Dark Matter BRN Working Group - Town Hall

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PRDs

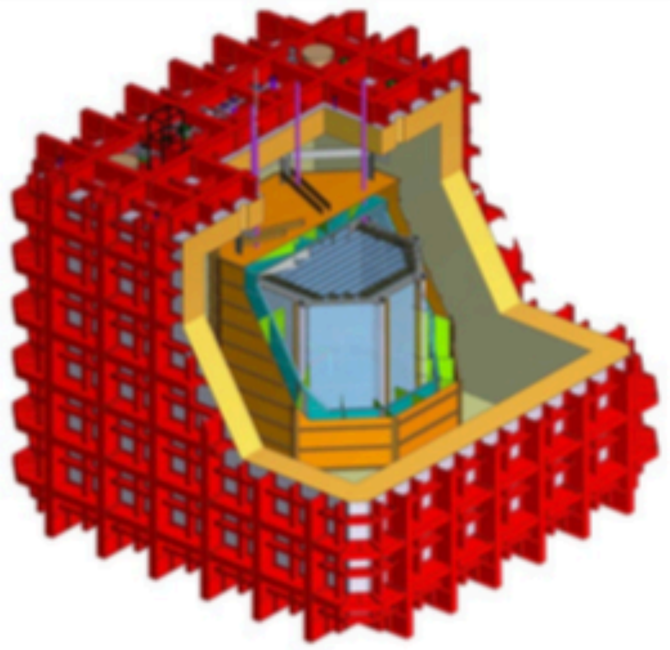
1. R&D on methods to extend the investments of DOE in G2 experiments to cover new physics reach.
2. Lower thresholds to probe particle dark matter candidates with very small mass.
3. Improved angular resolution for point source identification (to reduce astrophysical backgrounds) and greater sensitivity to weak sources for indirect detection experiments.
4. Develop quantum sensor technology needed to propel the entire QCD axion band.
5. Next Generation High-Q Resonators

Key Challenges

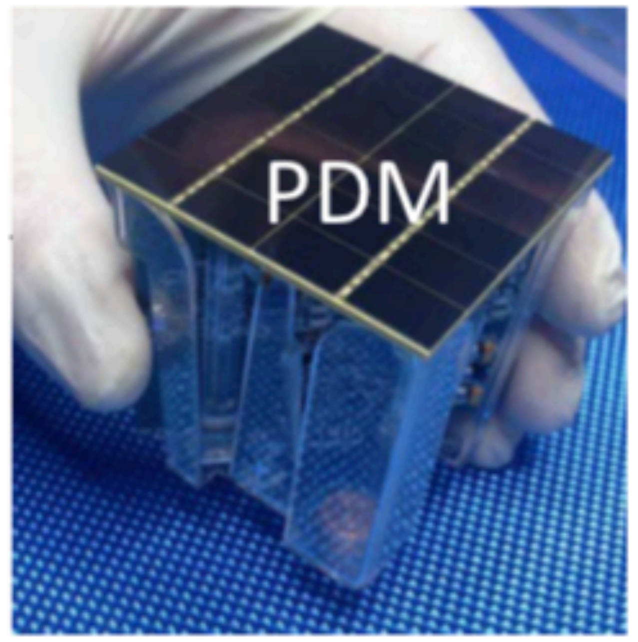
1. Identification of New Materials, Quantum Materials for Dark Matter Detection
2. Single photon counters from near-infrared to microwave
3. Background mitigation (includes radiogenic & noise)
4. High-field, cost-effective superconducting magnets
5. Ubiquitous cryogenics for cooling superconducting sensors

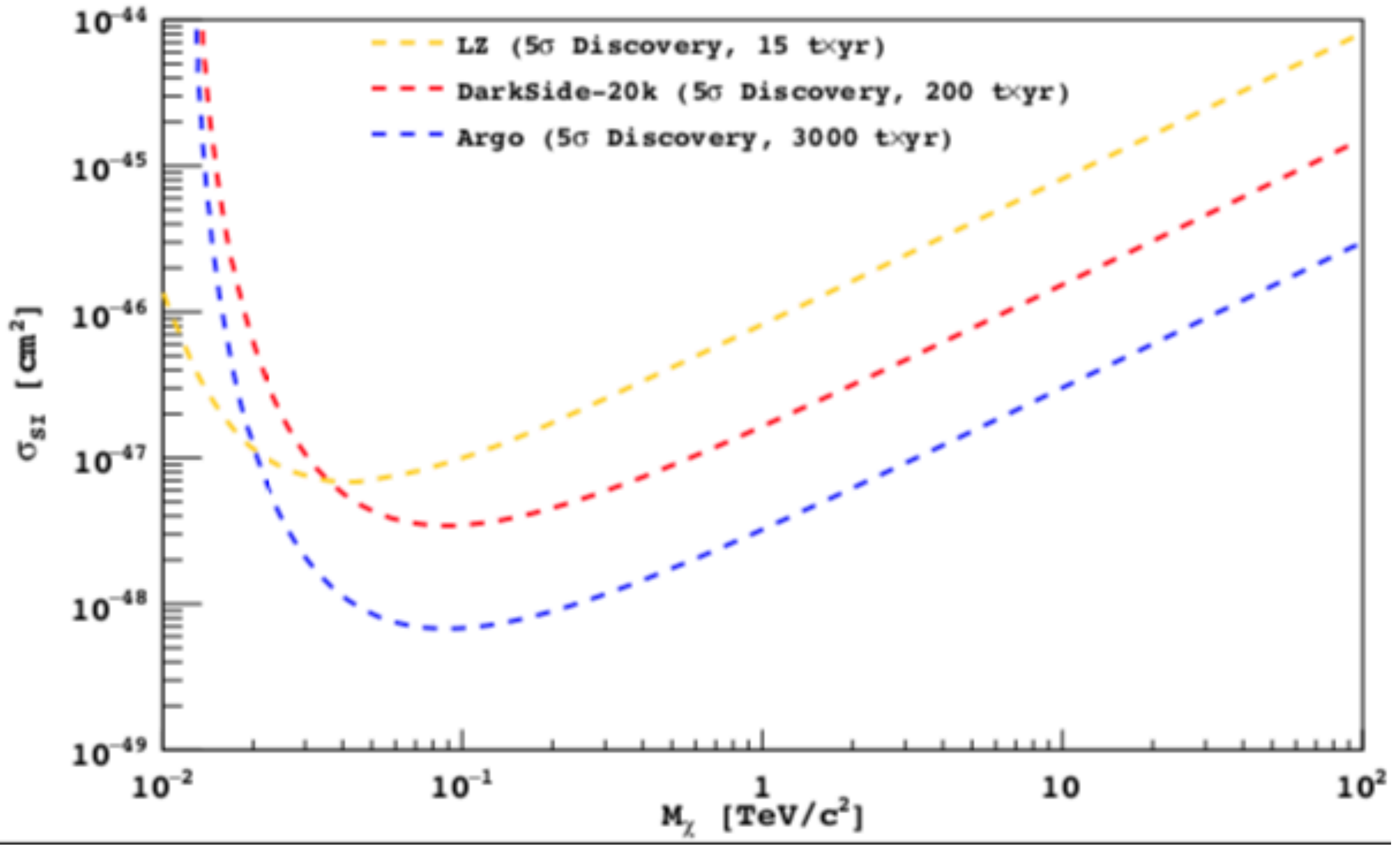
Global Argon Dark Matter Program: Probing for Dark Matter beyond Neutrino Floor

- Dark matter search with DS-20k detector (2022) and ARGO (2029) beyond neutrino floor in instrumental background free mode utilizes:
  - Powerful Pulse Shape Discrimination with > 10^9 background rejection of ER in liquid Ar.
  - Depleted argon (DAr) target with negligible ^{39}Ar contribution & facilities to produce 90 tonnes/year of DAr.
  - Novel SiPM based photon detector modules (PDMs): 5x5 cm^2, single pe resolution, SNR = 24, 50% PDE, > 10^6 gain, low dark count, ~5 ns time res. and radioclean.
  - Dual phase TPC provides full x,y and z reconstruction and is very radioclean.
  - High efficiency Active Gd doped acrylic neutron veto (< 0.1 n/(200 t y))
  - Housed in atmospheric argon filled cryostat.
- DarkSide-LM – ionization signal based DM search for low mass DM, enabled by isotopic separation of ^{39}Ar/^{40}Ar.



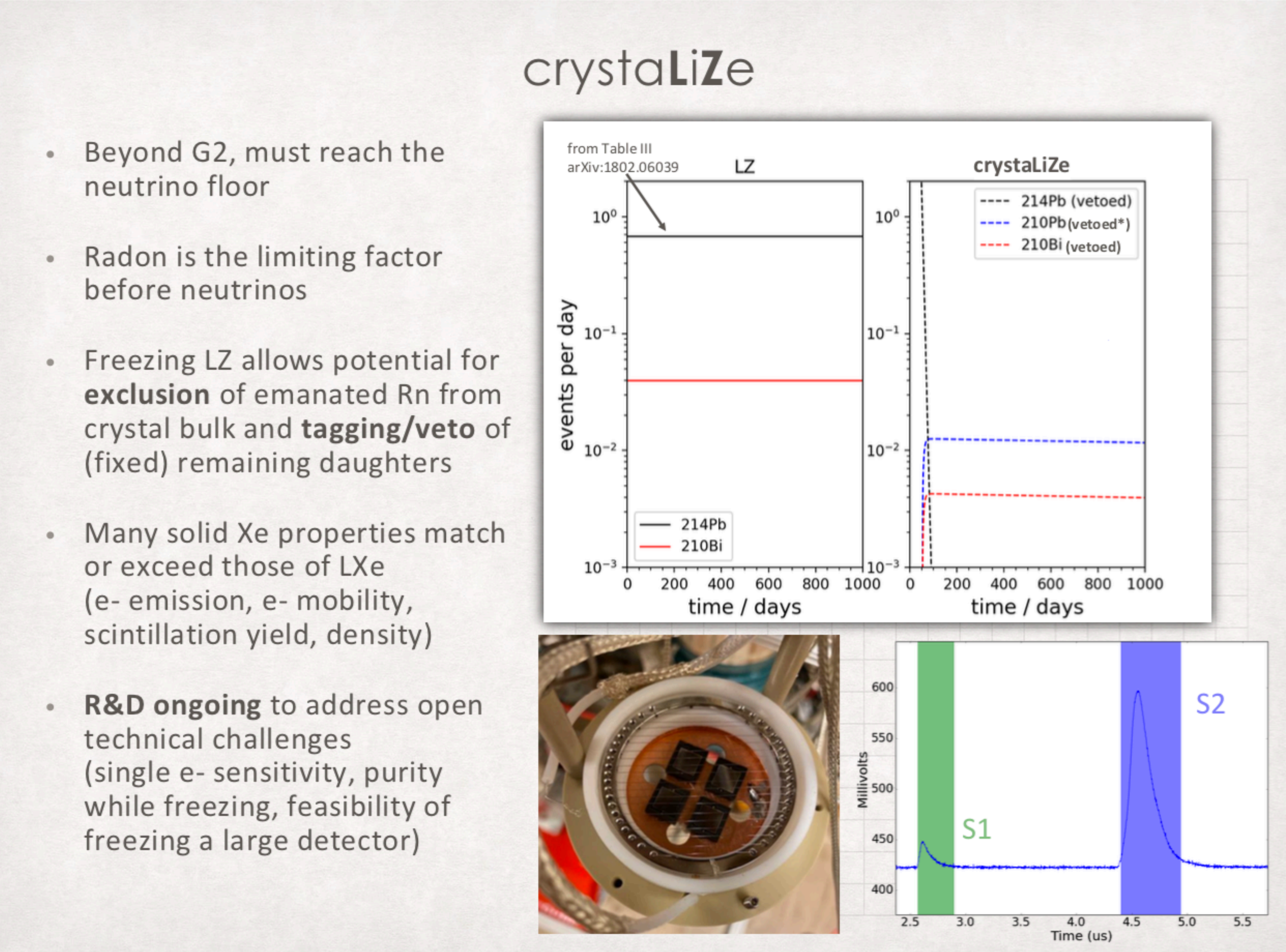
DarkSide-20k





Jelena Maricic

PRD 1: Extend reach of G2 investments



crystaLiZe

- Beyond G2, must reach the neutrino floor
- Radon is the limiting factor before neutrinos
- Freezing LZ allows potential for **exclusion** of emanated Rn from crystal bulk and **tagging/veto** of (fixed) remaining daughters
- Many solid Xe properties match or exceed those of LXe (e- emission, e- mobility, scintillation yield, density)
- **R&D ongoing** to address open technical challenges (single e- sensitivity, purity while freezing, feasibility of freezing a large detector)

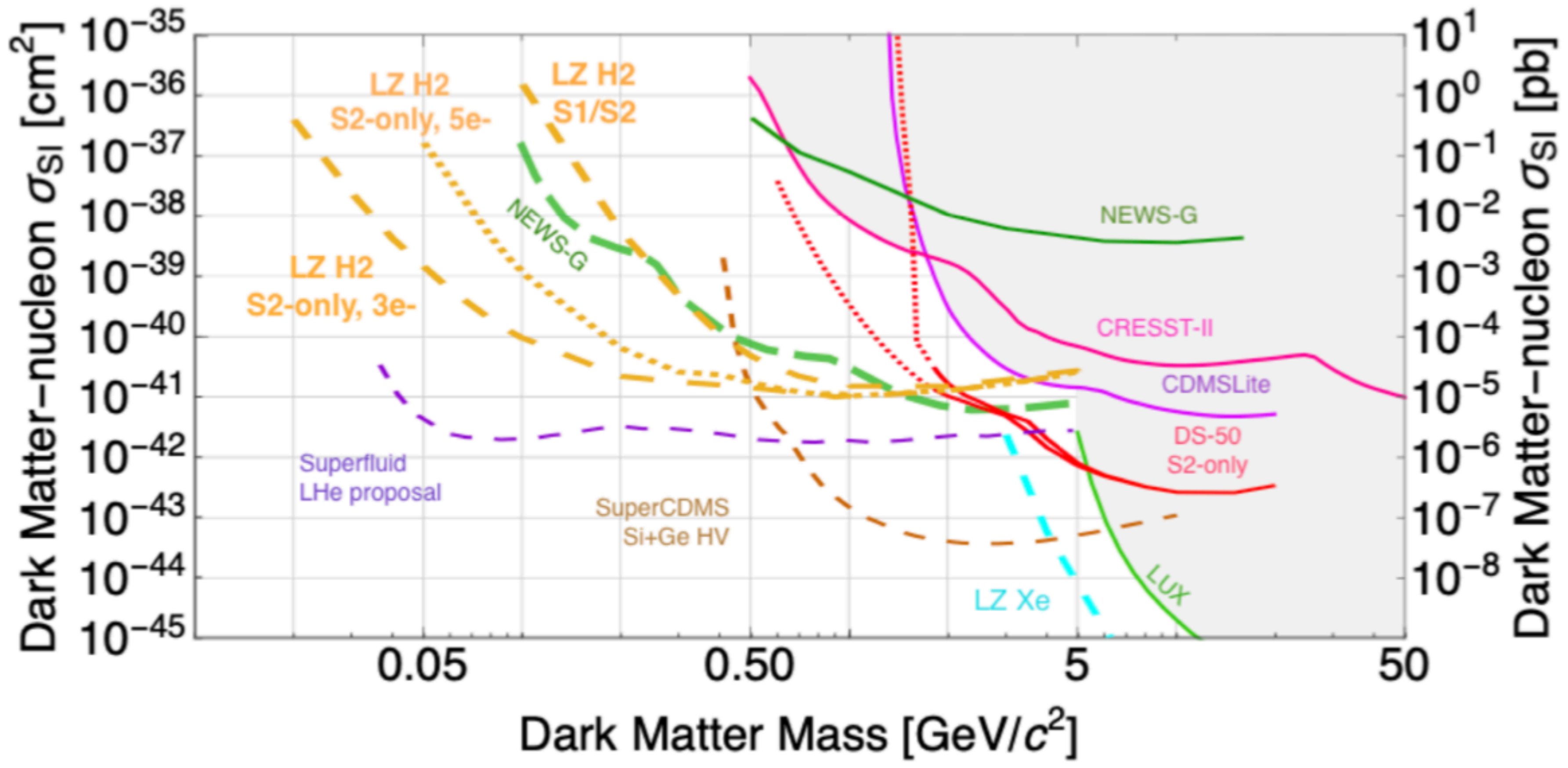
from Table III
arXiv:1802.06039

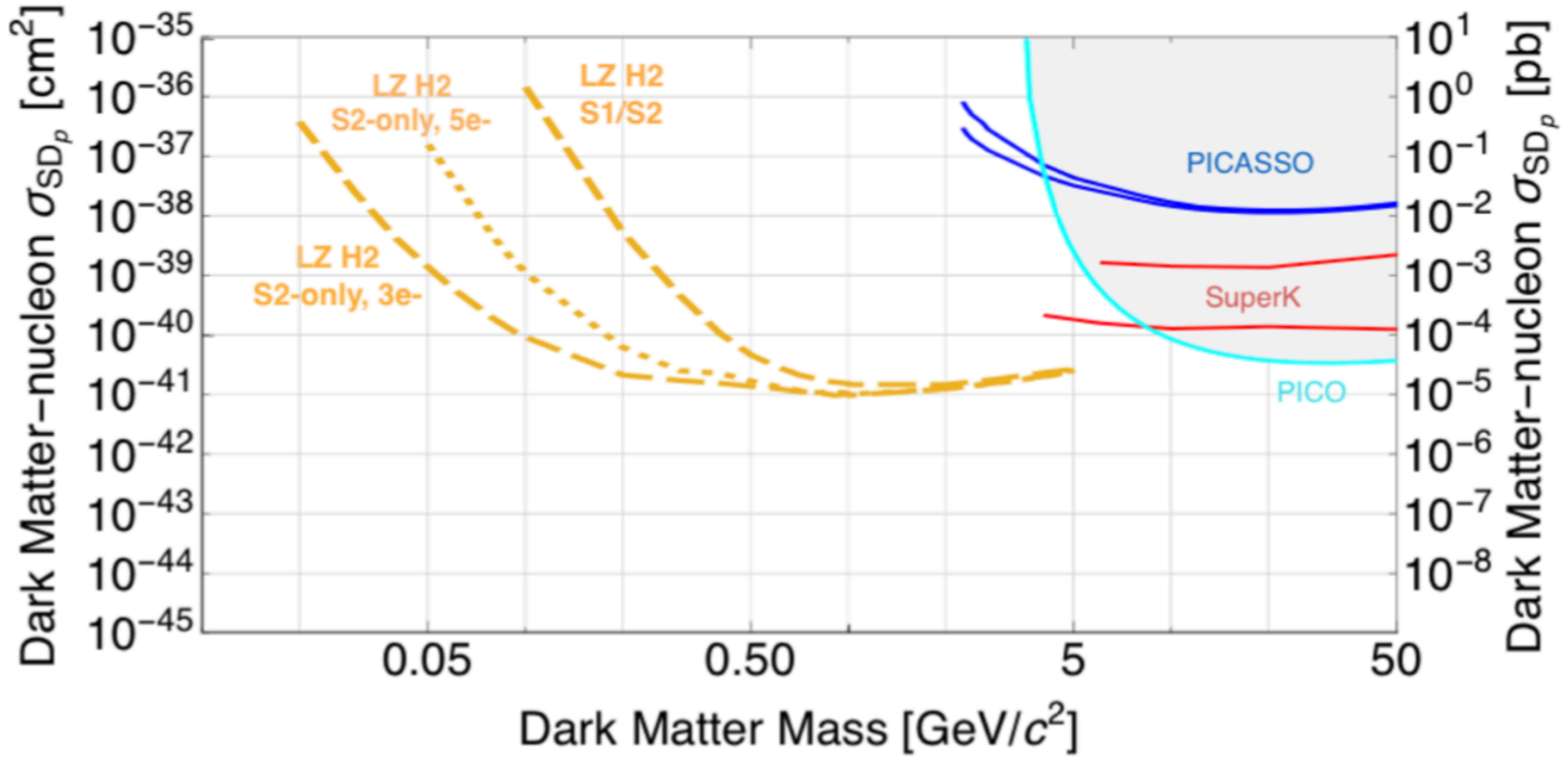
SW Kravitz

PRD 1: Extend reach of G2 investments

HydroX: Hydrogen-doped Xenon for Sub-GeV dark matter searches

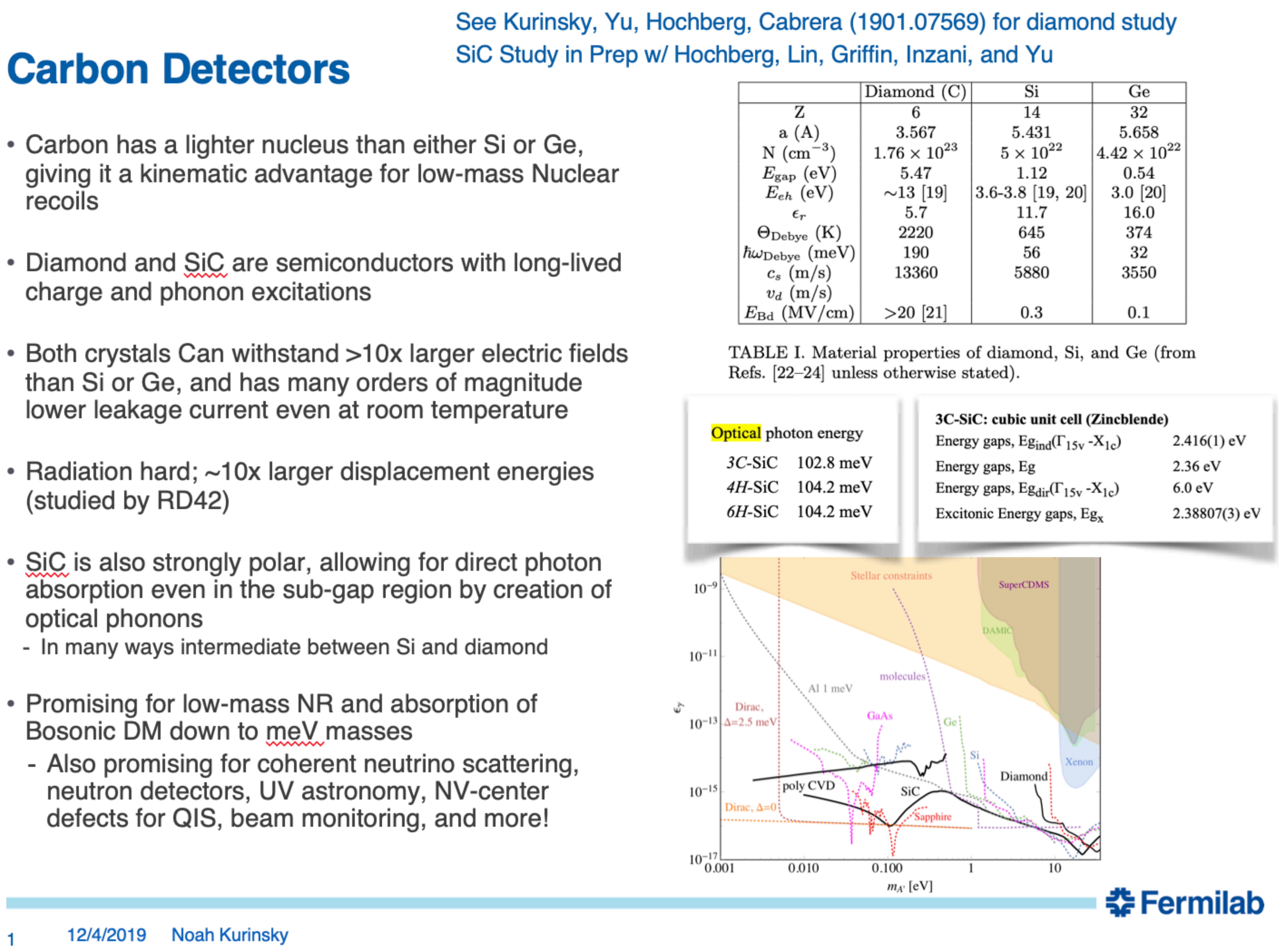
- Dissolve H_2 into LZ's liquid xenon at ~2% mol fraction, ~2 kg H_2 target
- Probe 0.1-5 GeV/c^2 dark matter masses
- Advantages:
  - Kinematic matching between target and low mass dark matter
  - Proton recoils have enhanced signal yield compared to Xe recoils, no Lindhard losses
  - Leverage success of conventional LXe TPCs: retain self-shielding of LXe, as well as all other BG mitigations
  - SI and SD sensitivity; SD sensitivity at low mass is unique
- R&D needed:
  - Measure Henry's coefficient
  - Measure effect of H_2-doping on signal generation (light and charge)
  - Circulation, purification, and cryogenics
  - Ultra low energy proton recoil calibration in LXe
- Achieved first proof-of-principle that dual-phase TPC works with H_2-doped xenon





Alden Fan

PRD 2: Low Thresholds



See Kurinsky, Yu, Hochberg, Cabrera (1901.07569) for diamond study
SiC Study in Prep w/ Hochberg, Lin, Griffin, Inzani, and Yu

Carbon Detectors

- Carbon has a lighter nucleus than either Si or Ge, giving it a kinematic advantage for low-mass Nuclear recoils
- Diamond and SiC are semiconductors with long-lived charge and phonon excitations
- Both crystals Can withstand >10x larger electric fields than Si or Ge, and has many orders of magnitude lower leakage current even at room temperature
- Radiation hard; ~10x larger displacement energies (studied by RD42)
- SiC is also strongly polar, allowing for direct photon absorption even in the sub-gap region by creation of optical phonons
  - In many ways intermediate between Si and diamond
- Promising for low-mass NR and absorption of Bosonic DM down to meV masses
  - Also promising for coherent neutrino scattering, neutron detectors, UV astronomy, NV-center defects for QIS, beam monitoring, and more!

	Diamond (C)	Si	Ge
Z	6	14	32
a (A)	3.567	5.431	5.658
N (cm^{-3})	1.76×10^{23}	5×10^{22}	4.42×10^{22}
E_{gap} (eV)	5.47	1.12	0.54
E_{eh} (eV)	~13 [19]	3.6-3.8 [19, 20]	3.0 [20]
ϵ_r	5.7	11.7	16.0
Θ_{Debye} (K)	2220	645	374
$\hbar\omega_{\mathrm{Debye}}$ (meV)	190	56	32
c_s (m/s)	13360	5880	3550
v_d (m/s)			
E_{Bd} (MV/cm)	>20 [21]	0.3	0.1

TABLE I. Material properties of diamond, Si, and Ge (from Refs. [22–24] unless otherwise stated).

Optical photon energy

3C-SiC	102.8 meV
4H-SiC	104.2 meV
6H-SiC	104.2 meV

3C-SiC: cubic unit cell (Zincblende)

Energy gaps, $Eg_{ind}(\Gamma_{15v}-X_{1c})$	2.416(1) eV
Energy gaps, Eg	2.36 eV
Energy gaps, $Eg_{dir}(\Gamma_{15v}-X_{1c})$	6.0 eV
Excitonic Energy gaps, Eg_x	2.38807(3) eV

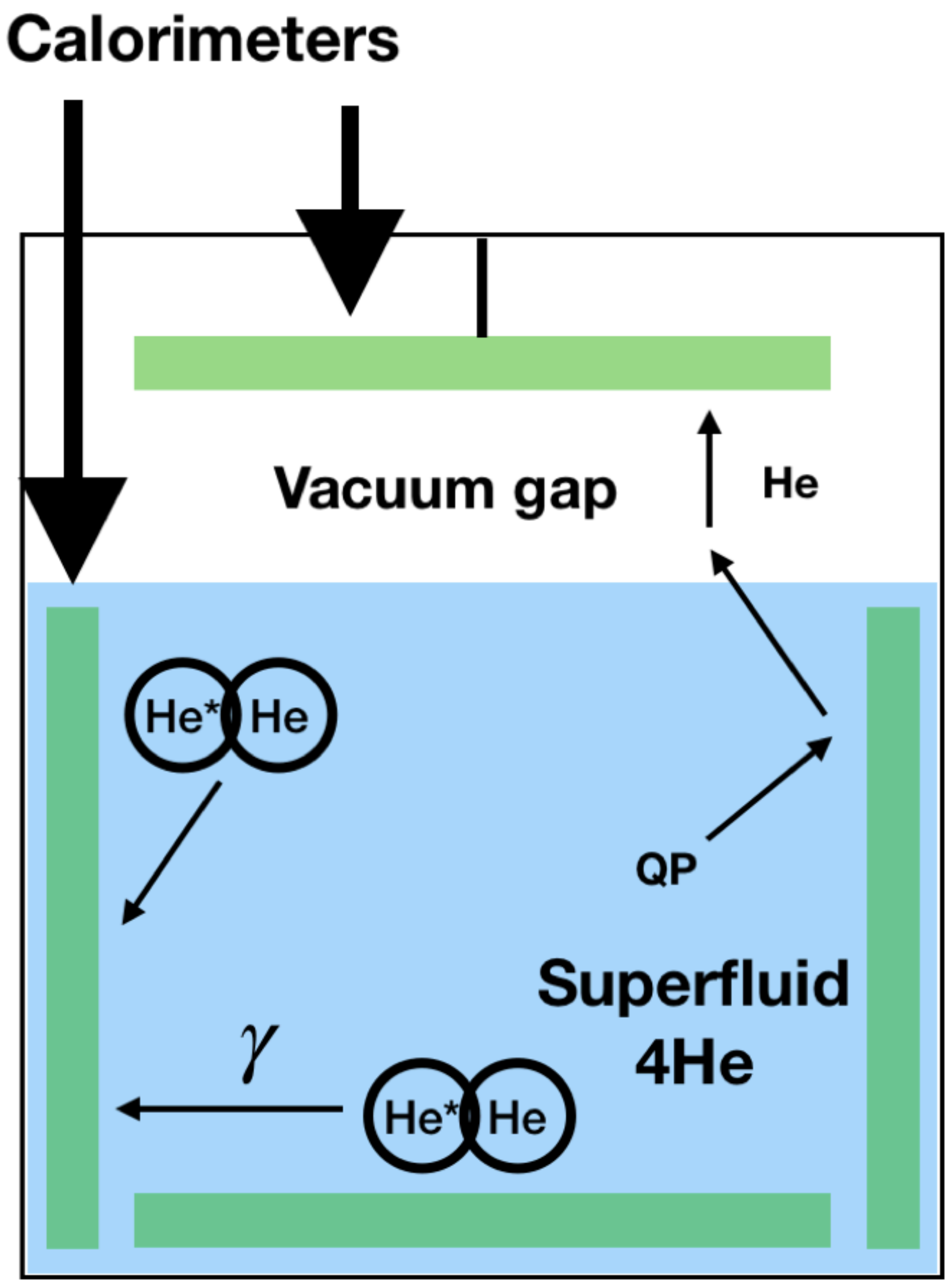
1 12/4/2019 Noah Kurinsky

Fermilab

PRD 2: Low Thresholds

HeRALD: Sub-GeV Dark Matter with Superfluid 4He

Phys. Rev. D 100, 092007



Motivations

- Low-mass nuclear target
- Above 20 eV: copious useful atomic excitations
- Primary signal channel below 20 eV: phonons, leading to evaporation of atoms
- ~10x gain from adsorption to dry sensor (lowers threshold)
- Cryogenic calorimetric readout of signal (TESs, mKIDs, etc.)

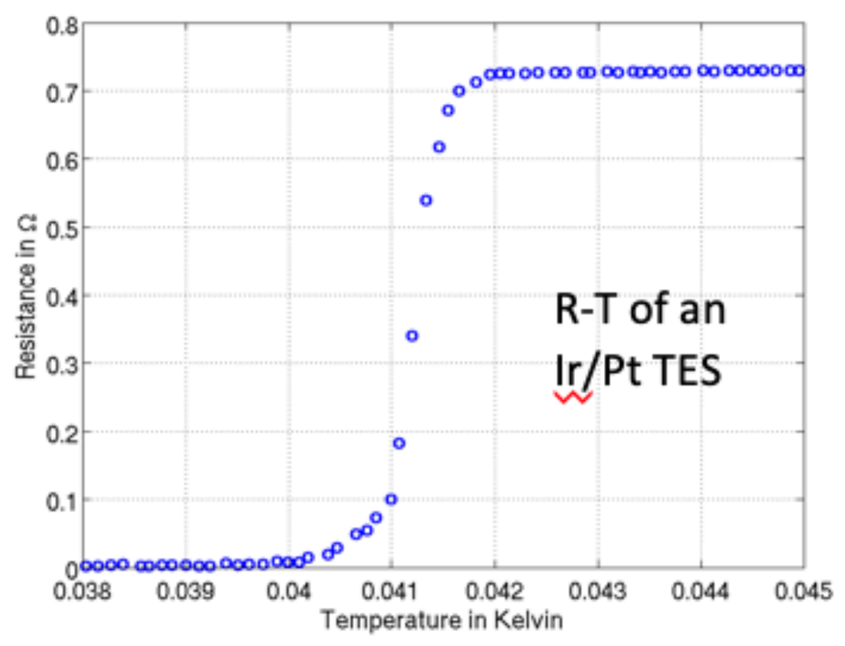
Ongoing R&D

- Stop 4He film flow with no heat: (Cs film or knife edge)
- Calorimeter threshold, and maximize adsorption gain
- Phonon reflection (leading to higher evaporation efficiency)
- Scintillation yield measurement
- Calibration sources (need low energy neutrons to reach low energies, eventually <keV)
- Optimization of immersed calorimeters

Doug Pinckney

Low-Mass Dark Matter Particle Detection Using Sensitive Low-Tc TES for Signal Readout

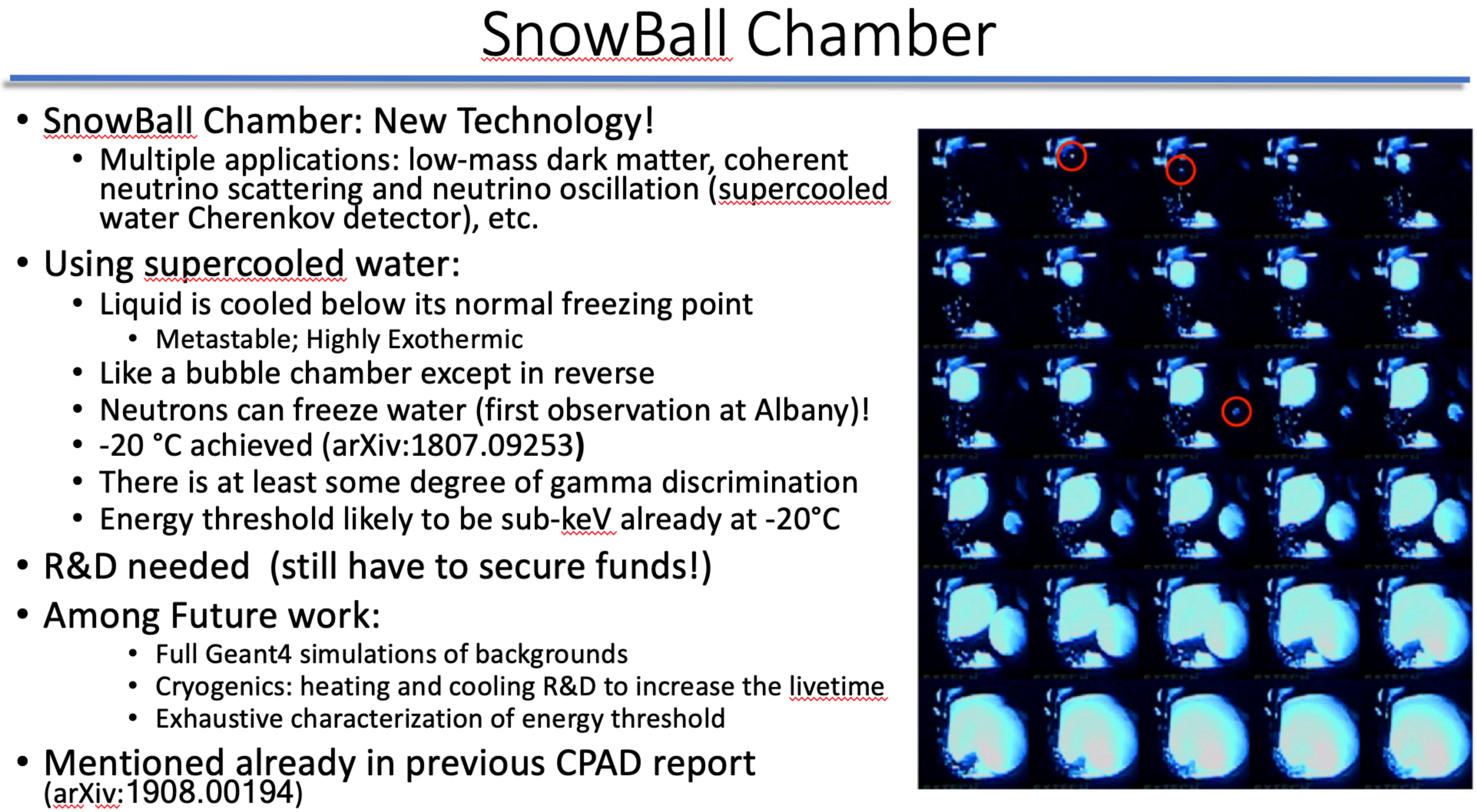
- Superfluid helium
  - DM – nuclear scattering
  - Measuring sinctilation photons
  - Measuring evaporated helium atoms
- Dielectric crystals (Al2O3, GaAs), superconducting crystals (Al, Nb)
  - Nucleus scattering, electron scattering, or DM particle absorption
  - Measuring athermal phonons in non-equilibrium detection with low-threshold TES arrays
  - Measuring heat in thermal detection with a single TES
- Enabling technology
  - Argonne National Lab has developed a low-Tc TES
  - Tc is tunable between 10 mK – 200 mK
  - Transition width < 0.3 mK
  - Energy resolution can be at the order of 10 meV



R-T of an Ir/Pt TES

Gensheng Wang

PRD 2: Low Thresholds

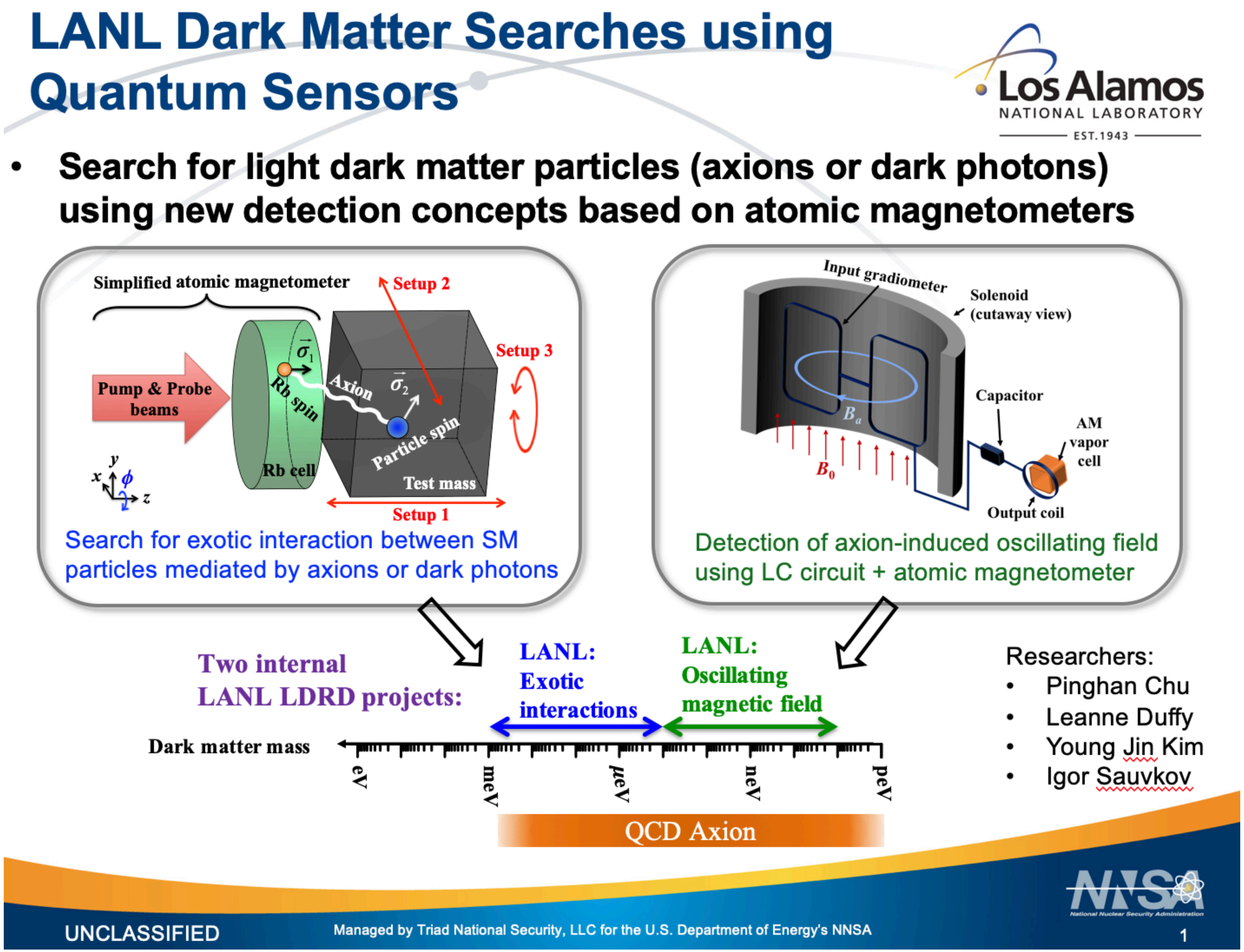


SnowBall Chamber

- SnowBall Chamber: New Technology!
  - Multiple applications: low-mass dark matter, coherent neutrino scattering and neutrino oscillation (supercooled water Cherenkov detector), etc.
- Using supercooled water:
  - Liquid is cooled below its normal freezing point
    - Metastable; Highly Exothermic
  - Like a bubble chamber except in reverse
  - Neutrons can freeze water (first observation at Albany)!
  - -20 °C achieved (arXiv:1807.09253)
  - There is at least some degree of gamma discrimination
  - Energy threshold likely to be sub-keV already at -20°C
- R&D needed (still have to secure funds!)
- Among Future work:
    - Full Geant4 simulations of backgrounds
    - Cryogenics: heating and cooling R&D to increase the livetime
    - Exhaustive characterization of energy threshold
- Mentioned already in previous CPAD report (arXiv:1908.00194)

Carmen Carmona

PRD 4: Develop quantum sensor technology



LANL Dark Matter Searches using Quantum Sensors

Los Alamos NATIONAL LABORATORY EST. 1943

- **Search for light dark matter particles (axions or dark photons) using new detection concepts based on atomic magnetometers**

Search for exotic interaction between SM particles mediated by axions or dark photons

Detection of axion-induced oscillating field using LC circuit + atomic magnetometer

Two internal LANL LDRD projects:

LANL: Exotic interactions

LANL: Oscillating magnetic field

Researchers:
- Pinghan Chu
- Leanne Duffy
- Young Jin Kim
- Igor Sauvkov

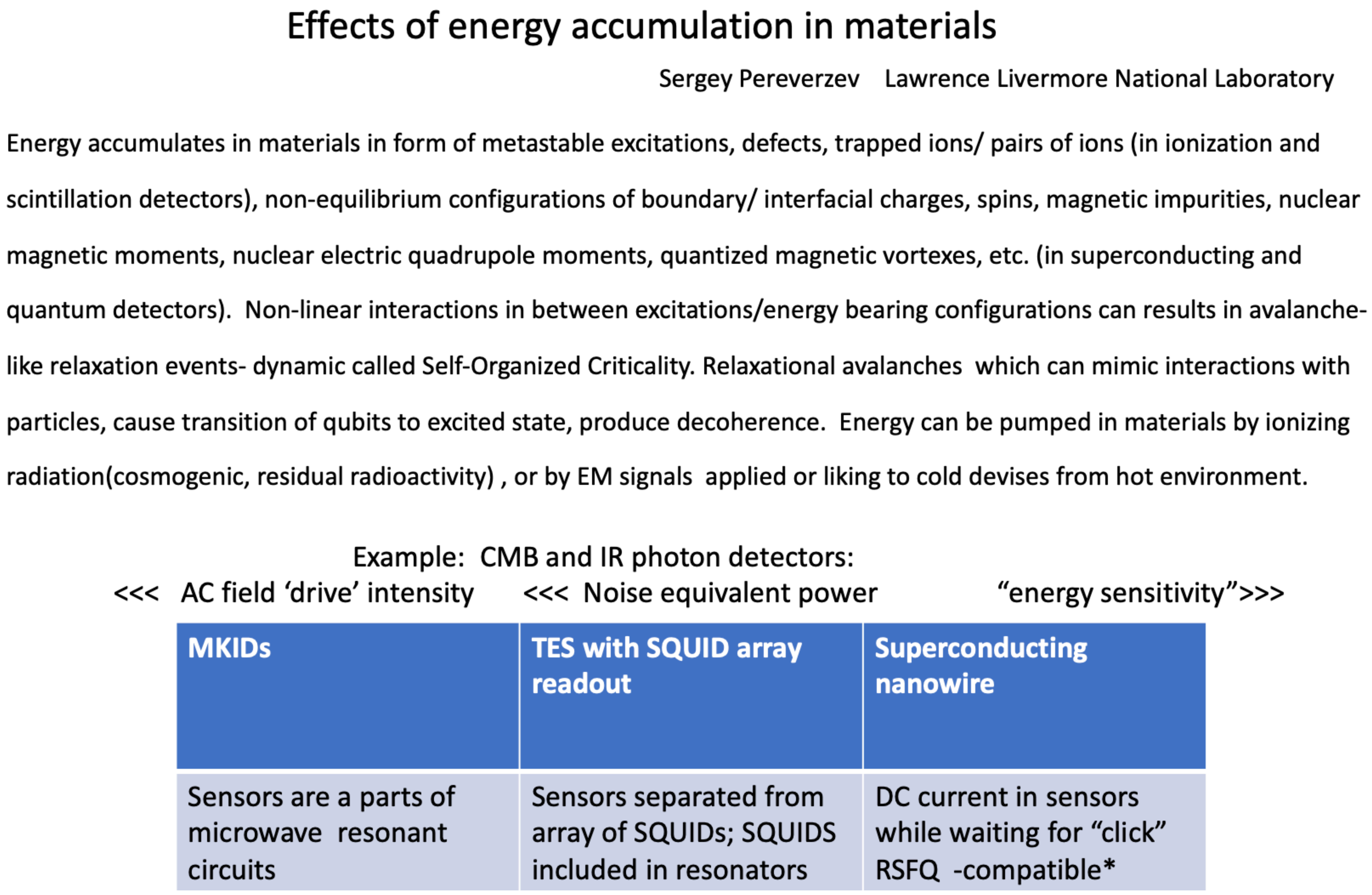
UNCLASSIFIED

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

NNSA National Nuclear Security Administration

Young Jin Kim

Key Challenge 3: Background Mitigation



Effects of energy accumulation in materials

Sergey Pereverzev Lawrence Livermore National Laboratory

Energy accumulates in materials in form of metastable excitations, defects, trapped ions/ pairs of ions (in ionization and scintillation detectors), non-equilibrium configurations of boundary/ interfacial charges, spins, magnetic impurities, nuclear magnetic moments, nuclear electric quadrupole moments, quantized magnetic vortexes, etc. (in superconducting and quantum detectors). Non-linear interactions in between excitations/energy bearing configurations can results in avalanche-like relaxation events- dynamic called Self-Organized Criticality. Relaxational avalanches which can mimic interactions with particles, cause transition of qubits to excited state, produce decoherence. Energy can be pumped in materials by ionizing radiation(cosmogenic, residual radioactivity) , or by EM signals applied or liking to cold devises from hot environment.

Example: CMB and IR photon detectors:

<<< AC field 'drive' intensity <<< Noise equivalent power "energy sensitivity">>>

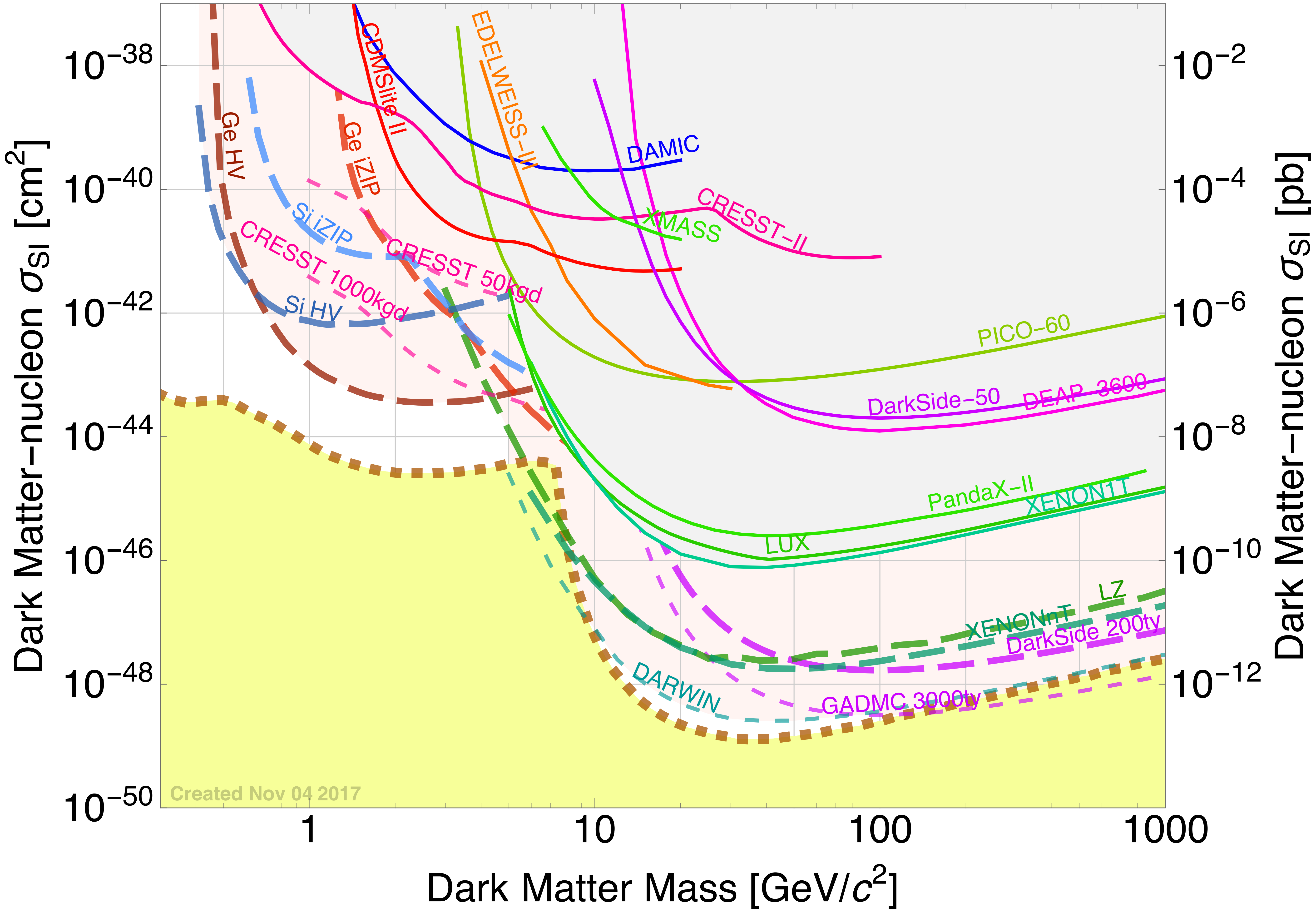
MKIDs	TES with SQUID array readout	Superconducting nanowire
Sensors are a parts of microwave resonant circuits	Sensors separated from array of SQUIDs; SQUIDS included in resonators	DC current in sensors while waiting for "click" RSFQ -compatible*

Back-up

Science Drivers (1)

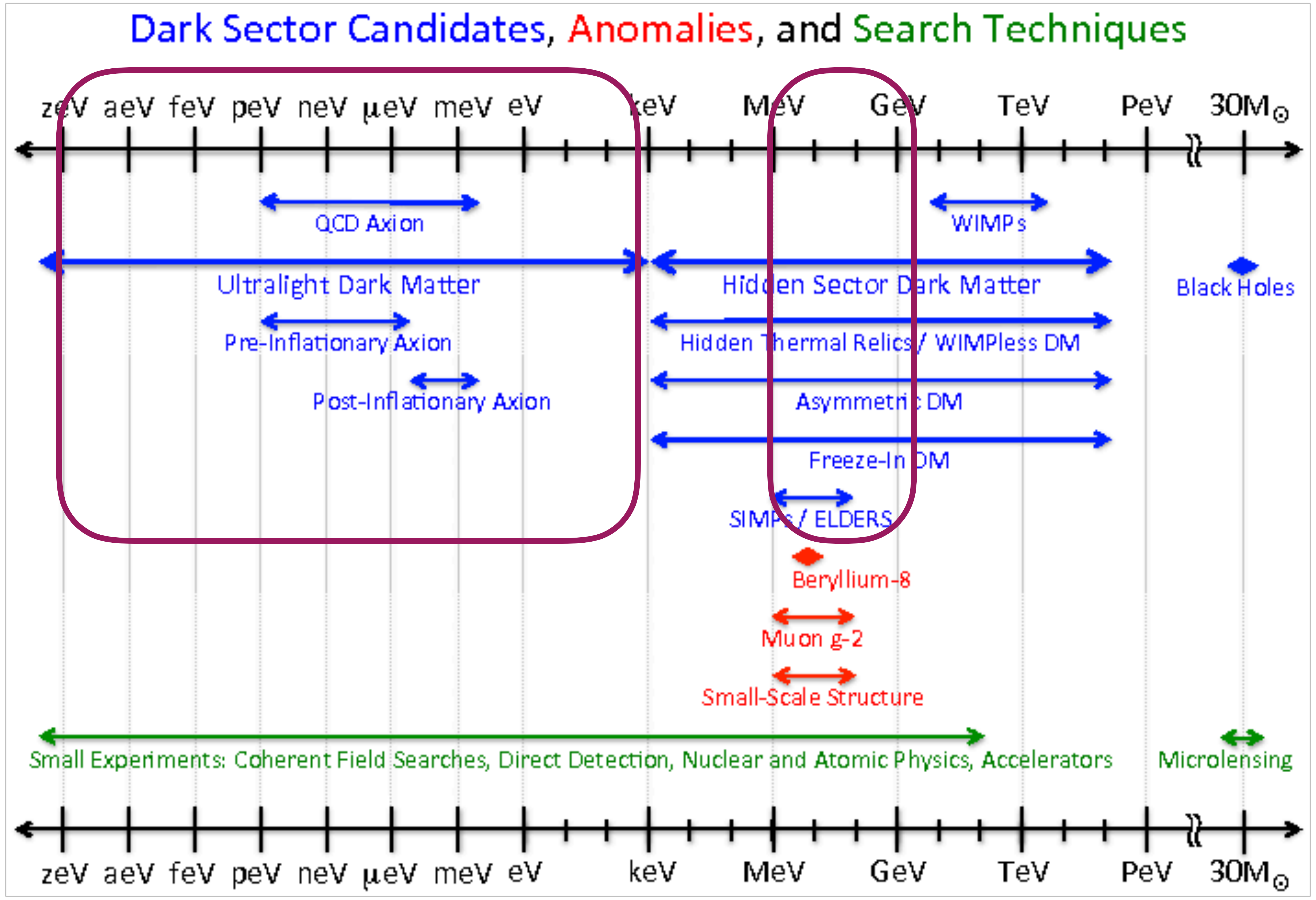
P5 identified the new physics of dark matter as one of six science drivers in its most recent report.

- Current direct detection experiments have made great progress in increasing sensitivity to dark matter interactions.
- G2 experiments will further constrain this space, but fall short of the neutrino floor.
  - Provides opportunities for **R&D in large detectors** to explore this final frontier.



Science Drivers (2)

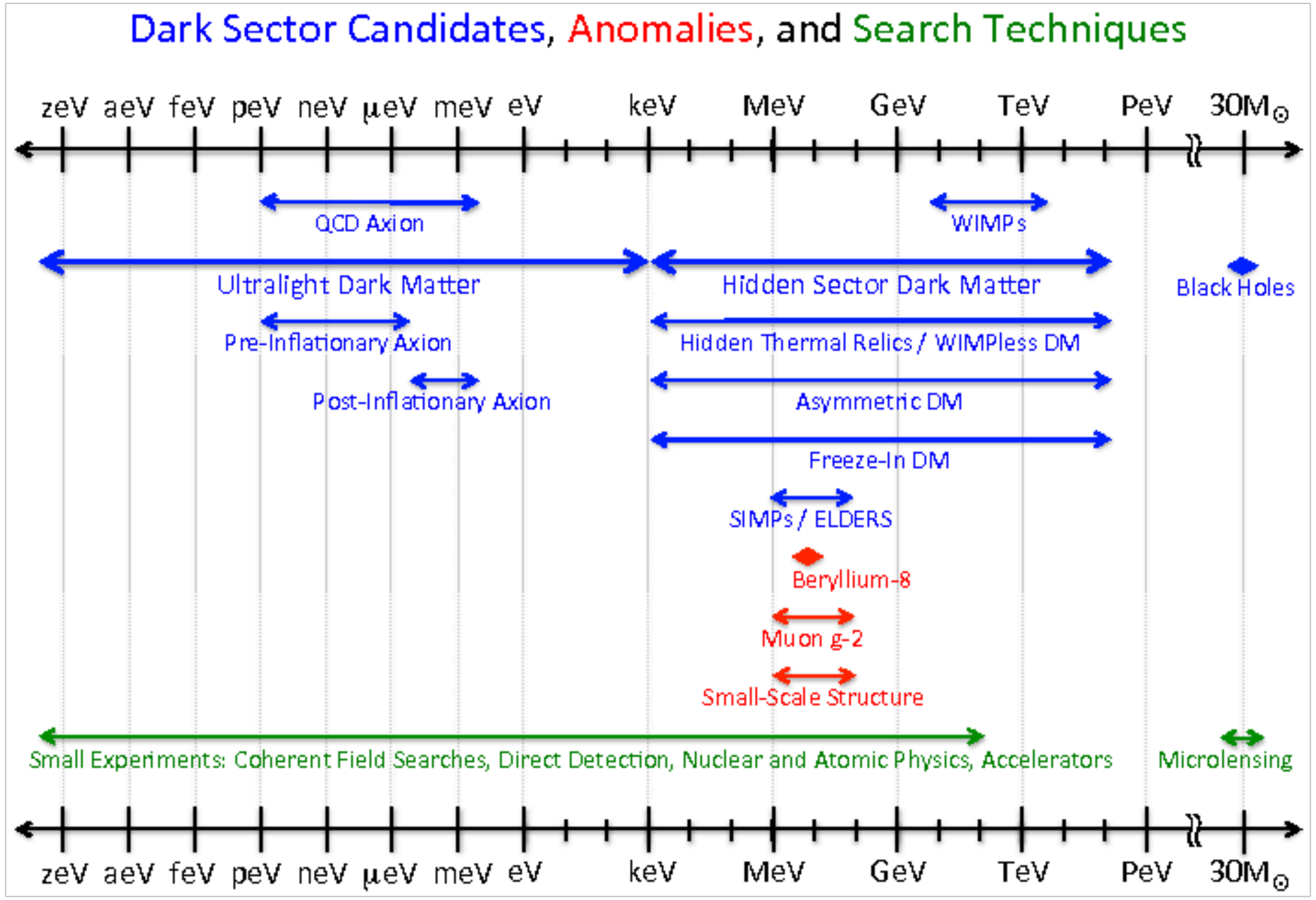
- Much work has gone into looking for the canonical WIMP
    - No evidence from direct searches and no evidence of SUSY from LHC
- If we broaden our perspective by loosening our cosmology or theory priors, we still have reasonable dark matter candidates — many with lower masses (1 MeV - 10 GeV)!
- There is theoretical work that indicate that very light dark matter may interact more like waves (QCD axions and ALPs).
- Exploration of these candidates provides opportunities for **R&D in developing new technologies.**



US Cosmic Visions: arXiv:1707.04591

Science Drivers (3)

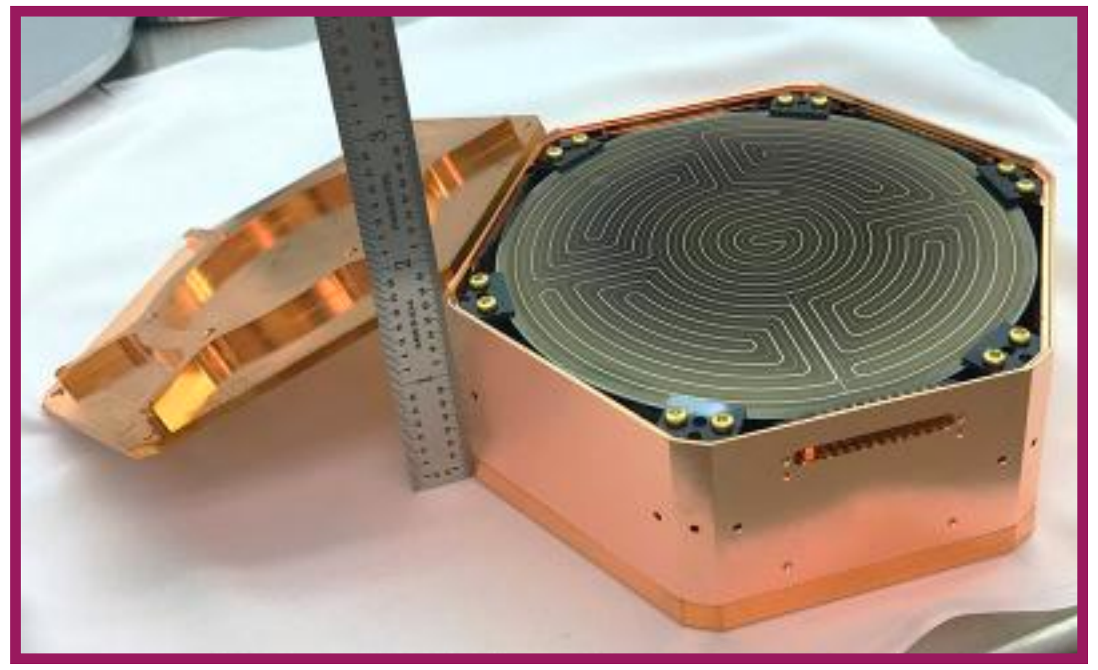
- If the dark matter particle has mass above the TeV scale - indirect detection techniques may be the most feasible discovery technology.
- Searching for signals of dark matter annihilations or decays in multiple source classes across the sky.
- **Increasing the sensitivity of indirect detection experiments to these sources provides opportunities for R&D.**



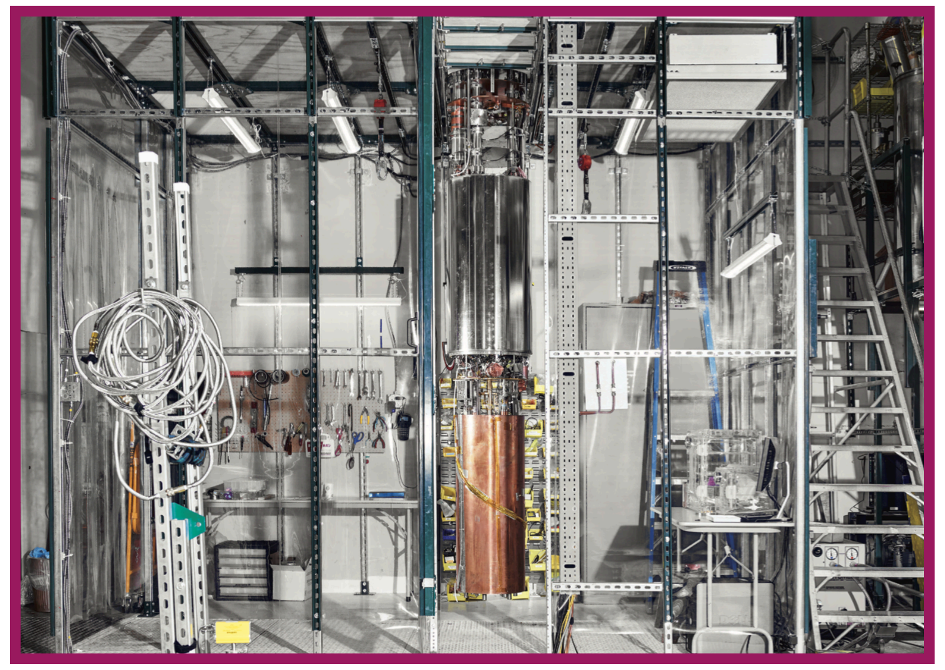
US Cosmic Visions: arXiv:1707.04591

PRDs - Preliminary

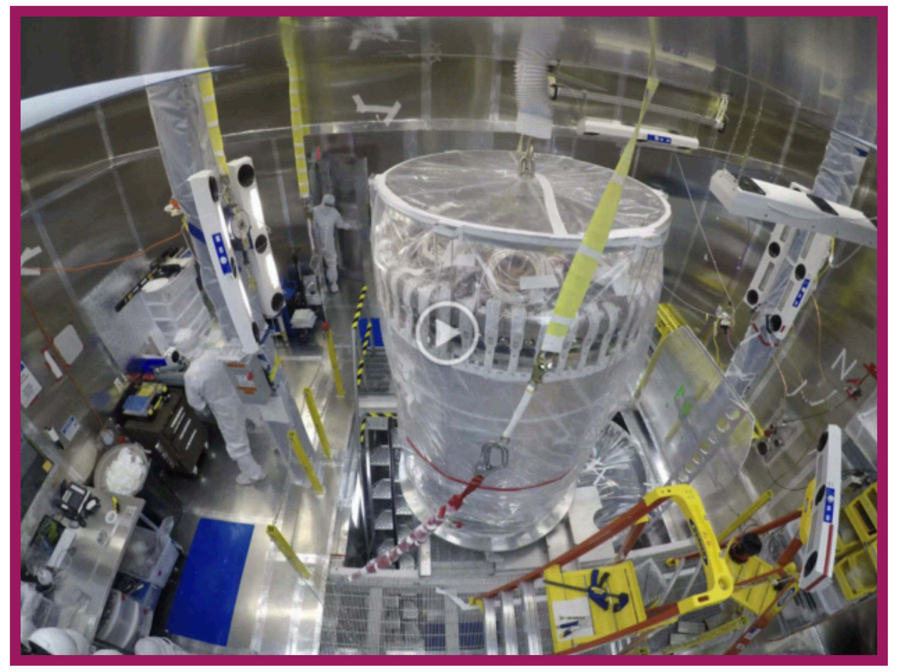
1. **R&D on methods to extend the investments of DOE in G2 experiments to cover new physics reach.**
   - Examples from Liquid Noble Experiments:
     - Reduction of backgrounds would require a combination of R&D and engineering (e.g. distillation of LXe, Crystalline Xe, production & purification LAr, grid emission of electrons)
     - Improve photon collection efficiency would require some R&D.



SuperCDMS SNOLAB



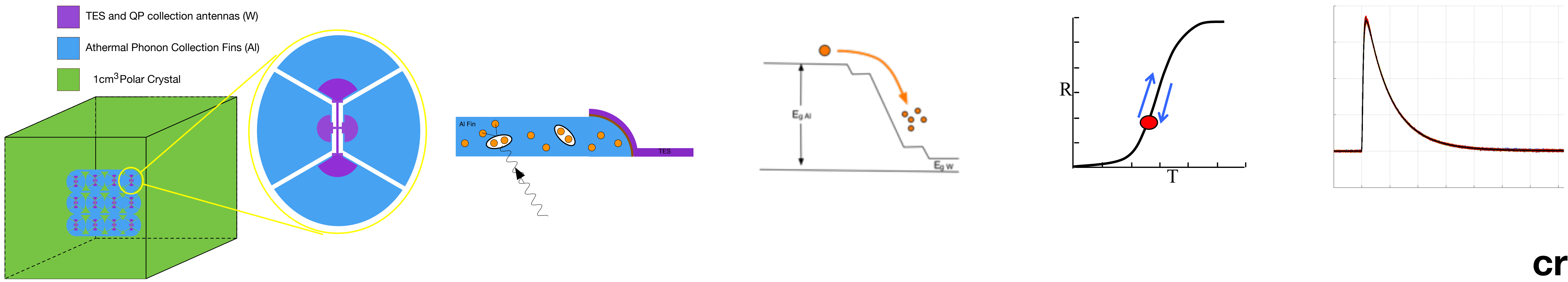
ADMX G2



LZ

PRDs - Preliminary

2. **Lower thresholds to probe particle dark matter candidates with very small mass.**
    - R&D need to further study exploitation of low energy excited states in materials (i.e. quasiparticle excitations in superconductors and superfluids, vibrational modes in molecules, and electron-hole pairs in narrow gap semiconductors)
    - As energy thresholds decrease —> calibration and background mitigation challenges will appear. Hence, R&D in these areas are also needed.



credit: Matt Pyle

PRDs - Preliminary

3. **Improved angular resolution for point source identification (to reduce astrophysical backgrounds) and greater sensitivity to weak sources for indirect detection experiments.**
   - R&D needed to scale existing technology for use in future experiments, reducing cost per channel, data volume and rate, and instrument infrastructure.
   - New technologies beyond silicon tracking are needed to scale necessary detection area at reasonable cost.
   - A future space based telescope could be based on scintillators, fiber-based trackers and calorimeters. This requires R&D into low dark count photodetectors with sufficiently high sensitivity to ultraviolet.

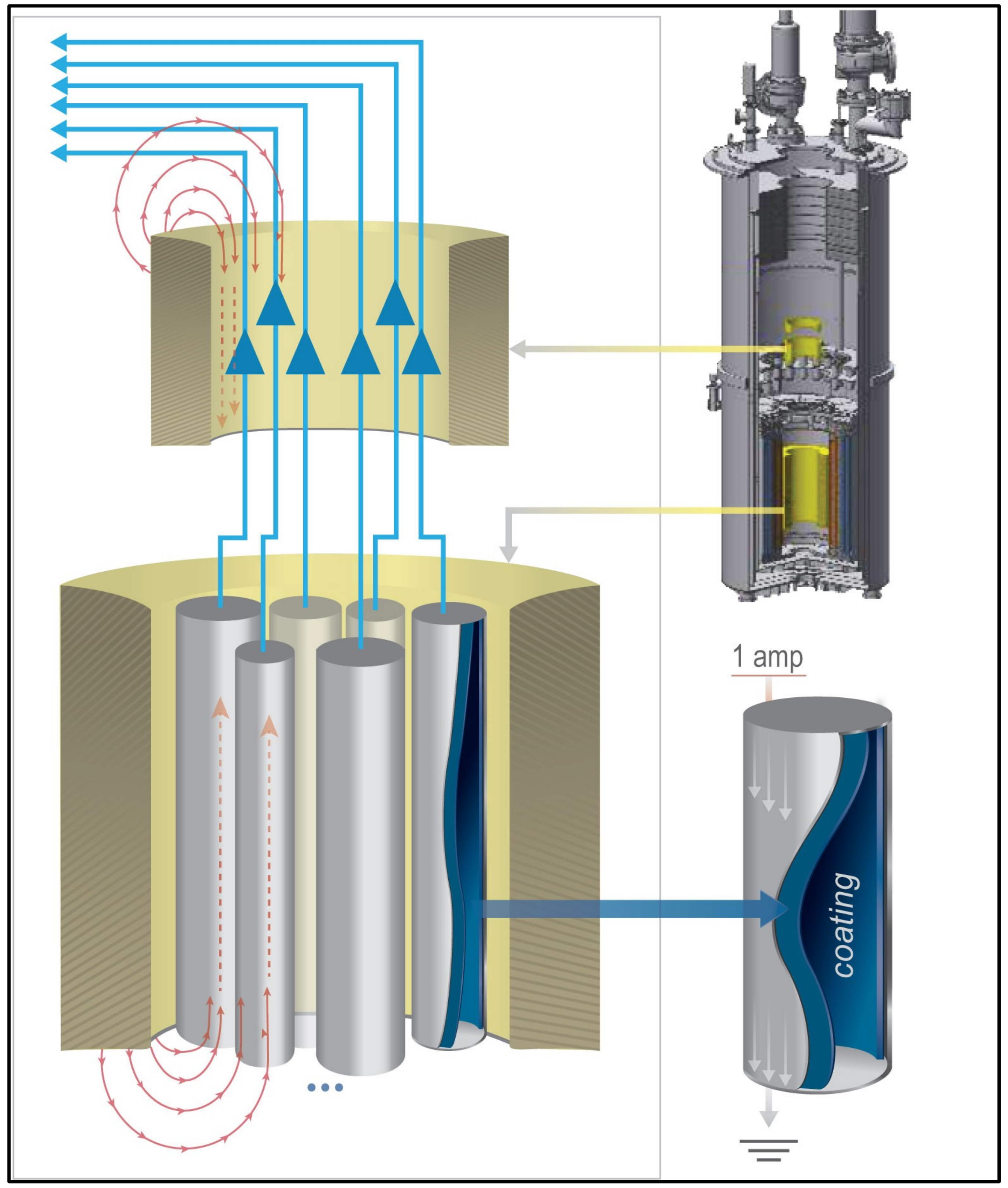
PRDs - Preliminary

4. **Develop quantum sensor technology needed to propel the entire QCD axion band. (See Quantum Sensor Talk)**
   - R&D is needed to improve sensitivity beyond the standard quantum limit for electromagnetic-coupling to QCD axions with mass between new and ~ 100 μeV.
   - New photon counting techniques are need to detected electromagnetic coupling to QCD axions about ~100 μeV.
   - New quantum protocols are necessary for the detection of short-range spin-dependent interactions above ~ 1 μeV.

PRDs - Preliminary

5. Next Generation High-Q Resonators

- Next generation experiments also propose to combine signals from large arrays of cavities operating in parallel.
- They will poses challenges in terms of tuning and materials selection to maintain high-Q
- They will also require the development of new, high channel-count cryogenic electronics.
- New techniques for building these devices will be required and paradigm-shifting new techniques, such as active resonant digital feedback

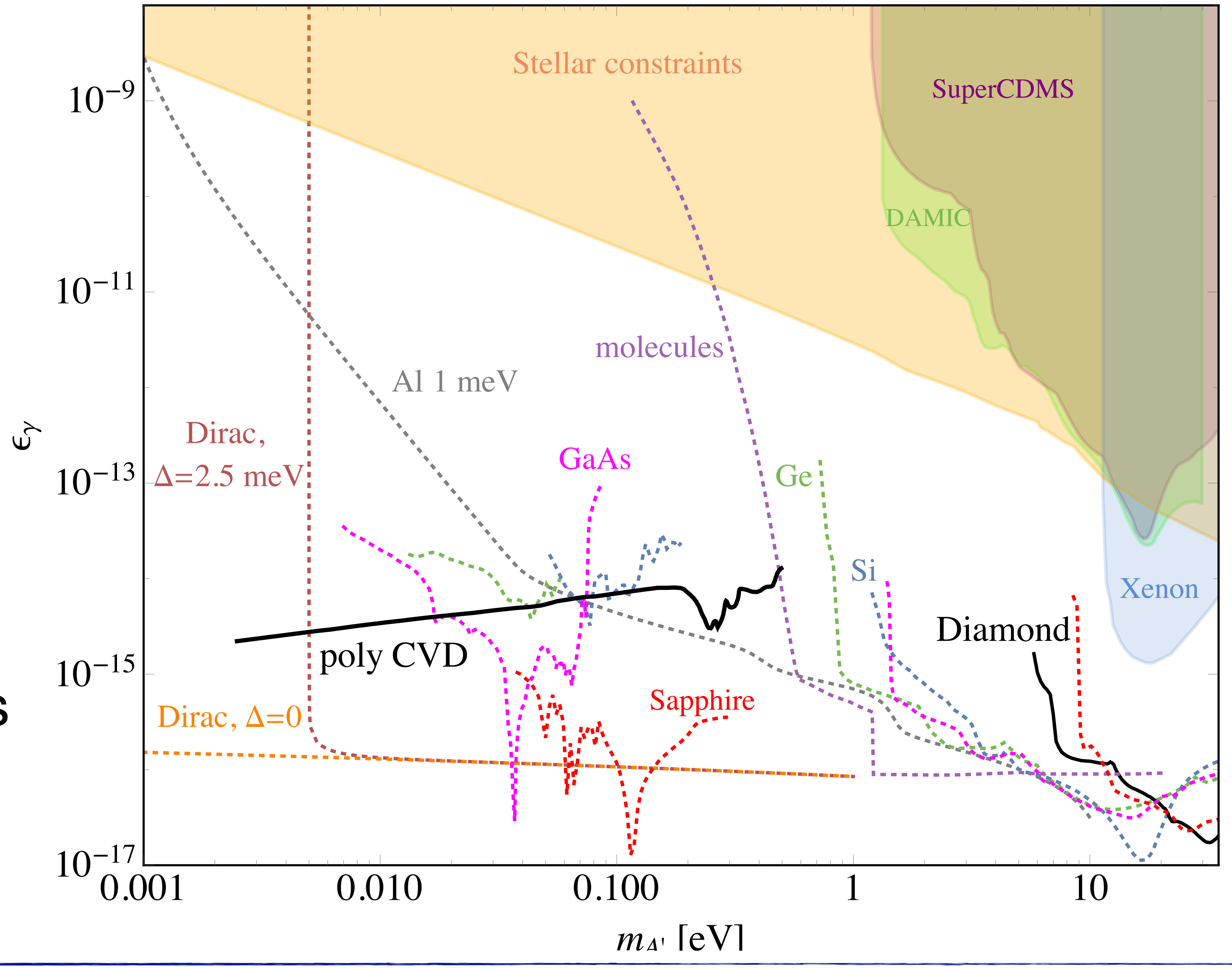


credit: Gp Carosi

Key Challenges - Preliminary

1. **Identification of New Materials, Quantum Materials for Dark Matter Detection**

   - R&D into new materials such as Dirac materials, polar materials and topological insulators could allow the investigation of dark matter candidates in the sub-MeV range.



Projected reach for absorption of kinematically mixed photons illustrating the potential for germanium, silicon, Dirac materials, polar crystals, molecules, and superconducting aluminum targets. *arXiv:1901.07569*

Key Challenges - Preliminary

2. **Single photon counters from near-infrared to microwave:**
    - Future searches for axions using electric field measuring techniques will become limited by the quantum noise that is a consequence of the non-commutative nature of measurements of the amplitude and phase of the field ("Standard Quantum Limit).
    - New photon counting techniques are need to detected electromagnetic coupling to QCD axions about ~100 μeV.
    - A dramatic improvement in technological capability such as this can be expected to have impacts well beyond the field of high energy physics.

Key Challenges - Preliminary

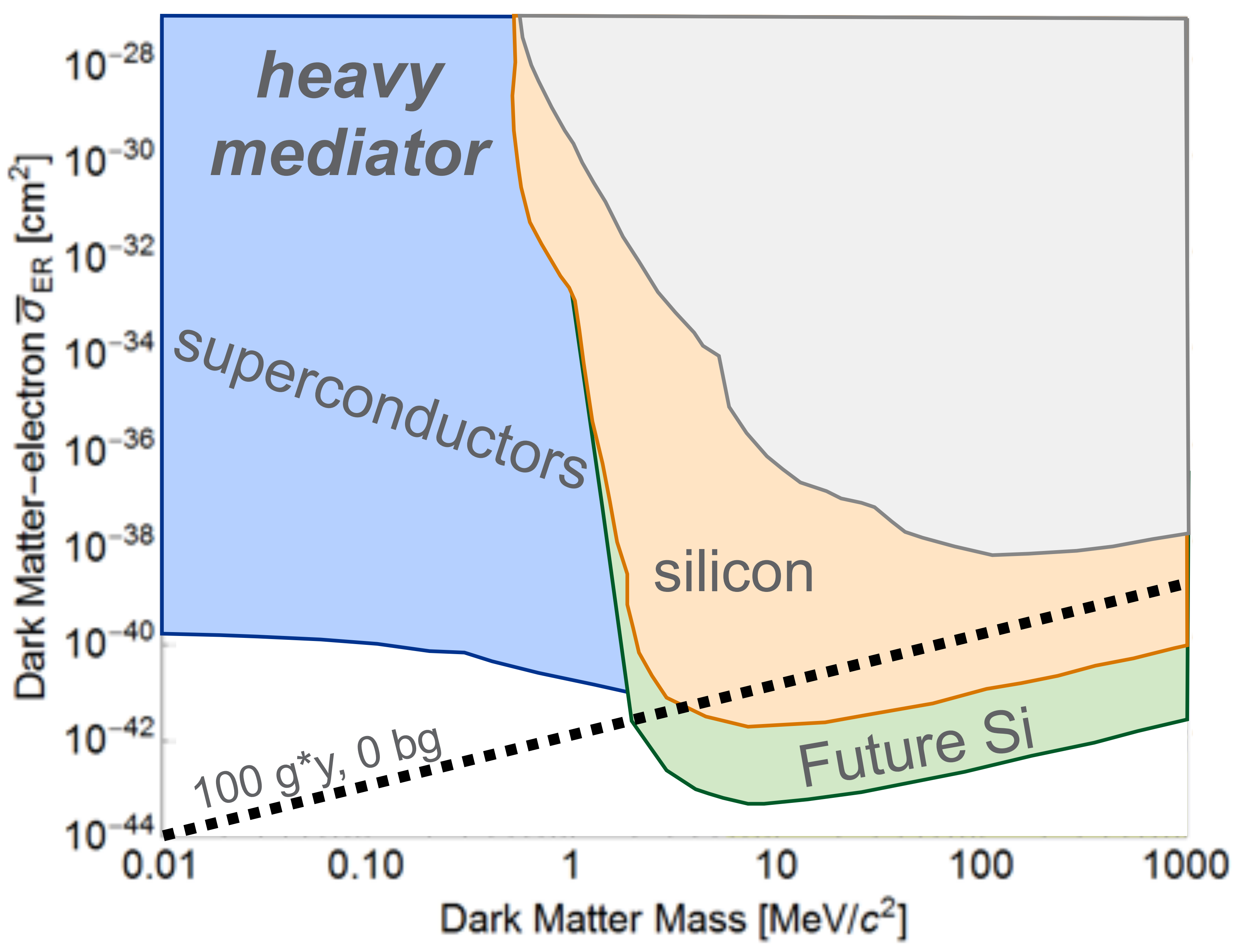
3. **Background mitigation**
   - Backgrounds will continue to play a key role as dark matter experiments make progress in the next 5 - 20 years.
   - R&D opportunities might include: Material handling, material cleaning (polymers, purification LXe and LAr,),material production (underground fabrication, sourcing of raw materials), measurement techniques for trace background analysis, identification of intrinsic backgrounds (acoustic sensors or other specialized instrumentation) and environmental controls.
   - R&D may be needed to understand energy transport mechanisms in the 0.1 - 10 eV range (plasmons, interbank transitions and phonons) for potential "scattering" style detector concepts & readout for detectors.

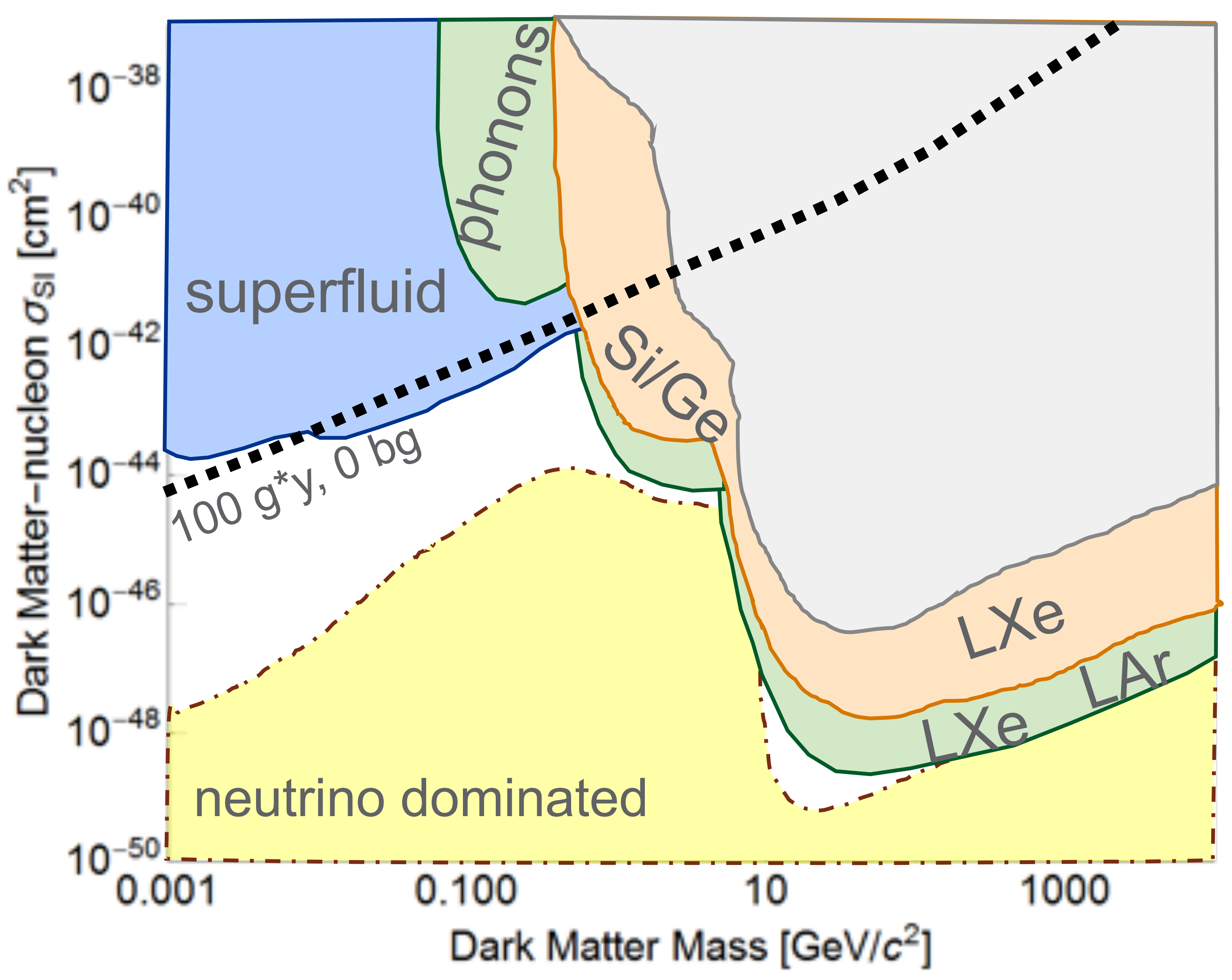
Key Challenges - Preliminary

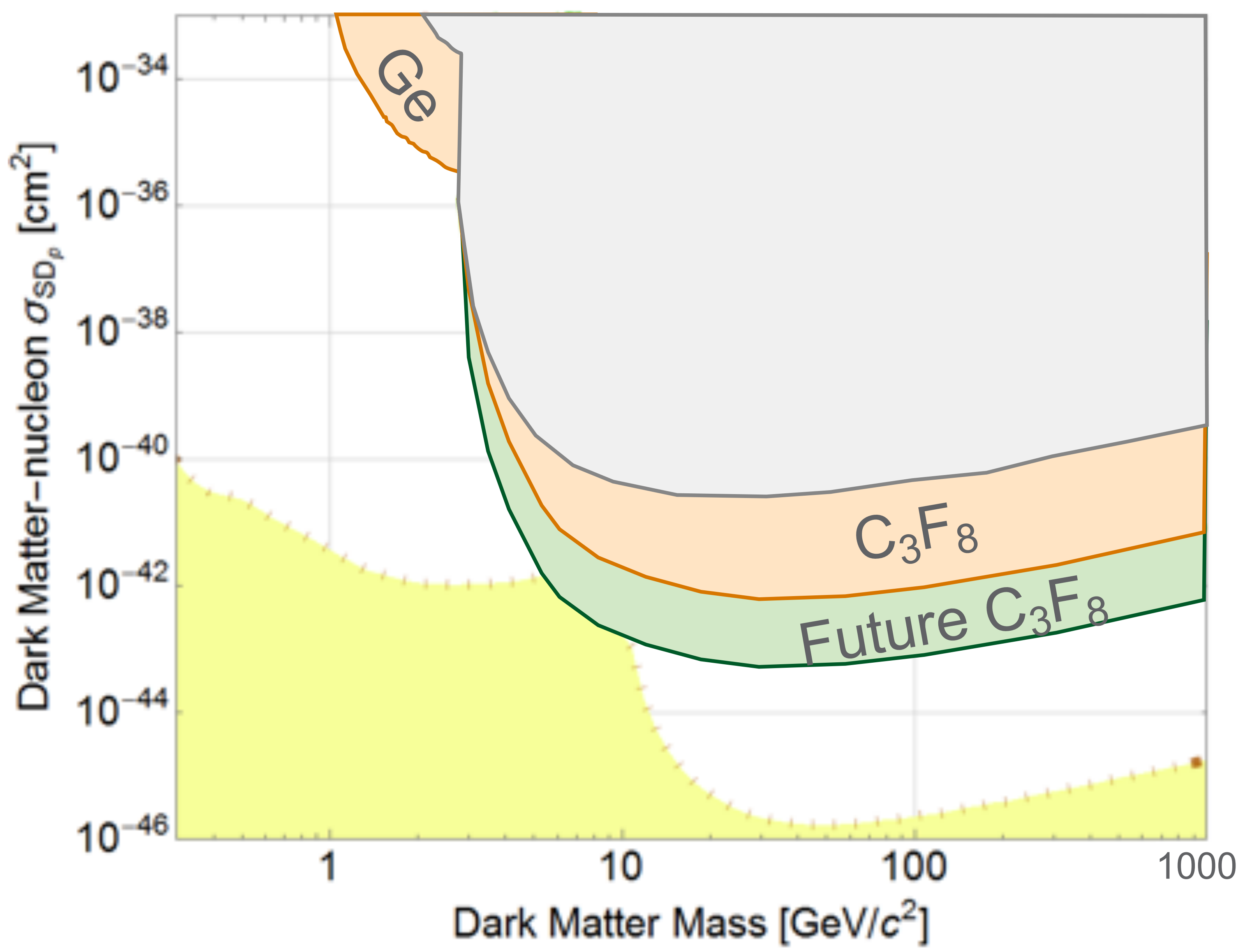
4. **High-field, cost-effective superconducting magnets.**
    - Cavity-based axion searches rely on high-field magnets.
    - Their is a synergy between the upsurge in interest in commercial Fusion reactors that has increased &D in developing high-field, high-T_c superconducting magnets and the R&D needs of next generation large, high-field magnets.

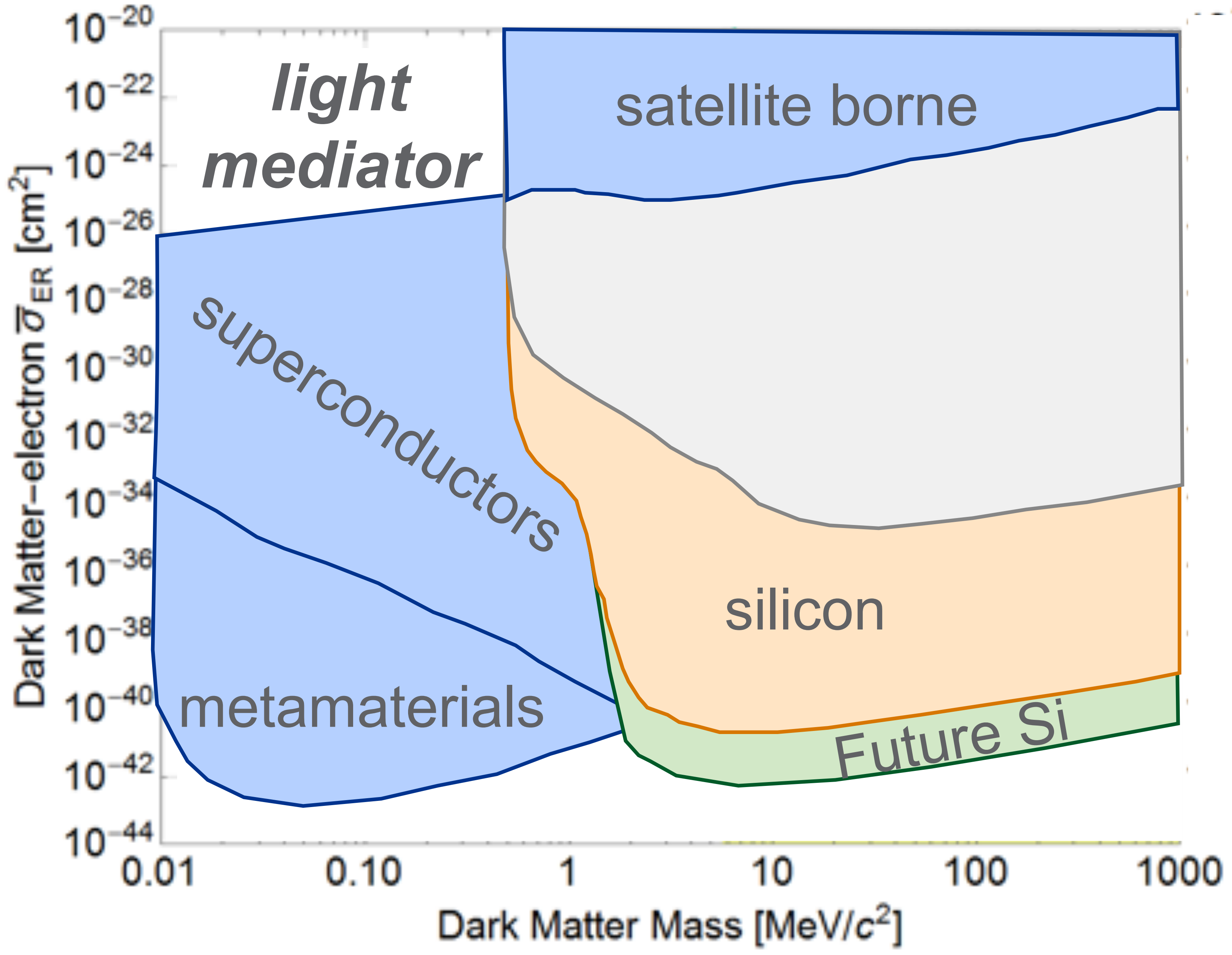
Key Challenges - Preliminary

5. **Ubiquitous cryogenics for cooling superconducting sensors**
    - Many new detector technologies, including space-based detectors, operate at sub-Kelvin temperatures.
    - Developing cost-effective and scalable methods to reach sub-Kelvin temperature would make these new technologies more accessible for R&D and allow implementation on scales that are currently unachievable.









⬜ Currently Excluded
🟧 Current funded sensitivity (5 years)
🟩 Next generation proposals (10 years)
🟦 Future R&D (20+ years)

credit: John Orrell

Thank You Contributors!

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