Dark Matter direct detection Part 3

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What will we talk about?

Background and Context

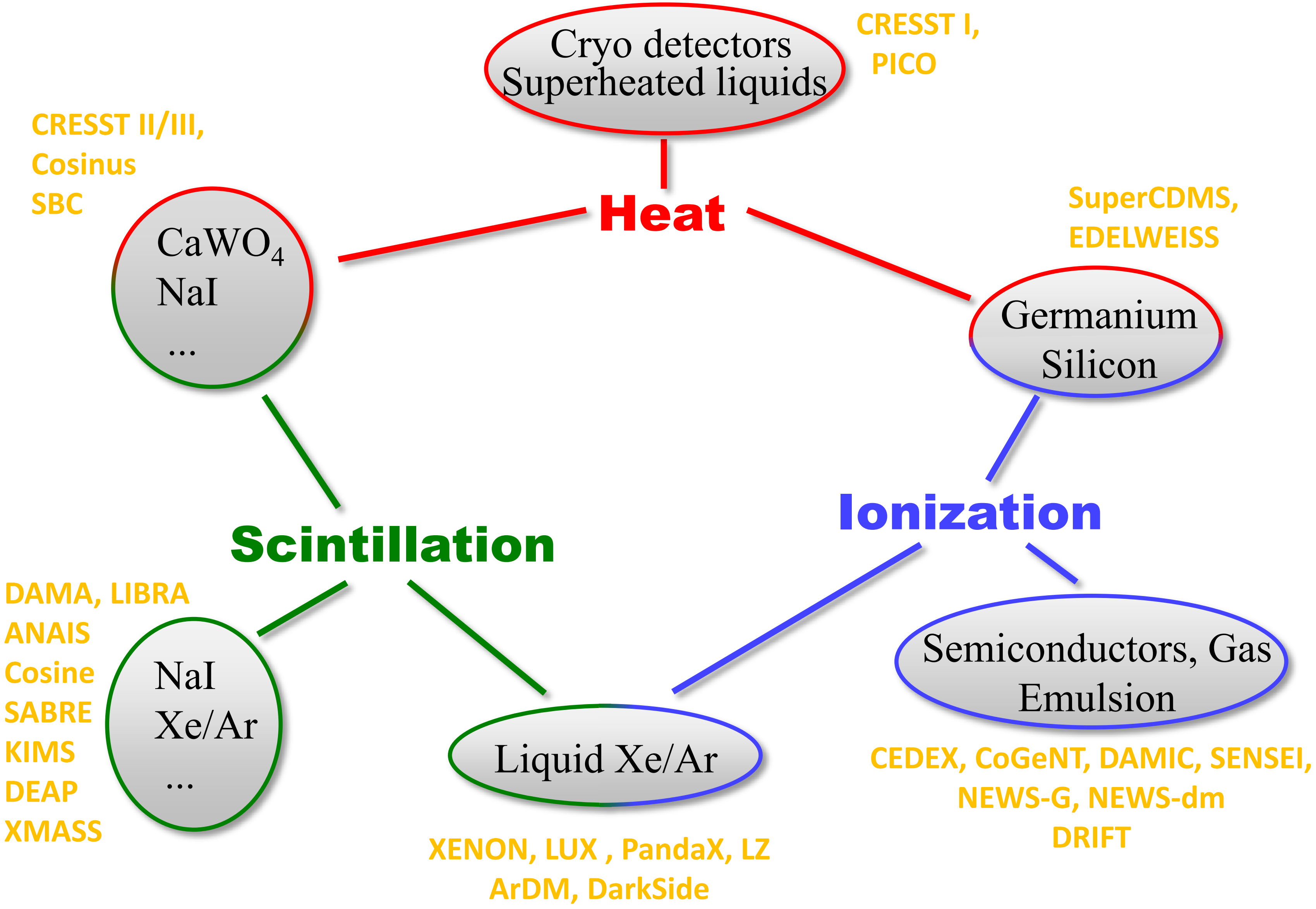
- Dark Matter interactions
    - Kinematics and other considerations
    - Expected DM signal spectra
    - DM signatures
- Background
    - Expected Signal Rates
    - Background sources and mitigation strategies
- Analysis
    - Assumptions
    - Extracting limits or confidence regions
- Detection Mechanisms
    - Electronic excitations and nuclear recoils
    - Special effects at low energy
- Calibration
    - Electron recoil energy scale
    - Nuclear recoil energy scale

Experiments

- The first Kids on the Block
- The Imag(e)inative Descendants
- The really cool ones
- The hot stuff
- The DAMA Drama
- The Xenon Frenzy
- Big, Bigger, Biggest
- The spherical Cow
- What else there is …

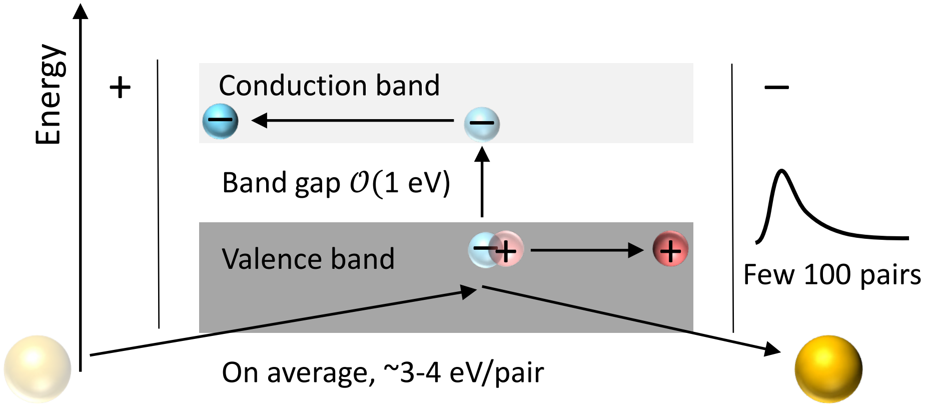
Results

Experiments

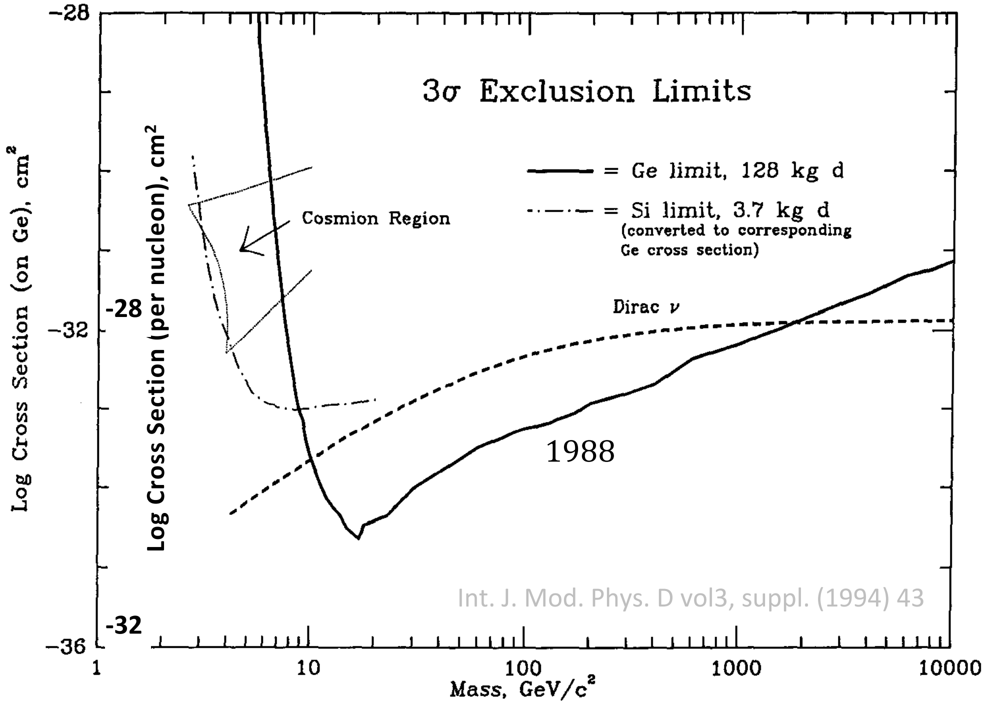


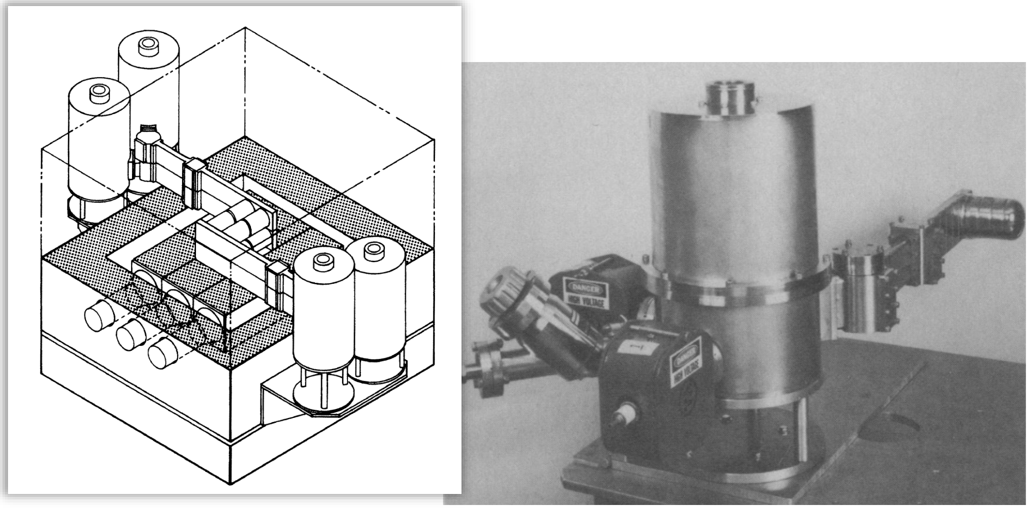
The first Kids on the Block

Semiconductors: high purity, low threshold



Ge detectors, developed for $0\nu\beta\beta$ search
With NaI veto, low-activity housing/shield
Oroville Experiment (1988)
Later also Si detectors (for DM search)





Since then: loads of Ge experiments with similar technique
Often tagged onto $0\nu\beta\beta$ experiments

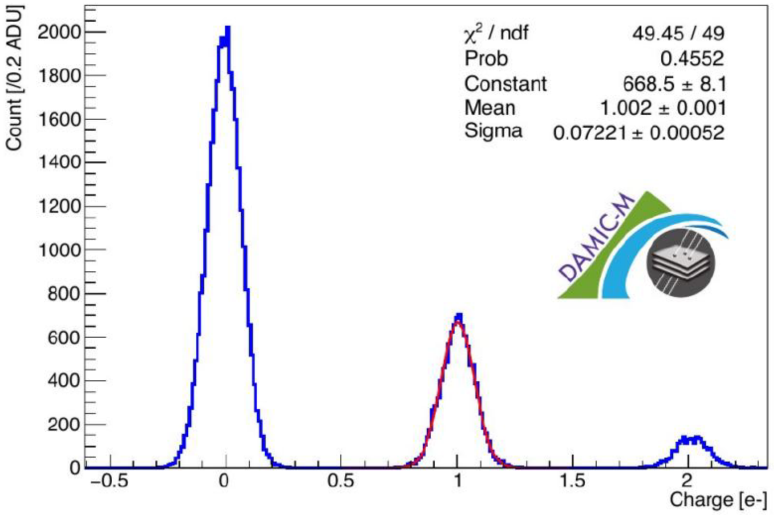
No Si as far as I know
However …

Imag(e)inative Descendants

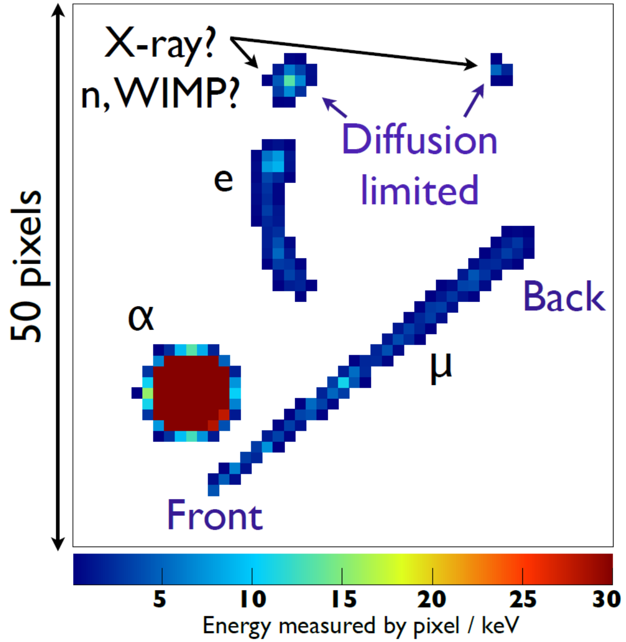
Dark Matter direct detection

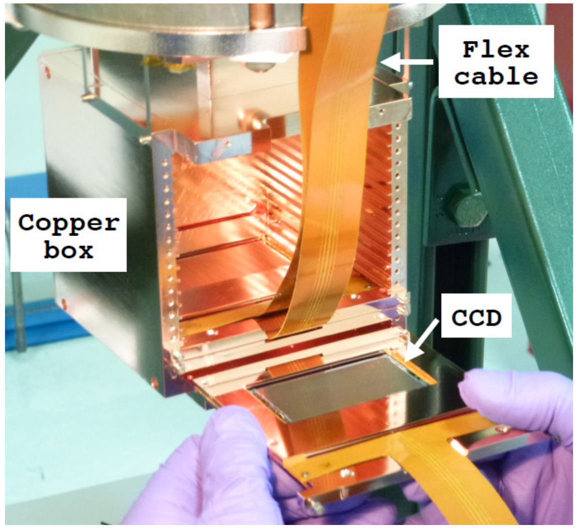
Silicon CCDs

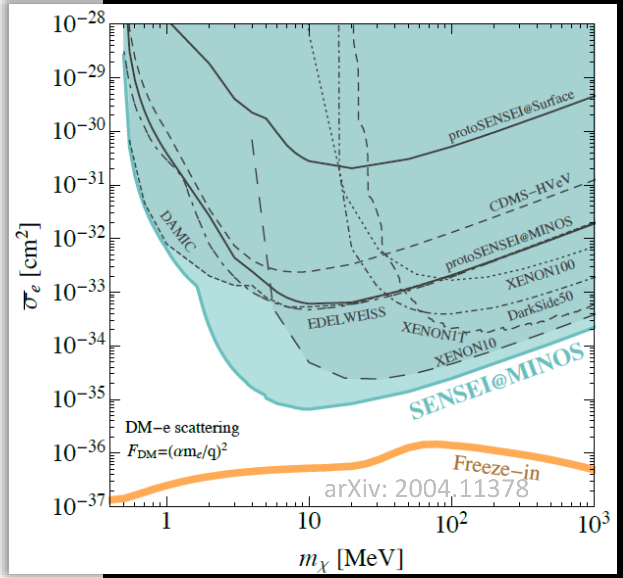
- Excellent position resolution (no timing though)
  $\rightarrow$ particle identification; background discrimination
- Improvements: 'Skipper CCD'
  measure same pixel often $\rightarrow$ single e^- resolution



arXiv: 2001.01209







- Relatively small mass per detector (build many)
- Primary contribution for electron-interacting DM (via Migdal, also very low-energy NR)

DAMIC (SNOLAB, Modane)
SENSEI (Fermilab, SNOLAB)

NOTE:
Mass scale is in MeV/c^2 (not GeV as usually for NR)

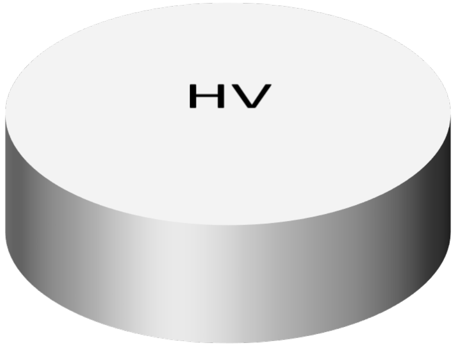
The really cool ones

Cryogenic detectors, typically operated @$\mathcal{O}$(10s of mK)

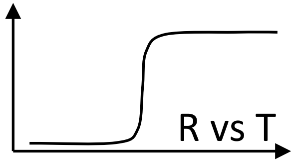
- Complex technology; (relatively) expensive detector production
- Excellent energy resolution
- Material flexible
- Can operate heterogeneous experiment
  (different materials, detector types)
- Semiconductors/scintillators: ER/NR discrimination
- Experiments
  - CDMS/SuperCDMS: Ge/Si (Stanford, Soudan, SNOLAB)
  - EDELWEISS: Ge (Modane, France)
  - CRESST: Al_2O_3 (sapphire), $CaWO_4$ (Gran Sasso, Italy)
  - Cosinus: NaI (Gran Sasso, Italy)
  - Future: SPICE/HeRALD (polar crystals (e.g. GaAs), suprafluid He)

The really cool ones – SuperCDMS

Dark Matter
direct detection

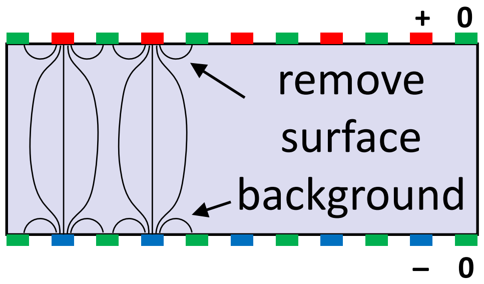


Phonon Readout:
Tungsten TES

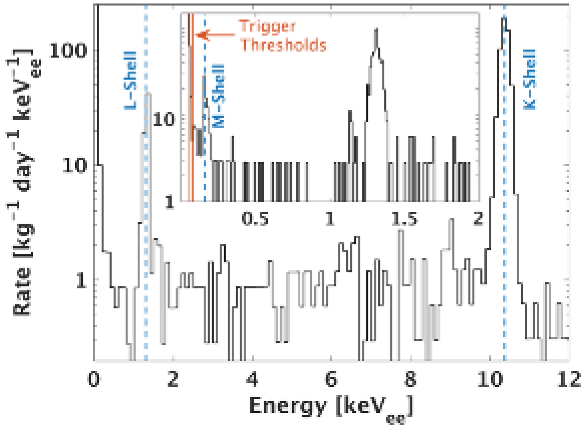


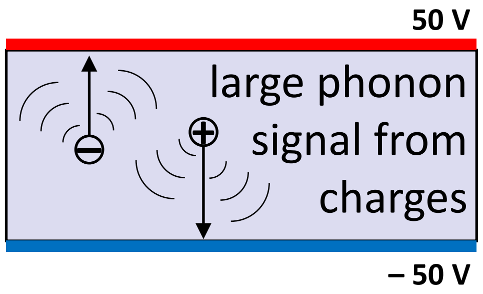
Add: charge readout (few V)
Background discrimination
Threshold < 1 keV

Add: high voltage 100 V)
Phonons from drifting charges
Threshold < 10 eV_{ee} (phonon)



< 1 background event for
whole exposure



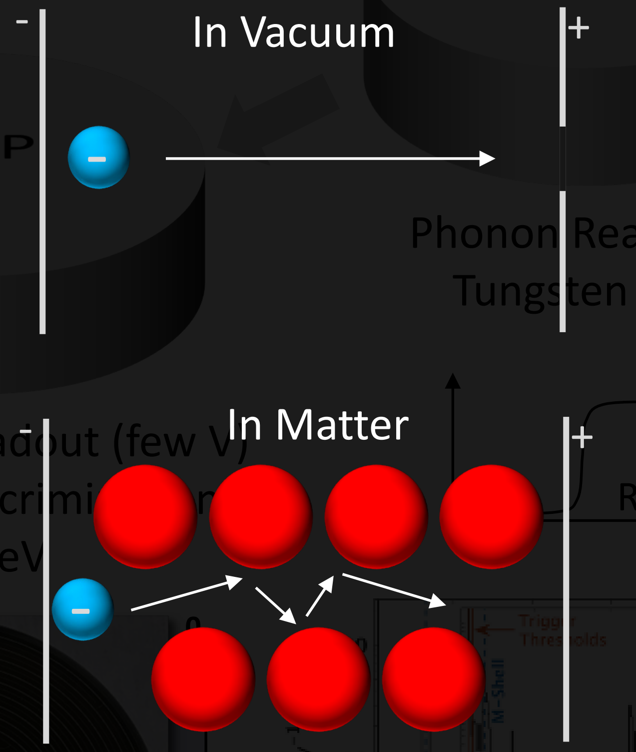


effective threshold: one
(or few) electron-hole pairs

The really cool ones – SuperCDMS

Dark Matter
direct detection

Neganov-Luke Effect



Electron gains kinetic energy
($E = q \cdot V \rightarrow 1\ eV$ for 1 V potential)

Deposited energy in crystal lattice:
Neganov-Luke phonons

$\propto$ V, # charges

- Luke phonons mix charge and phonon signal $\rightarrow$ reduced discrimination
- Apply high voltage $\rightarrow$ large final phonon signal, measures charge!!
- ER much more amplified than NR
  $\rightarrow$ gain in threshold; dilute background from ER

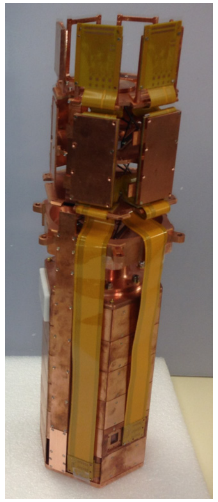
The really cool ones – SuperCDMS

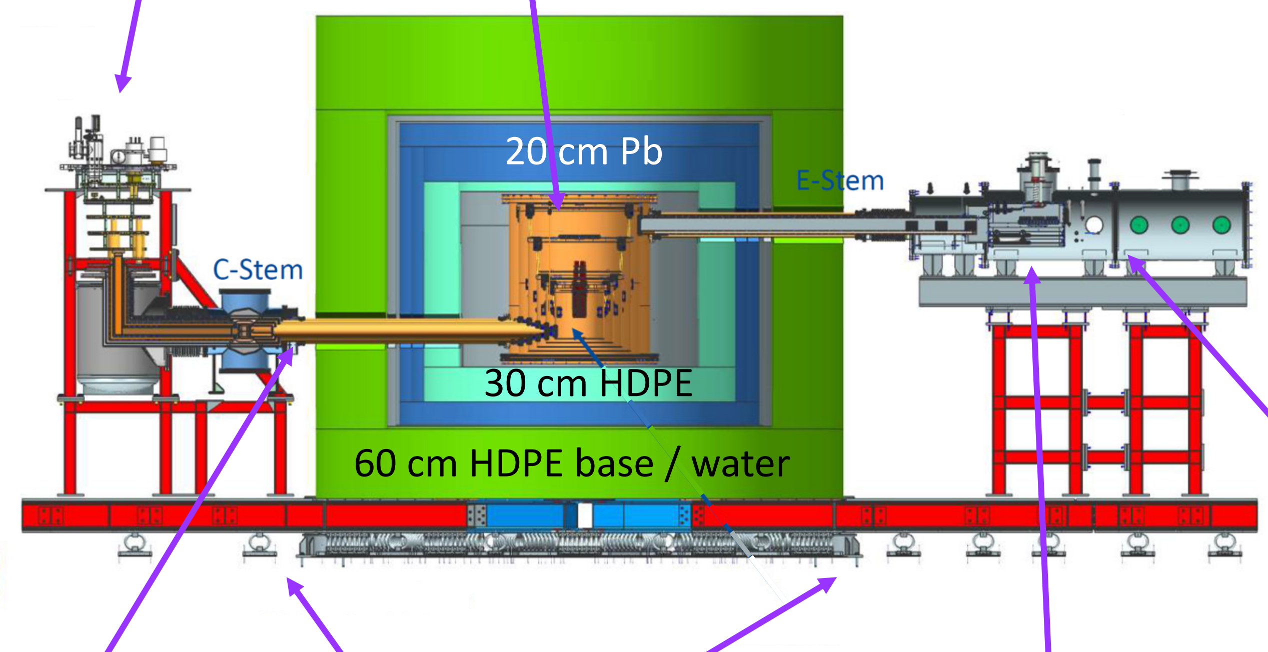
Implementation (SNOLAB setup)

Fridge to provide
<15 mK at the detector

Detector volume
(space for up to 7 “towers”)

Initial Payload:
2 HV towers (4 Ge/2Si)
1 Ge iZIP tower
1 Ge/Si iZIP tower (4/2)





6 detectors
→ 1 tower

Signal vacuum
feedthroughs

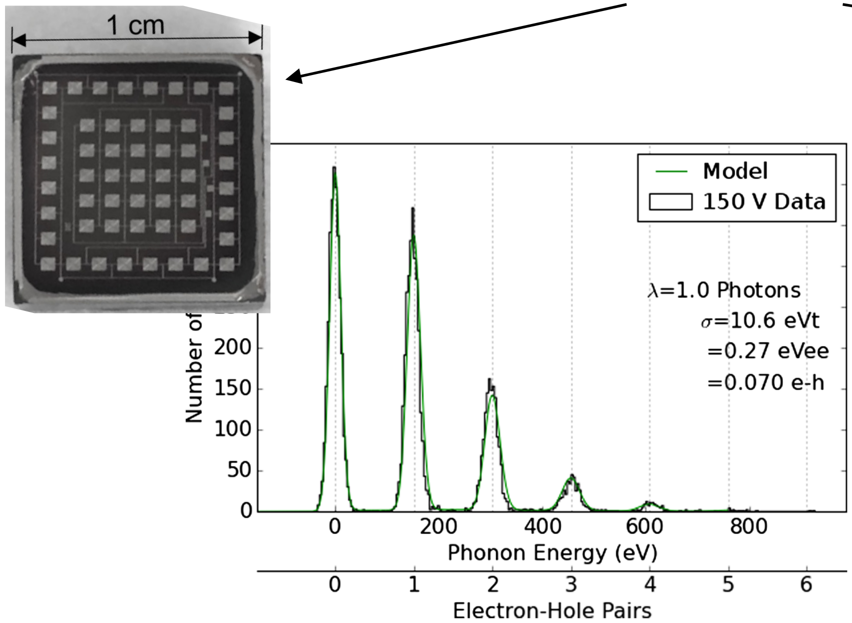
Cold finger

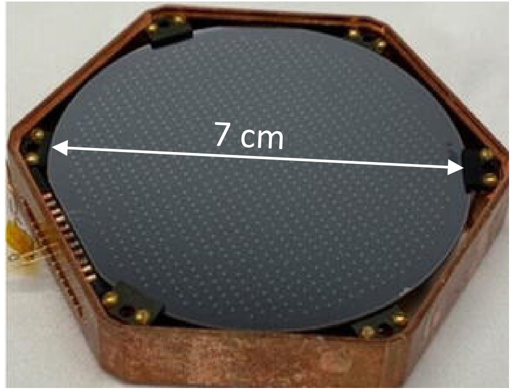
Mounted on spring-loaded
platform (seismic isolation)

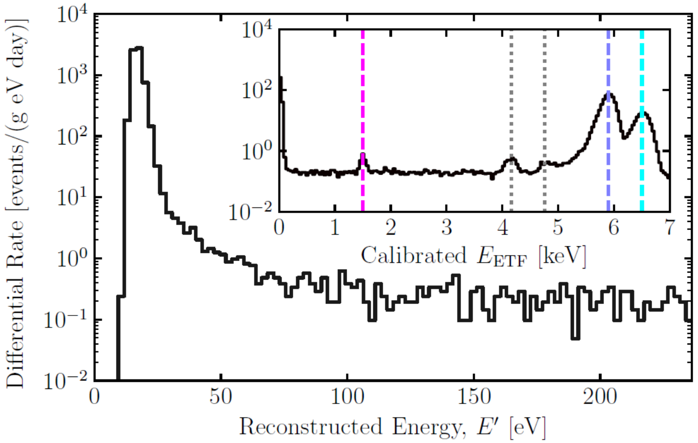
Additional cooling
(70 K/4 K)

The really cool ones – SuperCDMS

Low mass R&D detector (~1 g, Si / ~11 g Si)







- Same sensor technology
- Some improvements on sensor layout
- Neganov-Luke effect (150 V)
- Much higher E-field than in big detectors
- Designed for neutron scattering experiment

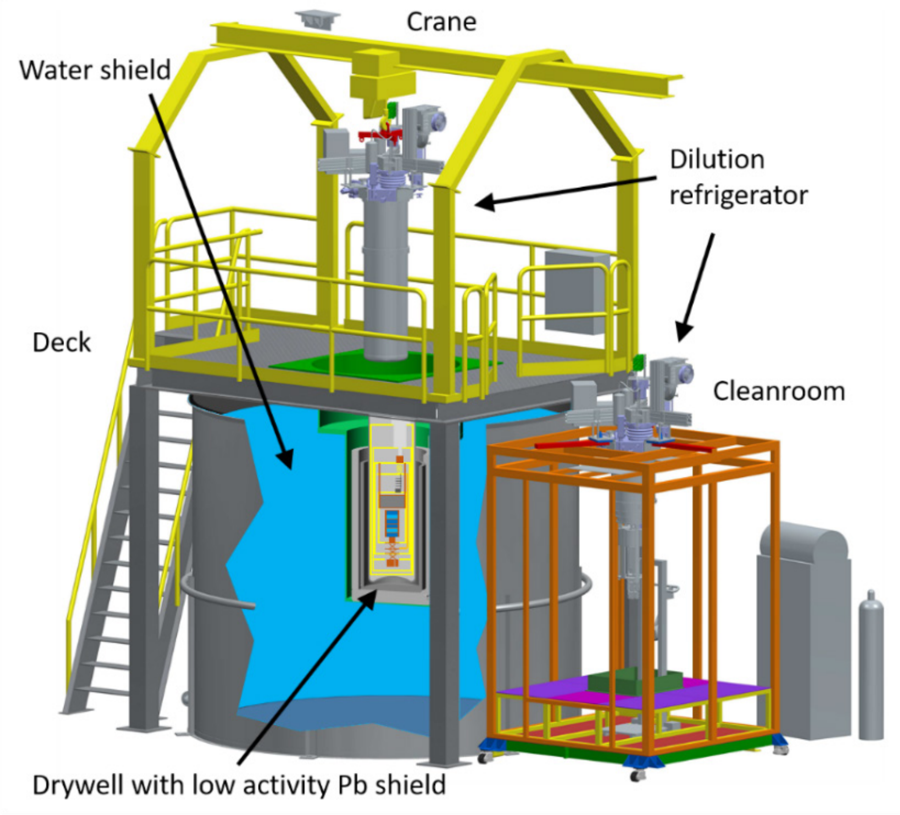
- Pure phonon detector (no bias voltage)
- Designed for photon detection at mK
- Baseline noise: σ< 4 eV
- Threshold <15 eV

The really cool ones – CUTE

Dark Matter
direct detection

Detector testing issues for SuperCDMS:
- Big detectors in unshielded lab: constant pile-up
- Cosmogenic radiation activates detectors
- Cannot check discrimination (ER/NR) due to BG

→ Need a well shielded
Cryogenic Underground TEst facility (CUTE)



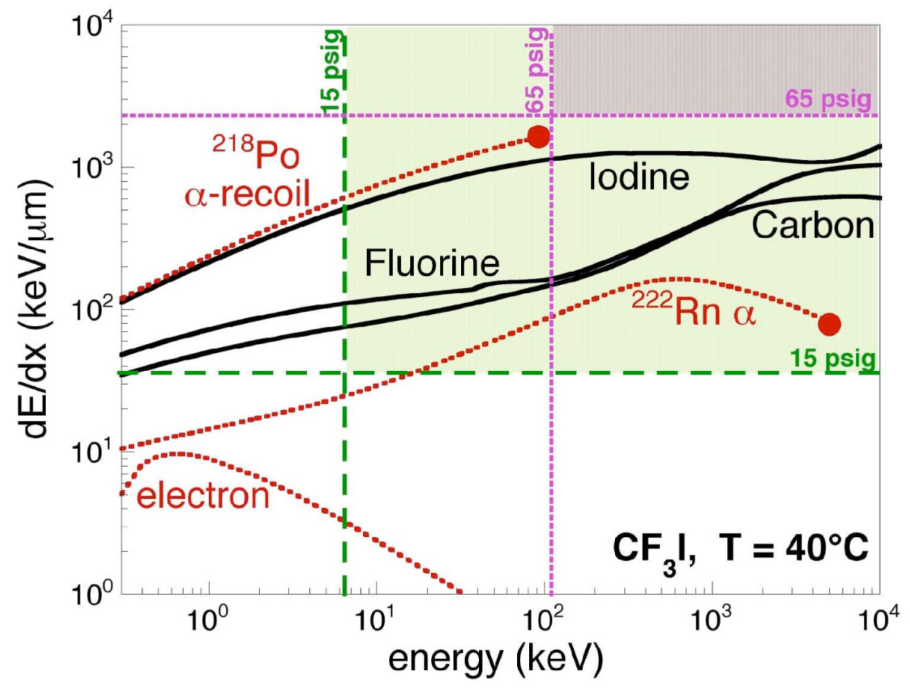
- Operational since 2019
- Operated a variety of detectors (testing facility and detectors
- First full test for big SuperCDMS detectors imminent
- Plans for DM search before full SuperCDMS setup is ready
- Later available for other projects

The hot stuff

Dark Matter direct detection

Superheated Liquids

- Liquid is above boiling temperature, but needs nucleation to evaporate
- Energy deposit from particle interaction forms tiny gas bubble
- If pressure in bubble is larger than surface tension: evaporation $\rightarrow$ need high enough ionization density



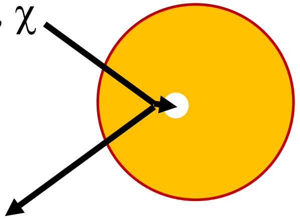
Discrimination:

- Nuclear recoils deposit their energy within a few Å
- Gammas Compton scatter and excite / ionize many atoms but far apart

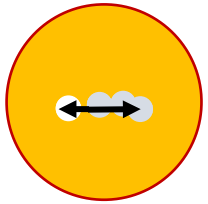
$\rightarrow$ Can choose operating conditions where sensitive to NR but not ER:
No gamma background; no gamma shielding necessary!!

- Alphas still trigger bubble formation – However…

n, χ



nuclear recoil:
one proto bubble



alpha decay:
many proto bubbles

alphas produce stronger pressure wave (aka: 'louder' bubbles)

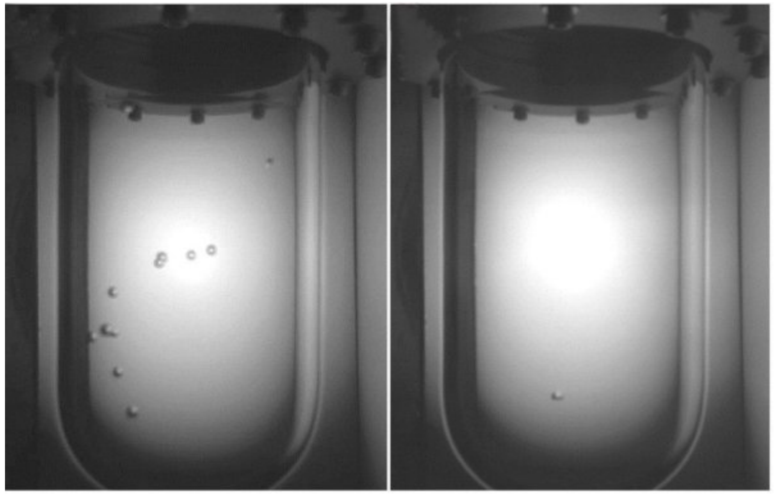
Neutrons: determine rate through multiple interactions

Can use different targt materials.
Present favourit: C_3F_8

F excellent for spin-dependent DM interactions (100 % ^{19}F)

The hot stuff

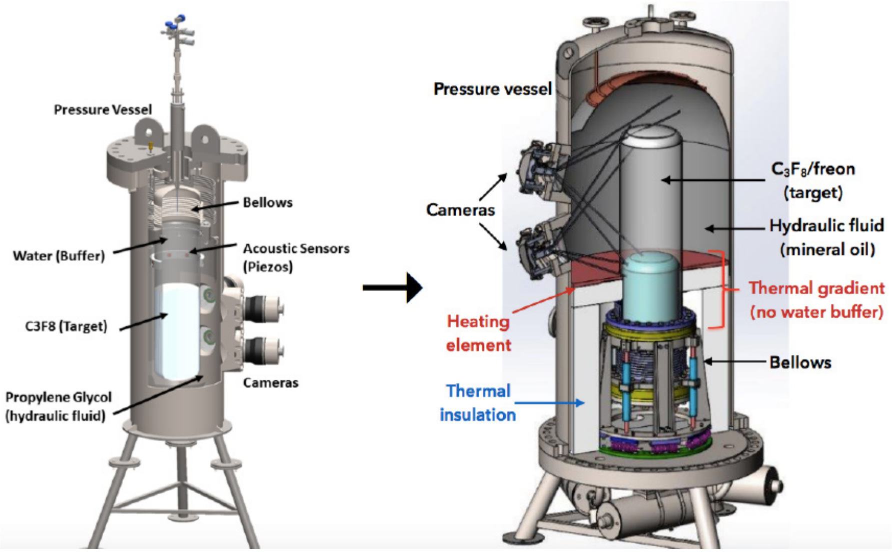
Two types of experiments:
- Droplets suspended in gel (PICASSO, SIMPLE): detect bursting bubbles by pressure waves; re-compress after a few hours
- Classical bubble chamber (COUPP, PICO) optical readout + acoustic/pressure compress after few ms to stop evaporation



Multi-bubble event in COUPP (neutron)

PICO/PICASSO: SNOLAB
COUPP: Fermilab
SIMPLE: LSBB (France)

PICO generations: 2L/60/40L/500
"Old" design: problem with debris



"New" design (40L/500): Right side up

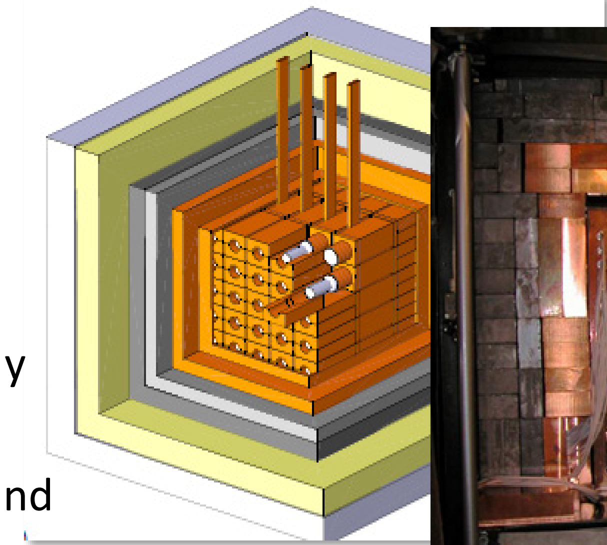
Spin-off: Scintillating bubble chamber ("SBC": liquid Ar/Xe; Fermilab/SNOLAB)

Scintillation suppresses bubbles: lower threshold without gamma background

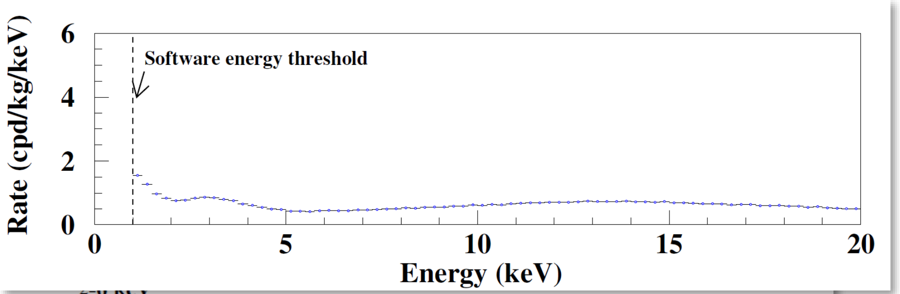
The DAMA Drama – DAMA/LIBRA

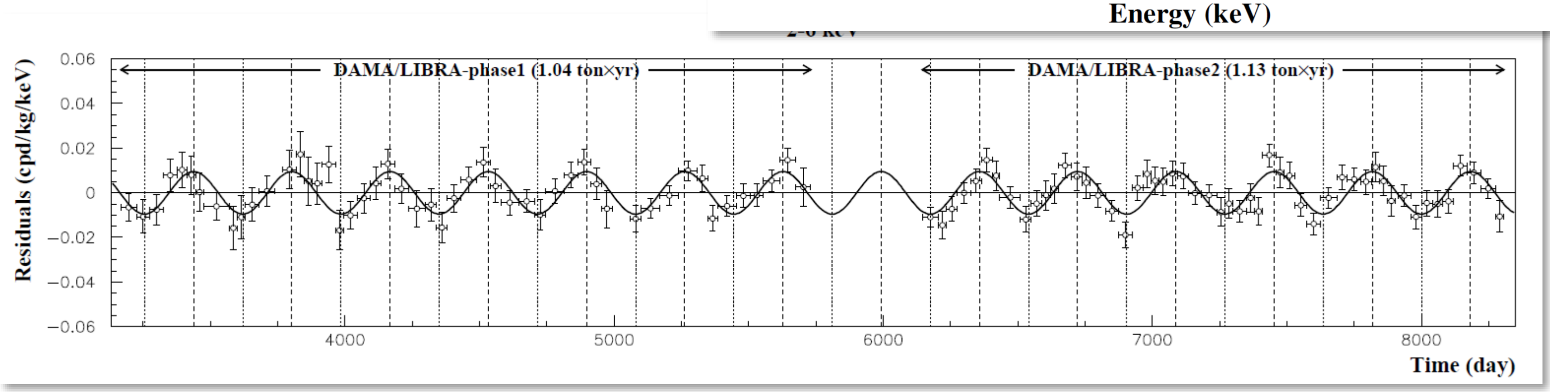
NaI scintillator, Gran Sasso

- Ultra low background NaI crystals (9.7 kg)
- Each crystal is watched by 2 PMTs
- Data: 7 years (1995-2002), 100 kg (DAMA) + 6 years (2003-2009), 250 kg (LIBRA) , 1.13 t y (as of 2018)
- Searching for annual modulation signal → found
- Interpretation controversial



Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere	**<0.2% S_m^{obs}**
TEMPERATURE	The installation is air-conditioned	**<0.5% S_m^{obs}**
NOISE	Effective noise rejection	**<1% S_m^{obs}**
ENERGY SCALE	Periodical calibrations + continuous monitoring of ^{210}Pb peak	**<1% S_m^{obs}**
EFFICIENCIES	Regularly measured by dedicated calibrations	**<1% S_m^{obs}**
BACKGROUND	No modulation observed above 6 keV; this limit includes possible effect of thermal and fast neutrons	**<0.5% S_m^{obs}**
SIDE REACTIONS	Muon flux variation measured by MACRO	**<0.3% S_m^{obs}**



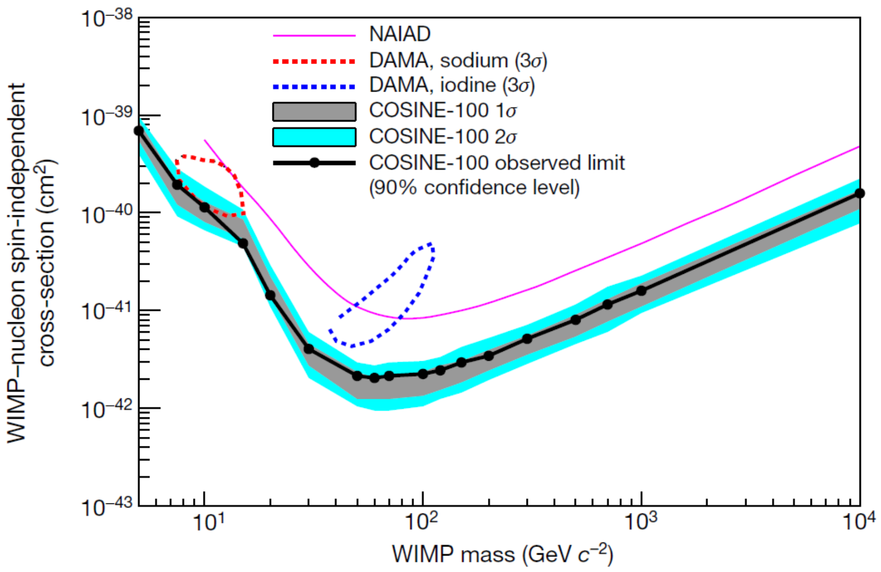


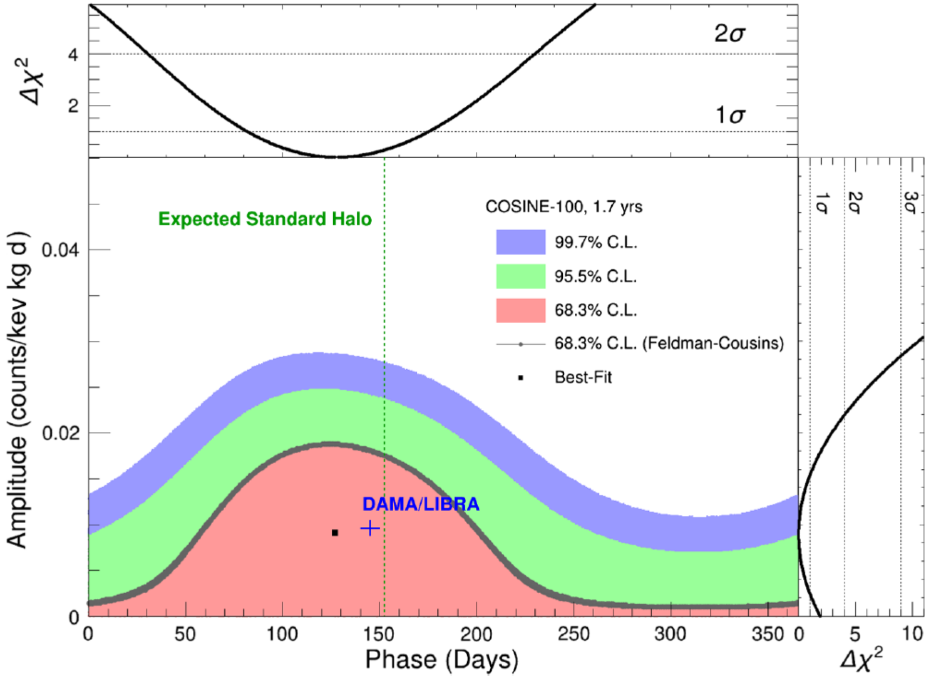
arXiv: 1805.10486

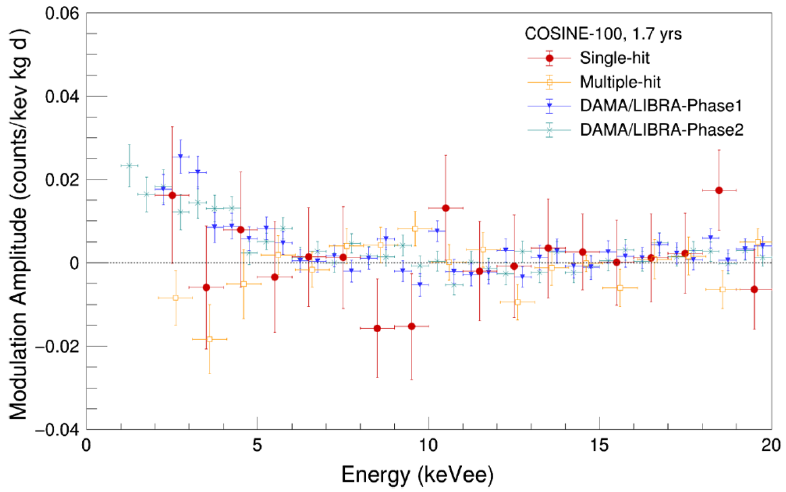
The DAMA Drama – COSINE

NaI, Yangyang Underground Lab (Y2L), Korea

- ~100 kg NaI with liquid scintillator veto
- Specifically built to test DAMA claim
- Challenging to get background low
- Rate based analysis in tension with DAMA
- First modulation analysis







- Consistent with DAMA/LIBRA – and with 0 …

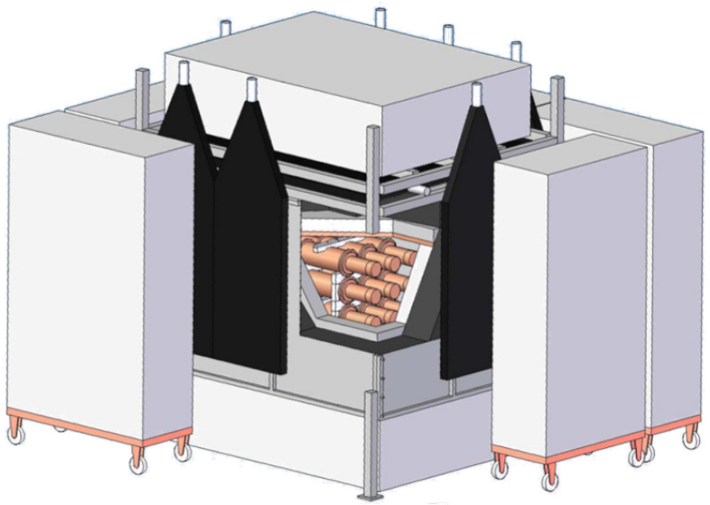
Nature 564 (2018) 83 & PRL 123 (2019) 031302

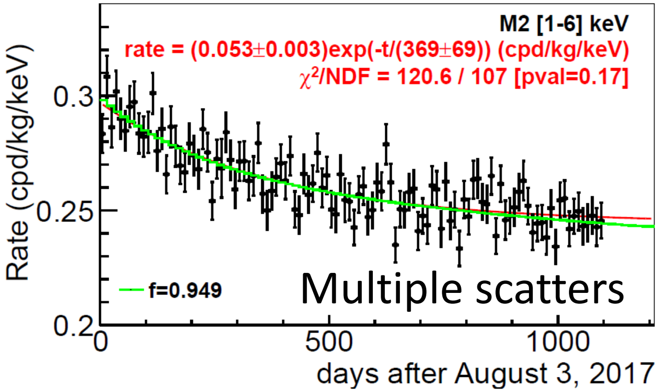
The DAMA Drama – ANAIS

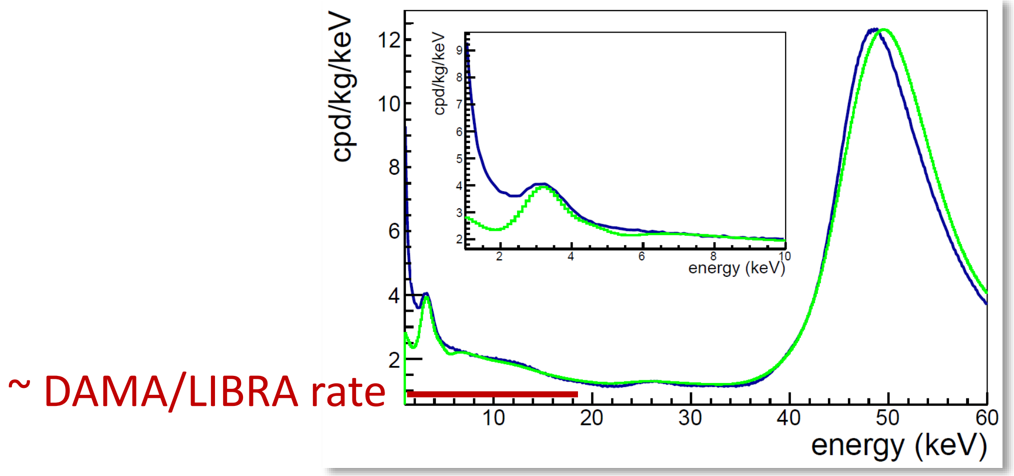
Dark Matter direct detection

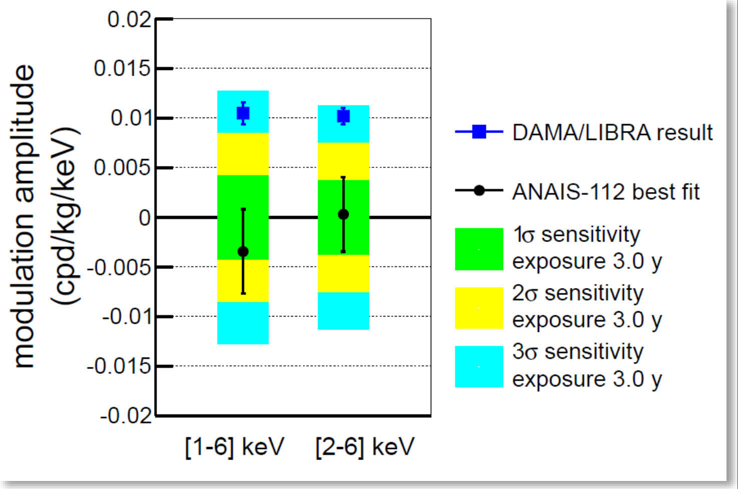
NaI, Canfranc Lab (LSC), Spain

- ~112 kg NaI, muon veto, passive shielding
- Specifically built to test DAMA claim
- Challenging to get background low
- Modulation analysis









The End ?

arXiv: 2103.01175

More NaI experiments:

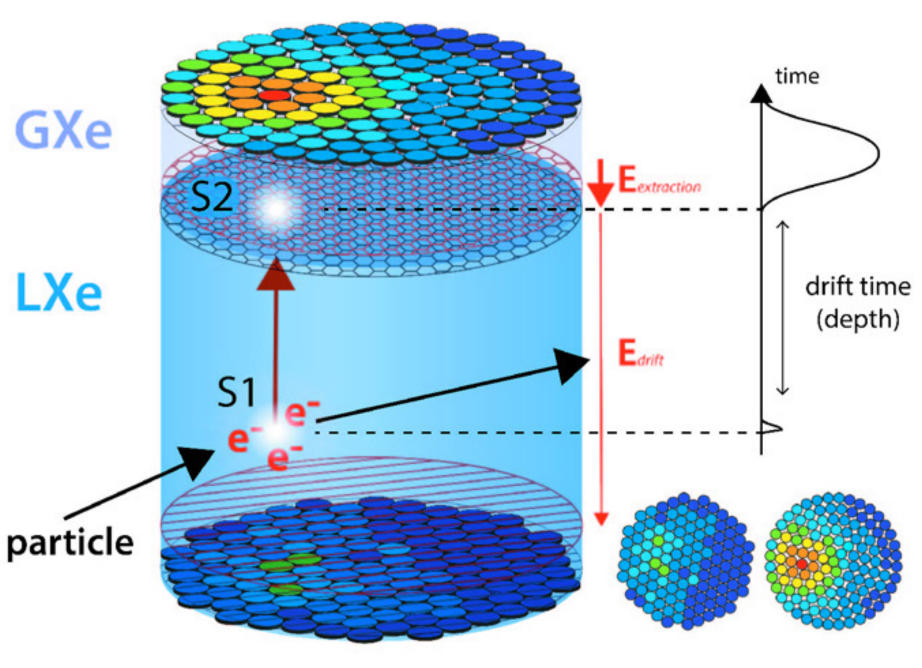
NaIAD (UK)
DM-ICE (South Pole)
SABRE (Italy/Australia)
COSINUS (Italy, cryo)

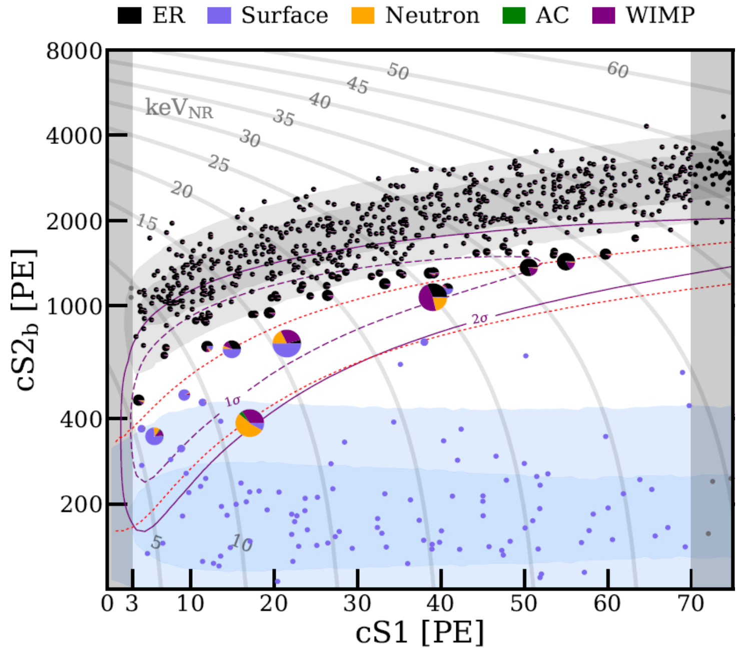
The Xenon Frenzy

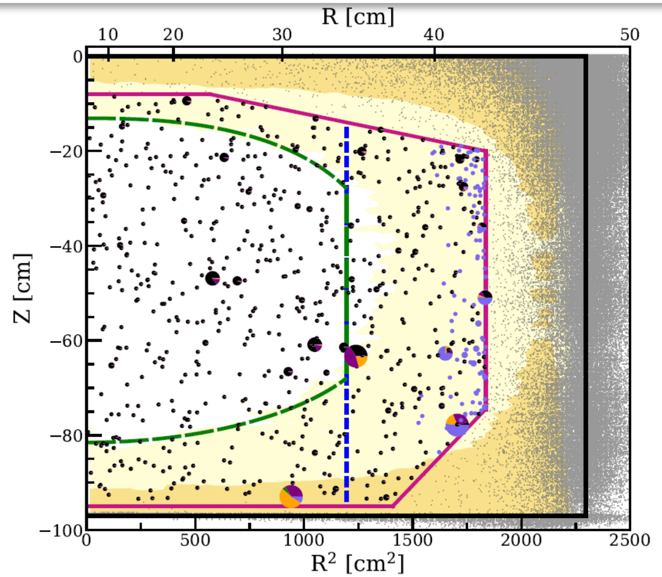
Dark Matter direct detection

Xenon: excellent scintillator, strong self-shielding

- Pure scintillators:
  DAMA/Xe (Italy), ZEPLIN I (UK), XMASS (Japan)
- Since ~2005: dual phase experiments
  ZEPLIN (UK), XENON (Italy), LUX/LZ (US), PandaX (China), DARWIN (Italy?)
- Ionization/scintillation discriminates ER/NR
  (not perfect, but ER rate overall low)



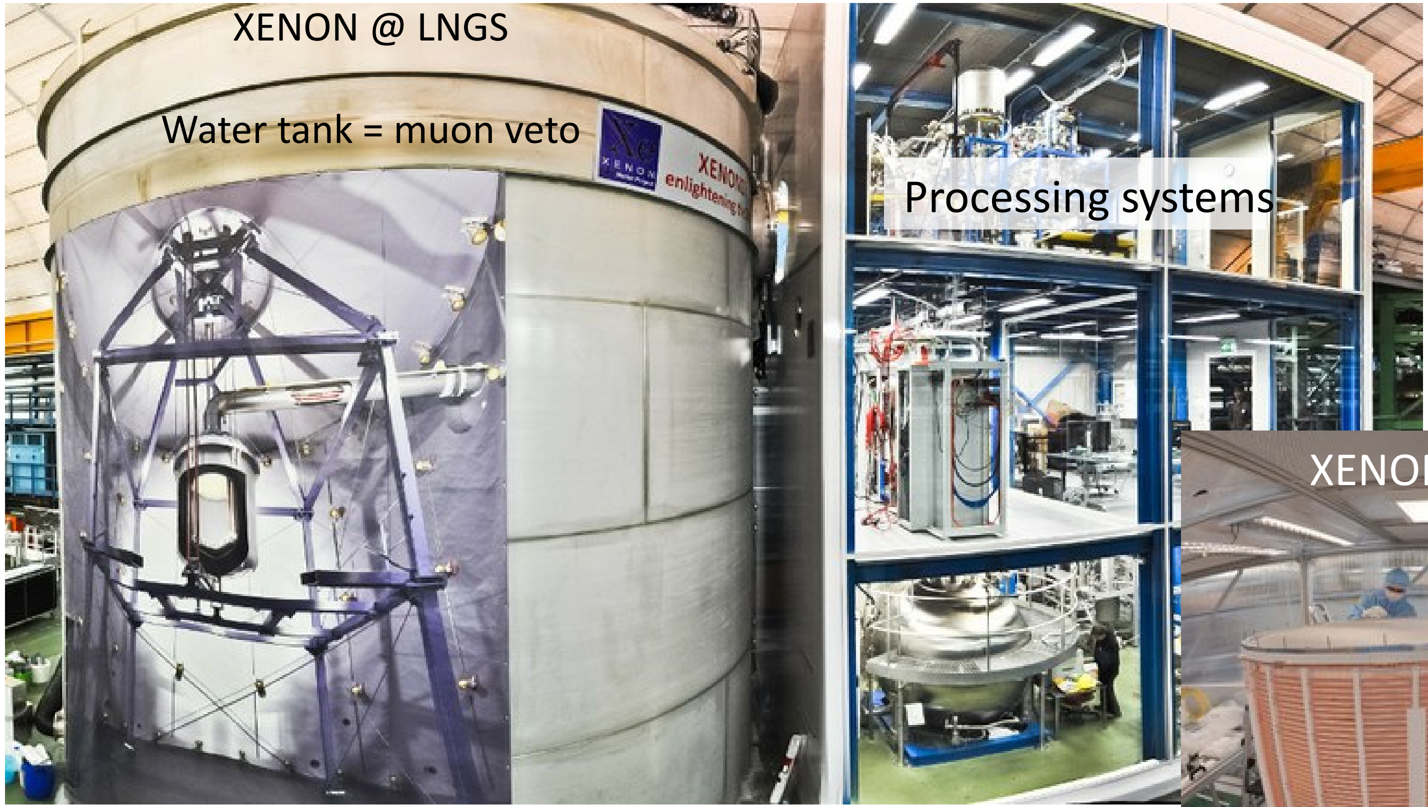




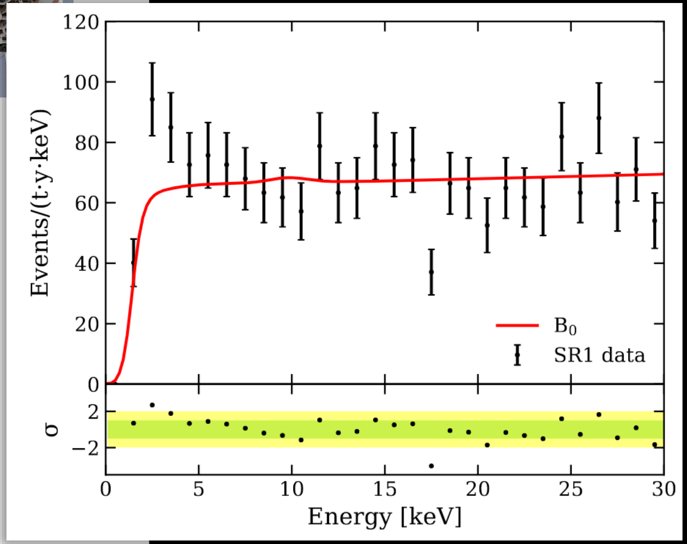
The Xenon Frenzy

Dark Matter
direct detection

Example XENON



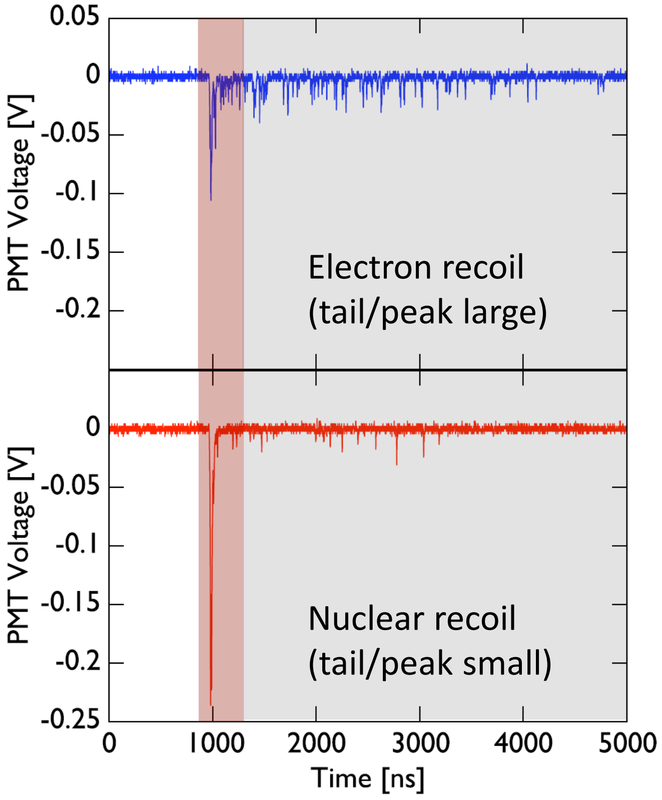
XENON1t: excess at low energy – Axions? (or ^3H?)



Big, Bigger, Biggest

Argon: excellent scintillator

- Strong pulse shape difference b/w ER and NR ($\mathcal{O}(10^{-9})$) ER rejection at 50 % NR efficiency
- Ionization/scintillation also discriminates ER vs. NR
- Problem: large contamination from ^{39}Ar (~1 Bq/kg)
- Solution: Ar from underground >1e3× less ^{39}Ar (in addition to discrimination)
- Many experiments:
  - Single phase: DEAP3600, MiniClean
  - Dual phase: WARP, ArDM, DarkSide
    TPC allows for very effective surface event rejection
    DarkSide uses underground Ar



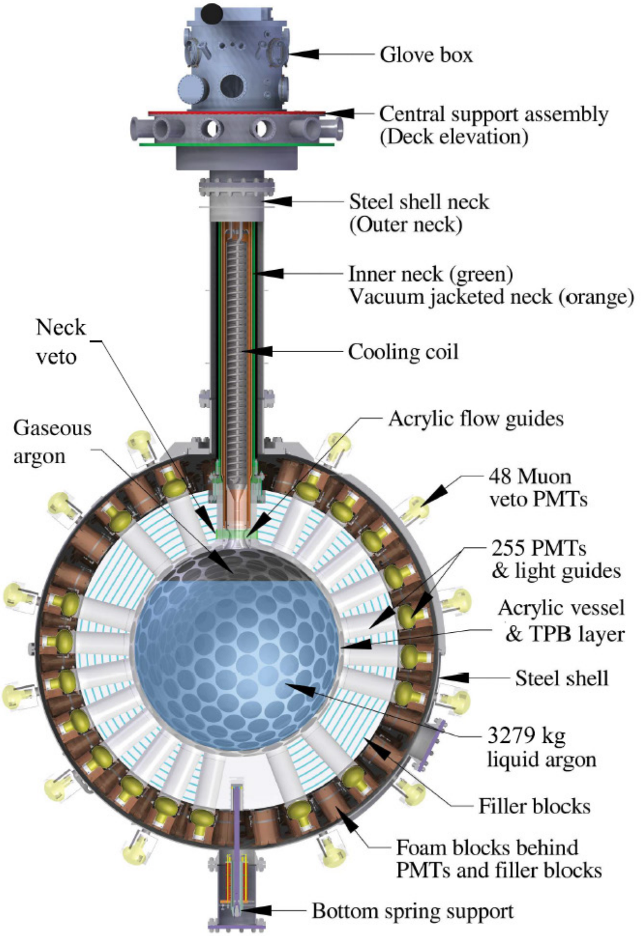
Dual phase technology used on very large scale for neutrino oscillation experiments (ICARUS, DUNE)

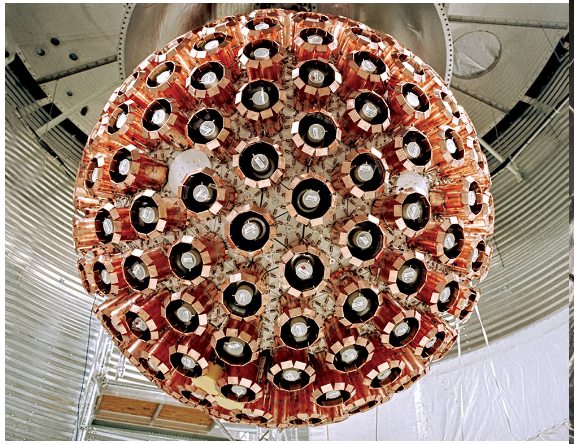
Big, Bigger, Biggest

Dark Matter direct detection

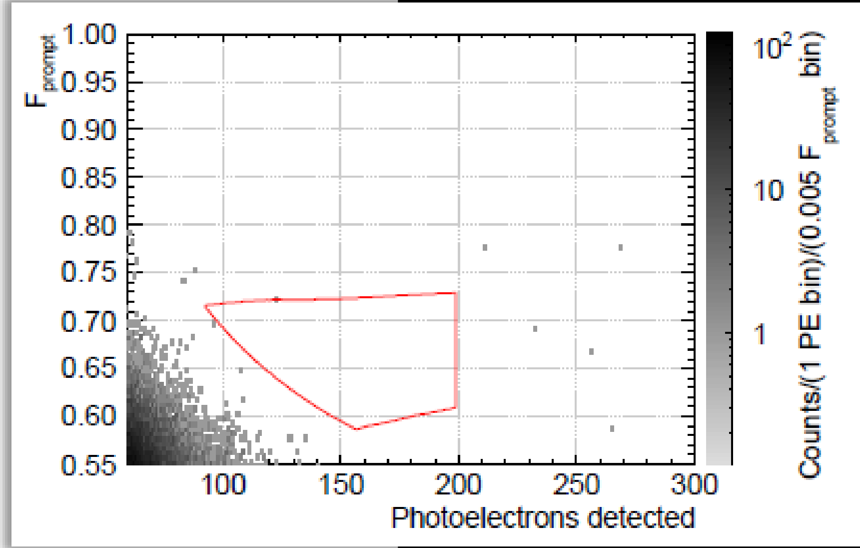
DEAP: 3.3 t single phase Ar at SNOLAB, water veto

- Start of operations: 2016
- ~2 ton-years of data published





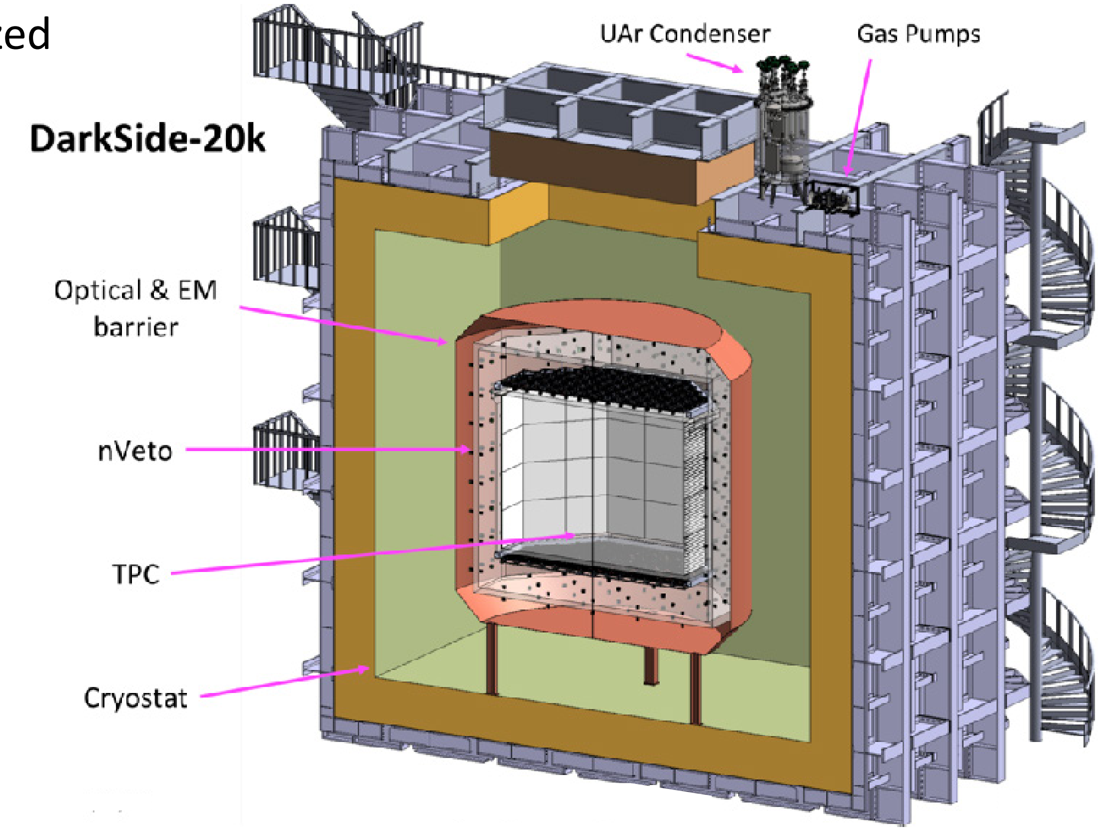
- Analysis: non-blind; no background found (but a few events very close)
- More data being analyzed
- Repair in progress (fix problem with 'neck', so can fill detector to the top)



Big, Bigger, Biggest

Future of the LAr program

- Expansion of underground Ar (UAr) production
- Attempt distillation for further isotopic enrichment
- Global LAr collaboration (DEAP, DarkSide, ArDM, CLEAN):
  - DarkSide-20k (20 t UAr) at Gran Sasso (Italy), under construction
  - Possibly DarkSide-LM (optimized for low mass search)
  - ARGO: 500 ton UAr at SNOLAB (proposed) single or dual phase (TBD)



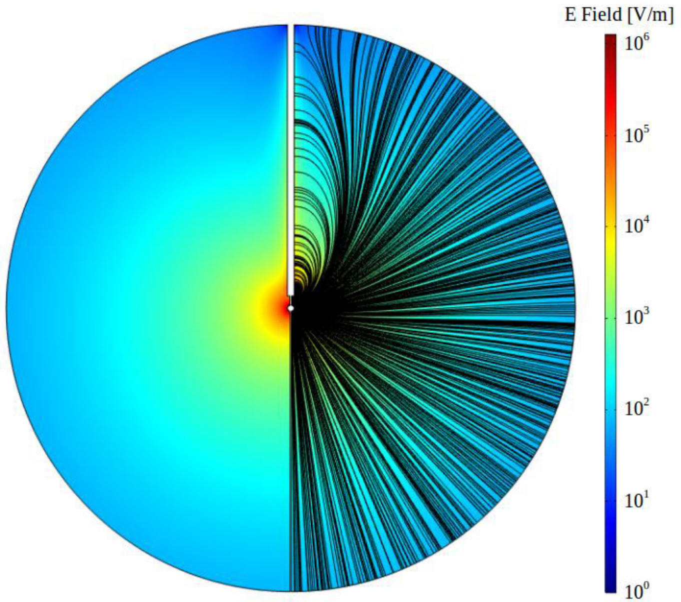
The Spherical Cow

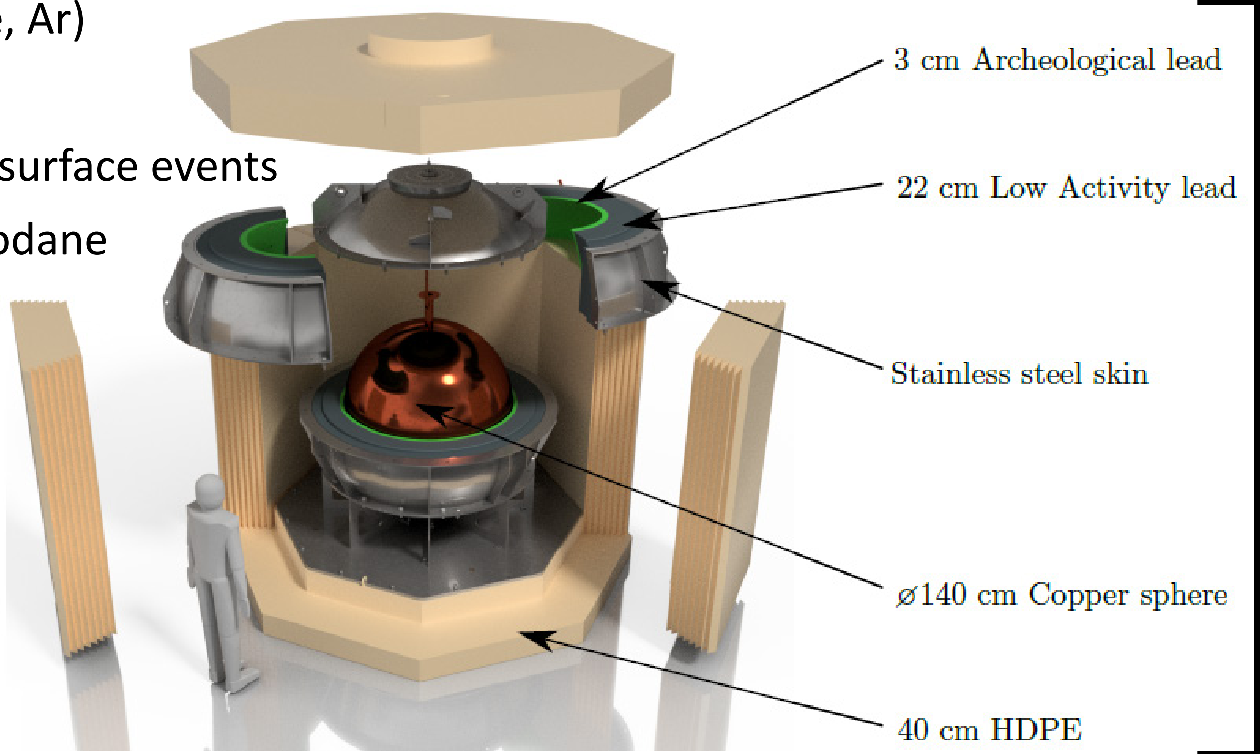
TRISEP 2021 PI · SNOLAB · TRIUMF

Dark Matter direct detection

Spherical gas detector at SNOLAB: NEWS-G

- Strong field in the centre: gas amplification (“avalanche”)
- Low-activity Cu sphere with low-activity Pb and PE shielding
- Can use different gases (CH_4, Ne, Ar)
- Simple readout, low threshold
- Pulse shape rejects long traces, surface events
- First data from operations at Modane

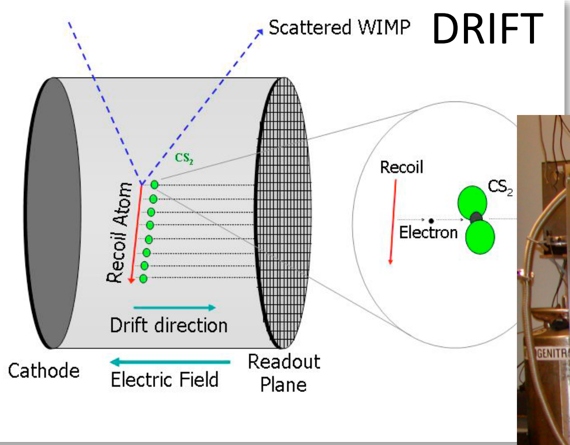


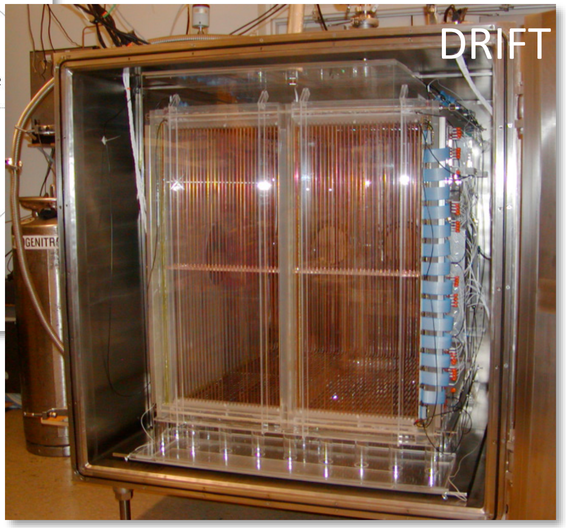


What else there is …

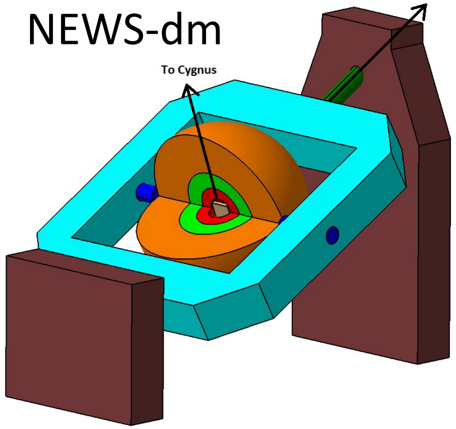
Examples for Directional Detection

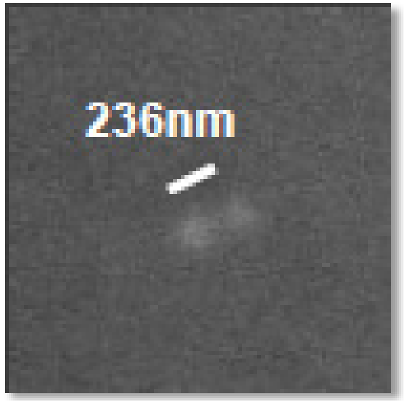
- DRIFT: gas TPC (Boulby Mine, UK)
  139 g/m^3 of $CS_2/CF_4/O_2$ (30:10:1)
  No ER sensitivity (ionization density)
- NEWS-dm: emulsion (R&D stage)
  Excellent position information but high threshold (10s of keV);
  no real-time information: keep orientation constant wrt galaxy
- General problem
  High-mass DM: need very large mass (presently not feasible)
  Low-mass DM: tracks for low-energy interactions too short
- New ideas exist (e.g. use un-isotropy of crystals for direction-dependent threshold for very low-energy interactions).





NEWS-dm

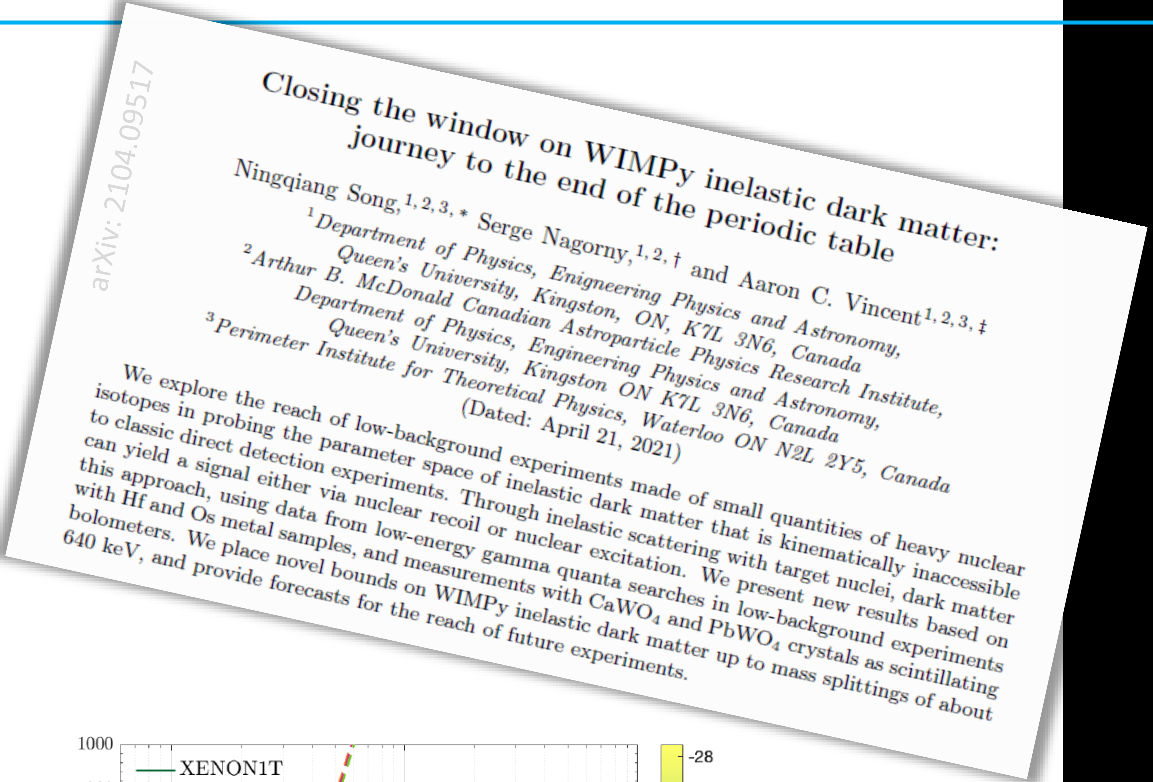




What else there is …

Example for Inelastic Dark Matter

- DM particles with excited state
- Scattering process differs from elastic scattering
- Limits on mass-splitting as function of DM mass


arXiv: 2104.09517

Closing the window on WIMPy inelastic dark matter: journey to the end of the periodic table

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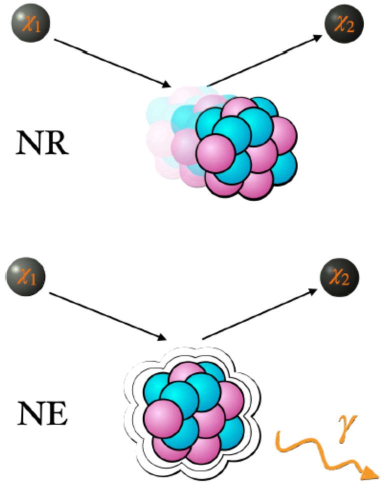
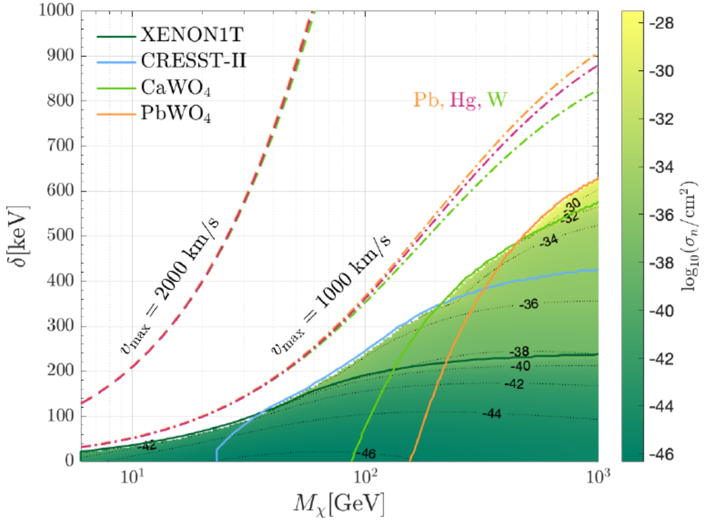
(Dated: April 21, 2021)

We explore the reach of low-background experiments made of small quantities of heavy nuclear isotopes in probing the parameter space of inelastic dark matter that is kinematically inaccessible to classic direct detection experiments. Through inelastic scattering with target nuclei, dark matter can yield a signal either via nuclear recoil or nuclear excitation. We present new results based on this approach, using data from low-energy gamma quanta searches in low-background experiments with Hf and Os metal samples, and measurements with $CaWO_4$ and $PbWO_4$ crystals as scintillating bolometers. We place novel bounds on WIMPy inelastic dark matter up to mass splittings of about 640 keV, and provide forecasts for the reach of future experiments.





What else there is …

Example for 'crazy' ideas

(however: real, not bogus)

Note: outside the mass range I promised to cover…

Death and Serious Injury from Dark Matter

Jagjit Singh Sidhu[a,*], Robert Scherrer[b], Glenn Starkman[a]

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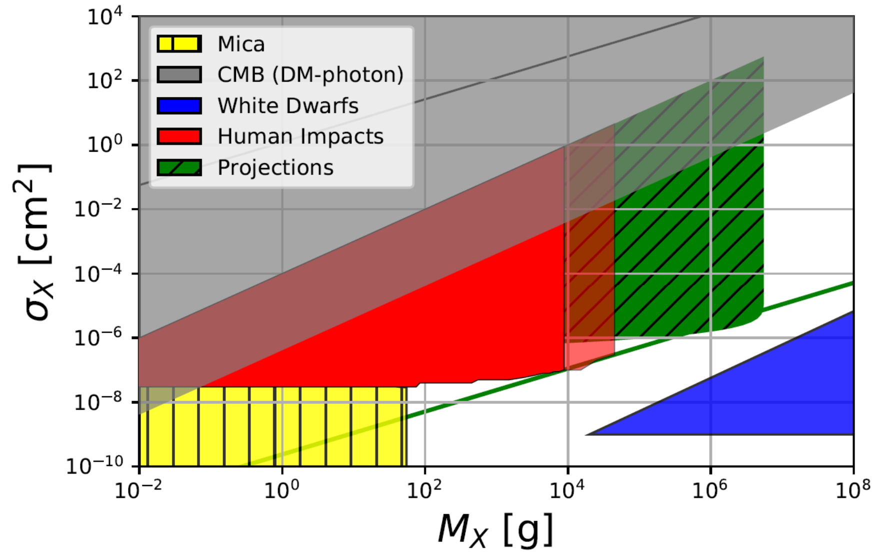
Abstract

Macroscopic dark matter (macros) refers to a class of dark matter candidates that scatter elastically off of ordinary matter with a large geometric cross-section. A wide range of macro masses M_X and cross-sections σ_X remain unprobed. We show that over a wide region within the unexplored parameter space, collisions of a macro with a human body would result in serious injury or death. We use the absence of such unexplained impacts with a well-monitored subset of the human population to exclude a region bounded by $\sigma_X > 10^{-8} - 10^{-7}$ cm^2 and $M_X < 50$ kg. Our results open a new window on dark matter: the human body as a dark matter detector



What will we talk about?

Background and Context

- Dark Matter interactions
  - Kinematics and other considerations
  - Expected DM signal spectra
  - DM signatures
- Background
  - Expected Signal Rates
  - Background sources and mitigation strategies
- Analysis
  - Assumptions
  - Extracting limits or confidence regions
- Detection Mechanisms
  - Electronic excitations and nuclear recoils
  - Special effects at low energy
- Calibration
  - Electron recoil energy scale
  - Nuclear recoil energy scale

Experiments

- The first Kids on the Block
- The Imag(e)inative Descendants
- The really cool ones
- The hot stuff
- The DAMA Drama
- The Xenon Frenzy
- Big, Bigger, Biggest
- The spherical Cow
- What else there is …

Results

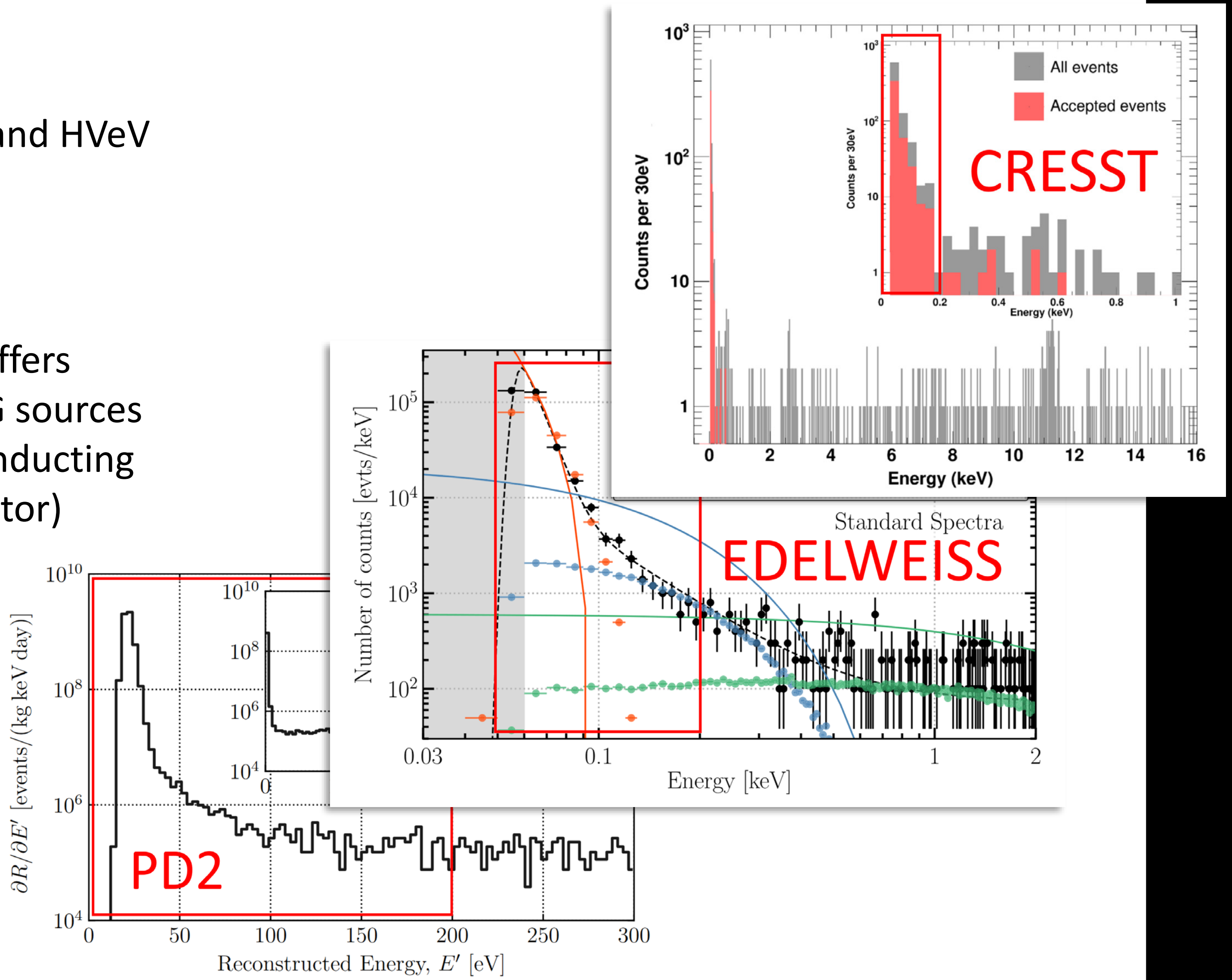
Results – Low energy excess

Several low-threshold experiments found an unexpected excess well below 1 keV:

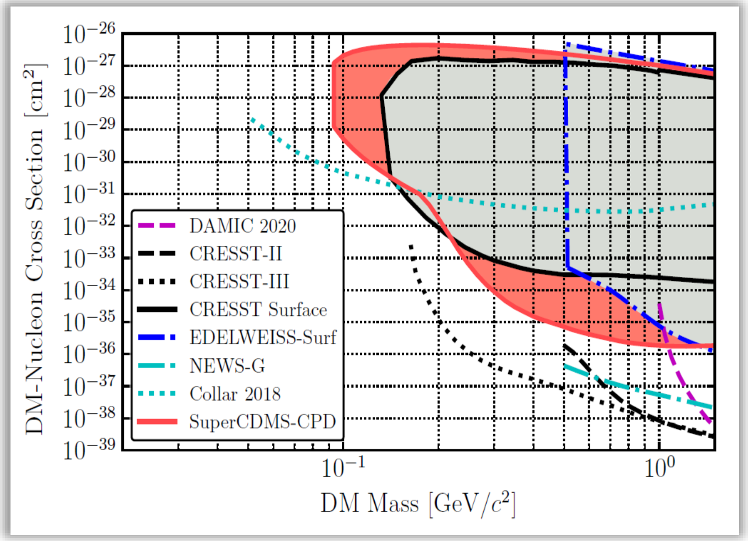
- CRESST
- EDELWEISS
- SuperCDMS (PD2/CPD) and HVeV
- DAMIC
- SENSEI

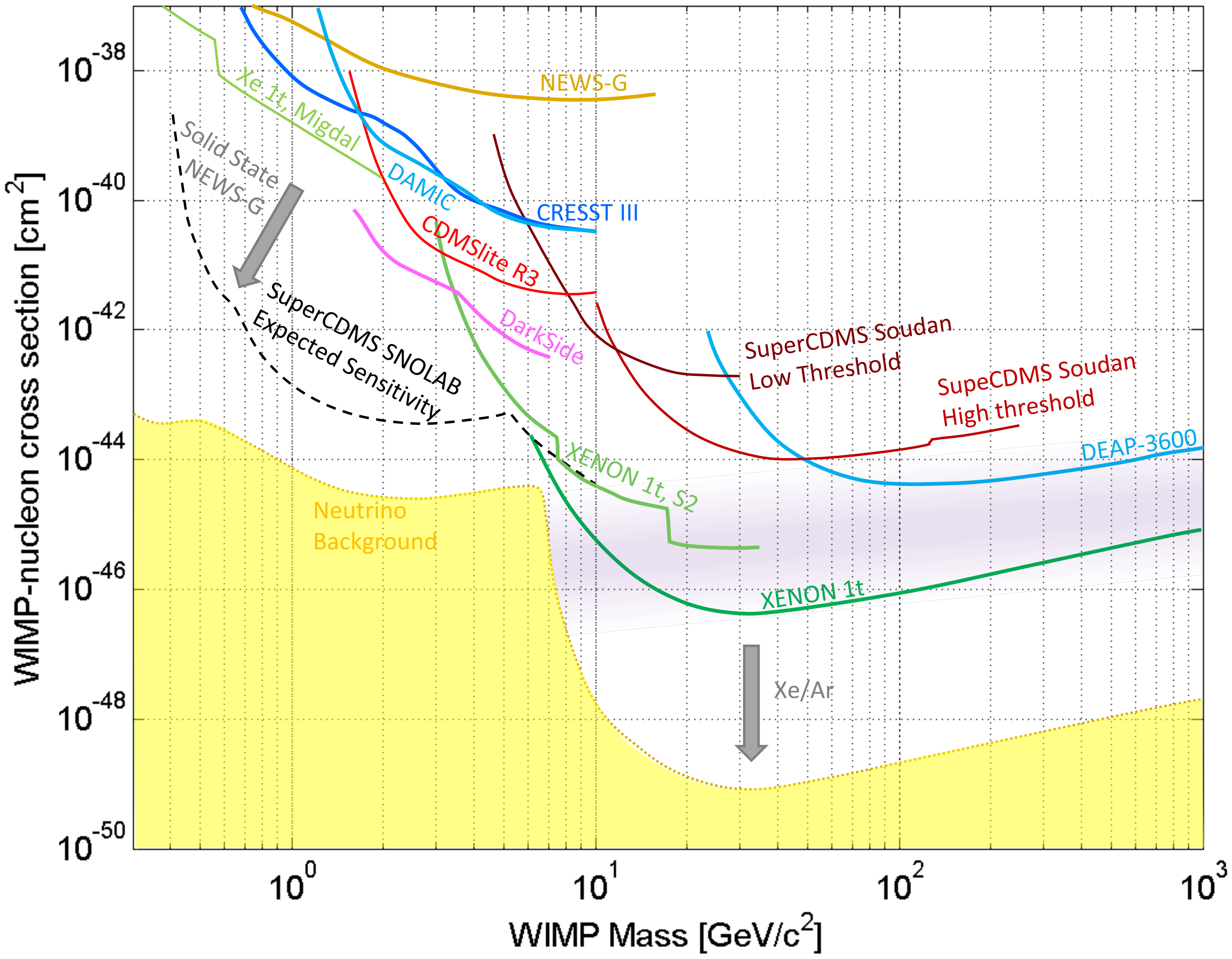
Could this be DM?

- Rate and energy scale differs
- Some suggestions for BG sources (fluorescence of non-conducting materials near the detector)
- Investigations underway



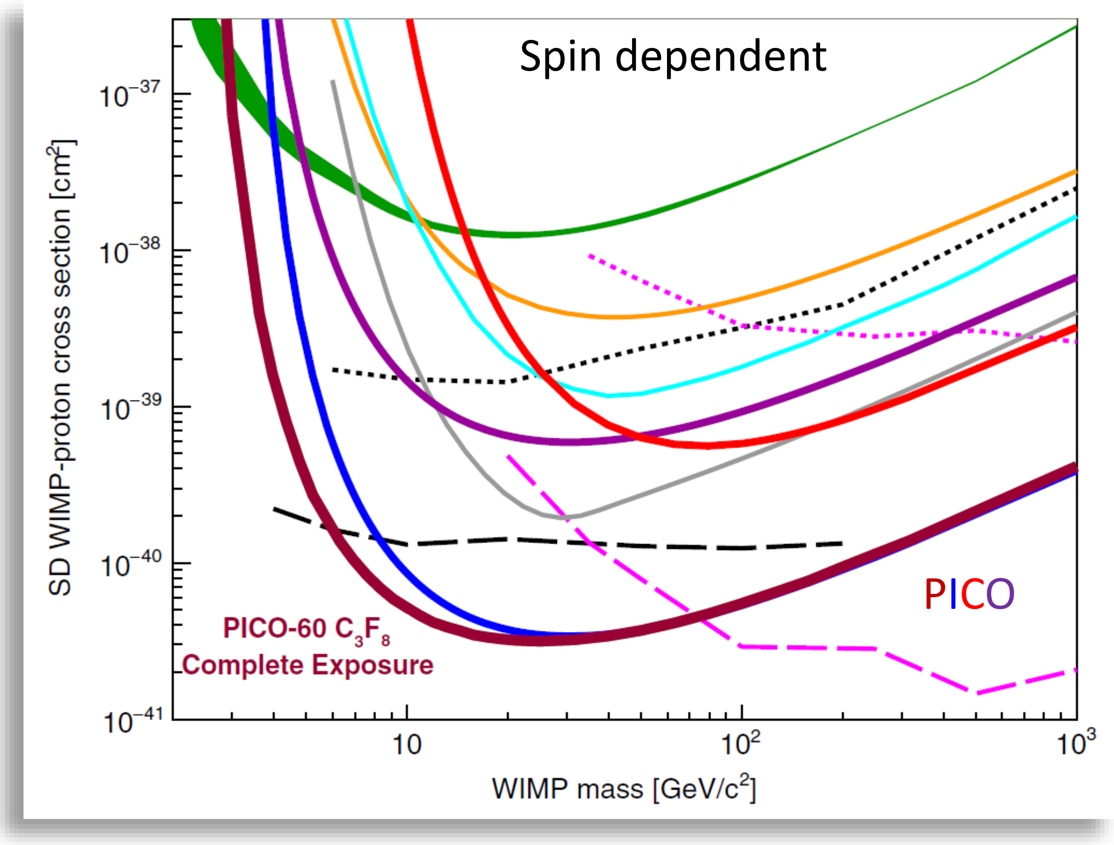
Results – DM limits (NR)



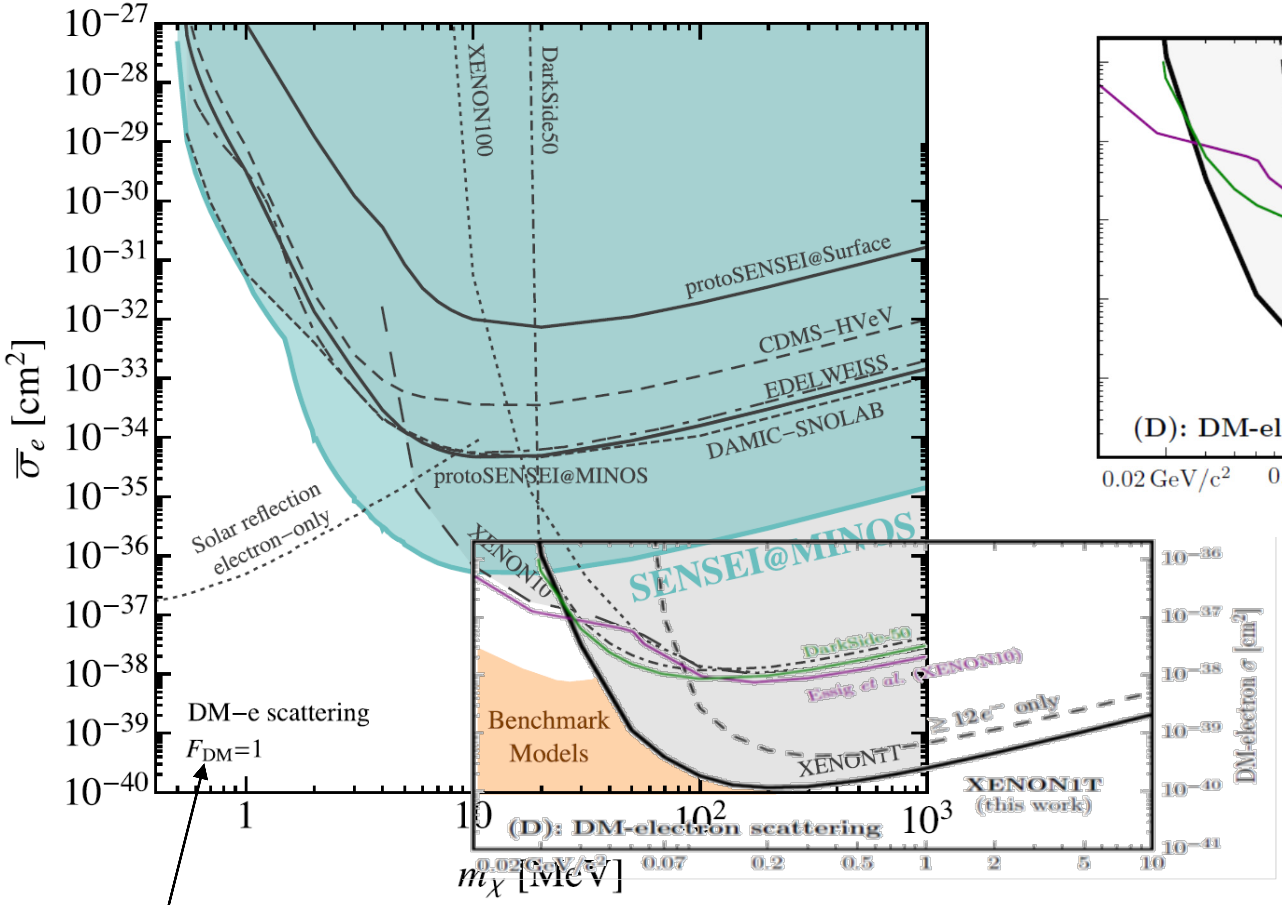


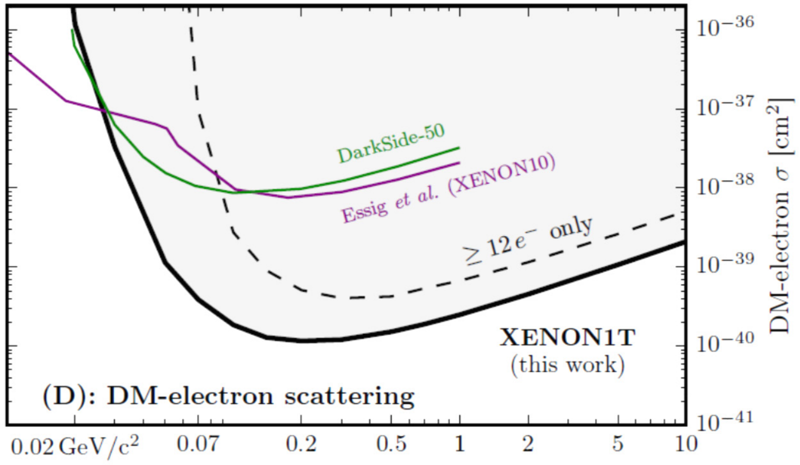
Results – DM limits (NR)

Dark Matter direct detection



Results – Electron-interacting DM

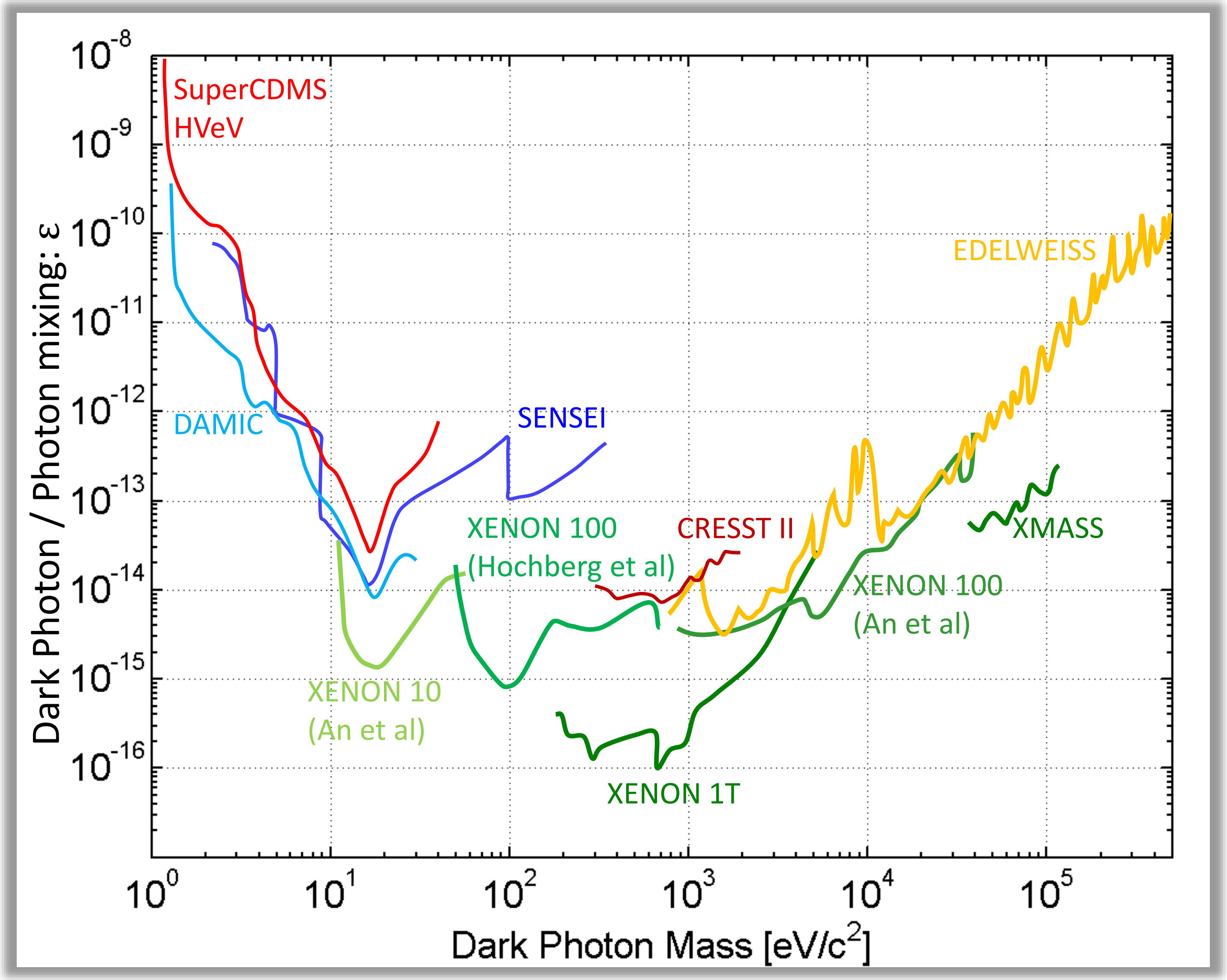




Form factor for a light mediator
(different limits apply for heavy mediators)

Results – Electron-interacting DM

Dark Matter direct detection



Conclusions

- Direct detection experiments improved their sensitivity by over 15 orders of magnitude since the start
- "Vanilla WIMP" search has reached (if not surpassed) prime time
- Experiments and analyses are branching out to alternative DM Models:
  - Lower masses (non-thermal production, dark sector …)
  - Alternative interaction mechanisms ("EFT")
  - Electron-interacting DM (scattering and absorption)
- Within the next 10-15 years: reach neutrino floor from a fraction of one to thousands of GeV/c^2; probably cover most of the mass range where particle-like DM can be found
- If DM is particle like, we have a good chance to find it soonish …