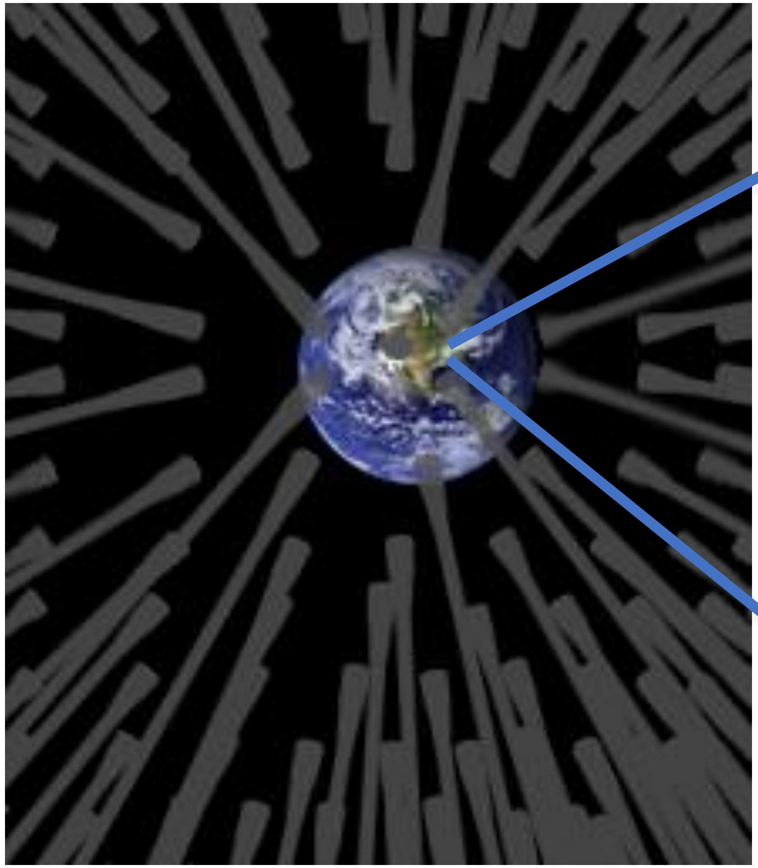
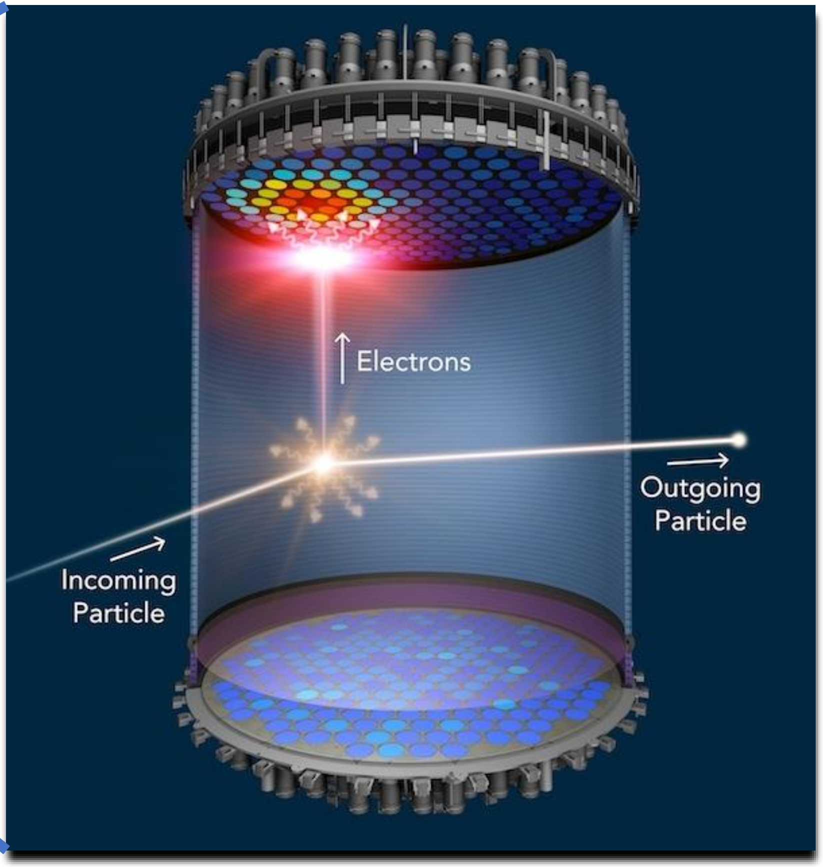
Dark Matter Direct Searches

COST Advanced School on Physics of Dark Matter and Hidden Sectors

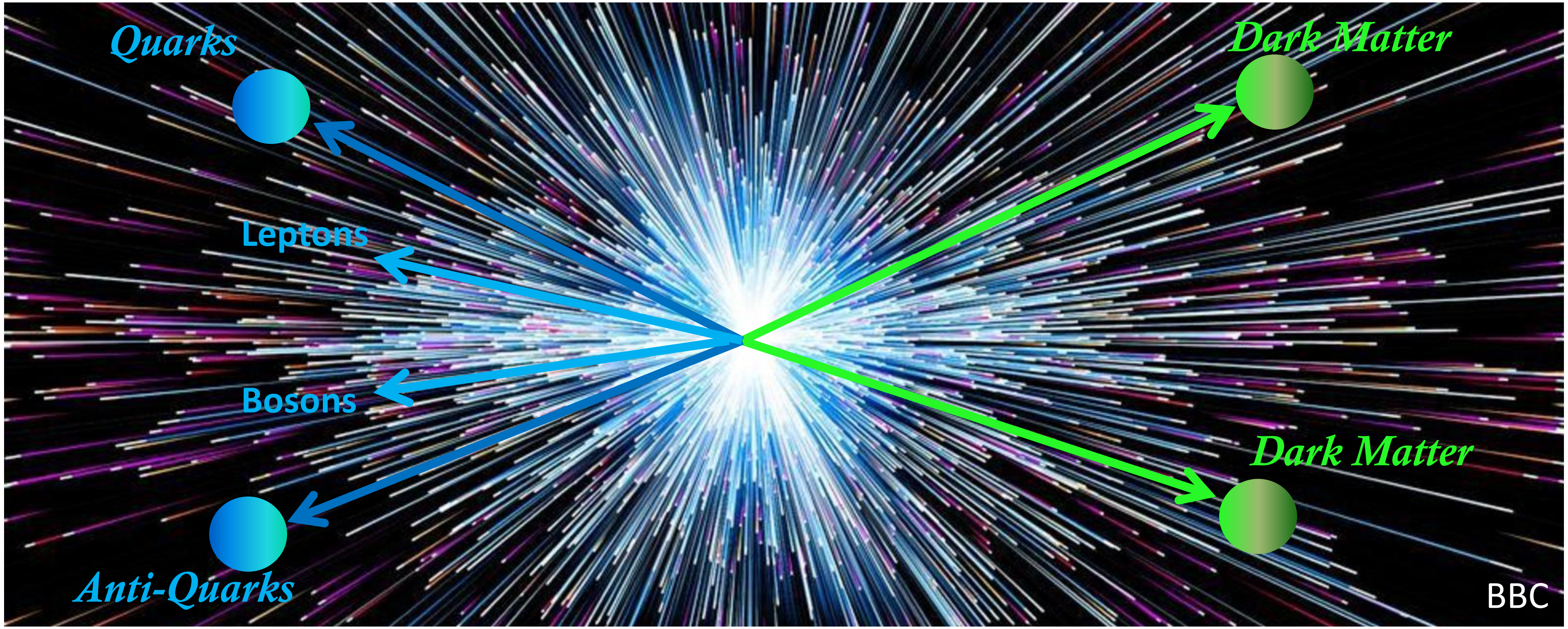
October 19, 2021

Sergey Burdin (University of Liverpool)



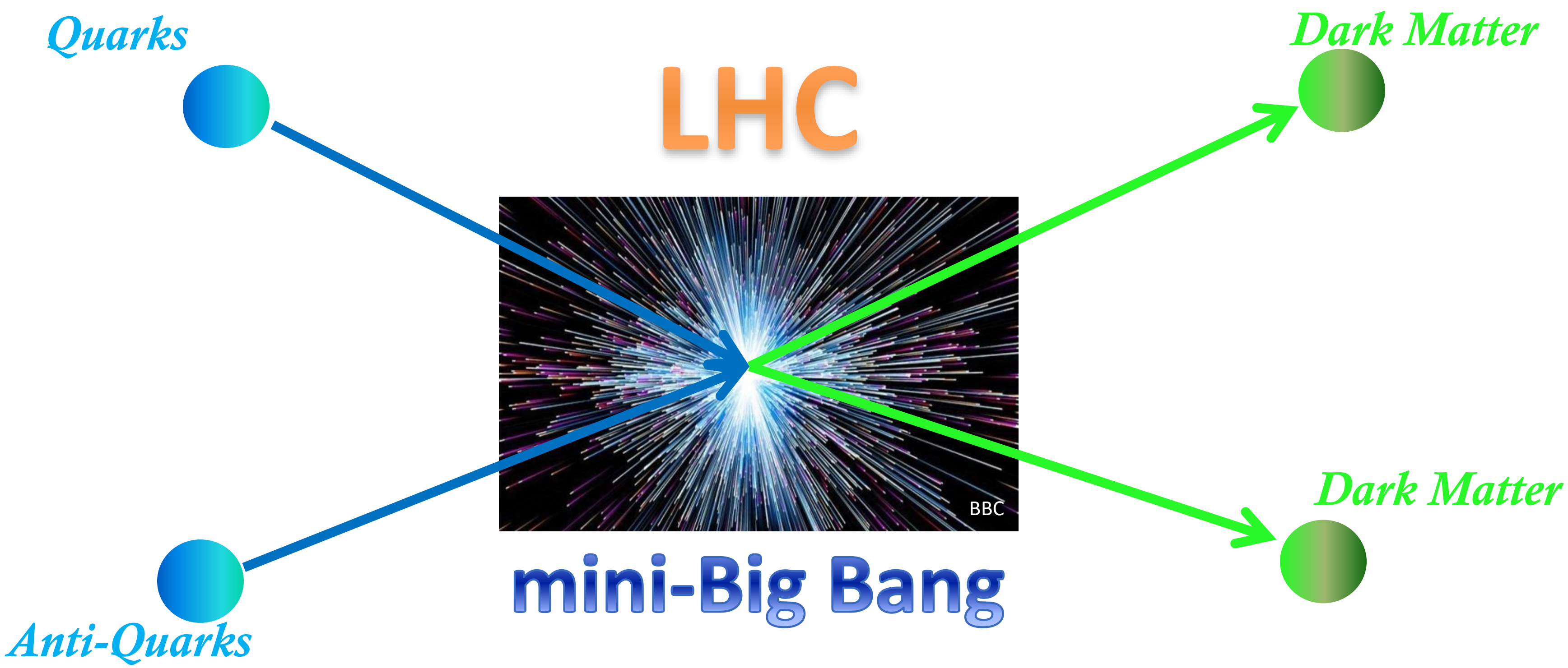


Big Bang!



Quarks
Leptons
Bosons
Anti-Quarks
Dark Matter
Dark Matter
BBC

Collider Dark Matter Searches



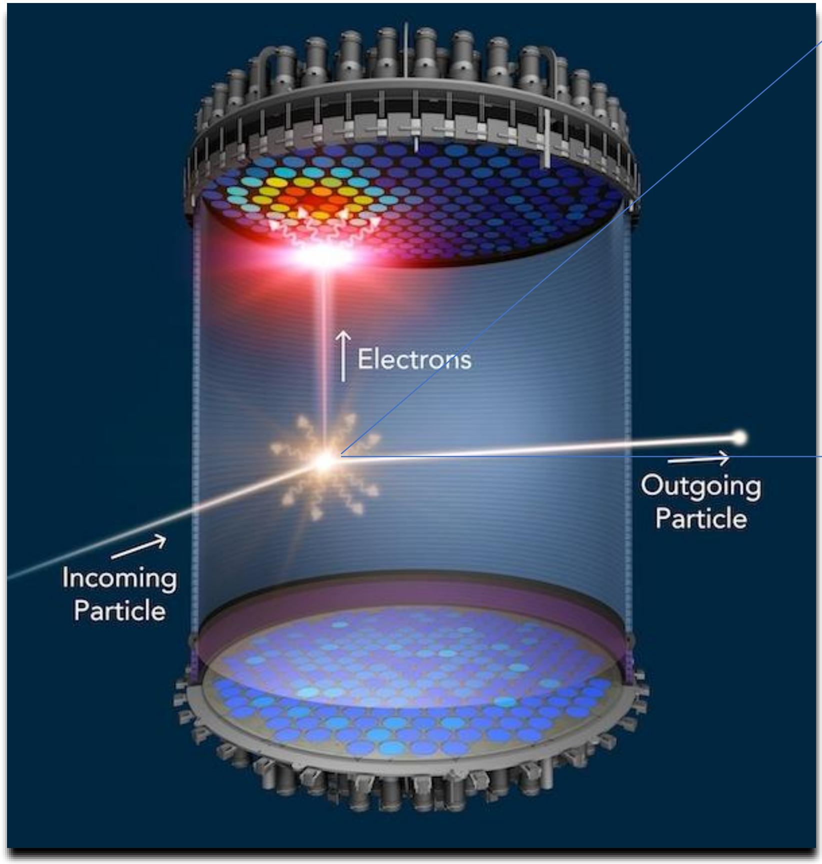
Standard Matter to Dark Matter annihilation

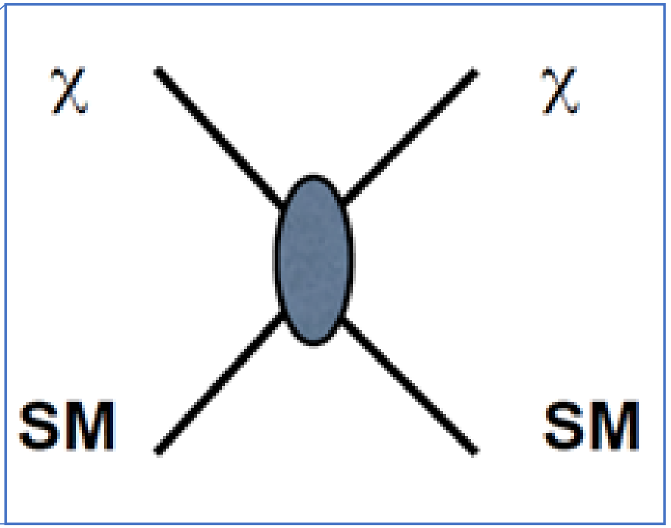
s-channel

Disclaimer: signatures @LHC could be much more complex

Direct Dark Matter searches = searches for interactions of DM particles with SM particles

- Simplest model of interactions considers elastic interactions of “Weakly” Interacting Massive Particles (WIMPs) with nuclei





scattering

t-channel

This Presentation

- **Is not** a review of recent experimental results on direct Dark Matter searches
  - See “Direct detection of dark matter (experimental review)” by Marc Schumann at TAUP 2021 (https://indico.ific.uv.es/event/6178/timetable/#20210831)
  - Also “Direct Detection of WIMP Dark Matter: Concepts and Status” by Marc Schumann (arXiv:1903.03026)

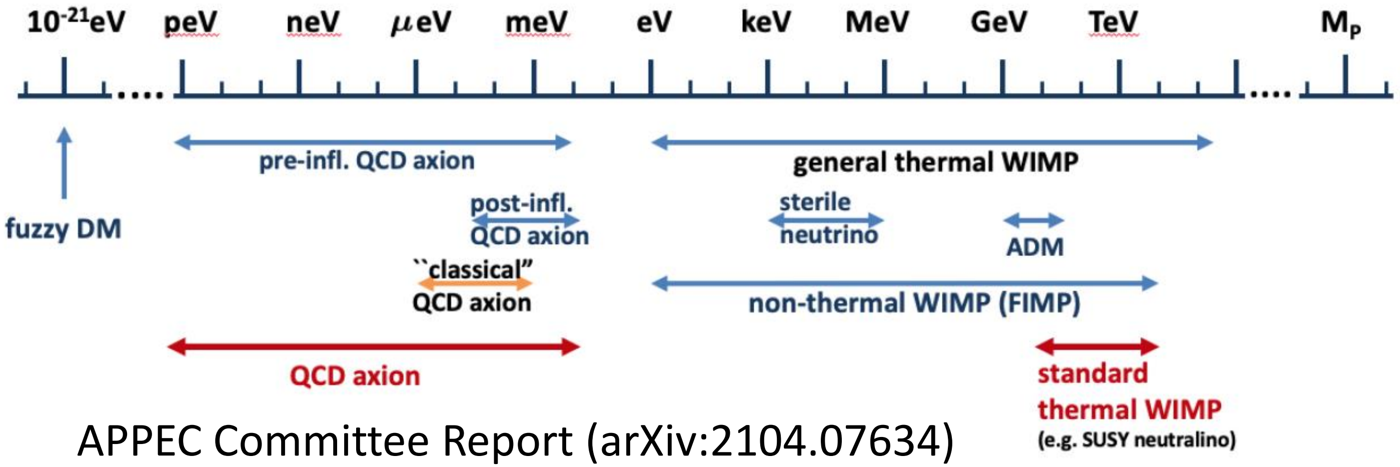
- **Is not** a status report on any particular experiment
  - See experimental presentations at TAUP 2021 or LIDINE 2021

- **Is** a discussion of experimental and analysis techniques supported by illustrations from some recent and current experiments

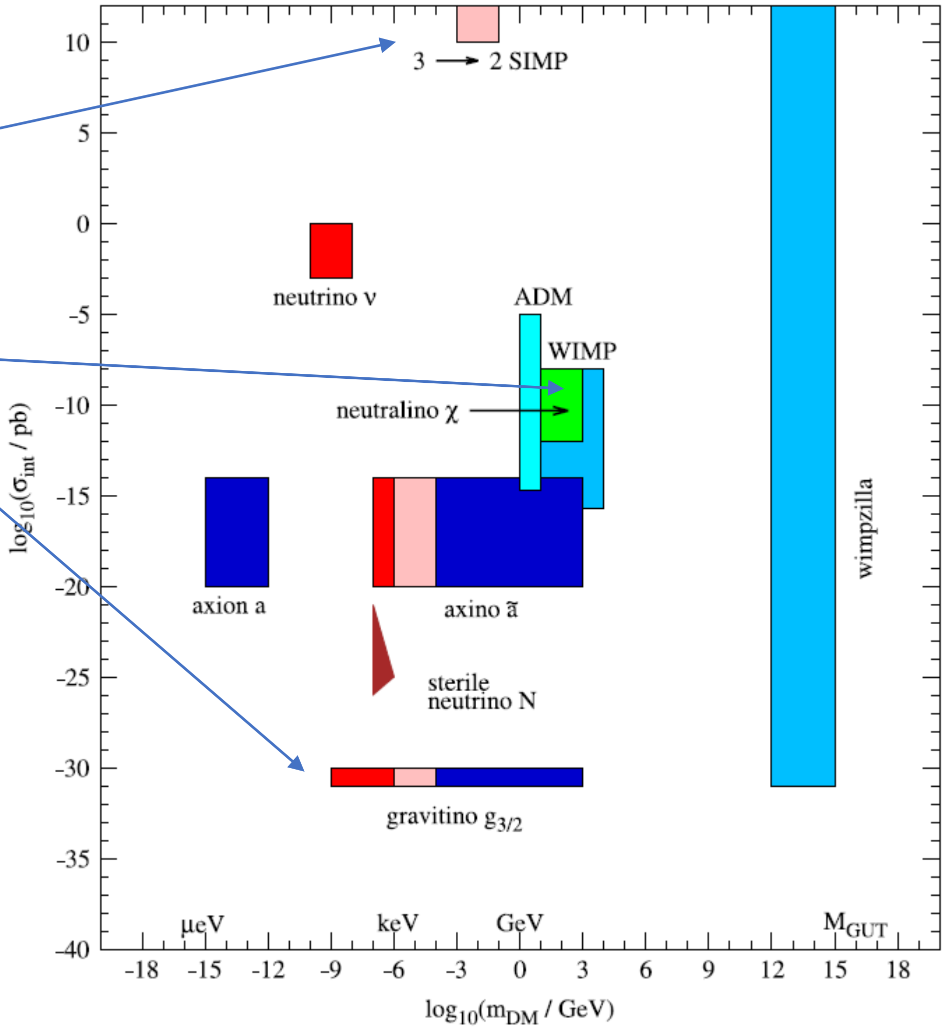
- **Is** limited to a WIMP paradigm only and Spin-Independent interactions interpretation

DM Properties

- Mass unknown
- Interactions feeble (with possibilities of some exceptions) or very feeble (gravitational scale)
  - Some arguments in favour of weak scale
- See theory review by Maxim Pospelov @TAUP2021



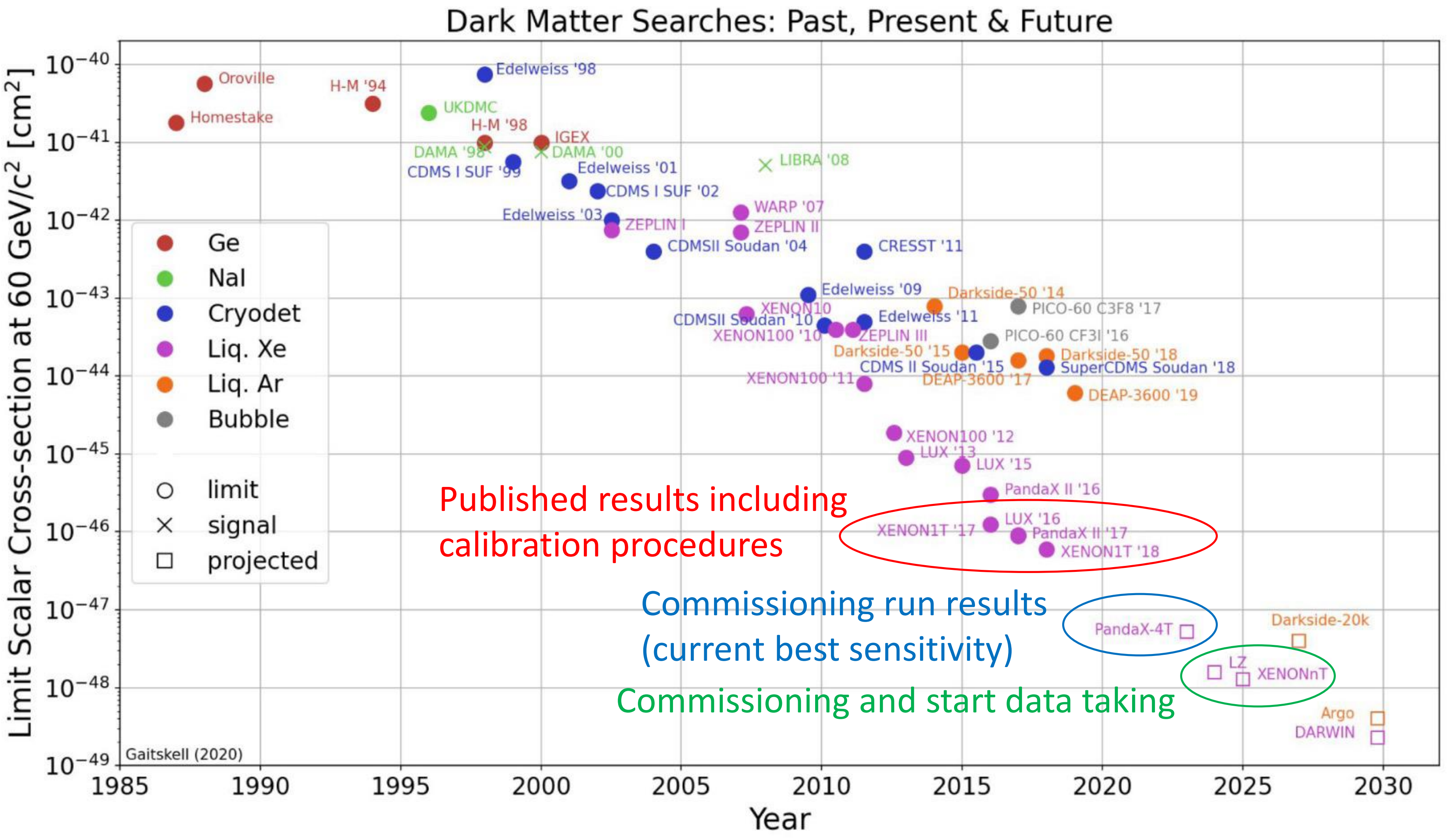
APPEC Committee Report (arXiv:2104.07634)



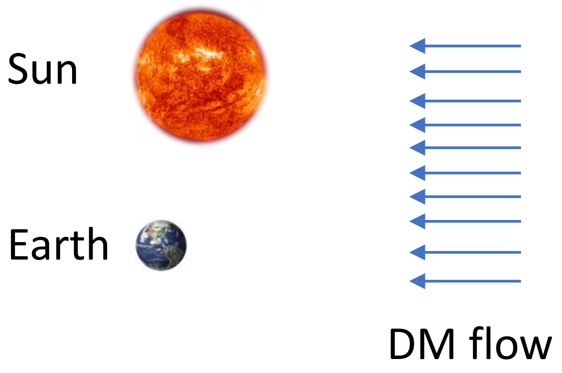
H. Baer et al. / Physics Reports 555 (2015) 1–60

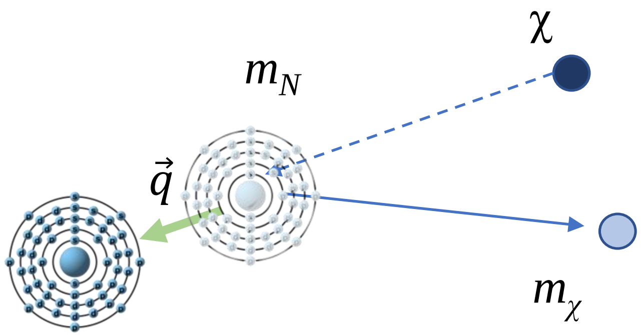
Experimental Techniques

- Liquid Xenon double-phase experiments (LUX/LZ, XENON, Panda) are leading DM searches in WIMP region
- This technique will be used as an example



Elastic Scattering Kinematics





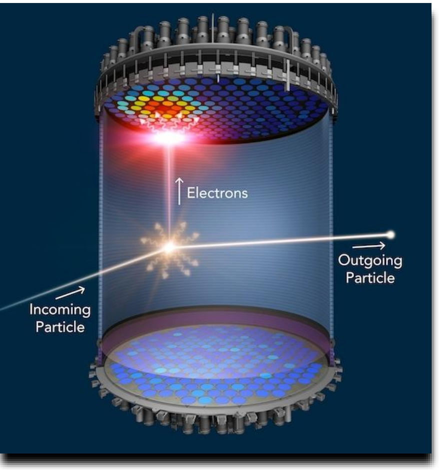
- The simplest approximation is an elastic scattering on a nucleus
  - Momentum transfer
    $|\vec{q}|^2 = 2\mu^2 v^2(1 - \cos\theta)$, where v is the DM particle velocity, θ is the scattering angle and $\mu = \frac{m_\chi m_N}{m_\chi + m_N}$ is reduced mass, where m_χ and m_N are dark matter and target nucleus masses.
  - Target atom (nucleus) recoil energy:

$$E_{NR} = \frac{|\vec{q}|^2}{2m_N}$$

Maximum recoil energy $E_{NR}^{max} = \frac{2\mu^2 v^2}{m_N}$

Event Rate

$$\frac{dR}{dE_{\rm nr}} = \frac{\rho_0 M}{m_N m_\chi}\int_{v_{\rm min}}^{v_{\rm esc}} v f(v) \frac{d\sigma}{dE_{\rm nr}}\, dv$$



- Detector parameters:
  - M – detector mass
  - m_N – detector material (mass of a nucleus of detector target material)
  - v_{min} – minimum detectable velocity of a DM particle (depends on a minimum detectable energy in the detector)

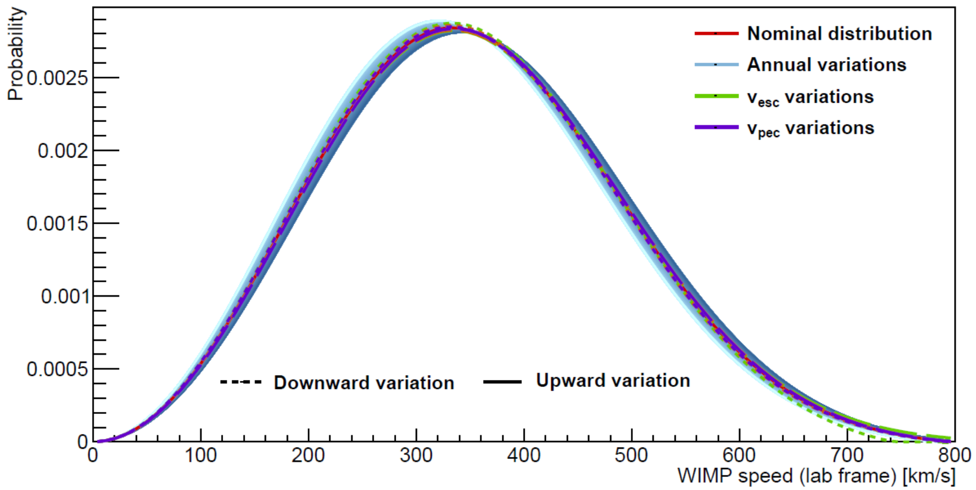
- DM model parameters:
  - ρ_0 – DM local density (0.3 GeV/c^2/cm^3 accepted)
  - m_χ – mass of DM particle (scan of a mass range)
  - $f(v)$ – DM velocity distribution
  - v_{esc} – escape velocity of a DM particle (544 km/s accepted)
  - $\frac{d\sigma}{dE_{nr}}$ – differential cross section of DM interactions with SM

Expected Number of DM Events in a detector

$$N = T \int_{E_{\rm low}}^{E_{\rm high}} dE_{\rm nr}\ \epsilon(E_{\rm nr})\ \frac{dR}{dE_{\rm nr}}$$

- T – exposure time
- $E_{high} = \frac{2\mu^2 v_{max}^2}{m_N}$ – maximum recoil energy
- $\epsilon(E_{nr})$ – detector efficiency
- E_{low} – energy threshold determined by detector efficiency and noise
  - determines minimum detectable velocity of a DM particle (not as useful as it is in the lab-frame)
  - **or a minimum detectable mass of a DM particle**

Velocity Model



$$f(\vec{v}_{\rm gal}) \propto \frac{\rho_\chi}{m_\chi} e^{-\frac{1}{2}|\vec{v}_{\rm gal}|^2/\sigma_0^2}\Theta(v_{\rm esc} - |\vec{v}_{\rm gal}|),$$

$$\vec{v}_{\rm gal} = \vec{v}_{\rm lab} + (\vec{v}_0 + \vec{v}_\circledast + \vec{v}_\oplus(t)),$$

arXiv:2105.00599

- $\vec{v}_{lab}$ – lab-frame DM velocity
- $\sigma_0 = {|\vec{v}_0|}/{\sqrt{2}}$ – velocity dispersion

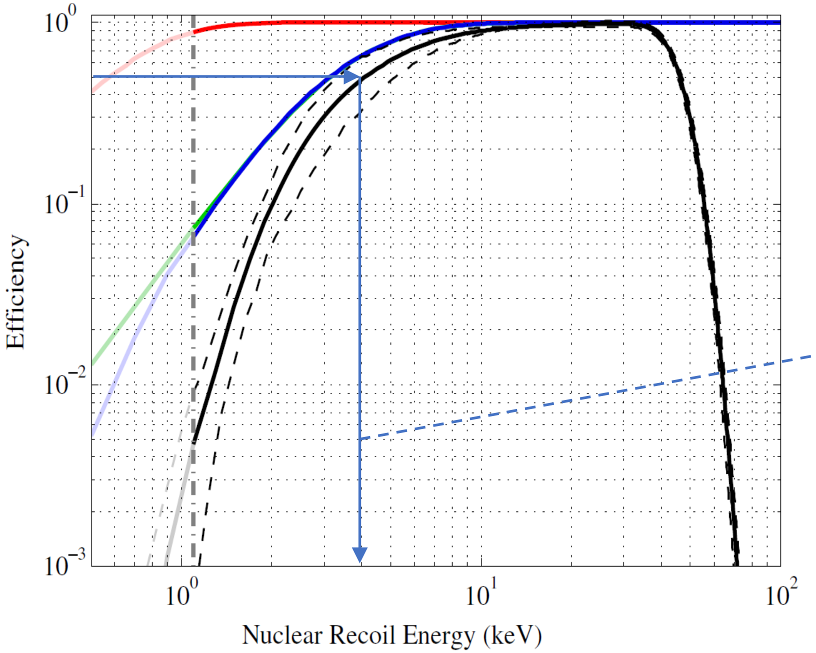
	Parameter	Value
	ρ_χ	$0.3\,\mathrm{GeV}/\mathrm{c}^2/\mathrm{cm}^3$
	$v_{\rm esc}$	$544\,\mathrm{km/s}$
Earth's velocity relative to the Sun	$\langle\lvert\vec{v}_\oplus\rvert\rangle$	$29.8\,\mathrm{km/s}$
Sun's peculiar velocity	$\vec{v}_\circledast$	$(11.1, 12.2, 7.3)\ \mathrm{km/s}$
Milky Way's rotation	$\vec{v}_0$	$(0, 238, 0)\ \mathrm{km/s}$

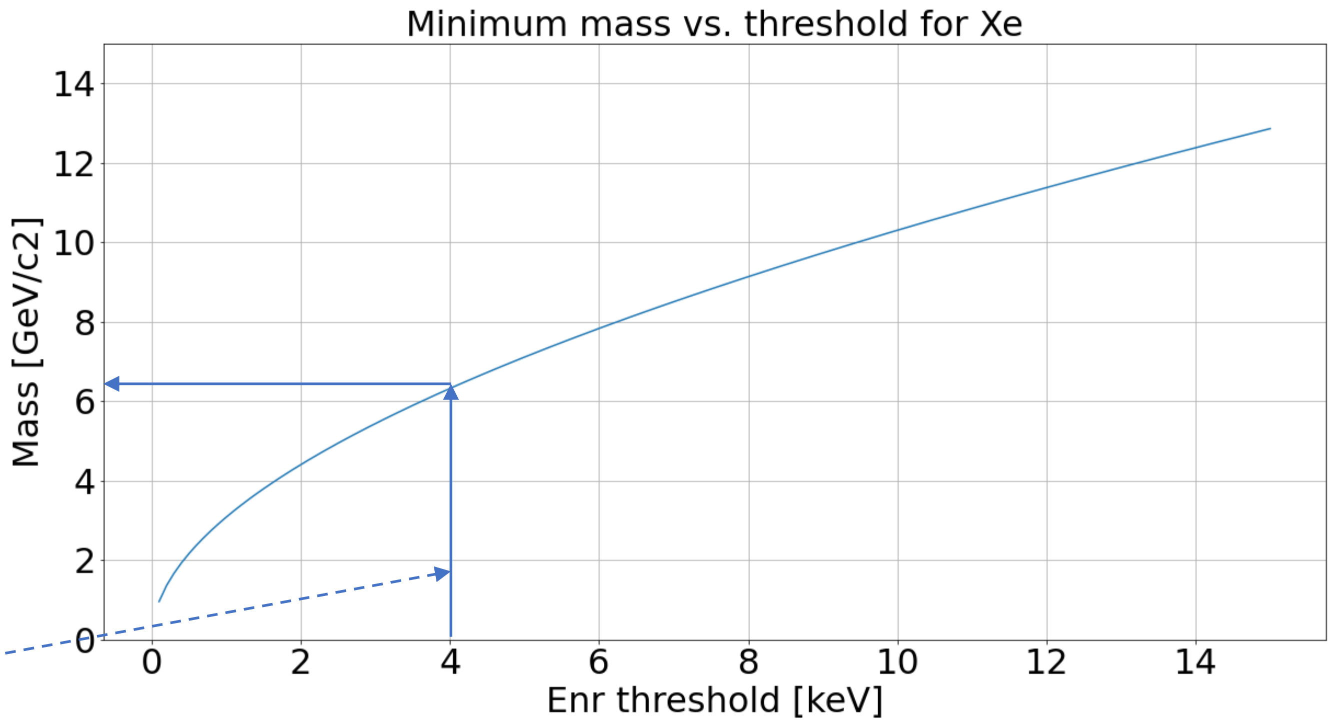
Minimum Detectable DM mass

$v_{max}^{lab} \sim v_{esc} + v_0 \sim 780\ km/s$

- $\boldsymbol{m_\chi^{min} = \dfrac{m_N}{\sqrt{\dfrac{2m_N}{E_{NR}^{Thr}} v_{max}^{lab} - 1}}}$

$\epsilon(E_{nr})$





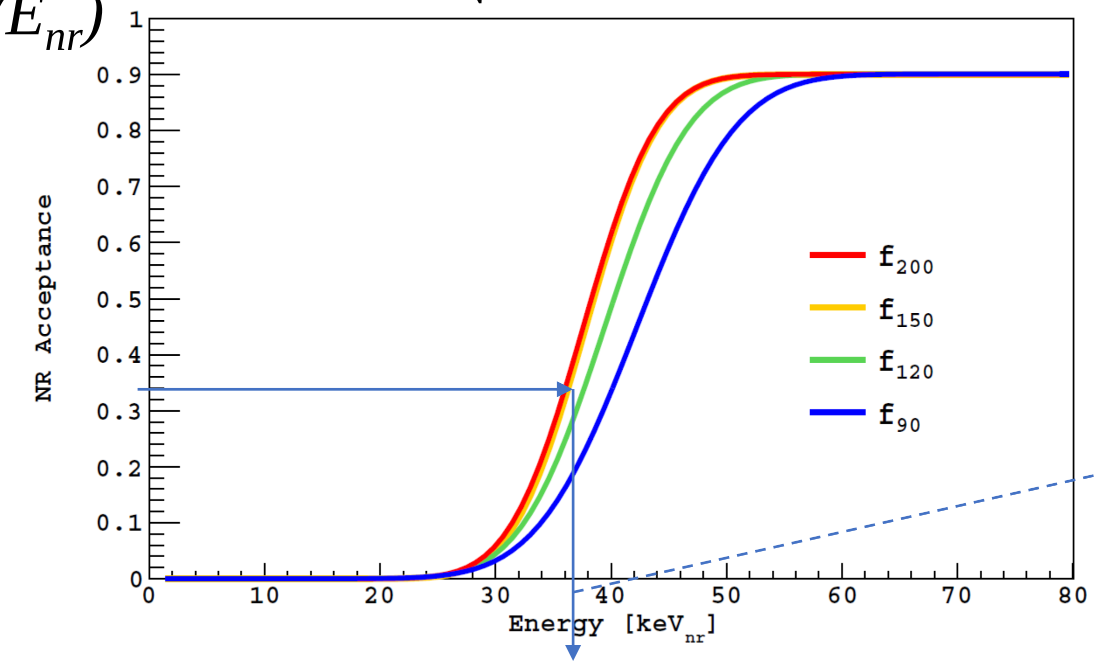
LUX efficiency from PRL 118, 021303 (2017)

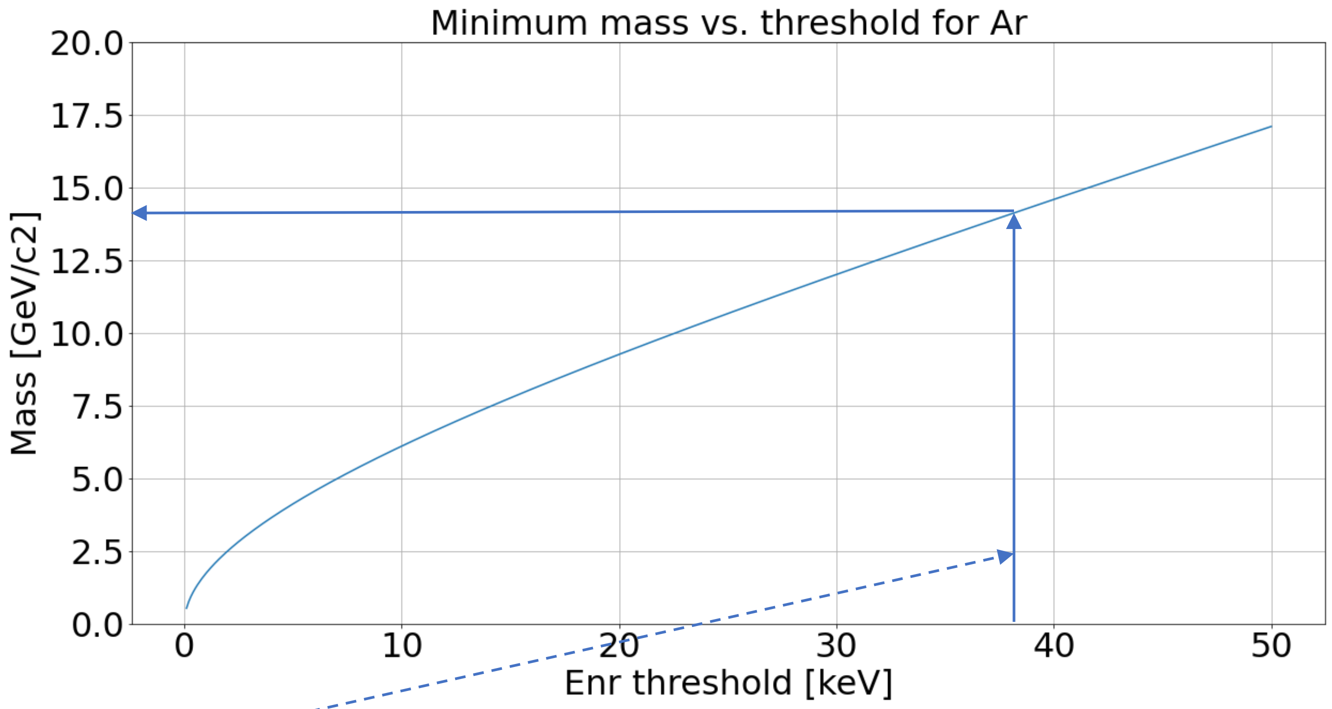
Minimum Detectable DM mass

$v_{max}^{lab} \sim v_{esc} + v_0 \sim 780\ km/s$

- $$m_\chi^{min} = \frac{m_N}{\sqrt{\frac{2m_N}{E_{NR}^{Thr}} v_{max}^{lab}} - 1}$$

$\epsilon(E_{nr})$



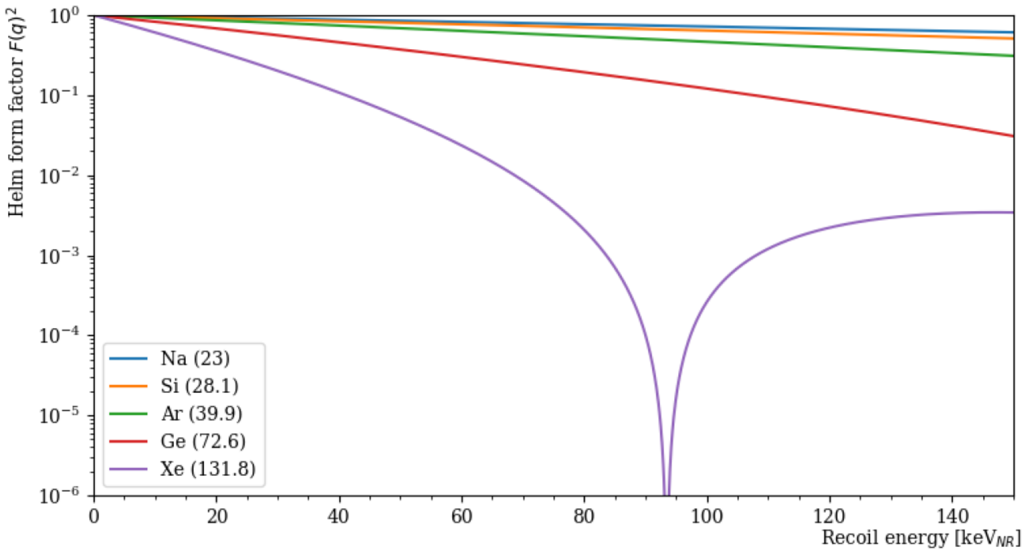


DarkSide-20k efficiency from Eur. Phys. J. Plus (2018) 133: 131

Interaction cross-section

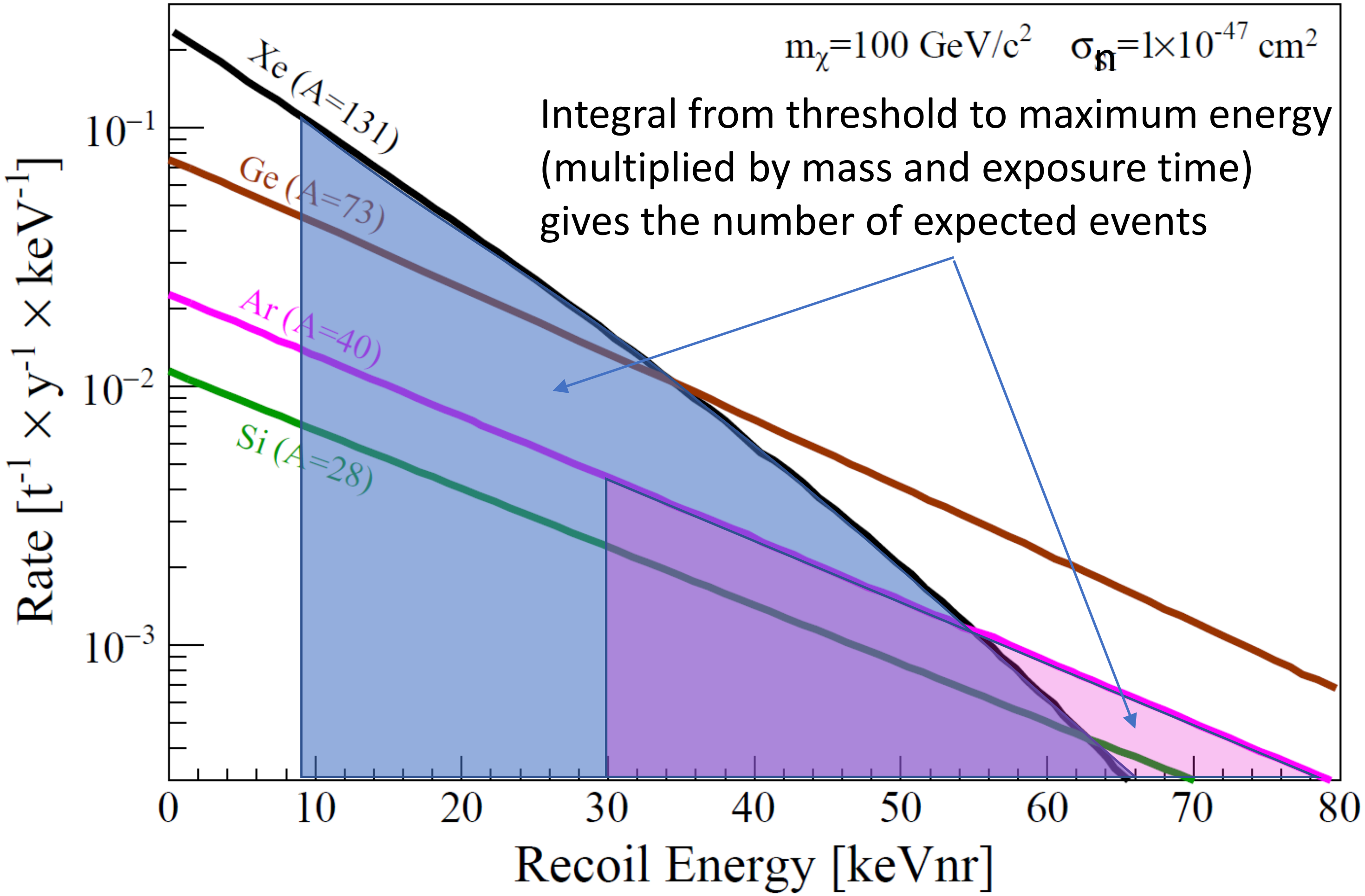
$$\frac{d\sigma}{dE_{\rm nr}} = \frac{m_N}{2v^2\mu^2}\left(\sigma_{SI}F^2_{SI}(E_{\rm nr}) + \sigma_{SD}F^2_{SD}(E_{\rm nr})\right)$$

- σ_{SI} – spin-independent cross-section
  - Coherent interaction with entire nucleus (cf. de Broglie wavelength of 100GeV WIMP $\lambda=h/(mv)\sim 17$fm with the size of a nucleus)
  - Higher momenta → smaller λ → loss of coherence taken into account by $F_{SI}(E_{nr})$
  - $\sigma_{SI} = \sigma_n \frac{\mu}{\mu_n} A^2$ where $\boldsymbol{\sigma_n}$ **– spin-independent WIMP-nucleon cross-section**, μ_n – reduced WIMP-nucleon mass, *A* – atomic number
    - $\boldsymbol{\sigma_n}$ **is used to compare results of different experiments**

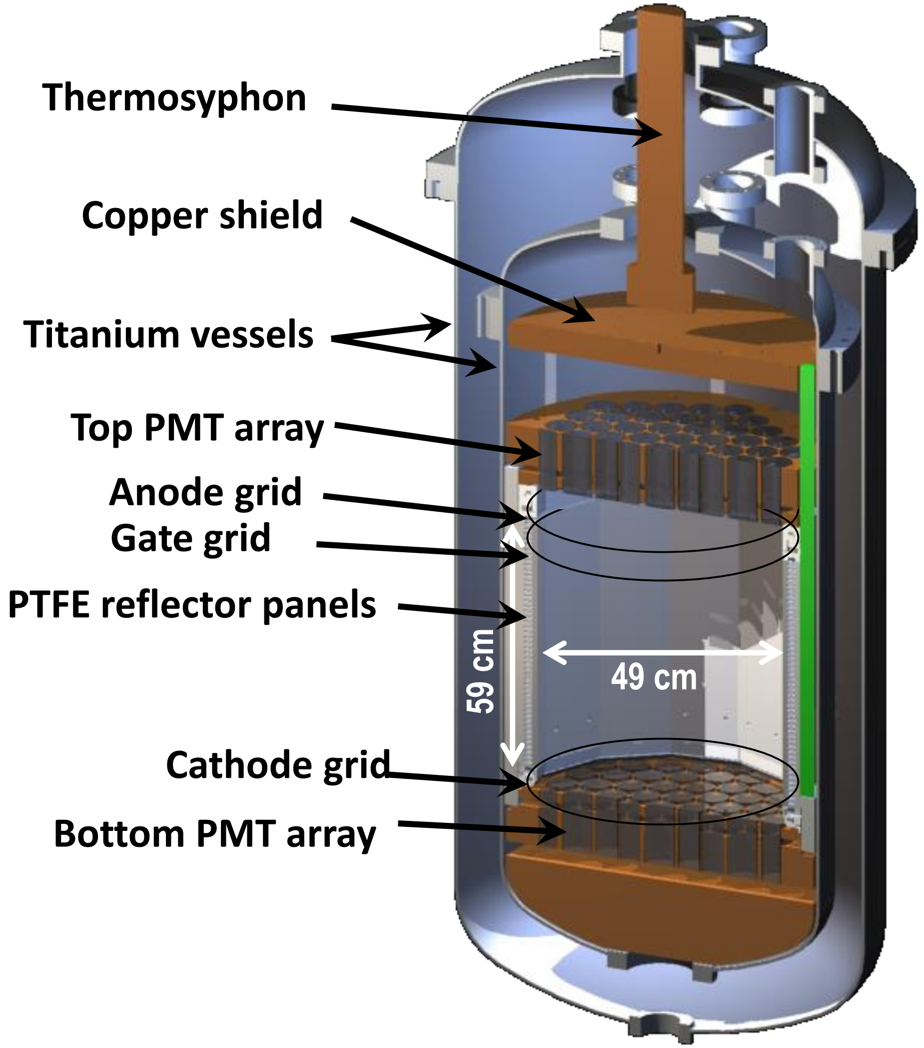


Rate in different target materials

- Xe is enhanced by A^2 dependence
- Rate for Xe starts to be affected by form-factor at high momentum transfers



Dual-phase Liquid Xenon Time Projection Chamber

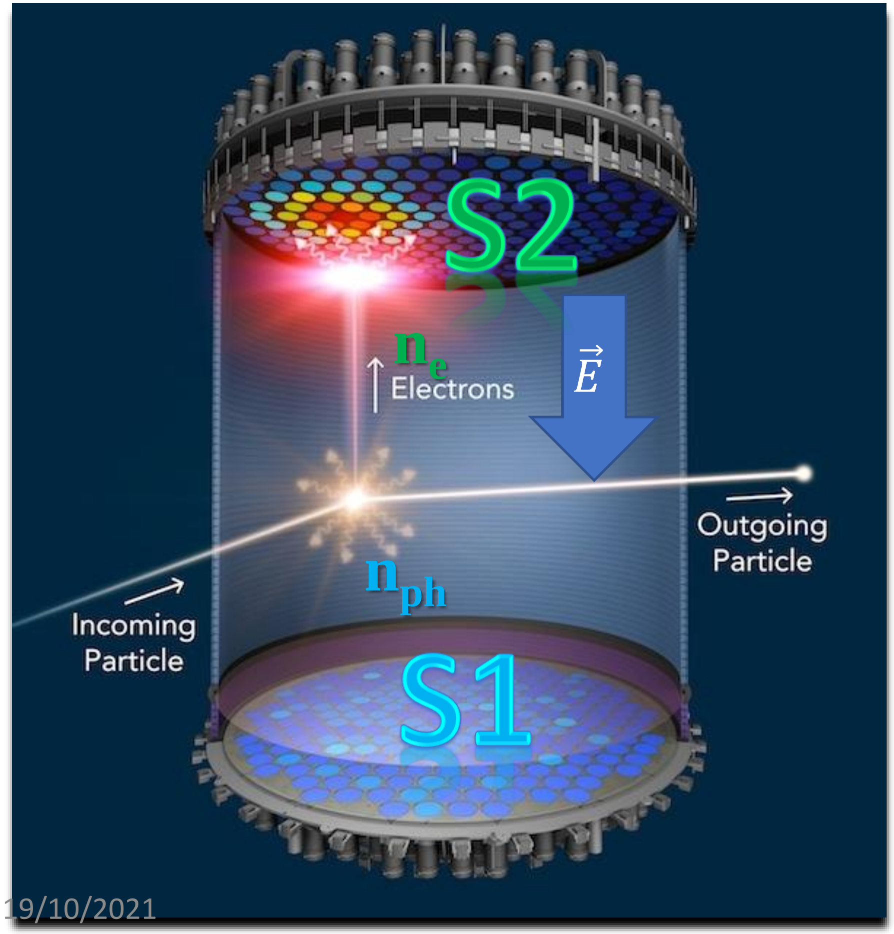


- LUX example
  - 61 top + 61 bottom ultra-low background PMTs
  - 370 kg of liquid xenon
    - 250 kg in the active region
    - 120 kg fiducial.
  - **Placed in the visitors' center in Lead (SD, USA)**

Interactions in Liquid Xenon TPC

- **Particle interaction → ionisation (n_e) + scintillation (n_{ph}) + heat (not detected)**

  $Xe^+ + e^-$ Xe^* $\hbar\omega$



Scintillation: $Xe^* \xrightarrow{+Xe} Xe_2^* \rightarrow 2Xe + h\nu$ → 178nm

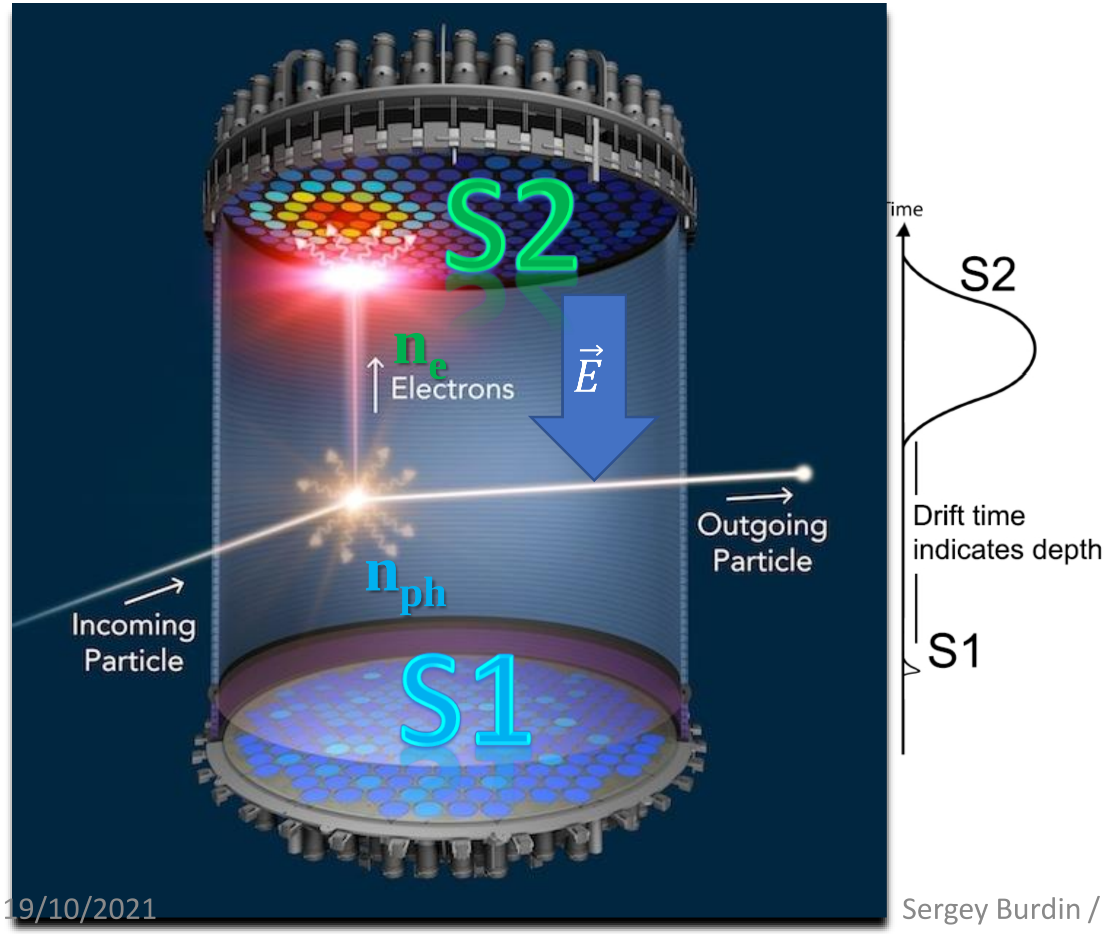
- Singlet (4ns)
- Triplet (22ns)

Ionisation: Xe^+ and e^- are pulled apart by electric field E or recombine producing scintillation photons

$$Xe^+ \xrightarrow{+2Xe} Xe_2^+ + Xe \xrightarrow{+e^-} 2Xe + Xe^{**} \rightarrow 2Xe + Xe^* + \hbar\omega \xrightarrow{+Xe} 4Xe + h\nu$$

Heat and recombination fractions are higher for nuclear recoils → lower total output of n_e and n_{ph} and lower relative output of n_e. The later is used for discrimination of nuclear recoils from electron recoils

S1 & S2 signals



- Scintillation photons n_{ph} are detected immediately after interaction by top and bottom PMT arrays though more light could be detected by the bottom PMT arrays due to internal reflection in LXe

→S1 ~ n_{ph}

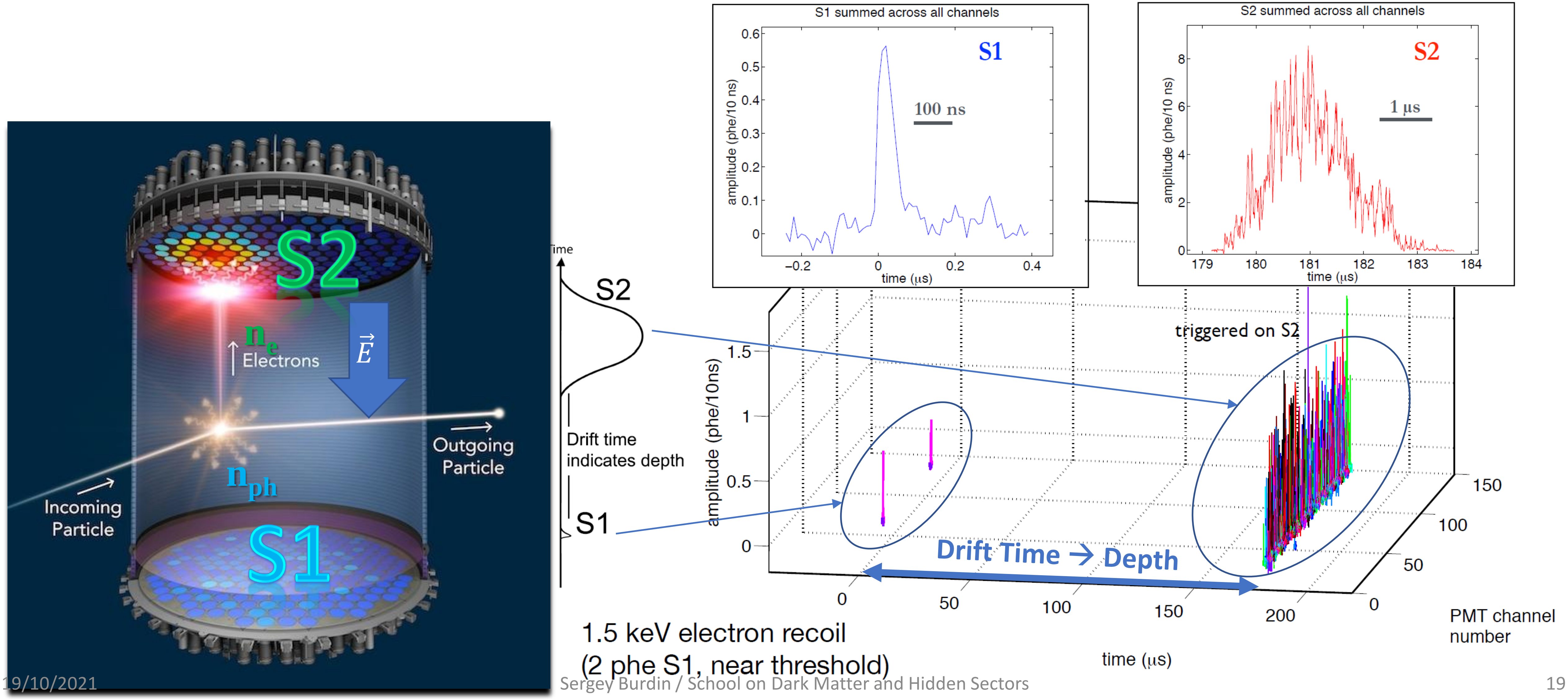
  - PHD - number of detected photons ≠ PHE as 178nm photons can produce double photoelectrons

- Ionisation electrons n_e drift up (drift velocity 0.15 cm/μs @ LUX) and produce scintillation light after extraction from liquid xenon and acceleration/amplification in the gaseous region

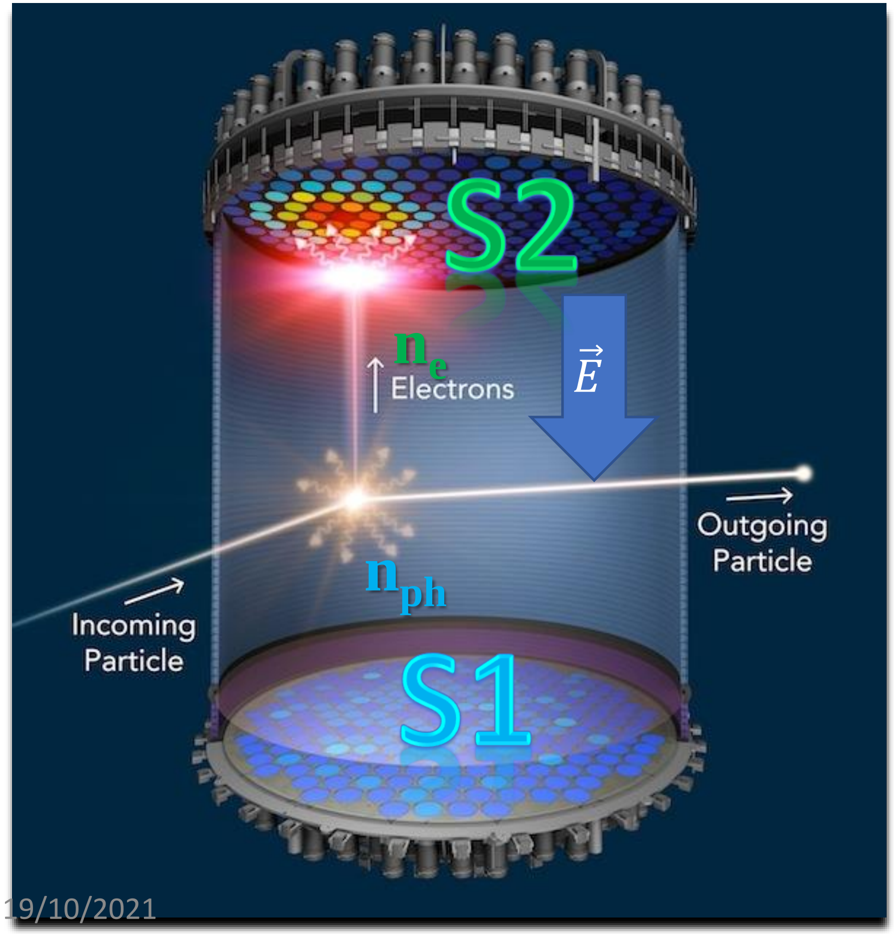
→S2 ~ n_e

  - Pattern in the top PMT array → x, y coordinates
  - Drift time → z coordinate
  - Resolution ~ mm

An example of LUX event



Energy Reconstruction

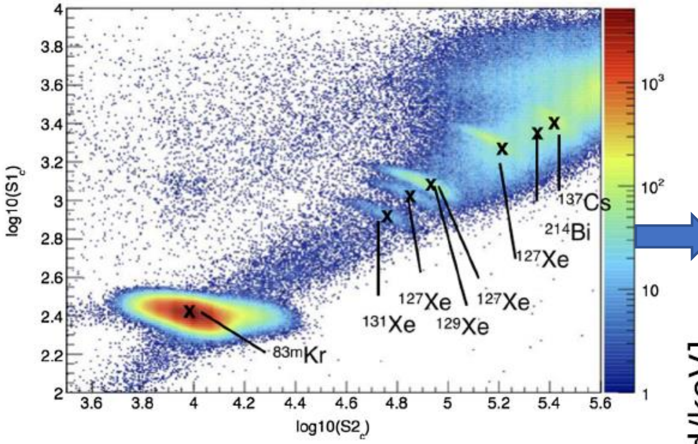


$$E_{ee} = W(n_{ph} + n_e) = W\left(\frac{S1c}{g_1} + \frac{S2c}{g_2}\right)$$

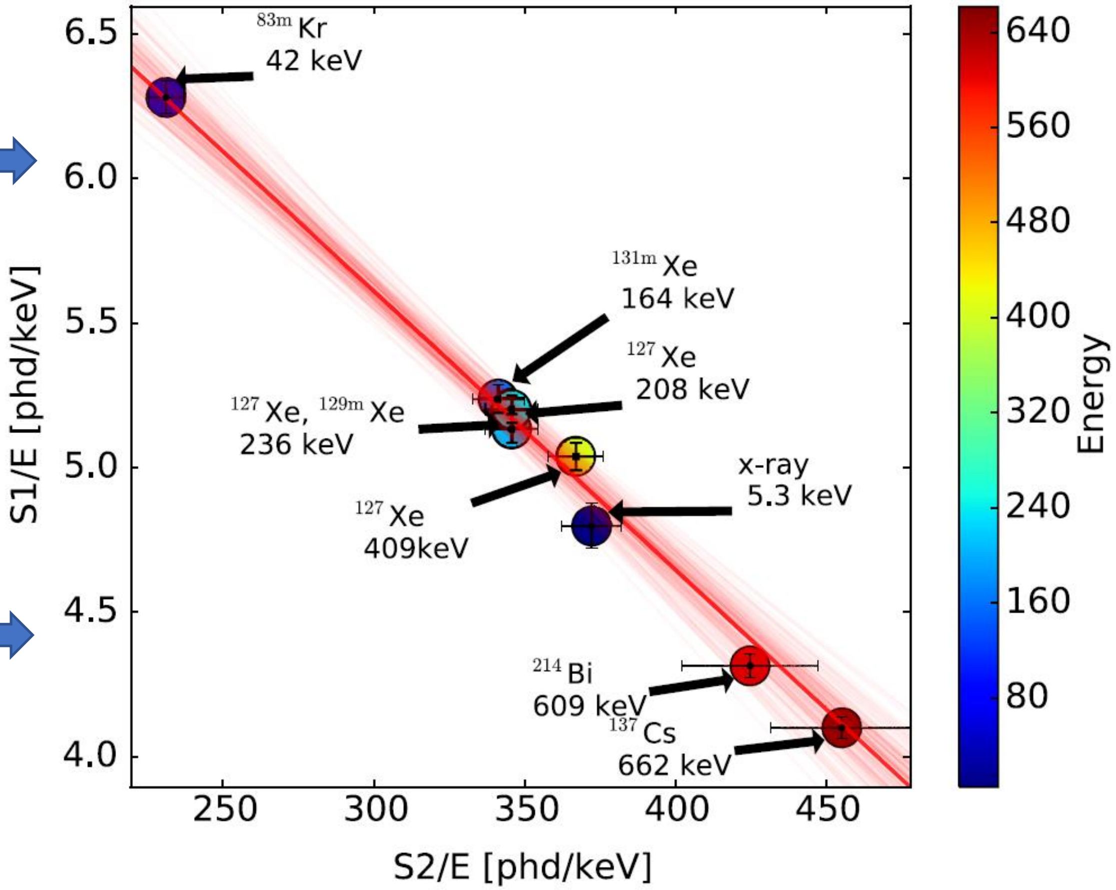
- E_{ee} – electronic equivalent energy
- $W = 13.7\ eV$ – the average energy required to generate a quantum (either a photon or electron)
- $S1c$ & $S2c$ – position corrected $S1$ and $S2$
- g_1 – number of photons detected for each photon leaving the recoil site → $S1c = n_{ph} \cdot g_1$
- g_2 – number of photons detected for each electron leaving the recoil site → $S2c = n_e \cdot g_2$
- $E_{ee} = 0.173 \cdot E_{nr}^{1.05}$ (from LUX calibration)
  - Detection of nuclear recoil energy is suppressed

Energy Calibration

$$E_{ee} = W\left(\frac{S1c}{g_1} + \frac{S2c}{g_2}\right) \quad \rightarrow \quad \frac{\langle S1c \rangle}{E_{ee}} = -\frac{g_1}{g_2}\frac{\langle S2c \rangle}{E_{ee}} + \frac{g_1}{W}$$



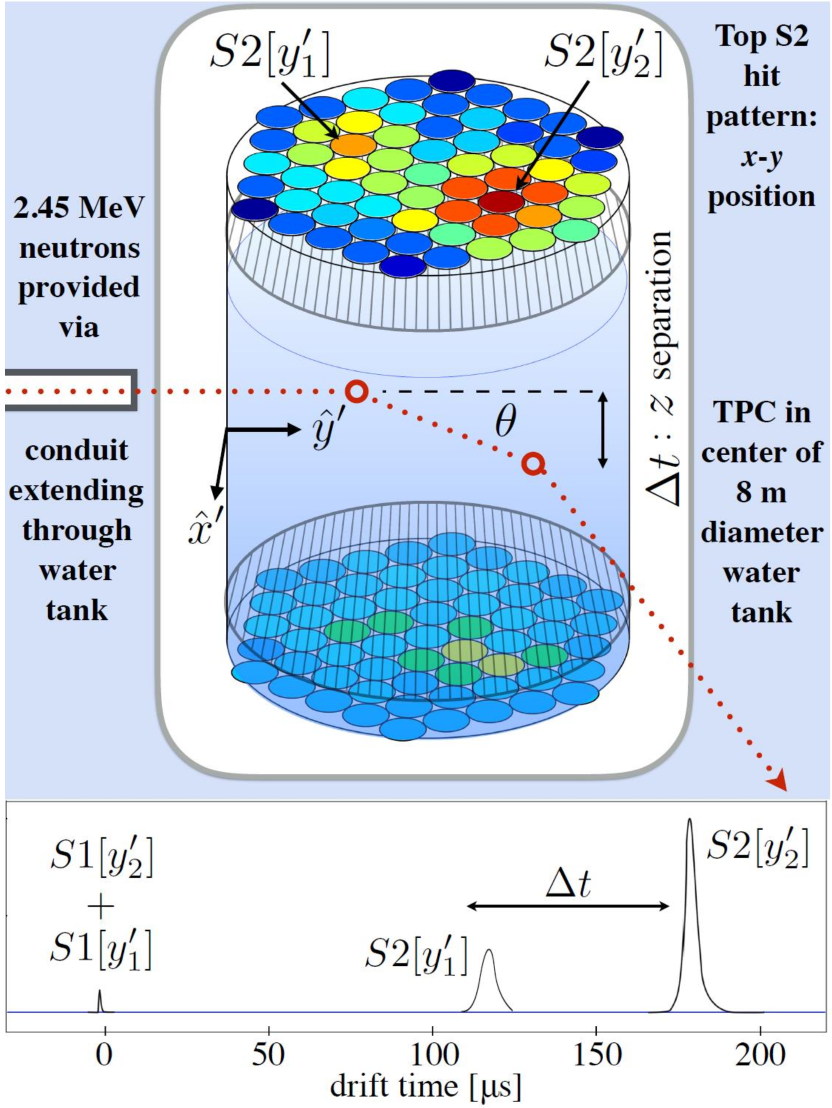
Source	E (keV)	Type
^{127}Xe	5.3	L-shell x ray
^{83m}Kr	41.55	IC
^{131m}Xe	163.9	IC
^{127}Xe	208.3	L-shell x ray + γ
^{127}Xe	236.1	K-shell x ray + γ
^{129m}Xe	236.1	IC
^{127}Xe	409	K-shell x ray + γ
^{214}Bi	609	γ
^{137}Cs	661.6	γ



- $g_1 = 0.117 \pm 0.003$ phd/photon
- $g_2 = 12.1 \pm 0.8$ phd/electron
- from fit to $\frac{\langle S1c \rangle}{E_{ee}}$ vs. $\frac{\langle S2c \rangle}{E_{ee}}$ dependence

LUX Calibration: PRD 97, 102008 (2018)

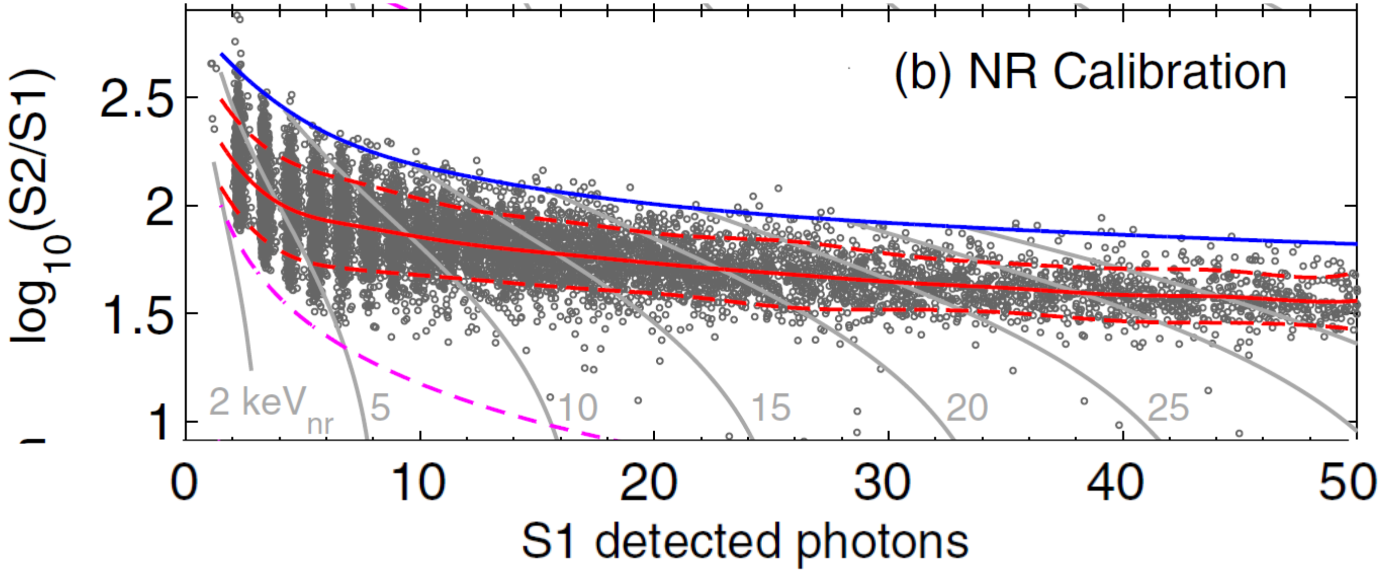
Nuclear Recoil Calibration



D-D generator: $^2_1\mathbf{H} + ^2_1\mathbf{H} \rightarrow ^3_2\mathbf{He} + ^1_0\mathbf{n} + 3.27\ \mathbf{MeV}$

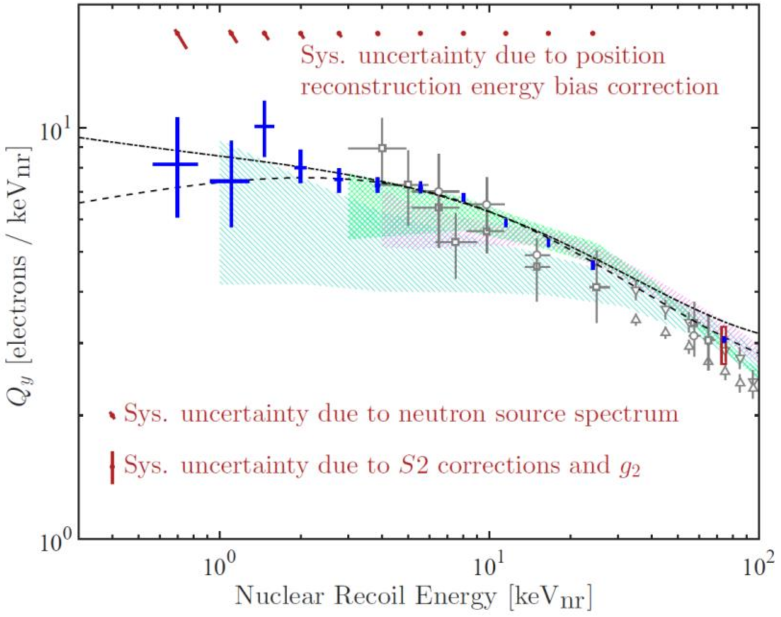
- D-D generator provides a mono-energetic beam of 2.45 MeV neutrons
- Double-scattering allows reconstruction of energy E_{nr} in the 1st interaction

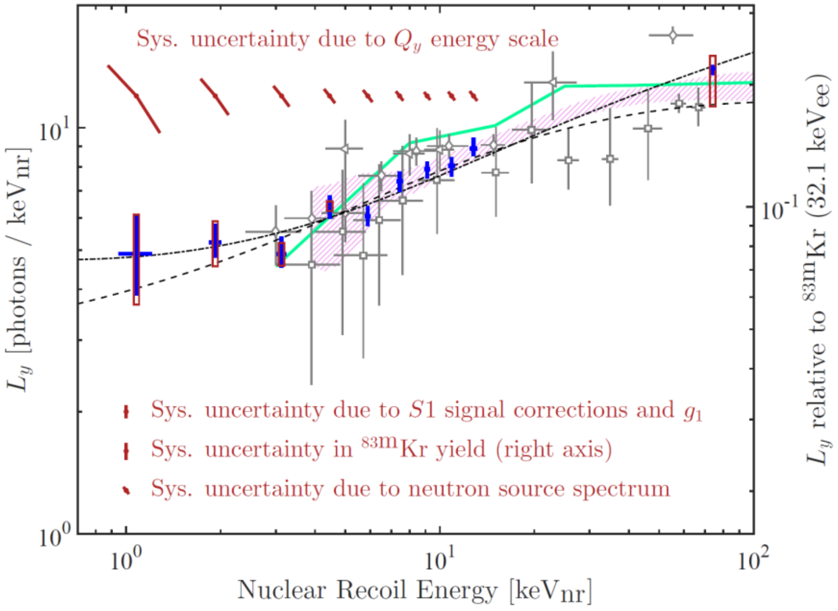
$$E_{\rm nr} = E_n \frac{4 m_n m_{\rm Xe}}{(m_n + m_{\rm Xe})^2} \frac{1 - \cos(\theta_{\rm CM})}{2}$$

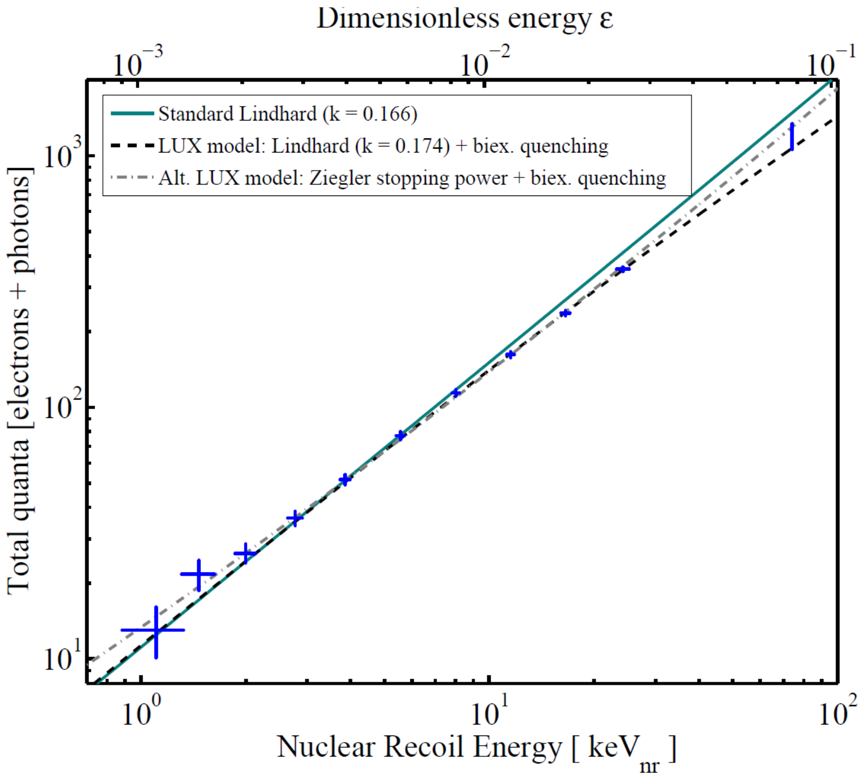


LUX Calibration: PRD 97, 102008 (2018)

Ionisation & Light yield for Nuclear Recoils



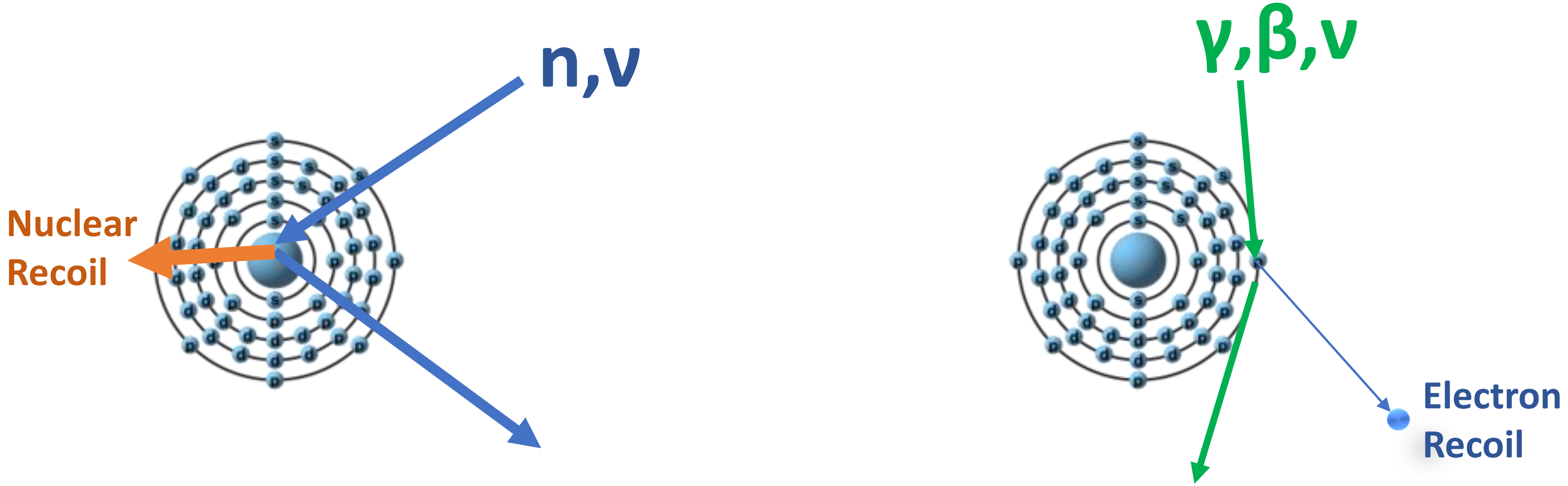




- Input to NEST simulation describing interactions in LXe TPC
  - See M. Szydagis et al. (NEST), https://zenodo.org/record/1314669
  - Instruments 2021, 5(1), 13 (arXiv:2102.10209)

arXiv:1608.05381

Background in DM Search Experiments



- Neutron interactions with Xe nucleus are similar to WIMP's interactions
  - The cross-section of neutron interactions is much higher therefore probability of multiple interactions in the detector is high (only single-scatter interactions for WIMPs)
- Coherent neutrino-nucleus scattering (CNNS) has very low probability but when the DM search sensitivity reaches "neutrino floor" it will represent irreducible background
- Electron recoil background is suppressed in LXe detectors by S2/S1 discrimination by factor ~10^3 and Fiducial Volume selection

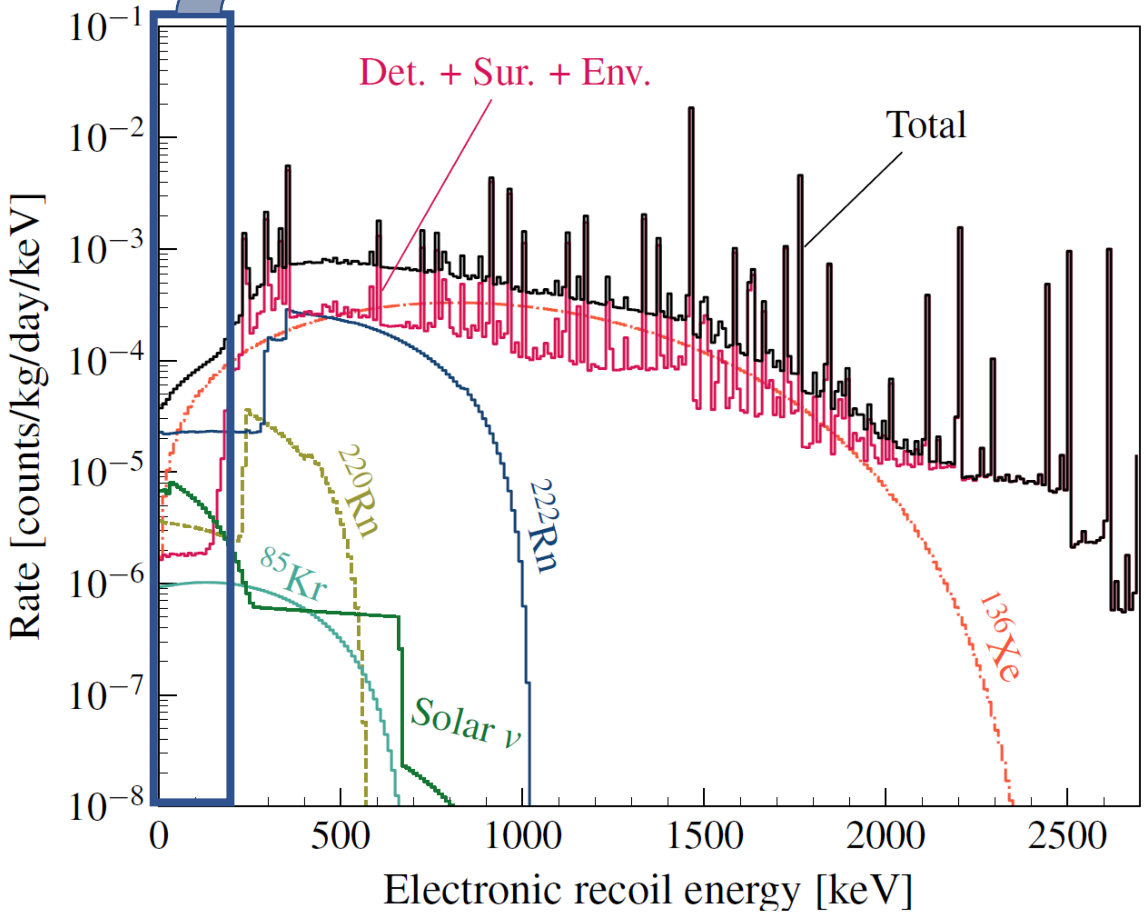
Example of Expected Background Table

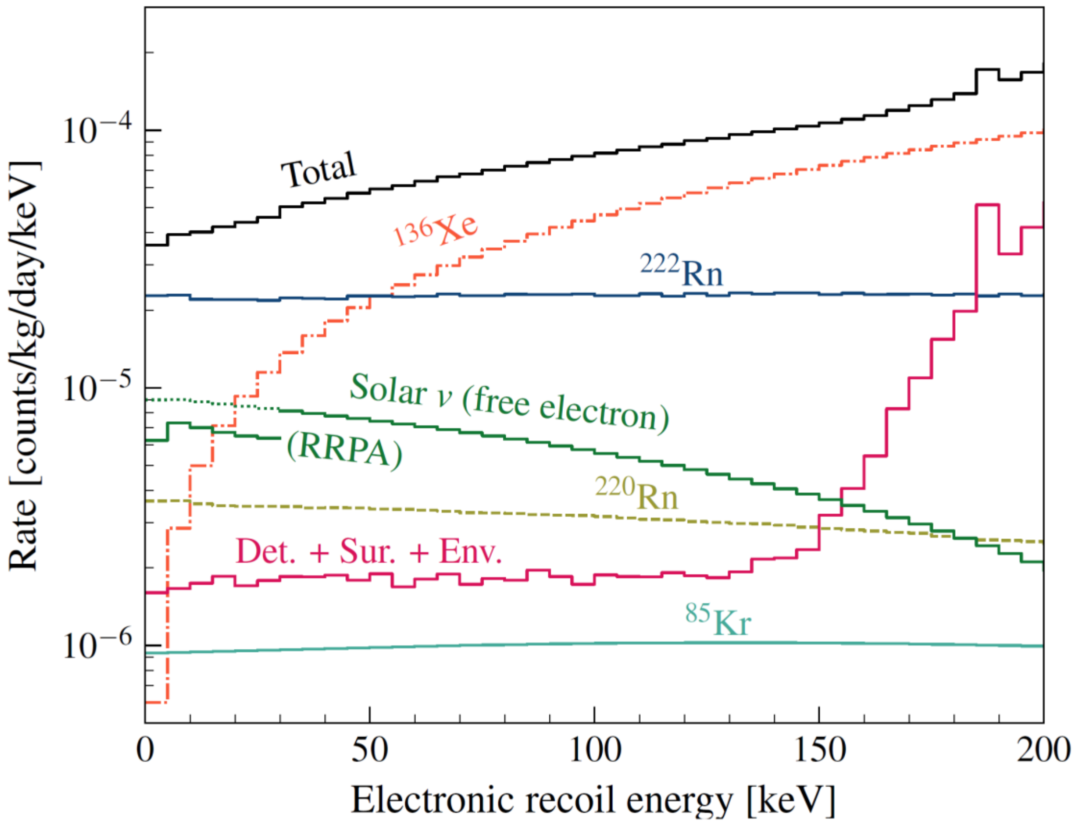
Background Source	Mass (kg)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
								subtotal	**9**	**0.07**
Surface Contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									-	0.05
^{210}Bi mobility (0.1 μBq/kg LXe)									40.0	-
Ion misreconstruction (50 nBq/cm^2)									-	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									-	0.12
								subtotal	**40**	**0.39**
Xenon contaminants										
^{222}Rn (1.8 μBq/kg)									681	-
^{220}Rn (0.09 μBq/kg)									111	-
^{nat}Kr (0.015 ppt g/g)									24.5	-
^{nat}Ar (0.45 ppb g/g)									2.5	-
								subtotal	**819**	**0**
Laboratory and Cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									-	0.06
Cosmogenic activation									0.2	-
								subtotal	**5**	**0.06**
Physics										
^{136}Xe $2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{13}N, ^{8}B+hep									191	0*
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
								subtotal	**258**	**0.51**
Total									1131	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.66	0.52
Sum of ER and NR in LZ for 1000 days, 5.6 tonne FV, with all analysis cuts									**6.18**	

- All components of multi-tonne detector are tested for intrinsic radioactivity
- Strict cleaning protocols to remove surface contaminations
- Expected background in 1000 days ~6 events in the NR band
  - Most of the background are expected leakage of electron recoil background
  - Radon background is expected to dominate the background rate
- Introduction of any “hot” material would be disastrous
  - Very difficult to check until detector is fully filled, closed and operational

Phys. Rev. D 101, 052002 (2020)

Background Spectra

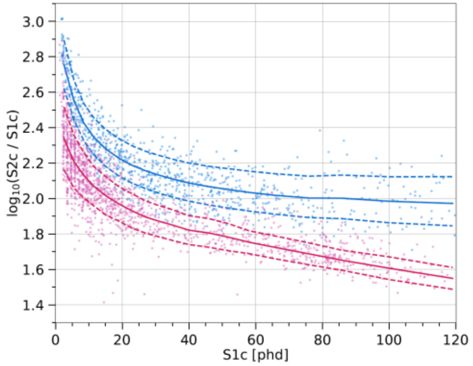




Phys. Rev. D 101, 052002 (2020)

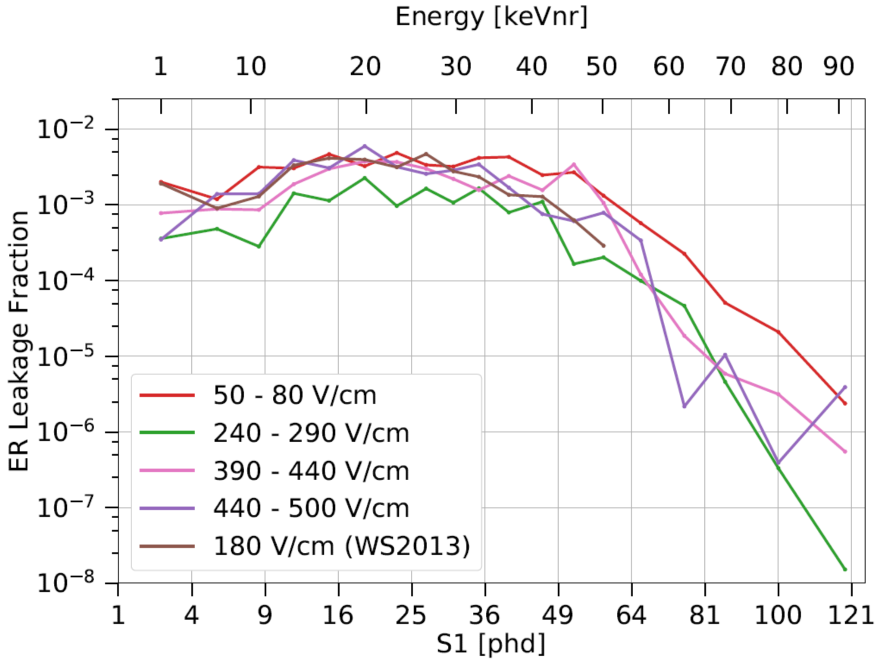
- Limiting the energy window to low region only suppresses most of the ER background

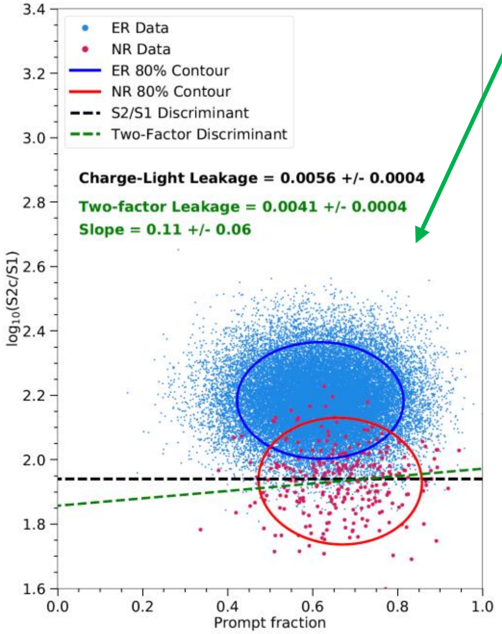
Study of ER Leakage

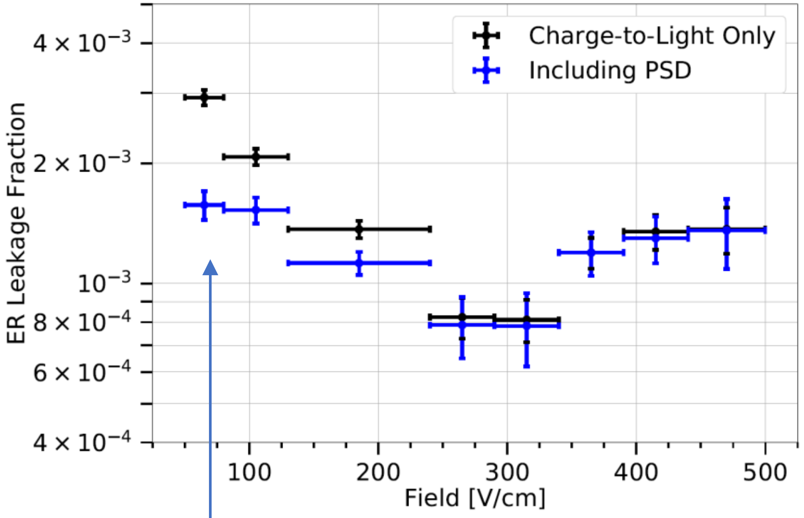


Scintillation: $Xe^{*} \rightarrow Xe_2^{*} \xrightarrow{} 2Xe + h\nu$ (+Xe)

- Singlet (4ns)
- Triplet (22ns)
- 178nm







LUX: Phys. Rev. D 102, 112002 (2020)

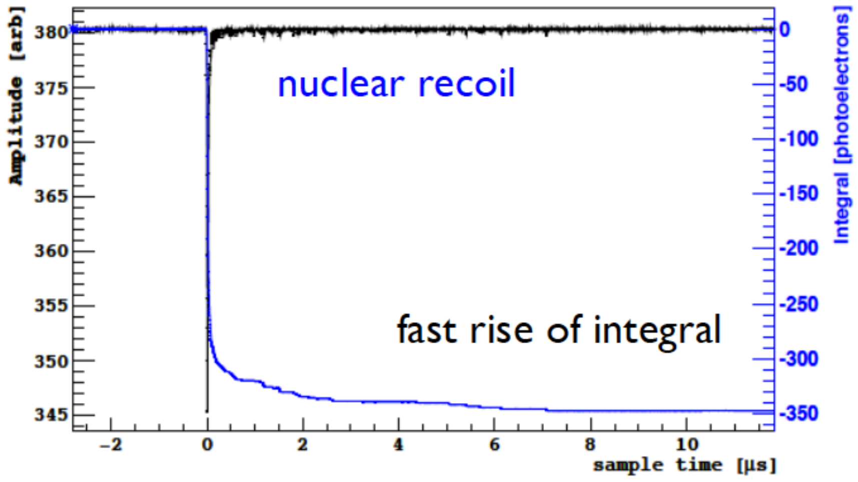
- Using Pulse Shape Discrimination can suppress the ER leakage to the NR band especially at lower drift fields

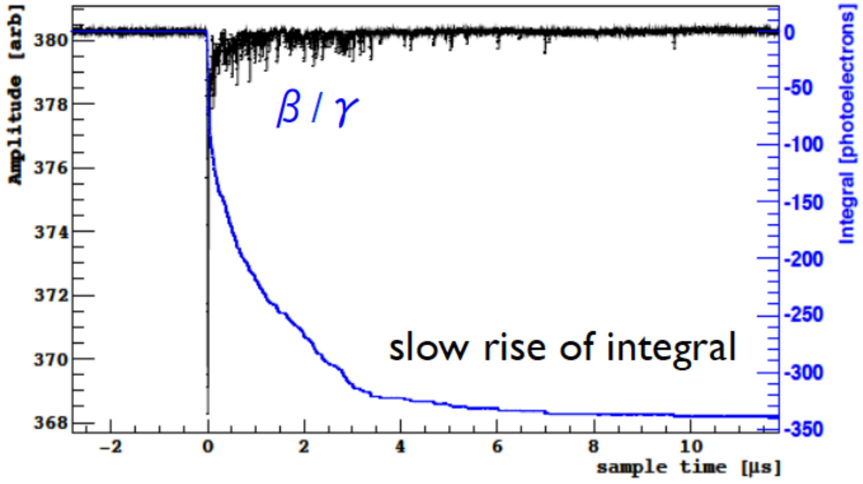
Compare to Argon

Scintillation: $Ar^* \rightarrow Ar_2^* \rightarrow 2Ar + h\nu$ (+Ar) → 128nm

WIMP, n → Singlet (7ns)

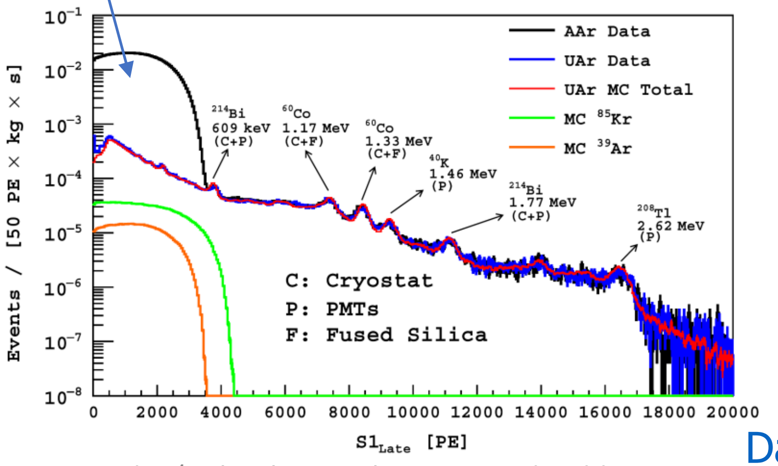
β, γ → Triplet (1.6μs)

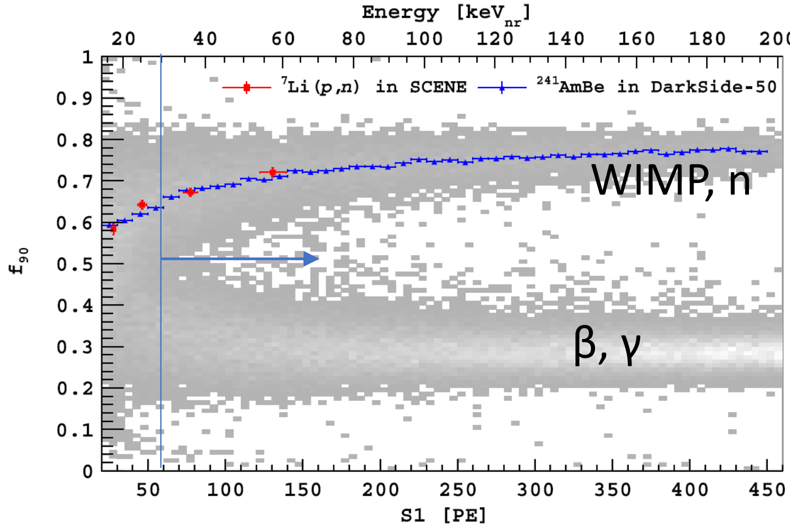


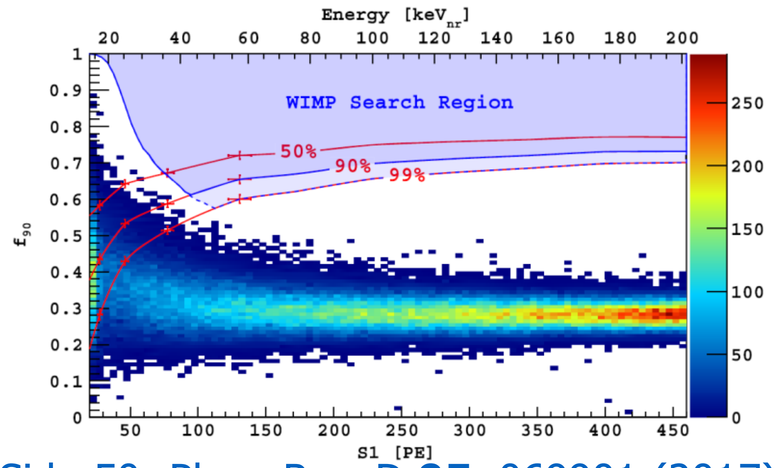


Luigi Rignanese @ICHEP2020

- Pulse Shape Discrimination in Ar allows very efficient (~10^9) ER suppression but above ~30keVnr → sensitivity to higher mass WIMPs if ER/NR discrimination is required
- ^{39}Ar β-decays produce a lot of background in ER band
  - Could be suppressed by ~1500 using Underground Ar
  - Still major background at low E_{nr}





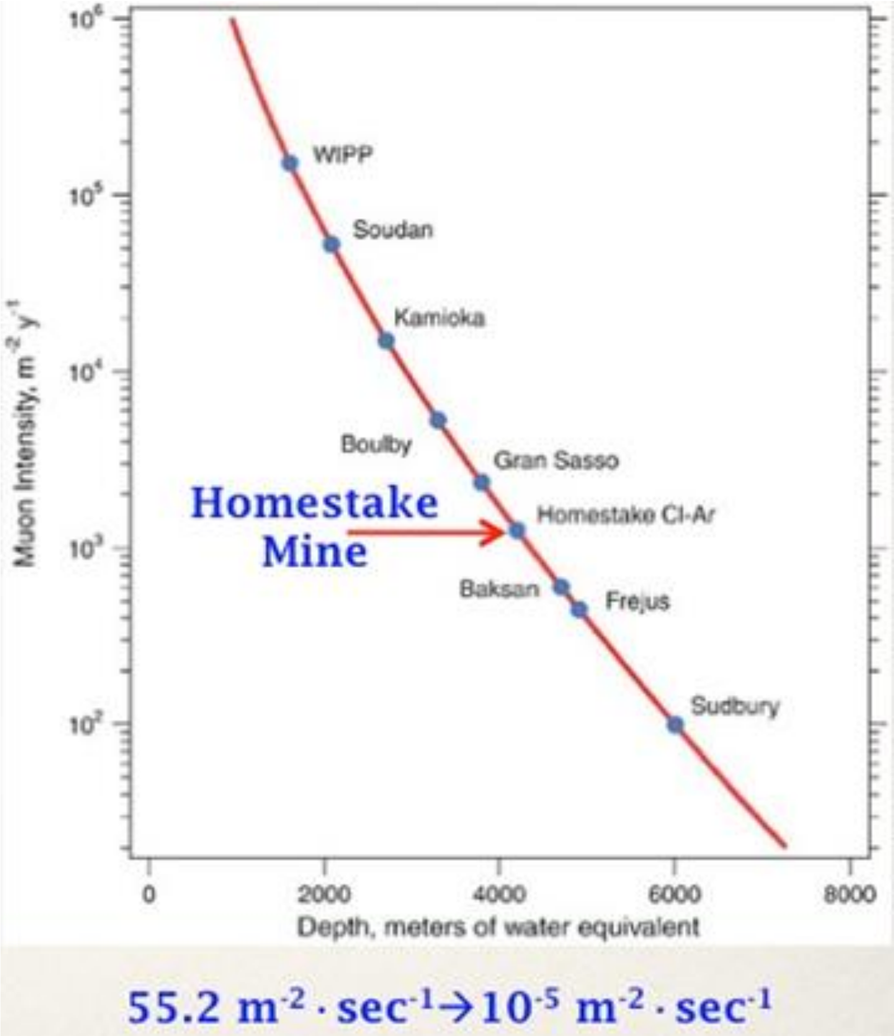


DarkSide-50: Phys. Rev. D **95**, 069901 (2017)

Laboratory and Cosmogenics Background

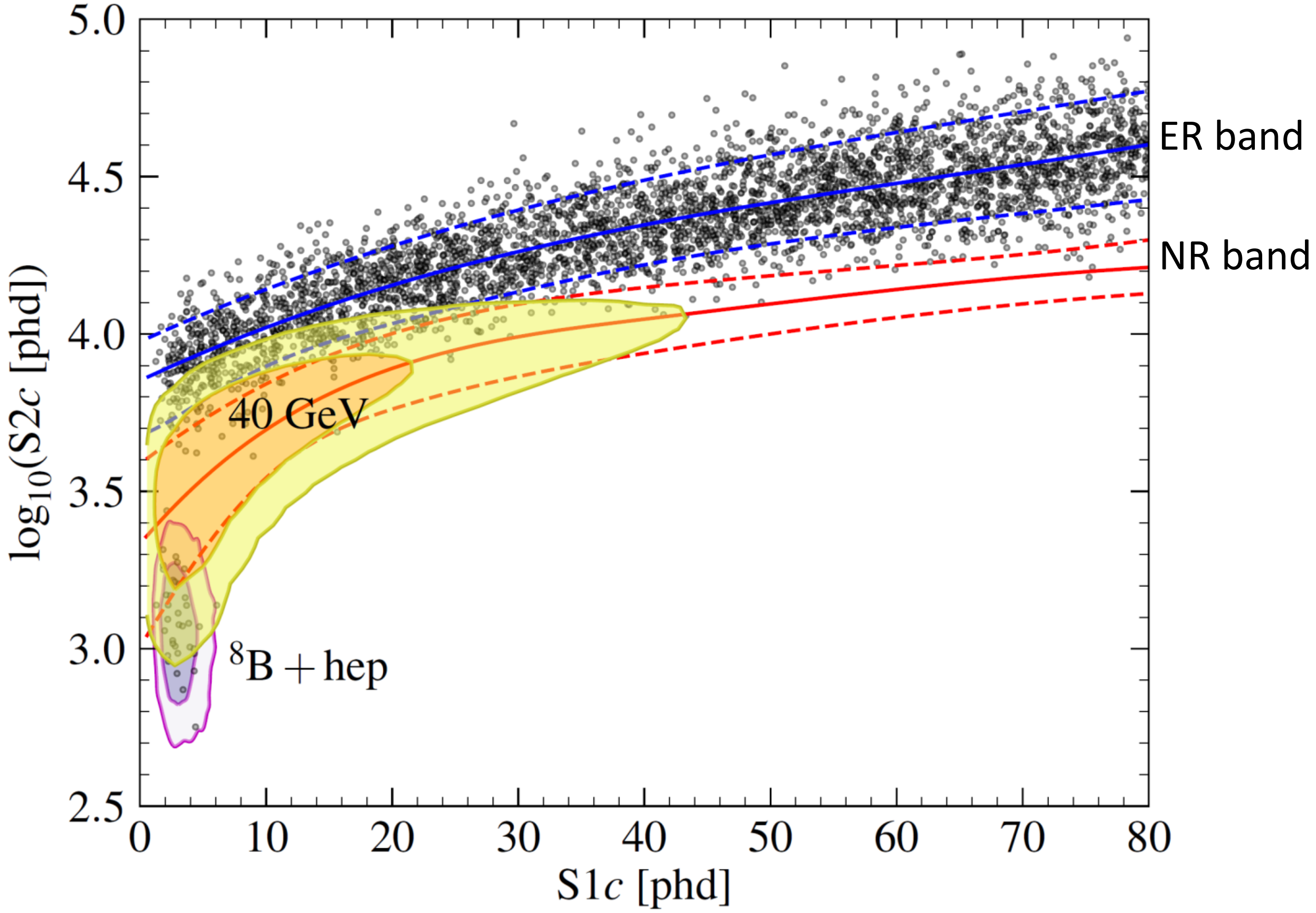
- Deep Underground Laboratories
  - Suppression of cosmic muons by factor ~10^7
  - Think about what would be the background on surface

Laboratory and Cosmogenics		
Laboratory rock walls	4.6	0.00
Muon induced neutrons	-	0.06
Cosmogenic activation	0.2	-
subtotal	**5**	**0.06**



- Passive (e.g. water shielding) and active (veto systems) background suppression are being used as well
  - Self-shielding properties of target material (skin layer is not used for DM searches)
  - Veto system can have additives with high neutron capture cross-section → can veto single-scatter neutron interactions in TPC

Expected signal



Phys. Rev. D 101, 052002 (2020)

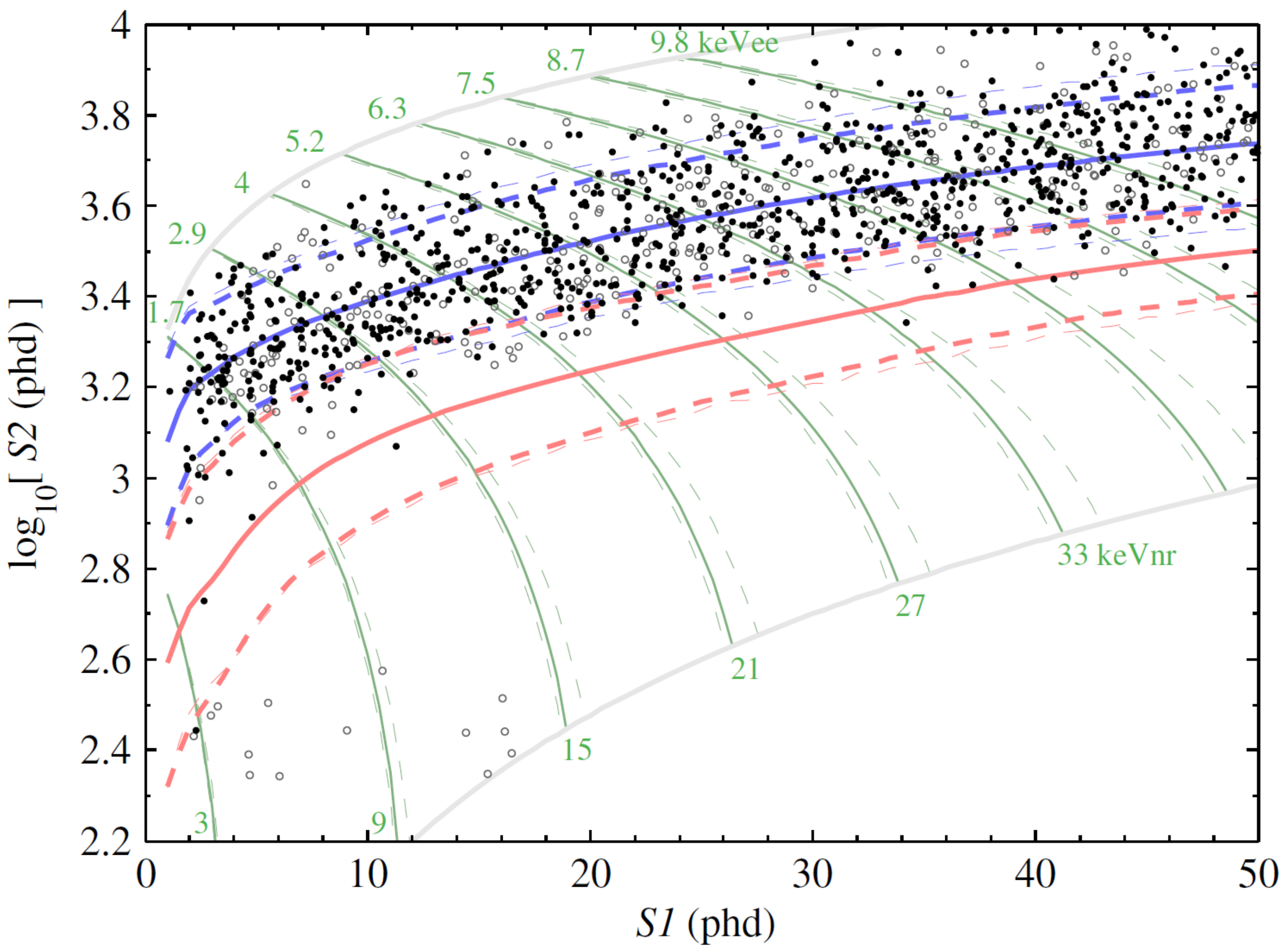
- A signal produced by 40 GeV WIMP occupies the NR band as expected
  - Rate depends on cross-section σ_n which is a parameter of interest in the limit setting procedure
  - No (signal) events observed → set an upper limit on the WIMP-nucleon spin-independent interaction cross-section σ_n
- CNNS signals from solar neutrinos ^{8}B (36 events in 1000 days) and hep (0.9 events in 1000 days) are expected in future experiments
  - $^8B \rightarrow {}^7Be^* + e^+ + \nu_e$
  - $^3He + p \rightarrow {}^4He + e^+ + \nu_e$

LUX Result

- WIMP search region is defined as a region below NR band median (red curve)
  - 50% efficiency
- Background

Parameter	Constraint	Fit value
Lindhard k [11]	0.174 ± 0.006	...
Low-z-origin γ counts	94 ± 19	99 ± 14
Other γ counts	511 ± 77	590 ± 34
β counts	468 ± 140	499 ± 39
^{8}B counts	0.16 ± 0.03	0.16 ± 0.03
PTFE surface counts	14 ± 5	12 ± 3
Random coincidence counts	1.3 ± 0.4	1.6 ± 0.3

~1200 mainly in ER band



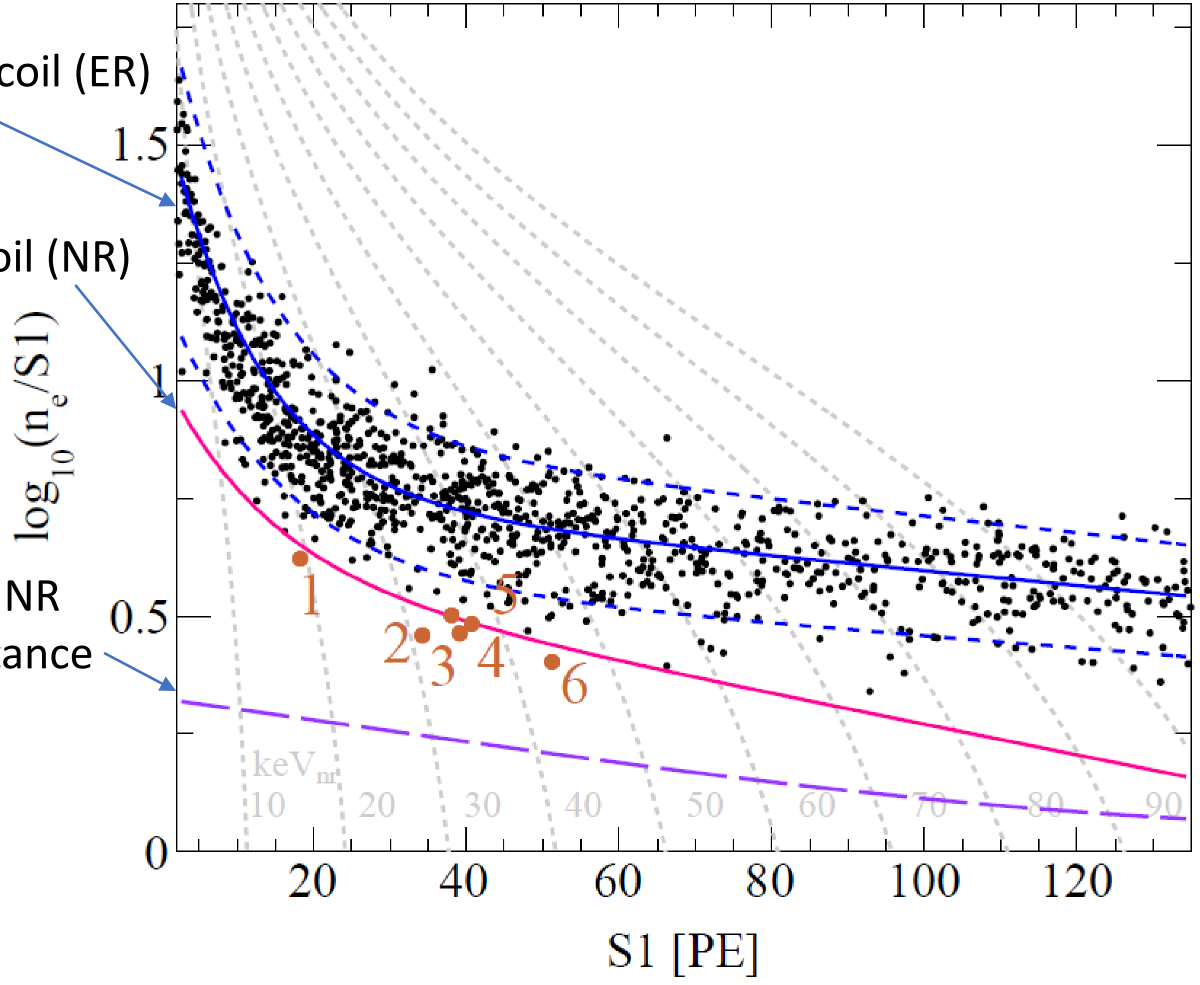
PandaX-4T Results

- Sometimes $\log_{10}(S2/S1)$ VS. S1 are plotted
- Events 1 – 6 are identified as leaked ER events.
- Spatially they seem to be distributed randomly but see where most of the background is.

Electron Recoil (ER) band

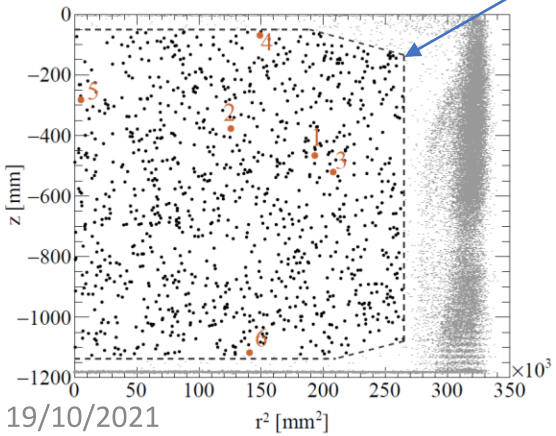
Nuclear Recoil (NR) median

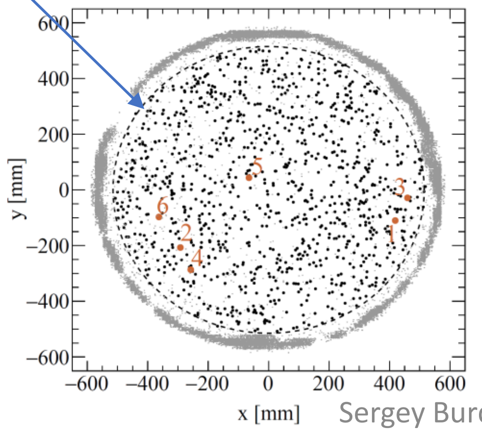
99.5% NR acceptance



PandaX-4T Commissioning Run (arXiv:2107.13438)

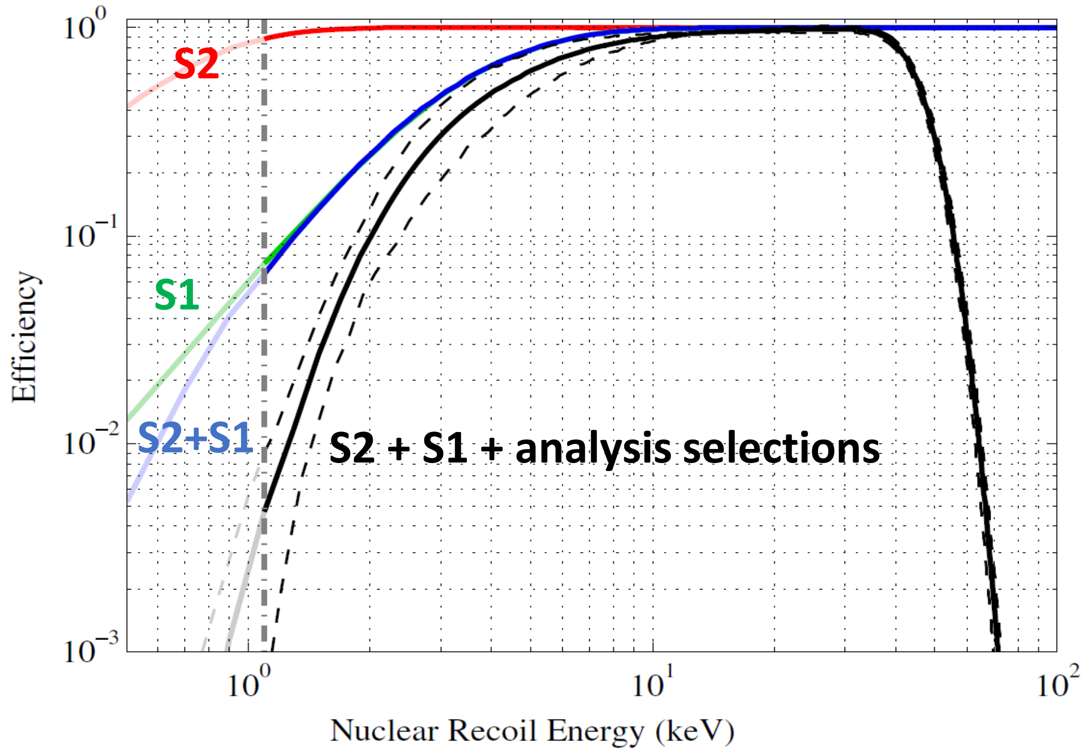
Fiducial Volume





Extending Sensitivity to Low Masses

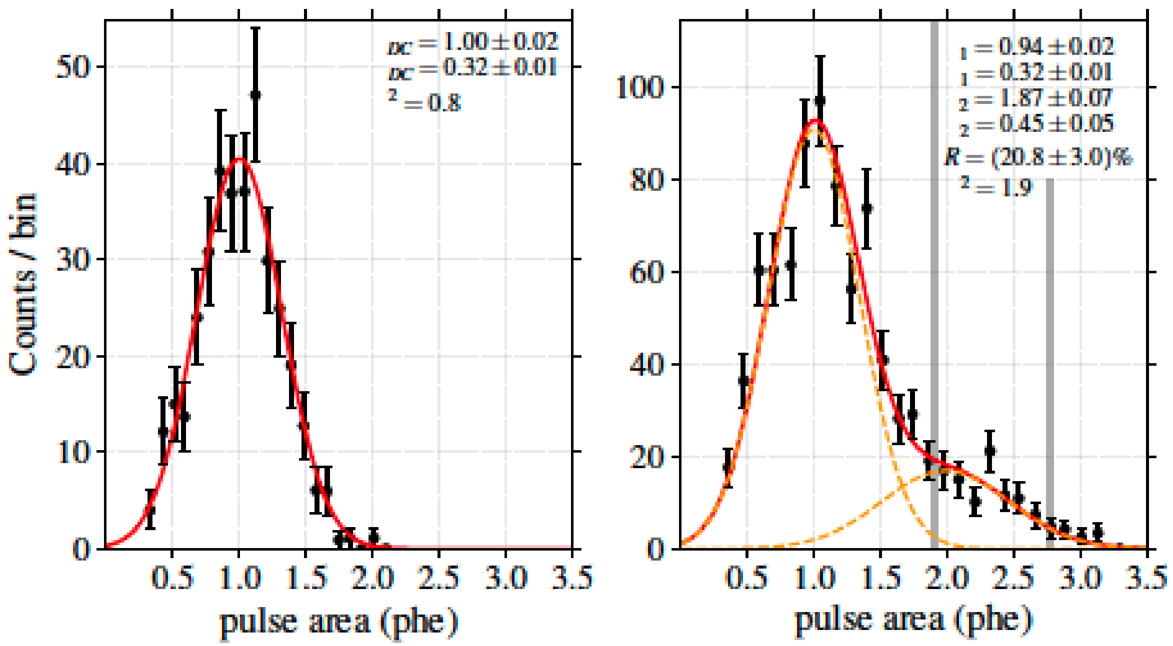
- S2-only searches
- Using Migdal effect and Bremsstrahlung
- Using high double photoelectron production efficiency for VUV light

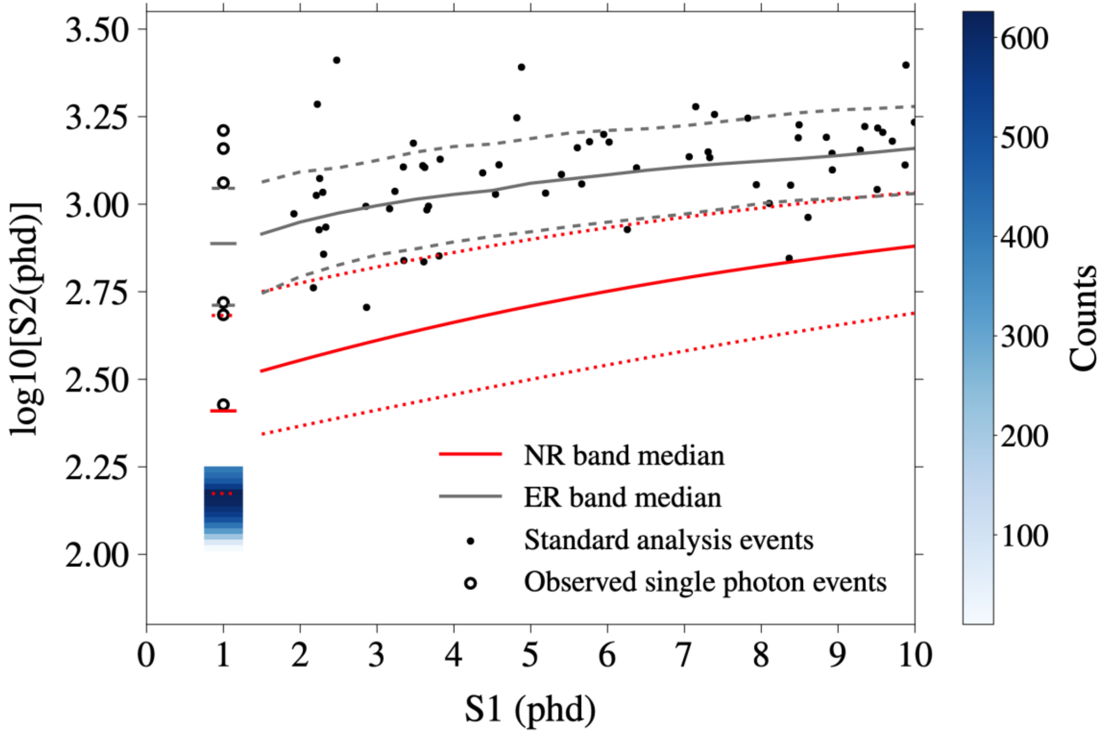


LUX efficiency from PRL 118, 021303 (2017)

Sensitivity @ Single Scintillation Photon level

Phys. Rev. D 101, 042001 (2020)





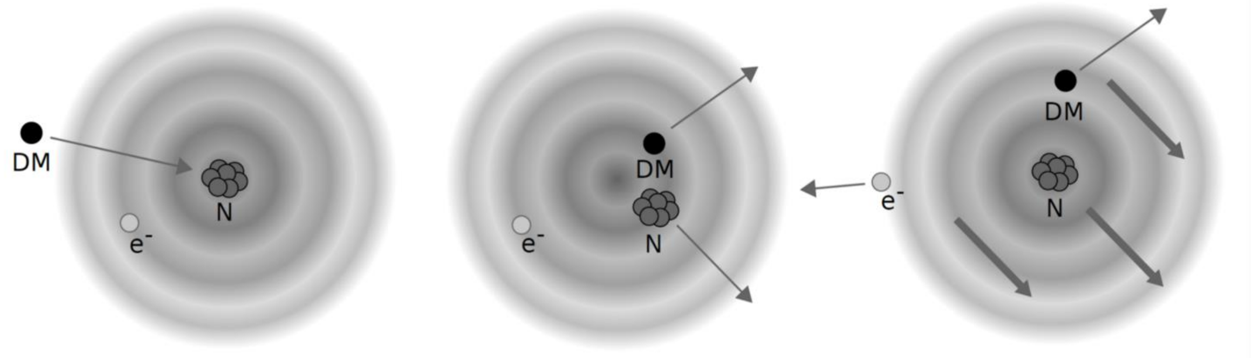
- Single VUV photon produces two photoelectrons (DPE) in LUX PMTs (~17% probability)
  - Requiring DPE in 1 PMT recovers some events cut but 2-fold coincidence requirement
  - Effective suppression of Dark Counts and visible light
- Improve S1 efficiency at low E_{NR} → keep ER/NR separation

- NR threshold could be lowered to 0.3 keV
- Tested with LUX 2013 data
- 6 detected events agree with background expectations (dark counts leakage coinciding with S2)

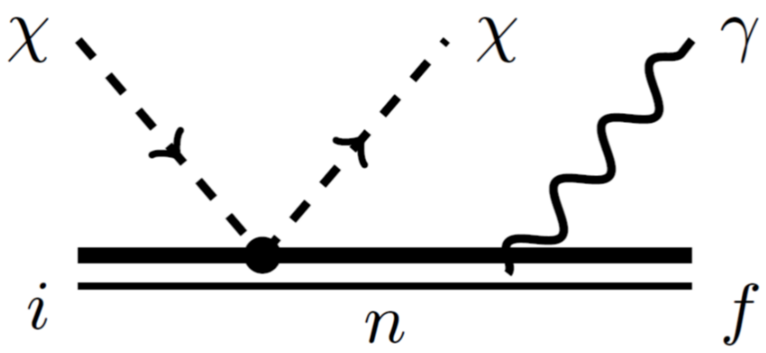
Sensitivity to Sub-GeV DM

- NR is too low in LXe detectors for Sub-GeV DM particles
- Still the Migdal effect and Bremsstrahlung could provide some sensitivity through detection of electron or photon
- Suggested by Chris Kouvaris and Josef Pradler (PRL 118, 031803 (2017))

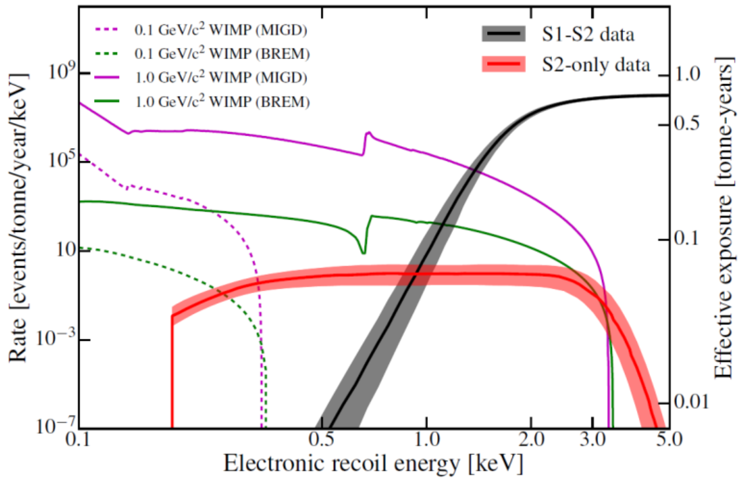
Migdal effect: Emission of electron due to recoiling nucleus
Theory in JHEP 03, 194 (2018)

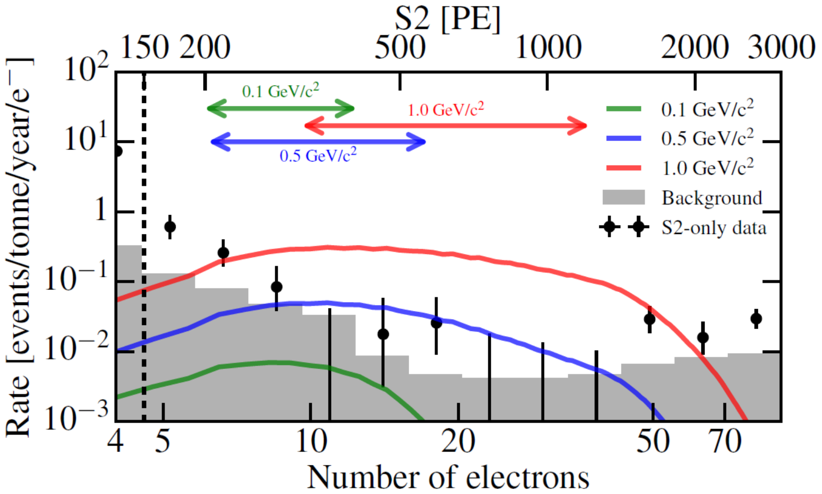


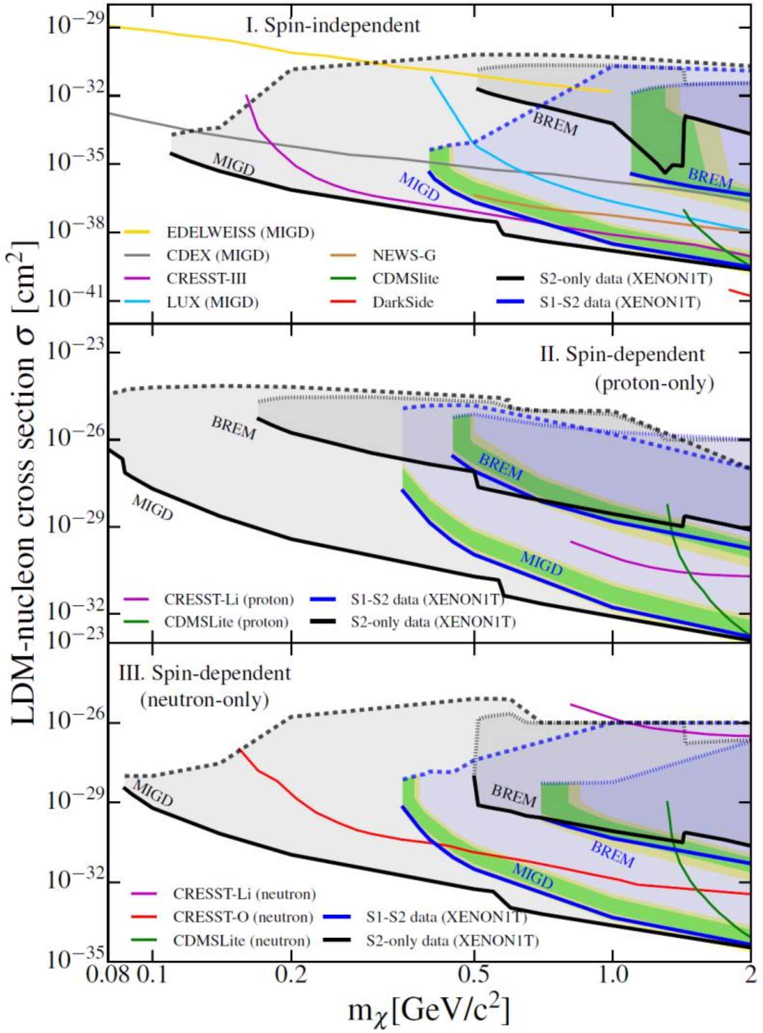
Bremsstrahlung: photon emission from Xe atom due to DM-nucleus scattering



XENON1T Migdal+Brem+S2-only result

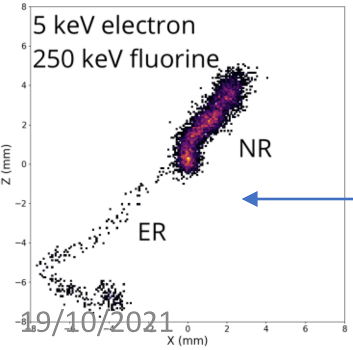






Phys. Rev. Lett. 123, 241803 (2019)

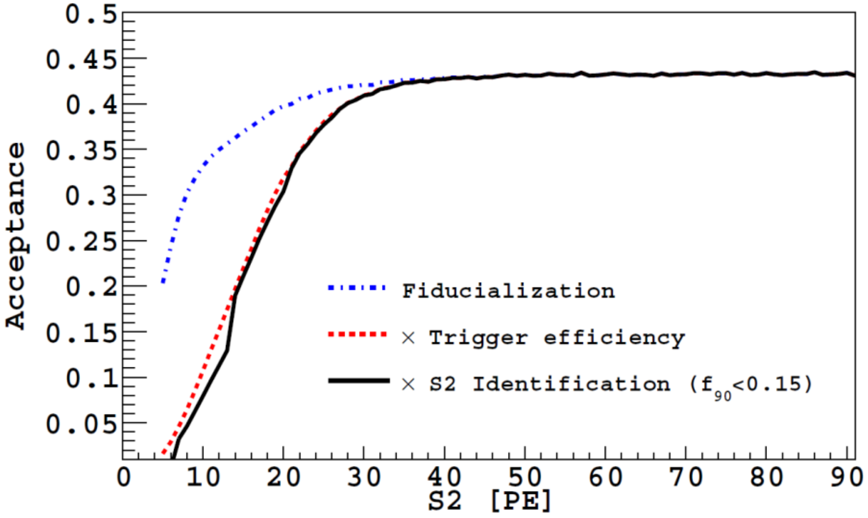
- Bremsstrahlung rate: $$\frac{d^2R}{dE_{\mathrm{ER}}dv} \propto \frac{|f(E_{\mathrm{ER}})|^2}{E_{\mathrm{ER}}}\sqrt{1-\frac{2E_{\mathrm{ER}}}{\mu_N v^2}}\left(1-\frac{E_{\mathrm{ER}}}{\mu_N v^2}\right)$$
- Migdal rate: $$\frac{dR}{dE_{\mathrm{ER}}} \simeq \int dE_{\mathrm{NR}}dv\frac{d^2R}{dE_{\mathrm{NR}}dv} \times \frac{1}{2\pi}\sum_{n,l}\frac{d}{dE_{\mathrm{ER}}}p^c_{q_e}(n,l \to E_{\mathrm{ER}}-E_{n,l})$$
  - $p^c_{q_e}$ – the probability for an atomic electron, with quantum numbers (n, l) and binding energy $E_{n,l}$ to be ionized and receive a kinetic energy $E_{ER} - E_{n,l}$.

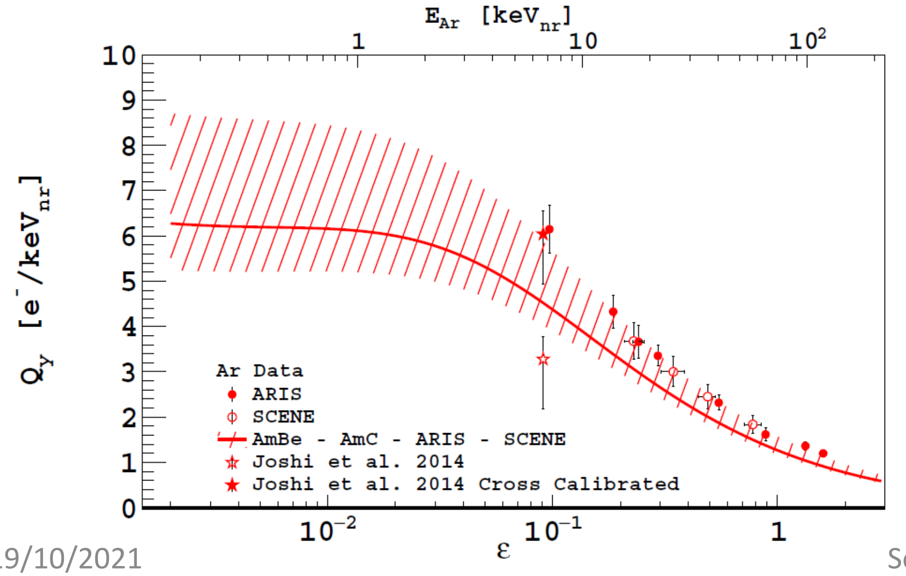


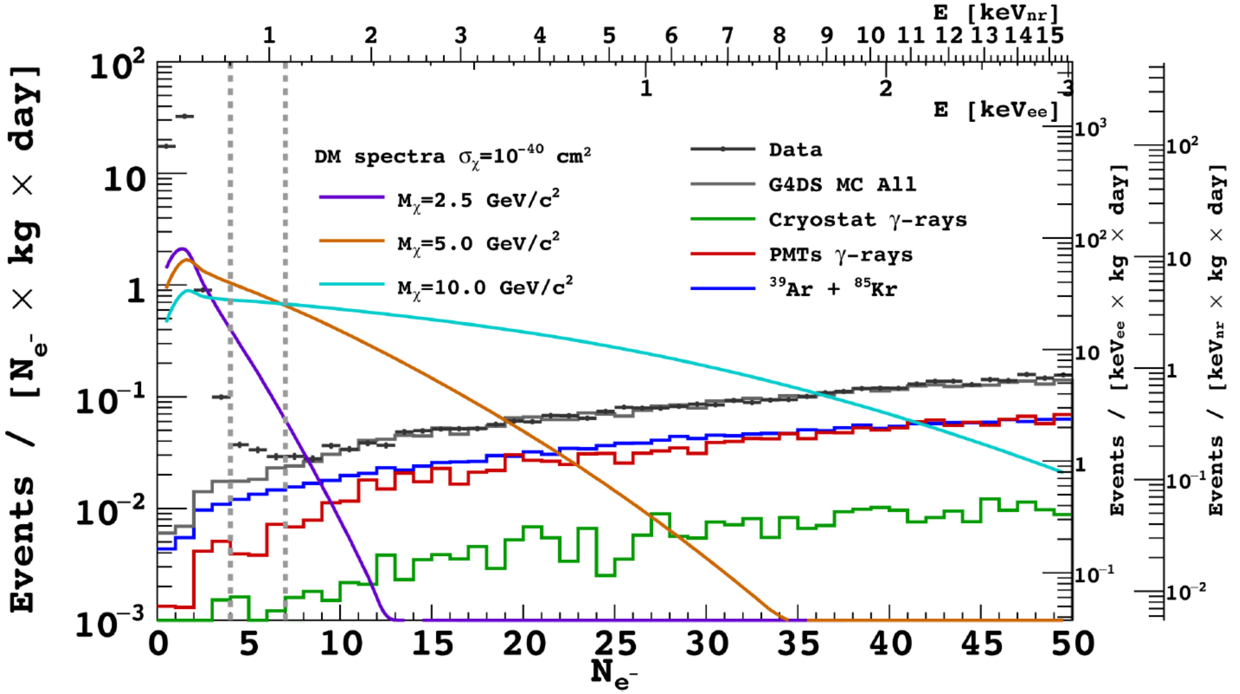
- **To be calibrated by MIGDAL collaboration**

Phys. Rev. Lett. 121, 081307 (2018)

S2-only DarkSide-50 result



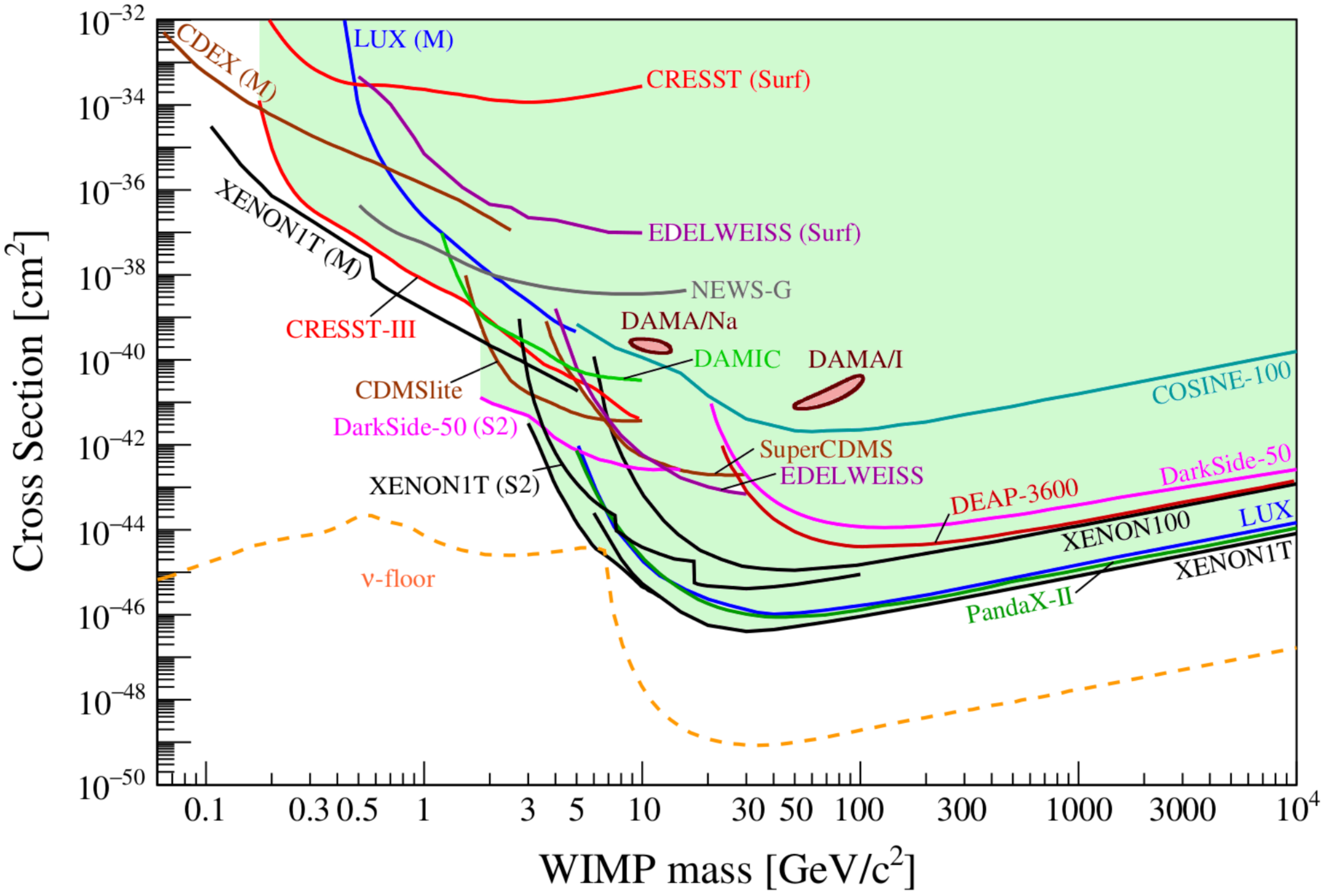




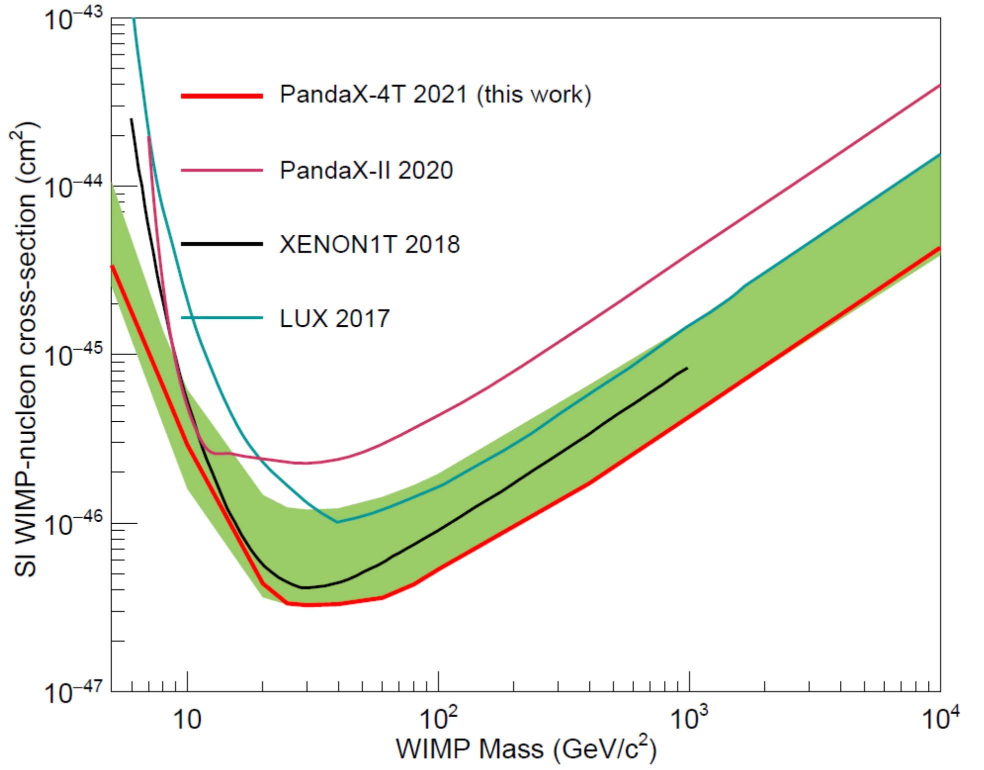
- If ER/NR separation is not required then S2-only data could be used by Ar experiments as well
- Lower mass of target nucleus → better momentum transfer for lower mass WIMPs → better sensitivity even without Migdal or Bremsstrahlung effects
- Ionisation calibration at low E_{nr} is needed

Current Status in MeV – TeV mass range

Spin-Independent elastic WIMP-nucleus scattering



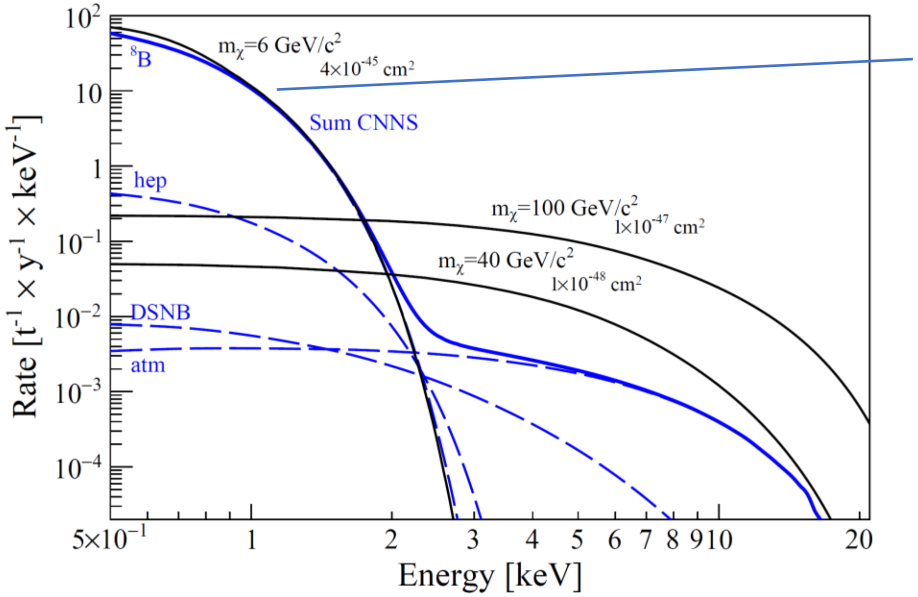
APPEC Committee Report (arXiv:2104.07634)

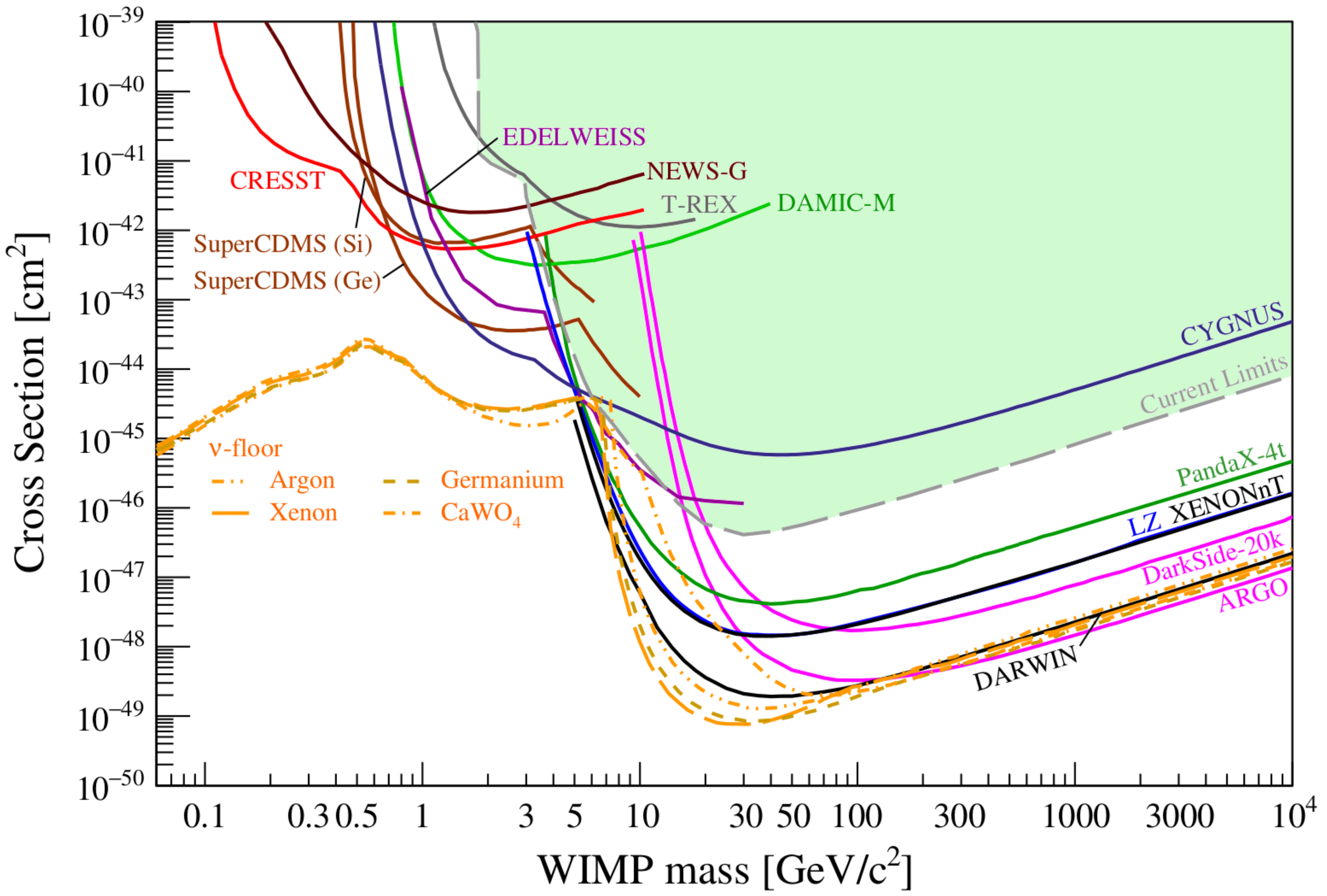


PandaX-4T Commissioning Run (arXiv:2107.13438)

Projections

- We could be reaching the neutrino floor in the >10GeV/c^2 region by 2030-2035 (by ~2025 @8-9 GeV/c^2)
  - Fuzzy signal in the NR band



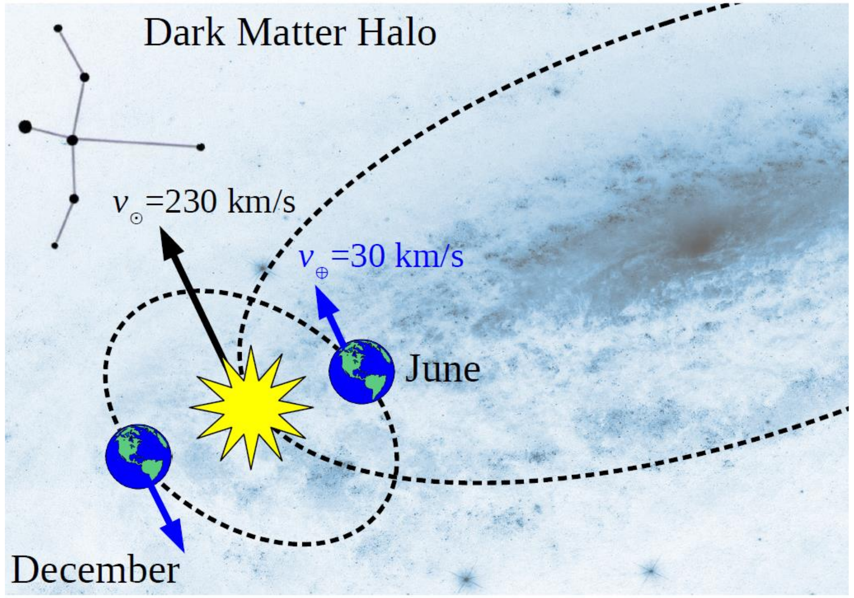


APPEC Committee Report (arXiv:2104.07634)

$$\frac{d\sigma}{dE_{\rm nr}} = \frac{G_F^2 m_N}{4\pi}\left[A - Z - (1 - 4\sin^2\theta_W)Z\right]\left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2}\right)F^2(Q^2)$$

arXiv:1903.03026

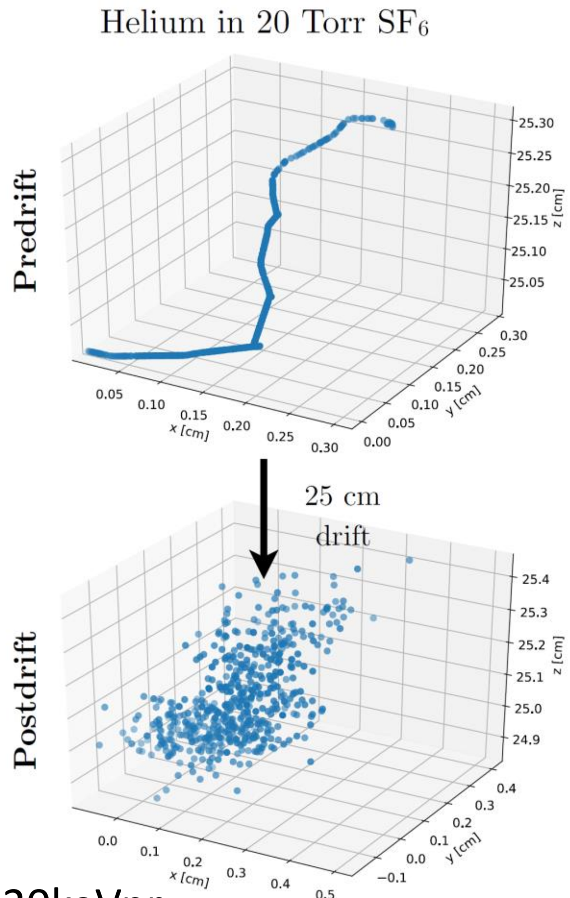
Prospects of Directional DM Detection



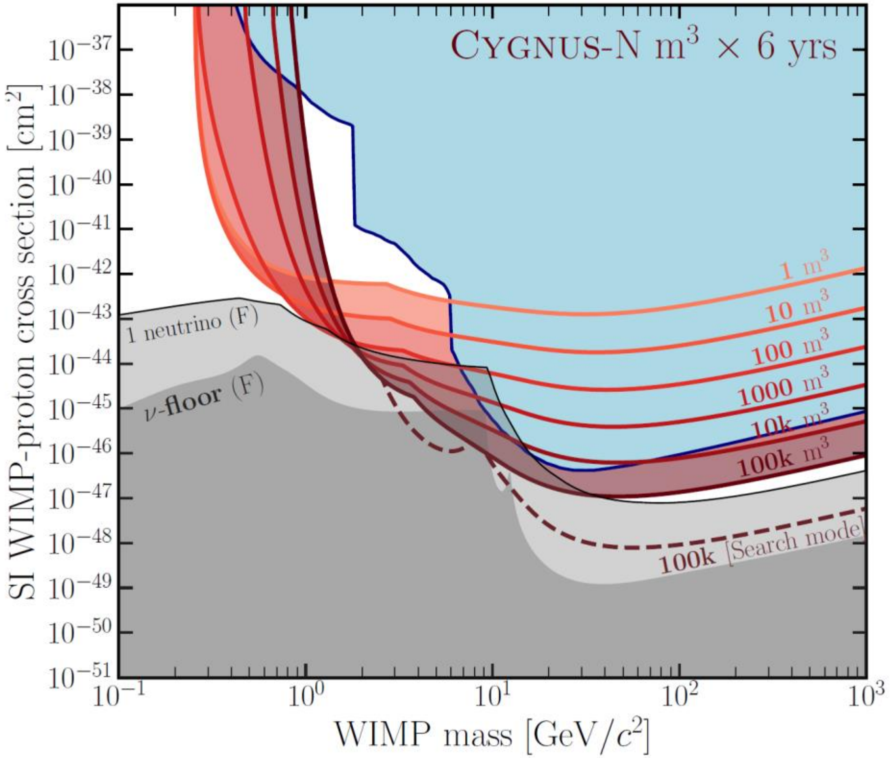
- Nuclear recoils are aligned with the Sun direction

$$\frac{d^2R}{dE_{\rm nr}\, d\phi} \propto \exp\left[\frac{2(v_\odot \cos\phi - v_{\rm min})^2}{3v_\odot^2}\right]$$

arXiv:1903.03026



20keVnr



~50x50x50 m^3 detector would allow reaching neutrino floor and use directional information

CYGNUS (arXiv:2008.12587)

Conclusion

- Understanding the nature of Dark Matter is one of the most interesting and important scientific tasks
- Direct Dark Matter searches improved the sensitivity by 6 orders of magnitude in 20 years
- Still the sensitivity even in the WIMP region differs by 14 orders of magnitude → a lot of room for improvement
- Extending mass range and tackling below neutrino floor cross-sections represent tremendous task
- New techniques (better purity, higher sensitivity, directional measurements, quantum sensors?) will play an important role in solving this task
- A lot of room for creativity and unconventional approaches