Direct Dark Matter (WIMP) Searches

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Director, SNOLAB

With thanks to W. Rau (Queen's), R. Gaitskell (Brown), F. Petricca (MPP), G. Gerbier (Queen's), J. Gascon (IN2P3), E. Aprile (Columbia), P. Myers (Princeton), J. Klein (Penn), A. Chavarria (Chicago), D. Snowden-Ifft (Occidental)

Talk overview

- Setting the scene for future talks and new results

- Challenges of Direct Dark Matter searches
- Environmental Backgrounds
- Detection Techniques
- Current status of several (quasi-random) Direct Dark Matter searches

Direct Dark Matter Search Results@TAUP

- Tuesday

DEAP-3600 Results: Mark Boulay

LOWER FRASER FA054 09:30 - 09:50

Results PICO experiment: Carsten Krauss

LOWER FRASER FA054 09:50 - 10:10

- Thursday

Xenon 1T Results: Manfred Lindner

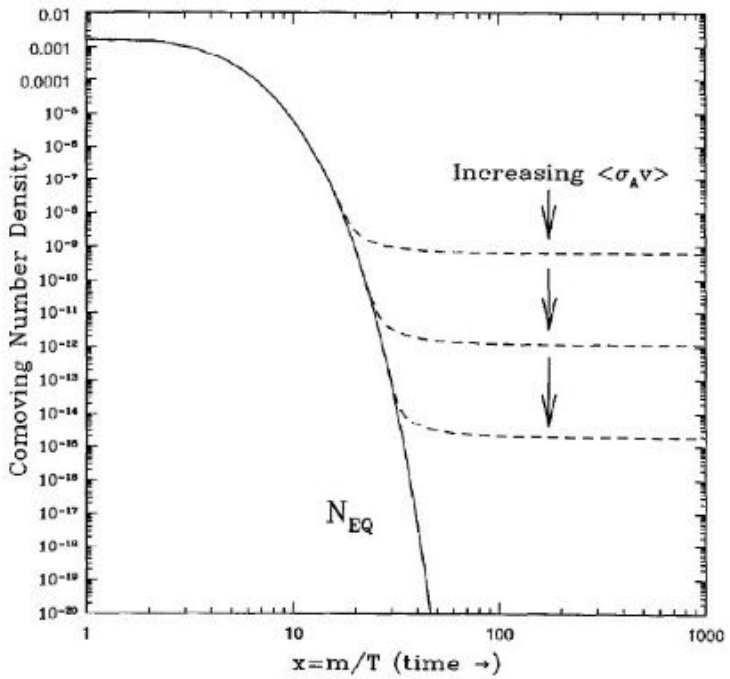
LOWER FRASER FA054 09:45 - 10:05

- 56 Parallel talks on dark matter
  - 33 on Direct WIMP searches:

XENON; PandaX; XMASS;
DEAP-3600; Darkside;
MiniCLEAN; SuperCDMS;
Edelweiss; CRESST-III;
ANKOK; NEWS-G; PICO;
CDEX; DAMIC; SABRE;
COSINE-100; PICOLON;
LUX-ZEPLIN; DARWIN;
MIMAC; HAWC; IceCube;
Super-K; MiniBooNE-DM

The WIMP solution

- SUSY models
  - Hierarchy problem $M_W << M_P$
- Produced in early Universe
  - In thermal equilibrium $T > m_X$
  - Production stalled when $T < m_X$
  - Freeze out if expansion>annihilation



Production:

$$\Omega_X h^2 \approx 0.1 \left(\frac{x_{\rm FO}}{20}\right)\left(\frac{g_\star}{80}\right)^{-1/2}\left(\frac{< \sigma_{X\bar{X}}|v| >}{3\times 10^{-26}{\rm cm}^3/{\rm s}}\right)^{-1}$$

Required DM density:

$$\alpha^2/(100\,{\rm GeV})^2 \sim 3\times 10^{-26}\,{\rm cm}^3/{\rm s}$$

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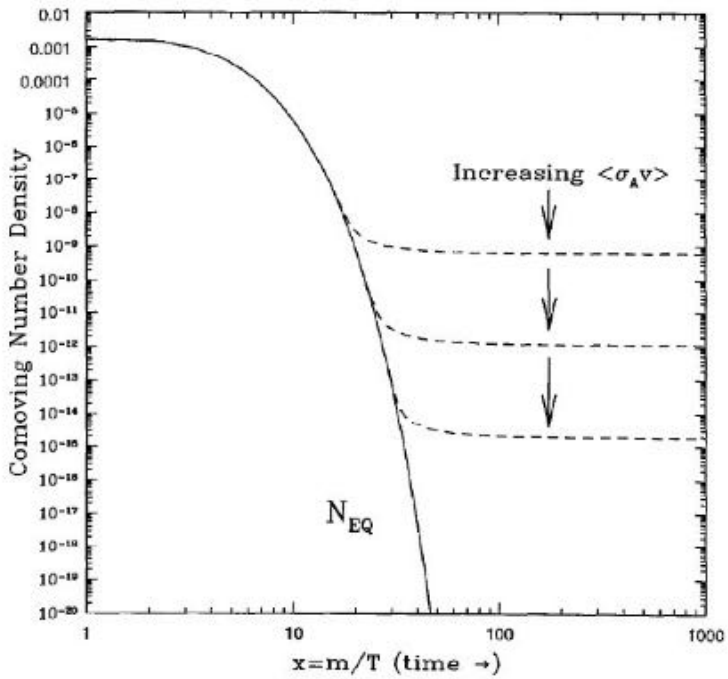

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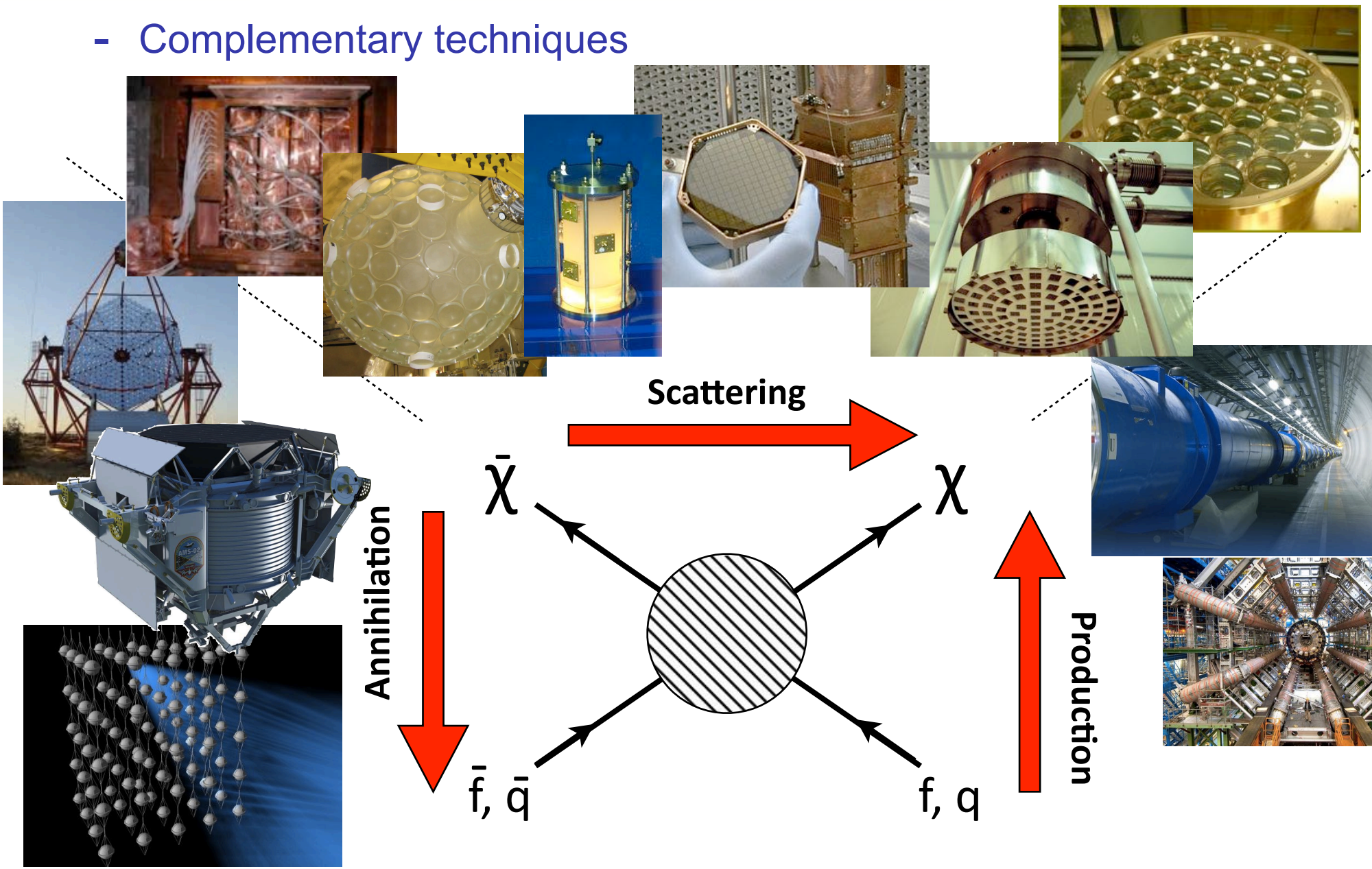
The 'WIMP miracle'

Required DM density:

$$\alpha^2/(100\,{\rm GeV})^2 \sim 3\times 10^{-26}\ {\rm cm}^3/{\rm s}$$

Experimental techniques

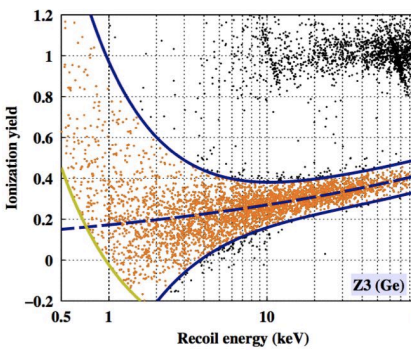
- Complementary techniques

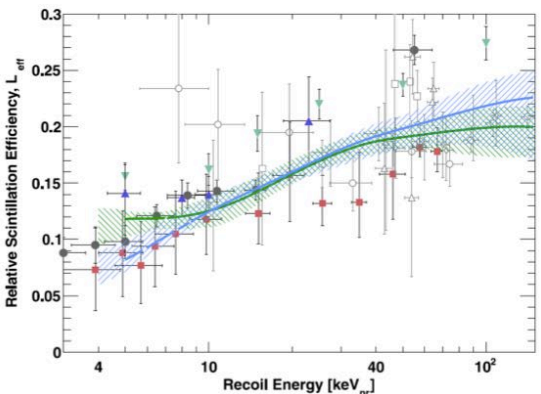


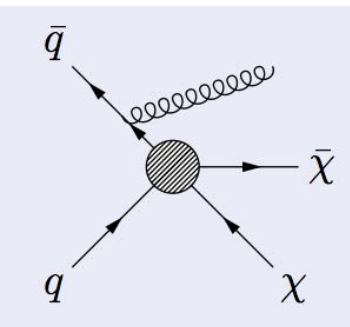
Why Complementarity?

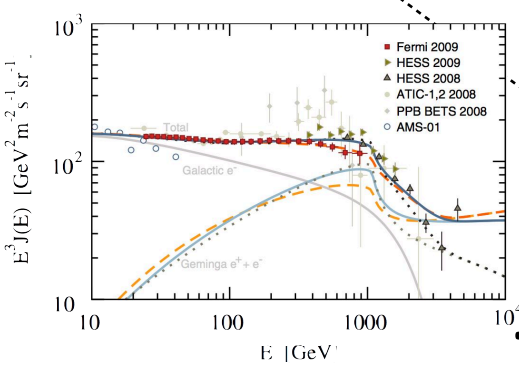
- Uncertainties associated with each technique:

- Backgrounds
- Rate of events
- Local DM distribution

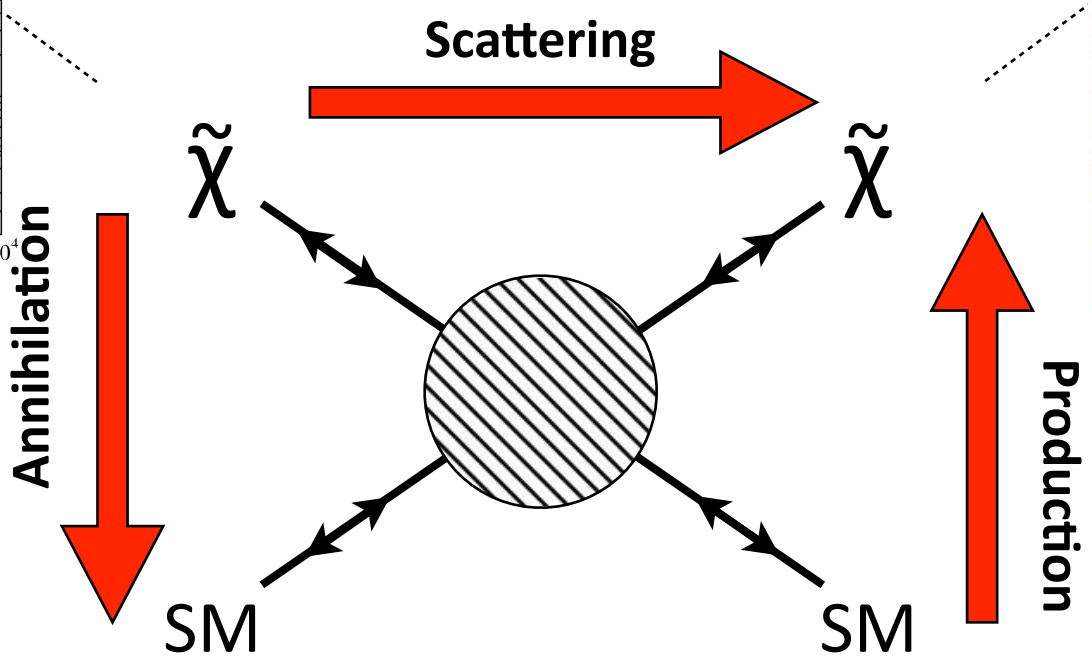


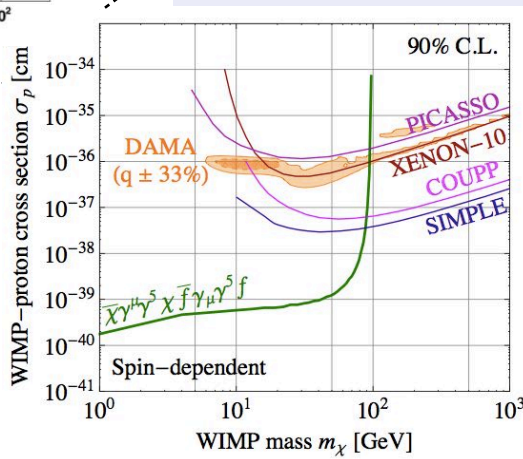






- Astrophysics sources
- Galactic DM distribution
- Annihilation product propagation





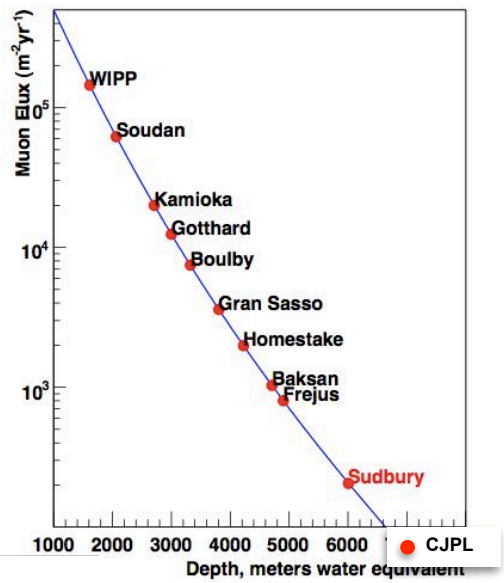
- PP Model assumptions
- Production of Candidates, not DM

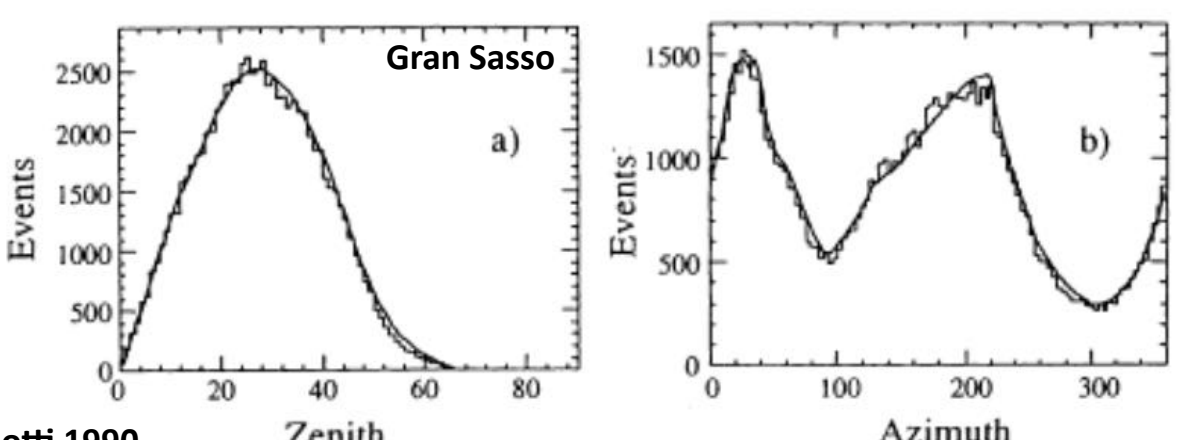
WIMP Direct Search Challenges

- WIMP nuclear recoil signal is:
  - Low rate (<~events/tonne/year)
  - Small energy (1-100 keV actual: observed is less)
- Detection technique must be:
  - Low background
    - Gamma, beta: from U/Th/Co/Pb/etc radio-impurities
    - Neutron: from U/Th radio-impurities and c.r. μ spallation
    - Radon daughters: environment and emanation
  - Low energy threshold
    - To minimise form factor, maximise energy spectrum
  - Discriminating & Position sensitivity
    - Discriminate between WIMPs/n and γ/β/α
    - Background rejection, neutron multiplicity calibrations
    - Directionality
  - Large mass

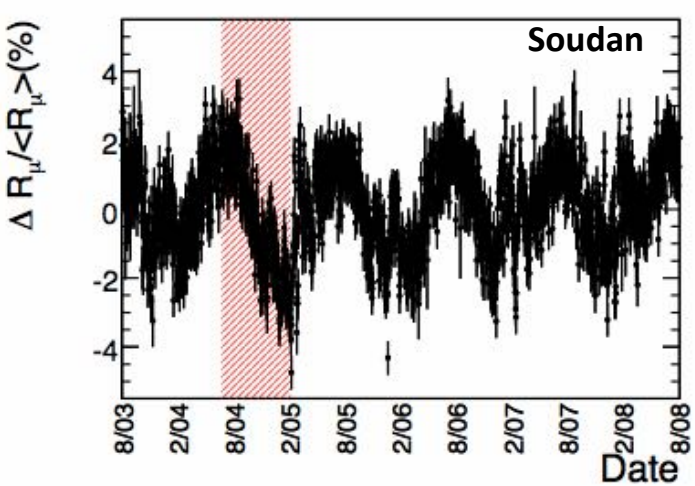
Effect of over-burden

- Deep underground facilities provide significant rock overburden and commensurate reduction in c.r. flux, and c.r.-spallation induced products (neutrons)
- Muons can be veto'd in anti-coincidence shield; secondary products may be an issue
- Cosmogenics may require underground material production or purification
  - May also contribute to b/grounds (e.g. ^{11}C)
- Muon flux depends on
  - overburden
  - overburden profile
  - seasonal effects





Bellotti 1990

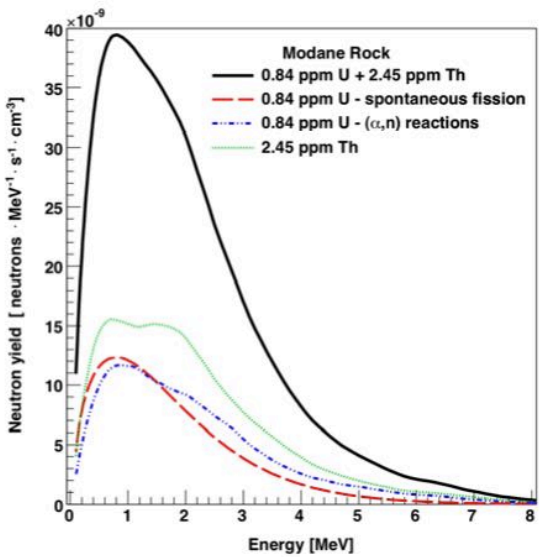


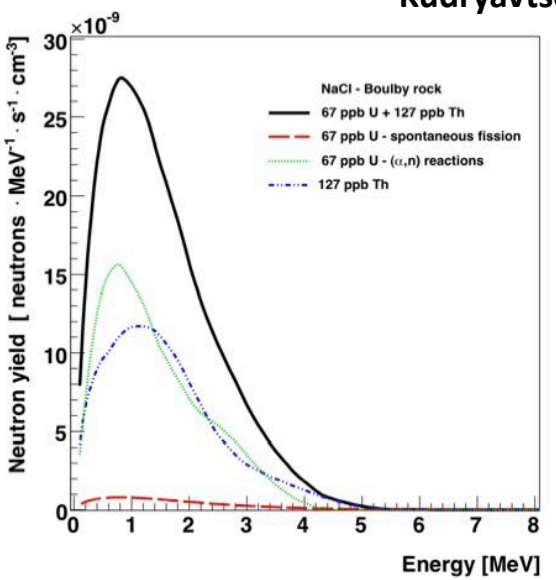
Adamson 2010

Neutron backgrounds

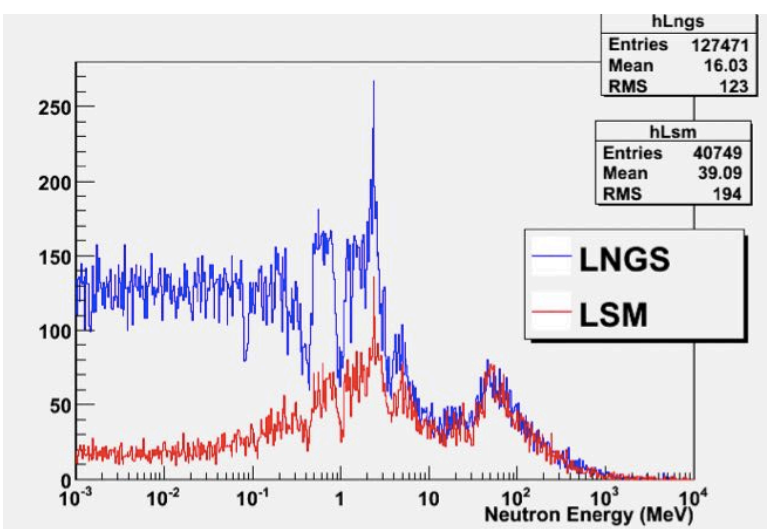
- Neutron production from
  - c.r. muon spallation
  - U/Th fission
  - α, n reactions
  - radon reactions

Kudryavtsev





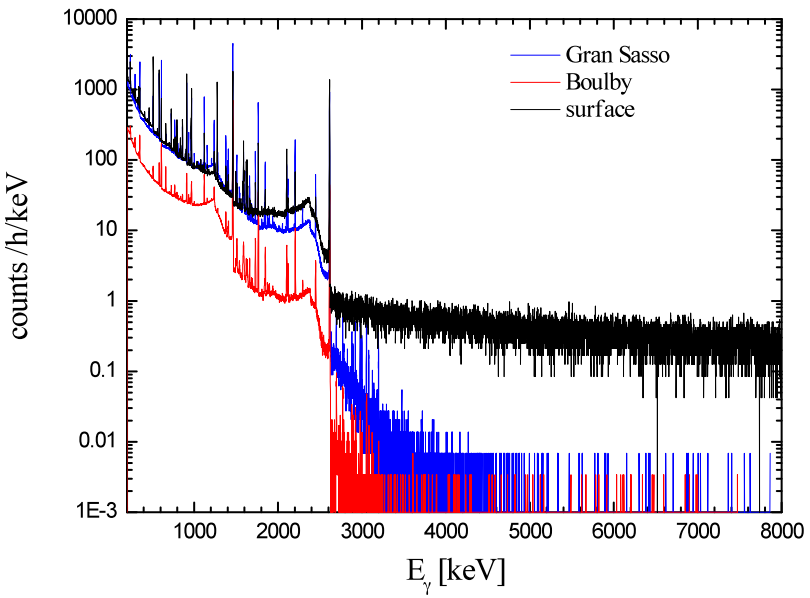
- Spectrum in laboratory depends on local geology (rock composition)
  - both for fast and thermal neutrons
  - U/Th + moderators
  - muons + moderators
  - small levels of high neutron cross-section contaminants make a big difference



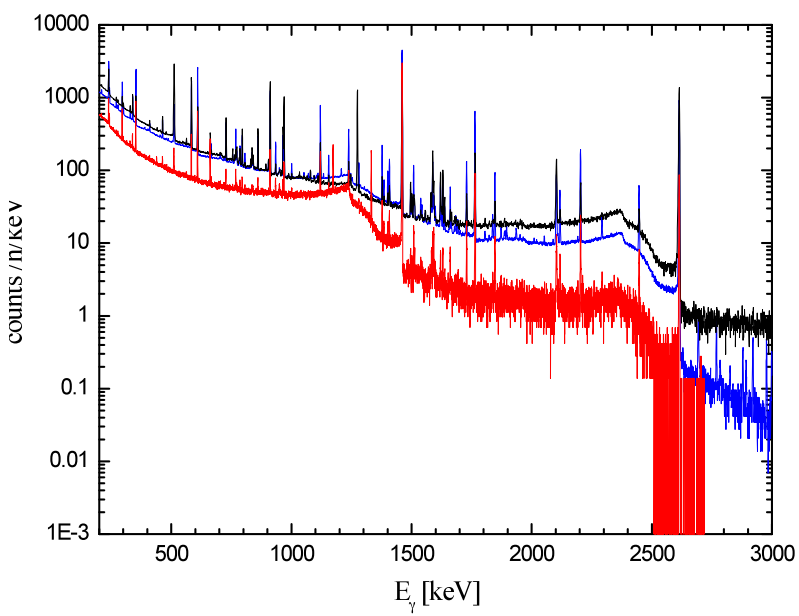
Persiani / Selvi

γ-ray Backgrounds

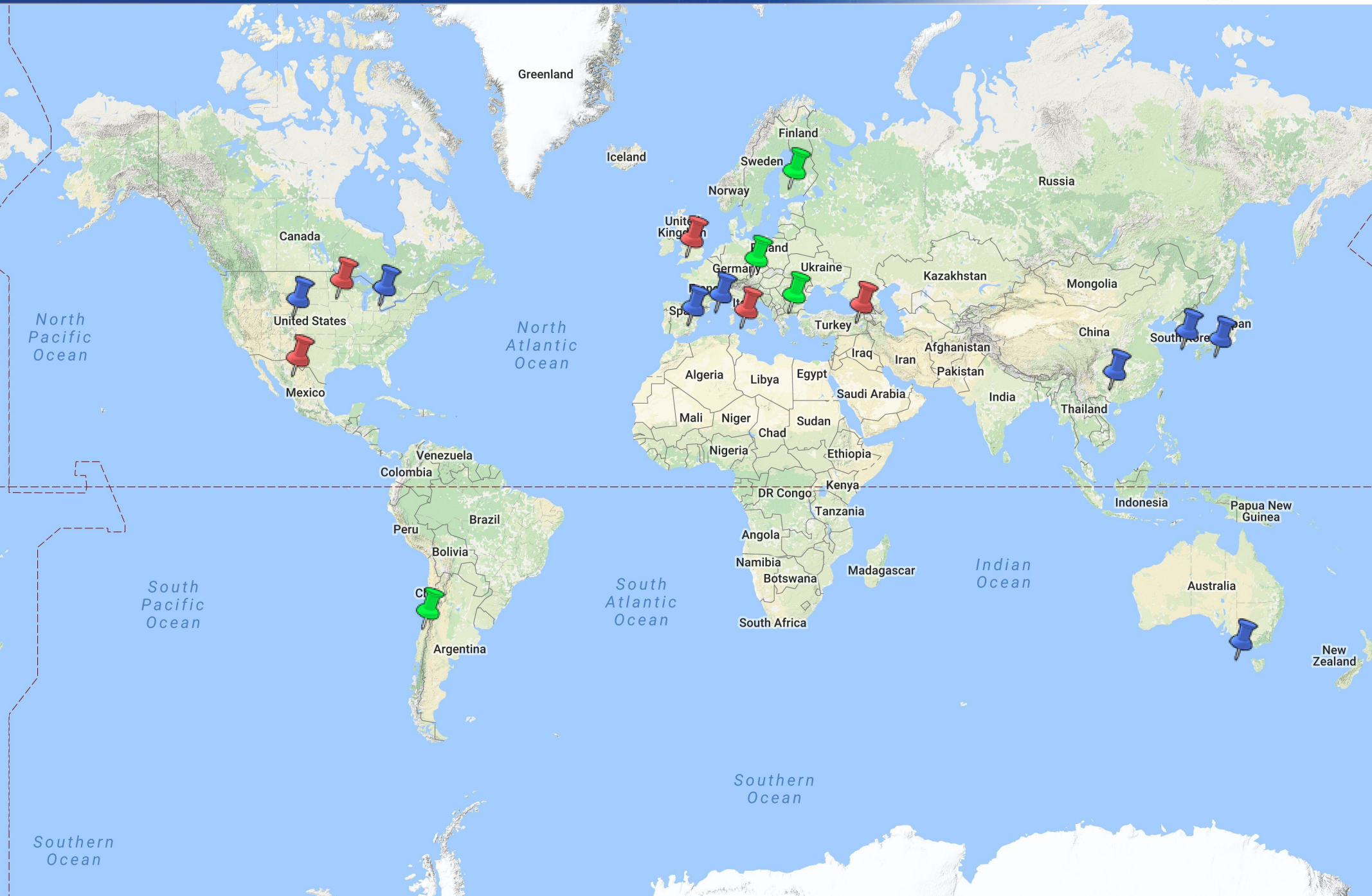
- Reduction in γ-ray background at higher energies from c.r. and neutron reduction
  - important for nuclear astrophysics dedicated beam experiments, and some 0νββ isotopes



- Below 3.5MeV dependent on local geology and rock material
  - Boulby (red)
  - Gran Sasso (blue)
  - surface (black)



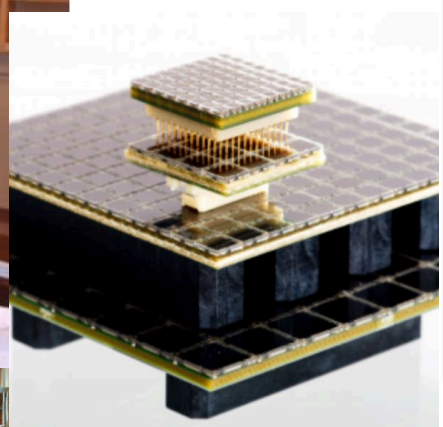
Underground Facilities



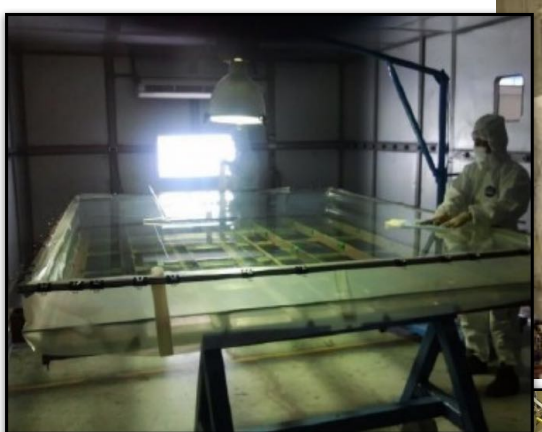
Intrinsic Backgrounds

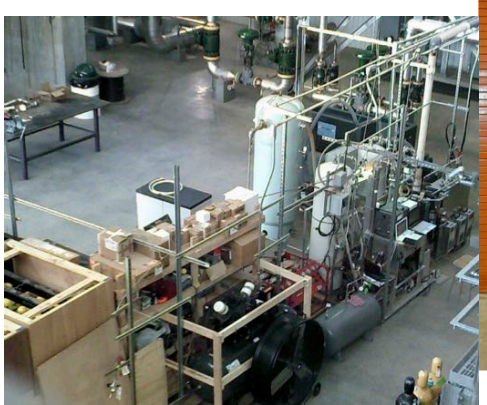
- Removal of external backgrounds by depth and shielding
- Challenge is now control of internal backgrounds:

Intrinsic activity and assay



Low background material production and assay



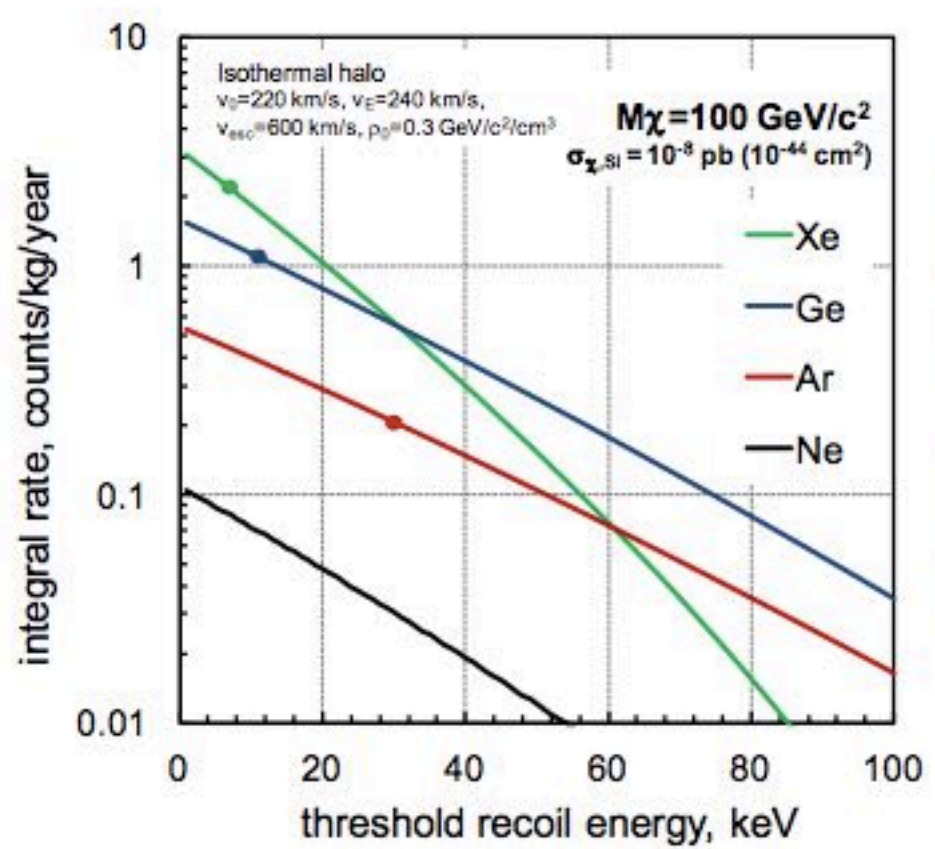


Target radionuclide reduction

Radon mitigation

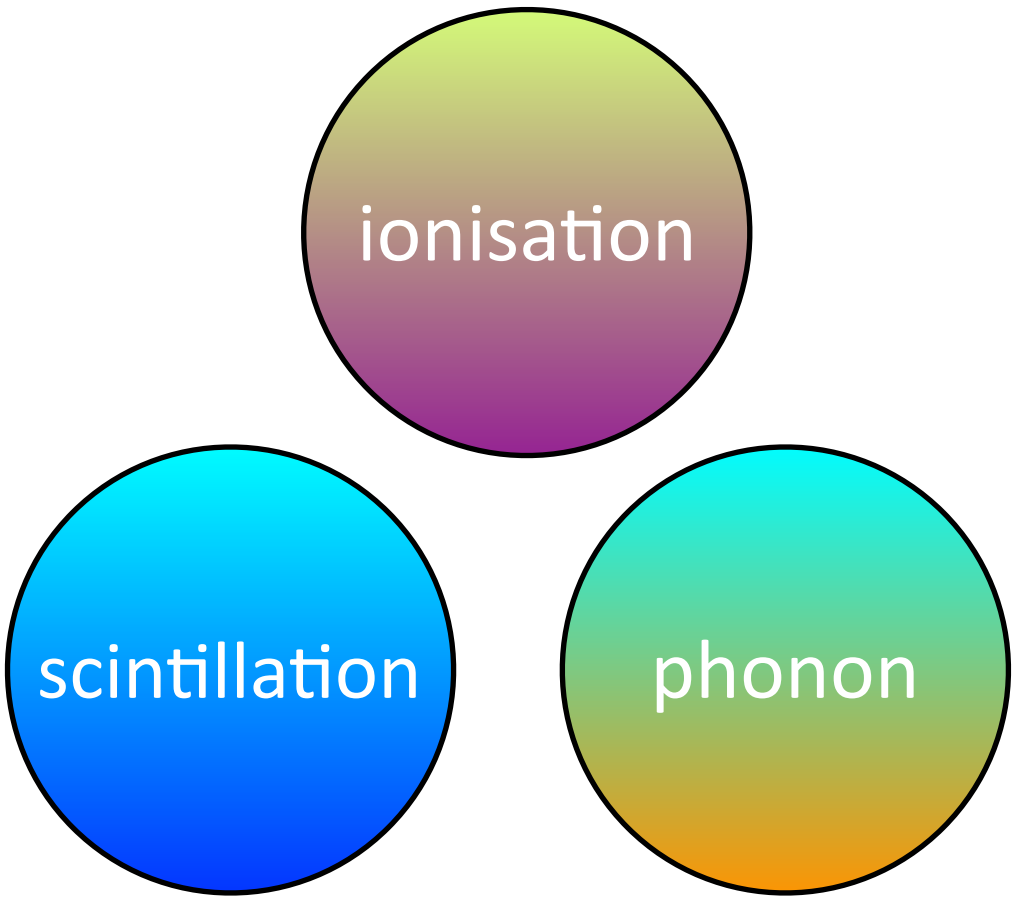
Response to elastic scattering

- Principle technique for WIMPs and neutrino detection is coherent elastic scattering off target nucleii
- For WIMP detection
  - low threshold required in xenon to maximise signal
  - higher threshold in argon for discrimination



Chepel/Araújo

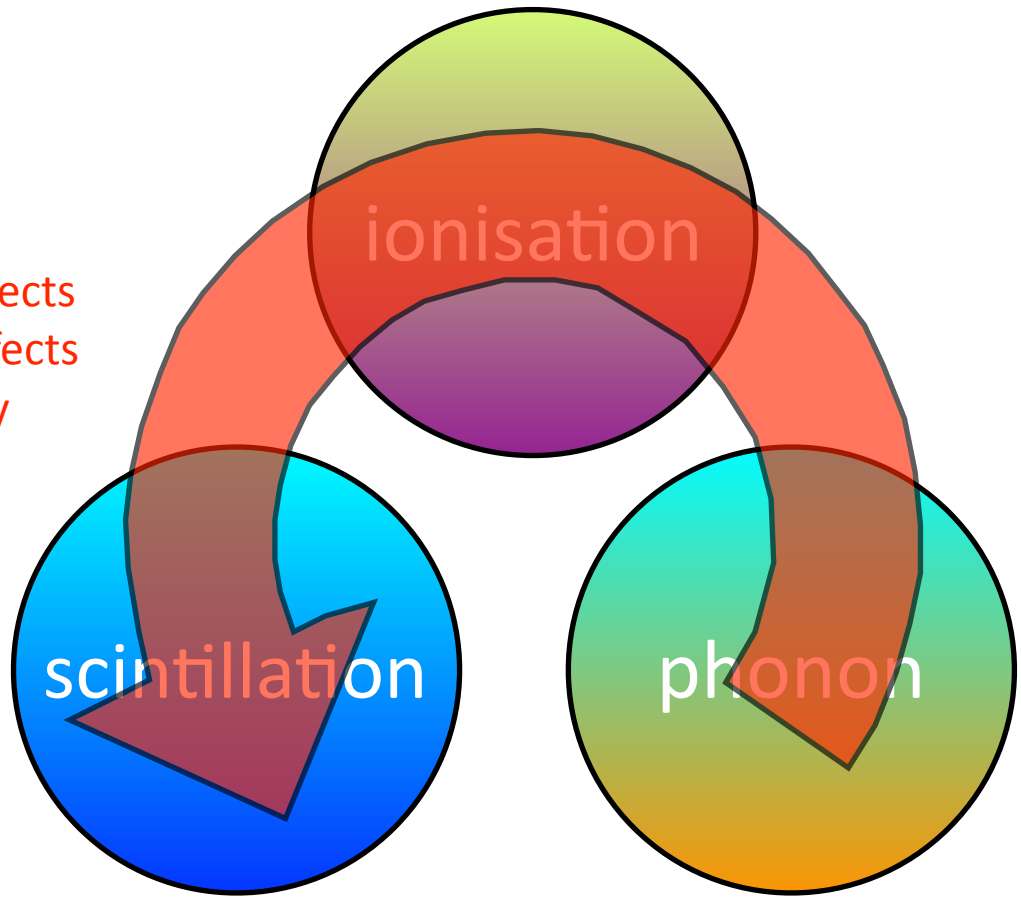
Detection techniques



Following Araujo

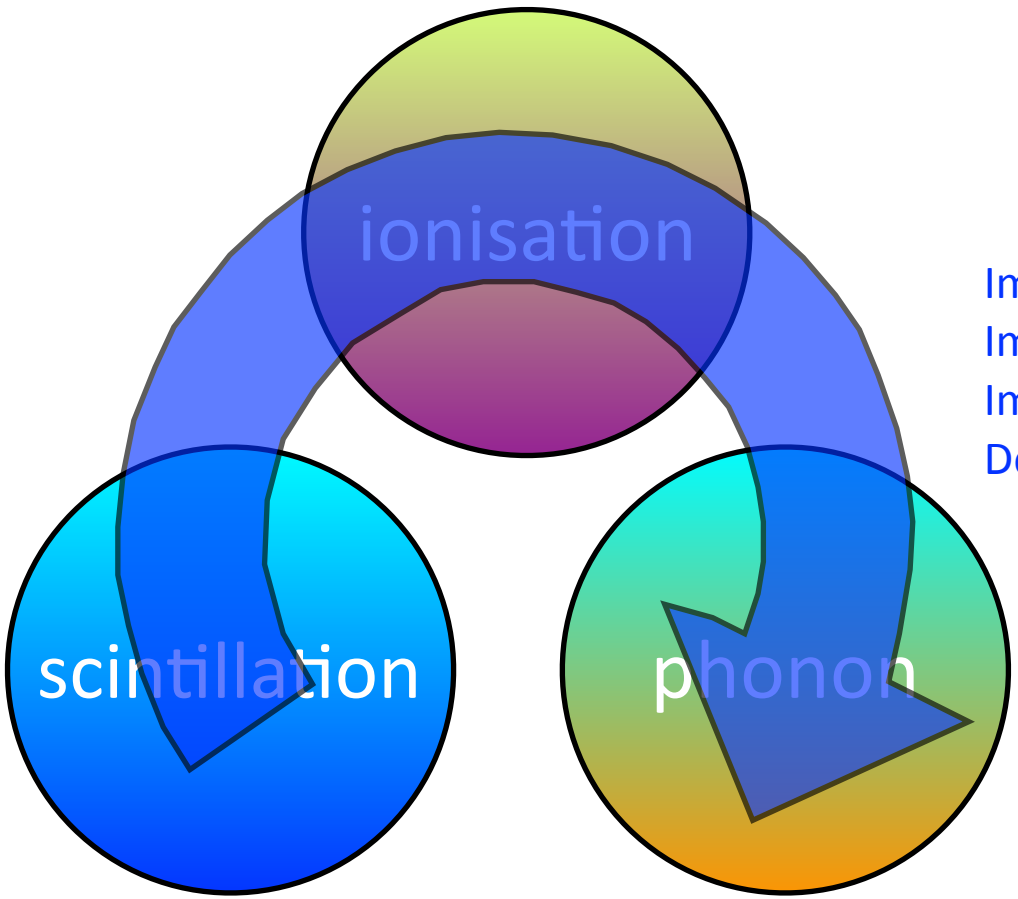
Detection techniques

Improve surface effects
Improve volume effects
Improve scaleability



Following Araujo

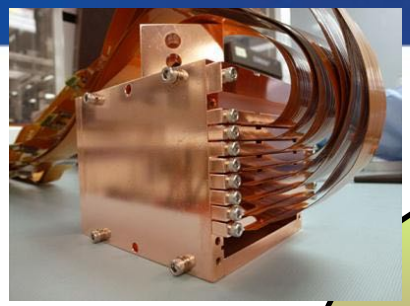
Detection techniques



Improve resolution
Improve threshold
Improve noise
Decrease temperature

Following Araujo

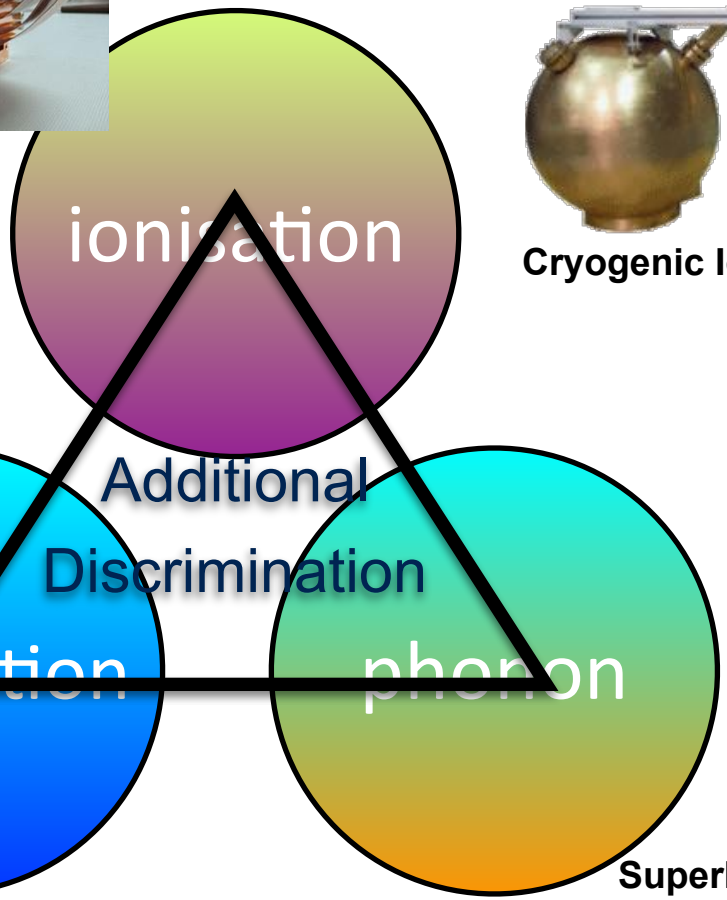
Detection techniques



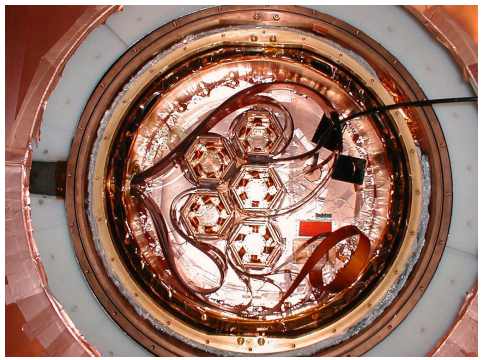
CCD

TPC / Directional

Two Phase Noble Gas



Cryogenic Ionisation



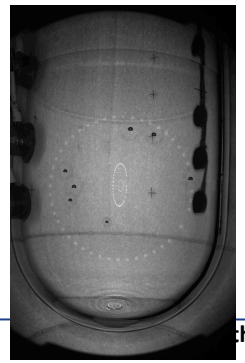
Cryogenic Bolometers

Single Phase
Noble Gas

Inorganic
Scintillators

Cryogenic Scintillators

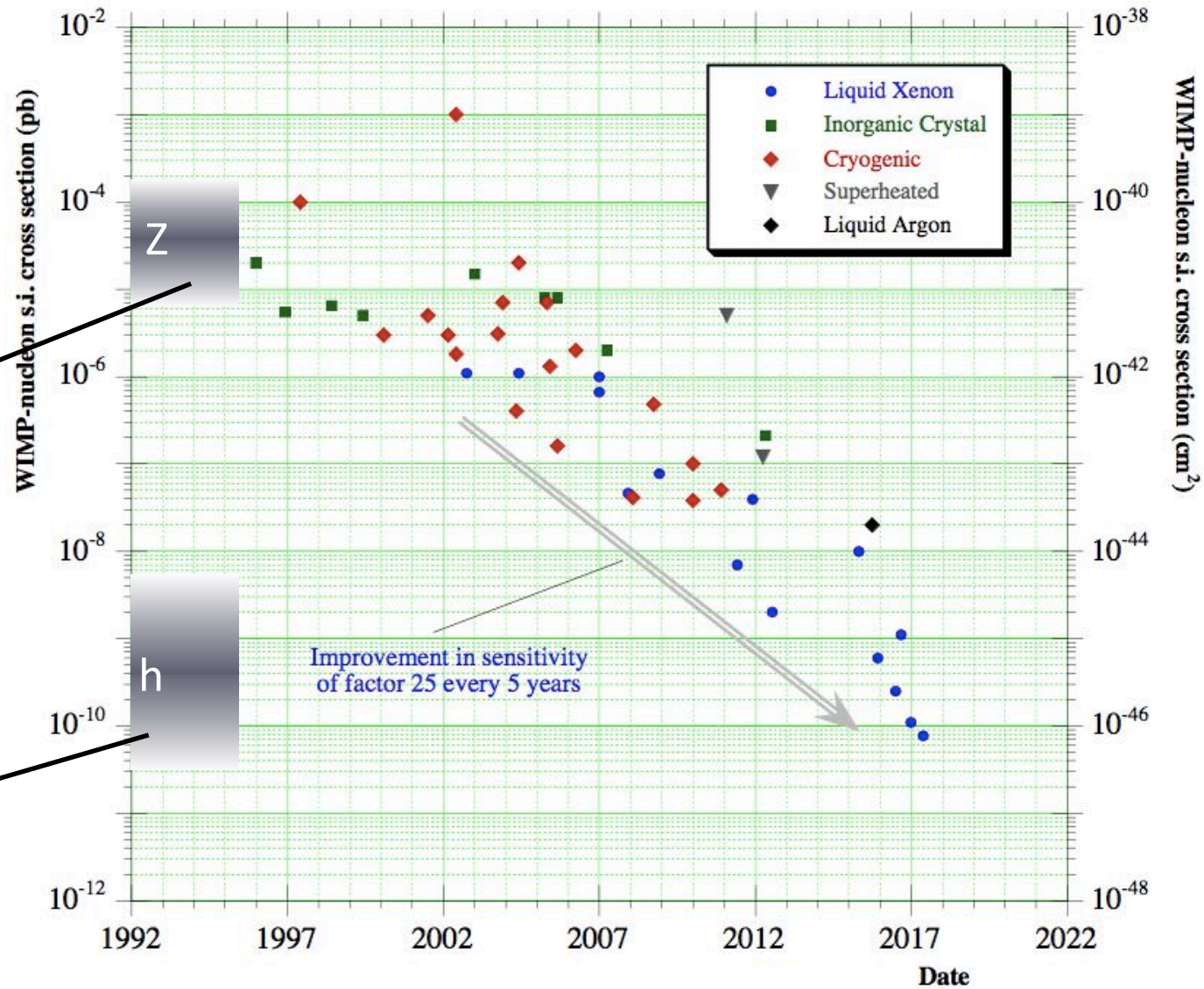
Superheated
Fluid



Following Araujo

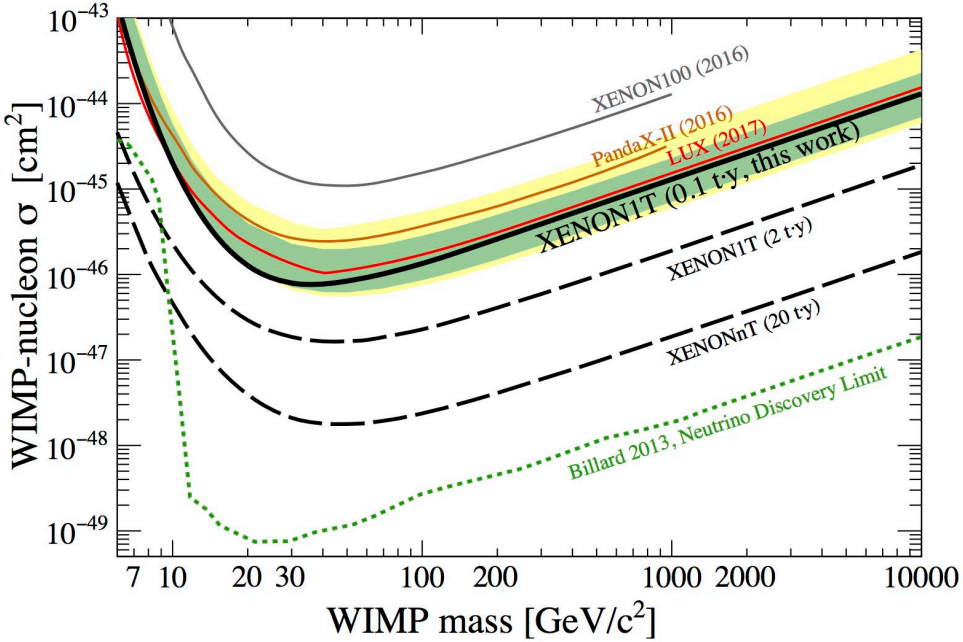
Strong and steady progress made

- Direct detection sensitivities improving factor 25 every 5 years
- Already (1990's) excluded Z-mediated exchanges (e.g. heavy neutrinos)
- Now into higgs-mediated cross sections



After Gaitskell

XENON1T



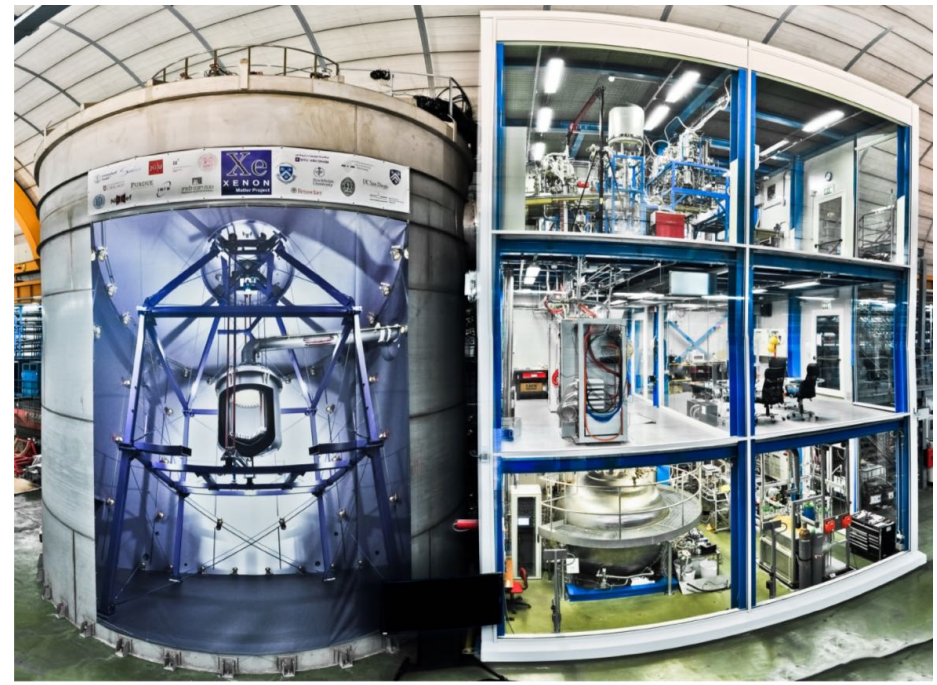
First science run: 34.2 live-days

- Largest ever Xe fiducial mass: 1042 kg
- Lowest ever low-E ER bg.: (0.193 ± 0.025) mDRU
- Most stringent SI-WIMP limit

Still running, >100 live-days taken

XENONnT upgrade planned for 2019

The first ton-scale LXe TPC

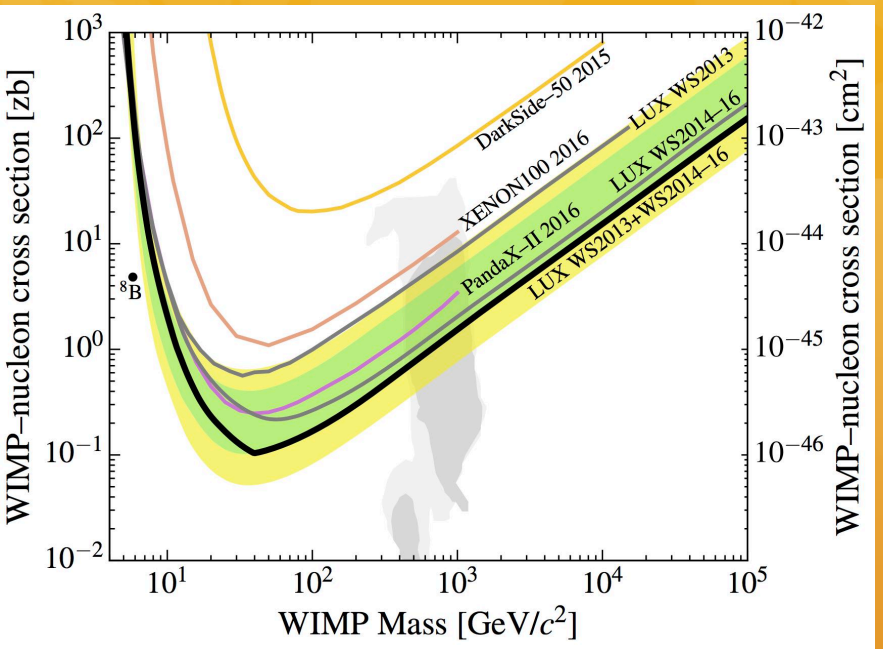


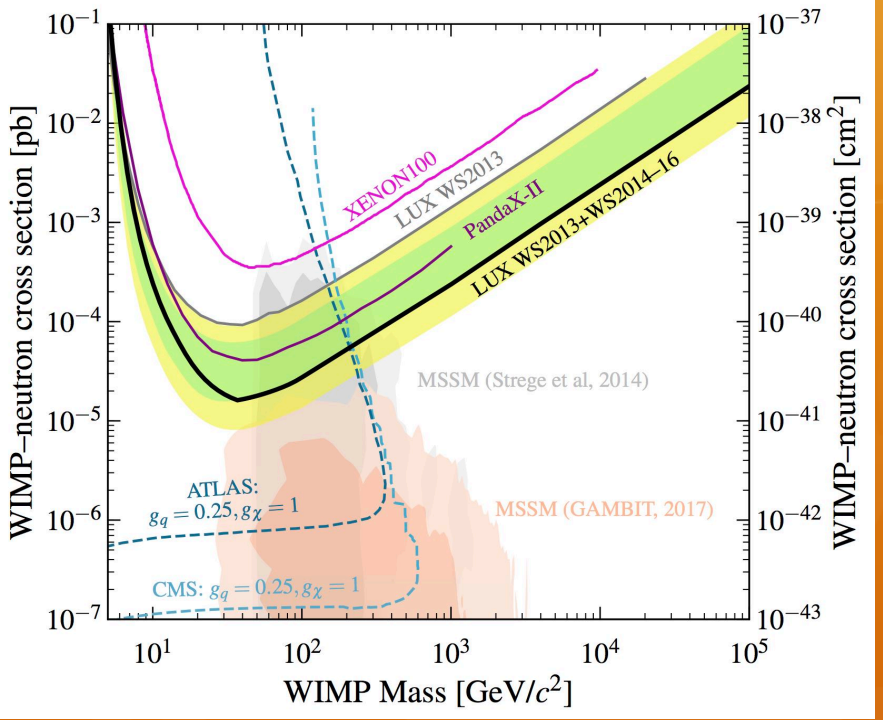
More information:

- Manfred Lindner's talk (Thursday)
- Paper preprint: arxiv:1705.06655
- http://xenon1t.org/
- https://twitter.com/Xenon1T

XENON Dark Matter Project

LUX Impact 2013/17





- LUX First Science Run in 2013
  Second Science Run 2014-2016
  Full exposure: 47,500 kg.days
  (427 live-days)
- Improved Spin-Indep. WIMP Sensitivity by Factor 20x since state prior to 2013.
  Also Neutron Spin-Dep. Sensitivity.
- Axion/ALP Search
- Full self-consistent models for all backgrounds events and detector response
- In parallel: Major program improving LXe ER and NR calibration over wide energy range (including sub keV) with high statistics and low systematics. Allowed significant improvement in accuracy of Xe response models. Also clearly establishes sensitivity to 8B coh. scattering.
- LZ: Kim Palladino Tues 15:30
  LZ: Christine Ignarra, Tues 15:45
  LUX: Rick Gaitskell Wed 14:00

LZ Detector - 10 tonnes Xe

Replacing LUX at the Sanford Underground Research Facility (SURF)

Technical Design Report arXiv:1703.09144 260 Authors, 400 Pages

DOE Project, Construction Fully Underway > CD4

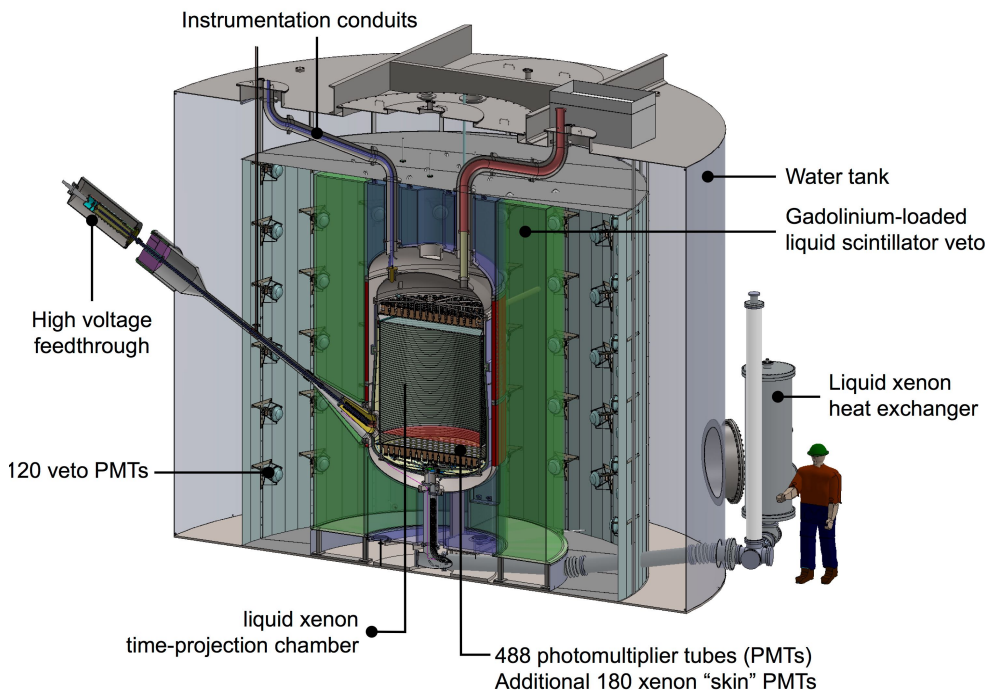
Commissioning April 2020, Physics in 2021, Goal 1000 days

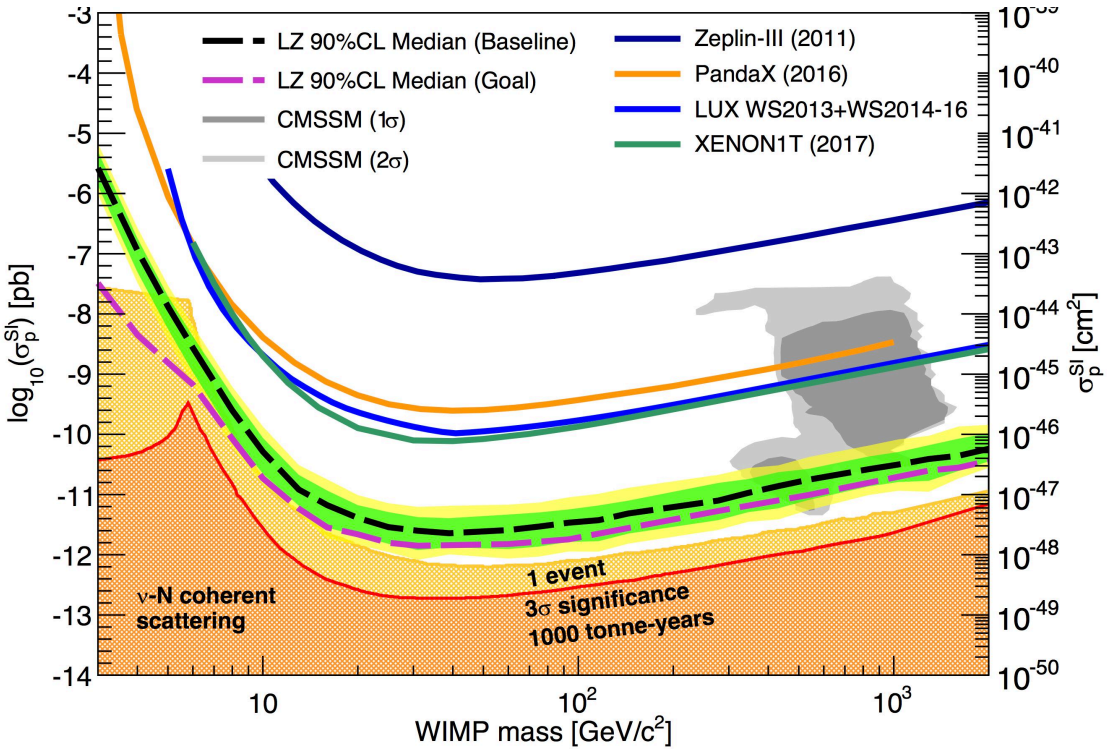
Baseline WIMP sensitivity @ 40 GeV is 2.3 x 10^{-48} cm^2

Other promising science targets:

ββ0n, pp & 8B solar neutrinos,

coherent neutrino scattering





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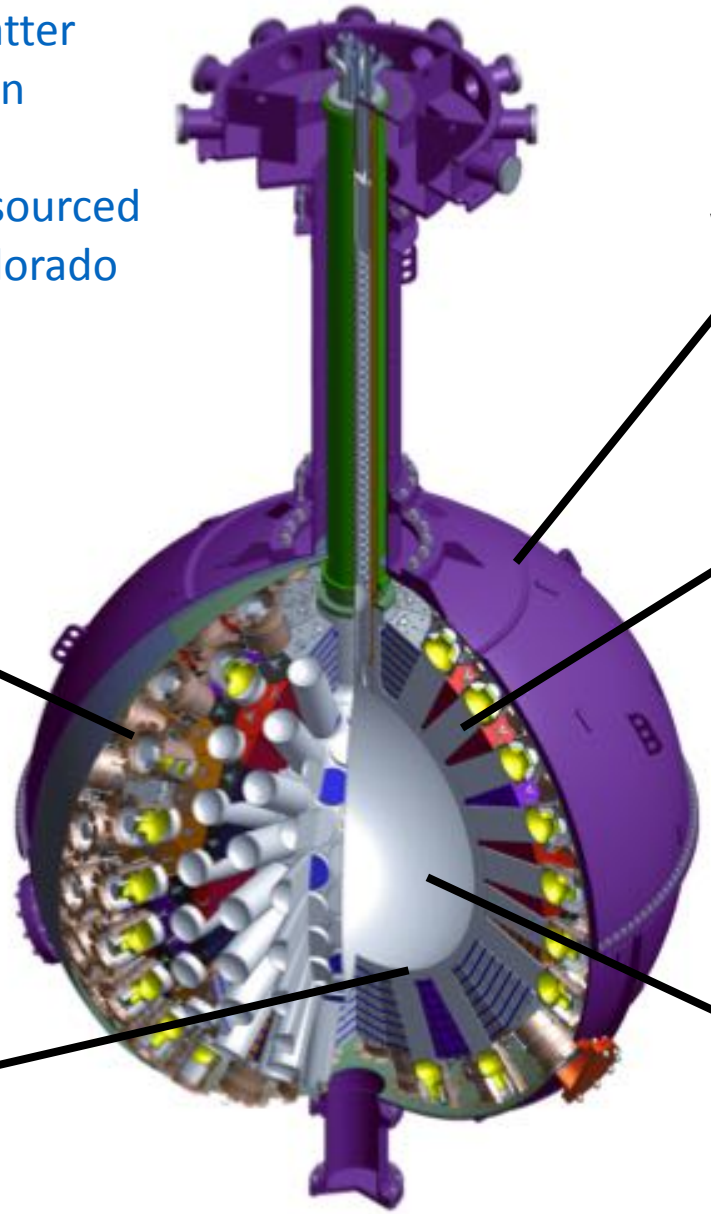
DEAP-3600

Uses liquid argon as a dark matter target with good discrimination

Low background argon being sourced from underground wells in Colorado



Steel Shell immersed in 8 m water shield at SNOLAB

255 Light sensors
Hamamatsu R5912 HQE PMTs
8-inch (32% QE, 75% coverage)

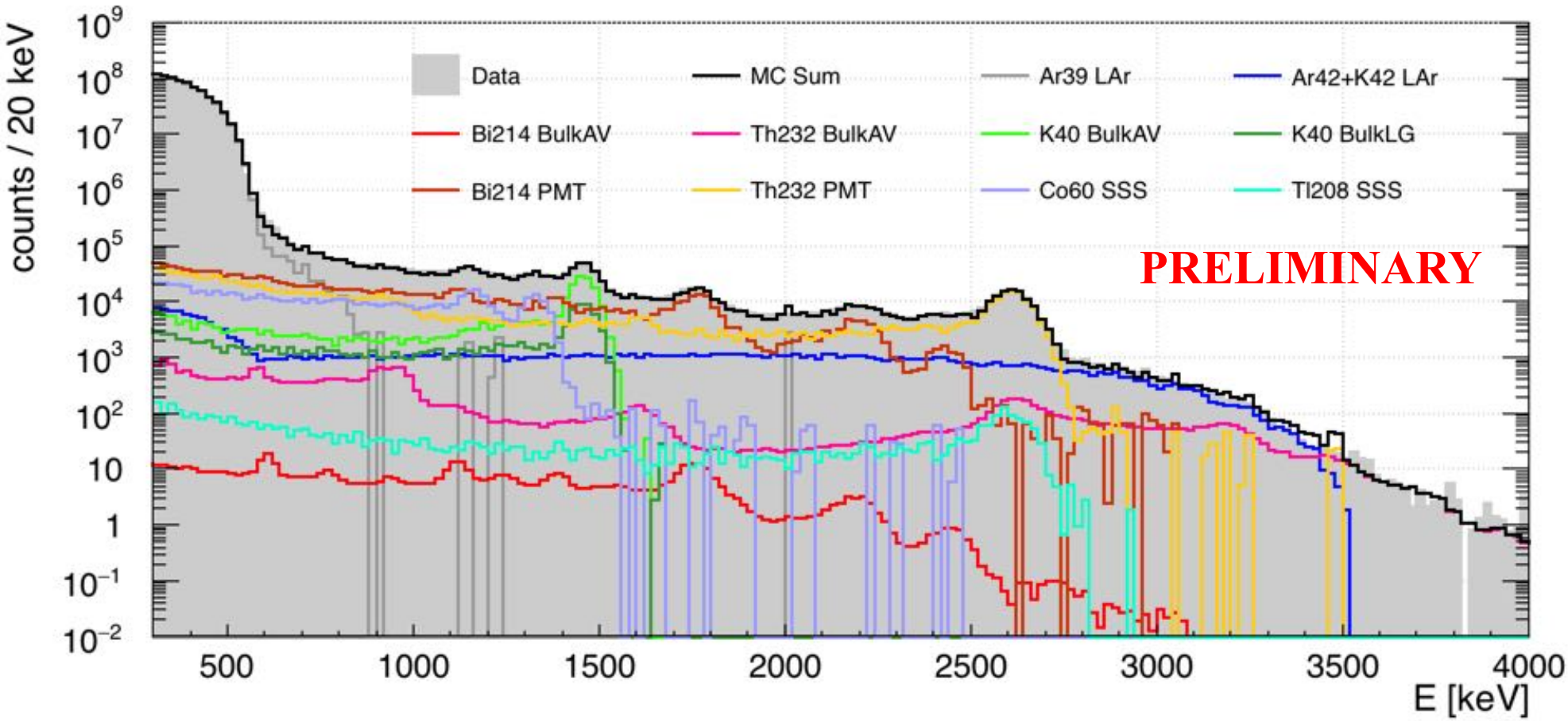
50 cm light guides + polyethylene shielding provide neutron moderation

Vessel is "resurfaced" in-situ to remove deposited Rn daughters after construction

3600 kg argon target (1000 kg fiducial) in sealed ultra-clean Acrylic Vessel

Electron Recoil Band Background Model

Background Model in ER Band (0.2 < fprompt < 0.4) MC components scaled to radioassay data



- Empiric energy calibration based on 1460 keV (^{40}K) and 2614 keV (^{208}Tl) peak
- Scaling of MC simulations to known screening / literature values (this is not a fit)
- Low energy region (< 0.5 MeV) dominated by ^{39}Ar
- Mid energy region (0.5 - 2.6 MeV) dominated by gamma from outside components (mainly PMT glass)
- High energy region (> 2.6 MeV) dominated by ^{42}K and beta components from very close ^{208}Tl sources

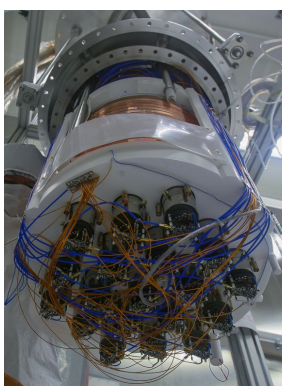
- **Gamma line measurements can be used to constrain (α,n) neutron production**

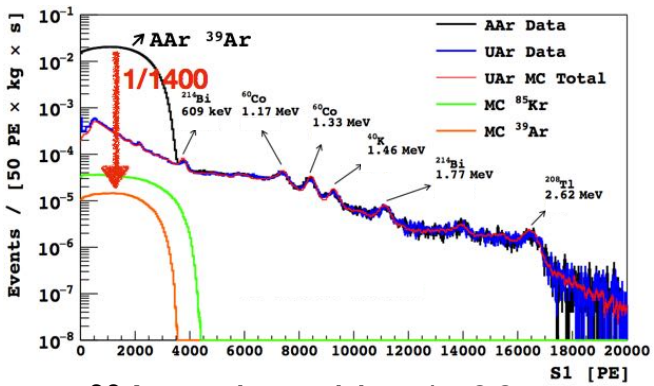
DarkSide: direct WIMP searches with two-phase argon TPCs

- High light yield: LAr Pulse Shape Discrimination >10^7
- Underground Argon: low ^{39}Ar
- TPC 3D event reconstruction
- High-efficiency neutron vetoing

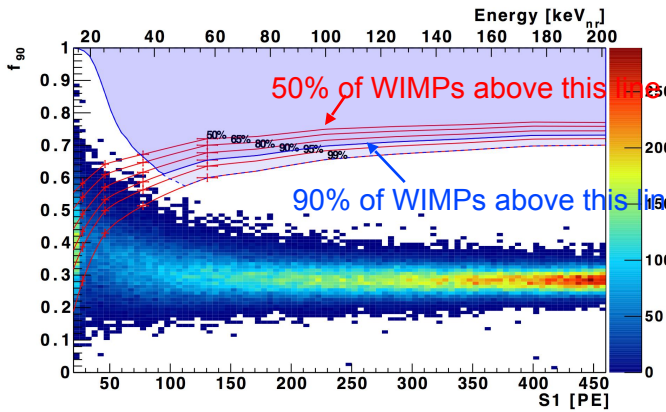
DarkSide-50

150/50/30 kg
total/active/fiducial
Sensitivity<10^{-44} cm^2
Data: 2013-present





^{39}Ar reduced by 1400

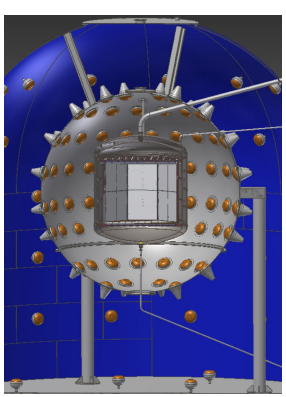


70-d of Underground Ar

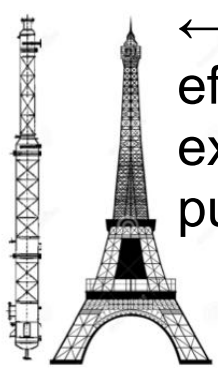
Blind analysis of 500-d underway

DarkSide-20k

30/23/20 T
tot/act/fiducial
Sensitivity<10^{-47} cm^2
Data: ~2021

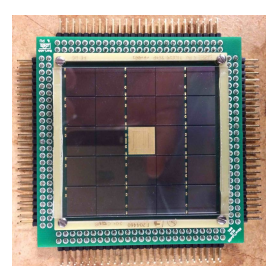


New Argon Collaboration
DarkSide
DEAP
MiniCLEAN
ArDM
} DS-20k→ Multi-100 ton



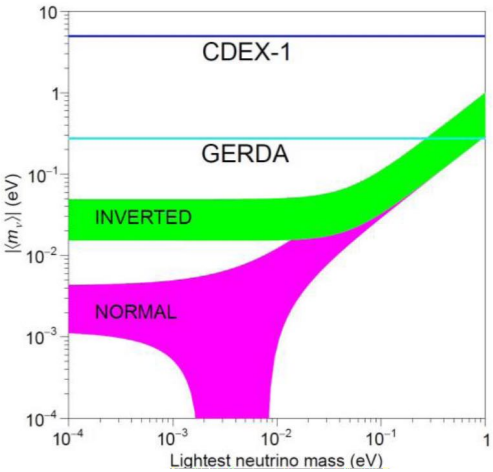
← Massive effort to extract and purify UAr

SiPMs replace → PMTs



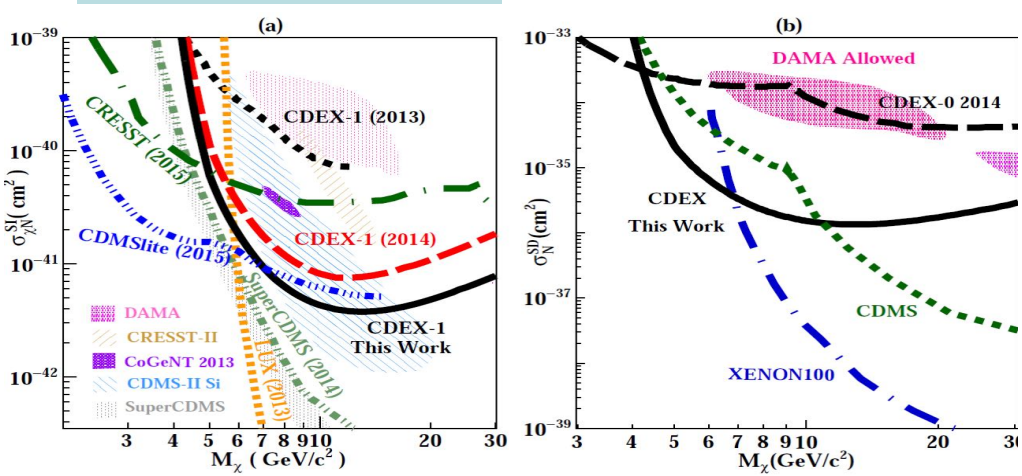
CDEX-1 results

- CDEX-1 prototype detector with ~1kg mass published the best sensitivities from PCGe detector;
- Axion results published based on the dataset, best sensitivity below 1keV for axion-electron coupling;
- AM analysis with >1 year data going on;
- ^{76}Ge 0νββ result published this year.

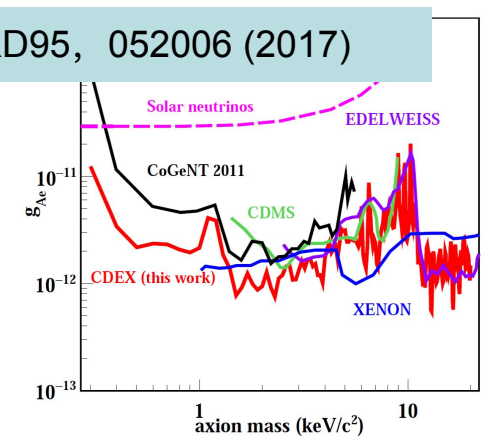


L. Wang, Q. Yue*, et al. Sci. China Phys. Mech. Astron. (2017) 60: 071011

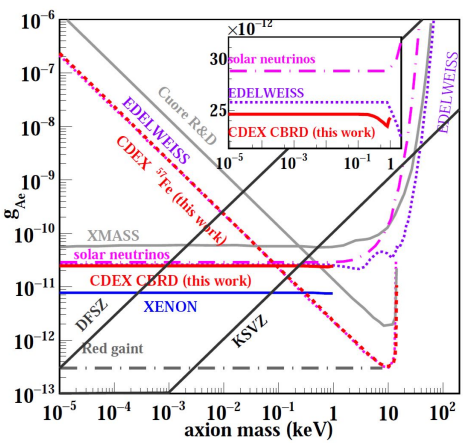
PRD93, 092003 (2016)



PRD95, 052006 (2017)



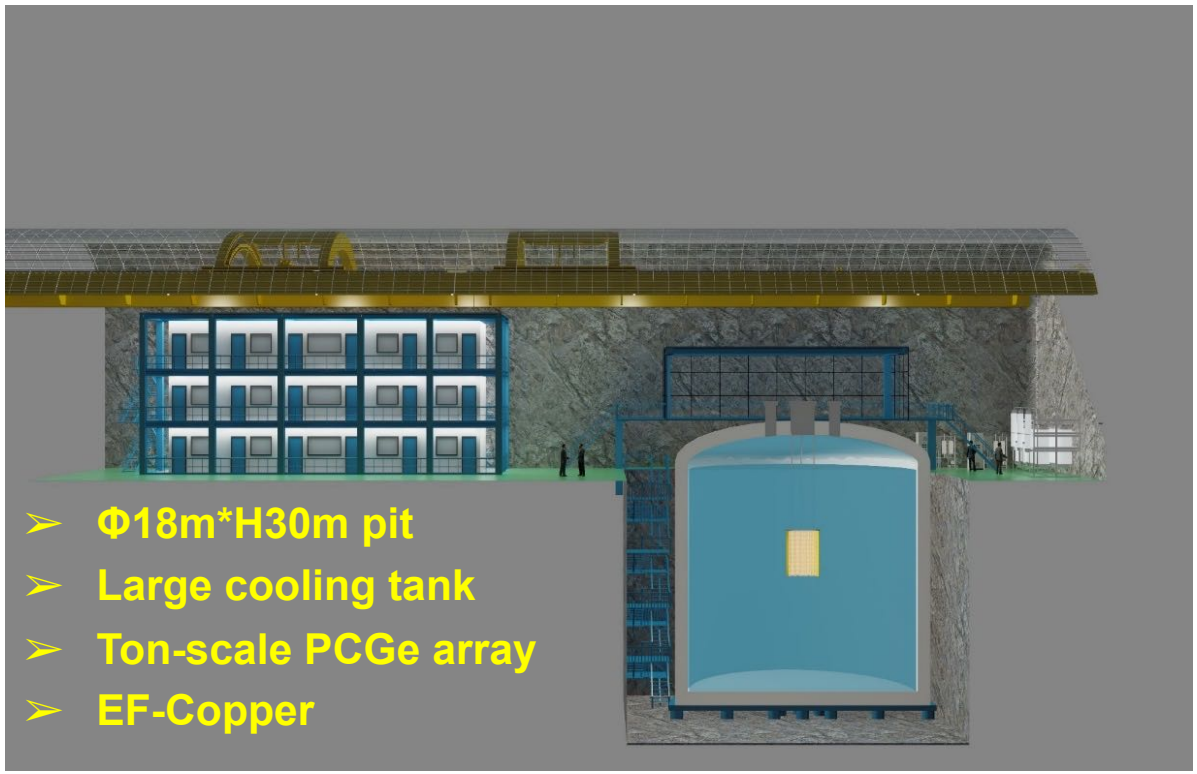
Axion-electon couplings with solar axions

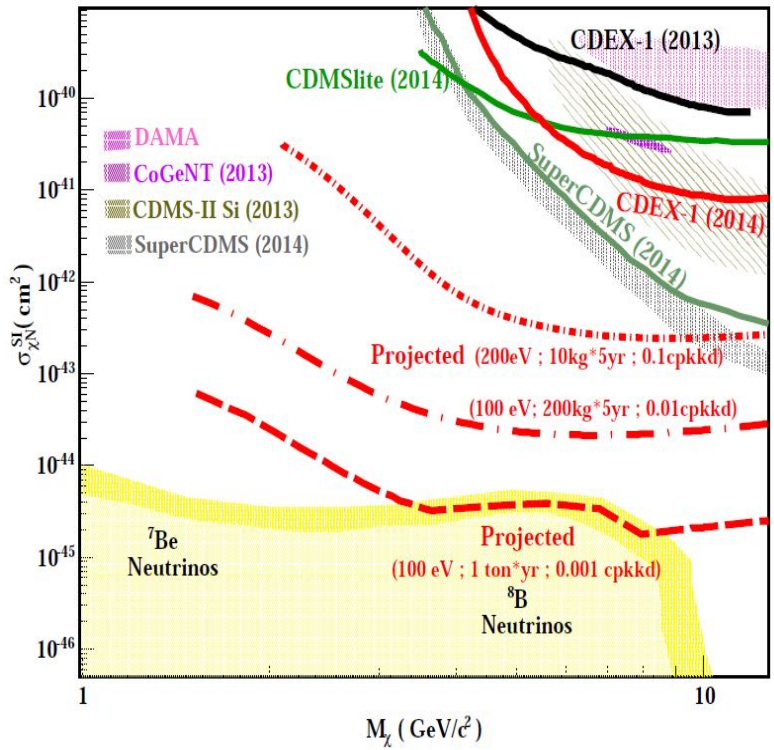


Axion-electon couplings with dark matter axions

CDEX future projects at CJPL-II

- A ton-scale Ge detector composed of the PCGe detector and LN shielding and cooling system in the CJPL-II
- Both Dark matter and Double Beta Decay

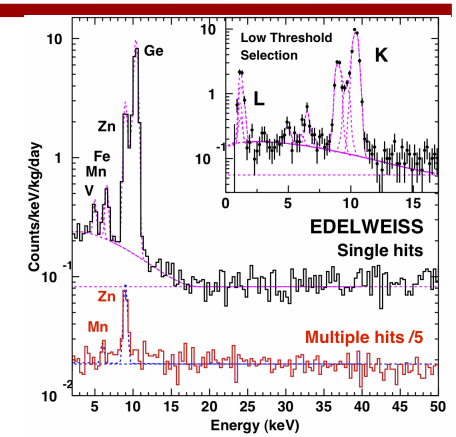




CJPL

EDELWEISS-III

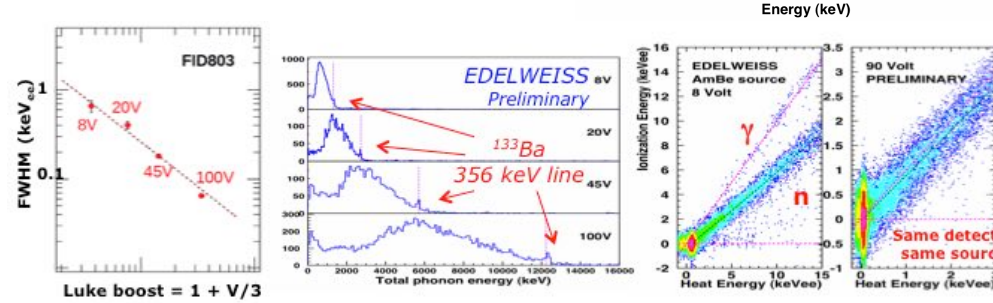
- Robust design, good reproducibility of performances *[arXiv:1706.01070]*
- Detailed description of backgrounds;
  first measurement of cosmogenic ^{3}H in Ge *[AstroPart. 91 (2017) 51]*
- Improved ionization resolution & thresholds lead to x40 improvement of WIMP sensitivity at ~5-10 GeV wrt EDELWEISS-II. *[JCAP05 (2016) 019] [EPJC 76 (2016) 548]*



Prospects: *[arXiv:1707.04309]*

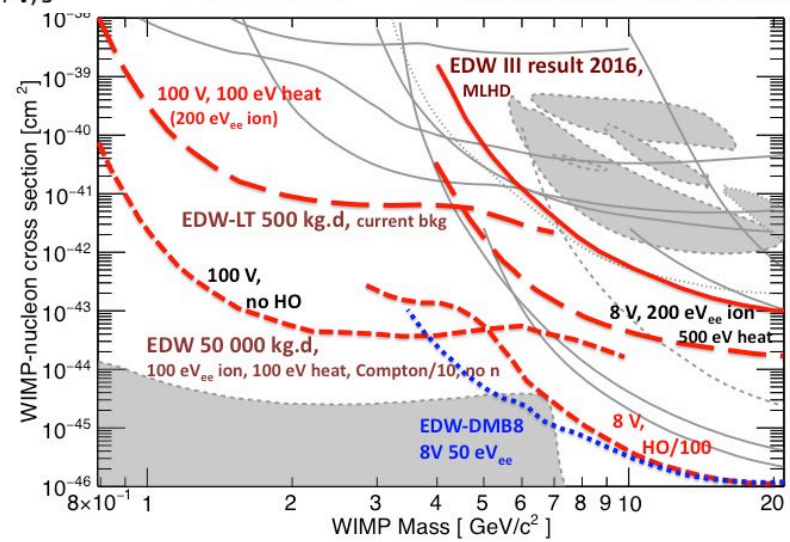
→ in the GeV-WIMP range: EDELWEISS-LT

- Improve thresholds x10 using boost
  8 to 100V (achieved)
- 10^{-41} cm^2 achievable at LSM with 4 detectors with present levels of backgrounds



→ in the ^{8}B region: EDELWEISS-DMB8

- 50 eV ionization resolution to obtain pure nuclear recoil sample + 10% resolution on recoil energy: clear spectral identification of ^{8}B ν
- Use HEMT preamplifier + reduce electrode capacitance (reduction by a factor of 2 of number of electrodes achieved)
- ~200 kg FIDs at SNOLAB to complement nicely the SuperCDMS-SNOLAB reach

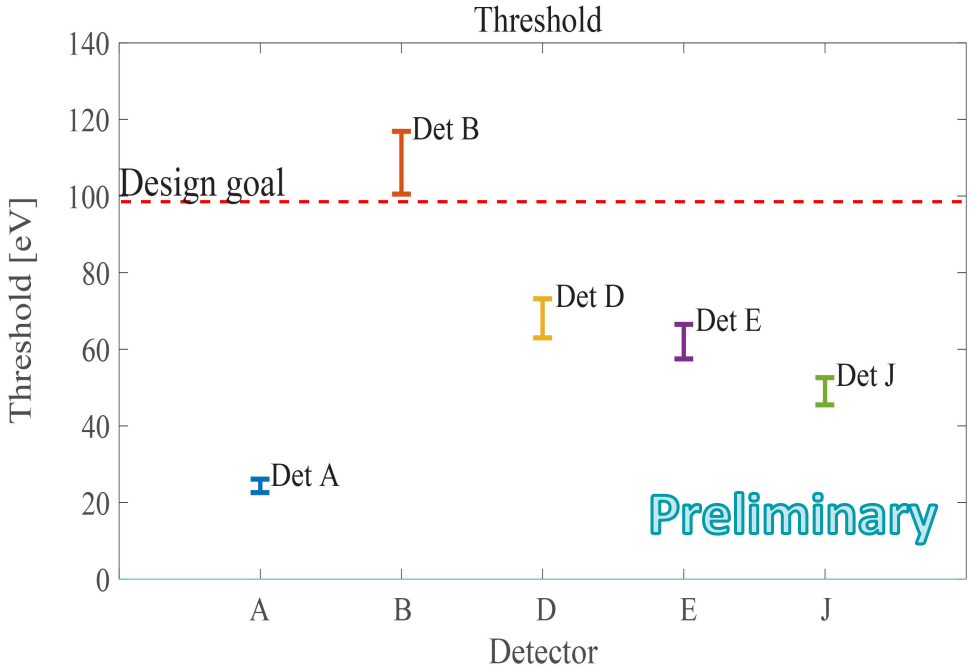


CRESST-III

New frontier in direct dark matter detection

Detectors optimized for low mass dark matter

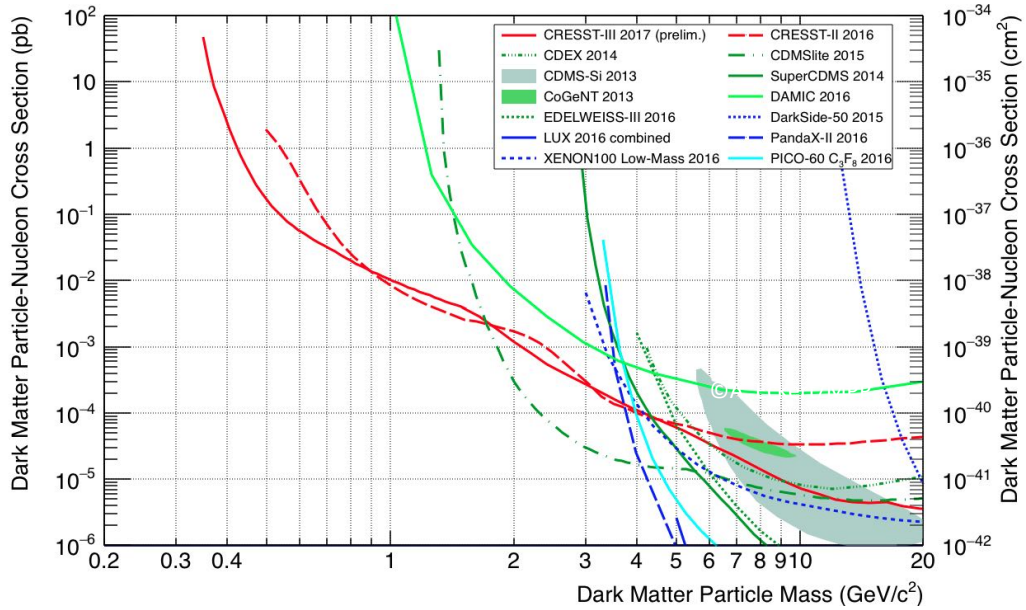
- Absorber volume reduced by a factor ~10 (≈24g)
- 100 eV threshold goal
- Veto surface related background



5 detectors reach/exceed threshold design goal

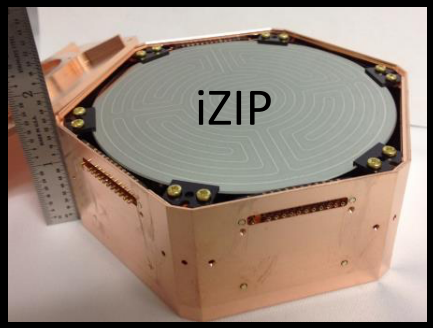
Analysis of one detector

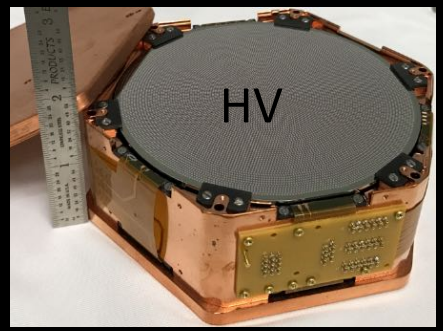
- Analysis threshold 100eV
- Net exposure 2.21 kg days



- One order of magnitude improvement at 0.5 GeV/c^2
- Reach of direct dark matter experiments extended to 0.35 GeV/c^2

- Cryogenic Ge and Si detectors (~30 mK)
- 2 types: optimized for low-background (iZIP) and low-threshold (HV)
- Initial payload ~30 kg; space for ~200 kg
- Focus on low-mass WIMPs (< 10 GeV/c^2); sensitivity goal of ~10^{-43} cm^2 (long-term goal: reach neutrino background)
- Main construction period: 2018/19; start of operation in 2020

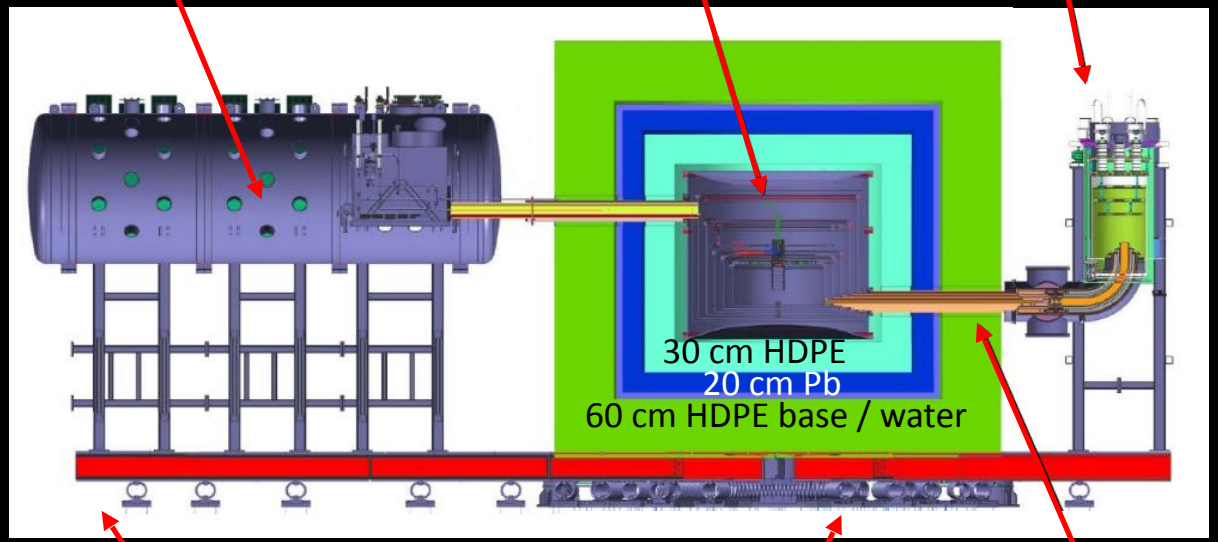




Signal vacuum feedthroughs

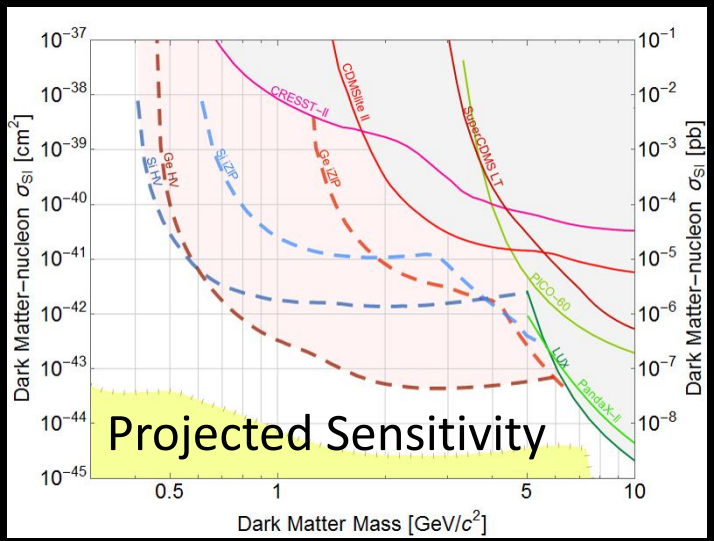
Detector volume (holds up to 200 kg)

Fridge to provide <15 mK at the detector



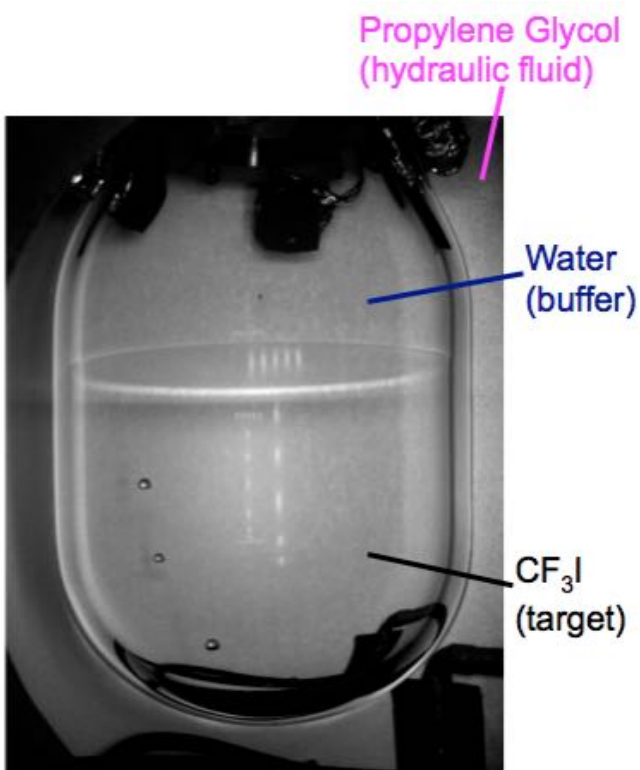
Mounted on spring-loaded platform (seismic isolation)

Cold finger

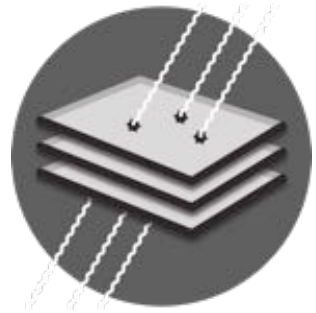


PICO Programme

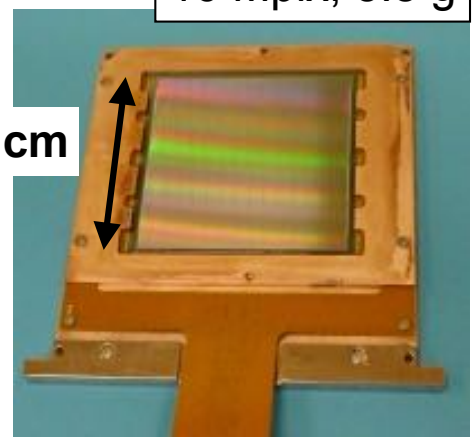
- Superheated fluid bubble chambers
- Particle interactions nucleate bubbles
  - Good discrimination against backgrounds
  - Alphas 'louder'
  - Gammas do not nucleate
- Visual and acoustic sensors

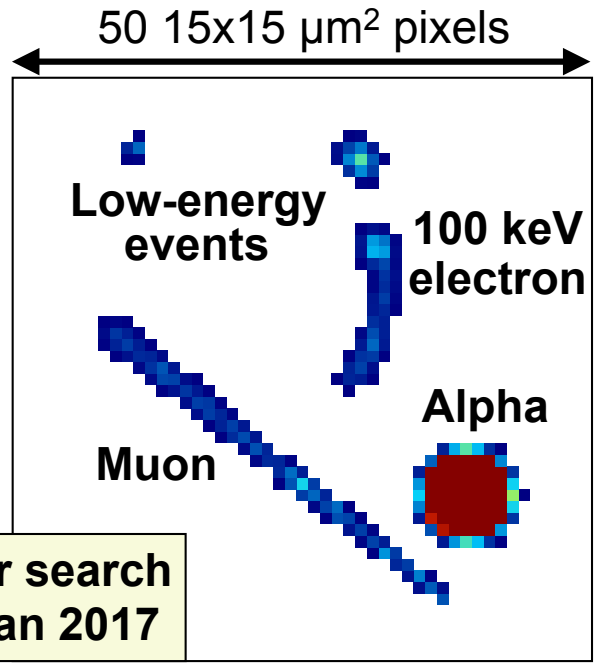


DAMIC at SNOLAB



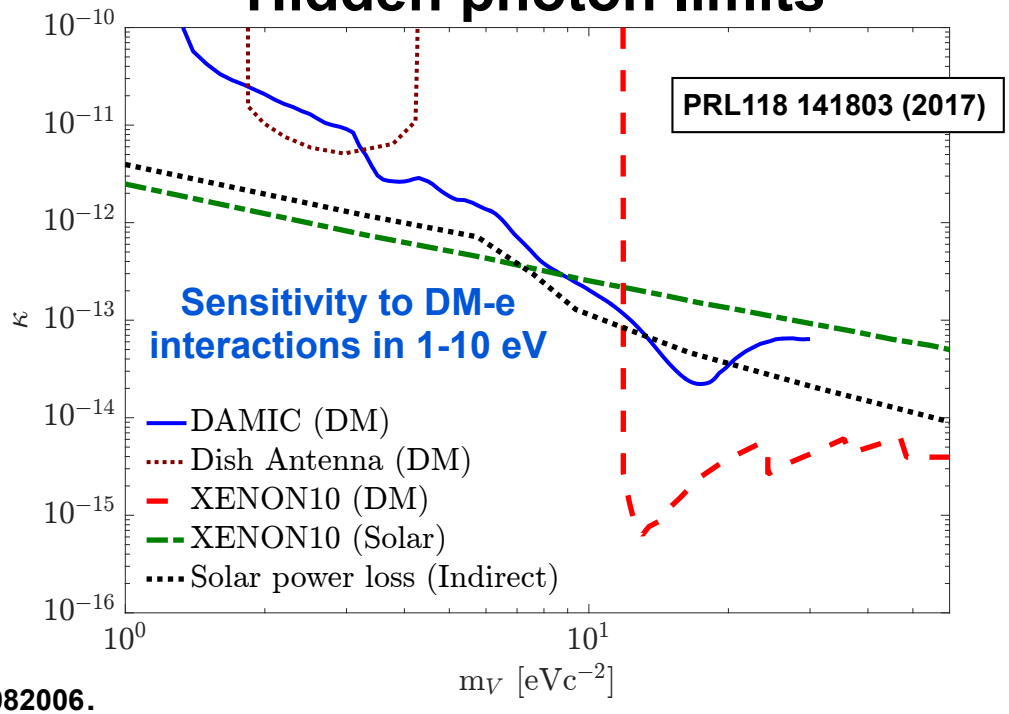
Charge-coupled devices (CCDs) to search for faint (few e^-) ionization signals from dark matter particles in the Galactic halo.



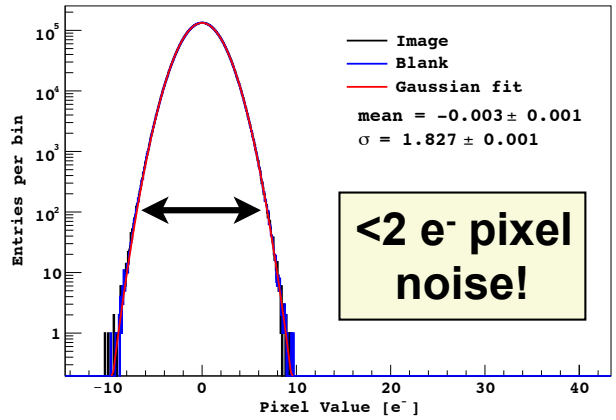


On-going dark matter search with 7 CCDs since Jan 2017

Hidden photon limits

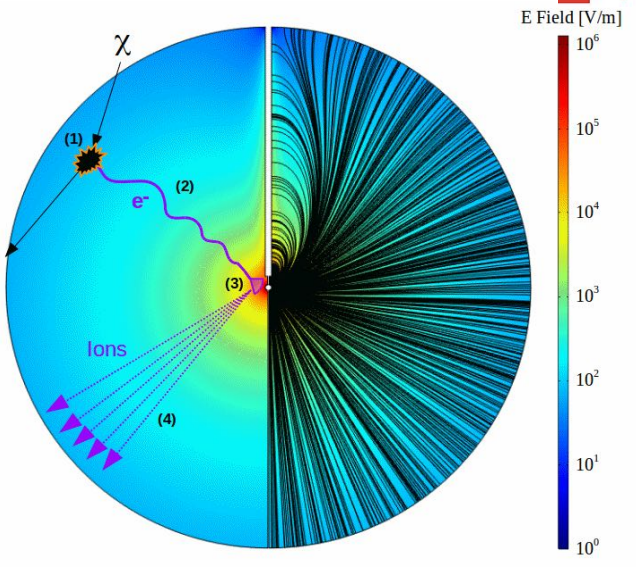


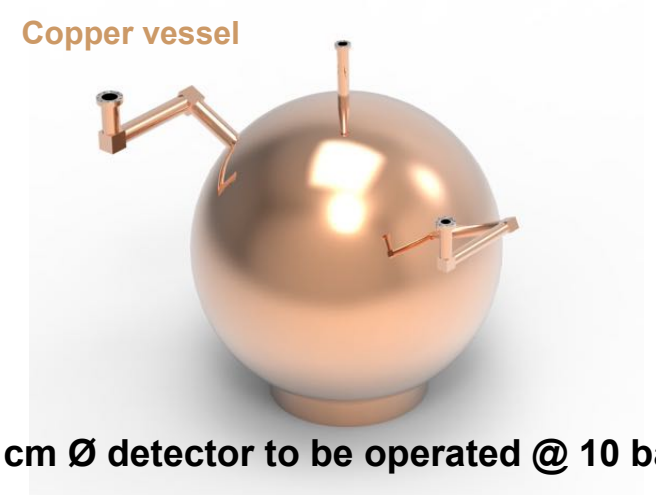
- Low-mass WIMP limits with 0.6 kg d exposure **PRD94 082006.**
- Nuclear / electron recoil response characterized down to 60 eV_{ee} threshold **PRD94 082007, JINST12 P06014, arXiv:1706.06053.**
- High-spatial resolution for powerful background rejection **JINST 10 P08014.**
- Lowest leakage current ever achieved in a silicon device **PRL118 141803.**
- Demonstrated single e^- detection with "skipper" technology for next generation **arXiv:1706.00028.**



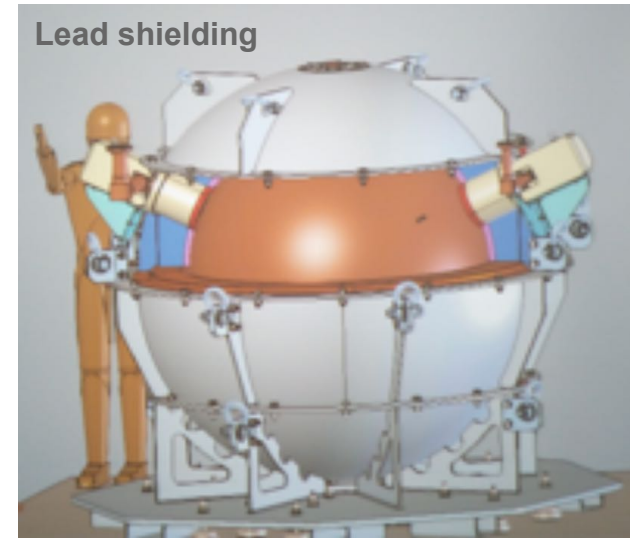
New Experiment With Spheres-Gas

Search for low-mass WIMPs with Spherical Proportional Counters (SPCs)





140 cm Ø detector to be operated @ 10 bars



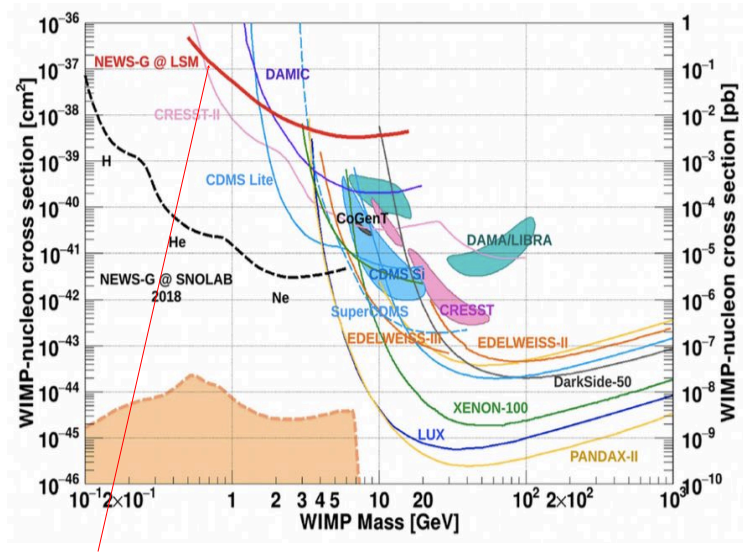
to be installed @ SNOLAB by summer 2018

Designed to search for low-mass WIMPs down to 0.1 GeV/c^2

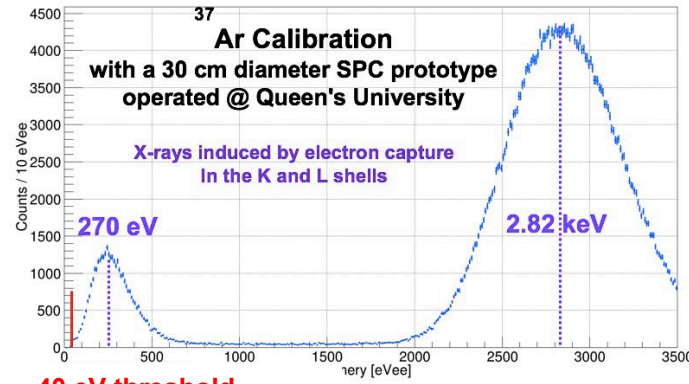
Low capacitance of the sensor & High amplification gain :
=> detection thresholds of 10 to 40 eVee

Light target gases (H, He, Ne) :
=> optimization of momentum transfers for low-mass particles

Rise-time based pulse-shape discrimination:
=> surface event rejection



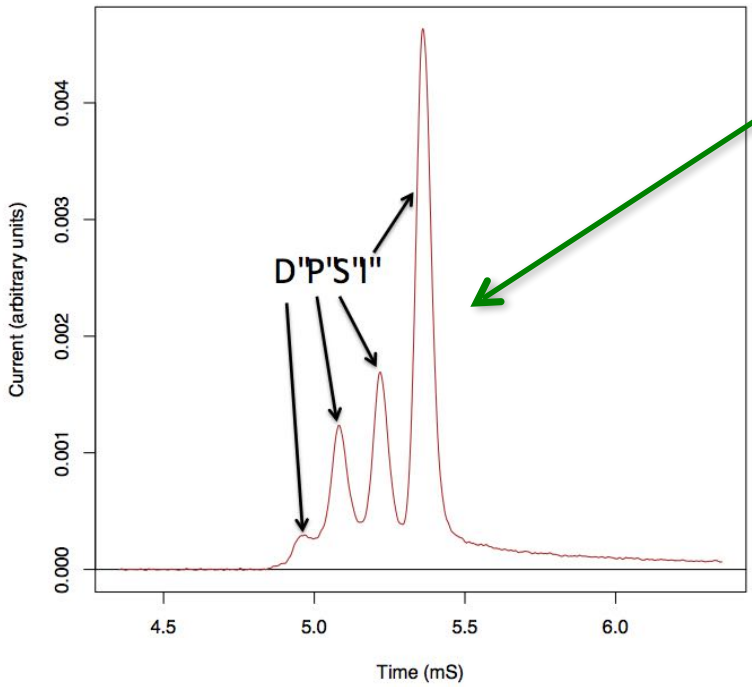
Results with Neon @ LSM :Q. Arnaud et al. [NEWS-G Collaboration], (2017) submitted to Astropart. Phys. (arXiv:1706.04934)



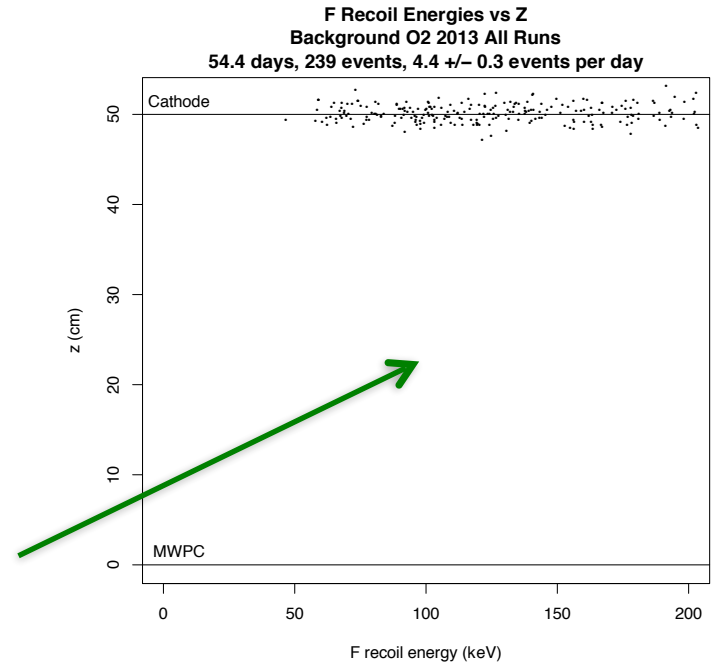
40 eV threshold

Optimisation of sensor to obtain low threshold and homogeneity of response

Background-Free DRIFT-IId

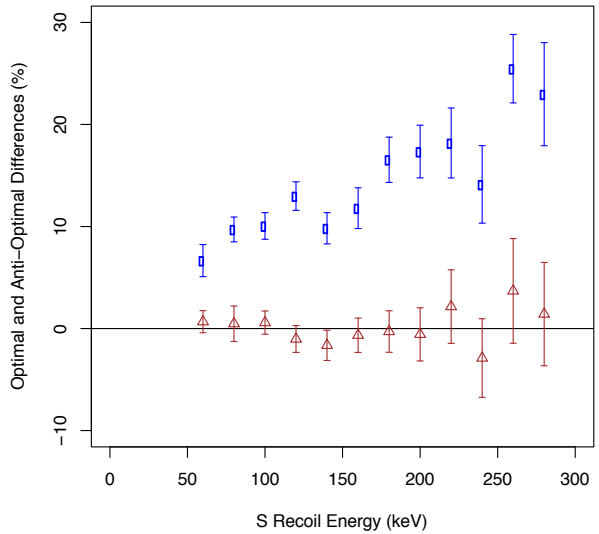


The addition of O_2 to a CS-CF_4 mixture produces minority peaks with separation proportional to distance.

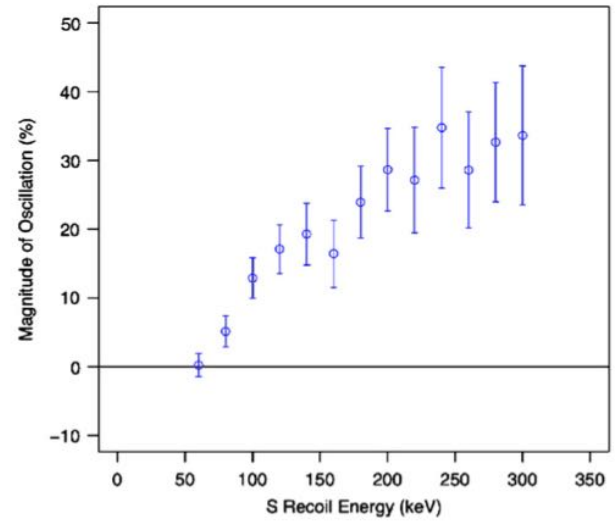


…allows us to run background free over ~75% of our available volume.

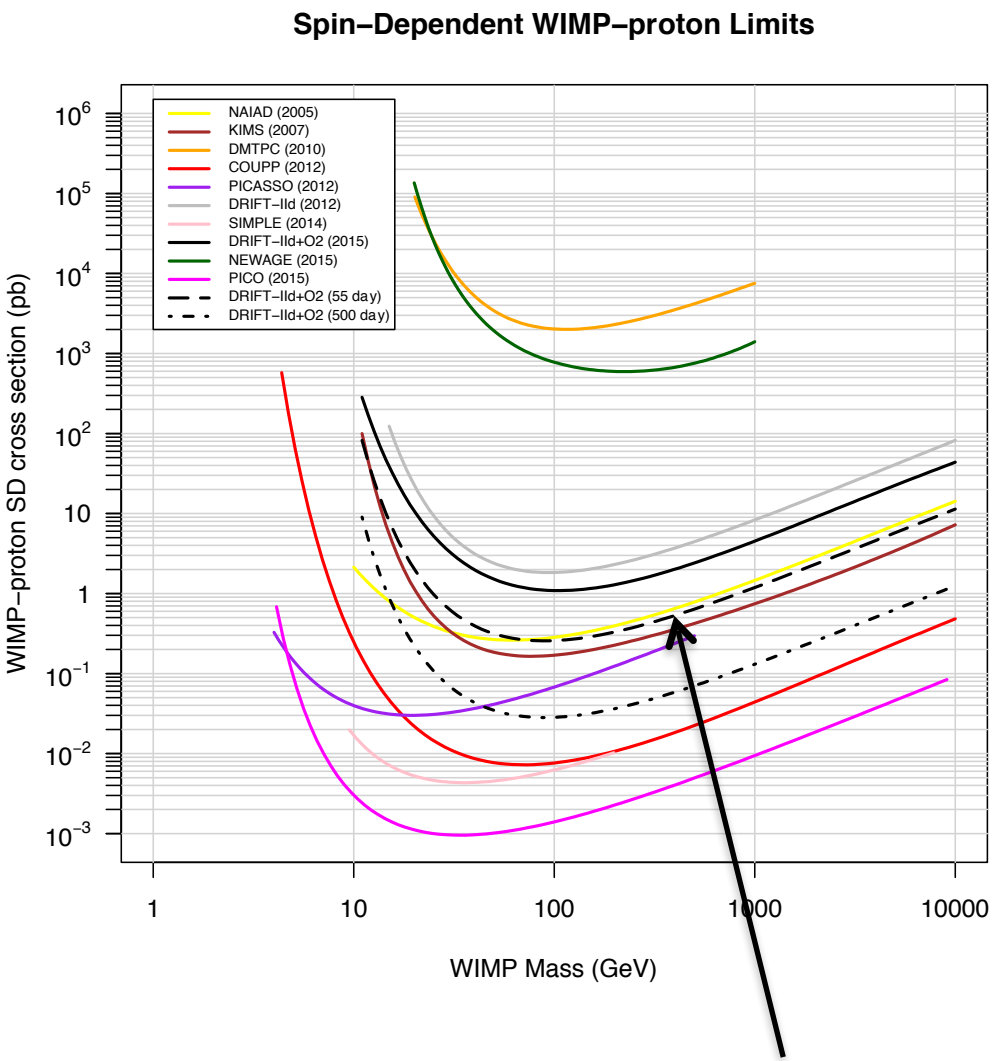
DRIFT Head-Tail Results

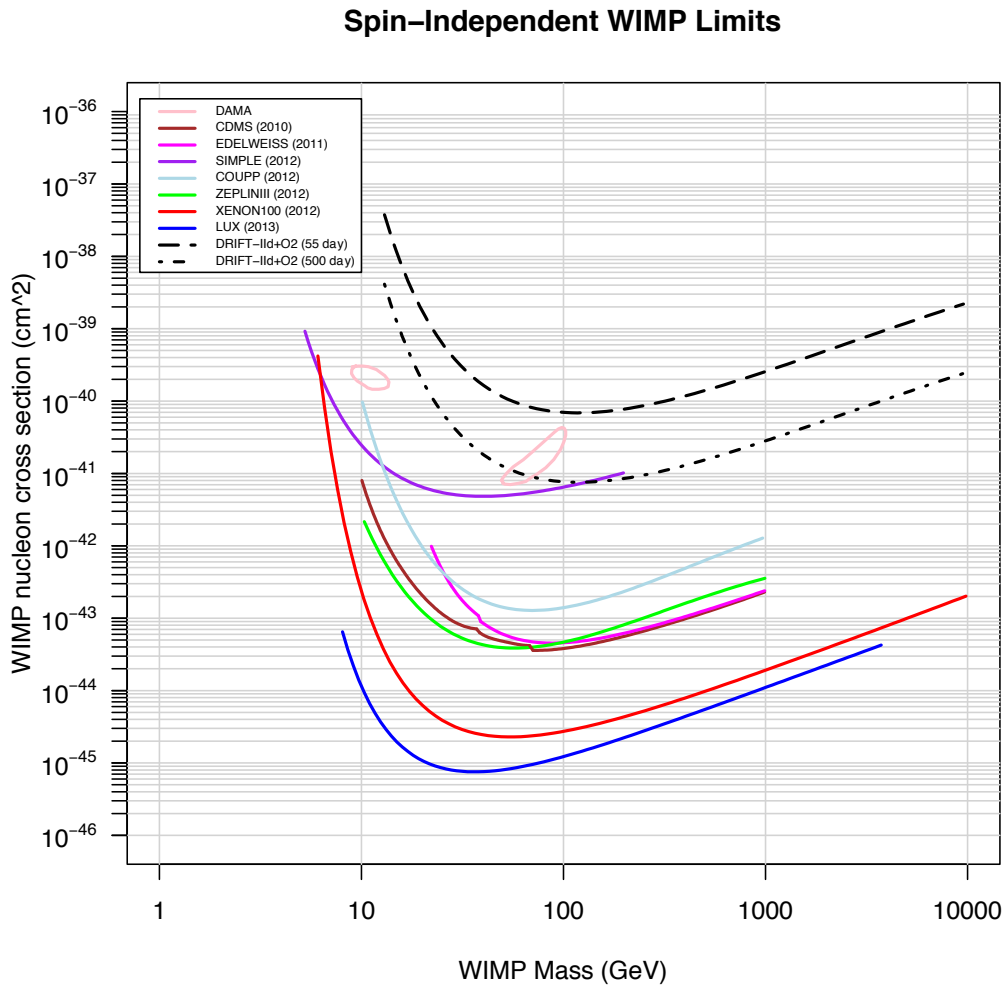


DRIFT Range Results



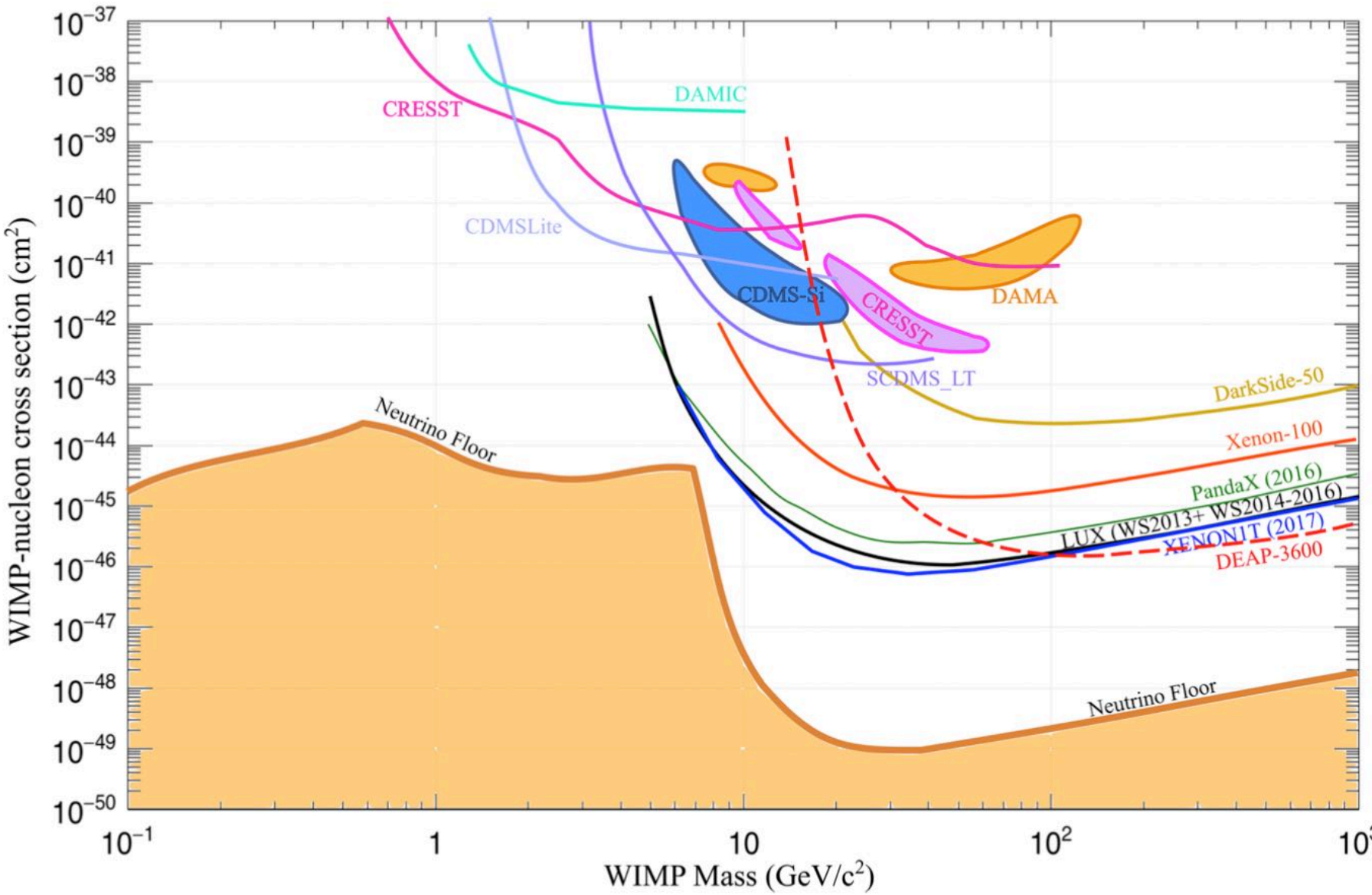
Future Plans for DRIFT





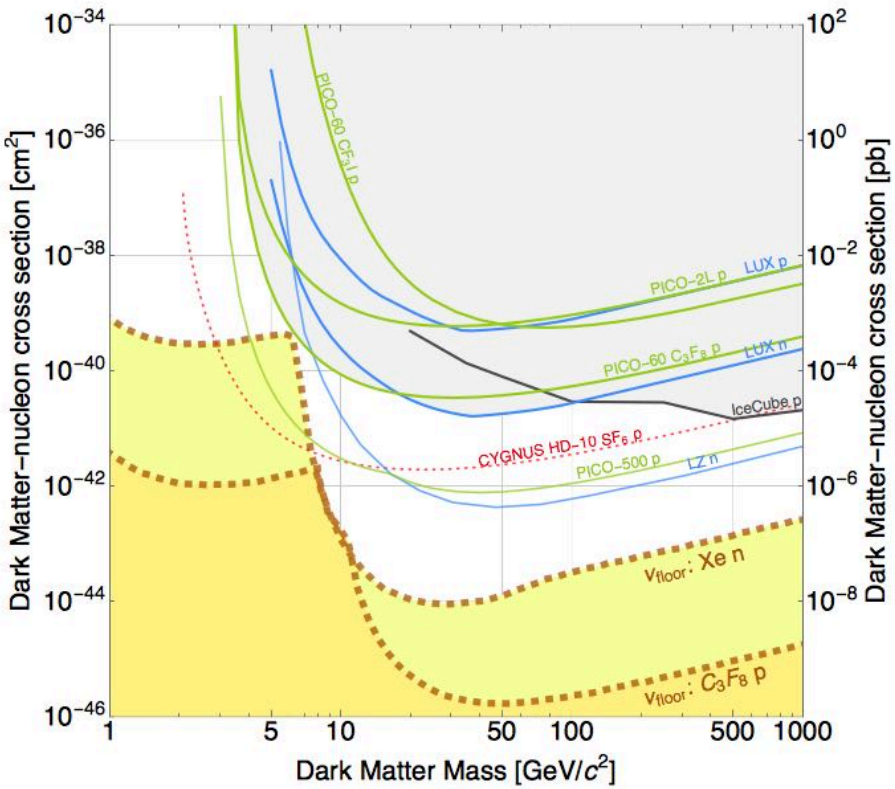
Just published
AstroPle 91 (2017) 65-74.

Current Status

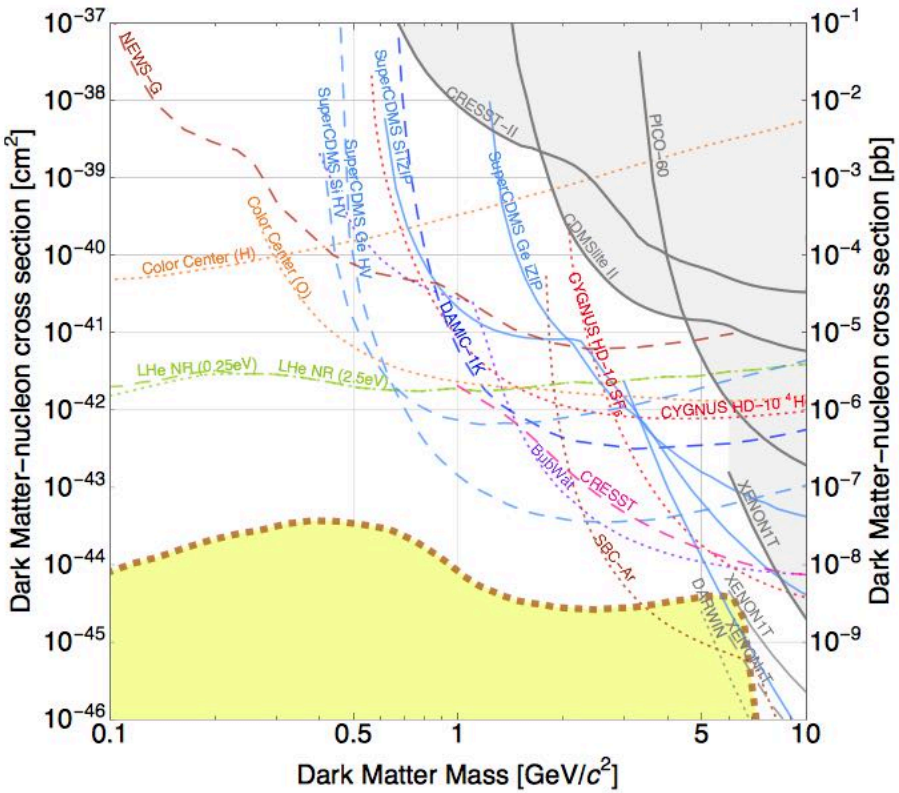


P. Gorel

Current status and projections



Spin-dependent
WIMP-nucleon (p or n) cross section



Spin-independent, low mass,
WIMP-nucleon cross section

US Cosmic Visions Report: arxiv.org/1707.04591

Talk overview

- Setting the scene for future talks and new results
  - Many more talks this week with new results
- Challenges of Direct Dark Matter searches
  - Background, background, background
- Environmental Backgrounds
  - Variations across environments
  - New challenges when reach neutrino coherent scattering mezzanine
- Detection Techniques
  - Many complementary approaches being taken
  - Several techniques maturing to tonne-scale detectors
- Current status of several Direct Dark Matter searches
  - Incredibly active field
  - Continued strong improvement over last 25 years
  - No sign of this stopping…