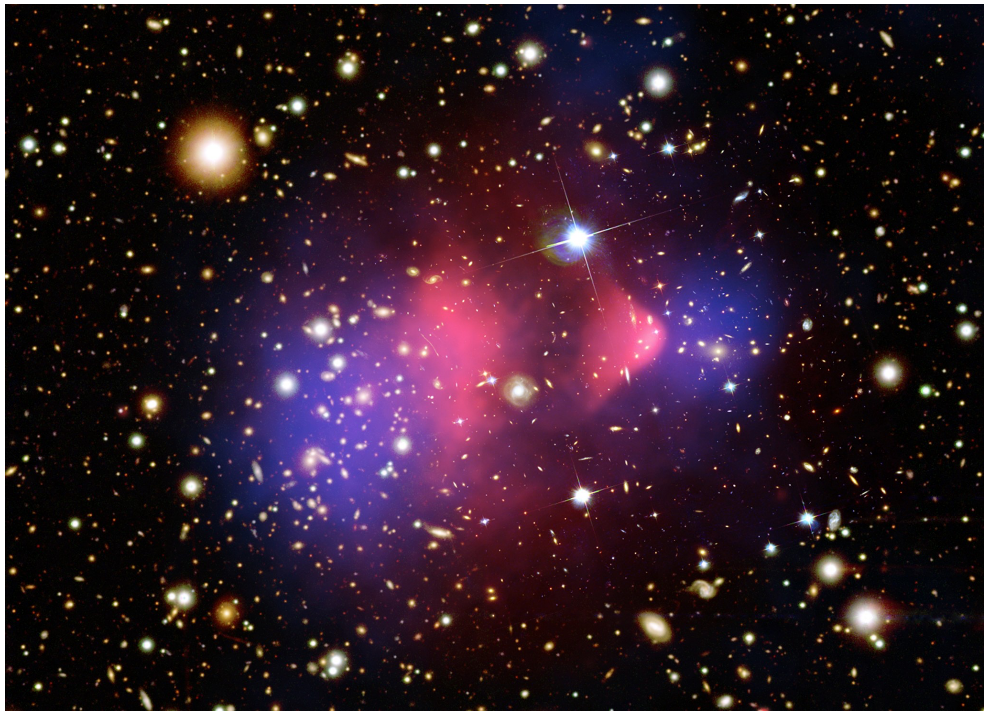
Detectors for Dark Matter

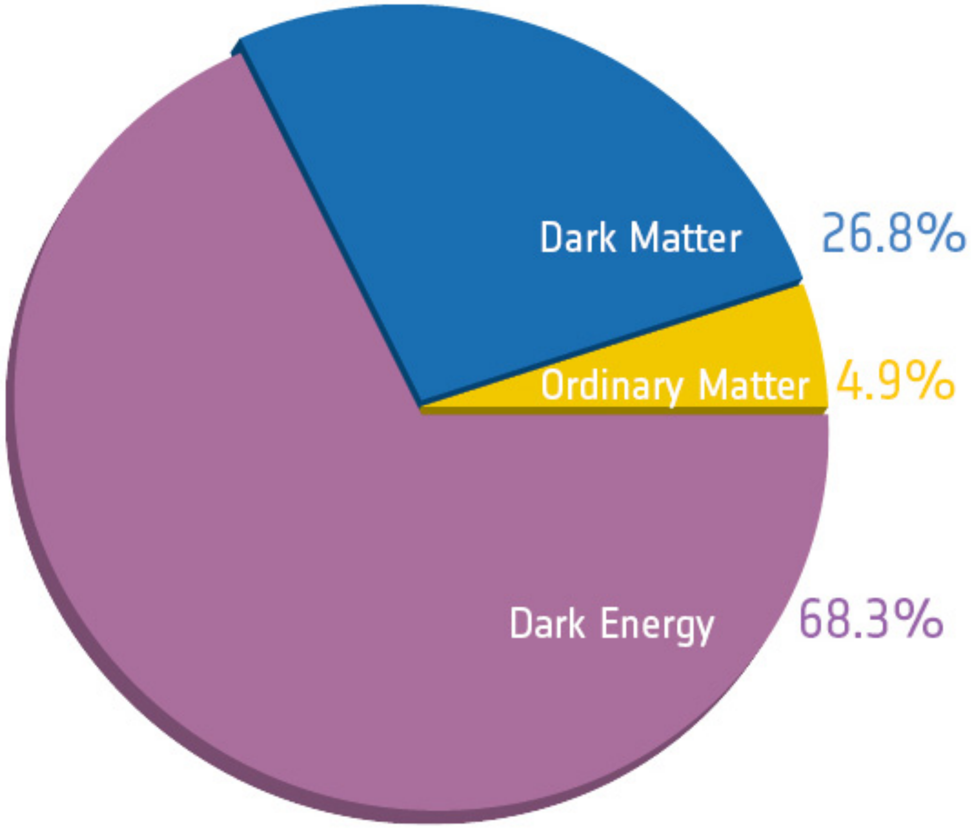
J. Estrada

Fermilab

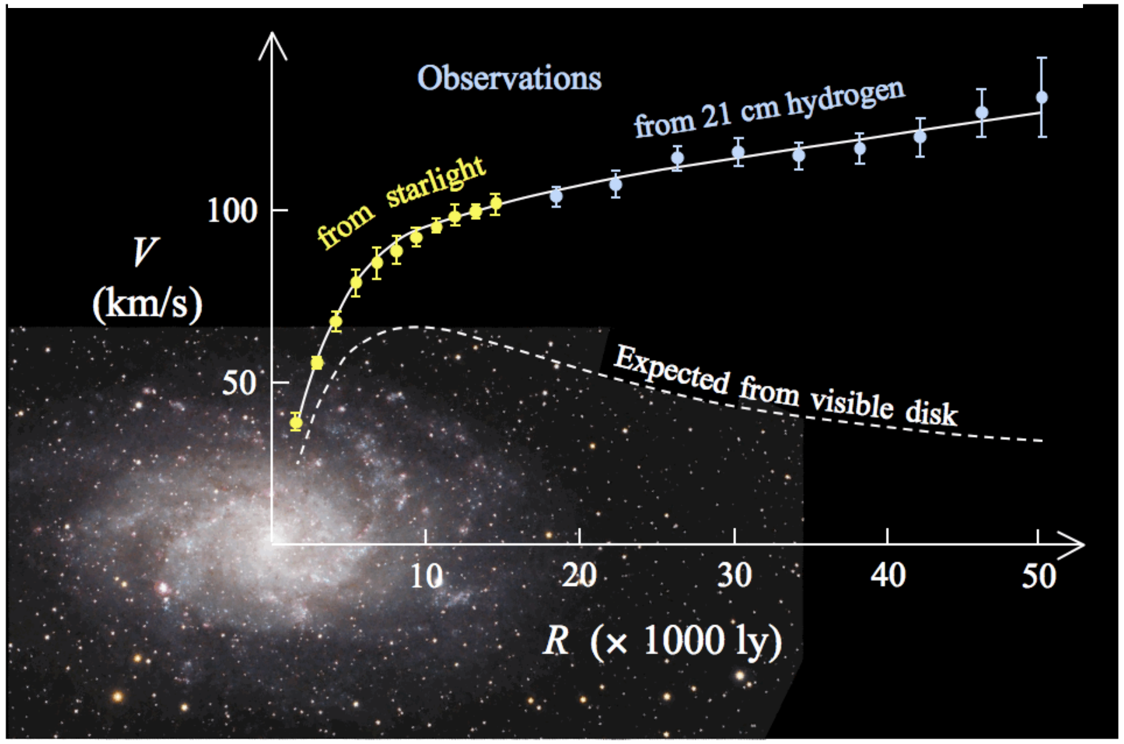
Outline

- The Generation 2 dark matters detectors.
- Motivation to go beyond G-2 program.
- Ideas for medium scale projects to go beyond G-2.
- Conclusion

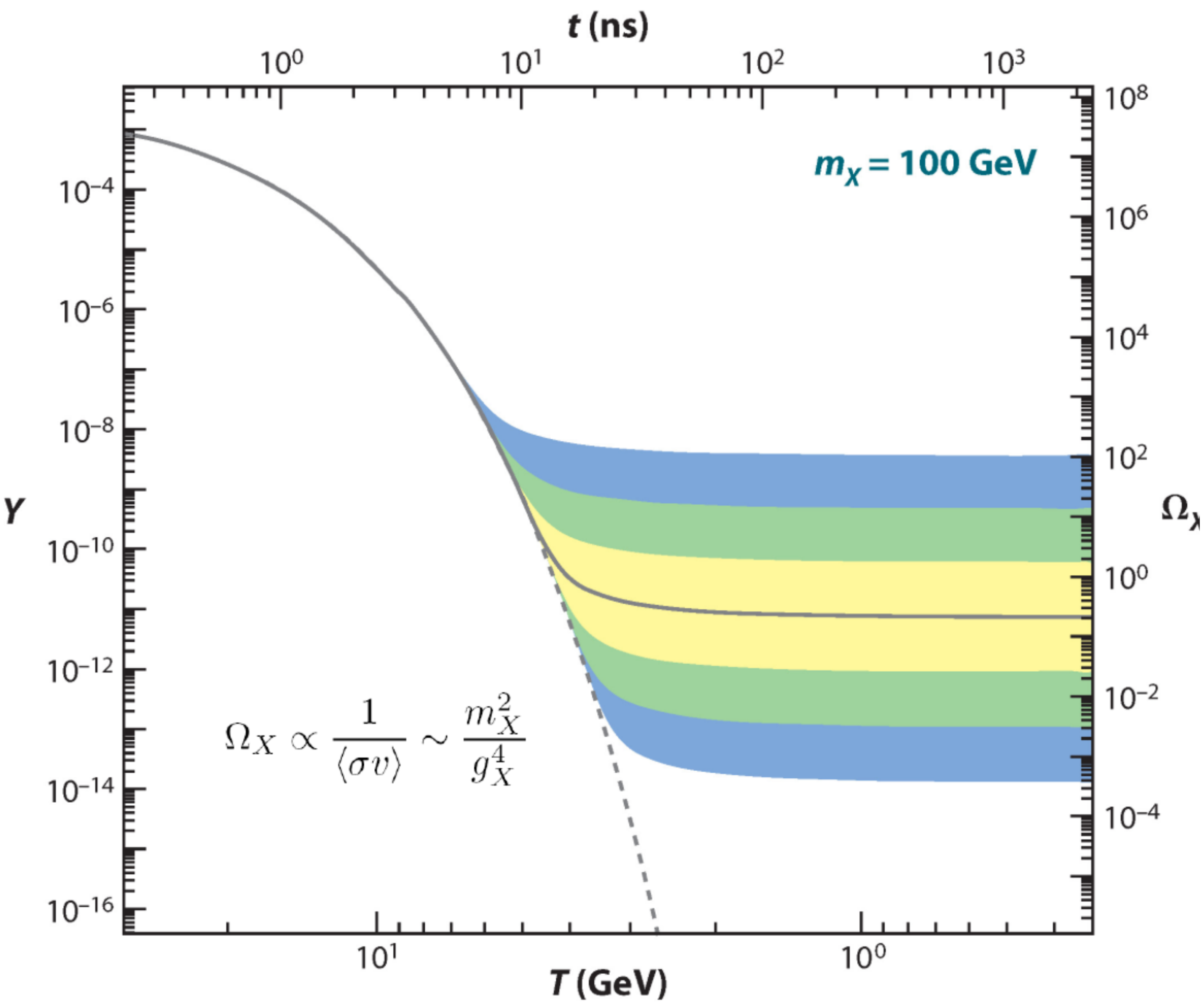




Rotation curves of galaxies, gravitational lensing, large scale structure of the universe and CMB.



Thanks Vera Rubin (1928-2016) !



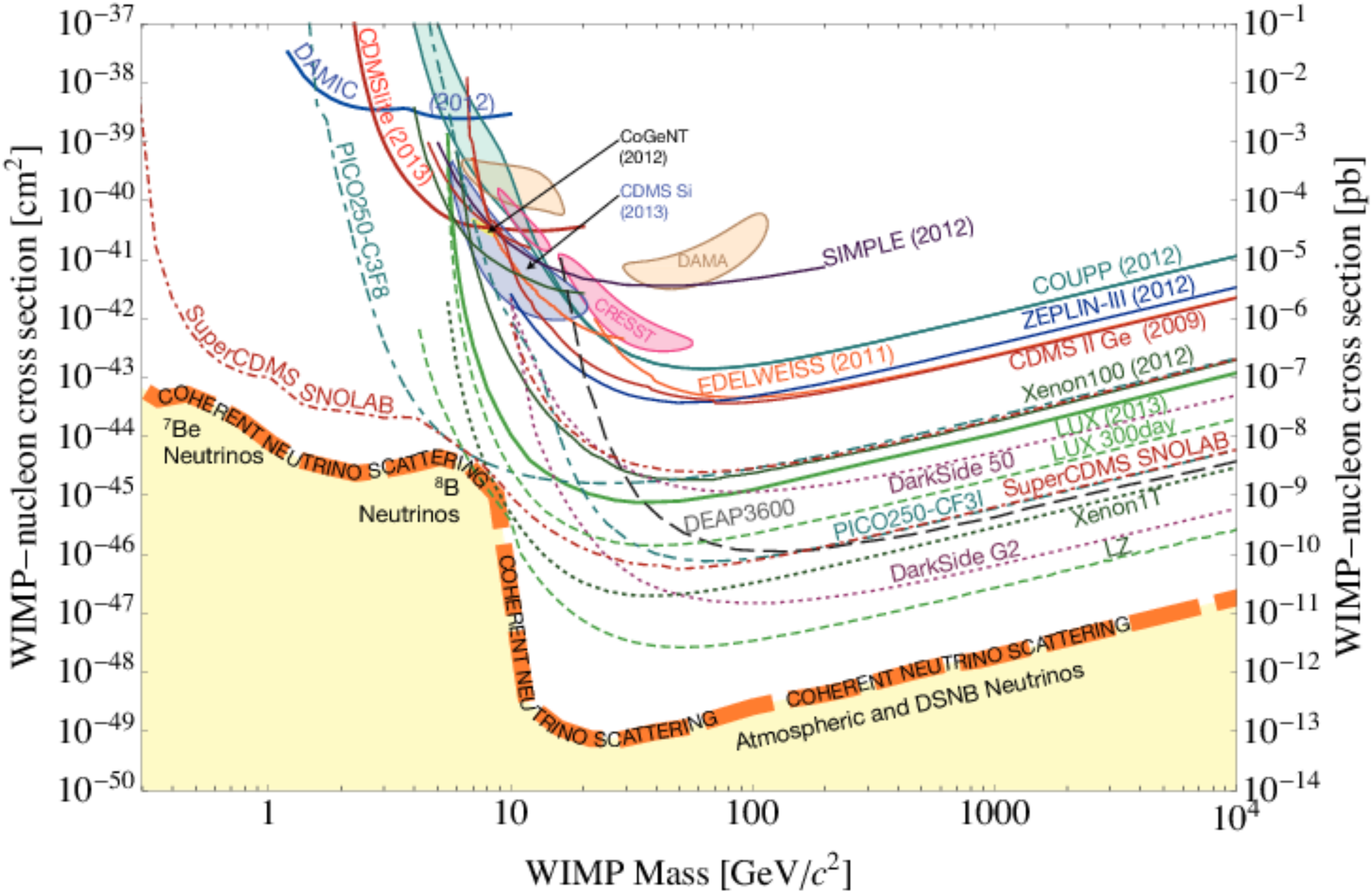
WIMP miracle:

Assuming that DM freeze-out as the universe cooldown gives a good motivation for WIMPs, with a mass scale of ~100 GeV

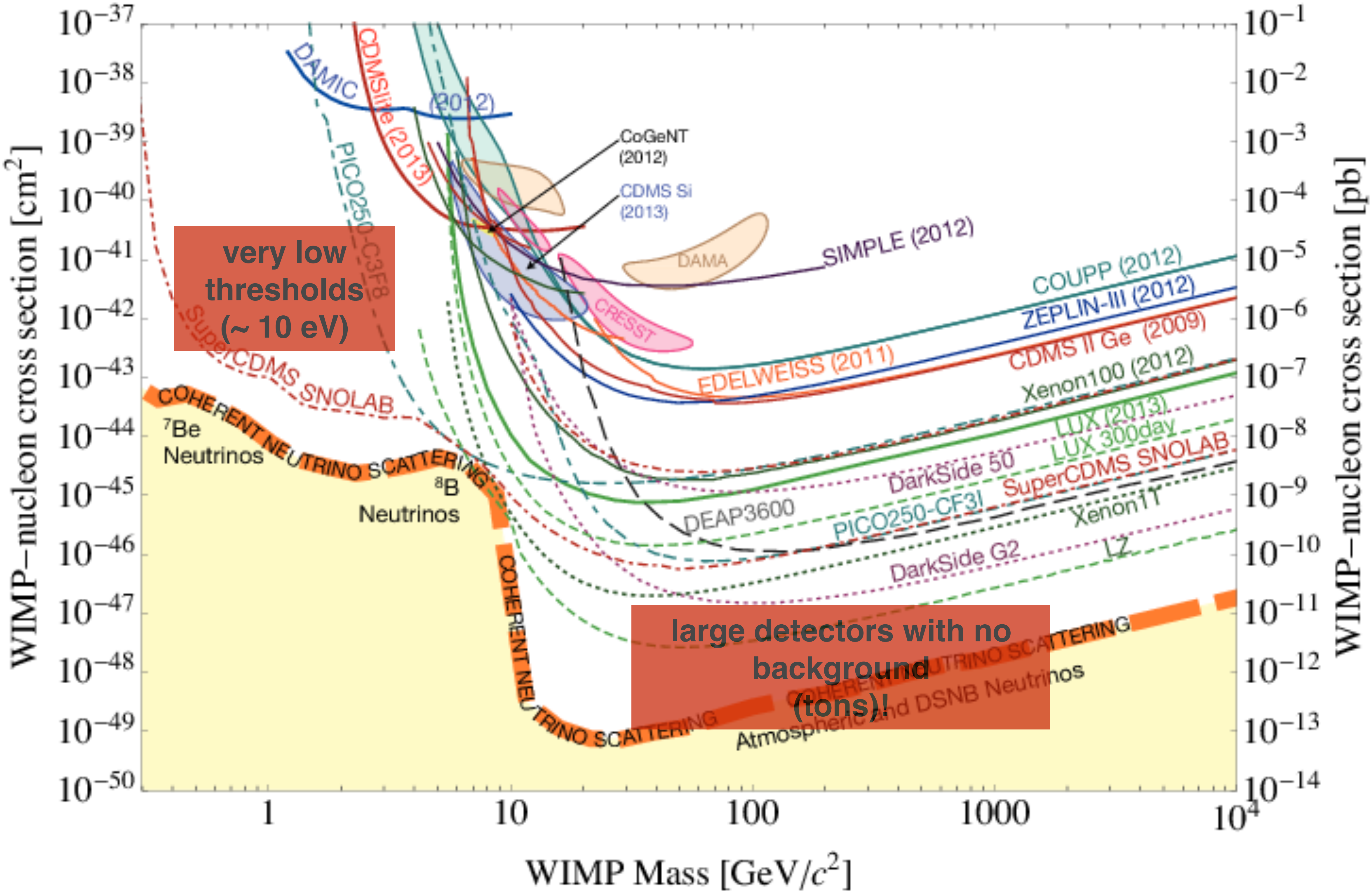
$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1}$$

this drove the field for many years, and is still the highest priority

snapshot of WIMP searches in 2013



snapshot of WIMP searches in 2013



G-2

DOE Office of High Energy Physics and the NSF Physics Division have jointly selected a portfolio of projects for the "second generation" of direct detection dark matter experiments.

Three projects:

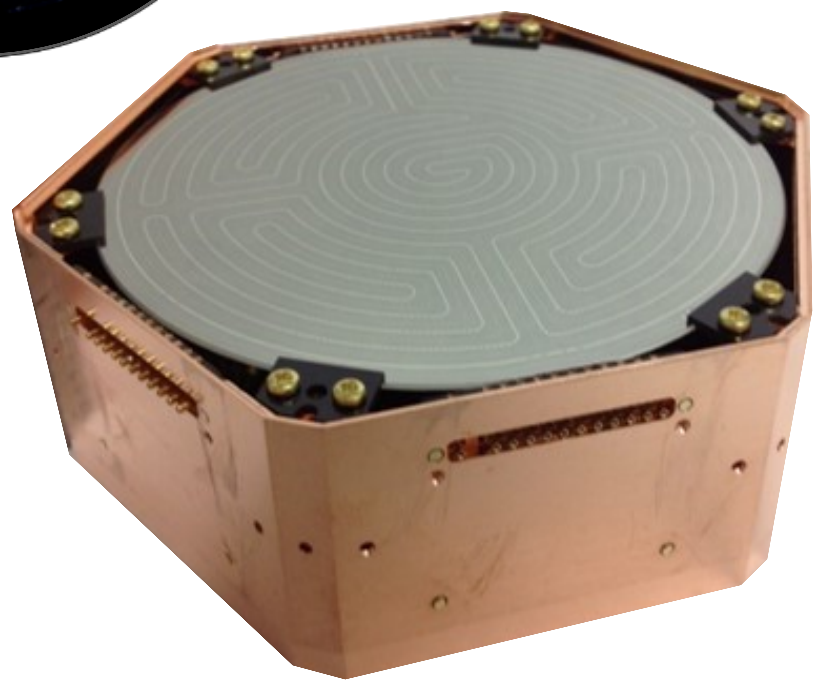
- SuperCDMS : focusing in low mass DM particles
- LZ : higher mass WIMPs, reaching very close to the "neutrino floor"
- ADMX : Axion Dark Matter Search

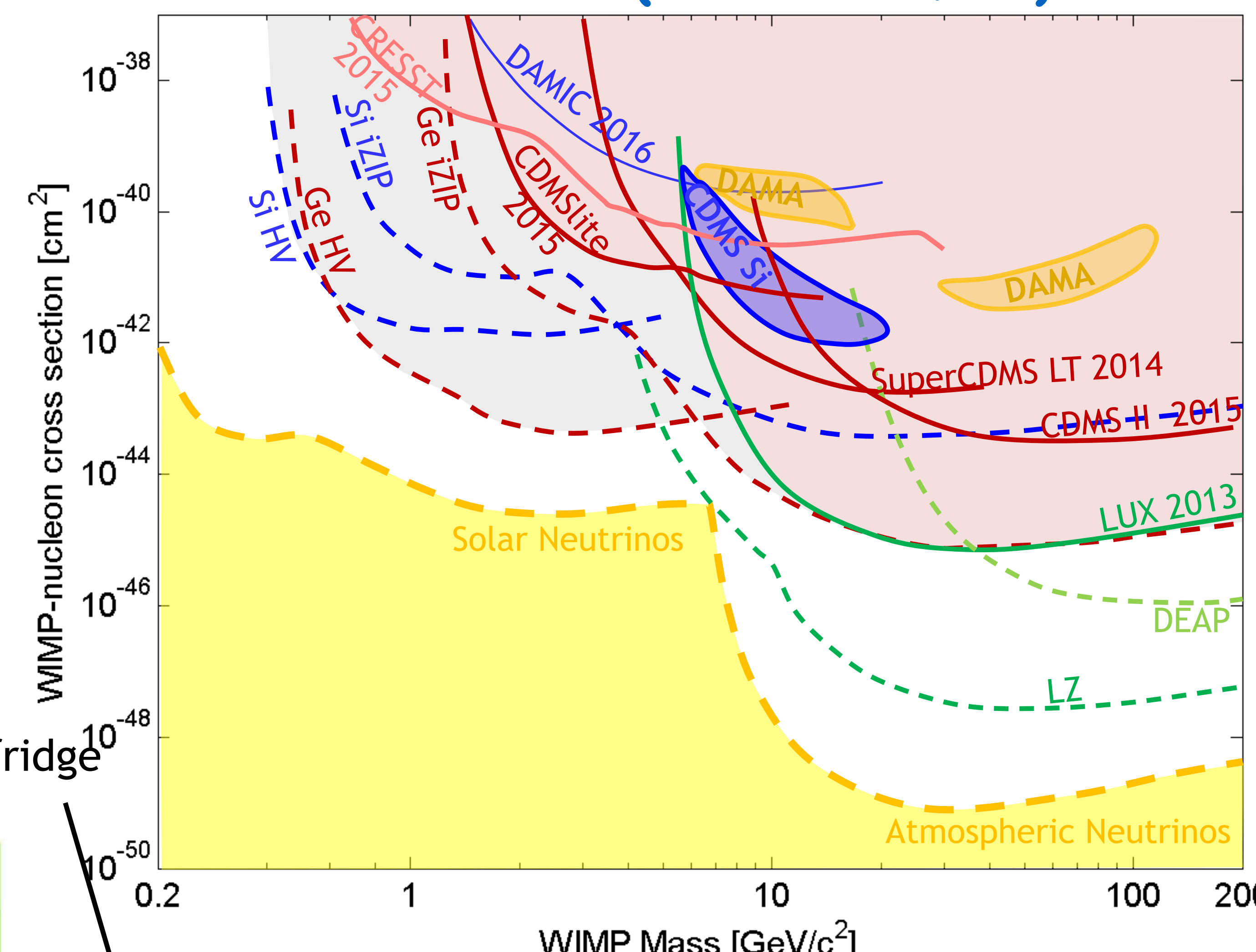
cryogenic detector ~10mK

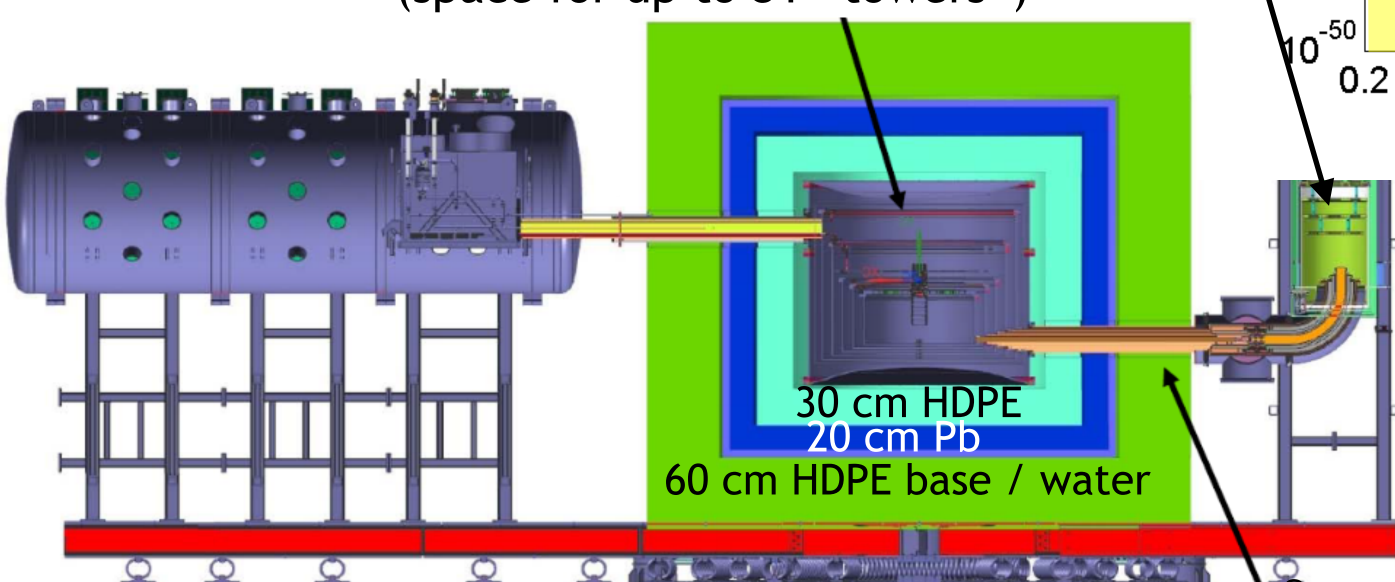
phonon readout Transition Edge Sensor (TES)

start of operations 2020 (~6 towers)

Main focus are low-mass WIMPs (< 10 GeV/c2)



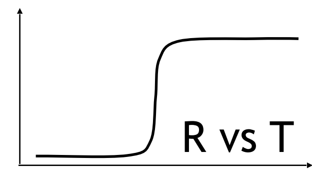


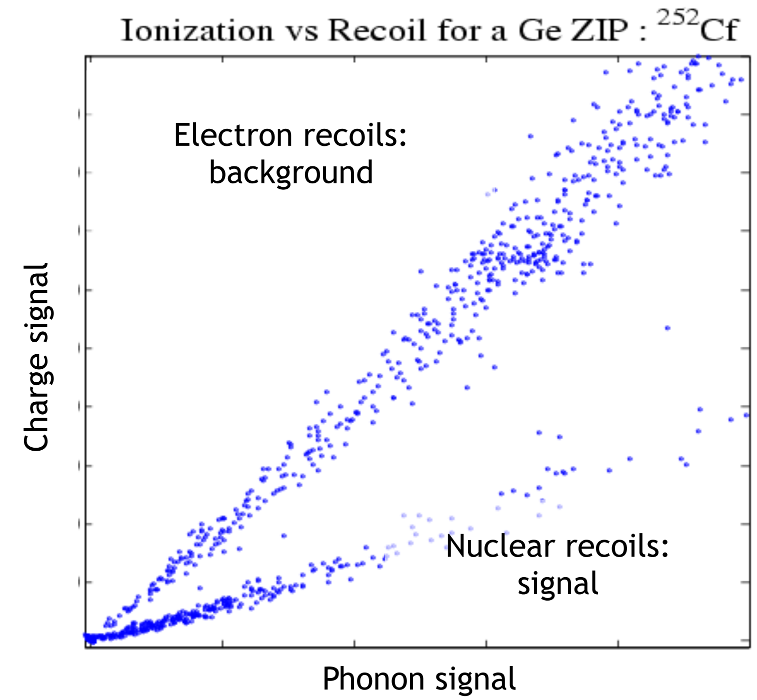


very significant low background

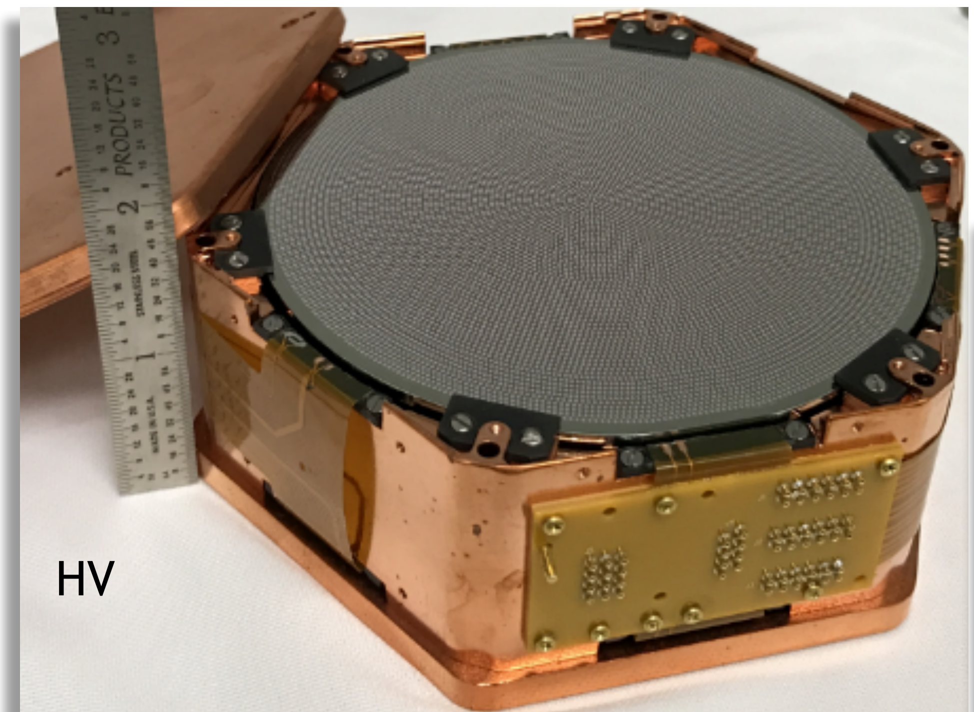
cryogenic facility at SNOLAB

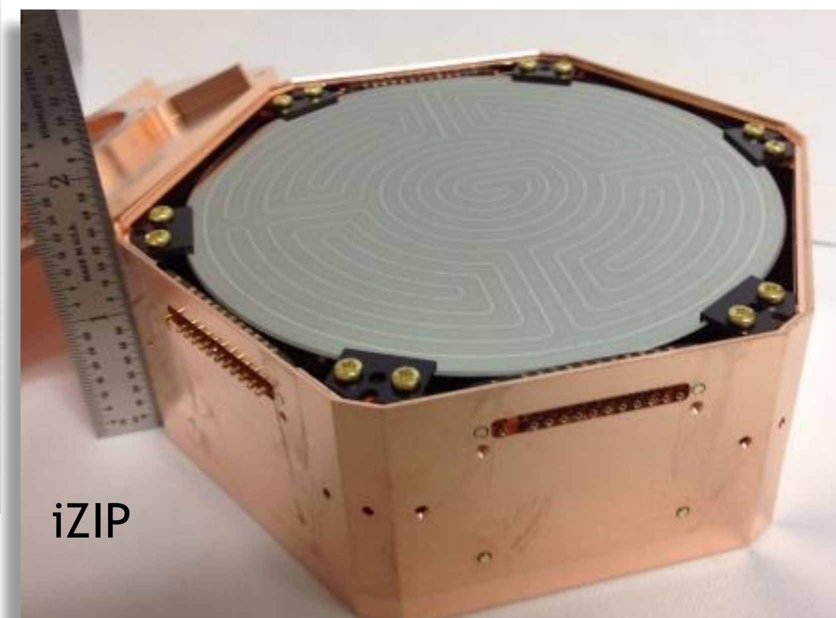
Phonon Readout:
Tungsten TES





high voltage (~100 V)
Phonons from drifting charges
Threshold < 0.1 keV (phonon)



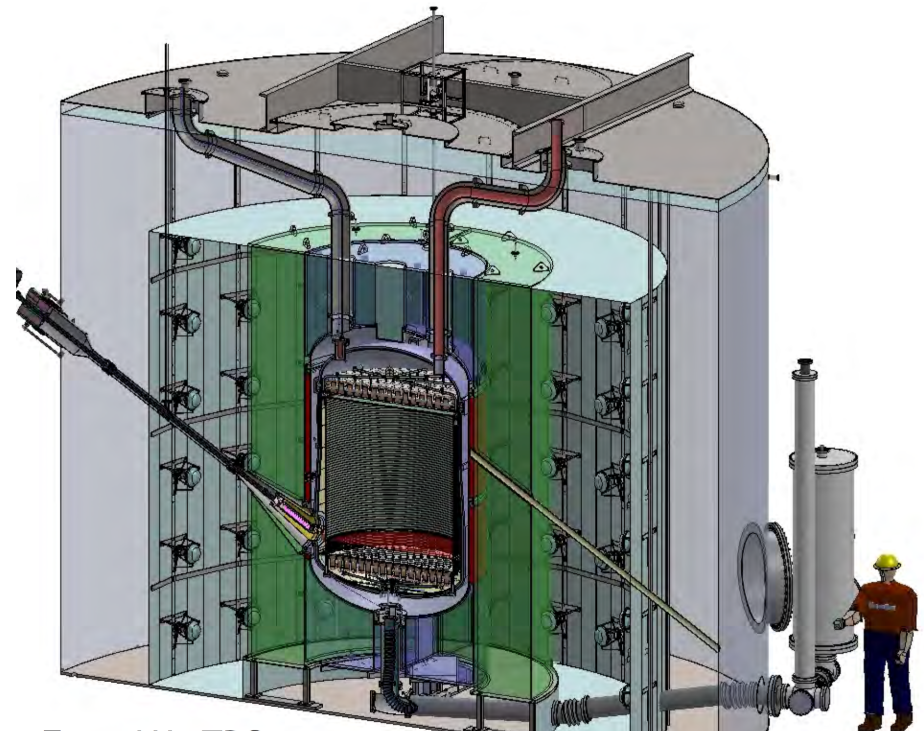


charge readout (few V)
Background discrimination
Threshold < 1 keV

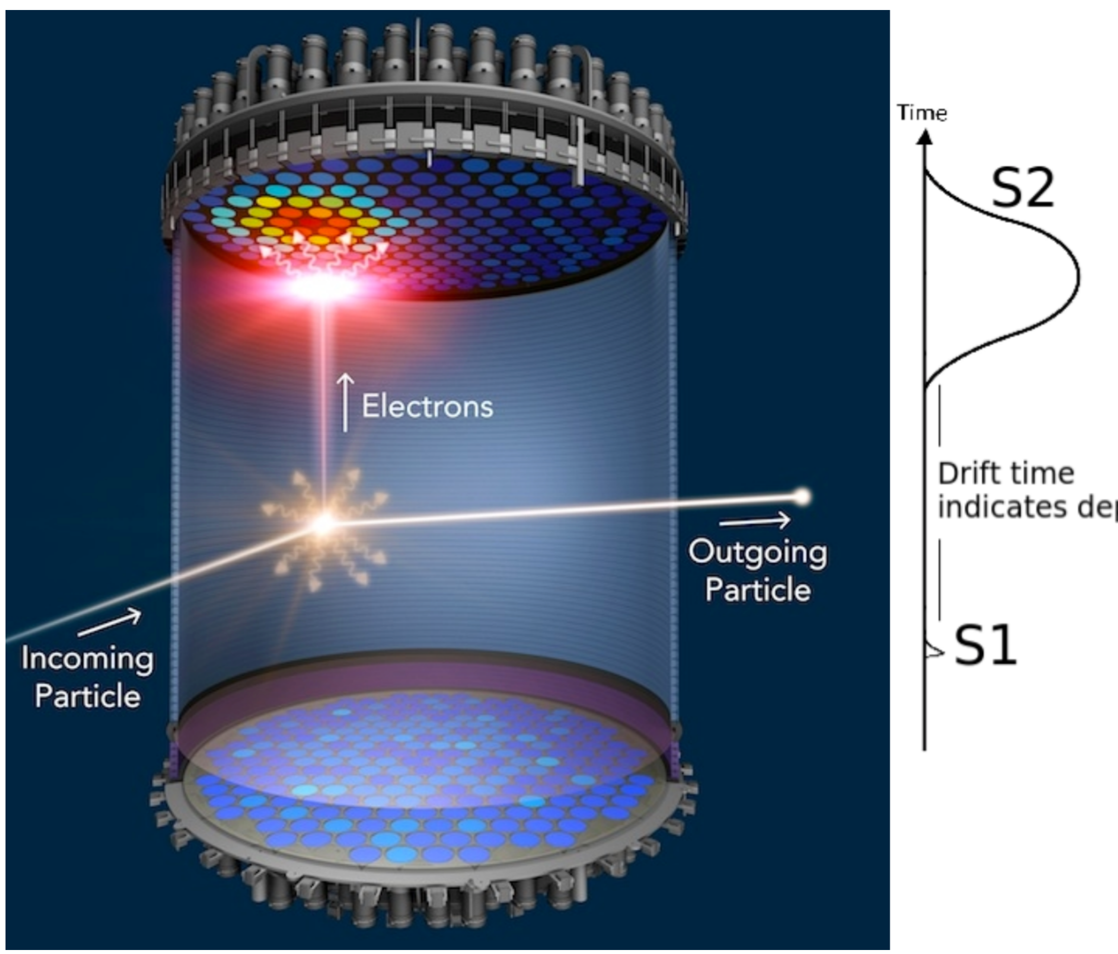
- Detectors: larger crystals; sensor layout optimized individually for iZIP and HV prototypes for both types been tested (using old electronics): performance meets or exceeds expectation
- Backgrounds: extensive material screening; tracking and monitoring; minimizing cosmogenic exposure; radon filter to be installed for detector assembly cleanroom at SNOLAB

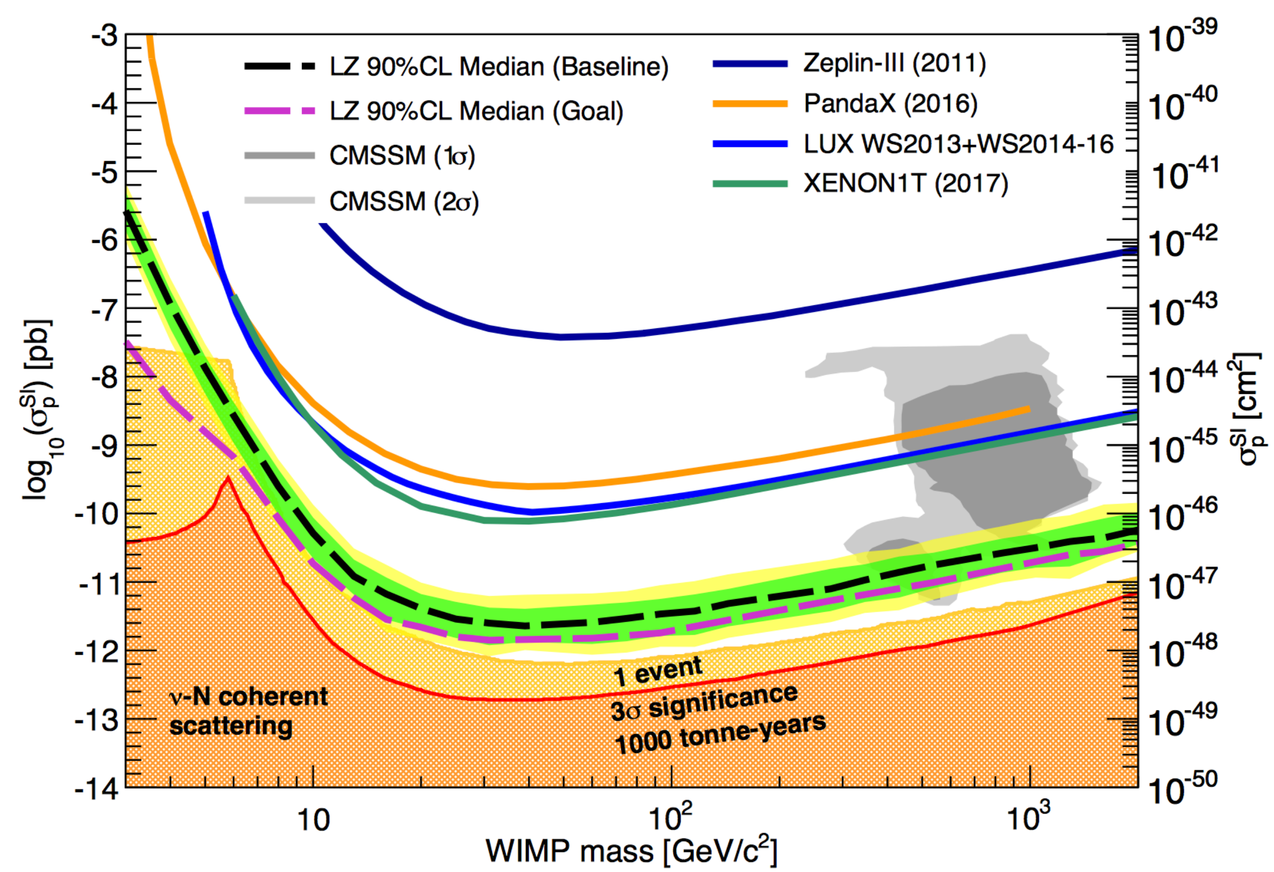
LUX-ZEPLIN Experiment

TPC with 7 tons of LXe at SURF, starting DM operation in 2021. Looking for nuclear recoils from WIMPs, with discrimination to e-recoils



7 ton LXe TPC





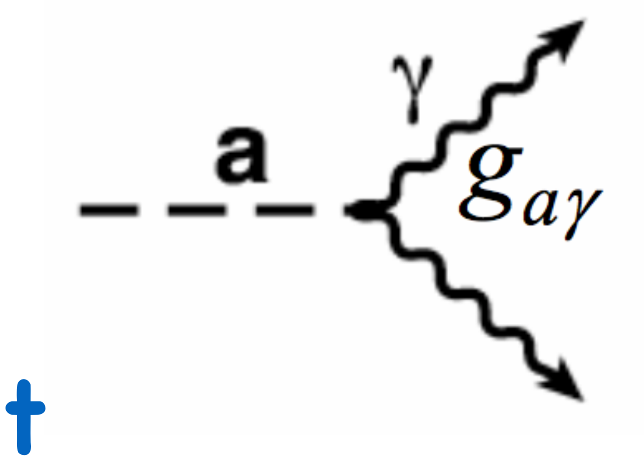
- Self shielding
- Scintillation (S1) and Ionization (S2) — particle ID

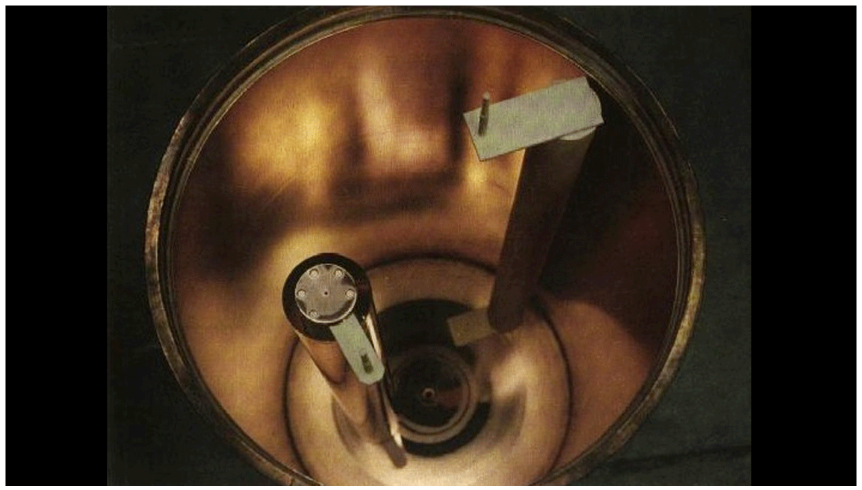
LUX-ZEPLIN Experiment

Performance drivers

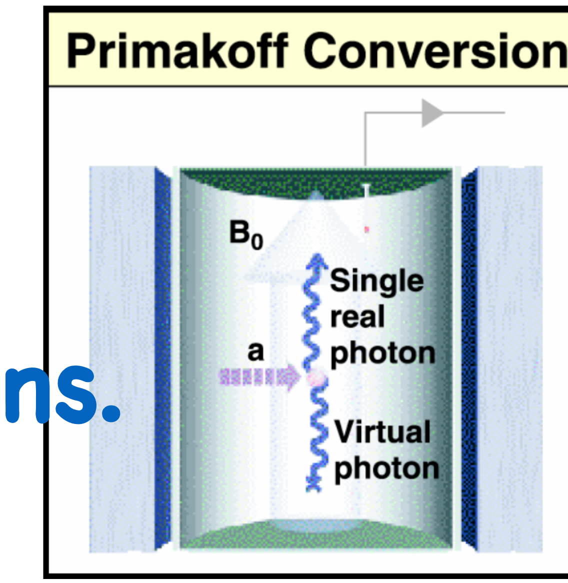
Detector Parameter	Reduced	Baseline	Goal
Light collection (PDE)	0.05	0.075	0.12
Drift field (V/cm)	160	310	650
Electron lifetime (μs)	850	850	2800
PMT phe detection	0.8	0.9	1.0
N-fold trigger coincidence	4	3	2
^{222}Rn (mBq in active region)	13.4	13.4	0.67
Live days	1000	1000	1000

- 5.8 keVnr S1 threshold
- 310 V/cm driftfield, 99.5%ER/NR discrimination efficiency

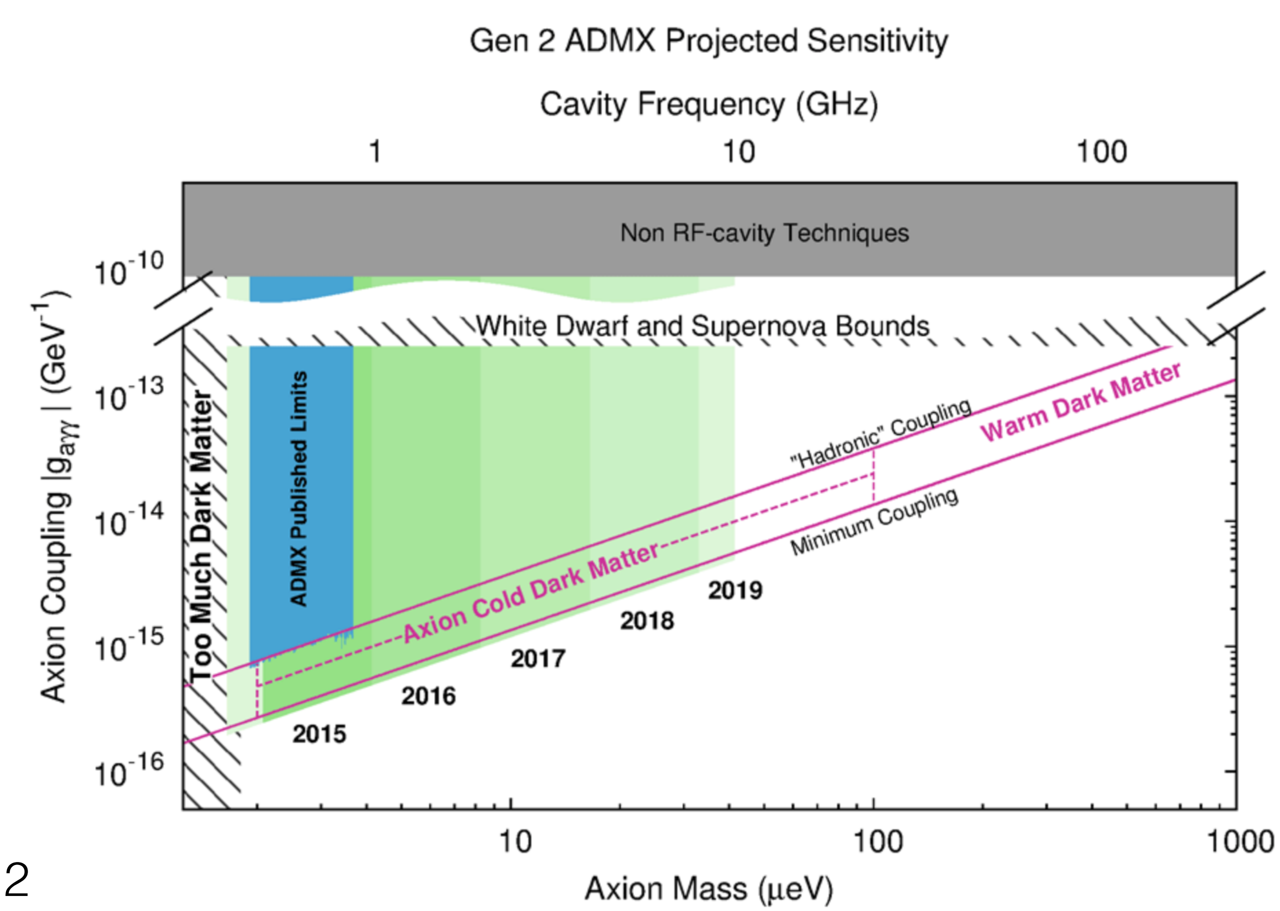




tunable resonant microwave cavity in magnet. Uses Primakoff effect to couple to axions.



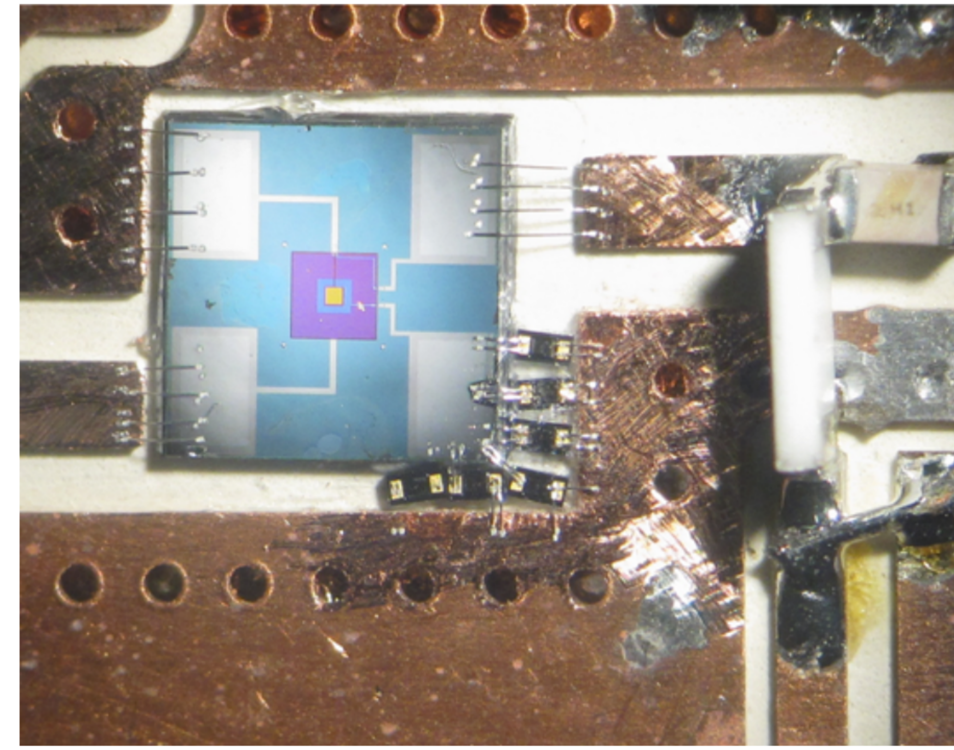
takes data in one mass range while developing systems for higher masses. Microwave cavities, amps, single mw photon counters, magnets.



ADMX

AXION DARK MATTER EXPERIMENT

squid amplifiers



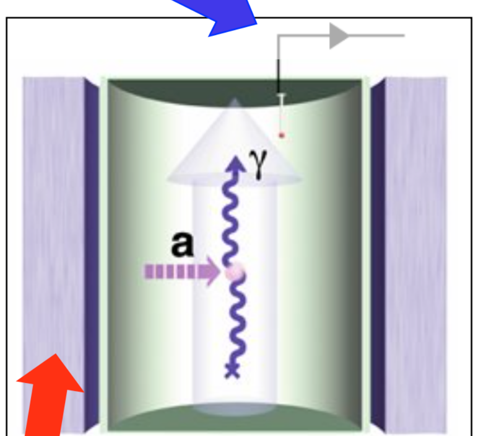
enabling technology: cryogenic low noise amplifiers.

slide from G. Carosi 2016

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

But integration time limited to ~ 100 sec

* *Dicke, 1946*



System noise temp. now

$T_S = T + T_N \sim 1.5 + 1.5$ K

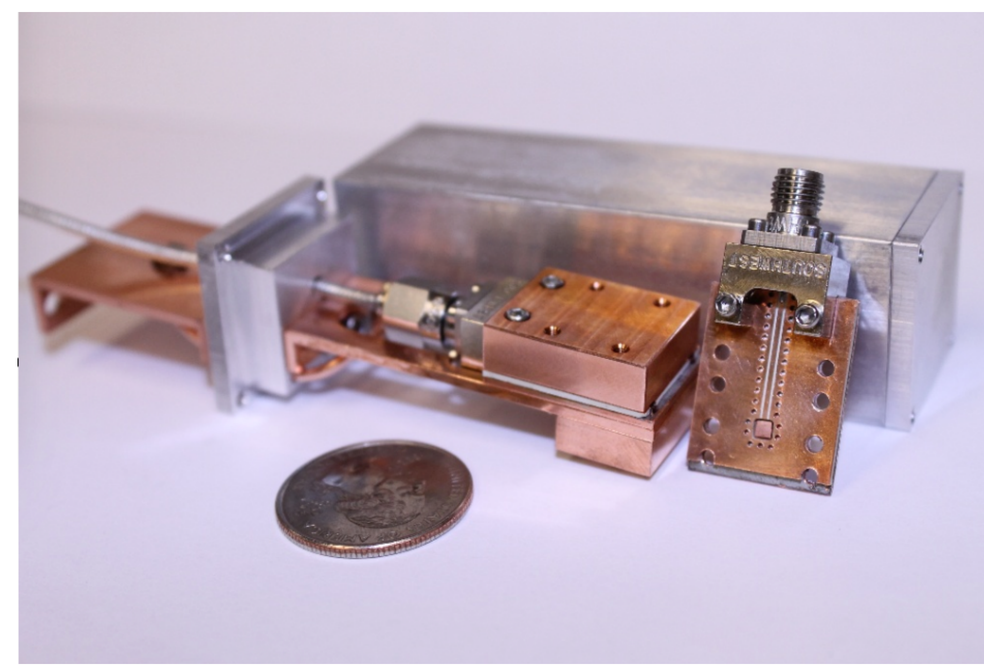
But $T_{Quant} \sim 30$ mK

This is where we invested to get to Gen 2

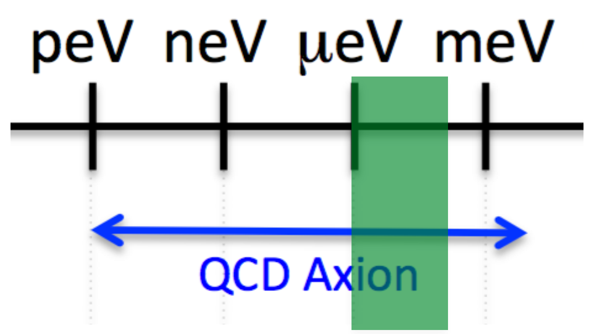
$$P_{sig} \sim (B^2 V\ Q_{cav})(g^2 m_a \rho_a)$$

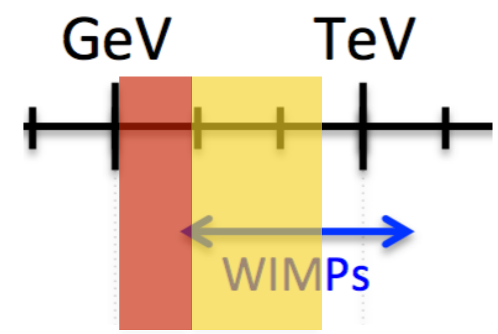
$\sim 10^{-23}$ *Watts for ADMX*

But magnet size, strength $B^2V \sim \$$

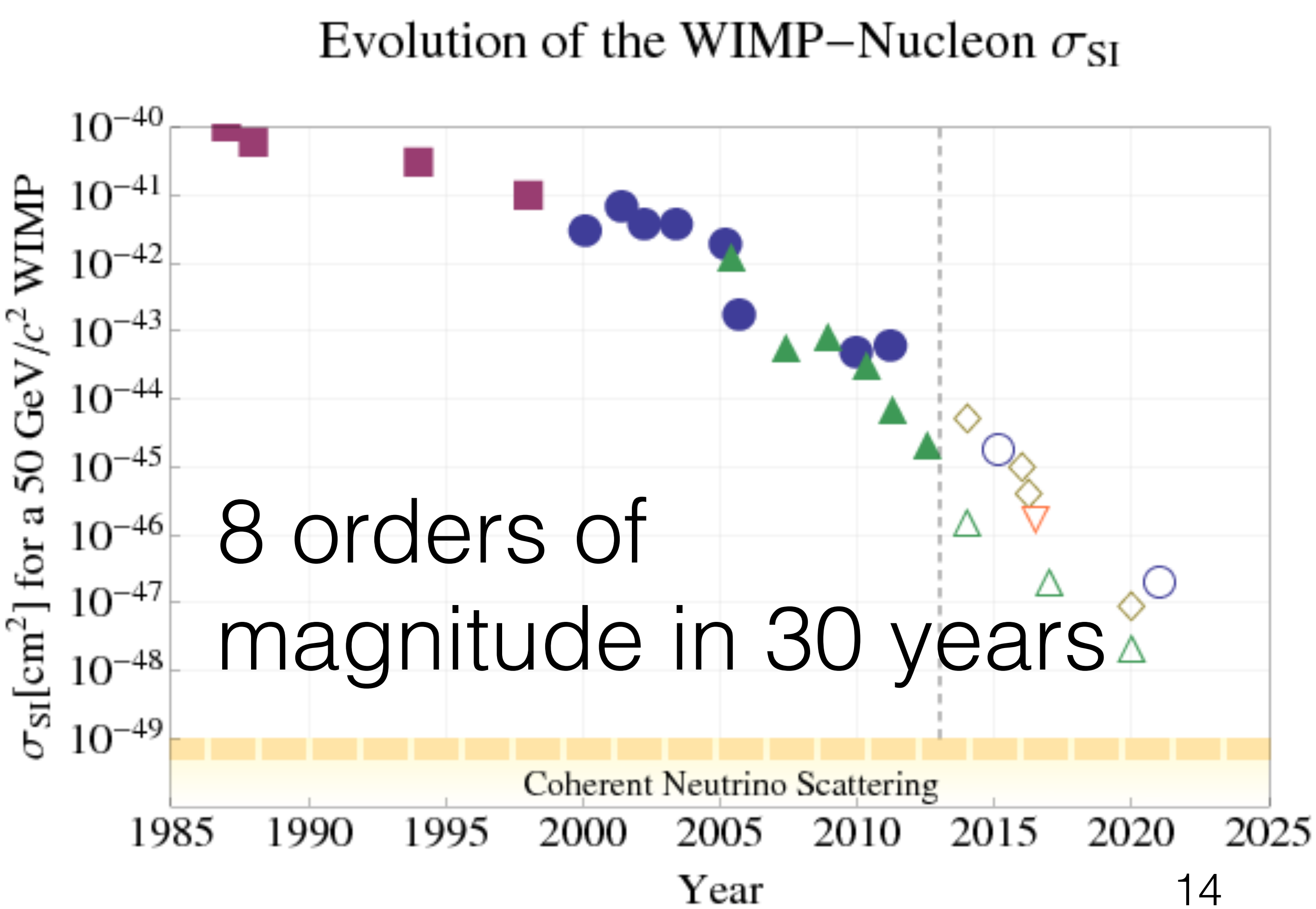


Josephson Parameter Amps



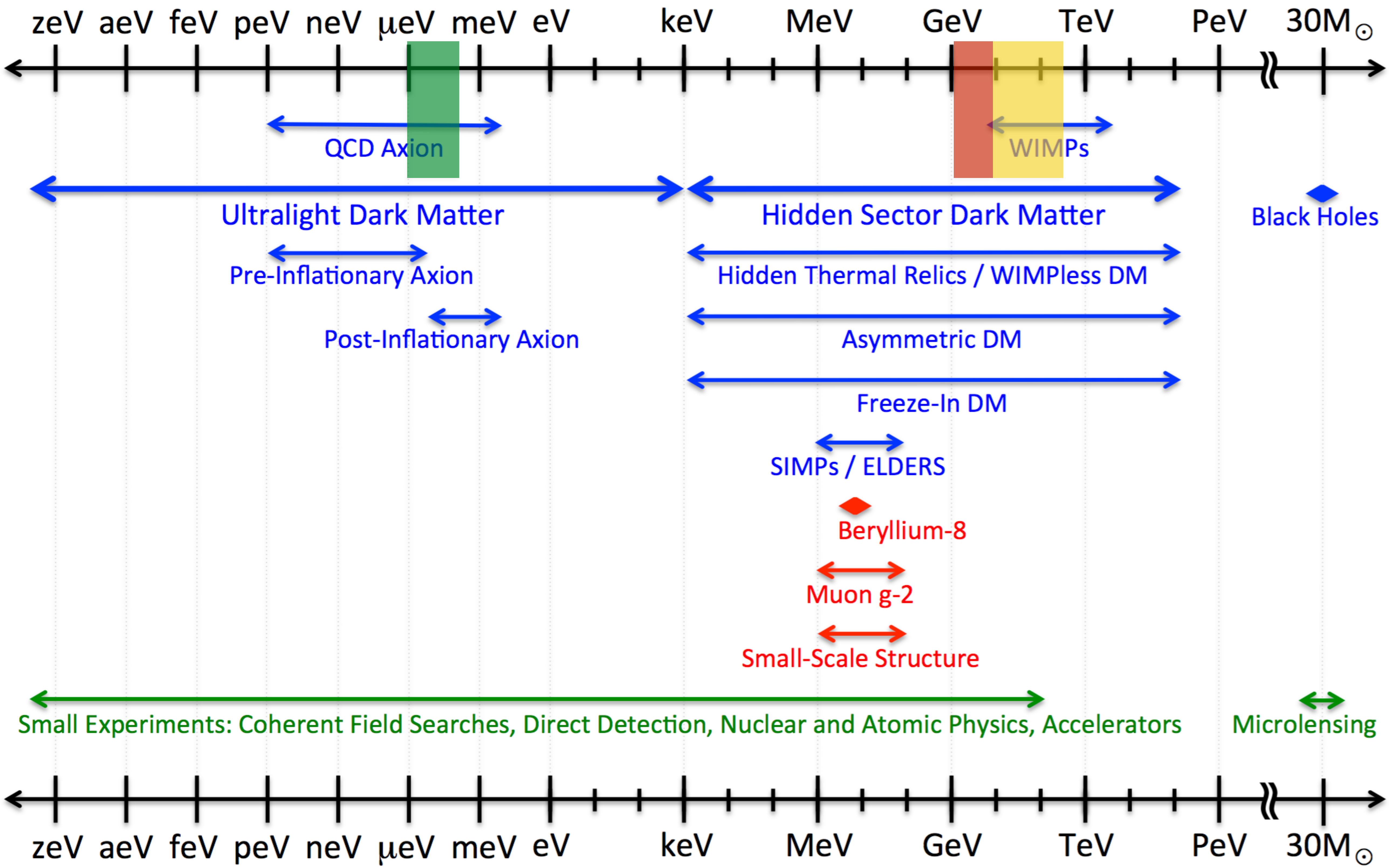


The ambitious G-2 program is aiming at very well motivated models. We have been doing this for many years.



a complete exploration of this parameter space remains the <u>highest priority for the dark matter community</u>

but the parameter space is much larger...



US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report arXiv:1707.04591

5 summary points

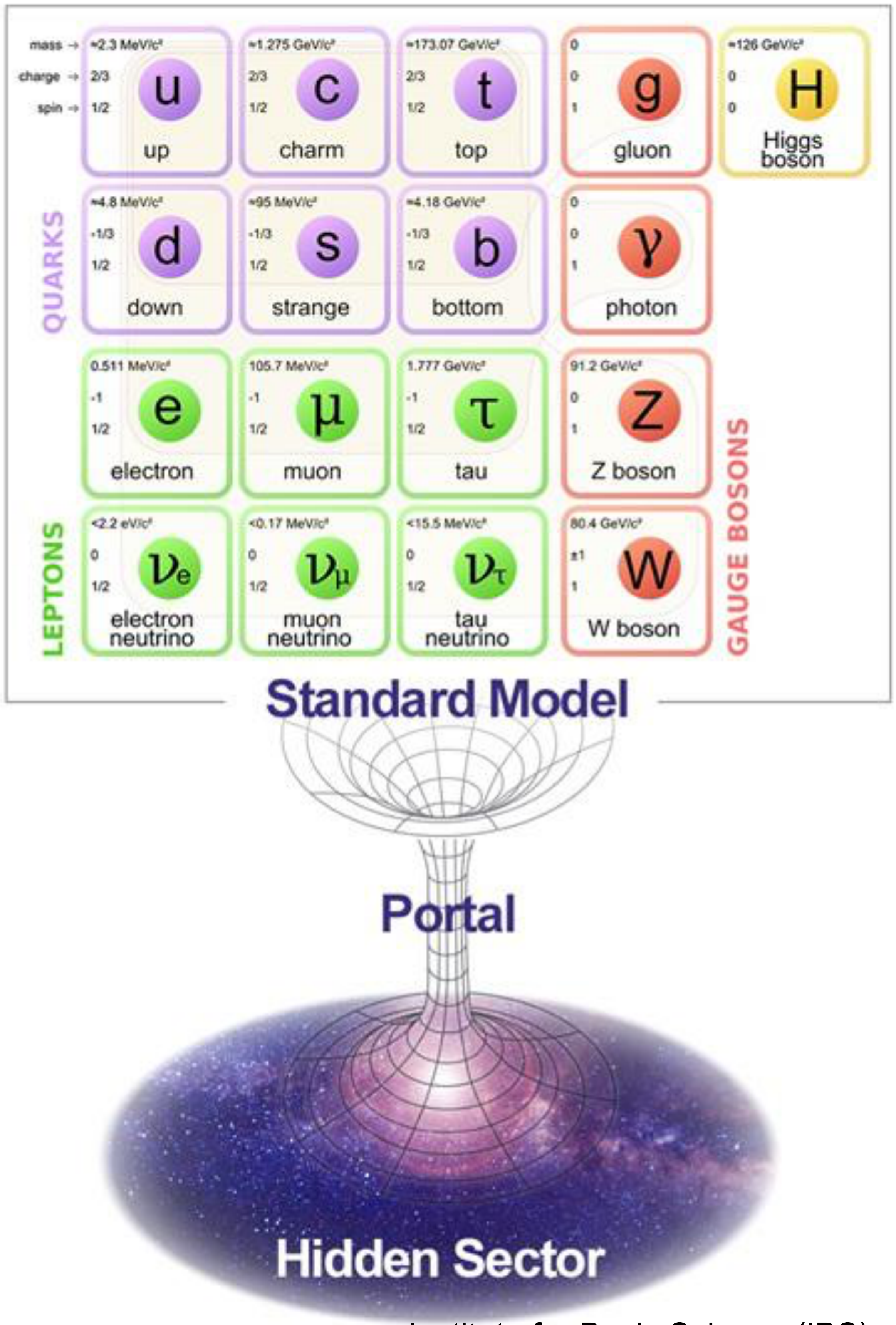
- **Low-threshold direct detection is an active field with a wealth of low-cost new and innovative ideas that can probe a variety of highly motivated Hidden-Sector and Ultralight DM candidates, and affords the only prospect to begin testing the tiny couplings associated with hidden-sector freeze-in through an ultralight mediator. It is important to pursue both DM-electron and DM-nuclear scattering experiments, as they have complementary sensitivities**. Some proposals are ready for small-project-scale funding now, while several will be ready for small-project-scale funding within the next 1 to 2 years. In addition, the potential to lower energy thresholds by orders of magnitude motivates continued technology R&D.
- **A suite of experiments using multiple technologies are required to explore the wide parameter space of light new-force carriers, and in particular the full mass range for QCD axions**. The ADMX G2 experiment is currently exploring an exciting region of QCD axion mass range, and many new experimental approaches are in pilot phases now. Together with ADMX, next-generation experiments at the small-project scale can explore much of the highly motivated QCD axion parameter space over the next decade.

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

5 summary points

- **Accelerator experiments** can both produce and detect new particles, such as dark matter and the particles mediating new interactions. This unique ability has enabled **beam dump, missing mass/energy, and visible mediator search experiments to achieve world-leading sensitivity to highly sought-after dark matter scenarios.** Building on these proven techniques and exploiting existing **US accelerator facilities, a small number of fixed-target experiments can broadly explore sub-GeV dark matter and associated forces with sufficient sensitivity to test all predictive thermal DM scenarios. This focused effort is based on established detector technology**, with a number of modest-cost proposals ready for funding now to achieve significant science in the next few years.
- Existing **data may already be pointing to dark sector physics**. **Anomalies in (g – 2) of the muon and in the properties of beryllium-8 nuclei provide tentative evidence for a new boson at the 10 MeV-scale that can be tested by nuclear and atomic spectroscopy experiments.** The small-scale structure of dark matter halo distributions may be explained by dark matter self-interactions with 1-100 MeV mediators. LIGO's discovery of colliding black holes motivates micro-lensing probes of solar mass black hole dark matter. These puzzles each define sharp, highly-motivated targets that can be resolved by small investments in experiment, simulations, and theory. Typical timescales are 1 to 2 years and budgets are a small fraction of the small projects threshold.
- Progress in **theory has been the driving force behind recent developments in dark matter,** particularly proposals for small-scale experiments and innovative connections to other subfields. Additional investments in theory are essential to exploit cosmological and astrophysical data to improve measurements of dark matter's particle properties and to develop the novel connections to nuclear, atomic, and condensed matter physics that have already been identified.

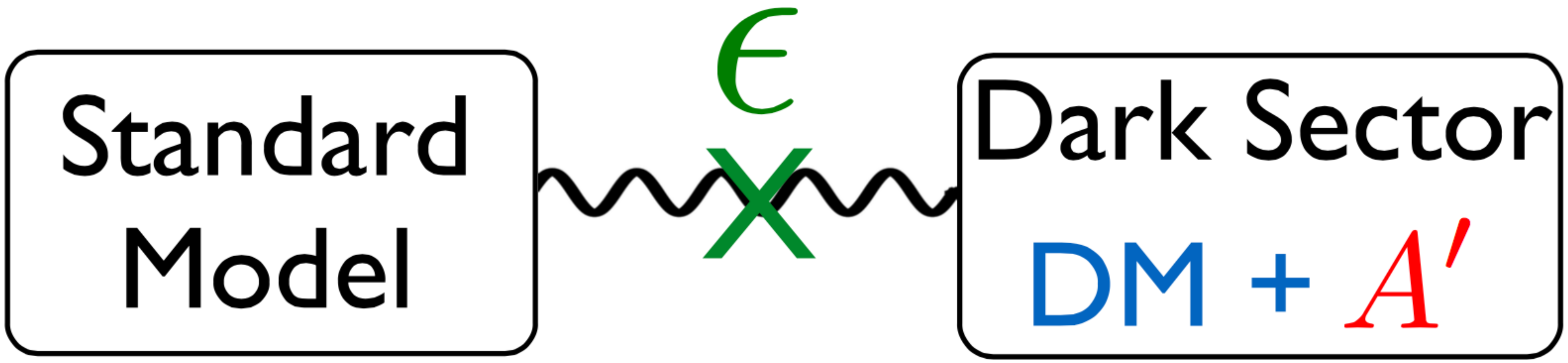
here will focus on the hidden sector



Institute for Basic Science (IBS)

DM w/ dark photon (A′) mediator

R. Essig

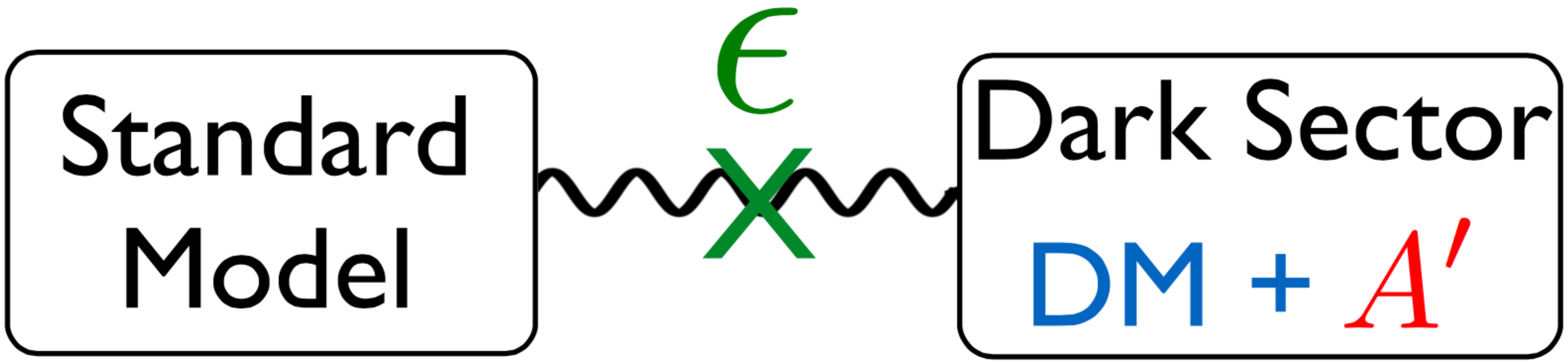


- light A′ (~m_{DM})
- ultra-light A′ ($\ll$ keV)

DM w/ dark photon (A′) mediator

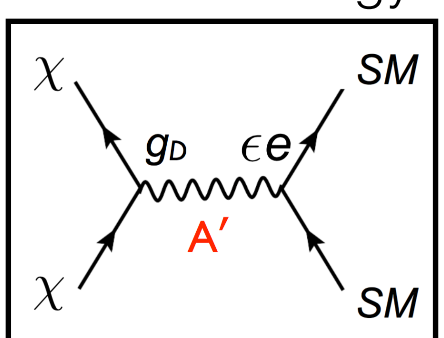
R. Essig

nice predictive model to target!



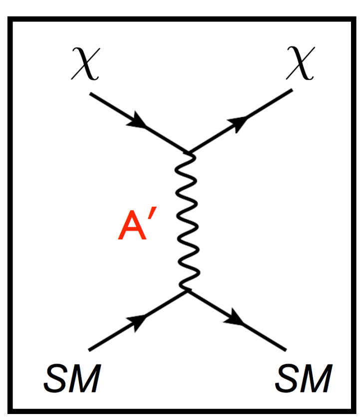
- light A′ (~m_{DM}) → $m_{A'} > 2m_\chi$
- ultra-light A′ (≪keV)

constrains from cosmology

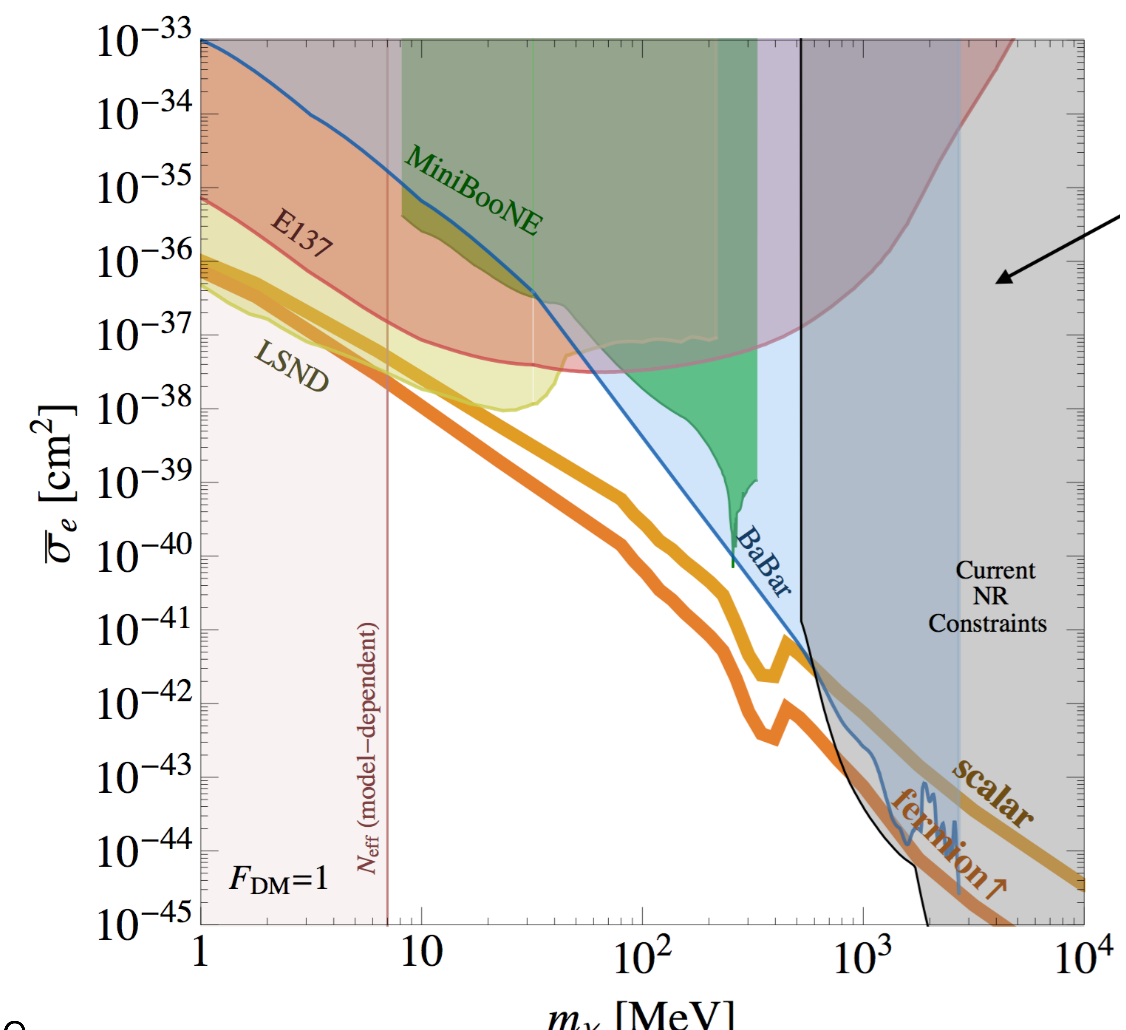


freeze out

direct detection



$$\bar{\sigma}_e \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} \mu_{\chi e}^2$$



DM w/ dark photon (A′) mediator

R. Essig

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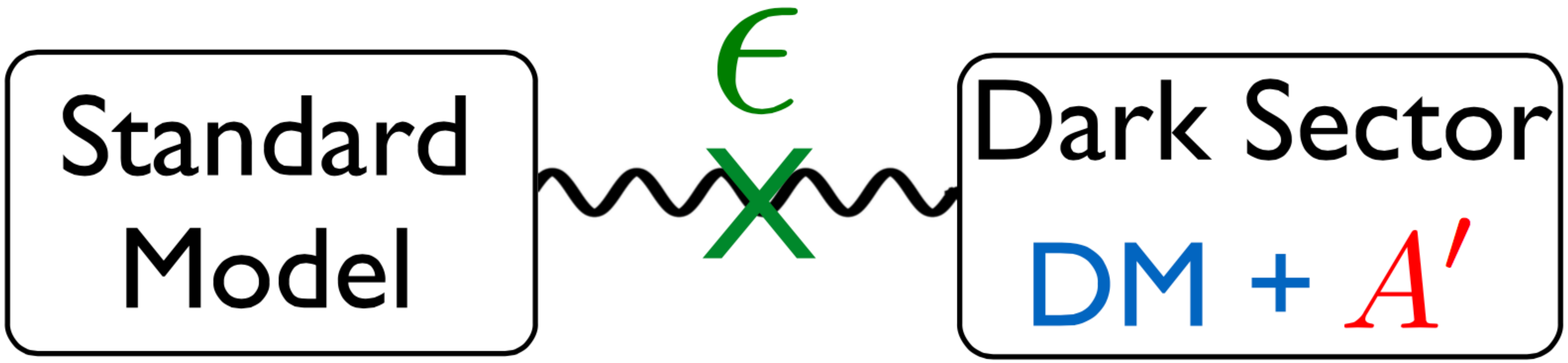
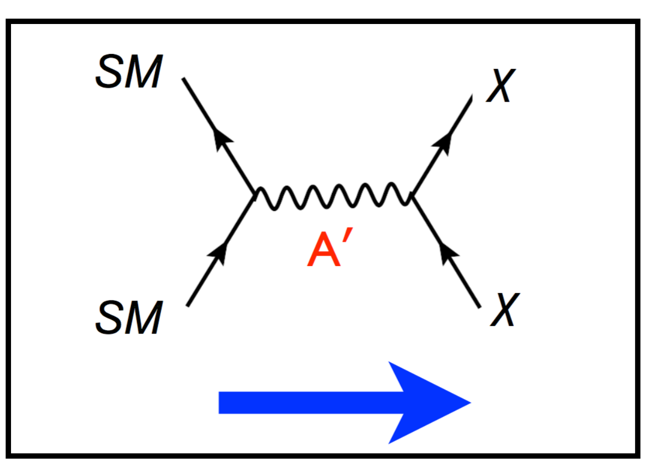
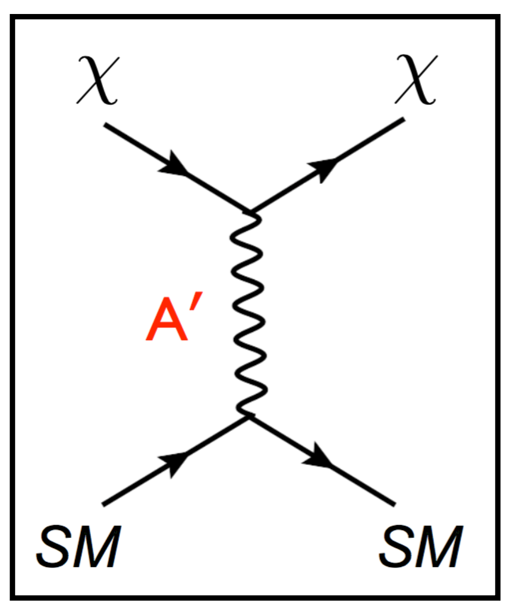


- light A′ (~m$_{DM}$)
- $\boxed{\text{ultra-light A}' \ (\ll \text{keV})}$

freeze IN
(build up abundance during cool-down)

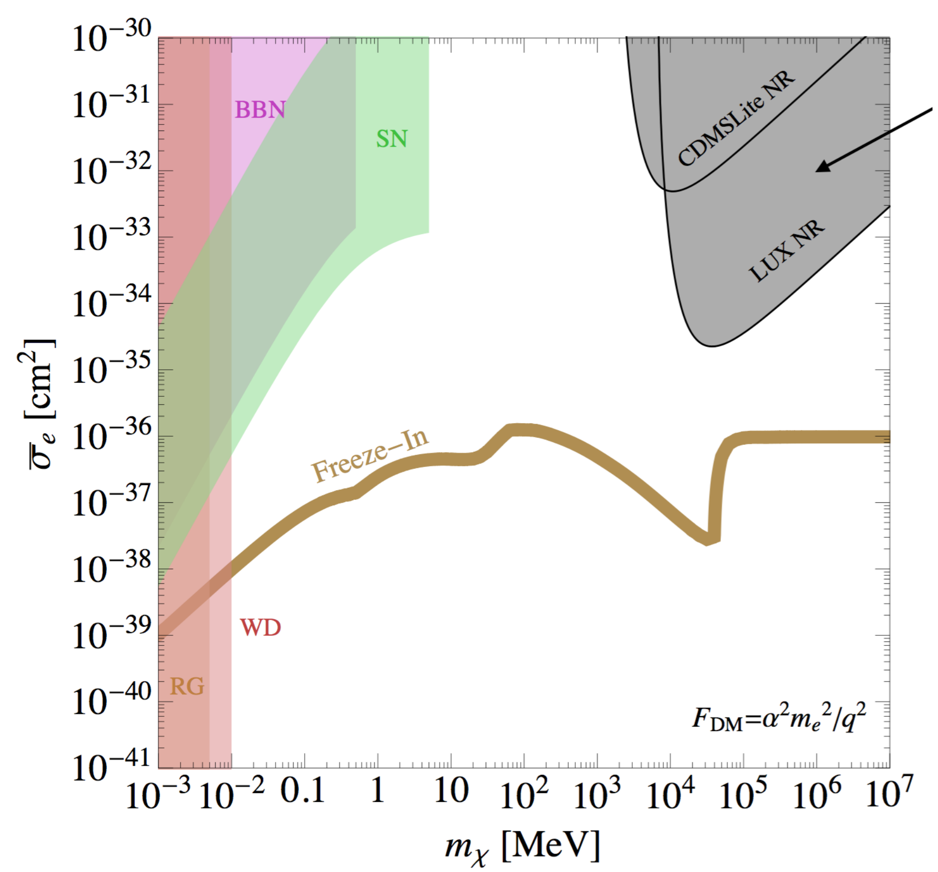


direct detection

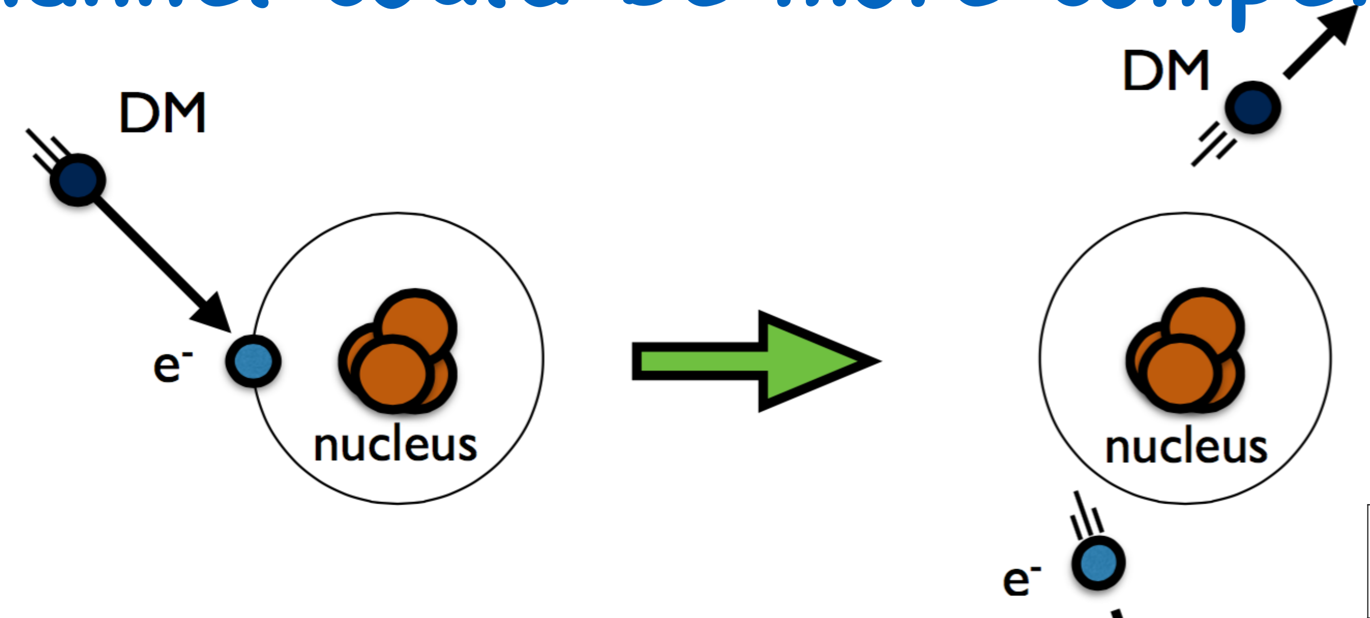


$$\sigma \propto \frac{16\pi\mu_{\chi e}^2 \alpha \alpha_D \epsilon^2}{q^4}$$

enhanced a low Q



the "classic" search for wimps looks for nuclear recoil, but when looking at lower mass particles the e-recoil channel could be more competitive.



biding energy (~1 eV)

$$E_{\rm DM} \sim \frac{1}{2} m_{\rm DM}\, v_{\rm DM}^2 > \Delta E$$

Type	Examples	E_{th}	mass threshold	Status
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV	Done w/ XENON10+100 data; improvements possible
Semi-conductors	Ge, Si	~1 eV	~200 keV	E_{th} ~ 40 eV (SuperCDMS, DAMIC*) E_{th} ~ 1 eV (SENSEI) R&D ongoing
Scintillators	GaAs, NaI, CsI, …	~1 eV	~200 keV	R&D required

$$v_{\rm DM} \lesssim 800\ {\rm km/s} \implies m_{\rm DM} \gtrsim 300\ {\rm keV}\left(\frac{\Delta E}{1\ {\rm eV}}\right)$$

for outer shell e-

$$q_{\rm typ} \sim \alpha m_e \sim 4\ {\rm keV}$$

$$\boxed{\Delta E_e \sim \vec{q}\cdot\vec{v}_{\rm DM}}$$

typical recoil energy: $\boxed{\Delta E \sim 4\ {\rm eV}}$

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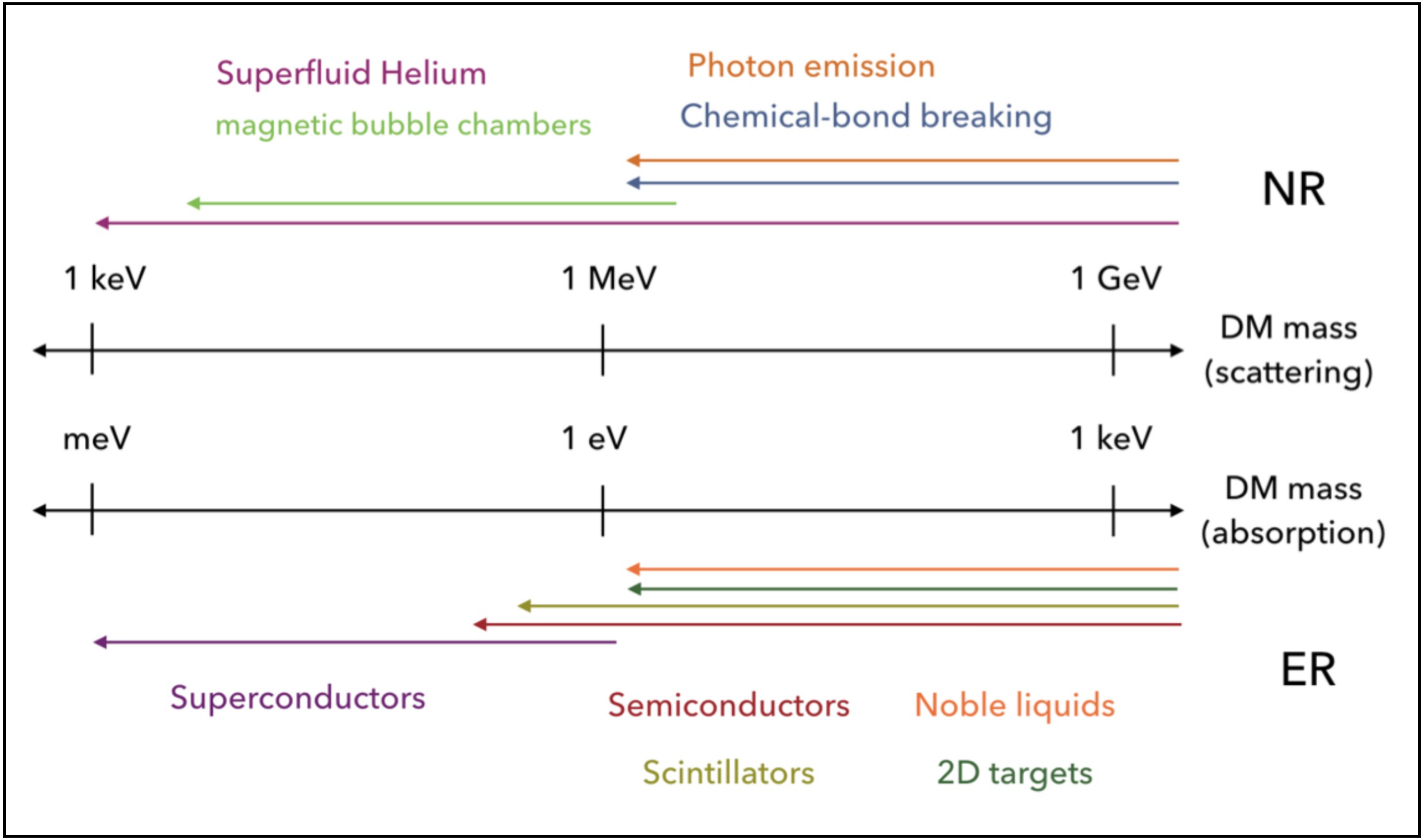

lots of ideas to scan the low mass parameter space

18 different ideas to go after these new models, pushing the direct dark matter searches beyond what we are doing the G-2.

Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
	supercond. Al cube	Al	heat	10+ yr program
Sub-GeV Dark Matter (Nucleon Interactions)	Superfluid helium with TES readout	He	heat, light	1 yr R&D; 2018 ready to start project; 2022 run
	Evaporation & detection of He-atoms by field ionization	superfluid helium, crystals with long phonon mean free path (e.g. Si, Ge)	heat	3 yr R&D; 2020 ready to start project R&D
	color centers	crystals (CaF)	light	R&D effort ongoing
	Magnetic bubble chamber	Single molecule magnet crystals	Spin-avalanche (Magnetic flux)	R&D effort ongoing
Searches down to Neutrino Floor for $\mathcal{O}$(GeV) Dark Matter	SuperCDMS-G2+	Ge	heat, ionization	3 yr R&D; 1 yr fabrication; 2022 start running
	NEWS-G	H, He	charge	140cm sphere installed at SNOLAB in 2018
	NEWS-dm emulsions	Si, Br, I, C, O, N, H, S	charge directionality	R&D phase complete. Now technical test
	CYGNUS HD-10	SF_6, He flexible	charge directionality	1 yr R&D; 1 yr 1 m^3; 2 yr 10 m^3
	Scintillating bubble chamber	Xe, Ar C_6F_6, H_20	light heat(bubble)	2 yr program; test 10kg Xe chamber with CENNS
Spin-Dependent (Proton) Interactions	PICO bubble chambers	wide range	heat(bubble)	40 l chamber now PICO 500 l next

will discuss details of some of these projects. Trying to show the diversity of the ideas. Some are ready, some are long term R&D.

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	supercond. Al cube	Al	heat	10+ yr program
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	Evaporation & detection of He-atoms by field ionization	superfluid helium, crystals with long phonon mean free path (e.g. Si, Ge)	heat	3 yr R&D; 2020 ready to start project R&D
	color centers	crystals (CaF)	light	R&D effort ongoing
	Magnetic bubble chamber	Single molecule magnet crystals	Spin-avalanche (Magnetic flux)	R&D effort ongoing
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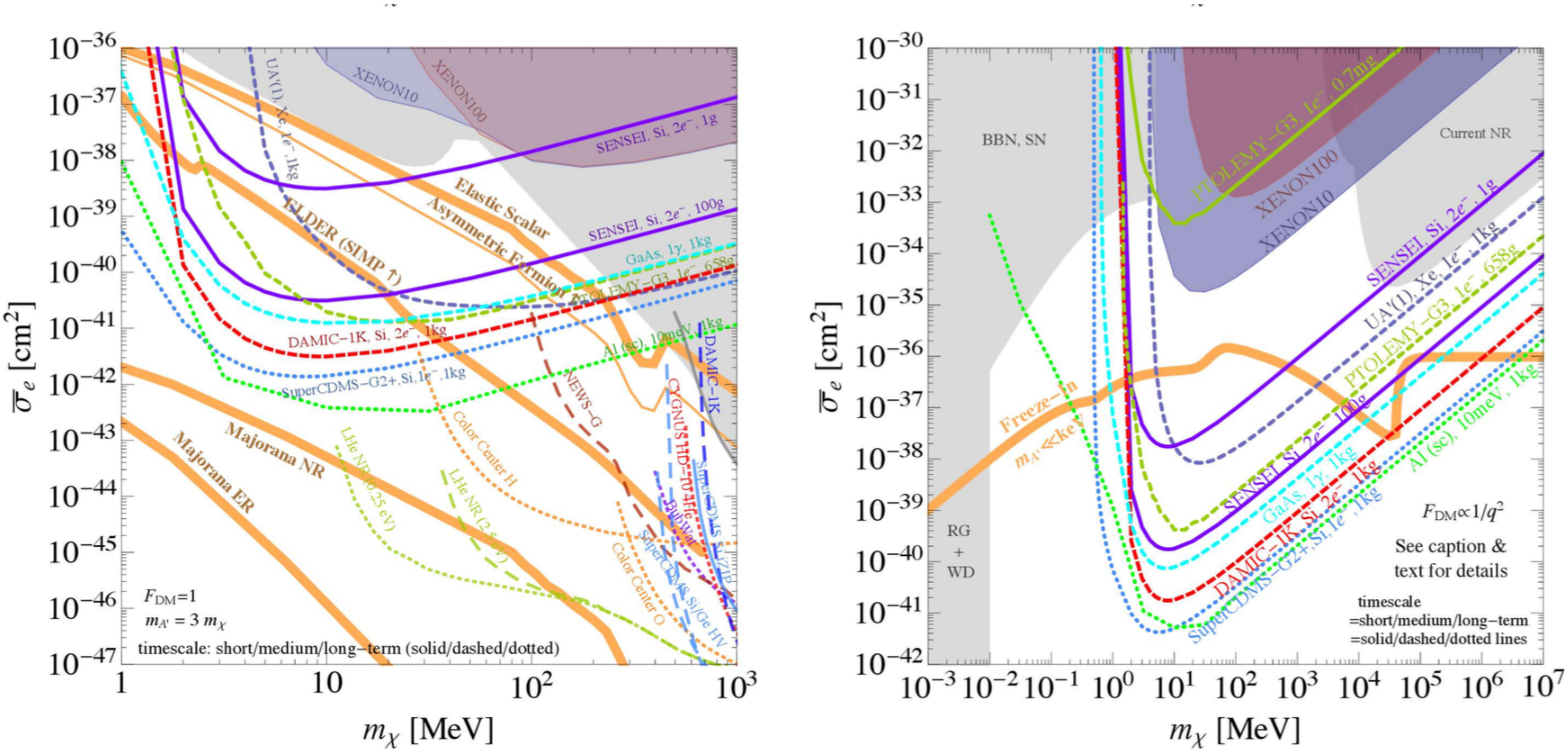
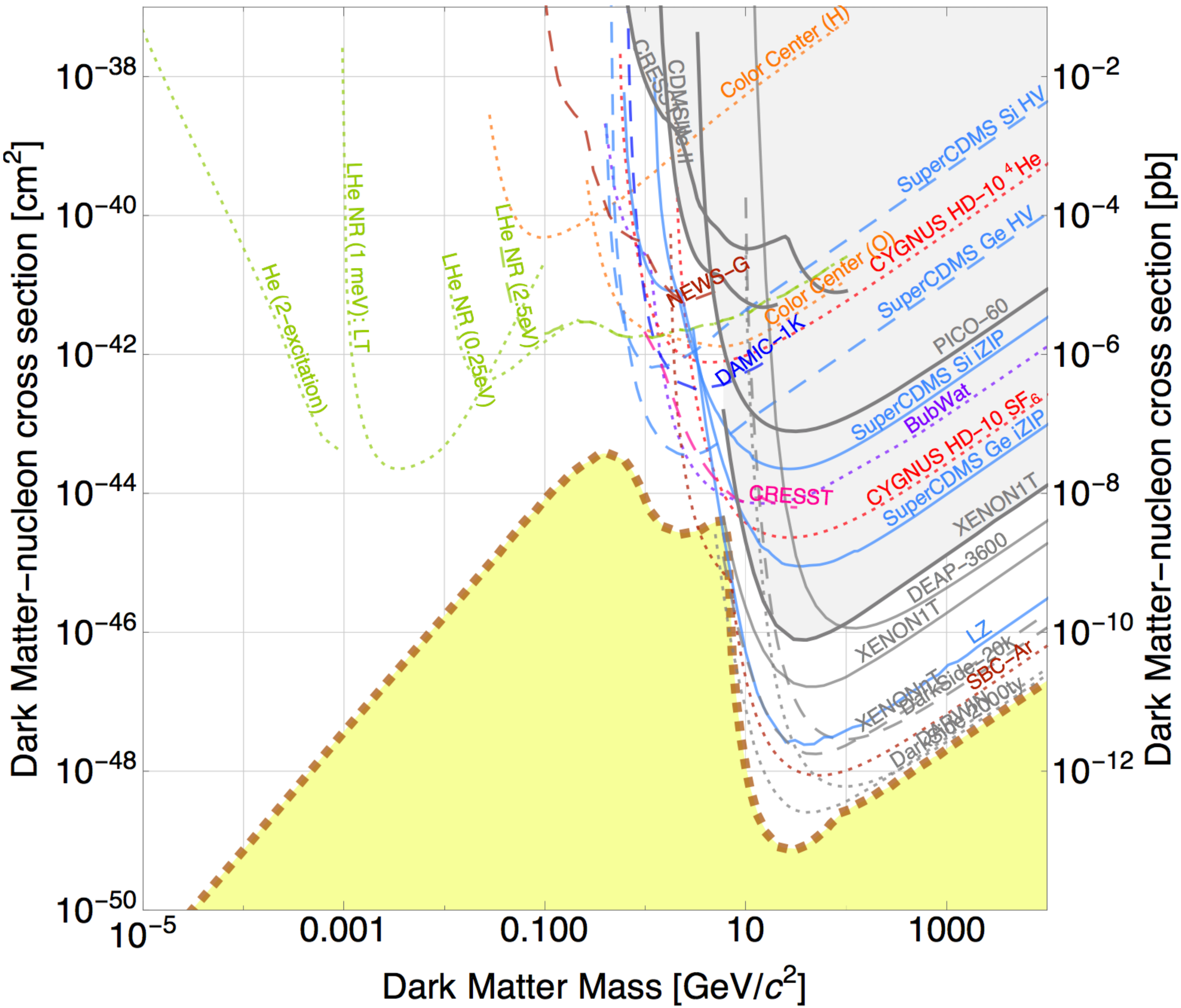
	Scintillating bubble chamber	Xe, Ar C_6F_6, H_20	light heat(bubble)	2 yr program; test 10kg Xe chamber with CENNS
Spin-Dependent (Proton) Interactions	PICO bubble chambers	wide range	heat(bubble)	40 l chamber now PICO 500 l next



the point here is that reasonable realization of the ideas in the table can reach well motivated targets outside the WIMP model.

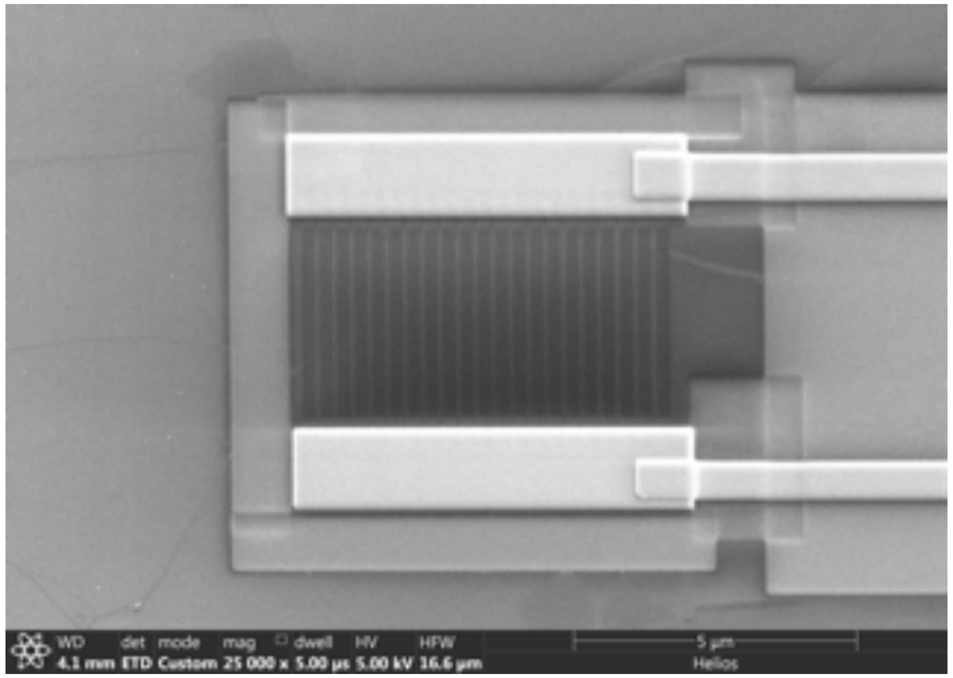

Dark Matter–nucleon cross section [cm²]
Dark Matter–nucleon cross section [pb]
Dark Matter Mass [GeV/c²]
10⁻³⁸
10⁻⁴⁰
10⁻⁴²
10⁻⁴⁴
10⁻⁴⁶
10⁻⁴⁸
10⁻⁵⁰
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁻¹²
10⁻⁵
0.001
0.100
10
1000
He (2-excitation)
LHe NR (1 meV): LT
LHe NR (0.25eV)
LHe NR (2.5eV)
Color Center (H)
Color Center (O)
CRESST
CDMSlite II
NEWS-G
DAMIC-1K
SuperCDMS Si HV
CYGNUS HD-10 ⁴He
SuperCDMS Ge HV
PICO-60
SuperCDMS Si iZIP
BubWat
CYGNUS HD-10 SF₆
SuperCDMS Ge iZIP
XENON1T
DEAP-3600
XENON1T
LZ
DarkSide-20k
SBC-Ar
XENONnT
DARWIN
DarkSide 2000ty

let's look at some of these ideas
(many other will be discussed
during this meeting)

PTOLEMY-G^3 C. Tully et al

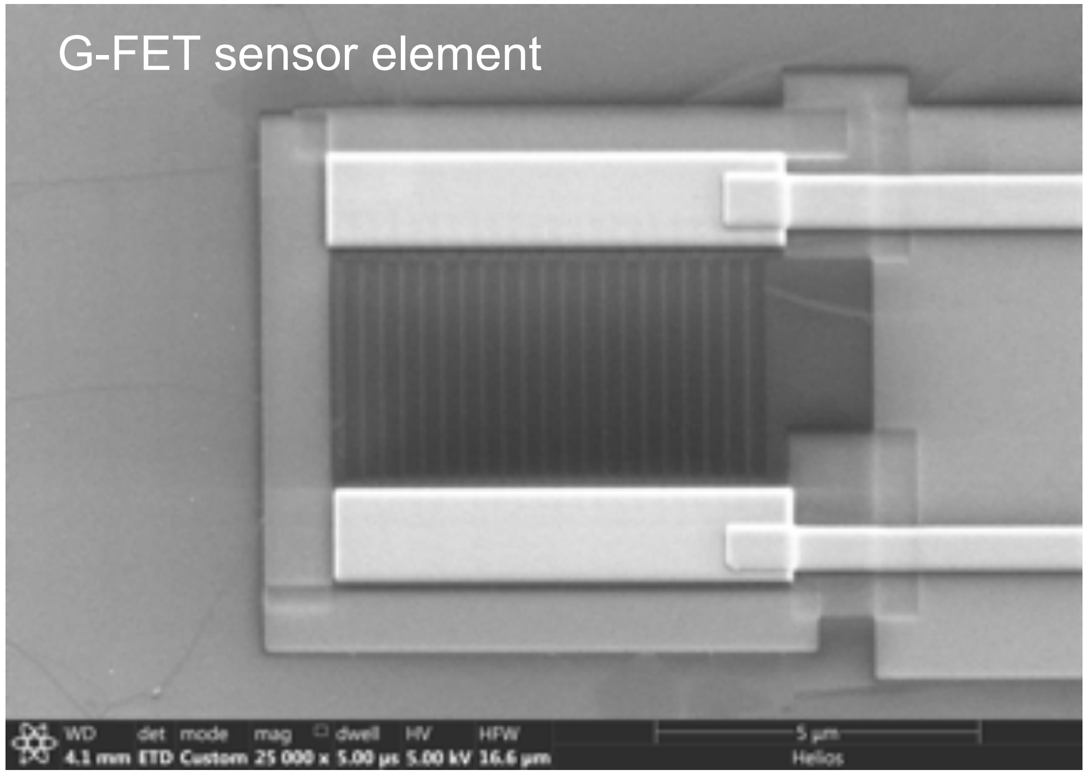
- Graphene field-effect transistors (G-FETs) arranged into a fiducialized volume of stacked planar arrays – Graphene cube (G^3)
  - Unprecedented sensitivity to electron recoil, at the level of single charge detection
- G-FETs provide tunable meV band gaps and provide high-granularity particle tracking when configured into arrays
  - A narrow, vacuum-separated front-gate of the G-FET imposes a kinematic discrimination on the maximum electron recoil energy, and the FET-to-FET hopping trajectory of an ejected electron indicates the scattering direction, shown to be correlated to the dark matter wind
- In this experiment we look for MeV dark matter scattering events that liberate an electron from the graphene target, in the absence of any other activity in the G^3

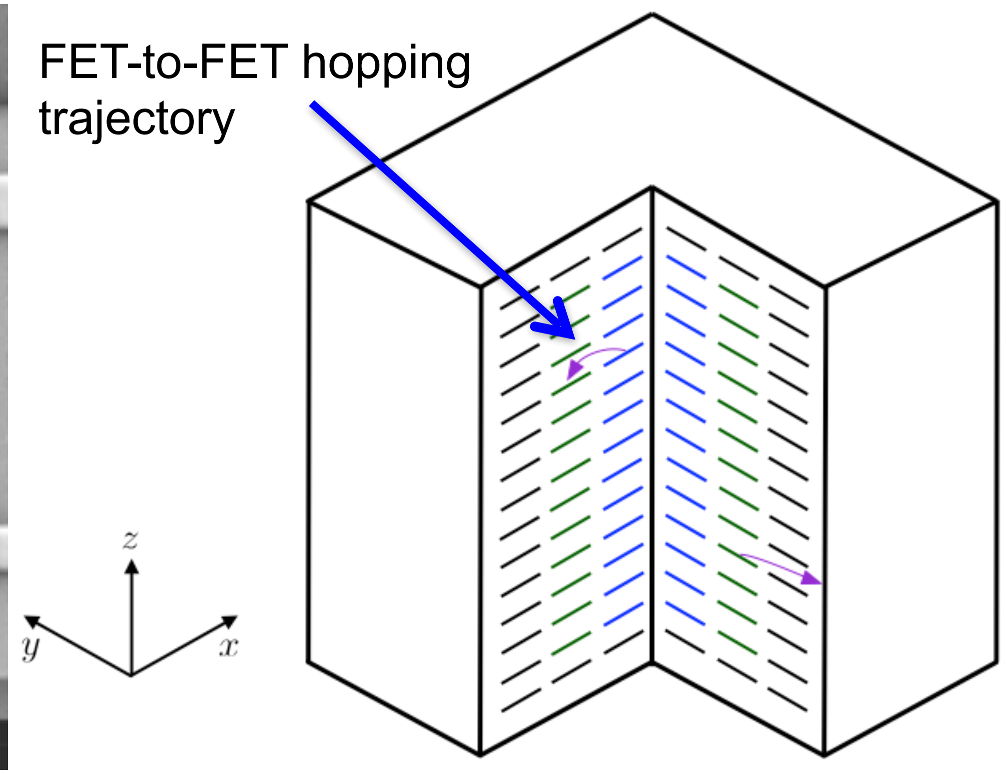
2D sensor element



large jump in conductivity from a single electron

PTOLEMY-G^3





20 Graphene Nanoribbon Array
(produced at Princeton University)
Resistance-Temperature (RT) and Current-Voltage (IV) curves in progress
Scalability to interdigitated capacitor with pixel areas of 1mm^2 or larger

Stacked planar arrays of G-FETs
1kg ~ 10^{10}cm^2 ~ 10^9cm^3
Cryogenically cooled (4.2K)

a modest, small-scale deployment of PTOLEMY-G^3, a fiducialized volume of 10^3 cm^3 will search down to σ~10^{-33} cm^2 at 4 MeV in one year, uncovering a diffcult blind spot inaccessible to current experiments

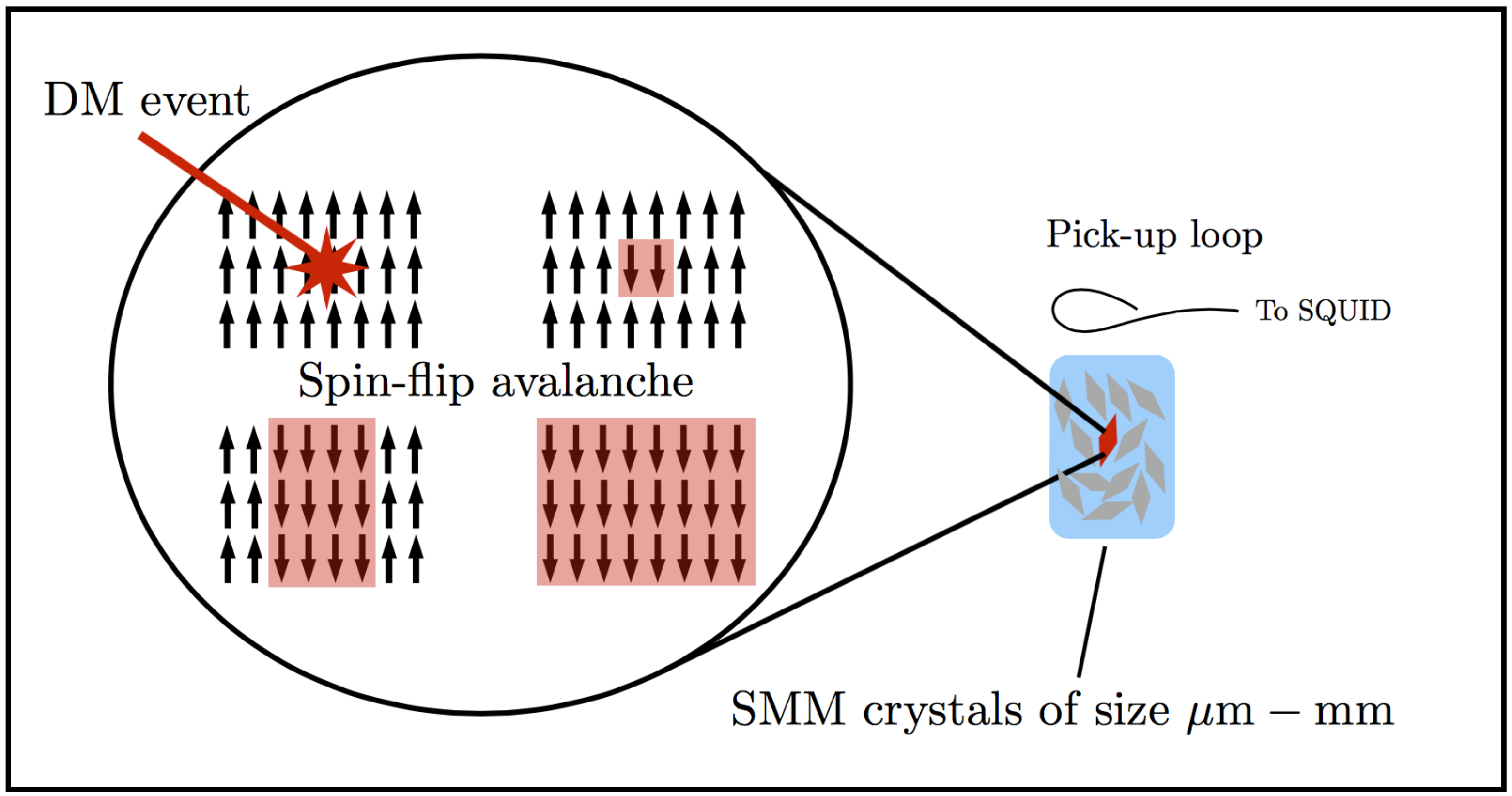
- READOUT : switched Capacitor Array Readout (DRS-style) : G-FET "capacitors" compared against threshold, time-multiplexed in a token ring and digital output barrel shifted out. Caps are reset following each read Number of transistors in PTOLEMY-G^3 comparable to a single Intel G4 processor

Magnetic Bubble Chambers and Sub-GeV Dark Matter Direct Detection

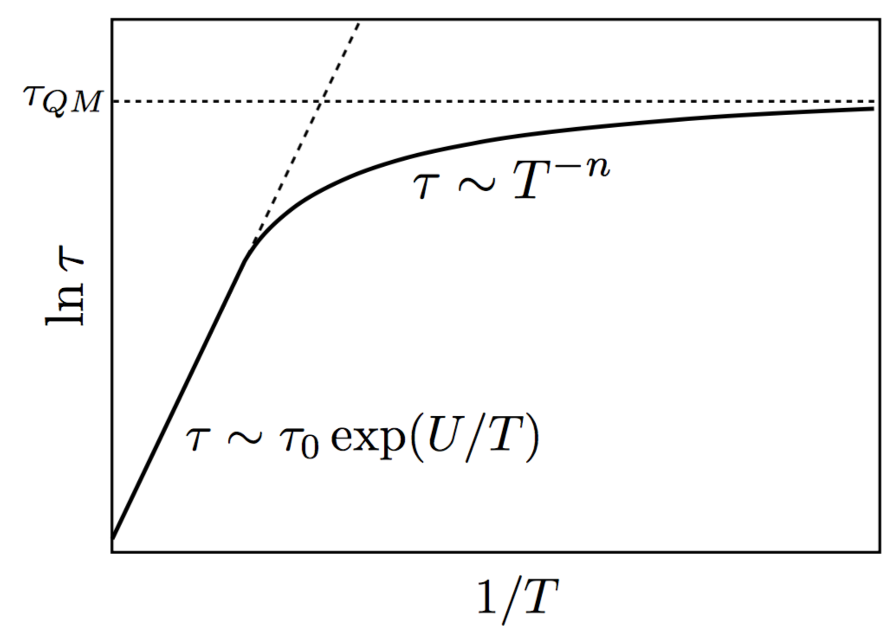
Philip C. Bunting,[1,*] Giorgio Gratta,[2,†] Tom Melia,[3,4,5,‡] and Surjeet Rajendran[3,§]

arXiv: 1701.06566

Single Molecule Magnets anti-aligned with an external magnetic field (meta-stable state achieved at low temperatures ~ 100 mK).



relaxation time is exponential with temperature. So local heating with (10^{-3} - 10 eV) will make some of this magnets flip. The Zeeman energy realized will amplify the effect.



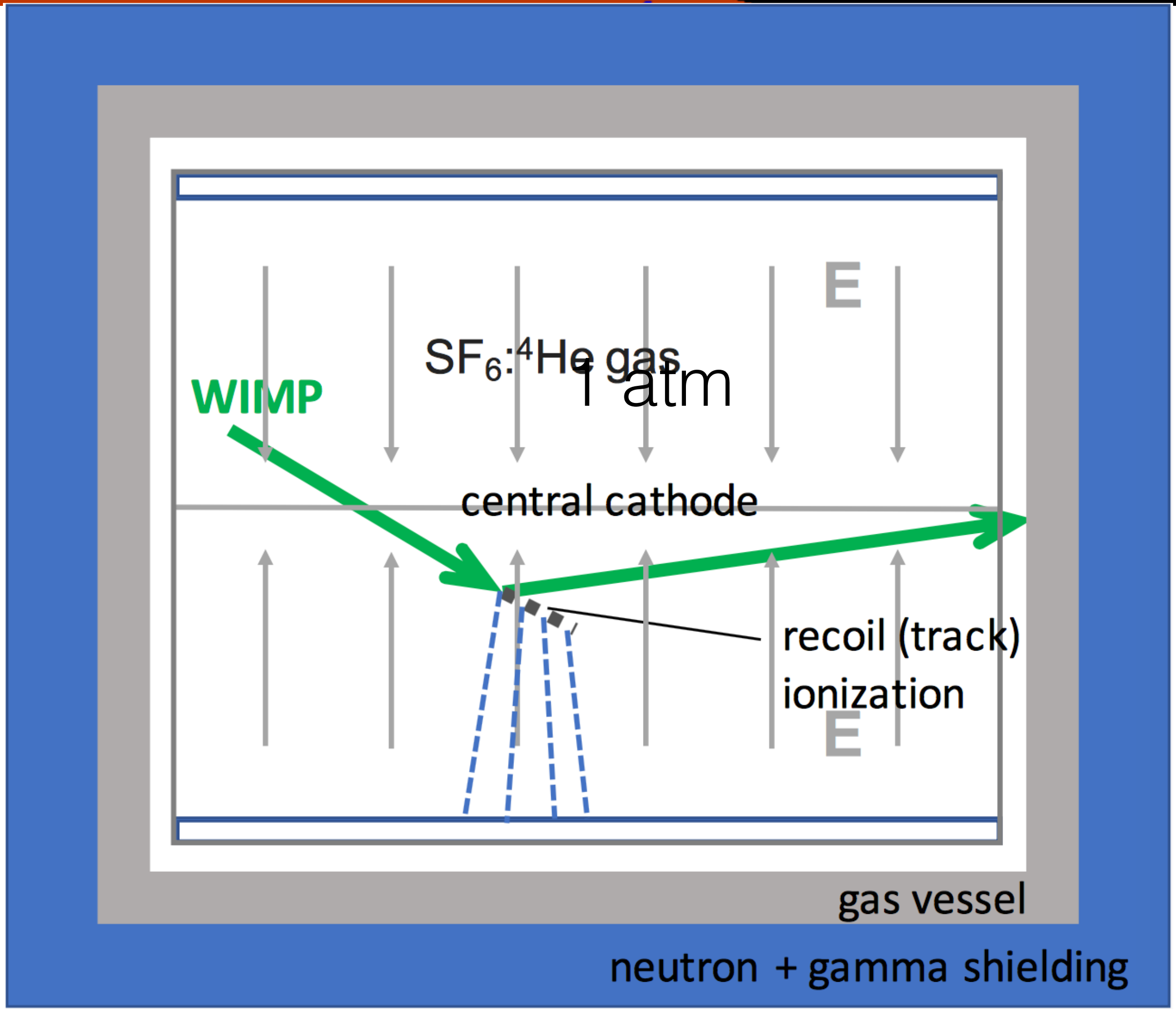
A DM event that deposits energy in the form of heat ignites a spin-flip avalanche in the crystal which is detected by the change in magnetic flux through a pick-up loop.

CYGNUS HD10

A low-mass dark matter search with directional sensitivity via charge cloud tomography

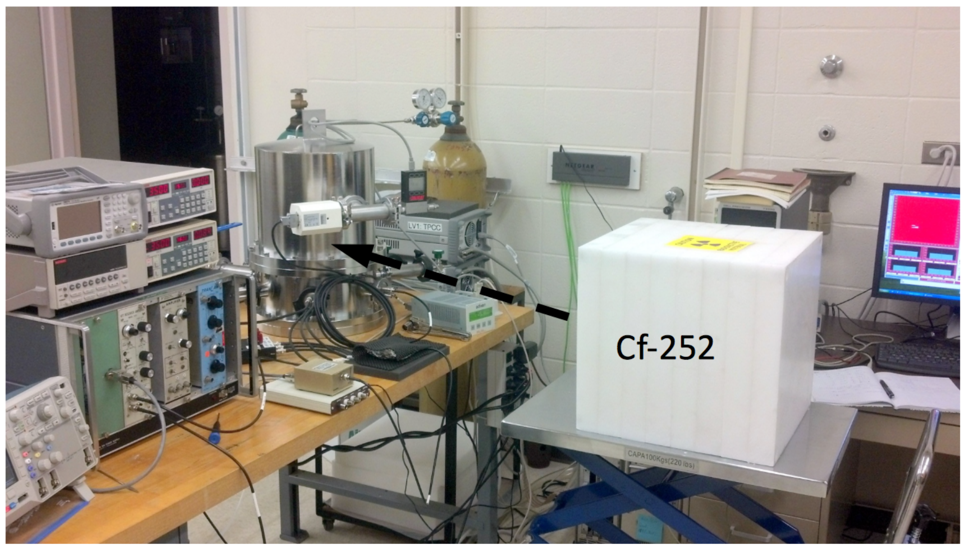
- gas TPC
- microMega for charge amplification
- upgrade to silicon pixels of strips for higher resolution tracks (head tail, particle id, fiducialization)
- Helium target for lower threshold, and get longer tracks.

10 m^3 CYGNUS HD-10 detector is expected to have sensitivity competitive with the G2 experiments, to both SD and SI interactions, with improved electron rejection for low WIMP masses.

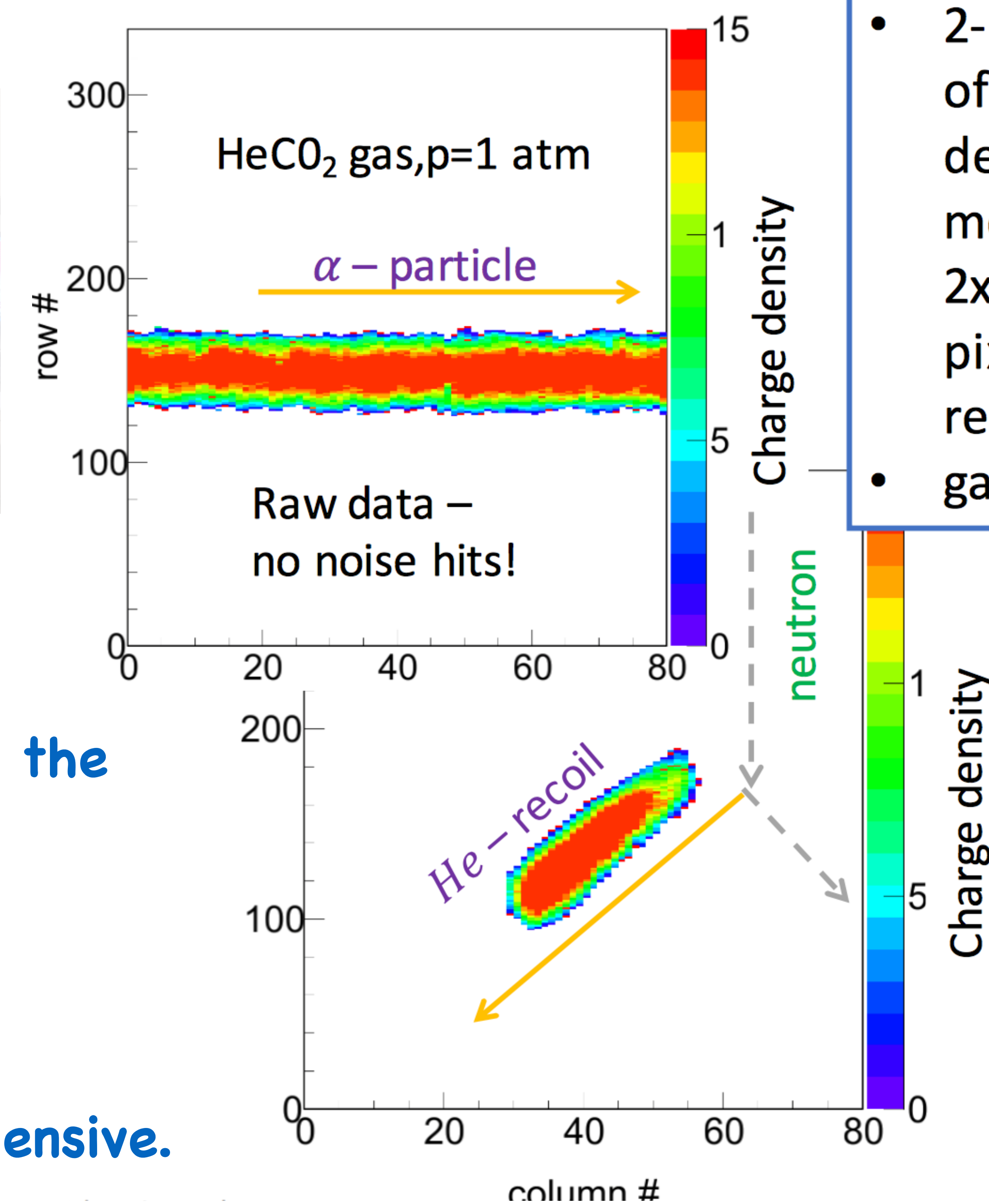


Long term: Build large-scale (>1000 m3) nuclear recoil detector capable of bbserving Dark Matter via diurnal directional oscillation (Measuring DM particle properties and physics WIMP astronomy).

CYGNUS HD10



27-sigma evidence for “neutron wind” in Hawaii!
Recoils point back to source, in 3D.

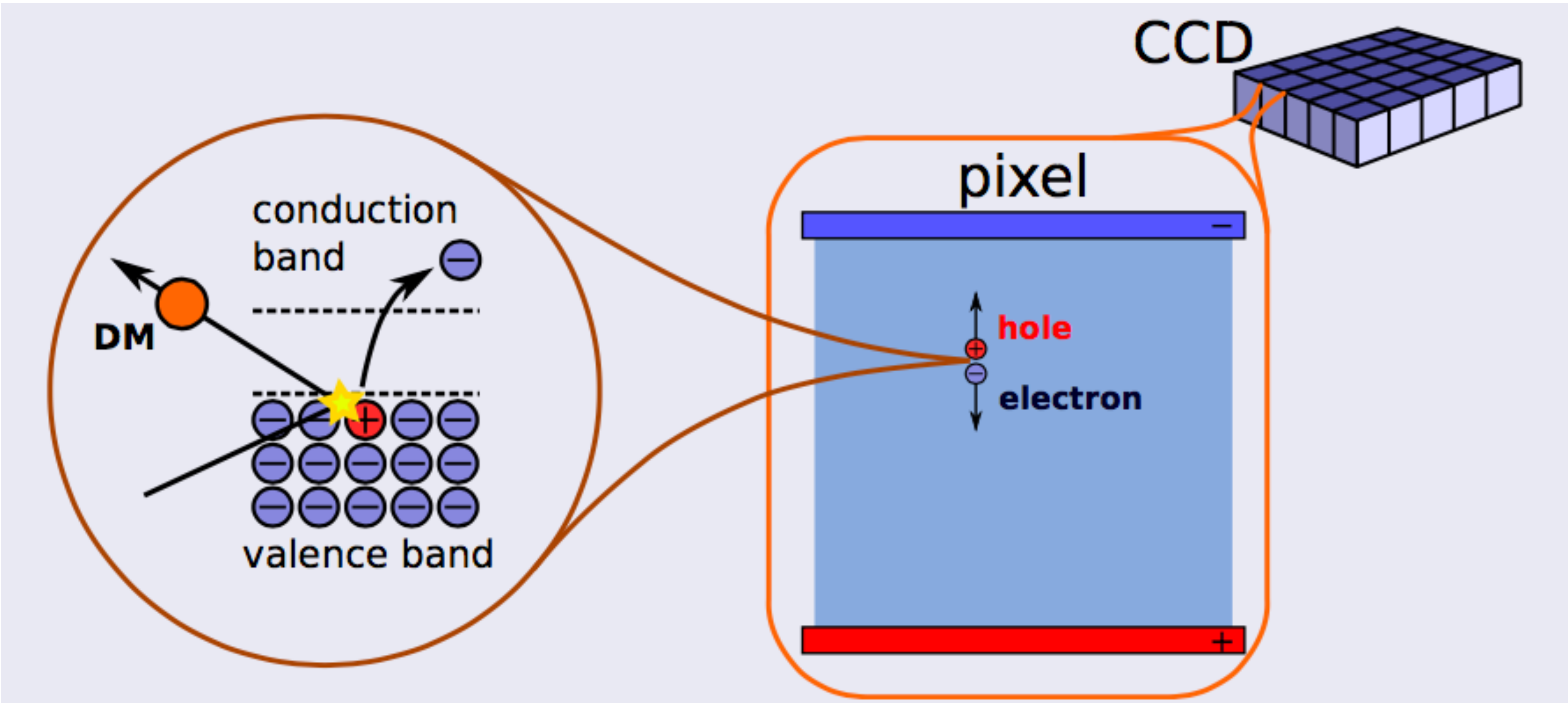


- 2-D projection of ionization density, measured w/ 2x2 cm ATLAS pixel chip readout
- gain ~ 3000

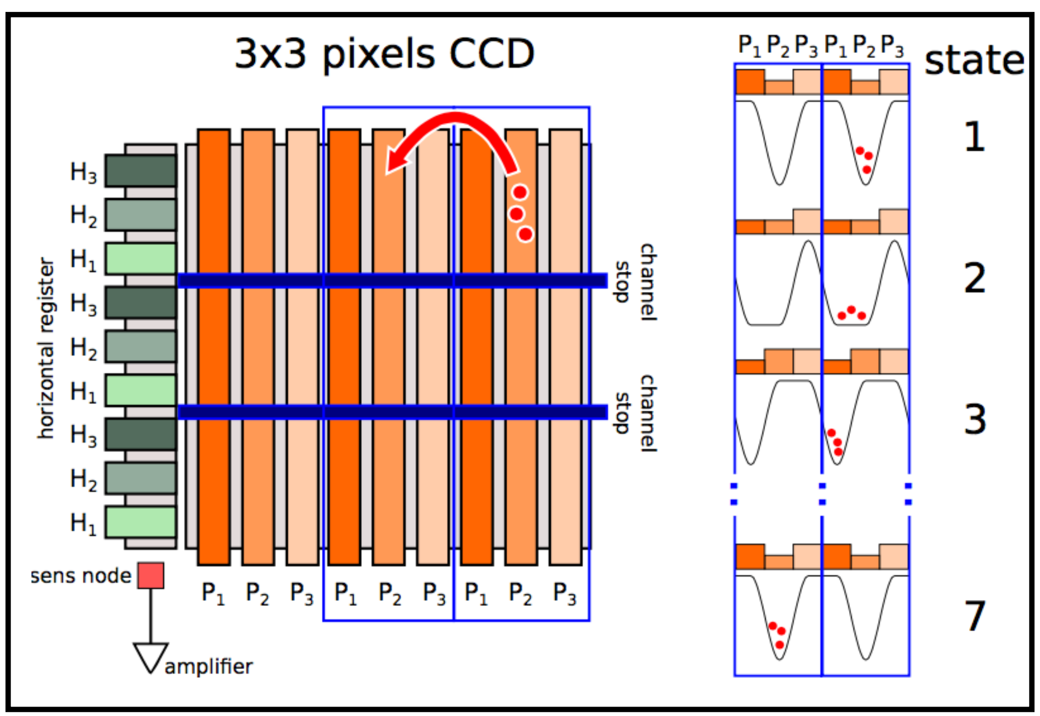
small scale demonstrations of the technology going on now. Demonstrated the directional detection.

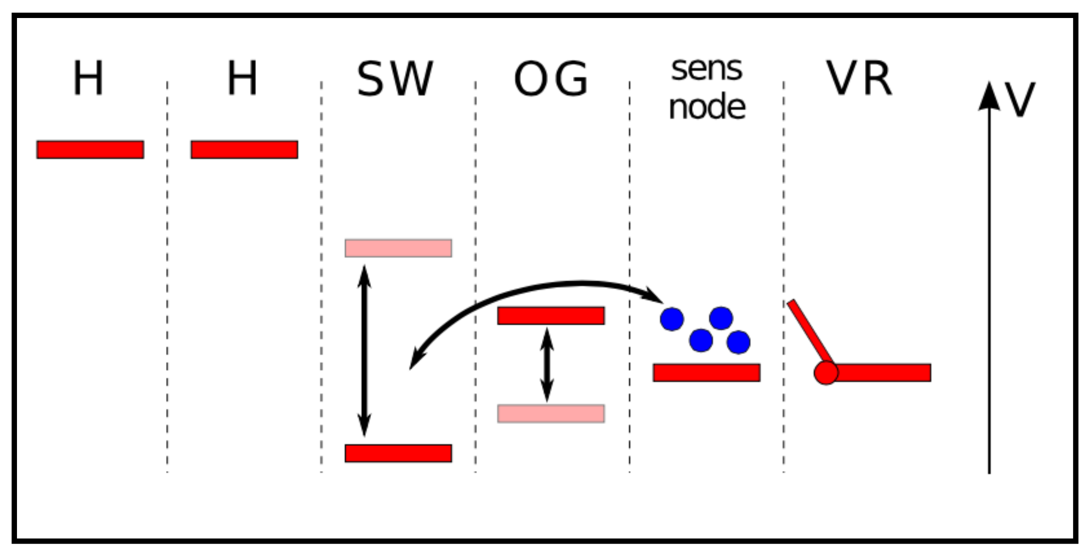
Full size with Si pixels is expensive.

SENSEI (J. Tiffenberg et al)



CCDs being used for DM search already (nuclear recoil), now we are looking also ar e-recoil.

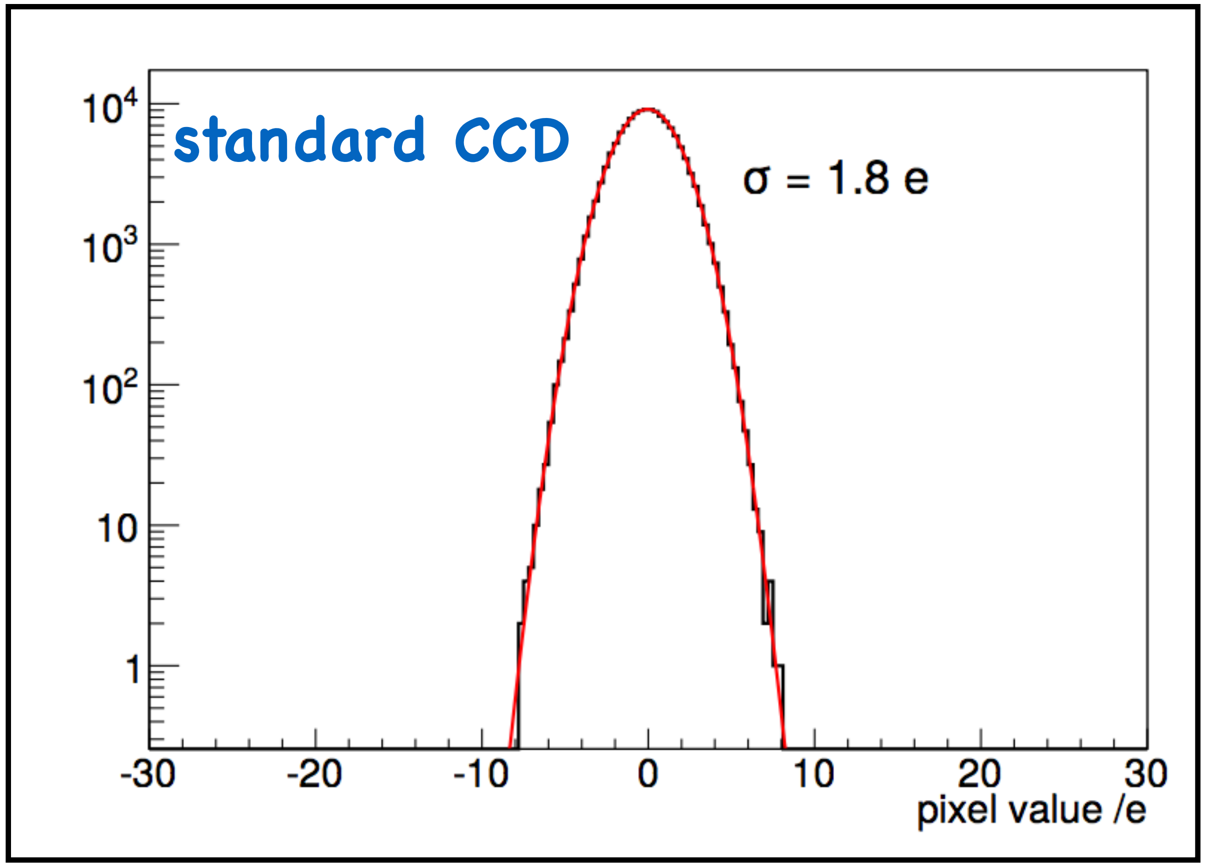


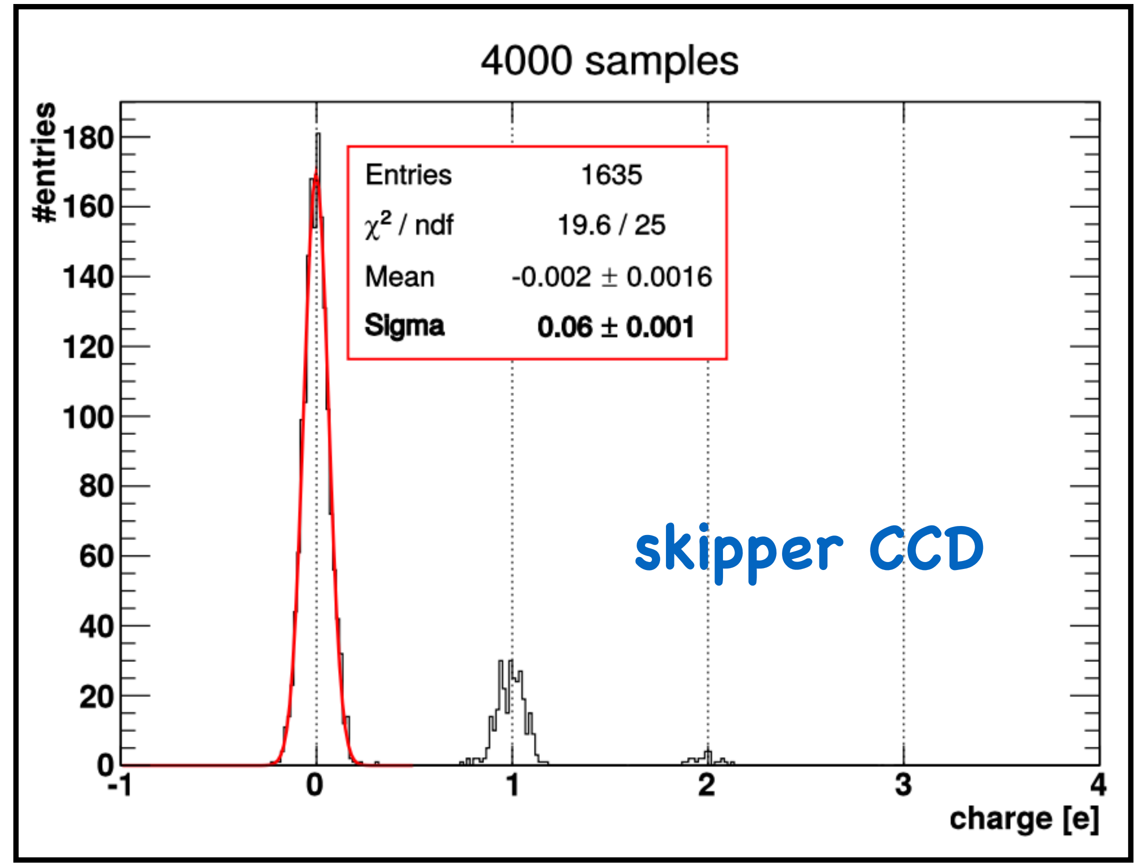


skipper CCD makes this the ideal sensor!

SENSEI

arXiv:1706.00028
Phys. Rev. Lett. 119, 131802 (2017)

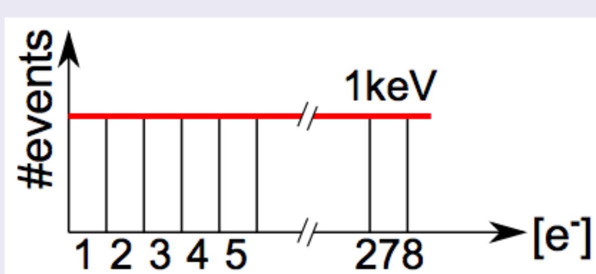




A 100g detector that takes data for one year $\rightarrow$ **Expo = 36.5kg · day**

Assuming same background as in DAMIC:

- **5 DRU** (events·kg^{-1}·day^{-1}·keV^{-1}) in the 0-1keV range
  $\rightarrow$ $\mathbf{N_{bkg}}$ = **36.5** kg · day × **5** DRU = **182.5** events
- Dominated by external gammas $\rightarrow$ **flat Compton spectrum**



182.5 events over the 278 charge bins in the 0-1keV range

Expect 0.65 bkd events in the lowest (2 e$^-$) charge-bin

technology demonstrated in the lab, ready for deployment in about 2 years.

Facilities

The capability of the direct DM search community to develop the next generation of detectors depends in great manner of the availability of facilities for detector R&D, calibration, and early science tests.

1. Nuclear Recoil Calibration Facility at TUNL

Precision measurements of the quenching factor for several detector technologies needed in order to perform direct DM searches with nuclear recoils. A facility to perform these measurements has been established at TUNL (Triangle Universities Nuclear Laboratory). Pulsed, tunable and quasi-monoenergetic neutron beams. Instrumentation to measured the scattering neutron is available.

2. Northwestern Experimental Underground Site at Fermilab (NEXUS)

A clean, low-background, testing facility with convenient access for prototyping and testing the next-generation cryogenic detectors (dilution fridge) is being set at the NuMI access tunnel at Fermi- lab (300 m.w.e.). The facility is being established by the Northwestern SuperCDMS group, and will also be available for other users 30% of the time

3. Cryogenic Test Underground Facility (CUTE) at SNOLAB

Queen's SuperCDMS group provides a very low background cryogenic test stand at SNOLAB. CUTE is set to perform low background studies, and can also be used as a science platform. A dilution fridge similar to the NEXUS (same vendor) will be available, with lower background of 3–30 dru. The fridge will be installed inside a water tank for shielding SuperCDMS cryogenic facility at SNOLAB

4. SuperCDMS cryogenic facility at SNOLAB

SNOBOX facility at SNOLAB. This is the di- lution fridge to be used for the G2 program with 5 μW cooling power at 15 mK. SNOBOX will have a very large volume available, capable of holding 31 SuperCDMS towers, with an expected background that is 30 times lower than CUTE. The SuperCDMS G2 program is scheduled to start science operations in 2020 with a 4 tower payload. The additional space available is the ultimate location for either a large payload or a very-low background mea- surement.

this could make our R&D efforts go faster

Conclusions

- Completing the G-2 program is the highest priority.

- Since WIMP has not been detected, new theoretical ideas are being considered. An array of "small" projects could probe a very significant part of these new models.

- DM is the most exciting field for detector development.