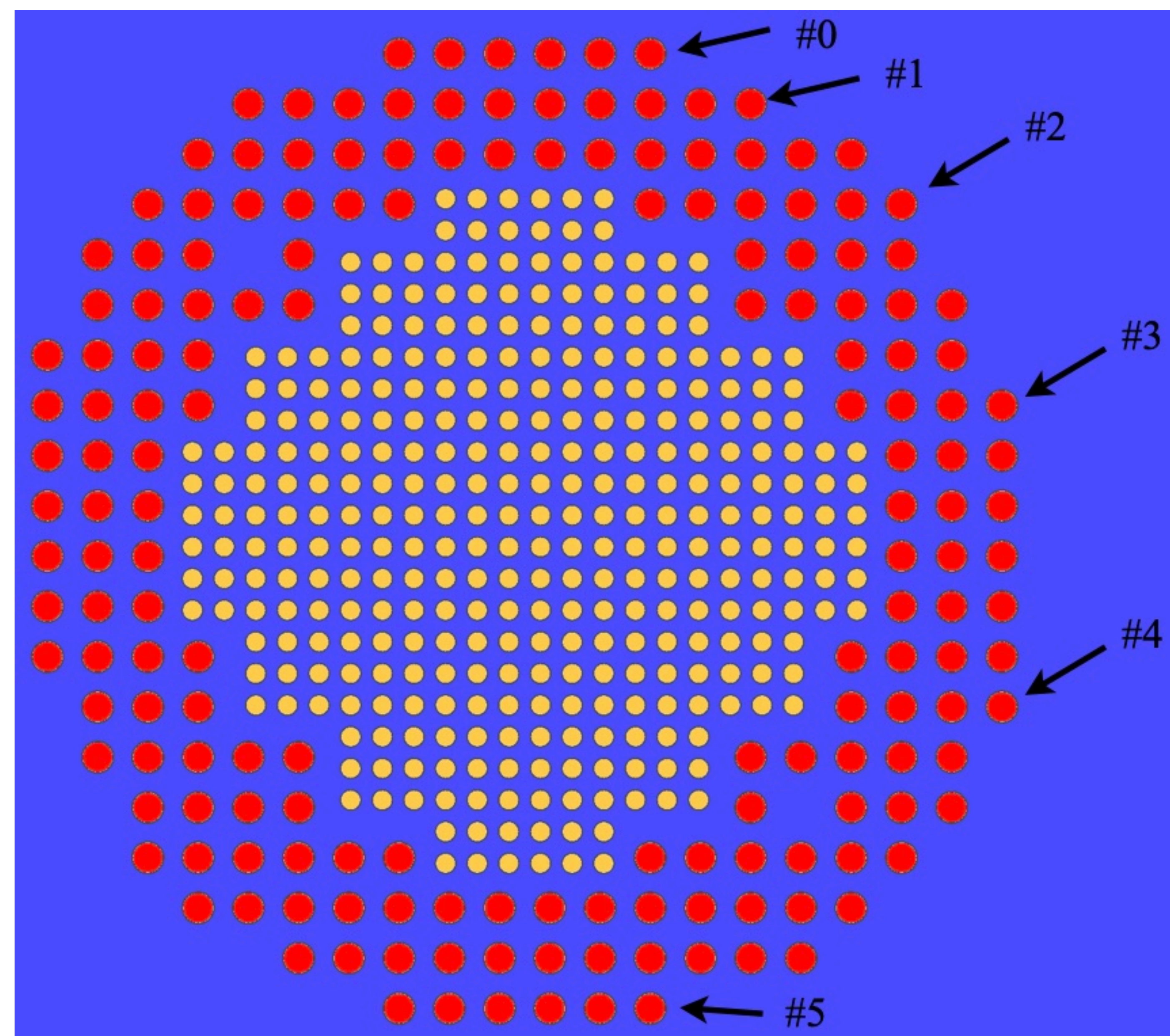


$\{\alpha_{n^c} \llbracket n \in 1, N \rrbracket\}$

$\vartriangleright \text{var}(\alpha) = \frac{N-1}{N} \sum_{n=1}^N (\alpha_{n^c} - \alpha_{\text{ref}})^2$

Test case using CROCUS reactor

- Reference (matrix) $\alpha_{\text{prompt}} = 155.9 \pm 0.1 \text{ s}^{-1}$
- Multiple detector positions along the reflector

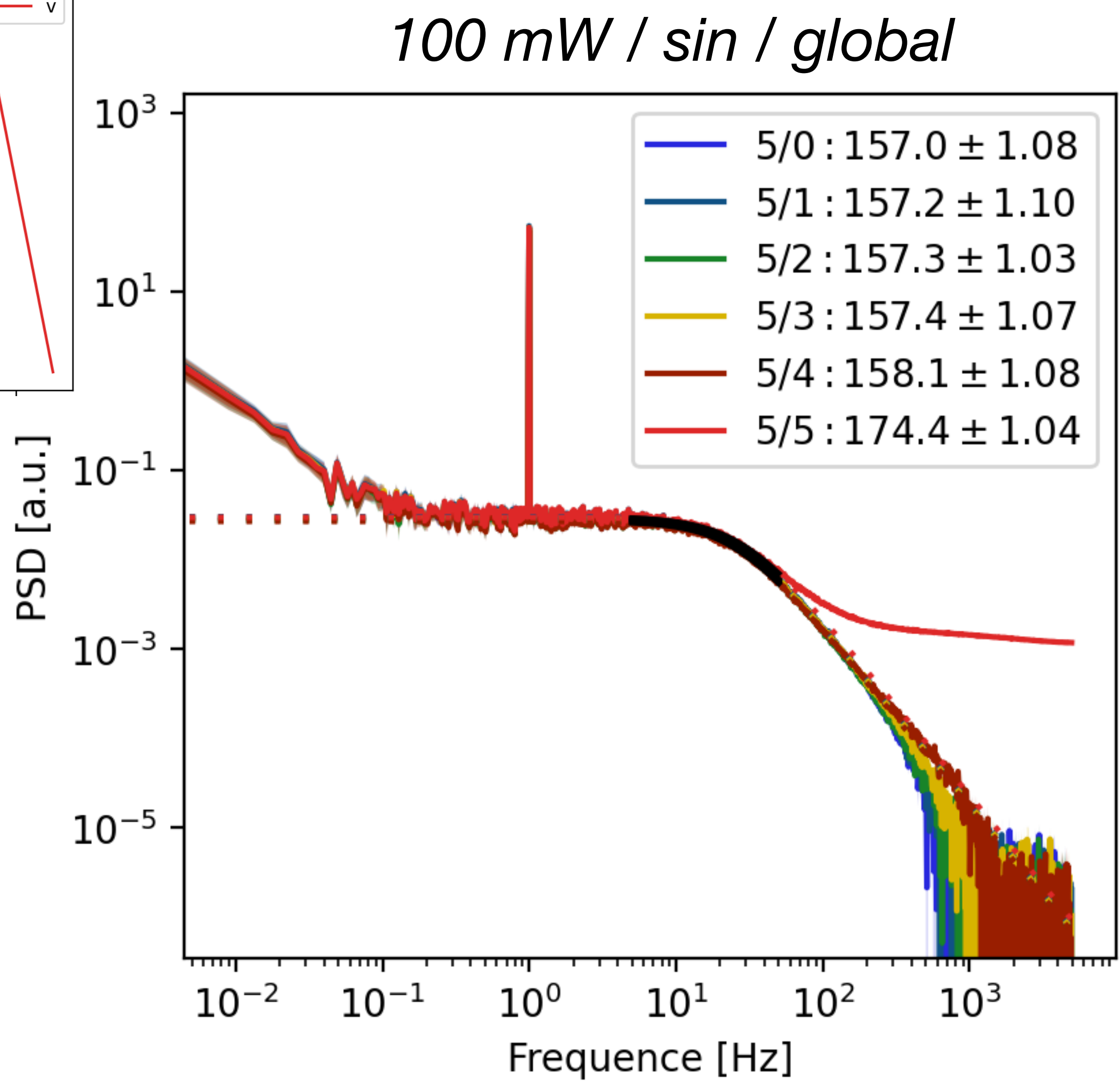
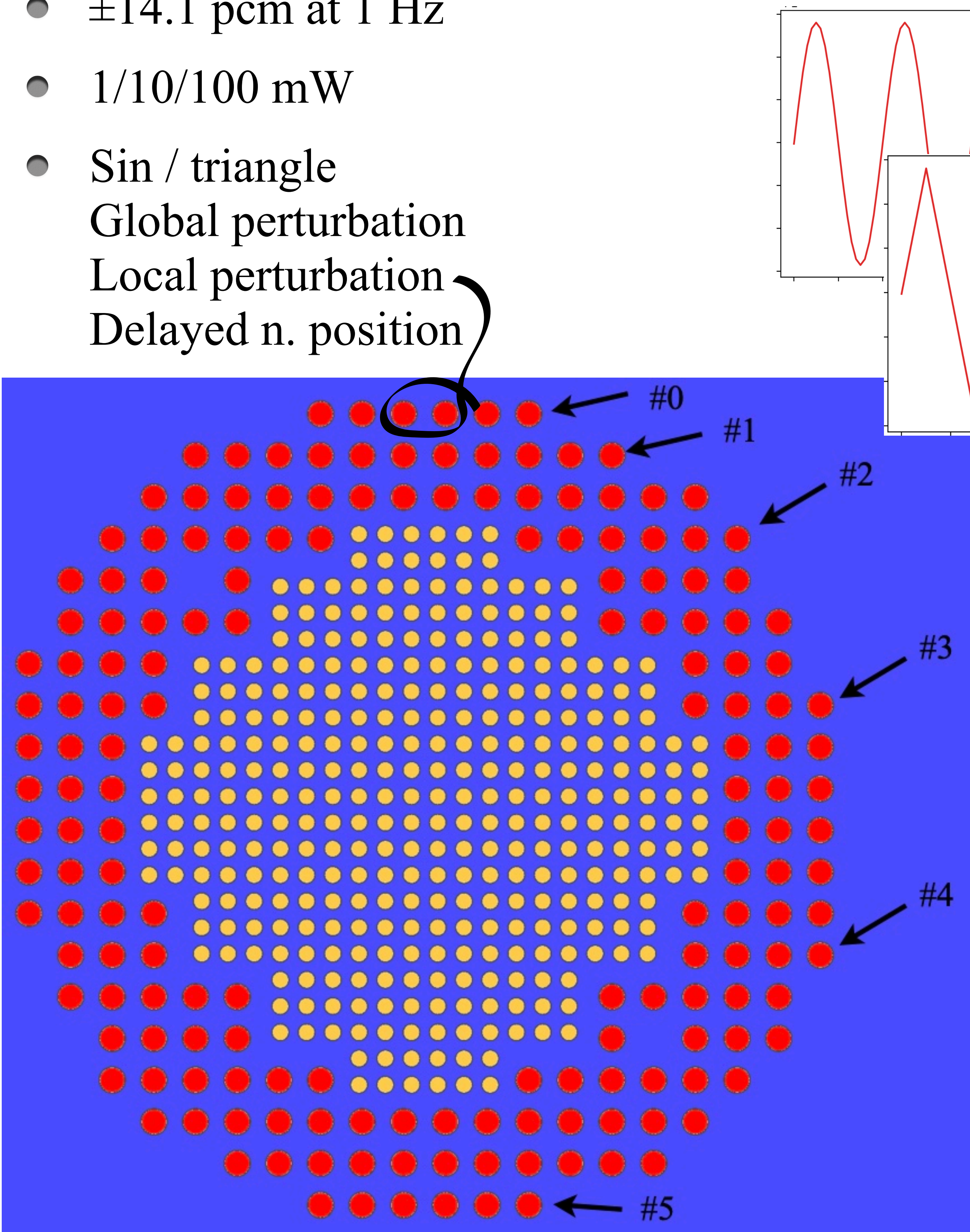


Conclusion

- Very good agreement between simulated noise "*measurement*" and the α_{prompt} contained in the TFM matrices
- Useful to study spatial effect on neutron noise: first singular generations depend on the delayed neutron *seed*

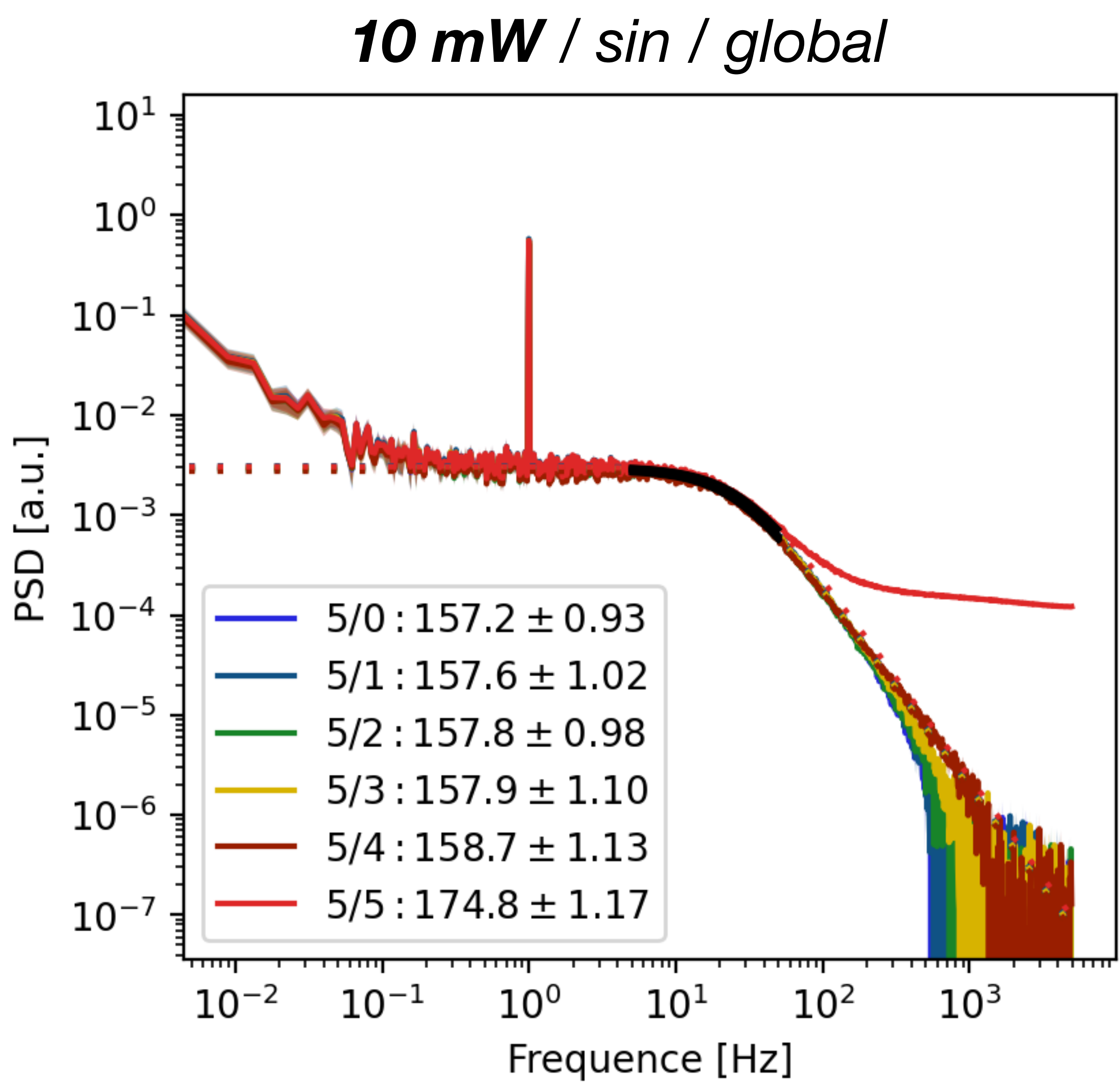
Test case using CROCUS reactor - modulation

- ±14.1 pcm at 1 Hz
- 1/10/100 mW
- Sin / triangle
Global perturbation
Local perturbation
Delayed n. position



ref:

5.18e+01	± 3.5e-01
5.44e+01	± 3.8e-01
4.95e+01	± 3.4e-01
5.22e+01	± 3.5e-01
4.82e+01	± 3.3e-01
5.22e+01	± 3.4e-01



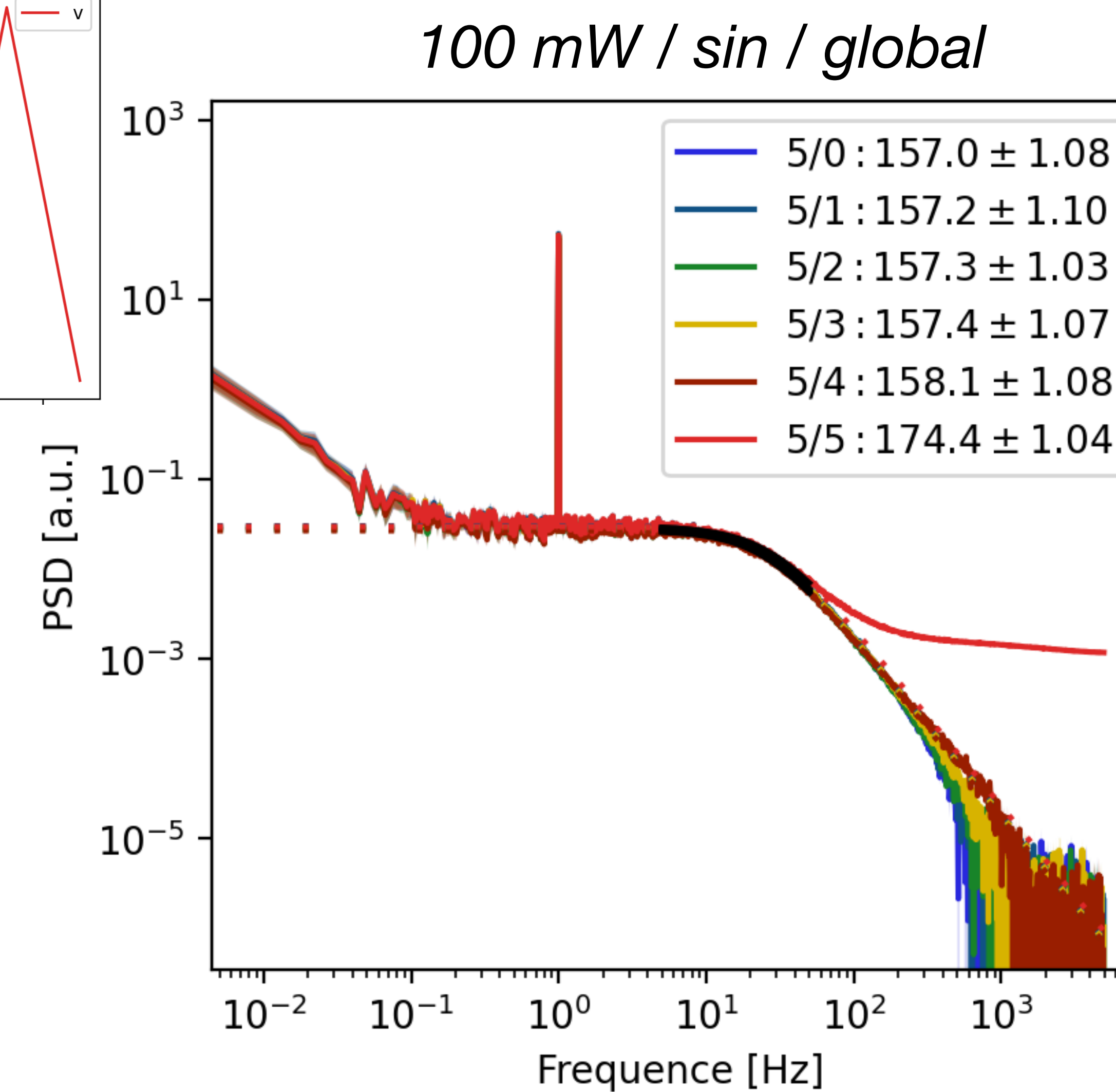
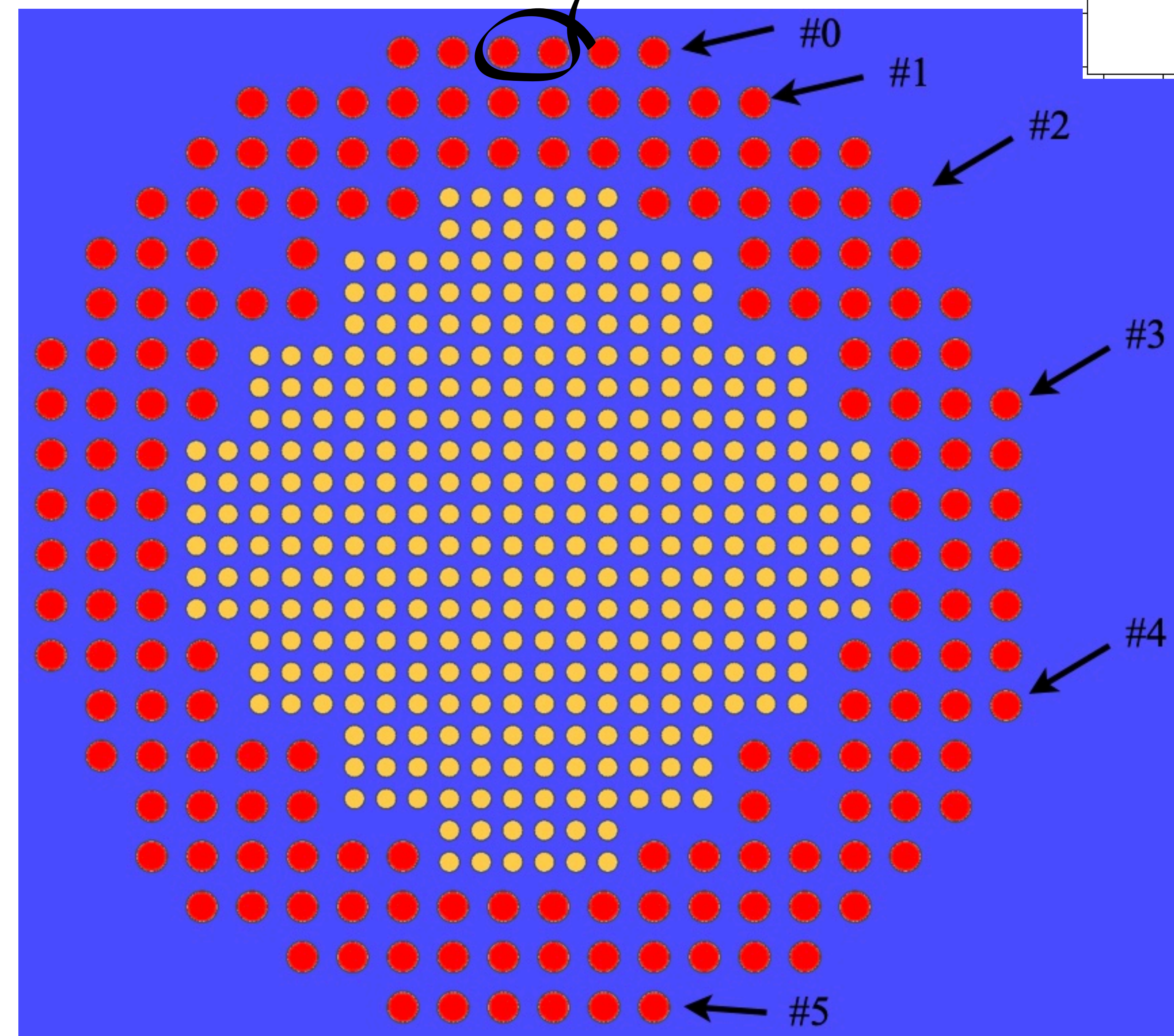
pert/ref:

1.07e-02	± 1.9e-04
1.07e-02	± 1.9e-04
1.08e-02	± 1.9e-04
1.07e-02	± 1.9e-04
1.07e-02	± 2.0e-04
1.07e-02	± 1.9e-04

Amplitude variation

Test case using CROCUS reactor - modulation

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$5.18e+01 \pm 3.5e-01$

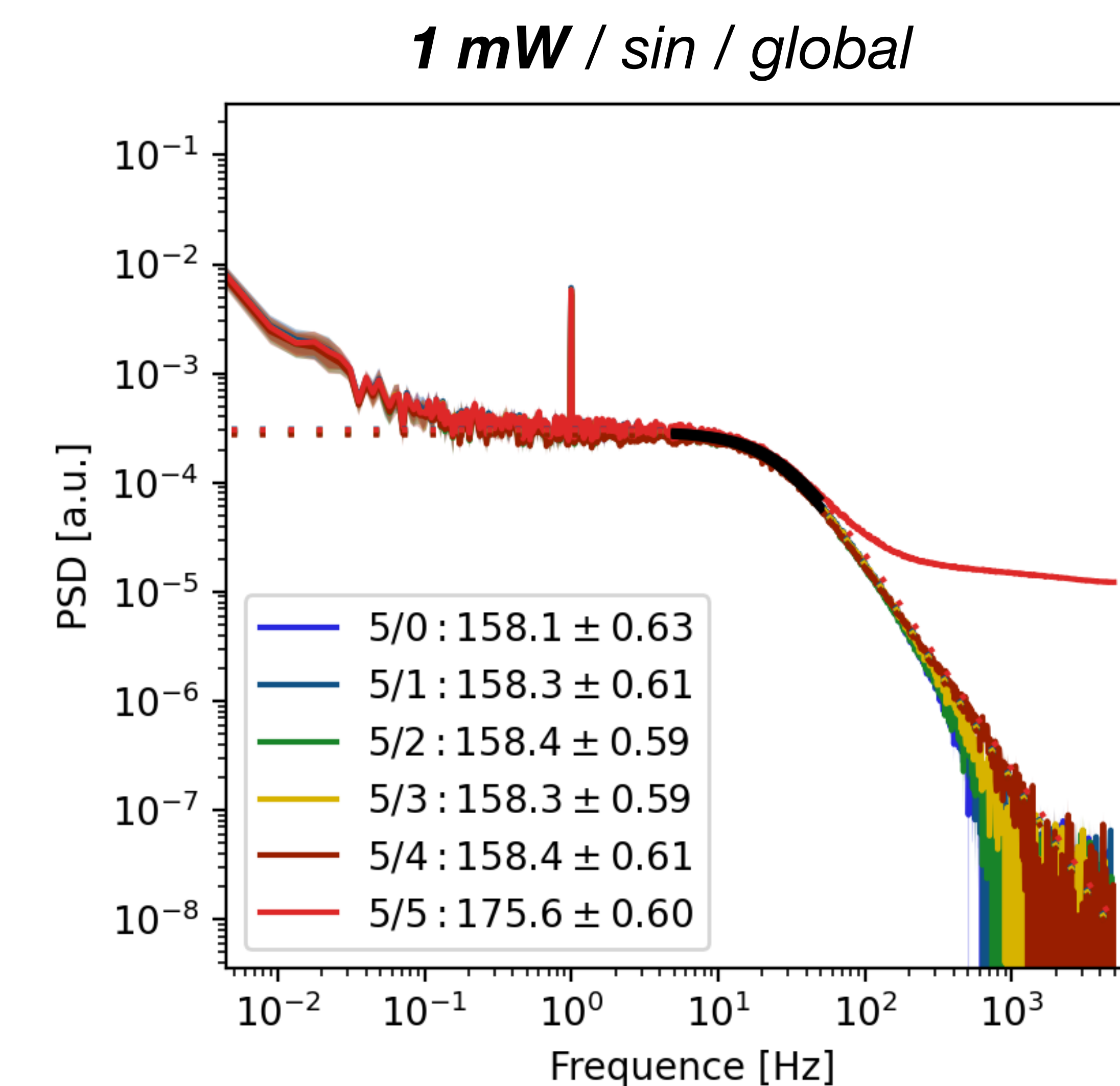
$5.44e+01 \pm 3.8e-01$

$4.95e+01 \pm 3.4e-01$

$5.22e+01 \pm 3.5e-01$

$4.82e+01 \pm 3.3e-01$

$5.22e+01 \pm 3.4e-01$



pert/ref:

$1.06e-04 \pm 4.3e-06$

$1.07e-04 \pm 4.1e-06$

$1.05e-04 \pm 4.5e-06$

$1.05e-04 \pm 4.7e-06$

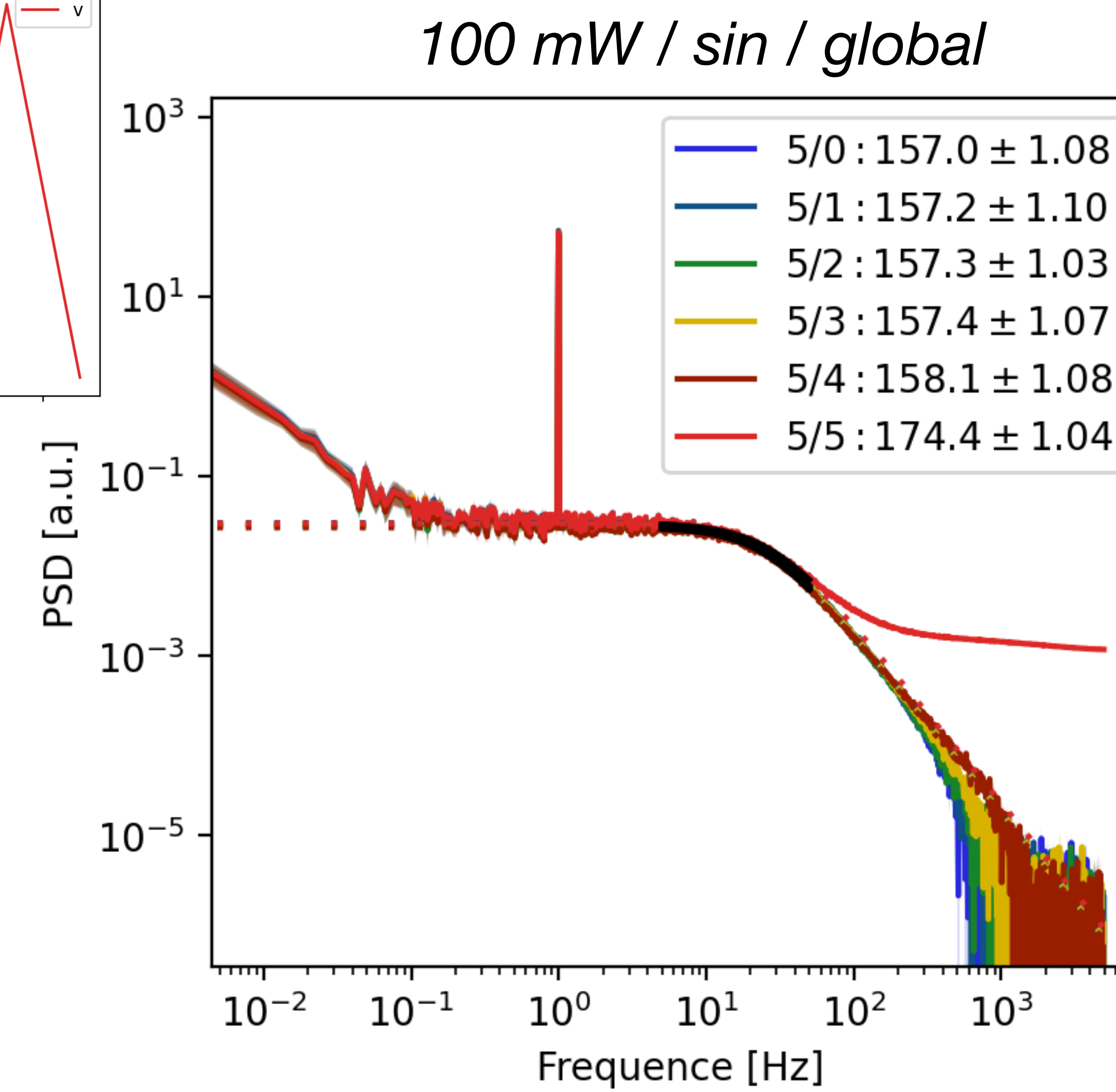
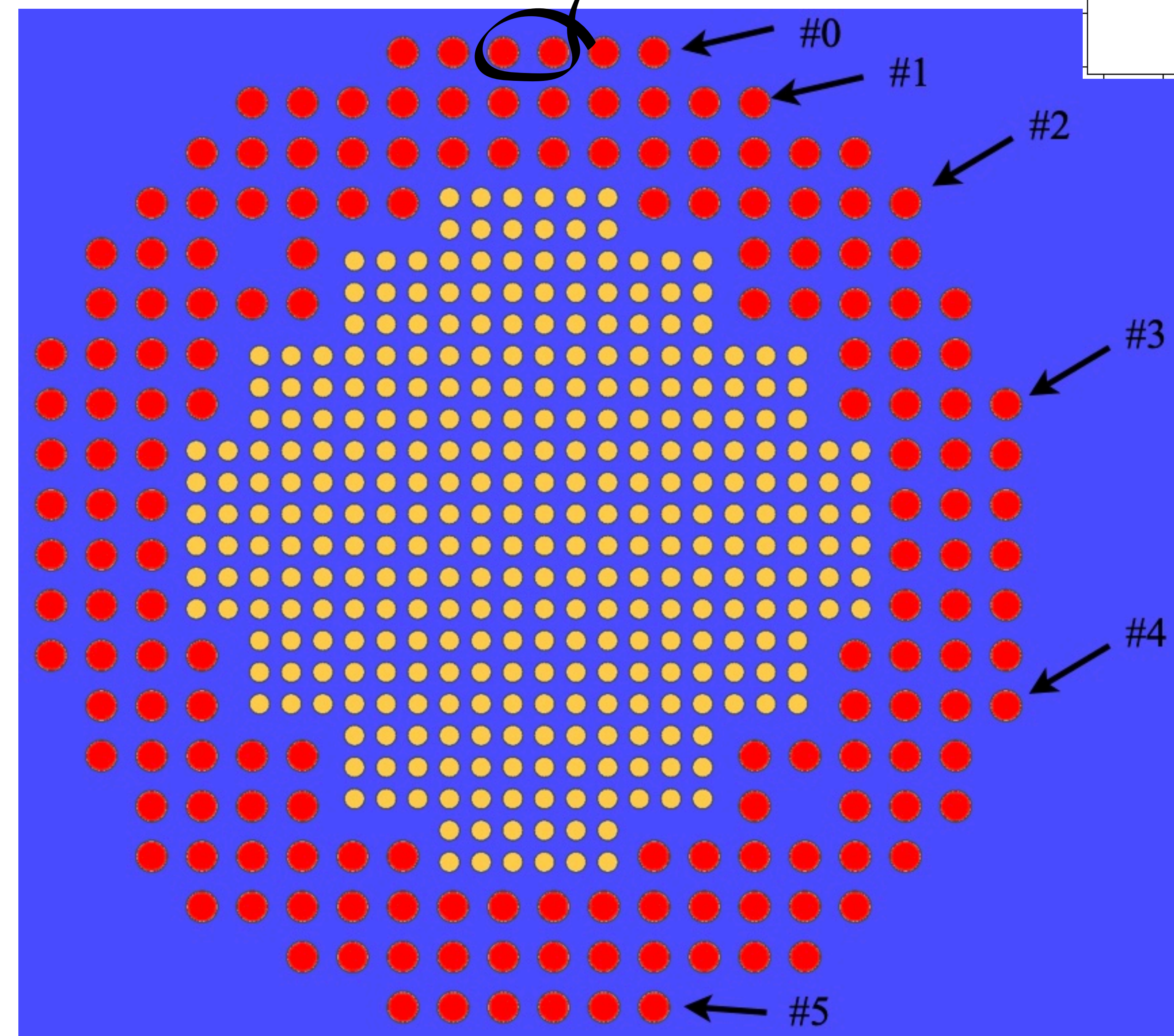
$1.04e-04 \pm 4.2e-06$

$1.07e-04 \pm 4.3e-06$

Amplitude variation

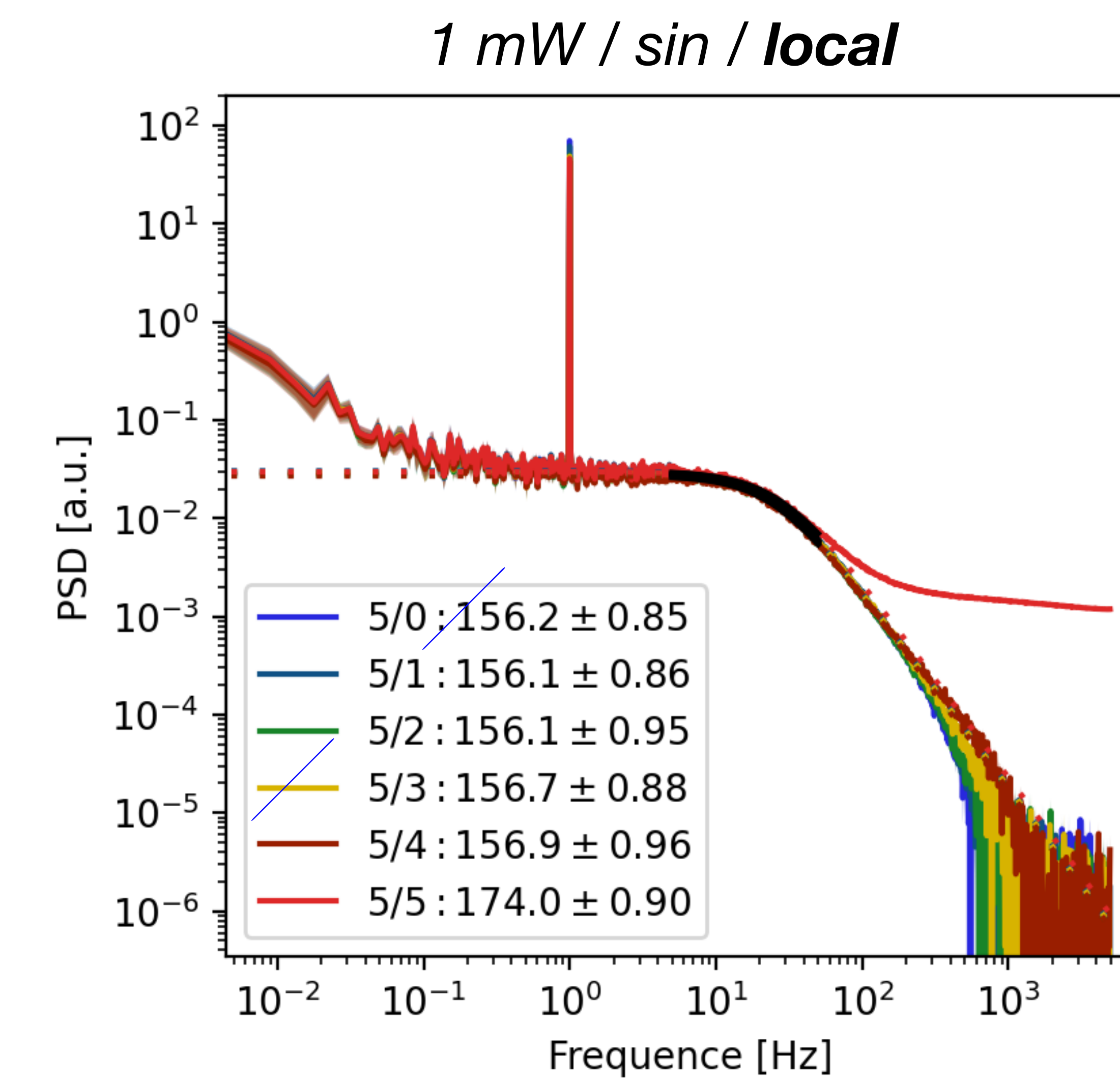
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pert/ref:

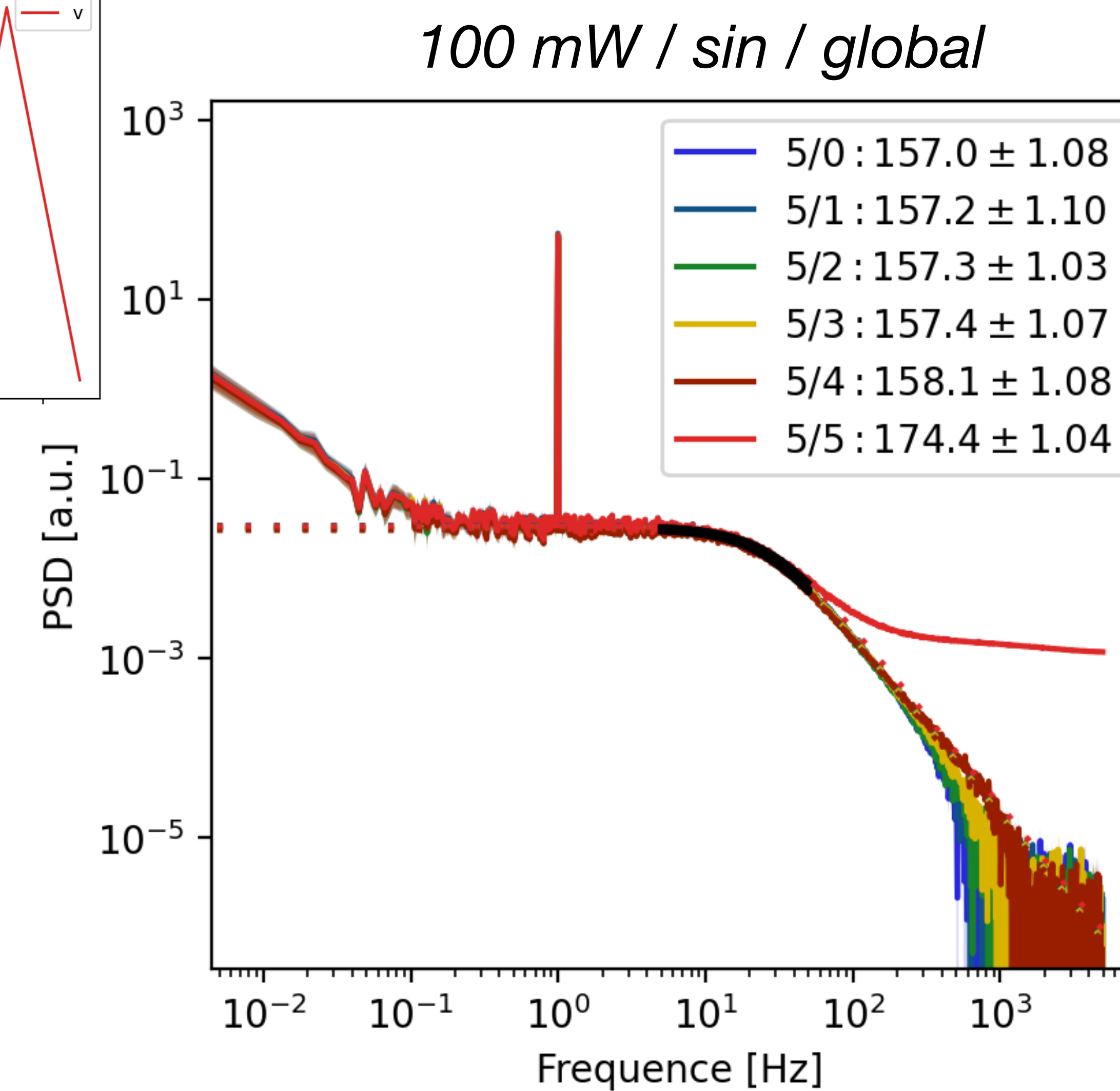
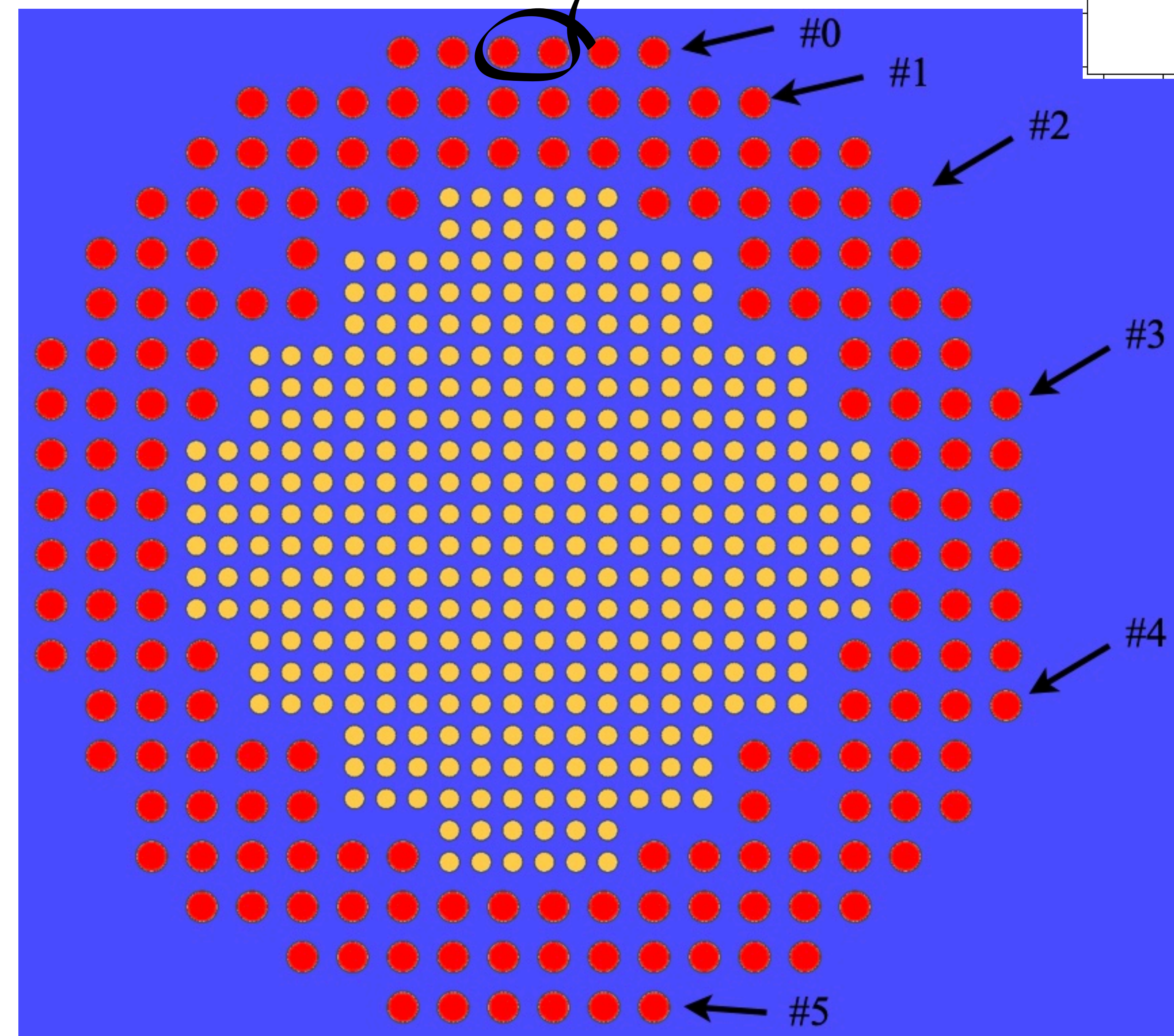
$1.35e+00 \pm 1.2e-02$
 $1.13e+00 \pm 1.1e-02$
 $9.94e-01 \pm 9.7e-03$
 $9.31e-01 \pm 9.0e-03$
 $9.02e-01 \pm 8.9e-03$
 $8.85e-01 \pm 8.8e-03$

larger if close to
perturbation

smaller if far from
perturbation

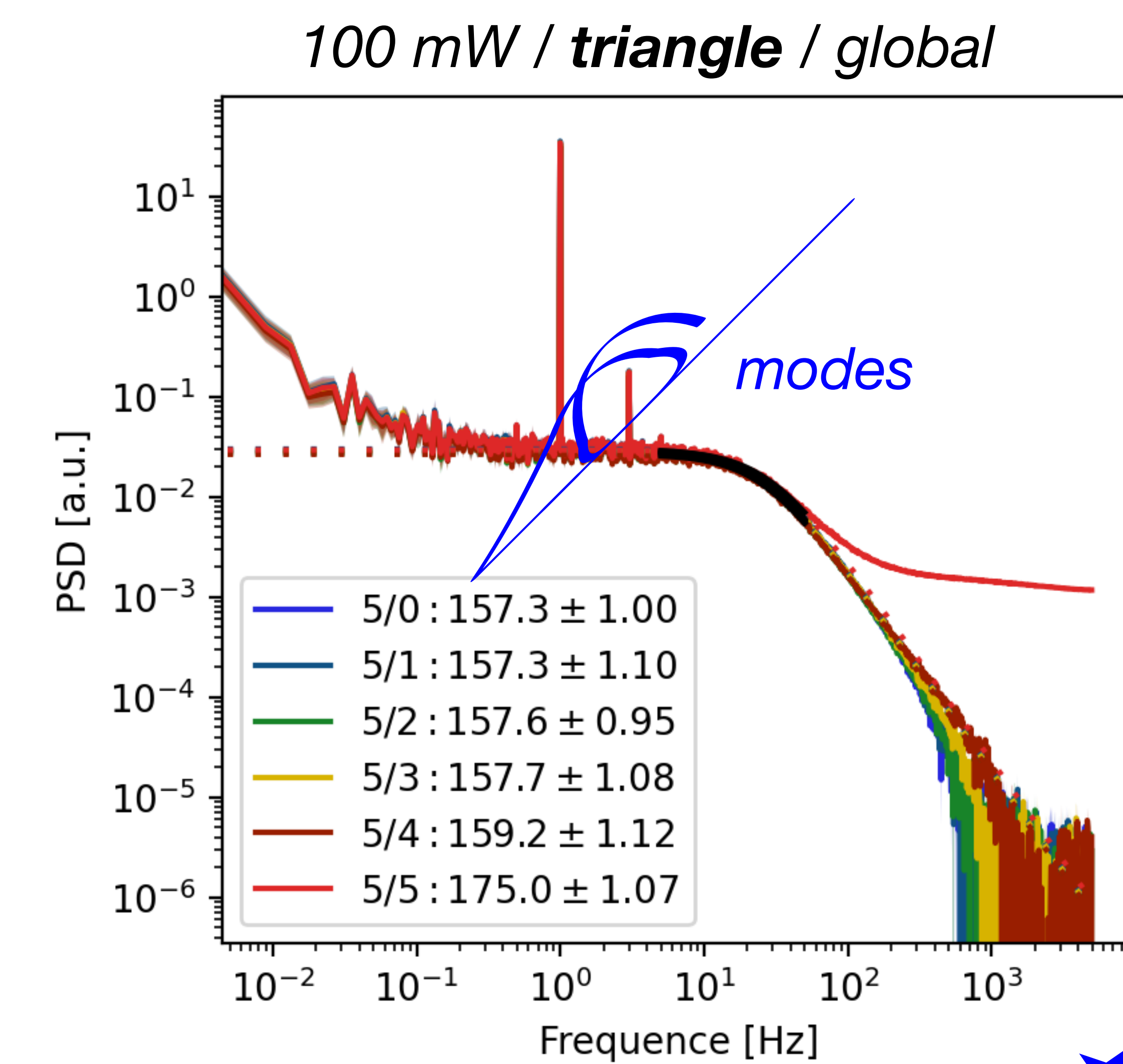
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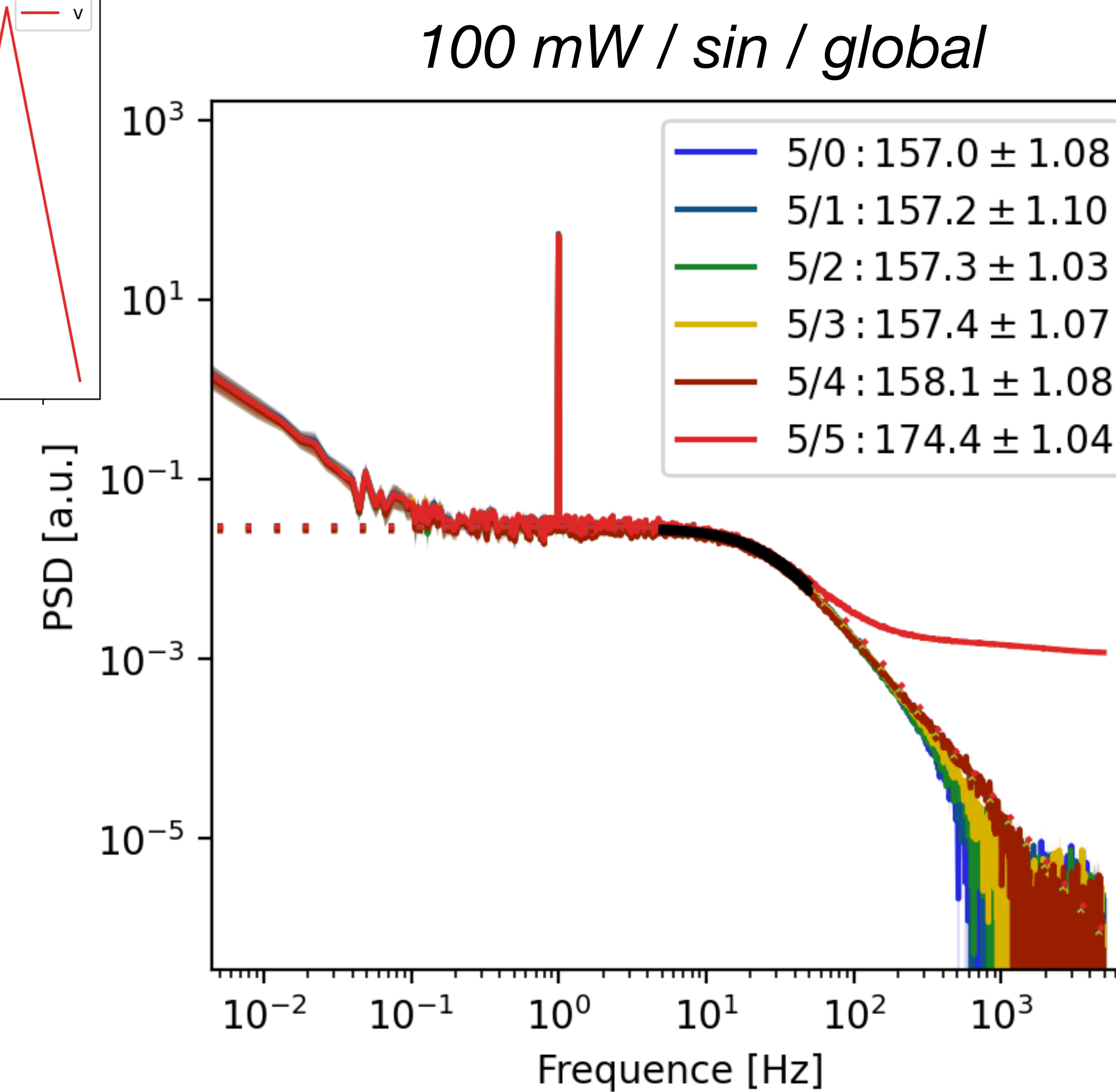
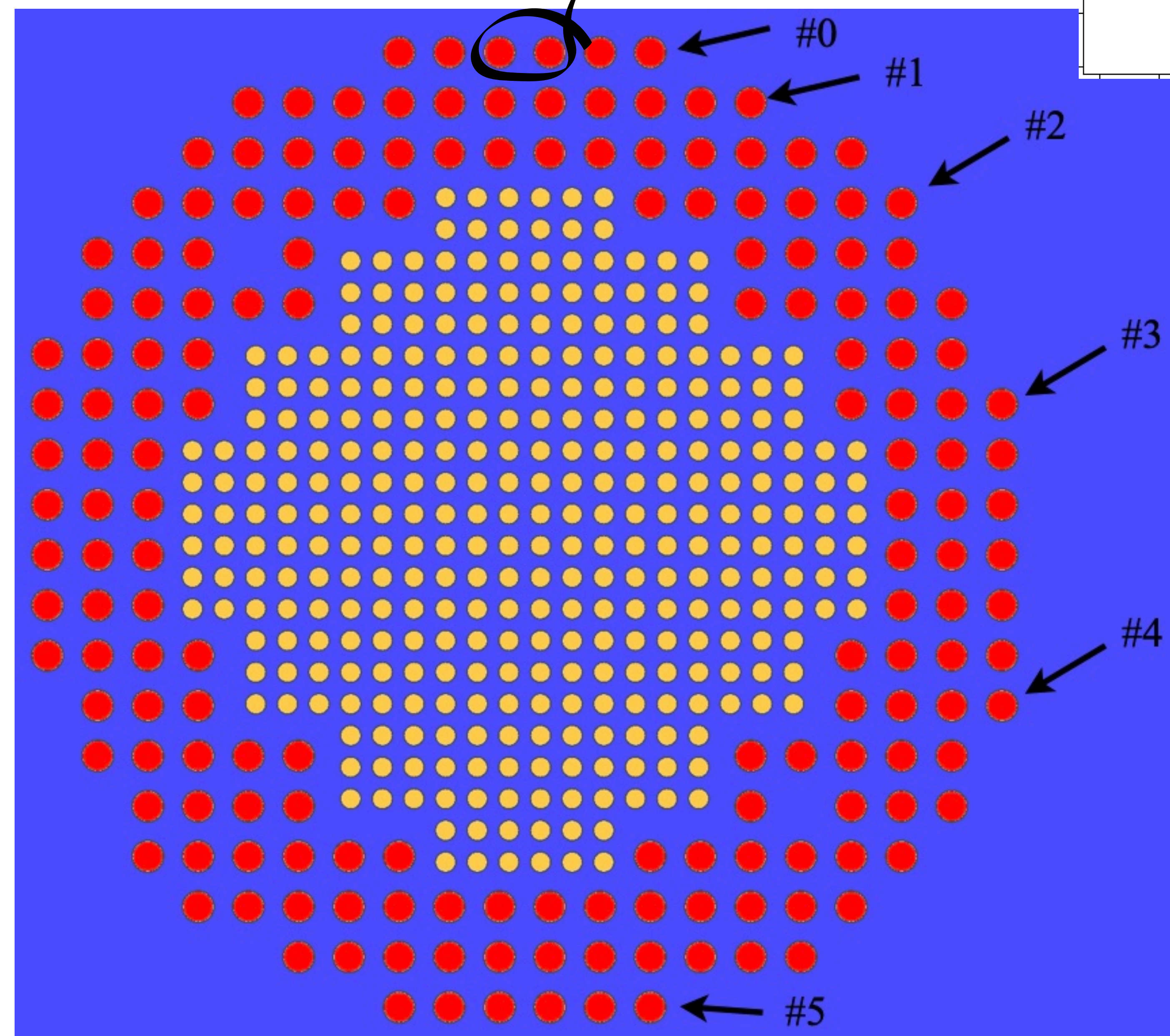
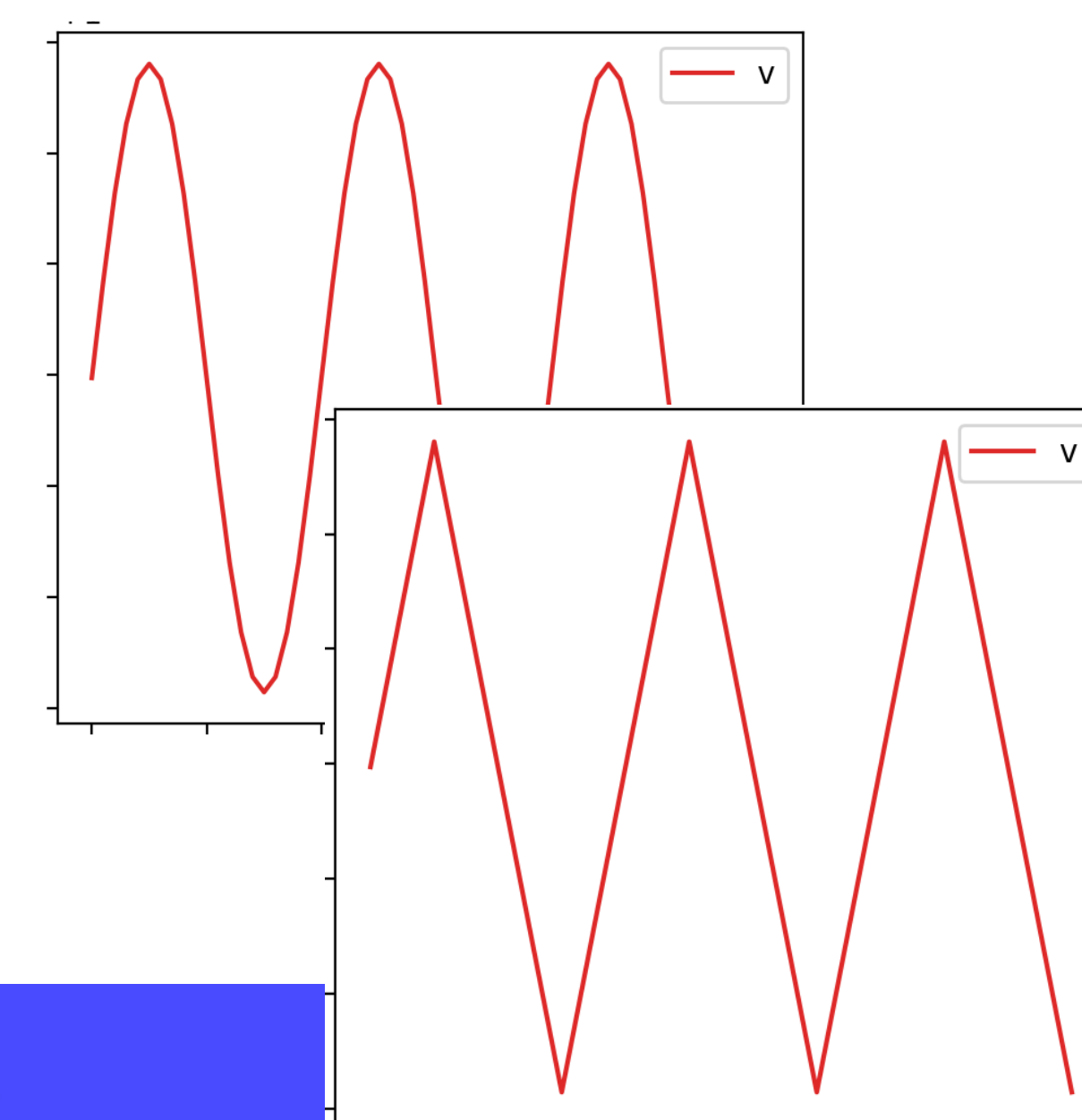


pert/ref:

	3Hz	5Hz
$6.56e-01 \pm 5.8e-03$	$2.66e-03 \pm 1.9e-04$	$2.28e-04 \pm 6.4e-05$
$6.56e-01 \pm 5.9e-03$	$2.67e-03 \pm 2.0e-04$	$2.06e-04 \pm 6.6e-05$
$6.57e-01 \pm 5.9e-03$	$2.71e-03 \pm 2.0e-04$	$2.26e-04 \pm 6.7e-05$
$6.55e-01 \pm 5.8e-03$	$2.68e-03 \pm 2.1e-04$	$2.32e-04 \pm 6.3e-05$
$6.56e-01 \pm 5.8e-03$	$2.68e-03 \pm 2.1e-04$	$2.18e-04 \pm 6.4e-05$
$6.57e-01 \pm 5.7e-03$	$2.72e-03 \pm 2.1e-04$	$2.57e-04 \pm 6.9e-05$

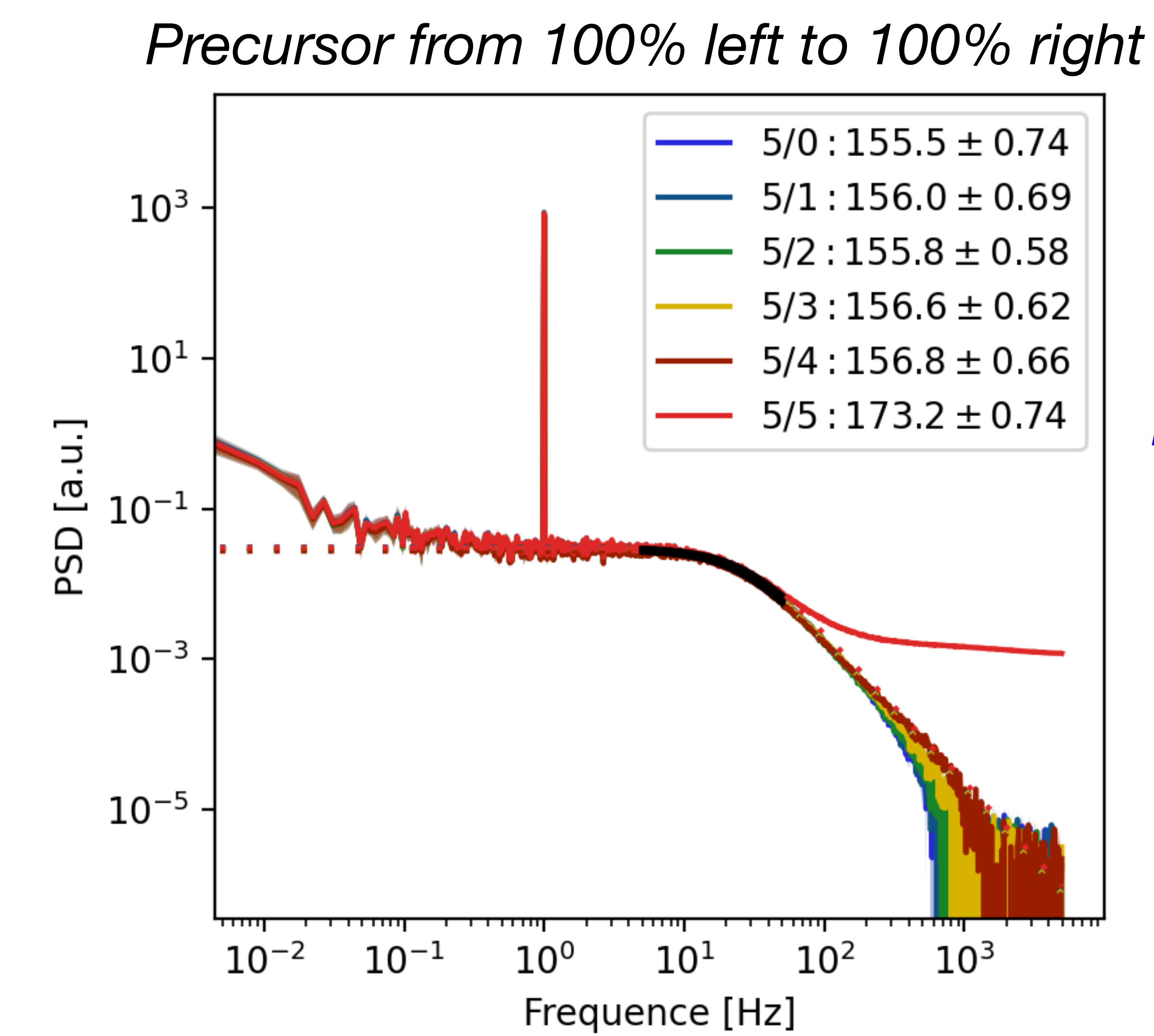
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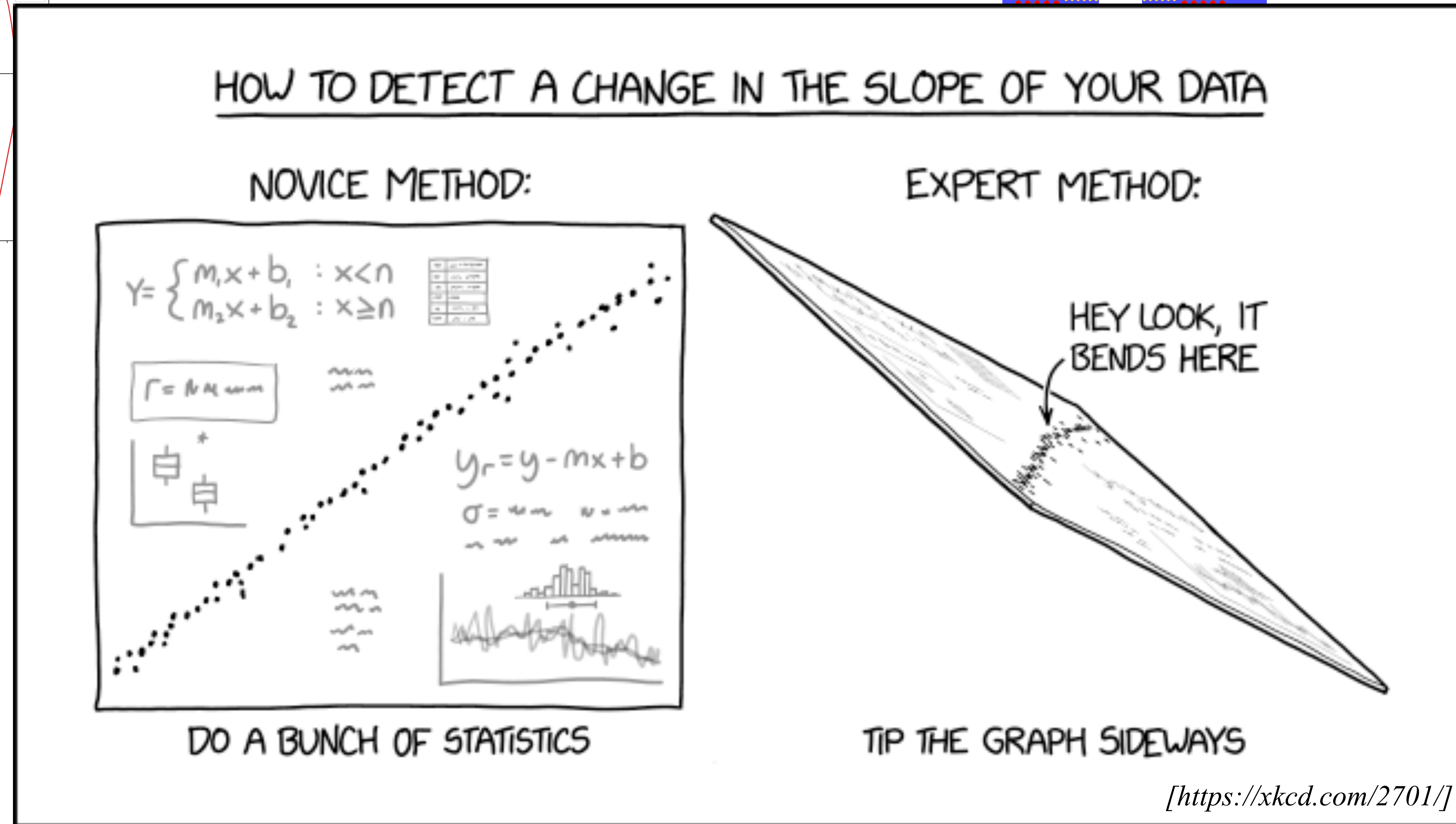
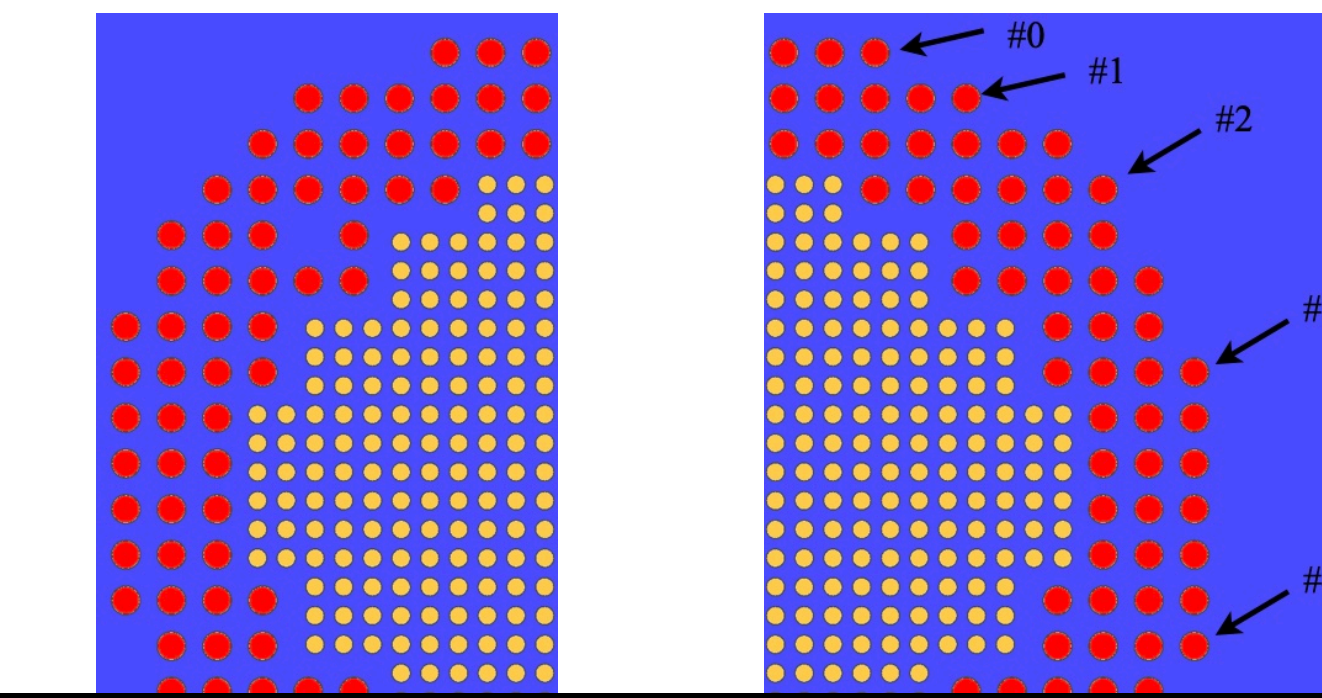
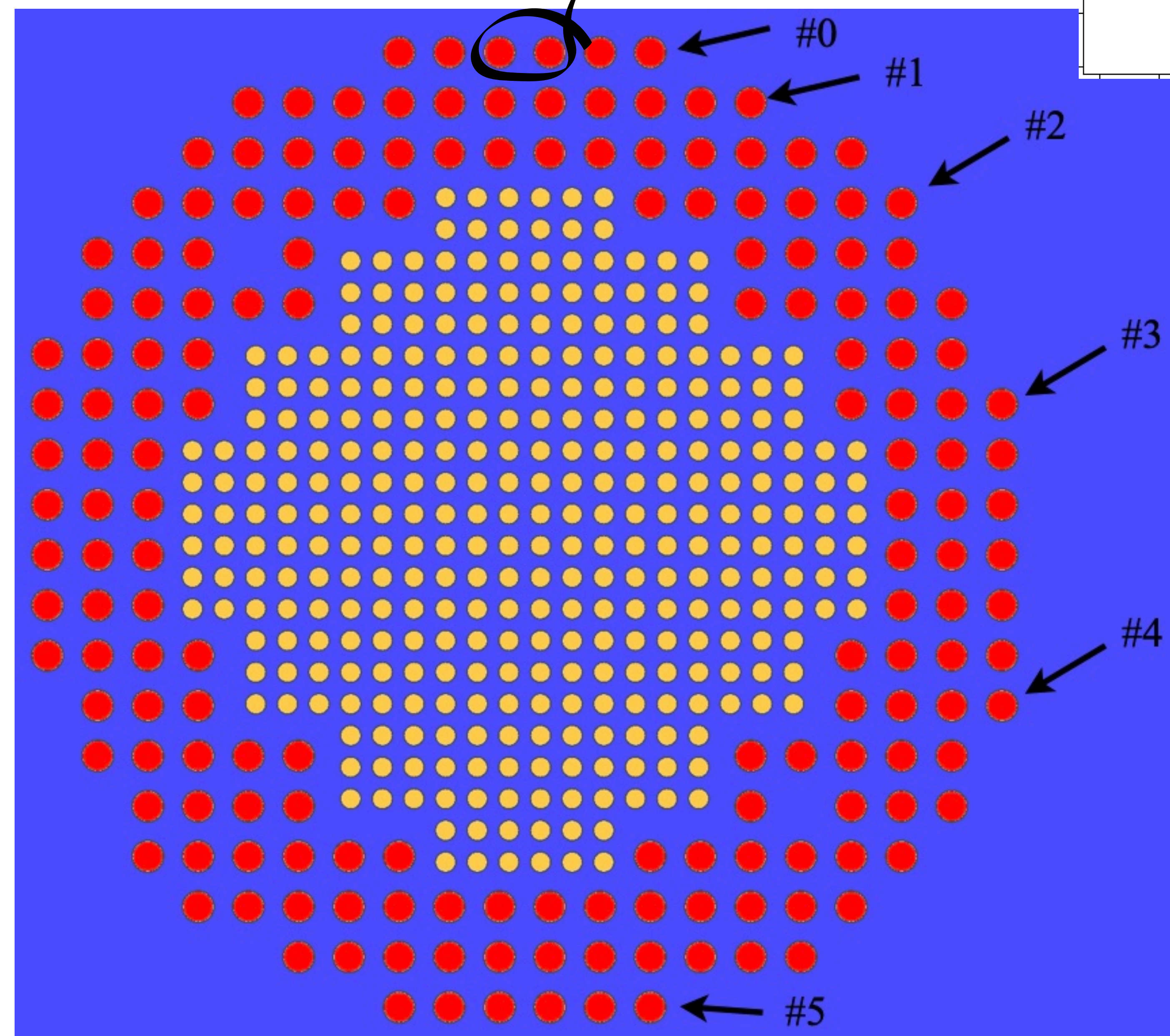
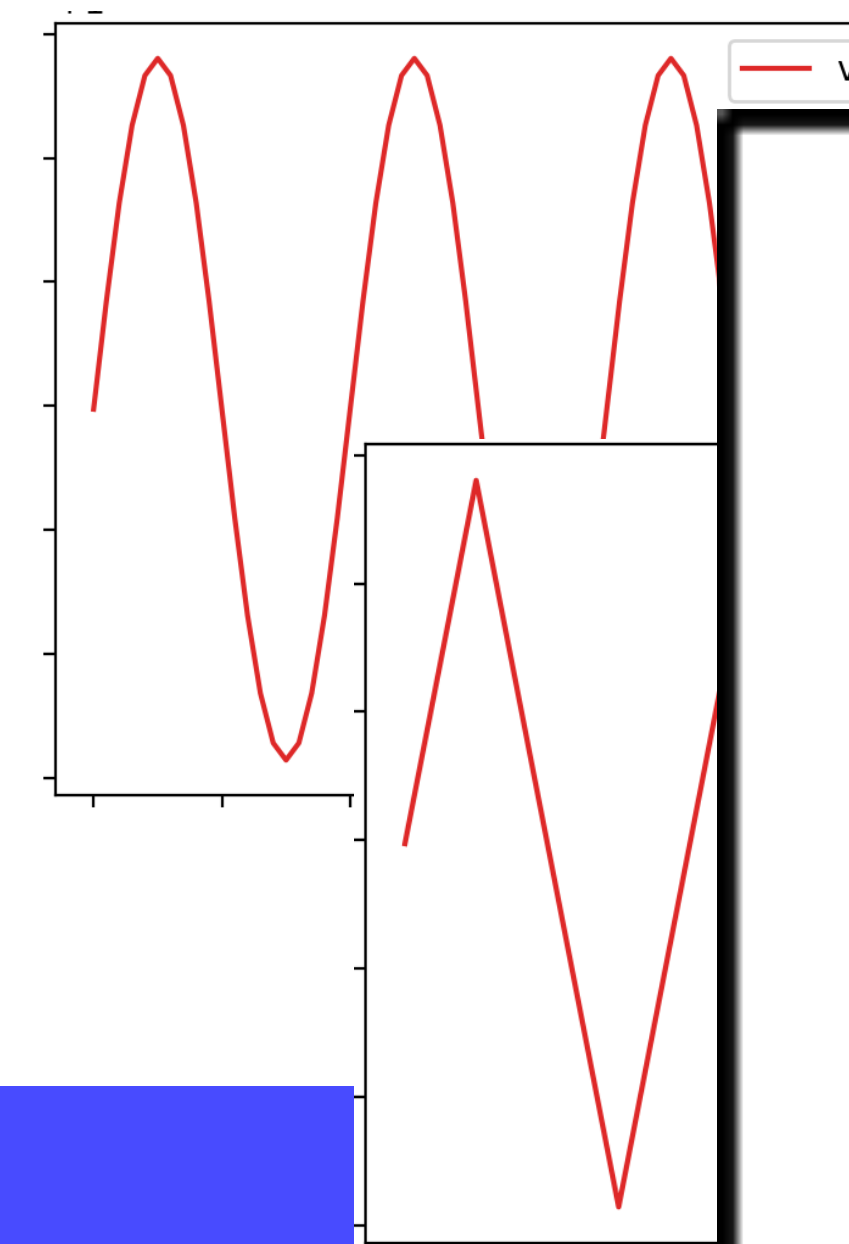
pert/ref:

$1.62e+01 \pm 1.2e-01$
 $1.62e+01 \pm 1.2e-01$
 $1.62e+01 \pm 1.2e-01$
 $1.62e+01 \pm 1.2e-01$
 $1.61e+01 \pm 1.2e-01$
 $1.62e+01 \pm 1.1e-01$

*Delayed n. position
resampled according
to user defined pdf
(one per family)
k is constant (!)*

Test case using CROCUS reactor - modulation

- ± 14.1 pcm at 1 Hz
- 1/10/100 mW
- Sin / triangle
- Global perturbation
- Local perturbation
- Delayed n. position



[<https://xkcd.com/2701/>]

OUTLINE

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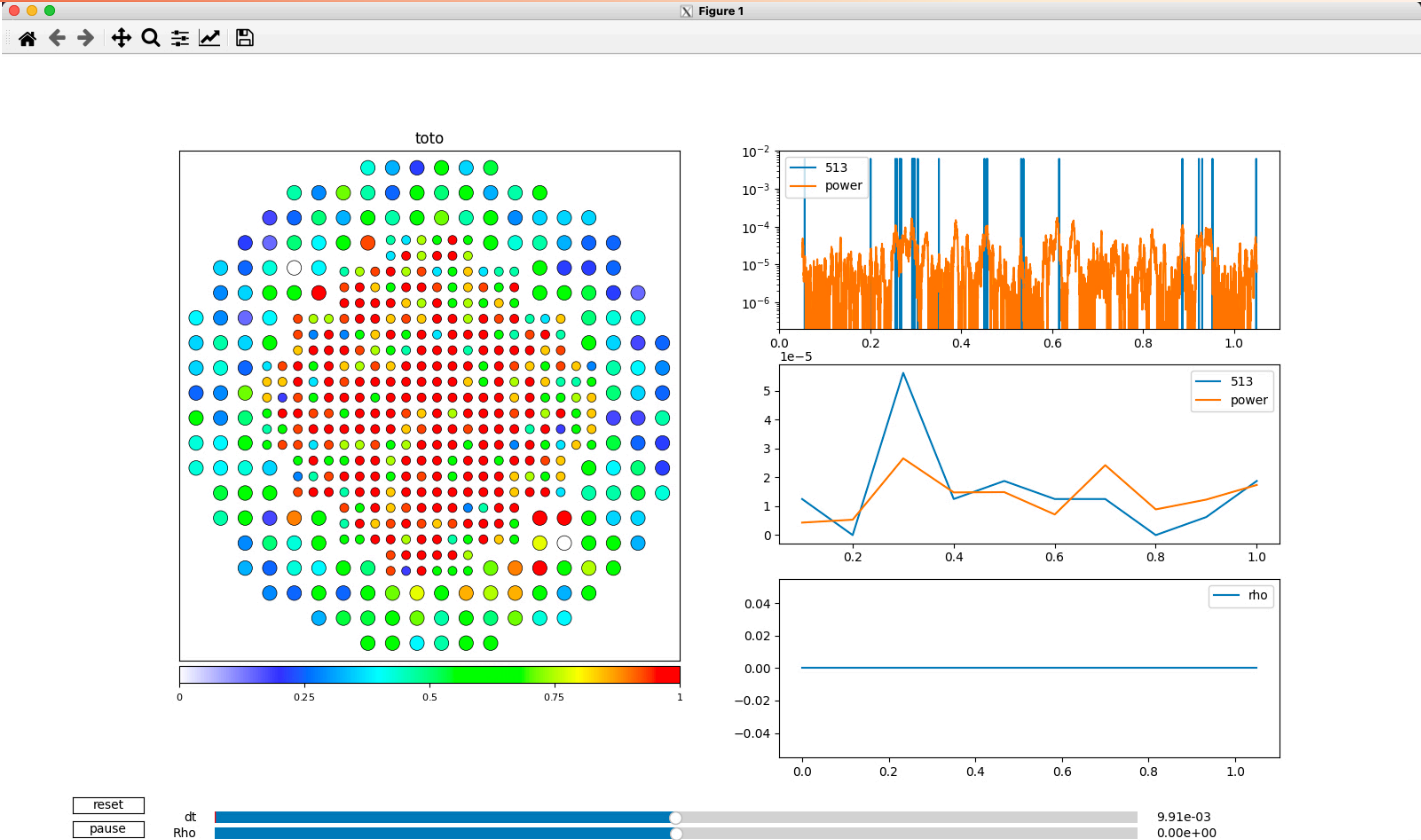
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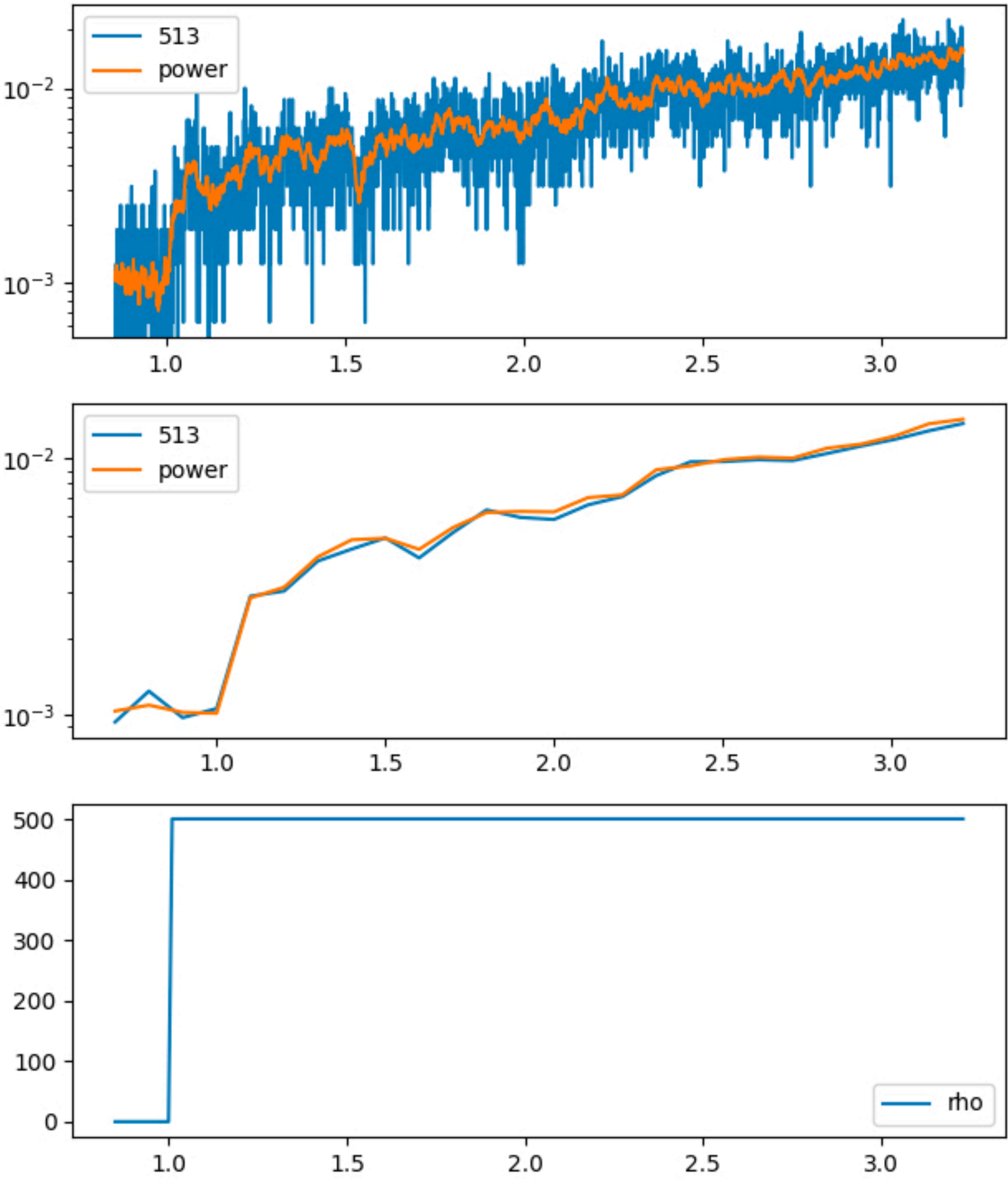
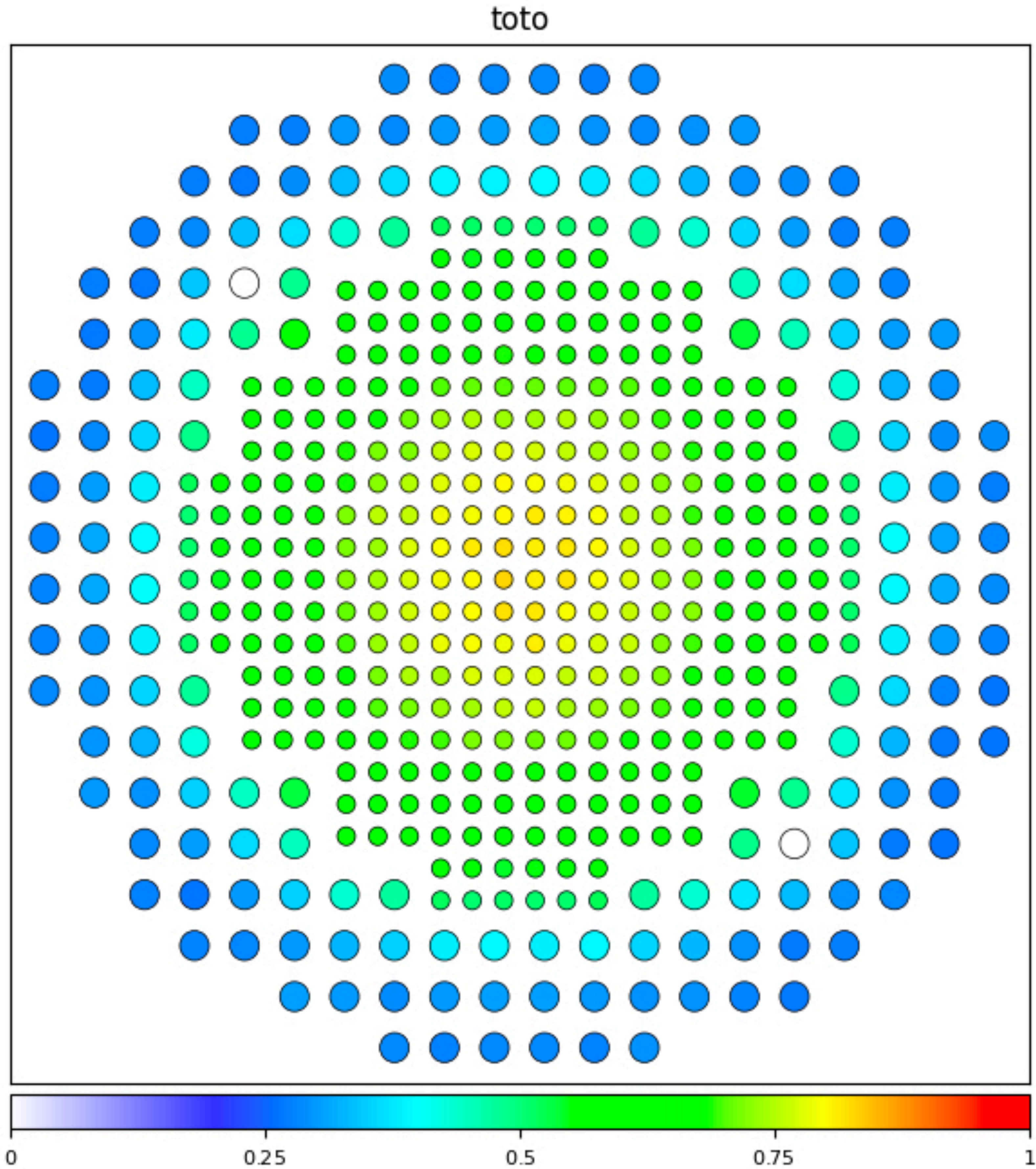
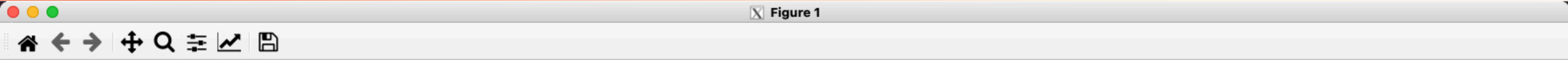
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reset

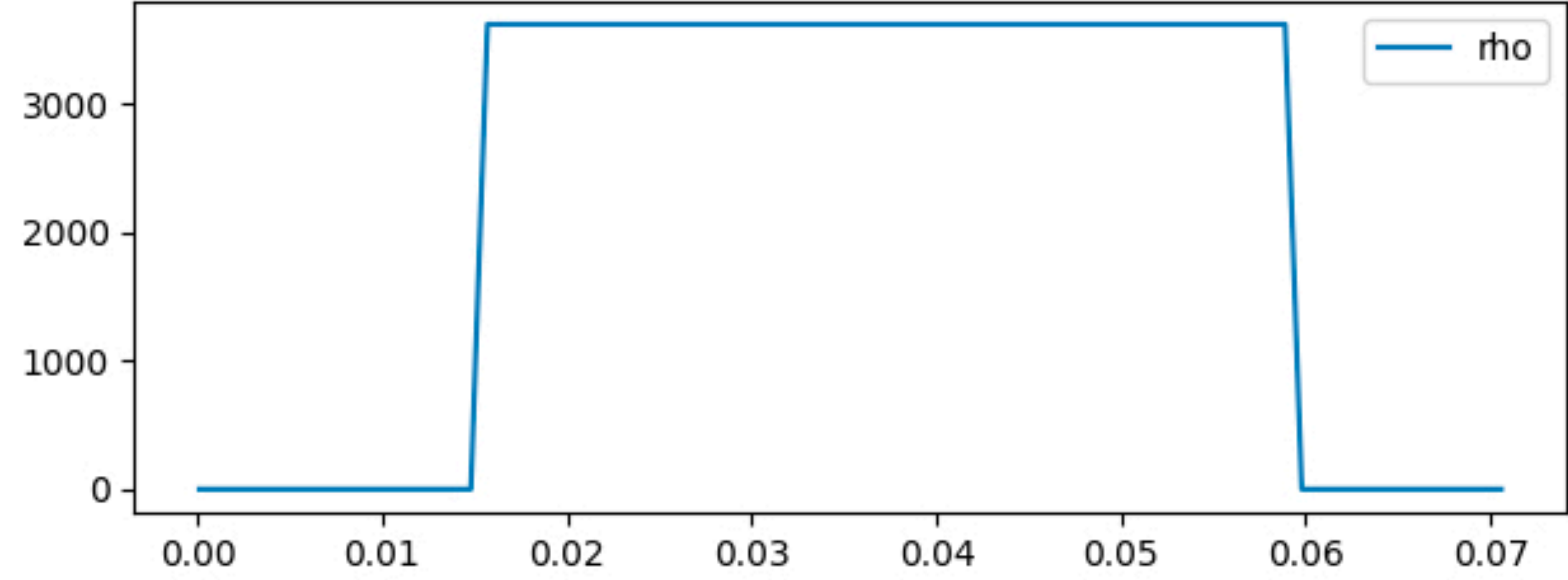
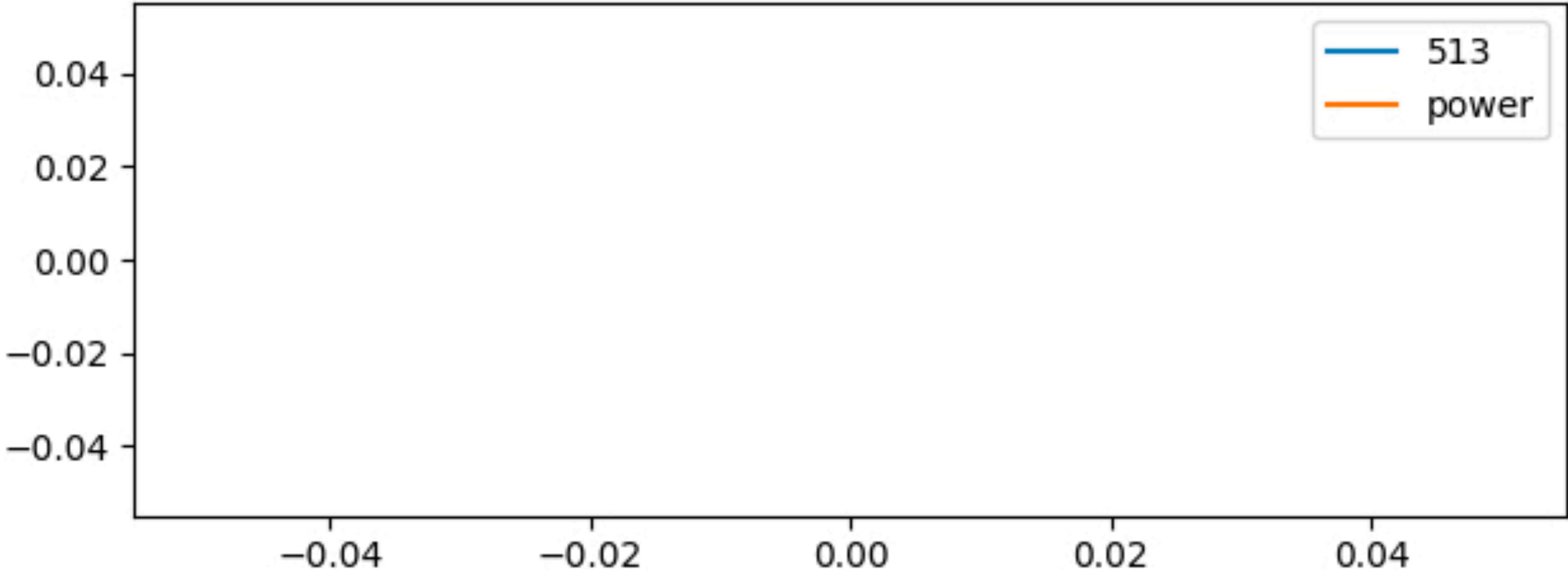
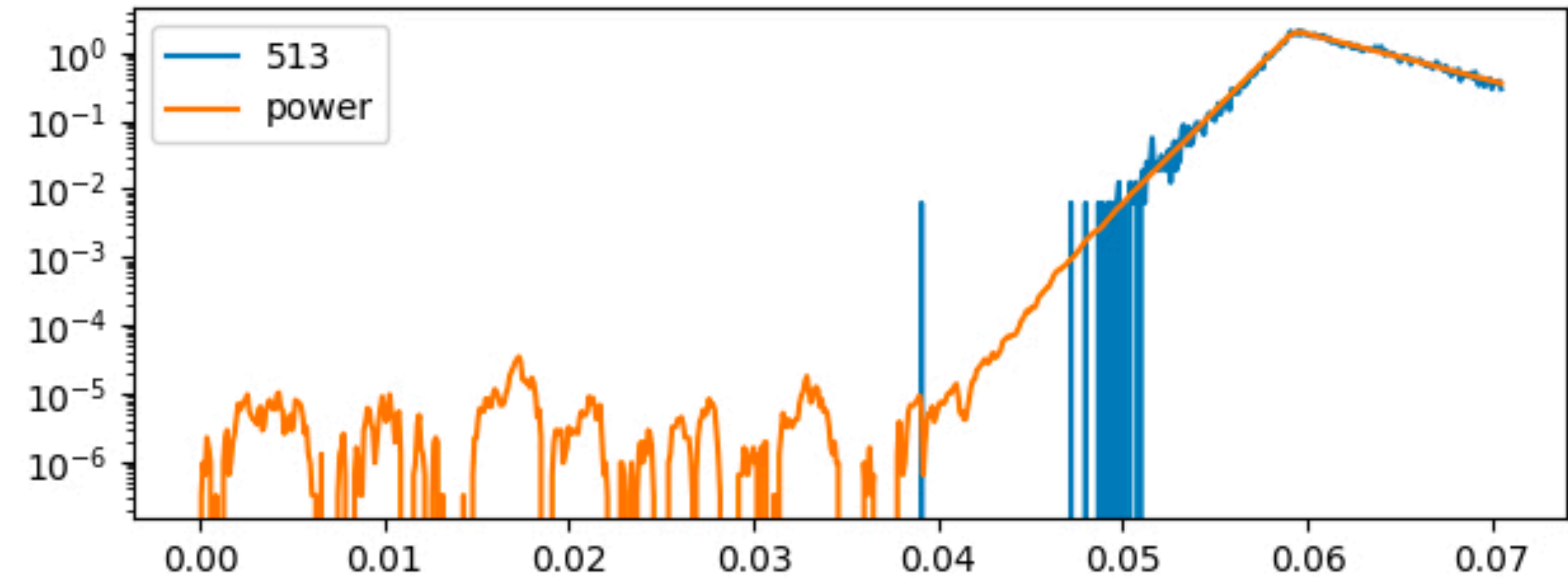
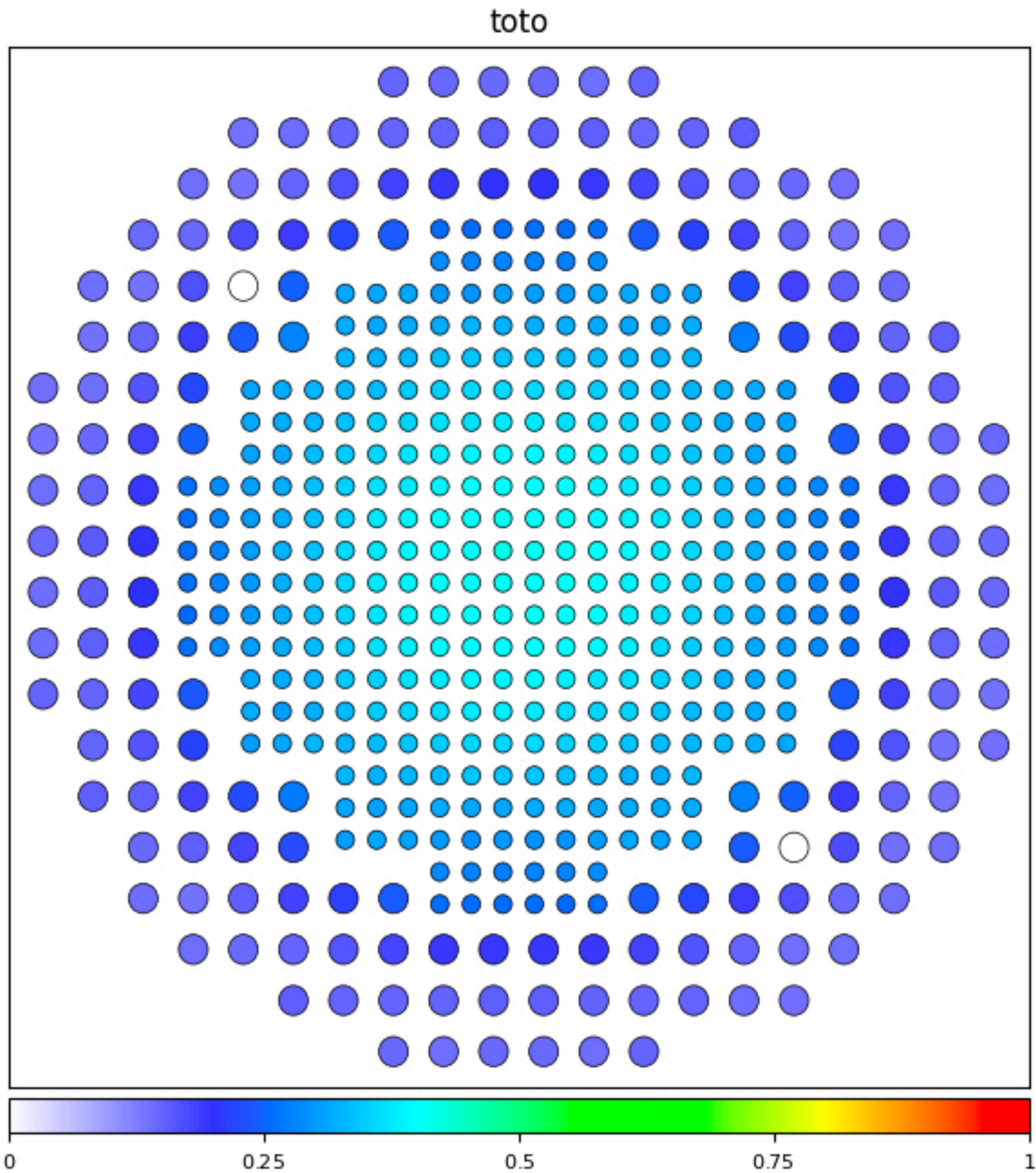
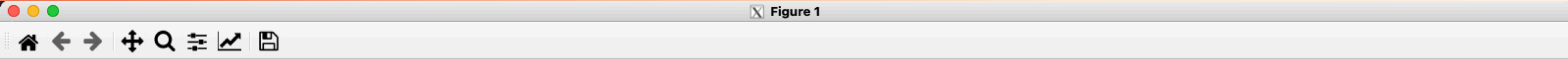
pause

dt

Rho

0.01

503



reset

pause

dt

Rho

9.48e-04

0.00e+00

CONCLUSIONS & PERSPECTIVES

Modeling

- TFM operators can provide CDF for n. shower generation
- Fast generation of time series
- Standard noise analysis
- Flexible framework to modify CDF and precursor position

Verification

- See @Max Begue presentation!

Modeling improvement

- Neutron multiplicity distribution
- Lifespan $j \rightarrow i$ distribution

Future studies

- Reactor study @Max Begue
- Impact of turbulence in liquid fuel
- Clustering in large cores
- Test other analysis technics
- Run on graphics cards

THANK YOU FOR YOUR ATTENTION!

Do you have some questions?

