Обзор экспериментов по прямому поиску темной материи

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Сессия ОЯФ РАН, 12 марта 2020

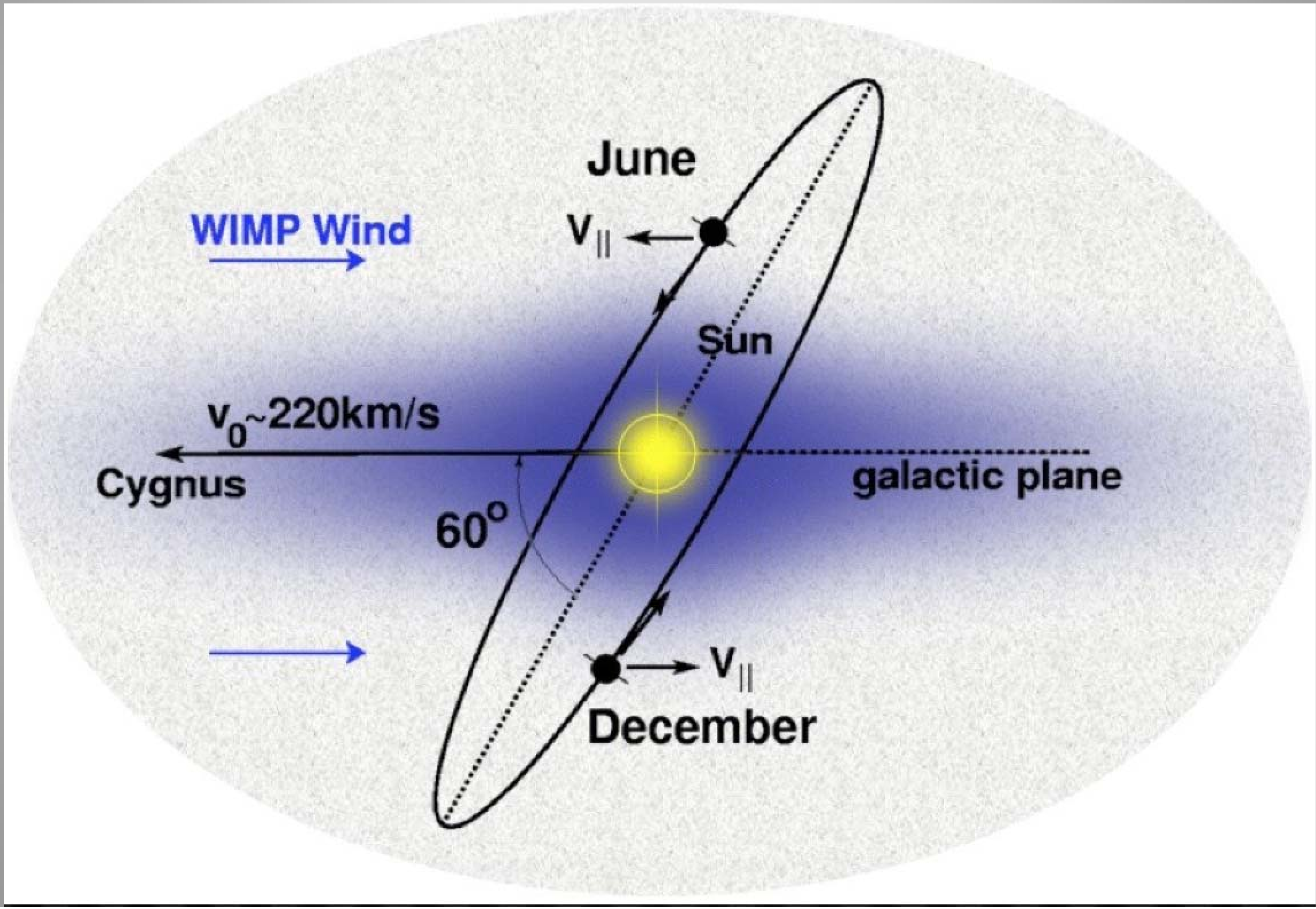
Проблема детектирования WIMP в экспериментах по поиску темной материи

WIMP = weakly interacting massive particle

Детекторы темной материи есть суть детекторы ядер отдачи. Ядра отдачи производят в детектирующей среде тепло, свет и ионизацию, т.е. фононы, фотоны и электроны.

Предельная чувствительность означает работу детекторов в режиме счета одиночных фононов, фотонов или электронов, в условиях предельно низкого фона. Ни один из существующих детекторов темной материи пока не достиг предельной чувствительности.

Direct Dark Matter (WIMP) search experiments: principles of detection



WIMP search experiments

Current experiments use:

crystals - CaWO4 (CRESST), CsI(Tl) (KIMS), Ge (CDMS, CoGeNT, EDELWEISS), Si (CDMS Si) and NaI(Tl) (DAMA/LIBRA, COSINE, ANAIS, DM-Ice);

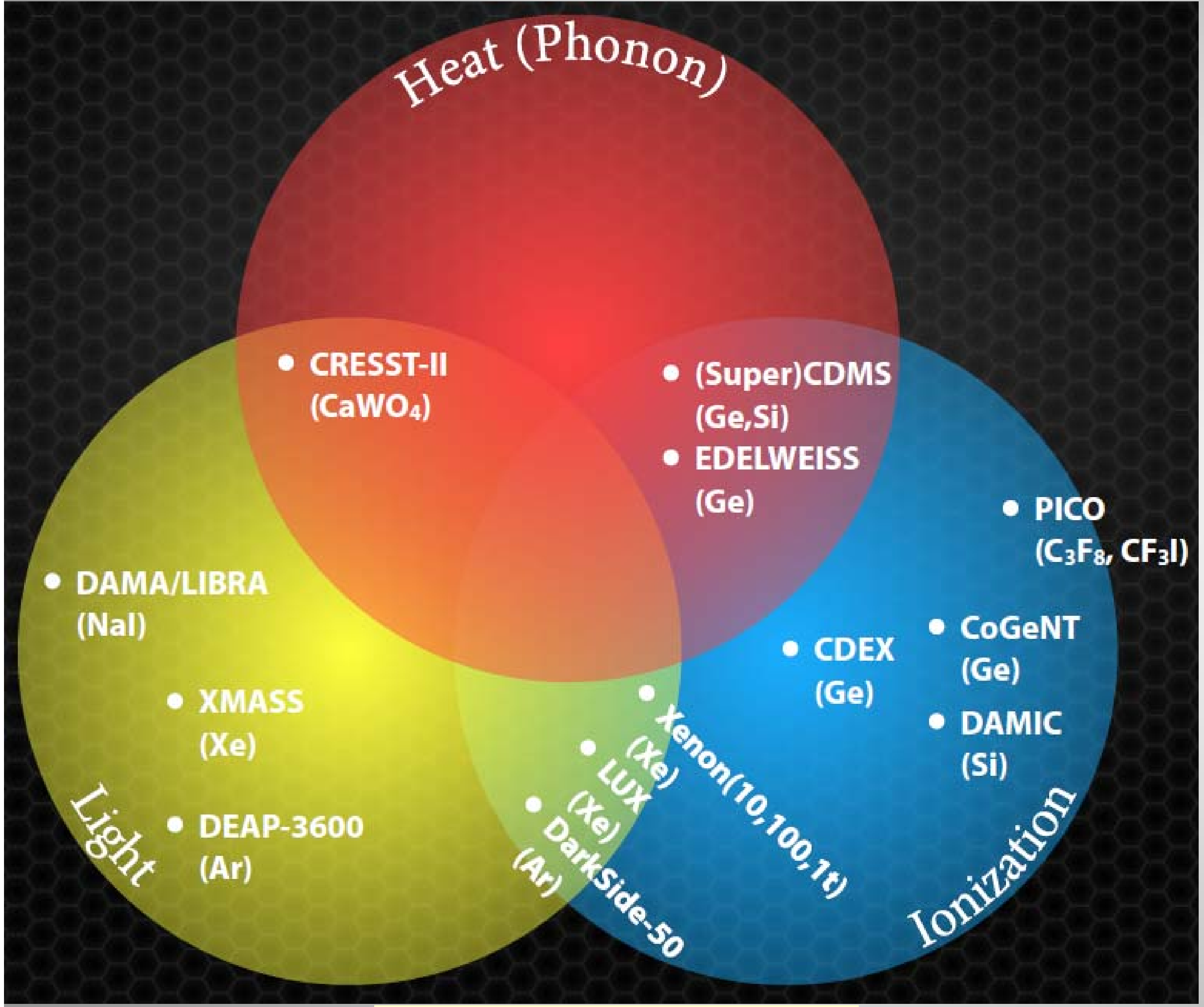
noble-gas liquids - Ar (DarkSide, DEAP) and Xe (LUX-LZ, XENON, XMASS, PandaX);

superheated freon liquids – bubble chambers (COUPP-PICASSO-PICO, SIMPLE);

directional (low-pressure gas and CCD) detectors (DAMIC, DRIFT, MIMAC, NEWAGE).

WIMP search experiments geography

WIMP search experiments: detection techniques



F. Reindl, EPS-HEP 2015

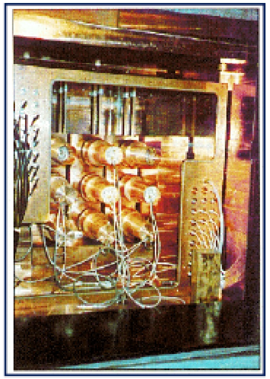
To discriminate the dark-matter signal from background processes, one exploits one or two out of three possible signals: heat (phonons), scintillation light (photons) and ionization (electrons).

WIMP search experiments: room temperature crystals - DAMA/LIBRA

Laboratori Nazionali del Gran Sasso, Italy

DAMA/NaI & DAMA/LIBRA (phase 1)

DAMA/NaI (1995-2002)



- 9 × 9.7 kg NaI(Tl)
- Produced by St. Gobain
- 7 annual cycles

DAMA/LIBRA (2003-2010)

- 25 × 9.7 kg NaI(Tl)
- 7 annual cycles

R. Bernabei et al, Eur. Phys. J. C 73 (2013) 2648

DAMA/LIBRA phase2 (2011-2018)

- PMTs replaced → software energy threshold at 1 keV
- 6 annual cycles

R. Bernabei et al, Nucl. Phys. At. Energy 19, 307 (2018)

Light WIMP puzzle: possible signal in DAMA/LIBRA Phase I+II

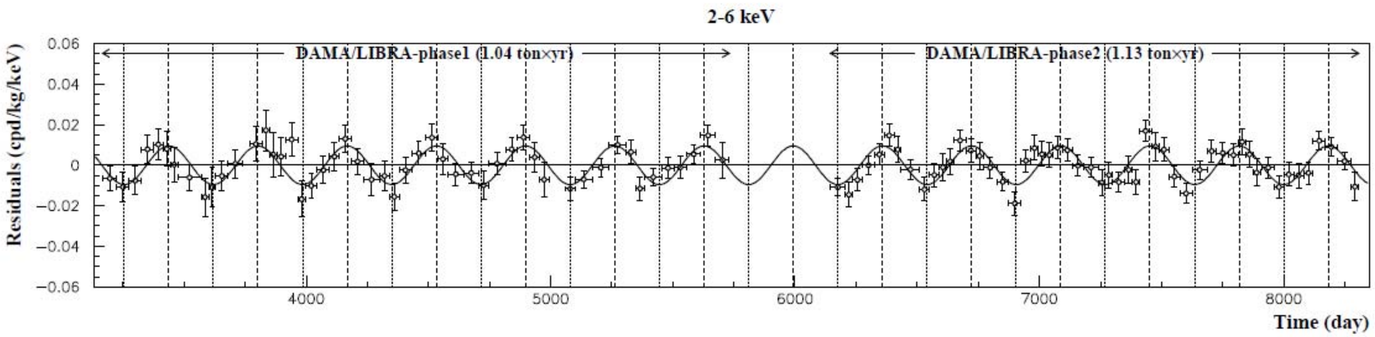


Figure 3: Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy intervals as a function of the time. The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, a phase $t_0=152.5$ day (June 2^{nd}) and modulation amplitude, A, equal to the central value obtained by best fit on the data points of DAMA/LIBRA–phase1 and DAMA/LIBRA–ph

- DAMA/LIBRA [R. Bernabei et al. Eur. Phys. J. C (2013) 73:2648]
- $E_{threshold}$=2 keVee corresponding to 7-20 keVnr

- DAMA/LIBRA [R. Bernabei et al. NUCL. PHYS. AT. ENERGY 19 (2018) 307]
- $E_{threshold}$=2 keVee corresponding to 7-20 keVnr

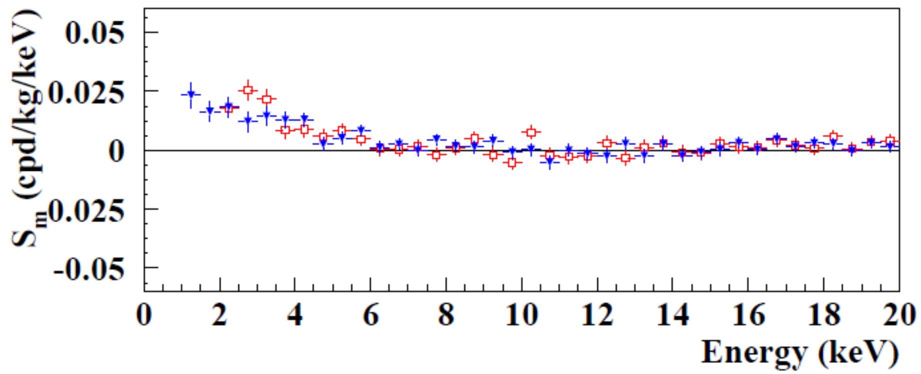
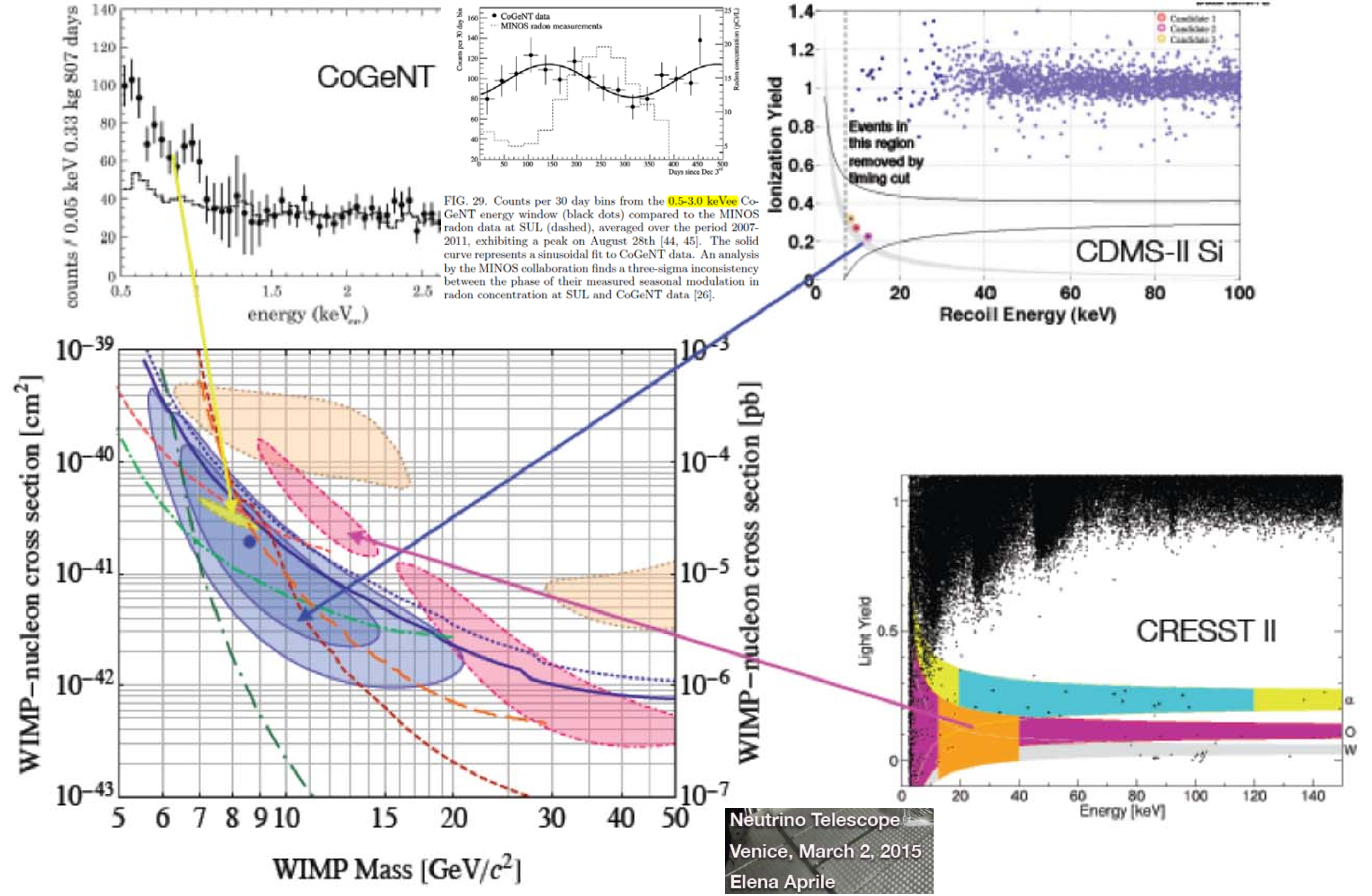


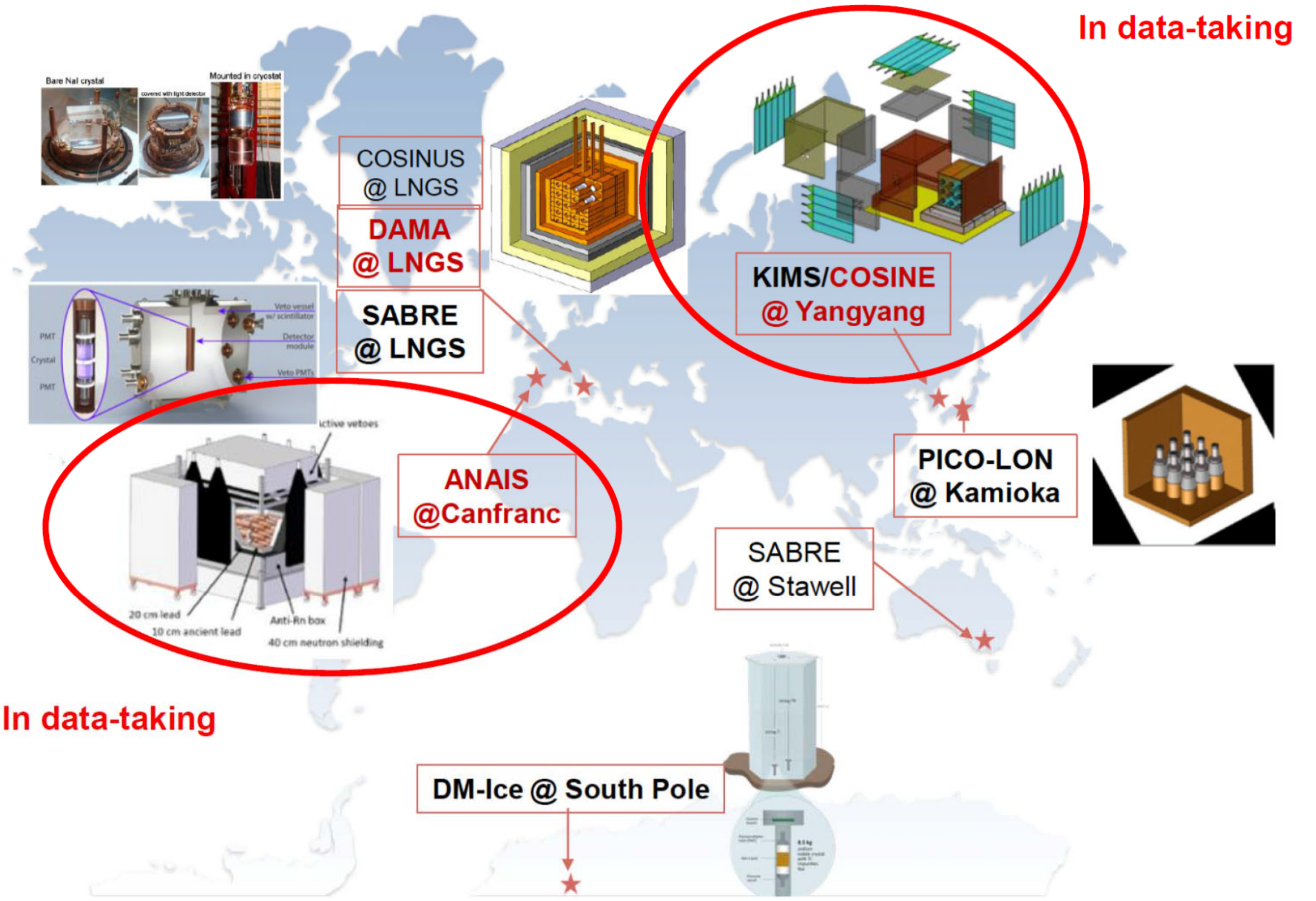
Figure 10: Modulation amplitudes, S_m, for DAMA/LIBRA–phase2 (exposure 1.13 ton×yr) from the energy threshold of 1 keV up to 20 keV (full triangles, blue data points on-line) – and for DAMA/NaI and DAMA/LIBRA–phase1 (exposure 1.33 ton×yr) [4] (open squares, red data points on-line). The energy bin ΔE is 0.5 keV. The modulation amplitudes obtained in the two data sets are consistent in the (2–20) keV: the χ^2 is 32.7 for 36 *d.o.f.*, and the corresponding P-value is 63%. In the (2–6) keV energy region, where the signal is present, the $\chi^2/d.o.f.$ is 10.7/8 (P-value = 22%).

Light WIMP puzzle: possible signal in CoGeNT and CDMS-Si: by 2015



Neutrino Telescope
Venice, March 2, 2015
Elena Aprile

Other NaI experiments



Light WIMP puzzle: COSINE-100 vs DAMA/LIBRA by 2019

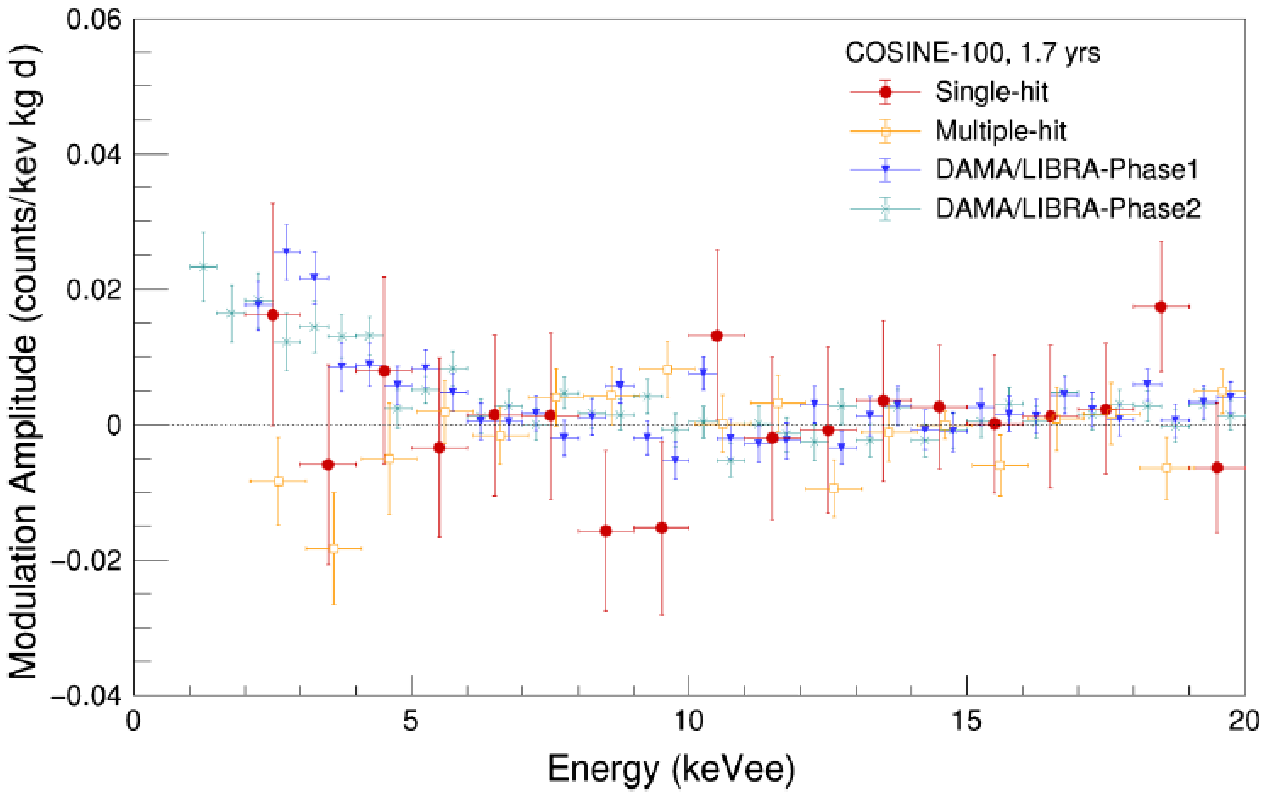


FIG. 5. Modulation amplitude as a function of energy in 1 keV bins for the 1.7 year COSINE-100 single-hit (red closed circle) and multiple-hit (orange open circle) events. DAMA/LIBRA phase 1 (blue) and phase 2 (green) from Ref. [12] are also shown

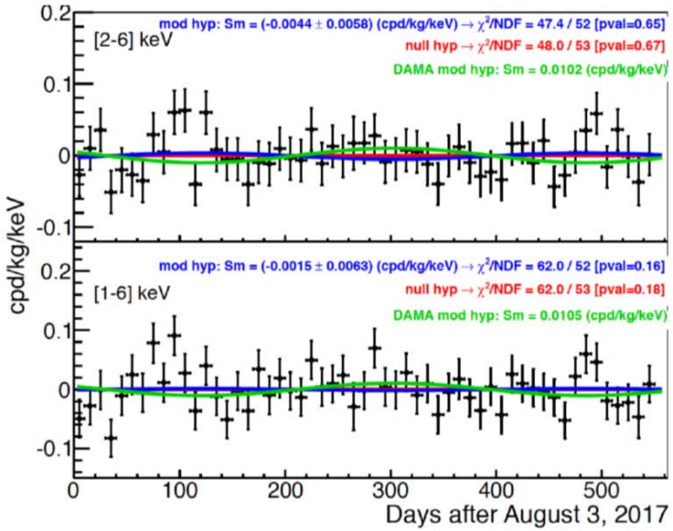
Cosine-100 [Adhikari et al. Phys. Rev. Lett. 123, 031302 (2019)]

Light WIMP puzzle: ANAIS vs DAMA/LIBRA by 2019

ANAIS

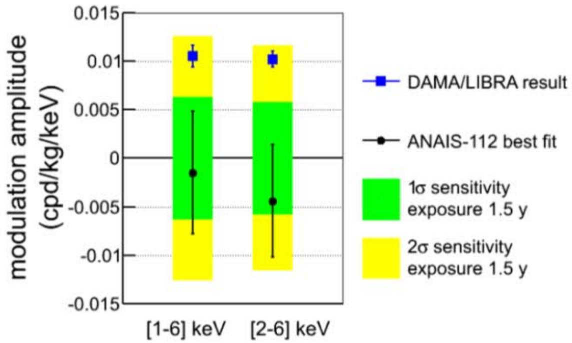
First results on annual modulation: August 2017-February 2019 (**1.5 y**)→**157.55 kg.y**

Least-squares fit to $R(t) = R_0 + R_1 \cdot exp(-t/\tau) + S_m \cdot cos(\omega \cdot (t+\phi))$



τ fixed from background model
$\boldsymbol{\omega}$ fixed corresponding to 1 year period
$\boldsymbol{\varphi}$ fixed to have the cosine maximum in June, 2nd
S_m fixed to 0 in the null hypothesis and left unconstrained for the modulation hypothesis

S_m best fits are **incompatible** with DAMA/LIBRA results at **2.5σ** (2-6 keV) or **1.9σ** (1-6 keV)



Null hypothesis well supported by the χ^2 test

Modulation hypothesis best fits for 2-6 and 1-6 keV

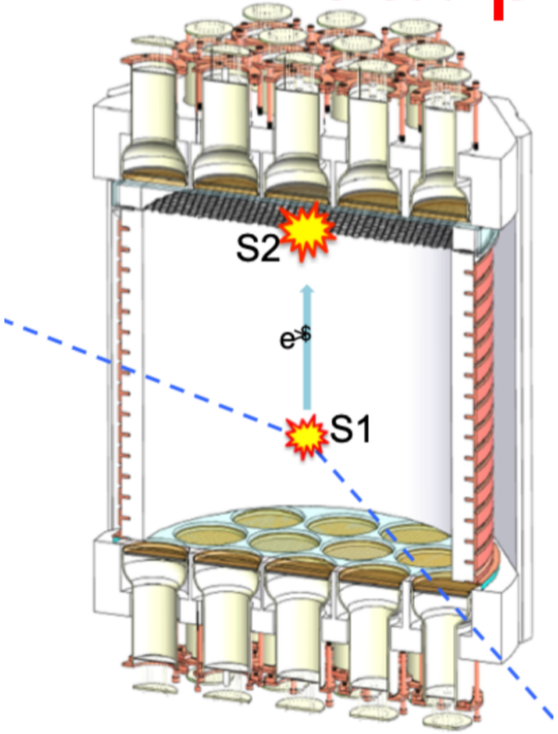
$$S_m = -0.0044 \pm 0.0058\ cpd/kg/keV$$
$$S_m = -0.0015 \pm 0.0063\ cpd/kg/keV$$

Results for **2 y** data to be presented this afternoon by **M. L. Sarsa**

S. Cebrián, TAUP2019, 11 September 2019

J. Amaré et al, Phys. Rev. Lett. 123 (2019) 031301

Dual phase LAr TPC principles



1 - Nuclear Recoil excites and ionize **Liquid Ar** producing scintillation **light** S1 detected by top and bottom photosensors

2 - ionization **electrons** are drifted to the **Ar gas** pocket region where they induce a second **delayed scintillation** light S2 signal

- **Time difference** between S1 and S2 gives **vertical position** while fraction of S2 in each photo-sensor gives **x-y position**.

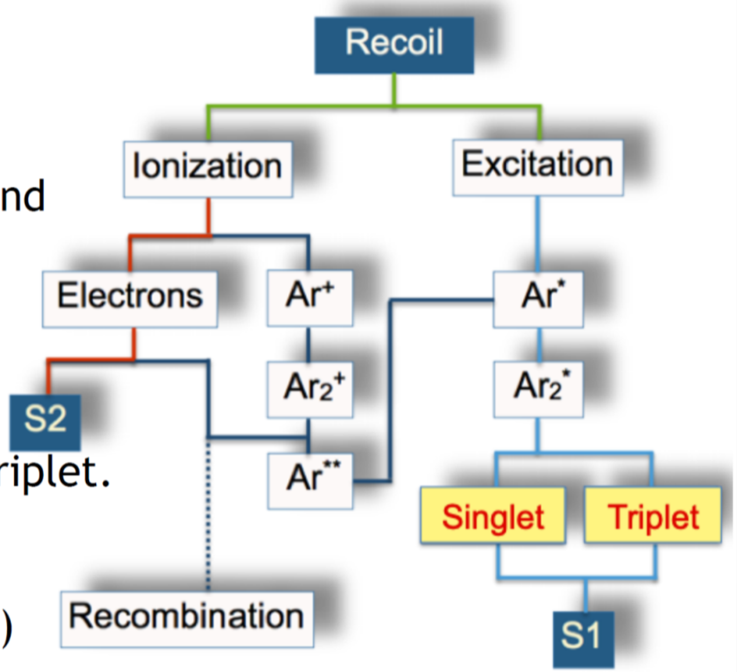
- Scintillation light at 128nm: use of **TPB wave-length shifter**.

Recoil can be with electrons (**ER**) or nuclei (**NR**). Ionization and direct excitation of Ar* to form Ar_2^* dimer that emits light.

Dimer excitons Ar_2^* emits light in **singlet** or **triplets**.

Different singlet/triplet fractions NR ~70% singlet, ER ~70% triplet.
Ar ions can recombine and form excited Ar** states.

Also, NR ion.+thermic energy loss → **NR quenching** (less S2)



Dual phase LAr TPC Electron Recoil rejection

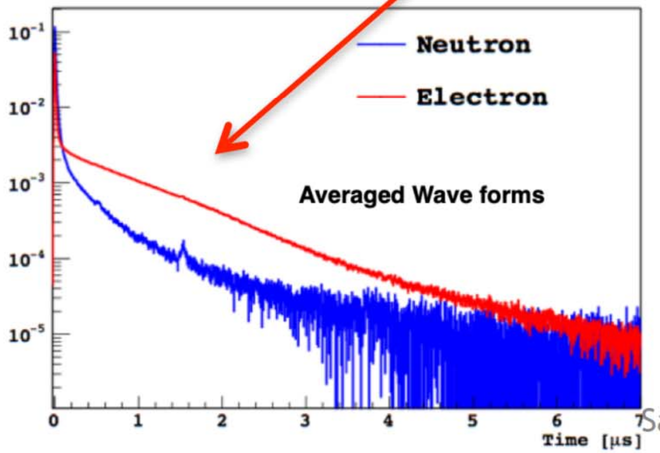
Due to Nuclear quenching, ionization signal and hence **S2** scintillation, is less intense for NR than for ER

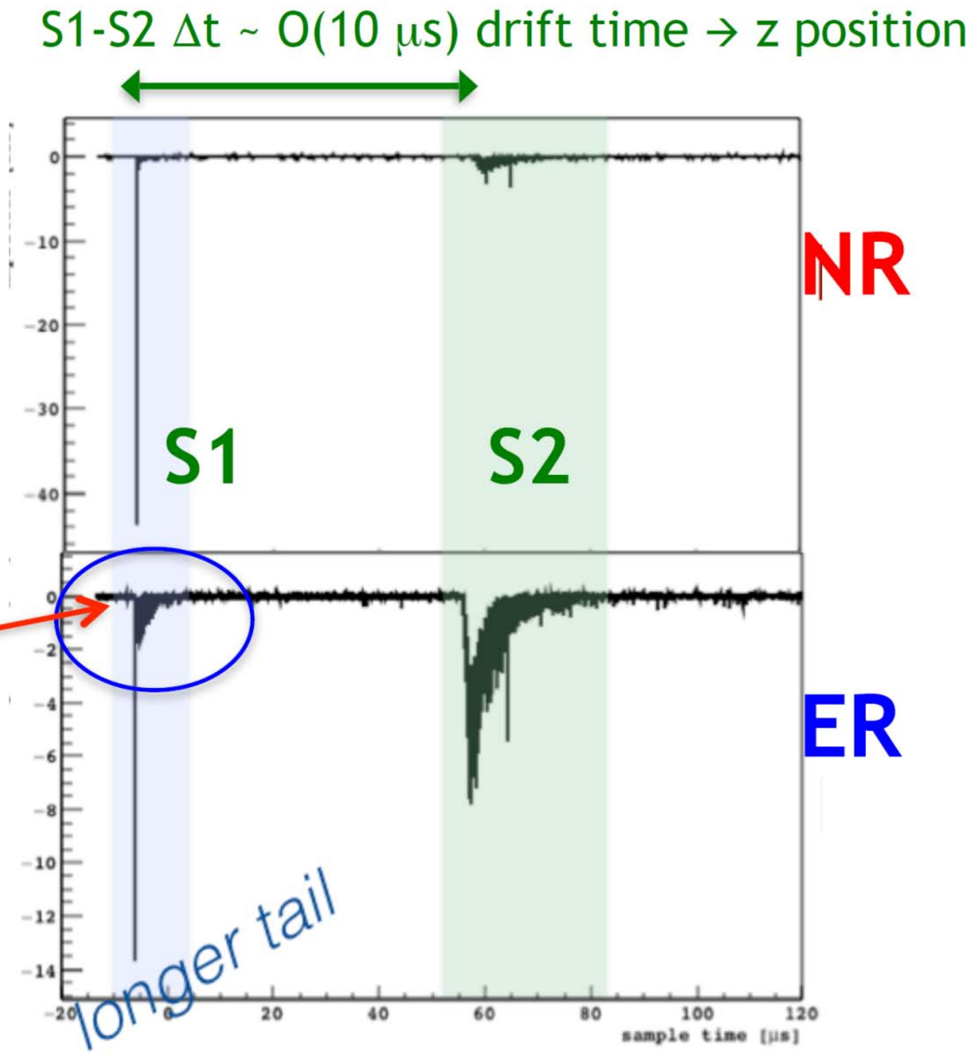
→ separation power in **S2/S1**

gives an **ER** rejection factor of 200-300 (only at high energy transfers)

Typically used in Xenon experiment (same in Argon) as only ER vs NR discriminant.

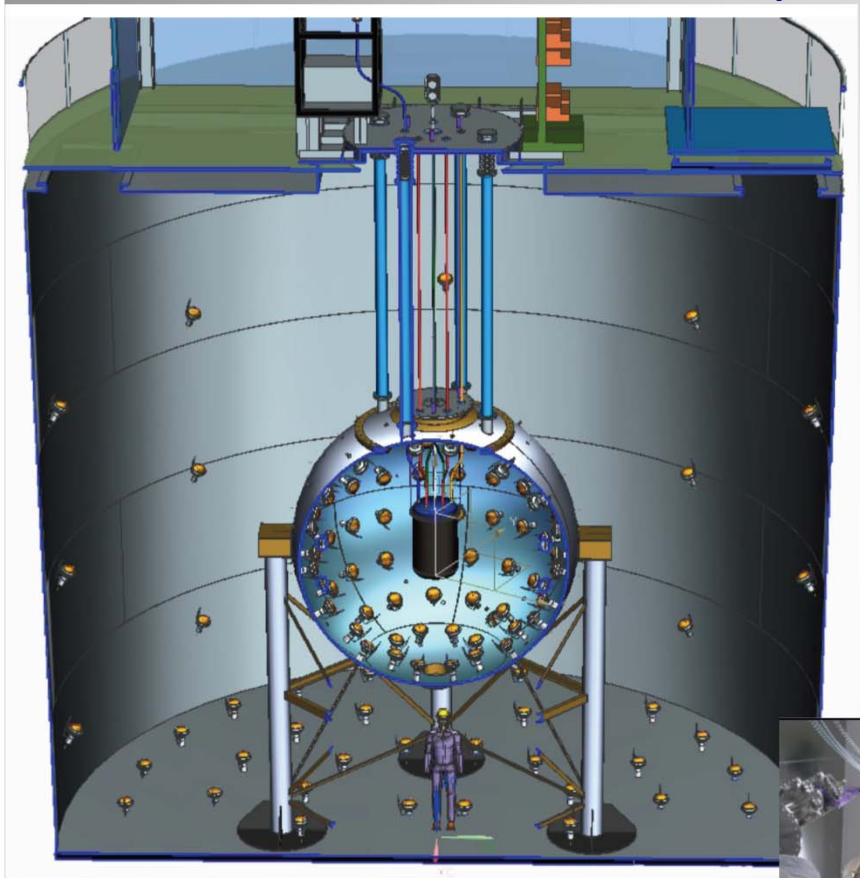
But, unique to Argon : **Pulse Shape Discrimination** (**PSD**) due to longer tails in ER S1 signal.

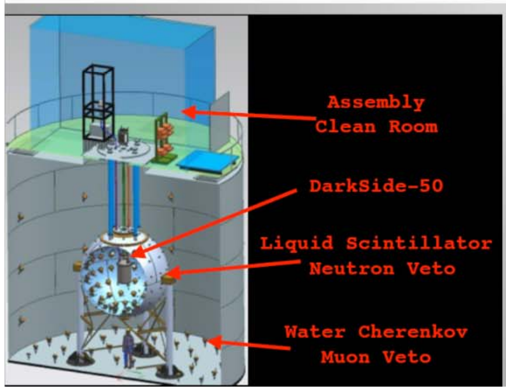


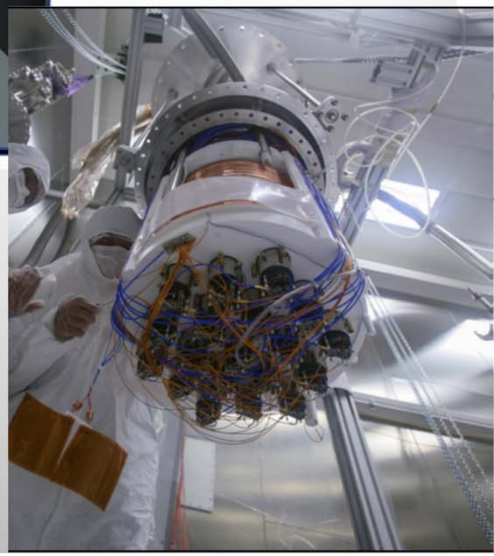


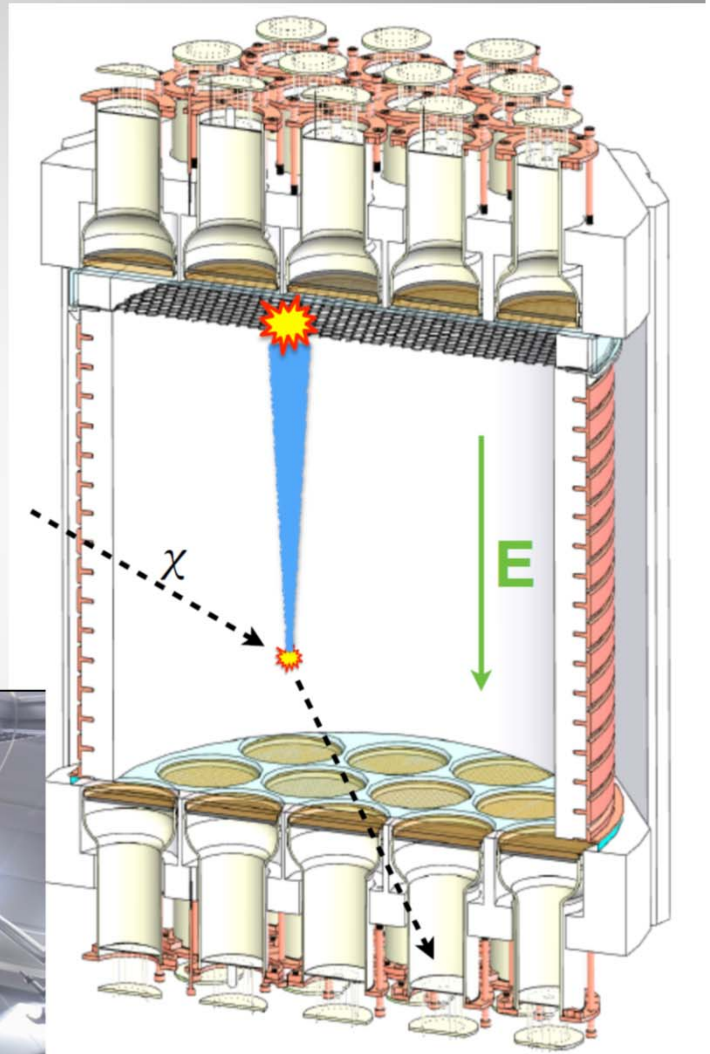
—> **PSD ER rejection ~ 10^9**

Typical direct WIMP search experiment: example of DarkSide









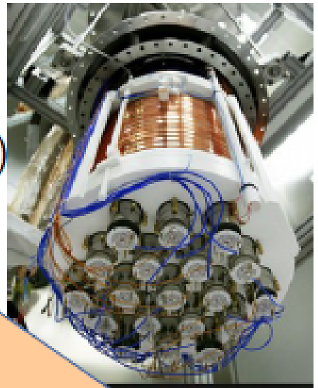
Liquid noble gas experiments

LAr detectors

2010

10 kg

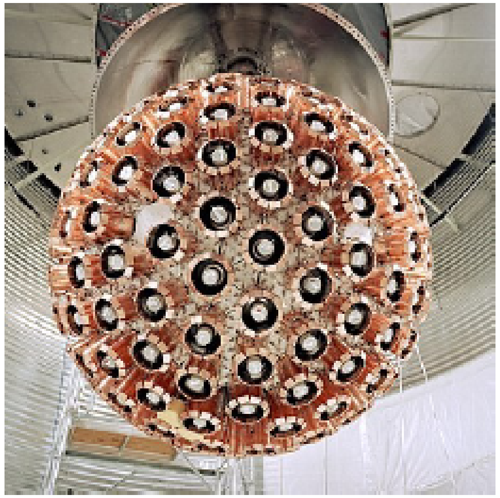
DarkSide-50
(50 kg, LNGS)



- More than 300 scientists from 15 countries and 60 institutions
- Officially supported by underground labs: LNGS, LSC, and SNOLAB

100 kg

ArDM (1t, LSC)

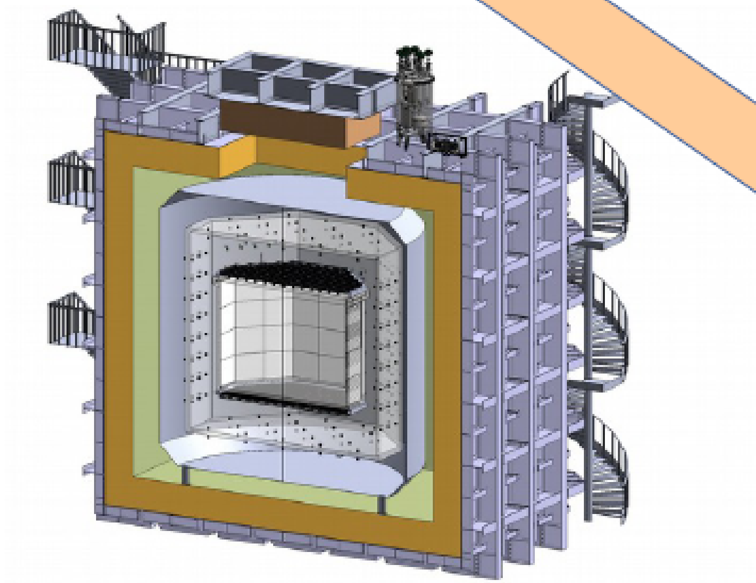


1000 kg

2015

DEAP-3600 (3.3t, SNOLAB)

Global Argon Dark Matter Collaboration formed



2020

DarkSide-20k
(50t, LNGS)

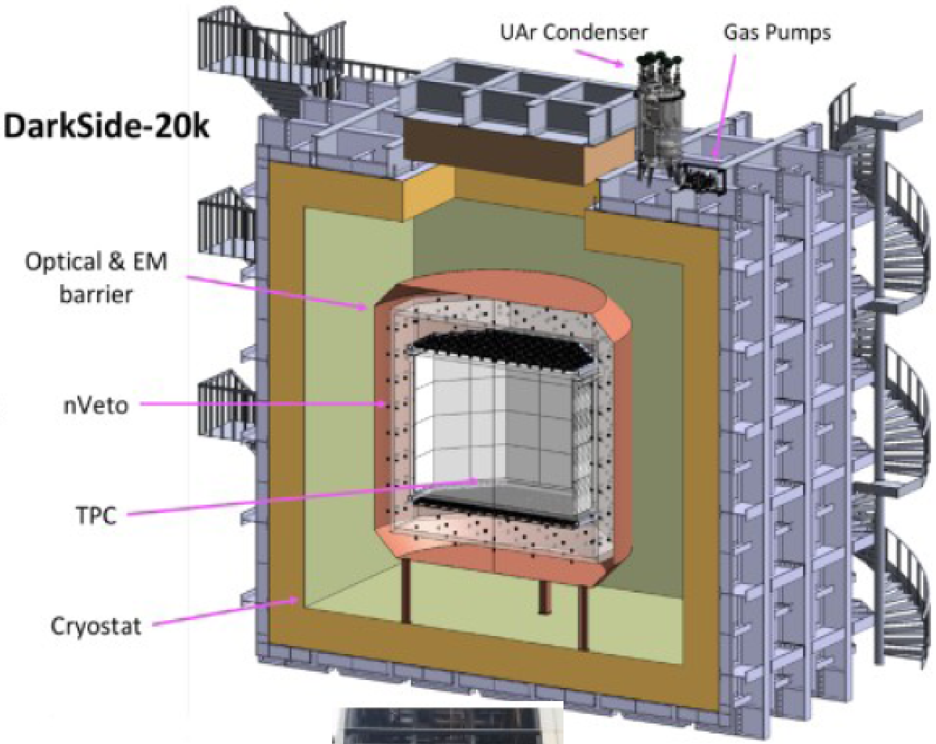
100000 kg

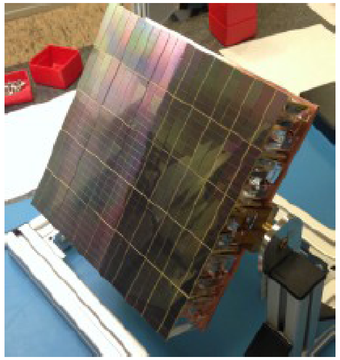
Argo: 400 t

Slide courtesy J. Monroe

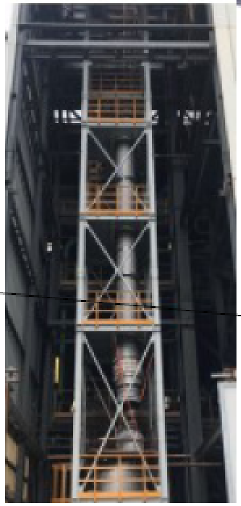
DarkSide-20k and beyond

- Sealed acrylic TPC filled with Underground Argon (UAr): 50 tonnes in total
- Membrane cryostat filled with Atmospheric Argon (AAr): based on the ProtoDUNE cryostat
- 2% Gd doped acrylic panels as neutron veto
- SiPMs as photosensors: 8280 channels in TPC, ~3000 channels in Veto

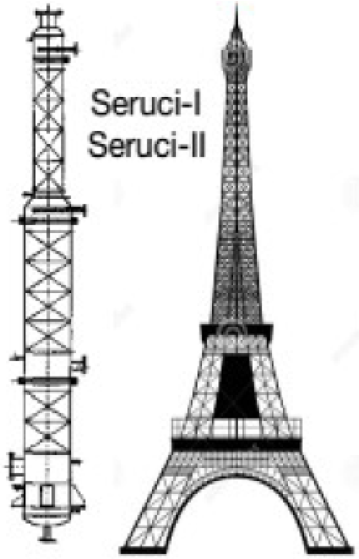




- Urania plant for underground argon extraction
- ARIA facility for chemical purification and isotopic separation
- Key projects also for Argo

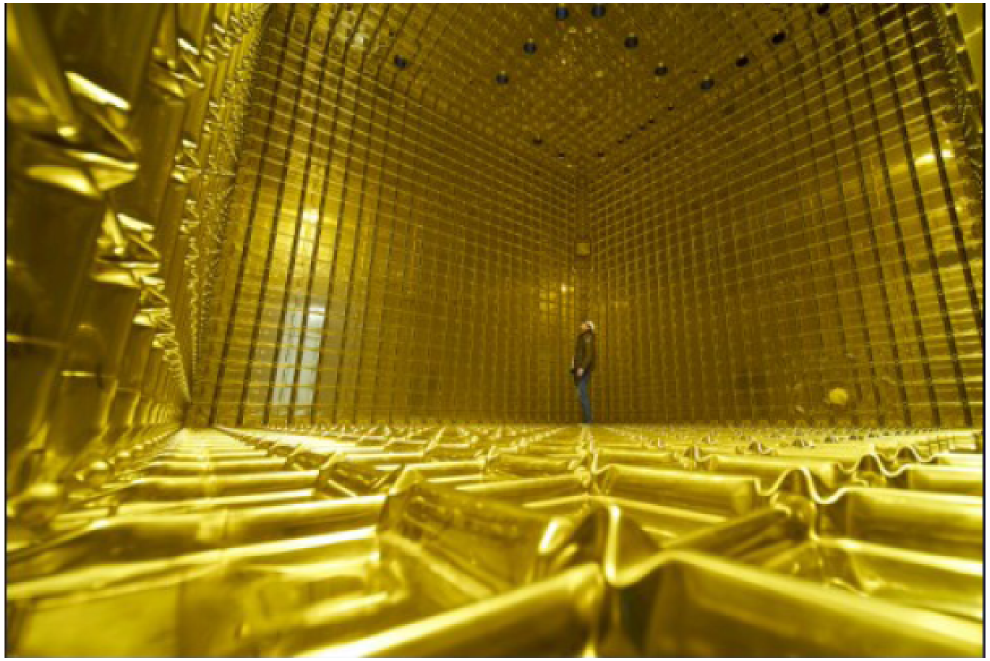


Seruci-0



DarkSide-20k LAr veto concept

CERN Neutrino Platform:



- 2 almost identical cryostats built for ProtoDUNE
- 8x8x8 m^3 inner volume, 750 t of LAr each
- Technology and expertise taken from LNG industry
- Construction time: 37-55 weeks
- Designed as installable underground

New approach: atmospheric Ar in ProtoDUNE style large cryostat to provide shielding and active VETO:

- Allows to eliminate Liquid Scintillator Veto
- New veto is a giant single phase LAr detector
- Simplify the overall system complexity and operation
- Design fully scalable to a 400 tonne detector

LXe detectors

2010

XENON10 (LNGS)
ZEPLIN II (Boulby)
ZEPLIN III (Boulby)

10 kg

100 kg

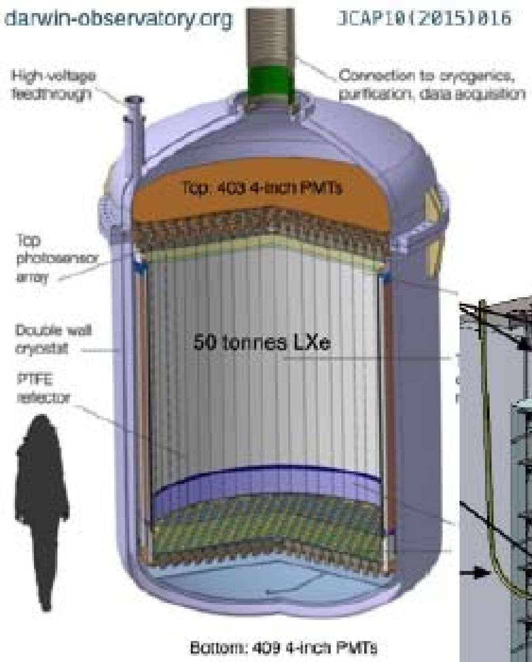
XENON100 (LNGS)
LUX (250 kg, SURF)
PandaX
(500 kg, CJPL)

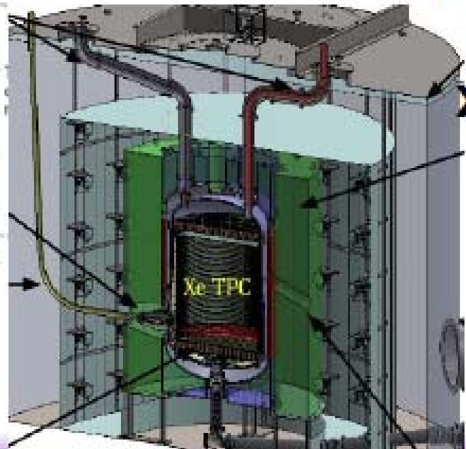
2015

XMASS
(0.8t, Kamioka)

1000 kg

XENON1T
(1t, LNGS)





PandaX-4 (4t, CJPL)
XENONnT: (6t, LNGS)
LZ: (7t, SURF)

2020

10000 kg

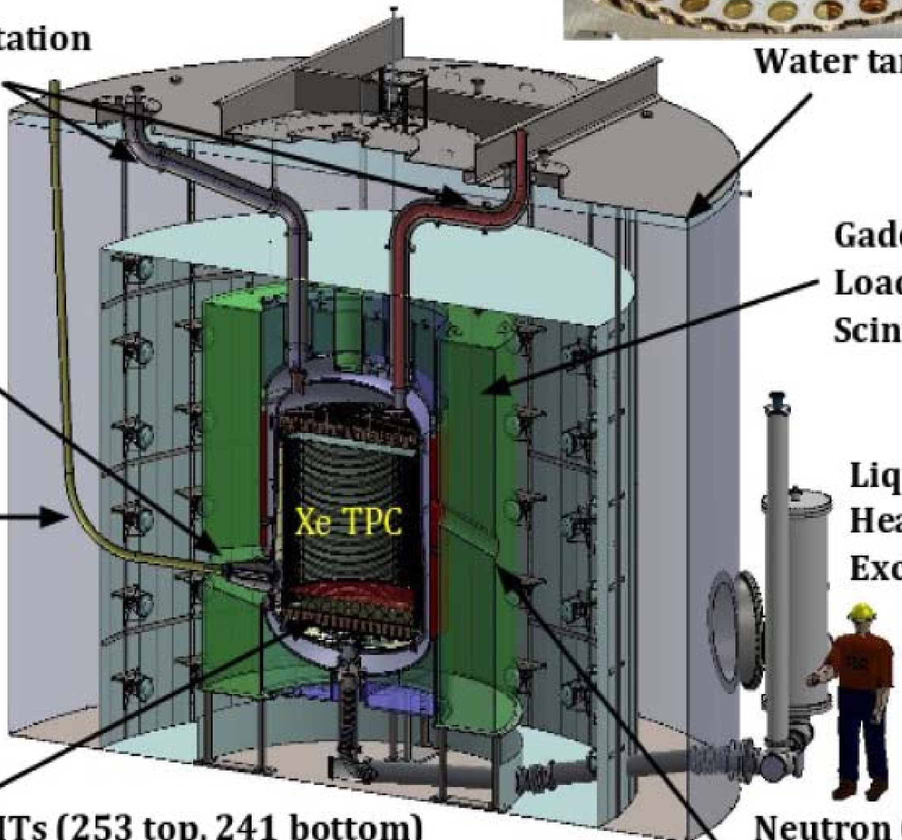
DARWIN: 50 t

Slide courtesy J. Monroe

Sanford lab (SURF),
South Dakota

LZ (LUX + ZEPLIN)

10 tons total, 7 tons active, ~5.6 ton fiducial mass



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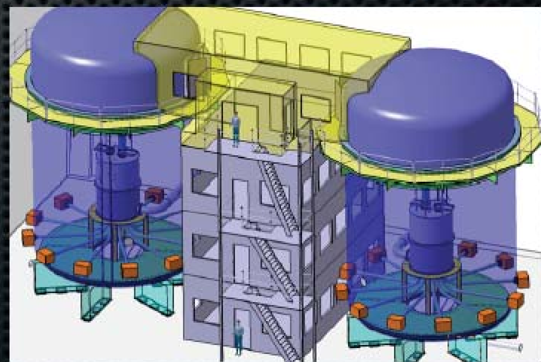
j.dobson@ucl.ac.uk, IDM2016

WIMP search experiments: “small-scale” low temperature crystals

CDMS, CRESST, EDELWEISS

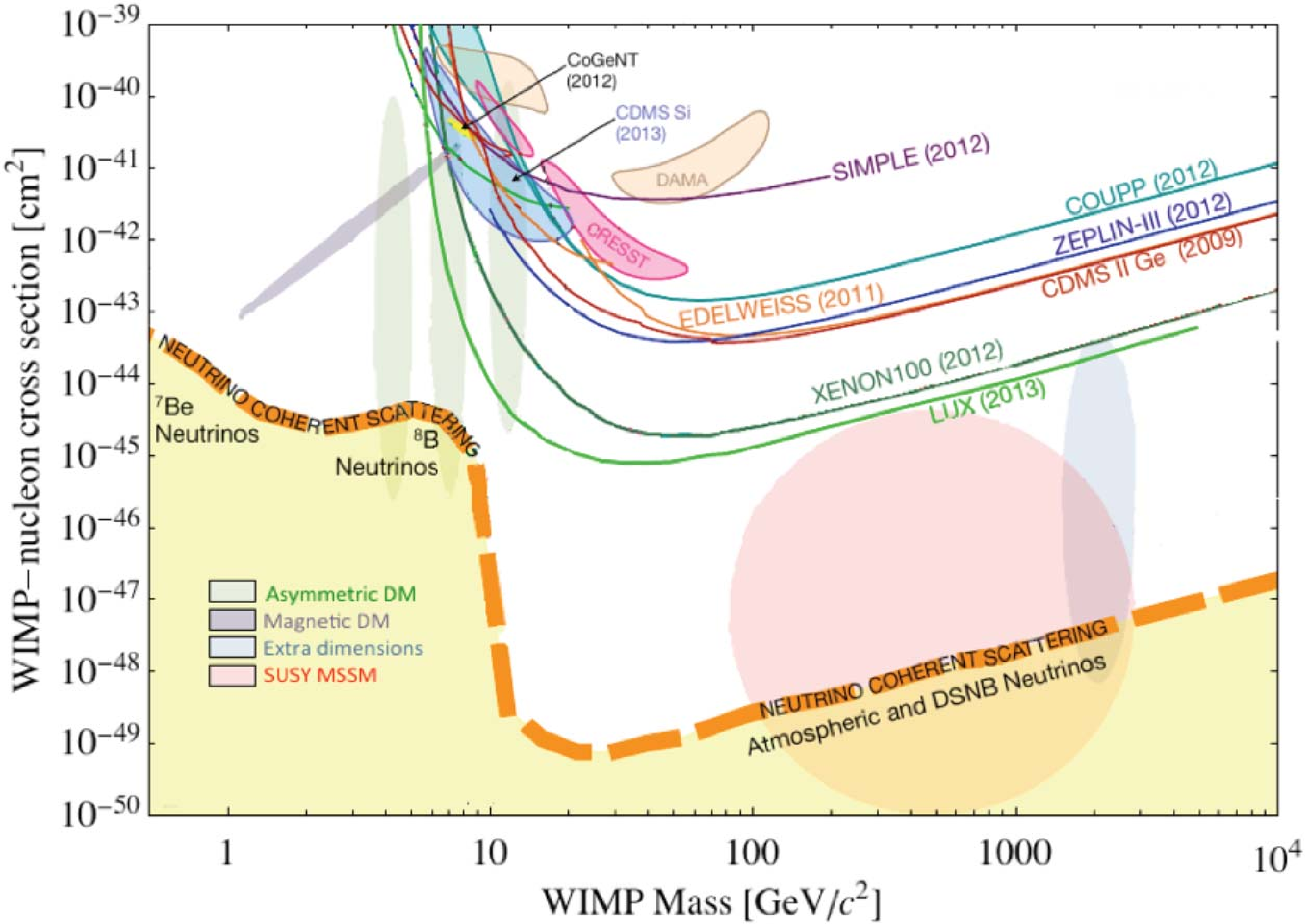
- Absorber masses from ~ 100 g to 1400 g (SuperCDMS at SNOLab)
- Currently running at Soudan, LNGS, Modane
- Future: EURECA (multi-target approach, up to 1 ton mass), SuperCDMS (150 kg) and GEODM (1 ton Ge detectors)

EURECA multi-target approach (Ge, $CaWO_4$, ...)

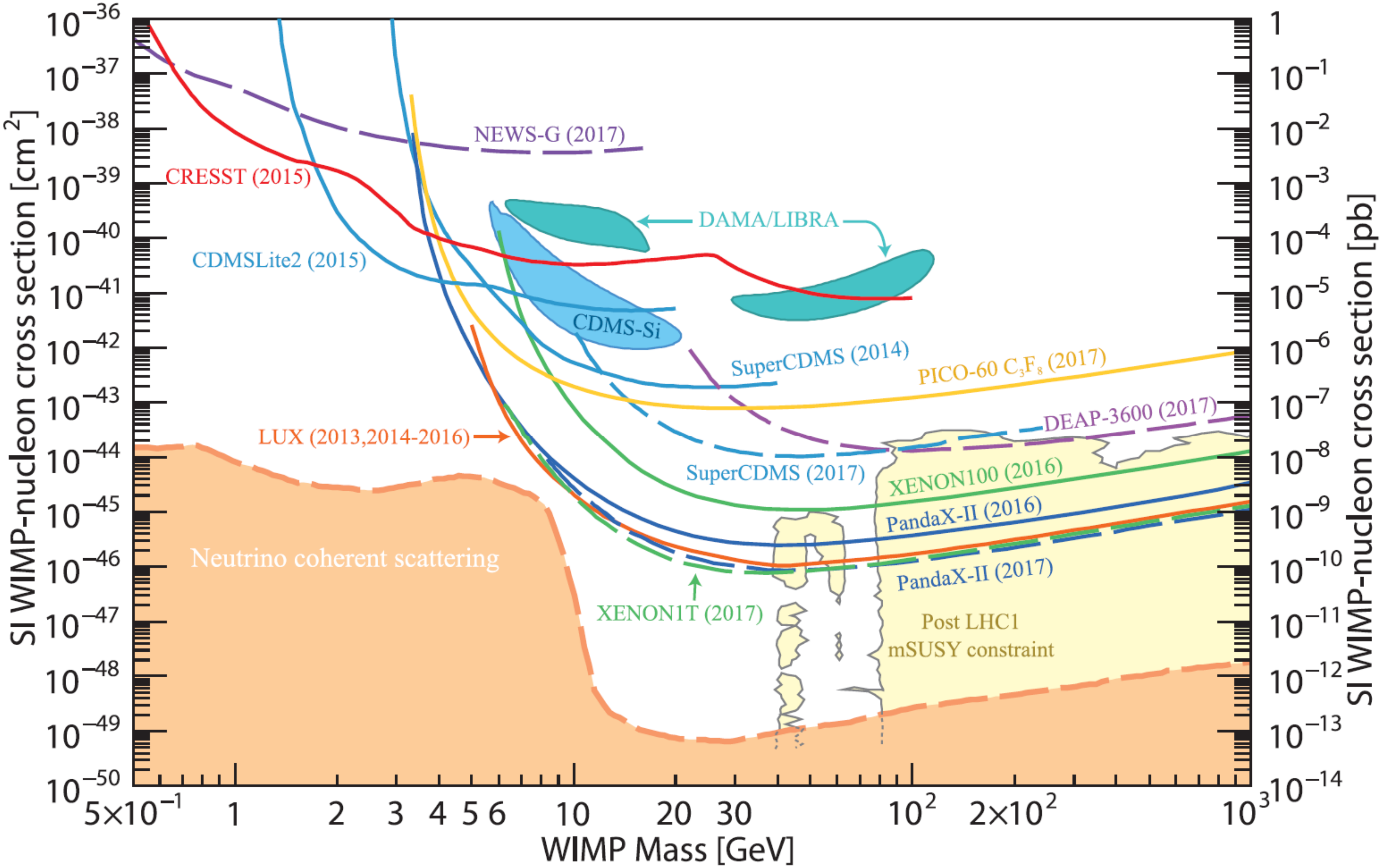


Laura Baudis, University of Zurich, VCI2013, Vienna

WIMP search results 2014



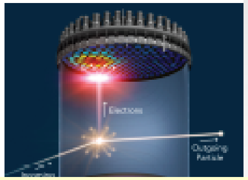
WIMP search results 2019: PDG



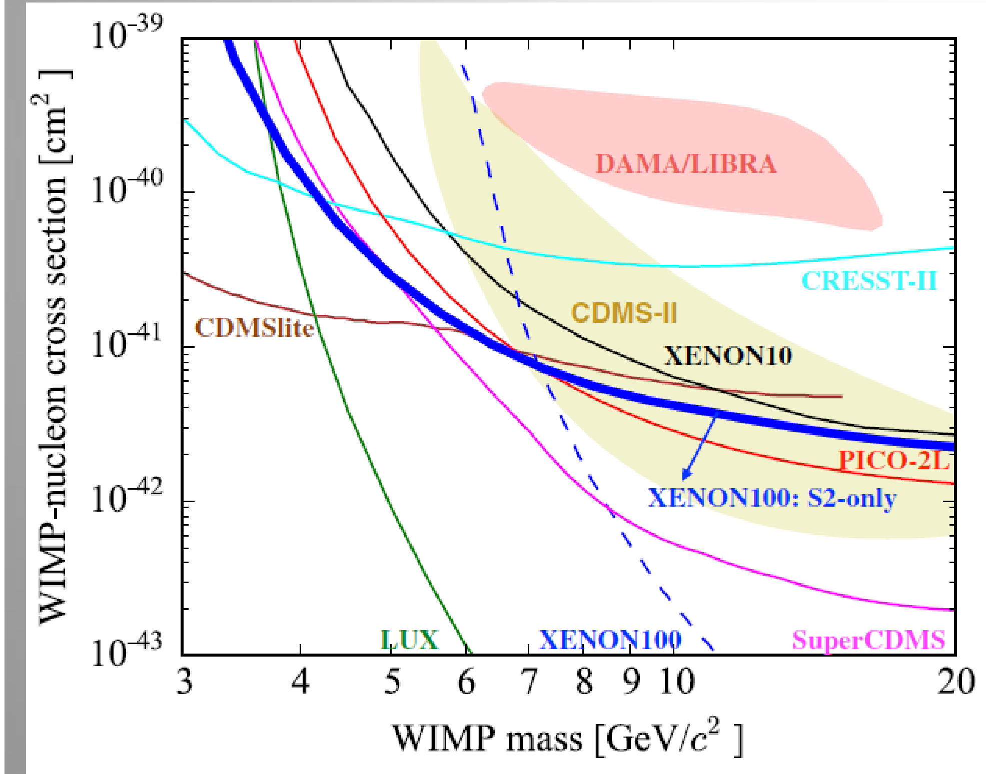
Light WIMP search results using "S2-only": 2016 vs 2019

Newish Idea: S2 only in LXe/Ar TPCs

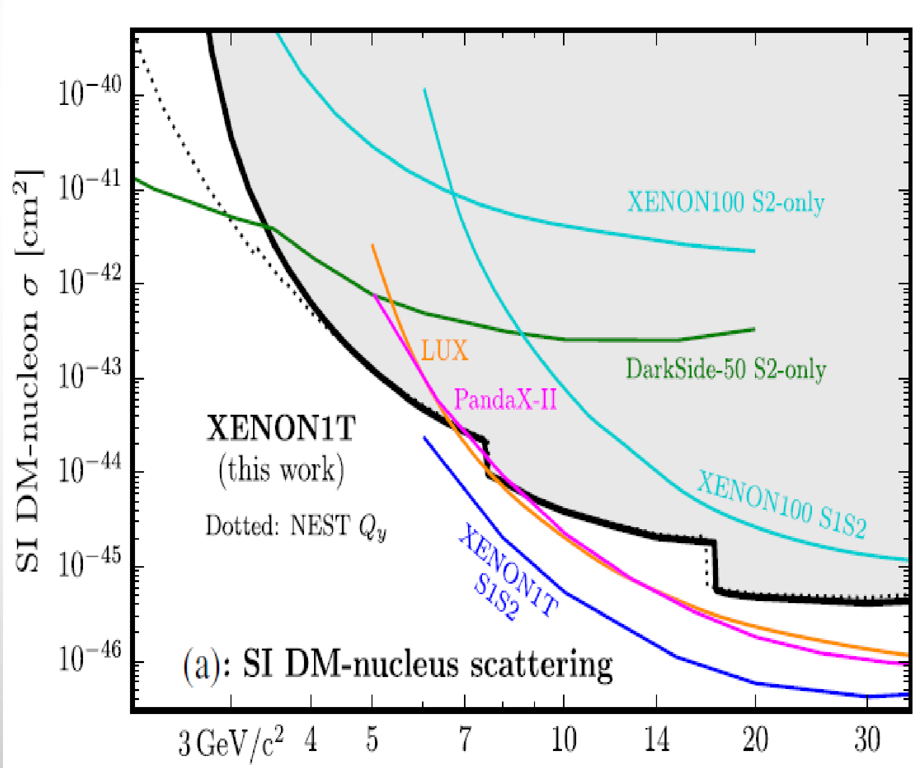
- # electrons, photons comparable
- Light collection ~10%, e- collection ~100%
- Substantially reduce *E* threshold



In absence of S1, Z cut is based on S2 width



2016

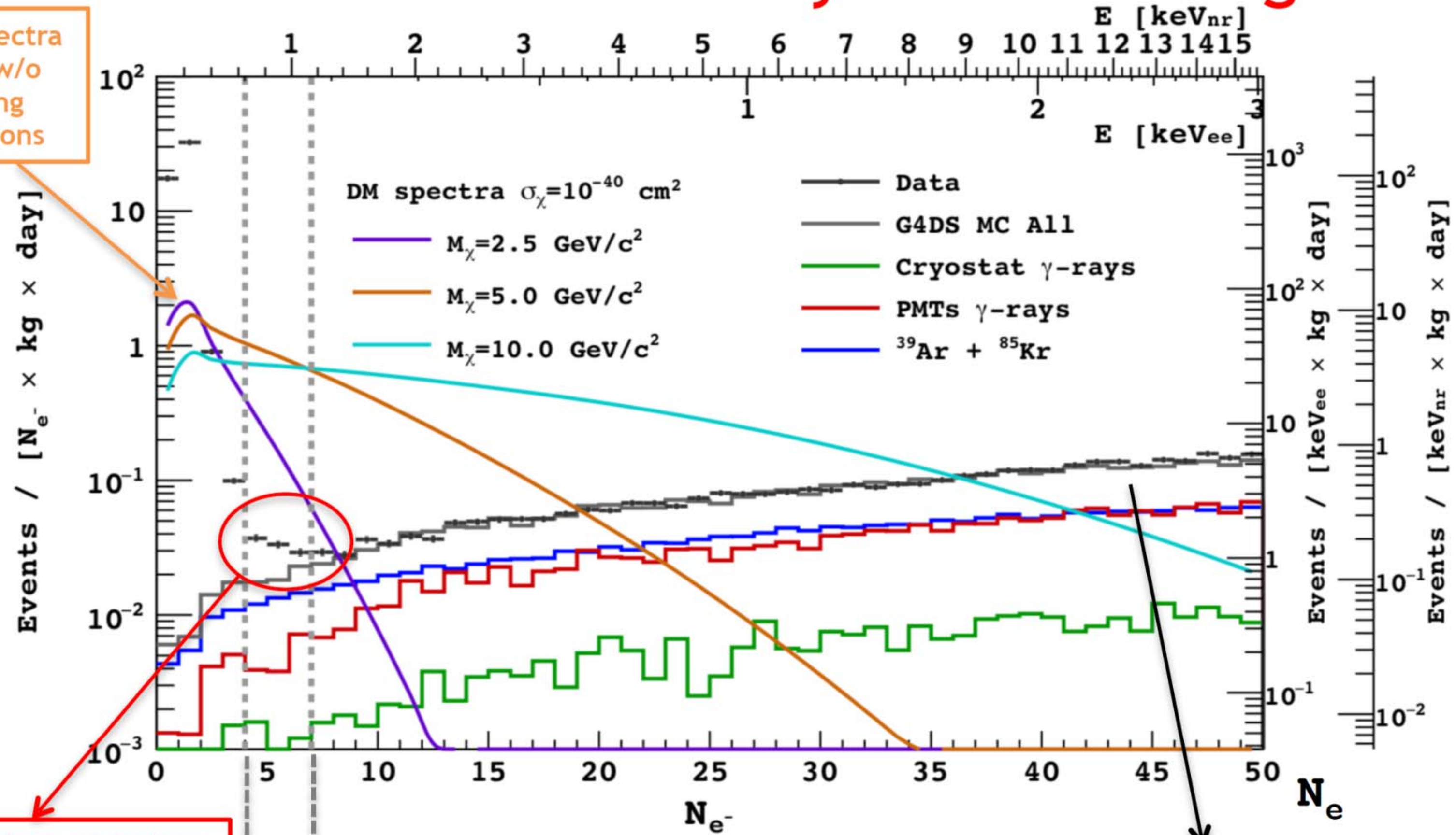


2019

Problems in light WIMP search using S2-only: DarkSide-50

Low Mass DM ionization only search background

WIMP spectra plotted w/o quenching fluctuations



Excess of events wrt to background prediction due to trapped/delayed electrons peak.

Also seen by XENON100. Further studies ongoing.

N_e > 7 analysis threshold for $M\chi$ > 3.5 GeV in Data-MC good agreement region.

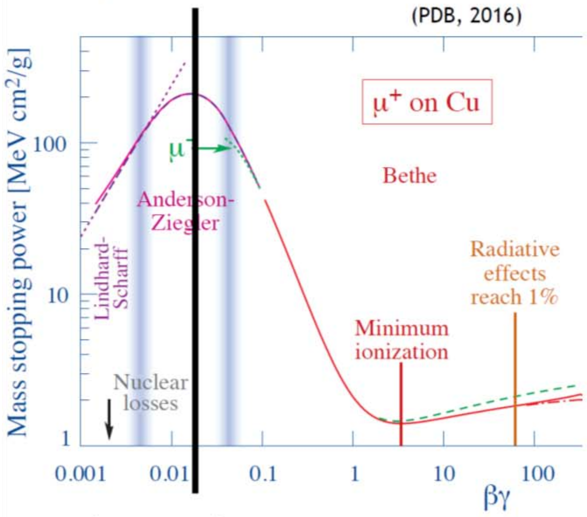
N_e > 4 analysis threshold for $M\chi$ < 3.5 GeV. Region dominated by excess of Data over MC

In high N_e region, dominant ER backgrounds, level prediction with extrapolation from high energy spectrum MC fit, in very good agreement with data (at % level).

Light WIMP search new ideas: Migdal and Bremsstrahlung effects

Low energy "Nuclear" Recoils

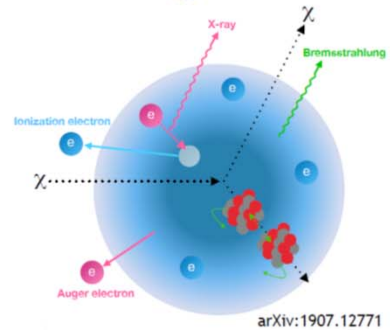
- Lindhard - "adiabatic" overlap of electron shells
- Most energy goes to heat
- Bigger effect at low energy

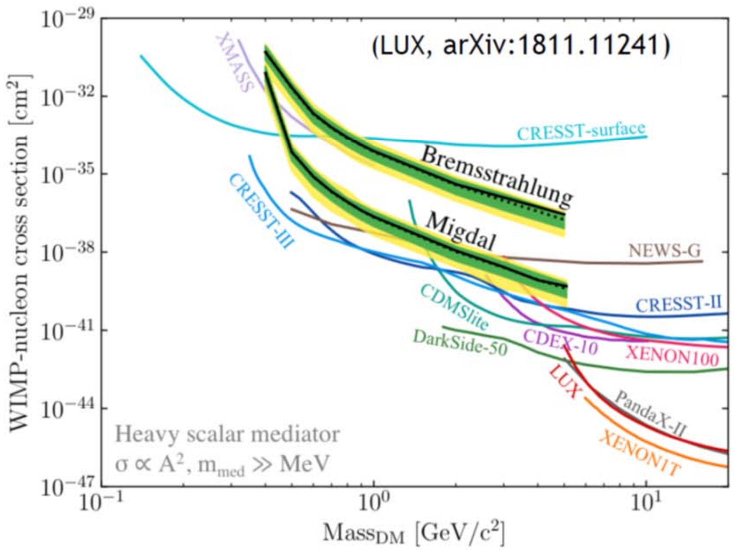


Electron velocity in target atoms

New Idea: different channel

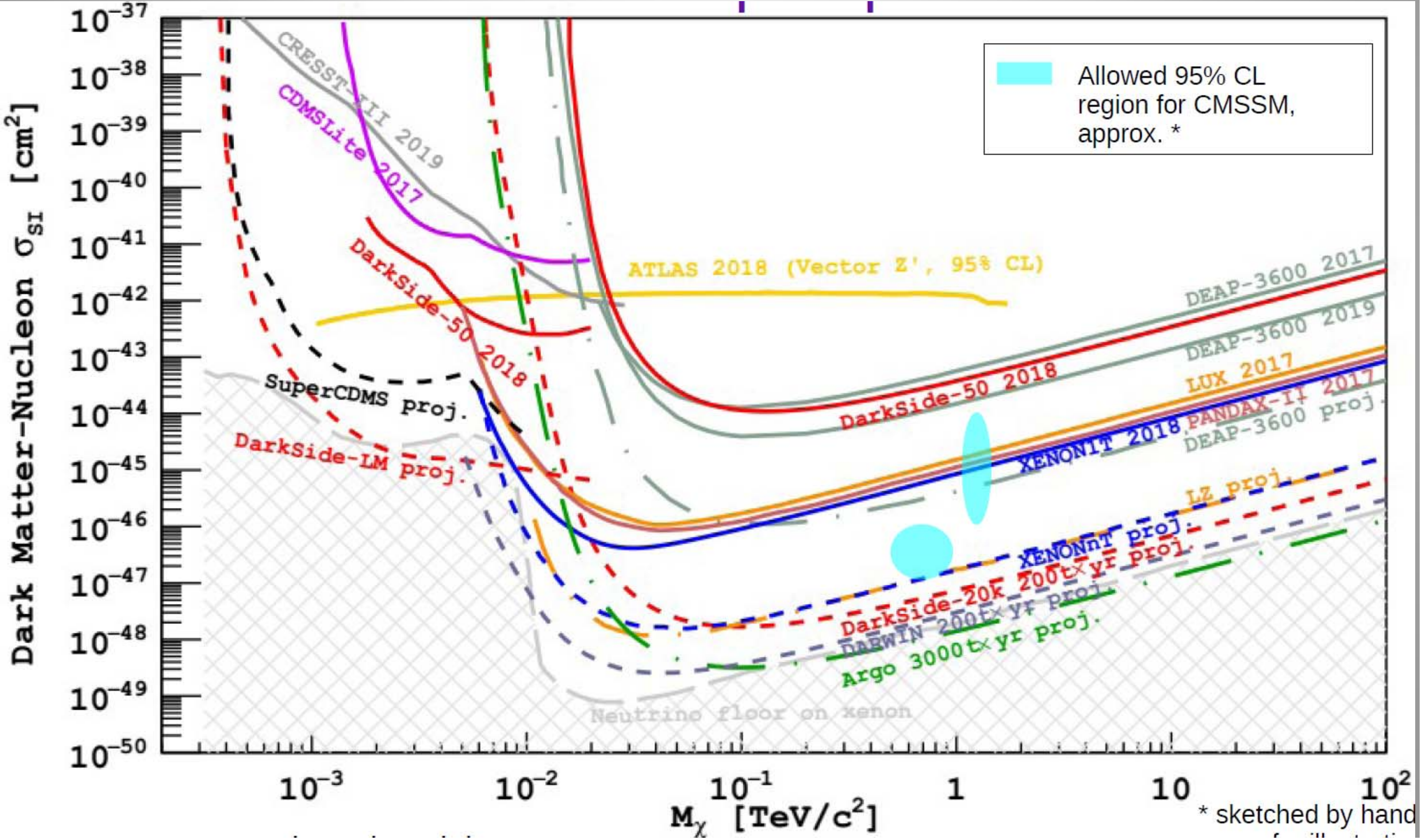
- Migdal: nuclear kick relative to electron shell generates ionization. (Ibe, et al., arXiv:1707.07258)
  - Small probability, depends on shells
  - Boosted energy in ER channel
  - Also "Bremsstrahlung" (Kouvaris, Pradler, arXiv:1607.01789)





Big penalty in rate

WIMP search prospects



* sketched by hand

Small scale WIMP search experiments

Small scale direct dark matter search experiments

- **Annual modulation:**
  DAMA/LIBRA, COSINE, ANAIS, SABRE, COSINUS, PICOLON
- **Directionality:**
  DRIFT, MIMAC, NEWAGE, DMTPC, CYGNUS, NEWSdm, other ideas
- **Low mass dark matter:** semiconductor or gas detectors
  CDEX, DAMIC, SENSEI, NEWS-G, TREX-DM
- **SD interaction:**
  PICO
- **New ideas**

TAUP 2019 TOYAMA

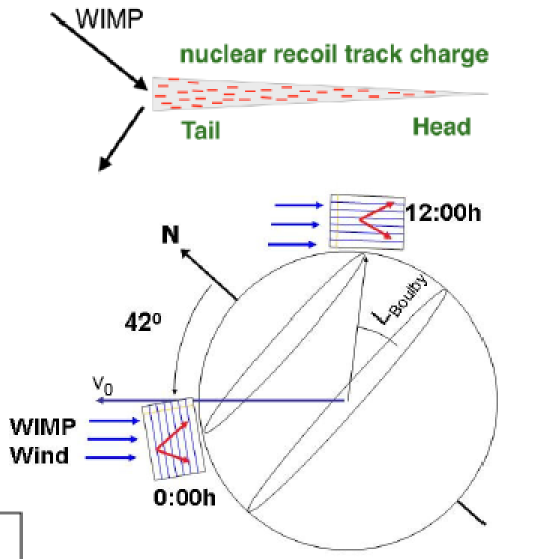
Susana Cebrián scebrian@unizar.es

Small scale WIMP search experiments: directional

Directionality

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

- To register direction (axis, sense) or at least a **head-tail asymmetry** (by measuring the relative energy loss along the track)
- **Daily modulation** of the WIMP direction due to the rotation of Earth

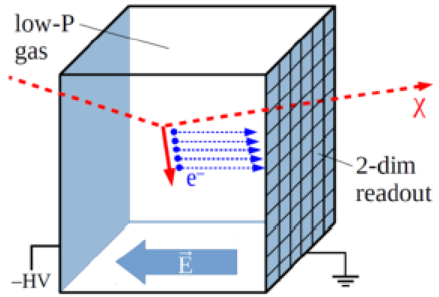


→ **Low pressure** (~0.1 atm) gas targets in **TPCs** with different electron amplification devices and track readouts:

Multi-wire proportional chambers (MWPC)
Micro pattern gaseous detectors (MPGDs)
Optical readouts

J.B.R. Battat et al., Phys. Rep. 662 (2016) 1

→ **Nuclear emulsions**



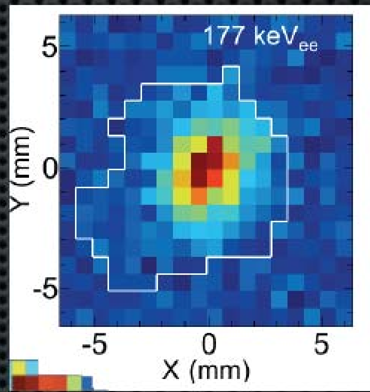
arXiv:1903.03026

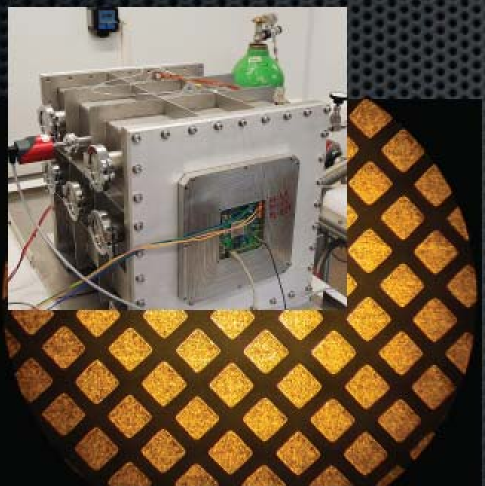
Small scale WIMP search experiments: directional

Directional detectors

- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus
- MicroTPCs: MIMAC (CF_4, CHF_3, H gas), NEWAGE (CF_4 gas)
- TPC: DRIFT (negative ion, CS_2), DM-TPC (CF_4 gas)
- New ideas: see talk by D. Nygren

DM-TPC
n-calibration

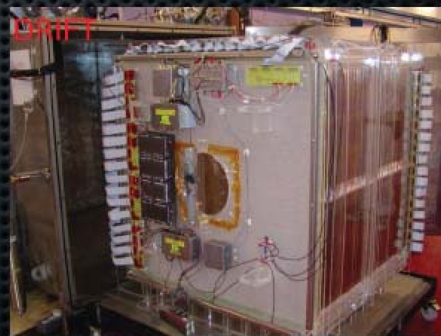




MIMAC 100x100 mm^2
5l chamber at Modane

18l DM-TPC at MIT
CCD readout

NEWAGE, Kamioka



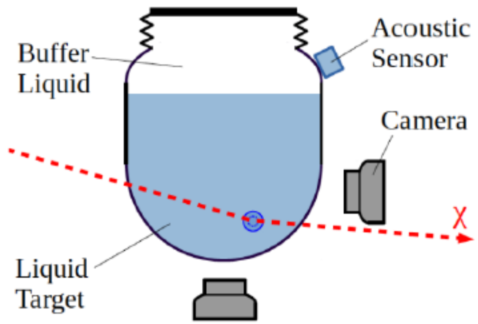
DRIFT, Boulby Mine

Small scale WIMP search experiments: PICO

Merging **PI**CASSO and **CO**UPP collaborations since 2012

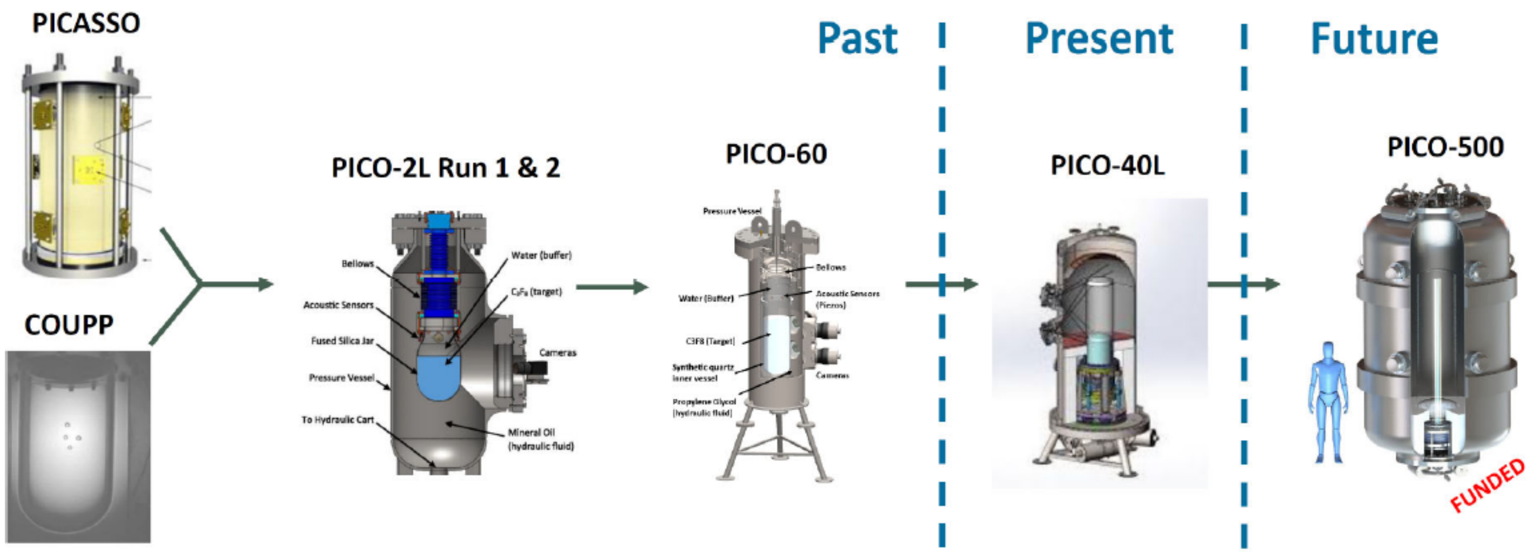
arXiv:1903.03026

Bubble chamber: target liquids in metastable superheated state; sufficiently dense energy depositions start the formation of bubbles; read by cameras



+ Almost immune to electronic recoil background sources
+ Different targets, most containing ^{19}F, highest sensitivity to **SD p couplings**
- Threshold detector: no direct measurement of recoil energy
- Long deadtime to compress/decompress the chamber after each event

- Operation of a series of bubble chambers at SNOLAB:



Search for charged primordial black-hole dark matter (not WIMP)

Direct detection of primordial black hole relics as dark matter

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Abstract. If dark matter is composed of primordial black holes, such black holes can span an enormous range of masses. A variety of observational constraints exist on massive black holes, and black holes with masses below 10^{15} g are often assumed to have completely evaporated by the present day. But if the evaporation process halts at the Planck scale, it would leave behind a stable relic, and such objects could constitute the entirety of dark matter. Neutral Planck-scale relics are effectively invisible to both astrophysical and direct detection searches. However, we argue that such relics may typically carry electric charge, making them visible to terrestrial detectors. We evaluate constraints and detection prospects in detail, and show that if not already ruled out by monopole searches, this scenario can be largely explored within the next decade using existing or planned experimental equipment. A single detection would have enormous implications for cosmology, black hole physics, and quantum gravity.

Keywords: primordial black holes, dark matter detectors, dark matter experiments, dark matter theory

ArXiv ePrint: 1906.06348

JCAP10(2019)046

Заряженные первичные черные дыры с массой Планка, 1.2×10^{19}ГэВ или 22мкг, и плотностью потока в Солнечной системе 1 штука в год на 4м^2, могут обеспечить всю темную материю в Галактике.

Такие черные дыры будут наблюдаться в детекторе в виде прямых треков, похожие на тяжелые заряженные ионы, с четкой и необычной сигнатурой: направленностью на созвездие Лебедя, фиксированной скоростью (200-300км/сек) и dE/dx~90МэВ/гсм^2.

Интересно, что если такая дыра вдруг потеряет заряд (стабилизирующий ее), то она мгновенно испарится с выделением энергии эквивалентной 450 кг тротила.

Заключение

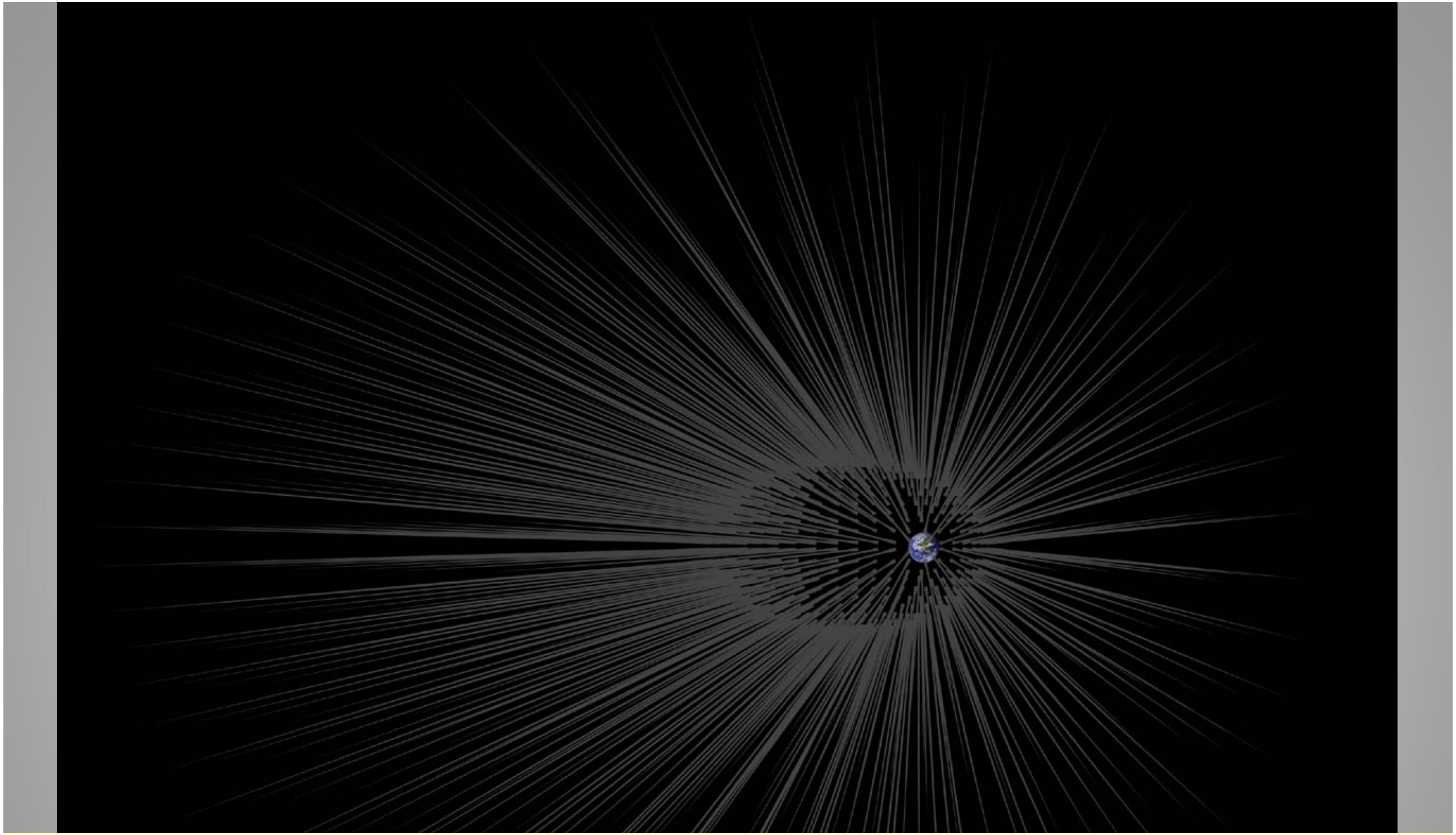
Ожидаются две основные тенденции в развитии экспериментов по поиску темной материи.

С одной стороны – это создание масштабных (десятки-сотни тонн) детекторов на основе жидкого аргона и ксенона.

С другой стороны – это эксперименты небольшого размера, зато либо предельной чувствительности в области малых масс ВИМП, либо чувствительные к направленности потока ВИМП.

Ожидается, что в течение десятилетия будет достигнуто «нейтринное дно» как в области малых, так и больших масс ВИМП, и будет либо подтверждена, либо опровергнута загадка Dama/Libra.

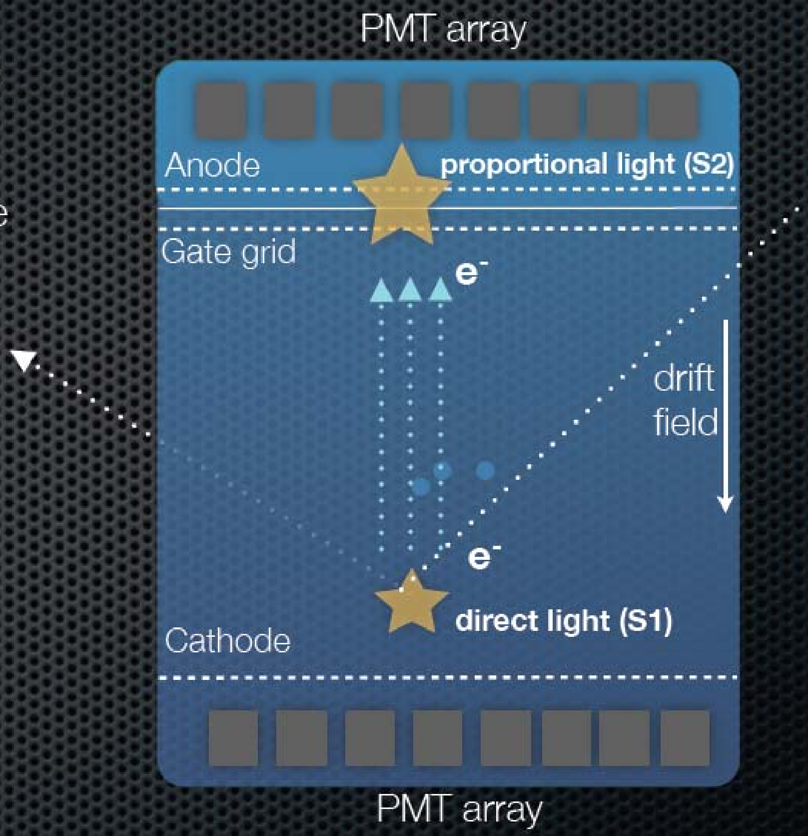
Backup slides

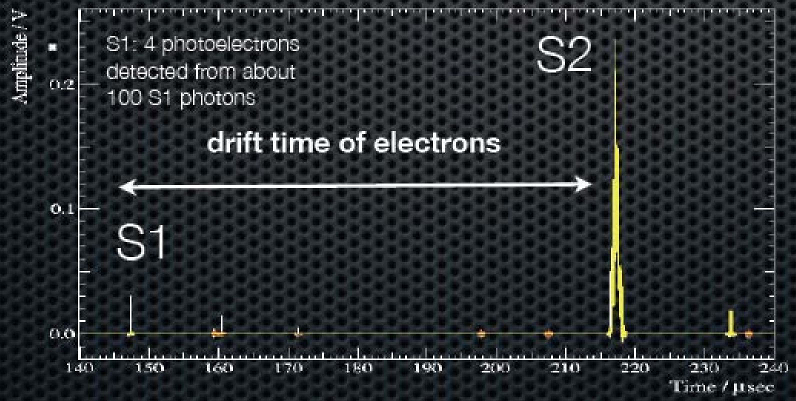


Этюд по мотивам темной материи. Астрофизики предположили, что темная материя вокруг планет Солнечной системы принимает форму длинных волос. При приближении к Земле, как рассчитал Гэри Презо (G. Prezeau, Astrophys. J. 814:122, 2015), частицы фокусируются в сверхплотные волокна, или «волоски». Такие волоски обладают как корнями (с наибольшей концентрацией частиц, до миллиарда раз выше среднего), так и кончиками. Корни волосков темной материи расположены примерно в миллионе километров от поверхности Земли, а кончики — в двух миллионах. Моделирование показало, что перепады плотности вещества внутри Земли (между ядром, мантией и корой) должны отражаться на структуре «волос», создавая в них характерные изгибы. Если ученые смогут получить доступ к этой информации, то у них получится выстраивать геологические карты небесных тел по темной материи и даже оценивать глубины подледных океанов на спутниках Сатурна и Юпитера.

Two-phase detectors for rare-event experiments: principles of operation

- *Prompt (S1)* light signal after interaction in the active volume
- Charge is drifted, extracted into the gas phase and detected as *proportional light (S2)*
- *Charge/light depends on dE/dx: particle identification*
- *3D-position resolution: fiducial volume cuts*





- S2: 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

Laura Baudis, University of Zurich, VCI2013, Vienna

L. Baudis, VCI 2013 talk

Two-phase Xe and Ar experiments: by 2015

XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs

still in operation
new DM still blinded
Modulation study completed

LUX at SURF:

370 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run and first results in 2013
new run started end 2014

PandaX-1 at CJPL:

125 kg LXe
(37 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
first results in Aug 2014
80 days DM data still blinded
Preparing 500kg PandaX-II

ArDM at Canfranc:

850 kg LAr
(~500 kg fiducial)?

28 3-inch PMTs

Filled in Feb 15. but no field. First science run in 2015?

DarkSide at LNGS:

50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)

38 3-inch PMTs

first result in late 2014. First run with DA in 2015

WIMP search experiments: single phase

Single-phase detectors (light only)

- XMASS at Kamioka (LXe), DEAP/CLEAN at SNOLab (LAr)
- Challenge: ultra-low absolute background

XMASS at Kamioka:
in water Cherenkov shield at Kamioka
835 kg LXe (100 kg fiducial), single-phase, 642 PMTs
soon to take science data

MiniCLEAN at SNOLab:
500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in summer 2013

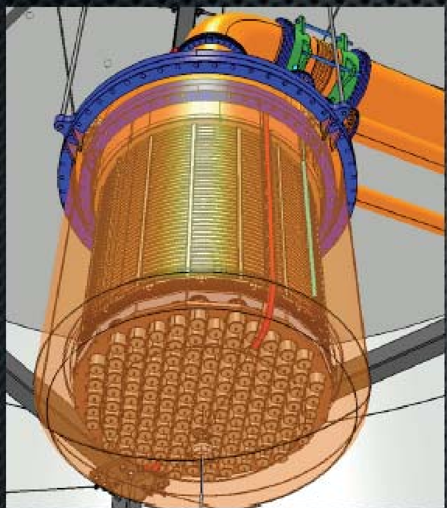
DEAP-3600 at SNOLab:
3600 kg LAr (1t fiducial)
single-phase detector
under construction
to run in 2014

Laura Baudis, University of Zurich, VCI2013, Vienna

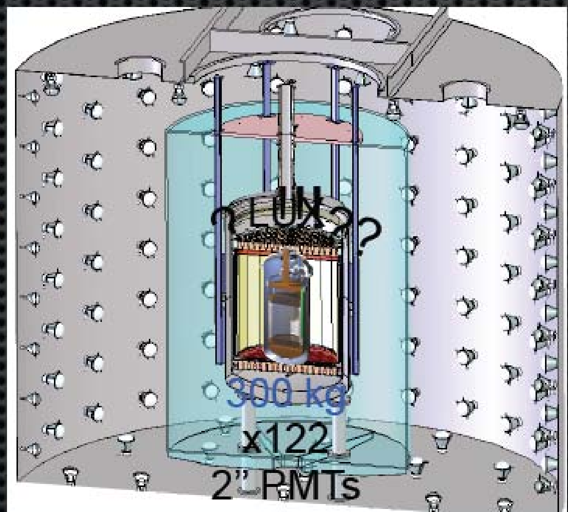
Proposed large-scale noble-gas liquids: by 2015

Liquid xenon and liquid argon detectors

- Under construction: XENON1T at LNGS, 3 t LXe in total
- Future and R&D: XMASS (5 t LXe), LZ (7 t LXe), DARWIN (20 t LXe/LAr)



XENON1T TPC



LZ (LUX + ZEPLIN) 7t LXe

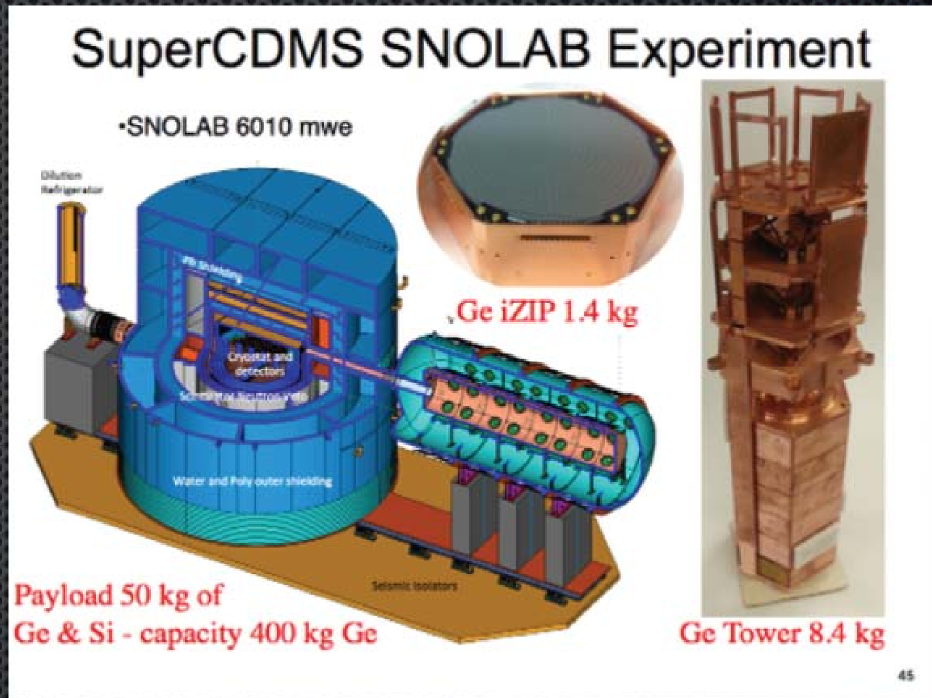
DARWIN 20 t LXe/LAr

Laura Baudis, University of Zurich, VCI2013, Vienna

Light WIMP search:
future SuperCDMS experiment by 2016

increase sensitivity to light WIMPs with next generation Cryogenic Experiments at T~ mK

- SuperCDMS at SNOLab. Low-temperature Ge/Si detectors. Focus on low mass 0.3-10GeV/c^2
  - Above 5 GeV/c^2 6 towers ≈50kg Ge full nuclear recoils recognition through ionization + athermal phonon
  - 0.3-5 GeV/c^2, 1 tower of e.g., 3 Ge, 3 Si, CDMS HV (Luke Neganov amplification of ionization). No discrimination. Background limited after 1 year
- Start data taking in 2018. Ultimate goal (SI) : 8×10^{-47} cm^2
- Collaboration with EURECA for multi-target approach ($CaWO_3$, Ge) and increased target mass. Potentially increase Ge mass to ~200 kg



Light WIMP detection threshold problem: nuclear recoil spectrum, local DM density and velocity in the Earth rest frame

In the Earth rest frame:

$$\frac{dR}{dE_r} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{min}}^{v_{esc}} v f(v) \frac{d\sigma}{dE_r} \, dv.$$

In the Galactic rest frame:

The dark matter velocity profile is commonly described by an isotropic Maxwell-Boltzmann distribution

$$f(\mathbf{v}) = \frac{1}{\sqrt{2\pi\sigma}} \cdot \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma^2}\right) \tag{12}$$

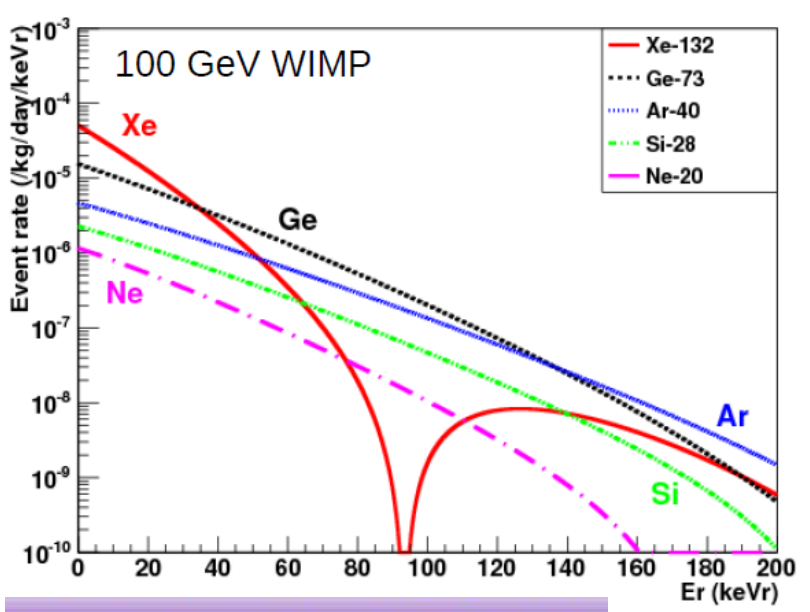
which is truncated at velocities exceeding the escape velocity. Here, the dispersion velocity σ is related to the circular velocity via $\sigma = \sqrt{3/2}\, v_c$. A standard value of $v_c = 220\,\mathrm{km/s}$ is used for the local circular speed. This value results from an average of

v_c=220 km/s; v_{esc}=544 km/s; ρ_0=0.3 GeV/c^2/cm^3

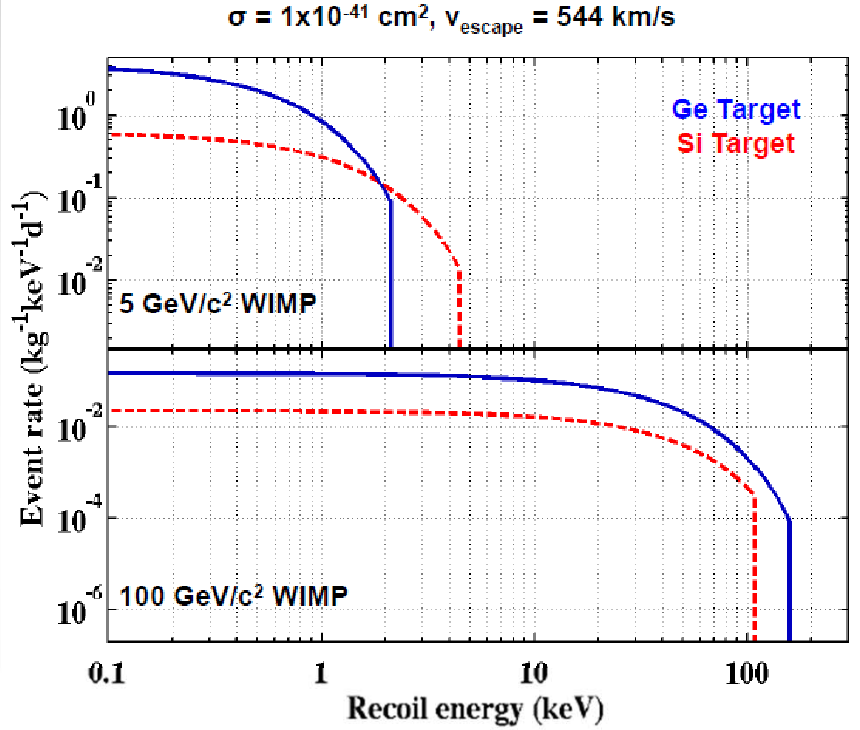
L. Baudis, arXiv:1211.7222

N M. Klasen, M. Pohlb, G. Sigl, arXiv:1507.03800

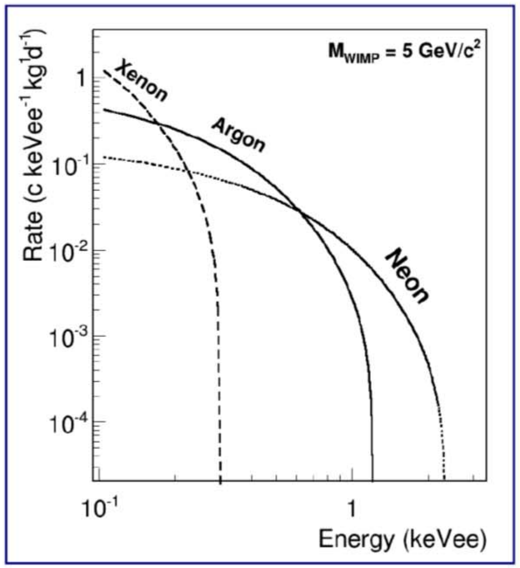
Light WIMP detection threshold problem: recoil energy spectrum cut-off



Marcin Kuźniak – LIDINE2019



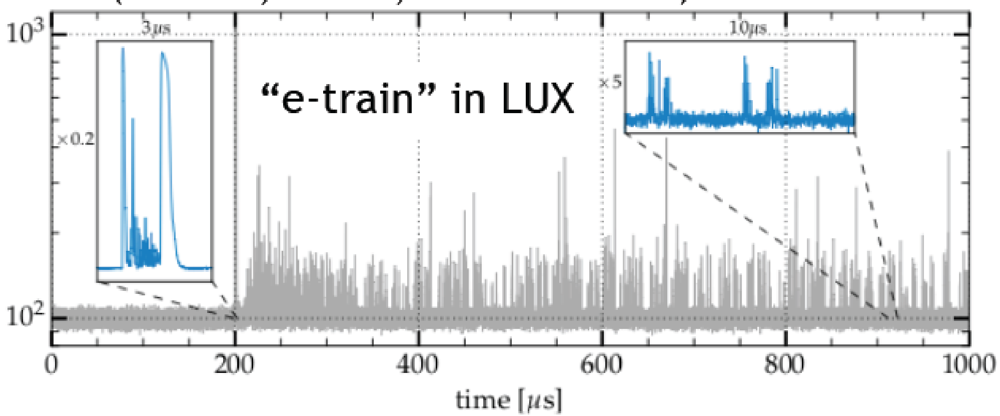
E. Yakushev, Nanpino13 talk

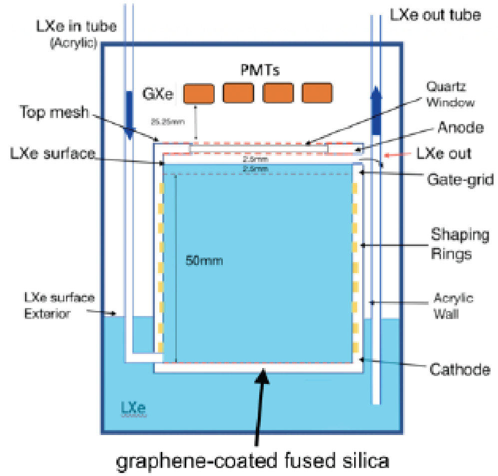


S. Cebrián, TAUP2019, 11 September 2019

Problems in light WIMP search using S2-only: LUX

S2 only electron background



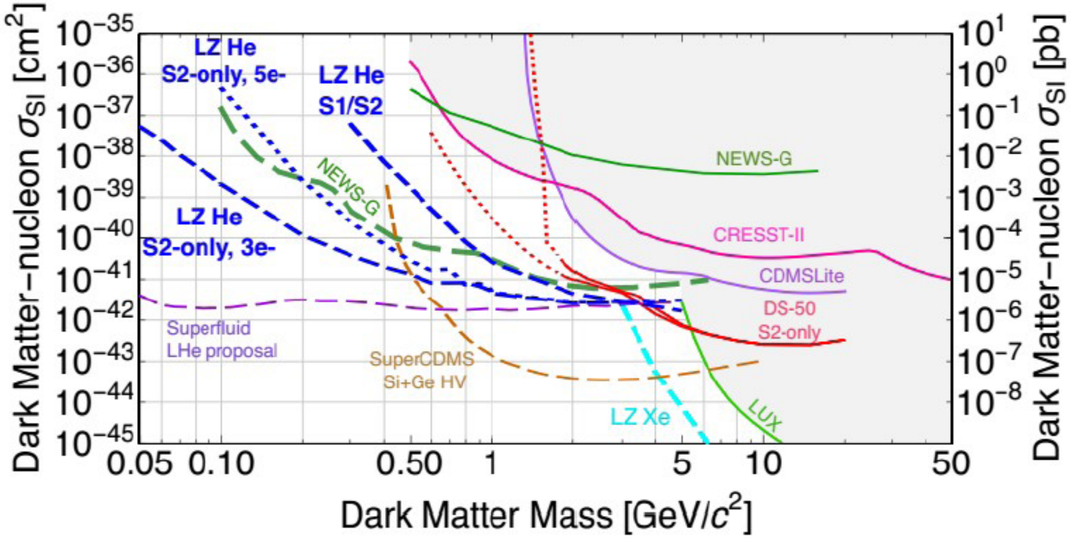


LBECA prototype - sealed chamber with high chemical purity
K. Ni, DM14

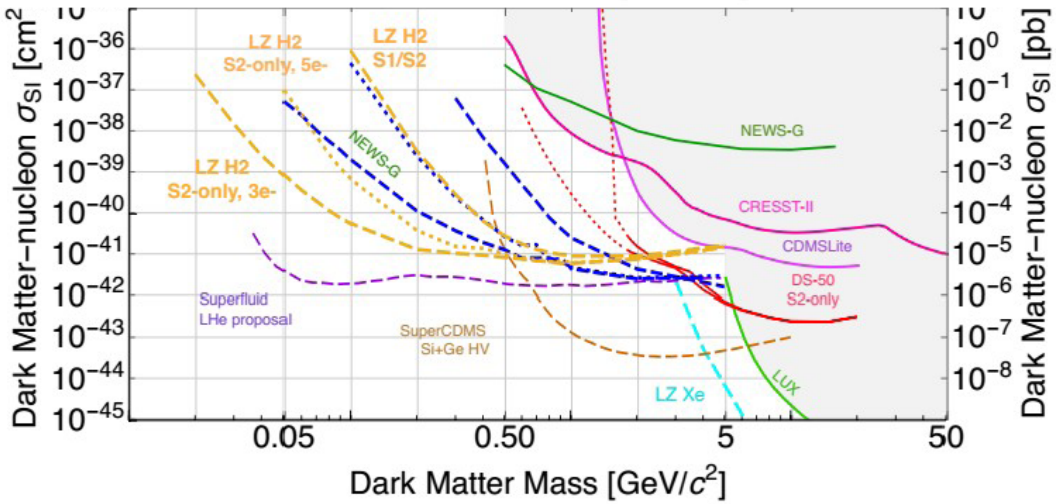
- Several sources of electrons
- LBECA: dedicated S2 only experiment
  - Electron reduction methods under study
  - 100 kg LXe detector planned
- LZ: major program to reduce emission from grids (Stifter, DM16)
  - electron signal ~4 times larger than LUX

Light WIMP search new ideas: doping with low-Z admixture

Enhancing LXe sensitivity at low mass



- Admixture of low-Z dopant can **dramatically increase the sensitivity to low mass WIMPs**
- R&D ongoing



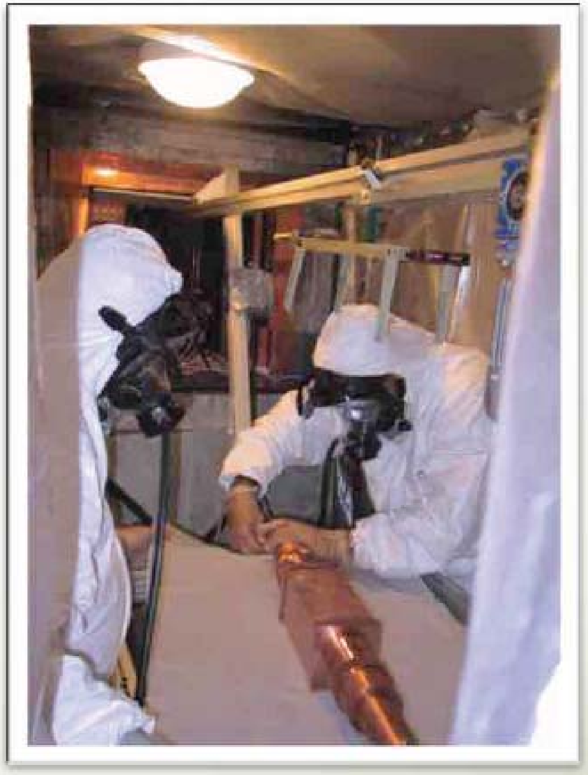
- Sensitivity and feasibility studies on LXe mixtures with hydrogen

Lippincott, talk at IDM 2018

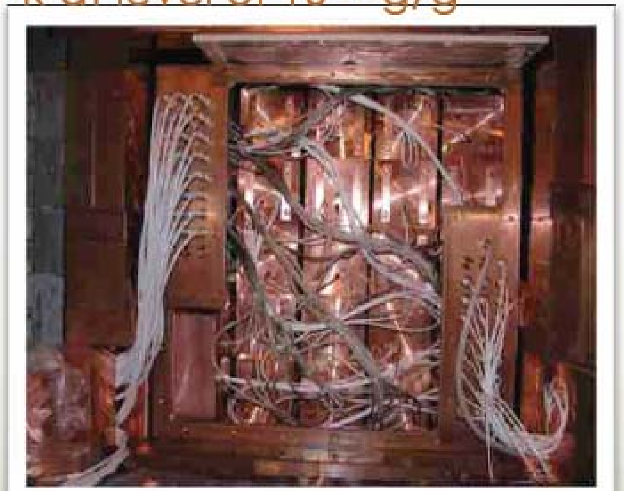
Dark Matter search experiments: room temperature crystals - DAMA/LIBRA

The DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques
(all operations involving - including photos - in HP Nitrogen atmosphere)



Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

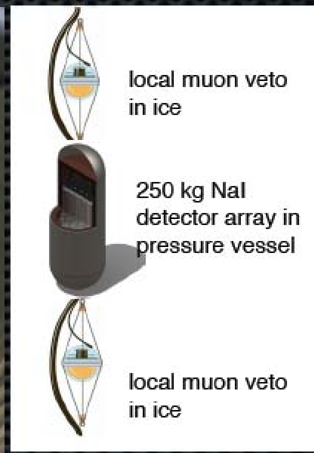


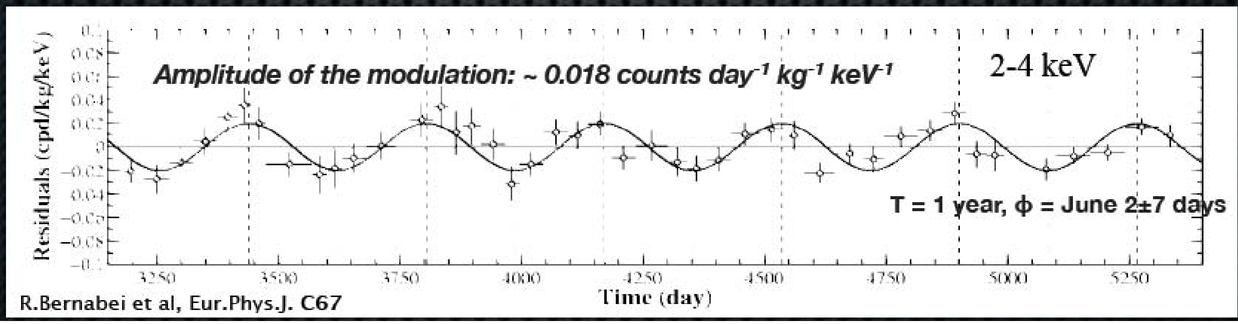
Direct Dark Matter search experiments

Room temperature scintillators

- NaI: DAMA/LIBRA, ANAIS; CsI: KIMS
- New idea: DM-Ice -> 17 kg NaI deployed as feasibility study at the South Pole (look for annual modulation in the southern hemisphere, 2.4 km deep in ice)
- Goal: build a 250-500 kg NaI detector array, closely packed inside a pressure vessel; use IceCube as a veto

DM-Ice





Dark Matter search experiments: bubble chambers by 2015

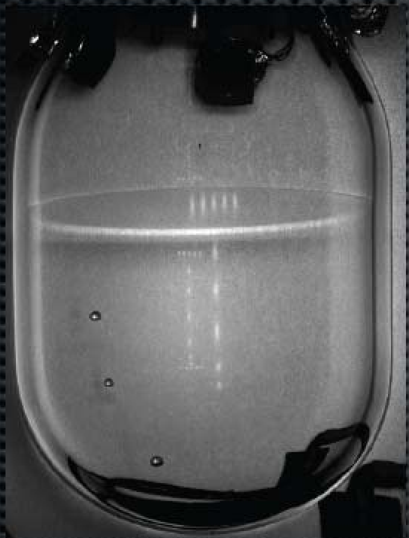
Bubble chambers

- Detect single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chambers (with acoustic, visual or motion detectors)
- Large rejection factor for MIPs (10^{10}), scalable to large masses, high spatial granularity
- Existing detectors: COUPP, PICASSO, SIMPLE
- Future: COUPP-500 -> ton-scale detector

Example:

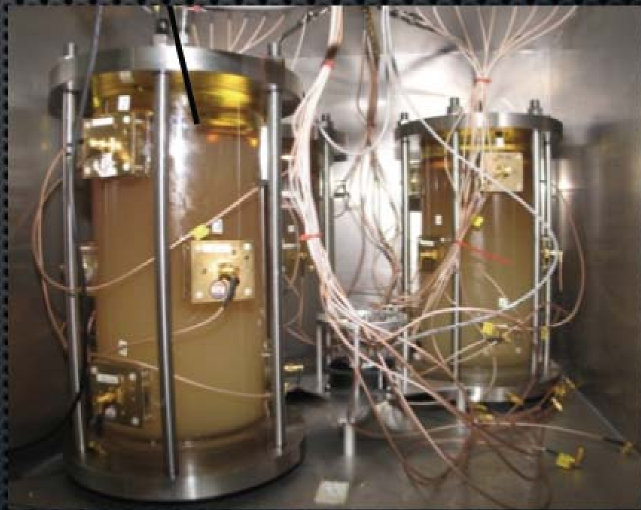
n-induced event (multiple scatter)

WIMP: single scatter



COUPP 4 kg CF_3I detector at SNOLAB

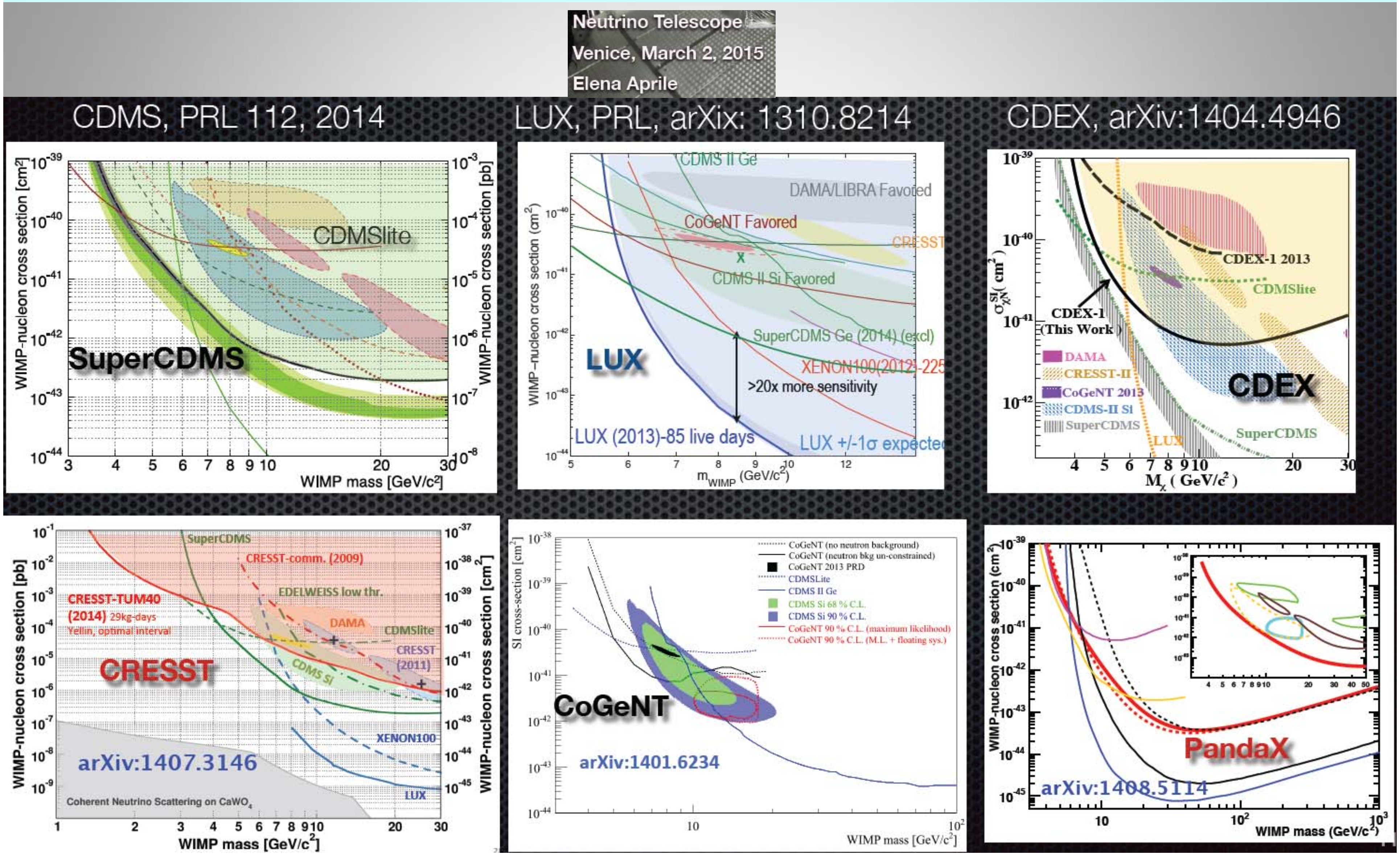
COUPP 60 kg CF_3I detector installed at SNOLAB; physics run in March 2013



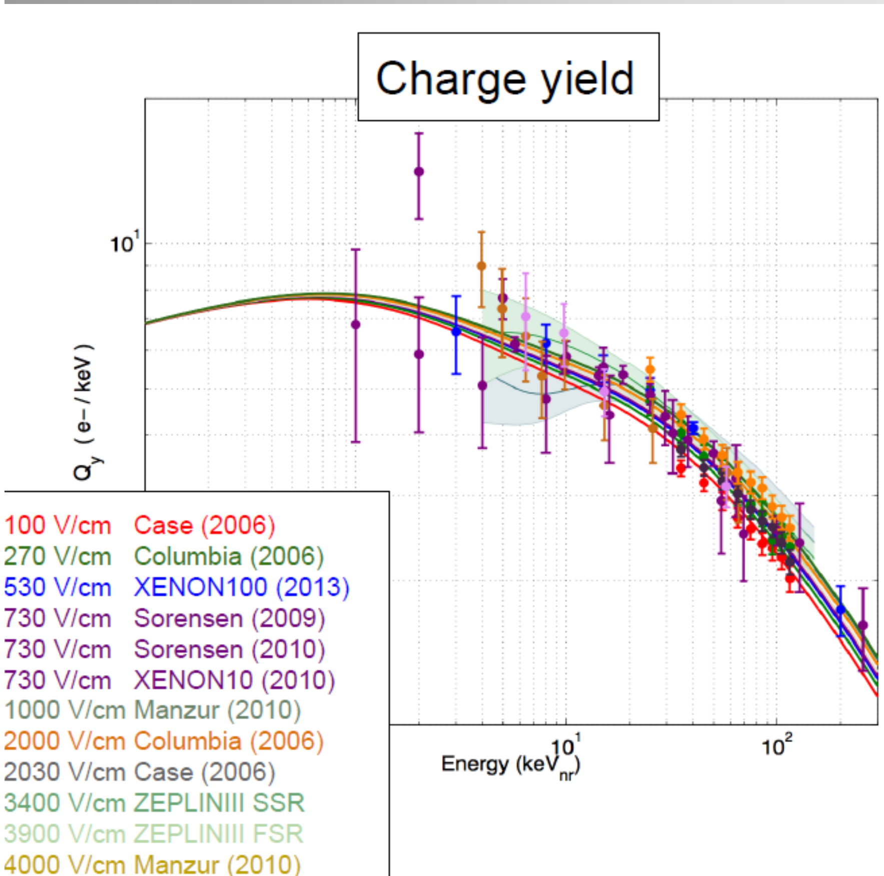
PICASSO at SNOLAB

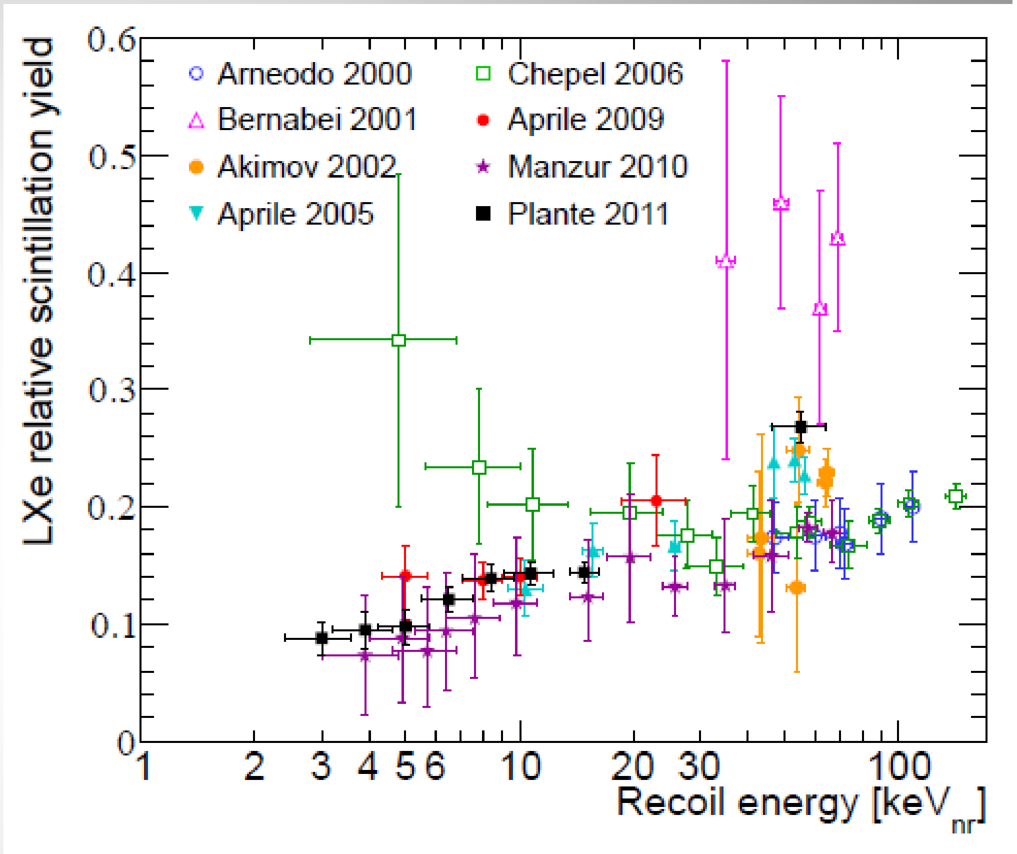
Recoil range << 1 μm in a liquid - very high dE/dx

On the other hand, light WIMPs disfavored by results from CDMS-Ge, XENON100, LUX, EDELWEISS, CRESST, CoGeNT (updated), CDEX and PandaX: by 2015



Nuclear recoil data in LXe

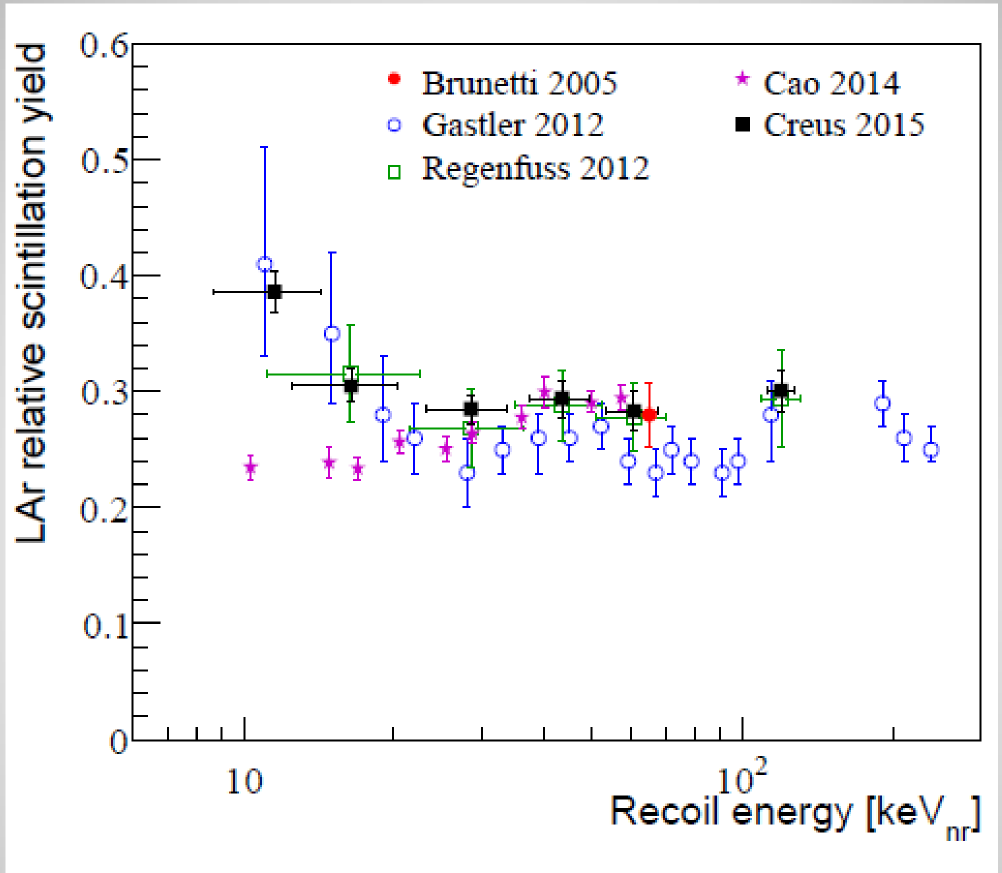




Ionization yield in LXe [B. Lenardo et al., arXiv:1412.4417]

Scintillation quenching factor in LXe [T. Undagoitia and L. Rauch, arXiv:1509.08767]

Nuclear recoil data in LAr: scintillation yields are conflicting



Scintillation quenching factor in LAr [T. Undagoitia and L. Rauch, arXiv:1509.08767]

Nuclear recoil data in LAr: ionization yields seems to be conflicting

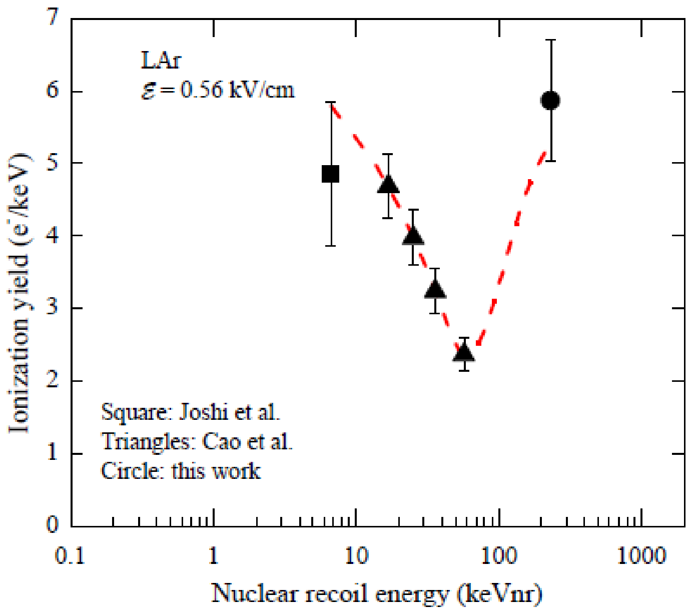


Figure 6. Ionization yield of nuclear recoils in liquid Ar at 0.56 kV/cm as a function of the energy, measured in Joshi et al. [5], Cao et al. [6] and this work. The curve is drawn by eye.

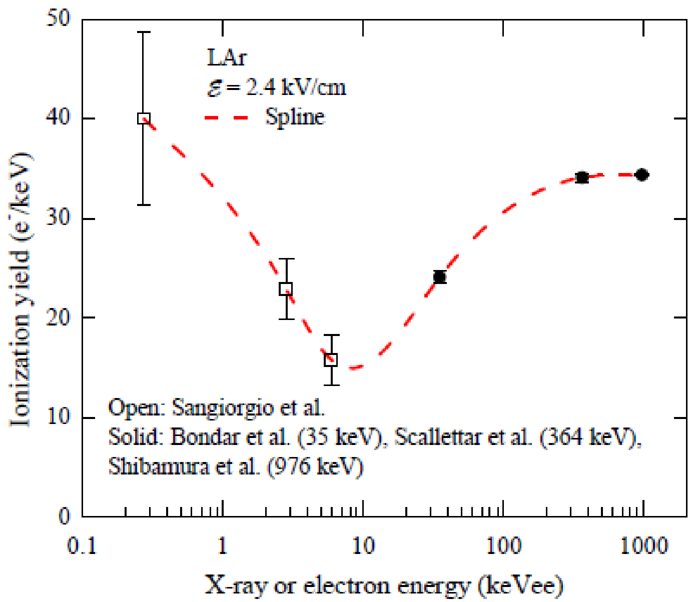


Figure 7. Ionization yield of electron recoils in liquid Ar at 2.4 kV/cm as a function of the energy, measured in Sangiorgio et al. [28] (at 0.27 keV, 2.8 keV and 5.9 keV), in Bondar et al. [14] (at 35 keV), in Scallettar et al. [29] (at 364 keV) and in Shibamura et al. [30] (at 976 keV). The spline function fit for the ionization yield is also shown. The figure is taken from [14].

Ionization yield: results of LLNL [PRL 112, 171303 (2014)] and BINP [EPL 108 (2014) 12001] and SCENE [PR D 91, 092007 (2015)]

Nuclear recoil data in LNe and LHe

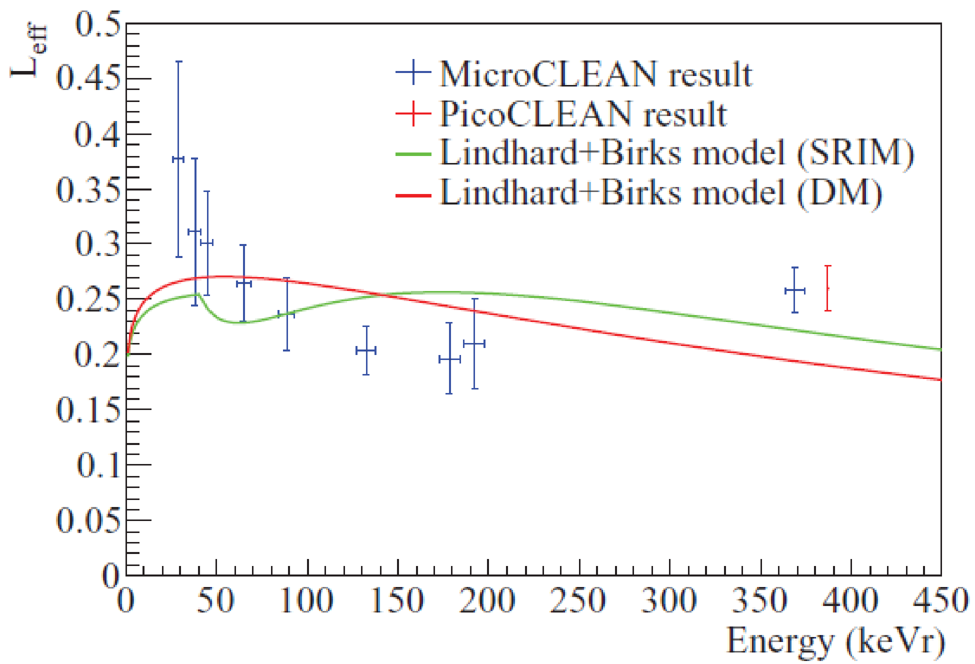


FIG. 13. (Color online) The observed nuclear recoil scintillation efficiency vs nuclear recoil energy in neon, along with the Lindhard + Birks model described in the text.

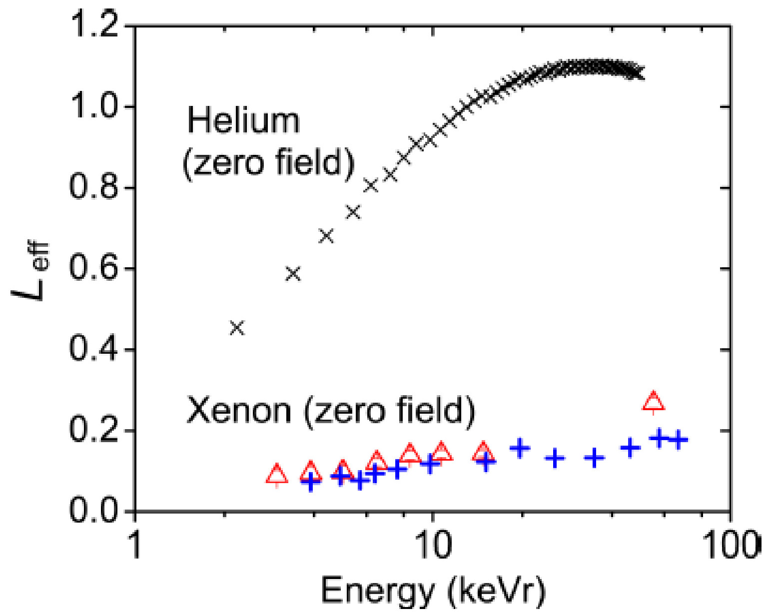
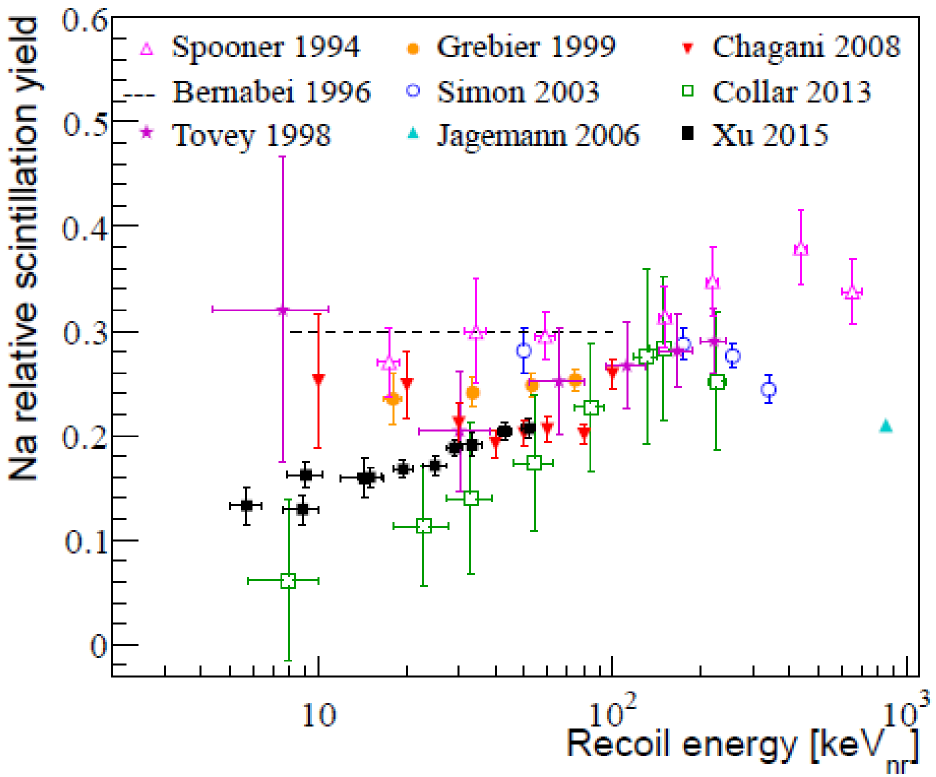


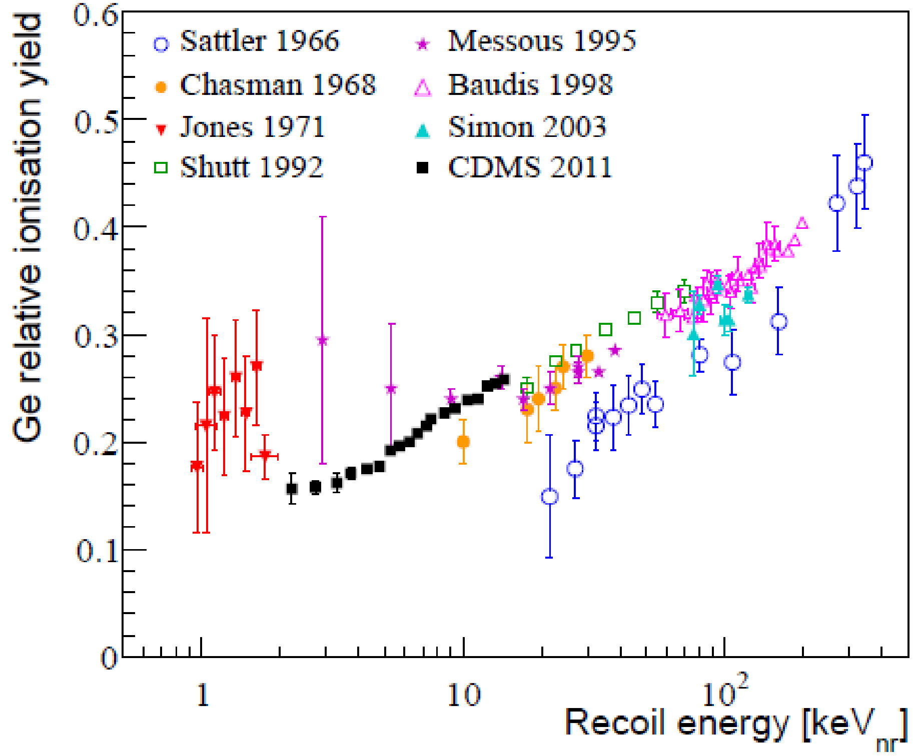
FIG. 11: (color online) The effective quenching factor L_{eff} as a function of the recoil event energy. The × represents the calculated L_{eff} for helium under zero applied electric field. The measured data for liquid Xenon by G. Plante *et al.* [88] (△) and by A. Manzur *et al.* [89] (+) are also shown.

Scintillation quenching factor in LNe, experiment [Lippincott et al. Phys. Rev. C 86, 015807 (2012)]

Scintillation quenching factor in LHe, theory [W. Guo, D.N. McKinsey arXiv:1302.0534]

Nuclear recoil data in NaI and Ge: confusing





Scintillation quench factor in NaI and ionization quench factor in Ge [T. Undagoitia and L. Rauch, arXiv:1509.08767]

Local DM density, velocity and nuclear recoil energy

The direct-detection rate depends on the local dark-matter density, currently estimated to be $\rho \simeq 0.39 \pm 0.03$ GeV cm^{-3} [127]. The systematic un-

distribution $f(\mathbf{v})$. If we assume the velocity distribution at the solar circle to follow a Gaussian and take into account the orbit velocity of the Sun around the galactic center, $v_0 = 220$ km s^{-1}, and the orbit speed of the Earth around the Sun, v_e, we obtain the normalized one-dimensional Maxwell-Boltzmann distribution

$$f(v)\mathrm{d}v = \frac{v\mathrm{d}v}{v_e v_0 \sqrt{\pi}} \left\{ \exp\left[-\frac{(v-v_e)^2}{v_0^2}\right] - \exp\left[-\frac{(v+v_e)^2}{v_0^2}\right] \right\}, \quad (30)$$

which must in addition be truncated at the local escape velocity from the Milky Way $v_{\rm esc} = 533^{+54}_{-41}$ km s^{-1} [129]. The dark-matter flux passing through a detector on Earth can therefore be quite large, $nv = \rho v/m_X \simeq 10^5$ cm^{-2} s^{-1} for $m_X = 100$ GeV.

[130]. In the elastic case ($\delta = 0$) and for $m_X \leq m_N$, the maximum

$$E_R^{\rm max} \simeq 90 \left(\frac{m_X}{100\,\mathrm{GeV}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m_N}\right) \left(\frac{v}{200\,\mathrm{km\,s^{-1}}}\right)^2 \mathrm{keV} \quad (33)$$

ranges typically between 1 and $\mathcal{O}(100)$ keV, the upper limit imposed by $v_{\rm esc}$. Dark matter with masses below 1 GeV is typically below the detection

M. Klasen, M. Pohlb, G. Sigl, arXiv:1507.03800

Light WIMP detection threshold problem: which DM experiment does really match recoil energy cut-off?

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Nucleus	Maximum recoil energy for WIMP mass 6 GeV, keVnr	Experiment	Detection threshold energy, keVnr	Can see the signal from WIMP
^{23}Na	20	DAMA/LIBRA	7-14	Yes
^{28}Si	17	CDMS-Si	7	Yes
^{40}Ar	12	DarkSide-50	50	No
$^{72.6}$Ge	6.5	CDMS-Ge CoGeNT	1 3	Yes Yes
$^{131.3}$Xe	3.6	LUX Xenon100	3 7	No No

Detector energy threshold for nuclear recoils should be $E_{th} < E_R^{max}$. Which DM experiment does really match such energy threshold?

Here we take $v_{max} = v_{esc} + v_c$