CERN Academic Training Lectures: Dark Matter Searches

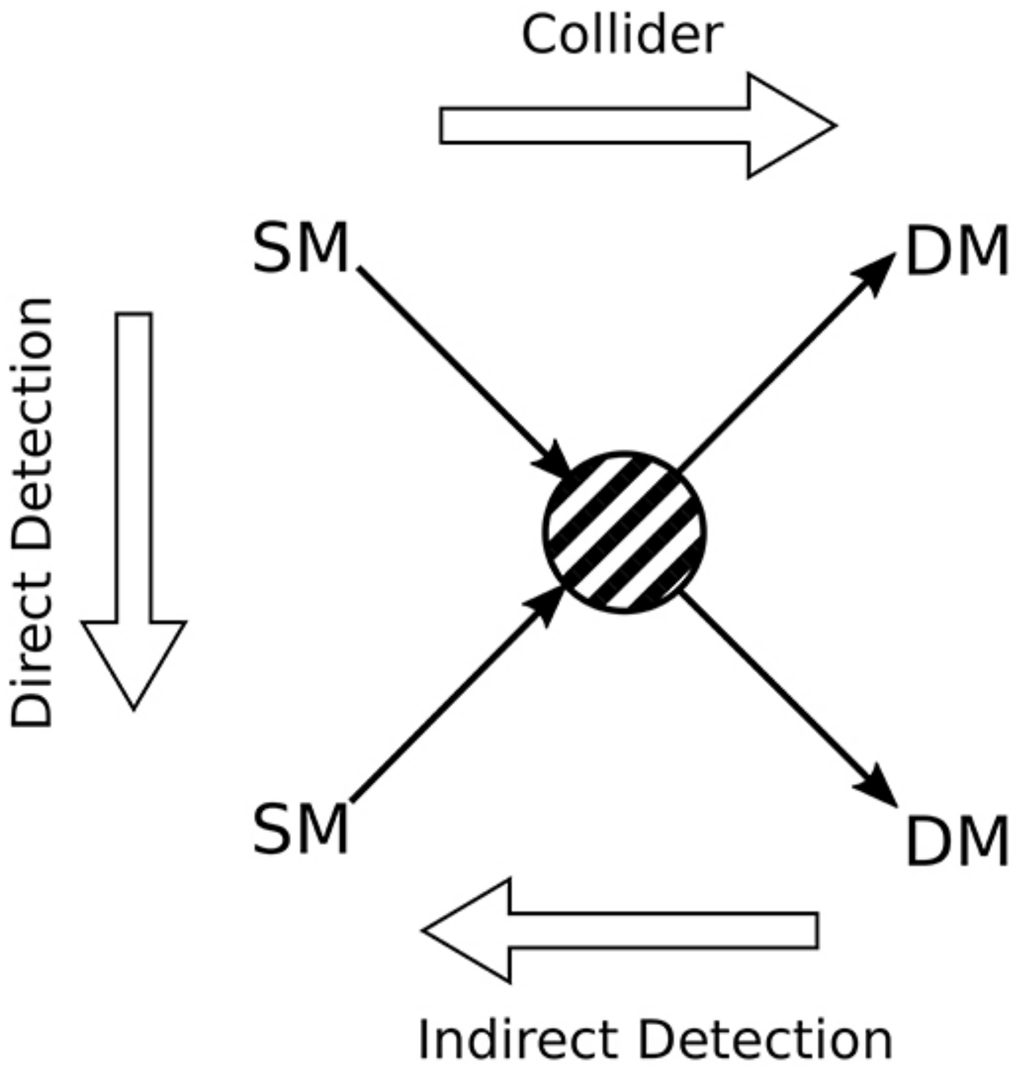
Lecture 2: Direct Searches for Galactic WIMPs

Dan Tovey

University of Sheffield

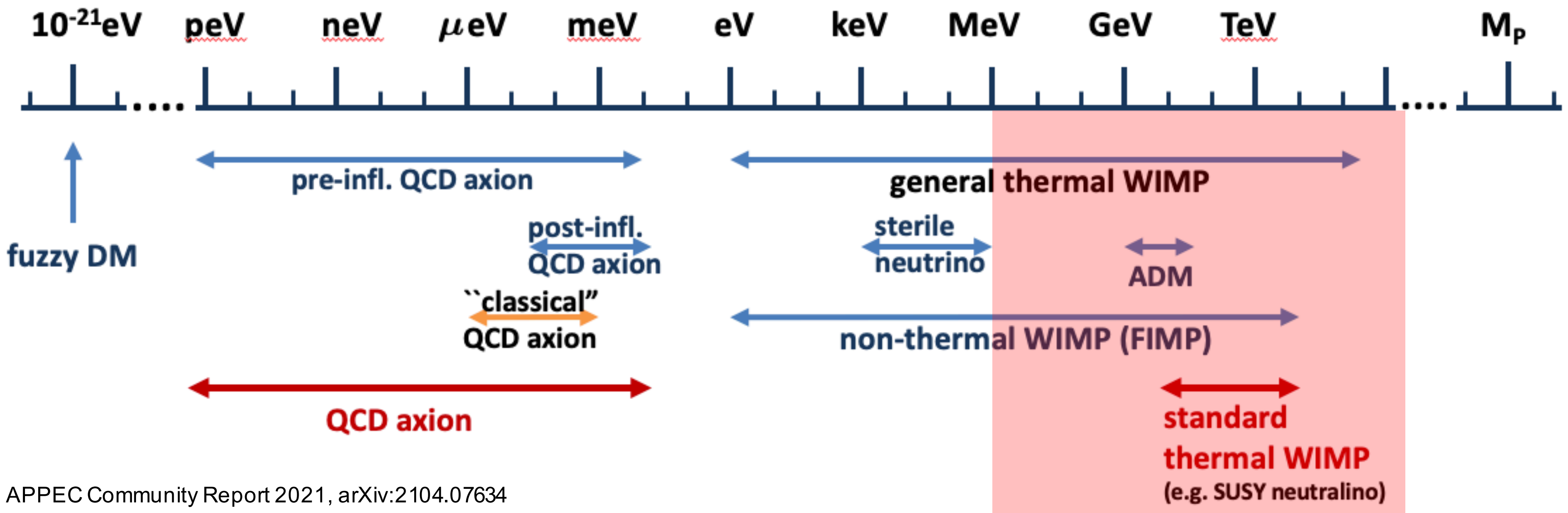
Recap: Dark Matter Searches

- Three main ways to search for evidence of particle DM via non-gravitational interactions
- Indirect: Seek evidence for annihilation or decay products of DM particles trapped in galactic / solar / planetary potential wells
  - X-rays, gamma rays, neutrinos, anti-matter ….
  - May prove DM but not identify particle
- Direct: Seek evidence for DM particle interactions with targets in terrestrial detectors
  - Nucleons, nuclei, electrons, photons …
  - May prove DM but not identify particle
- Accelerator/Collider: Seek evidence for invisible particle production in SM particle collisions
  - May identify particle but cannot prove DM



S. Giagu, https://doi.org/10.3389/fphy.2019.00075

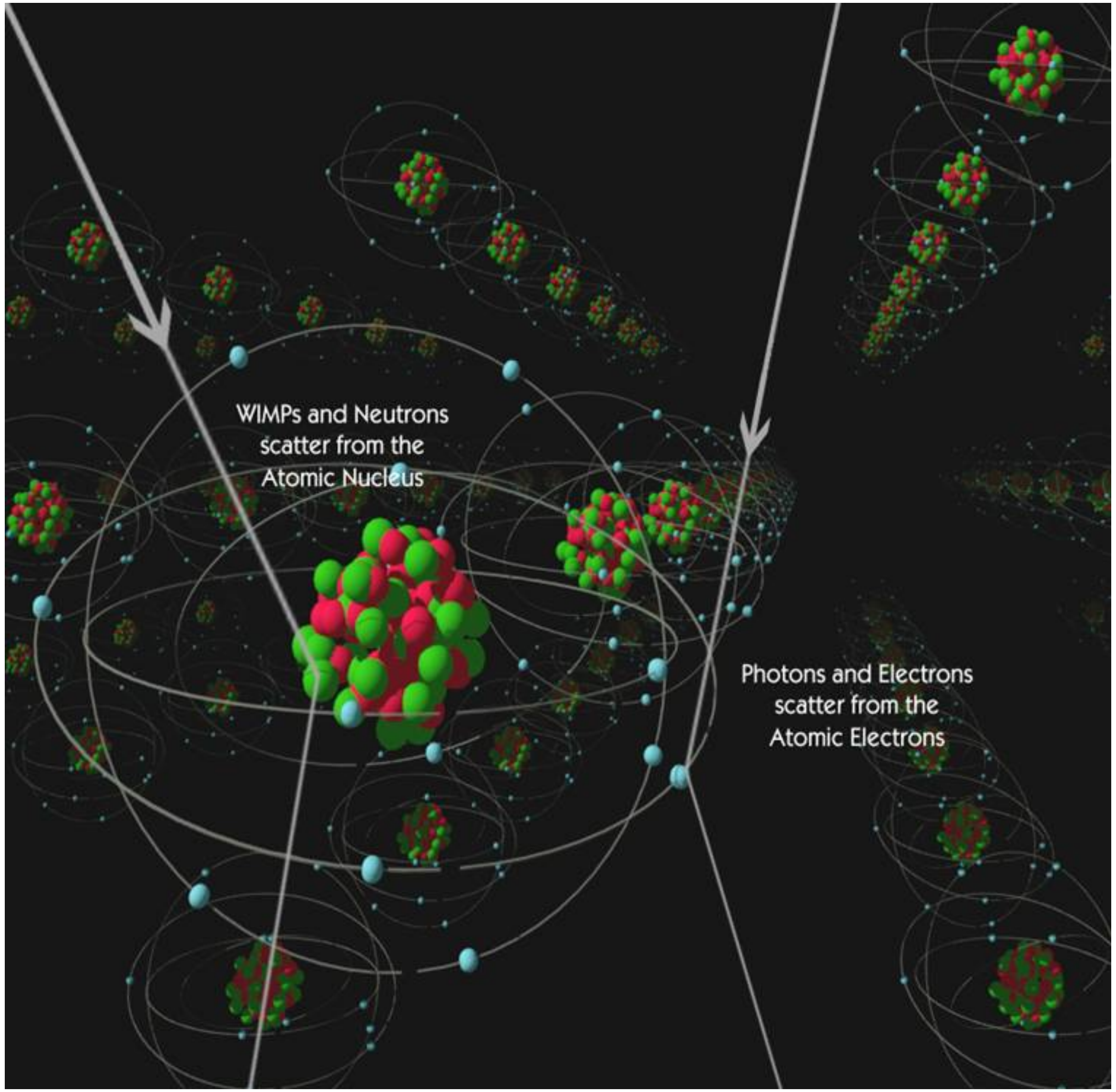
Search Strategy



APPEC Community Report 2021, arXiv:2104.07634

Searches for Low Energy Nuclear Recoils

- Basic idea (Goodman and Witten 1985): WIMPs couple weakly to baryonic matter so search for anomalous sources of low energy nuclear recoils
- Majority of backgrounds due to electron recoils (beta decay, compton scattering etc.), from radioactive contamination
- Residual nuclear recoils from neutron scattering from fission and CR spallation so use deep, clean UG lab
- Energy spectrum of recoils driven by kinematics of WIMPs in galactic halo:
  - Assume $m_\chi \sim m_A \sim 100$ GeV
  - $E_K(A) \sim E_K(\chi) = \frac{1}{2} m_\chi (v/c)^2 \sim 25$ keV



Nuclear Recoil Energy Spectrum

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \left(\frac{\rho_\chi}{m_\chi}\right) \left(\sigma_0^{\mathrm{SI}} F_{\mathrm{SI}}^2(E_R) I_{\mathrm{SI}} + \sigma_0^{\mathrm{SD}} F_{\mathrm{SD}}^2(E_R) I_{\mathrm{SD}}\right) \frac{1}{2\mu^2} \int_{v_{\mathrm{min}}}^{v_{\mathrm{esc}}} \frac{f(\vec{v}, \vec{v}_E)}{|\vec{v}|} \mathrm{d}^3\vec{v}$$

- Nuclear recoil energy spectrum obtained by integrating recoil energy spectrum from scattering from WIMP of fixed velocity over WIMP velocity distribution
- Normally assume isothermal (Maxwellian) halo velocity distribution (see Lecture 1):

$$f(\vec{v}, \vec{v}_E) = \frac{1}{\pi^{3/2} v_0^3} e^{-(\vec{v}+\vec{v}_E)^2/v_0^2}$$

- If assume target at rest with respect to halo then obtain:

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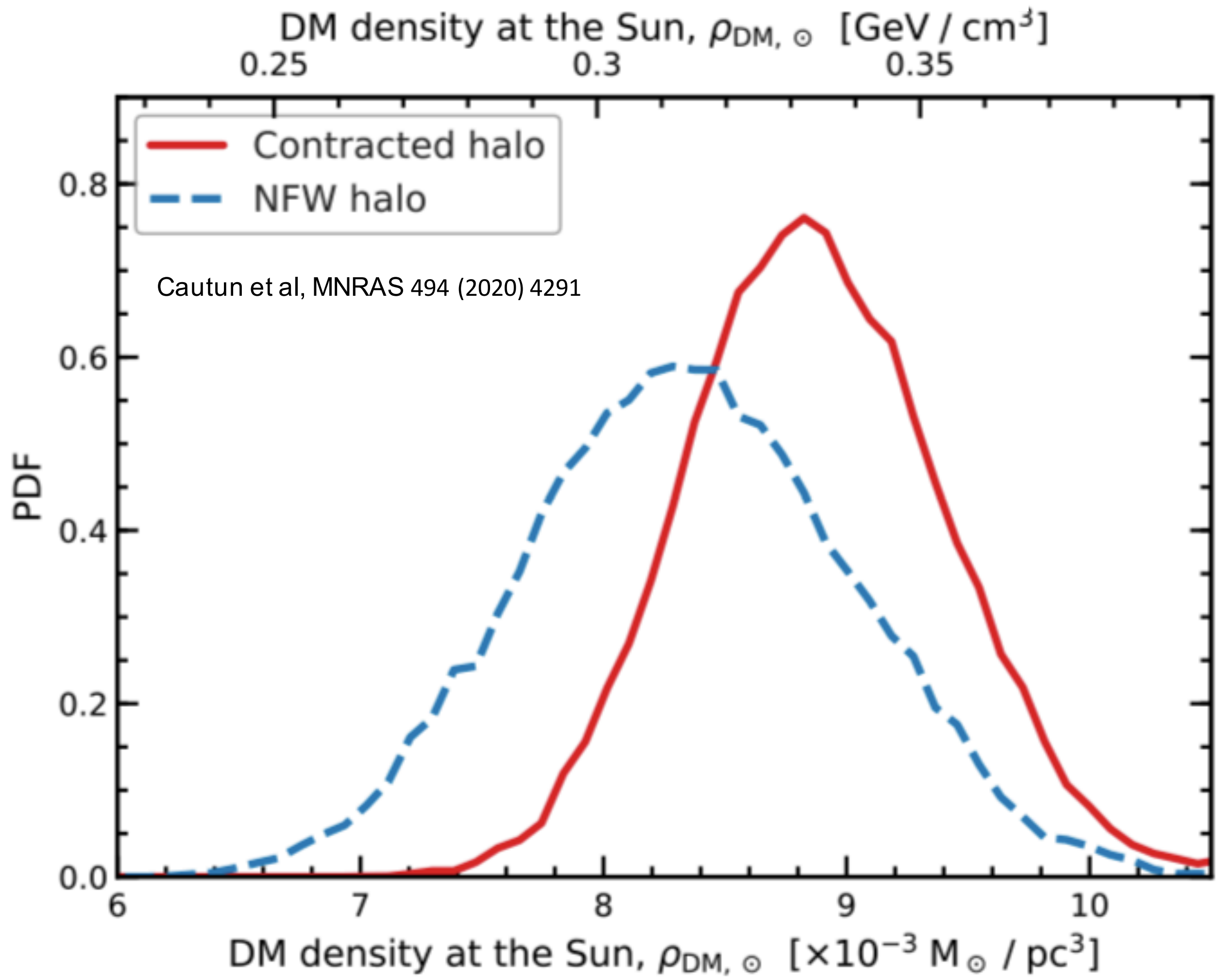
- Particle physics:
  - WIMP mass m_χ
  - WIMP coupling e.g. scalar, pseudo-scalar (determines coupling to nucleus)
  - WIMP-nucleon cross-sections σ_0^{SI}, σ_0^{SD}
- Astrophysics:
  - Local WIMP density ρ_χ
  - DM halo velocity dispersion v_0 (+other params e.g. v_E, v_{esc})
- Nuclear physics:
  - Spin-dependent / spin-independent coupling enhancements I_{SD}, $I_{SI}=(\mu/\mu_n)^2A^2$ for scalar
  - Form-factors $F_{SI}^2(E_R)$, $F_{SD}^2(E_R)$ – Fourier Transform of scattering centres



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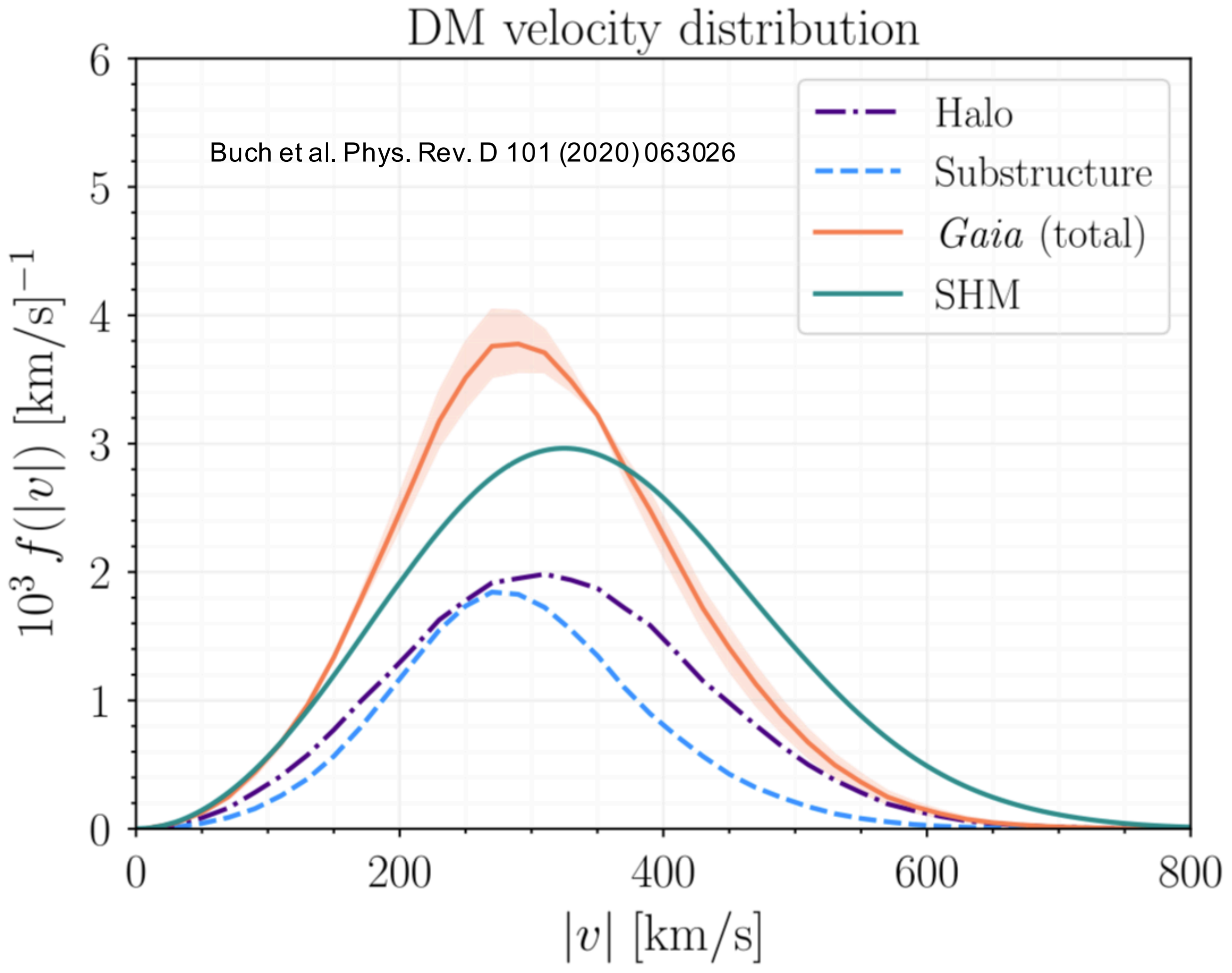

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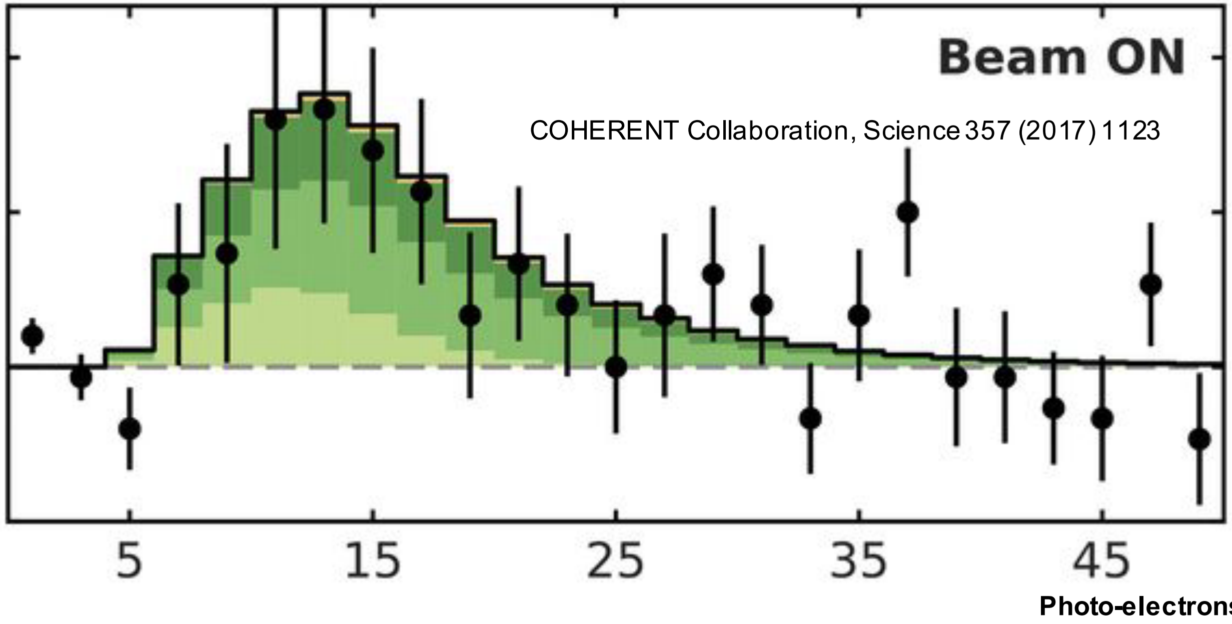

First observation of coherent neutrino-nucleus scattering

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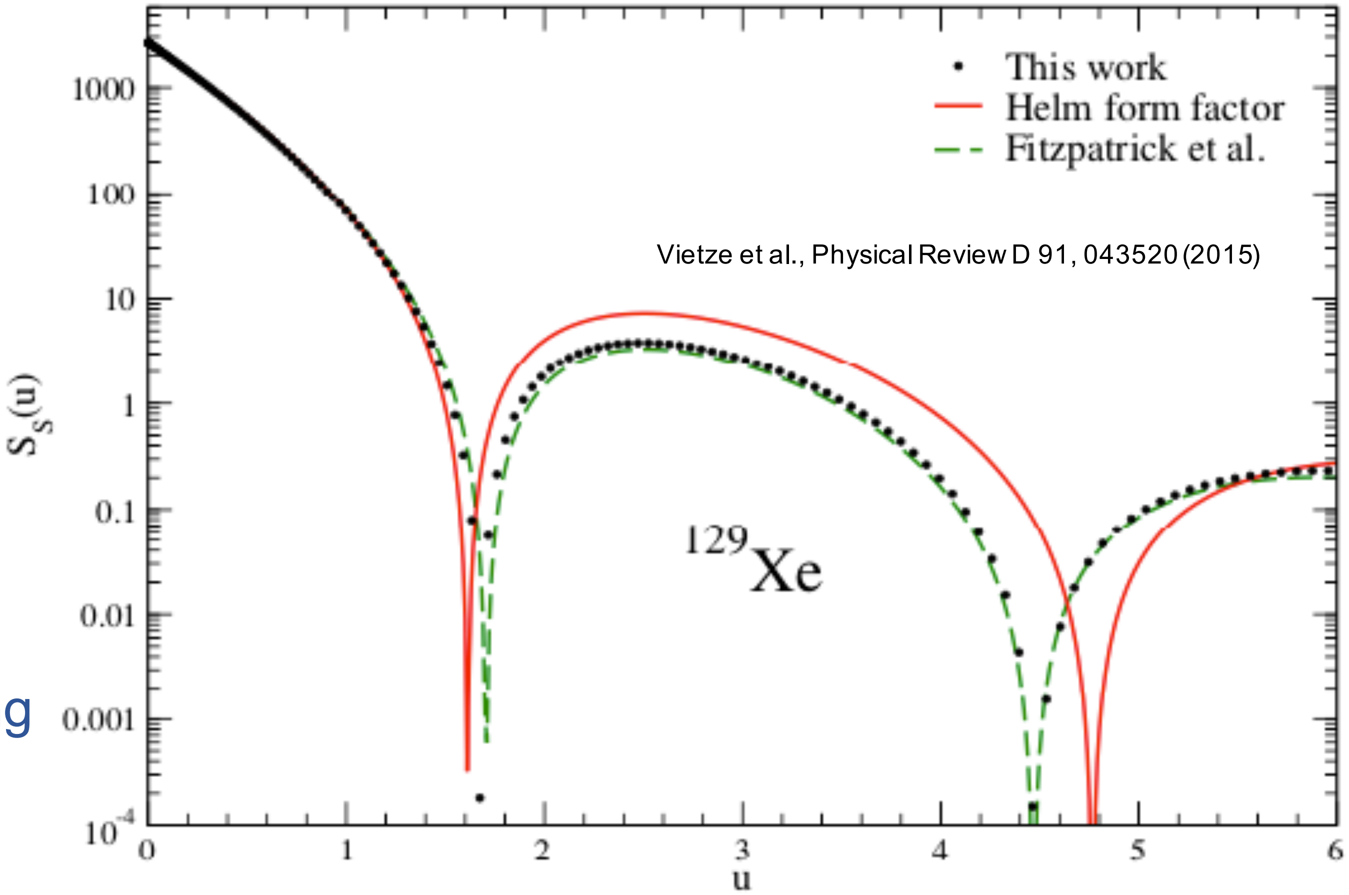

Vietze et al., Physical Review D 91, 043520 (2015)

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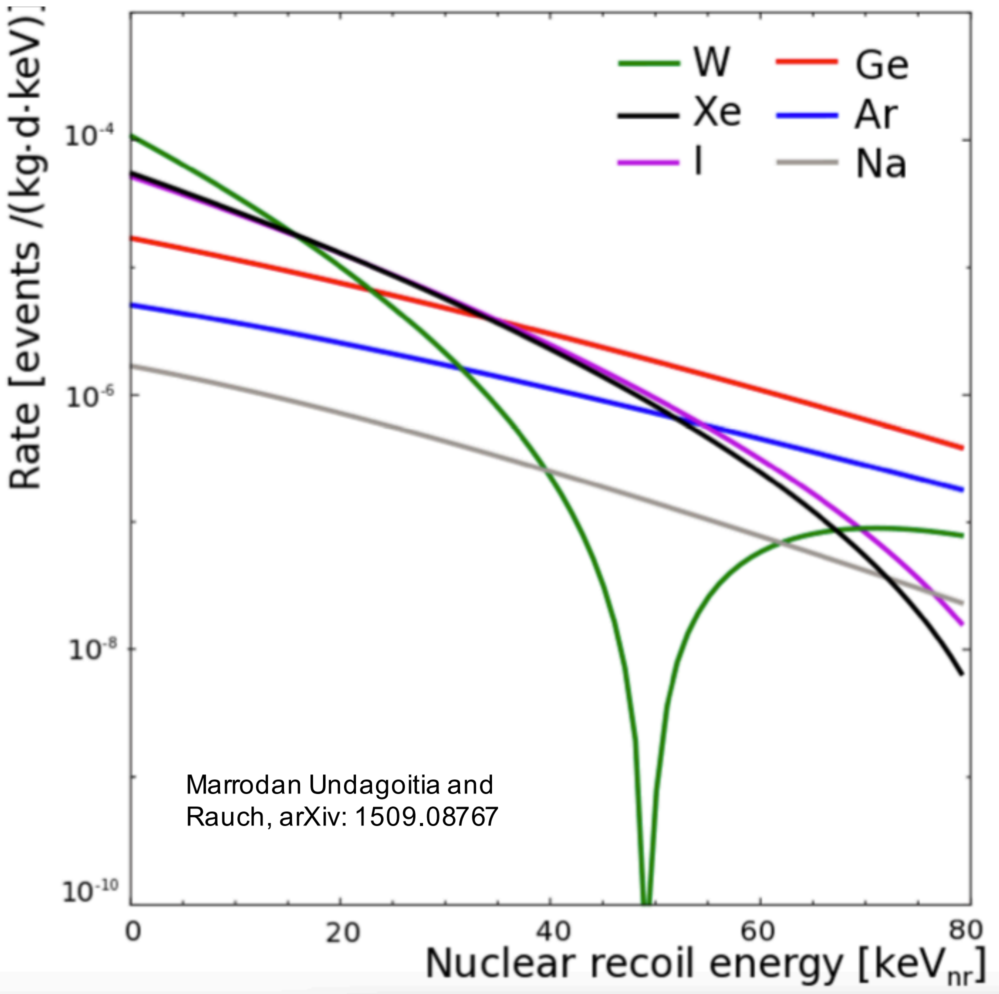


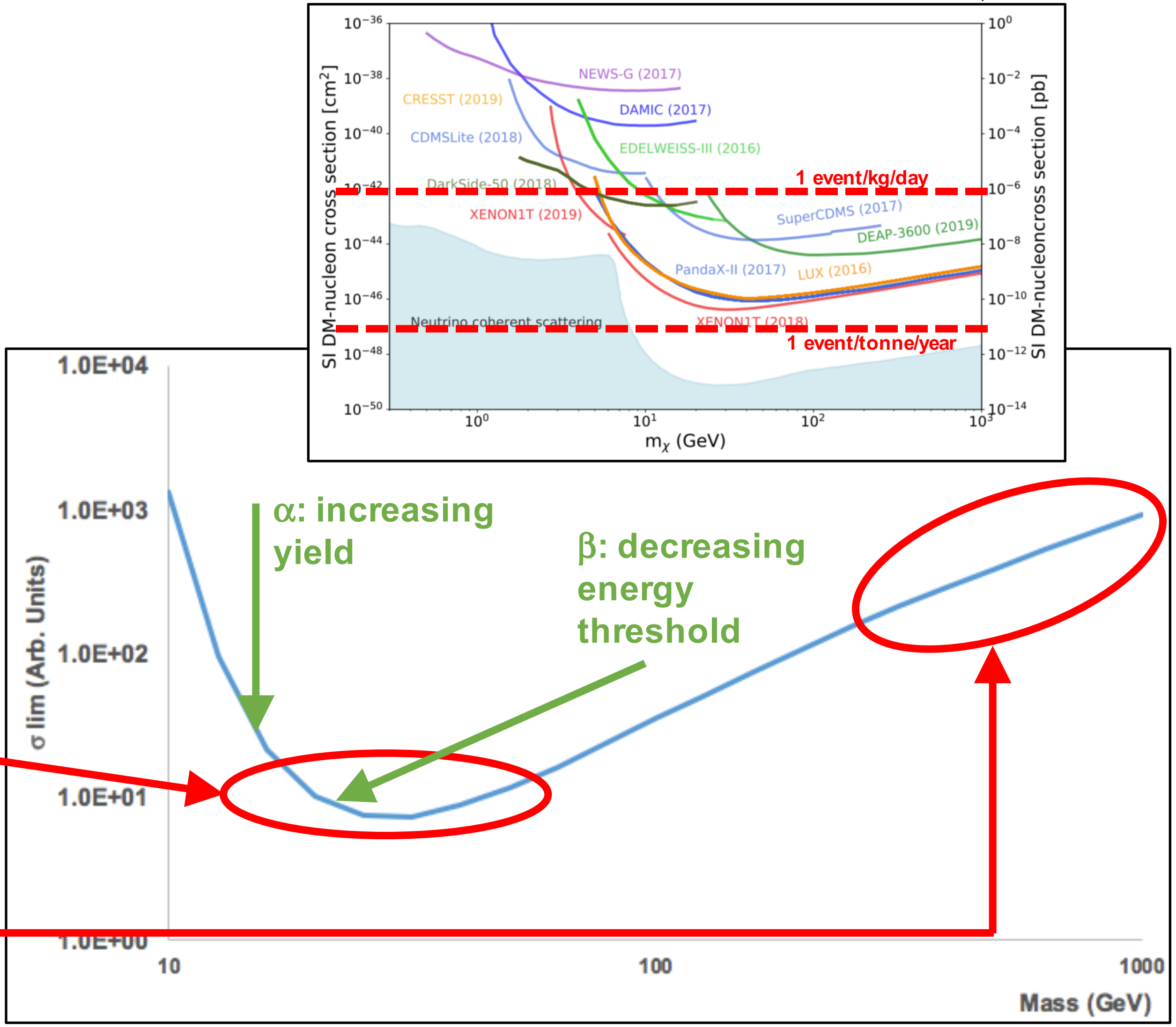
Direct Search Parameter Space

- Results typically quoted as limits on WIMP-nucleon cross-section vs. WIMP mass, assuming only one interaction (SI/SD), normalised (for SD) to one type of nucleon
- Steeply falling spectrum → sensitivity dominated by **detector energy threshold**
- Approximate form:

$$\sigma_0^{\mathrm{lim}} \sim \alpha m_\chi \mu^2 e^{\beta m_A/\mu^2}$$

  - α determined by limit on yield at threshold
  - β determined by value of threshold
  - Greatest sensitivity when $m_\chi \sim m_A$ (kinematics)
  - At high mass, spectrum asymptotically independent of m_χ. Sensitivity ~ 1 / WIMP number density ~ m_χ for fixed ρ_χ
- Spin-dependent limits differ for proton and neutron. Sensitivity ~A^2~10^4 less (coherence)

L. Baudis and S. Profumo, PDG 2020

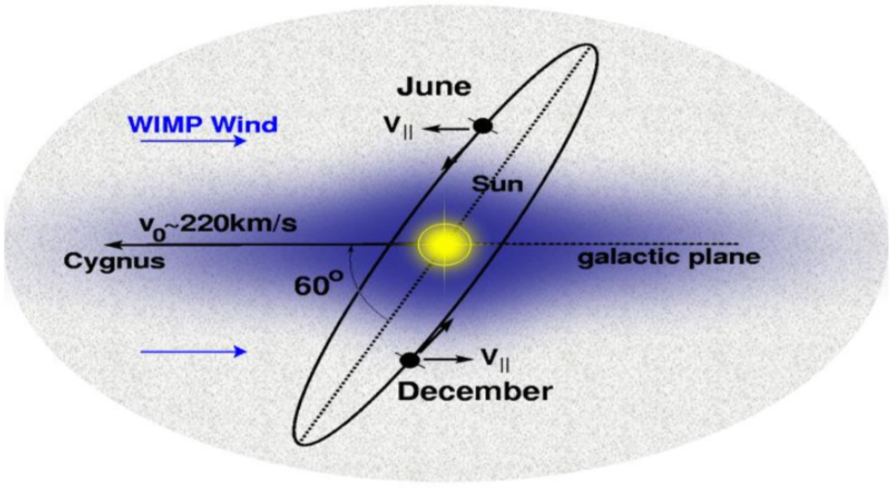


Halo Signatures

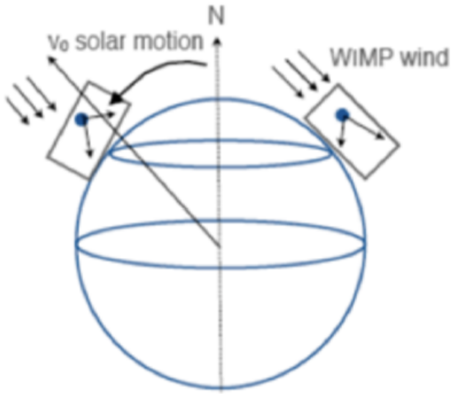
- Motion of terrestrial detector through halo gives further possibilities for signal identification
- Annual modulation: flux varies annually with max/min in Jun/Dec (depends on energy).

$$v_E \simeq 244 + 15\sin(2\pi(t - t_0))\ \mathrm{km\ s^{-1}}$$

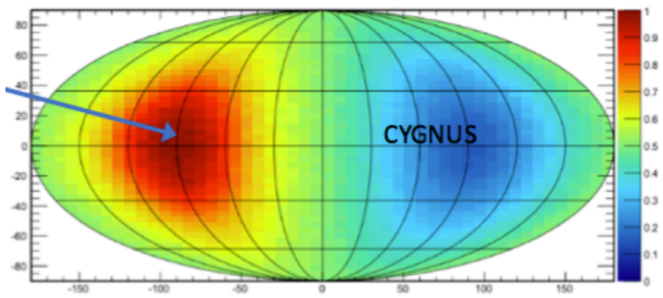
- Directional modulation: mean direction of WIMP flux relative to terrestrial detector modulates diurnally → modulation in mean direction of recoils



$$f(\vec{v},\vec{v}_E) = \frac{1}{\pi^{3/2}v_0^3}e^{-(\vec{v}+\vec{v}_E)^2/v_0^2} \qquad \vec{v}_E = \vec{u}_R + \vec{u}_S + \vec{u}_E$$



P. Cushman et al, Snowmass 2013



Sky map in galactic coordinates of recoils from 100 GeV WIMPs on ^{19}F, E>50 keV

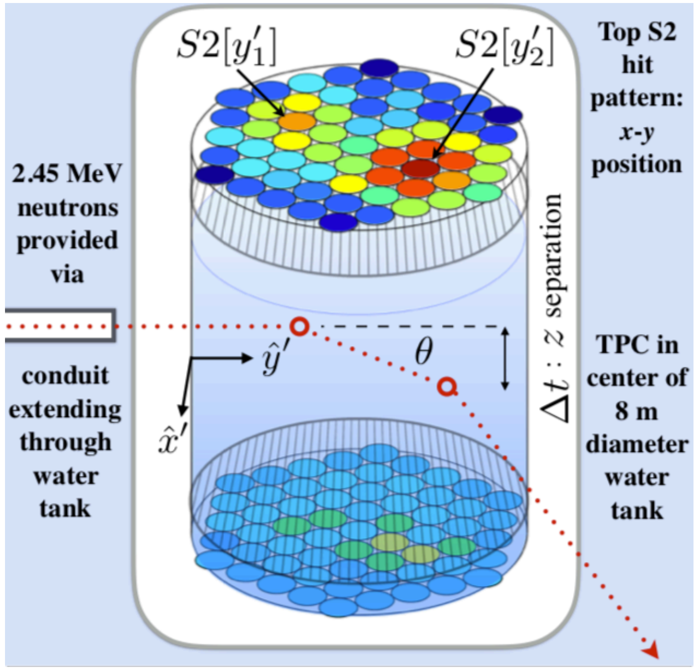
N. Spooner

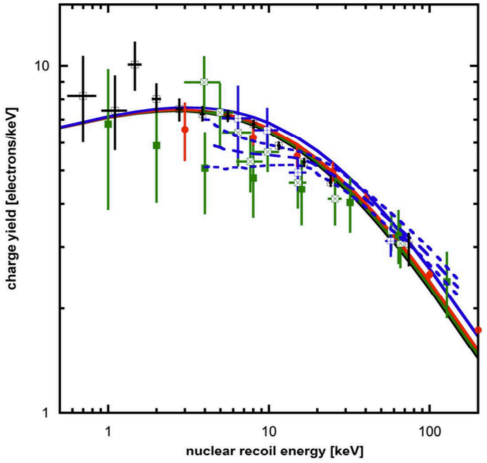
Energy Calibration

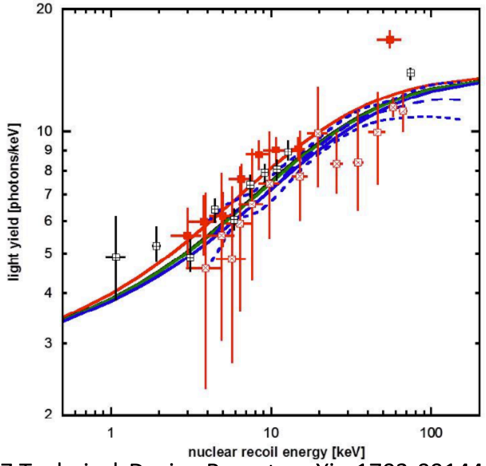
- Added complication – not all kinetic energy of recoiling nucleus visible in detector
  - Visible energy threshold >> recoil energy threshold ☹
- Quantified by energy-dependent Lindhard factor (keV_{nr}/keV_{ee})
  - e.g. ~25% for LXe scintillator detectors
- Detector media calibrated with nuclear recoils generated by neutron scattering with (usually) mono-energetic beam.
- Allows run-time calibration with electron recoils

$$E_e = W(n_\gamma + n_e) \quad E_A = W(n_\gamma + n_e)/\mathcal{L}$$

LUX Collaboration



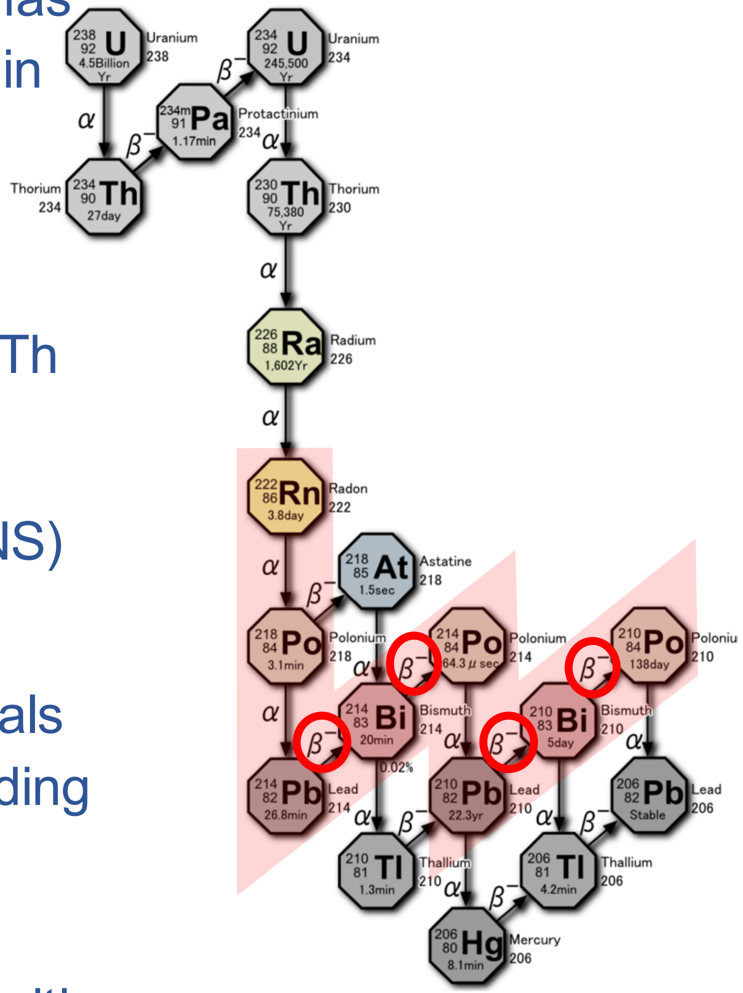


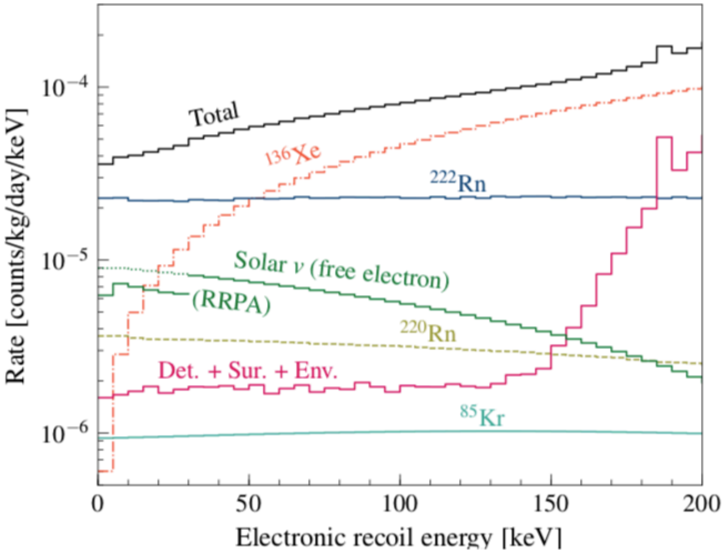


LZ Technical Design Report, arXiv:1703.09144

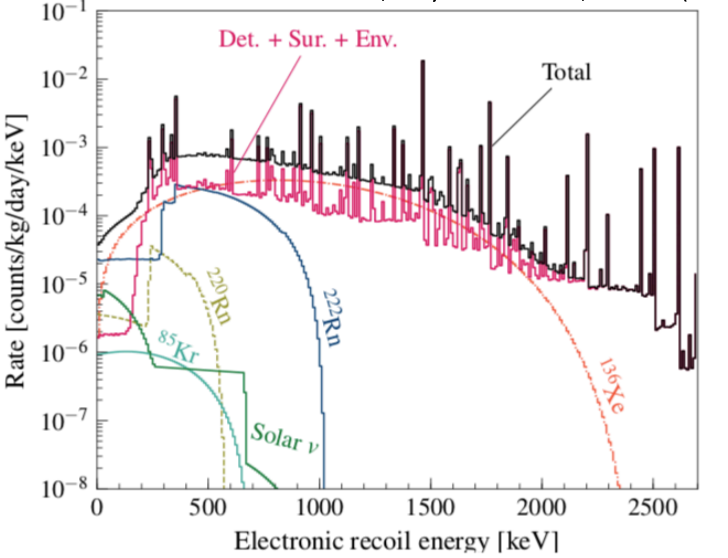
Backgrounds

- Electron recoils (reducible):
  - Compton scattering of external gammas
  - β (and 2ν-ββ) decay of contaminants in target volume, e.g. ^{85}Kr, ^{39}Ar, ^{136}Xe, ^{222}Rn daughters
- Nuclear recoils (irreducible):
  - Elastic scattering of neutrons from U/Th chain fission and CR spallation
  - Coherent elastic scattering of solar, atmospheric and SN neutrinos (CEνNS)
- Mitigation:
  - Radiopure target and detector materials
  - Shielding: Pb, Cu, H_2O and self-shielding
  - Operation deep underground
  - Veto electron recoil events
  - Veto U/Th chain gammas coincident with neutrons or neutrons themselves

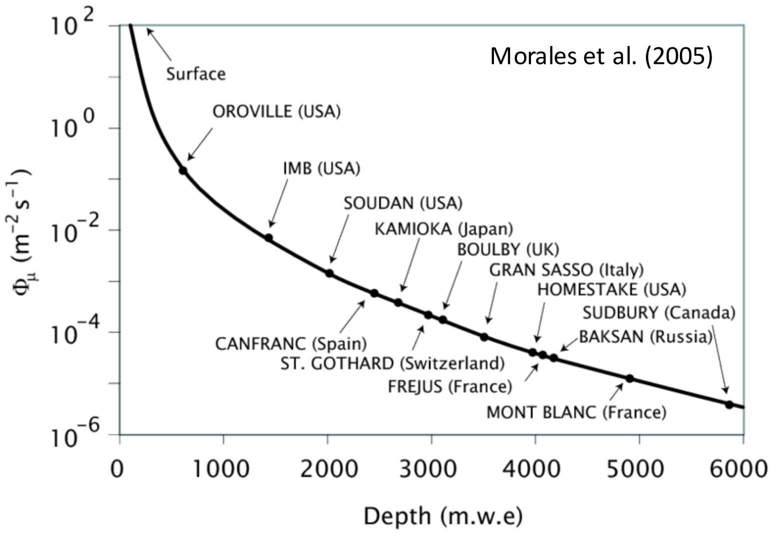




LZ Collaboration, Phys. Rev. D 101, 052002 (2020)

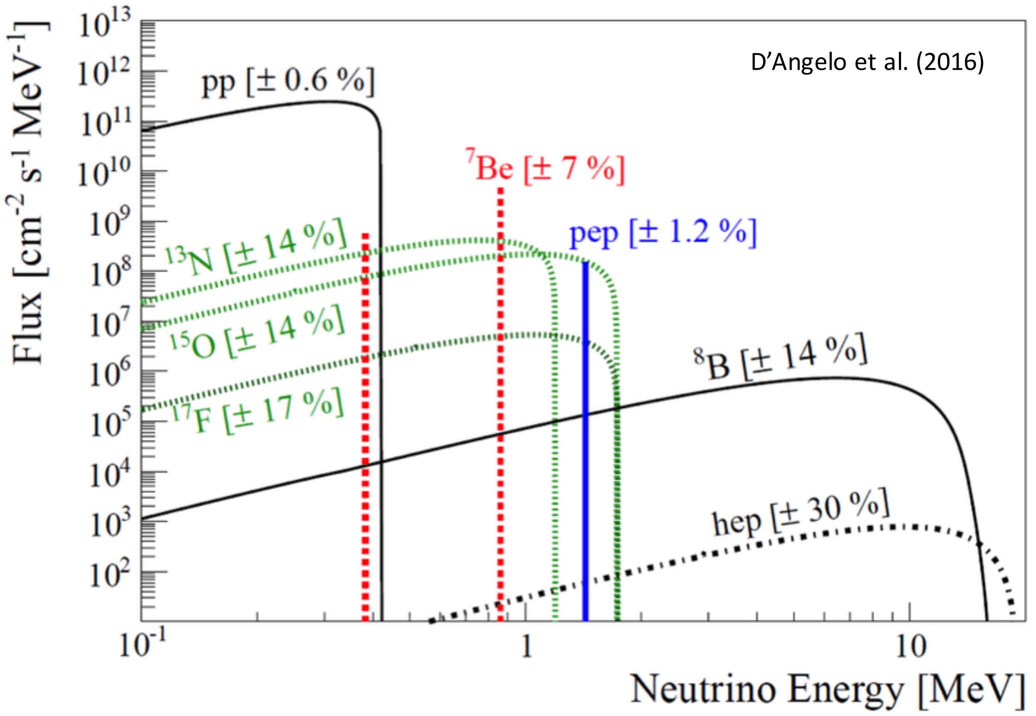


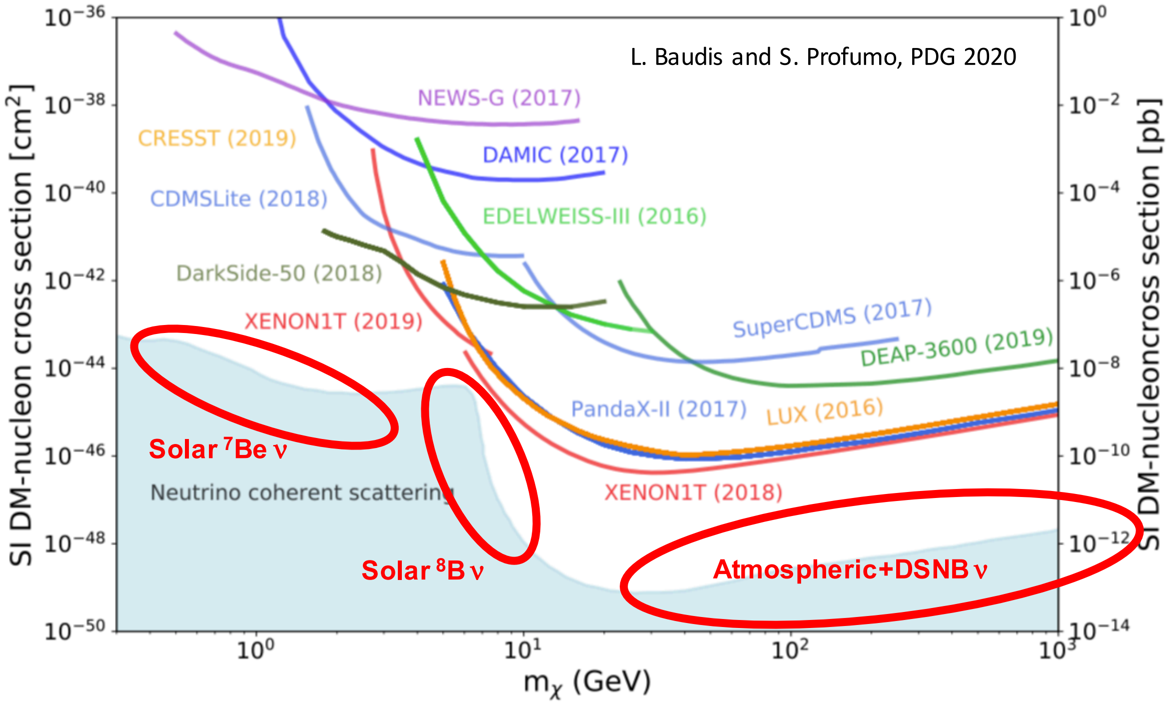
Underground Labs



Coherent Elastic ν-Nucleus Scattering (CEνNS)

- Irreducible nuclear recoil background to WIMP searches from neutrino scattering
- Observed at Spallation Neutron Source by COHERENT
- Provides the neutrino floor beyond which direct search performance dominated by background systematics (flux, form-factor)
- Substantial progress probably requires use of halo signatures (e.g. directionality)

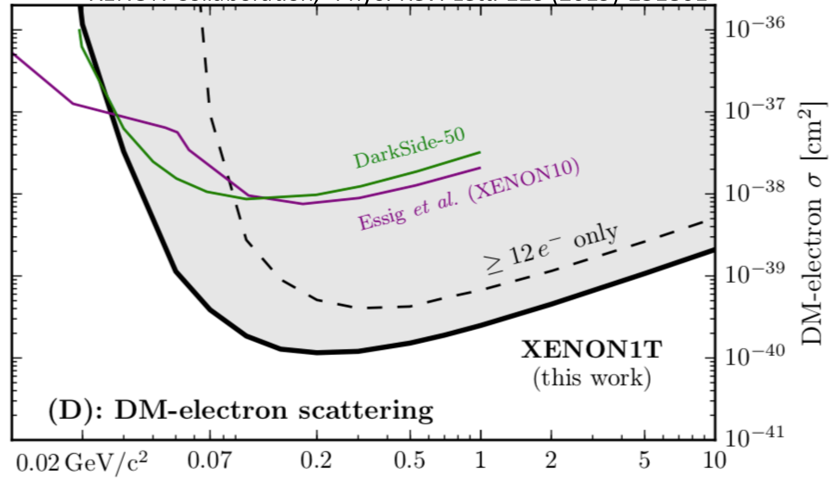




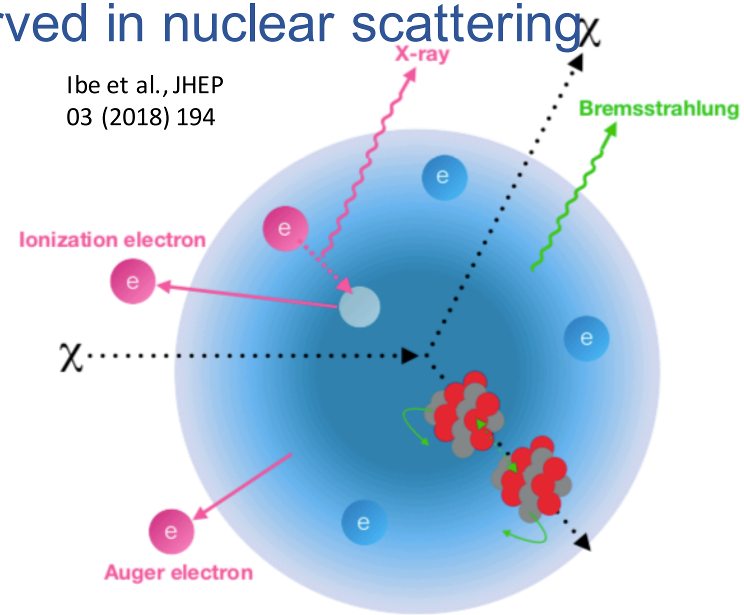
Low Mass WIMPs

- Elastic nuclear recoil searches lose sensitivity for m_χ less than a few GeV (kinematics)
- If WIMPs couple to electrons then kinematics more favourable, but large e-recoil background
- Low energy n-recoil signals accessible by discarding discrimination, or seeking more ‘electron-like’ n-recoil signals due to brem or Migdal effect (Ibe et al.)
  - NB Migdal effect not yet observed in nuclear scattering

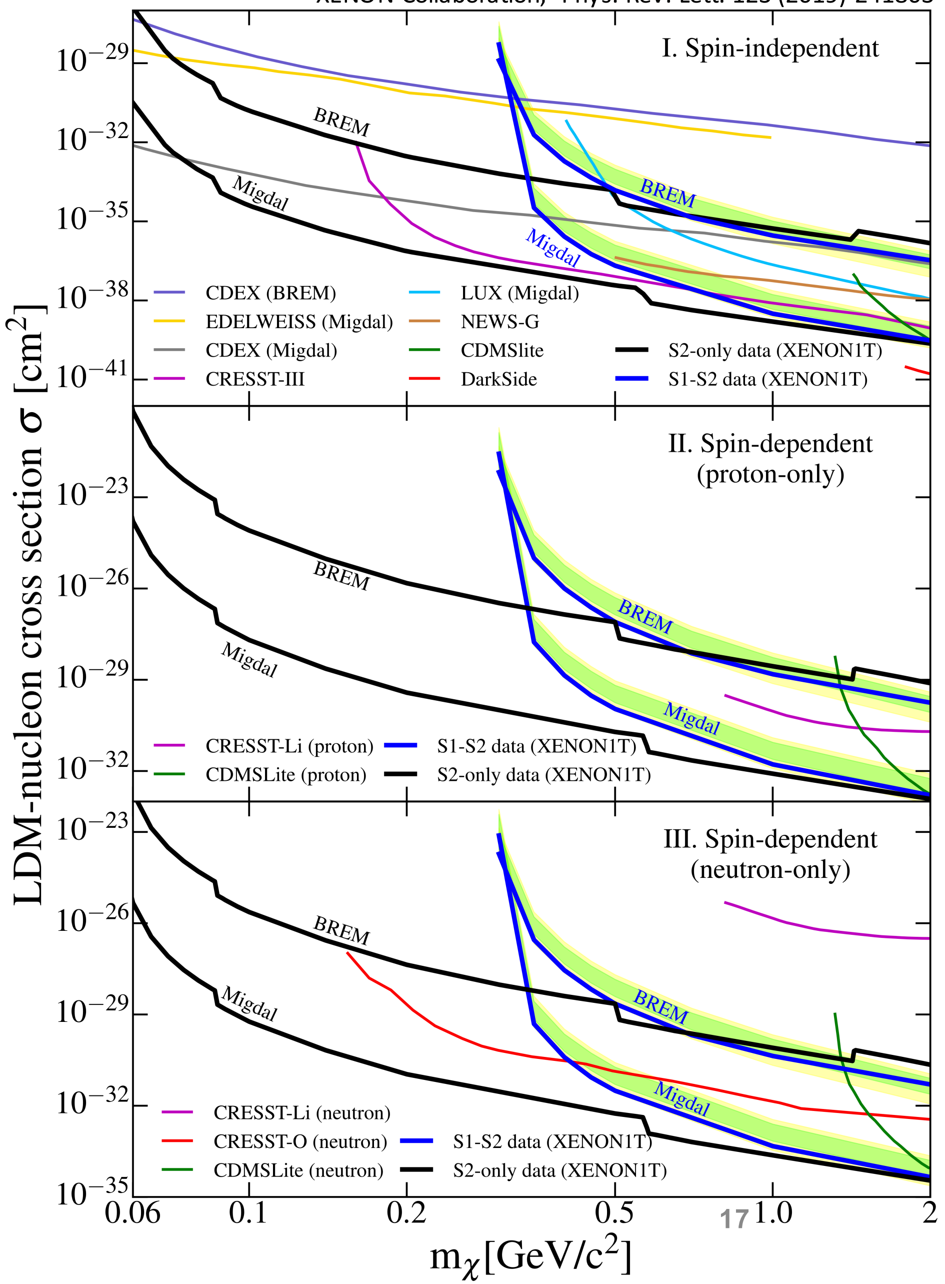
XENON Collaboration, Phys. Rev. Lett. 123 (2019) 251801



Ibe et al., JHEP 03 (2018) 194

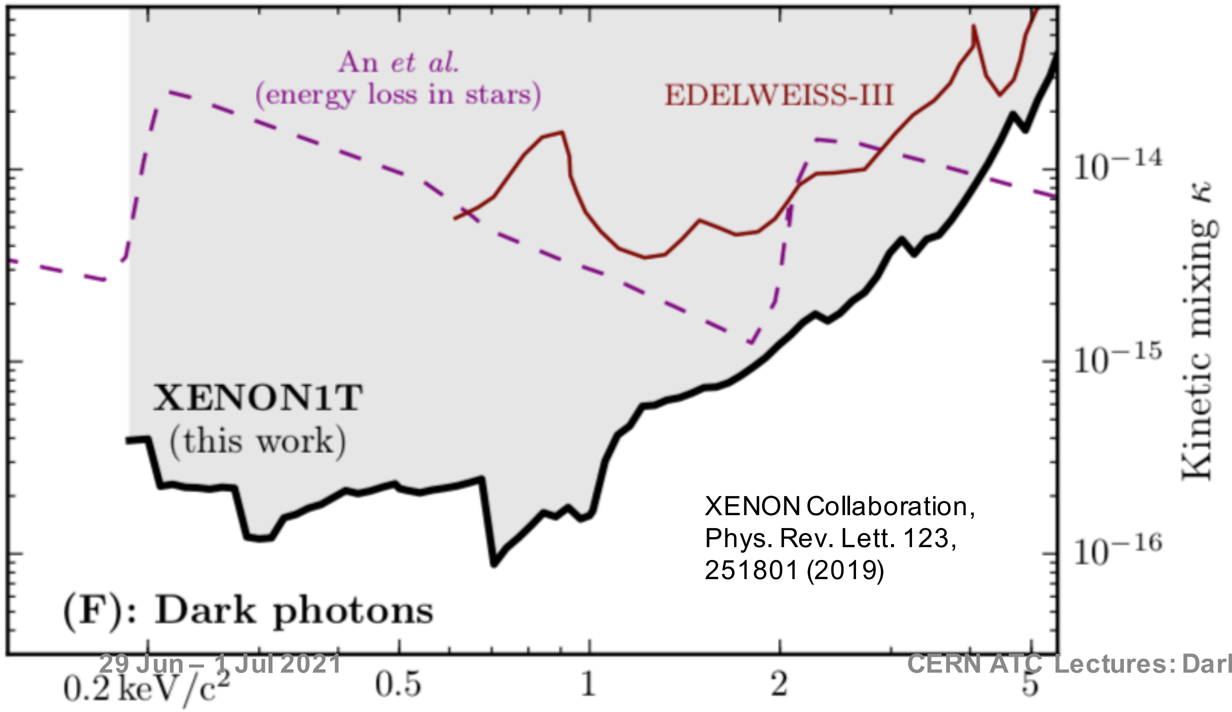


XENON Collaboration, Phys. Rev. Lett. 123 (2019) 241803

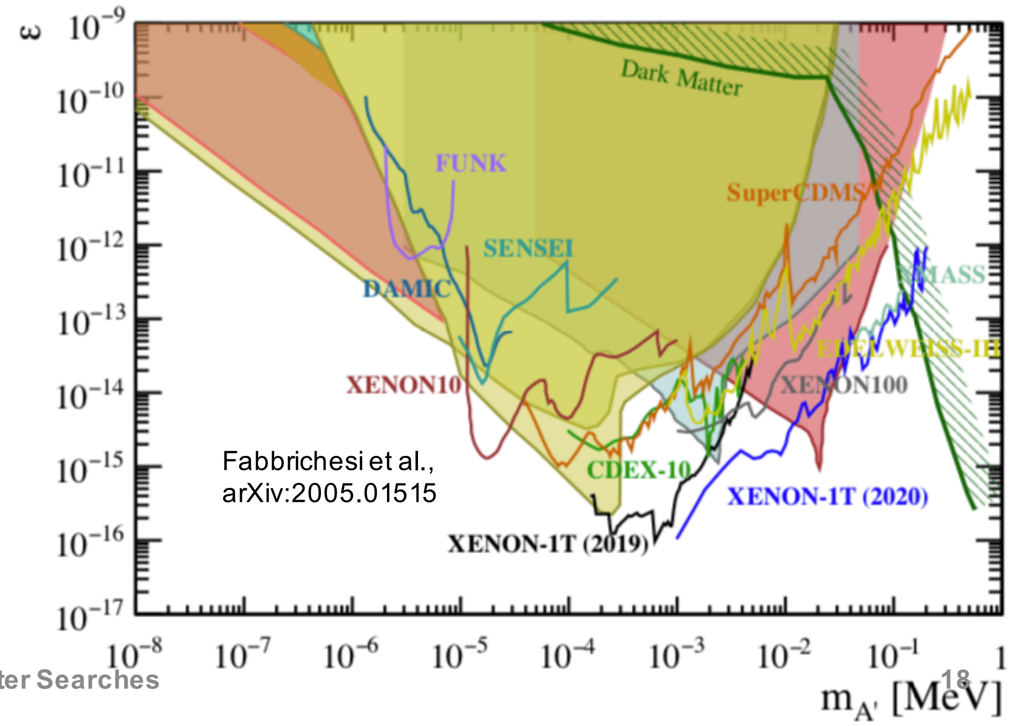


Dark Photon DM

- Motivated by models with extra U(1) gauge symmetry
  - Boson A' mixes with photon → weak coupling to matter
  - If light ($m_{A'}<2m_e$) cosmologically stable. Broad mass range to below 10^{-20} MeV
- Dark photon DM constraints:
  - Stellar astrophysics (anomalous cooling in sun, WD, RG, HB stars etc.)
  - Direct searches for electron recoil signals from dark photoionisation

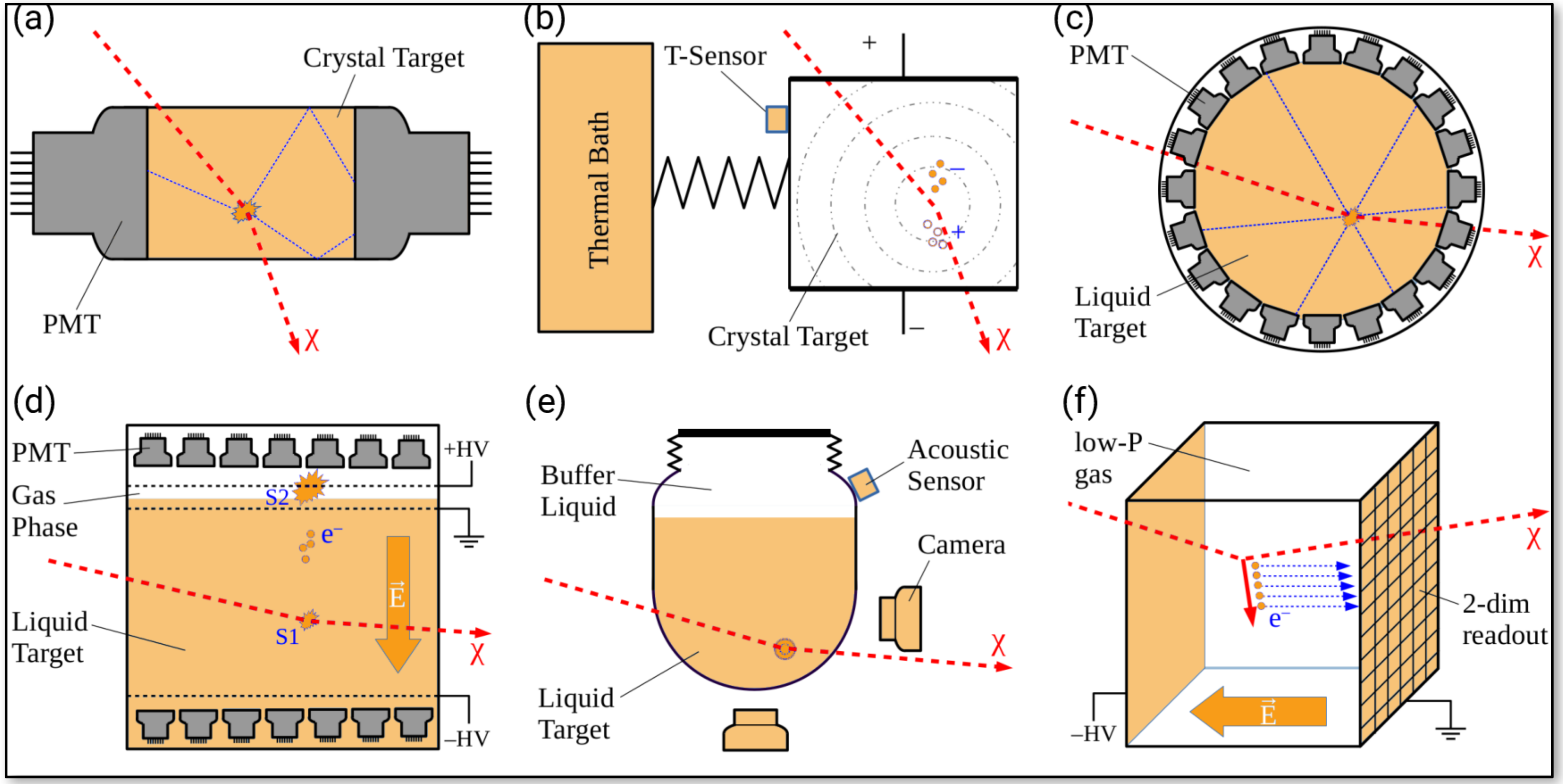


XENON Collaboration, Phys. Rev. Lett. 123, 251801 (2019)



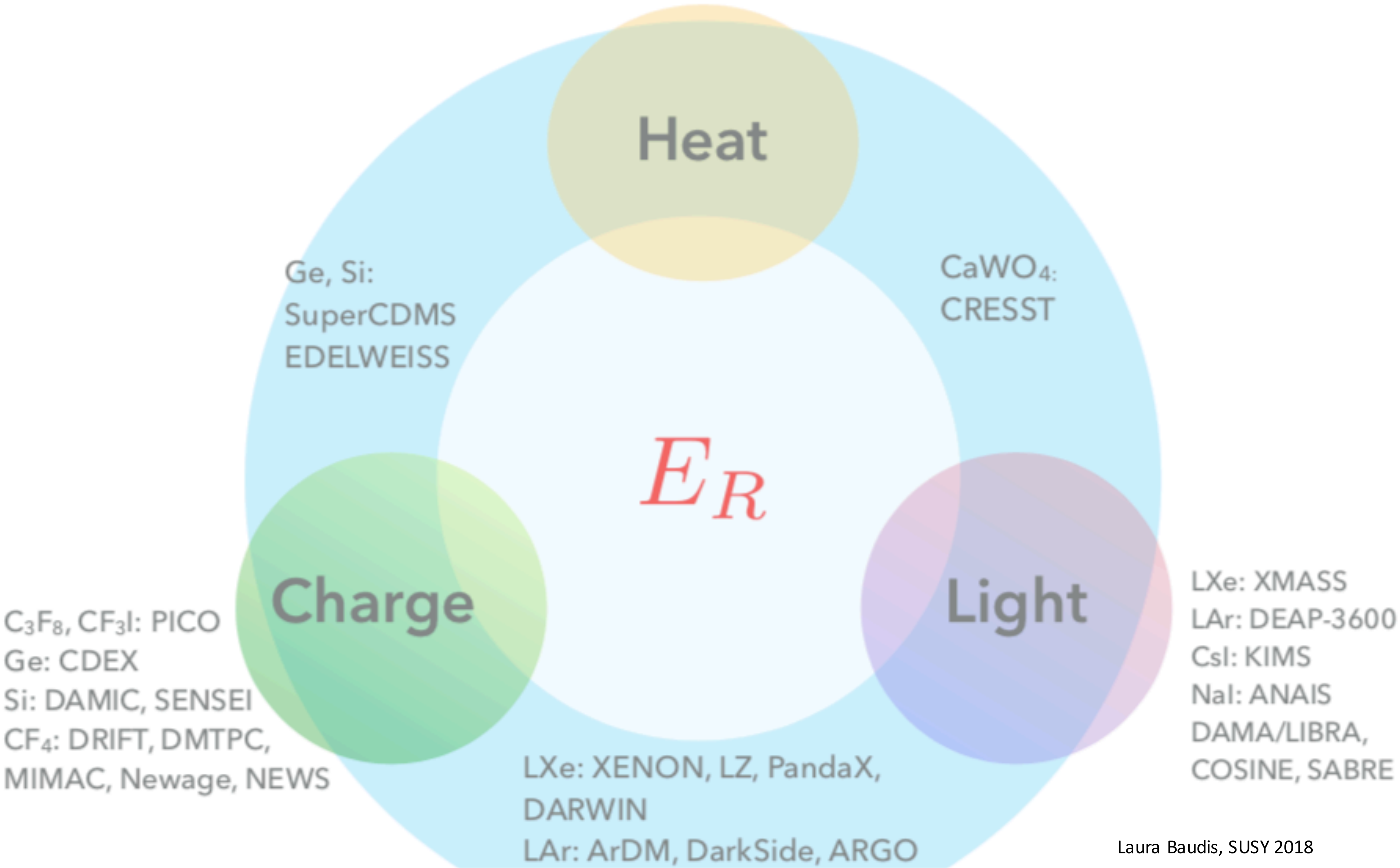
Fabbrichesi et al., arXiv:2005.01515

Search Experiments



APPEC Community Report 2021, arXiv:2104.07634

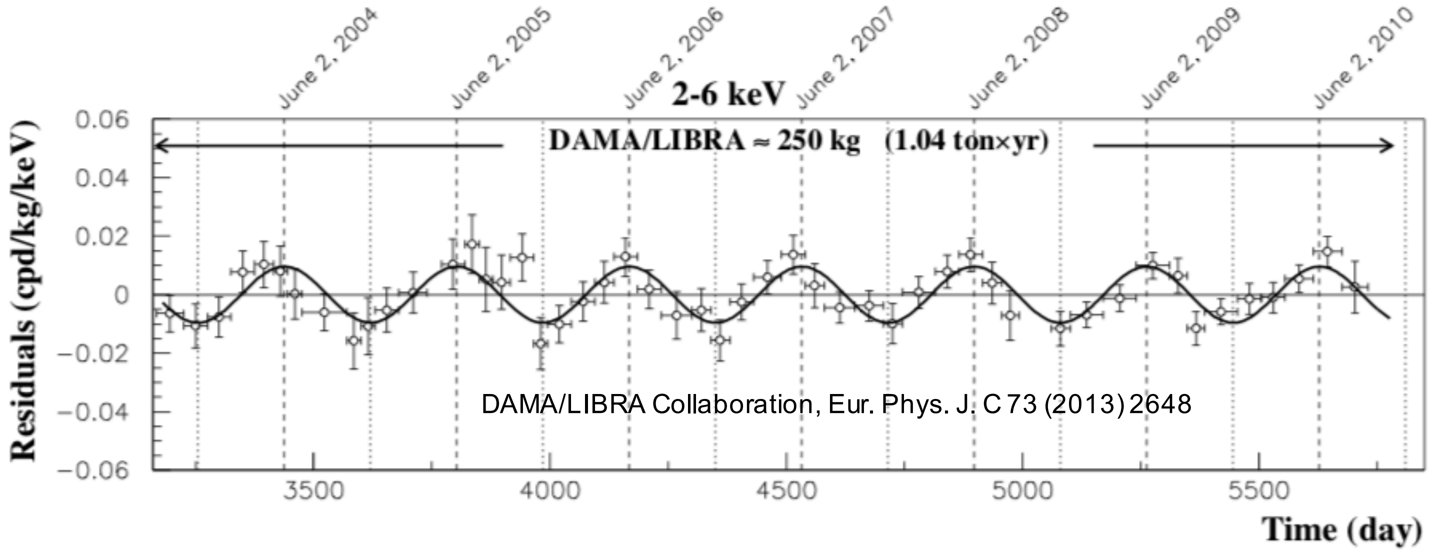
Background Rejection



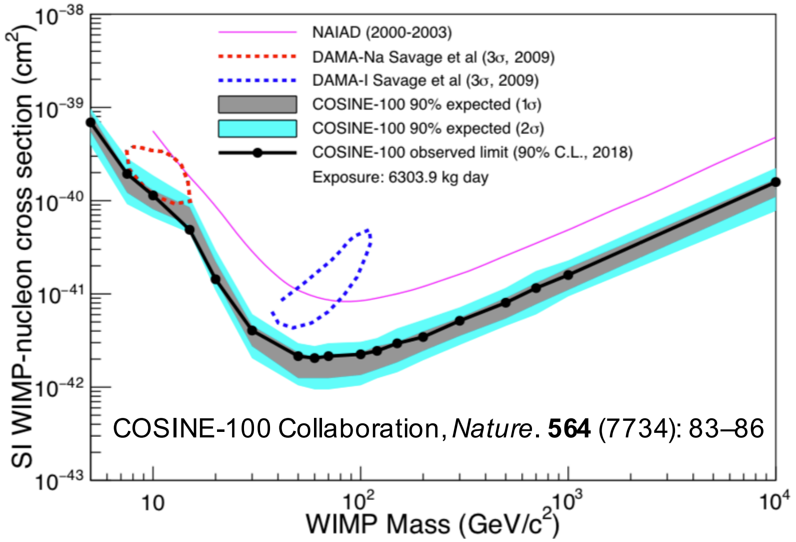
Laura Baudis, SUSY 2018

NaI(Tl) Detectors (Scint)

- First experiments based on room temp NaI(Tl)
  - Iodine A=127 (heavy, good A^2)
  - Pulse shape discrimination
  - Radiopure
  - Cost-effective
- DAMA + DAMA/LIBRA(Gran Sasso) claims annual modulation in 2-6 keV_{ee} bin at 9.3σ
  - Excluded by other targets / methods
- Excluded with same target by COSINE-100 (Yangyang, 2018) and ANAIS-112 (Canfranc, 2021)
- Explanation?
  - Modulation of environment
  - Affects backgrounds e.g. Rn?



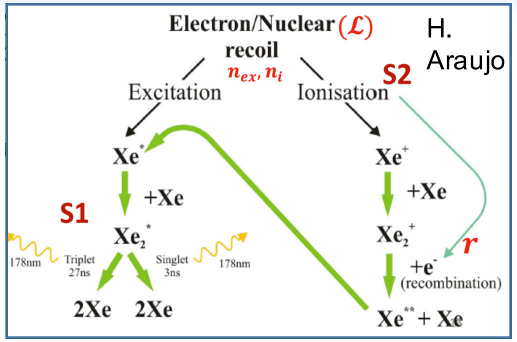
DAMA/LIBRA Collaboration, Eur. Phys. J. C 73 (2013) 2648



COSINE-100 Collaboration, *Nature*. **564** (7734): 83–86

Liquid Xenon Detectors

- Liquid Xenon TPC
  - Recoil generates excitation and ionisation
  - PMT S1 light (VUV 175 nm) read-out
  - Gas-phase charge read-out with electro-luminescence (S2)
- S2 light measures x-y, drift time S1-S2 z
  - Allows fiducialisation / self-shielding
  - Veto multi-scatter γ/n background
- Advantages:
  - A~131, spin-dependent isotopes
  - Very radiopure
  - ~99.7% e/n-recoil discrimination (50% eff.)
  - Mature, well understood technology
- Disadvantages:
  - Xe relatively expensive (~1000 $/kg)



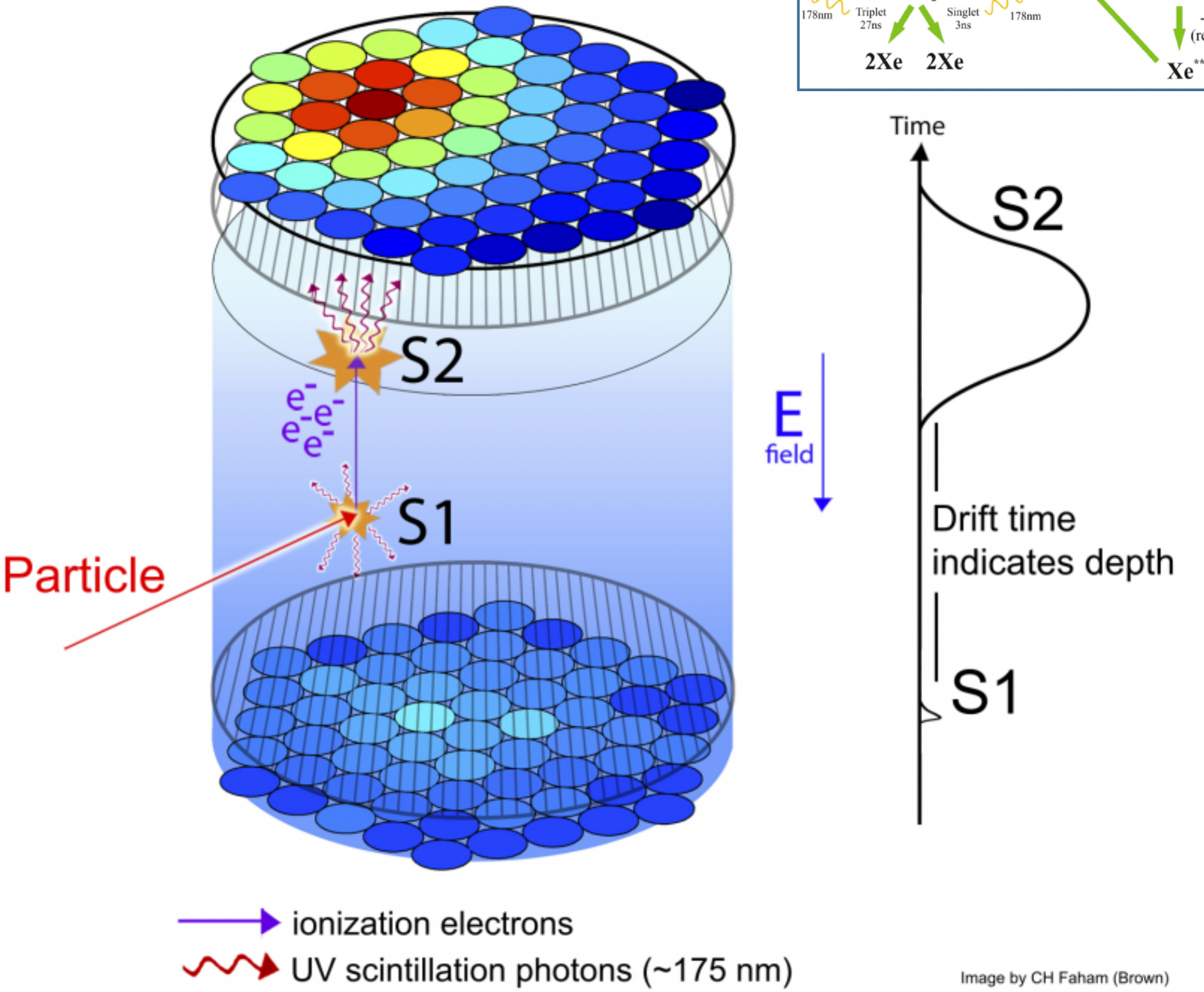
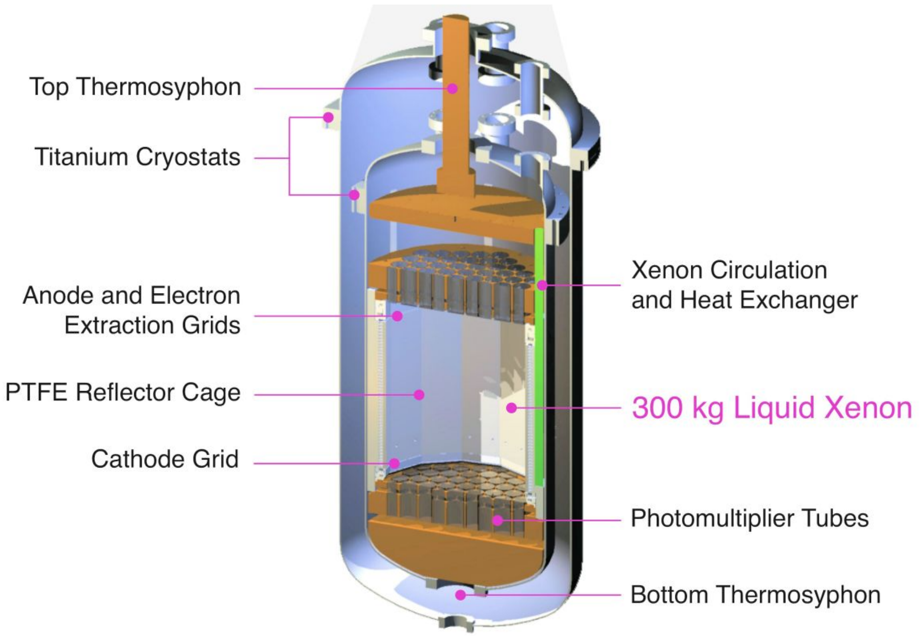


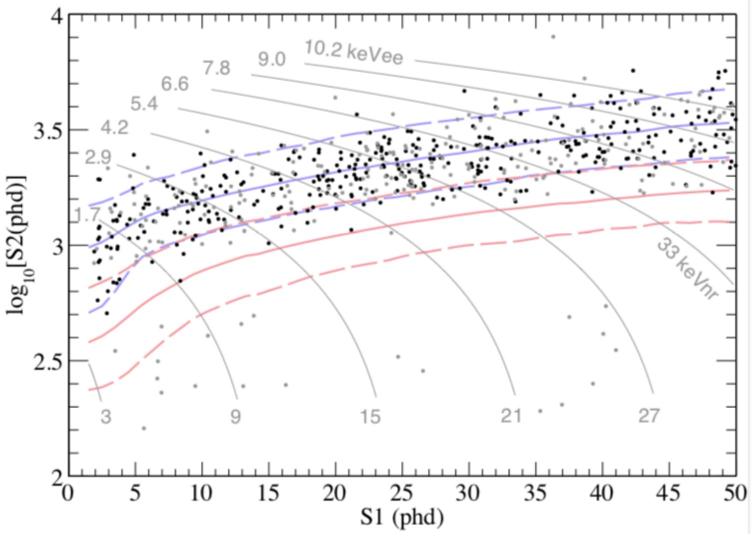
Image by CH Faham (Brown)

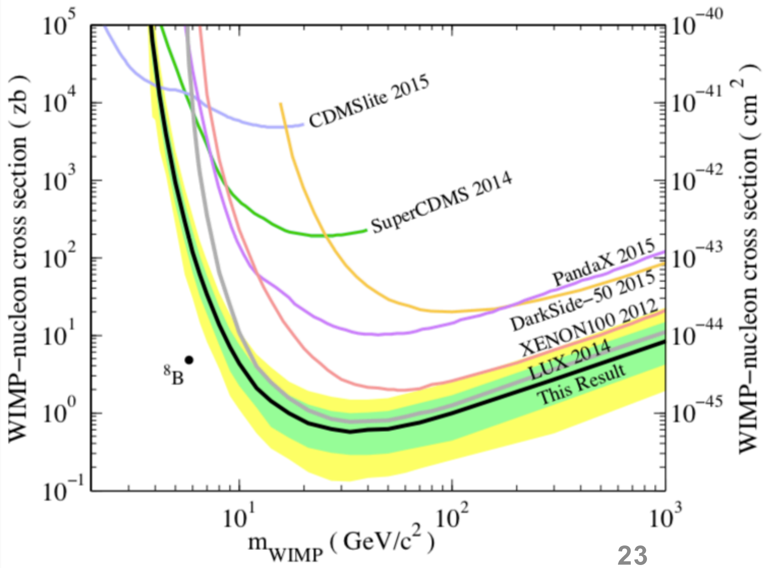
Liquid Xenon Detectors (Scint+Ion)

- LUX (2015/2017):
  - SURF (US)
  - 1.4x10^4 kg.days (145 kg fiducial)
  - ^{85}Kr removal by chromatography
- PandaX-II (2017)
  - Jianping (China)
  - Follows PandaX-I
  - 3.3x10^4 kg.days (300 kg fiducial)
- XENON1T (2018)
  - Gran Sasso (It)
  - Follows XENON-10/100
  - 3.6x10^5 kg.days (1300 kg fiducial)
  - ^{85}Kr removal by distillation



LUX Collaboration Phys. Rev. Lett. 116, 161301 (2016)





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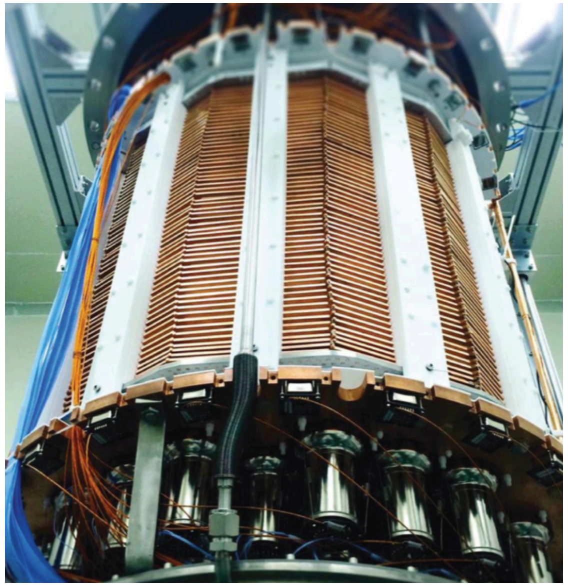
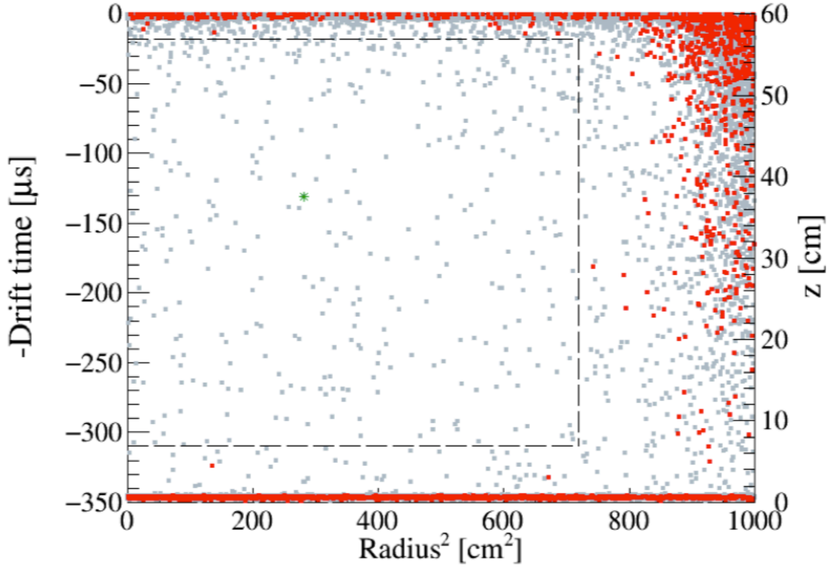
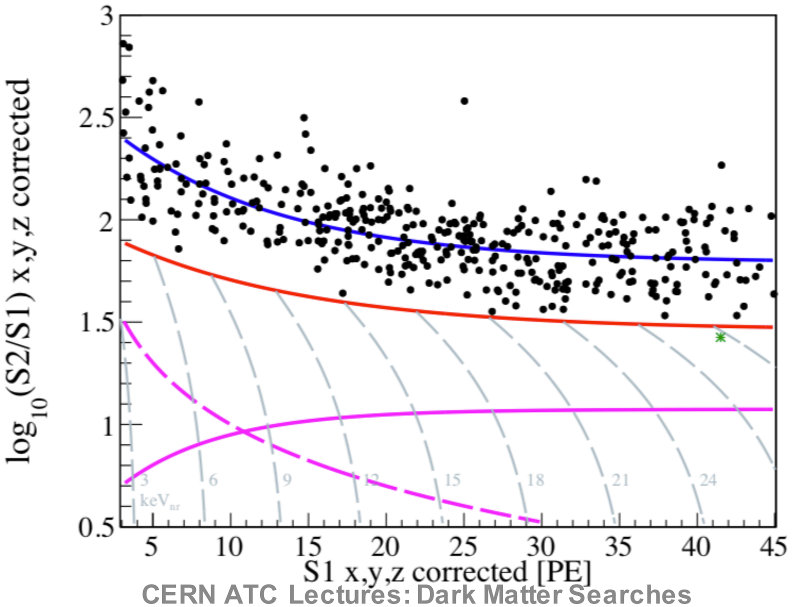
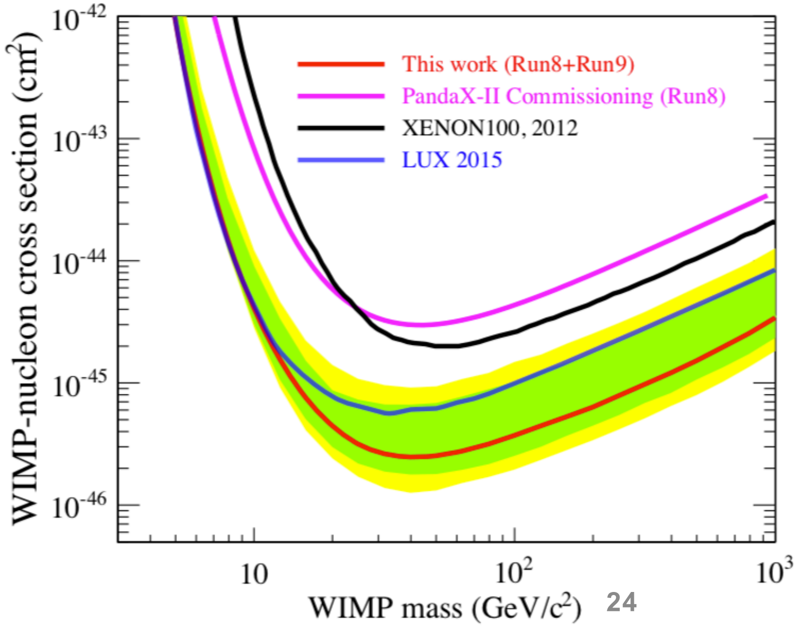
  - Gran Sasso (It)
  - Follows XENON-10/100
  - 3.6x10^5 kg.days (1300 kg fiducial)
  - ^{85}Kr removal by distillation



PandaX-II Collaboration, Physical Review Letters. **117** (12): 121303



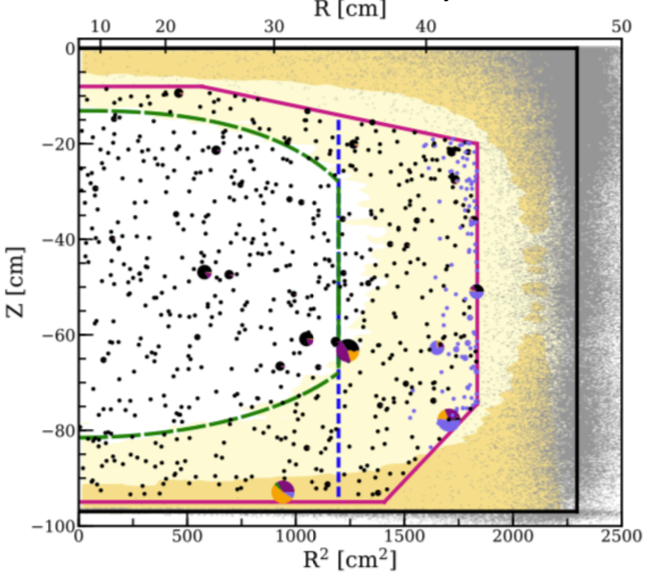


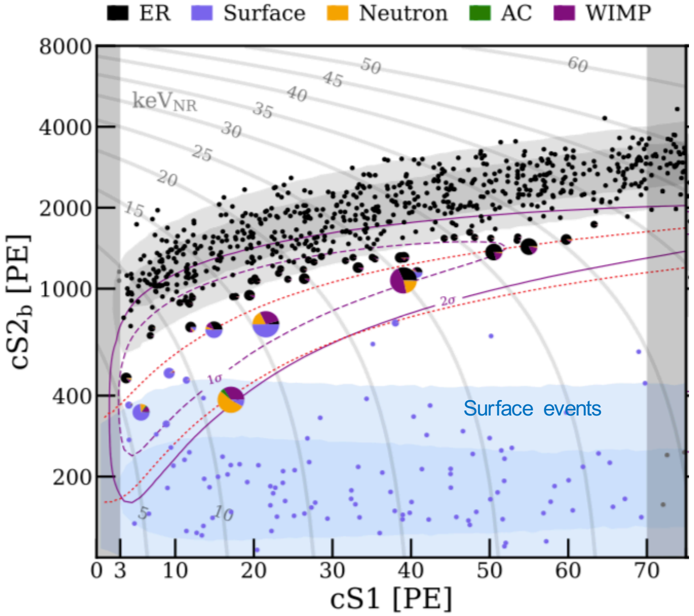


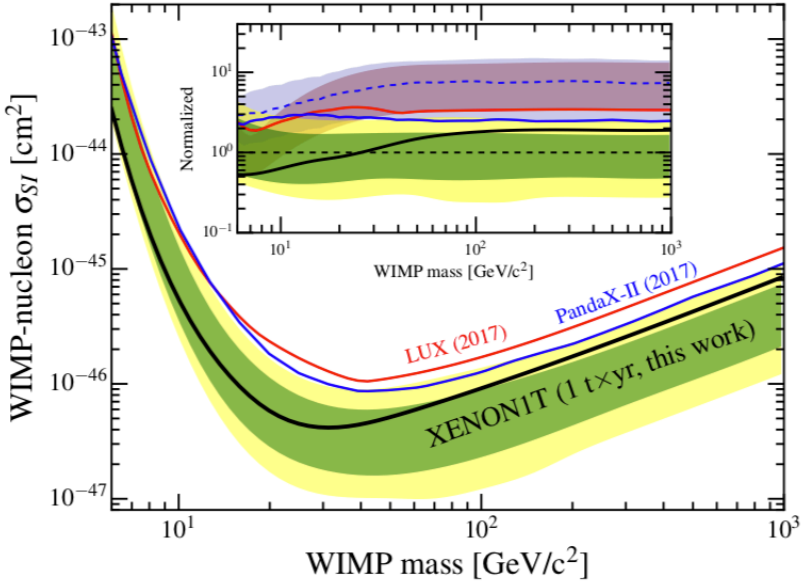
Liquid Xenon Detectors (Scint+Ion)

- LUX (2015/2017):
  - SURF (US)
  - 1.4×10^4 kg.days (145 kg fiducial)
  - ^{85}Kr removal by chromatography
- PandaX-II (2017)
  - Jianping (China)
  - Follows PandaX-I
  - 3.3×10^4 kg.days (300 kg fiducial)
- XENON1T (2018)
  - Gran Sasso (It)
  - Follows XENON-10/100
  - 3.6×10^5 kg.days (1300 kg fiducial)
  - ^{85}Kr removal by distillation

XENON Collaboration Phys. Rev. Lett. 121, 111302 (2018)







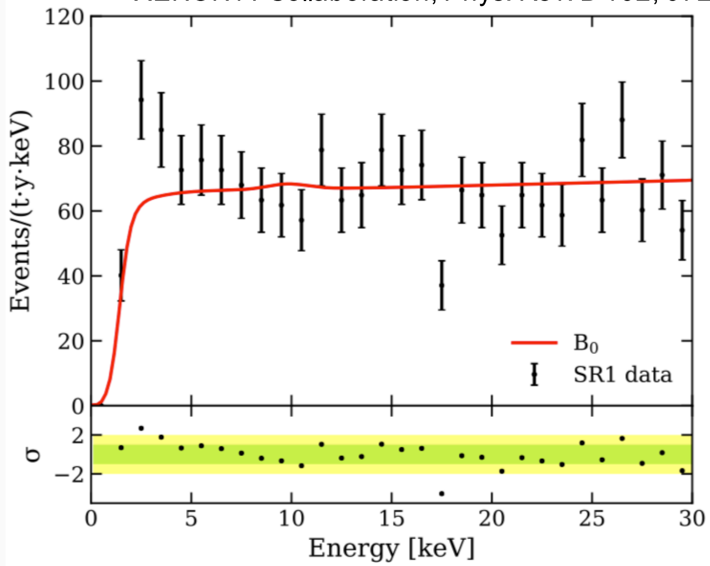
XENON1T Low Energy Excess

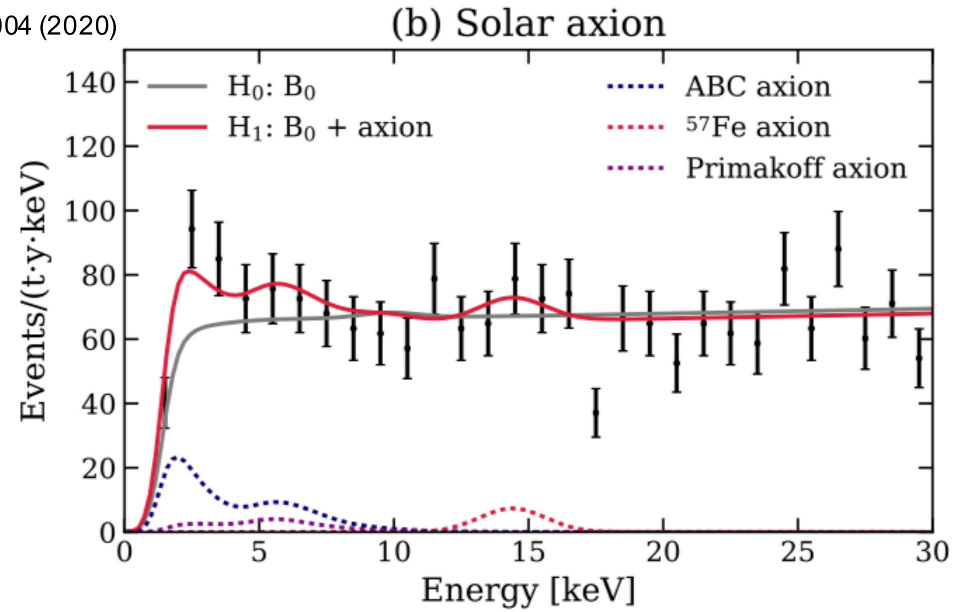
- Excess of ~50 electron recoil events near threshold ~2-3 keV_{ee}
  - Possible evidence for solar axion or bosonic DM at >3σ
  - Could be due to additional ^{3}T β-decay background
- PandaX-II data compatible with both S+B and B-only

PandaX-II Collaboration, Chin. Phys. Lett. 2021, 38, 011301

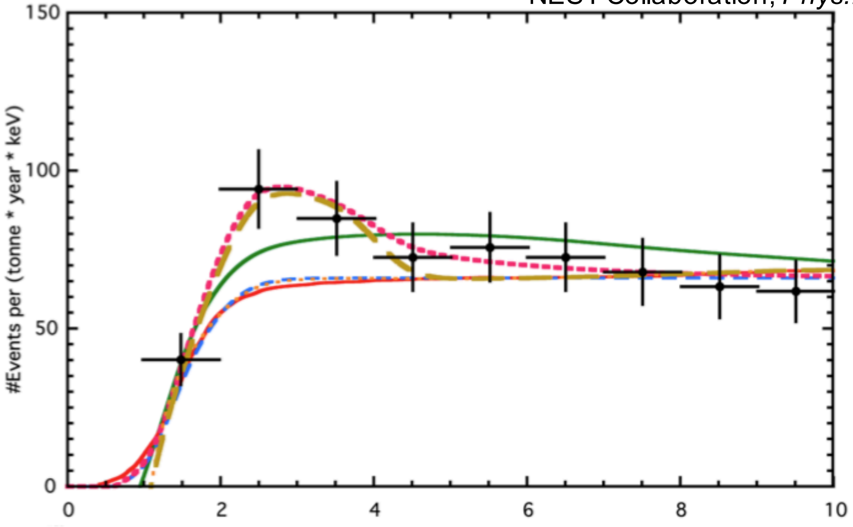
- Follow-up from NEST (Szydagis et al.) identifying 2.8 keV γ-rays from ^{37}Ar EC as a possible cause
  - Good fit to energy spectrum
  - Some evidence for $t_{1/2}$=35 days in time spectrum

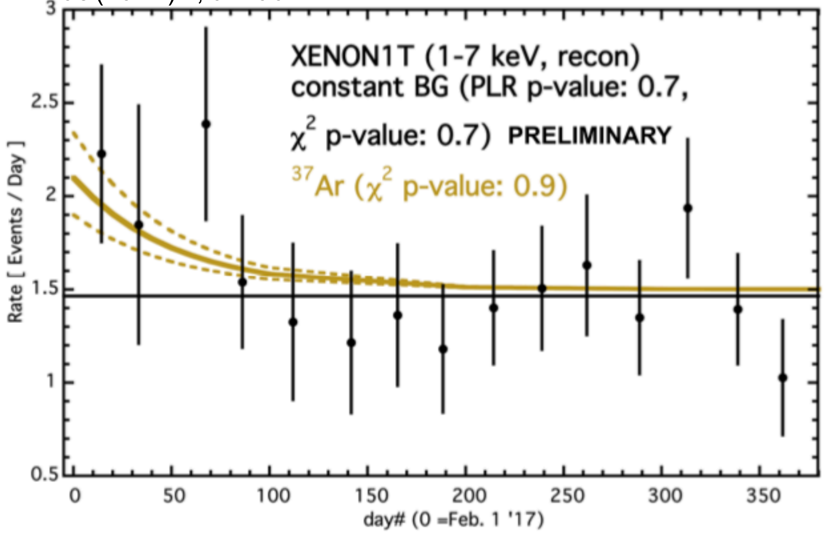
XENON1T Collaboration, Phys. Rev. D 102, 072004 (2020)





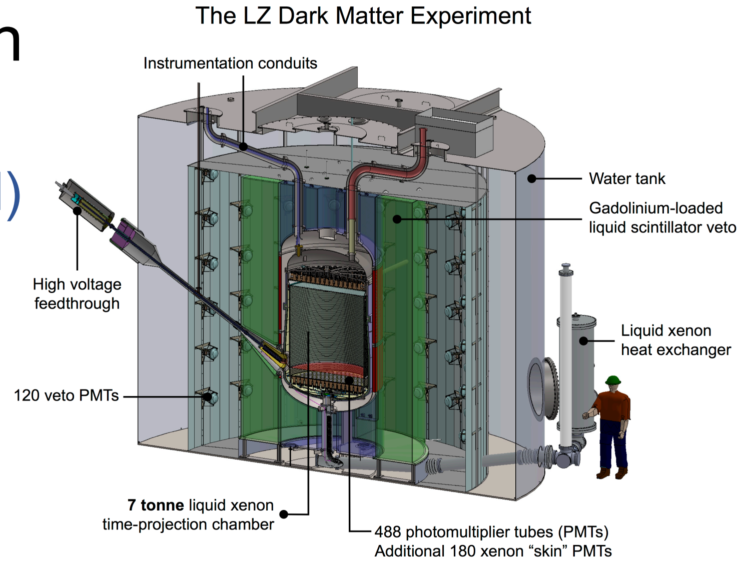
NEST Collaboration, *Phys.Rev.D* 103 (2021) 1, 012002

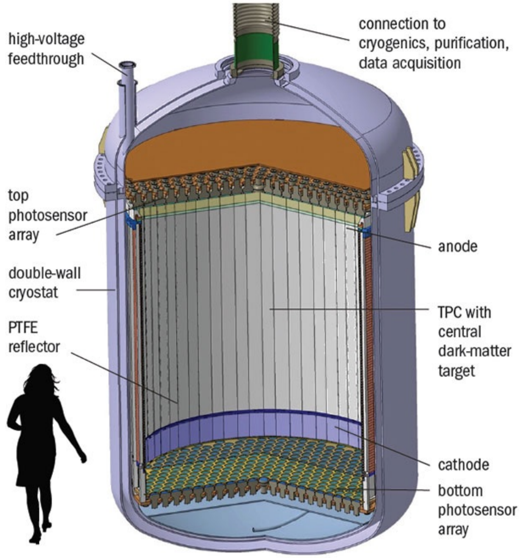


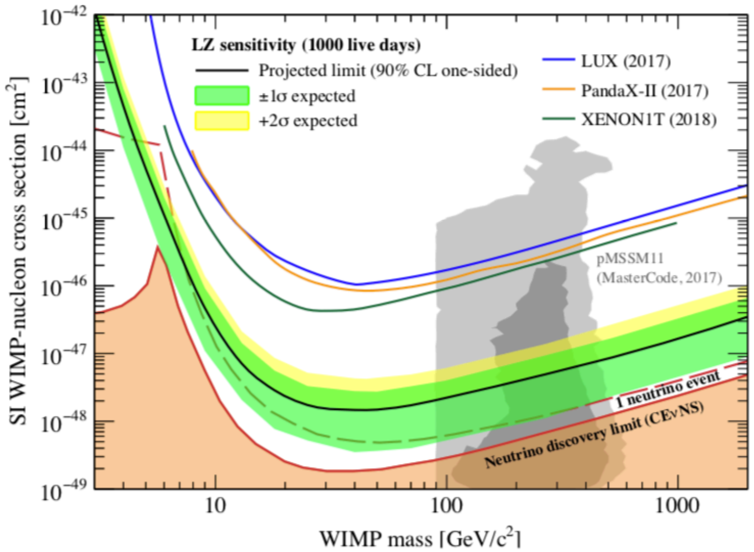


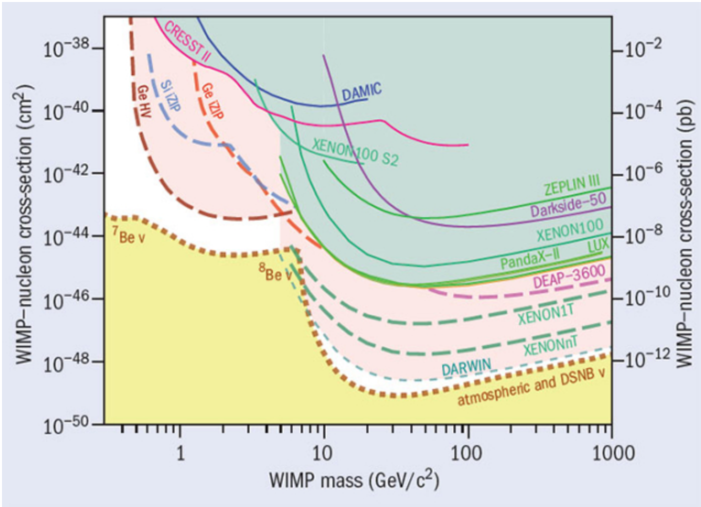
Future LXe Detectors (Scint+Ion)

- Next generation experiments commissioning / close to operation
  - XENONnT (8.3 t non-fiducial)
  - LUX-ZEPLIN 10 t (non-fid) / 5.6 t (fid)
  - PANDA-4T (4 t non-fiducial)
- Future experiments should approach neutrino floor
  - DARWIN (50 t, EU)
  - G3 (US)
  - MoU for LZ+XENON merger
  - PandaX-xT
- Key challenges:
  - Rn removal
  - Cleanliness
  - Rn chain tagging
  - HV system + Grids



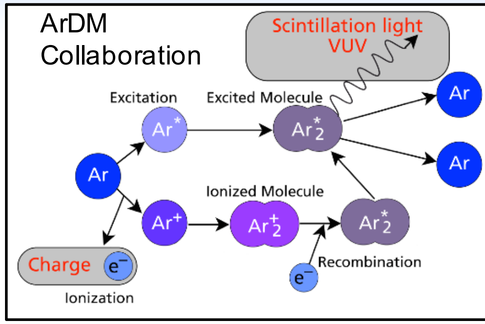


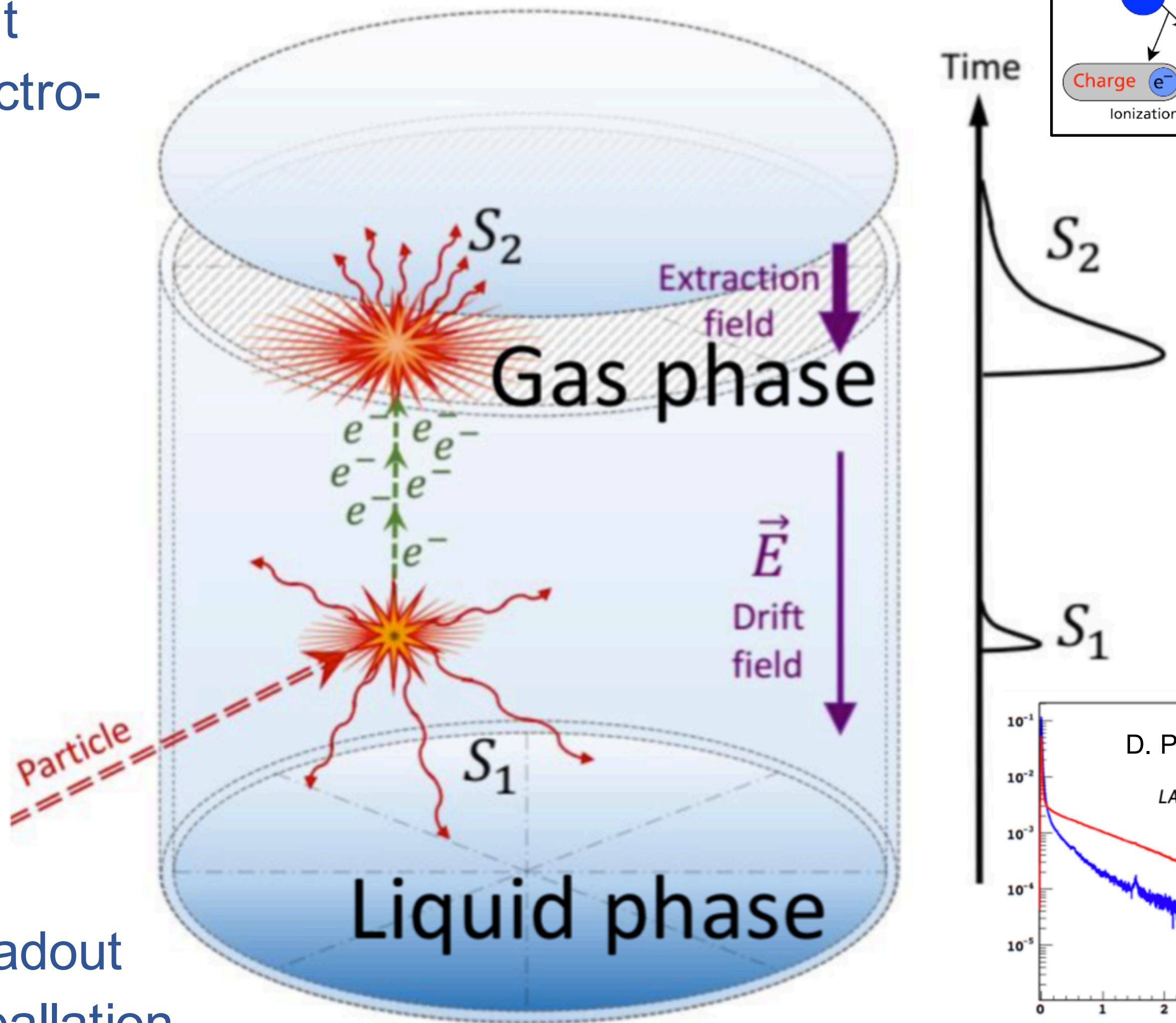




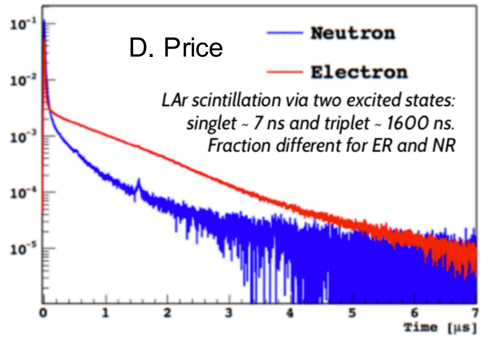
Liquid Argon Detectors

- Liquid Argon TPC
  - Recoil generates excitation and ionisation
  - PMT S1 light (VUV 128 nm) read-out
  - Gas-phase charge read-out with electro-luminescence (S2)
- S2 light x-y, drift time S1-S2 z
  - Fiducialisation / self-shielding
  - Veto multi-scatter γ/n background
- Advantages:
  - Low cost (but requires purification)
  - $>10^8$ PSD e-recoil rejection
  - Leverage ν experiment expertise
- Disadvantages:
  - A = 40 → A^2 factor 10 less than Xe
  - WLS (TPB) required for deep UV readout
  - Background ^{39}Ar ($t_{1/2}$=269 y) - CR spallation



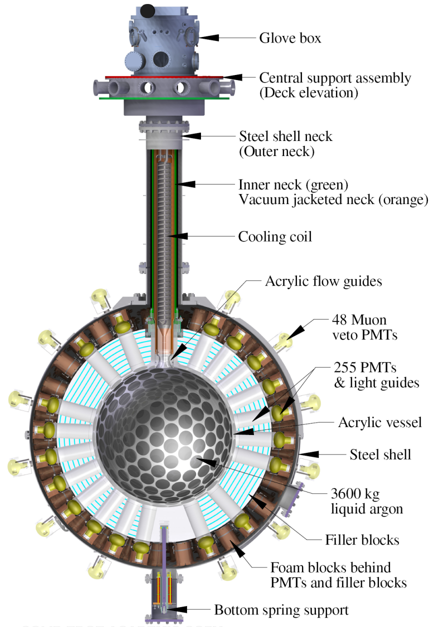


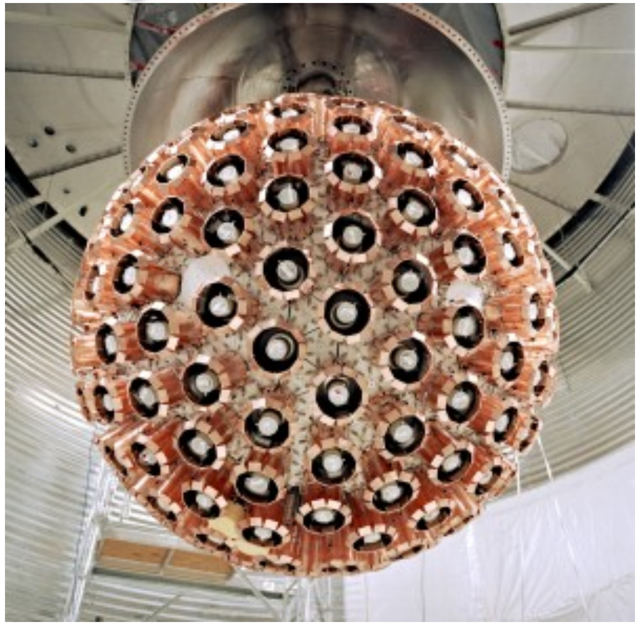
DarkSide-20k Collaboration

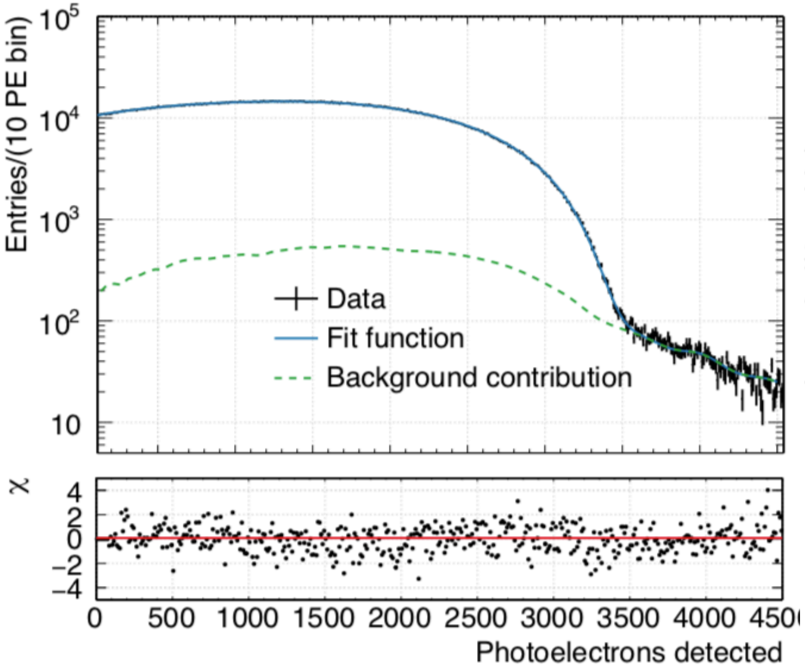


LAr Single-Phase (Scint)

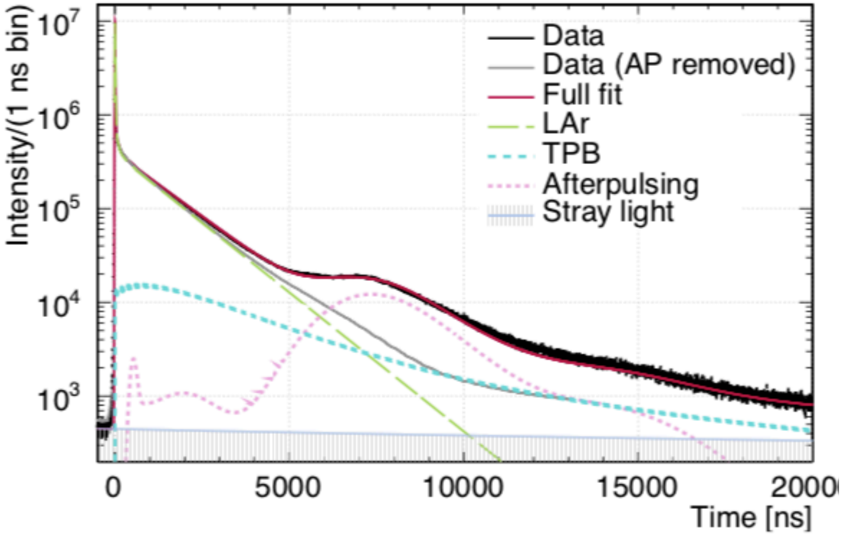
- DEAP-3600 (SNOLAB)
  - Scintillation signal only – slow charge recombination generates tail in pulse-shape
  - TPB coating on spherical vessel
  - Pulse shape discrimination (PSD)
- 1.9×10^5 kg.days (824 kg) fiducial
- Background dominated by ^{39}Ar

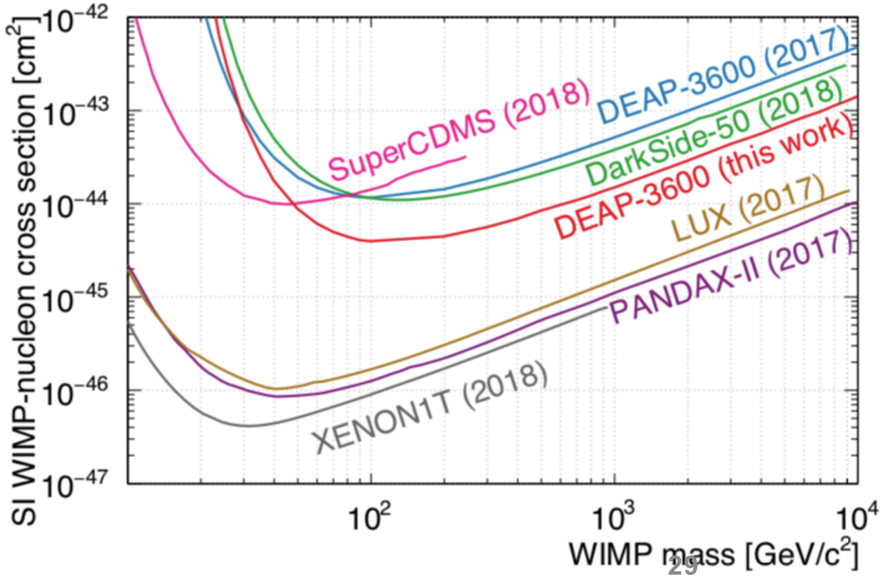






DEAP-3600 Collaboration Phys. Rev. D 100, 022004 (2019)

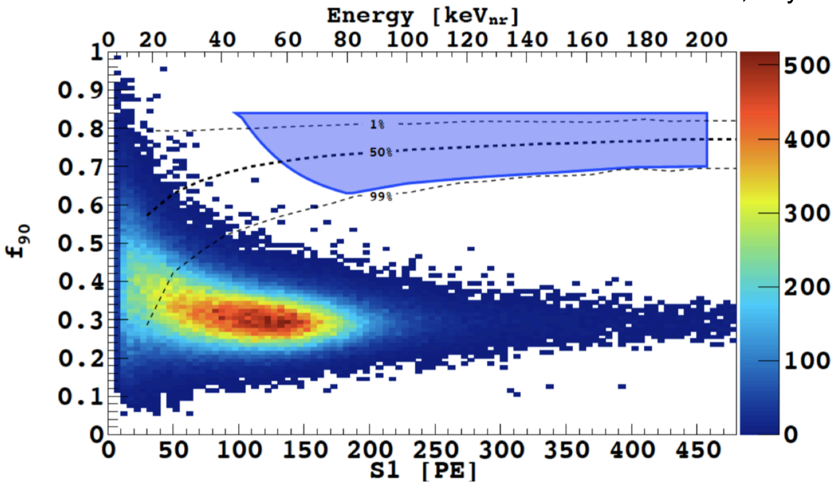


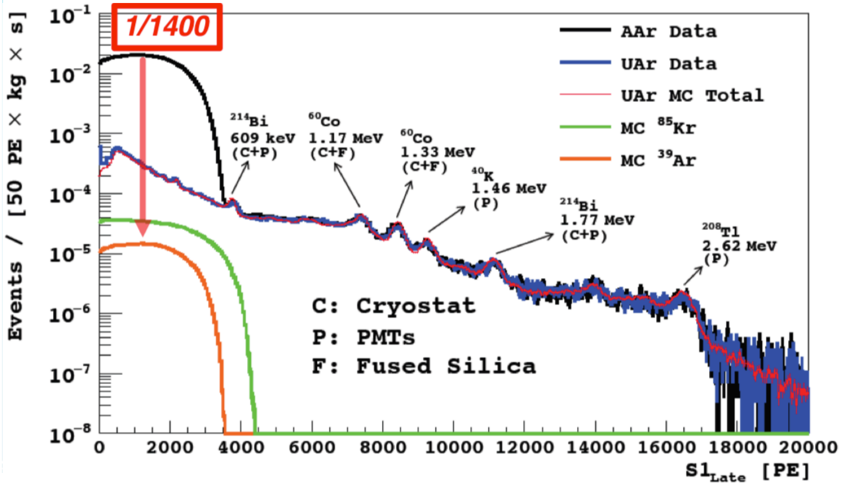


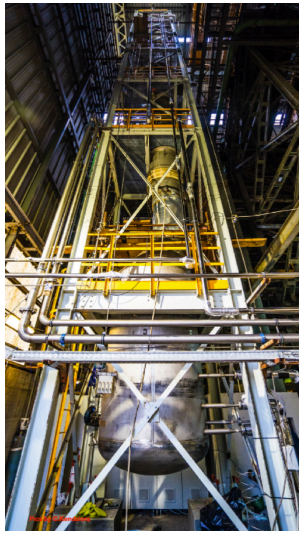
LAr Dual-Phase (Scint+Ion)

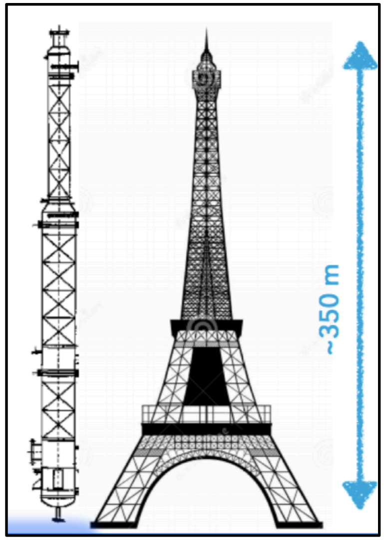
- DarkSide-50 (2018, Gran Sasso)
  - LAr double-phase read-out
  - ‘Underground’ Ar depleted x1400 in ^{39}Ar
  - 1.7×10^{4} kg.days (36.9 kg)
  - Also low mass search 6786 kg.days ionisation only
- DarkSide-20k under preparation by GADMC
  - 40 t fiducial with SiPM readout
  - 350 m cryogenic distillation column (ARIA Sardinia)
  - Goal: reduce ^{39}Ar x100 vs. UAr
- Next stage – ARGO
  - ~360 t target

DarkSide-50 Collaboration, Phys. Rev. D 98, 102006 (2018)

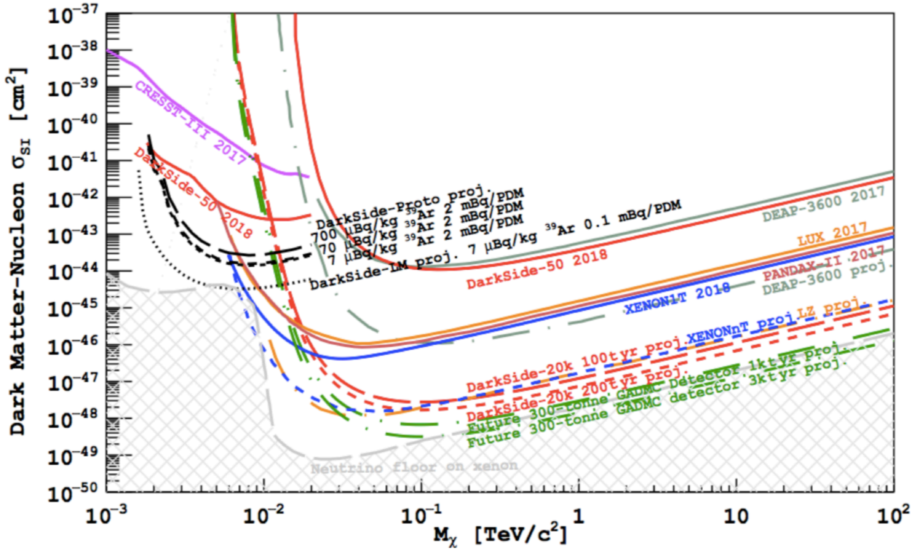






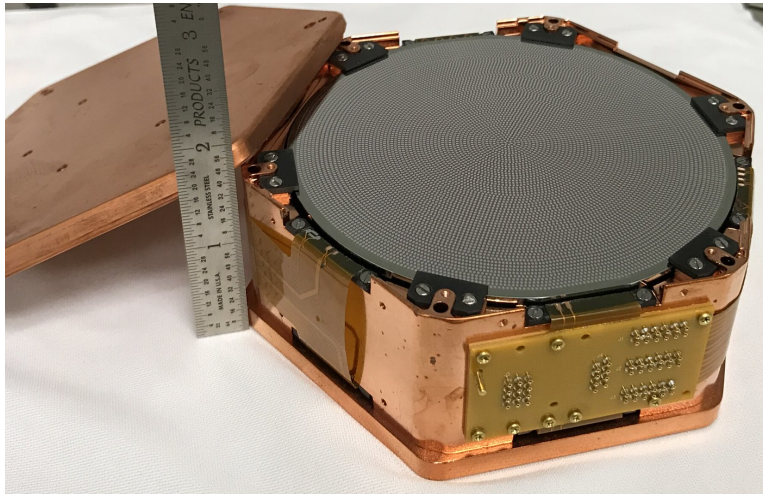


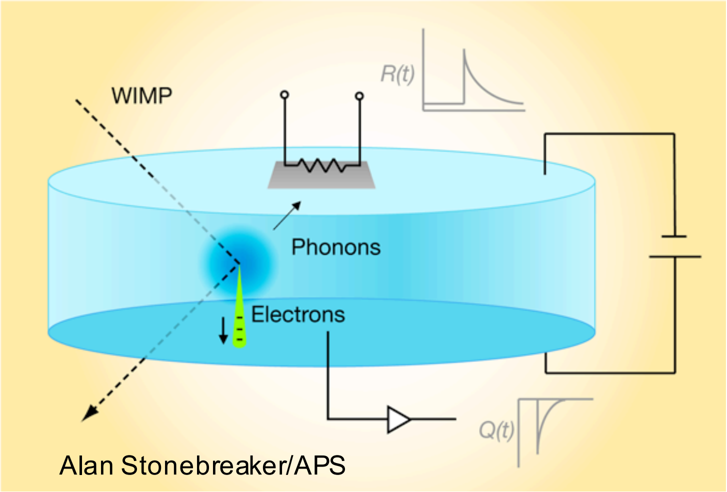
DarkSide-20k Collaboration, Eur. Phys. J. Plus (2018) 133:131

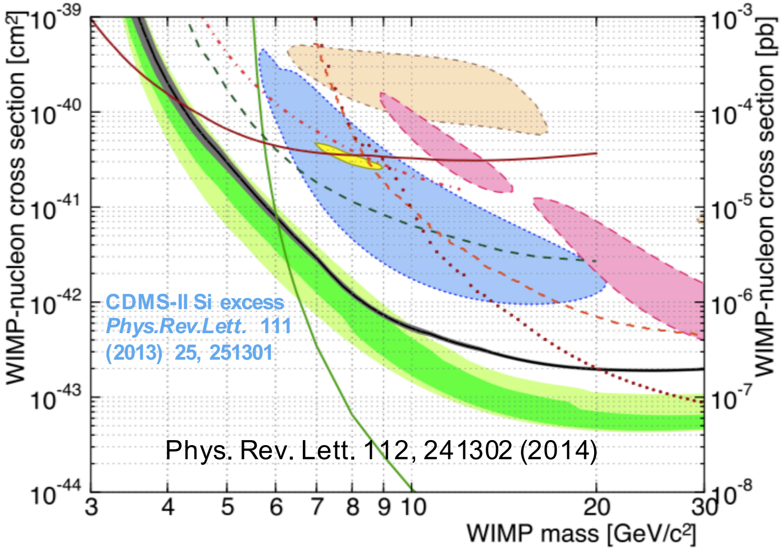


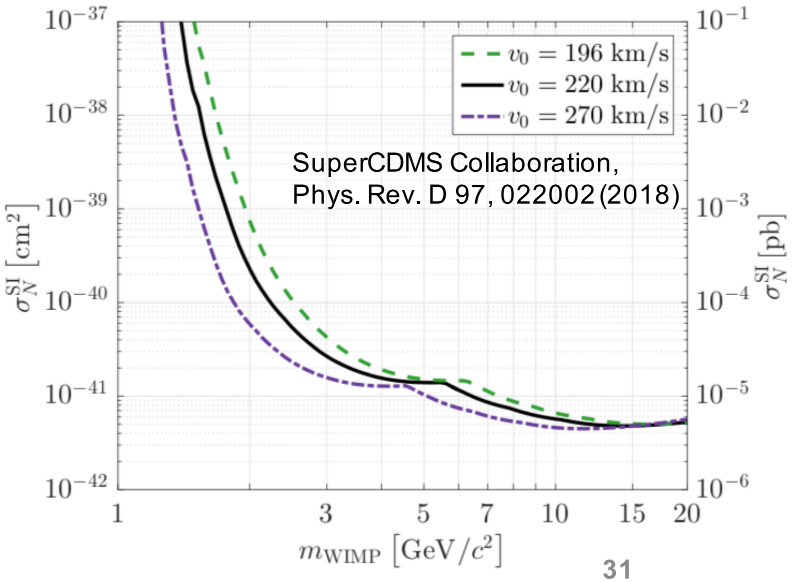
Cryogenic Semiconductors (Ion+Heat)

- Mostly Germanium detectors
  - Low threshold – low m_χ
  - A~73 (Ge)
  - Charge+phonon readout
  - Cryogenic – dilution fridge
  - Care with surface events
  - CDMS-II (Si) excess (2014) excluded by other expts.
- SuperCDMS (Soudan, 2014)
  - Follows CDMS-I/II etc.
  - Germanium 577 kg.days
  - CDMSlite (2018) phonon-only – sensitive to low m_χ
- SuperCDMS SNOLAB under construction
  - ~220 kg Ge/Si (75%/25%)



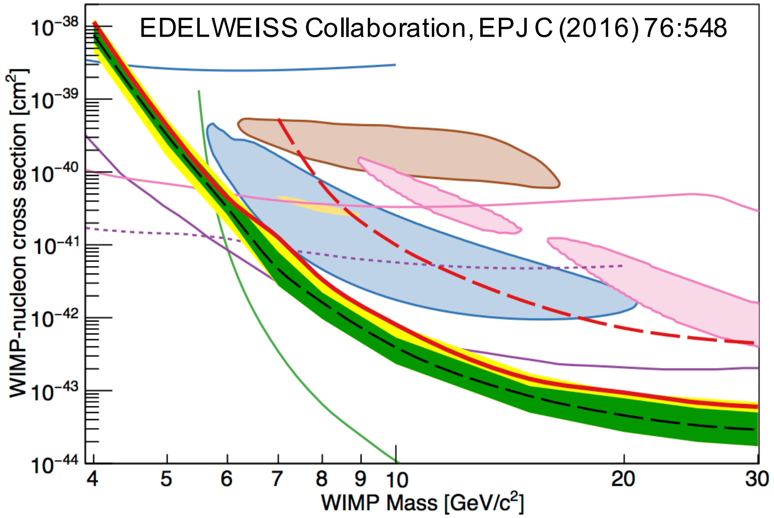


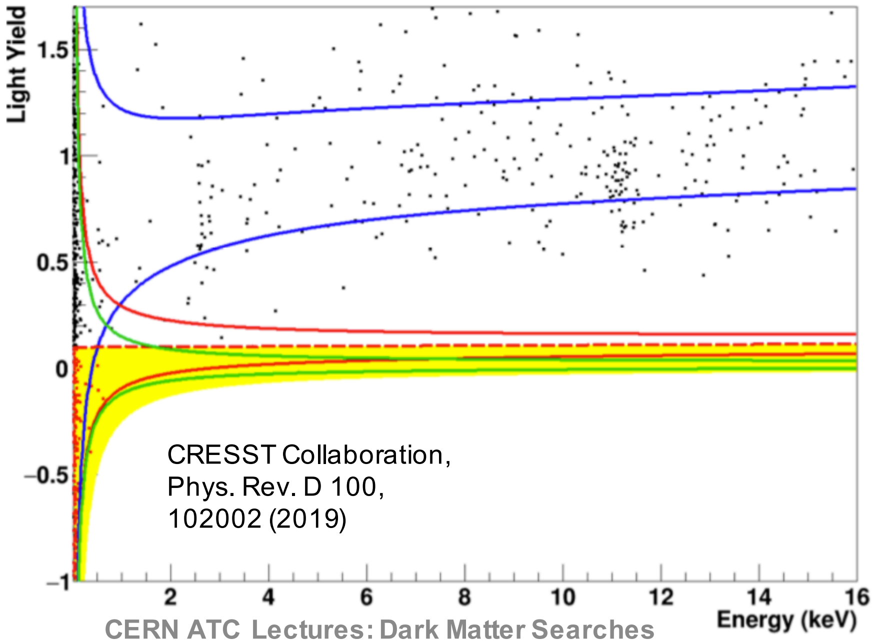


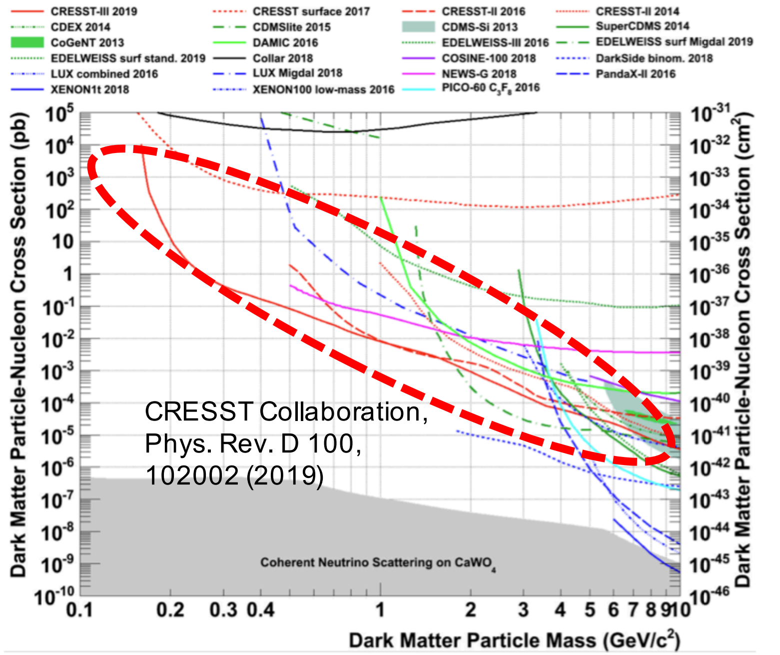


EDELWEISS (Ion+Heat) / CRESST (Scint+Heat)

- EDELWEISS-III (Modane, 2016)
  - Ge ion/phonons - similar to CDMS
  - 496 kg.days
- CRESST-III (Gran Sasso)
  - $CaWO_4$ - cryogenic scintillator
  - Discrim. with photons+phonons
  - Tungsten A~184
  - Dilution fridge
  - Ultra-low threshold 30 eV_{nr}
  - Care with surface events
  - 3.64 kg.days (23.6 g)
- Next stage – EURECA
  - EDELWEISS/CRESST merger
  - 1000 kg mixed target

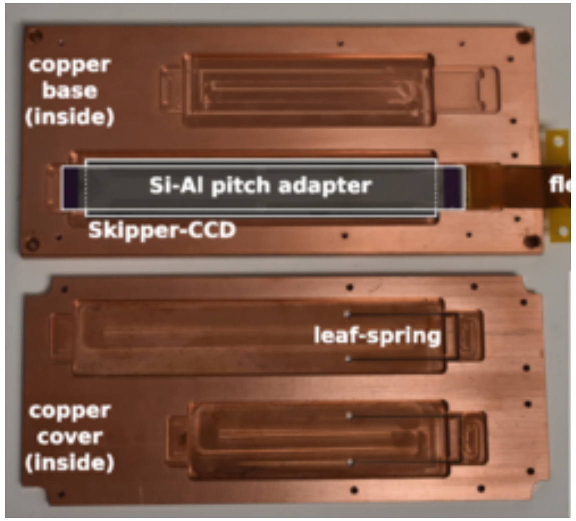




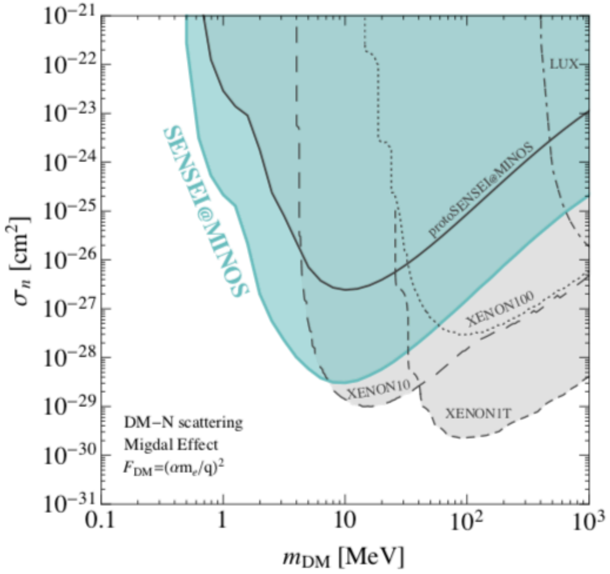


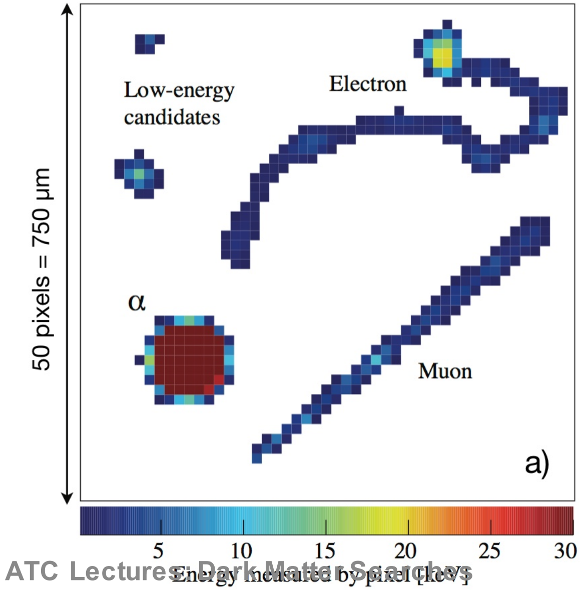
CCD Detectors (Ion)

- Very low mass, low A=28, but very low threshold
  - 'Skipper' CCD – multiple charge measurements reduces noise
  - Segmentation rejects multiple scatter / track background
- SENSEI (2020, Soudan)
  - 0.048 kg.days (2 g)
  - Uses Migdal effect
  - 100 g target planned
- DAMIC (2020, SNOLAB)
  - Larger mass, higher threshold
  - Imaging background tracks
  - 11 kg.days (42 g) (SNOLAB)
  - Plan kg-scale detector at Modane

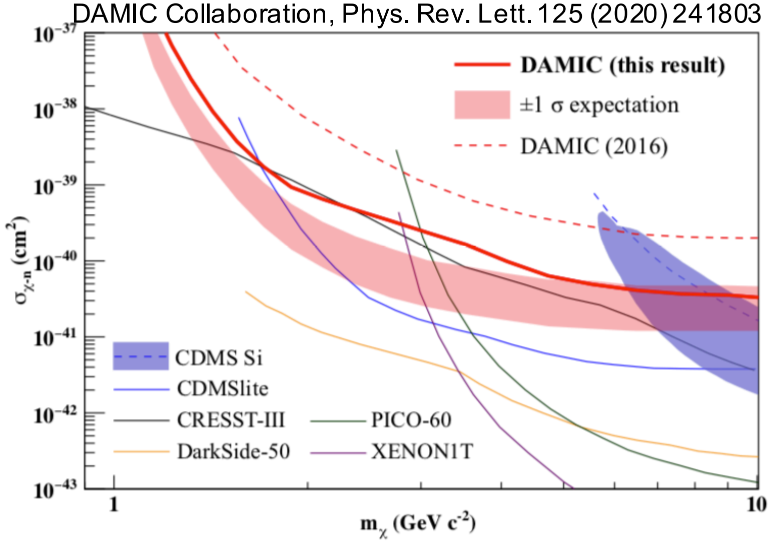


SENSEI Collaboration, Phys. Rev. Lett. **125** (2020) 171802



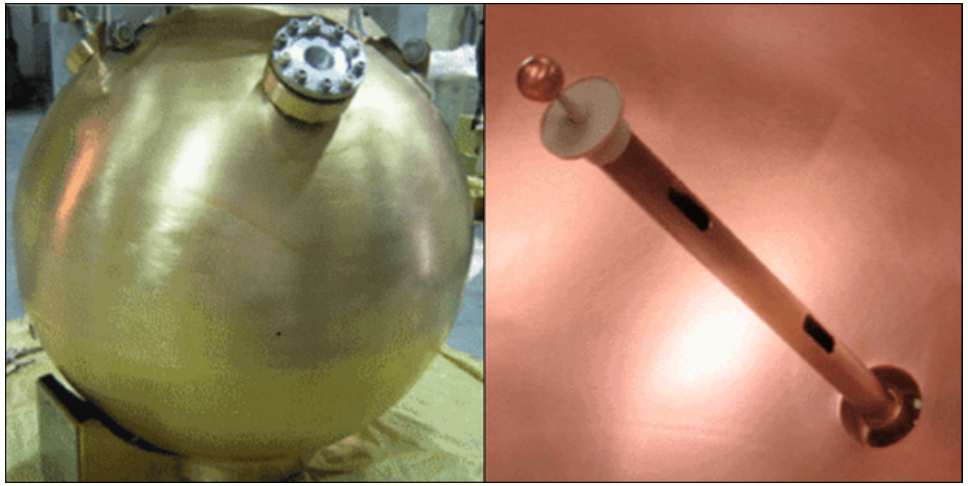


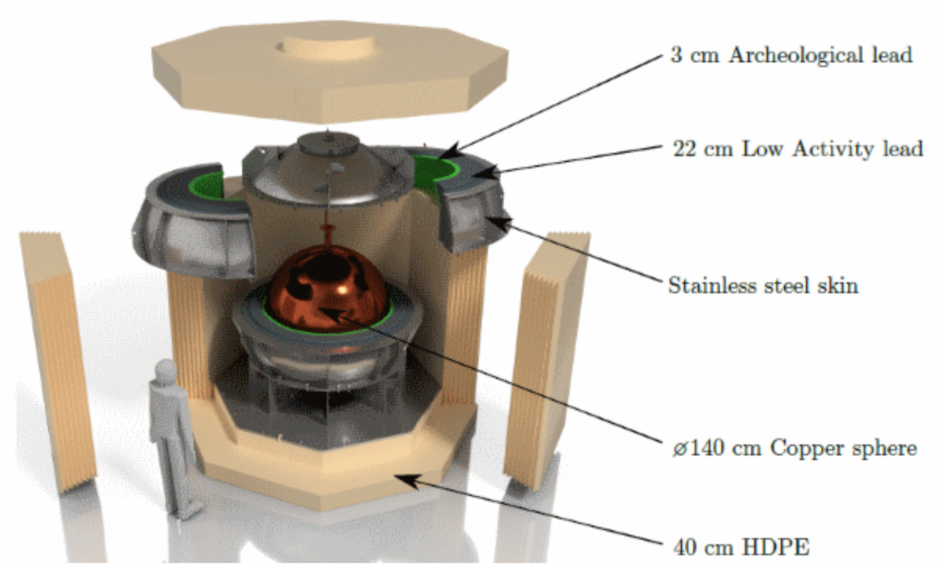
DAMIC Collaboration, Phys. Rev. Lett. 125 (2020) 241803



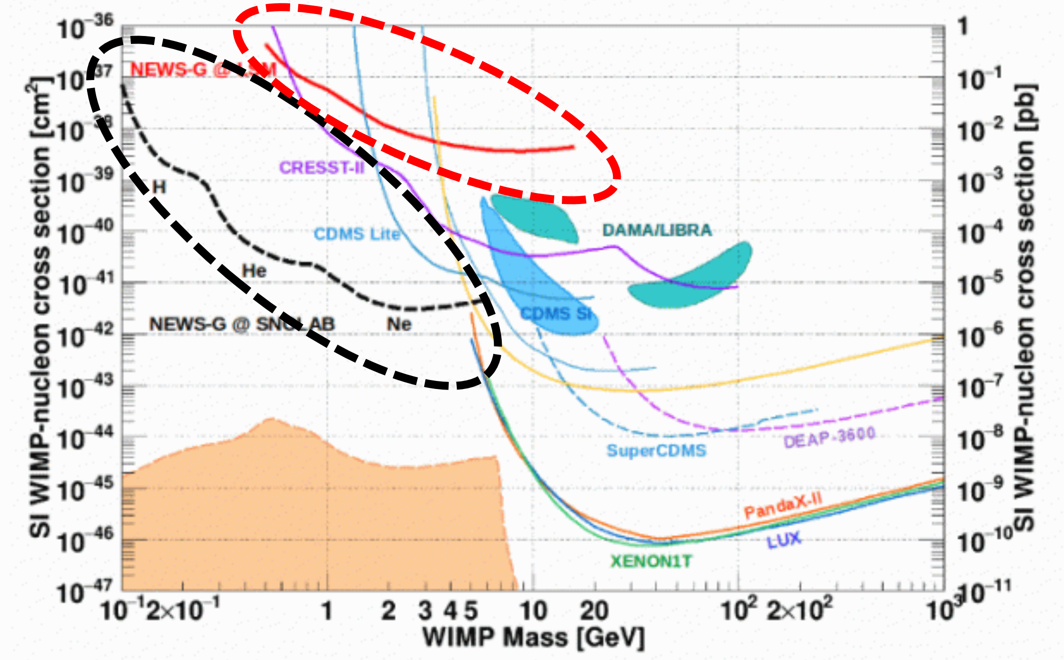
NEWS-G (Ion)

- Spherical gas proportional counter
  - Low energy threshold (~10 eV_{ee})
  - Flexible target choice (noble gases)
- Prototype 9.6 kg.days (Modane, 2018)
  - Ne (target) + CH_4 (0.7%)
- Installed 1.4 m diameter detector at SNOLAB end 2020



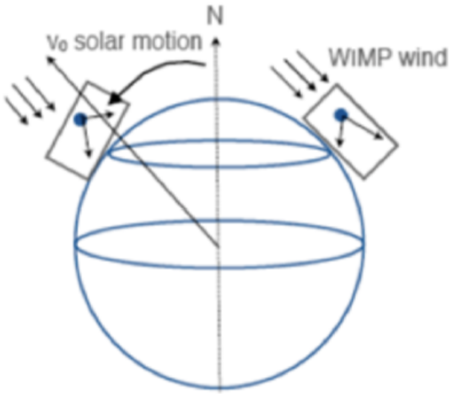


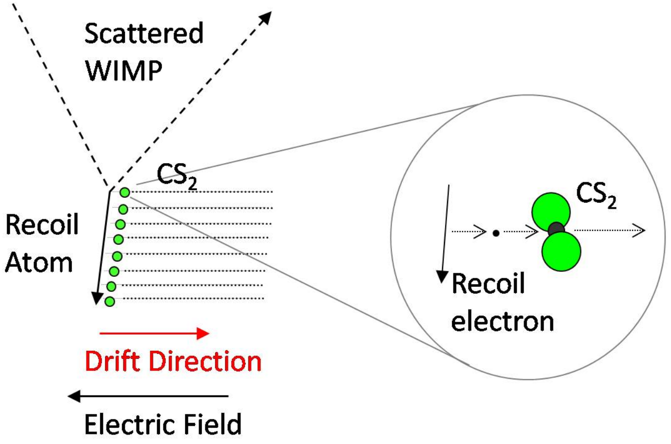
NEWS-G Collaboration, Astropart. Phys., 97 (2018) 54

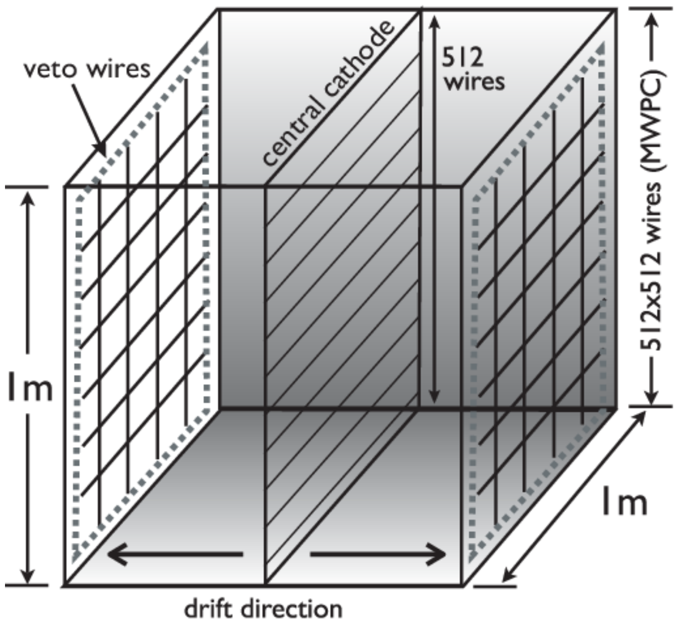


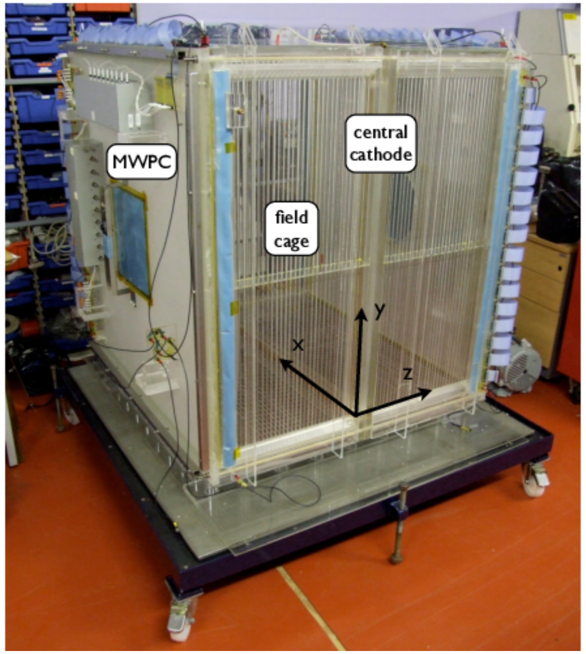
Directional Detectors (Ion)

- Gas TPC to image nuclear recoil tracks
- Advantages:
  - Recoil direction – correlated with WIMP 'wind
  - Excellent electron/nuclear recoil discriminatio
- Disadvantages:
  - Low density = low mass target
  - Requires excellent position resolution over long drift distances
  - Ideally head/tail discrimination – difficult!
- Low pressure CS_2 negative ion drift
  - DRIFT Collaboration (Boulby)
- Low pressure He-CF_4 electron drift
  - NEWAGE (Kamioka)
  - MIMAC (Modane)
  - DMTPC (MIT)



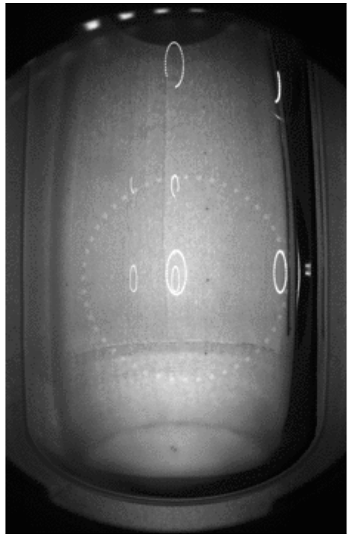


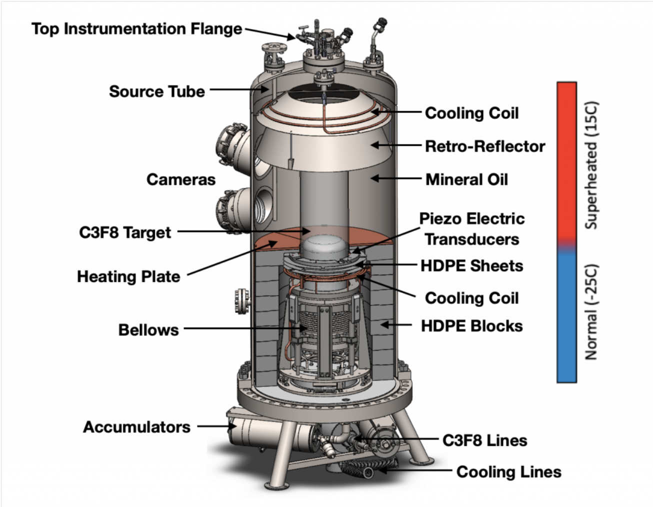




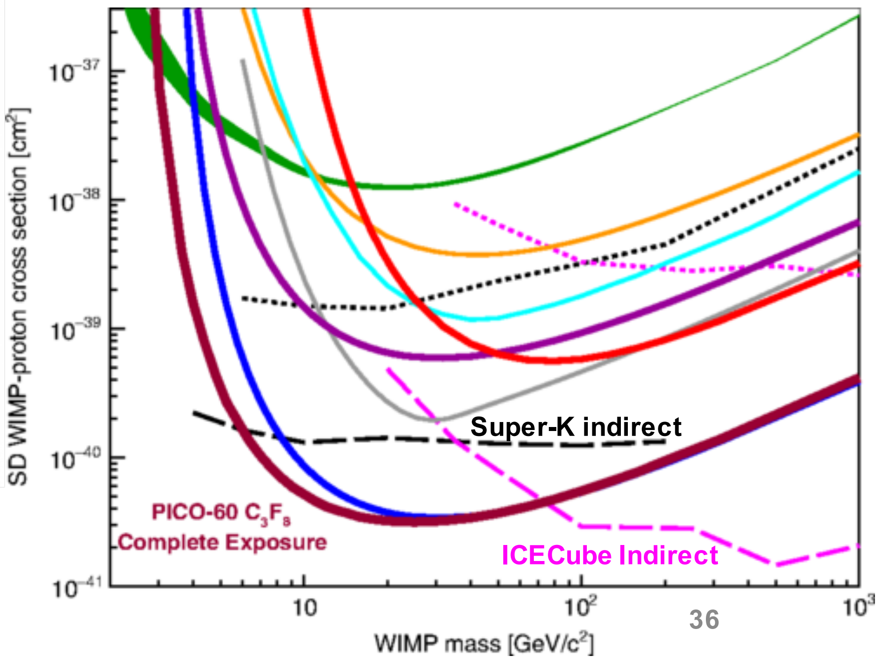
Bubble Chambers (Heat)

- Superheated bubble chamber
  - Technology used in nuclear industry
  - Insensitive to low LET electron recoils
  - Acoustic and optical detection of bubbles
  - Energy-integrated signal (no spectral info)
  - C_3F_8 target rich in ^{19}F – superior target for spin-dep. WIMP-proton interactions
- COUPP+PICASSO→PICO
- PICO-60L (2019, SNOLAB)
  - $1.4x10^3$ kg.days (49 kg)
  - 1-3 keV_{ee} threshold
- Future scale-up:
  - PICO-40L (57kg) commissioning
  - PICO-500 (250 litres) proposed
- NB: Indirect searches with neutrinos competitive





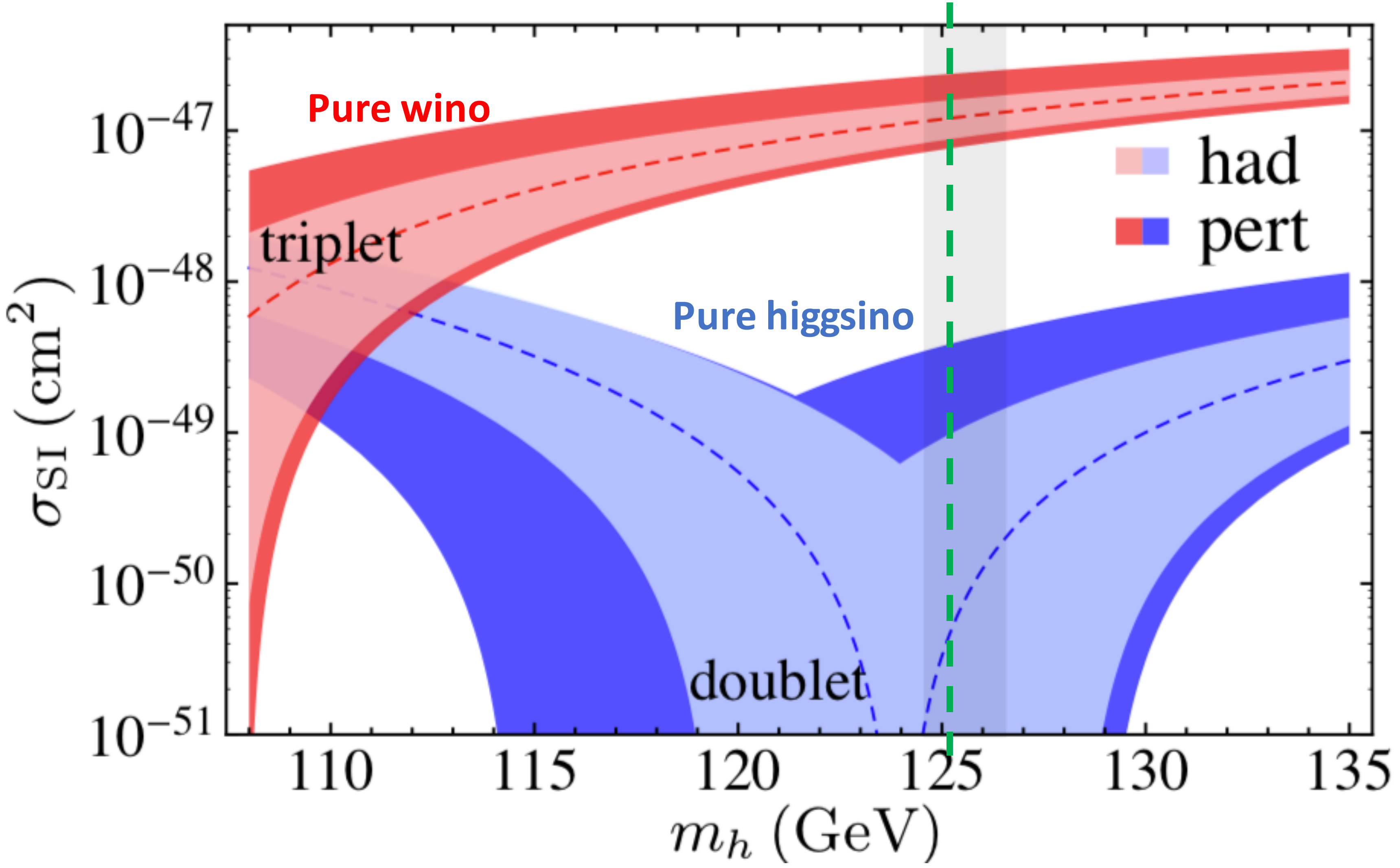
PICO Collaboration, Phys. Rev. D **100**, 022001



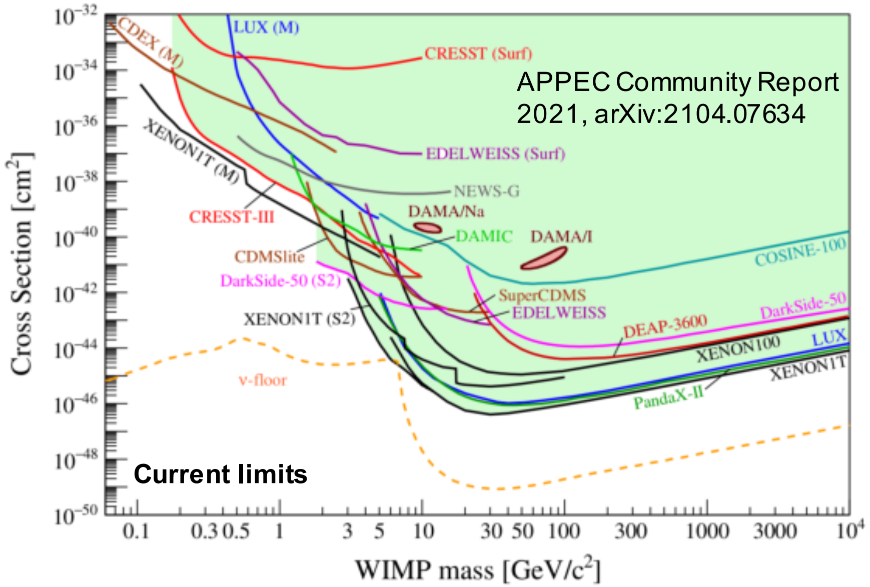
Higgsino/Wino Dark Matter

- Direct detection challenging in pure higgsino case (nature has not been kind!)

Hill and Solon, *Phys.Rev.Lett.* 112 (2014) 211602



Direct WIMP Search Summary



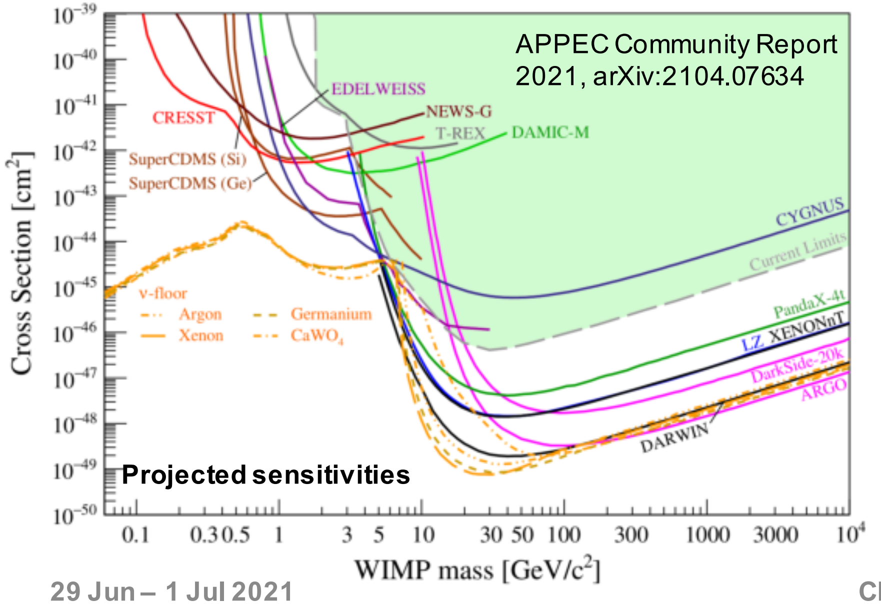
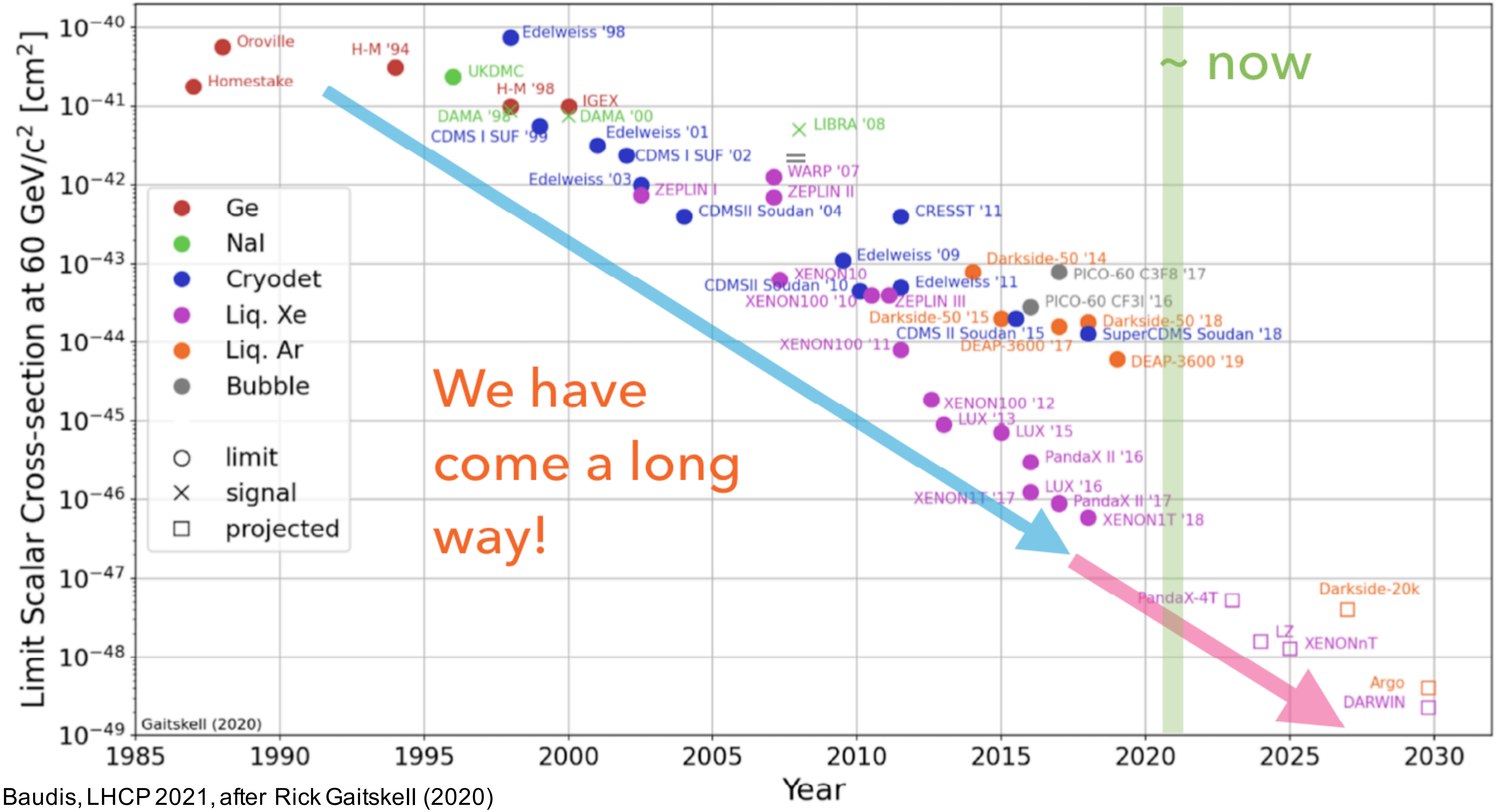


Table 27.1: Best constraints from direct detection experiments on the SI (at high >5 GeV and low < 5 GeV masses) and SD DM-nucleon couplings.

Experiment	Target	Fiducial mass [kg]	Cross section [cm^2]	DM mass [GeV]	Ref.
Spin independent high mass (>5 GeV)					
XENON1T	Xe	1042	4.1×10^{-47}	30	[145]
PandaX-II	Xe	364	8.6×10^{-47}	40	[144]
LUX	Xe	118	1.1×10^{-46}	50	[143]
SuperCDMS	Ge	12	1.0×10^{-44}	46	[135]
DarkSide-50	Ar	46	1.14×10^{-44}	100	[146]
DEAP-3600	Ar	2000	3.9×10^{-45}	100	[147]
Spin independent low mass (<5 GeV)					
LUX (Migdal)	Xe	118	6.9×10^{-38}	2	[149]
XENON1T (Migdal)	Xe	1042	3×10^{-40}	2	[150]
XENON1T (ionisation only)	Xe	1042	3.6×10^{-41}	3	[151]
DarkSide-50 (ionisation only)	Ar	20	1×10^{-41}	2	[152]
SuperCDMS (CDMSlite)	Ge	0.6	2×10^{-40}	2	[138]
CRESST	$CaWO_4$ - O	0.024	1×10^{-39}	2	[137]
NEWS-G	Ne	0.3	1×10^{-38}	2	[169]
Spin dependent proton					
PICO60	C_3F_8 - F	49	3.2×10^{-41}	25	[170]
Spin dependent neutron					
XENON1T	Xe	1042	6.3×10^{-42}	30	[192]
PandaX-II	Xe	364	1.6×10^{-41}	40	[193]
LUX	Xe	118	1.6×10^{-41}	35	[194]

L. Baudis and S. Profumo, PDG 2020

Direct WIMP Search Summary



Laura Baudis, LHCP 2021, after Rick Gaitskell (2020)

To Be Continued …