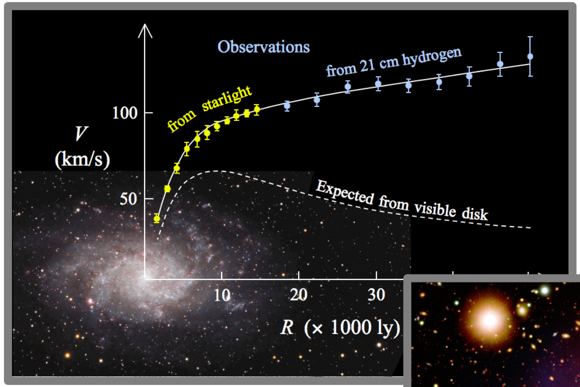
Low temperature dark matter detectors

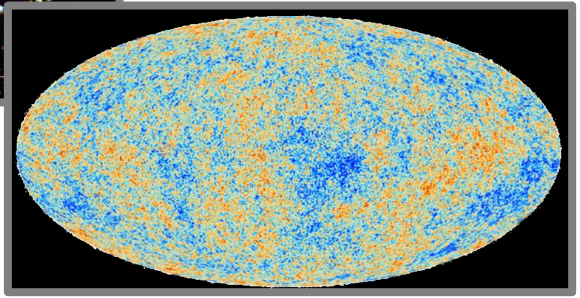
MILANO 22-26 JULY 2019

LTD 18 LOW TEMPERATURE DETECTORS

Federica Petricca
MPP Munich

THE DARK MATTER PROBLEM





Compelling evidence for dark matter on various cosmological scales

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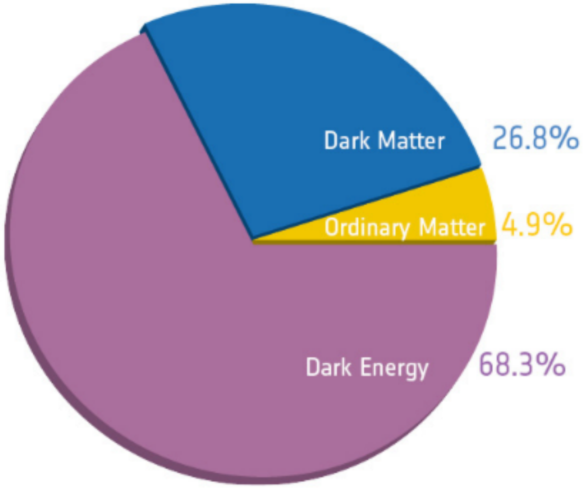
THE DARK MATTER PROBLEM

One model fits all the observations...



Source: © European Space Agency / Planck

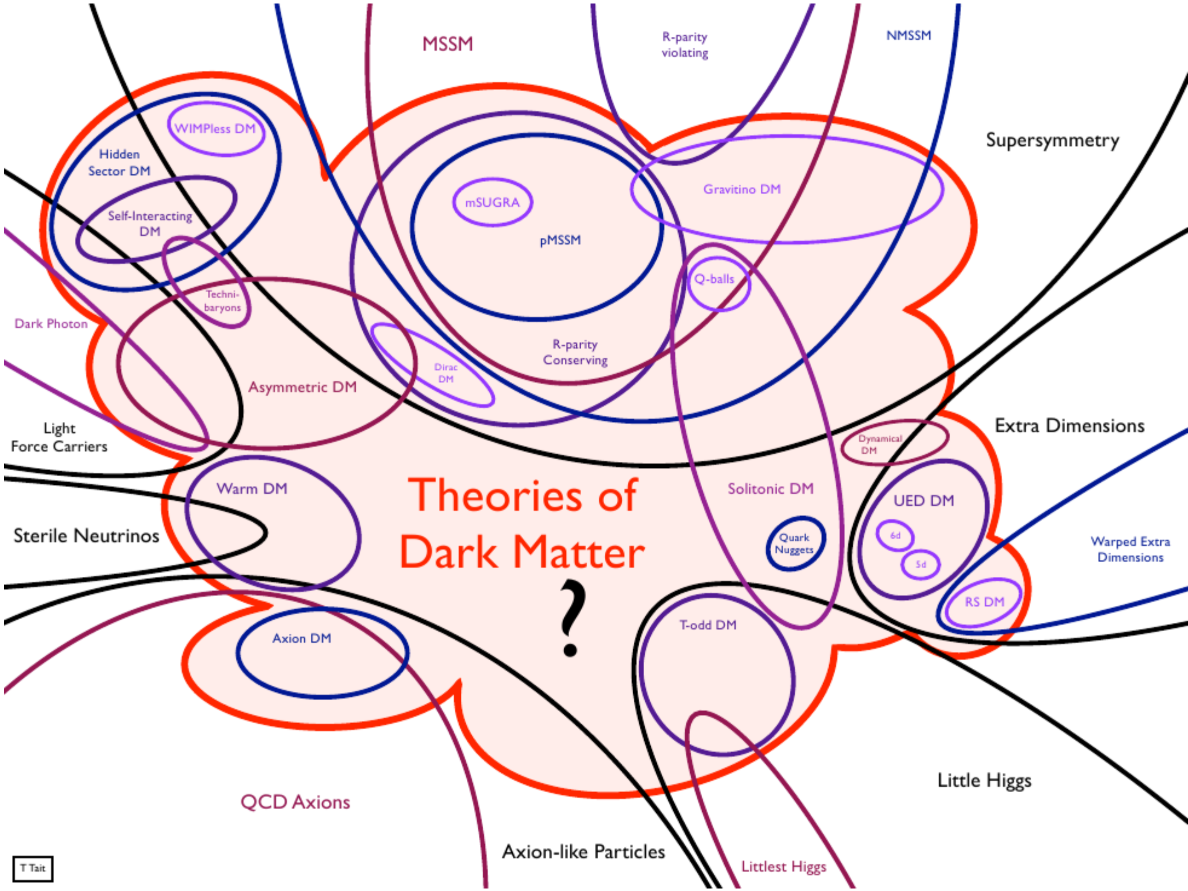
...but raises some fundamental questions:

What is dark matter?

What is dark energy?

AFTER >80 YEARS…

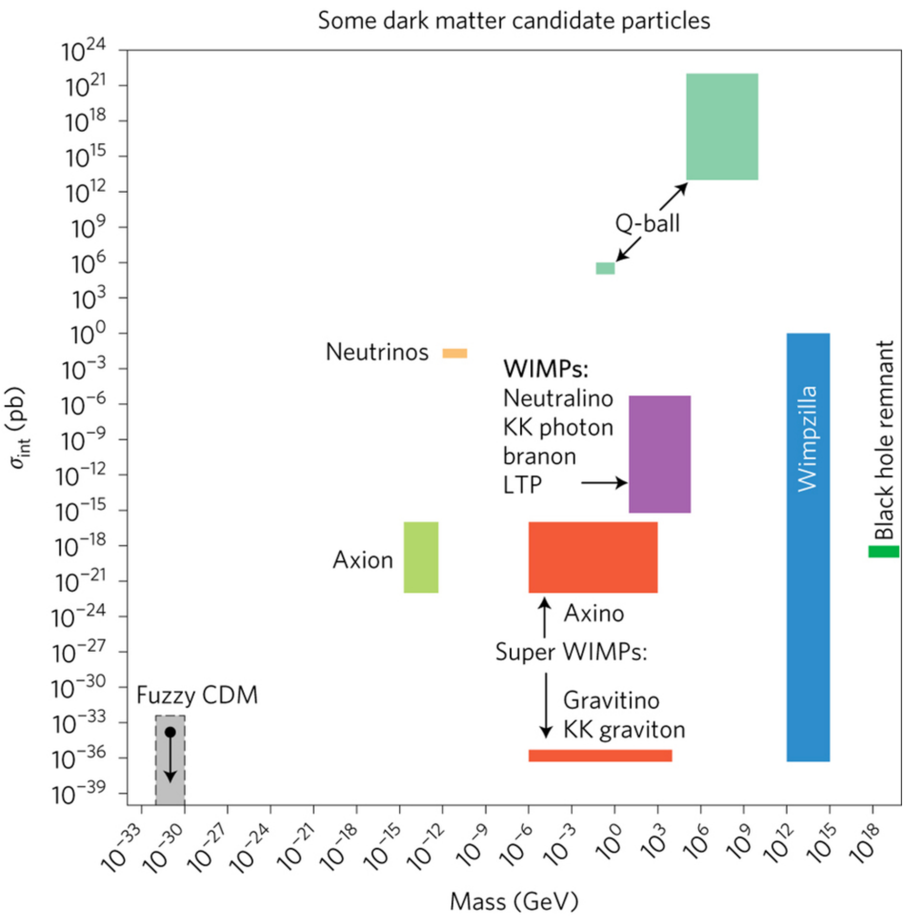
- **Non-baryonic**
  - Height of acoustic peaks in the CMB
  - Power spectrum of density fluctuations
  - Primordial nucleosynthesis
- **Cold (non-relativistic)**
  - Structure formation
- **Interacts via gravity and (maybe) some sub-weak scale force**
- **STILL HERE!**
  - Stable (or extremely long-lived)



SEARCH FOR DARK MATTER

Progress in ruling out parameter space resulted in a broadening of efforts

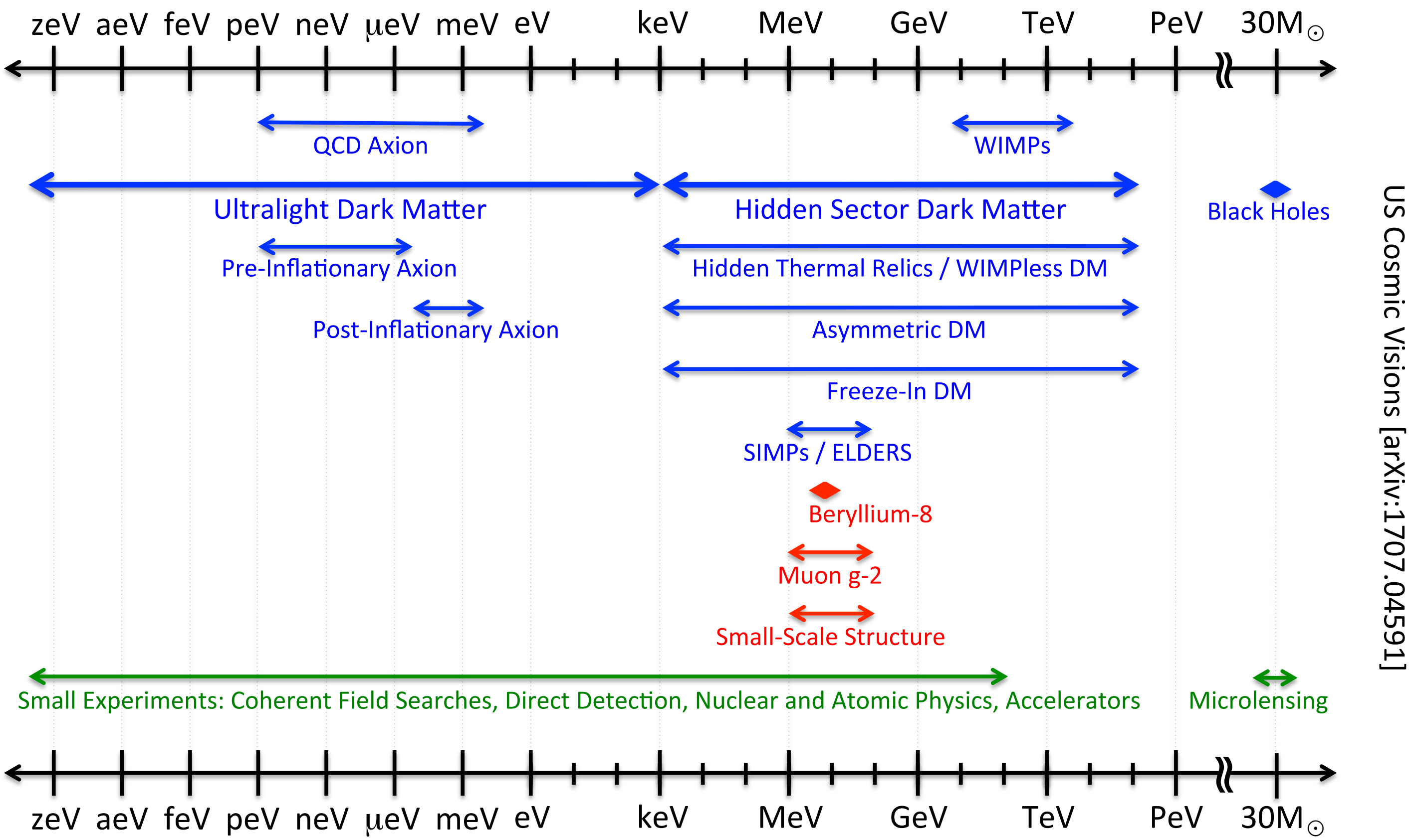
Experimental community struggeling to gain sensitivity in a broad mass range with complementary approaches



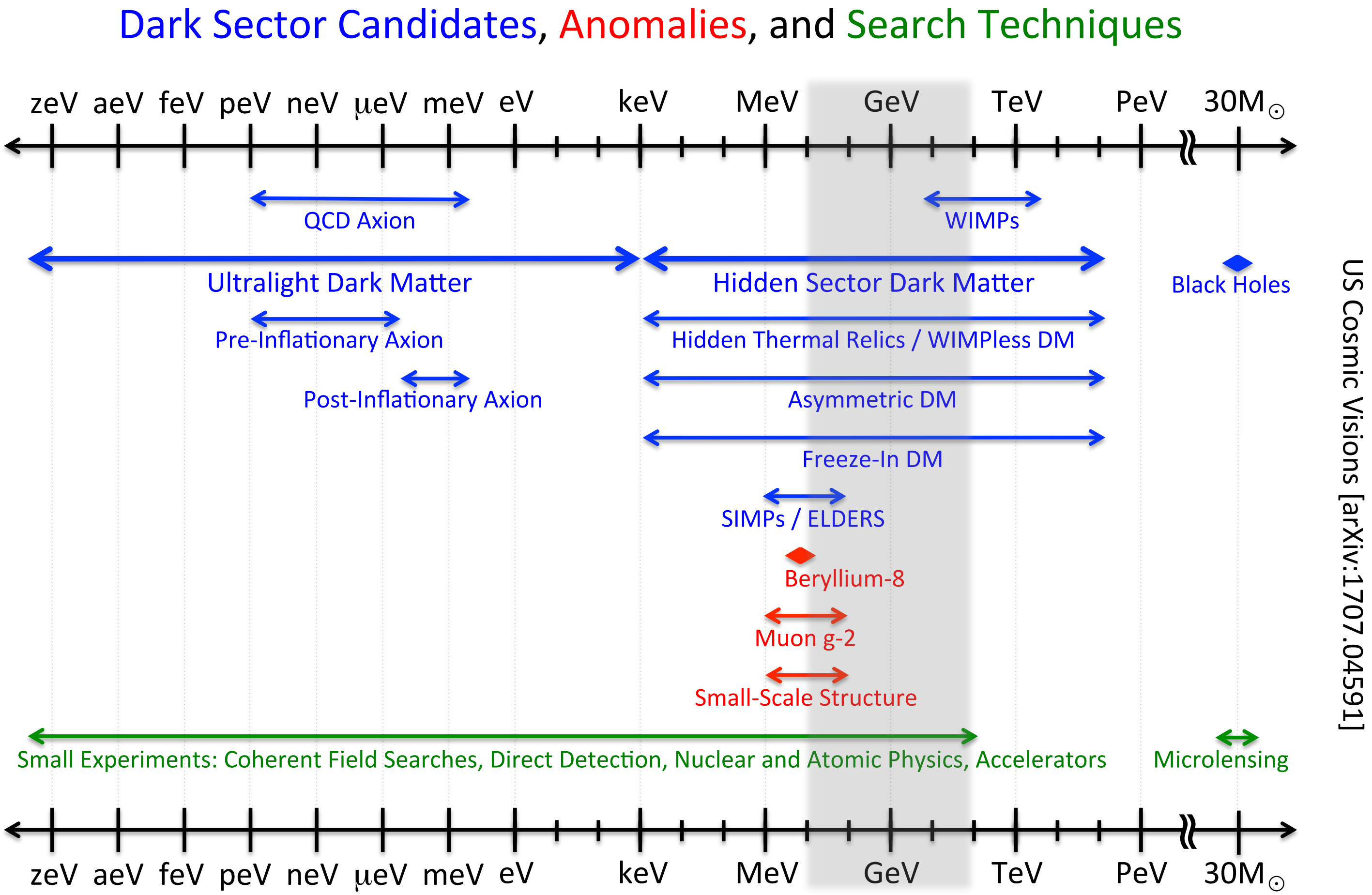
Conrad & Reimer, Nature Physics 13 (2017) 224-231

THE LANDSCAPE

Dark Sector Candidates, Anomalies, and Search Techniques

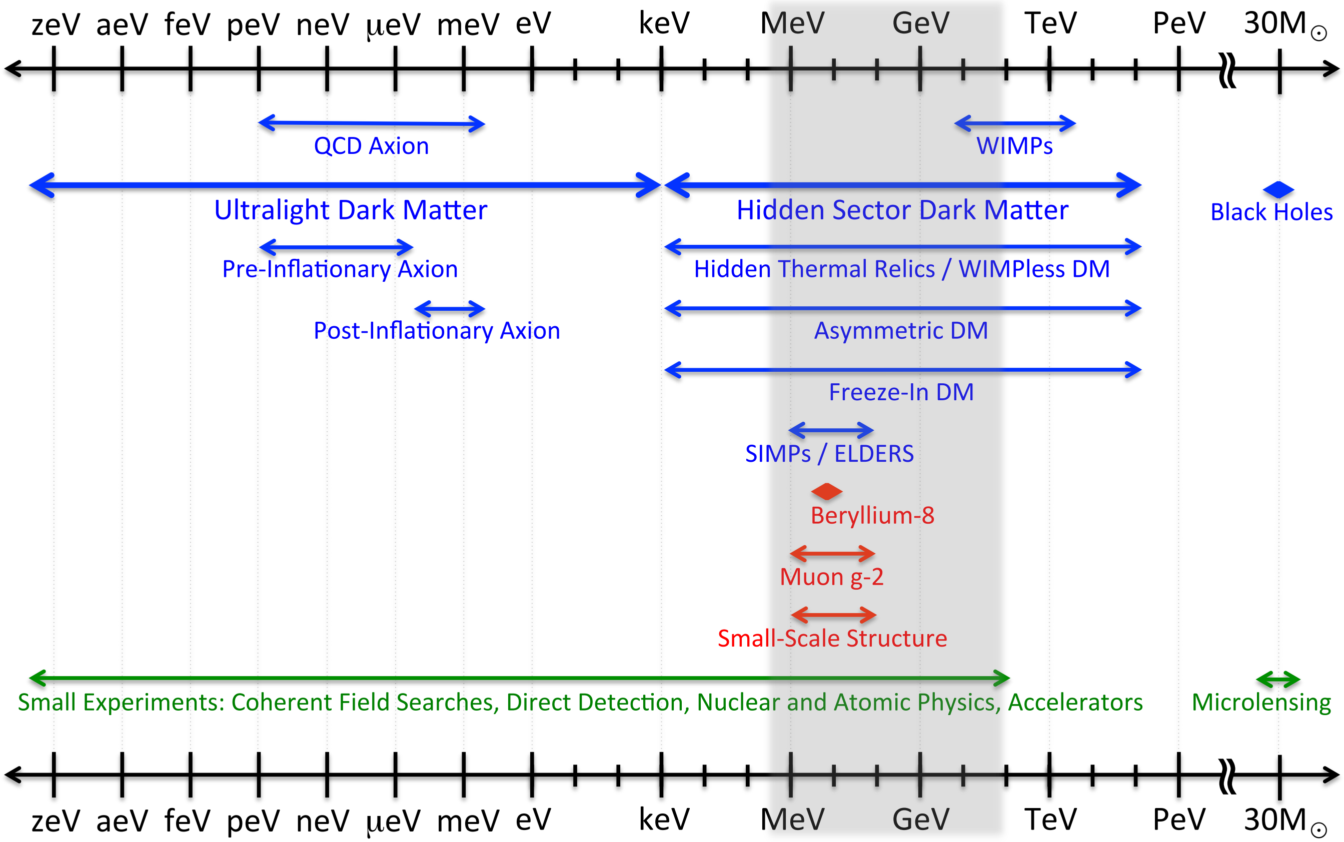


THE LANDSCAPE



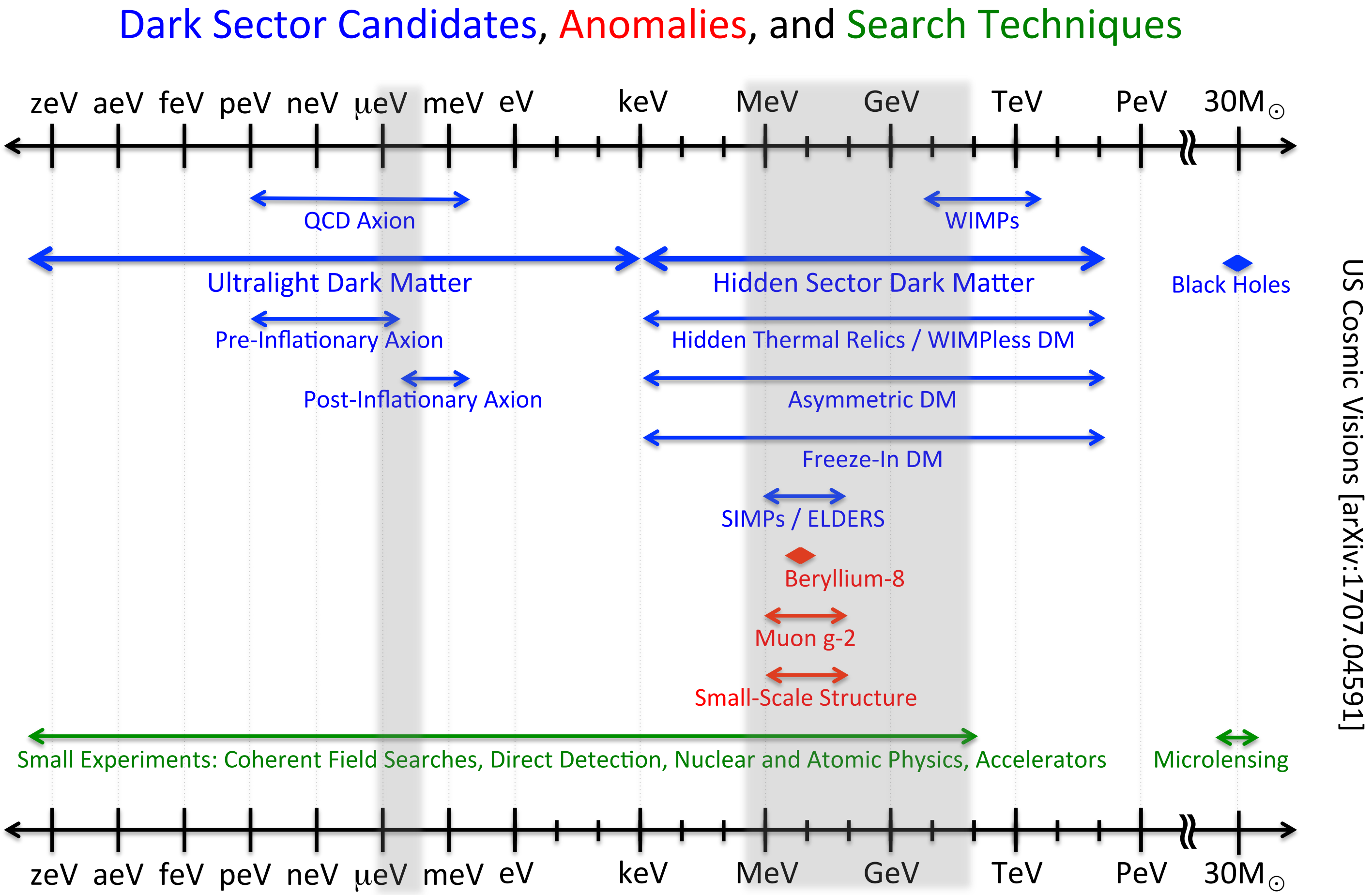
THE LANDSCAPE

Dark Sector Candidates, Anomalies, and Search Techniques



US Cosmic Visions [arXiv:1707.04591]

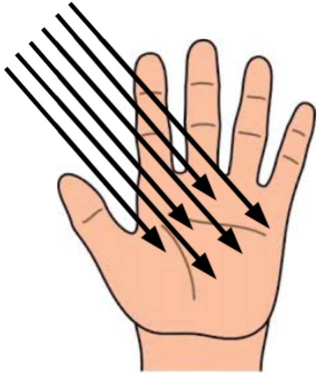
THE LANDSCAPE

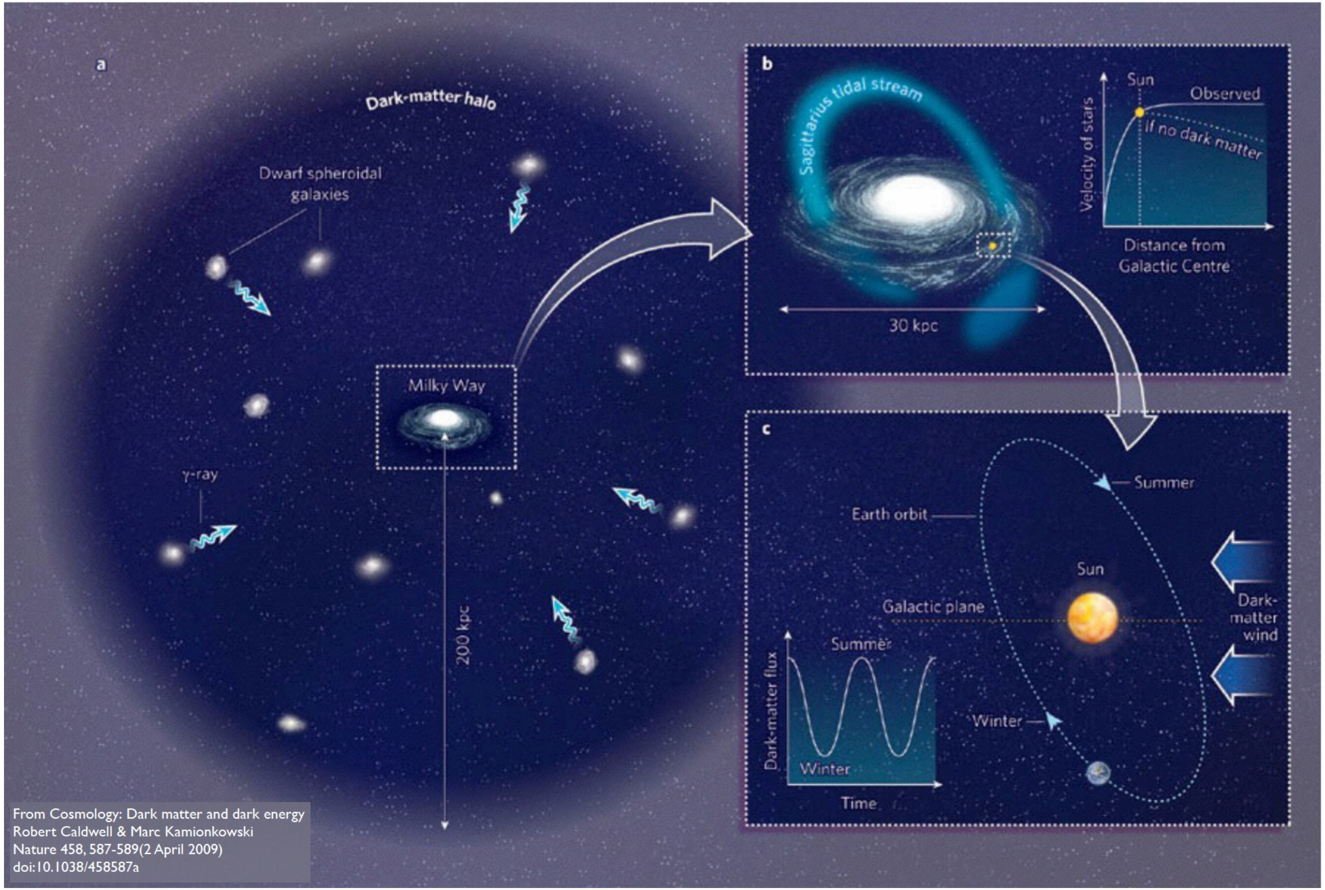


WE LIVE IN A DARK MATTER HALO

Halo model:

- Velocity distribution
- Earth's velocity around the Sun
- Sun's velocity around the center of the Galaxy
- Local dark matter density





DARK MATTER DIRECT DETECTION

Basic idea

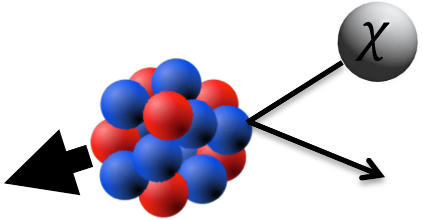
Dark matter is made of particles
which interact with Standard Model particles

Most common scenario

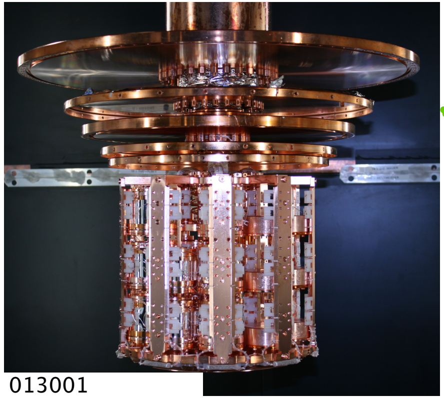
Dark matter particles scatter off nuclei:

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

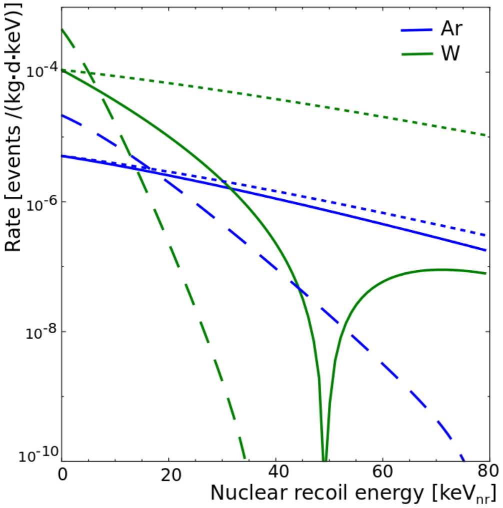
$$\frac{dR}{dE_r} \propto \frac{\rho_0}{m_\chi \mu^2} \sigma_0 F^2(E_r) \int_{v_{min}(E_r)=\sqrt{\frac{E_r m_N}{2\mu^2}}}^{v_{esc}} d^3v \frac{f(\bar{v})}{v}$$



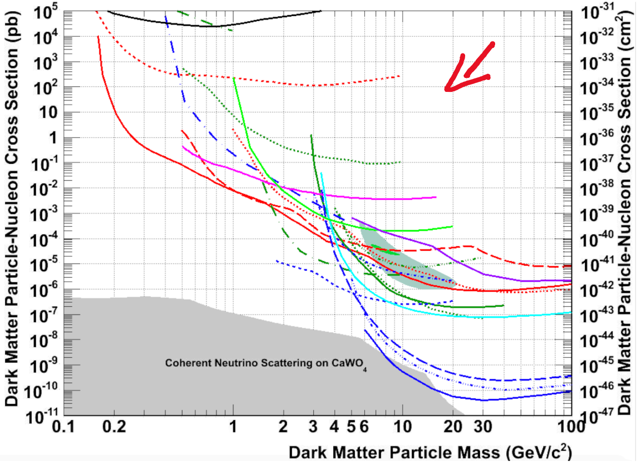
DIFFERENTIAL INTERACTION RATE



J. Phys. G43 (2016) no.1, 013001



$$\frac{dR}{dE_r} \propto \frac{\rho_0}{m_\chi \mu^2} \sigma_0 F^2(E_r) \int_{v_{min}(E_r)=\sqrt{\frac{E_r m_N}{2\mu^2}}}^{v_{esc}} d^3v \frac{f(\bar{v})}{v}$$



Credit: ESO/L. Calçada

SENSITIVITY

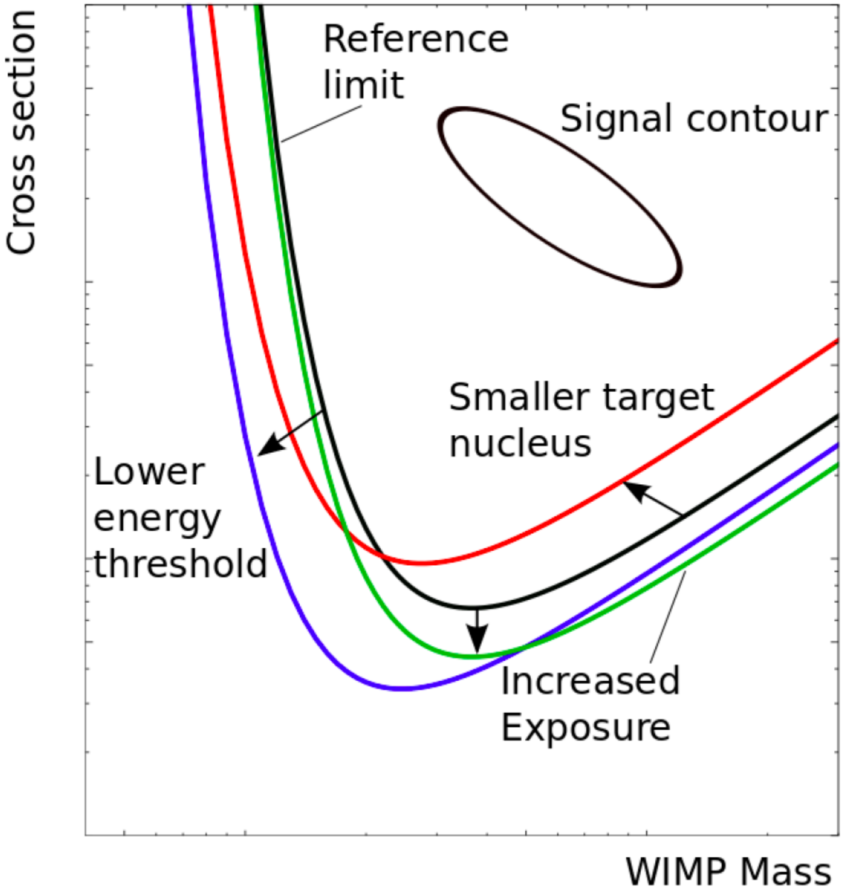
At large dark matter masses sensitivity is dominated by exposure

- target mass

At light dark matter masses sensitivity is dominated by performances

- energy threshold

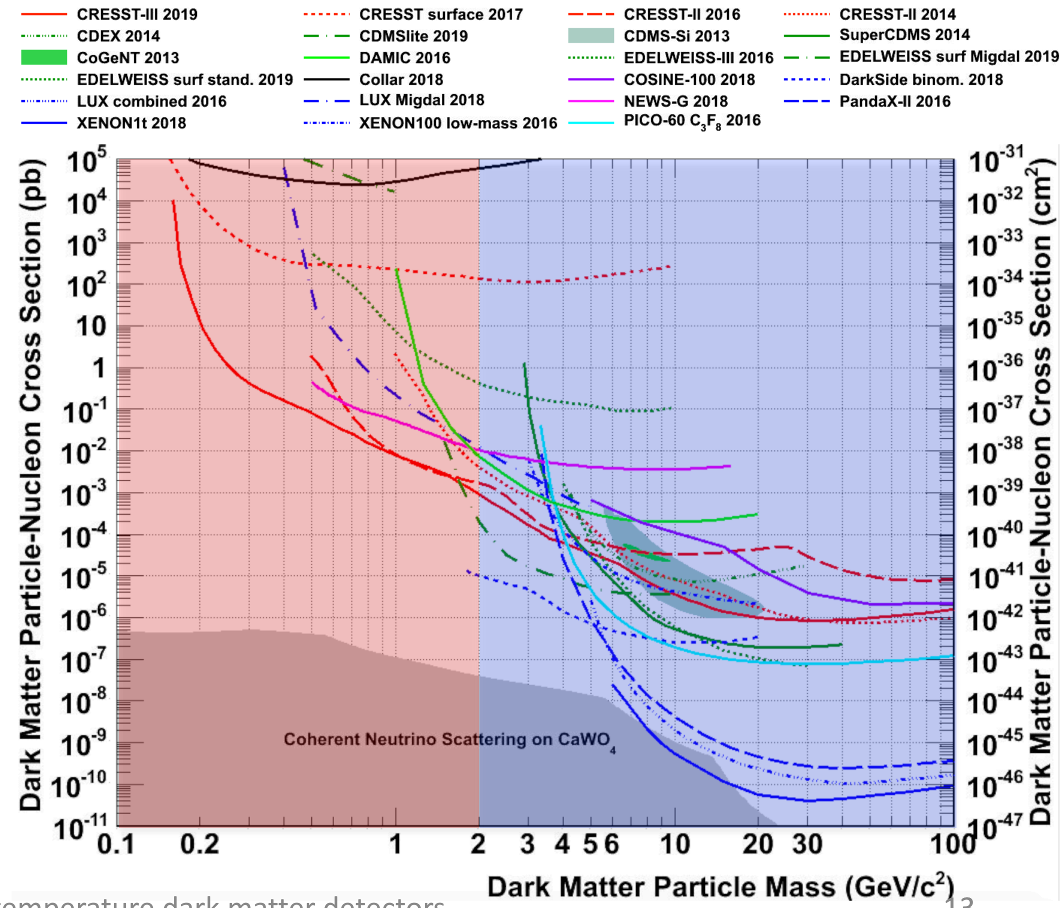
J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767



SENSITIVITY

Cryogenic detectors,
CCDs, He TPCs, Ge-Migdal

Xe, Ar
dual phase TPCs



At large dark matter masses sensitivity is dominated by exposure

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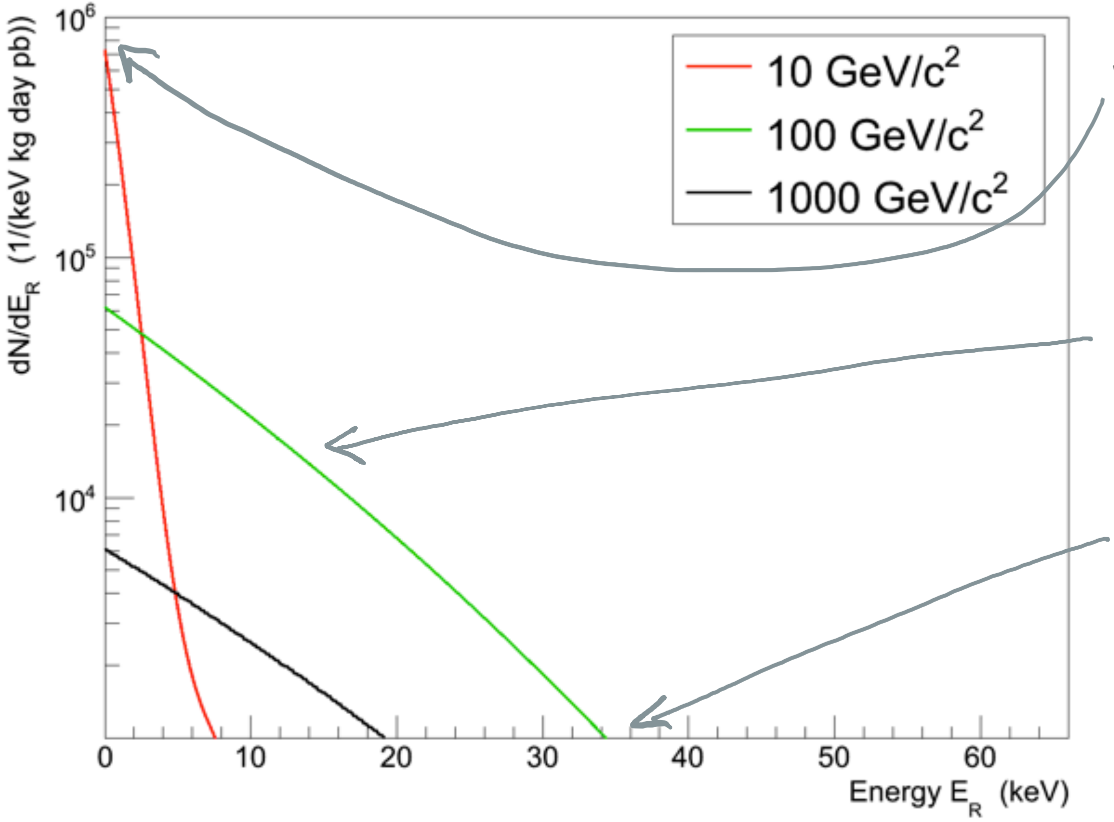
EXPERIMENTAL CHALLENGES

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



Very rare

current limit*

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

Featureless spectrum

Small recoil energies

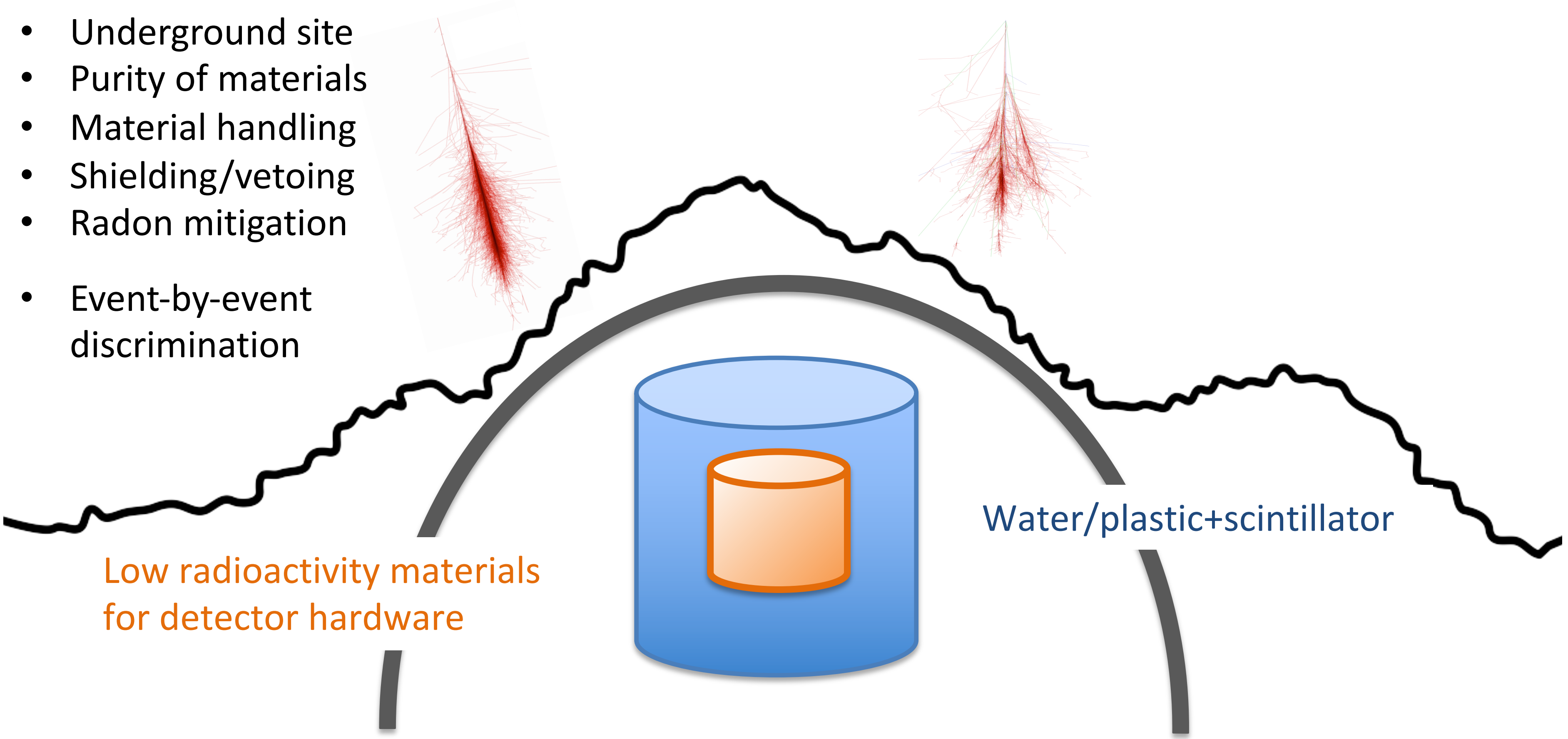
~ keV range

* Xenon1T: Phys. Rev. Lett. 121, 111302 (2018)

MINIMISING BACKGROUND

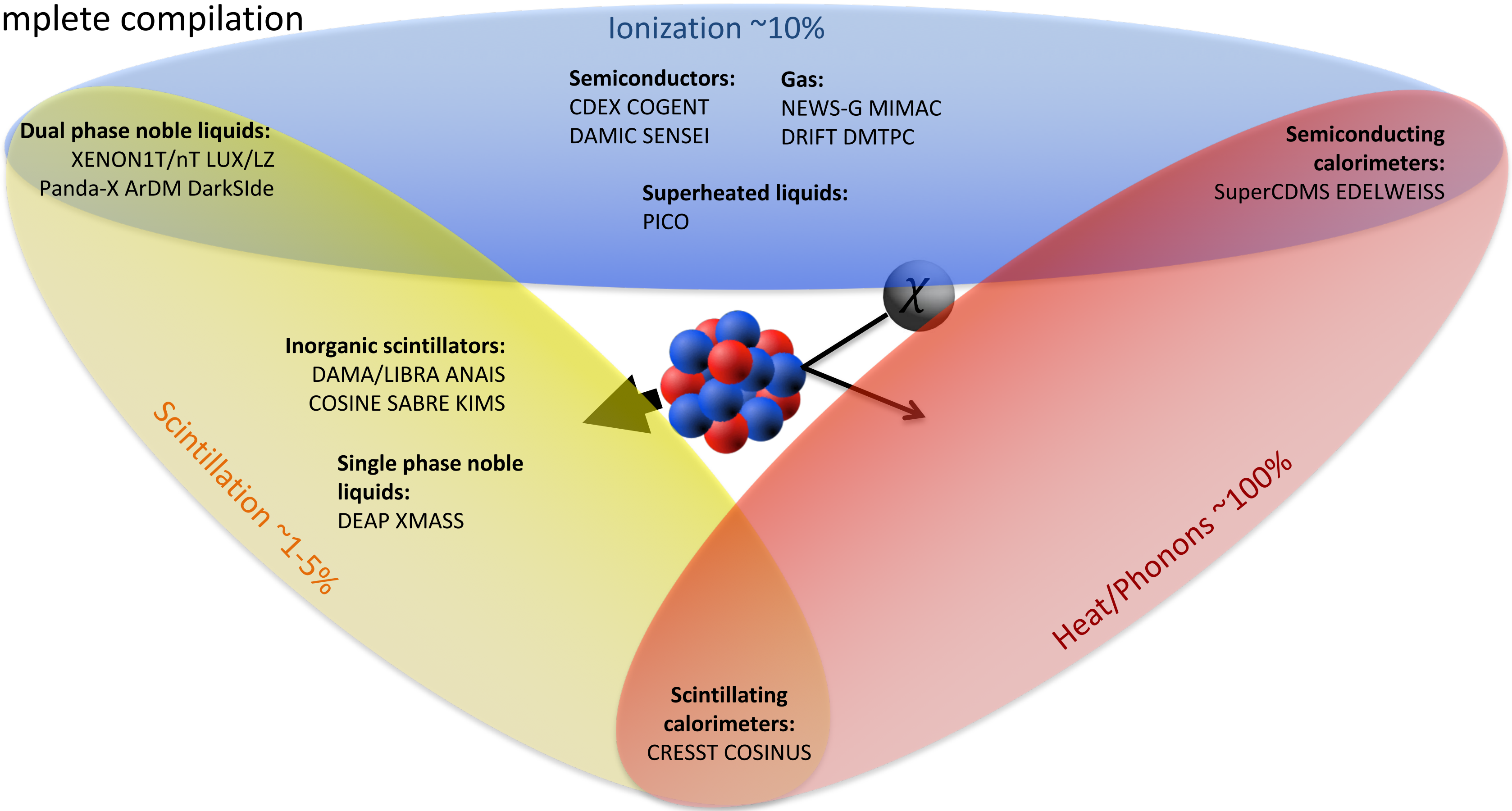
- Underground site
- Purity of materials
- Material handling
- Shielding/vetoing
- Radon mitigation

- Event-by-event discrimination

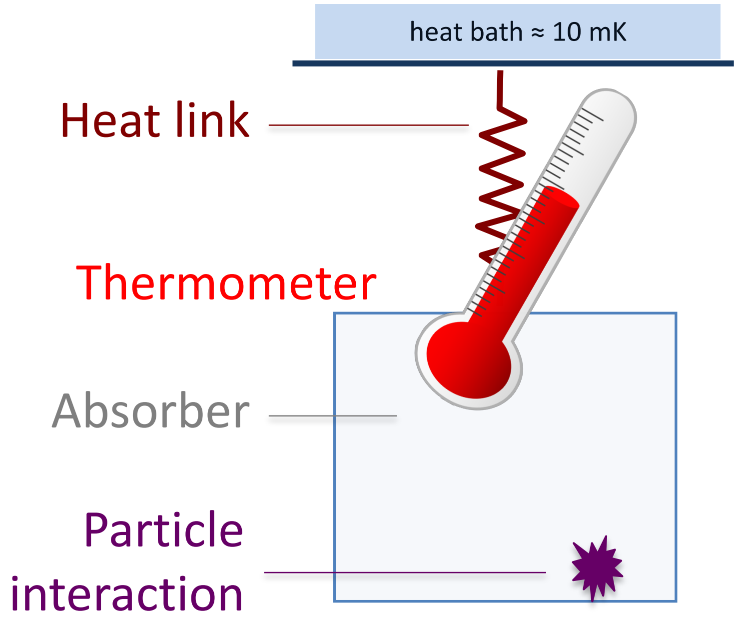


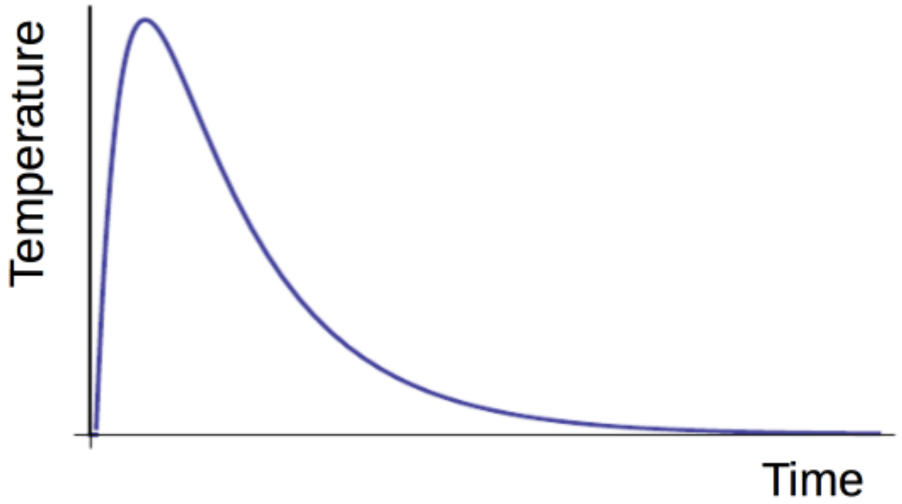
DIRECT DARK MATTER SEARCHES

An incomplete compilation



CALORIMETERS





$$\Delta T = \Delta E/C$$

- Direct measurement of the full energy deposition
- Cryogenic temperatures

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*(10 to few 100g))
  - Small exposures
- Complex technology

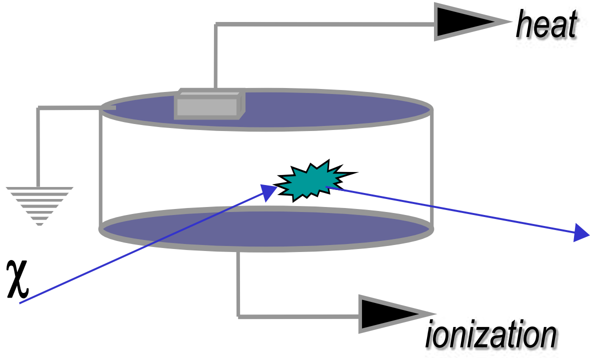
SEMICONDUCTING CALORIMETERS

Material courtesy
EDELWEISS and SuperCDMS collaborations

Phonon + Ionization

EDELWEISS, SuperCDMS

Heat: $\Delta T = E/C_{cal}$

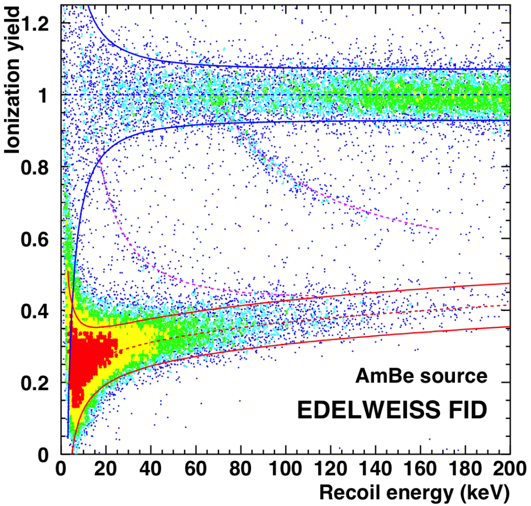


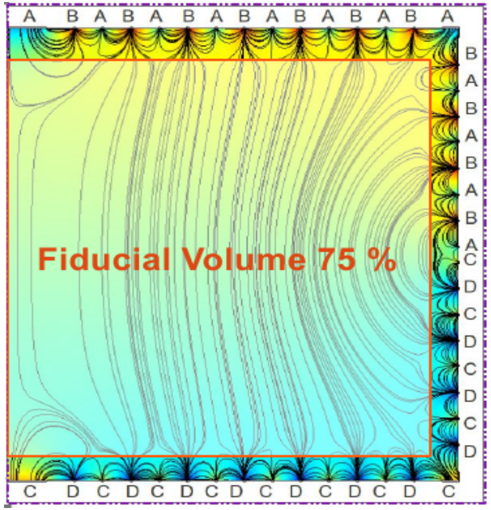
Ionization: $N_{pairs} = E/\varepsilon_{\gamma}$ or ε_{n}

Low bias voltage (iZIP, FID):

Phonon and charge sensors on both sides

- Particle identification via ratio of ionization to primary phonon
- Fiducialization





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Phonon + Ionization

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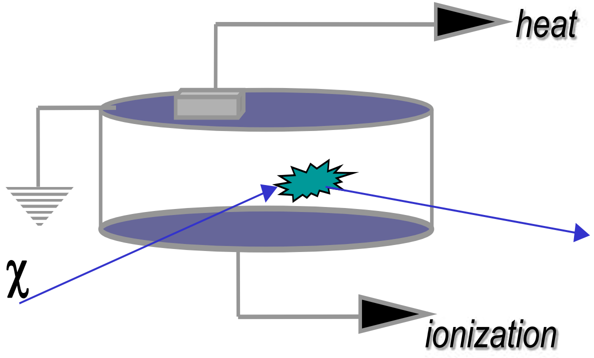
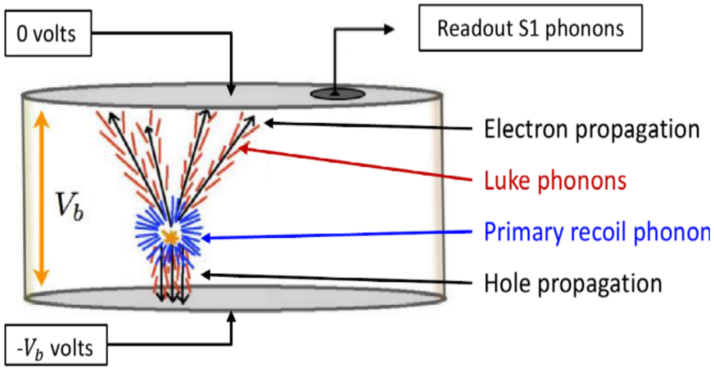


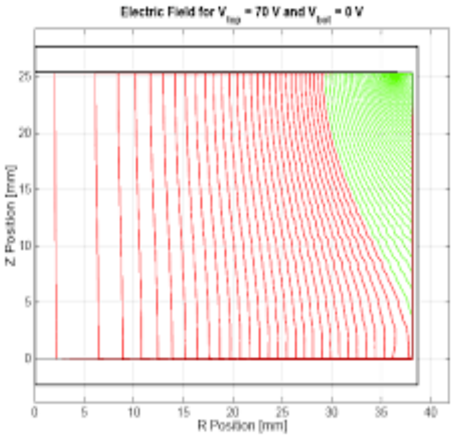
Ionization: $N_{pairs} = E/\varepsilon_{\gamma}$ or ε_{n}

High bias voltage:

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

- Gain in threshold
- Dilution of background from electron recoil events
- Reduced discrimination





SEMICONDUCTING CALORIMETERS

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EDELWEISS and SuperCDMS collaborations

Phonon + Ionization

EDELWEISS, SuperCDMS

New SuperCDMS
SNOLAB Detectors

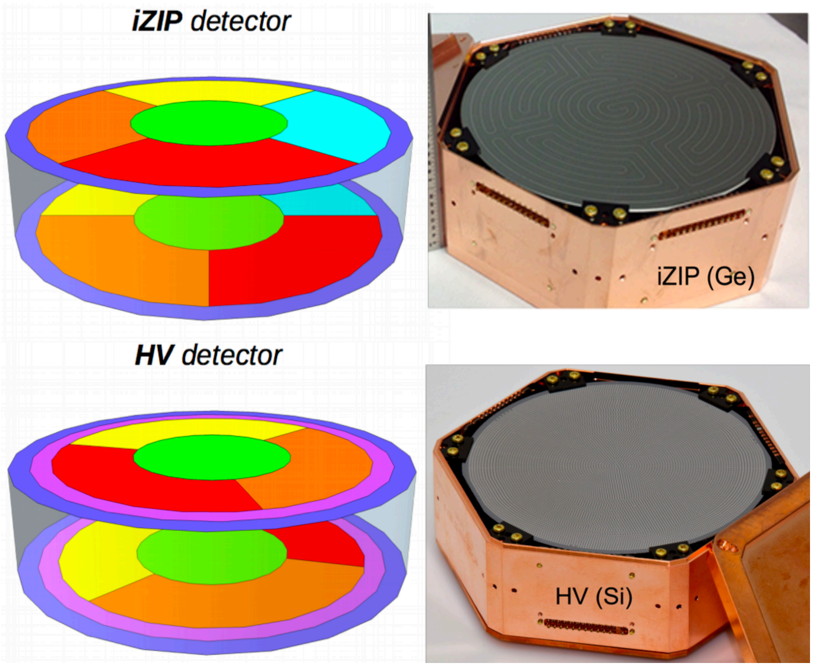
TES phonon channels optimized differently for the two techniques, both in channel arrangement and in patterning on the surfaces

Fast but technologically complicated

100mm diameter, 33mm thick

Ge 1400g per detector

Si 600g per detector



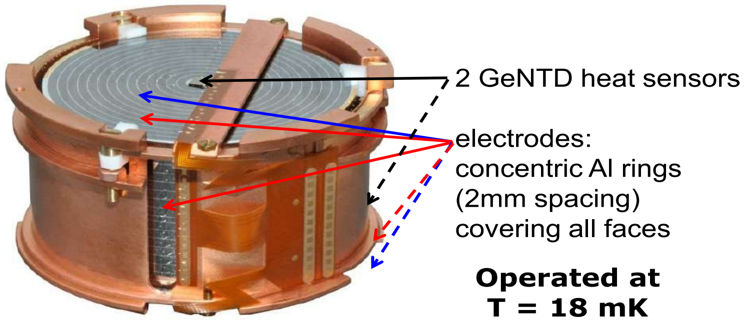
SEMICONDUCTING CALORIMETERS

Material courtesy
EDELWEISS and SuperCDMS collaborations

Phonon + Ionization
EDELWEISS, SuperCDMS

EDELWEISS-III FID

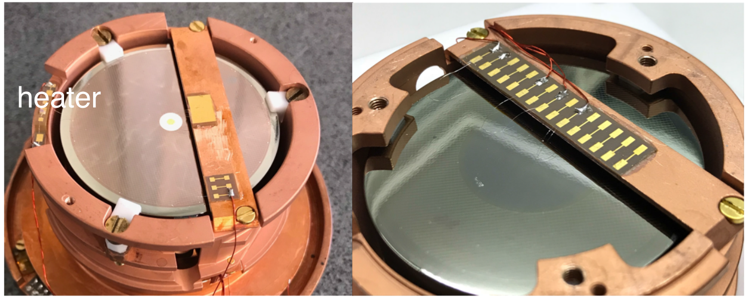
NTD phonon channels on each surface
Slow but technologically simple
70mm diameter, 40mm thick
Ge 870g per detector



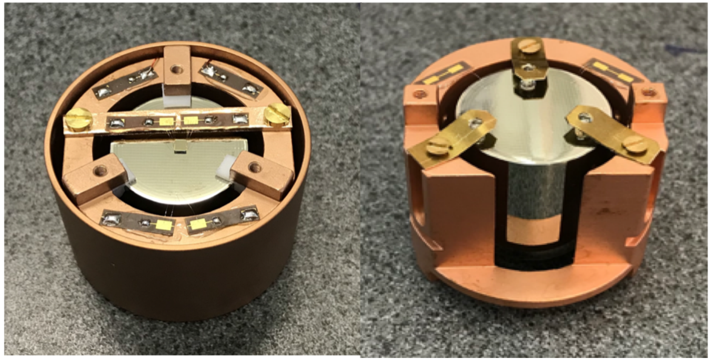
Operated at
T = 18 mK

EDELWEISS high-voltage R&D program

NbSi209: 200g Ge with TES thermal sensor



RED30 : 33 g Ge Al electrodes, NTD thermal sensor

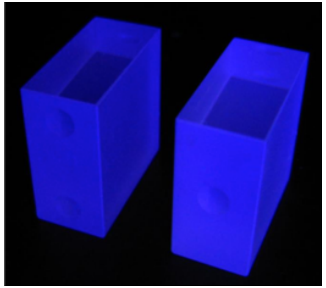


SCINTILLATING CALORIMETERS

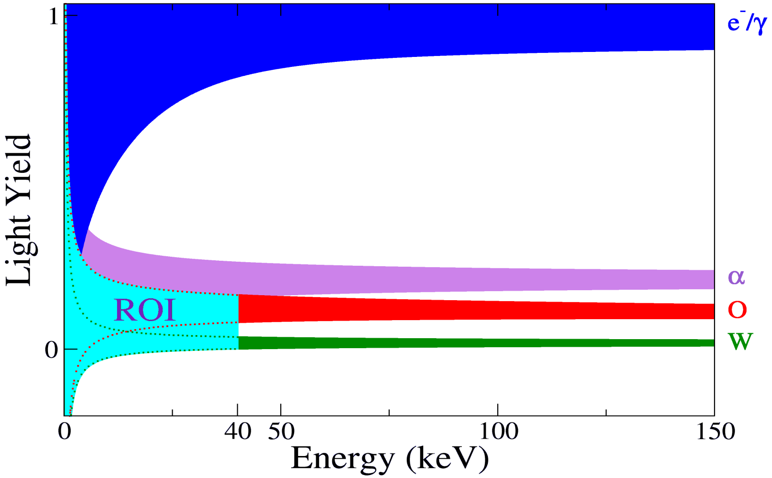
Phonon + Light

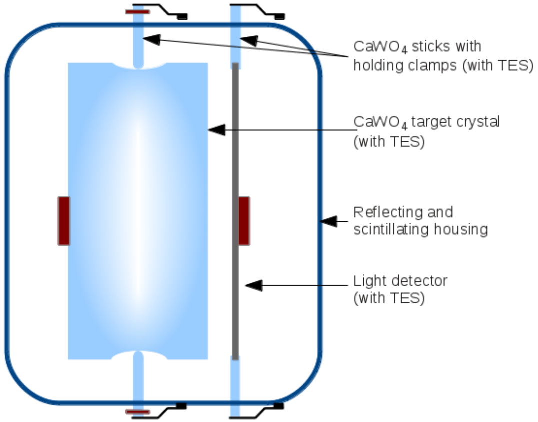
CRESST

CRESST: Scintillating crystals as target



- Target crystals operated as **cryogenic calorimeters** (~15mK)
- Separate **cryogenic light detector** to detect the scintillation light signal





SCINTILLATING CALORIMETERS

Phonon + Light

CRESST

CRESST-III

Layout optimized for low-mass dark matter

TES phonon sensor on target crystal

TES phonon sensor on light detector absorber

Absorber crystal (20×20×10)mm^3

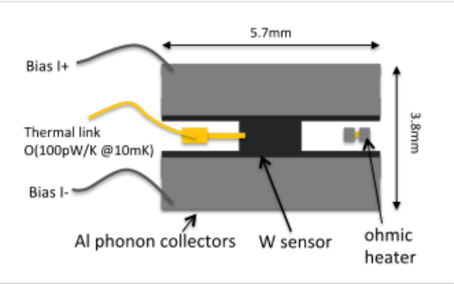
$CaWO_4$ 24g

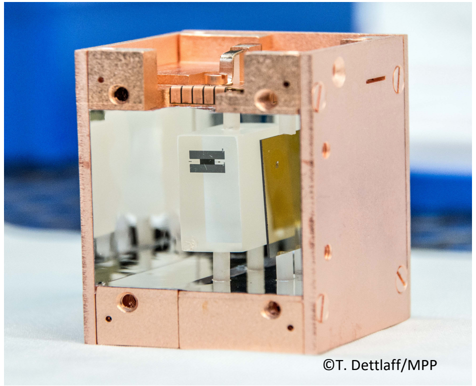
Light detector absorber (20×20×0,4)mm^3

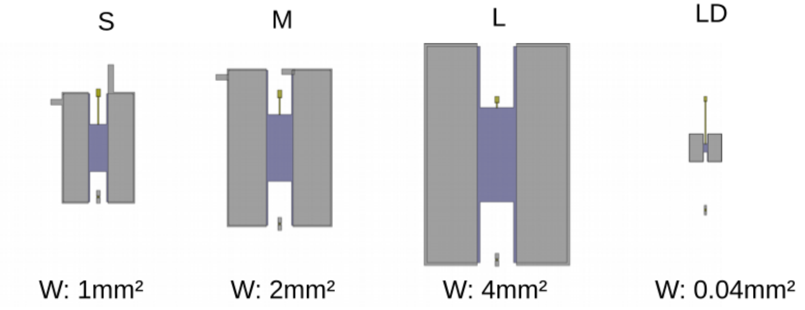
Silicon-on-Sapphire

Nuclear recoil threshold of 30.1 eV

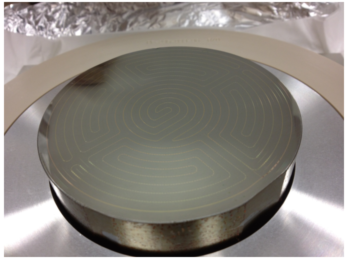
Resolution at zero energy σ = 4.5eV

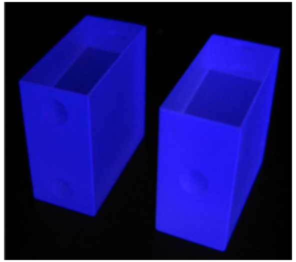






SEMICONDUCTORS vs. SCINTILLATORS





Pros:

- Ultrapure material
- Identification of surface events
  - Fiducialization

Cons:

- Limited choice of materials
- In high-voltage require model to derive energy scale of nuclear recoils

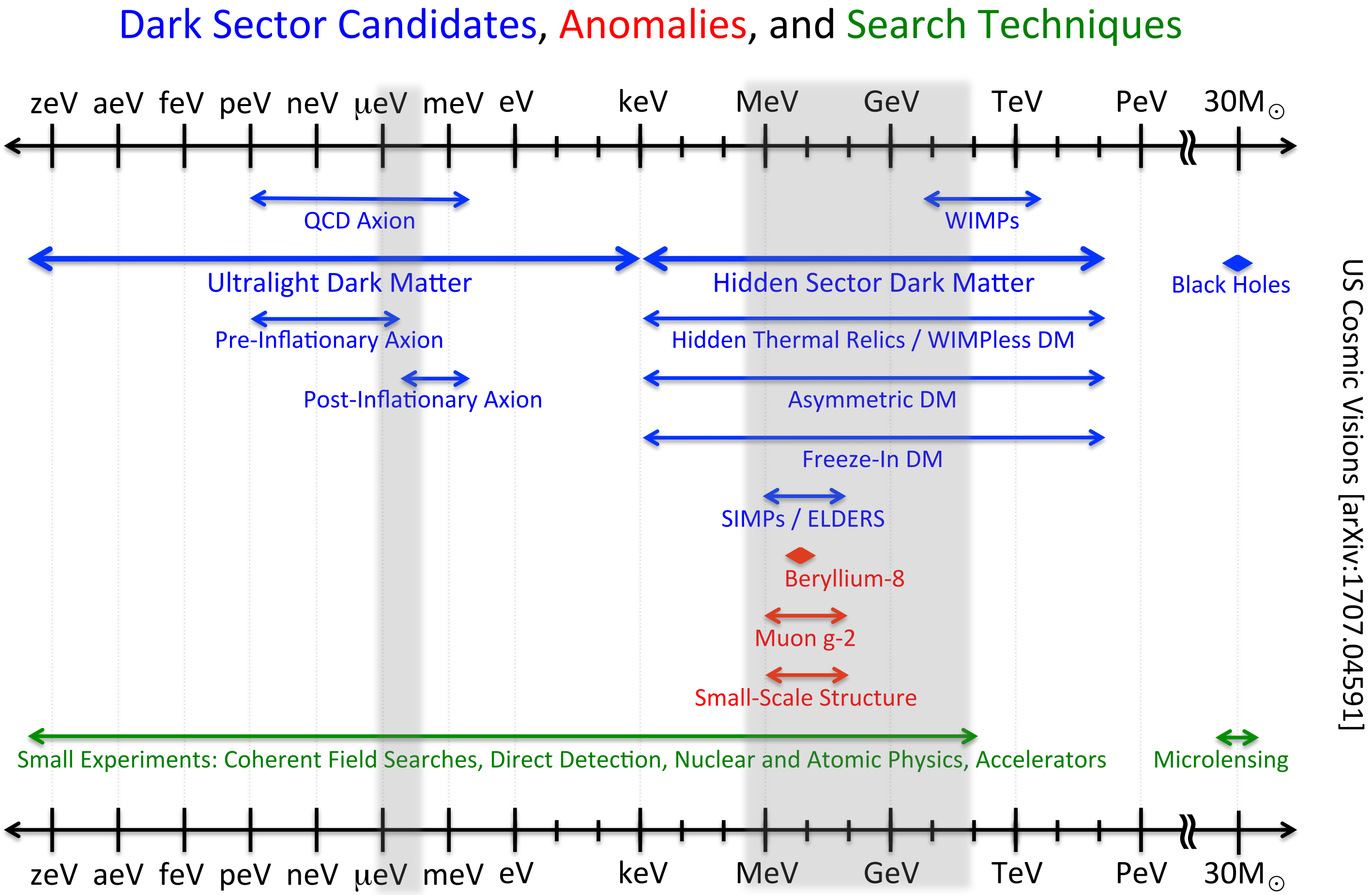
Pros:

- 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
- No fiducialization
- Non-commercial materials

THE LANDSCAPE



AXION HALOSCOPES

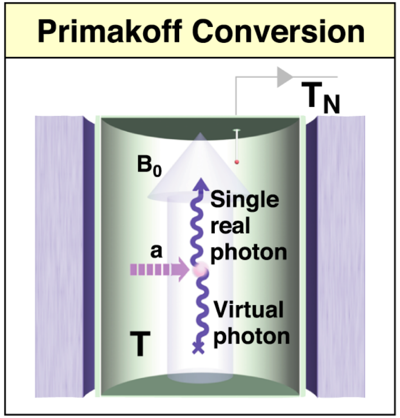
Material courtesy
ADMX collaboration

Basic idea

Dark Matter Axions convert to photons in a magnetic field through the inverse Primakoff effect

Resonating cavities

The conversion rate is enhanced if the photon's frequency corresponds to a cavity's resonant frequency

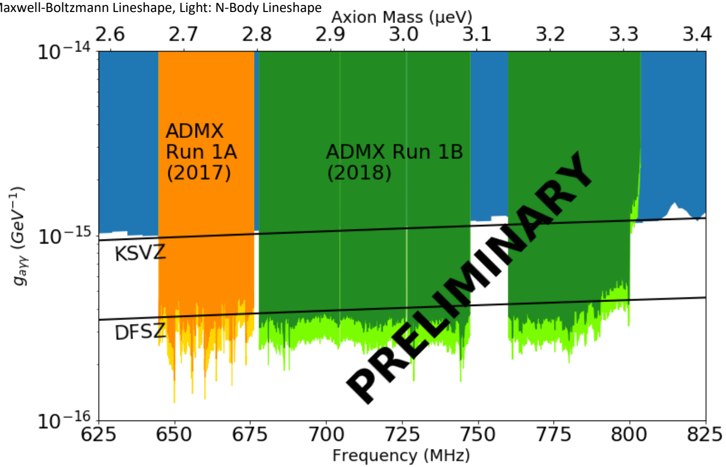


$$P \propto g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C Q$$

AXION HALOSCOPES

Material courtesy
ADMX collaboration

Dark: Maxwell-Boltzmann Lineshape, Light: N-Body Lineshape

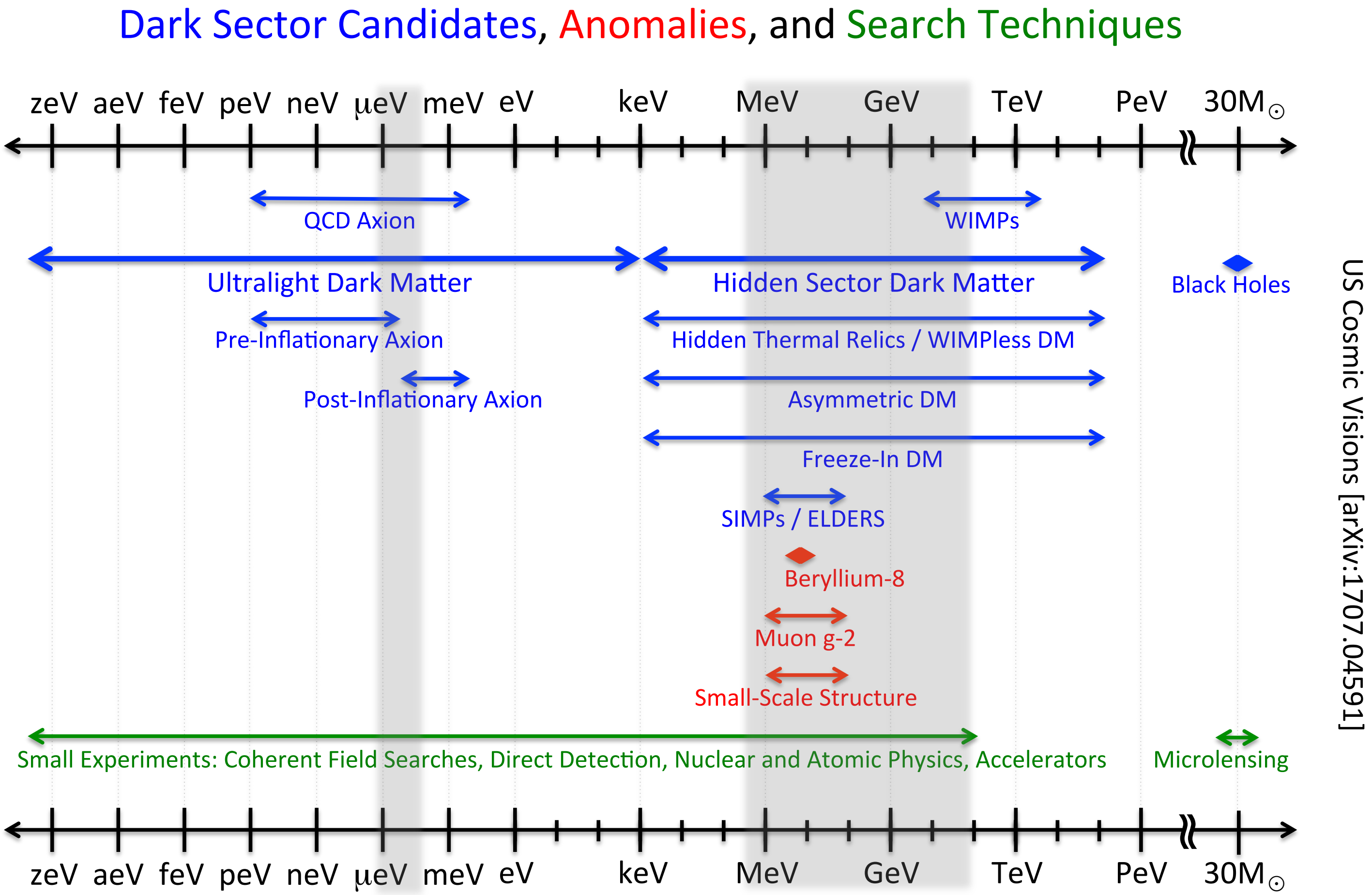


$$P \propto g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C Q$$

Credit: ESO/L. Calçada

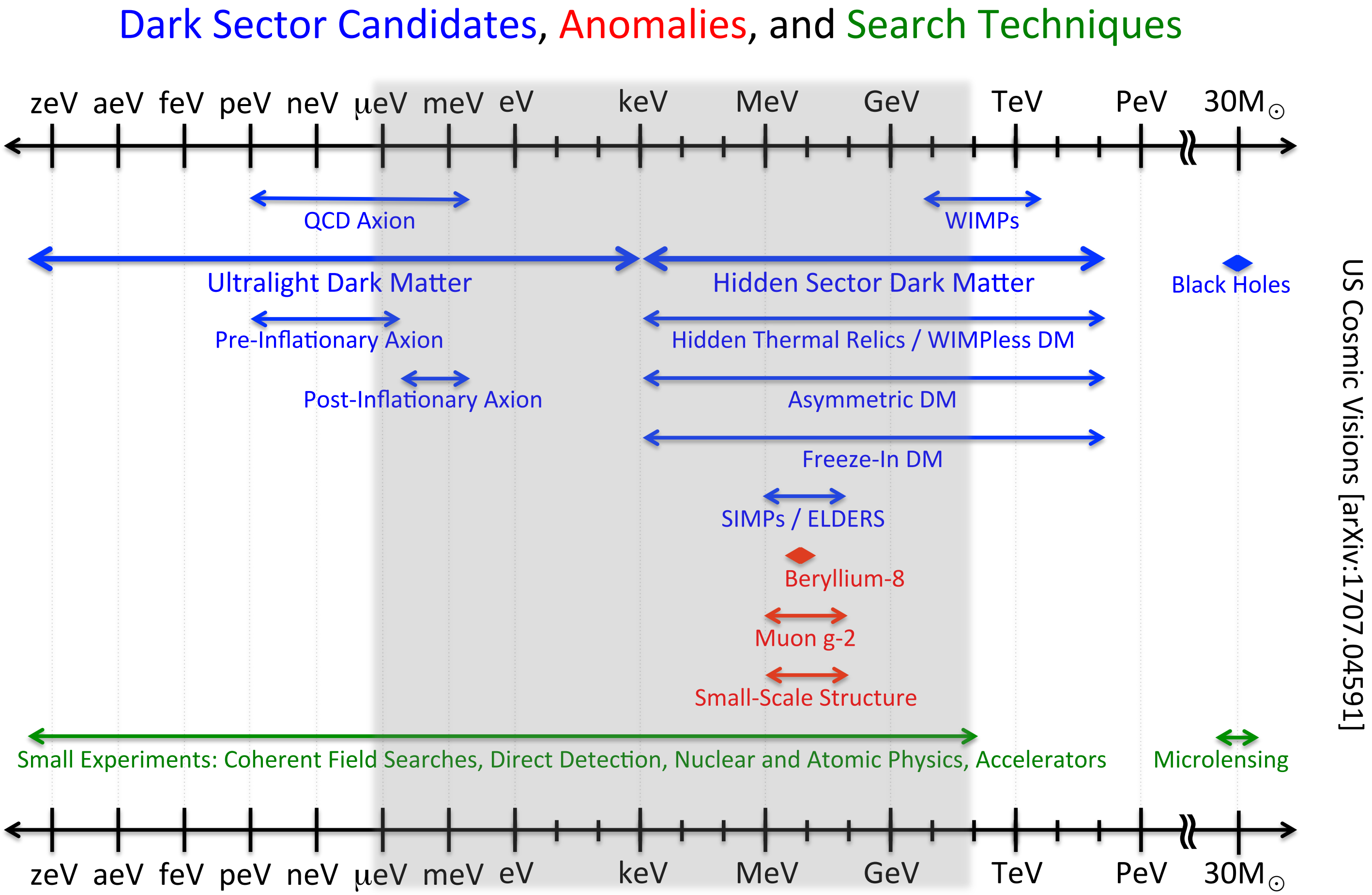
THE LANDSCAPE

Status



THE LANDSCAPE

Goal



LOW TEMPERATURE DARK MATTER DETECTORS

Posters

Contribution ID : 21 Diamond Detectors for Direct Detection of Sub-GeV Dark Matter
Contribution ID : 56 SuperCDMS HV Detector R&D
Contribution ID : 71 Impact Ionization in SuperCDMS HVeV Detectors
Contribution ID : 85 Overview of SuperCDMS Experiment
Contribution ID : 86 SuperCDMS IMPACT: an Ionization Yield Calibration Program
Contribution ID : 89 Large Area TES Chip with 40meV Resolution
Contribution ID : 103 Low temperature measurement on directional dependence of phonon-scintillation signals from a zinc tungstate crystal
Contribution ID : 115 Development of TES microcalorimeters for solar axion search
Contribution ID : 121 Development of large array of Kinetic Inductance Detectors using commercial level foundry
Contribution ID : 133 Lithium-containing crystals for light dark matter search experiments in underground laboratories
Contribution ID : 154 Diamond cryogenic detector for low-mass Dark Matter searches
Contribution ID : 168 COSINUS: Cryogenic calorimeter for the direct dark matter search with NaI crystals
Contribution ID : 187 NEXUS@FNAL
Contribution ID : 191 High Voltage New Interface Studies
Contribution ID : 218 Development of low threshold detectors for light dark matter detection
Contribution ID : 230 New Approaches to Very Low-energy Calibration of Cryogenic Detectors
Contribution ID : 248 Dynamic characterization of cryogenic optical photon detectors with Ir/Pt bilayer transition edge sensors
Contribution ID : 269 Modeling low-Tc Transition-Edge Sensors Made of Multi-layer Metal Films: Thickness Dependence of Electron Transparency at Interfaces
Contribution ID : 274 Kinetic inductance detectors on CaF2 for spin-dependent dark matter search
Contribution ID : 288 The Dark Matter Radio Pathfinder
Contribution ID : 290 BULLKID - Bulky and low-threshold kinetic inductance detectors
Contribution ID : 303 Optimizing Readout for Nuclear Magnetic Resonance Axion Searches
Contribution ID : 305 Quantum Sensors for Quantum Coherent Dark Matter Detectors
Contribution ID : 312 HeRALD, a new detector concept for light dark matter direct detection
Contribution ID : 336 Development of MMC based combined photon and phonon detector for rare event searches
Contribution ID : 376 Development of Ge bolometers using NbSi transition edge sensors for the EDELWEISS and RICOCHET projects
Contribution ID : 386 Noise temperature measurements for Axion haloscope experiment at CAPP
Contribution ID : 388 Status of the SIMP project: Towards the Single Microwave Photon Detection
Contribution ID : 403 Innovative technique for large scale production of W-TES
Contribution ID : 409 Progress on a KID-Based Phonon-Mediated Dark Matter Detector

Low temperature dark matter detectors have a unique potential to explore the unknown!