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

**Marcello Messina Ricercatore INFN ai LNGS**  
**PID-LNGS 2022, Programma per docenti**



# A World of Dark Matter Searches





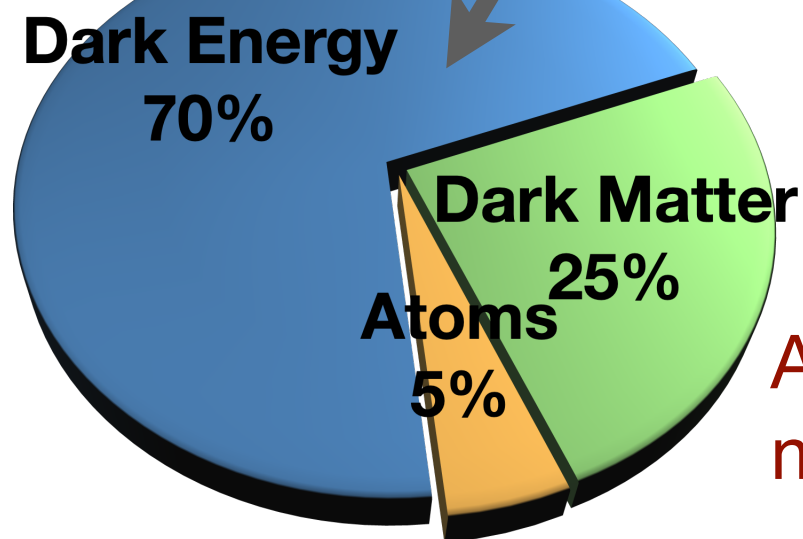
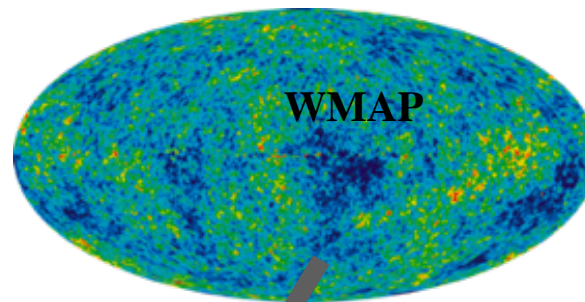
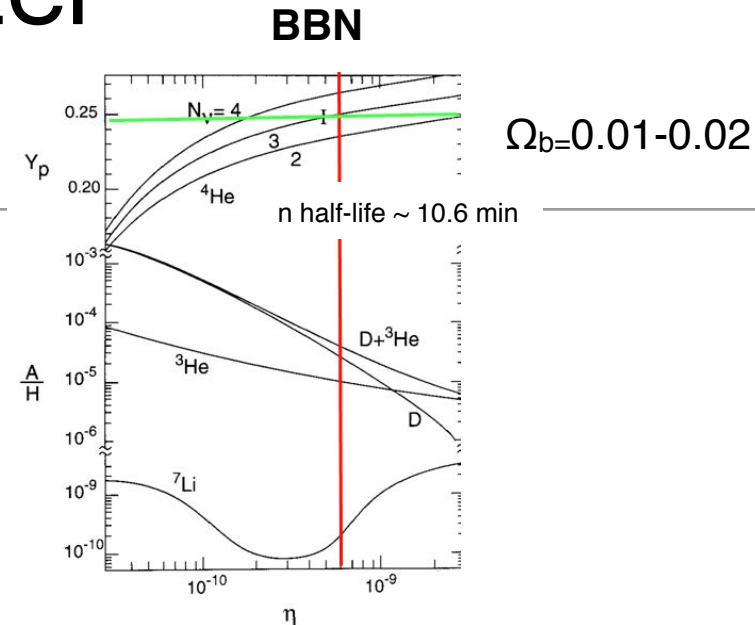
# Evidence for Dark Matter

## Astrophysical Observations

Beginning of the story



$\Omega_m=0.3$

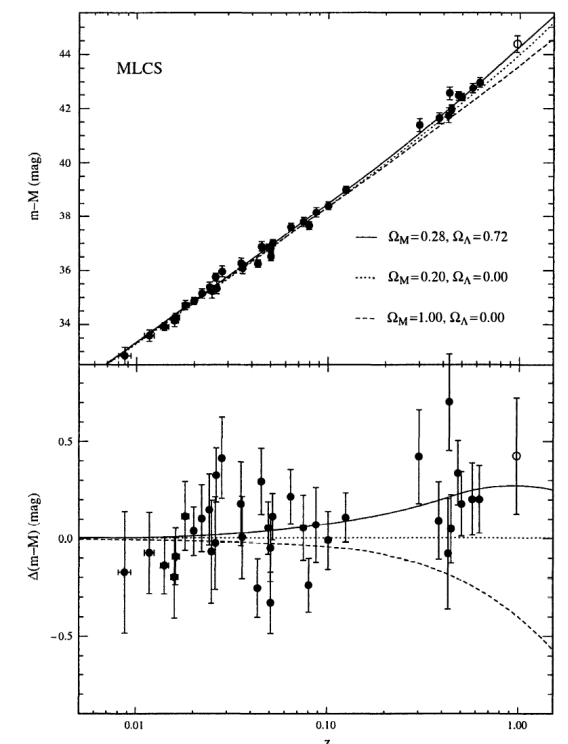


All consistent with ~25% dark matter (give or take).

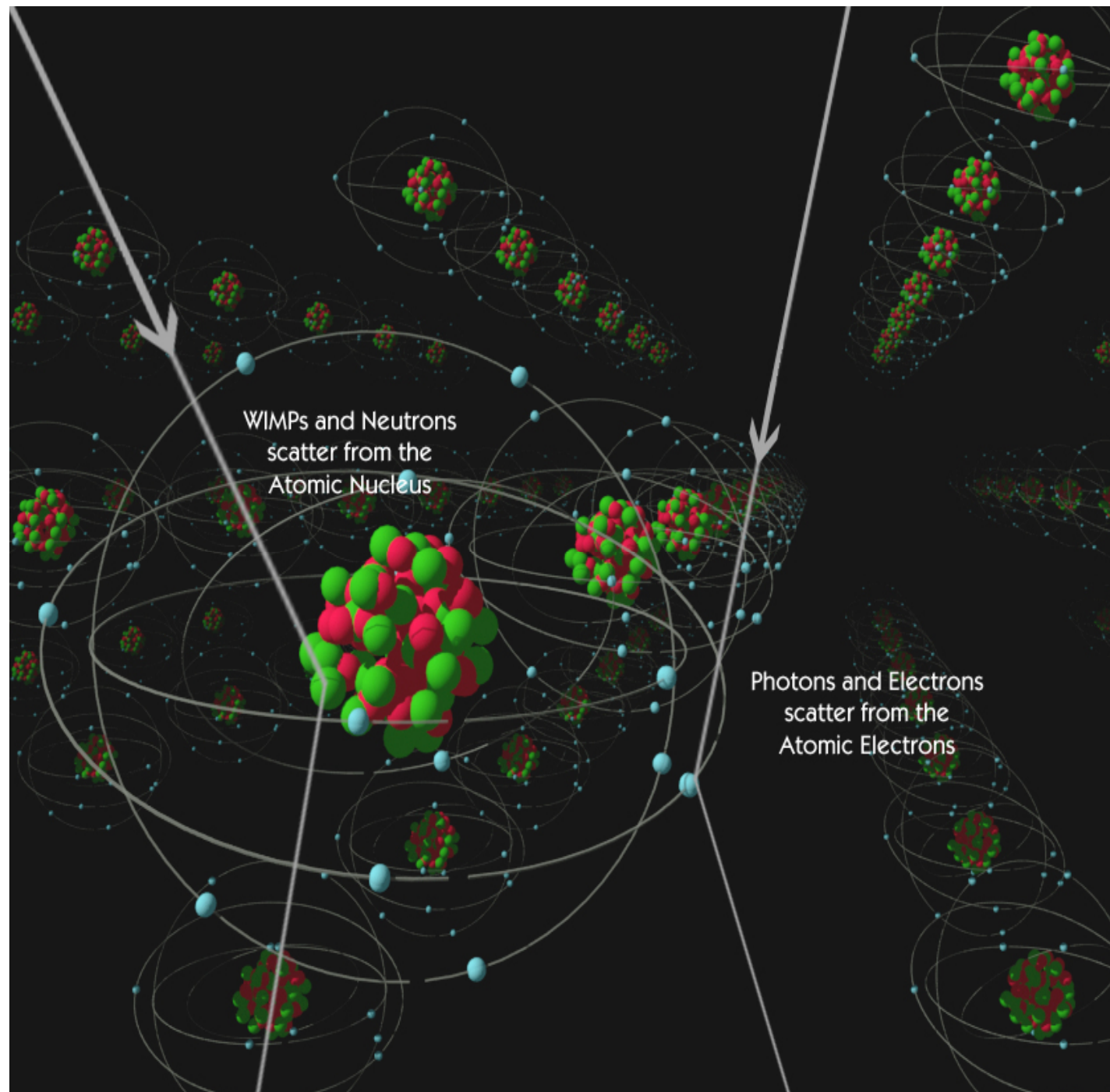
Possible candidates:

**WIMPs**

$\Omega_v=0.7$



# 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.



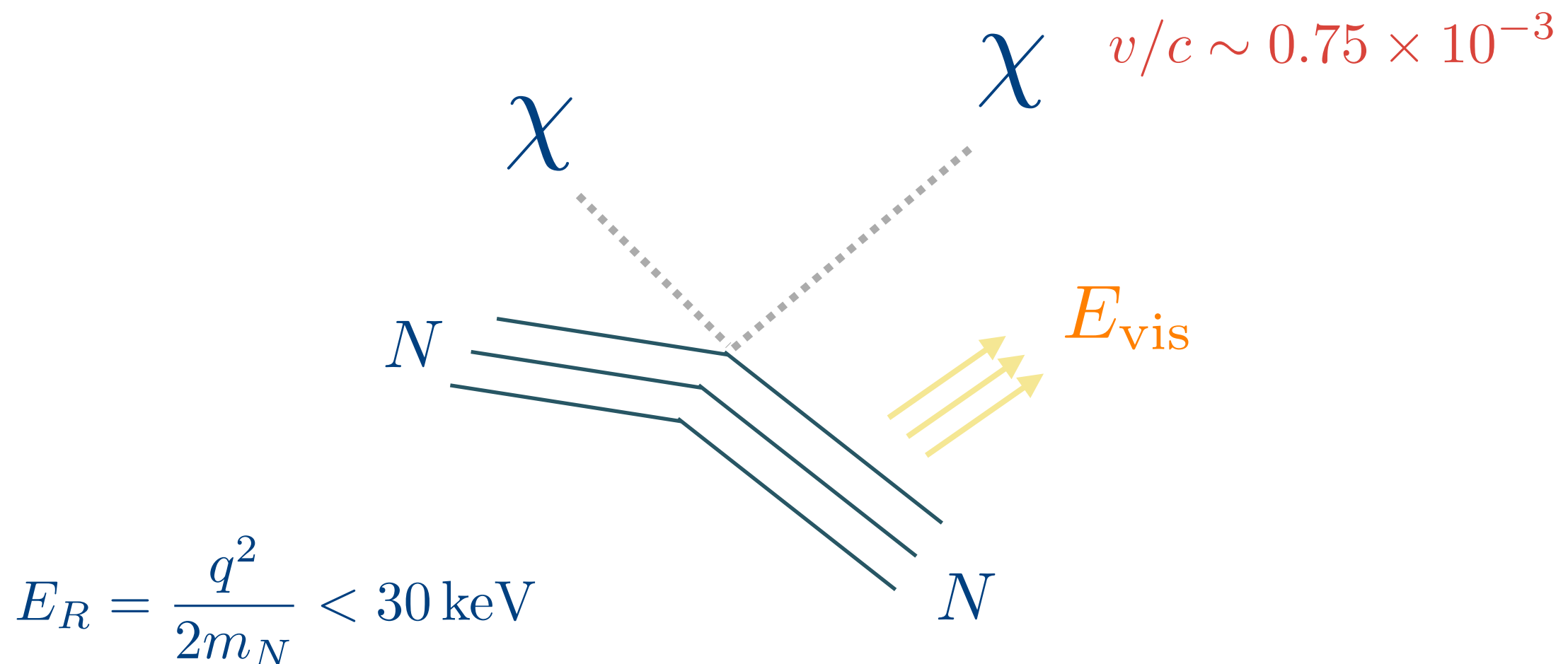
# Direct detection principle

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Scattering of a WIMP with an atomic nucleus

Momentum transfer  $\sim$  few tens of MeV

Energy deposited in the detector  $\sim$  few keV - tens of keV



# Observables: Rate

Event rate in a terrestrial detector

Detector physics

$$N_N, E_{th}$$

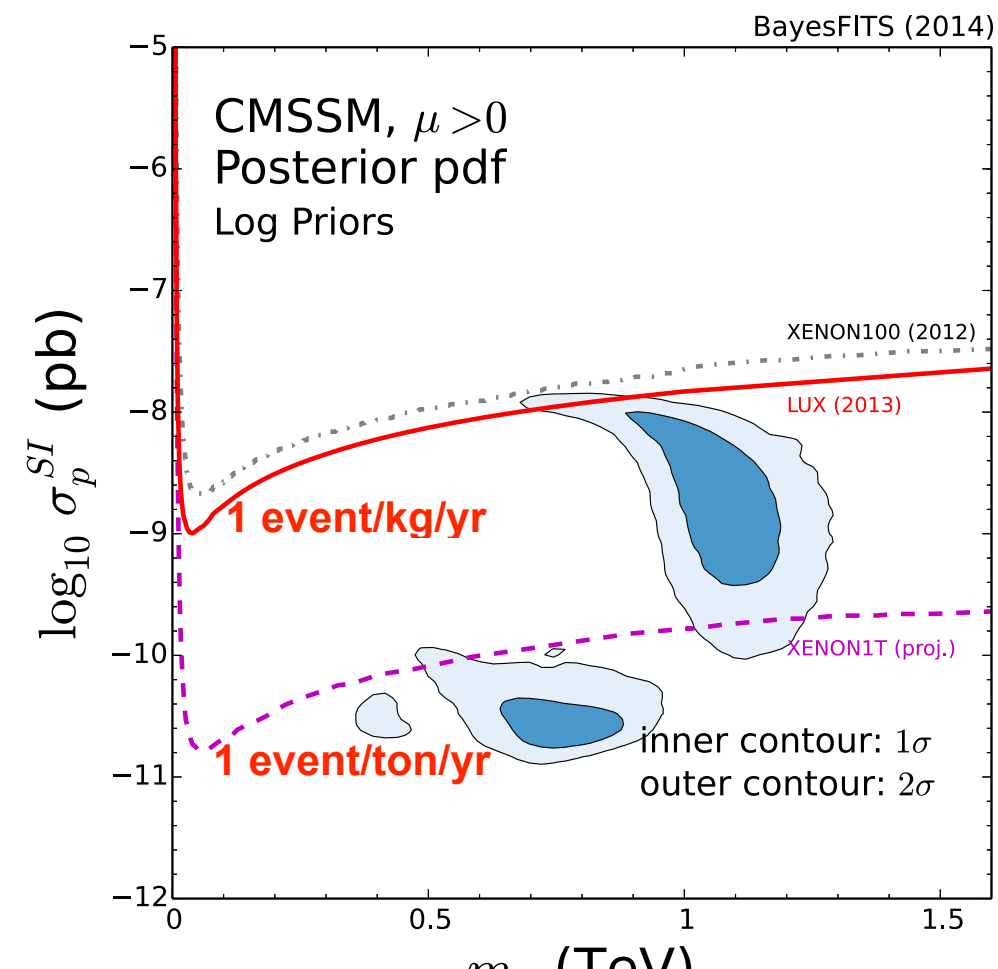
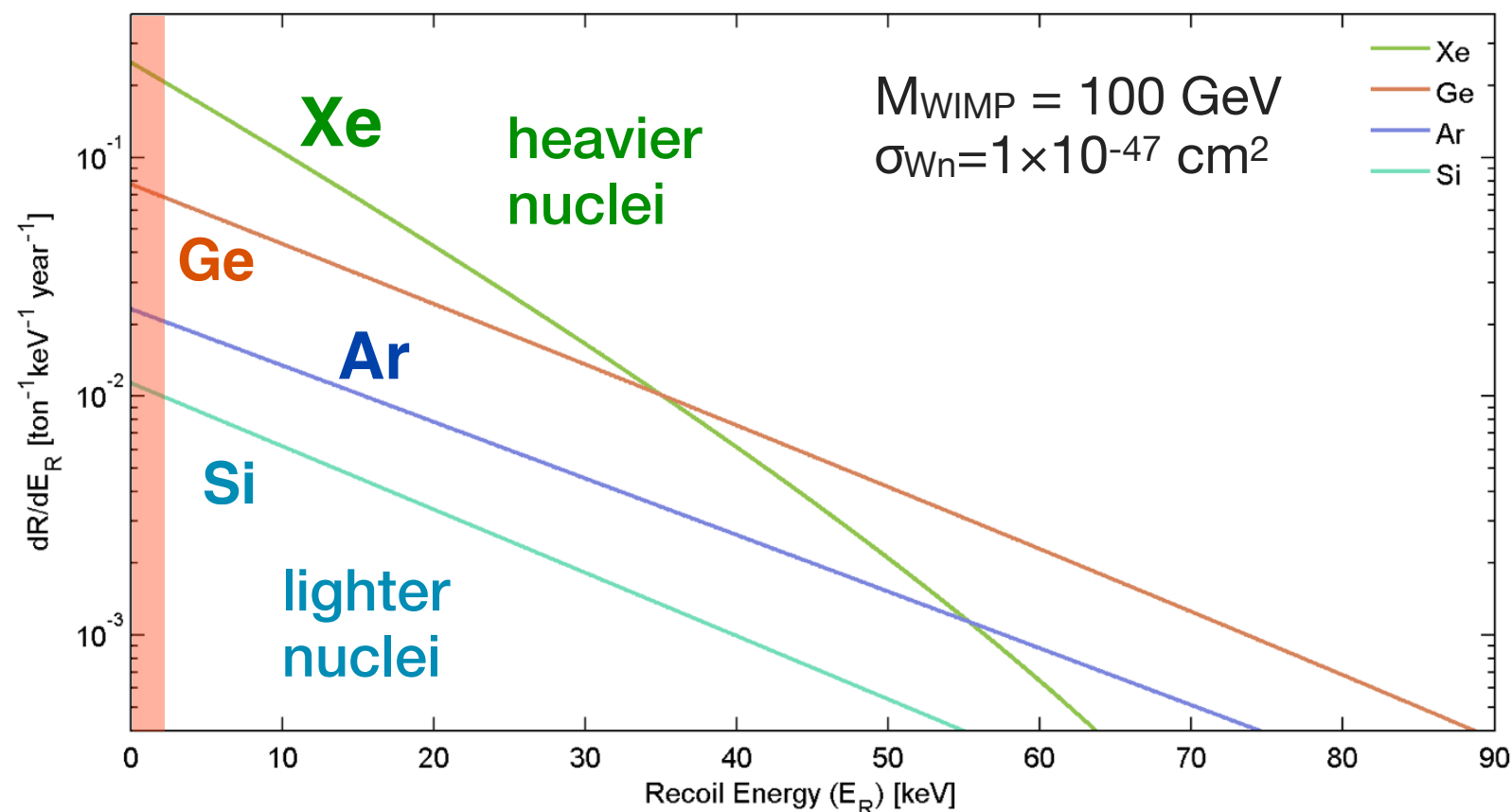
Particle/nuclear physics

$$m_W, d\sigma/dE_R$$

Astrophysics

$$\rho_0, f(v)$$

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

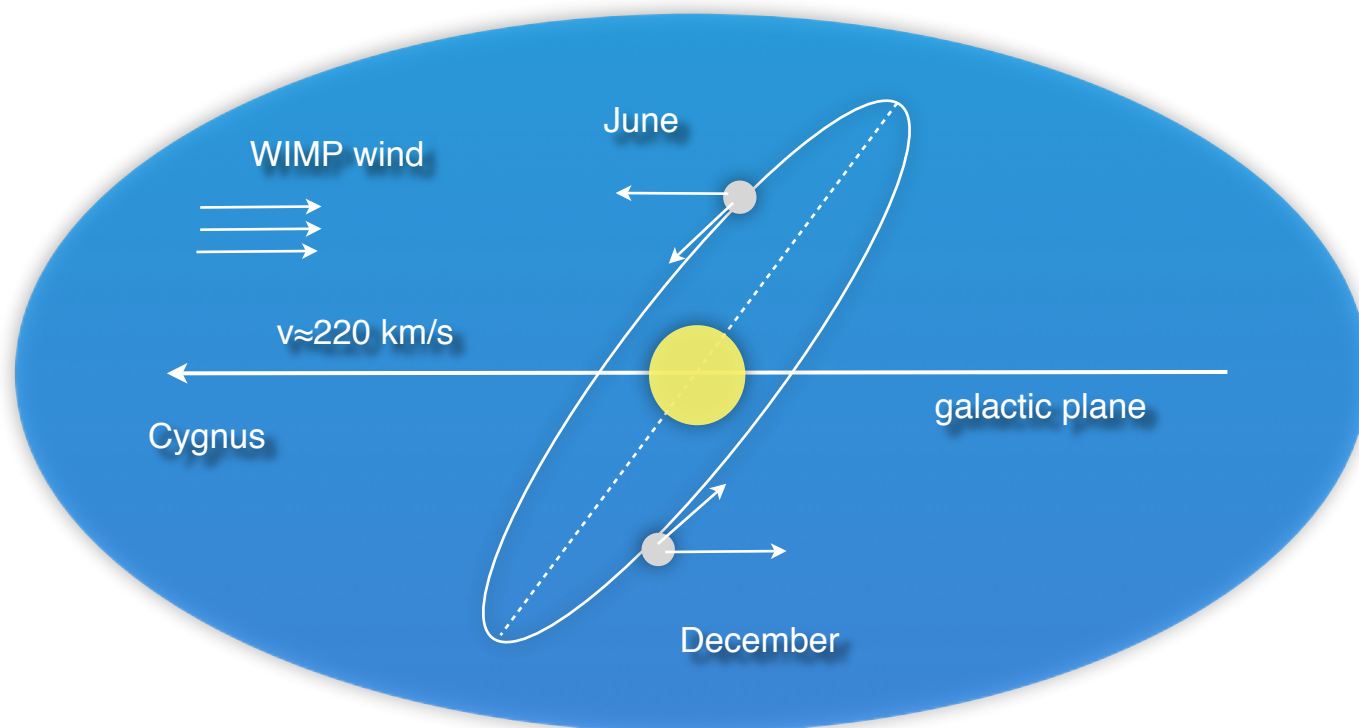




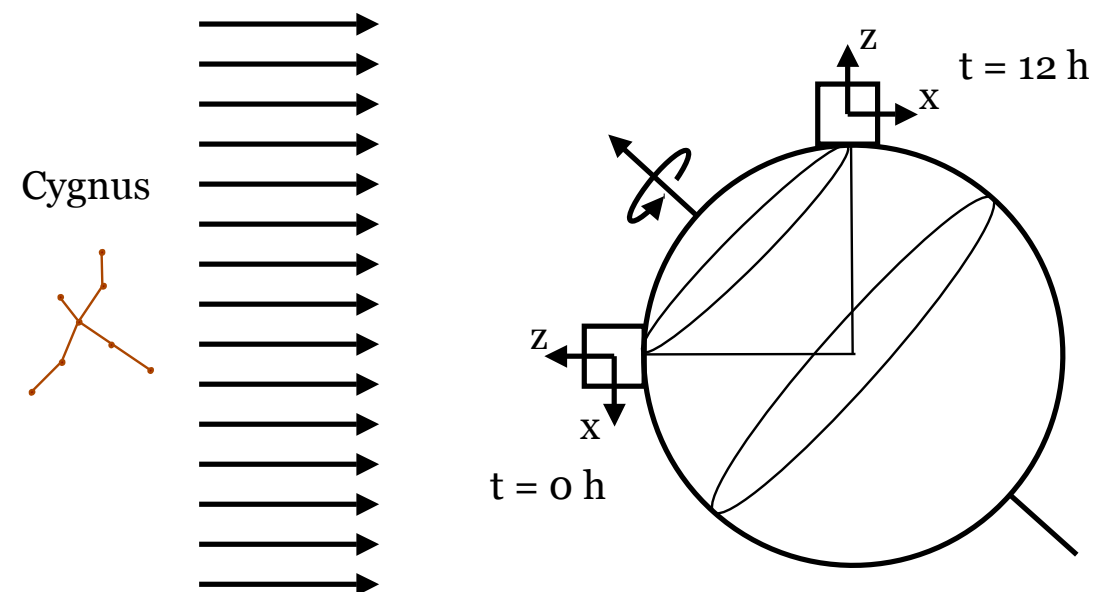
# Observables: rate modulations

## 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  $\sim 2\text{-}10\%$
  - sidereal directional modulation: asymmetry  $\sim 20\text{-}100\%$  in forward-backward event rate



Drukier, Freese, Spergel, PRD 33, 1986



D. Spergel, PRD 36, 1988

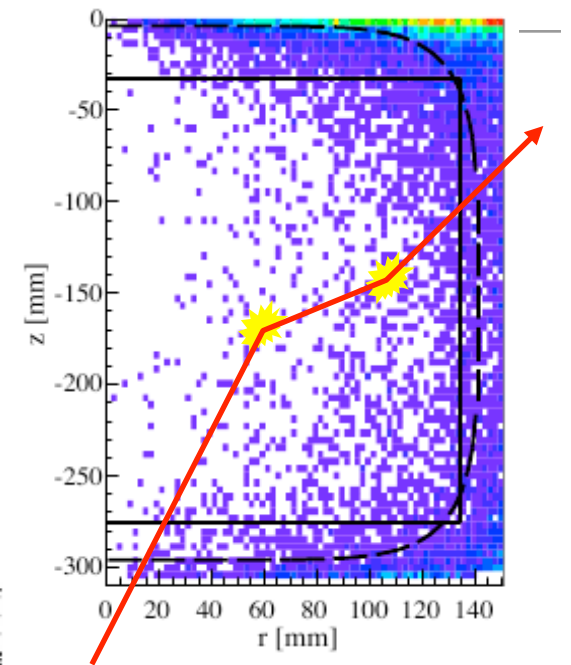
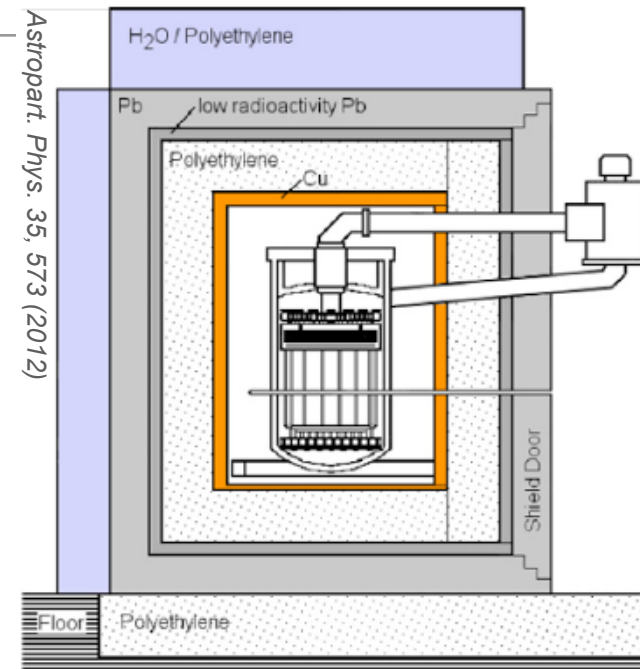
# Background Suppression: the holy grail

## Avoid Backgrounds

### *Shielding*

deep underground location  
large shield (Pb, water, poly)  
active veto ( $\mu$ , coincidence)  
self shielding  $\rightarrow$  fiducialization

### *Select radiopure materials*



## Use knowledge about expected WIMP signal

### *WIMPs interact only once*

$\rightarrow$  single scatter selection  
requires some position resolution

### *WIMPs interact with target nuclei*

$\rightarrow$  nuclear recoils  
exploit different  $dE/dx$  from  
signal and background  $\longrightarrow$

### *Examples:*

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



# WIMPs Direct Detection Experiments

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

*CRESST-I*  
*CUORE*

Phonons

Tracking:  
*DRIFT, DMTPC*  
*MIMAC,*  
*NEWAGE*

*SuperCDMS*  
*EDELWEISS*

*CRESST*

Superheated  
Liquids:  
*COUPP* *PICO*  
*PICASSO*  
*SIMPLE*

*CoGeNT*  
*CDEX*  
*Texono*  
*Malbek*  
*DAMIC*

Charge

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

Light

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





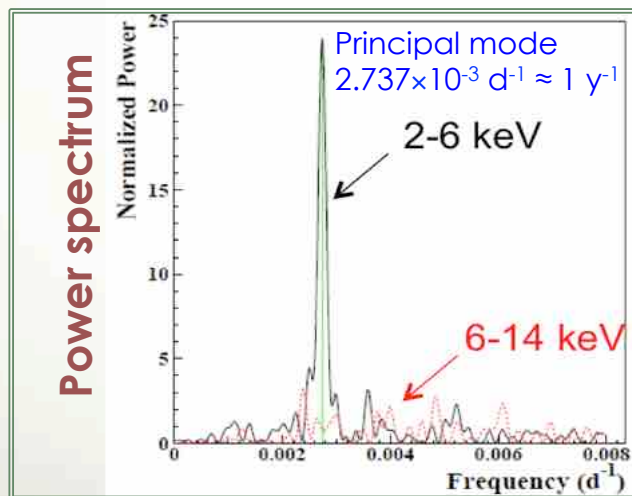
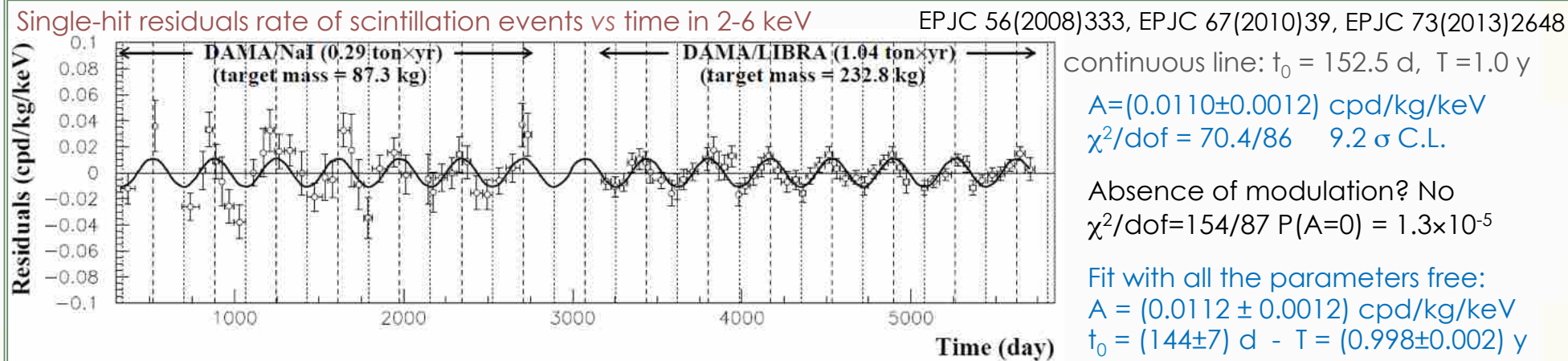
# DAMA/Libra experiment

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

Belli - IDM 2016

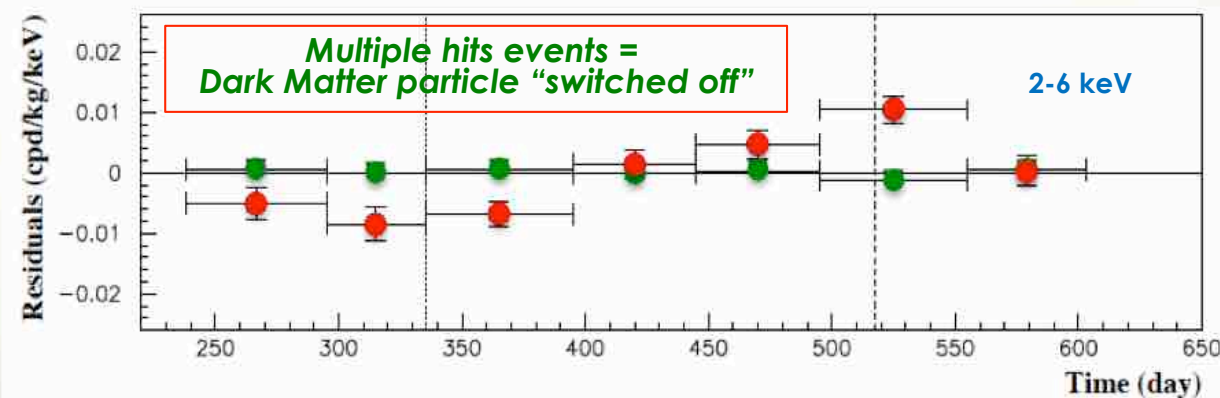
## Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**



No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

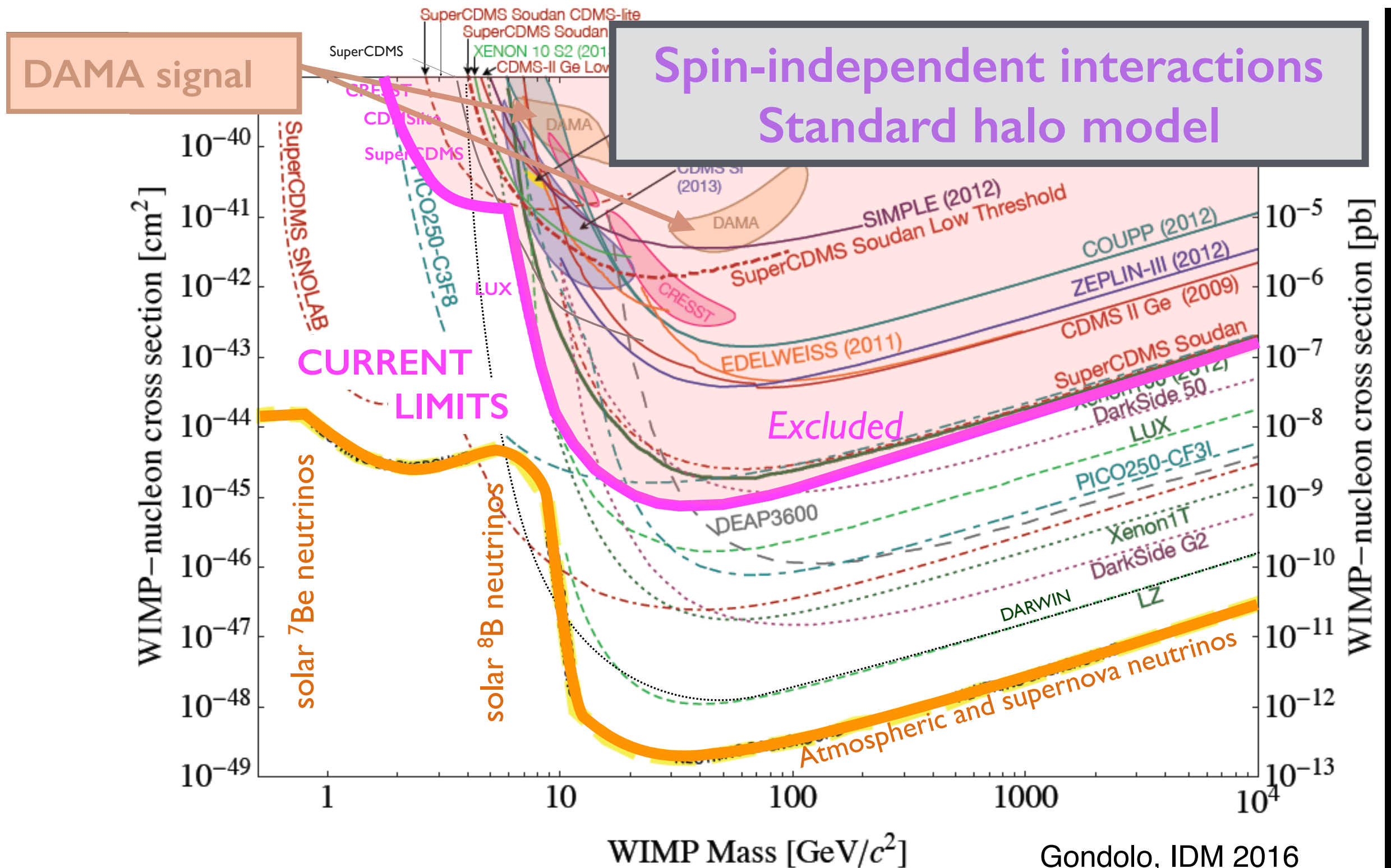
Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events  
 $A = -(0.0005 \pm 0.0004)$  cpd/kg/keV



This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2 $\sigma$  C.L.

# DAMA Incompatible with Other Experiments



Gondolo, IDM 2016

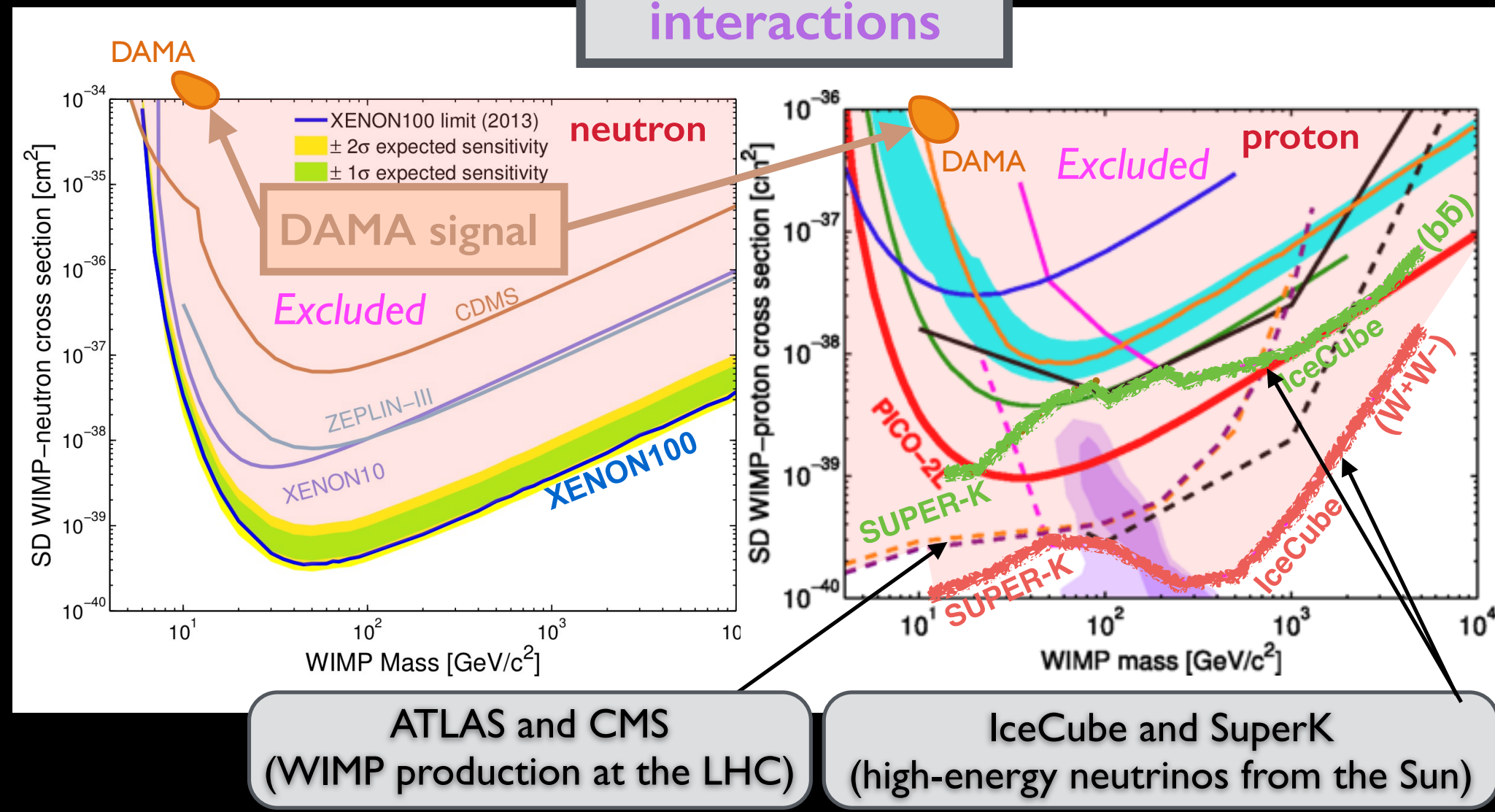


# DAMA Incompatible with Other Experiments

Aprile et al (XENON100) 2013

Spin-dependent  
interactions

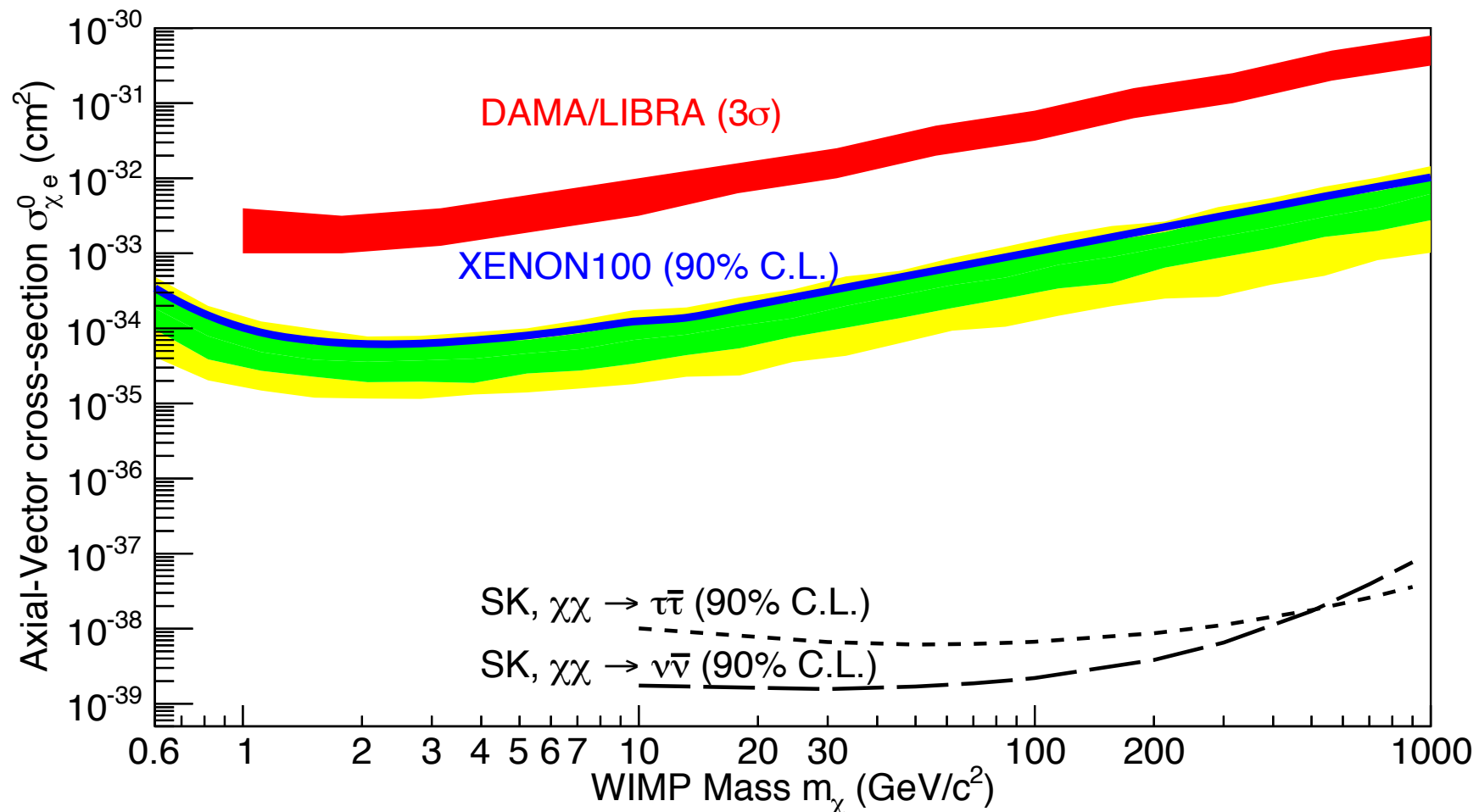
Amole et al (PICO) 2015



# 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





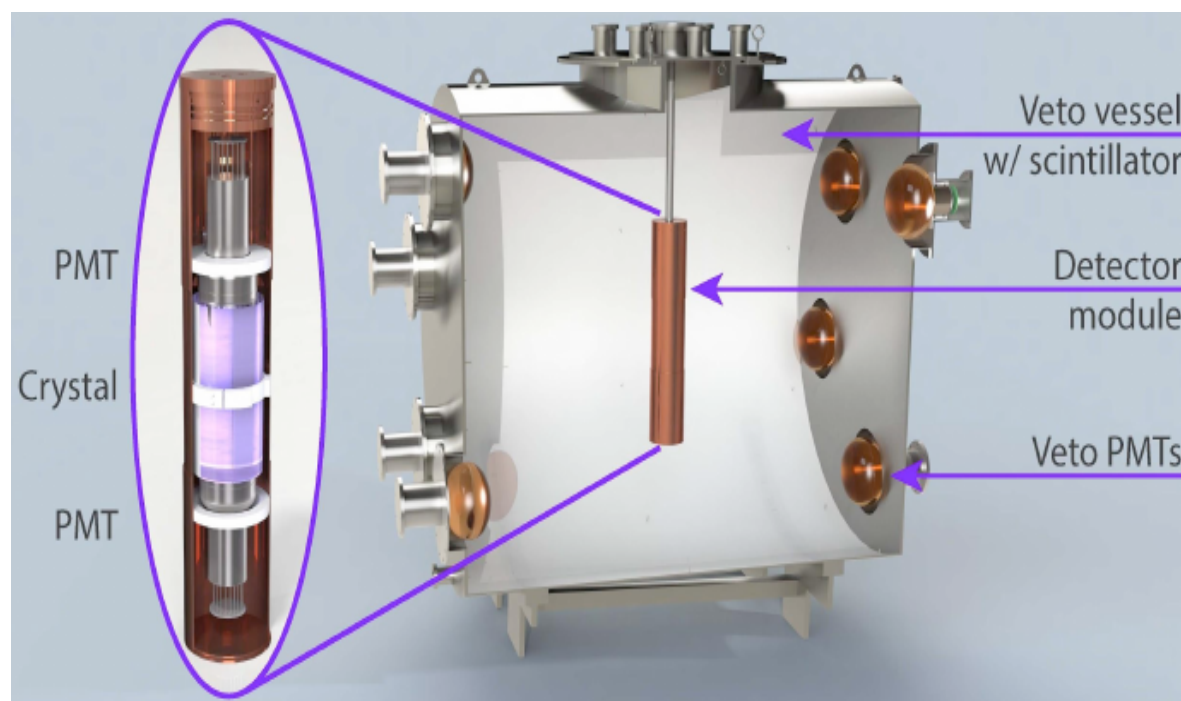
# Upcoming NaI Projects to directly test DAMA

## **SABRE @ LNGS**

Sodium-iodine with Active Background REjection

### *Strategy:*

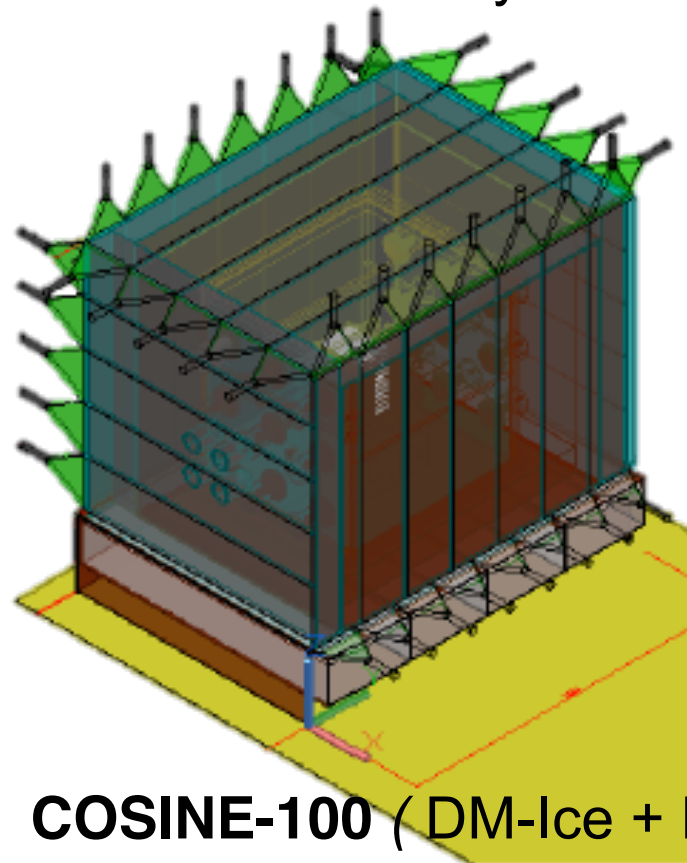
- lower background: better crystals, PMTs
- liquid scintillator veto against  $^{40}\text{K}$  (factor 10)
- lower threshold (PMTs directly coupled to NaI)
- Eliminate seasonal effects :North (LNGS) and South Hemisphere(Australia: Stawell Underground Physics Laboratory)
- *Status:* 2 crystals ready, 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](https://arxiv.org/abs/1602.05939)

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

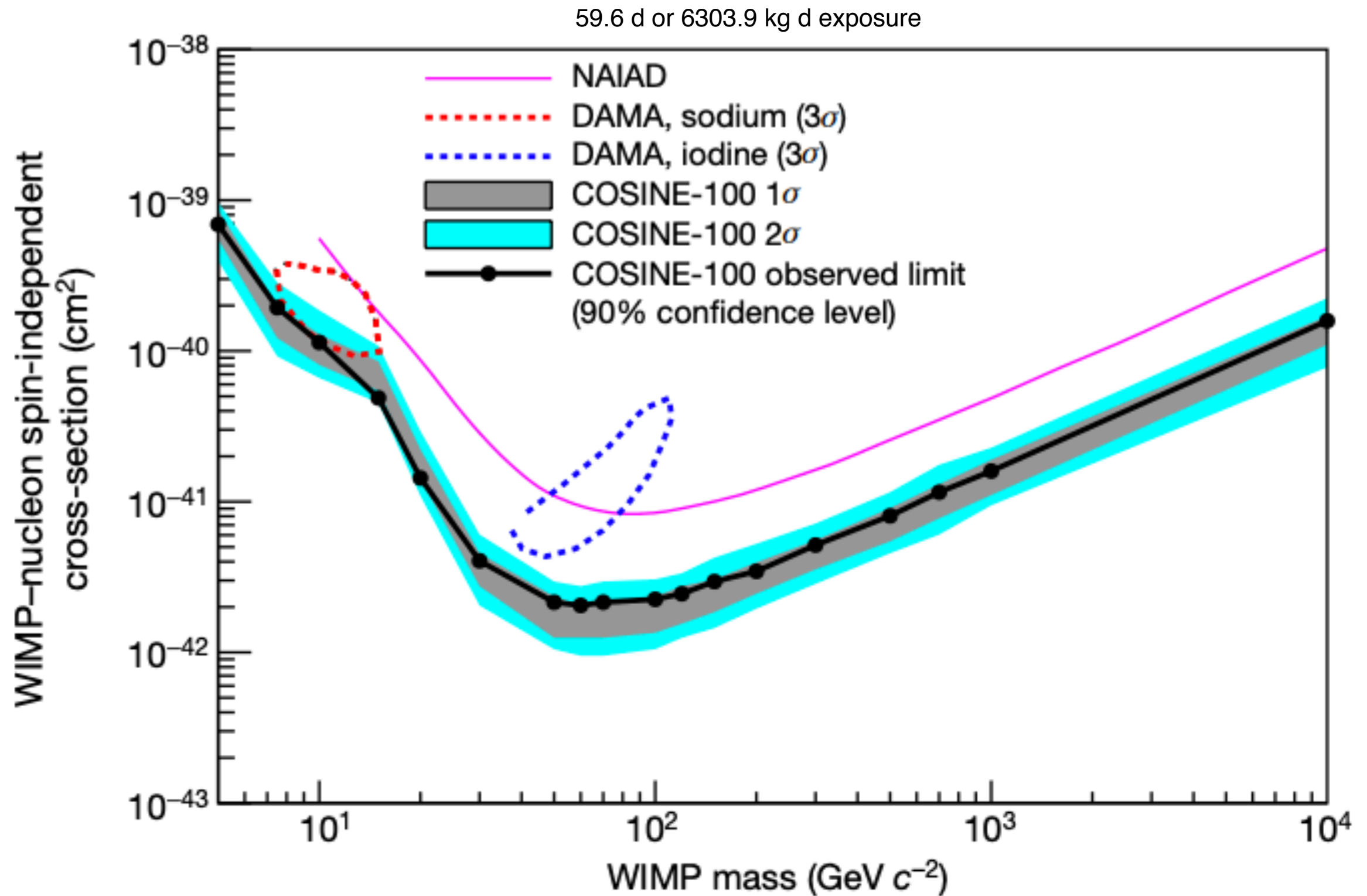
## **ANAIS @ Canfranc**

113 kg in Pb shield

→ start of data taking soon

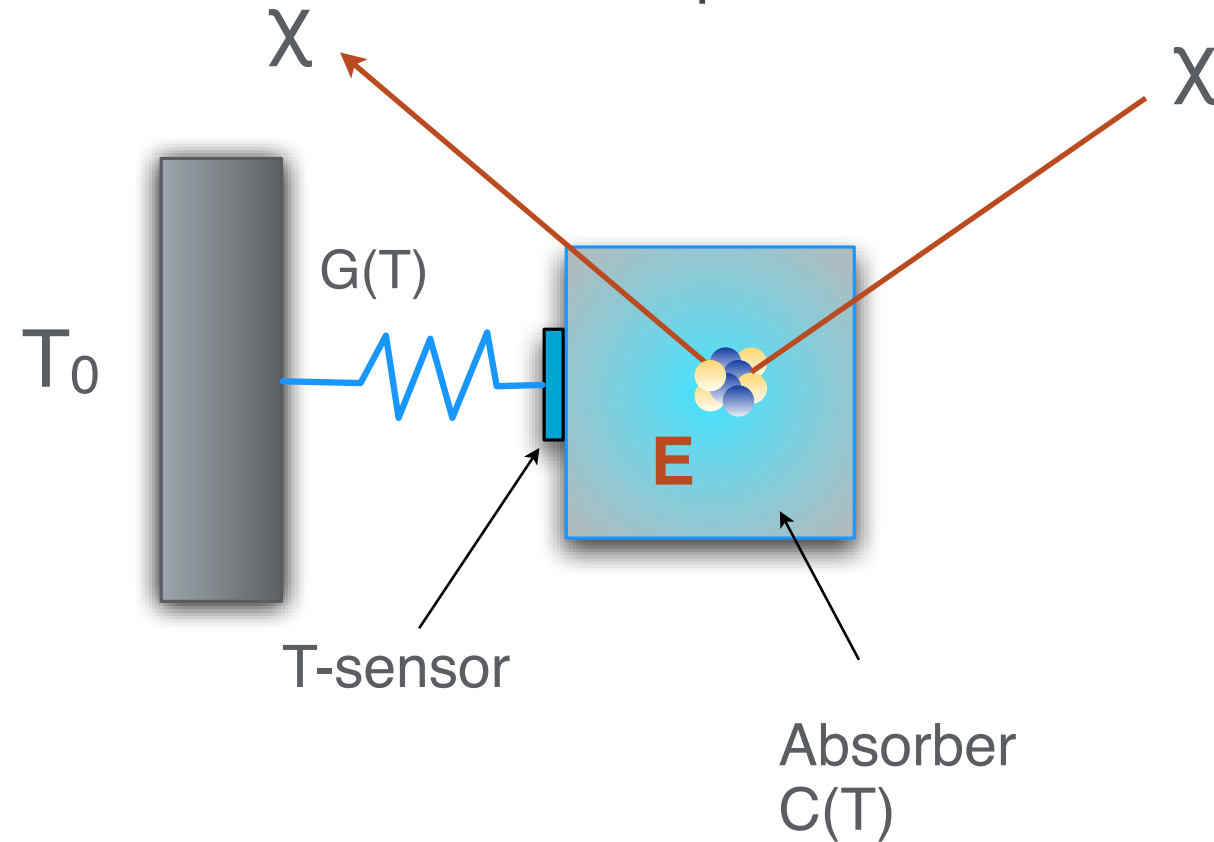
→ background 2-3x DAMA (no veto)

# Upcoming NaI Projects to directly test DAMA

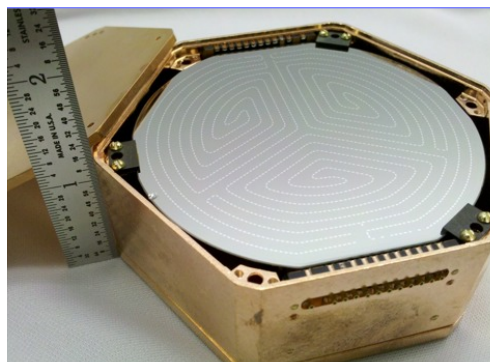


# Cryogenic micro-calorimeter at $T \sim \text{mK}$

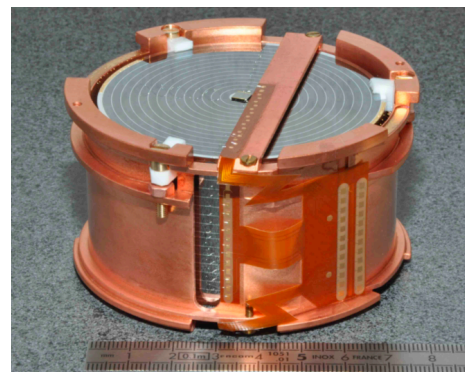
- Detect a temperature increase after a particle interacts in an absorber



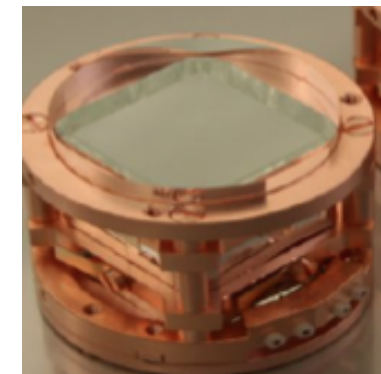
$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$
$$\tau = \frac{C(T)}{G(T)}$$



SuperCDMS: Ge, Si



EDELWEISS-III (Ge)



CRESST ( $\text{CaWO}_4$ )



# 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 accommodate 400 kg)

- low threshold → focus on 1-10 GeV/c<sup>2</sup> 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 kgxd in HV mode to optimize 1-10 GeV sensitivity

Future: ton scale together with CDMS (EURECA)

## CRESST II @ LNGS: EPJ C, 76, 25 (2016)

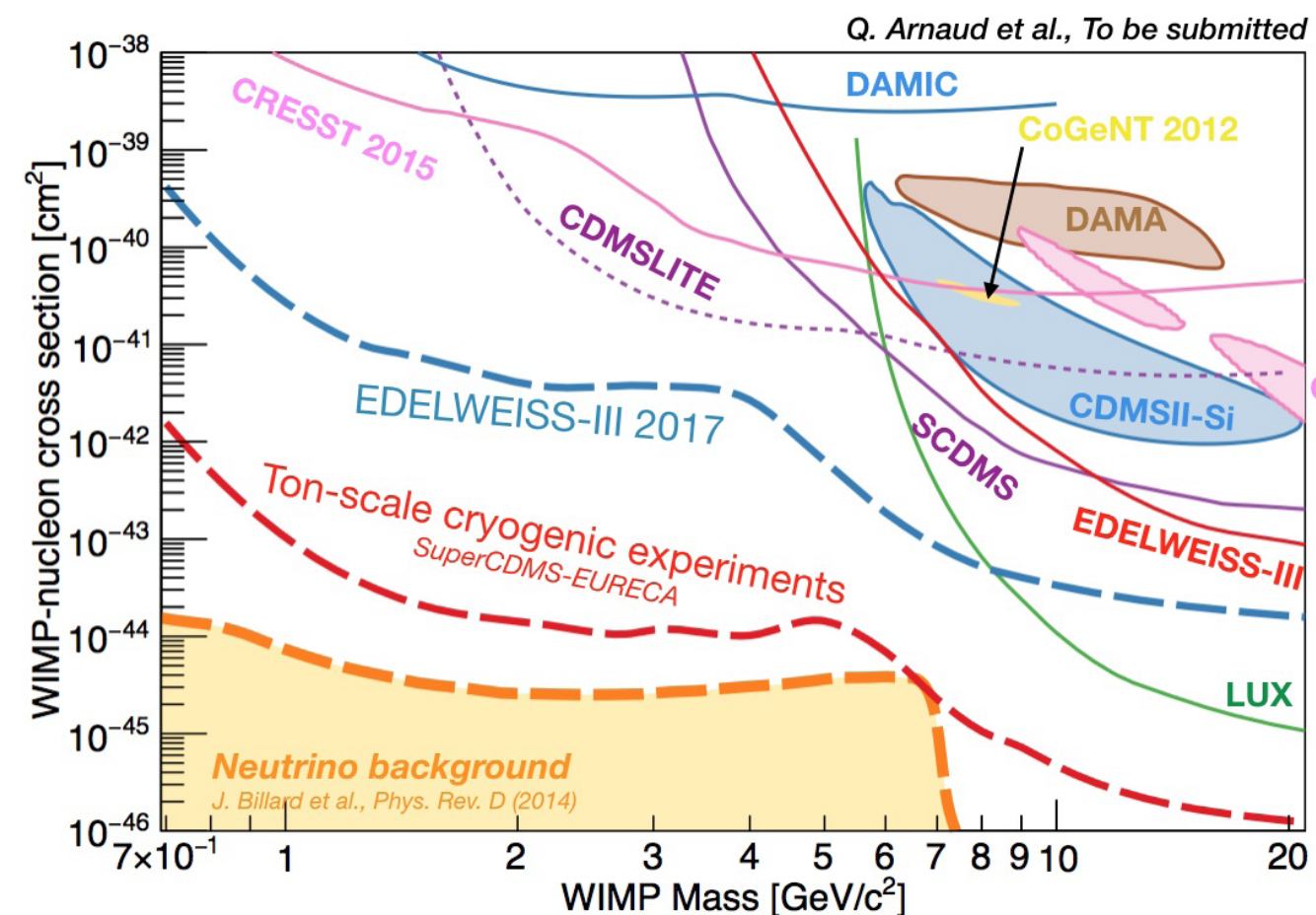
read phonons and scintillation light from CaWO<sub>4</sub>

successful background reduction;

data taking 2013-2015, 52 kgxd

2016: lowest thresh 300 eVnr

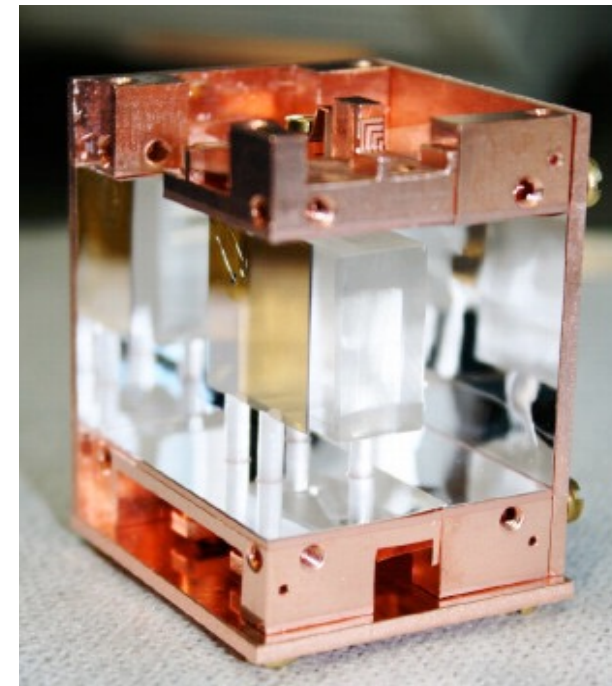
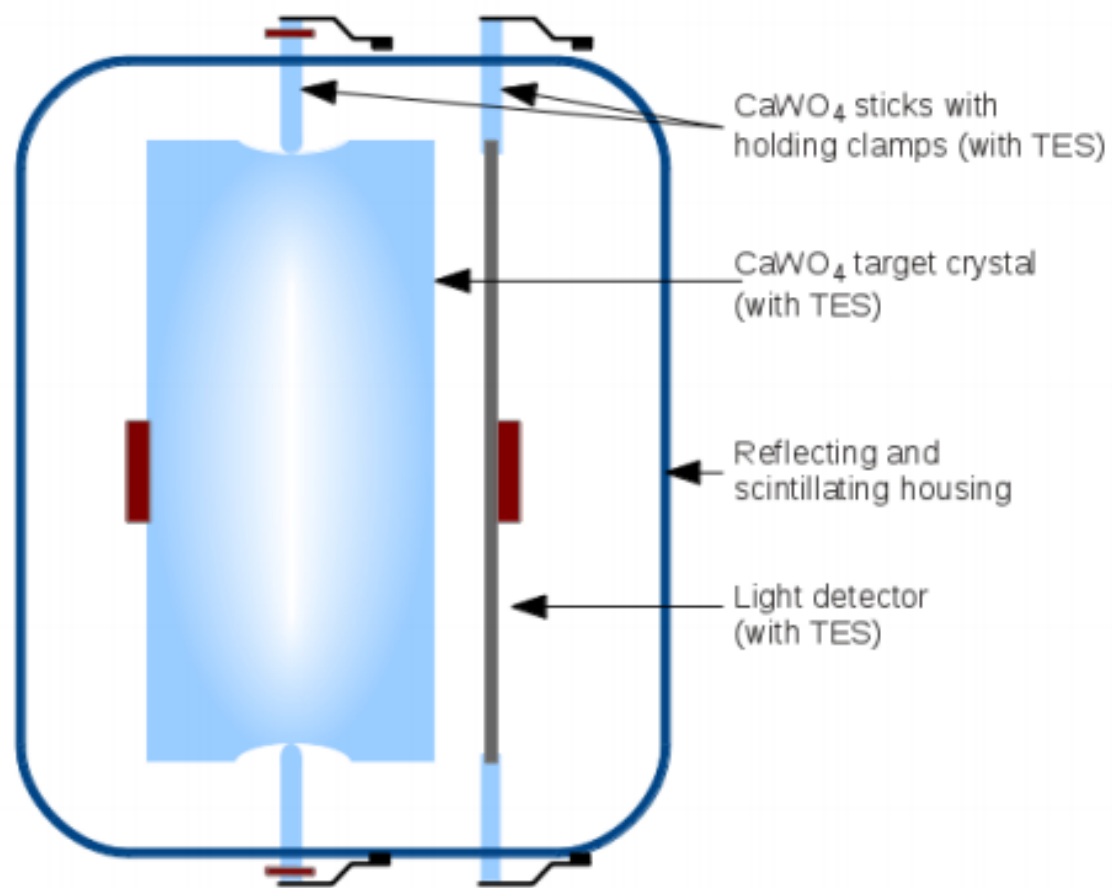
Record sensitivity below 1.7 GeV WIMP mass



# CRESST-III

## Goal: lower threshold to 100 eV<sub>nr</sub>

- 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 eV<sub>nr</sub> threshold

# CRESST-III

## Phase 1

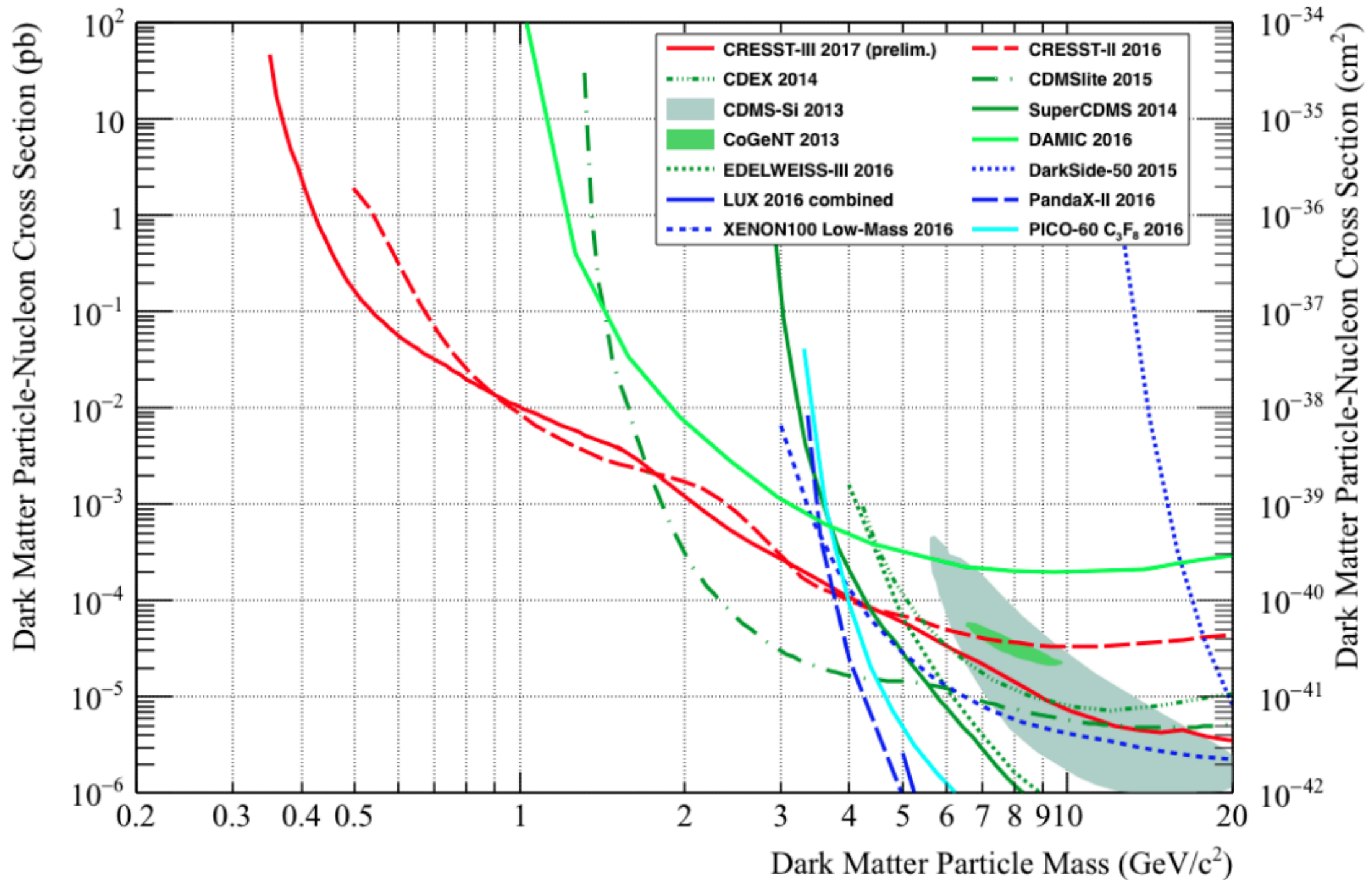
- 50 kg-days 1year of running with 10 small modules

Go

→  
→  
→

Sta

• Pi





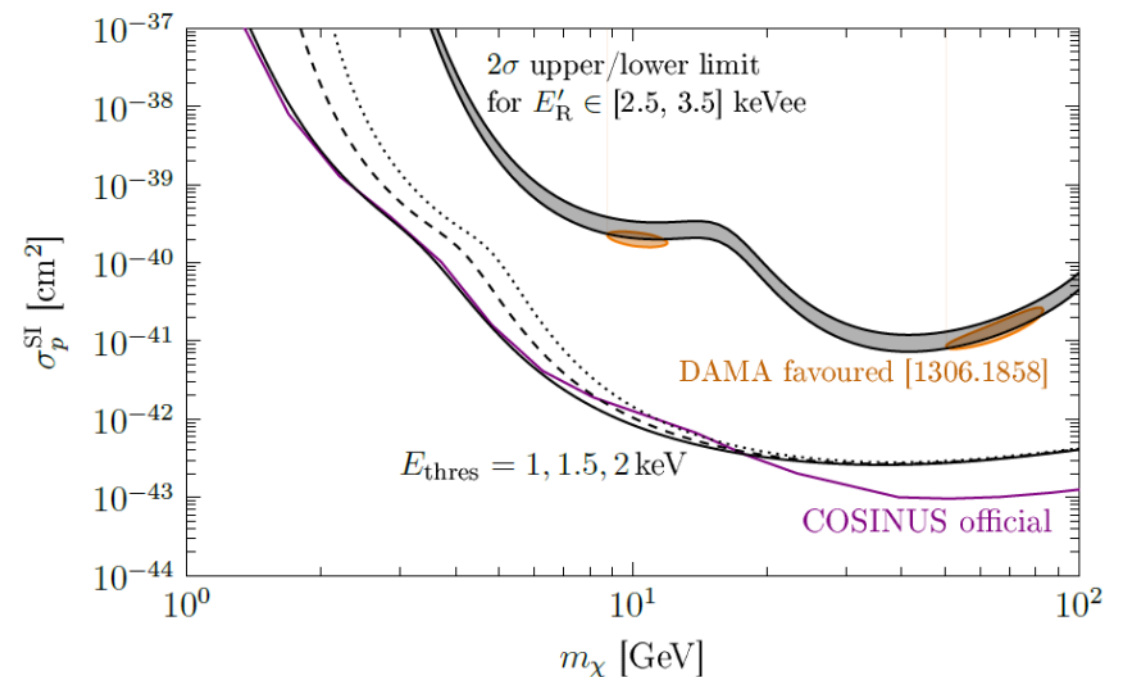
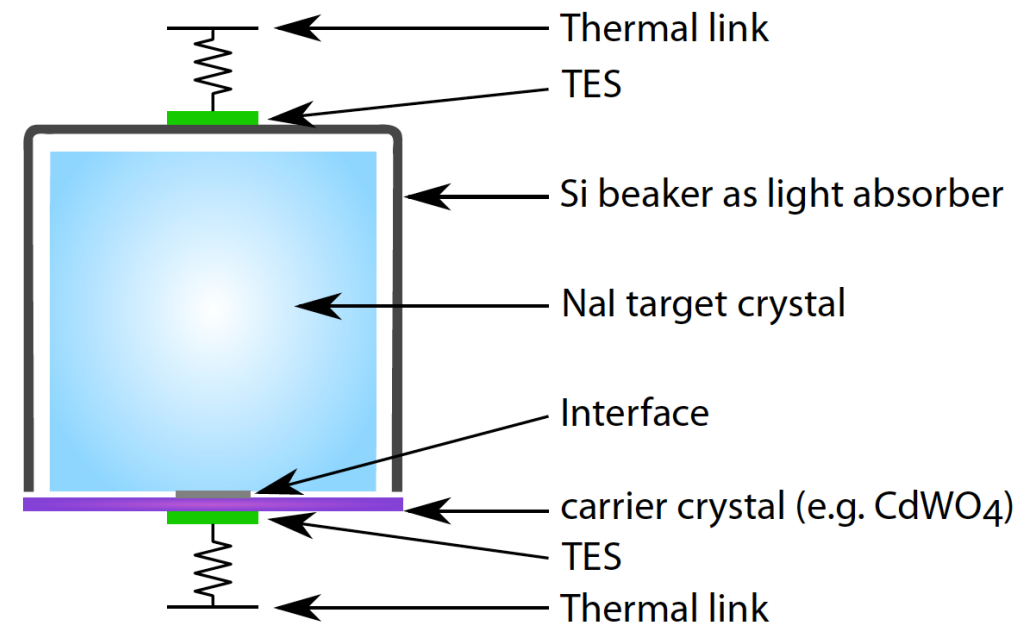
# COSINUS a Promising R&D project: Cryogenic NaI detectors at $T \sim \text{mK}$

**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)

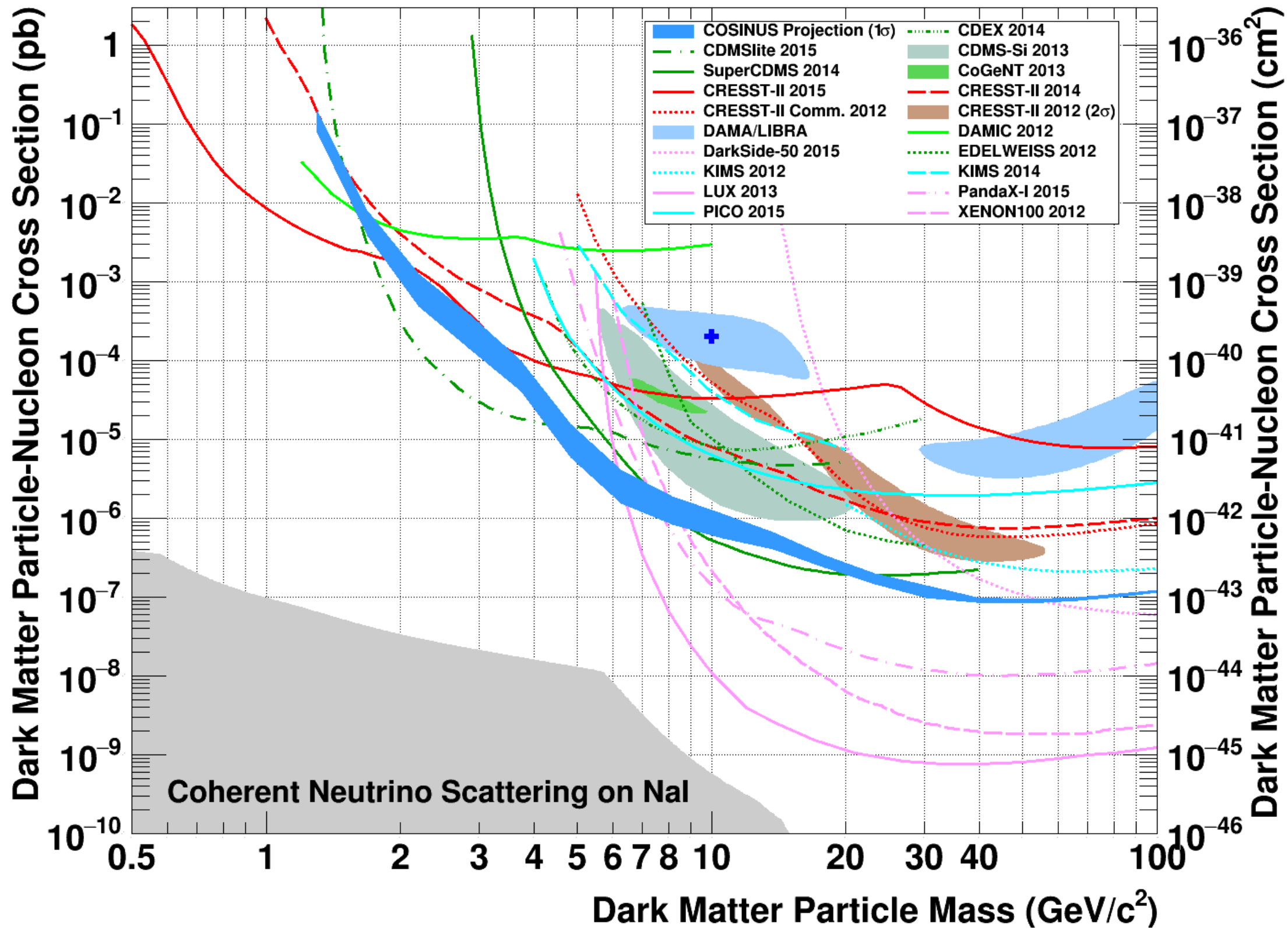


COSINUS should be able to exclude or confirm DAMA signals by about two orders of magnitude in cross section with an exposure of 100 kg days

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

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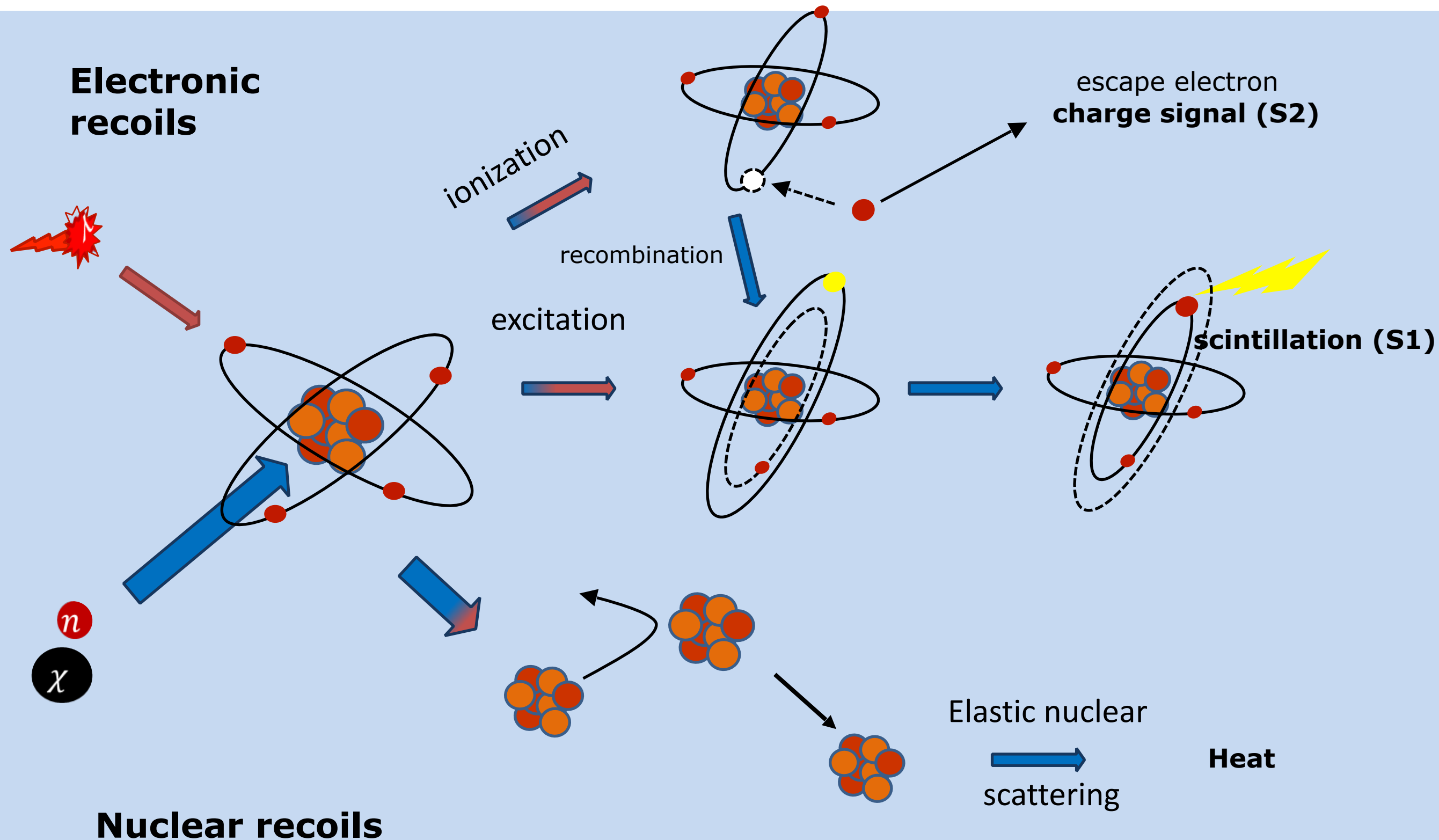
# In The High Mass Region: noble liquid experiments continue to lead the race





# Noble Liquid Detectors

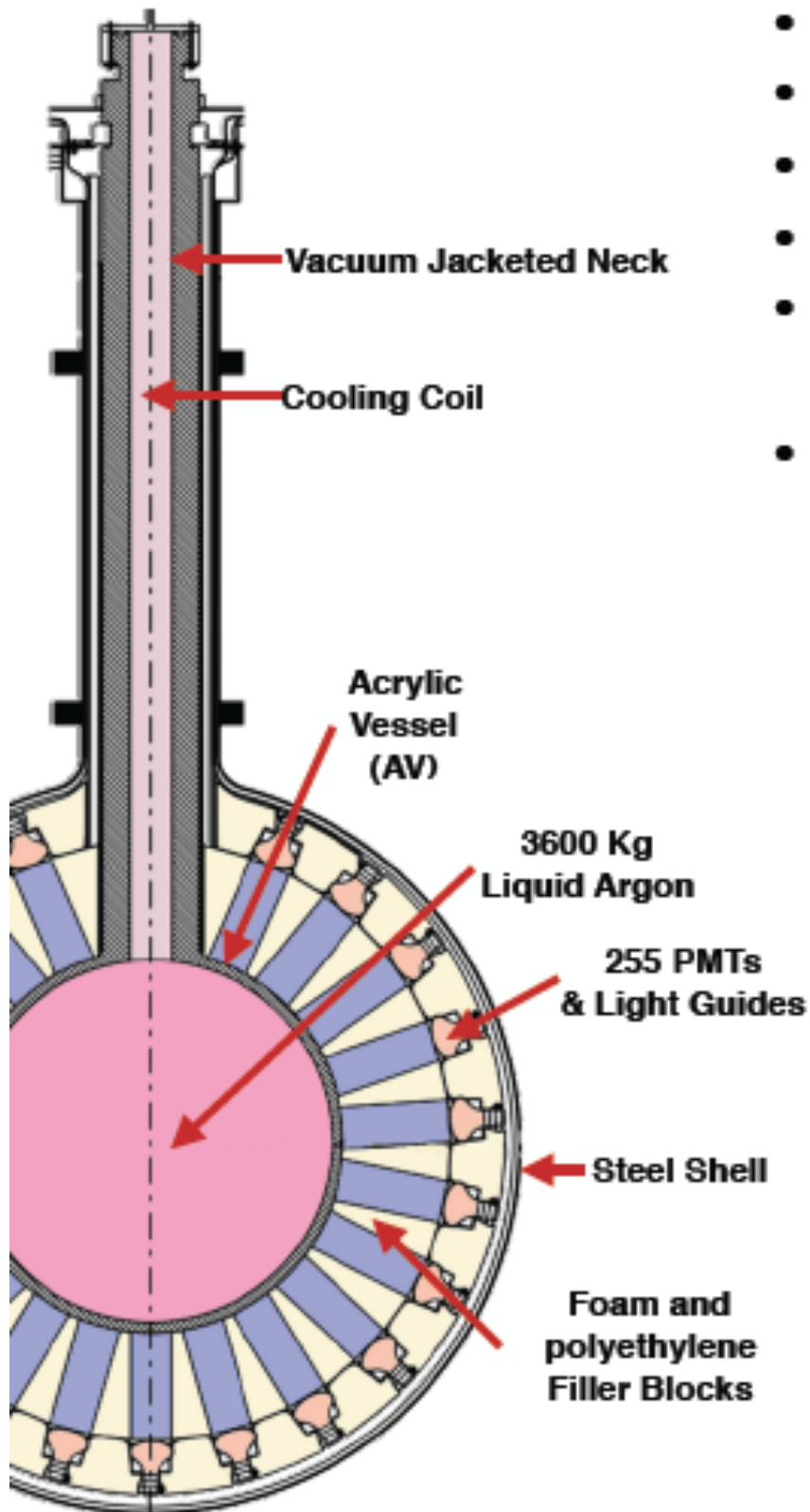
- Detect either on ly light or light and charge signals simulataniously produced by a particle interaction in the sensitive liquid target



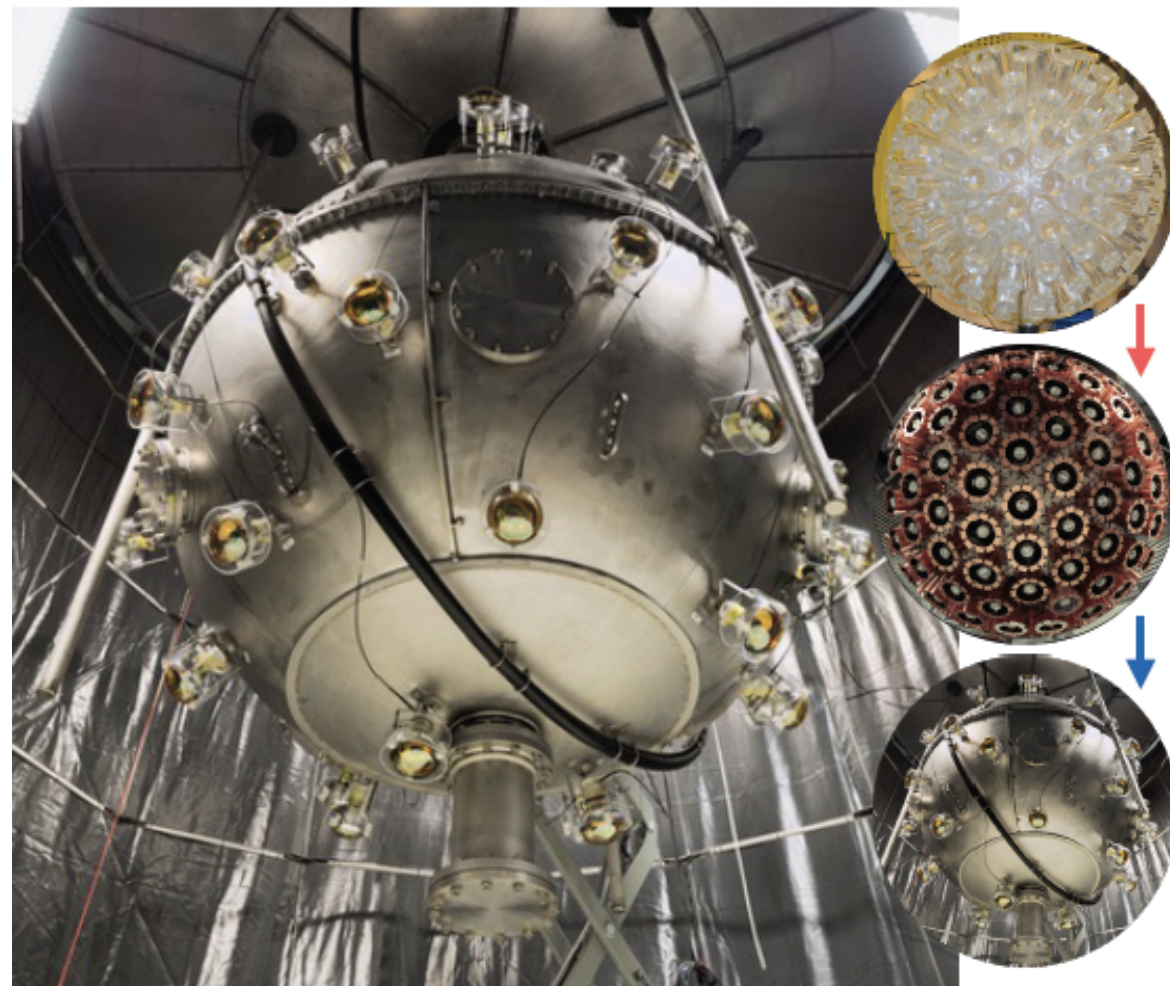
# Review of detection principles IV

A	element	Long lived Isotopes	S2/S1 separation	pulse-shape separation	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	<sup>39</sup> 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 experiment DEAP @ SNOLAB : DEAP-3600 - Ready for Physics Run!

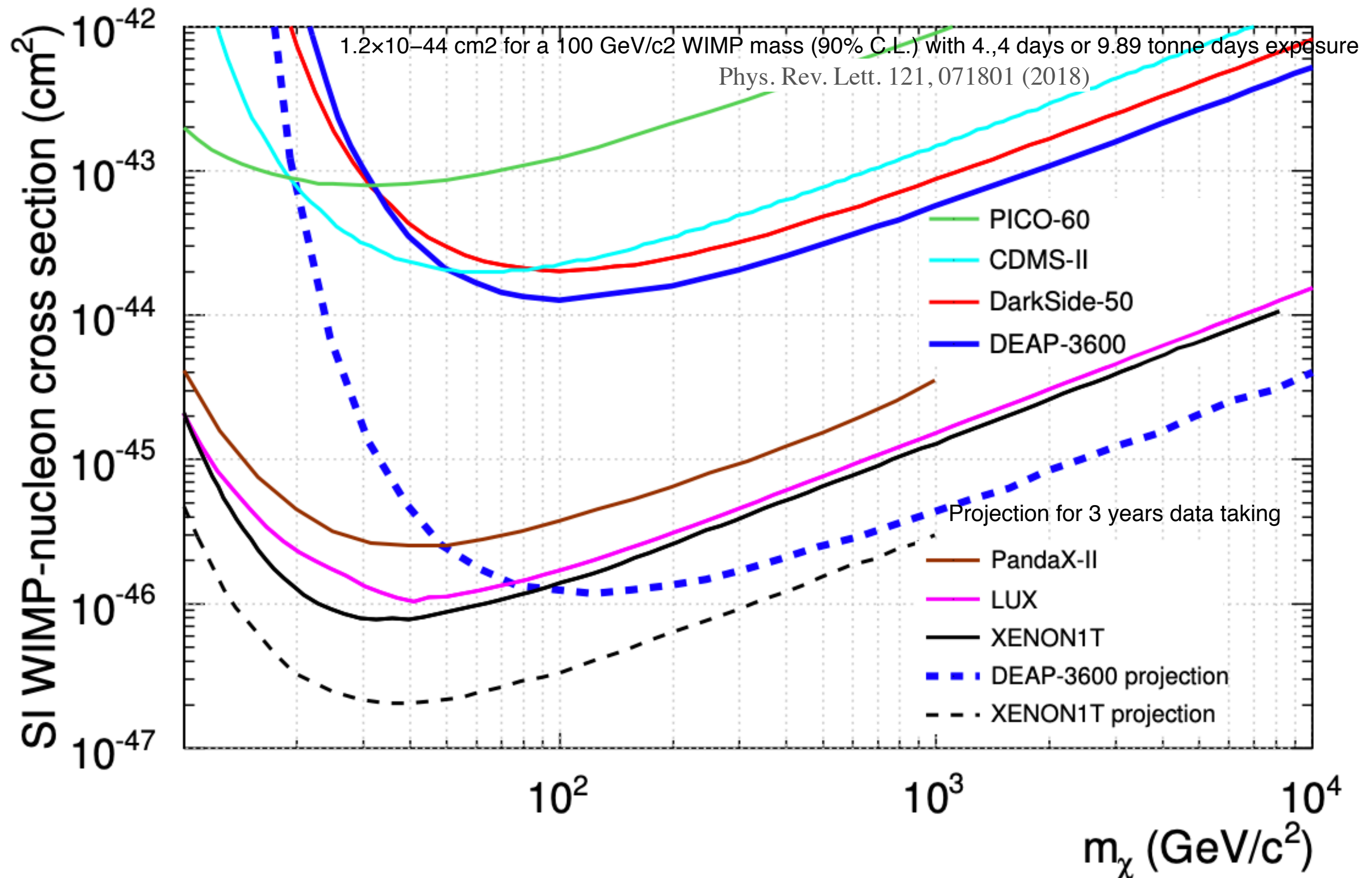


- Single phase LAr, 3.6 tonne (1 tonne fiducial).
- Spherical ultra-pure acrylic vessel (AV).
- 255 HQ Hamamatsu PMTs, coupled via acrylic light guides.
- Foam and polyethylene provide further shielding.
- 3  $\mu\text{m}$  layer of wavelength shifter (TPB) converts 128 nm scintillation light into the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





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

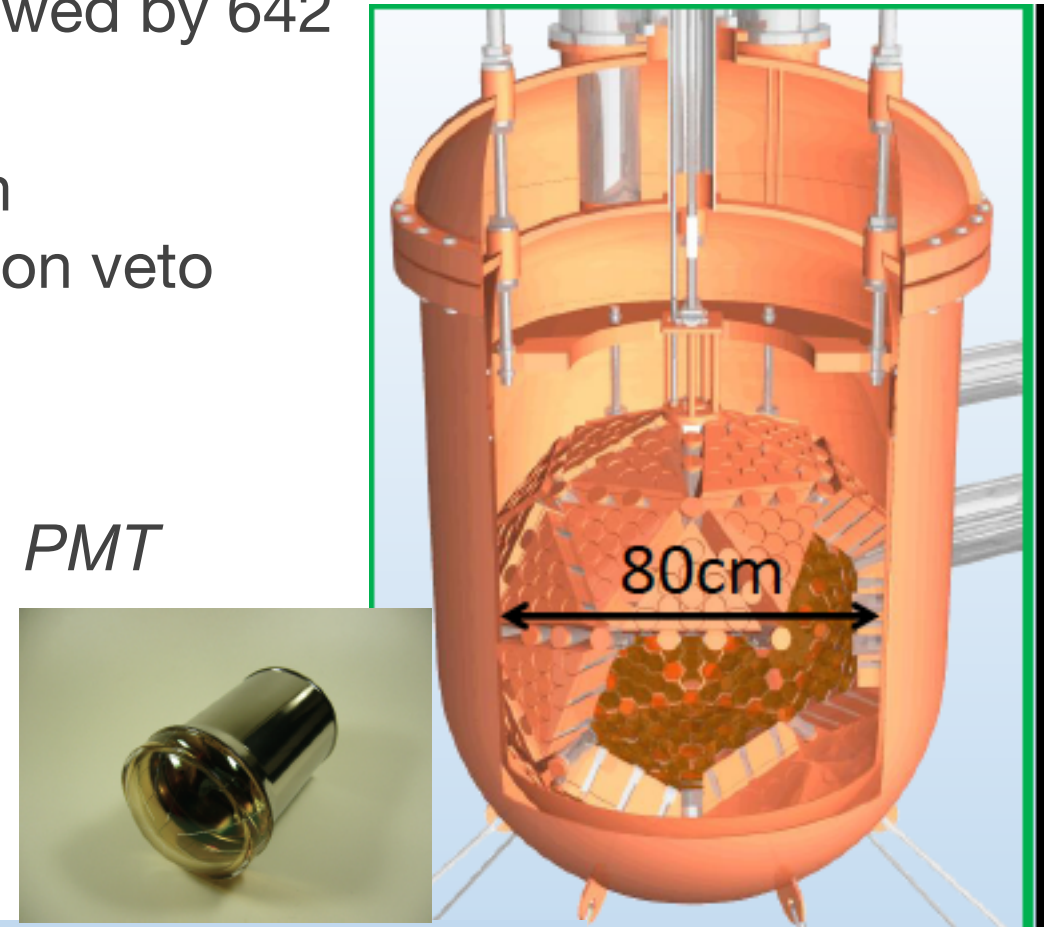
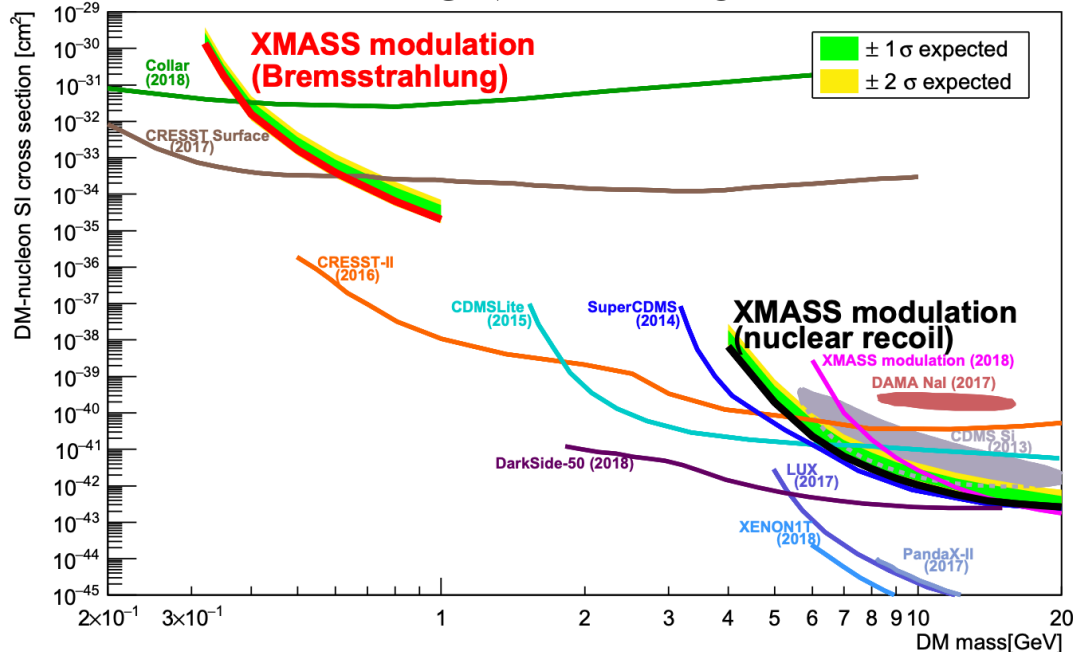


# XMASS @ Kamioka : present and future

- 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:  $\sim 10^{-47} \text{ cm}^2 @ 50 \text{ GeV}$  in 3-5 y*

$1.6 \times 10^{-33} \text{ cm}^2$  at 0.5 GeV/c<sup>2</sup> at 90% C.L.

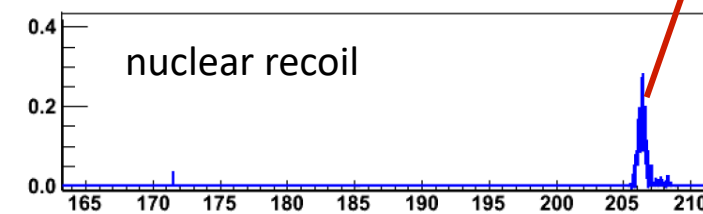
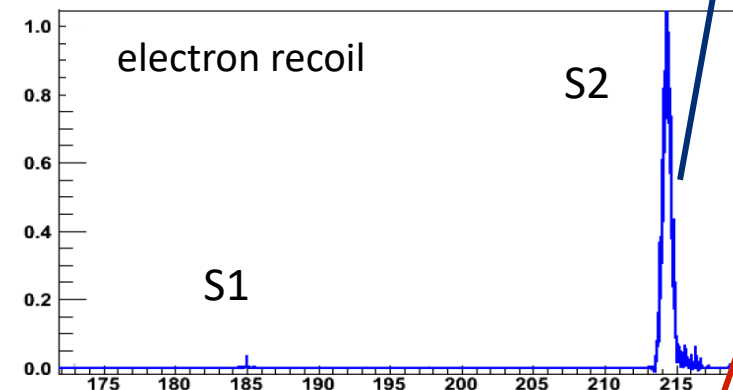
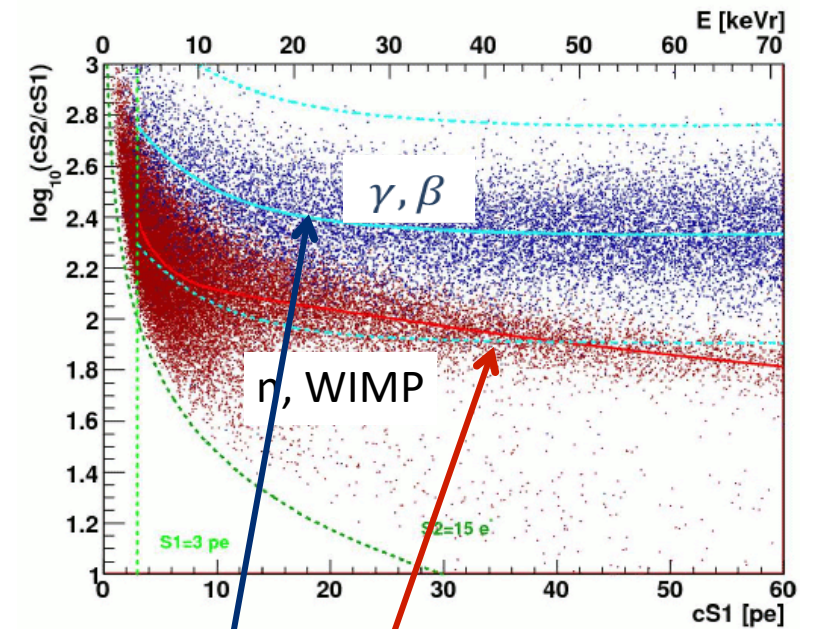
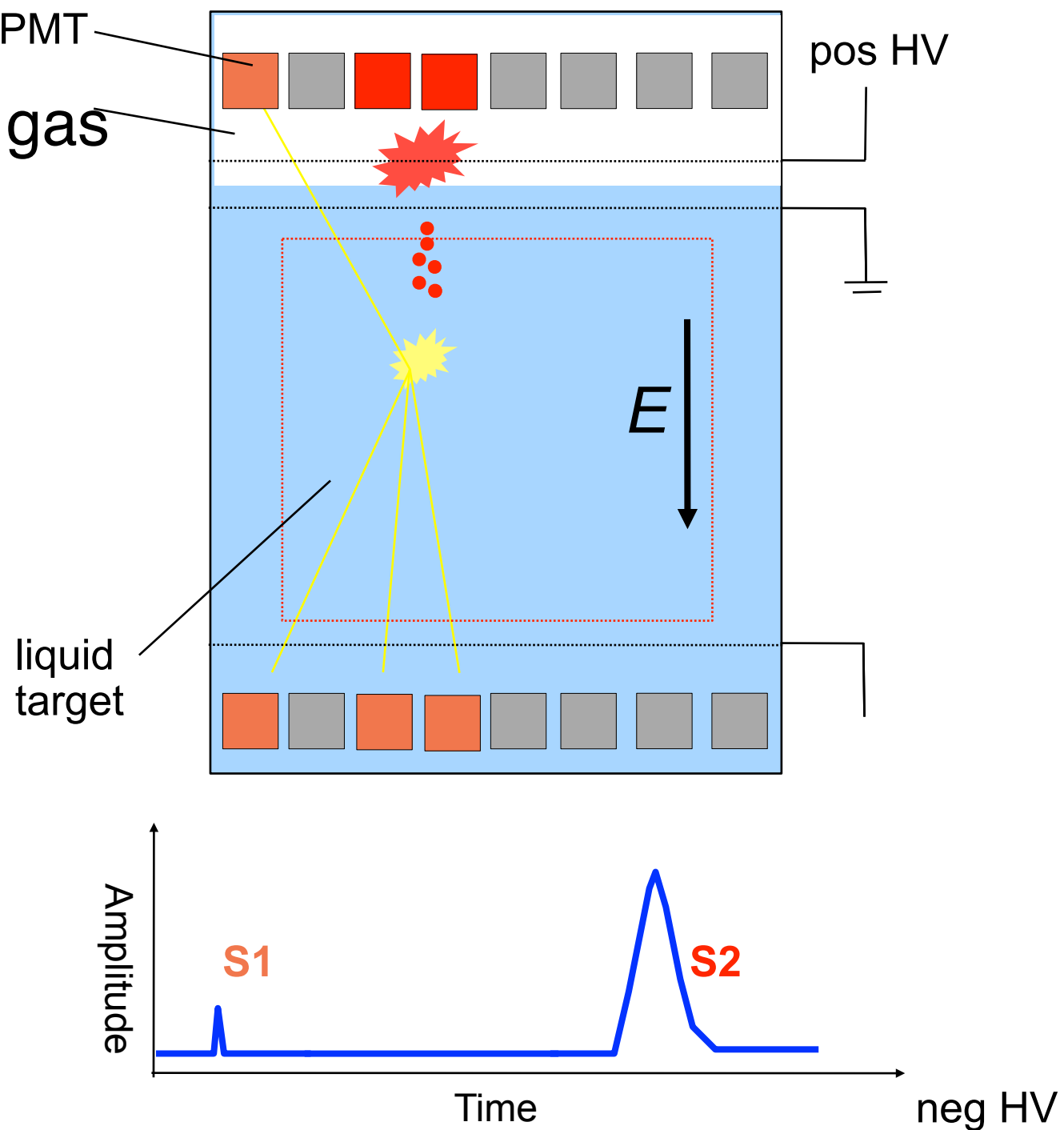
$2.9 \times 10^{-42} \text{ cm}^2$  at 8 GeV/c<sup>2</sup> at 90% C.L.



# Noble Liquid Detector Concepts

Time Projection Chamber (TPC)

a doppia fase



# Dual Phase TPC Experiments: present and future

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# 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)*

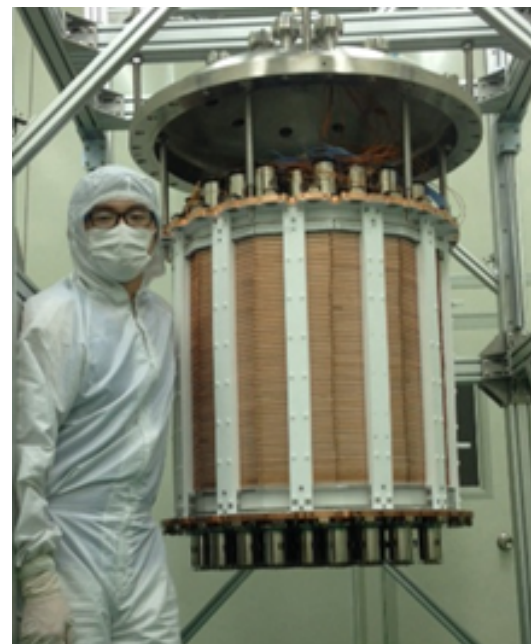
- latest result from 332 days presented at IDM2016
- **250 kg** LXe
- published first limit in 2013
- in 2013 - best world limit
- reanalysis published in 2016
- will be removed by 2017



## PandaX-II @ CJPL

*arXiv:1602.06563*

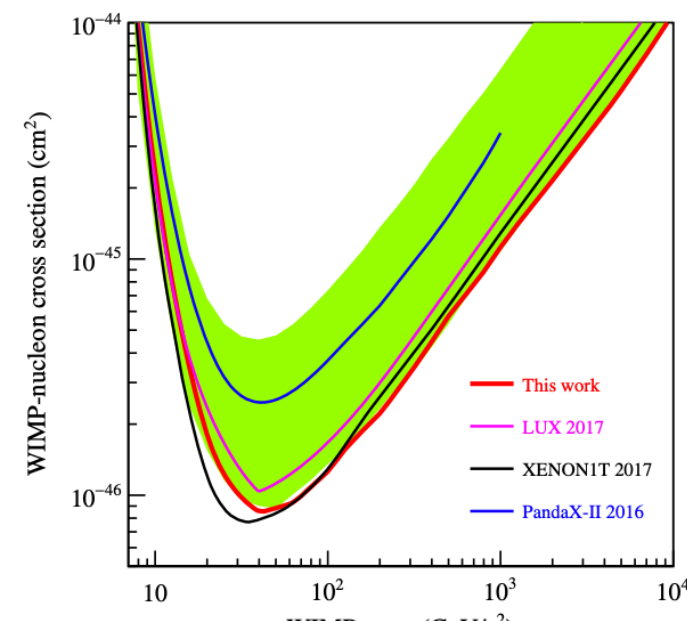
- at present largest LXe TPC
- still taking data
- new SS cryostat  
→ lower radioactivity
- TPC: 60cm×60cm,  
**400 kg target**



*New result from 98.7 days:*

- *Best upper limit :*
- $2.5 \times 10^{-46} \text{ cm}^2$  at 40 GeV

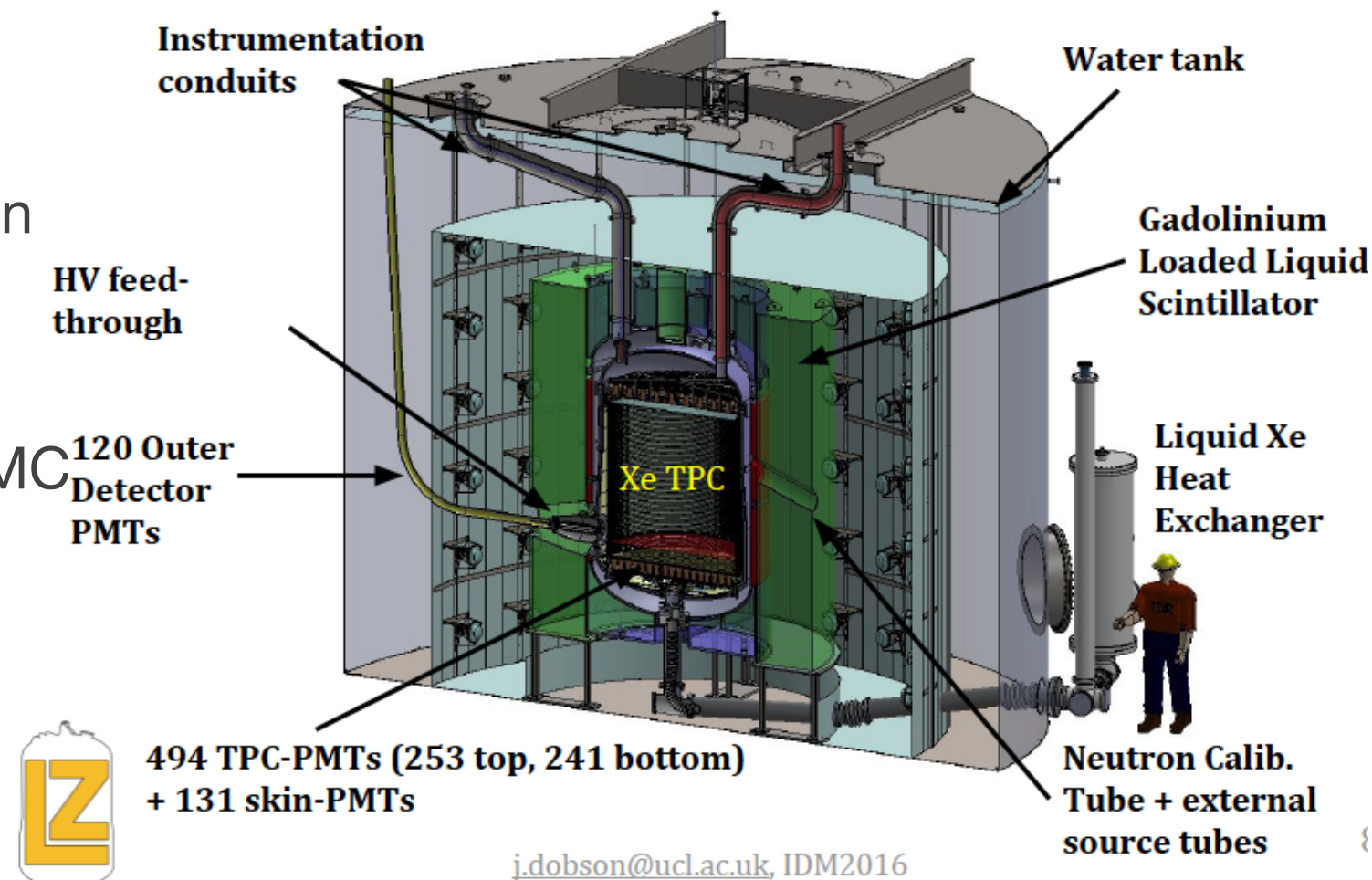
*arXiv:1607.07400v1*



# 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):**

-  $3 \times 10^{-48} \text{ cm}^2 \text{ at } 40 \text{ GeV}$

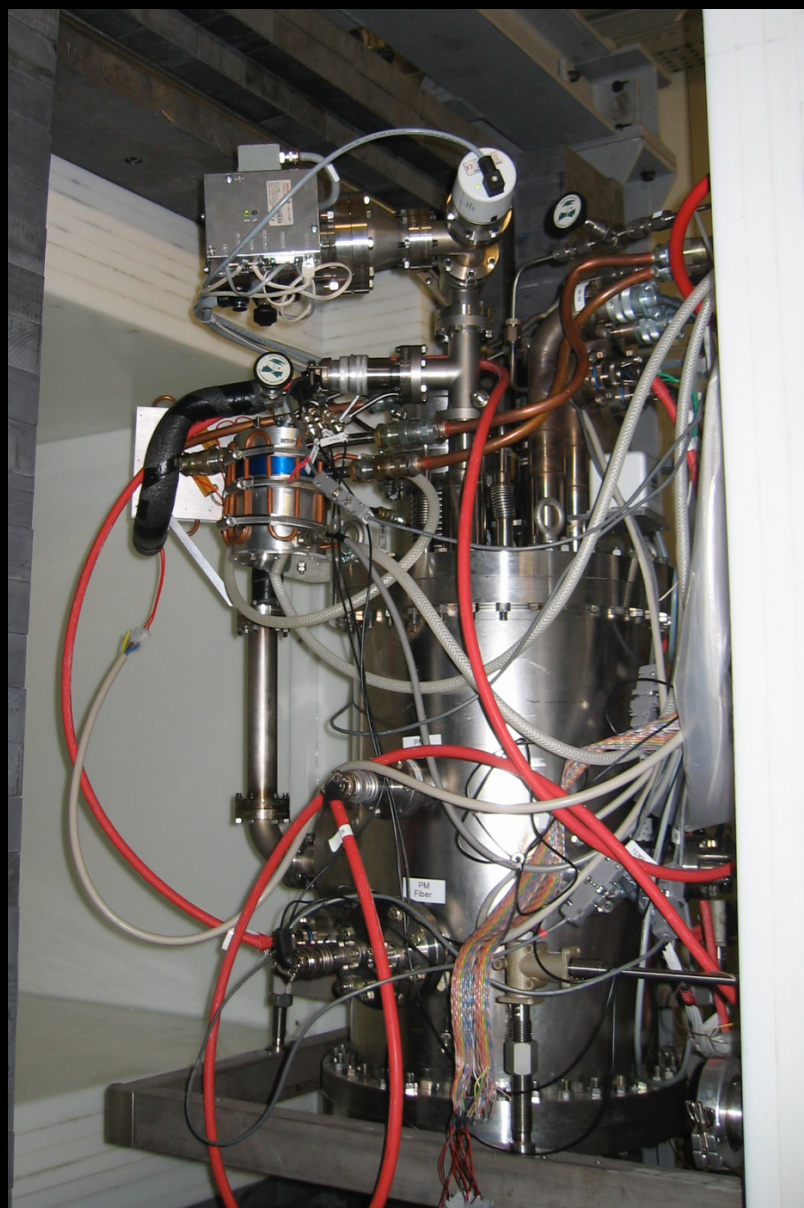




# XENON @ LNGS - present and future



2005-2007



**XENON10**

15 cm drift TPC - 25 kg  
 $\sim 10^{-43} \text{ cm}^2$

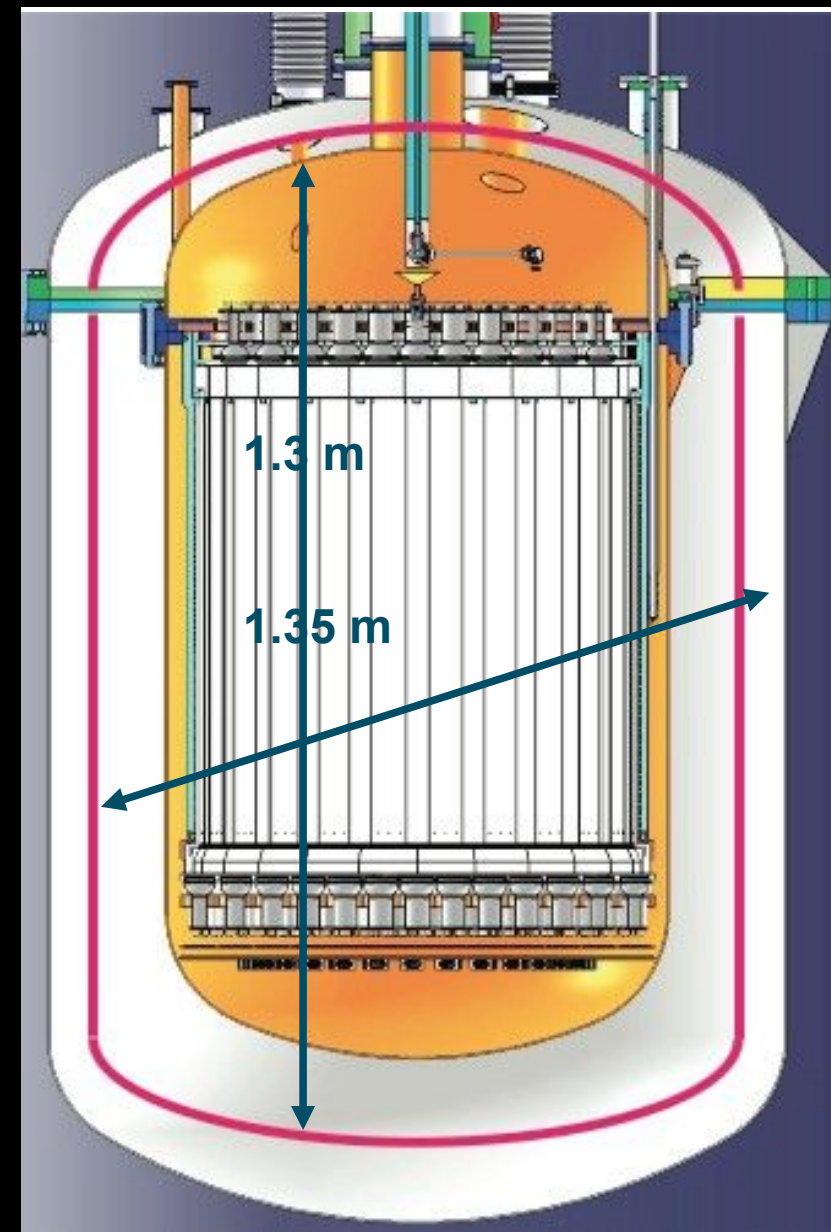
2007-2015



**XENON100**

30 cm drift TPC - 161 kg  
 $\sim 10^{-45} \text{ cm}^2$

2012-2022



**XENON1T/XENONnT**

100 cm drift TPC - 3500 kg/7000 kg  
 $\sim 10^{-47} \text{ cm}^2 / 10^{-48} \text{ cm}^2$



# 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:**  $4.1 \times 10^{-47} \text{ cm}^2 @ 30 \text{ GeV}$  in 1 ty





# The XENON1T experiment: inner detector

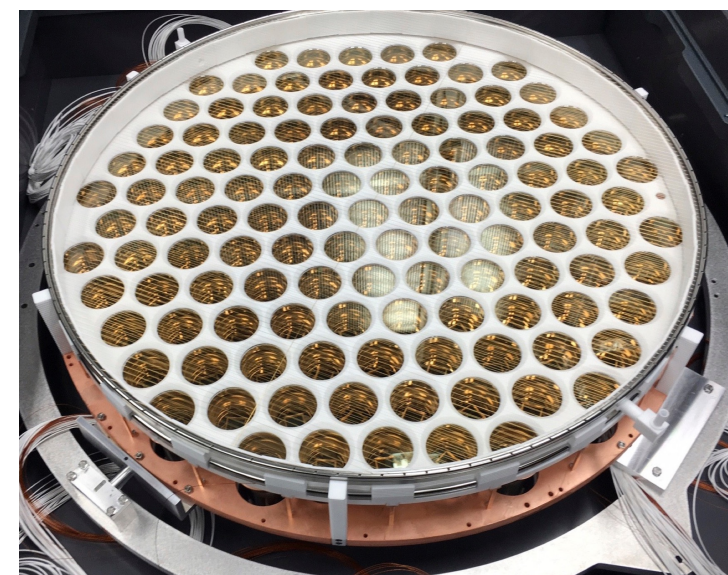
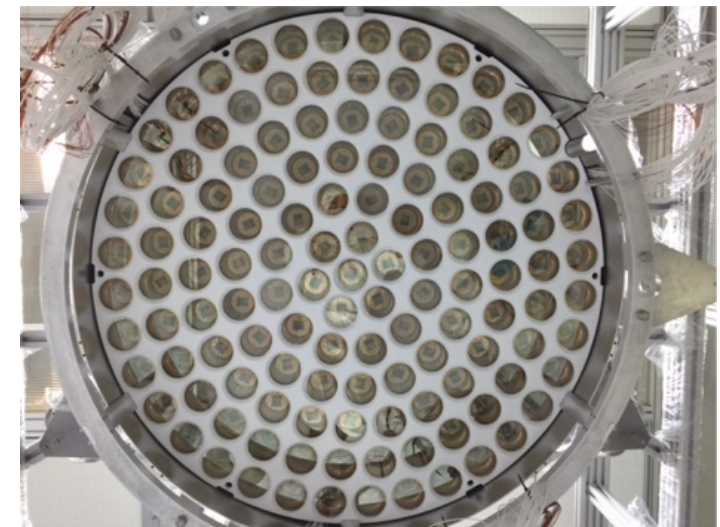
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The TPC



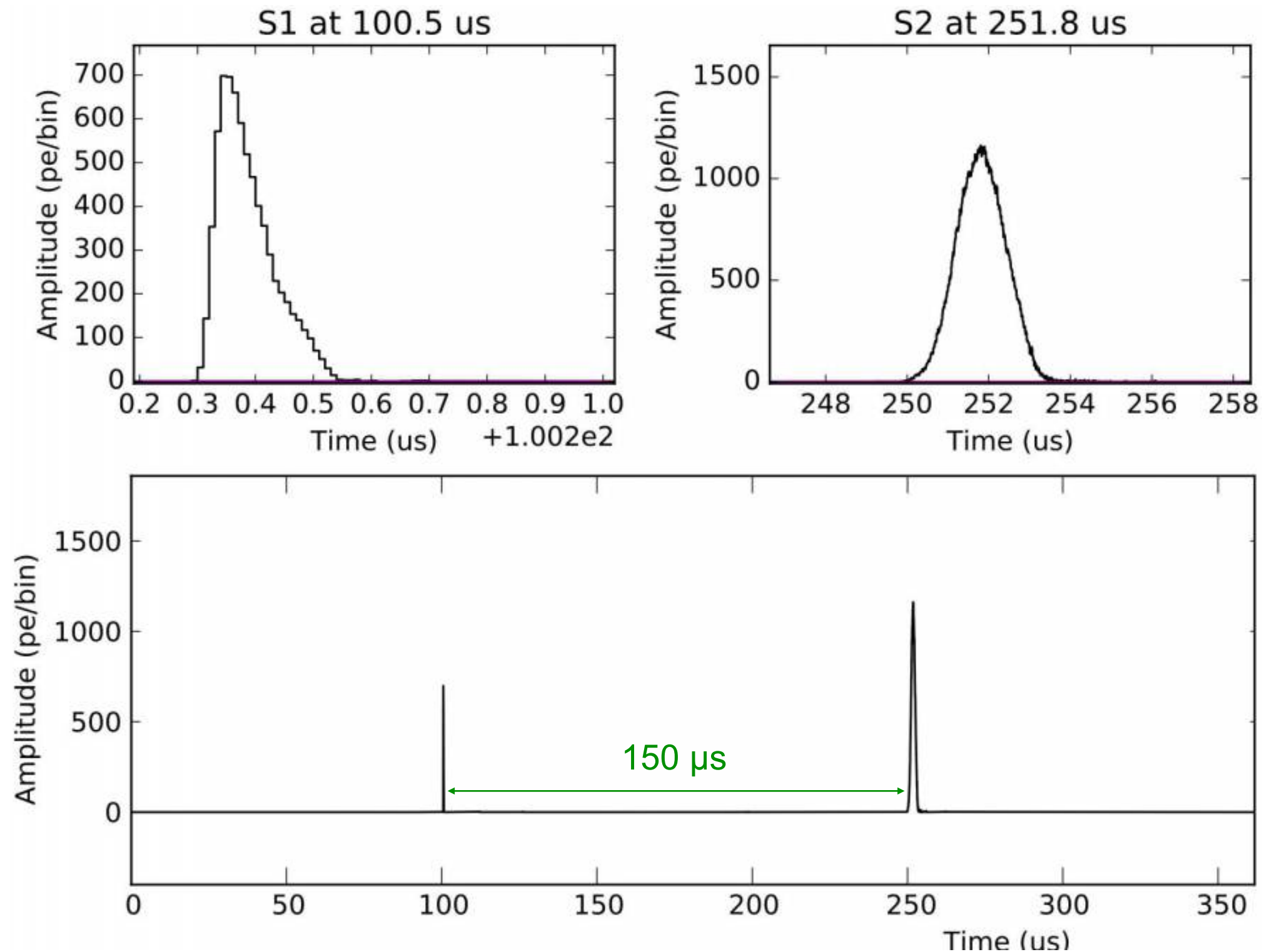
TPC installation underground



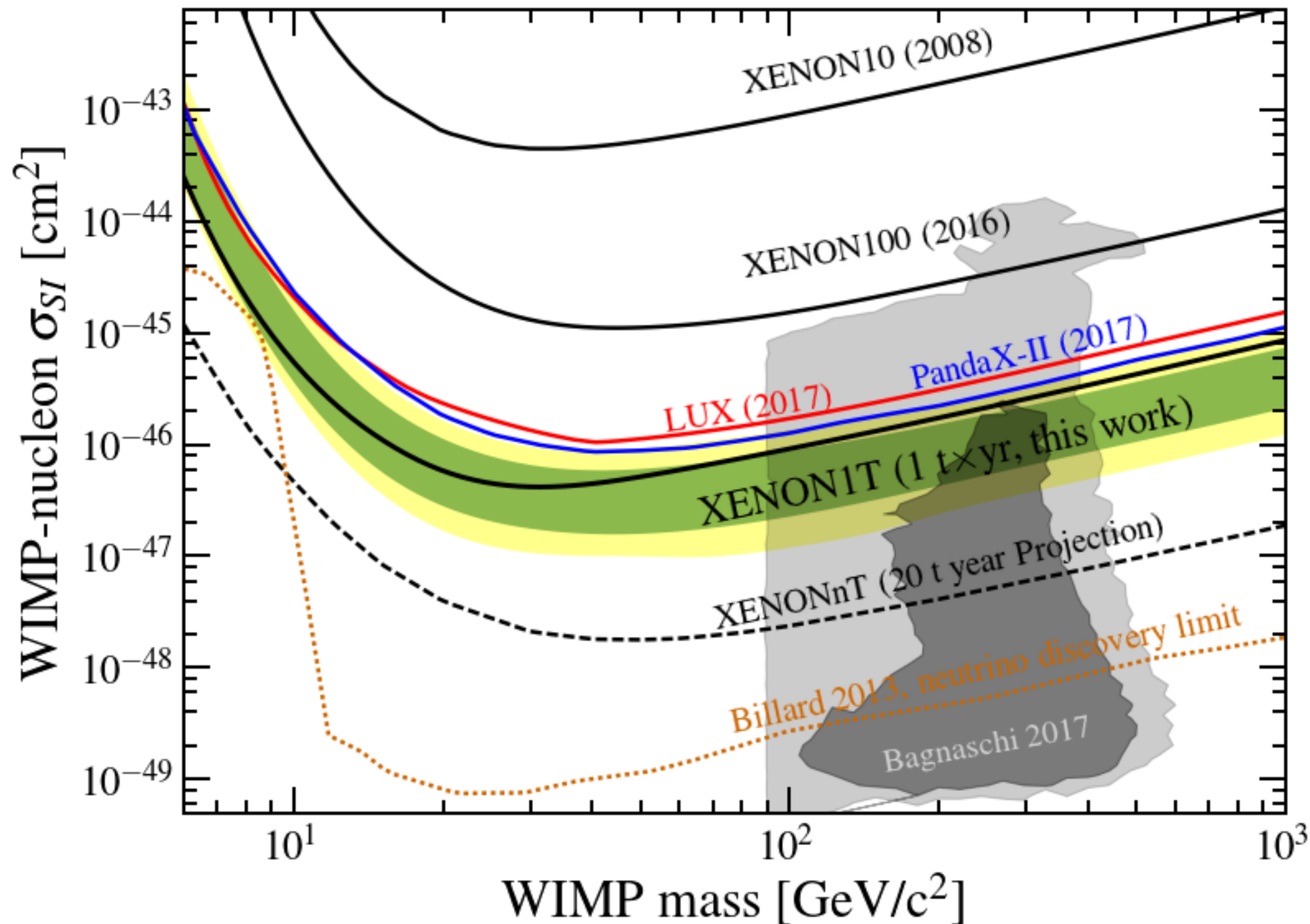
PMT arrays



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



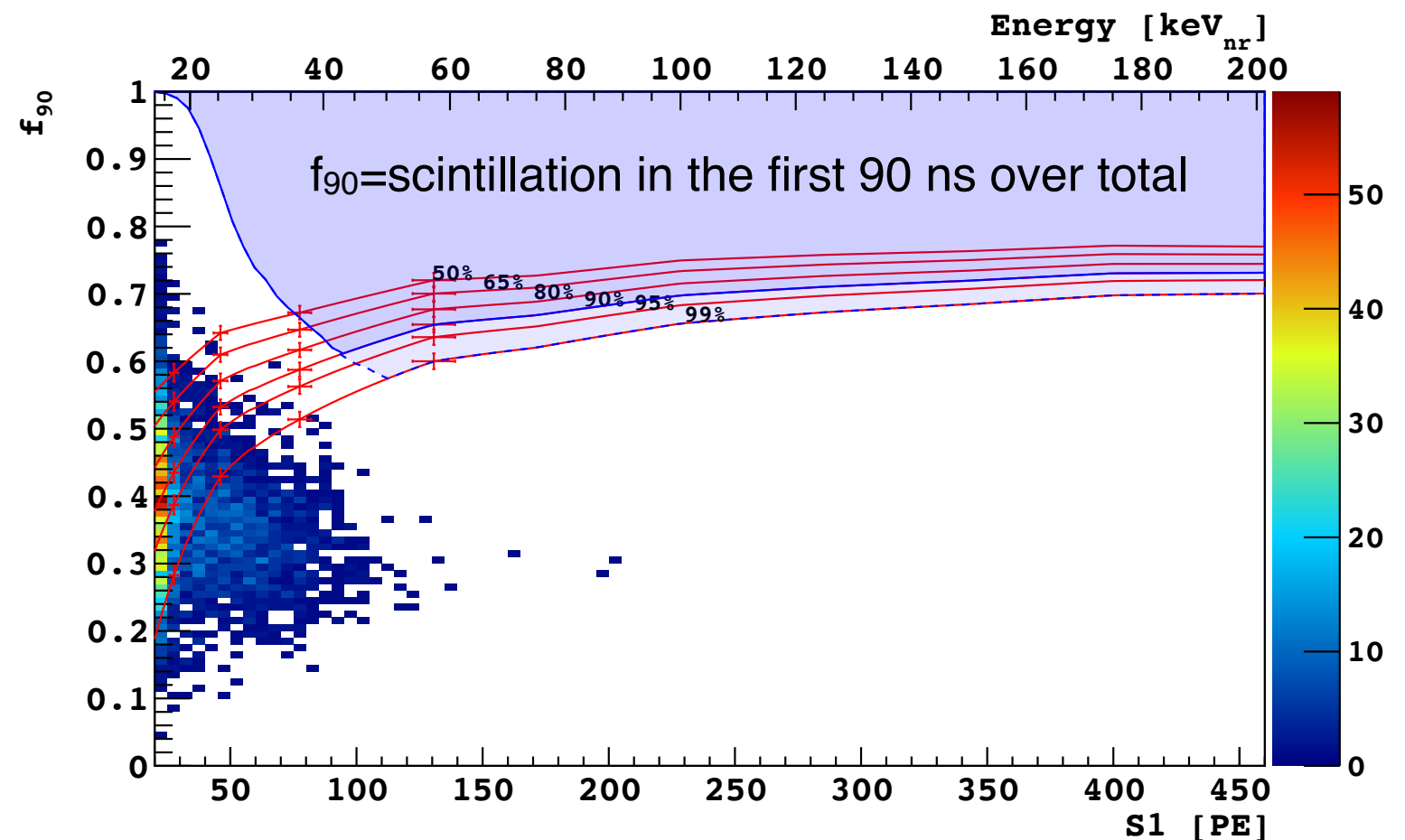
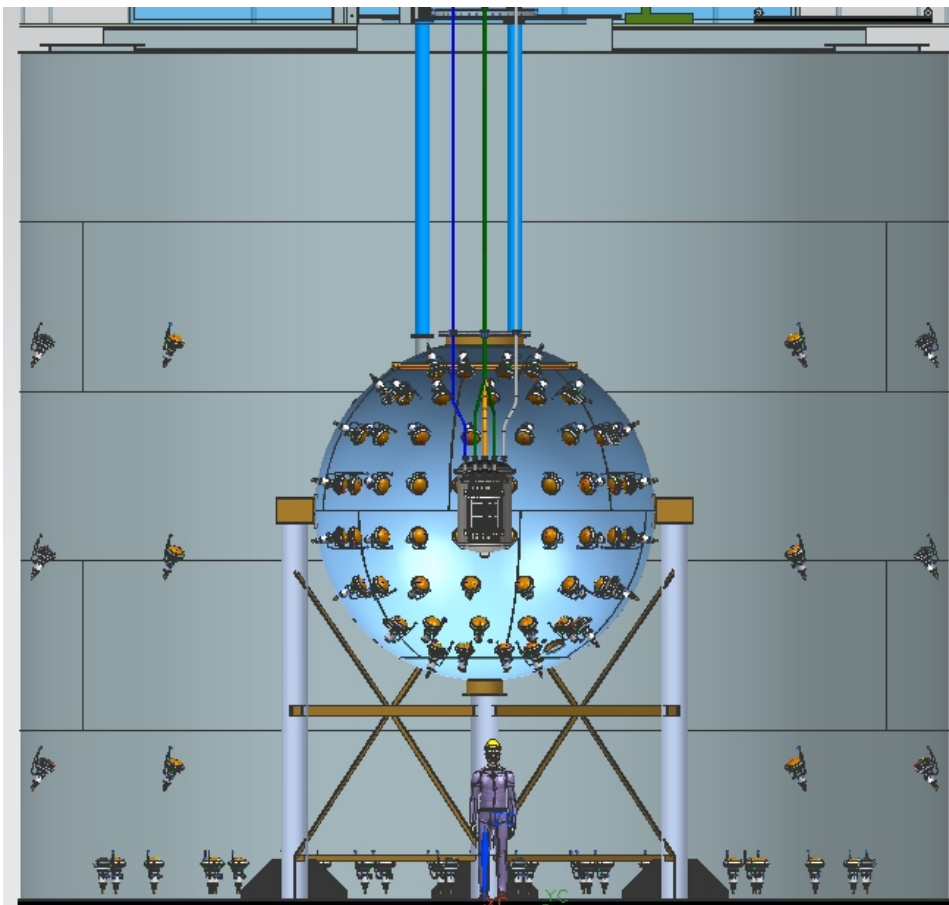
# XENON1T latest results and XENONnT\_expected sensitivity





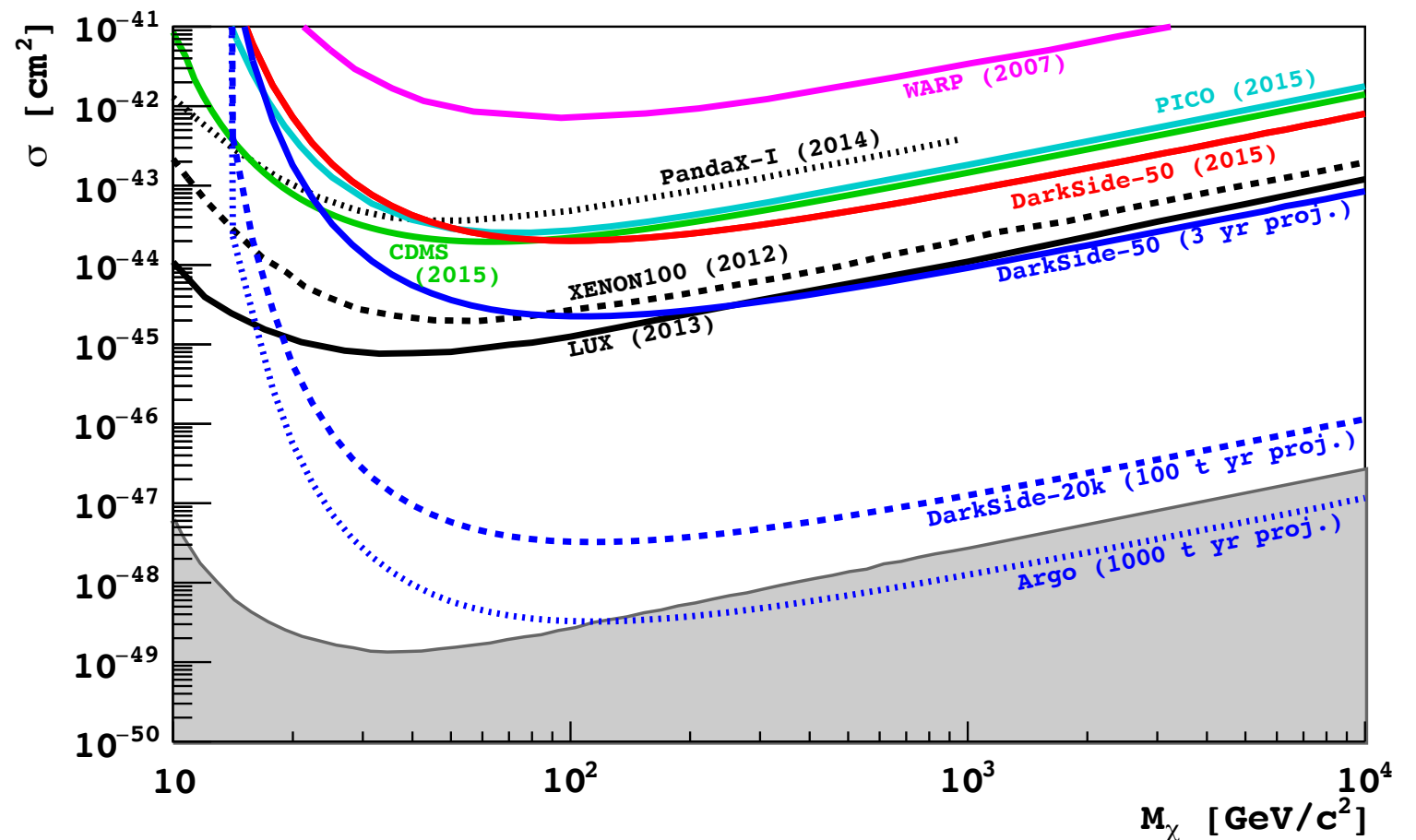
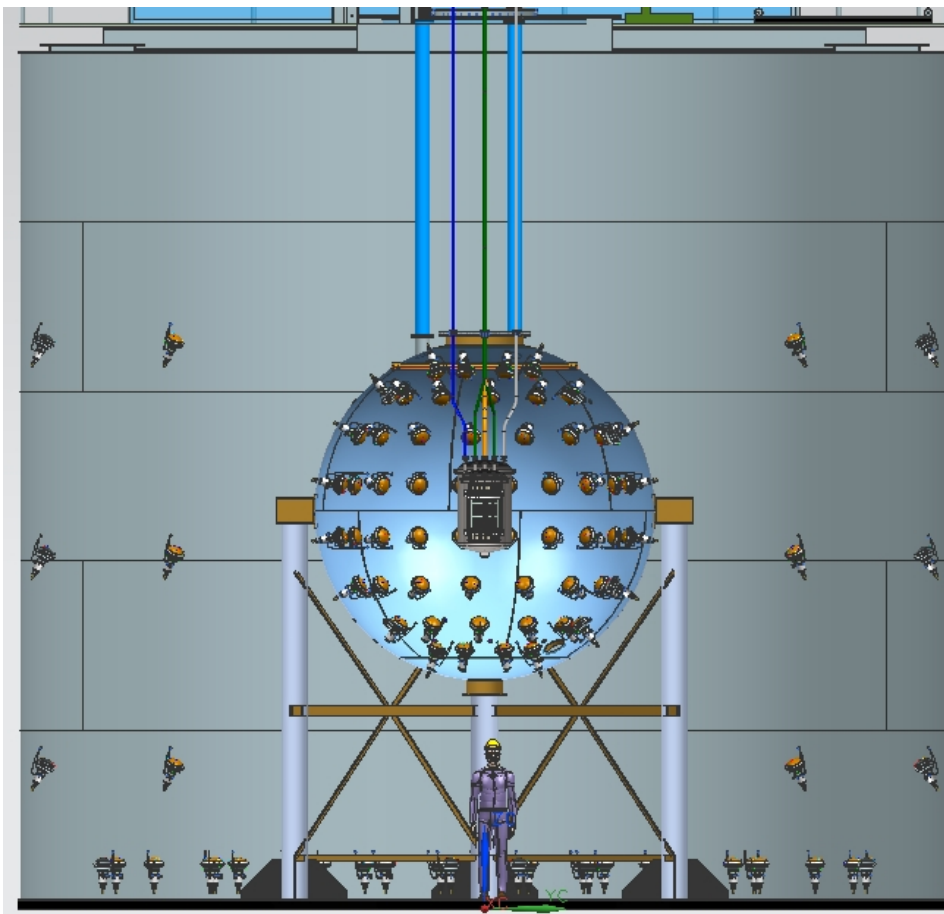
# DarkSide @ LNGS : present and future

- Dark Side 50: dual phase TPC with 46 kg  $^{39}\text{Ar}$ -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  $\rightarrow$  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

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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