Particle-like Dark Matter

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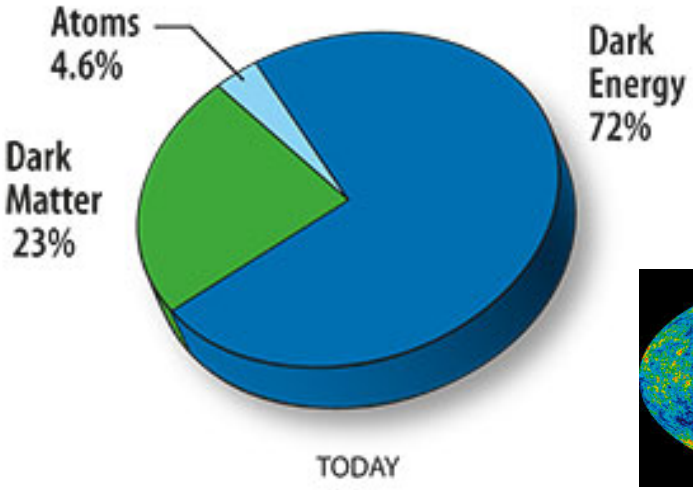
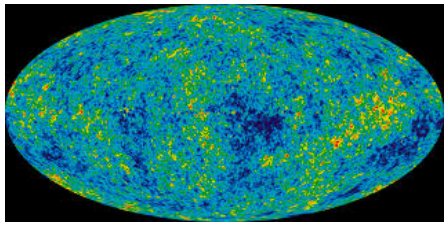
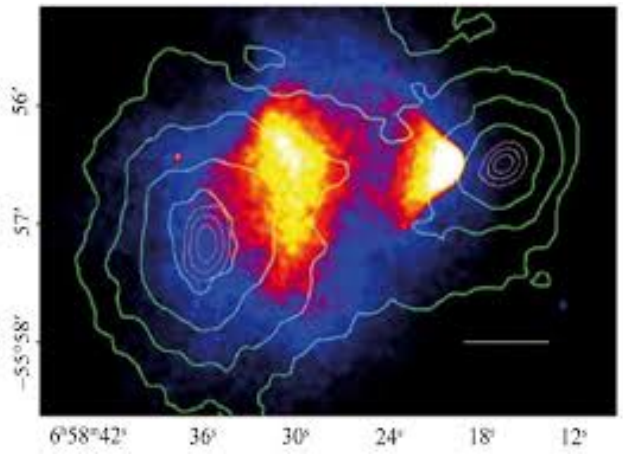
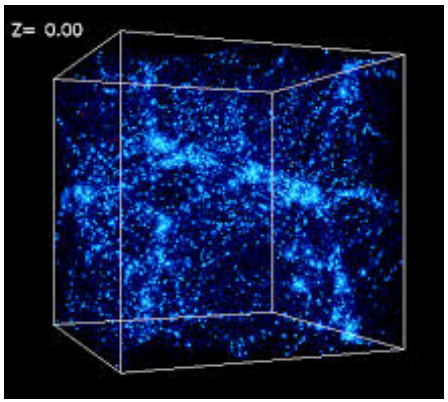
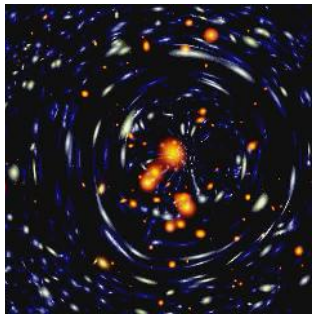
Abundant evidence for Dark Matter





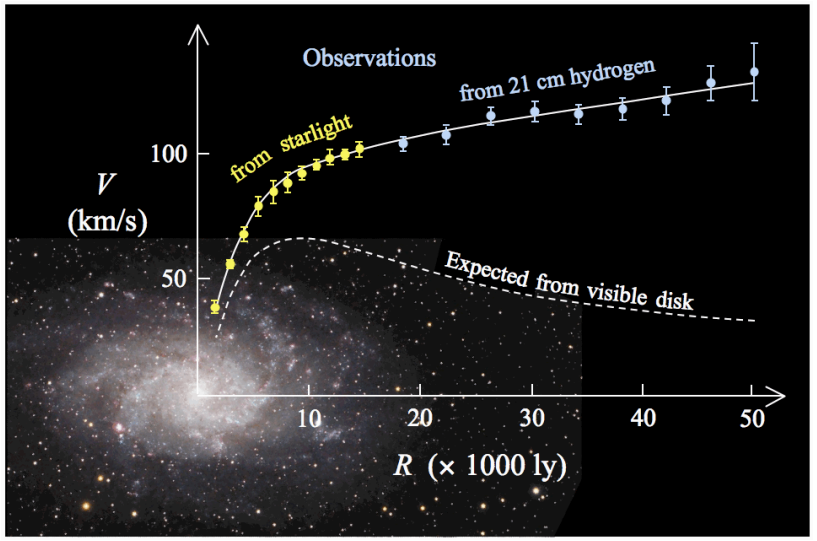






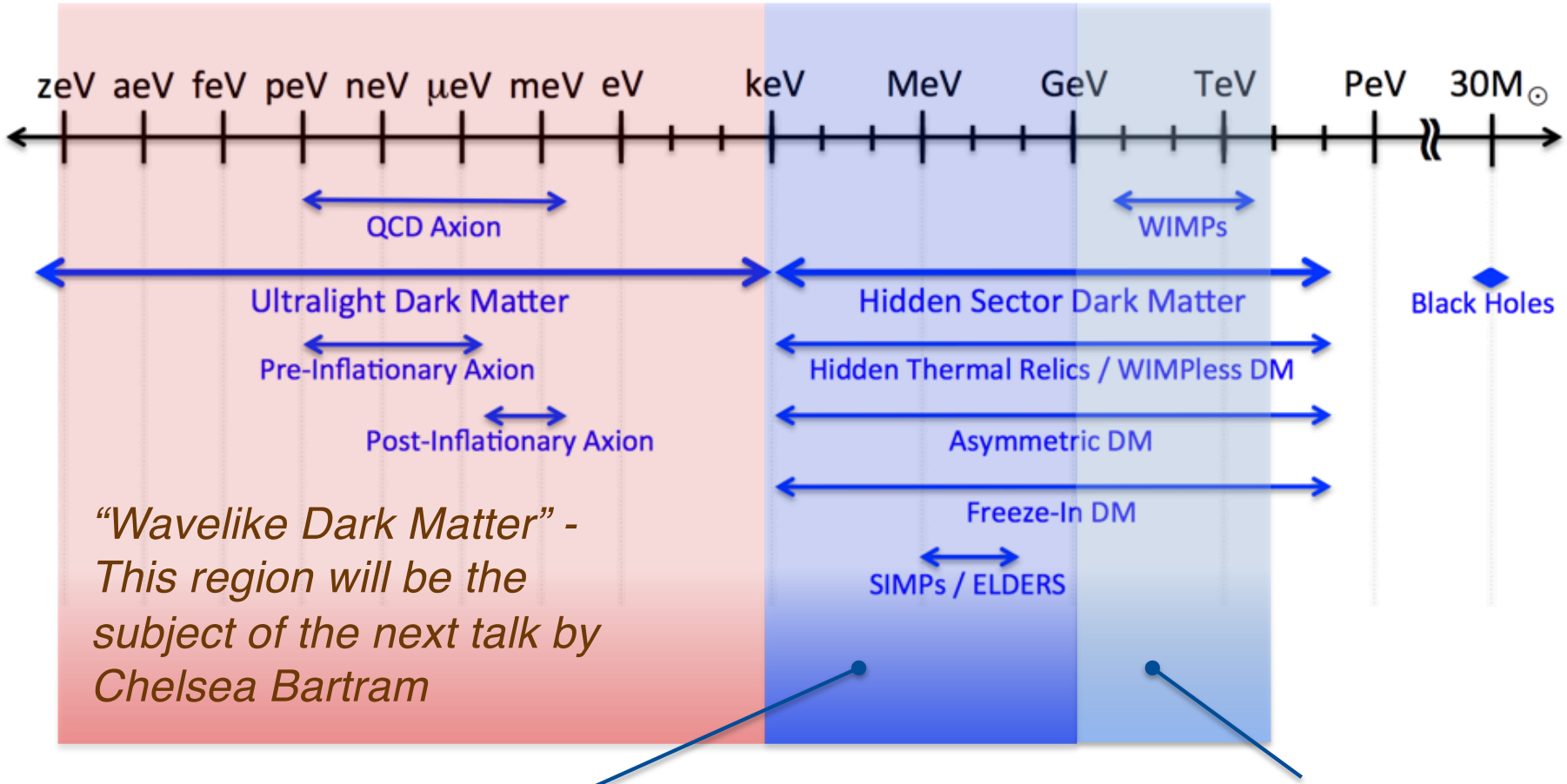
The particle nature of dark matter is a great puzzle of modern science.

In recent decades we have come a long way in our understanding about dark matter…*but we still don't know if it interacts any other way than through gravity*



Dark Matter Candidates

There is a wide range of possible dark matter candidates and an equally broad range of masses that dark matter may have

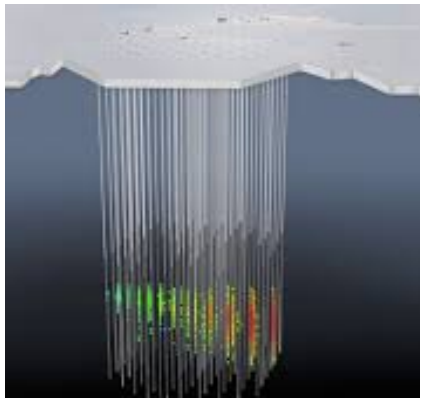


"Low Mass Dark Matter" - New ideas in direct detection and accelerator-based experiments will push into this range

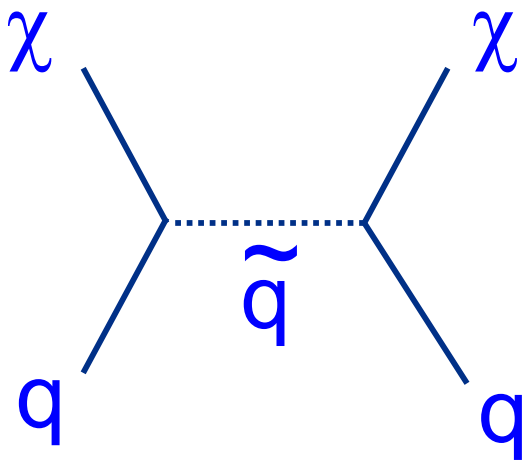
"High Mass Dark Matter" Traditional focus of direct detection experiments looking for nuclear recoils

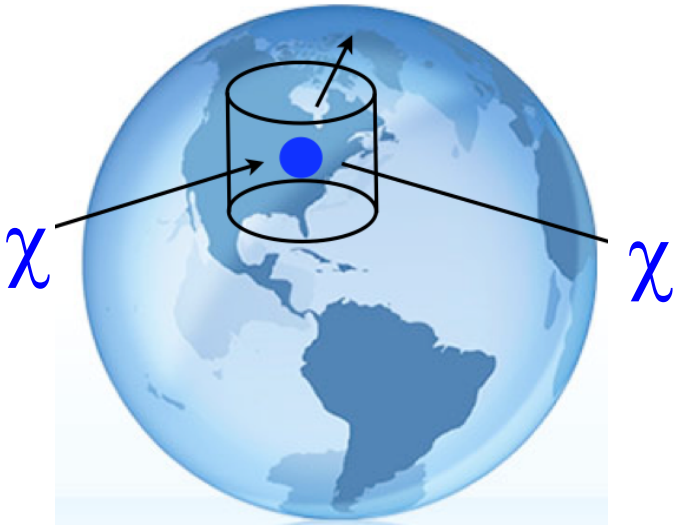
Ways to search for particle-like dark matter

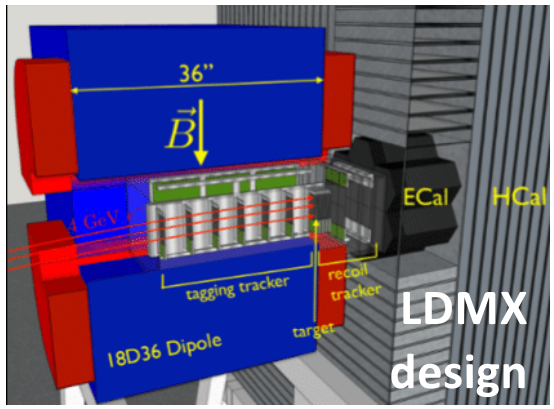
36 talks presented in DM parallel sessions last week (!) I apologize for not covering every talk, but will do my best to capture as much as possible



1. Detect annihilation products from cosmos: e.g. DM searches w/ ICECUBE, FERMI, etc. *e.g. analysis of ICECUBE HESE data (DM Session II)*







2. Production via an accelerator (e.g. LHC, b-factories, fixed target facilities) *–See talks by B. Carlson and R. Khurana on LHC searches (DM Sessions I & IV)*

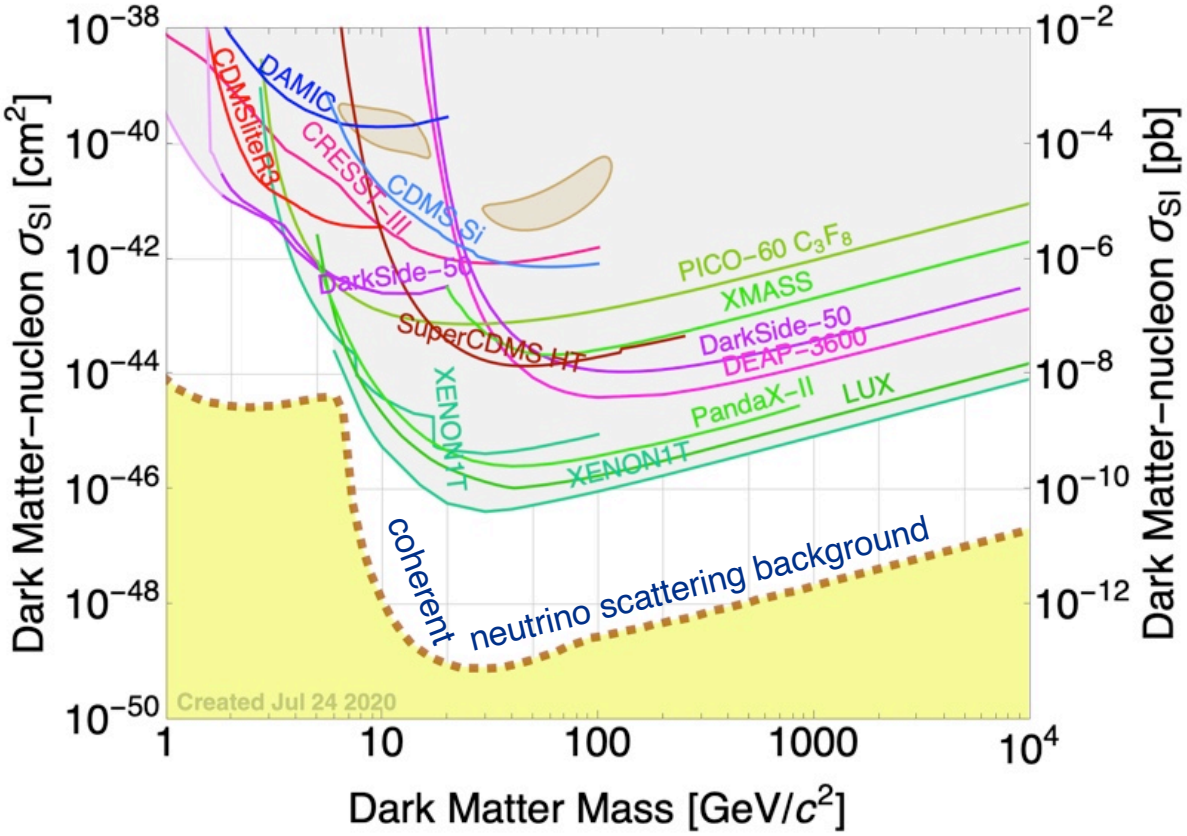
3. Detect interaction of dark matter in earth-bound detector, typically elastic scatter off nuclei. – *the bulk of this talk*

See talk by G. Lanfranchi on iDMEu: an effort to build a common platform to build synergies among physicists working on dark matter

Direct Detection:
Recent Results and Coming Soon

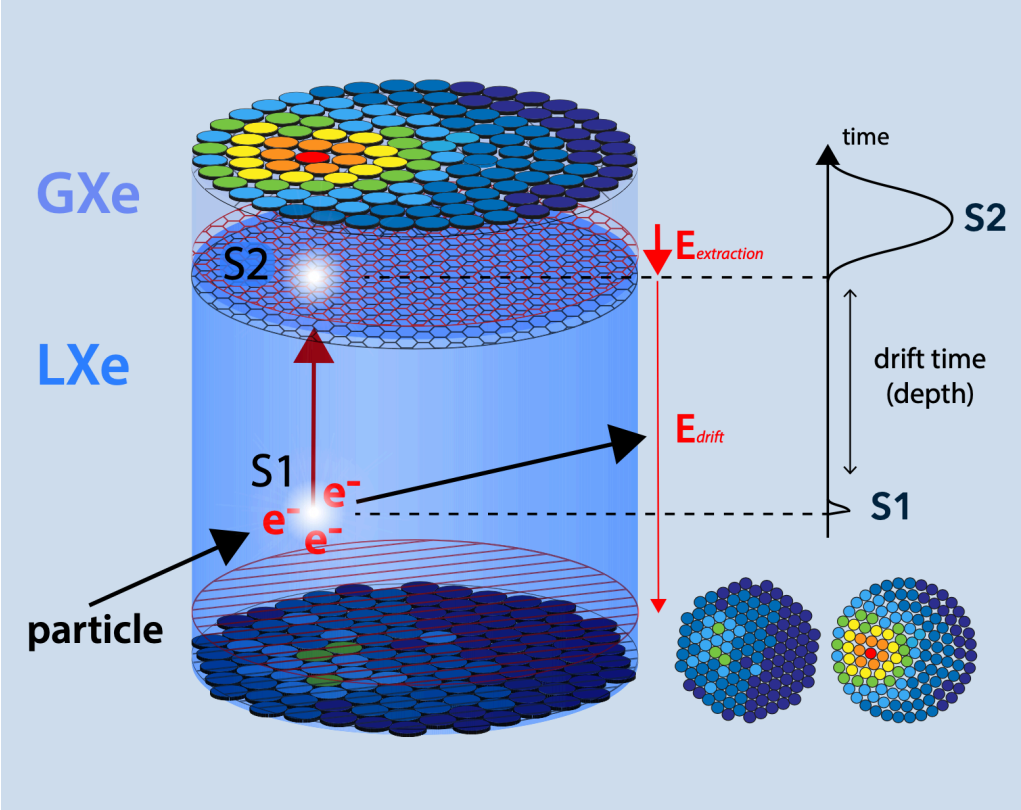
Current Status: Dark Matter with Mass > 10 GeV/c^2

- **Good News:** Speed of progress is tremendous! Experimental sensitivity has increased by several orders of magnitude in past decade
- **Bad News:** No confirmed dark matter signal yet. Are WIMPs dead? – *No, not yet at least!*



- Target is still WIMPs, but now looking for those that couple via Higgs; expected signal is (coherent) elastic scatter from target nuclei and with tiny cross section
- Most sensitive to DM with mass close to target nuclei (Xe, Ar, Ge, I)
- Dual phase xenon TPC's in the lead and are a mature technology. Have achieved exquisite control over backgrounds, yielding fewer than 100 events/ton/yr/keV$_{ee}$; Among the "quietest known places in the universe"
- Dominant backgrounds are still from trace radioactivity and cosmogenic activity

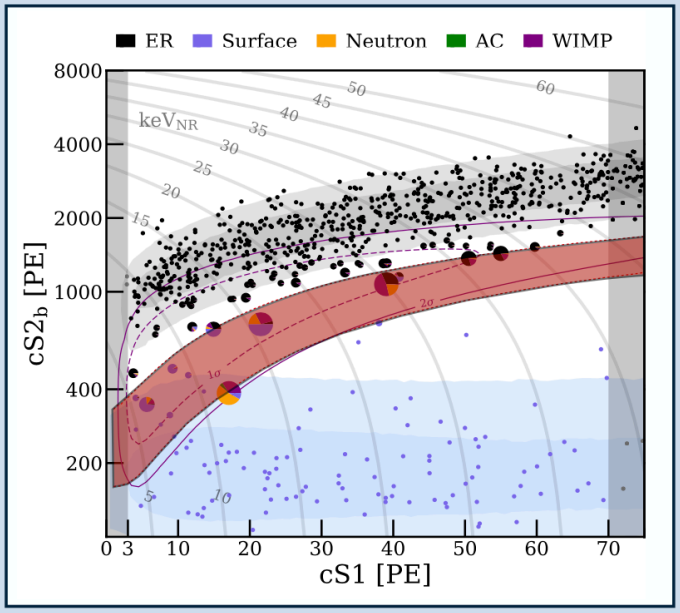
XENON1T: Liquid Xe Time Projection Chamber



Achieved most stringent limit on WIMP Dark Matter down to 3 GeV/c^2 masses

- Operated at LNGS from 2016-2018
- Low background, low threshold (~5 keV_{NR}), and large exposure (~1 t-y)
- Distinguishes electron recoils from nuclear recoils
- Energy and 3D position reconstruction

NR searches...

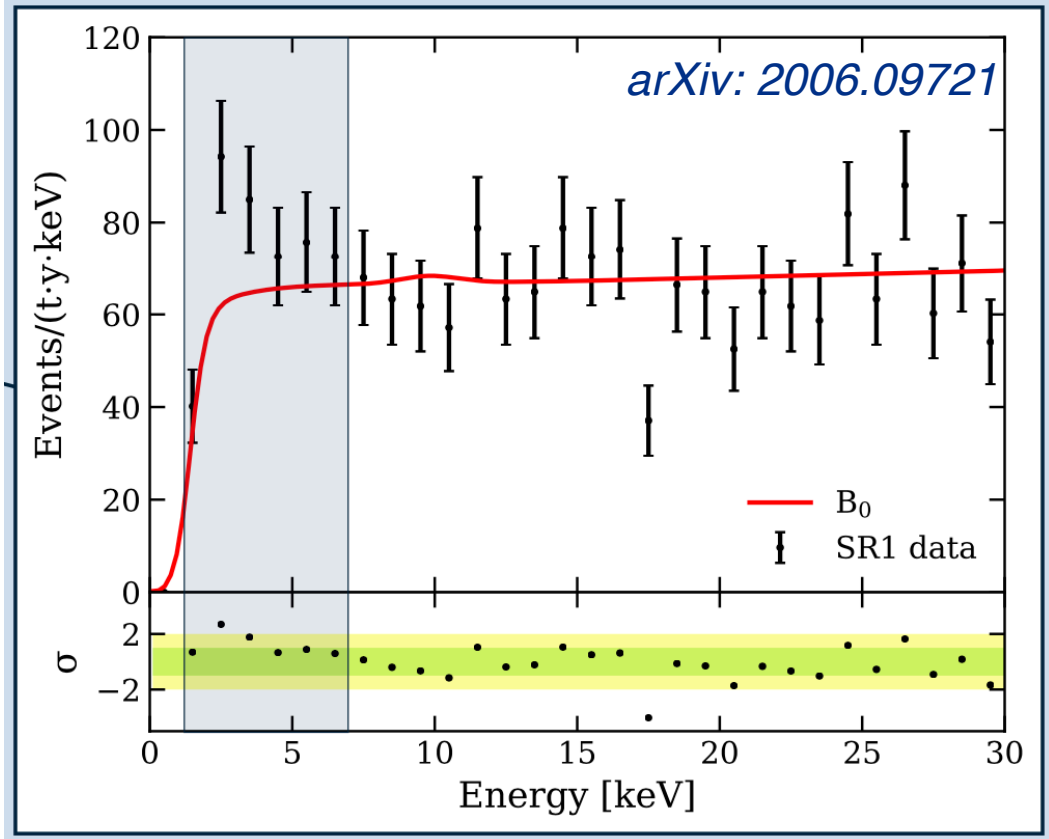


PRL 121, 111302 + PRL 123, 251801

XENON1T: Electron Recoil Analysis

- Extraordinarily low electron recoil background (76±2 events/t-y-keV) enables searches for new physics
- Data yielded small excess, at low energy, over modeled backgrounds
- Fit to data prefers component from solar axion or neutrino magnetic moment (both at > 3σ), however results are in tension with stellar cooling constraints
- Fit also prefers tritium over no tritium. *Cannot confirm or rule out tritium as a contribution*

For more, including status of XENONnT, see talk by A. Elykov (DM Session IV)



Excess between 1-7 keV

285 *events observed*

vs.

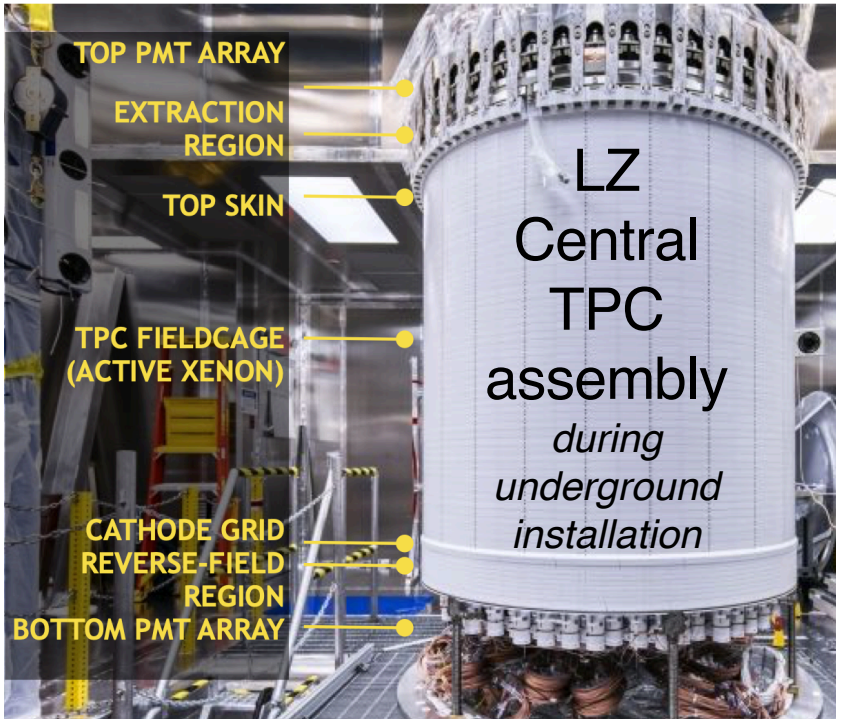
232 (+/- 15) *events expected (from best-fit)*

Would be a ***3.5σ*** *fluctuation*

(naive estimate – we use likelihood ratio tests for main analysis)

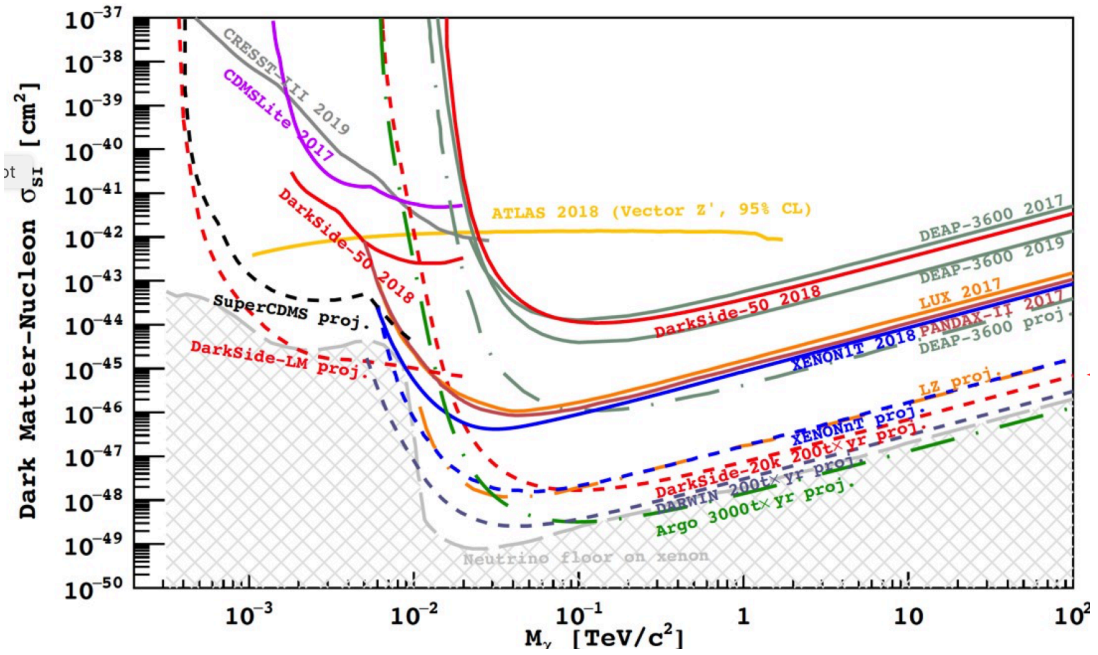
Future High Mass Dark Matter Searches

Next-generation experiments will probe down to the neutrino floor



- LZ in late stages of integration, first science expected in 2021
- 6X bigger than XENON1T; ~40x better sensitivity than current limits and discovery potential

See H. Lippincott's talk for details (DM session IV)

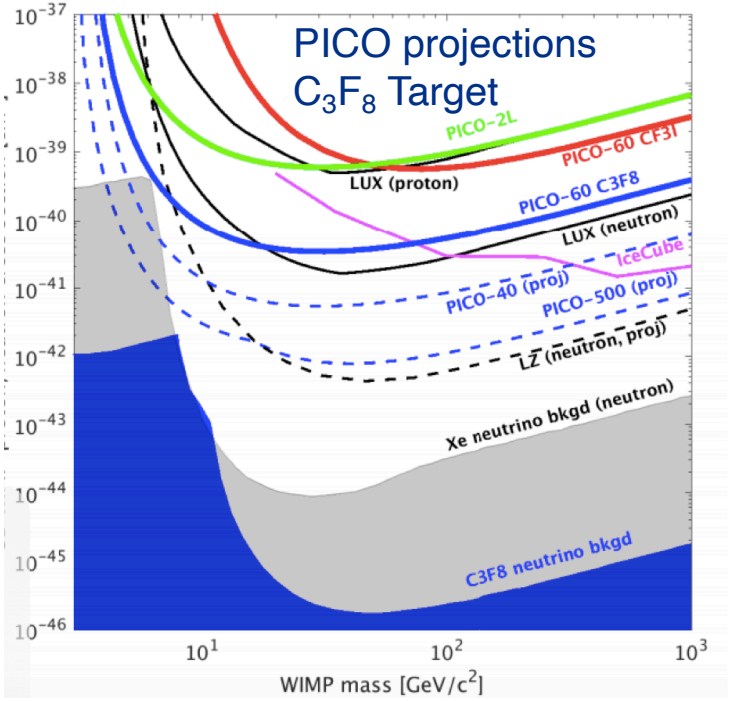


For other current and future liquid noble experiments see following talks:

- *PandaX-4T, and new results for PandaX-II, with roughly similar excess in low energy ER spectrum as XENON1T - by N. Zhou*
- *DarkSide-20k/ARGO - by L. Rignanese (Session I)*
- *DARWIN - by A. Di Giovanni*
- *DEAP-3600 - by S. Viel*

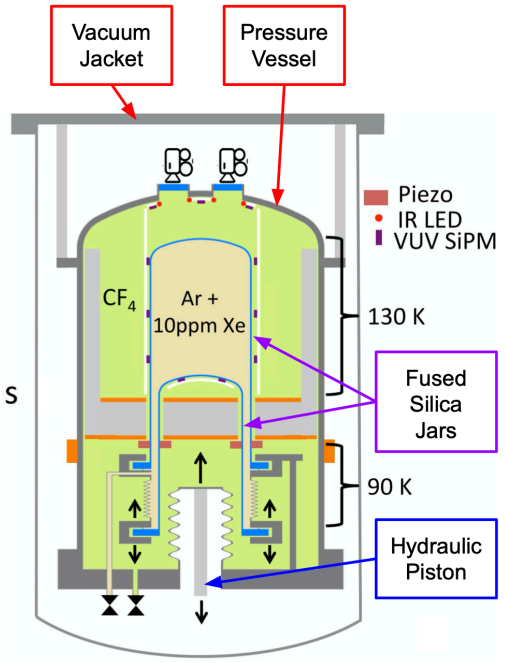
Bubble Chambers

Can be operated with wide range of fluids (and thus target nuclei). This allows for exploration of spin-dependent and low mass interactions. They are also insensitive to electrons, giving potential for background free nuclear recoil searches



- Commissioning PICO-40L at SNOLAB this year
- Expect 1 yr bg-free exposure, **will probe spin-dependent interactions** to 10x better sensitivity than current best limit

For more, see talk by E. Vazquez Jauregui (DM Session III)

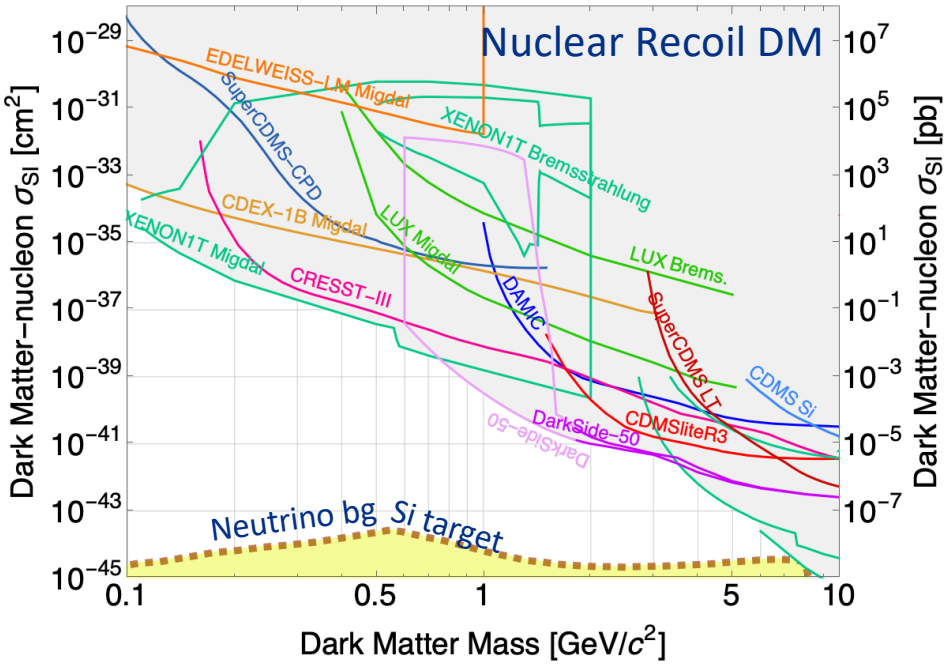


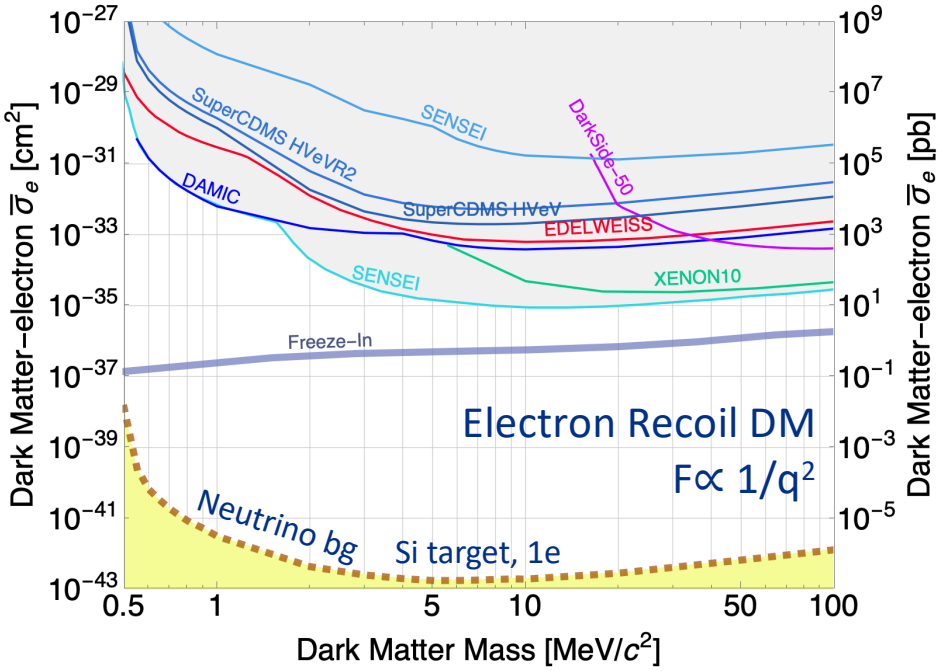
- The Scintillating Bubble Chamber Experiment (SBC) takes things one step further by using noble liquid targets and reading out scintillation light

For more, see talk by P. Giampa (DM Session II)

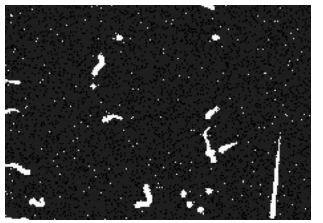
Current Status: Dark Matter with Mass < 10 GeV/c²

- Many well-motivated light particles outside standard "WIMP paradigm"; Large unexplored space!
- Optimal targets not necessarily nuclei and SM interaction may be through a mediator. *Signal could be DM scattering off electrons, absorption of dark photons or another inelastic process.*
- Energy threshold is key; recent detector R&D advances enable enormous progress w/ thresholds <<1 keV
- High relic number densities → competitive w/ gram-days of exposure (not ton-years)
- Radiogenic and cosmogenic backgrounds still problematic but also many new backgrounds (IR radiation, dark currents, trapped charges, vibrational noise, etc.)



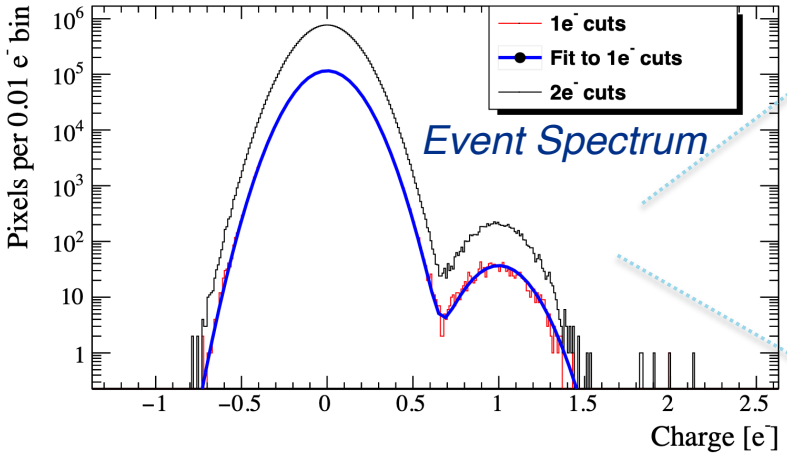


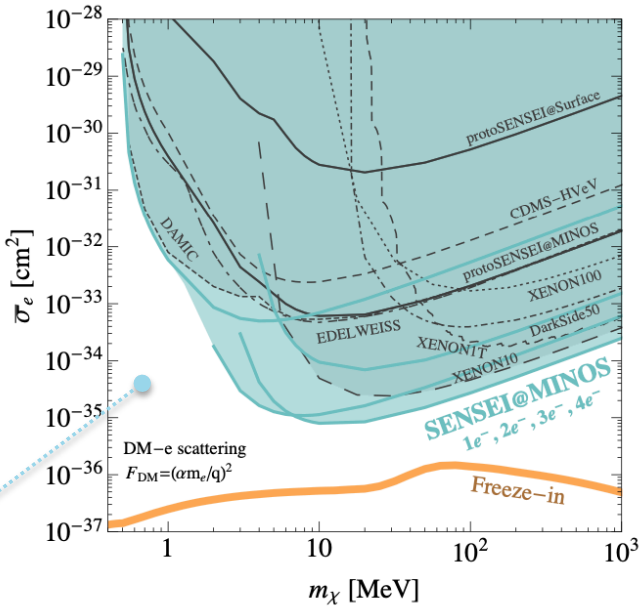
SENSEI: Sub-GeV DM with Skipper CCD's

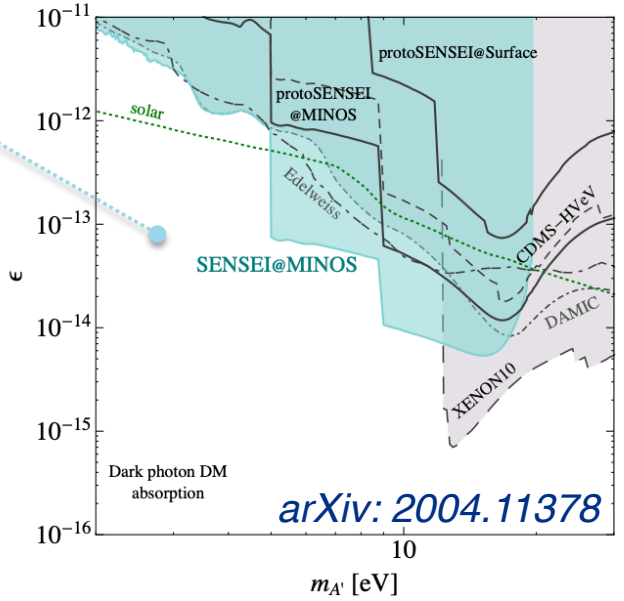


- DAMIC pioneered searches using CCD's; low thresholds achievable w/ small Si bandgap (~1 eV), allows for low mass DM searches through electron and nuclear recoils *(see new result in arXiv:2007.15622)*
- Skipper CCD's allow for multiple, non-destructive measurements of charge to beat 1/f noise, achieved <0.1 e^- noise baseline and single e/h pair sensitivity

Recent results from SENSEI running underground at Fermilab. *See talk by M. Cababie (DM session III).*







Upgrade Path:

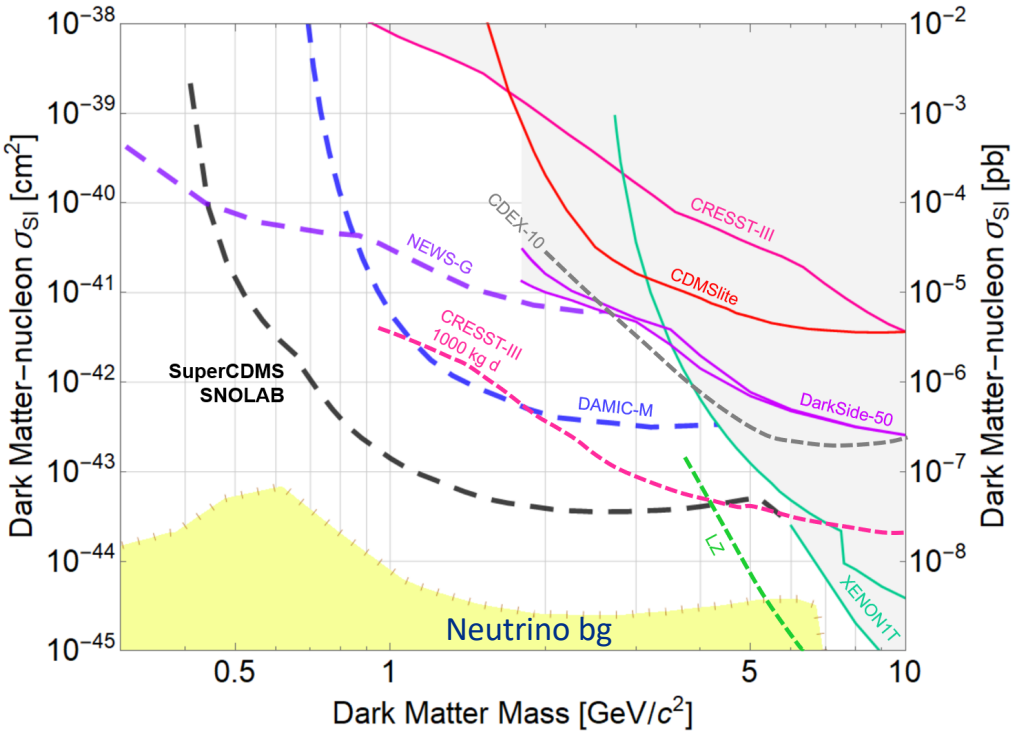
SENSEI: 100 g-yr (~2021, SNOLAB)

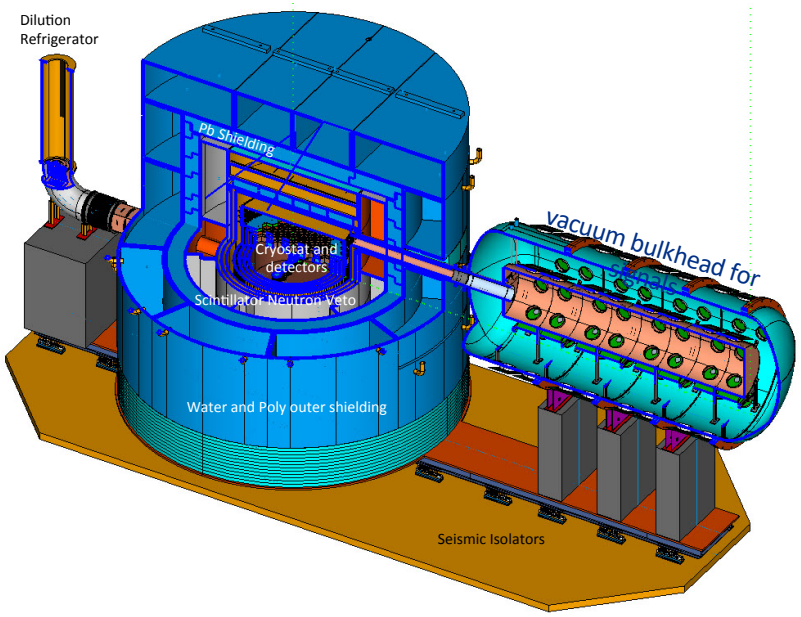
↳ DAMIC-M: 1 kg-yr (~2024, Mondane)

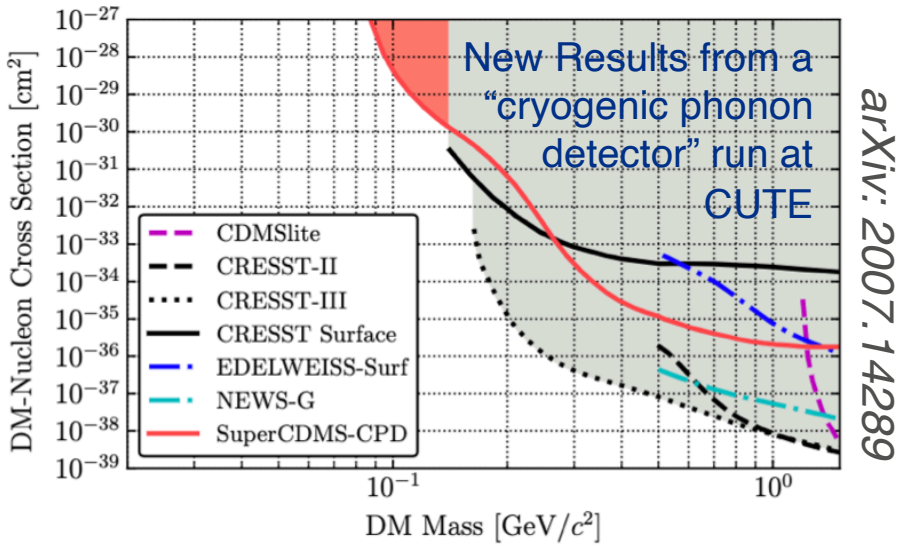
↳ Oscura: 30 kg-yr (~2026)

SuperCDMS SNOLAB

- Will probe light dark matter with superb sensitivity using an array of Ge and Si detectors operated in SNOLAB
- Installation is underway and proceeding though 2021
- Meanwhile, science runs taking place at CUTE and NEXUS test facilities with R&D and prototype detectors

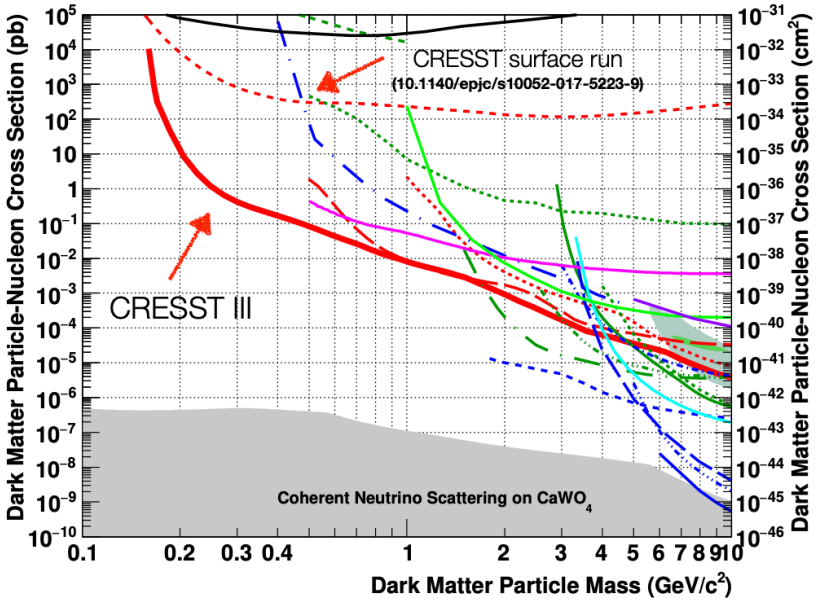


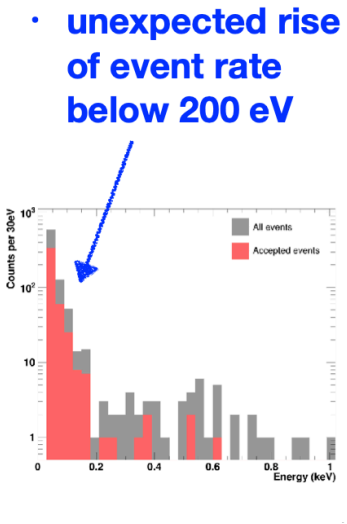




For more results from SuperCDMS, including DM searches with a device sensitive to single e/h pairs, see N. Kurinsky's talk (DM session II)

Some Additional Promising Searches



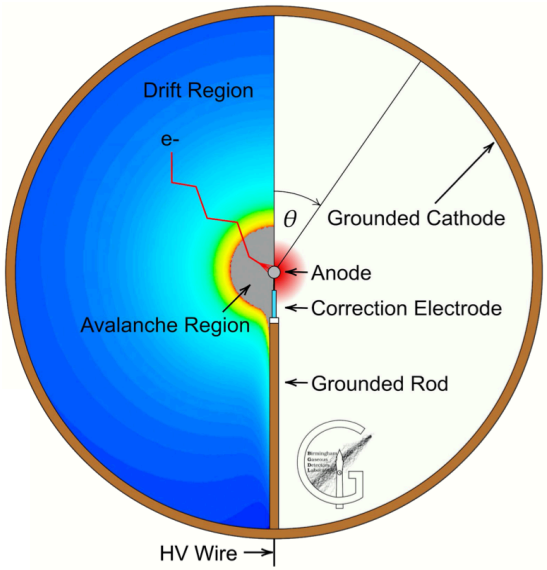


- CRESST III (cryogenic detector) achieved a threshold of 30 eV with ~24g CaW_4O detectors, setting stringent limits below 0.5 GeV/c^2
- Have since made hardware changes to address unexplained bg events, cooling down now for next run

For more, see talk by J. Schieck (DM Session IV)

- NEWS-G is a spherical proportional counter
- Can run with various gases that are kinematically matched for light dark matter
- First science results set competitive limits below 1 GeV/c^2; Next phase is bigger, cleaner and being installed at SNOLAB this year.

For more, see talk by P. Knights (DM Session II)



NEWS-G detector

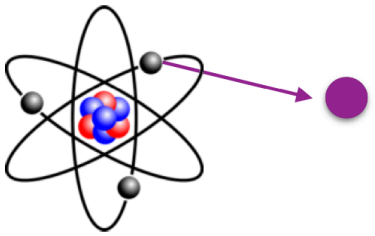
Comment on Inelastic Dark Matter Interactions

Sub-GeV DM energy transfers are small enough that targets cannot be treated as free particles. Migdal effect and plasmons (in semiconductors) may play an important role in a DM signal. Such effects have yet to be calibrated in detectors!

For sub-GeV DM, think response functions, **not** free-particle scattering

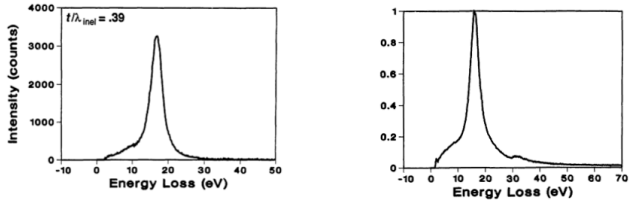
$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q}) S(\mathbf{q}, \omega_\mathbf{q})$$

Migdal effect is an inelastic response function for atoms

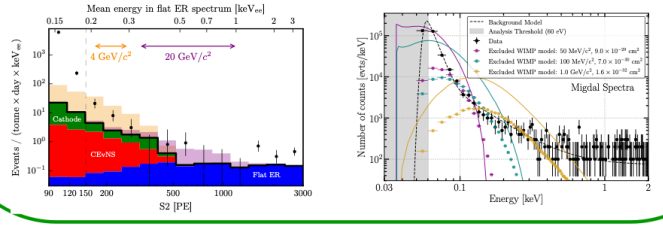


See talks by H. Lin (CDEX), P. Agnes (Darkside-50) and A. Elykov (XENON1T) for recent Migdal search results

Semiconductor response functions contain plasmons: no single particle description!



Maybe all these low-energy excesses are hints of Migdal or plasmons…



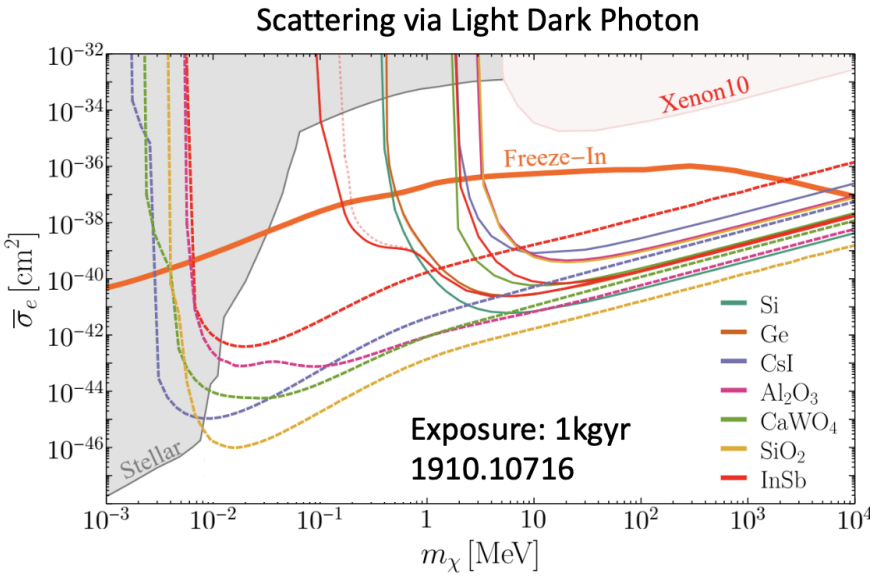
For more on inelastic DM channels, see talk by Y. Kahn (DM Session I)

New Ideas and Alternative Techniques

Traveling Further Down the Mass Scale

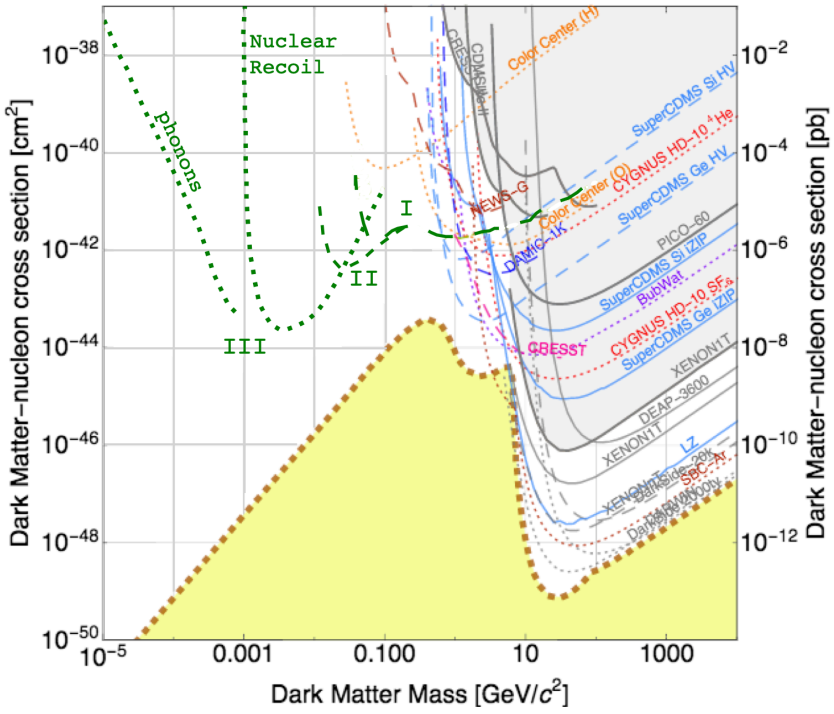
For DM below 1 MeV, need to measure collective excitations. Consider materials such as superfluid helium, polar materials, and superconductors - see S. Knapen's talk on DM phonon scattering (DM Session I)

SPICE: **S**ub-eV **P**olar **I**nteractions **C**ryogenic **E**xperiment



- In ionic crystals (e.g. GaAs, Al_2O_3,…), optical phonons have large coupling to dark photons
- Need O(100) meV phonon resolution

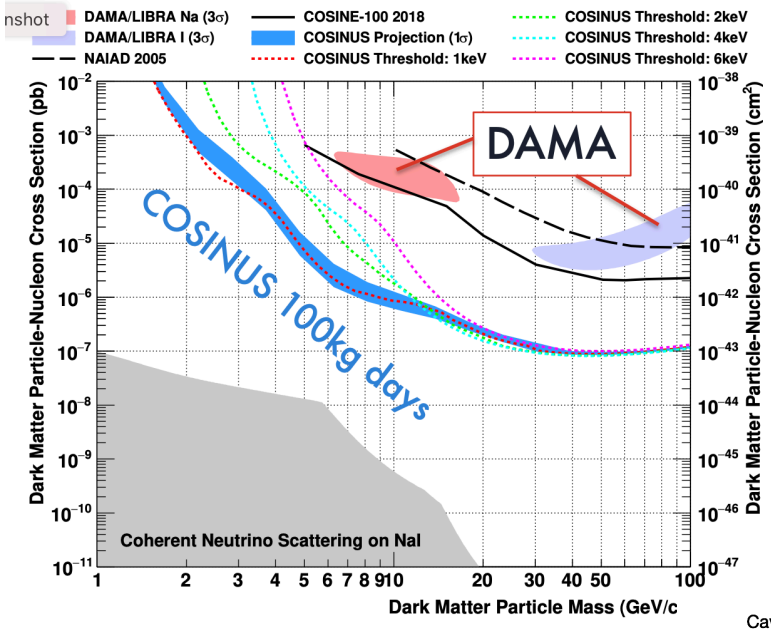
HeRALD: Helium **R**oton **A**pparatus for **L**ight **D**ark **M**atter

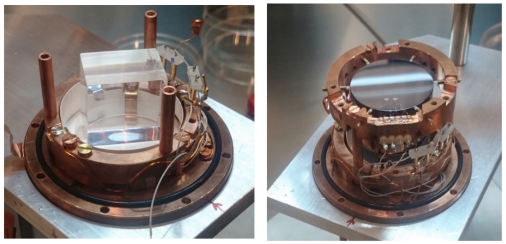


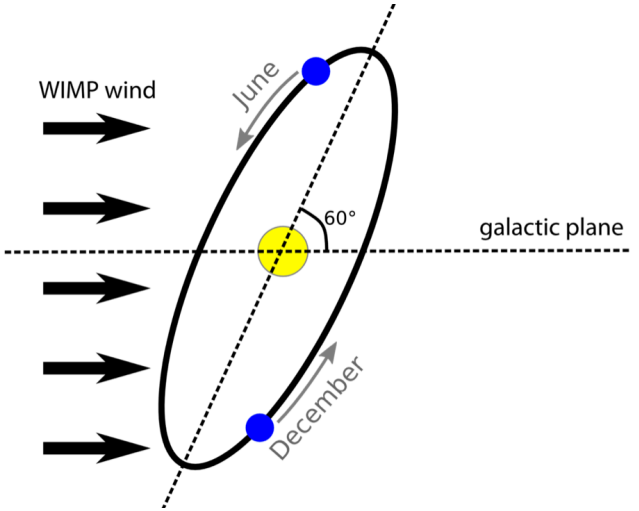
phonons and rotons excited by dark matter scattering to be detected using quantum evaporation.

Detecting the Dark Matter "Wind"

"Relative velocity of DM modulates and so should interaction rate"



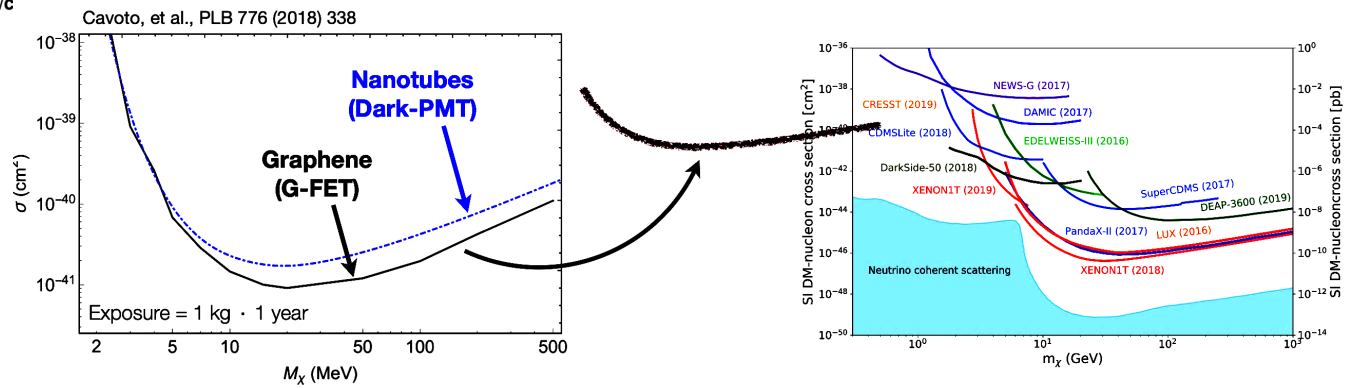




DAMA/LIBRA annual modulation signal still not definitively confirmed or ruled out by another NaI experiment

See F. Reindal's talk (DM Session III) on how COSINUS can do this.

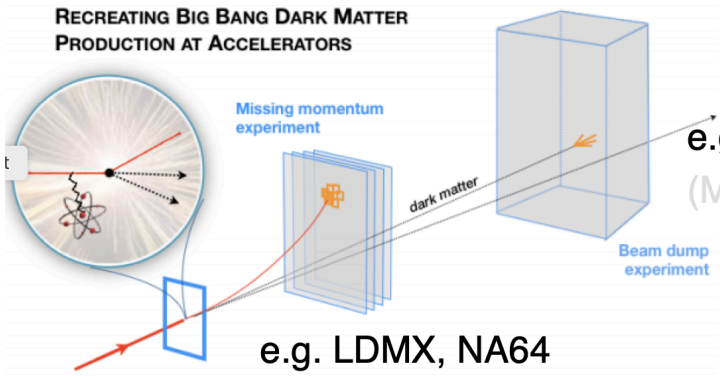
- Or instead, correlate direction of recoils with DM wind
- Carbon nanotubes and graphene detectors have directional sensitivity to sub-GeV dark matter



See F. Pandolfi's talk (DM Session II) for more on carbon nanostructures, and A. Alexandrov's talk on nuclear emulsion directional sensitivity (DM Session III)

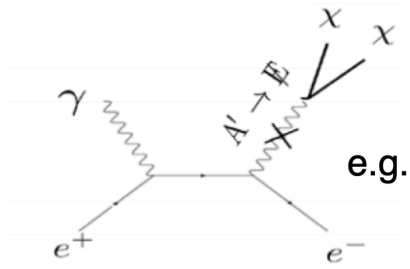
Accelerator-based Searches

To achieve the correct relic abundance, light dark matter requires new mediators connecting the dark sector to the SM



e.g. BDX (MiniBoone)

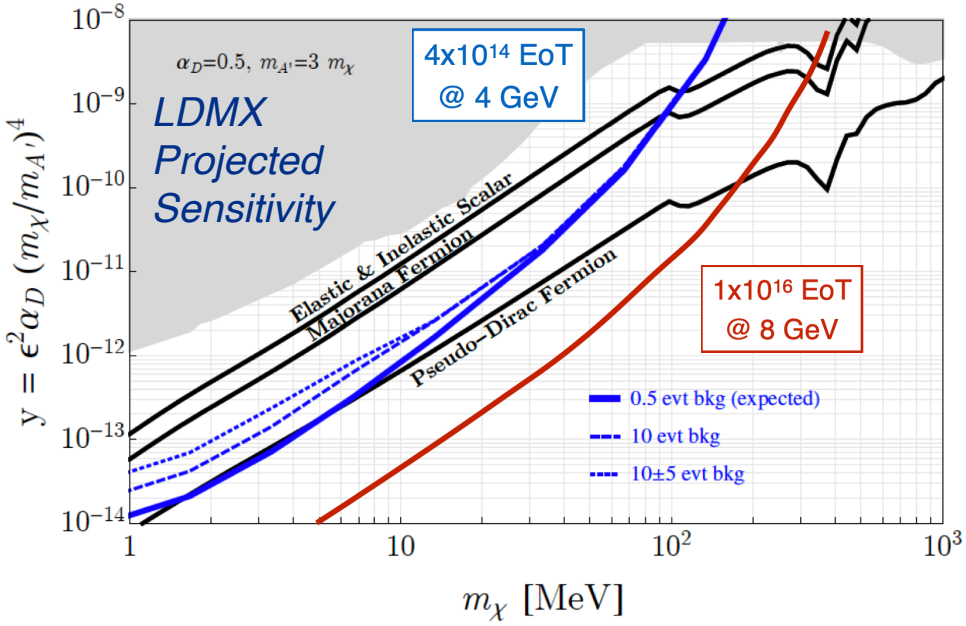
e.g. LDMX, NA64

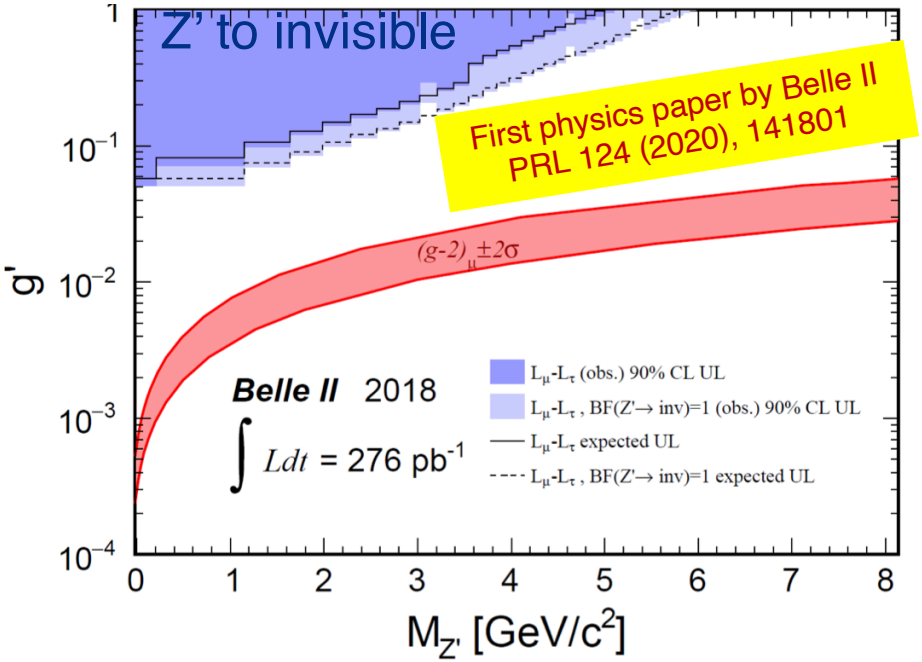


e.g. Belle II (LHC)

LDMX, Belle II and BDX are just a few examples of the many experiments searching for light dark matter at an accelerator facility.

For more on status of LDMX, see talk by A. Whitbeck





For more on new Belle II results, see talk by E. Graziani (DM Session I)

Summary

- Whether Dark Matter interacts with Standard Model particles continues to be one of the great unresolved questions of modern physics
- Direct detection experiments searching for WIMP-like dark matter with mass > 10 GeV/c^2 have excluded significant parameter space using ton-scale detectors and unprecedented low background levels.
- Direct detection experiments searching for low-mass dark matter must achieve very low detector thresholds and better understanding of inelastic detector processes. R&D holds much promise for significant gains in this area in the next few years.
- The search for particle dark matter continues to be a fast-paced and quickly evolving field, stay tuned!

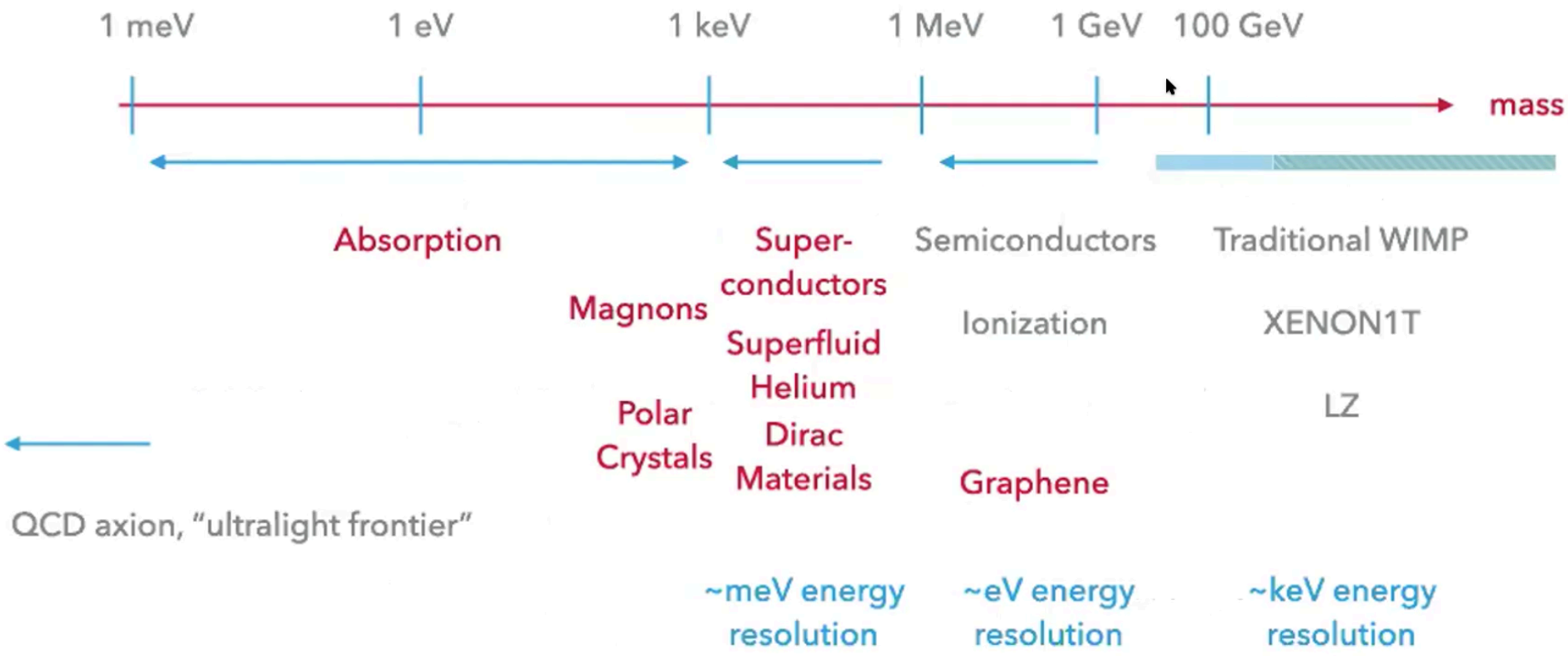
Thanks for your attention!

Exclusion curves in this presentation were created with Dark Matter Limit Plotter, maintained by T. Saab and available here: https://supercdms.slac.stanford.edu/dark-matter-limit-plotter

Backup

PROMISE: NEW DETECTION PARADIGMS FOR LIGHT DARK MATTER

- Experimental Panorama



Slide by K. Zurek, from IDM 2020