INFN
Istituto Nazionale di Fisica Nucleare

KSETA

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Searches for a possible violation of the Pauli Exclusion Principle in the Gran Sasso underground laboratory: the VIP-2 experiment

28 October 2022

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KIT
Karlsruher Institut für Technologie

Symposium: 10 years of KSETA

Why Fermi-Dirac and Bose-Einstein are distinct?

WE DON'T KNOW

Pauli Exclusion Principle?

Beyond Standard Model ideas

- **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)

Both break the anti-/symmetric commutativity with an amplitude β.
In a system of two fermions (i.e., two electrons),
PEP is violated with a probability of $\beta^2/2$

VIP-2 GOAL

searching **VI**olation of **P**auli Exclusion Principle

Limits exists but only for hadron-hadron or hadron-lepton cases!
VIP-2 aims to lepton-lepton case!

Pauli Exclusion Principle?

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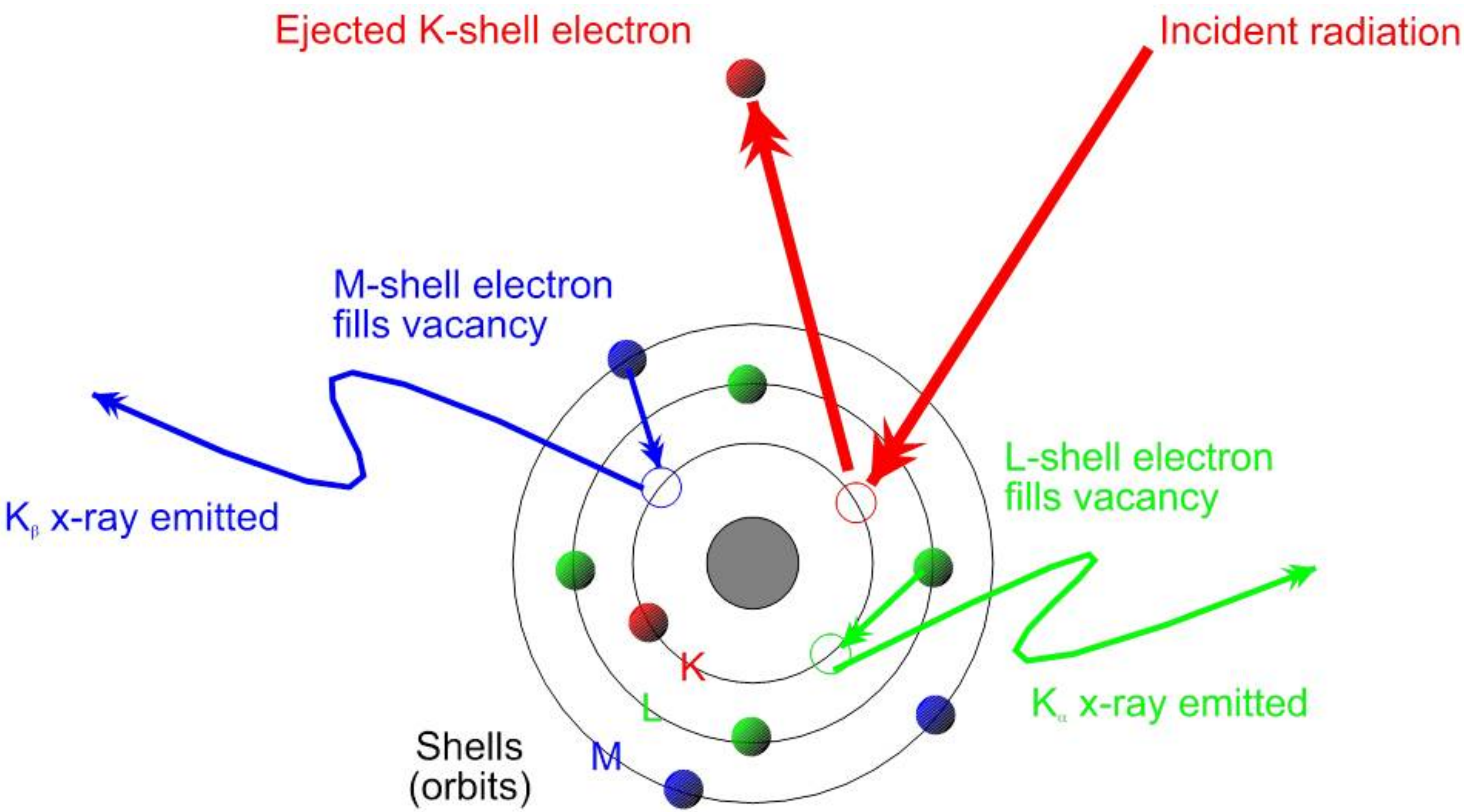
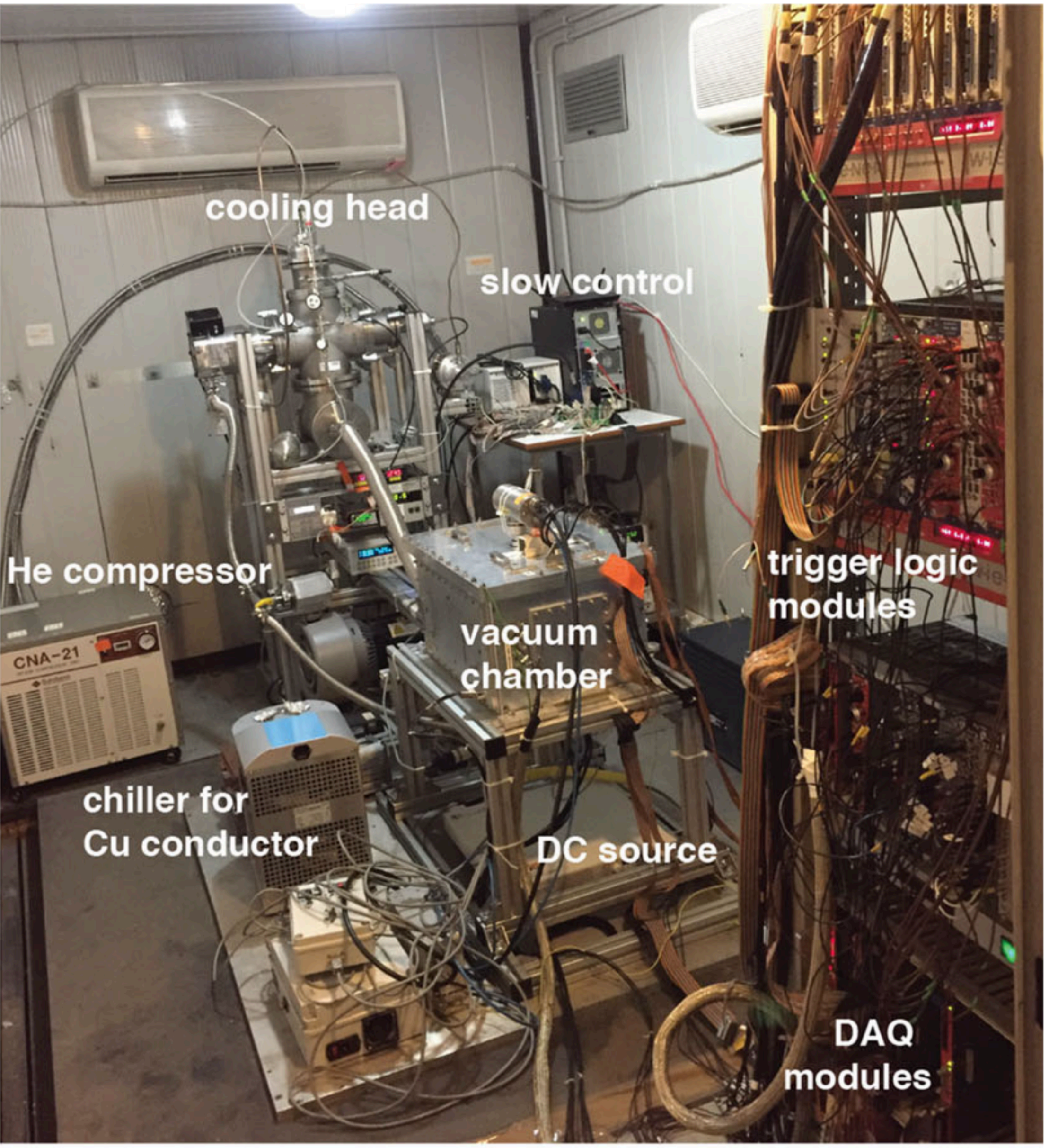
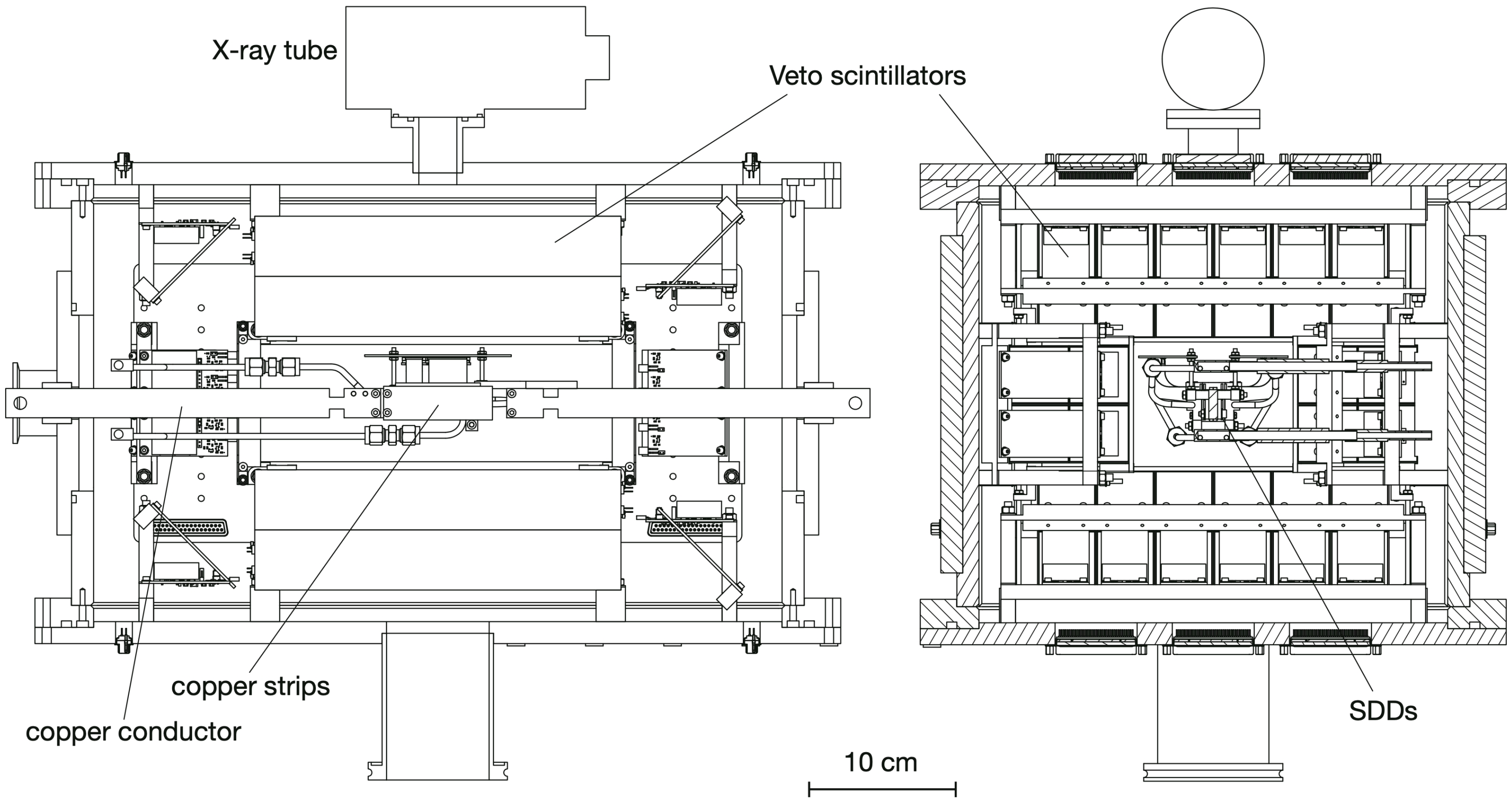
Signal: X-Rays



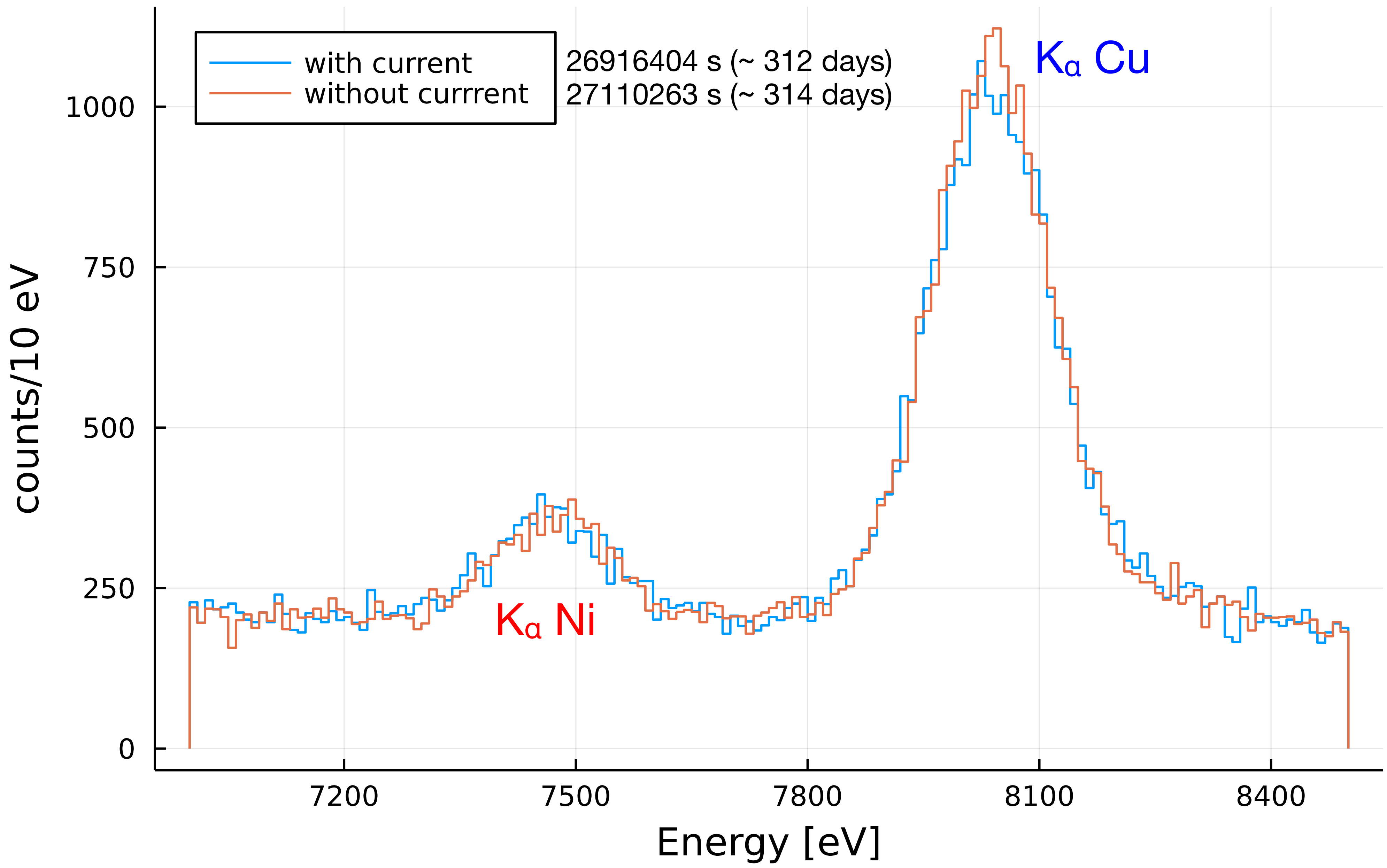
VIP-2





- **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

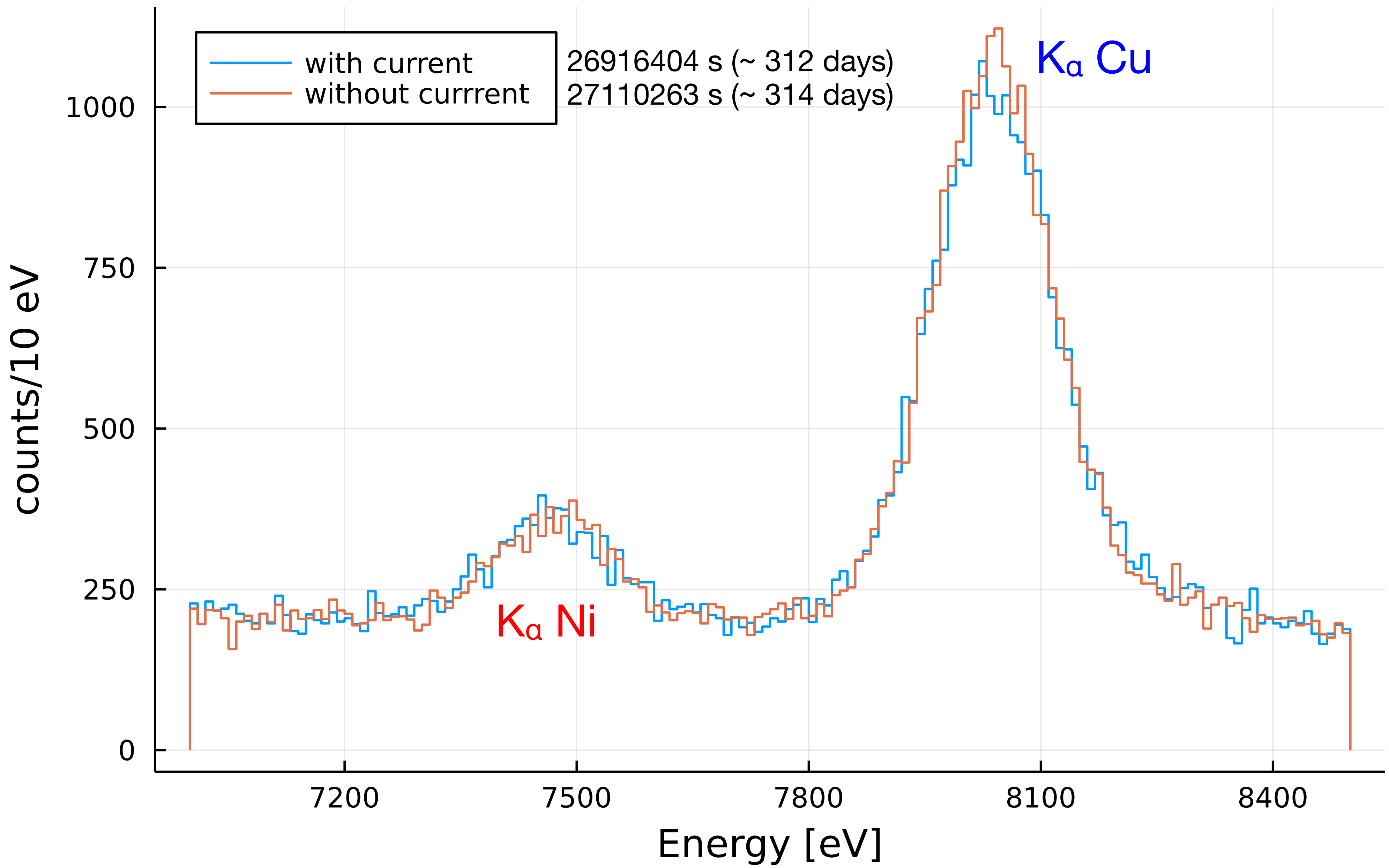
Data model



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

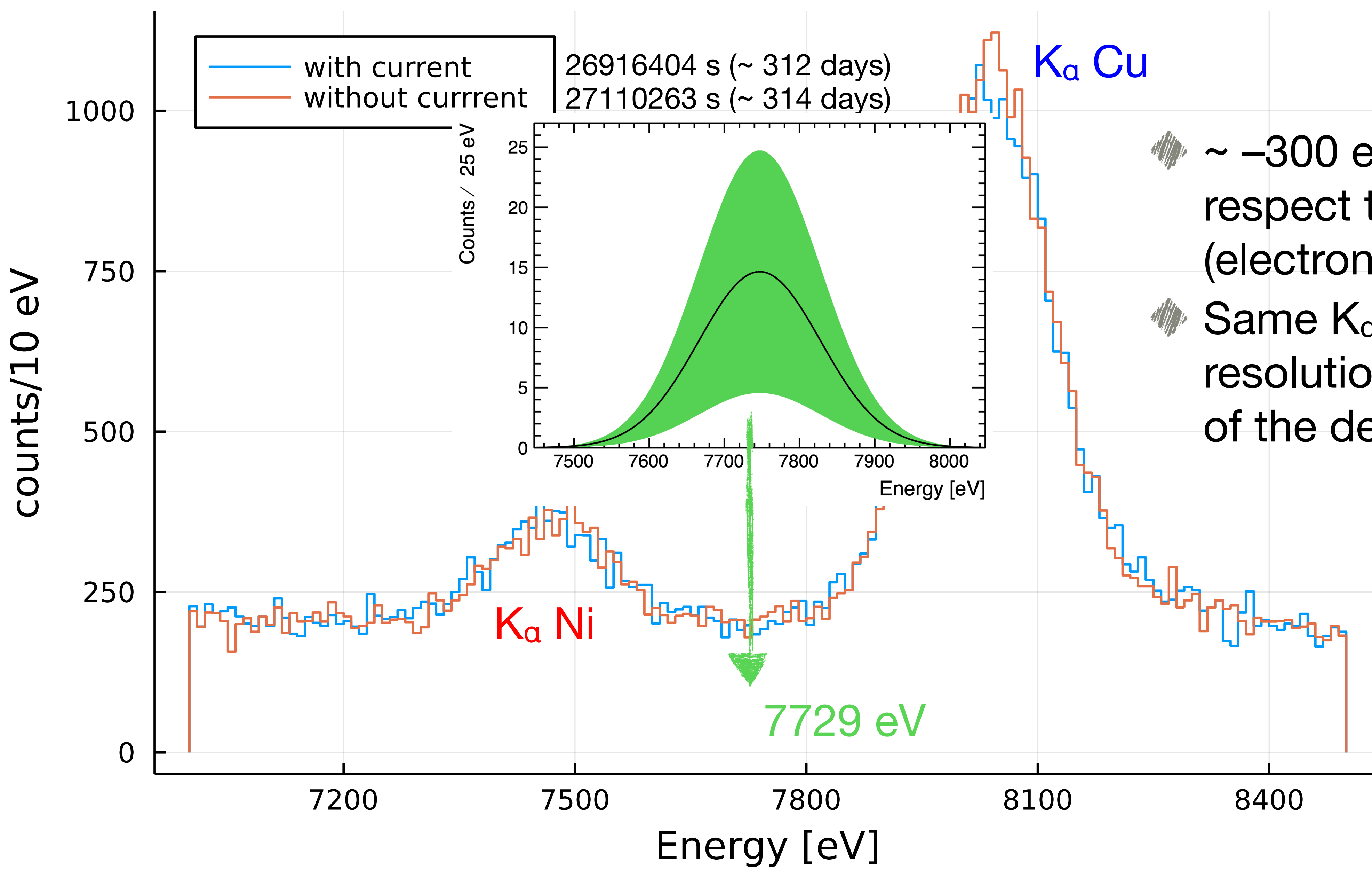
Data model

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



Data model

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



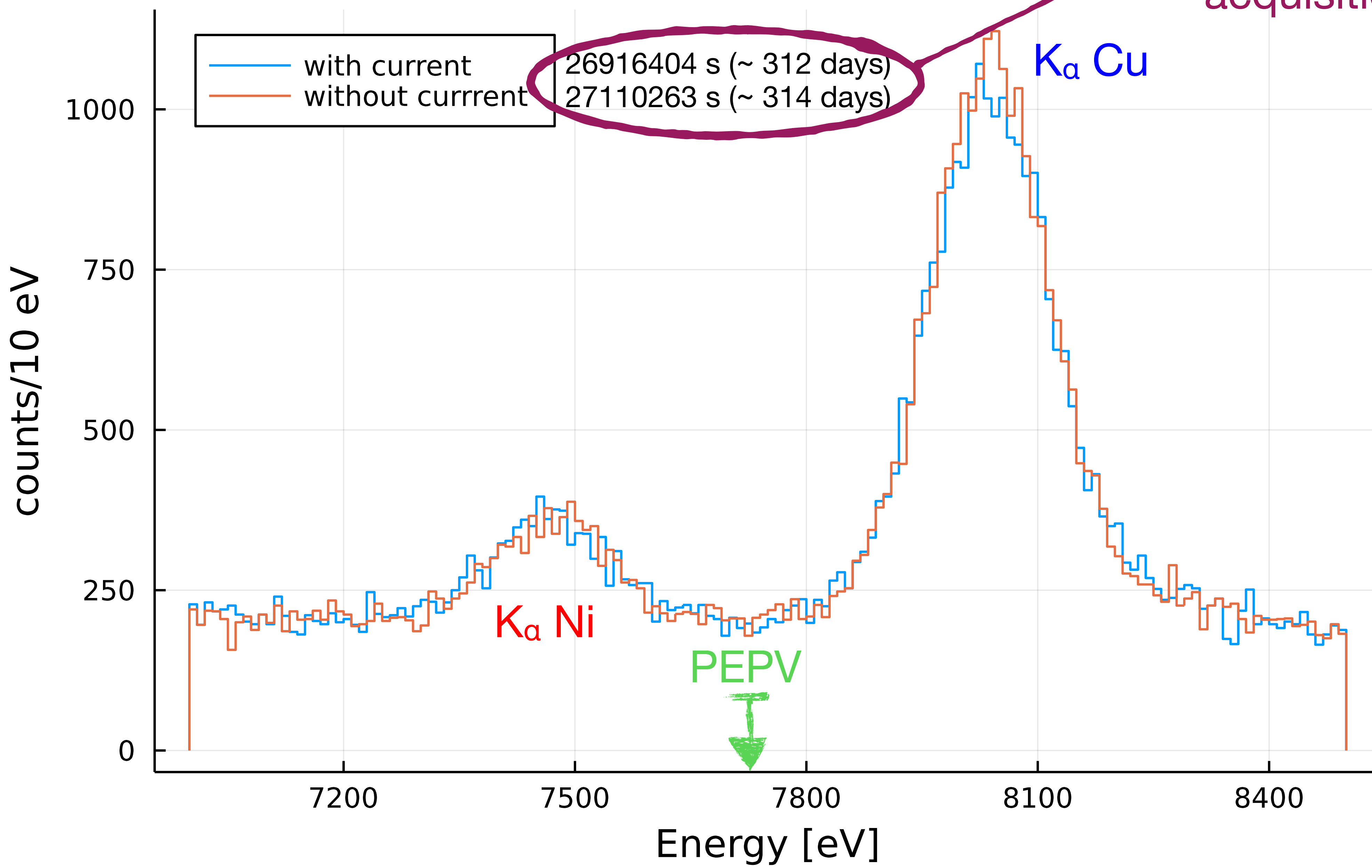
- ~ –300 eV with respect to Kα Cu (electron shielding)
- Same Kα Cu resolution (i.e., σ of the detector)

Data Likelihood

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

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

Ratio of data acquisition time



Bayesian approach

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

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

- 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

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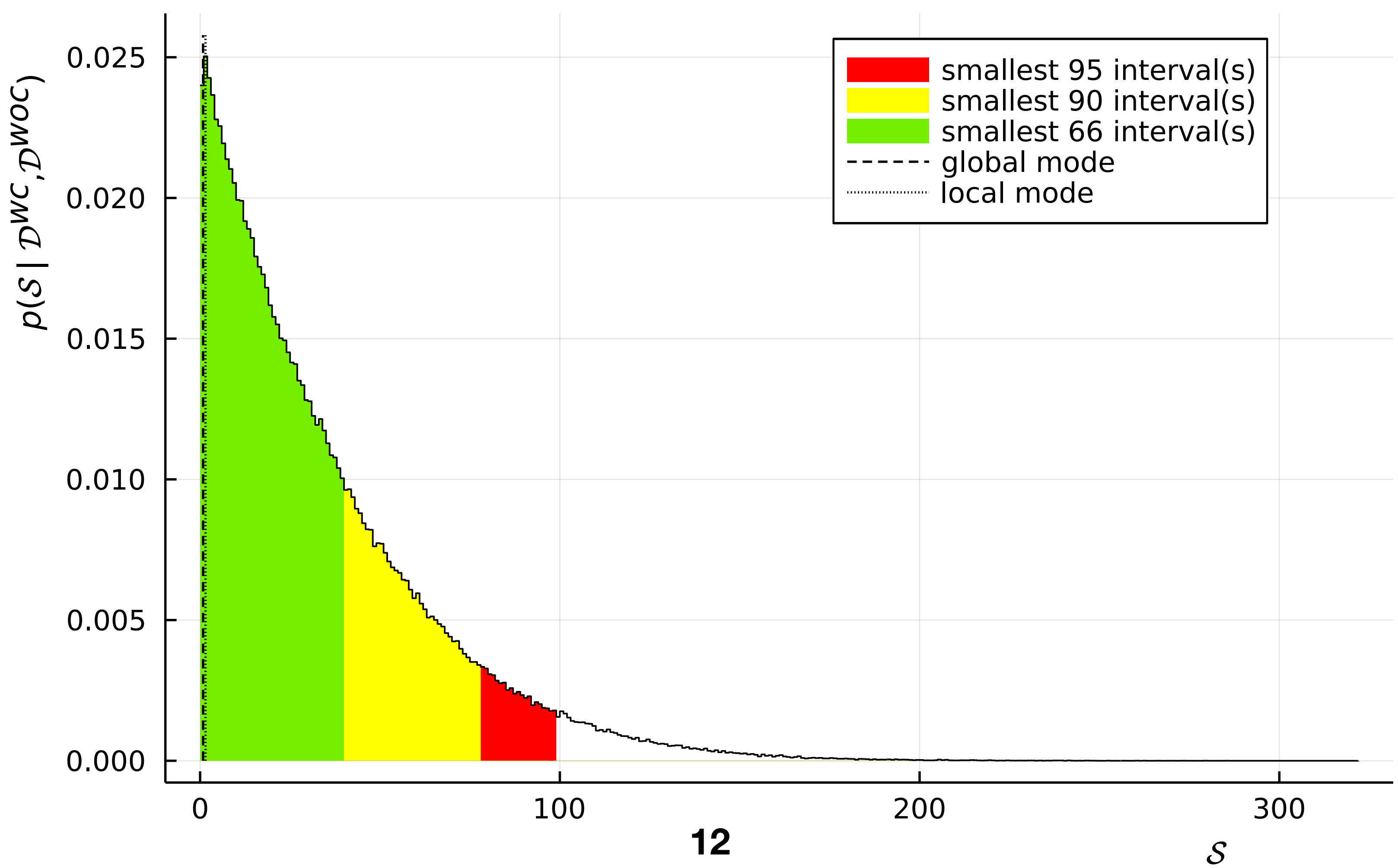
Integrals with
Markov Chain Monte Carlo method



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Modified frequentist: CLs

$$\mathscr{L}(\boldsymbol{\theta}, \boldsymbol{y}, \mathscr{S}) = \mathscr{L}(\mathscr{D}^{wc}, \mathscr{D}^{woc} | \boldsymbol{\theta}, \boldsymbol{y}, \mathscr{S}) p(\boldsymbol{\theta}, \boldsymbol{y}, \mathscr{S})$$

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

one-sided Likelihood Test statistic

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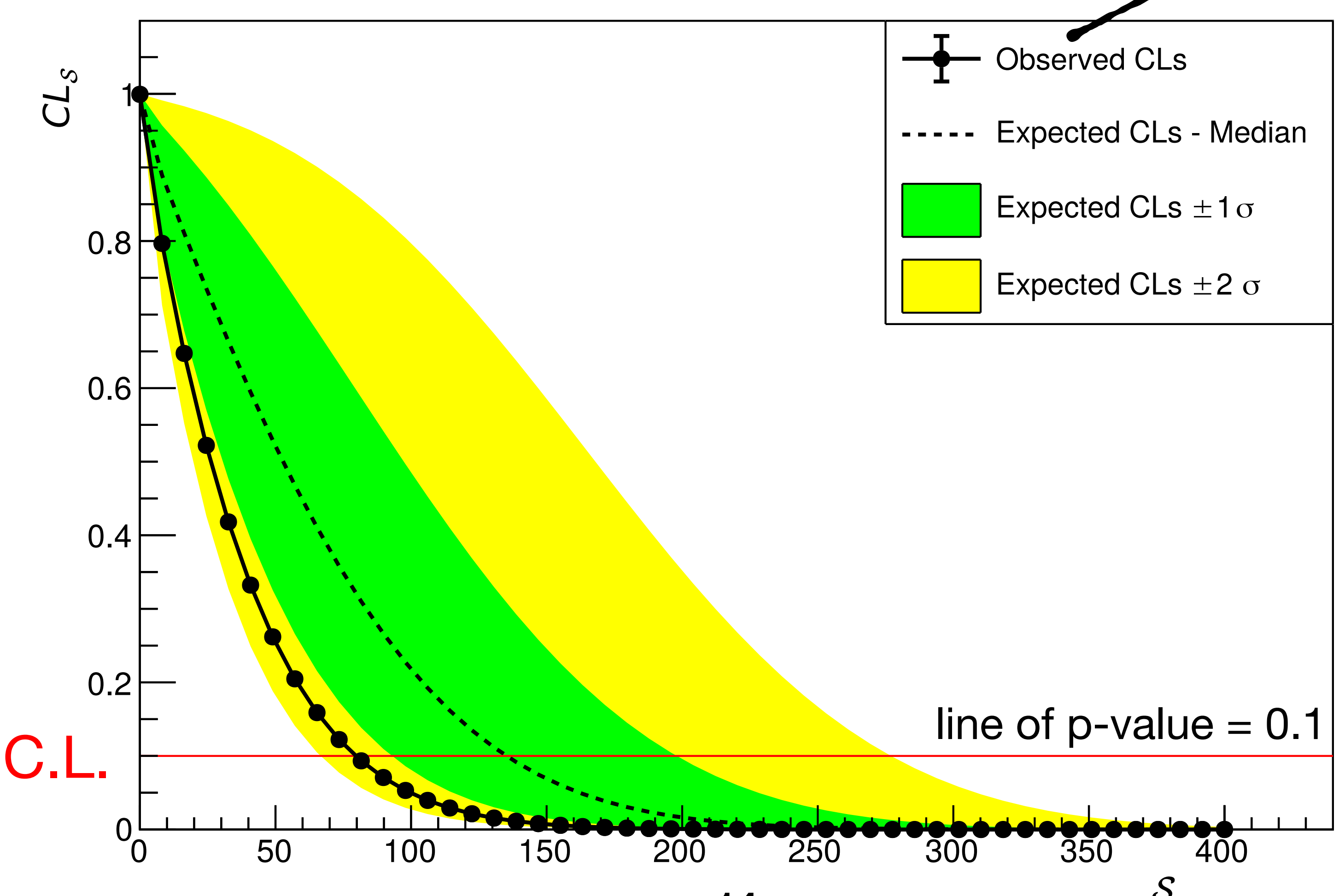
Computation with RooFit

CL_s expected with measured $\mathscr{S}$



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

90% of C.L.

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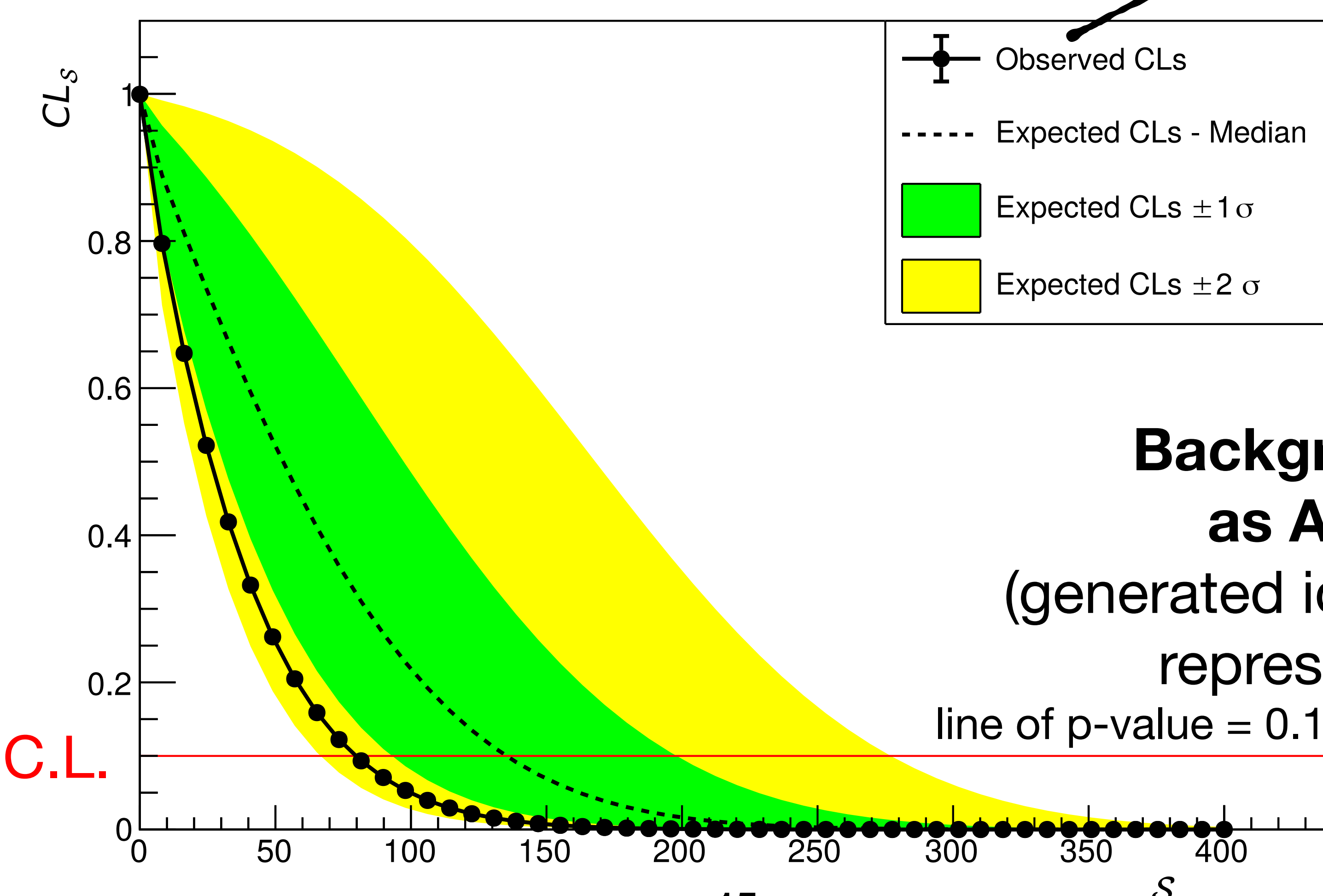

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Background Hypothesis as Asimov Dataset

(generated ideal dataset most likely representing the model)

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

$$\mathcal{S} \simeq \frac{\beta^2}{2} \cdot N_{\mathrm{new}} \cdot \frac{N_{\mathrm{int}}}{10} \cdot 7.25 \times 10^{-2}$$

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

Number of interactions; every ~10 interactions, 1 cascade

Newly injected electrons!

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

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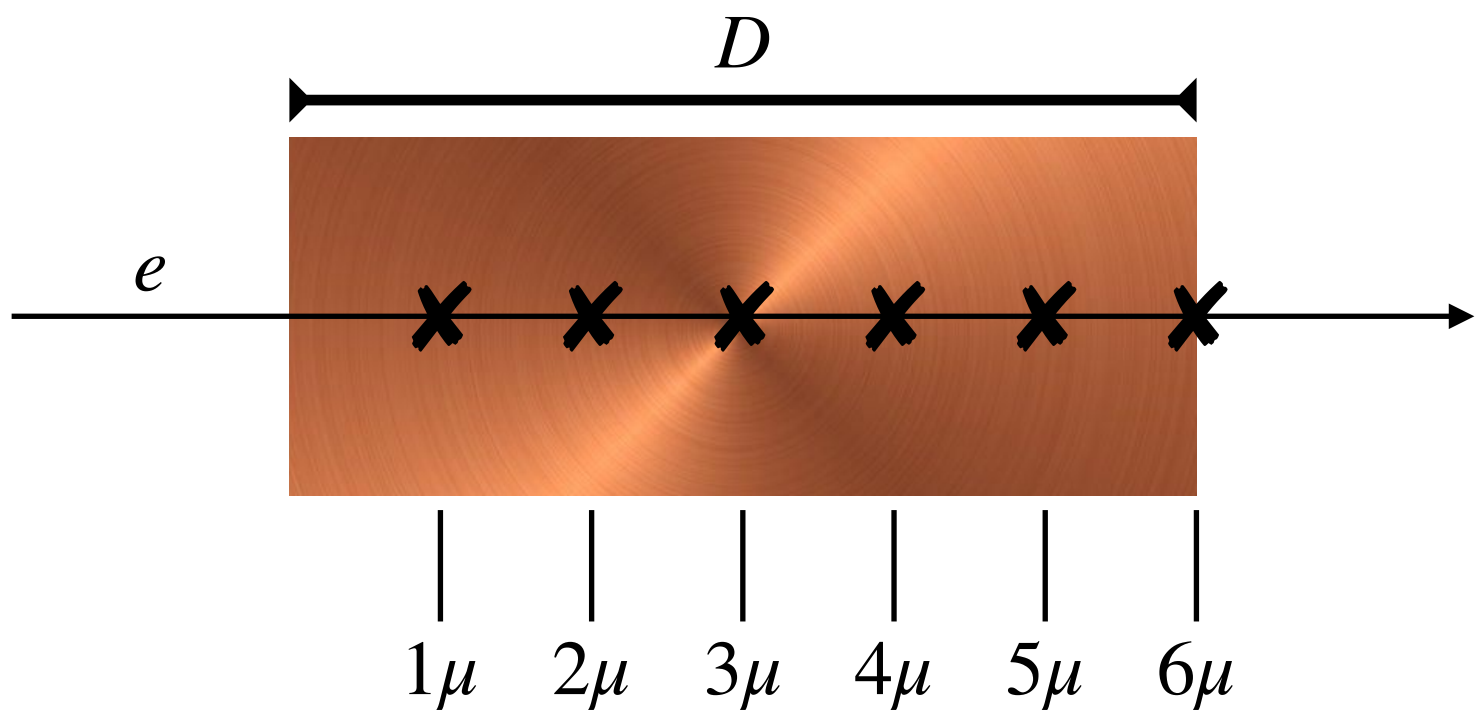
N_{int} is the normalization that decides the order of magnitude of $\beta^2/2$

Let's discuss e–atoms interaction Models!

N_{int} by Linear Scattering



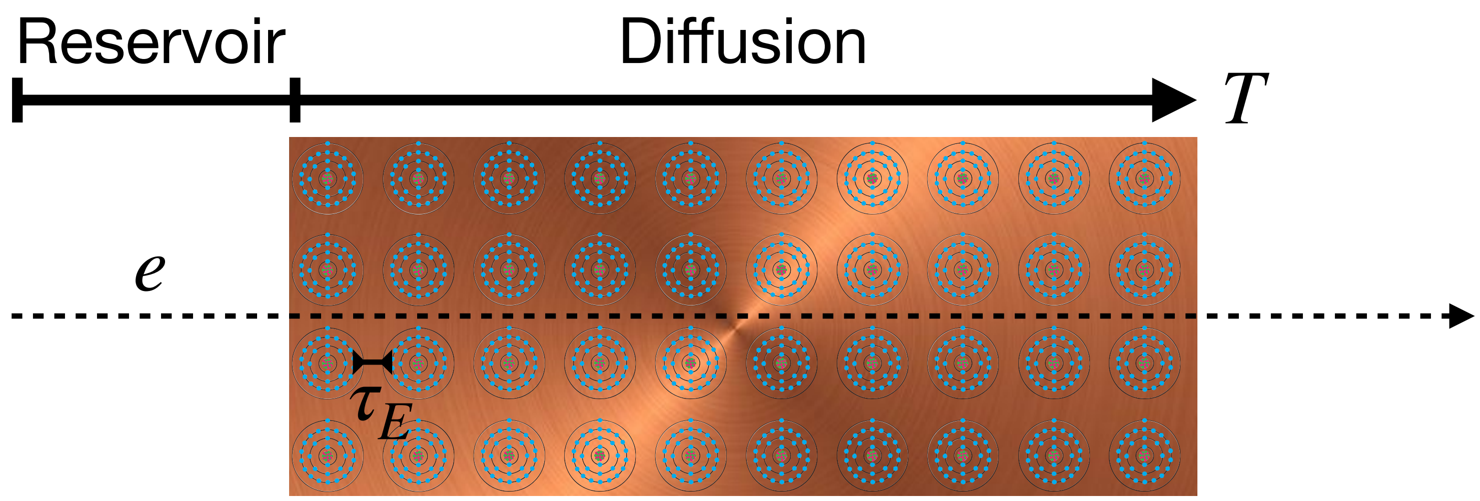
Through Copper Resistance,

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

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

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

Outlook

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}

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  - ✓ 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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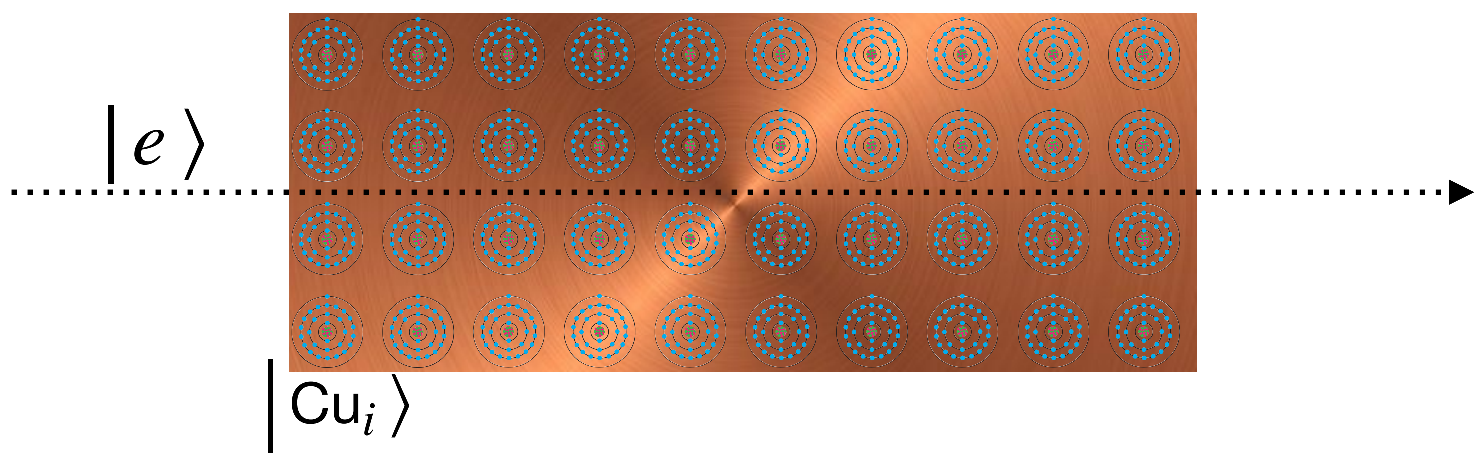
THANK YOU

BACKUPS

TO DO: a quantum N_{int}?



How many interactions between Cu atomic and electron fields occur?