Sensitivity of nEXO to ^{136}Xe Charged-Current Interactions: Background-free Searches for Solar Neutrinos and Fermionic Dark Matter (arXiv:2506.22586)

TAUP: Neutrino Physics and Astrophysics - 8/26/25

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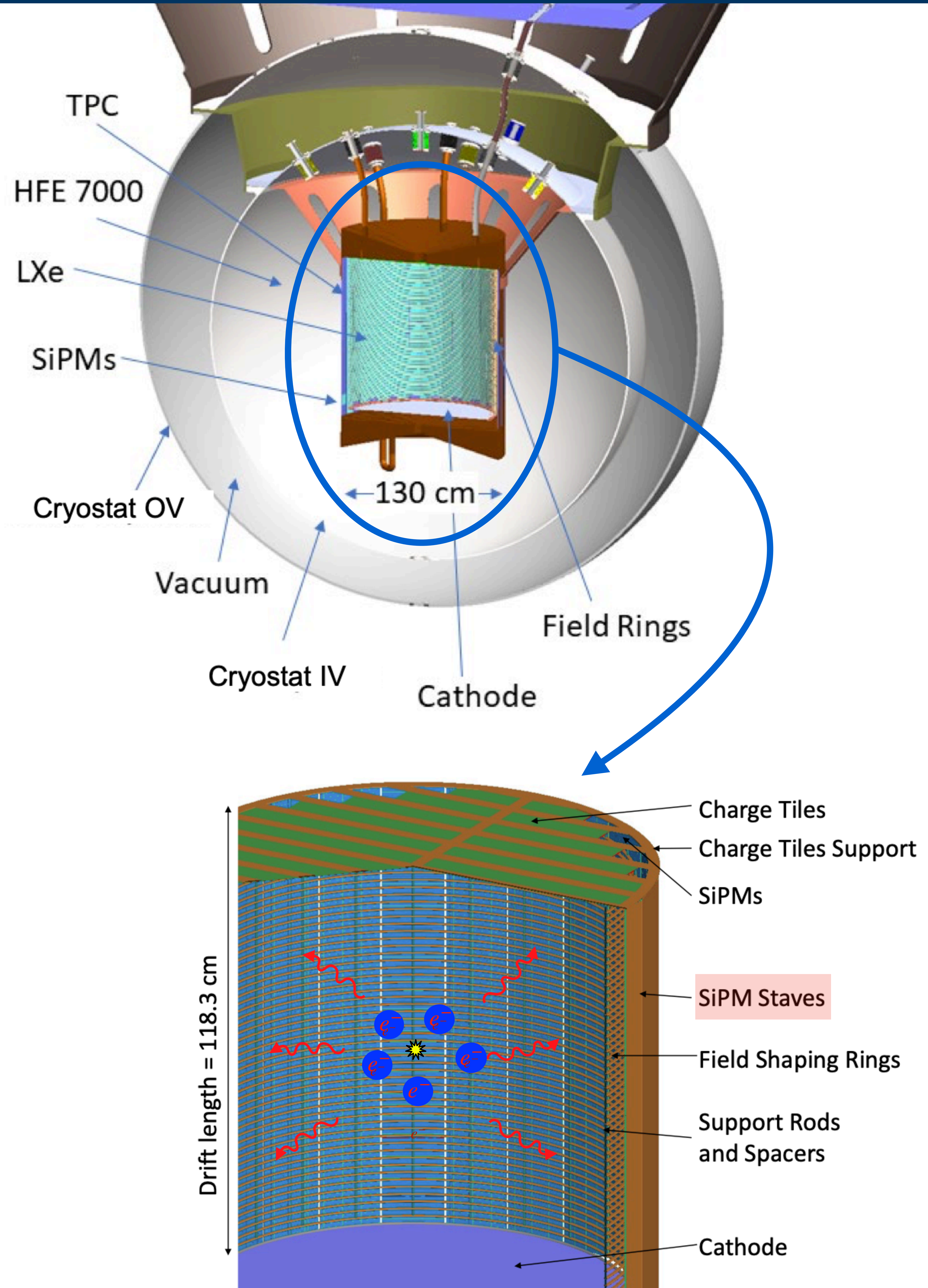
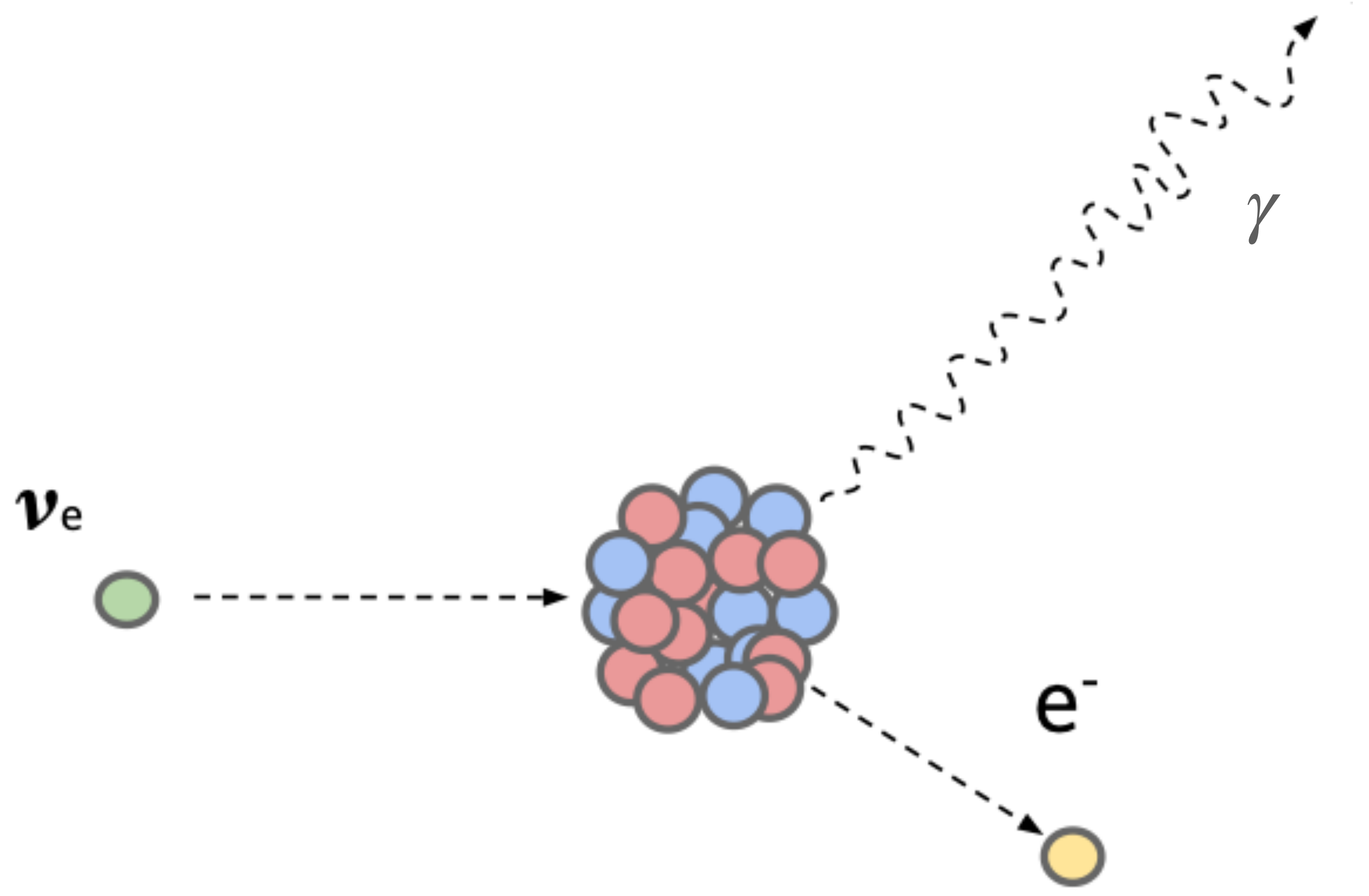
The nEXO Detector

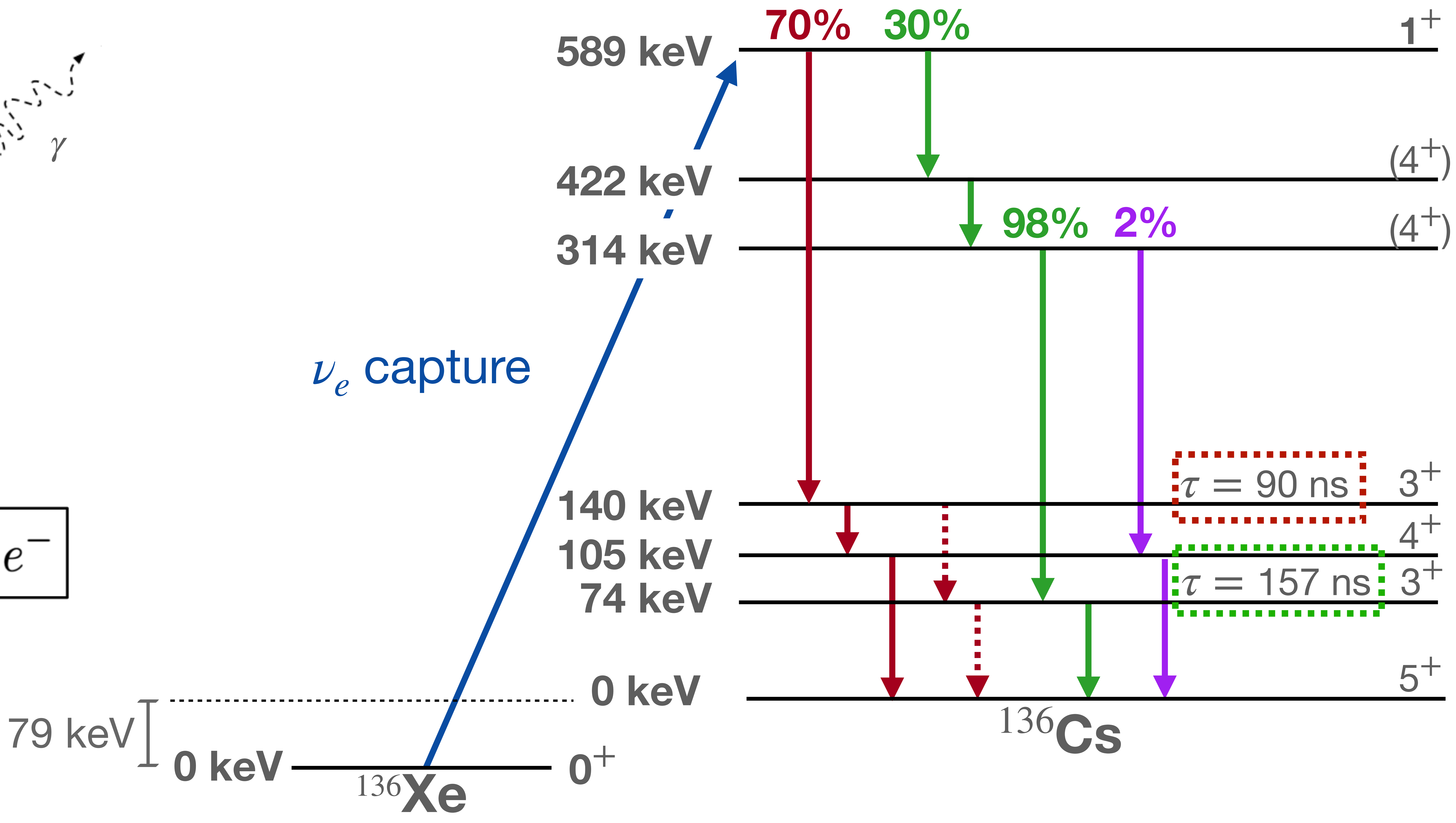
- Proposed 5 tonne LXe time projection chamber (TPC) enriched to 90% in ^{136}Xe
  - Search for $0\nu\beta\beta$ with sensitivity $T^{0\nu}_{1/2} > 10^{28}$ years
- Events will produce scintillation light and ionization electrons
  - Collected by the SiPM staves and charge collection tiles
  - Measures energy, position, topology, and timing of events



Charged Current Interactions

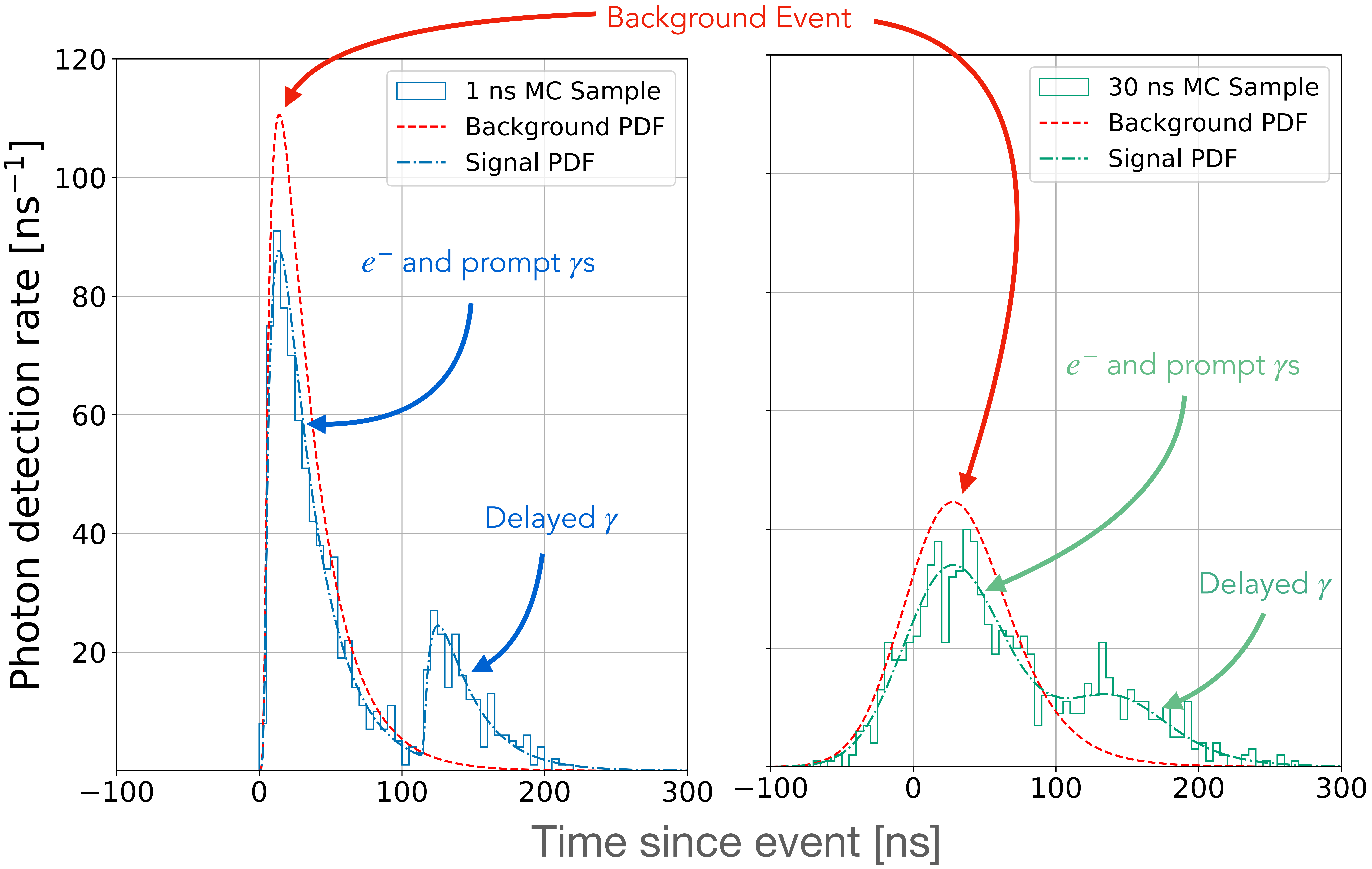


$$\nu_e + {}^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Cs}^* + e^-$$



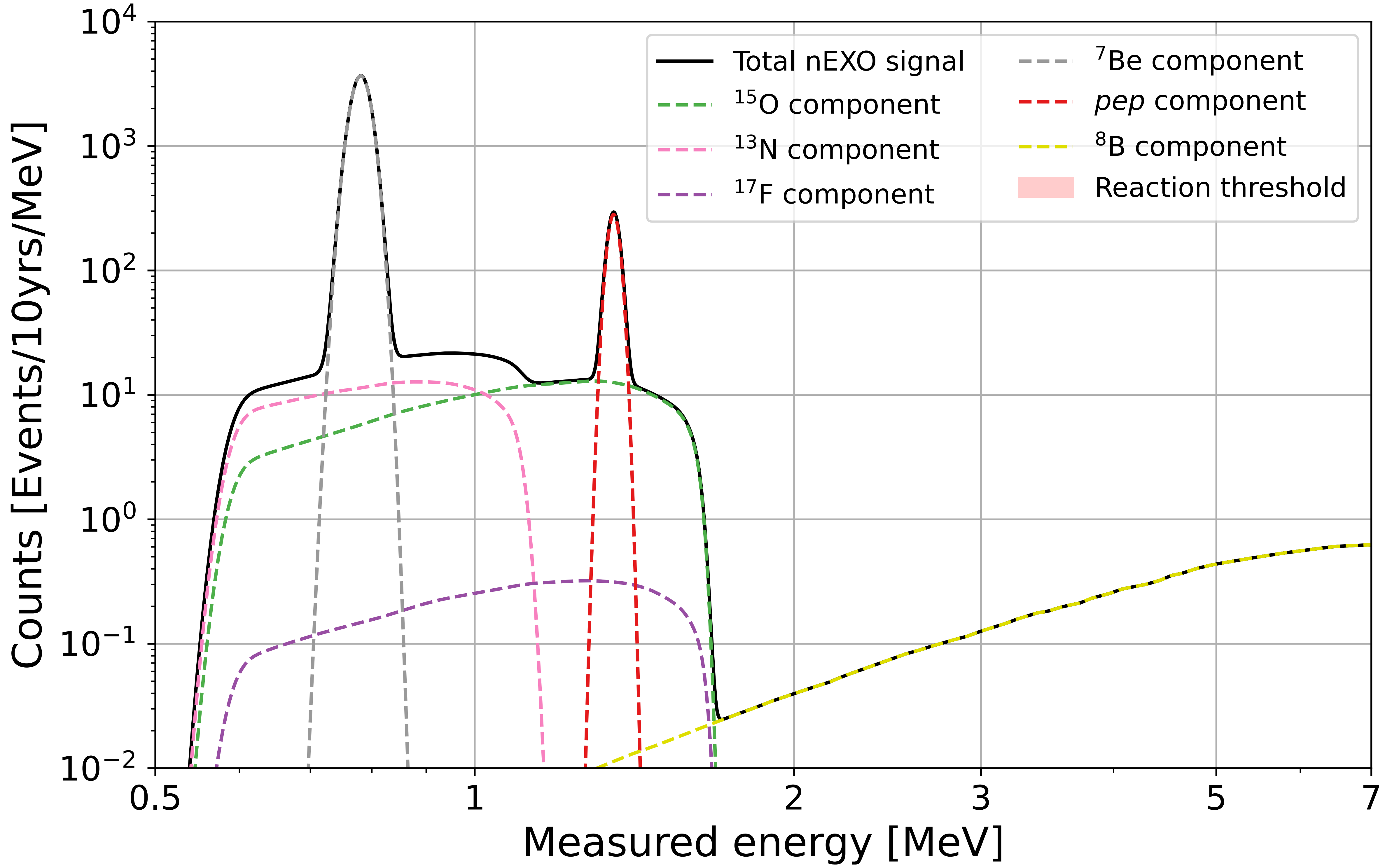
10.1103/PhysRevLett.131.052502

Simulated Scintillation Signals



Potential Applications

1) Solar Neutrinos



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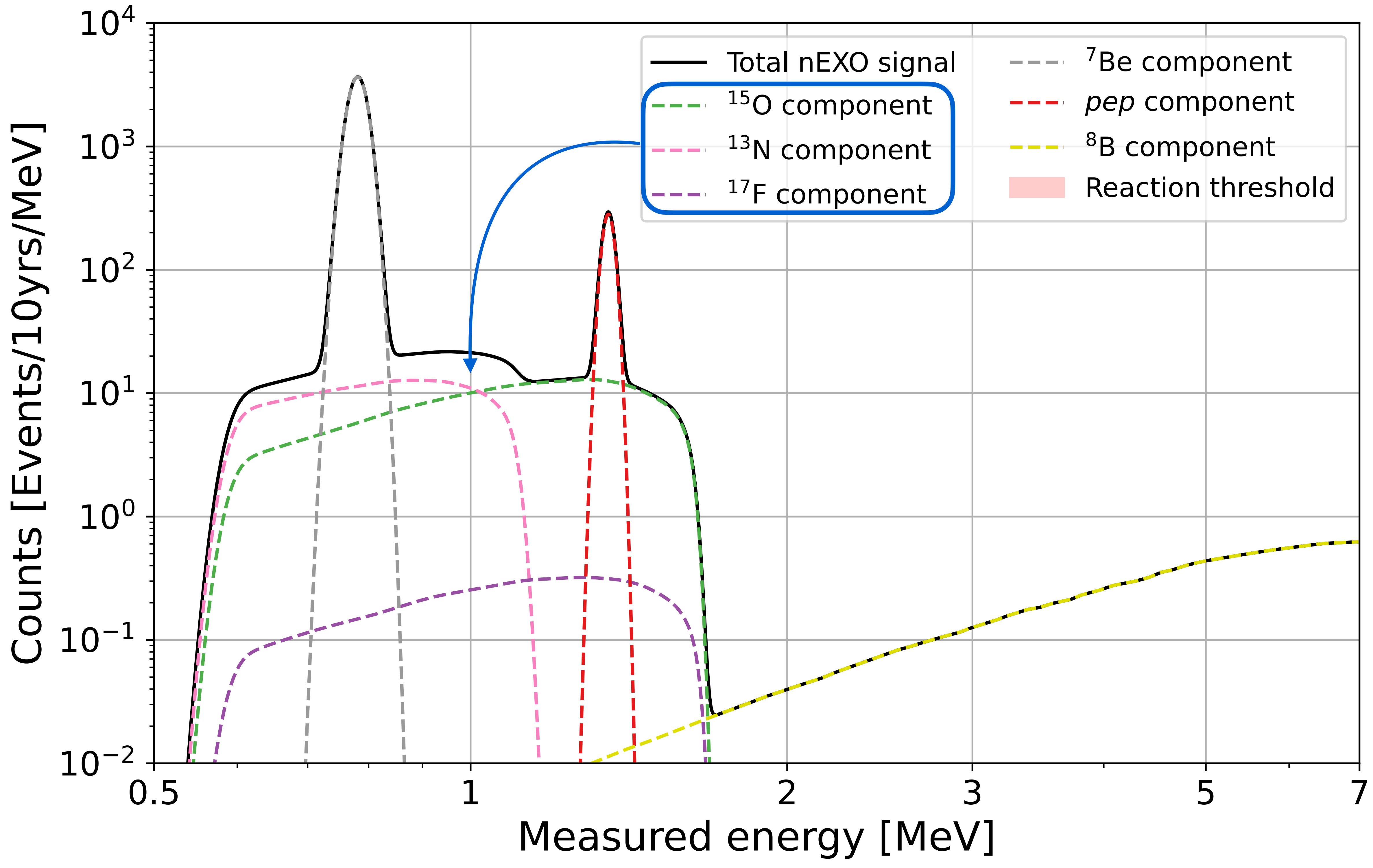
i) Solar metallicity - Flux of the CNO neutrinos

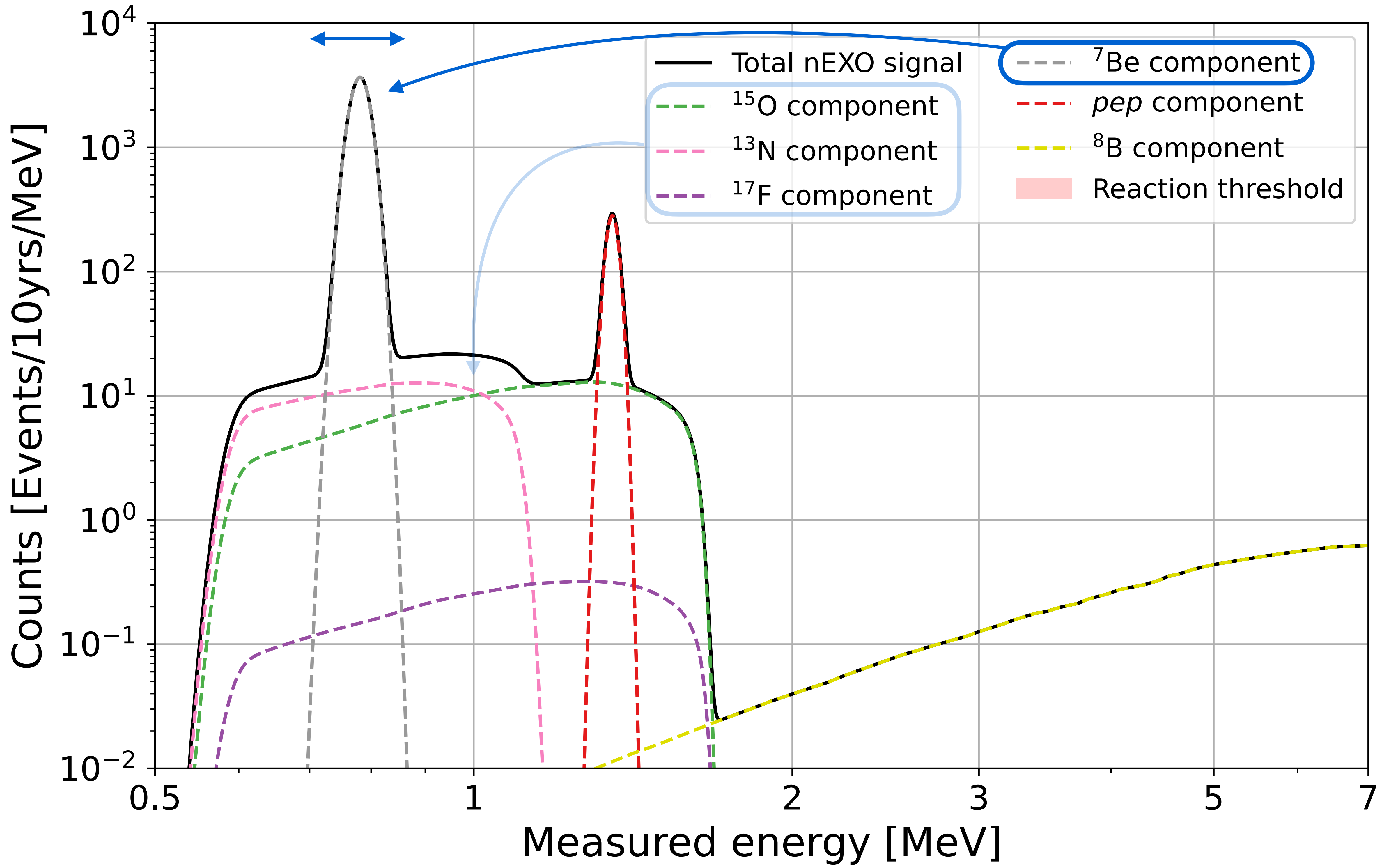


Potential Applications

1) Solar Neutrinos

i) Solar metallicity - Flux of the CNO neutrinos

ii) Solar temperature - Energy of the ^{7}Be neutrinos



Potential Applications

1) Solar Neutrinos

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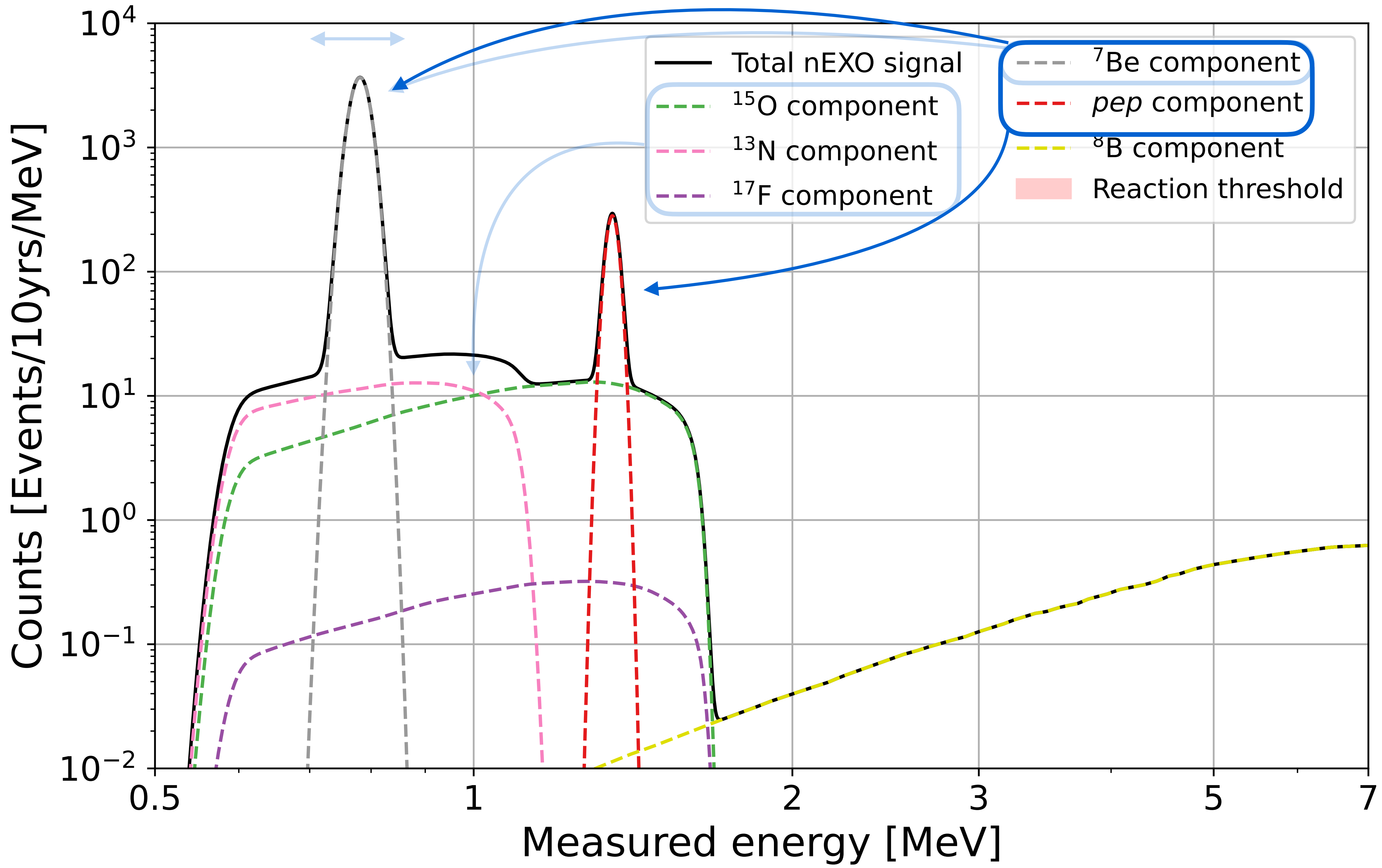
iii) Non-standard interactions - ν_e component of the ^{7}Be and *pep* flux



Potential Applications

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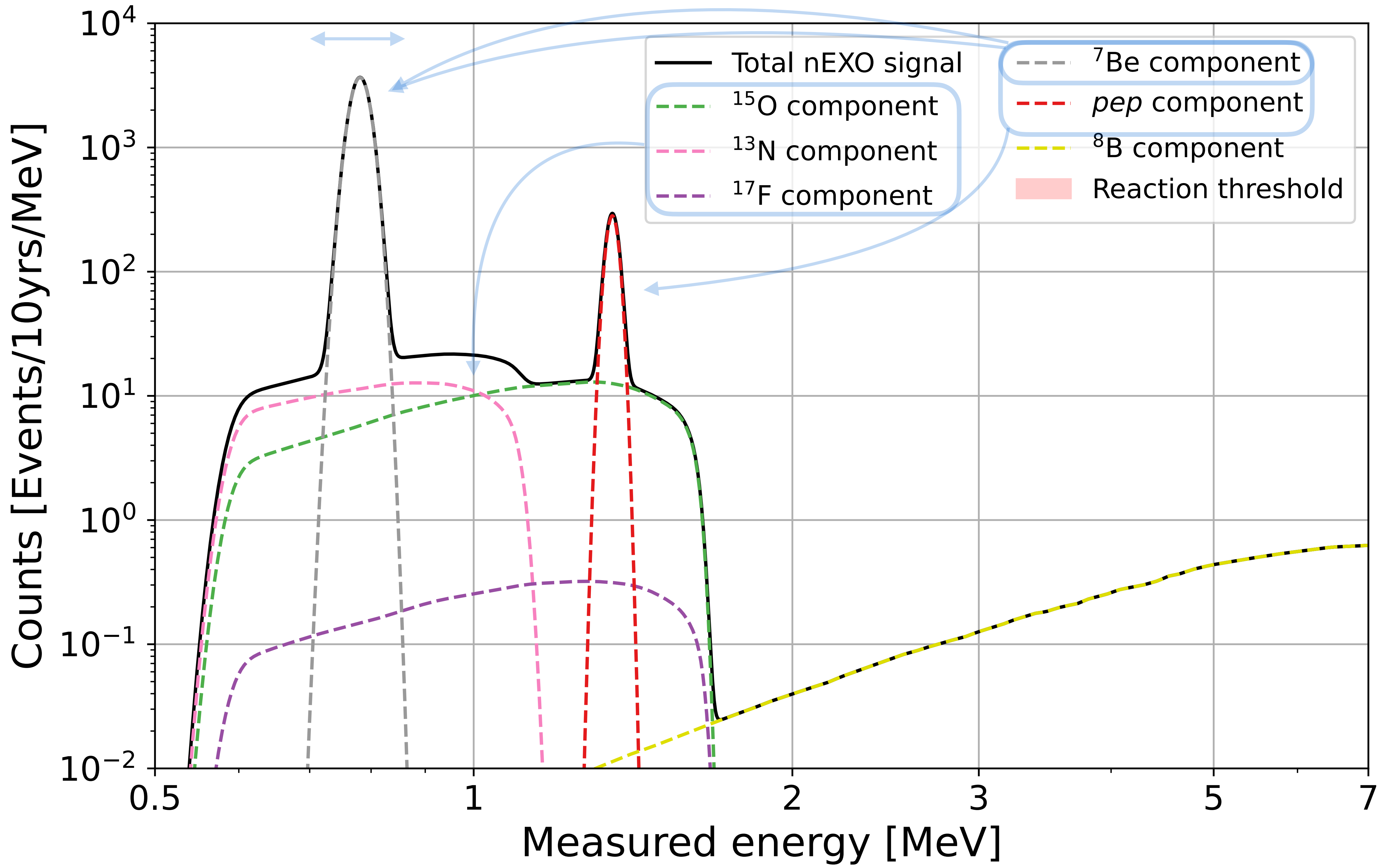
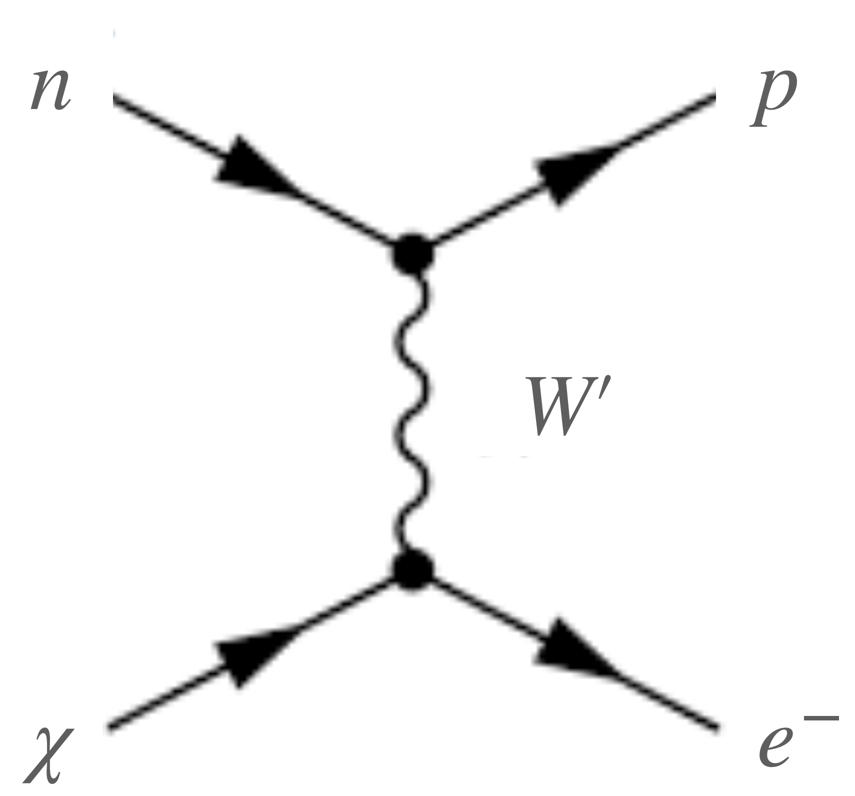
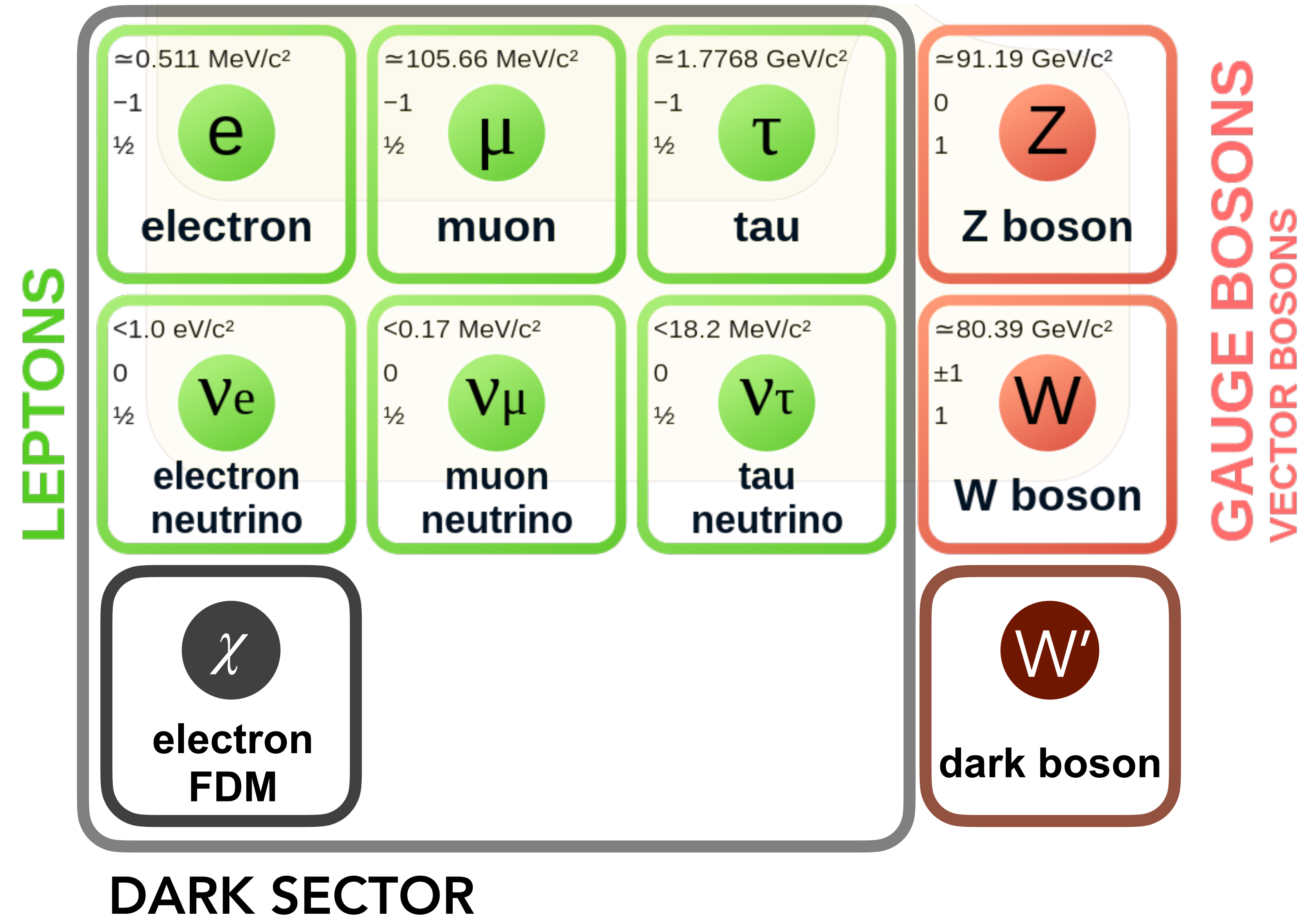
2) Electron-coupling Fermionic Dark Matter

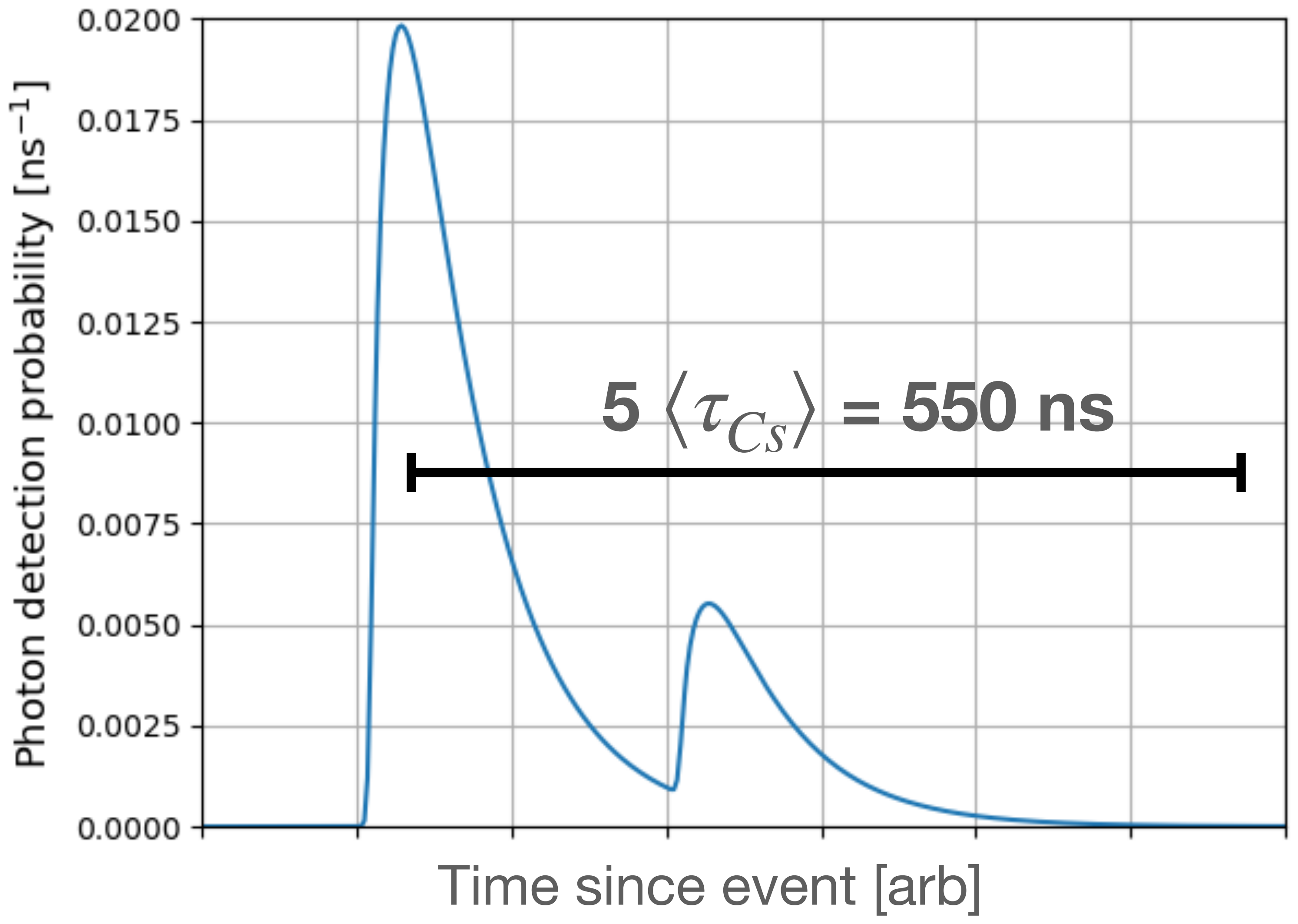


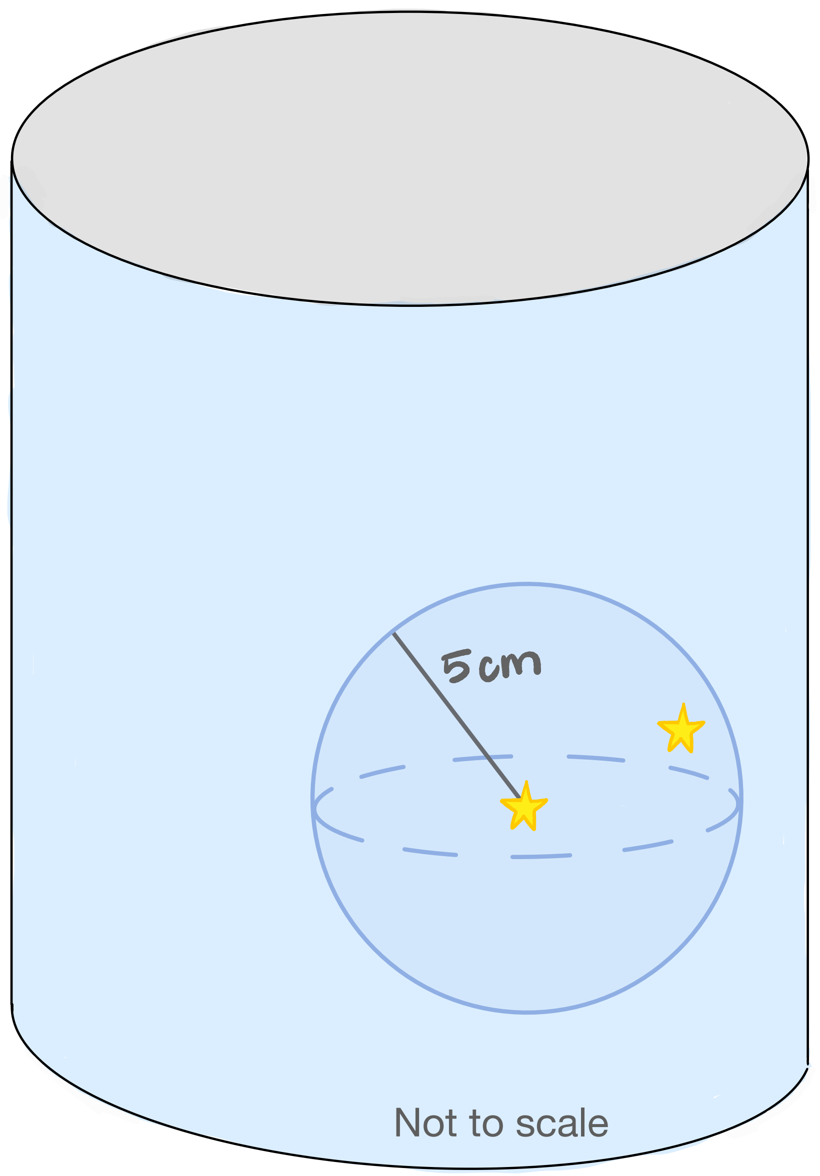




Backgrounds

- Pile up backgrounds must satisfy precise criteria
  - Close in time and space
  - With correct delayed energy
- Expect $< 10^{-5}$ events in 10 years





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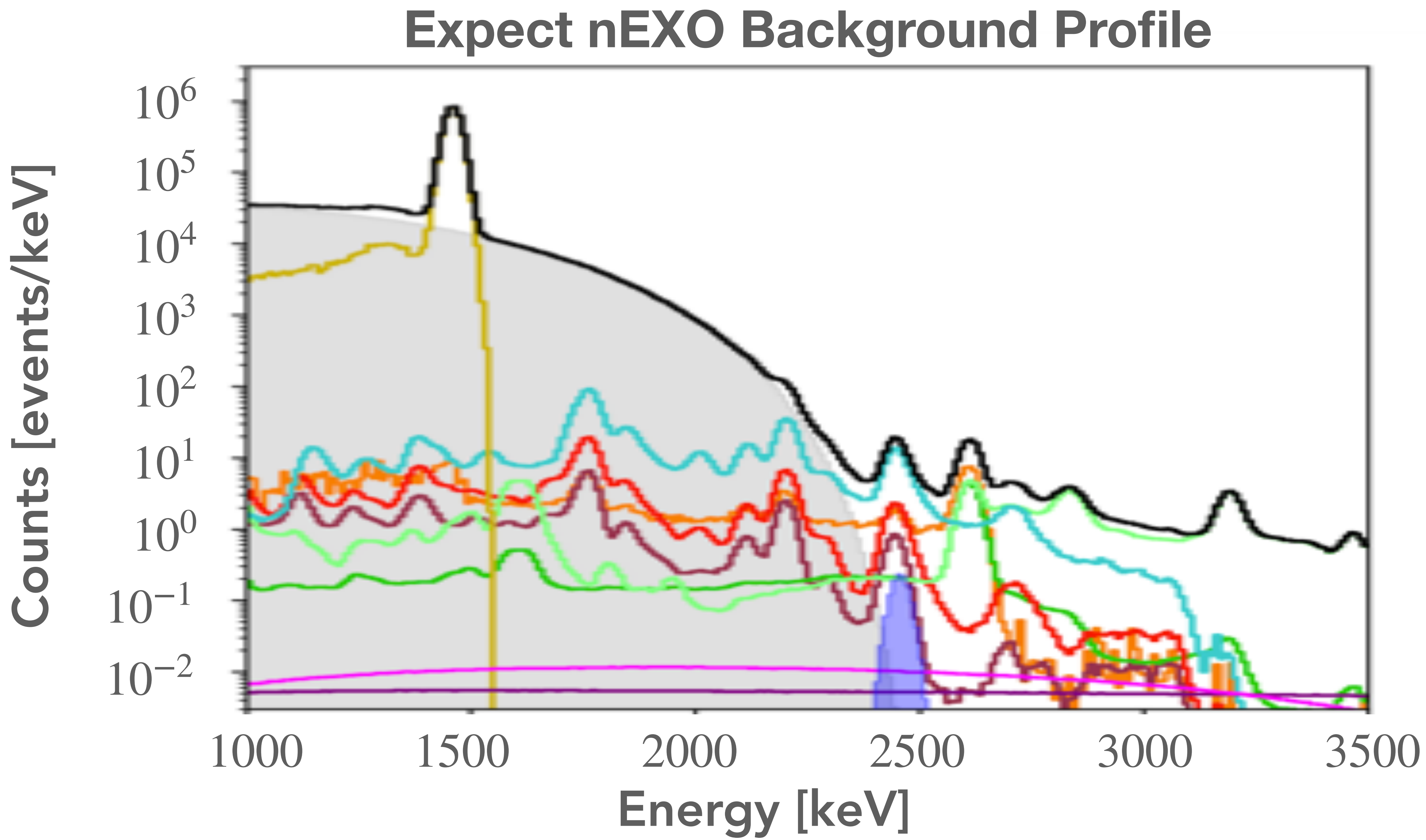
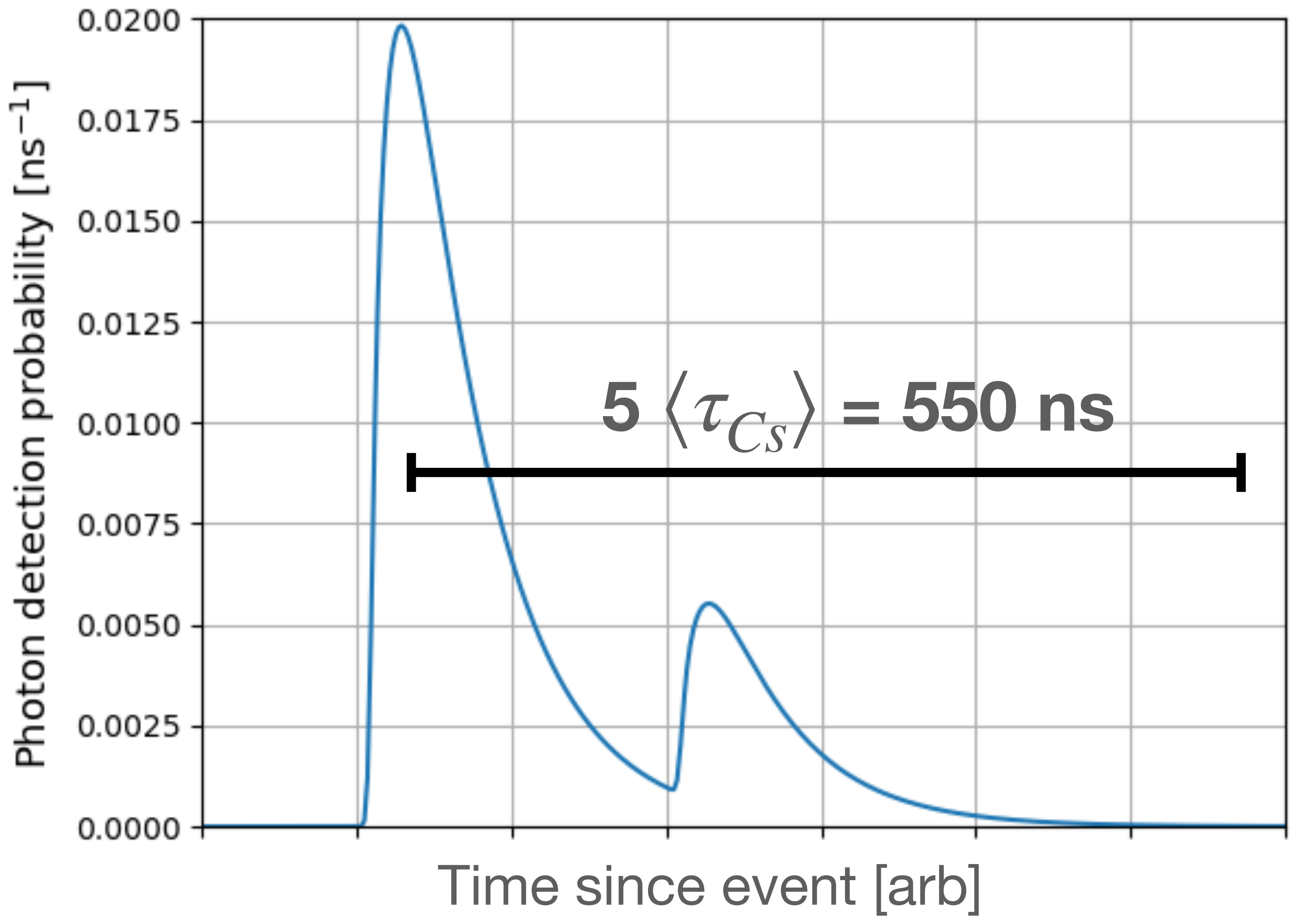
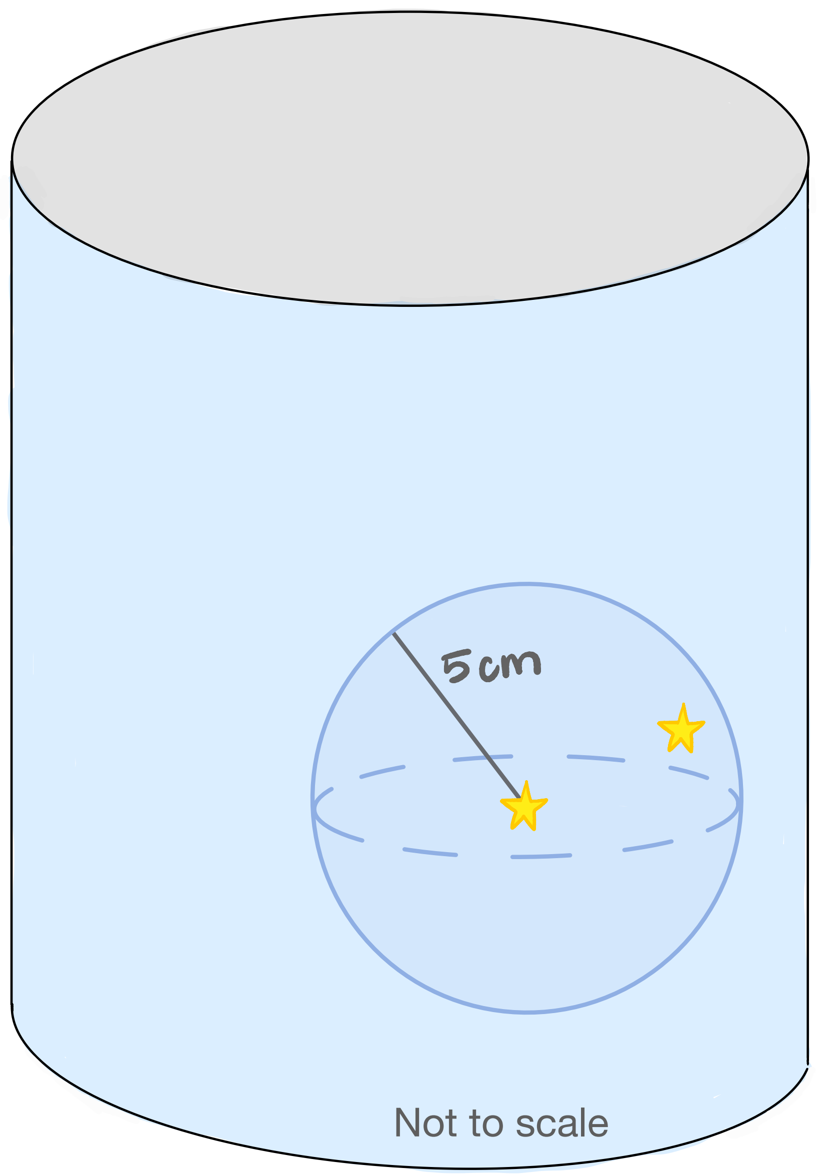
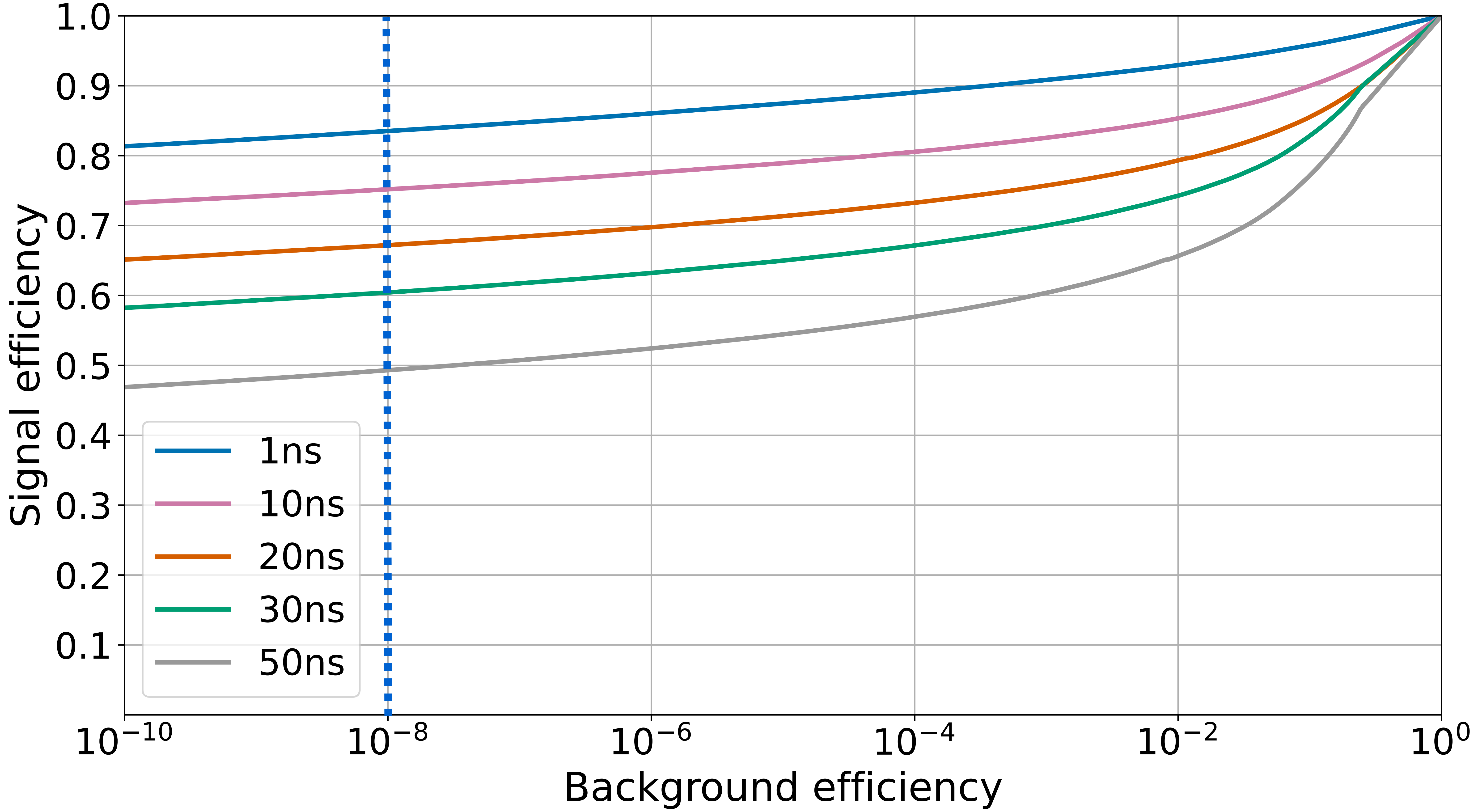






- $\underline{E < 2.5 \text{ MeV}}$: Dominated by $2\nu\beta\beta$ and ^{40}K
  - $\mathcal{O}(10^7)$ events in 10 years
- $\underline{2.5 < E < 5 \text{ MeV}}$: Dominated by ^{232}Th
  - $\mathcal{O}(10^3)$ events in 10 years
- $\underline{E > 5 \text{ MeV}}$: Dominated by cosmogenic activation
  - $\mathcal{O}(1)$ events in 10 years

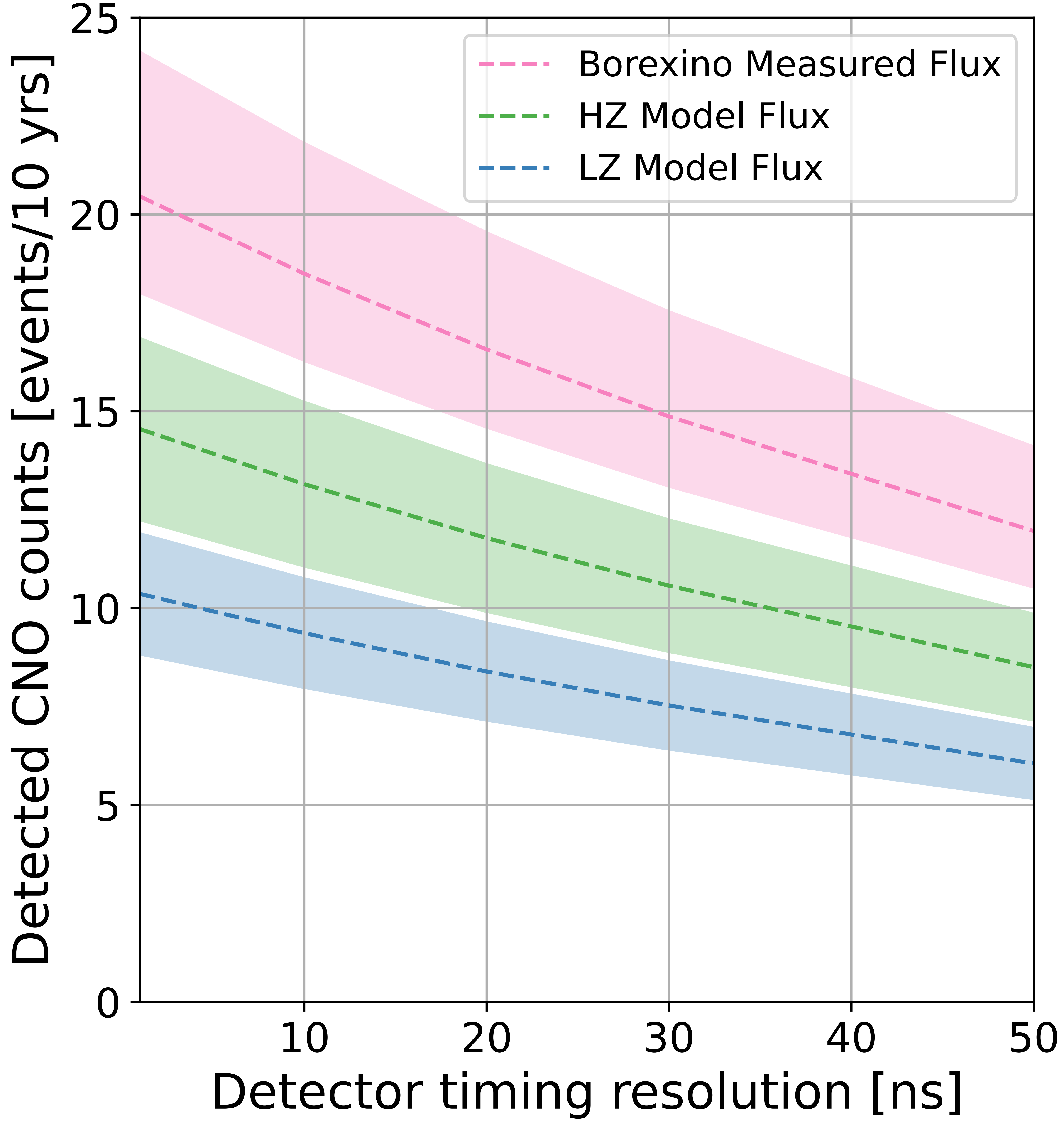
Background Discrimination



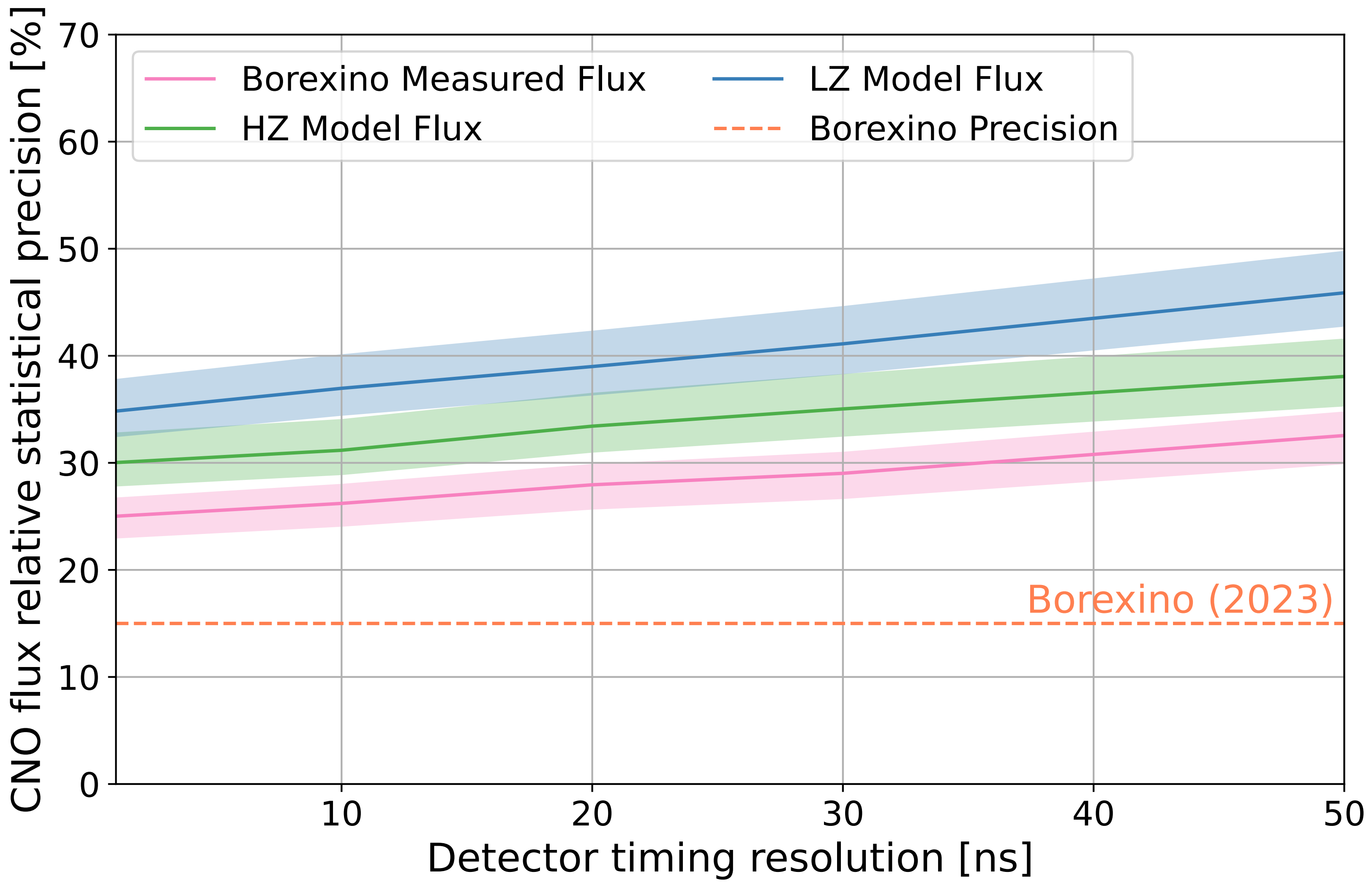
- Can achieve background discrimination of $\mathcal{O}(10^{-8})$ with $\sim 70\,\%$ signal efficiency
- Expect ~ 0.5 background events in 10 years of runtime

Solar-ν Signal Counts

- Expected counts are a function of
  - Timing resolution
  - Neutrino flux (solar model)
- **CNO**: Expect $\sim 10 - 20$ events
- ^{7}**Be**: Expect $\sim 140 - 150$ events
- ***pep***: Expect $\sim 12 - 13$ events
- ^{8}**B**: Expect $\sim 1 - 2$ events



Scientific Reach



- **Solar Metallicity**: Can achieve up to 25% statistical precision of CNO flux
  - Comparable to current leading result

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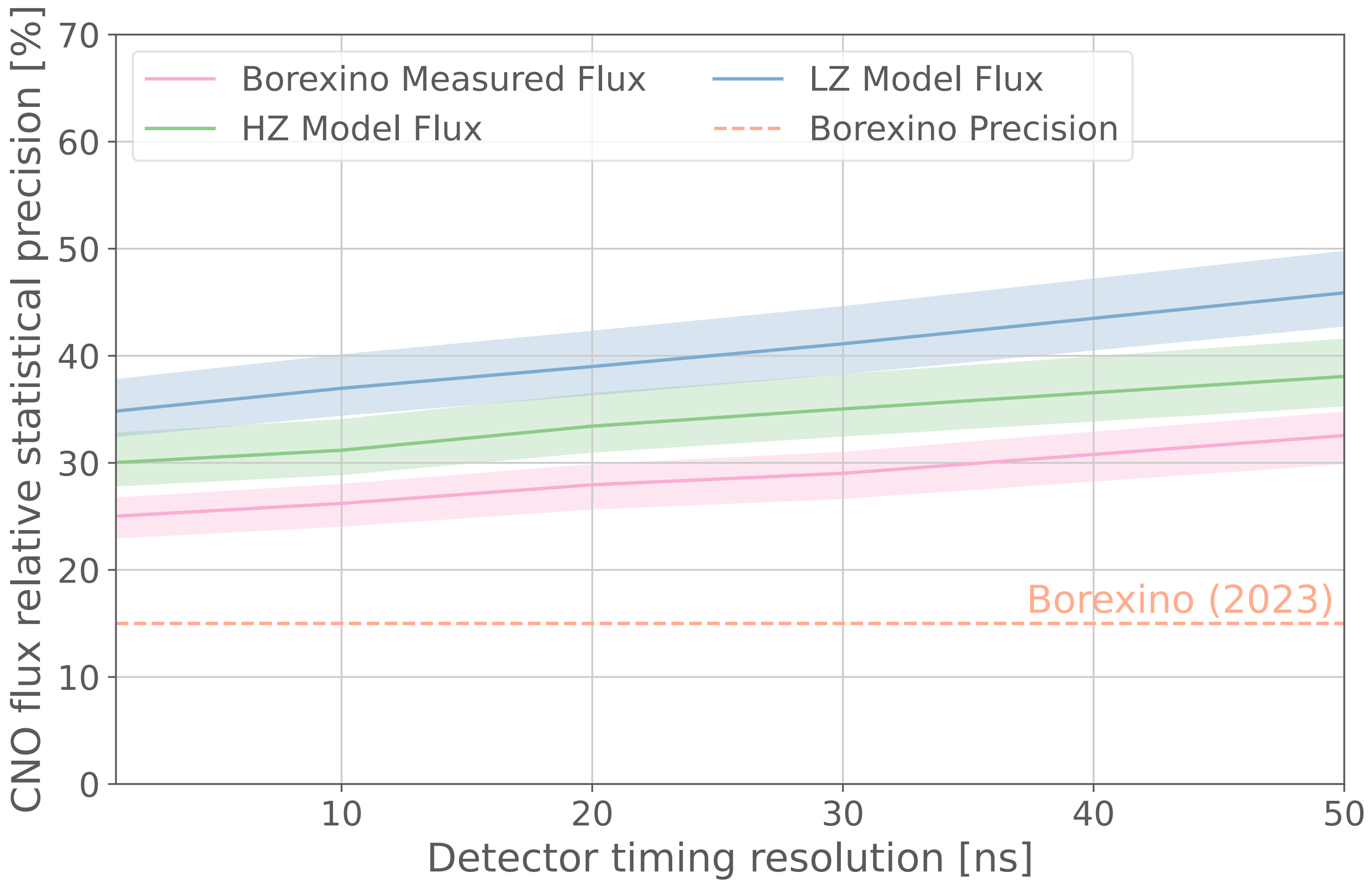

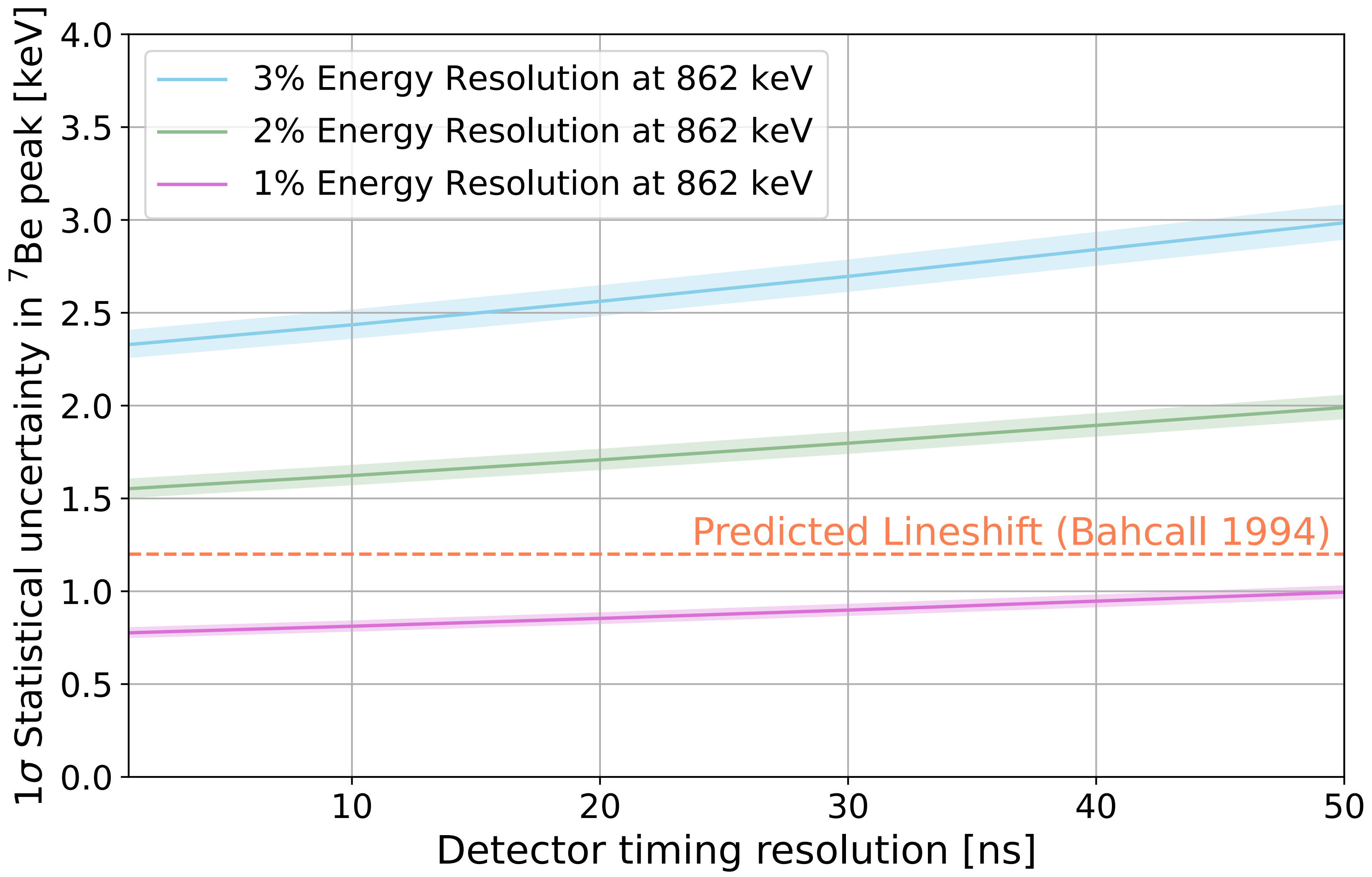

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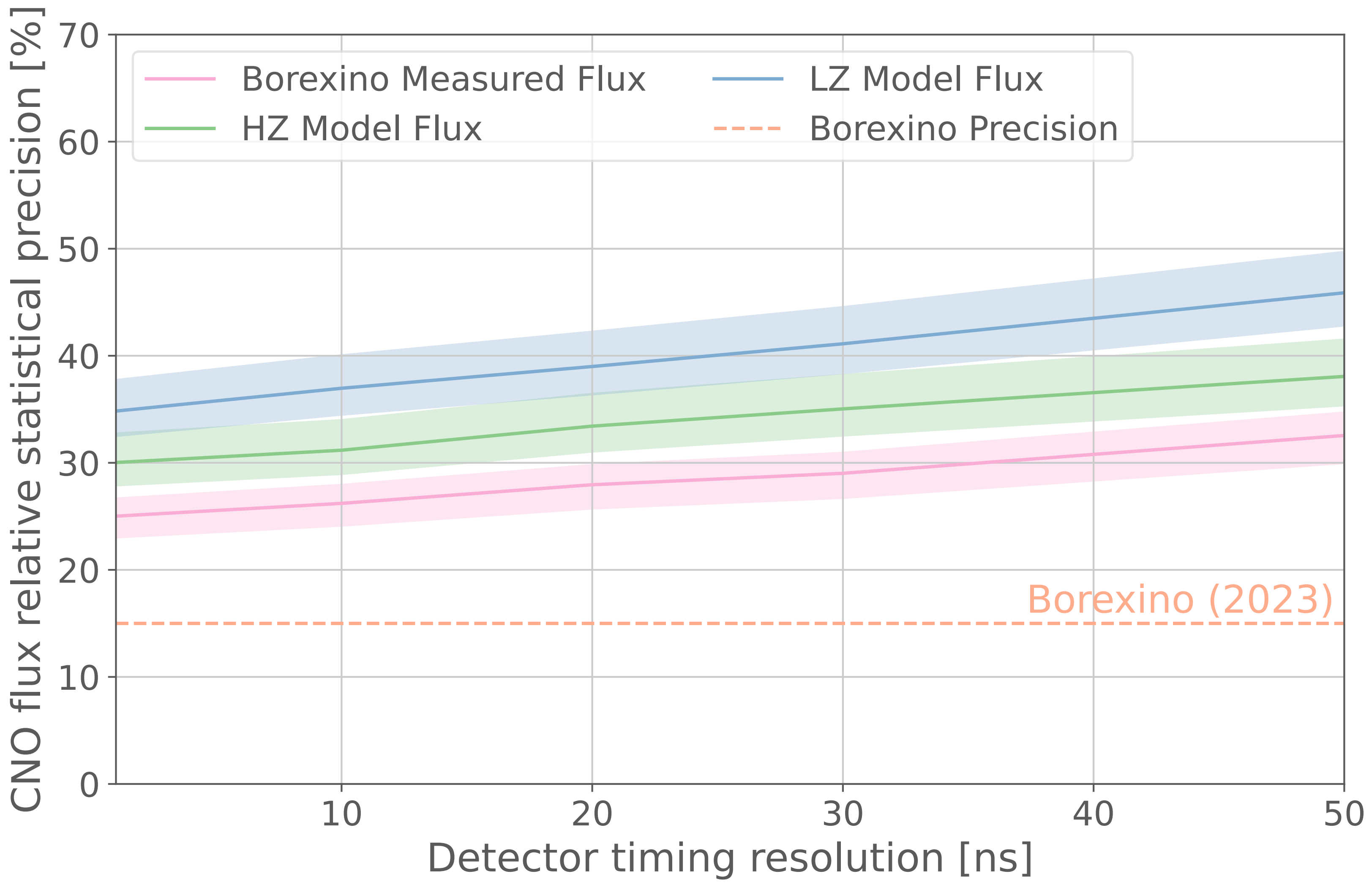

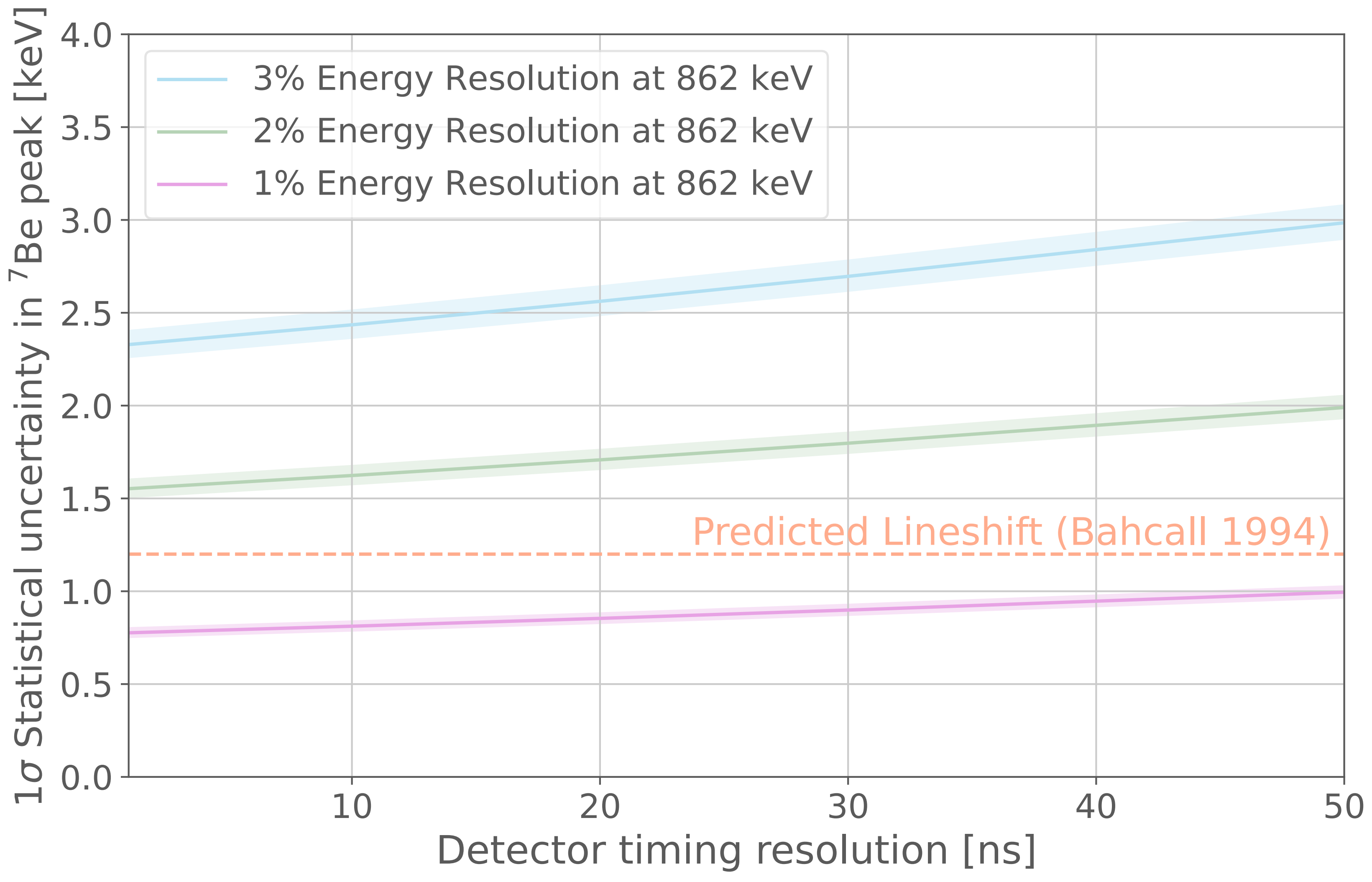

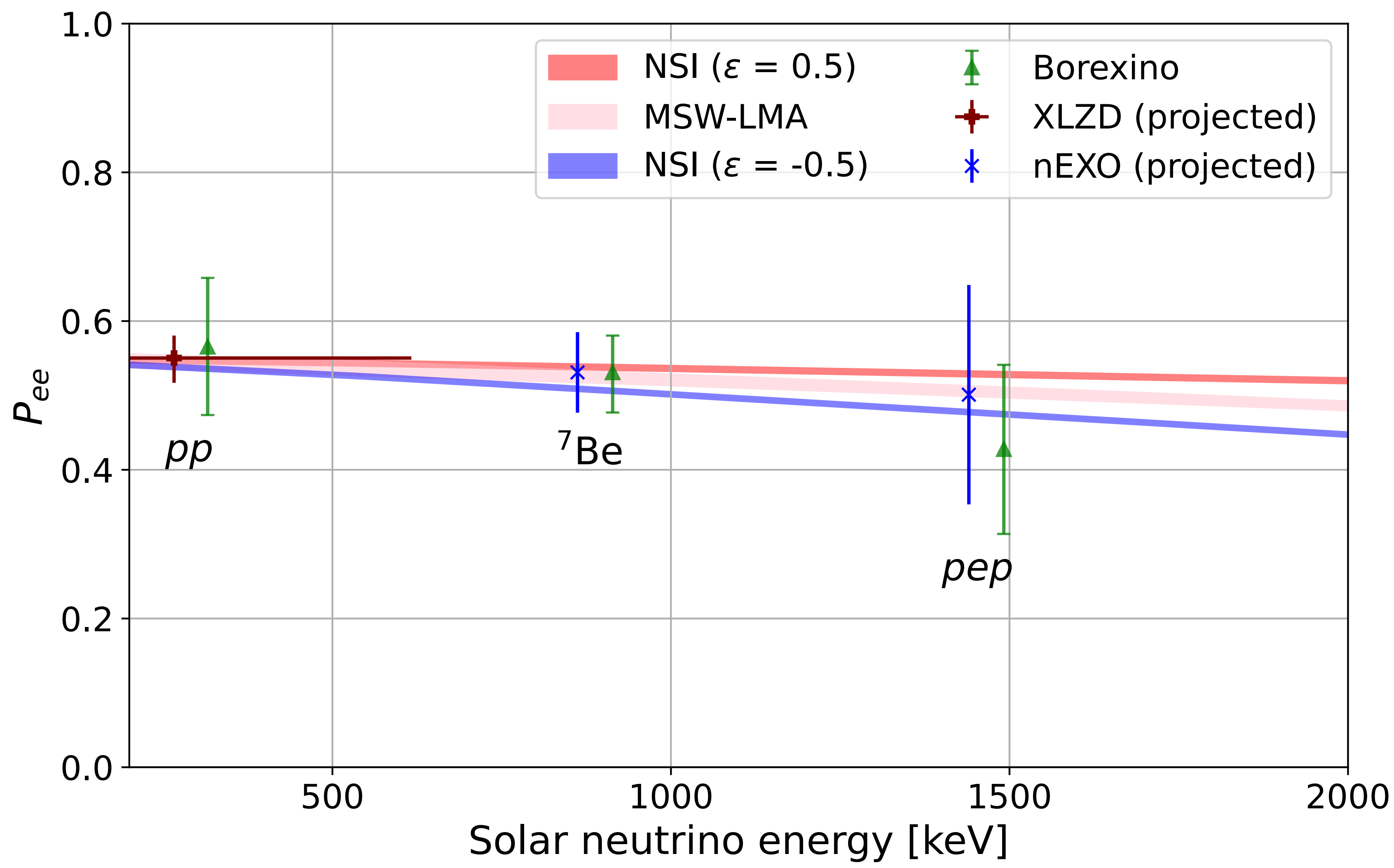

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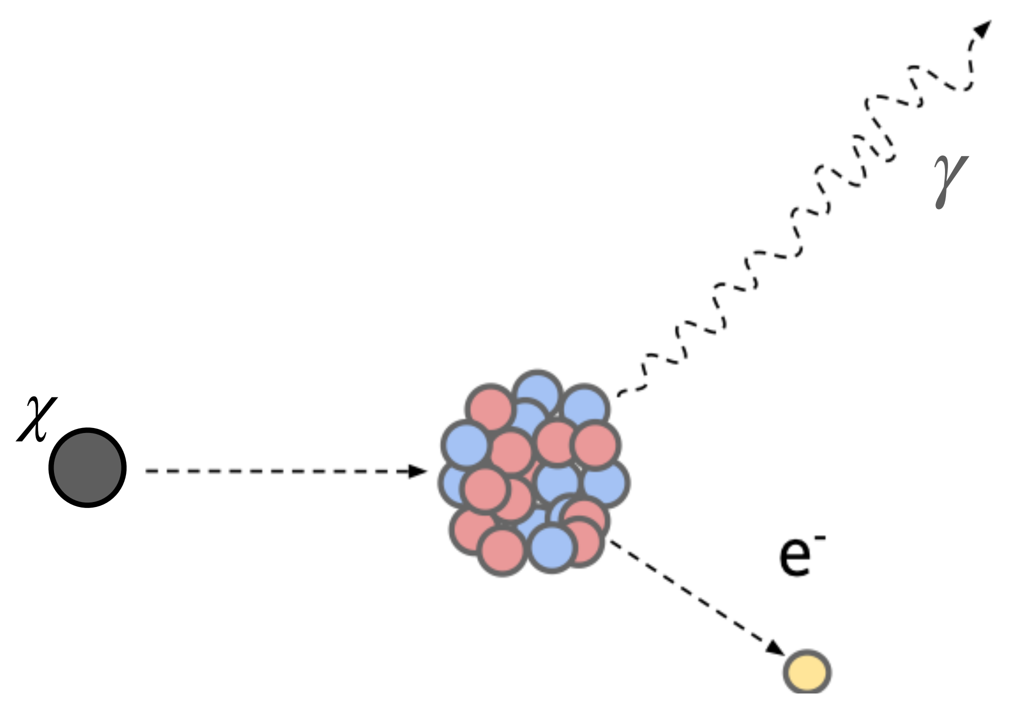
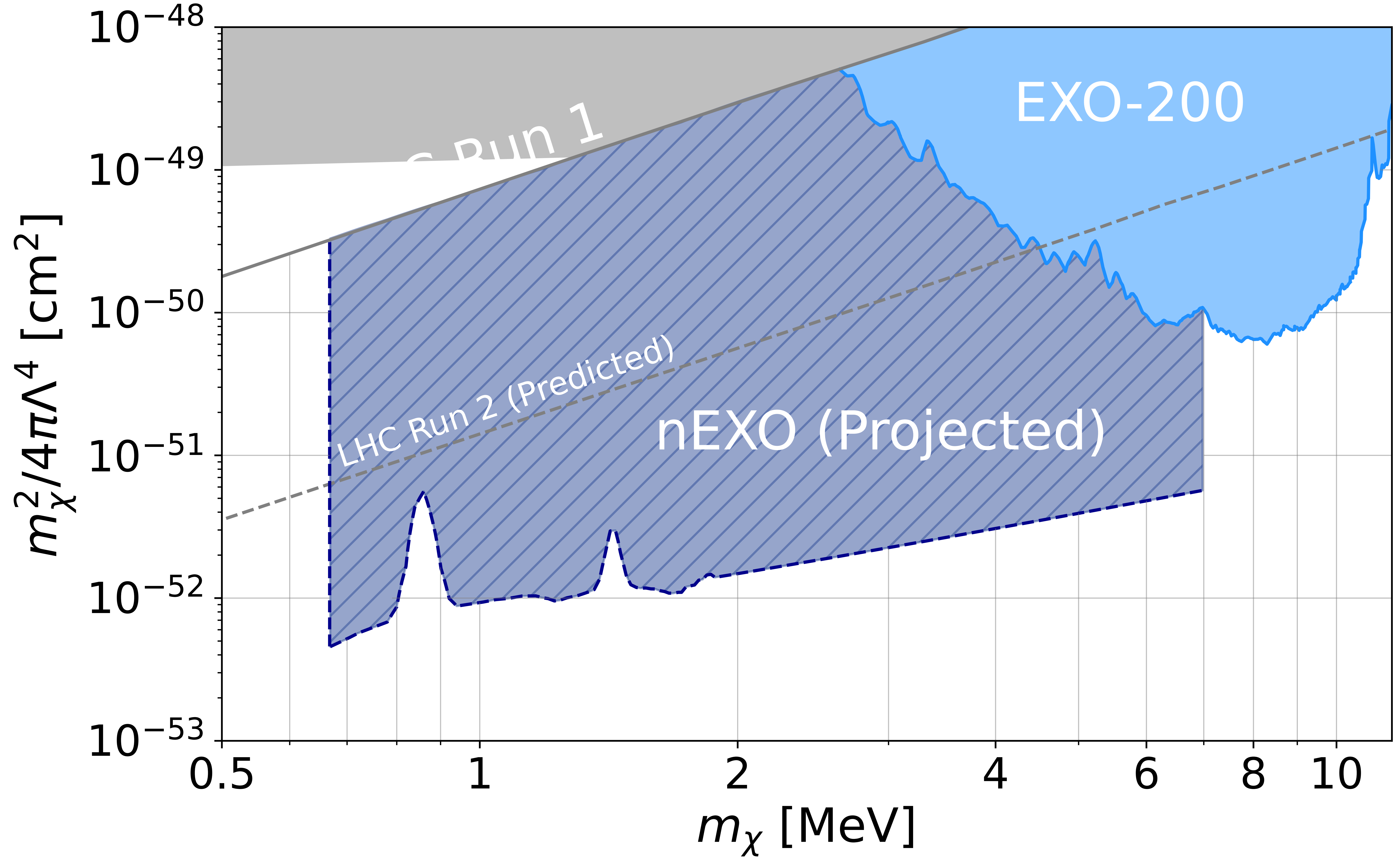
- **Solar Core Temperature**: Sensitive to ~ 1 keV shift in ^{7}Be energy
  - Order of magnitude improvement over current measurement
- **Non-Standard Interactions**: Set limits on NSI effects with $10-30\,\%$ resolution
  - Comparable to current leading results

Fermionic Dark Matter

- Electron-coupling FDM can also capture on ^{136}Xe
- Dominant background is solar neutrino signal
  - Produces same event signature
- Could improve searchable parameter space by more than three orders of magnitude





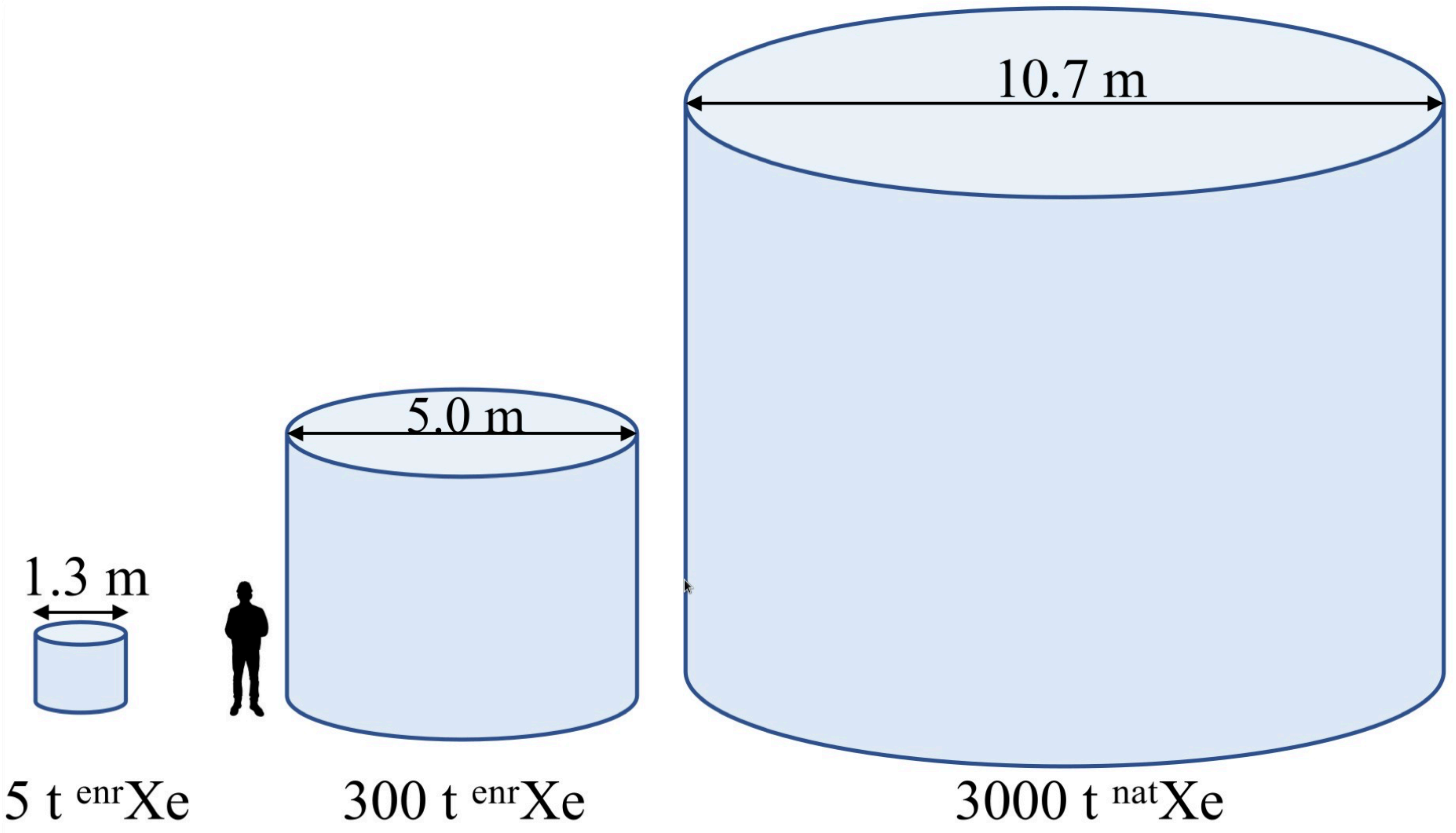
Beyond nEXO - Future LXe TPCs

- While $0\nu\beta\beta$ detectors are well suited to this detection channel any LXe TPC with ^{136}Xe can use it

- Next generation dark matter detectors expected to have comparable ^{136}Xe exposure as nEXO

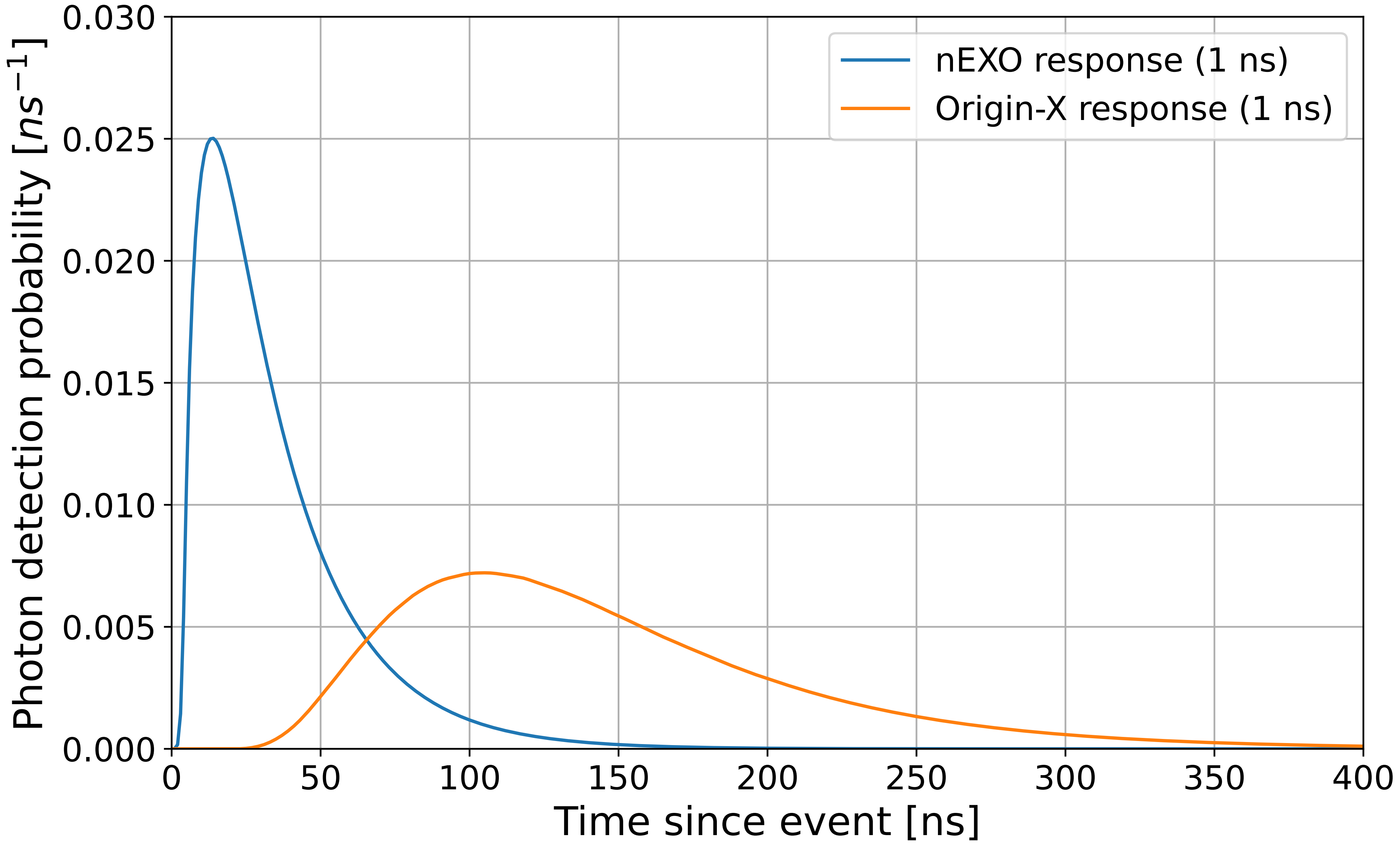
- Though the larger detector might affect photon travel time
  - Detailed optical simulations needed

- Thinking ahead can imagine a ktonne detector



Ktonne Detector Scientific Reach

- At ktonne scales Rayleigh scattering becomes significant
  - Increases average photon travel time
- Becomes more difficult to tag delayed de-excitation
  - ~ $33\,\%$ loss in signal efficiency compared to nEXO
- ~ 100x more exposure



Measurement	nEXO	Origin-X	Leading Result
ϕ_{CNO}	29%	4%	15% (Borexino [57])
δ_{Be}	±1.4 keV	±0.08 keV	±16 keV (KamLAND [69])
$P_{ee}(E_{Be})$	9%	4%	9% (Borexino [60])
$P_{ee}(E_{pep})$	29%	4%	26% (Borexino [60])
$P_{ee}(E_B)$	78%	10%	5% (SNO [15])

Conclusions

- Isomeric states in ^{136}Cs could create time-delayed coincident signals in nEXO
  - Can tag the interaction reducing backgrounds to 0.5 events per 10 years
- nEXO can use this channel to perform state-of-the-art solar neutrino measurements
  - **Solar metallicity** - up to 25% precision of CNO flux
    - Comparable to leading measurement
  - **Solar core temperature** - ~1 keV precision to ^{7}Be line-shift
    - Order of magnitude improvement over current measurement
  - **Non-standard interactions** - Set limits with 10-30% precision
    - Comparable to leading measurements
- nEXO can also search for electron-coupling fermionic dark matter
  - Improve sensitivity by more than three orders of magnitude compared to current limits
- A ktonne LXe TPC could use this channel to achieve world leading measurements across multiple aspects of solar physics

Thank You!

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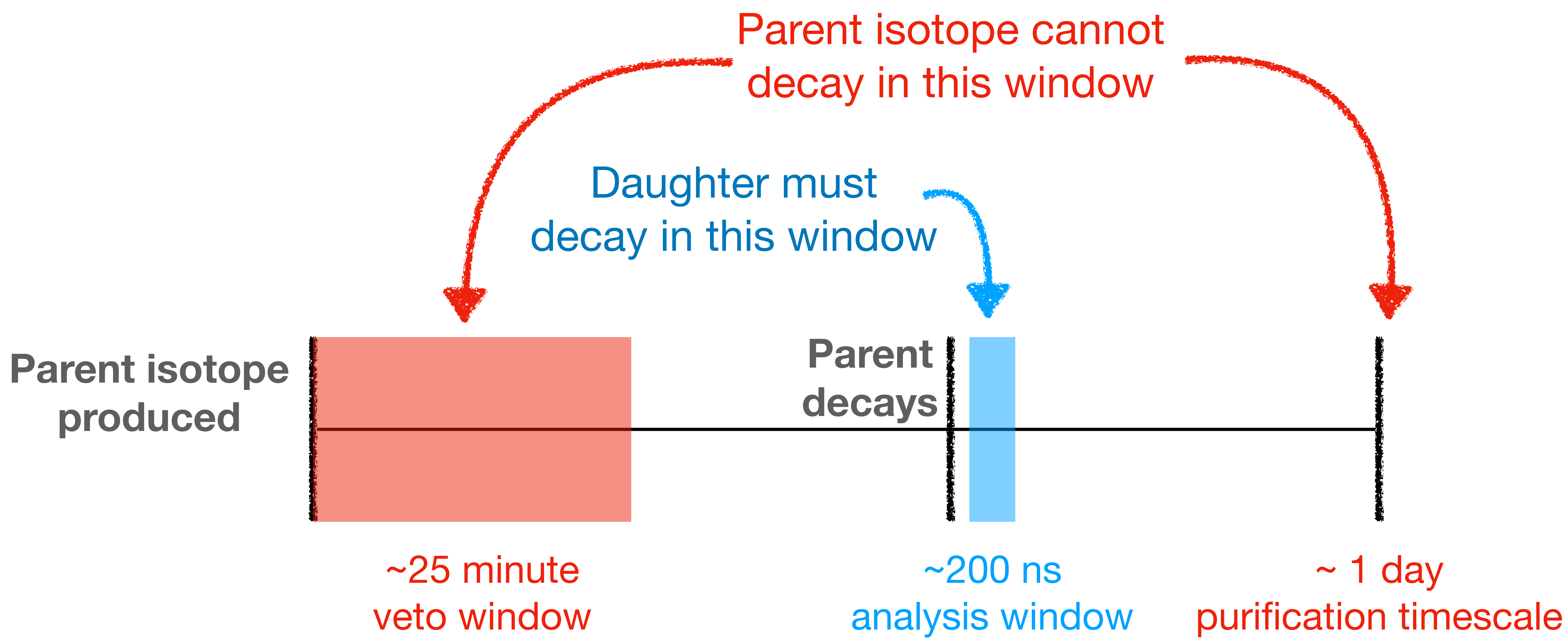
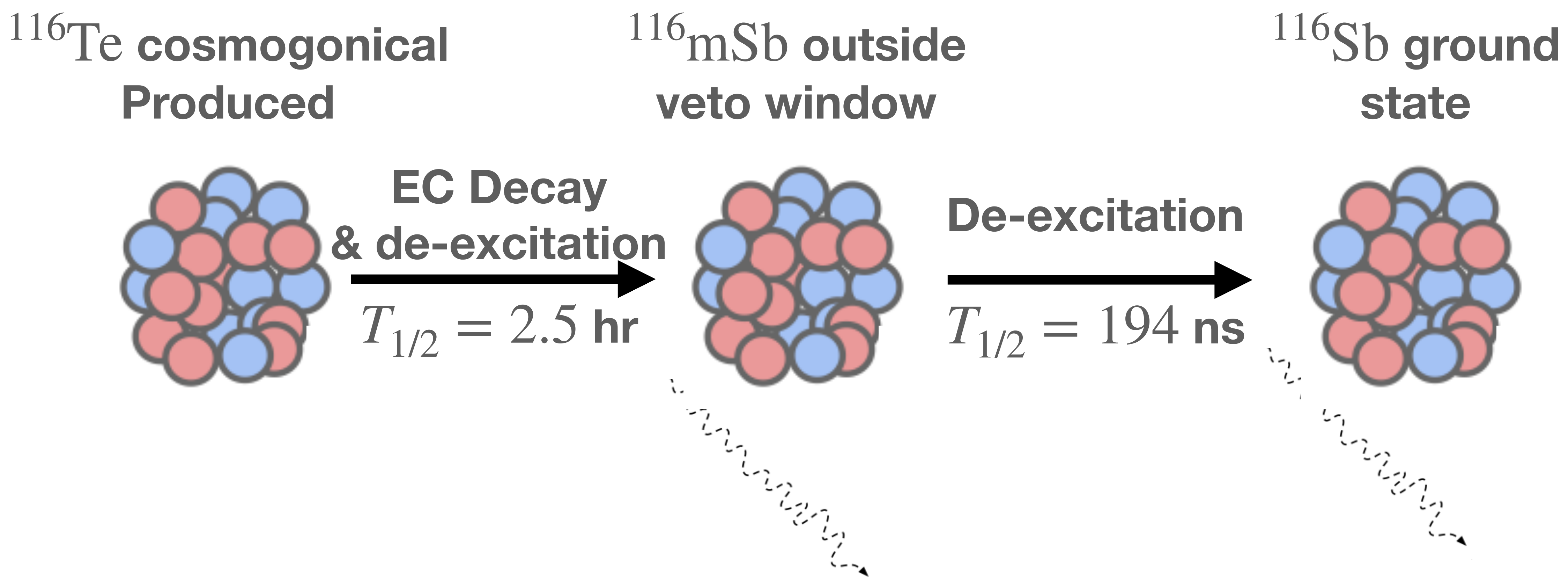
Backgrounds (Cosmogenic)

- Backgrounds could also occur from delayed nuclear decays produced from cosmogenic activity
- This must also satisfy stringent criteria
  - Delayed and prompt signals must both be of correct energy and ratio
  - Signal must be fed by another decay to push it outside of the veto and purification windows

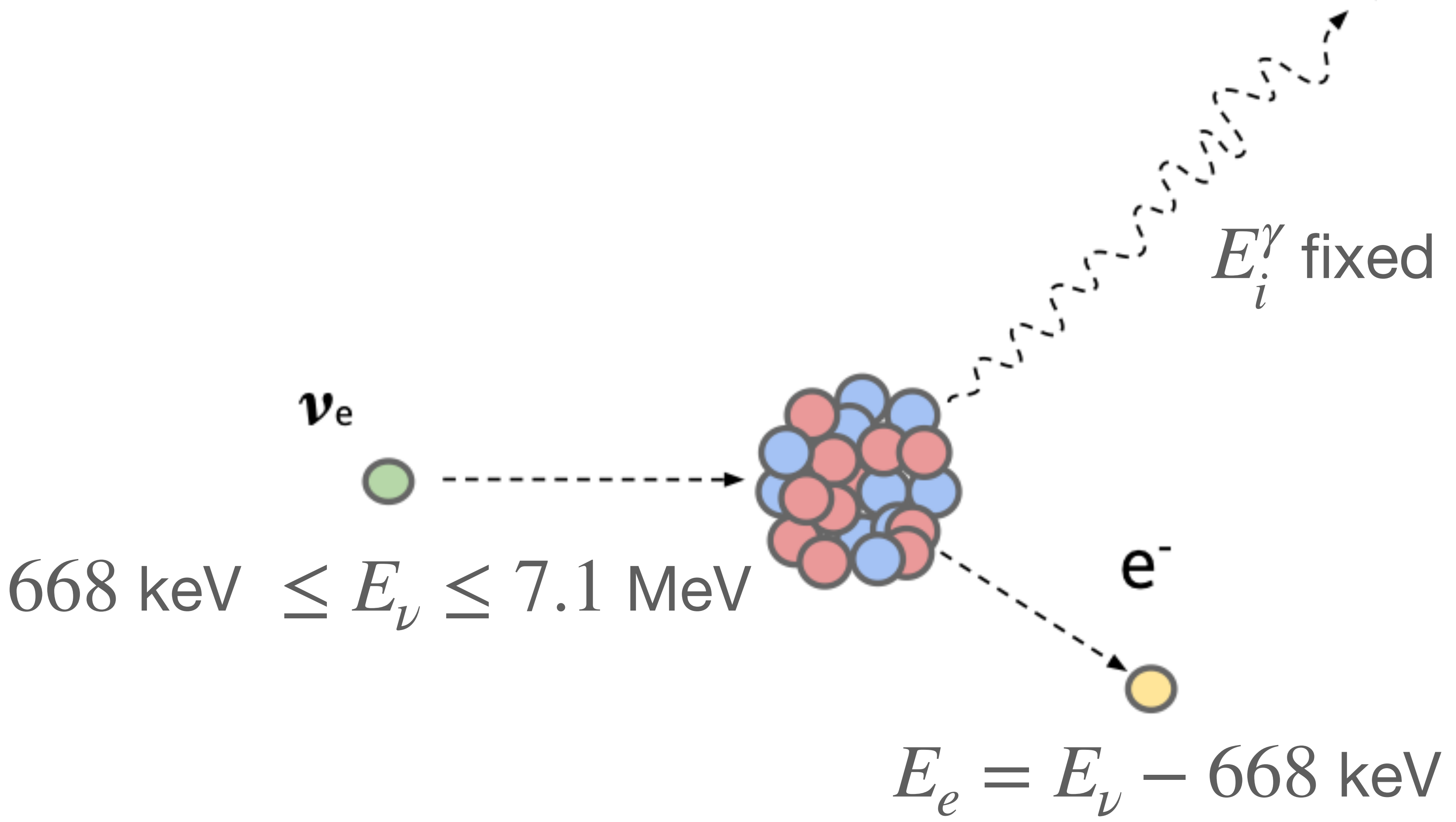
- Dedicated Geant4 simualtions of nEXO have been used to estimate cosmogenic activation
- Most backgrounds are expected to occur at a rate of $\mathcal{O}(10^{-3})$ events per 10 years
  - In total we expect ~0.05 such events in 10 years

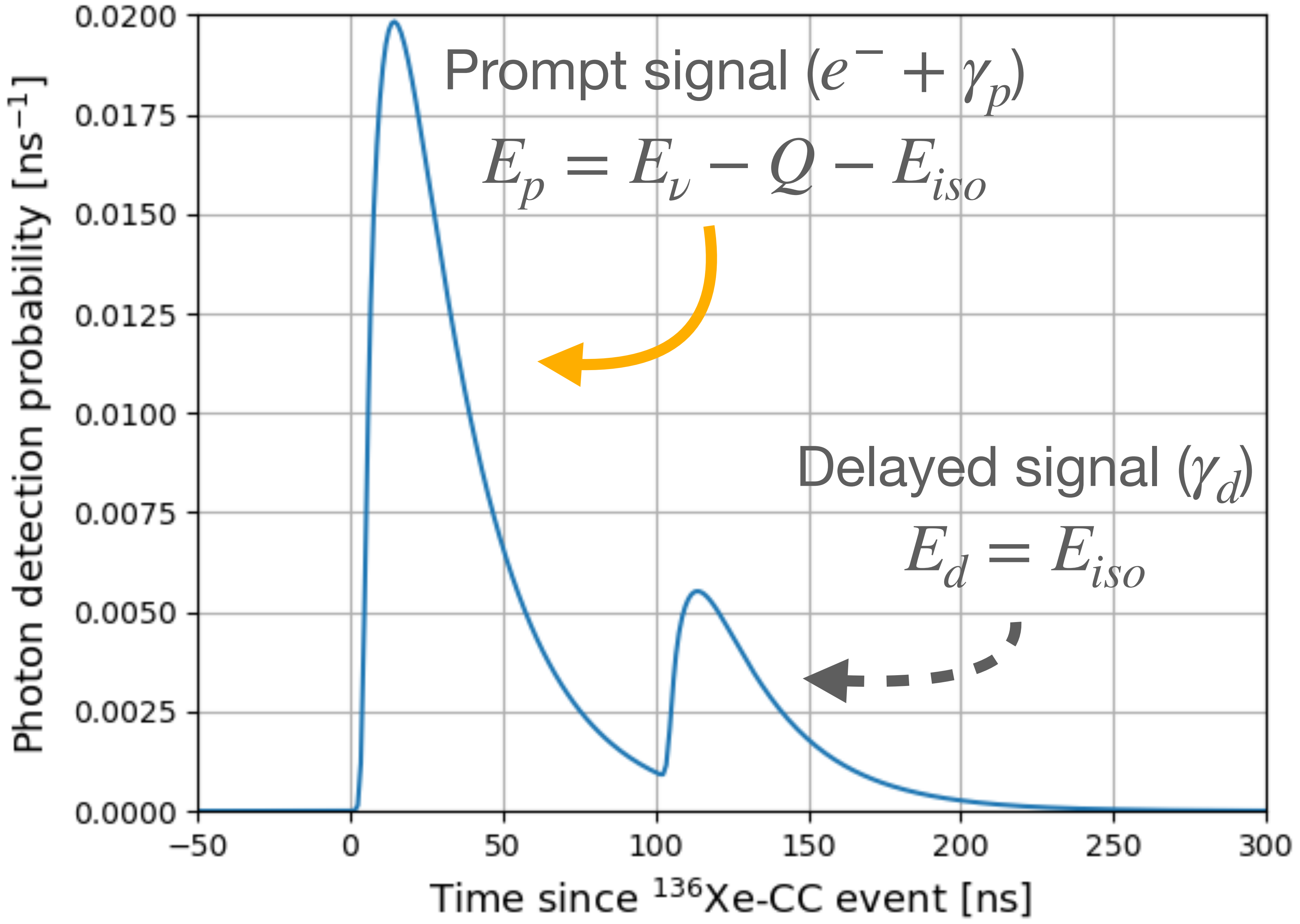




The Energetics

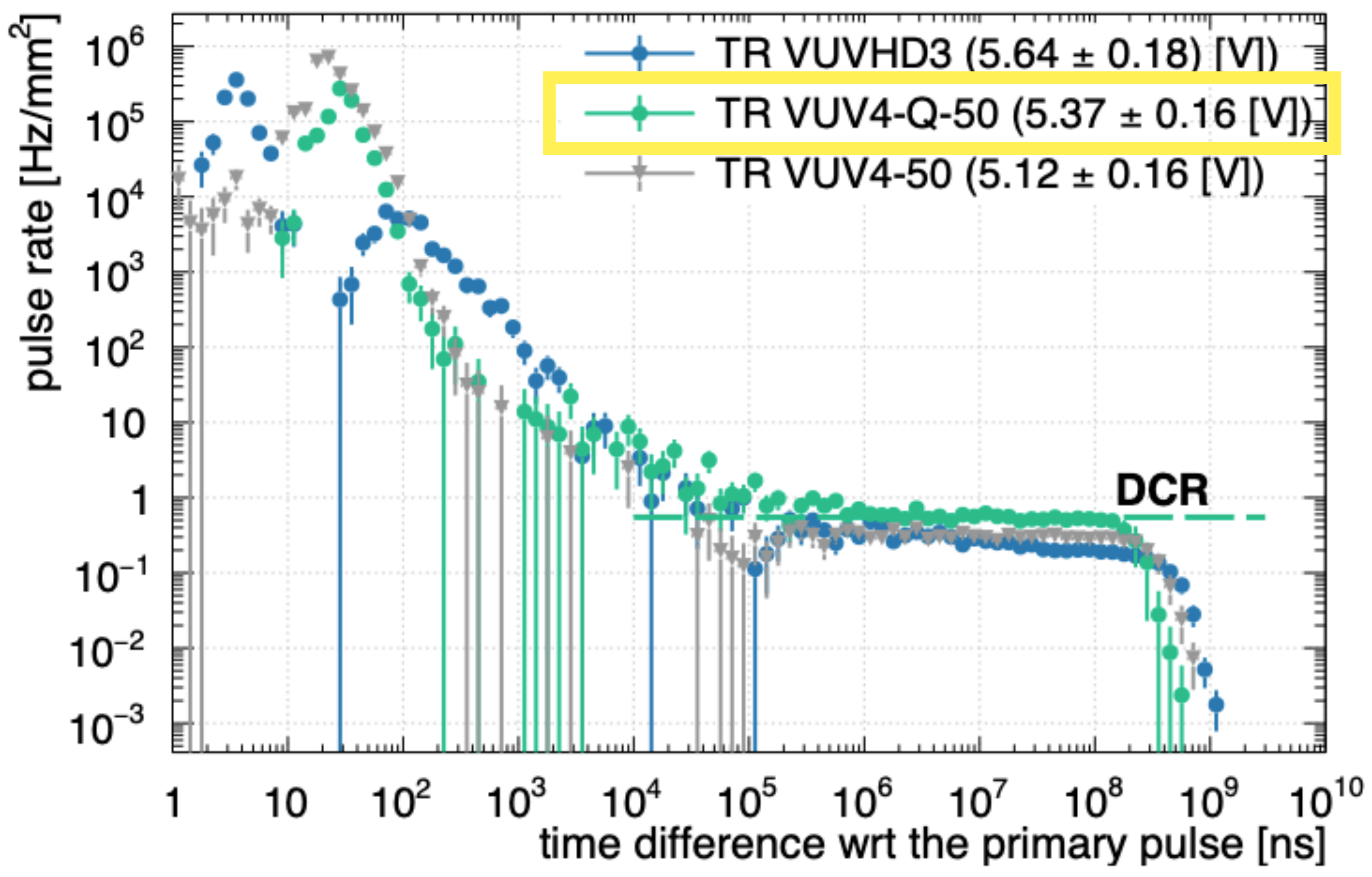
- Reaction threshold is $E_{thresh} = E_{1^+} + Q = 668$ keV
- Upper-limit for this analysis is $S_n^{136} + Q \approx 7$ MeV where S_n^{136} is the neutron separation energy of ^{136}Cs
  - Can extend this limit further but is non-trivial
- Signal will consist of one electron and multiple gammas
  - Prompt electron will have energy $E_e = E_\nu - E_{thresh} \rightarrow$ scales with E_ν
  - Prompt and delayed gammas will have energy fixed by the structure of ^{136}Cs $\rightarrow$ independent of E_ν
- Total energy visible in the detector will be $E_{vis} = E_\nu - Q$
  - Because this is an absorption interaction we will measure E_ν directly

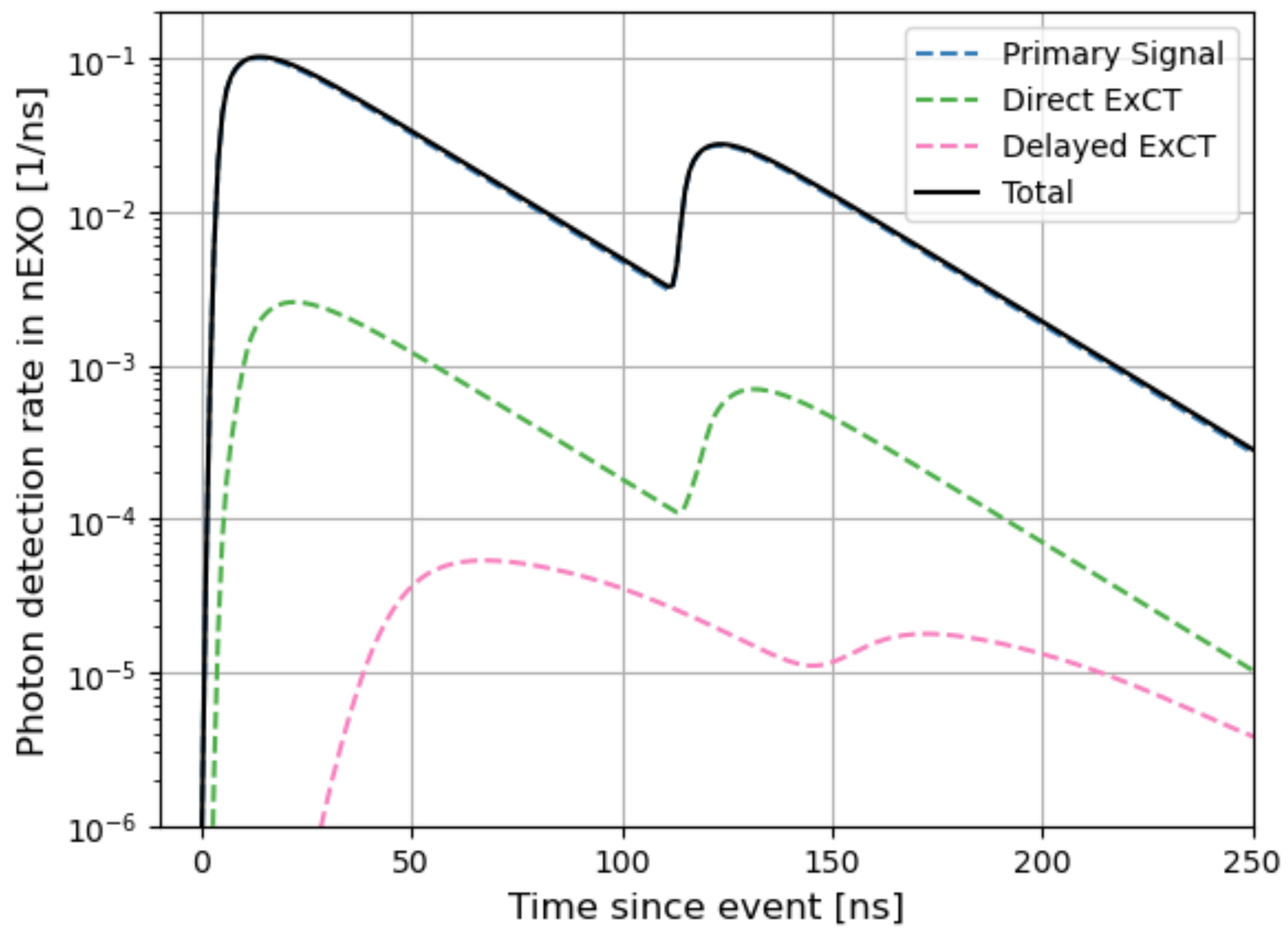




Modelling Scintillation - dExCT

- In addition to ExCT, SiPM channels can also after-pulse with some delay
  - These after-pulses have a chance to ExCT causing delayed ExCT (dExCT)
- Average dExCT delay is ~50 ns for the SiPMs we're modeling
- dExCT photons are then propagated using the same method as ExCT photons

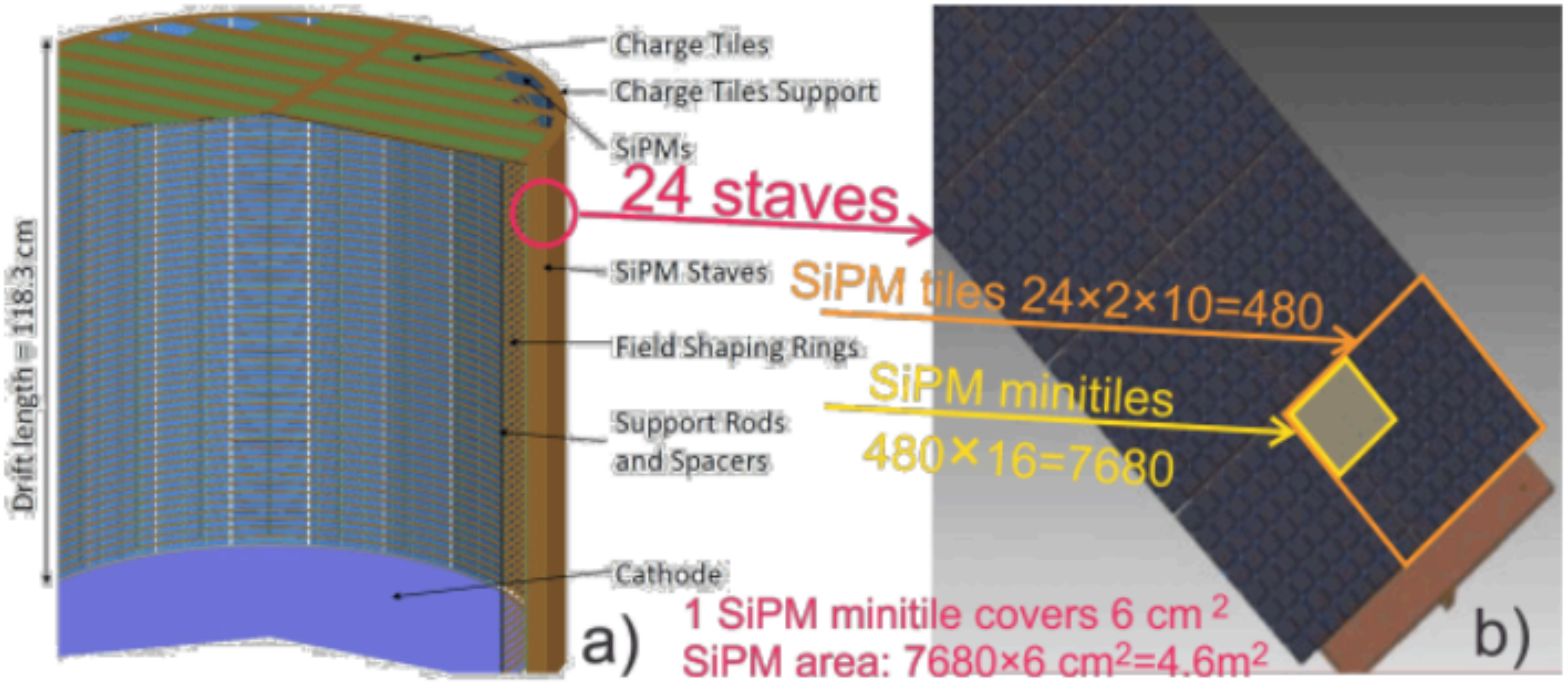




https://doi.org/10.1140/epjc/s10052-022-11072-8

SiPM Channels in nEXO

- nEXO will have 7680 SiPM channels
  - 24 SiPM staves in nEXO
  - Each stave is composed of 2x10 SiPM tiles for 20 tiles per stave
  - Each SiPM tile is composed of 16 mini-tiles



Fluorescence

- nEXO doesn't plan to use plastics commonly known to fluoresce in LXe TPC
  - e.g PTFE
- The only non-metallic surfaces exposed to the active volume are
  - Pure silicon
  - Fused silica
  - Thin MgF2
- none of which exhibit %-level fluorescence in high purities and low-radiation environments

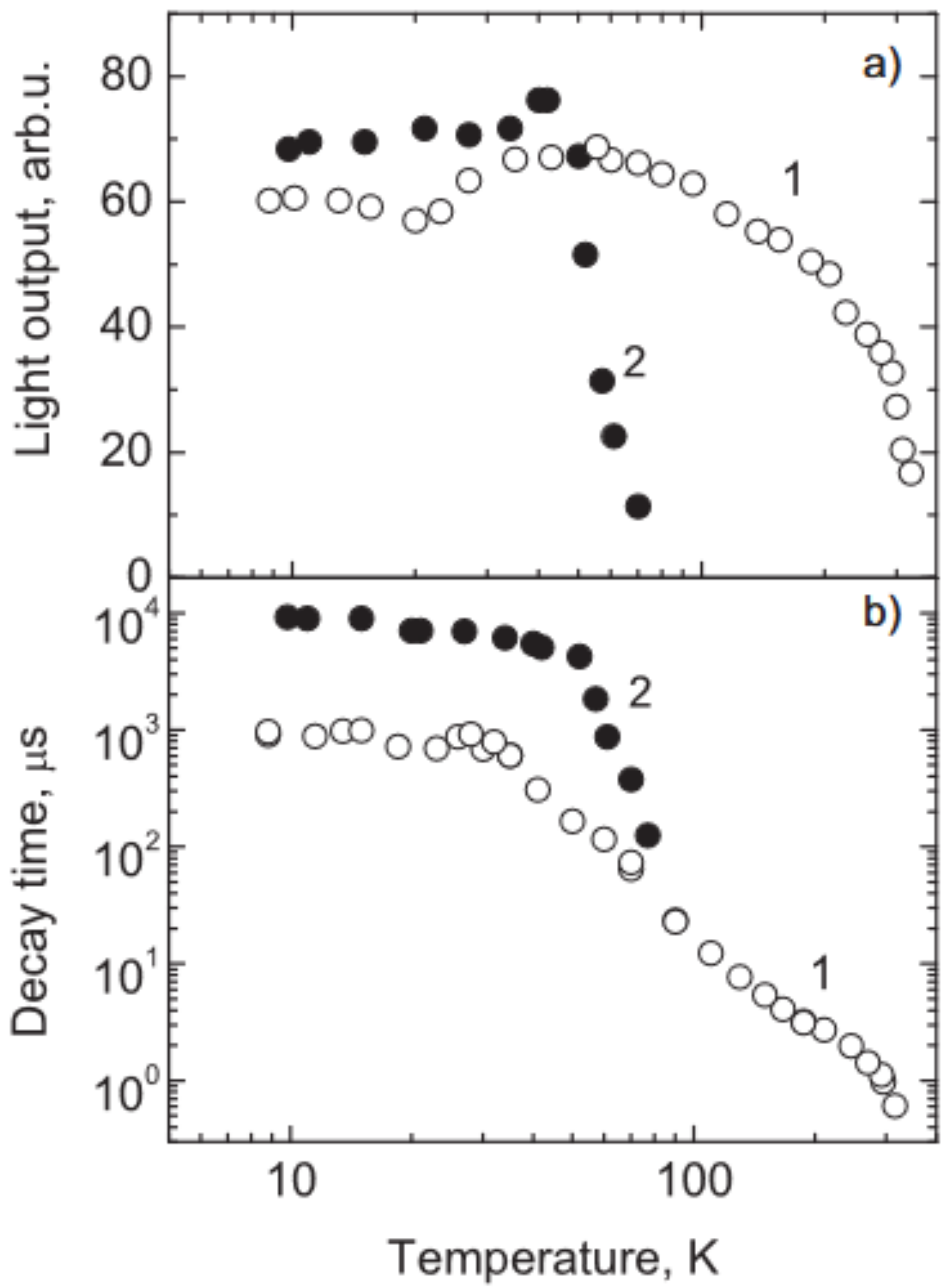
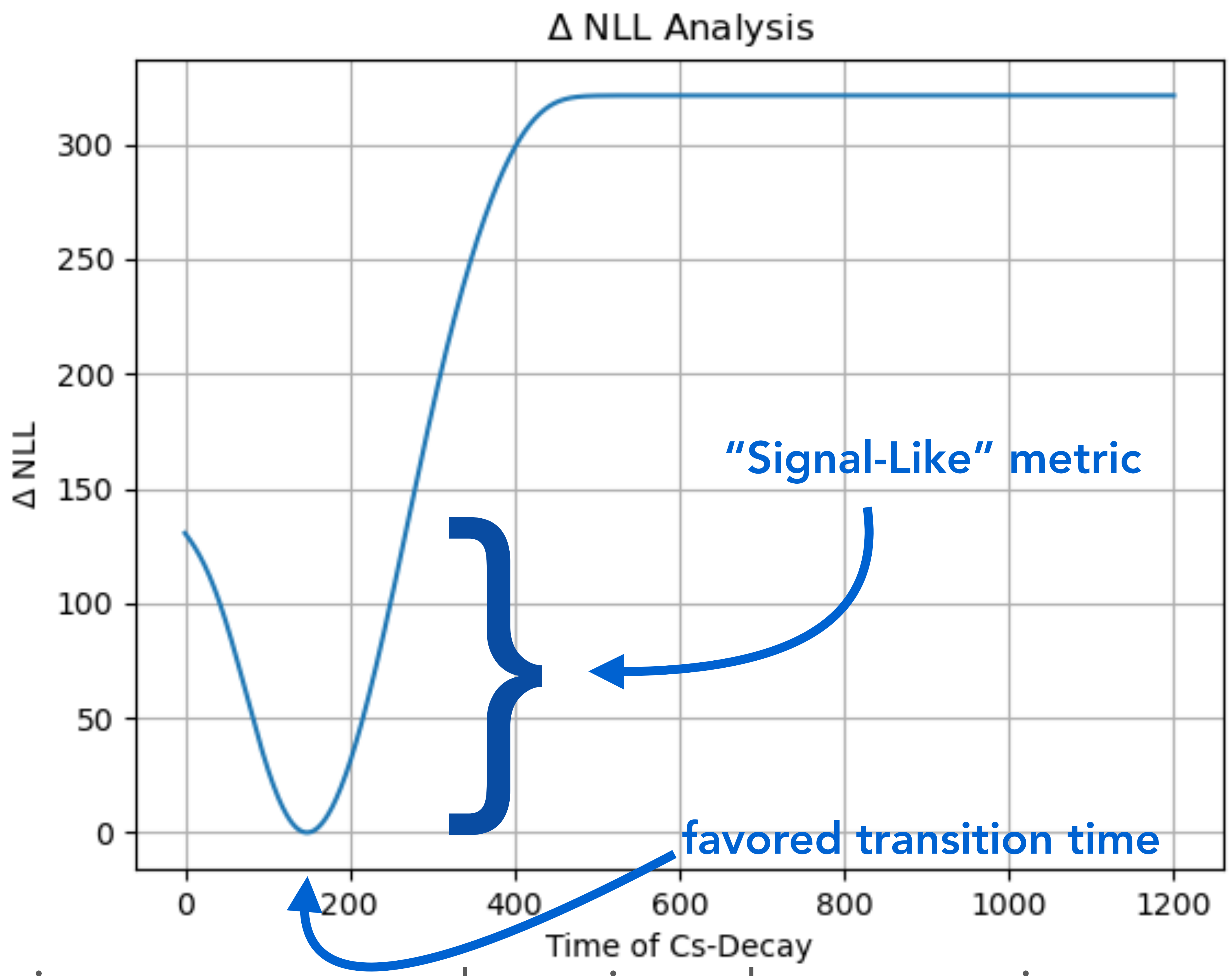


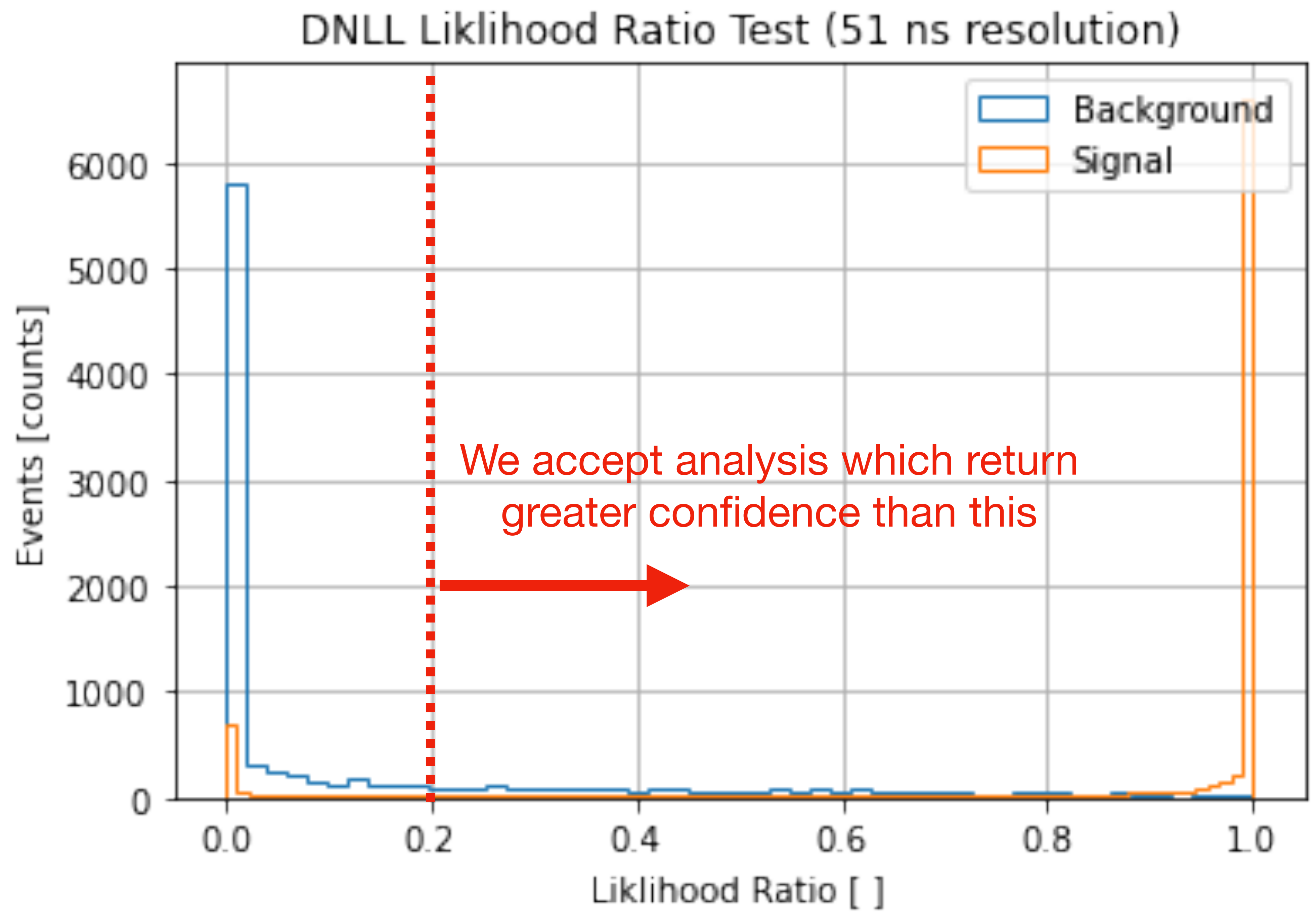
Figure 9 (a) Temperature dependence of the scintillation light output in CaF_2 (1) and MgF_2 (2). (b) Temperature dependence of the main scintillation decay time constant of CaF_2 (1) and MgF_2 (2).

ΔNLL Analysis

- Once an MC sample (either signal or background) is made a ΔNLL analysis is done

- The Δ in this analysis is used as the metric for how "signal-like" an MC event is found to be

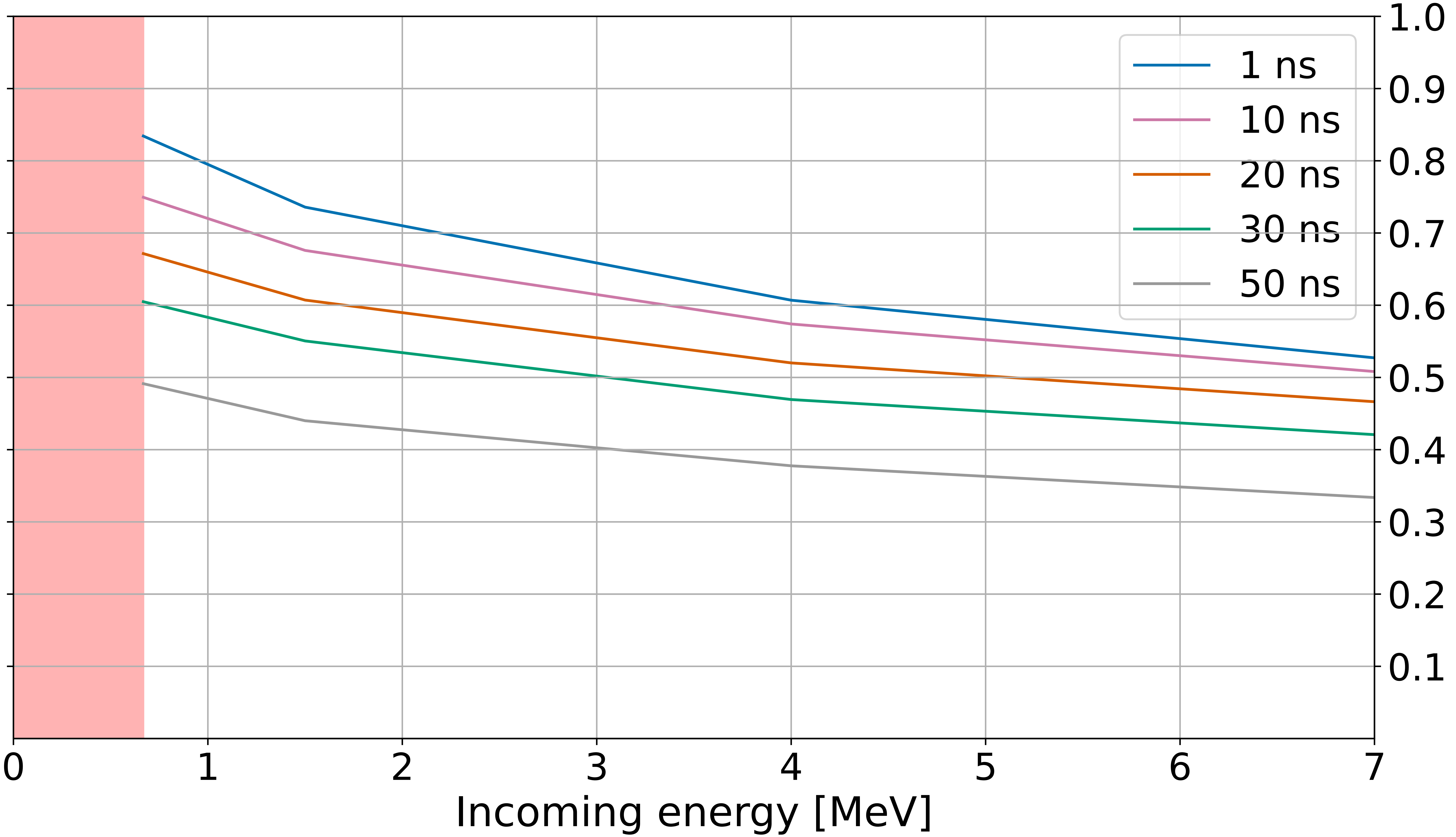




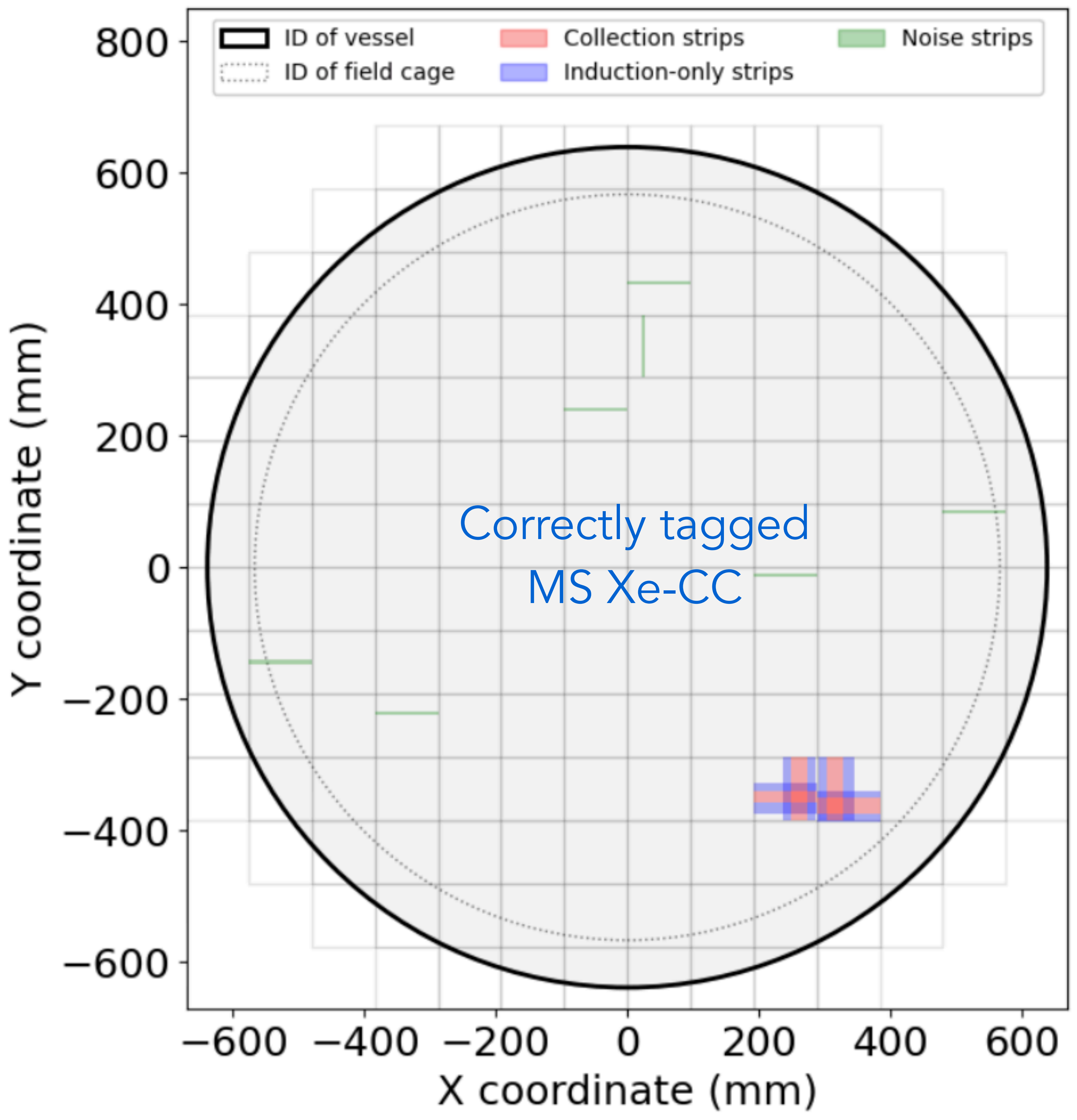
- For a given energy and res time these metrics are then compiled and mapped from [0,1] using q = 1-$e^{-\Delta}$

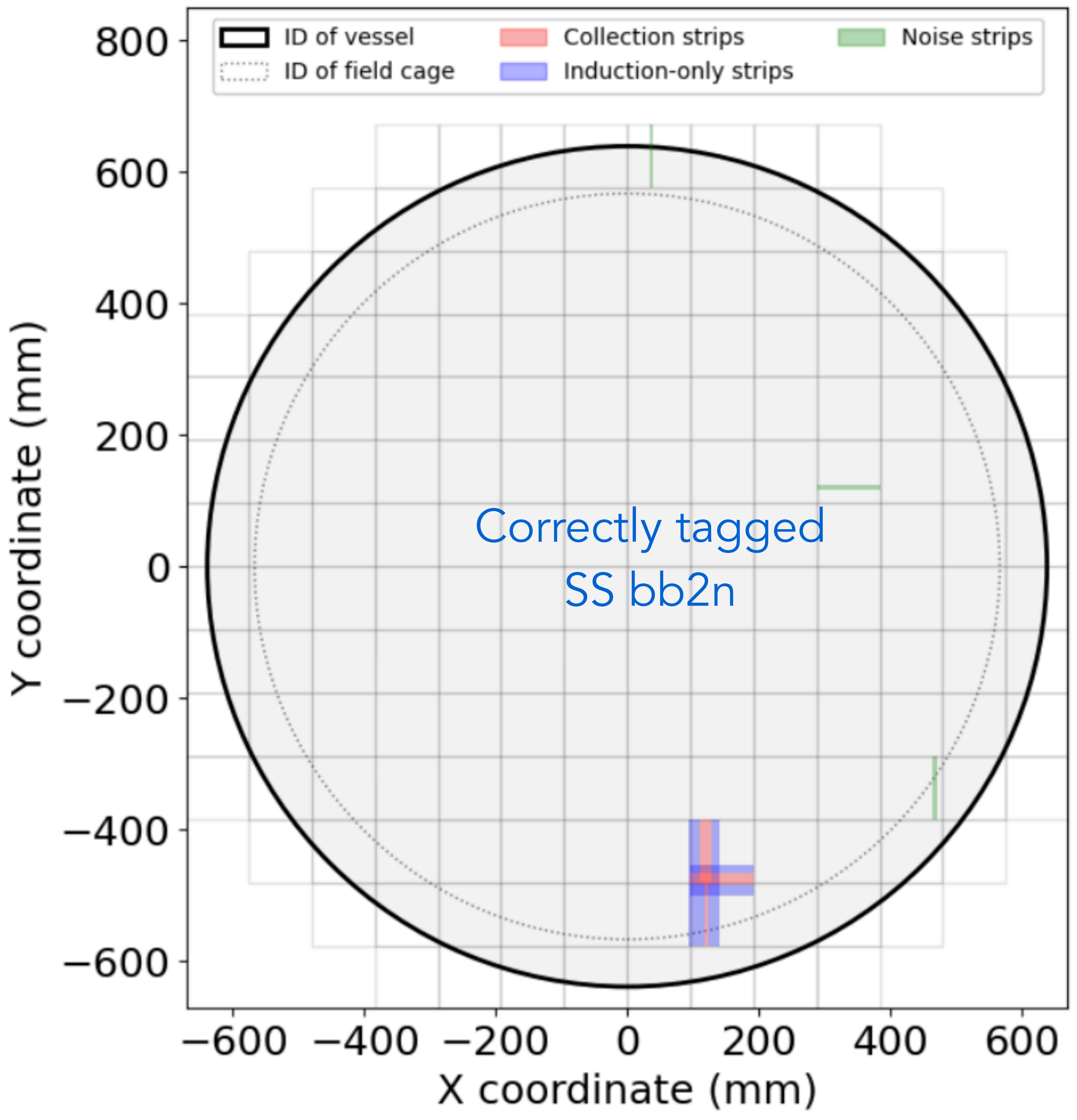
- A vertical line is then drawn on this plot and the integral is taken above the line to generate an ROC data point for that energy and res time

Energy Dependance



Ionization Signal





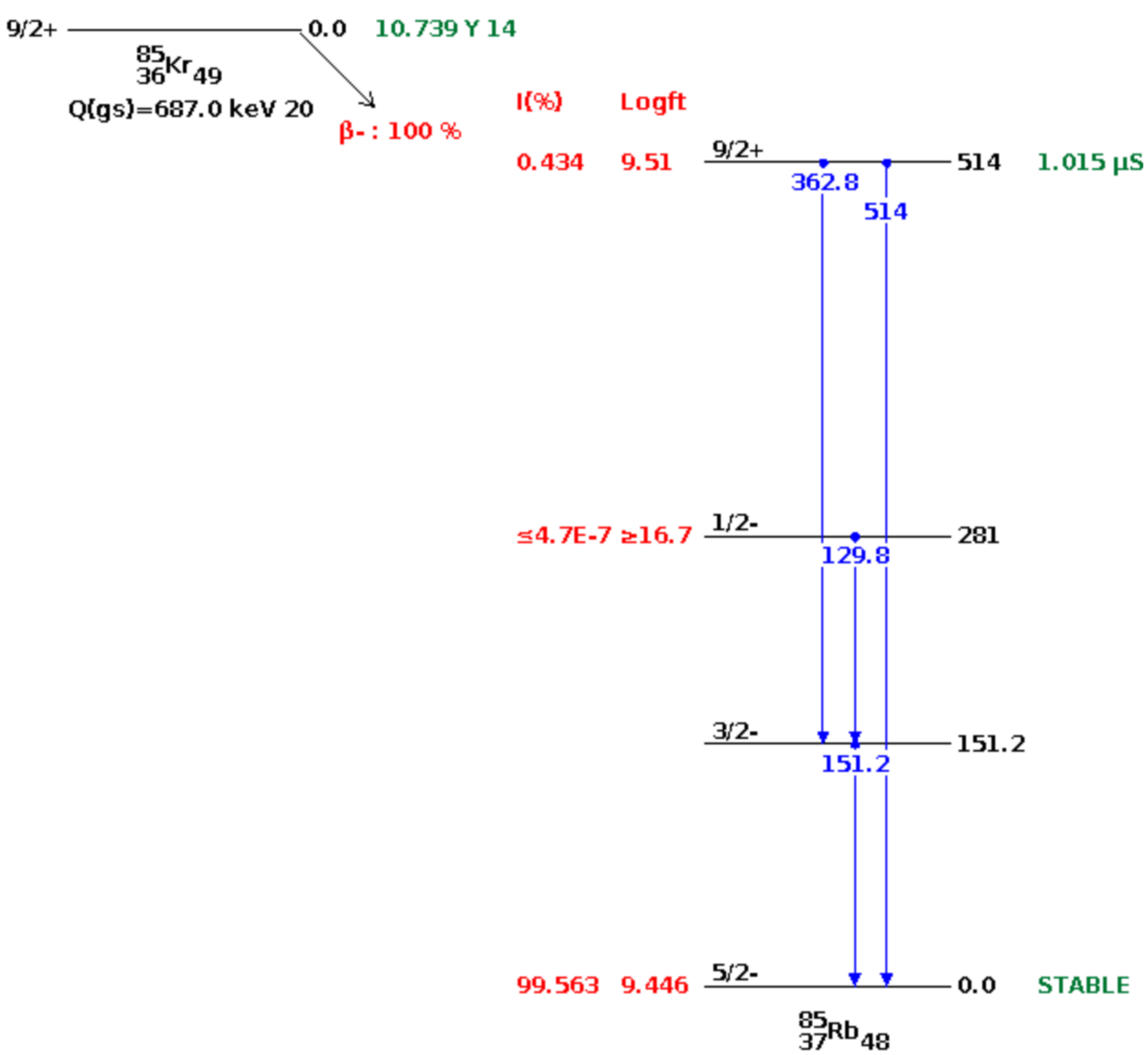
- Delayed de-excitation cannot easily be seen in ionization channel due to relatively slow drift of electrons
- ^{136}Xe-CC signal will tend to create multiple interaction vertexes in the LXe
- Can be used to tag signals over backgrounds as well
  - Not nearly as efficient as scintillation timing though

Extending the Reach of nEXO (FDM & ^{8}B)

- The 7 MeV upper limit is set by the neutron separation energy of ^{136}Cs
  - EXO-200 was able to go beyond this limit because it considered multiple isotopes
- This will be necessary if we want to make competitive measurements of ^{8}B neutrinos
- Three ways nEXO could extend its range
  1. Recent studies suggest the neutron separation channel is suppressed so it may not matter
  2. Account for the free neutron in the analysis as was done in the supernova paper
  3. Consider capture on ^{134}Xe as well

Delayed Transition Backgrounds

- Two most common delayed transitions in LXe TPCs are ^{85}Kr and ^{212}Bi
- ^{212}Bi has a ~9 MeV alpha as it's delayed component
  - Easily taggable
- ^{85}Kr can be discriminated against using the ratio of prompt to delayed signal
  - $R_{Kr} < 0.34$
  - $R_{Cs} > 3.21$



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Systematic Uncertainty

- Dominant source of systematic uncertainty in this study will be from the total solar neutrino flux on Earth
- Will also be systematic uncertainty on the charged-current cross-section
  - Currently estimated to be at ~11% due to uncertainty in the Gamow-Teller transition strength
- Assume for this work that in the ~15 years it would take to build nEXO and take this data, this uncertainty can be reduced to negligible levels
  - If this is not the case, the ^{7}Be solar neutrino line can be used as an in-situ calibration source
    - Could reduce this uncertainty down to ~8%

https://journals.aps.org/prc/abstract/10.1103/PhysRevC.84.051305

$0\nu\beta\beta$ Isotopes as Solar Neutrino Detectors

- $0\nu\beta\beta$ isotopes are theorized to make good solar neutrino detectors for several reasons
  - **β-decay forbidden**
    - Reduced backgrounds
    - Lower reaction thresholds
  - **Rich odd-odd daughter structure**
    - Lower reaction thresholds
    - Propensity for long-lived states