DIRECT DETECTION OF PARTICLE DARK MATTER:

WHERE DO WE STAND, WHERE ARE WE GOING?

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JULY 3, 2020

University of Zurich[UZH]

European Research Council
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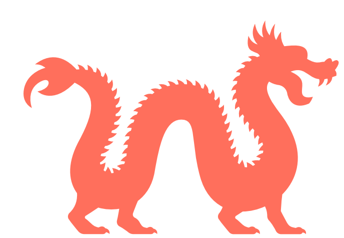
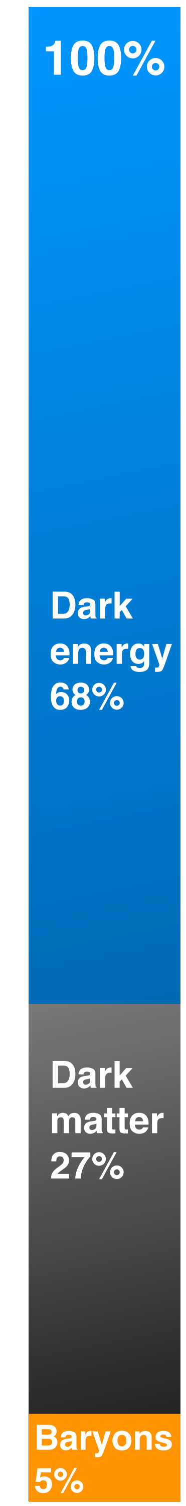
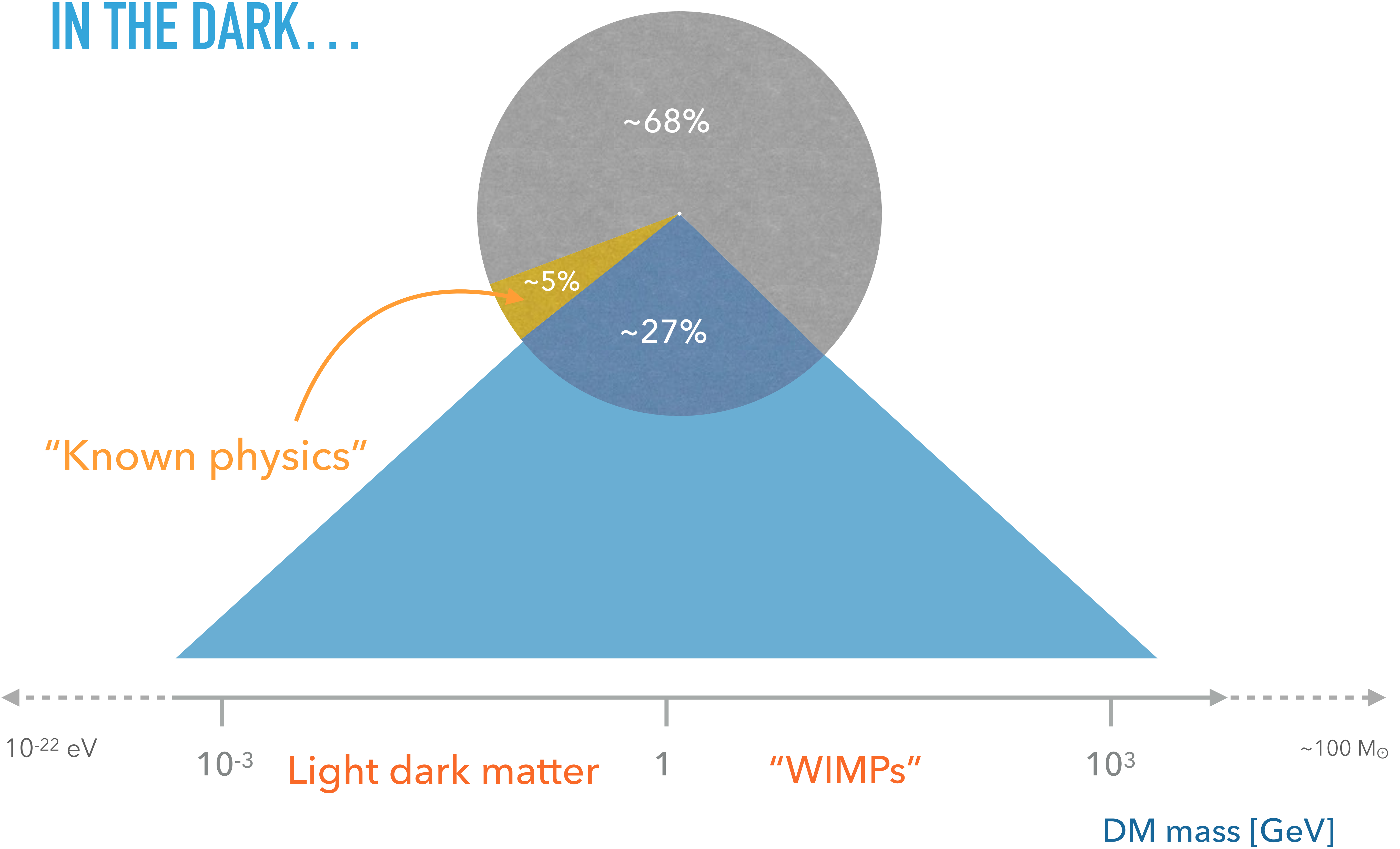
IN THE DARK…

- The evidence for dark matter is overwhelming
  - Early and late cosmology (CMBR, LSS)
  - Clusters of galaxies
  - Galactic rotation curves
  - BBN, …
- And ΛCDM describes all observations well
- No idea about its composition at the microscopic level!



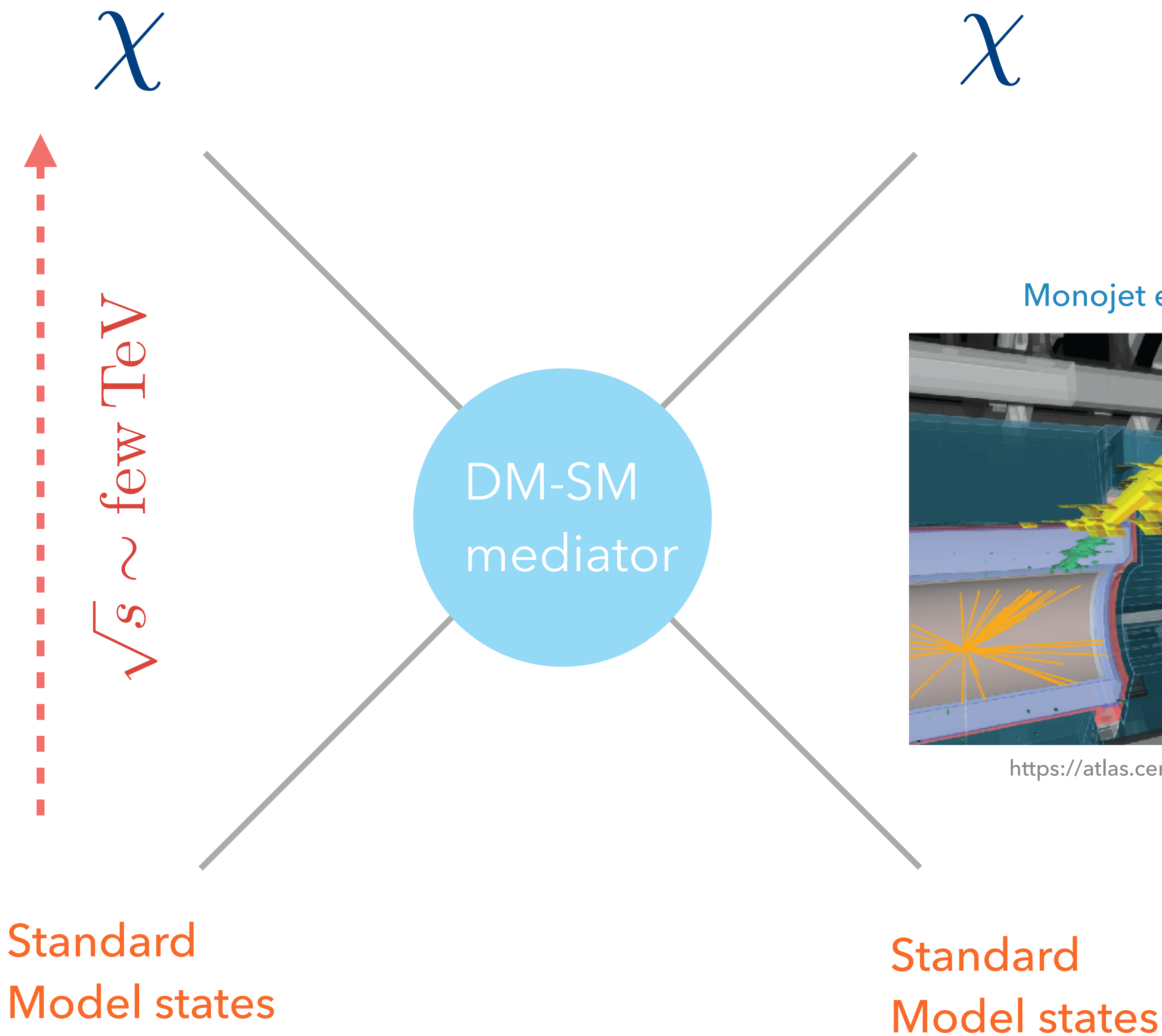


IN THE DARK…

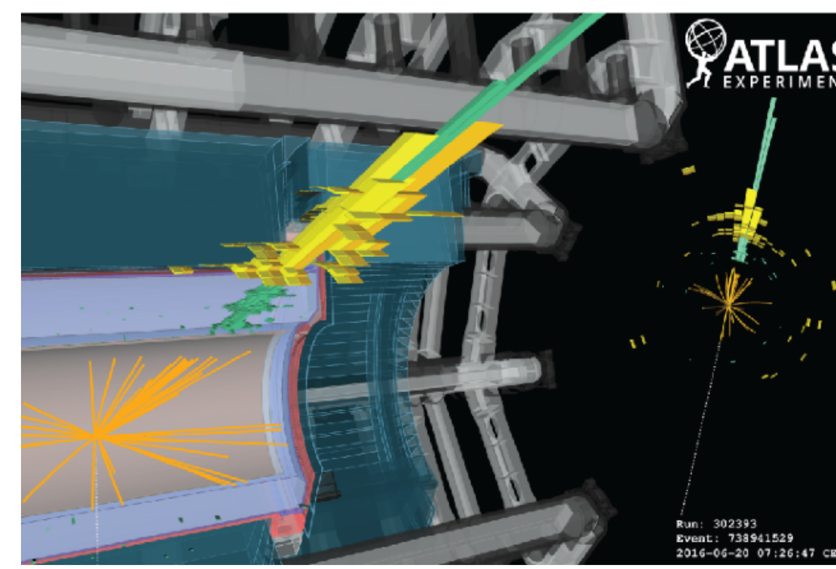

~68%
~5%
~27%
"Known physics"
10^{-22} eV
10^{-3}
Light dark matter
1
"WIMPs"
10^{3}
~100 $M_\odot$
DM mass [GeV]

HOW TO SEE IN THE DARK?

- light dark matter searches at colliders, fixed target and beam dump experiments (new, light mediator) to probe the 'dark sector'

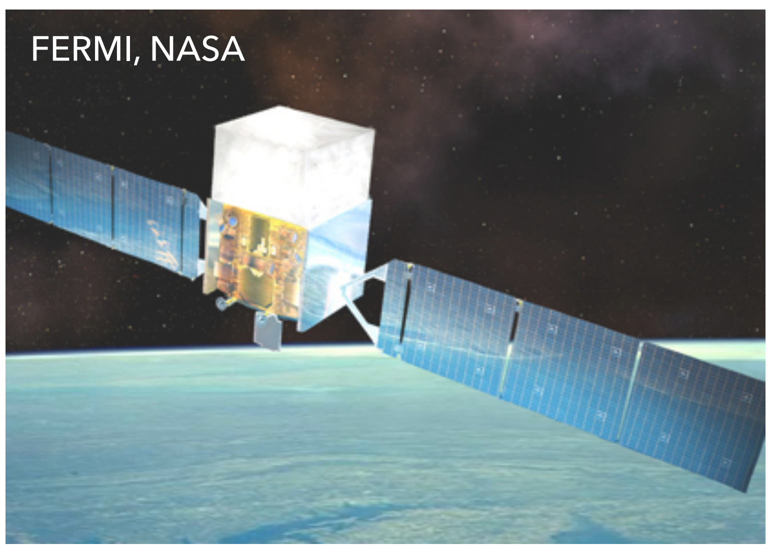


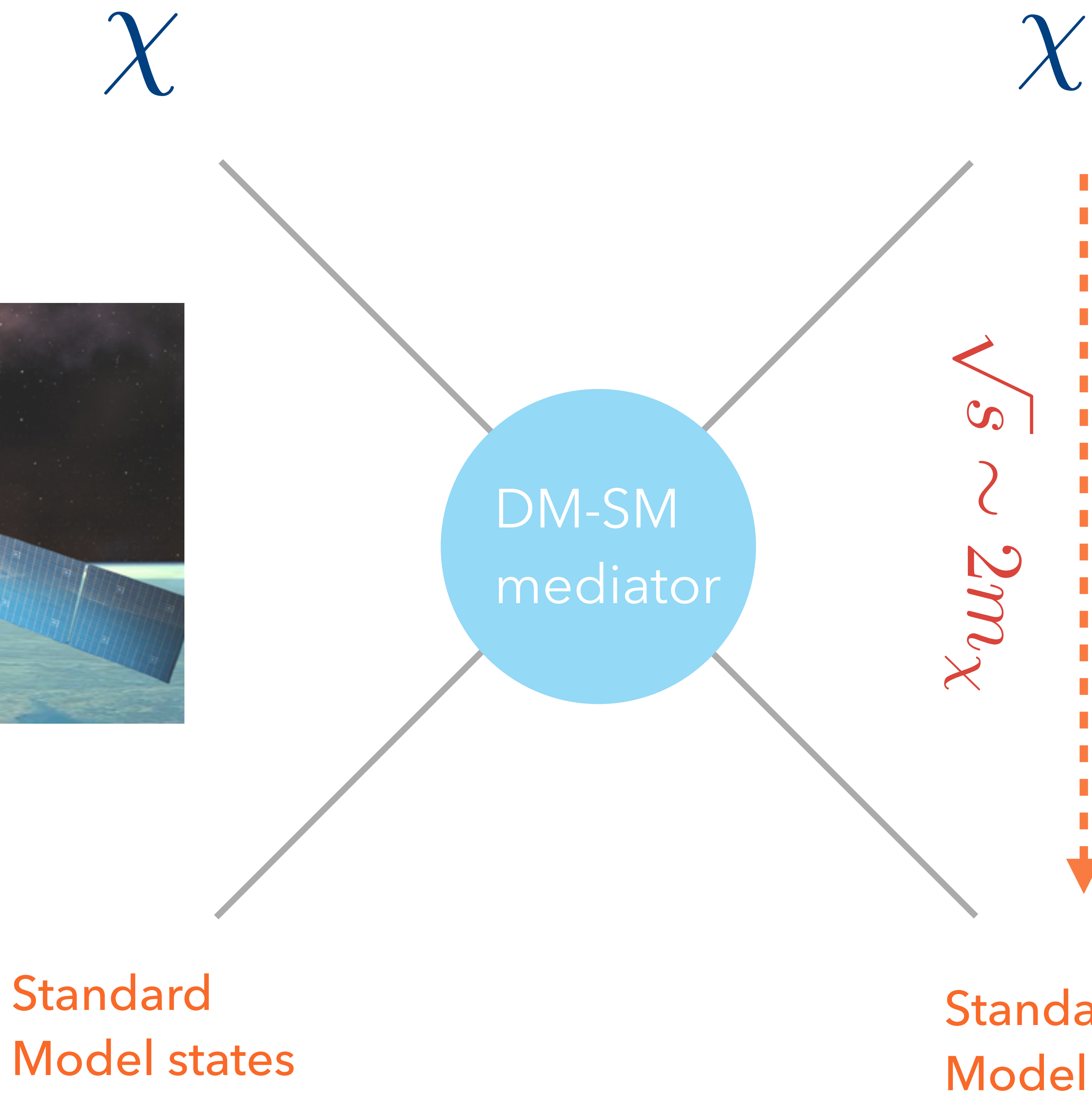
Monojet event in ATLAS at CERN



https://atlas.cern/updates/atlas-feature/dark-matter

HOW TO SEE IN THE DARK?



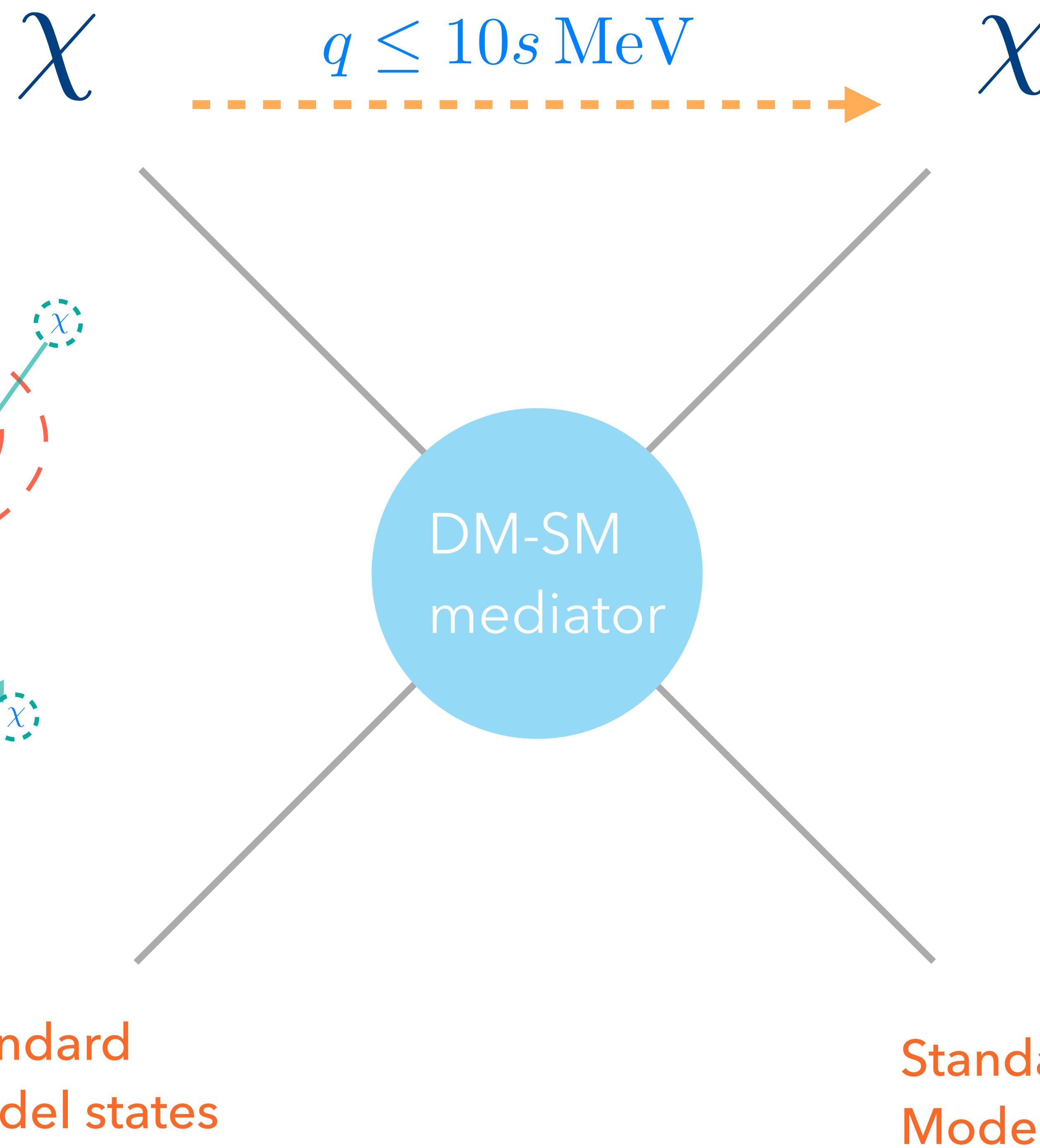


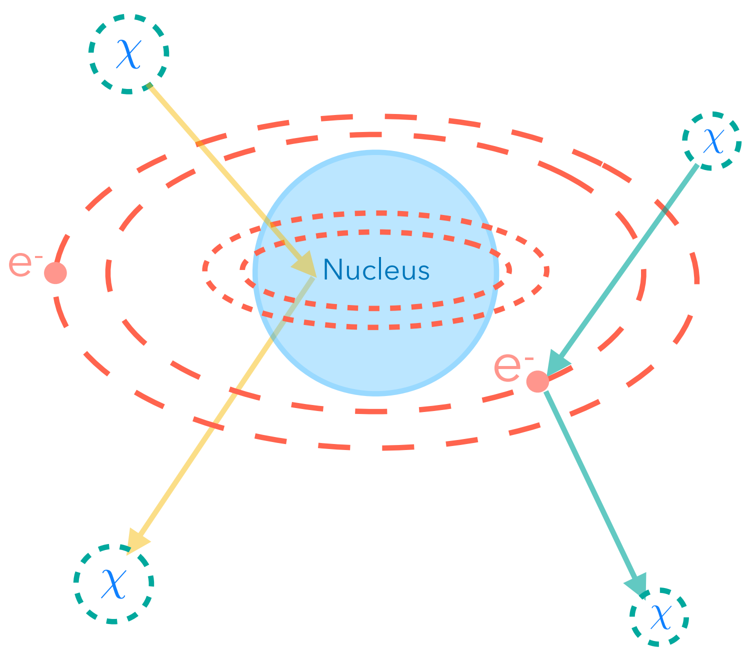
+ astrophysical probes, e.g. observations of structures on small scales & comparison with simulations

+ early Universe annihilation, e.g., constraints from CMB

see M. Buckley and A. Peter for a review 1712.06615

HOW TO SEE IN THE DARK?



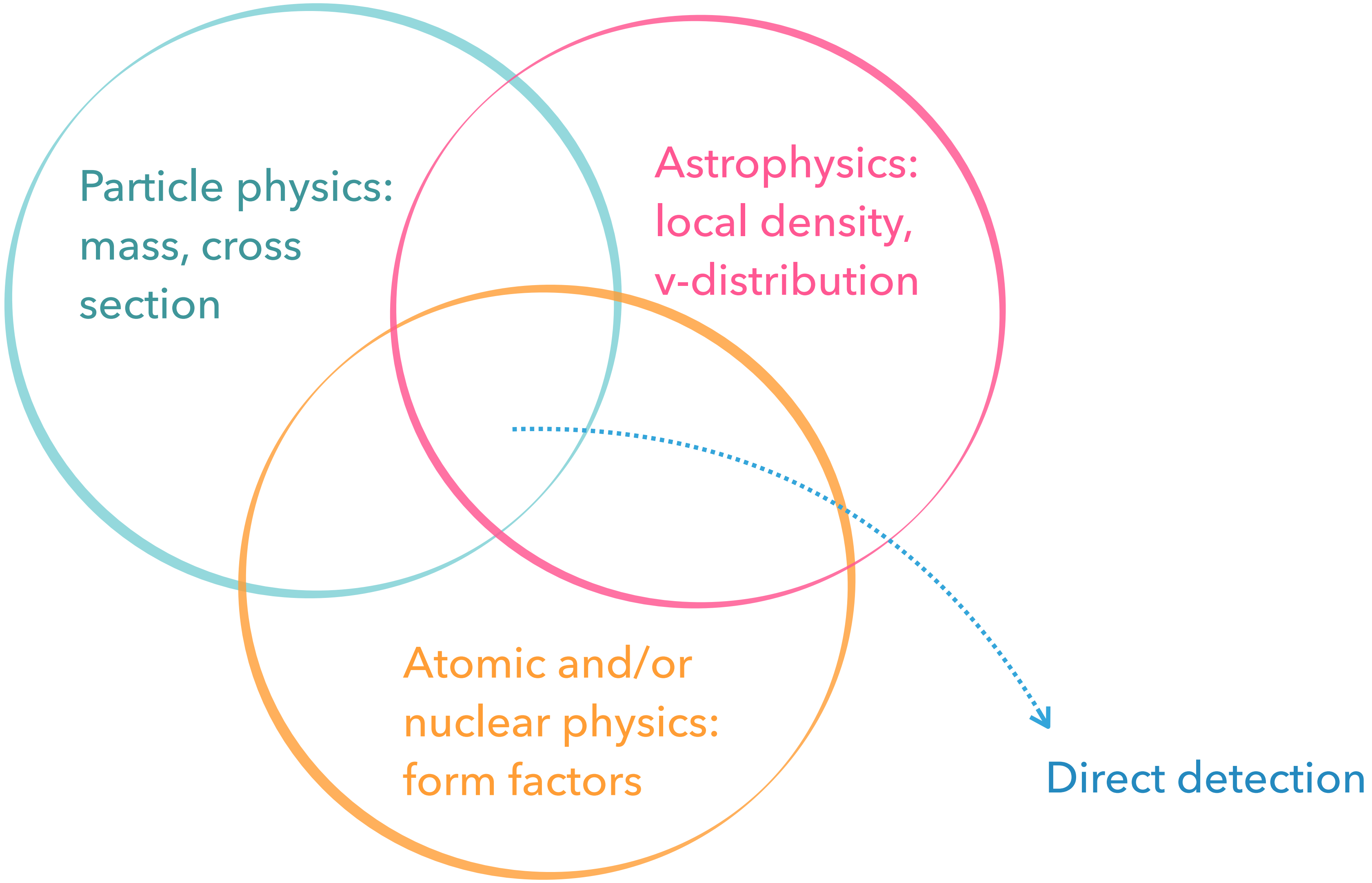


- collisions with electrons in the atomic shell, or absorption of light bosons via the axio-electric effect
- Bremsstrahlung from polarised atoms; e- emission due to so-called Migdal effect

see Kouvaris, Pradler, McCabe; M. Ibe et al.

DIRECT DETECTION PRINCIPLE

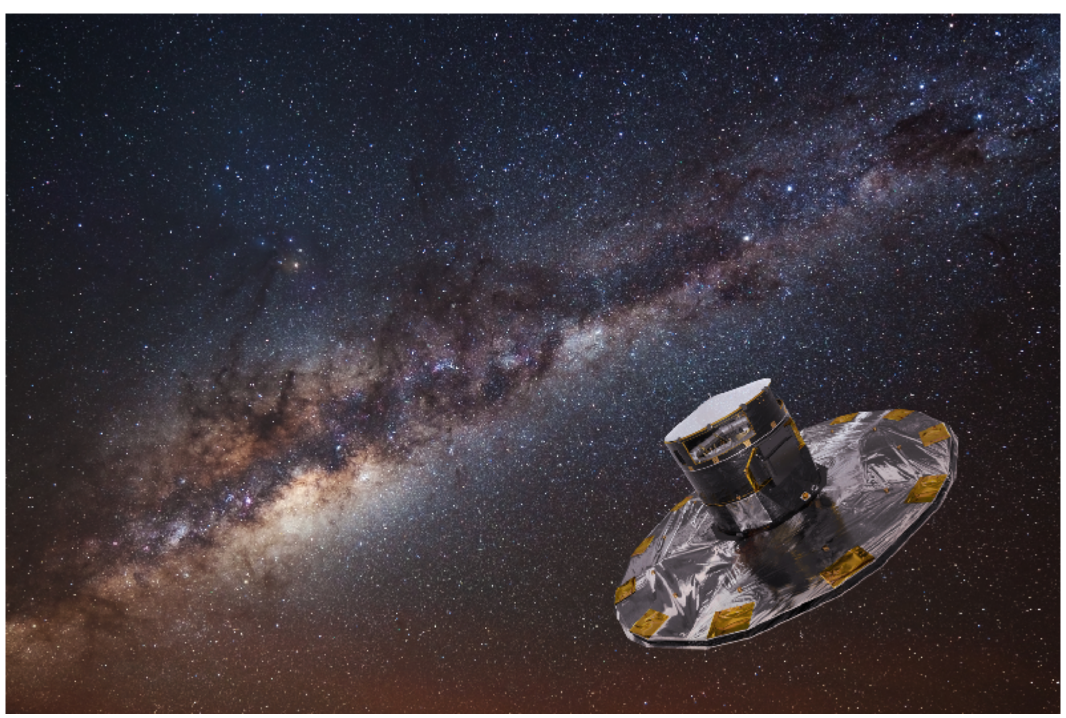
- Main physical observable: a differential recoil spectrum
- Its modelling relies on *several phenomenological inputs:*



LOCAL DARK MATTER DENSITY

- Local measures: vertical kinematics of stars near Suns as ‘tracers’ (smaller error bars, stronger assumptions about the halo shape)
- Global measures: extrapolate the density from Milky Way’s rotation curve derived from kinematic measurements of gas, stars… (larger errors, fewer assumptions)

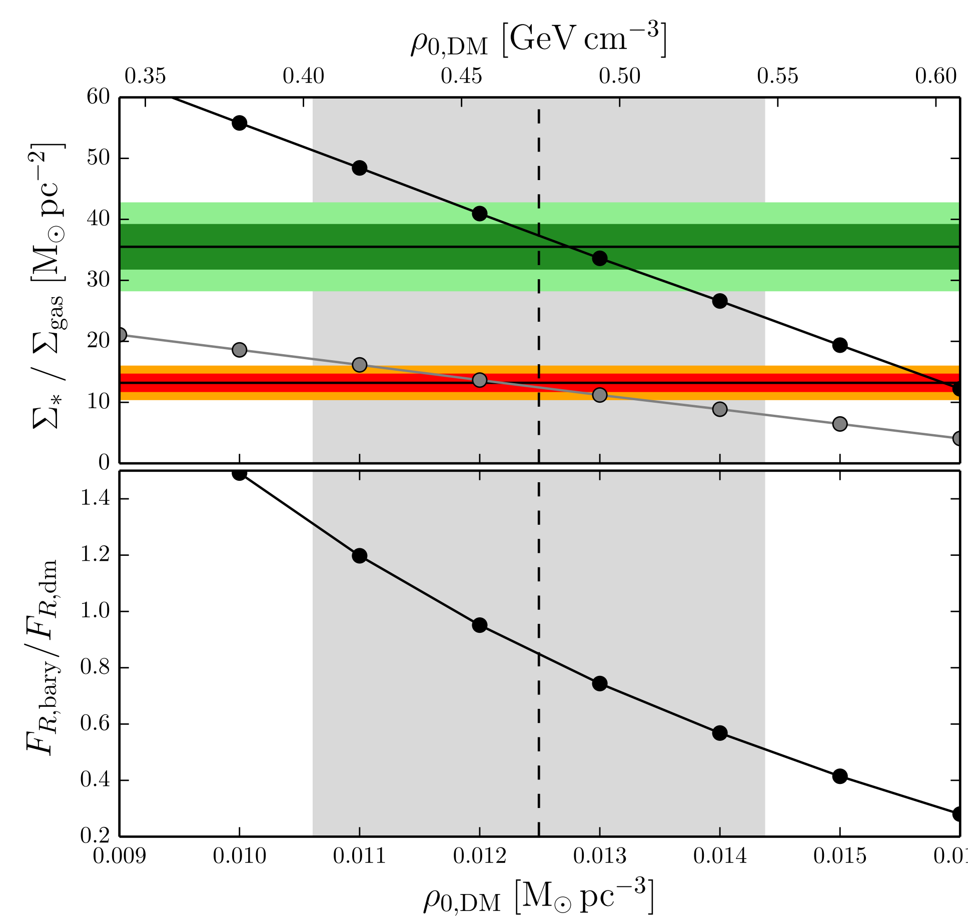
See review by Justin Read, Journal of Phys. G 41 (2014)



Gaia DR2 2018: positions, parallaxes, and proper motions for 1.3 x 10^9 stars

Major source of uncertainty: the contribution of baryons (stars, gas, stellar remnants, …) to the local dynamical mass

Piffl et al, MNRAS 445 (2014)
see also : J. Hagen & A. Helmi, A&A 615 (2018) for somewhat higher local densities (0.018 $M_\odot/pc^3$) and R. Guo et al, MNRAS 495, 2020 (0.0133 $M_\odot/pc^3$)



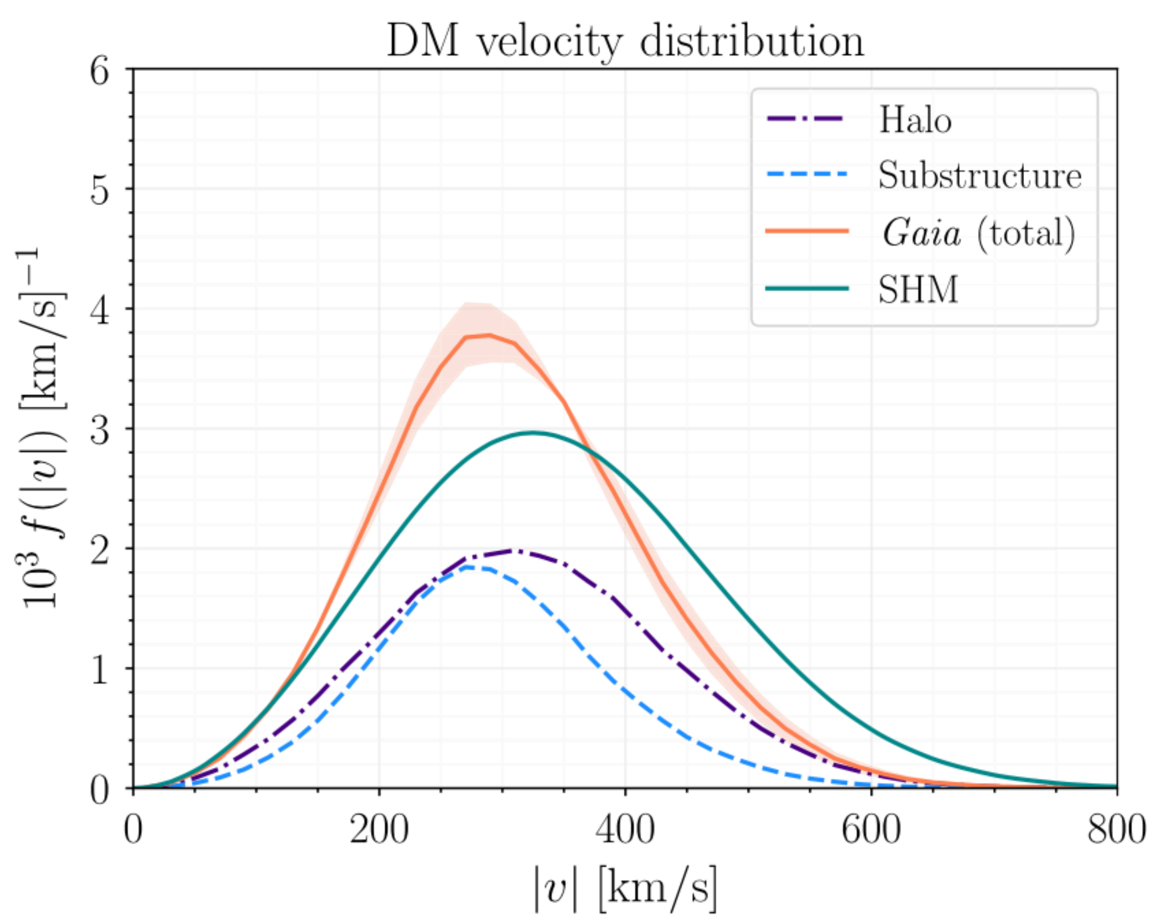
DARK MATTER VELOCITY DISTRIBUTION

- Standard halo model: Maxwellian distribution (isotropic velocities)

$$\rho(r) \propto r^{-2}$$

- Goal: determine f(v) from observation (e.g., study motion of stars that share kinematics with DM)
- Recent studies: some deviations from SHM, due to anisotropies in the local stellar distribution (in Gaia data)
- These arise from accretion events, where the "Gaia-sausage" seems to be the dominant merger in the solar neighbourhood
- Effects: changes mostly at low dark matter masses

See, e.g., Necib, Lissanti, Belorukov 2018, Evans, O'Hare, McCabe, PRD99, 2019, Buch, Fan, Leung, PRD101, 2020



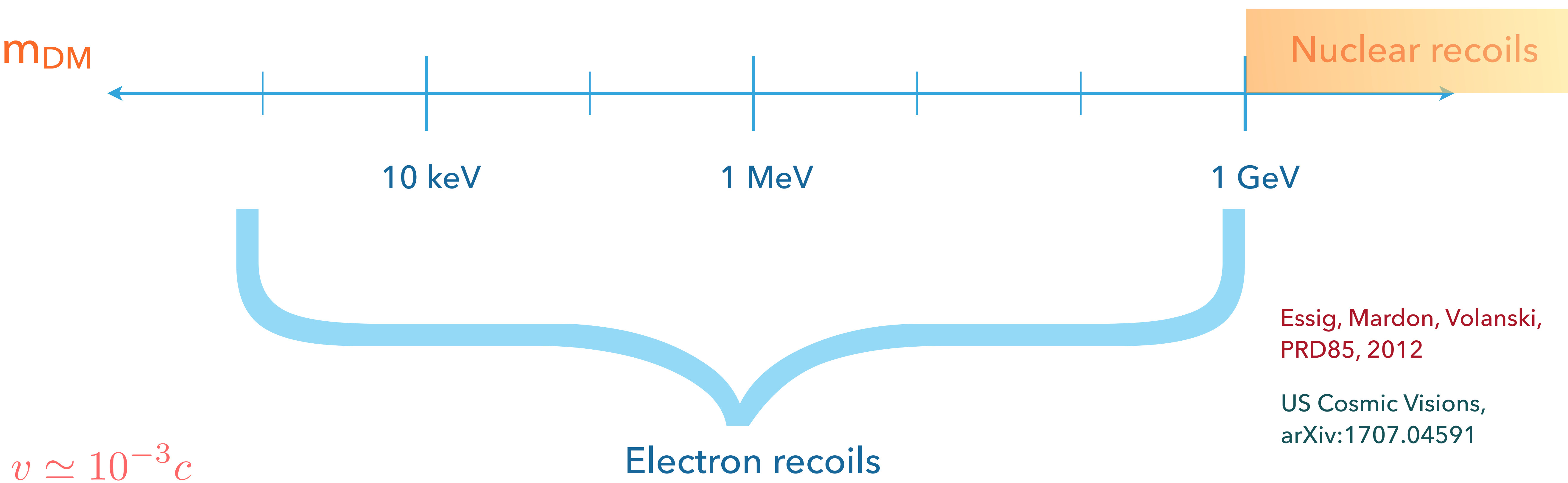
Normalised Gaia DM velocity distribution in heliocentric frame

KINEMATICS: DARK MATTER PARTICLE MASS

- Light DM: nuclear recoil energy - well below the threshold of most experiments
- Total energy in scattering: larger, and can induce inelastic atomic processes -> visible signals

$$E_e \leq \frac{m_{DM} v^2}{2} \leq 3\,\mathrm{eV} \times \frac{m_{DM}}{1\,\mathrm{MeV}}$$

$$E_{NR} = \frac{q^2}{2m_N} \simeq 1\,\mathrm{eV} \times \left(\frac{m_{DM}}{100\,\mathrm{MeV}}\right)^2 \times \frac{10\,\mathrm{GeV}}{m_N}$$

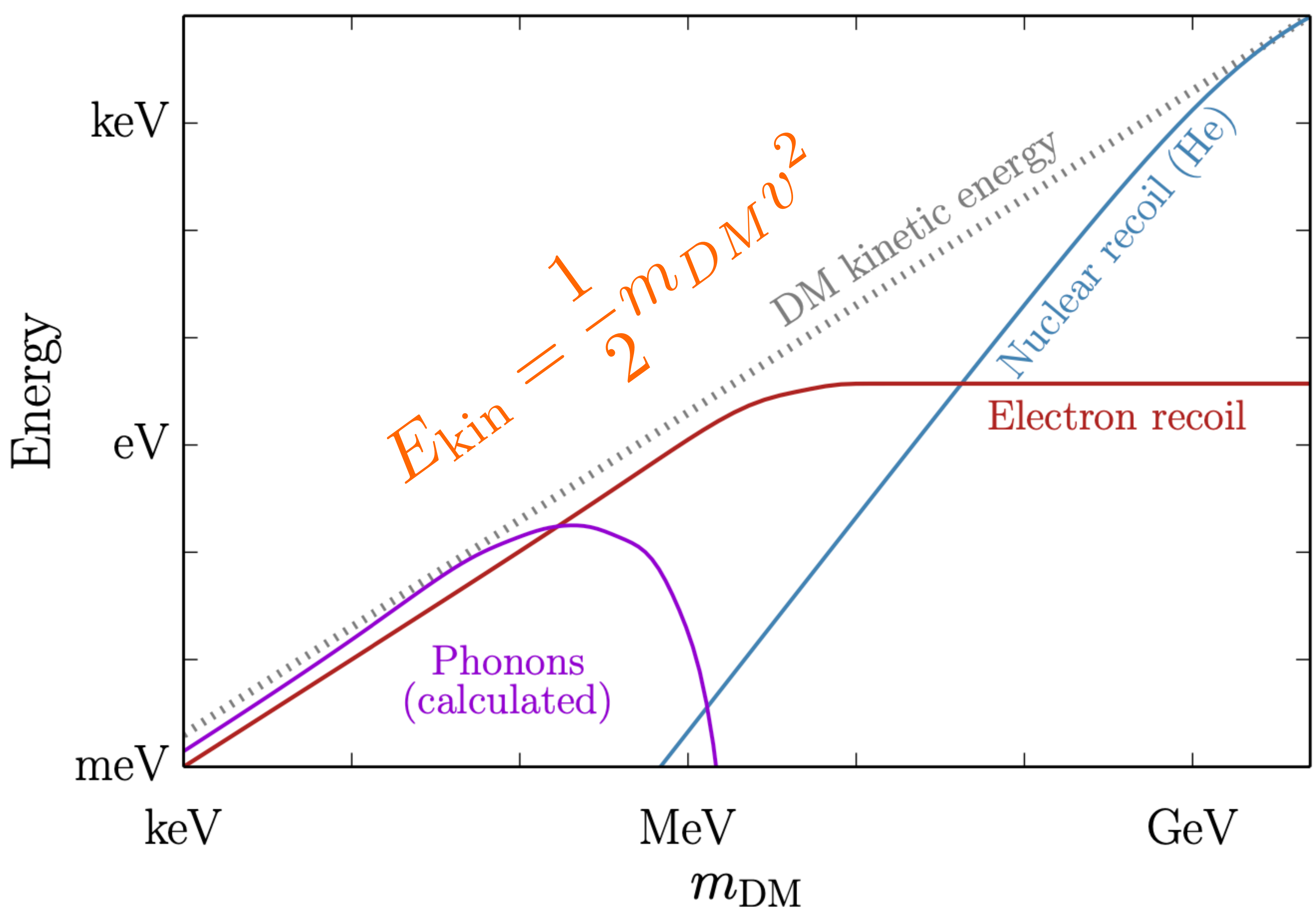


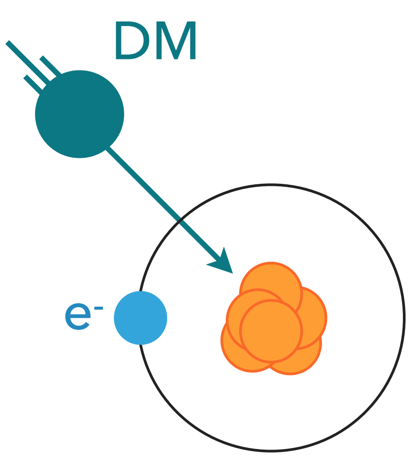
Essig, Mardon, Volanski, PRD85, 2012

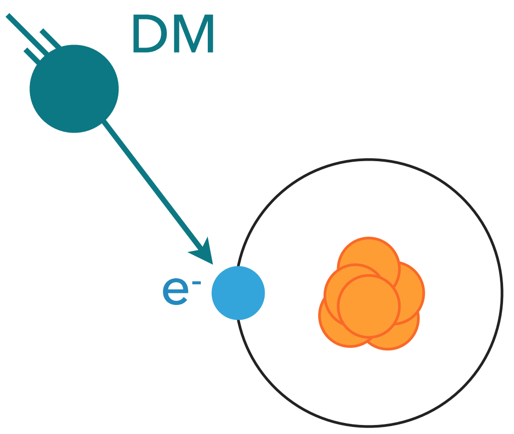
US Cosmic Visions, arXiv:1707.04591

$v \simeq 10^{-3} c$

KINEMATICS: DARK MATTER PARTICLE MASS

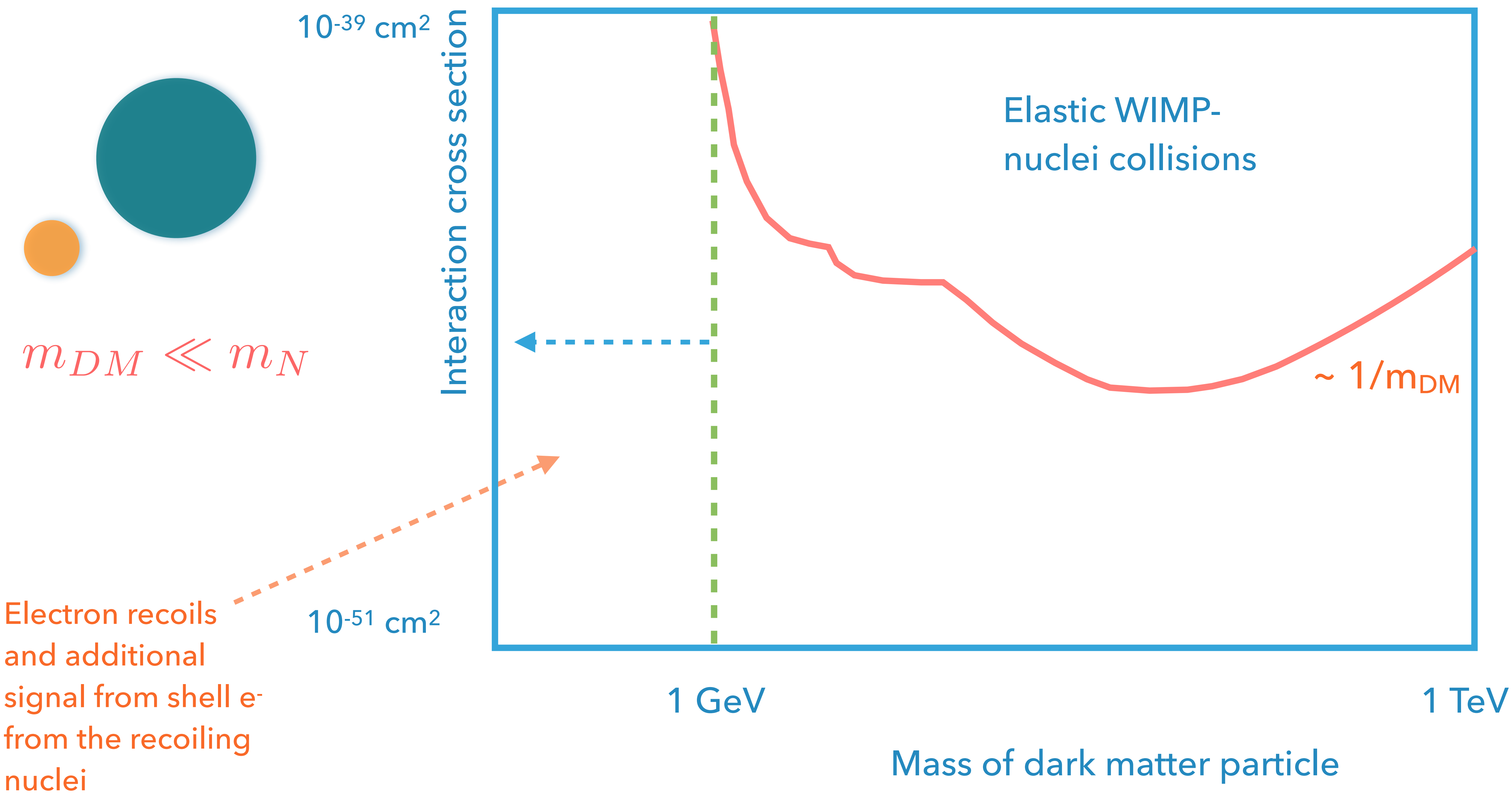






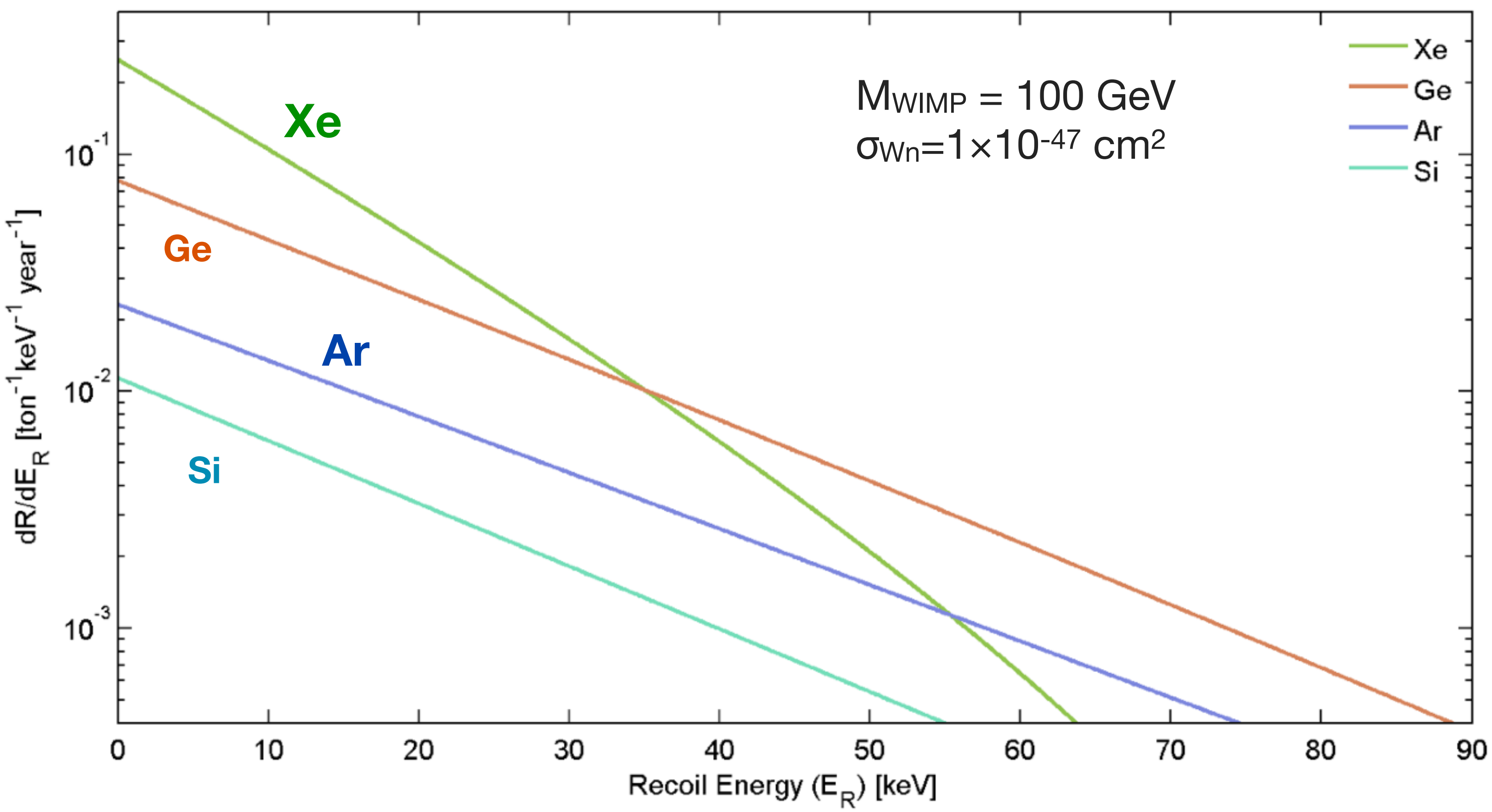
Tongyan Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915

INTERACTION CROSS SECTION VS MASS



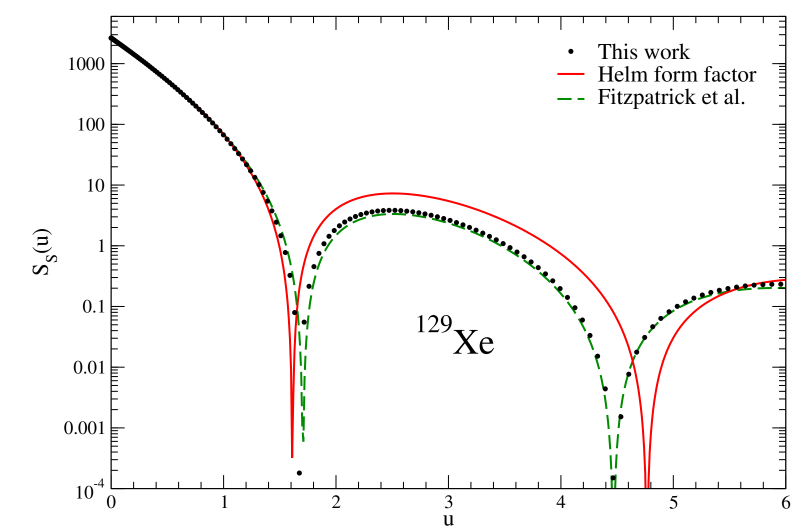
INTERACTION RATES: DM-NUCLEUS SCATTERING

$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

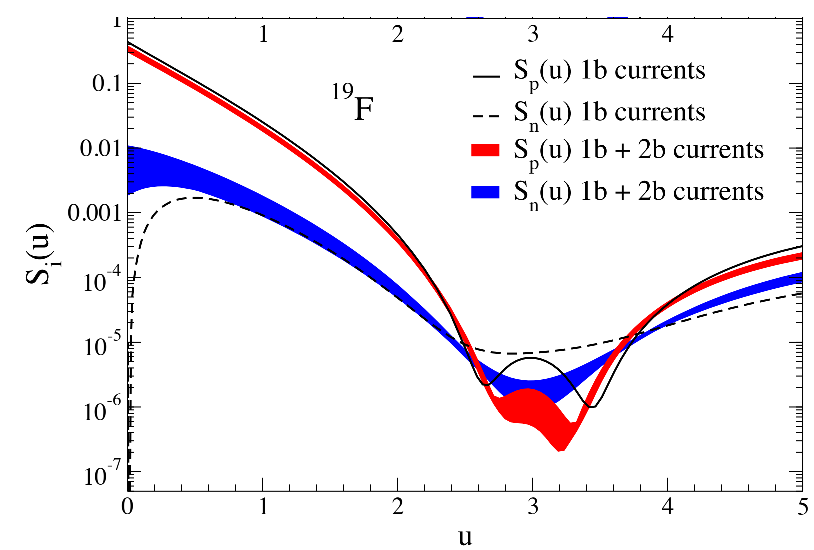


Spin-independent (SI) nuclear recoil spectrum

L. Vietze, W. Haxton et al., Phys.Rev. D91 (2015)



SI



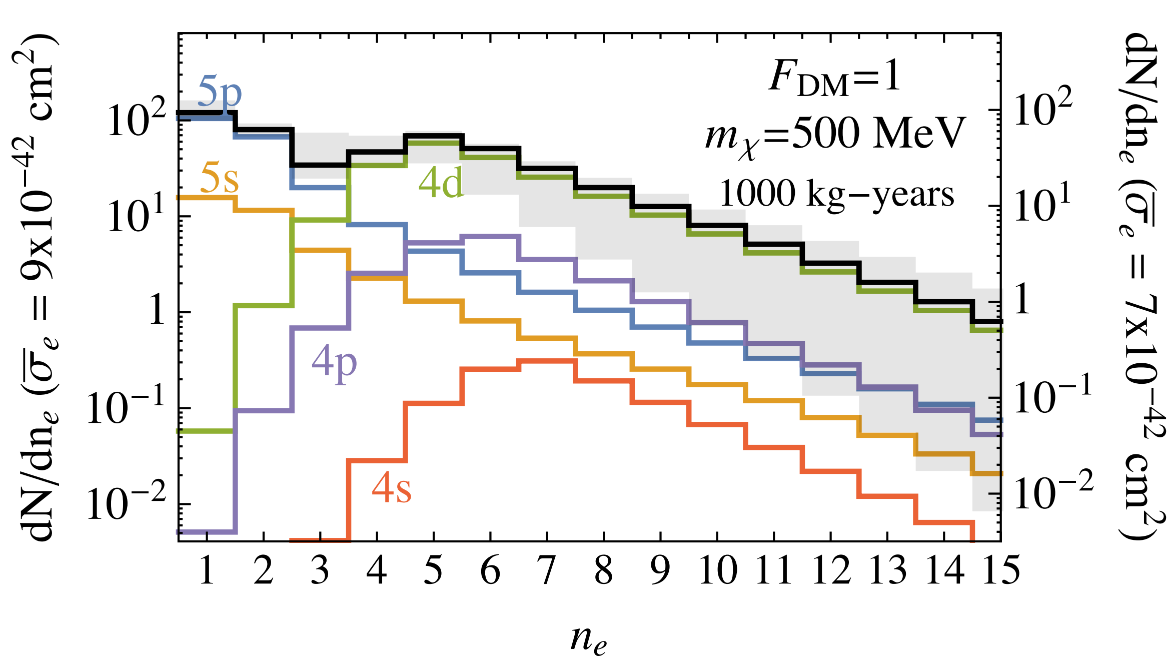
SD

P. Klos et al., PRD 88 (2013)

INTERACTION RATES: DM-ELECTRON SCATTERING

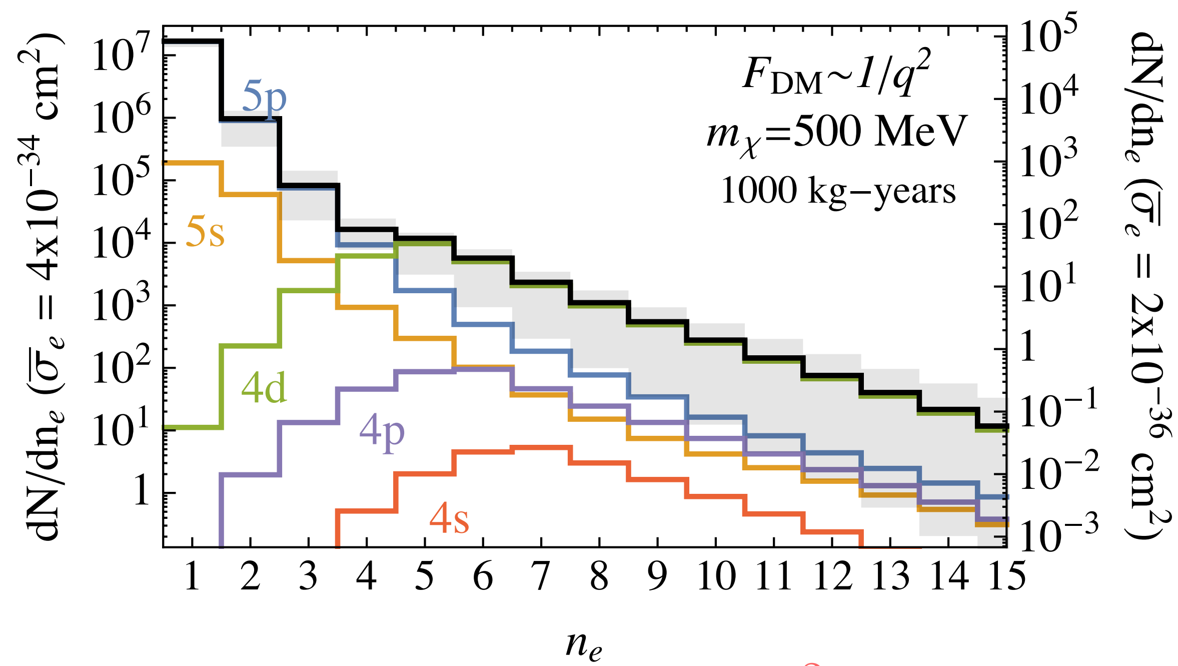
$$\frac{dR_{ion}}{d\ln E_R} = \frac{6.2}{A}\left(\frac{\rho_0}{0.4\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\sigma_e}{10^{-40}\mathrm{cm}^2}\right)\left(\frac{10\,\mathrm{MeV}}{m_{\mathrm{DM}}}\right)\times\frac{d\langle\sigma_{ion}v\rangle/d\ln E_R}{10^{-3}\sigma_e}\,\frac{\mathrm{events}}{\mathrm{kg\,d}}$$

Expected number of events for a xenon detector with 1 tonne year exposure



$$F_{DM} = 1$$

Heavy dark photon A' mediator



$$F_{DM} = \alpha^2\frac{m_e^2}{q^2}$$

Ultra-light dark photon A' mediator

Essig, Volanski, Yu, PRD 96, 2017

INTERACTION RATES: DM ABSORPTION

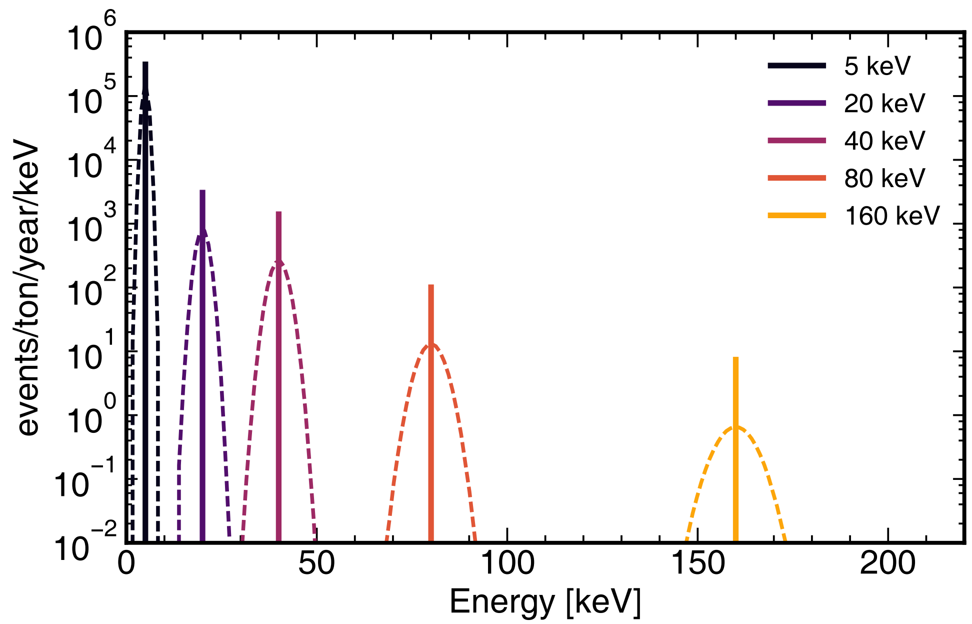
- Absorption of bosonic DM (ALPs, dark photons) via the axioelectric effect
- Rates ~ φ x σ ~ ρ x v/m x σ (here below for ρ = 0.3 GeV/cm³)

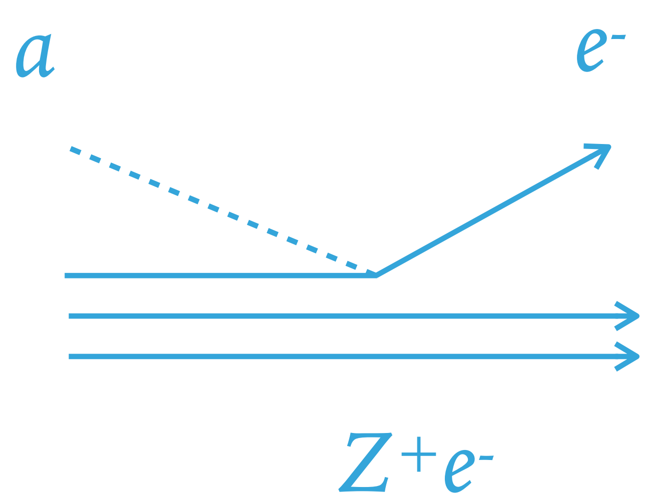
$$R \simeq \frac{1.5 \times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

$$R \simeq \frac{4.7 \times 10^{23}}{A} \kappa^2 \left(\frac{\mathrm{keV}}{m_V}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2}\left(1 - \frac{\beta^{2/3}}{3}\right)$$

$$\sigma_v \simeq \frac{\sigma_{pe}}{\beta}\kappa^2$$



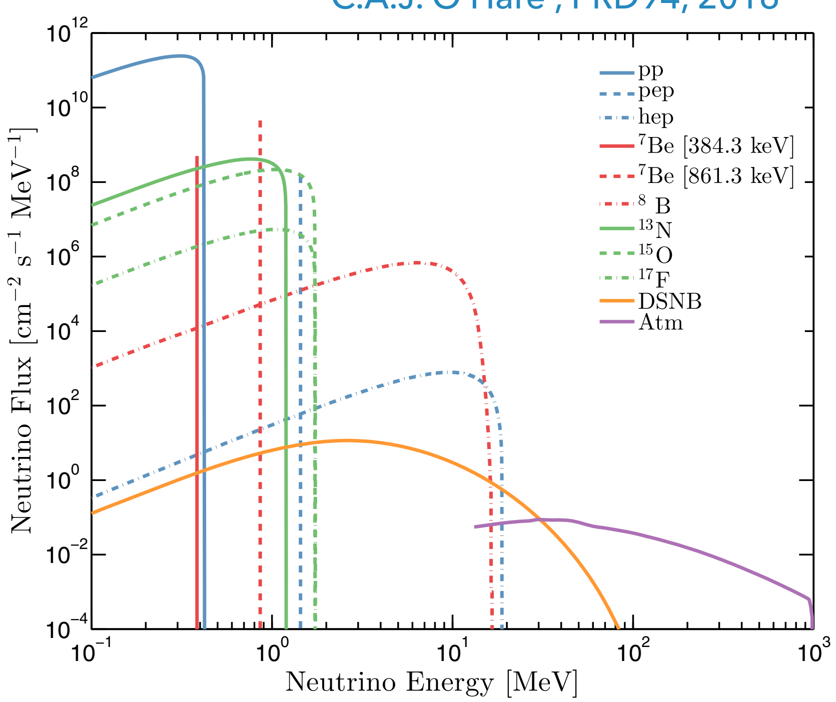


Pospelov, Ritz, Voloshin, PRD 78, 2008; An, Pospelov, Pradler, Ritz, PLB747, 2015, …

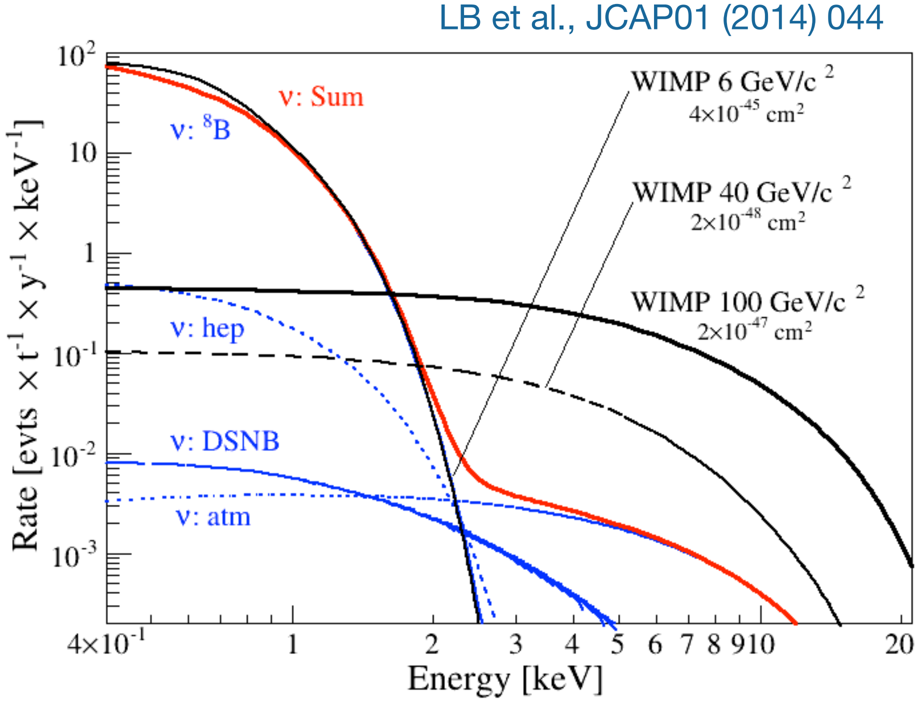
BACKGROUNDS

- In the ideal case: below the expected signal
  - Muons & associated showers; cosmogenic activation of detector materials
  - Natural (^{228}U, ^{232}Th, ^{40}K) and anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ,e⁻,α,n
  - Neutrinos: coherent elastic neutrino-nucleus scattering and elastic neutrino-electron scattering

C.A.J. O'Hare , PRD94, 2016

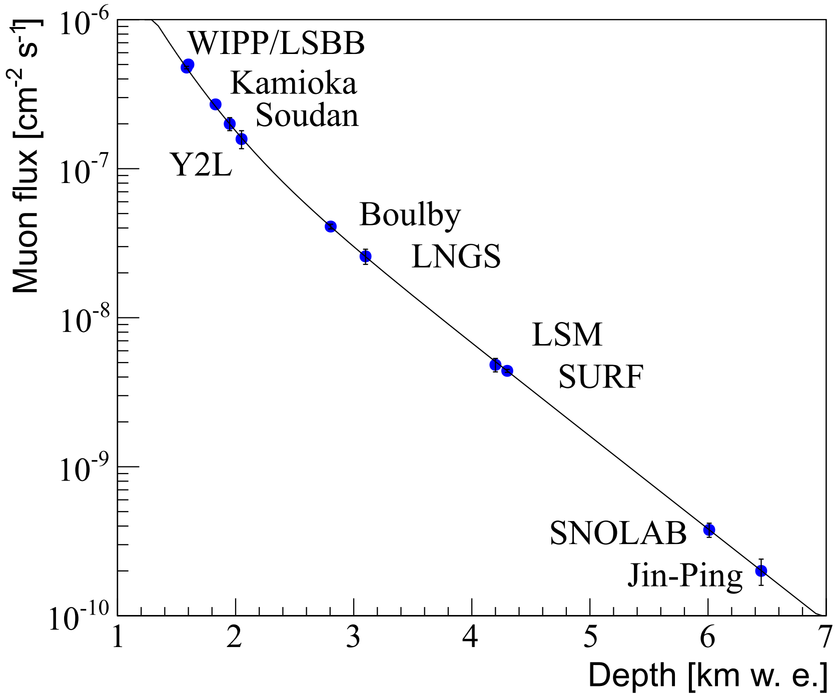


LB et al., JCAP01 (2014) 044



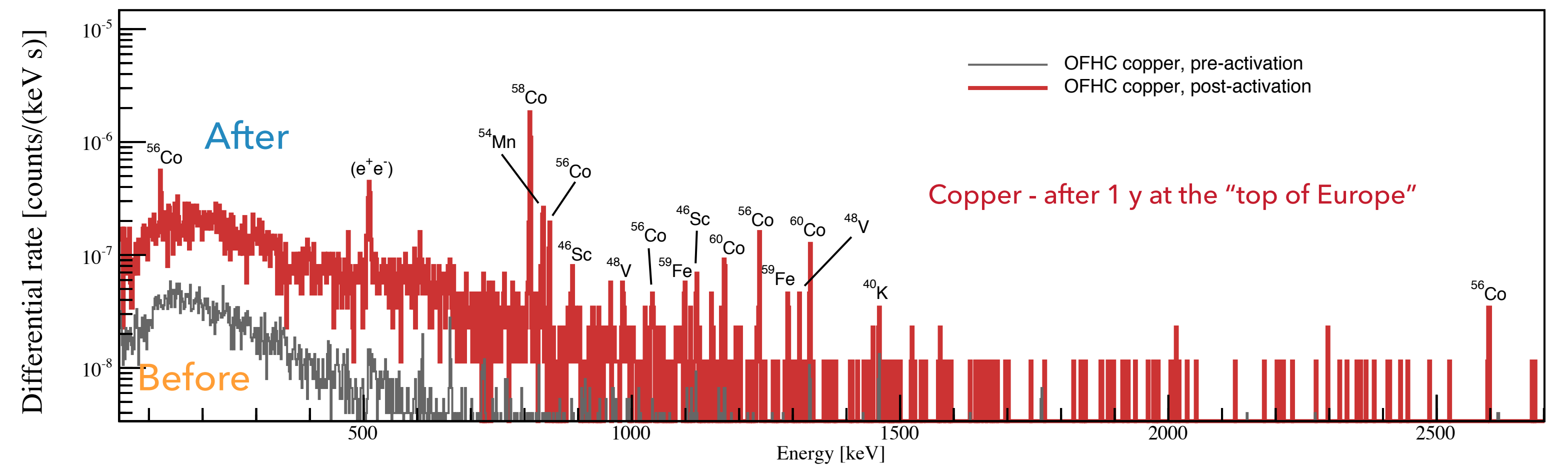
BACKGROUND REDUCTION

- Go deep underground

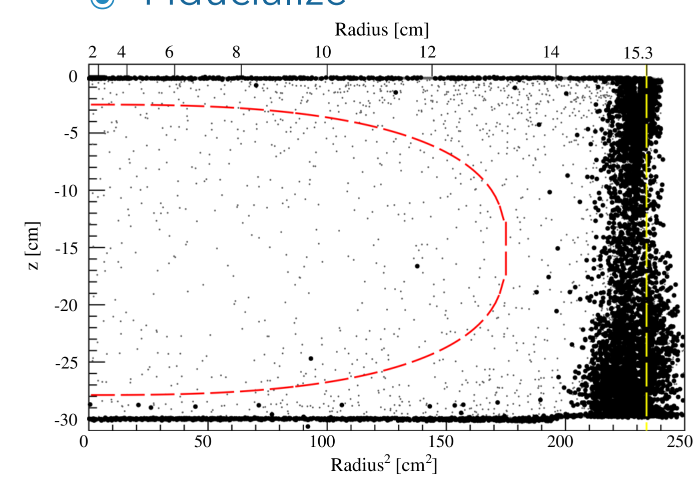


- Avoid cosmic activation

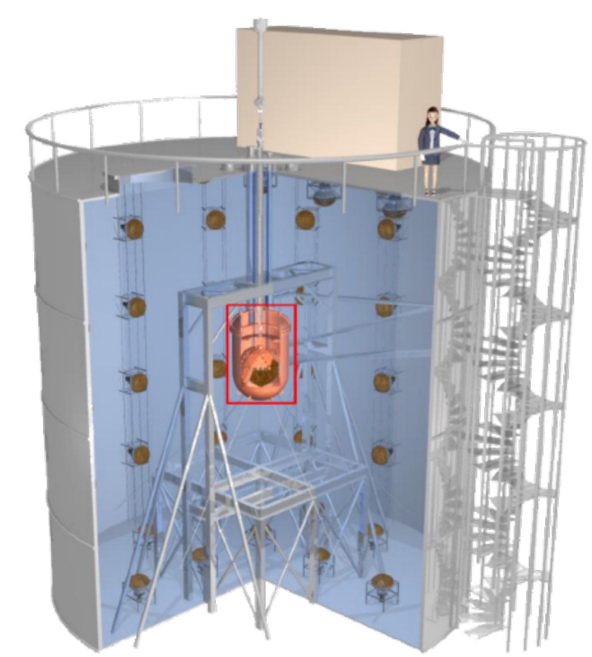
LB et al., Eur. Phys. J. C75 2015



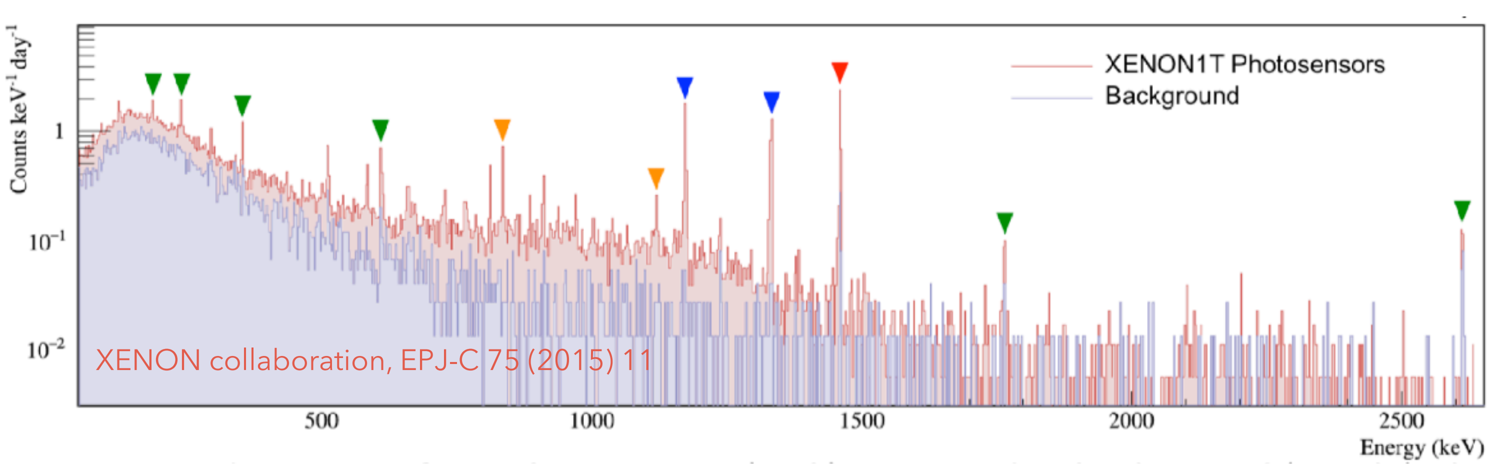
- Fiducialize



- Use active shields



- Select low-radioactivity materials

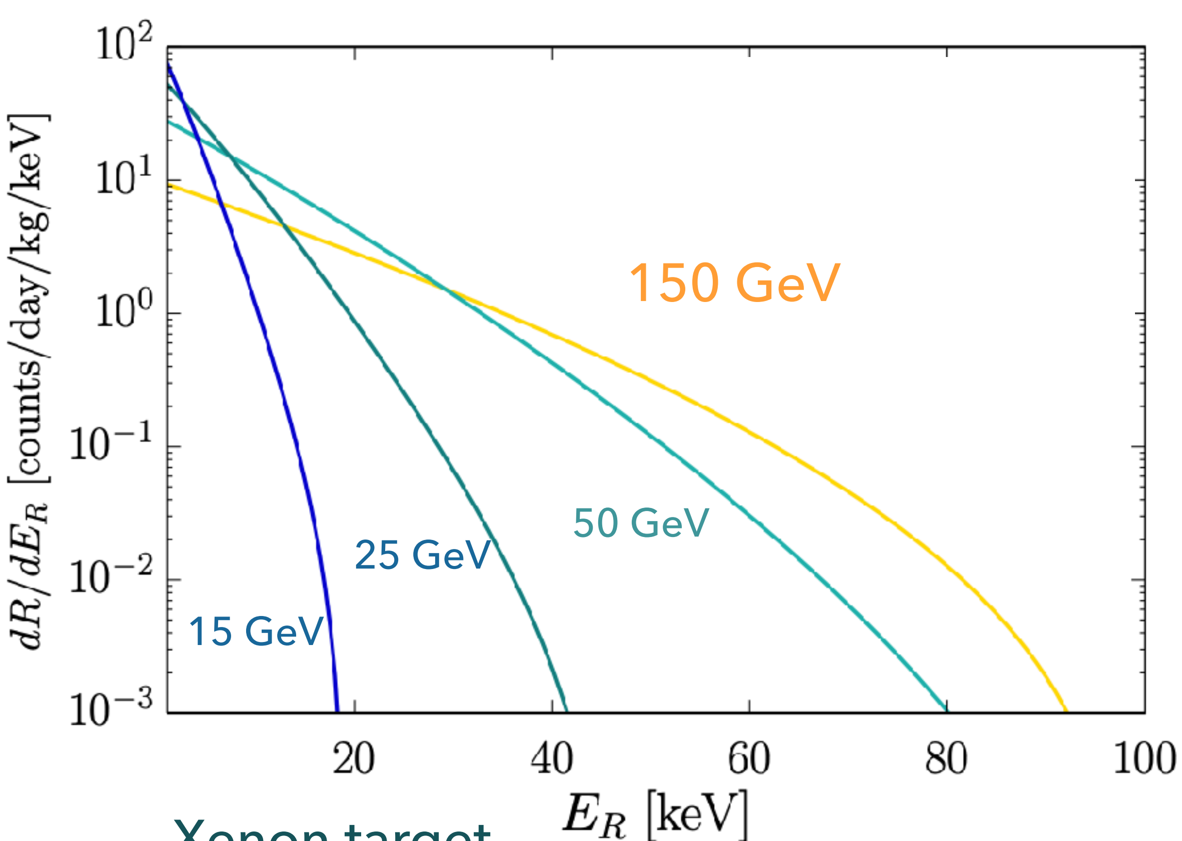


SIGNATURES

Rate and shape of recoil spectrum depend on:

DM particle mass

target material

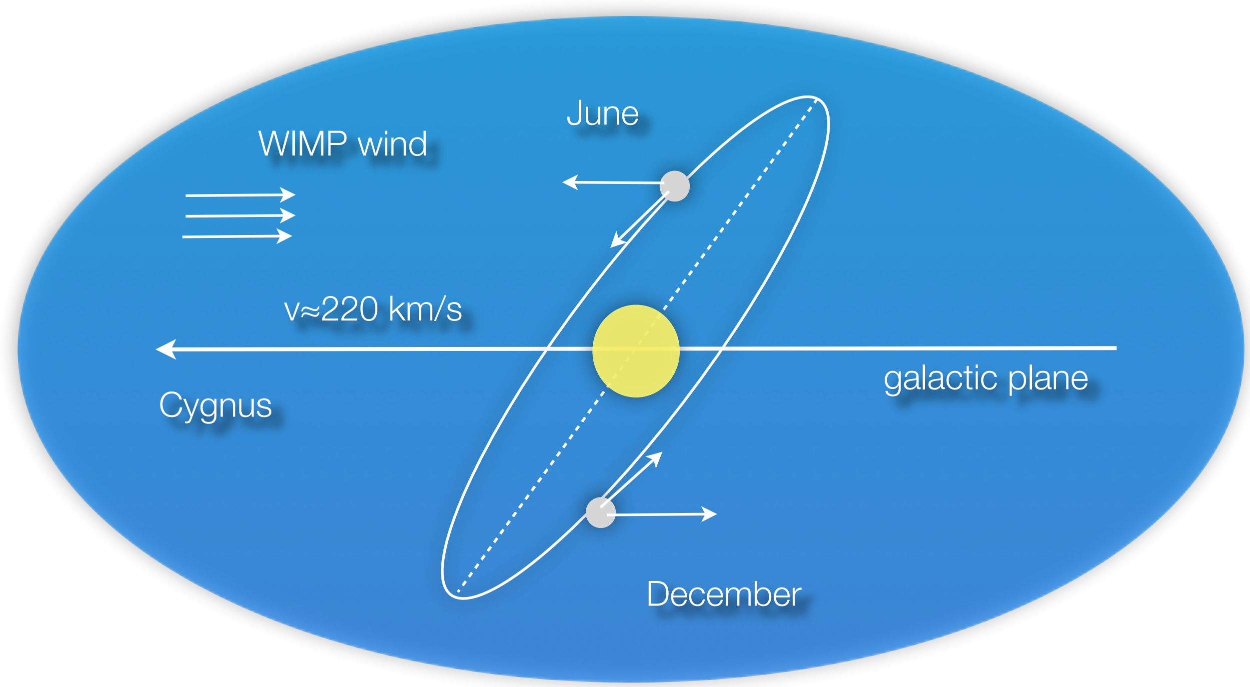


Xenon target

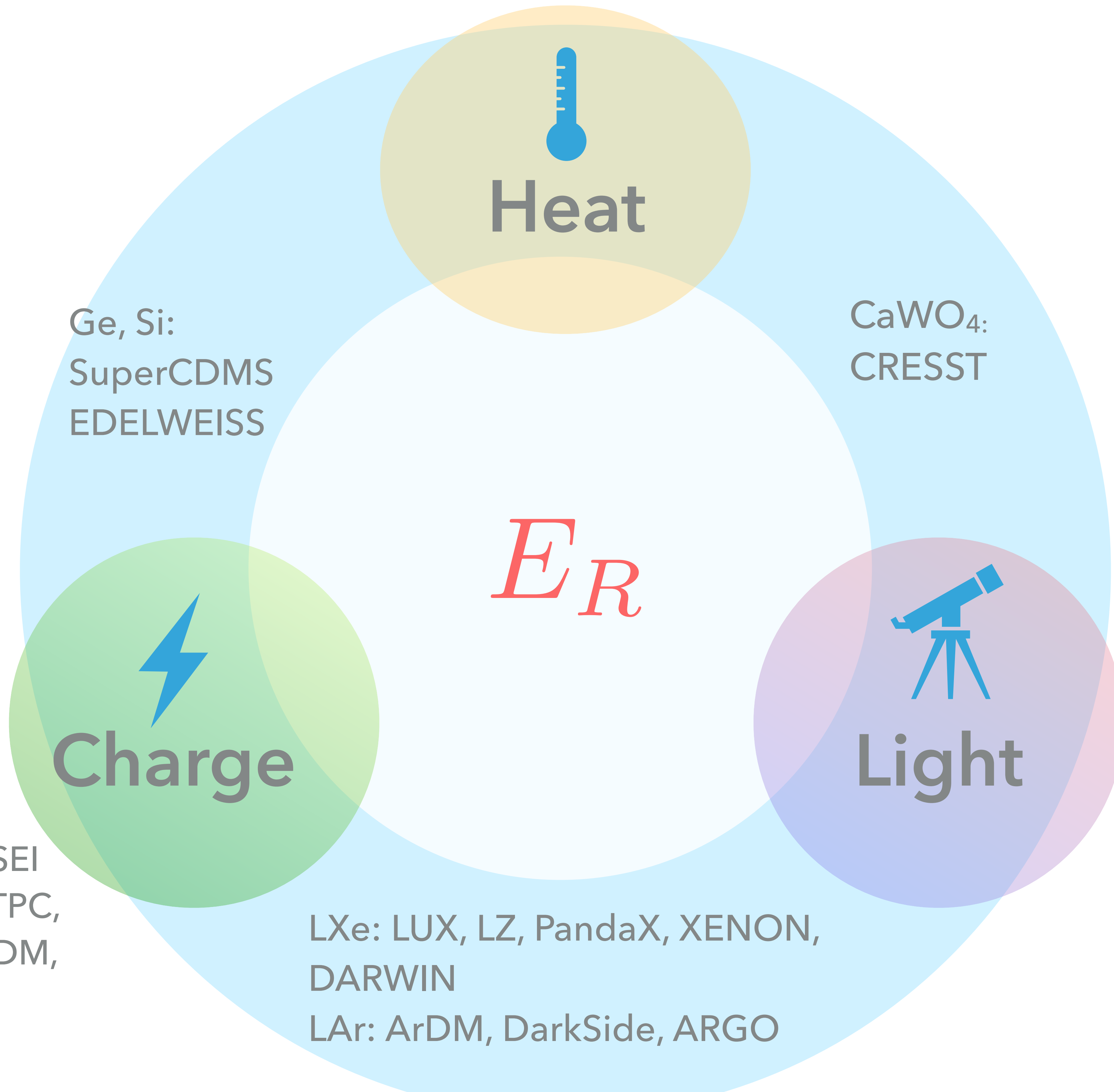
Motion of Earth causes:

annual event rate modulation: June - December asymmetry ~ 2-10%

sidereal directional modulation: asymmetry ~20-100% in forward-backward event rate



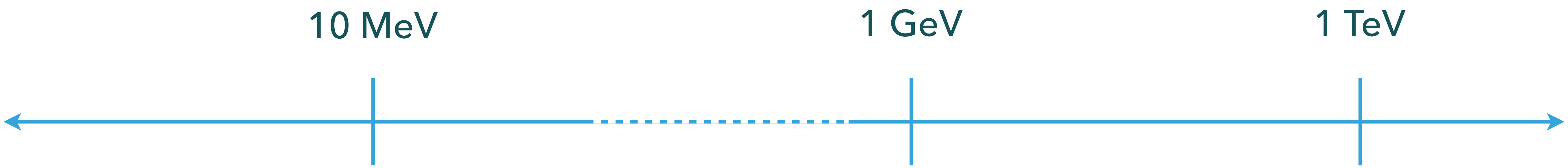
DIRECT DETECTION SIGNALS

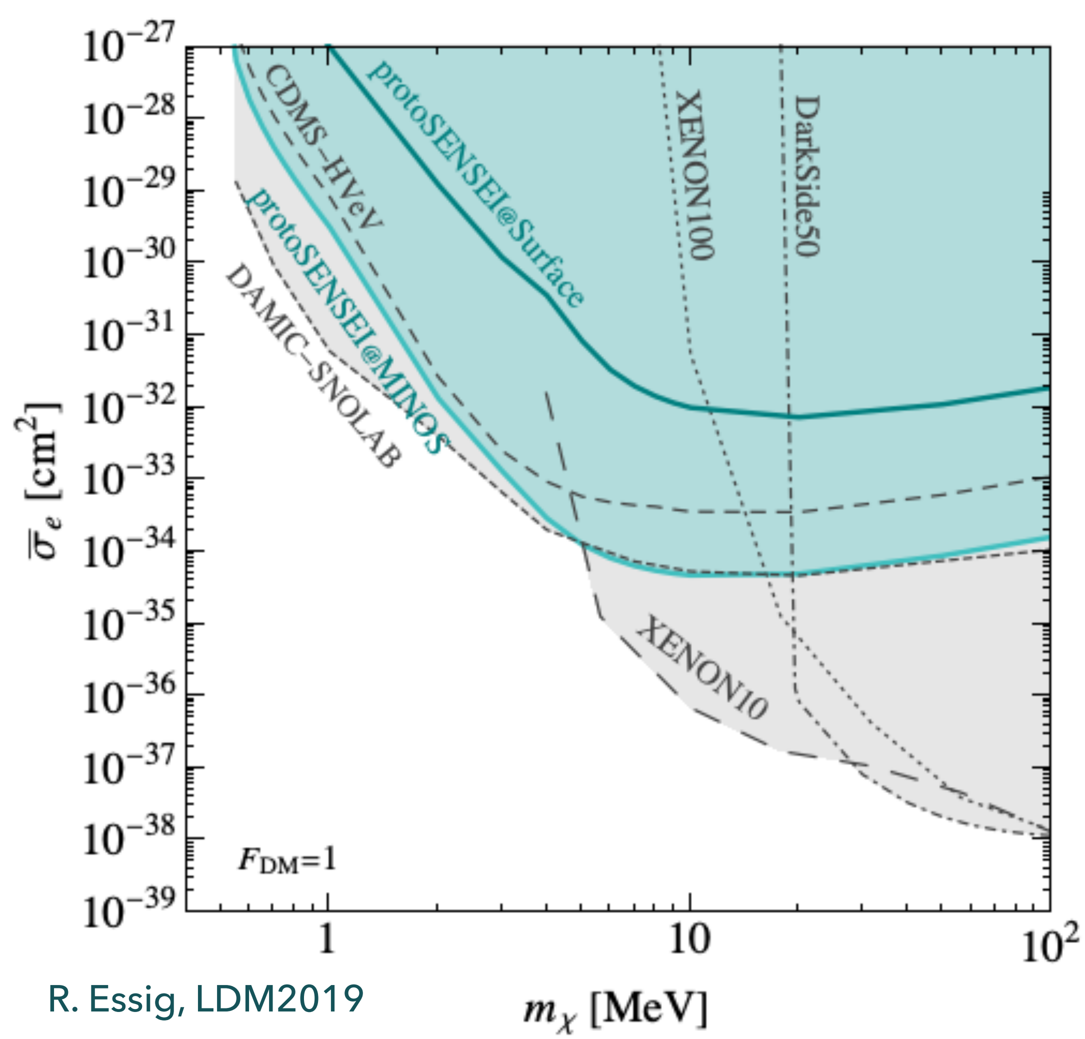


C_3F_8, CF_3I: PICO
Ge: CDEX
Si: DAMIC, SENSEI
CF_4: DRIFT, DMTPC,
MIMAC, NEWS-DM,
NEWS-G

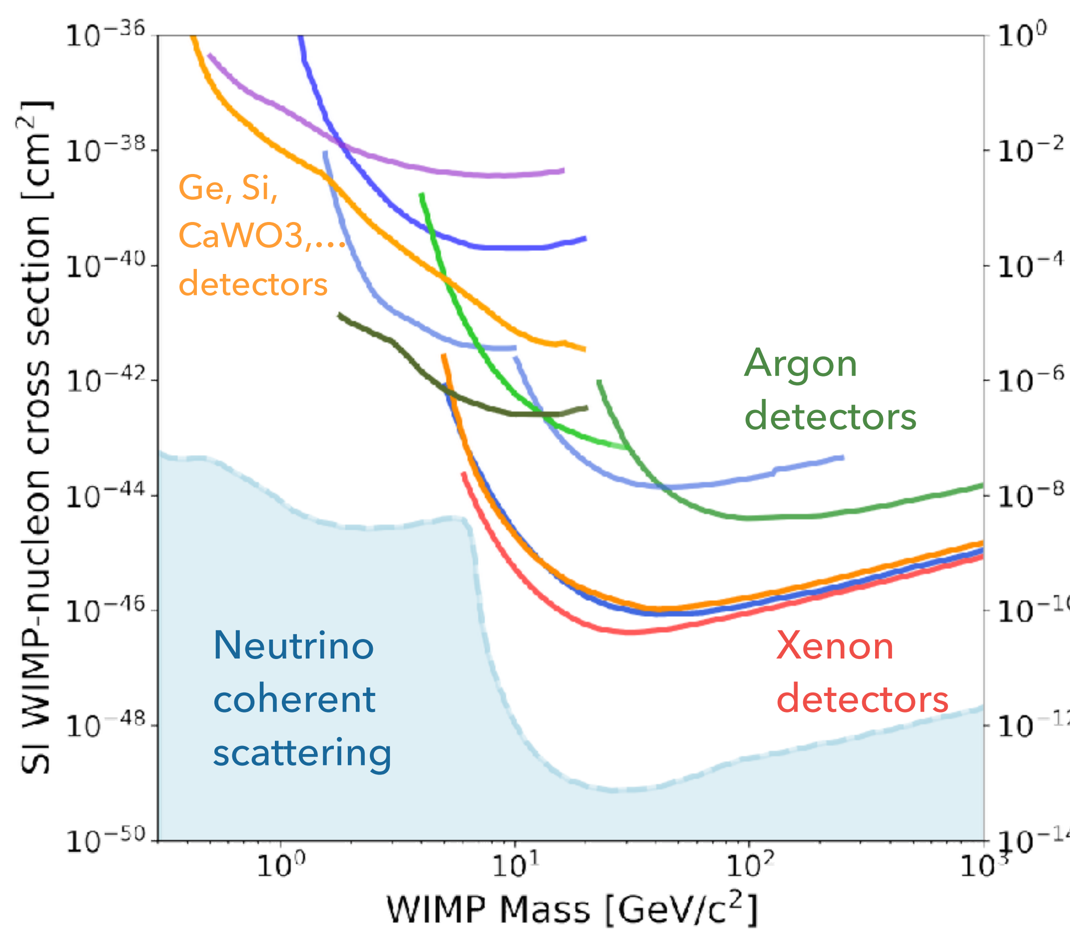
LXe: XMASS
LAr: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE

THE DIRECT DETECTION LANDSCAPE IN ~2020





R. Essig, LDM2019



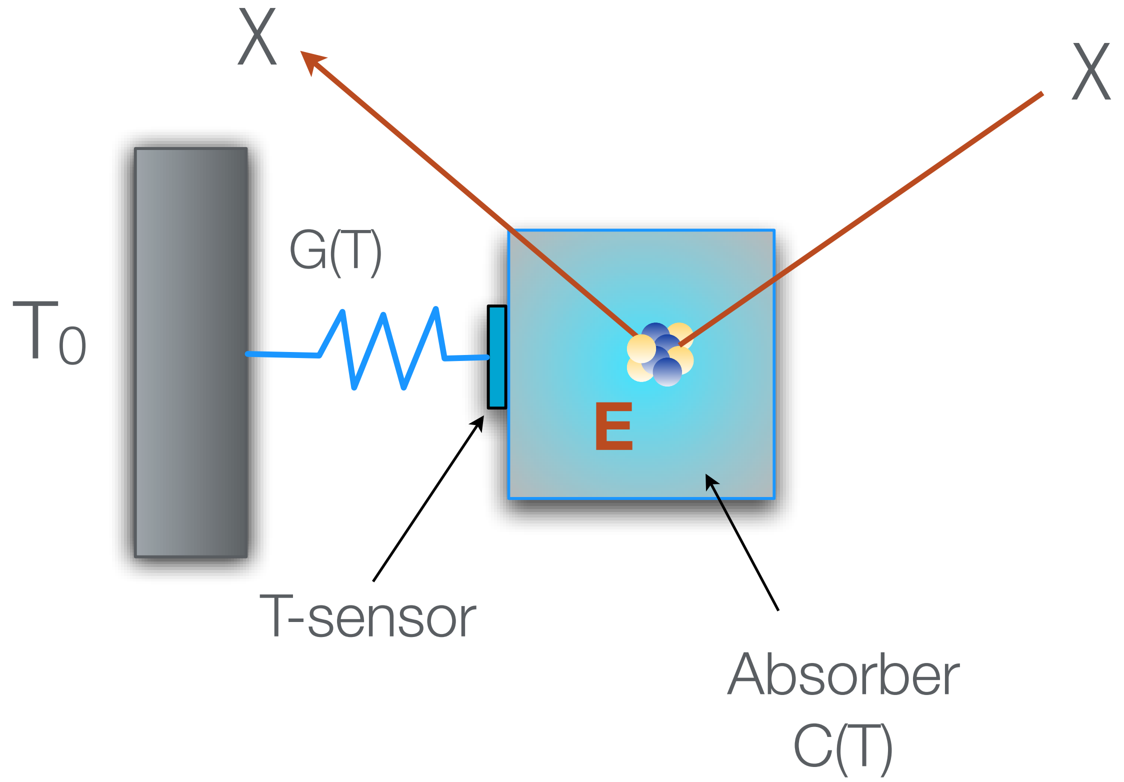
Scattering off electrons

Scattering off nuclei

CRESST, SUPERCDMS, EDELWEISS, DAMIC, SENSEI,. . .

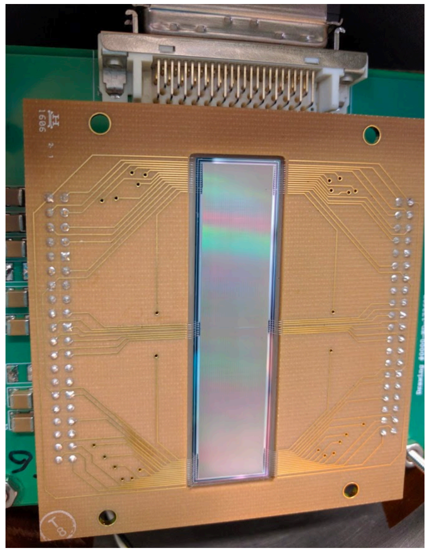
- Sub-keV energy thresholds
- Probe sub-GeV particle masses
- Phonons and/or ionisation and light

+ R&D on new technologies

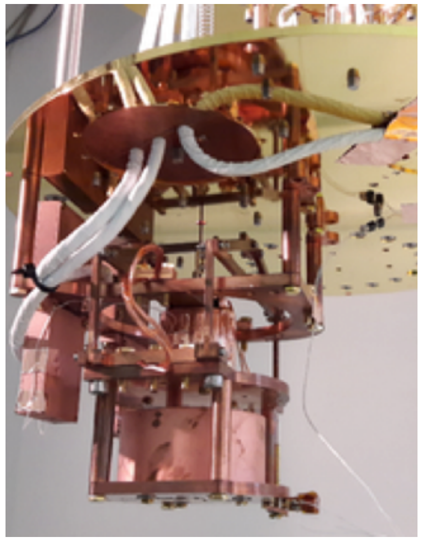


CRESST

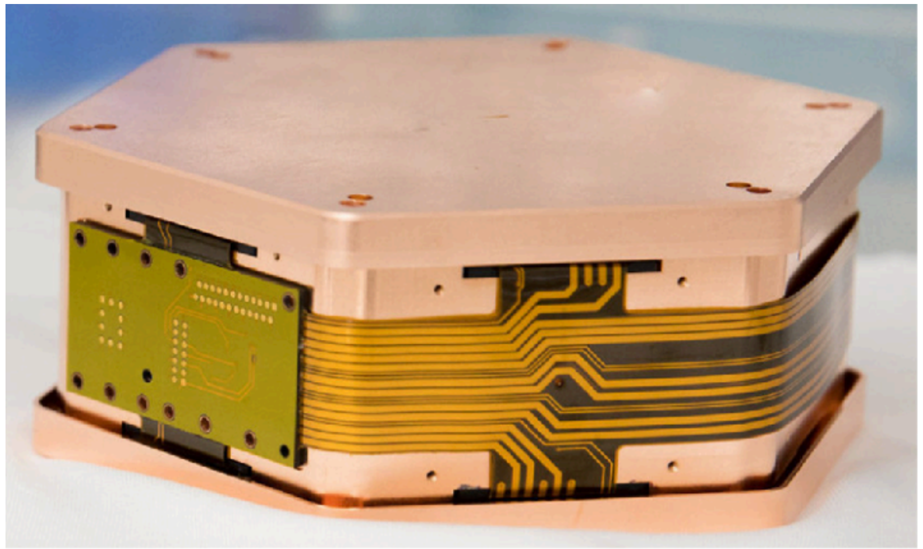
SENSEI



EDELWEISS

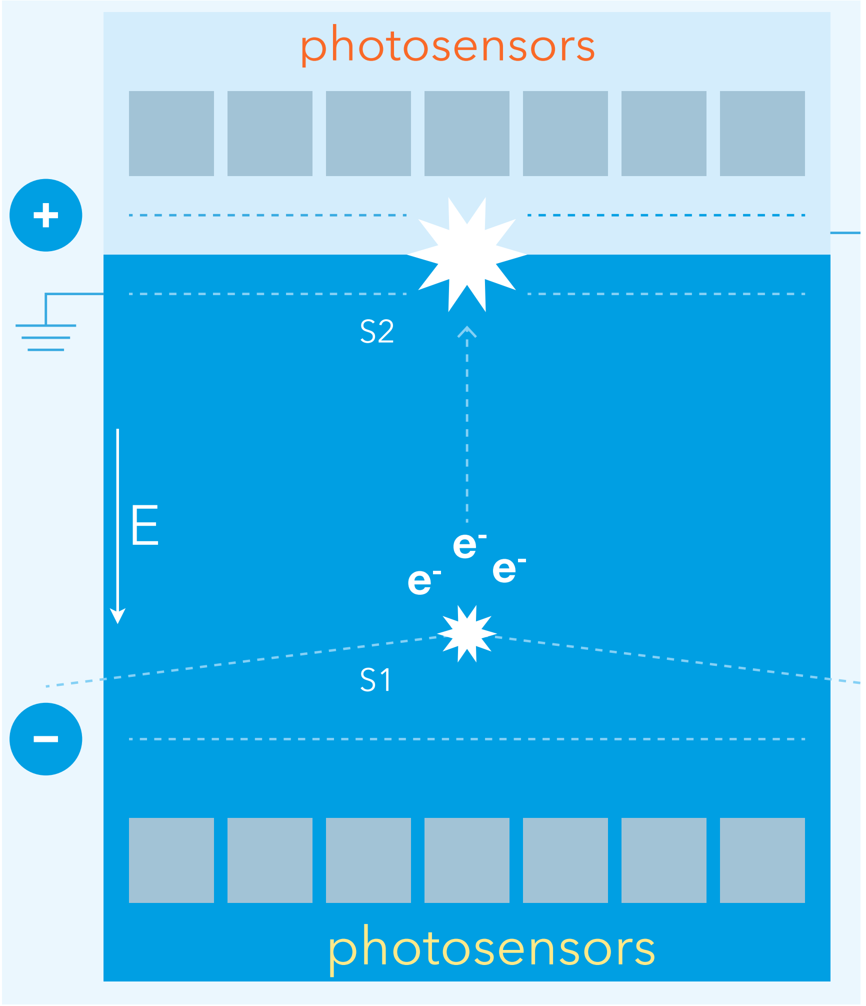


Super-CDMS



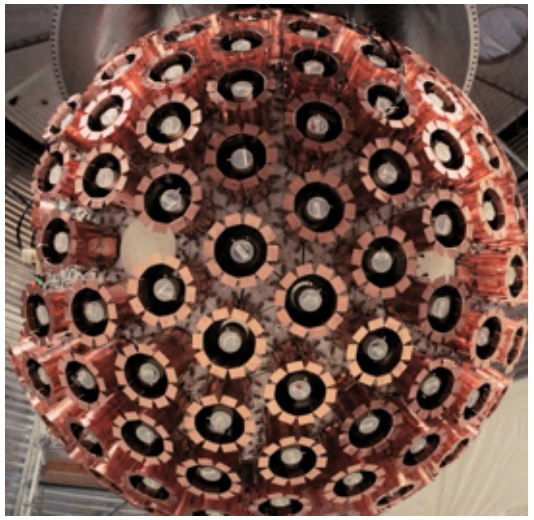
LIQUEFIED NOBLE GASES

- Single and two-phase Ar & Xe detectors
- Time projection chambers:
  - 3D position resolution via light (S1) & charge (S2): fiducialisation
  - S2/S1 –> particle ID
  - Single versus multiple interactions

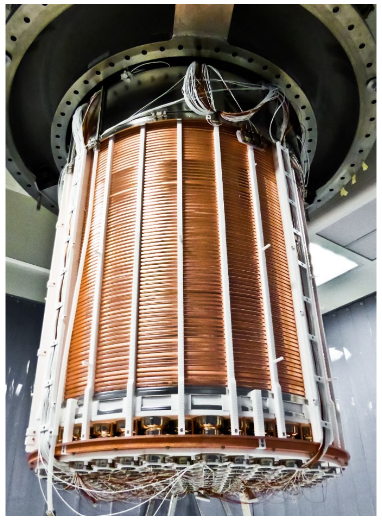


XMASS

DEAP-3600



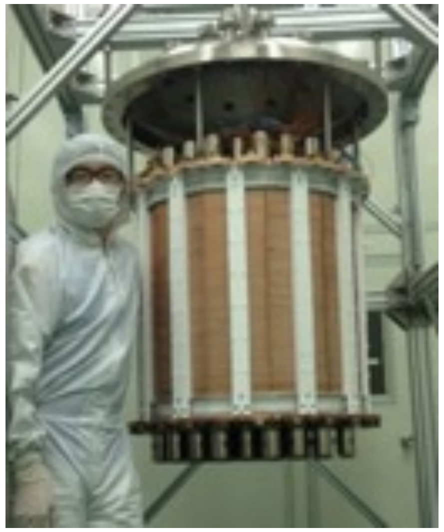
XENON1T



LUX

DarkSide-50

PandaX-II



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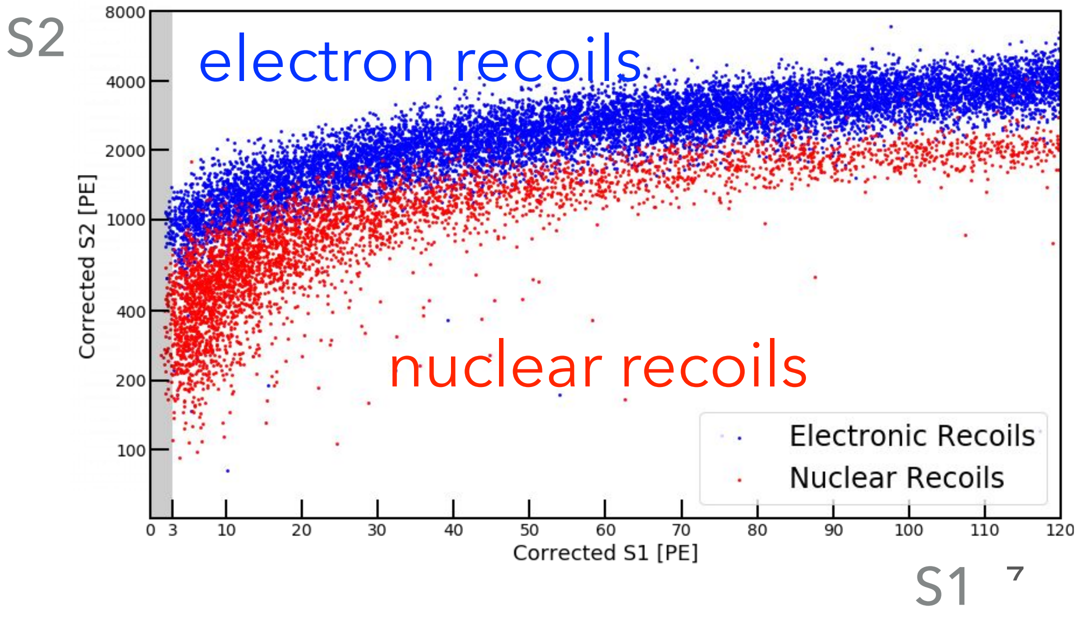
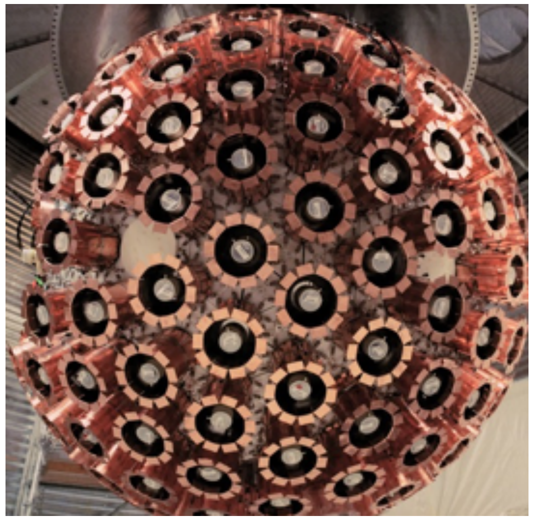
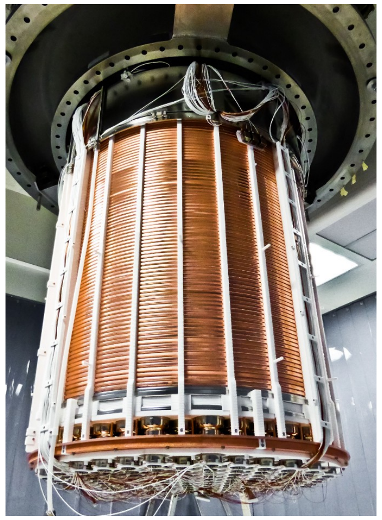


XMASS

DEAP-3600



XENON1T



LUX

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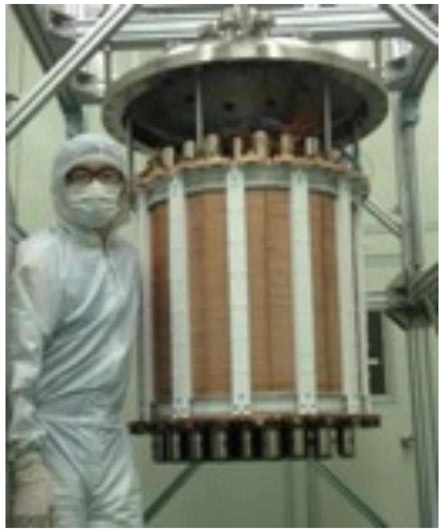
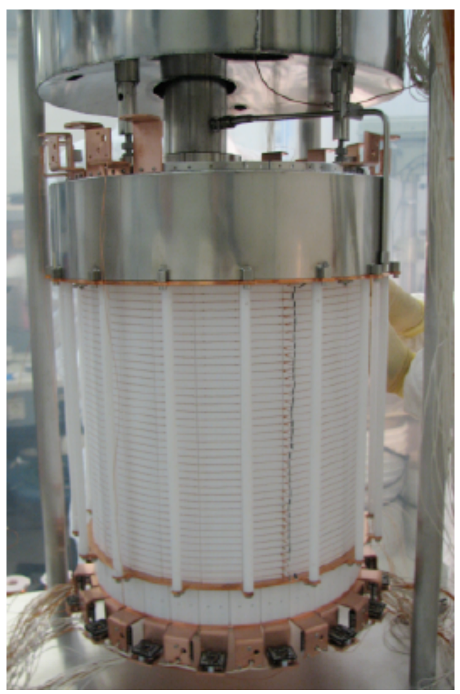
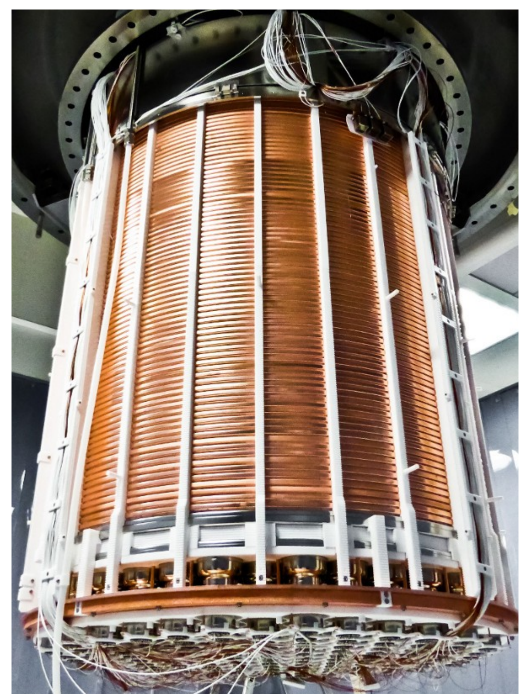
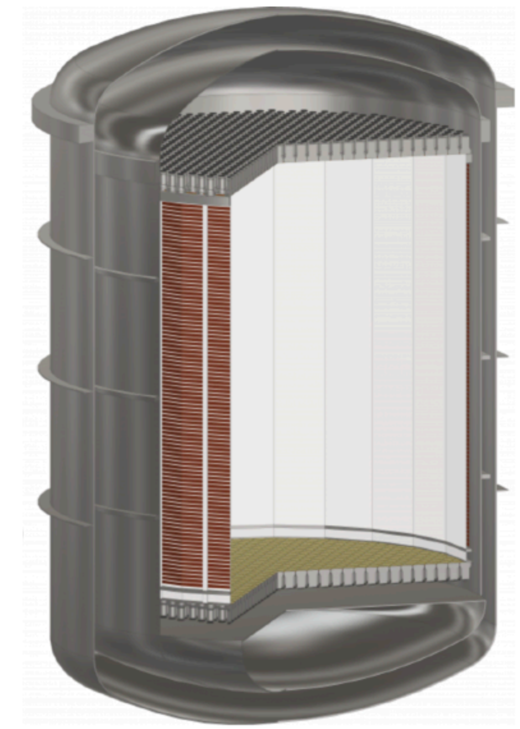


THE XENON/DARWIN TIMELINE

XENON10 XENON100 XENON1T XENONnT DARWIN

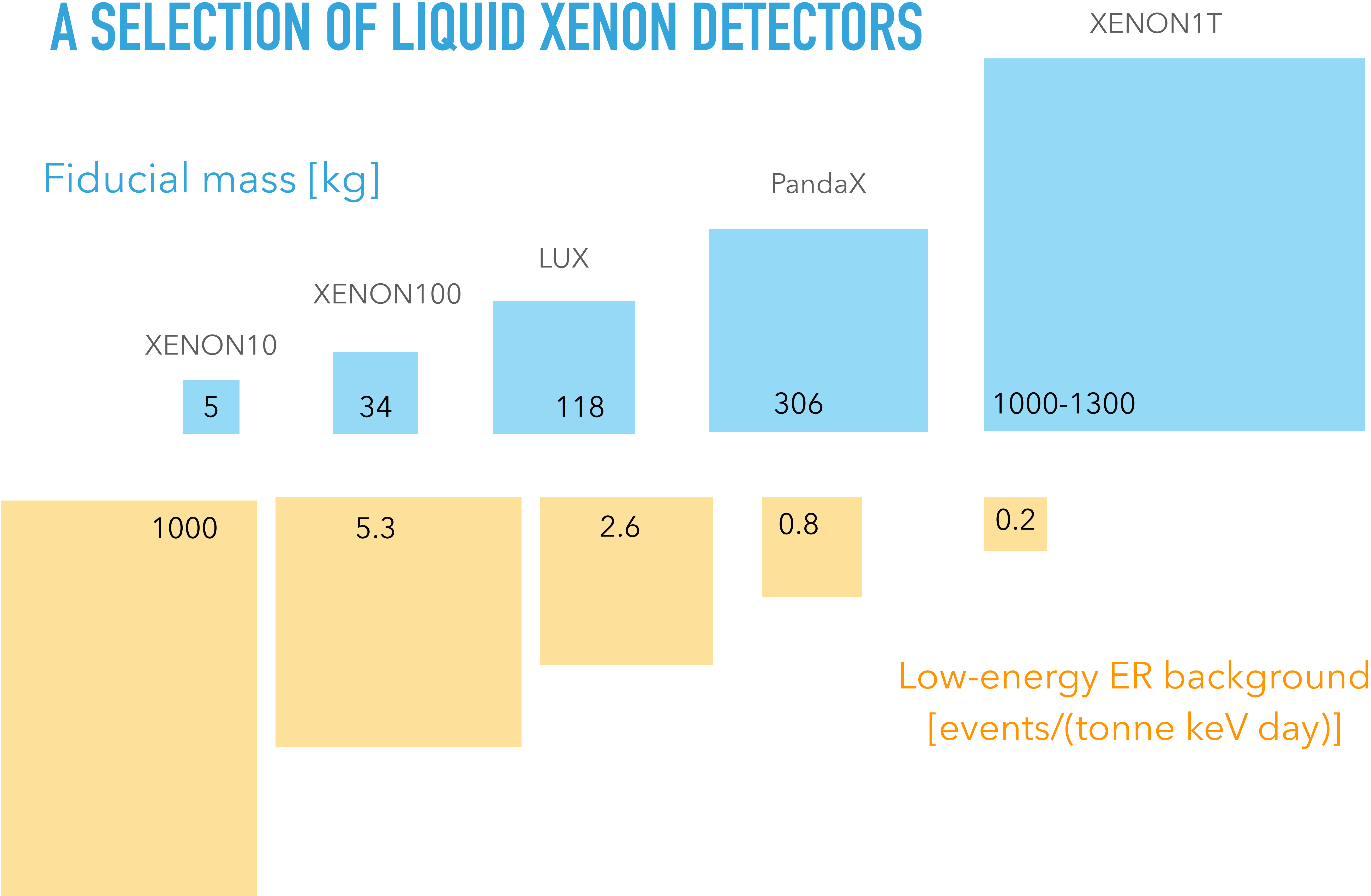






XENON10	XENON100	XENON1T	XENONnT	DARWIN
2005-2007	2008-2016	2012-2018	2020-2024	2027–
15 kg	161 kg	3200 kg	8400 kg	50 tonnes
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2	$\sim 10^{-49}$ cm^2

A SELECTION OF LIQUID XENON DETECTORS



XENON1T AT THE GRAN SASSO LABORATORY

Water tank and Cherenkov muon veto

Cryostat and support structure for TPC

Time projection chamber

Cryogenics pipe (cables, xenon)

Cryogenics and purification

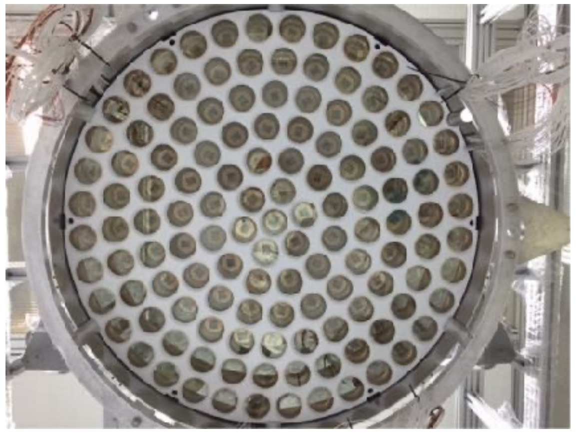
Data acquisition and slow control

Xenon storage, handling and Kr removal via cryogenic distillation

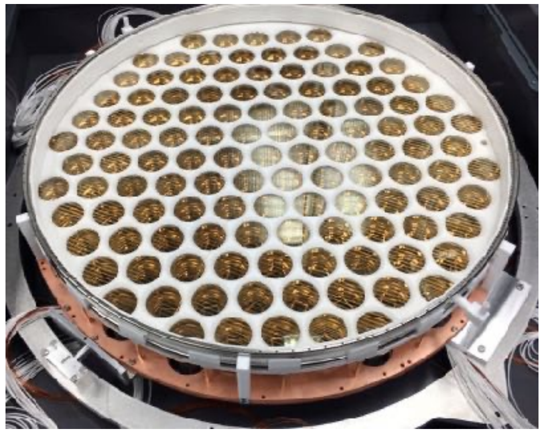
THE TIME PROJECTION CHAMBER

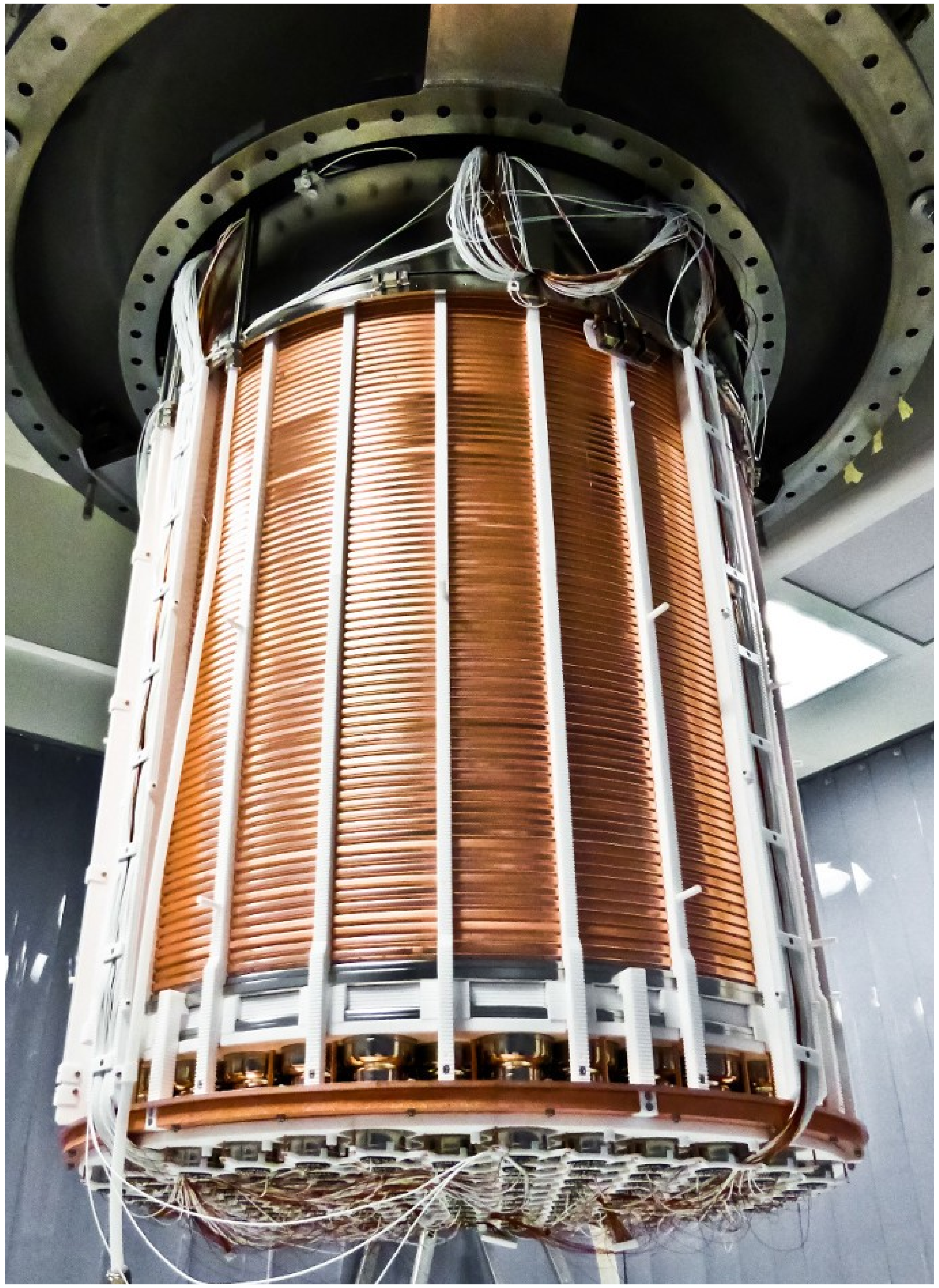
- 3.2 t LXe in total, 2 t in the TPC
- 97 cm drift, 96 cm diameter
- 248 3-inch PMTs
- 74 Cu field shaping rings, 5 electrodes, 4 level meters

127 PMTs top array

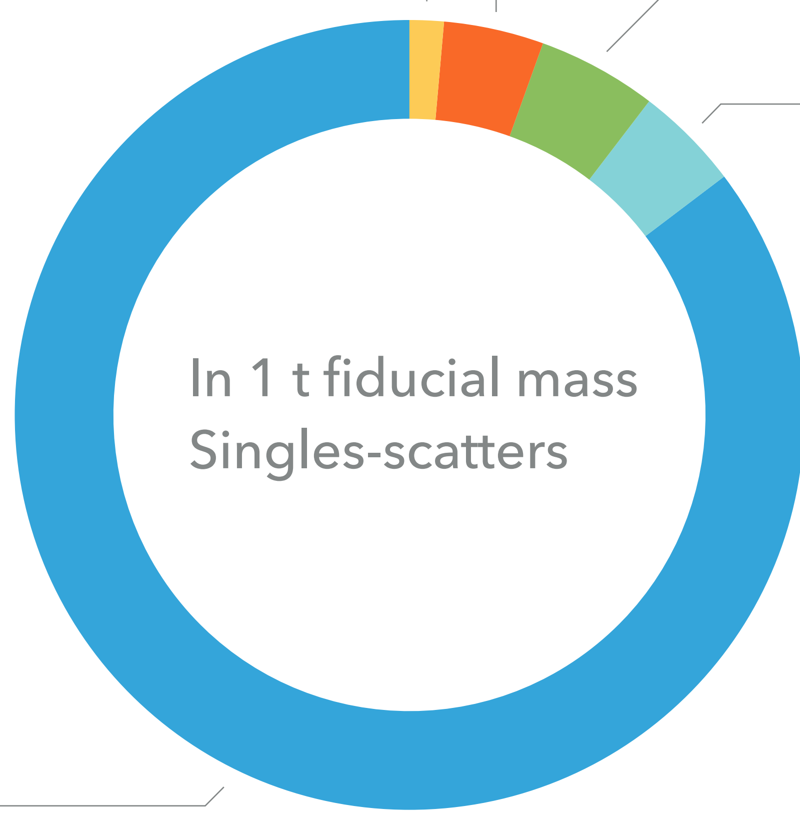


121 PMTs bottom array

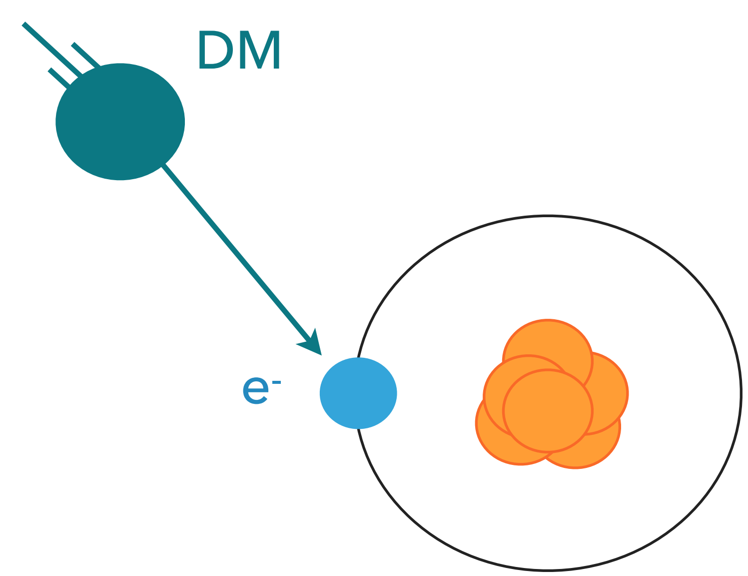


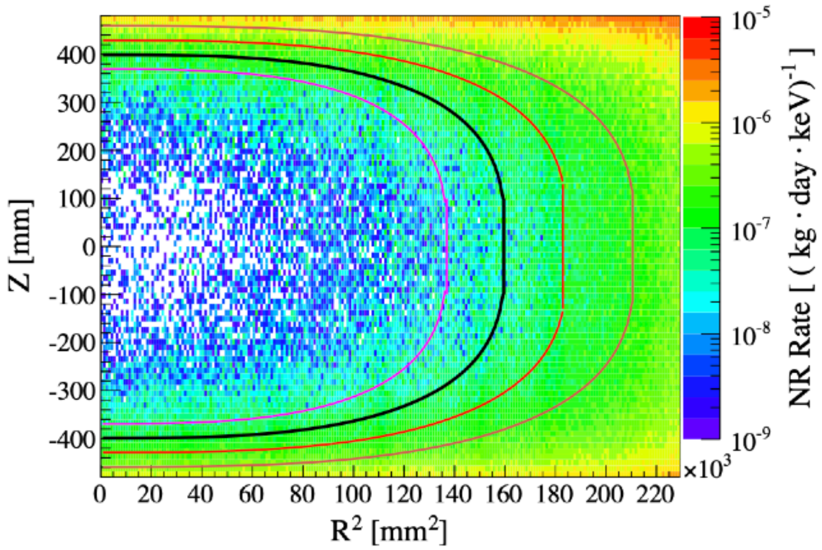


- ER rate: (82±5) events/(keV t y), in 1.3 t and below 25 keV_{ee}
- Lowest background in a dark matter detector



Control surface emanation
Reduce by online distillation



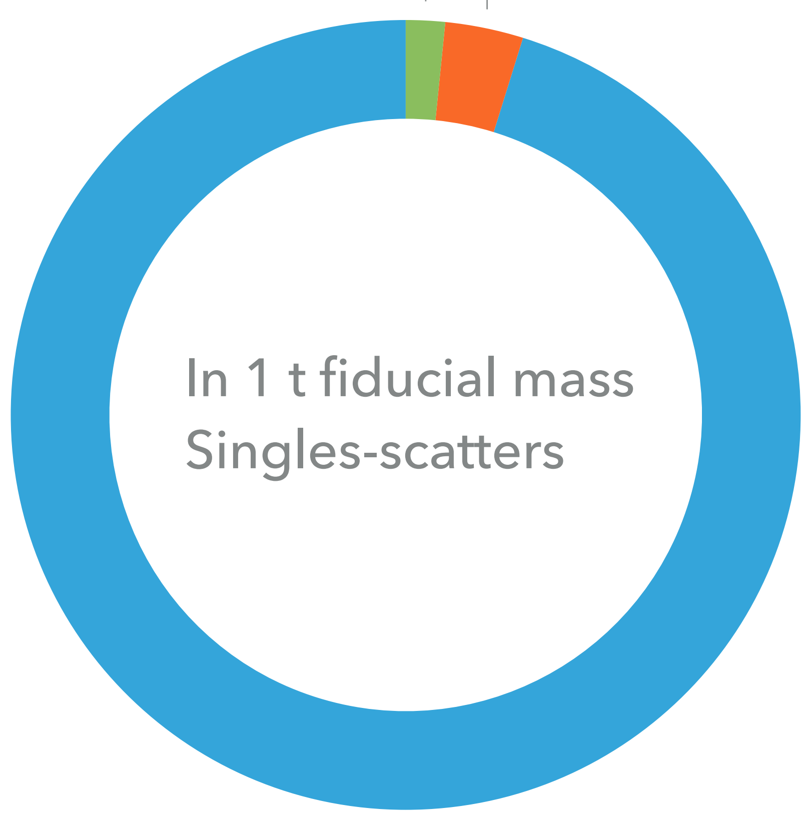


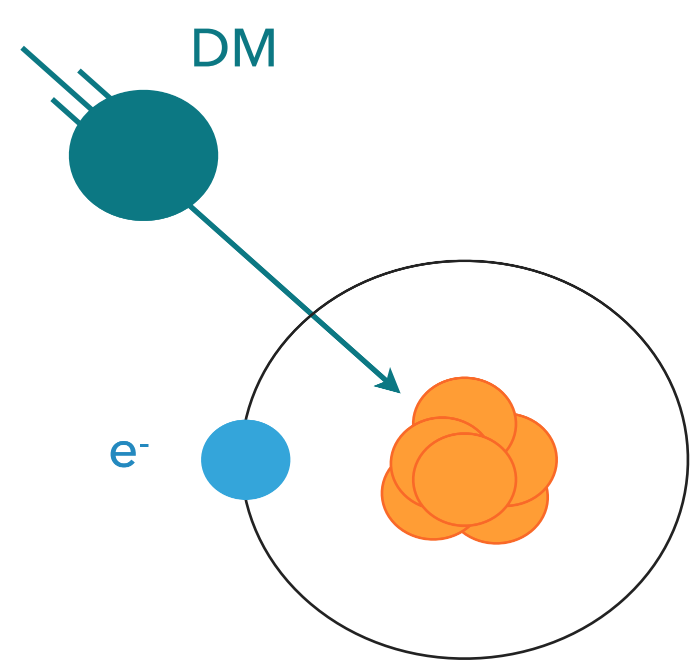
Cosmogenic neutrons (muon induced neutrons); rock overburden, water Cherenkov shield (here upper limit)

1.6%

3.2%

Coherent neutrino-nucleus scattering from ^{8}B neutrinos; irreducible, but relevant at low (<1 keV) energies





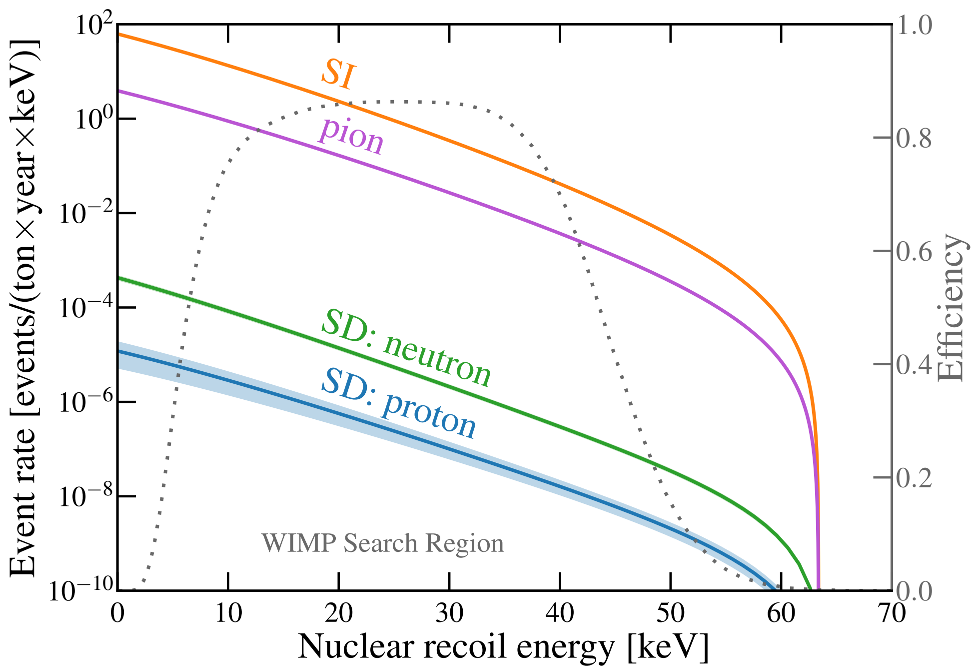
95.2%

Radiogenic neutrons

From (α,n) and SF reactions; material selection; single versus multiple-scatters

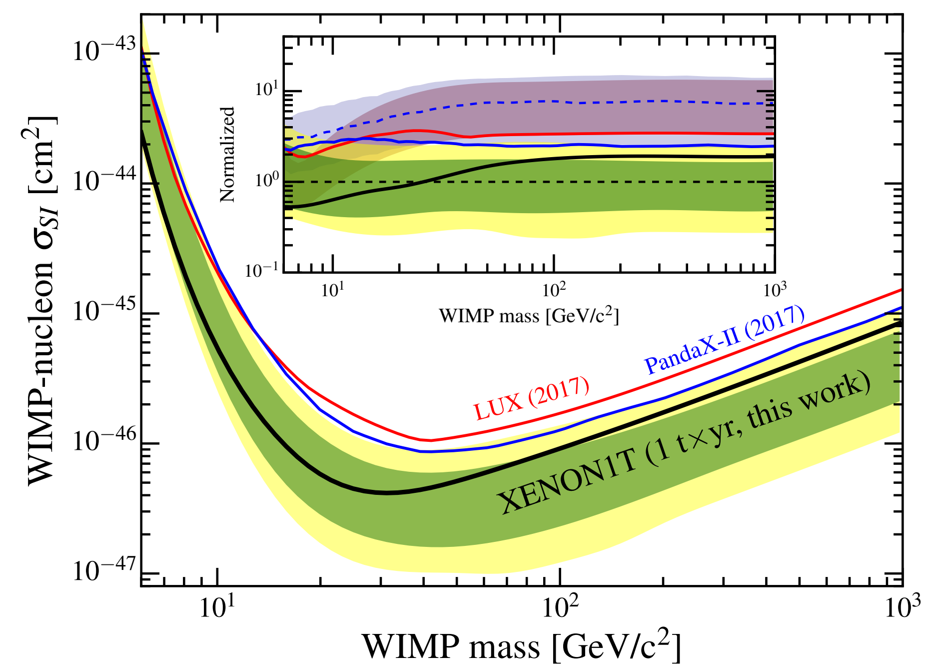
WIMP SEARCHES

30 GeV WIMP, $\sigma = 1 \times 10^{-45}$ cm^2

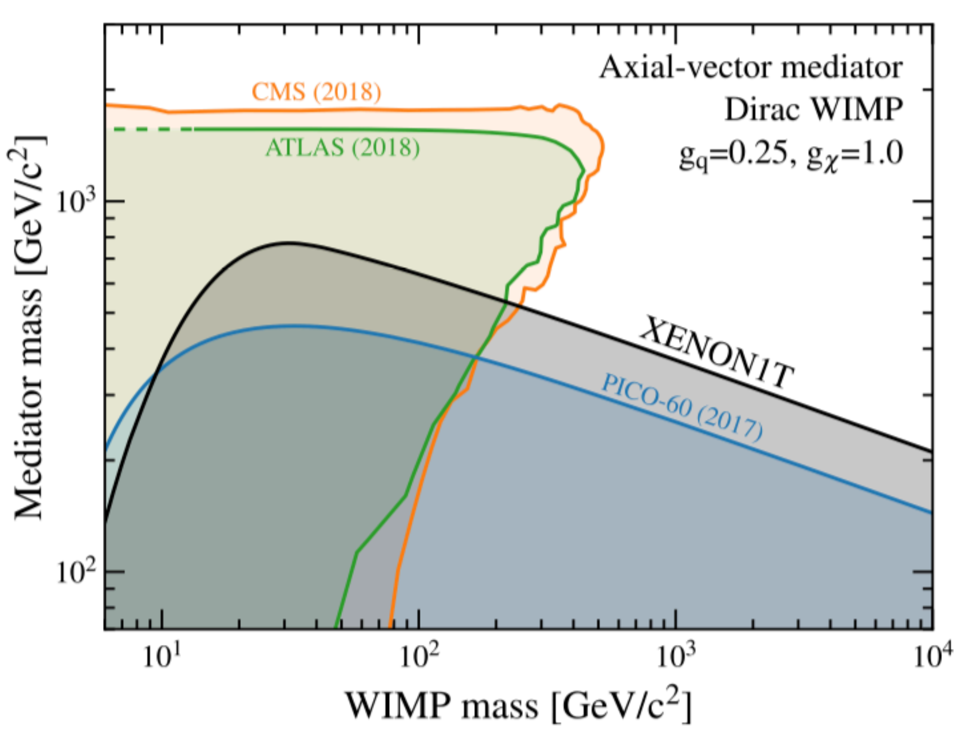


- Strongest upper limit (at 90% CL) on SI WIMP-nucleon cross sections > 6 GeV

$$\sigma_{\rm SI} < 4.1 \times 10^{-47} {\rm cm}^2 \text{ at } 30\,{\rm GeV/c}^2$$



Axial-vector mediator and a Dirac WIMP, with fixed mediator-quark and mediator-WIMP coupling

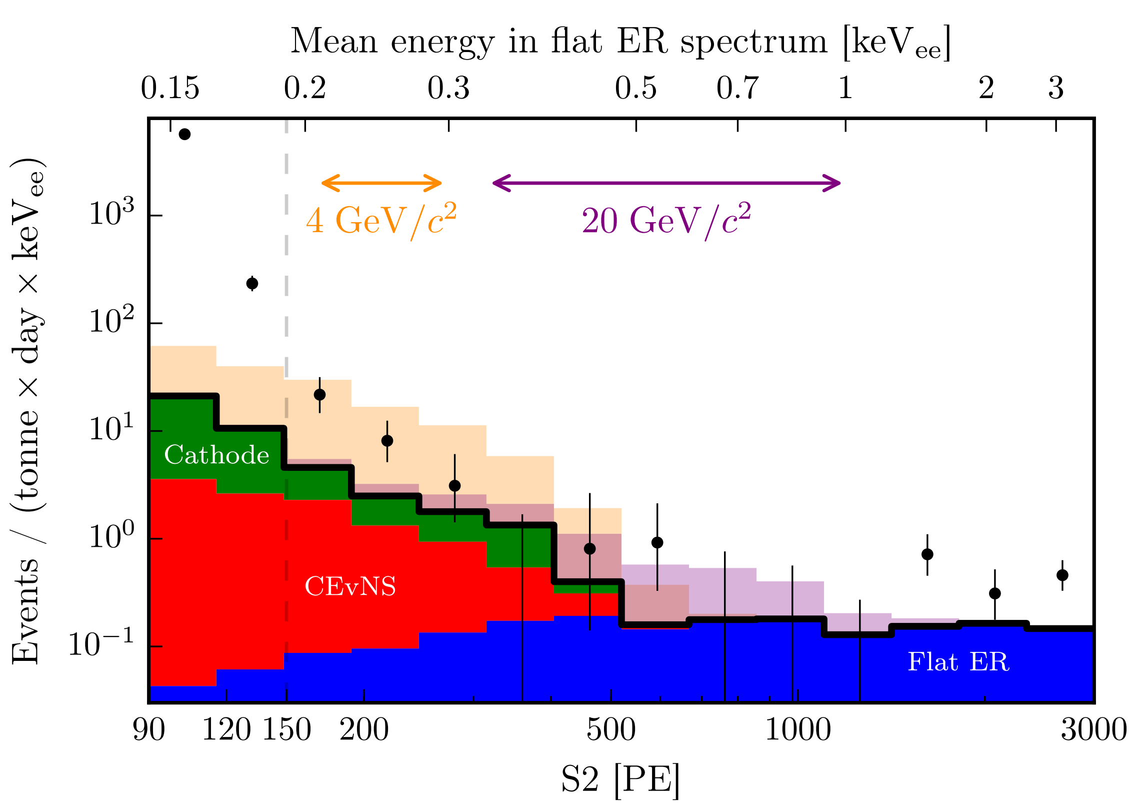


XENON collaboration, PRL 122, 2019

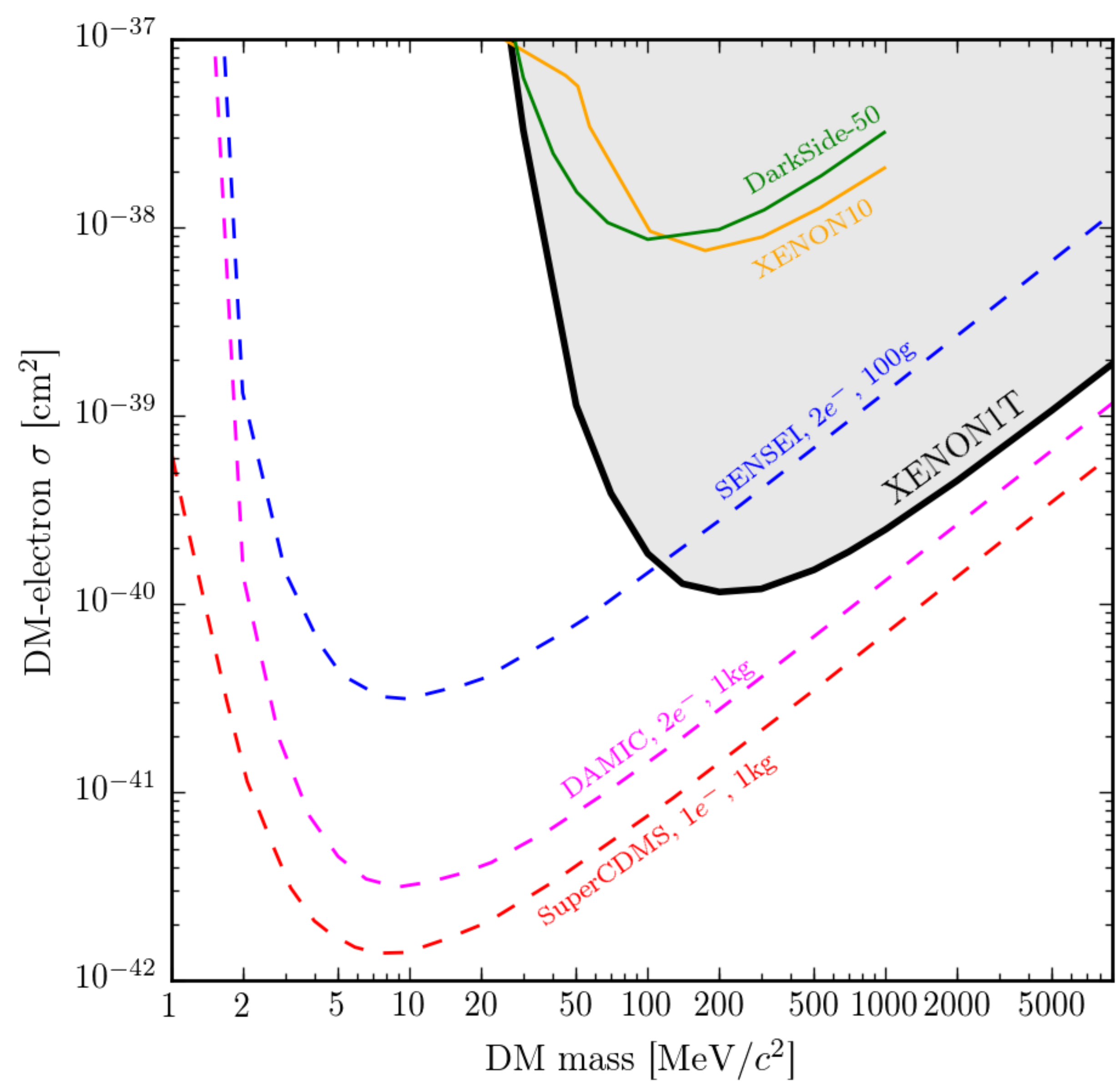
XENON collaboration, PRL 123, 2019

LIGHT DARK MATTER

- Use charge signal (S2) only
- Achieve lower energy threshold (at the expense of higher backgrounds)
- 22 t yr exposure; < 1 events/(t d keV) above 0.4 keV

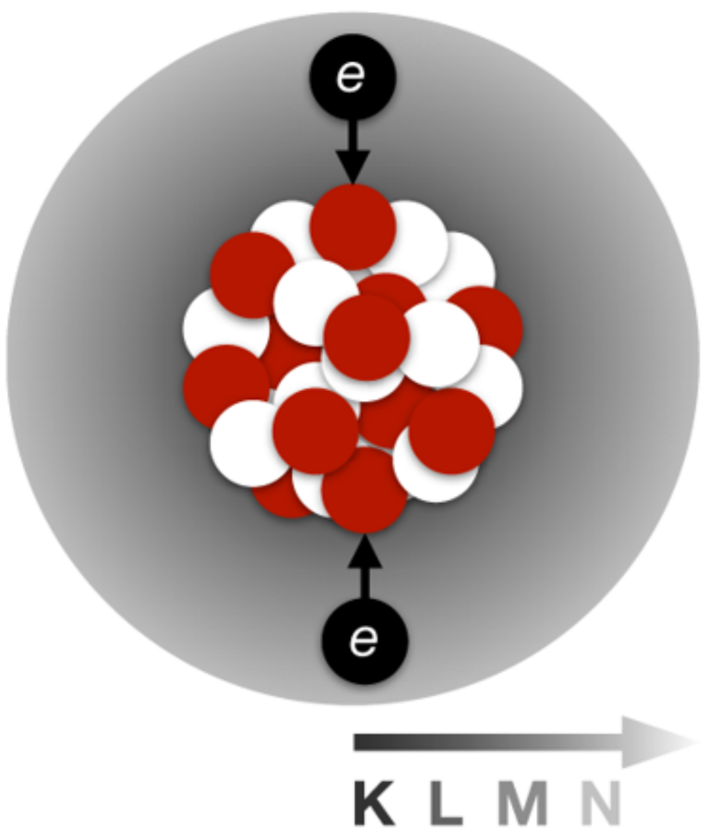


DM electron scattering: comparison with the reach of other experiments

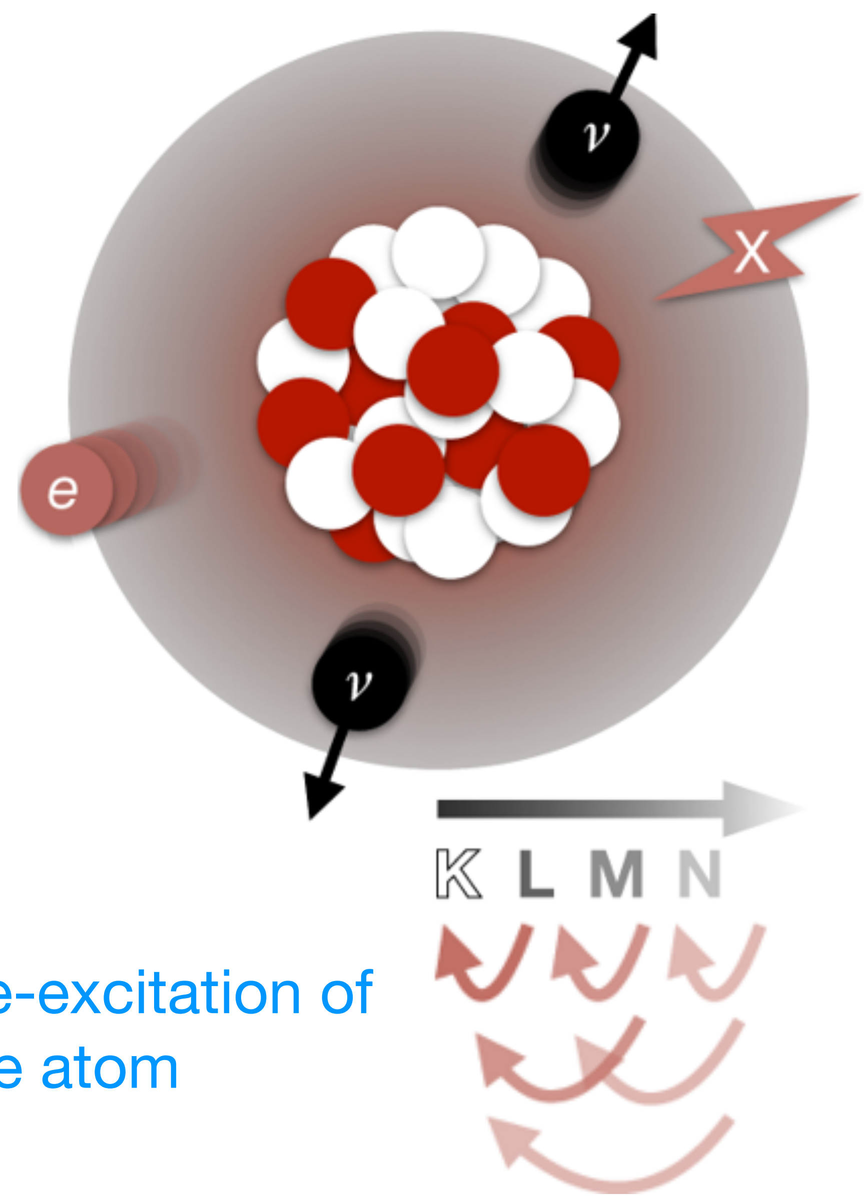


DOUBLE ELECTRON CAPTURE

$$^{124}\mathrm{Xe} + 2\mathrm{e}^{-} \rightarrow {}^{124}\mathrm{Te} + 2\nu_e$$



2 electrons are captured from the atomic shell



De-excitation of the atom

The 2 neutrinos leave the detectors unnoticed

X-rays with at ~ 64 keV are observed (Q-value: 2.96 MeV)

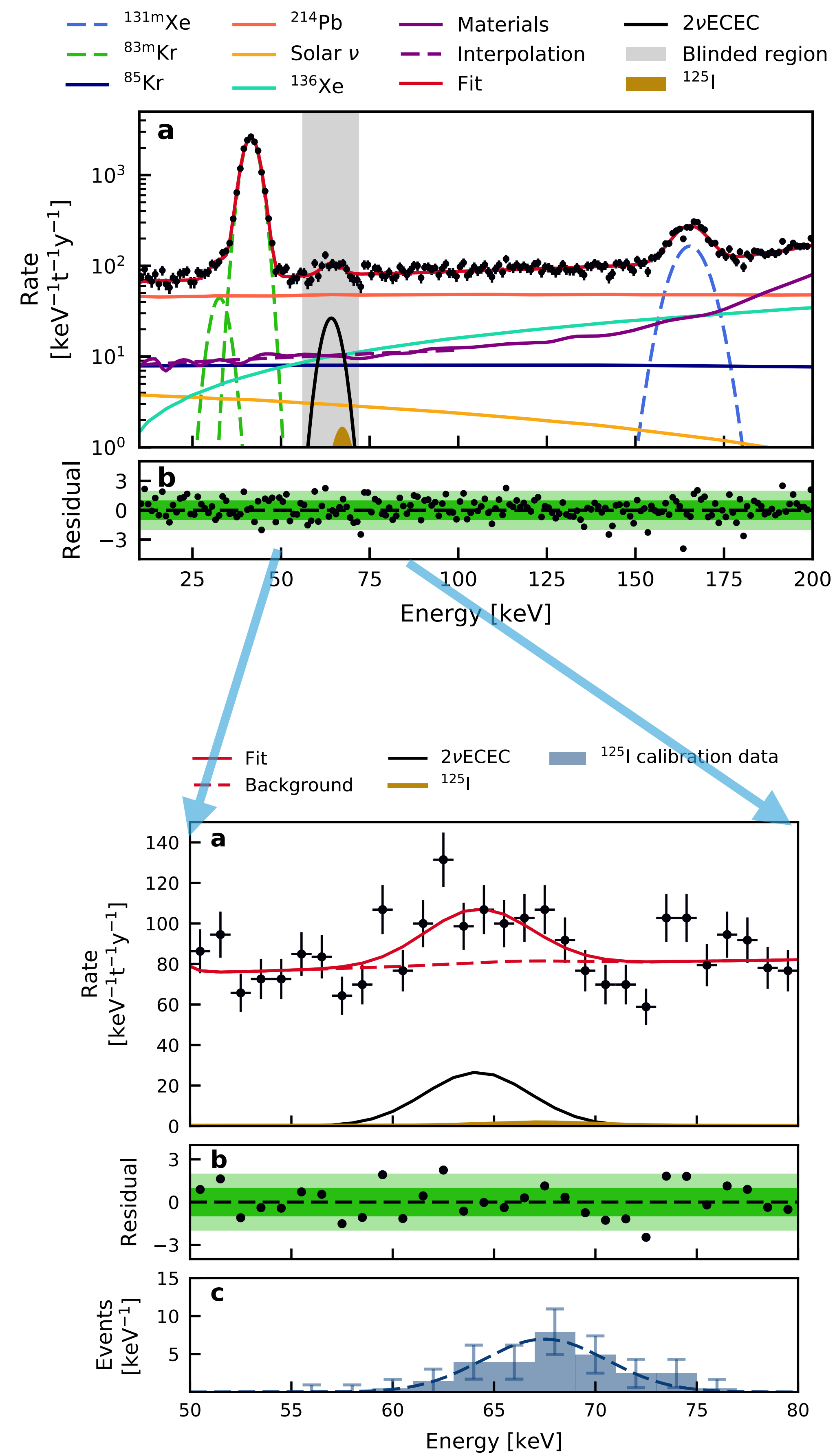
σ/E = (4.1 ± 0.4)% at 64 keV

XENON collaboration, Nature 568, April 25, 2019

DOUBLE ELECTRON CAPTURE

- ^{124}Xe in ^{nat}Xe: 0.095%
- 1 t ^{nat}Xe ≈ 1 kg ^{124}Xe
- Total observed energy: 64.33 keV (2 x K-shell binding energy; Q-value = 2.86 MeV)
- Blind analysis: (56-72) keV region masked
- Number of signal events: (126±29), expected background from ^{125}I: (9±7) events (at 67.5 keV)

$$T_{1/2} = (1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}\ \text{y}$$



XENON collaboration, Nature 568, April 25, 2019

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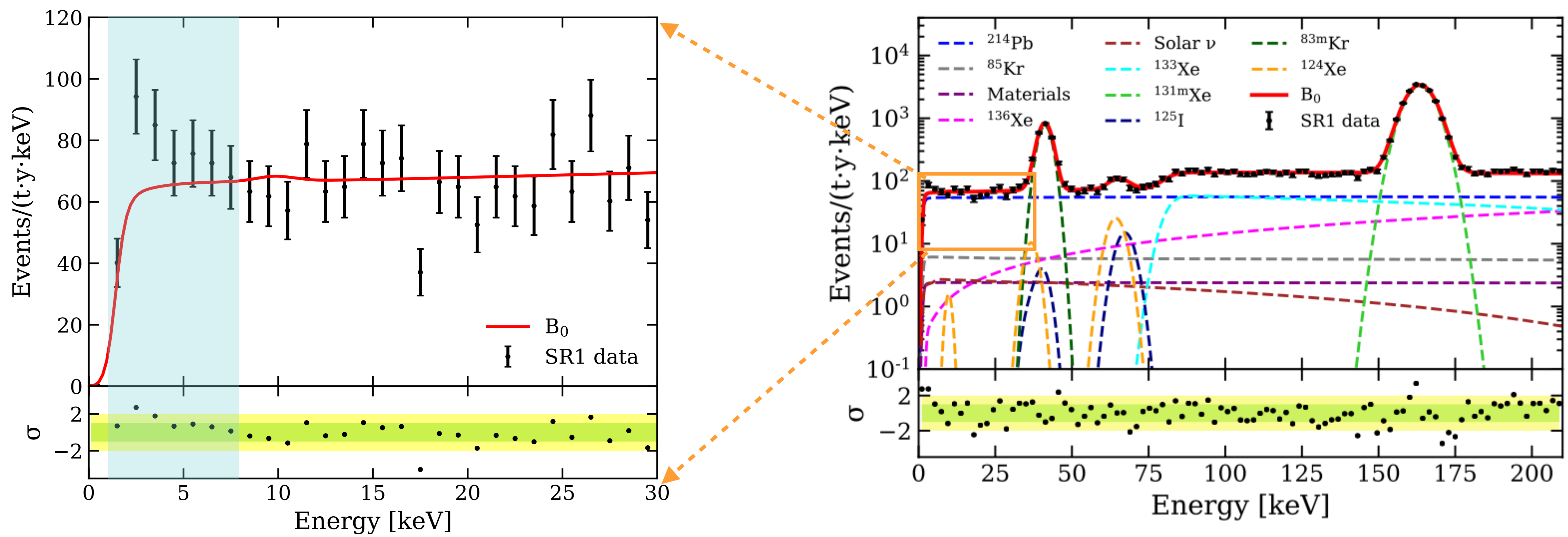
SEARCHES FOR SOLAR AXIONS, ALPS, DARK PHOTONS…

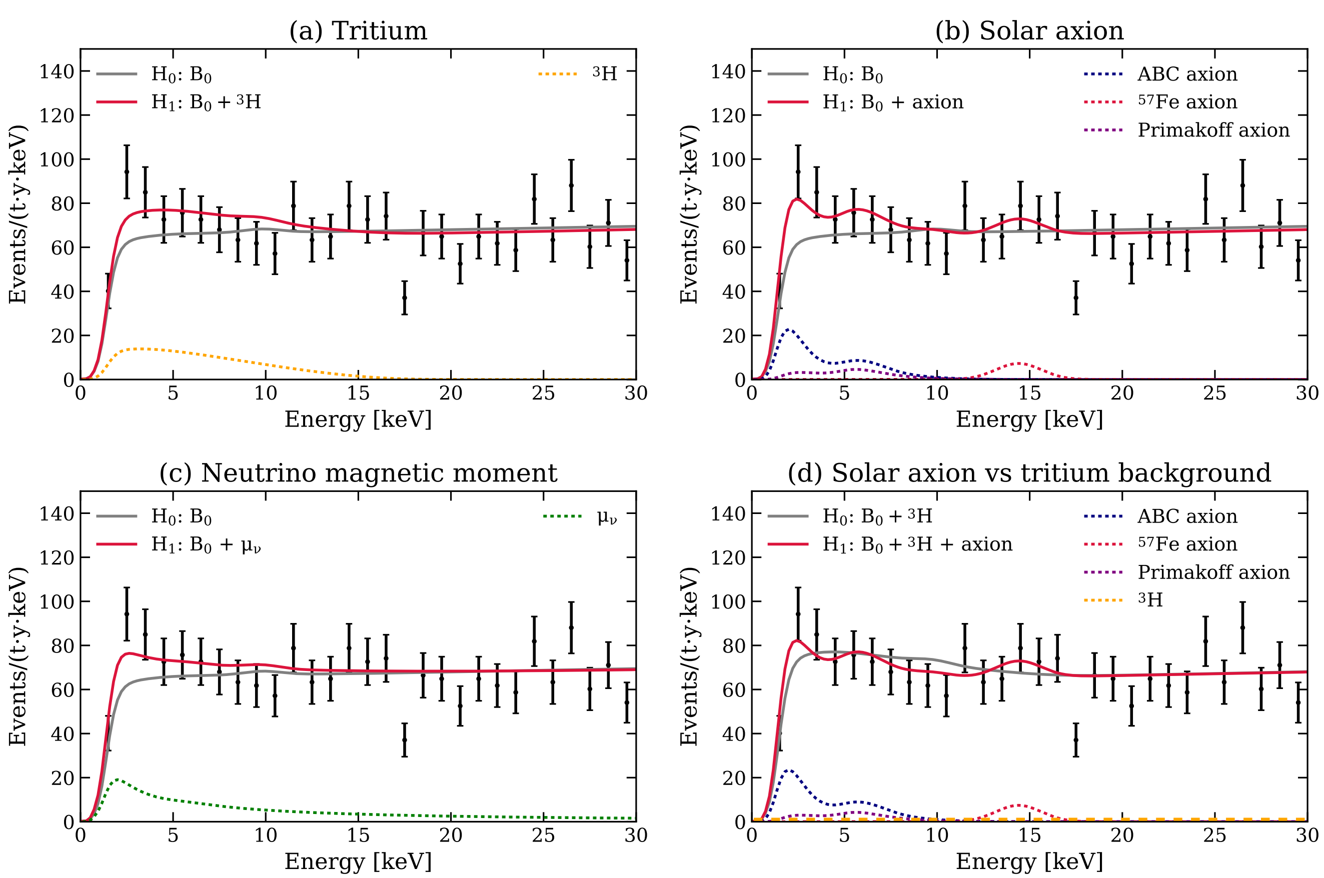
- Energy region: (1, 210) keV; 10 components in the background model
- Good fit over most of the energy region; excess between (1,7) keV: number of observed events: 285, expected from background: (232±15) events
- Lowest background between (1,30) keV: 76±2 events/(t y keV)

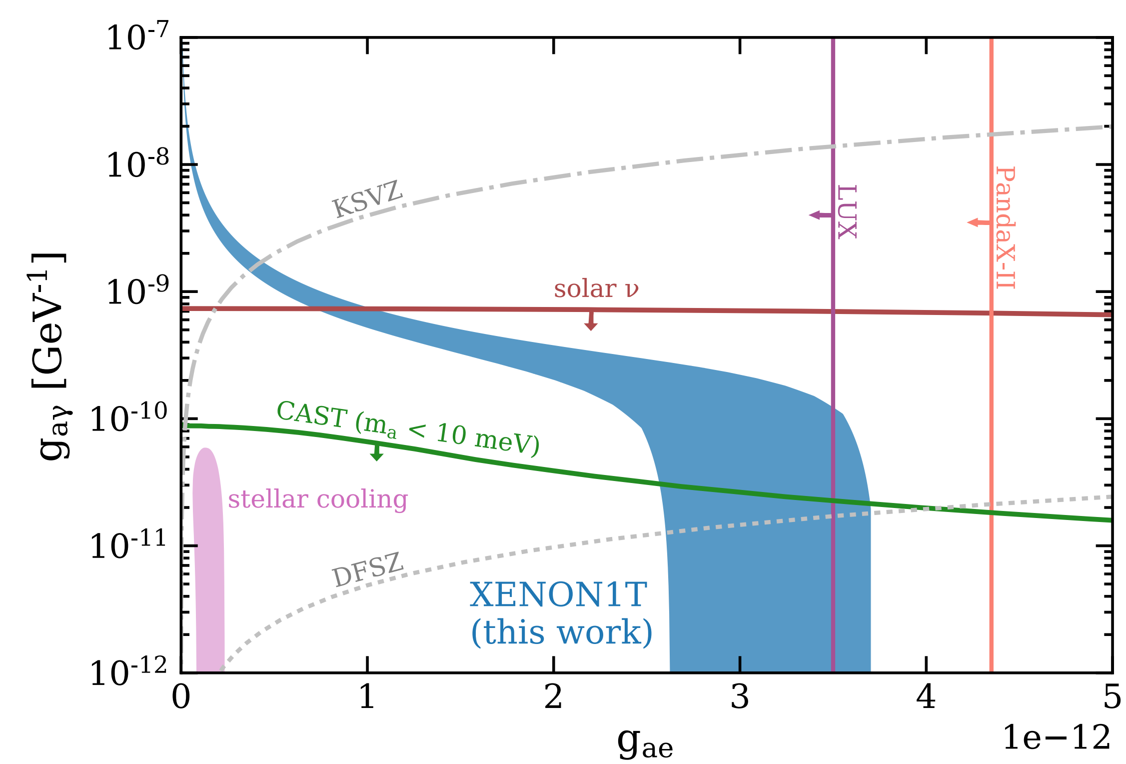


XENON collaboration, arXiv:2006.09721

SEARCHES FOR SOLAR AXIONS, ALPS, DARK PHOTONS…

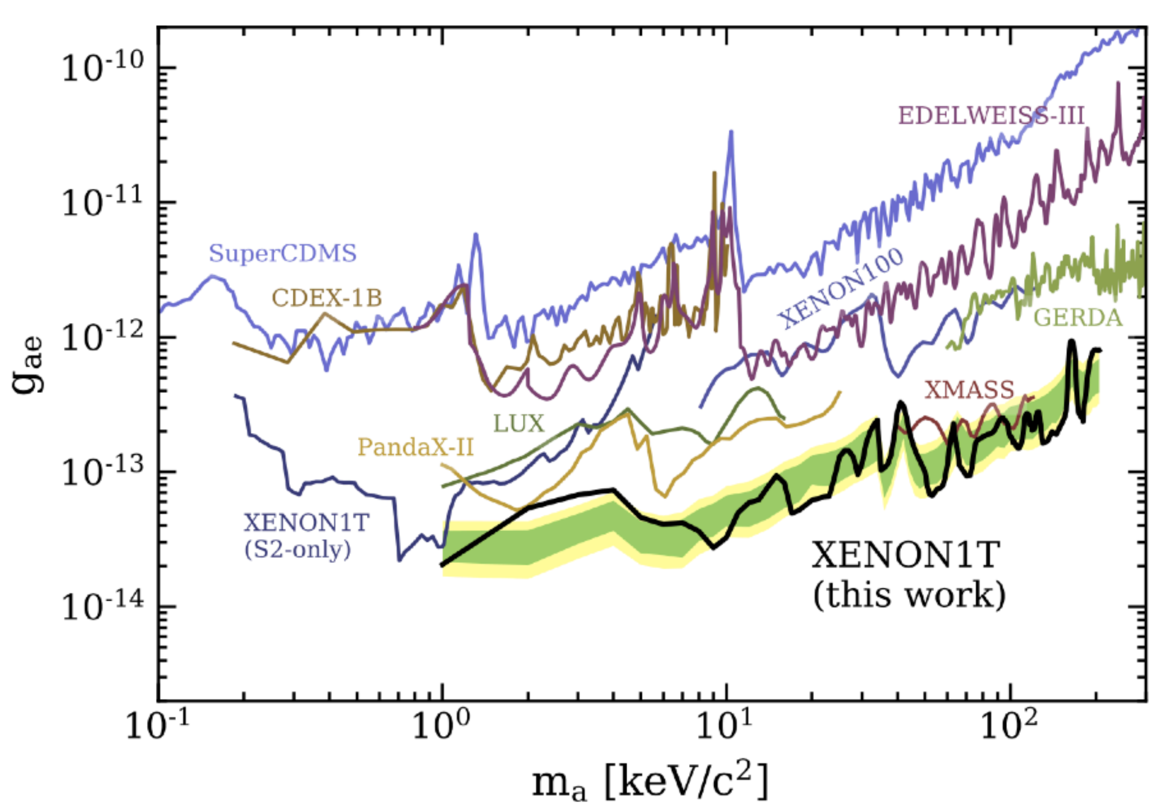
- Considered “signals”: ^3H β-decay, solar axions, neutrino magnetic moment
- Solar axion and neutrino magnetic moment favoured over background-only at 3.5 σ and 3.2 σ (however discrepancy with stellar cooling constraints, see e.g. 2006.12487)
- Tritium favoured over background-only at 3.2 σ, corresp. to (6.2 ± 2) x 10^{-25} mol/mol

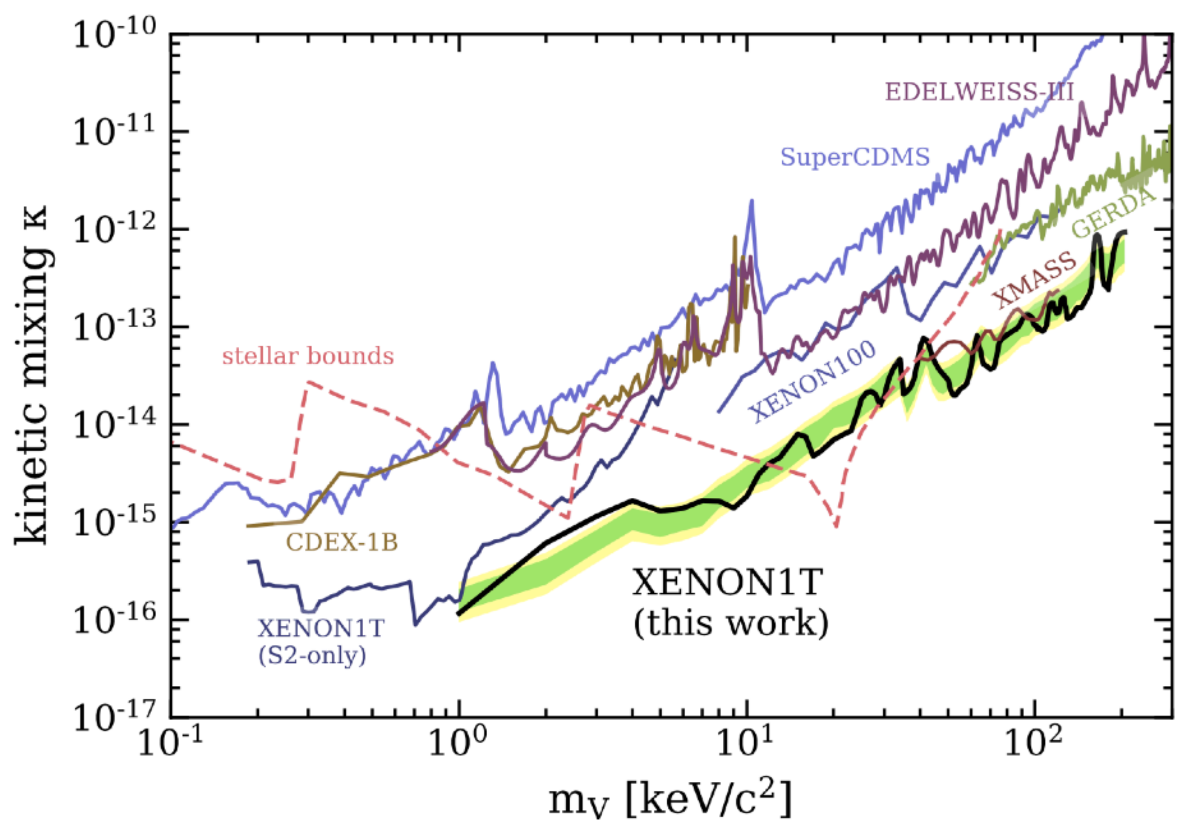




SEARCHES FOR SOLAR AXIONS, ALPS, DARK PHOTONS…

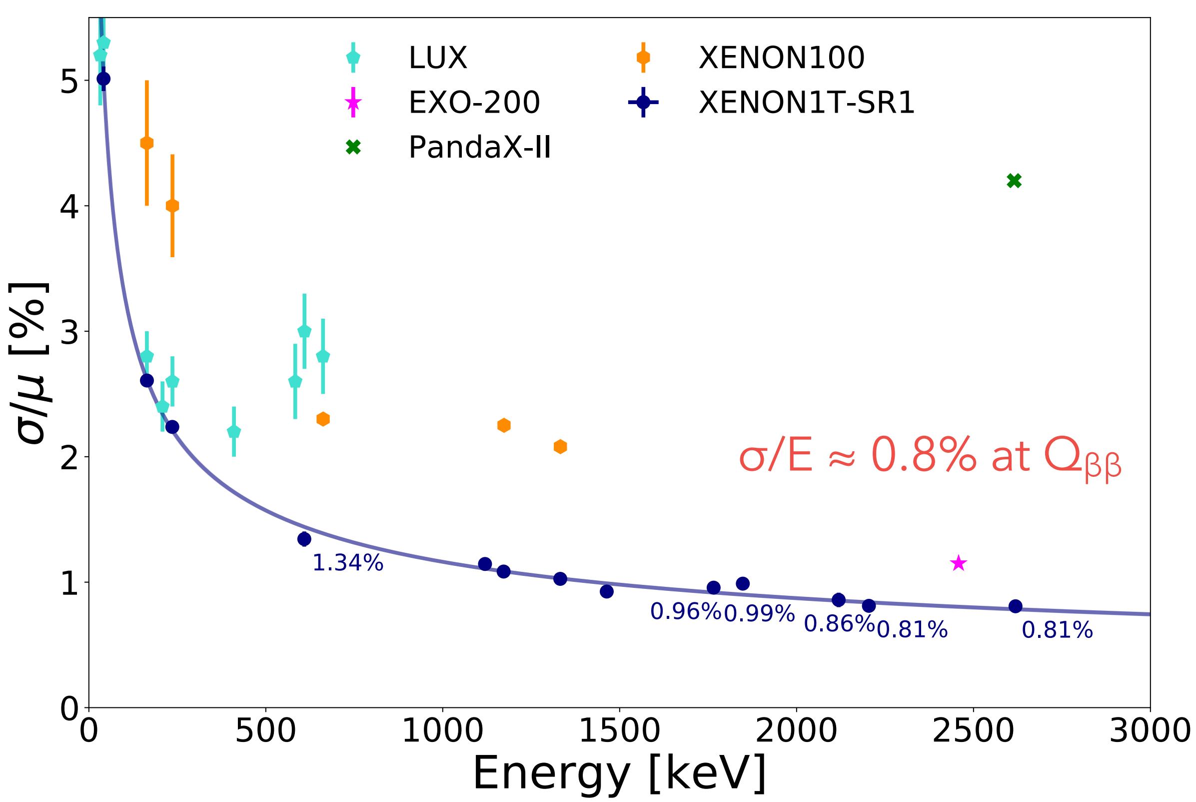
- Constraints on couplings for bosonic pseudoscalar DM with masses (1, 210) keV
- No global significance above 3-σ under the background model
- A 3-σ global (4-σ local) significance for a peak at (2.3±0.3) keV (68% CL)
- ALPs and dark photons: 90% CL upper limits and sensitivities

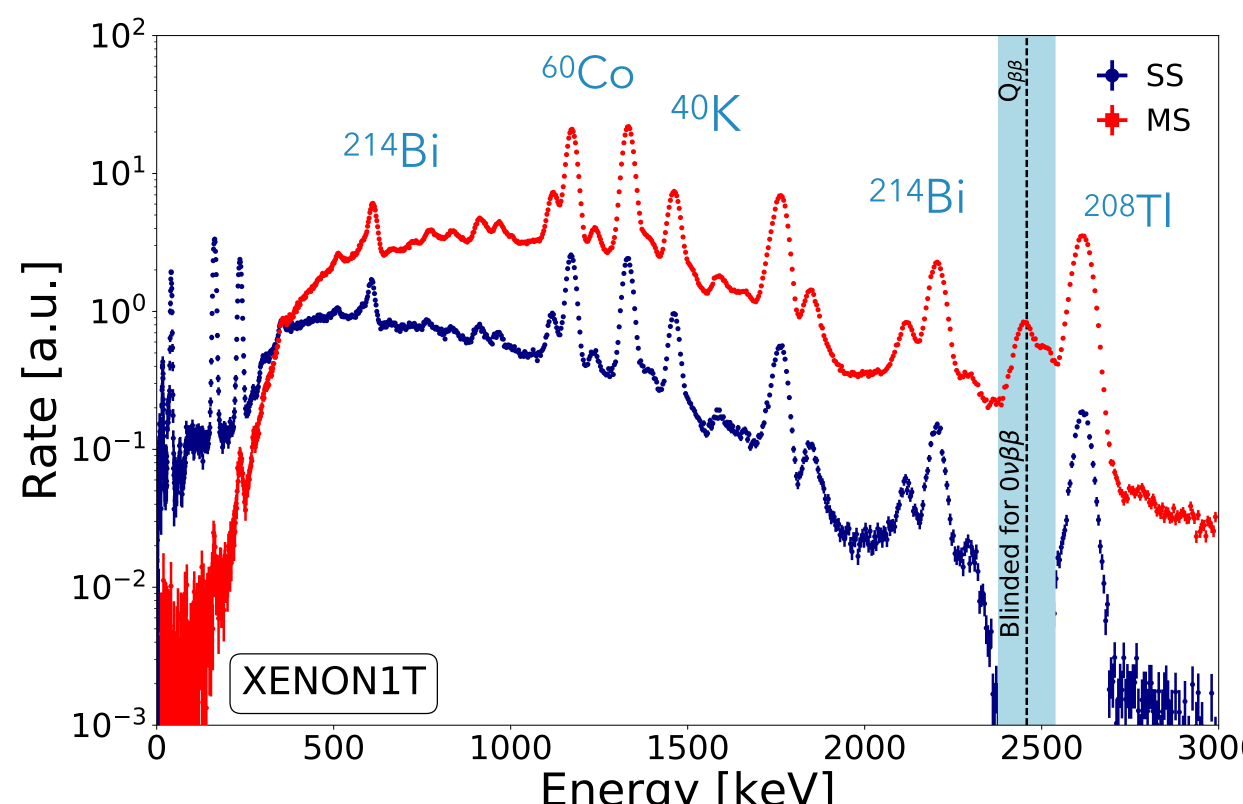




HIGH-ENERGY ANALYSIS FOR A DOUBLE BETA SEARCH OF ^{136}XE

- Motivation: search for $0\nu\beta\beta$-decay of ^{136}Xe, at $Q_{\beta\beta}$= (2457.83±0.37) keV, understand background rate and spectrum at high energies
- Correct for signal saturation, determine event multiplicity, energy scale, resolution
- Achieved σ/E ~0.8%; $0\nu\beta\beta$-decay data analysis and data/MC matching in progress

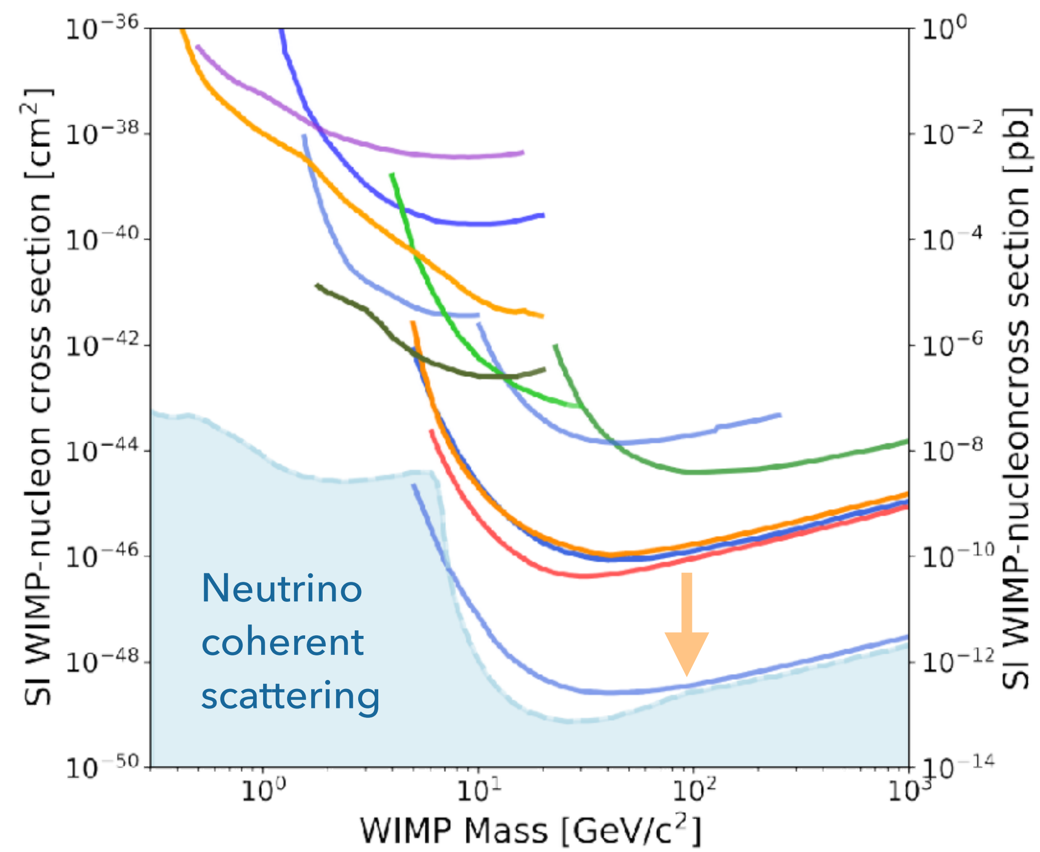


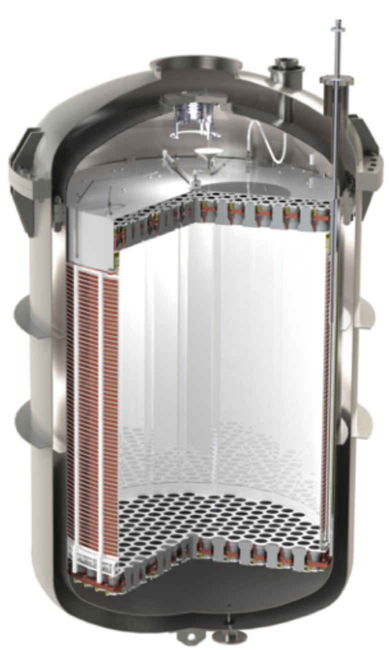


XENON collaboration, arXiv:2003.03825

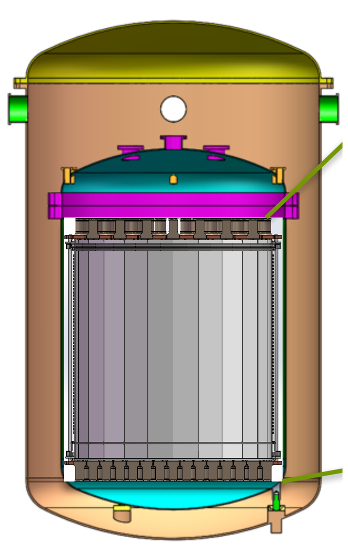
LIQUEFIED NOBLE GASES

- **In construction:**
  - LUX-ZEPLIN, XENONnT, DarkSide-20k, PandaX-4t
- **Planned (design and R&D stage)**
  - DARWIN (50 t LXe), ARGO (300 t LAr)

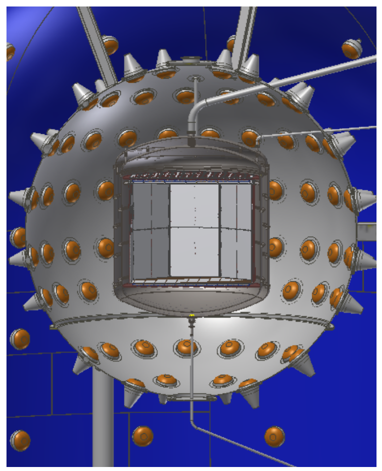




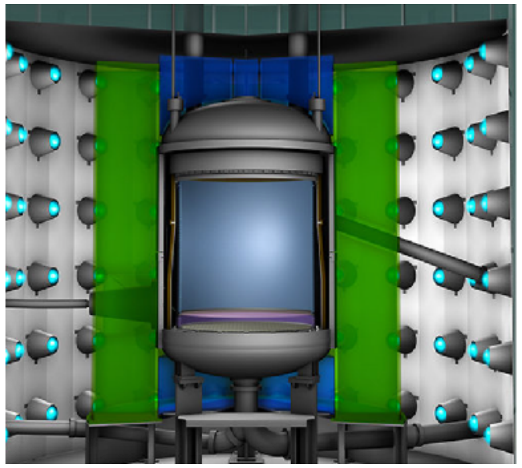
XENONnT: 8t LXe
Data taking 2020



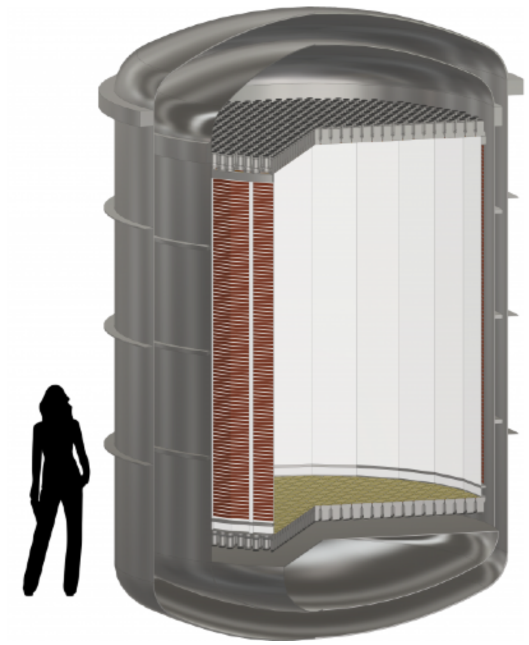
PandaX-4t LXe
Data taking 2021



DarkSide: 20 t LAr
Data taking 2021



LUX-ZEPLIN: 8 t LXe
Data taking 2020



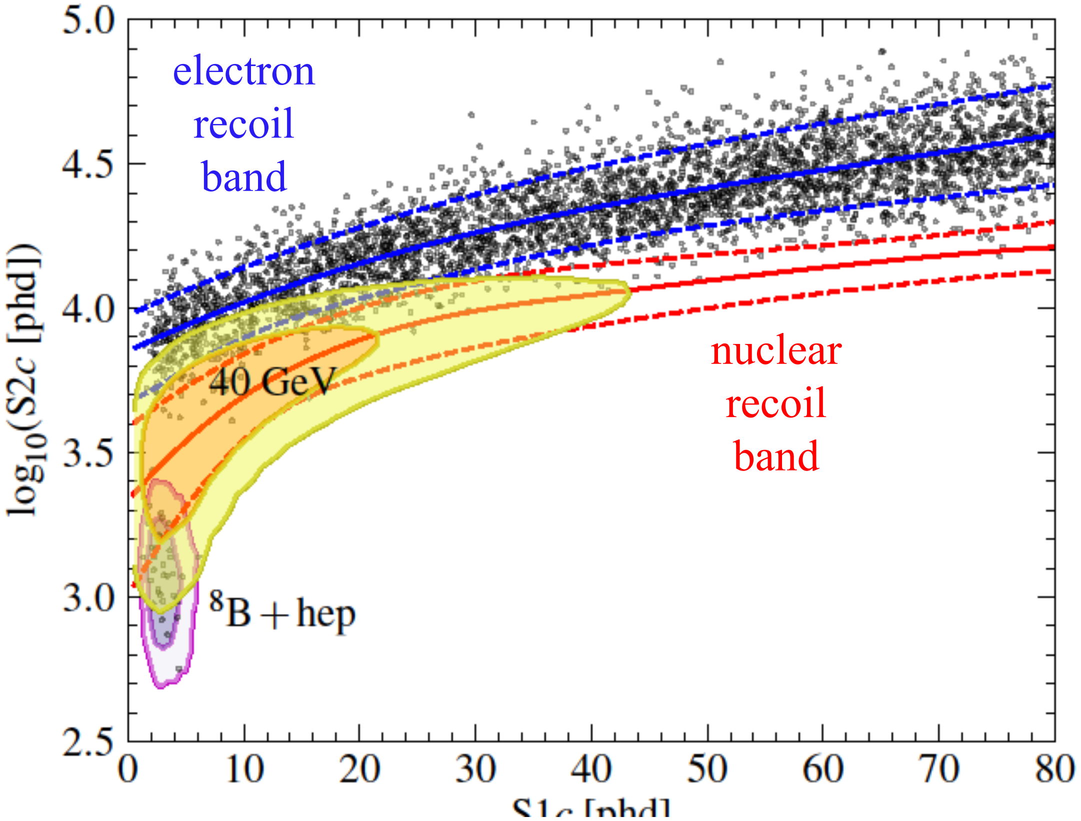
DARWIN: 50 t LXe
Data taking ~2027

LZ collaboration, NIM. A953 (2020) 163047

LUX-ZEPLIN

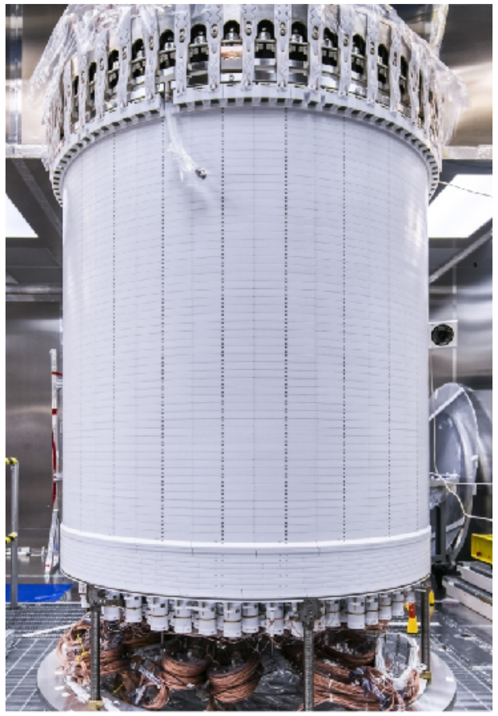
- Titanium cryostat, TPC field cage underground at SURF
- 10.7 tonnes of xenon procured, at SLAC for removal of trace amounts of Kr
- Liquid xenon filling in 2020; 5 (3) σ for 6.7 (3.8) x 10^{-48} cm^2

40 GeV WIMP, 1000 days, 5.6 t fiducial



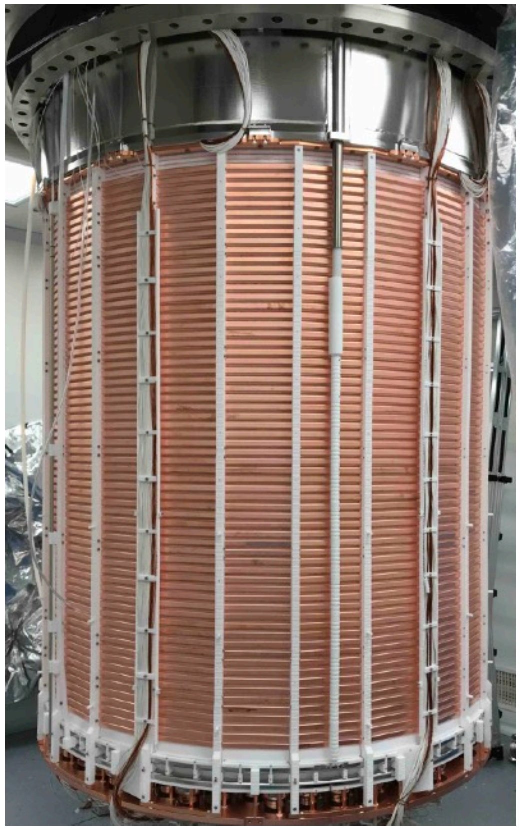
LZ Ti cryostat

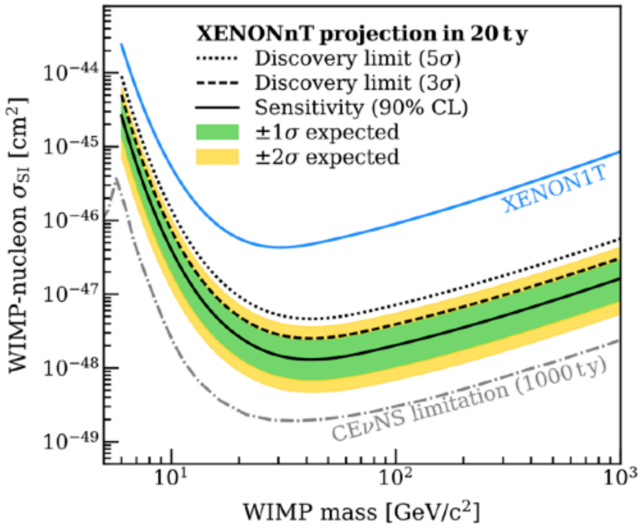
TPC

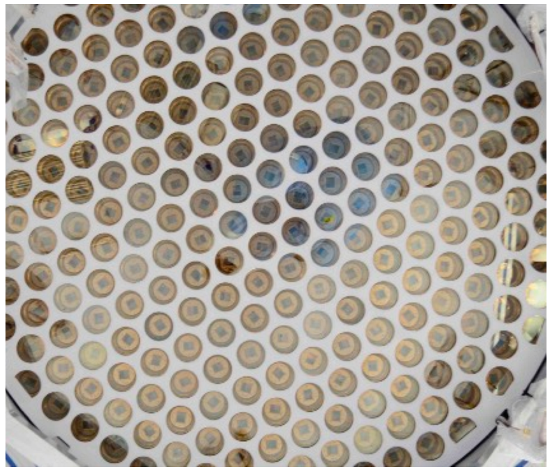


XENON-NT

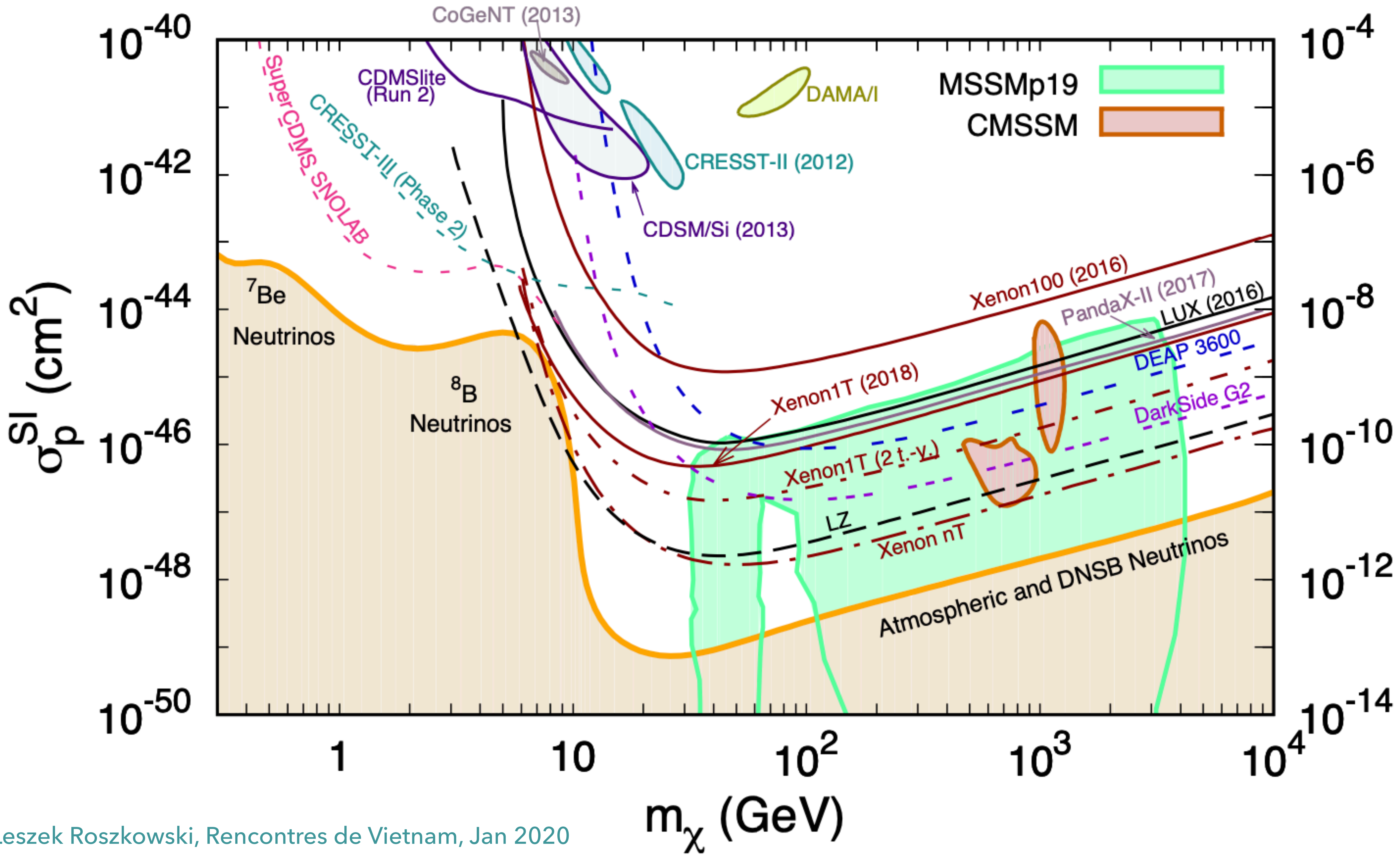
- Upgrade to 8.4 t of LXe, 5.9 t in the TPC
- Many sub-systems in place from XENON1T, however:
  - New inner cryostat, new TPC, 494 PMTs
  - Neutron veto: Gd doped (0.5% $Gd_2(SO_4)_3$) water Cherenkov detector
  - ^{222}Rn distillation tower, additional xenon storage system, faster LXe purification
- Commissioning at LNGS in progress
- Start data taking by the end of 2020







WIMPS: THEORY AND EXPERIMENT



Leszek Roszkowski, Rencontres de Vietnam, Jan 2020

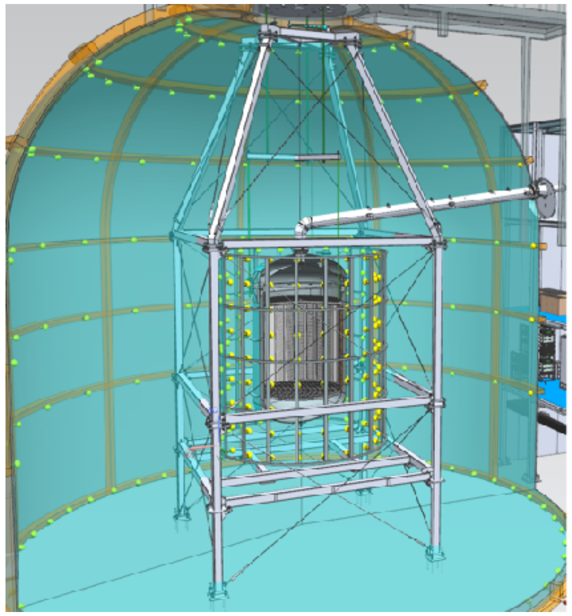
DARWIN PHYSICS PROGRAMME

DIRECT DARK MATTER DETECTION

SOLAR AXIONS

NEUTRINOLESS DOUBLE BETA DECAY ^{136}XE

DARWIN Collaboration, arXiv:2003.13407



GALACTIC ALPS, DARK PHOTONS

LOW-ENERGY SOLAR NEUTRINOS

DARWIN Collaboration, arXiv:2006.03114

COHERENT NEUTRINO NUCLEUS SCATTERS

SUPERNOVA NEUTRINOS

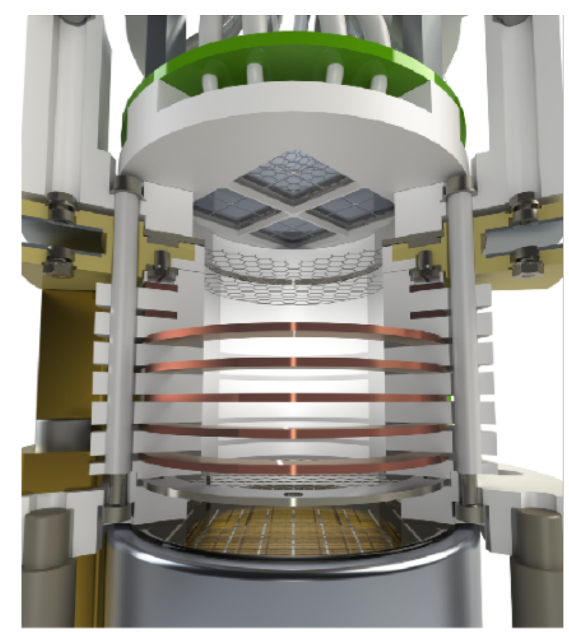
European Research Council
Established by the European Commission

DARWIN R&D

- Detector, Xe target, background mitigation, photosensors, etc
- Two large-scale demonstrators (in z & in x-y) supported by ERC grants
- Demonstrate electron drift over 2.6 m, operate large (2.6 m diameter) electrodes, etc
- Stay tuned: @DarwinObserv

Test e- drift over 2.6 m (purification high-voltage)

Test electrodes and homogeneity of extraction field

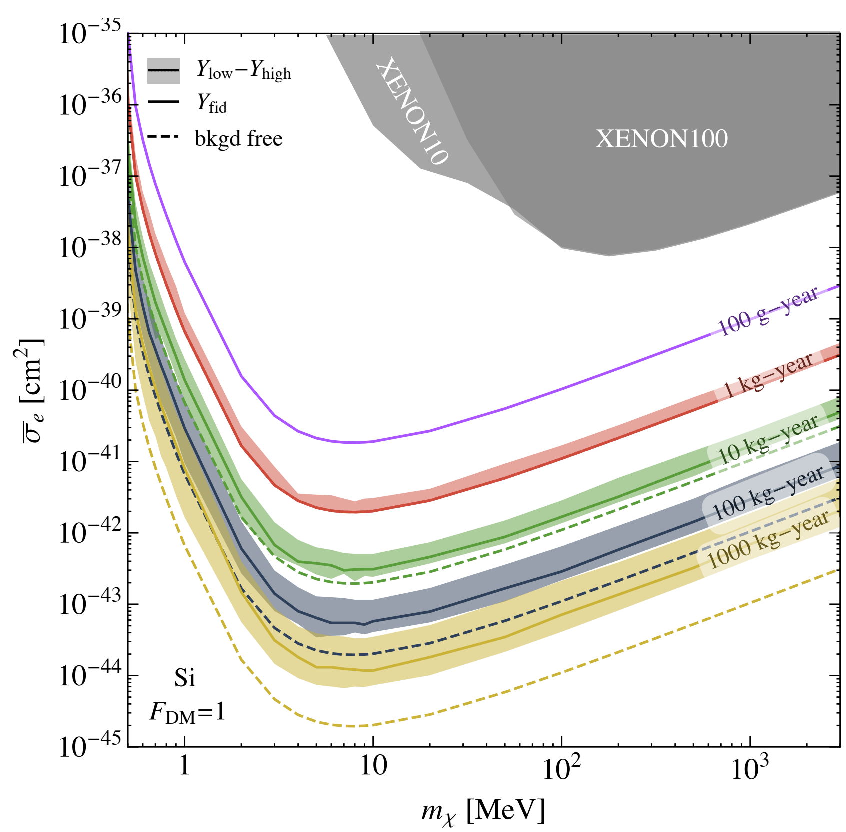


First LXe-TPC with SiPM arrays,EPJ- C 80, 2020

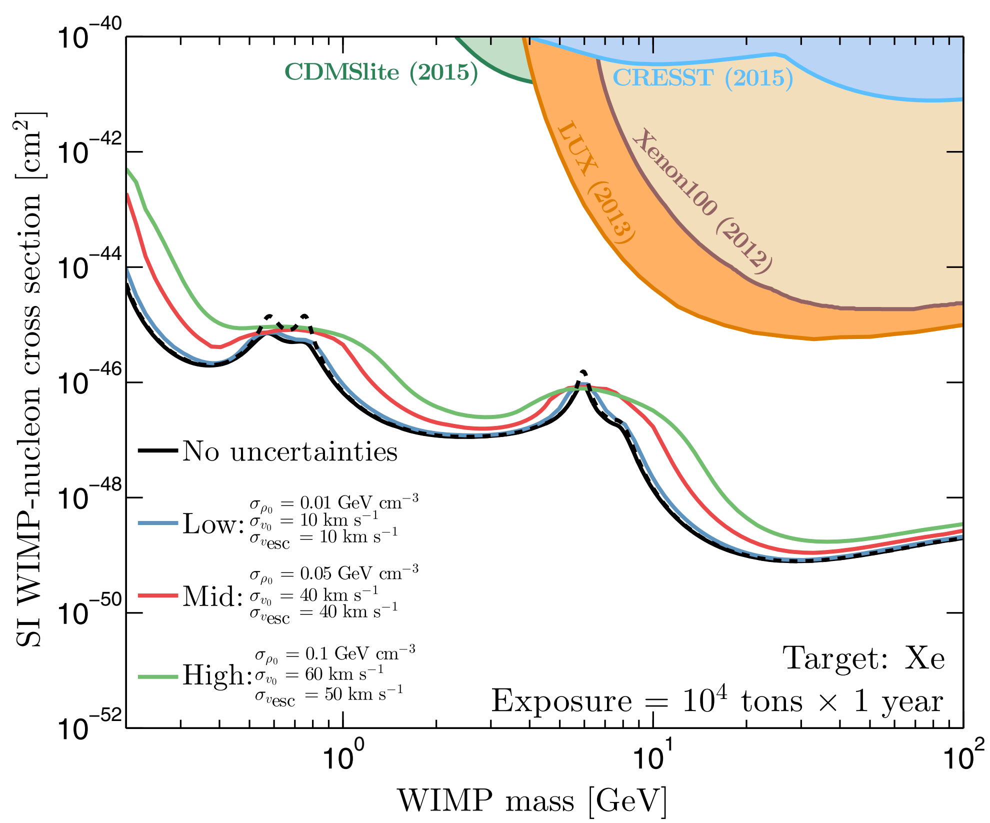
NEUTRINO BACKGROUNDS

- Low mass region: limit at ~ 0.1- 10 kg year (target dependent)
- High mass region: limit at ~ 10 ktonne year
- But: annual modulation, directionality, momentum dependance, inelastic DM-nucleus scatters, etc

Discovery limits (2-σ) for various ionisation efficiencies Y, solar ν background only



DM-electron scatters (R. Essig et al, PRD97, 2018)



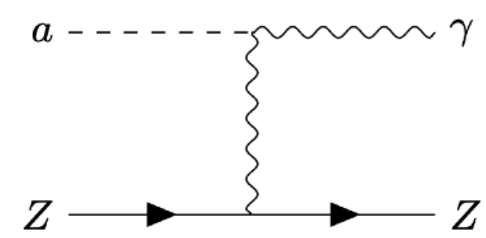
DM-nucleus scatters (C.A.J. O'Hare, PRD94, 2016)

SUMMARY & OUTLOOK

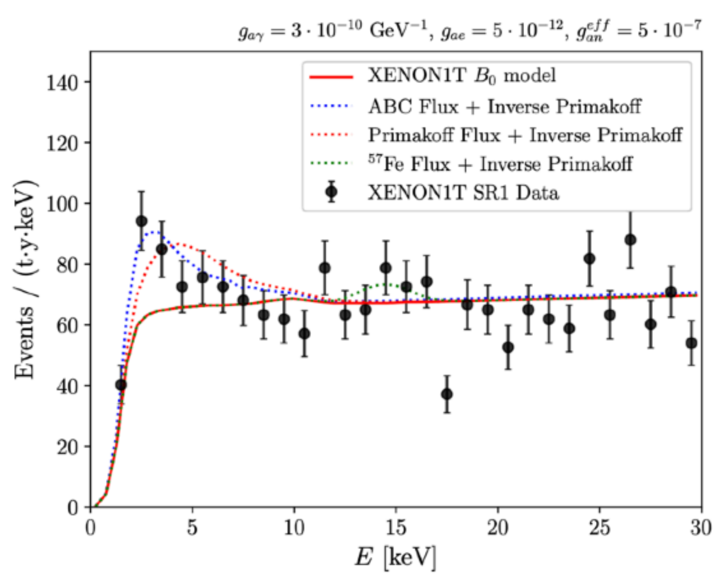
- Dark matter particle candidates cover large mass & cross section range
- A variety of technologies employed for their detection & many new ideas
- So far: we have mostly learned what dark matter is not… we have been narrowing down the options
- However, tremendous progress over the past decades & expected for next
- Pragmatic goal: broaden the searches & probe the experimentally accessible parameter space
- Rich non-WIMP physics programme: neutrinos, solar axions, ALPs, dark photons, etc
- Remember that yesterday's background might be today's signal ;-)

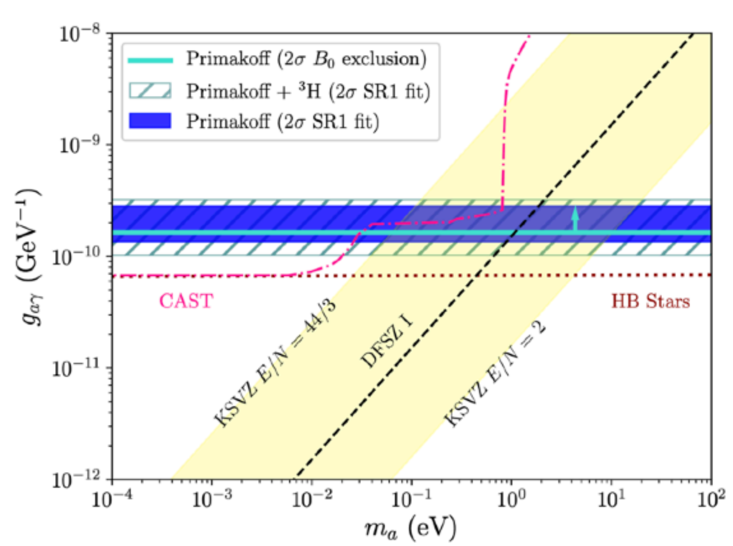
ADDITIONAL MATERIAL

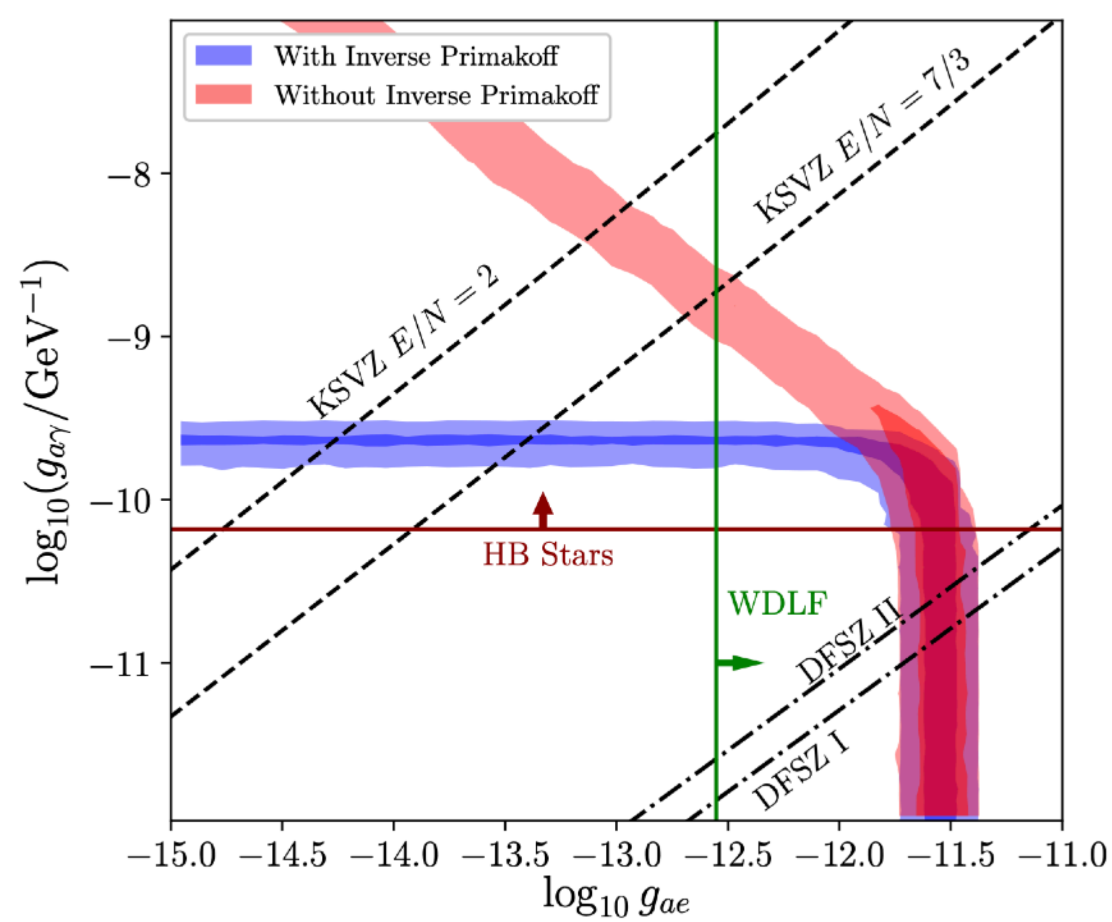
INVERSE PRIMAKOFF EFFECT



- Incident axion scatters off charged particle through $g_{a\gamma}$ coupling -> through coherent sensitivity to the atomic form factor

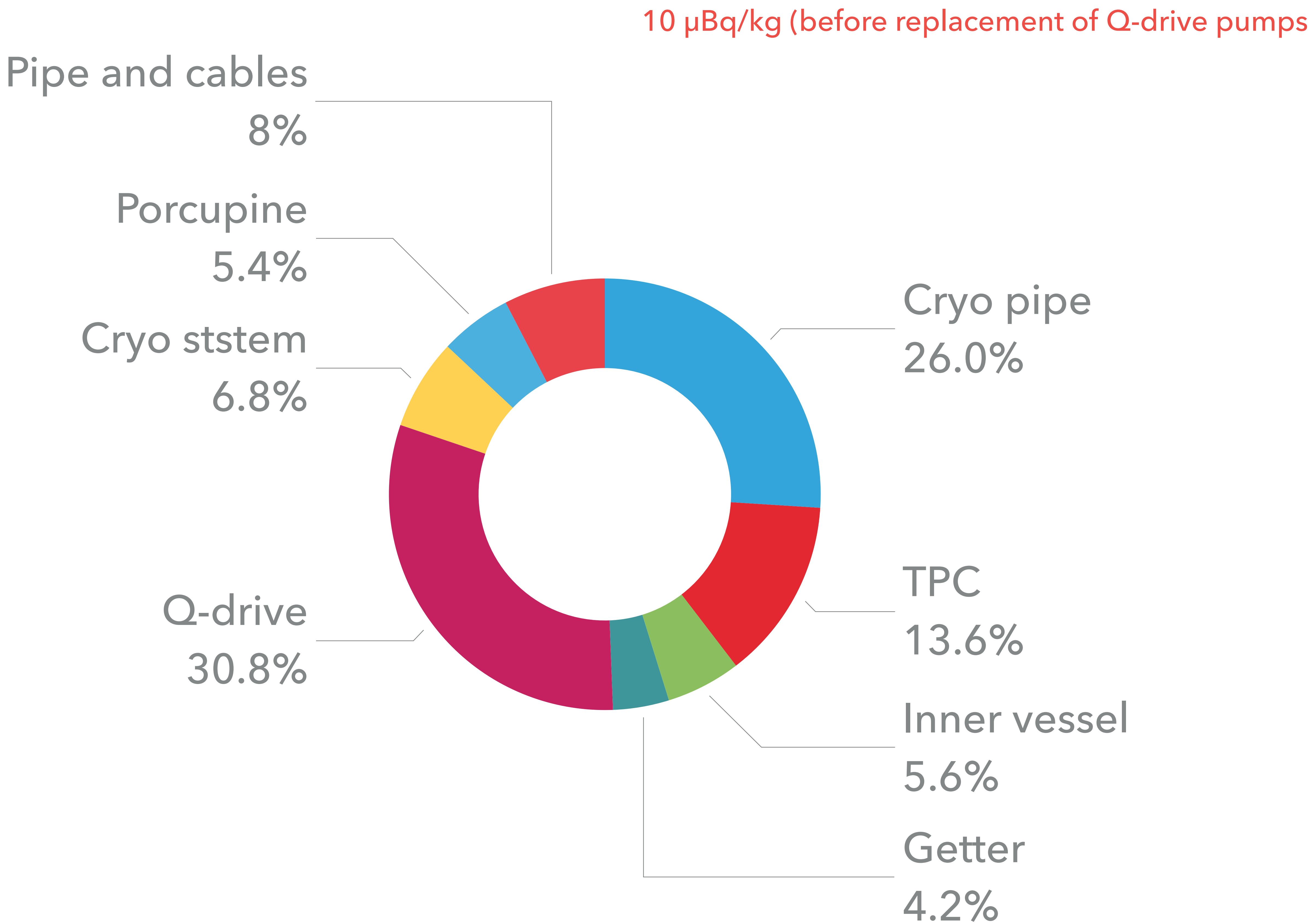






Dent, Dutta, Newstead, Thomspon, arXiv:2006.15118, Gao, Liu, Wang. Wang, Xue, arXiv 2006.14598

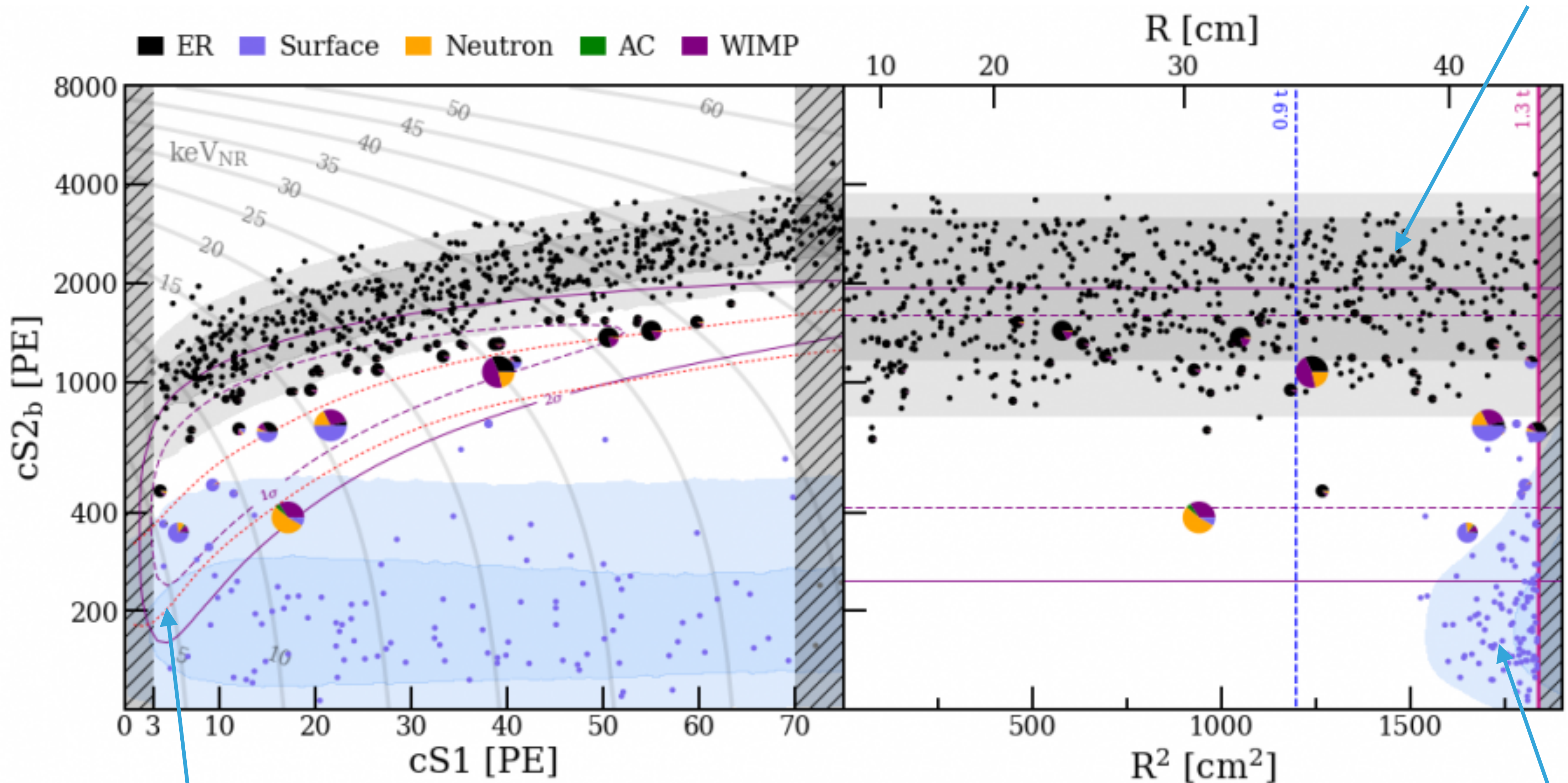
RADON BUDGET IN XENON1T



XENON Collab., PRL 121 (2018)

EVENTS IN THE WIMP REGION-OF-INTEREST

ER component



1-σ and 2-σ percentile of 200 GeV WIMP component

Surface component

XENON, arXiv:1907.12771, PRL 123

LIGHT DARK MATTER

- Exploit the Migdal effect
- Sudden nuclear momentum change (with respect to e-) after NR
- Kinematic boost of e-