Sensitivity to Neutrino Mass and Secondary Physics of the Project 8 Experiment

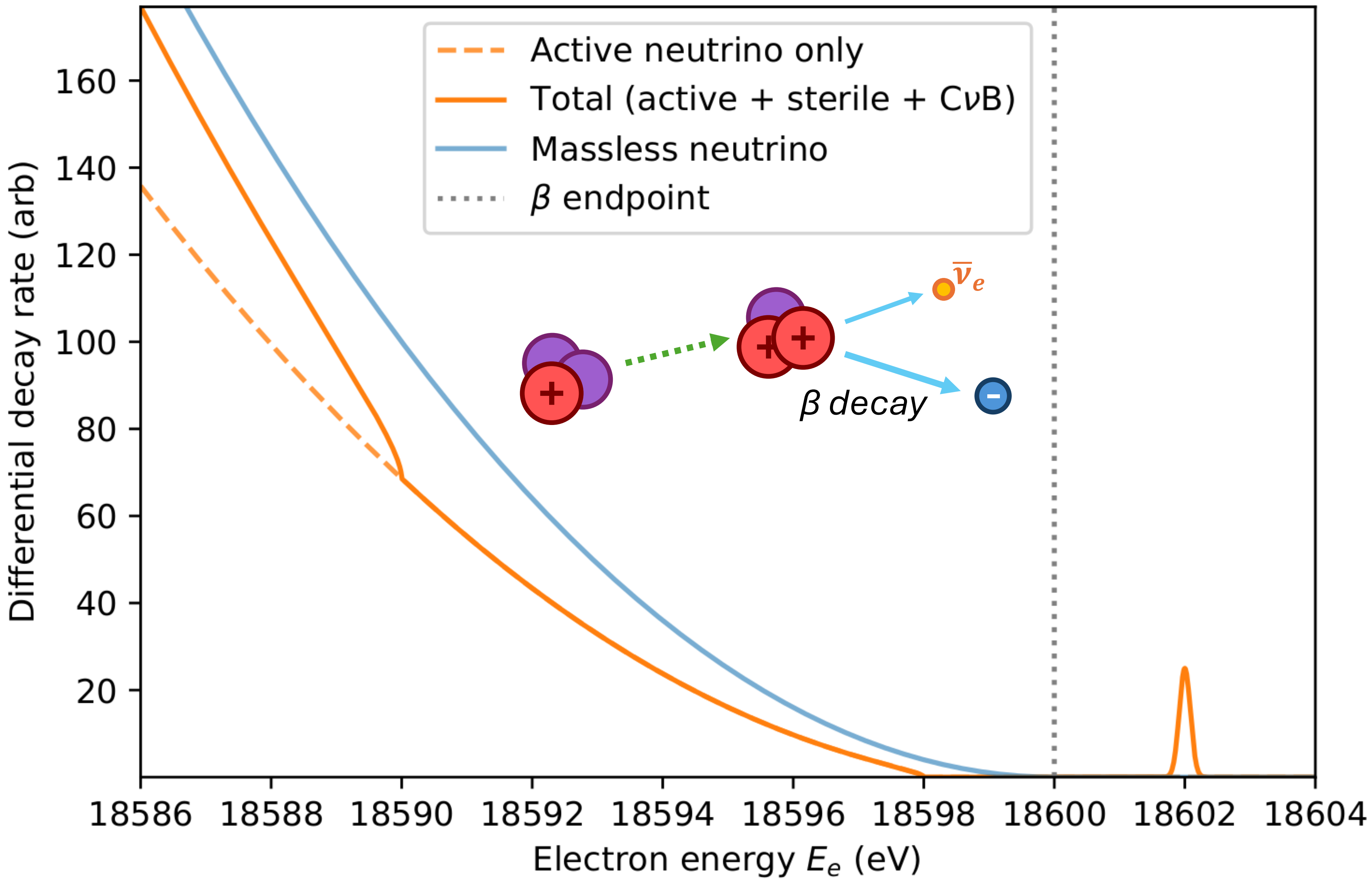
Chi-Ho Lam on behalf of the Project 8 Collaboration

PHENO 2026

May 11, 2026

One β-spectrum to rule them all

Scale exaggerated for illustrative purposes



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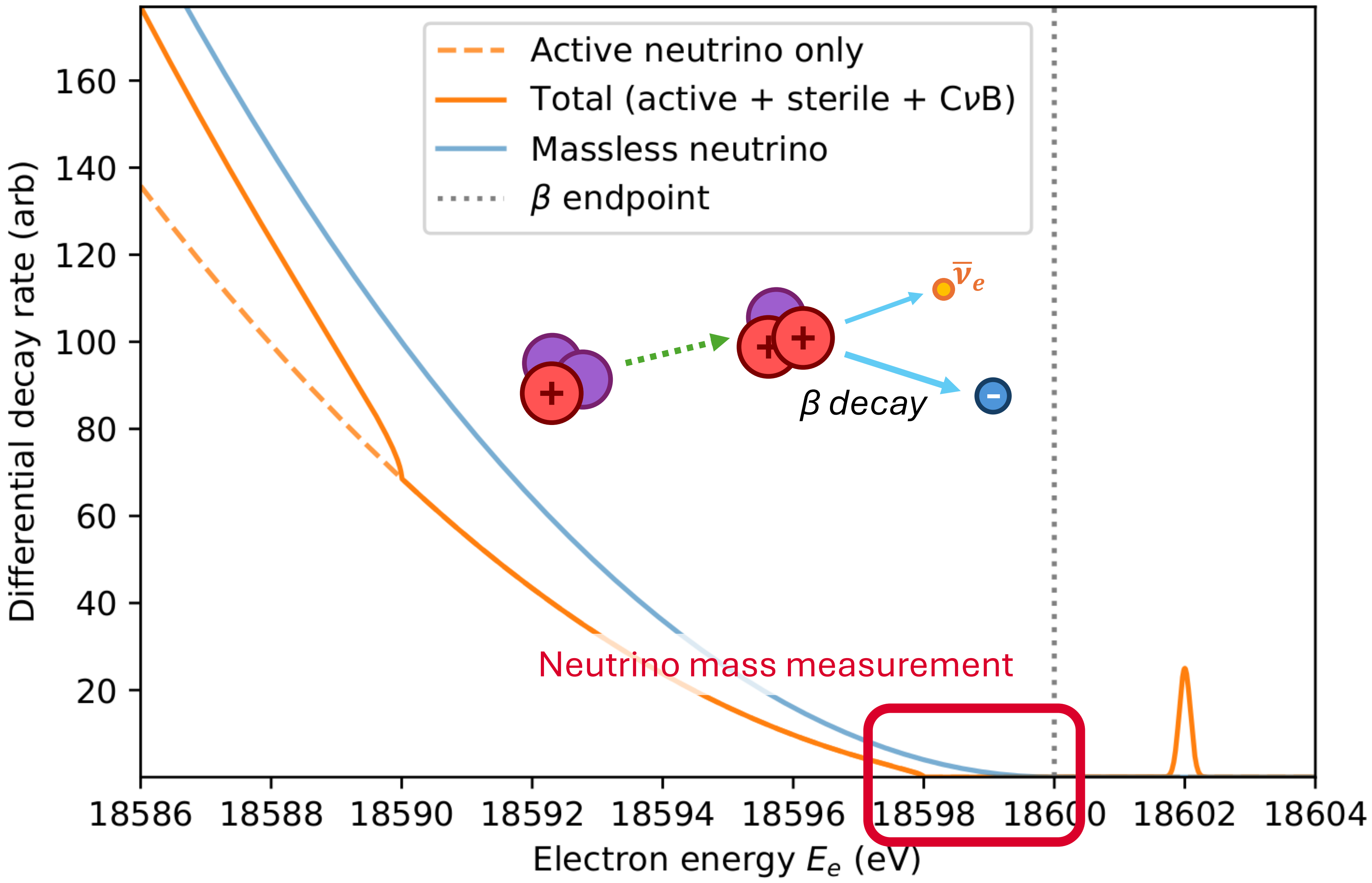

Project 8: probing neutrino mass with Cyclotron Radiation Emission Spectroscopy (CRES)

- Goal: Determine **neutrino mass from tritium β-spectrum**

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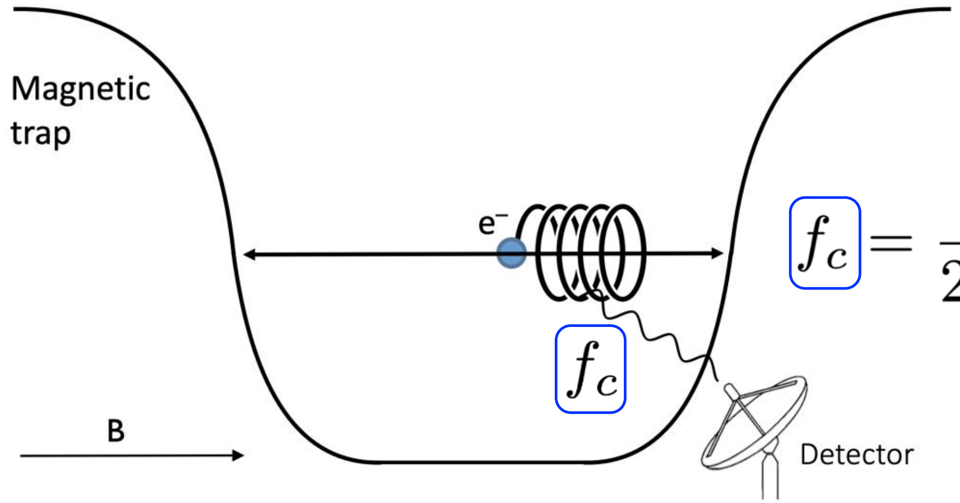

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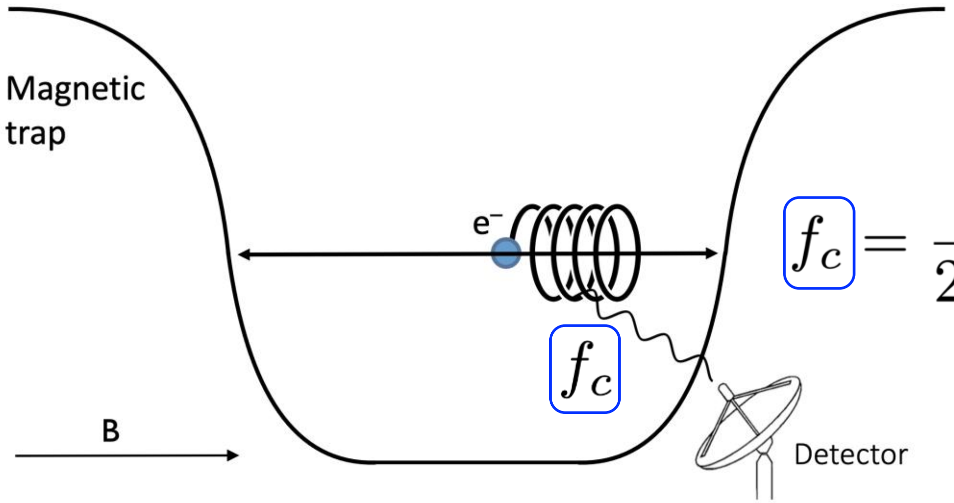

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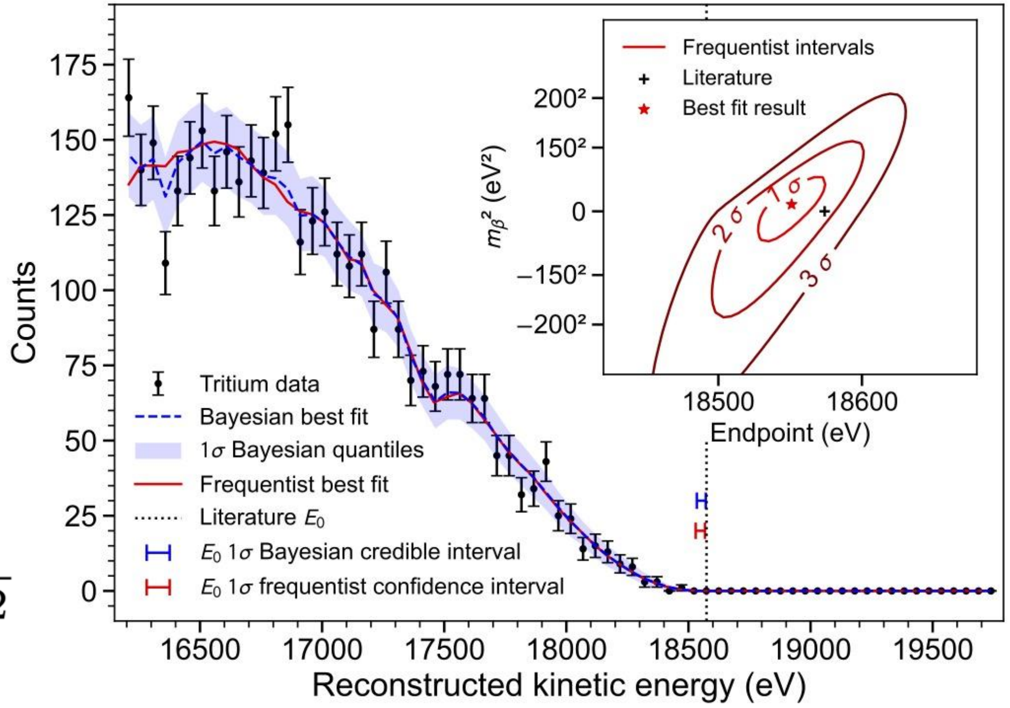
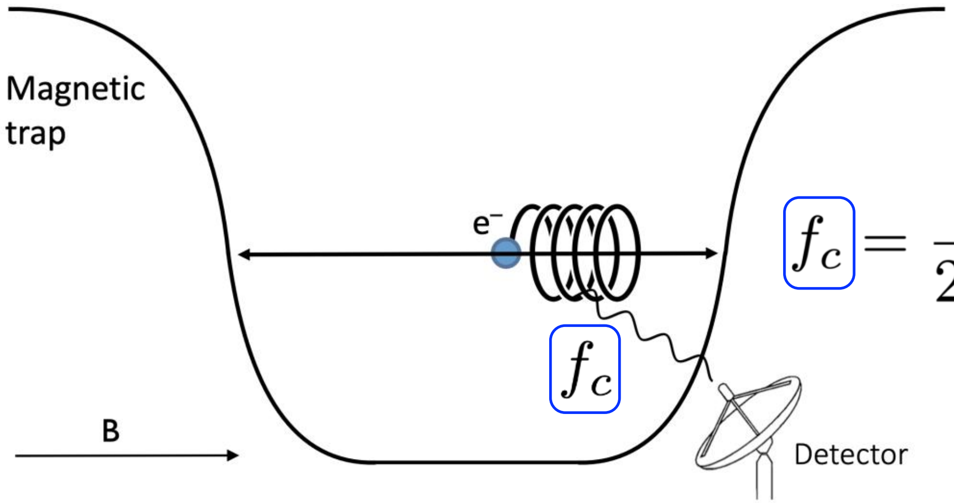
Phys. Rev. Lett. ***131****, 102502*



Project 8: probing neutrino mass with Cyclotron Radiation Emission Spectroscopy (CRES)

- Goal: Determine **neutrino mass from tritium *β*-spectrum**
- Phase II (past): Limit on m_β with CRES.
- Phase III (ongoing): Combine CRES with atomic tritium source – Low-Frequency Apparatus (LFA)
- **Phase IV (future): Reach m_β < 40 meV (90% C.L.)**



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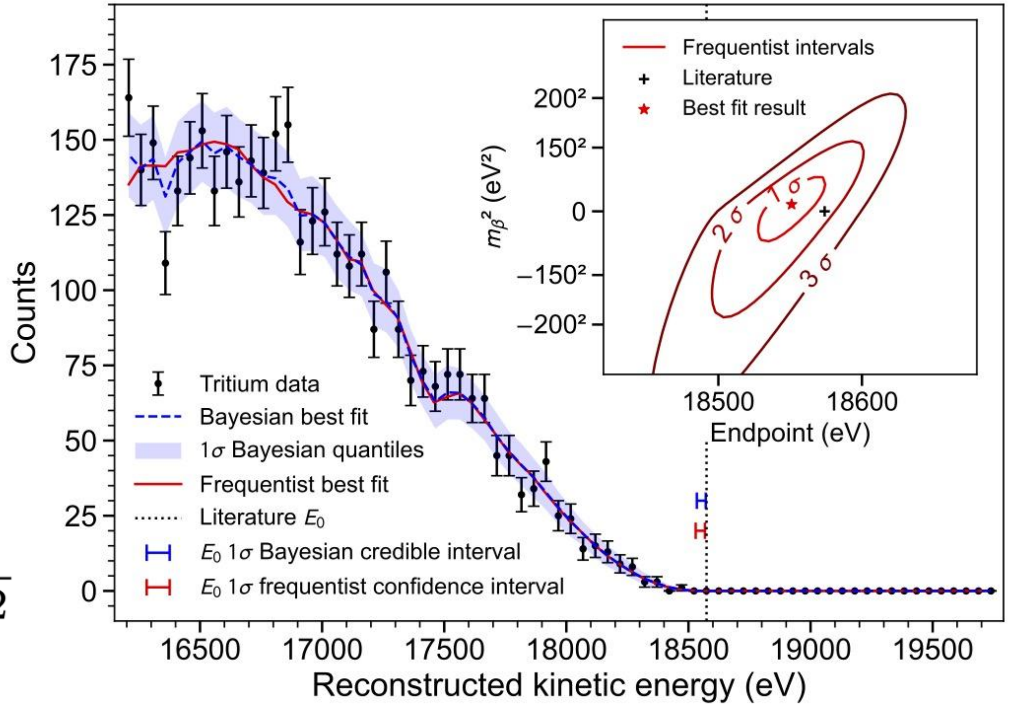
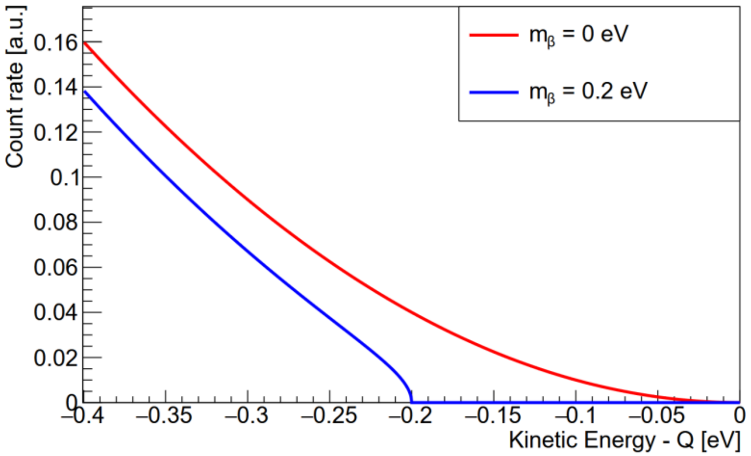


Analytic model of Project 8 sensitivity

See Physics Reports 914, 1-54 (2021)



Set-up: To estimate m_β, imagine we count events in window ΔE near endpoint.

- Fewer events in ΔE → we know m_β is larger.
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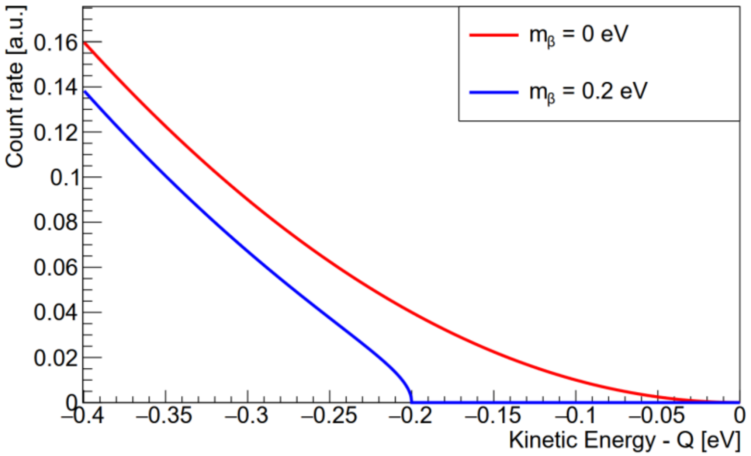

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Uncertainty on m_β^2:

$$\sigma_{m_\beta^2} = 4\sqrt{\frac{1}{(6\, C_T\, V_{\text{eff}}\, n\, t)^2}\left[C_T\, V_{\text{eff}}\, n\, t\, \Delta E + \frac{b\, t}{\Delta E}\right] + \sum_i \sigma_i^2(n) \cdot \delta\sigma_i^2}$$

Source gas density

Uncertainties on response function

Effective volume (Volume × Efficiency)

Runtime

Background

Response function stdevs (resolution)

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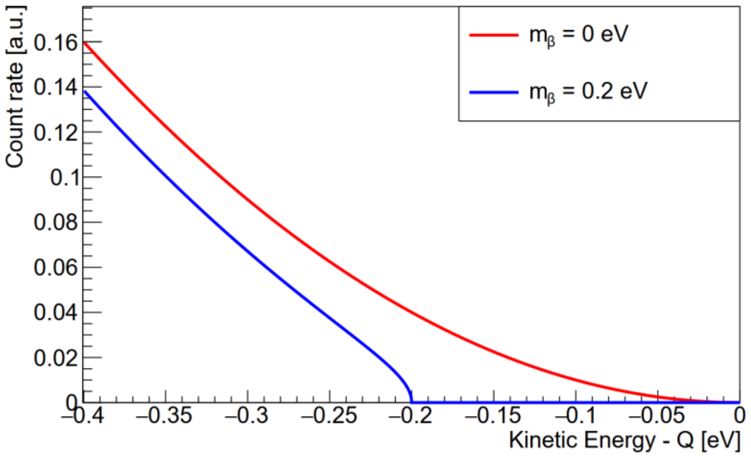

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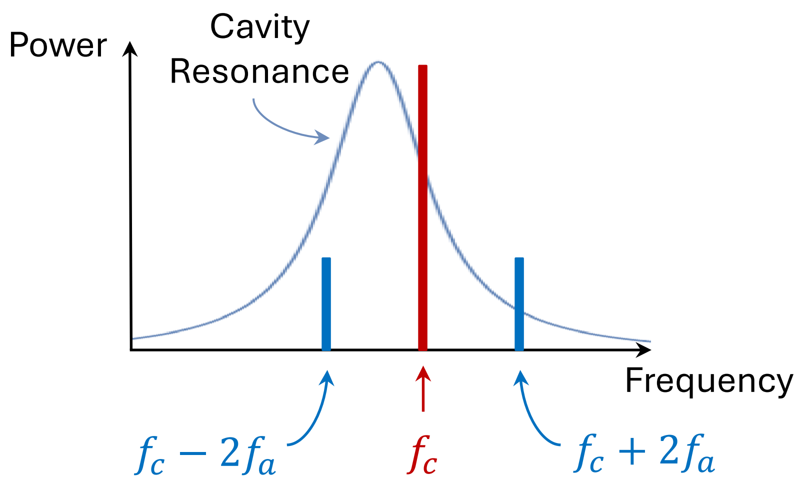
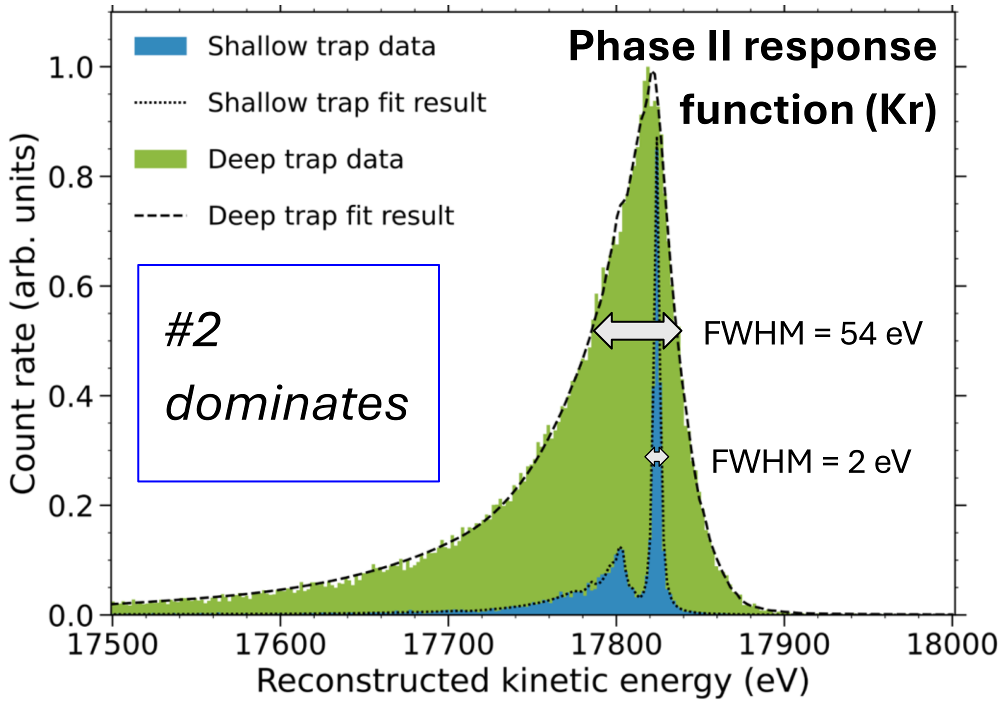
If best fit m_β^2 is zero:

$$Upper\ limit(m_\beta)\ \ [90\%\ \text{C.L.}] = \sqrt{1.64\sigma_{m_\beta^2}} \quad \longrightarrow \quad \sim (\textbf{signal rate})^{-1/4}$$

Contributions to response function (energy resolution): σ_i

1. **Frequency resolution from noise for frequency reconstruction**





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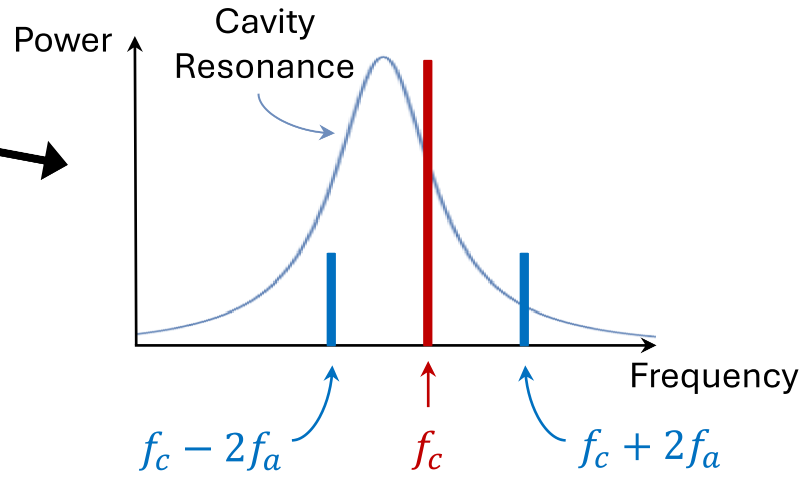

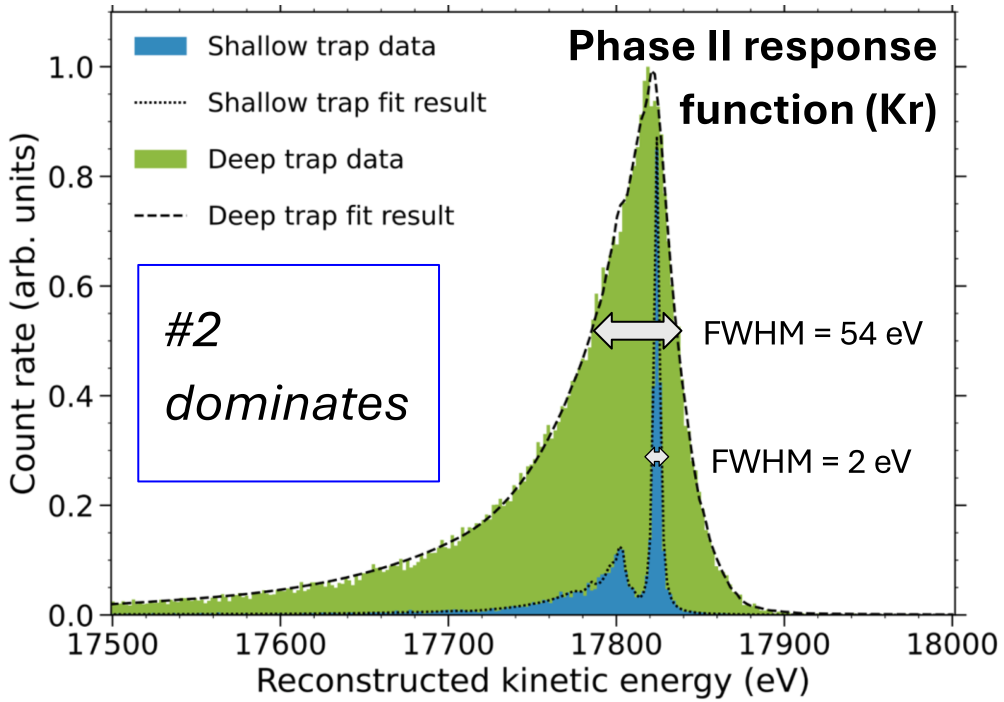

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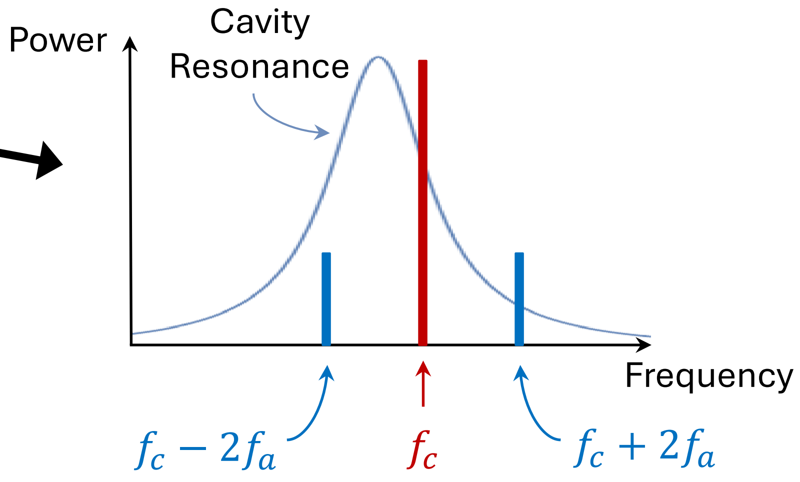

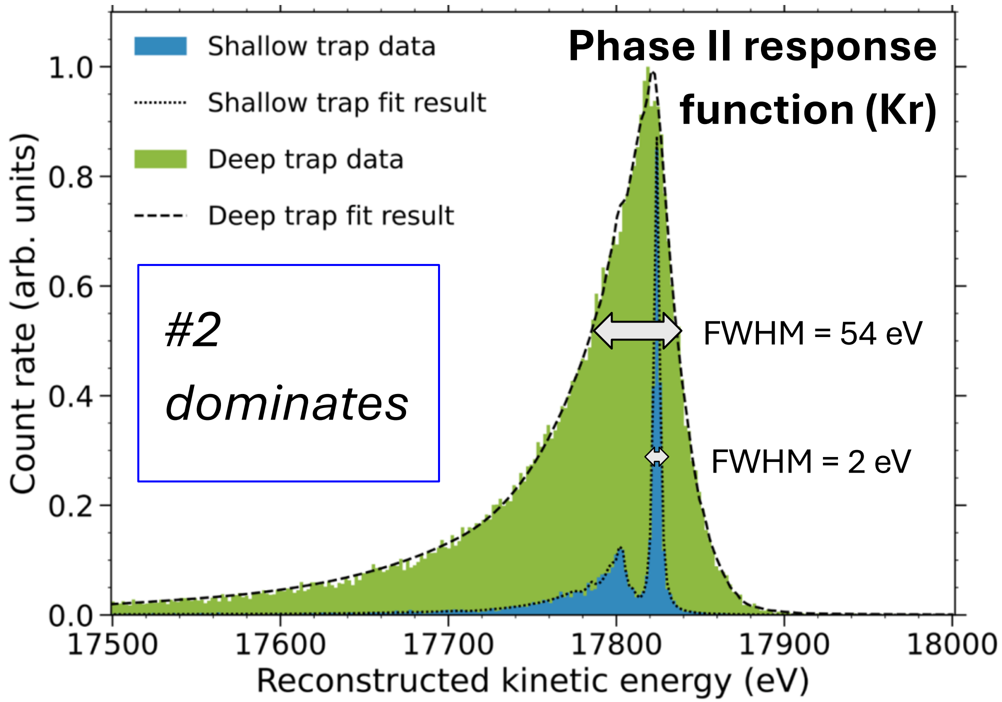

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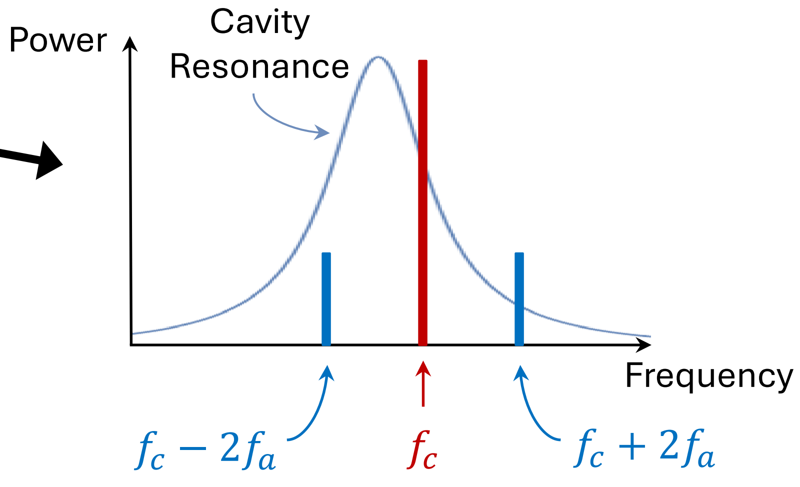

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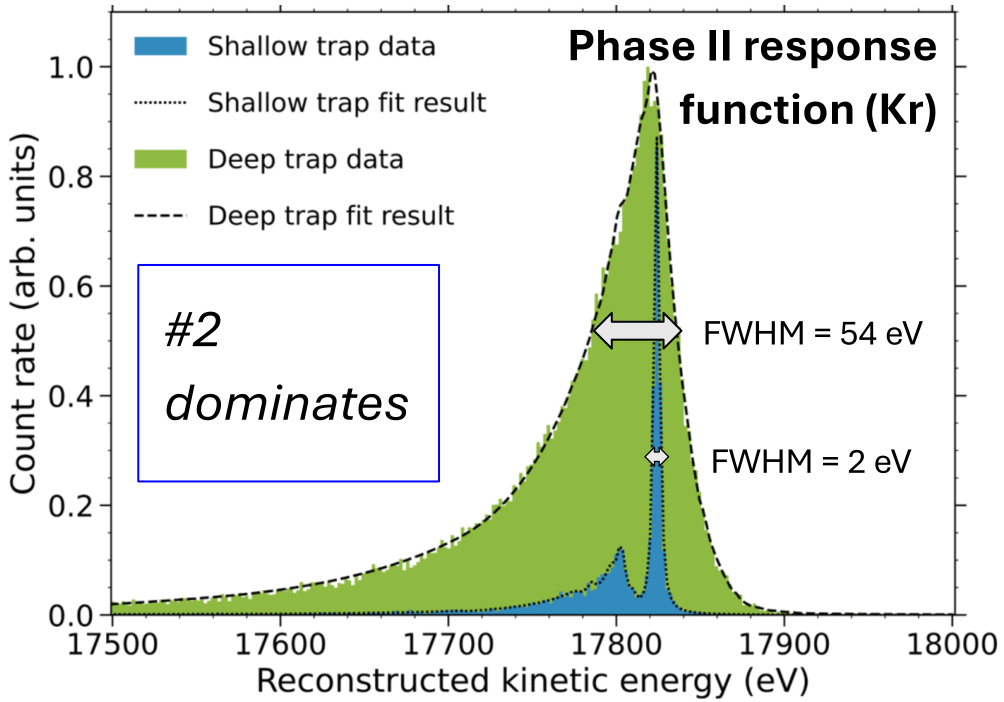

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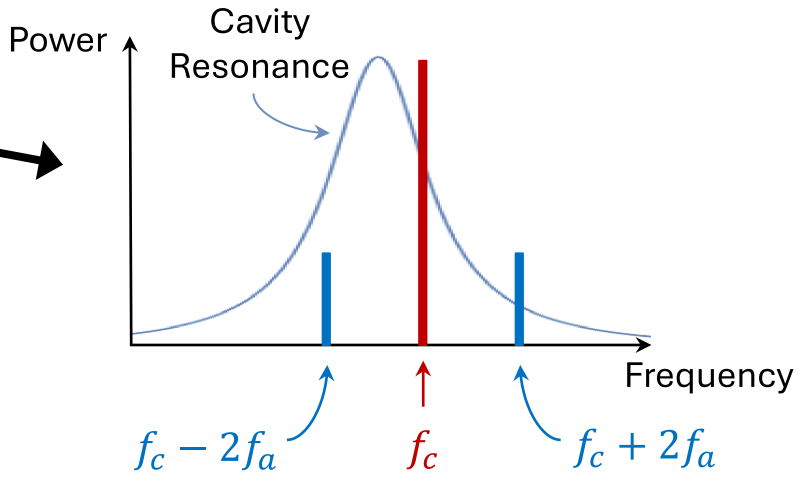

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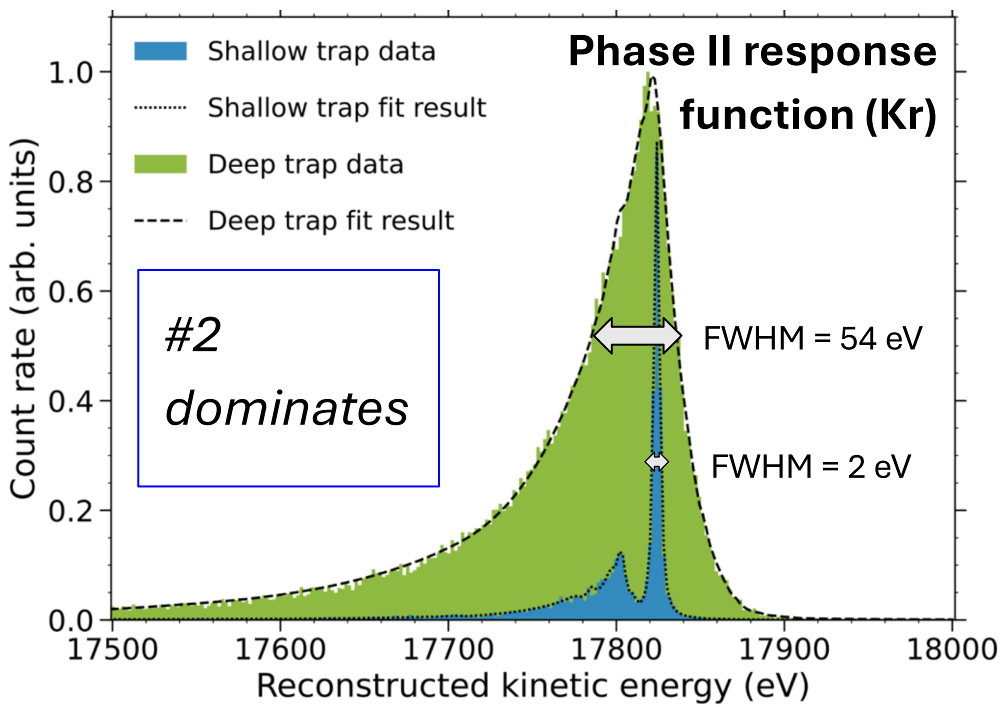

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Contributions to response function (energy resolution): σ_i

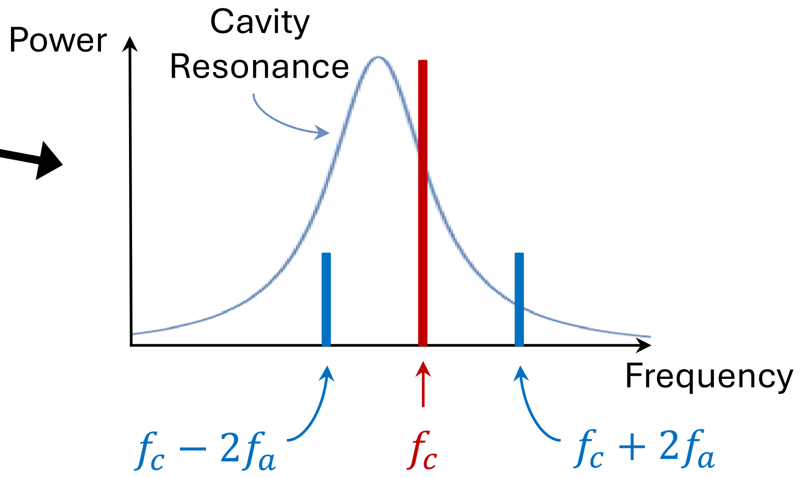
1. **Frequency resolution from noise for frequency reconstruction**

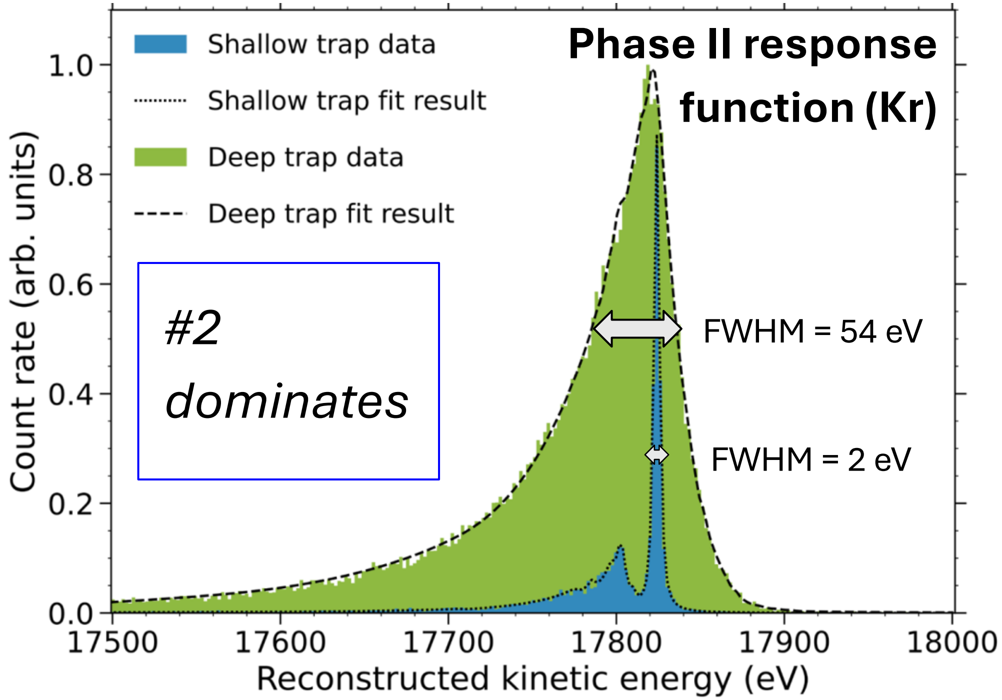
2. **B-field variation and energy reconstruction**

3. **Thermal Doppler broadening**

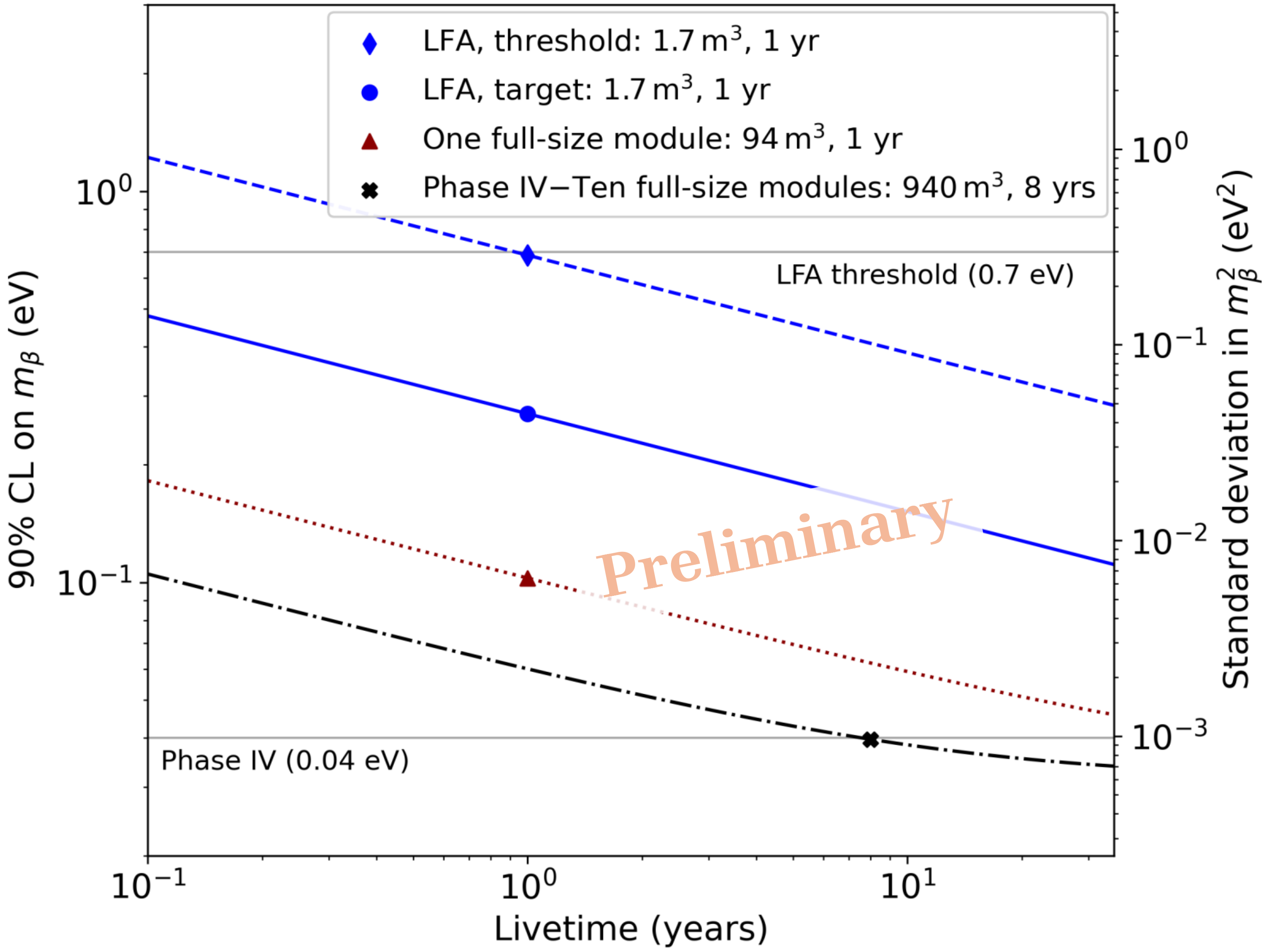
4. **Work to make sub-dominant:**
   Scattering, plasma effects; efficiency vs. energy; mis-reconstruction due to pileup.

Aim to calibrate all to ~2% precision ($\frac{\delta\sigma_i^2}{\sigma_i^2}$).





Project 8 sensitivity to neutrino mass



Example Phase IV scenario:

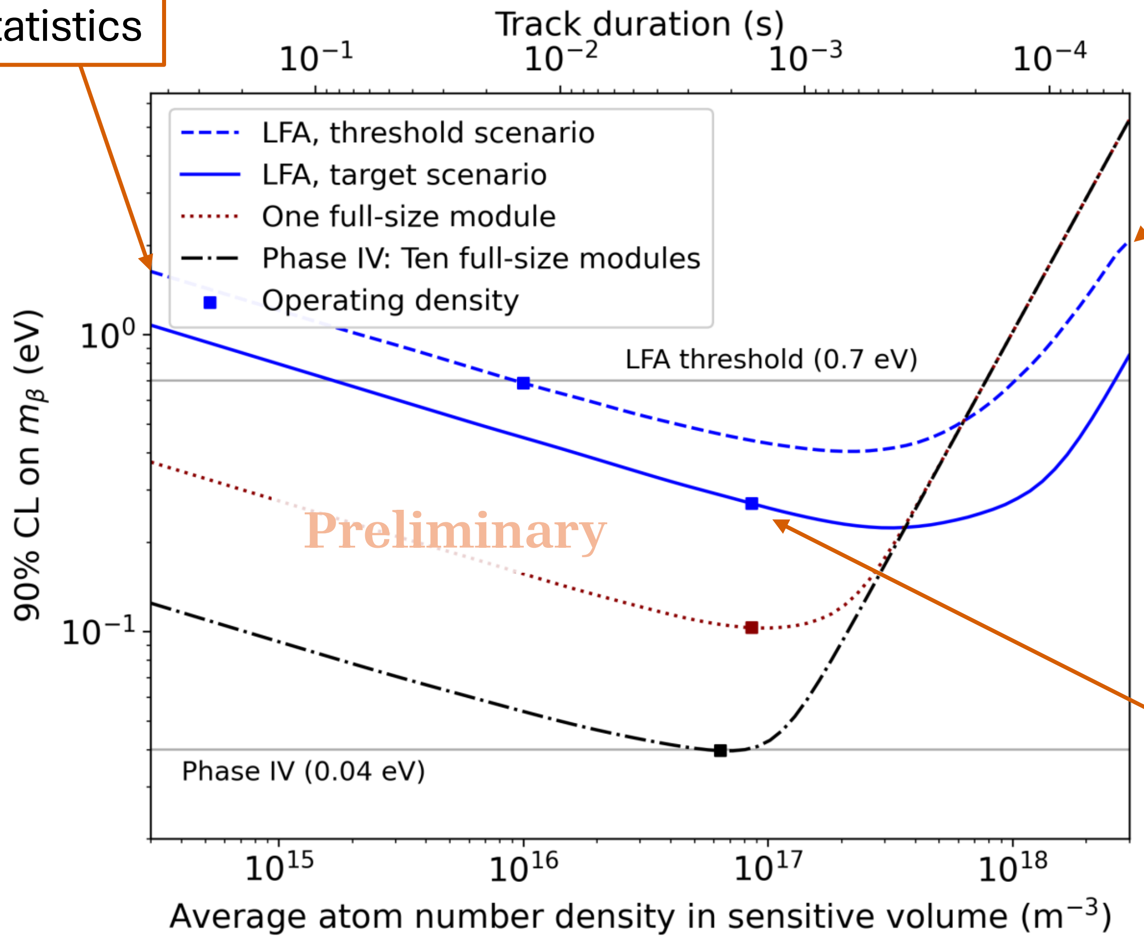
- Total cavity volume = ~1000 m^3
- TE011 mode at 150 MHz
- Livetime = 8 yrs
- Background field = 5.5 mT
- Trap length = 17.5 m
- Cavity temperature = 2 K
- Resolution contribution from magnetic field variation and reconstruction = 85 meV

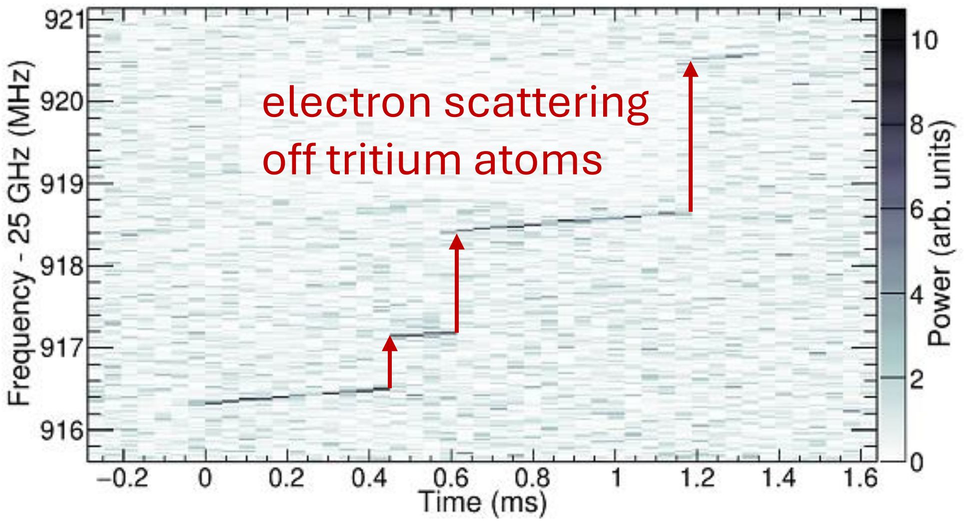
Current R&D effort at cavity design on improving energy resolution!

Example parameter optimization: source gas density (n)

Low density
⇒ few decays
⇒ poor statistics

High density
⇒ frequent collisions
⇒ short CRES tracks
⇒ poor resolution and
detection efficiency

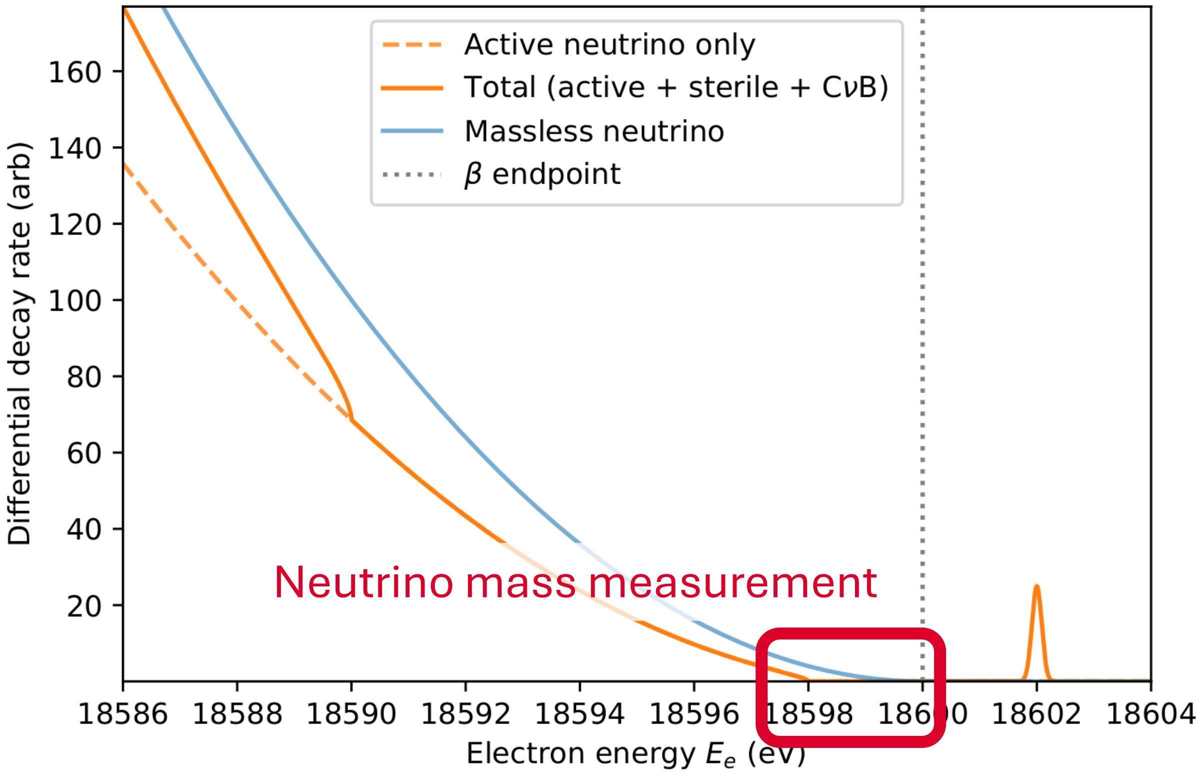




Operating densities are below optima, to reduce atom current flow requirements

Secondary physics at Project 8

- With the low background, good resolution, and high event rate targeted by Project 8 Phase IV, we can explore more than just neutrino mass



- Side quests that also make use of the differential beta decay spectrum as observable

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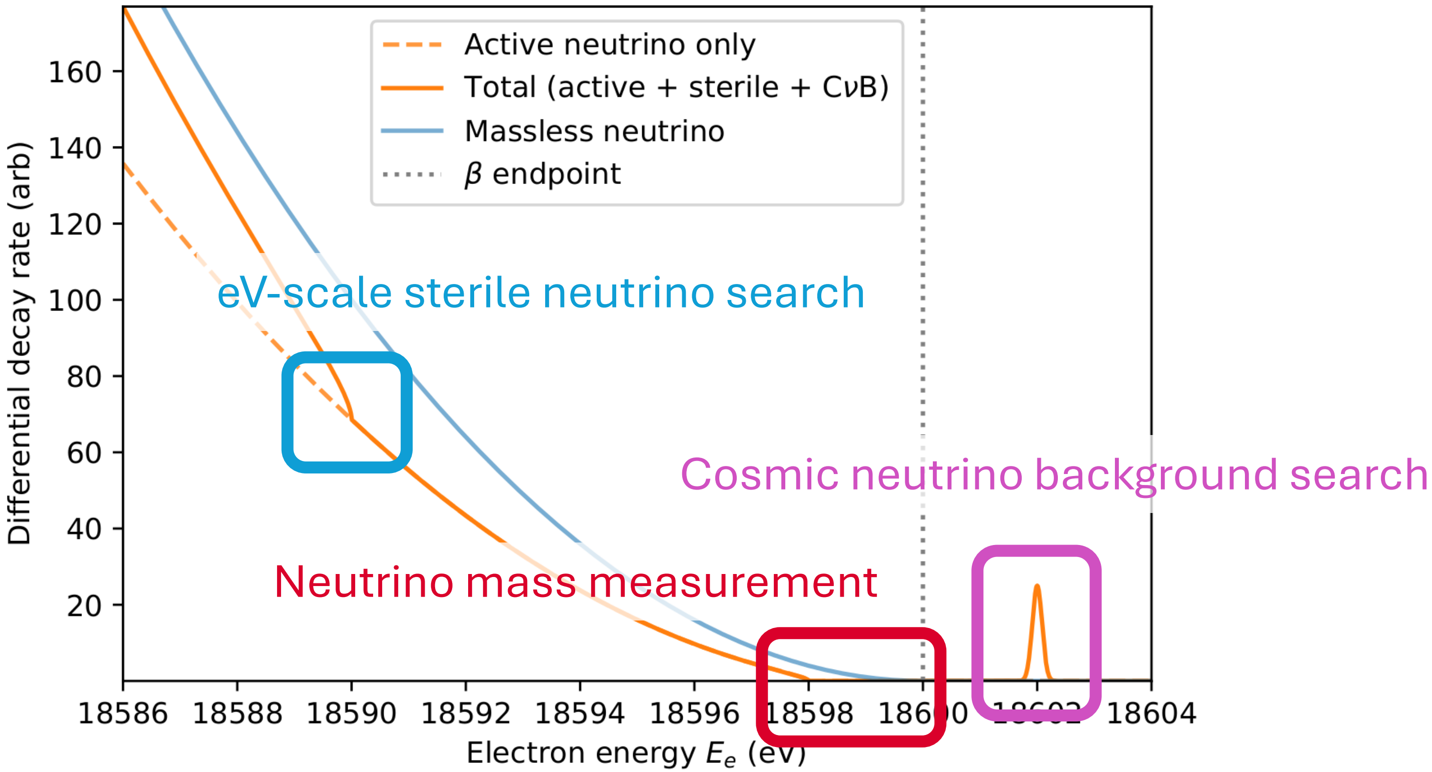


- Side quests that also make use of the differential beta decay spectrum as observable

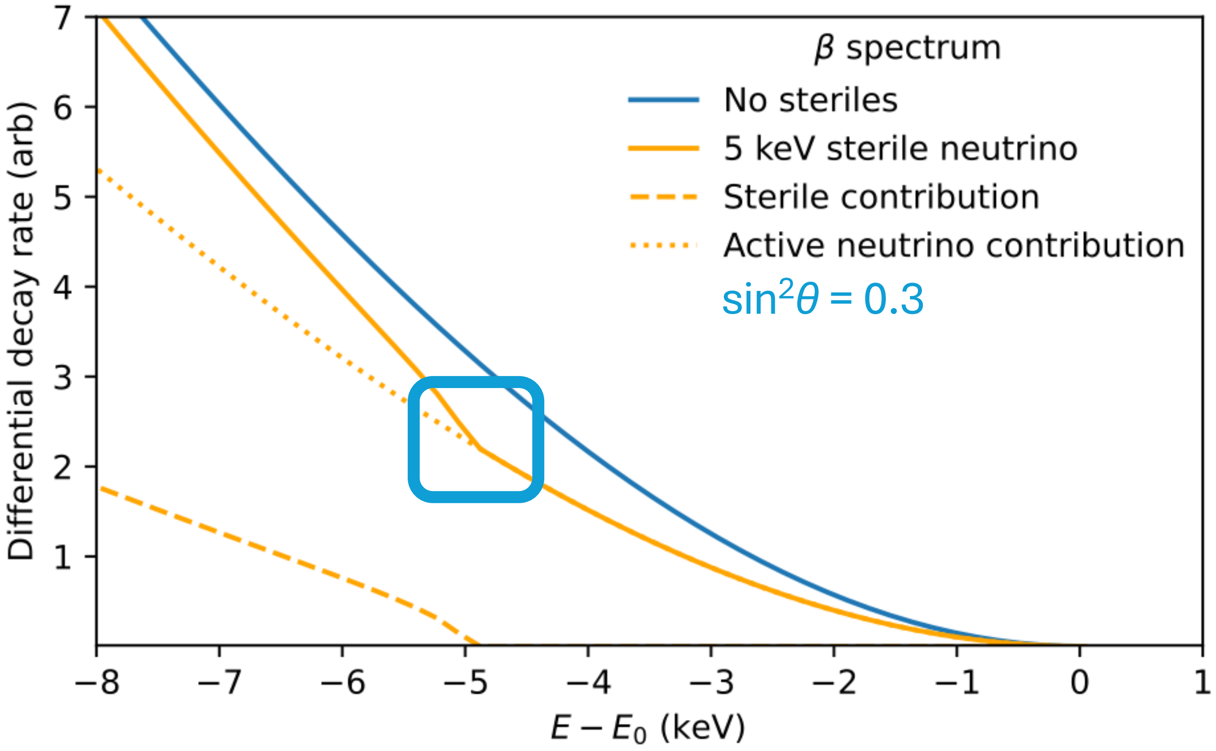
eV-scale sterile neutrino

- Additional sterile neutrino state mixes with the active flavors with a small mixing angle θ
- Appears as a **distortion/kink** in β-spectrum
- Location depends on mass of sterile state m_4
- Amplitude proportional to the mixing element

$$|U_{e4}|^2 = \sin^2\theta$$

active sterile

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} \propto p_e E_e \left[\left(1-|U_{e4}|^2\right) F\left(E_e, m_\beta\right) + |U_{e4}|^2 f\left(E_e, m_4\right)\right]$$



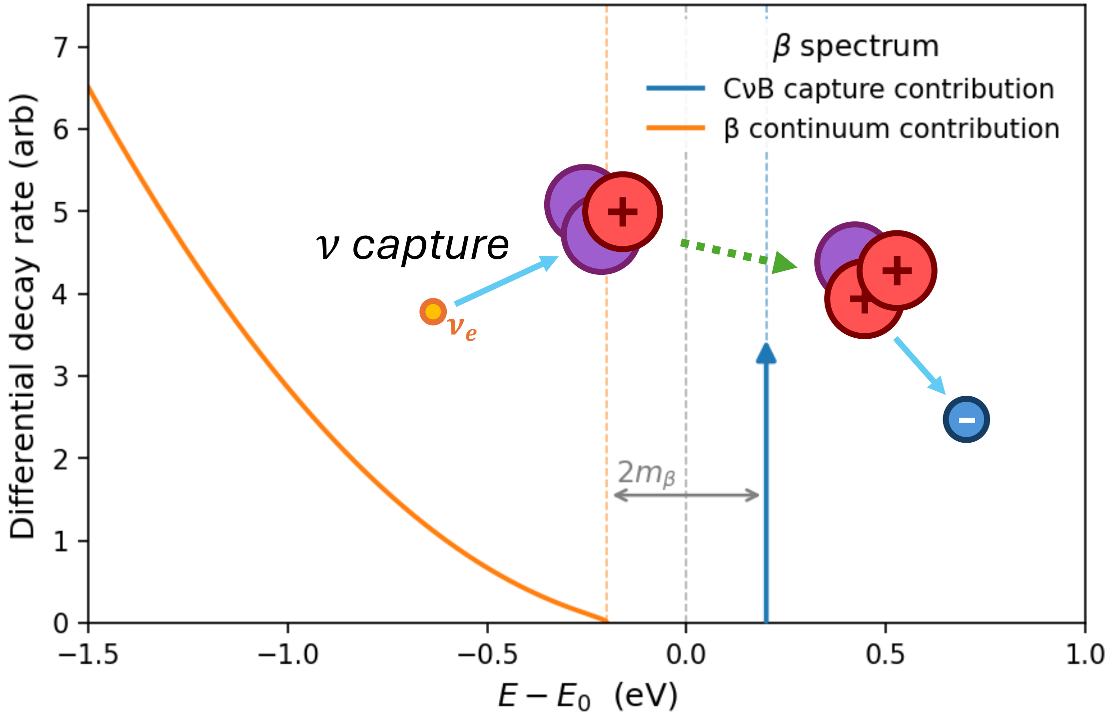
Cosmic neutrino background (CνB)

- Relics from neutrino decoupling as the universe cools down after the Big Bang
- Define overdensity $\eta = \frac{n_{\text{loc}}}{n_0}$
  - Average density $n_0 = 56/\text{cm}^3$
  - Gravitational clustering with local density n_{loc}
- (Very rarely) via ν capture: $\nu_e + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$
- Appears as **monoenergetic peaks** at $2m_i$ above maximum beta energy for each eigenstate
- Capture rate proportional to η

$$\Gamma_{\text{cap}} = n_{\text{loc}}\bar{\sigma}v_{\text{rel}} = n_0\eta\bar{\sigma}v_{\text{rel}}$$

β decay CνB capture

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} \propto p_e E_e (E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m_\beta^2} + \Gamma_{\text{cap}}\delta(E_e - E_0 - m_\beta)$$



Spectral shape simplified

Hypothesis testing

	Null hypothesis H_0	Alternative hypothesis H_1
Sterile neutrino	$(m_4^2, \|U_{e4}\|^2 = 0)$	$(m_4^2, \|U_{e4}\|^2)$
CνB	$(m_{\text{lightest}}, \eta = 1)$	$(m_{\text{lightest}}, \eta)$

- **Model**

$$\mu_i(\vec{\theta}) = A_\beta \cdot N_\mathrm{T} \cdot S_i(\delta E_0, \sigma_E) + A_\mathrm{b} \cdot \Gamma_\mathrm{b} \cdot t \cdot \Delta E$$

Smeared electron energy spectrum

where $\vec{\theta} = (\vec{\mu}_{\text{sig}}, \vec{\eta})$ ← Nuisance parameters

Parameters of interest ↑

$$\vec{\eta} = (A_\beta, A_{\text{bkgd}}, \sigma_E, \delta E_0)$$

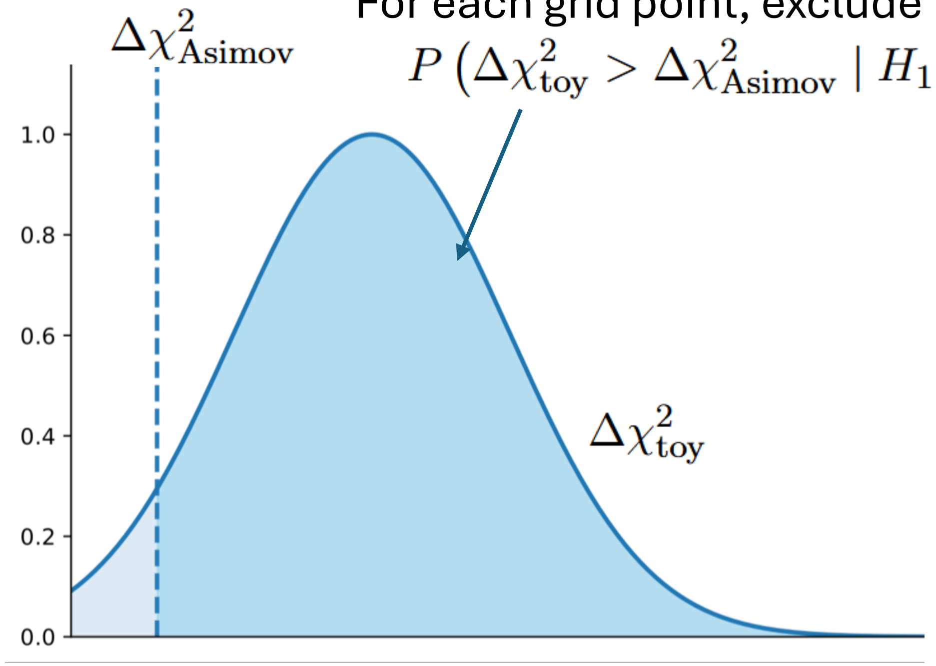
- **Profiled test statistic**

$$\Delta\chi^2_{\text{prof}} = \chi^2_{\text{BC}}(H_0, \hat{\vec{\eta}}_{H_0}) - \chi^2_{\text{BC}}(H_1, \hat{\vec{\eta}}_{H_1})$$

- Scan over parameter space using
  - **Asimov dataset** under null hypothesis
  - **MC datasets** under alternative hypothesis with sampled nuisance parameters

For each grid point, exclude if

$$P\left(\Delta\chi^2_{\text{toy}} > \Delta\chi^2_{\text{Asimov}} \mid H_1\right) \geq 0.95$$



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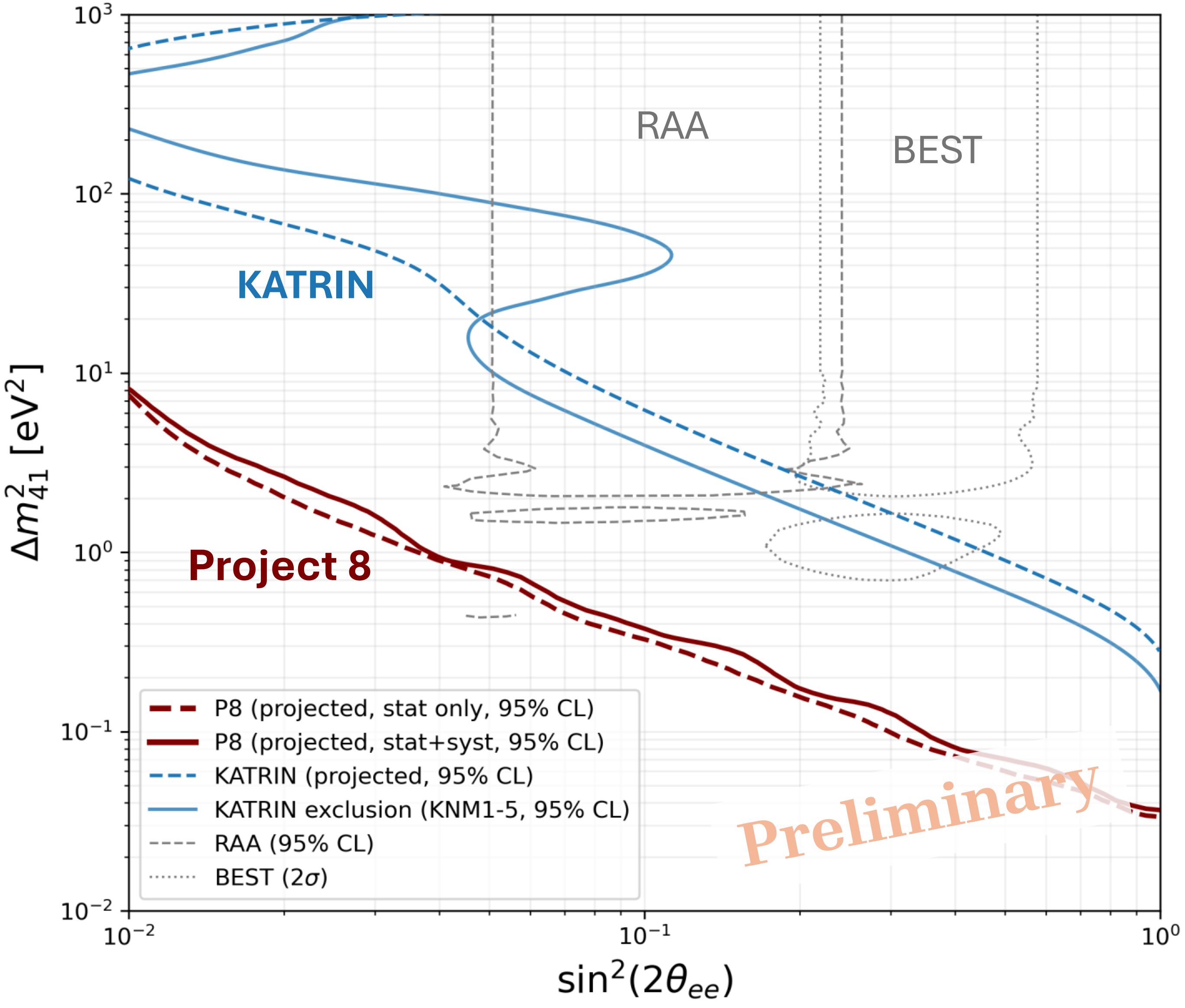
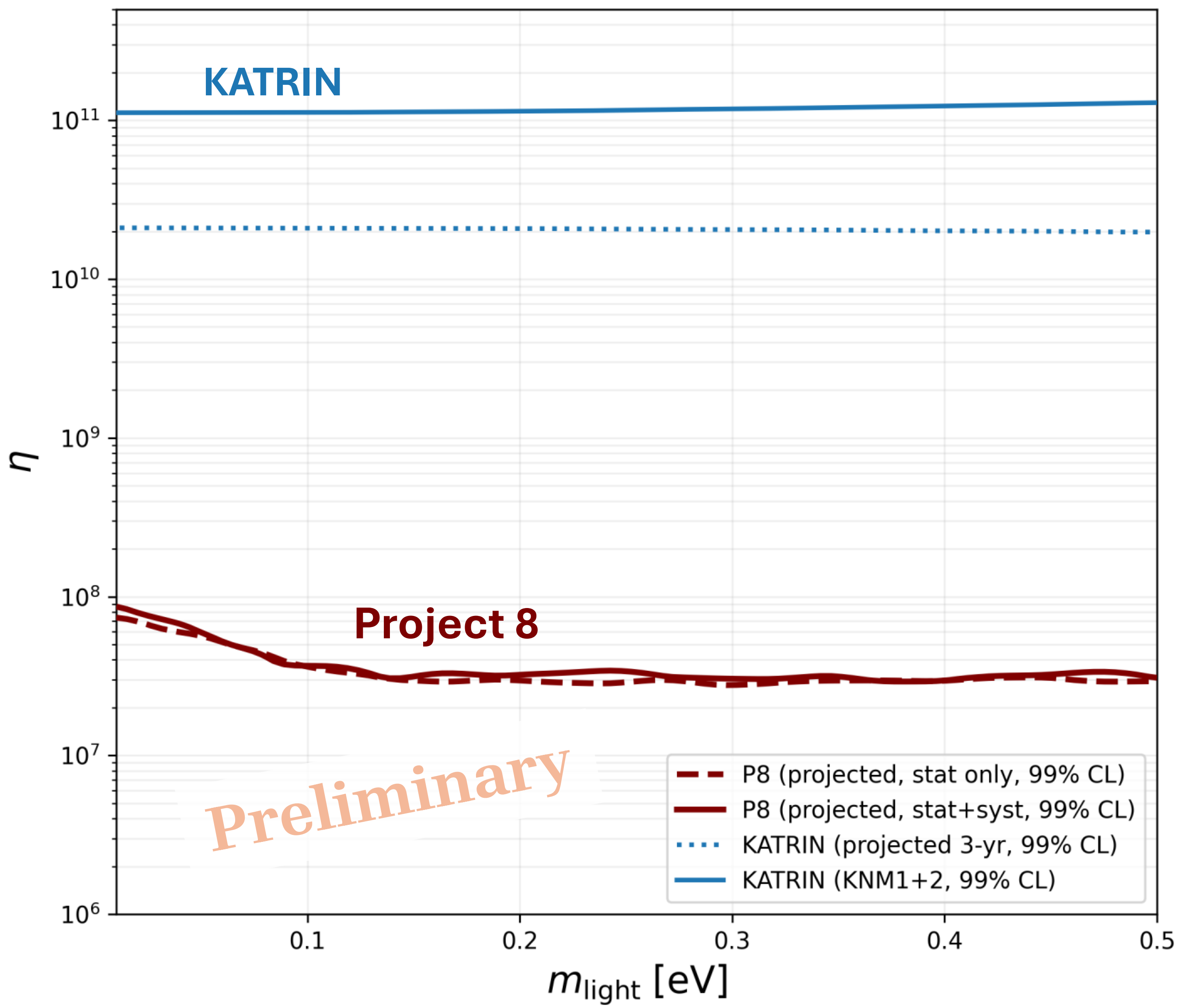


Cosmic neutrino background (CνB)



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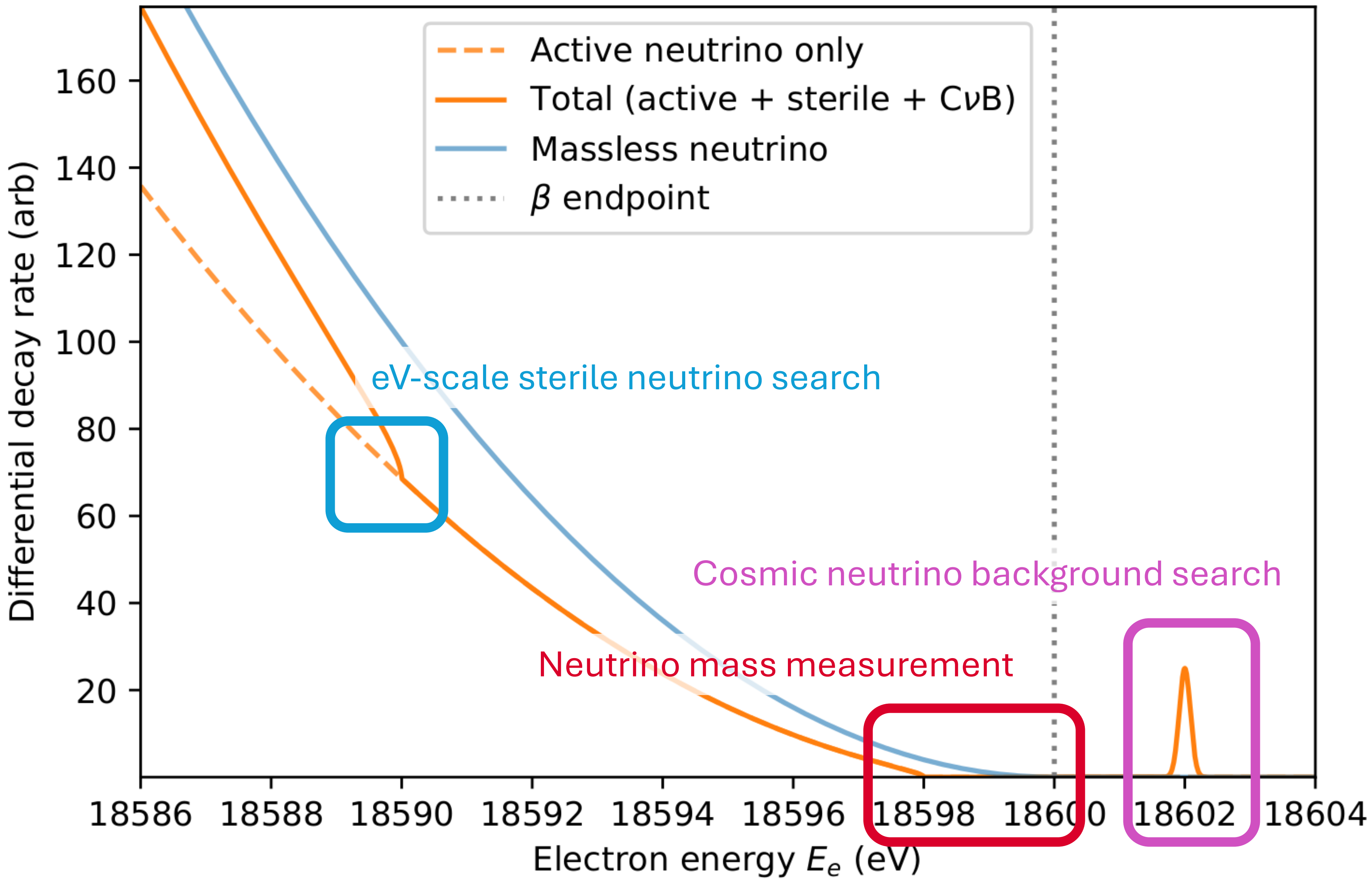

Summary

- Project 8 is targeted to reach a neutrino mass sensitivity of **m_β < 40 meV (90% C.L.)** with tritium β-spectrum using CRES.
- Sensitivity depends on factors including the **field uniformity, atomic T current** etc. that we should optimize for **low background, good resolution, and high event rate.**
- We use an **analytic sensitivity model**, accounting for features of CRES signal detection in a **resonant cavity with trapped electrons.**
- We can inform the **objectives for R&D** for Phase IV to find a path to the ultimate sensitivity.
- With the scale expected for Phase IV, Project 8 is expected to push limits in secondary physics as well, such as **sterile neutrino** and **cosmic neutrino background.**

Thank you!

PROJECT 8

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