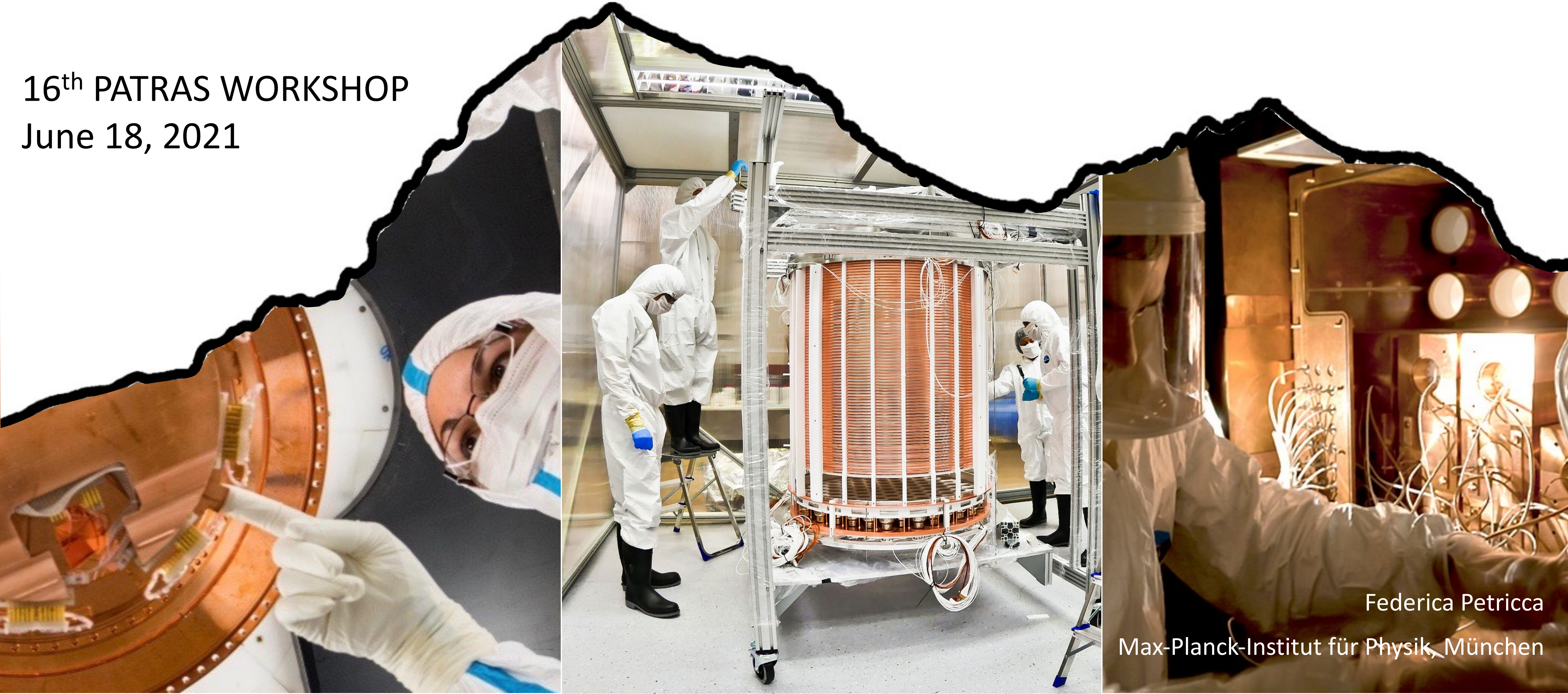
WIMP DIRECT DETECTION EXPERIMENTAL STATUS AND OUTLOOK 2021

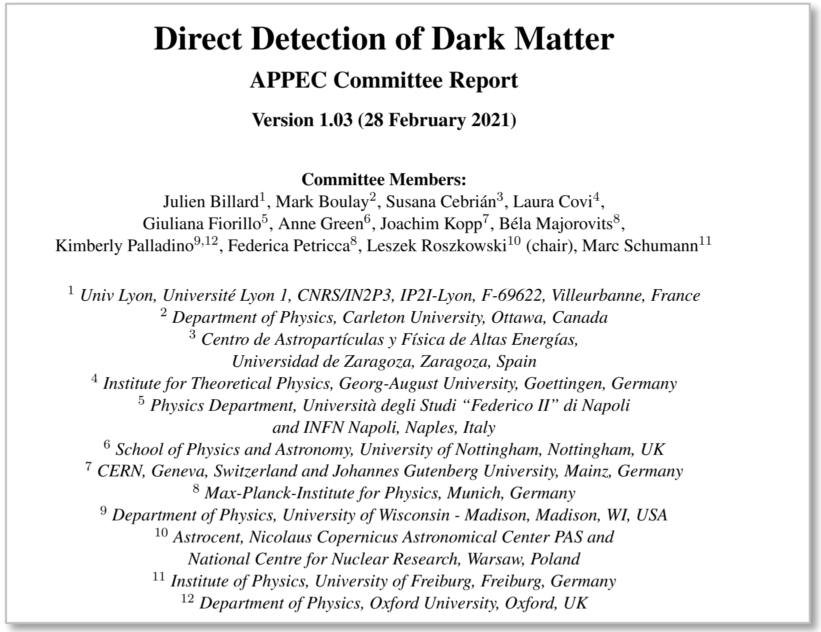
16th PATRAS WORKSHOP
June 18, 2021



Federica Petricca
Max-Planck-Institut für Physik, München

SOURCES

Largely taking advantage of:



Direct Detection of Dark Matter

APPEC Committee Report

Version 1.03 (28 February 2021)

Committee Members:
Julien Billard[1], Mark Boulay[2], Susana Cebrián[3], Laura Covi[4],
Giuliana Fiorillo[5], Anne Green[6], Joachim Kopp[7], Béla Majorovits[8],
Kimberly Palladino[9,12], Federica Petricca[8], Leszek Roszkowski[10] (chair), Marc Schumann[11]

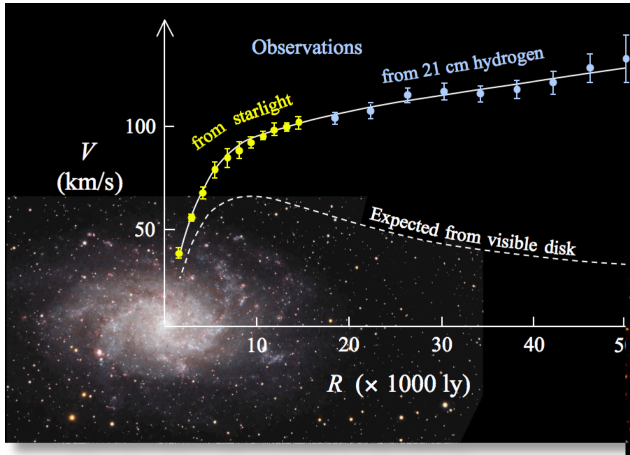
[1] *Univ Lyon, Université Lyon 1, CNRS/IN2P3, IP2I-Lyon, F-69622, Villeurbanne, France*
[2] *Department of Physics, Carleton University, Ottawa, Canada*
[3] *Centro de Astropartículas y Física de Altas Energías, Universidad de Zaragoza, Zaragoza, Spain*
[4] *Institute for Theoretical Physics, Georg-August University, Goettingen, Germany*
[5] *Physics Department, Università degli Studi "Federico II" di Napoli and INFN Napoli, Naples, Italy*
[6] *School of Physics and Astronomy, University of Nottingham, Nottingham, UK*
[7] *CERN, Geneva, Switzerland and Johannes Gutenberg University, Mainz, Germany*
[8] *Max-Planck-Institute for Physics, Munich, Germany*
[9] *Department of Physics, University of Wisconsin - Madison, Madison, WI, USA*
[10] *Astrocent, Nicolaus Copernicus Astronomical Center PAS and National Centre for Nuclear Research, Warsaw, Poland*
[11] *Institute of Physics, University of Freiburg, Freiburg, Germany*
[12] *Department of Physics, Oxford University, Oxford, UK*

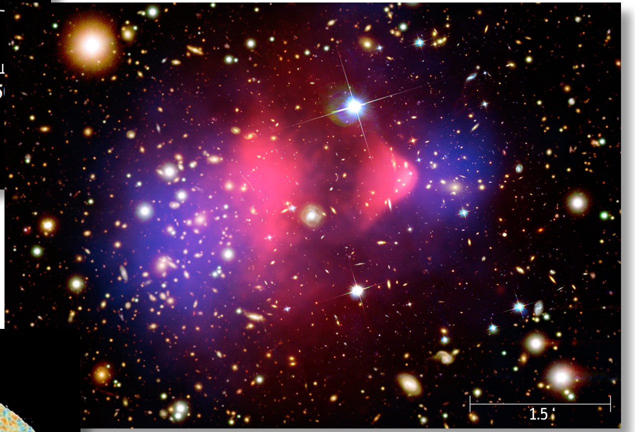
https://arxiv.org/abs/2104.07634

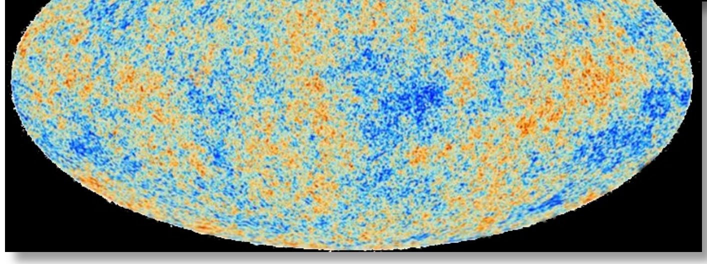
You will be able to find details I cannot include here!

DISCLAIMERS:
- The perspective on the speaker in a review is unavoidable.
- No complete list of experiments presented.
- Focus on differences and complementarities and not on results.

THE DARK MATTER PROBLEM

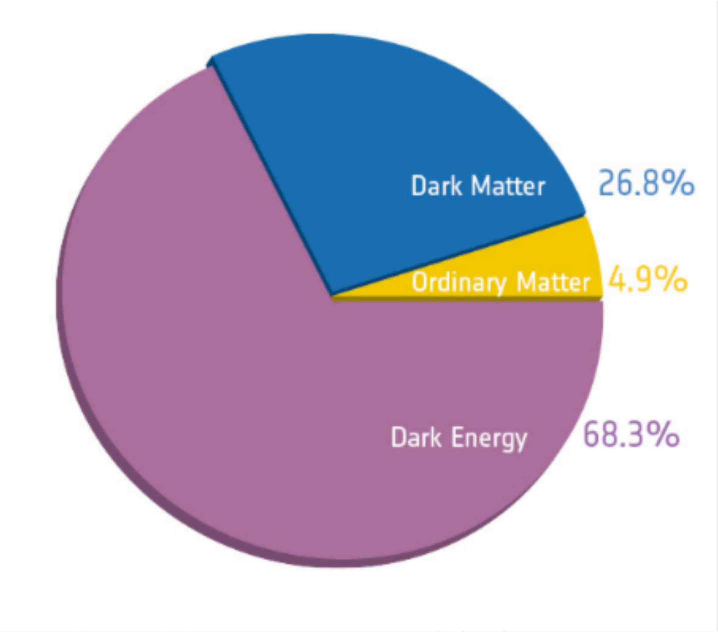




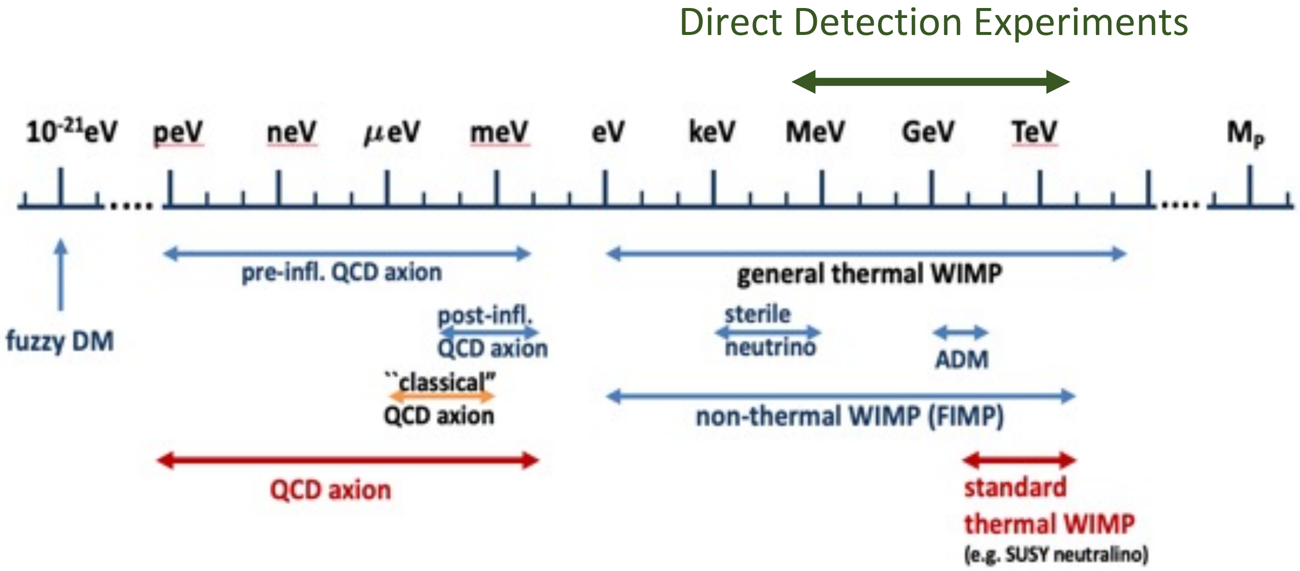


Compelling evidence for dark matter on various cosmological scales

THE DARK MATTER PROBLEM



Source: © European Space Agency / Planck



https://arxiv.org/abs/2104.07634

Fore more information on mass scale:

-*Dark matter production in the early Universe: beyond the thermal WIMP paradigm,* Phys. Rept. 555 (2015) 1–60

-*WIMP dark matter candidates and searches current status and future prospects,* Rept. Prog. Phys. 81 (2018), no. 6 066201

DARK MATTER DIRECT DETECTION

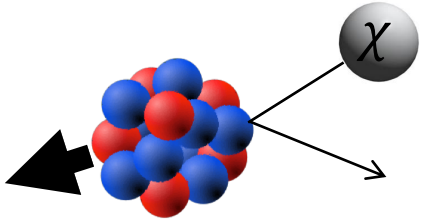
Search for signals induced by dark matter from the Galactic dark matter halo in terrestrial detectors

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

Most common scenario

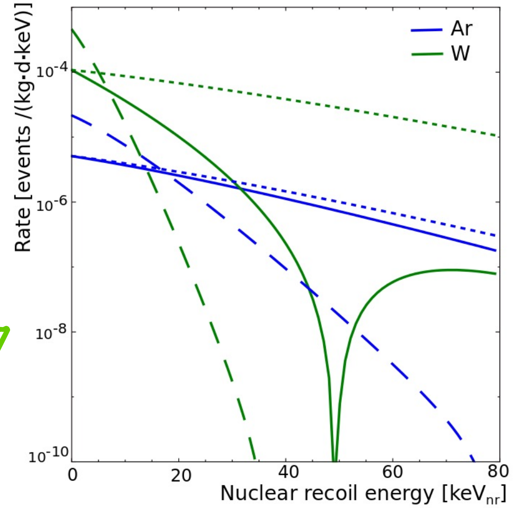
- (in)elastic scattering off a target nucleus
- momentum transfer gives rise to a nuclear recoil

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

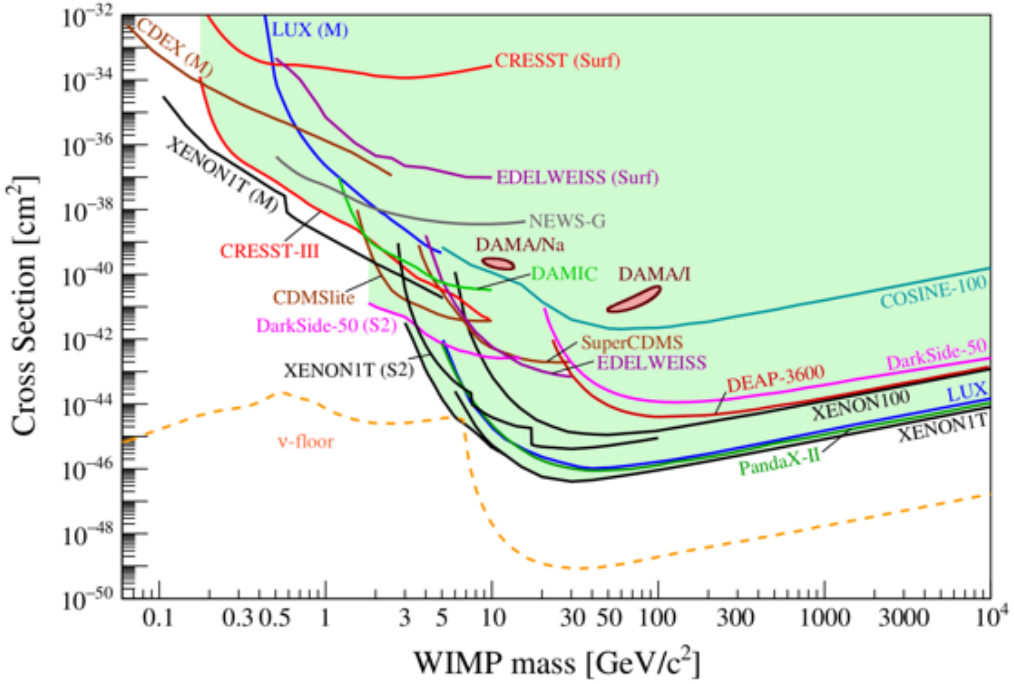


DARK MATTER DIRECT DETECTION

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



Picture from: Direct Detection of Dark Matter APPEC Committee Report
submitted to APPEC for final approval



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

Credit: ESO/L. Calçada

SCATTERING CROSS SECTION

Dark matter particle-nucleus scattering:

- Spin Independent – coupling to mass

$$\sigma_{SI} \propto \frac{\mu^2}{m_\chi^2}\left[Zf_p + (A-Z)f_n\right]^2$$

f_n, f_p scalar couplings to *n* and *p*

nuclei with large A favourable (but nuclear form factor corrections)

- Spin Dependent – coupling to nuclear spin

$$\sigma_{SD} \propto \mu^2 \frac{J_N + 1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

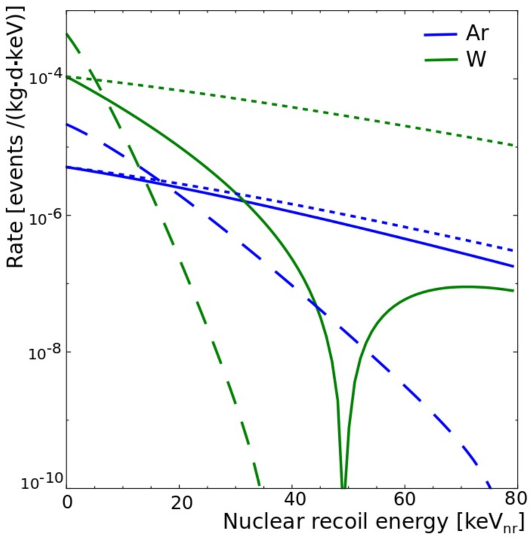
a_n, a_p effective couplings to *n* and *p*

$\langle S_n\rangle, \langle S_n\rangle$ expectation values of *n* and *p* spins within the nucleus

nuclei with non-zero angular momentum

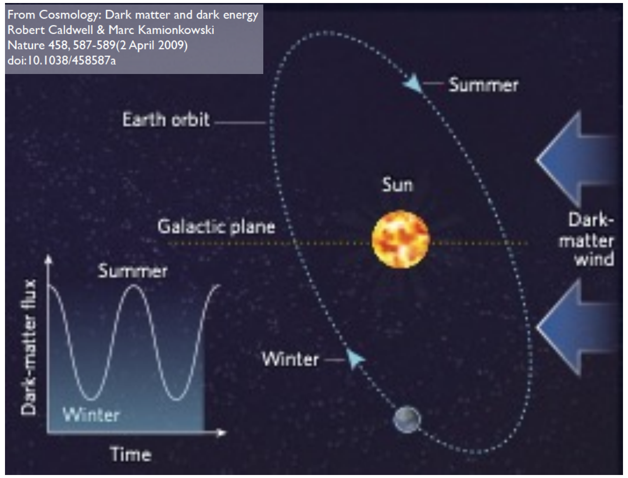
EXPERIMENTAL SIGNATURES

Spectral shape


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

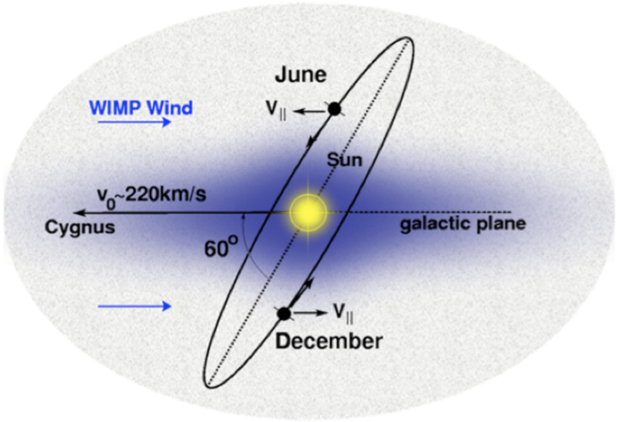
Shape of recoil spectra (on different target materials)

Annual modulated rate


From Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)
doi:10.1038/458587a

Motion on the Earth orbiting around the Sun leads to a periodic modulation of the signal

Directional dependence



Motion of the Sun with respect to the Galactic rest frame leads to a directional dependence of nuclear recoils due to dark matter scattering

MINIMISING BACKGROUND

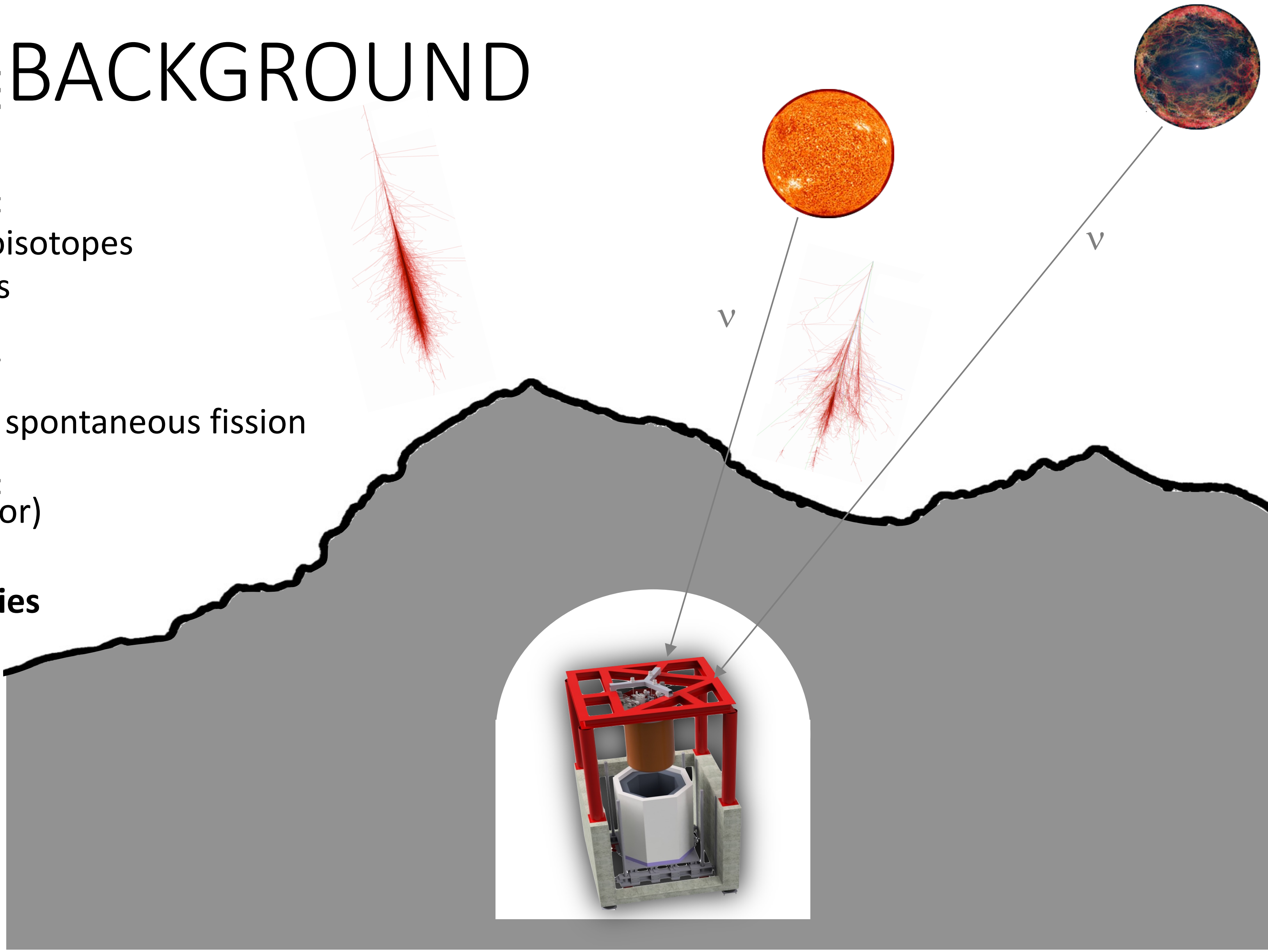
Beta and gamma background
- long-lived natural radioisotopes
- anthropogenic isotopes

Alpha background

n background
- radiogenic (alpha,*n*) or spontaneous fission
- muon-induced

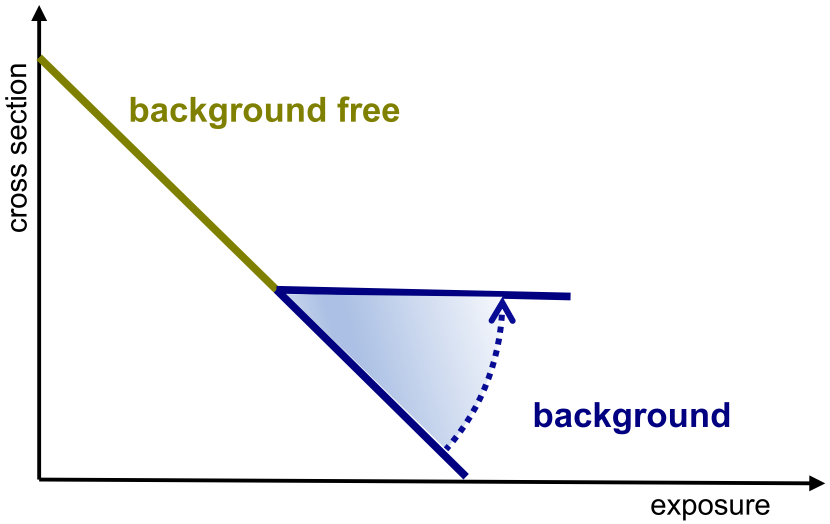
ν background (the neutrino floor)

Background mitigation strategies
- Underground site
- Shield/veto/fiducialisation
- Radon mitigation
- Purity of materials
- Material handling
- Event-by-event discrimination



Images from Wikimedia Commons
http://www.spacetelescope.org/images/opo1438a/
http://sdo.gsfc.nasa.gov/assets/img/browse/2010/08/19/20100819_003221_4096_030

MINIMISING BACKGROUND



- The scaling of the sensitivity with exposure is linear in a background free situation
- In presence of background the scaling of the sensitivity with exposure depends on the capability of identifying signal on top of background (the more background is “signal-like” the more sensitivity is limited)

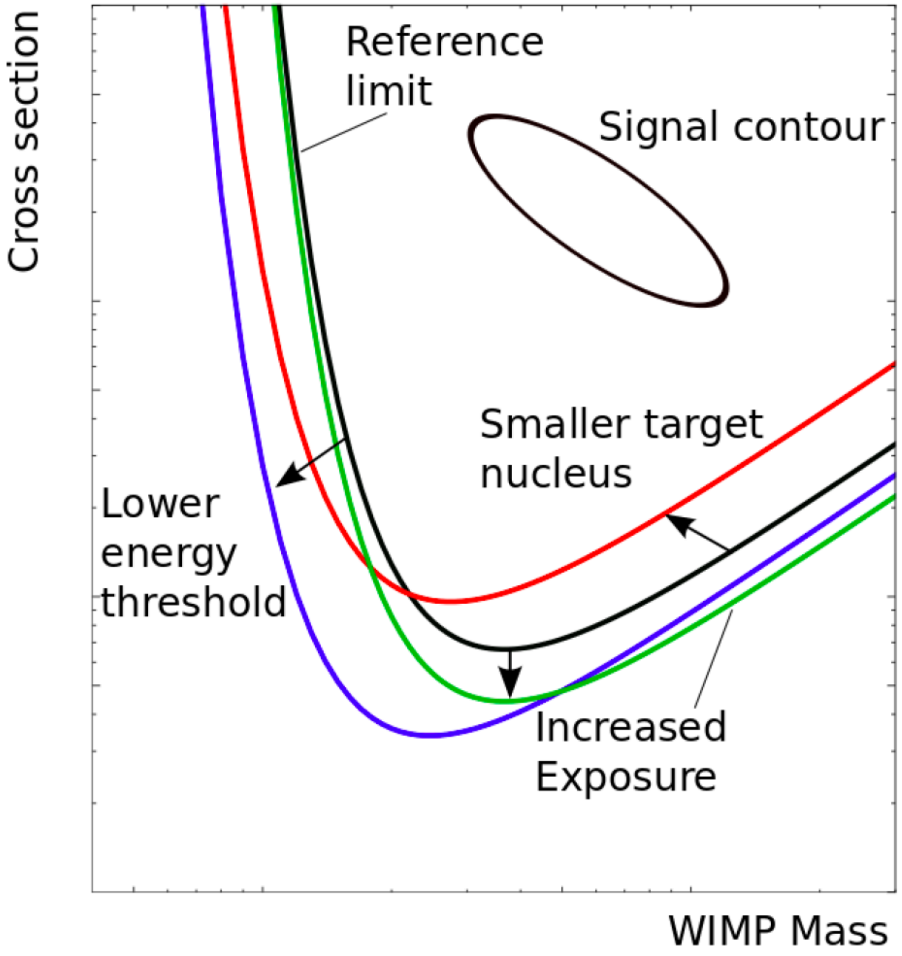
For a discovery:
understand residual background
(resolution, position reconstruction, background modelling,…)

SENSITIVITY

At large dark matter masses sensitivity is dominated by exposure
- target mass

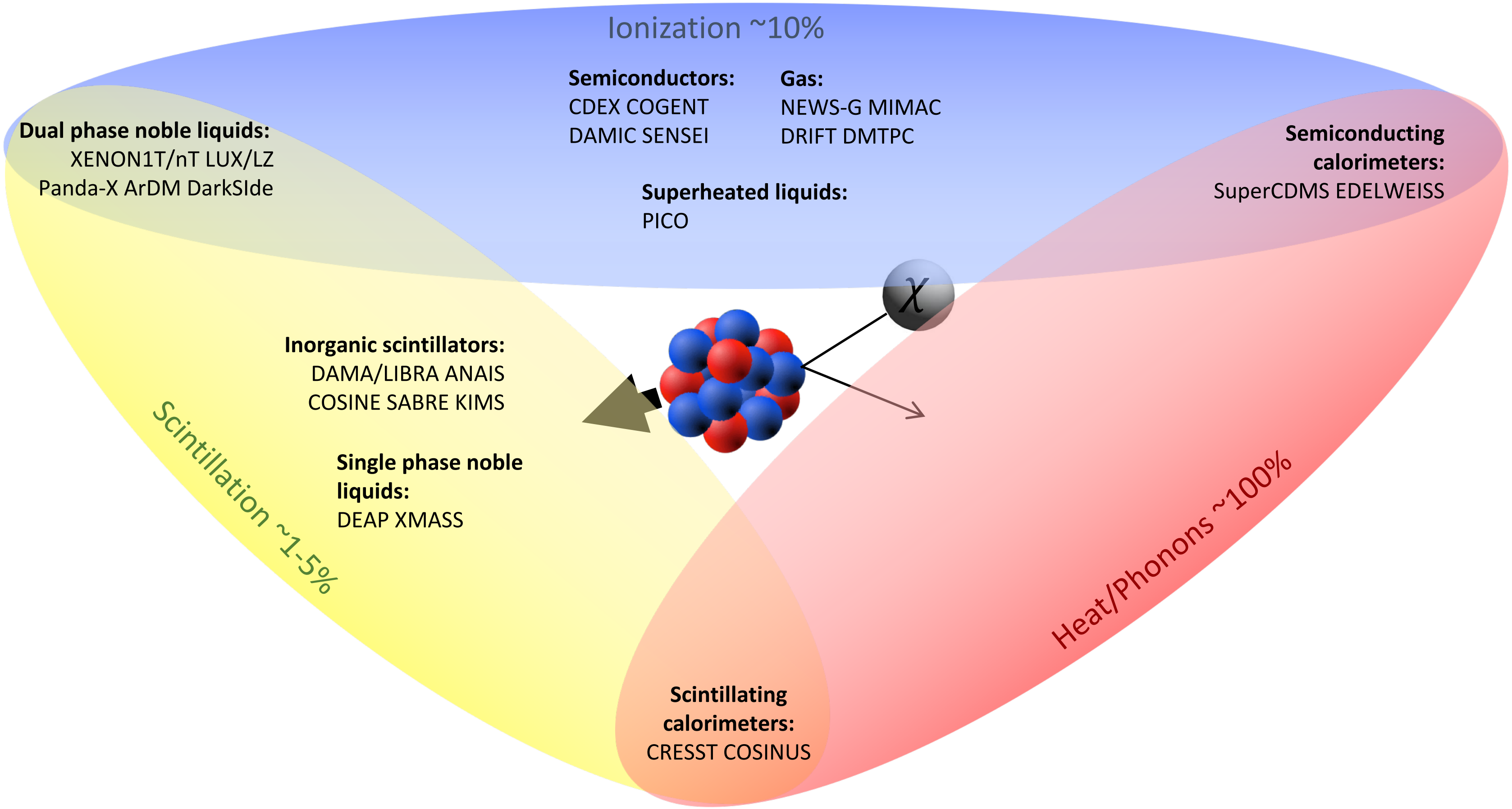
At light dark matter masses sensitivity is dominated by performances
- energy threshold

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



DIRECT DARK MATTER SEARCHES

An incomplete compilation



Ionization ~10%

Semiconductors:
CDEX COGENT
DAMIC SENSEI

Gas:
NEWS-G MIMAC
DRIFT DMTPC

Superheated liquids:
PICO

Dual phase noble liquids:
XENON1T/nT LUX/LZ
Panda-X ArDM DarkSIde

Semiconducting calorimeters:
SuperCDMS EDELWEISS

Inorganic scintillators:
DAMA/LIBRA ANAIS
COSINE SABRE KIMS

Single phase noble liquids:
DEAP XMASS

Scintillation ~1-5%

Heat/Phonons ~100%

Scintillating calorimeters:
CRESST COSINUS

A HISTORICAL OVERVIEW

1984 – Drukier and Stodolsky proposed the use of superconducting micro-grains to detect, with high cross-section, neutrinos scattering coherently off nuclei
Drukier, A. K., and Stodolsky L., *Phys. Rev.* D **30** 2295 (1984)

1985 – Following this idea, Goodman and Witten proposed to use cryogenic detectors for detecting dark matter candidates
Goodman, M. W. and Witten, E. 1985 *Phys. Rev.* D **31** 3059 (1985)

1986 – Drukier, Freese and Spergel propose to use the annual modulation signature
Drukier, A. K., Freese, K. and Spergel, D. N. *Phys. Rev.* D, **33** 3495 (1986)

1986 – First direct DM searches with Ge
S.P. Ahlen, F.T. Avignone, et al, *Phys. Lett.* B 195, Issue 4 (1987) - Homestake
O. Cremonesi ESO Conf. Workshop Proc. 23 265-268 (1986) – Mont Blanc

1987 – 1995 Proposal e prototyping of CDMS, CRESST, EDELWEISS based on cryogenic detectors

1988 – DM searches with Ge at the Oroville dam
Caldwell D.O., et al. PRL 61, 510 (1988) – Oroville dam

1993 – Proposal to use LXe scintillation
Benetti P. et al NIM A327 203-206 (1993)

1998 – First results from DAMA on annual modulation
Bernabei, R., et al. *Phys.Lett.* B424, 195 (1998) – Gran Sasso

2000 – First CDMS Si and Ge cryogenic detectors result
Abusaidi, R.A., PRL 84, 5699-5703 (2000) – Stanford University

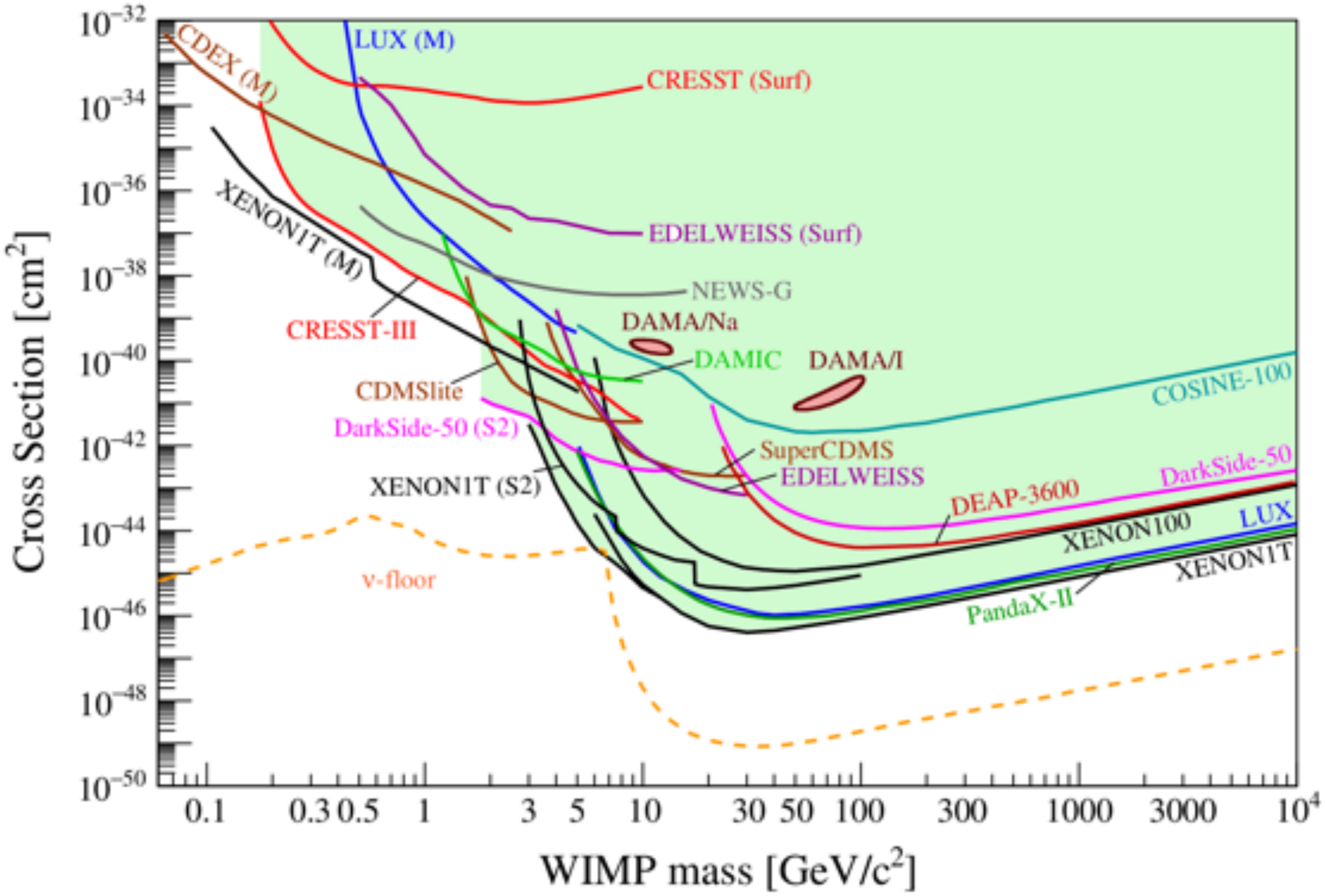
2000 – First results from IGEX Ge detectors
Morales, A., et al, *Phys. Lett.* B 489 268–272 (2000) - Canfranc

2001 – First EDELWEISS DM result with Ge cryogenic detectors
A. Benoit et al. - Phys. Lett. B 513 (2001) 15-22 - Modane

2002 – First CRESST DM result with Al_2O_3
Angloher, G., et al *Astropart. Phys.*, 18 43–55 (2002)) – Gran Sasso

2005 - First ZEPPELIN-I result with LXe
Alner, G.C., et al *Astropart. Phys.*, 23 444–462 (2005) – Boulby Mine

THE EXPERIMENTAL LANDSCAPE



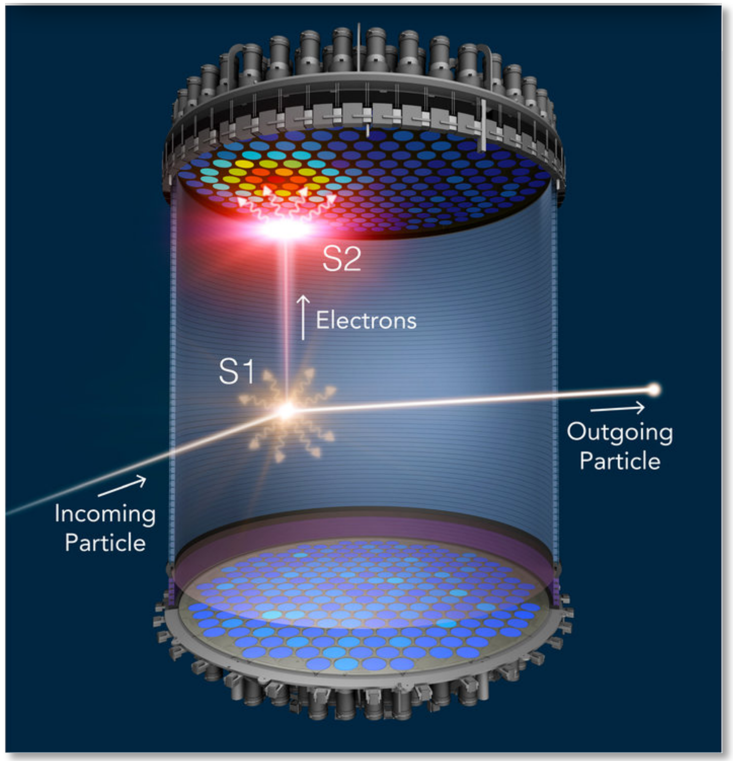
Picture from: Direct Detection of Dark Matter APPEC Committee Report
https://arxiv.org/abs/2104.07634

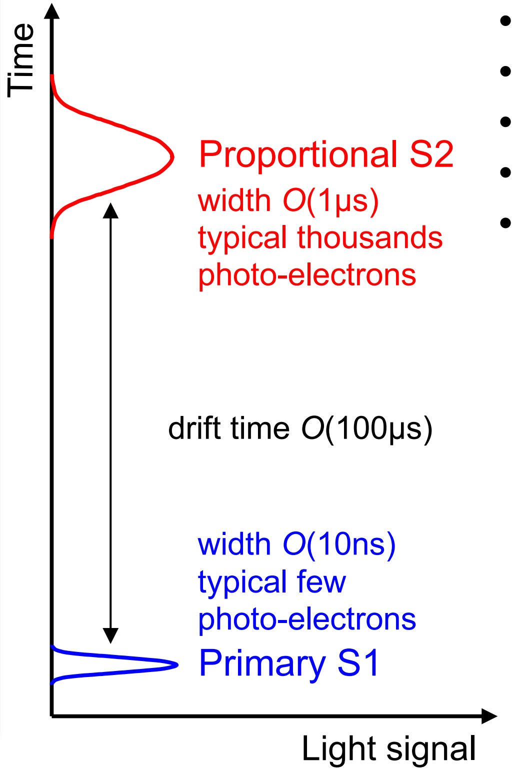
Current status* of searches for spin-independent elastic WIMP-nucleus scattering assuming the standard parameters for an isothermal WIMP halo: ρ_0 = 0.3 GeV/cm^3, v_0 = 220 km/ s, v_{esc} = 544 km/s. Results labelled "M" were obtained assuming the Migdal effect. Results labelled "Surf" are from experiments not operated underground. The ν-floor shown here for a Ge target is a discovery limit defined as the cross section σ_d at which a given experiment has a 90% probability to detect a WIMP with a scattering cross section $\sigma > \sigma_d$ at ≥3 sigma.

* Published in a peer reviewed journal at the time of writing

LIQUID NOBLE GASES TPCs

LUX/LZ, XENON, PandaX, DarkSide, ArDM




Time

Proportional S2
width $O(1\mu s)$
typical thousands photo-electrons

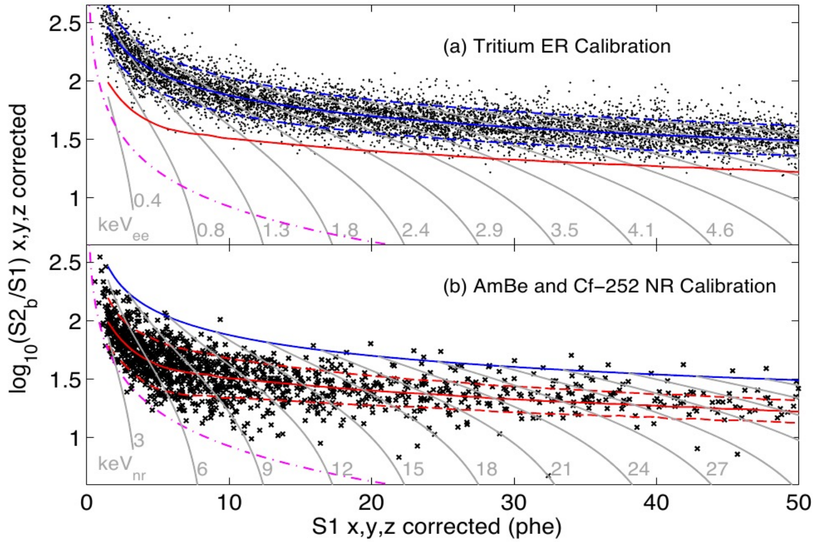
drift time $O(100\mu s)$

width $O(10ns)$
typical few photo-electrons
Primary S1

Light signal

Dual-phase time projection chambers

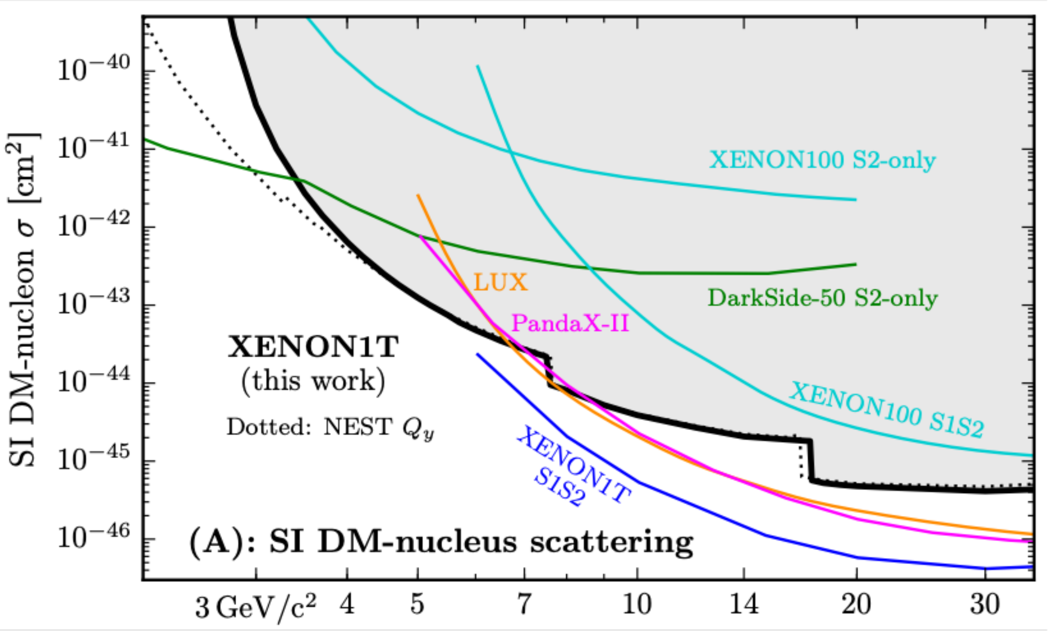
- measure the primary scintillation signal (S1) in the liquid and ionisation electrons via secondary scintillation (S2) in the gas
- ratio S2/S1 used to distinguish electronic from nuclear recoils
- reconstruction of the interaction position with mm-precision
- multi-scatter rejection
- Ar detectors employ PSD for background reduction
- limited threshold in standard operating mode



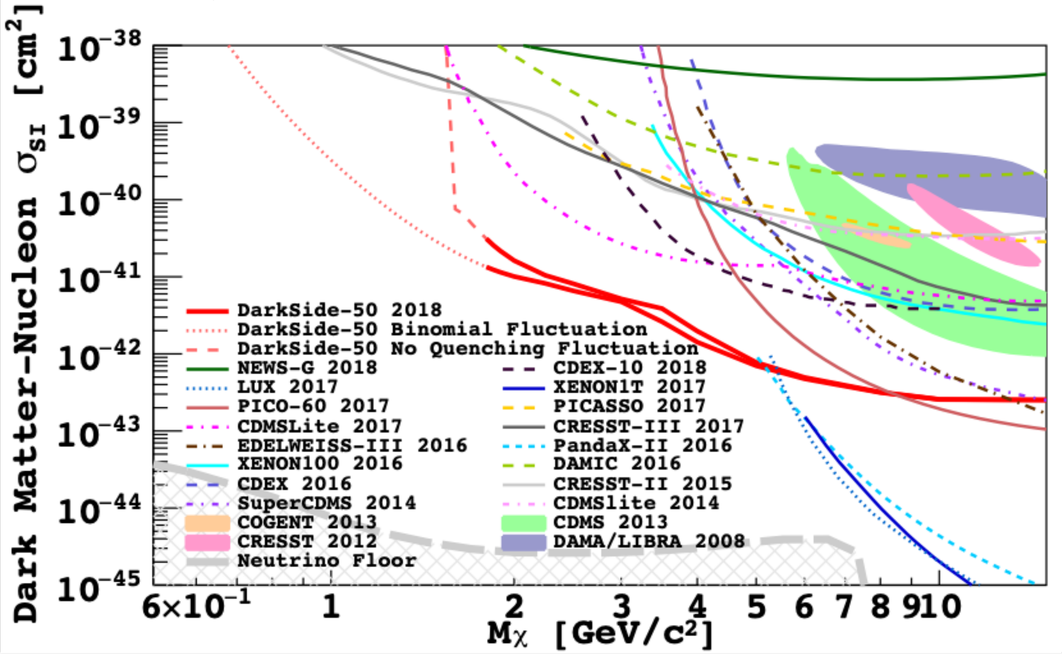
S2 ONLY IN LIQUID NOBLE GASES TPCs

- Light collection less efficient than e^- collection
- Use S2 signal only
- ~~Time Projection~~ Chamber
- Sensitive to single extracted electrons
- Substantially reduce *E* threshold (e.g. XENON1T ~5keV$_{nr}$ in TPC mode, ~1,6keV$_{nr}$ in S2 only mode)

Phys.Rev.Lett. 123 (2019) 25, 251801



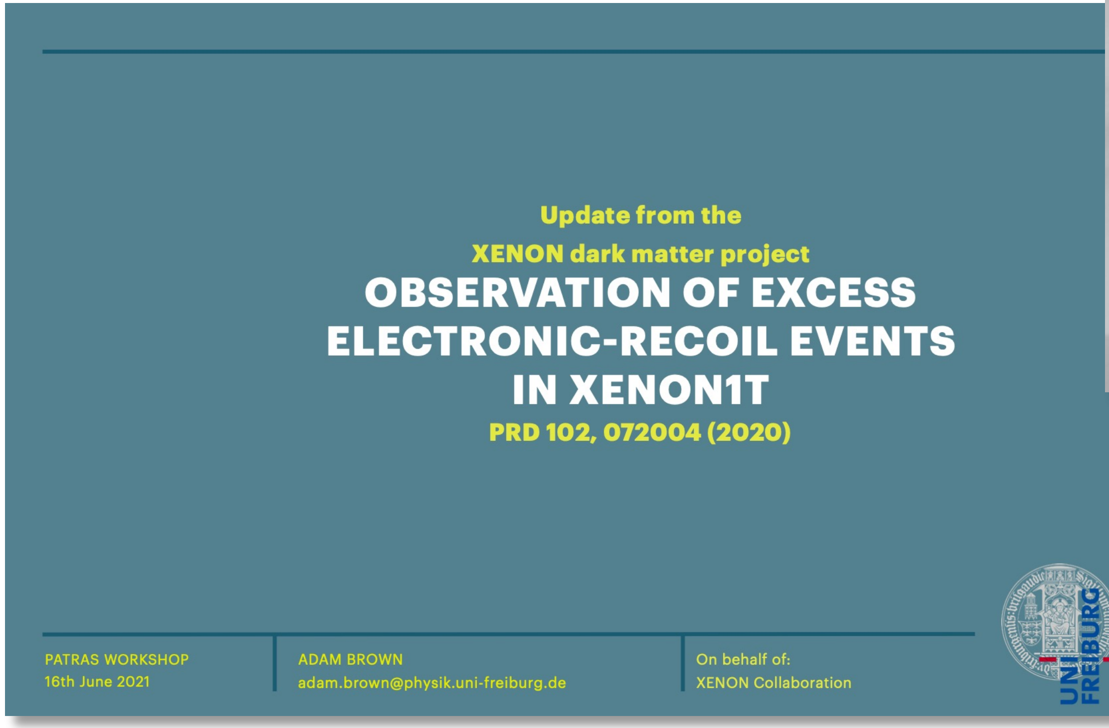
Phys.Rev.Lett. 121 (2018) 8, 081307



LIQUID NOBLE GASES TPCs

Overview and Status of the LUX-ZEPLIN (LZ) Experiment

Amy Cottle,
University of Oxford,
16th Patras Workshop



Update from the
XENON dark matter project

OBSERVATION OF EXCESS ELECTRONIC-RECOIL EVENTS IN XENON1T

PRD 102, 072004 (2020)

PATRAS WORKSHOP
16th June 2021

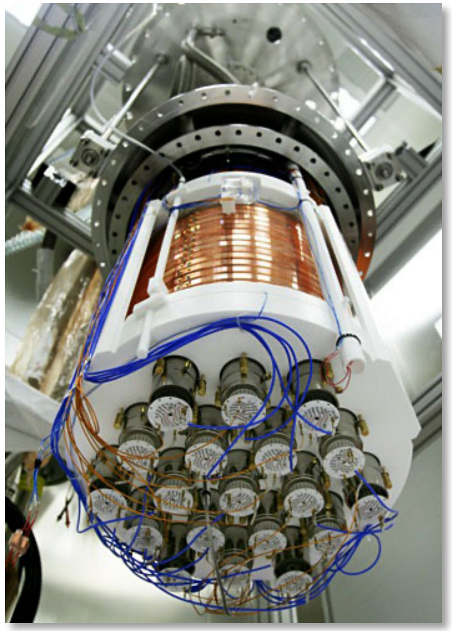
ADAM BROWN
adam.brown@physik.uni-freiburg.de

On behalf of:
XENON Collaboration

LIQUID NOBLE GASES TPCs

In the last decades dual phase liquid noble gas experiments have consolidated their role as the leading technology in the mass range from few GeV/c^2 to the TeV/c^2 scale.

DarkSide



XENON

- Easily scalable to very large masses (multi-tonne)
- Fiducialisation (self-shielding)
- Limited E threshold in standard operating mode
- Very effective in the WIMP-like scenario and for heavy dark matter

Ar

Pros:

- Better background discrimination using pulse shape

Cons:

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

Xe

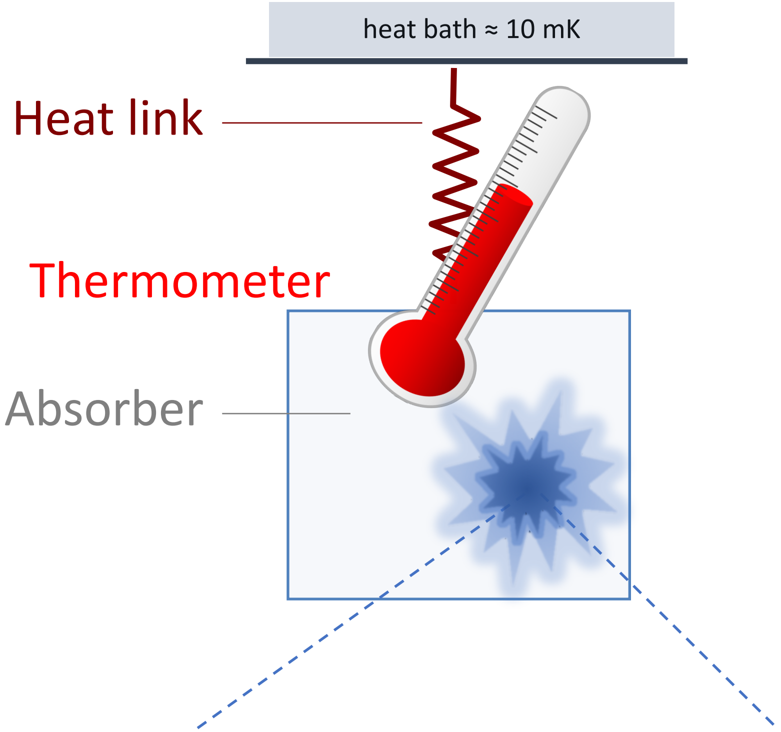
Pros:

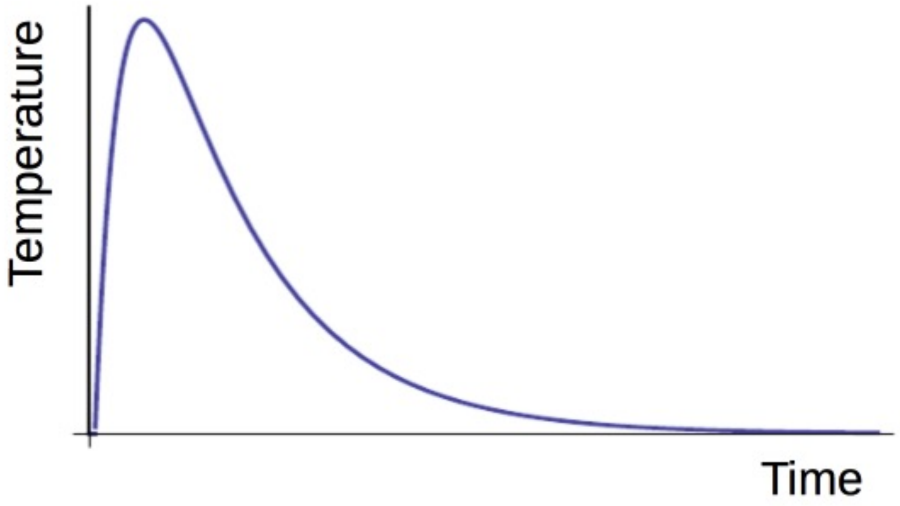
- Heavy
- High liquid density
  - compact detector
- No radioactive isotopes

Cons:

- Low fraction in atmosphere
  - more expensive than natural Ar

CALORIMETERS





$\Delta T = \Delta E/C$

- Direct measurement of the (almost) full energy deposition
- Low (< 100eV) nuclear recoil energy thresholds
- Background rejection down to low energy
- mK operating temperature

SEMICONDUCTING CALORIMETERS

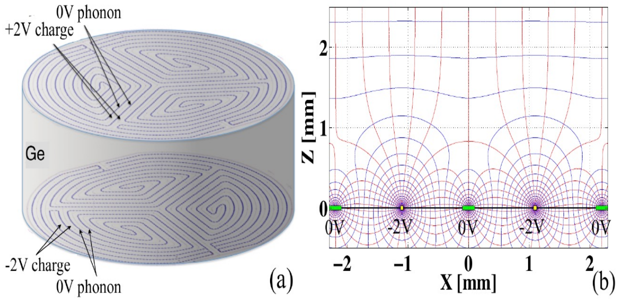
Phonon + Ionization

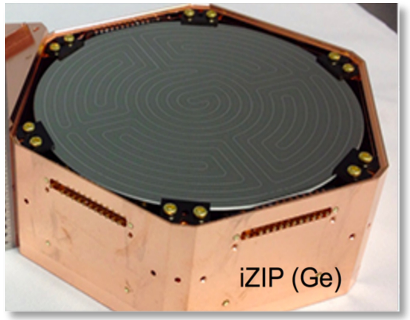
EDELWEISS, SuperCDMS

- Phonon and charge sensors on the target crystal
- Particle identification via ratio of ionization to primary phonon
- Surface events identified thanks to ID electrodes

SuperCDMS interleaved Z-sensitive Ionization Phonon (iZIP) detector

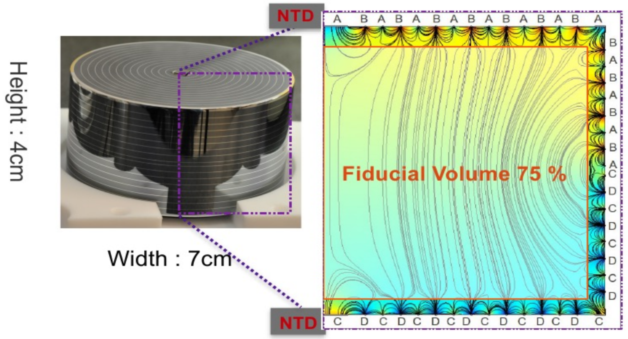
- 15 x 600g detectors
- 2 charge + 2 charge
- 4 + 4 TES – fast phonon channel

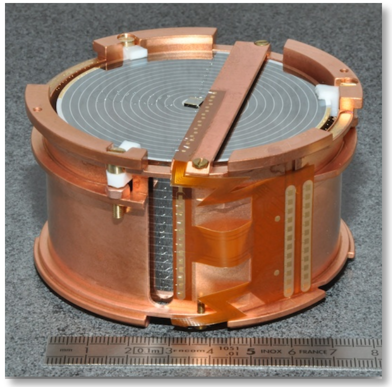




EDELWEISS FID800

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





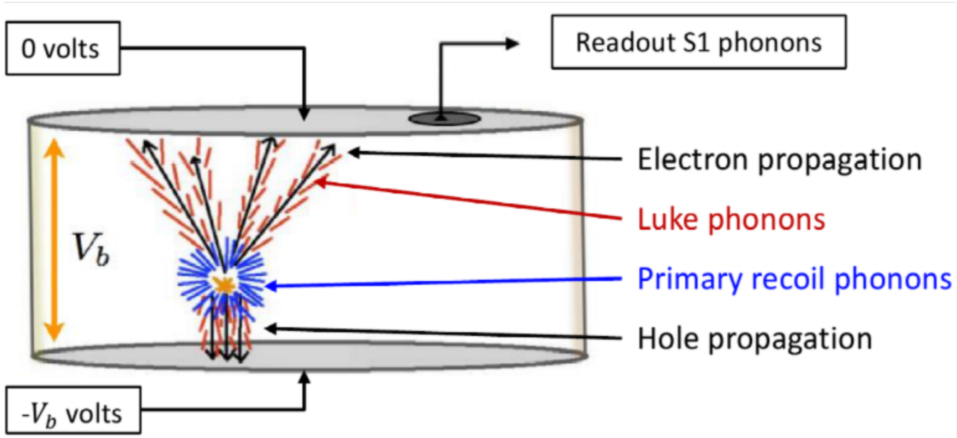
SEMICONDUCTING CALORIMETERS

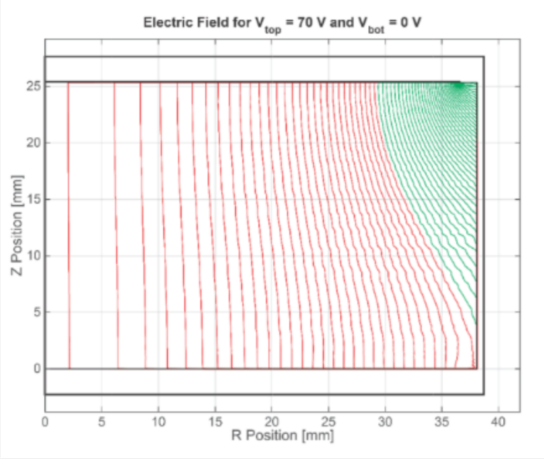
Phonon + Ionization

EDELWEISS, SuperCDMS

Lite/HV-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

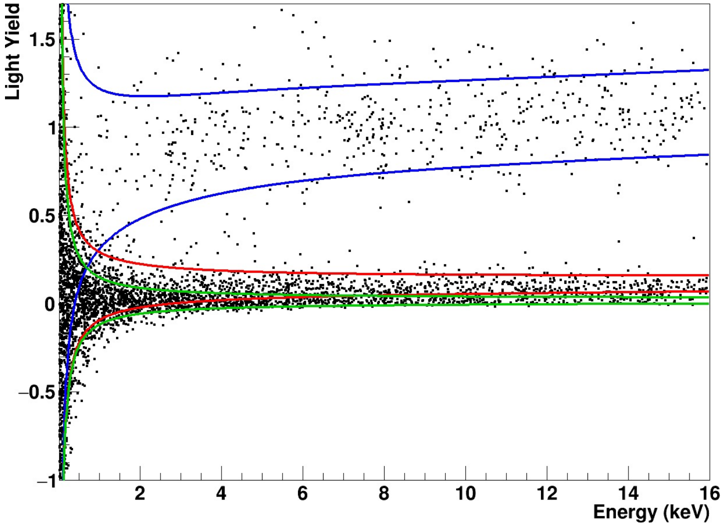
NTL effect mixes charge and phonon signal reducing discrimination

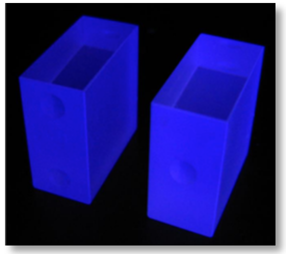
SCINTILLATING CALORIMETERS

Phonon + Light

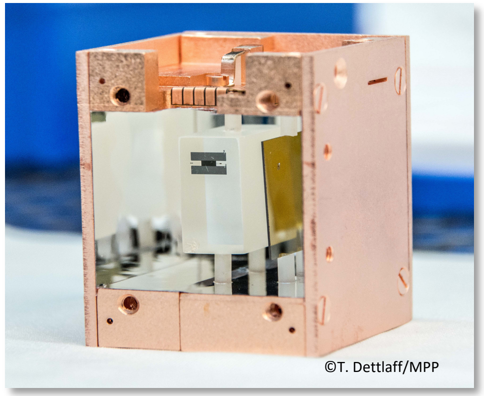
CRESST

- Phonon sensor on the target crystal, separate cryogenic detector for light signal
- Particle identification via ratio of light to primary phonon

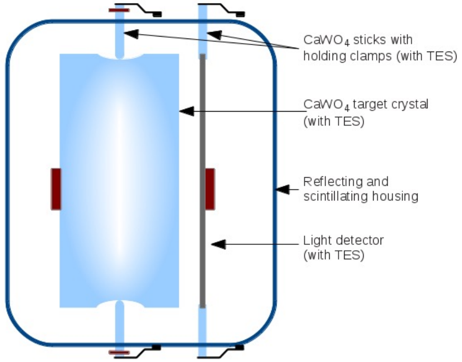




Scintillating target crystals ($CaWO_4$)



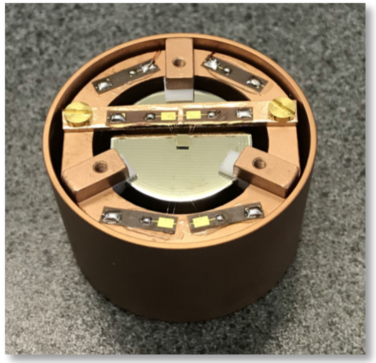
©T. Dettlaff/MPP



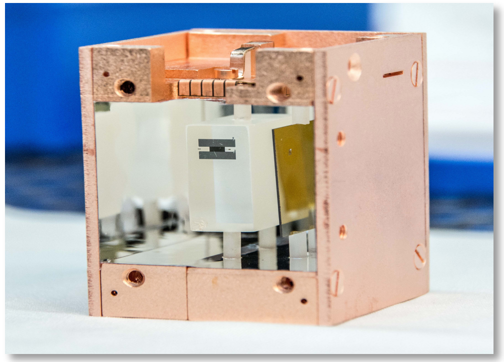
CRESST-III detector layout optimized for low-mass dark matter

CRYOGENIC EXPERIMENTS

EDELWEISS



CRESST



- Unique in exploring the low mass range down to the MeV/c^2 regime
- Possibility of using different target materials – complementary sensitivities to different models
- Slow scalability to large exposures
- Technology being exploited for CEvNS

Pros:

- Ultrapure material
- Identification of surface events
  - Fiducialisation

Cons:

- Limited choice of materials
- Rejection capabilities and fiducialisation lost in high-voltage mode

Pros:

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

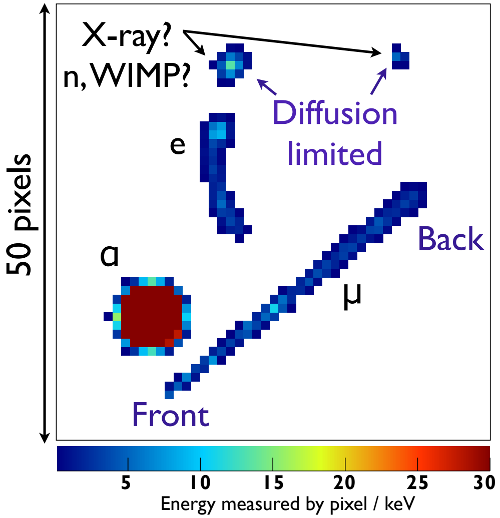
Cons:

- Independent cryogenic light detector
  - Increase number of channels
- No fiducialisation

SILICON CHARGE-COUPLED DEVICES (CCDs)

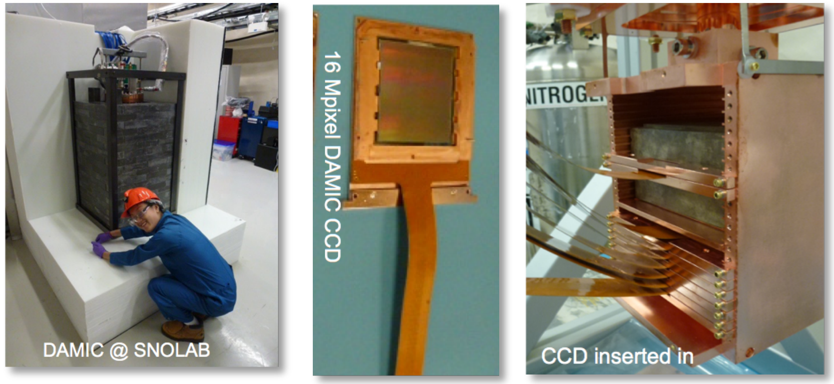
DAMIC, SENSEI

High sensitivity to single-electron signals
Very low energy threshold (≈ 50 eV_{ee})

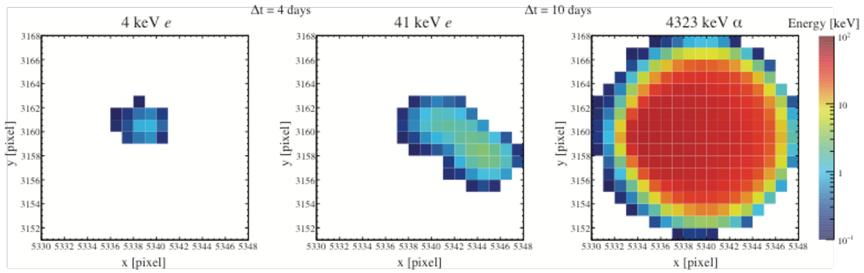


Exquisite spatial resolution:

- Particle identification
- Surface background rejection
- Background measurements



Pictures courtesy DAMIC collaboration



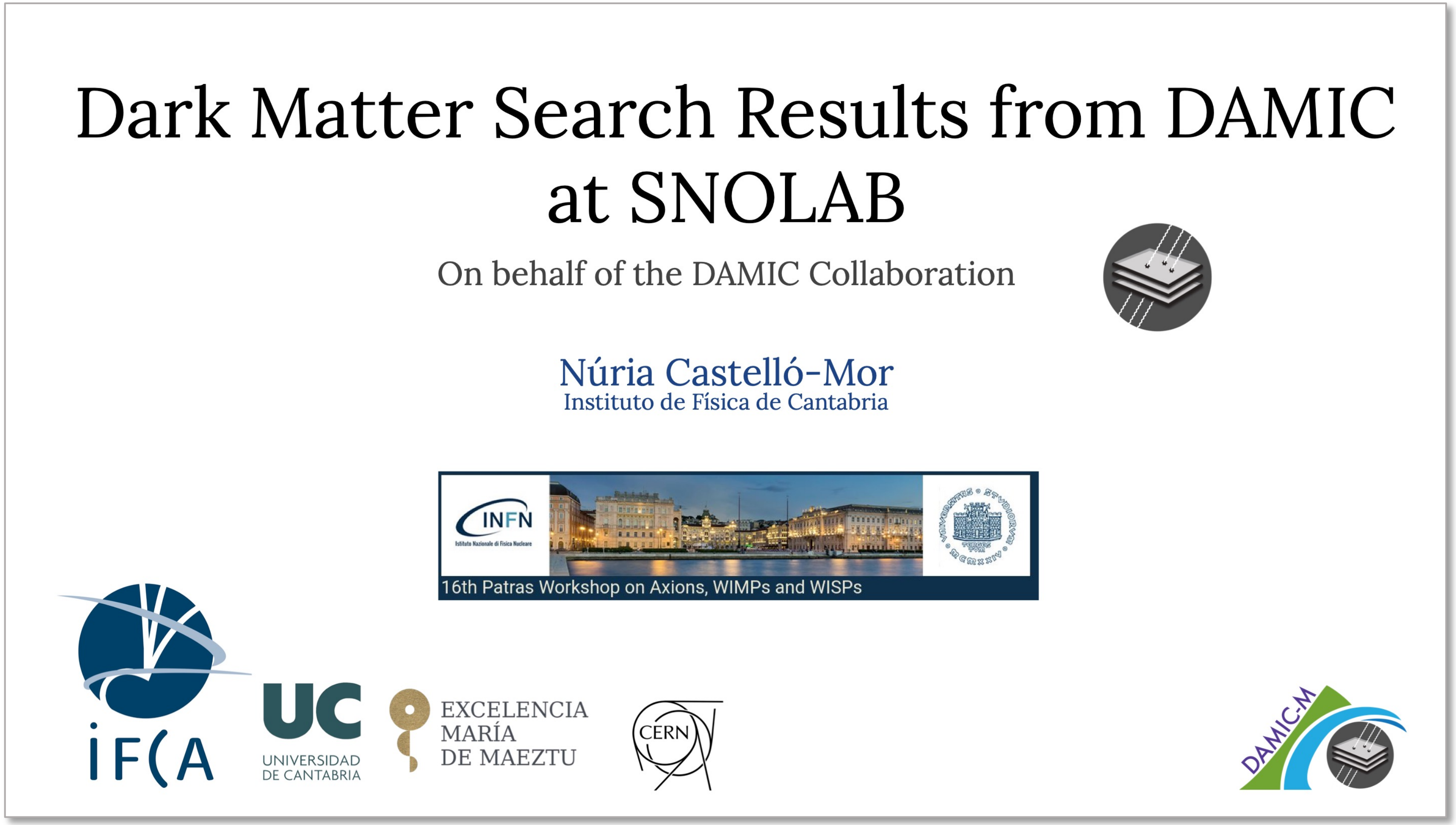
Two betas and one alpha occurring in the same location separated by days: example of a single ^{210}Pb nucleus decay chain

Key features:

- Fiducialisation (self-shielding)
- Well established technology
- Reproducible and scalable
- Low threshold for electron interactions
- Very clean detector
- Long signal collection time
  - No time coincidence
  - Need of deep underground labs
- Limited nuclear recoil threshold

Unique capability to measure and reject ^{32}Si and ^{210}Pb

SILICON CHARGE-COUPLED DEVICES (CCDs)



Dark Matter Search Results from DAMIC at SNOLAB

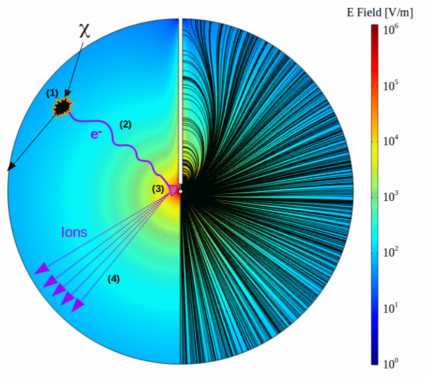
On behalf of the DAMIC Collaboration

Núria Castelló-Mor
Instituto de Física de Cantabria

16th Patras Workshop on Axions, WIMPs and WISPs

SPHERICAL PROPORTIONAL COUNTERS

NEWS-G

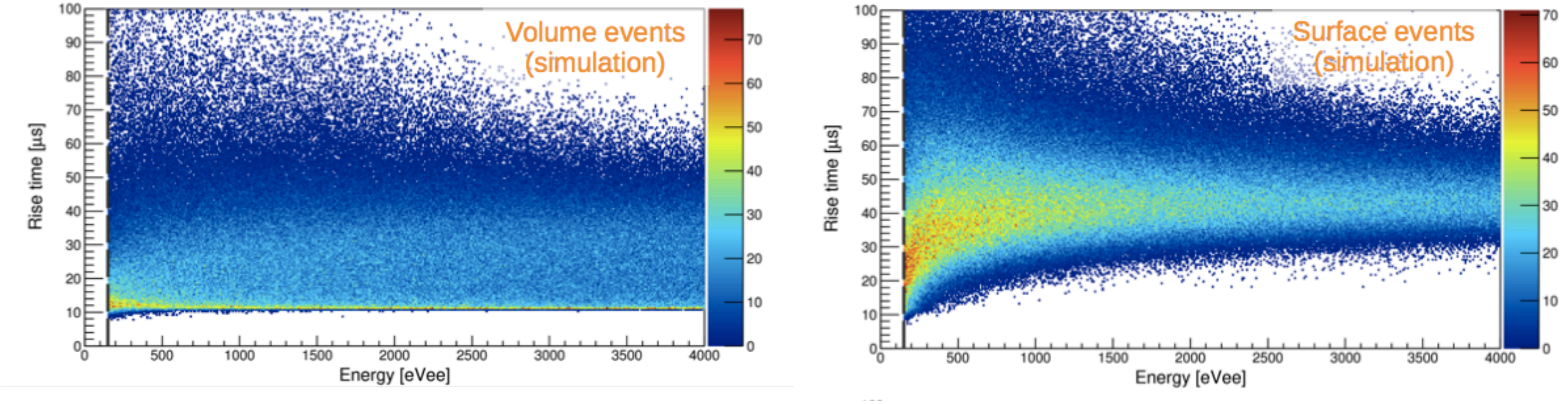


Unconventional gas detector; able to achieve very low energy threshold thanks to very low capacitance (<1 pF) for a large volume.

Key features:

- Light target (Ne, He, H)
- Pulse shape discrimination against surface events down to low energy
- Low threshold of 10-40 eV_{ee}
    - Low capacitance
    - High amplification gain for the avalanche

The SEDINE prototype detector at LSM



THRESHOLD DETECTORS

PICO (PICASSO + COUPP)

Tiny energy deposition

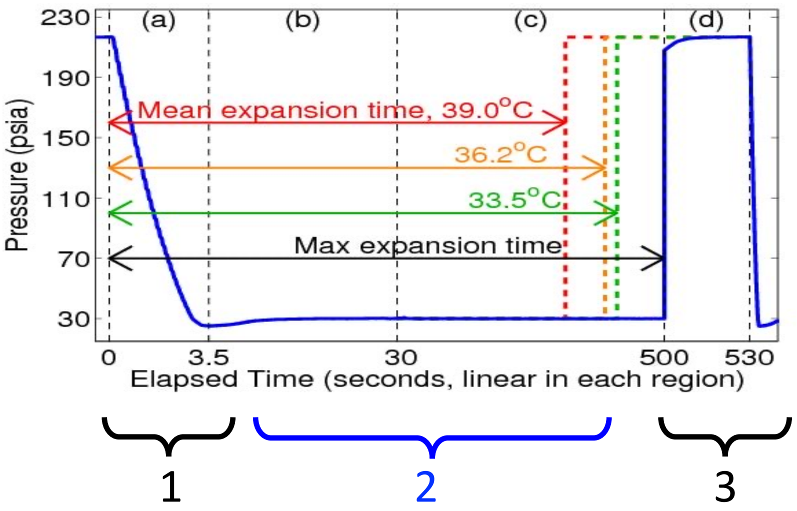
→ Macroscopic phase transition

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

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

- Fluid in a metastable state which can be quenched by energy depositions
- Threshold device with integrating response, no information on the energy of the event
- Can be tuned to be immune to e-recoils
- Alpha-particles can be rejection based on acoustics of bubble explosion
- Highest sensitivity for SD couplings to protons thanks to F-targets



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)

SCINTILLATION DETECTORS

DAMA/LIBRA, ANAIS, COSINE (in data taking), COSINUS, SABRE, PICOLON (in preparation)

ANAIS

COSINE

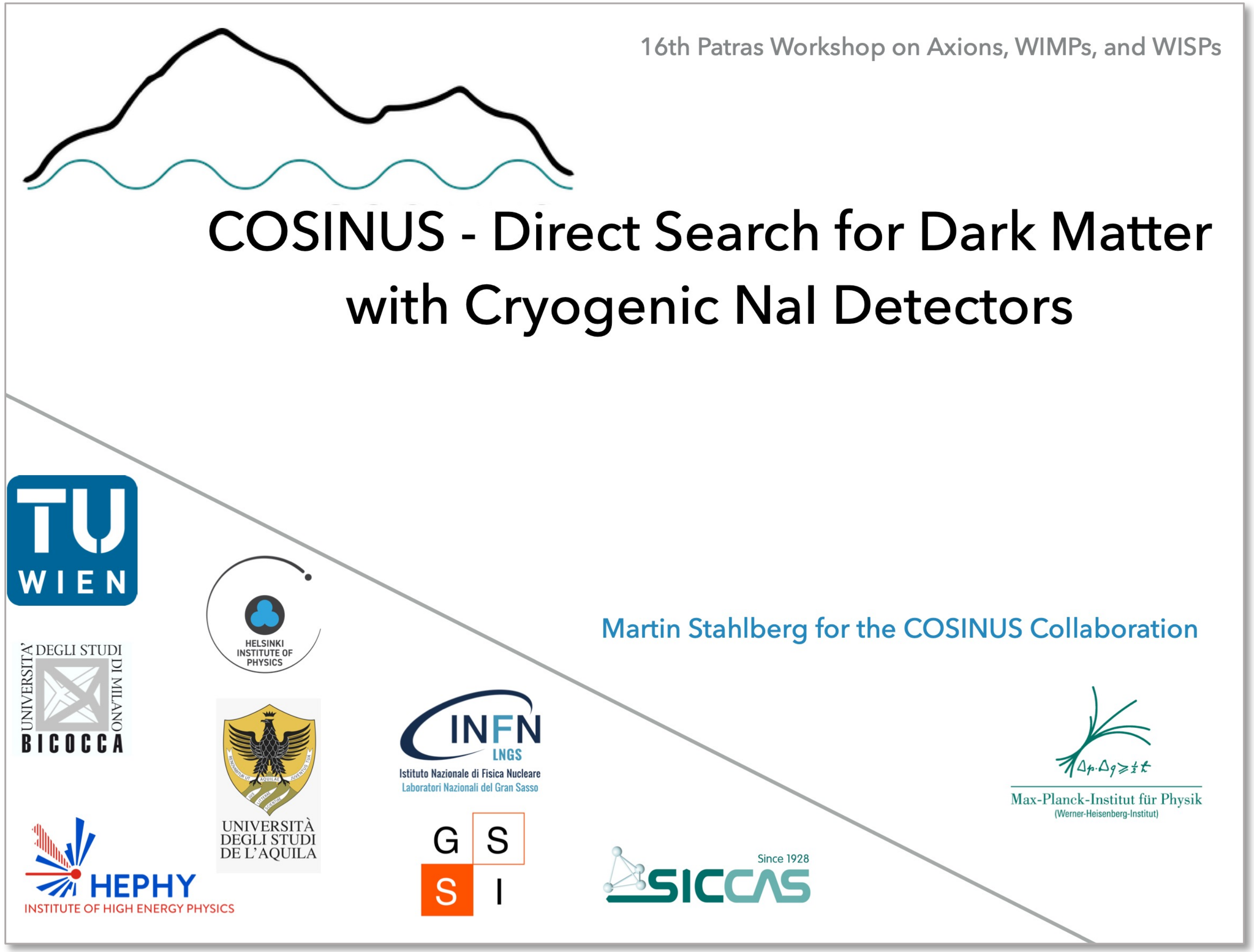
DAMA/LIBRA

Arrays of high-purity scintillator crystals

- measure only scintillation signal
- simple design
- long time stability
- relatively high background level
- absence of fiducialisation and electronic recoil rejection
- concentrate on exploiting the annual modulation signature*

NaI scintillators experiments focus on the necessary test of the DAMA/LIBRA annual modulation signal

SCINTILLATION DETECTORS



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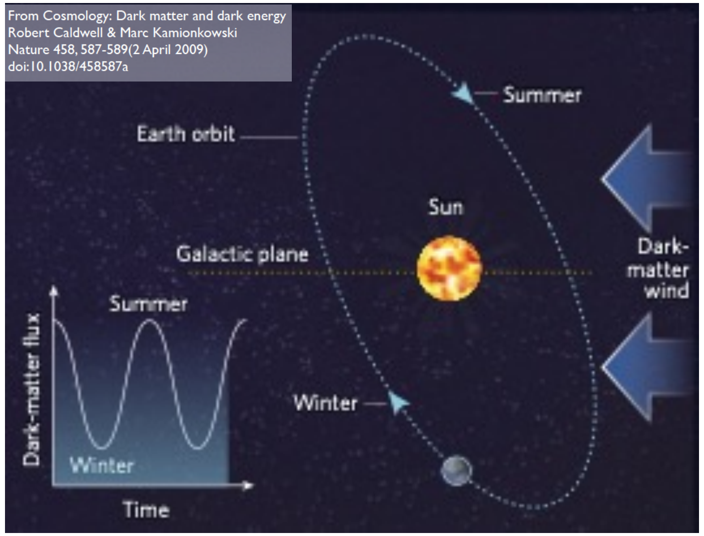
COSINUS - Direct Search for Dark Matter with Cryogenic NaI Detectors

Martin Stahlberg for the COSINUS Collaboration

ANNUAL MODULATION



From Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)
doi:10.1038/458587a

Distinctive signature in the interaction rate of dark matter interactions*:

- Cosine behaviour
- 1 year period
- Maximum around June 2nd
- Weak effect (1-10%)
- Only noticeable at low energy

*“For standard assumptions, the count rate has a cosine dependence with time, with a maximum in June and a minimum in December. Well-motivated generalizations of these models, however, can affect both the phase and amplitude of the modulation.”
K.Freeze et al. Rev. Mod. Phys. Vol. 85 Iss 4 Pag: 1561-1581 DOI: 10.1103/RevModPhys.85.1561

On the meaning of “model independent”:

- Annual modulation can be a very strong signature of dark matter but is not “model independent”.
- The interpretation of a modulation signal as originated from dark matter interactions is done under assumptions on the halo composition and on particle and astrophysics models for the dark matter.

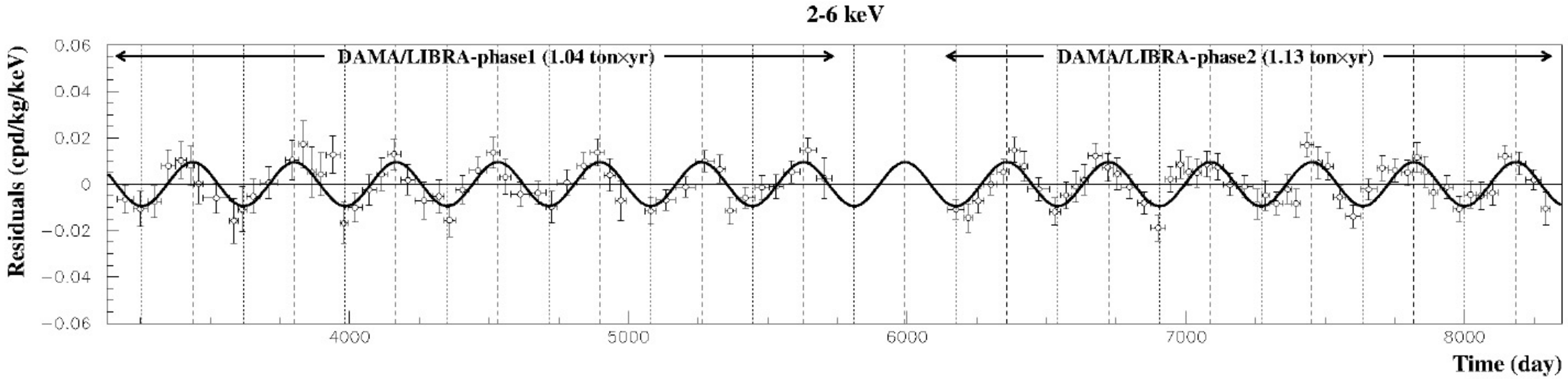
Experimental data is model independent. Interpretation of data is done under some assumption!

DAMA/LIBRA

- 250kg of NaI(Ti) with PMTs (scintillation light)
- 13 annual cycles

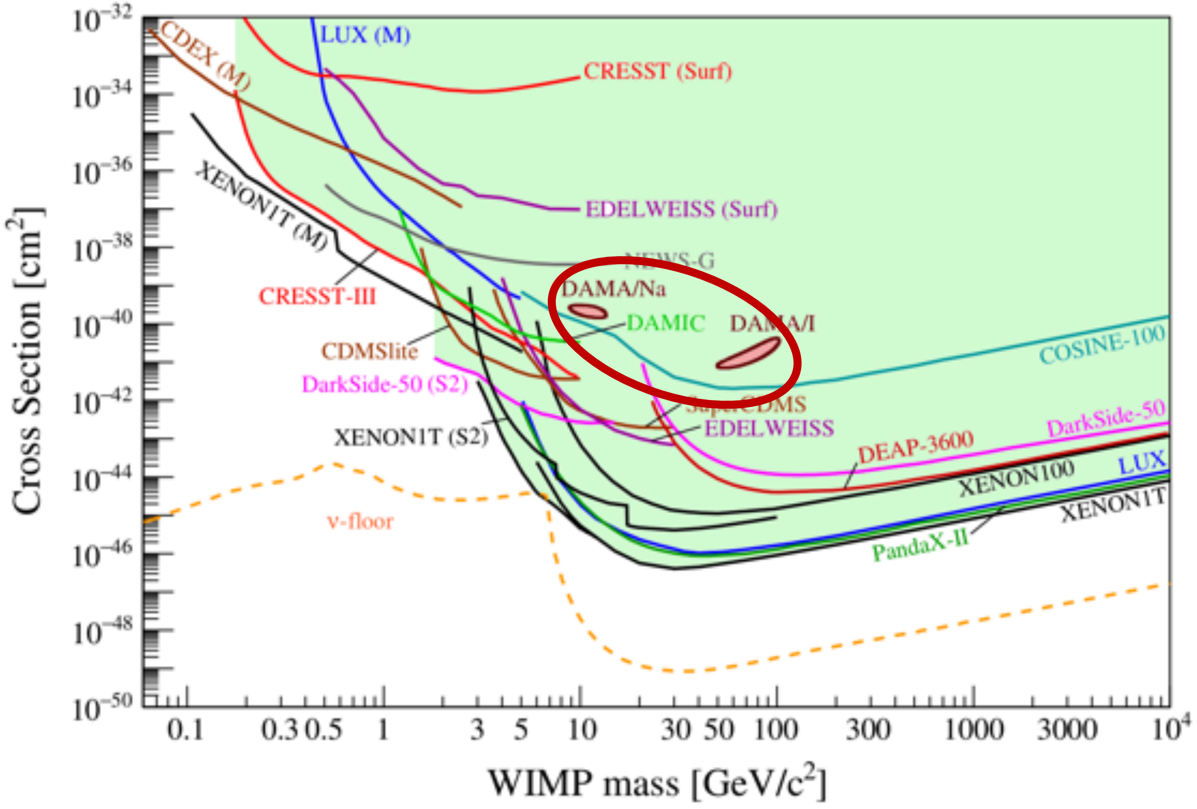
The data of DAMA/LIBRA phase1+phase2 favour the presence of a modulation with proper features at 12.9σ CL (2.46 tonne × yr)

BUT…



Nucl.Phys.Atom.Energy 19 (2018) 4, 307-325

DAMA/LIBRA

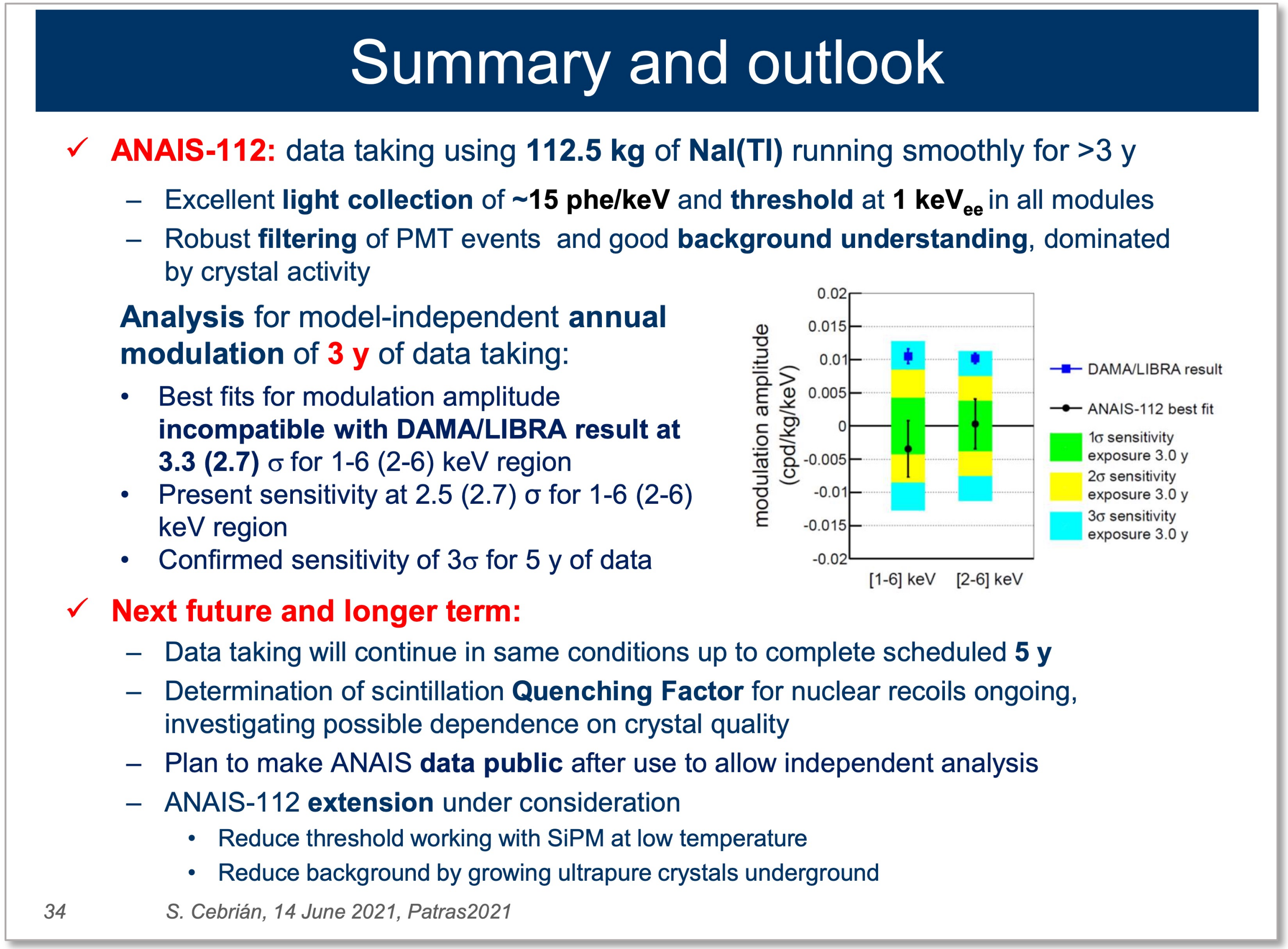


… if we consider standard assumptions, the dark matter interpretation of the DAMA/LIBRA signal is incompatible with all other experiments.

Nature could be very exotic (we are not here to judge) and there could be scenarios in which the DM interpretation of the DAMA observation is compatible with the other observations.

Need to prove the DAMA signal with similar detectors

ARE WE CLOSE TO AN ANSWER?



Summary and outlook

- ✓ **ANAIS-112:** data taking using **112.5 kg** of **NaI(Tl)** running smoothly for >3 y
  - – Excellent **light collection** of **~15 phe/keV** and **threshold** at **1 keV_{ee}** in all modules
  - – Robust **filtering** of PMT events and good **background understanding**, dominated by crystal activity

Analysis for model-independent **annual modulation** of **3 y** of data taking:

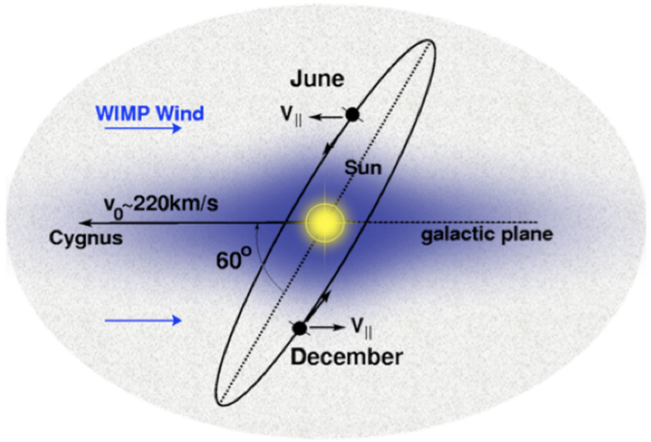
- Best fits for modulation amplitude **incompatible with DAMA/LIBRA result at 3.3 (2.7)** σ for 1-6 (2-6) keV region
- Present sensitivity at 2.5 (2.7) σ for 1-6 (2-6) keV region
- Confirmed sensitivity of 3σ for 5 y of data

- ✓ **Next future and longer term:**
  - – Data taking will continue in same conditions up to complete scheduled **5 y**
  - – Determination of scintillation **Quenching Factor** for nuclear recoils ongoing, investigating possible dependence on crystal quality
  - – Plan to make ANAIS **data public** after use to allow independent analysis
  - – ANAIS-112 **extension** under consideration
    - Reduce threshold working with SiPM at low temperature
    - Reduce background by growing ultrapure crystals underground

34 *S. Cebrián, 14 June 2021, Patras2021*

DIRECTIONAL EXPERIMENTS

DRIFT, MIMAC, NEWAGE, DMTPC, NEWSdm



The average direction of the "WIMP wind" through the solar system comes from the constellation of Cygnus

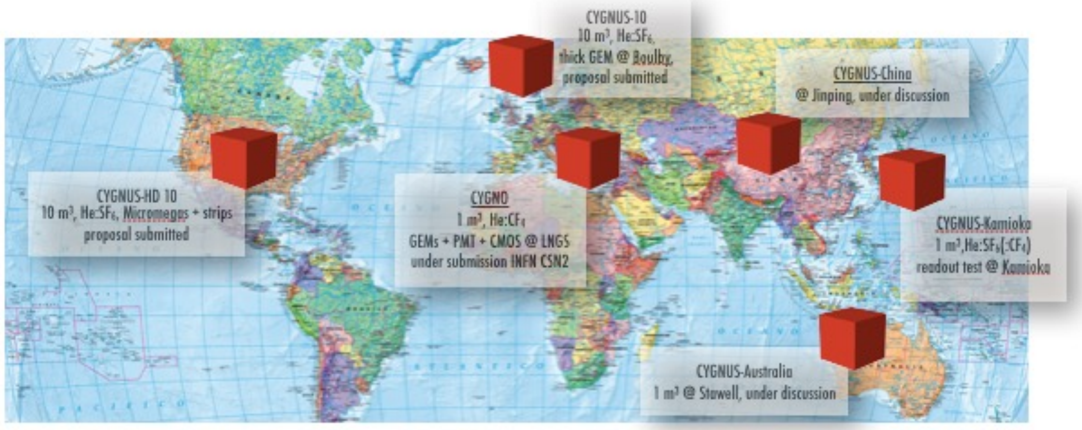
A **measurement of the track direction** of nuclear recoils could be used to distinguish a dark matter signal from background events (expected to be uniformly distributed) and to prove the galactic origin of a possible signal

- Aim at reconstructing the direction of the WIMP-induced nuclear recoil
- Very promising technology for unambiguous signature and halo exploration (in case of positive signal)
- Immune to neutrino floor
- Still very far from competitive exposure
- Highest sensitivity for SD couplings to protons thanks to F-targets

Challenge: to reconstruct the track being very short (~1 mm in gas, ~0.1 µm in solids) for keV scale nuclear recoils

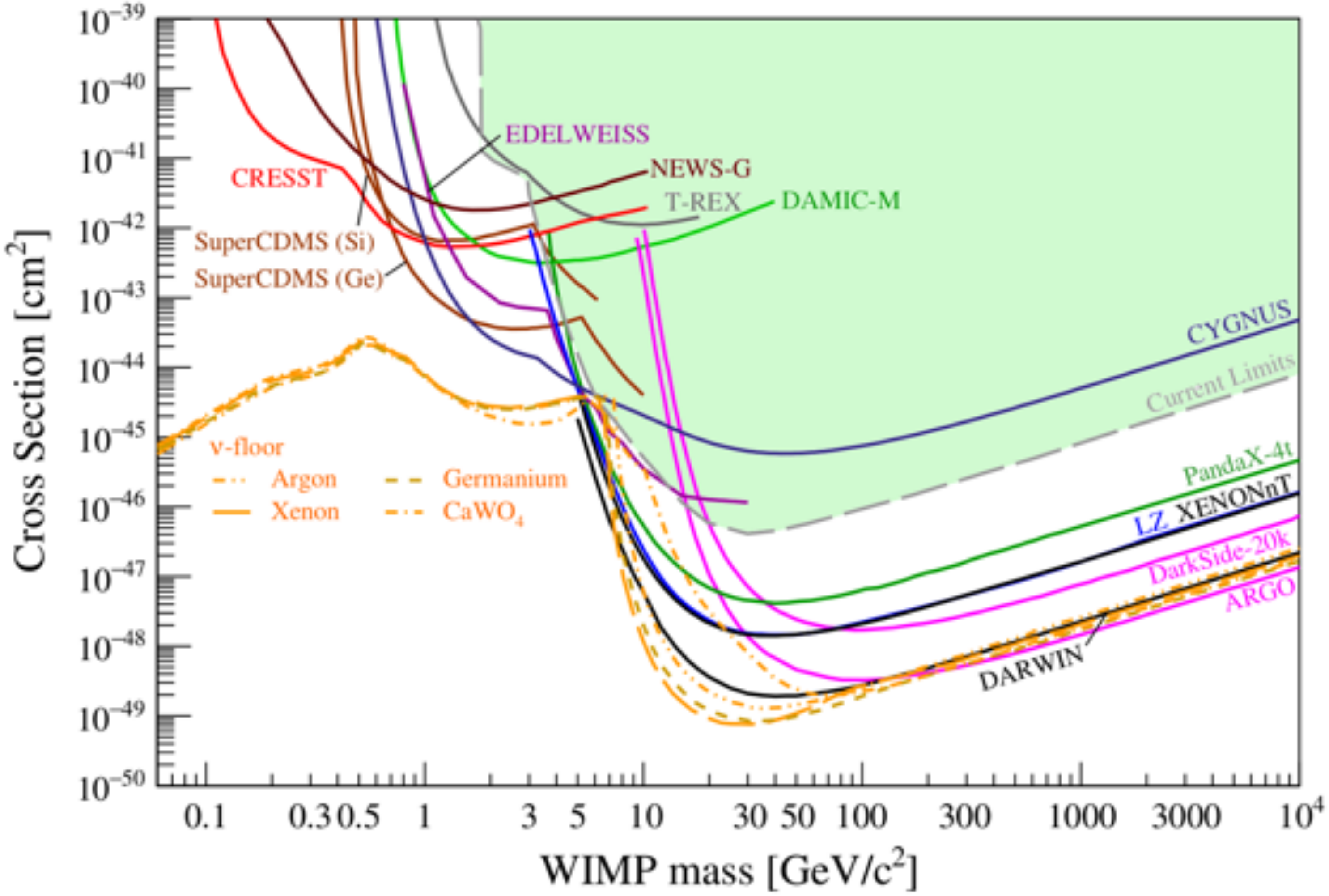
- **Nuclear emulsions**
- **Low pressure** (~40-100mbar) gas targets in **TPCs** with different electron amplification devices and track readouts, mostly based on CF_4 mixtures with ^{19}F
  - Multi-wire proportional chambers (MWPC)
  - Micro pattern gaseous detectors (MPGDs)
  - Optical readouts

CYGNUS proto-collaboration formed carrying out R&D to determine the optimum configuration for a large target mass directional detector.



THE FUTURE

Predictions for the (far) future come with some uncertainty. Based on best-guess assumptions but include quite some extrapolation.



Picture from: Direct Detection of Dark Matter APPEC Committee Report submitted to APPEC for final approval

Diversified approach to probe the broadest experimentally accessible ranges of particle mass and interactions.

A discovery could happen any time!

Would be the beginning of a new exciting era of exploration!