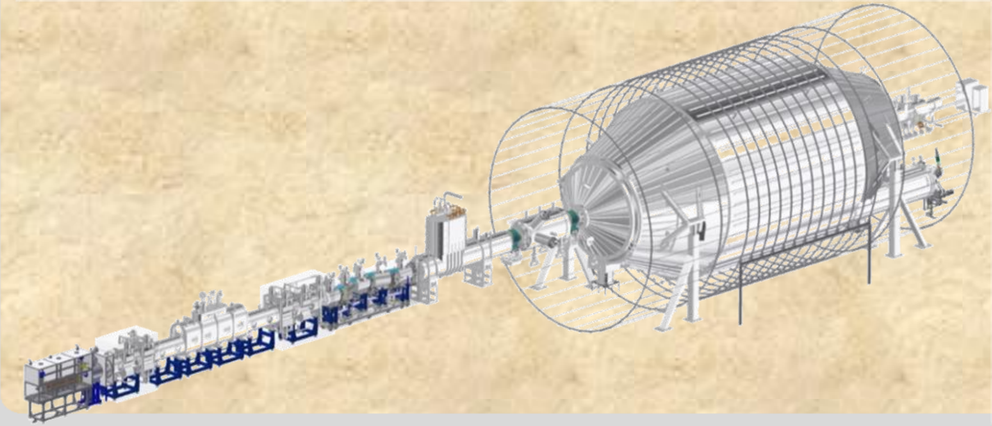
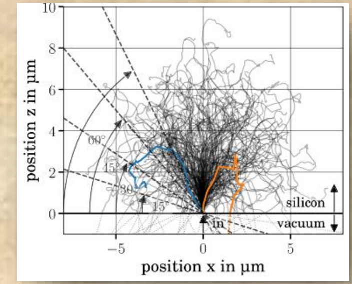
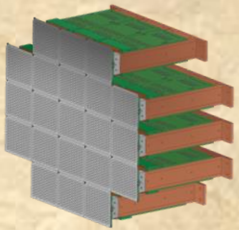
Silicon drift detector upgrade for a sterile neutrino search at KATRIN: *detector systematics*

Marc Korzeczek

Institute of Experimental Particle Physics (ETP), Karlsruhe Institute of Technology (KIT)



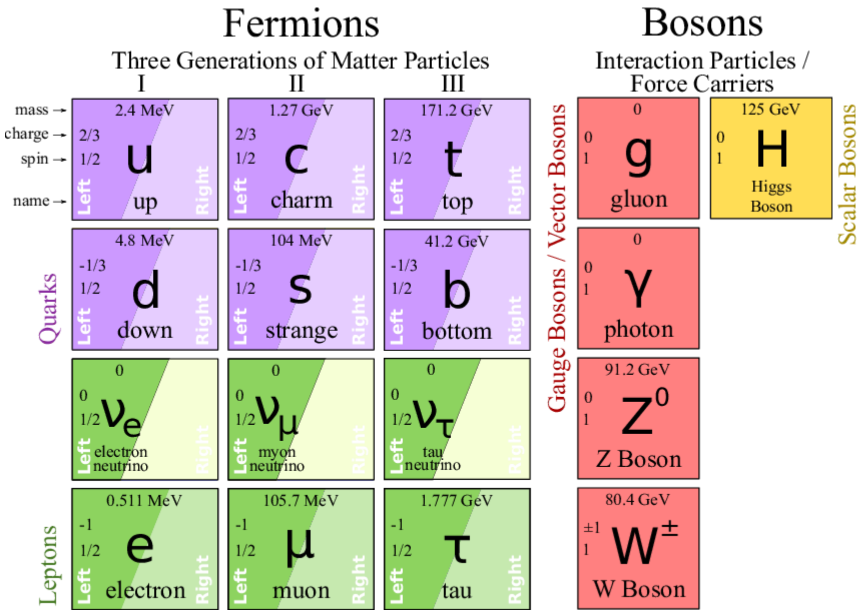




What?

- Sterile neutrinos?
- Signature at KATRIN?

Introduction – neutrinos



- Standard model of particle physics

  → neutrinos defined as …

  … ***mass-less*** and with

  left-handed helicity only

  → but: neutrino oscillation experiments

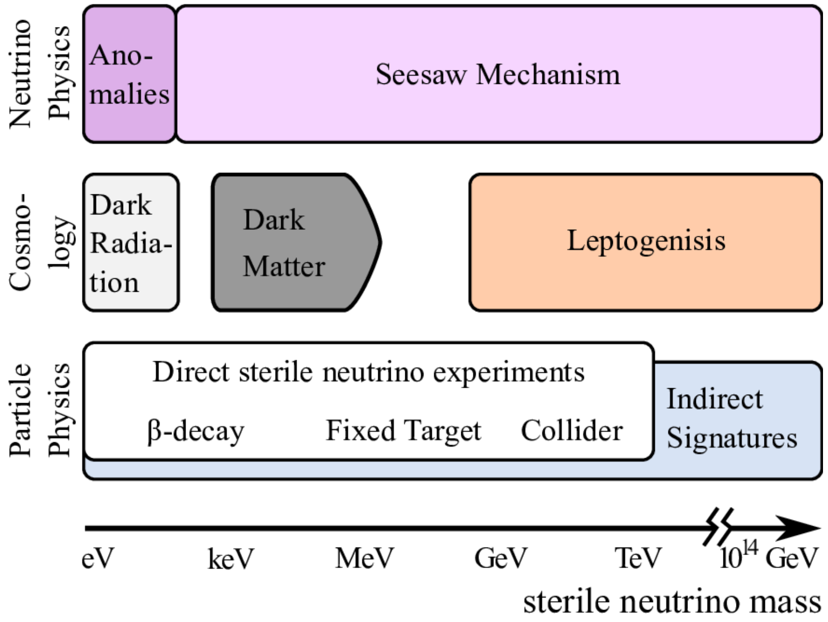
  find non-zero ***mass***-eigenstates

- Right-handed, sterile neutrinos?

  → non-zero Dirac & Majorana mass terms

Mikhail Shaposhnikov 2013
J. Phys.: Conf. Ser. 408 012015

Introduction – sterile neutrinos



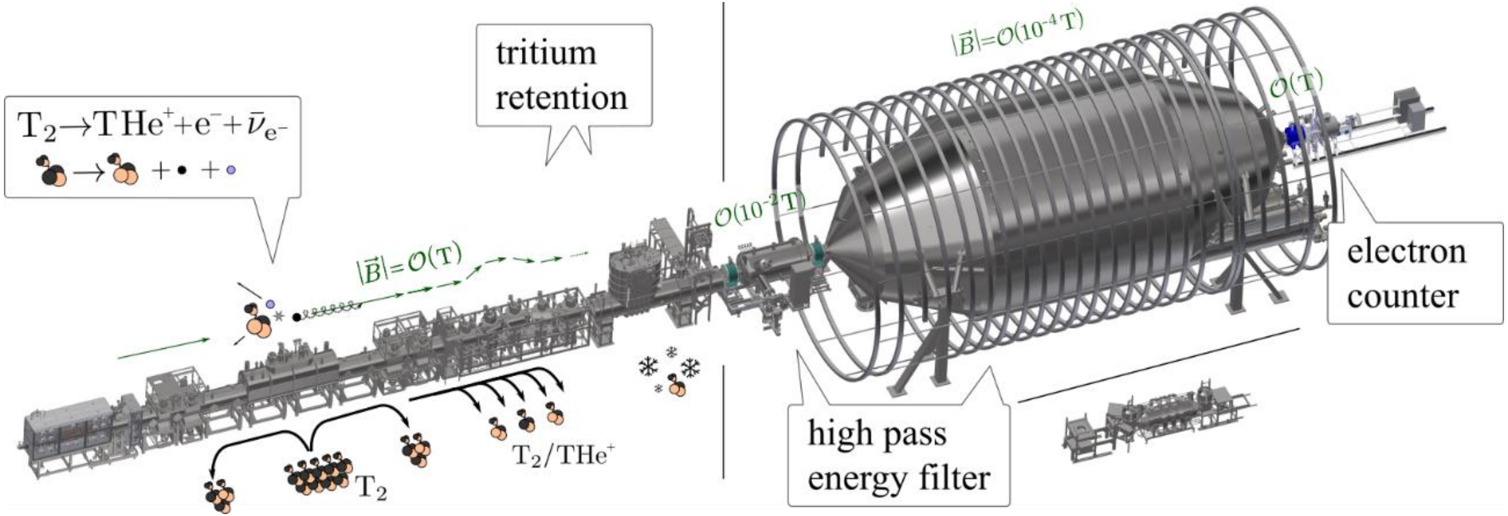
Marco Drewes 2019
Phys. J. 18 2

- Depending on mass, sterile neutrinos could …
  - … explain smallness of **neutrino masses**
  - … be candidate for **Dark Matter**
  - … solve **matter–antimatter asymmetry**
- Experimentally investigated through …
  - … direct signature in ***β-decay*** → **KATRIN**

Introduction – KATRIN

***KA**rlsruhe **TRI**tium **N**eutrino experiment*

- Spectroscopic investigation of tritium β-decay endpoint
- Goal: → $m_{\text{eff}} \leq 200\ \text{meV}\ (@90\text{CL})$



Introduction – KATRIN

__KA__rlsruhe __TRI__tium __N__eutrino experiment

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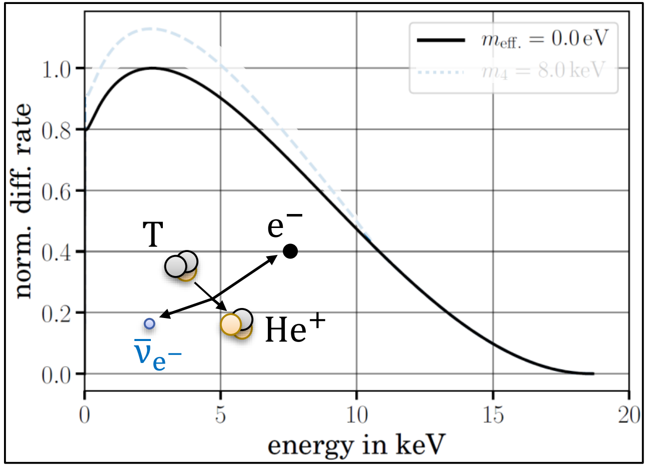
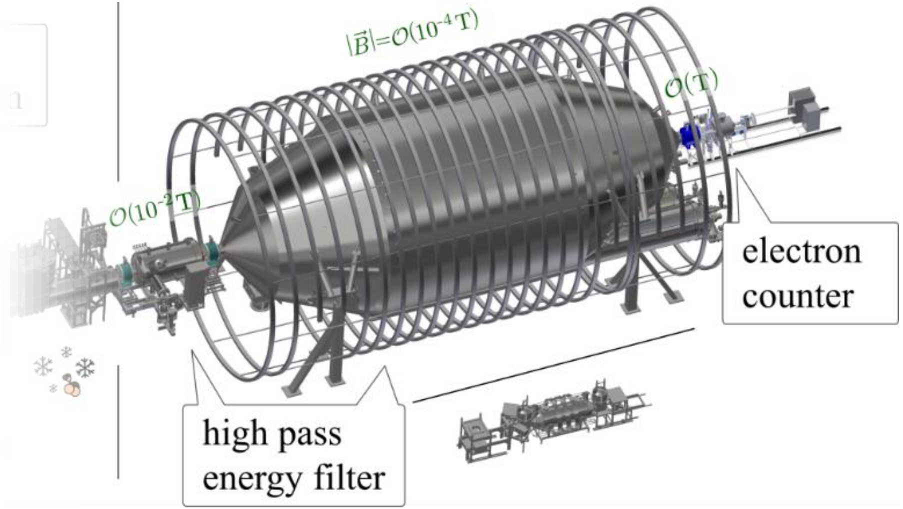


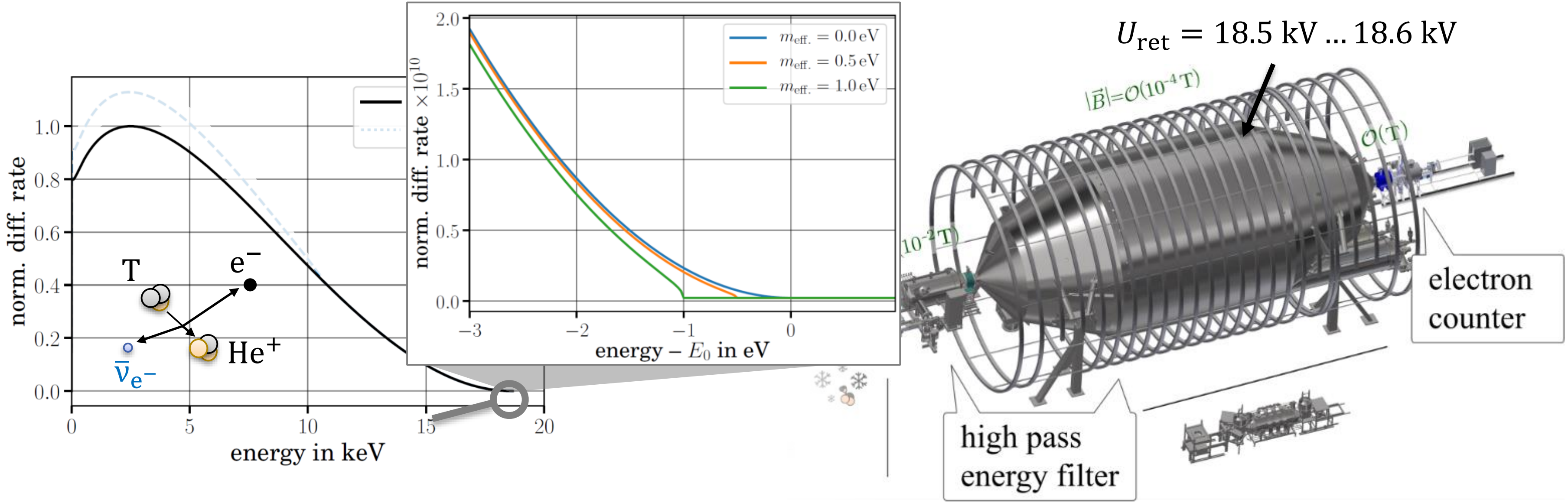


Introduction – KATRIN

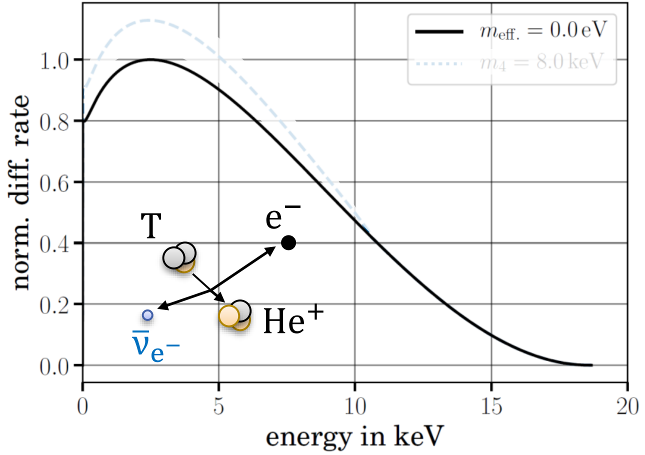
__KA__rlsruhe __TRI__tium __N__eutrino experiment

- Spectroscopic measurement of tritium β-decay endpoint
- *<u>Goal</u>:* → $m_{\mathrm{eff}} \leq 200$ meV (@90CL)

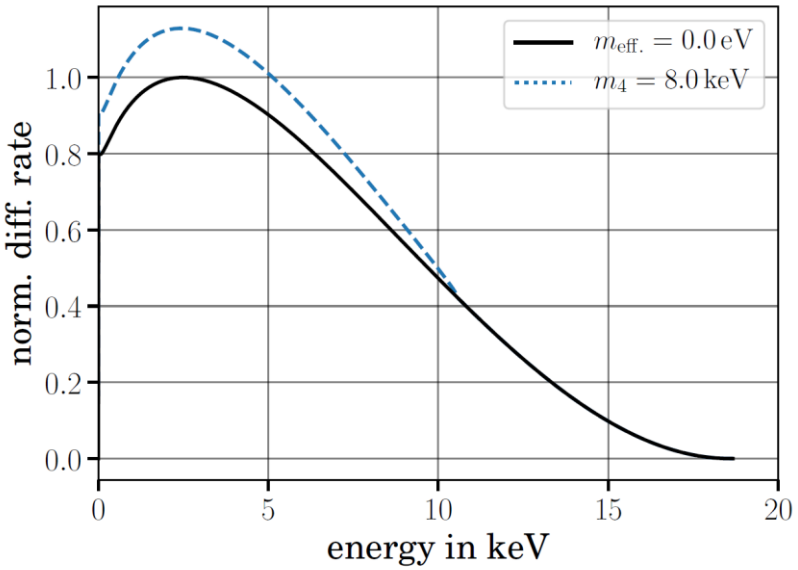
<u>Exemplary measurement</u>
Set point 1: $U_{\mathrm{ret}} = 18.55$ kV
Set point 2: $U_{\mathrm{ret}} = 18.56$ kV
Set point 3: $U_{\mathrm{ret}} = 18.57$ kV
…



Introduction – KATRIN and sterile neutrinos



Introduction – KATRIN and sterile neutrinos

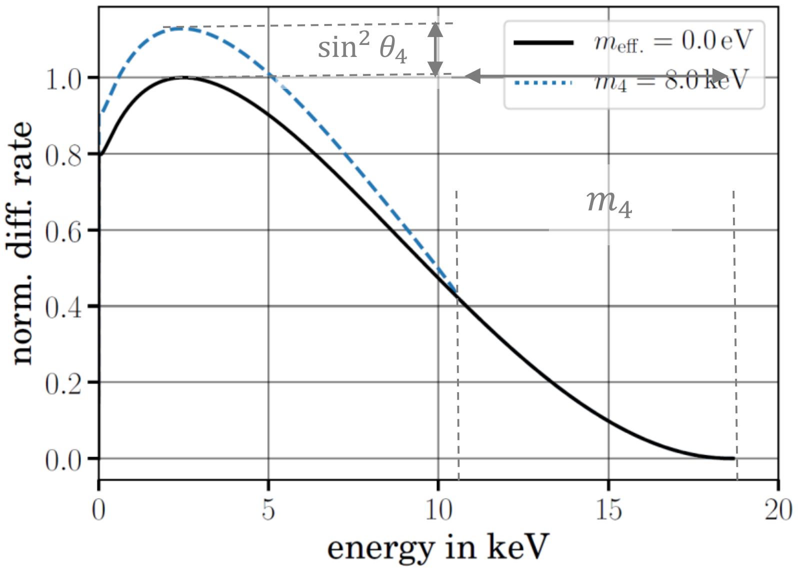


- Imprint of sterile neutrinos …

  … mass $\boldsymbol{m_4}$ & mixing $\boldsymbol{sin^2\,\theta_4}$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \frac{\mathrm{d}\Gamma(m_{\mathrm{eff}})}{\mathrm{d}E}\cdot\cos^2\theta_4 + \frac{\mathrm{d}\Gamma(m_4)}{\mathrm{d}E}\cdot\sin^2\theta_4$$

Introduction – KATRIN and sterile neutrinos



- Imprint of sterile neutrinos …

  … mass $\boldsymbol{m_4}$ & mixing $\boldsymbol{\sin^2\theta_4}$

  $$\frac{d\Gamma}{dE} = \frac{d\Gamma(m_{\text{eff}})}{dE} \cdot \cos^2\theta_4 + \frac{d\Gamma(m_4)}{dE} \cdot \sin^2\theta_4$$

- Experimental consequences …

  … differential measurement $U_{\text{ret}} \approx 0\ \text{V}$

  … high electron rates $\Gamma_{\text{det}} = \mathcal{O}(10^{10}\ \text{cps})$

  → **TRISTAN** project

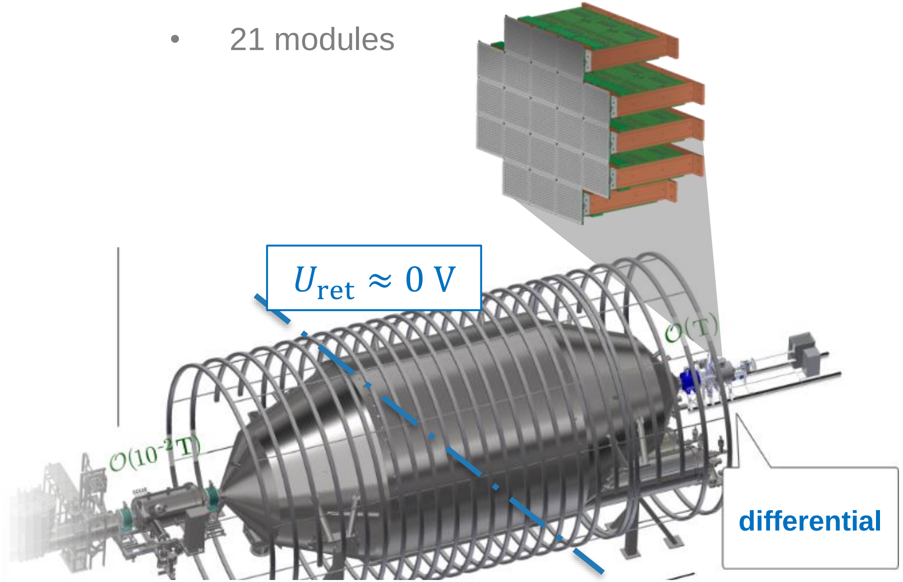
Introduction – KATRIN, TRISTAN project

TRitium **I**nvestigation on **ST**erile (**A**) **N**eutrinos

- Measurement: differential tritium β-decay spectrum

TRISTAN detector

- **S**ilicon **D**rift **D**etector (SDD)
- ~3500 SDD pixels
- 21 modules

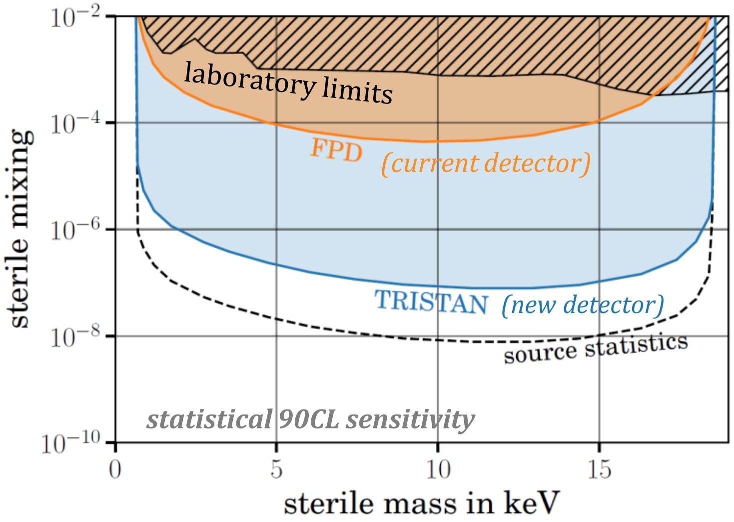


Susanne Mertens et al 2019
J. Phys. G: Nucl. Part. Phys. 46 065203

Introduction – KATRIN, TRISTAN project

TRitium **I**nvestigation on **ST**erile (**A**) **N**eutrinos

- Measurement: differential tritium β-decay spectrum
- *Goal:* $\sin^2\theta_4 \leq 10^{-7}, m_4 \in [0, 18.6\text{ keV}]$ @90CL



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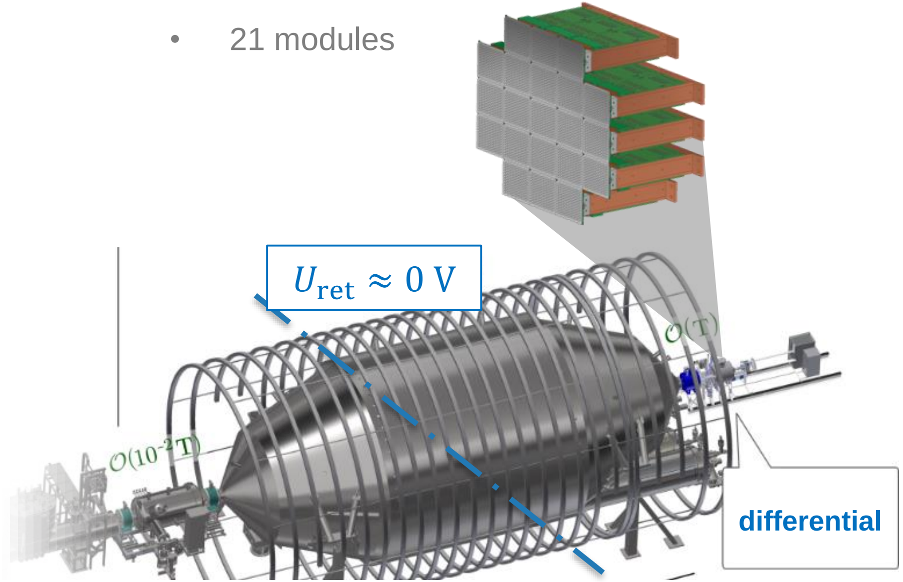

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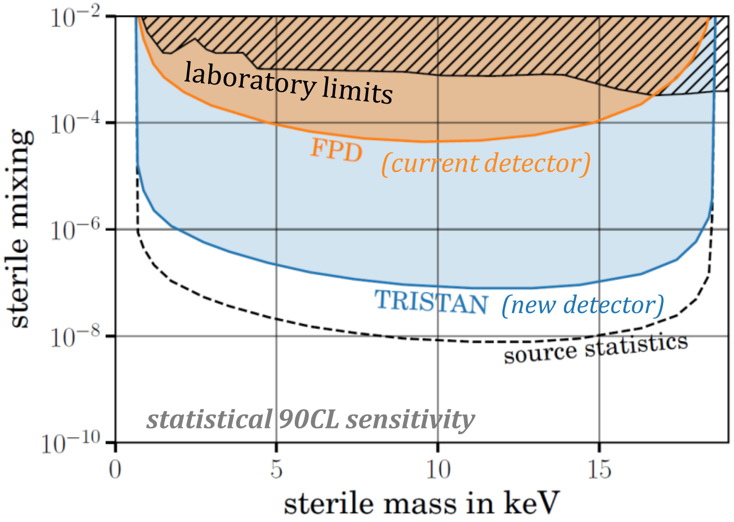

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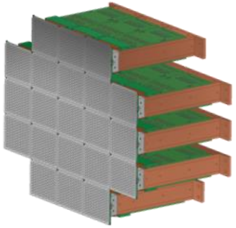


Influence of systemtics?

E.g. electric/magnetic fields?

→ R&D detector optimization

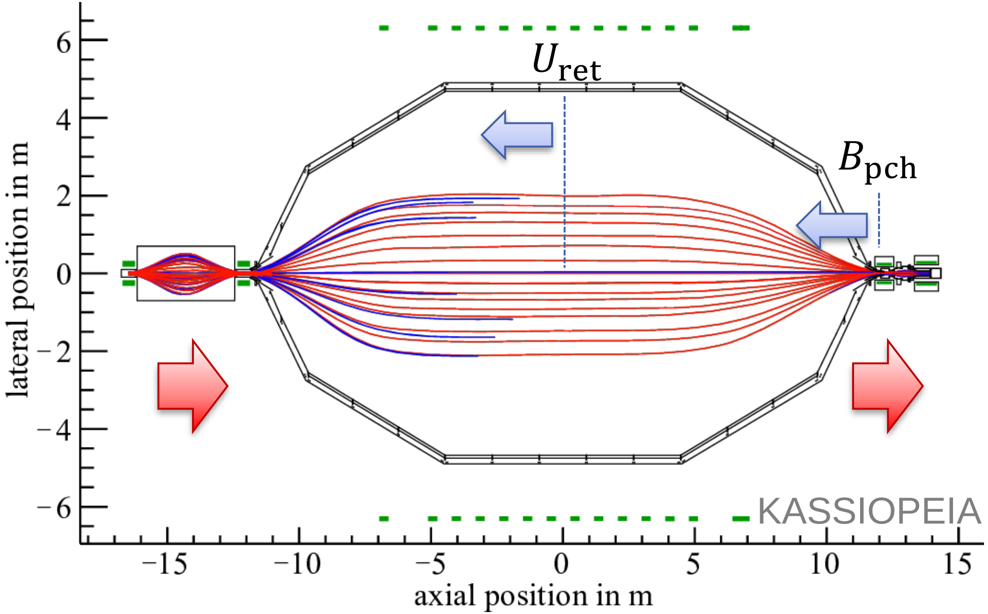
What?

- Back reflection?
- Detector section design?

KATRIN geometry

Electrons from tritium beta-decay

- Created in WGTS
- Magnetically guided to detector *(red tracks)*



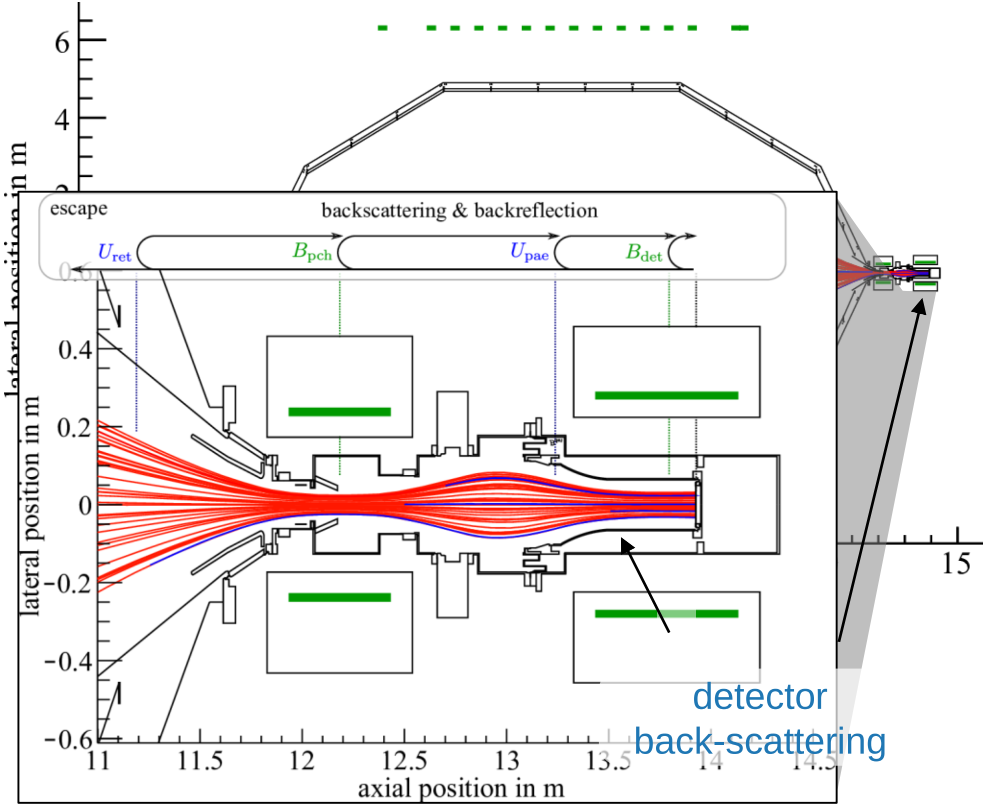
KATRIN geometry

Electrons from tritium beta-decay

- Created in WGTS
- Magnetically guided to detector

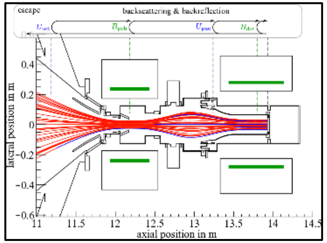
Back-scattered electrons $\mathcal{O}(20\%)$

- Electromagnetically **reflected** back to the detector $> 99\%$
- Small fraction transmitted through spectrometer and **escapes** $\leq 1\%$



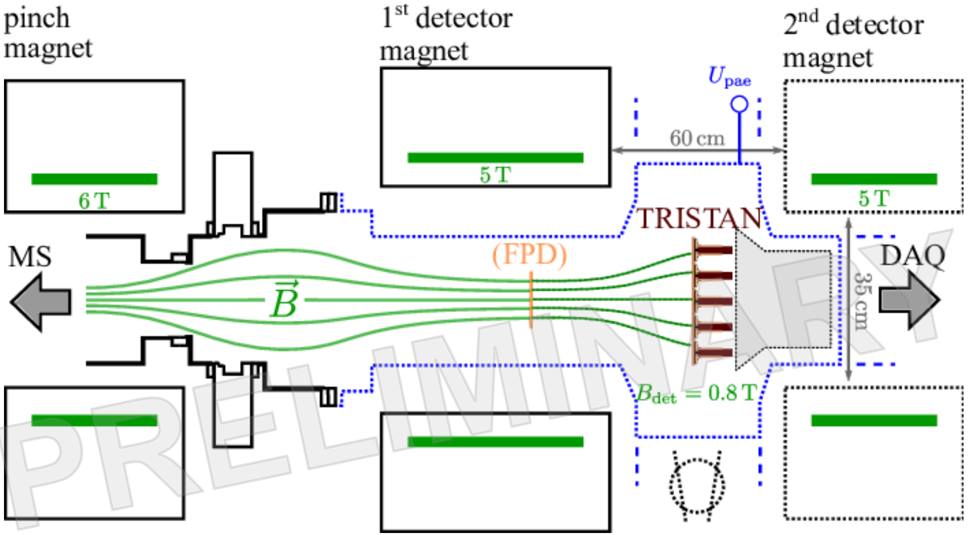
Modified detector section

current design



- Detector rate $R_{\mathrm{det}} = 10^8$ cps
- Signal pile up → $N_{\mathrm{px}} \approx 3500$
- Detector backrefl. → $B_{\mathrm{det}} = 0.7 \ldots 0.8$ T
- + charge sharing → $r_{\mathrm{px}} = 1.6 \ldots 1.5$ mm
- Intercorrelations → $\mathrm{U}_{\mathrm{pae}} \geq E_0$
  → $\mathrm{t}_{\mathrm{rise}}$ online-cuts

optimized for „sterile“ neutrinos



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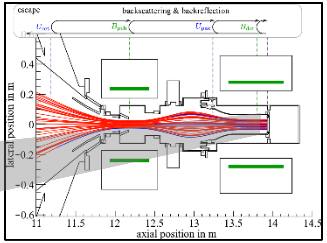
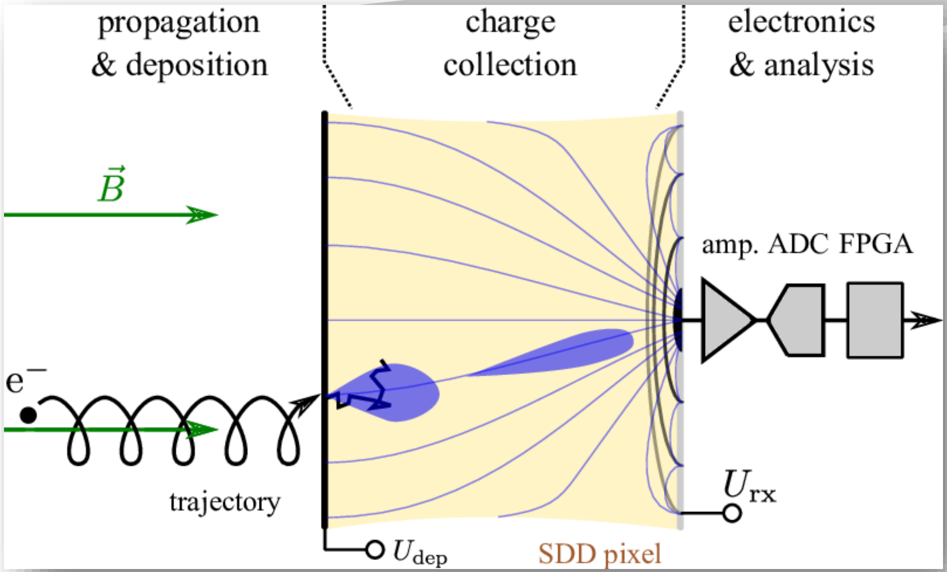
What?

- Detector response
- Modeling

Modeling – framework

current design

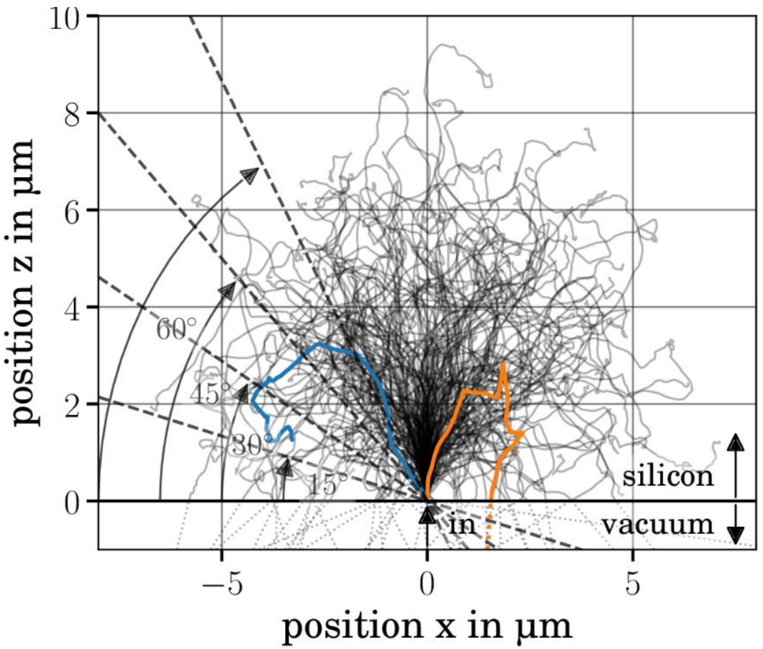




1/2 3 4 5

1. Energy deposition: $E = E_{\text{in}} - E_{\text{dl}} - E_{\text{bs}}$
2. Fano noise: $E \rightarrow \mathcal{N}(\mu = E, \sigma \propto \sqrt{E})$
3. Charge sharing: $E \rightarrow (E_1, E_2),\ E = E_1 + E_2$
4. Electronic noise: $E \rightarrow \mathcal{N}(\mu \propto E, \sigma = \text{const.})$
5. Signal pile up: $(E_1, E_2) \rightarrow E = E_1 + E_2$

Modeling – energy deposition simulation



Energy measurement:

- Electrons lose ionize silicon at various scatterings off lattice atoms
  → small chance to back-scatter

- Charge collection close to surface
  → non-conducting $\mathrm{SiO_2}$-layer $\mathcal{O}(10\,\mathrm{nm})$
  → doping profile irregularities $\epsilon(z)$

Approximation:
discrete deadlayer at $z_{\mathrm{dl}} = \mathcal{O}(50\,\mathrm{nm})$

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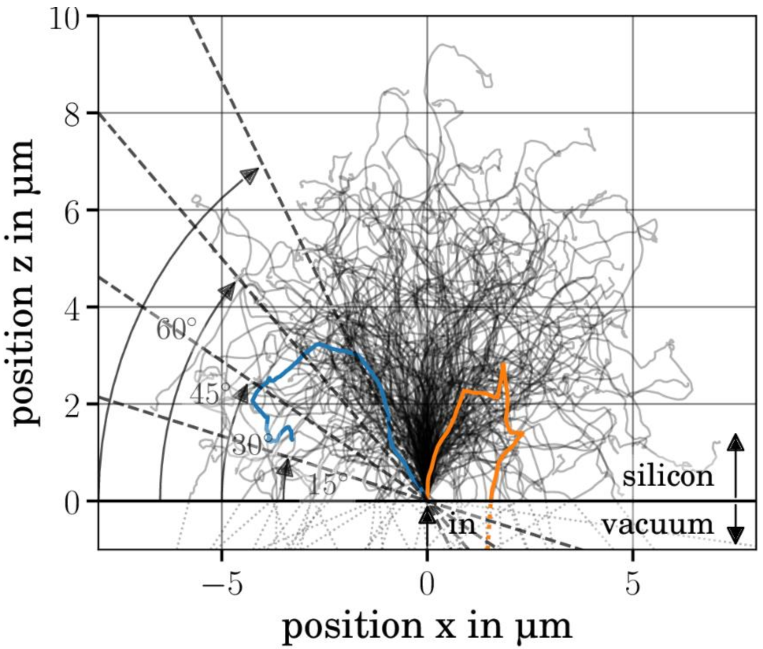

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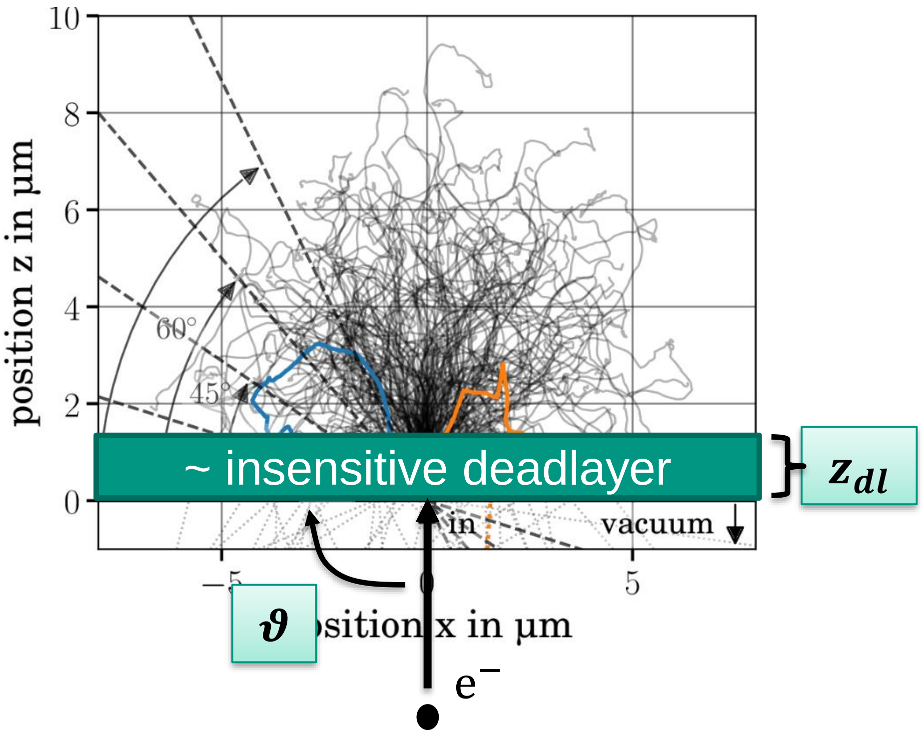

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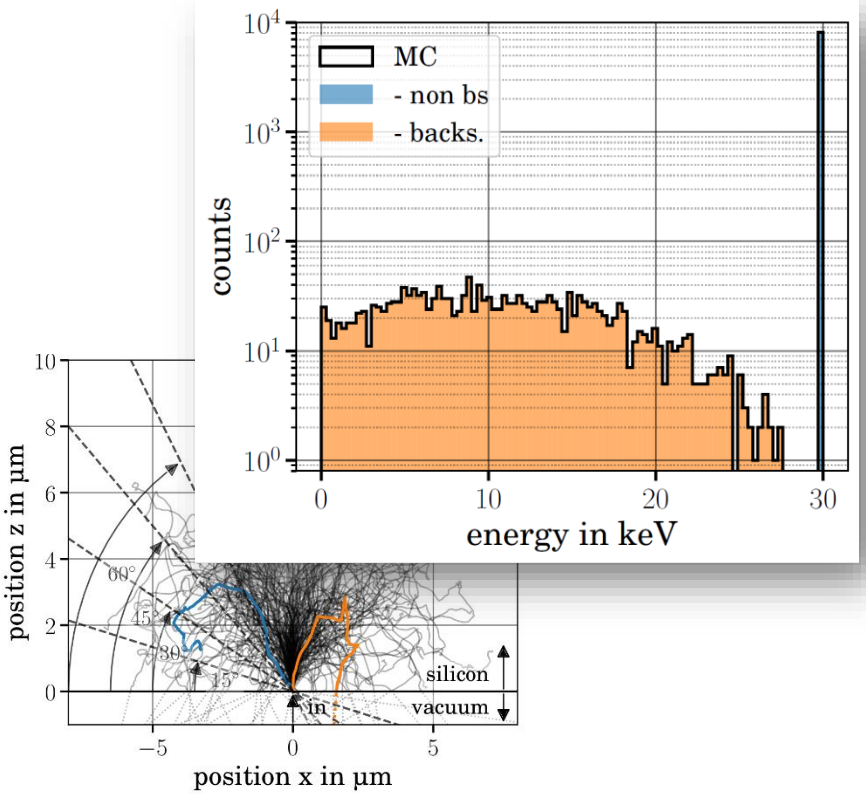

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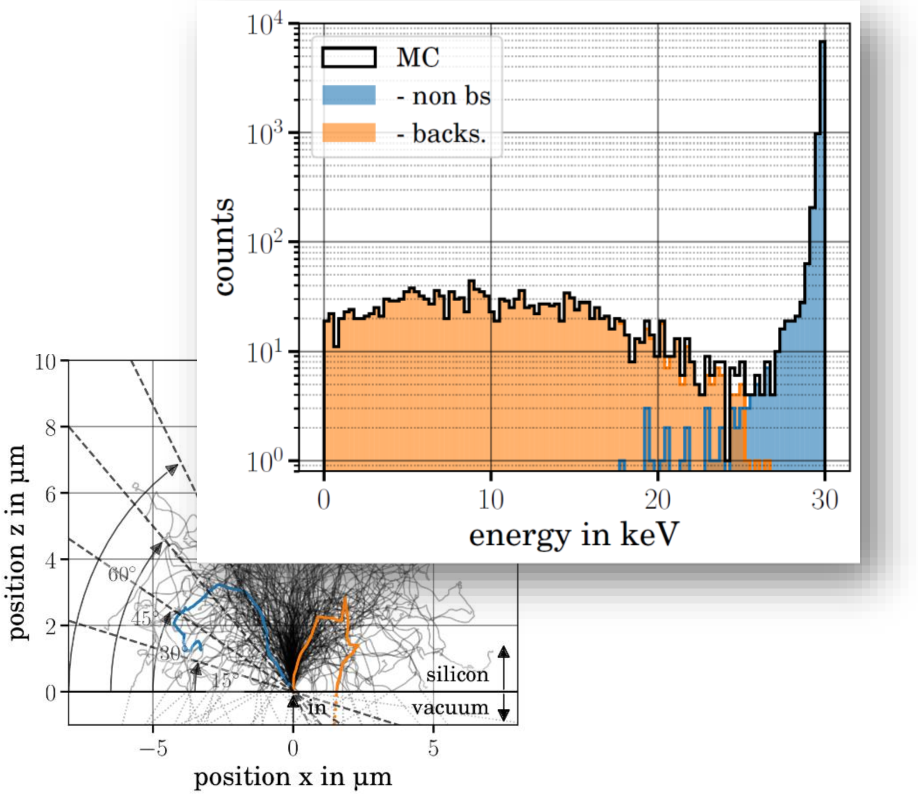

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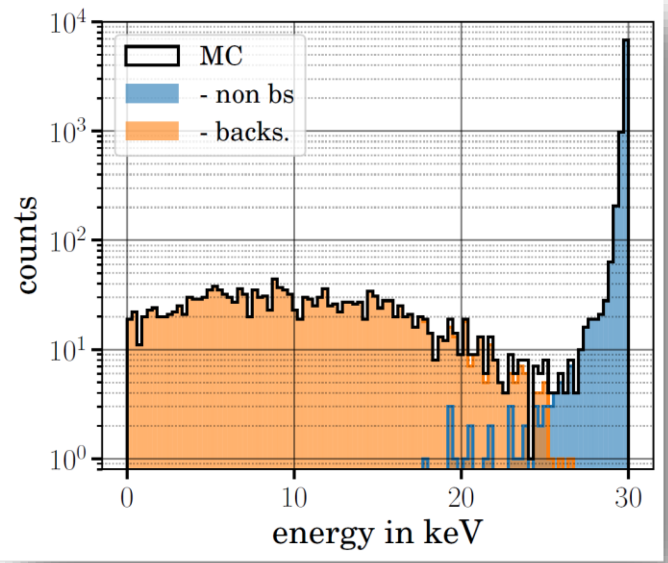
Modeling – simulation interpolation



Ideal for understanding of individual parameters …

BUT: very slow

Goal: find numeric/functional representation

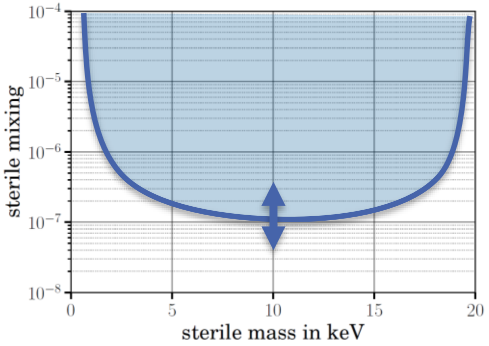
Database interpolation technique

$$f(E) \equiv f_{DB}(E, E_{in}, z_{\mathrm{dl}}, \vartheta_{\mathrm{p,in}})$$

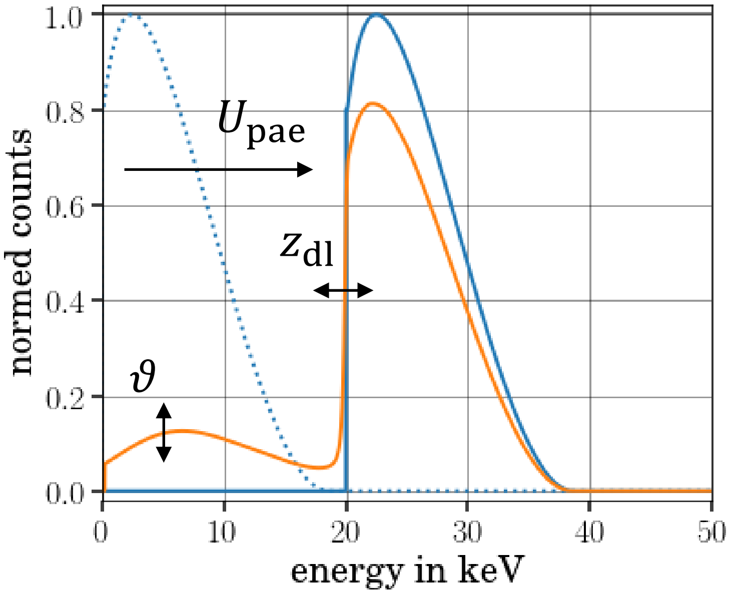
- 21k simulations with 10^7 electrons
- Three parameters $E_{in}, z_{\mathrm{dl}}, \vartheta_{\mathrm{p,in}}$
- Single evaluation time $\mathcal{O}(\mathrm{ms})$

What?

- Systematic uncertainties
- Sensitivity



Systematic uncertainty



Influence of …

- Post acceleration voltage

  $$U_{pae} = \mathbf{0} \;/\; \mathbf{20\,kV}$$

- deadlayer thickness

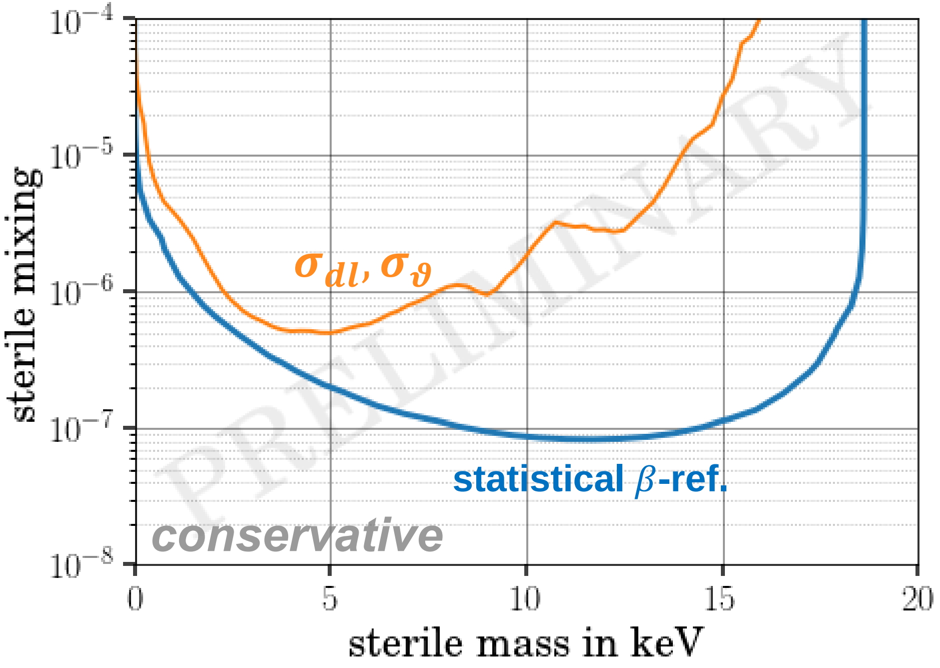
  $$z_{dl} = 50, \;\; \sigma_{dl} = \mathbf{0} \;/\; \mathbf{5}\,\mathrm{nm}$$

- electron incident angle

  $$\vartheta = 0°, \quad \sigma_{\vartheta} = \mathbf{0} \;/\; \mathbf{5}°$$

conservative

Systematic sensitivity



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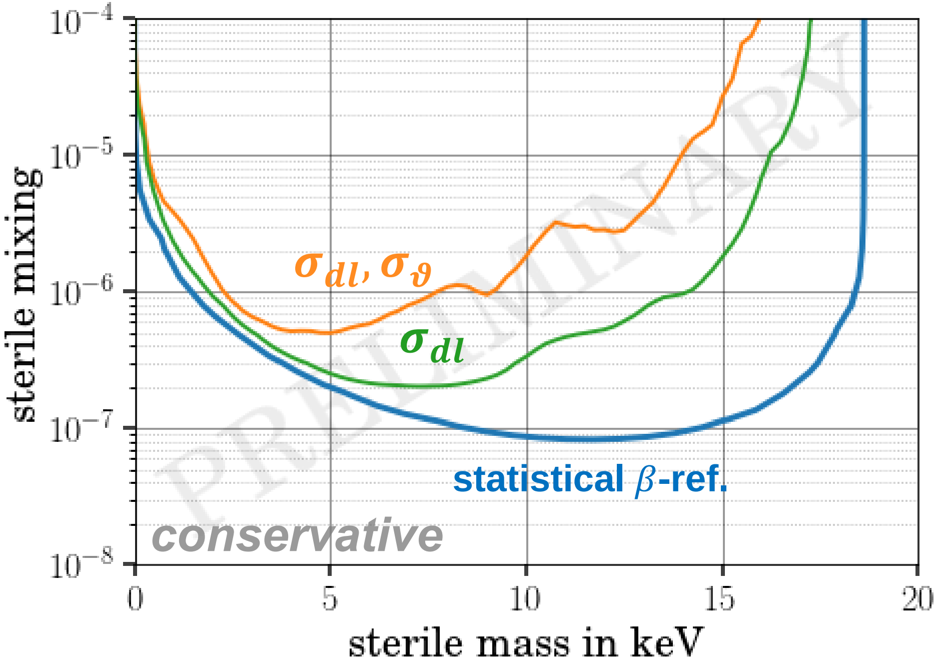

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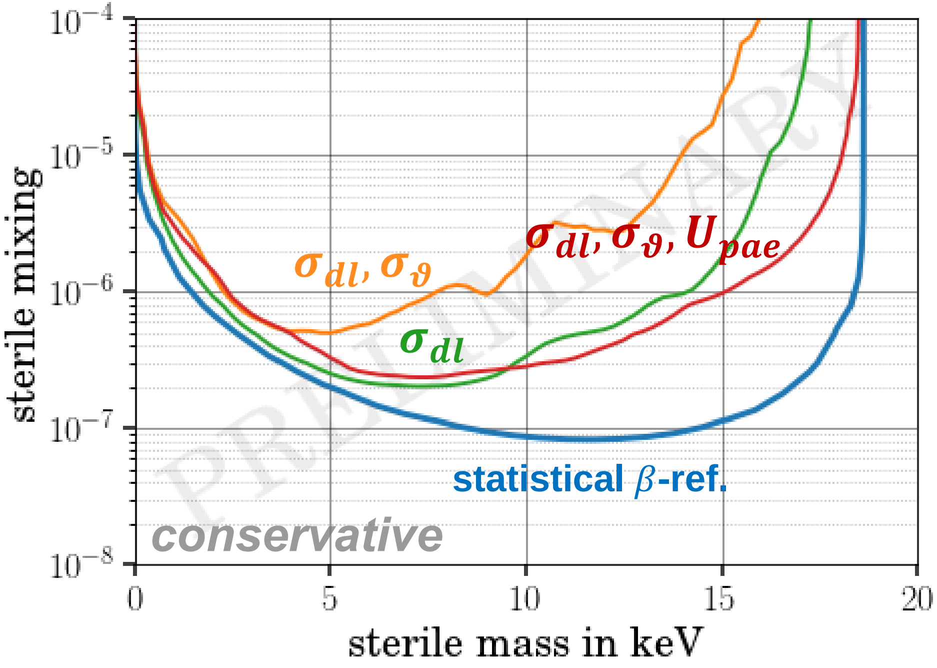
Systematic sensitivity



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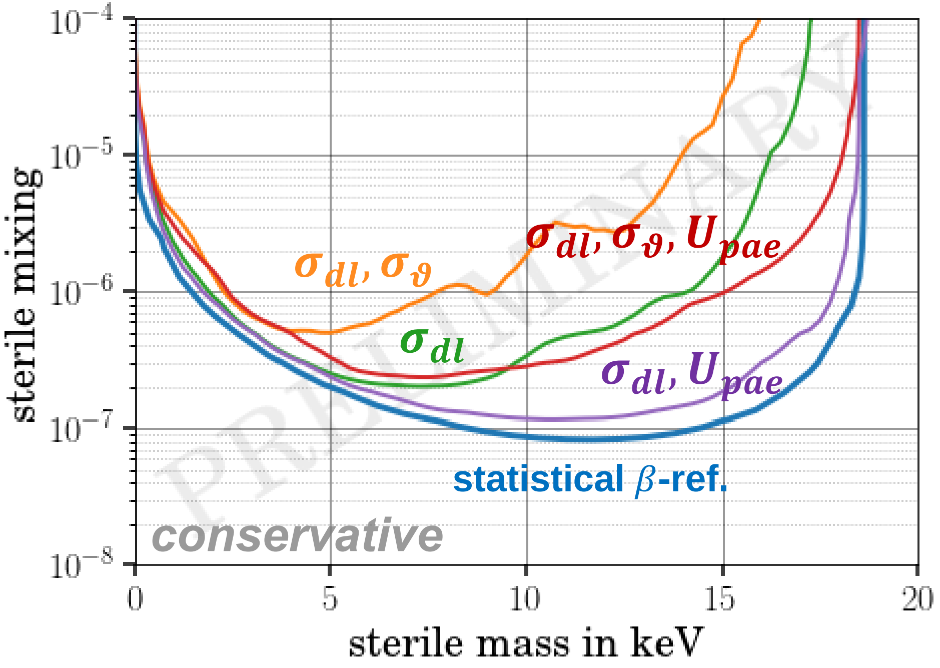

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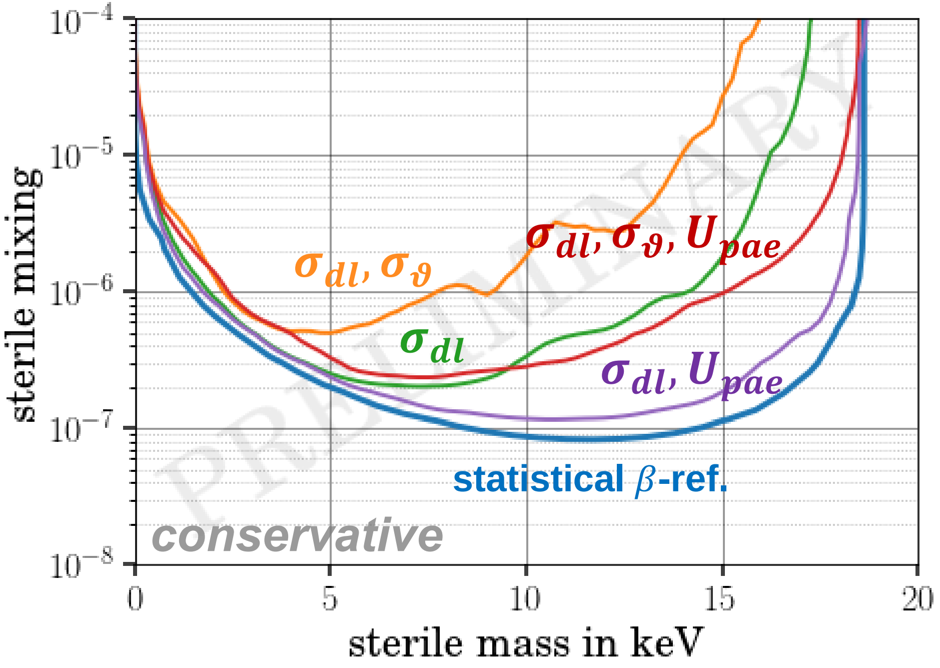
Systematic sensitivity

Karlsruhe Institute of Technology



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<u>Conclusion</u>

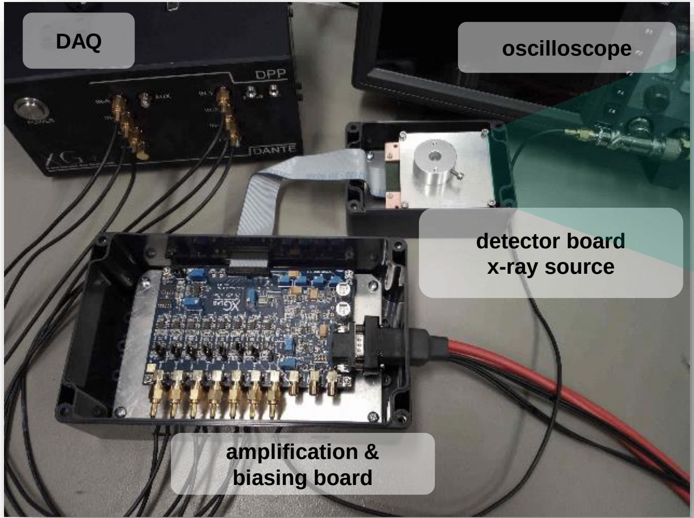
- Post acceleration → $U_{\mathrm{pae}} > E_0$
- Homogeneity → $\sigma_{\mathrm{dl}} \approx \mathcal{O}(\mathbf{5}\ \mathrm{nm})$
- Alignment → $\boldsymbol{\sigma_\vartheta \approx \mathcal{O}(1^\circ)}$
- Decorellate syst. → e.g. $\mathrm{t_{rise}}$

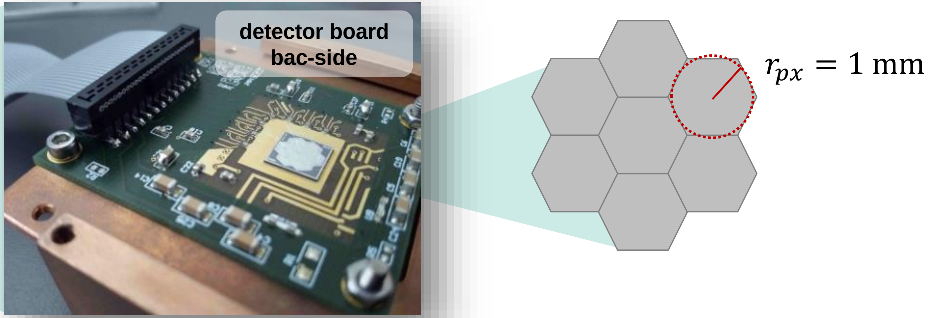
Thanks to KSETA

What?

- Simulation interpolation
- Total detector response
- Measurement setup?
- Mono-energetic detector response?
- Sensitivity framework
- Sensitivity constraints

Characterization



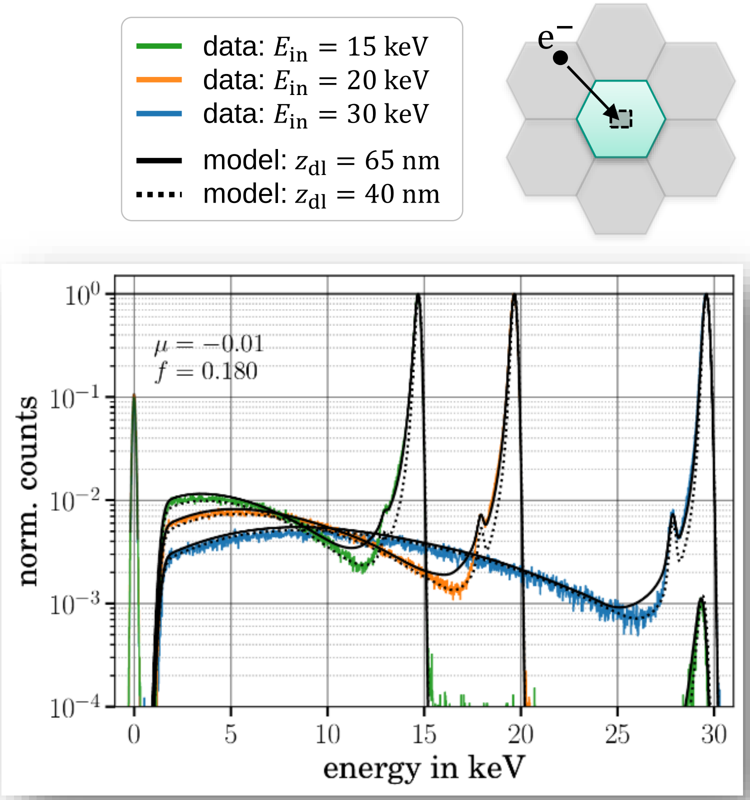


- Detector produced at HLL/MPG Munich
- Amplifier & acquisition from XGLab/Bruker

<u>Measurement</u>:

- Prototype 0 detector with seven pixels
- Calibration via Am241 x-ray (above)
- Scanning Electron Microscope

Characterization



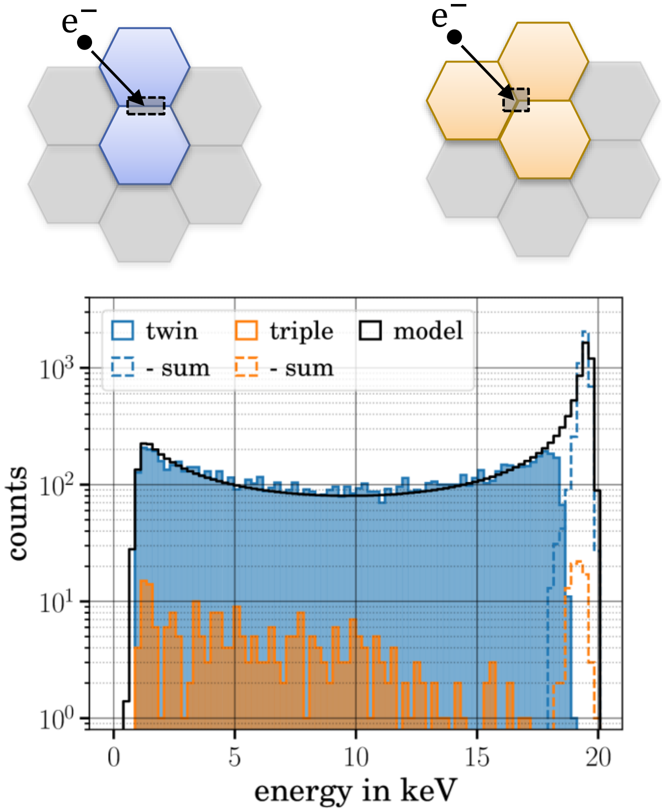
Details:

- Scanning Electron Microscope
- Mono-energetic E_{in}
- Perpendicular incidence $\vartheta_{in} = 0°$
- Focus pixel center → dominated by deposition
- Model: $z_{dl} = 40/65$ nm (dotted/solid lines)

→ decent match model *("not fitted")*

→ quick evaluation times $\mathcal{O}(1\ \mathrm{ms})$

Characterization



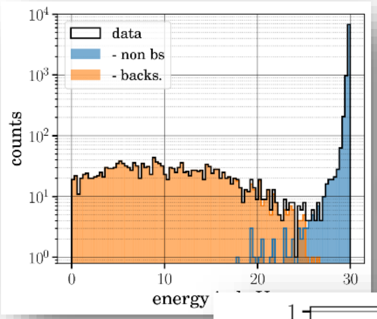
<u>Details</u>:

- Scanning Electron Microscope
- Mono-energetic $\mathrm{E_{in}}$
- Perpendicular incidence $\vartheta_{\mathrm{in}} = 0°$
- Homogeneous illumination
- Select coincident events $\Delta t \leq 0.2\ \mu\mathrm{s}$
- → check charge sharing: $E \rightarrow E_1 + E_2 (+E_3)$

→ decent match model *("not fitted")*

→ quick evaluation times $\mathcal{O}(1\ \mathrm{ms})$

Modeling – simulation interpolation



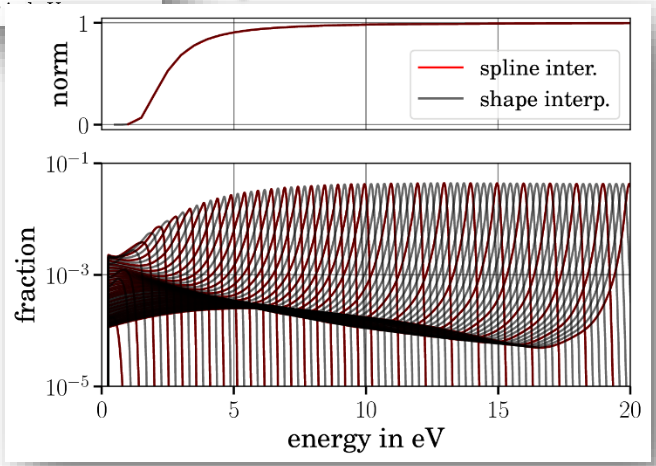


Illustration of

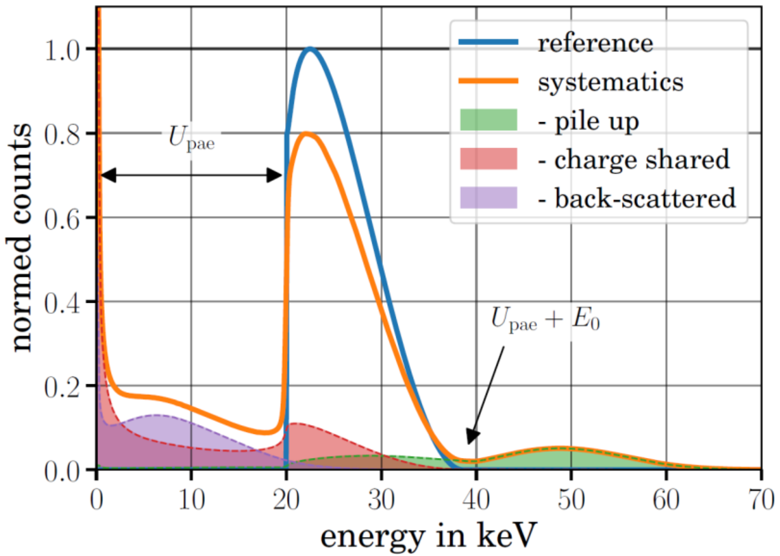
- 29 splines $f(E)|_{E_\mathrm{in}, 50\text{ nm}, 0°}$
- 80 shapes $f(E, E_\mathrm{in})|_{50\text{ nm}, 0°}$

Transformation algorithm

- Simulation N_sim → $\mathrm{hist}(\mathrm{E}_i)|_{E_\mathrm{in}, p_1, p_2, \ldots}$
- Spline interpolate → $f(\mathrm{E})|_{E_\mathrm{in}, p_1, p_2, \ldots}$
- Shape interpolate → $f(E, E_\mathrm{in})|_{p_1, p_2, \ldots}$
- Repeat for p_i → $f(E, E_{in}, p_1, p_2, \ldots)$

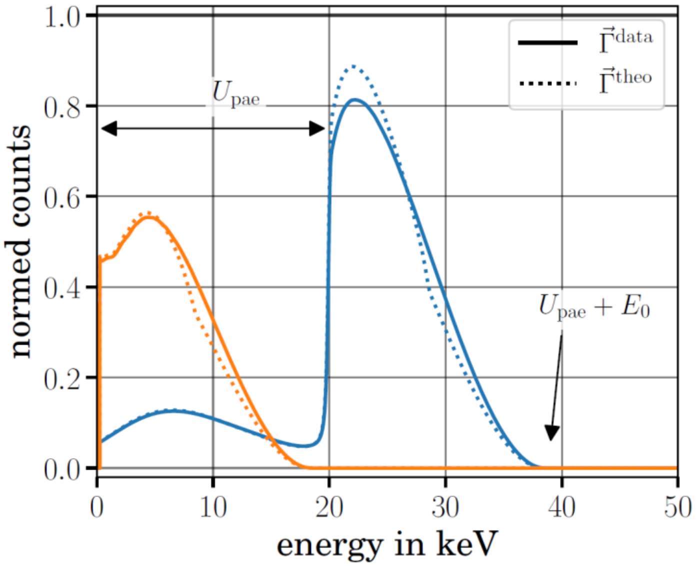
- Function of $f(E) \equiv f\left(E, E_\mathrm{in}, z_\mathrm{dl}, \vartheta_\mathrm{p,in}\right)$
- 21k simulations each 10^7 electrons

Detector response



- Energy deposition: $E = E_{\text{in}} - E_{\text{dl}} - E_{\text{bs}}$
- Charge creation: $E \rightarrow \mathcal{N}(\mu = E, \sigma \propto \sqrt{E})$
- Charge sharing: $E \rightarrow (E_1, E_2),\ E = E_1 + E_2$
- Electronic noise: $E \rightarrow \mathcal{N}(\mu \propto E, \sigma = \text{const.})$
- Signal pile up: $(E_1, E_2) \rightarrow E = E_1 + E_2$

Sensitivity – framework



- $m_4 \in [0{,}20\ \text{keV}]$
- $\sin^2\theta_4 \in [10^{-2}, 10^{-8}]$

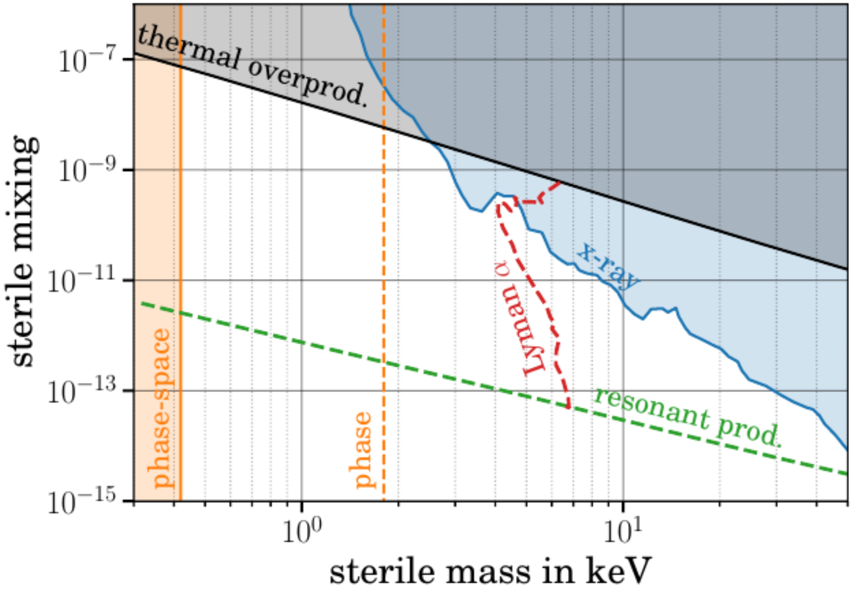
<u>Model</u>: $\Gamma \equiv \Gamma_\beta \times f_{bs}$

- Tritium β-decay: $\Gamma_\beta \equiv \Gamma_\beta(E - U_{\text{pae}}, m_4, \sin^2\theta_4)$,
  with acceleration U_{pae}, sterile mass m_4 & mixing $\sin^2\theta_4$
- Energy deposition: $f_{bs} \equiv f_{bs}(z_{\text{dl}}, \vartheta_{\text{p,in}})$,
  with detection deadlayer z_{dl} & incidence angle $\vartheta_{\text{p,in}}$

<u>Sensitivity</u>: $\chi^2 = \vec{\text{r}} \cdot \mathbf{cov}^{-1} \cdot \vec{\text{r}}$ (@90CL)

- Chi-square: $\chi^2 \equiv \chi^2(m_4, \sin^2\theta_4\, | R_{\text{det}}, R_{\text{bkg}}, E_0)$,
  marginalization over rates $R_{\text{det}}/R_{\text{bkg}}$ and endpoint E_0
- Residuals: $\vec{\text{r}} \equiv \vec{\Gamma}^{\text{data}}(0\ \text{keV}, 0) - \vec{\Gamma}^{\text{theo}}(m_4, \sin^2\theta_4)$
  using asimov data and $f_{\text{bs}}^{\text{data}} \equiv f_{\text{bs}}^{\text{theo}}$
- Covariance: $\text{cov} \equiv \text{cov}[\vec{\Gamma}_1^{\text{data}}, \vec{\Gamma}_2^{\text{data}}, \dots]$,
  with syst. uncertainties $\Gamma_i^{\text{data}} \equiv \Gamma^{\text{data}}(z_{\text{dl},i}, \vartheta_{\text{p,in},i})$

BACKUP – sterile neutrino dark matter constraints



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