Cherenkov Light Separation in LXe for Improved Bkg Rejection

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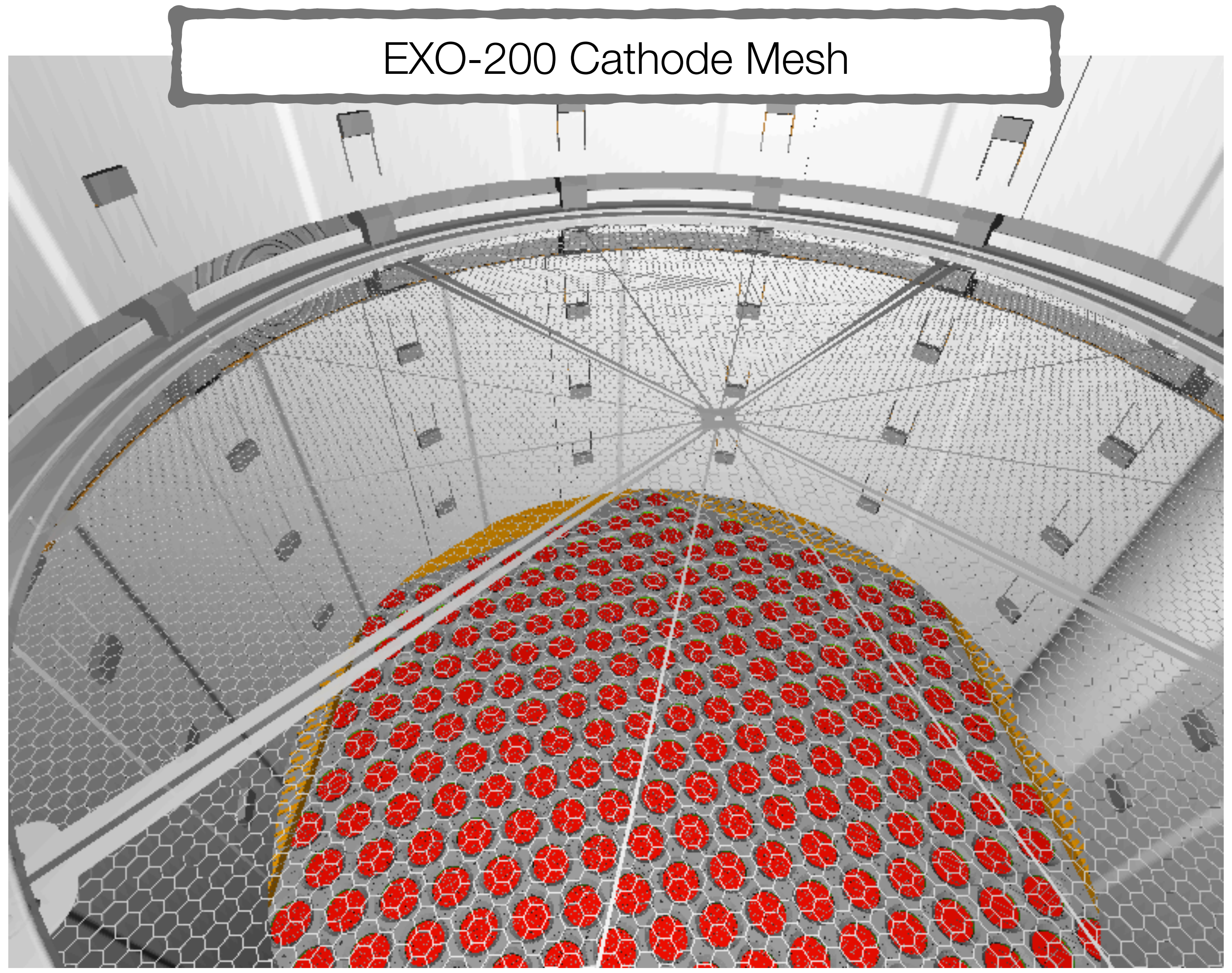
Workshop on Xenon Detector 0vbb Searches, SLAC

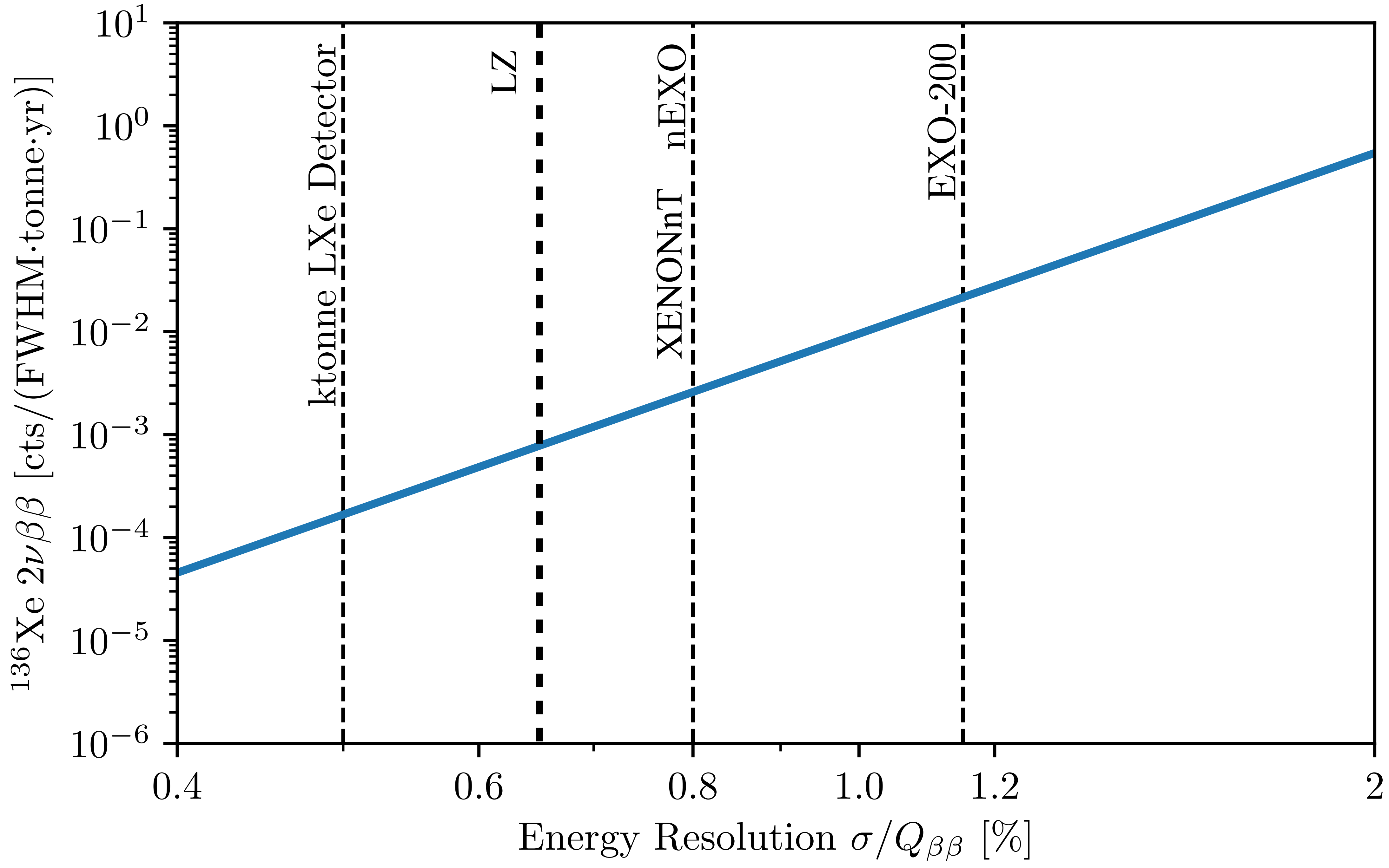
Light Transport Simulations With Chroma



- Main Advantages:
  - Easy to use
  - Detailed geometry possible through CAD model import
  - GPU-acceleration allow up to 300x faster photon propagation than Geant4
- Being/was used in other experiments/projects:
  - EXO-200, nEXO, MicroBoone, PROSPECT, SNO(+), DUNE
- Publications with simulations based on Chroma:
  - Phys. Rev. D 97, 052006 (2018)
  - Phys. Rev. D 101, 072002 (2020)
  - JINST 17 (2022) P07018

Goal #1: Energy Resolution ($0\nu\beta\beta$ background reduction)

- Require energy resolution on the order of $\sigma/Q_{\beta\beta} \sim 0.5\ \%$ to suppress leakage of $2\nu\beta\beta$ background events into the ROI
- Energy resolution in large LXe detectors typically limited by noise in the light channel
  - Limited by total light collection efficiency ϵ (dependent on λ_{abs} and λ_{scat} of LXe)
- **What is the total light collection efficiency achievable in a ktonne LXe detector? (Need at least 10%)**



For sufficiently low charge noise the energy resolution is dominated by the light collection efficiency ϵ

$$\frac{\sigma_{\langle E\rangle}}{\langle E\rangle} = \frac{\sqrt{\overset{\substack{\text{Fano noise}\\ \uparrow}}{F\cdot\langle E\rangle} + \underbrace{\overset{\substack{\text{Charge collection}\\ \uparrow}}{\frac{Q(1-e^{-t/\tau})}{e^{-t/\tau}}} + \overset{\substack{\text{e- lifetime systematic}\\ \uparrow}}{\frac{Q^2}{(e^{-t/\tau})^2}\left(\frac{t}{\tau}\right)^2\sigma_\tau^2} + \overset{\substack{\text{charge electronics}\\ \uparrow}}{\frac{\sigma^2_{Q,\text{noise}}}{(e^{-t/\tau})^2}}}_{\text{Charge Noise}} + \underbrace{\frac{S}{\epsilon}\left[\overset{\substack{\text{Light collection}\\ \uparrow}}{(1-\epsilon)} + \overset{\substack{\text{Correlated avalanches}\\ \uparrow}}{\frac{\Lambda}{(1+\Lambda)^2}}\right] + \overset{\substack{\text{Dark current and gain}\\ \uparrow}}{\frac{\text{DC}+\eta_{\text{noise}}}{\epsilon^2(1+\Lambda)^2}} + \overset{\substack{\text{Lightmap Error}\\ \uparrow}}{S^2\sigma_{lm}^2}}_{\text{Light noise}}}}{\langle E\rangle}$$

PTE vs Absorption Length in LXe

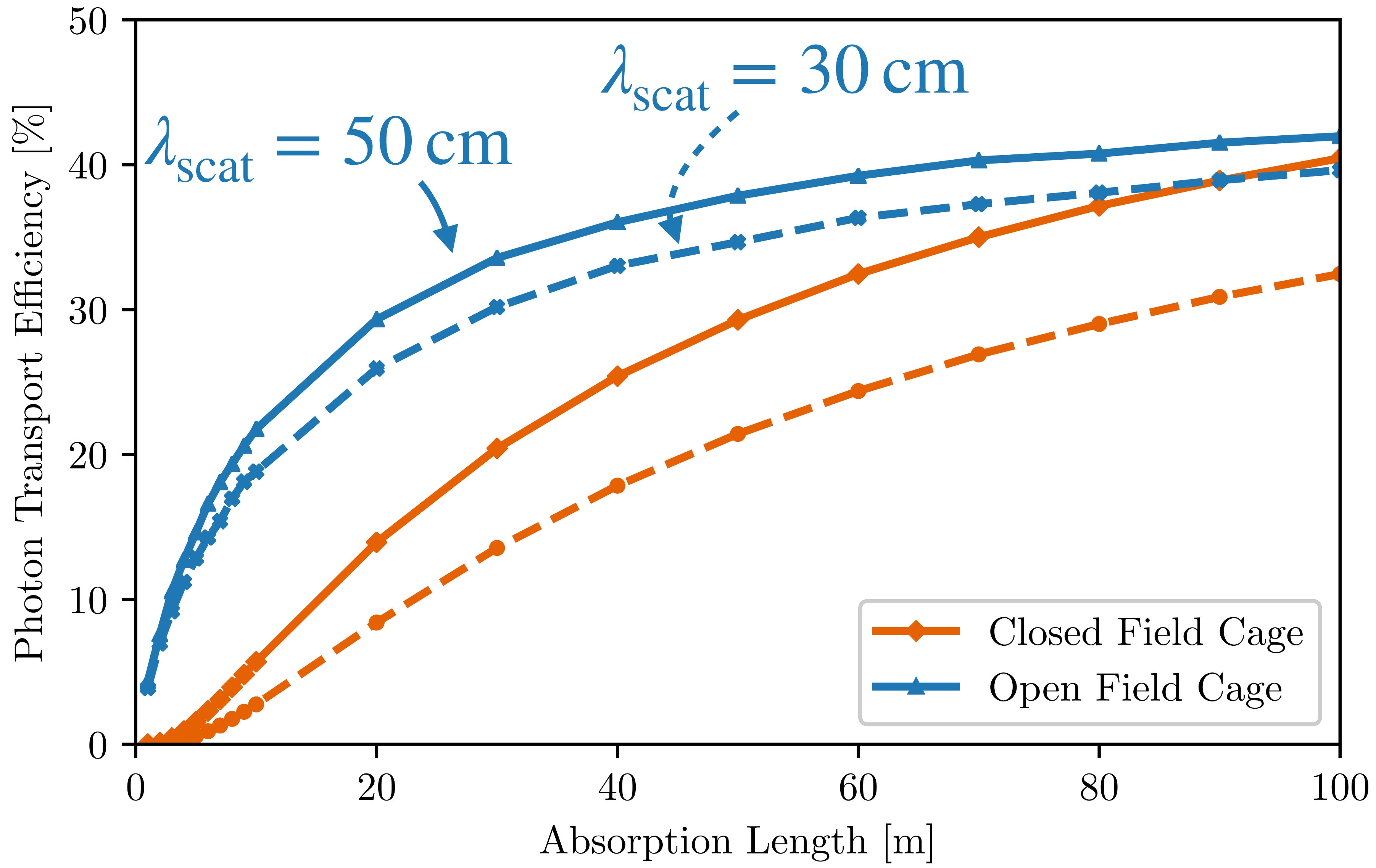
- The photon transport efficiency (PTE) is defined as

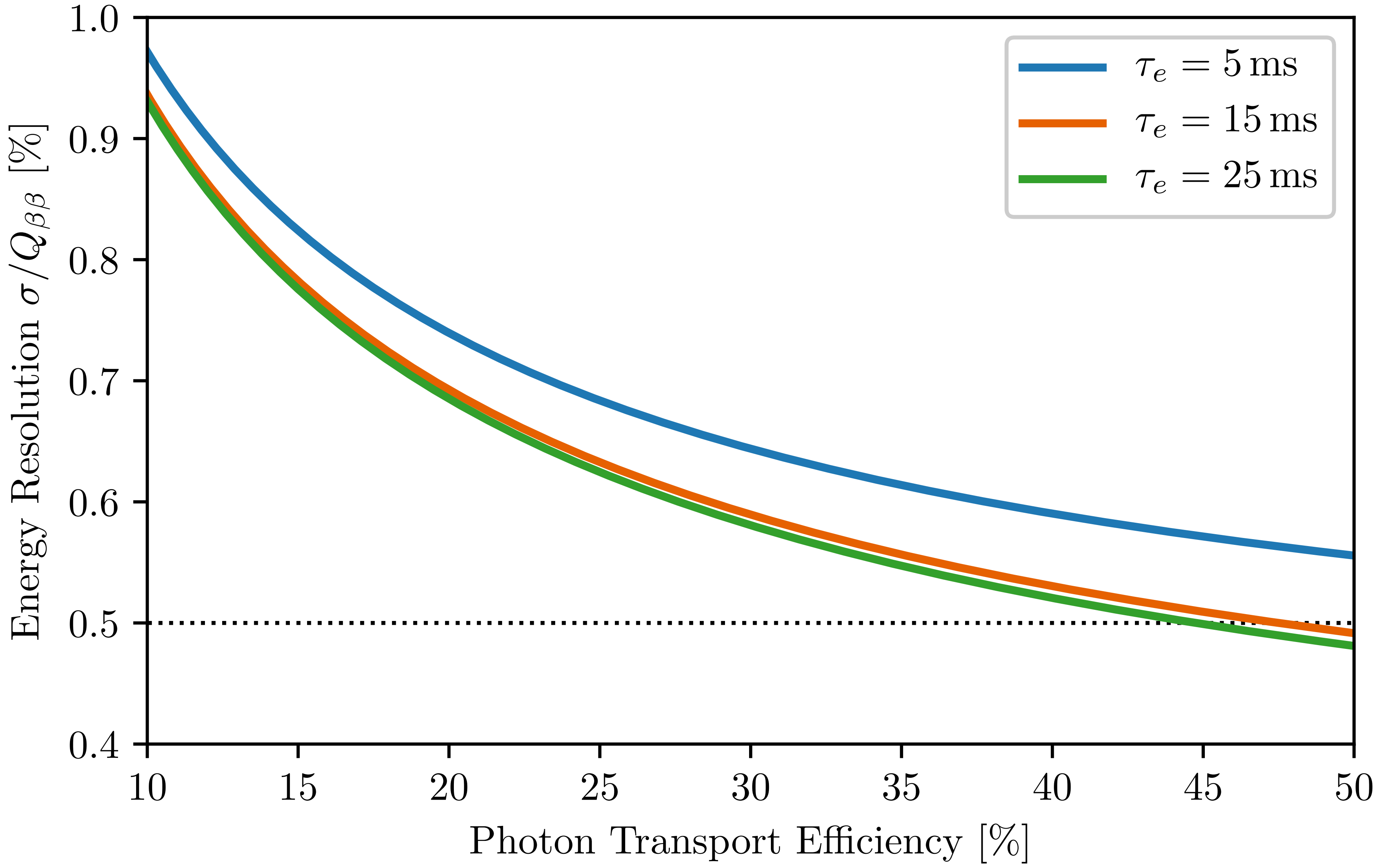
$$\mathrm{PTE} = \frac{N_{\mathrm{abs}}}{N_0}$$

Photon transport is mostly diffuse due to length scale of the detector and relative short scattering length

- Simulation at each point includes 10^8 photons
- λ_{abs} poorly constrained due to size of previous experiments
  - Scales with xenon purity (no upper bound)
  - LZ and XENON1T use $30\,\mathrm{m}$ and $50\,\mathrm{m}$, respectively

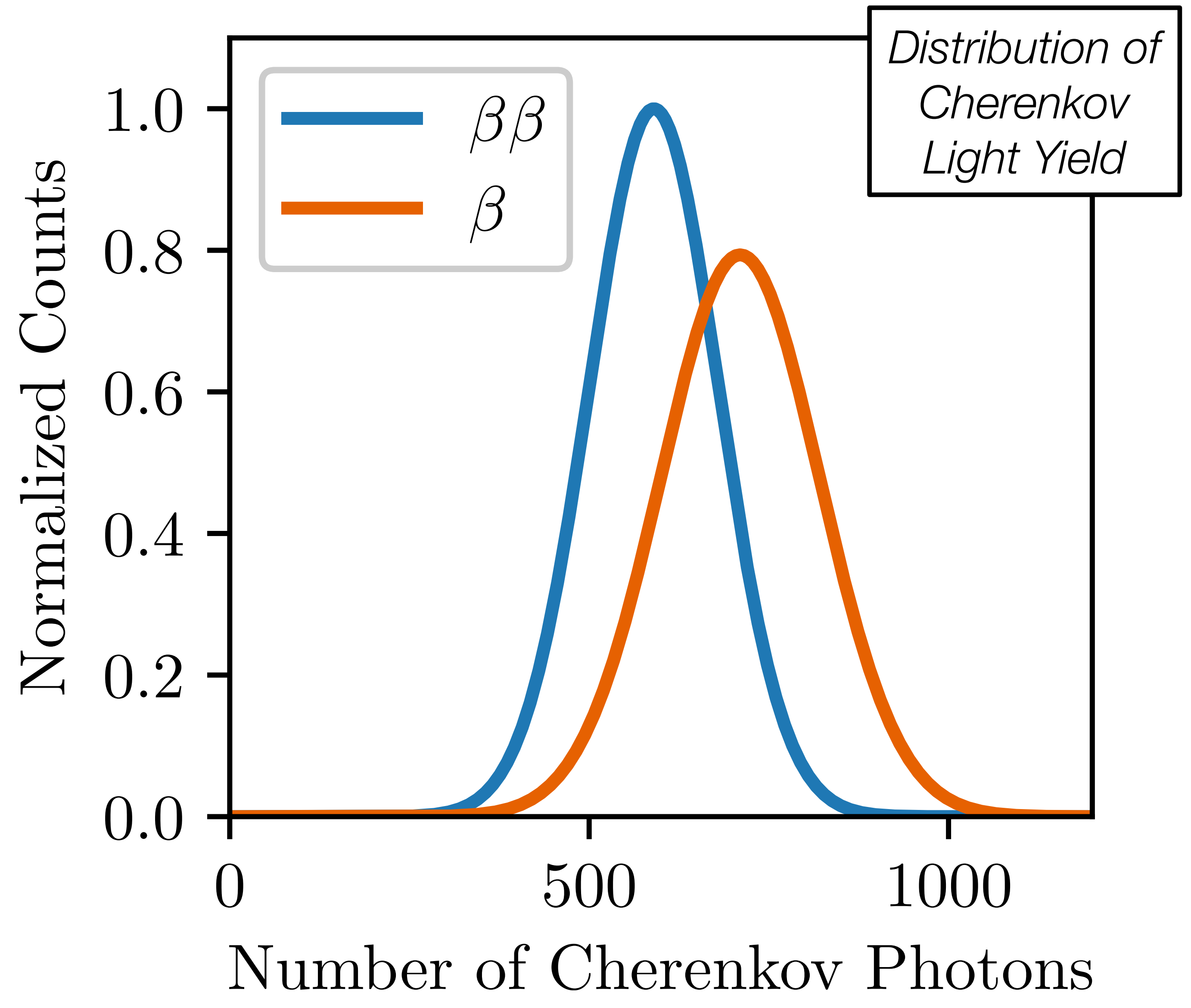
→ *Detector parameters and simulation inputs in the backup slides*



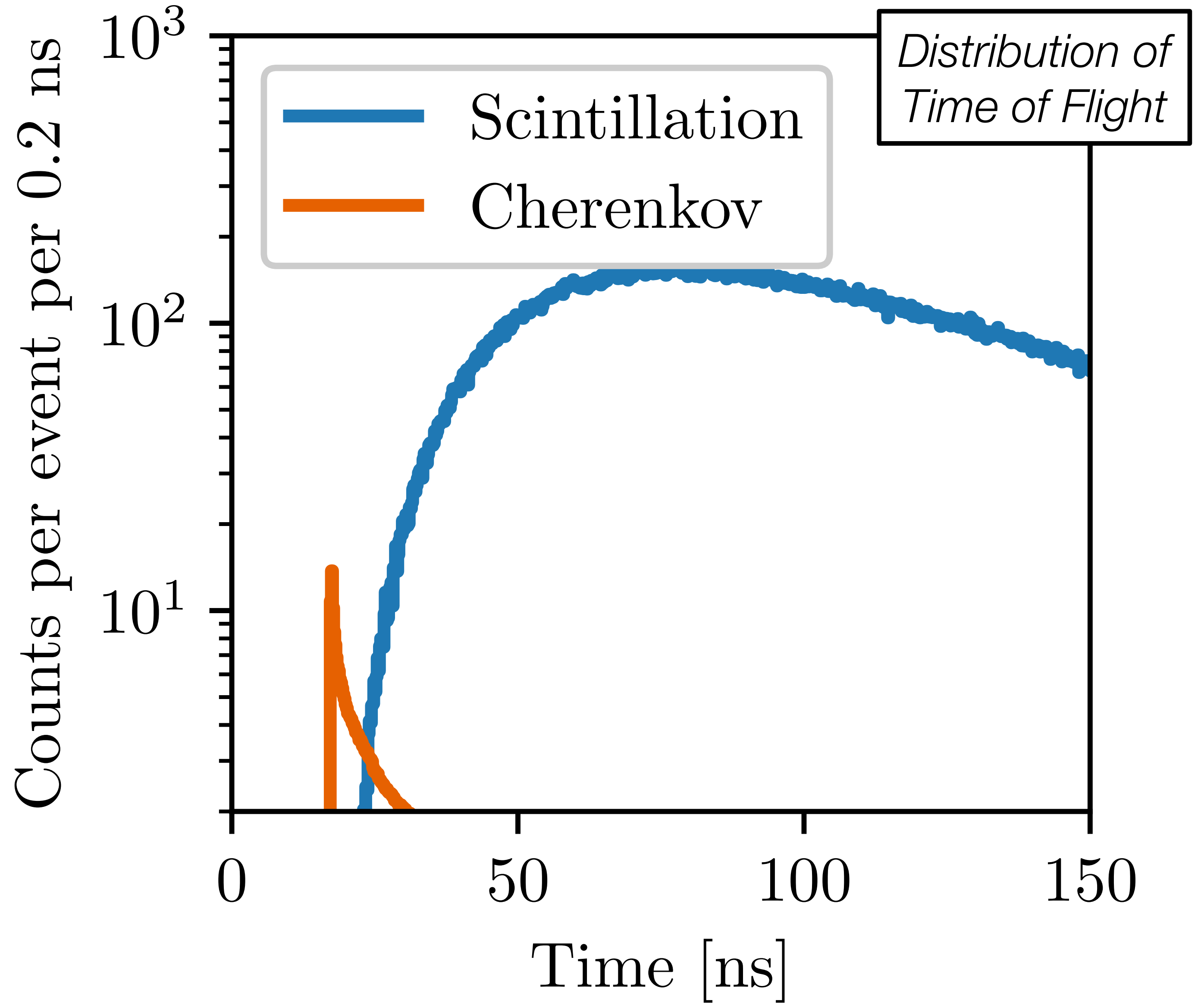


Goal #2: Time Resolution (Solar ν background reduction)

- Based off: Nucl.Instrum.Meth.A 922 (2019) 76-83
- Rejection of solar neutrinos from $^{8}\mathrm{B}$ based on time of flight separation between scintillation and Cherenkov light
  - Charge current interactions are considered negligible: $\nu + {}^{136}\mathrm{Xe} \longrightarrow e^{-} + {}^{136}\mathrm{Cs}^{(*)}$
  - Elastic scattering of neutrinos off of electrons more tricky: $\nu + e^{-} \longrightarrow \nu + e^{-}$
  - Discrimination of single β of energy $E_{\beta} = Q_{\beta\beta} \pm \mathrm{FWHM}/2$ against $0\nu\beta\beta$
- Use of Chroma allows more realistic detector geometry including reflections off of components



Distribution of Cherenkov Light Yield

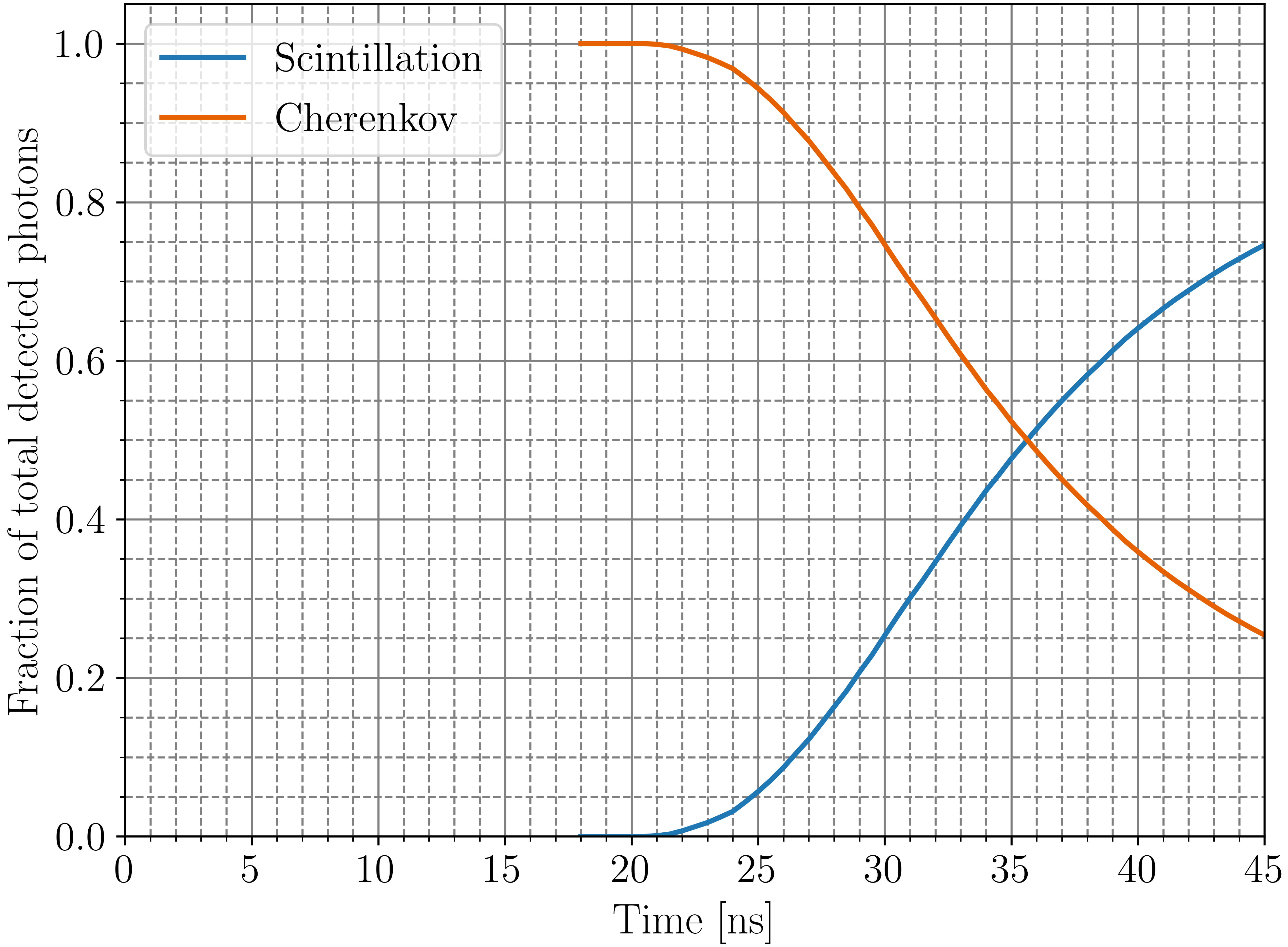


Distribution of Time of Flight

Fraction of Photons vs Time

- Cherenkov and scintillation photons better separated in time in a ktonne detector compared to a tonne-scale detector

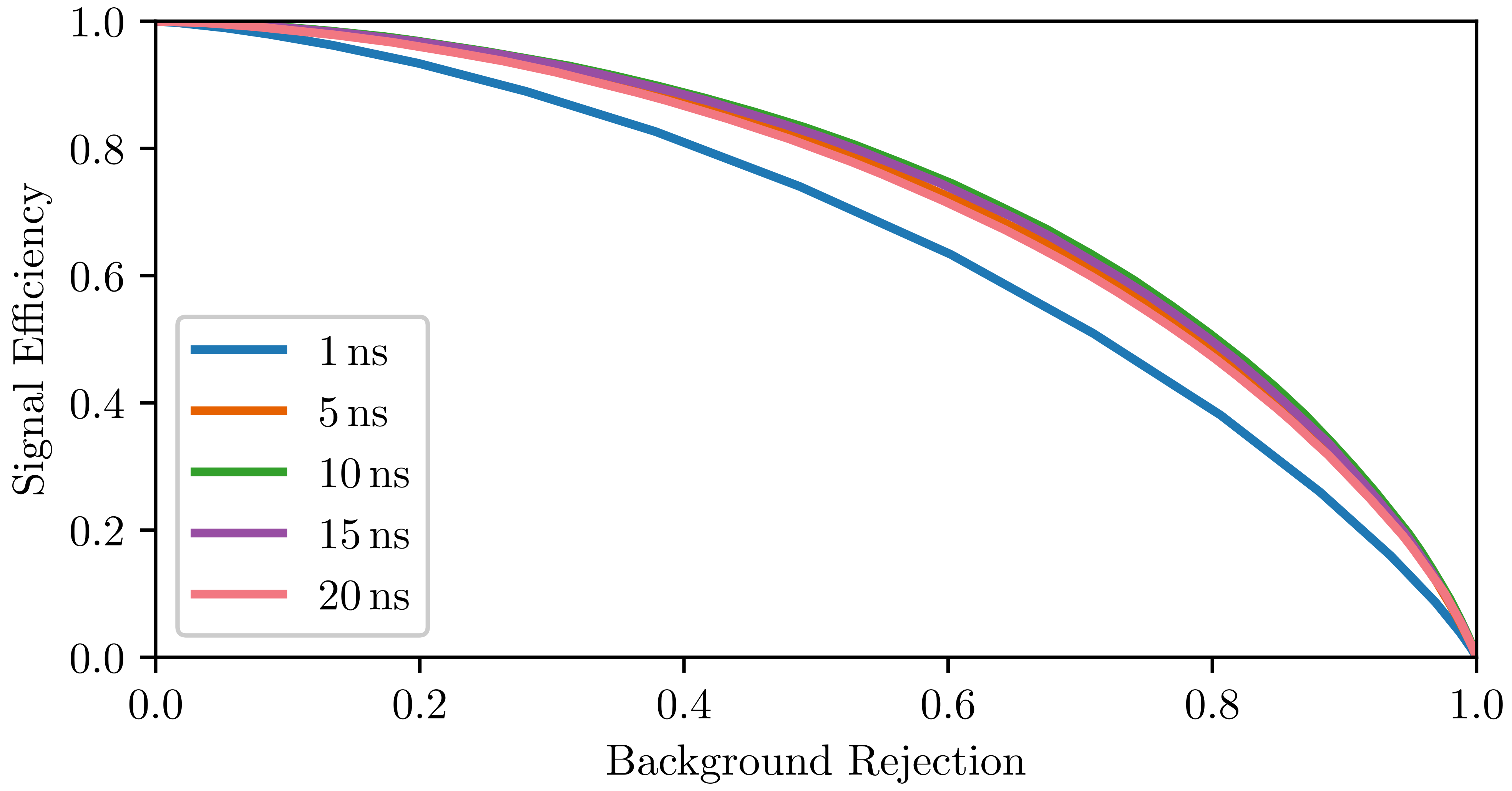
- Within first $10\,\mathrm{ns}$ Cherenkov photons make up $80\,\%$ of all detected photons

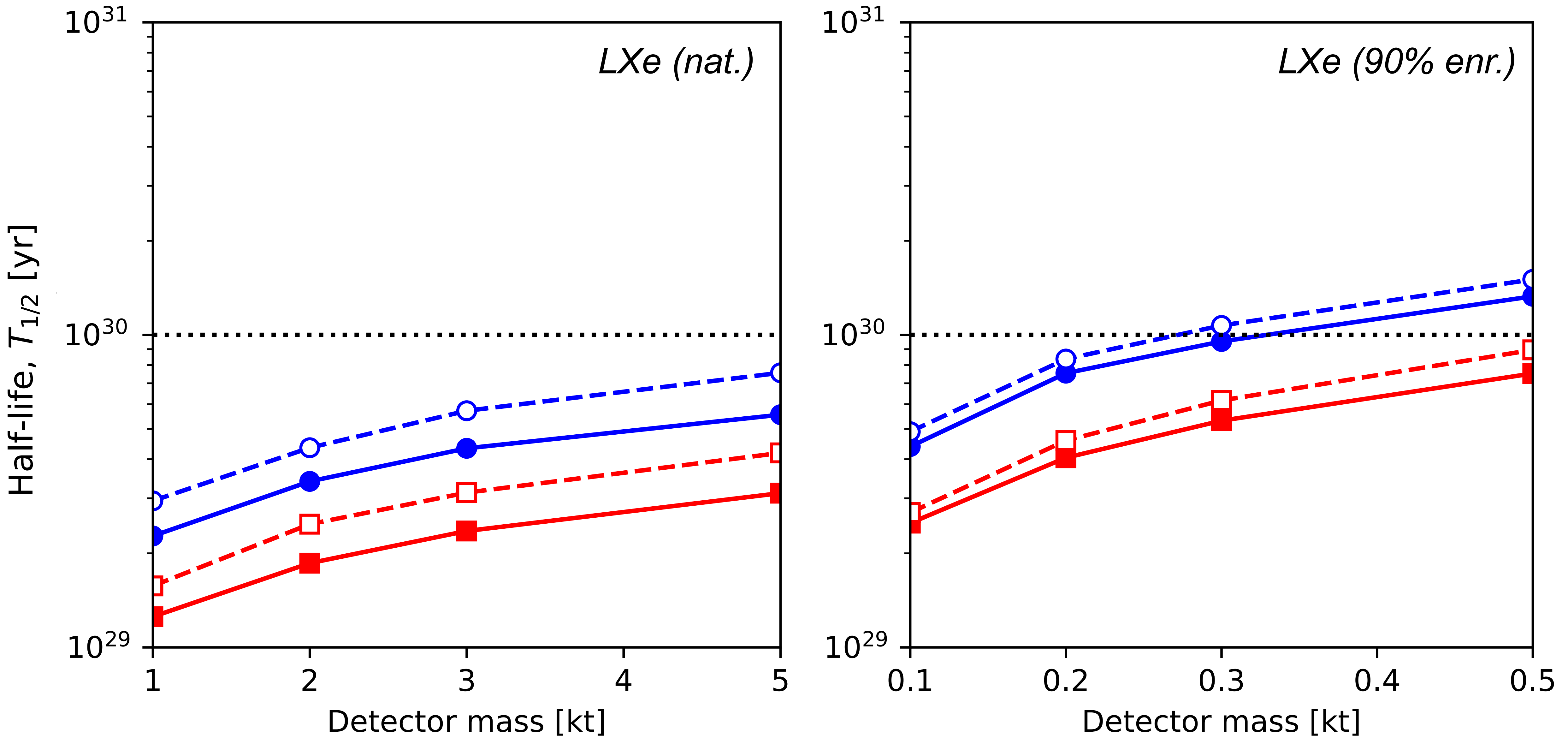


Impact on Sensitivity

- A $\mathbf{10\,ns}$ time resolution yields best result with $\mathbf{65\,\%}$ signal efficiency at $\mathbf{65\,\%}$ background rejection
- Increase in sensitivity $\sim 13\,\%$ or $\sim 35\,\%$ for a enriched or natural LXe detector
- Sub-ns 3D Photon-To-Digital Converter feasible and under development

3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works, [J.-F. Pratte et al., Sensors 21 (2021) 2, 598]()





Summary

- Simplifications used in this analysis:
    - Single wavelength used instead of full spectrum for scintillation and Cherenkov light
    - Directionality of Cherenkov light not exploited
    - Events only simulated in the center of the detector
- Simplified detector design allows to reach necessary $\mathbf{PTE} \sim \mathbf{40\,\%}$ with reasonable absorption and scattering lengths in LXe
- A $\mathbf{10\,ns}$ time resolution yields best result with $\mathbf{65\,\%}$ signal efficiency at $\mathbf{65\,\%}$ background rejection

BACKUP SLIDES

Wavelength Dependence

- For simplicity only simulate scintillation photons at $178\,\mathrm{nm}$ and Cherenkov photons at $300\,\mathrm{nm}$

- Optical properties at
  - $178\,\mathrm{nm}$ taken from nEXO
  - $300\,\mathrm{nm}$ either scaled from values at $178\,\mathrm{nm}$ or found literature values

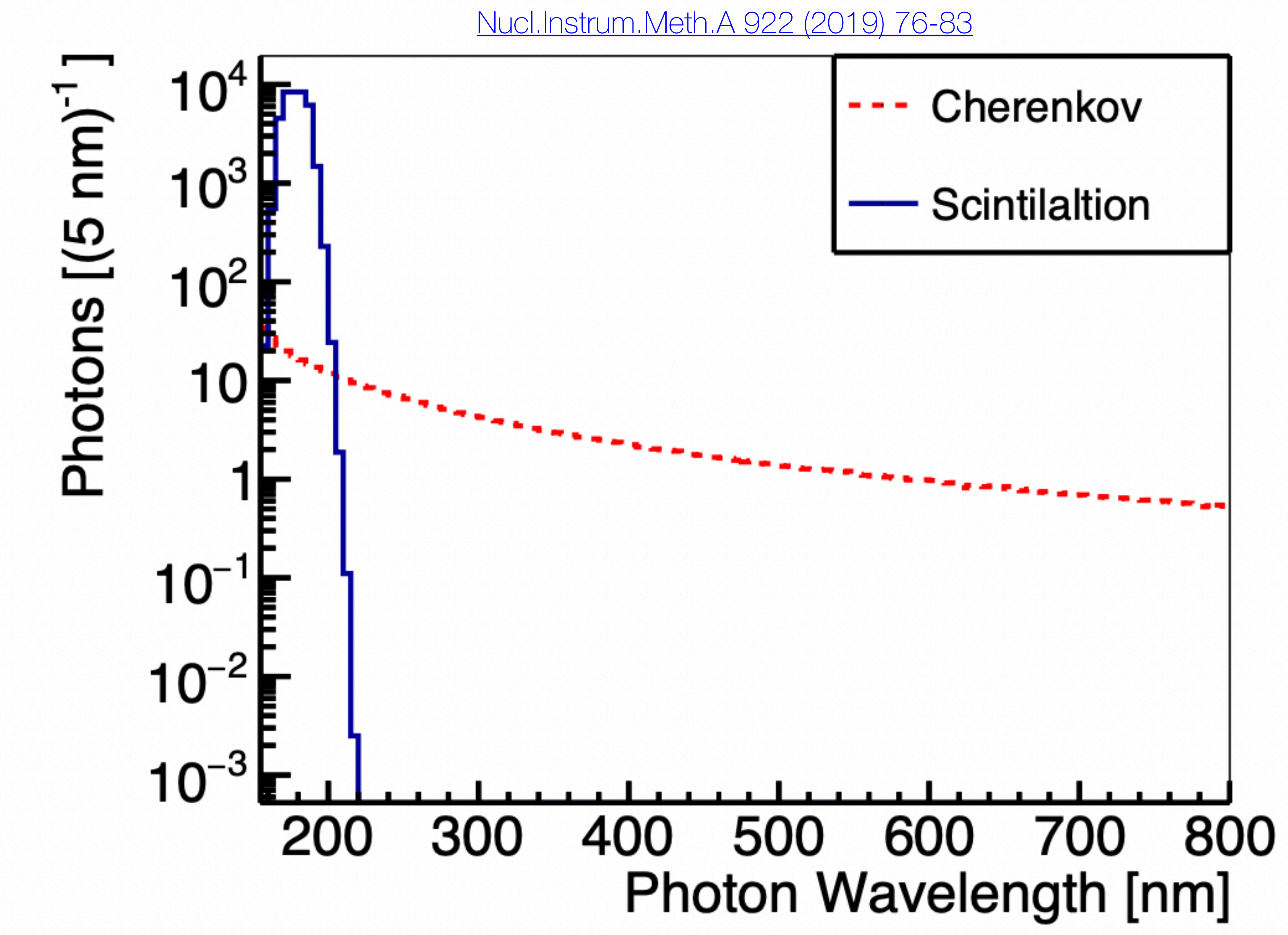
Isothermal compressibility of LXe

Index of refraction of LXe

$$\lambda_{\text{scat}}^{-1} = \frac{16\pi^2}{6\lambda^4}\left[kT\rho^2\kappa_T\left(\frac{(n^2-1)(n^2+2)}{3}\right)^2\right]$$

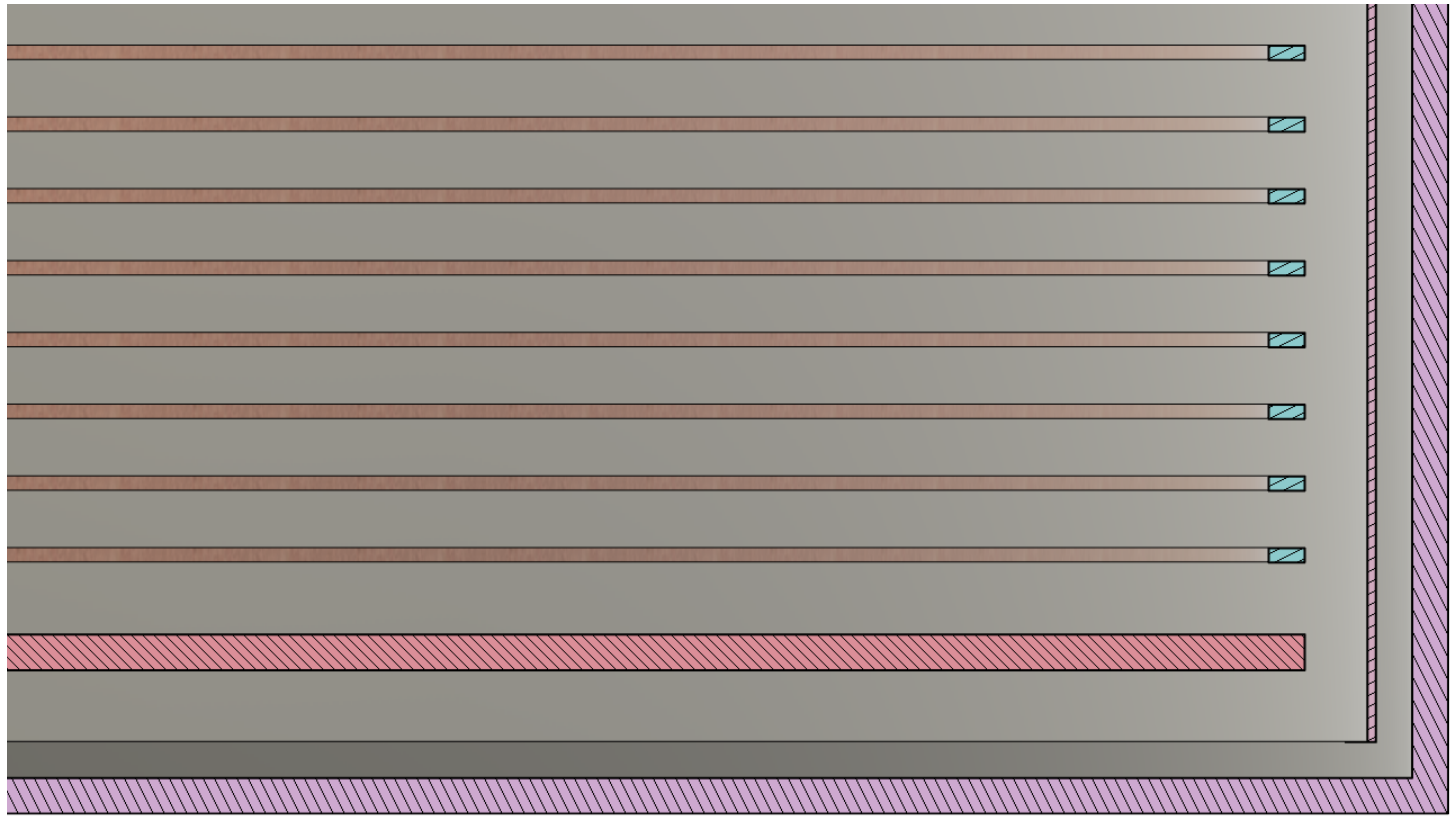
Wavelength of scintillation light

Density of LXe


Nucl.Instrum.Meth.A 922 (2019) 76-83

Parameters of a ktonne Detector

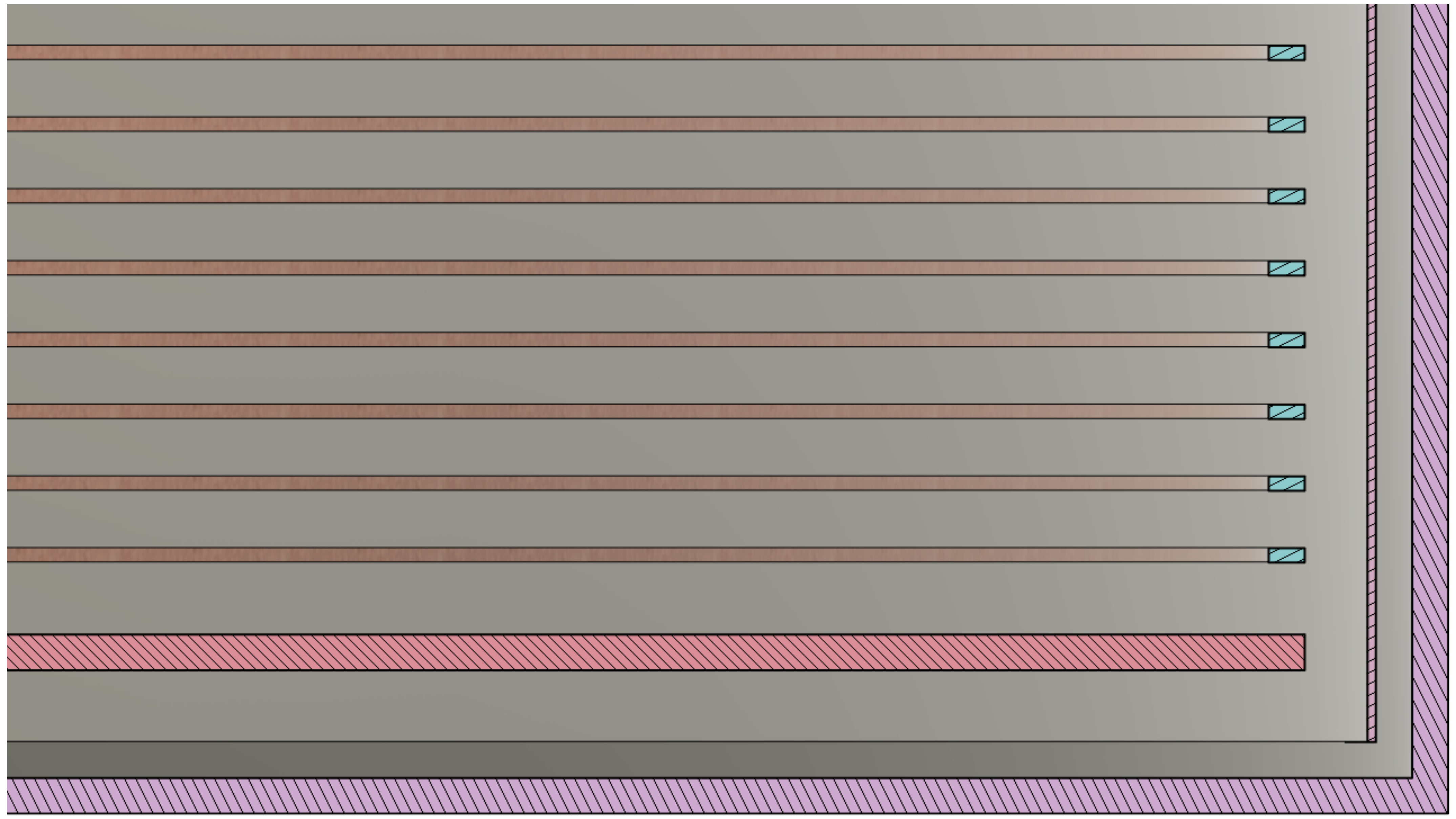
PARAMETER	VALUE	UNITS
Vessel height	7,4	m
Vessel diameter	7,4	m
Drift length	7,32	m
Field ring inner diameter	7,3	m
Field ring width	10	mm
Field ring height	4	mm
Field ring spacing	20	mm
Number of field rings	365	



→ nEXO-like Design:
Photo-detectors (SiPMs) covering barrel behind the FSRs

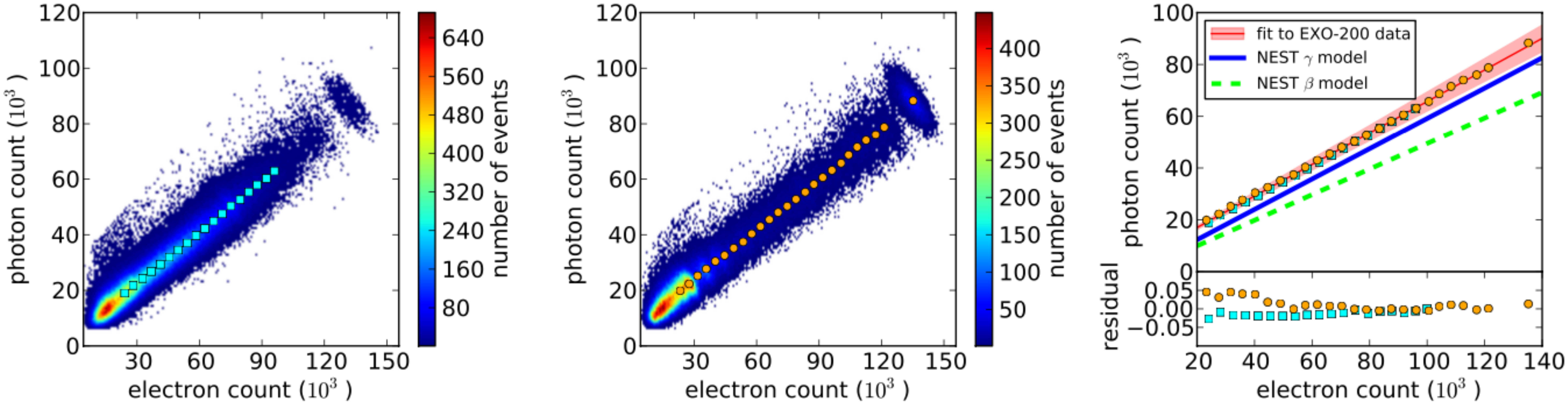
Parameters of a ktonne Detector

PARAMETER	SCINT.	CHERENKOV
Wavelength	178nm	300nm
LXe Absorption Length	20m	50m
LXe Scattering Length	30cm	242cm
LXe Index of Refraction	1,69	1,43
Cathode	80%	90%
Field Shaping Rings	80%	90%
Anode	20%	38%
Vessel	0%	0%
Diffuse Reflectivity of all components above	0%	0%
Teflon Specular Reflectivity	0%	0%
Teflon Diffuse Reflectivity	95%	95%
SiPMs	https://arxiv.org/abs/1910.06438	



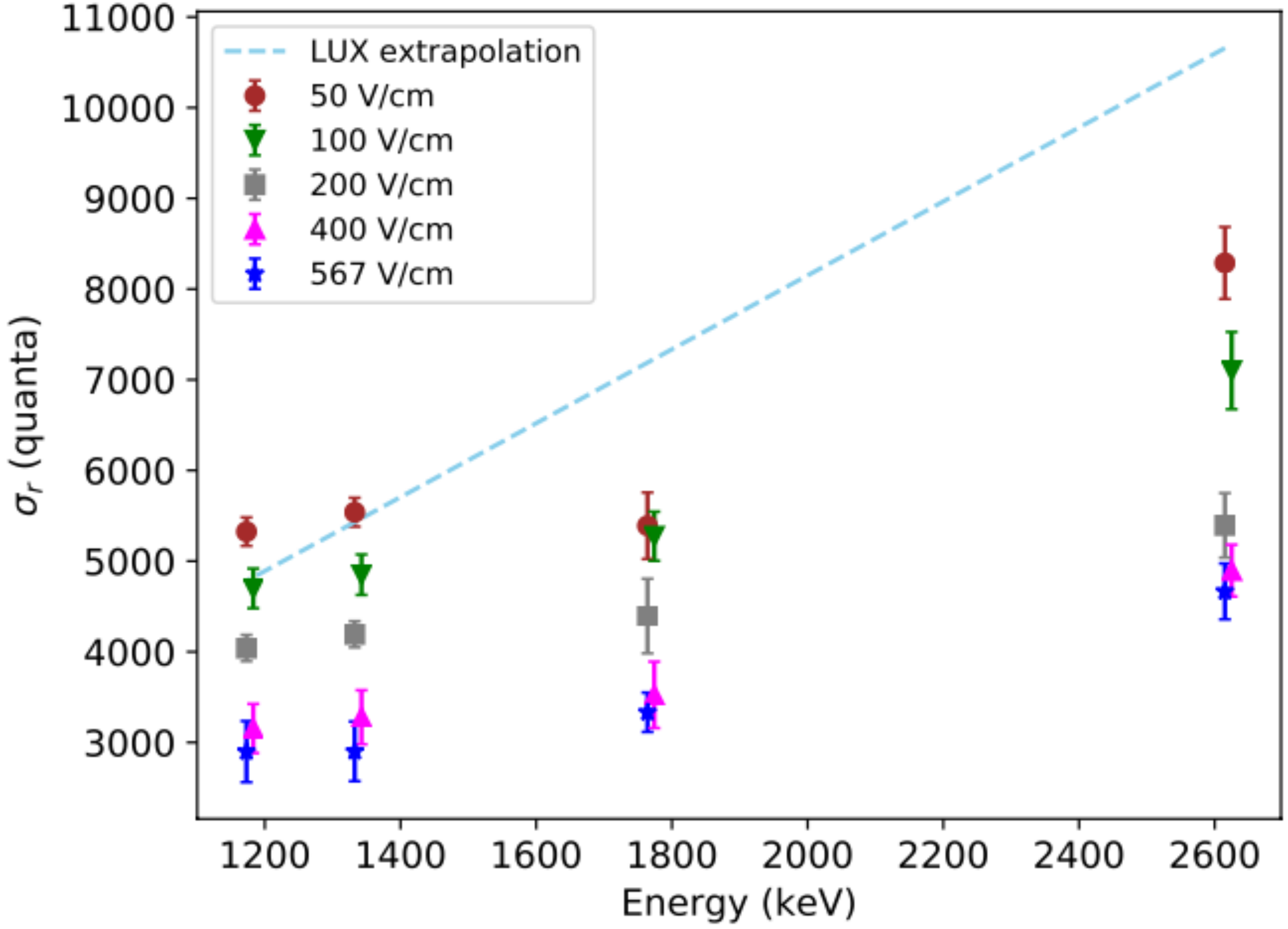
→ nEXO-like Design:
Photo-detectors (SiPMs) covering barrel behind the FSRs

Scintillation Light Yield from EXO-200

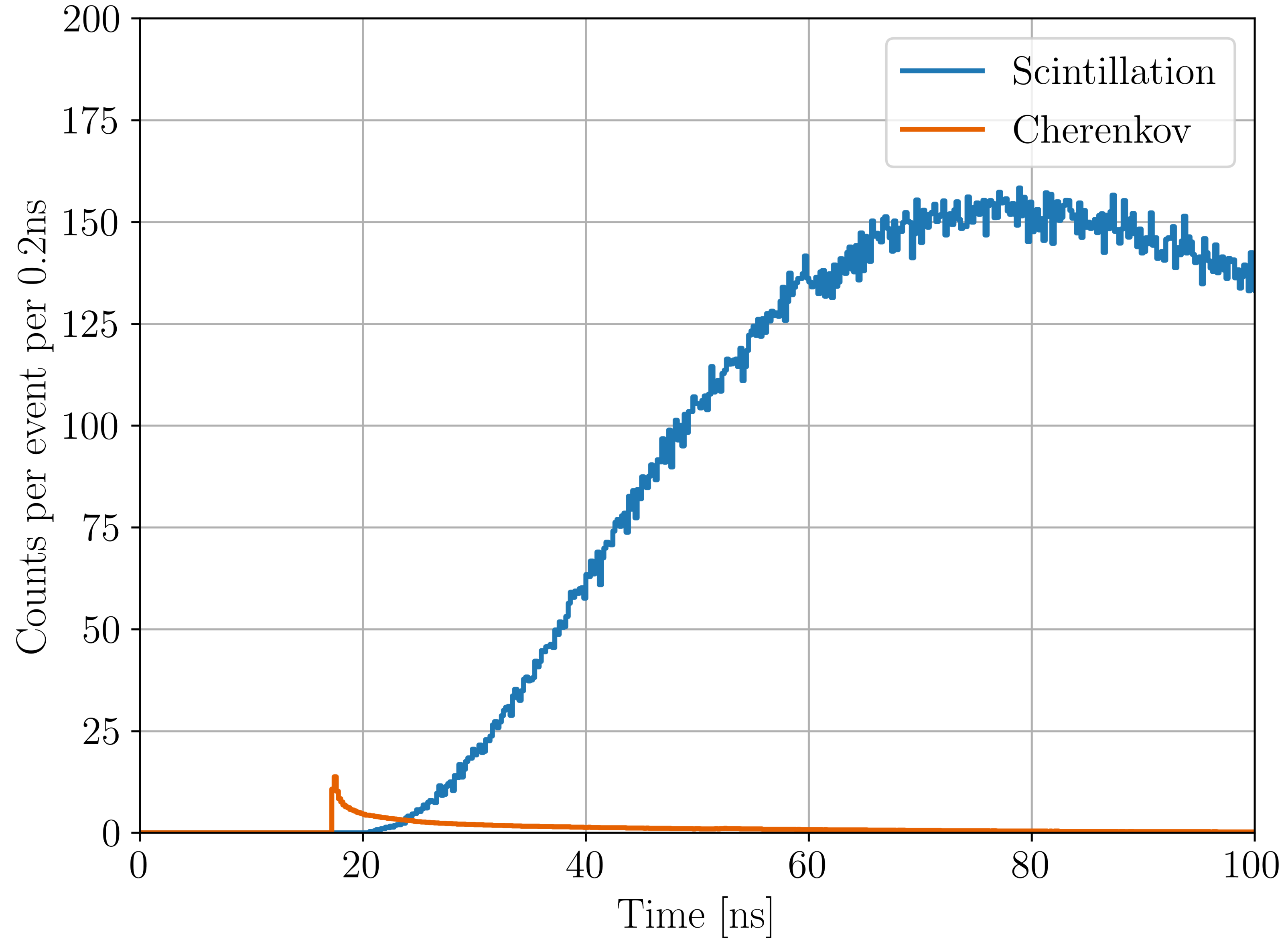


(a) (b) (c)

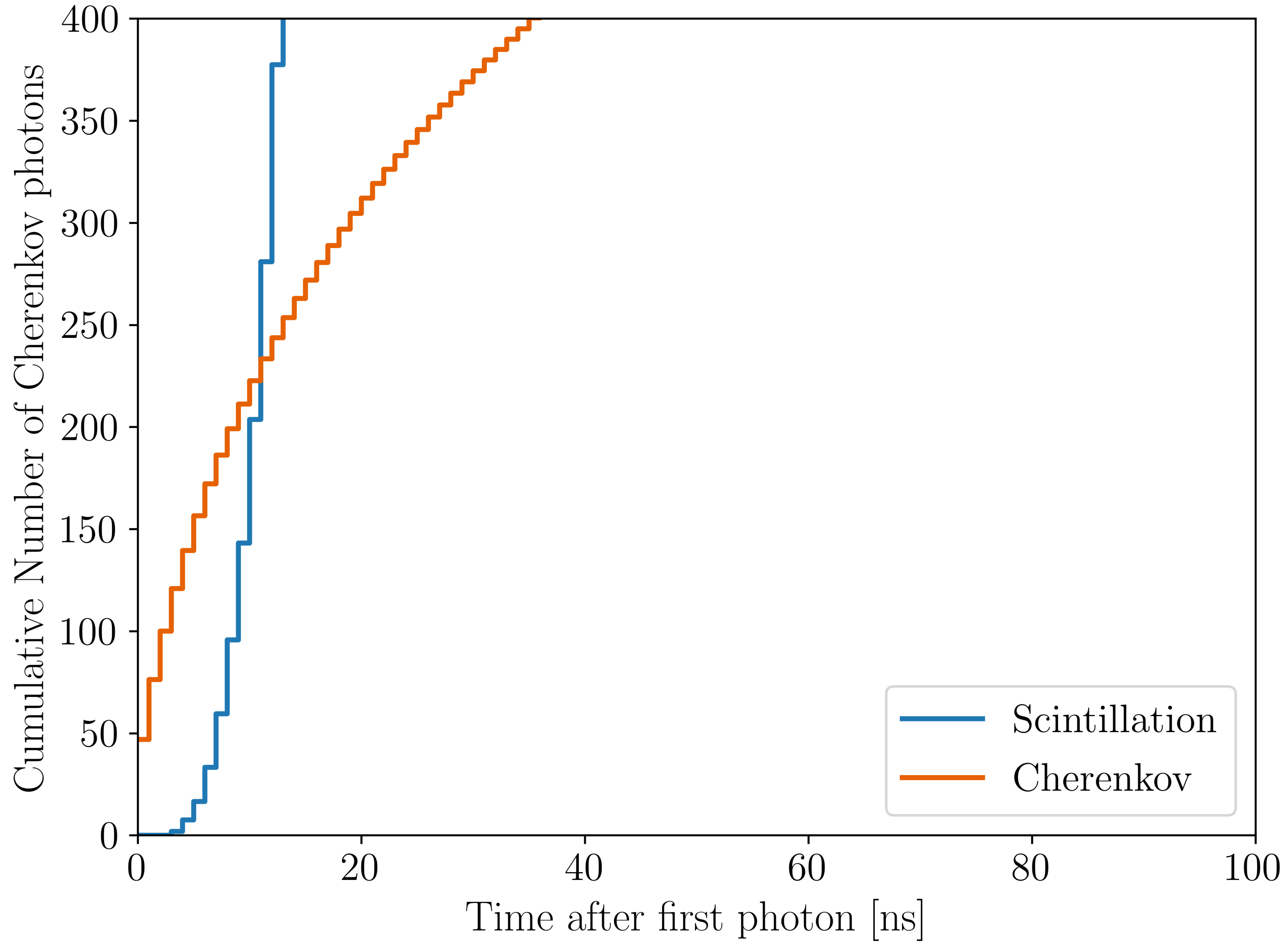
Recombination Fluctuations from EXO-200



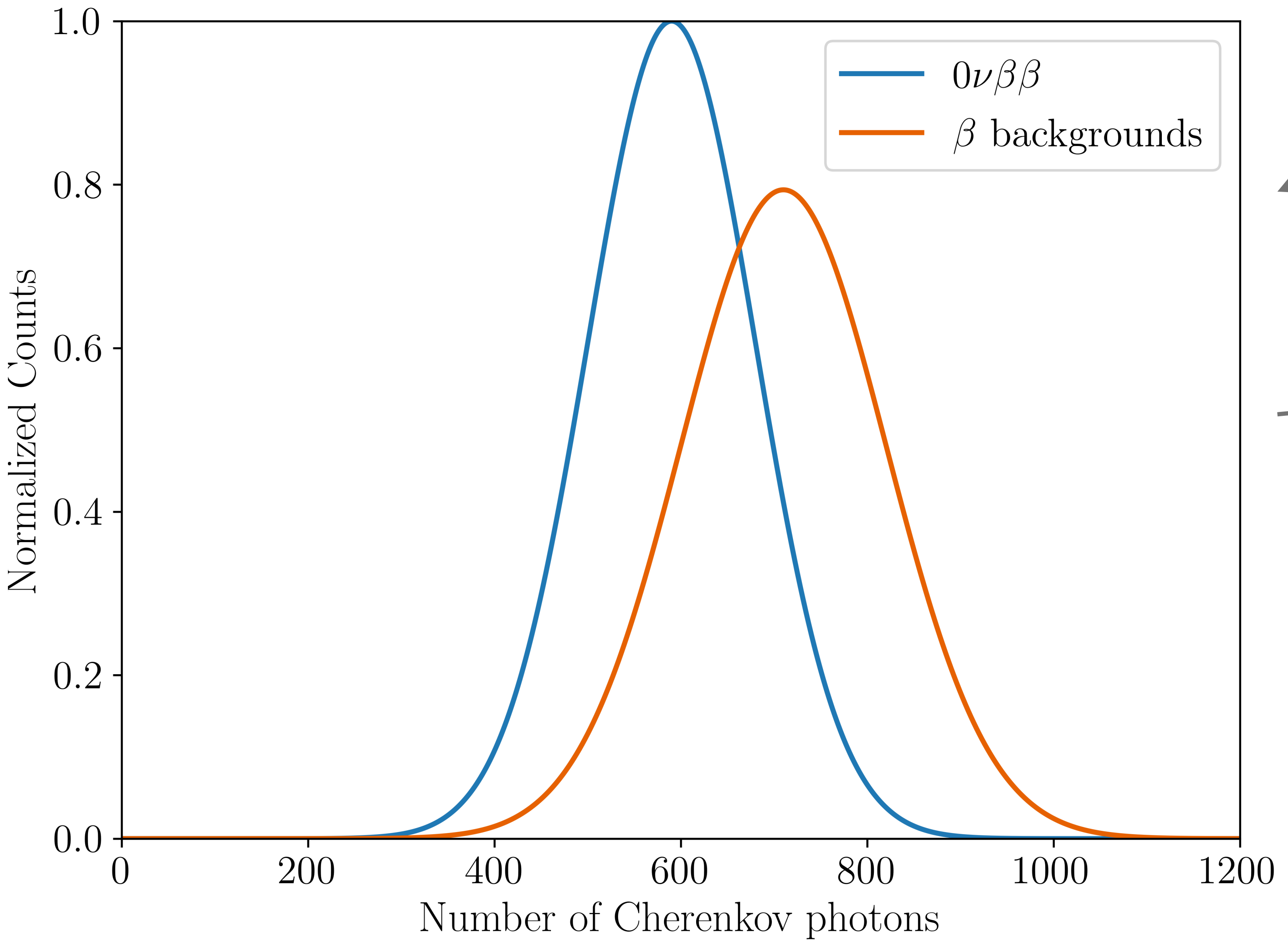
Procedure for Estimating Background Rejection (Design #1)



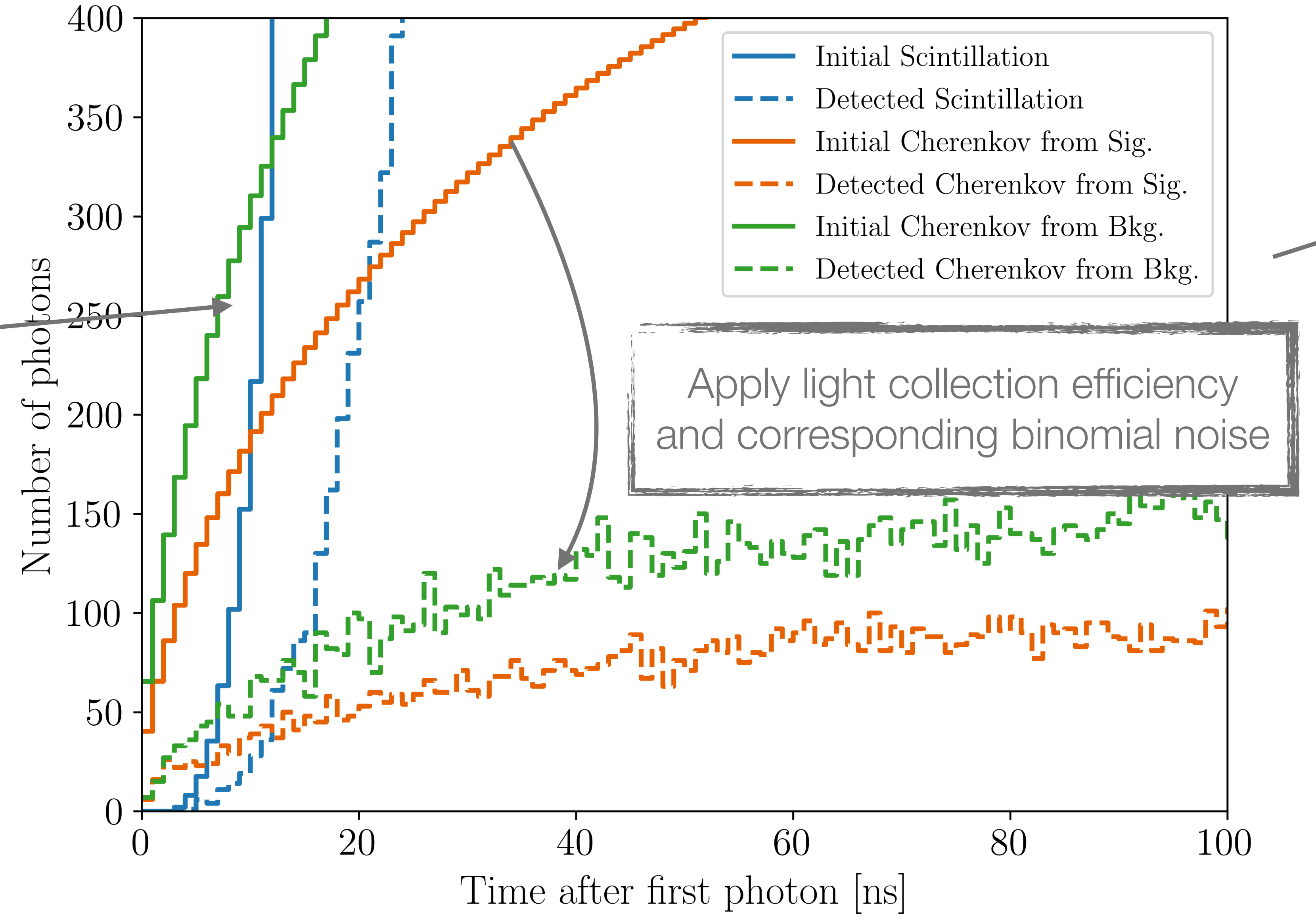
Calculate cumulative number of photons



Sample from light yield distribution



Scale distribution for signal and background by sampled light yield

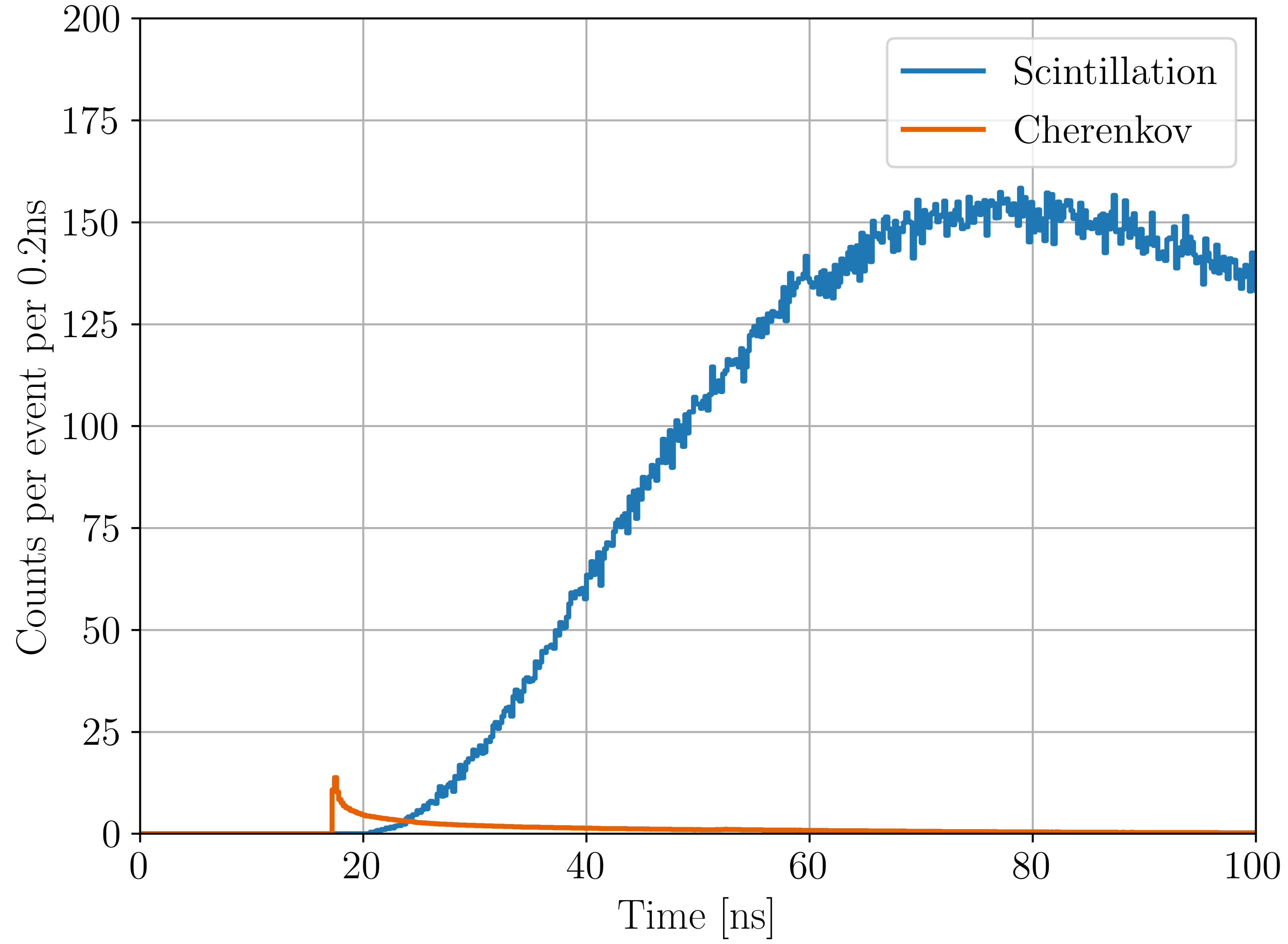


Apply light collection efficiency and corresponding binomial noise

Histogram number of photons in each time bin

Repeat many times

Procedure for Estimating Background Rejection (Design #1)



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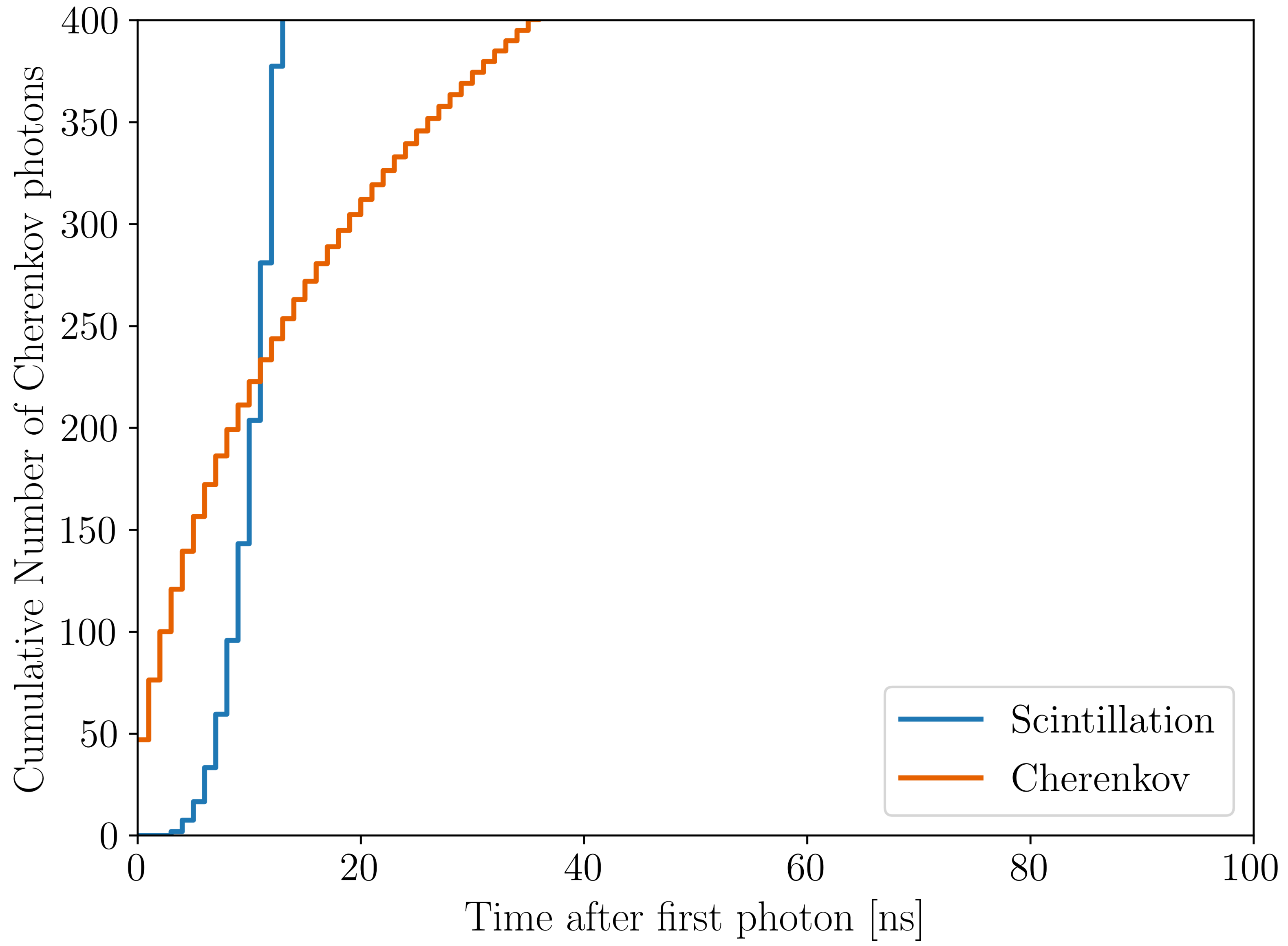
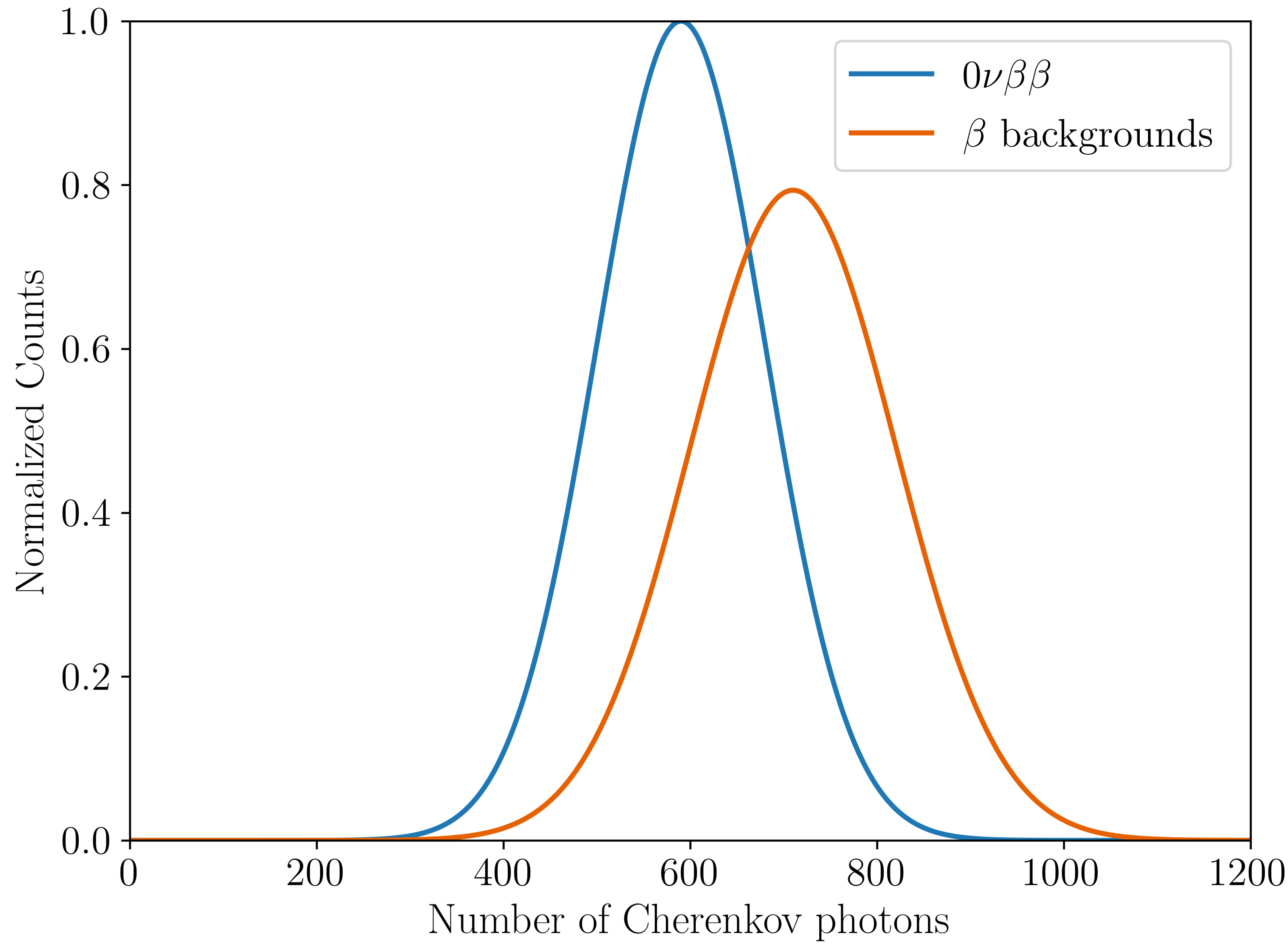


Sample from light yield distribution



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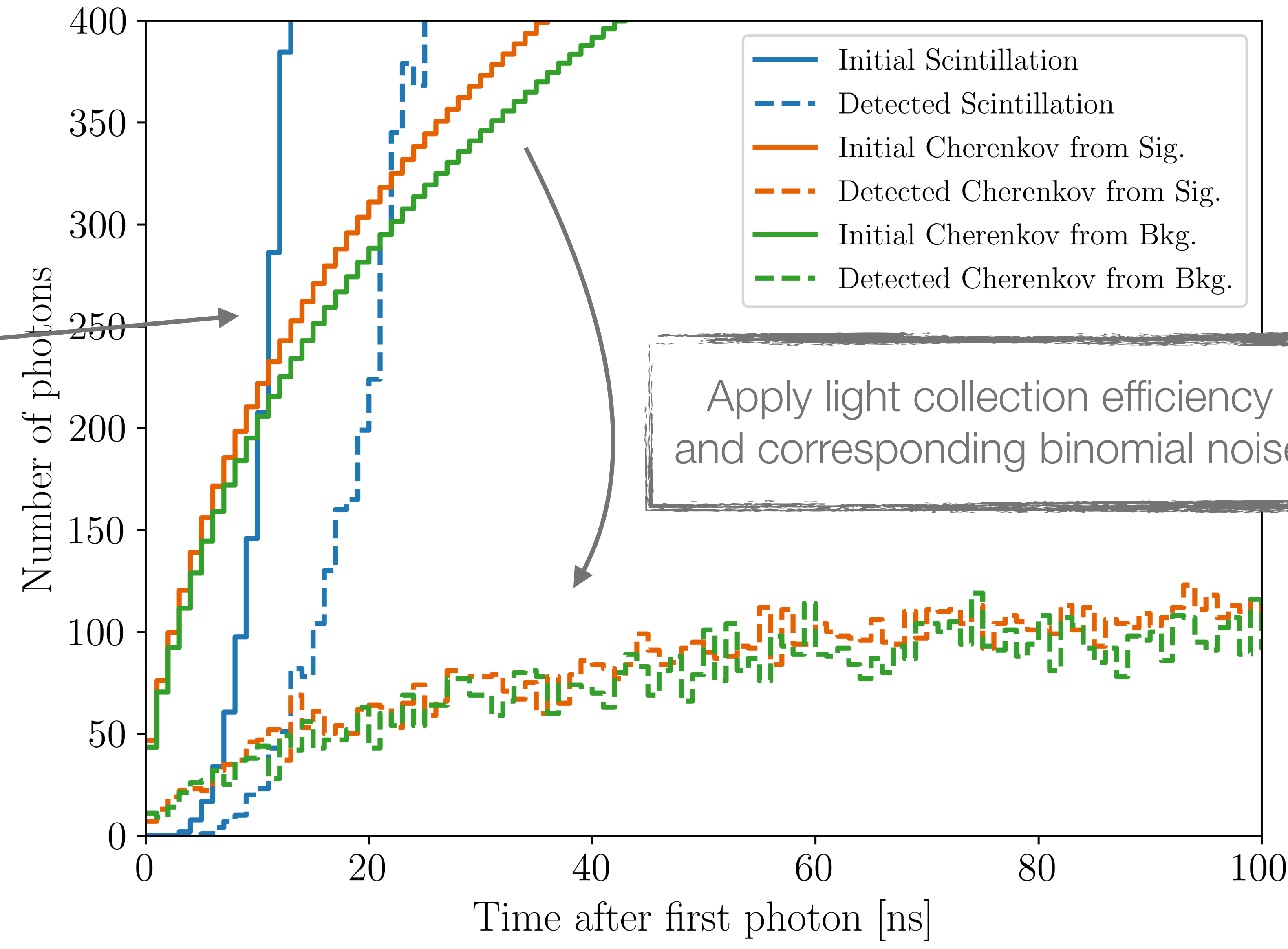


Apply light collection efficiency and corresponding binomial noise

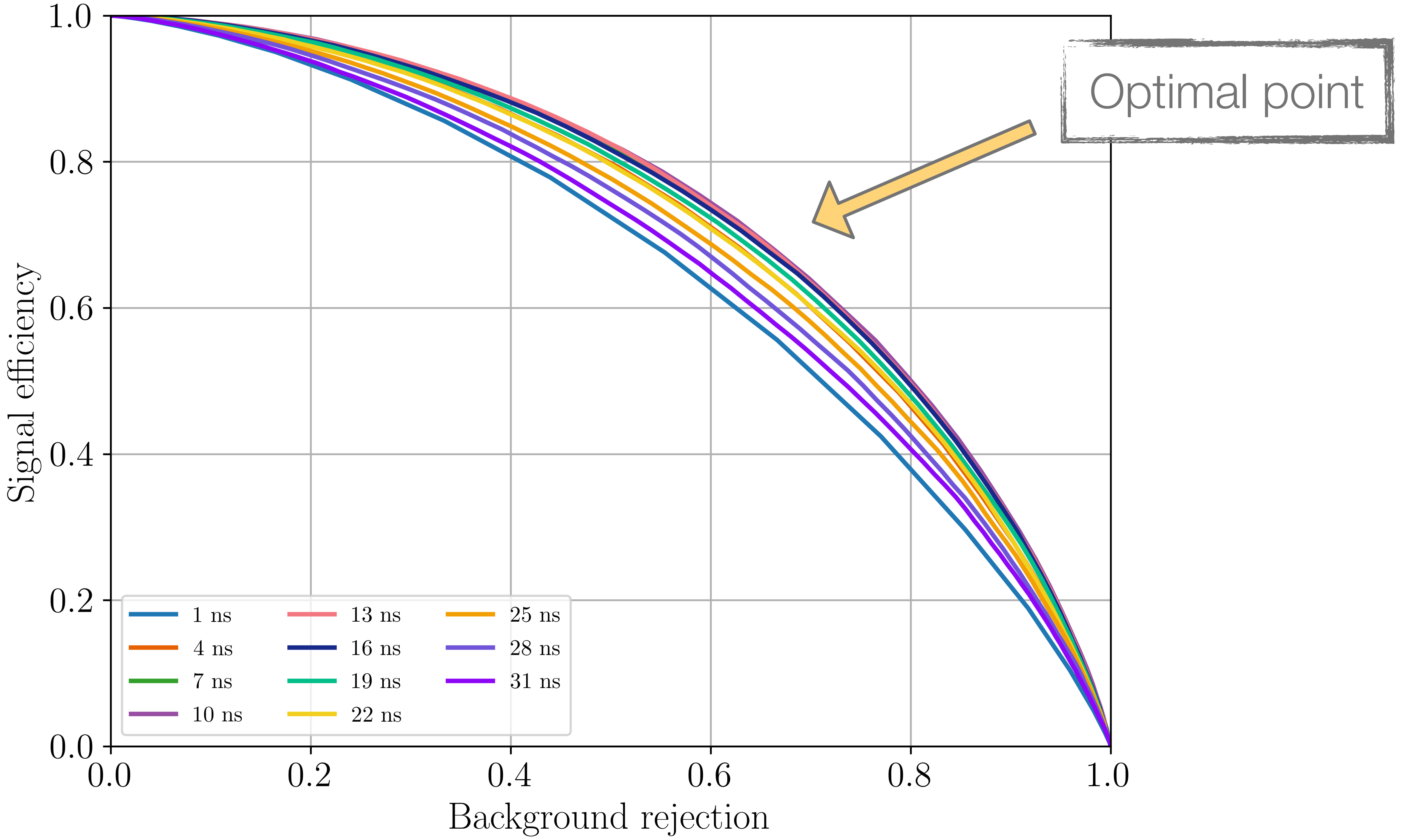
Histogram number of photons in each time bin

Repeat many times

ROC Curves

- The slower the light readout the larger the fraction of scintillation photons
- Optimal point around **10 ns** with **65 %** signal efficiency with **65 %** background rejection
- Sub-ns 3D Photon-To-Digital Converter feasible and under development

3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works, J.-F. Pratte et al., Sensors 21 (2021) 2, 598



Optimal point