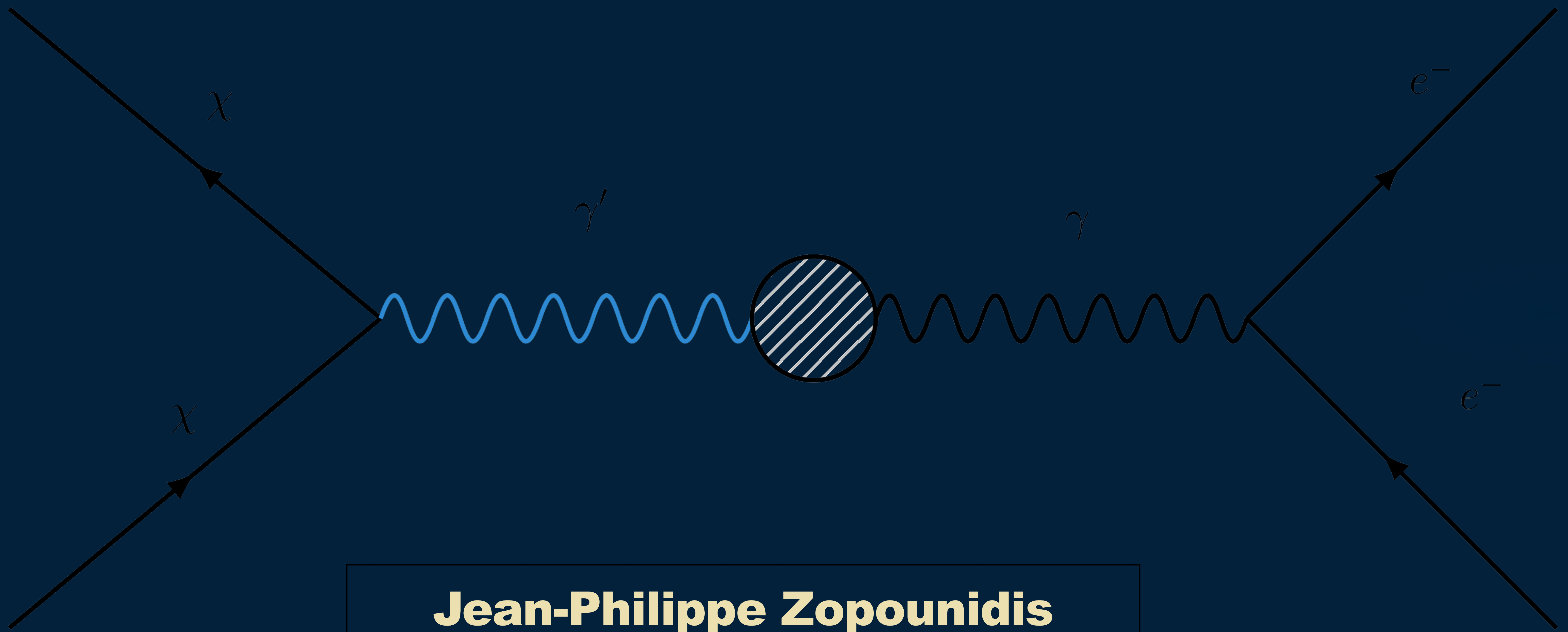
Search for sub-GeV dark matter in XENON1T



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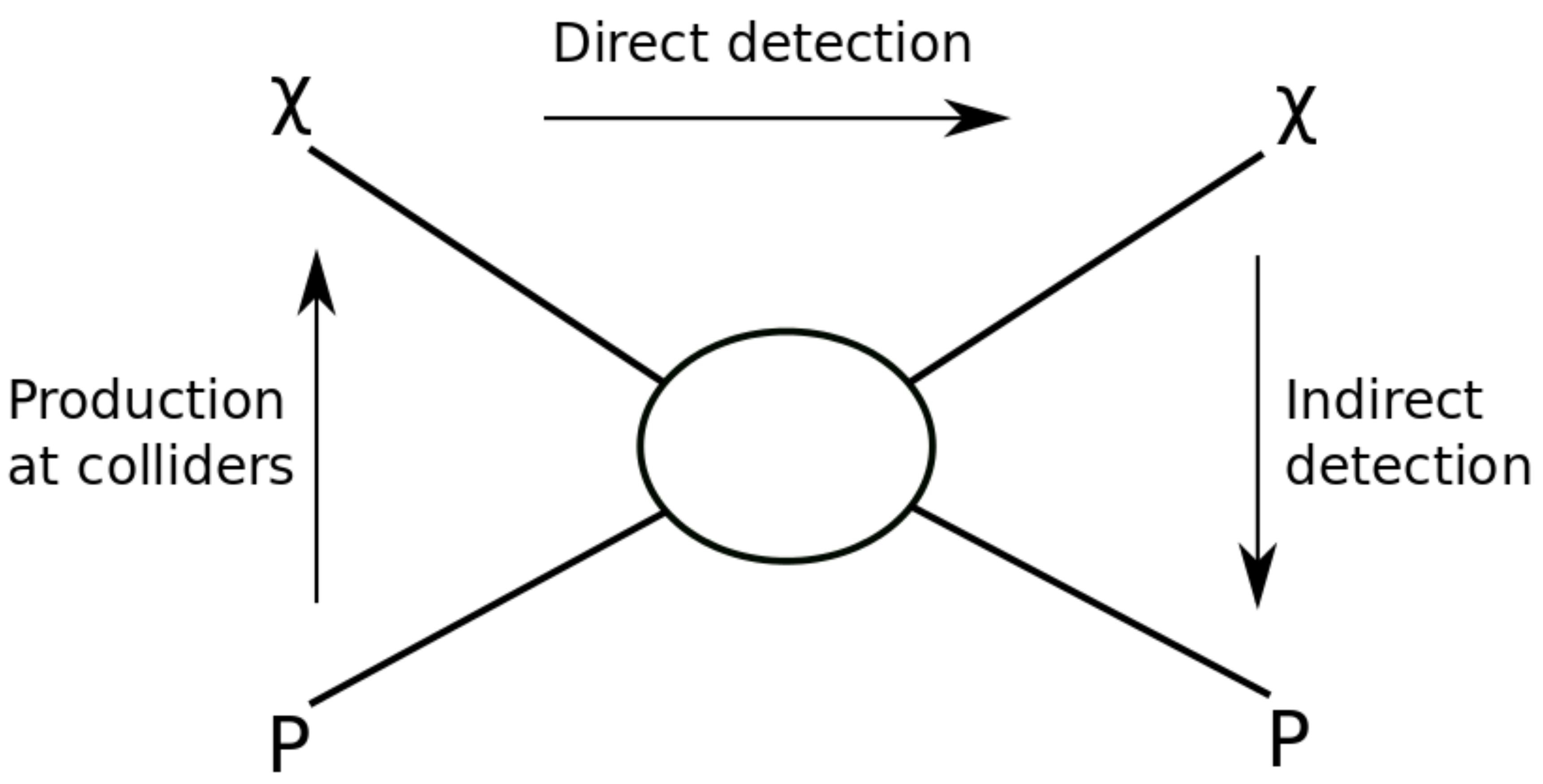
Direct Detection of Dark Matter

Investigation of the hypothesis that the non-luminous component of Milky Way consists of WIMPs arising from SUSY

The rate of elastic scattering off nuclei of the detector's medium relates various physics scales

Strategy of direct detection: DM Energy deposition via elastic scattering off **nuclei** can produce a clear signal in low-background underground detectors



$$E_r = \frac{\mu_{\chi,N}^2 u^2}{m_N}(1 - \cos\theta)$$

Differential event rate expected for an earth based detector

$$\frac{dR}{dE_r}(E_r) = \left(\frac{\sigma}{2\mu_{\chi,N}^2 m_\chi}\right) \times F^2(E_r) \times \left(\rho_{DM} \int_{u \geq u_{min}}^{u \leq u_{esc}} d^3u \frac{f(\mathbf{u}, t)}{u}\right)$$

Particle Physics Term

Nuclear Physics Term

Astrophysical Term

Sub-GeV Dark Matter

In the absence of a Direct Detection of WIMP DM a variety of theories predicting sub-GeV DM particles with leptonic interactions gained interest

Physics channels

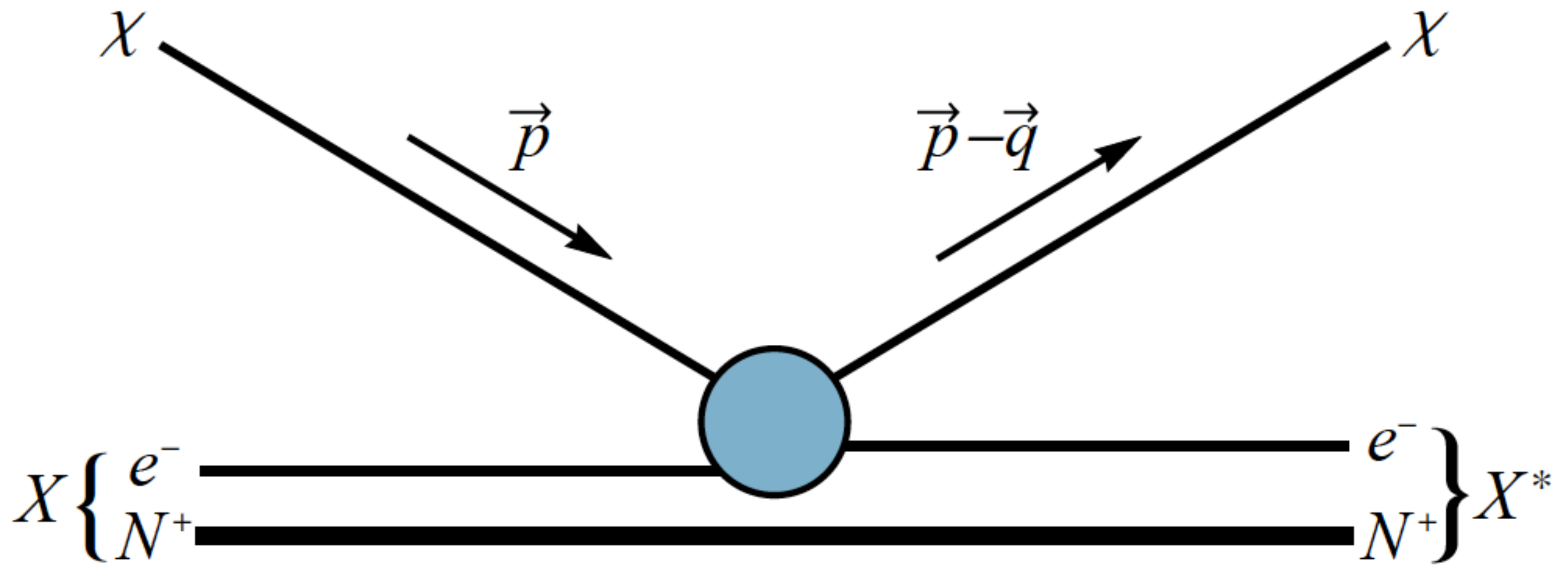
- DM-electron scattering

Particle candidates for a light dark matter

$$\mathscr{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

A hypothetical massive vector boson A' of a broken (dark) gauge group $U(1)_D$ that kinetically mix with the SM hypercharge. At low energies the mixing is between A' and a photon

The Dark Sector interacts with the SM via the gauge boson A'.
DM particles can scatter off bound electrons of the Xe atom via A' exchange.



$$\frac{dR_{ion}}{d\ln E_{er}} \sim \frac{d\langle\sigma^{nl}_{ion}u\rangle}{d\ln E_R} = \frac{\bar{\sigma}_e}{8\mu^2_{\chi,e}}\int q\,|f^{nl}_{ion}(p',q)|^2\,|F_{DM}(q)|^2\,\eta(u_{\mathrm{min}})\,dq$$

The rate depends on the initial and final state of the electron, the particular interaction and the Halo model

Two cases are of interest

- $F_{DM}(q) = 1$, heavy mediator, $(m_{A'} \gg \alpha m_e)$
- $F_{DM}(q) = (\alpha m_e/q)^2$, ultra-light vector mediator. $(m_{A'} \ll \alpha m_e)$

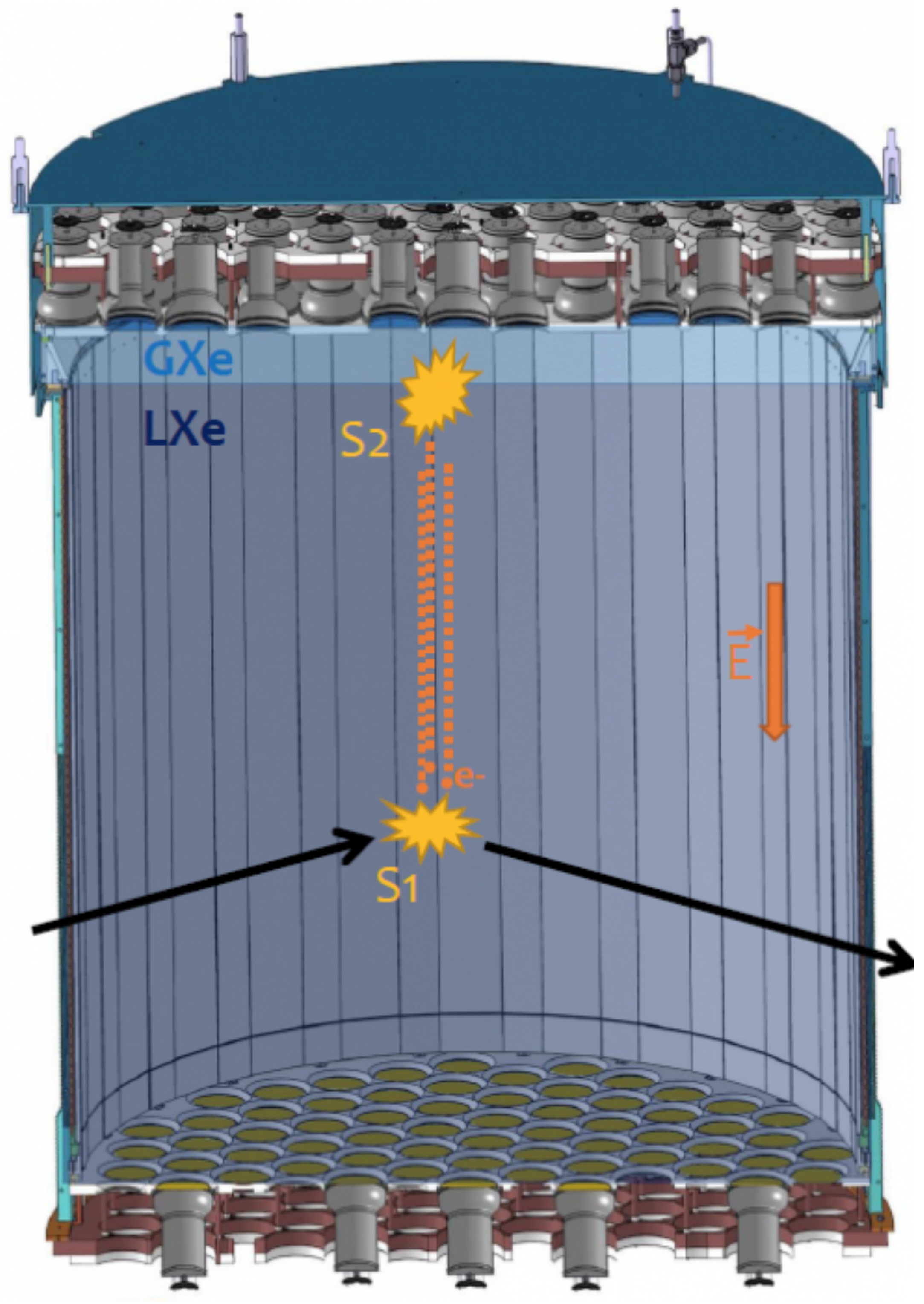
Sub-GeV Dark Matter

Detectors of ionization created by particle interactions are sensitive to sub-GeV DM

Examples are:

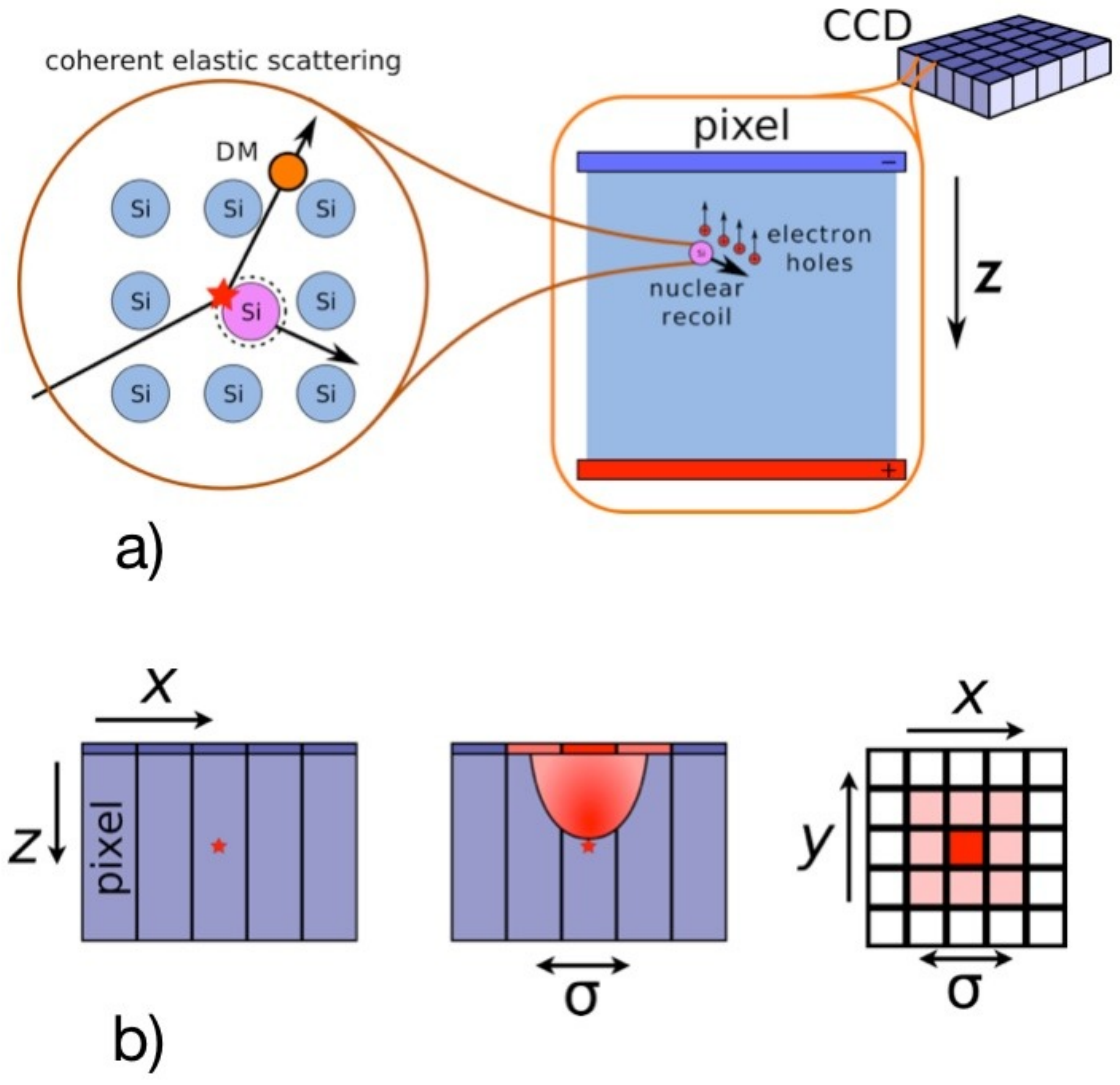
XENON

Dual-phase noble liquid TPCs



- Possibility of very large exposure
- Unknown ER backgrounds at very low energies

DM searches using CCDs



- Background model even for the few-electrons energy range
- Smaller exposures

The XENON1T TPC

Cylindrical TPC: 96 cm length and diameter

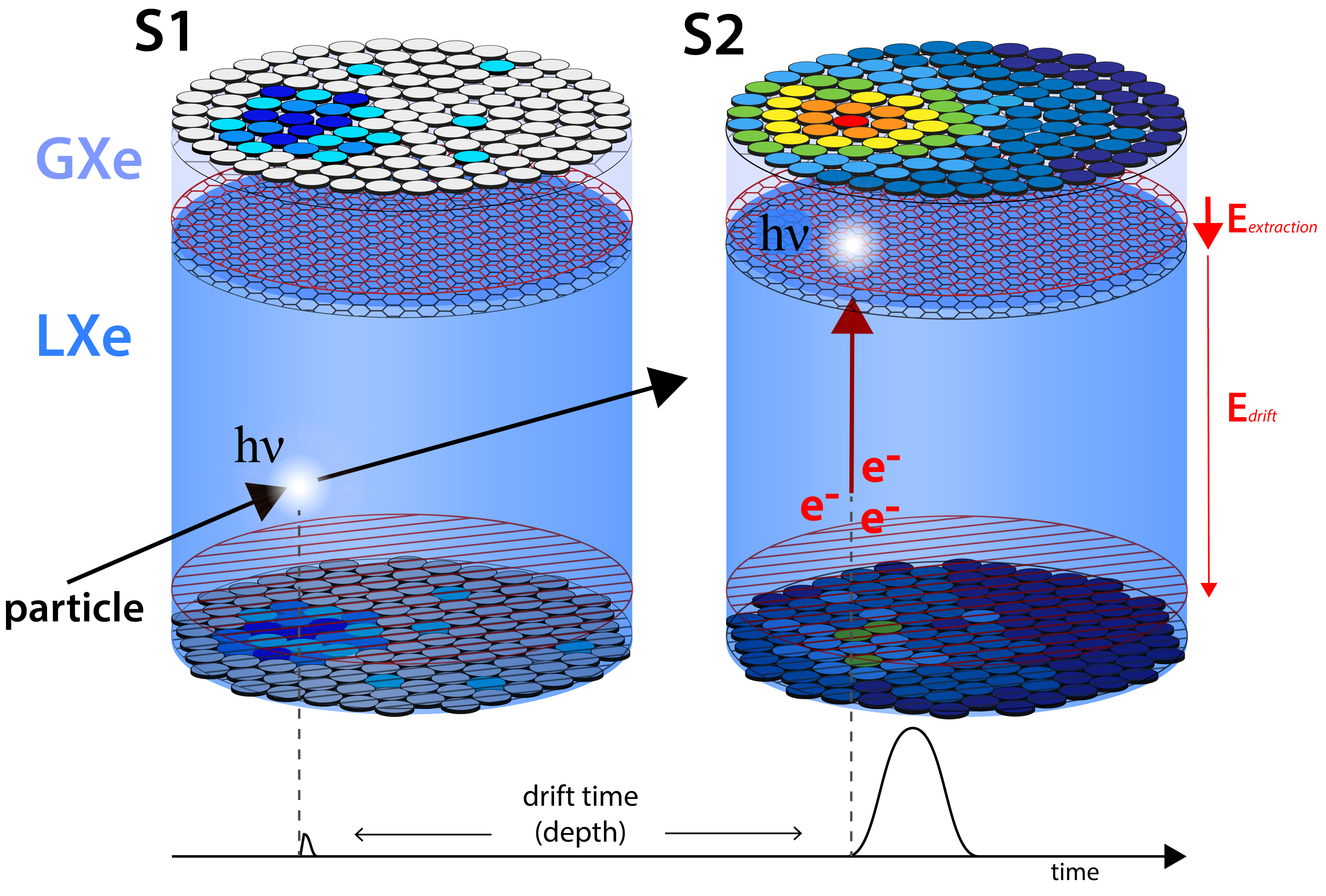
Target: 2 tons of LXe

2 arrays of PMTs:121 bottom & 127 top

(x,y) position reconstructed from the light patterns on the top PMTs

Z-coordinate reconstructed from the S1-S2 temporal separation by the electrons drift time

Detection Principle



Detection of signals from excitation and ionisation

S1: prompt scintillation light
S2: proportional scintillation light

Sub-GeV Dark Matter

In the absence of a Direct Detection of WIMP DM a variety of theories predicting sub-GeV DM particles with leptonic interactions gained interest

- Sub-GeV DM → orbital electrons → ionization
- XENON1T sensitive to detect **few-electron signals**
- **Presence of only an S2 signal**
- **No complete background model** in XENON1T for few-electron signals. Nevertheless we can set an upper limit.
- Improvements can be made with the empirical knowledge of part of the background.

Sub-GeV DM search with XENON1T

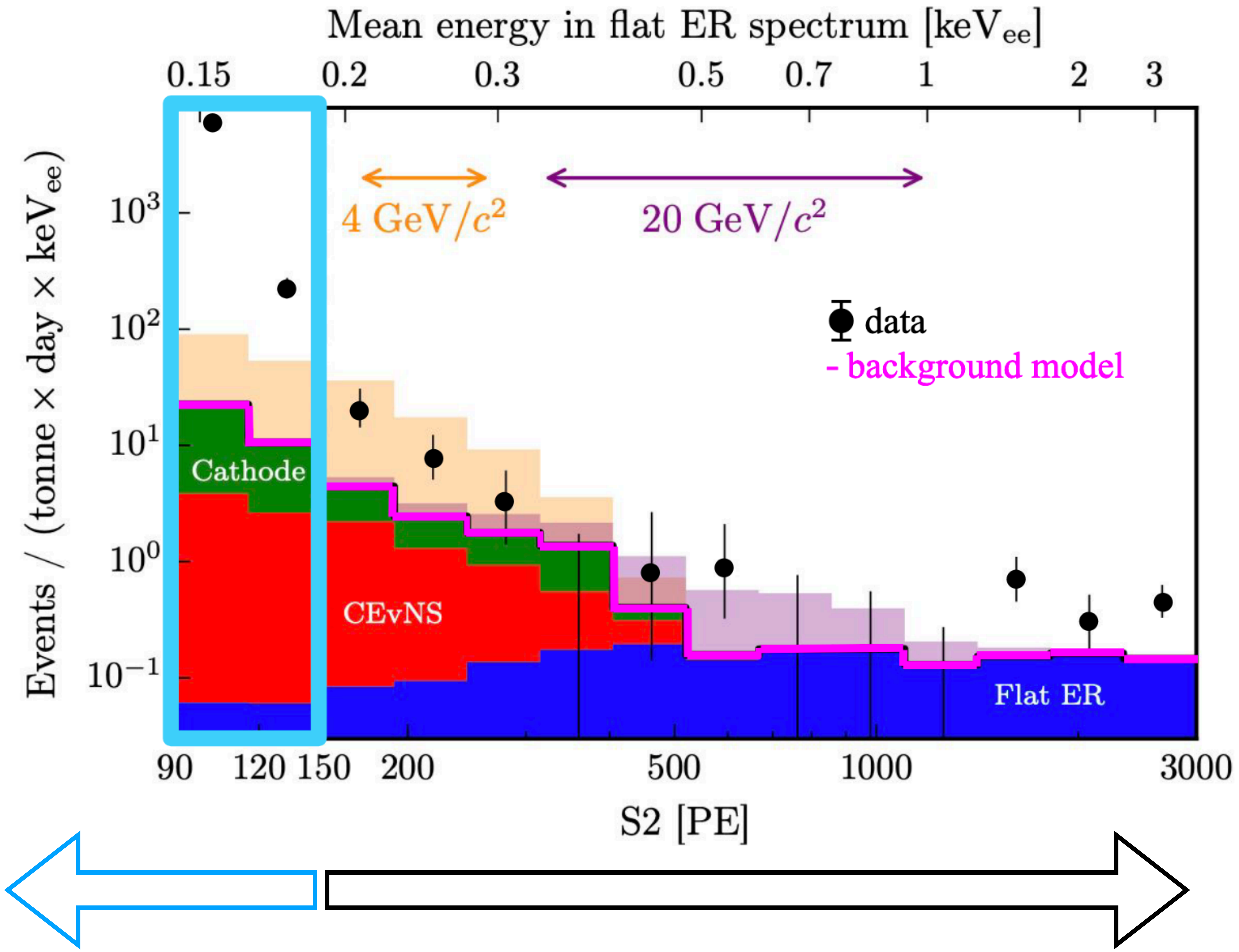
S1 light is detected with > 10% efficiency for E>3.5 keV

The detector is more sensitive for $m_\chi \geq 6\ \mathrm{GeV/c^2}$

Drop the requirement of S1

↓

Obtain sensitivity for lighter DM masses or sub-GeV DM-e^- interactions



Aggressive S2-only

Results to be published soon

Published S2-only analysis

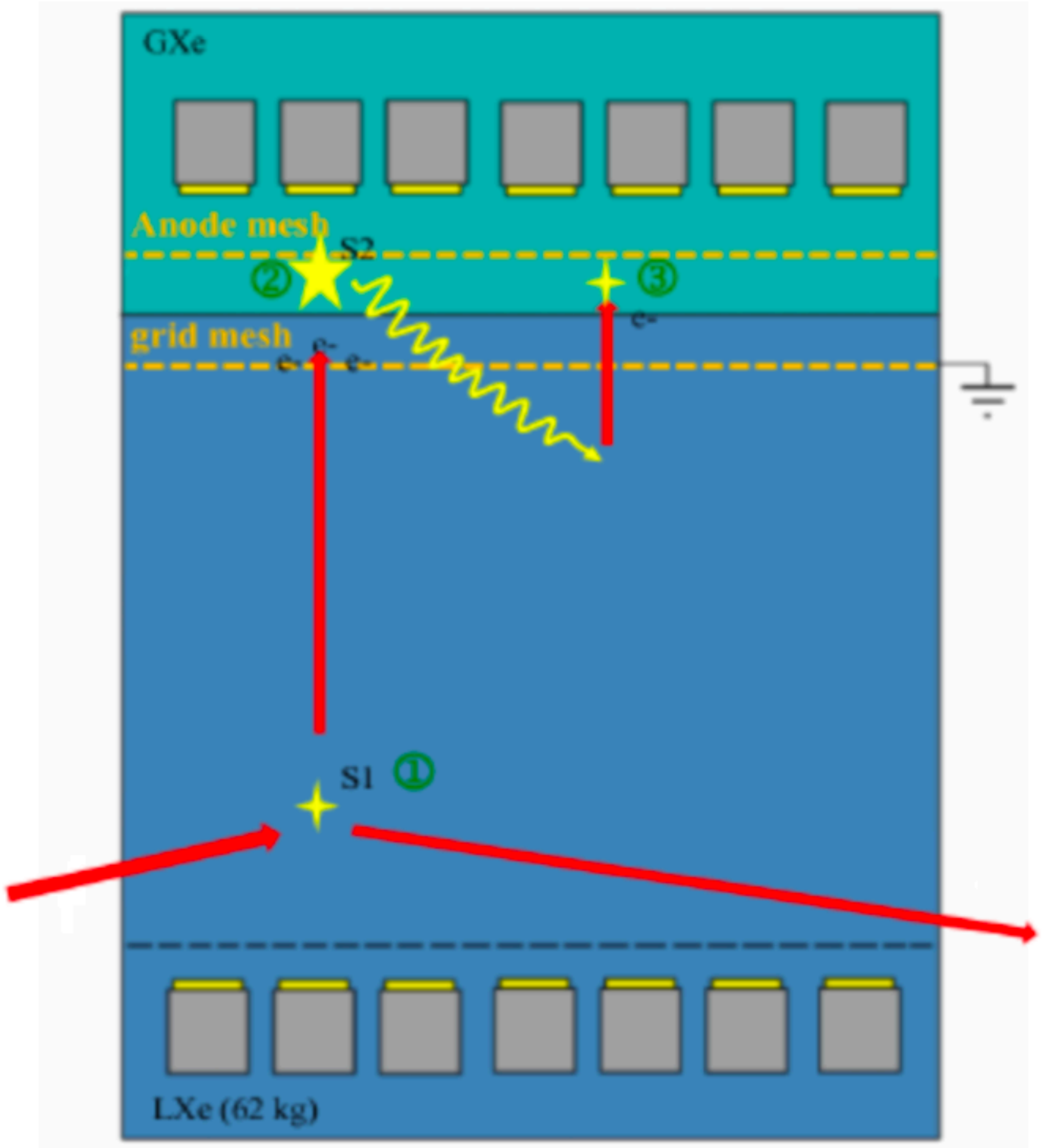
Phys. Rev. Lett. 123, 251801 (2019)

The single-electron background

Many sources

- Photoionization on metal surfaces and impurities from the primary S2 light
- Electrons trapped in the liquid-gas interface
- Possible existence of long-lived excited states of xenon or impurities
- Malter effect

Illustration of the main mechanism of production of Single Electrons



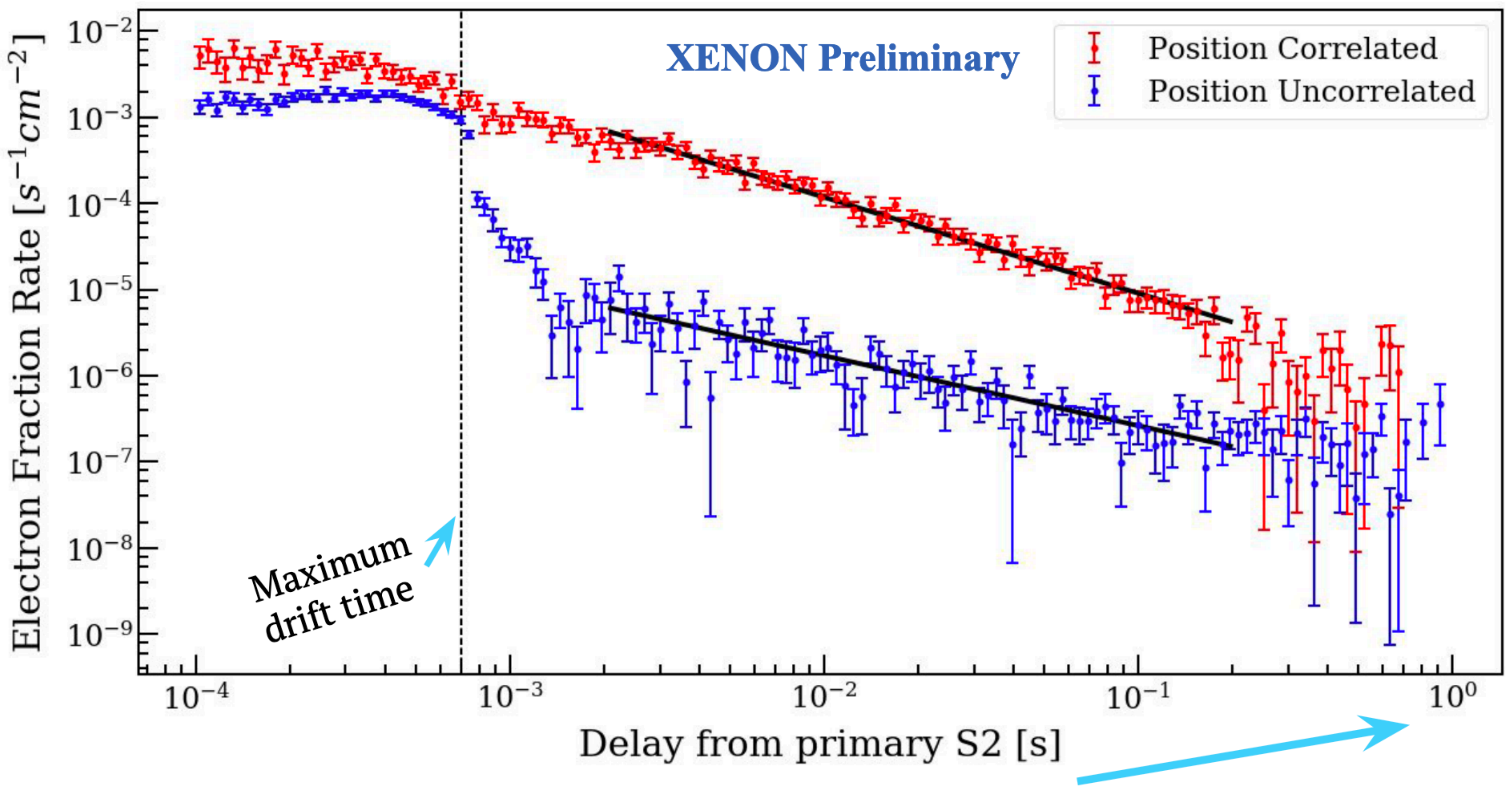
A photon of a strong main S2 interacts with an impurity inside the LXe and producing an electron via photoionization. The electron drifted to the LXe/GXe interface and extracted produces proportional scintillation.

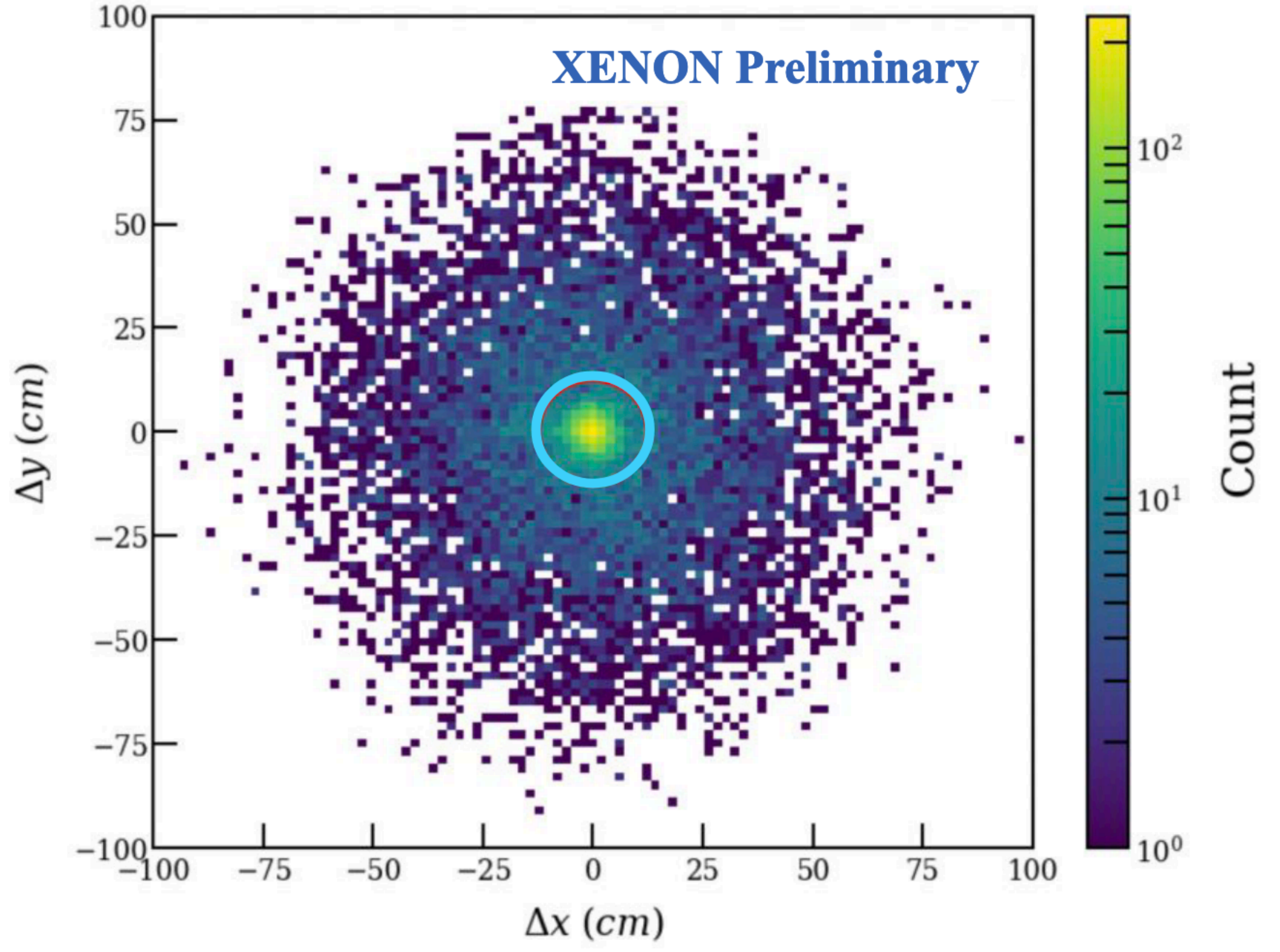
The single-electron background

The current understanding of the SE background

- The main SE background for DM search is due to SE trains extending in $\mathcal{O}(ms)$ time scales.
- The SE trains present a position correlation with the position of the previous S2
- The SE trains has a monotonic decreasing with Δt from previous S2, following a power law.

SE rate strongly depends on the **temporal separation** and the **position** of this **previous S2**





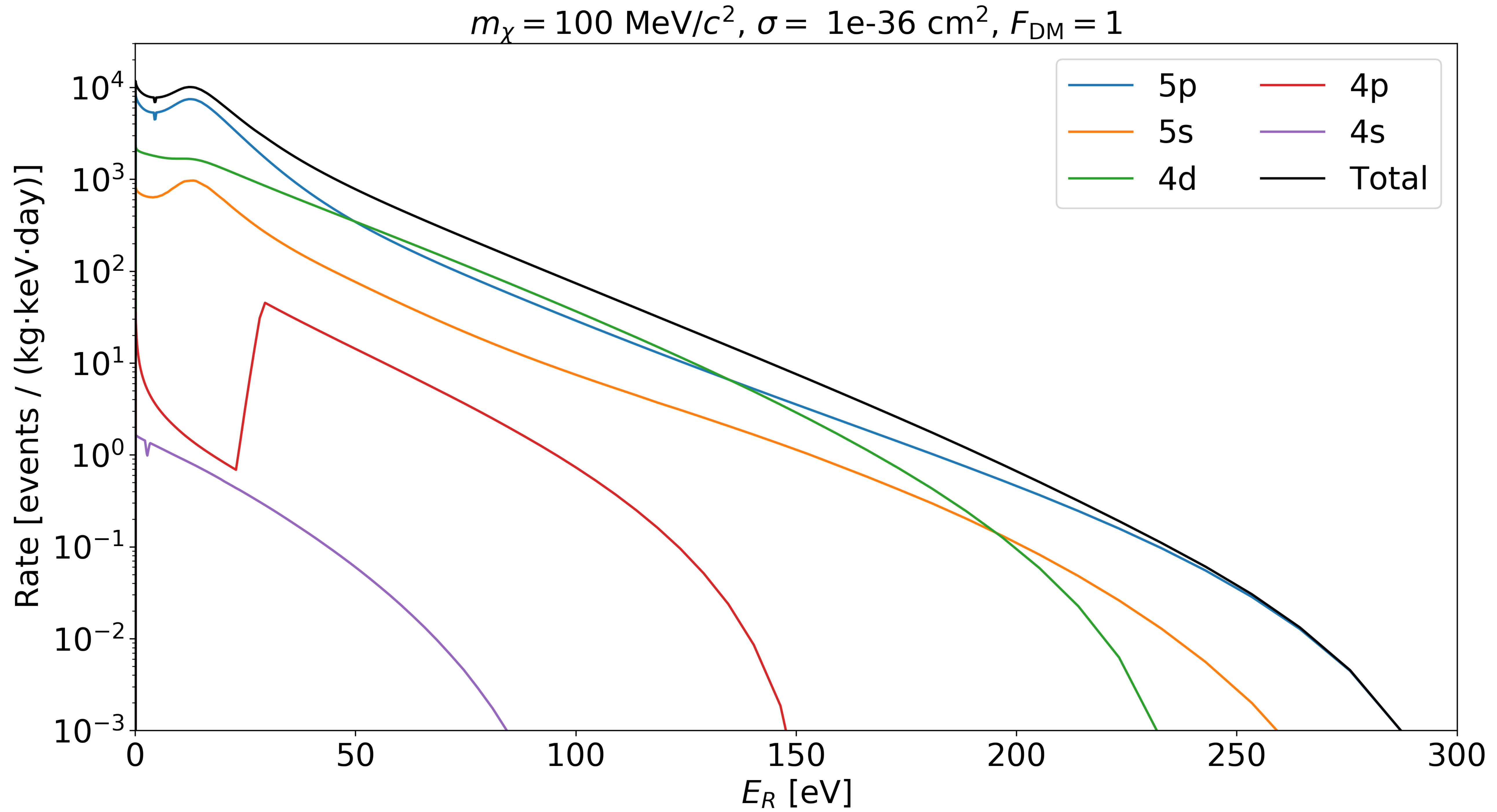
Optimisation of the life-time reducing cuts based on the position and time of primary S2

Two main cuts
Δt of peak from previous S2
Δr of peak prom previous S2

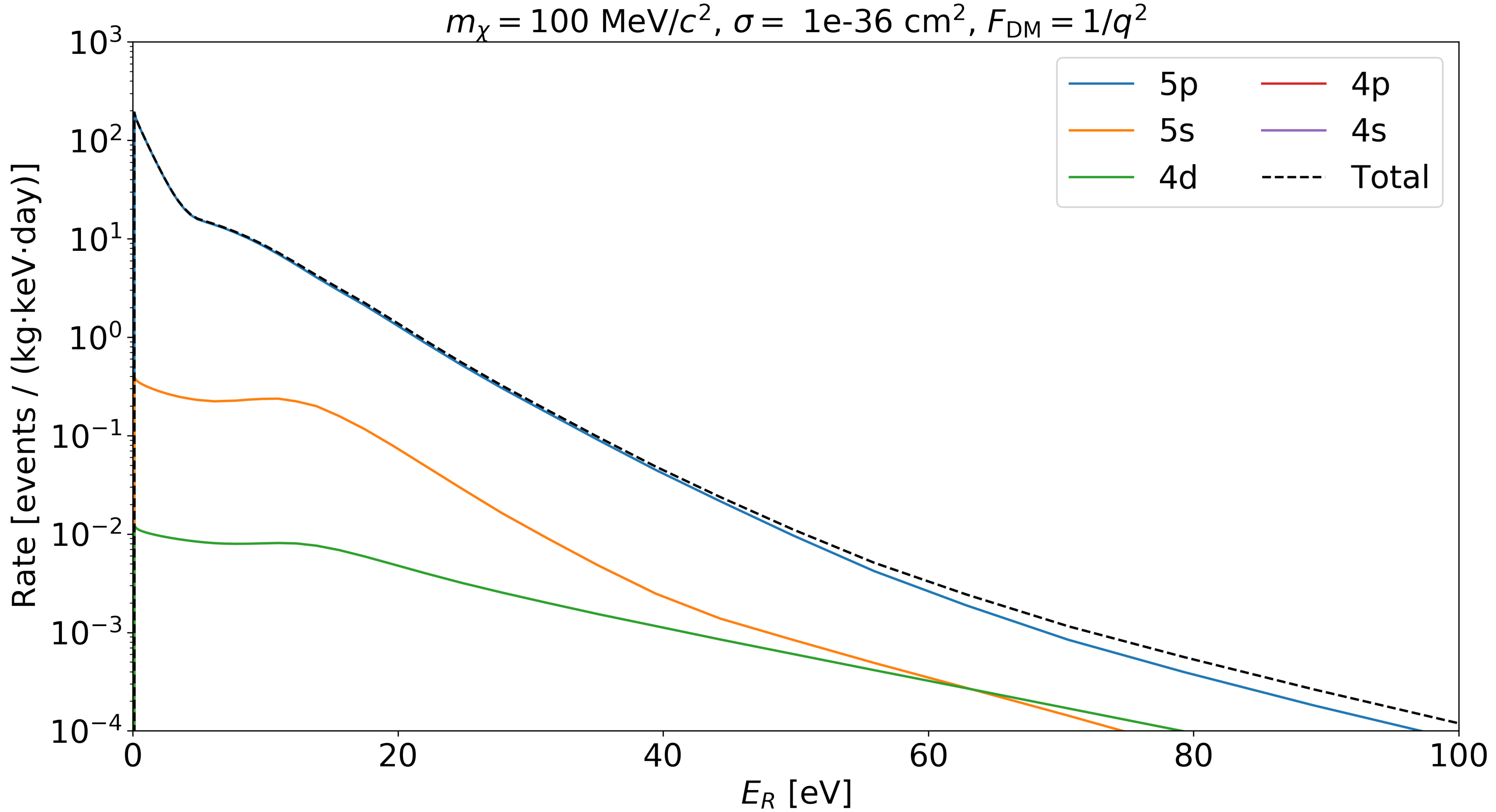
Signal model

Calculation of the theoretical spectrum

The contribution of lower atomic orbitals is suppressed even more in the case os an ultra-light mediator



$$F_{DM} = 1$$



$$F_{DM} = 1/q^2$$

Detector response

Detector response

- We must take into account the response of LXe to ionisation
- Drift and extraction of ionisation electrons
- Reconstruction effects

- $n^{(1)} = \text{Floor}(E_R/W)$ quanta will be generated from the first ionisation electron

- $n^{(2)} = \text{Floor}((E_i - E_j)/W)$ additional quanta will be created if the scattered electron originates from an inner shell

- There is a probability $f_e = (1 - f_R)(1 + N_{ex}/N_i)^{-1} = 0.87$ that these will be electrons

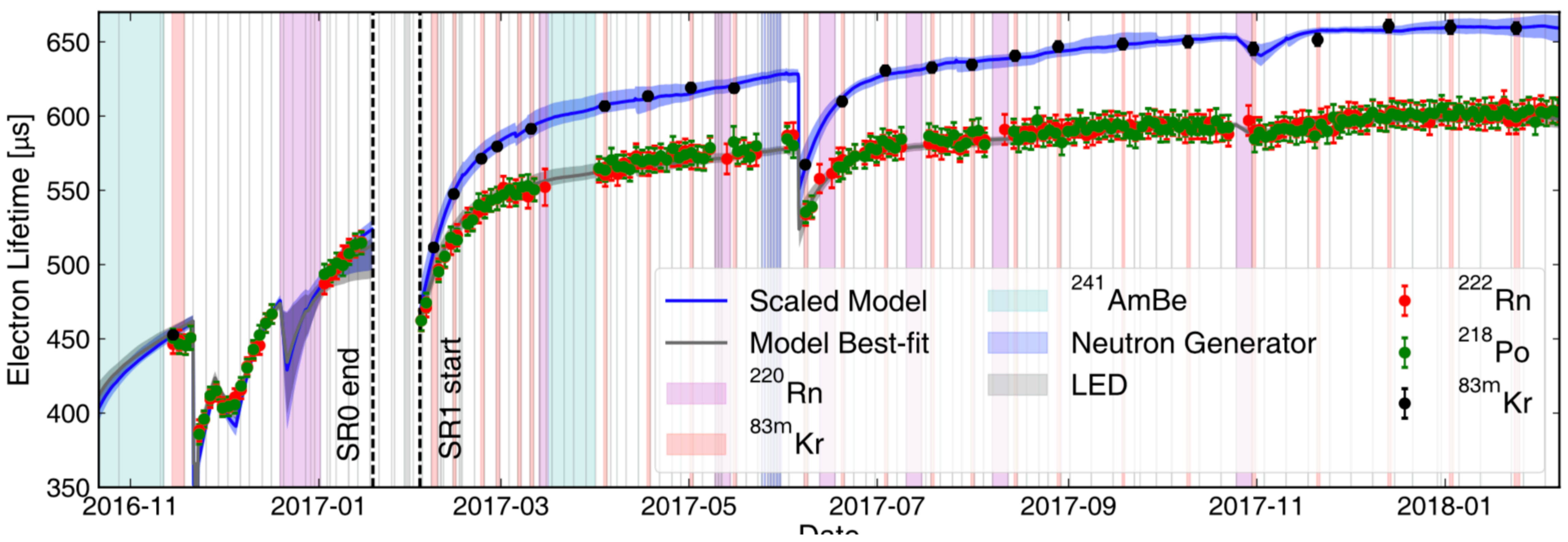
Detector response

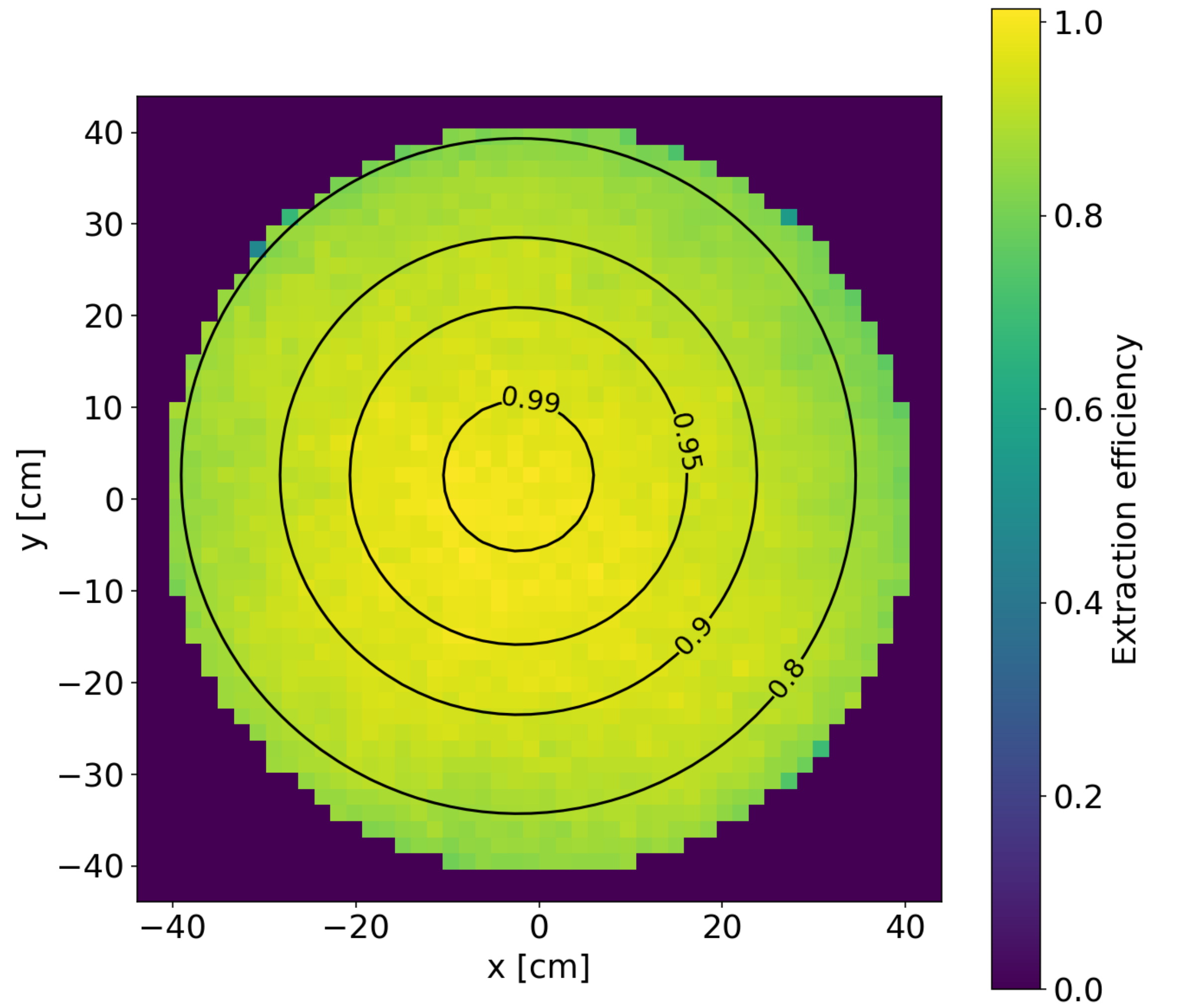
Detector response

- We must take into account the response of LXe to ionisation
- Drift and extraction of ionisation electrons
- Reconstruction effects

- Survival probability of drifted electrons: $P_{drift}(\tau_e) = e^{-t_{drift}/\tau_e}$ with t_{drift} the drift time and τ_e the electron lifetime.
- Extraction efficiency $P_{ext} = 0.95$

Inferred from (x,y) distribution of the extraction efficiency





The final signal model

Detector response

- We must take into account the response of LXe to ionisation
- Drift and extraction of ionisation electrons
- **Reconstruction effects**

The reconstruction effects are taken into account by folding the theoretical signal plus the LXe response with the

$$r_d(S2) = \sum_n \int \frac{dR}{dE} dE \sum_k P(k \,|\, n^{(1)}, n^{(2)}, f_e, f_R)\, \mathrm{Binom}(n \,|\, k, P_{\mathrm{drift}}(\tau_e) \times P_{\mathrm{extr}})\, \mathrm{Normal}(S2 \,|\, n\mu, \sqrt{n}\sigma)$$

$n^{(1)} + n^{(2)}$ quanta produced

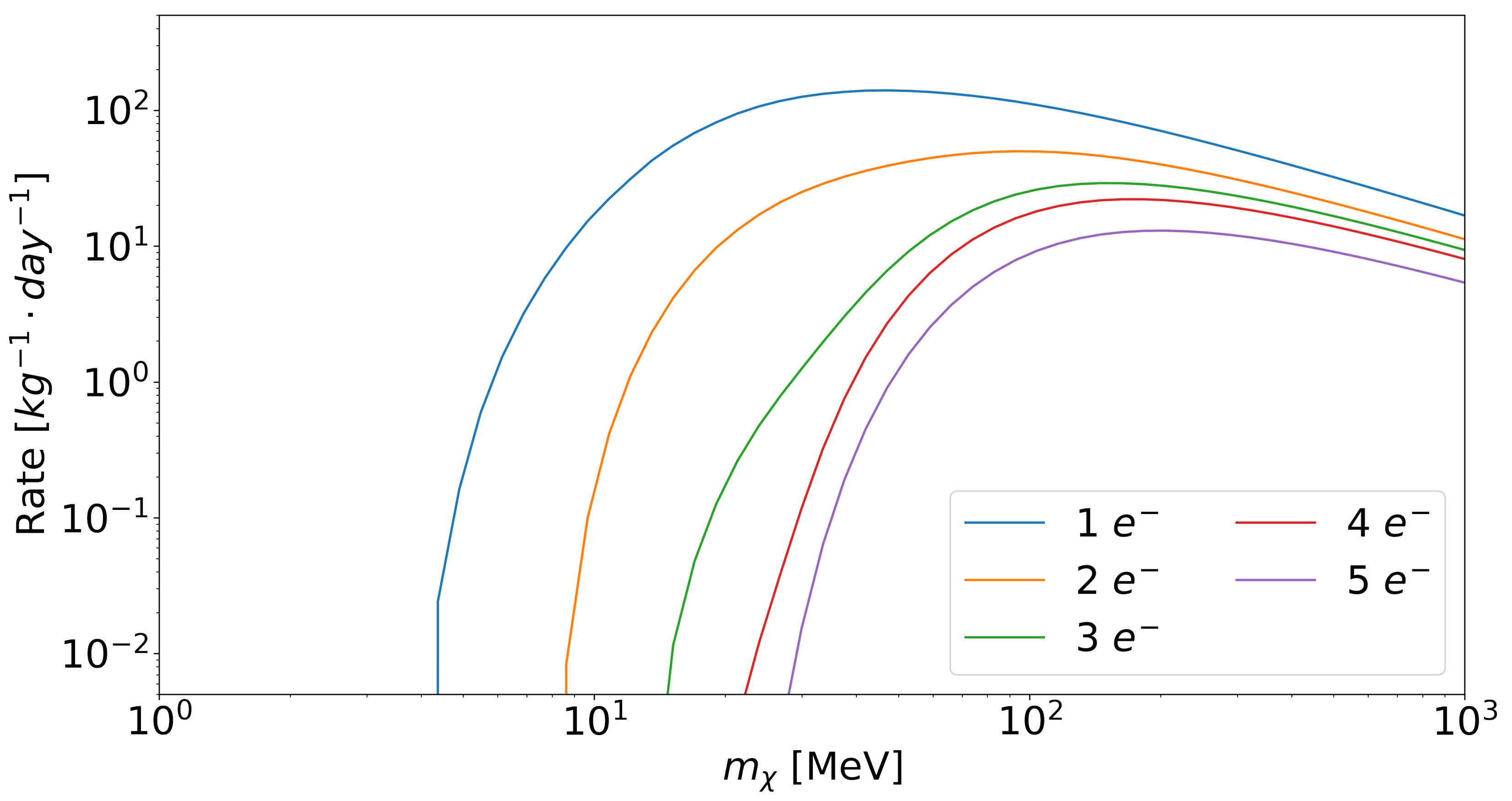
k ionisation electrons start drifting

n electrons producing S2 light

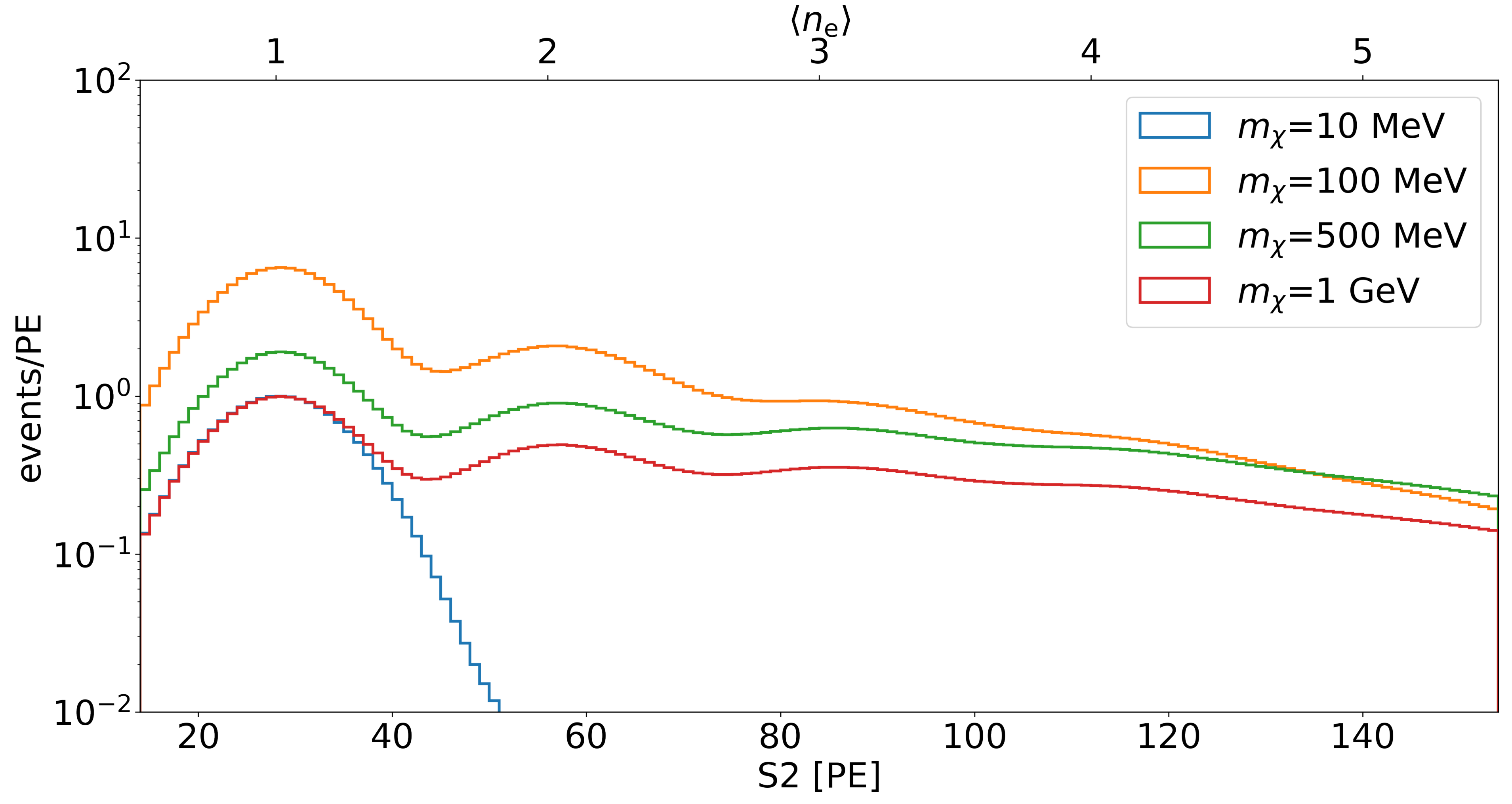
These are giving k electrons

n electrons are finally extracted

Few-electrons rate



Rate as a function of S2



Limit setting

- A limit setting with an incomplete background model, consists in considering that the totality of the unknown background is due to the signal and to constrain from above this signal, given the number of observed events.

- Since the background is unknown we are forced to set upper limits.

We set a limit in that value of σ_e for which the expected number of events does not exceed the s_{up} of the observed events at 90% C.L.

The upper limit for the unknown signal, s_{up}, at a C.L. α, is given from:

$$s_{up} = \frac{1}{2} F^{-1}_{\chi^2}\left(1 - \alpha, 2(n+1)\right)$$

Alternative method

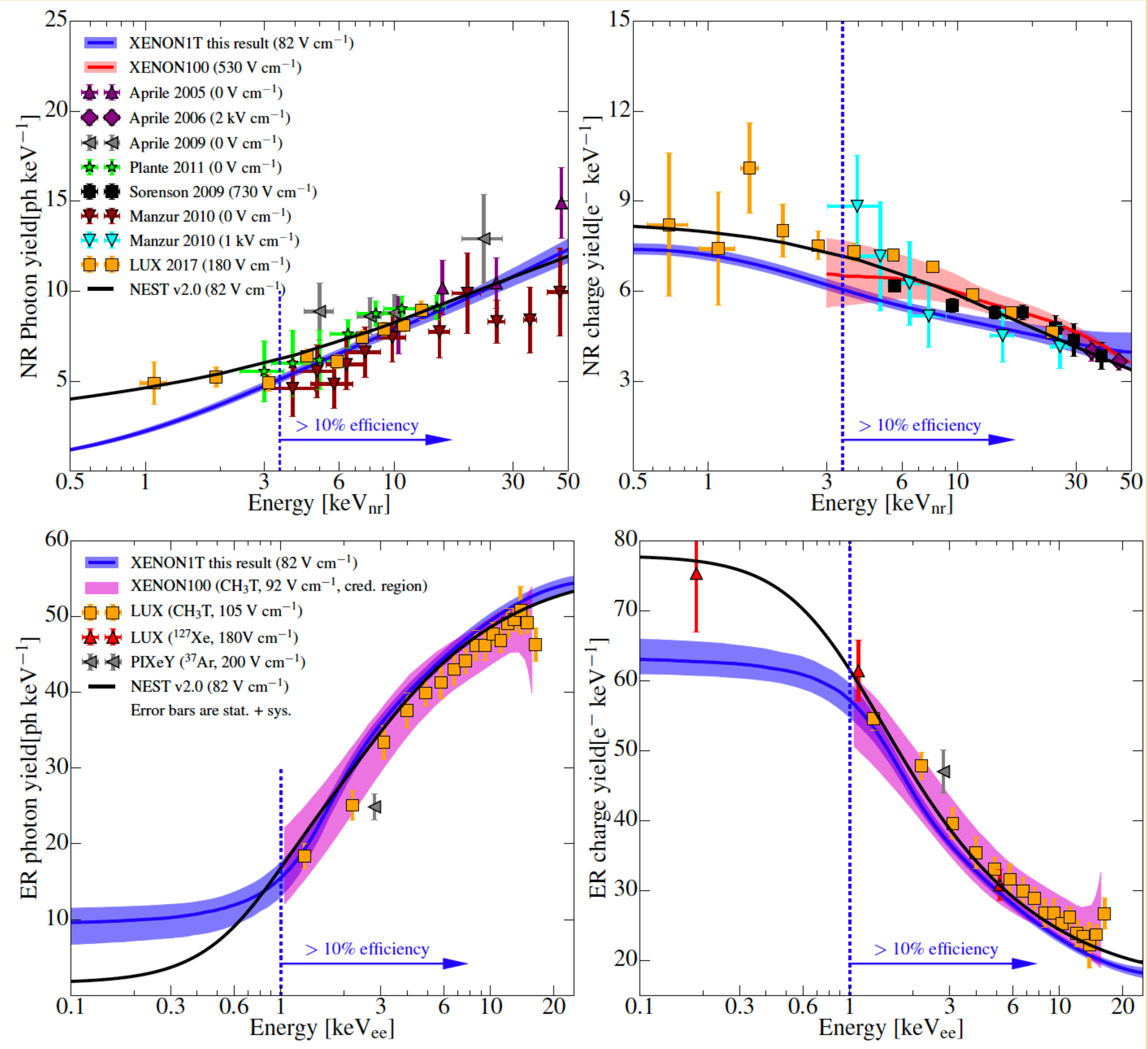
- Maximum-gap method
- Optimum interval

Conclusion

- We can use the sensitivity of the detector to small charge signals for the search of light DM interacting leptonically
- Large unmodeled background arises due to Single Electrons
- Empirical understanding of the SE background
- Conservative limit setting on physics models can be made

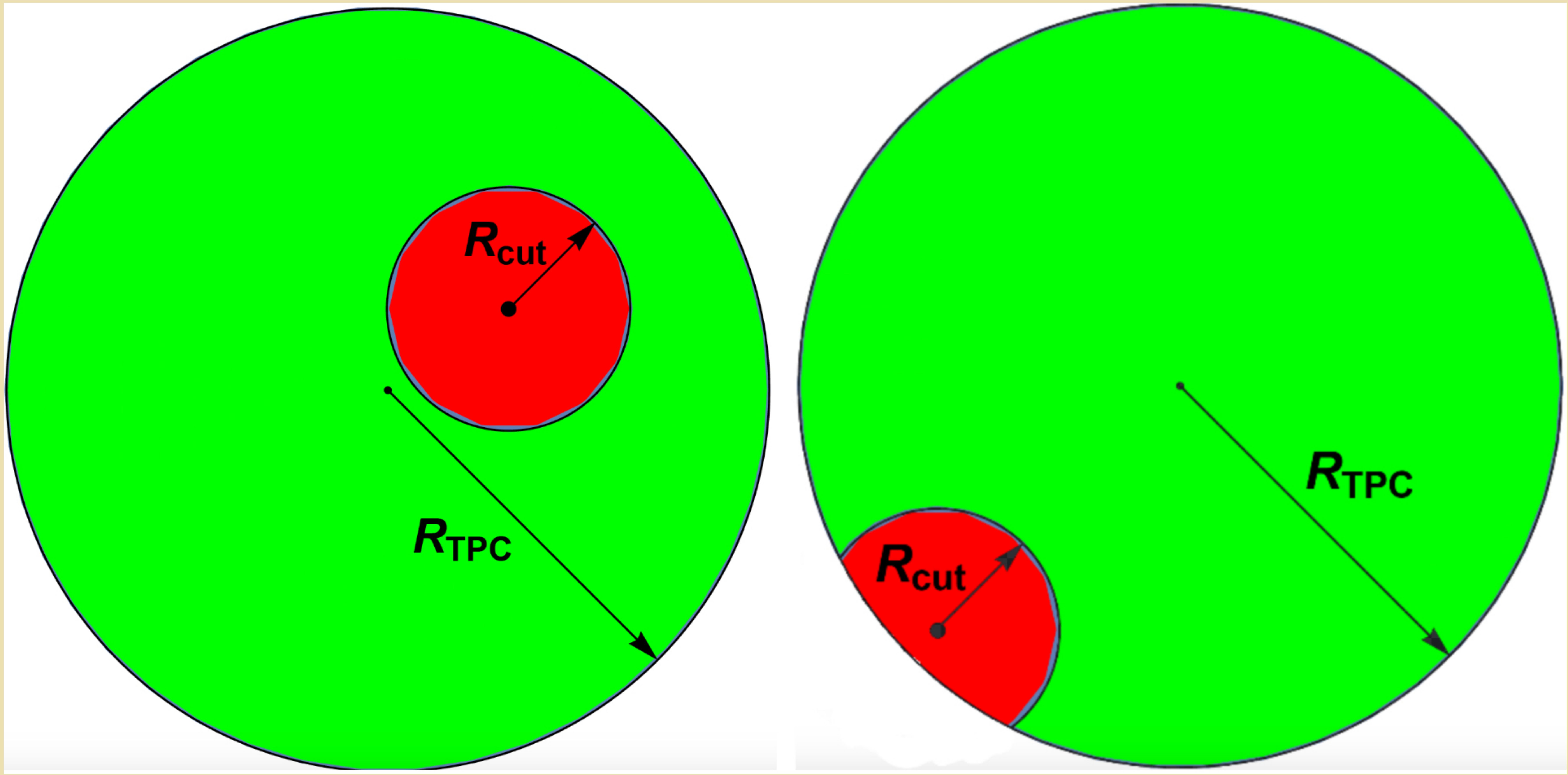
Large dual-phase liquid xenon detectors haven't reach the limit of their scientific potential for the search of light dark matter → R&D is needed to develop a background model for SE or to eliminate it in a hardware manner.

Backup Slides



ER and NR charge and light yield measurements

Sub-GeV Dark Matter



We must account for the fact that the exposure now is reduced, in the target mass part. Thus, we must carefully evaluate the fiducial volume that, in the presence of this cut, is limited in the exterior of the cylinder defined by $R_{S2} - R_{\text{cut}} < 15$ cm and -97 cm $< z < 0$ cm

Bosonic candidate for a light dark matter: Dark Photon

$$\mathscr{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

The Dark photon A' could constitute all the DM for sufficiently small kinetic mixing and $m_{A'}$ because the lifetime of the dark photon can be longer than the age of the Universe

$$\text{Rate} \simeq \frac{\rho_{DM}}{m_{A'}}\epsilon^2 \sigma_{PE}(E = m_{A'})$$

The dark photon could be absorbed as a massive non-relativistic particle with coupling $e\epsilon$ to electrons. The expected signal is monoenergetic with $E = m_{A'}$ and is a function of the photoelectric absorption cross section of the target atom

Another bosonic DM candidate: ALP

$$\mathscr{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + i g_{ae} a \bar{e} \gamma_5 e$$

Axion-like particle

ALPs could obtain the correct relic density in a wide mass range, via the misalignment mechanism, or by thermal or non-thermal production. In direct detection ALPs are constrained without assuming a particular production mechanism (Bloch, I.M. *et. al.*, J. High Energ. Phys. 2017, 87 (2017))

$$\text{Rate} \simeq \frac{1.5 \times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{keV}\right) \left(\frac{\sigma_{PE}(E = m_a)}{b}\right) \text{kg}^{-1}\text{d}^{-1}$$

The ALP interaction with electrons is responsible for the “axioelectric” effect. Axions may be absorbed by bound electrons, of the target atom resulting in a monoenergetic signal with energy $E = m_a$

Sub-GeV Dark Matter

A possible combination with the annual modulation analysis

- A possible discriminant between signal and background could be the annual modulation

- If f_{mod} is the expected is the modulation amplitude, the significance of a signal S over a flat background B is $sig = f_{mod} S/\sqrt{S+B}$

- If we require the significance of the annual modulation signal to be less than sig then the corresponding fraction that could produce a significance larger than sig **should be accounted to the background**, resulting in a new limit:

$$\sigma_{mod} = \frac{sig \times \sigma_e}{f_{mod}\sqrt{R \times exposure}}$$

R is the event rate and σ_e the limit without taking account of the annual modulation