Dark Matter Experiments: Technologies and Techniques

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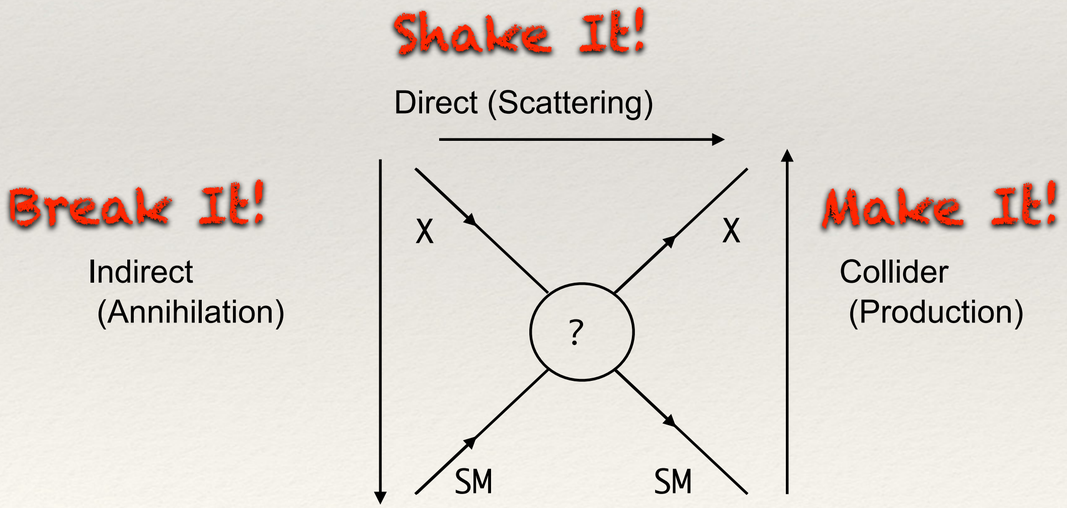
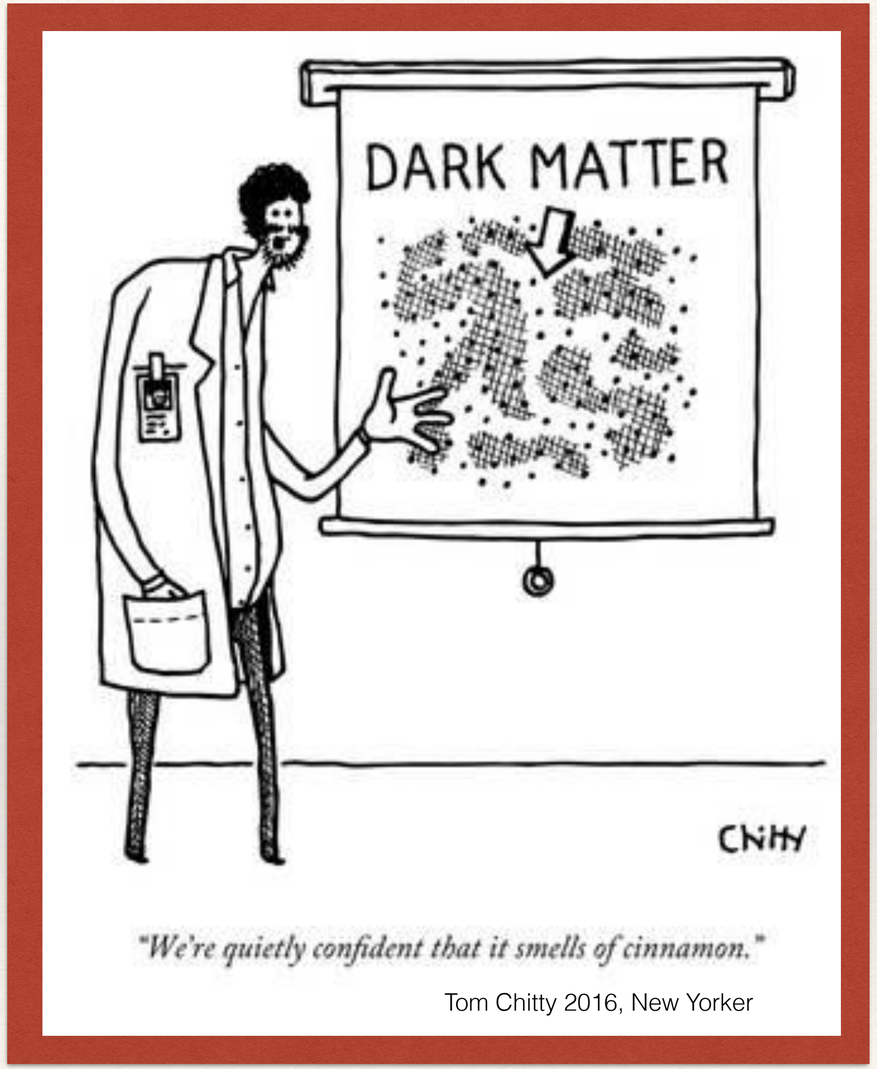
LNGS Summer School
8 September 2025

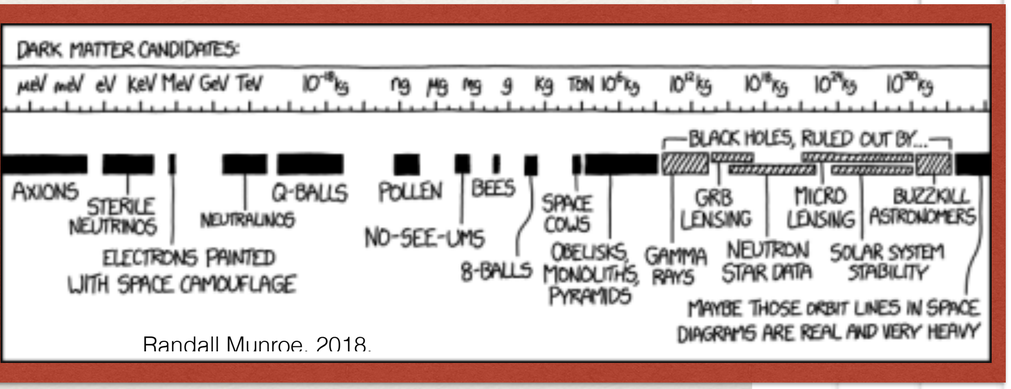
Outline

- Particle Dark Matter
- Technology Overview
- Search techniques for:
  - >10 GeV/c^2 Dark Matter
  - 1-10 GeV/c^2 Dark Matter
  - <1 GeV/c^2 Dark Matter

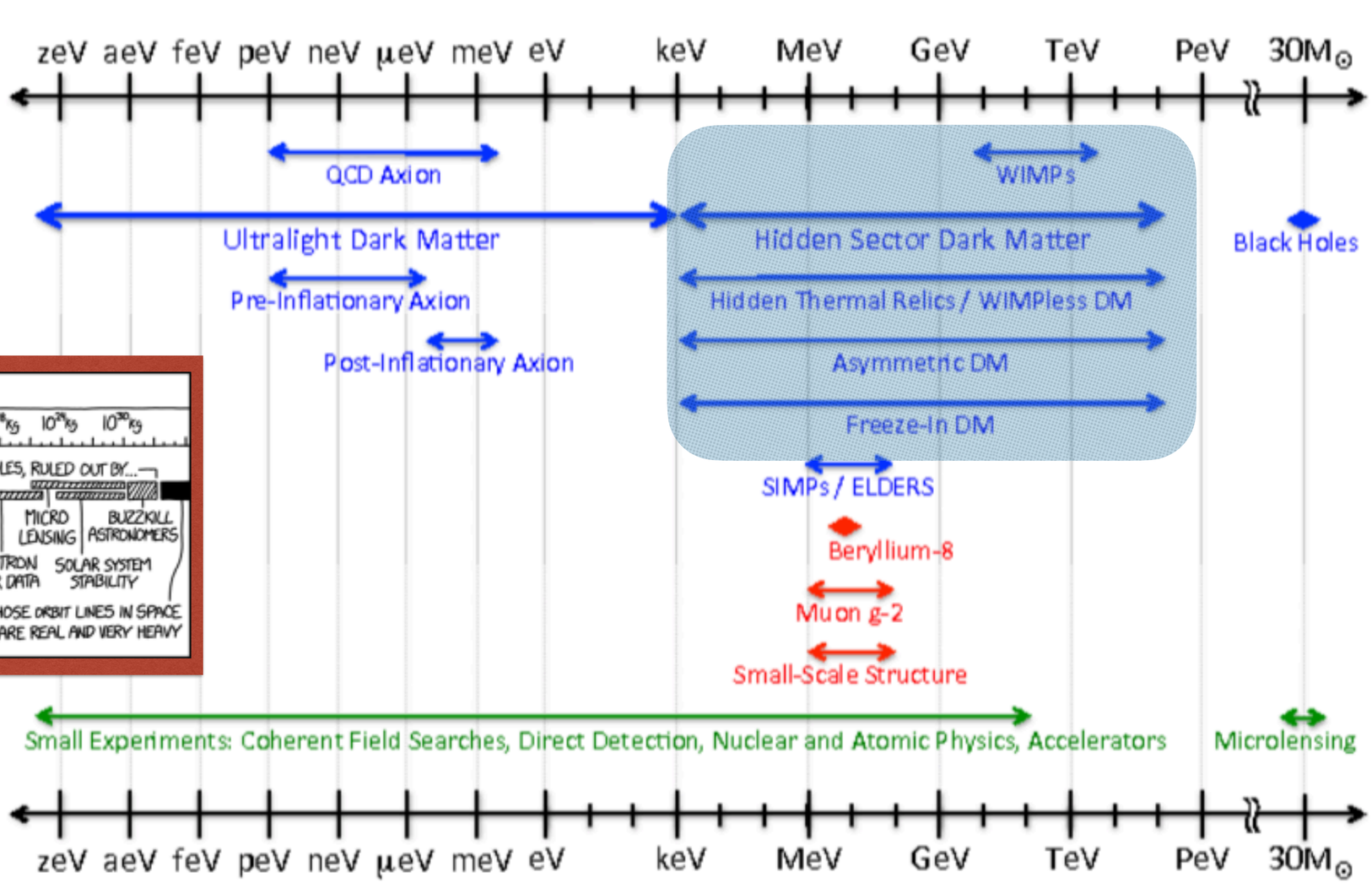




Models

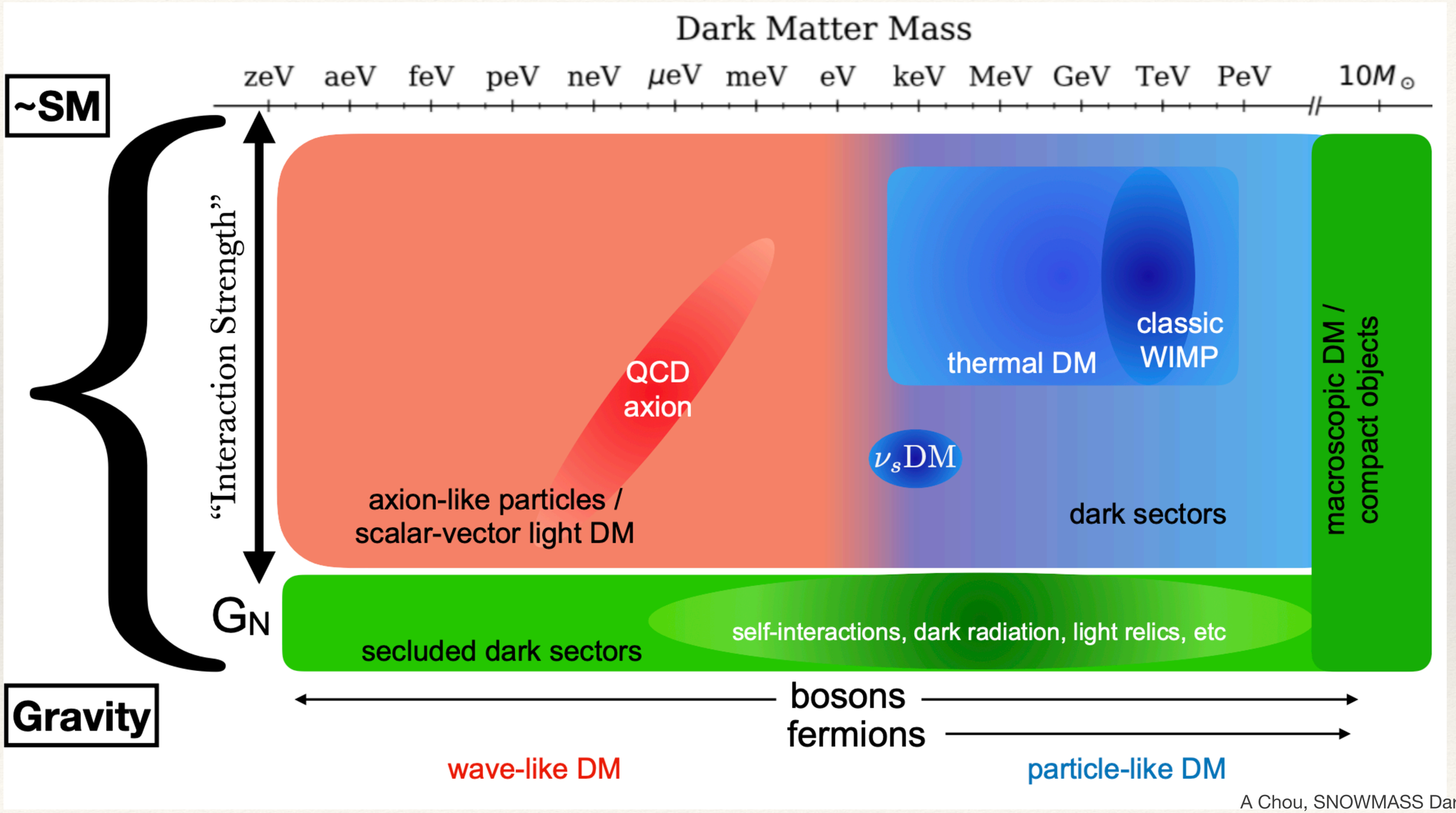


Randall Munroe, 2018.



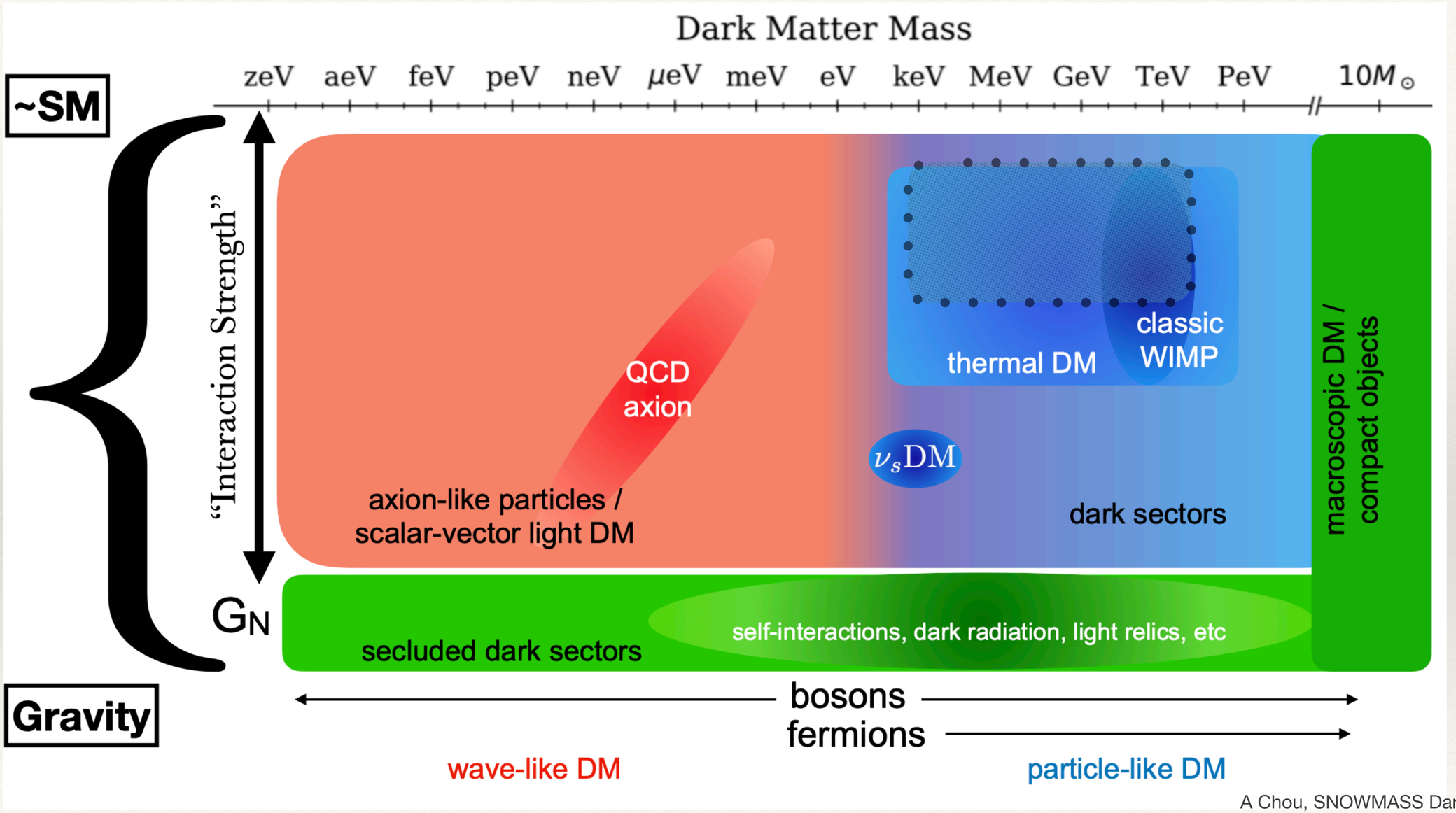
US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

A Unified Vision coming from SNOWMASS



A Chou, SNOWMASS Dark Matter Plenary

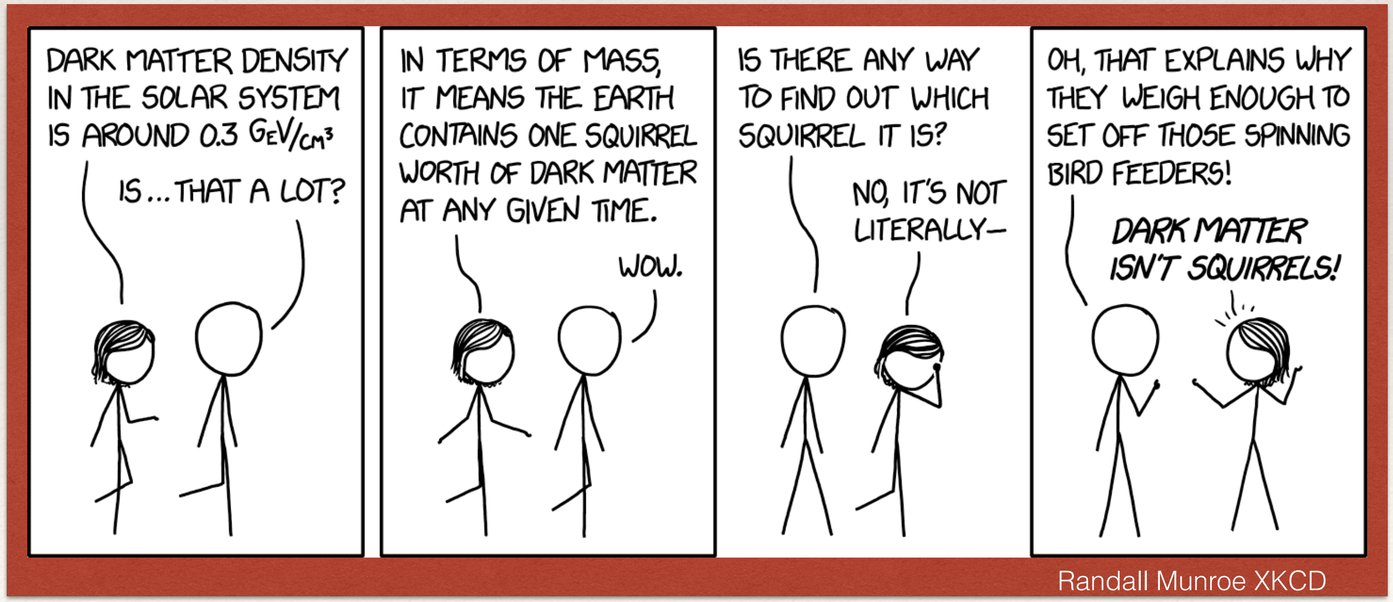
A Unified Vision coming from SNOWMASS



A Chou, SNOWMASS Dark Matter Plenary

This talk will cover:

- How we detect energy deposits due to interactions with our detectors
  - Induced by collisions with the Galactic Dark Matter particles
  - Unspecified interactions with atomic nuclei or electrons
  - Many different targets and quanta detection techniques
- Focus on experiments that need to be UG for cosmic shielding
- What I'm not going to cover
  - Analysis techniques
  - Interpretations of the events
    - Spin Independent
    - Spin Dependent
    - Effective Field Theories
    - Electronic recoils
    - Inelastic scatters

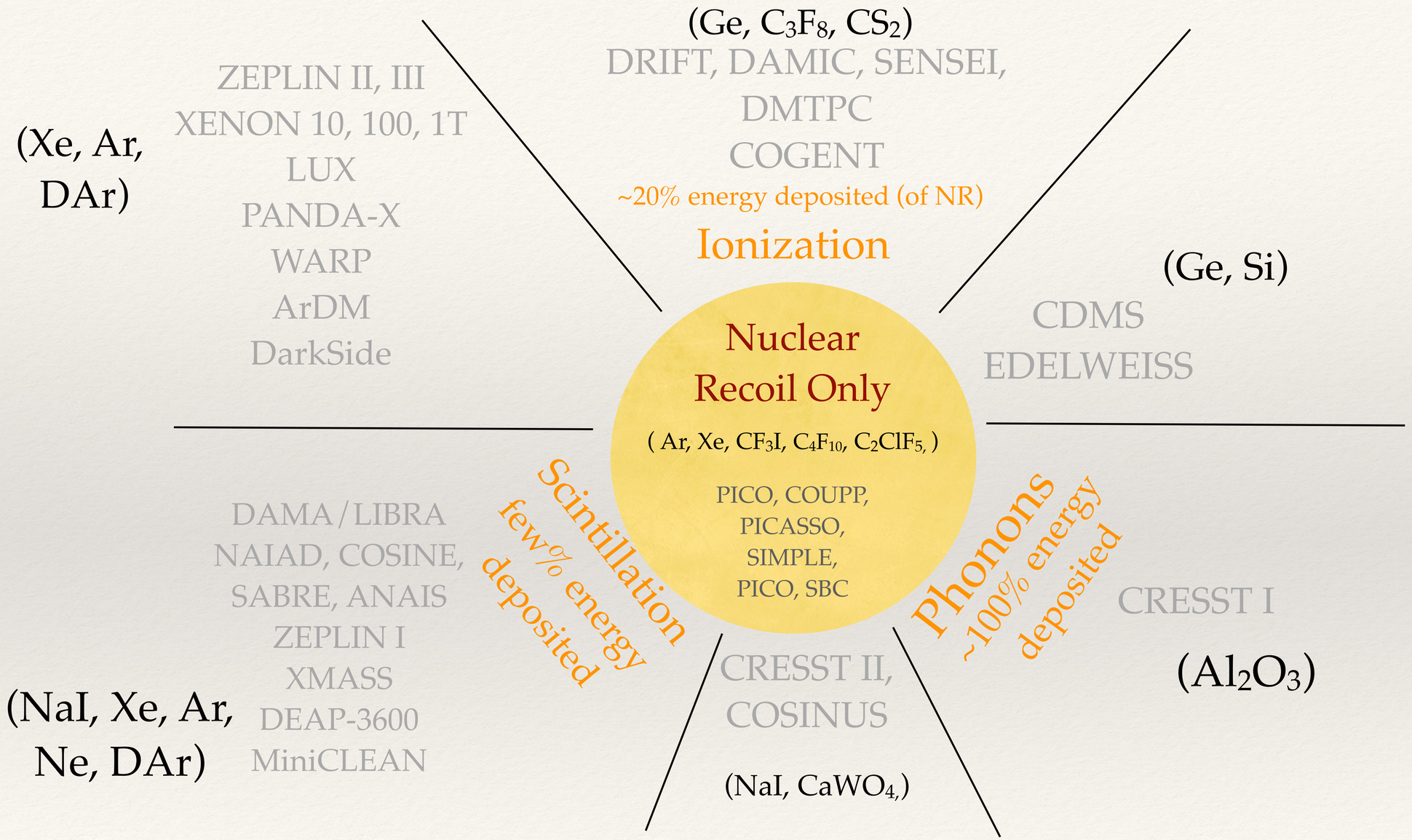


Randall Munroe XKCD

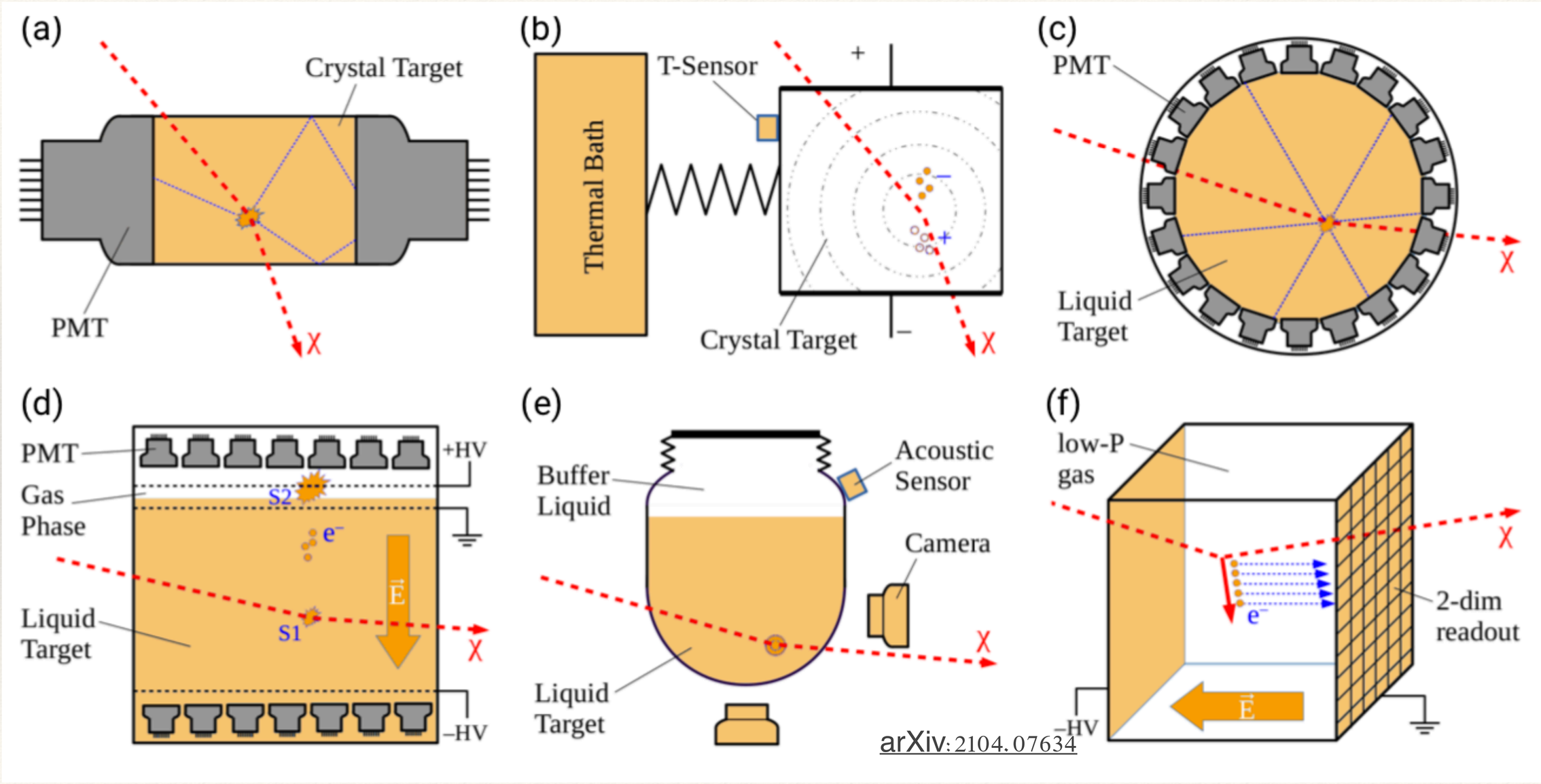
What do we need to detect dark matter?

- Ability to see low energy DM induced recoils
  - Low radioactivity
  - Low energy threshold
- Ability to distinguish nuclear recoils
  - Difference between hitting an electron & a nucleus
  - Difference between alpha particles (nucleus of a helium atom) and target nucleus recoiling
  - Position reconstruction and a low background area
- Calibrations of energy, position corrections, and particle ID
- Shielding from radioactivity and particles from space, and vetoing

A simple picture of technologies

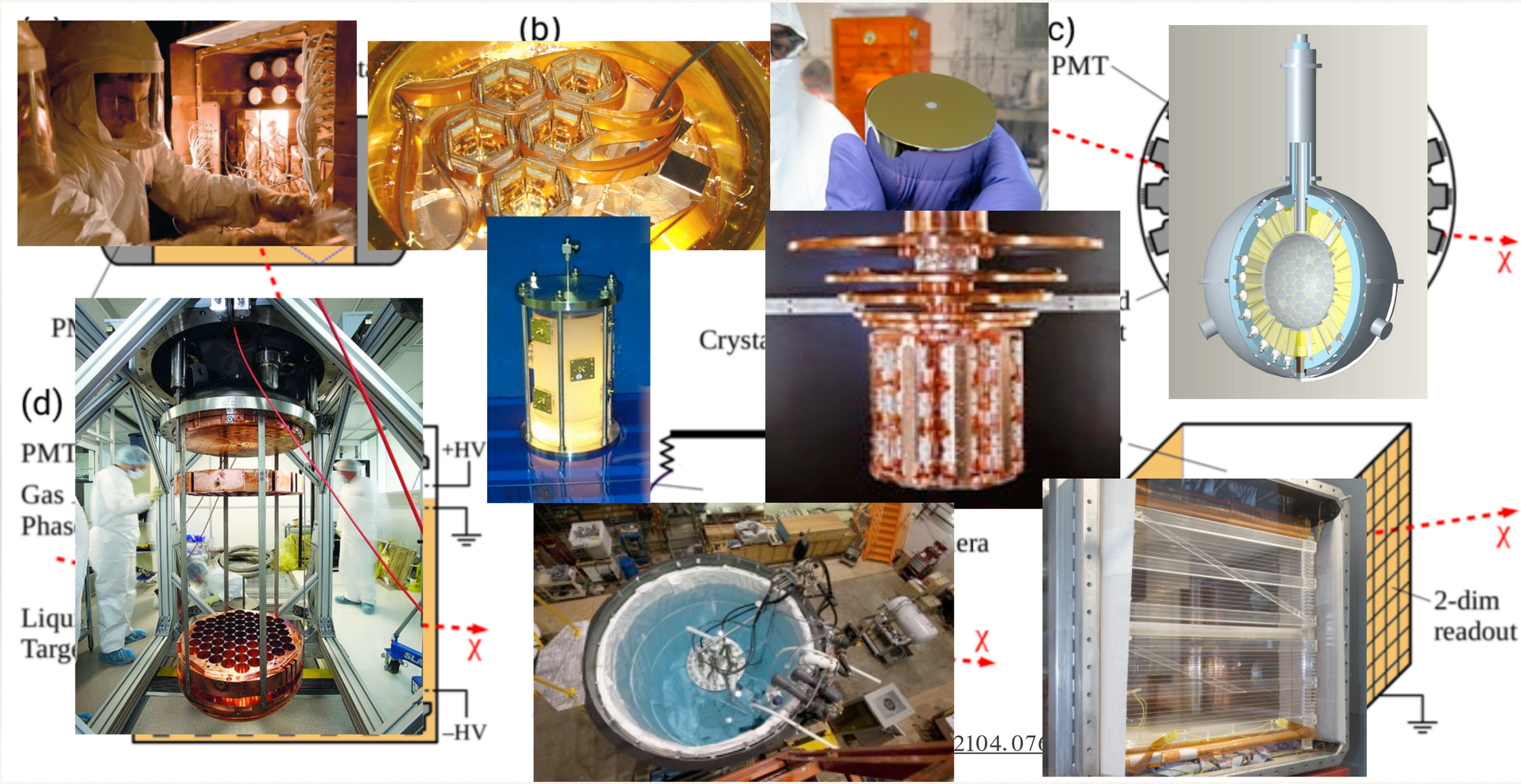


Detectors in 1 Figure!

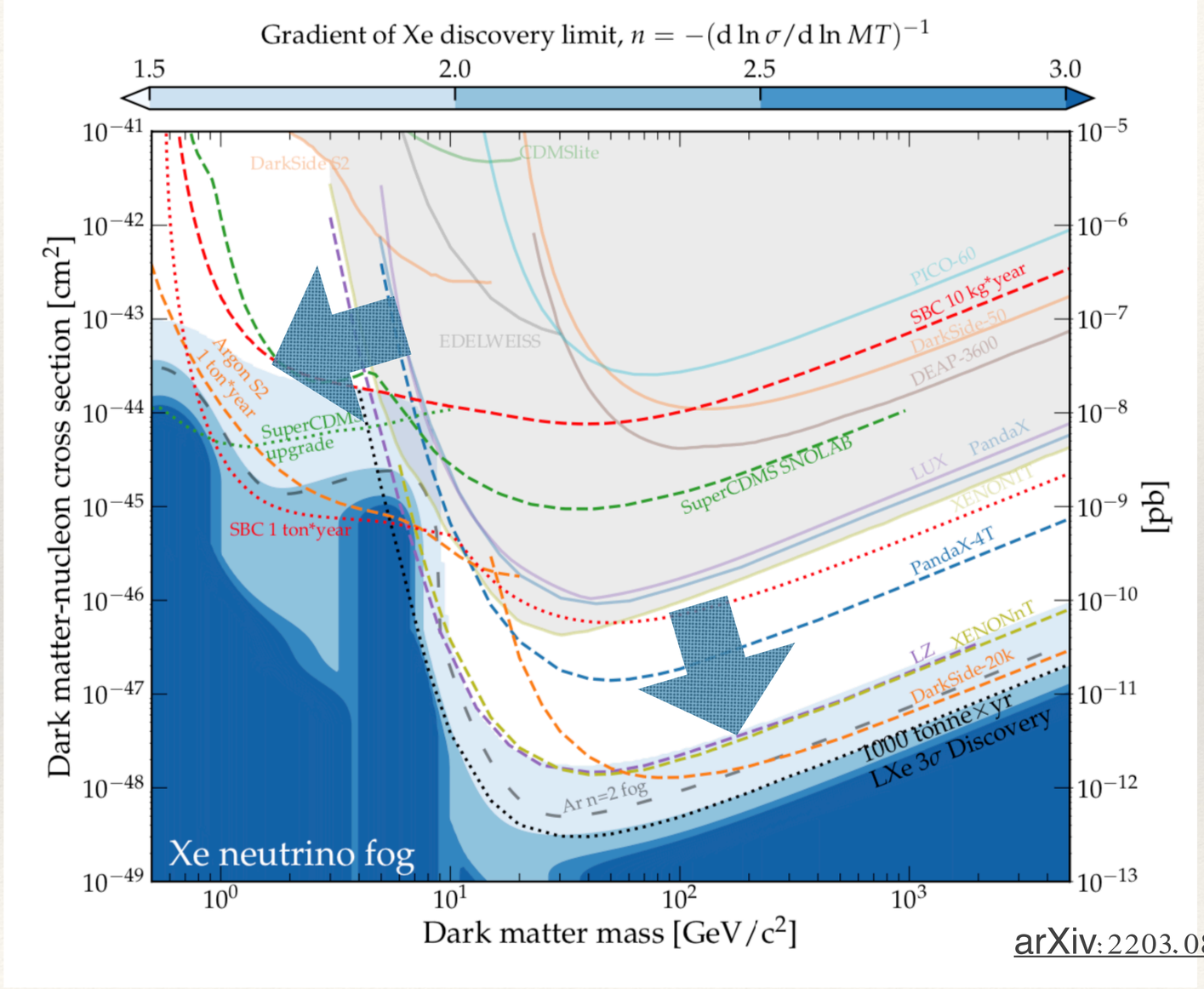


arXiv: 2104.07634

Detectors in 1 Figure!



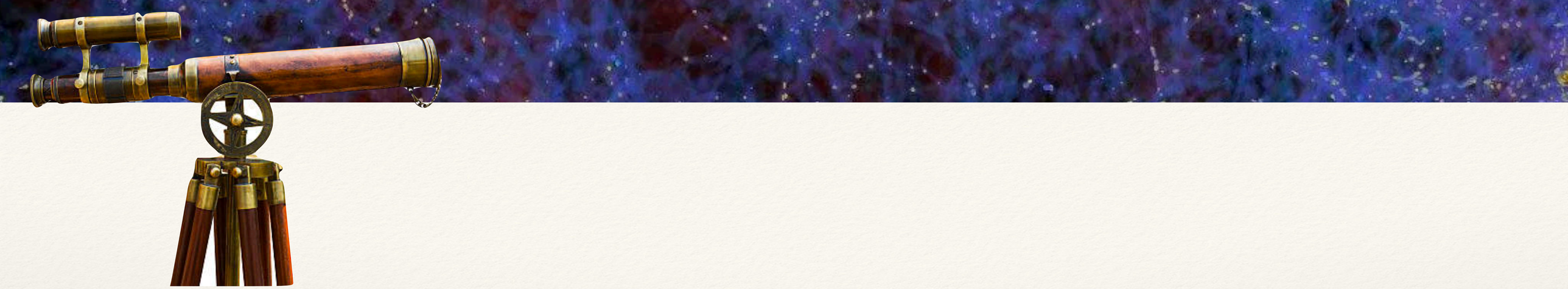
Spin Independent Direct DM status



arXiv:2203.08084

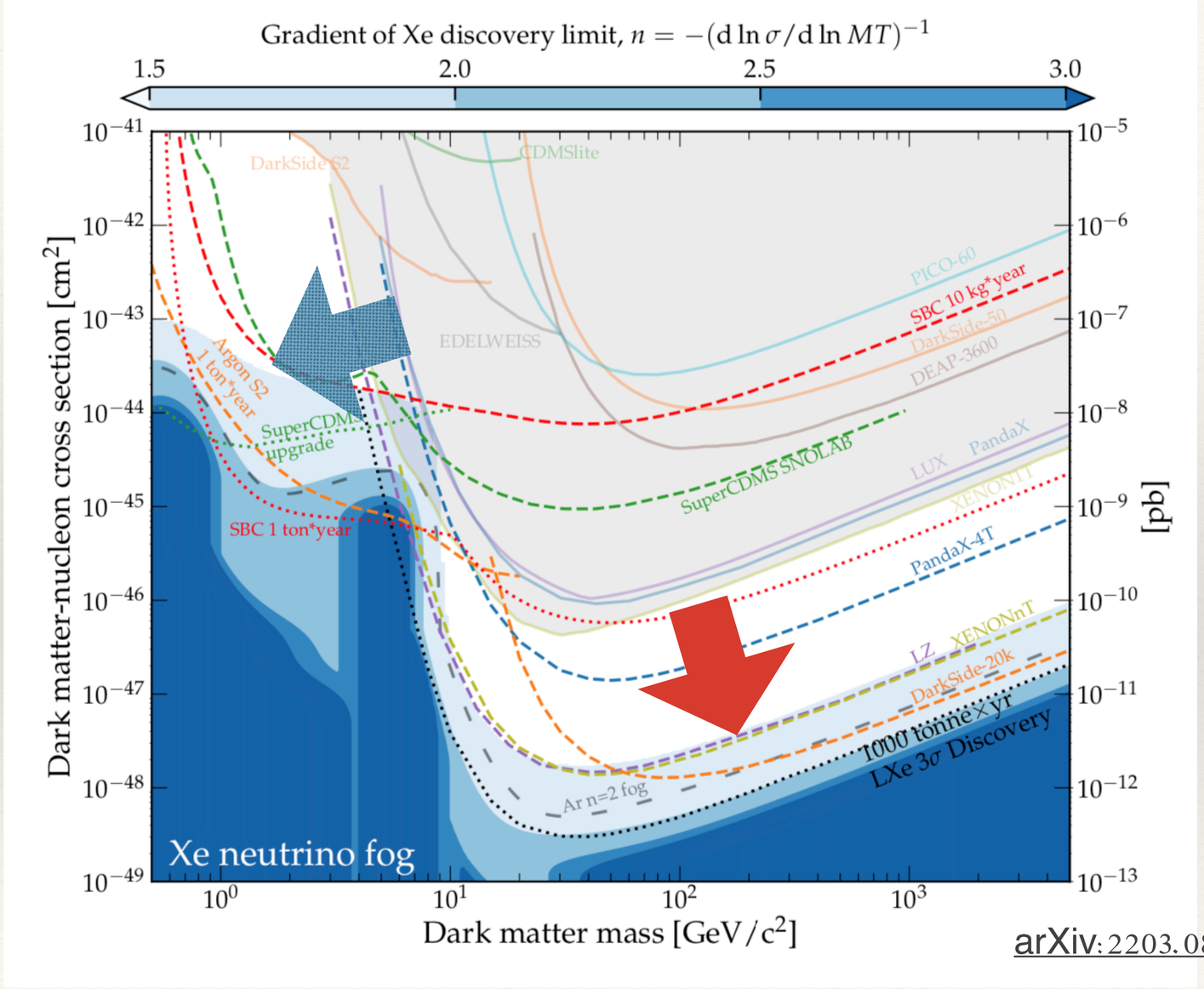
Focus on spin-independent DM-nuclear scattering

Michael Lucibella 2014, APS.org



For DM masses > 10 GeV/c^2,
liquid noble detectors are the right technology,
and future experiments can get to the neutrino fog.

Spin Independent Direct DM status



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Focus on spin-independent DM-nuclear scattering

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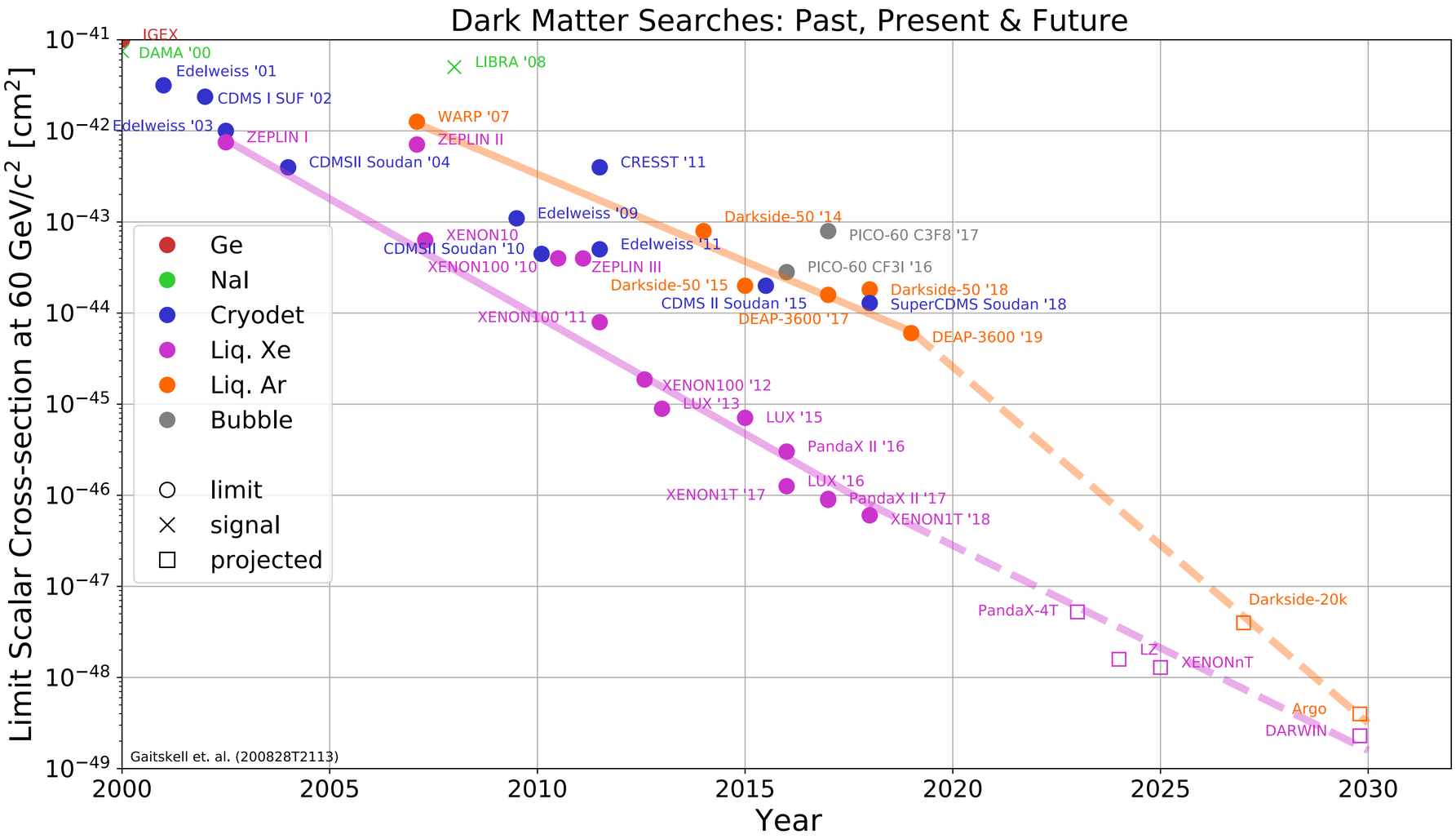
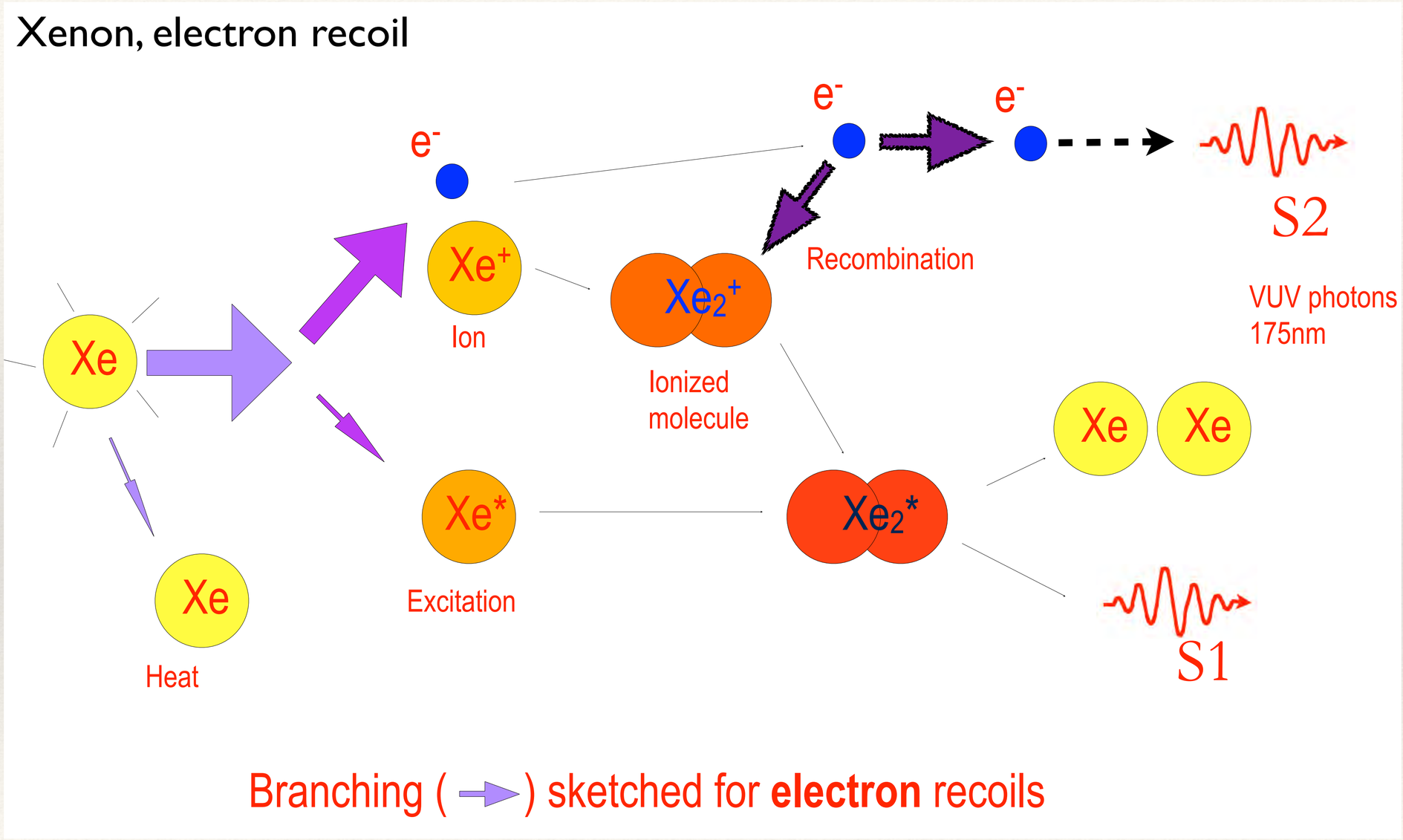
Global Sensitivity Vs Time at 60 GeV

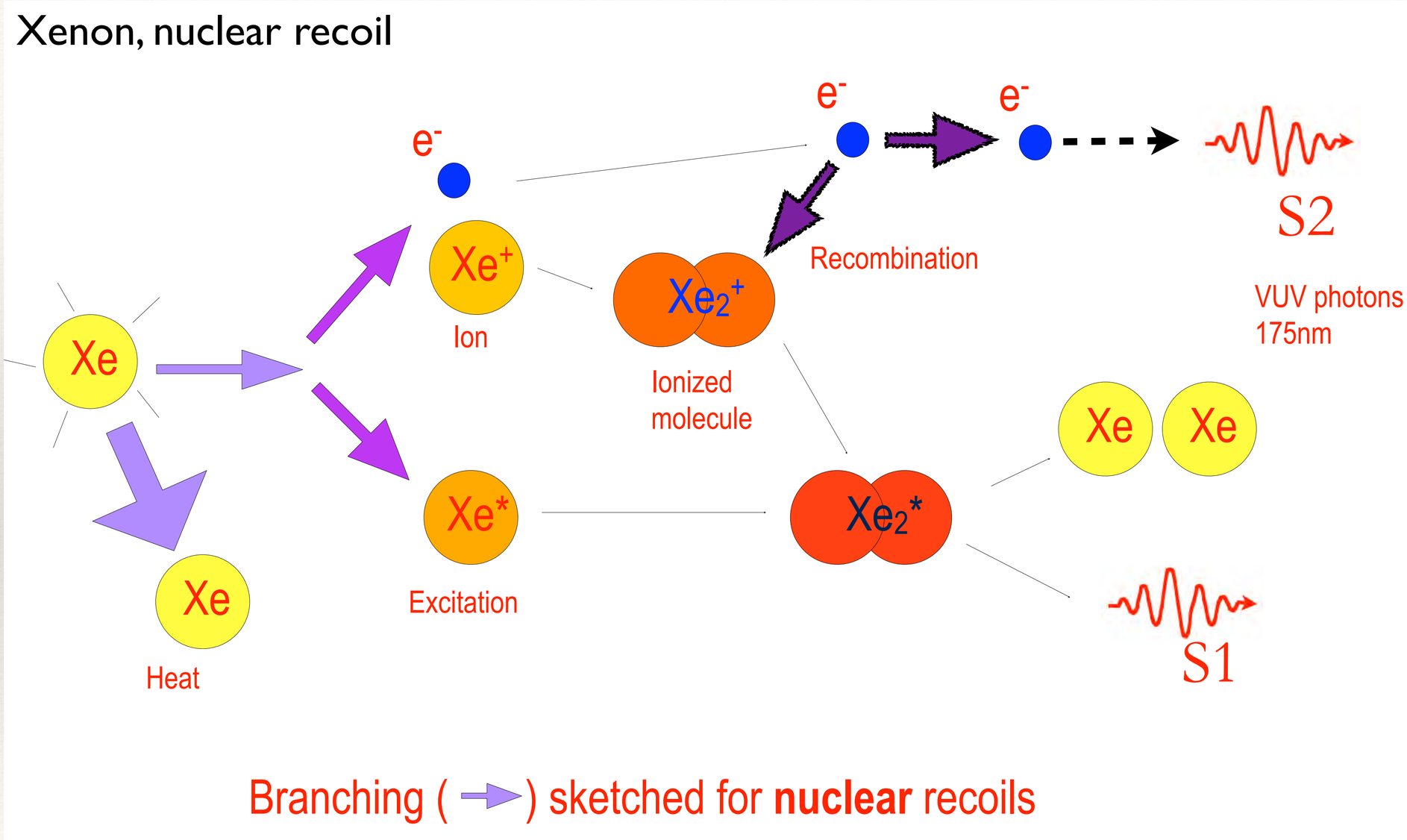


Xenon: Electric Recoil

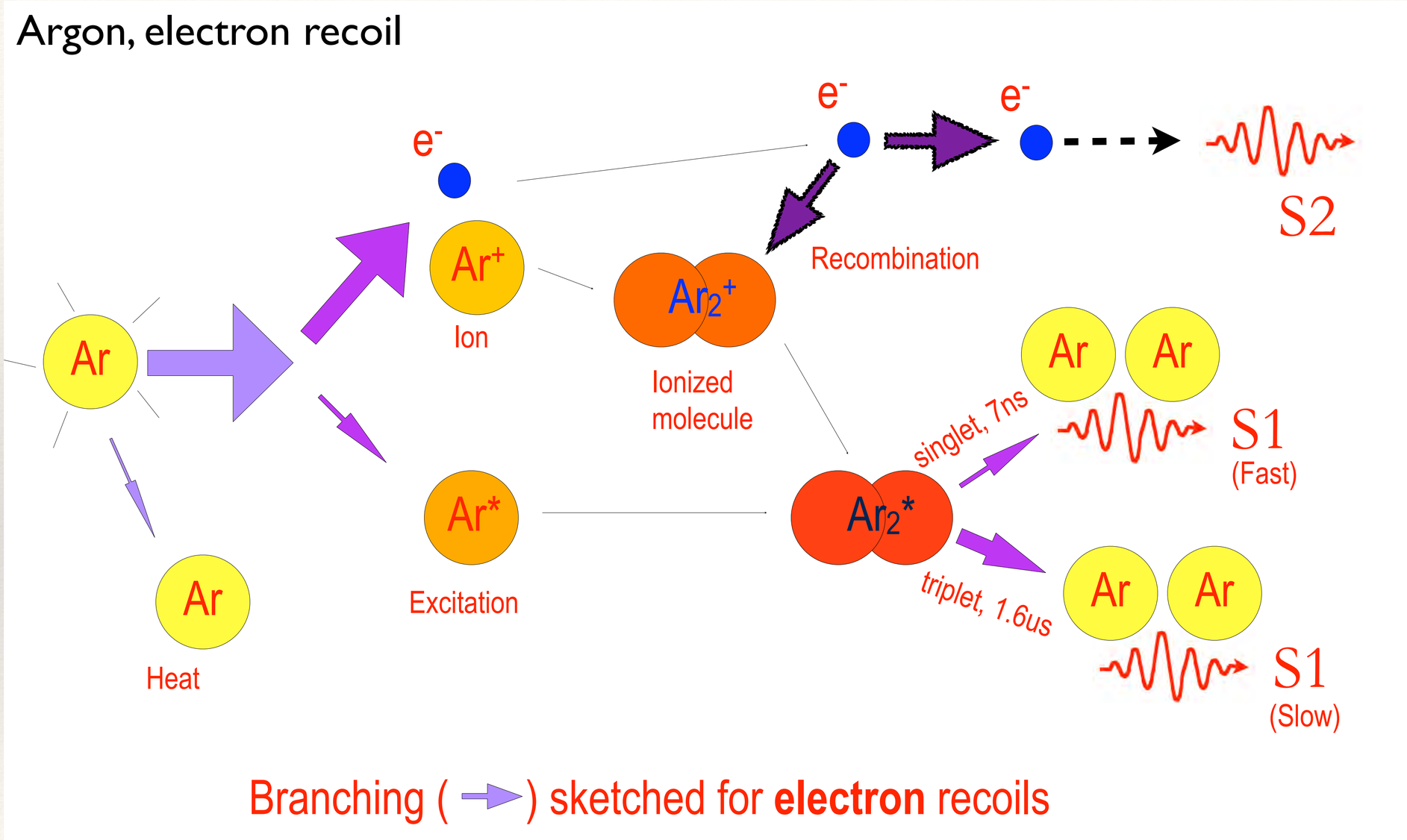


cartoons from Akerib and Shutt

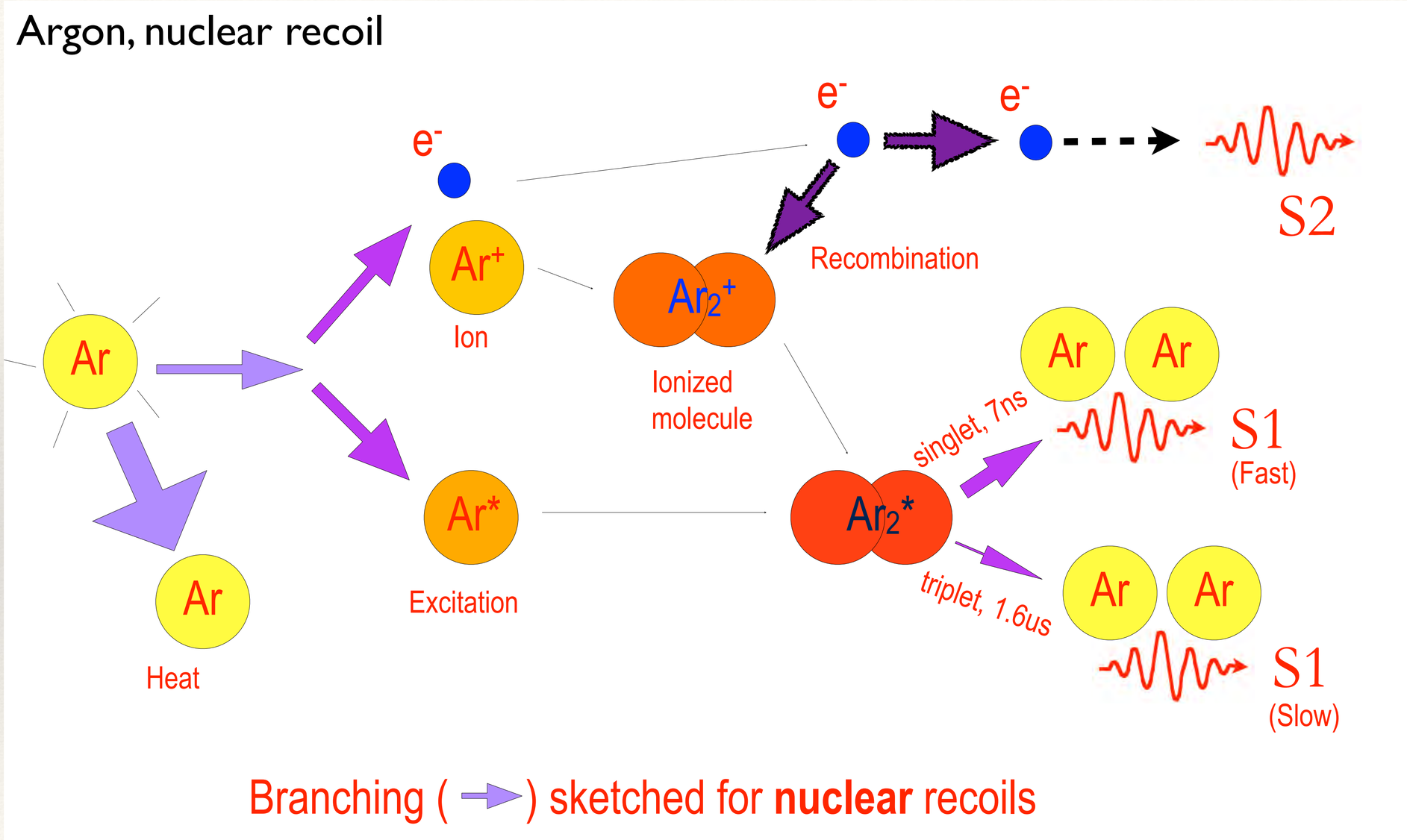
Xenon: Nuclear Recoil



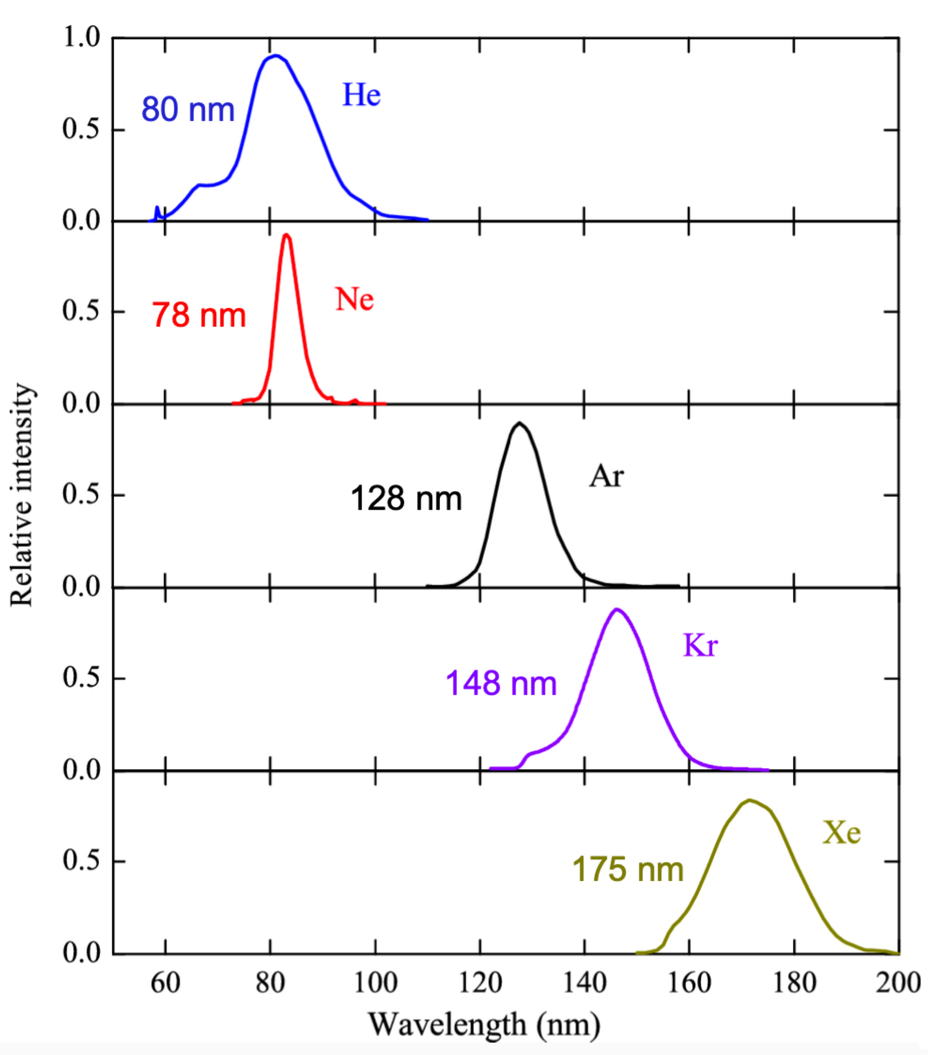
Argon: Electric Recoil



Argon: Nuclear Recoil



Noble gases



Sun

New

Lazy

Hidden

Strange

Table 3: Scintillation parameters for liquid neon, argon, and xenon.

Parameter	Ne	Ar	Xe
Yield ($\times 10^4$ photons/MeV)	1.5	4.0	4.2
prompt time constant τ_1 (ns)	2.2	6	2.2
late time constant τ_3	15 μs	1.59 μs	21 ns
I_1/I_3 for electrons	0.12	0.3	0.3
I_1/I_3 for nuclear recoils	0.56	3	1.6
λ(peak) (nm)	77	128	174
Rayleigh scattering length (cm)	60	90	30

Lippincott et al Phys Rev C78; 035801 (2008)

Xenon and Argon Properties

Argon

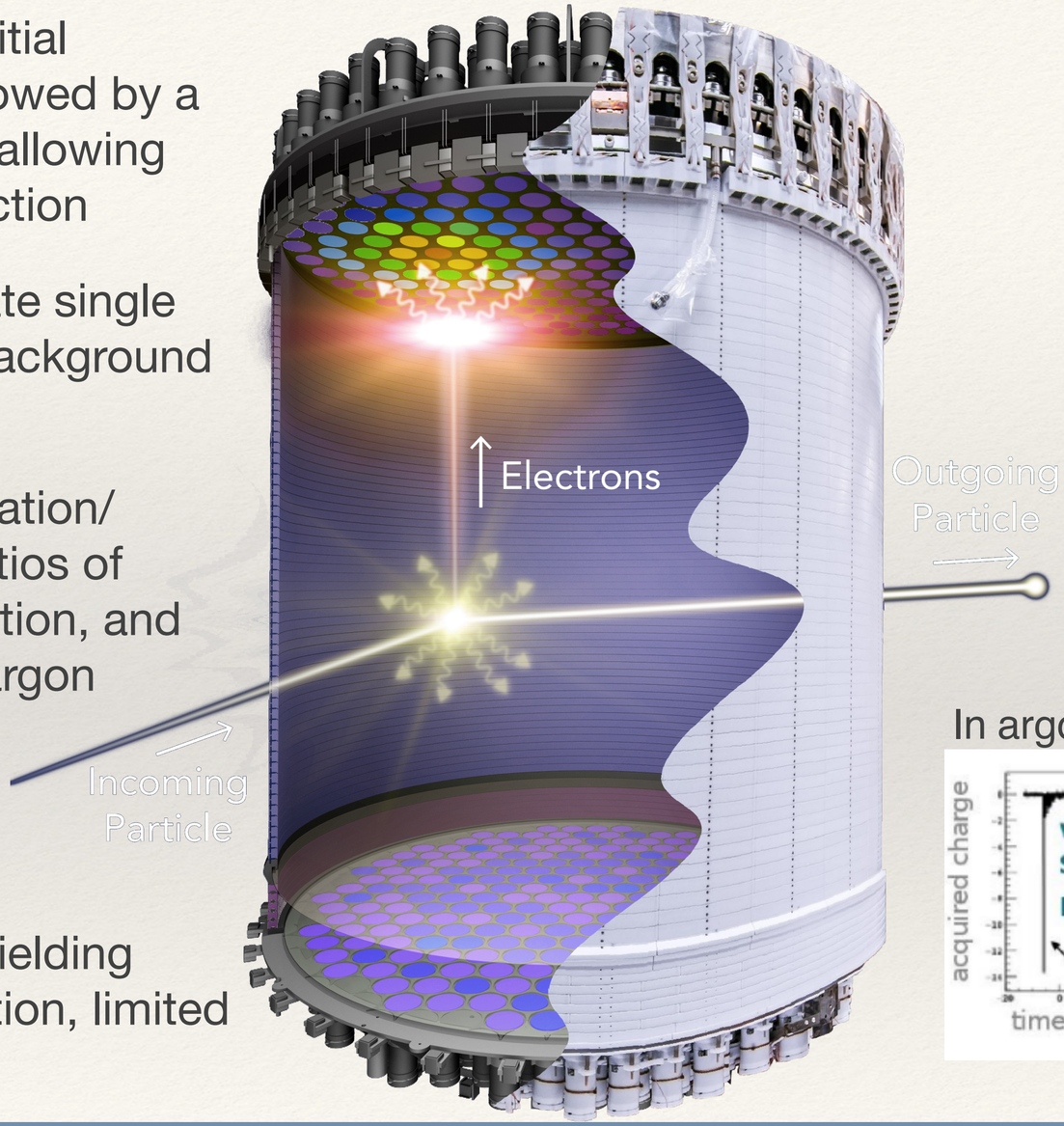
Property	Value
Normal boiling point (NBP)	87.303(2) K
Normal freezing point	83.8(3) K
Density at NBP	1.396(1) g/ml
Heat of vaporization	161.14 kJ/kg
Heat capacity	1.117 kJ/kg/K
Mean energy per ionization w	23.6(3) eV/pair
Fano factor	0.107
Moliere radius R_M	10.0 cm
Radiation length X_0	14.0 cm
Critical energy E_c	30.5 MeV
Nuclear interaction length λ_I	85.7 cm
Minimum ionization loss $dE\,/\,dx_{mip}$	2.12 MeV/cm

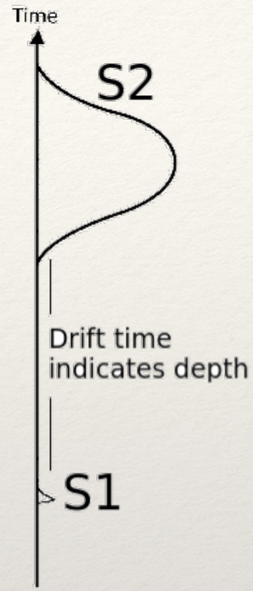
Xenon

Property [unit]	Xe
Atomic number	54
Mean atomic mass [g/mol]	131.29
Boiling point T_b **at 1 atm [K]**	165.0
Melting point T_m **at 1 atm [K]**	161.4
Gas density at 1 atm & 298 K [g/l]	5.40
Gas density at 1 atm & T_b **[g/l]**	9.99
Liquid density at T_b **[g/cm^3]**	2.94
Volume ratio	526
Dielectric constant of liquid	1.95
Volume fraction in Earth's atmosphere [ppm]	0.087
Isotopes with spin, abundance [%]	^{129}Xe, 26.44; ^{131}Xe, 21.18
Radioactive isotopes,	^{136}Xe, 8.87; 2.2×10^{21} [8, 9]
abundance [%] and $T_{1/2}$ **[y]**	^{124}Xe, 0.095; 1.1×10^{22} [10, 11]
	^{134}Xe, 10.4; $> 8.7\times10^{20}$ (90% C.L.) [12]
	^{126}Xe, 0.089; $> 1.9\times10^{22}$ (90% C.L.) [13]

Liquid Noble Time Projection Chambers

- Interactions give an initial scintillation signal followed by a signal from ionization allowing for position reconstruction
- Good ability to separate single scatter signals from background multiple scatters
- Background discrimination/ particle ID given by ratios of scintillation and ionization, and scintillation timing in argon
- Other benefits: self shielding against external radiation, limited radioactivity in targets

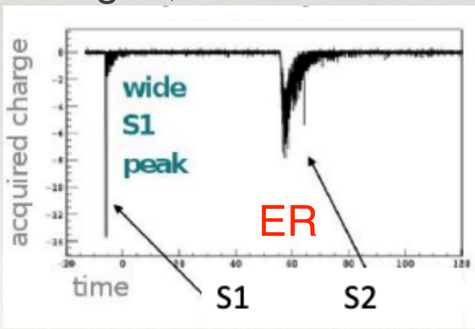


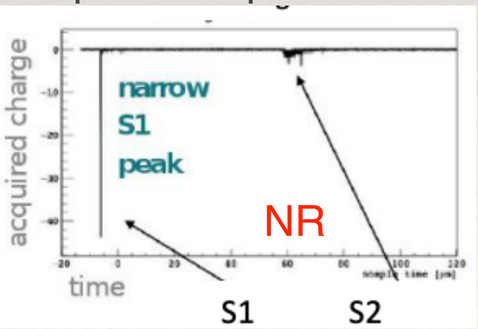


Large detectors with sensitivity over many orders of magnitude of DM mass.

Physics beyond WIMP searches also.

In argon, scintillation timing also provides particle ID

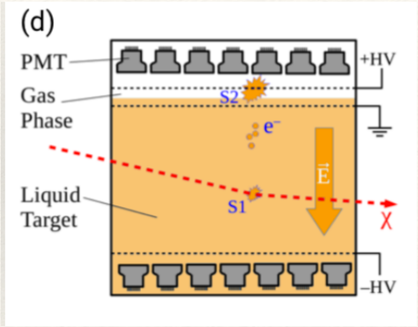




Collection of Scintillation Light

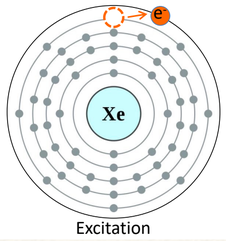
Xenon TPCs

- High reflectivity of PTFE in LXe for 175 nm, >97%
- Some loss of light on electrodes
- low radioactivity VUV PMTs currently used
- R&D ongoing into VUV SiPMs
- total scintillation collection ~10-15%



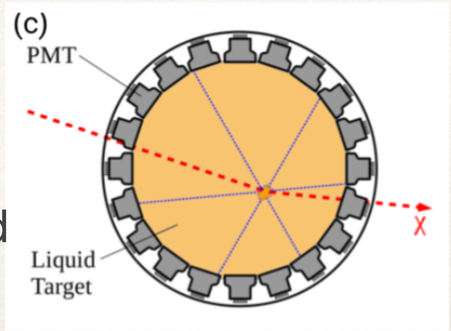
- Excitation: Produces scintillation light as it de-excites (n_γ, measured as S1)

$$Xe^* + Xe \longrightarrow Xe_2^* \longrightarrow 2Xe + \gamma \quad \text{(simplified)}$$



Argon TPCs and Single Phase

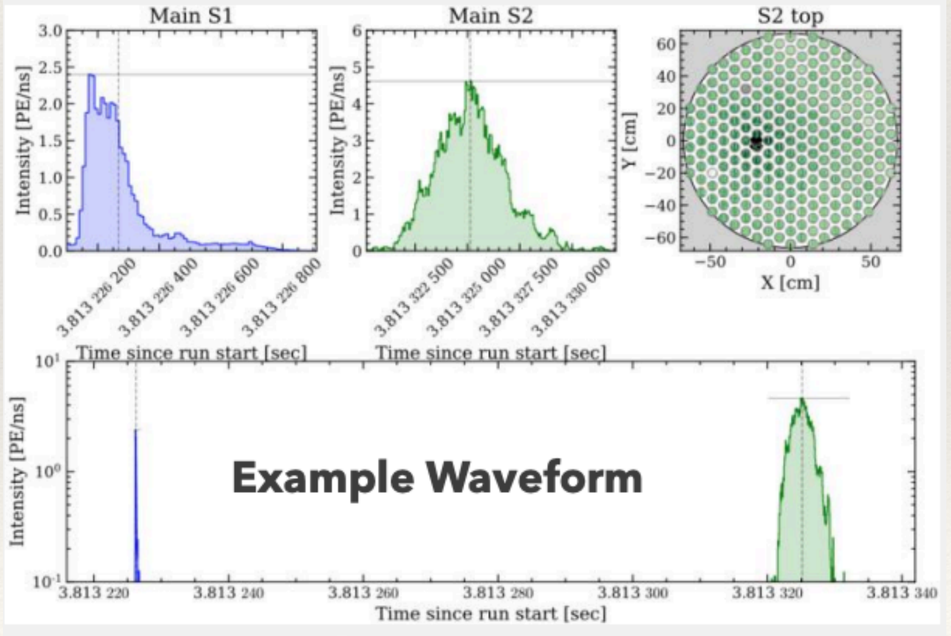
- Wavelength shifters TPB and PEN used to take 128 nm to more visible light
  - then more optical reflectors can be used
- Since S1 timing can give particle ID, greater attention to photon timing and electronics
- Generally moving to SiPMs for lower radioactivity, esp against neutrons
  - DEAP-3600 used large PMTS and uses acrylic lightguides to provide neutron shielding
- R&D ongoing into VUV SiPMs



Basic Principles of Ionization Operation

Ionisation and recombination → **Drift in Electric field** → **Electron loss** → **Diffusion and Dispersion** → **Charge detection**

- LXe/LAr TPCs for Dark Matter
  - but analogous in solid crystal detectors



Ionisation+ Recombination

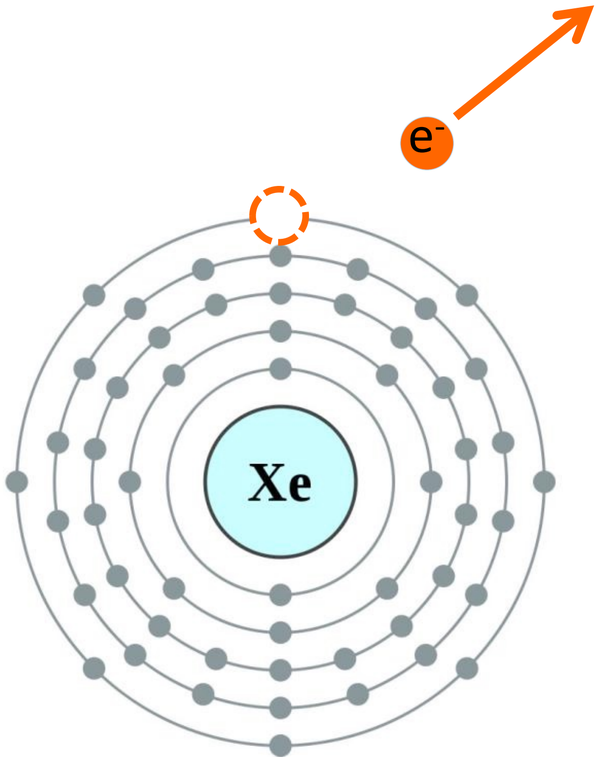
Ionisation and recombination

- Ionization: Can be extracted by an external electric field (n_e, measured as S2)

OR can recombine and give a scintillation photon (n_γ, S1)

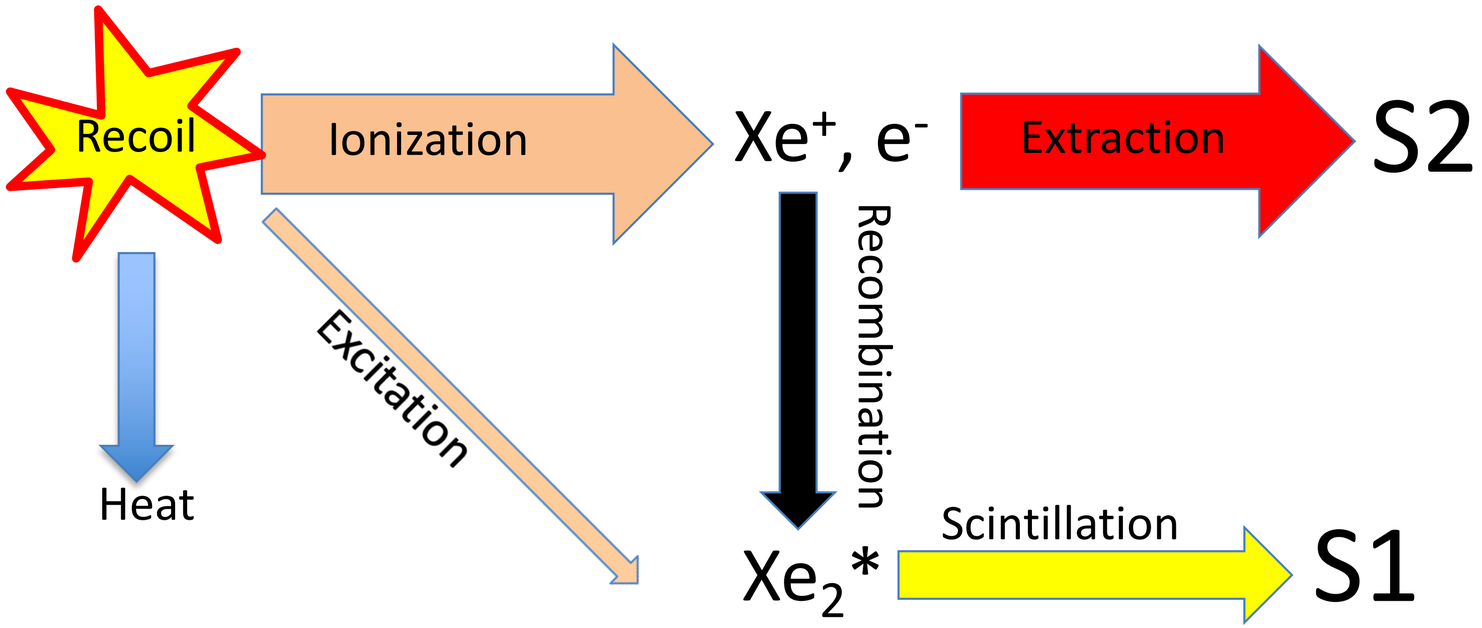
$$Xe + Xe^+ + e^- \longrightarrow Xe_2^* \longrightarrow 2Xe + \gamma$$

(simplified)



Ionization

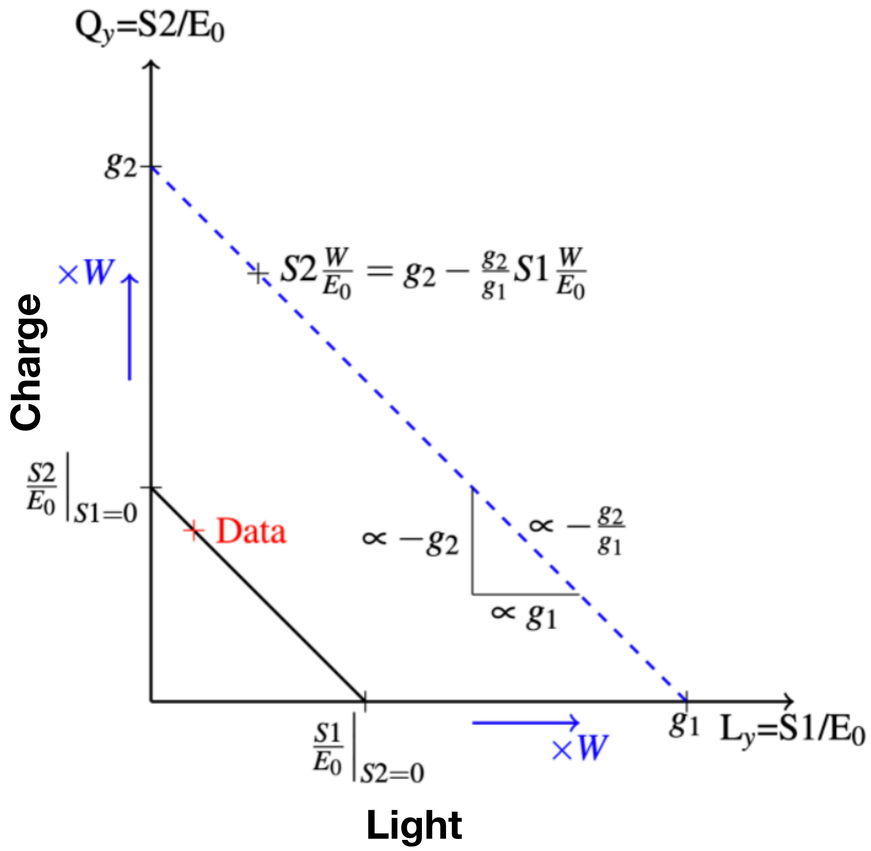
Implications

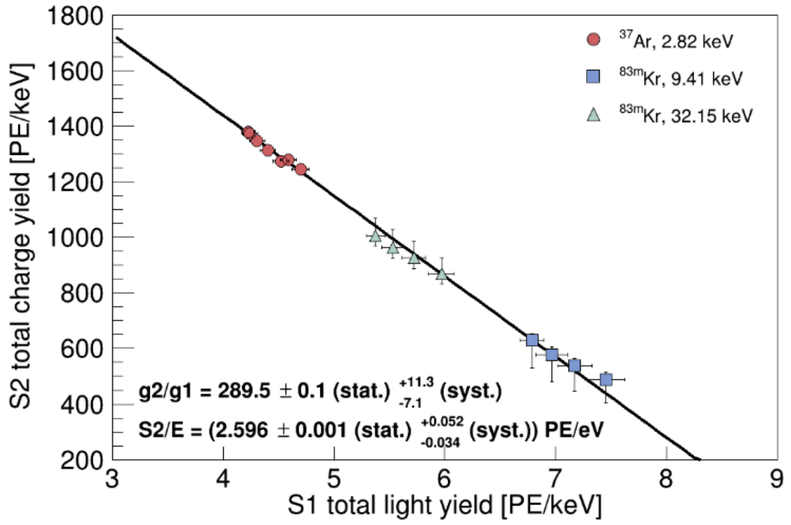


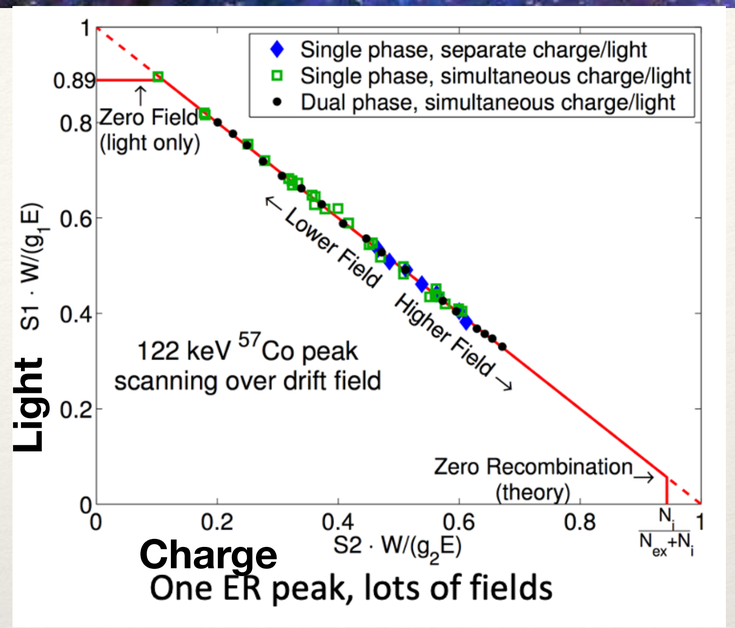
$$n_e = (1-r)N_i, \quad n_\gamma = N_{ex} + rN_i$$

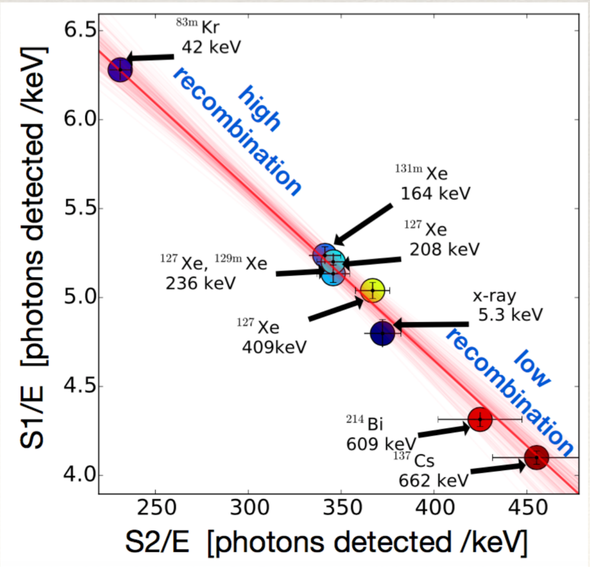
$$n_e + n_\gamma = N_{ex} + N_i$$

Charge vs scintillation yield (Xe): Doke plot









Charge production in LAr

- To produce an electron-ion pair in gaseous Ar: 26.4 eV
- To produce an electron-ion pair in liquid Ar: 23.6 eV
- -> Conduction bands in LAr (like in solids)

Birk's Law-like

$$Q = A\frac{Q_0}{1 + (k / \mathcal{E})\langle dE / dx\rangle}$$

Q is charge collected at anode
Q_0 is initial ionization charge
ϵ is the electric field (.1-1 kV/cm)
dE/dx is the particle stopping power
k, A determined from data

At 500 V/cm about 70% of initial charge is collected due to recombination

Drift velocity in Gaseous Xenon

Drift in Electric field

Slightly different form than given in the Detector textbook, and maybe than what you saw in lecture

$$v_{drift} = \frac{\alpha(\frac{E}{N}) + \beta(\frac{E}{N})^6}{1 + \gamma(\frac{E}{N})^{5.8}} + \delta(\frac{E}{N})exp(-\epsilon(\frac{N}{E}))$$

Drift velocity calculation
-Equations of motion (basically F = ma)

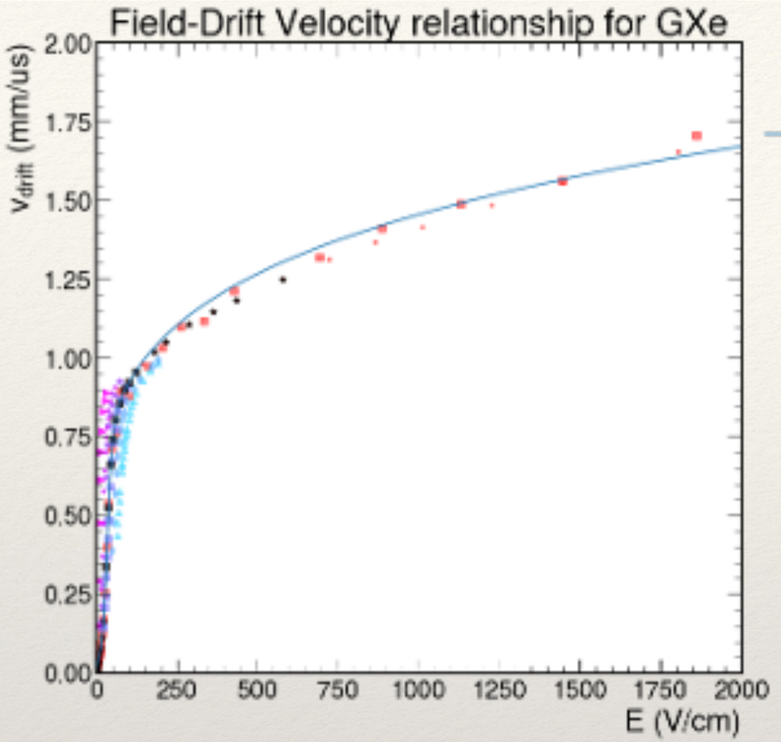
$$\mathbf{u}_e = -eb_e\mathbf{E} - (D_e/N_e)\cdot\mathrm{grad}(N_e); \qquad \mathbf{u}_i = eb_i\mathbf{E} - (D_i/N_i)\cdot\mathrm{grad}(N_i);$$
$$\mathrm{div}(N_e\mathbf{u}_e) = \nu_i N_e; \quad \mathrm{div}(N_i\mathbf{u}_i) = \nu_i N_e; \quad \mathrm{div}(\mathbf{E}) = 4\pi e(N_i - N_e).$$

Terms :

- e is the charge of a electron;
- u are the average velocities;
- b are the mobilities;
- D are the diffusion coefficients;
- N are the charge densities;
- E is the electric field strength;
- e,i indices for electrons vs ions

utilizing PV=NRT for an ideal gas: pressure and temperature are rolled into the charge density

Theory and experiment: velocity in Gas Xe

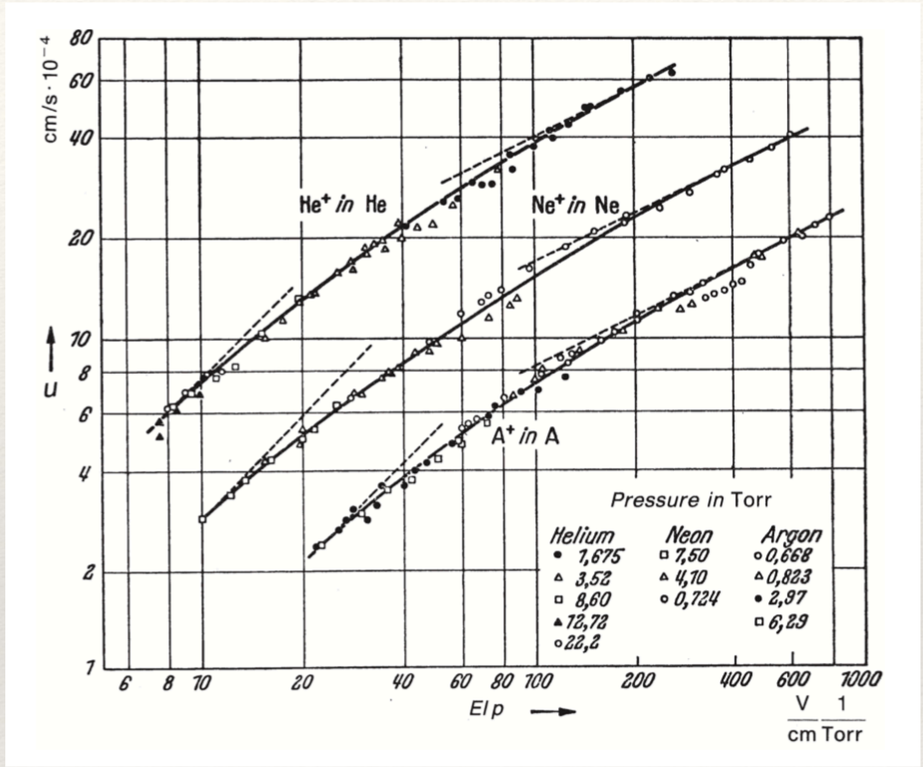


Analytical
Pack 1992 (300K)
Kusano 2012 (299K):1.73x10^21 cm^-3
Kusano 2012 (299K):1.27x10^21 cm^-3
Kusano 2012 (299K):8.69x10^20 cm^-3
Kusano 2012 (299K):5.38x10^20 cm^-3
Kusano 2012 (299K):4.82x10^20 cm^-3
Kusano 2012 (299K):2.55x10^20 cm^-3
Hunter 1988 (301.2K)
NEXT 2019 (294K):1 bar
NEXT 2019 (294K):3 bar
NEXT 2019 (294K):6 bar
NEXT 2019 (294K):9 bar

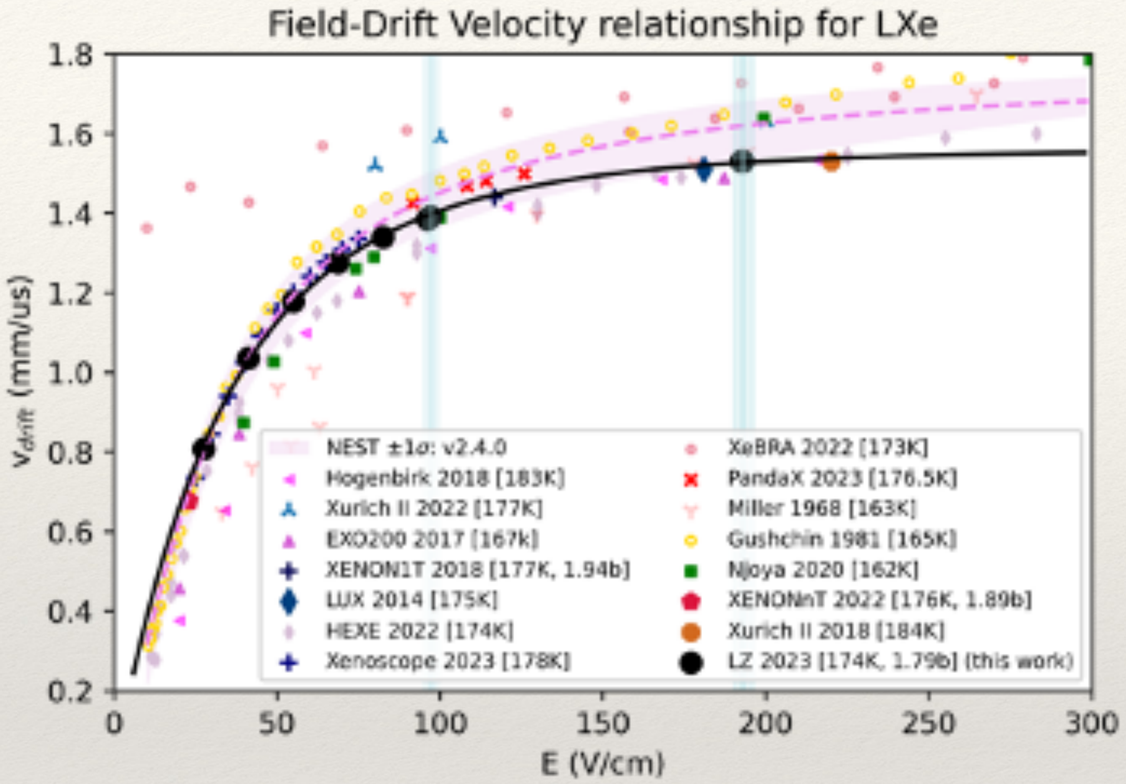
1 mm/us=10e-4 cm/s

$$v_{drift} = \frac{\alpha(\frac{E}{N}) + \beta(\frac{E}{N})^6}{1 + \gamma(\frac{E}{N})^{5.8}} + \delta(\frac{E}{N})exp(-\epsilon(\frac{N}{E}))$$

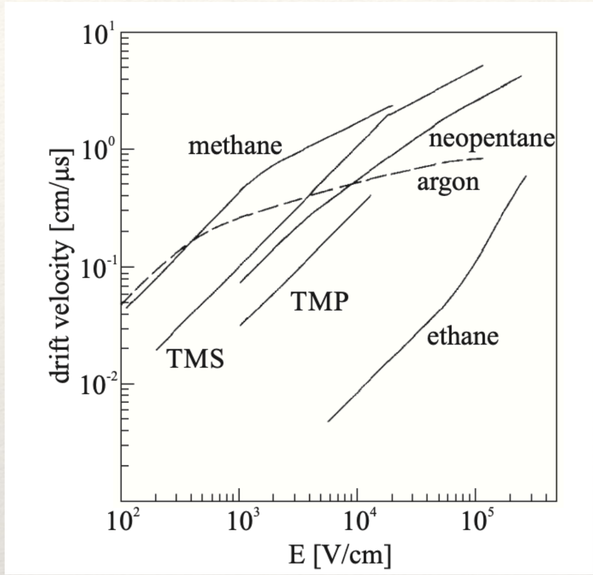
Parameter	Fit Value
α	4.18*(10**22)
β	1.44*(10**115)
γ	4.06*(10**106)
δ	4.18*(10**21)
ε	6.82*(10**17)
N (cm^{-3})	8.6266e+19



Drift velocity in Liquid Xenon



- **Non-trivial relationship** between **p,T** and **drift velocity** in LXe
- More complex as we can't ignore the impact of "space charge" - particle interactions more complex
- Empirically defined due to the above but functional form is consistent with **Cohen-Lekner's theory of two free mean paths**
  - **Energy transfer Λ_0** (molecule structure-independent)
  - **Momentum transfer Λ_1** (structure-dependent therefore field-dependent)



Electron loss

- Electron attachment rate to various impurities was measured by Bakale et al. - usually given in Oxygen equiv.
- Attachment rate depends on both the type of electronegative and on the drift field strength

$$\tau \simeq \frac{300}{[O_2]\ (\text{ppb})} \mu\text{s}.$$

for Argon

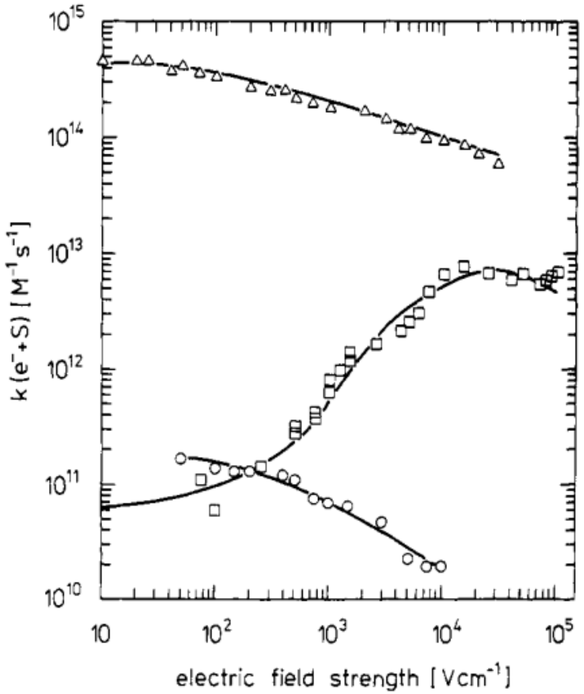
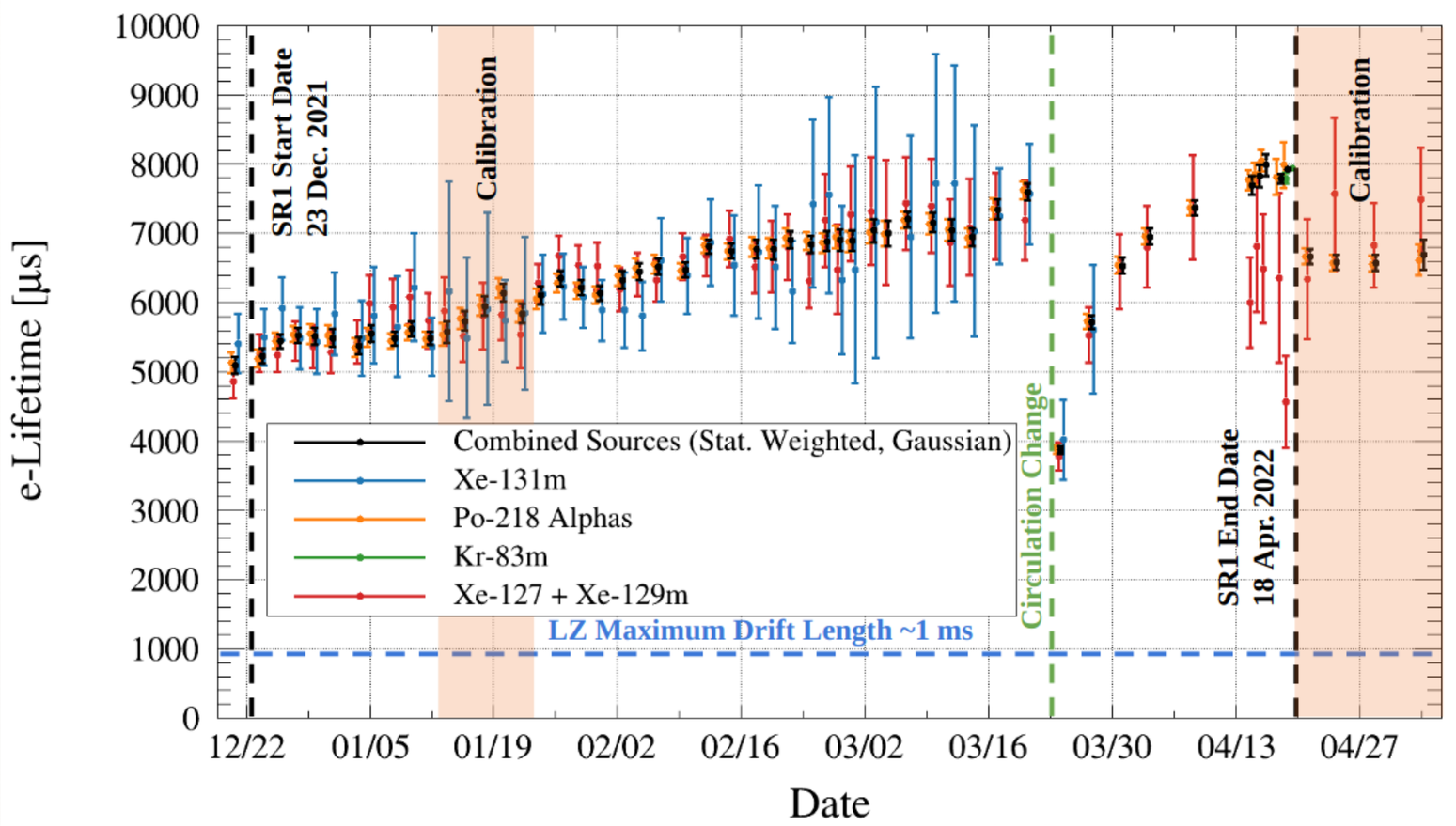


Figure 2. Rate constant for the attachment of electrons in liquid xenon (T = 165 K) to several solutes: (△) SF_6, (□) N_2O, (○) O_2. The solid line through the N_2O data corresponds to the cross section of Figure 4. The solid line through the SF_6 data corresponds to a $\sigma \propto v^{-2}$ dependence.

Electron Lifetime



LZ SR1 electron lifetime

Attenuation length λ is defined as the distance traveled d needed to have 1/e surviving electrons:

$$N_{e^-}(d) = N_{e^-}(0)e^{\left(\frac{-d}{\lambda}\right)}$$

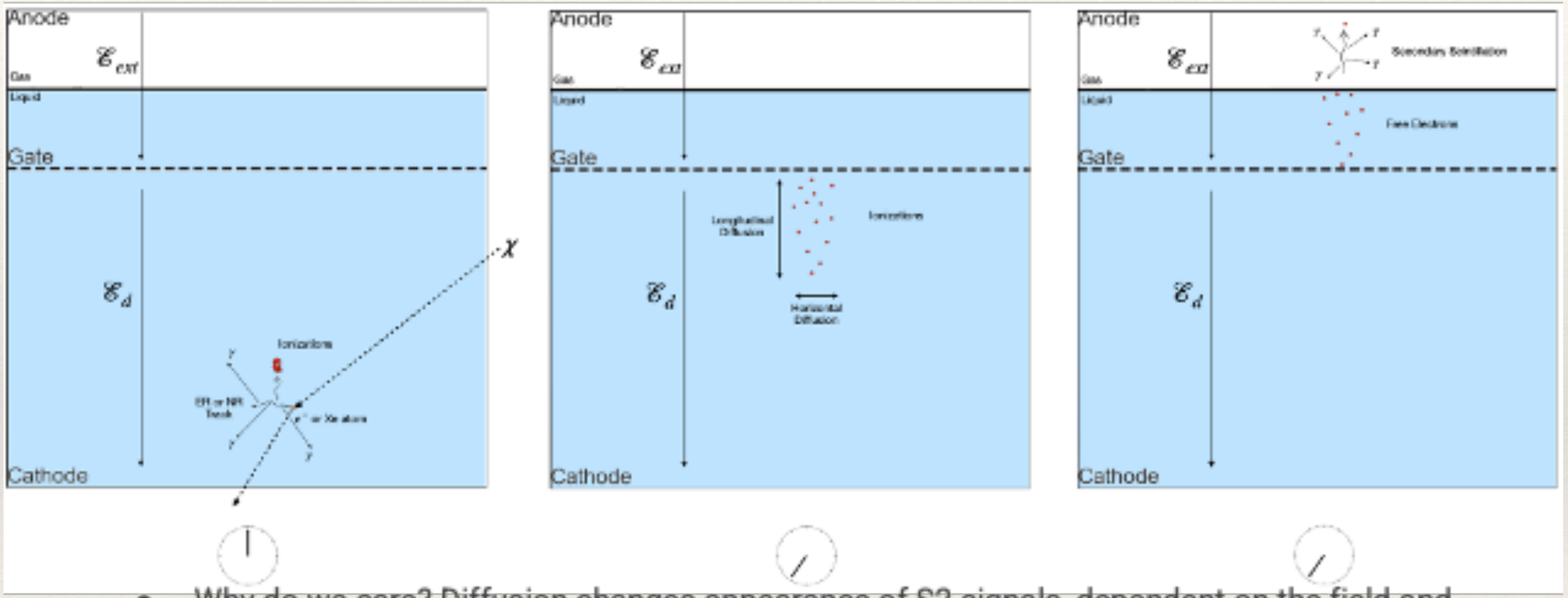
Electron lifetime τ is calculated by dividing the electron attenuation length by electron drift velocity v_d:

$$\tau = \frac{\lambda}{v_d}$$

Understanding diffusion

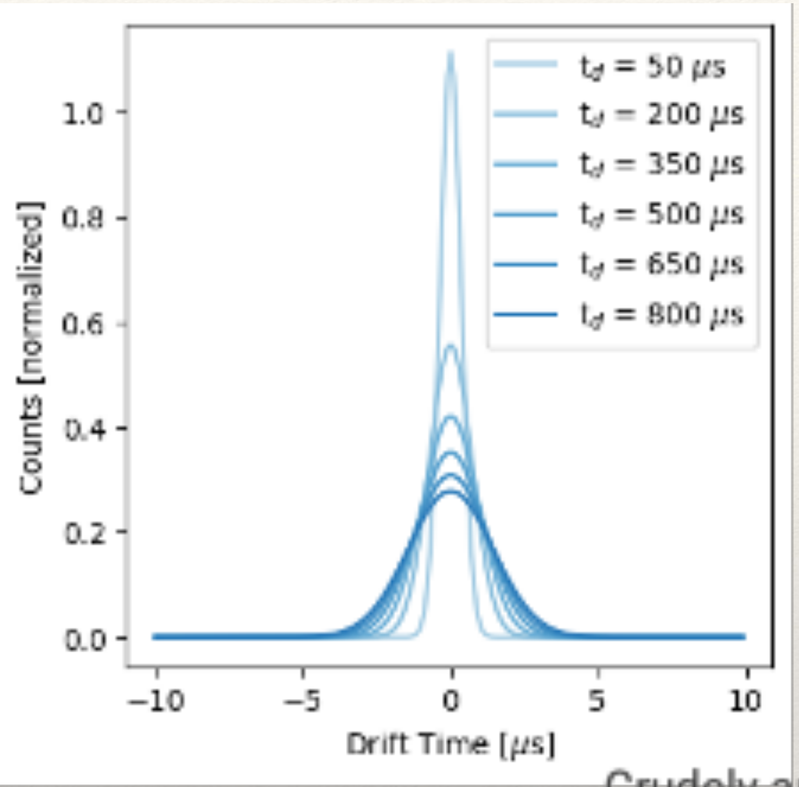
Diffusion and Dispersion

- The diffusion of electrons after drifting in LXe can be described by a Gaussian distribution [PhysRev.181.290]



- Why do we care? Diffusion changes appearance of S2 signals, dependent on the field and the drift velocity (and pressure, temperature, etc.)

Diffusion in LXe



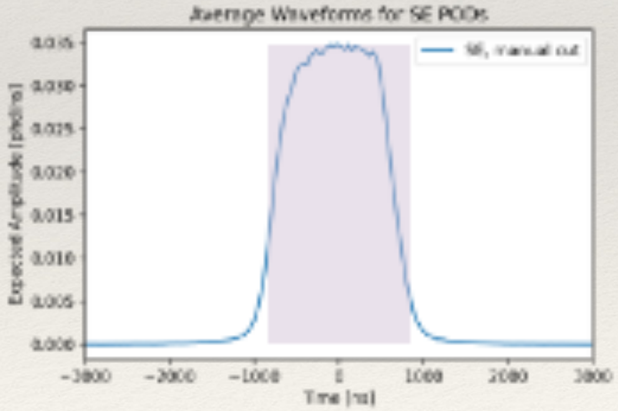
- The diffusion of electrons after drifting in LXe can be described by a Gaussian distribution [PhysRev.181.290]
  - Clear drift time dependence expected
- But even a single electron does not provide a point-like signal
  - Often modelled as an empirical function as in XENONnT:

$$\frac{dN_{ph}}{dz} = \left(a \frac{\mathcal{E}_{mult}(z)}{P} + b \right) P,$$

- Final S2 signal is a convolution of SE response and gaussian smearing due to diffusion

Crudely approximate SE response as a boxcar distribution for the next derivation

- Boxcar: Proportional scintillation in ~ mm gap of gaseous xenon under high E field with ~flat probability per unit path length.



Signal spread by diffusion

Describing Longitudinal Diffusion

- Start with point-like emission at t=0 of n_0 electrons
- Time evolution of n electrons (no transverse effects):

Gaussian $$n = \frac{n_0}{\sqrt{4\pi D_L t}} \exp\left(\frac{-z^2}{4D_L t}\right).$$

- Mean square displacement

$$\sqrt{\overline{z^2}} \equiv \sigma_z = \left(\frac{1}{n_0}\int_{-\infty}^{+\infty} n z^2 dz\right)^{1/2} \longrightarrow \sigma_z = \sqrt{2D_L t}.$$

- S2 = Gaussian diffusion x boxcar (approx) SE response
  - σ_0 boxcar standard dev
  - σ_e is the S2 pulse width
  - $\sigma_t = \sigma_z / v_d$

$$\sigma_e^2 \simeq \sigma_t^2 + \sigma_0^2 \longrightarrow \sigma_e = \sqrt{\frac{2D_L t}{v_d^2} + \sigma_0^2},$$ boxcar

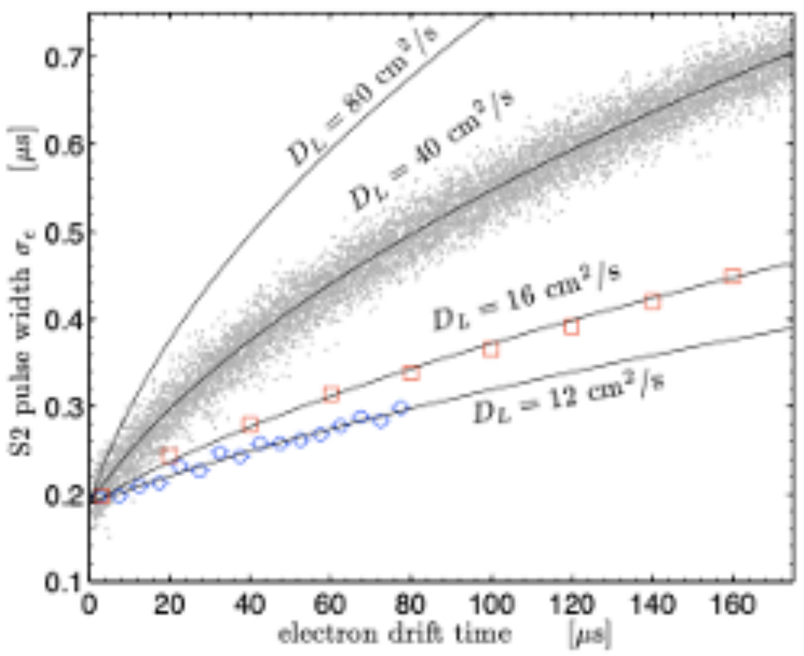


Figure 2: Width of S2 pulses as a function of drift time through liquid xenon. Measurements from XENON10 [9] at E_d = 730 V/cm and v_d = 0.188 cm/μs (circles, 1σ error smaller than data points) and XENON100 [20] at E_d = 530 V/cm and v_d = 0.174 cm/μs (squares). The total drift distance was 15 cm and 30.6 cm, respectively. D_L was obtained from a fit of Eq. 5 in each case. The predicted width vs. drift time for two larger values of D_L are shown, assuming σ_0 = 0.19 μs and v_d = 0.174 cm/μs. A simulated distribution of events with Gaussian width σ = 0.02 μs are shown for D_L = 40 cm^2/s.

As field varies, different values of diffusion coefficient measured (as expected)

Dispersion

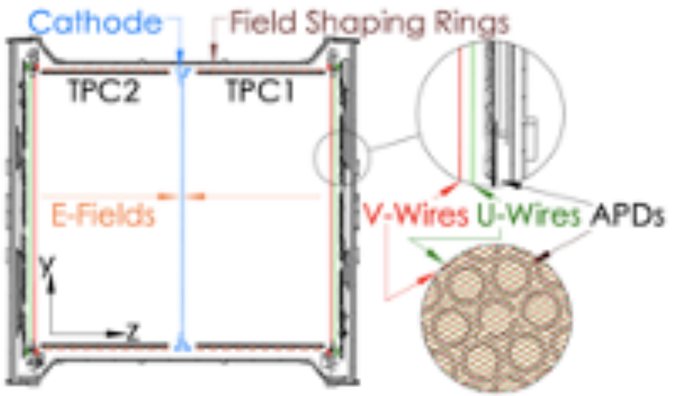
Transverse Diffusion?

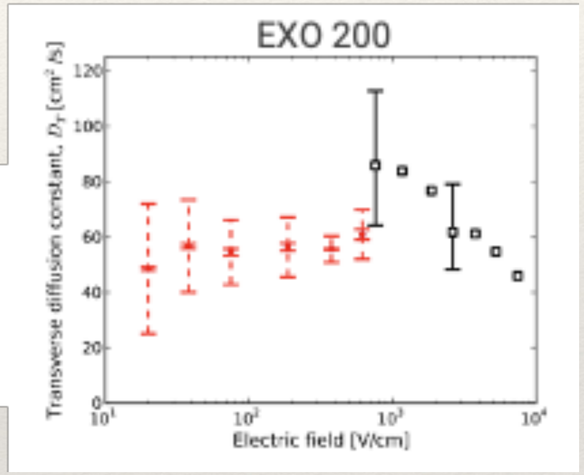
- Diffusion can impact z reconstruction (longitudinal) but also x and y (transverse)
- Can affect multiple scatter rejection if we don't understand this or select fields carefully

$$D_T = \left(\sigma/\sqrt{Z}\right)^2 v_d/2$$

3D diffusion equation in LXe for a charge density of n at time t

$$n(\vec{x},t) = \frac{N}{4\pi D_T t\sqrt{4\pi D_L t}} \exp\left[\frac{-(x^2+y^2)}{4D_T t}\right] \times \exp\left[\frac{-(z-v_d t)^2}{4D_L t}\right] \quad (1)$$





Self-repulsion of charge clouds is ignored in the full simulation (< 3% impact)

LAr drift and diffusion

More generally, the evolution of a macroscopic swarm of electrons produced in a medium is given by Li et al. (2016):

$$n(\rho, z, t) = \frac{n_0}{4\pi D_T t \sqrt{4\pi D_L t}} \exp\left(-\frac{(z - vt)^2}{4D_L t} - \lambda v t\right) \exp\left(-\frac{\rho^2}{4D_T t}\right) \quad (4)$$

where the drift occurs in the z direction. n is the electron charge density distribution at the position (x, y, z) and time t. ρ is the transverse coordinate $\sqrt{x^2 + y^2}$ and λ is the electron mean-free-path in the medium. Note that – unlike an ideal gas – λ depends on electron recombination and secondary ionization. Secondary ionization, i.e. the probability that an electron produces new electrons by inelastic collision with the atoms, is negligible in LAr detectors operated at moderate fields but recombination critically depends on the argon purity. Since the electric field perturbs the electron motion in the z direction only, the transverse mobility is given by the classical Einstein-Smoluchowski formula of the kinetic theory:

$$D_T = \frac{kT}{e}\mu. \quad (5)$$

However, the longitudinal diffusion depends on the change of the mobility due to the electric field:

$$D_L \simeq \frac{kT}{e}\left(\mu + |\mathbf{E}|\frac{\partial \mu}{\partial |\mathbf{E}|}\right). \quad (6)$$

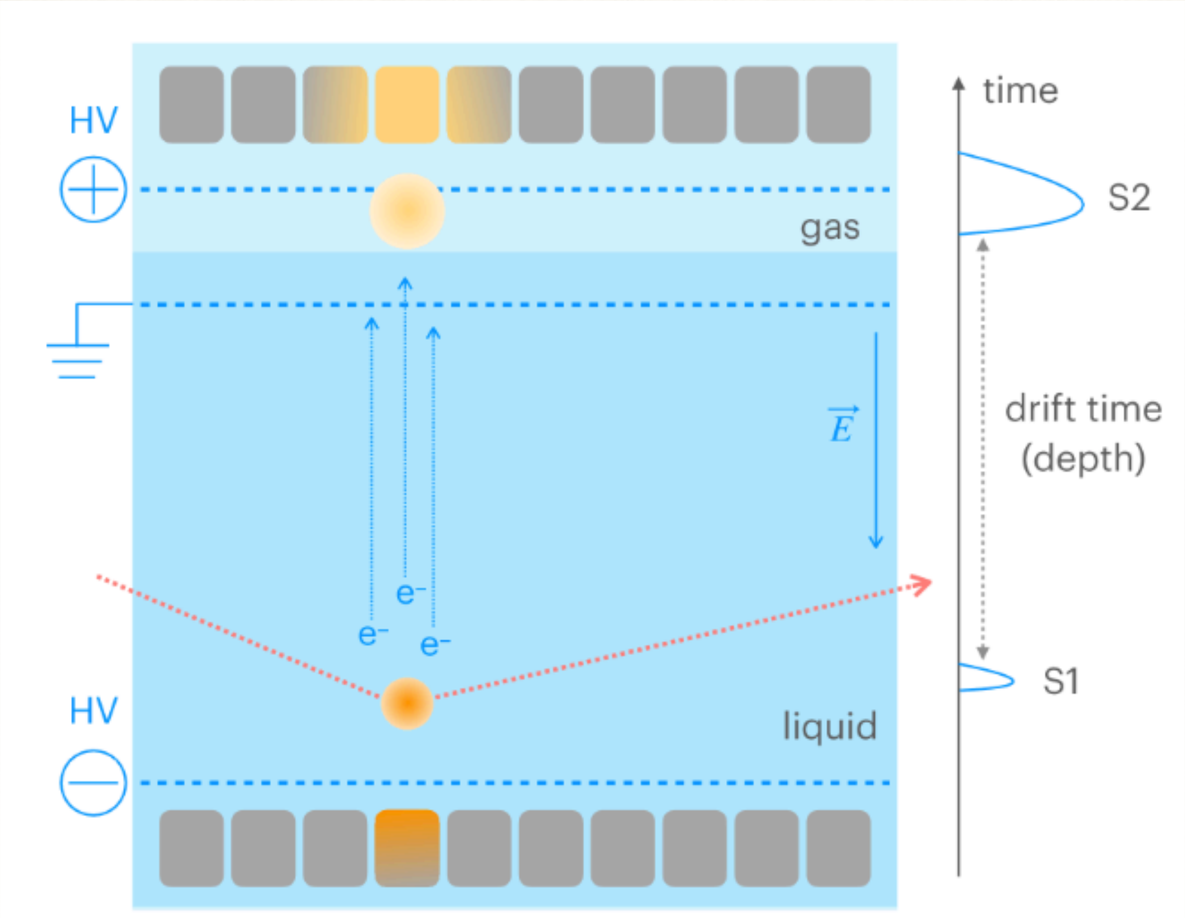
Property	Value
Electron mobility μ	320.2272 $cm^2\ V^{-1}\ s^{-1}$
Electron drift velocity v	0.1601 cm/μs
Longitudinal diffusion coefficient D_L	6.6270 cm^2/s
Transverse diffusion coefficient D_T	13.2327 cm^2/s
Attachment rate constant (O_2) k_A	$3.3410 \times 10^{12}\ s^{-1}$
Electron lifetime (for 0.1 ppb O_2)	τ=2.9931 ms

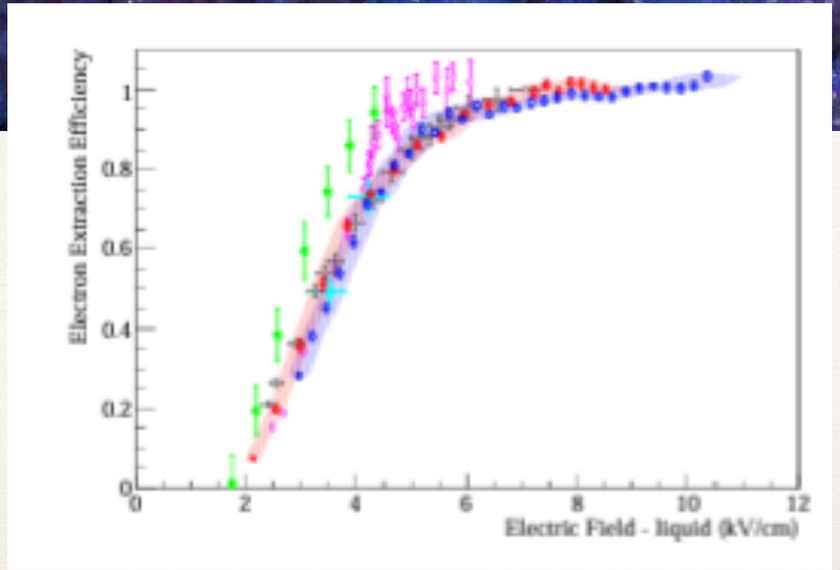
Table 3: Drift and diffusion parameters of liquid argon at $|\mathbf{E}| = 500$ V/cm and $T = 87$ K Li et al. (2016). See also `https://lar.bnl.gov/properties/`.

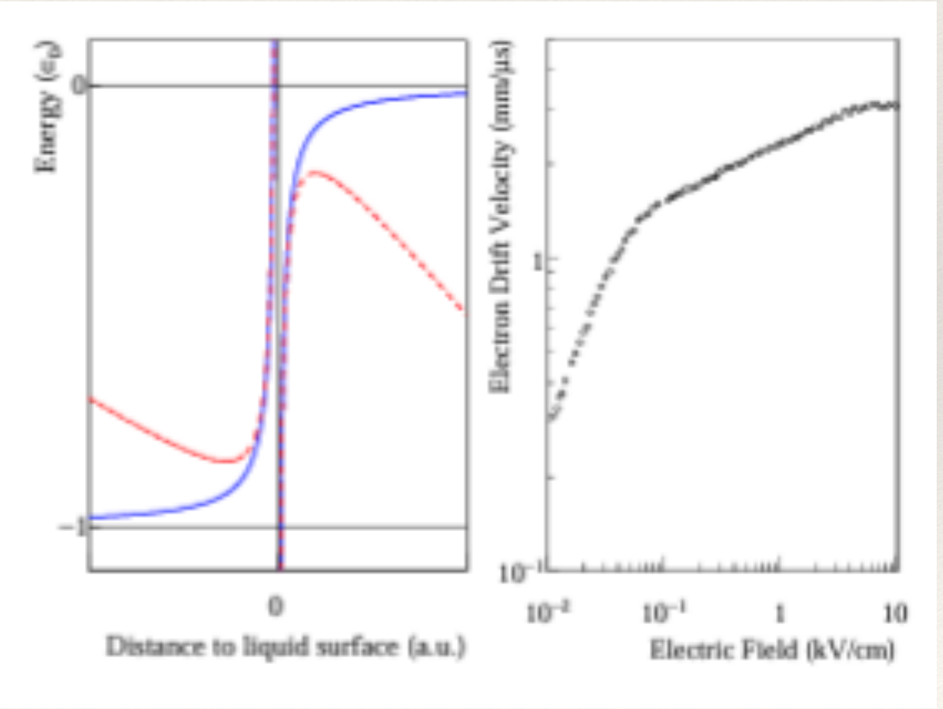
TPC charge readout

Charge detection

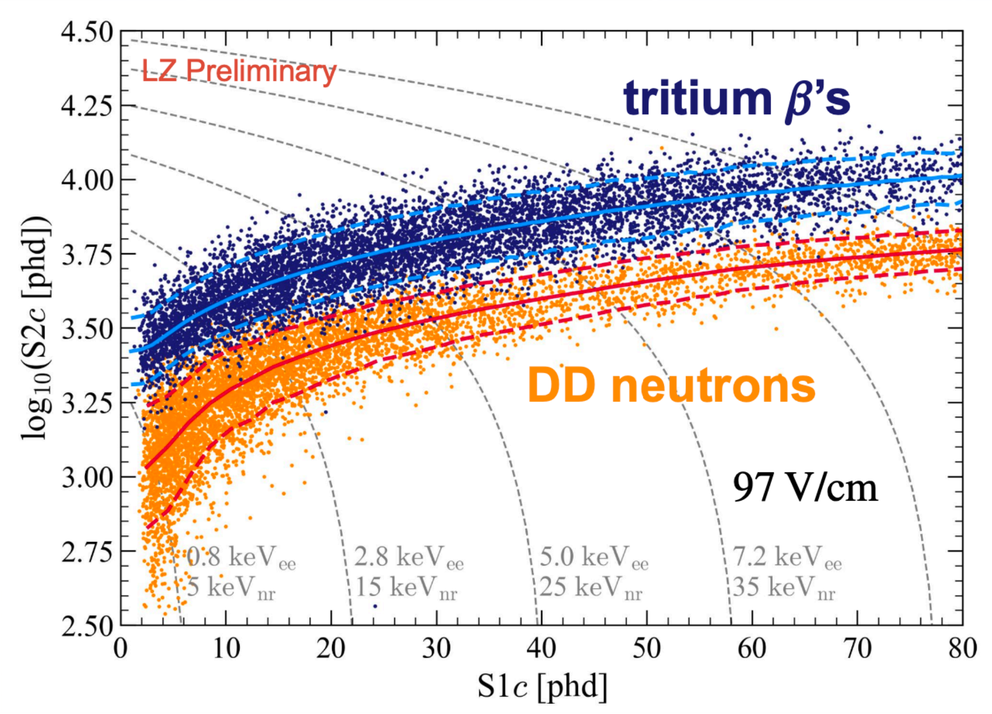
- Extract into gas, then electroluminescence

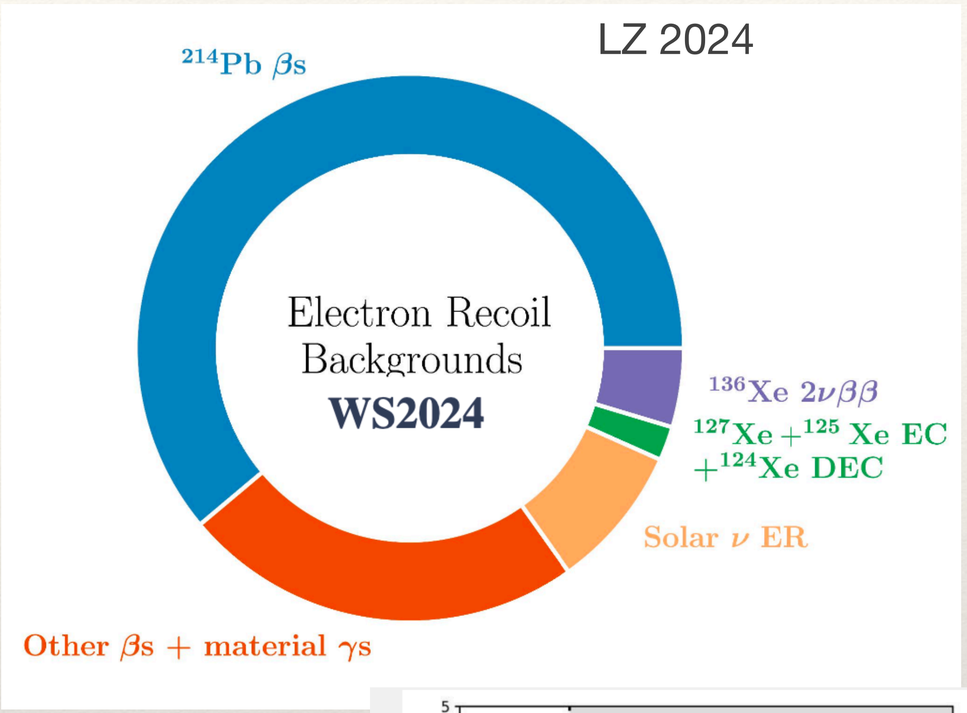






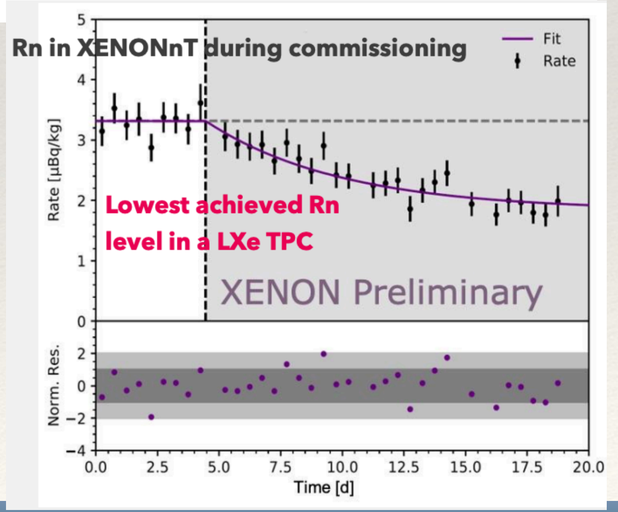
Calibrations and Backgrounds



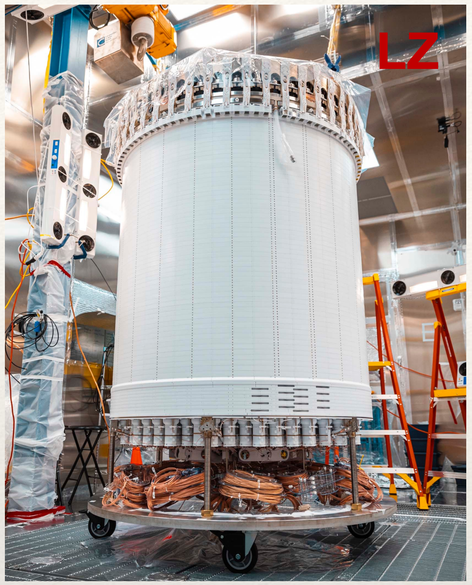


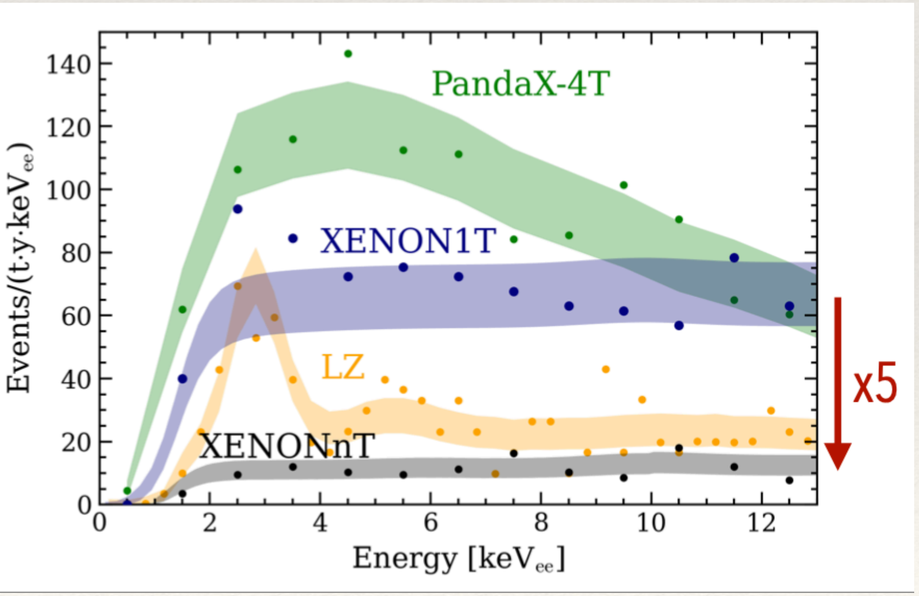
- Calibrations include:
  - injected sources that either decay away, or can be removed by pruification or distillation methods
  - external gamma sources
  - neutron sources: photoneutron, radiogenic, D–D generators

- Backgrounds:
  - Electronic recoils:
    - from Rn biggest issue, but XENONnT has shown that can be controlled
  - Nuclear recoils: seeing neutrinos, neutrons from materials



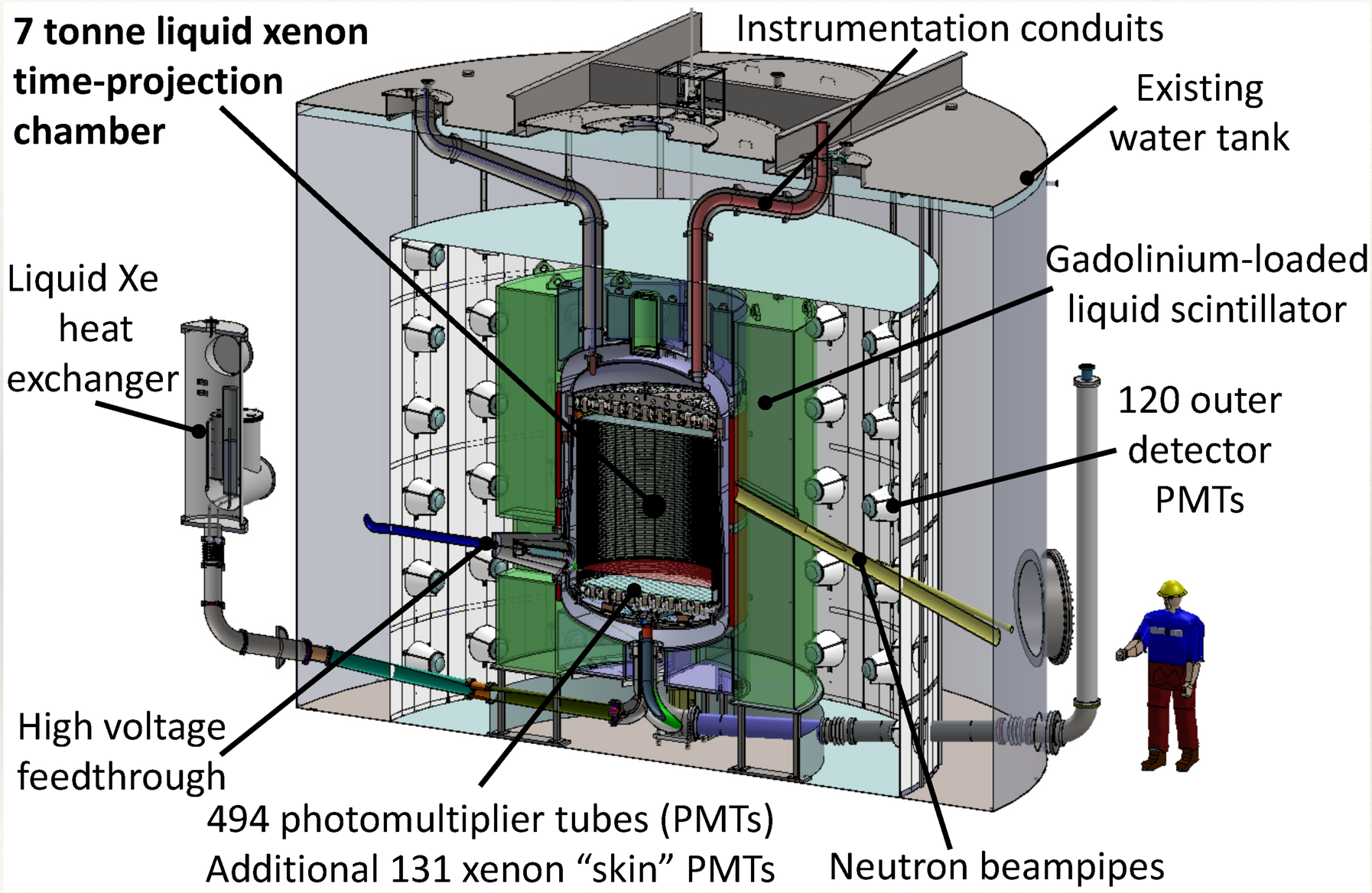
Running Xenon Experiments





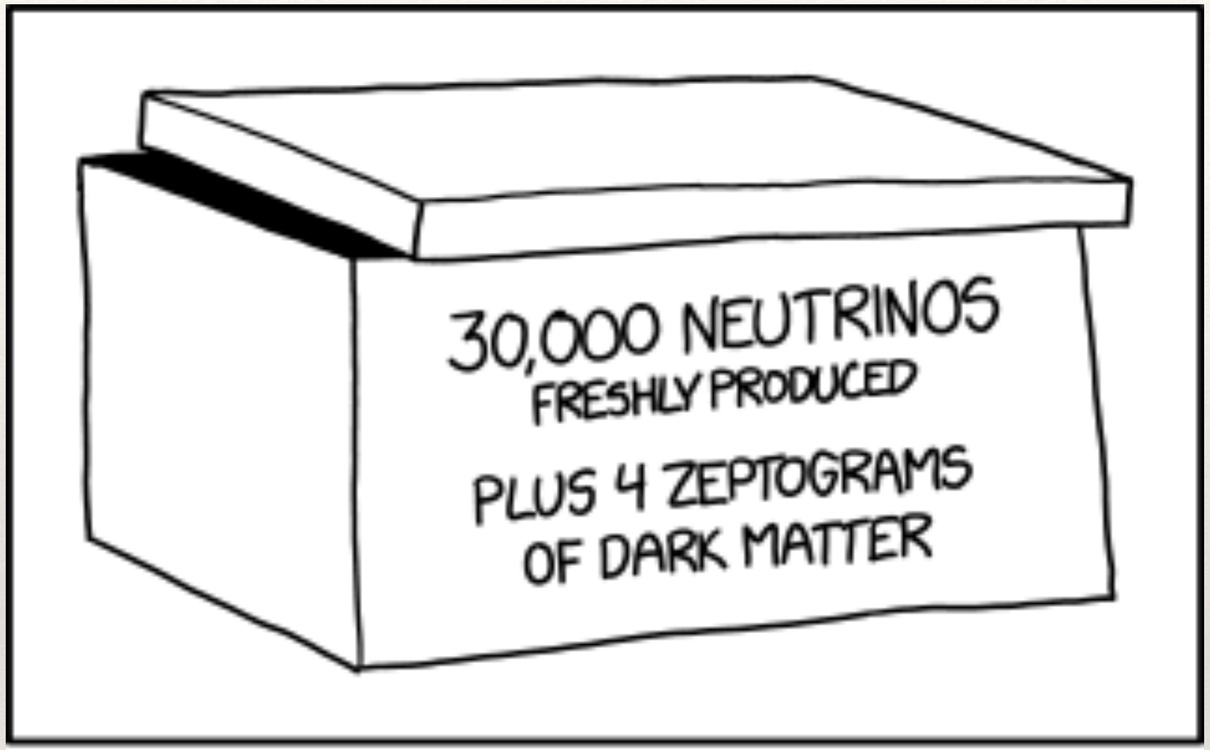
- 3 running experiments that will continue ~3 years
- World leading sensitivity
- Continuing their understanding of xenon microphysics
- Science also with electronic recoils, effective field theory models, MIMPs, 0vbb and double electron capture, solar neutrinos, ….

LZ design, highlighting subsystems



- Light collection
- High Voltage
- Calibration
- Circulation
- Vetoes
- Shielding

The Future

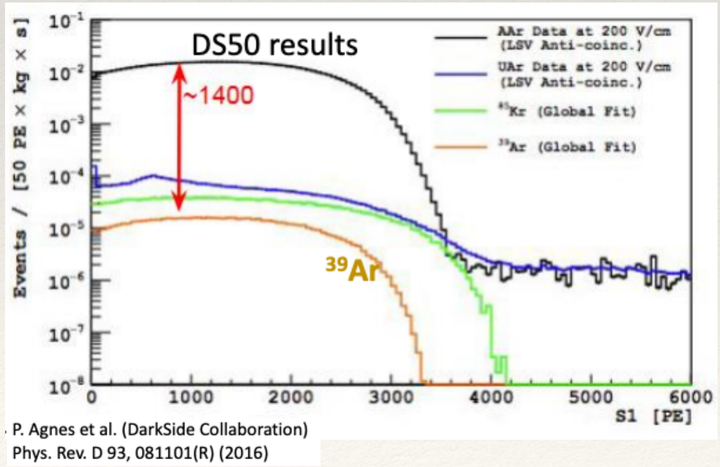


COSMOLOGISTS ARE EASY TO SHOP FOR
BECAUSE YOU CAN JUST GET THEM A BOX.

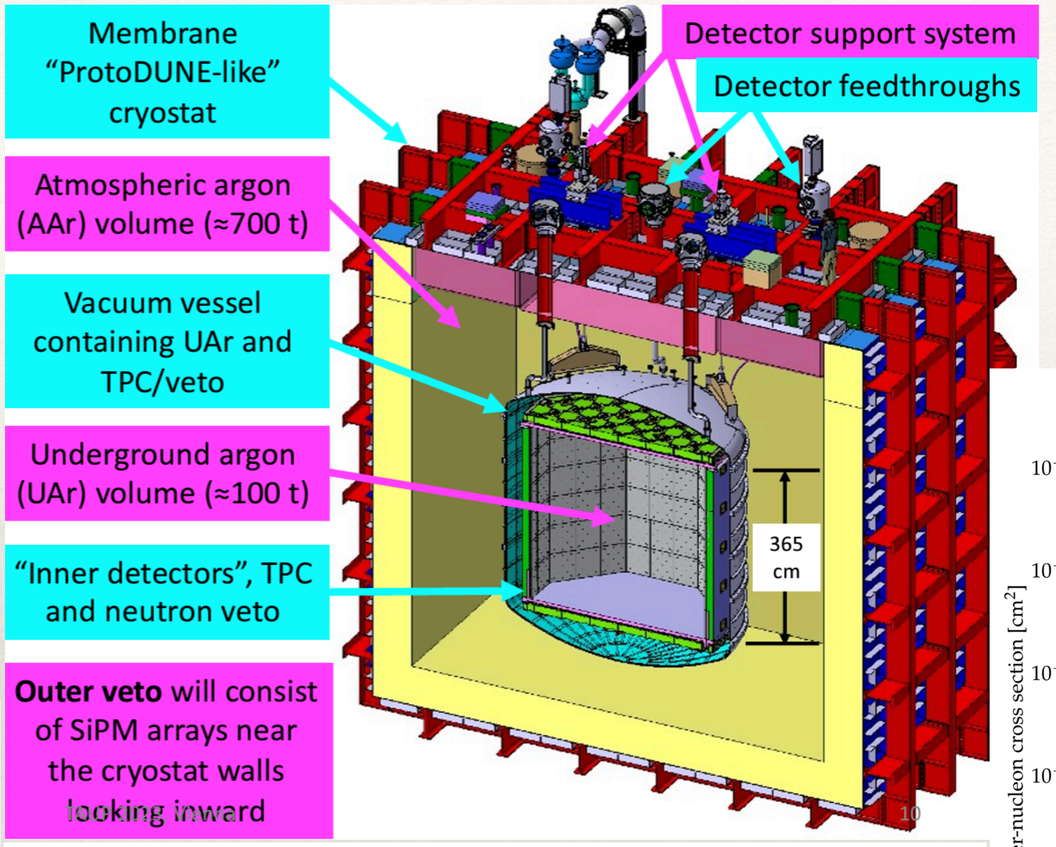
But particle astrophysicists want DETECTORS to find Dark Matter

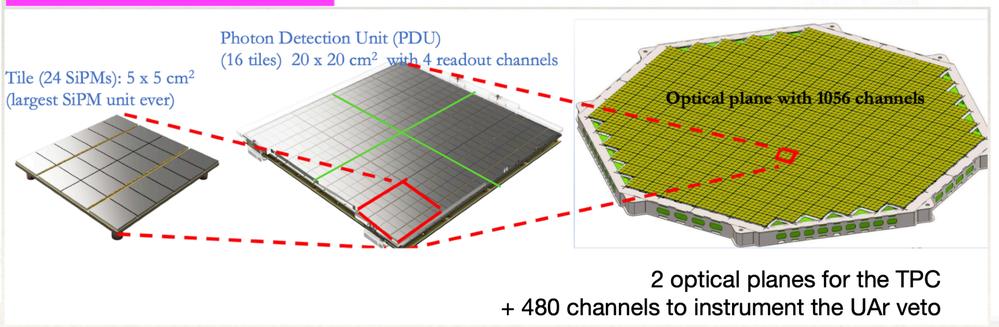
Argon Experiments

- Single phase DEAP-3600 underwent hardware upgrades
- DarkSide-20k under construction at LNGS, data taking expected to start in 2027
  - Technology advances in SiPMs, Gd-loaded acrylic, Ar distillation



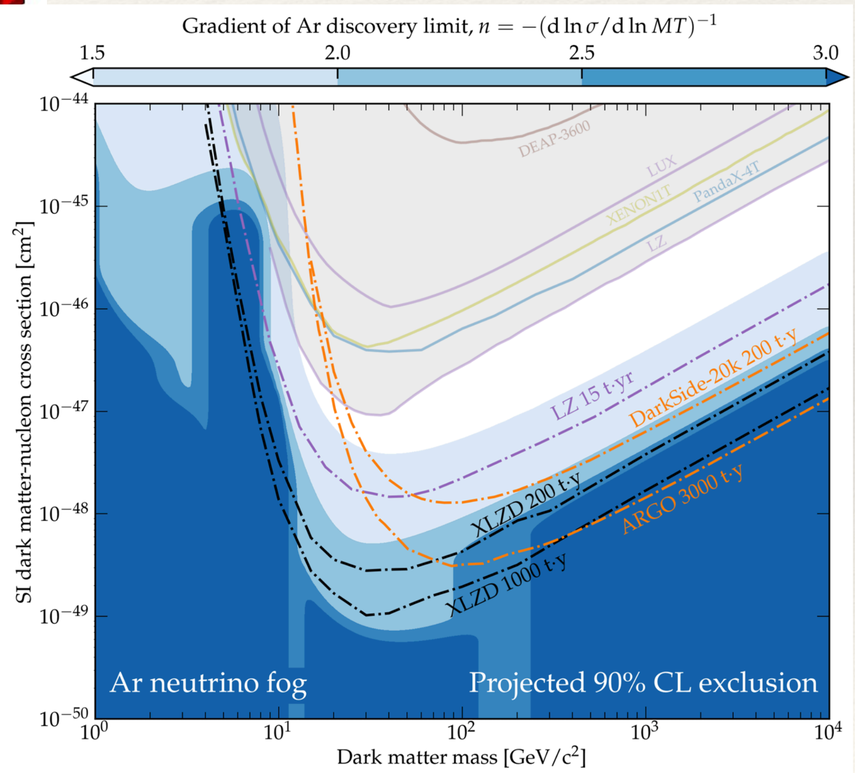
P. Agnes et al. (DarkSide Collaboration)
Phys. Rev. D 93, 081101(R) (2016)



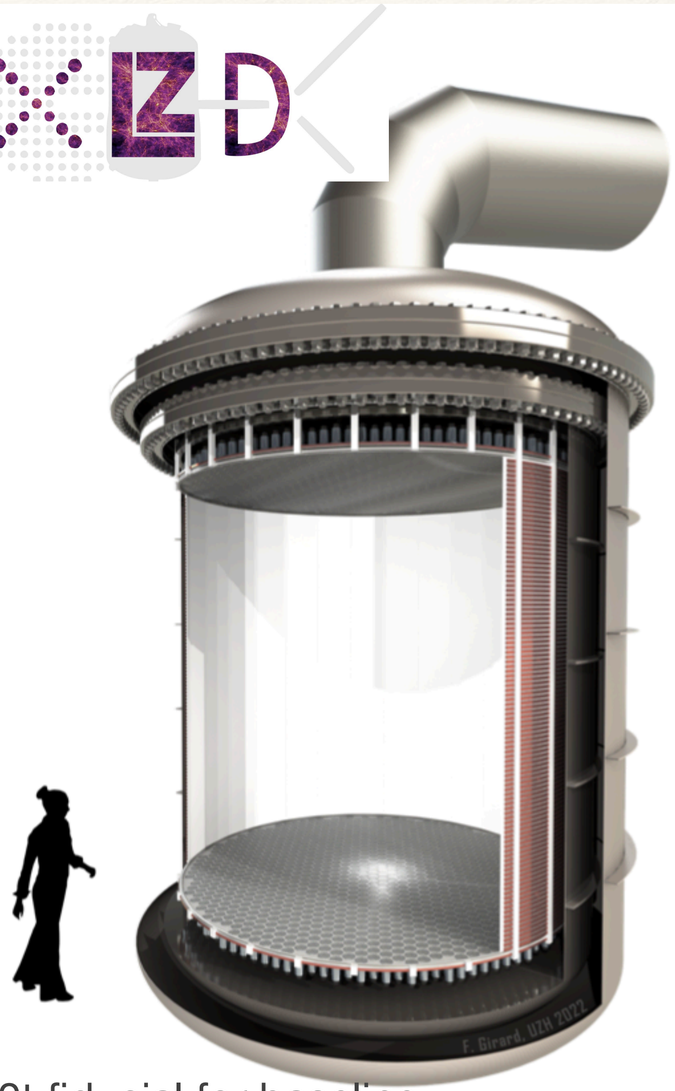


2 optical planes for the TPC
+ 480 channels to instrument the UAr veto

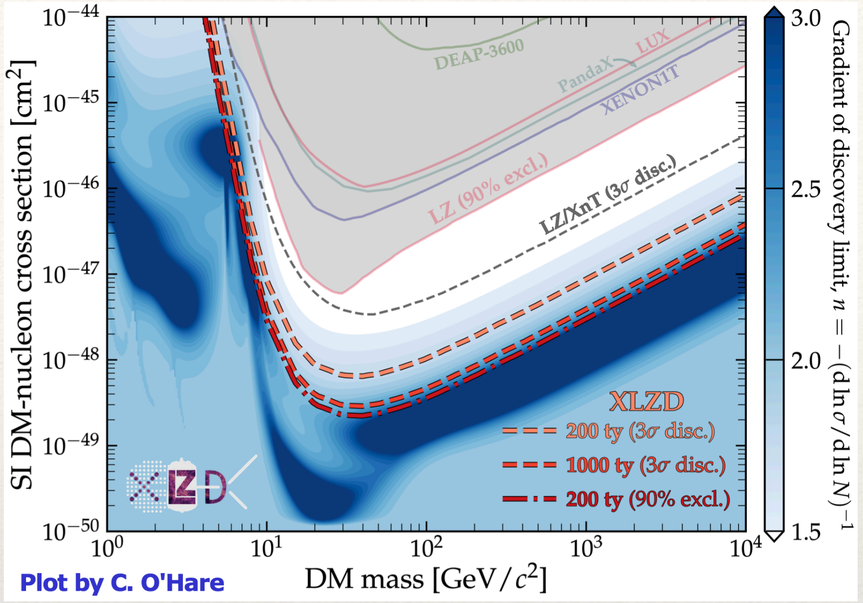
- Future ARGO detector to get to neutrino fog, 300t fiducial, 2035?
  - UAr in demand by other projects too (LEGEND, DUNE, COHERENT)

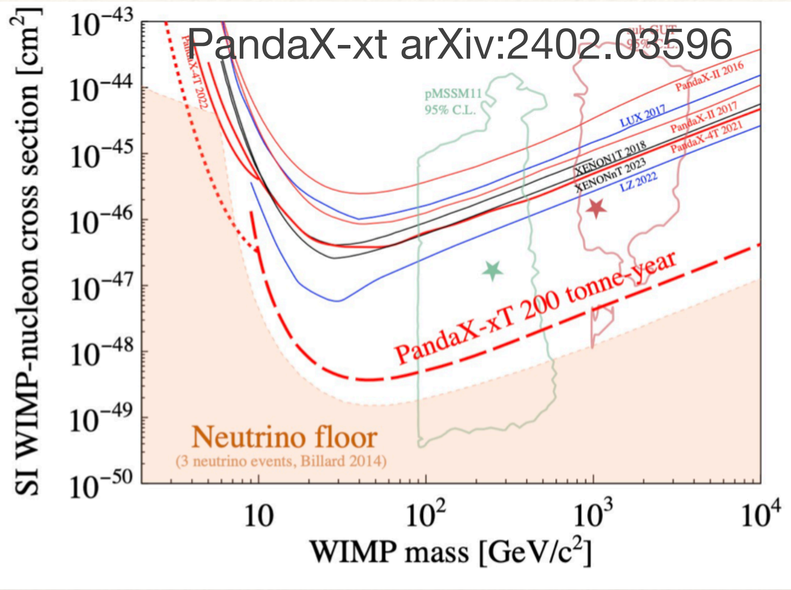


Future Xenon Experiments

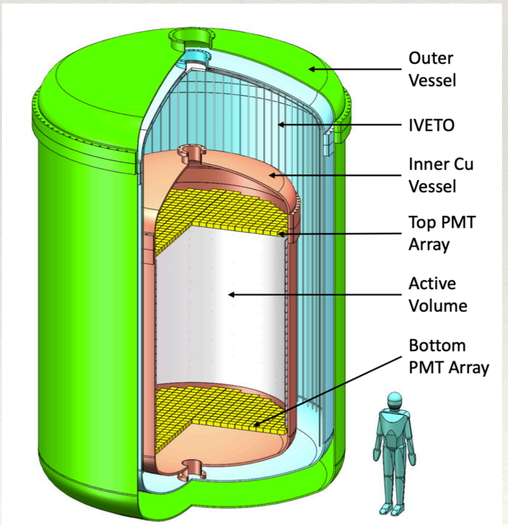


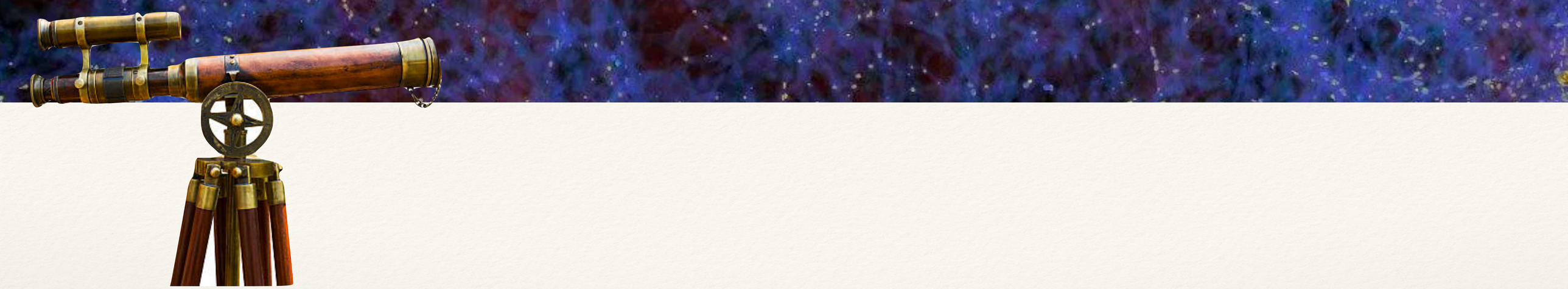
60t fiducial for baseline





- XLZD: XENON, LZ (LUX-ZEPLIN), DARWIN
  - 60t fiducial baseline detector, with early science with initial xenon, starting ~2032
- PandaX-xt
  - staged growth of PandaX-4t to 20t (operations in 2028) and final >40t fiducial, most infrastructure in place

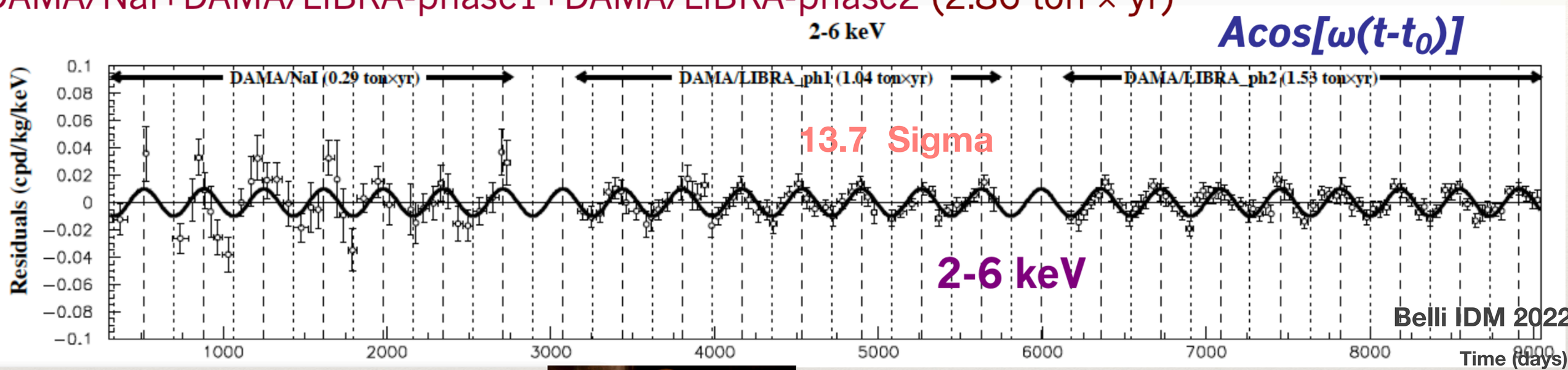




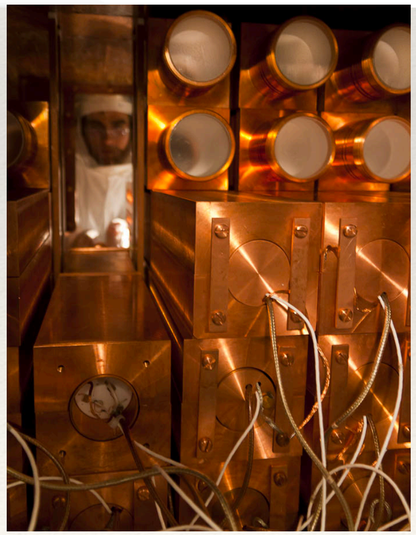
We will have definitive refutation (or confirmation) of the DAMA/LIBRA signal in NaI soon.

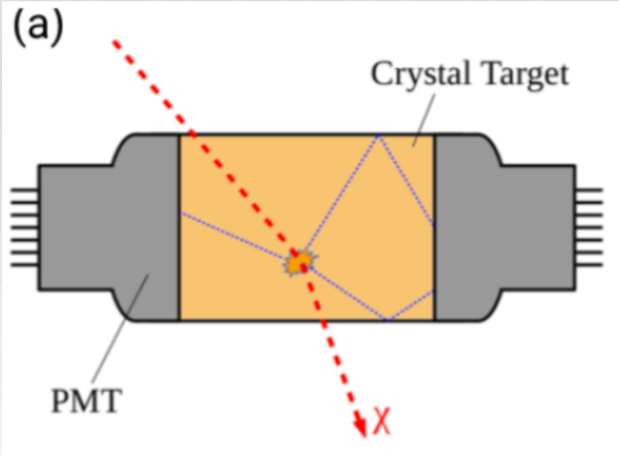
NaI crystals: DAMA/LIBRA signal

DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr)

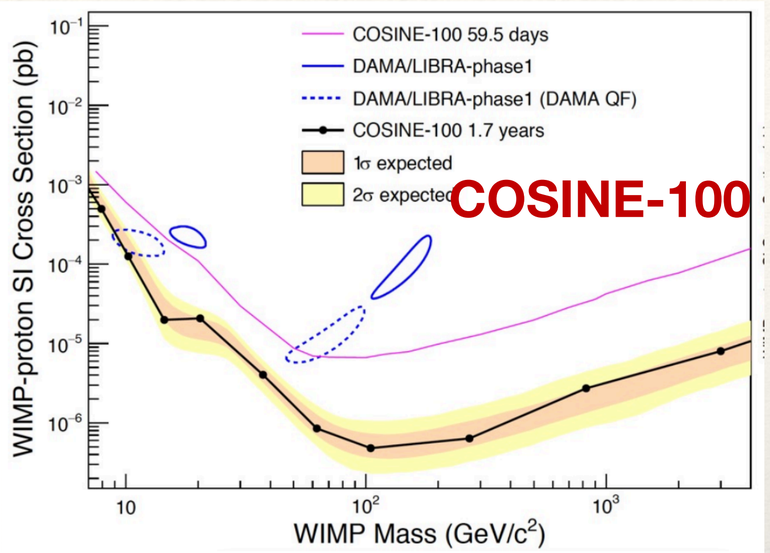


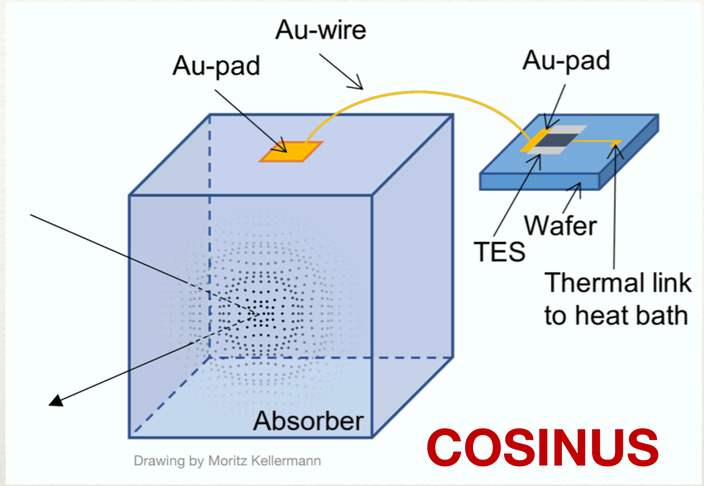
- Annual Modulation seen at $>13\sigma$
- Not SI isospin-conserving
- Isospin-violating SI at ~10 GeV/c^2,
  - or SD at 10 or 45 GeV/c^2
- Also studied with updated quenching





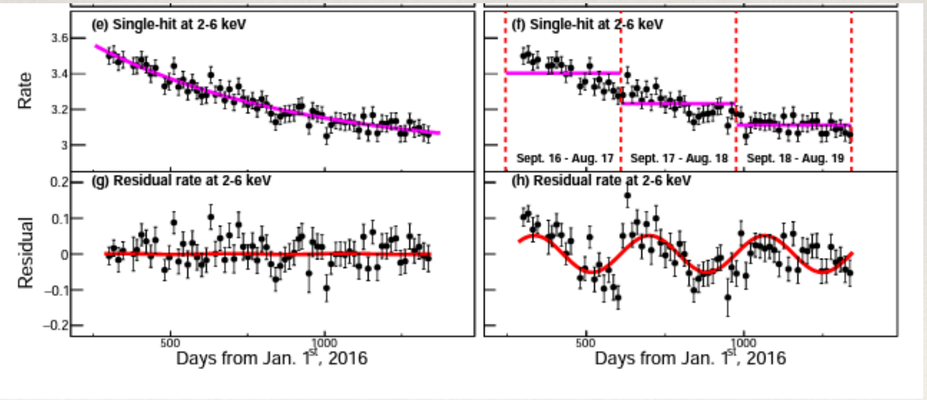
NaI tests: ongoing and future

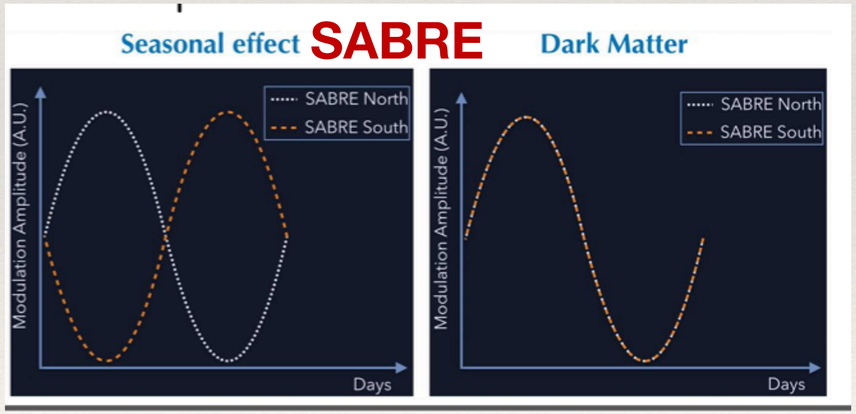


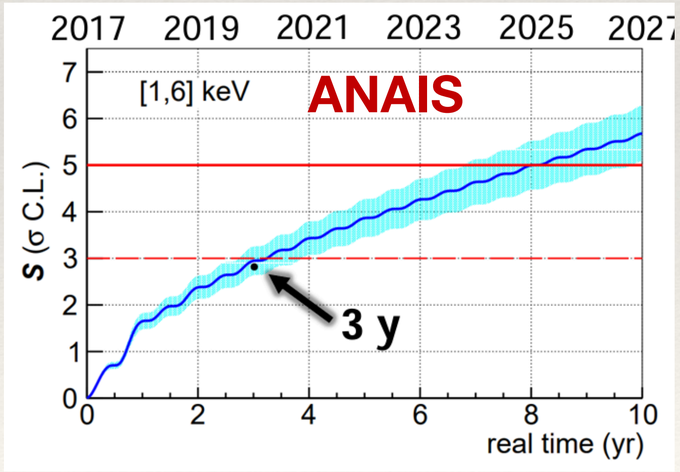


- Multiple NaI detectors - we'd like to know the cause of the modulation, not just rule out DM.
- ANAIS-112, running, could be on track for 5 σ rejection of DAMA by 2025.
- COSINE saw that how calibrations are handled can induce a modulation of residuals, Moved lab in 2023.
- COSINUS cryogenic search with discrimination, starting this year.
- SABRE: low bkgd crystals, with Northern and Southern sites, also starting this year.

SciAdv 7 46 '21



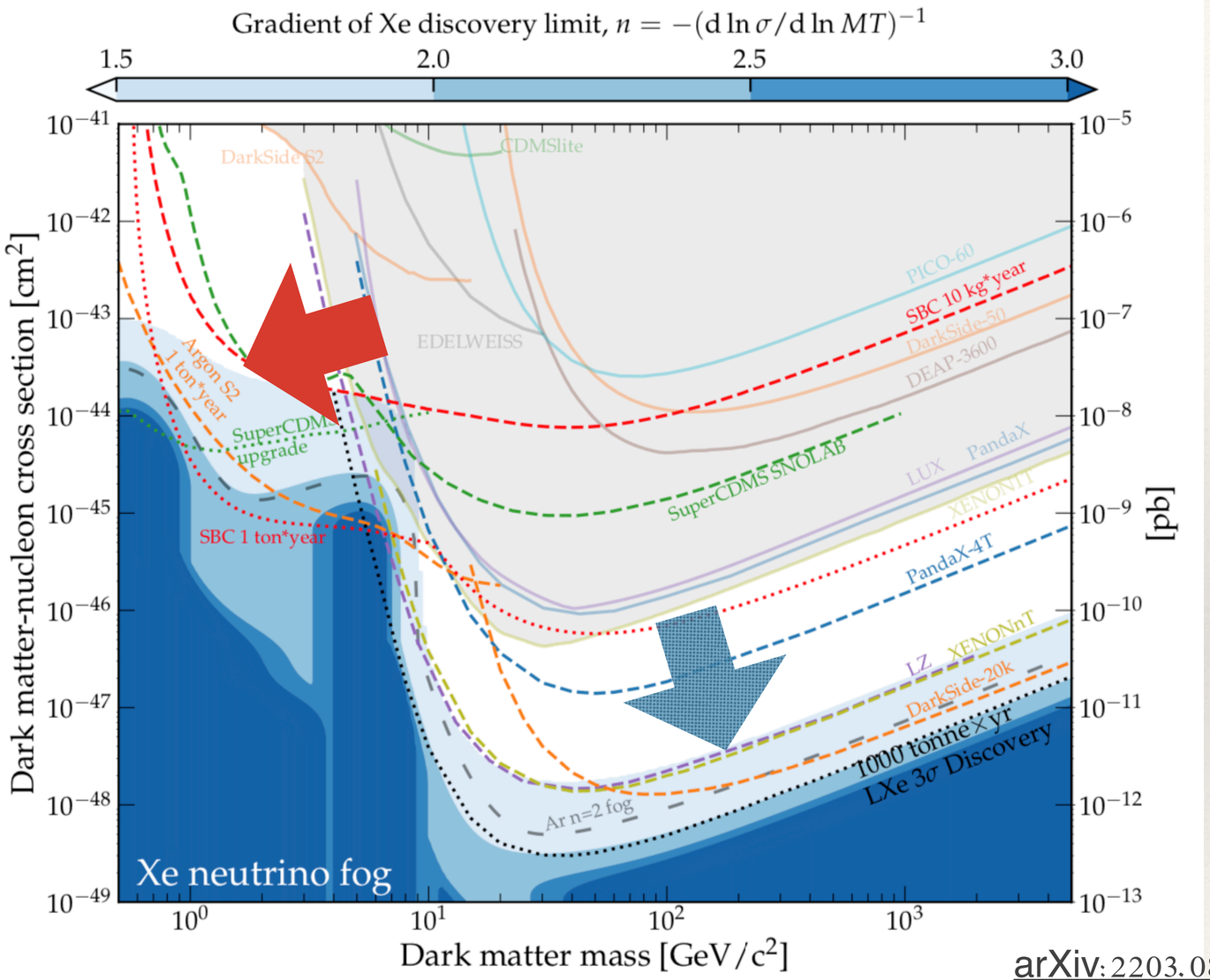




Is it just an analysis artifact? arXiv:2208.05158

For DM masses 1-10 GeV/c^2,
there is a lot of activity!
Timing may be more important than technology.

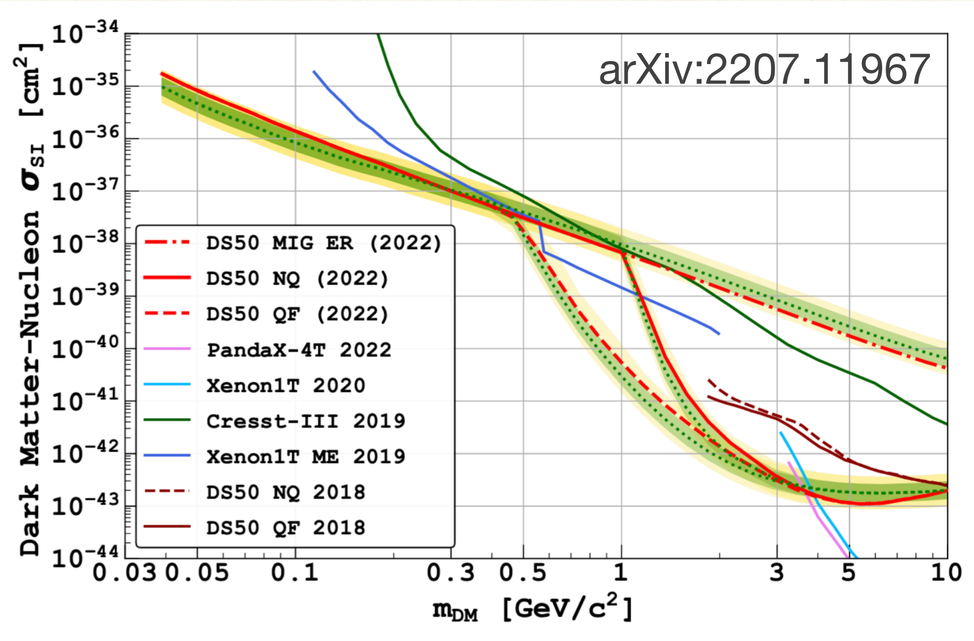
Going to Lower Masses



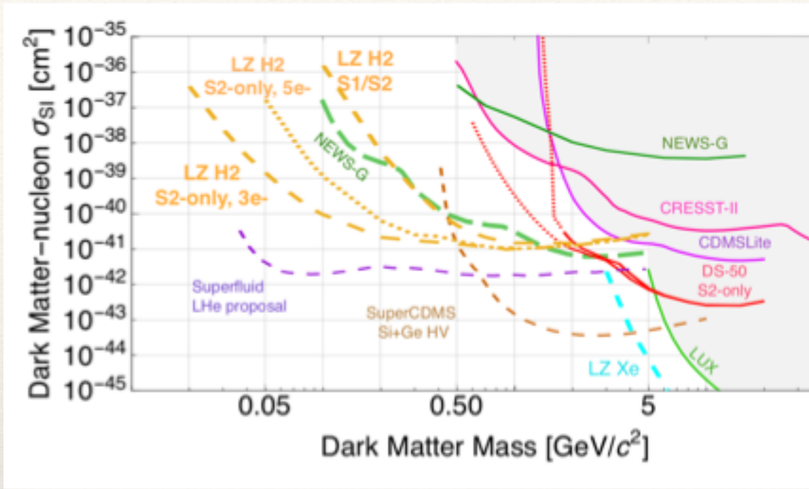
- Lower mass region can be reached by multiple technologies, ones with long histories in the search for dark matter, as well as new.
- Generally smaller target masses (both in total mass, as well as atomic masses), and interest in spin-dependent models too.

arXiv:2203.08084

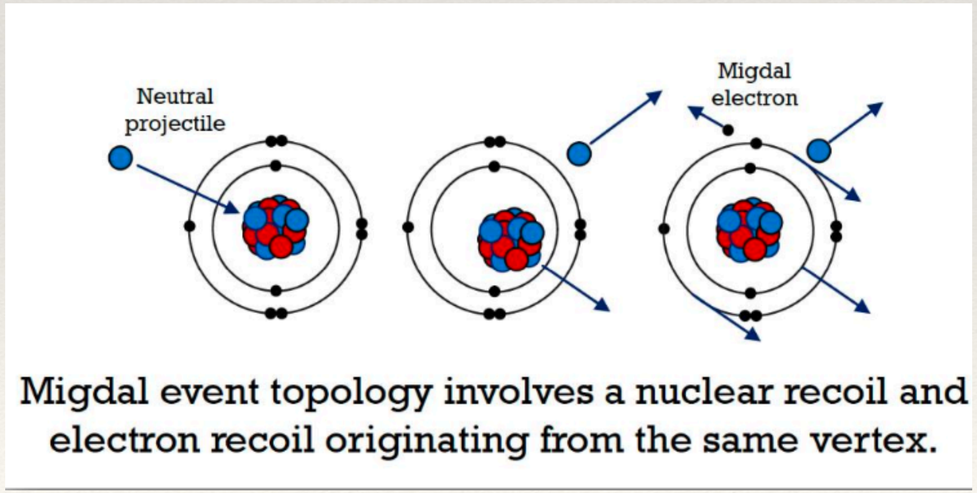
Once more, from the nobles…

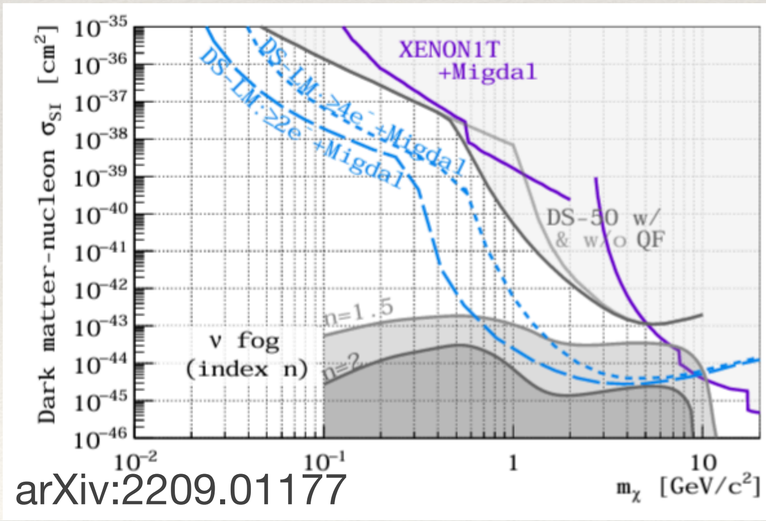


- Future: S2-only searches from current detectors (with Migdal?)
- HydroX
  - Proposed doping of LXe detector with H
- DarkSide-LowMass
  - Proposed 1T detector to get to neutrino fog in 1t-yr exposure



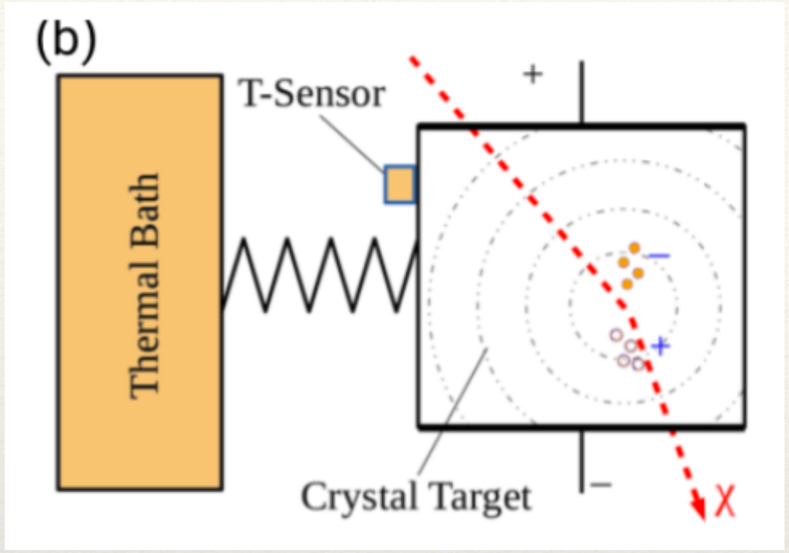
- Leading limits are from DarkSide-50 with a low threshold enabled by ionization only signals (no background discrimination)
- These signals may be enhanced by the Migdal effect, but **this needs to be confirmed**!
- Microphysics uncertainties too

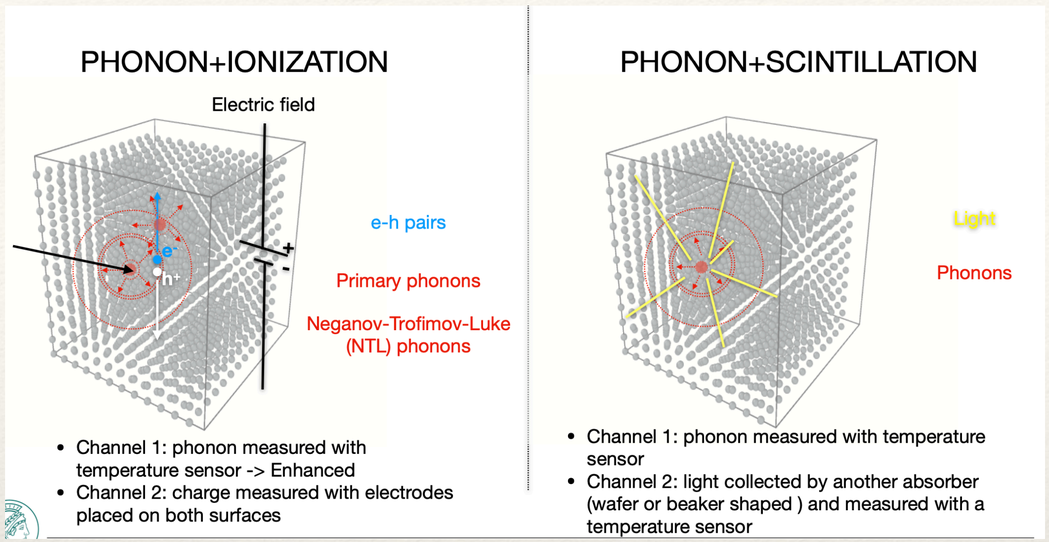


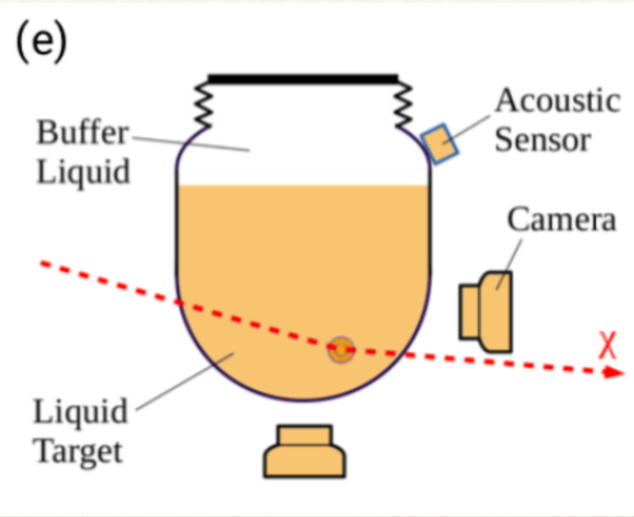


arXiv:2209.01177

Low Mass Dark Matter Search technologies



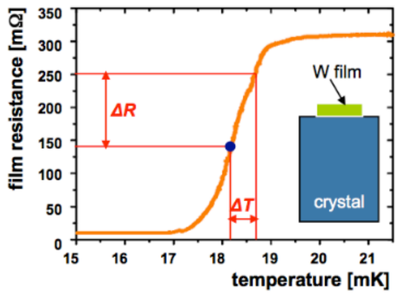


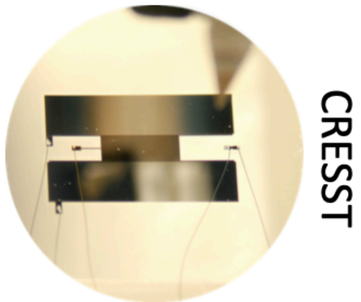


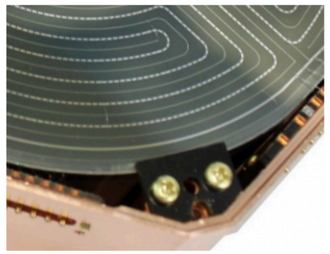
CRESST, SuperCDMS, COSINUS, EDELWEISS NEW

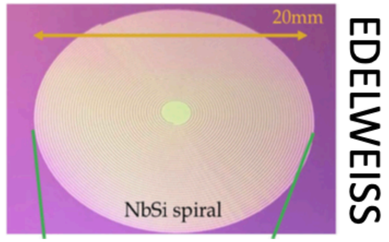
Transition-Edge-Sensor (TES)

- Thin-film deposited on crystals
- Strong R-T dependence at superconducting transition
- Sensitive to athermal phonons



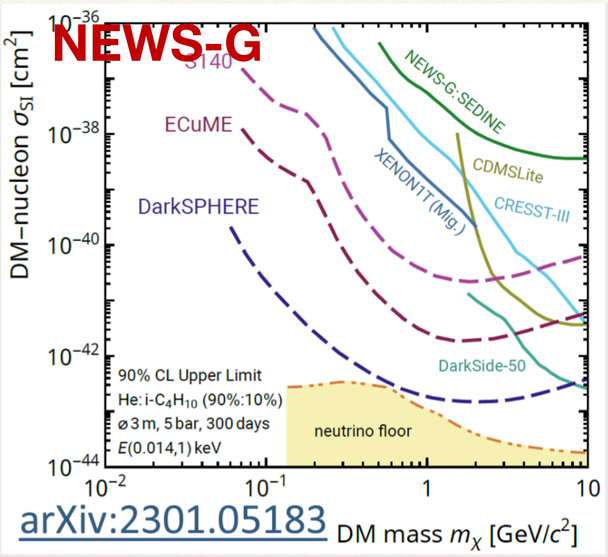




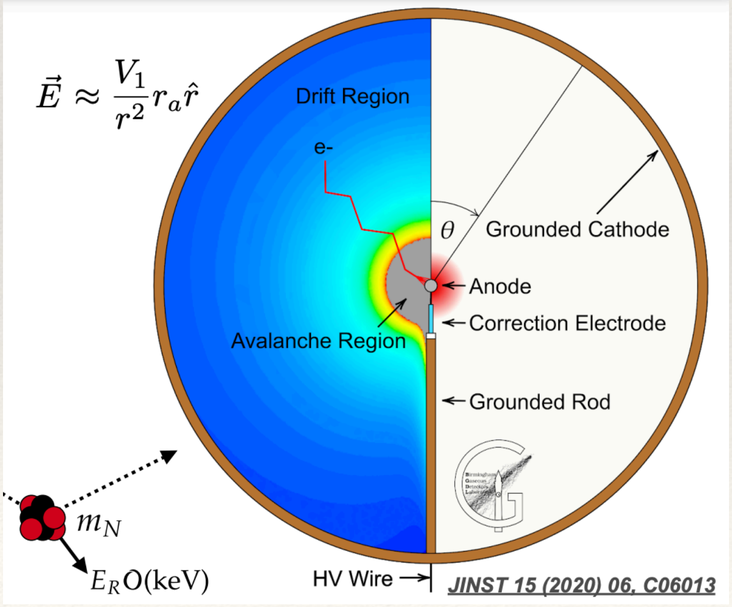


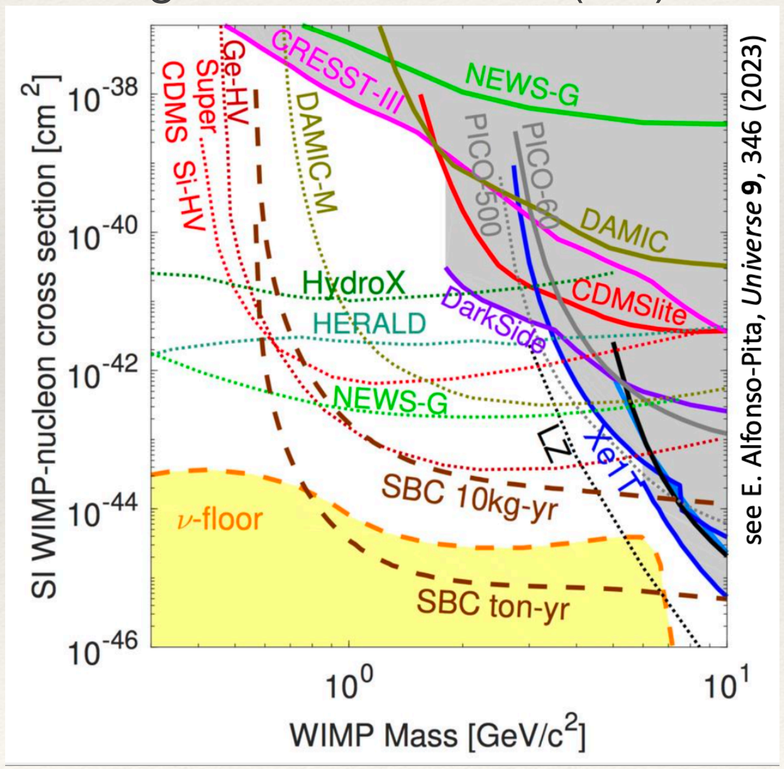
- Bubble chambers have a benefit of being insensitive to electron recoils
  - the dE/dx is too low to nucleate a bubble
  - but need to worry about alphas and neutrons
  - additional acoustic or optical channels help

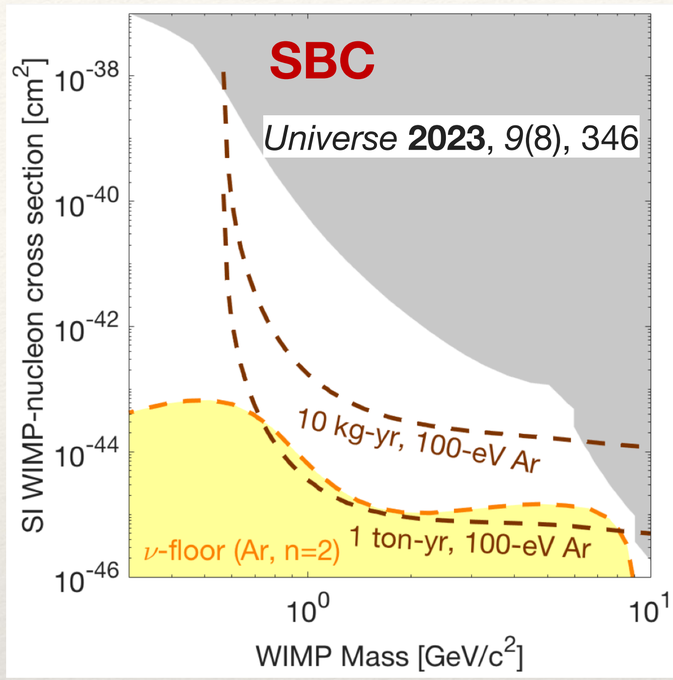
Technologies new and old

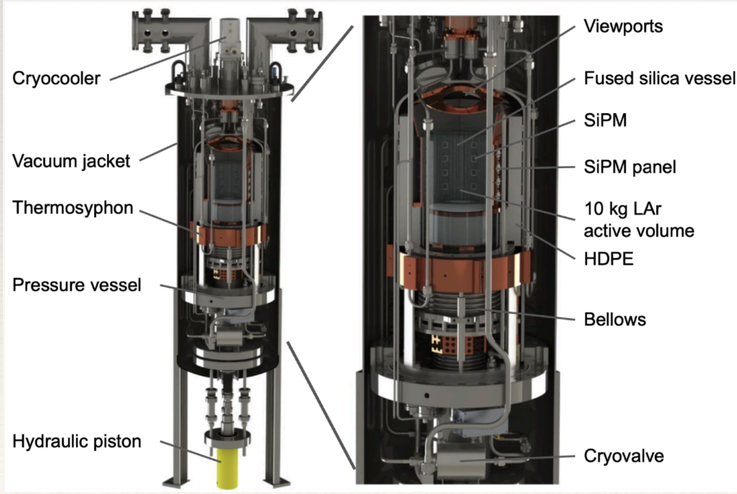


- Signals from nuclear recoils
- Semiconductor targets: Si, Ge
- Scintillating bolometers $CaWO_4$
- Spherical Proportional Counter
- Scintillating Bubble Chamber (LAr)

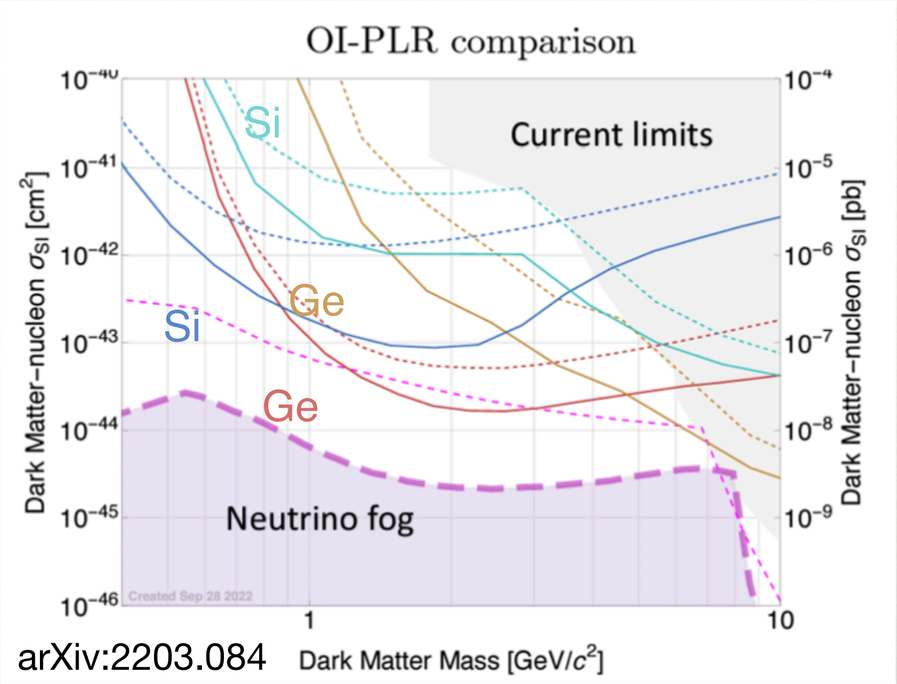






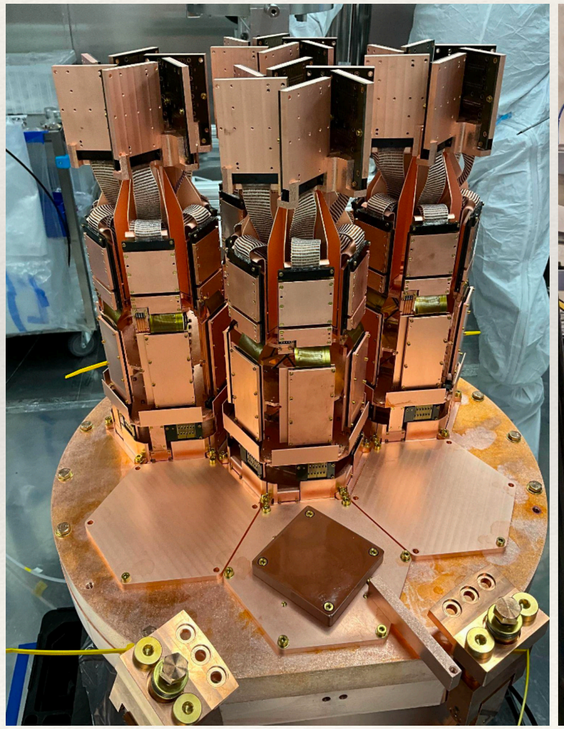


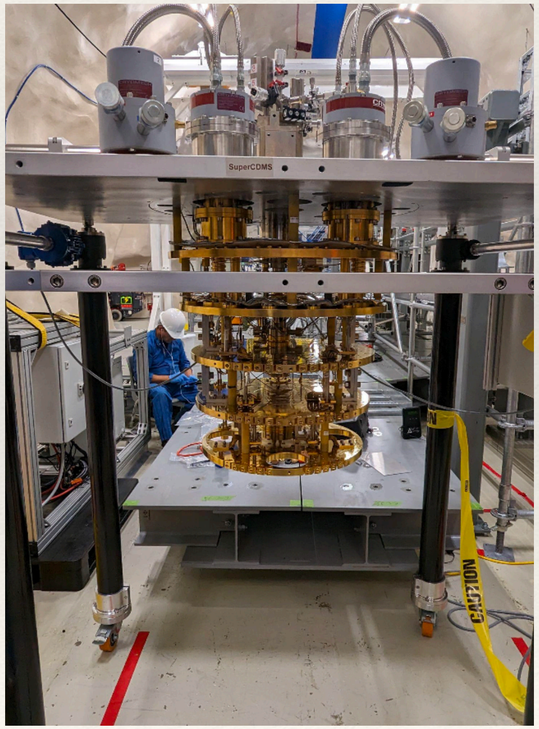
SuperCDMS



	Germanium	Silicon
HV	Lowest threshold for low mass DM Larger exposure, no ^{32}Si bkgd	Lowest threshold for low mass DM Sensitive to lowest DM masses
iZIP	Nuclear Recoil Discrimination Understand Ge Backgrounds	Nuclear Recoil Discrimination Understand Si Backgrounds

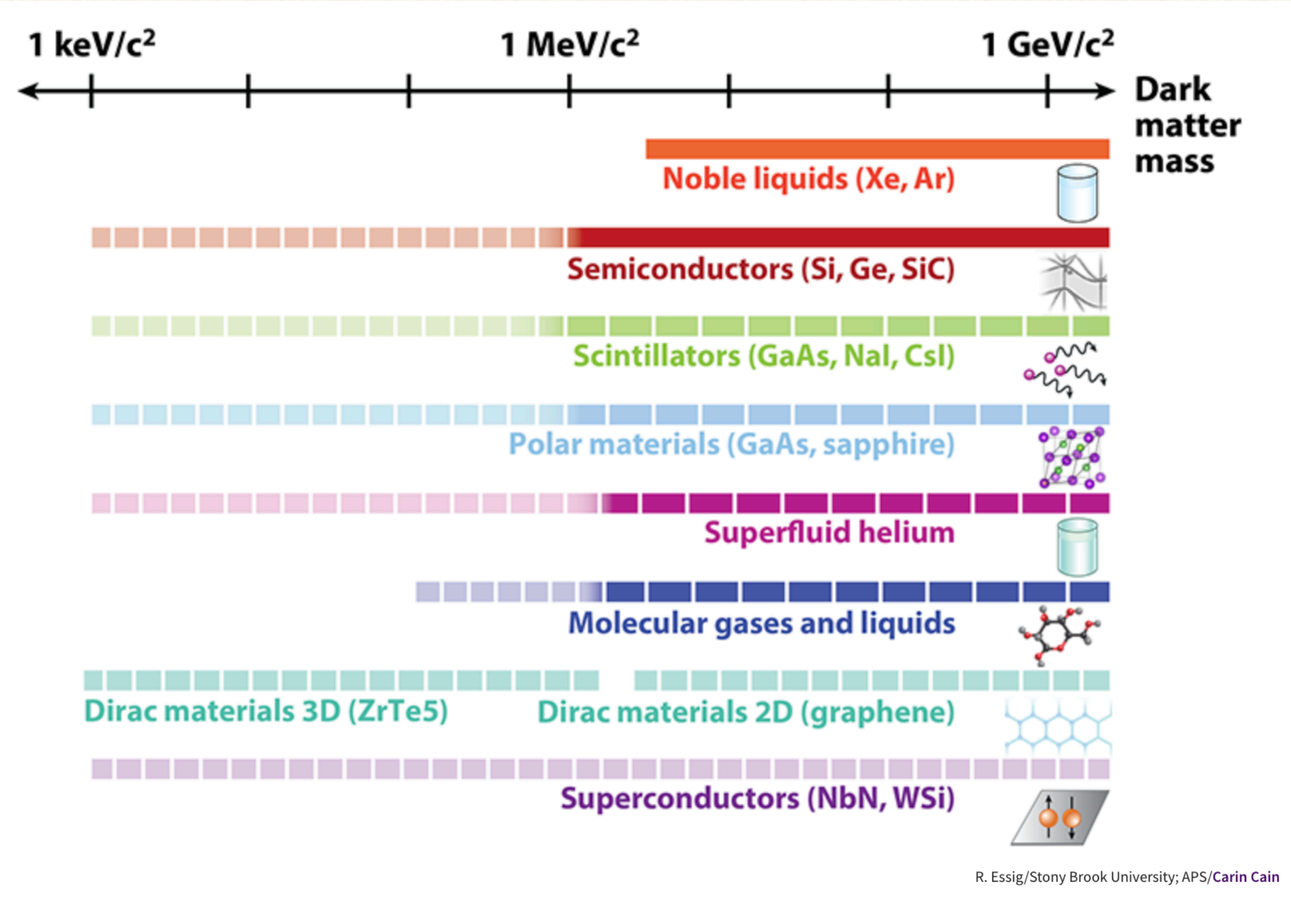
- Under construction at SNOLAB: running this year…
- 4 towers: 1 Ge iZIP, 1 Ge & Si iZIP, 2 Ge &Si HV
- Programme, including new detectors and upgrades discussed at arXiv:2203.08463

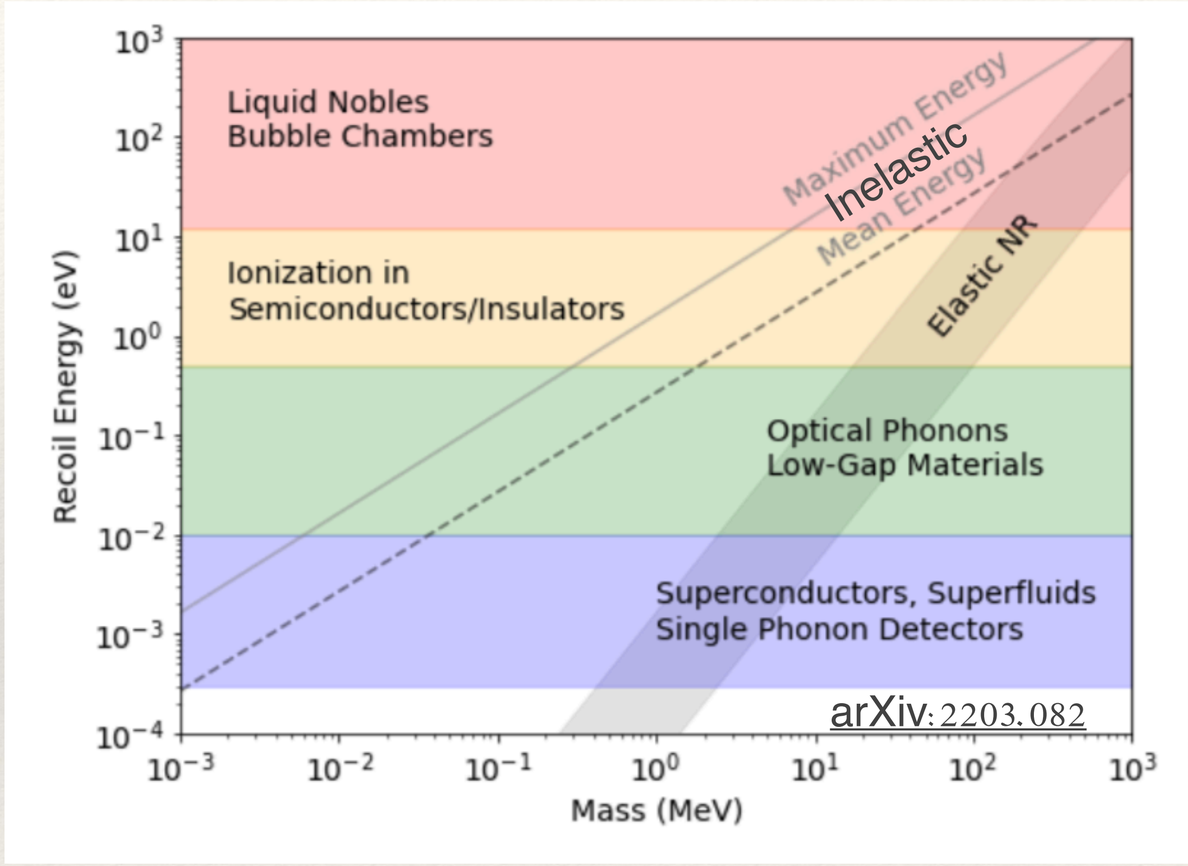




For DM masses <1 GeV/c^2,
gram scale detectors can produce leading results.
Lots of new ideas, many exploiting quantum technologies.
There are many unknowns.

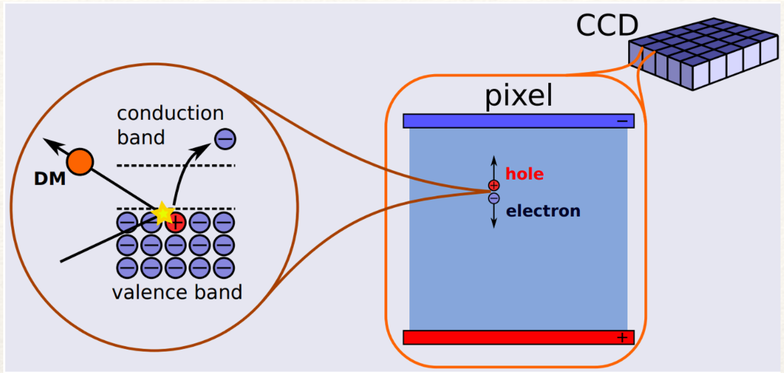
Below a GeV: technologies

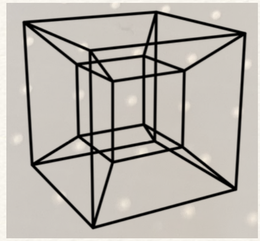


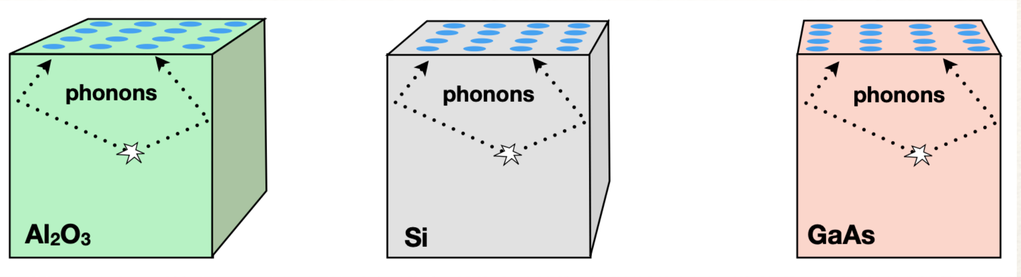


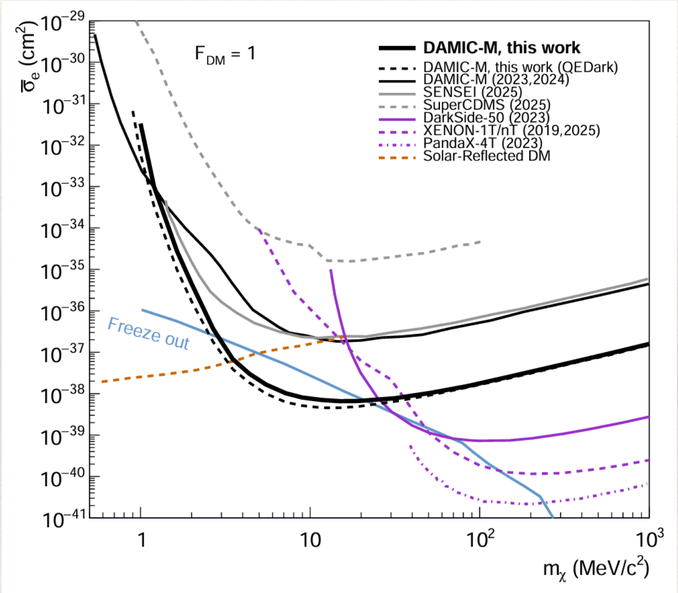
DM–electron scattering and absorption now of interest

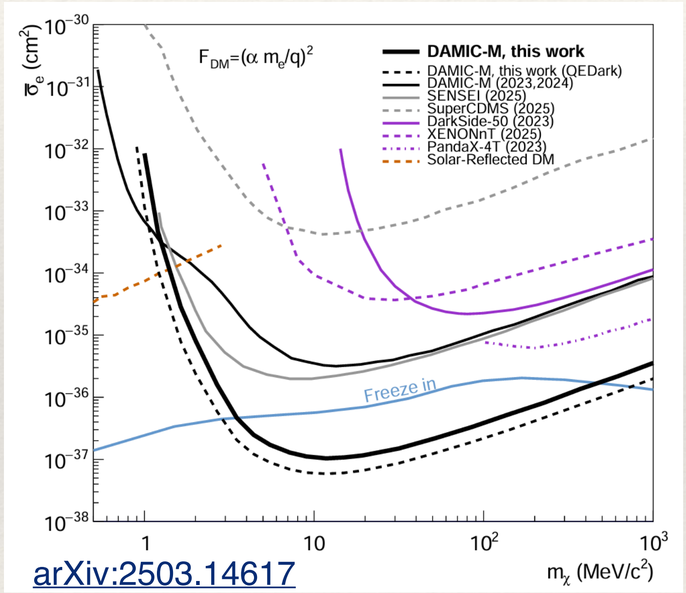
Recent Updates



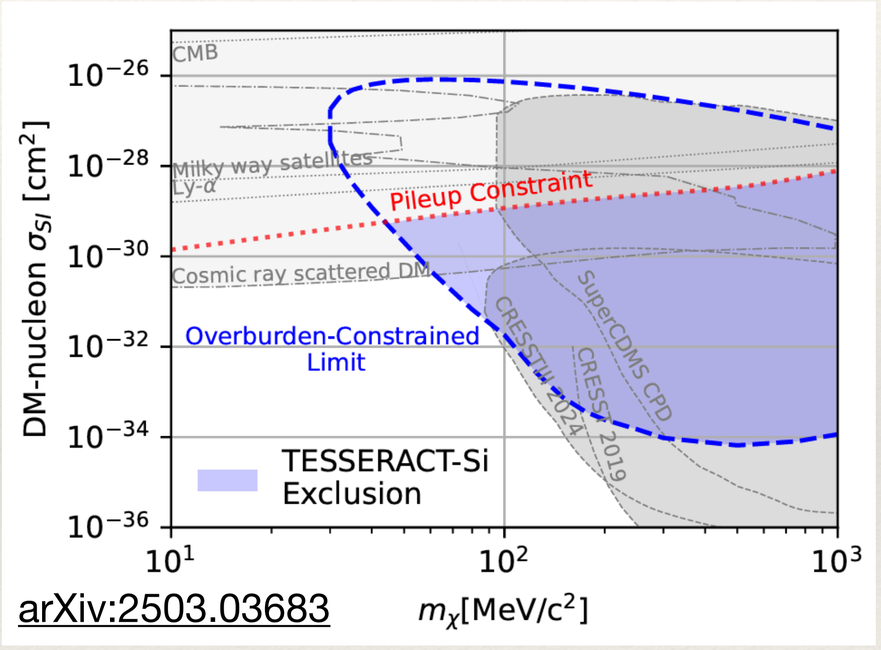








arXiv:2503.14617



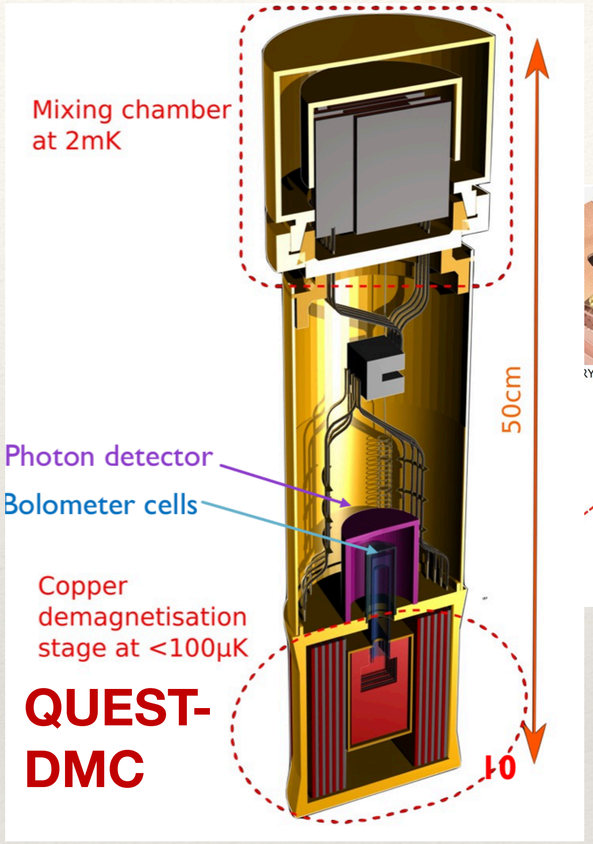
arXiv:2503.03683

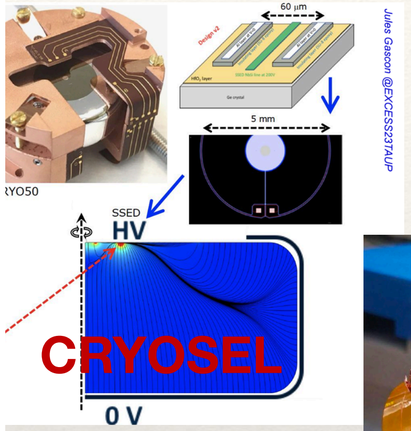
- DAMIC-M prototypes at LSM with 1.3 kg-day : limits on DM- electron
- (New updates from SENSEI running at SNOLab with 1 e- threshold)
- DAMIC-M running this year-> going for kg-yr exposure
- OSCURA planned for 2029 with 10 kg

- TESSERACT with <3 g-hr on surface SI nucleon interactions
  - energy resolution of ~360 meV
- TESSERACT planned for 2028 operations

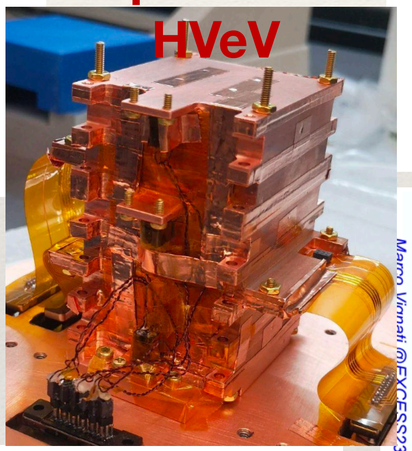
So many new detectors…

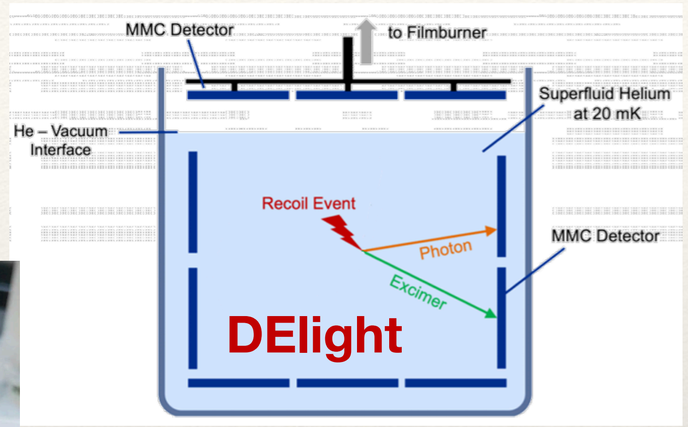
so many ~~hot~~ cold technologies: SNSPDs, TESs, KIDs, MMCs, superfluid He, superconducting QUBITs …

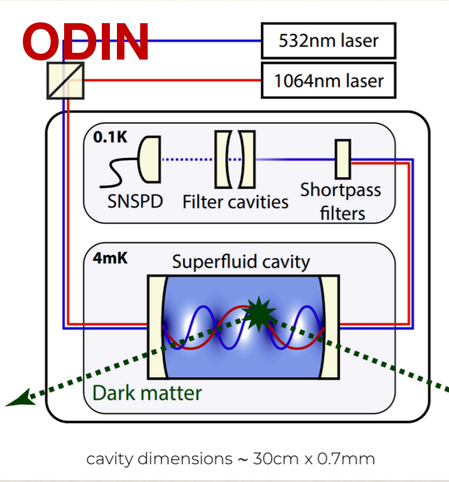


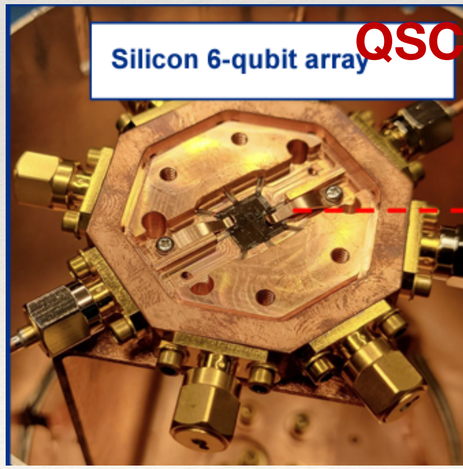


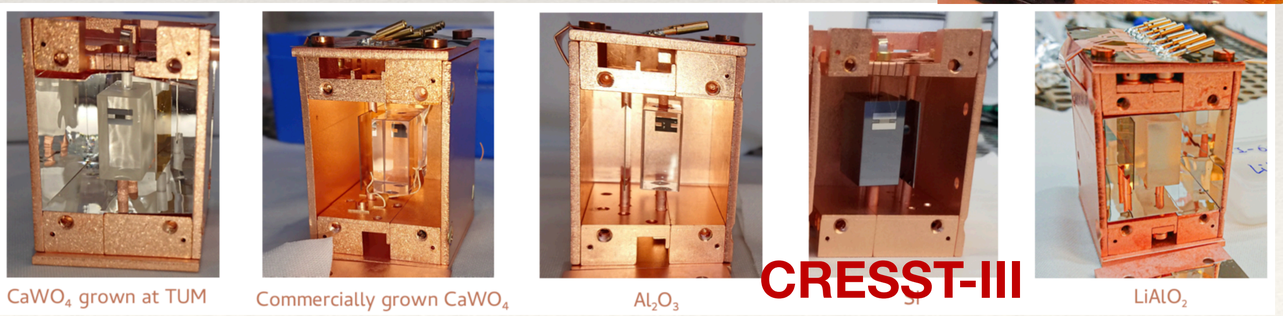
SuperCDMS HVeV



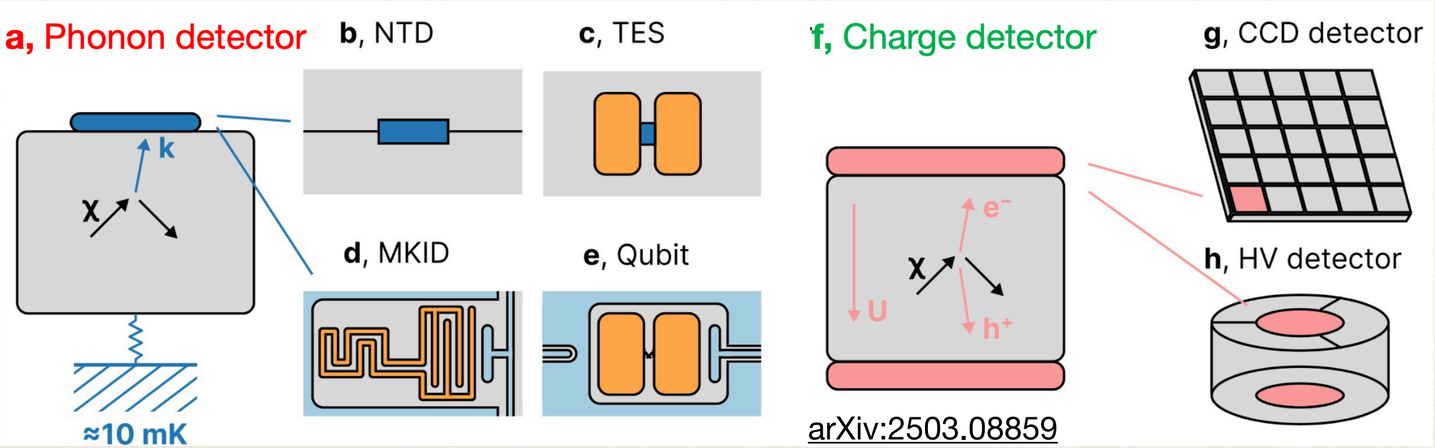






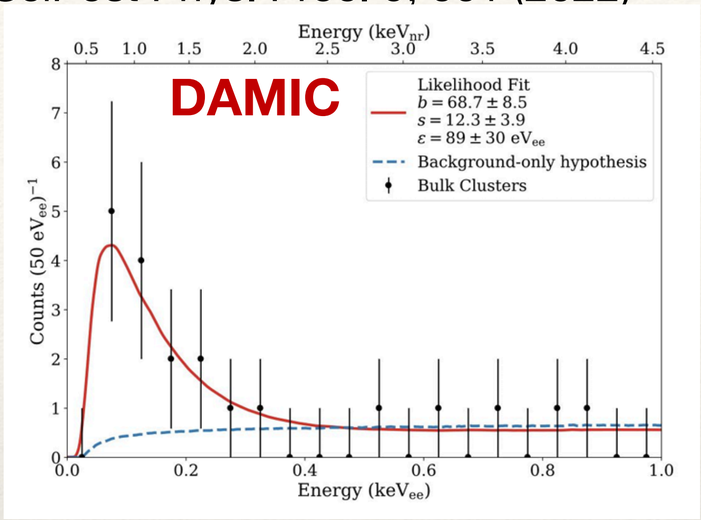


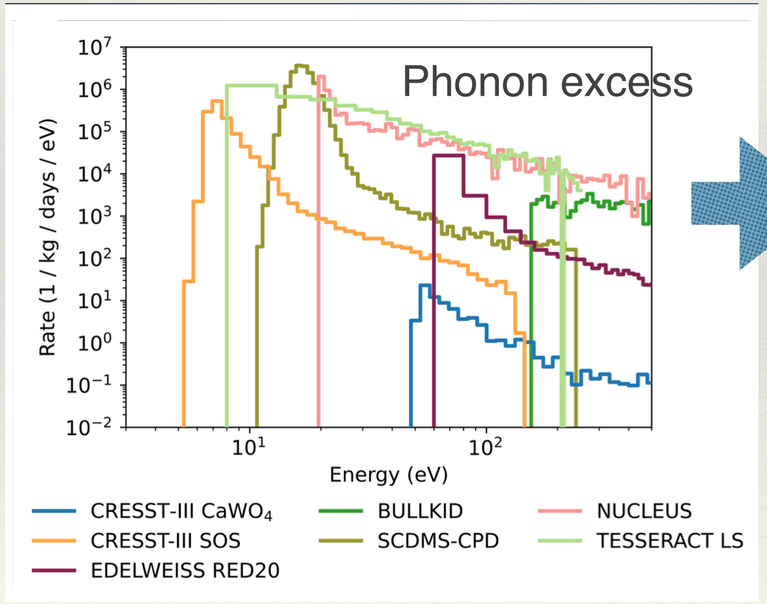
Low energy excess (LEE)

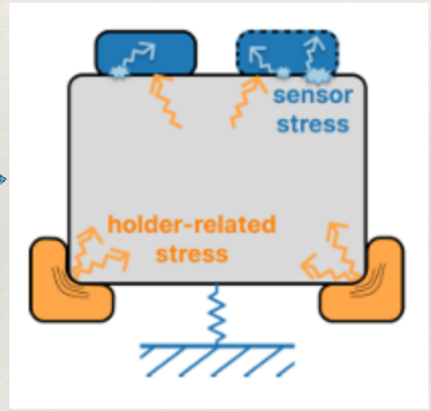


arXiv:2503.08859

EXCESS initiative: SciPost Phys. Proc. 9, 001 (2022)

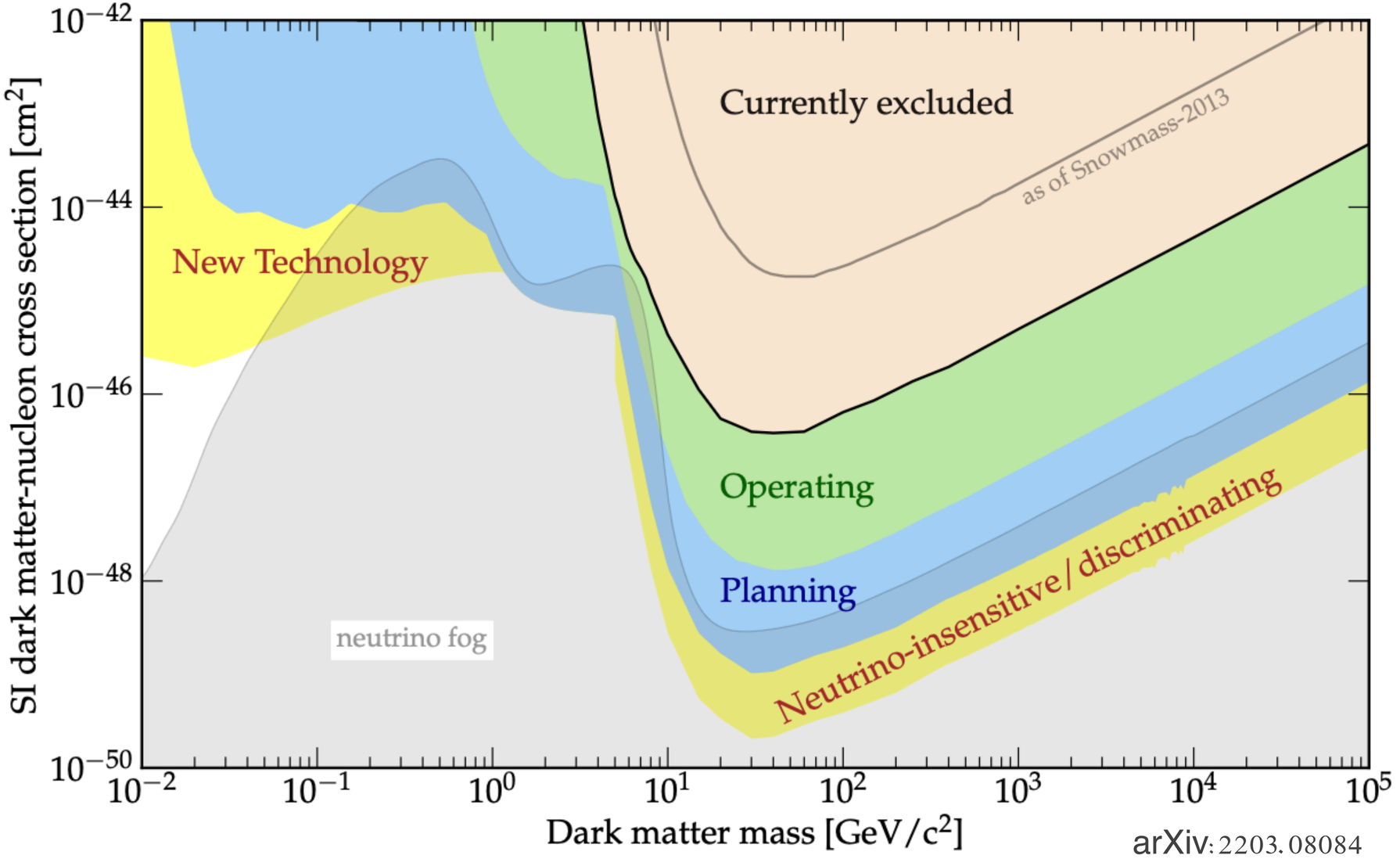






- Not Dark Matter
- Not (all) the same backgrounds
  - Phonons affected by both holder and inter-layer sensor stresses
  - Charge readout affected by radiation induced backgrounds
- DAMIC (SNOLAB) LEE levels not yet probed by new experiments
- General quantum effect? Wider Impact

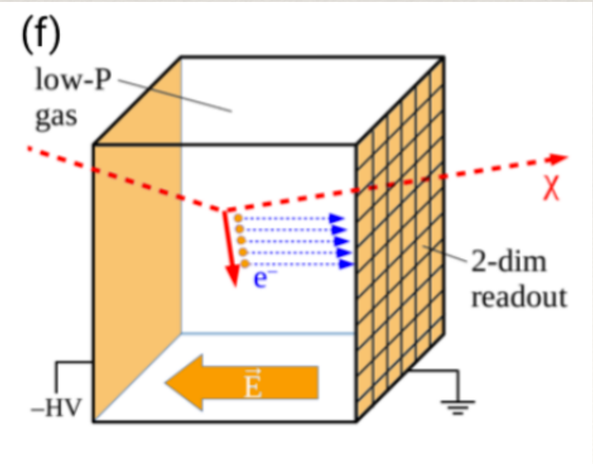
Going into the neutrino fog



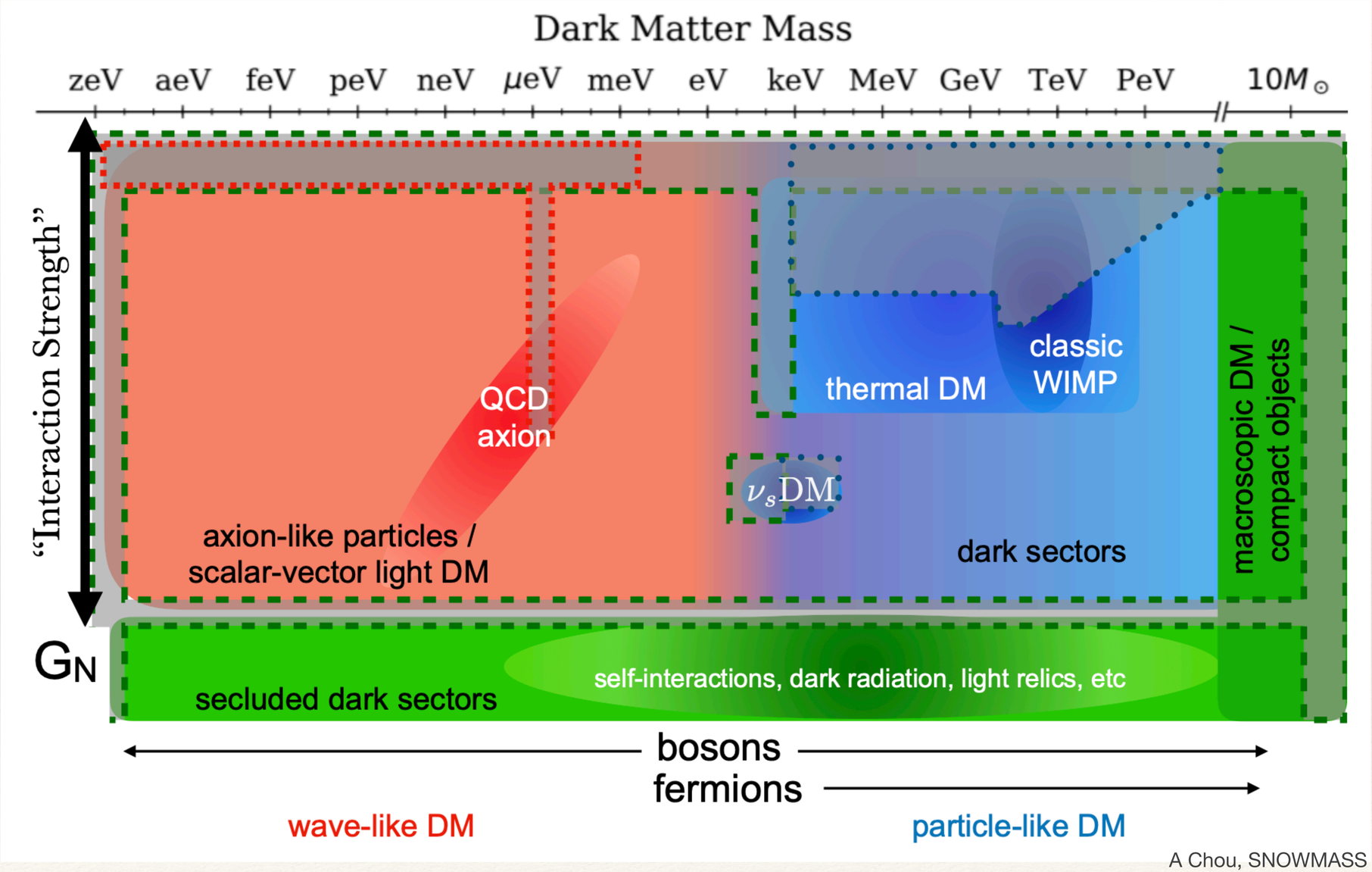
arXiv: 2203.08084

Directional detection offers the best current approach to explore into the neutrino fog

Sandbox Studio, Chicago with Corinne Mucha

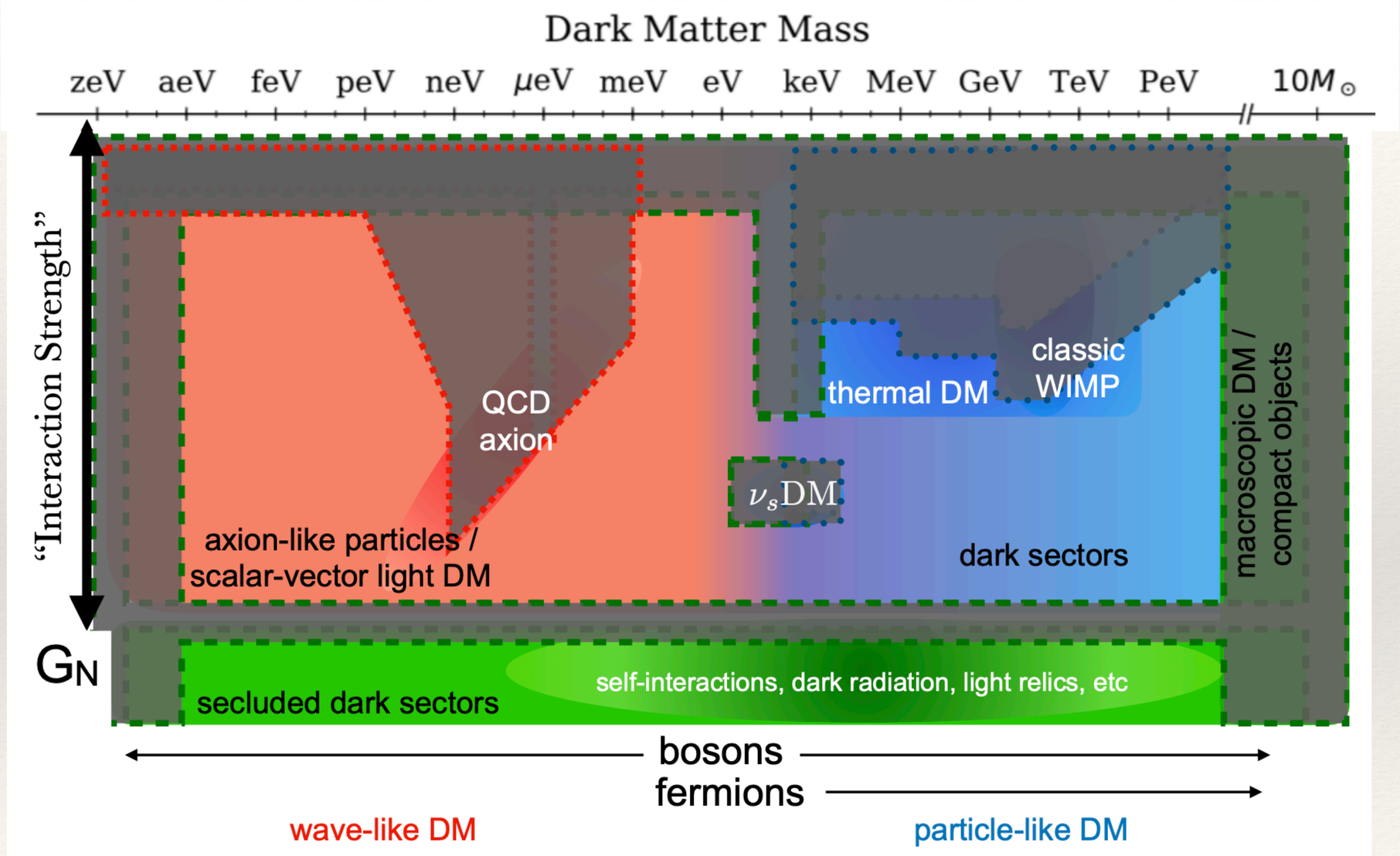


Our Current Status



A Chou, SNOWMASS Dark Matter Plenary

If we Search Deep and Wide, in 20 years



A Chou, SNOWMASS Dark Matter Plenary

Direct Detection uses a wide variety of technologies to search for dark matter, pushing the boundaries of radiopurity, energy threshold, and target mass.

This must all be taken in conjunction with axion/wavelike DM searches, collider searches, and astrophysical evidence.

I hope there is a dark sector with many interesting new particles, which solve current mysteries and open new ones.

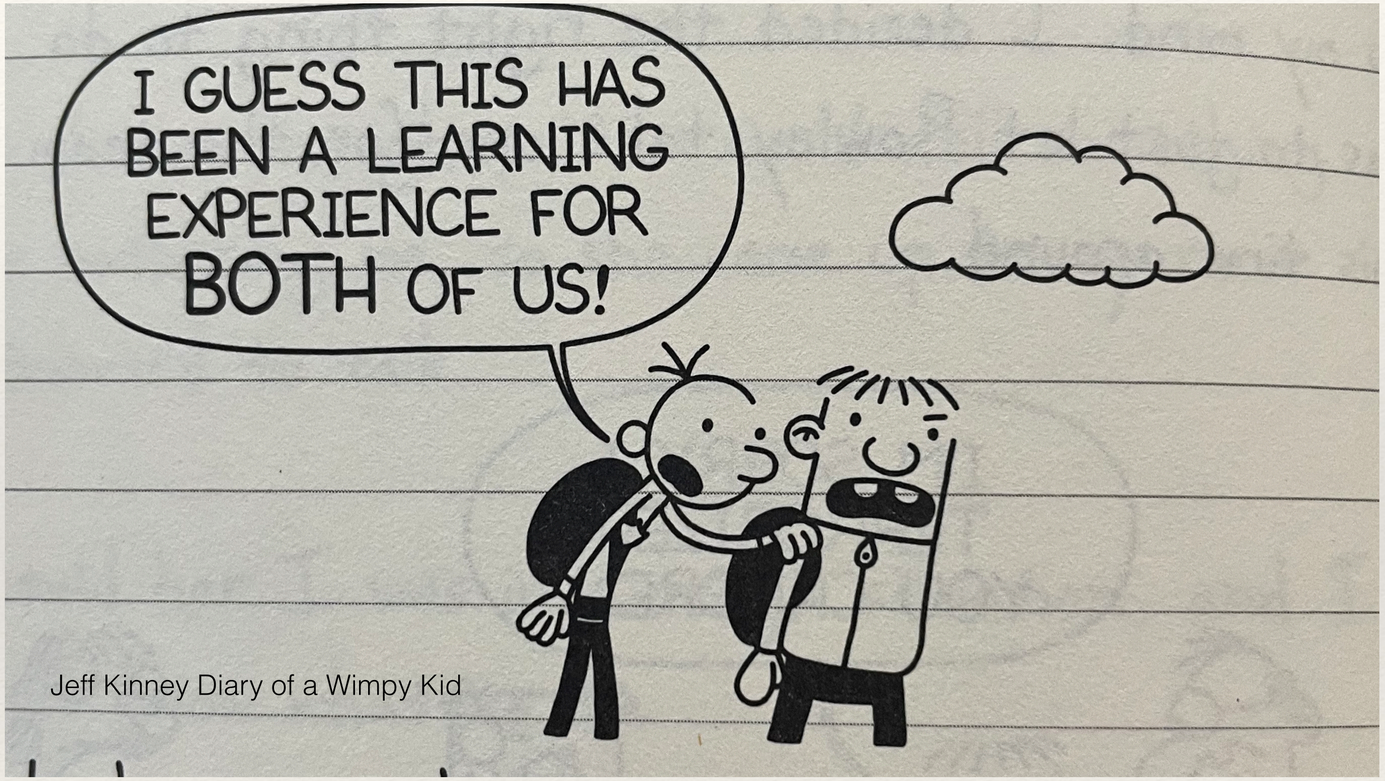
Current favorite resources:

J. D. Lewin and P. F. Smith, Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil, Astropart. Phys. 6 (1996) 87–112. https://doi.org/10.2016/S0927-6505(96)00047-3

Billard et al Direct Detection of Dark Matter - APPEC Committee report Rep. Prog. Phys. (2022) 86, 056201 https://doi.org/10.1088/1361-6633/ac5754

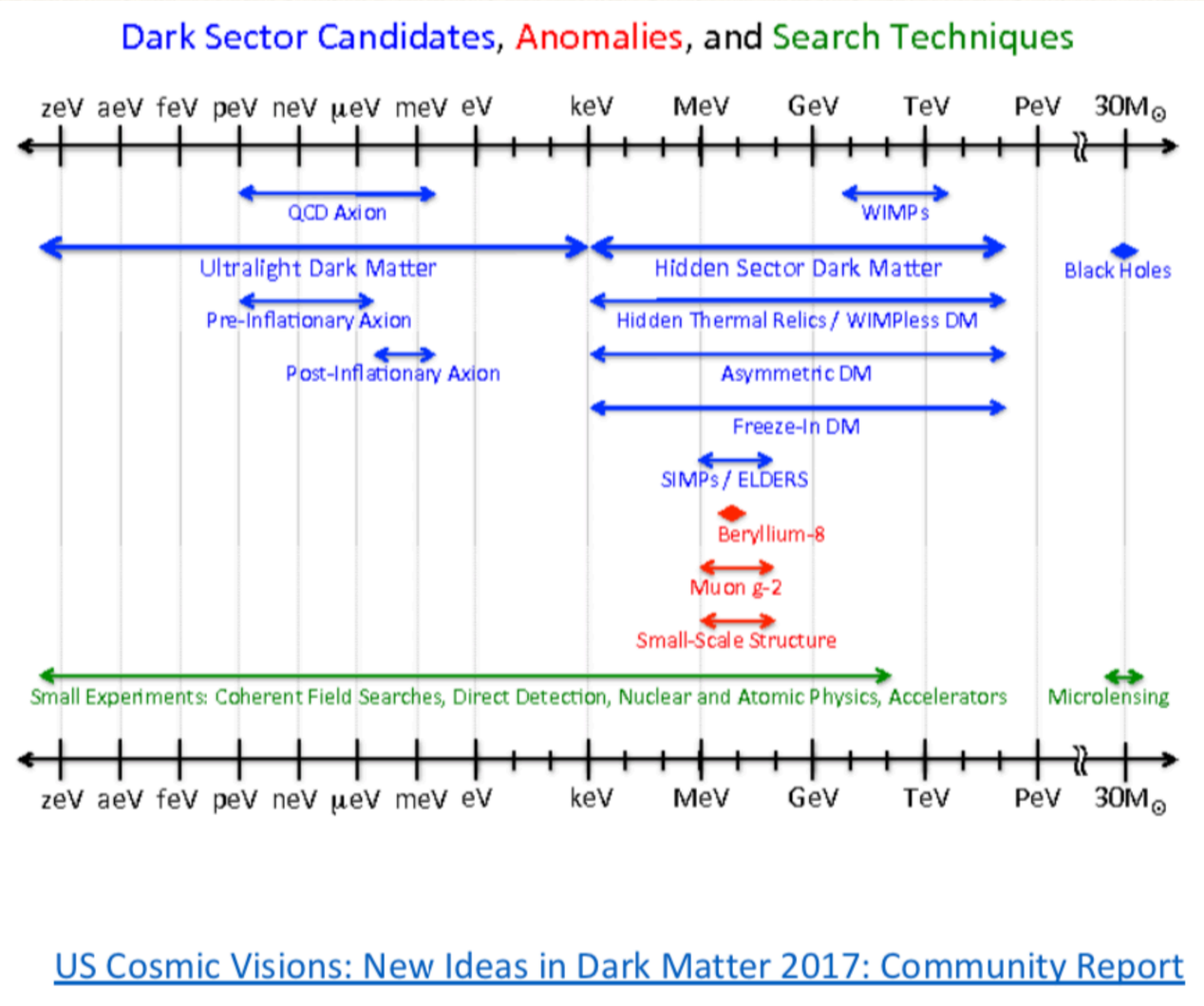
- D. S. Akerib, P. B. Cushman, C. E. Dahl, R. Ebadi, A. Fan, R. J. Gaitskell, et al. "Dark Matter Direct Detection to the Neutrino Fog", arXiv:2203.08084 [hep-ex] (pdf).
- Rouven Essig, Graham K. Giovanetti, Noah Kurinsky, Dan McKinsey, Karthik Ramanathan, Kelly Stifter, Tien-Tien Yu. "The landscape of low-threshold dark matter direct detection in the next decade", arXiv:2203.08297 [hep-ph] (pdf).
- D. Antypas, A. Banerjee, C. Bartram, M. Baryakhtar, J. Betz, et al. "New Horizons: Scalar and Vector Ultralight Dark Matter", arXiv:2203.14915 [hep-ex] (pdf). (also under RF03, TF09, IF01)
- Rebecca K. Leane, Seodong Shin, Liang Yang, Govinda Adhikari, et al. "Puzzling Excesses in Dark Matter Searches and How to Resolve Them", arXiv:2203.06859 [hep-ph] (pdf). (also under TF09)

https://snowmass21.org/submissions/cf

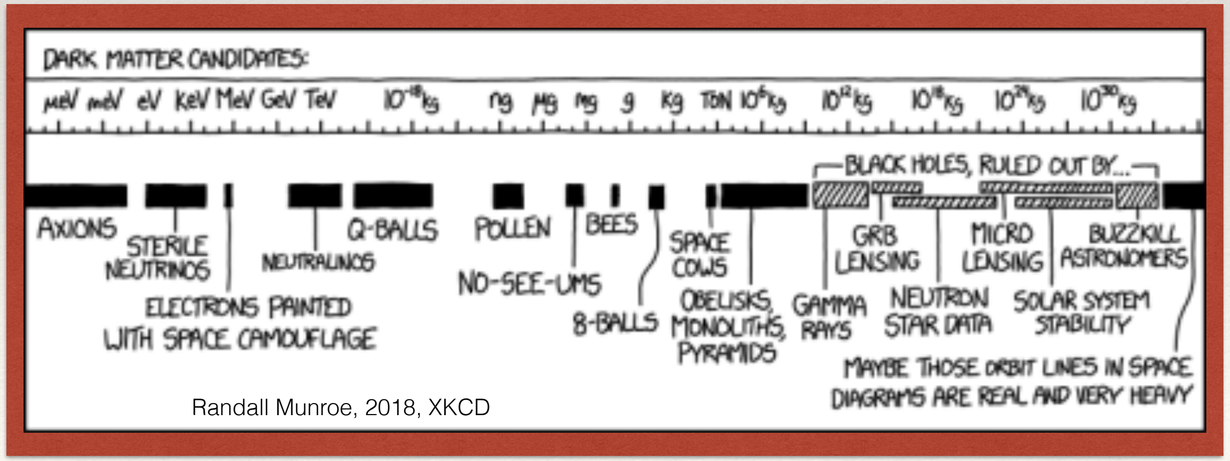


Jeff Kinney Diary of a Wimpy Kid

Models

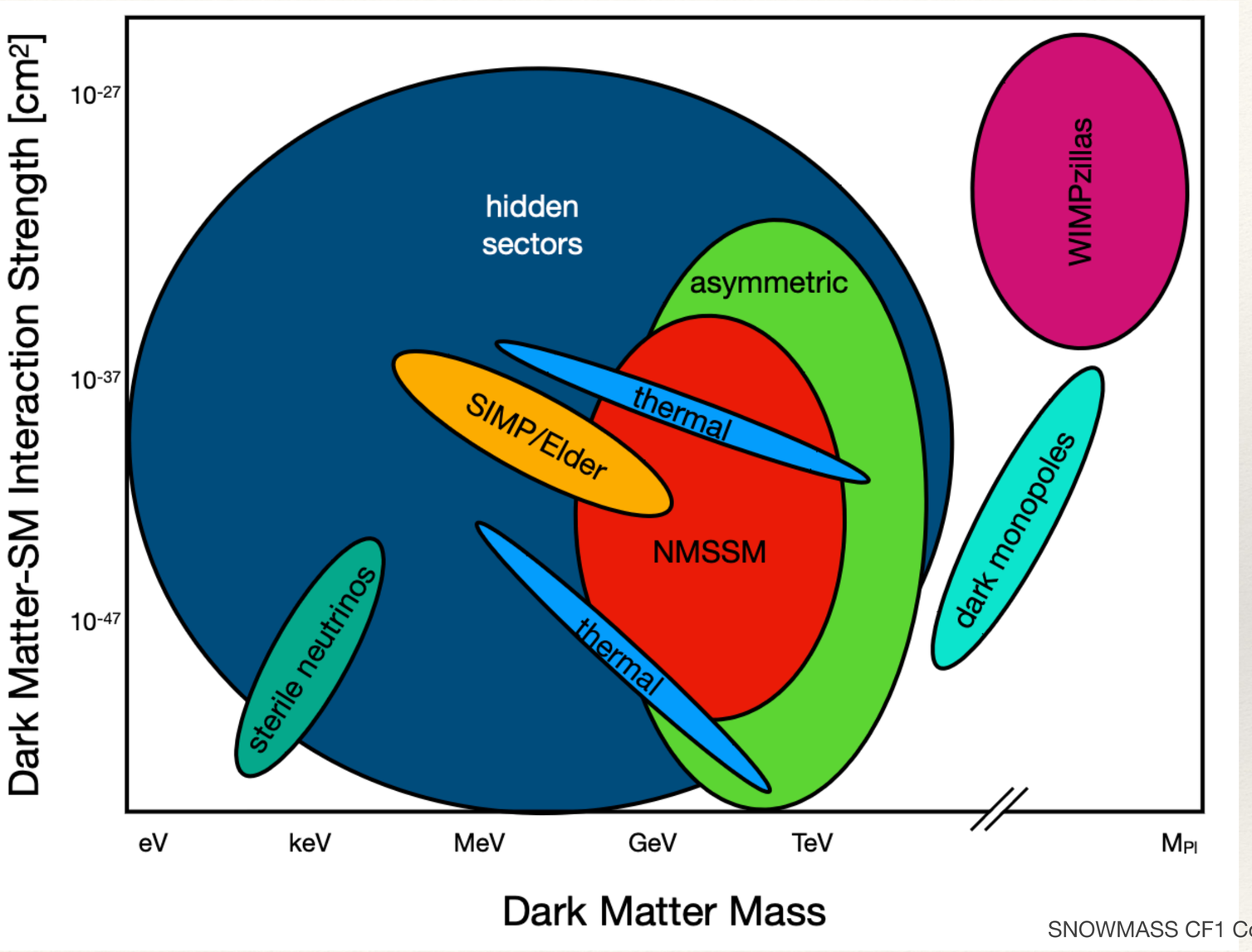


- Canonical Dark matter is:
  - non-relativistic
  - electrically neutral
  - limited self-interactions
  - density of DM ~0.3-0.45 GeV/cm^3
  - Some theories push these boundaries
  - Can dark matter candidates fit with other theories or open problems?

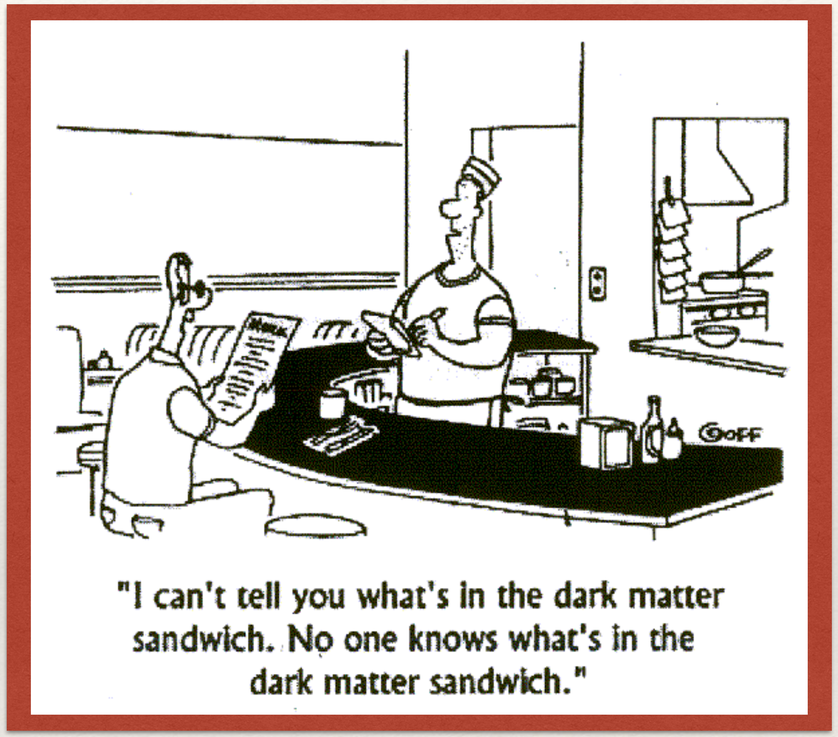


Randall Munroe, 2018, XKCD

An updated cartoon for particle dark matter

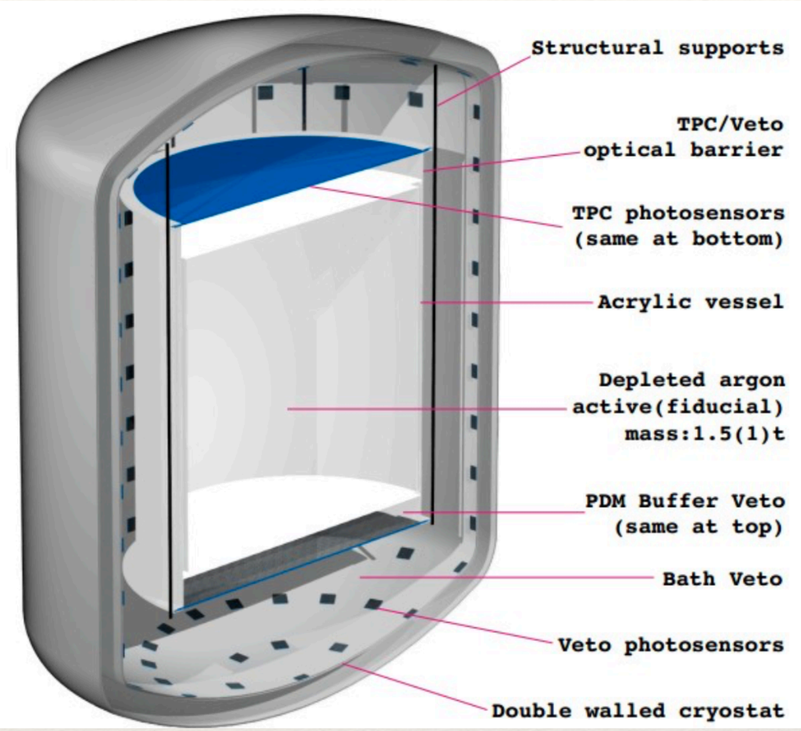


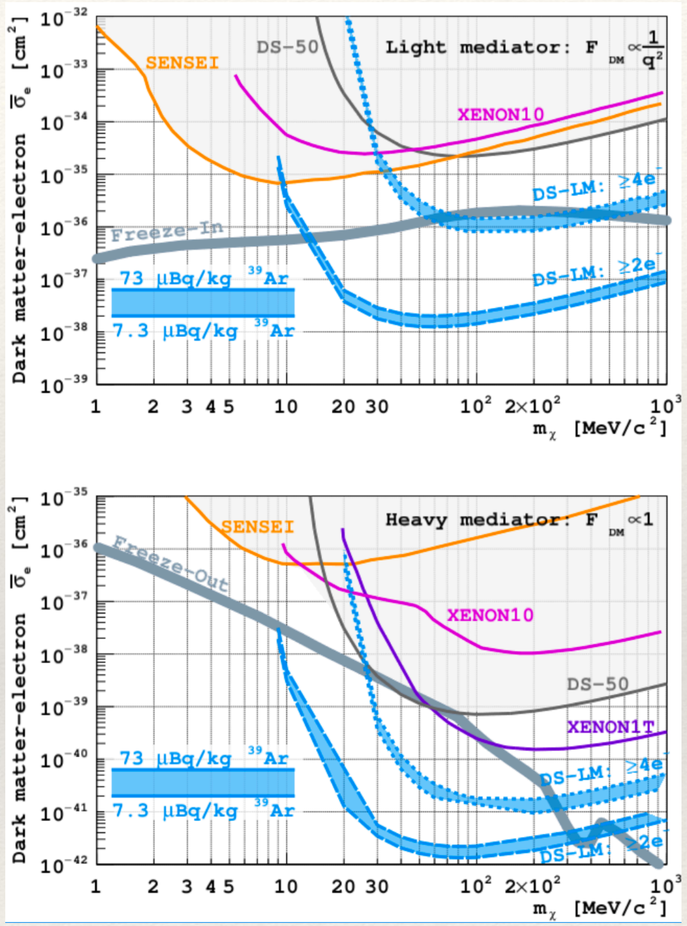
SNOWMASS CF1 Convener's Report



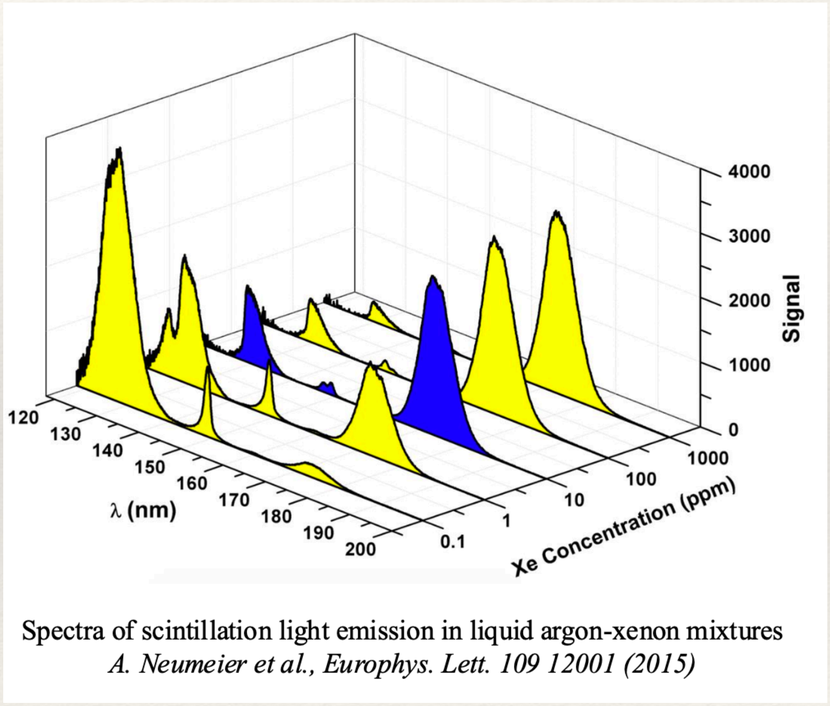
Proposed: Low Mass Liquid Nobles

DarkSide-Low-Mass
Westerdale UCLA DM 2025





CHILLAX: Xe doped (low %) Ar -best of both targets?

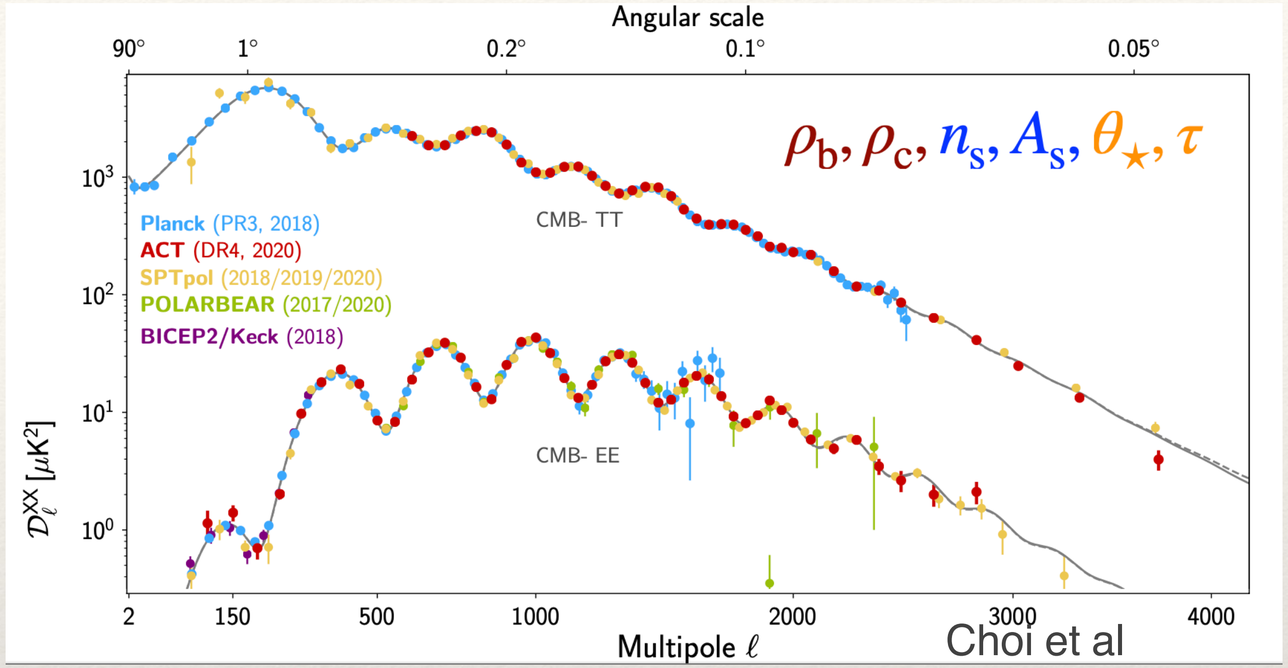


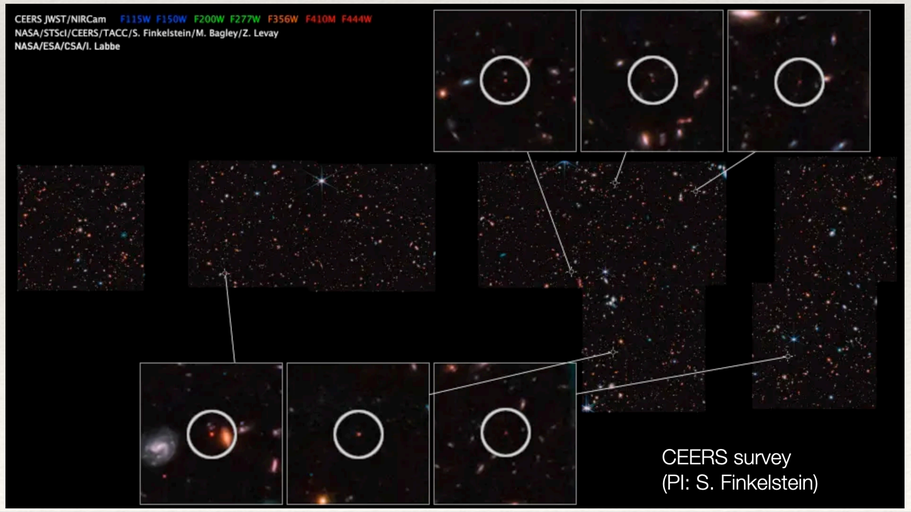
Spectra of scintillation light emission in liquid argon-xenon mixtures
A. Neumeier et al., Europhys. Lett. 109 12001 (2015)

Astronomy and Cosmology

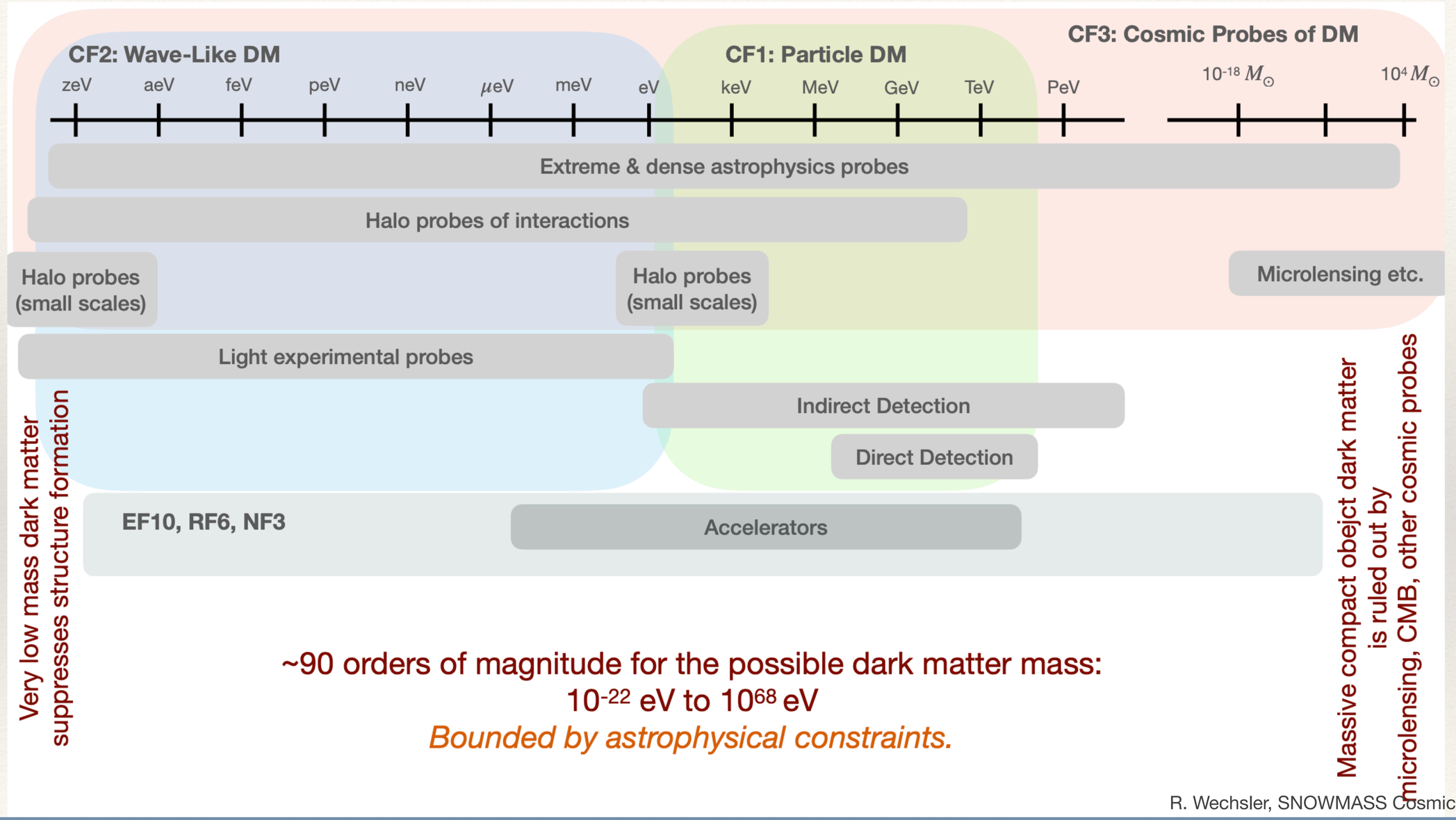
- Our cosmological models work really well

- But…
  - many big young galaxies seen by the James Webb Space telescope
  - different measured values for the Hubble constant
  - Black Holes are surprising us too, could they be dark matter?





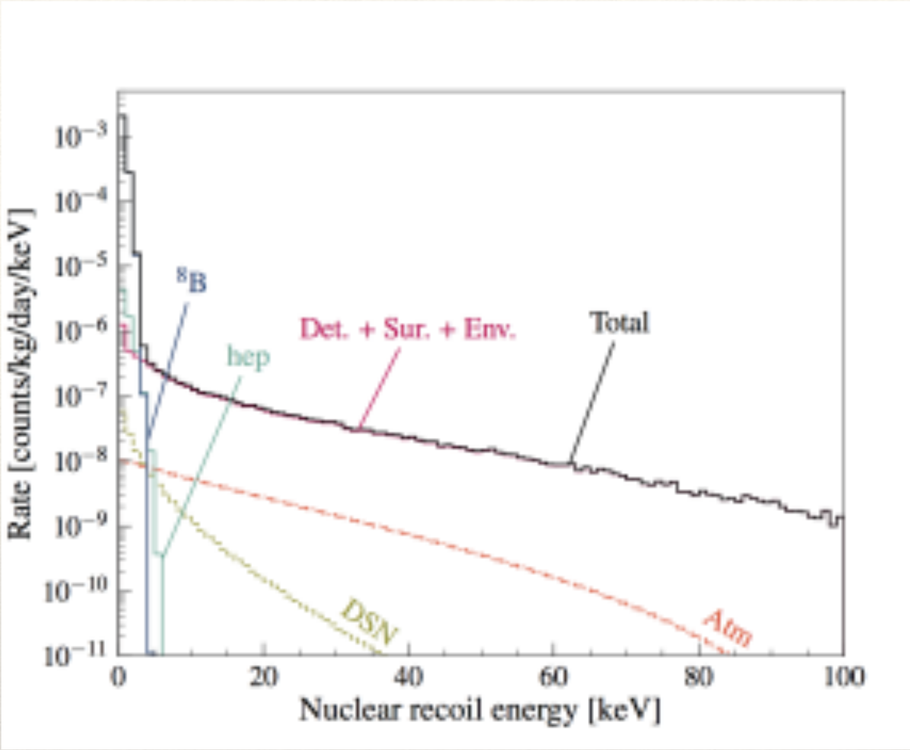
Complementarity

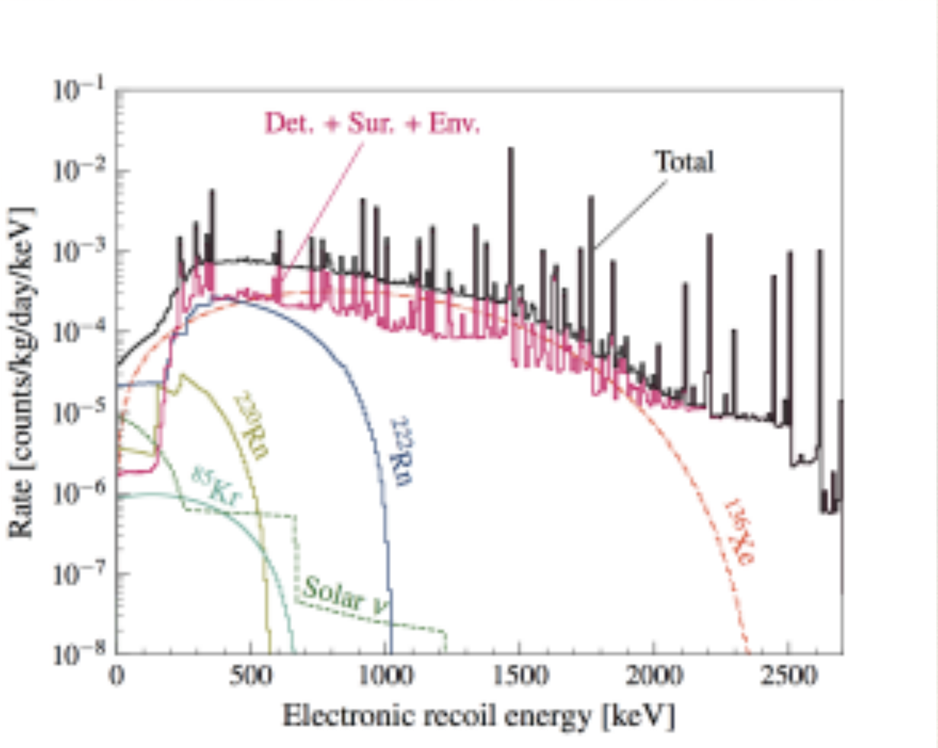


R. Wechsler, SNOWMASS Cosmic Probe Plenary

Backgrounds

- Besides unprecedented Spin-Independent cross-section sensitivity, ~50% of the natural Xe isotopes also have unpaired neutrons giving Spin-Dependent couplings
- LZ will also be sensitive to electrophilic DM or axion-like-particles
- Largest background will be pp solar neutrino electronic recoils



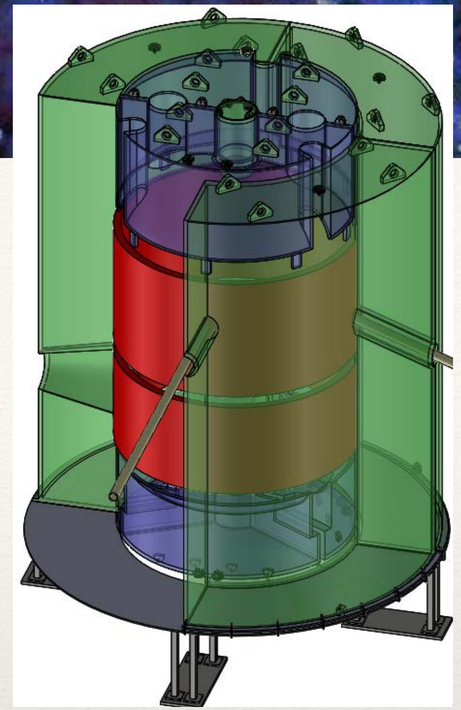


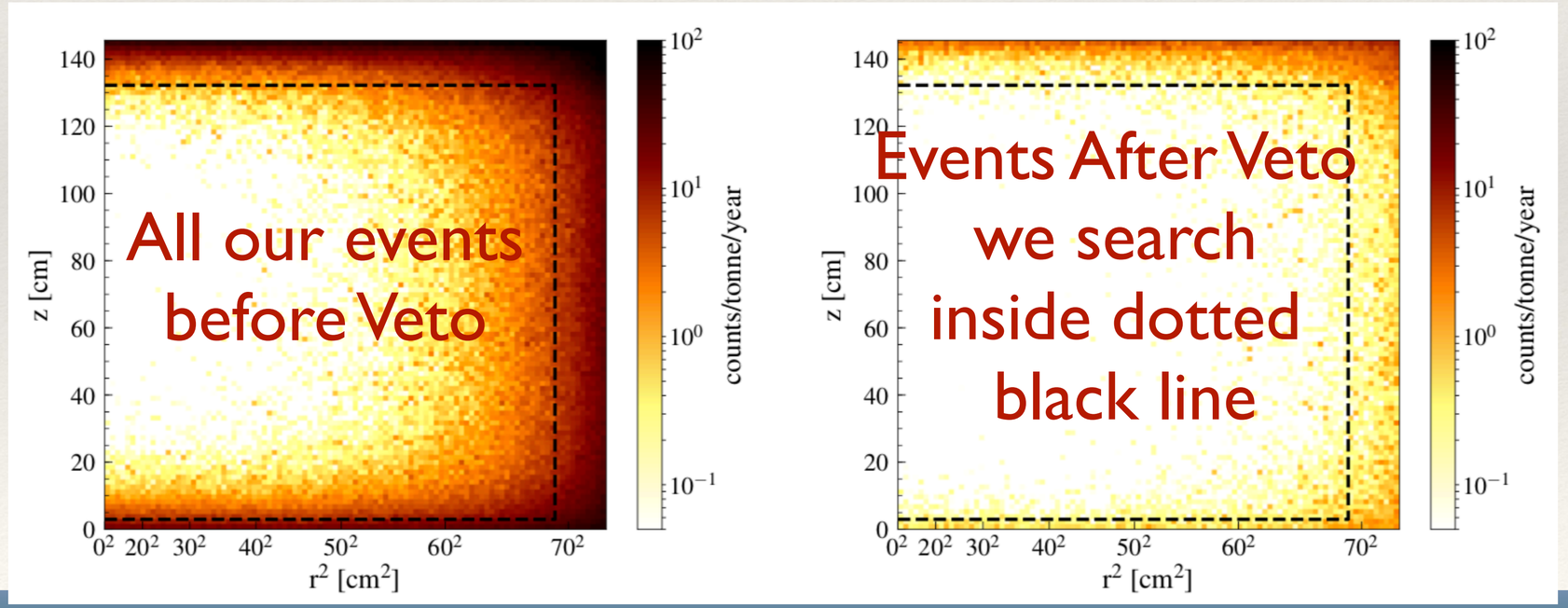
arXiv:1802.06039

External Vetoes

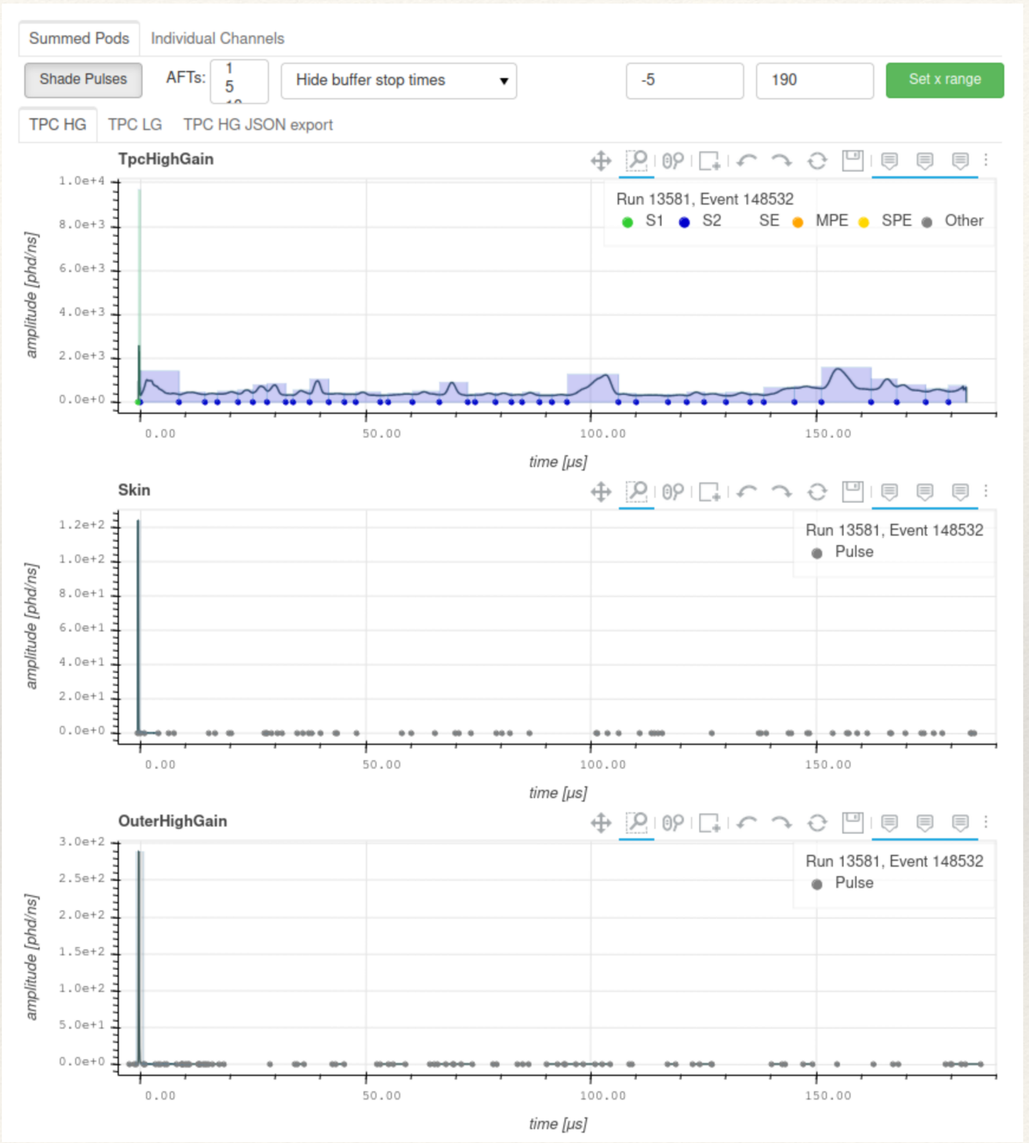
1.5 m height and diameter of TPC
10 t total Xe
20x LUX mass
Active Xe skin and Gd loaded LAB veto

- External tagging allows greater fiducial volume for analysis
- 60 cm thick, 17.2 T of Gadolinium- loaded liquid scintillator, 120 8” PMTs
- 97% efficiency for neutrons in simulations



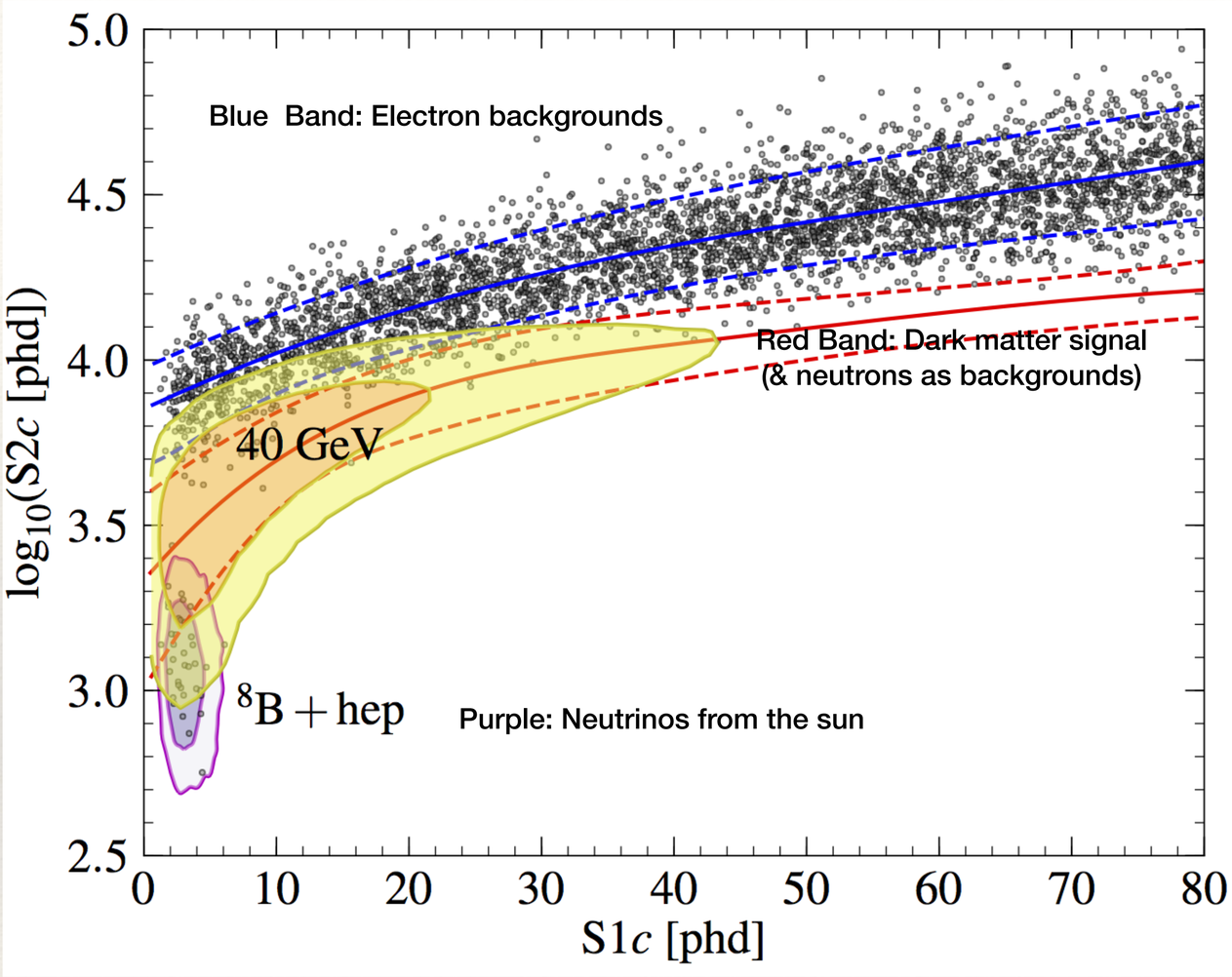


Muons in 3 detectors



What would a signal look like in LZ?

- Besides unprecedented Spin-Independent cross-section sensitivity, ~50% of the natural Xe isotopes also have unpaired neutrons giving Spin-Dependent couplings
- LZ will also be sensitive to electrophilic DM or axion-like-particles
- Largest background will be pp solar neutrino electronic recoils



arXiv:1802.06039

Experiments Currently running

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Currently Running or Under Construction						
LZ	TPC	LXe	7,000 kg	SURF	2021	2026
PandaX-4T	TPC	LXe	4,000 kg	CJPL	2021	2025
XENONnT	TPC	LXe	7,000 kg	LGNS	2021	2025
DEAP-3600	Scintillator	LAr	3,300 kg	SNOLAB	2016	202X
Darkside-20k	TPC	LAr	50 t	LNGS	2025	2030
DAMA/LIBRA	Scintillator	NaI	250 kg	LNGS	2003	
ANAIS-112	Scintillator	NaI	112 kg	Canfranc	2017	2022
SABRE PoP	Scintillator	NaI	5 kg	LNGS	2021	2022
COSINE-200	Scintillator	NaI	200 kg	YangYang	2022	2025
CDEX-10	Ionization (77K)	Ge	10 kg	CJPL	2016	
EDELWEISS III (High Field)	Cryo Ionization / HV	Ge	33 g	LSM	2019	
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg	SNOLAB	2020	2022
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg	SNOLAB	2023	2028
CRESST-III (HW Tests)	Bolometer Scintillation	CaWO4		LNGS	2020	
PICO-40	Bubble Chamber	C3F8	35 kg	SNOLAB	2020	
NEWS-G	Gas Drift	CH4		SNOLAB	2020	2025

Experments Currently running, cont'd

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Currently Running or Under Construction						
DAMIC-M prototype	CCD Skipper	Si	18 g	LSM	2022	2023
DAMIC-M	CCD Skipper	Si	1 kg	LSM	2024	2025
SENSEI	CCD Skipper	Si	2 g	Fermilab	2019	2020
SENSEI	CCD Skipper	Si	100 g	SNOLAB	2021	2023

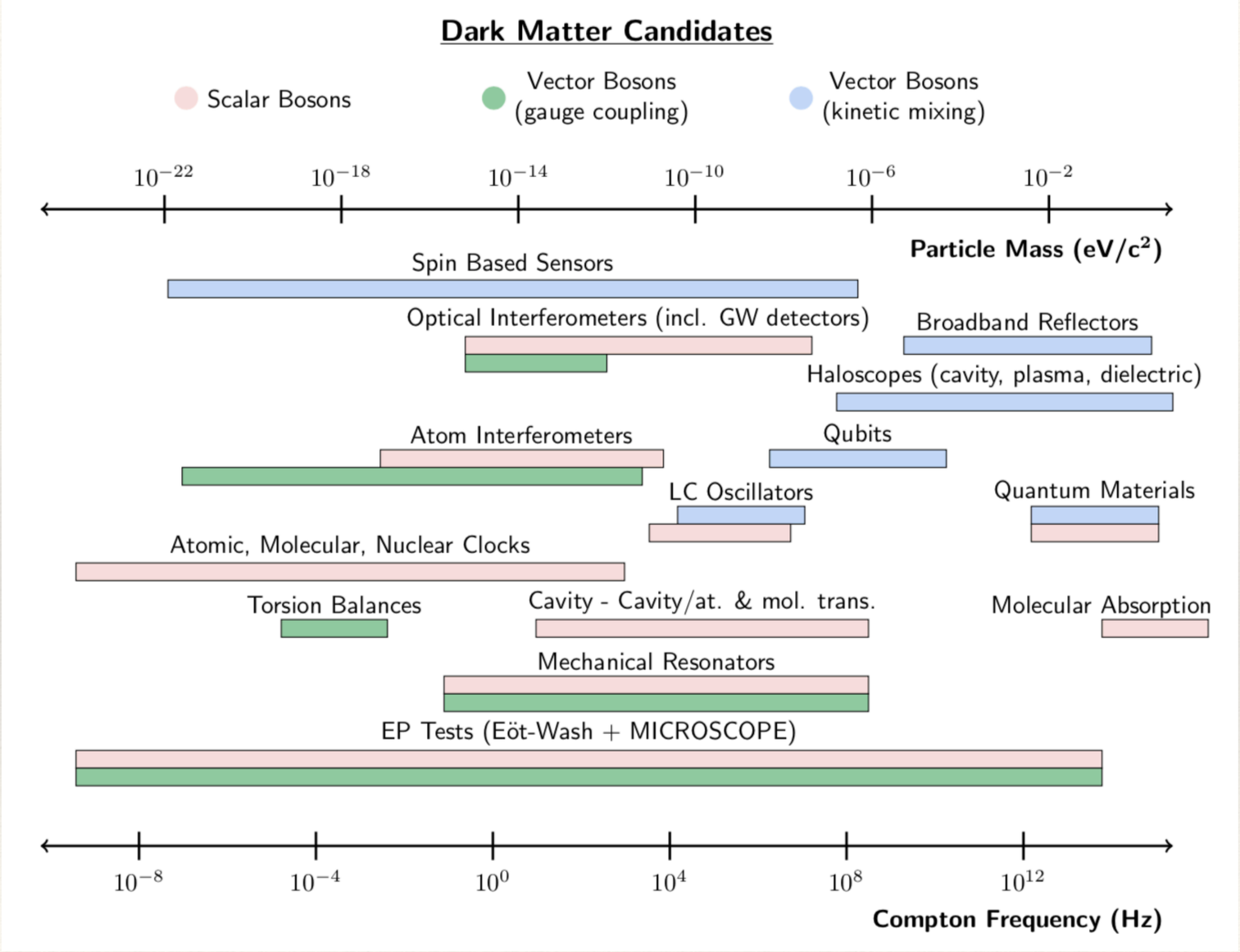
Planned Experiments

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Planned						
SABRE (North)	Scintillator	NaI	50 kg	LNGS	2022	2027
SABRE (South)	Scintillator	NaI	50 kg	SUPL	2022	2027
COSINE-200 South Pole	Scintillator	NaI	200 kg	South Pole	2023	
COSINUS	Bolometer Scintillator	NaI		LNGS	2023	
Darwin / XLZD (US LXe G3)	TPC	LXe	50,000 kg	undetermined	2028	2033
ARGO	TPC or Scintillator	LAr	300 t	SNOLAB	2030	2035
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg	CJPL	202X	
PICO-500	Bubble Chamber	C3F8	430 kg	SNOLAB	2021	

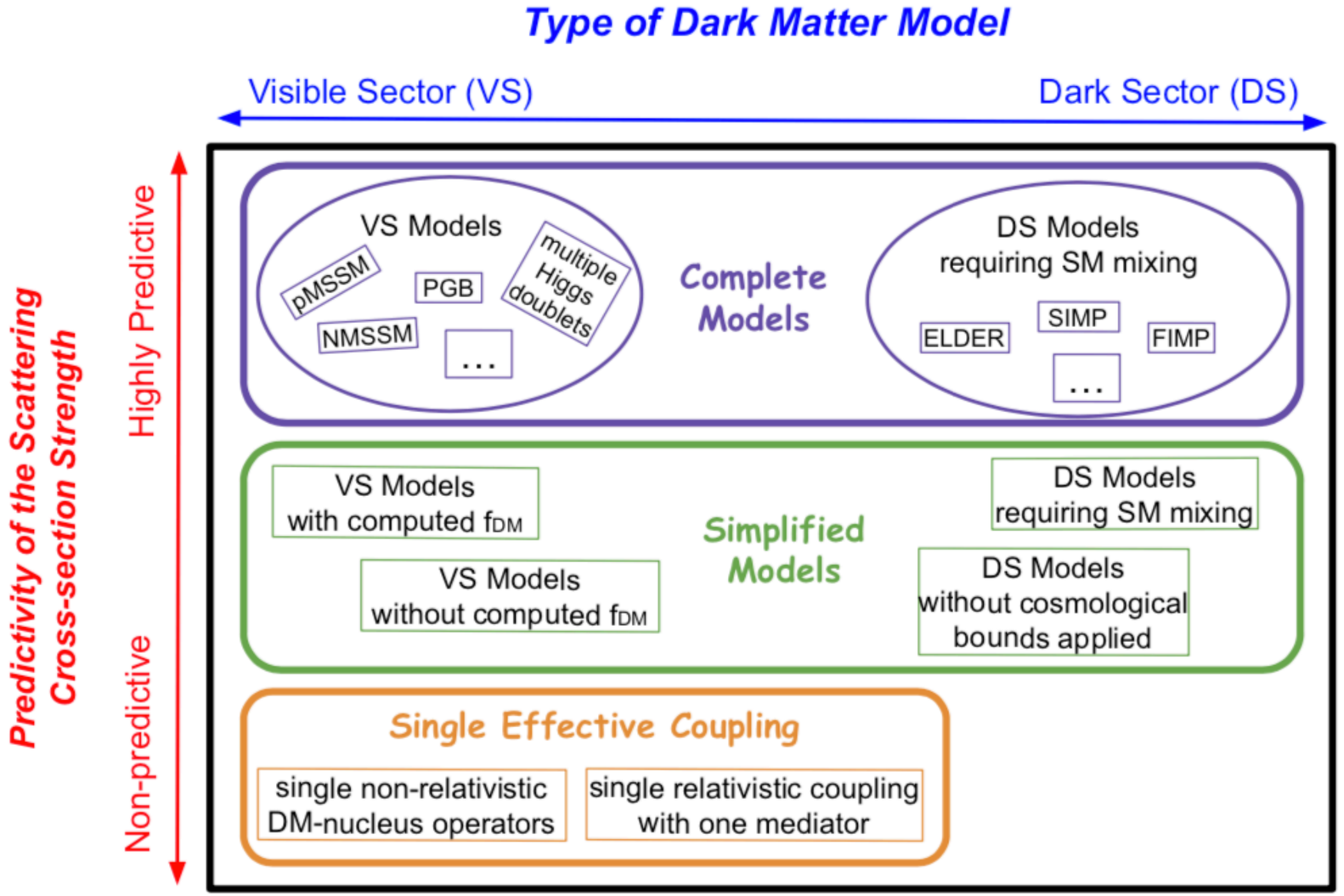
Potential Future Experiments

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Concept or R&D						
Oscura	CCD Skipper	Si	10 kg Si	SNOLAB	2025	2028
SBC	Bubble Chamber	LAr	1 t	SNOLAB	2028	
SNOWBALL	Supercooled Liquid H2O					
DarkSide-LowMass	TPC	LAr	1.5 t			
ALETHEIA	TPC	He		China Inst. At. Energy		
TESSERACT	Cryo TES	LHe, SiO_2, Al_2O_3, GaAs		undetermined	2026	
CYGNO	Gas Directional	He + CF_4	0.5 - 1 kg	LNGS	2024	
CYGNUS	Gas Directional	He + SF_6/CF_4		Multiple sites		
Windchime	Accelerometer array			Multiple sites	2	

Wavelike Dark Matter



arXiv:220



arXiv:2203.08084