Technische Universität München

Sensitivity studies

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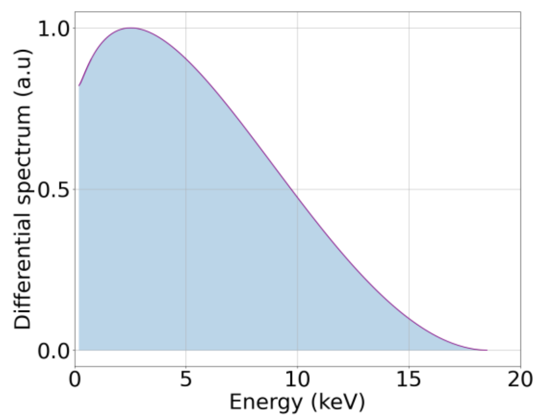
TRISTAN workshop
05/07/2022

Summary

Sensitivity study

- How does the parameters of the experimental setup affect the sterile neutrino sensitivity
- How does the uncertainty on the parameters affect the sterile neutrino sensitivity
- Identify / classify of the most critical parameters

Sensitivity performed with the TRmodel



Theoritical prediction

Experimental effects

Rear wall
- Backscattering
- Activity

$\Rightarrow$ *Geant4 simulations*

Detector
- SDD response
- Backscattering, Backreflection
- Post-acceleration

$\Rightarrow$ *Geant4/Kassiopeia sim. + calibration data*

Source
- Scattering
- Magnetic traps
- Stability

$\Rightarrow$ *Binned convolution method / MC*

Spectrometer
- Retarding potential
- HV stability
- Adiabatic transport

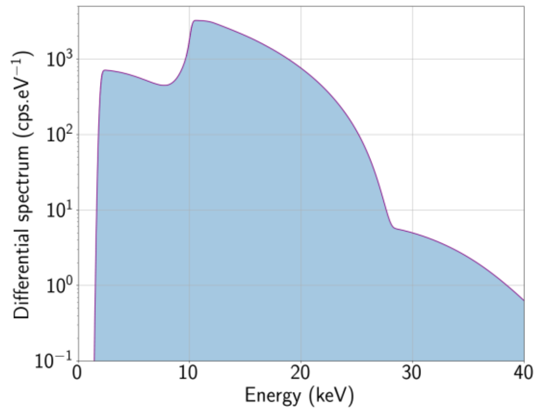
$\Rightarrow$ *Analytical evaluation*

Transport
- Magnetic mirror
- Magnetic collimation
- Synchrotron radiation

$\Rightarrow$ *Analytical evaluation*

DAQ
- Threshold
- Electronics noise
- Pileup, non-linearity

$\Rightarrow$ *Analytical evaluation*



Expected spectrum

Not included:

- Backscattered and backreflected electrons at the detector (see Andrea's talk)
- Magnetic trapping (see Susanne's talk)
- T-decay on RW (see Dominic's talk)

1st TRISTAN review talk

- TRISTAN Review Part 1 (Sensitivity – April 2022) : https://indico.scc.kit.edu/event/2701/overview

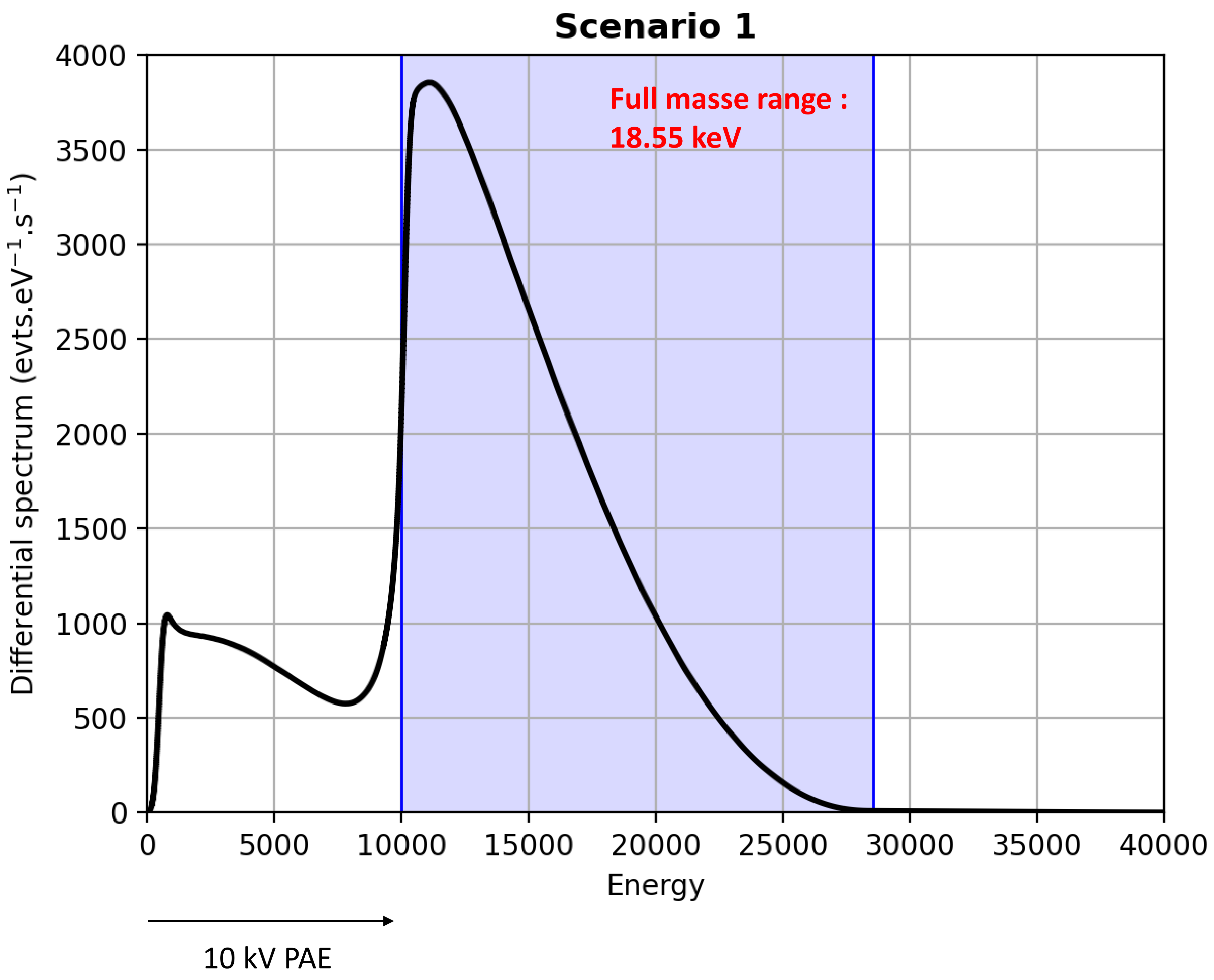
Disclamer : all plots of this presentation are preliminary!

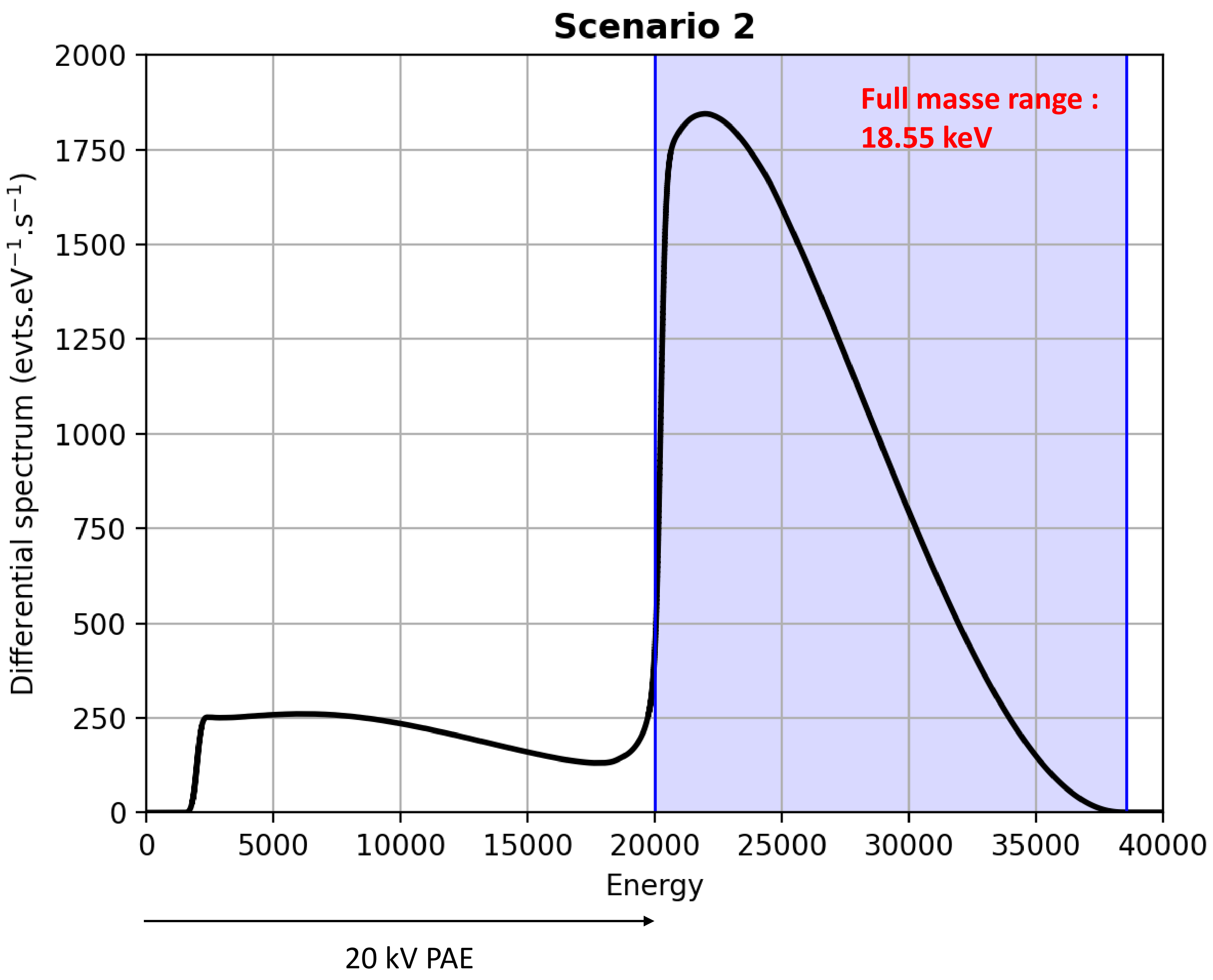
2a – Benchmark scenarios

2 scenarios

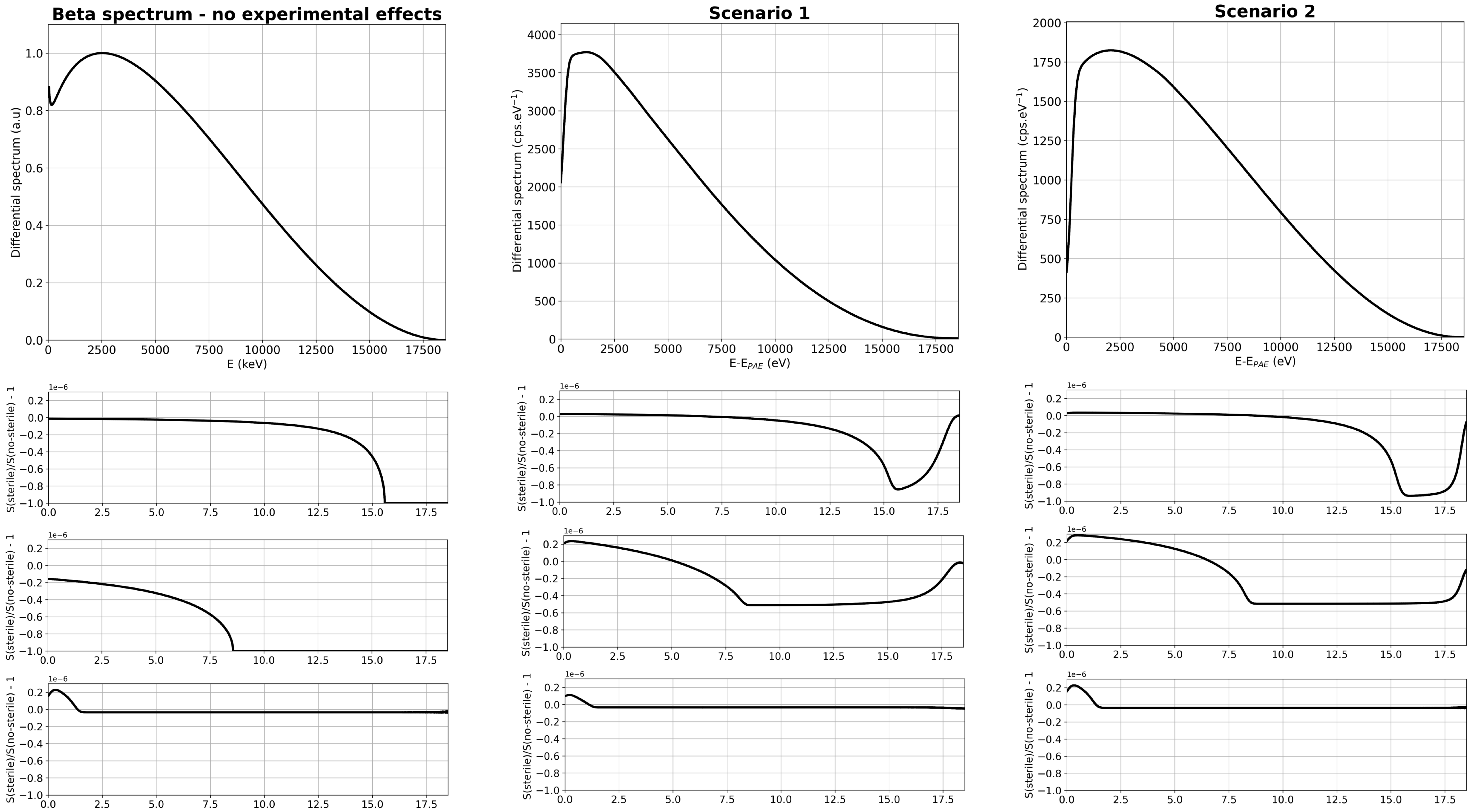
- **Basic**
  - ➢ Nominal B-fields - current KATRIN configuration
  - ➢ RW: Gold
- **Advanced**
  - ➢ Optimised B-fields, RW material (Be) and PAE = 20 kV
    - reduced RW events and backscattered detector events
    - reduce pile-up, charge-sharing and dead-layer events in the ROI

Component	Scenario 1	Scenario 2
Rear wall	Gold	Beryllium
B_{RW}	1.26 T	0.32 T
B_{source}	2.52 T (Θ_{RW} = 45°)	2.52 T (Θ_{RW} = 21°)
B_{pinch}	4.2 T (Θ_{max} = 51°)	2.52 T (Θ_{max} = 90°)
B_{det}	2.52 T (map 100% of source)	1 T (map 40% of source, and full large RW)
Post acceleration	10 kV	20 kV





2b – Neutrino signal



m_s = 3 keV
$\sin^2\theta = 10^{-6}$

m_s = 10 keV
$\sin^2\theta = 10^{-6}$

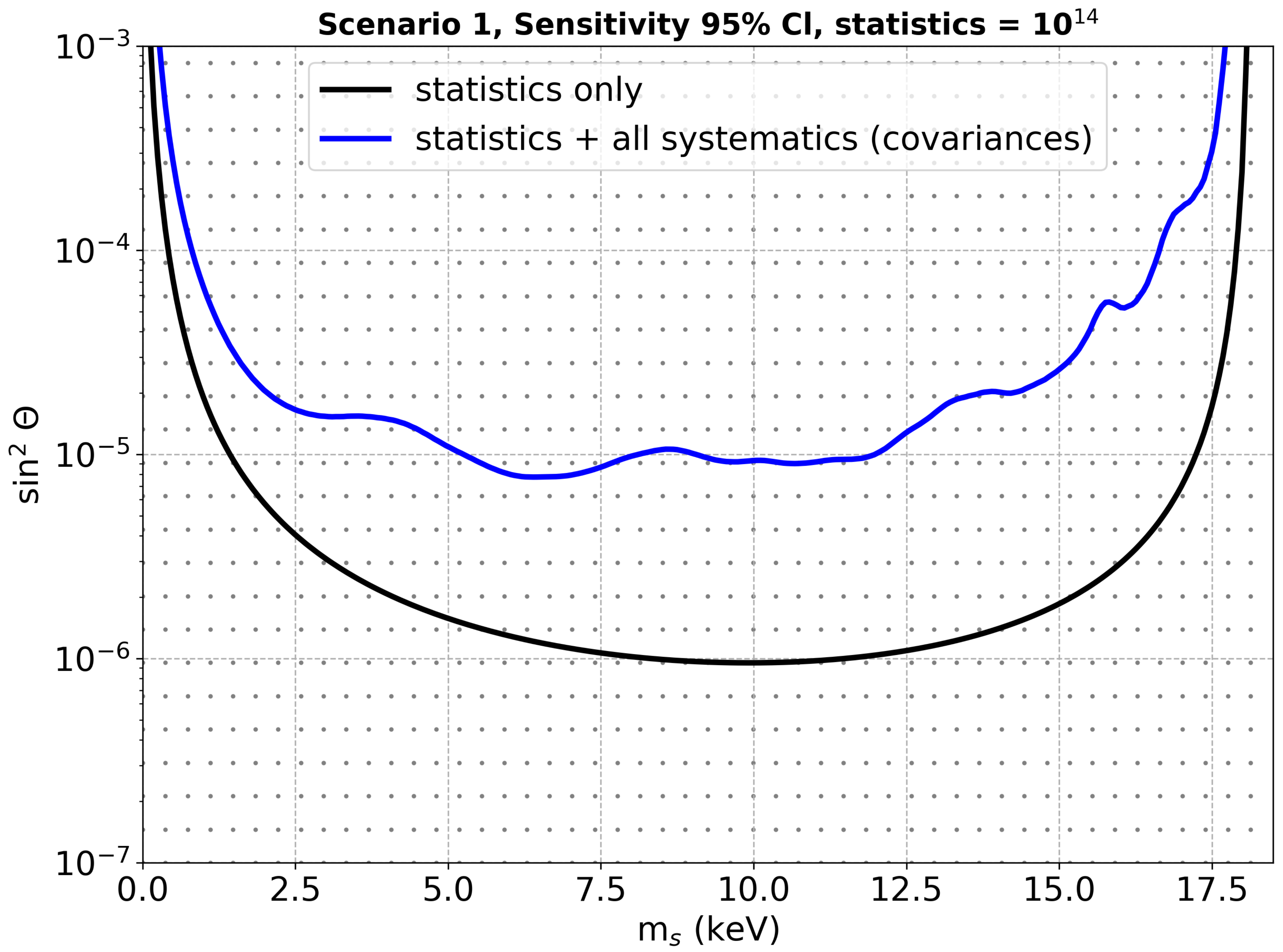
m_s = 17 keV
$\sin^2\theta = 10^{-6}$

- Low sterile mass : signal shape distorted because of the pile-up
- Mid-range sterile mass : signal shape distorded, signal sift because of the backscattering at the detector & spectrum normalisation
- High and low sterile mass : signature closer to the edge of the ROI → lower statistical sensitivity expected

- Sensitivity for a differential measurement
- Same procedure as for eV-sterile neutrino search in KATRIN
- Grid scan in m_s and $\sin^2\theta$
  - χ^2 computed at each grid point – contour draw @95% CL
  - statistic and systematic uncertainties included via covariance matrix
  - nuissance parameter : global signal amplitude

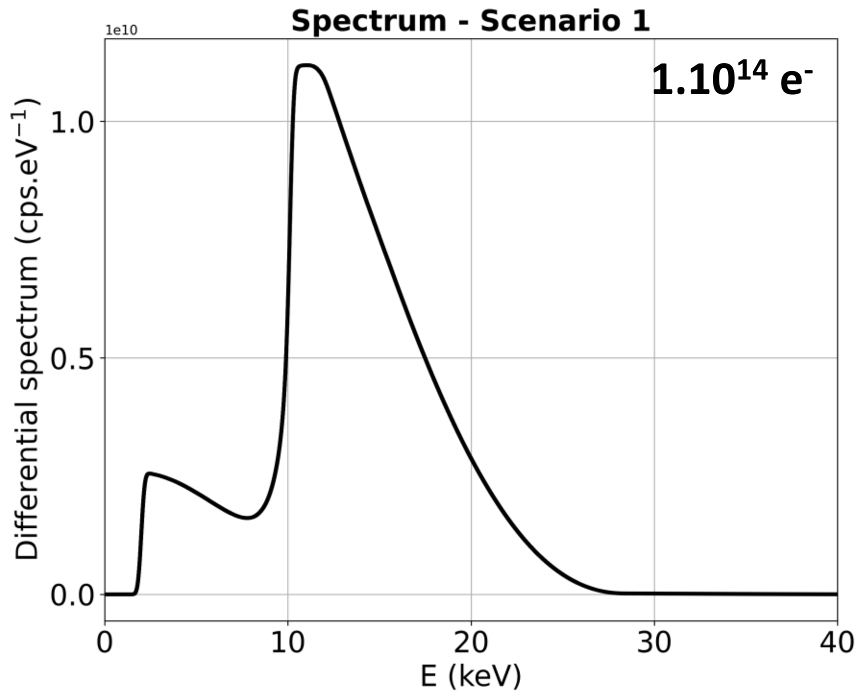
$$\chi^2 = \sum_{ij} \left(S_i^{H0} - S_i^{H1}\right)\left(\Sigma^{-1}\right)_{ij}\left(S_j^{H0} - S_j^{H1}\right)$$

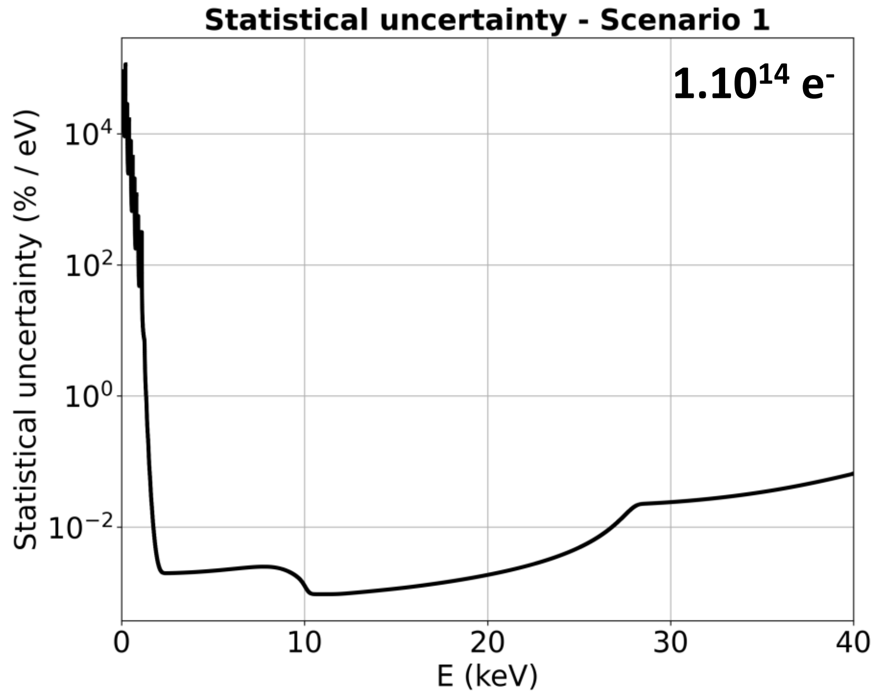
- S^{H0} : spectrum for the null hypothesis
- S^{H1} : spectrum for the alternative hypothesis, sterile neutrino admixture with m_s and $\sin^2\theta$ at the grid point
- $\sum$: covariance matrix - statistics + systematics

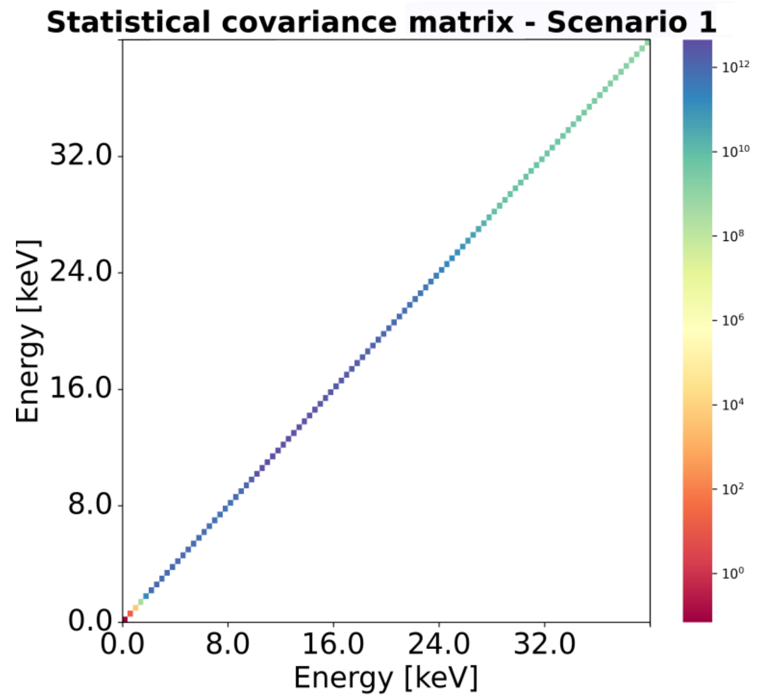


Statistical uncertainty (analytical calculation)

- Diagonale covariance matrix
- Bin uncertainty: $\sigma_N = \sqrt{N}$

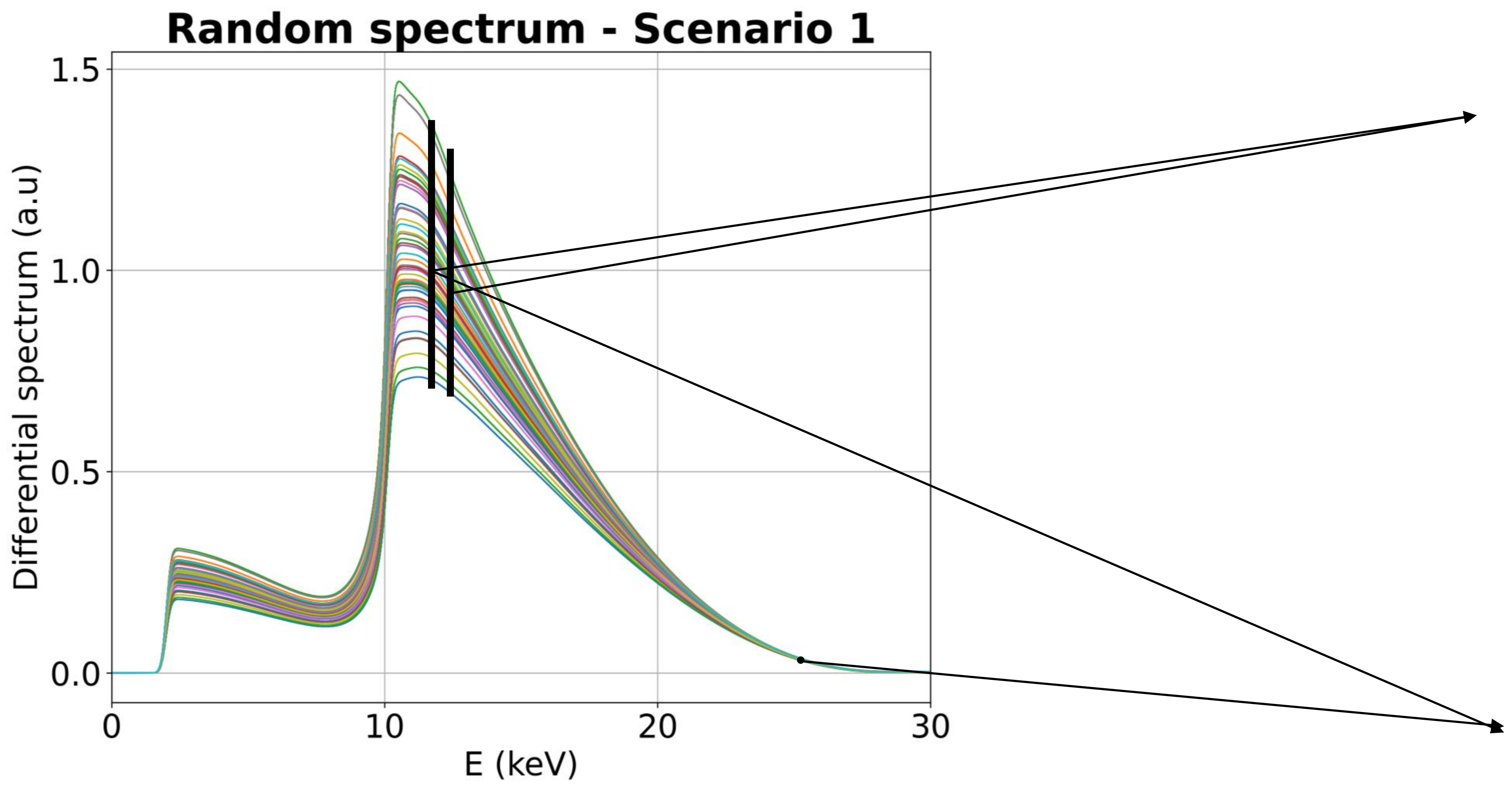


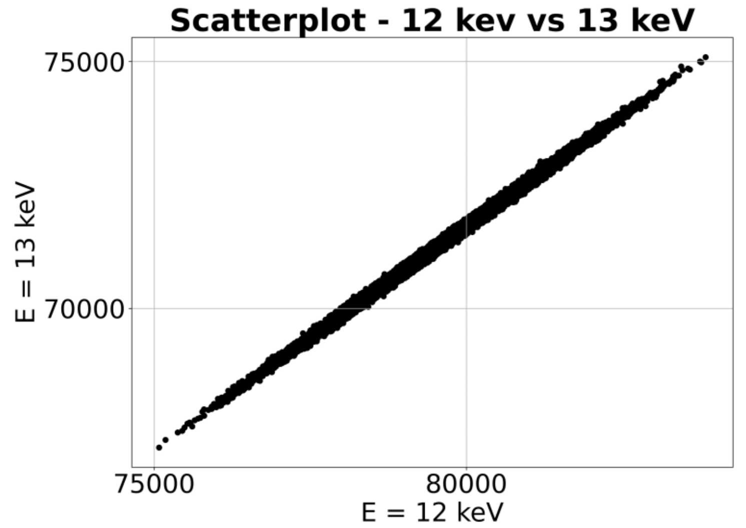




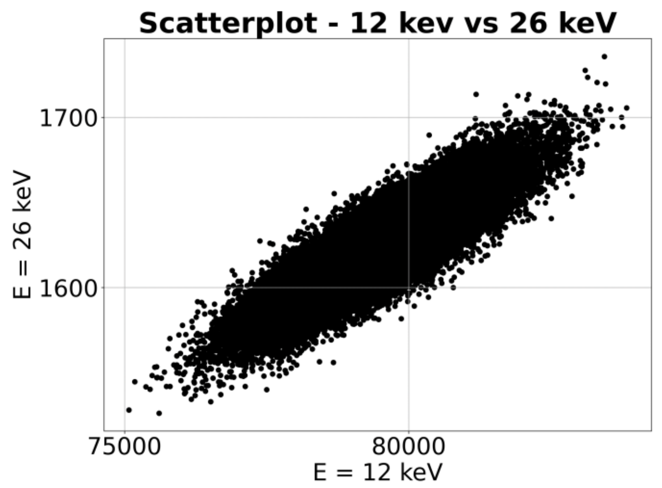
Systematic uncertainty (MC method)

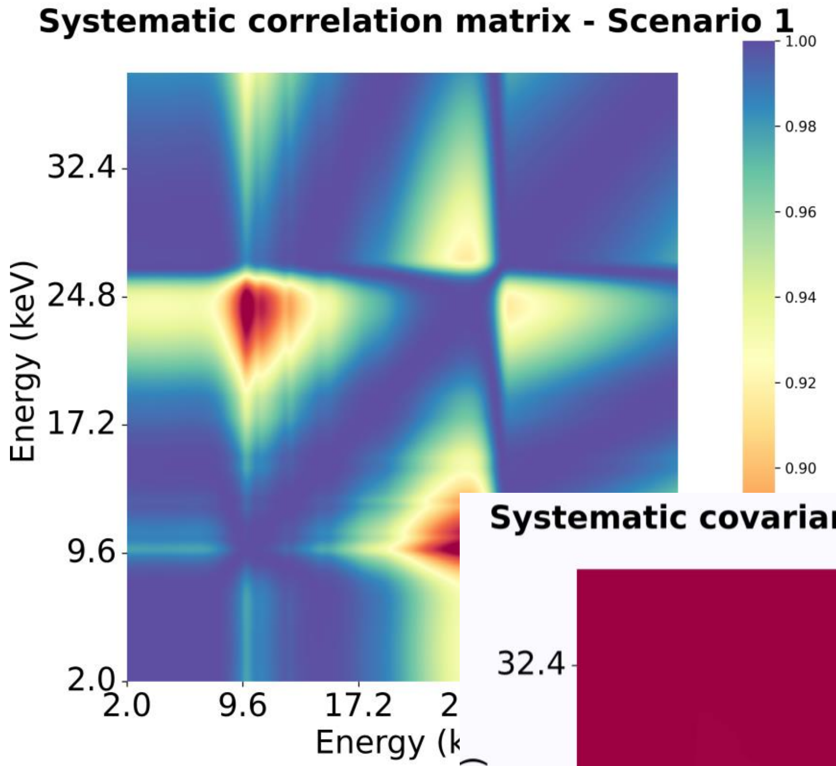
- Simulation of a large number (~50 000*) of random spectrum with different value of one input parameters assuming a gaussian pdf (e.g. deadlayer: $\mathrm{N}(dl = 58\ nm, V_{dl} = 4\ nm)$)
- Compute covariance/correlation matrices



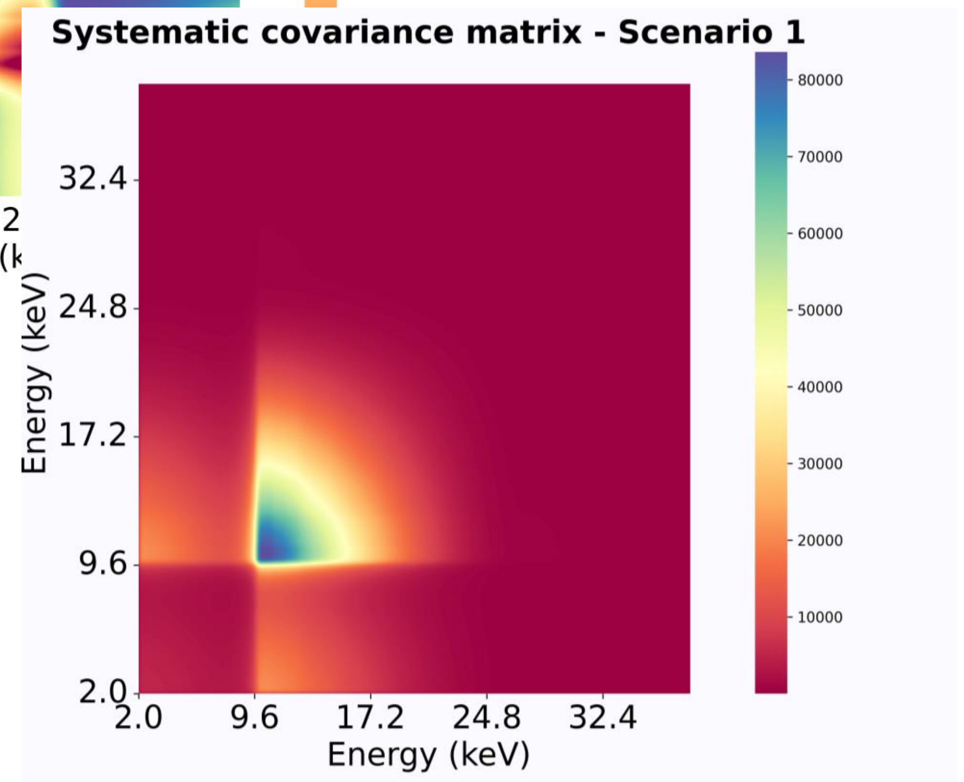


$$cov(X,Y) = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{n-1}$$





Correlation matrix



Covariance matrix

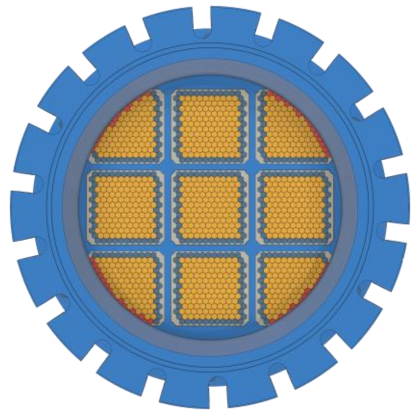
*With 50 000 spectra: statistical uncertainty on the estimated standard deviation of each bin <0.5% & <0.005 (absolute) on the correlation coefficients

3a – Statistical limit : rate consideration

Plots: M. Deschner

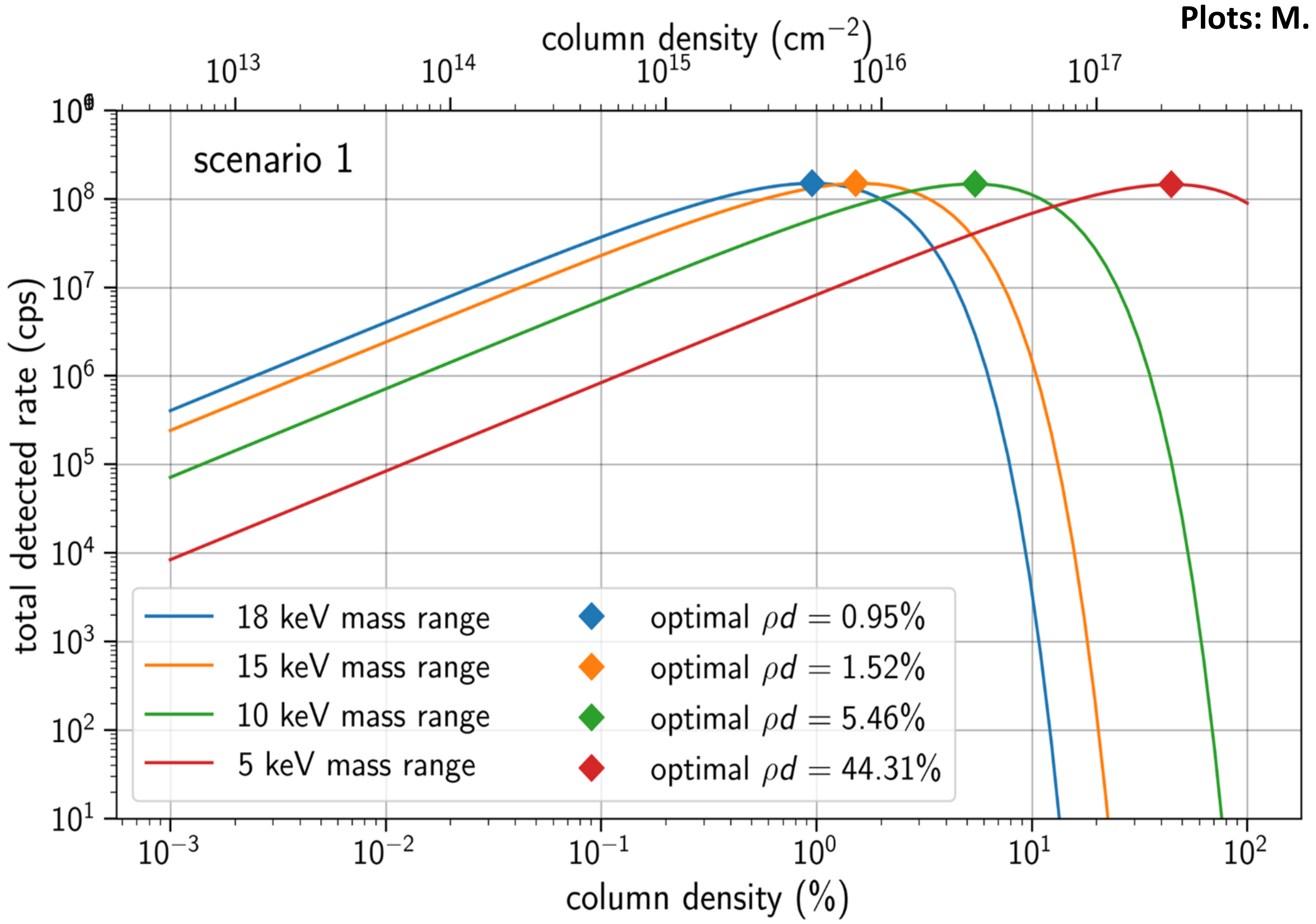
Rate per pixel limited to 100 kcps due to dead time
 ⇒ Maximal total rate: 10^8 cps = 100 Mcps

Rate can be adjusted via
- Column density
- Retarding potential (mass range)
- Magnetic fields (acceptance angles)



Phase-1: 9 modules

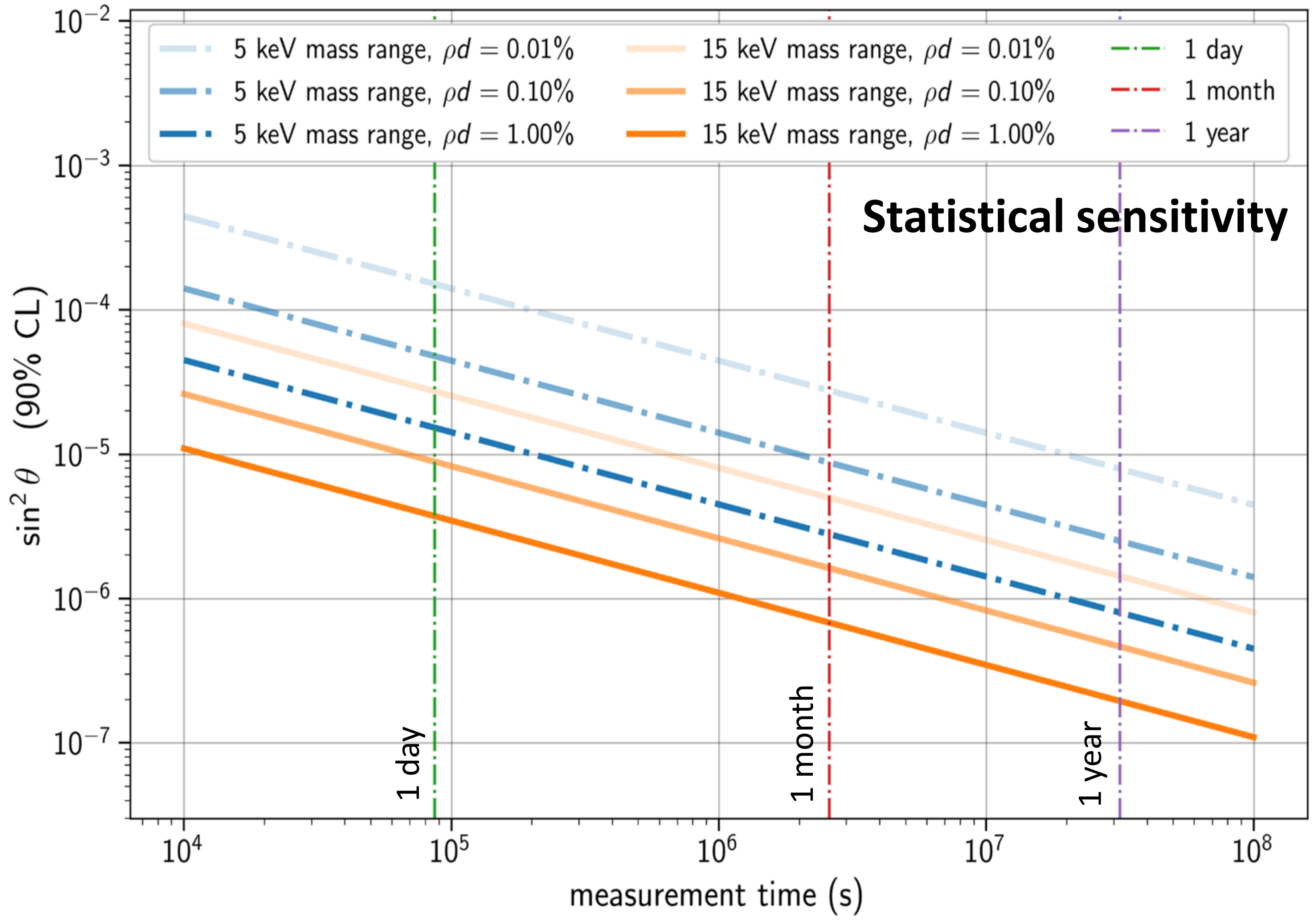
Total pixels: 1494
Golden pixels: 936 (63%)



Optimal column density ~1% for the full mass range

Statistical sensitivity at the 10^{-4} level is reached within days, even with 0.01% column density

Statistical sensitivity at 2.10^{-7} is reachable in 1 year for all mass ranges

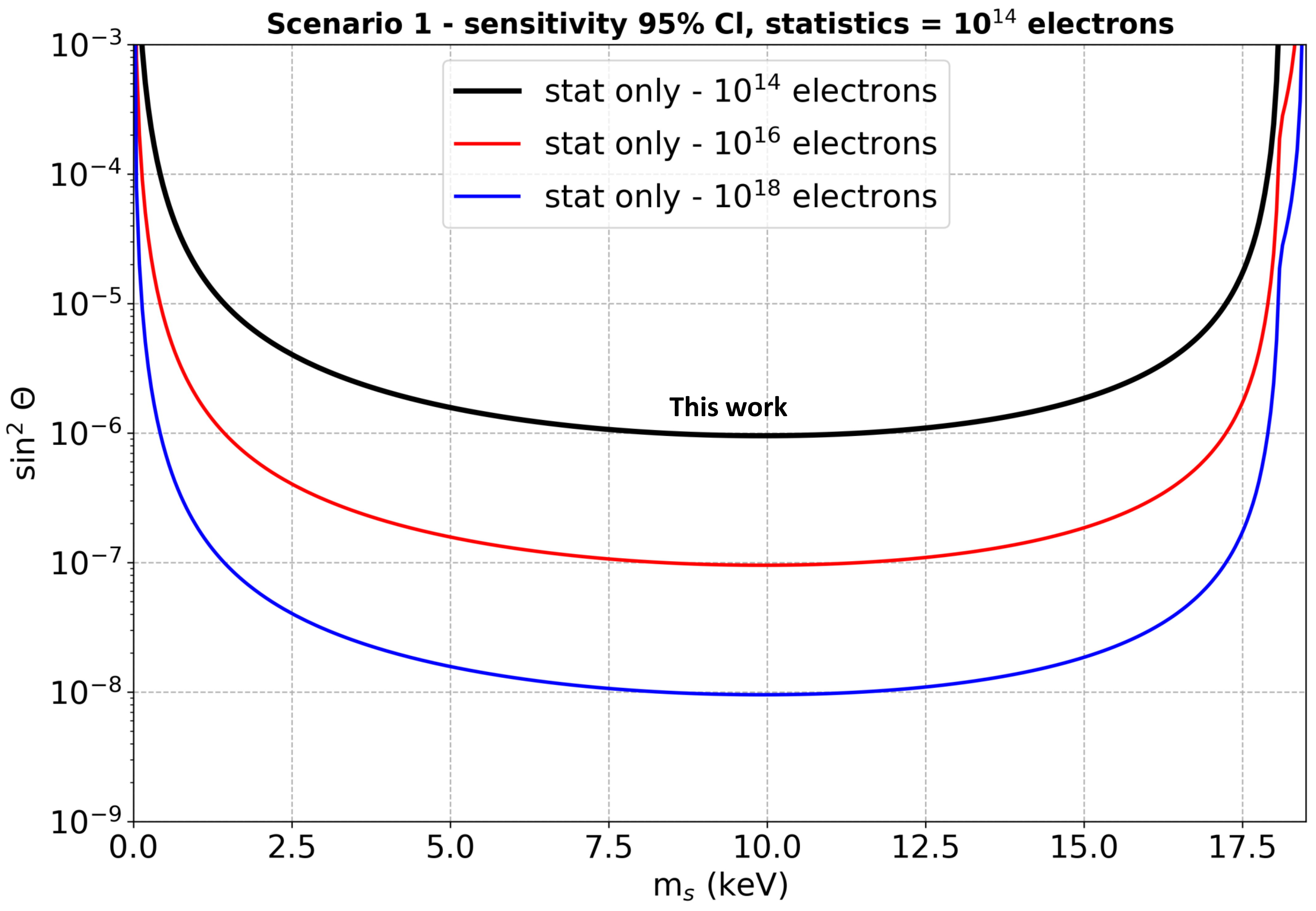


This work: focus on 1.10^{14} electrons in the full mass range (18.55 keV)

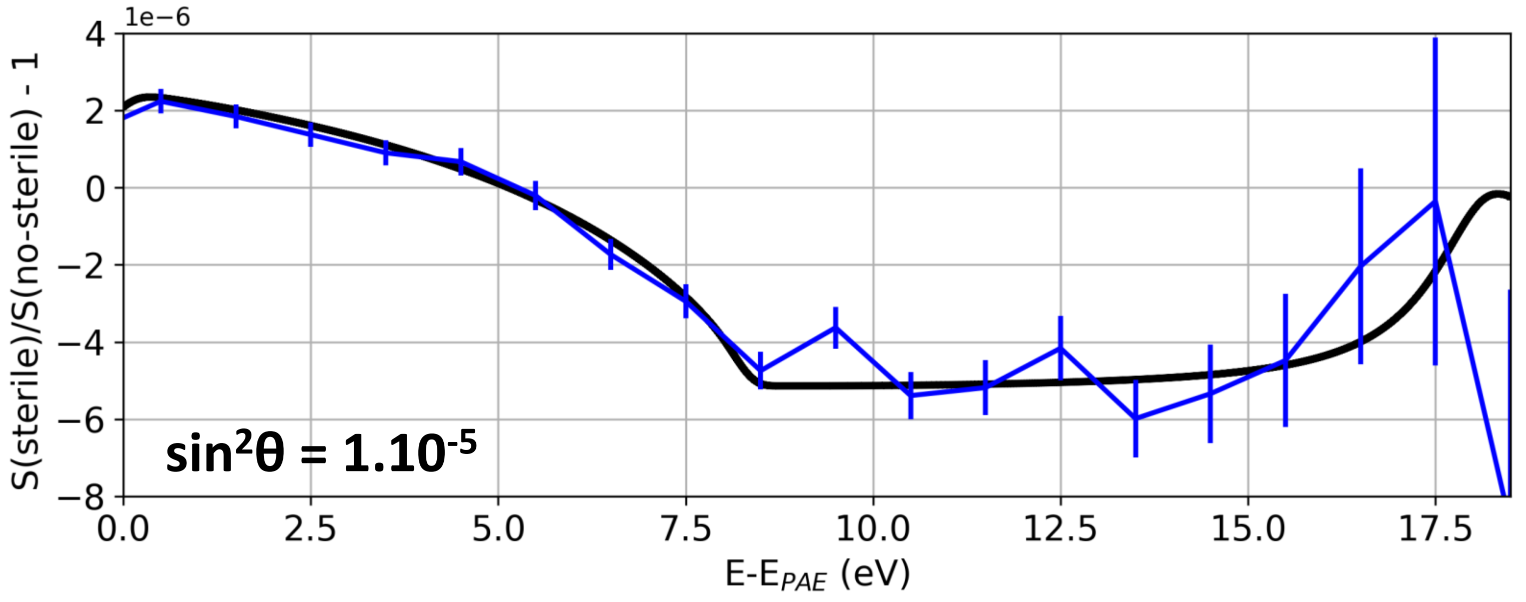
- ρd = 0.1% → 1 years of data taking
- ρd = 1% → 1 month of data taking

This work: 1.10^{14} electrons, full mass range

- ➢ **sensitivity at the 10^{-6} level @10 keV**
- ➢ **sensitivity < 10^{-5} in the range 2-17 keV**



Impact of the total statistics



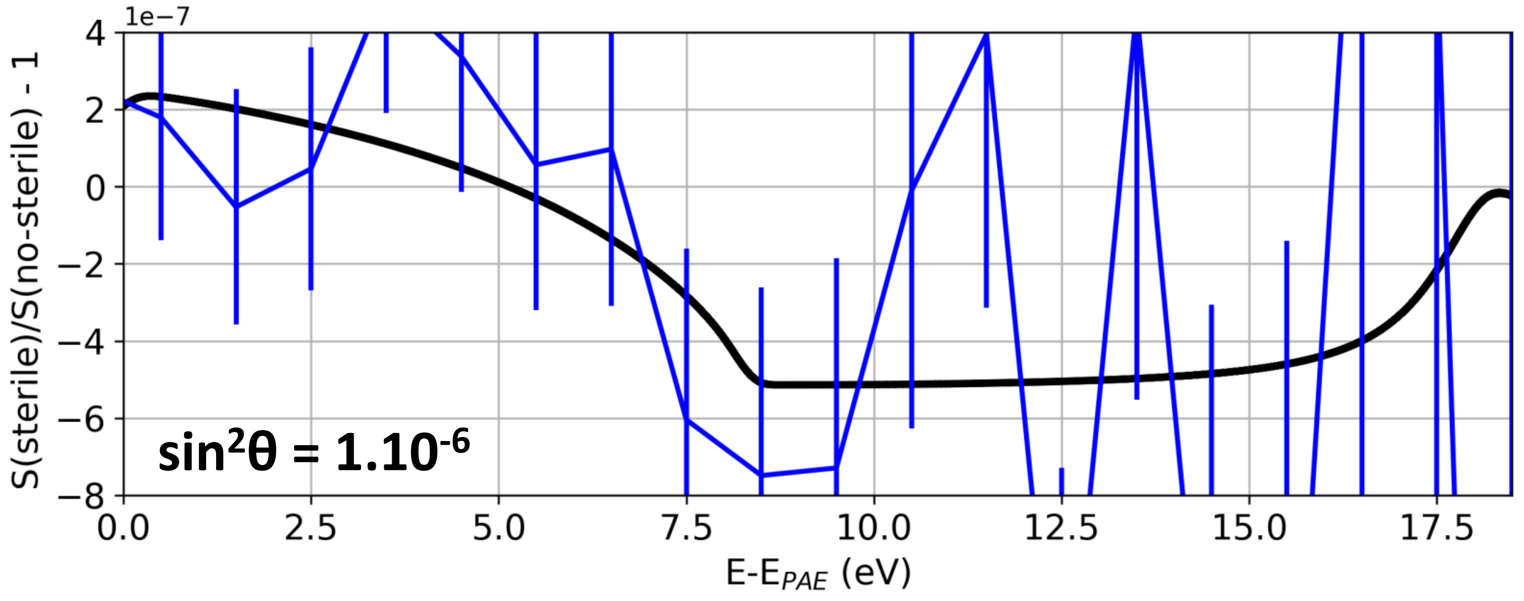
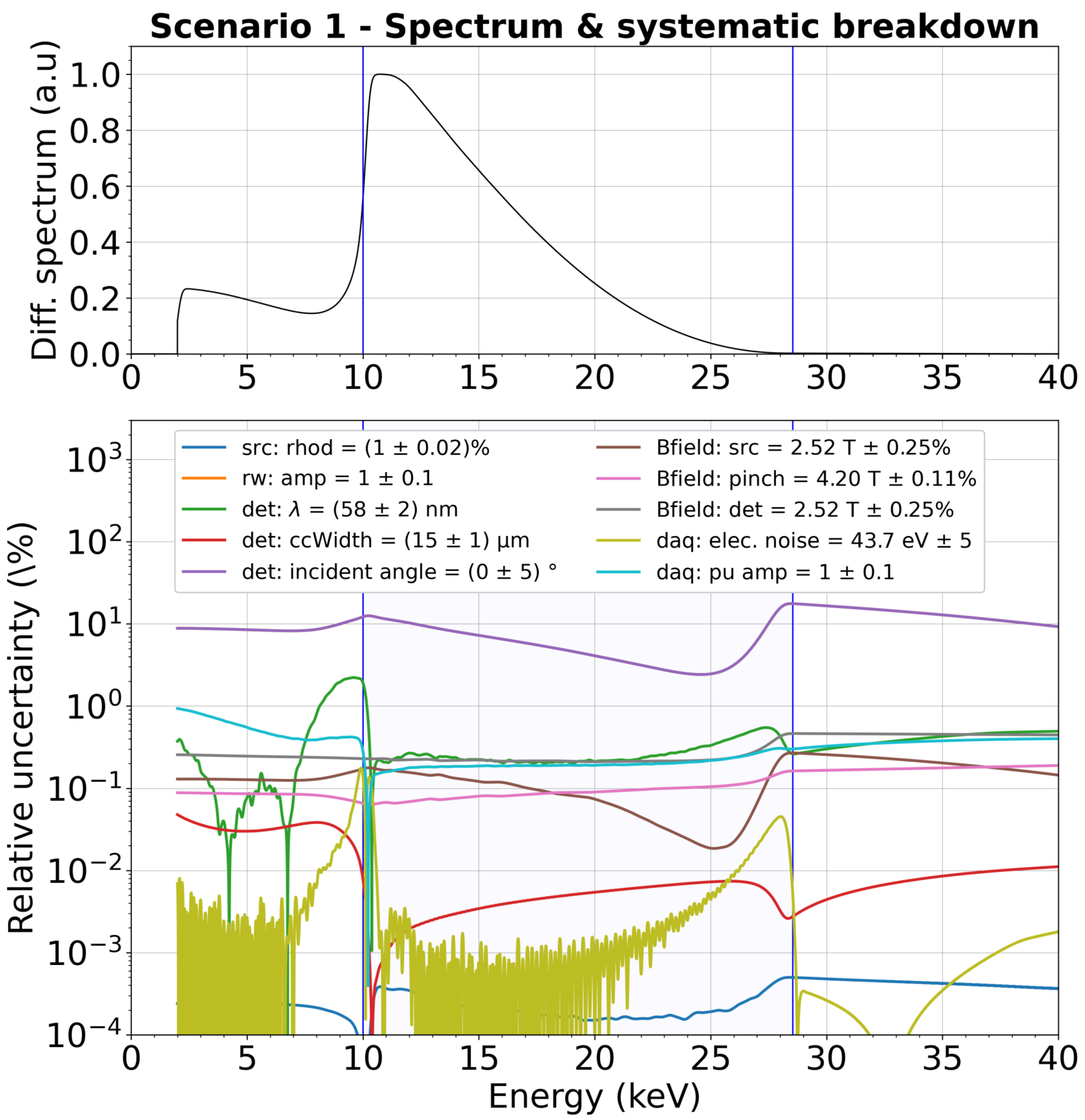


Fig. Sterile signal for a moke data sample (blue) for m_s = 10 keV and 1.10^{14} electrons (scenario 1). bins width = 1 keV.

Systematic included in this work

	Component	Value/Comment	Uncertainty
Rear Wall	Backscattering	Gold (30%), Beryllium (2.8 %)	10%
Source	Source scattering	0.1%, 1%, 10%	2%
Detector	Dead layer	58 nm	2 nm
	Charge sharing	15 µm	20%
	Backscattering	simulated via incidence angle	5°
	Resolution	FWHM @ 20 keV = 241 eV	10 eV
B-field	Source	S1: 1.26 T / S2: 0.32 T	0.1%
	Pinch magnets	S1: 2.52 T / S2: 2.52 T	0.25%
	Detector	S1: 4.2 T / S2: 2.52 T	0.25%
Read-out	Pile-up	Time resolution : 112 ns	10%
	Electronic noise	1σ smearing width : 43.7 eV	10%
Background	Constant and arbitrary shape	>10^{-3} cps/keV	1-10%



- Systematic effect on the spectrum typically at the sub percent level but multiple order above the sterile neutrino signal
- Very smooth effect – no kink link effect
- Effect strongly correlated accross the energy bins → sensitive to the shape (i.e. can the parameter systematic mimic the neutrino signal?) rather its strengh

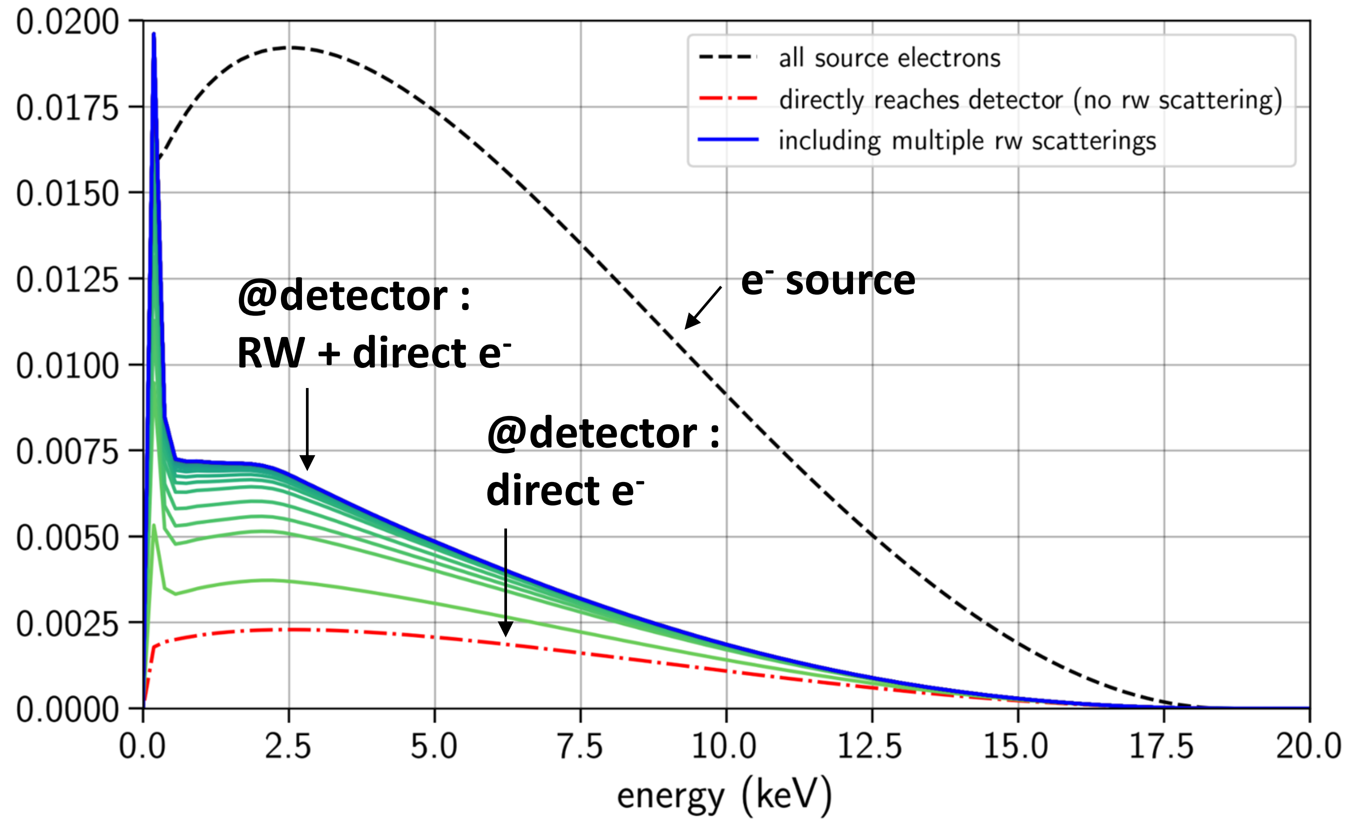
4b – Individual effects : rear wall

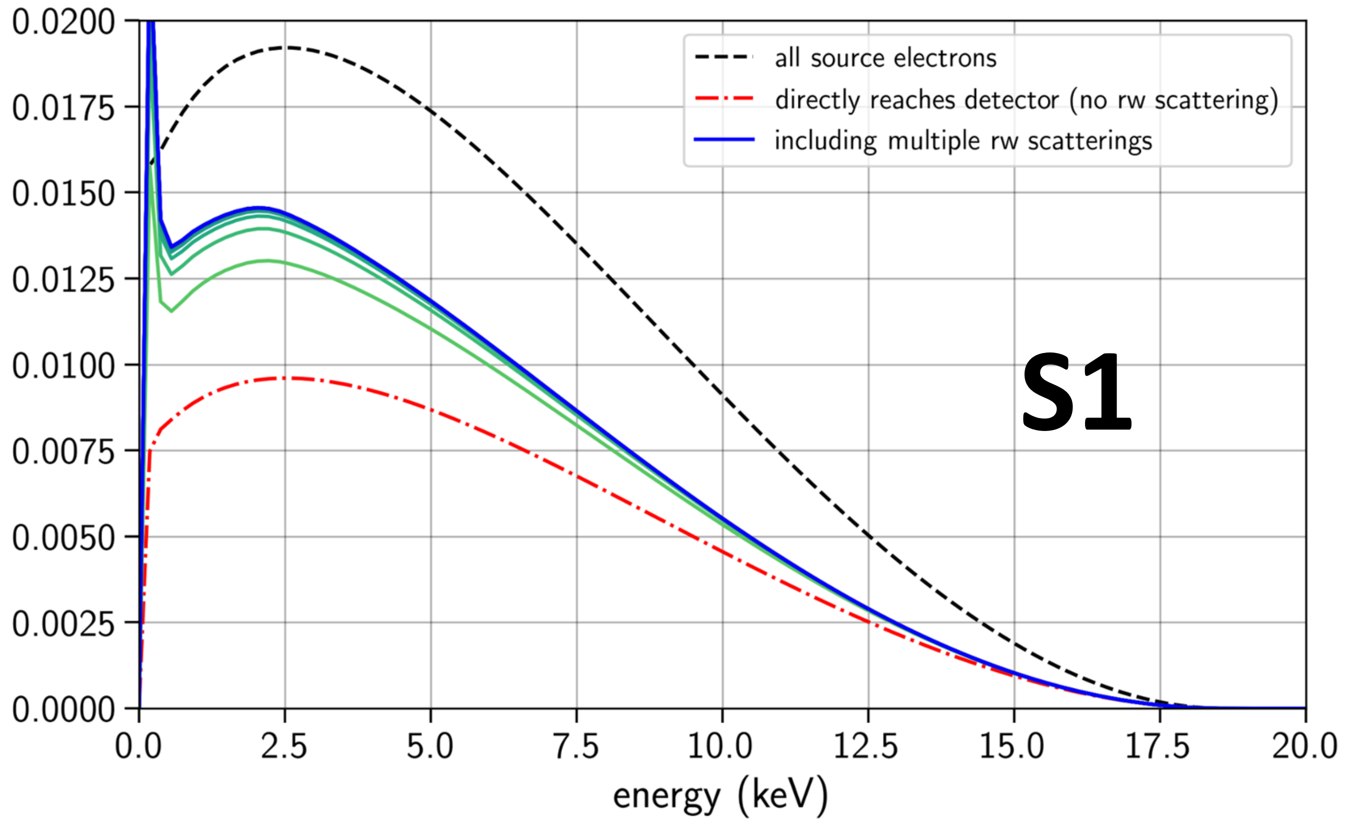
Plot by M. Descher

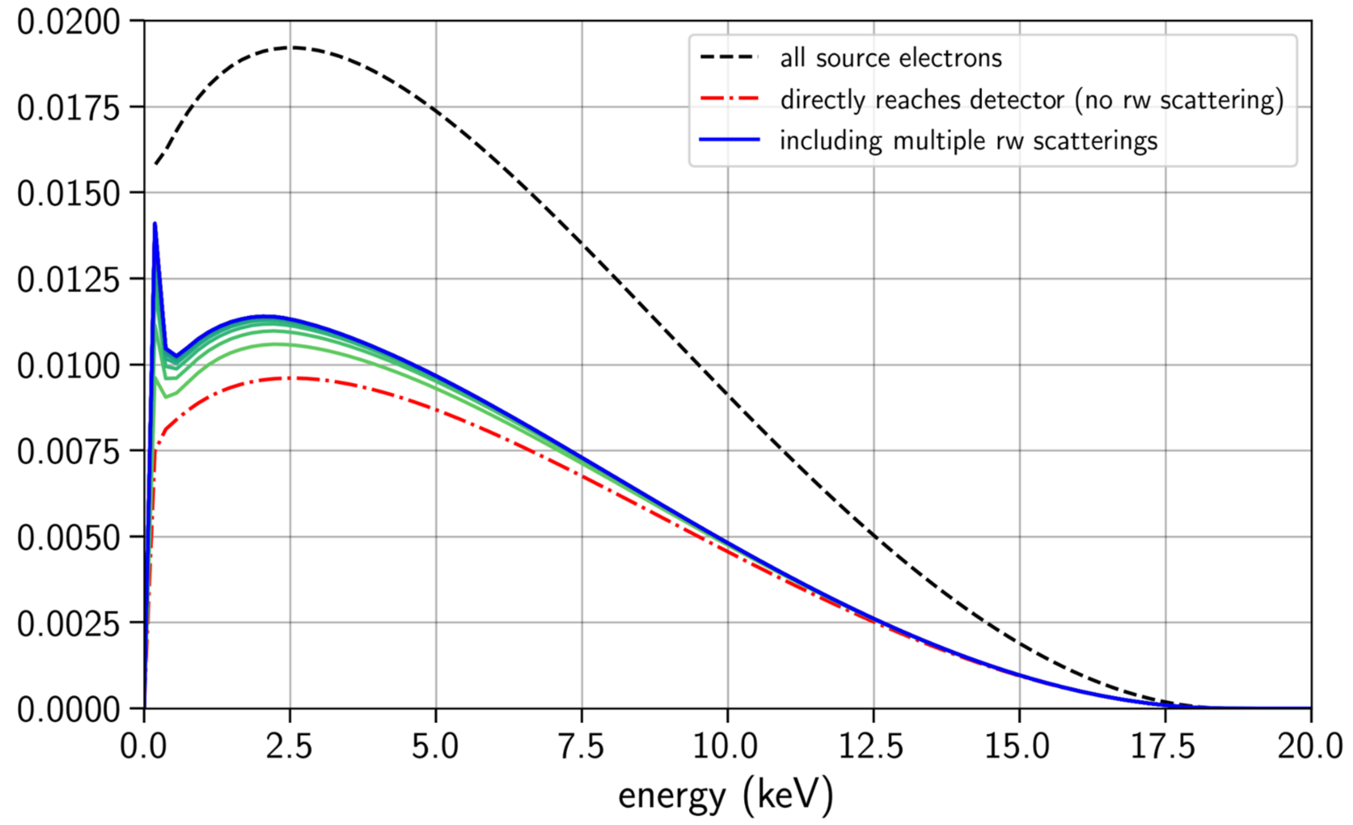
Rear Wall

	B_{pinch} = 6.00 T, B_{RW} = 1.26 T	B_{pinch} = 2.52 T, B_{RW} = 1.26 T	B_{pinch} = 2.52 T, B_{RW} = 0.32 T

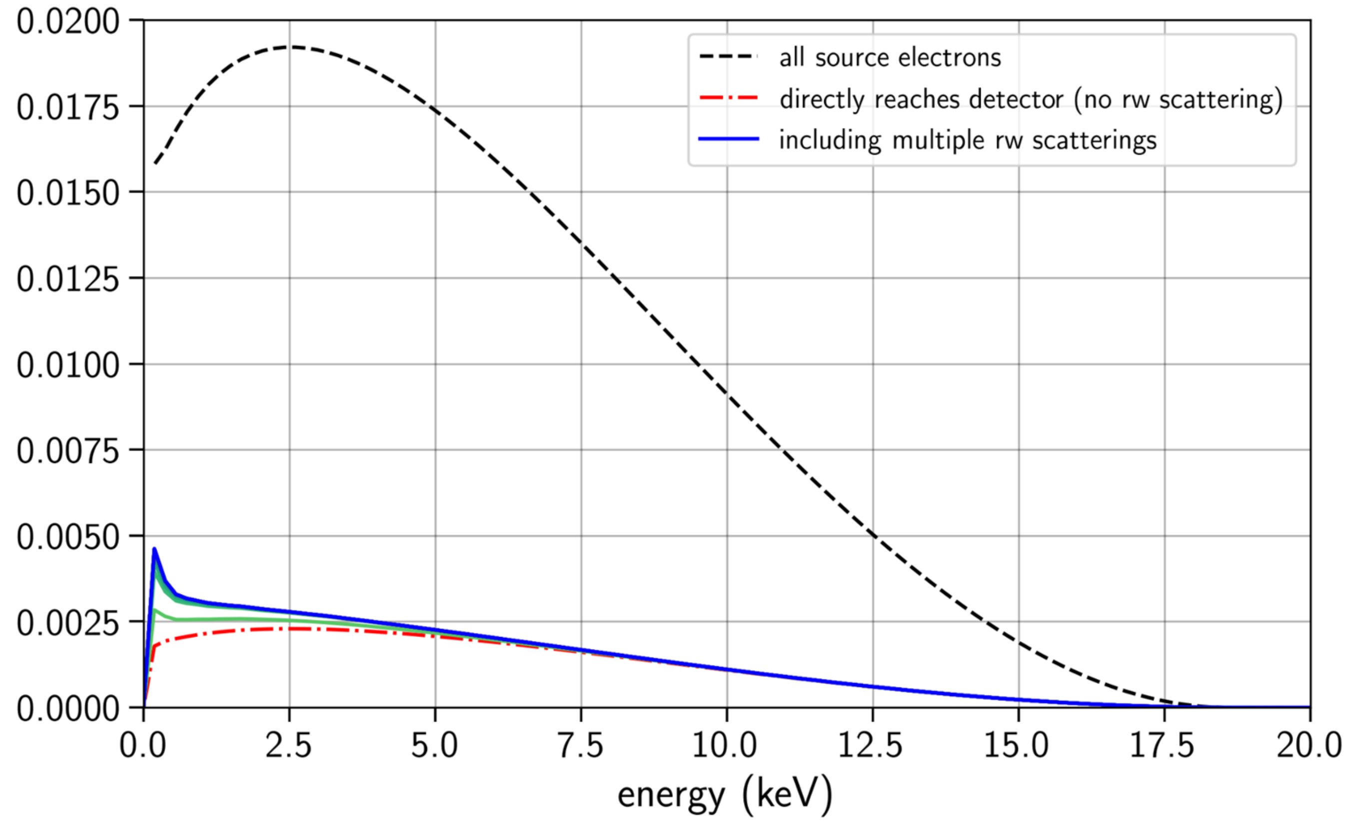
Gold

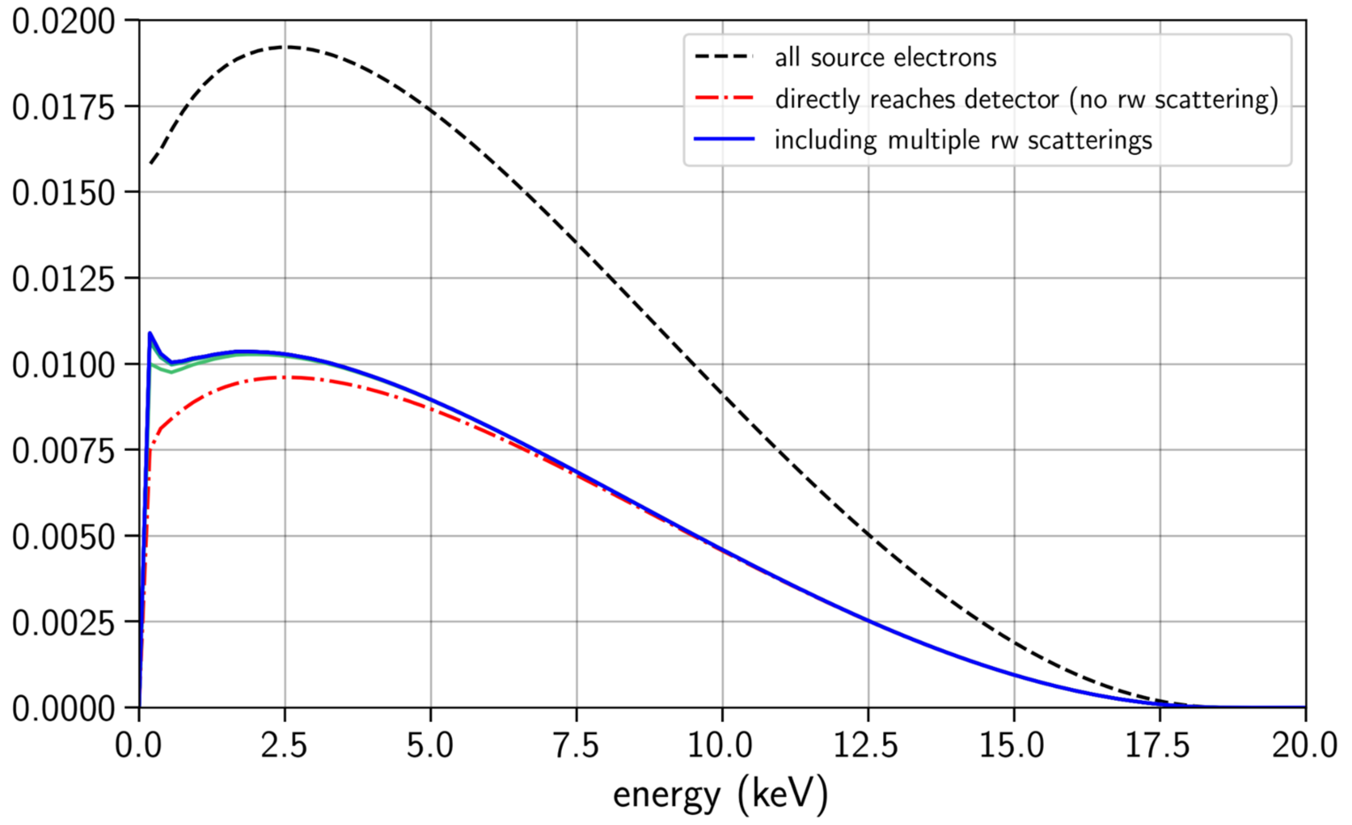


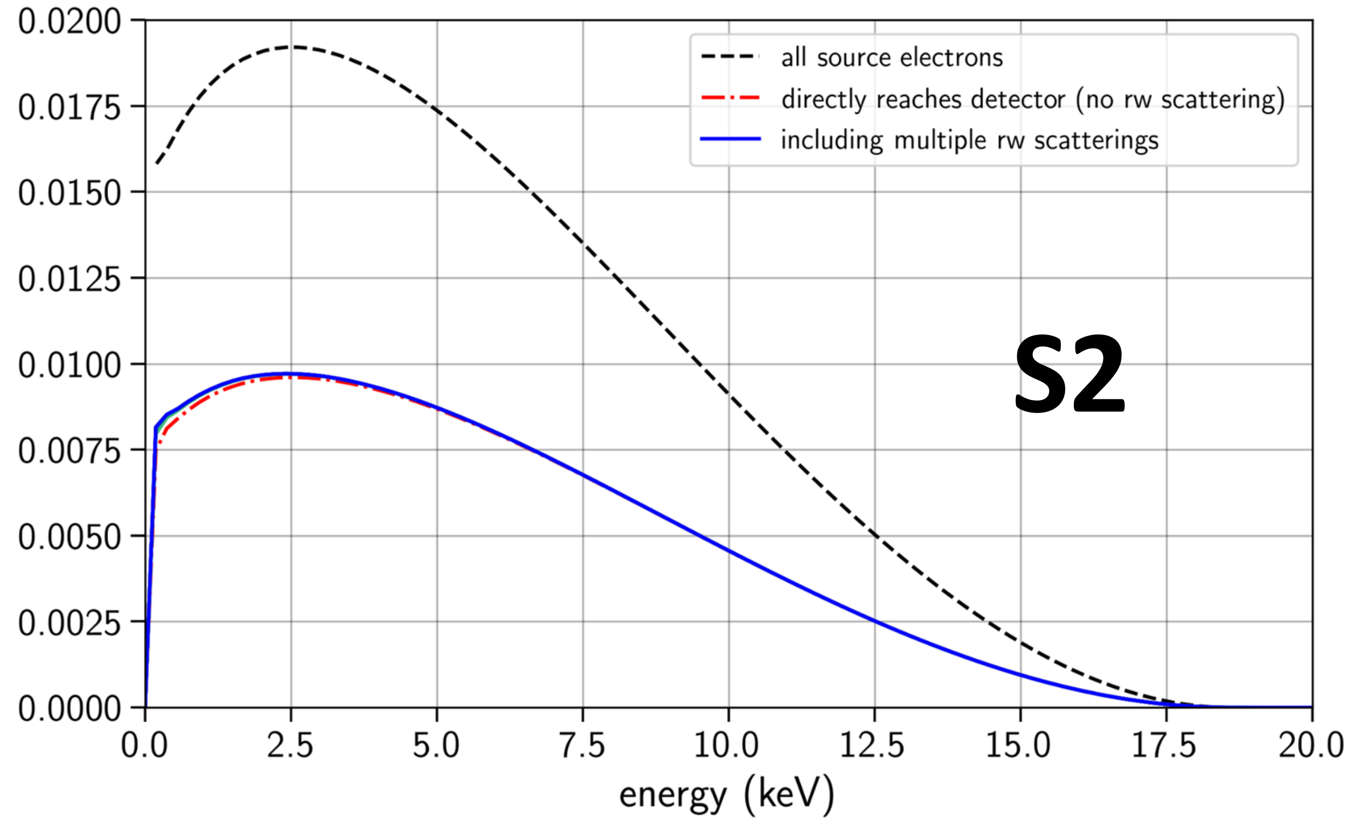




Beryllium







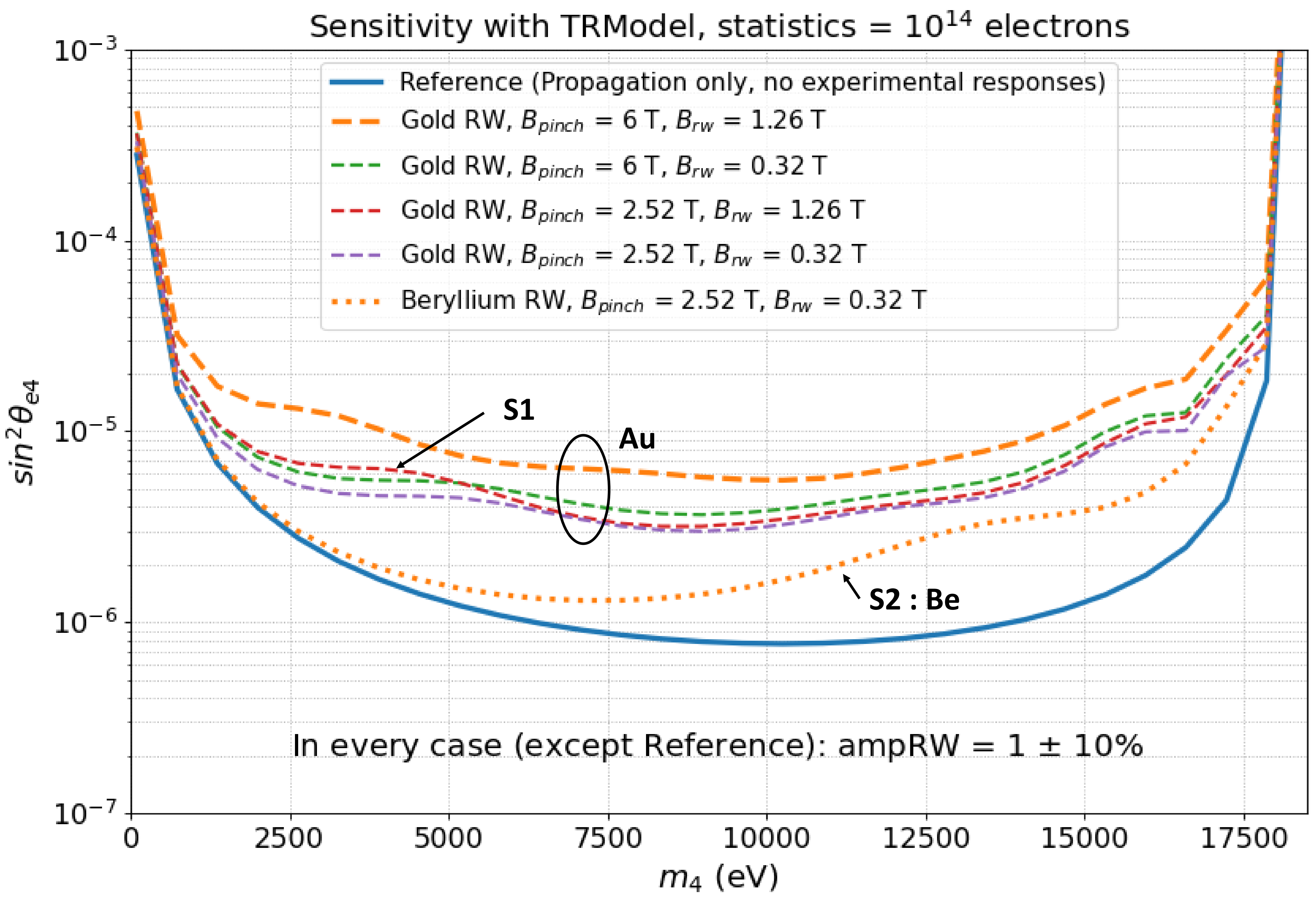
RW contribution to the total spectrum (full mass range) :

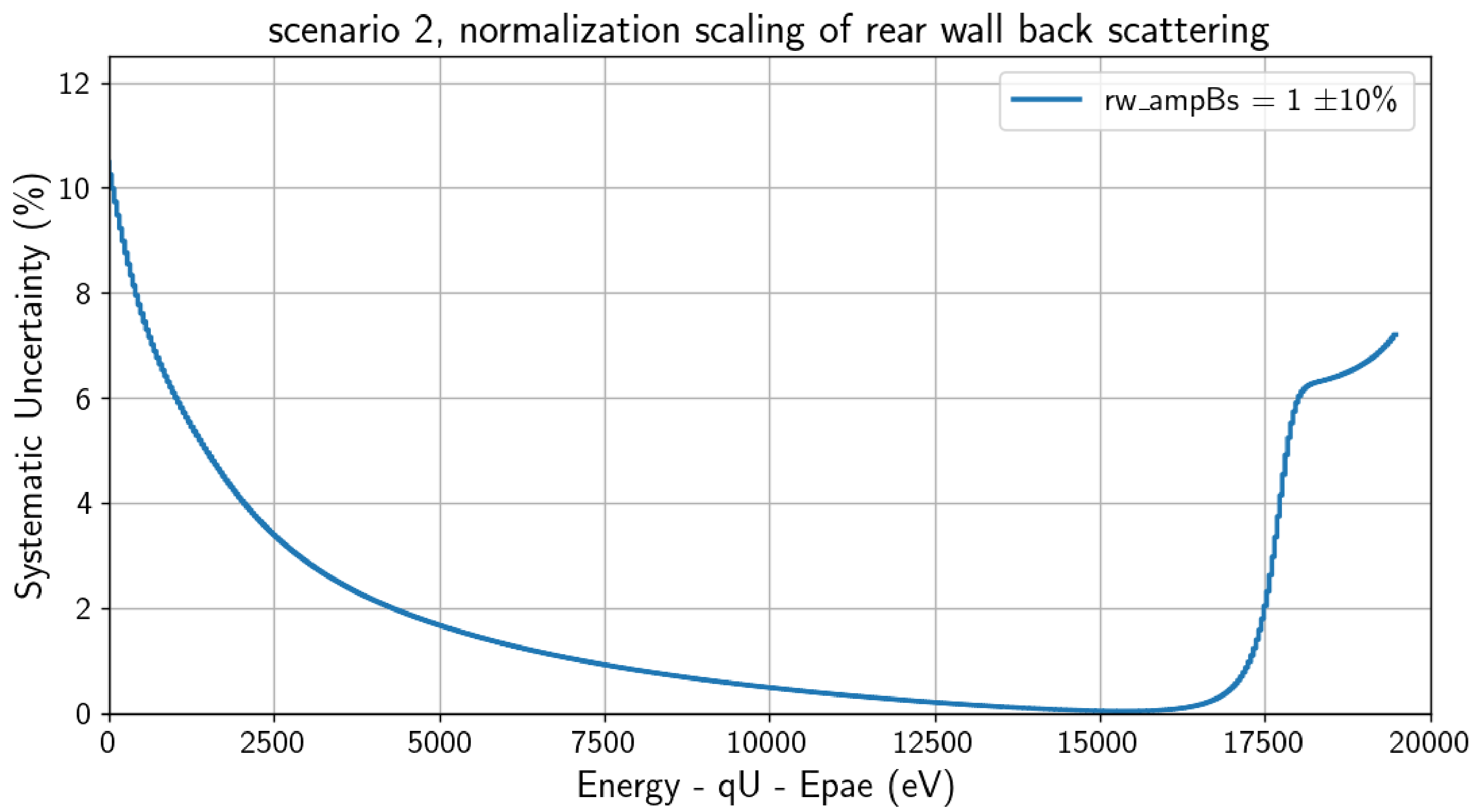
- **Scenario 1 : 54.7%**
- **Scenario 2 : 0.6%**

Plot by A. Nava

Rear Wall

- Assume uncertainty of 10% on backscattering probability
- High impact of RW in nominal configuration
- **Effect can be mitigated with new RW and magnetic field optimization**

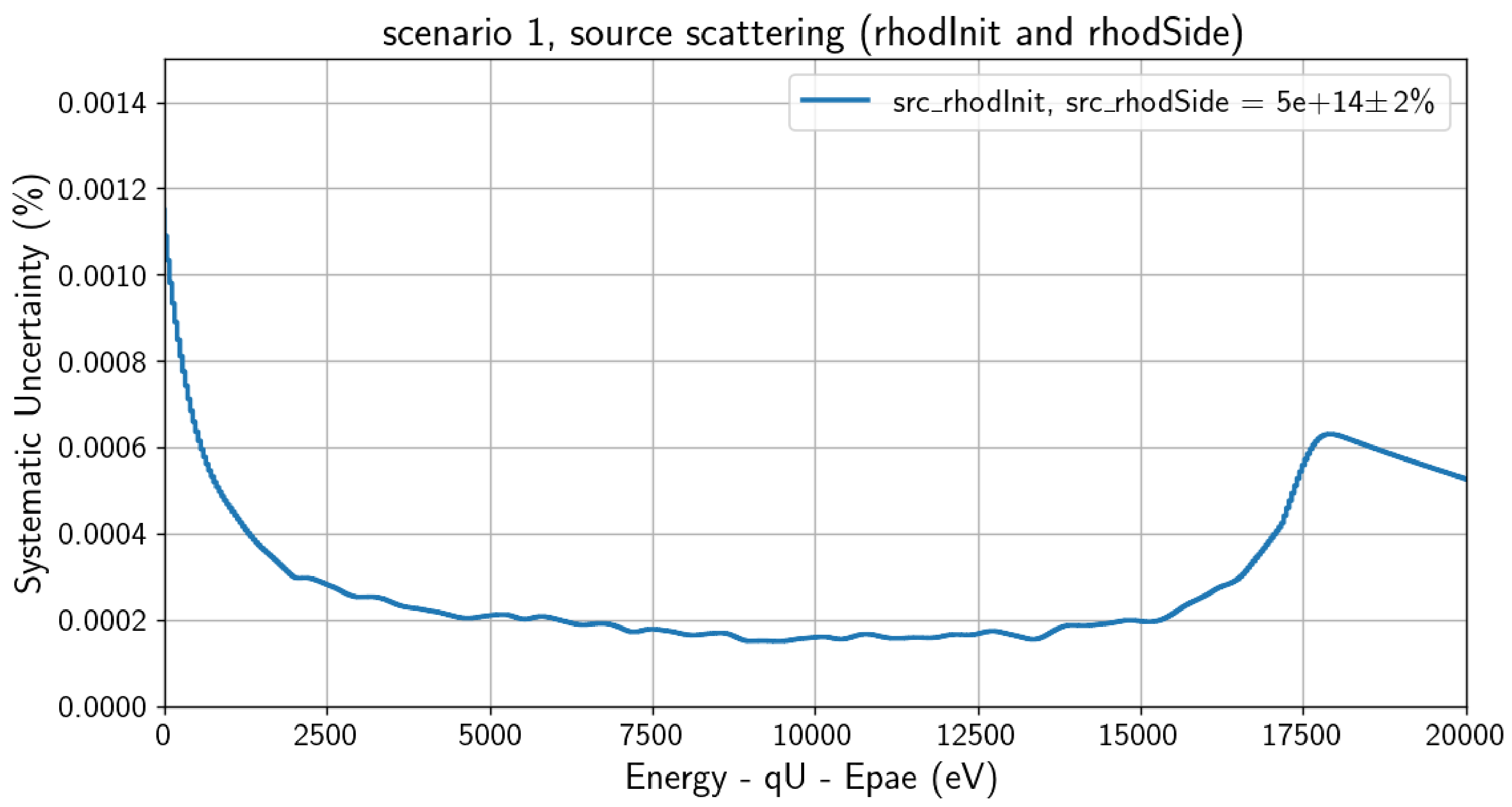


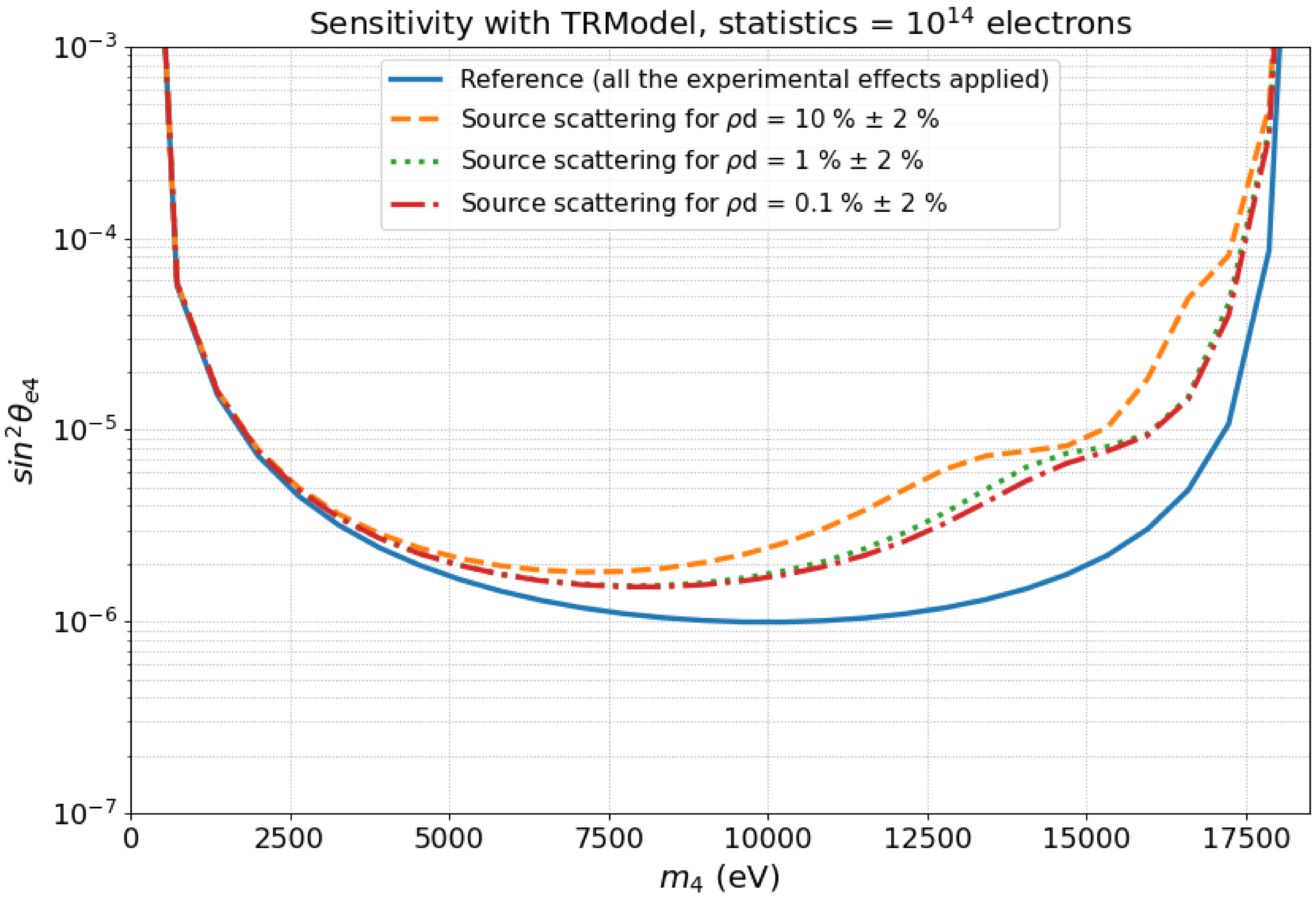


Plot by A. Nava

Column density

- Assume uncertainty of 2% on column density
- Scattering effects sub-dominant, due to reduced column density
- **Effect can be mitigated with less density**

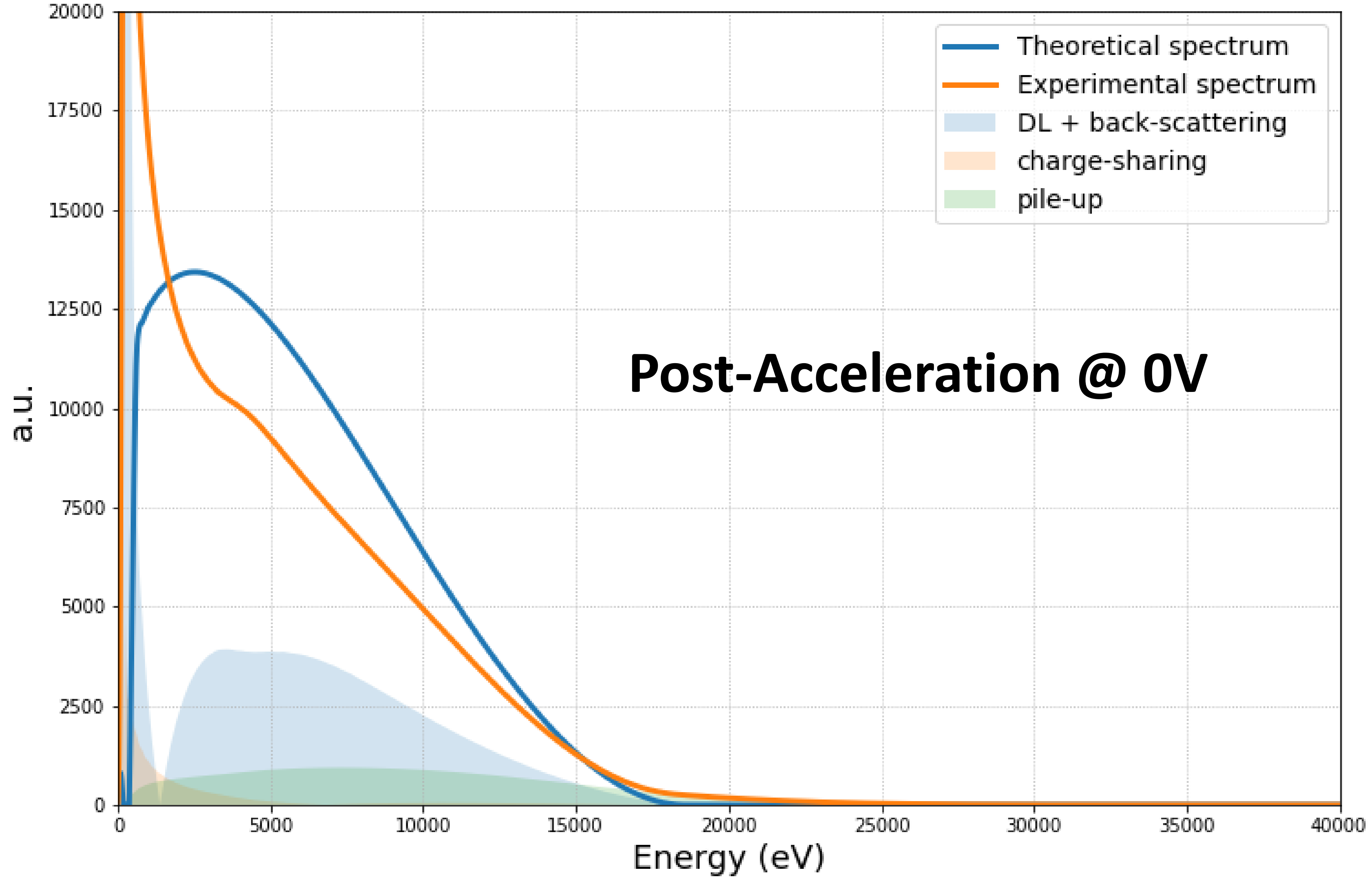


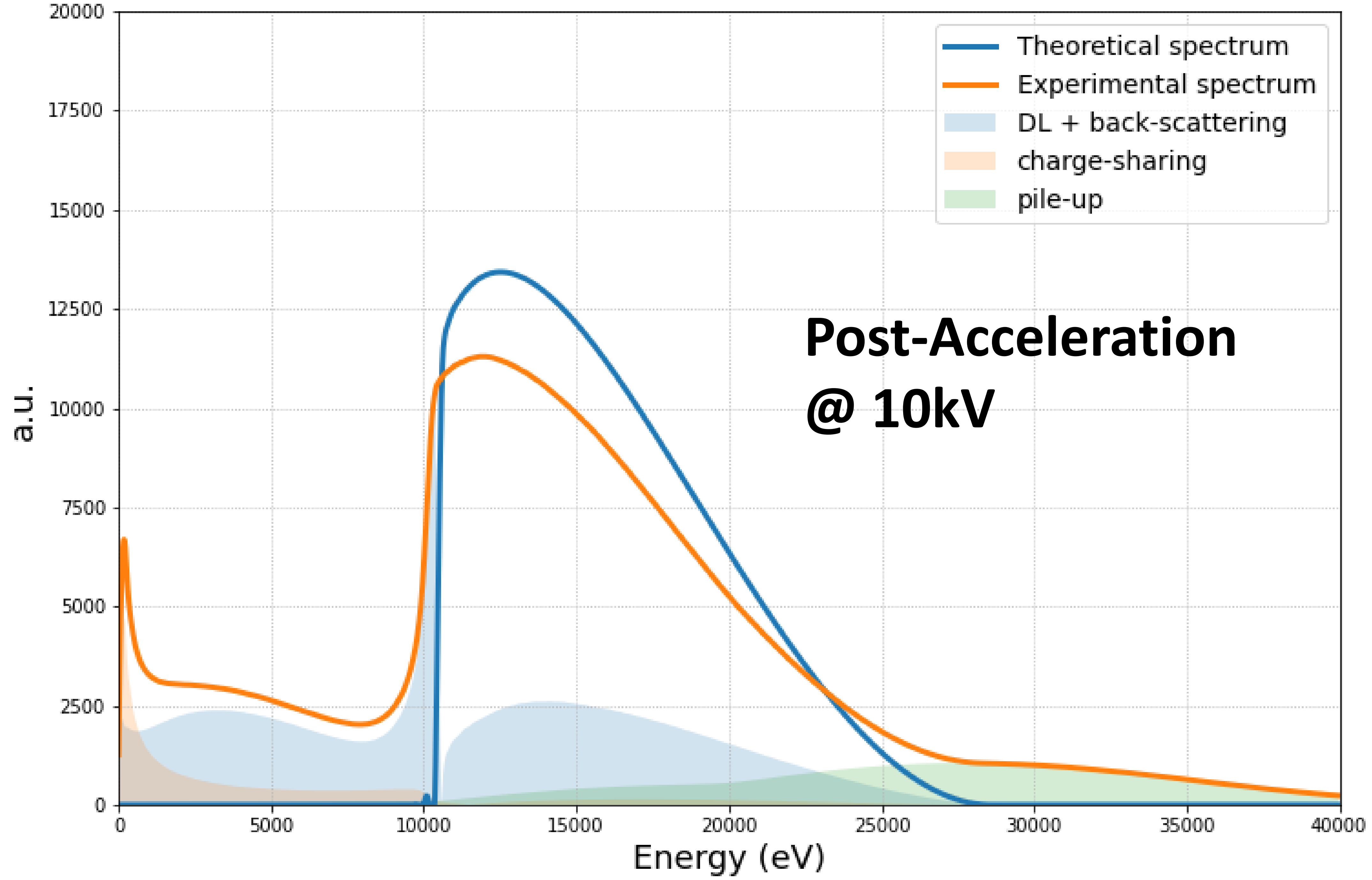


4d – Individual effects : detector

Plot by A. Nava

Detector : post-acceleration



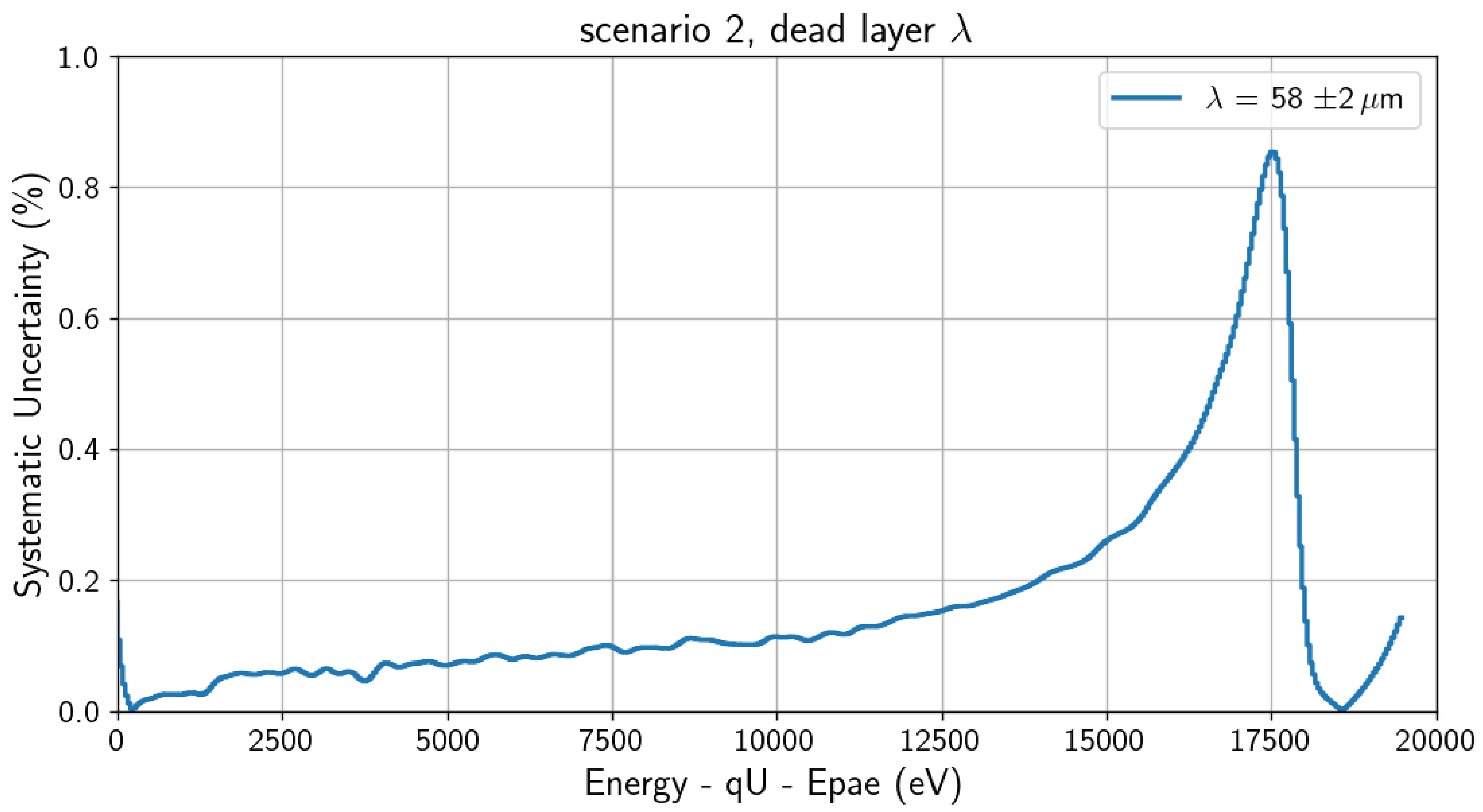


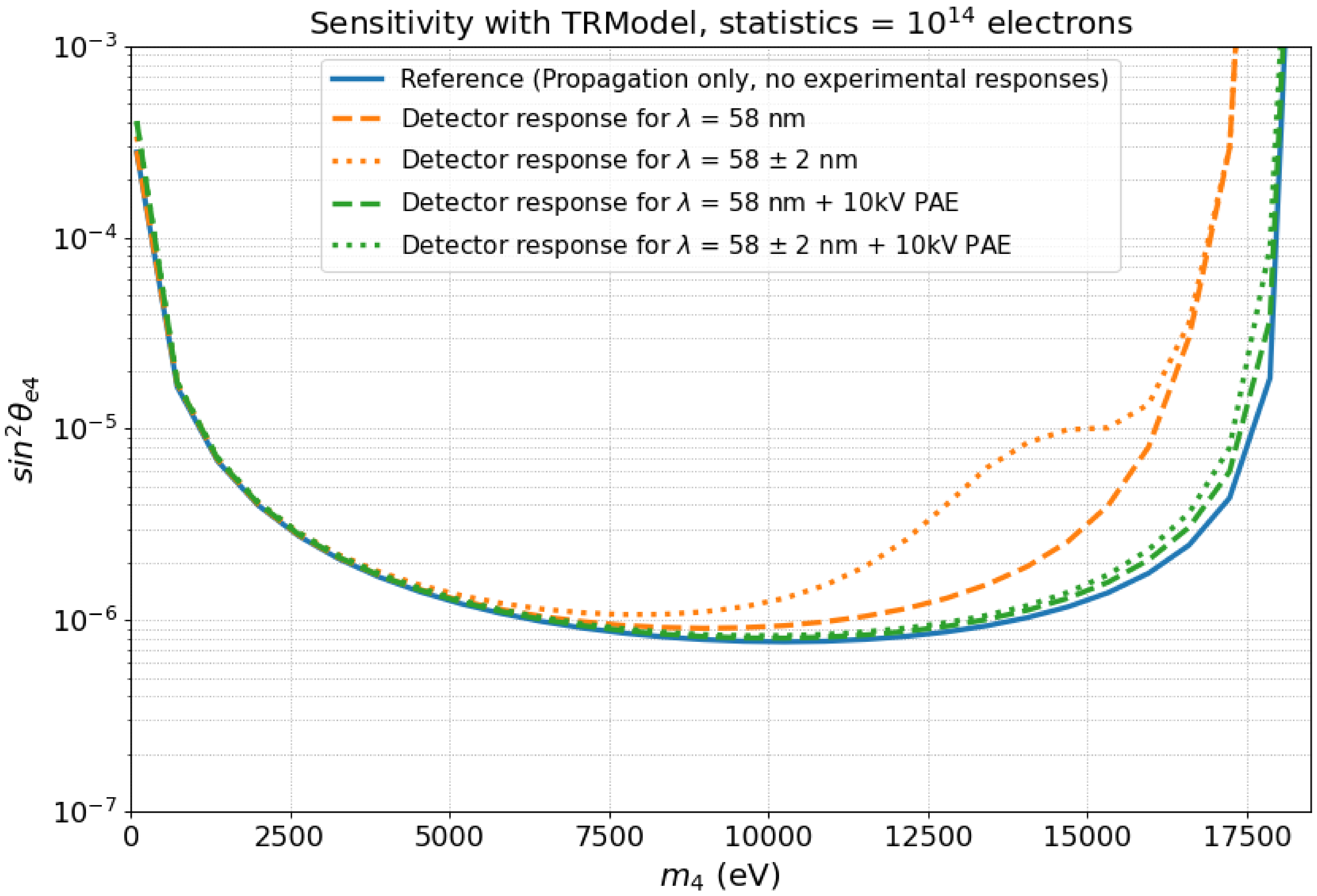
- **Post acceleration** increases the incident angle → **reduced backscattering**
- **Post acceleration** shifts **pile-up events** above the endpoint
- **Post acceleration** shifts spectrum above **charge-sharing and dead-layer events**

Plot by A. Nava

Detector : dead-layer

- Assume uncertainty of 2 nm on dead-layer thickness
- **Effect can be mitigated by post acceleration**

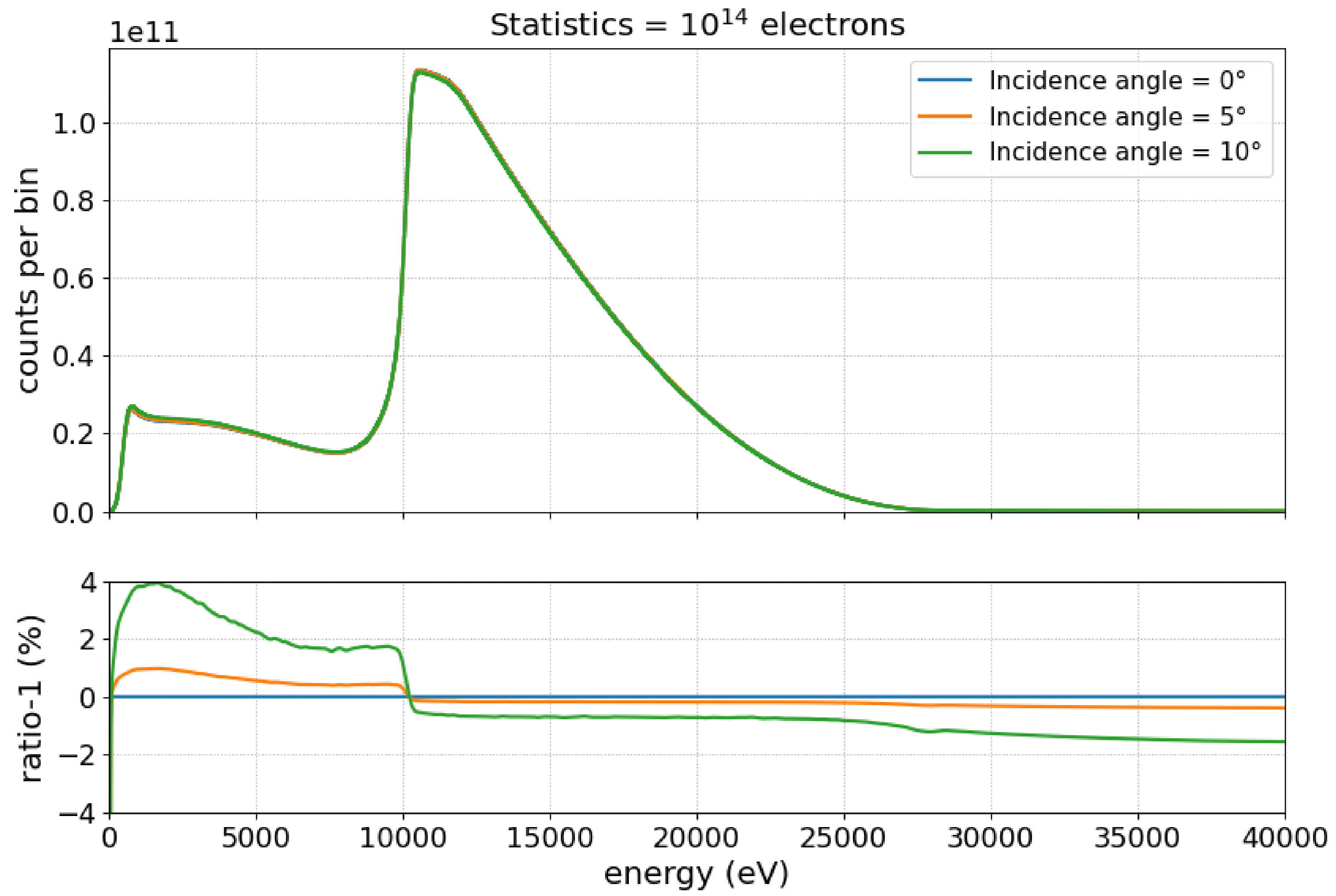


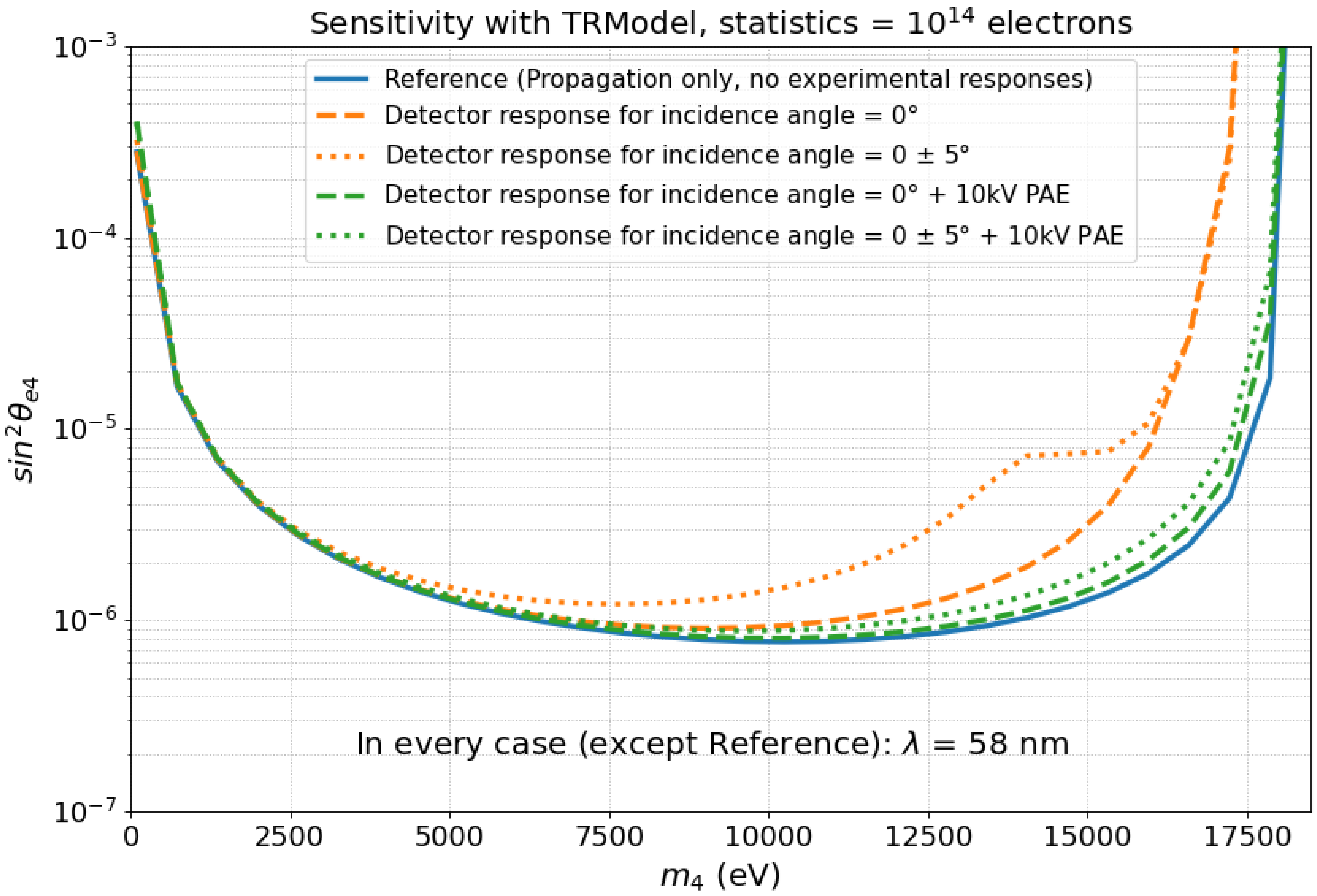


Plot by A. Nava

Detector : backscattering

- Assume uncertainty of 5° on incidence angle → emulate backscattering uncertainty
- **Effect can be mitigated by post acceleration**

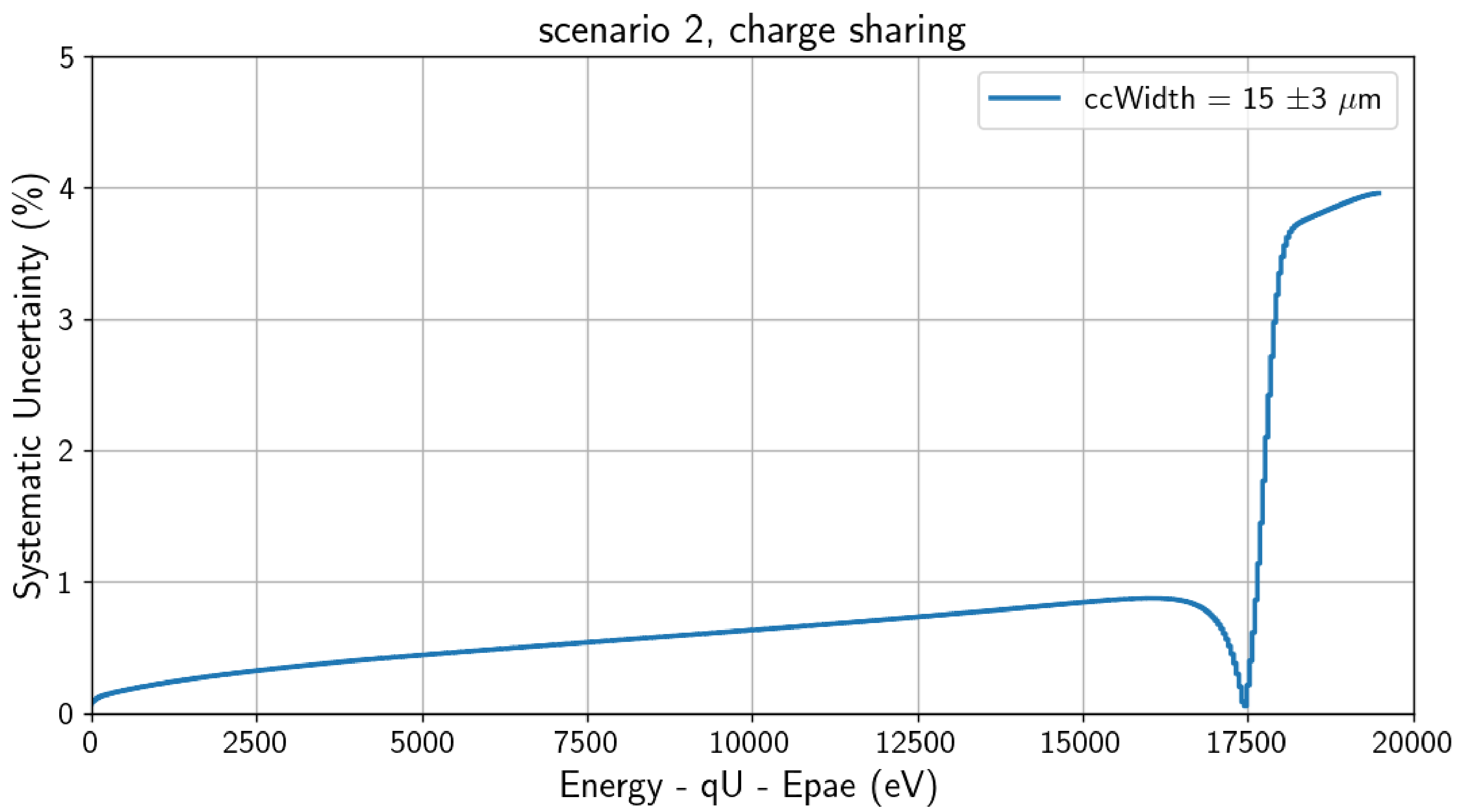


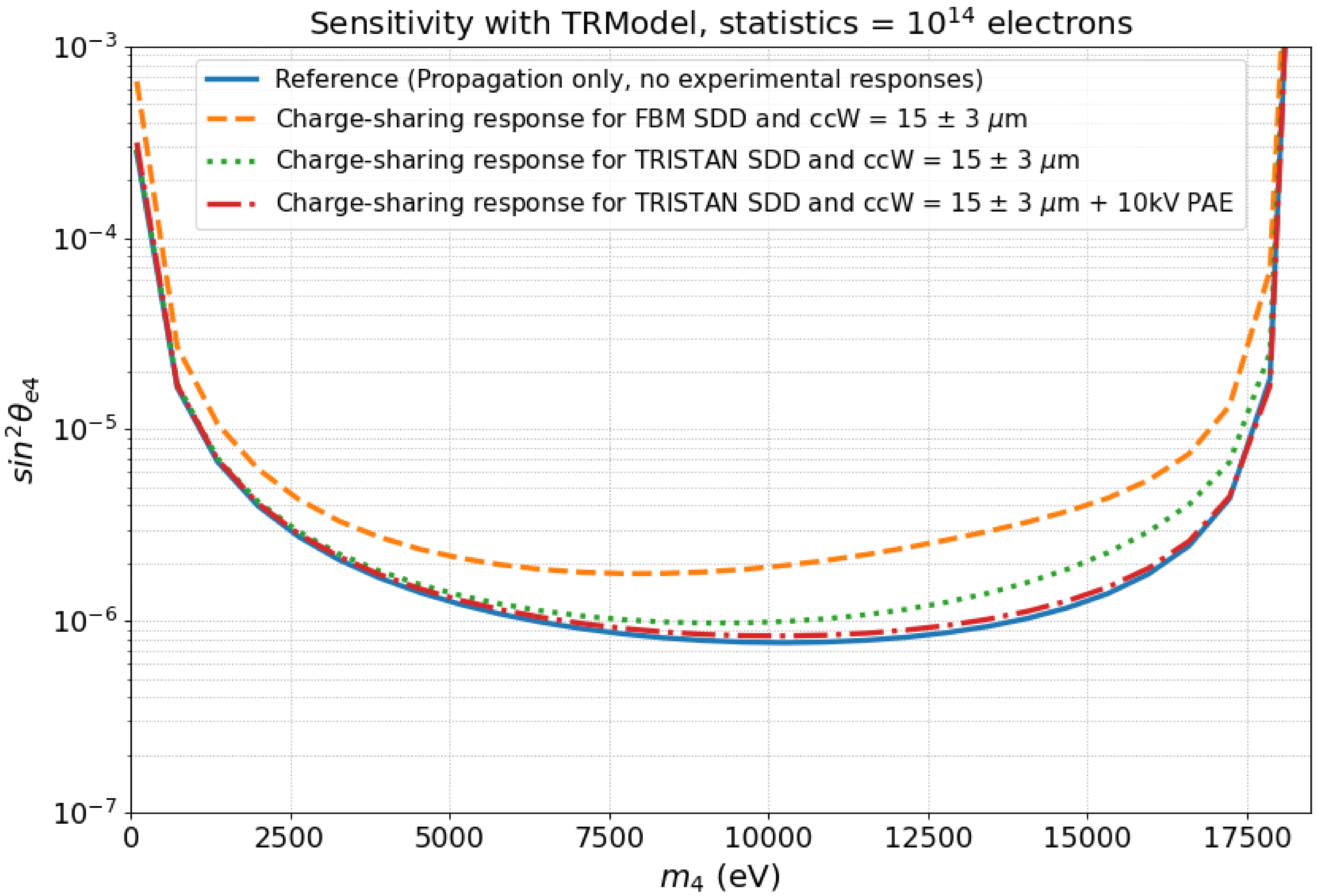


Plot by A. Nava

Detector : charge-sharing

- Assume uncertainty of 3 µm on charge cloud size
- **Effect can be mitigated by post acceleration**

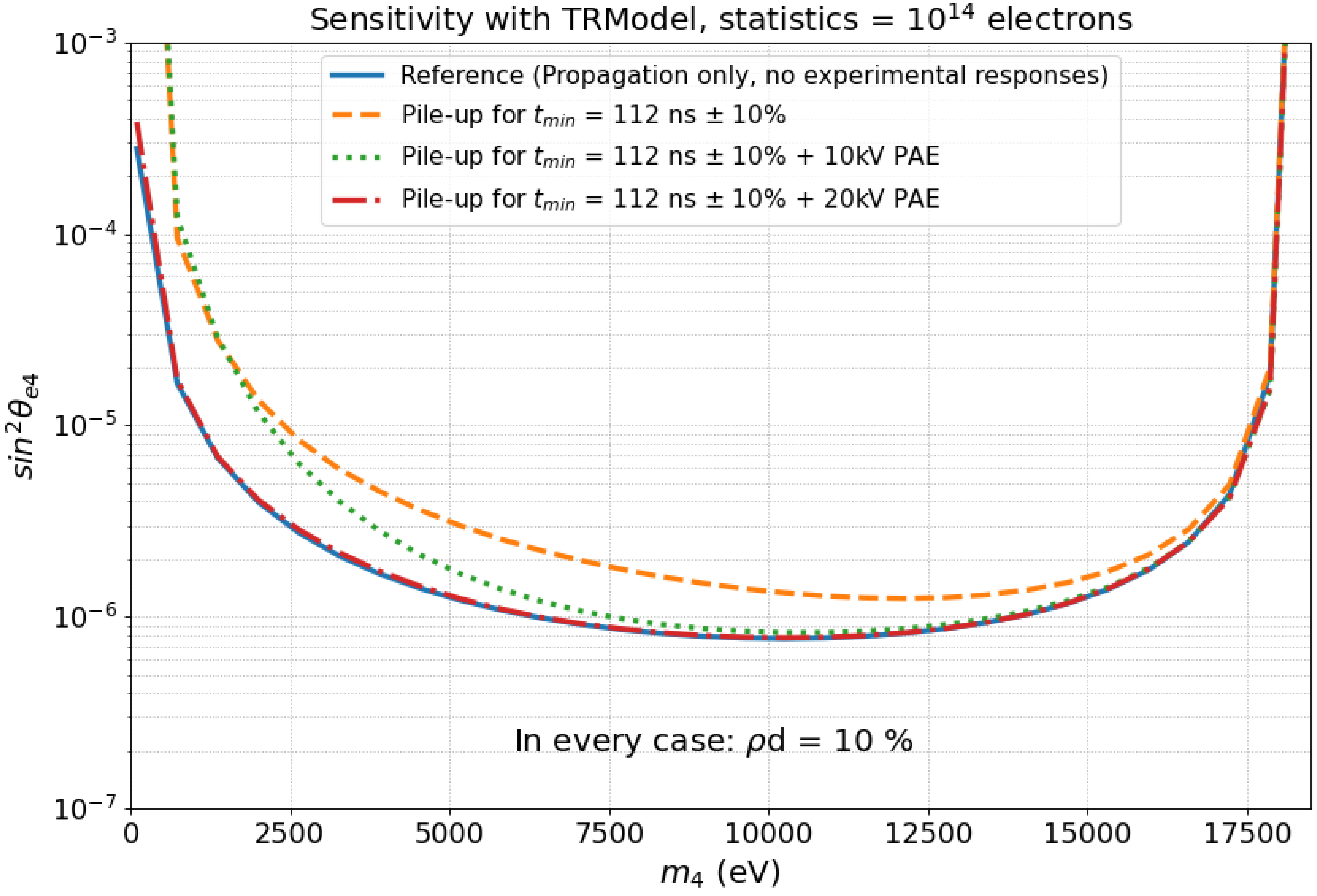


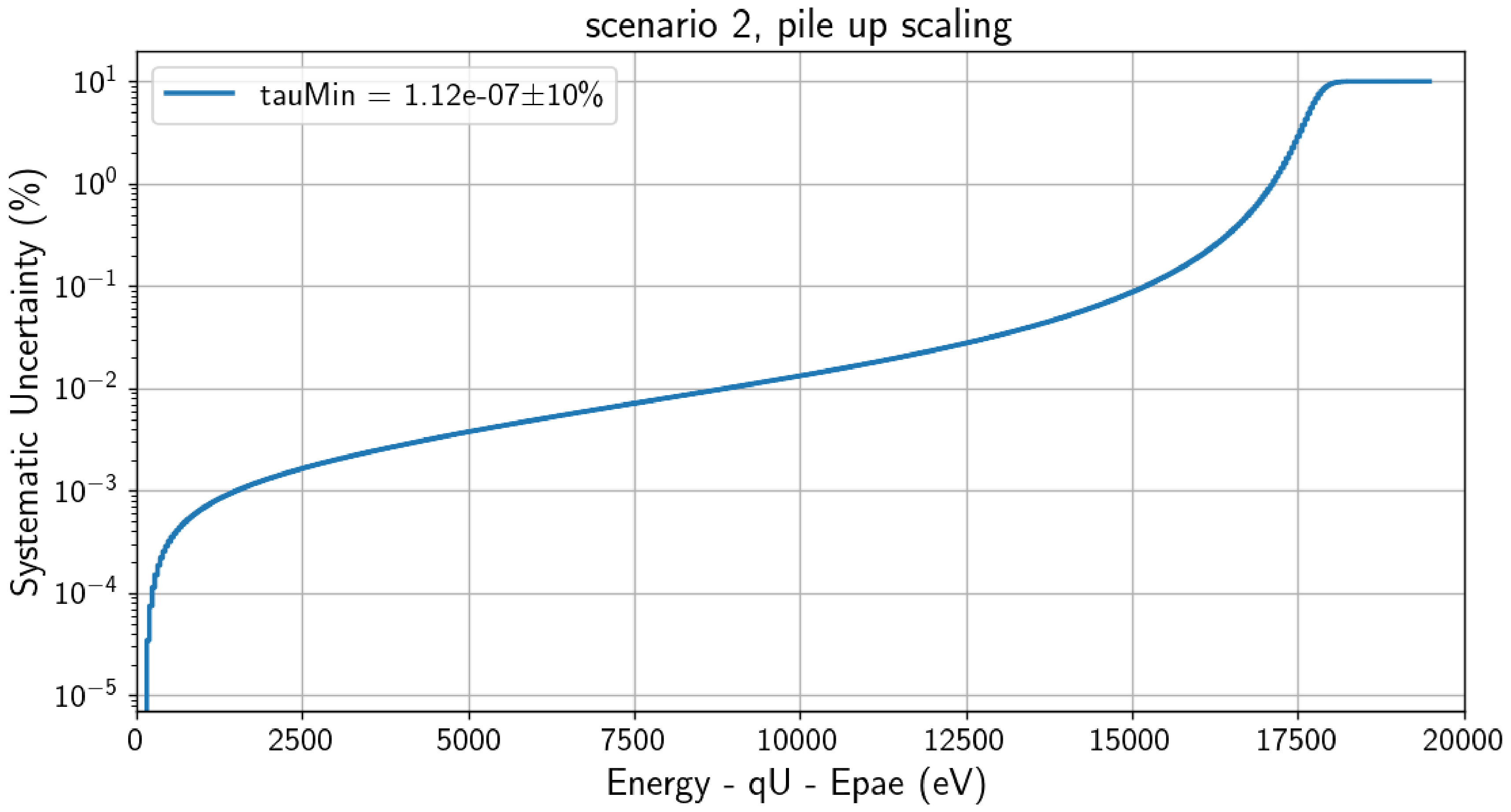


Plot by A. Nava

Detector : pile-up

- Assume uncertainty of 10% on time resolution
- **Effect can be mitigated by post acceleration**

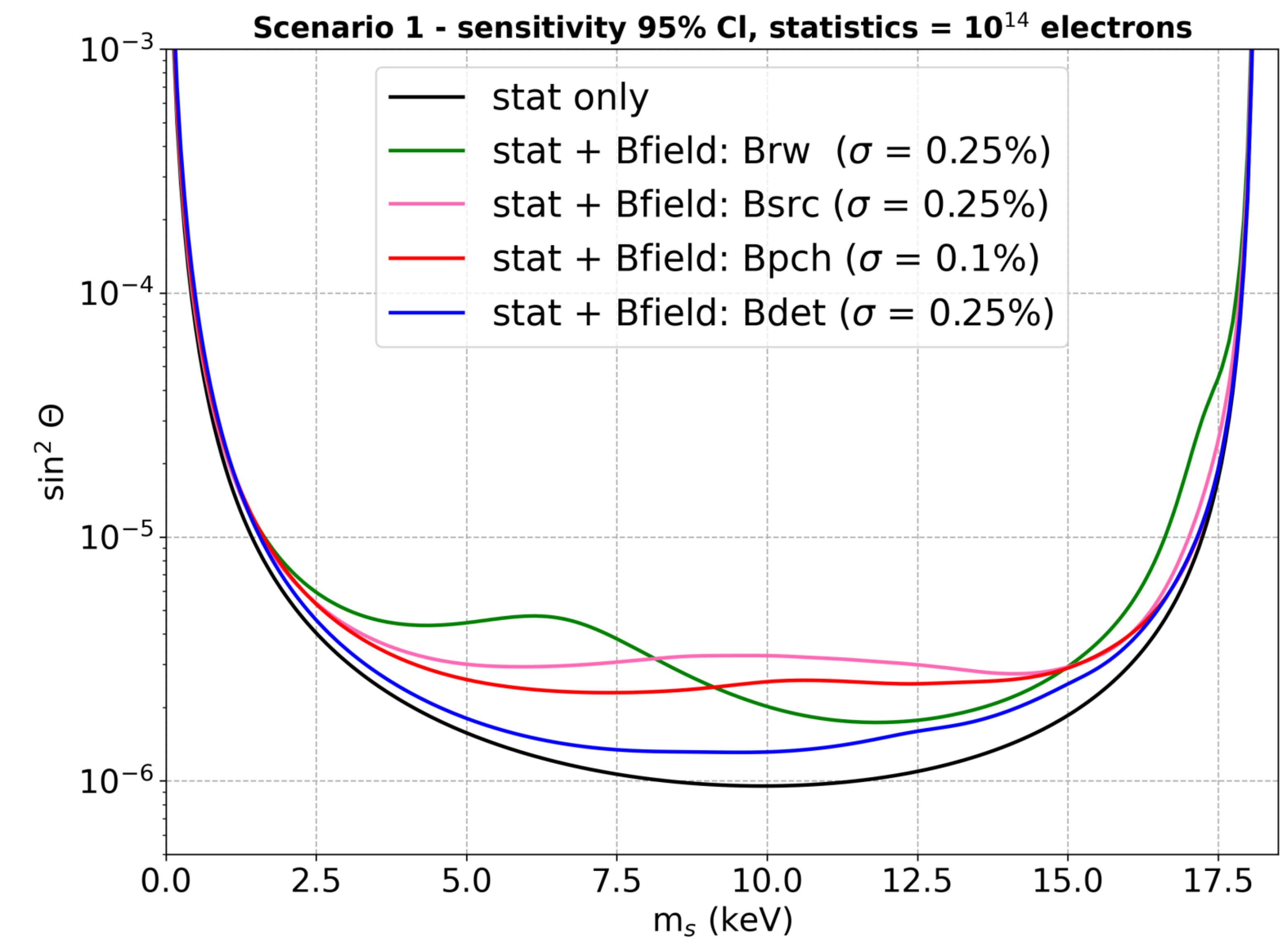


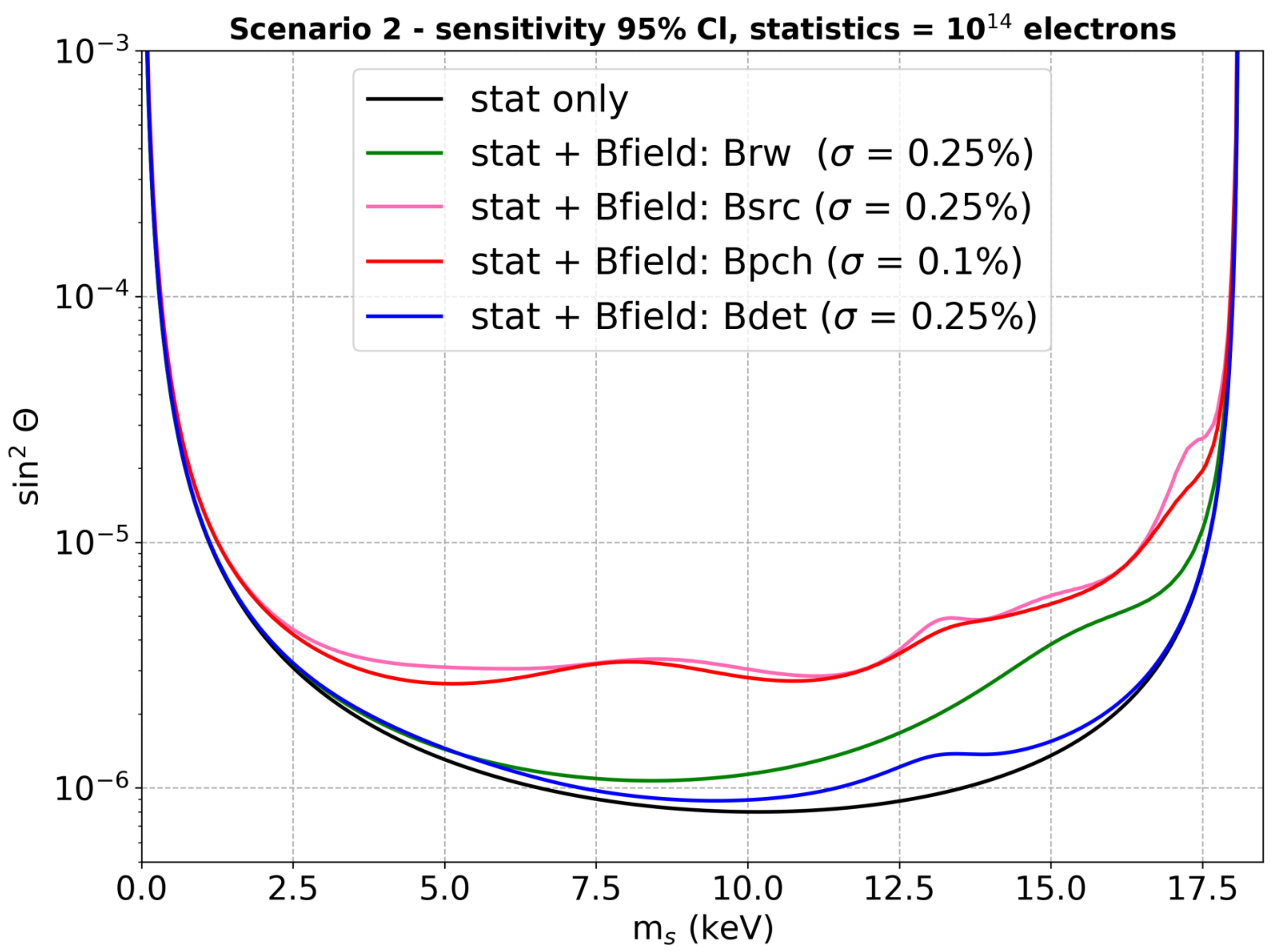


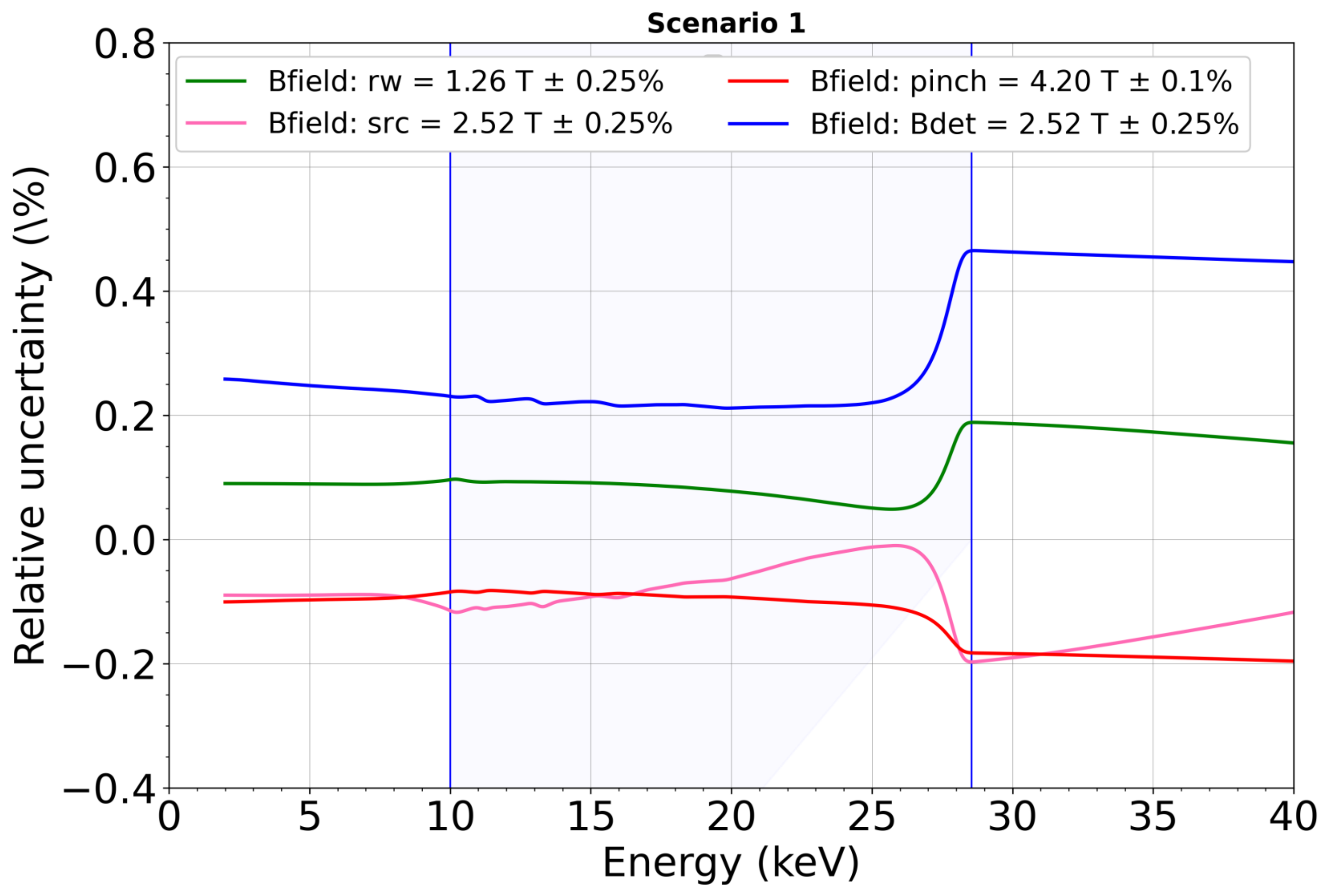
4e – Individual effects : propagation

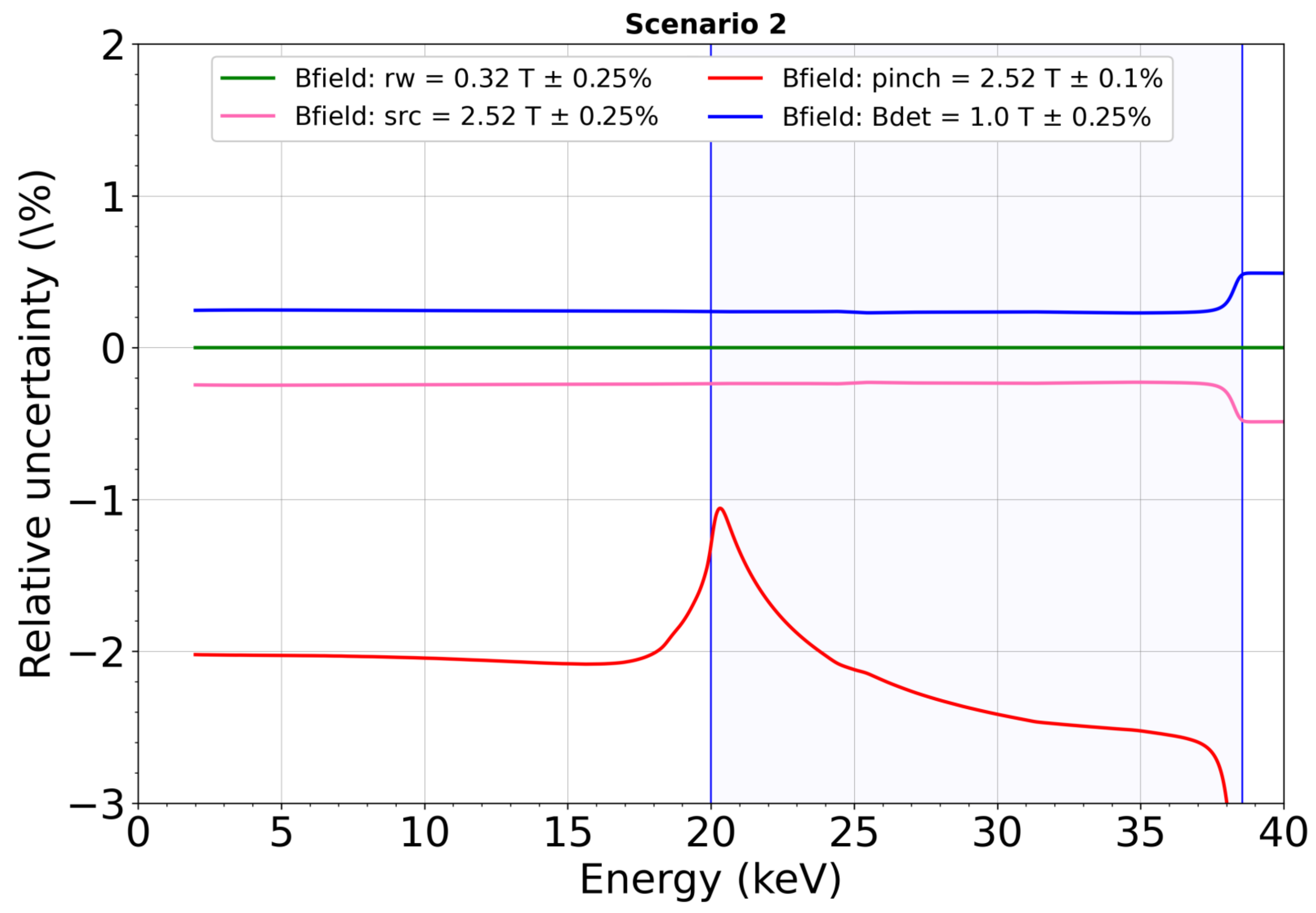
Magnetic fields

- Bfields assumed stable
- Assume respectively 0.25% and 0.1% for Bsrc and Bpinch as KNM5. 0.25% for Bdet
- Brw impact tested with 0.25% but not inluded in the final uncertainty budget (redondant with amp_rw = 1 ± 0.1)
- High impact of Bpinch and Bsrc for both configuration



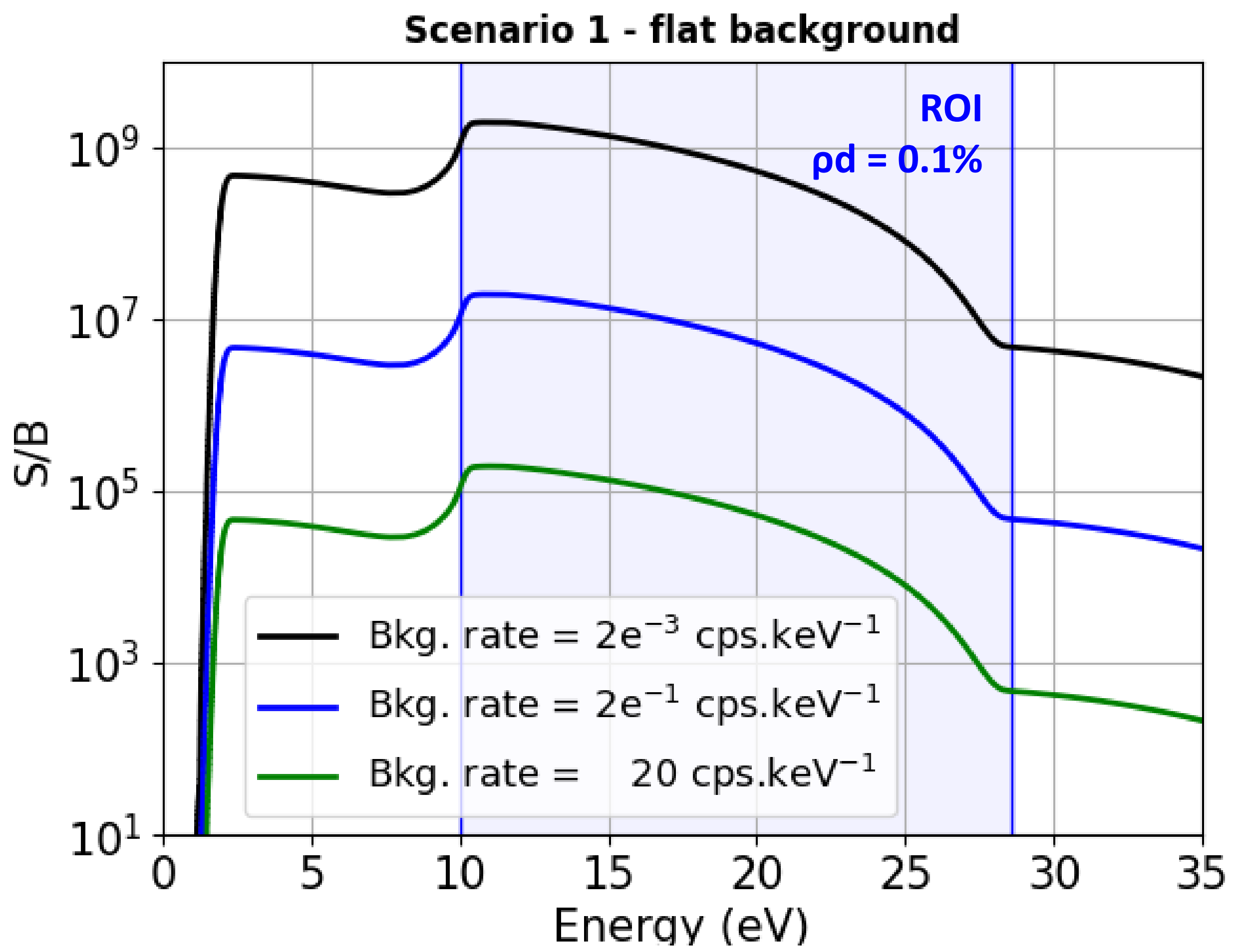






Background

- Expect background level of **10^{-3} cps/keV** (F. Harms PhD)
- Signal to background at the level of 10^8 (ρd = 0.1%)

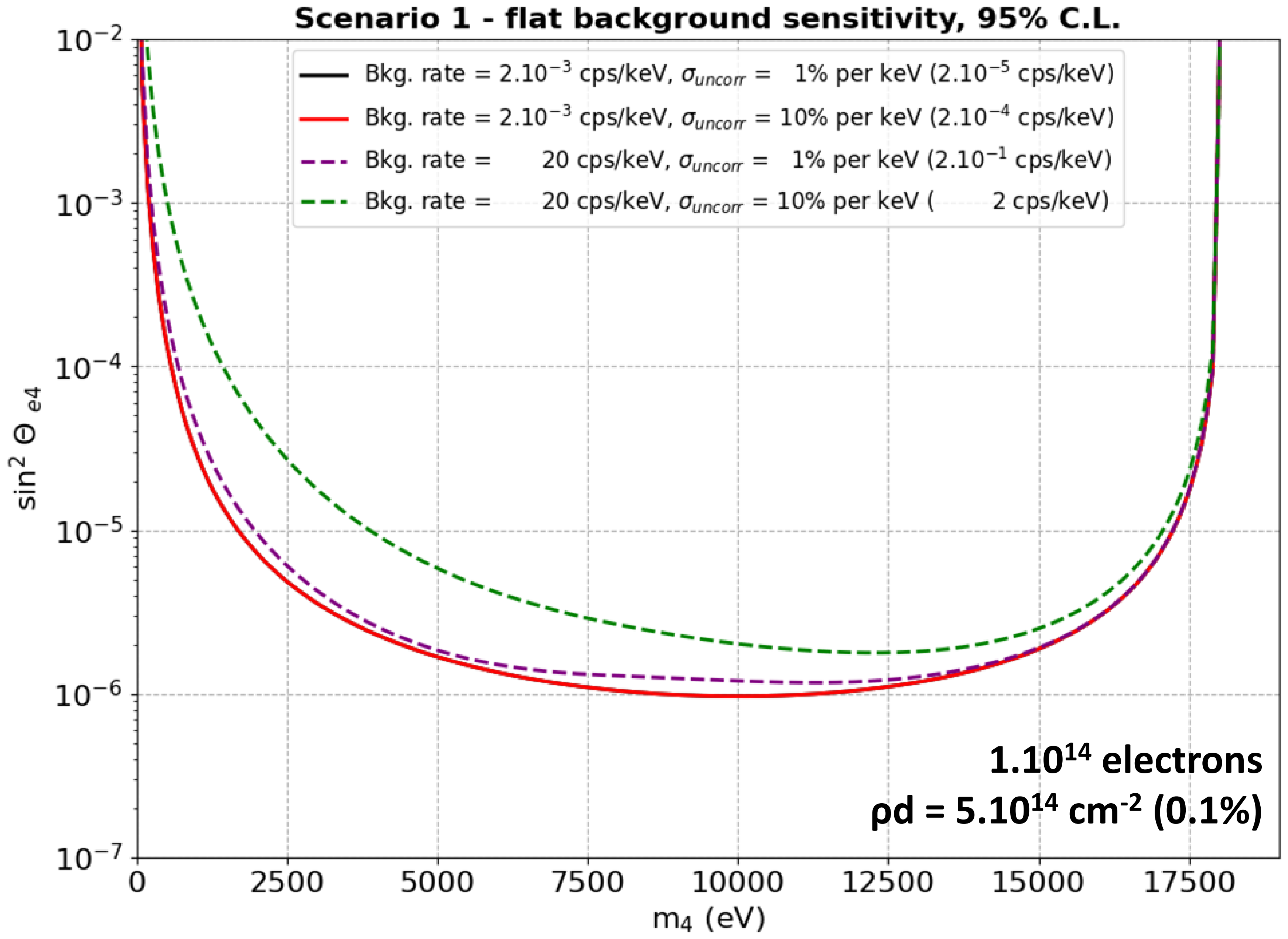


Test 1 : check for impact of constant background rate

⇒ no significant impact of the background even for unrealistically high rate

Test 2 : check for impact of background shape knowledge

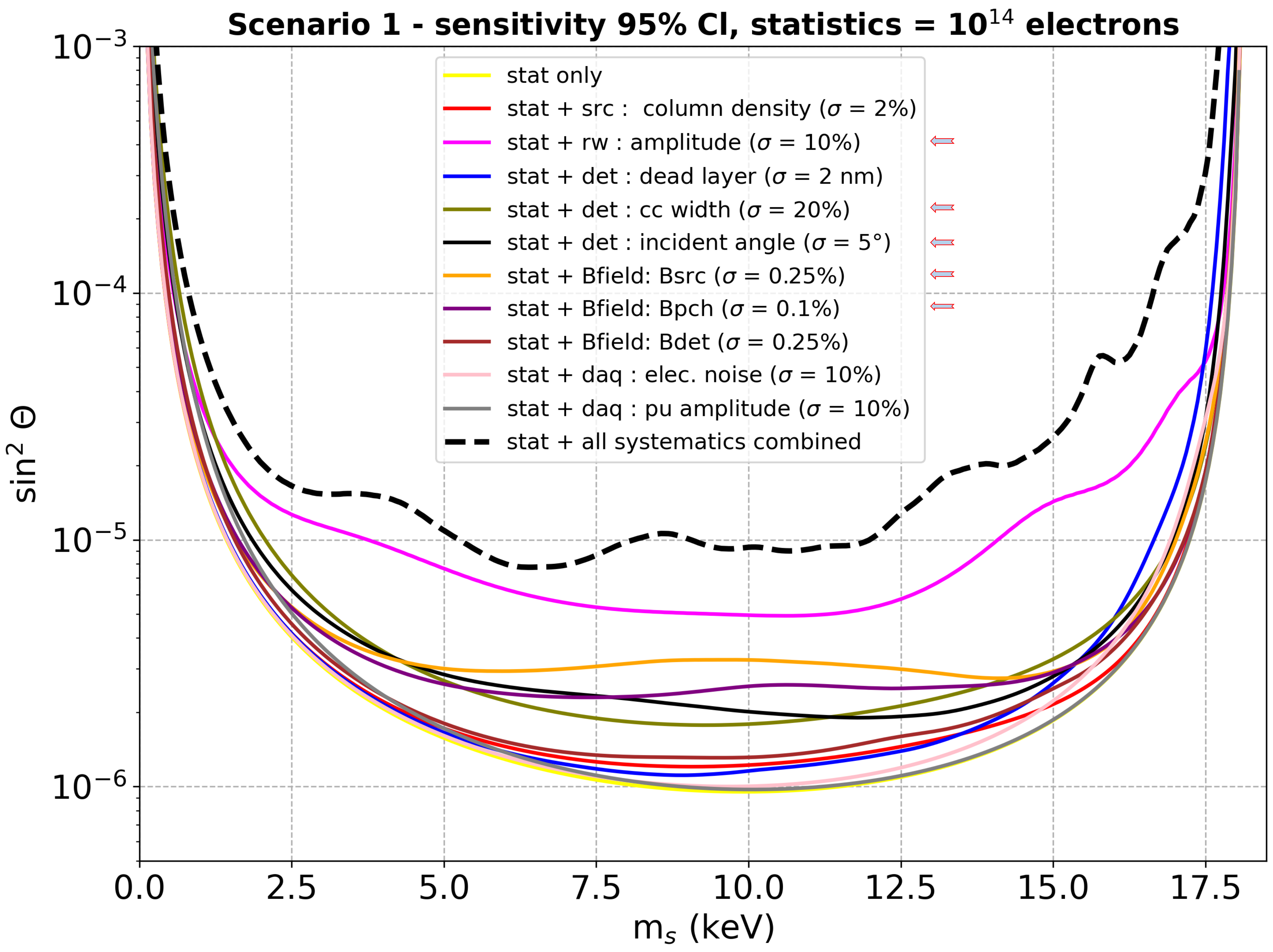
flat spectrum: shape unknown (accounted with uncorrelated uncertainties between the bins)

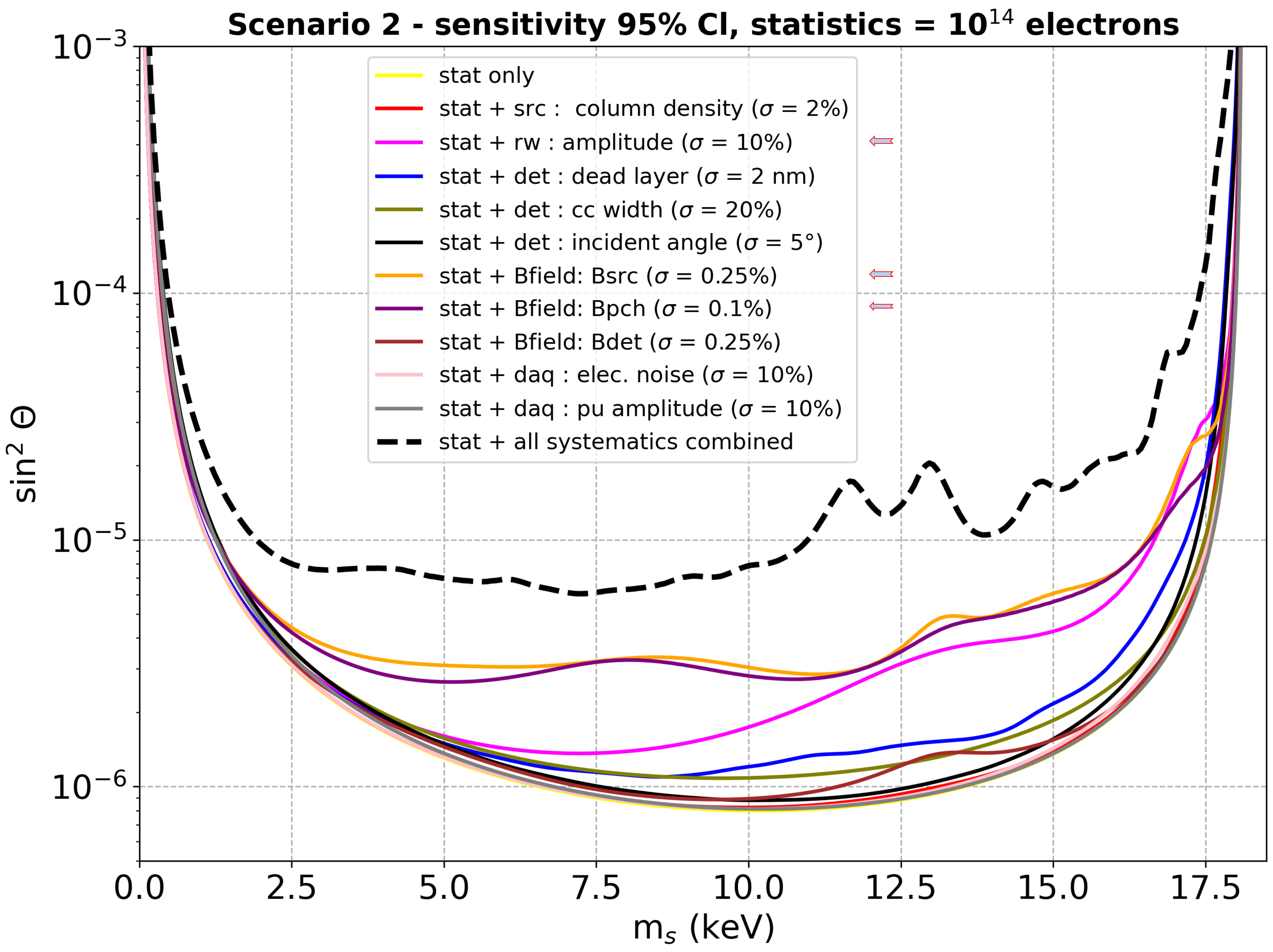


⇒ Background starts to matter only for very high rates, and large uncertainties

⇒ **Additional test in progress**

5a – Combined systematic uncertainty





Scenario 1

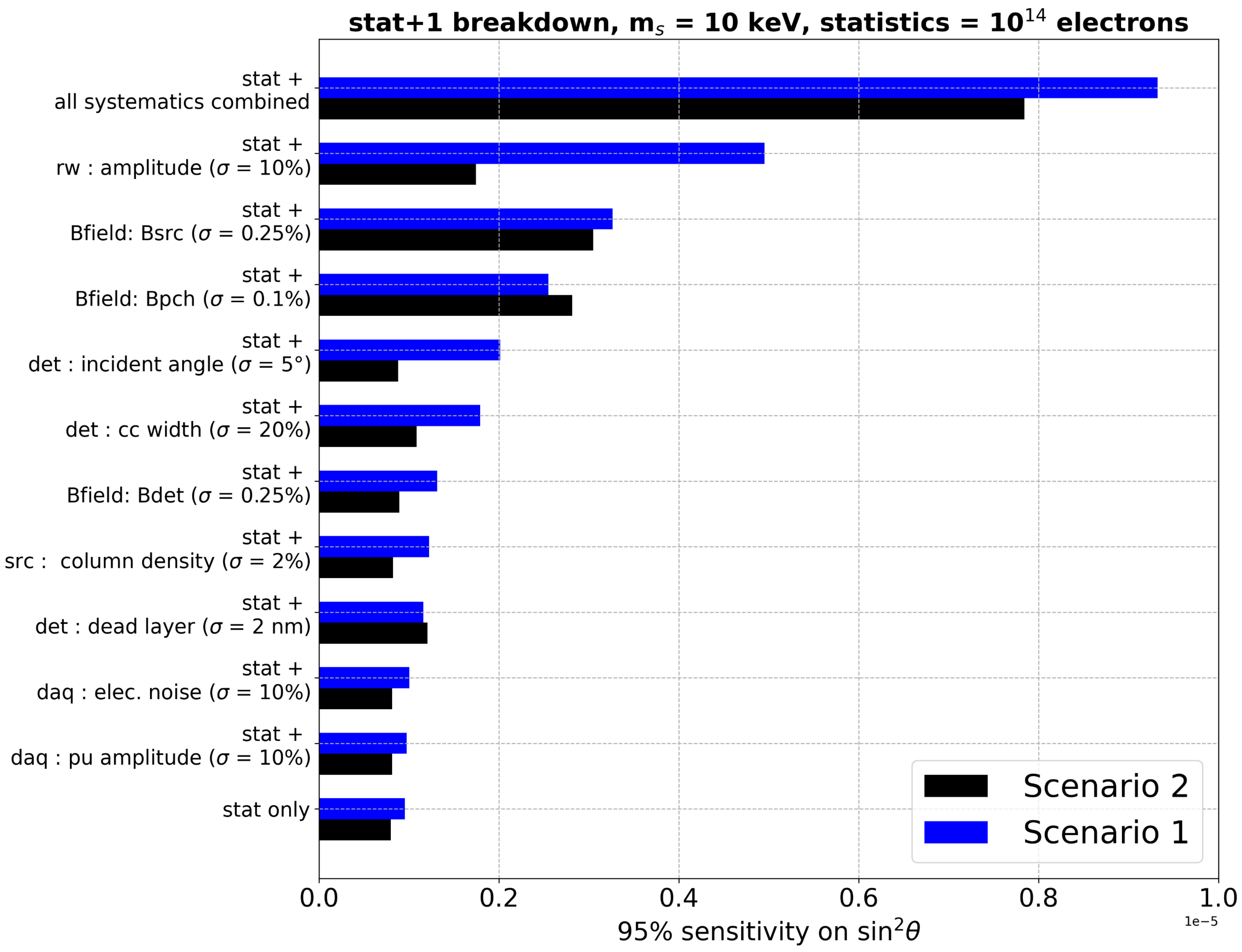
- PAE = 10 kV
- RW: gold
- Nominal B-fields

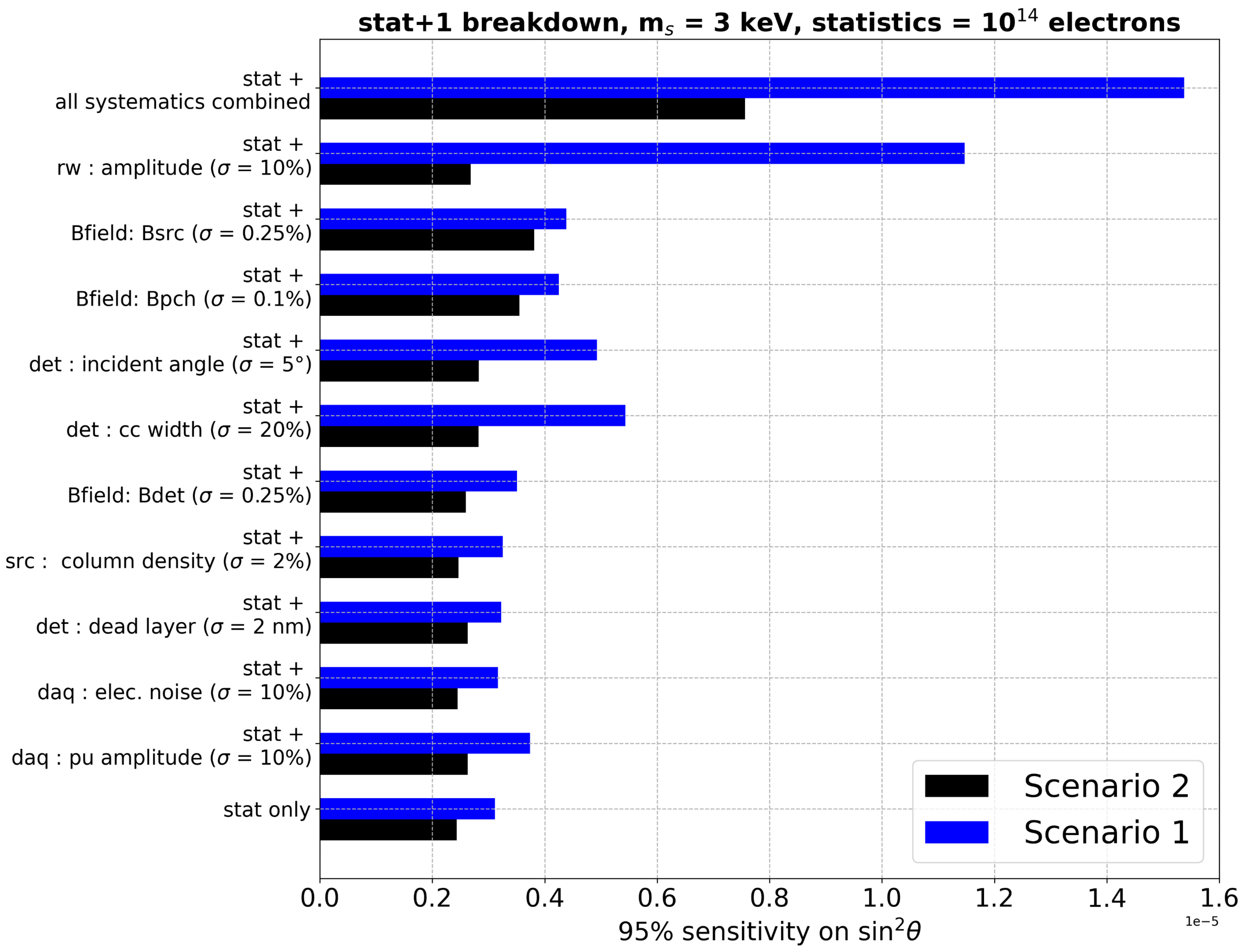
Scenario 2

- PAE = 20 kV
- RW: Beryllium
- Optimal B-fields

⇒ Systematic effects reduce the sensitivity by (at least) one order of magnitude

5b – Systematic breakdown

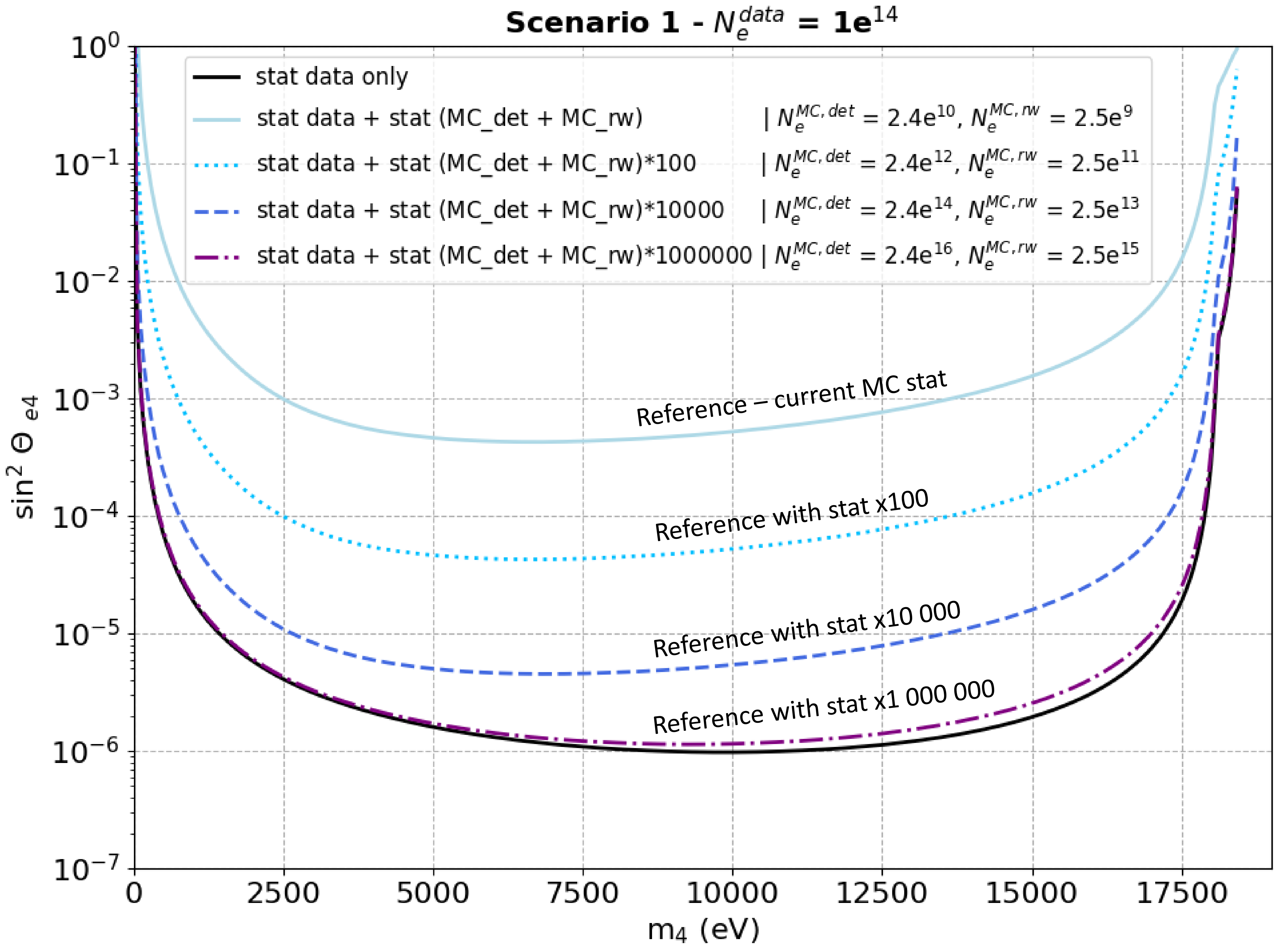




- @10keV: 3 dominant contributors: RW, Bsrc & Bpch (RW contribution strongly decreased for S2)
- @3keV: no strongly dominant contibutor beside RW for S1

Response of the experimental setup from simulations

- RW and detector response from G4 simulations – potentially the source later on
  - ↳ limited G4 statistic → non-negligeable statistical uncertainty
- Impact investigated with a MC
  - ↳ Random spectra with statistical fluctuations added on the detector and RW response matrices



➡ **For a full MC-based experimental response (1st phase), ~500 years of computing with 100 cores required for the MC statistical uncertainty to be non-dominante**

New approach need to be considered!
↳ Investigation on-going : parametrized response (from MC) with parameters from calibration data

See TRISTAN review part 3 (Calibration)

Conclusion

First version of deep tritium model

- Allows to study systematic effects
- Probably not precise enough to fit the data

Statistical sensitivity

- **1×10^{-4}** can be reached after days (at rho-d = 0.01 - 0.1%)
- **1×10^{-6}** requires 1 month @ rhod = 1% or 1 year @ rho-d = 0.1%
- **2×10^{-7}** requires 1 year @ rhod = 1% → maximum in Phase-1 (9 modules)

Systematic

- 12 systematics investigated
- effects reduce the sensitivity by (at least) one order of magnitude
  - Rear wall → need to **block RW** electrons
  - Detector effects → need **Post Acceleration**
  - Non adiabatic motion → need probably **new LFCS** to extend the interval to 15 keV below E_0

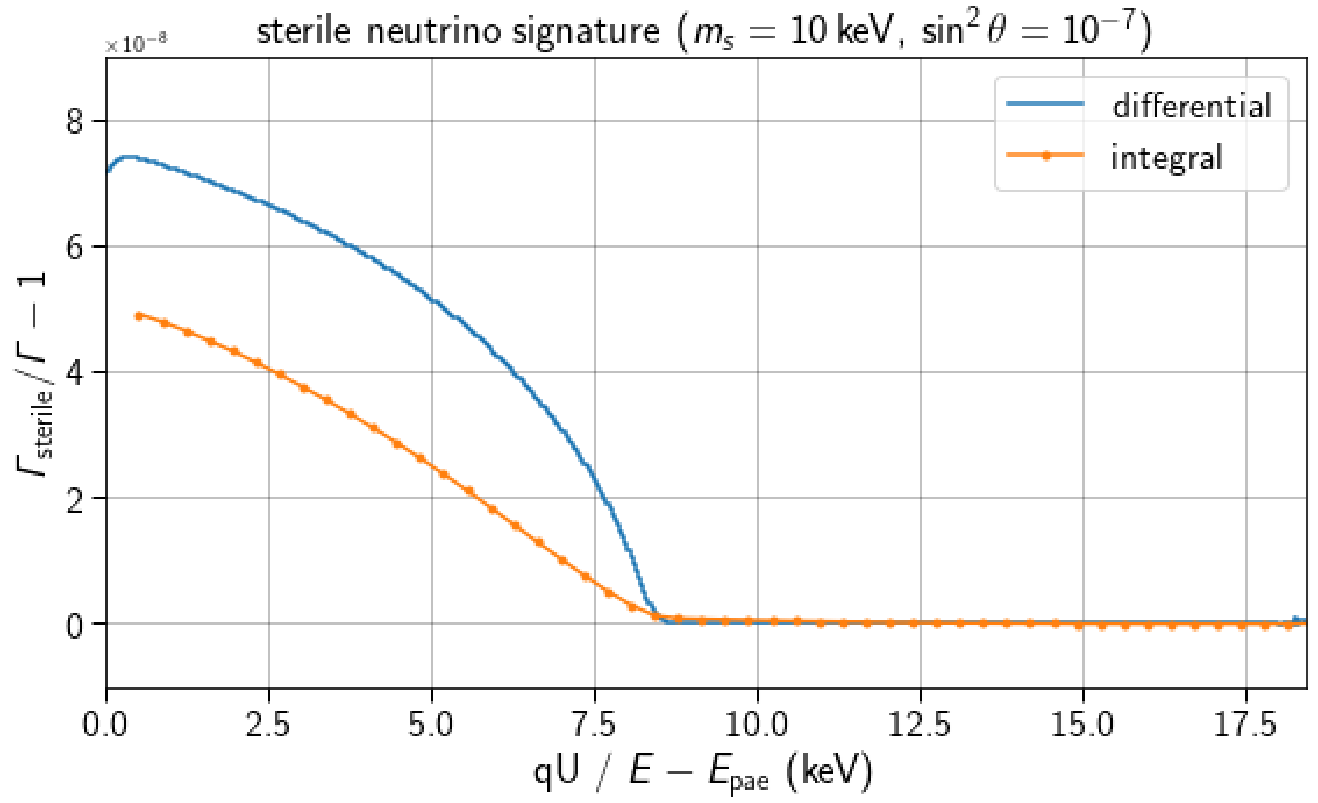
Perspectives

- Include systematic not yet considered

Effect	Status
T-decays on the RW Shape uncertainties of RW backscattering spectrum	In progress
Plasma	Not started
Magnetic trapping in the WGTS	In progress
Uncertainties of cross-section and energy loss function	Not started
Detector backscattering + backreflection	In progress
FSD uncertainty and energy dependence	Collaboration with Saenz started
Theoretical uncertainties	Considered in publication, has to be reevaluated (arXiv:1409.0920)
Statistical uncertainties of response matrices	In progress
DAQ – non linearity	In progress

- Investigate the impact of non-linear correlation coefficients on the individual & combined systematics
- Sensitivity with empirical model – *starting soon*
- Integral mode (MS) – *in progress*

See TRISTAN review part 3 (Calibration)



Plot: M. Deschner

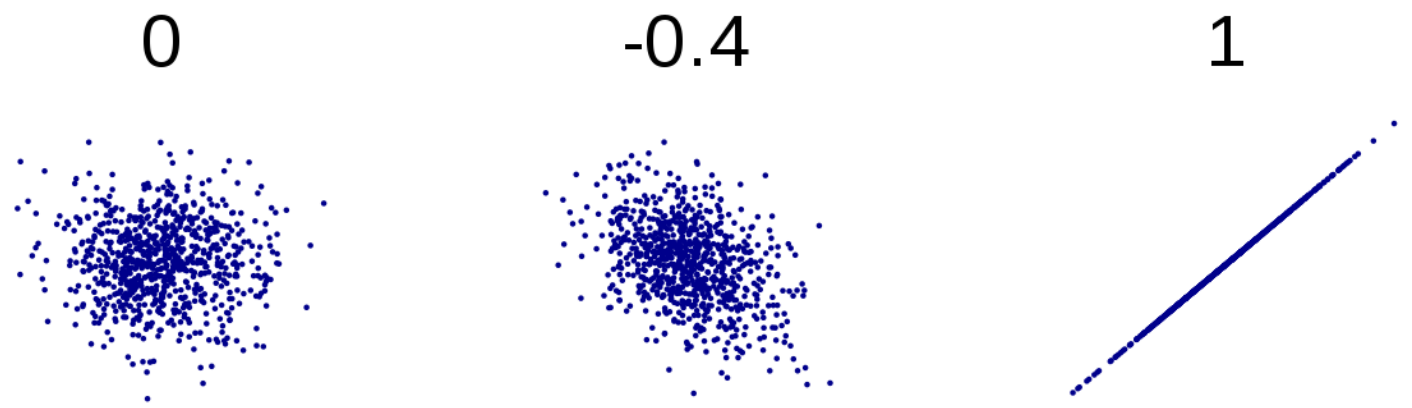
Annexe

6b – Potential limitation of the covariance matrix approach

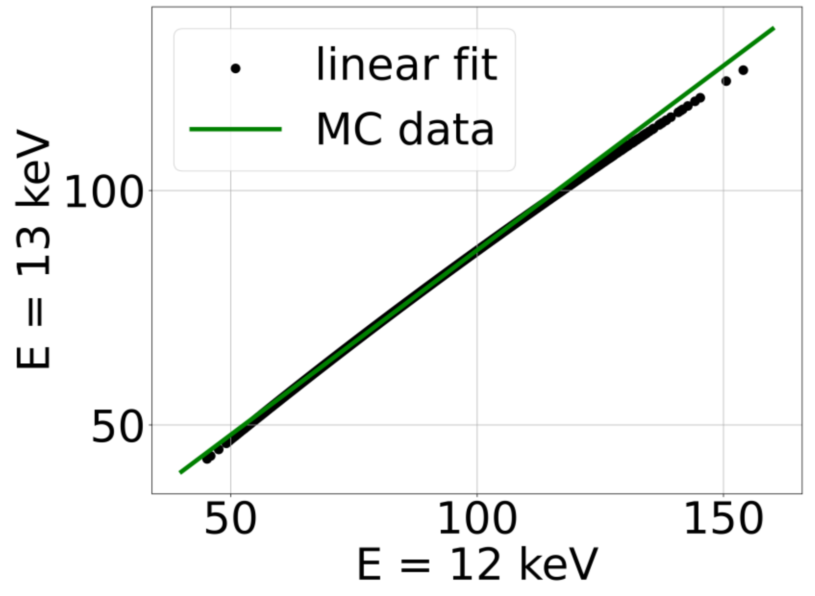
Sensitivity with covariance matrices

Assumed linear correlation (person correlation coefficient) between the energy bins of the spectrum

What we expect

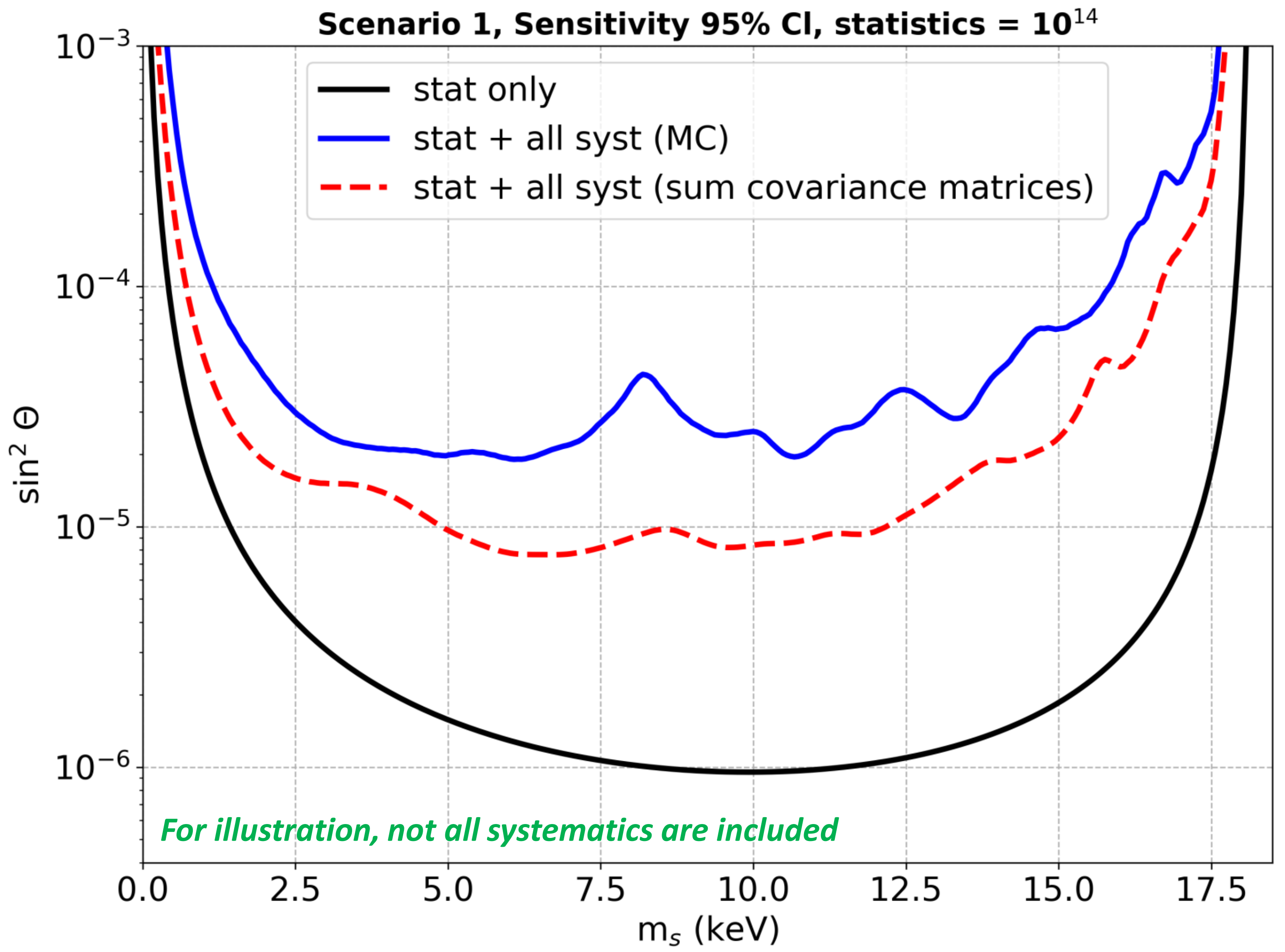


What we have



Observations

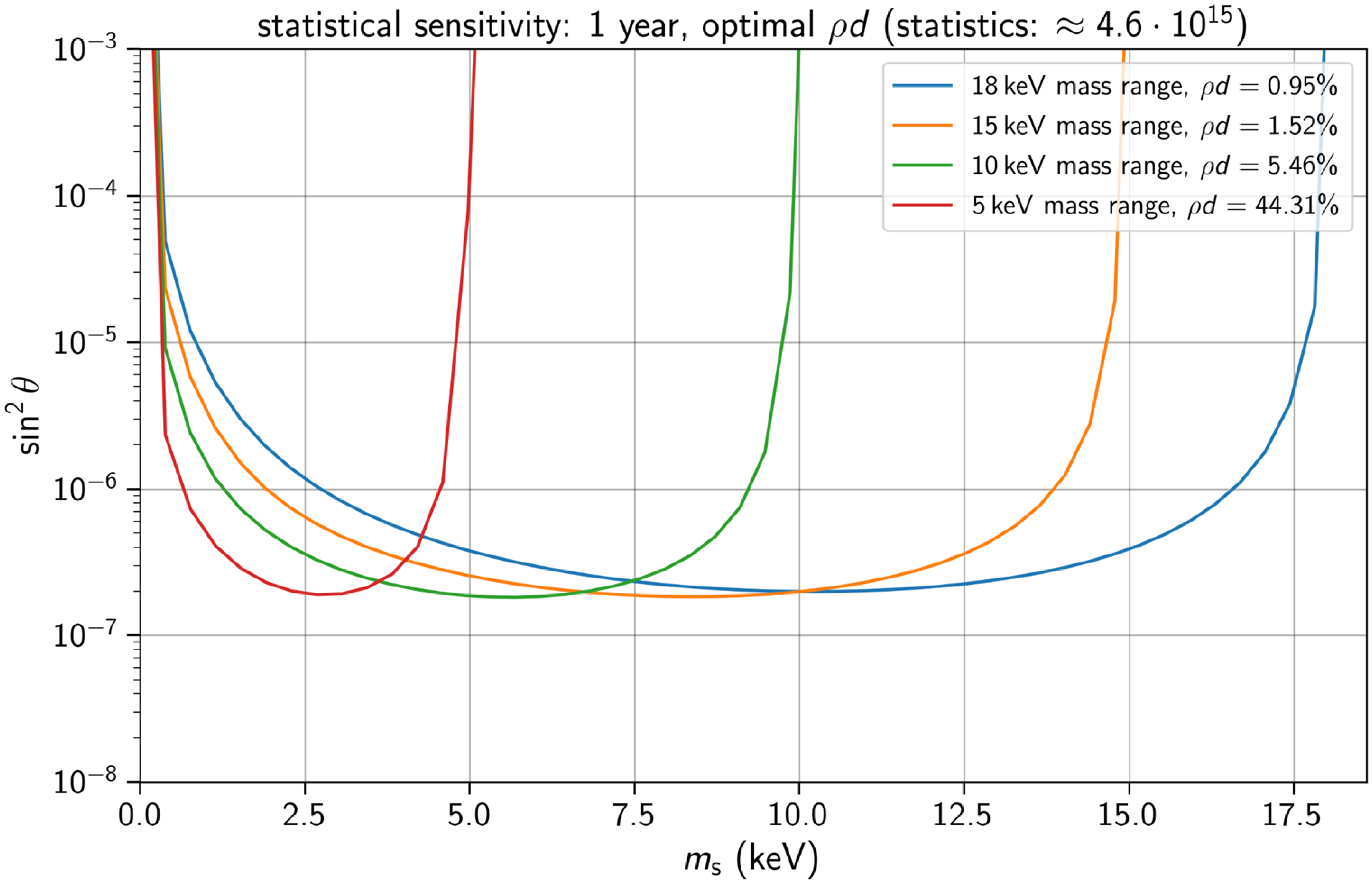
- Non linear correlations between the bins
- Correlation matrix never fully correlated : small uncorrelated componant that change with the value of the systematic uncertainty
- Different sensitivity for the combined systematic case if the total covariance matrix is obtained
  - from a MC with all parameters randomized simultaneously
  - uncorrelated sum of the covariance matrix of each single systematic



$\Rightarrow$ **Investigation ongoing**

$\Rightarrow$ Based on preliminary work, no indication that the computed sensitivity are underestimated

Plot by M. Deschner



Impact of the mass range (optimal ρd)

Combined systematic uncertainty

Plot by A. Nava

- Can we push this?
- Maximum:

  1 year @ ρd = 1% → 100 kcps/pixel
  - Total stat: 5×10^{15} electrons
- systematic uncertainties decrease with increasing statistics
- even higher rates would require Phase-2 detector:
  - 21 modules = 3000 golden pixels