The worldwide experimental effort ongoing in the field of direct Dark Matter search

Amaldi Research Center Seminar
University of Rome La Sapienza, 14/05/2019

Marcello Messina Senior Research Scientist at

جامعة نيويورك أبوظبي

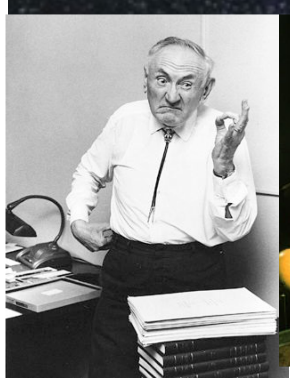
NYU | ABU DHABI

A World of Dark Matter Searches

Evidence for Dark Matter

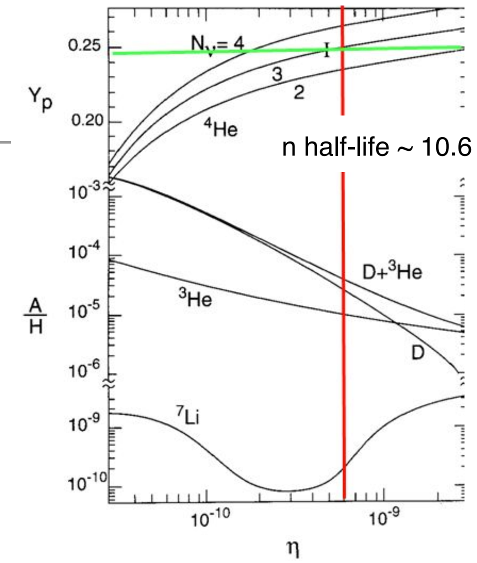
Astrophysical Observations

Beginning of the story



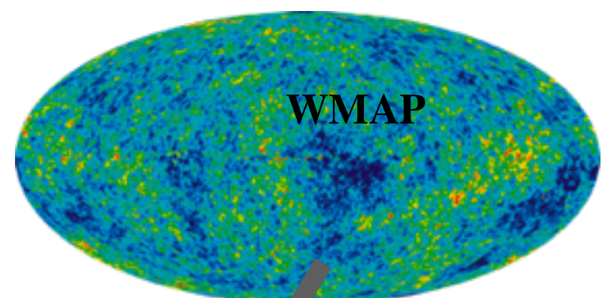
Ω_m=0.3

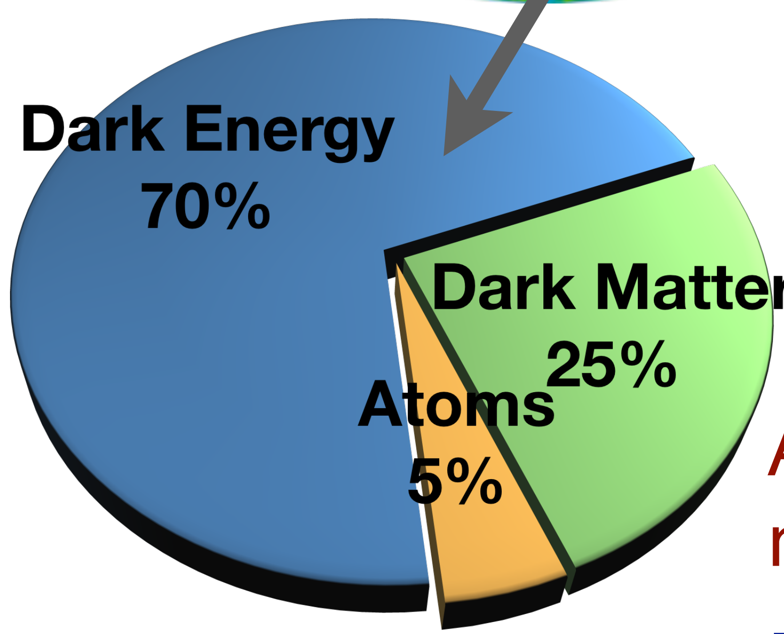
BBN



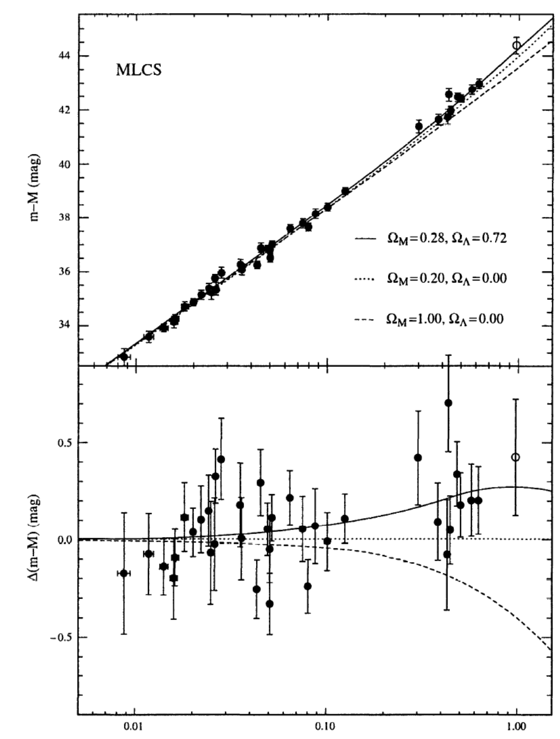
Ω_b=0.01-0.02

n half-life ~ 10.6 min





Ω_V=0.7

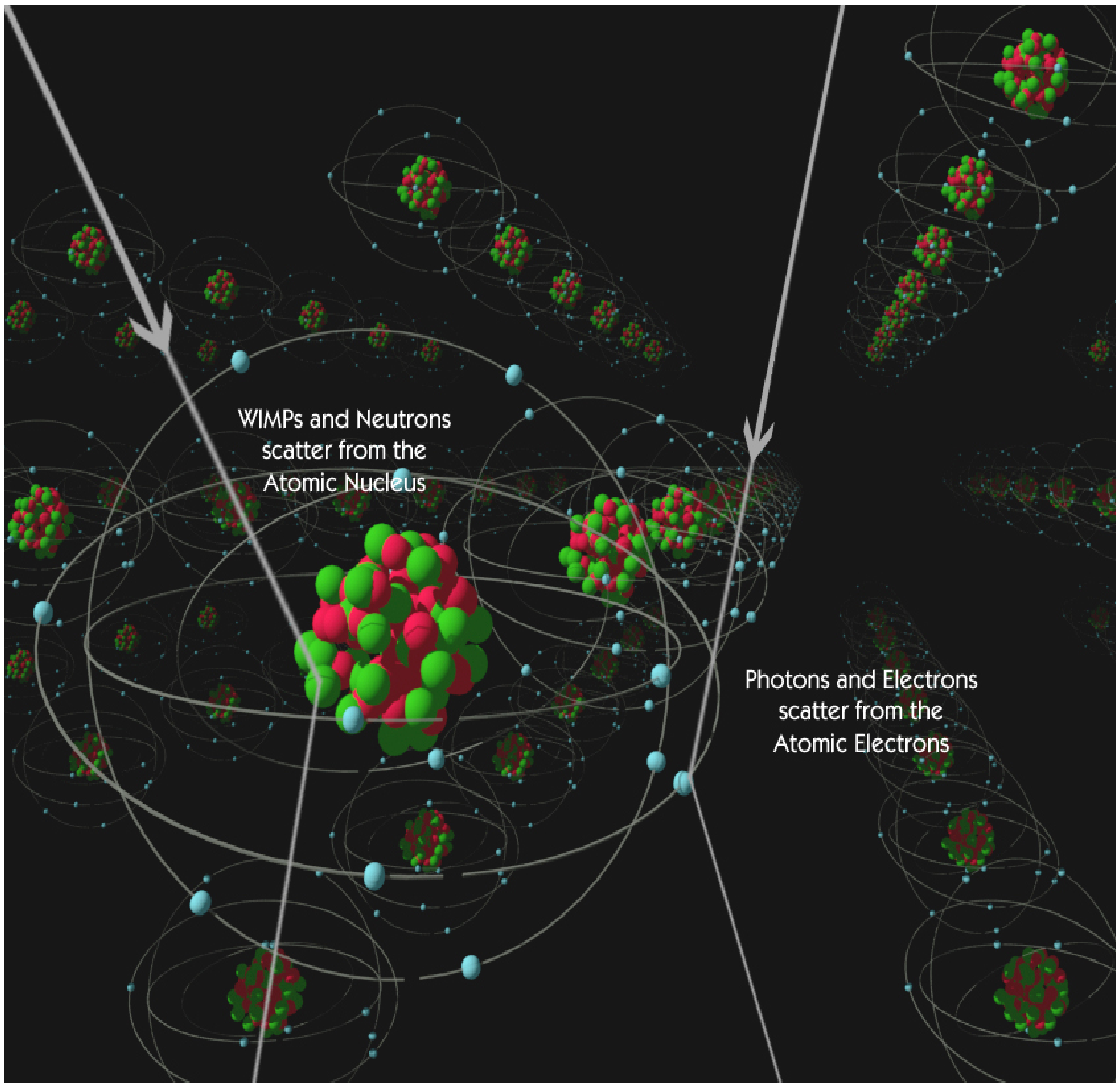


All consistent with ~25% dark matter (give or take).

Possible candidates:

WIMPs

Direct detection principle



Collisions of invisibles particles with atomic nuclei

REVIEW D VOLUME 31, NUMBER 12

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

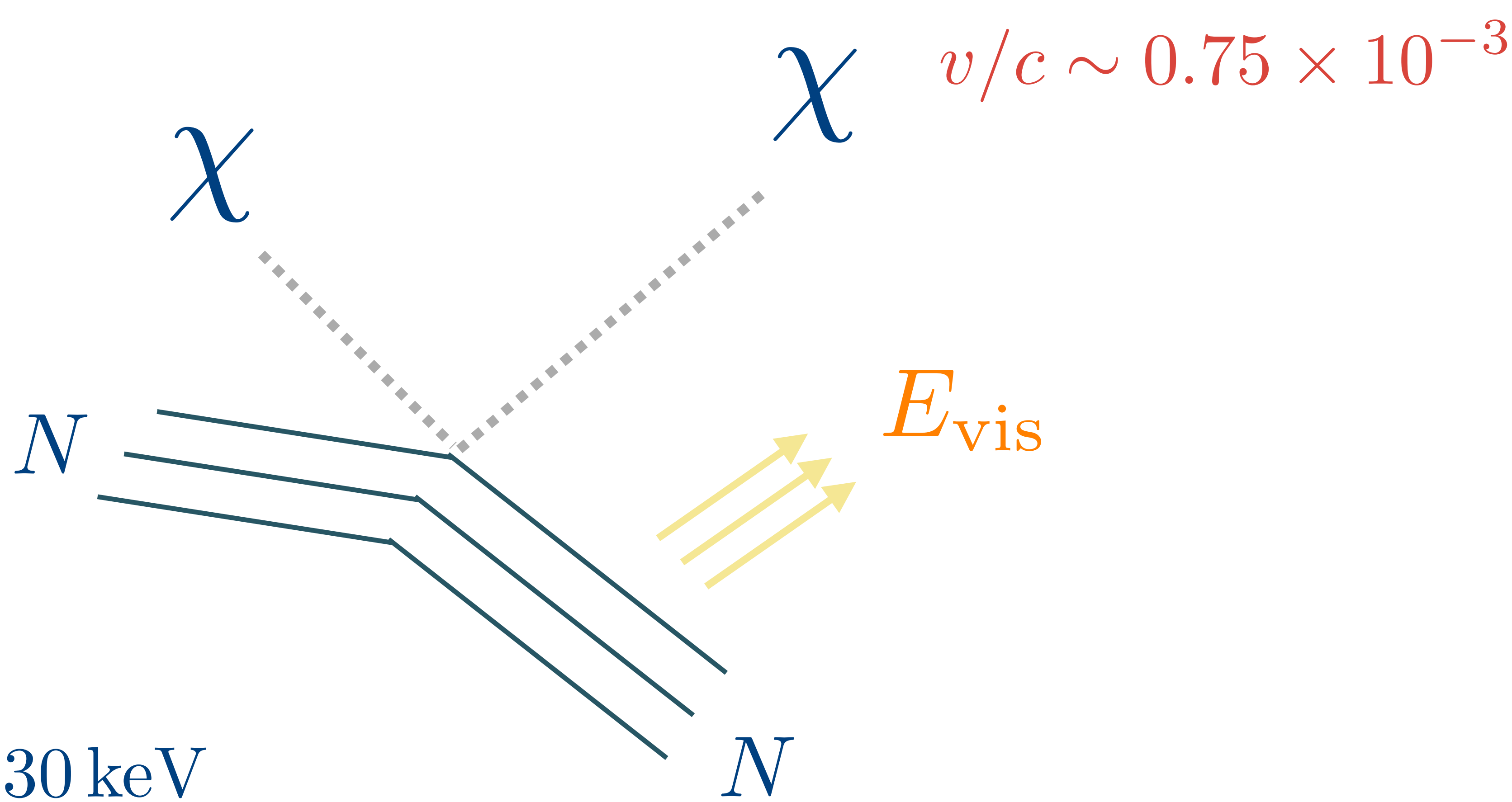
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Direct detection principle

Scattering of a WIMP with an atomic nucleus

Momentum transfer ~ few tens of MeV

Energy deposited in the detector ~ few keV - tens of keV



$$E_R = \frac{q^2}{2m_N} < 30\,\mathrm{keV}$$

Observables: Rate

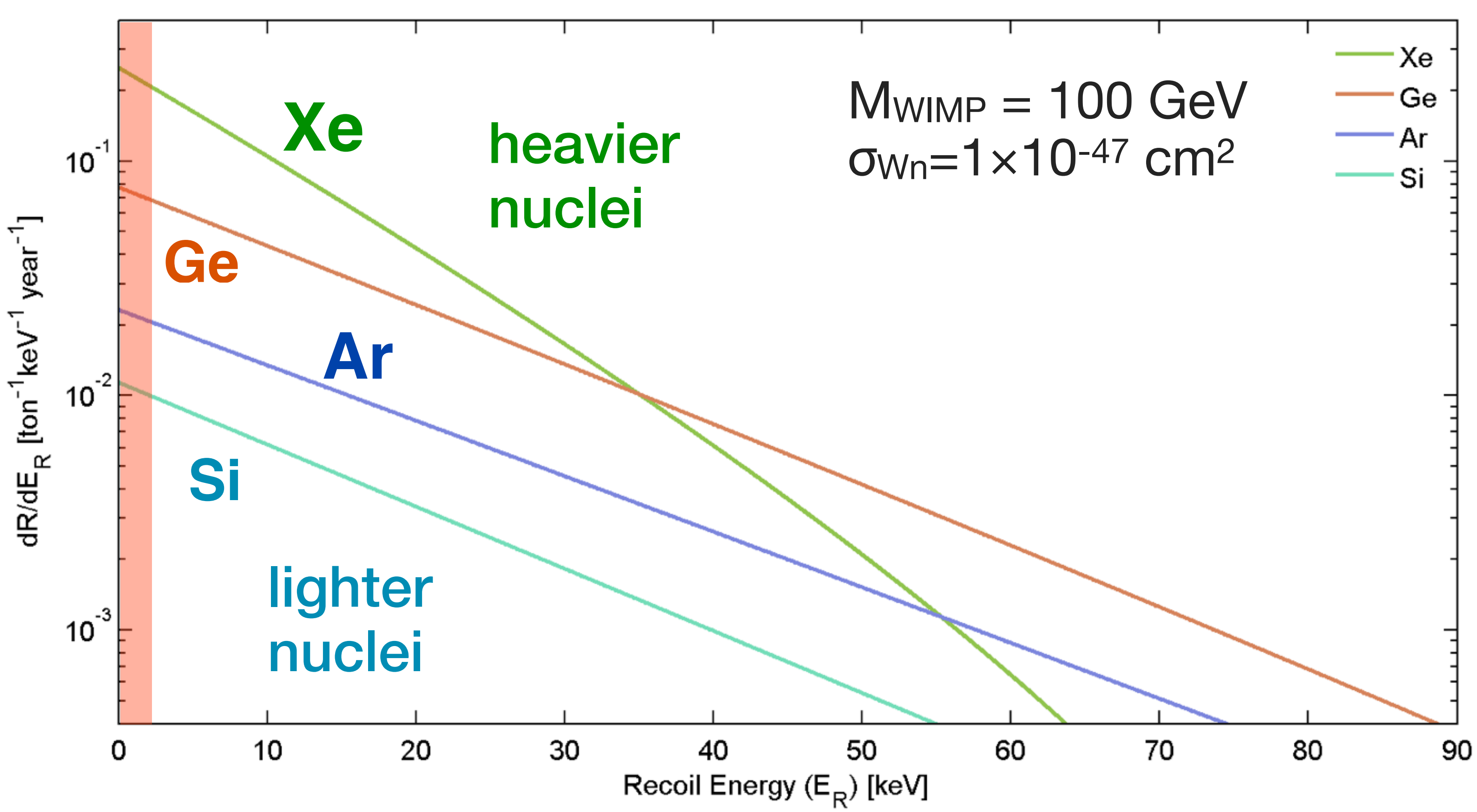
Event rate in a terrestrial detector

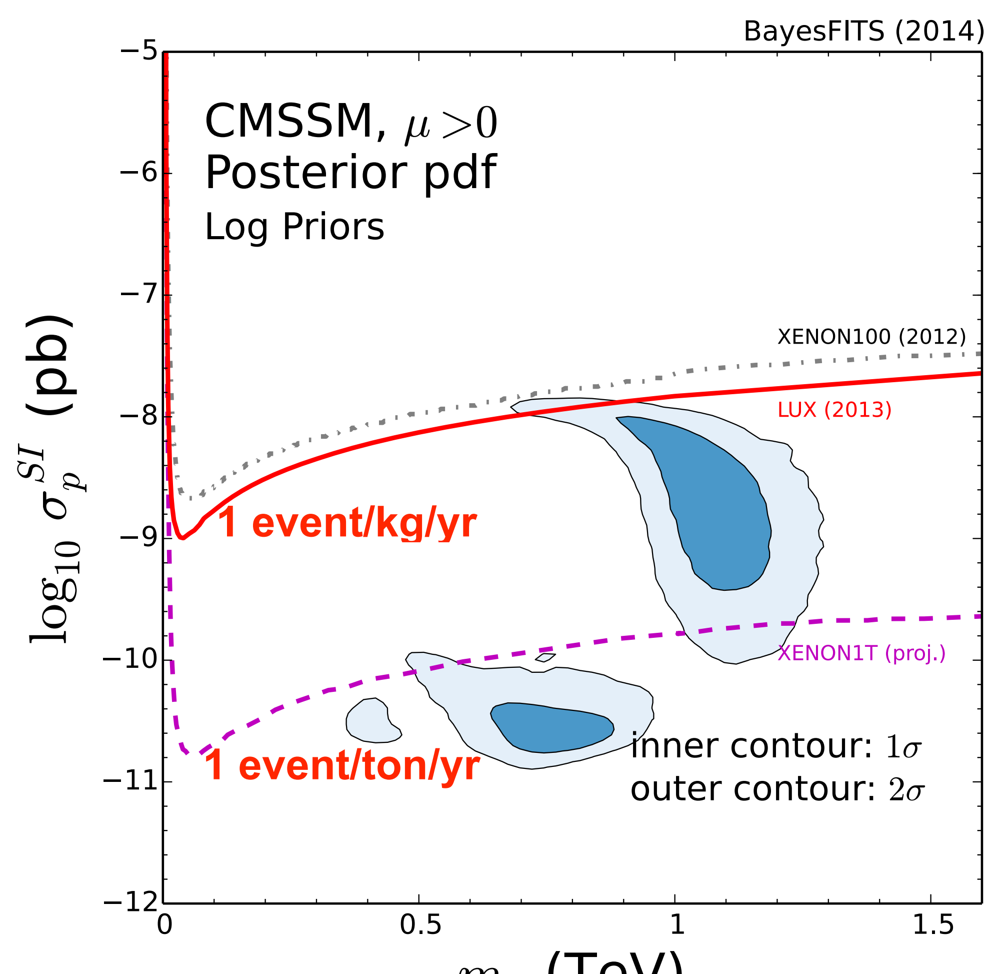
Detector physics — N_N, E_{th}

Particle/nuclear physics — $m_W, d\sigma/dE_R$

Astrophysics — $\rho_0, f(v)$

$$R \sim N_N \times \frac{\rho_0}{m_W} \times \langle v \rangle \times \sigma$$





Scattering cross section on nuclei

- In general, interactions leading to WIMP-nucleus scattering are parameterized as:
  - **scalar interactions** (coupling to WIMP mass, from scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}[Z f_p + (A - Z) f_n]^2$$

f_p, f_n: scalar 4-fermion couplings to p and n

=> nuclei with large A favourable (apart nuclear form factor corrections)

  - **spin-spin interactions** (coupling to the nuclear spin J_N, from axial-vector part of L)

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

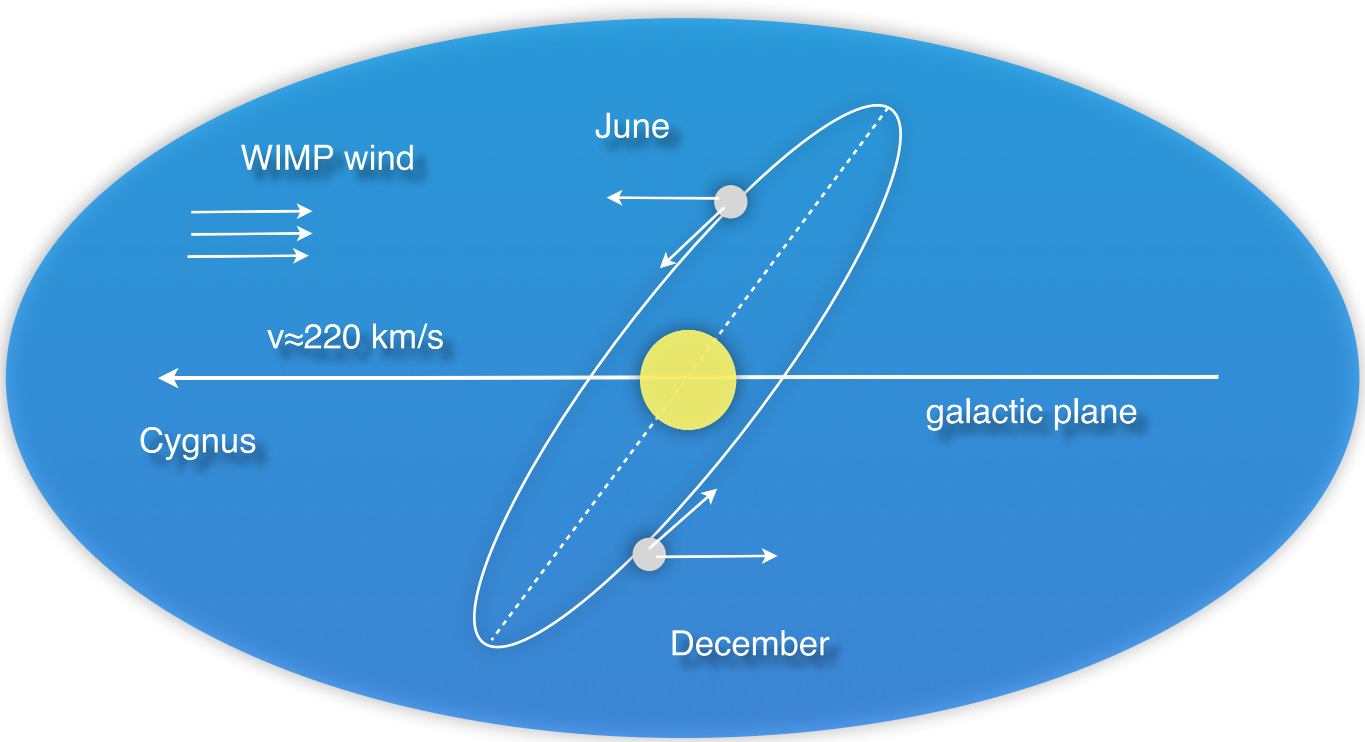
a_p, a_n: effective couplings to p and n; $\langle S_p \rangle$ and $\langle S_n \rangle$ expectation values of the contribution of p and n to the spin within nucleus

=> nuclei with non-zero angular momentum (corrections due to spin structure functions)

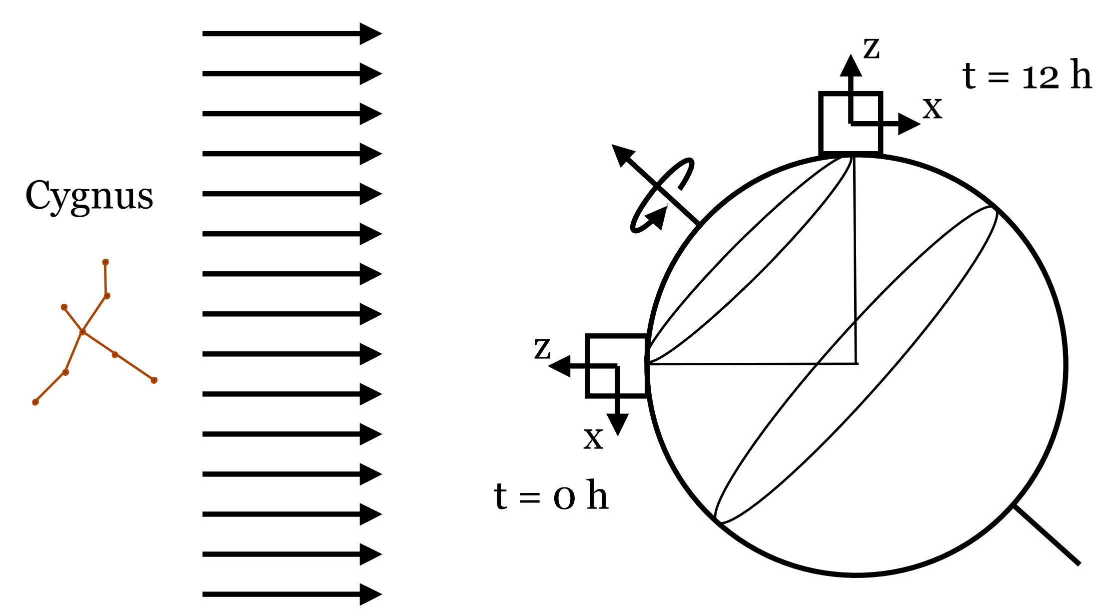
Observables: rate modulations

The soft WIMP wind

- Rate and shape of nuclear recoil spectrum depend on target material
- Motion of the Earth causes:
  - annual event rate modulation: June - December asymmetry ~ 2-10%
  - sidereal directional modulation: asymmetry ~20-100% in forward-backward event rate



Drukier, Freese, Spergel, PRD 33,1986



D. Spergel, PRD 36, 1988

Background Suppression: the holy grail

Avoid Backgrounds

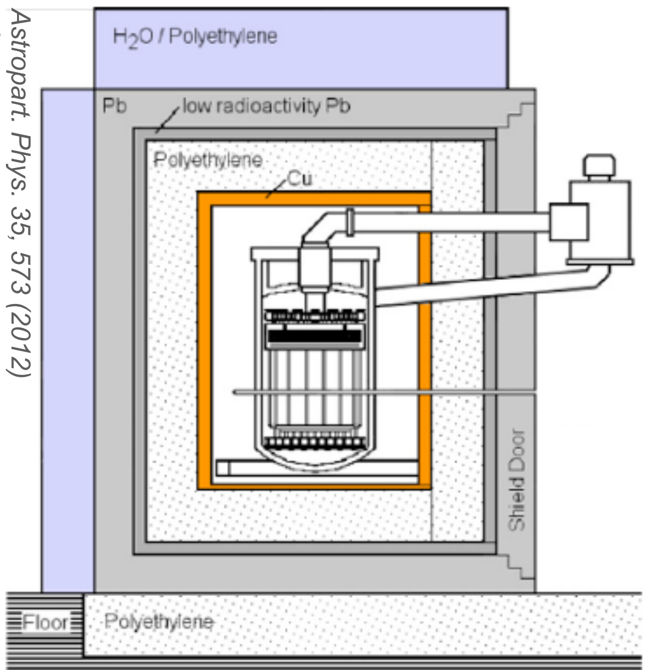
Shielding

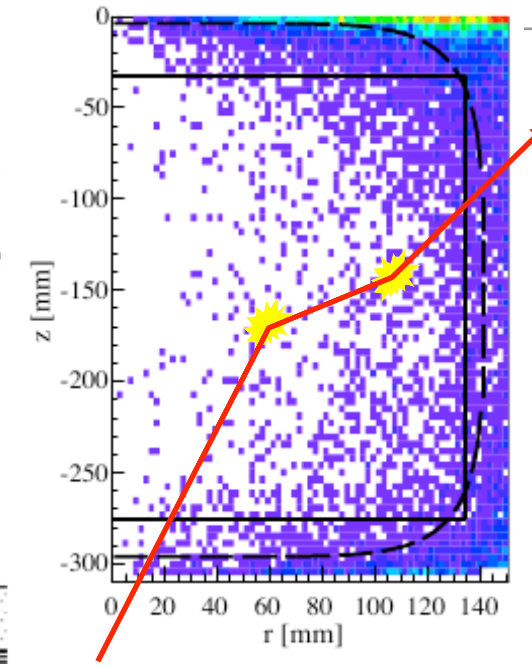
deep underground location
large shield (Pb, water, poly)
active veto (μ, coincidence)

self shielding → fiducialization

Select radiopure materials

Astropart. Phys. 35, 573 (2012)





Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection

requires some position resolution

WIMPs interact with target nuclei

→ nuclear recoils
exploit different dE/dx from signal and background →

Examples:

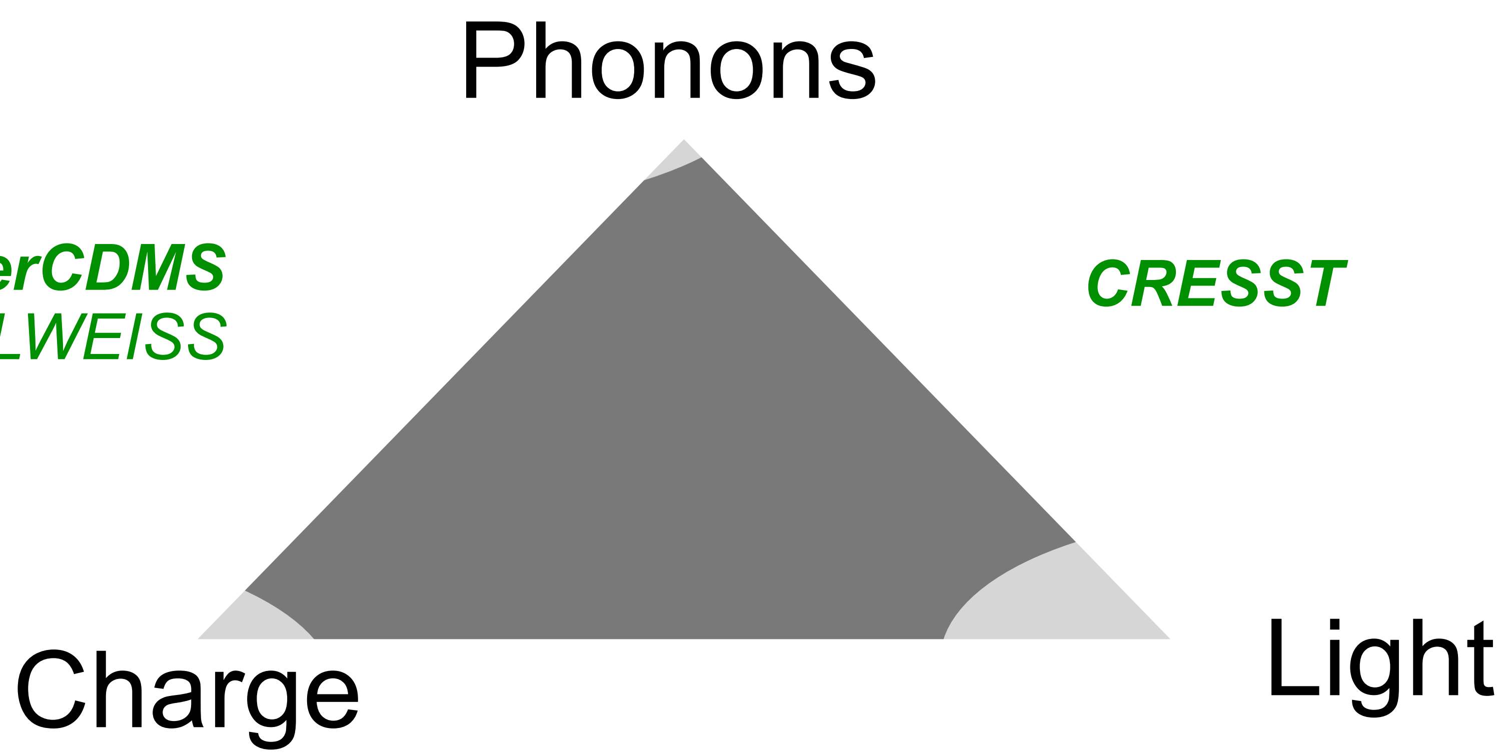
- scintillation pulse shape
- charge/light ratio
- ionization yield

WIMPs Direct Detection Experiments

Crystals (NaI, Ge, Si)
Cryogenic Detectors
Liquid Noble Gases

CRESST-I
CUORE

Tracking:
DRIFT, DMTPC
MIMAC,
NEWAGE



SuperCDMS
EDELWEISS

CRESST

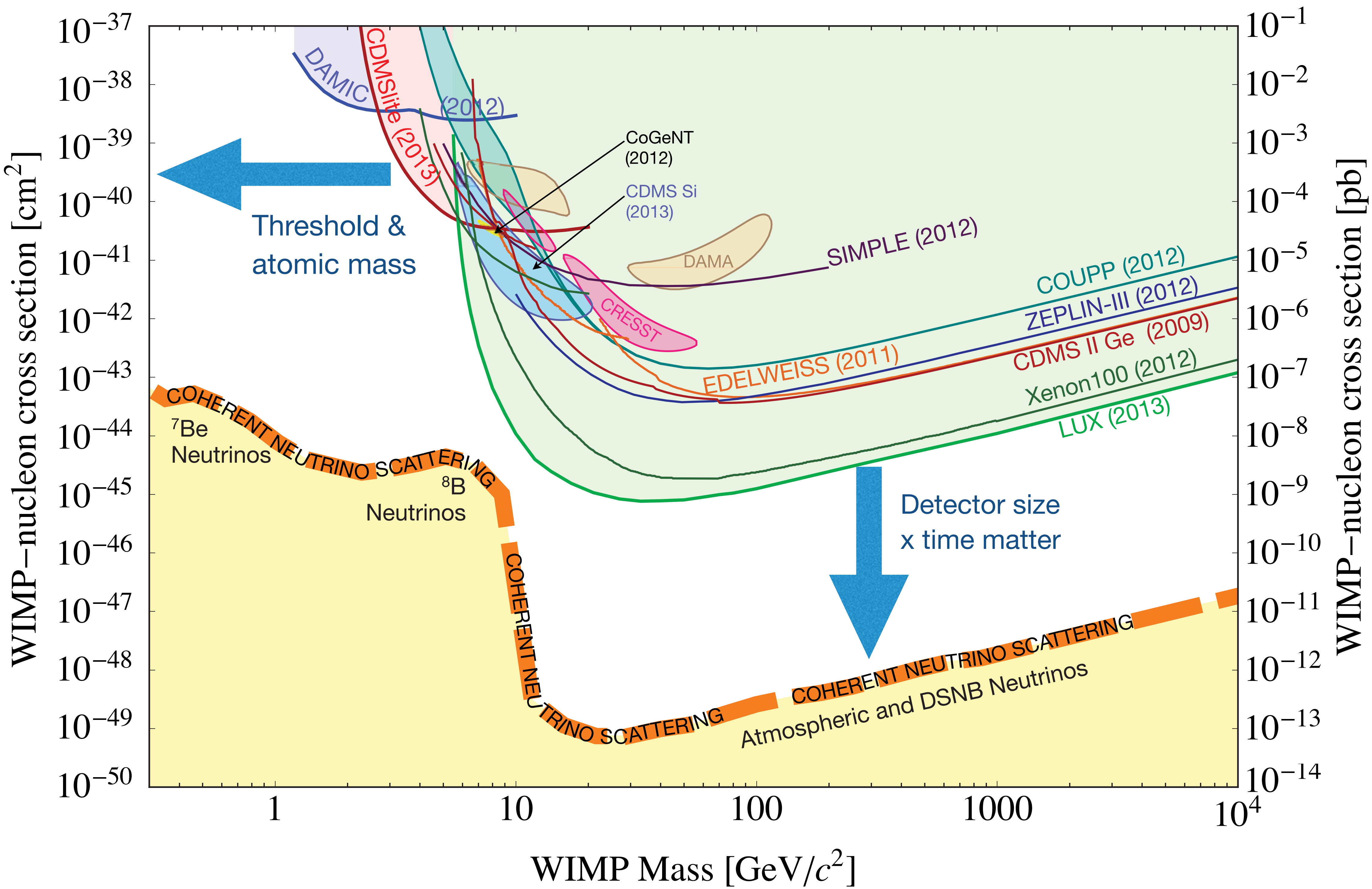
Superheated Liquids:
COUPP → PICO
PICASSO → PICO
SIMPLE

CoGeNT
CDEX
Texono
Malbek
DAMIC

XENON**, **LUX/LZ
*ArDM, **Panda-X***
Darkside, DARWIN

***DEAP-3600**, CLEAN*
***DAMA**, KIMS*
***XMASS**, DM-Ice,*
*ANAIS, **SABRE***

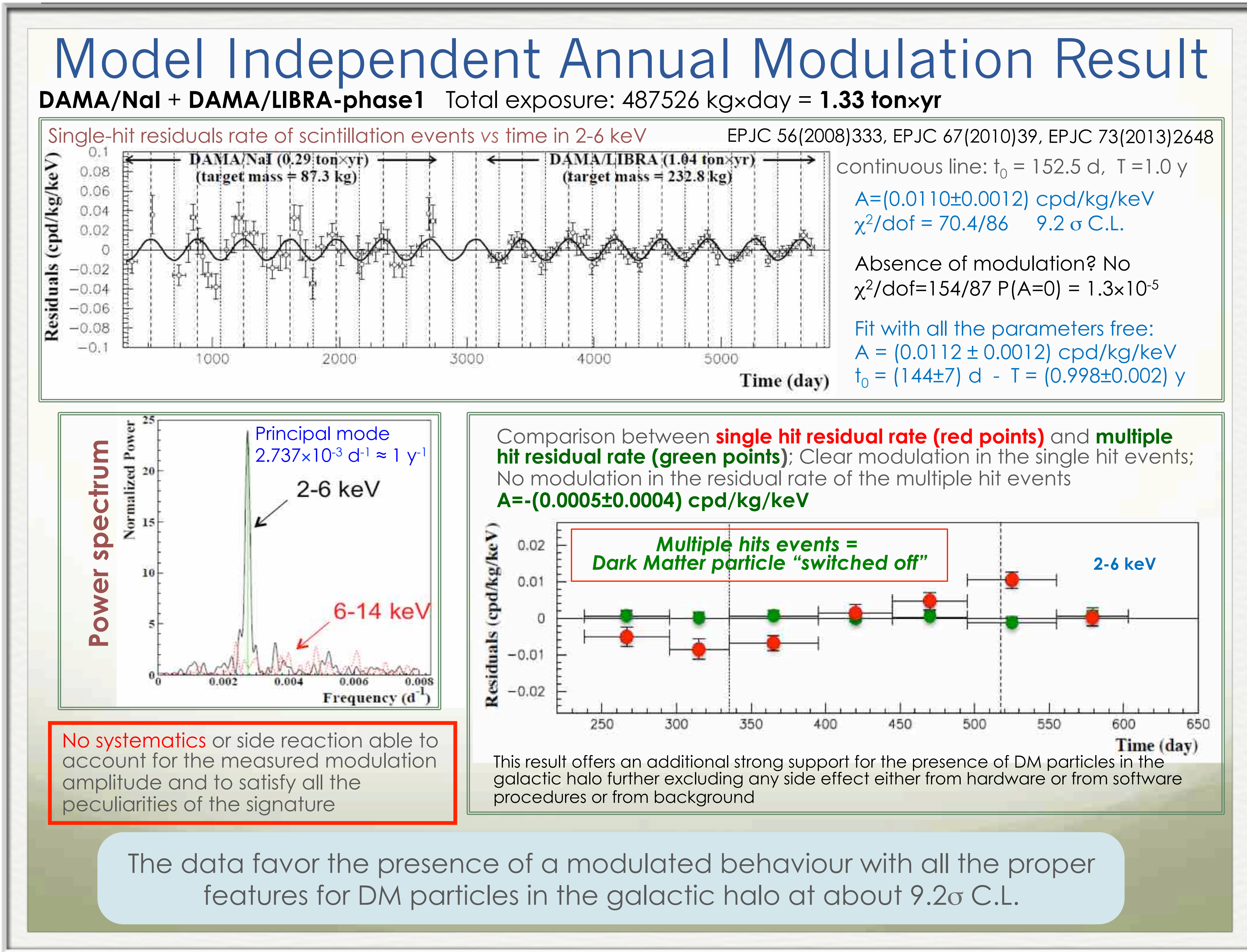
The WIMP landscape



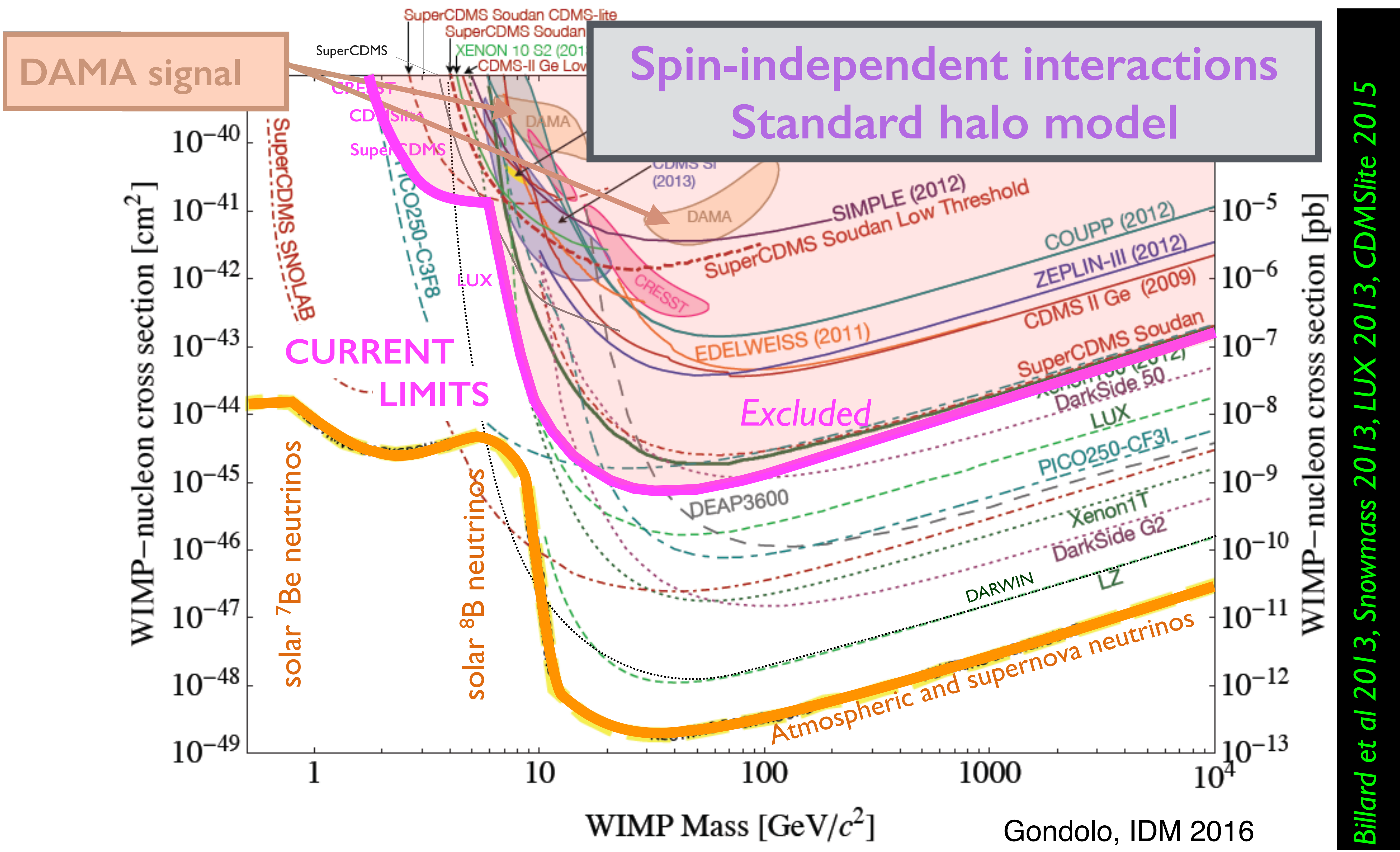
DAMA/Libra experiment

233 kg of pure NaI crystals readout by PMTs
with a screen of concrete, polipropilene, Pb and Cu

Belli - IDM 2016

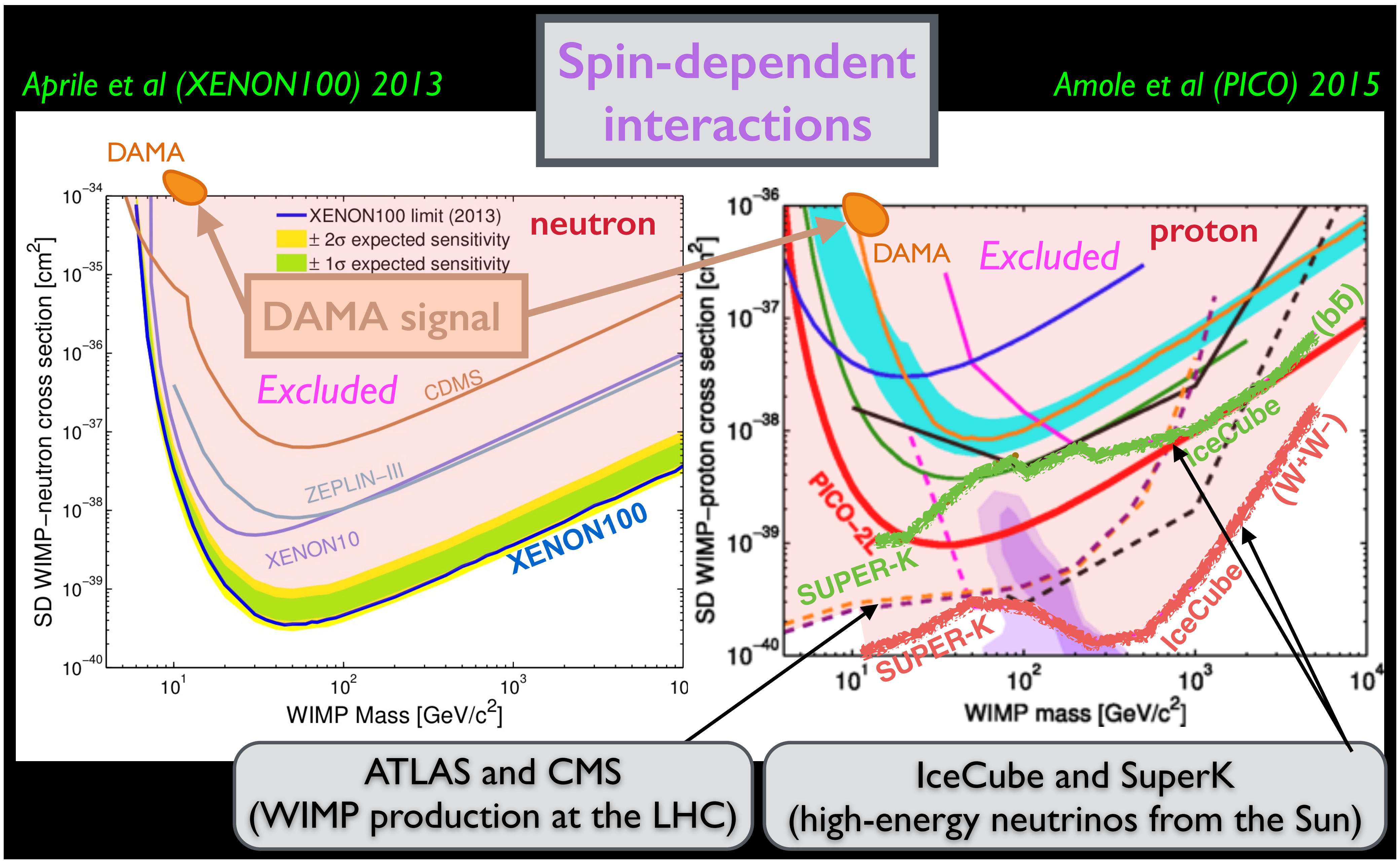


DAMA Incompatible with Other Experiments



Gondolo, IDM 2016

DAMA Incompatible with Other Experiments



Gondolo, IDM 2016

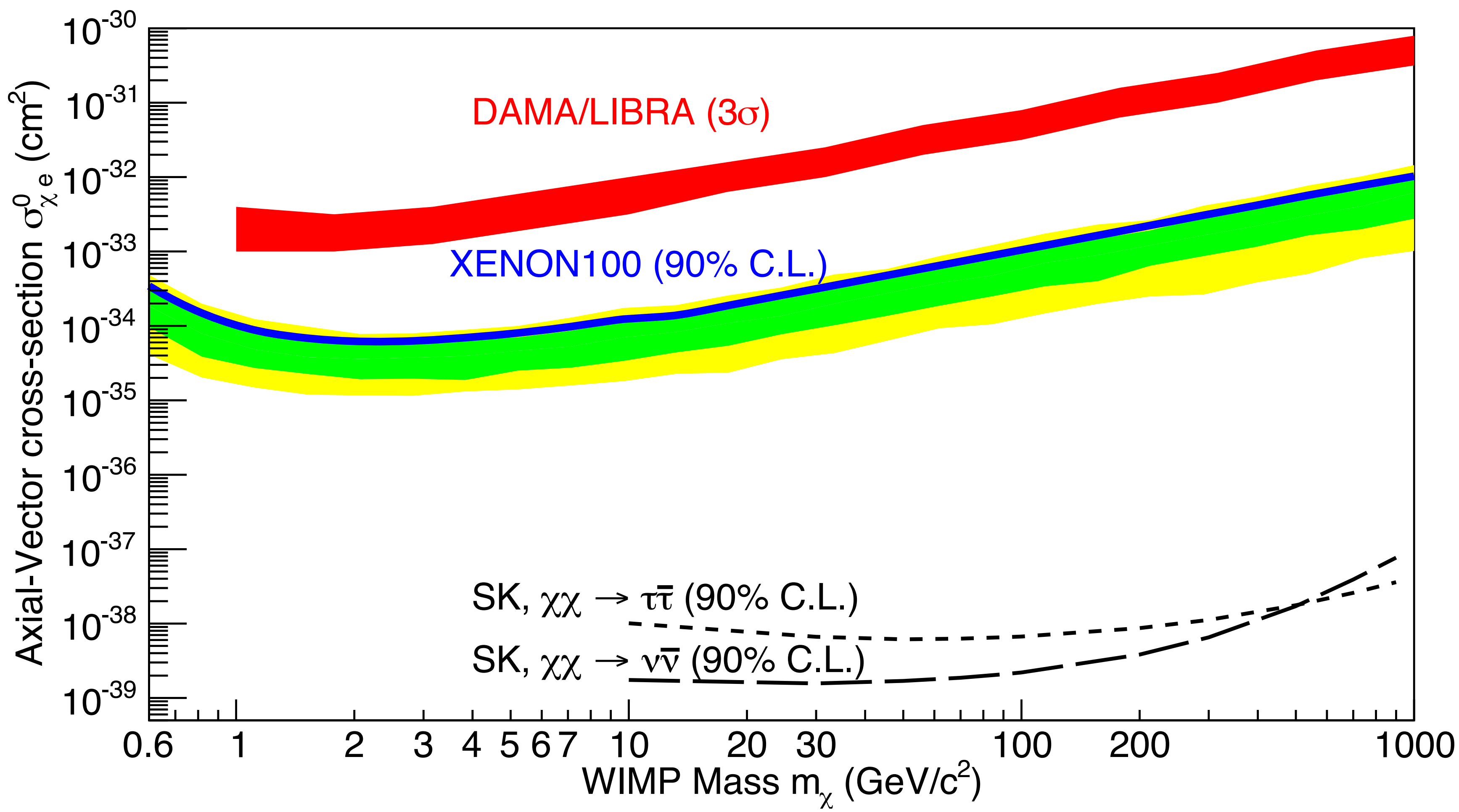
XENON100 excludes leptophilic models

- Dark matter particles interacting with e⁻

   1. No evidence for a signal

   2. Exclude various leptophilic models as explanation for DAMA/LIBRA

XENON collaboration, Science 349, 2015, Phys. Rev. Lett. 115, 2015



Upcoming NaI Projects to directly test DAMA

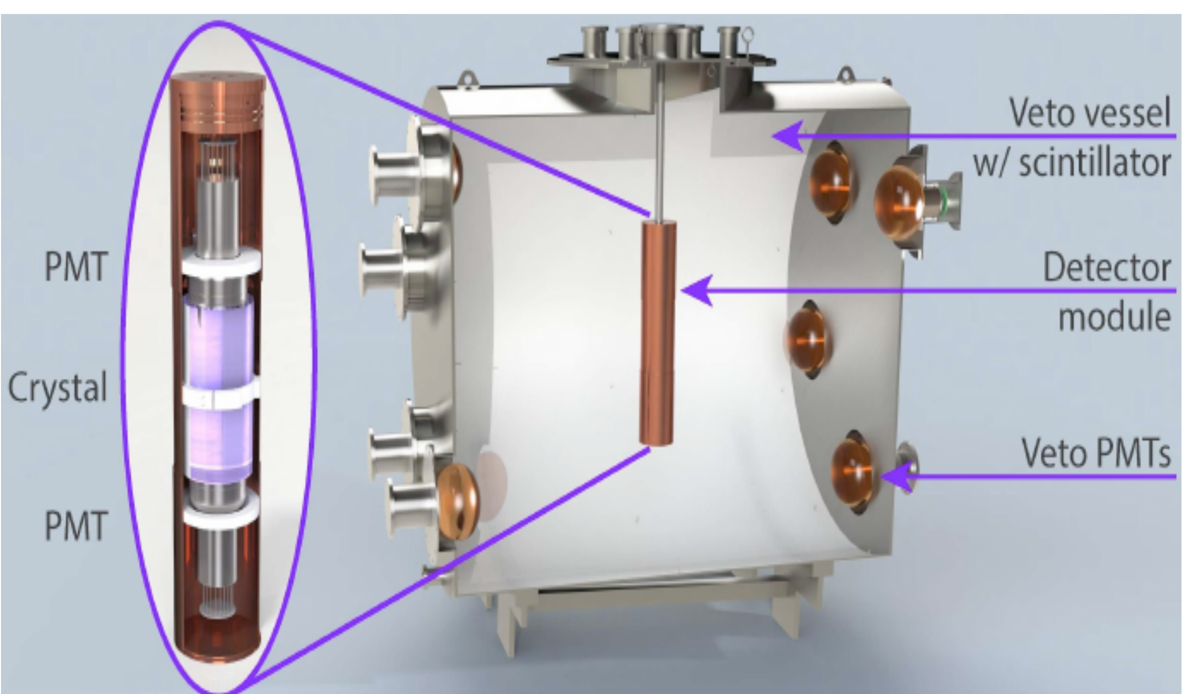
SABRE @ LNGS

*S*odium-iodine with *A*ctive *B*ackground *RE*jection

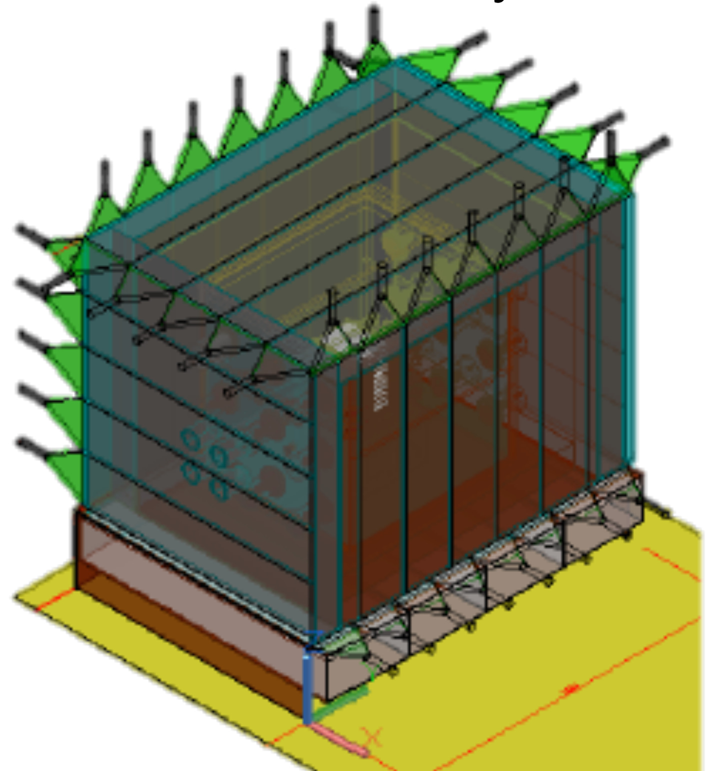
Strategy:

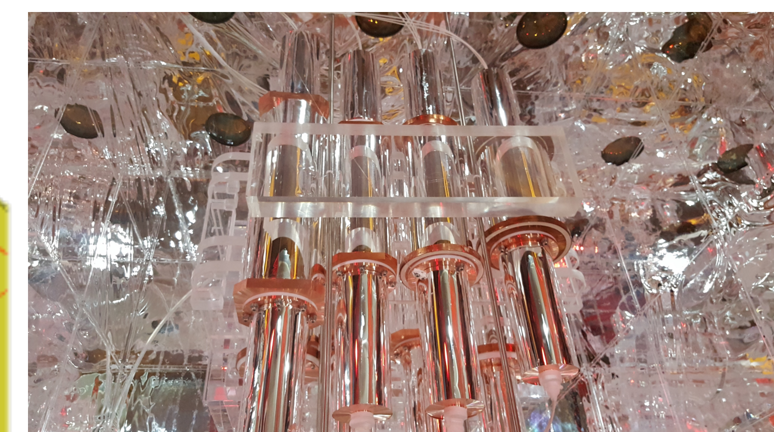
- lower background: better crystals, PMTs
- liquid scintillator veto against ^{40}K (factor 10)
- lower threshold (PMTs directly coupled to NaI)
- Eliminate seasonal effects :North (LNGS) and South Hemisphere(Australia: Stawell Underground Physics Laboratory)

- *Status*: 2 crystals ready, foreseen to start the run in Summer 2019.



Predecessors:
DM-Ice: 17 kg 2 Crystals of 8.5 kg NaI@ South Pole
KIMS: 12 CsI crystals for 104.4 kg @ Y2L, Korea





COSINE-100 (DM-Ice + KIMS) **@Yangyang**

arxiv:1602.05939

107 kg of NaI pure Crystal, LS veto and Pb shield - commissioning

ANAIS @ Canfranc
113 kg in Pb shield

→ start of data taking soon
→ background 2-3x DAMA (no veto)

Upcoming NaI Projects to directly test DAMA

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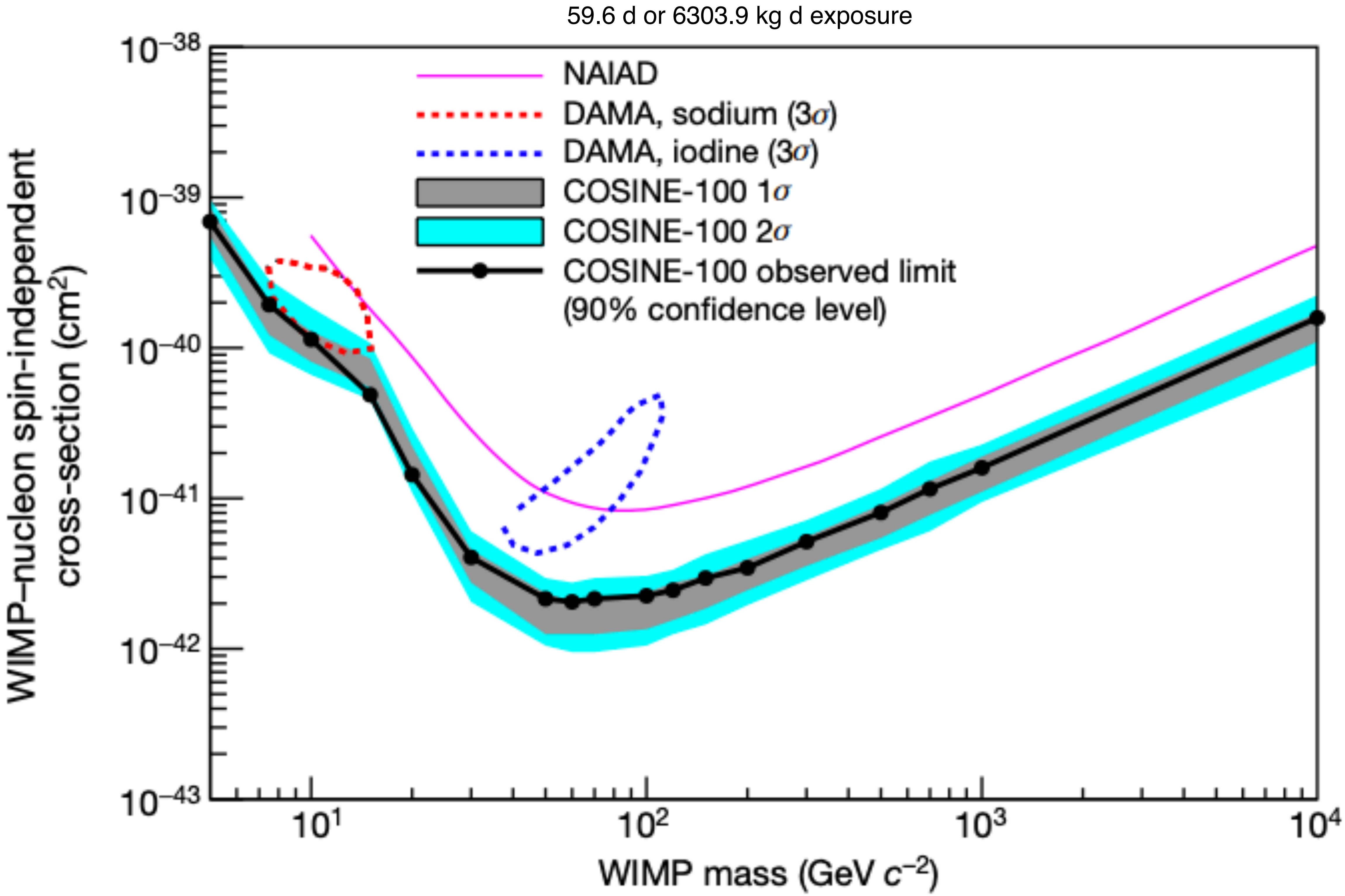
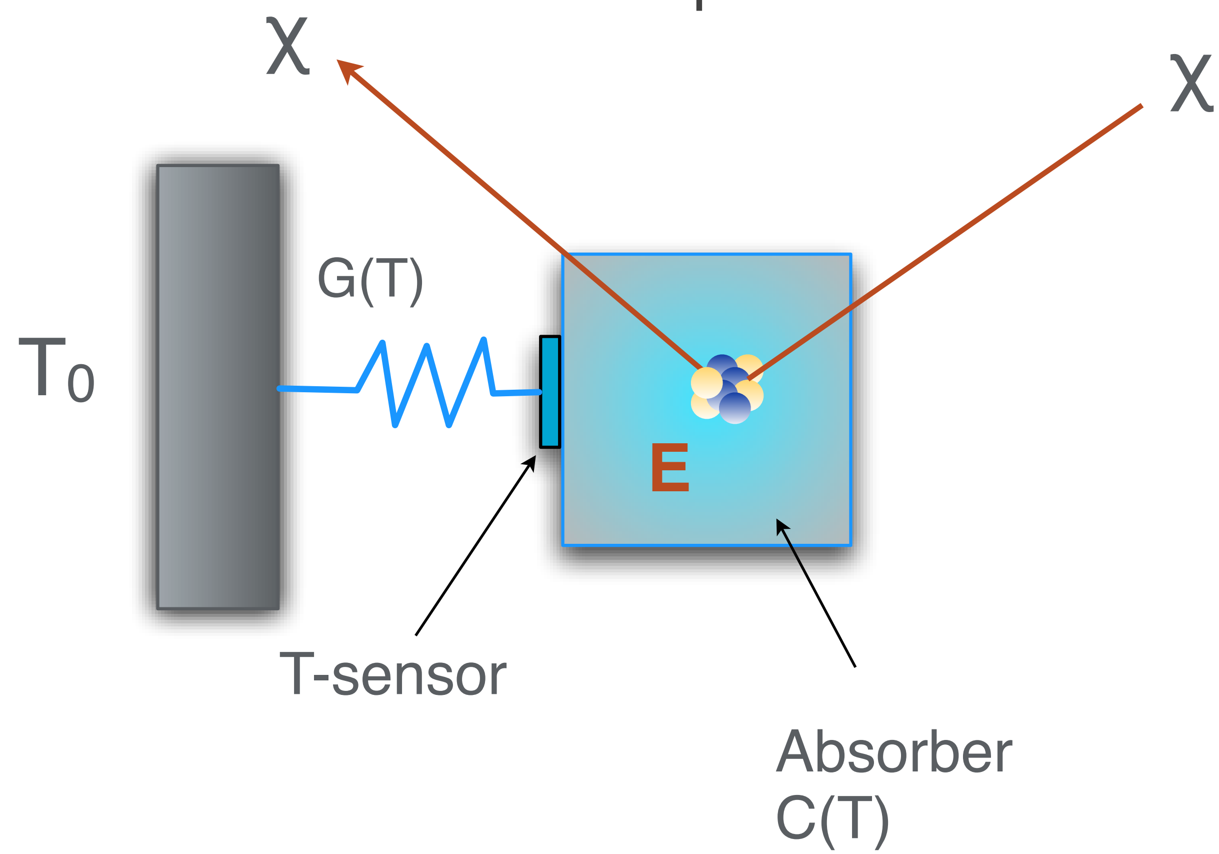


ble

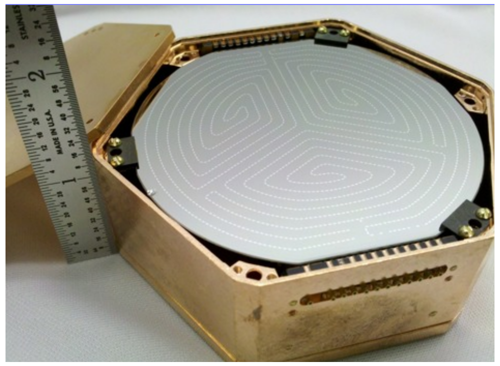
Cryogenic micro-calorimeter at T ~ mK

- Detect a temperature increase after a particle interacts in an absorber

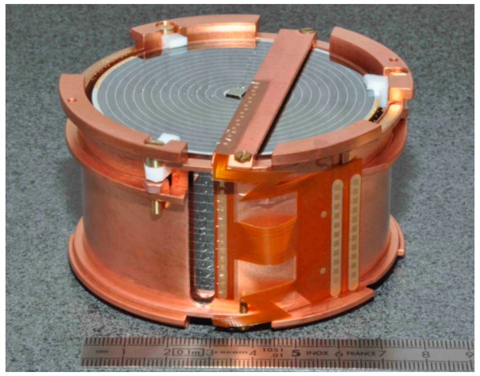


$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$

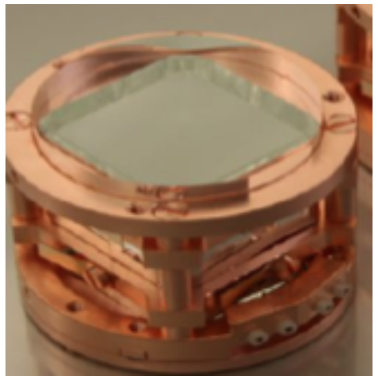
$$\tau = \frac{C(T)}{G(T)}$$



SuperCDMS: Ge, Si



EDELWEISS-III (Ge)



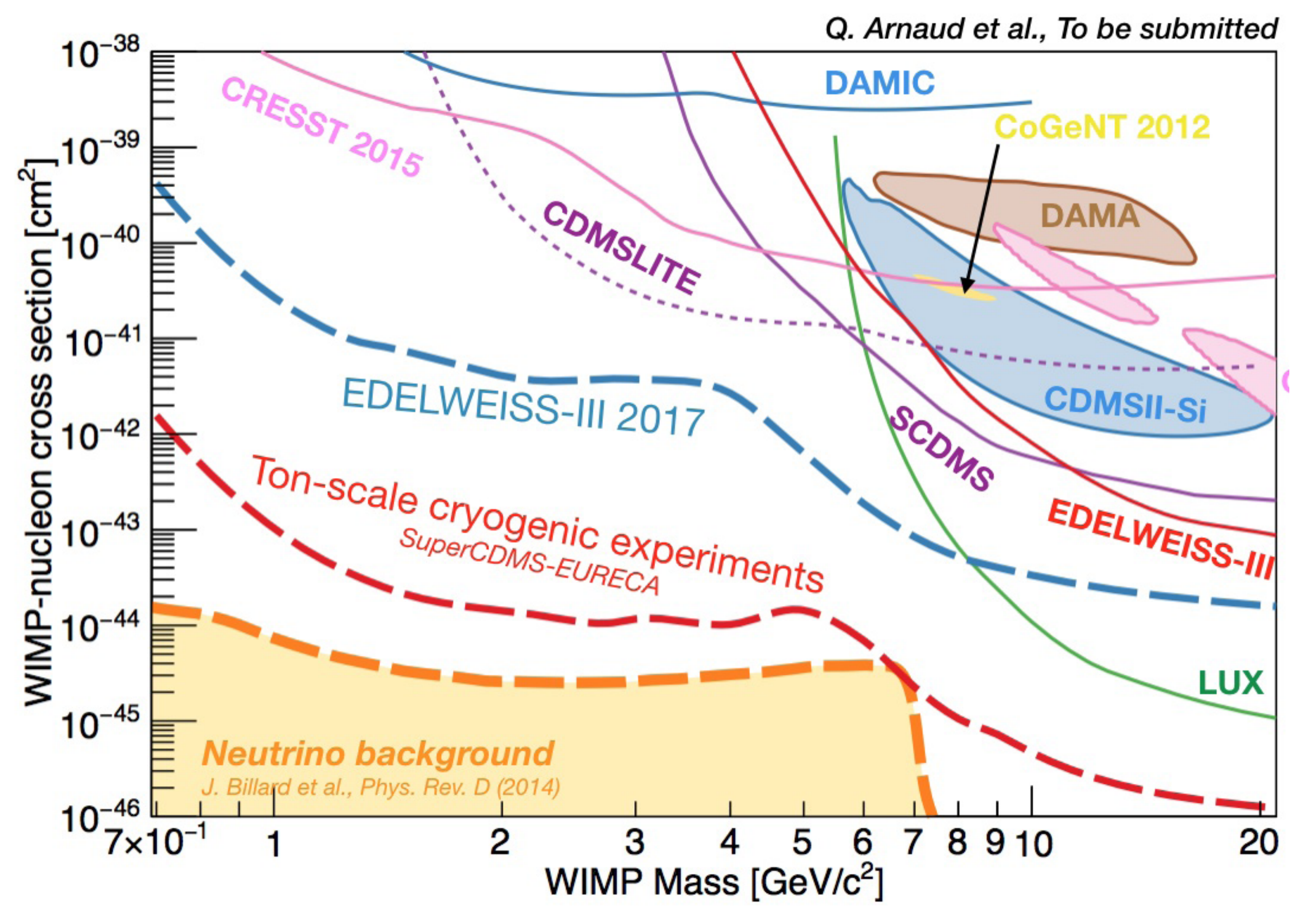
CRESST ($CaWO_4$)

EDELWEISS - SuperCDMS - CRESST: the race for the low WIMP mass region

SuperCDMS @ SNOLAB
read phonons and charges from Ge crystals
•aim for 50 kg-scale experiment (cryostat can accomodate 400 kg)
low threshold → focus on 1-10 GeV/c² mass range
• Improvements: deeper lab, better materials, better shield, improved resolution, upgraded electronics, active neutron veto?
• 100 x 33.3 mm ZIPs (1.4 kg Ge, 0.6 kg Si) → fabrication protocol established
2018-20: construction
2020: begin data taking

EDELWEISS @ LSM : arXiv:1603.05120
read phonons and charges from Ge crystals
2016: largest (20 kg) Ge array in operation
2017: 350 kg×d in HV mode to optimize 1-10 GeV sensitivity
Future: ton scale together with CDMS (EURECA)

CRESST II @ LNGS: *EPJ C, 76, 25 (2016)*
read phonons and scintillation light from $CaWO_4$
successful background reduction;
data taking 2013-2015, 52 kg×d
2016: lowest thresh 300 eVnr
Record sensitivity below 1.7 GeV WIMP mass



CRESST-III

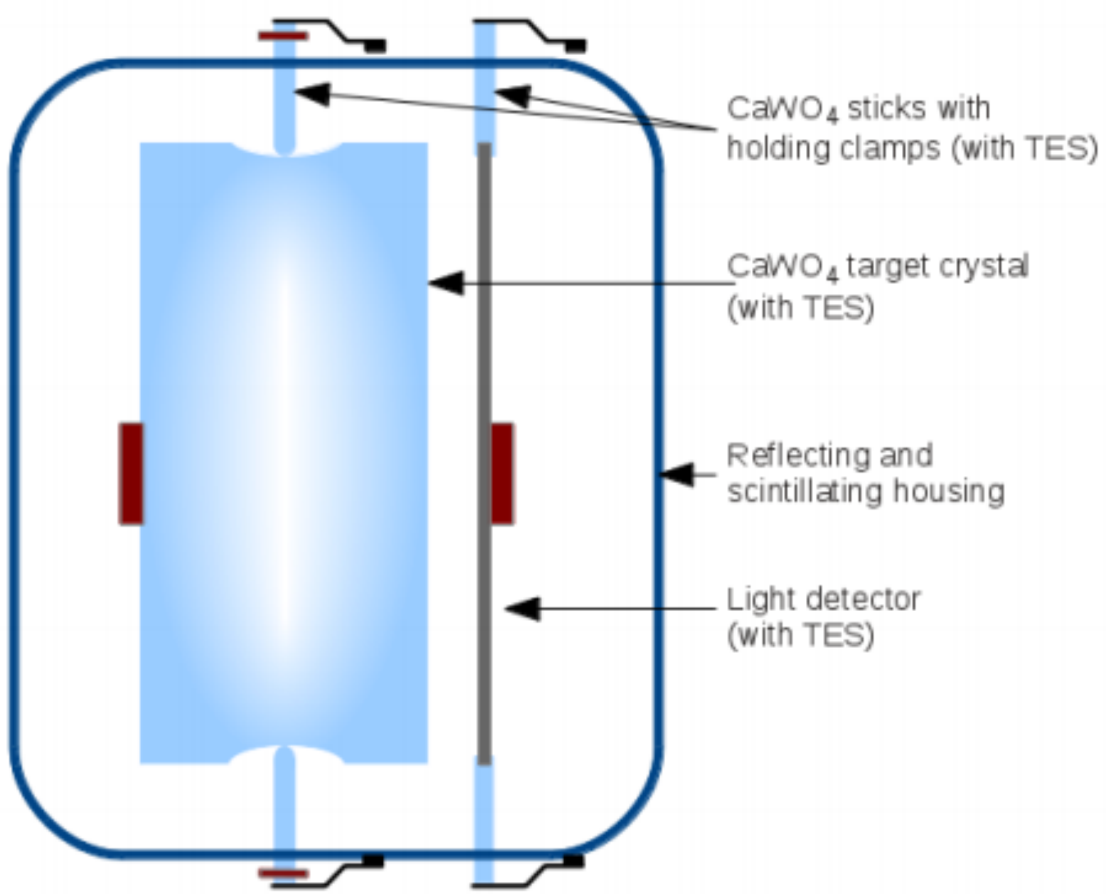
Goal: lower threshold to 100 eVnr

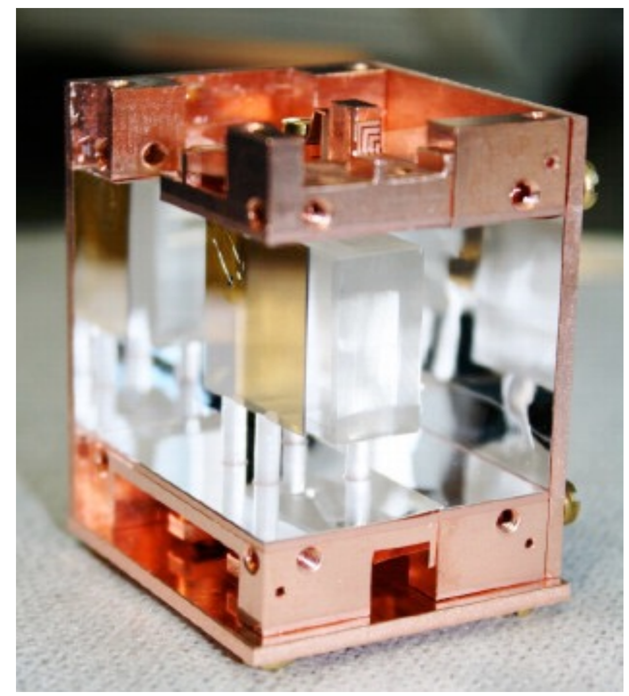
→ smaller crystals of best background quality (250 g → 24 g)

→ all-scintillating detector design

all material surrounding the detectors is scintillating → avoid partial energy depositions

→ improve signal-to-noise





Reindl @ Lake Louise 2016

Status

- Prototype exceeded design goal: 50 eVnr threshold
- first 4 modules were mounted in February 2016

CRESST-III

Phase 1

- 50 kg-days 1year of running with 10 small modules

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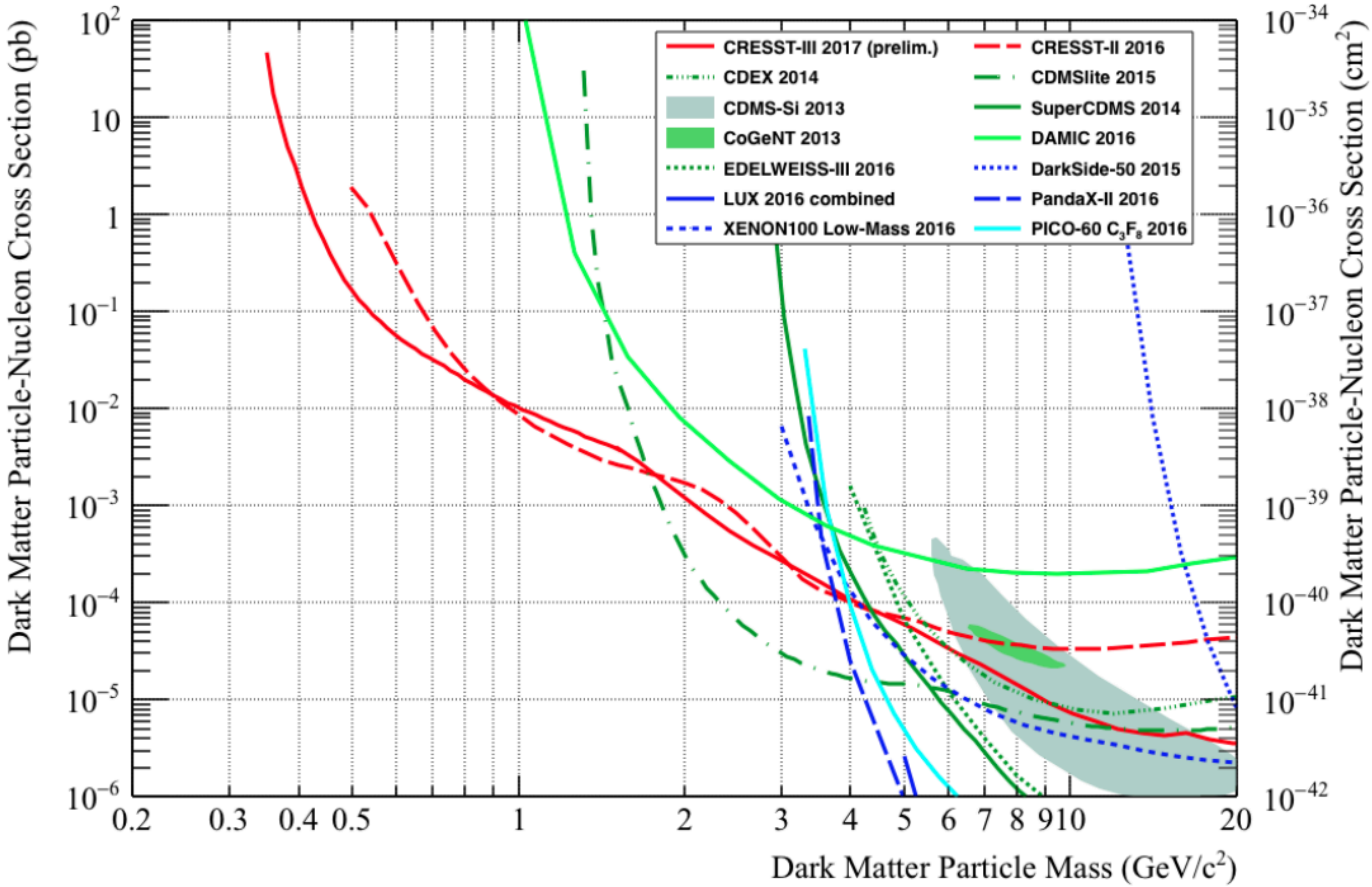

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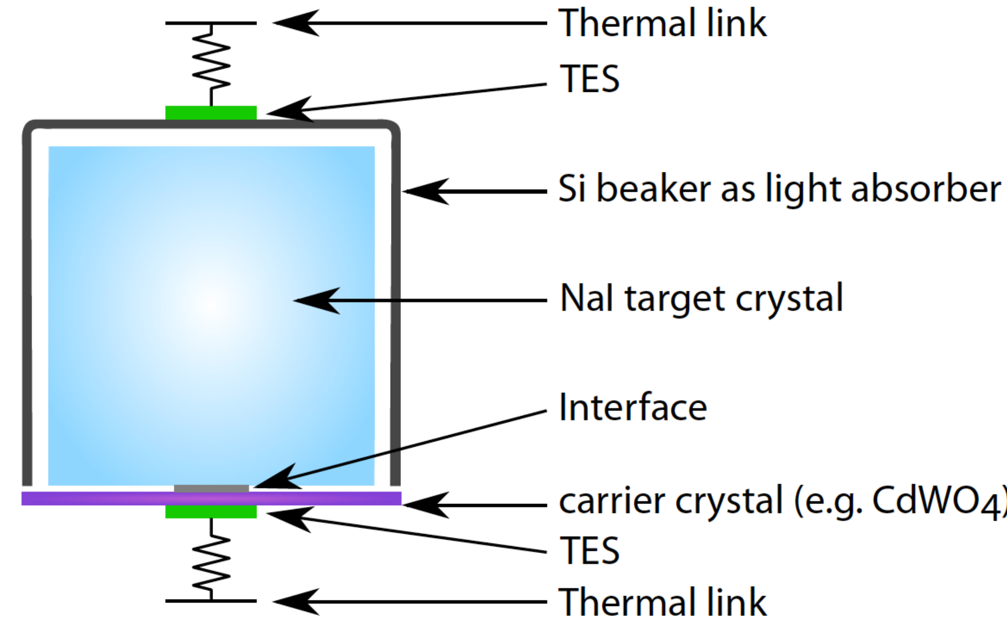
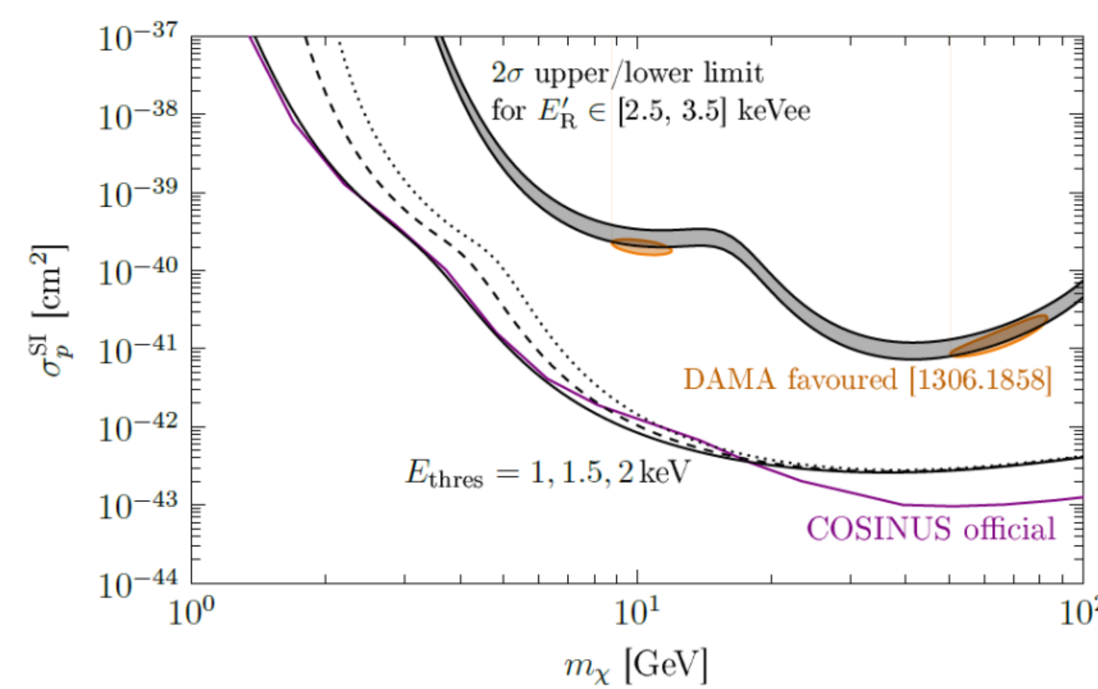
COSINUS a Promising R&D project: Cryogenic NaI detectors at T ~ mK

Recently granted by
Max-Planck Research Group (MPRG) grant:
duration 5 years, starting 2019

COSINUS (arXiv:1603.02214)

Strategy:
- first NaI detector with particle discrimination
- precise measurement of deposited energy
- design goal: 1 keV threshold on NR
- light channel (quenching) strongly particle type dependent-
- Status: started in 2016 at LNGS; first NaI prototype detector (66g) assembled and cooled down in the CRESST test facility
- reaching performance of existing scintillating bolometers (CRESST)

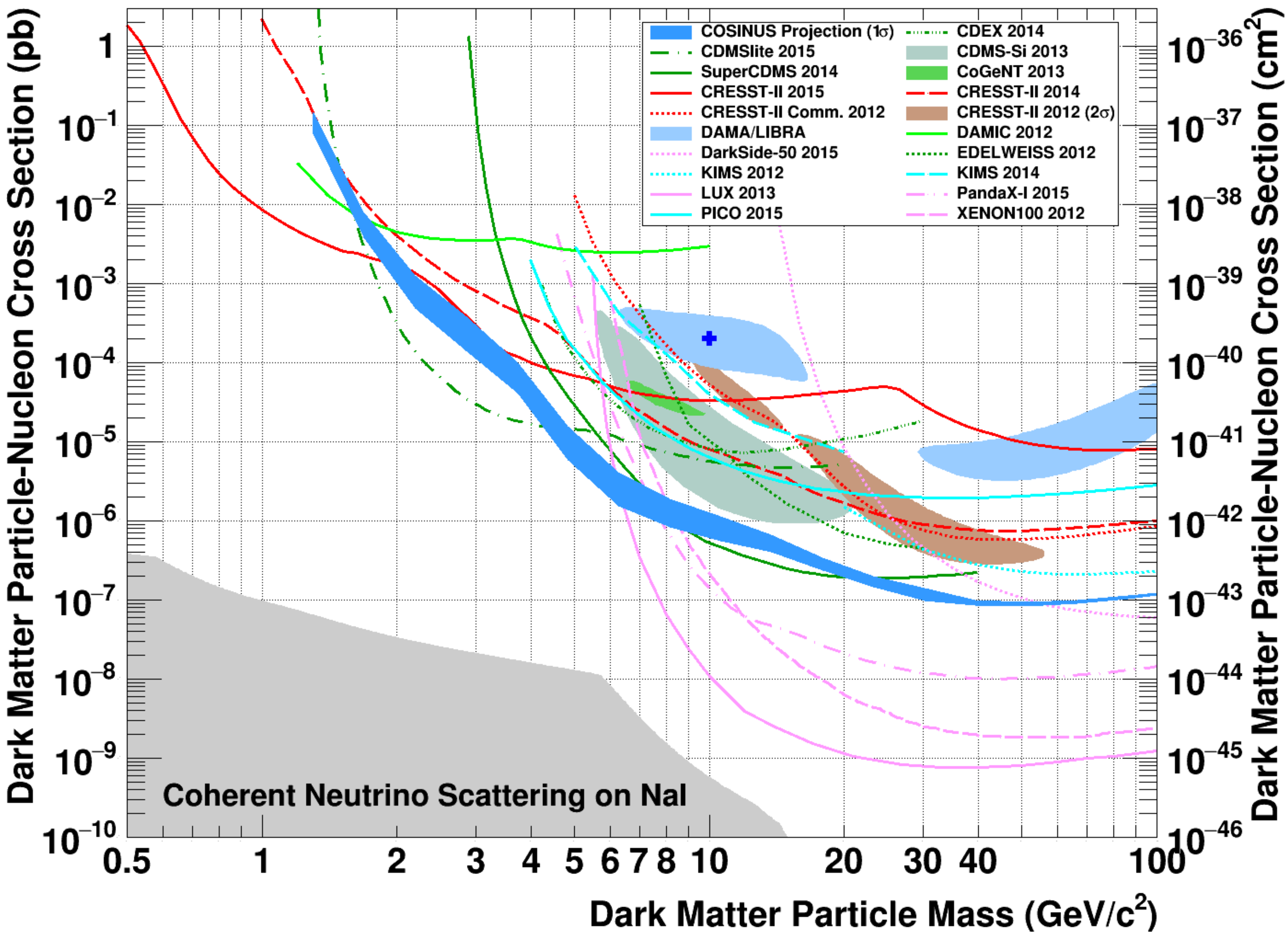




COSINUS should be able to exclude or confirm DAMA signla by about two orders of magnitude in cross section with an exposure of 100 kg days

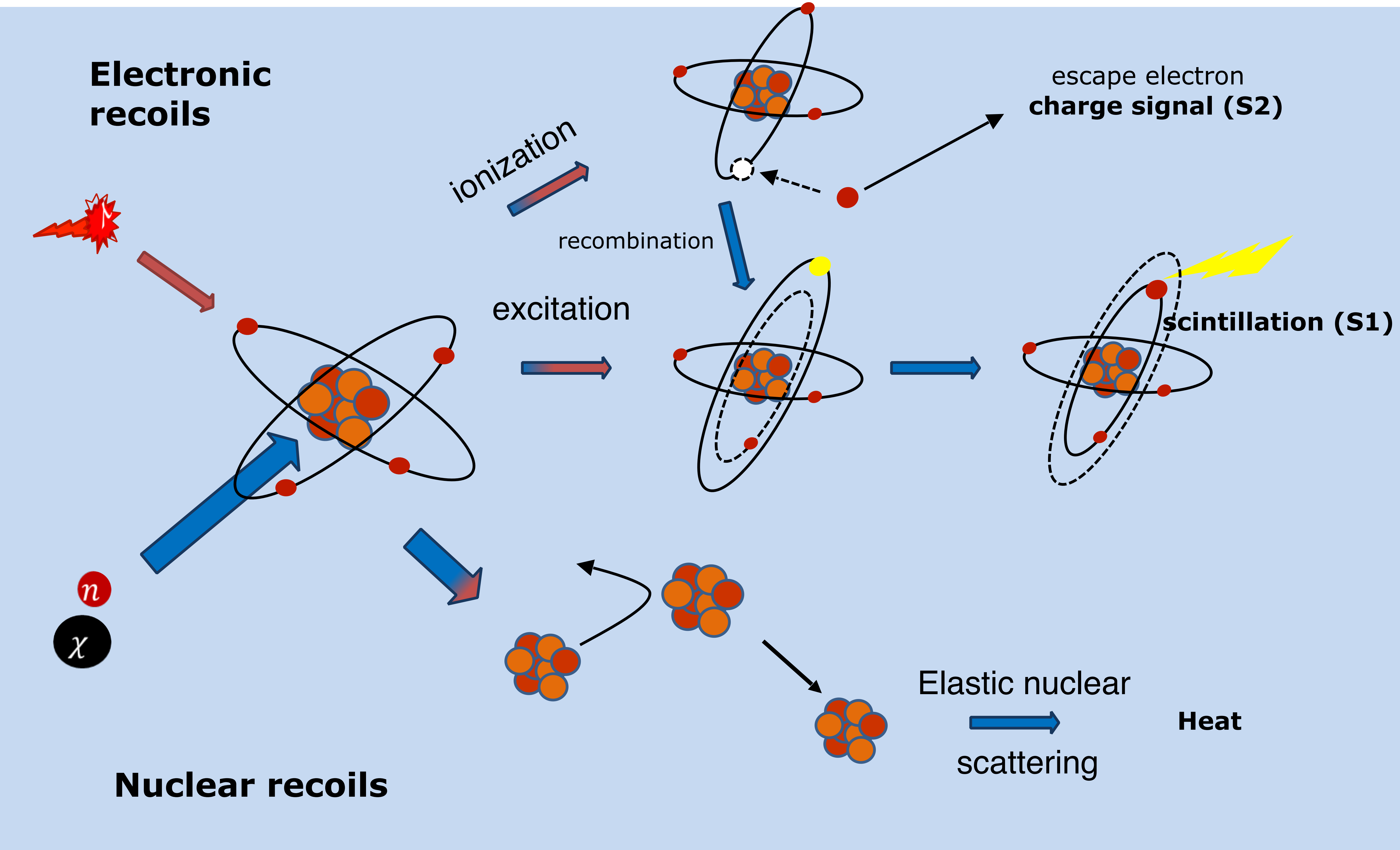
Let’s have a look in the High Mass WIMP sensitivity region

In The High Mass Region: noble liquid experiments continue to lead the race



Noble Liquid Detectors

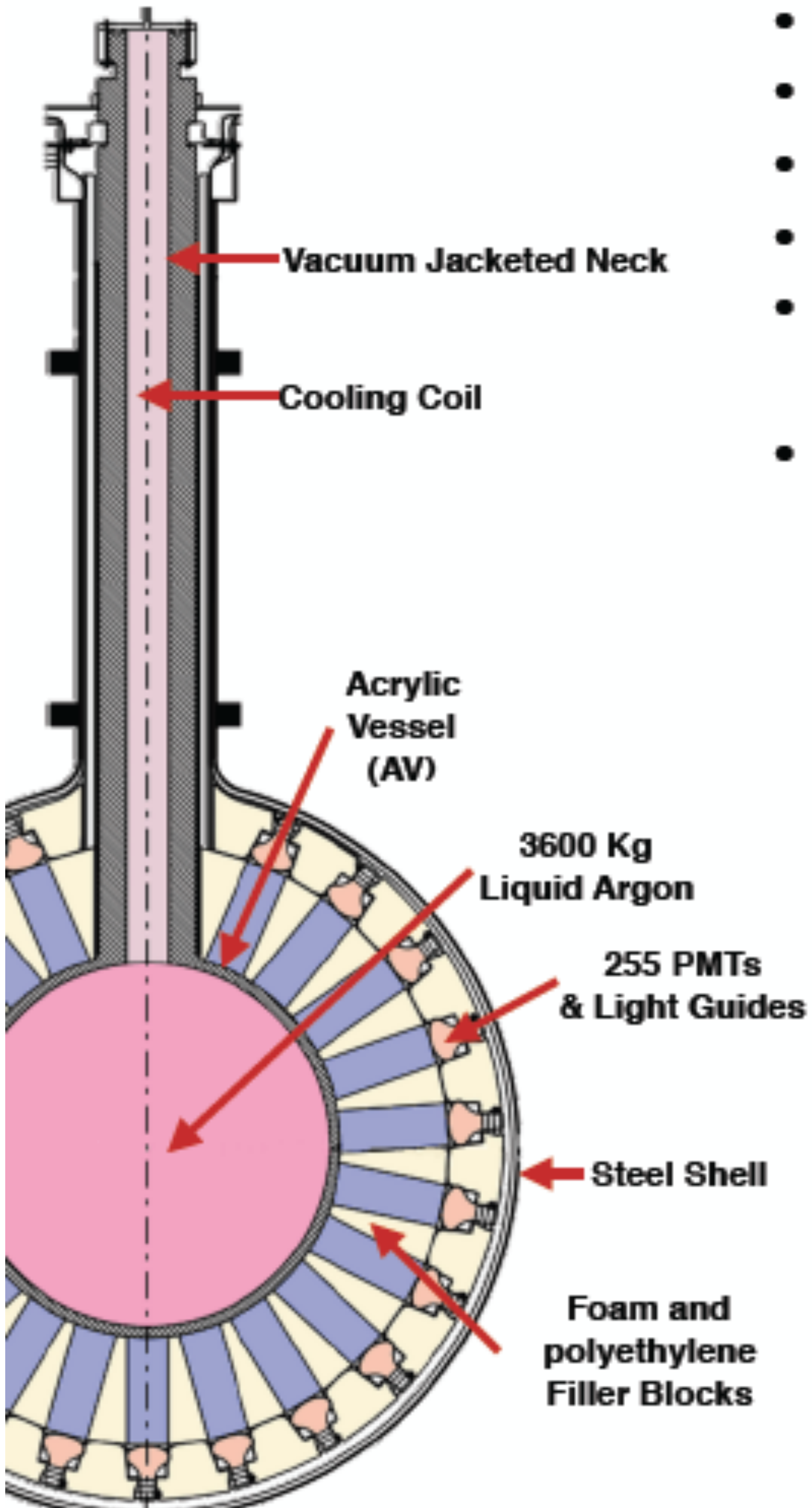
- Detect either on ly light or light and charge signals simulataniously produced by a particle interaction in the sensitive liquid target



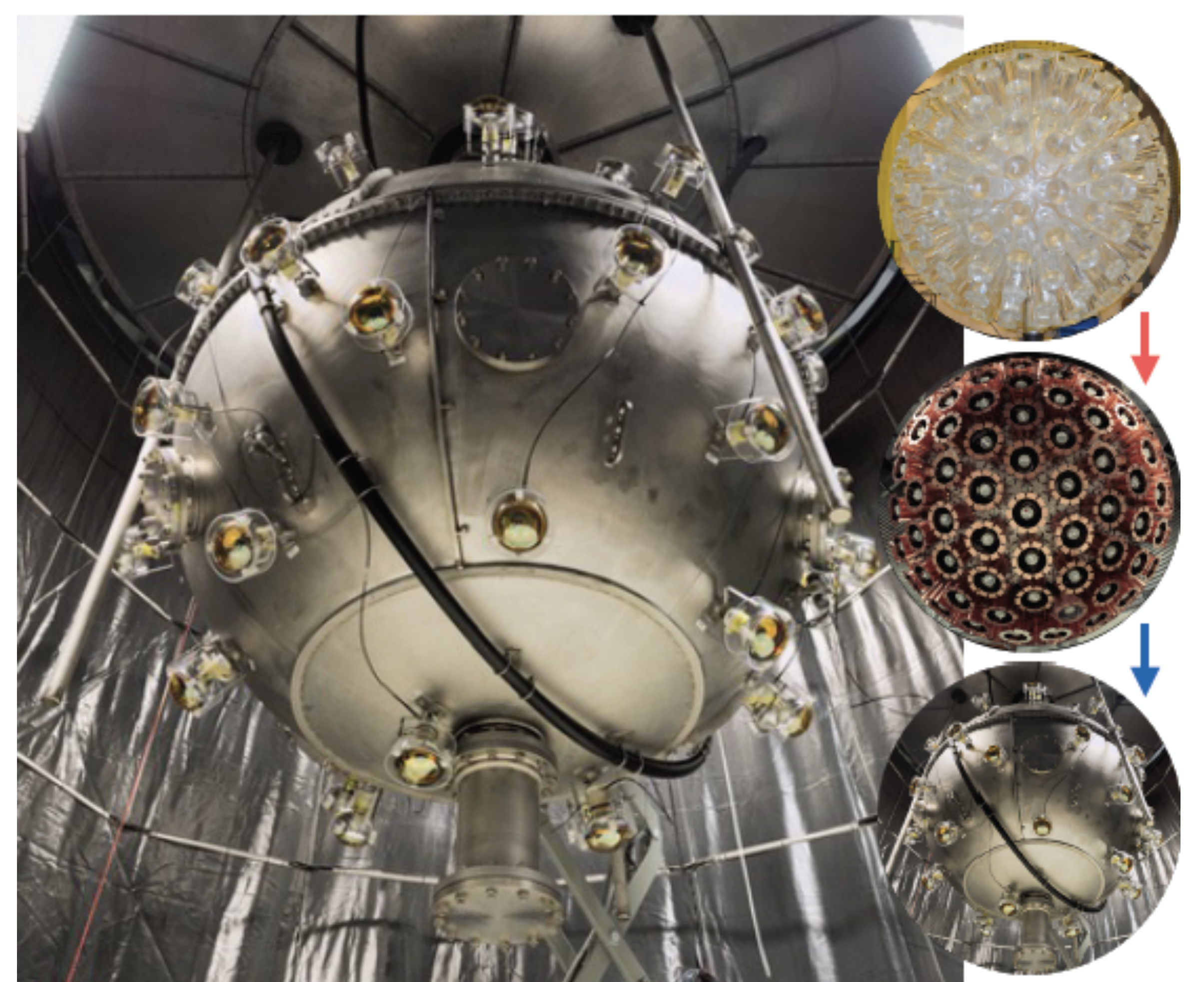
Review of detection principles IV

A	eleme nt	Long lived Isotopes	S2/S1 seprati on	pulse-shape separtion	Energy transfer	Use in Double phase	Light yield	optimal Field of application
4	He	none	-	E-G	best	—	—	CNS/LightDM
20	Ne	none	-	V-G	-	—	—	CNS/LightDM
40	Ar	^{39}Ar (can be removed)	G	V-G	-	prooved	G	CNS/DM/ calorimetry
83	Kr	many	-	-	-	—		calorimetry
131	Xe	none	G	Poor perfomance	worst	prooved	V-G	CNS/DM(SI/ SD)/Calorimetry bb

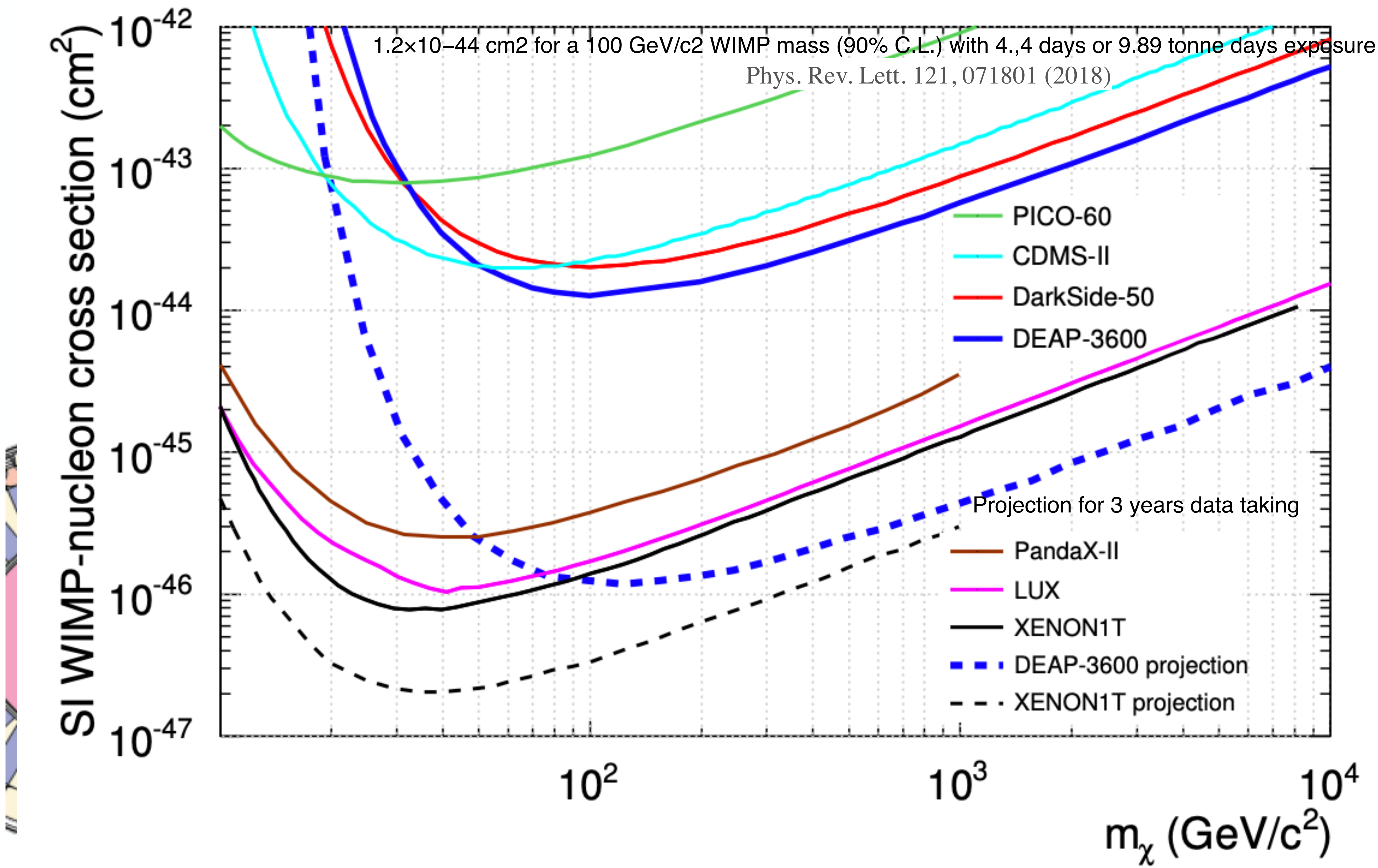
Single Phase Liquefied Noble detector expriement
DEAP @ SNOLAB : DEAP-3600 - Ready for Physics Run!



- Single phase LAr, 3.6 tonne (1 tonne fiducial).
- Spherical ultra-pure acrylic vessel (AV).
- 255 HQ Hamamatsu PMTs, coupled via acrylic light guides.
- Foam and polyethylene provide further shielding.
- 3 um layer of wavelength shifter (TPB) converts 128 nm scintillation light into the visible range.
- AV enclosed inside Steel Shell, immersed in 403 m^3 water tank with 45 veto PMTs



Single Phase Liquefied Noble detector expriement
DEAP @ SNOLAB : DEAP-3600 - Ready for Physics Run!



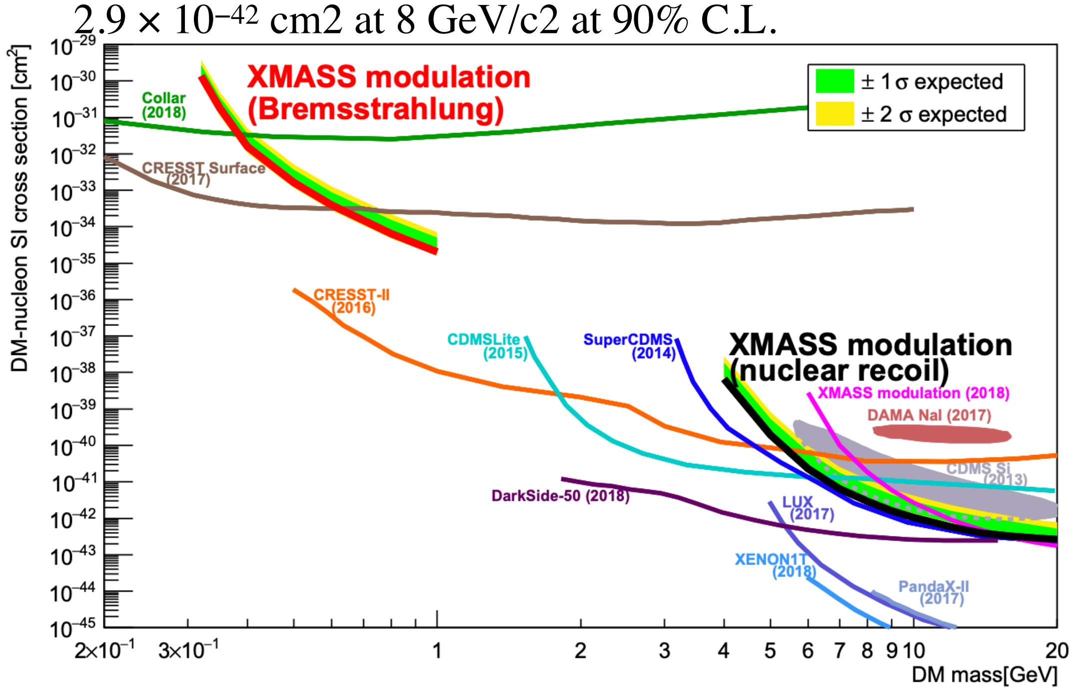
XMASS @ Kamioka : present and future

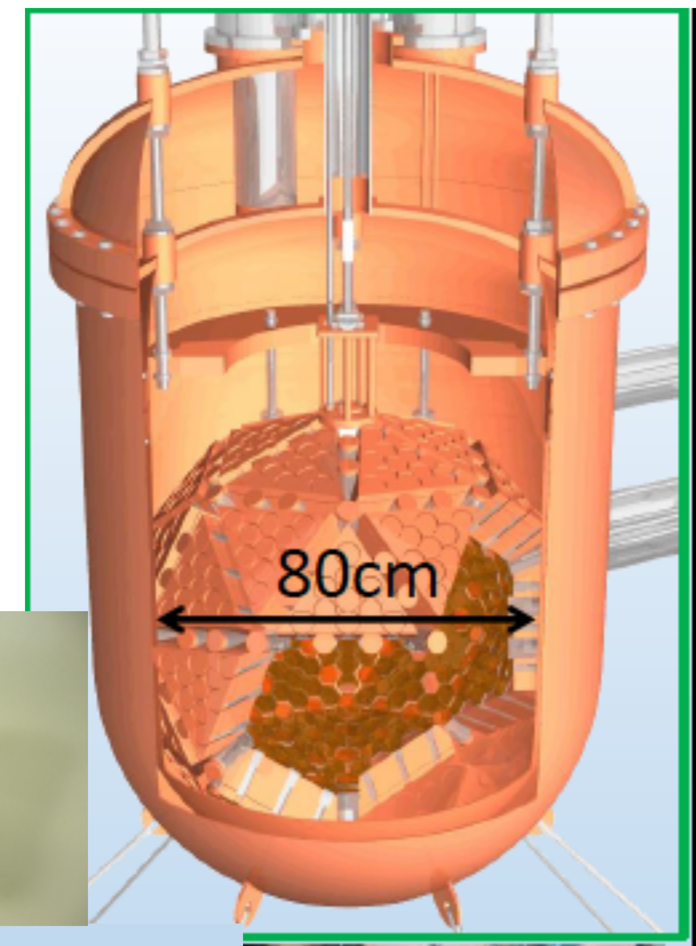
- XMASS -1: spherical Cu vessel with 830 kg LXe viewed by 642 PMTs (photocathode coverage >62%)
- 14 PE/keV but no possibility to reject NRs; position reconstruction/ self-shielding /water Cherenkov muon veto
- Many results, including modulation study:

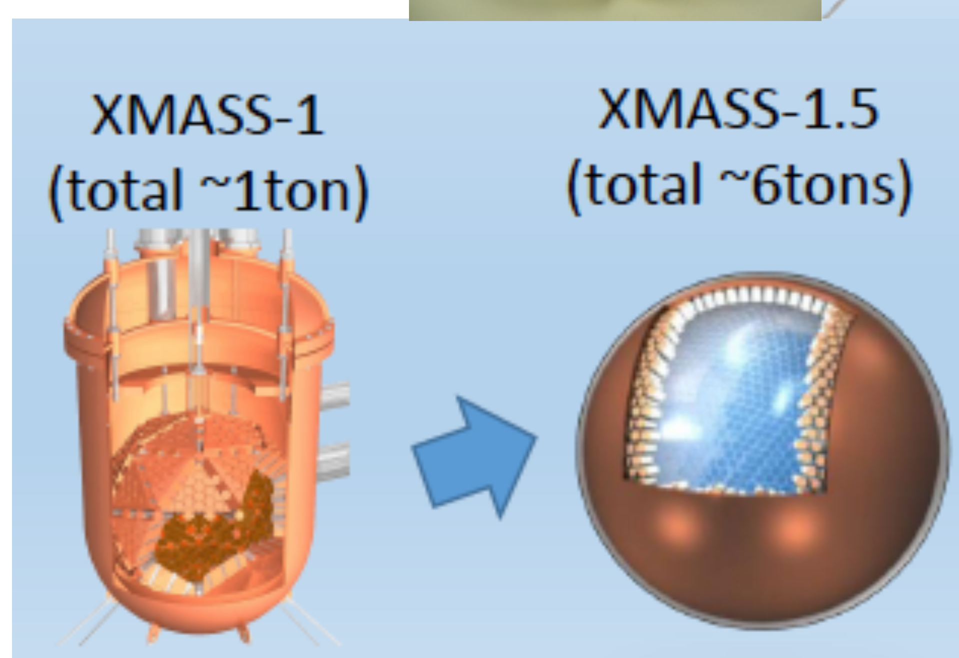
  PHYSICAL REVIEW D 97, 102006 (2018),
- *Still taking data - R&D on PSD - new dome-shaped PMT development for XMASS 1.5 (1000 PMTs)*
- *Sensitivity Goal:* ~ 10^{-47} cm^2 @ 50 GeV in 3-5 y

1.6×10^{-33} cm2 at 0.5 GeV/c2 at 90% C.L.

2.9×10^{-42} cm2 at 8 GeV/c2 at 90% C.L.

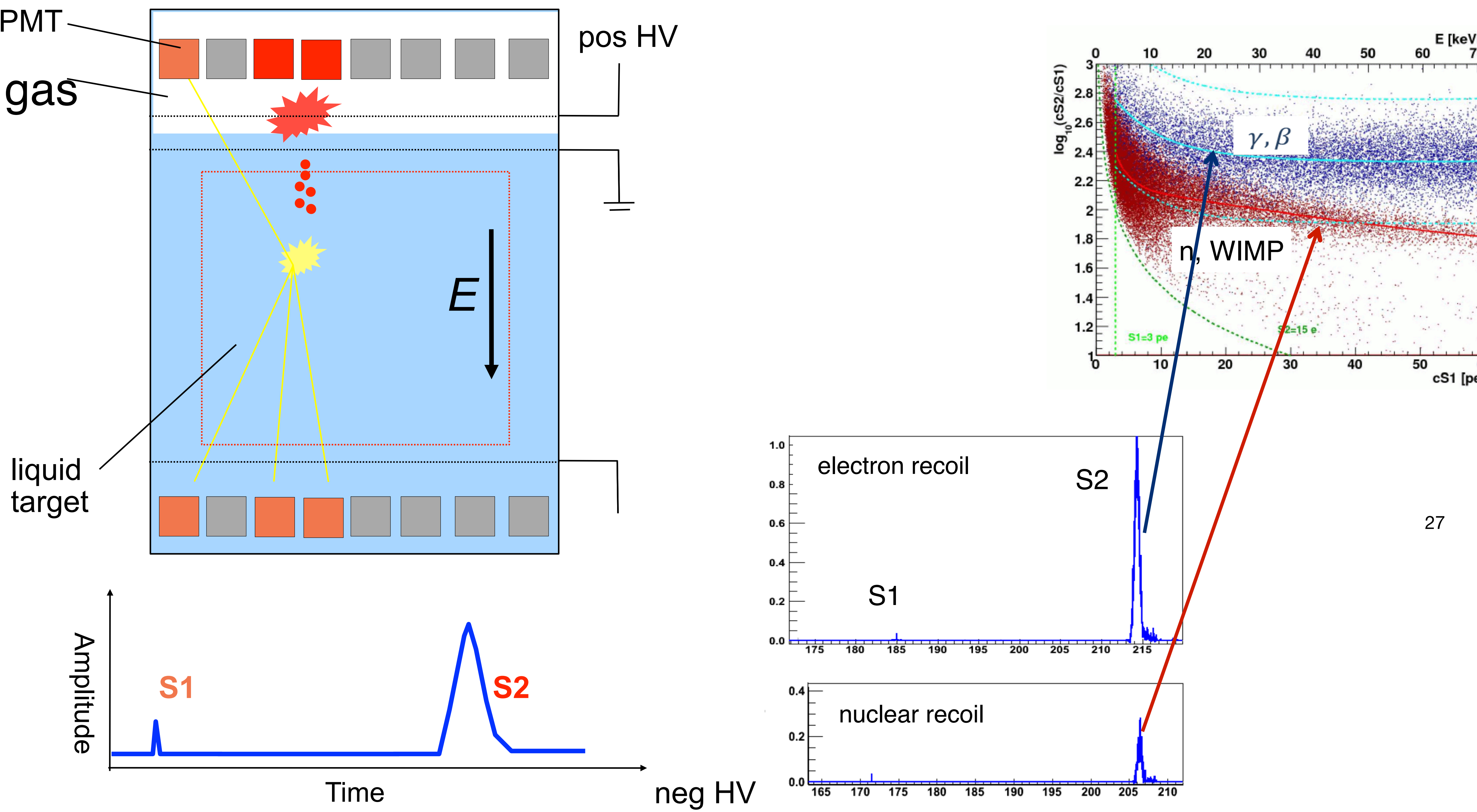






Noble Liquid Detector Concepts

Time Projection Chamber (TPC)
a doppia fase



Dual Phase TPC Experiments: present and future

LXeTPCs: 50- 500 kg scale

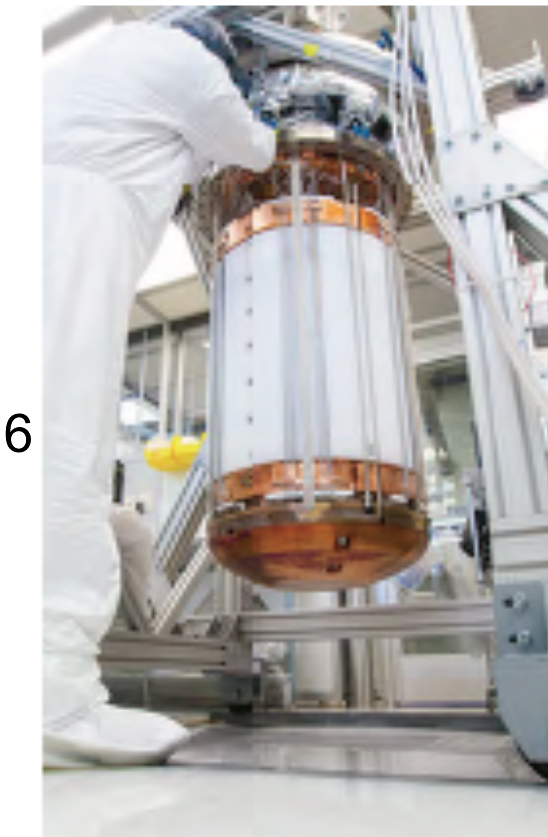
XENON100 @ LNGS
Astropart. Phys. 35, 573 (2012)

- **62 kg** LXe,

- reached WIMP science goal
- inelastic DM, spin-dependent, modulation, axions, light WIMP, Bosonic Super WIMPs, ..
- still running as test facility for XENON1T/nT

LUX @ SURF
NIM A 704, 111 (2013)

- latest result from 332 days presented at IDM2016
- **250 kg** LXe
- published first limit in 2013
- in 2013 - best world limit
- reanalysis published in 2016
- will be removed by 2017

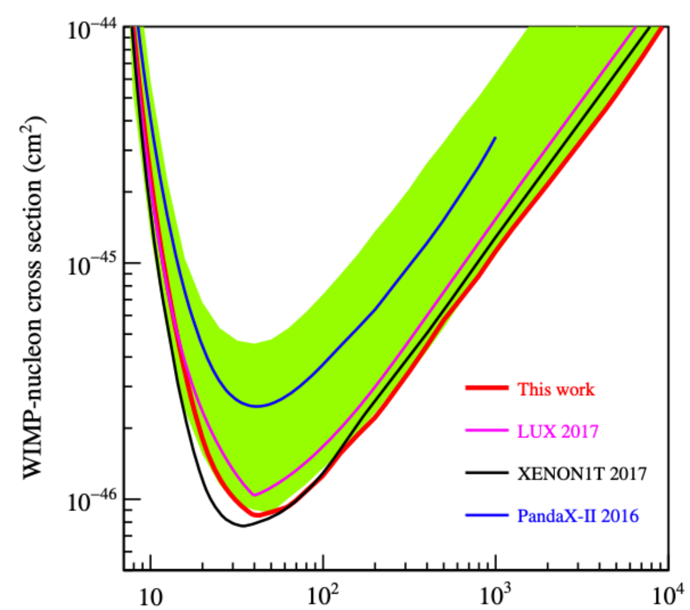


PandaX-II @ CJPL
arXiv:1602.06563

- at present largest LXe TPC
- still taking data
  - new SS cryostat
    → lower radioactivity
  - TPC: 60cm×60cm, **400 kg** target

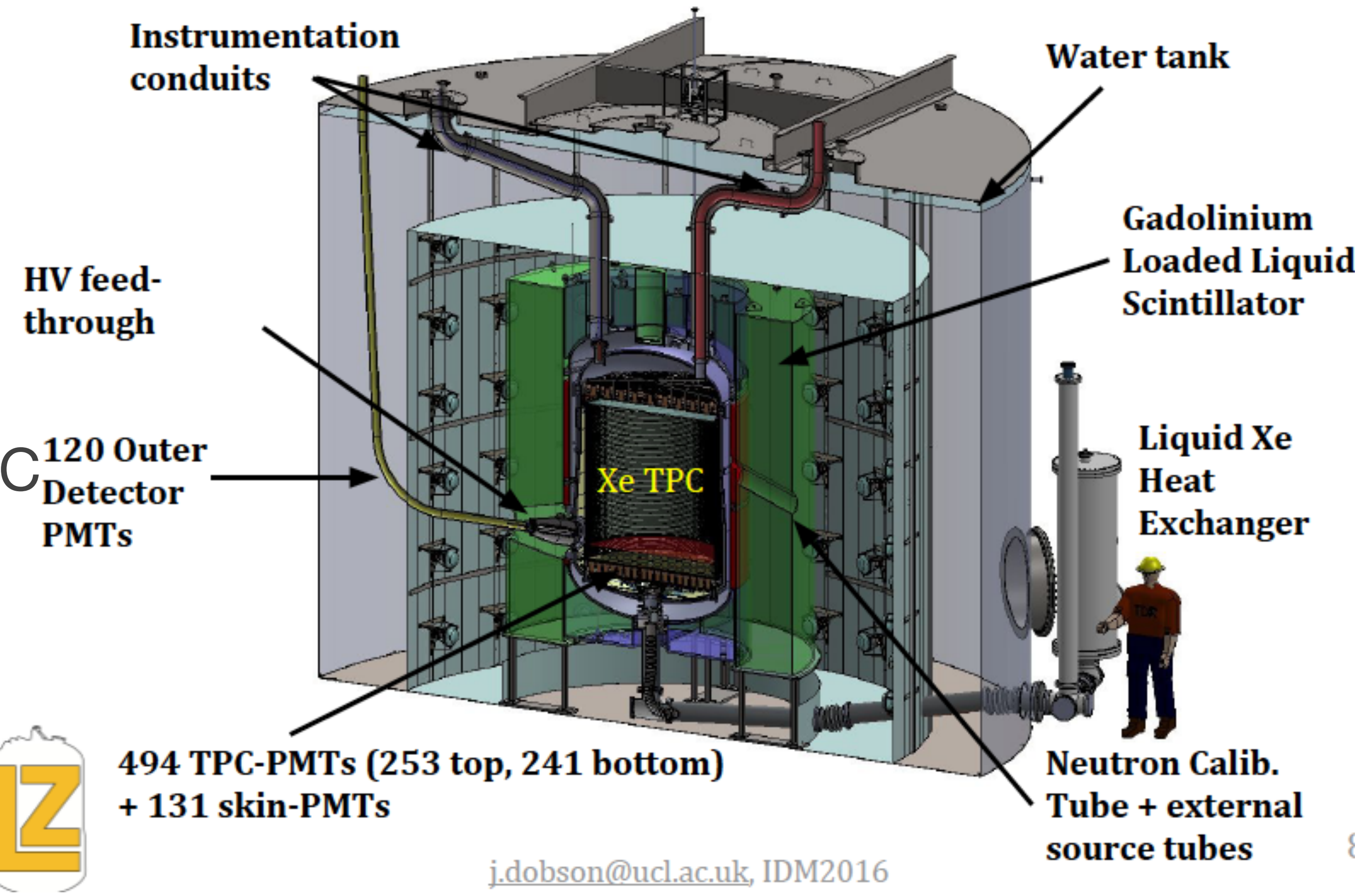
New result from 98.7 days:
- *Best upper limit :*
- *2.5 x 10^{-46} cm^2 at 40 GeV*

arXiv:1607.07400v1



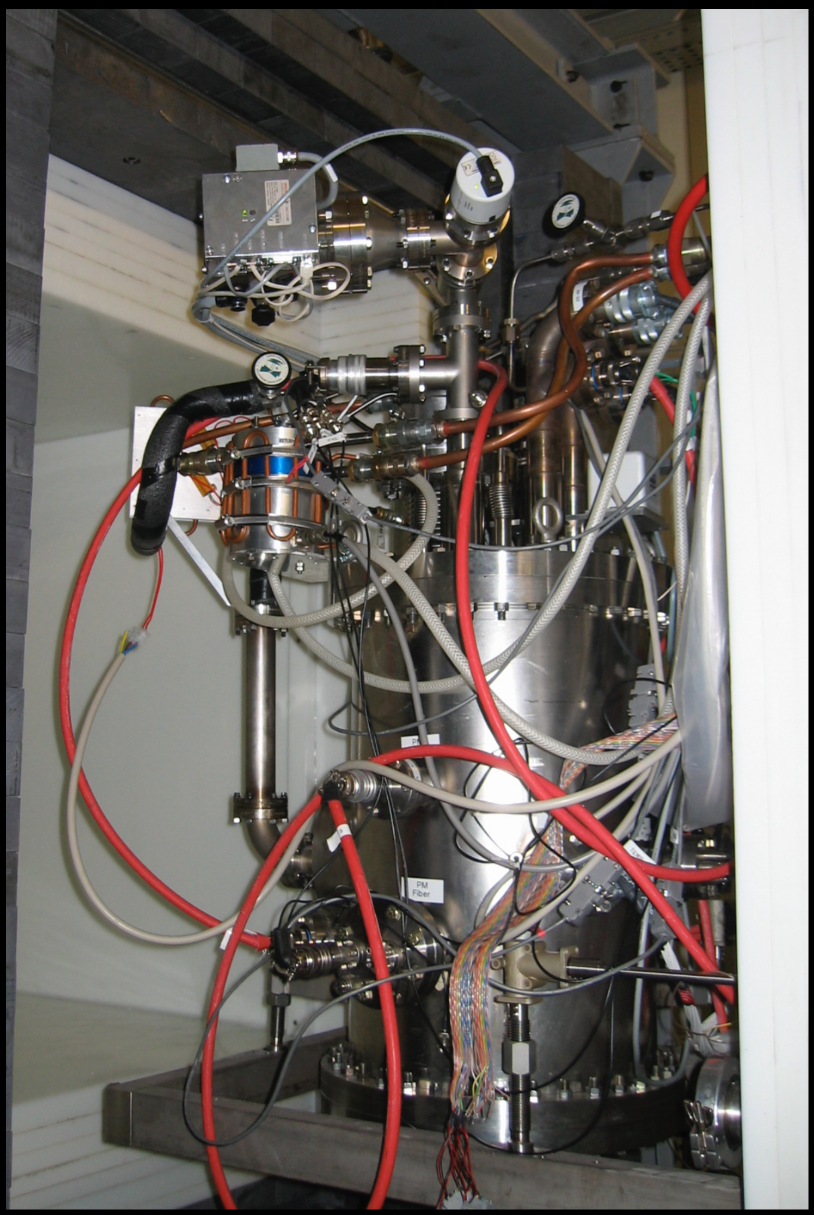
From LUX to LZ @ SURF

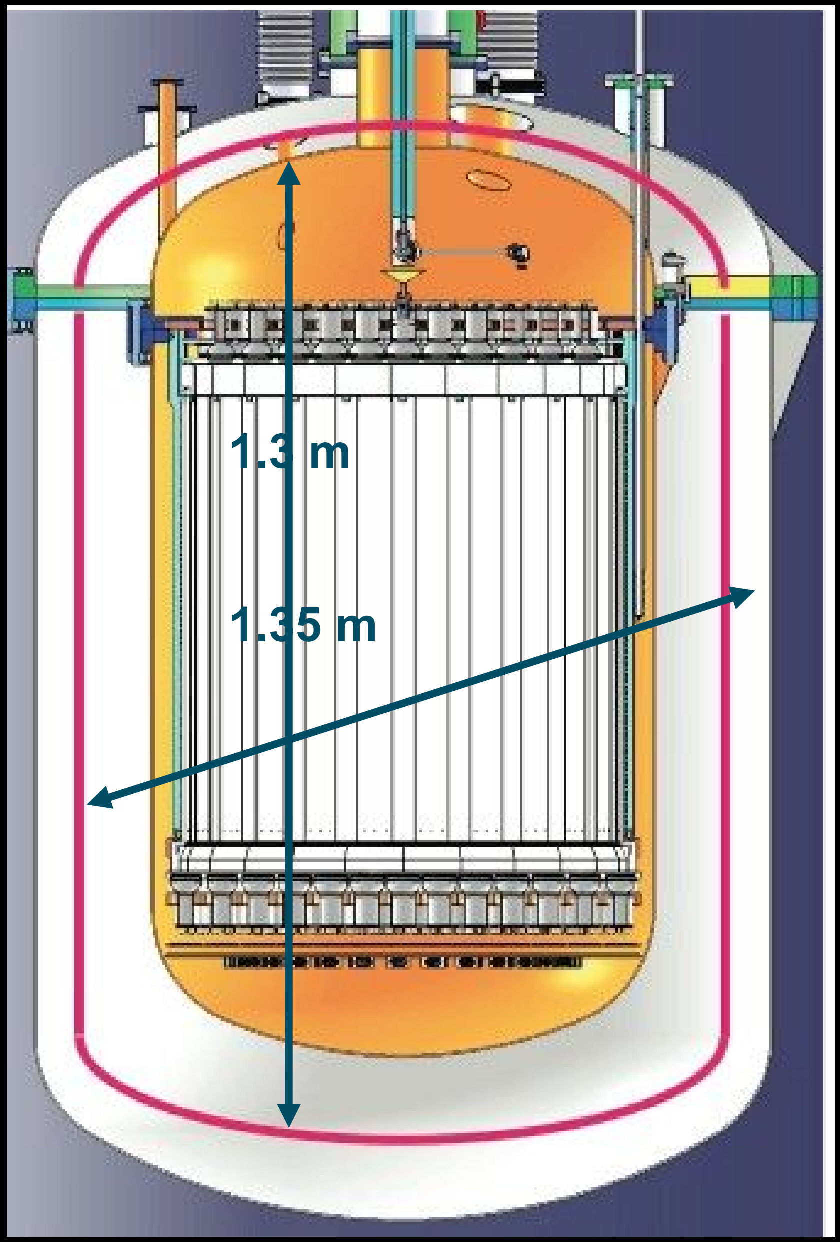
- Scale LUX by 40 in Fiducial
- New detector with 7 ton active LXe
- Aimed at 5.6 ton FV with combination of active LXe and LS veto
- Use same water shield of LUX
- Extensive screening campaign and MC simulations
- **Timeline**:
- 2017/18: prepare for surface / UG assembly at SURF
- 2019: start UG installation
- 2020: start operation by end of the year
- 2025+ : plan 5+ years of operation
- **Sensitivity Goal (1000 live days)**:
    - *3 x 10^{-48} cm^2 at 40 GeV*



XENON @ LNGS - present and future

2005-2007	2007-2015	2012-2022





XENON10
15 cm drift TPC - 25 kg
~10^{-43} cm^2

XENON100
30 cm drift TPC - 161 kg
~10^{-45} cm^2

XENON1T/XENONnT
100 cm drift TPC - 3500 kg/7000 kg
~10^{-47} cm^2 / 10^{-48} cm^2

The XENON1T Experiment

The XENON1T Experiment

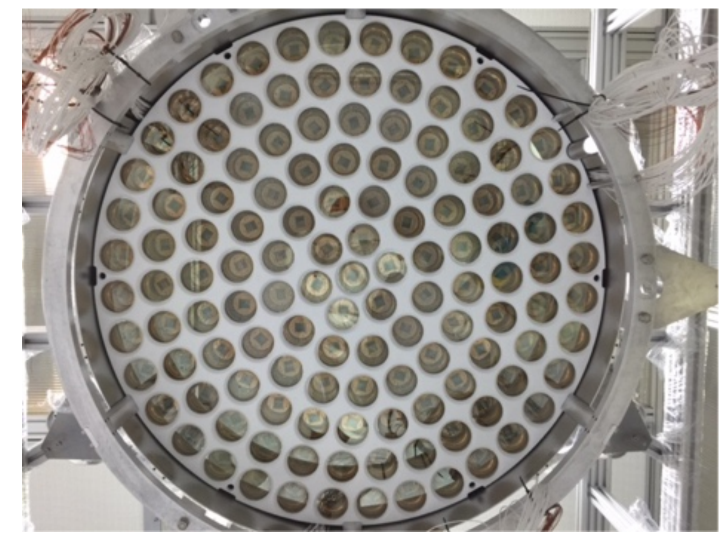
The XENON1T Experiment

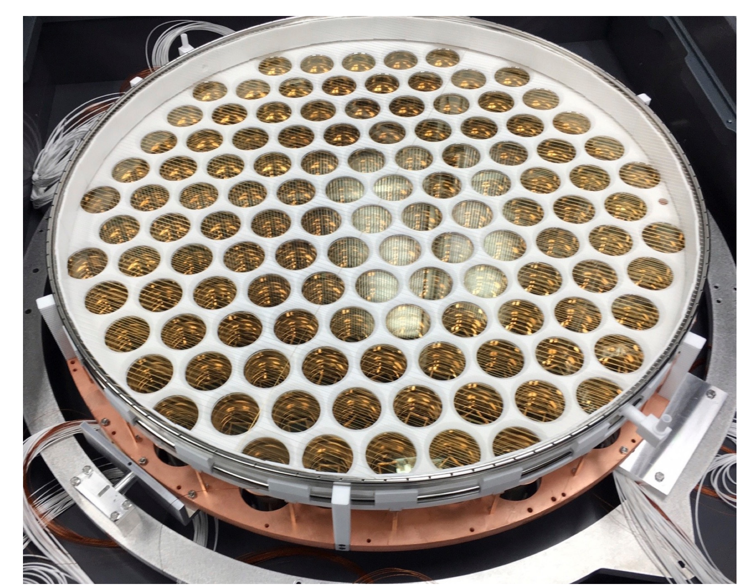
- Science goal: 100 x more sensitive than XENON100
- Target/Detector: 3.5 ton of Xe/ dual-phase TPC with 250 high QE - low radioactivity PMTs.
- Shielding: water Cherenkov muon veto.
- Cryogenic Plants: Xe cooling/purification/distillation/storage systems designed to handle up to 10 ton of Xe. Upgrade to a larger detector (XENONnT) planned for fall 2019
- Status: data taking stopped in December 2018.
- Exclusion limit: 4.1 x 10^{-47} cm^2 @ 30 GeV in 1 ty

The XENON1T experiment: inner detector

The TPC

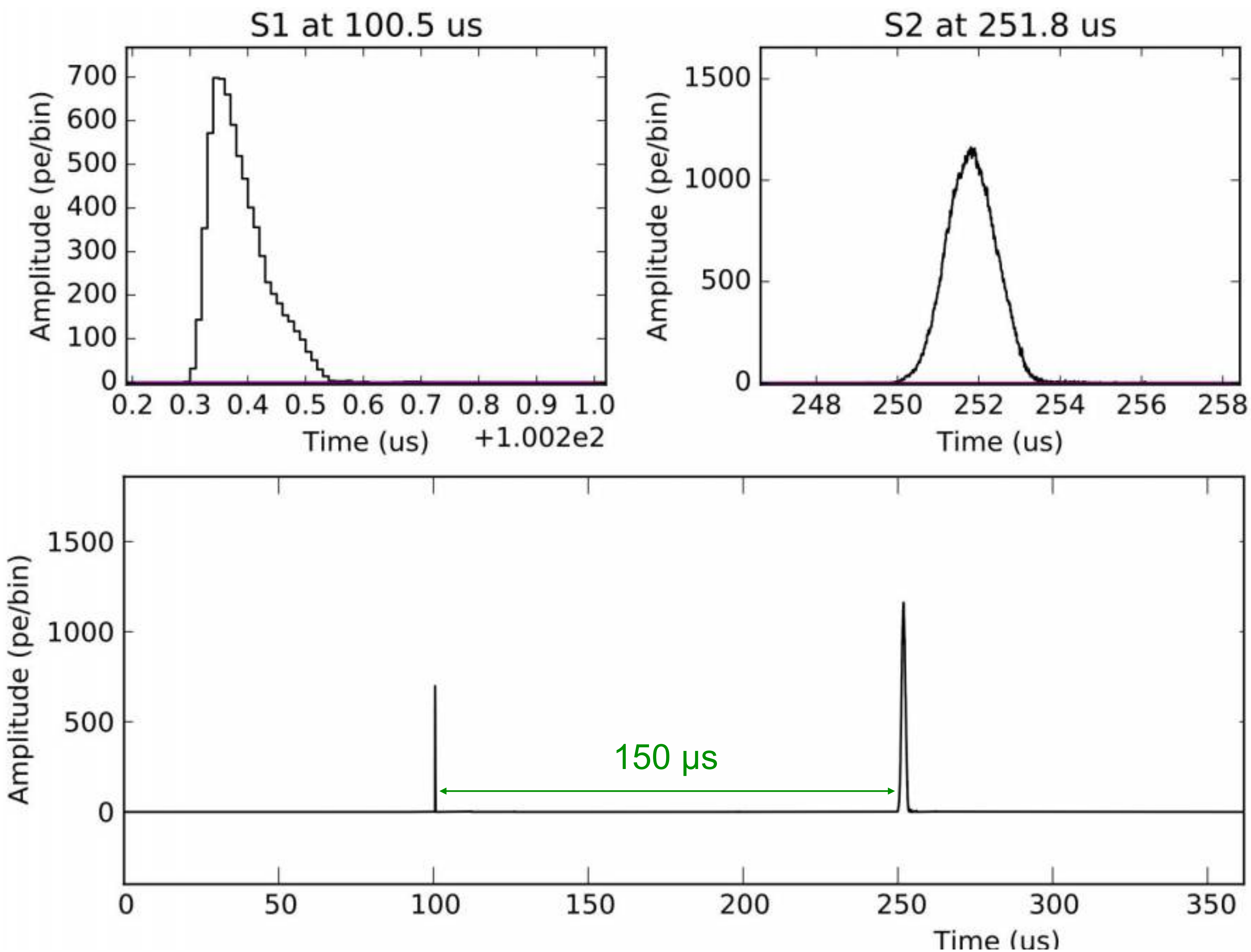
TPC installation underground



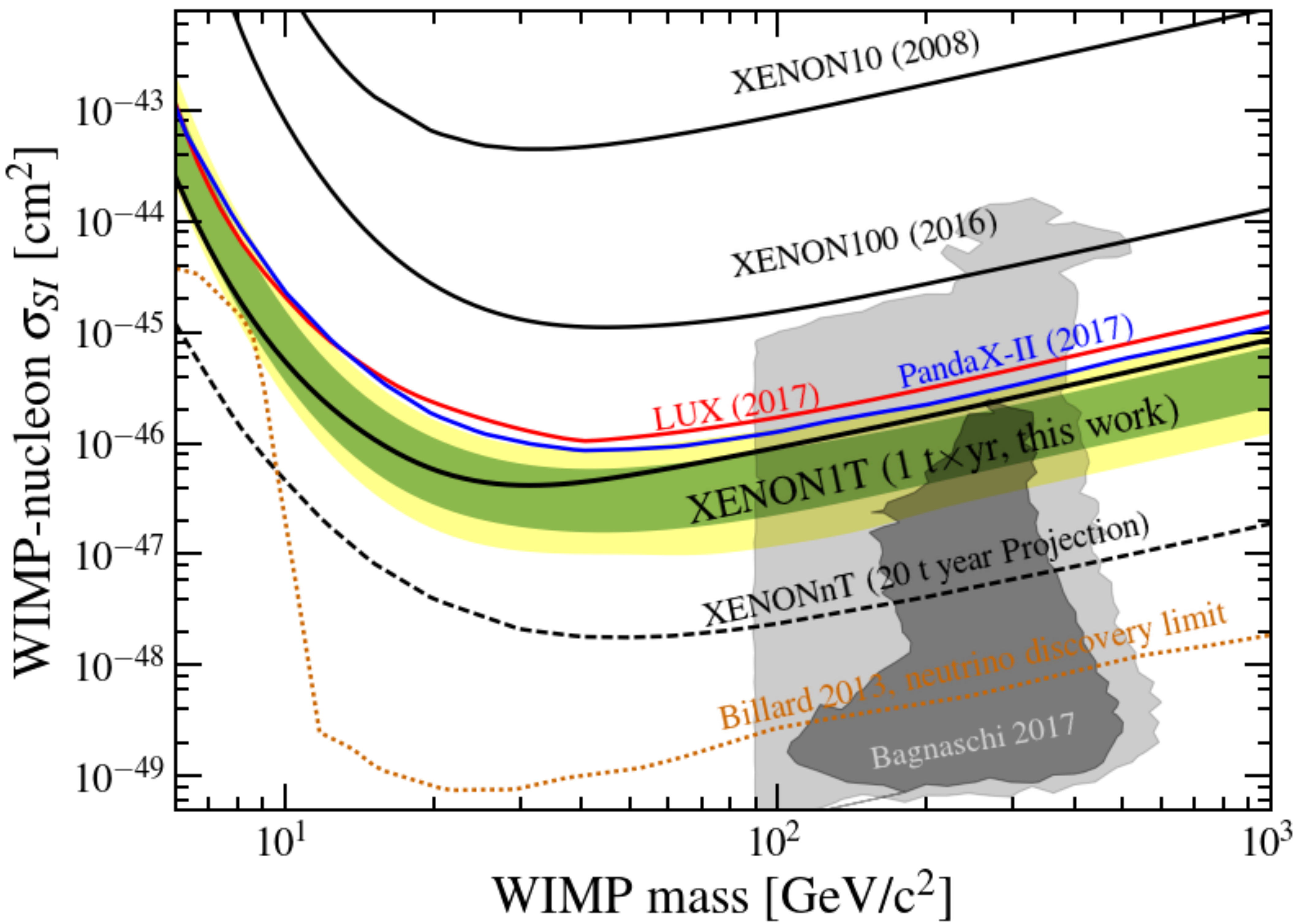


PMT arrays

e-lifetime and TPC performance rapidly improving -
- Kr-distillation started- getting ready for WIMPs time !!

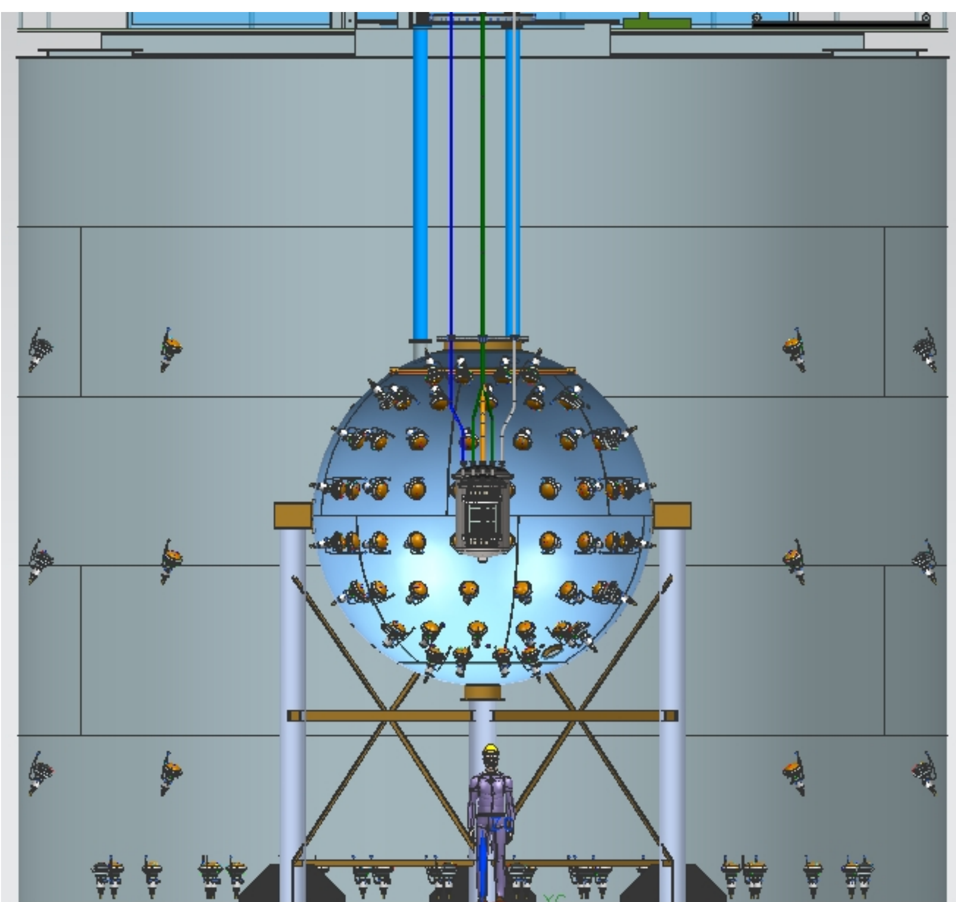


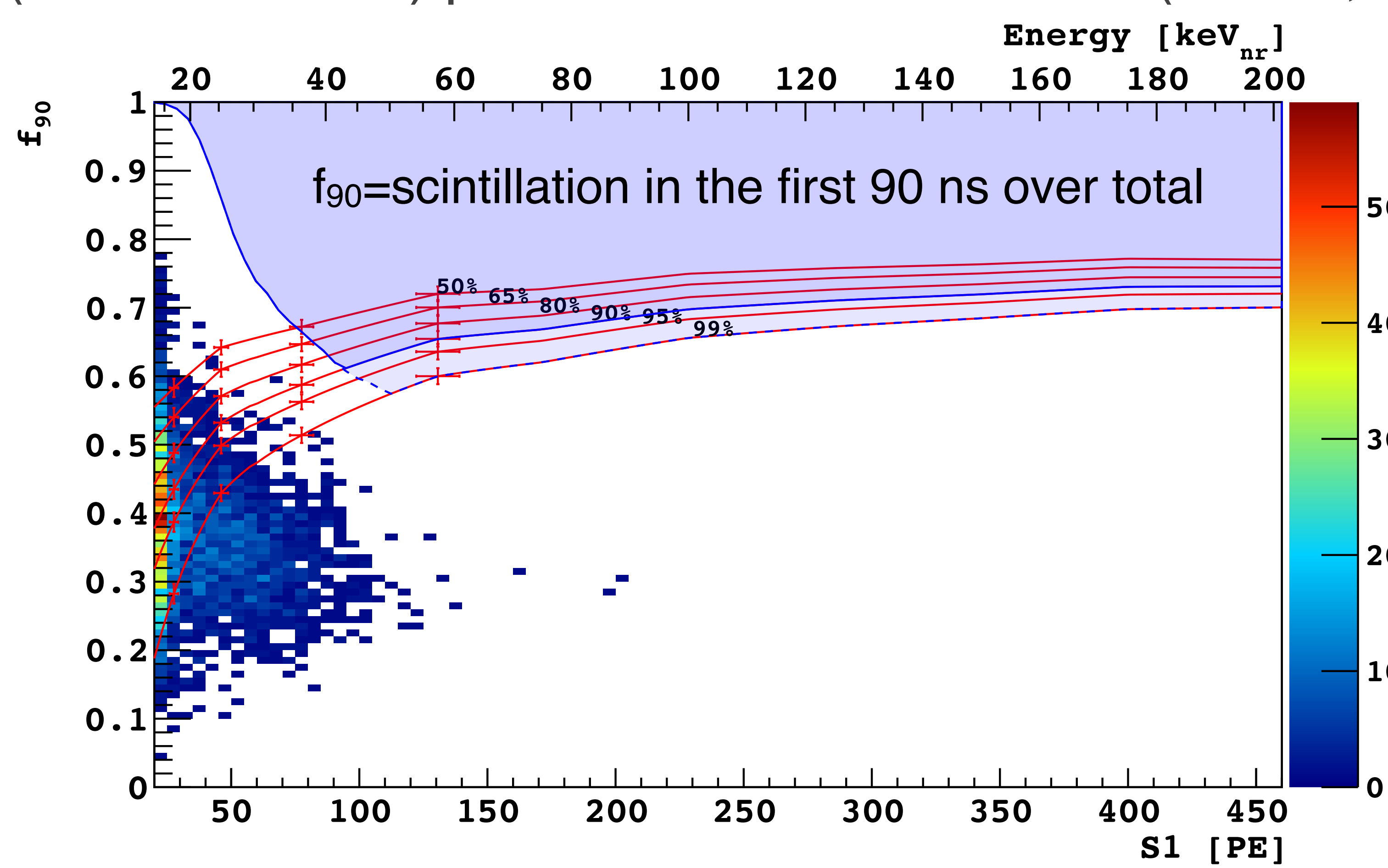
XENON1T latest results and XENONnT_expected sensitivity



DarkSide @ LNGS : present and future

- Dark Side 50: dual phase TPC with 46 kg ^{39}Ar-depleted LAr (1400 background reduction factor) inside 30 tons LS neutron veto inside a 1000 tons water Cherenkov muon veto
- 1st result from 2616 kg d with depleted Ar -> no event in search region . Still taking data
- Proposed DS20k. Large R&D effort on SiPMs and other technologies. Construction of the very large distillation facility (350 m column) placed inside a coal mine (Seruci, Sardinia) has started.





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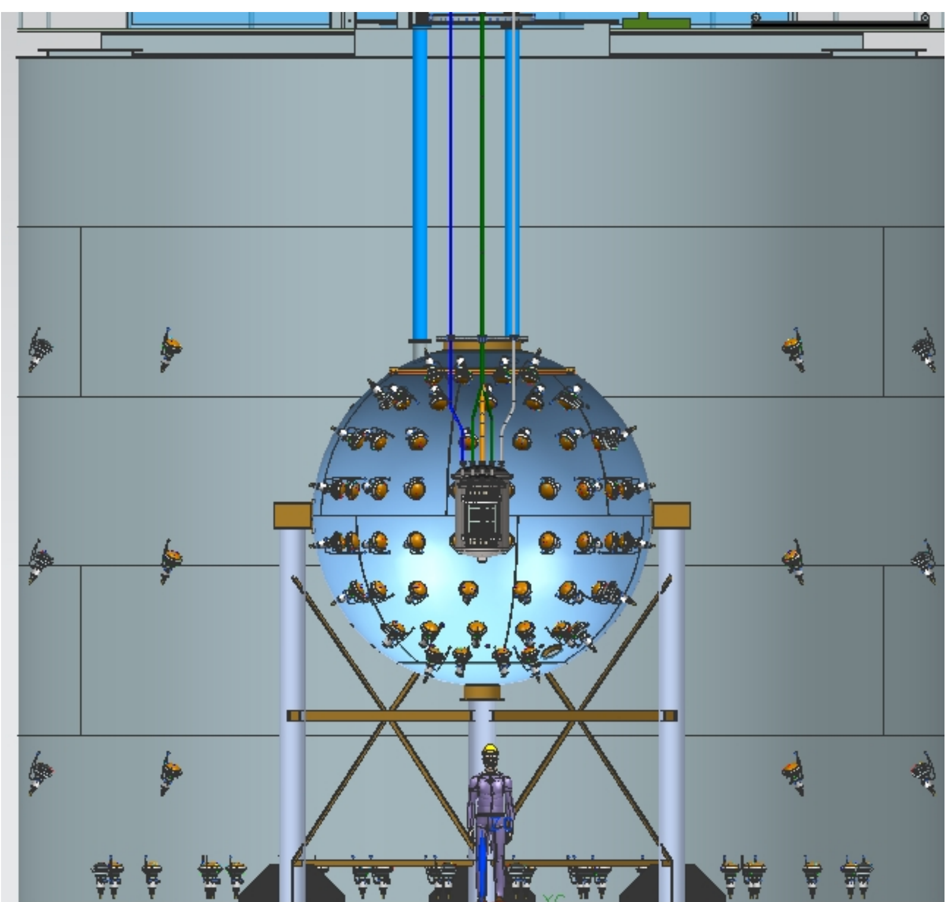

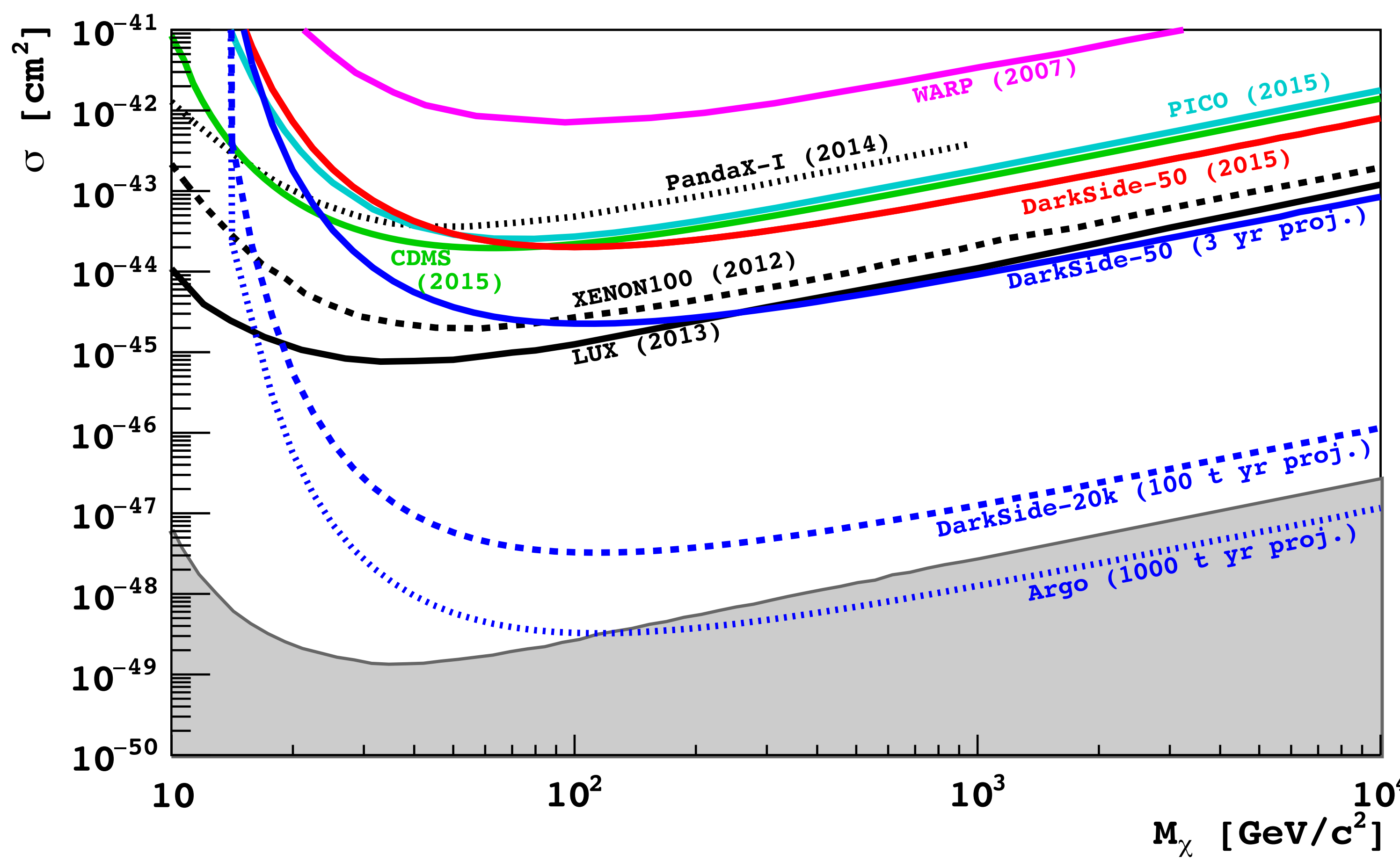

Conclusions

Cold dark matter is a explanation for many cosmological & astrophysical observations

It could be made of WIMPs - thermal relics from an early phase of our Universe

So far, no convincing evidence of a dark matter particle was found

However, DAMA/LIBRA experiment is claiming an observation of an annual modulation since long time.

Excellent prospects for discovery and clarification

New experiments, based on NaI technology, are getting ready to run in view of clarifying once and for all the nature of the DAMA/LIBRA longstanding annual modulation. Better late than never.

Direct detection: increase in WIMP sensitivity by 2 orders of magnitude in the next few years

reach neutrino background (measure neutrino-nucleus coherent scattering!) this/next decade

high complementarity with indirect & LHC searches