Istituto Nazionale di Fisica Nucleare

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High sensitivity analysis on Pauli's Exclusion Principle violation with VIP-2

31 October 2022

Alessio Porcelli

Hitchhiker's Advanced Guide to Quantum Collapse Models

and their impact in science, philosophy, technology, and biology

Why Fermi-Dirac and Bose-Einstein are distinct?

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WE DON'T KNOW

Beyond Standard Model…

- **Green's general quantum field:** paronic particles
  - Order 1: fermionic/bosonic fields
  - Order>1: parafermionic/parabosonic fileds
  - Messiah-Greenberg Super-Selection: no fermion/boson decays into parafermion/paraboson (and vice-versa)
  - **Paronic**: a mixture of fermionic/bosonic and parefermionic/parabosonic states
- **Non-Commutative Quantum Gravity**
  - **θ-Poincaré**: distortion of Lorentz symmetry (visible in a two identical particles system)

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Both break the anti-/symmetric commutativity with a coefficient β.

$$a^\dagger \left|0\right\rangle = \left|1\right\rangle \quad a^\dagger \left|1\right\rangle = \beta \left|2\right\rangle \quad a^\dagger \left|2\right\rangle = 0$$

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PEP is violated with an amplitude probability of $\boldsymbol{\beta^2/2}$

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In a system of two fermions (i.e., two electrons),
PEP is violated with an amplitude probability of $\beta^2/2$

How about so far?

- **Ramberg and Snow (1988):** $\beta^2/2 \lesssim 10^{-26}$
- **DAMA (2009):** $\beta^2/2 \lesssim 10^{-47}$
- **Borexino (2011):** $\beta^2/2 \lesssim 10^{-60}$

Models scenarios implications

☐ Democratic scenario

all type of particles have the same degree of violation β

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Models scenarios implications

- [x] **Democratic scenario** ✗

  all type of particles have the same degree of violation $\boldsymbol{\beta}$

- [ ] **Despotic scenario**

  each type of particle has its degree of violation $\boldsymbol{\beta}_i$

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Models scenarios implications

✗ Democratic scenario

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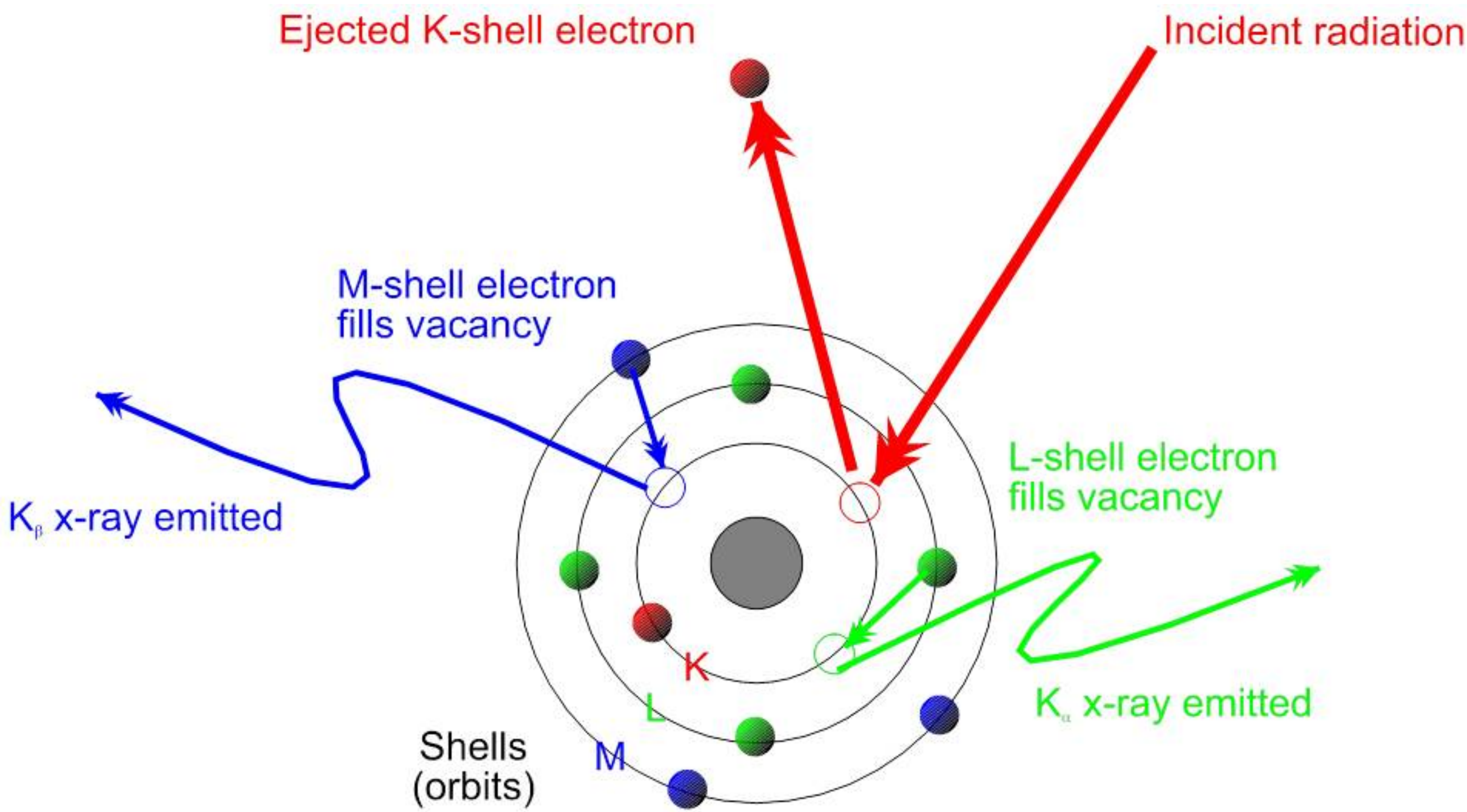
? Despotic scenario

each type of particle has its degree of violation β_i

X-Rays


Ejected K-shell electron
Incident radiation
M-shell electron
fills vacancy
K_β x-ray emitted
L-shell electron
fills vacancy
K_α x-ray emitted
K
L
M
Shells
(orbits)

VIP group

VIolation of **P**auli Exclusion Principle

Open Systems

testing newly injected electrons

VIP

VIP-2

VIP-3

GATOR

Close System

testing spontaneous emissions

VIP-Lead

BEGe

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VIolation of **P**auli Exclusion Principle

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$\beta^2/2 \lesssim 4.7\ 10^{-29}$ **VIP**

[publishing soon] **VIP-2**

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+Wave Function Collapse (CSL, DP)

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[THIS WORK!] **VIP-2**

[Future] **VIP-3** **GATOR**

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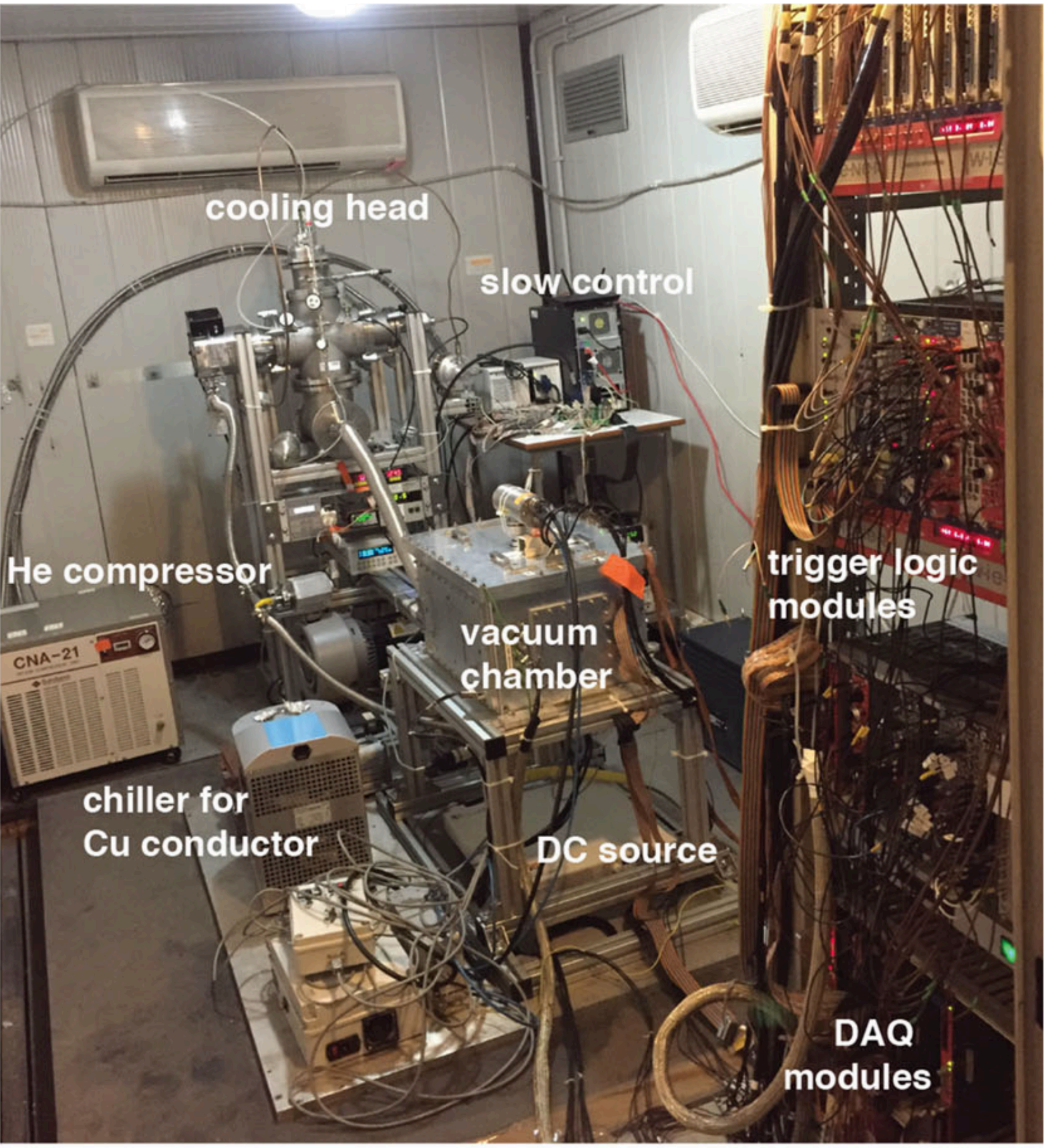
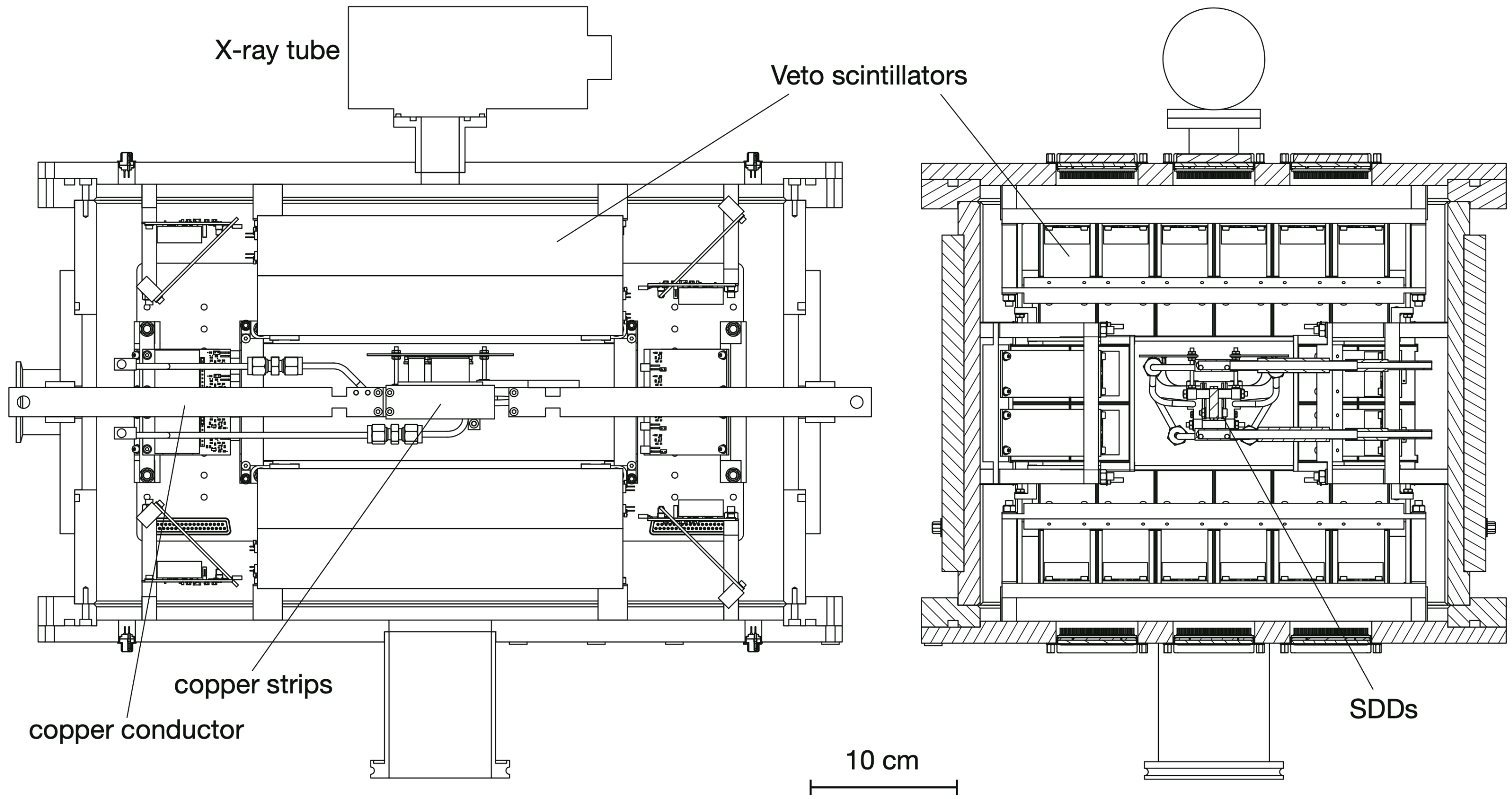
[see Kristian Piscicchia's and Fabrizio Napolitano's talks]

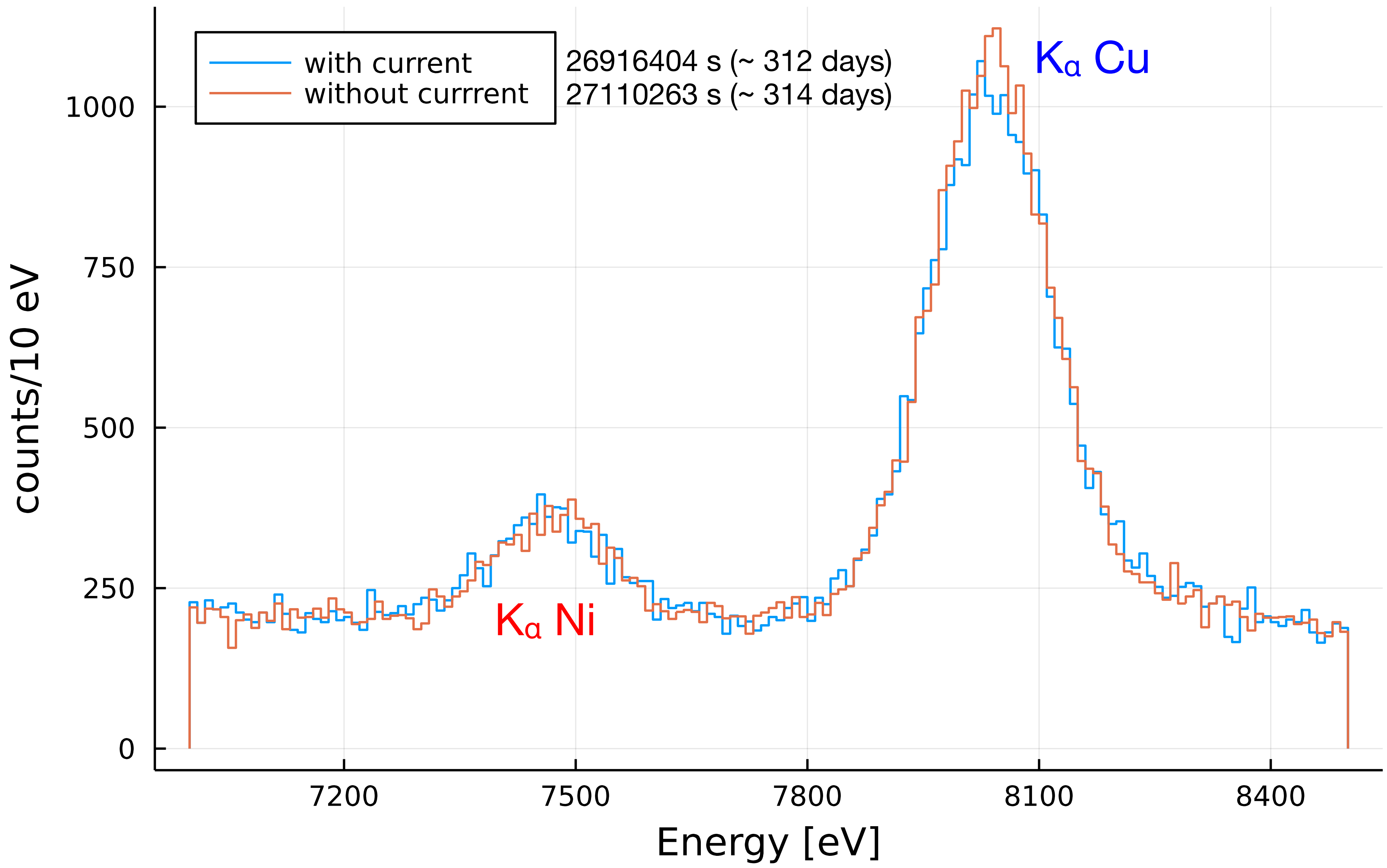
VIP-2





- **Target**: Copper strips
  - WITHOUT CURRENT configuration: regime case (stable states: background)
  - WITH CURRENT configuration (180 A): dynamic case (PEP violation through electron capture)
- **SDD**: 32 detectors by SDDs, stably kept @ -170^{+1}_{-0} °C even with the current in Cu
- **@LNGS Underground** (beneath Gran Sasso Mountain – IT): ~1400 m of rock shielding

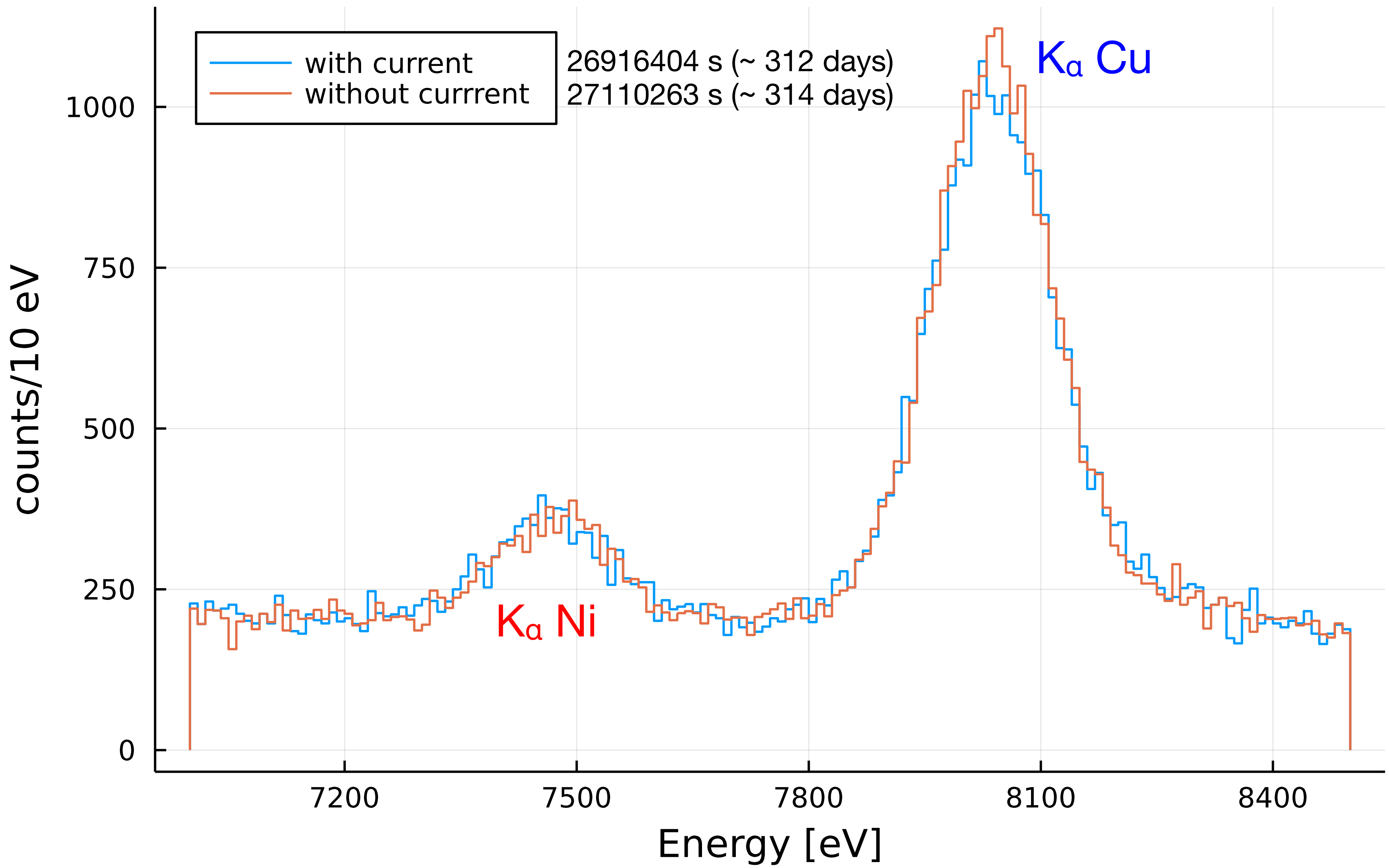
Data model



with current
without currrent
26916404 s (~ 312 days)
27110263 s (~ 314 days)
Kα Cu
Kα Ni
1000
750
500
250
0
7200
7500
7800
8100
8400
counts/10 eV
Energy [eV]

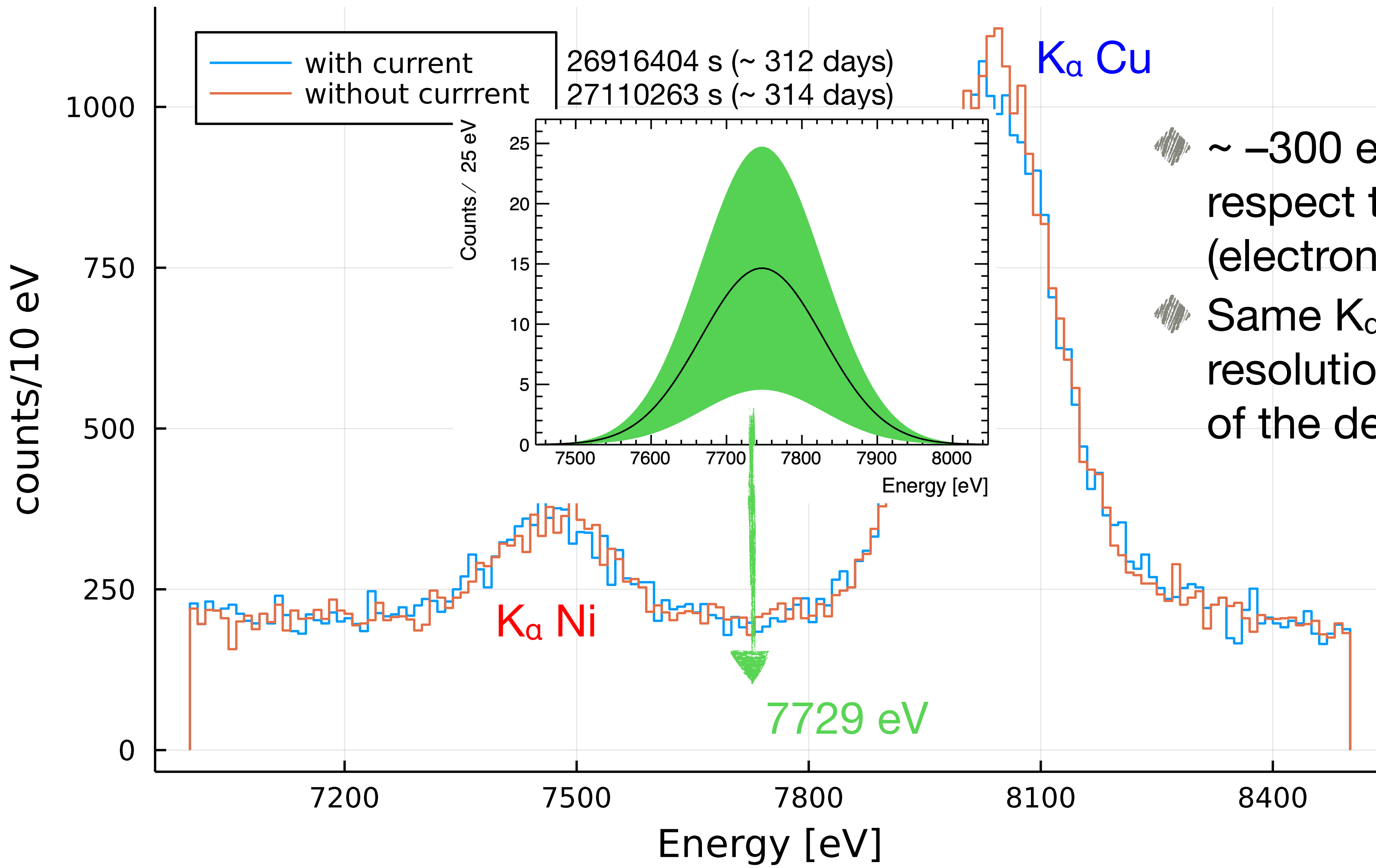
Data model

$$\mathcal{F}^{woc}(\boldsymbol{\theta}, \boldsymbol{y}) = y_1 \times Ni(\theta_1, \theta_2) + y_2 \times Cu(\theta_3, \theta_4) + y_3 \times \mathrm{pol}_1(\theta_5)$$



Data model

$$\mathscr{F}^{wc}(\boldsymbol{\theta}, \boldsymbol{y}, \mathscr{S}) = y_1 \times Ni(\theta_1, \theta_2) + y_2 \times Cu(\theta_3, \theta_4) + y_3 \times \mathrm{pol}_1(\theta_5) + \mathscr{S} \times PEPV(\theta_4)$$

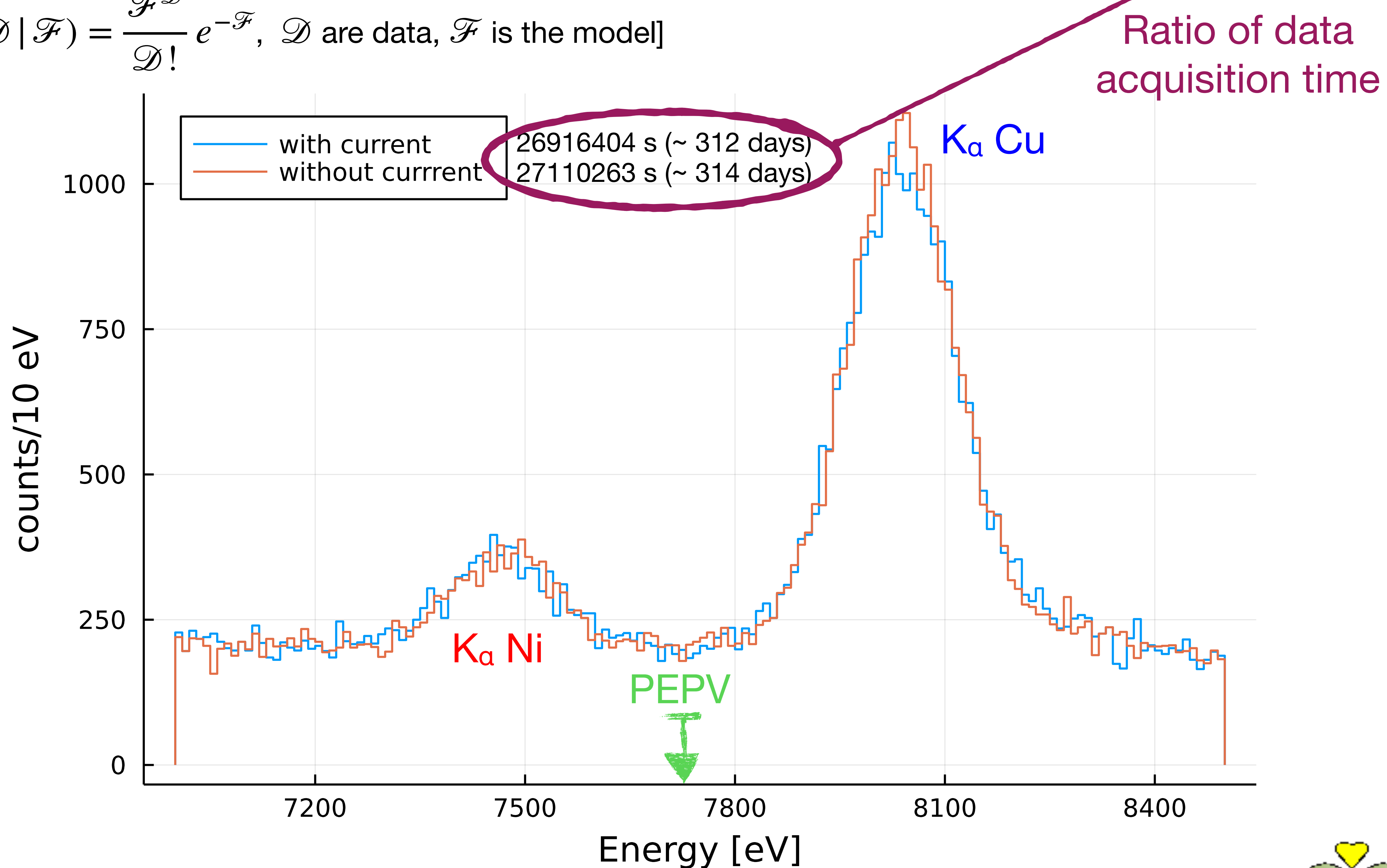


- ~ –300 eV with respect to Kα Cu (electron shielding)
- Same Kα Cu resolution (i.e., σ of the detector)

Data Likelihood

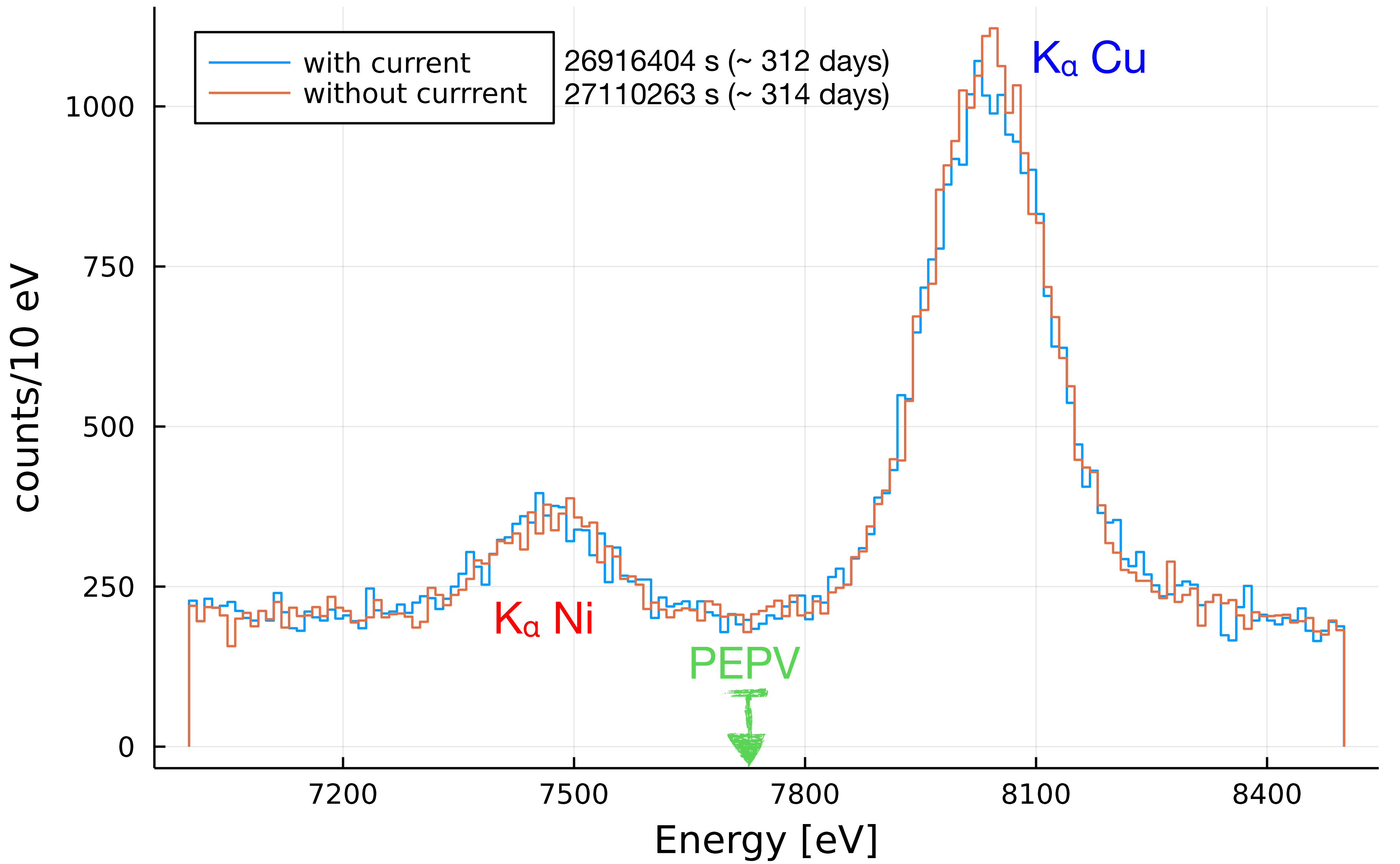
$$\mathscr{L}(\mathscr{D}^{wc}, \mathscr{D}^{woc} \,|\, \boldsymbol{\theta}, \boldsymbol{y}, \mathscr{S}) = \text{Poiss}(\mathscr{D}^{wc} \,|\, \mathscr{F}^{wc}(\boldsymbol{\theta}, \boldsymbol{y}, \mathscr{S})) \times \text{Poiss}(\mathscr{D}^{woc} \,|\, \mathscr{F}^{woc}(\boldsymbol{\theta}, \boldsymbol{y} \times \mathscr{R}))$$

[mind: $\text{Poiss}(\mathscr{D} \,|\, \mathscr{F}) = \dfrac{\mathscr{F}^{\mathscr{D}}}{\mathscr{D}\,!} e^{-\mathscr{F}}$, $\mathscr{D}$ are data, $\mathscr{F}$ is the model]



Bayesian approach

$$p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S} \,|\, \mathcal{D}^{wc}, \mathcal{D}^{woc}) = \frac{\mathcal{L}(\mathcal{D}^{wc}, \mathcal{D}^{woc} \,|\, \boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S}) p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S})}{\int d\boldsymbol{\theta} d\boldsymbol{y} \mathcal{L}(\mathcal{D}^{wc}, \mathcal{D}^{woc} \,|\, \boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S}) p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S})}$$

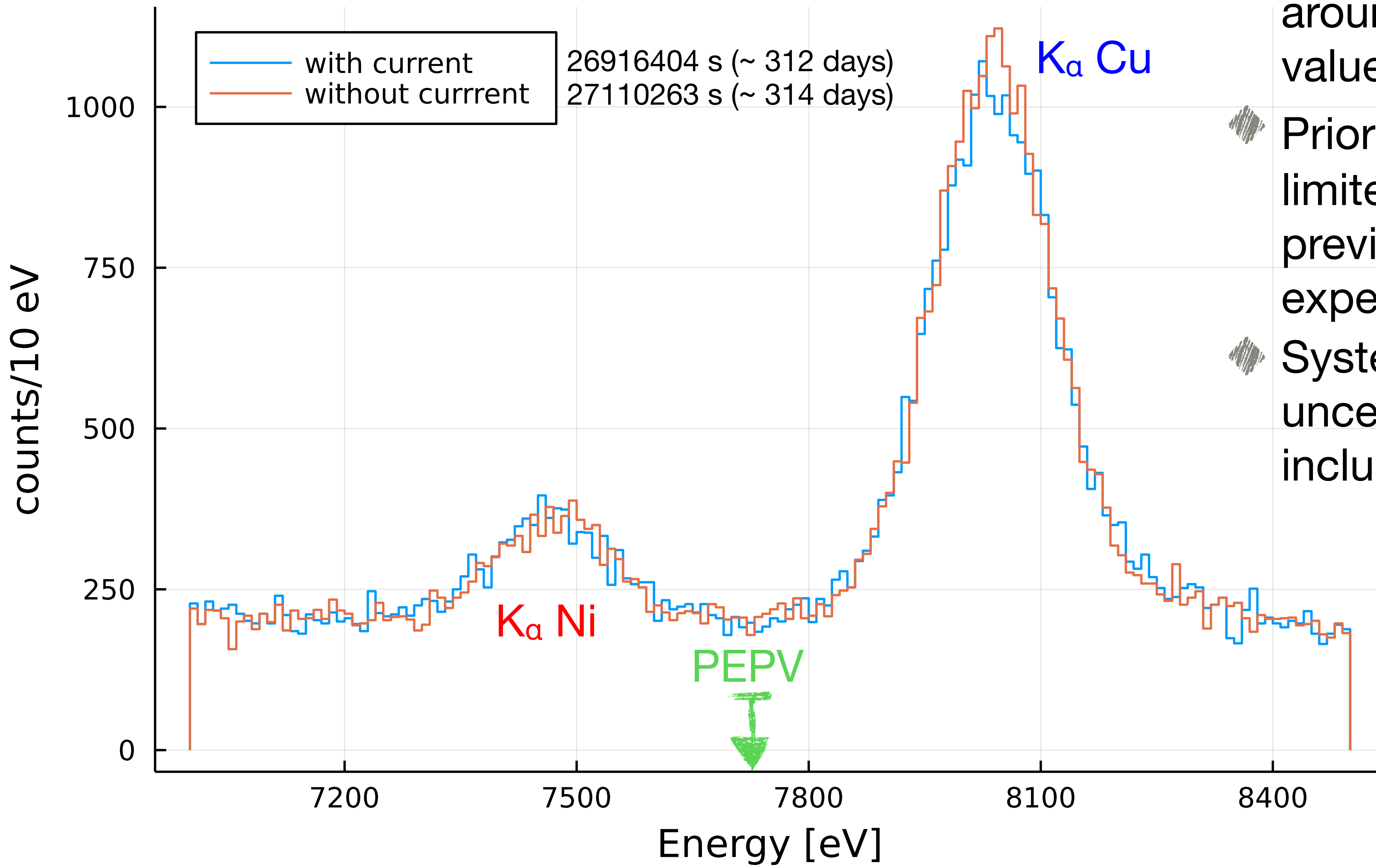


Bayesian approach

Posterior

$$p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S} \,|\, \mathcal{D}^{wc}, \mathcal{D}^{woc}) = \frac{\mathcal{L}(\mathcal{D}^{wc}, \mathcal{D}^{woc} \,|\, \boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S})\, p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S})}{\int d\boldsymbol{\theta} d\boldsymbol{y}\, \mathcal{L}(\mathcal{D}^{wc}, \mathcal{D}^{woc} \,|\, \boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S})\, p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S})}$$

- Priors of $\boldsymbol{\theta}$ and $\boldsymbol{y}$ are Gaussians: statistical fluctuations around known values
- Prior of $\mathcal{S}$ is flat, limited from previous experiments
- Systematic uncertainties included

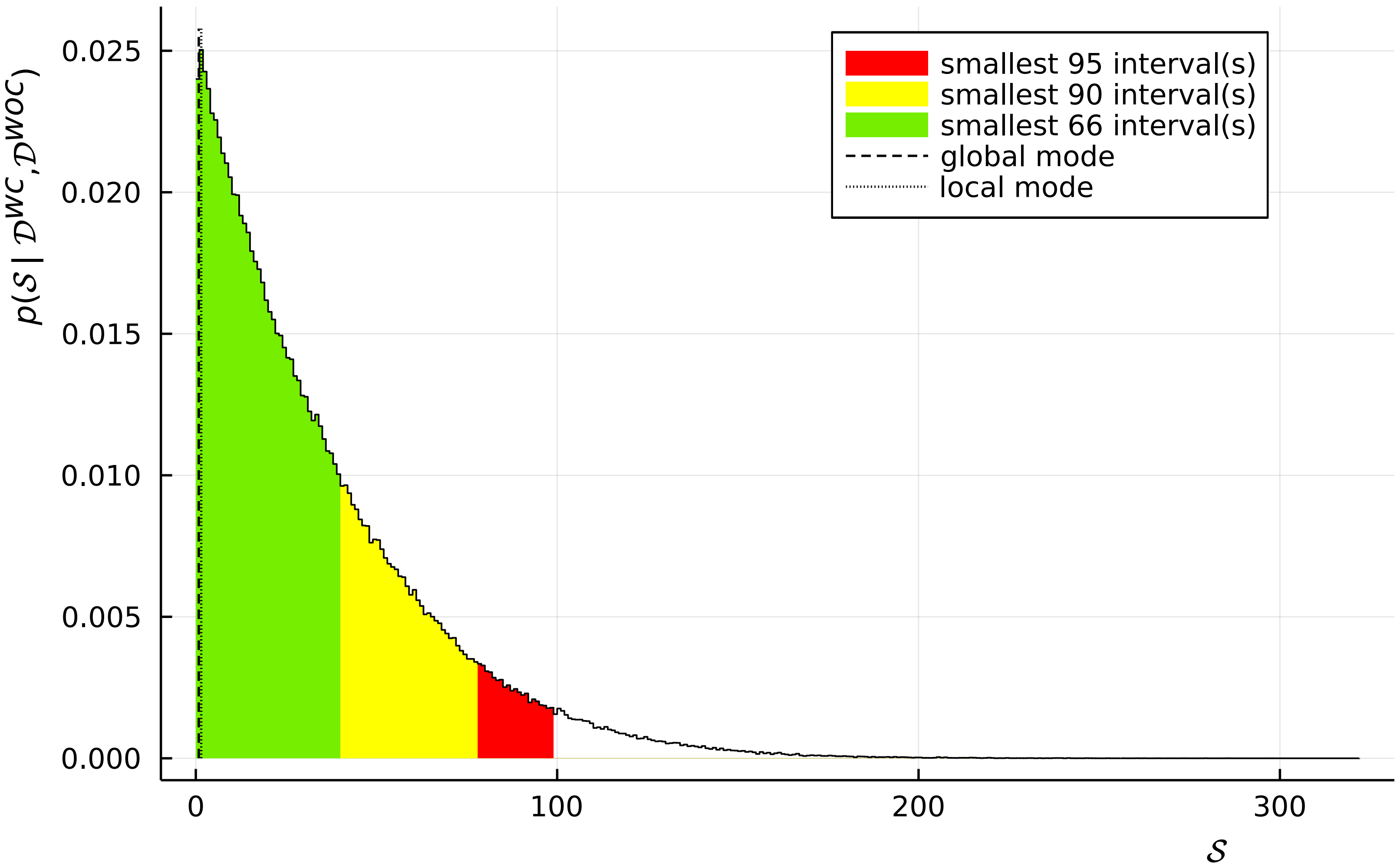


Bayesian result

(marginalized Posterior)

$$p(\mathcal{S} \mid \mathcal{D}^{wc}, \mathcal{D}^{woc}) = \int p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S} \mid \mathcal{D}^{wc}, \mathcal{D}^{woc}) d\boldsymbol{\theta} d\boldsymbol{y}$$

Integrals with Markov Chain Monte Carlo method



Modified frequentist CLs

one-sided Likelihood Test statistic

$$t_{\mathscr{S}} = -2 \ln \Lambda(\mathscr{S}) = -2 \ln \frac{\mathscr{L}(\hat{\hat{\boldsymbol{\theta}}}, \hat{\hat{\mathbf{y}}}, \mathscr{S})}{\mathscr{L}(\hat{\boldsymbol{\theta}}, \hat{\mathbf{y}}, \hat{\mathscr{S}})}$$

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Profile Likelihood;

$\mathscr{L}$ now includes multiplicative penalties given by experimental uncertainties: i.e., the priors in the Bayesian

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$\hat{\boldsymbol{\theta}}, \hat{\boldsymbol{y}}, \hat{\mathscr{S}}$ are the values that maximize the Likelihood; i.e., the denominator is the standard maximum Likelihood

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i.e., a set of parameters for each test-value $\mathscr{S}$

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$t_{\mathscr{S}}$ distribution, given $\mathscr{S}$

$$p_{\mathscr{S}} = \int_{t_{obs}}^{\infty} f(t_{\mathscr{S}}\,|\,\mathscr{S})\,dt_{\mathscr{S}}$$

$t_{\mathscr{S}}$ of observed $\mathscr{S}$

$$\mathrm{CL_S} = \frac{p_{\mathscr{S}}}{1-p_0} < 1 - \mathrm{C.L.} \quad (\text{i.e., } 90\%\ \mathrm{C.L.} \Rightarrow \mathrm{CL_S} < 0.1)$$

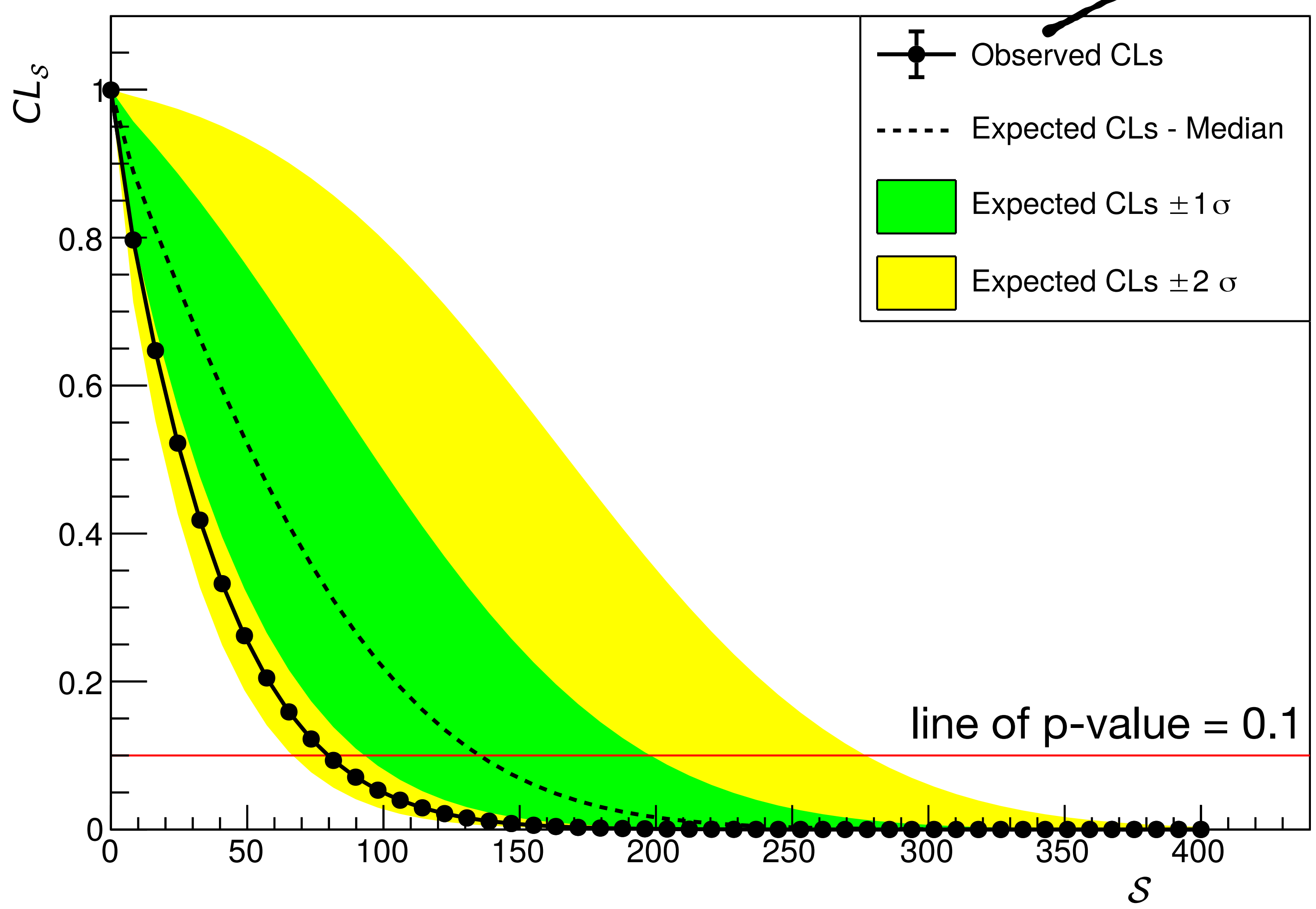
background case (i.e., $\mathscr{S} = 0$)

$\mathrm{CL_s}$ result

$$t_{\mathscr{S}} = -2\ln\Lambda(\mathscr{S}) = -2\ln\frac{\mathscr{L}(\hat{\hat{\boldsymbol{\theta}}}, \hat{\hat{\mathbf{y}}}, \mathscr{S})}{\mathscr{L}(\hat{\boldsymbol{\theta}}, \hat{\mathbf{y}}, \hat{\mathscr{S}})} \qquad p_{\mathscr{S}} = \int_{t_{obs}}^{\infty} f(t_{\mathscr{S}}\,|\,\mathscr{S})\,dt_{\mathscr{S}} \qquad \mathrm{CL_S} = \frac{p_{\mathscr{S}}}{1-p_0} < 1 - \mathrm{C.L.}$$

Computation with RooFit

$\mathrm{CL_s}$ expected with measured $\mathscr{S}$



$\mathrm{CL_s}$ expected in case of $\mathscr{S} = 0$ but measured $\mathscr{S}$

CLs result

$$t_{\mathcal{S}} = -2\ln\Lambda(\mathcal{S}) = -2\ln\frac{\mathcal{L}(\hat{\hat{\boldsymbol{\theta}}}, \hat{\hat{\boldsymbol{y}}}, \mathcal{S})}{\mathcal{L}(\hat{\boldsymbol{\theta}}, \hat{\boldsymbol{y}}, \hat{\mathcal{S}})} \qquad p_{\mathcal{S}} = \int_{t_{obs}}^{\infty} f(t_{\mathcal{S}} \,|\, \mathcal{S})\, dt_{\mathcal{S}} \qquad \mathrm{CL_S} = \frac{p_{\mathcal{S}}}{1 - p_0} < 1 - \mathrm{C.L.}$$

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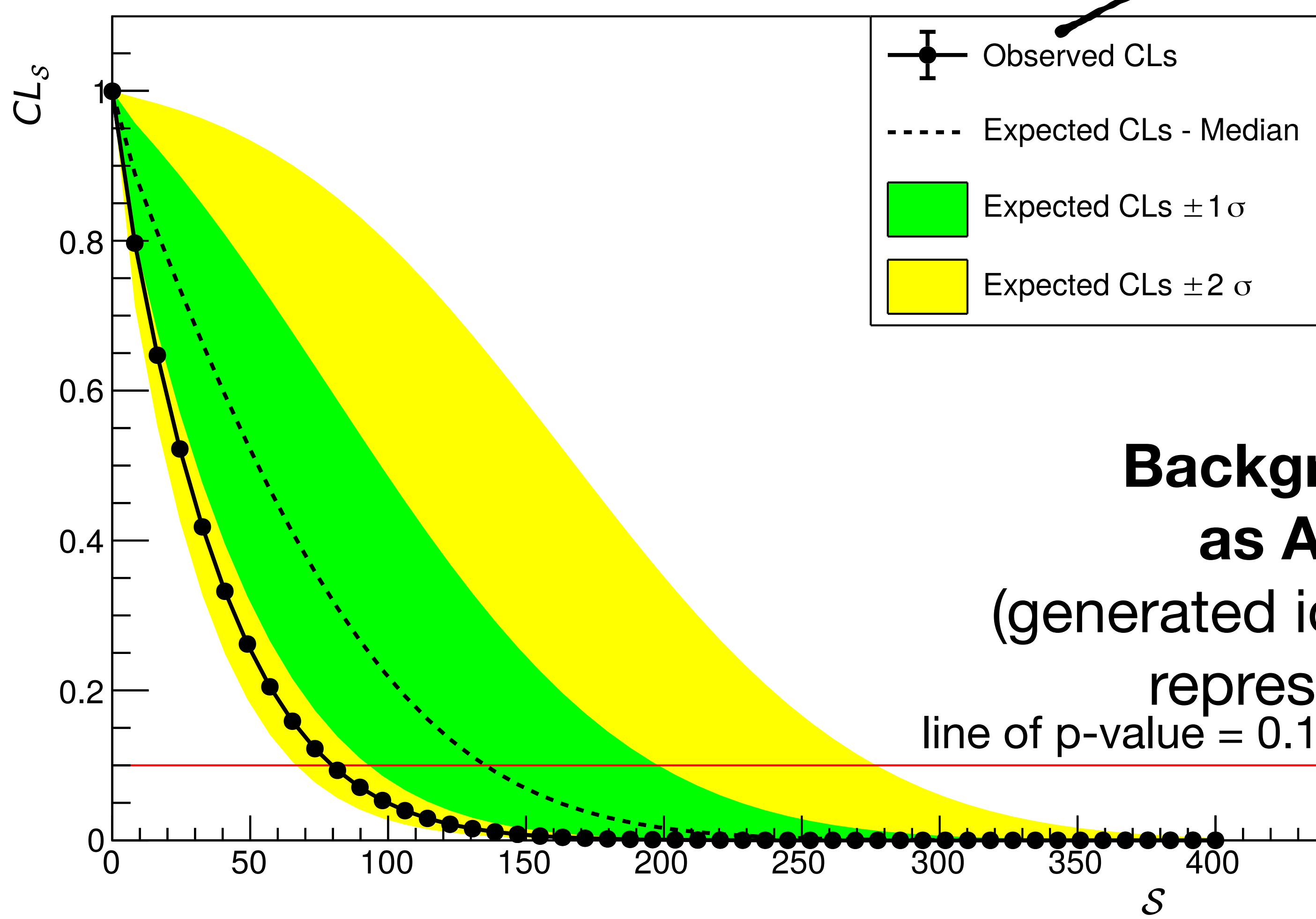

CLs expected in case of $\mathcal{S} = 0$ but measured $\mathcal{S}$

Background Hypothesis as Asimov Dataset

(generated ideal dataset most likely representing the model)

From $\mathcal{S}$ to $\beta^2/2$

$$N_x \simeq \frac{\beta^2}{2} \cdot N_{\text{new}} \cdot \frac{N_{\text{int}}}{10} \cdot 7.25 \times 10^{-2}$$

From $\mathcal{S}$ to $\beta^2/2$

This is our $\mathcal{S}$!

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Newly injected electrons!

$$\sum_i^{\text{runs}} I_i \Delta t_i / e \; (= I \Delta t / e \;\; \text{for simplicity})$$

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Number of interactions;
every ~10 interactions, 1 cascade

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efficiency simulated: considered X-ray absorption + geometry acceptance + SDDs efficiency

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$$\sum_i^{\text{runs}} I_i \Delta t_i / e \; (= I\Delta t / e \;\; \text{for simplicity})$$

$$\Downarrow$$

$$\frac{\beta^2}{2} \simeq \mathcal{S} \cdot \frac{10}{N_{\text{int}}} \cdot \frac{e}{I\Delta t} \cdot \frac{1}{7.25 \times 10^{-2}}$$

From $\mathscr{S}$ to $\beta^2/2$

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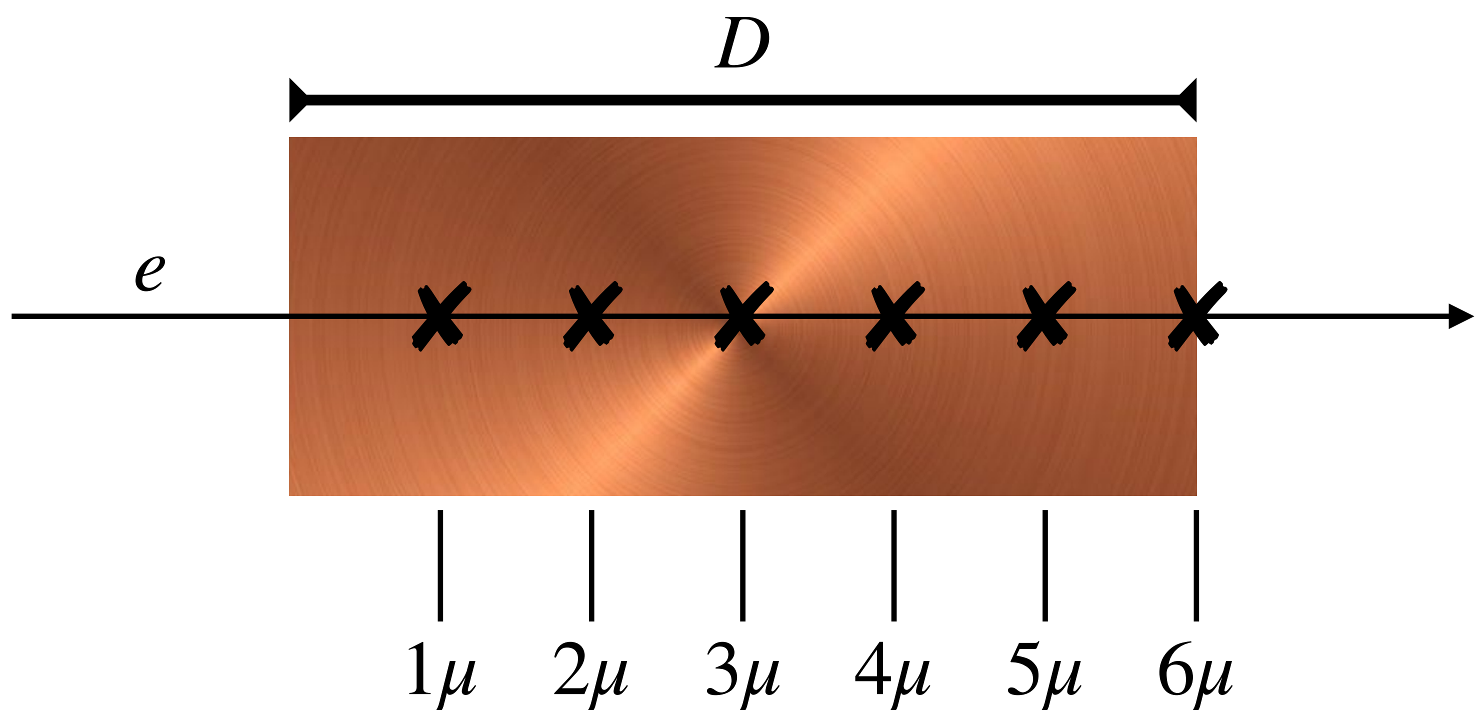
N_{int} is the normalization that decides the order of magnitude of $\beta^2/2$

Let's discuss e–atoms interaction Models!

N_{int} by Linear Scattering

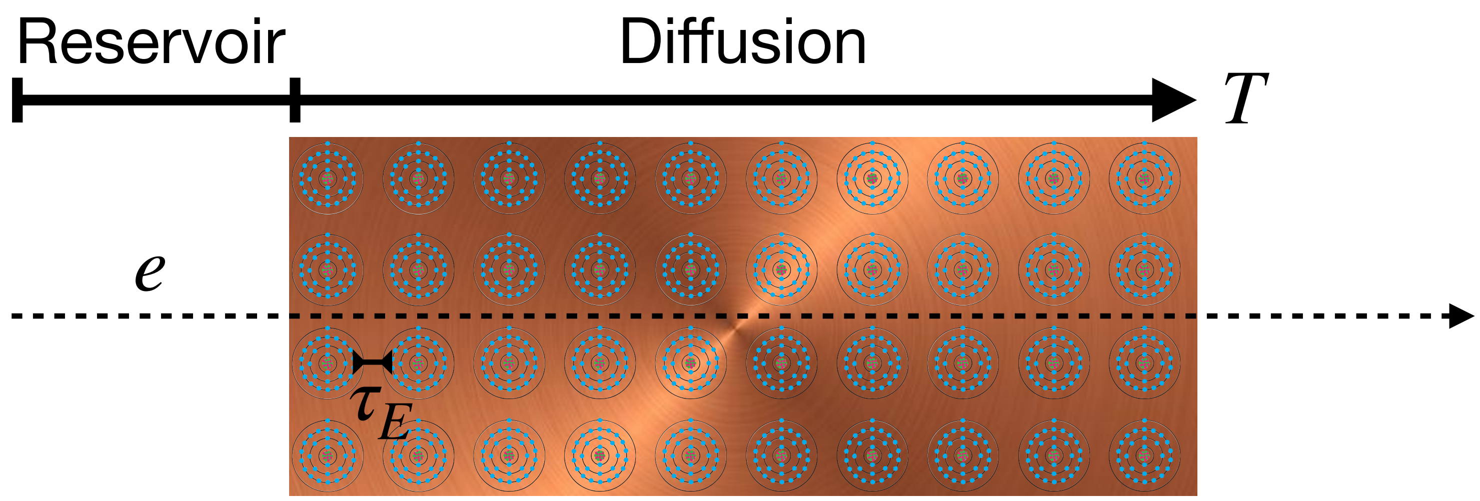


Through Copper Resistance,
we know the average interaction length μ

$$N_{\text{int}} = D/\mu \simeq 1.95 \times 10^6$$

$$\Rightarrow \frac{\beta^2}{2} \lessapprox 10^{-31}$$

N_{int} by Close Encounters



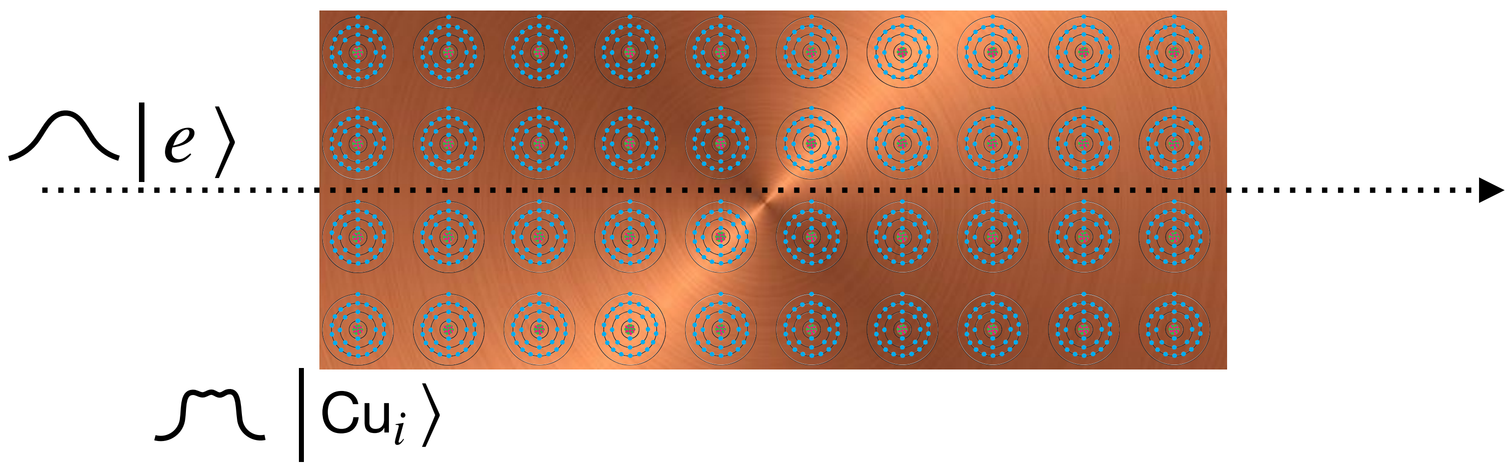
Through Diffusion-Transport theory and Copper atomic density, we know:

- the average time τ_E on atomic encounter for a diffused electron
- the average time T of target crossing by an electron

$$N_{\text{int}} = T/\tau_E \simeq 4.29 \times 10^{17}$$

$$\Rightarrow \frac{\beta^2}{2} \lessapprox 10^{-43}$$

TO DO: a quantum N_{int}?



How many interactions between Cu atomic and electron fields occur?

Outlook

How to high sensitivity measurement in Open System?

Data Analysis

- **Bayesian**
  - Well established: excellent for low statistical signals
  - Systematic uncertainty is the combination of different priors for the various factors
- **CL_s**
  - Models with little or no sensitivity to the null hypothesis, e.g., if the data fluctuate very low relative to the expectation of the background-only hypothesis: the lower/upper limit might be anomalously low; more robust compared to the classic p-value
  - Sensible to small parameter fluctuations

N_{int} modelling

- **Linear Scattering**: due to phonons and lattice irregularities
  - ✓ Safest hypothesis
  - ✗ Largely underestimation of how many interactions an electron does
- **Close Encounters**: a more realistic model of e-atom encounters, but still approximated
  - ✓ 12 order of magnitudes larger than Linear Scattering!
- **This is the key element to improve the measurement!**

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THANK YOU