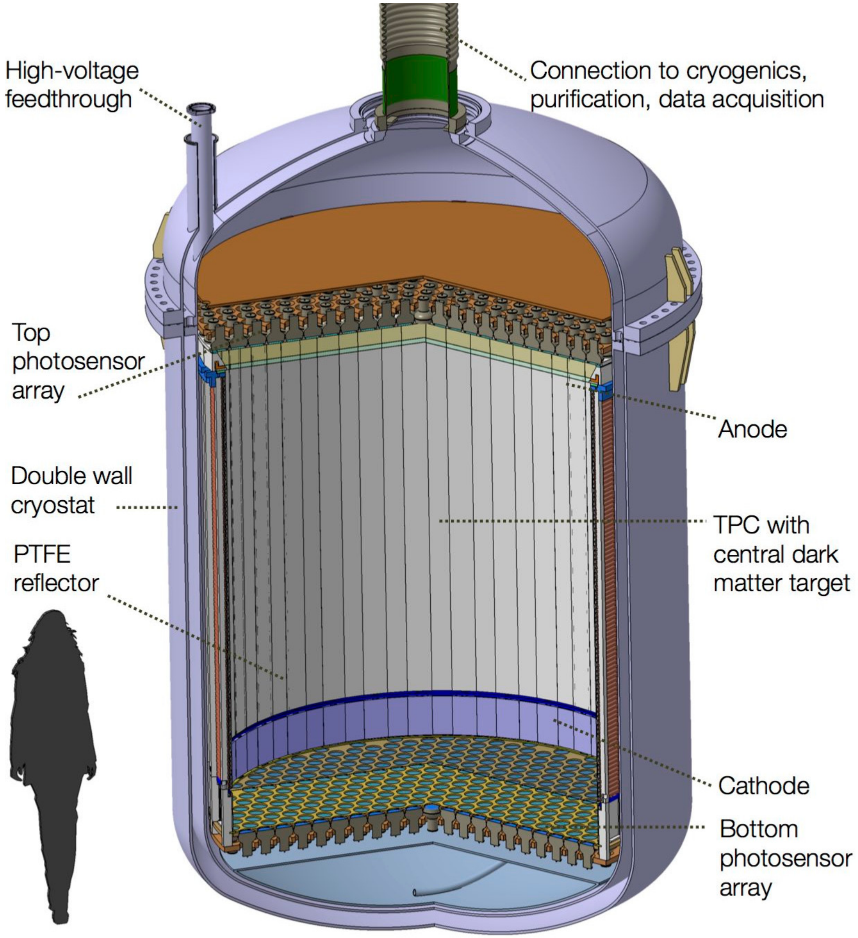
# Sensitivity and detector design simulation studies

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# Outline

-Dark matter overview

-Dark matter detection with DARWIN

-Darwin simulation pipeline

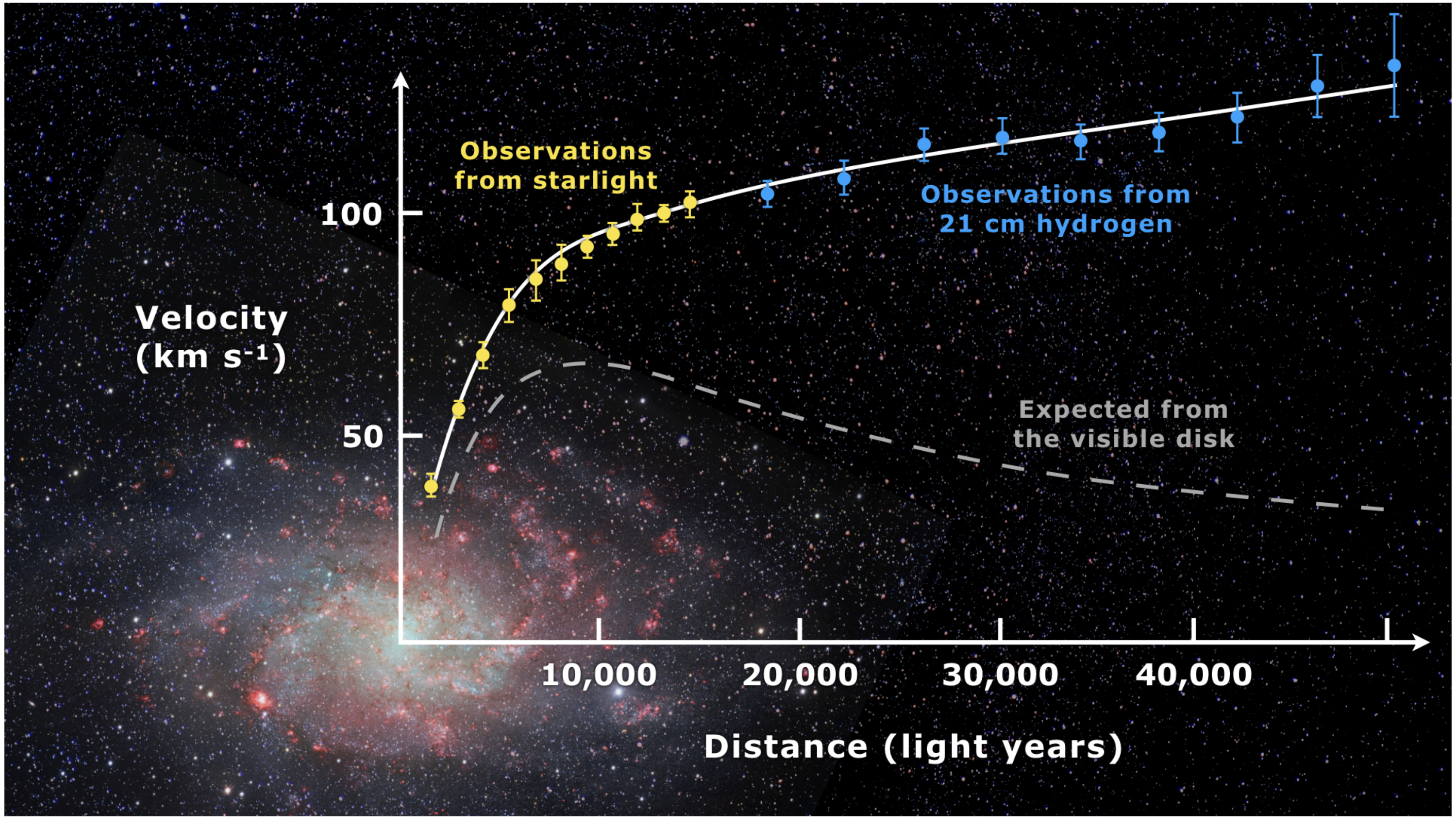
-WIMP sensitivity studies

# Dark matter overview

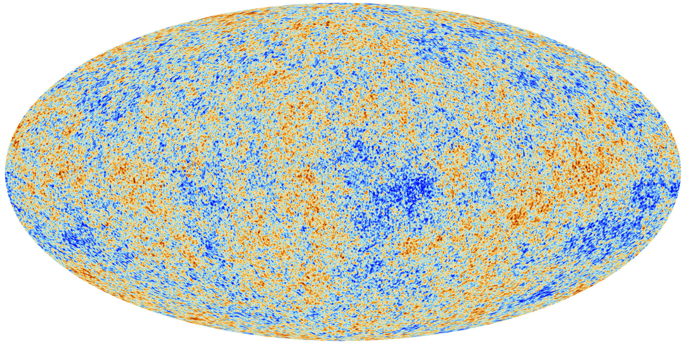
# Rotation curve

First hint: 1933
→movement of Coma cluster galaxies

1960: galaxies rotation curves→ observed curve indicates missing mass



# Dark matter overview

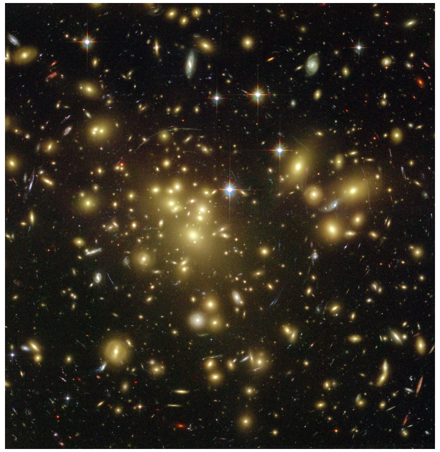


Cosmological: Anisotropy of the CMB

**Evidence for dark matter**

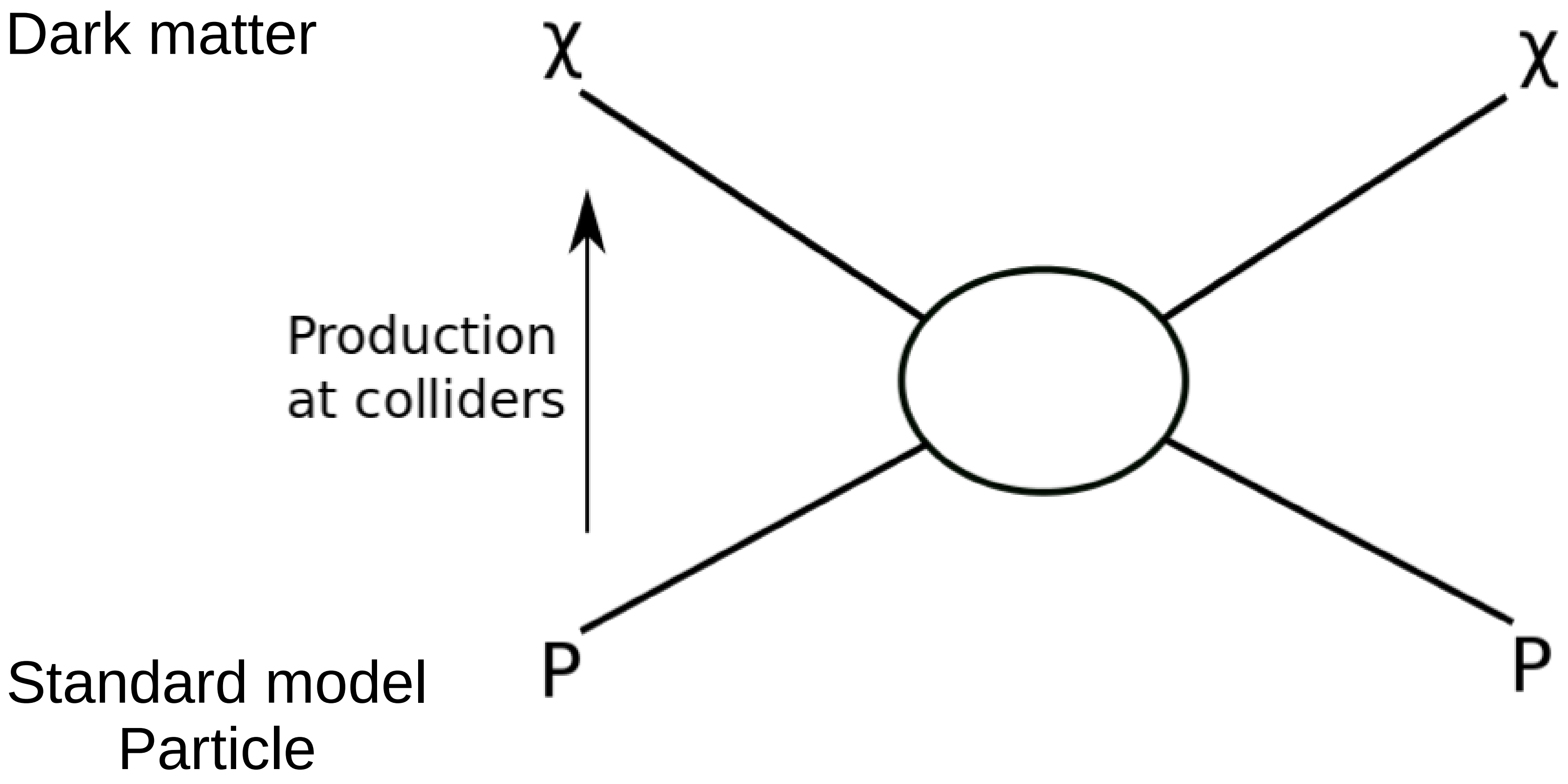
Astrophysical (Bullet cluster)

Gravitational lensing



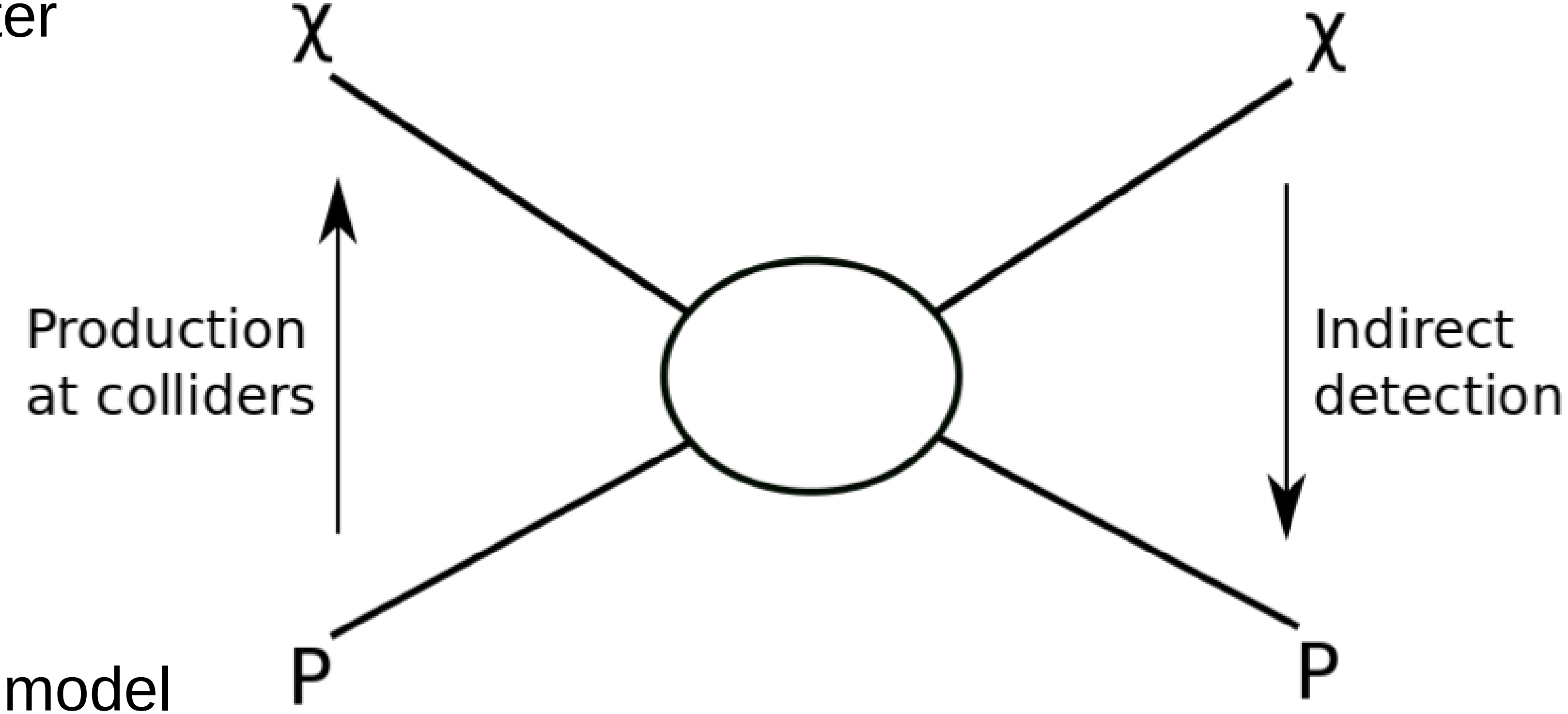
Current observations: about 5 times more dark matter than visible matter

# Dark matter detection



# Dark matter detection

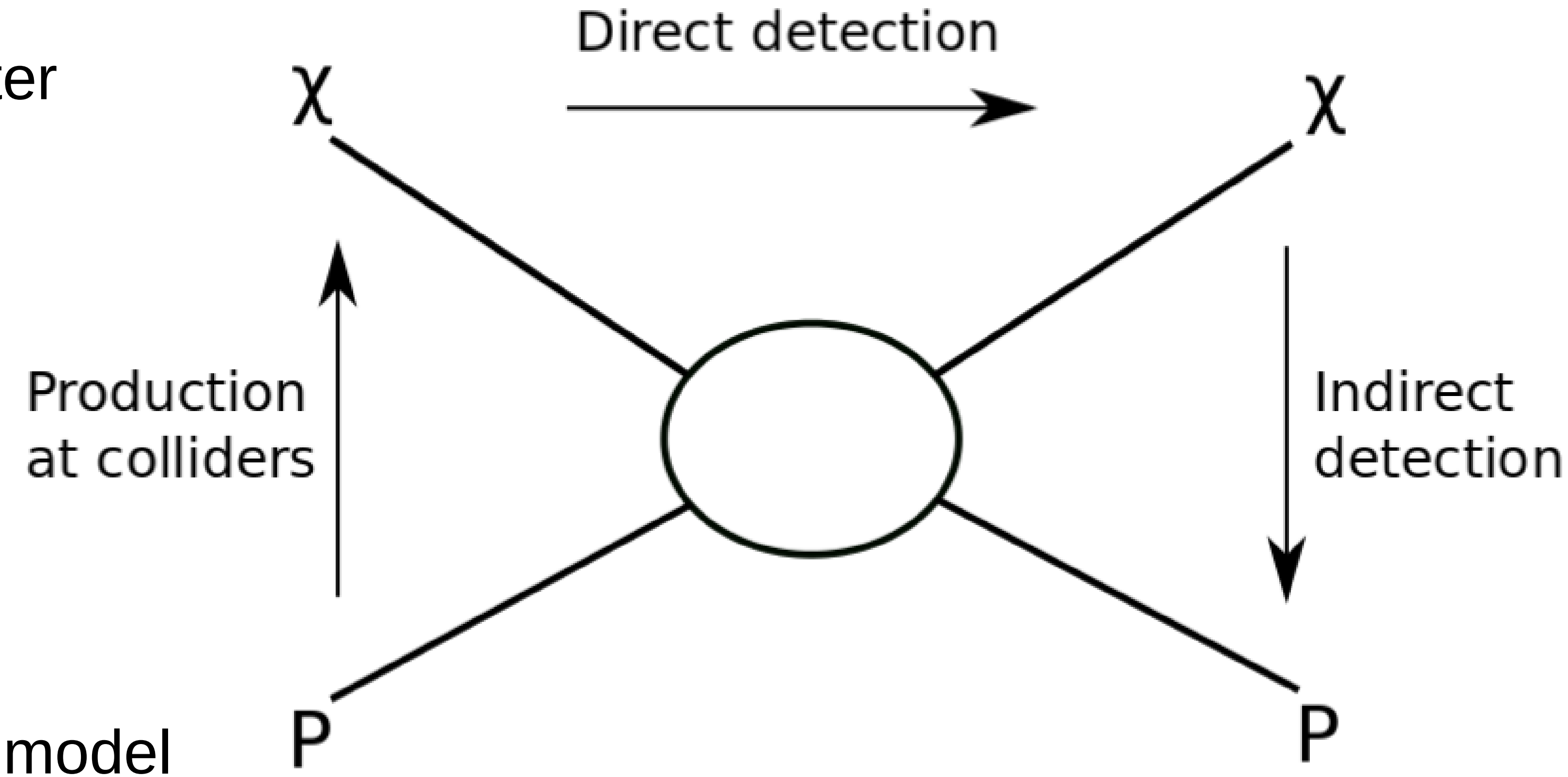
Dark matter




Standard model
Particle

# Dark matter detection

Dark matter




Standard model
Particle

# Dark matter detection with DARWIN

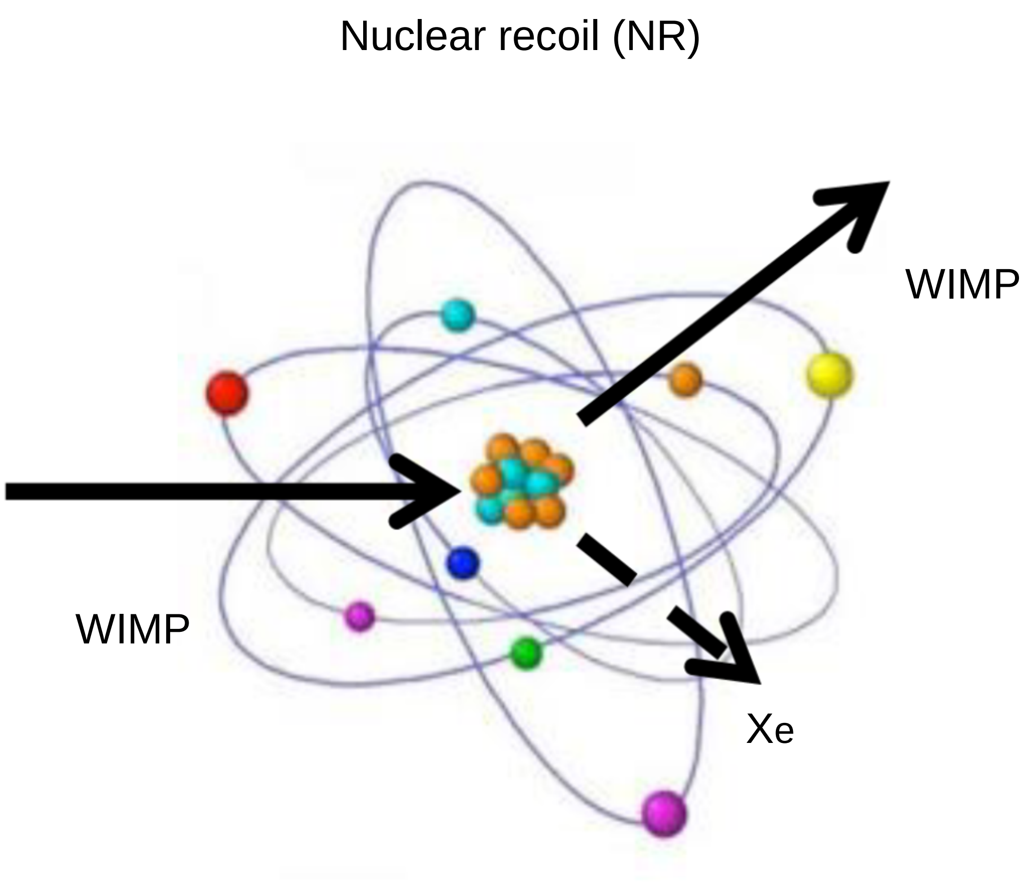
# WIMP direct detection

Weakly interaction massive particle (WIMP):

- Arised naturally from certain beyond the standard model theories
- Production in WIMP model naturally leads to 25% DM of the total energy content of the universe.

Interaction→ elastic nuclear scattering of WIMP with Xenon nucleus

Mass range: 1 to $10^5$ GeV



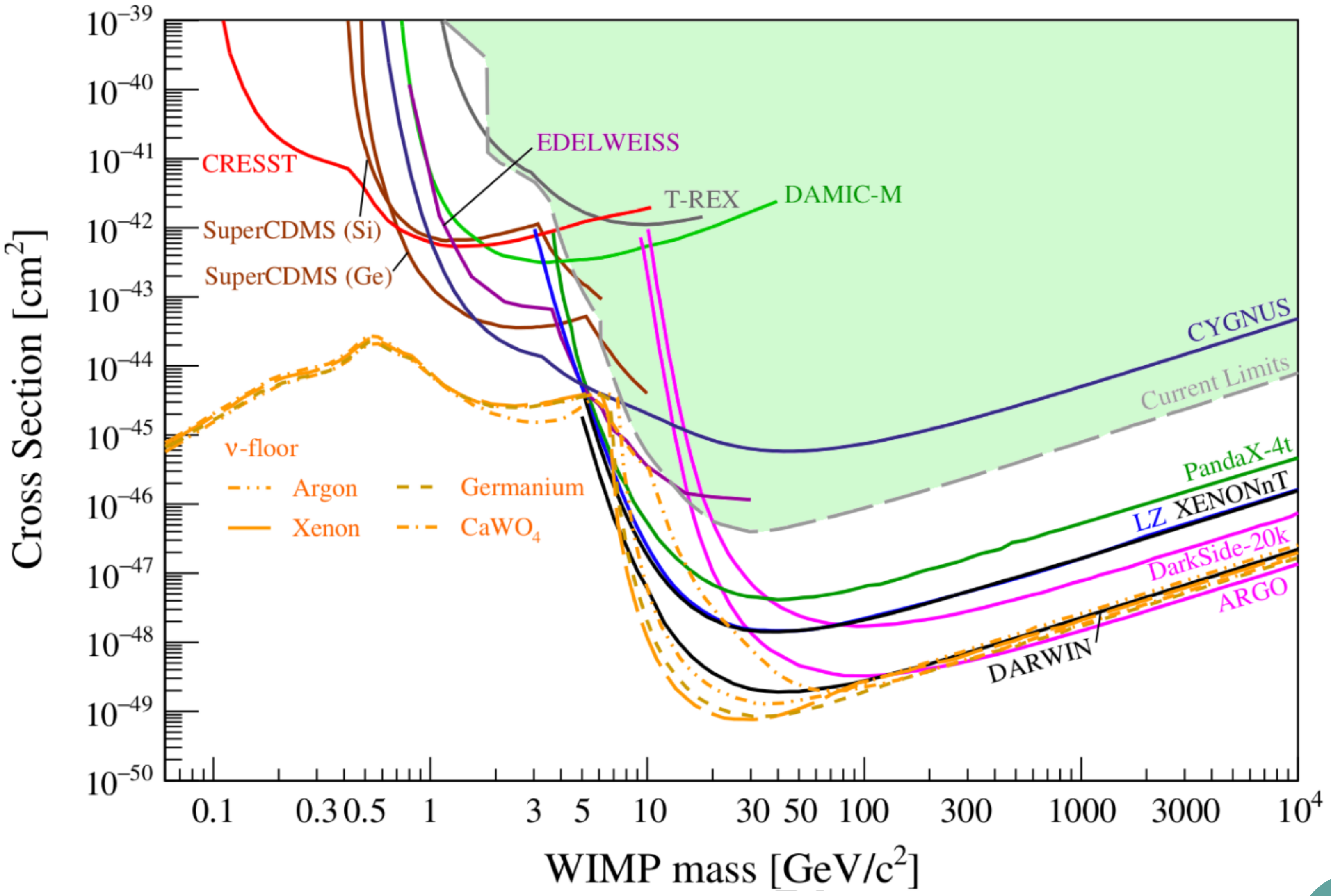
# Limits and sensitivity of direct detection

Estimated sensitivity of future experiments

DARWIN Goal→ most sensitive direct detection experiment

Small cross section→ need to reduce background

Other possible science channel



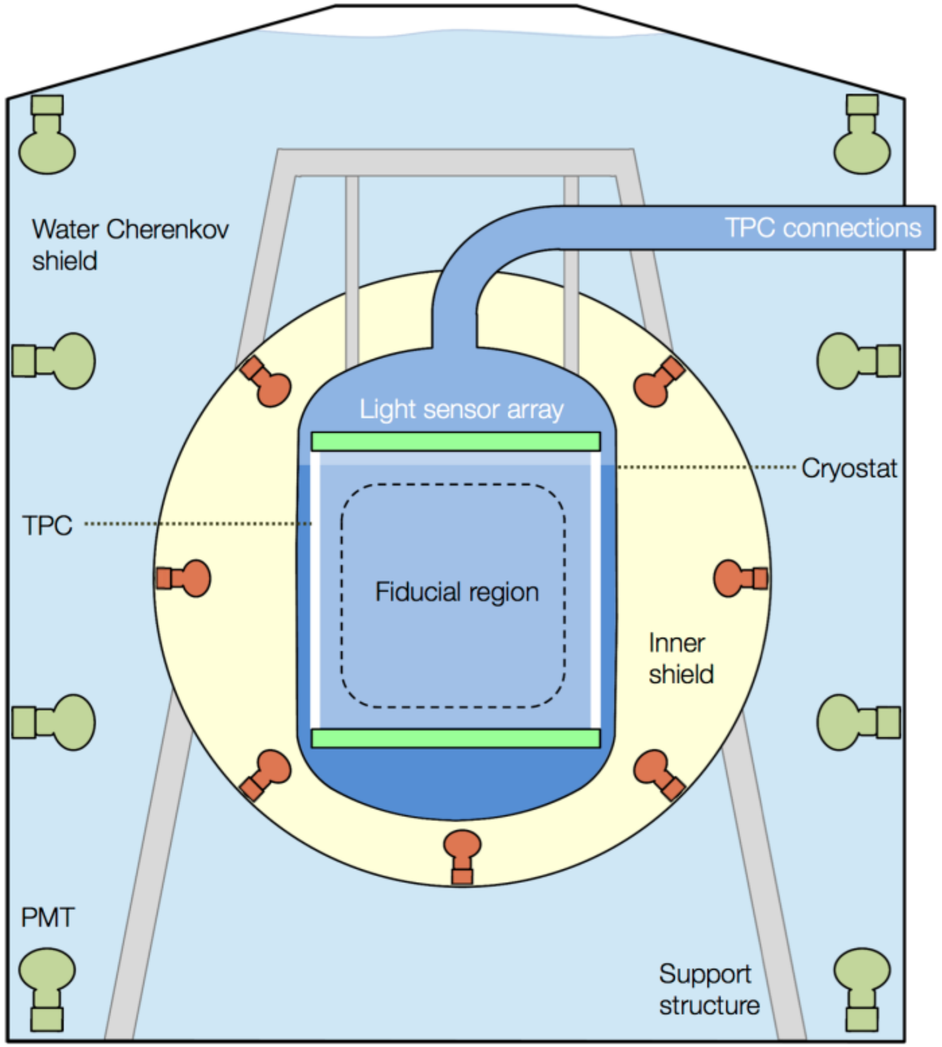
# DARWIN design

DARWIN:  Future experiment →R&D phase

50t liquid Xenon Time Projection Chamber

Main challenge→ background reduction:

- Xenon: good self shielding, low internal background, good scintillation and ionization yield
- Improved Xenon purification system
- Detector material choice→ reduce radioactivity
- External muon shield
- Internal neutron shield



# Detection principle

Dual phase xenon TPC

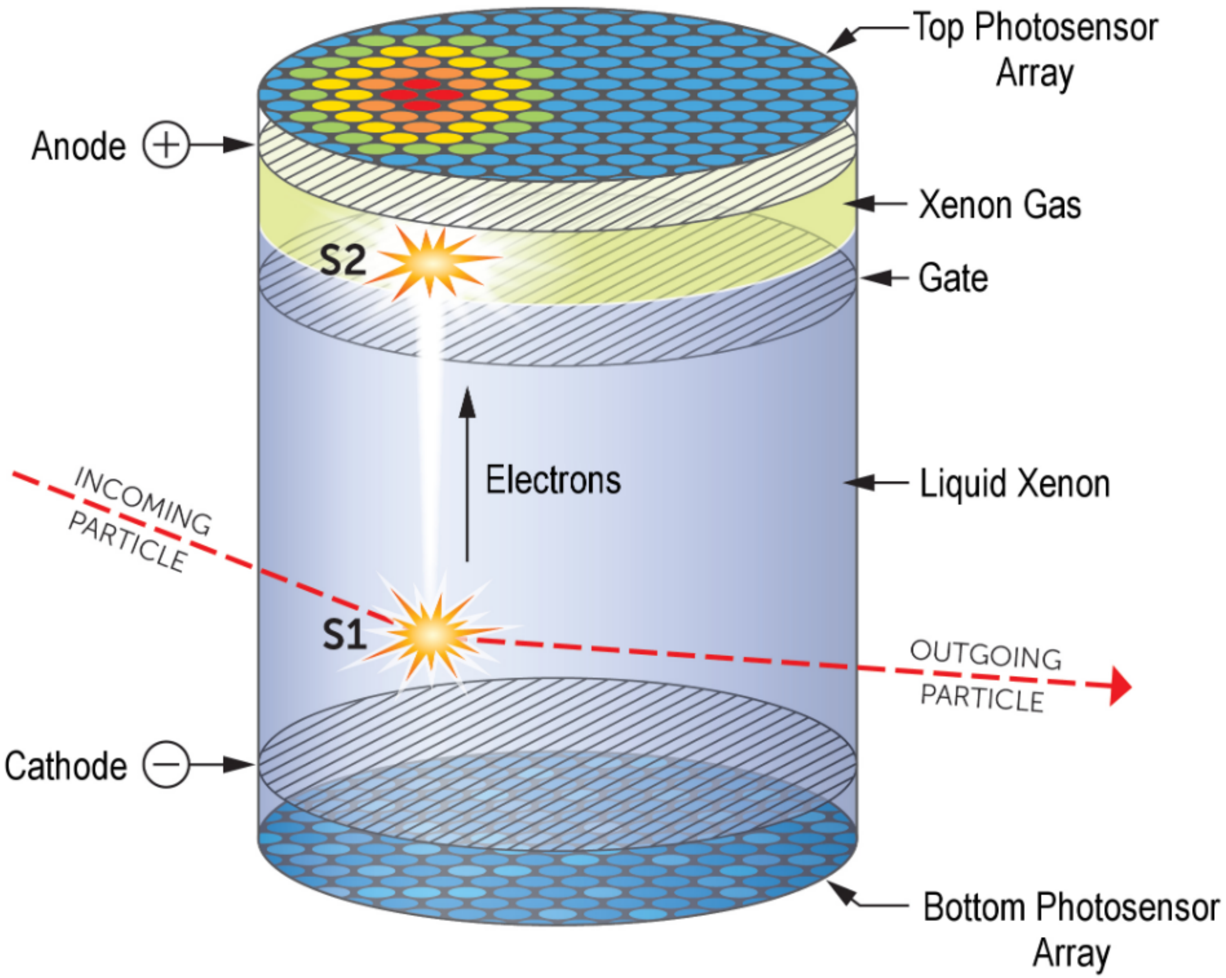
Energy deposit (background and signal):

- Primary scintillation→ S1 signal
- Ionization electrons: drift and proportional scintillation in the gas phase of the TPC→ S2 signal

Interaction position:

- xy from S2 pattern
- z from S1-S2 time delay

S1/S2 ratio: ER/NR discrimination (background rejection)



# DARWIN simulation pipeline

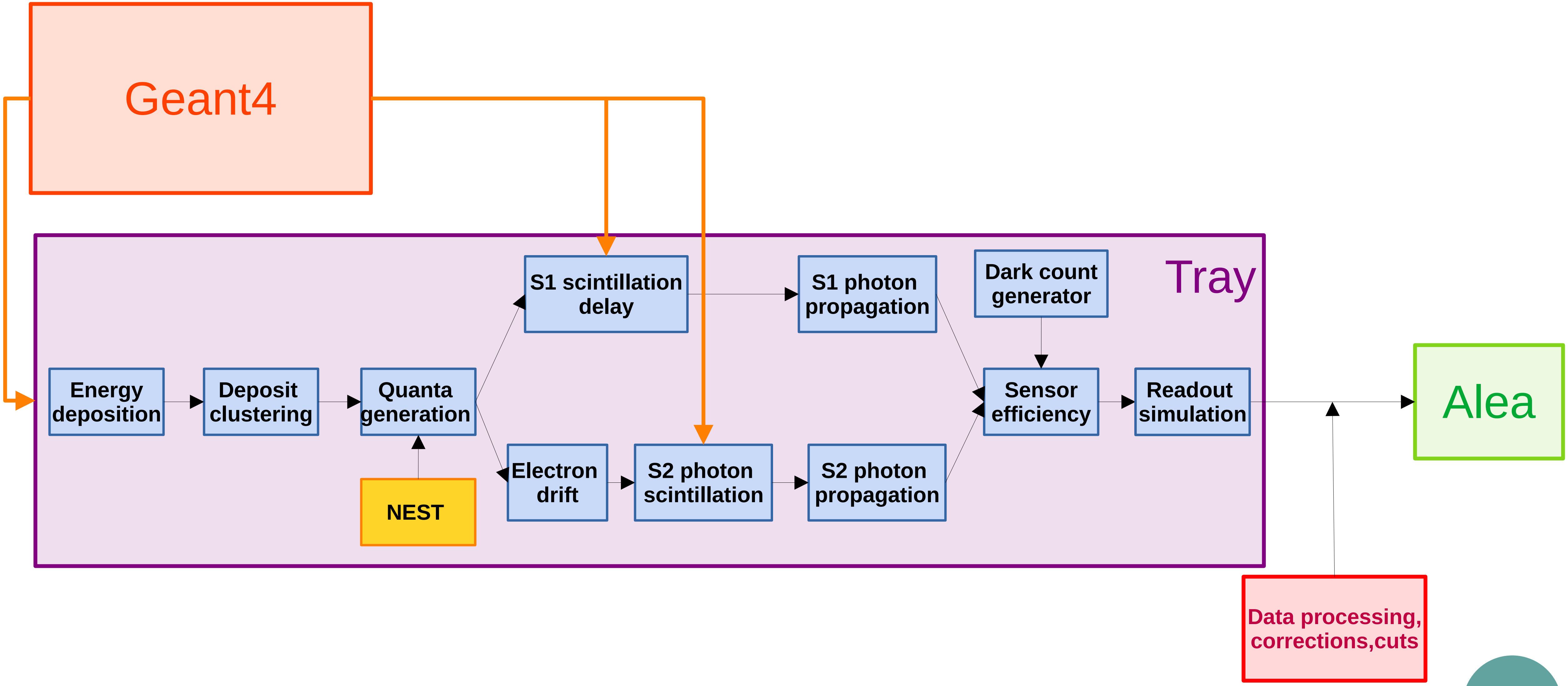
# Motivation

-DARWIN is a future detector currently in the design phase→ Input are needed to make detector design choice (electrode design, photodetectors, important parameters)

-Modular simulation framework: allow for easily testing different design choice

-Sensitivity: used as a tool to study impact of design choice and background reduction one the capacity of DARWIN to detect a WIMP signal

# Simulation pipeline

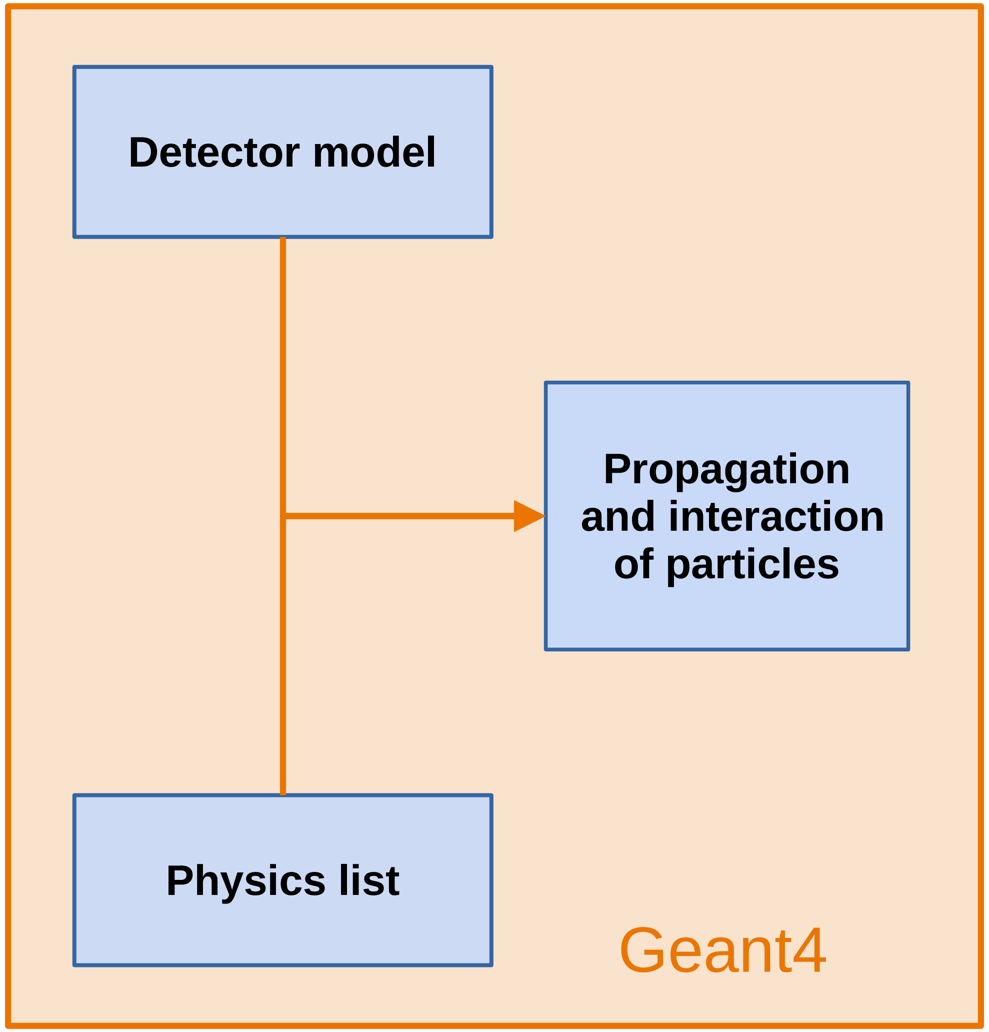


# Geant4

Simulation of the passage of particle trough matter

Two current uses for DARWIN:

- Simulate energy deposit:
  - Recoil energy, interaction type, position→mainly used for neutrons
- Optical simulation:
  - Propagation of S1 and S2 photons
  - Generation of Light Collection Efficiency maps (used for speed up)

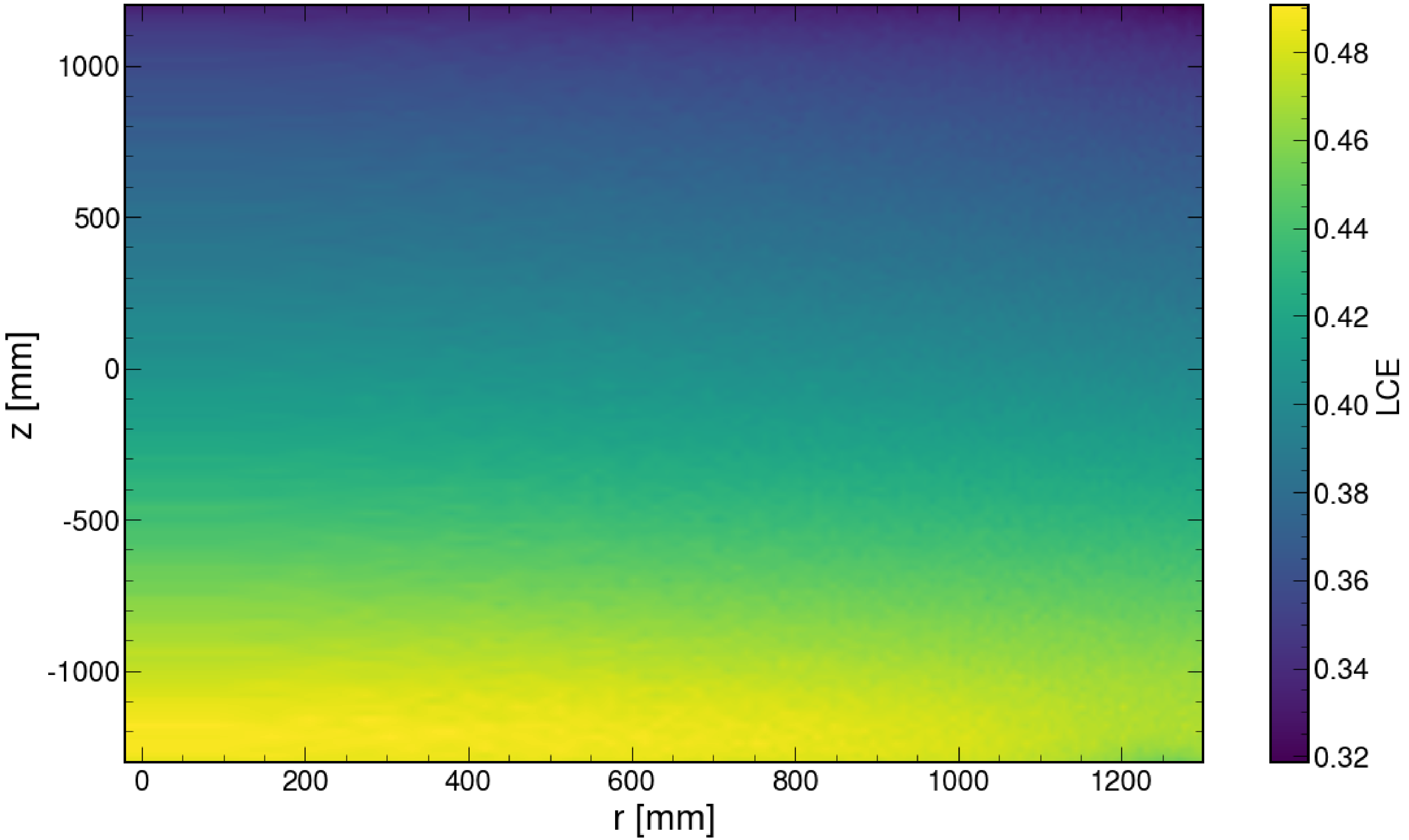


# Light collection efficiency

Propagation of photons uniformly generated in the DARWIN TPC

LCE map→ position dependent fraction of photons hitting PMTs

Used to speed up S1/S2 photon propagation



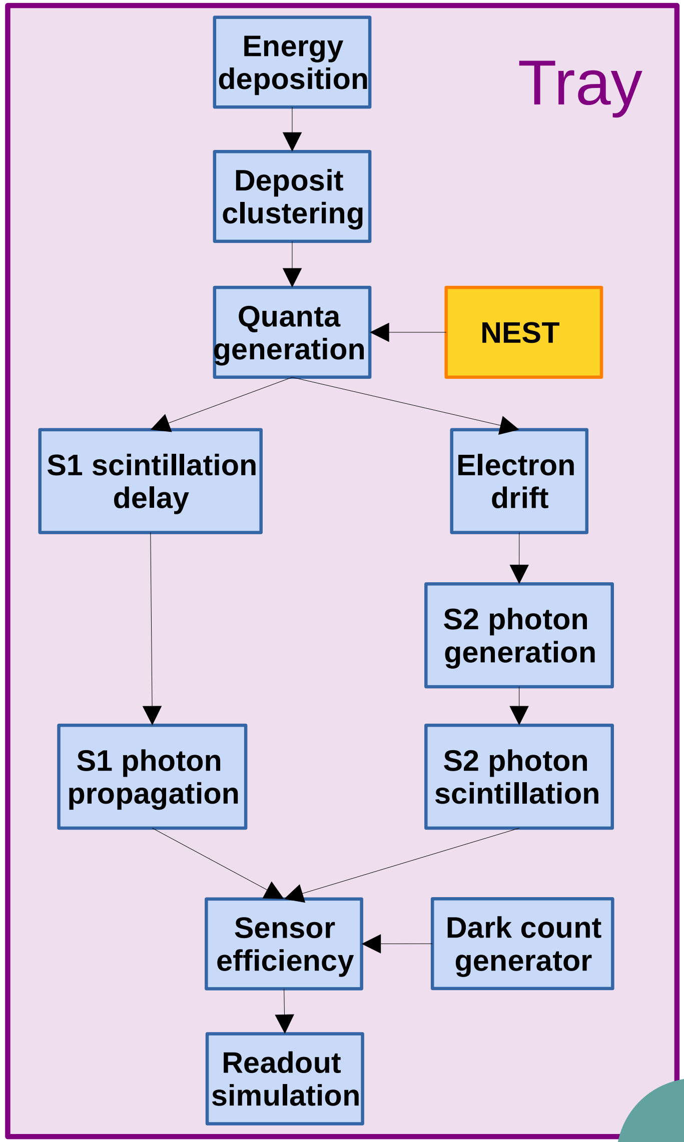
# Tray simulation

Detector response to an energy deposit for ER and NR

Compute the S1 and S2 signal for different deposit type

Simulation steps:

- Energy deposit: Energy,position,interaction type (ER/NR)
- Quanta generation: number of photons and electrons
- S1 simulation: Photons propagation using LCE maps
- S2 simulation: Electrons drift and scintillation in the gas phase, photons propagation
- PMTs effects



# S2 electron propagation

Electron propagation: Drift, diffusion and electron absorption

Constant field: 200 V/cm

Timing distribution: gaussian smearing

Travel length

$$\mu = \frac{L_t}{v_d}$$

Drift velocity

Longitudinal diffusion

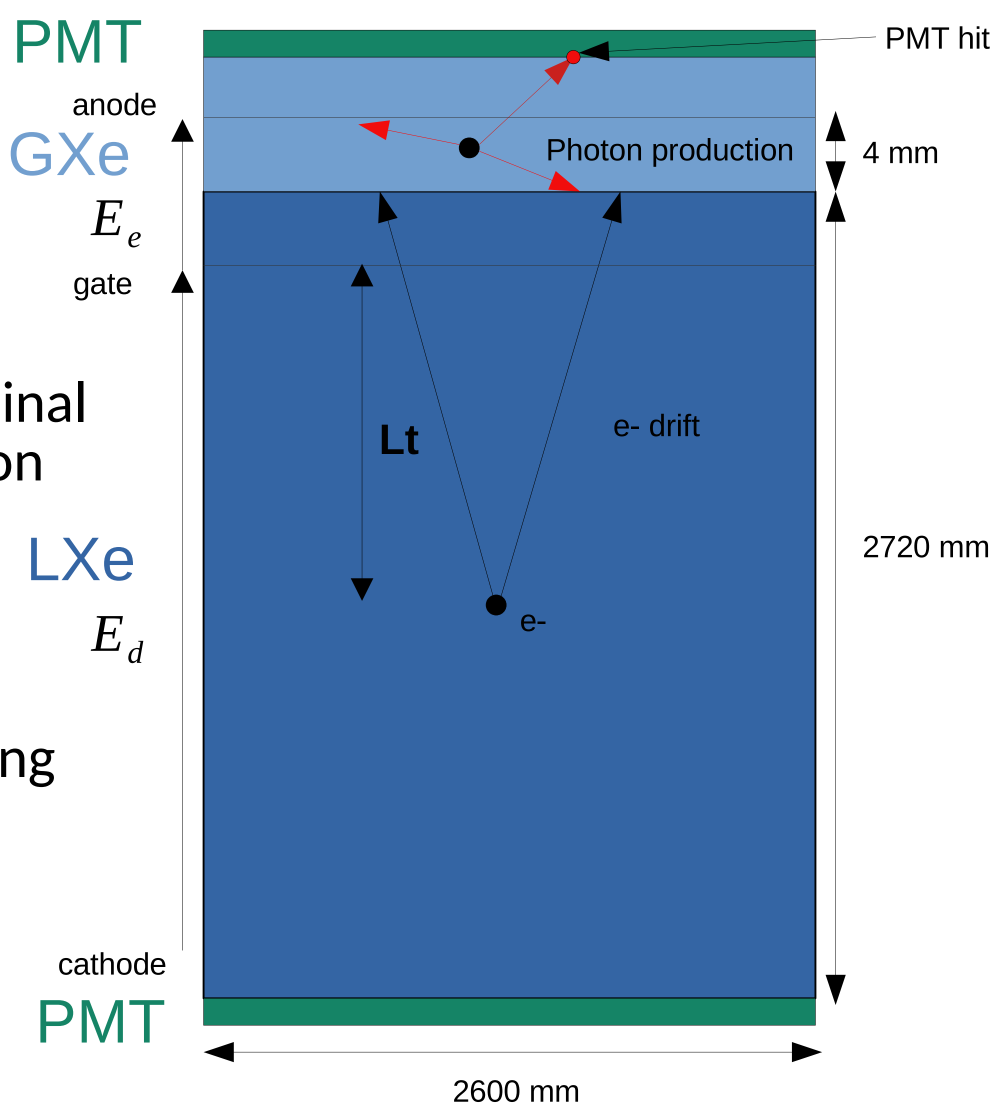
$$\sigma^2 = \frac{2 D_L \mu}{v_d^2}$$

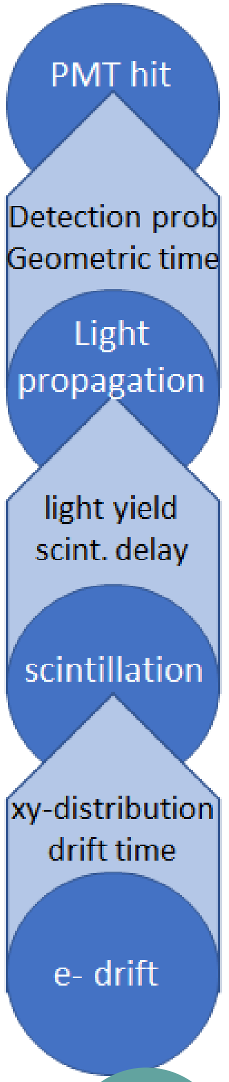
Transverse diffusion

Timing

xy distribution: gaussian smearing: $\sigma^2 = \frac{2 D_T t}{v_d^2}$

Electron survival probability: $P = e^{-\frac{t}{\tau_e}}, \tau_e = 10\, ms$



# S2 electrons scintillation

**Photon yield :**

Electric field

$$\text{Yield} = \left(0.140\frac{E_e}{N} \times 10^{17} - 0.474\right) \times N \times 10^{-17} \quad photon/cm$$

Density

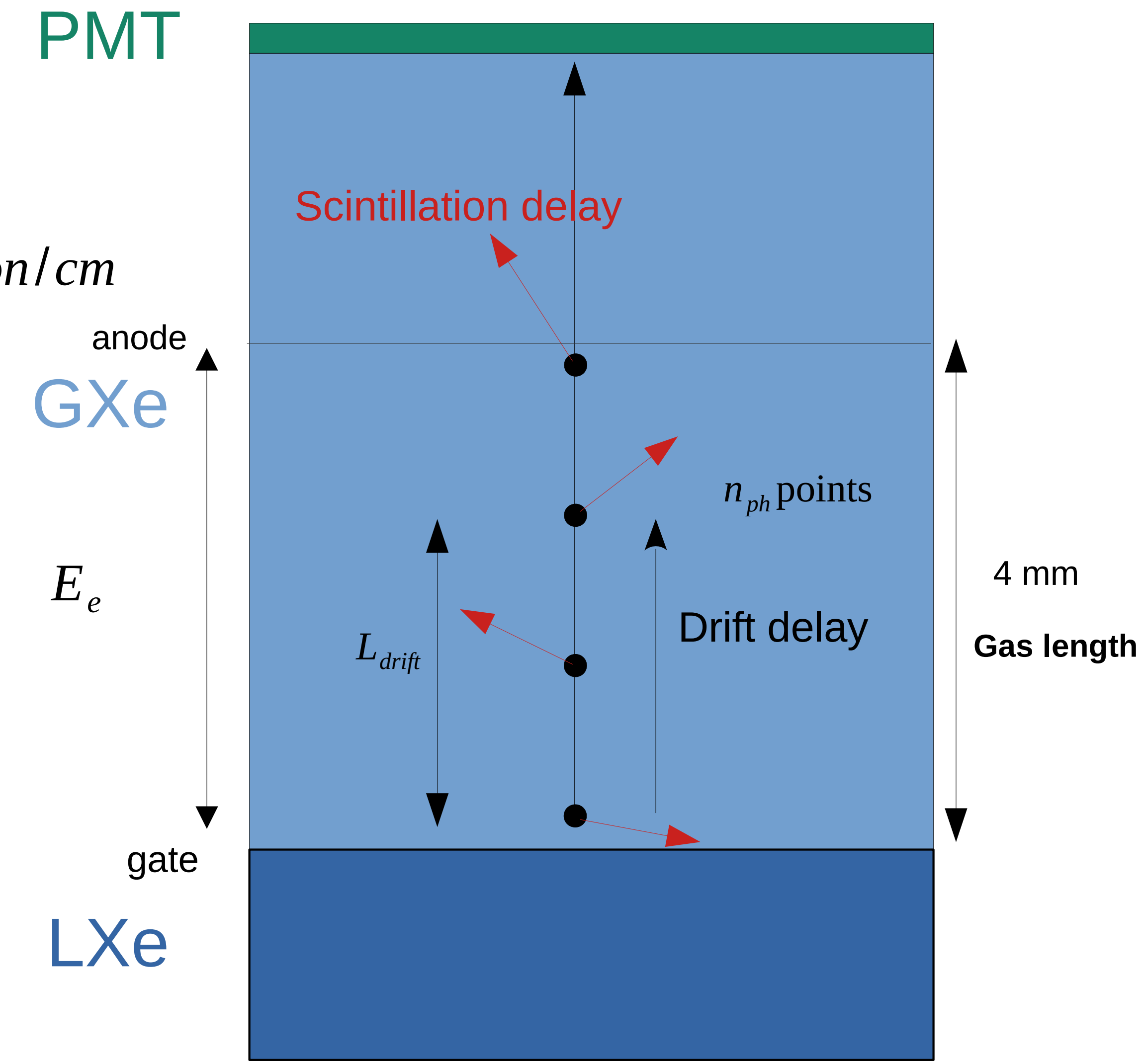
$n_{ph}$ = yield*gas length

$\boxed{n_{ph} = 398}$

**S2 timing:**

Drift delay: $\frac{L_{drfit}}{v_d}$

Scintillation delay: decay state $\tau_1$ or $\tau_3$



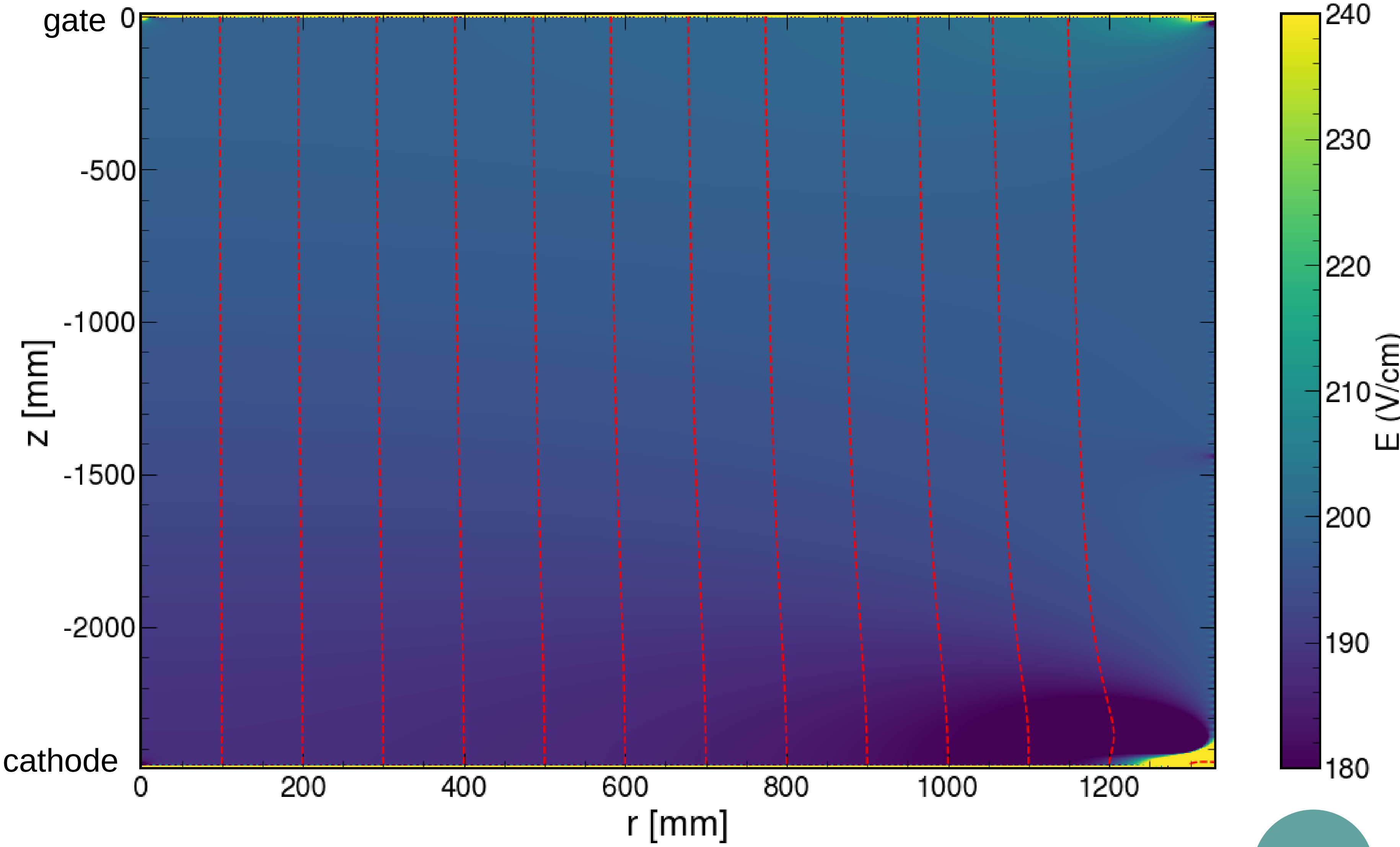
# Realistic field

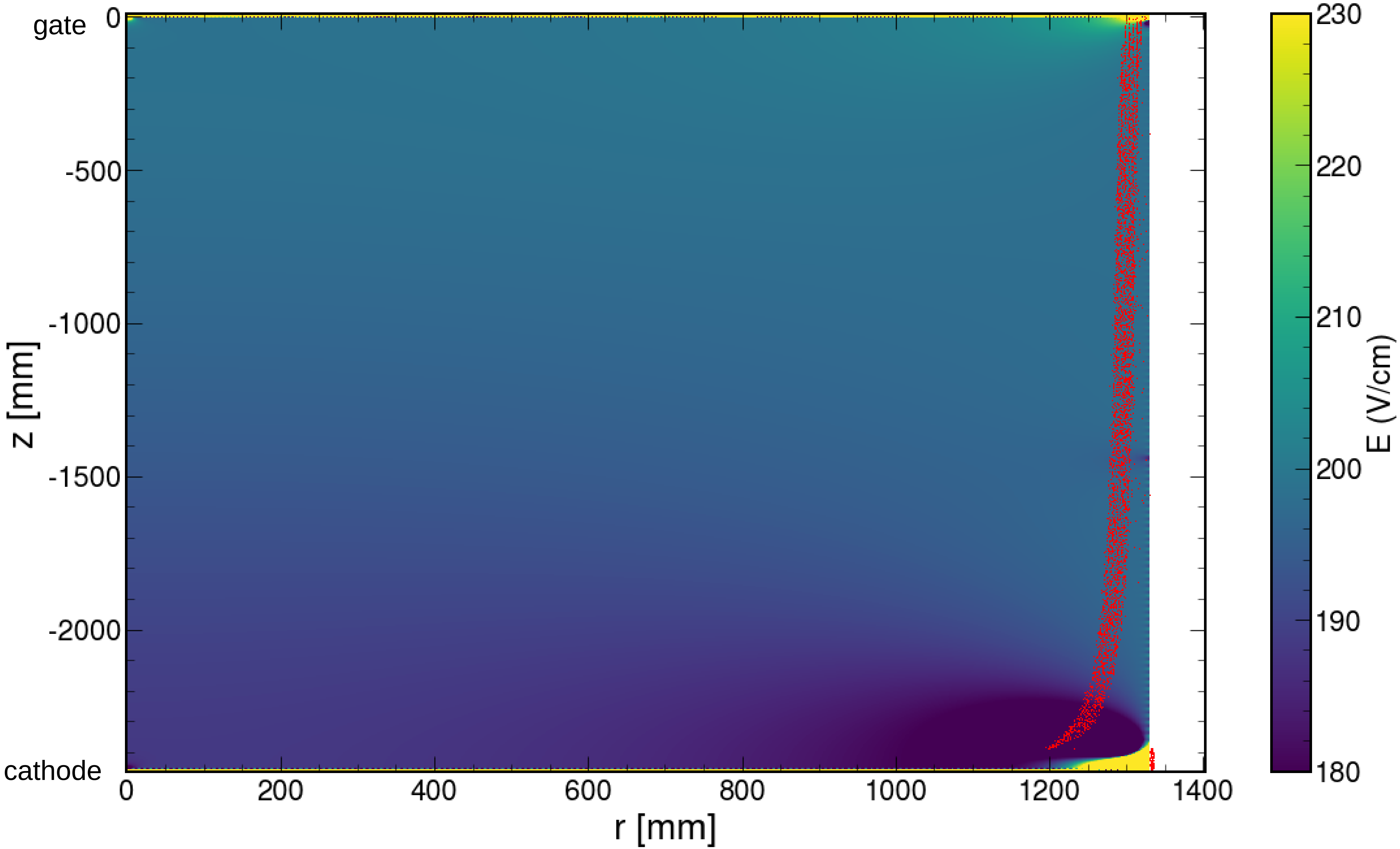
DARWIN realistic field: simulated using COMSOL (from Vera Hiu-Sze Wu)

Electron diffusion: follow the field line, done using PyCOMEs (from Francesco Toschi)

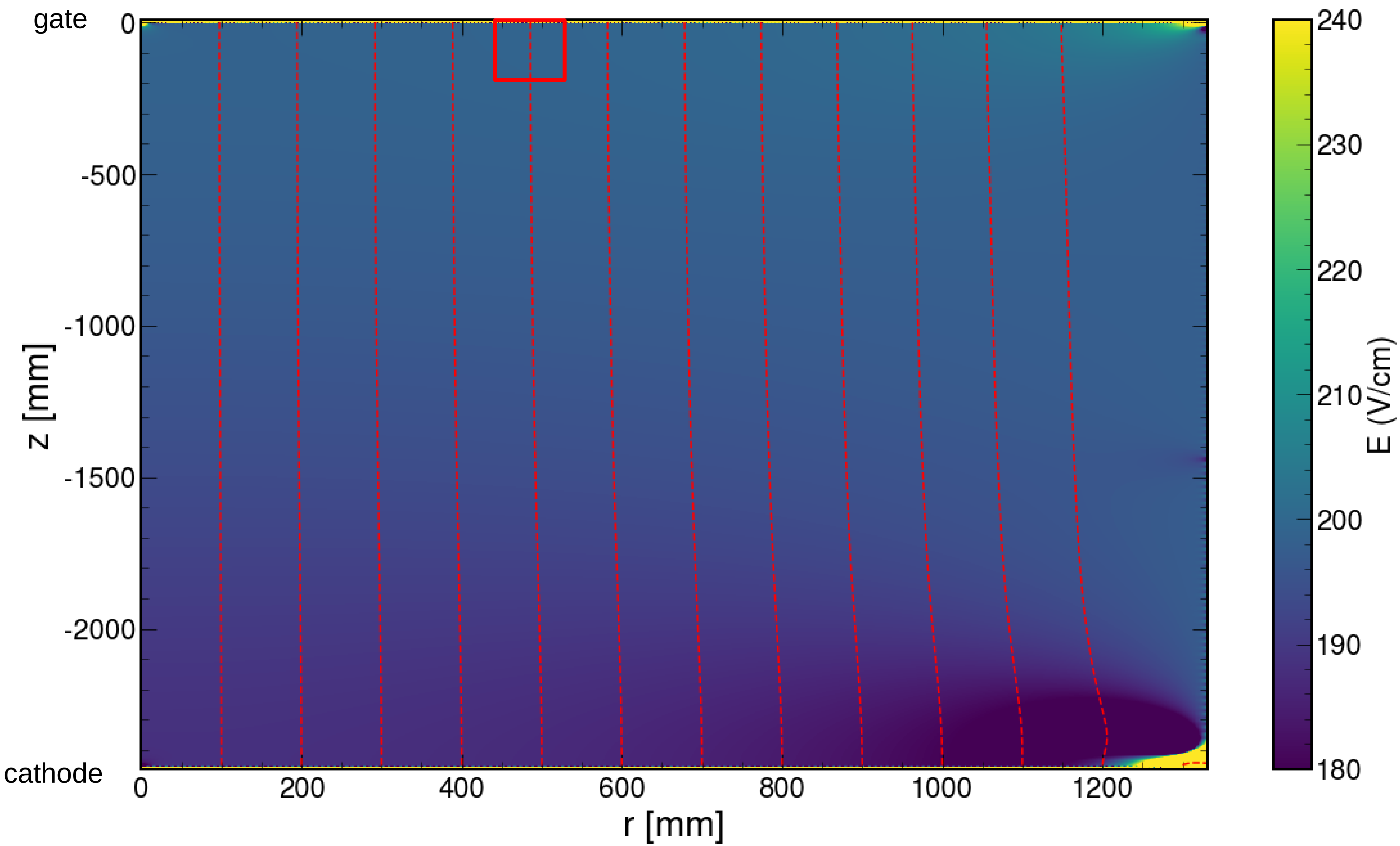
Integrate realistic field to the simulation pipeline

Impact on sensitivity: uncertainty on the position reconstruction





gate
cathode
z [mm]
0
-500
-1000
-1500
-2000
r [mm]
0
200
400
600
800
1000
1200
1400
E (V/cm)
230
220
210
200
190
180


gate
0
-500
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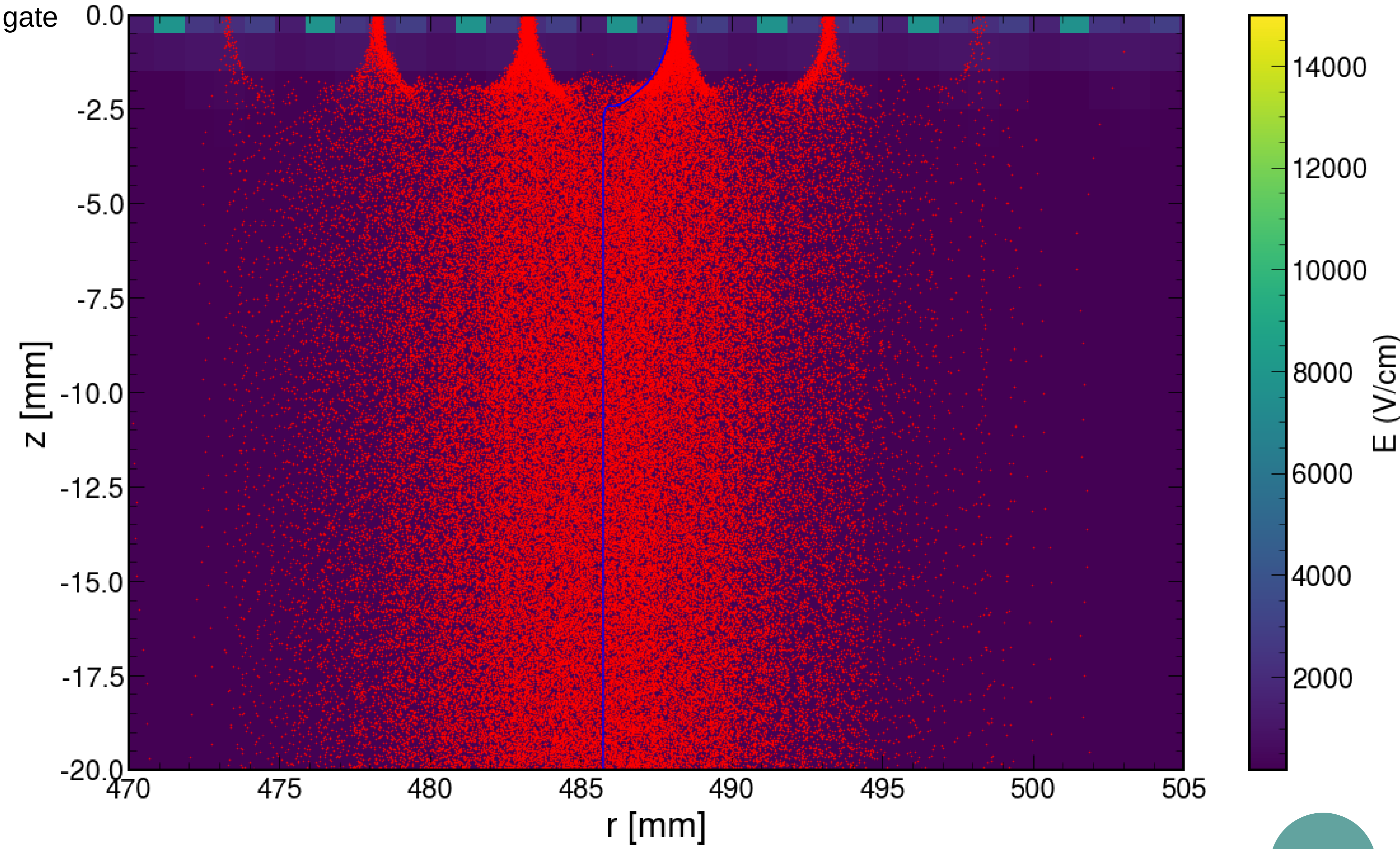
-1500
-2000
cathode
z [mm]
0
200
400
600
800
1000
1200
r [mm]
240
230
220
210
200
190
180
E (V/cm)

Red: successive position of the electron cloud

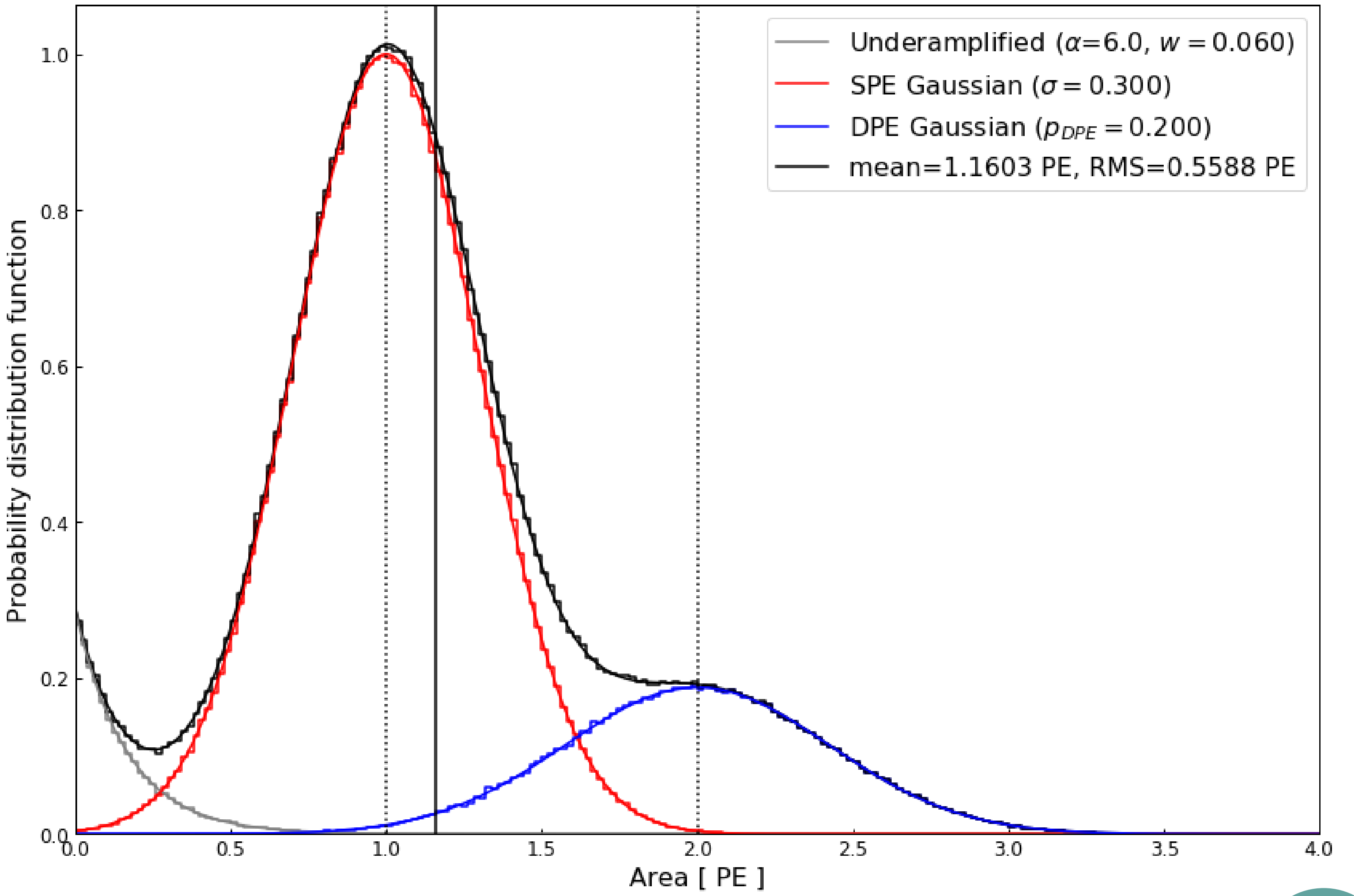
Electrons are focused between the electrodes



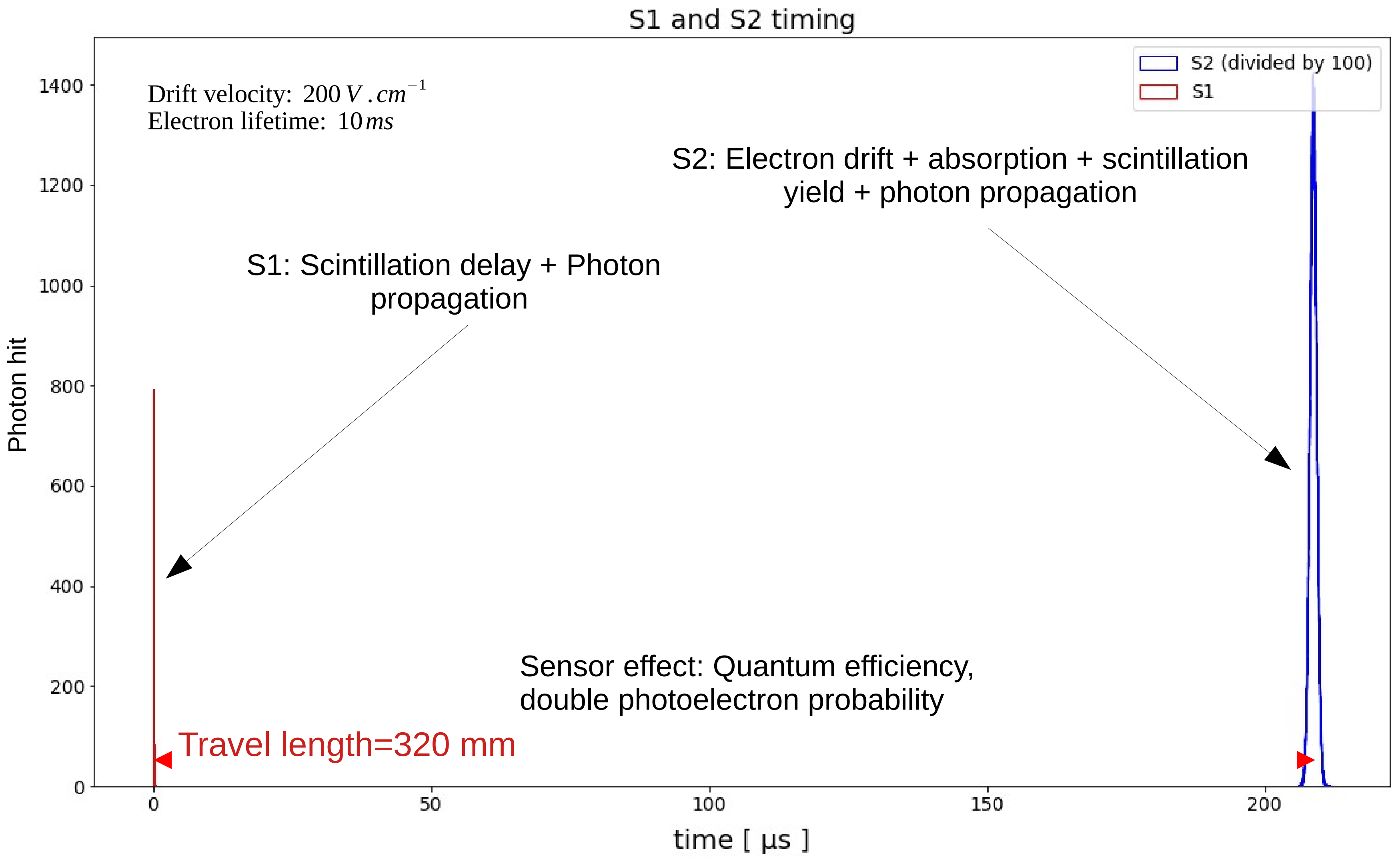
# PMTs effects

Simulation of PMT response:

- Calculate number of photoelectrons from quantum efficiency
- Take into account Double Photoelectron probability



# Detector response



# Corrections

**Motivation for correction:** Compare signal generated on different parts of the detector

$$g'_1(x,y,z) = \epsilon_{LCE}(x,y,z) \cdot \epsilon_{QE},$$

$\epsilon_L$ : Light collection Efficiency

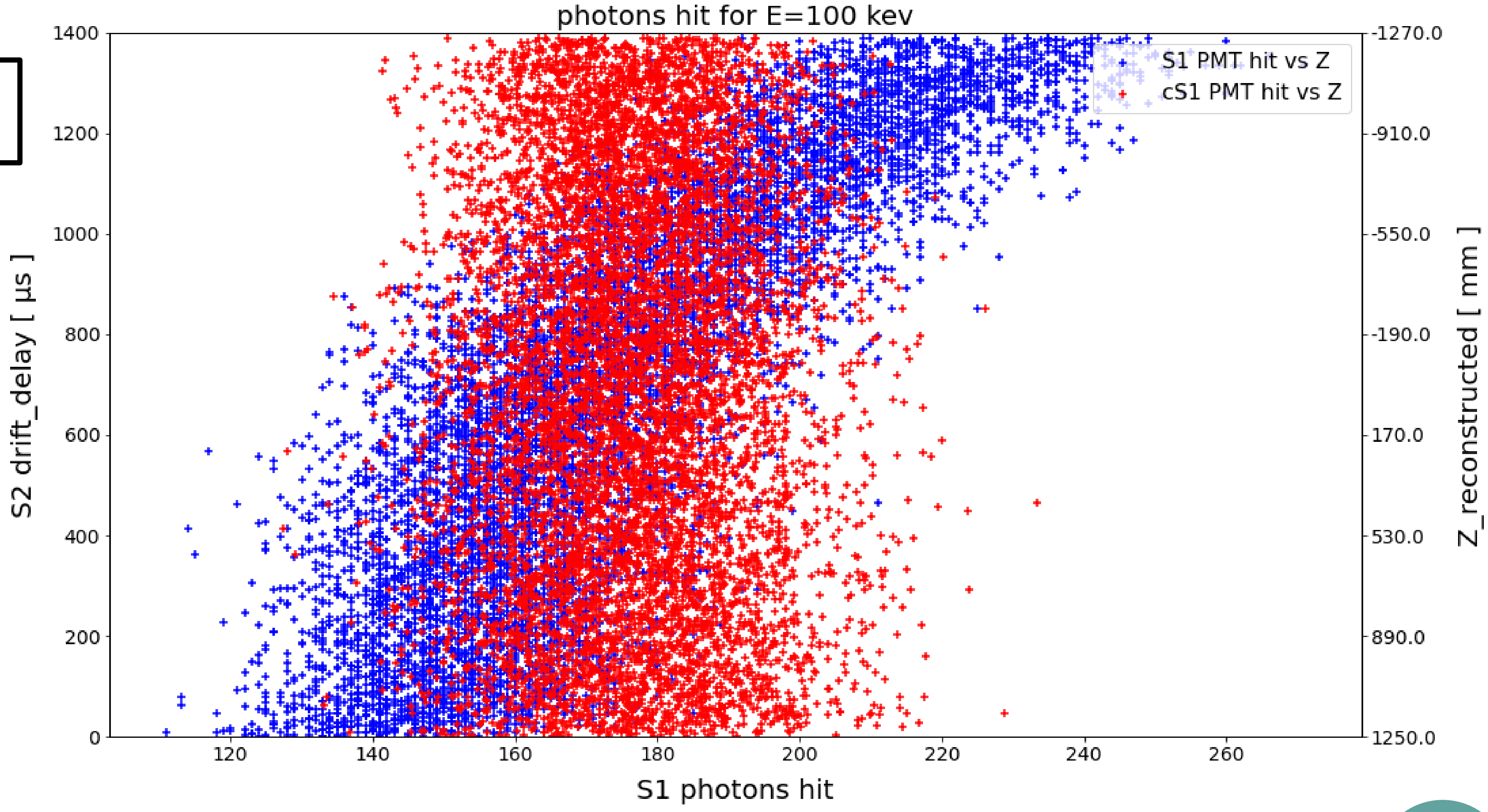
$\epsilon_{QE}$ : Quantum Efficiency

Correction averaged over the detection volume:

$$cS1 = S1 \cdot \frac{< g'_1 >}{g'_1(x,y,z)}.$$

$< g'_1 >$ : Mean value of $g_1$

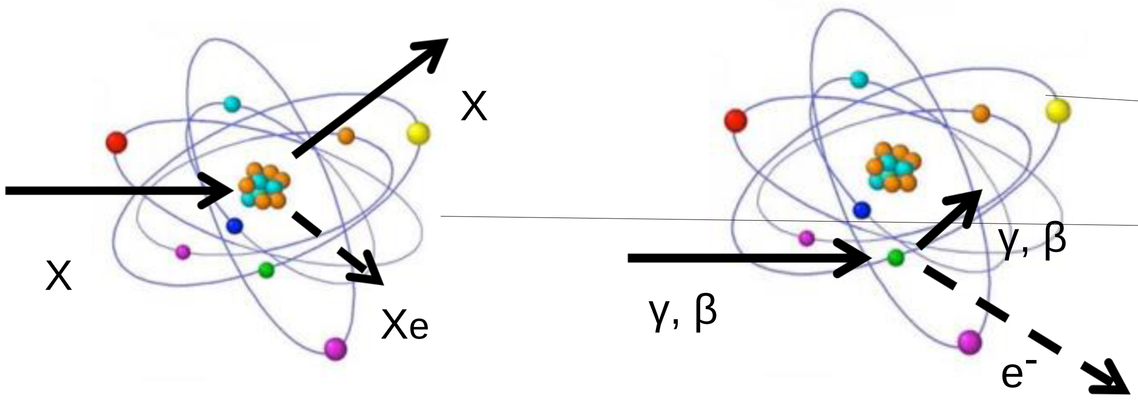
S2 correction: correct for electron absorption

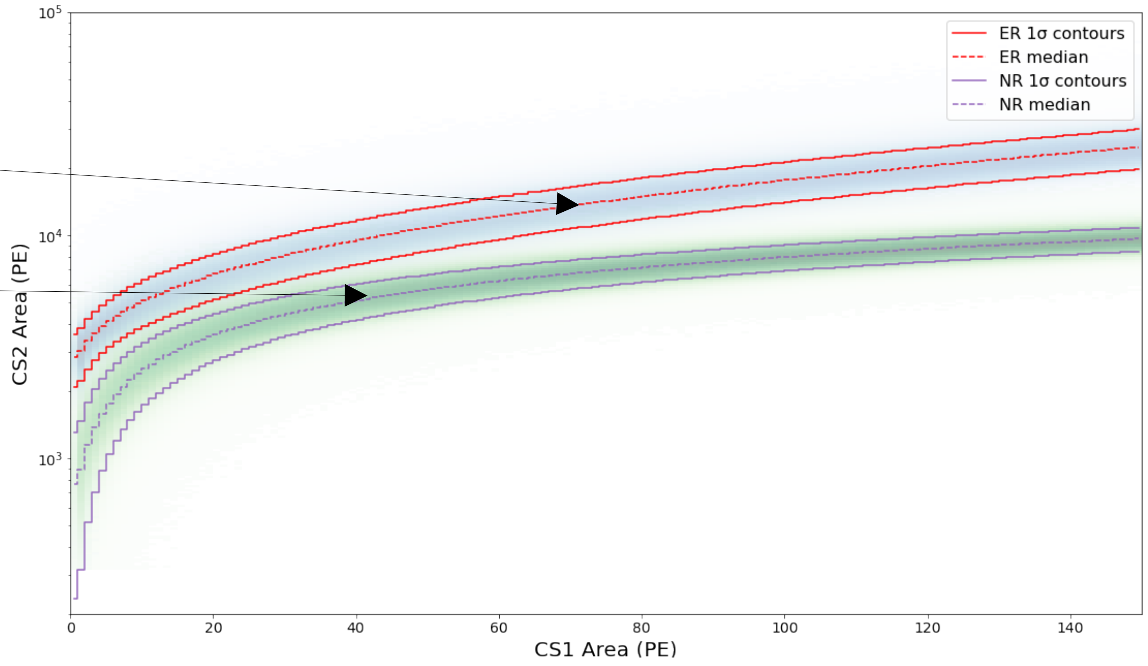


# WIMP sensitivity studies

# Background discrimination

Nuclear recoil (NR) Electronic recoil (ER)



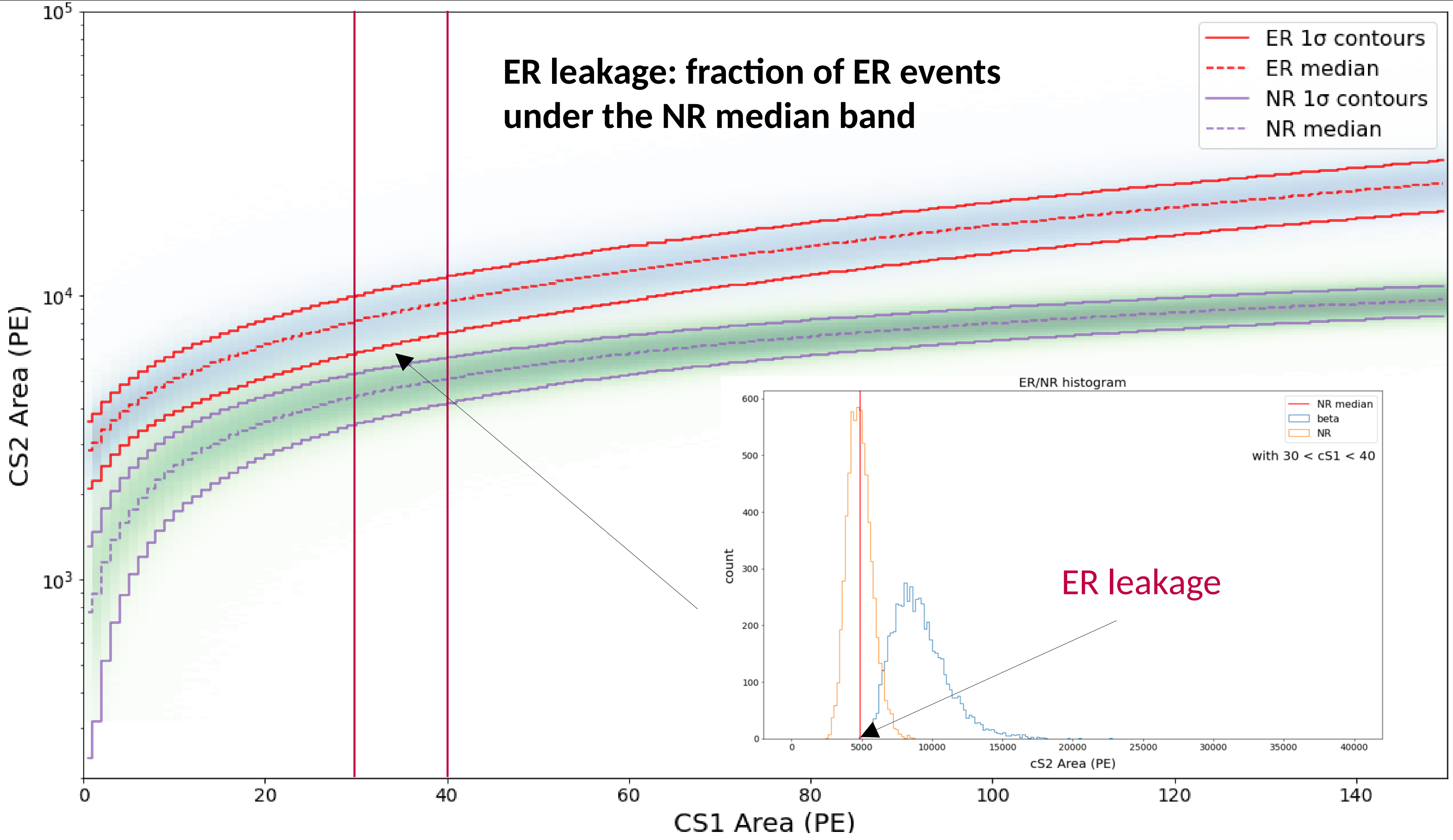




Electronic recoil: interaction with electron of xenon→ background only

Nuclear recoil: interaction with xenon nucleus→ background + signal

ER/NR discrimination→ cS1/cS2 ratio

# NR and ER band separation

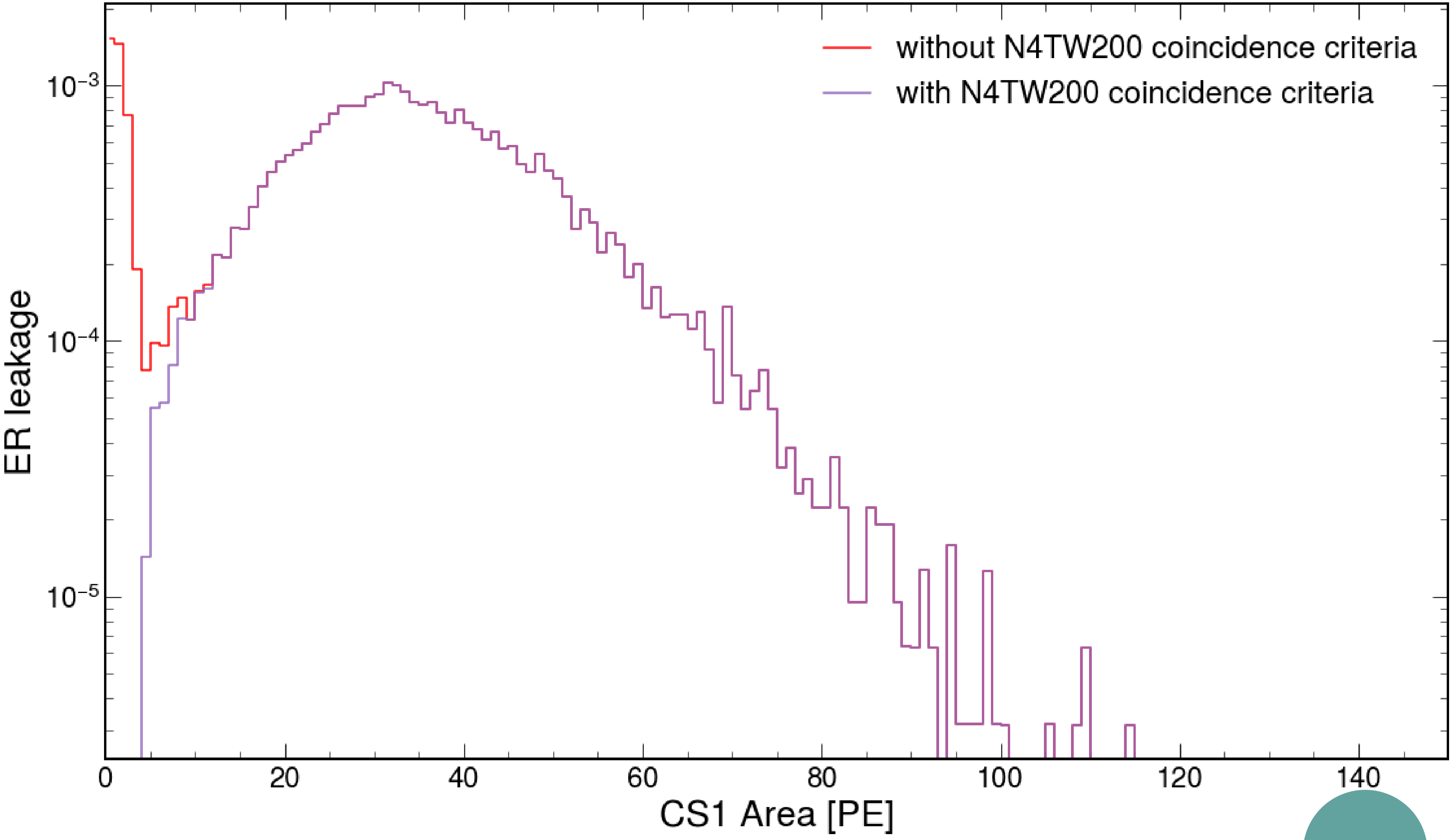


# Isolated events

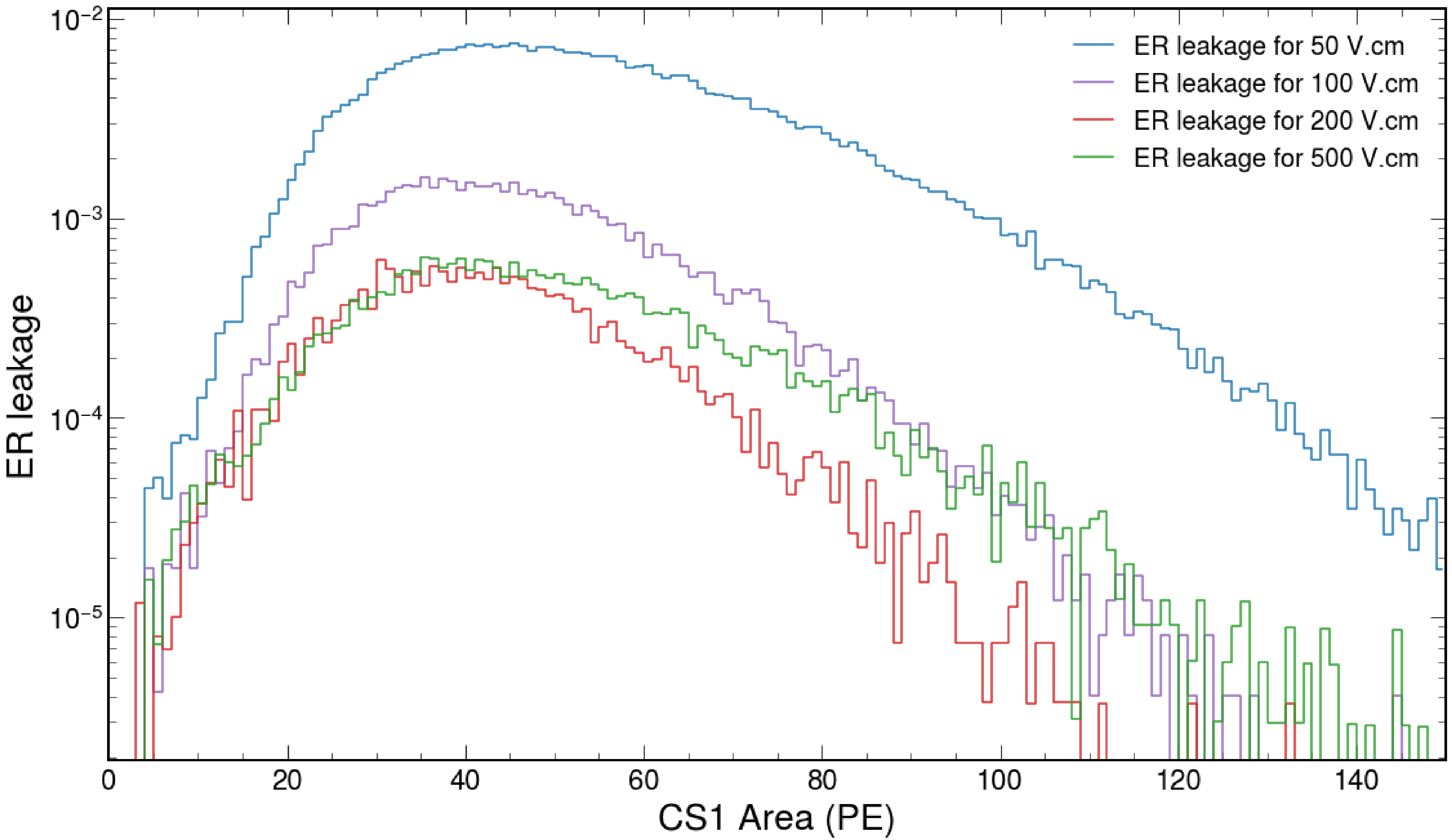
Isolated events: dark count or isolated photons→ participate to background

N4TW200 coincidence criteria: four photons in a time window of 200ms

Rejection of isolated events:from 34kHz→ 1.87 mHz



# ER leakage



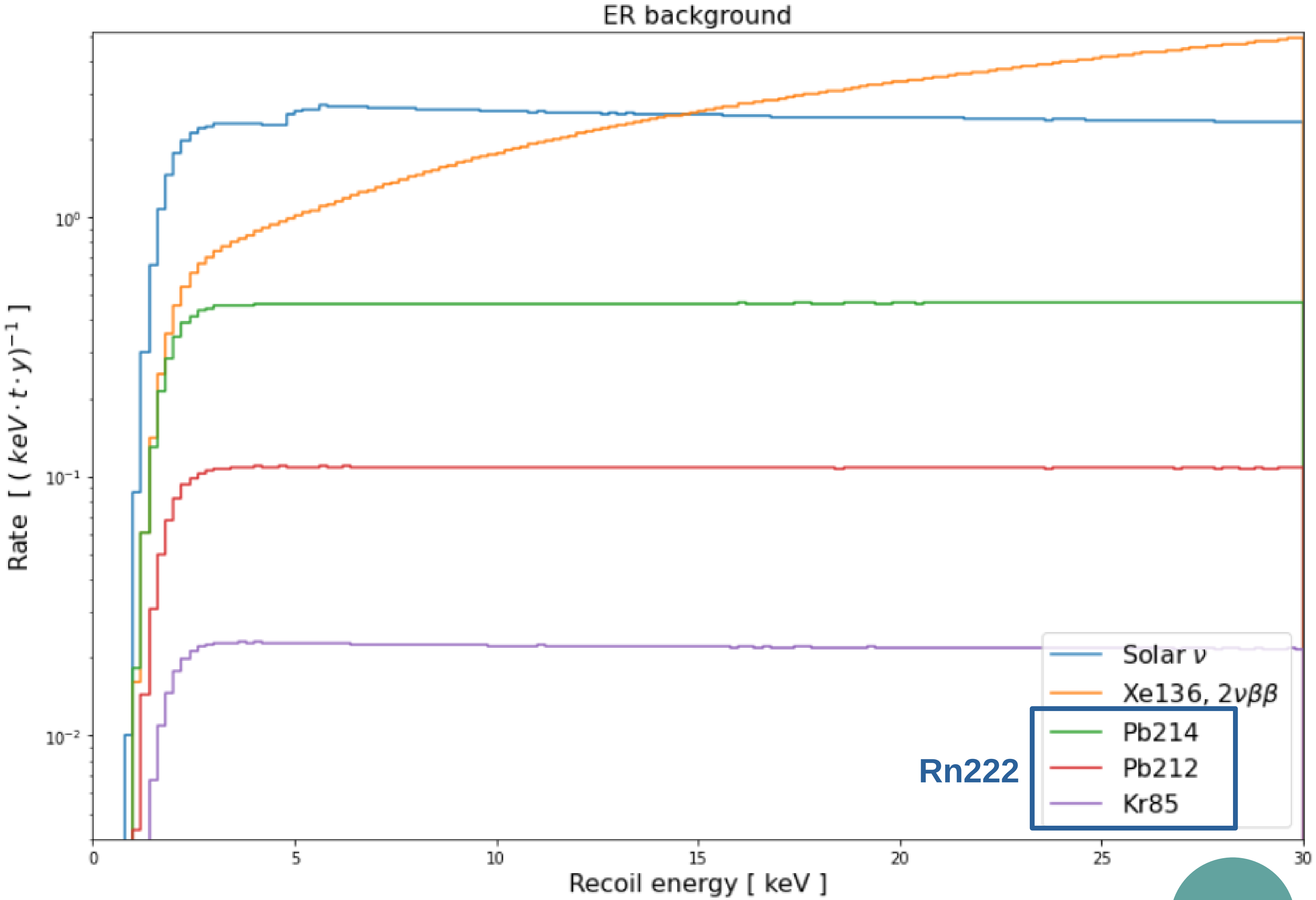
ER leakage for 50 V.cm
ER leakage for 100 V.cm
ER leakage for 200 V.cm
ER leakage for 500 V.cm
ER leakage
CS1 Area (PE)
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
0
20
40
60
80
100
120
140

# Backgrounds

For baseline design:

ER background: : solar ν, Xe136 2vbb, Rn222 (baseline rate: 0.1 μBq/kg)

NR background: CEvNS, Radiogenic neutrons



# Re-weighting

Background and signal integration:
Re-weighting of NR and ER files

Normalization weight: Detector mass

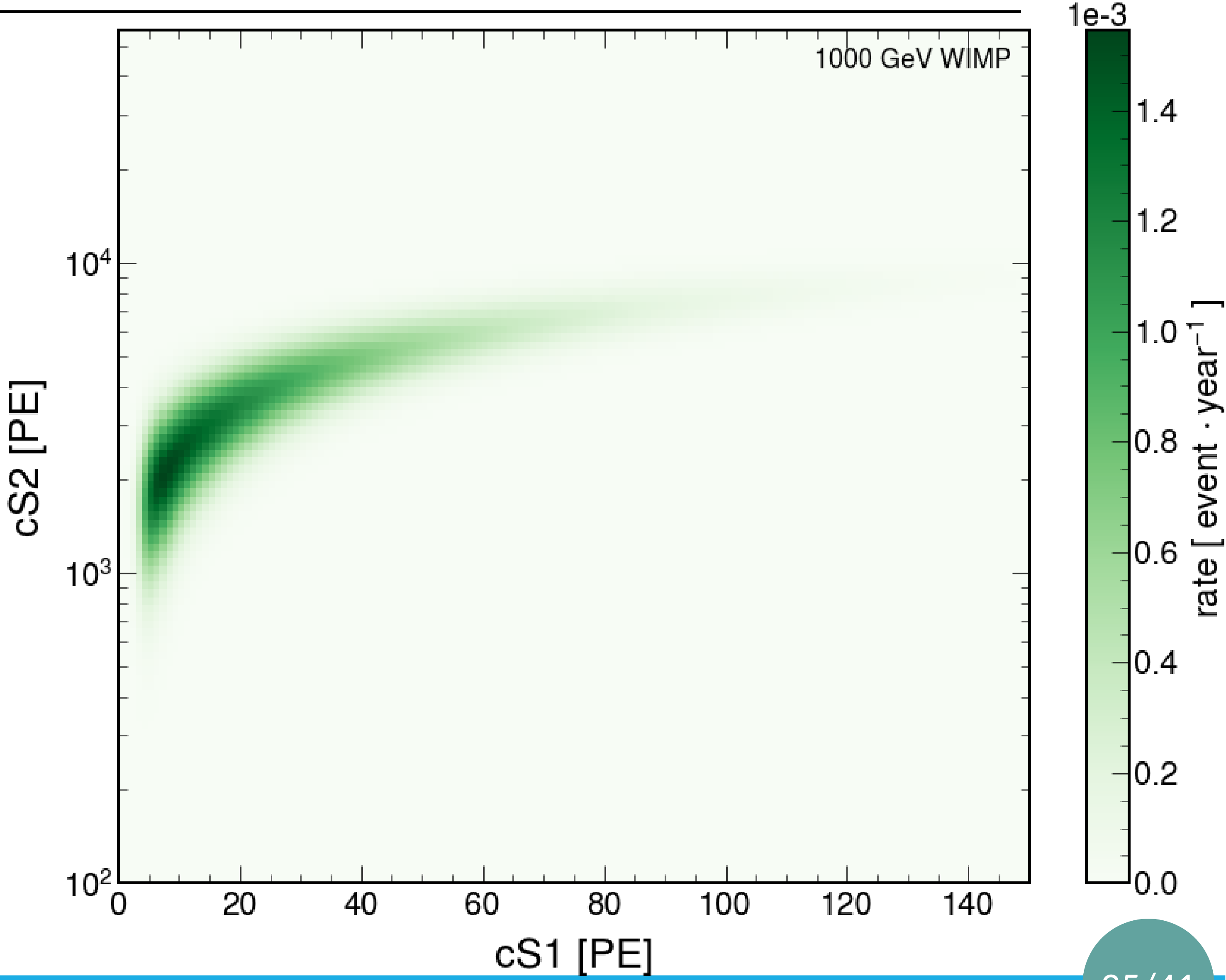
$$ow_i^{norm} = \frac{M_{det}}{p_{gen}(E_i) * n_{gen}}$$

Event probabiltiy

Event weight: Background rate

$$w_i = R_{background}(E_i) * ow_i^{norm}$$

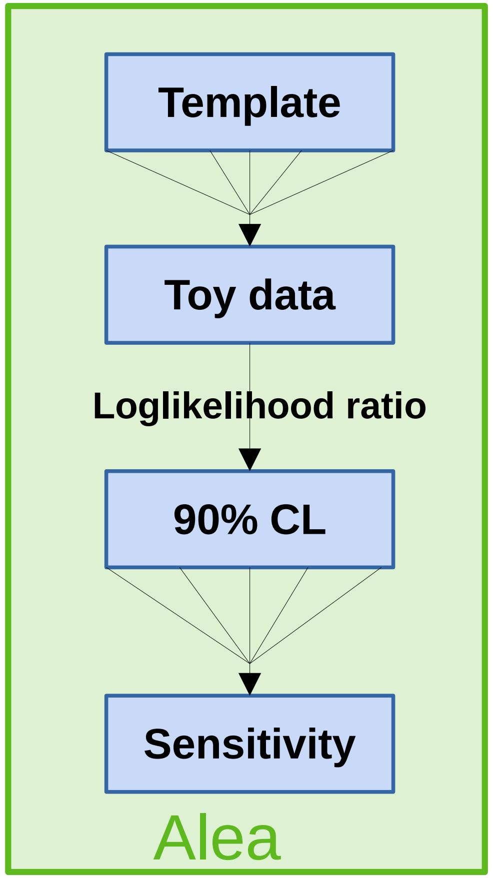
Template: proportional to the pdf in the cS1/cS2 space



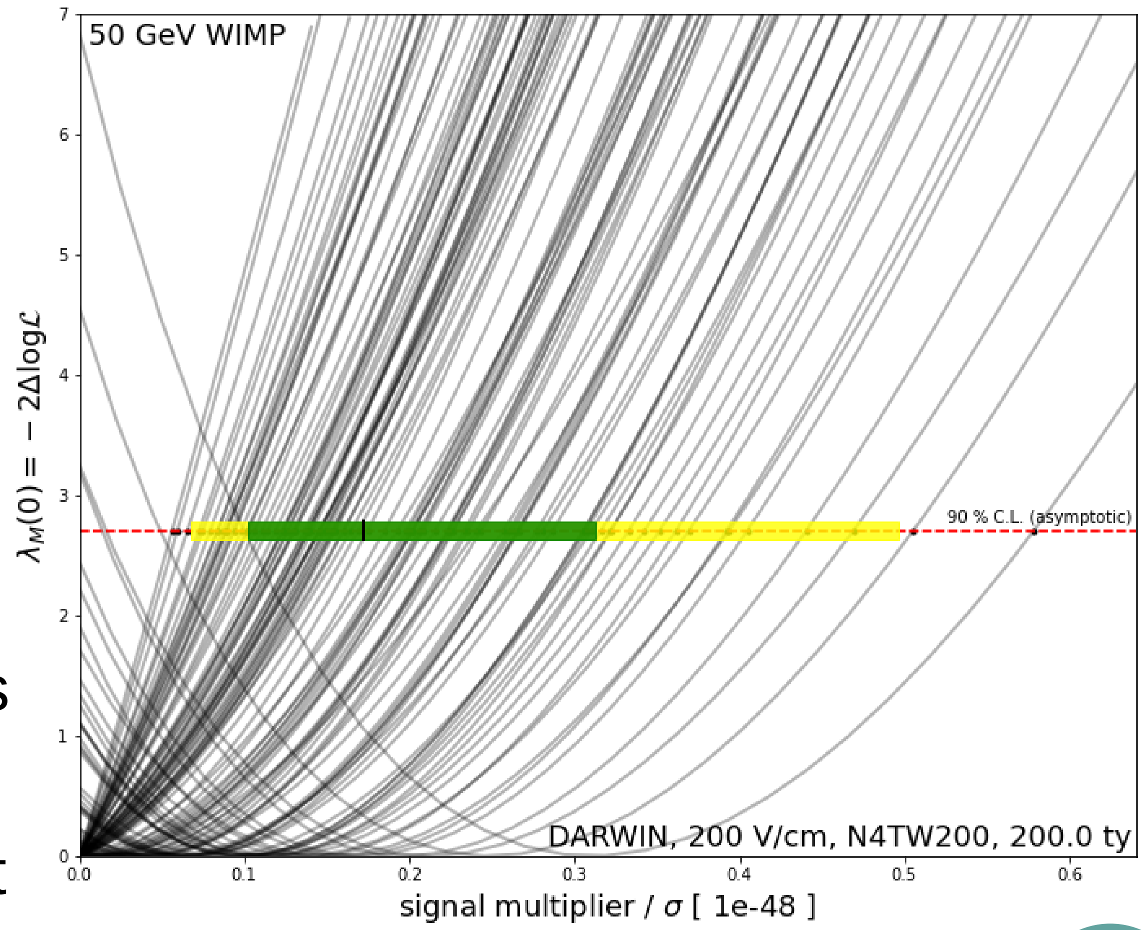
# Alea

Statistical inference package from Xenon collaboration (currently being developed)

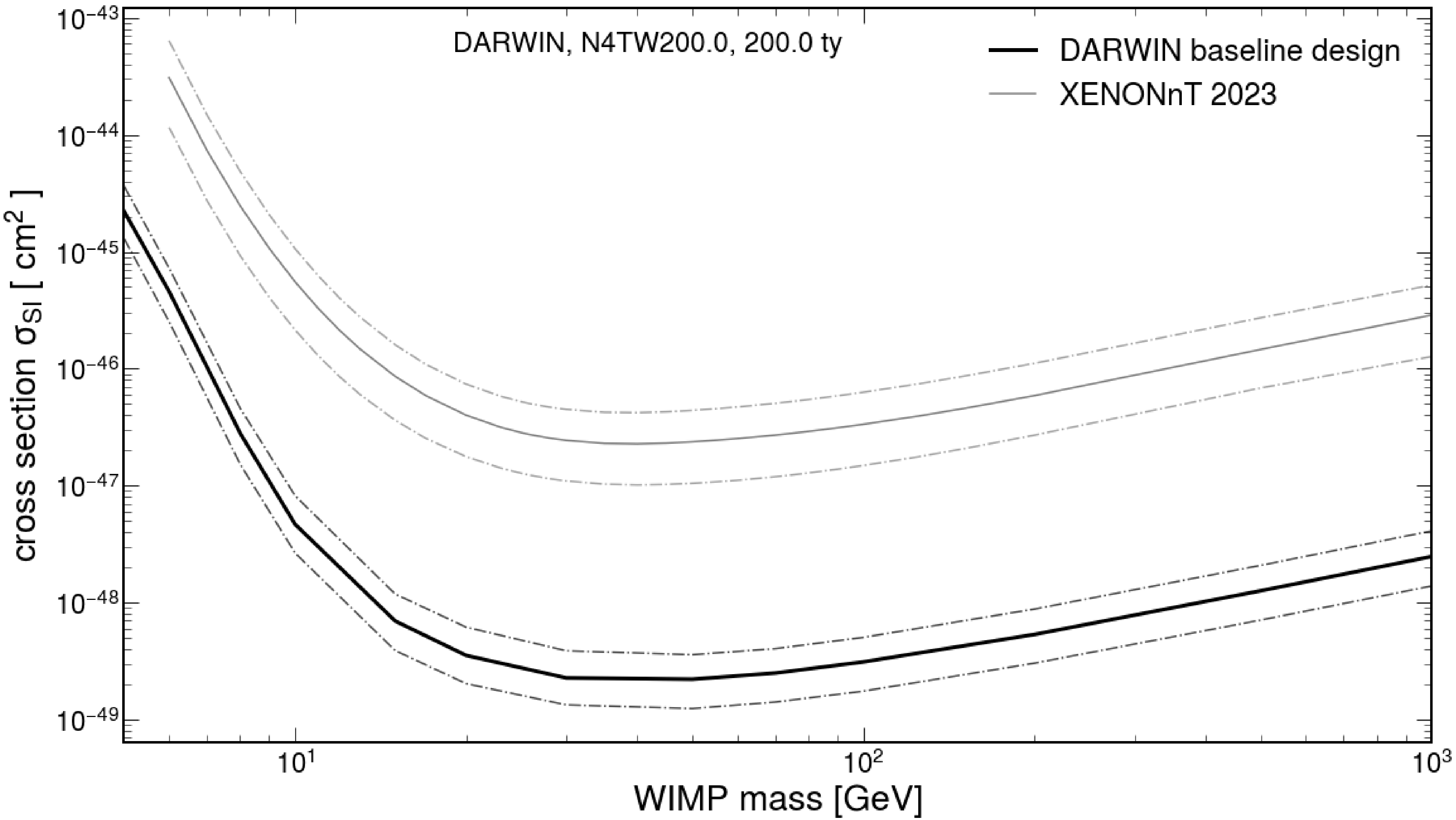
Use templates to find sensitivity



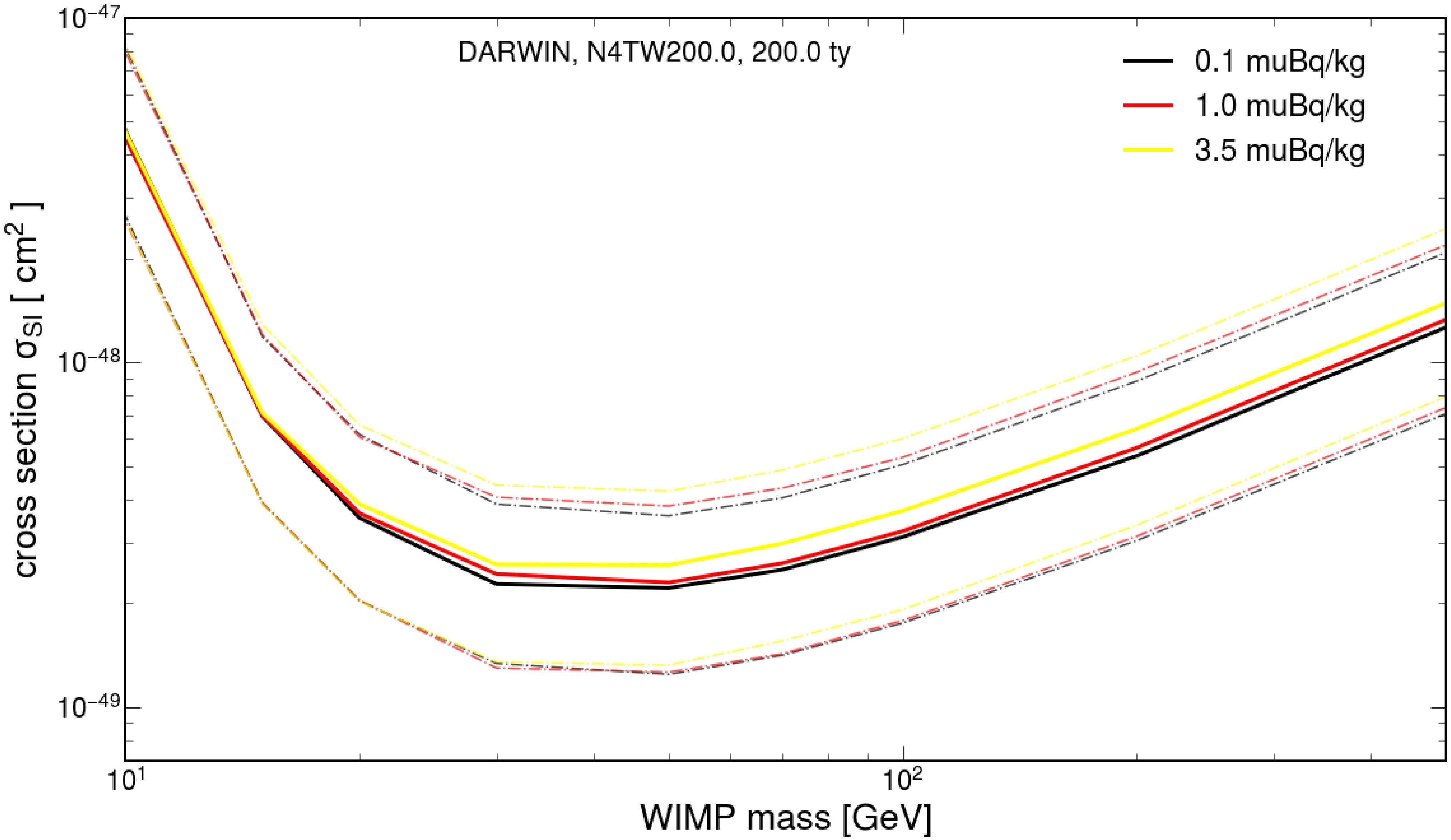

- Simulate MC toys from templates
- Compute likelihood ratio functions
- Find upper limit (90% CL) per toy
- Find median of upper limits → sensitivity
- Repeat for each masspoint



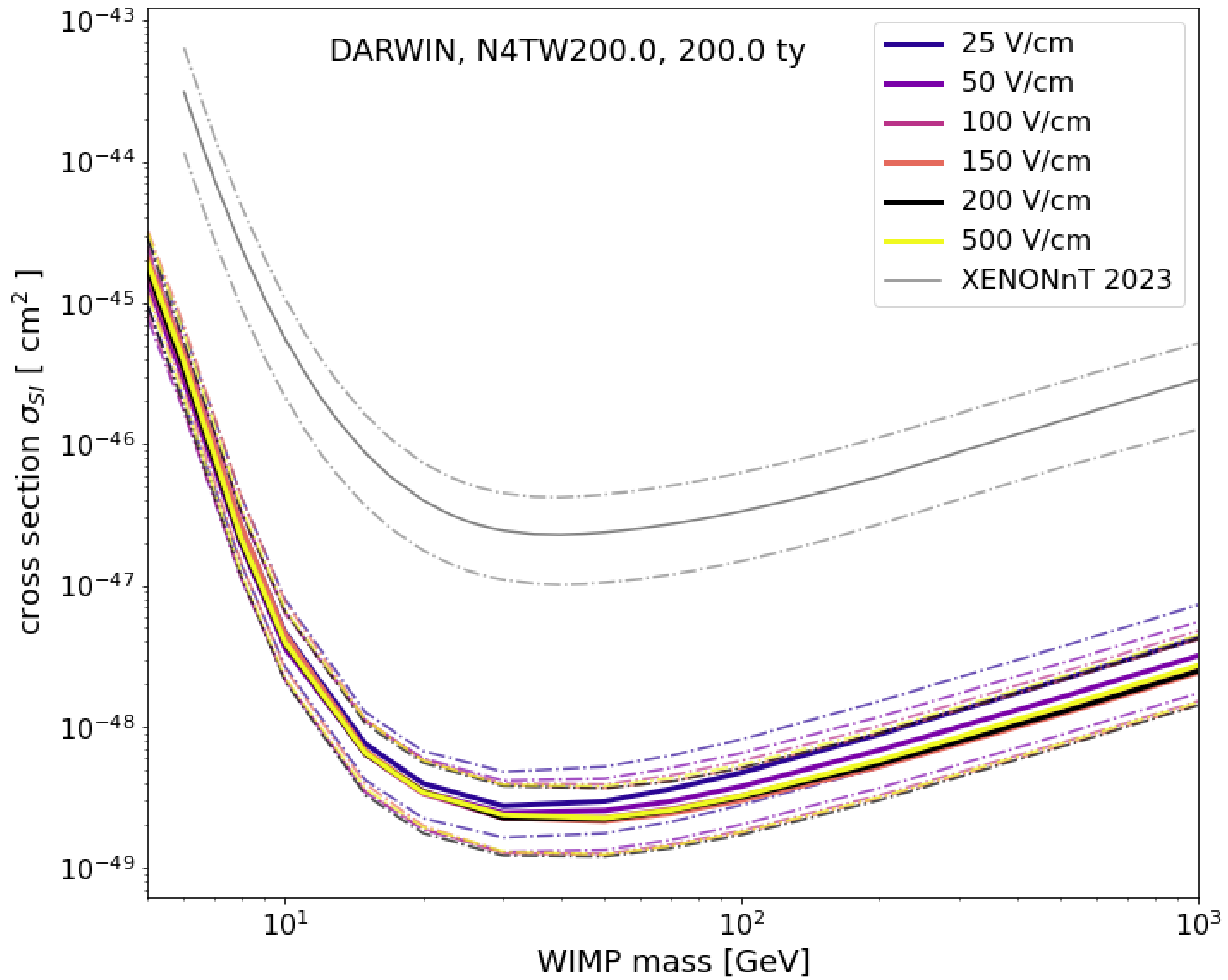
# Baseline sensitivity



# Impact of Rn222



# Impact of the field



# Conclusion

-Dark matter: One important missing element in our comprehension of our actual universe

-DARWIN: dual phase Xenon TPC for direct dark matter detection→ Improved sensitivity to WIMP

-Development of a simulation pipeline for production of signal and background events in the DARWIN TPC

-Estimation of the DARWIN sensitivity to WIMP

-Sensitivity used as a tool for estimating detector design impact

**Next Steps:**

-General improvement of the simulation pipeline: position reconstruction, additional background, low field improvement

-Simulation and estimation of the impact of a realistic field

-Impact of photodetectors choice; SiPMs, other PMTs

Thank you for your attention