What's up with dark matter?
Direct dark matter searches

NUCLEI IN THE COSMOS

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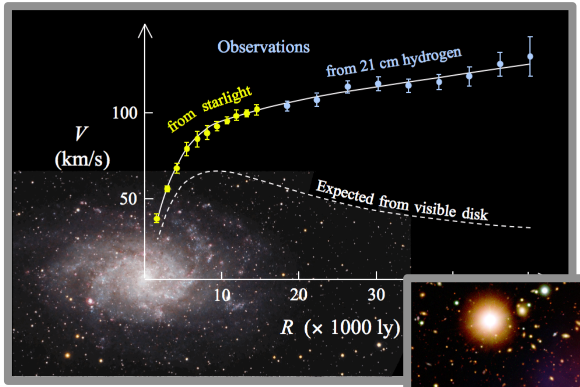
NIC XV

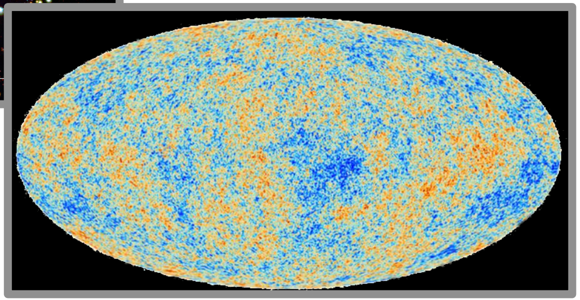
LNGS ITALY

Federica Petricca

MPP Munich

The dark matter problem



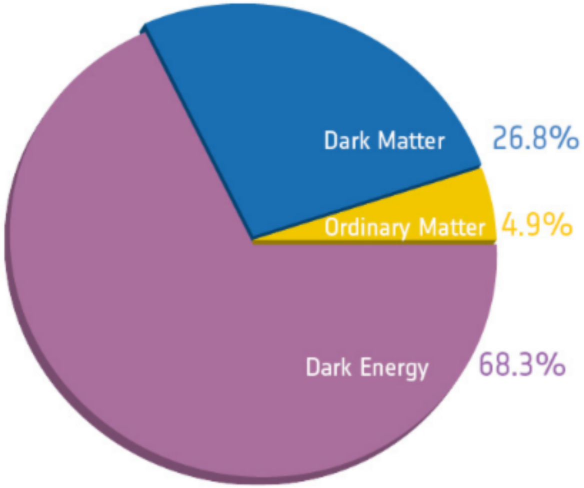


Compelling evidence for dark matter on various cosmological scales

• • •

The dark matter problem

One model fits all the observations...

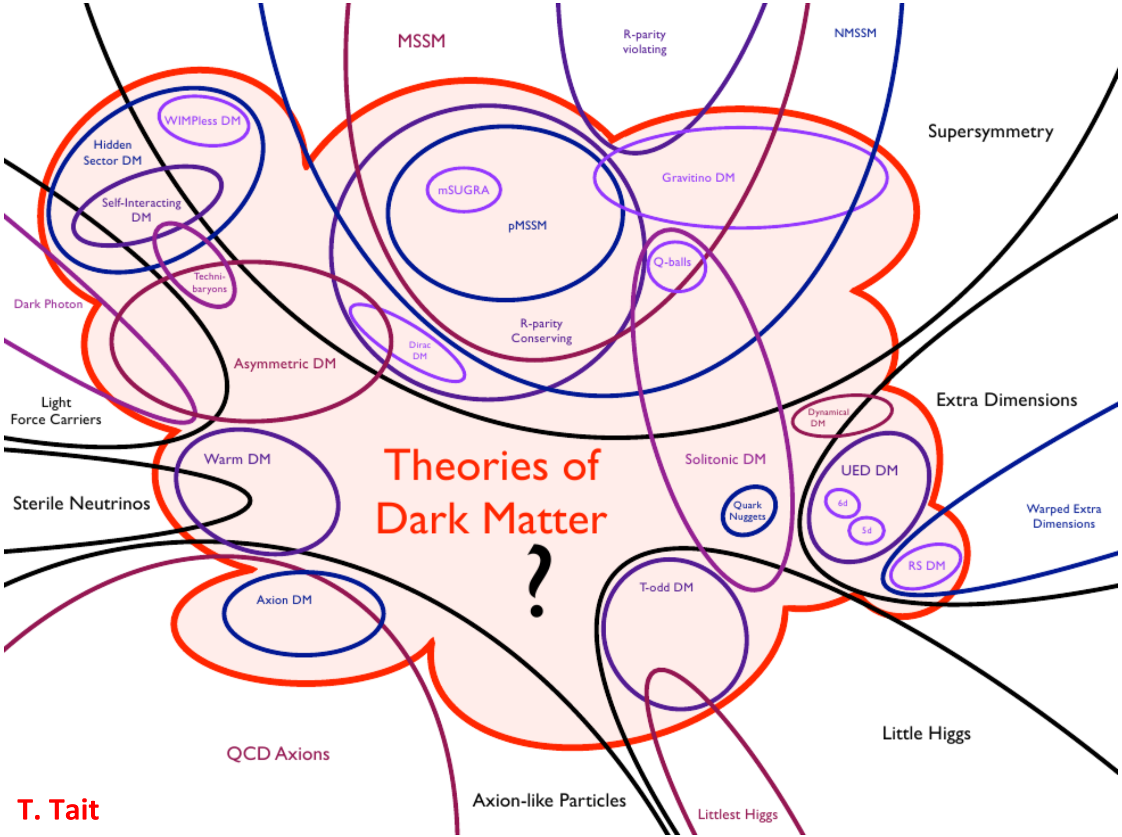


Source: © European Space Agency / Planck

...but raises some fundamental questions:
What is dark matter?
What is dark energy?

After 80 years…

- **Non-baryonic**
  - Height of acoustic peaks in the CMB
  - Power spectrum of density fluctuations
  - Primordial nucleosynthesis
- **Cold (non-relativistic)**
  - Structure formation
- **Interacts via gravity and (maybe) some sub-weak scale force**
- **STILL HERE!**
  - Stable (or extremely long-lived)

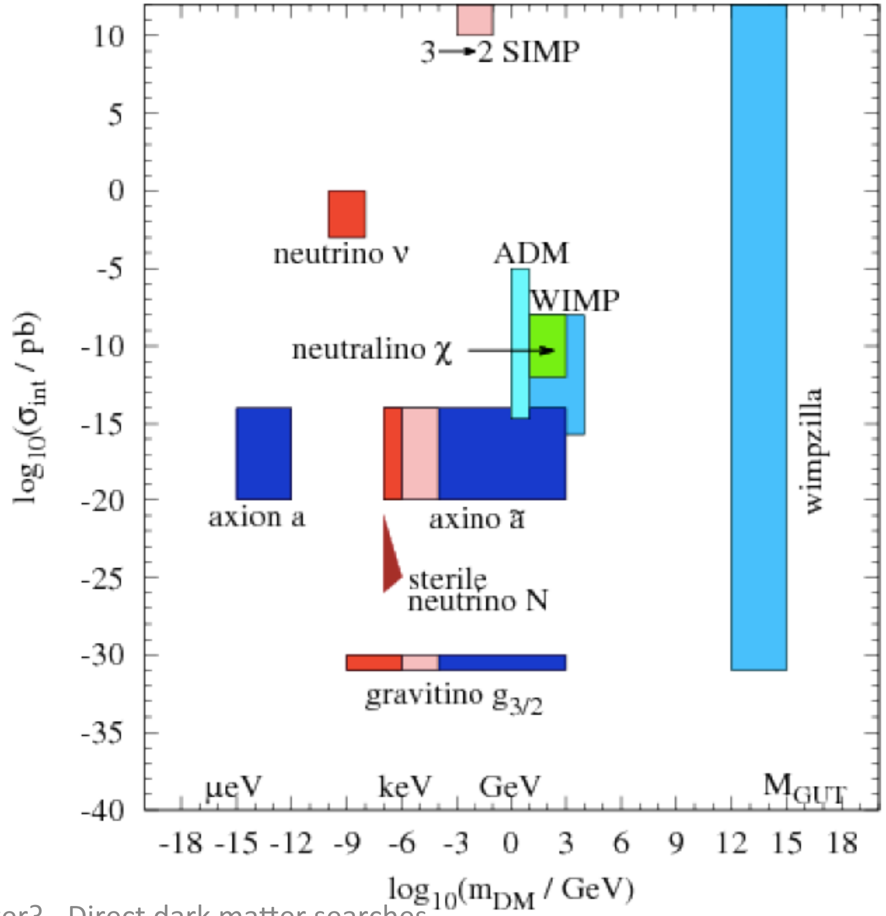


T. Tait

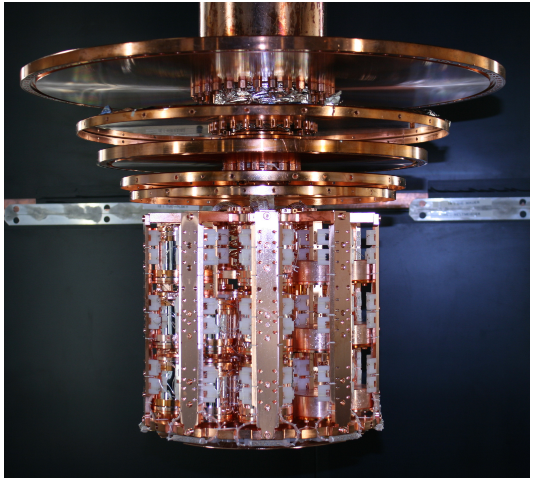
The nature of dark matter

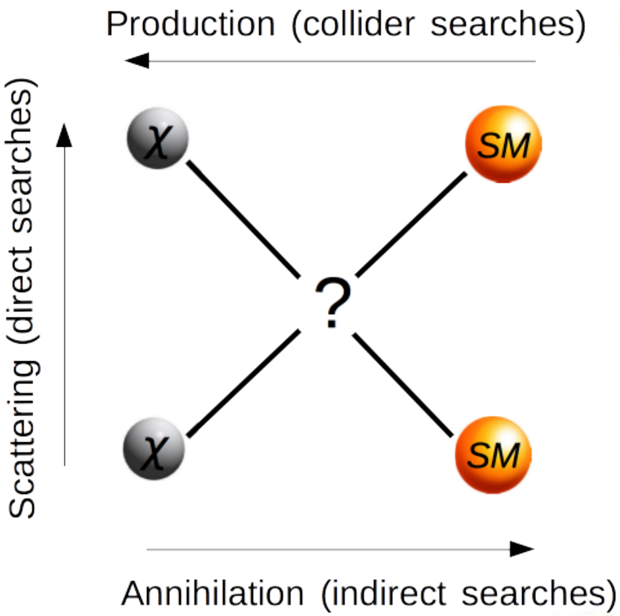
Once there was only the WIMP miracle...

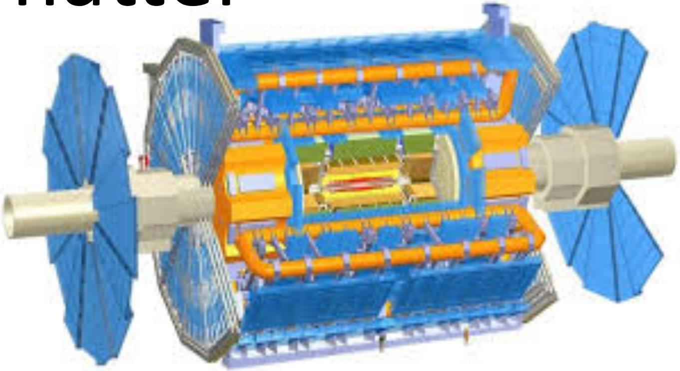
Now WIMP only one out of a range of theoretical motivated dark matter candidates with wide range of mass and cross section



The hunt for dark matter



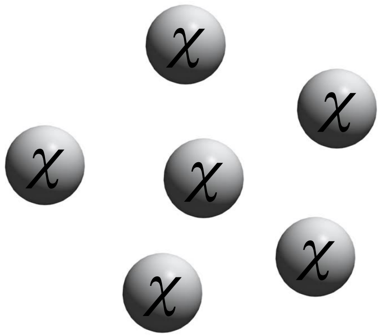




Direct dark matter detection

Basic idea

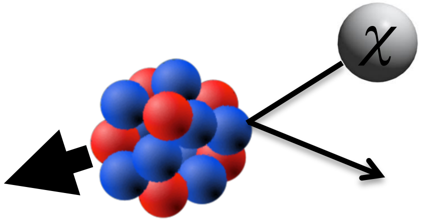
Dark matter is made of particles which interact with Standard Model particles



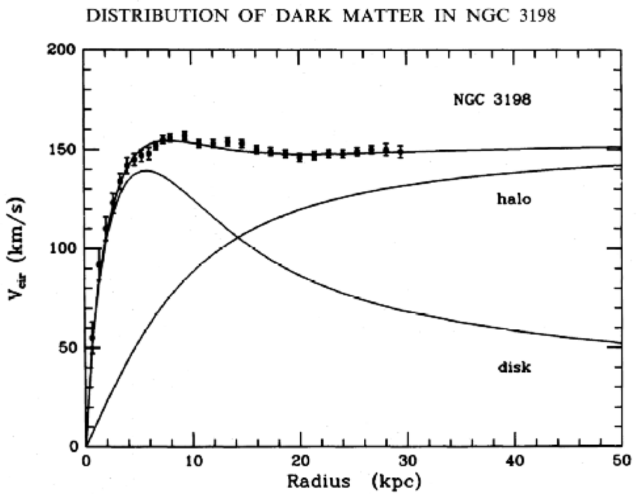
Most common scenario

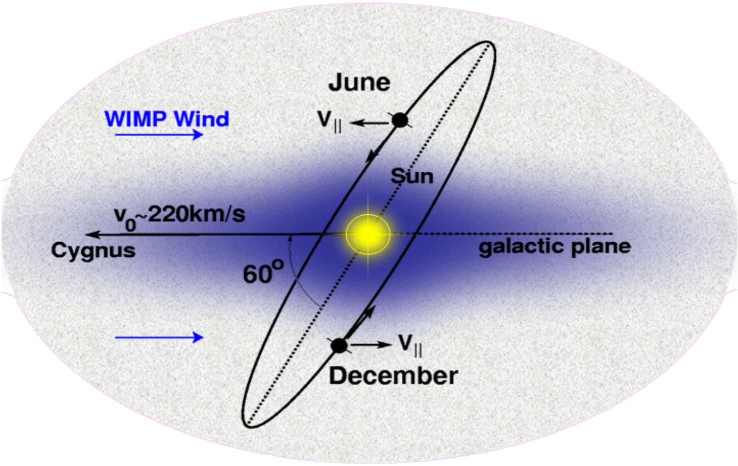
Dark matter particles scatter off nuclei:

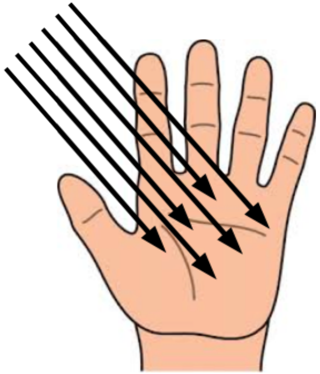
- elastically
- coherently: ~ A^2
- (spin-independent)



Dark matter in the Milky Way





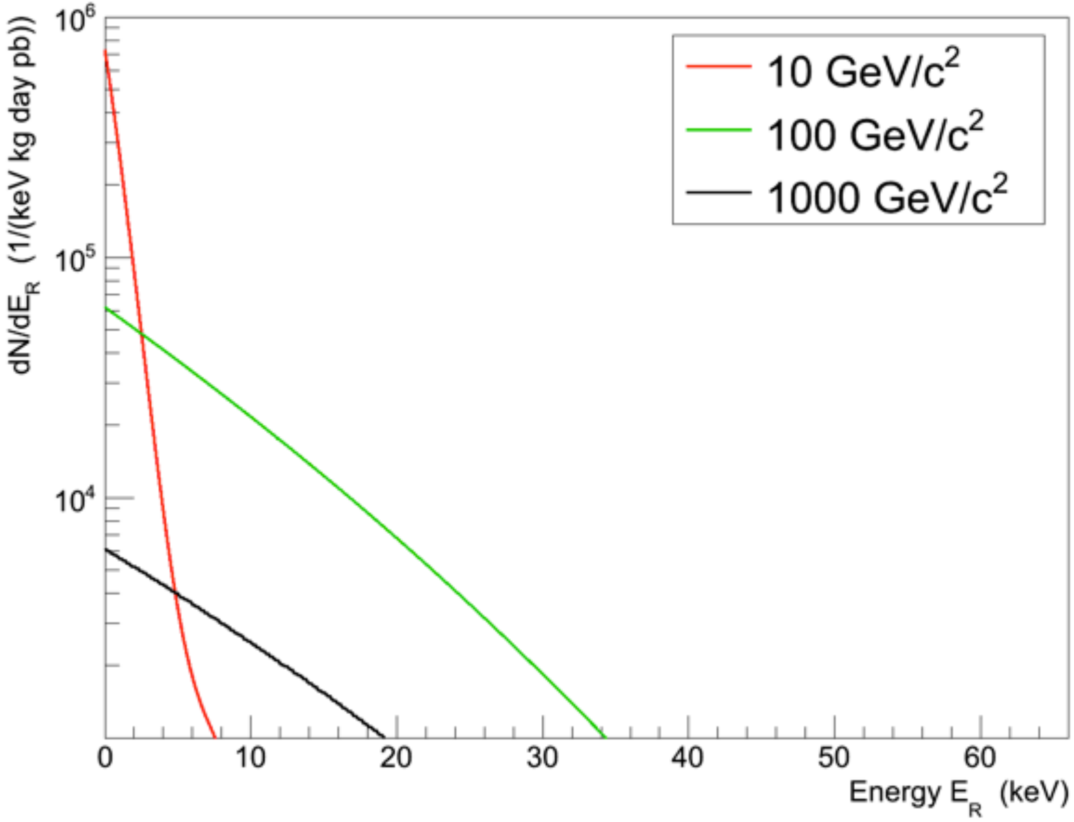


Standard assumptions:

- Maxwellian velocity distribution
- asymptotic velocity of 220 km/s
- galactic escape velocity of 544 km/s
- local dark matter density of 0.3 GeV/cm^3

Experimental challenges

Dark matter recoil spectrum: $CaWO_4$ target , ideal detector



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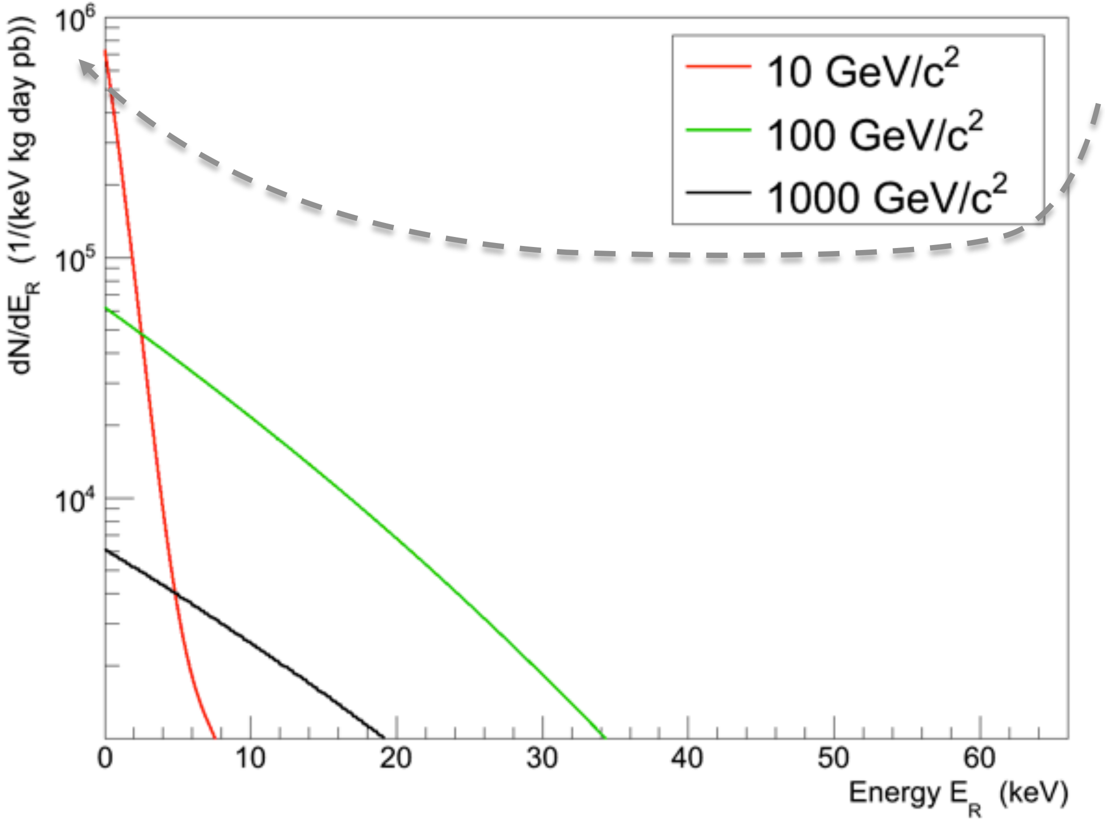

Very rare

current limit*

$\mathcal{O}(0.01)$ counts/tonne day

* Xenon1T: arXiv:1805.12562

Experimental challenges

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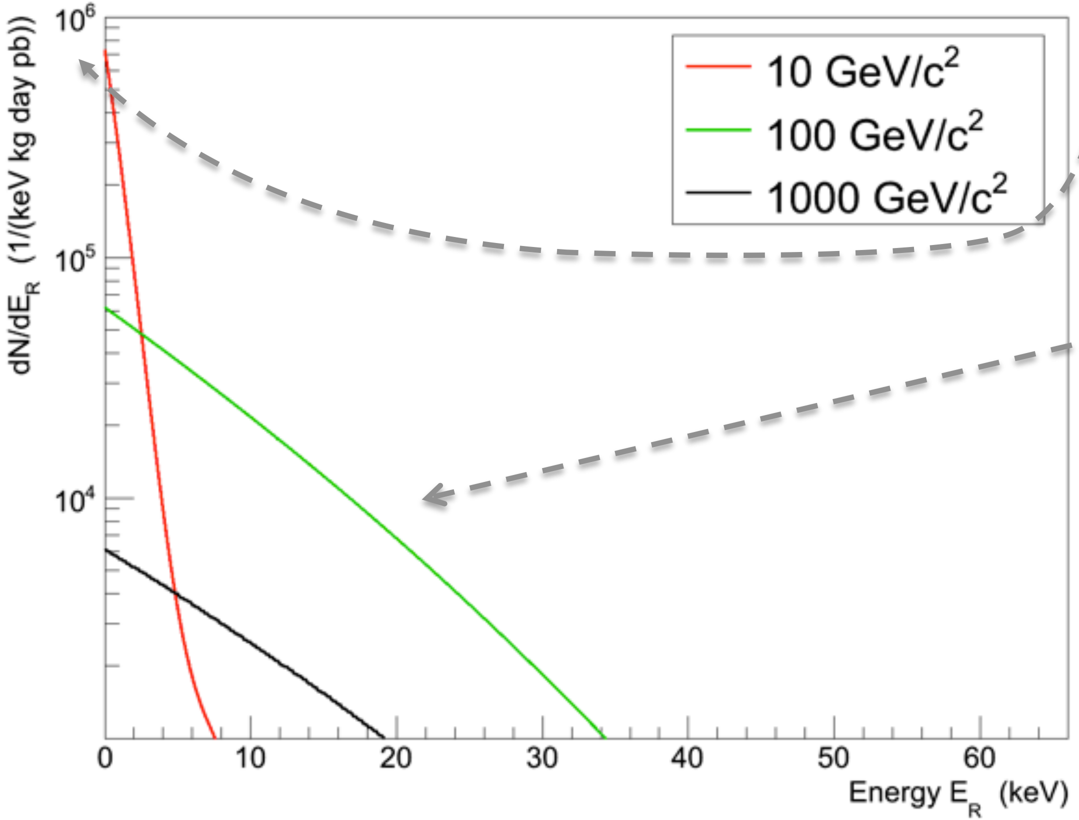

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Featureless spectrum

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Experimental challenges

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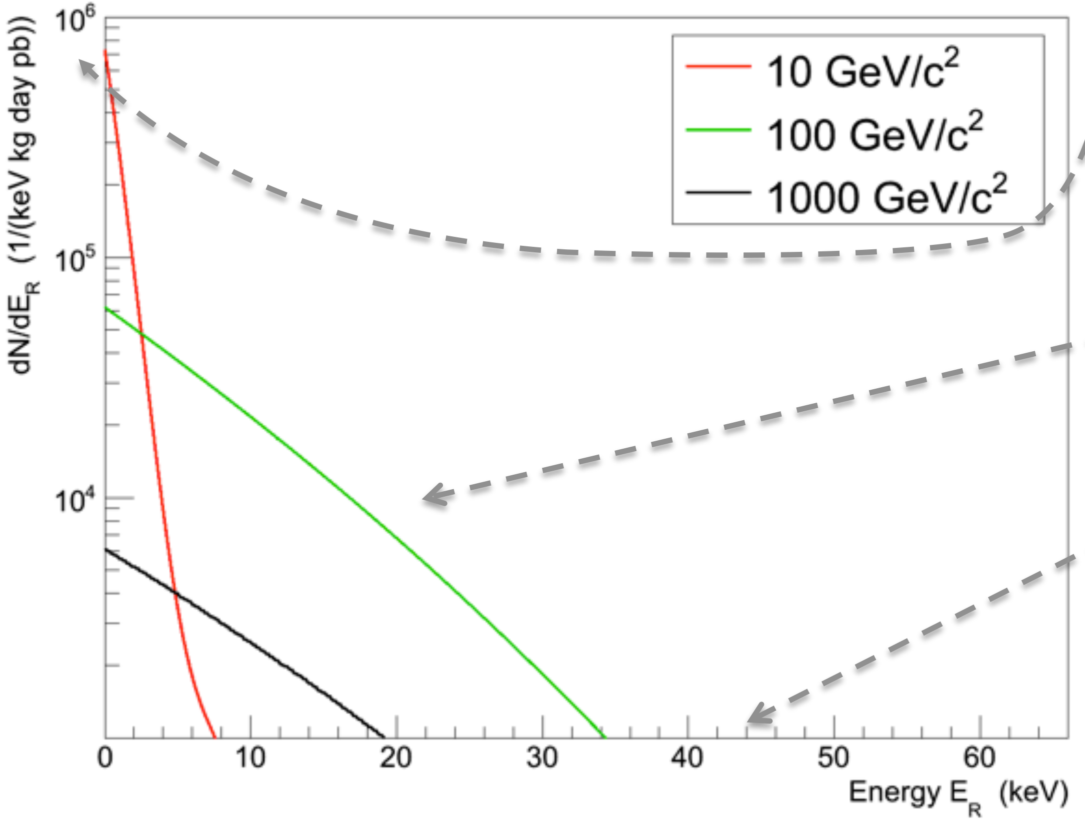


Very rare

current limit*

$\mathcal{O}(0.01)$ counts/tonne day

Featureless spectrum

Small recoil energies

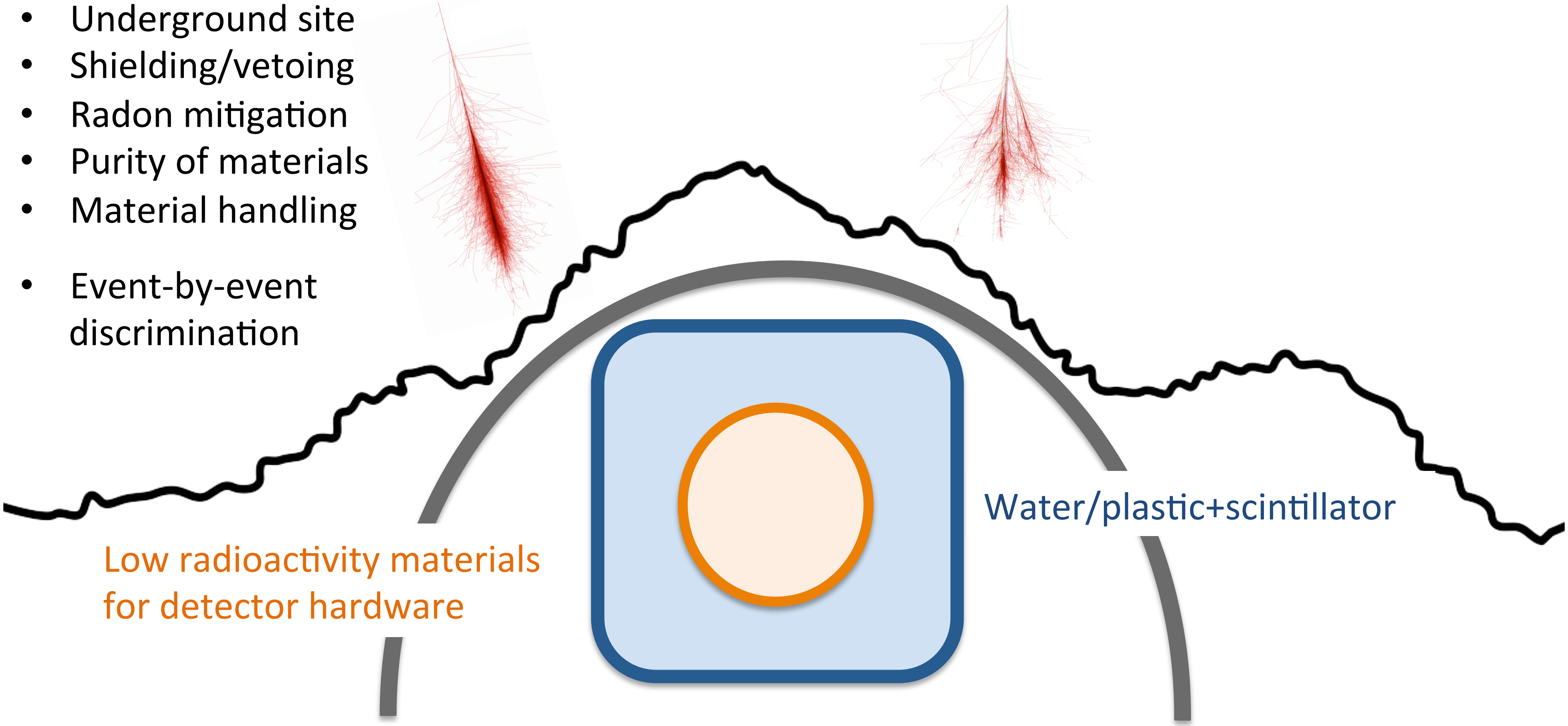
~ keV range

* Xenon1T: arXiv:1805.12562

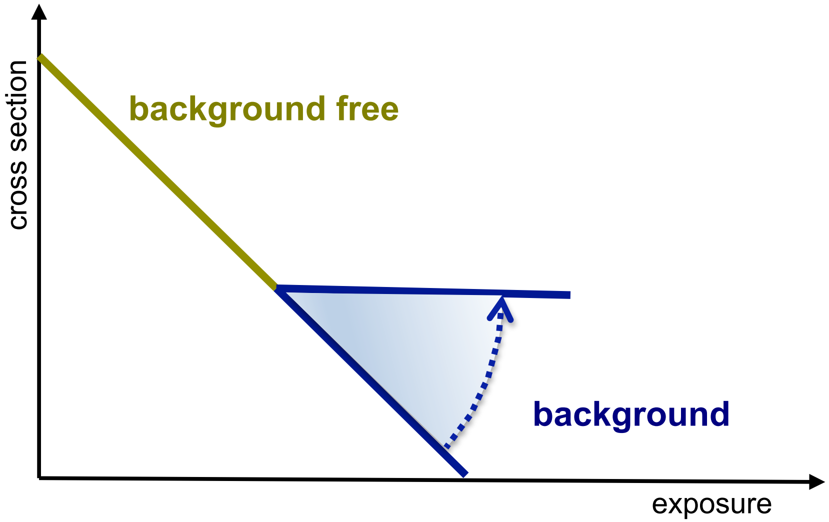
Minimising background

- Underground site
- Shielding/vetoing
- Radon mitigation
- Purity of materials
- Material handling

- Event-by-event discrimination



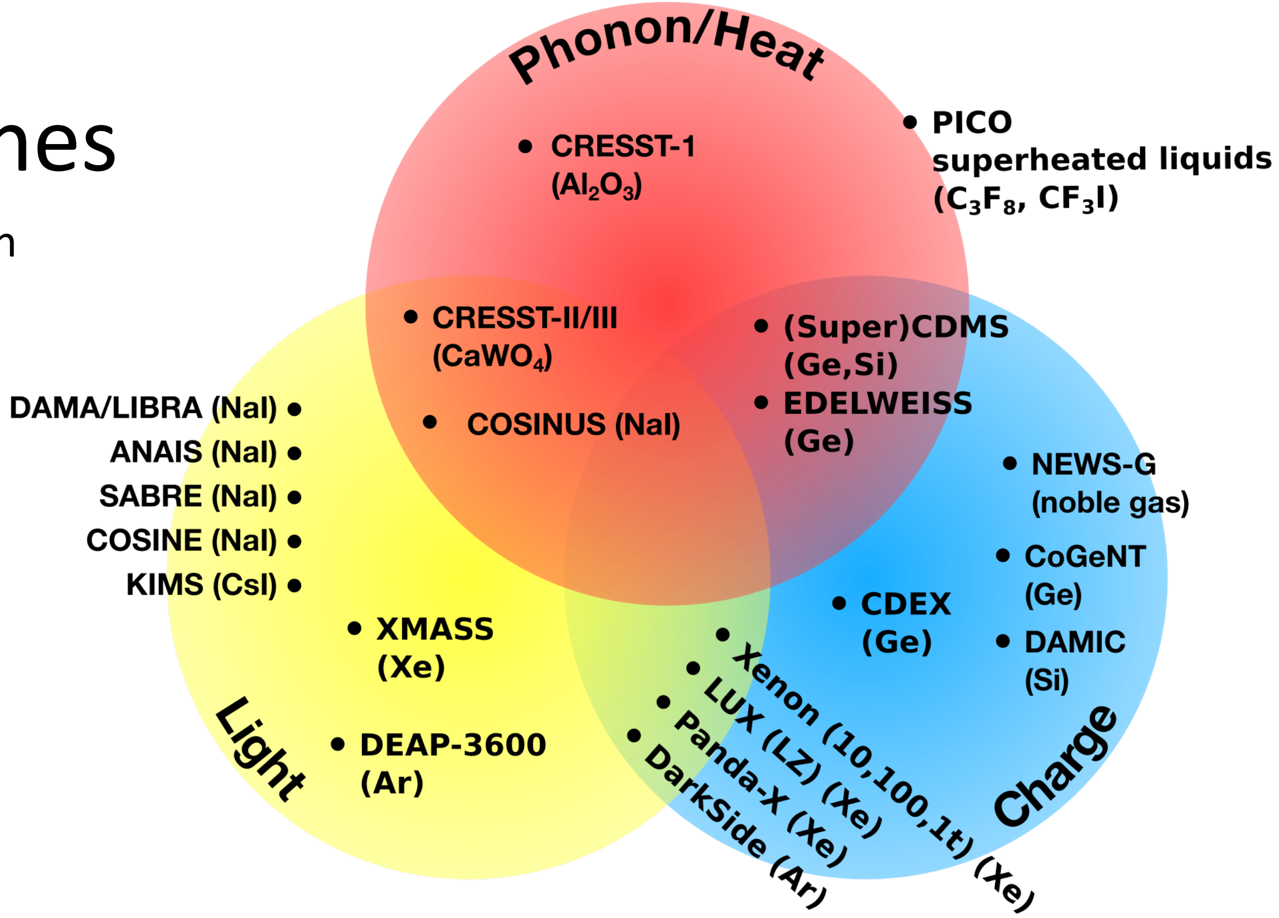
Minimising background



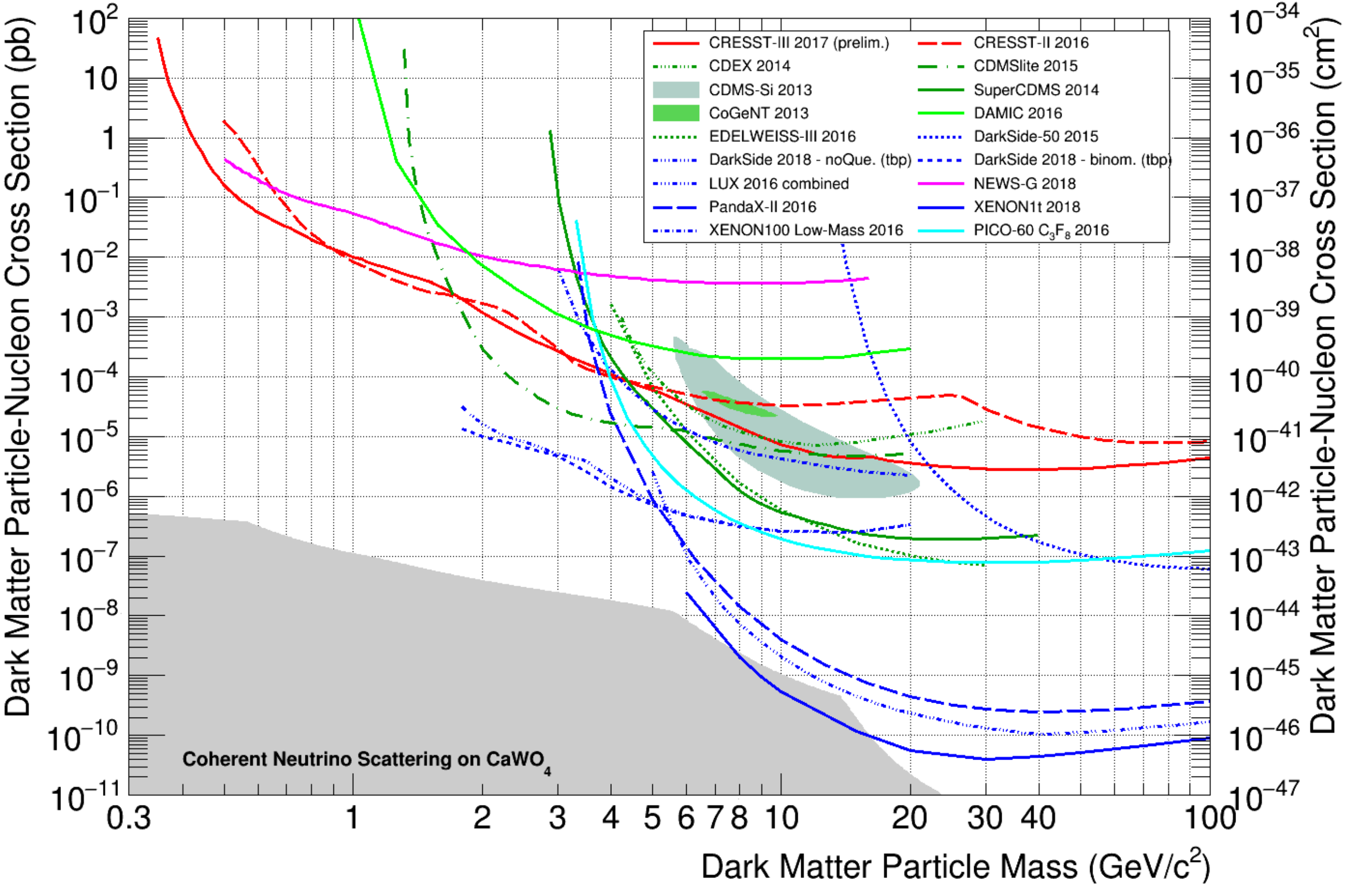
For a discovery:
understand residual background

Direct dark matter searches

An incomplete compilation

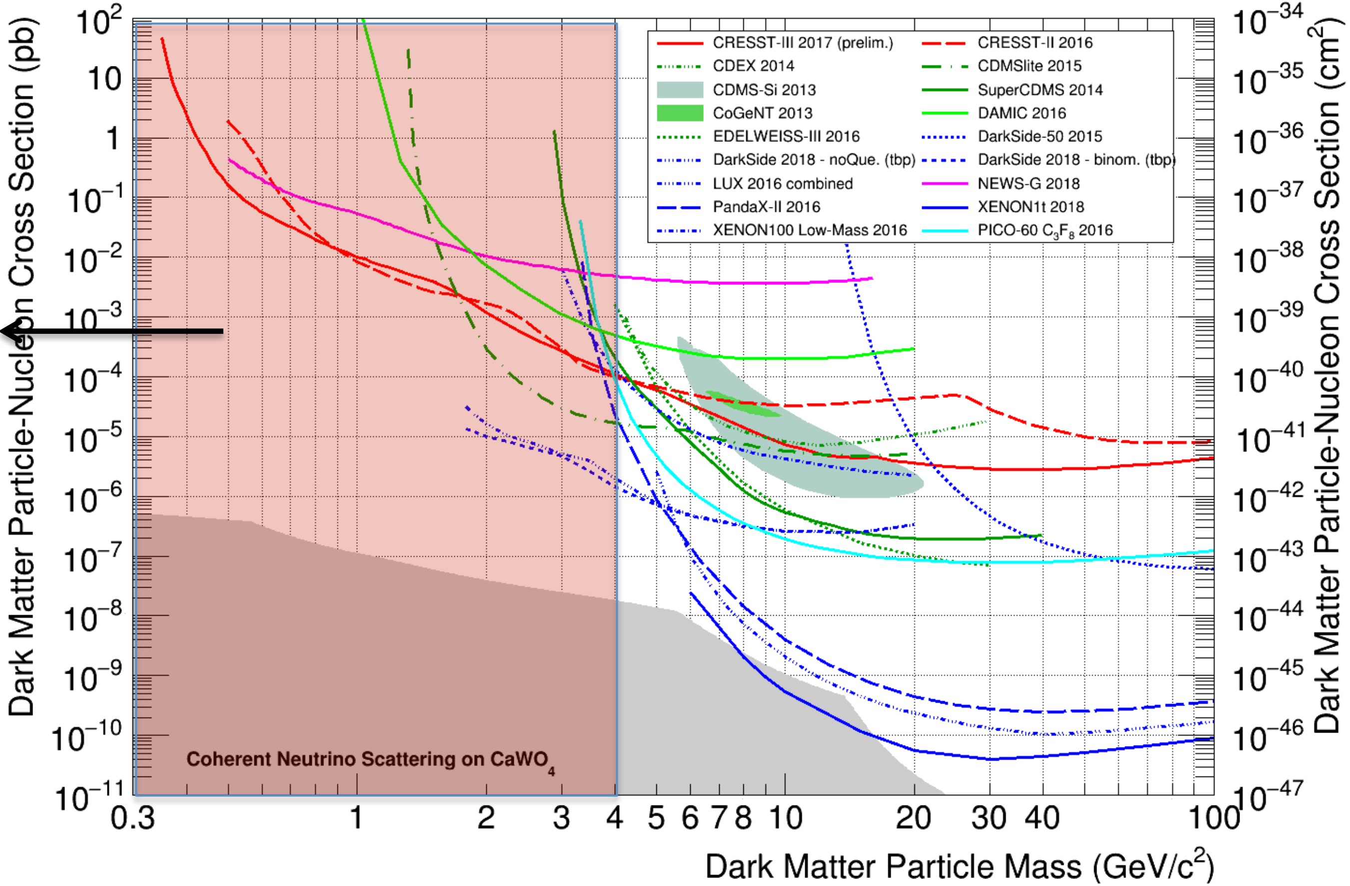


Direct dark matter searches



Direct dark matter searches

Cryogenic detectors, CCDs, He TPCs



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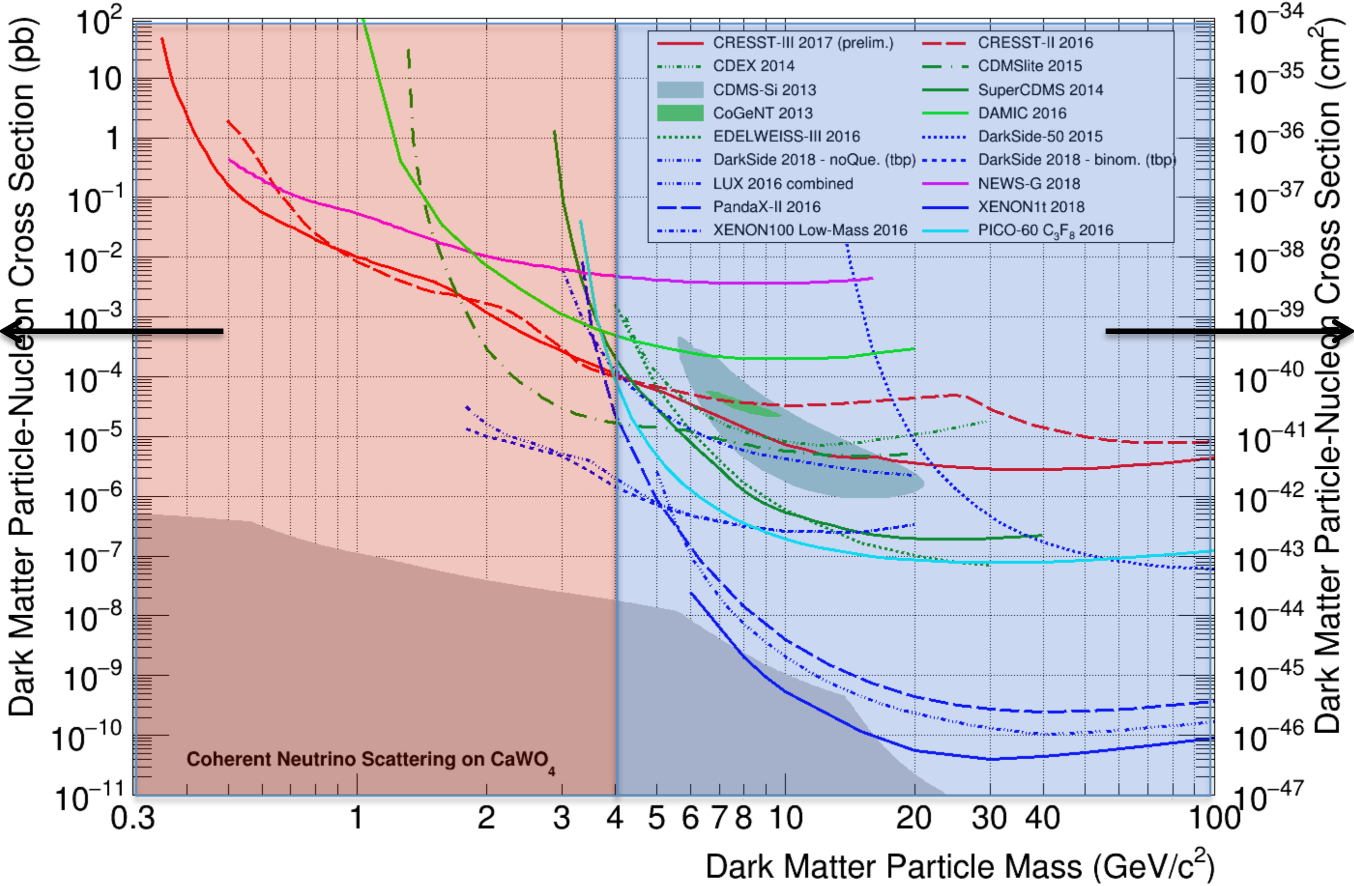
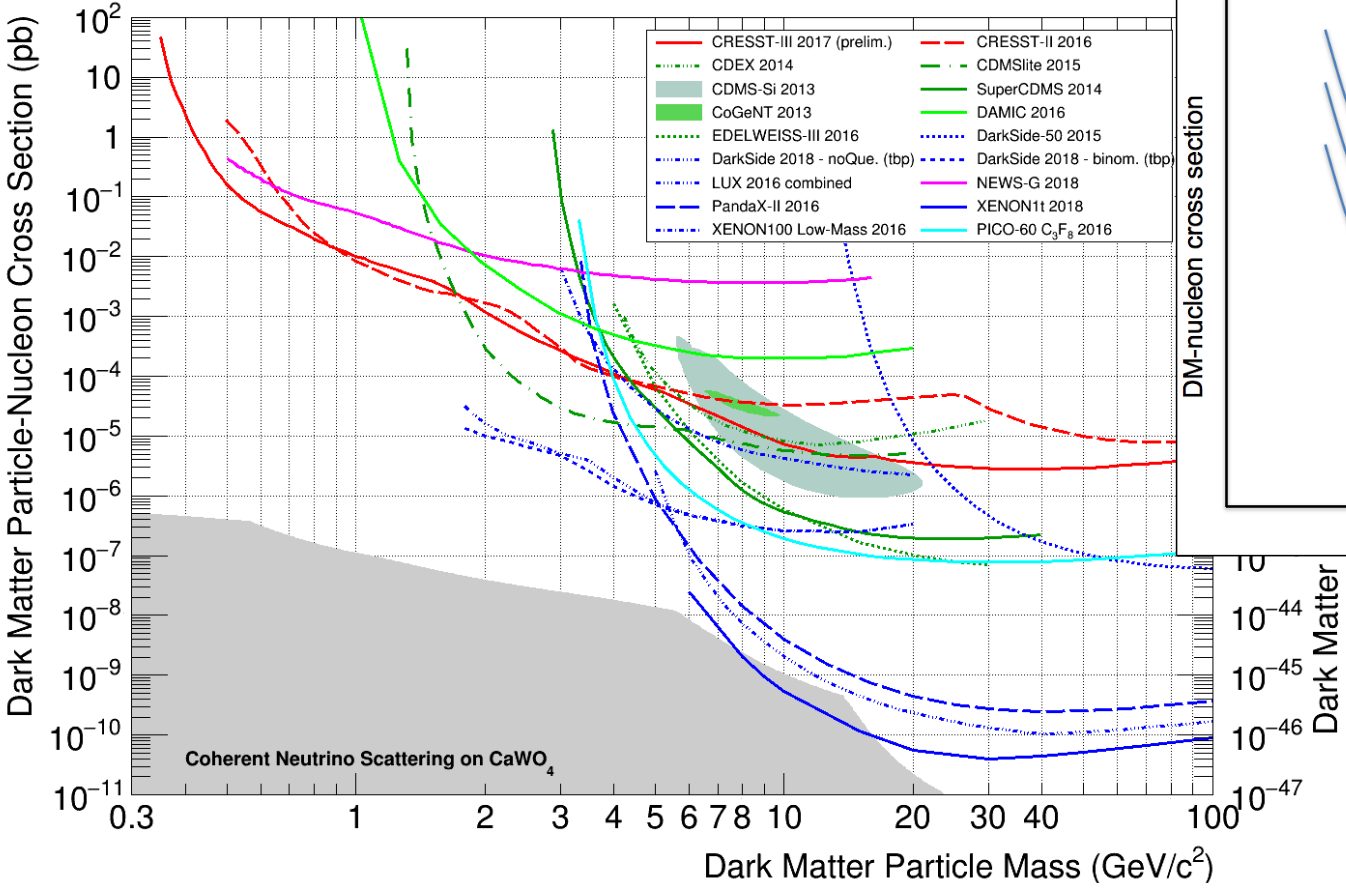
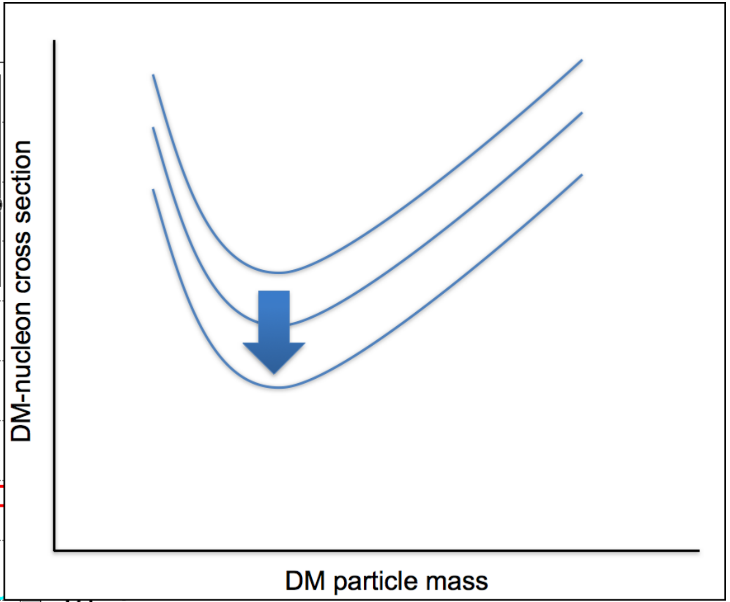


Liquid noble gases (xenon and argon)

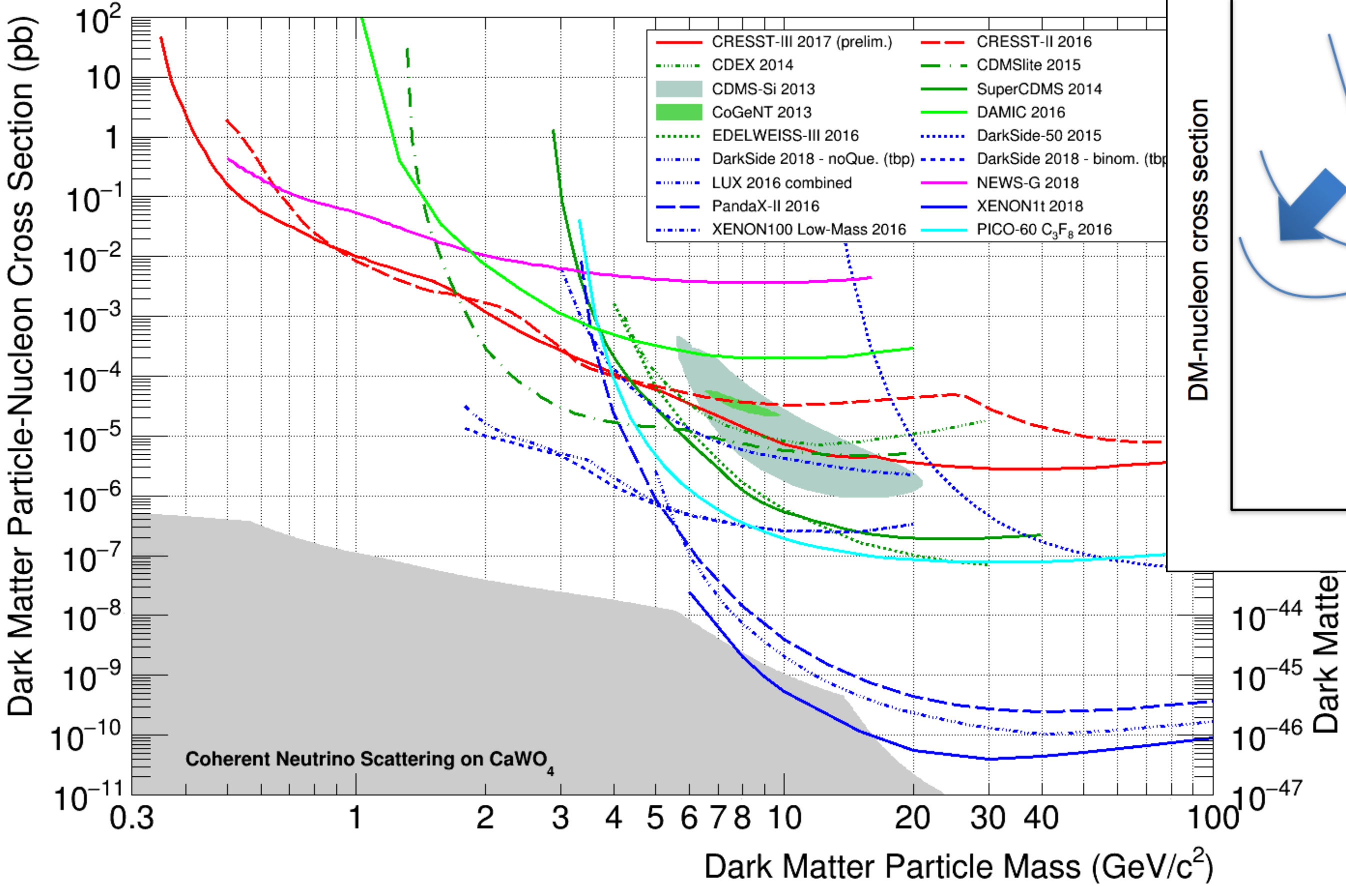
Sensitivity

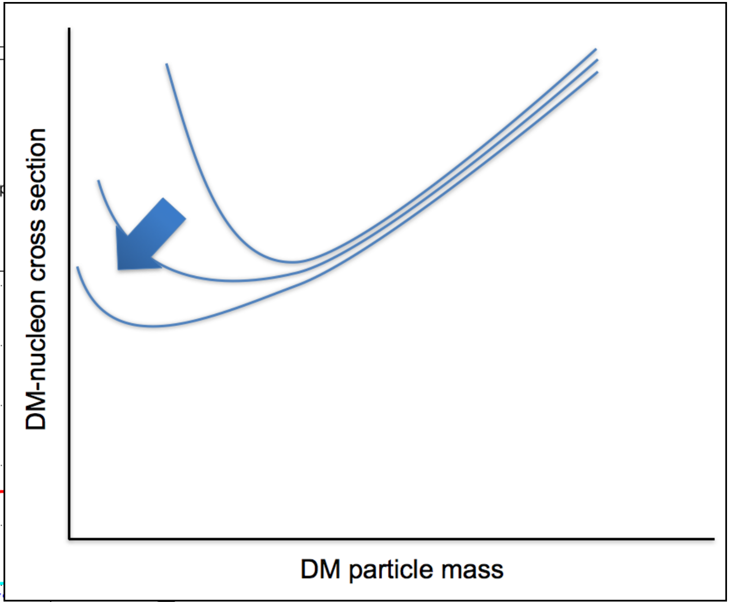




At large DM masses sensitivity is dominated by exposure (target mass)

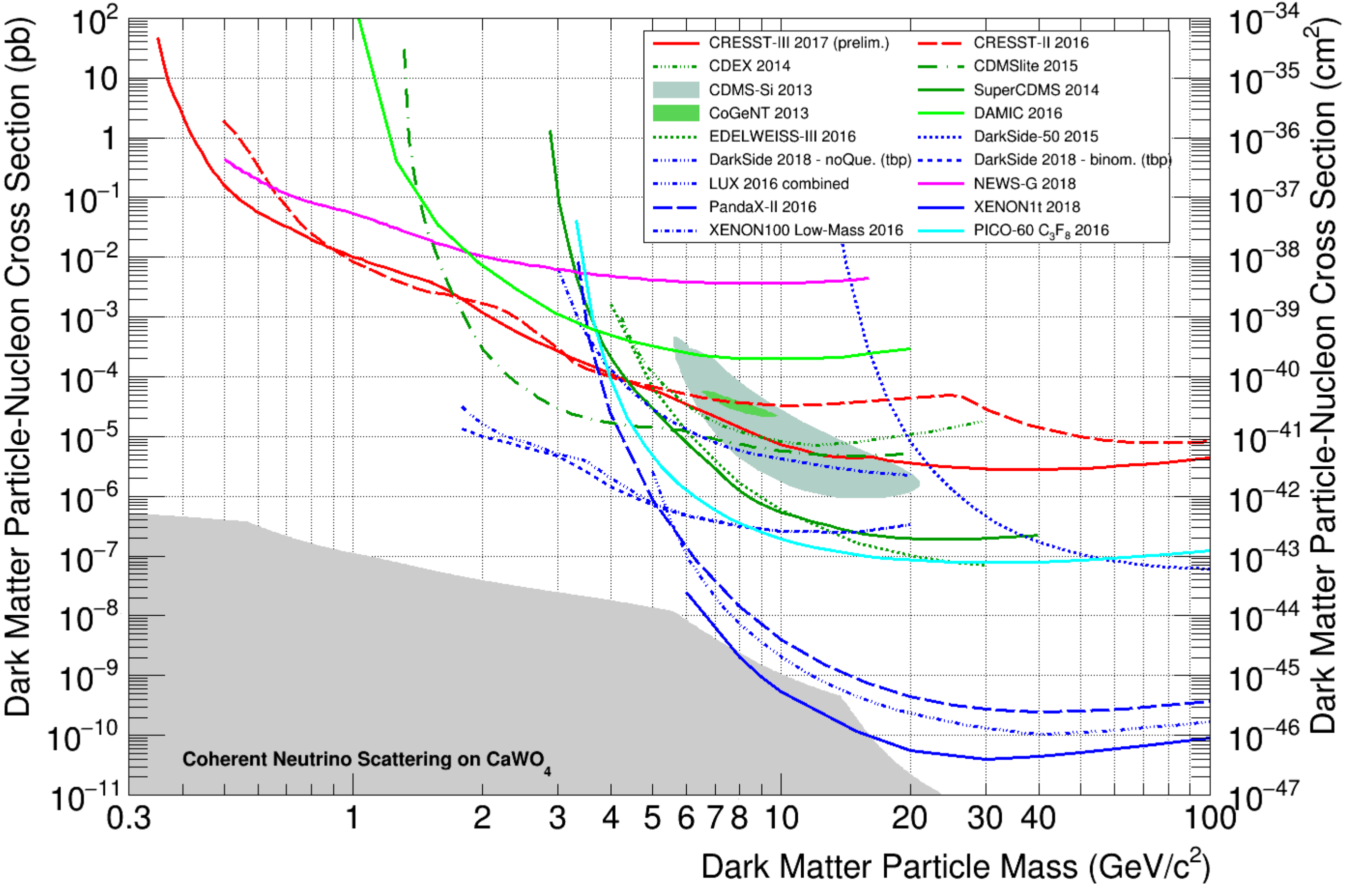
Sensitivity



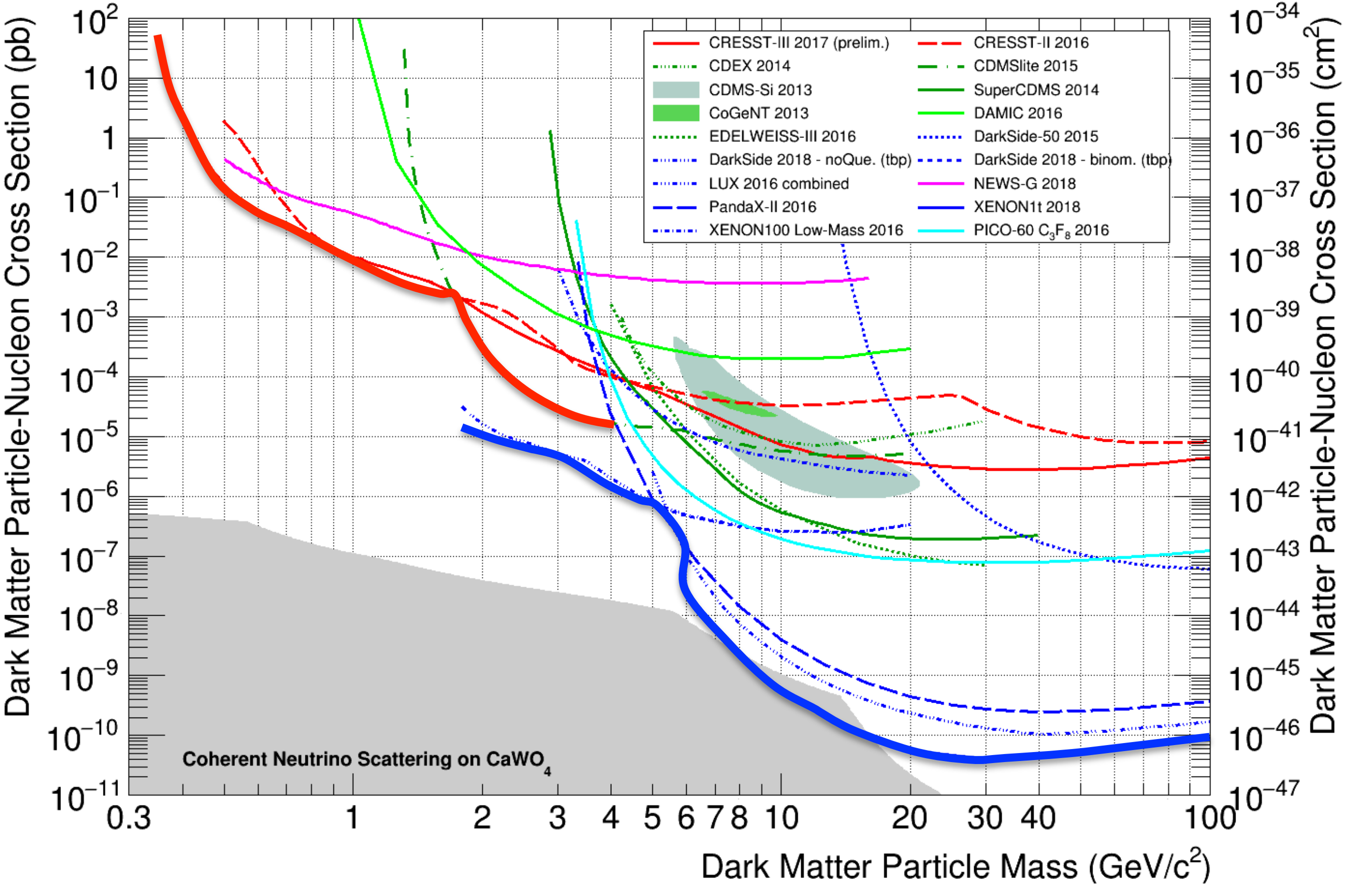


At low DM masses sensitivity is dominated by performances (energy threshold)

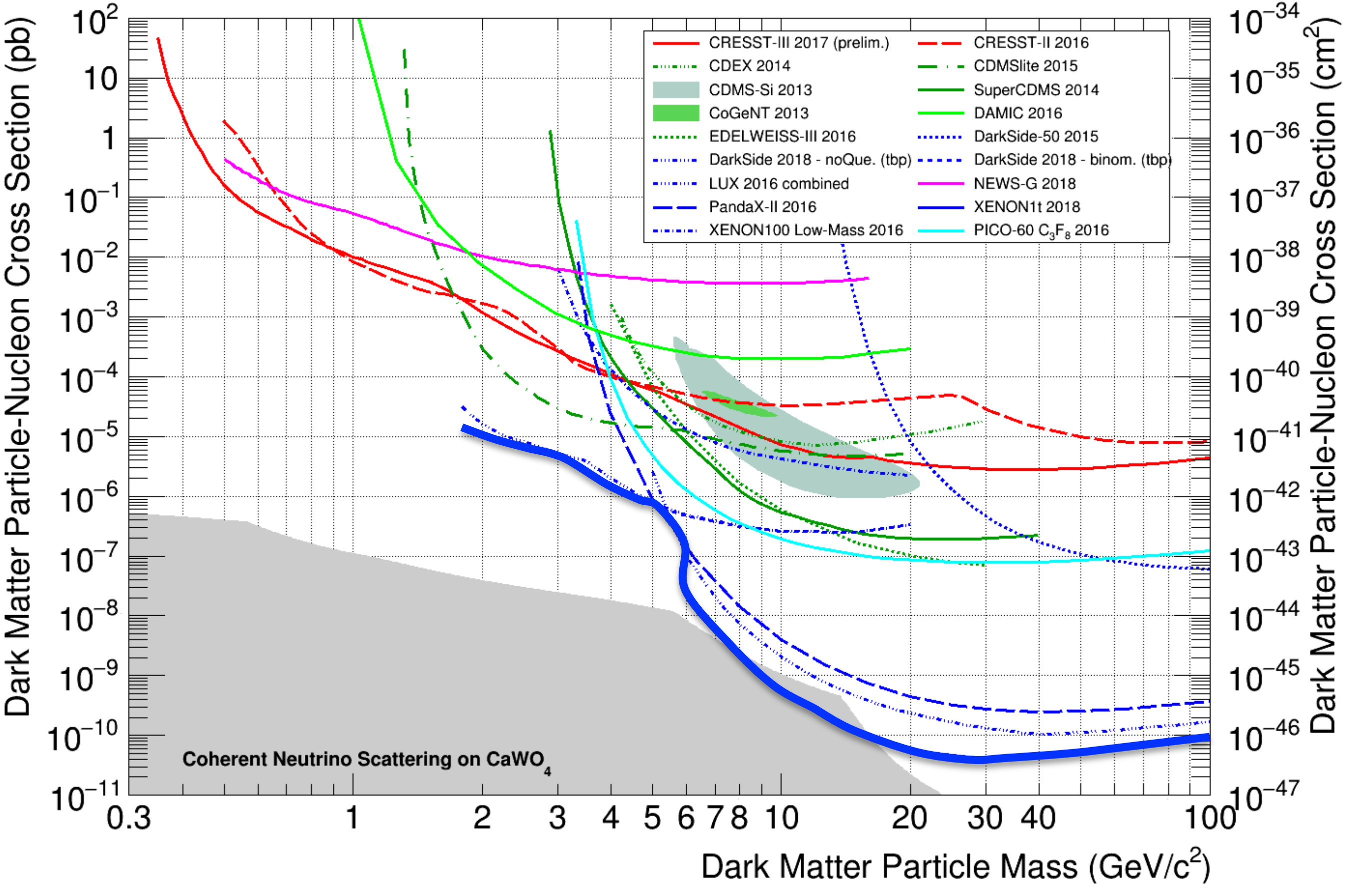
Direct dark matter searches



Direct dark matter searches



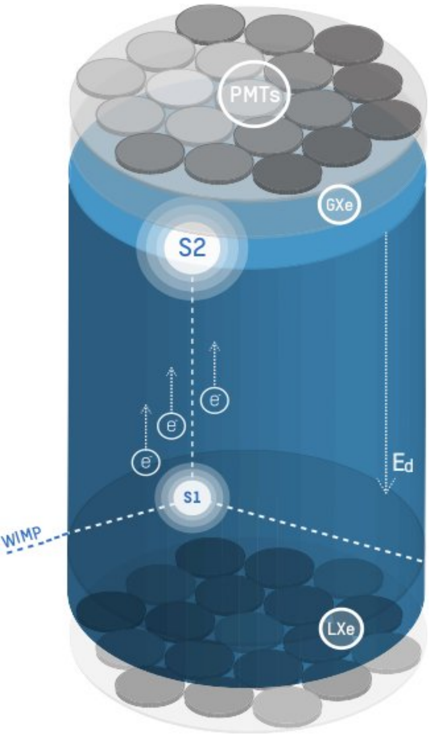
Direct dark matter searches

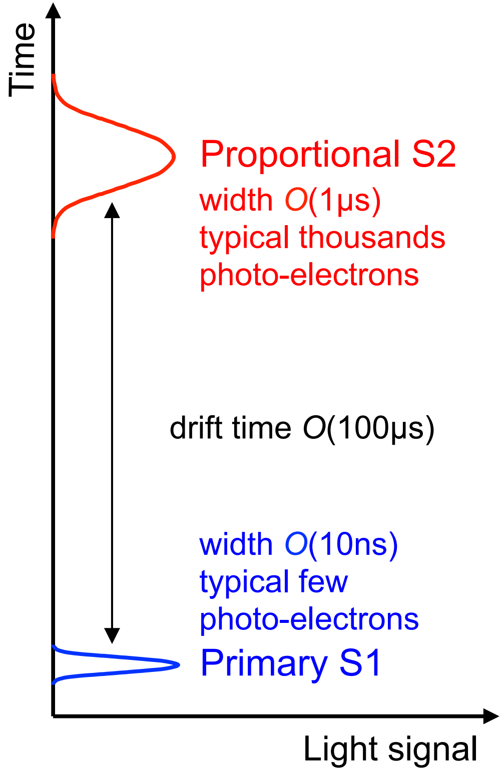


Liquid Noble Gas Experiments

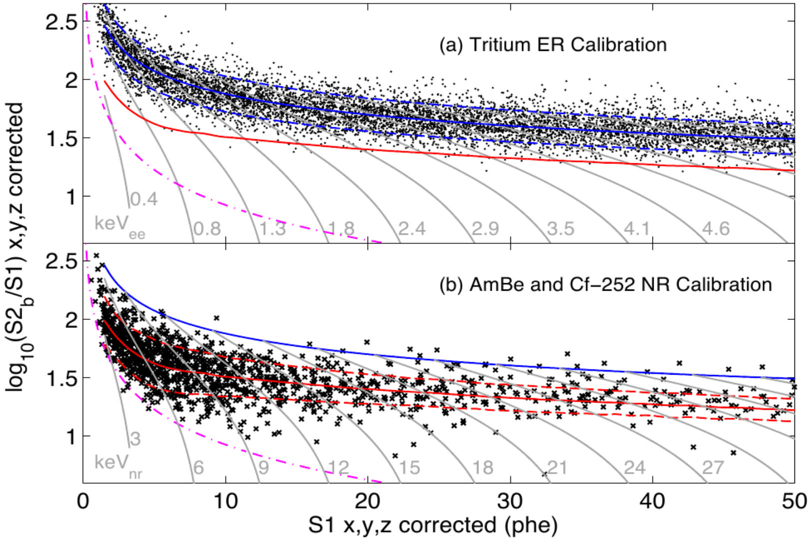
Dual Phase - TPC

LUX/LZ, XENON, PandaX, DarkSide, ArDM





- XY from top PMT array (few mm)
- Z from timing difference (fraction of mm)
- S2/S1 different for nuclear recoils and electrons recoils



Liquid Noble Gas Experiments

Pros:

- Fiducialization (self-shielding)
- Scalable to large target masses
  - long attenuation length (nominally transparent, depends on impurities)
  - long charge drift length (requires significant engineering for purification and high voltage)
- Constant purification

Cons:

- "Rather high" energy thresholds
  - few keV for nuclear recoils
- Calibration
  - energy scale for nuclear recoils derived from S1 using an independently measured scintillation efficiency

Xe vs. Ar

http://periodictable.com

http://periodictable.com

Pros:
- Heavy
- High liquid density
  - compact detector
- No radioactive isotopes

Cons:
- Low fraction in atmosphere
  - more expensive than natural Ar
- Ineffective pulse shape discrimination

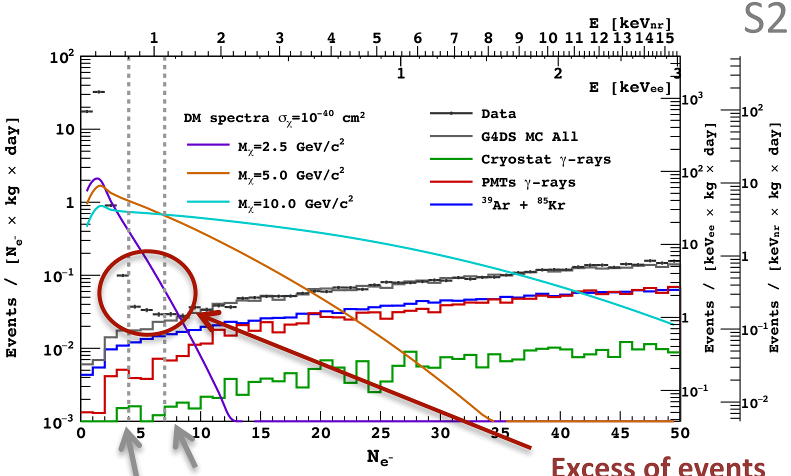
Pros:
- Effective pulse shape discrimination

Cons:
- ^{39}Ar in atmospheric Ar
  - isotopic separation
  - underground Ar

Slide courtesy G. Fiorillo

Ar for low-mass DM

S2-only result



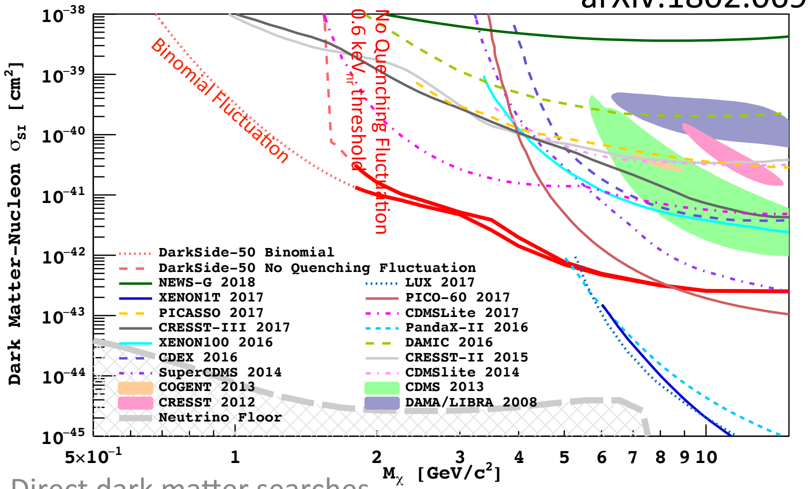
Ionization signal (S2): threshold < 0.1 keV_{ee} / 0.4 keV_{nr}

Sensitive to low mass WIMPs

- Use Ionization (S2) Only.
- PMTs have almost zero dark rate at 88K
- Amplified in the gas region (~23 PE/e^-)
- Sensitive to a single extracted electron
- Radioactivity rate in the detector is remarkably low
- No need of PSD
- The electron yield for nuclear recoils increases at low energy

DS-50 can detect down to **single electron**.

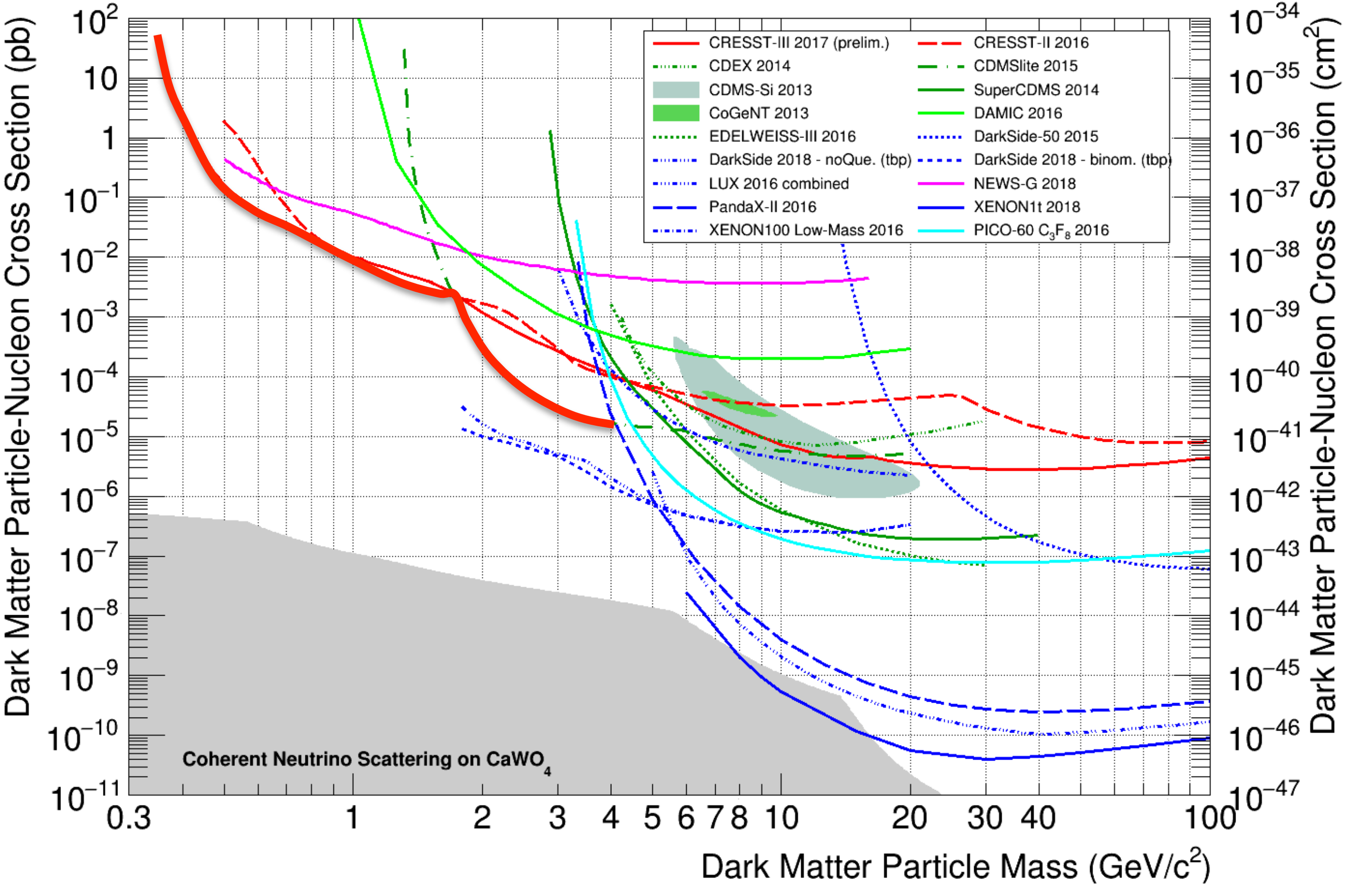
arXiv:1802.06994



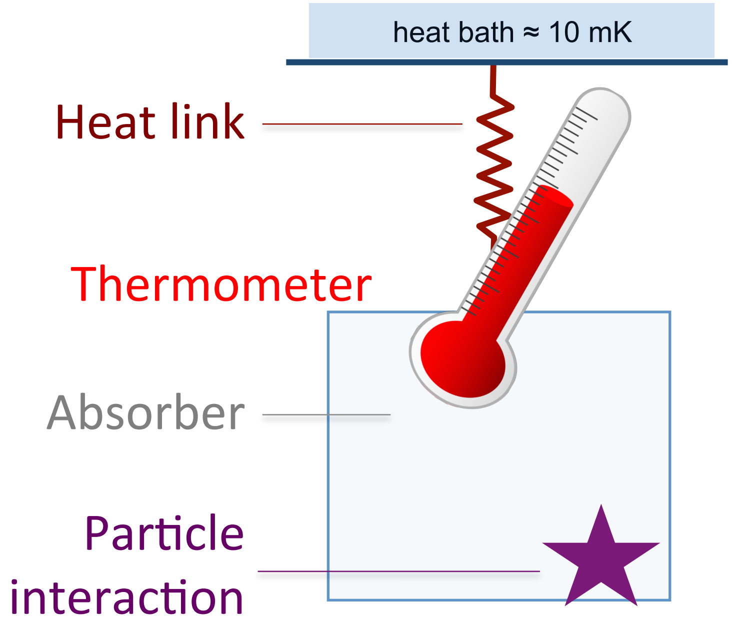
Profile Likelihood Method is used

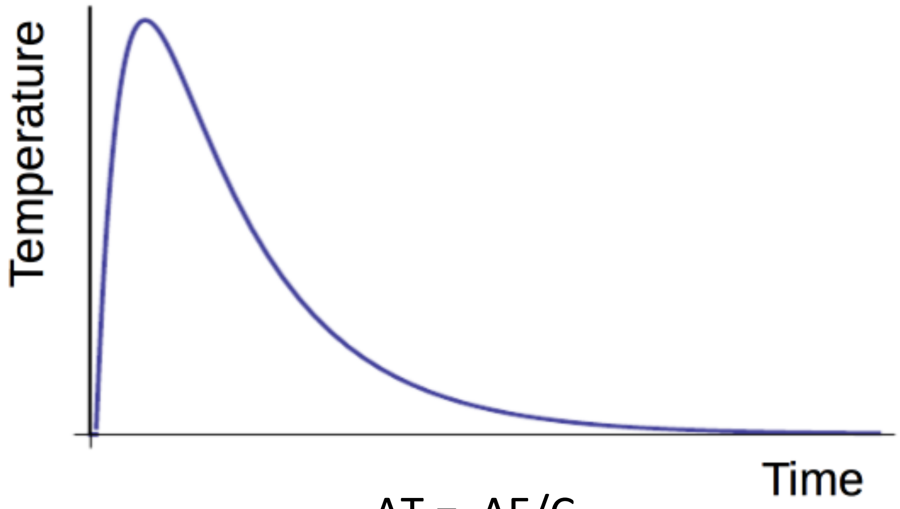
- BG components are fitted at high energy and extrapolated.
- Uncertainties from both WIMP signals (NR ionization yield, single electron yields) and BG spectrum (rates, ER ionization yield) are included.

Direct dark matter searches



Cryogenic calorimeters



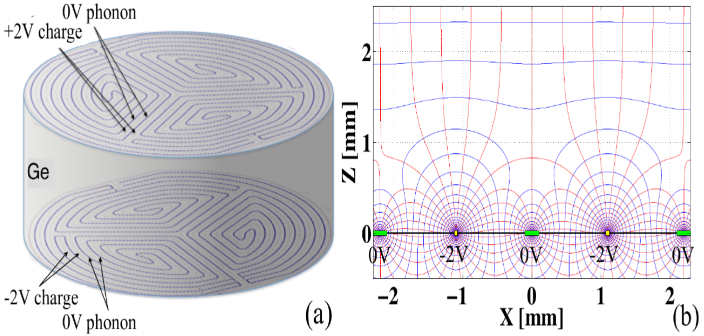


$\Delta T = \Delta E / C$

Semiconducting calorimeters

Phonon + Ionization

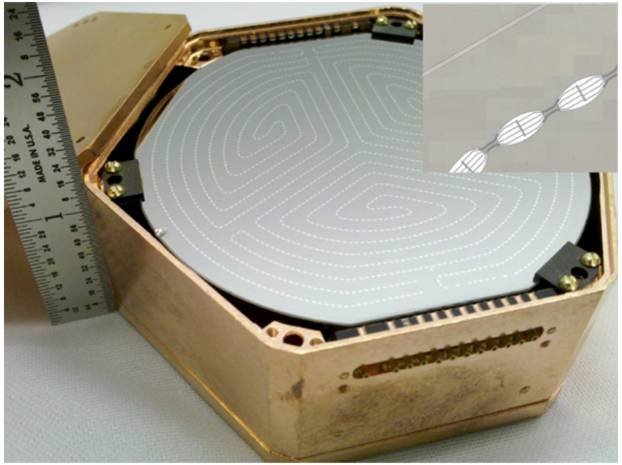
EDELWEISS, CDMS



- Cryogenic temperatures (20-50mK)
- Discrimination of e/γ- events via ionization yield
- Low threshold (sub keV)
- Surface events identified thanks to ID electrodes

CDMS interleaved Z-sensitive Ionization Phonon (iZIP) detector

- 15 x 600g detectors
- 2 charge + 2 charge
- 4 + 4 TES – fast phonon channel

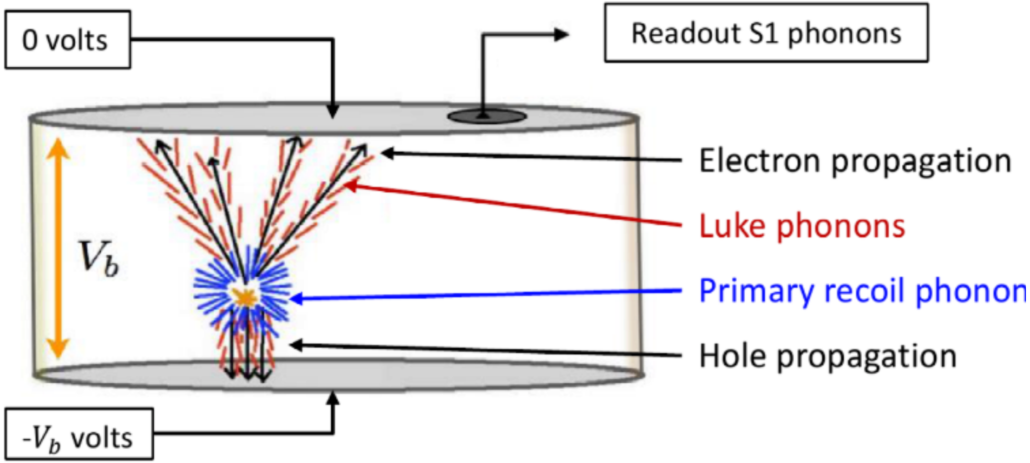


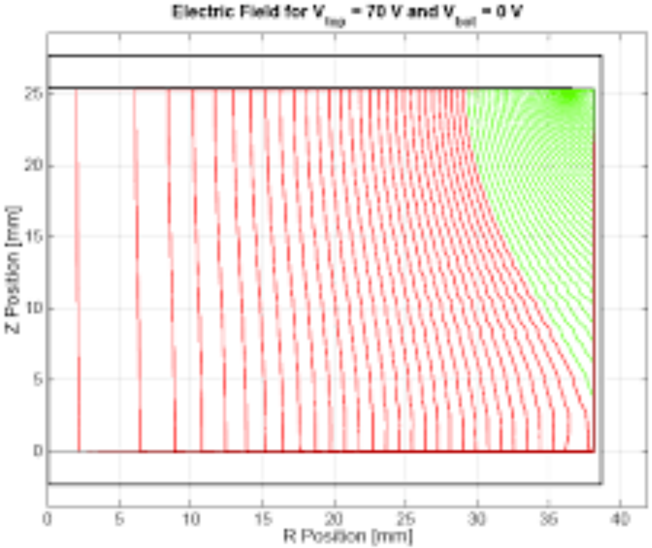
Pictures courtesy of the CDMS collaboration

Semiconducting calorimeters

Lite-mode

Charge mediated phonon amplification (Neganov-Trofimov-Luke Effect)





- Drifting charges produce large phonon signal proportional to ionization
- Electron recoils much more amplified than nuclear recoils
  - gain in threshold AND dilute background from electron recoil events

NTL effect mixes charge and phonon signal reducing discrimination
Requires Lindhard Model to convert to nuclear recoil equivalent energy

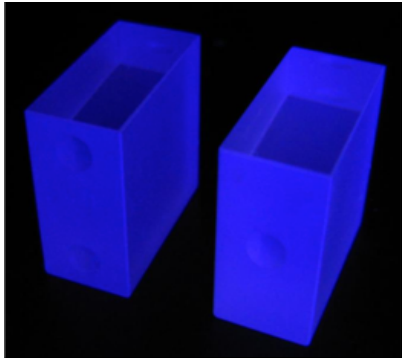
Pictures courtesy of the CDMS collaboration

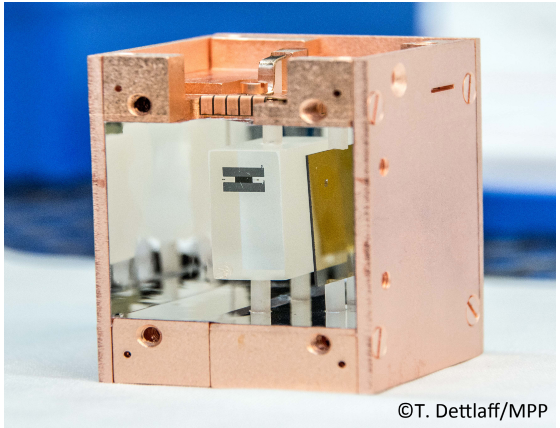
Scintillating calorimeters

Phonon + Light

CRESST

- Scintillating $CaWO_4$ crystals as target
- Cryogenic temperatures *O*(10mk)
- Separate cryogenic light detector to detect the scintillation light signal
- Discrimination of e/γ- events via light yield
- Multi element target
- Low threshold (sub keV)





Energy deposition in a detector module:

- mainly phonons (independent of the type of particle)

→ **Measurement of deposited energy**

- few % into scintillation light (characteristic of the type of particle)

→ **Particle discrimination**

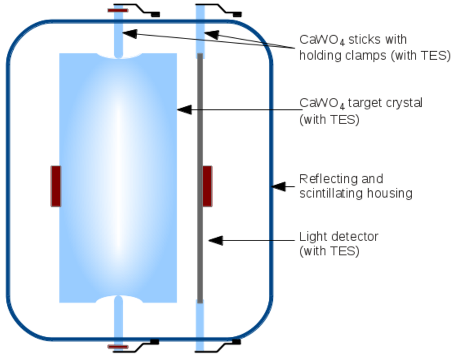
Scintillating calorimeters

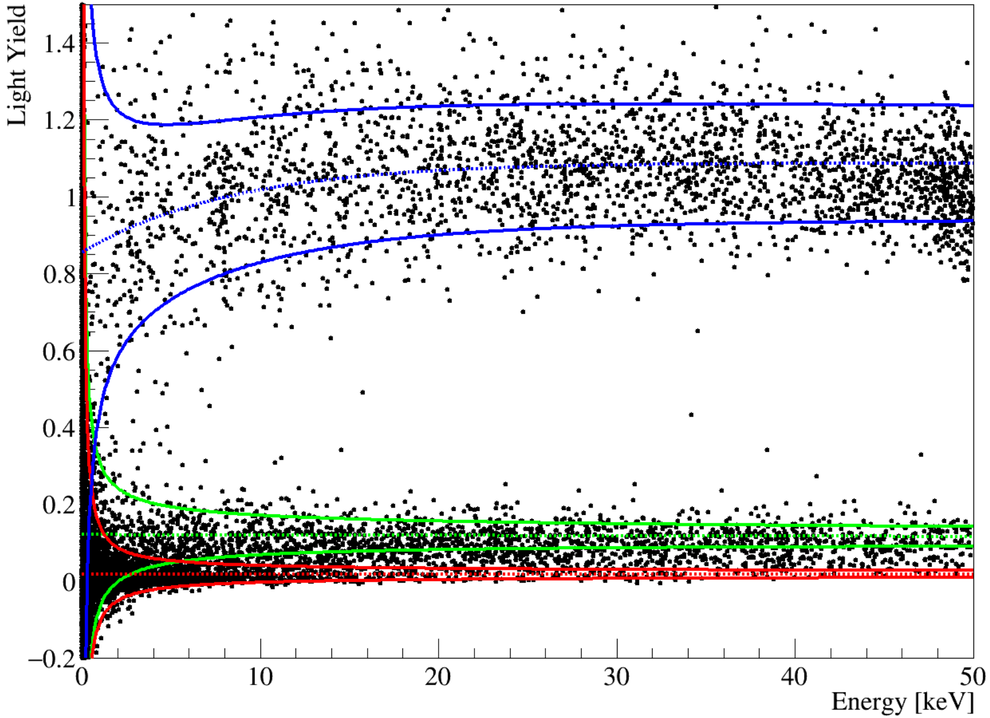
Phonon + Light

CRESST

$$\text{Light Yield} = \frac{\text{Light signal}}{\text{Phonon signal}}$$

Excellent discrimination between potential signal events (**nuclear recoils**) and dominant radioactive background (**electron recoils**)





Calorimeters

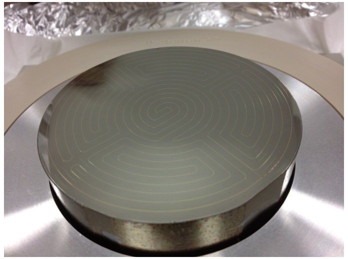
Pros:

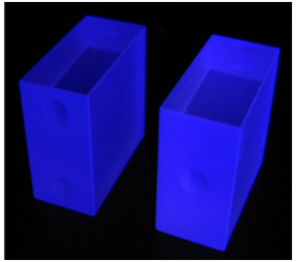
- Total energy measurement
  - Phonon signal (almost) not quenched
- Excellent energy resolution
  - Detailed study of dark matter signal
  - Detailed study of background sources
- Low threshold (sub-keV for nuclear recoils)

Cons:

- Small detectors (*O*(few 100g))
  - Small exposures
- Difficult technology

Semiconductors vs. scintillators





Pros:

- Ultrapure material
- Identification of surface events
    - Fiducialization

Cons:

- Limited choice of materials
- In lite-mode require Lindhard model to derive energy scale of nuclear recoils

Pros:

- Total energy measurement at low threshold
- Large choice of material
    - Multi element target
- No surface effects (in selected materials)

Cons:

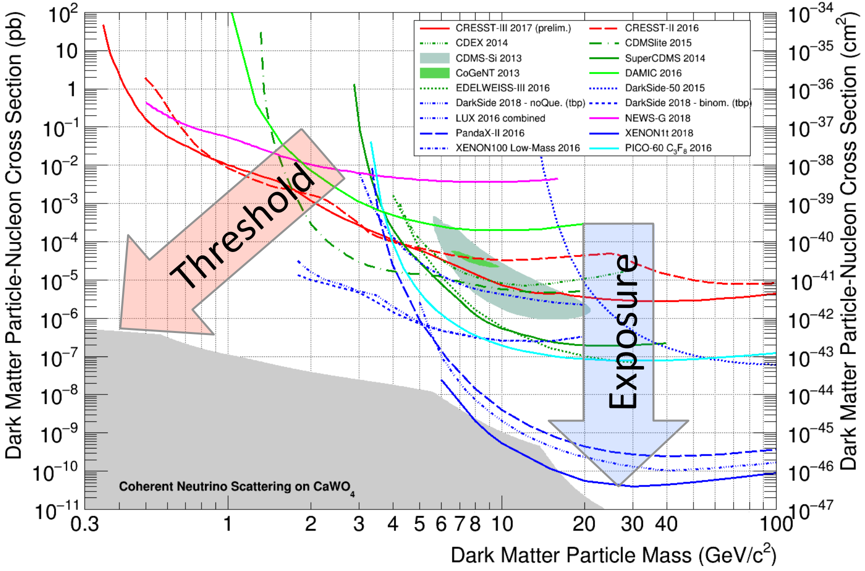
- Independent cryogenic light detector to detect the scintillation light signal
    - Increase number of channels
- Non-commercial materials

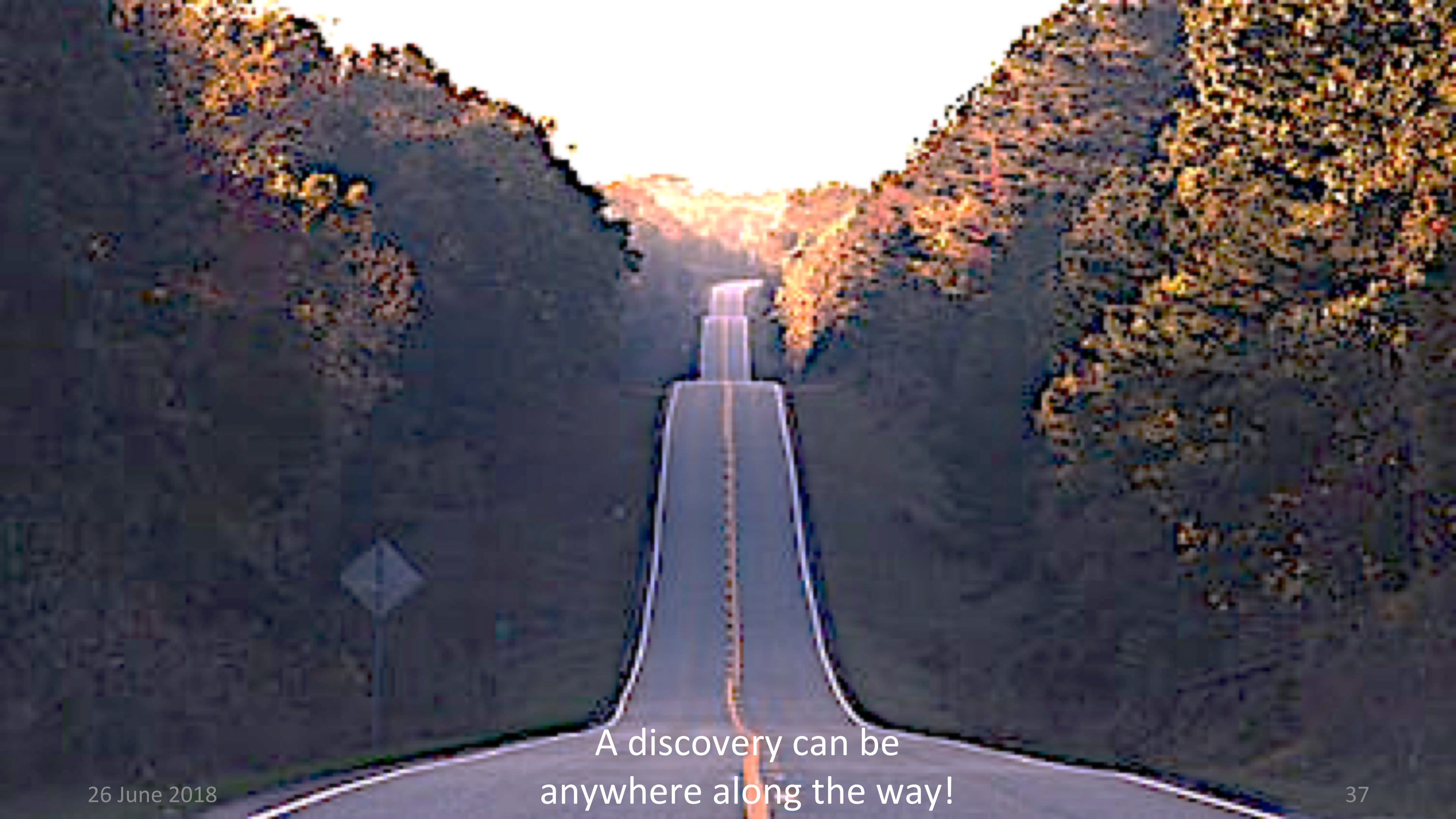
Conclusions

What's up with dark matter?

Detectors racing to the neutrino floor

- Large detector mass to collect large exposures
  - Dual phase liquid noble gas detectors still advantageous?
  - Technological challenge of large scale cryogenic detectors affordable?
- Fight emerging backgrounds
  - Directional detectors?
  - Multiple targets and technologies?





A discovery can be
anywhere along the way!

More material to follow

Differential interaction rate

$$\frac{dR}{dE_r} = \frac{\sigma_0}{m_\chi} \frac{F^2(E_r)}{\mu^2} \frac{\rho_\odot T(E_r)}{v_\odot \sqrt{\pi}}$$

counts per kg, day and keV recoil energy Er

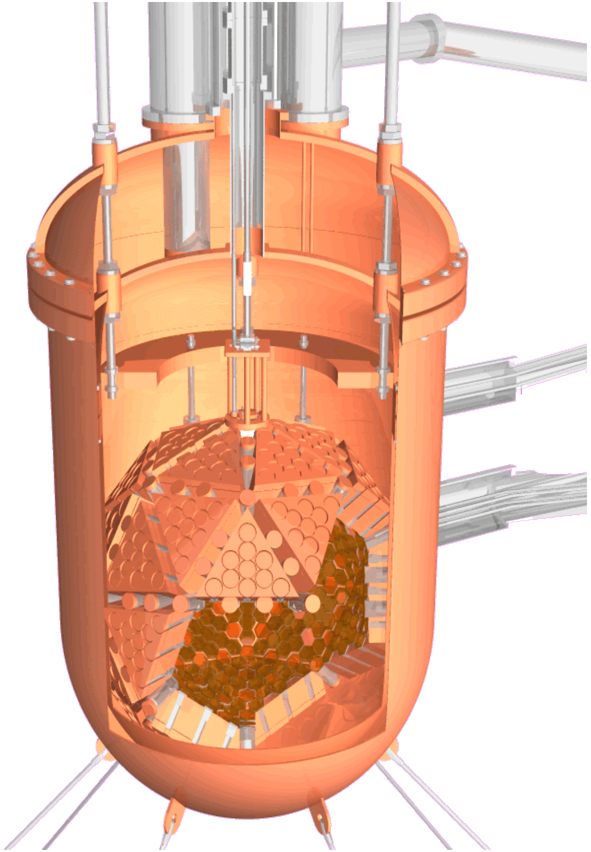
σ_0	interaction cross section at zero momentum transfer
m_χ	dark matter particle mass
$F(E_r)$	nuclear form factor
$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$	reduced mass
$T(E_r) = \frac{\sqrt{\pi}}{2} v_\odot \int_{v_{min}}^{v_{esc}} \frac{f_1(v)}{v} dv$	integral over local dark matter velocity distribution
$v_{min} = \sqrt{\frac{E_r m_N}{2\mu^2}}$	minimal velocity to produce a recoil of given energy E_r

Liquid Noble Gas Experiments

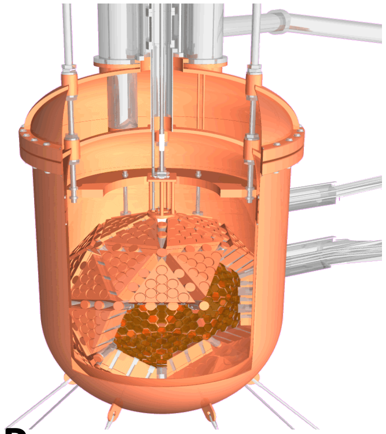
Single Phase - 4π scintillation

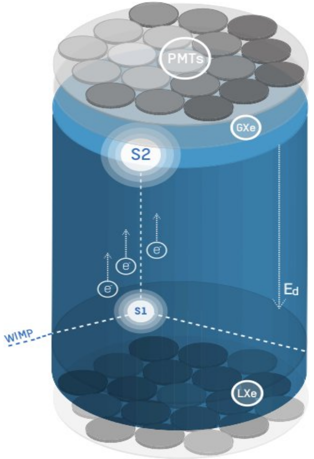
DEAP, MiniClean, XMASS

- Self shielding
- Discrimination of e/γ- events possible via pulse shape



Single phase vs. dual phase





Pros:

- "Simple" detectors
- High light yield
  - For Ar pulse shape discrimination

Cons:

- For Xe less information per event
- Bad space resolution
  - Heavy fiducialization for self shielding

Pros:

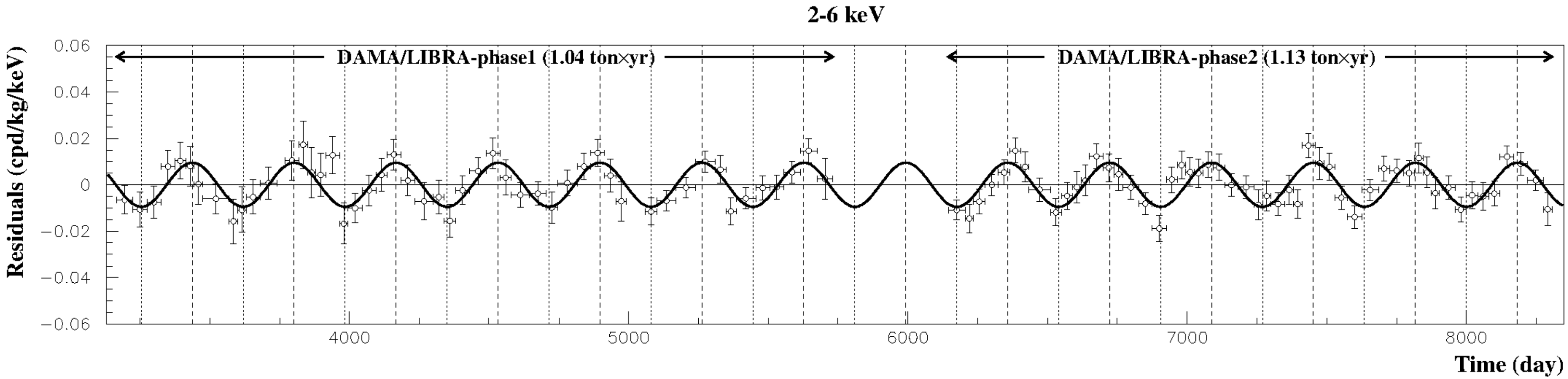
- ER vs. NR discrimination from S2/S1
- Good space resolution
  - Large fiducial volume

Cons:

- Reduced light yield
  - Worse pulse shape discrimination (require depleted Argon)
- "Complicated" detectors

DAMA/LIBRA

Experimental residuals of the single-hit scintillation events rate vs time and energy



- 250kg of NaI(Ti) with PMTs (scintillation light)
- DAMA/LIBRA Phase 1 + 2 : 2.17 tonne years
- Statistical significance: 11.9σ
- Model independent
- Excluded by other DM searches

DAMA/LIBRA

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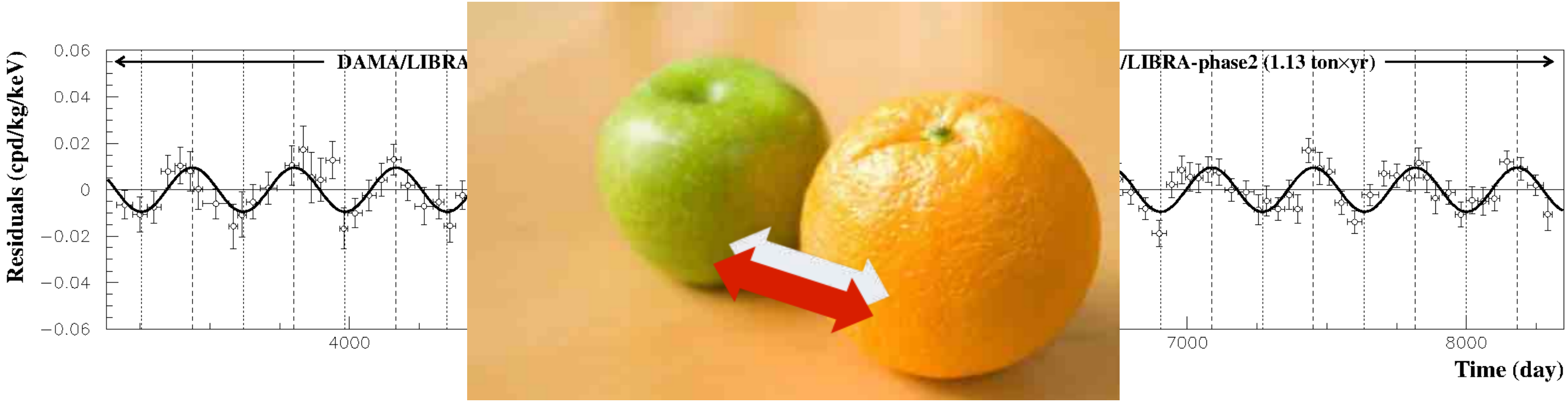


- 250kg of NaI(Ti) with PMTs (scintillation light)
- DAMA/LIBRA Phase 1 + 2 : 2.17 tonne years
- Statistical significance: 11.9σ
- Model independent
- Excluded by other DM searches under standard assumptions

DAMA/LIBRA

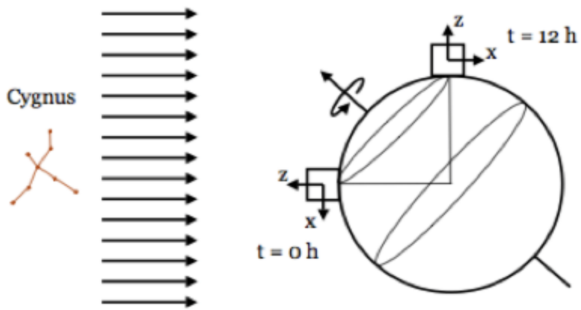
Only possible strategy:

- Modulation with NaI
    - Sabre (NaI in liquid scintillator veto) KIMS, DM-Ice, ANAIS

- NaI with different technology
    - COSINUS (cryogenic scintillating calorimeter)

Gas directional

MIMAC, DRIFT, DMTPC

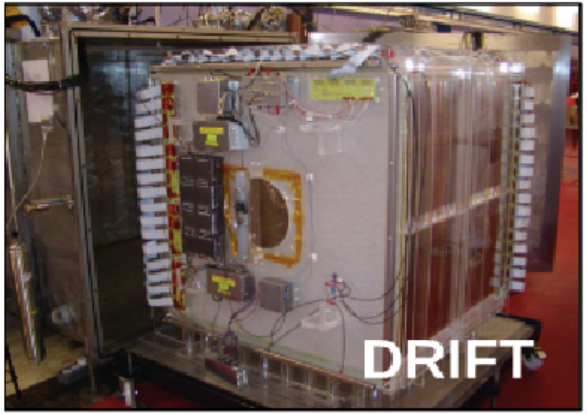


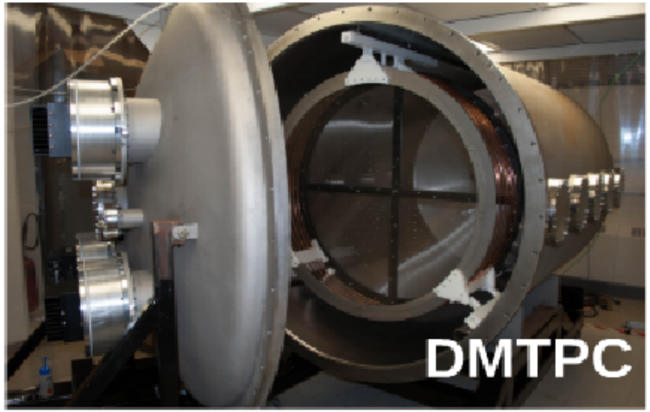
Pros:

- Strong day/night modulations expected
- Low pressure TPC's CF_4, CS_2.....
- Powerful background rejection
- Important to consolidate signals

Cons:

- Up to now small mass (100g)
- Huge detector volumes required > 1000 m^3

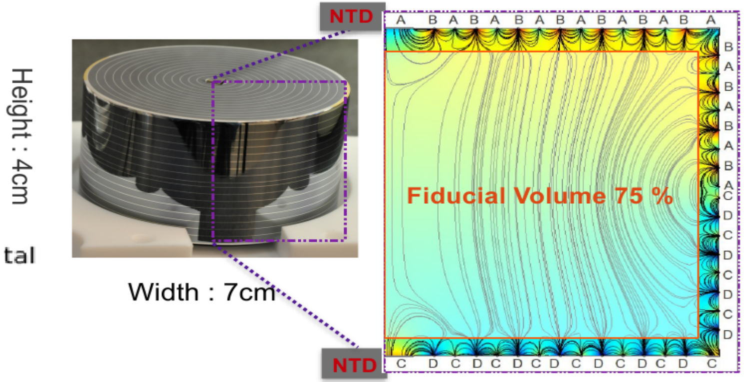




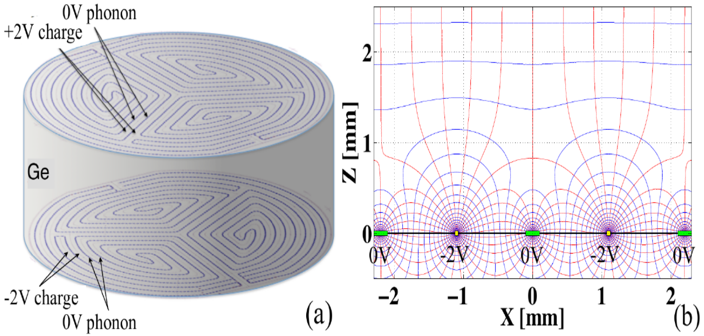
Semiconducting calorimeters

Phonon + Ionization

EDELWEISS, CDMS



Pictures courtesy of the EDELWEISS collaboration



Pictures courtesy of the CDMS collaboration

EDELWEISS

- 36 x 800 g detectors
- 2 charge + 2 charge
- 2 NTD – simple phonon channel

CDMS interleaved Z-sensitive Ionization Phonon (iZIP) detector

- 15 x 600g detectors
- 2 charge + 2 charge
- 4 + 4 TES – fast phonon channel

Ge/Si Detectors

Ionization only

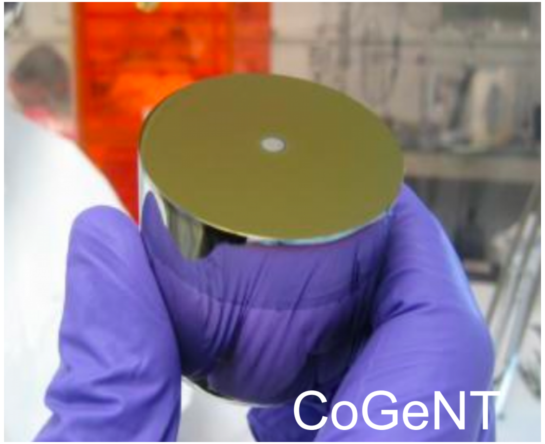
CDEX, CoGeNT

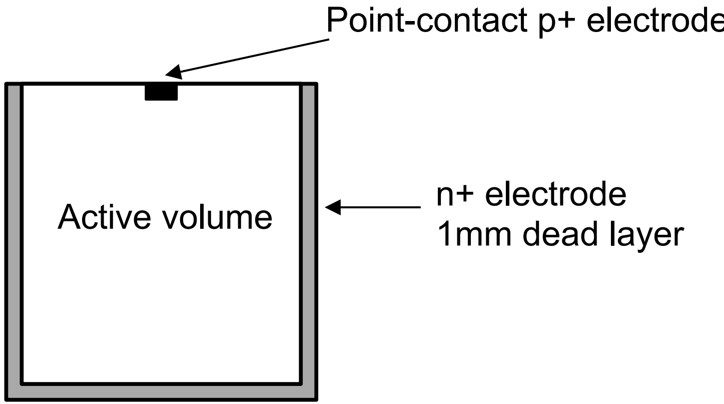
Pros:

- P-type Point-Contact (P-PC) detector
- Position reconstruction via signal rise time
- Low intrinsic background
- <200eV$_{ee}$ threshold

Cons:

- No discrimination of e/γ- events
- Dead layer
- Energy scale for nuclear recoils requires model

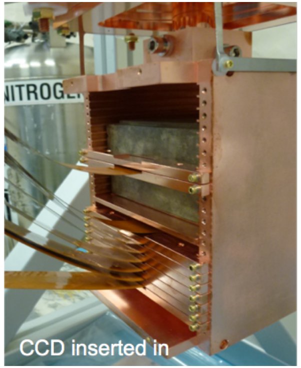


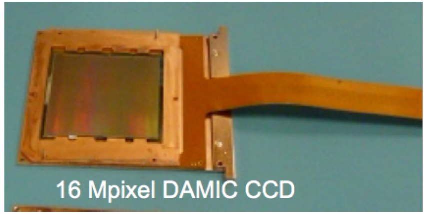


DArk Matter In CCDs

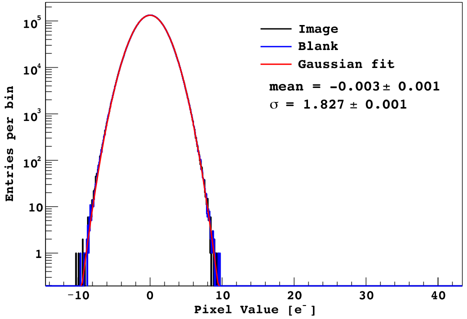
Material courtesy P. Privitera

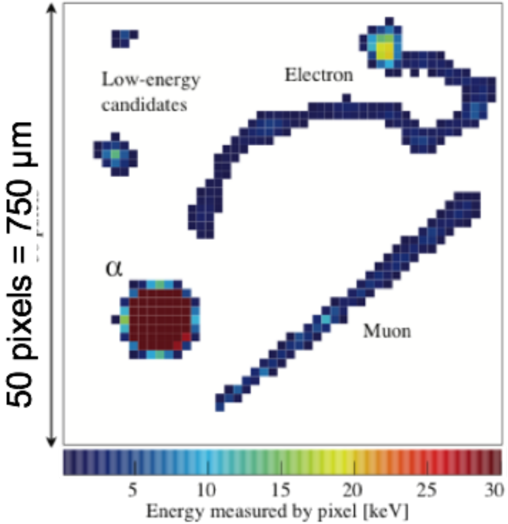
High resistivity, fully depleted, ≈ 40 cm^2, 675 µm world-thickest CCDs





Very low energy threshold (≈ 50 eVee)
→ sensitive to low mass dark matter



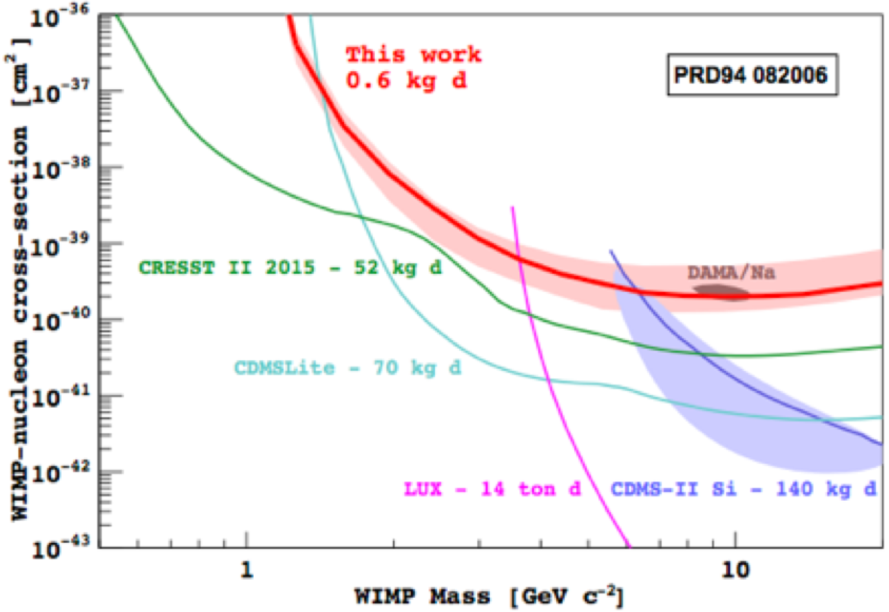


Current status:
- 40 g detector (7 CCDs, each ≈ 6 g)
- bkg. < 5 events/keV/kg/day
- in data taking

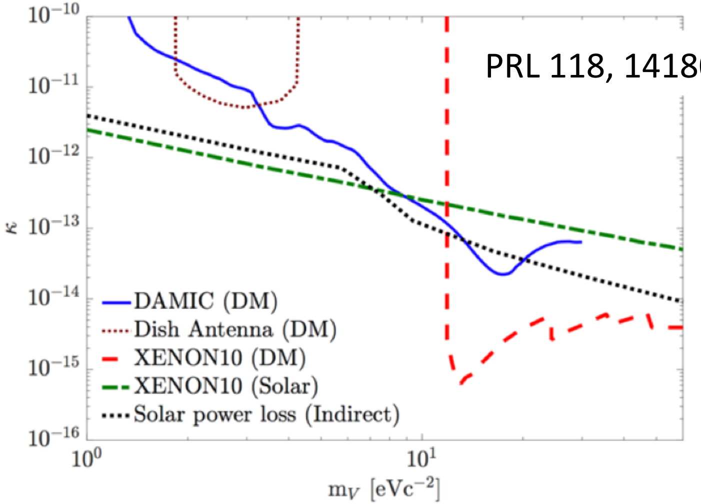
Exquisite spatial resolution:
- particle id
- surface bkg. rejection
- bkg. measurements

DArk Matter In CCDs

Material courtesy P. Privitera



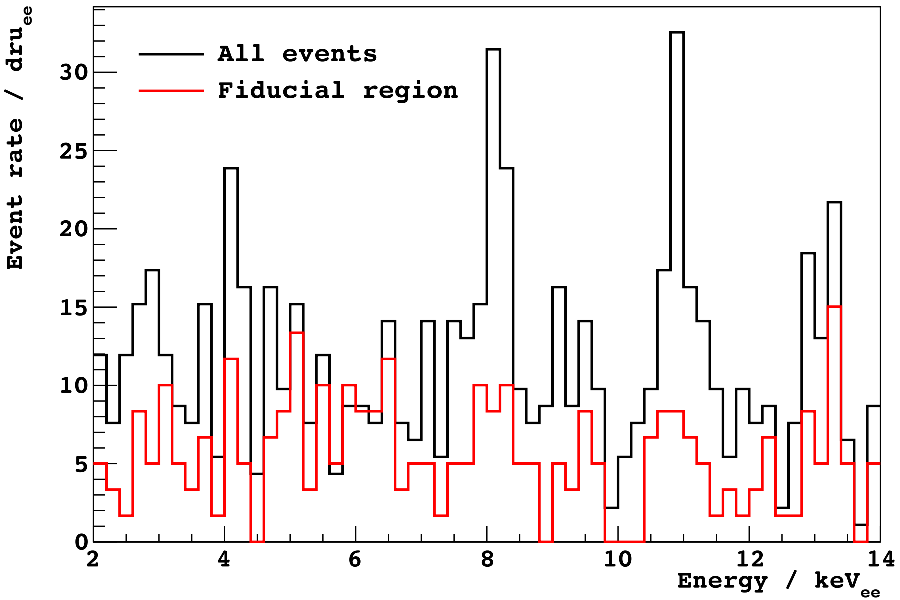
Search for eV mass hidden-photon DM (with only one week of data and a single CCD) yielded best direct limit in the eV range. Achieved the lowest leakage current ever in a silicon detector (0.5×10^{-3} e/pixel/day ≃ 5×10^{-22} A/cm^2 at 140 K)



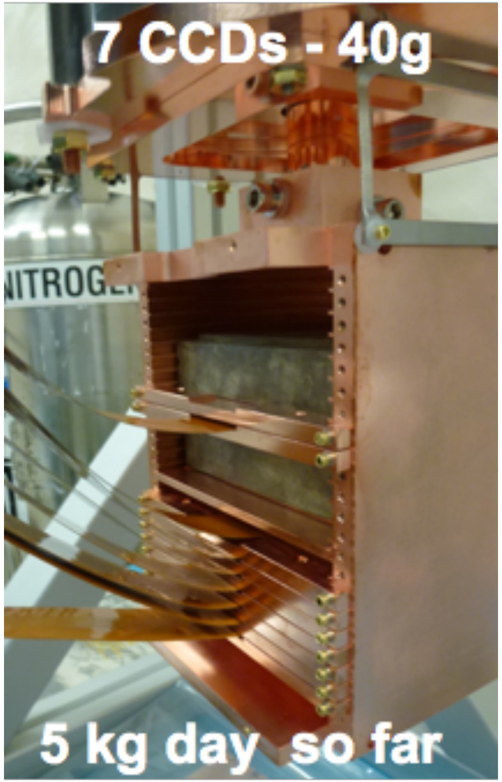
WIMP search (with limited exposure taken with R&D detectors) demonstrated the stable, low-threshold operation of DAMIC CCDs

DArk Matter In CCDs

Material courtesy P. Privitera



achieved background level as low as **≃2 dru** (events/keV/kg/day)



Data from **50 eV to 2 keV**, which provide most sensitivity to low mass WIMPs, are being analyzed

CCDs

Pros:
- Well established technology
- Reproducible and scalable
- Low threshold for electron interactions
- Very clean detector

Cons:
- Long signal collection time
- No time coincidence
- Need of deep underground labs
- Nuclear recoil threshold limited

Threshold detectors

Picasso, Coupp, PICO, Simple

- Fluid in a metastable state which can be quenched by energy depositions of particles
- Tiny energy deposition → Macroscopic phase transition

Bubble chamber principle: (D. Glaser, 1952)

- $E_{dep} < E_{thr}$ within R_{crit} → proto-bubble collapses
- $E_{dep} > E_{thr}$ within R_{crit} → irreversible bubble expansion

$$E_{dep} = \frac{dE}{dx} R_{crit} \geq E_{thr}$$

To be sensitive, particle must deposit enough energy within a critical radius.

Threshold detectors

Picasso, Coupp, PICO, Simple

Pros:

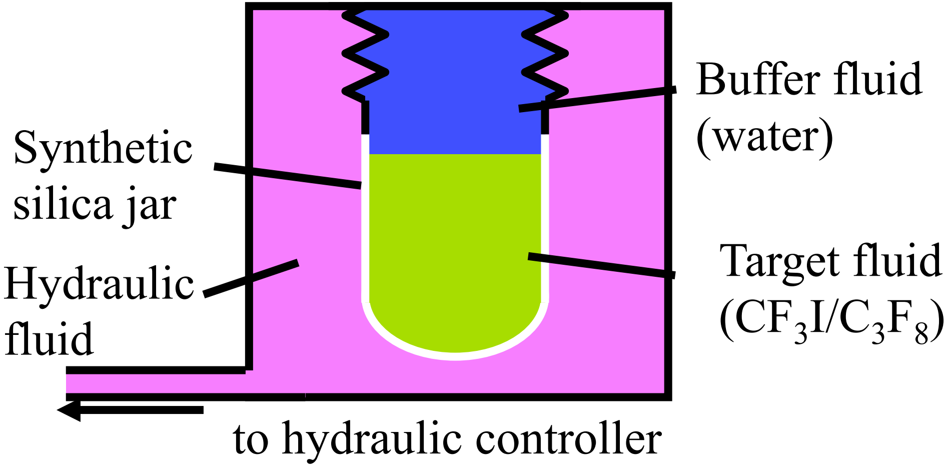
- Could make a dark matter bubble chamber with any liquid.
- Can tune detector to be sensitive only to certain particle types
  - Very good rejection of β and γ
- Fluorinated halocarbons: C_3F_8, C_4F_{10}, CF_3I
  - Sensitivity for spin-dependent interactions

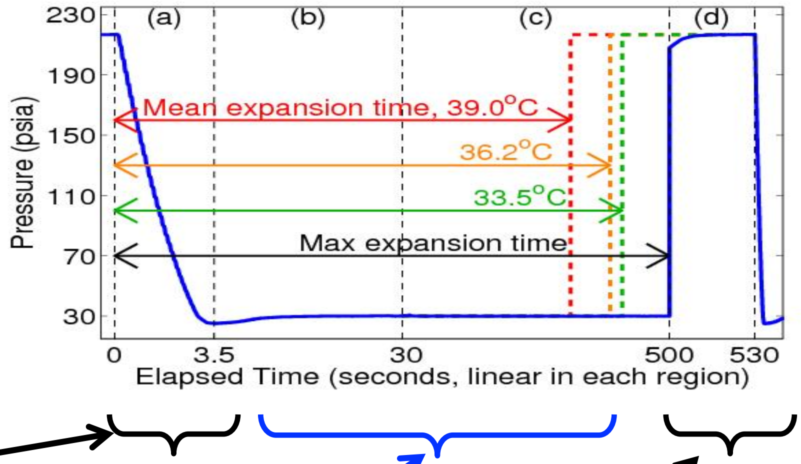
Cons:

- Long dead time
- Threshold device with integrating response
  - No information on the energy of the event

Slide courtesy T. Noble

Principle of Operation: Original Bubble Chambers



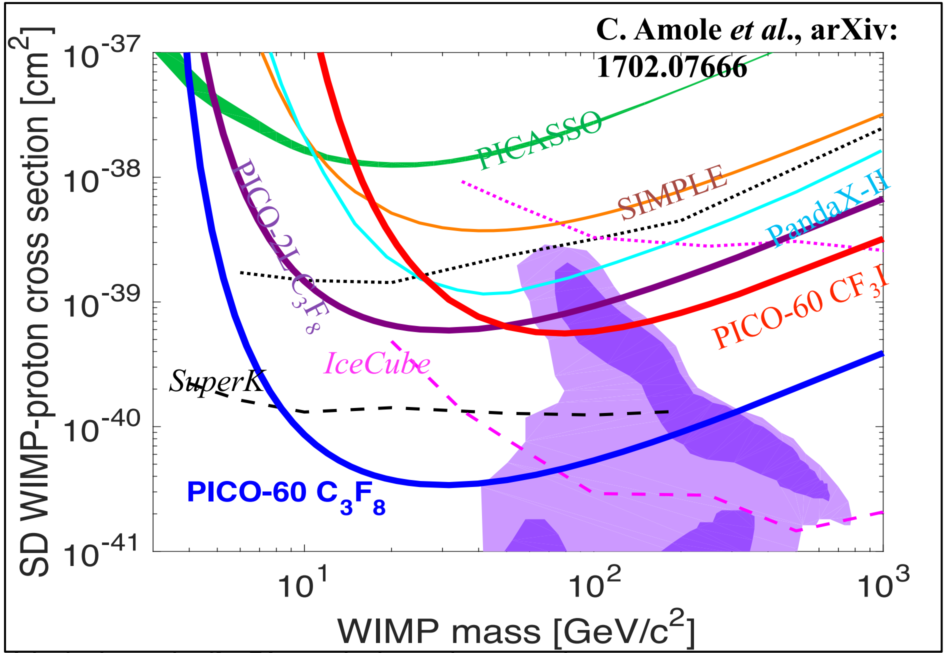


1. Lower the pressure to a superheated state.
2. See the bubble:
   - Cameras trigger, record position, multiplicity
   - Microphones record acoustic trace
   - Fast pressure transducer recording
3. Raise pressure to stop bubble growth (100ms), reset chamber (30sec)

Slide courtesy T. Noble

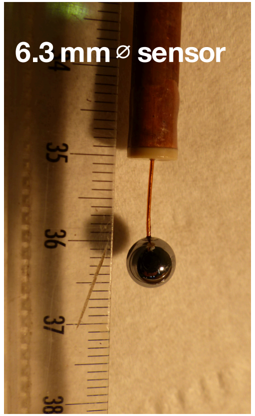
Summary

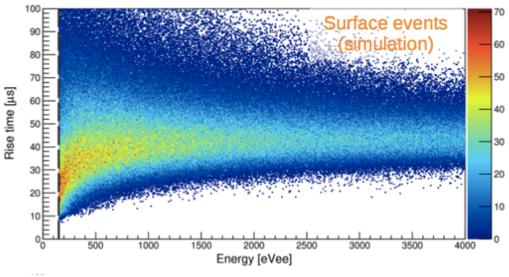
- PICO bubble chambers at the 40L scale can be built background-free
- PICO dominates the search for spin-dependent WIMP-proton couplings
- Construction of PICO 40 is well underway
- The design of PICO 500 is very advanced. Fine details of engineering design to be made based on PICO 40 experience.

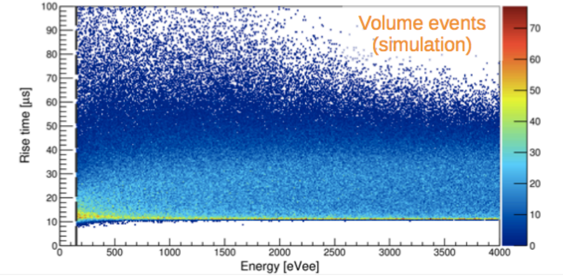


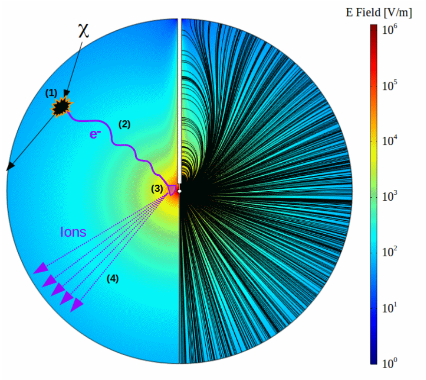
Spherical proportional counter

NEWS-G









Key features:

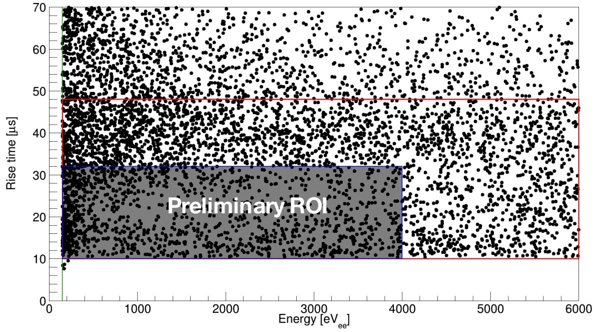
- Light target (Ne, He, H)
- Pulse shape discrimination against surface events down to low energy
- High amplification gain for the avalanche
- Sensitivity to single electron
  - Threshold of 10-40 eVee

Spherical proportional counter

NEWS-G

Good understanding and modelling of the detector response in energy and rise time

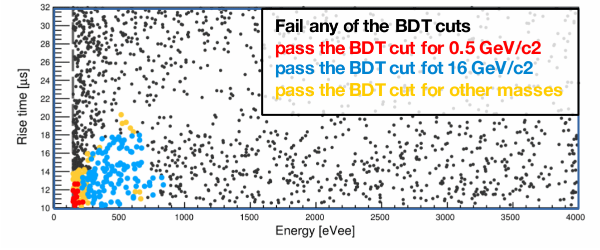
WIMP search run at the LSM

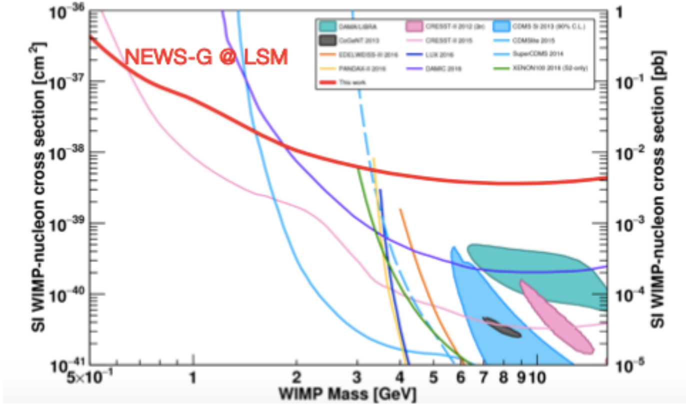


Neon + 0.7 % **CH4** @ **3.1 bars**
Total exposure = 34.1 live-days x 0.28 kg = **9.6 kg.days**
Analysis threshold = **150 eVee** (~720 eVnr)
Trigger threshold ~ **35 eVee** (~100% efficiency @ 150 eVee)
Sensitivity to single electrons from upper fluctuations of the avalanche gain

Boosted Decision Tree used to identify the fine-tuned ROI that maximizes expected sensitivity for WIMP masses between 0.5 and 16 GeV
=>Astroparticle Physics 97 (2018) 54–62

Events in the Preliminary ROI





Spherical proportional counter

Pros:

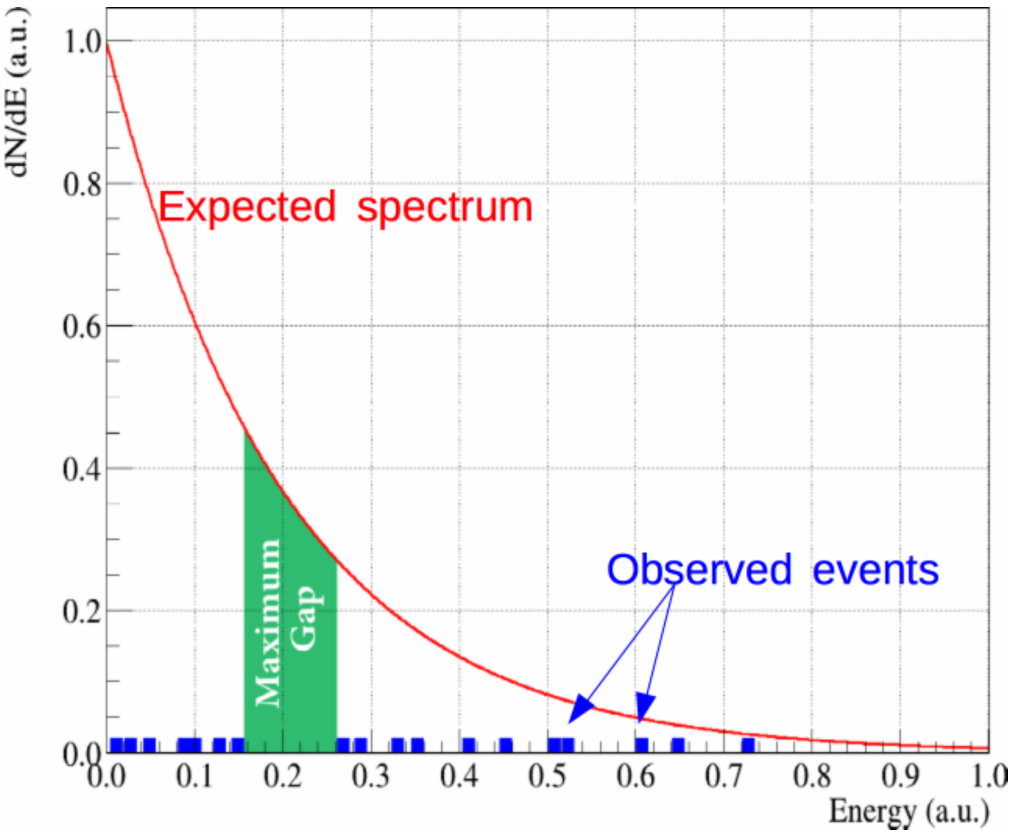
- Simple detector
- Large choice of gasses to explore different masses
- Low threshold

Cons:

- Scalability to large masses
- Calibration

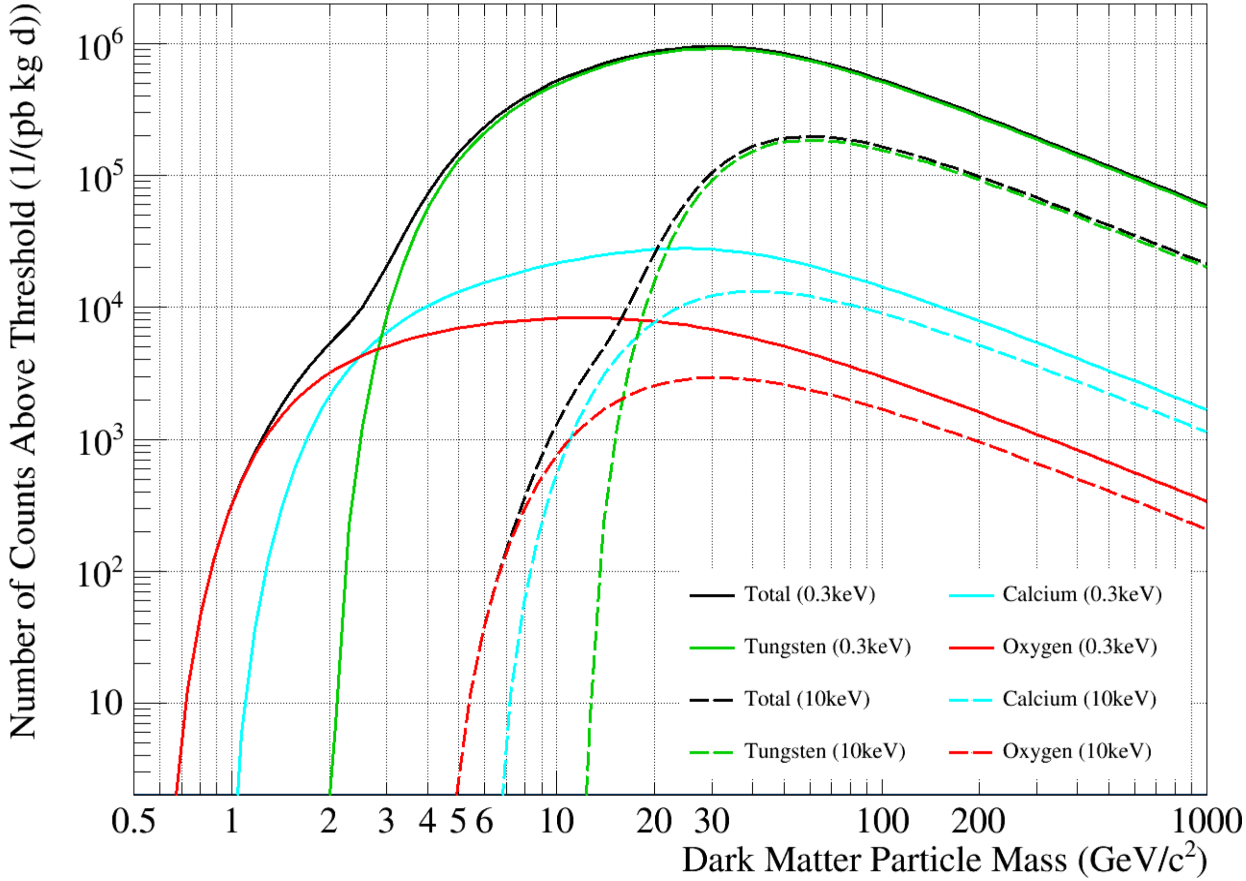
Yellin methods

"Finding an Upper Limit in the Presence of Unknown Background"



- Maximum Gap: Search for gap without events (N = 0)
- Optimum Interval: Search for largest interval with N=1,2,3... events

The A² dependency



Rate Xenon1T

From arXiv: 1805.12562

TABLE I: Best-fit expected event rates with 278.8 days live-time in the 1.3 t fiducial mass, 0.9 t reference mass, and 0.65 t core mass, for the full ($cS1$, $cS2_b$) ROI and, for illustration, in the NR signal reference region. The table lists each background (BG) component separately and in total, the observed data, and the expectation for a 200 GeV/c^2 WIMP prediction assuming the best-fit $\sigma_{SI} = 4.7 \times 10^{-47}$ cm^2.

Mass	1.3 t	1.3 t	0.9 t	0.65 t
($cS1$, $cS2_b$)	Full	Reference	Reference	Reference
ER	627±18	1.62±0.30	1.12±0.21	0.60±0.13
neutron	1.43±0.66	0.77±0.35	0.41±0.19	0.14±0.07
CEνNS	0.05±0.01	0.03±0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106±8	4.84±0.40	0.02	0.01
Total BG	735±20	7.36±0.61	1.62±0.28	0.80±0.14
WIMP$_{\text{best-fit}}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

278.8 days * 1.3 t / 3.56 counts
= 101days t/count
→ 0.01 counts/day t