Future DM Direct Detection Experiments

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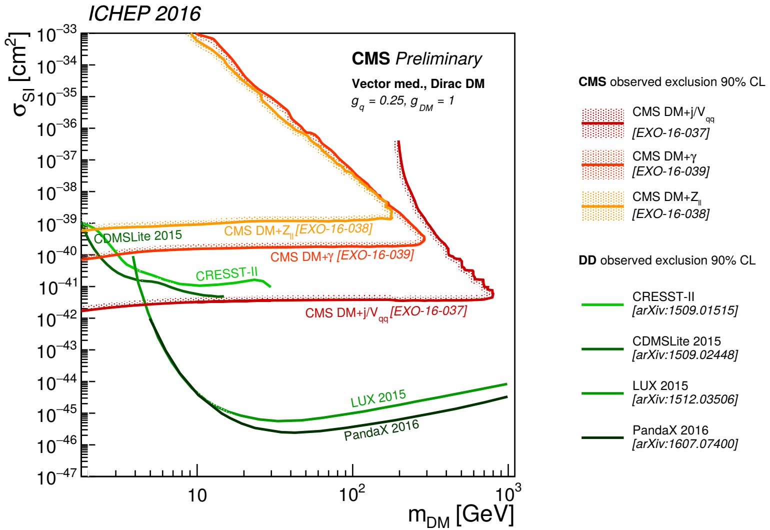
Fermilab

Talk index

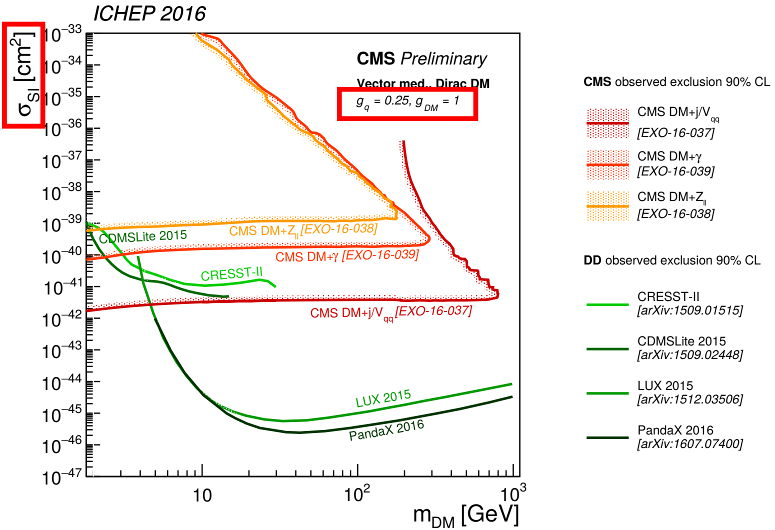
This talk..

- Why we need *Future Direct Detection Experiments*?
- Direct detection channels and techniques
- Summary of future experiments
- Timeframes

We have an LHC, do we really need DD?

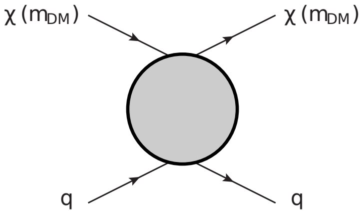


We have an LHC, do we really need DD?

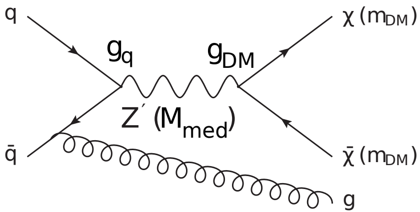


Energy scales are very different

Direct detection probes σ^0_{SI}



Production at colliders depends on interaction structure



$$\sigma^0_{SI} \propto \frac{g_q^2 \; g_{DM}^2 \quad \mu_{n\text{-}DM}}{M^4_{med}}$$

IE: in simplified models

production vanishes if g_q is tiny but σ^0_{SI} is unchanged if M_{med} is small

Direct Detection and production of DM

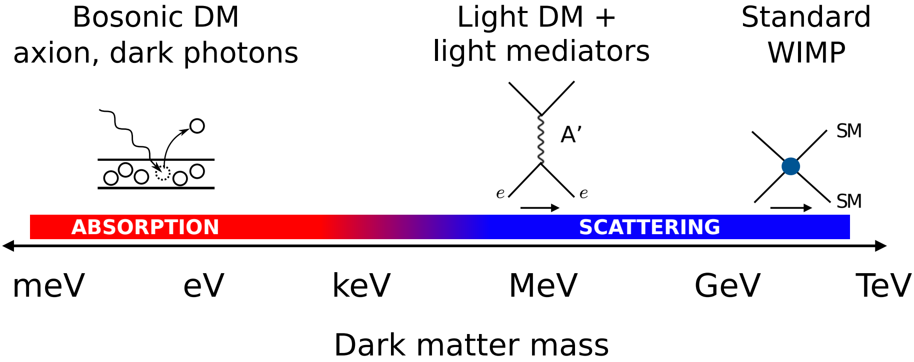
Complementarity

- production is hard if mediator is light
- DD is less dependent on the detailed structure of the interaction
- production does not depend on the astrophysical assumptions

Take away

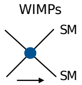
- We don't know what DM is, we need a to cast a wide net
- DD and accelerator experiments look at different things. Fortunately there is some overlap. It would be great to have both signals.
- Convincing power: a positive signal is not enough. Extraordinary claims require extraordinary evidence.

Direct detection candidates

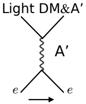


Adapted from Lin-17

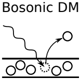
Direct detection candidates



- Nuclear recoil to get coherent enhancement of $\sigma_{\text{n-DM}}$
- Nuclear / electron recoil discrimination is desired
- Light targets for WIMPs masses < 10 GeV
- Targets: noble gases, cryogenic crystals, semiconductors, scintillators

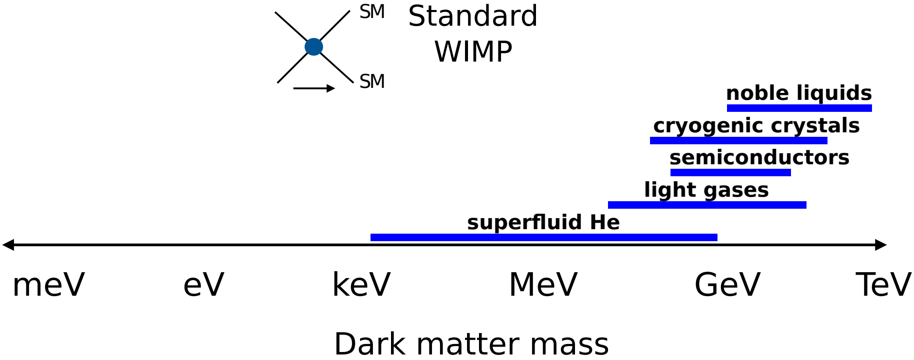


- Electron recoil
- Targets: Novel gases, cryogenic crystals, semiconductors



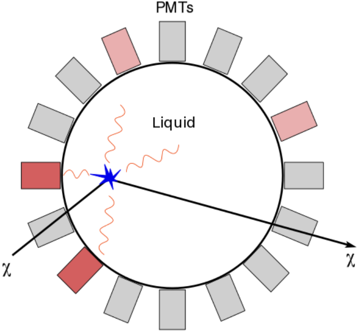
- Conversion into photon, photoelectric absorption
- Targets: resonant cavities, semiconductors

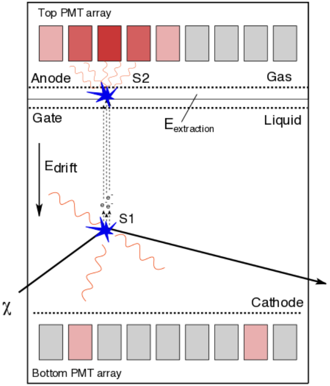
Standard WIMP direct detection program



Standard WIMP: noble liquids

Single phase | Dual phase





e/N recoil discrimination in LAr but not in LXe

e/N recoil discrimination in LAr and in LXe

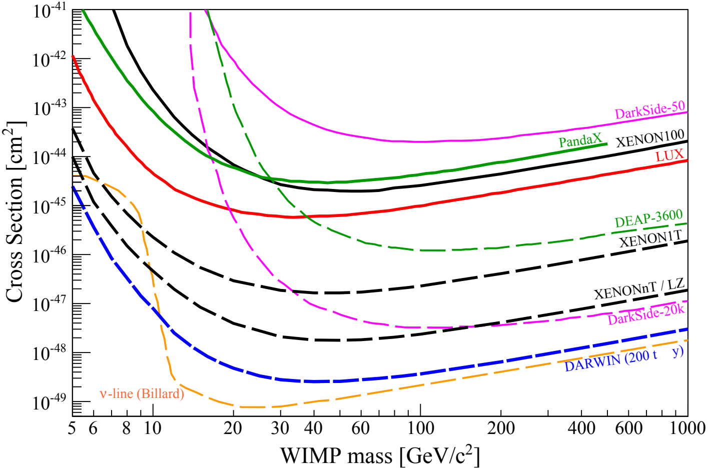
Marrodán Undagoitia, Teresa et al. J.Phys. G43 (2016)

Standard WIMP: noble liquids

Experiment	Technique	Fiducial target
DarkSide-20k	Single phase	20T - LAr
DEAP-50T	Single phase	50T - LAr
XMASS-1.5	Single phase	1.5T - LXe
XENON-nT	Dual phase	4.5T - LXe
LZ	Dual phase	5.7T - LXe
DARWIN	Dual phase LXe	30T - LXe

There is a well defined program for the next 15-20 years

Standard WIMP: noble liquids

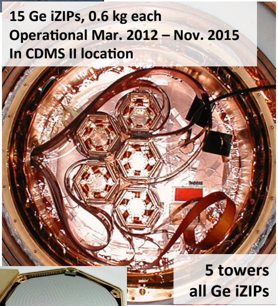


Standard WIMP: SuperCDMS and EURECA

SuperCDMS

SOUDAN

Leading limits published on low mass WIMPs



15 Ge iZIPs, 0.6 kg each
Operational Mar. 2012 – Nov. 2015
In CDMS II location

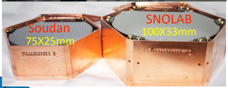
5 towers
all Ge iZIPs

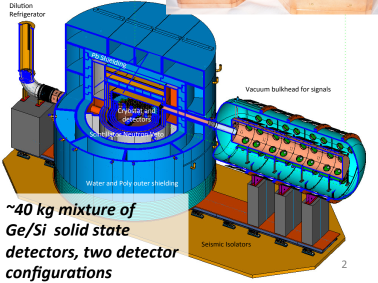
Operation ended late 2015

SNOLAB

Generation-2 experiment, beginning ~2019

Aiming for unique sensitivity to low mass WIMPs



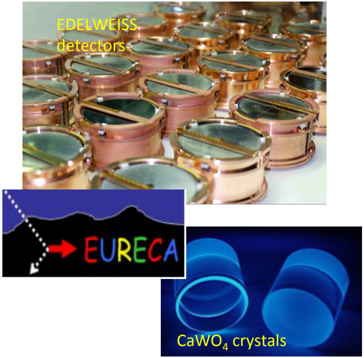


~40 kg mixture of Ge/Si solid state detectors, two detector configurations

Standard WIMP: SuperCDMS and EURECA

SuperCDMS/EURECA

Cryostat will be sized to hold much more than initial G2 payload; offers prime real-estate in the sub-40 mK, ultra-low radioactive background, ultra-low noise zone!



- Active development in adapting SuperCDMS cryogenics, towers and readout to EURECA specifications
- EURECA: next-generation “cryogenic” dark matter experiment; joint collaboration between present-day EDELWEISS (Ge) and CRESST ($CaWO_4$).
- Positioned to expand payload to explore high mass WIMPs if a signal is seen, *OR upgrade with improved detectors to reach neutrino floor in 1-10 GeV/c^2 region.*

ICHEP, August 2016 15

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Standard WIMP: SuperCDMS and EURECA

SuperCDMS Rough Timeline

2012-2014: Ongoing R&D

July 2014: Selected as a next-generation dark matter experiment by DOE & NSF (!)

Fall 2015: CD-1

Fall 2015: End of Soudan Operations

We are here

2016-2017: Design, work towards DOE CD-3

2018-19: Construction

2020: commissioning and first science running

Beyond 2024: Upgrade to multi-100 kg or merge with EURECA

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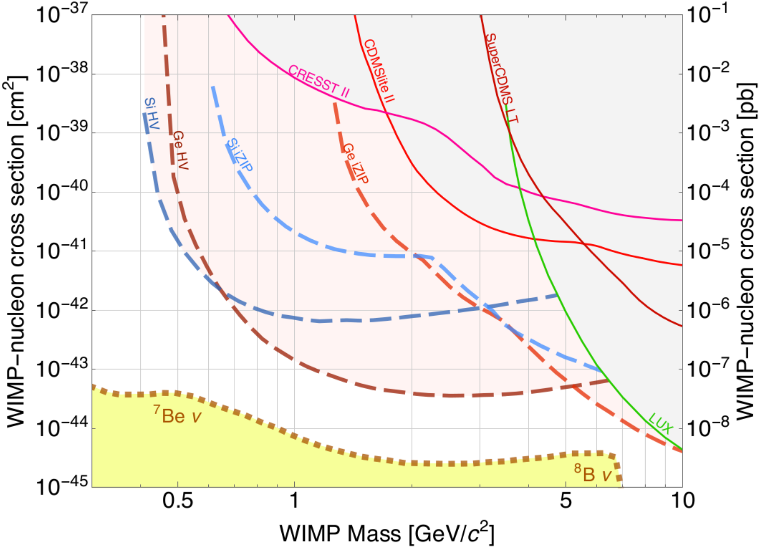
Standard WIMP: SuperCDMS and EURECA



Standard WIMP: CRESST-III

Upcoming projects:
CRESST-III

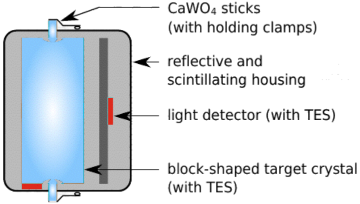
arXiv:1503.08065

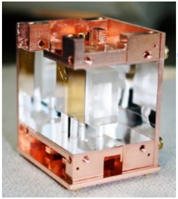
Goal: lower threshold to 100 eVnr

→ smaller crystals of best background quality (250 g → 24 g)

→ all-scintillating detector design
  all material surrounding the detectors is scintillating → avoid partial energy depositions

→ improv



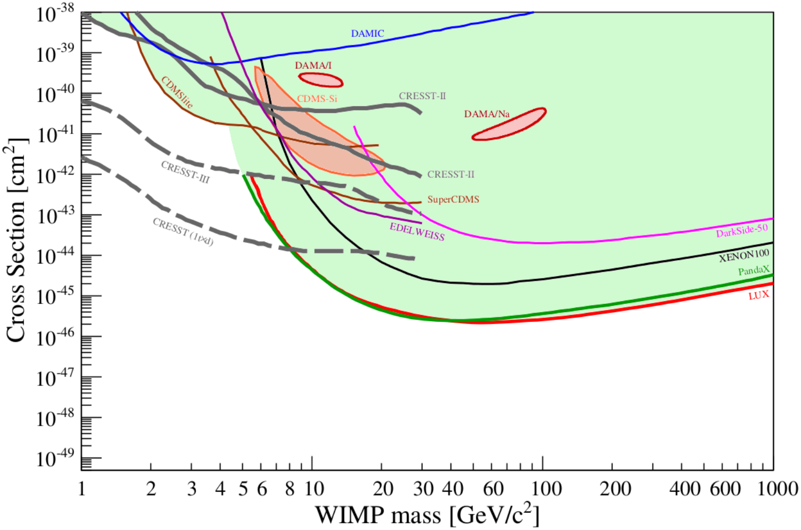


Reindl @ Lake Louise 2016

Status:

- Prototype already exceeds design goal: 50 eVnr threshold
- first 4 modules were mounted in February 2016
- cool-down soon

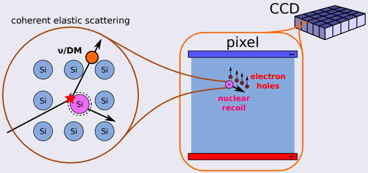
Standard WIMP: CRESST-III

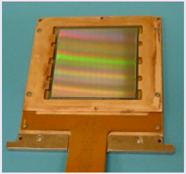


Standard WIMP: semiconductor detectors

DAMIC

DAMIC uses scientific CCD as target material to detect the ionization produce by nuclear recoils in the silicon lattice

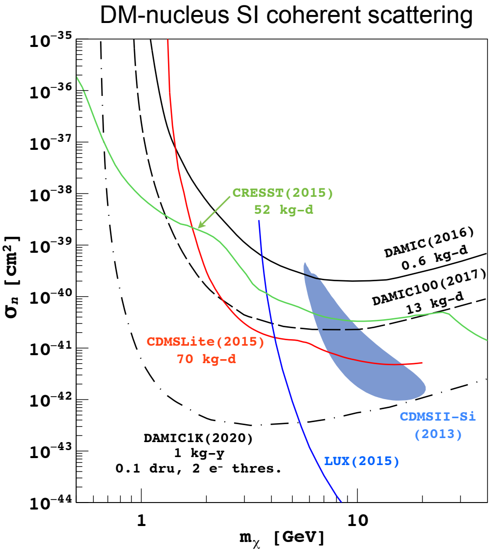




DAMIC-1K

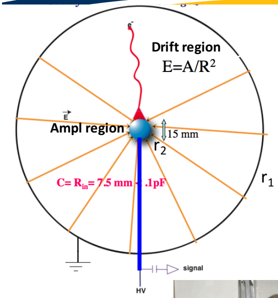
- A kg-size experiment with 0.1 dru background and $\leq$ 2e- threshold
- exploration of low-mass WIMPs and dark sector candidates

Standard WIMP: semiconductor detectors



Standard WIMP: light gases

Spherical gas detectors
New **E**xperiments **W**ith **S**pheres



- Sphere cavity + spherical sensor + HT
- **=> Low threshold (low C), does not depend on size**
- **Fiducial volume selection by risetime**
- **Flexible (P, gaz)**
- Large mass / large volume (30 kg) with single channel
- Simple, sealed mode
- 2 LEP cavity 130 cm Ø tested
- **1 low activity 60 cm Ø in operation @ LSM**

$$C = 4\pi\epsilon\rho$$

$$1/\rho = 1/r_2 - 1/r_1$$

$$\rho \approx r_2$$

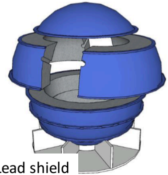
$$E(r) = \frac{V_0}{r^2}\rho$$

Standard WIMP: light gases

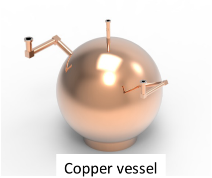
140 cm diameter project with compact shield option

implementation at SNOLAB by 2018

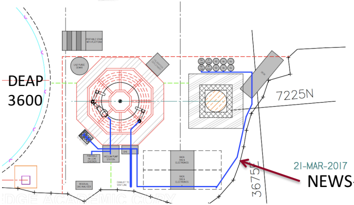
- 140 cm Ø detector, 10 bars, Ne, He, CH_4
- 25 cm compact lead –3cm ancient - LSM
- 40 cm PE + Boron sheet



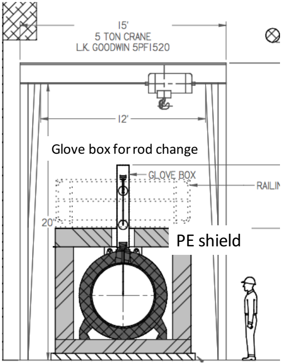
Lead shield



Copper vessel

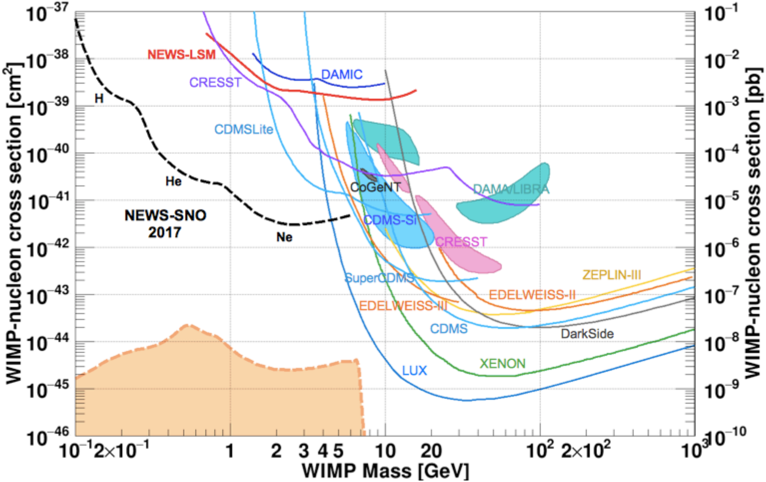


NEWS-G in Cube Hall



35 t shields

Standard WIMP: light gases



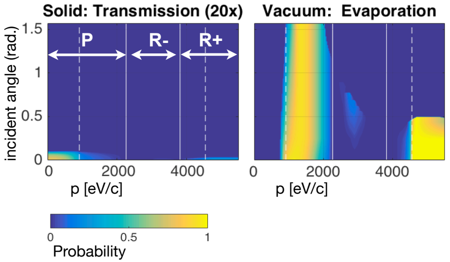
Timescale for data taking: 2018

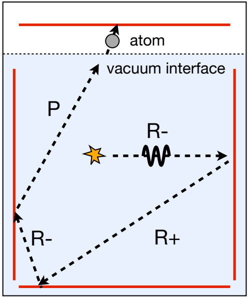
Standard WIMP: super fluid He

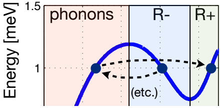
Reading Out ^{4}He Quasiparticles (quantum evaporation)

crossing into solid extremely suppressed
(Kapitza resistance)

...saved by significant probability
of single-atom evaporation at vacuum







Standard WIMP: super fluid He

Signal: Standard Elastic NR

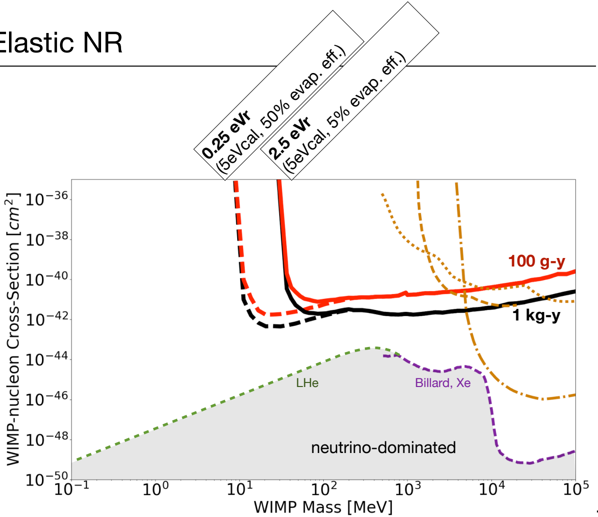
detector parameters assumed

calorimeter threshold of 5eV
(approximately today's abilities)

40meV per evaporated atom
(bonding to graphene-fluorine)

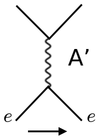
5% evaporation efficiency
(already achieved, HERON)

50% evaporation efficiency
(assuming some improvement)

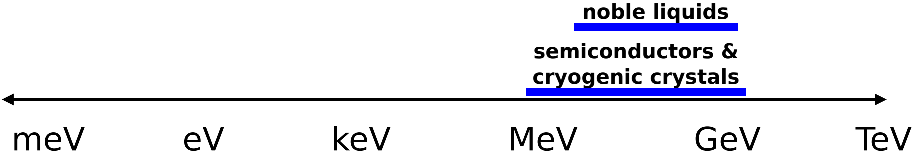


Times for data taking: 2022

Light dark matter: electron recoil



Light DM +
light mediators

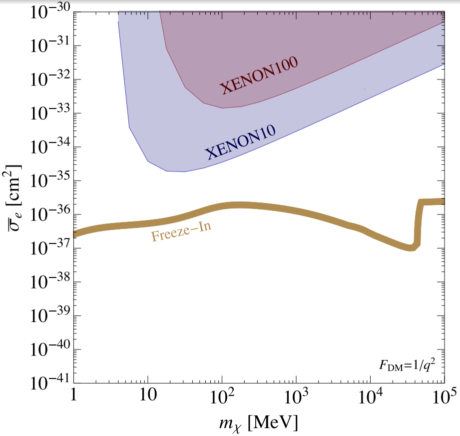


Dark matter mass

Light dark matter: electron recoil

Dark photon: Essig et al, cf. arXiv:1703:00910

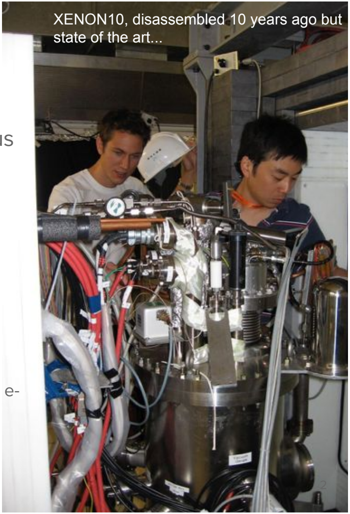
There are well motivated light DM candidates that can be detected via electron scattering. Models with light mediators can be explored.



Light dark matter: electron recoil in LXe

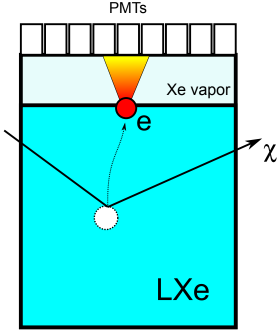
$U_{A'}(1)$ concept

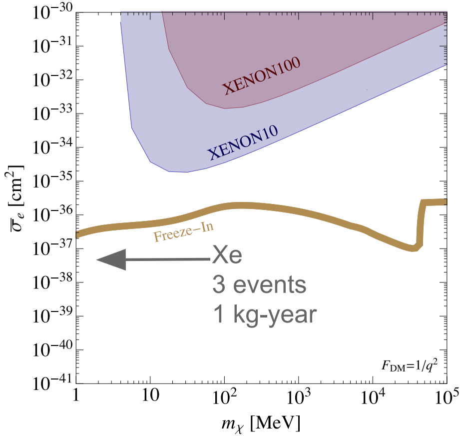
- 10 kg scale liquid xenon TPC with complete focus on S2 signal and mitigation of e- backgrounds
- Without concern for S1 (primary scintillation collection)
    - the design is far simpler
    - and cheaper
    - contains less plastics (easier to achieve purity)
- A 2 kg scale prototype is already built
    - LLNL detector for CENNS
    - Update prototype design for 10 kg active while studying e- background mitigation
- Underground deployment at SURF
    - Small footprint, likely compatible with BLBF space



XENON10, disassembled 10 years ago but state of the art...

Light dark matter: electron recoil in LXe



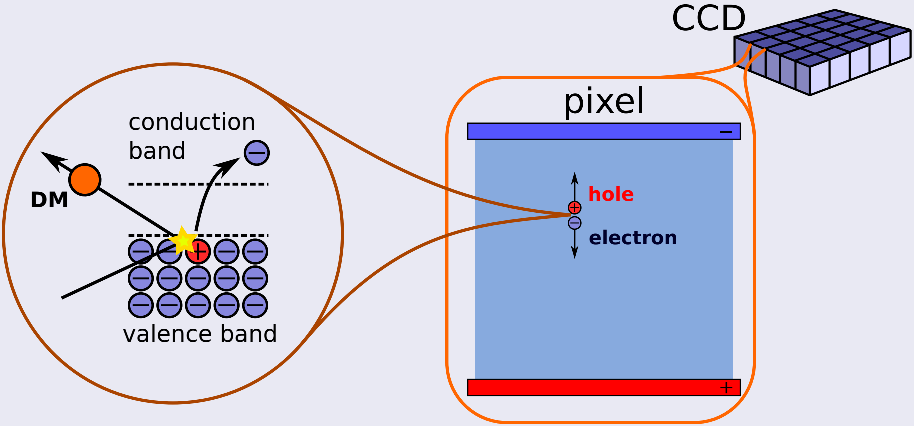


A 10 Kg experiment can have discovery potential if dark-counts are low.

Timescale for data taking: 2020

Light dark matter: electron recoil in silicon

SENSEI: **S**ub-**E**lectron-**N**oise **S**kipperCCD **E**xperimental **I**nstrument



use CCDs as target to record the ionization produced by DM

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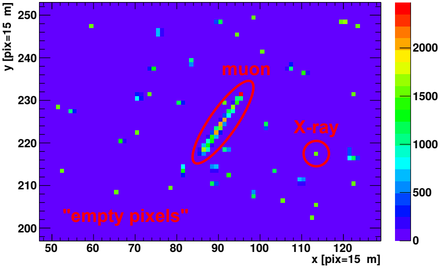
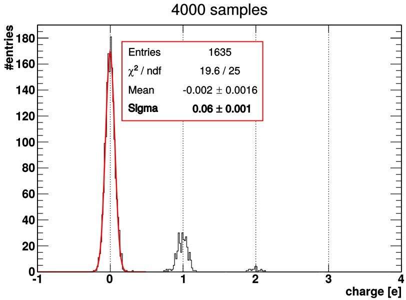
Light dark matter: electron recoil in silicon

The SENSEI project

- It uses SkipperCCDs as target material to detect DM-e interactions
- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- **Pixel value** $= \frac{1}{N}\Sigma_i^N\,(\text{pixel sample})_i$
- Zero noise detector. Threshold can be set to 2e limited by dark counts





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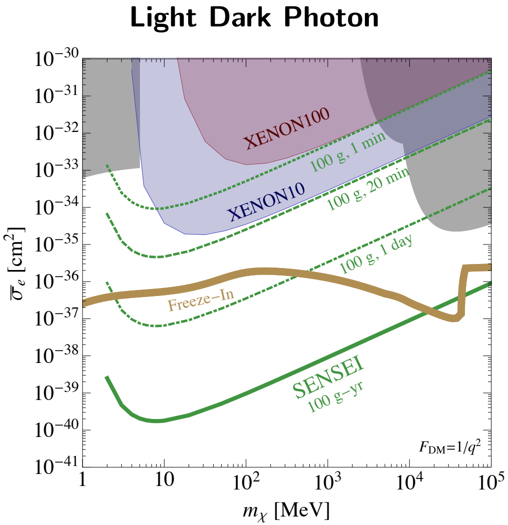

Timescale for data taking: 2017 for 1g detector 2019 for 100g

Direct detection future

Summary

- Direct detection is a very active area
- We need both DD and accelerator based experiments
- Most of the larger efforts are focused on WIMPs
- Several new techniques to explore DM candidates beyond the WIMP paradigm
- Electron recoil experiments can explore large areas of the parameter space
- I apologize in advance to all the experiments that I didn't include

BACK UP SLIDES

SENSEI: electron recoil background requirements

Back of the envelope calculation

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
  $\rightarrow \mathbf{N_{bkg} = 36.5}\ \text{kg} \cdot \text{day} \times \mathbf{5}\ \text{DRU} = \mathbf{182.5}$ events
- Dominated by external gammas $\rightarrow$ **flat Compton spectrum**

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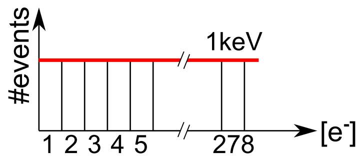


182.5 events over the 278 charge bins in the 0-1keV range

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

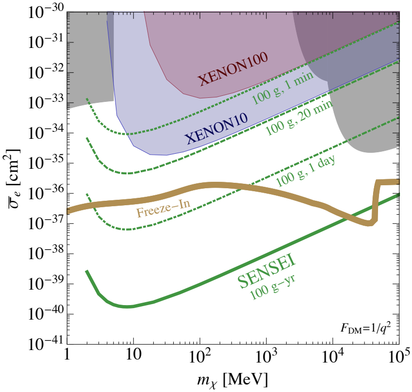
SuperCDMS SNOLAB projected background

"Singles" Background Rates (counts/kg/keV/year)	Electron Recoil				Nuclear Recoil ($\times 10^{-6}$)	
	Ge HV	Si HV	Ge iZIP	Si iZIP	Ge iZIP	Si iZIP
Coherent Neutrinos					2300.	1600.
Detector-Bulk Contamination	21.	290.	8.5	260.		
Material Activation	1.0	2.5	1.9	15.		
Non-Line-of-Sight Surfaces	0.00	0.03	0.01	0.07	–	
Bulk Material Contamination	5.4	14.	12.	88.	440.	660.
Cavern Environment	–	–	–	–	510.	530.
Cosmogenic Neutrons					73.	77.
Total	27.	300.	22.	370.	3300.	2900.

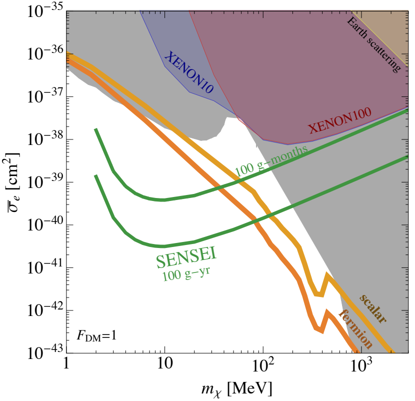
From arXiv:1610.00006

SENSEI

Light Dark Photon



Heavy Dark Photon



Plots from: Rouven Essig, Tomer Volansky & Tien-Tien Yu.