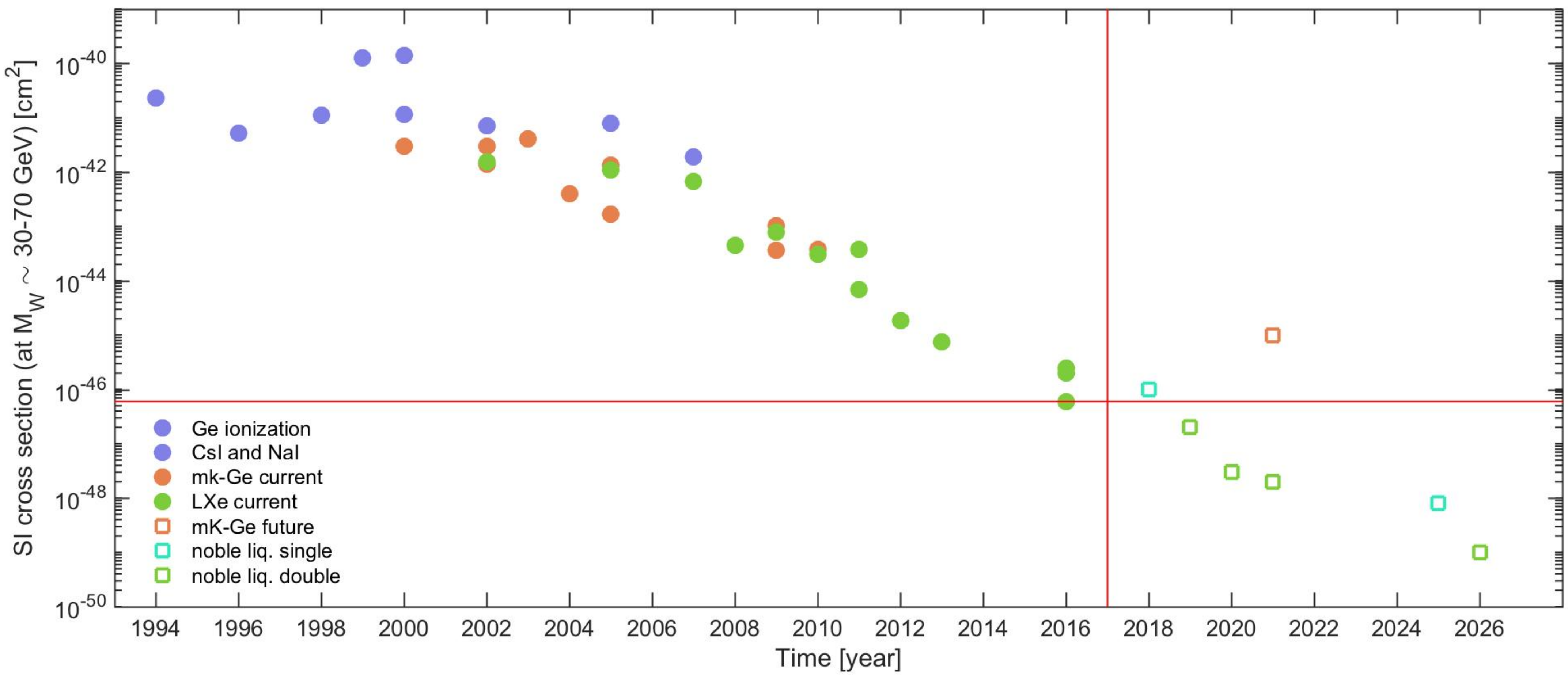
Universität Zürich[UZH]

Direct dark matter detection - an overview



Laura Baudis
University of Zurich

ZPW17
ETH Zurich, January 10, 2017

Direct dark matter detection

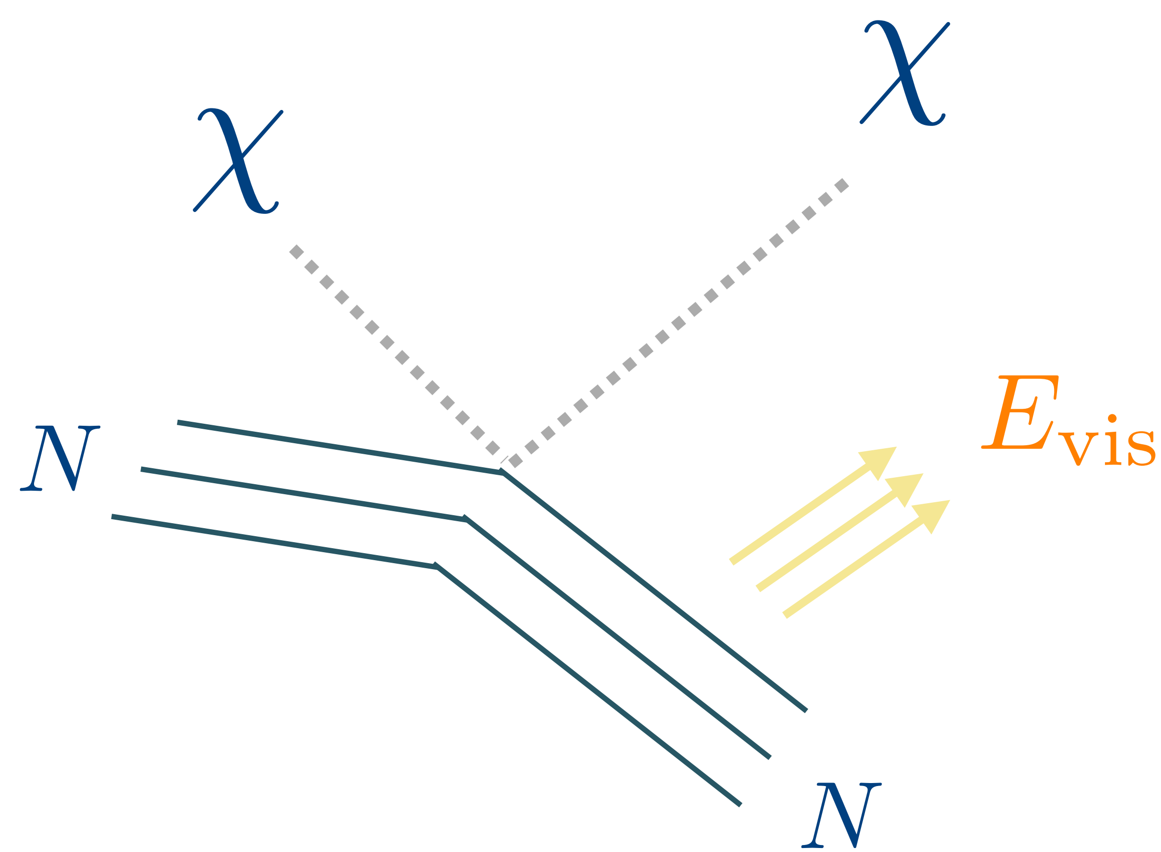
Collisions of invisibles particles with atomic nuclei* => E_{vis} (q ~ tens of MeV):

very low energy thresholds

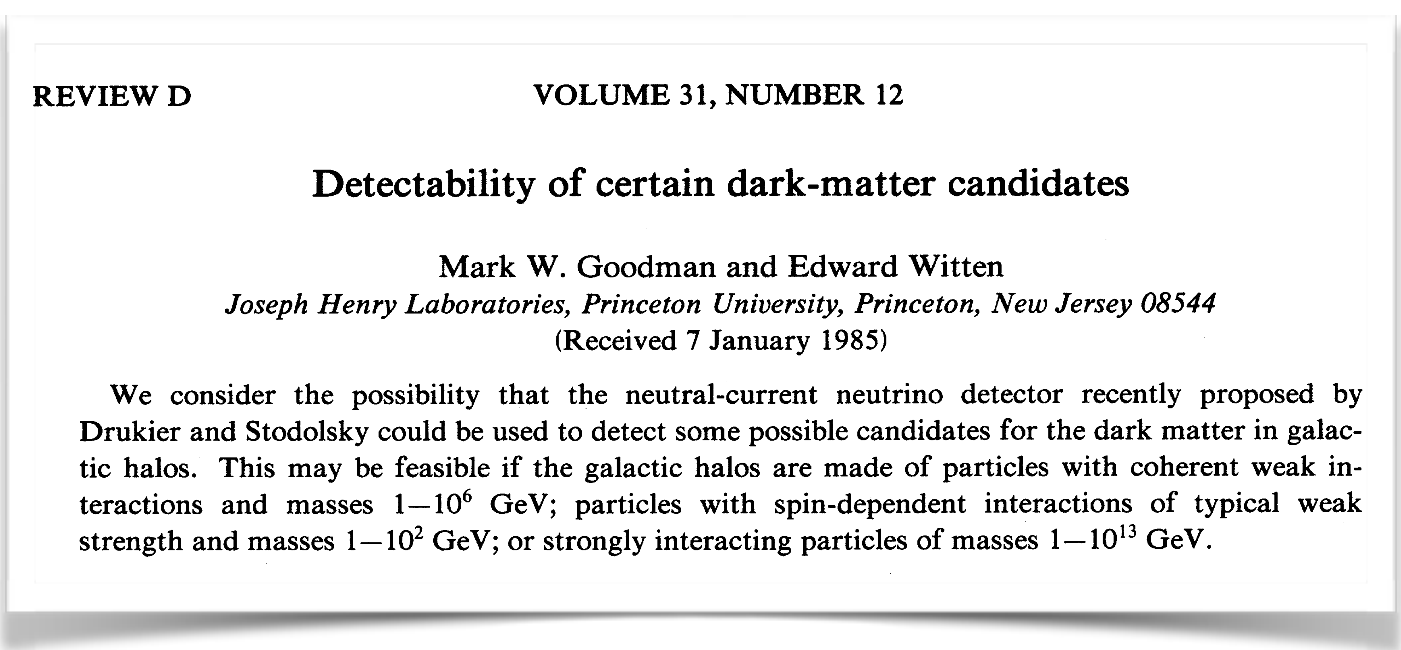
ultra-low backgrounds, good background understanding (no "beam off" data collection mode), and particle ID

large detector masses

$$v/c \sim 0.75 \times 10^{-3}$$



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


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.

* also with electrons

Rates in a terrestrial detector

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

Detector physics

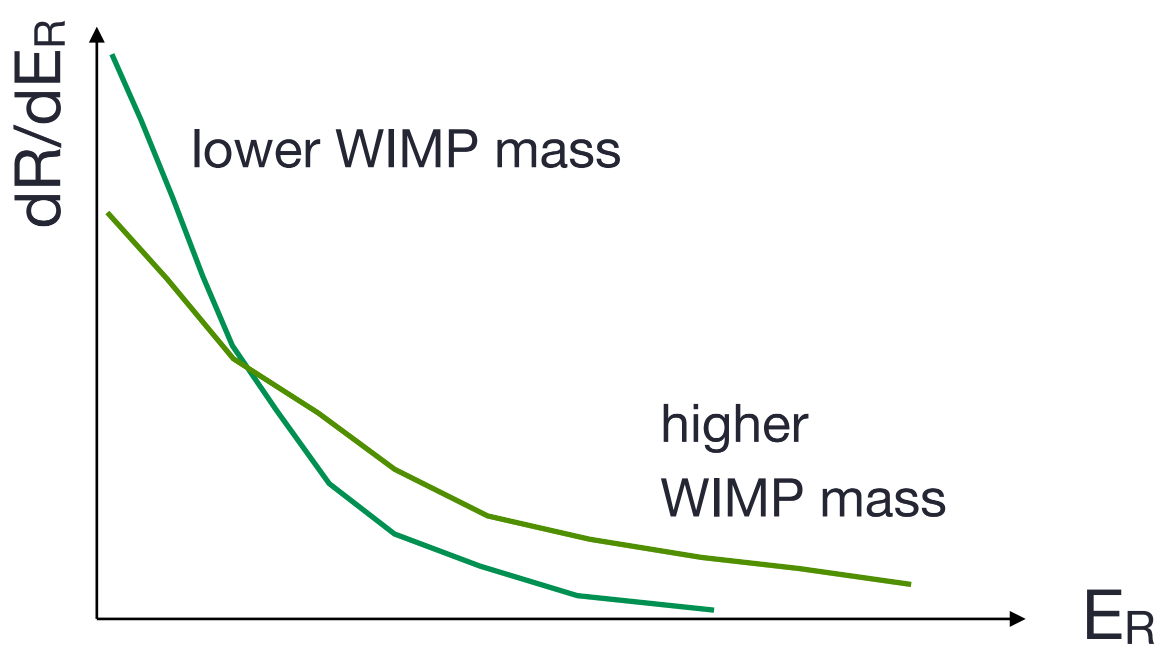
N_N, E_{th}

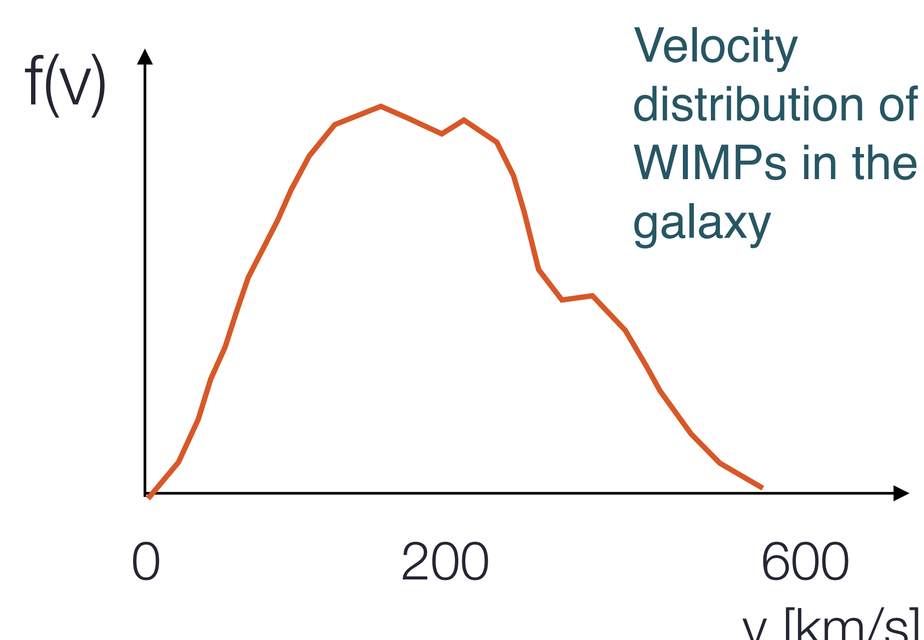
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$





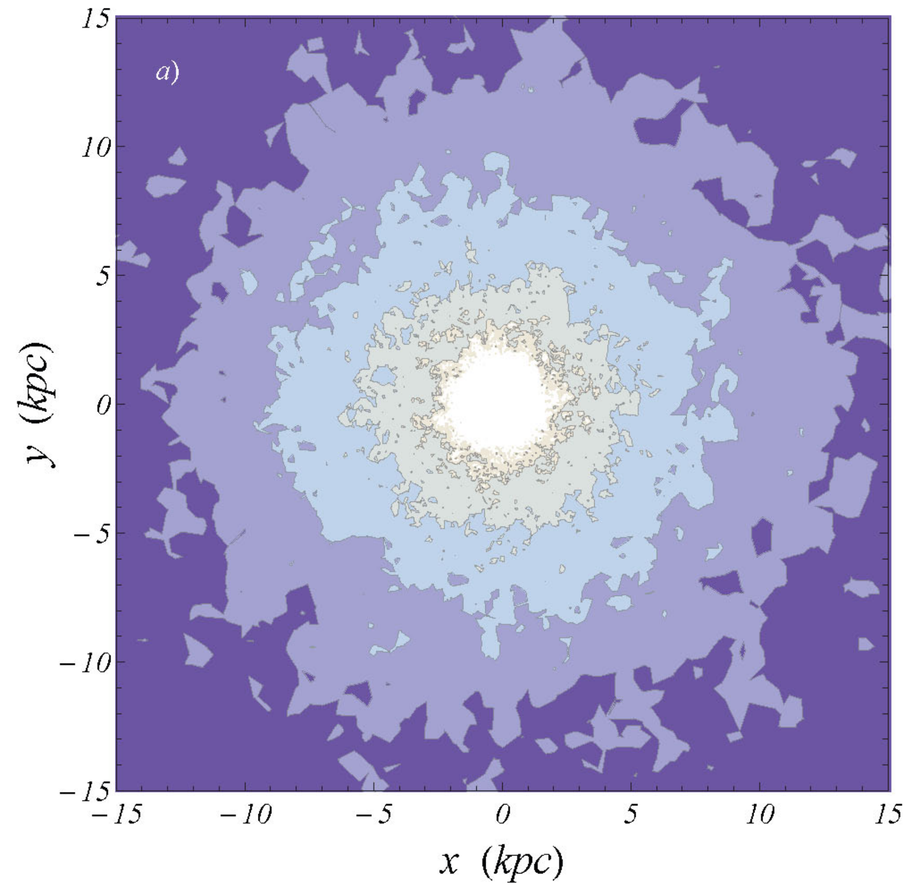
Astrophysics

Local density (at R_0 ~ 8 kpc)

local measures use the vertical kinematics of stars near the Sun as 'tracers' (smaller error bars, but stronger assumptions about the halo shape)

global measures extrapolate the density from the rotation curve (larger errors, but fewer assumptions)

Density map of the dark matter halo
rho = [0.1, 0.3, 1.0, 3.0] GeV cm^{-3}



High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$$

J. Read, Journal of Phys. G41 (2014) 063101

=> **WIMP flux on Earth: ~10^5 $cm^{-2}s^{-1}$** (M_W=100 GeV, for 0.3 GeV cm^{-3})

Particle physics

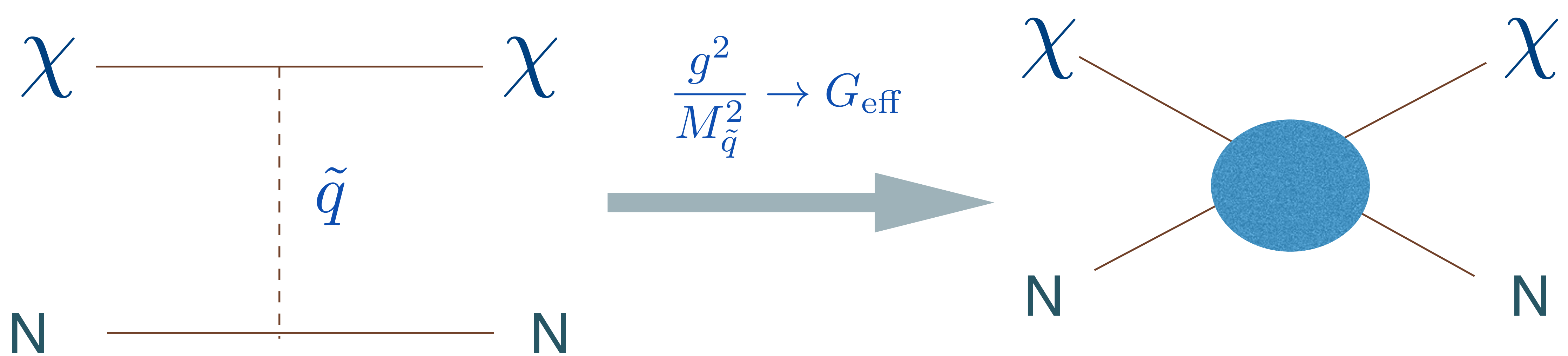
- Use effective operators to describe WIMP-quark interactions

- **Example: vector mediator**

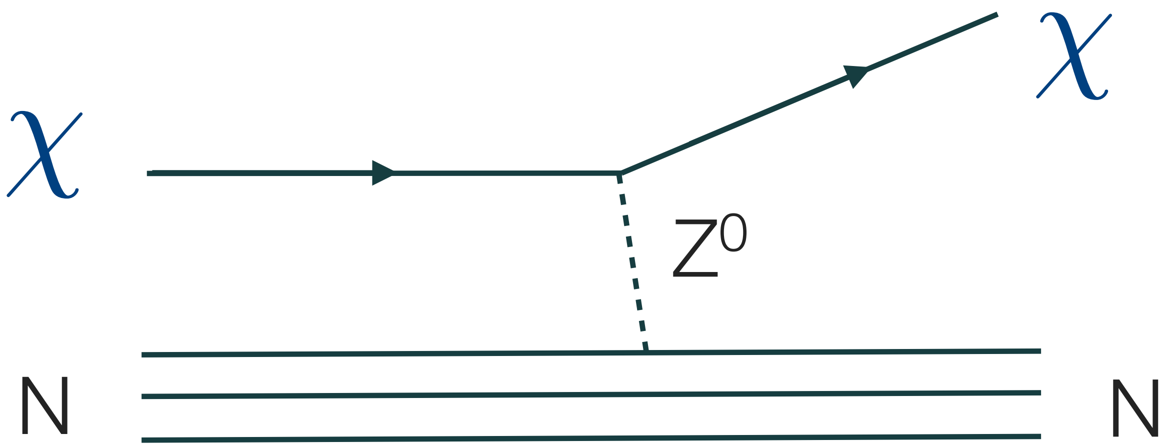
contact interaction scale

$$\mathcal{L}_{\chi}^{\rm eff} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q \qquad \Lambda = \frac{M}{\sqrt{g_q g_\chi}} \Rightarrow \sigma_{\rm tot} \propto \Lambda^{-4}$$

- The effective operator arises from “integrating out” the *mediator with mass M and couplings g_q and g_χ to the quark and the WIMP*

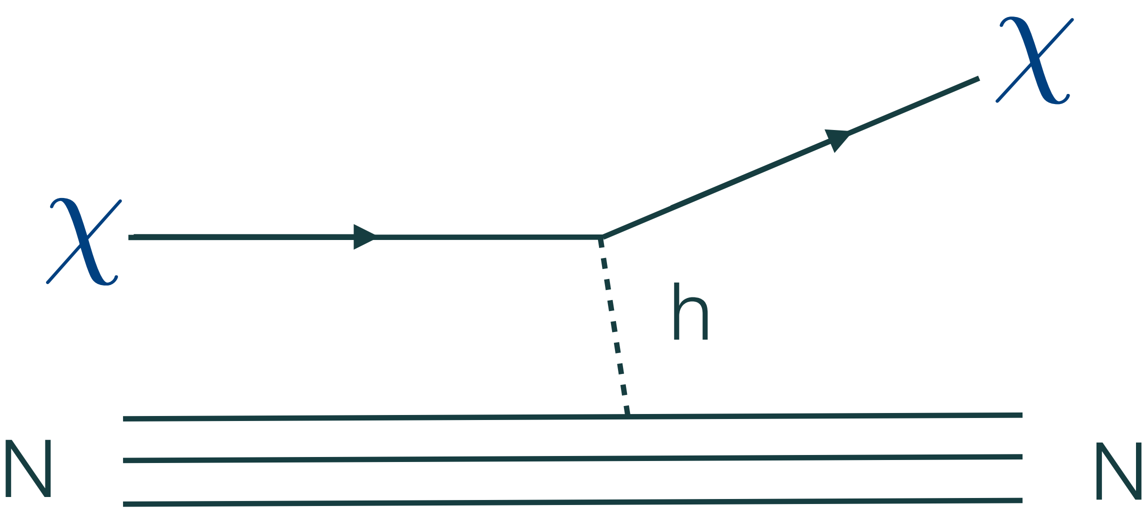


WIMP-nucleus example cross sections



$\sigma_0 \sim 10^{-39}\mathrm{cm}^2$

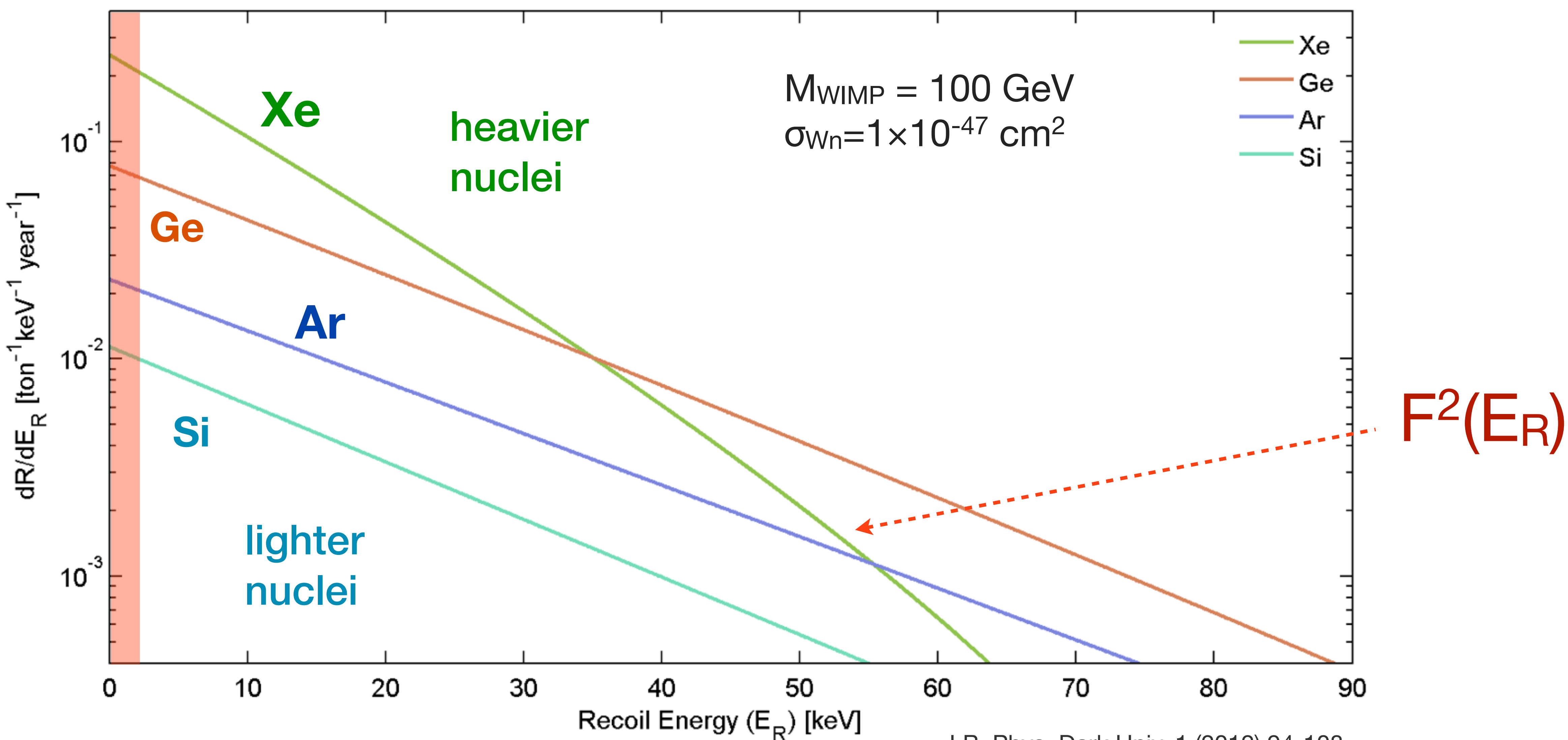
Excluded by direct detection experiments



$\sigma_0 \sim 10^{-44} - 10^{-47}\,\mathrm{cm}^2$

Expected interaction rates

$$R \sim 0.13\ \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\,\text{cm}^{-3}} \right]$$

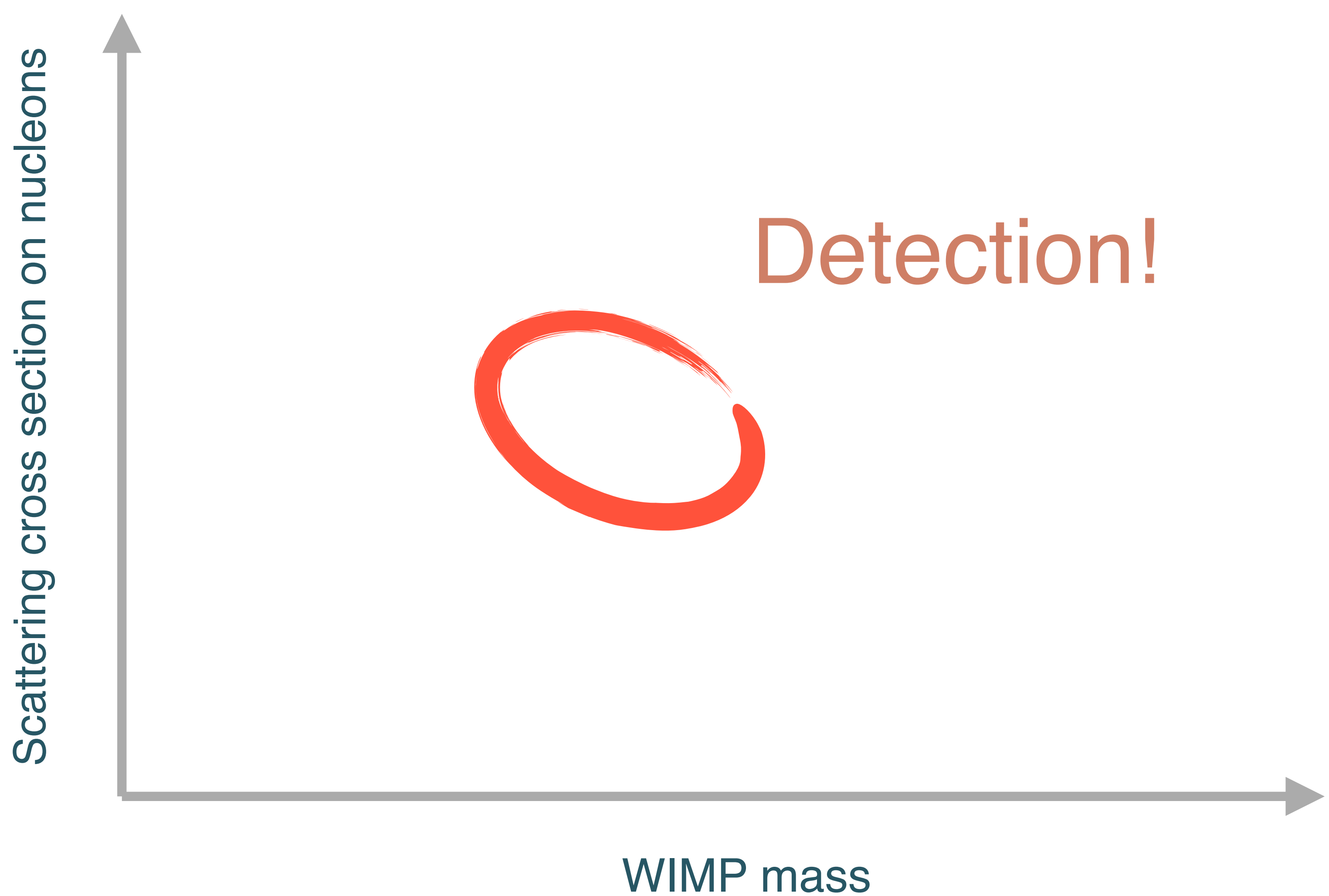


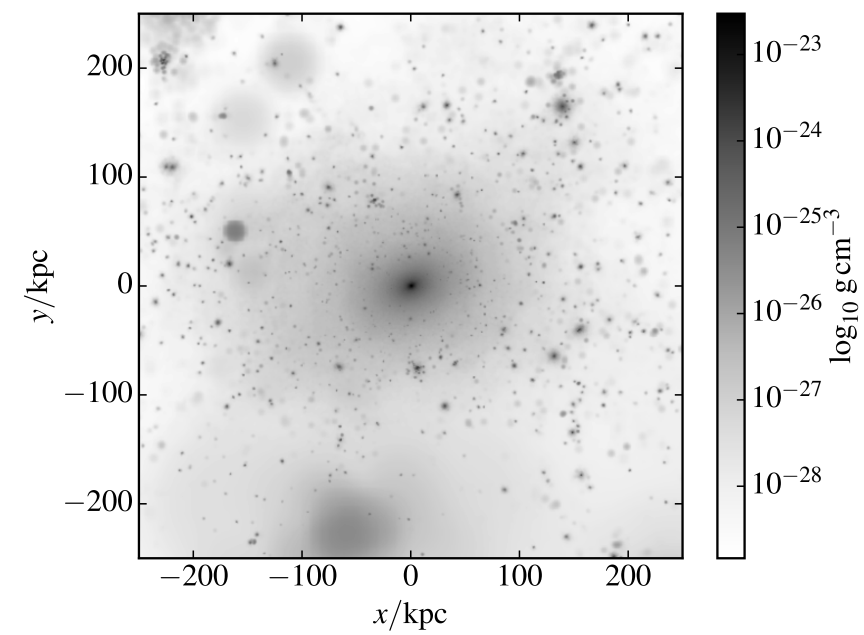
LB, Phys. Dark Univ. 1 (2012) 94-108

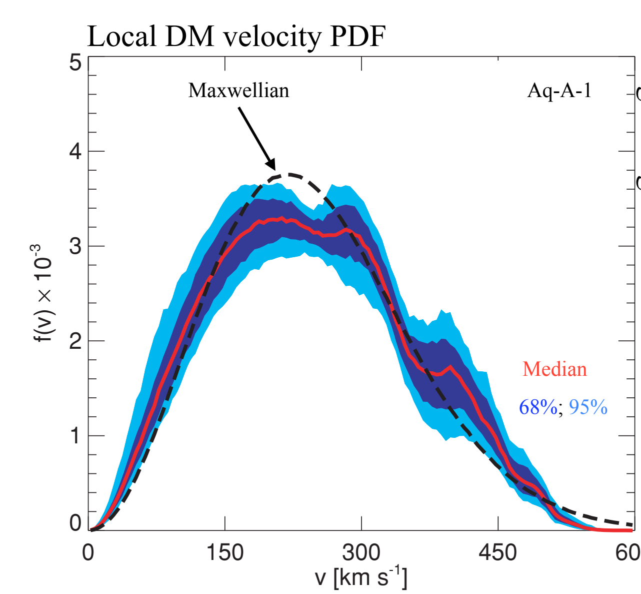
What can we learn about WIMPs?

- Constraints on the mass and scattering cross section

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}}^{v_{max}} dv\, f(v) v \frac{d\sigma}{dE_R}$$





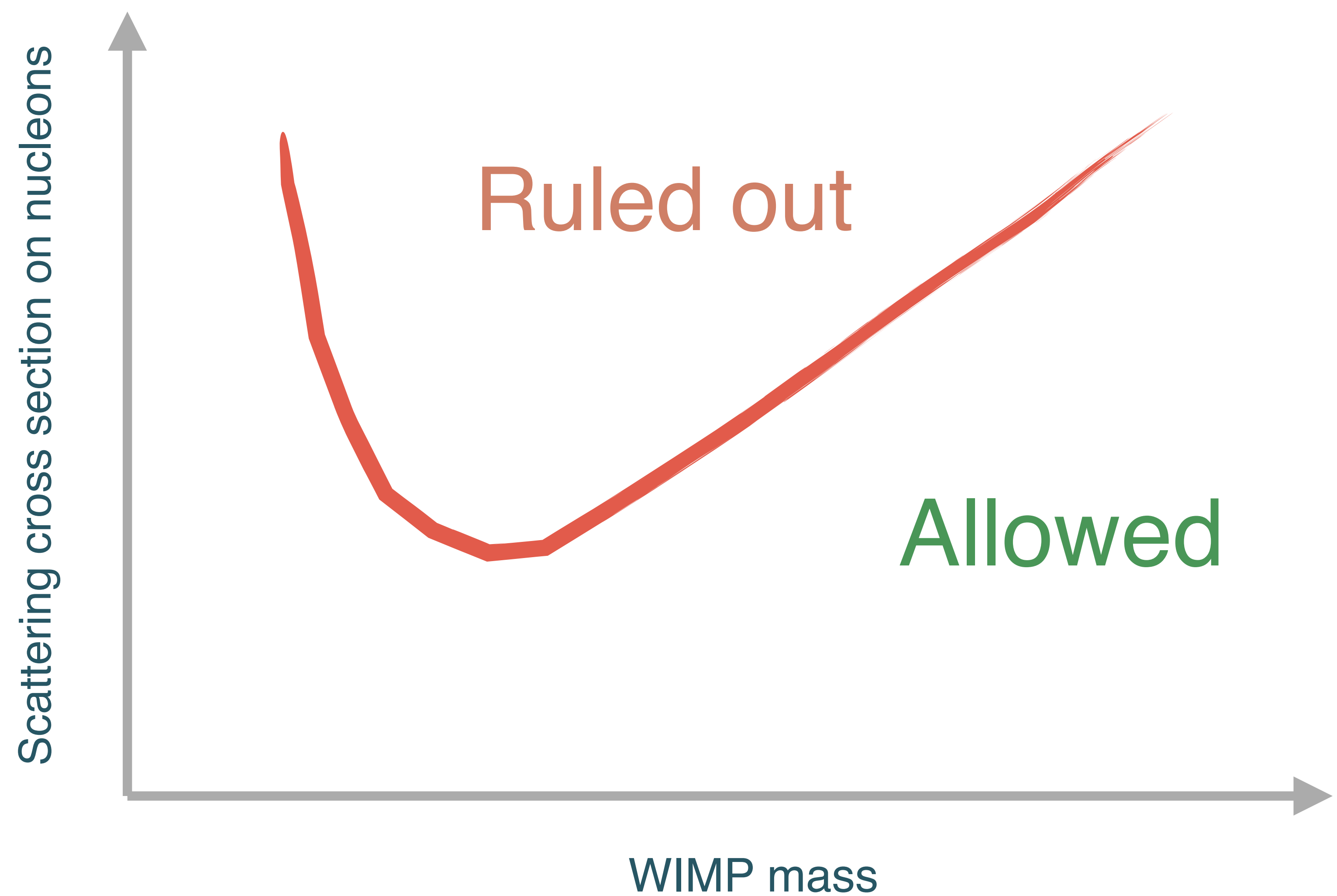


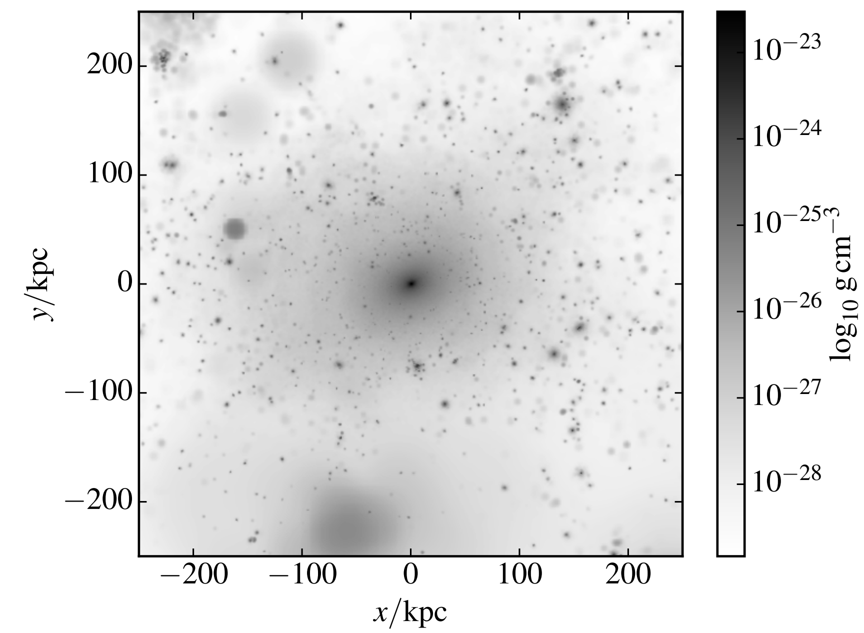
Vogelsberger et al. 2009

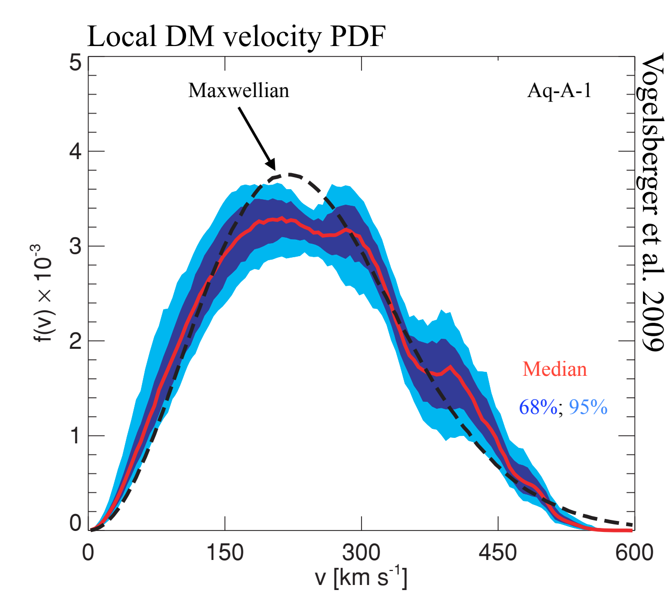
What can we learn about WIMPs?

- Constraints on the mass and scattering cross section

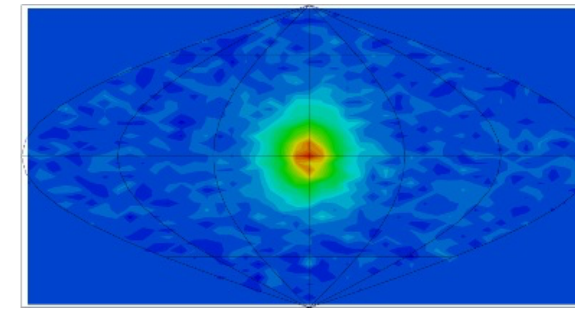
$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{\boxed{m_W}} \int_{v_{min}}^{v_{max}} dv\, f(v)\, v \boxed{\frac{d\sigma}{dE_R}}$$



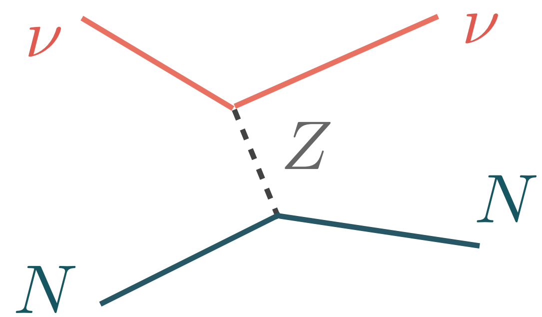


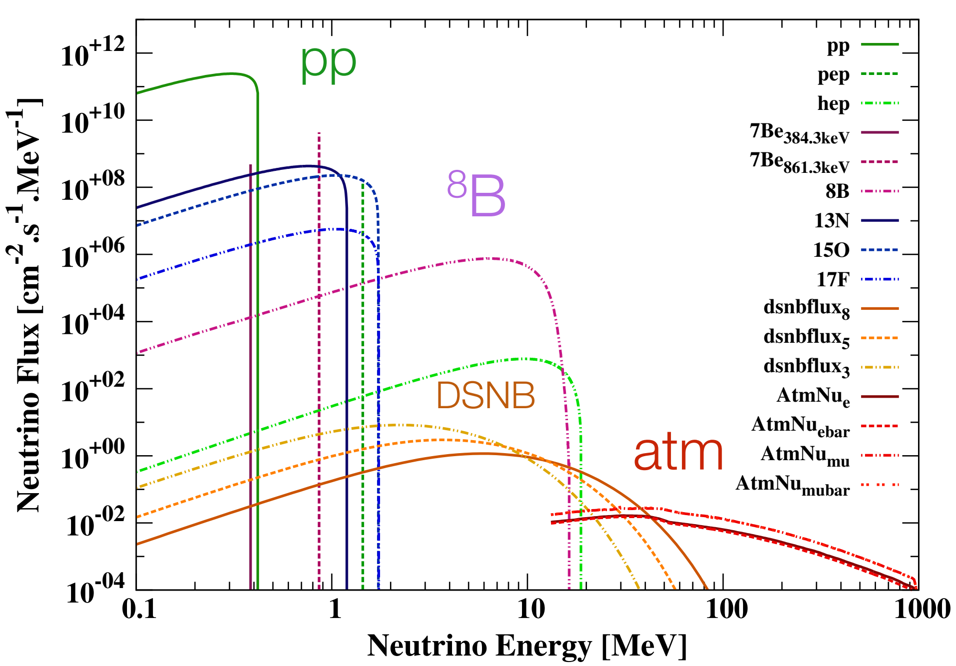


Expected backgrounds

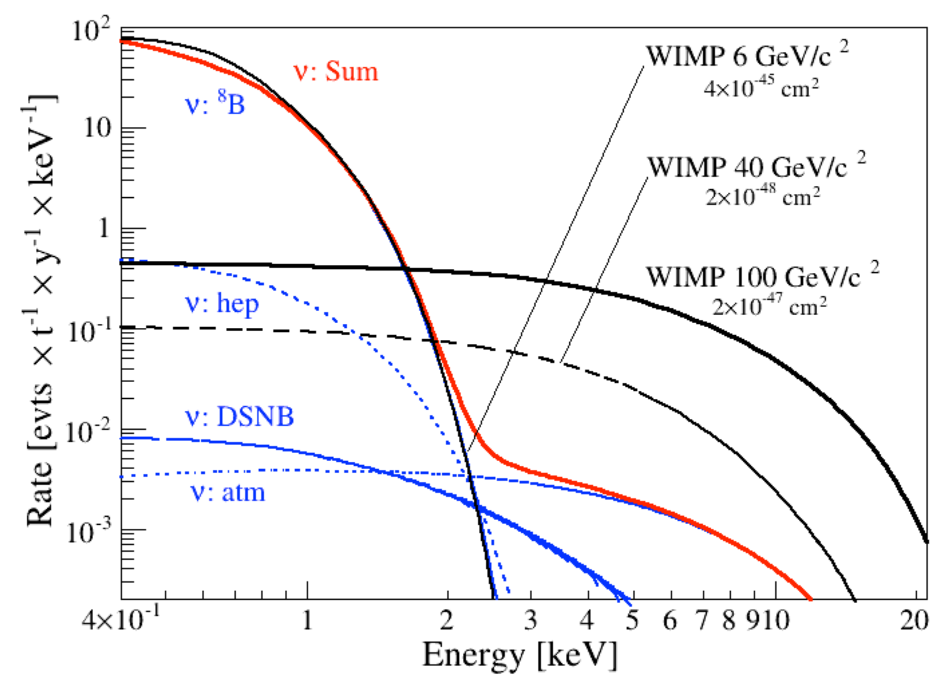


- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: **neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)**



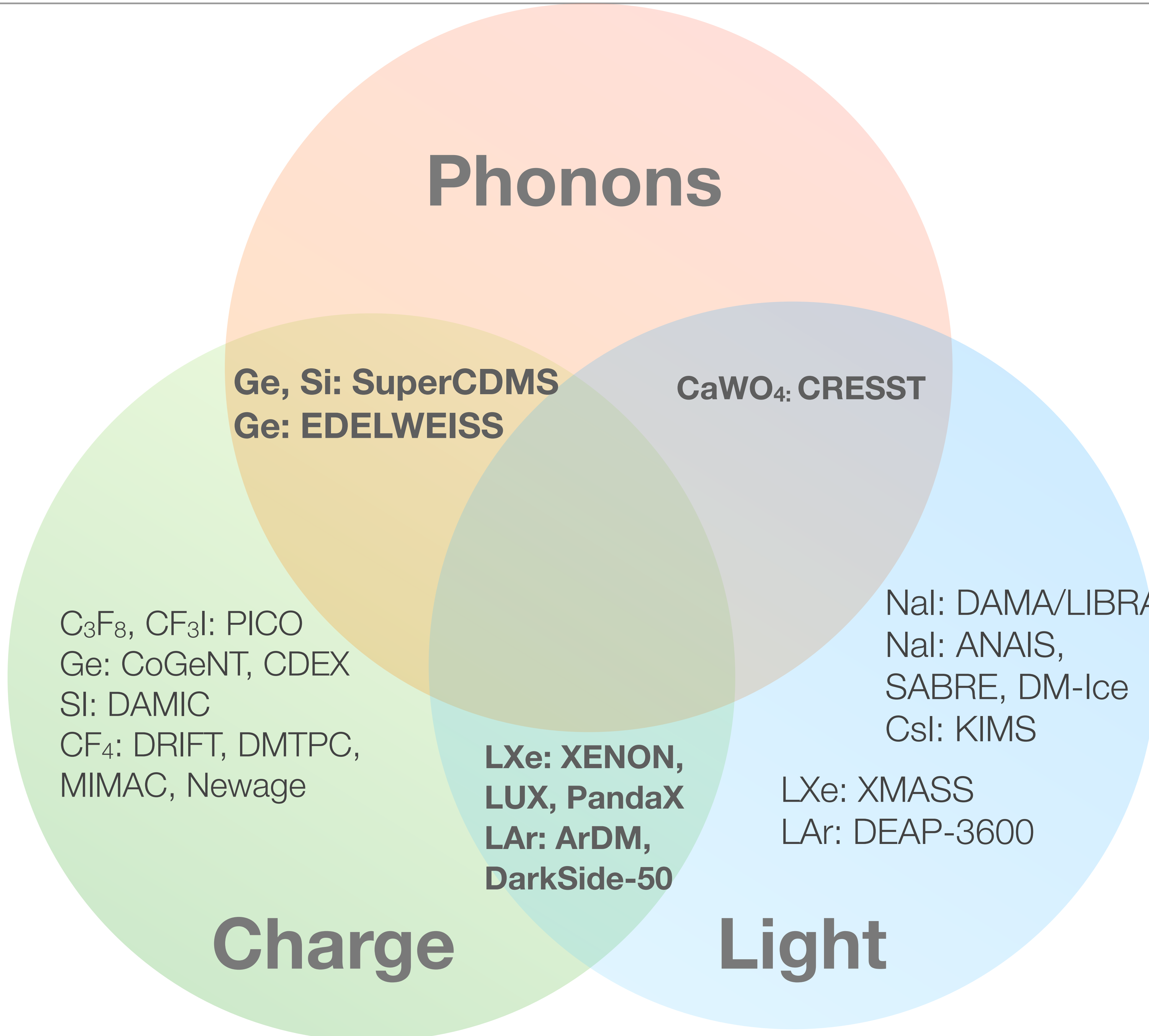


F. Ruppin et al., 1408.3581, PRD 90, 2014

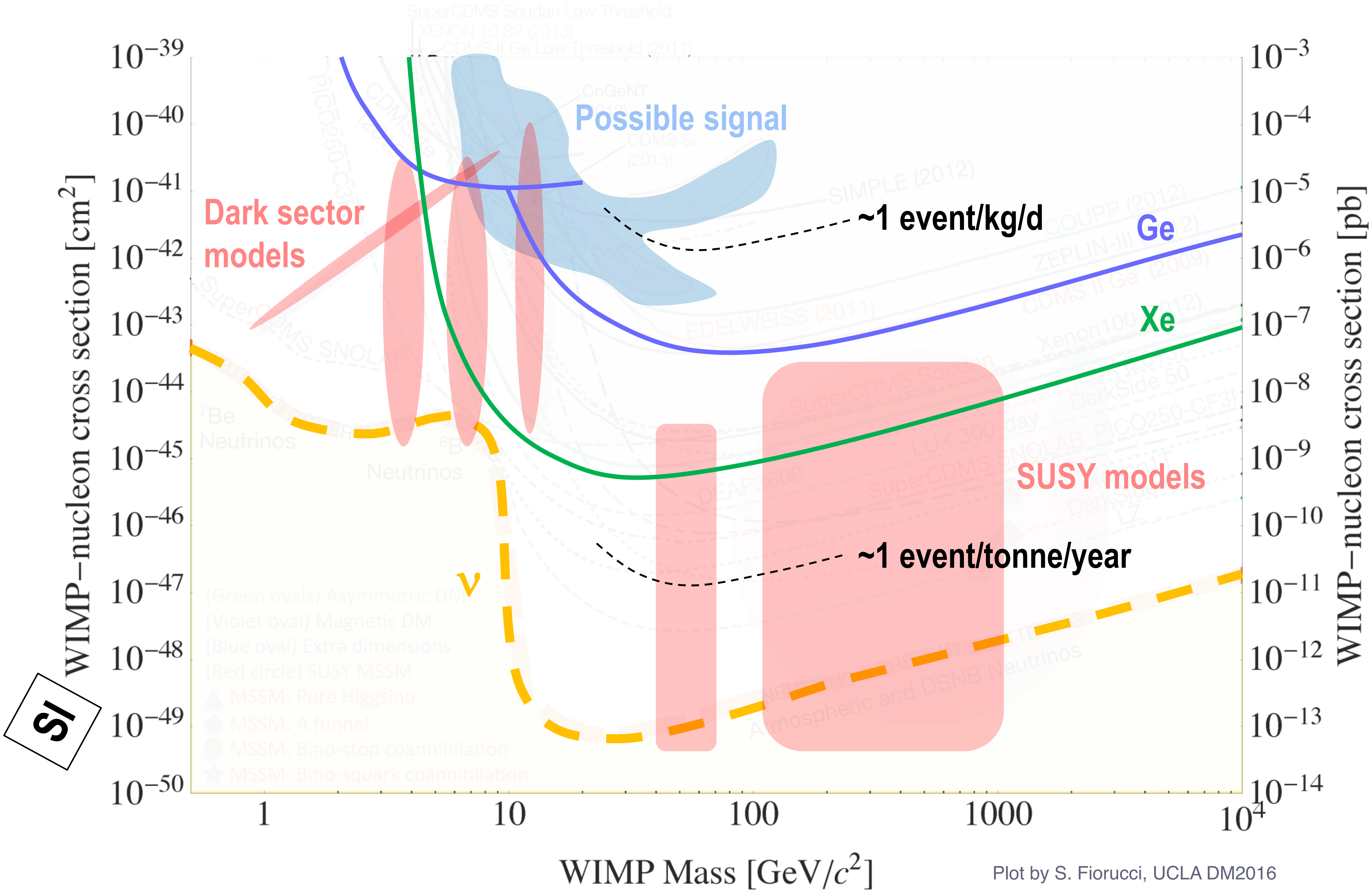


LB et al., JCAP01 (2014) 044

The direct dark matter detection zoo



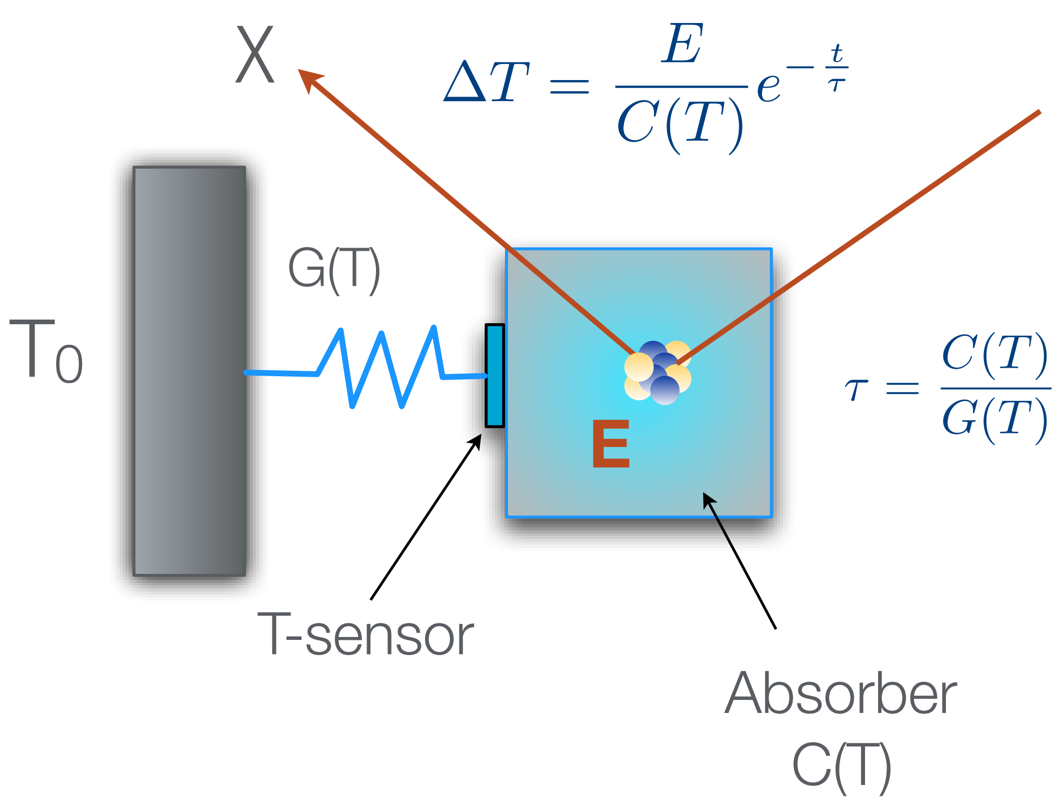
The WIMP landscape

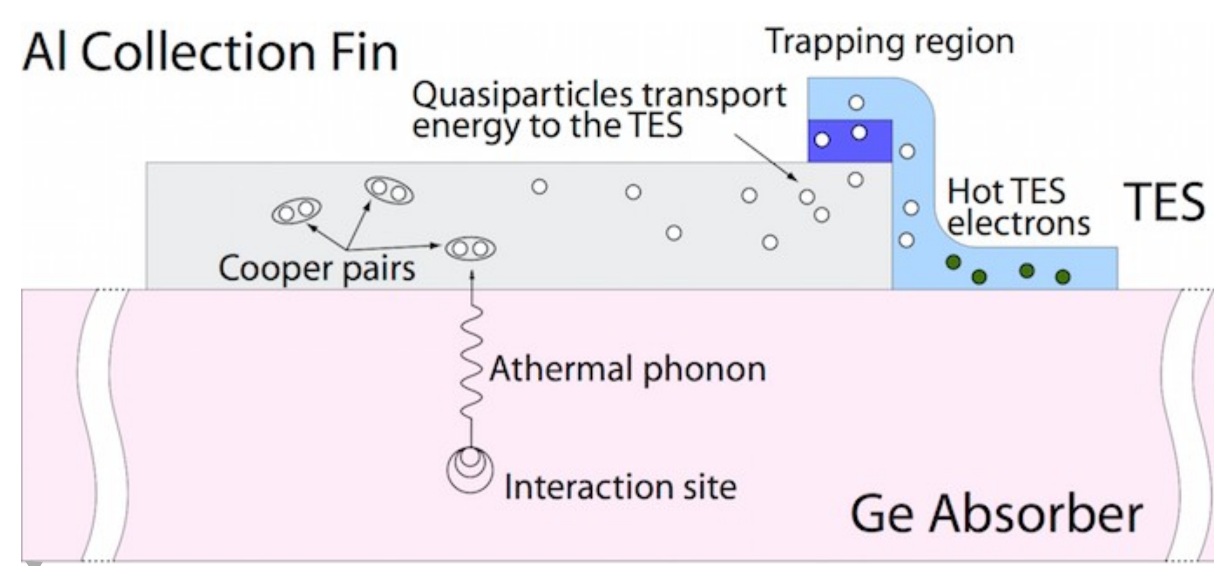


Plot by S. Fiorucci, UCLA DM2016

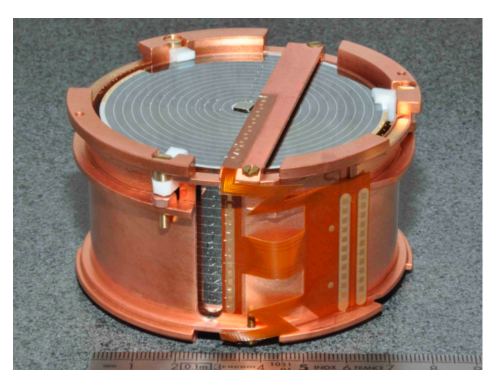
Cryogenic detectors at T ~ mK

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

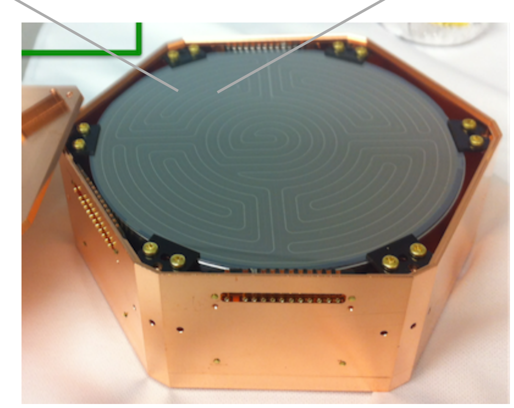




CRESST ($CaWO_4$)



EDELWEISS-III (Ge)



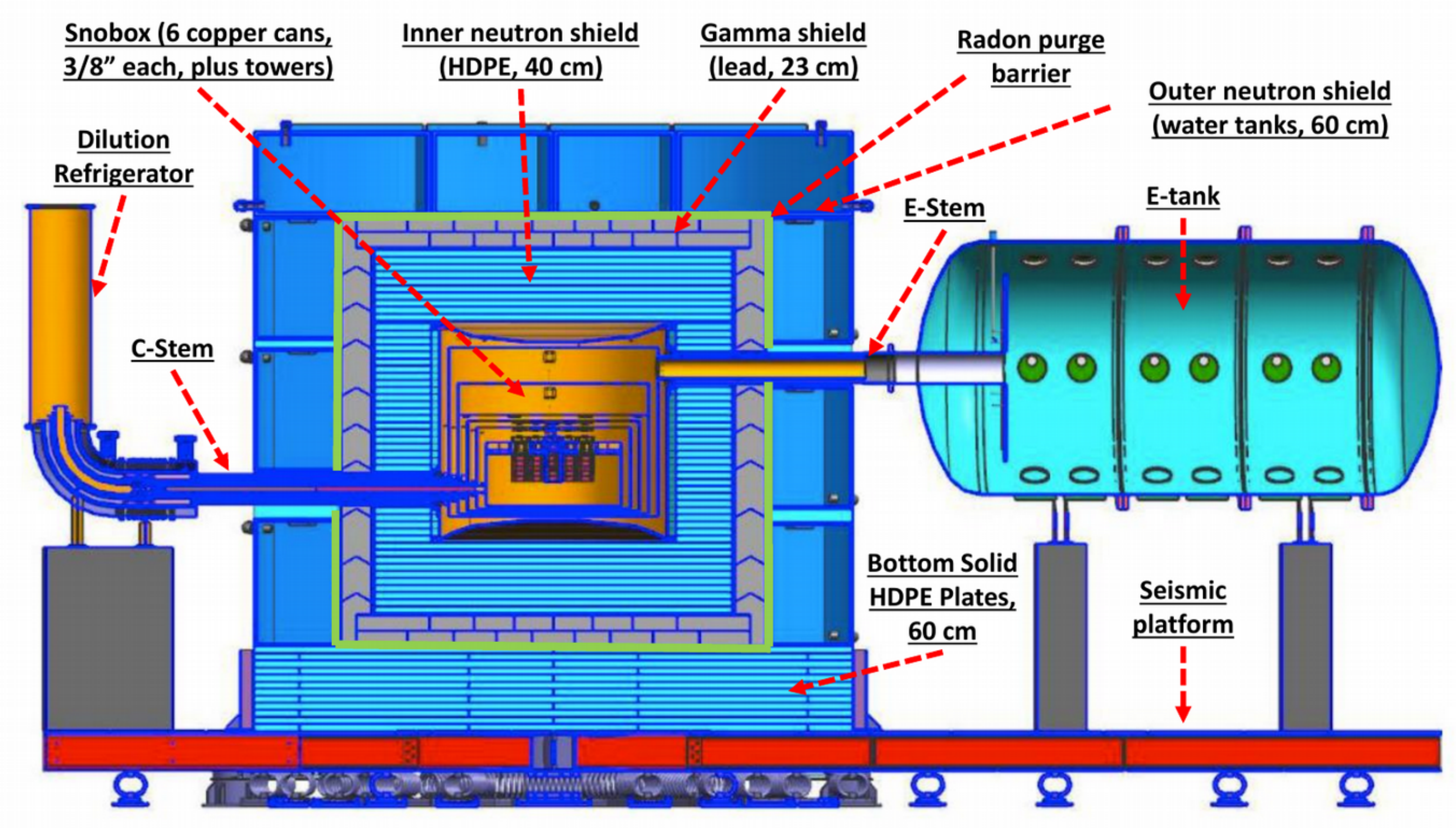
SuperCDMS: Ge, Si

Cryogenic detectors at T ~ mK

CREST-III: 10 modules, 24 g each
Energy threshold ~ 100 eV

Started science run in 2016

SuperCDMS @SNOLAB conceptual design



Commissioning in ~2020

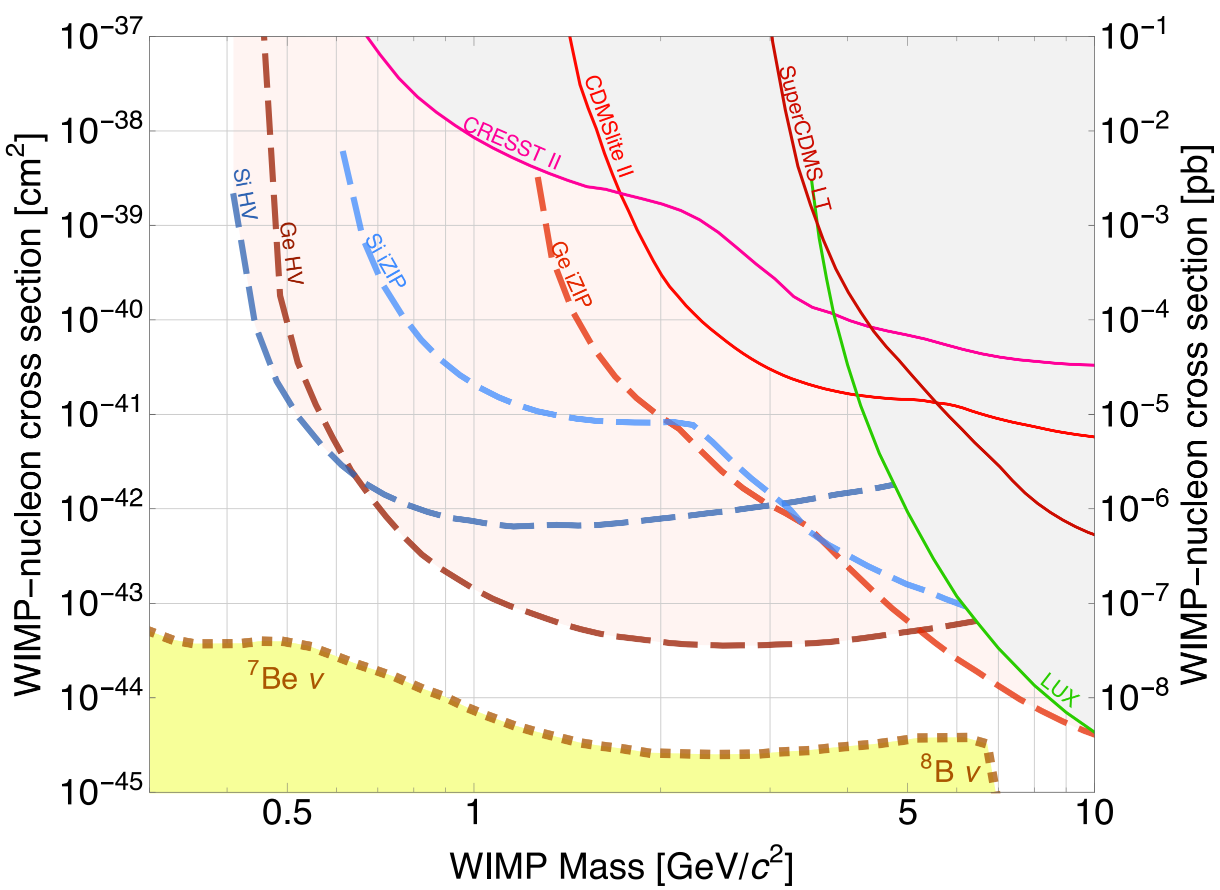
EDELWEISS will join SuperCDMS at SNOLAB

Cryogenic detectors at T ~ mK

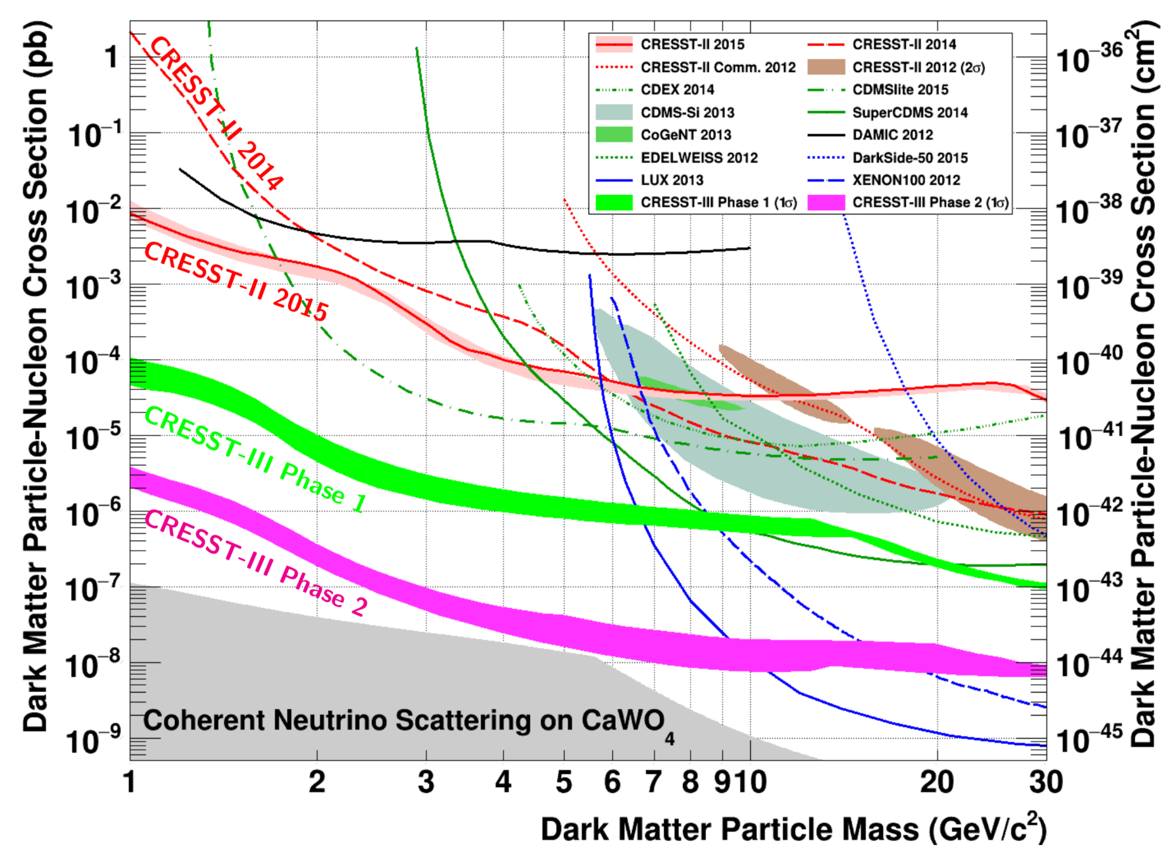
- Goal: reach energy thresholds ≤ 100 eV
- **Probe low-mass WIMP region (sub-GeV to few GeV)**

SuperCDMS and CRESST-III predictions

SuperCMDS arXiv:1610.00006



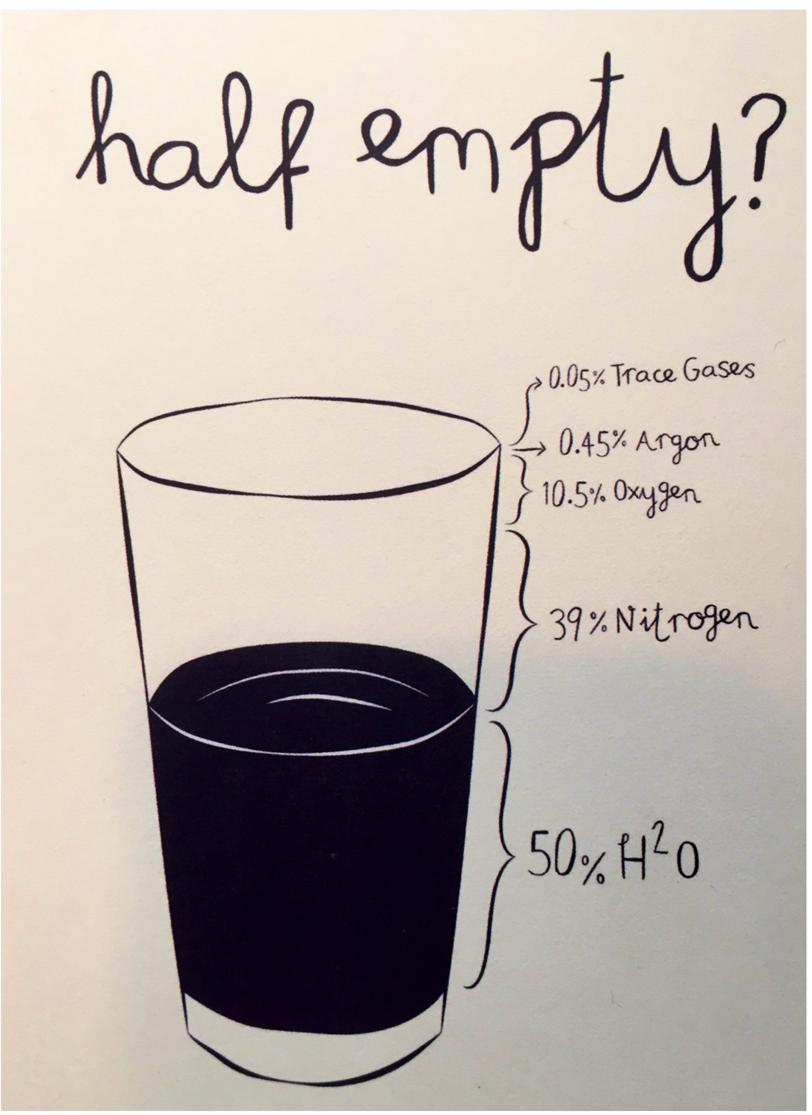
CRESST-III J.Phys.Conf.Ser. 718 (2016)

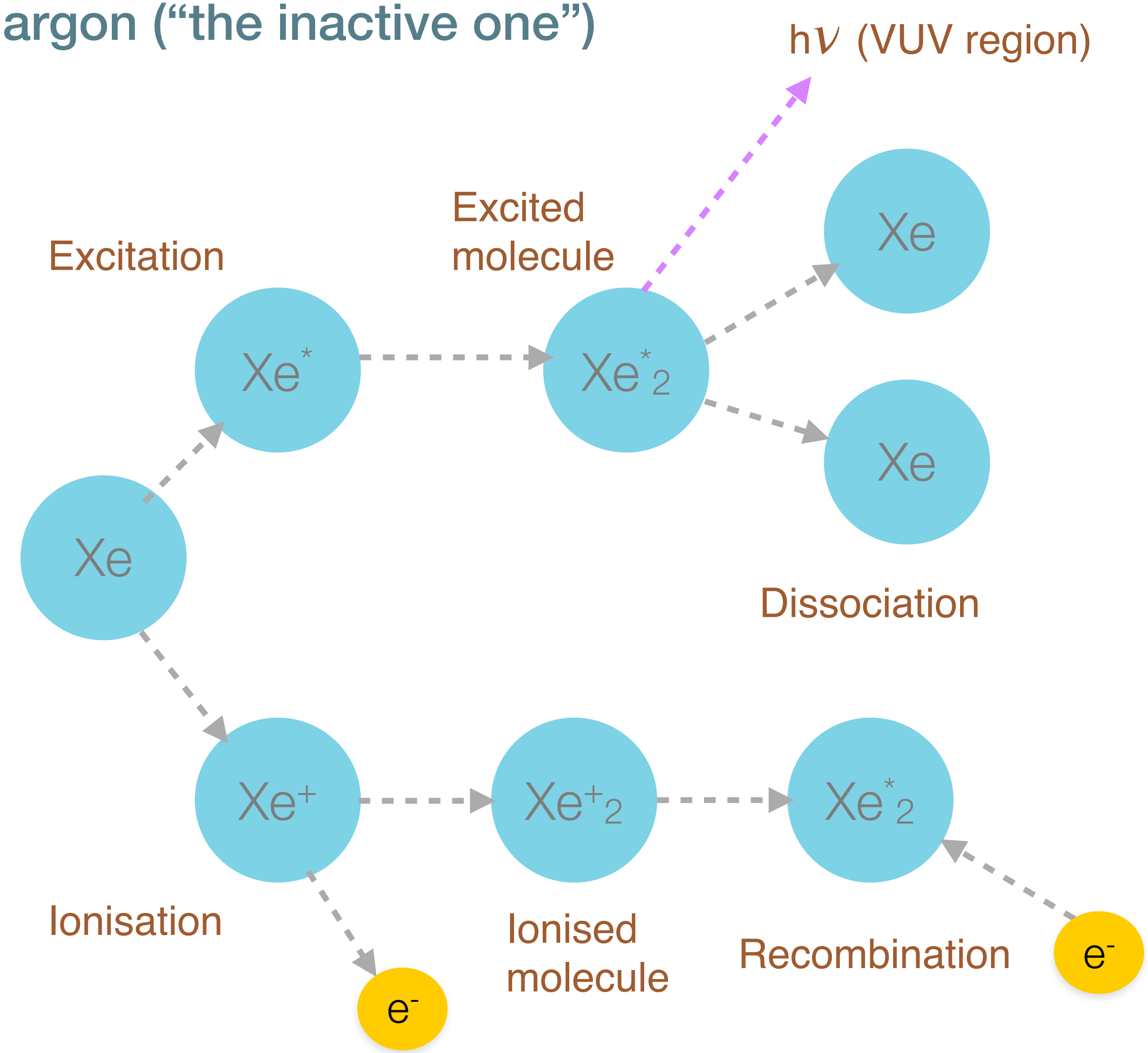


Phase I started science run in 2016

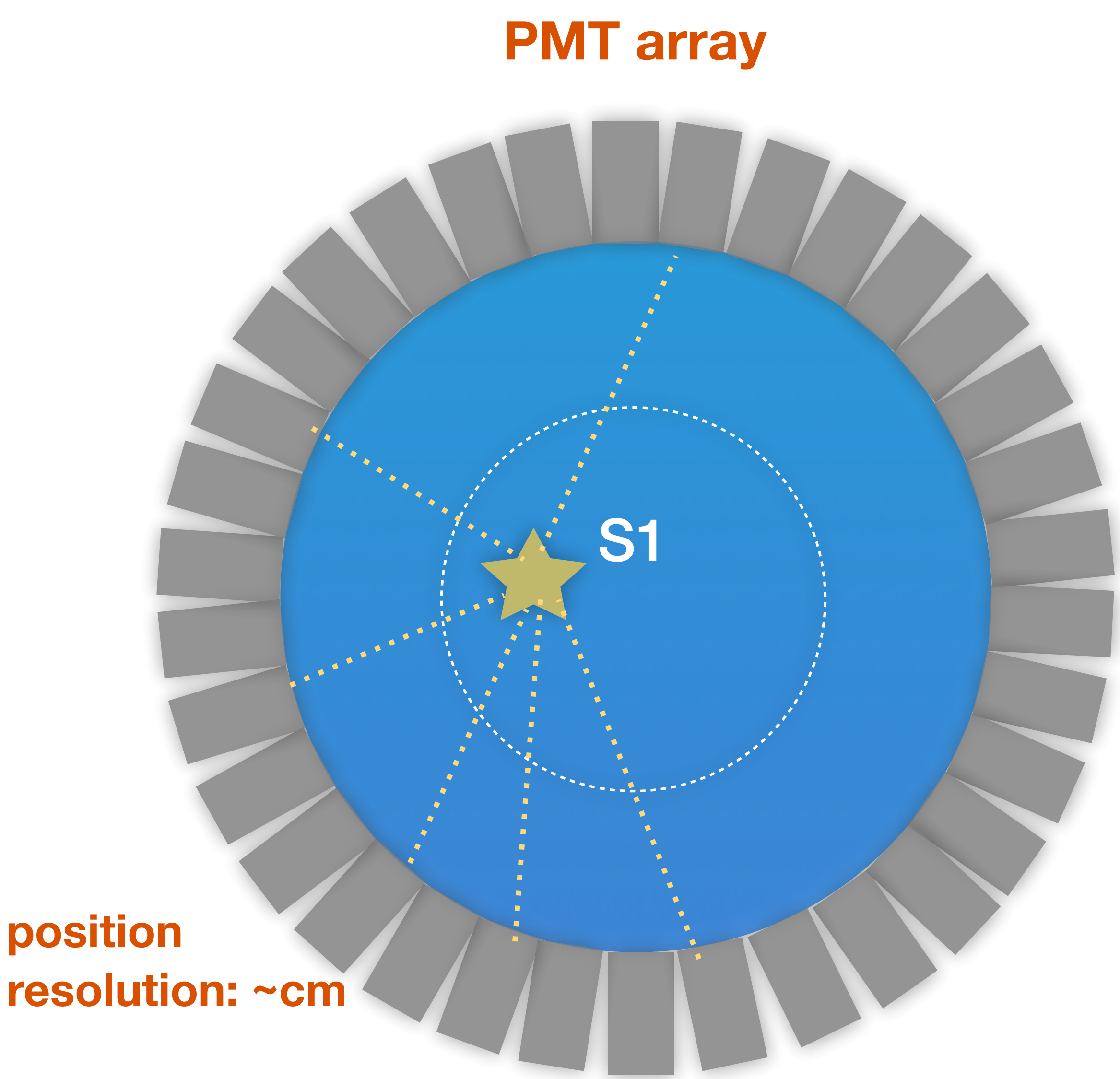
Liquefied noble gases

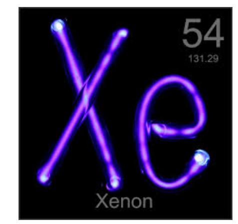
- Xenon ("the strange one") and argon ("the inactive one")

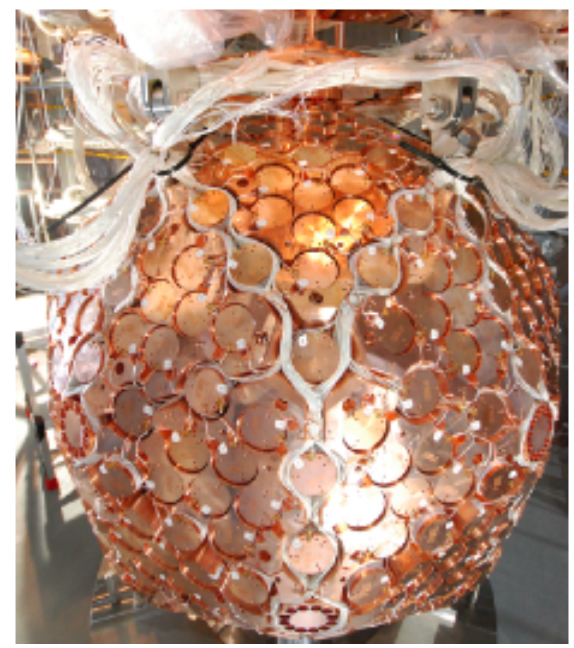


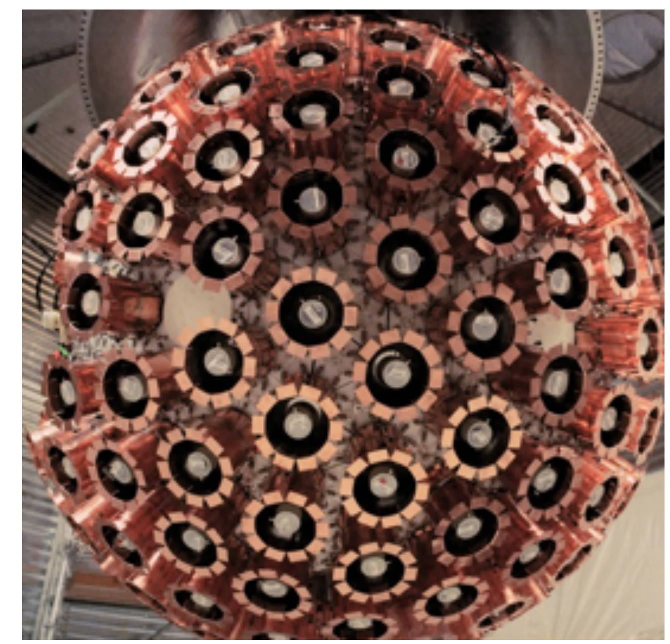


Single-phase noble liquid detectors









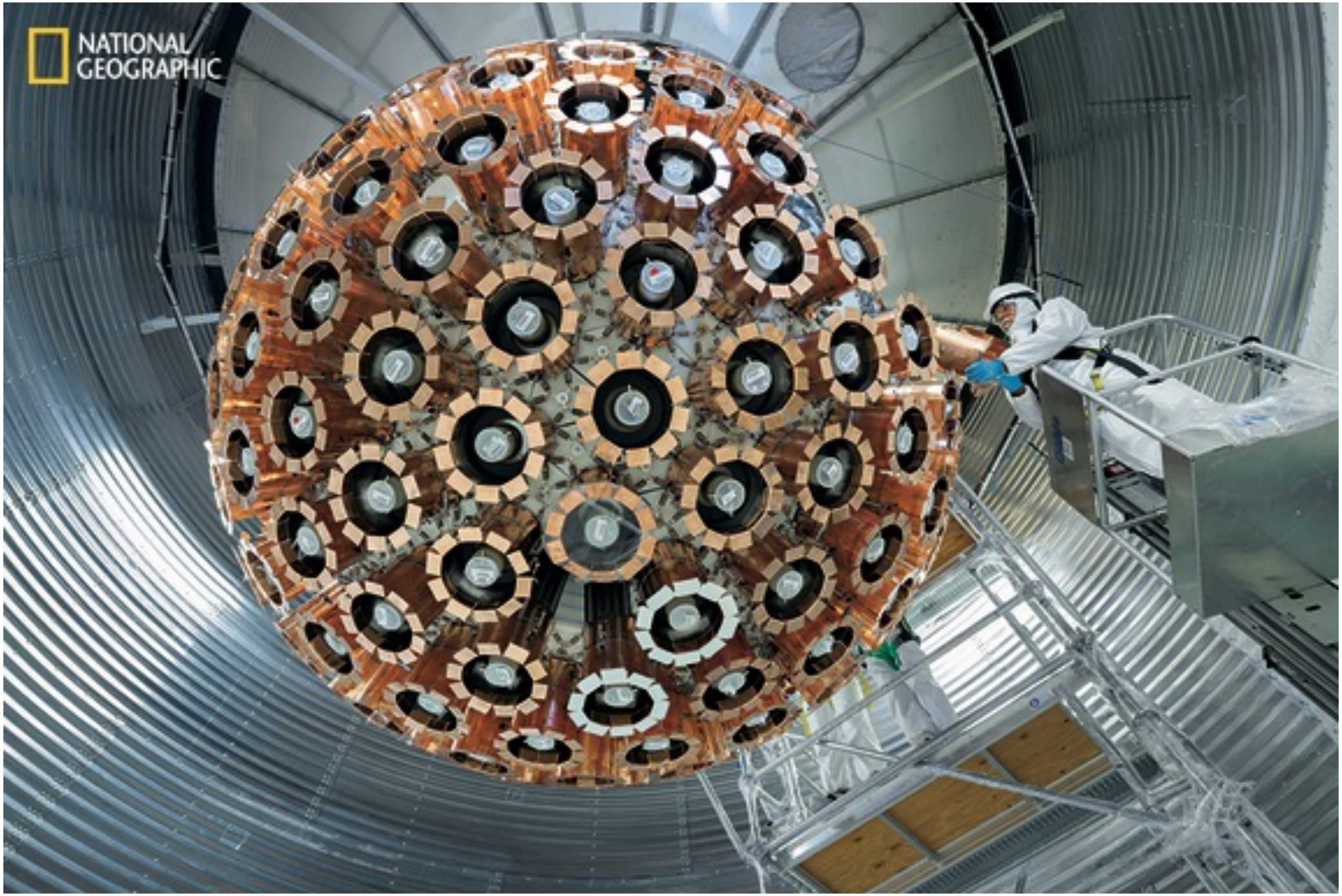
XMASS at Kamioka:

835 kg LXe (100 kg fiducial), single-phase, 642 PMTs
new run since fall 2013
several results

DEAP at SNOLab:

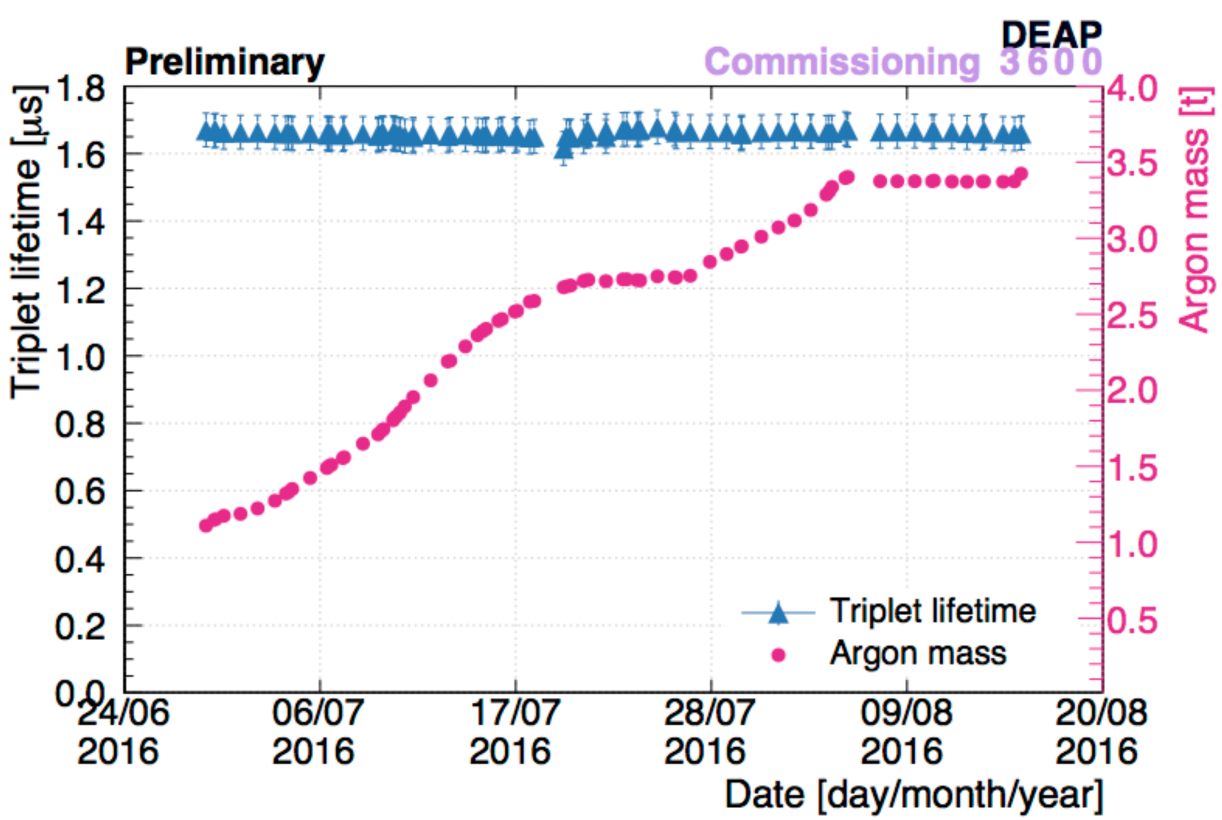
3600 kg LAr (1t fiducial)
single-phase detector
dark matter run in 2016

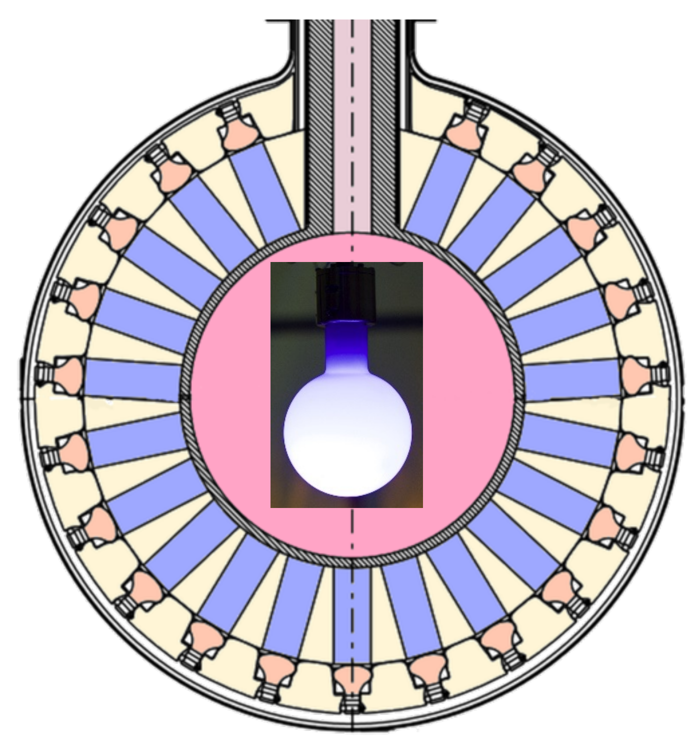
DEAP-3600 at SNOLAB



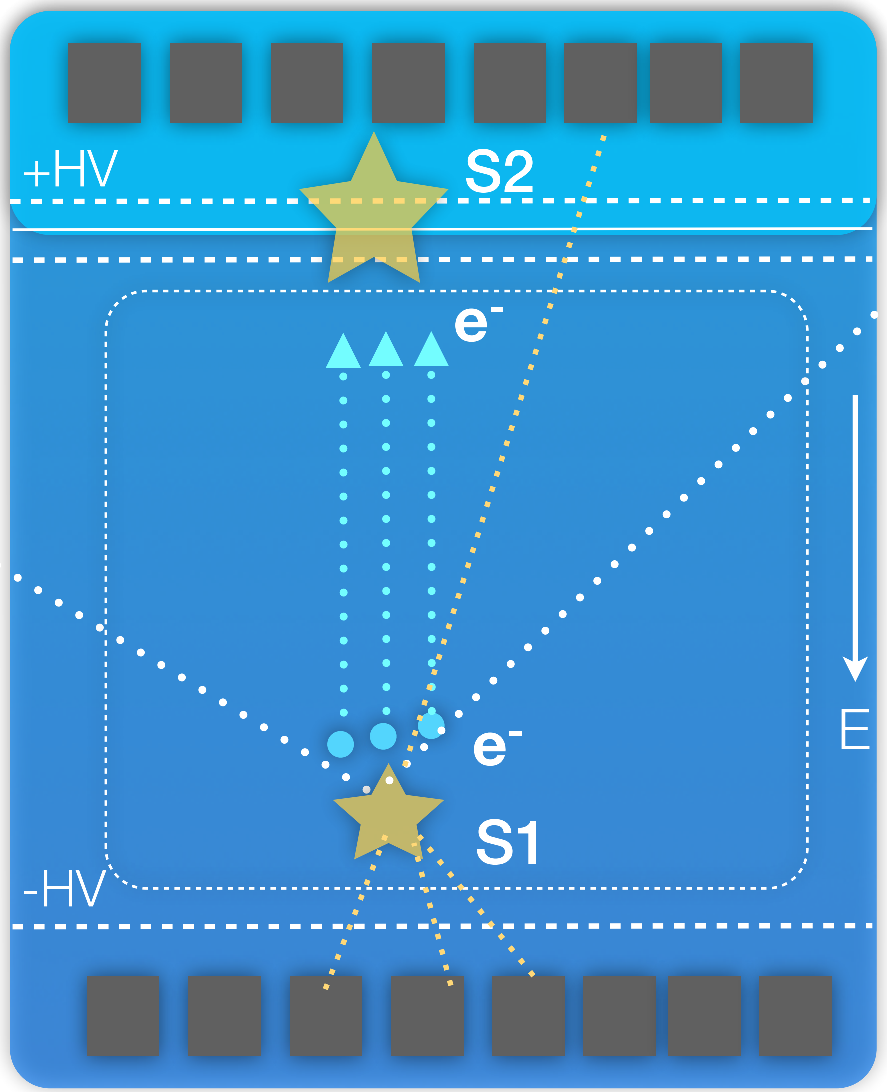
DEAP-3600 at SNOLAB

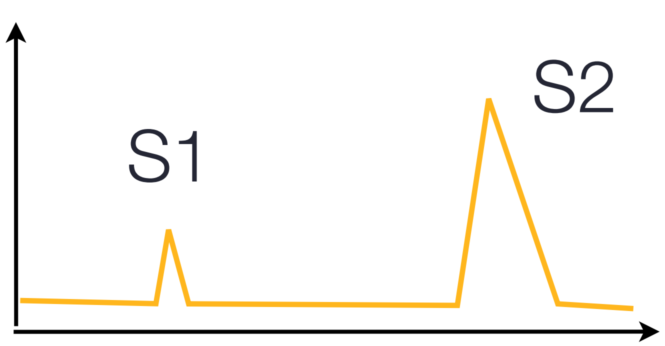
- Construction was completed in 2016
- Commissioning of all subsystems, including detailed, in-situ PMT characterisation with light source in the centre of the detector
- Started dark matter run, currently analysis of data collected during LAr filling
- Exposure so far: 100 t days, first results in early 2017



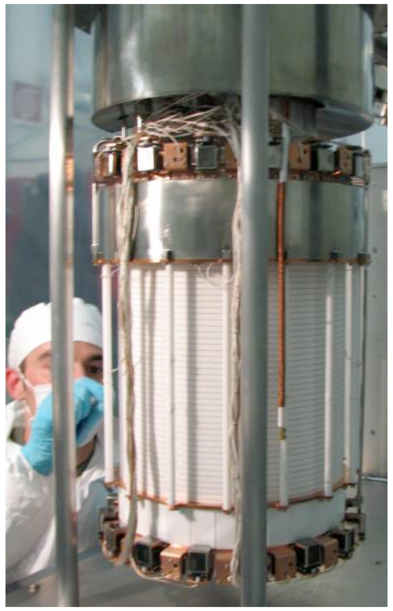


Dual-phase noble liquid detectors



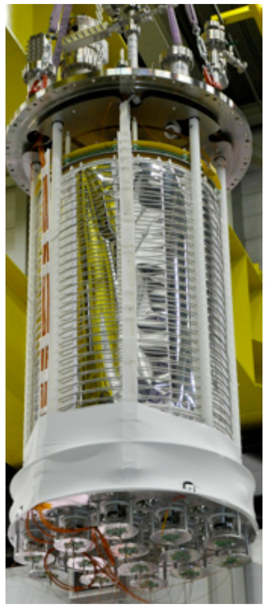


XENON100



LUX

ArDM



DarkSide-50

Xenon

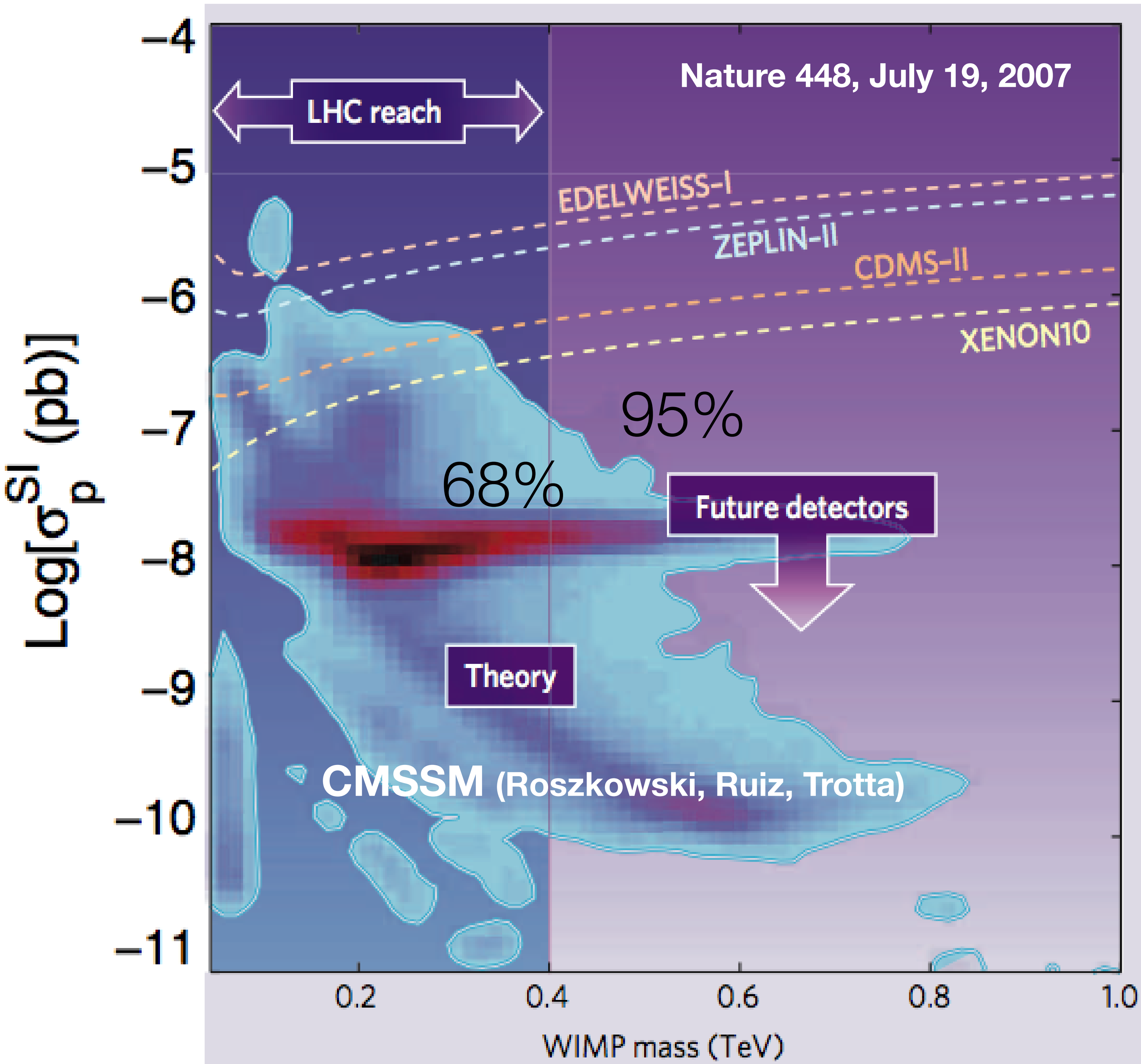
XENON100 at LNGS, LUX at SURF, PandaX at CJPL

Argon

DarkSide-50 at LNGS, ArDM at Canfranc

Target masses between ~ 50 kg - 1 ton

Results 10 years ago…

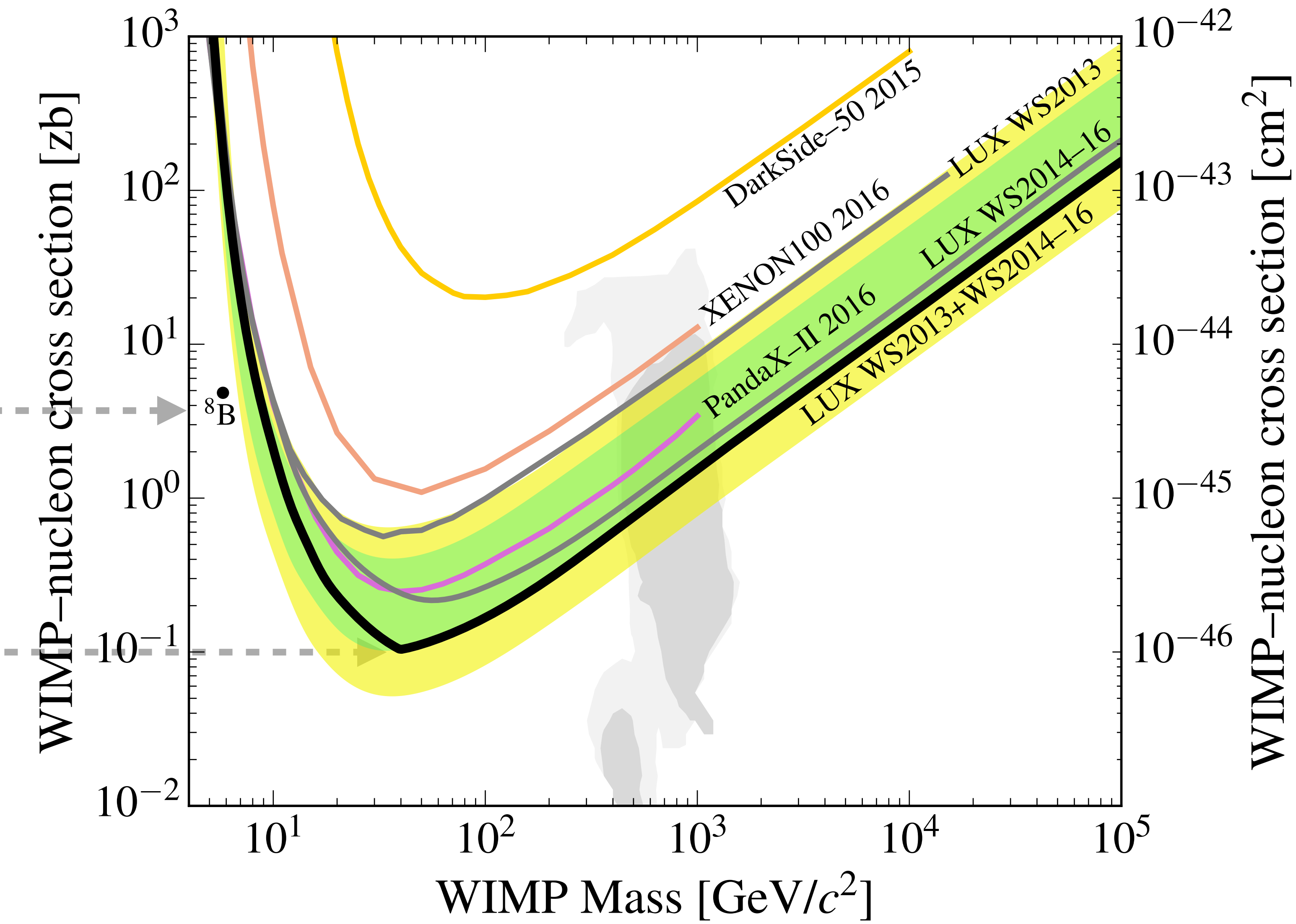


Recent results: no evidence (yet) for WIMPs

LUX collaboration, PRL 116, 161301 and arXiv:1608.07648
PandaX collaboration: PRL, August 2016

Expected events from ^{8}B neutrinos

Minimum at 0.1 zb

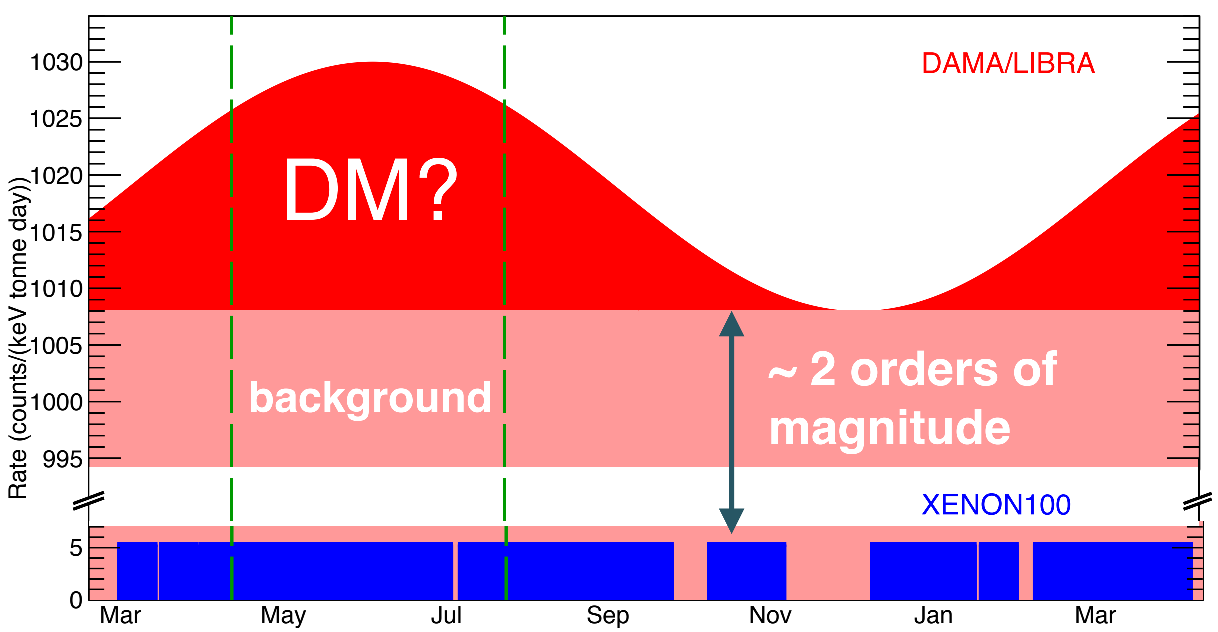


Latest XENON100 results

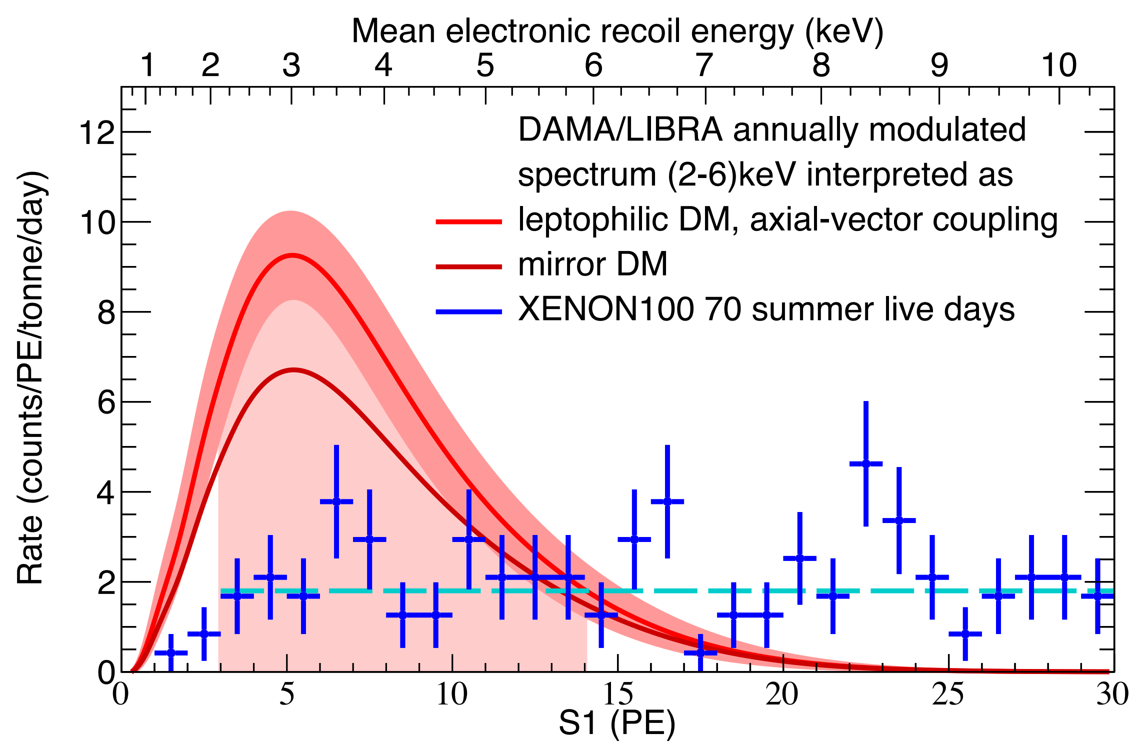
- Dark matter particles interacting with e^-
  - XENON100's ER background lower than DAMA modulation amplitude

➡ search for a signal above background in the ER spectrum

XENON collaboration, arXiv: 1507.07747, Science 349, 2015



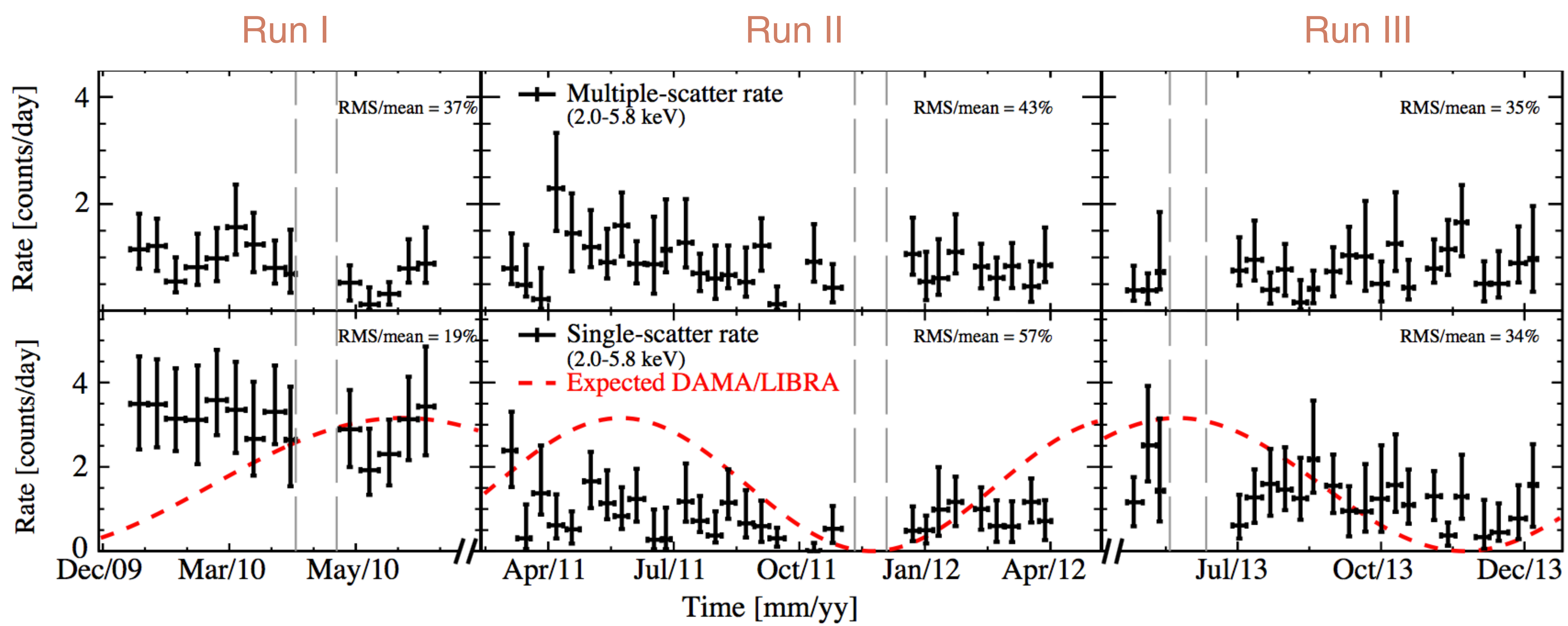
Consider the 70 days with the largest signal



DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-e^- scattering)

Latest XENON100 results

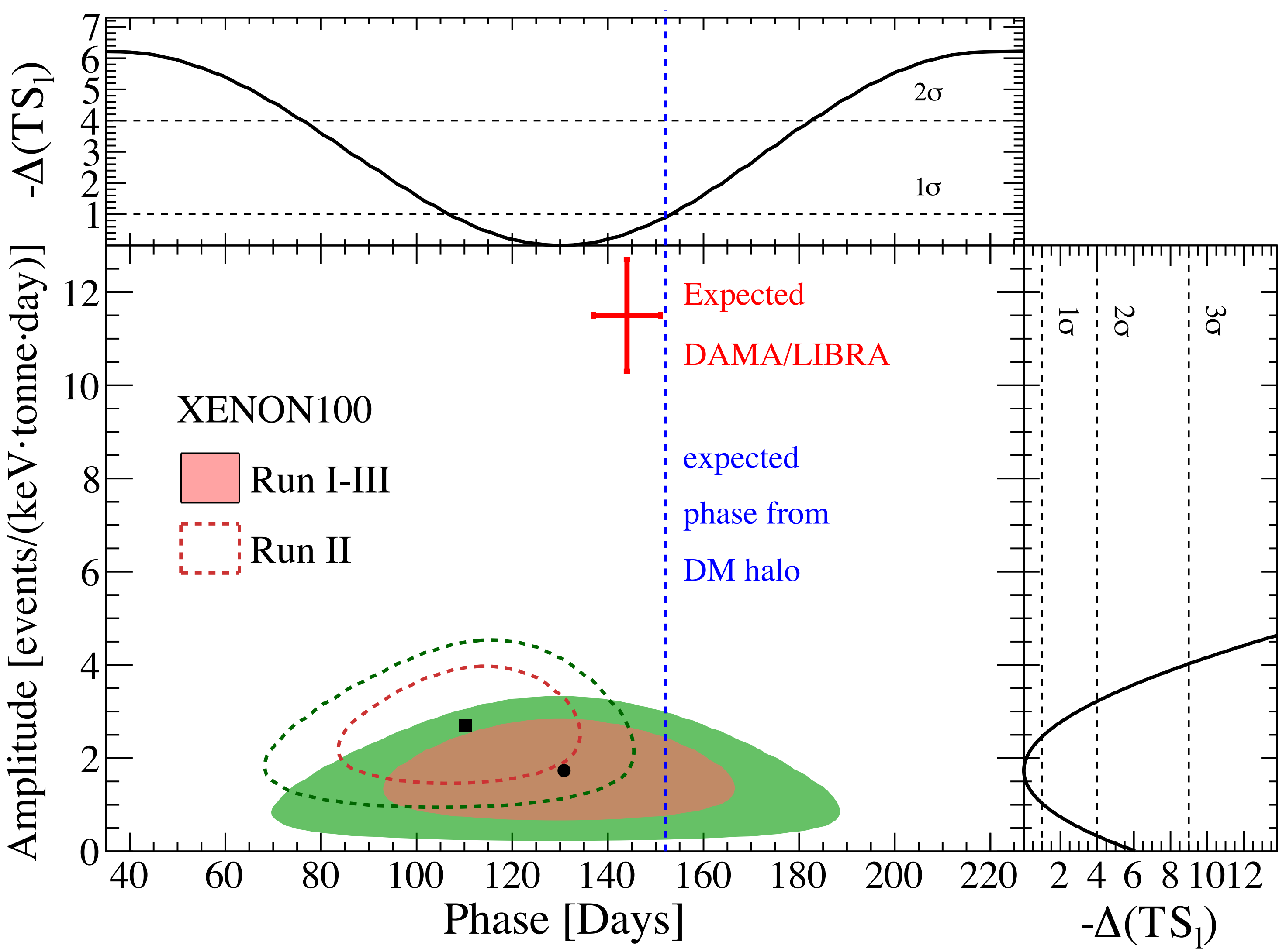
- Dark matter particles interacting with e^-
    - ➡search for periodic variations of the ER rate in the 2-6 keV region , in 4 years of data



XENON collaboration, arXiv:1701.00769

Latest XENON100 results

- Dark matter particles interacting with e^-
  - ➡ no significant modulation is seen; exclude DAMA/LIBRA at 5.7-sigma

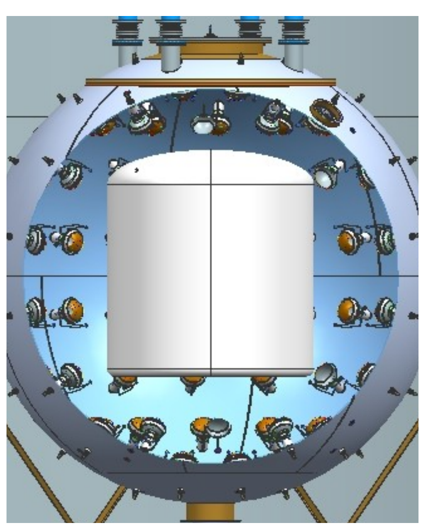


XENON collaboration, arXiv:1701.00769

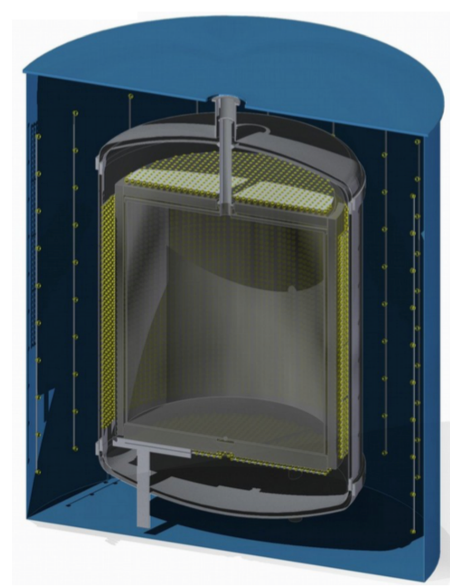
New and future noble liquid detectors

- Acquiring science data: XENON1T 3.3 t LXe
- Approved LXe: LUX-ZEPLIN 7t, XENONnT 7t
- Proposed LAr: DarkSide-20k, DEAP-50T; Proposed LXe: XMASS 5t
- Design & R&D: DARWIN 50 t LXe; ARGO 300 t LAr, DEAP-50T LAr

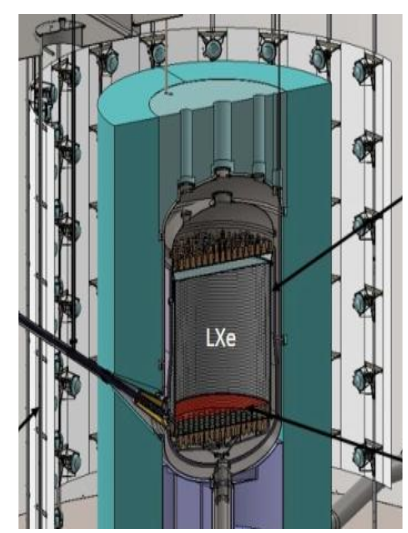
XENONnT: 7t LXe



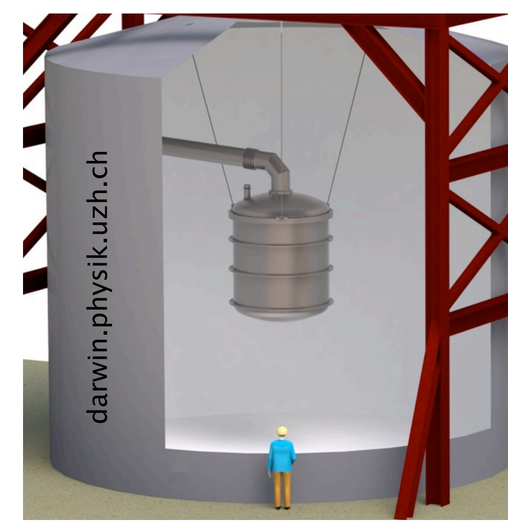
DarkSide: 20 t LAr



DEAP-50T: 50 t LAr



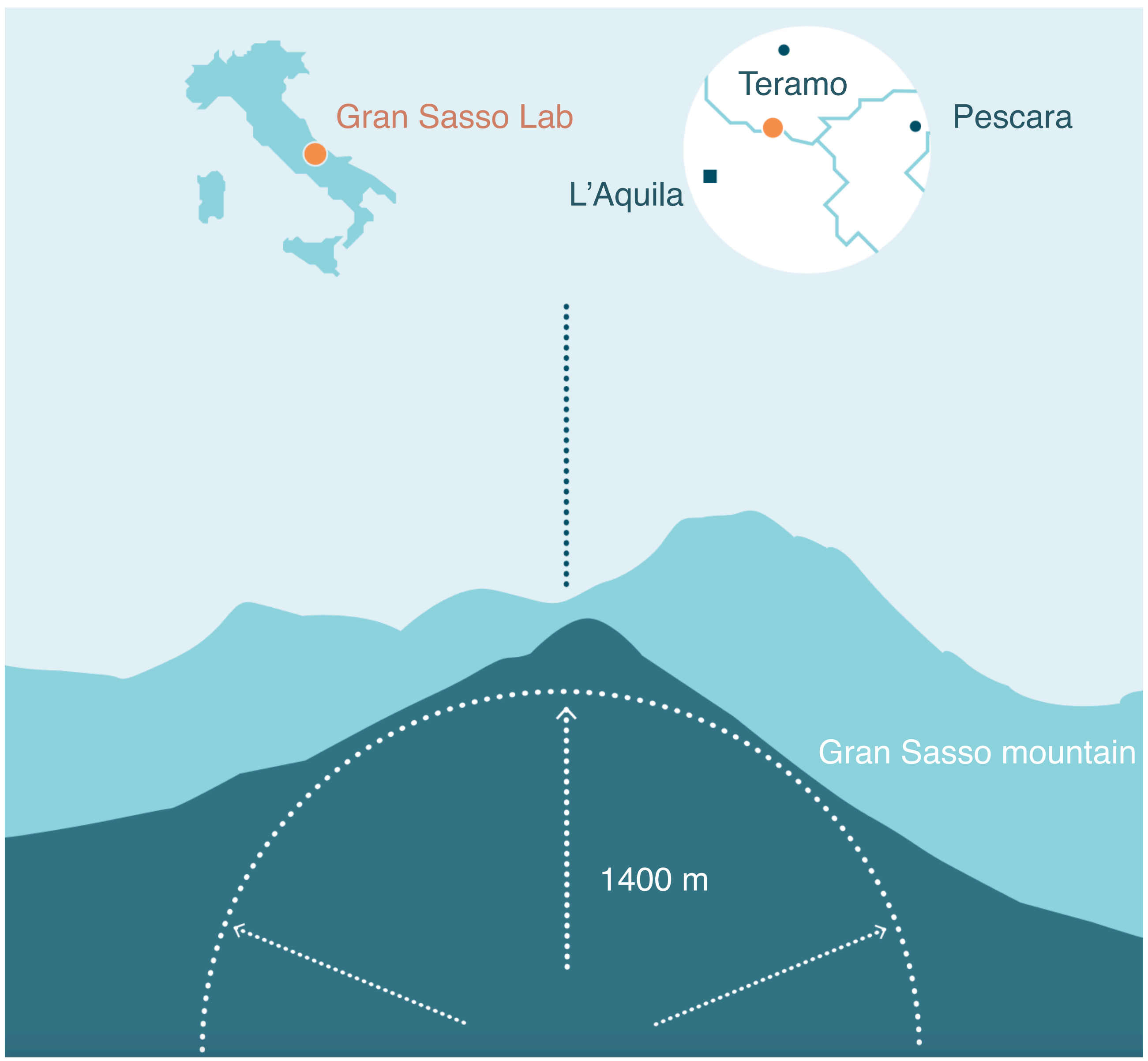
LZ: 7t LXe

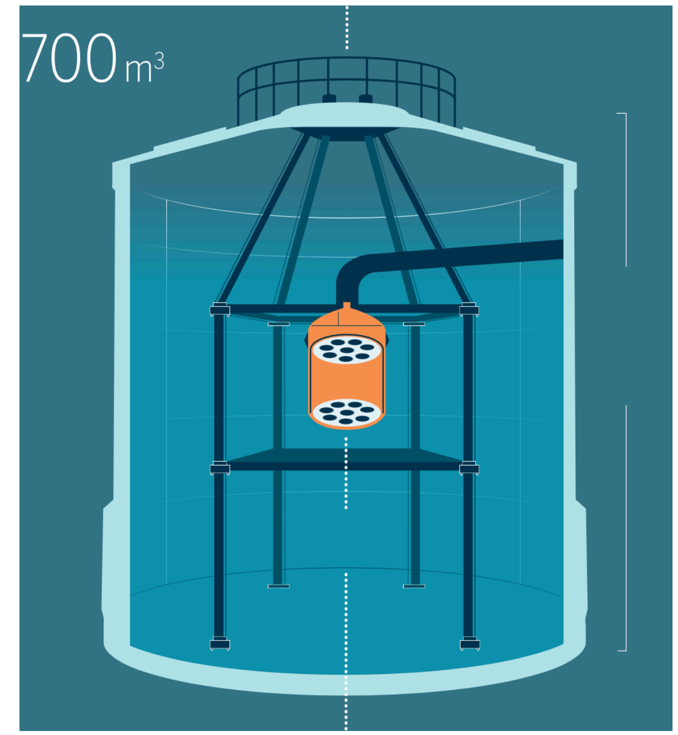


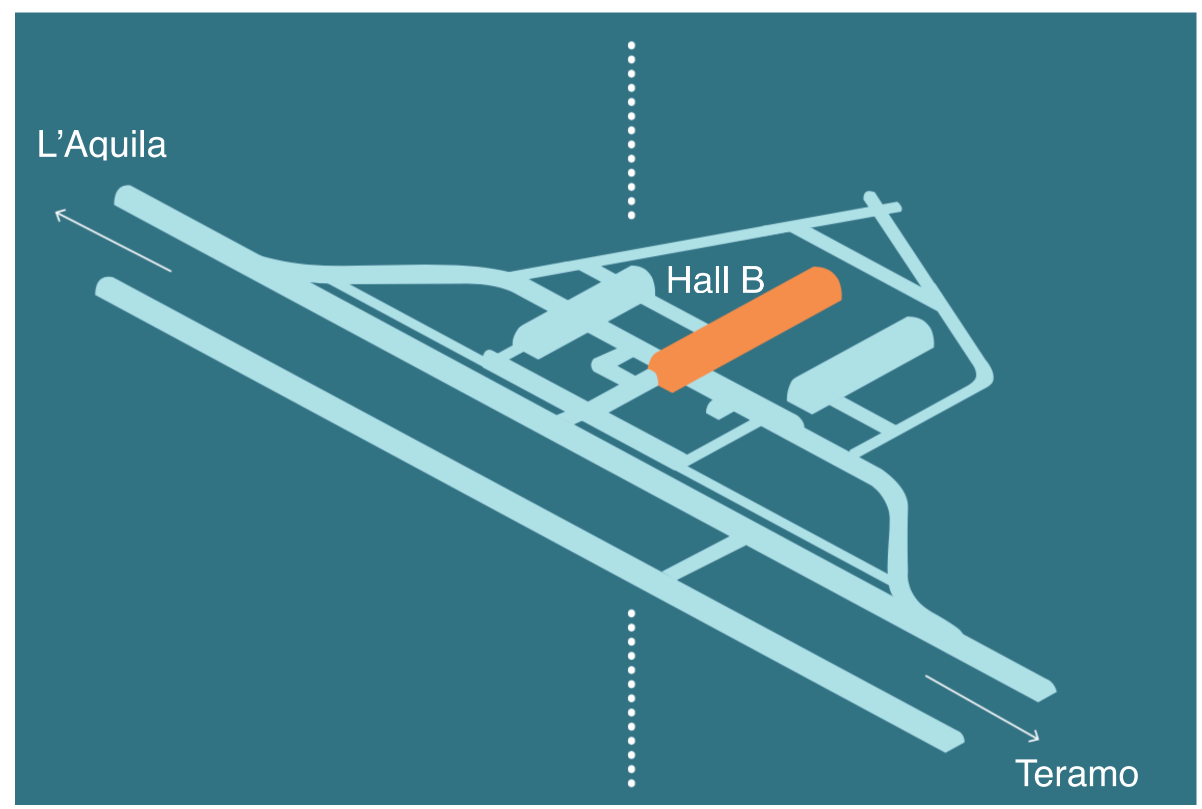
DARWIN: 50 t LXe

XENON1T at LNGS

- Total (active) LXe mass: 3.3 t (2 t), 1 m electron drift
- 248 3-inch PMTs in two arrays







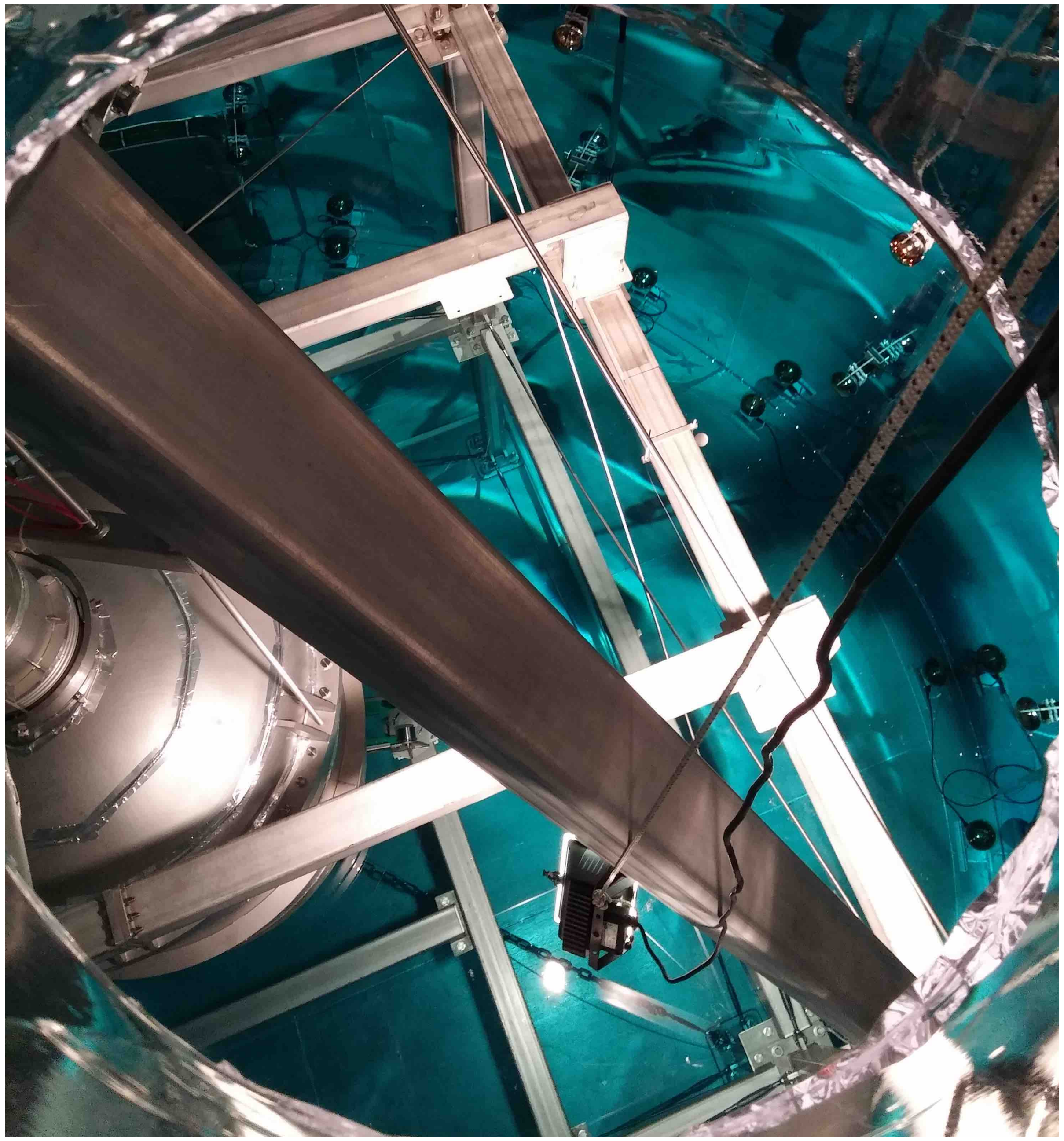
Tagesanzeiger December 2016

XENON1T at LNGS

- Background goal: 100 x lower than XENON100 ~ 5×10^{-2} events/(t d keV)

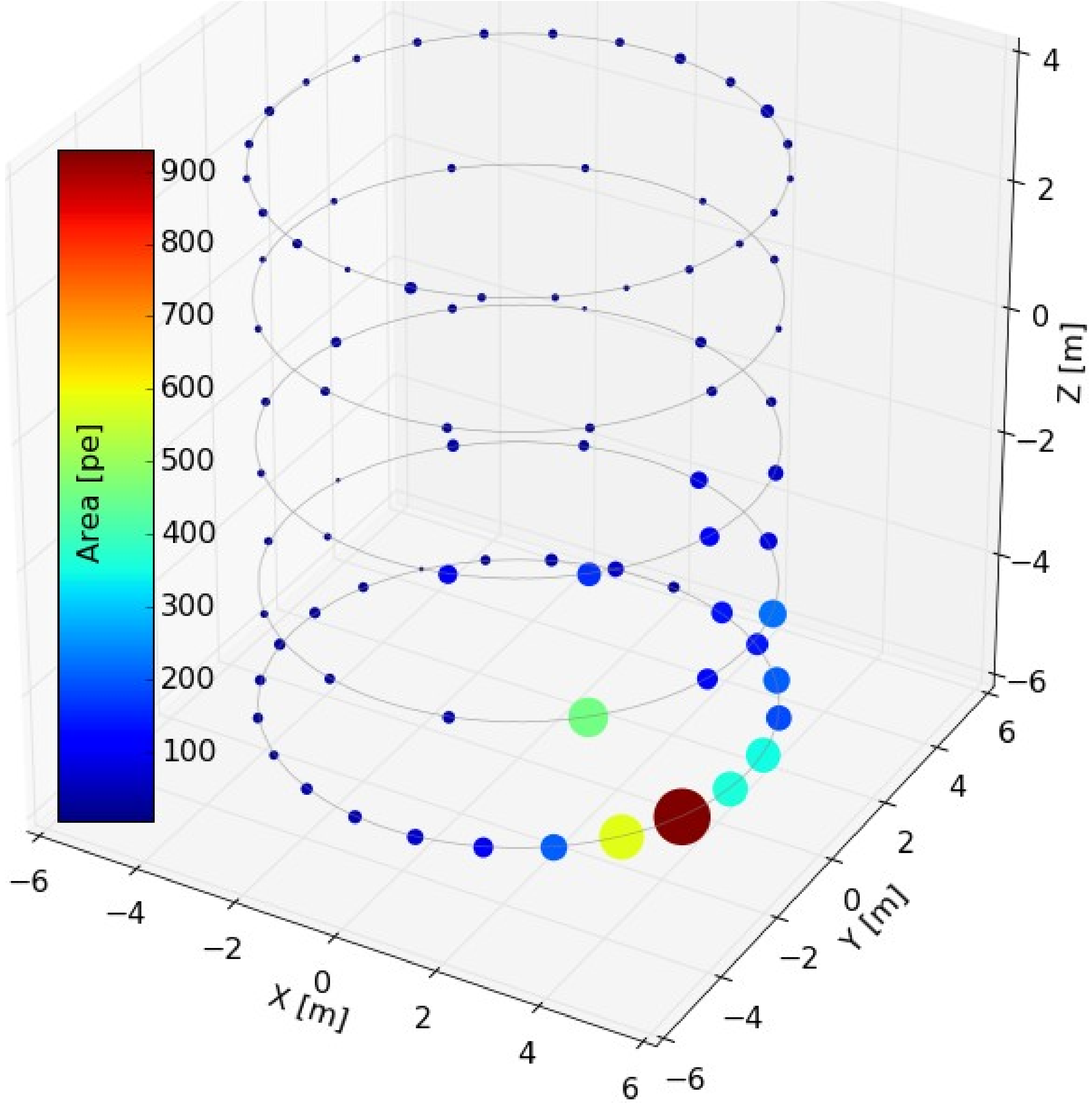
The XENON1T muon veto

Water tank instrumented with 84 8-inch PMTs

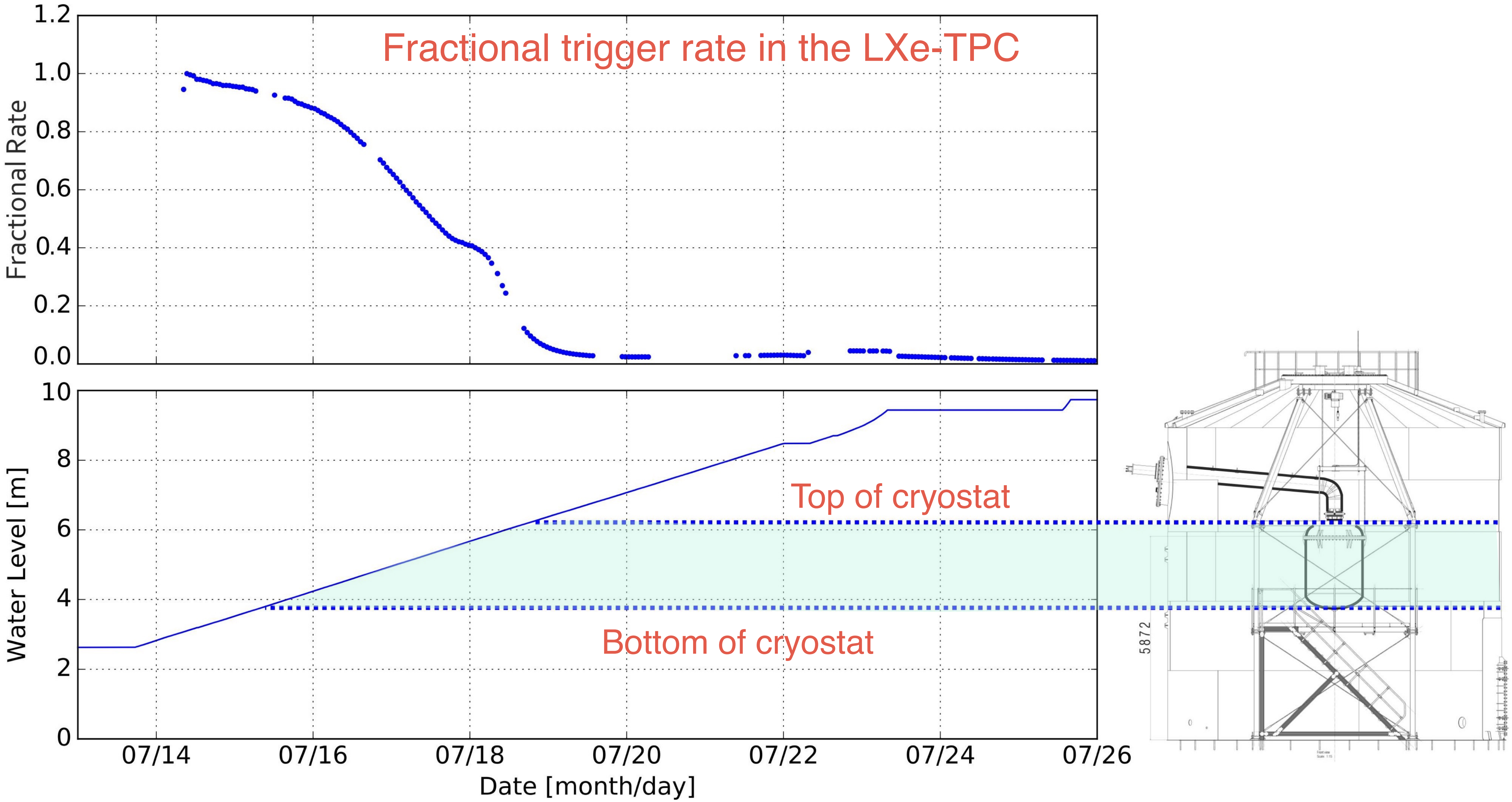


Tag > 99.5% of events where μ's cross the water and >70% of events with only n's (and showers)

One of the first muons seen in the XENON1T muon veto



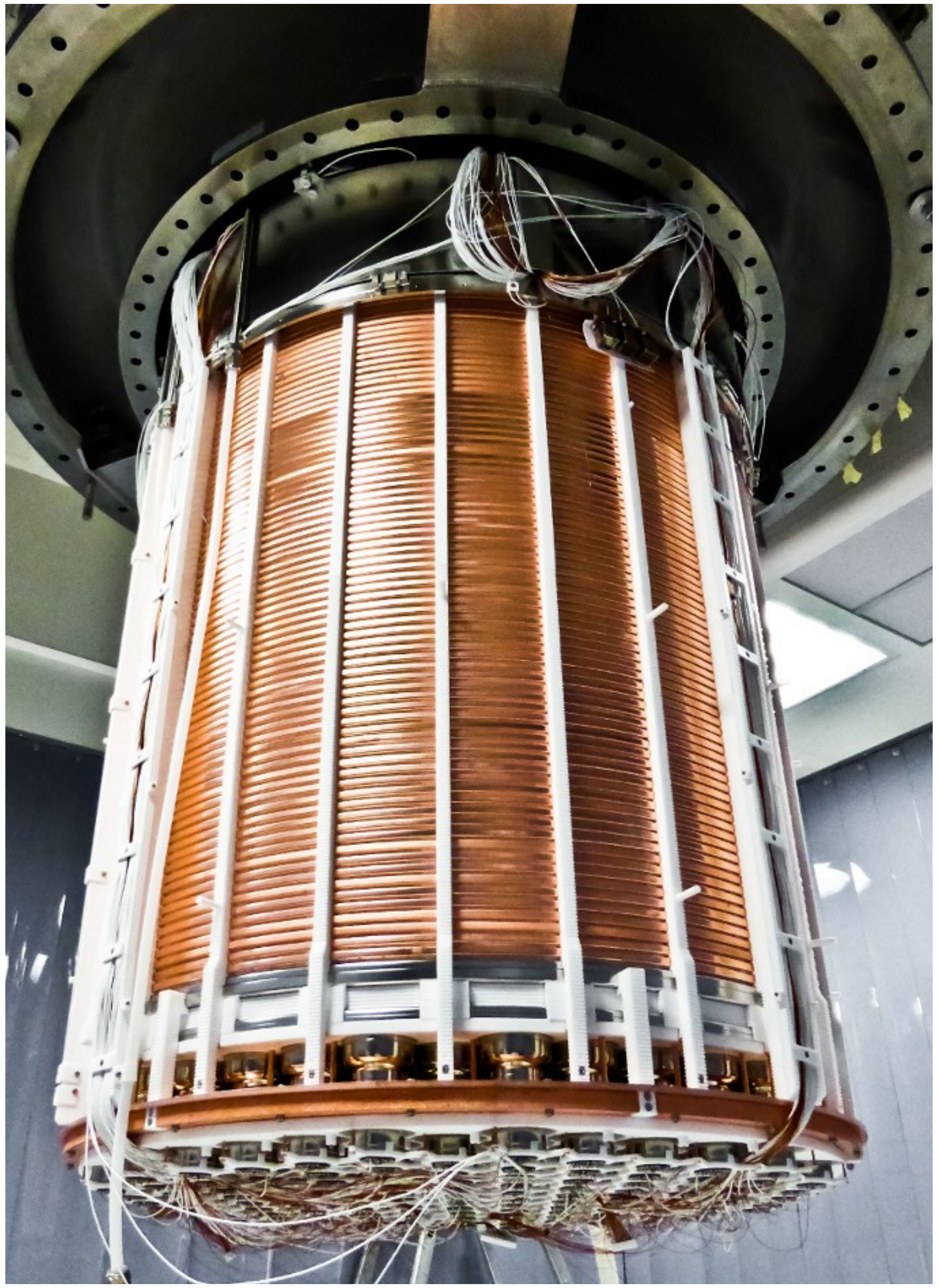
XENON1T commissioning at LNGS

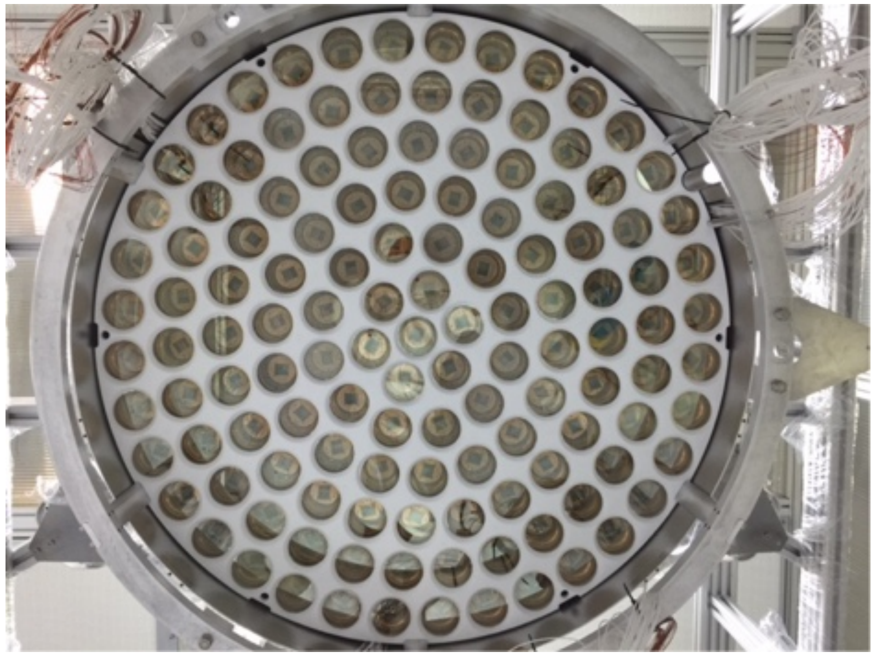


The XENON1T time projection chamber

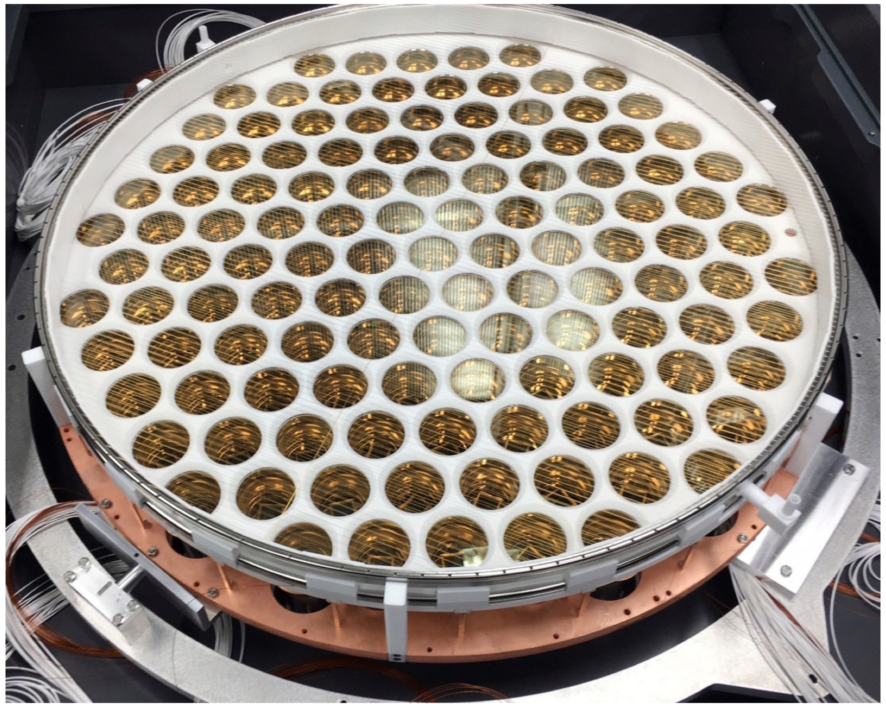
- Active liquid xenon volume observed by 248 3-inch, low-radioactivity PMTs

3.3 tons LXe in total, at 180 K





127 PMTs in the top array



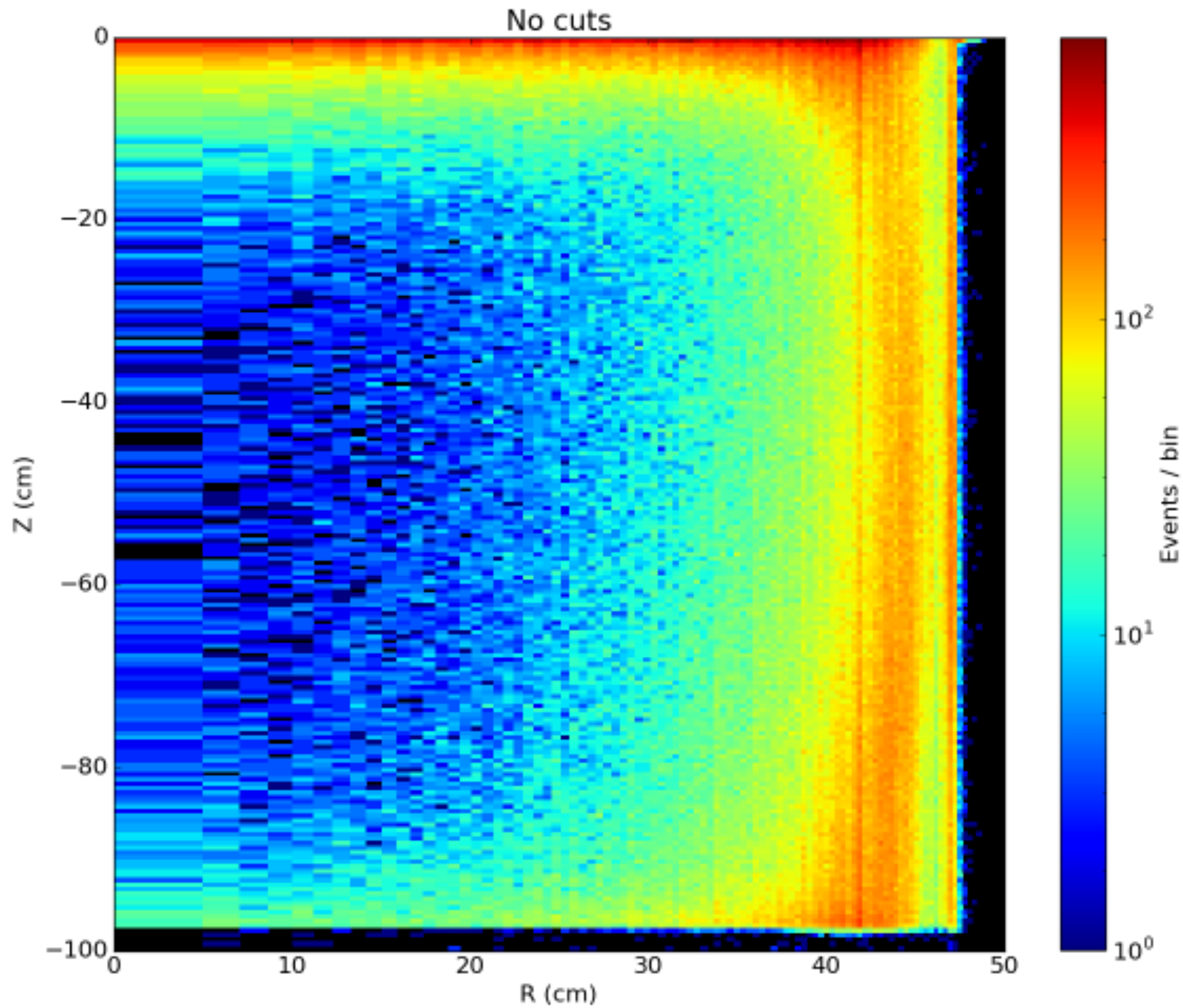
121 PMTs in the bottom array

The XENON1T experiment: inner detector

- PMTs tested at cryogenic temperatures; arrays were assembled in October 2015
- TPC assembly and cold tests completed at UZH; installation at LNGS in November 2015

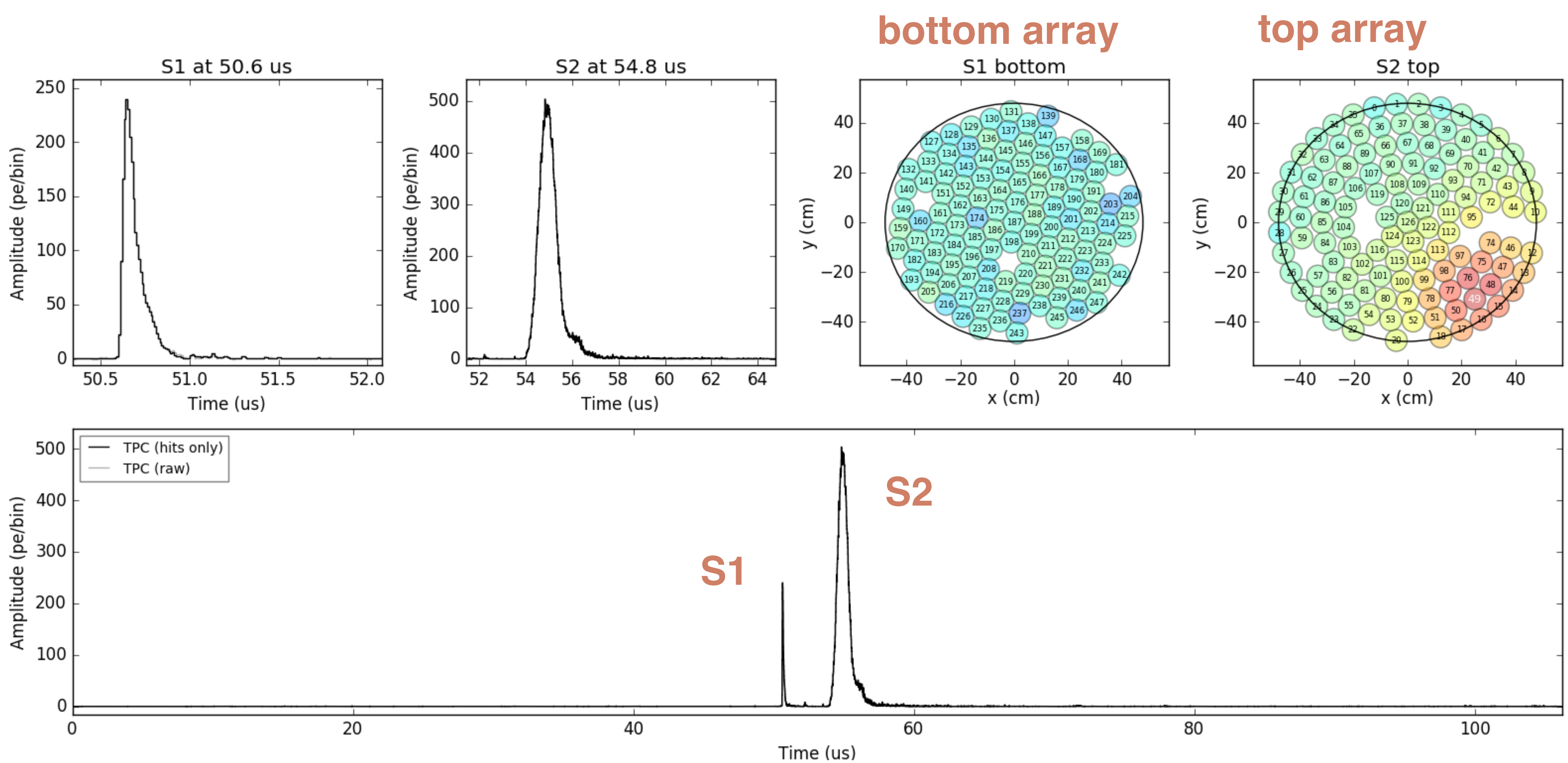
XENON1T: events in the TPC

- Distribution of events in the TPC
  - 12 h of data, no cuts
- Requirement:
  - an S1/S2 pair
- No optimisation of position reconstruction etc



The XENON1T experiment: first light and charge

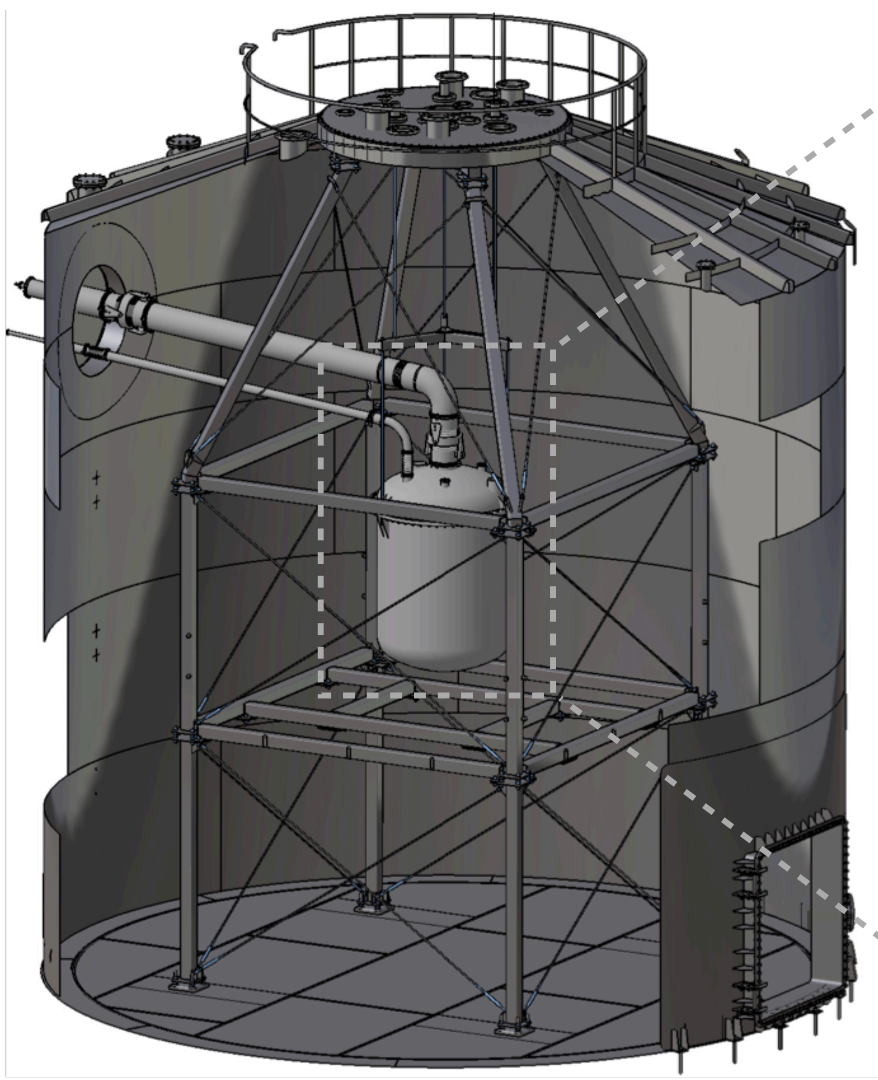
- **All sub-systems commissioned in 2016**
- **First science run started in December 2016, to last until April 2017**

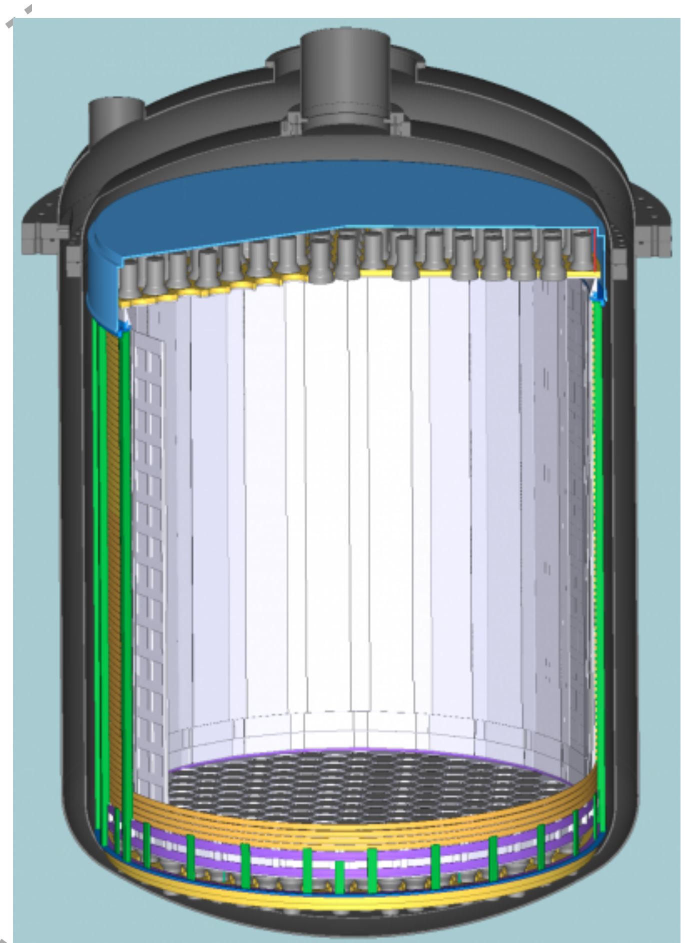


First S1- and S2 signals in the XENON1T TPC

XENONnT: 2019-2021

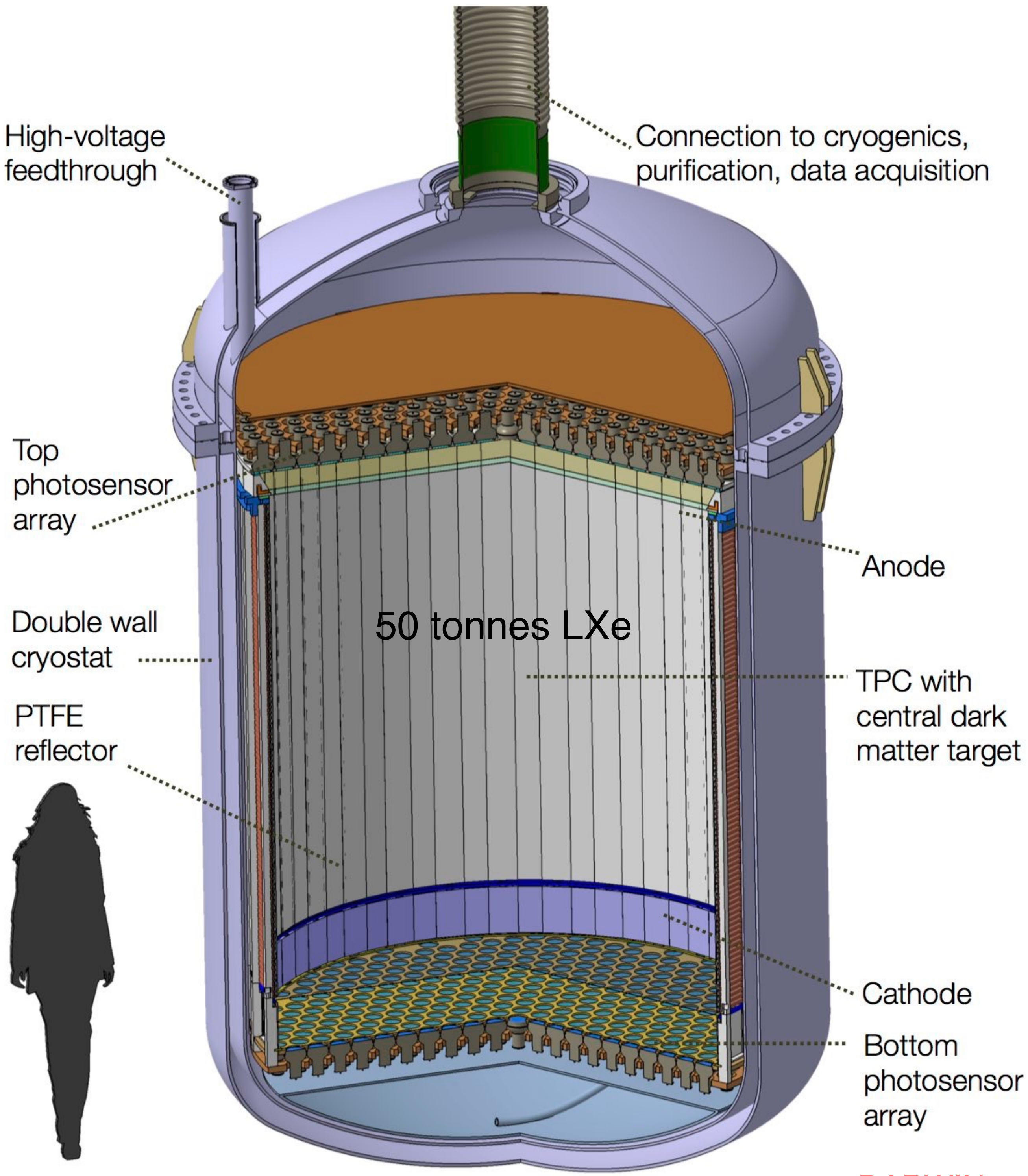
- Double the amount of LXe (~7 tons), double the number of PMTs
- XENON1T is constructed such that many sub-systems will be reused for the upgrade:





- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics and purification system
- LXe storage system
- Cables installed for XENONnT as well
- LXe, inner cryostat, PMTs, electronics needed

DARWIN Dark matter WIMP search with noble liquids



Ultimate LXe TPC at LNGS

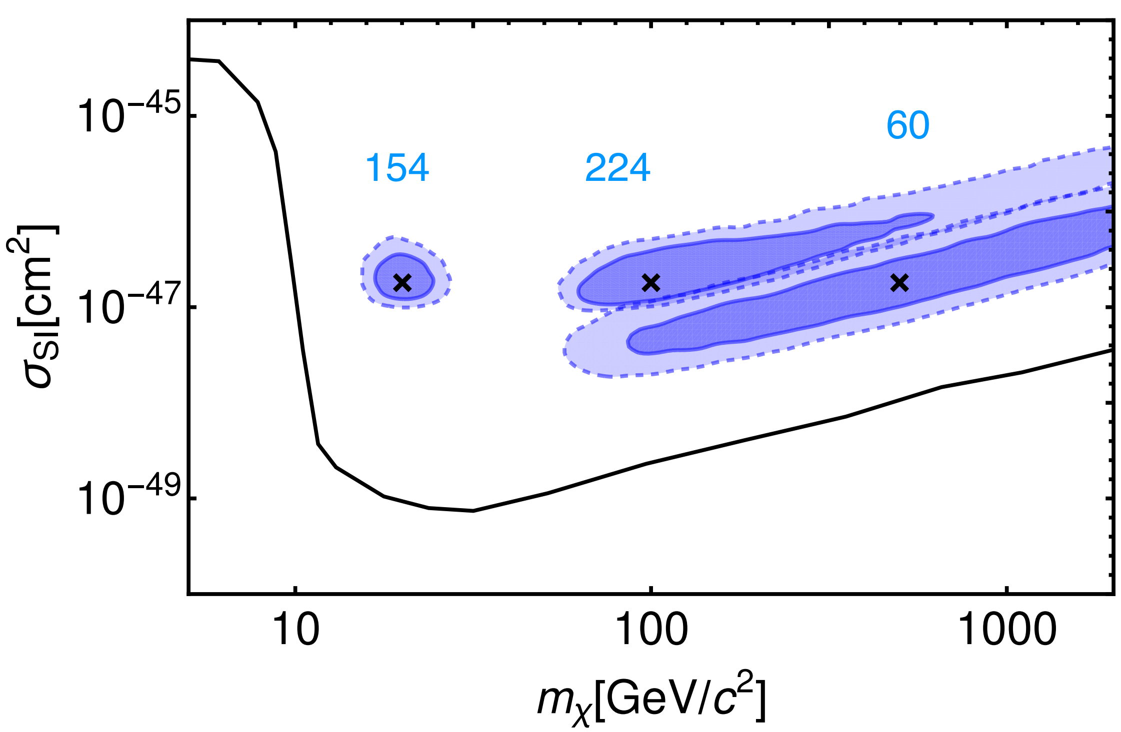
- 50 t (40 t) LXe in total (in the TPC)
- ~ 10^3 photosensors
- 2.6 m drift length, 2.6 m diameter TPC
- **Background: dominated by neutrinos**
- WIMP spectroscopy, and *lots of non-WIMP science:*
    - axion/ALP and dark photon searches
    - solar pp neutrinos (<1% precision)
    - ^{8}B and SN neutrinos (CNNS)
    - $0\nu\beta\beta$-decay of ^{136}Xe

DARWIN collaboration, JCAP 1611 (2016) 017

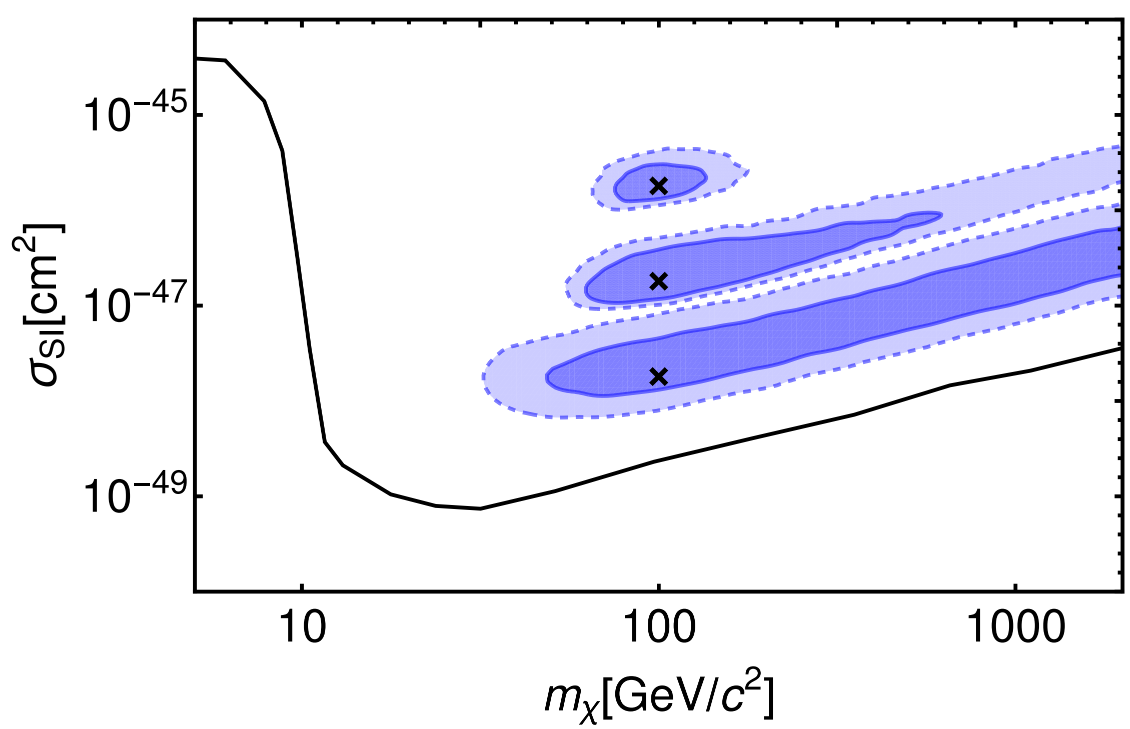
Dark matter spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses (**20, 100, 500 GeV/c²**) and cross sections

Exposure: 200 t y



Exposure: 200 t y



1 and 2 sigma credible regions after marginalising the posterior probability distribution over:

$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

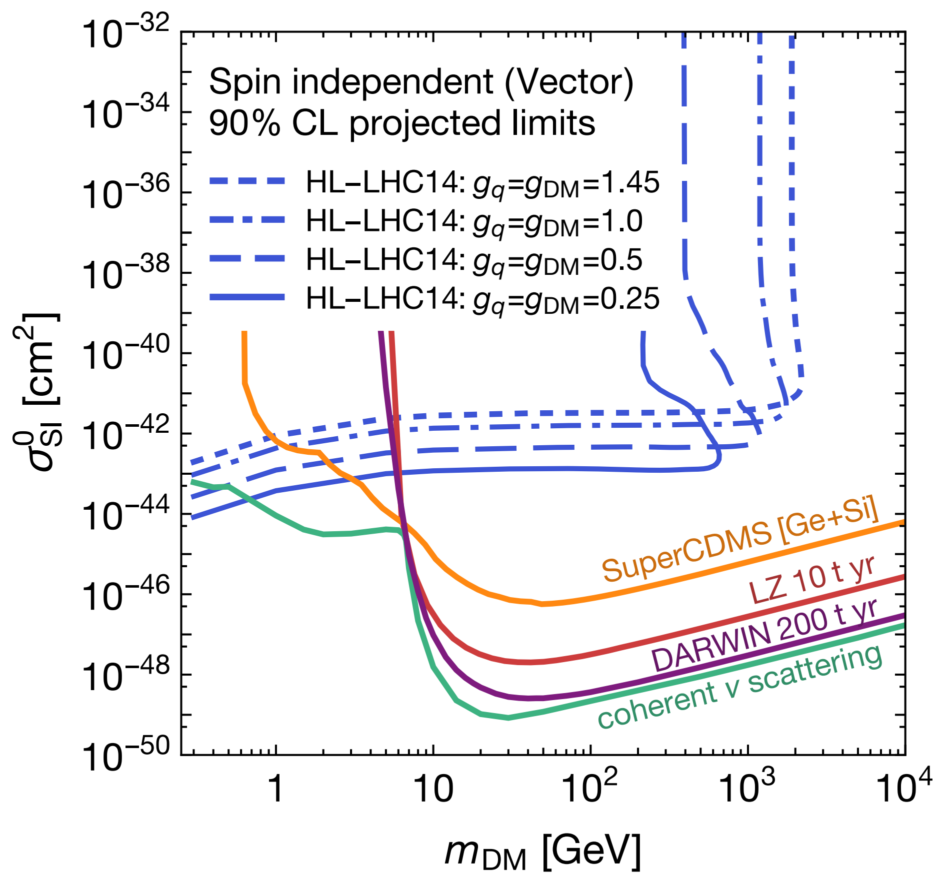
DARWIN collaboration, JCAP 1611 (2016) 017

WIMP physics: complementarity with the LHC

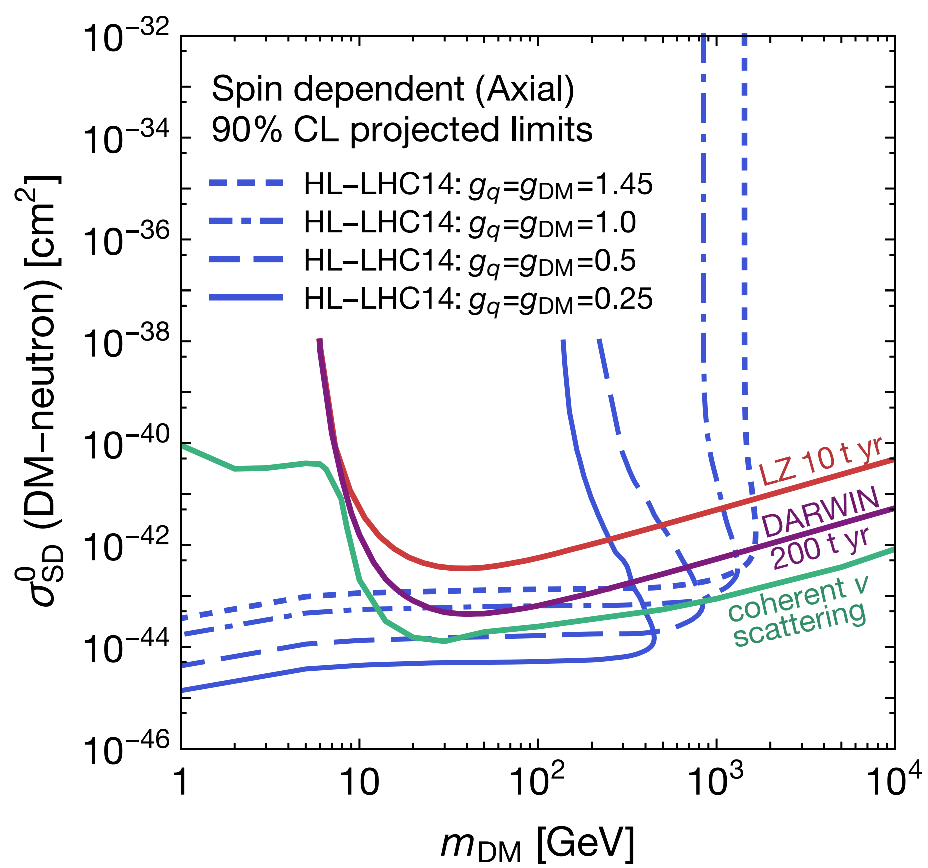
- Minimal simplified DM model with only 4 variables: m_{DM}, M_{med}, g_{DM}, g_q
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

$$\sigma_{\mathrm{DD}} \propto \frac{g_{\mathrm{DM}}^2 g_q^2 \mu^2}{M_{\mathrm{med}}^4}$$

Spin independent



Spin dependent



S. Malik et al., Phys. Dark Univ. 9-10 (2015) 51-58

Conclusions

Cold dark matter is (still) a viable paradigm that explains all cosmological & astrophysical observations

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

- this hypothesis is testable: direct detection, indirect detection, accelerators

- so far, no convincing detection of a dark matter particle in the laboratory

But: direct detection experiments offer excellent prospects for discovery

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

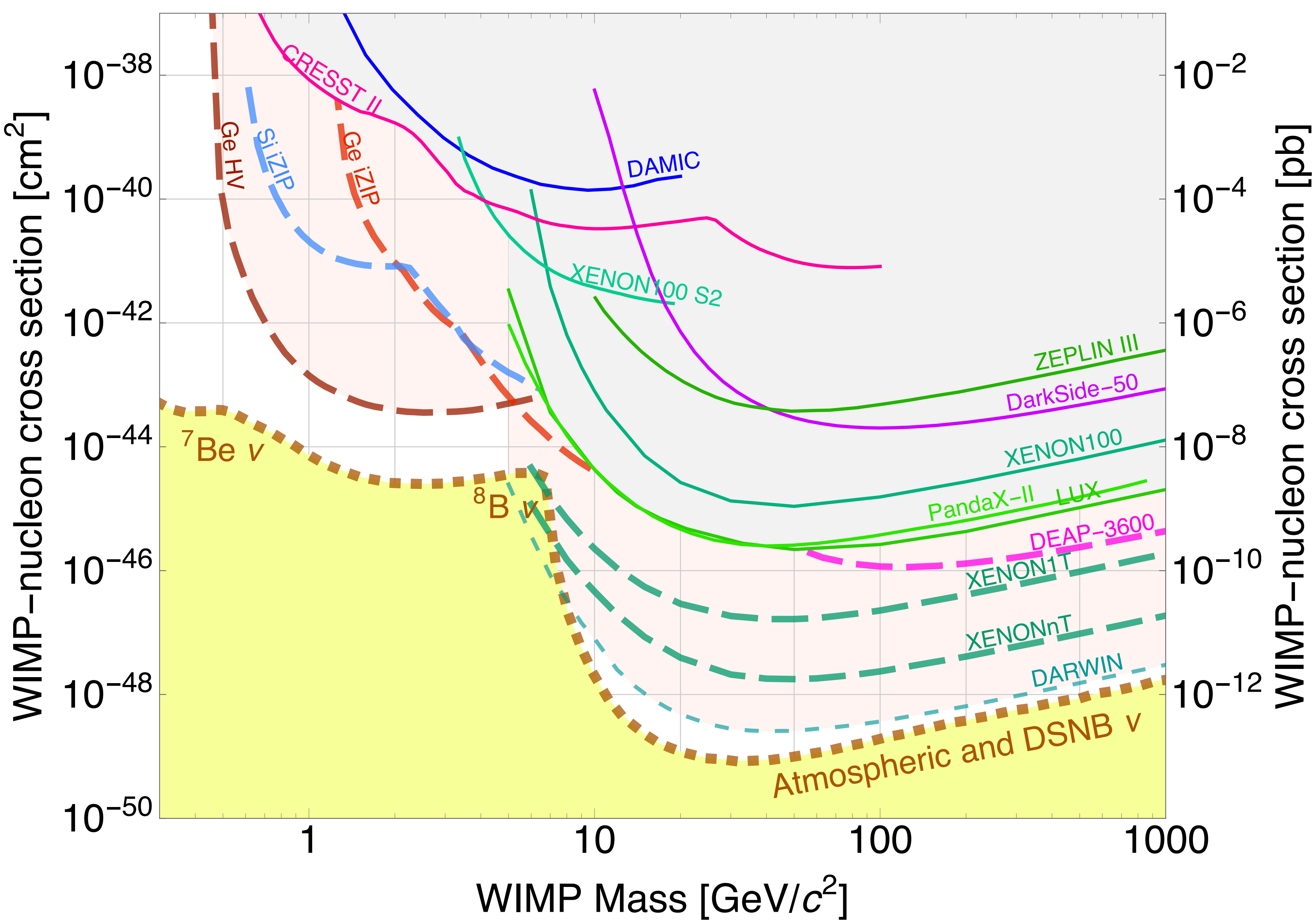
reach neutrino background (measure neutrino-nucleus coherent scattering from solar/atm/SN neutrinos!) this & next decade

high complementarity with indirect searches & with HL-LHC

The end

Of course, **"the probability of success is difficult to estimate, but if we never search, the chance of success is zero"**

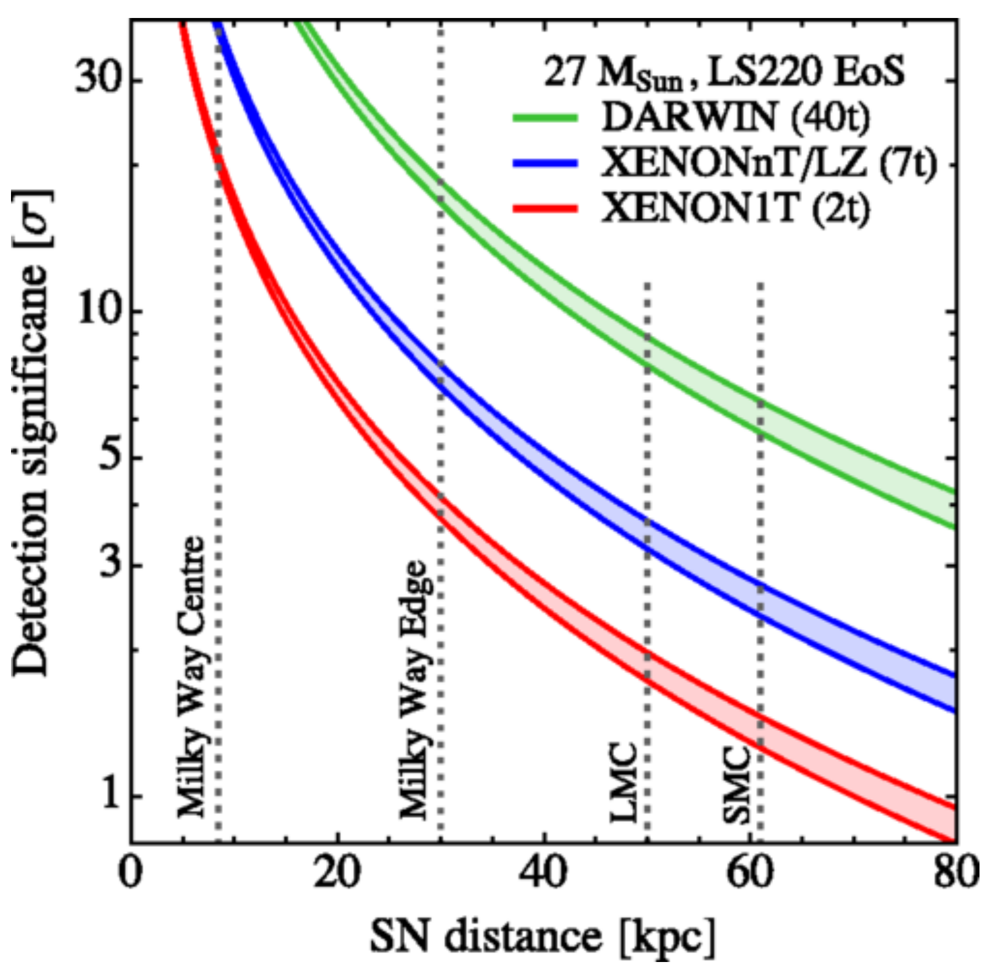
G. Cocconi & P. Morrison, Nature, 1959



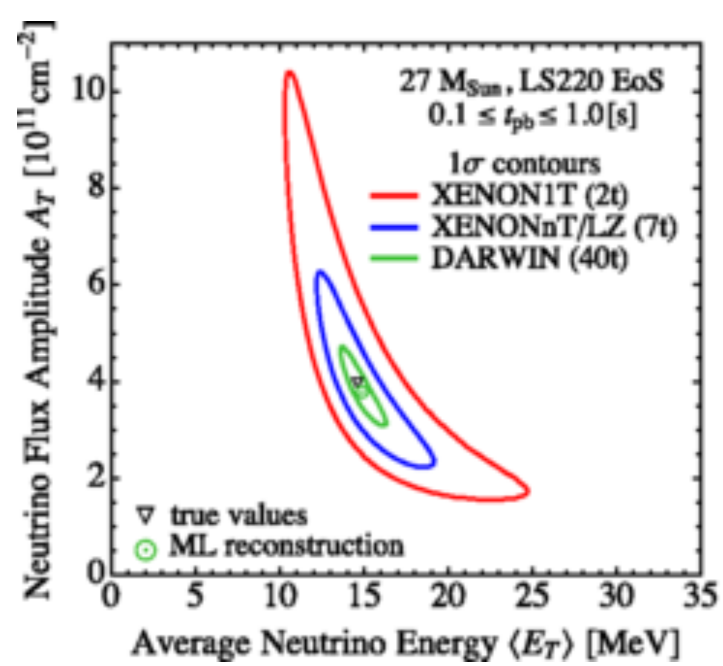
Backup slides

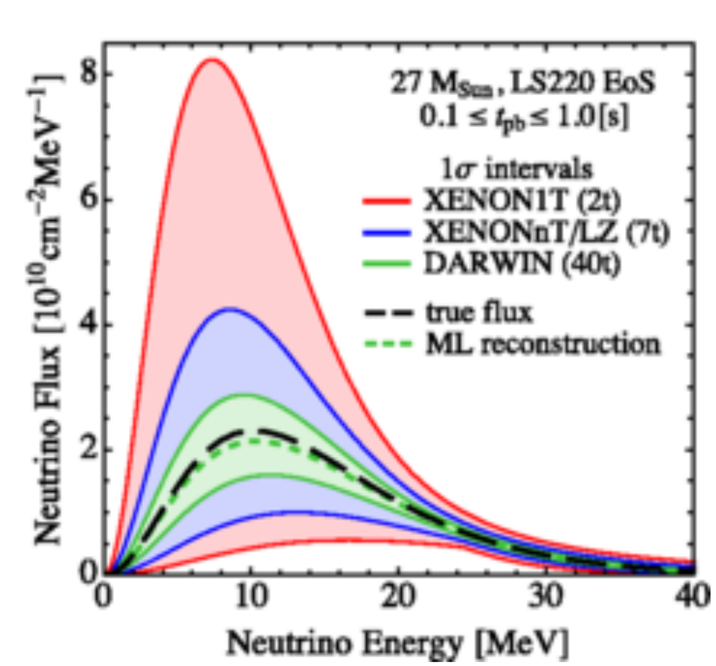
DARWIN and SN neutrinos

- Sensitive to SN neutrino bursts up to 65 kpc, at > 5-sigma significance
- About 700 events from a 27 M_{solar} SN at 10 kph
- Measure the *average neutrino energy of all flavours*



Signal integrated from [0, 7] s





R. F. Lang, C. McCabe, S. Reichard, M. Selvi, and I. Tamborra
Phys. Rev. D **94**, 103009

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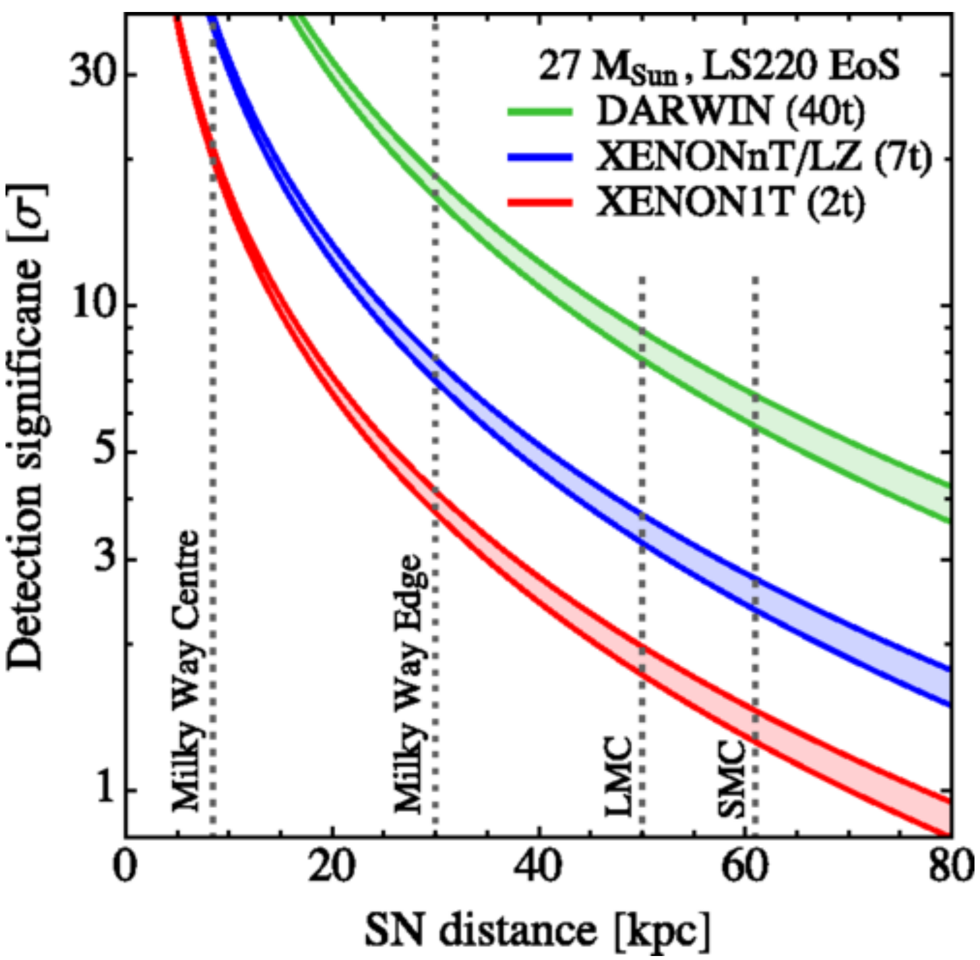

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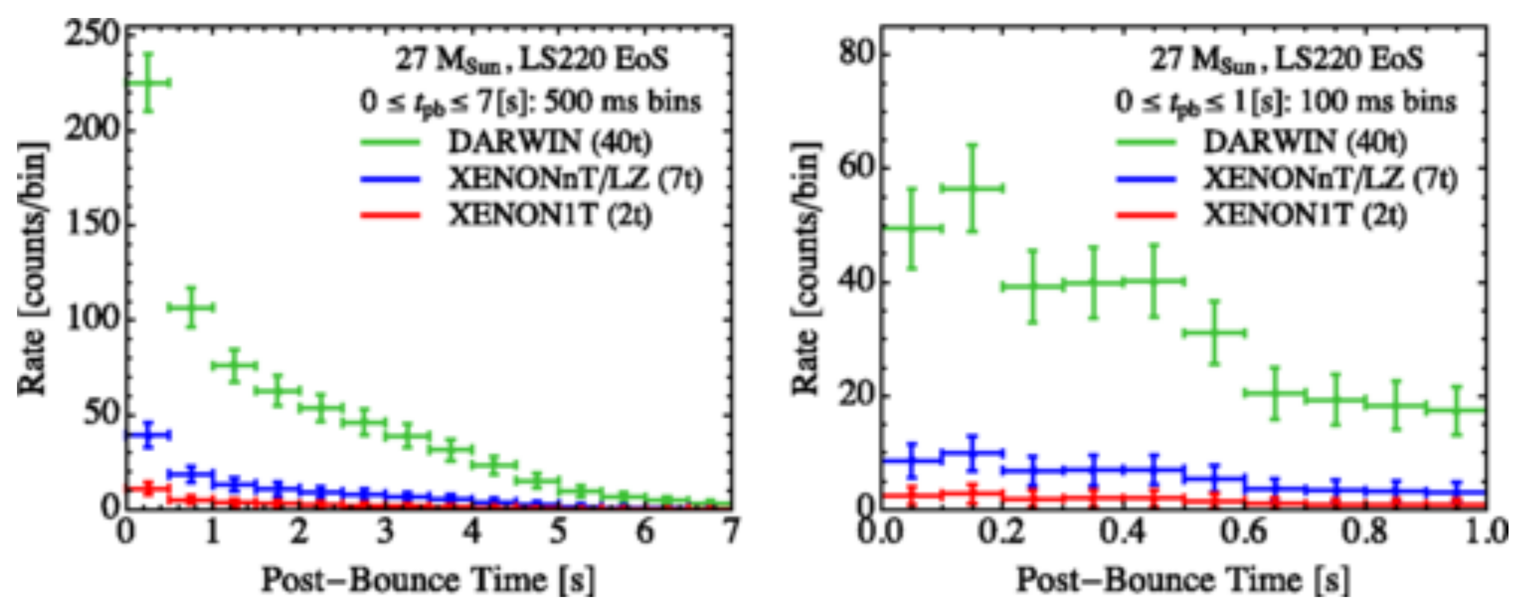
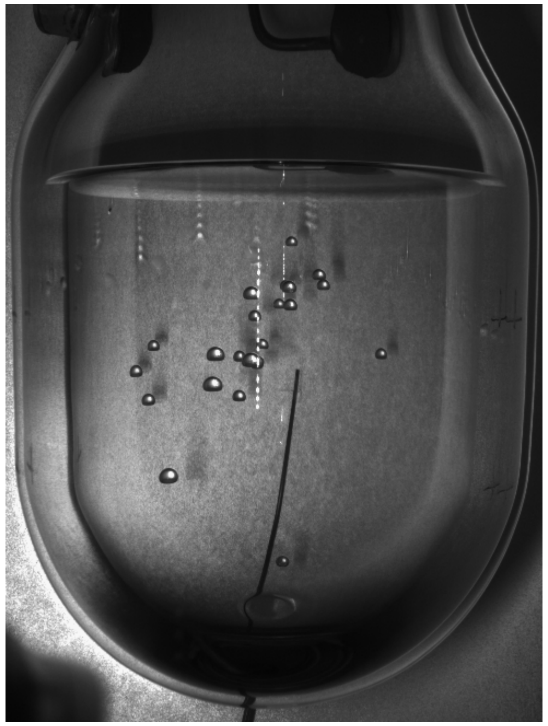


R. F. Lang, C. McCabe, S. Reichard, M. Selvi, and I. Tamborra
Phys. Rev. D **94**, 103009

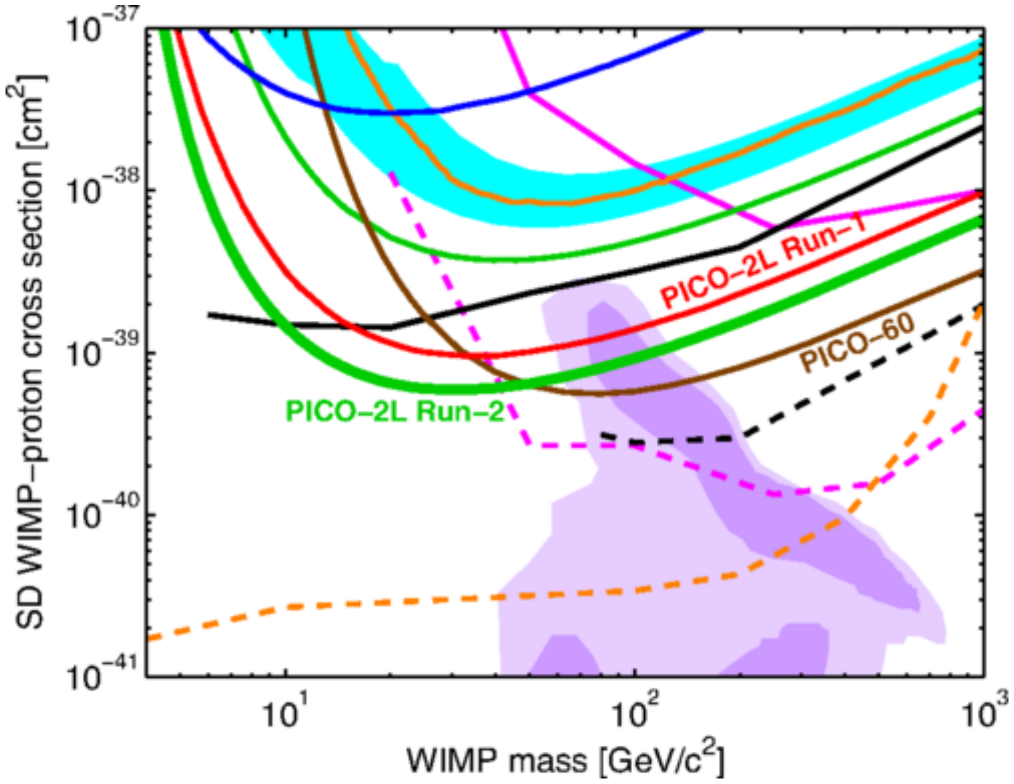
Bubble chambers

- Detect single bubbles induced by high dE/dx NRs in superheated liquid target:
  - acoustic and visual readout; measure integral rate above threshold
  - large rejection factor (~10^{10}) for MIPs; scalable to large masses; high spatial granularity
- New results: PICO-2L (PICASSO + COUP), 2.9 kg C_3F_8 target, best SD WIMP-proton limit
- PICO-60L running since 2016; proposed: PICO-250L C_3F_8 target at SNOLAB



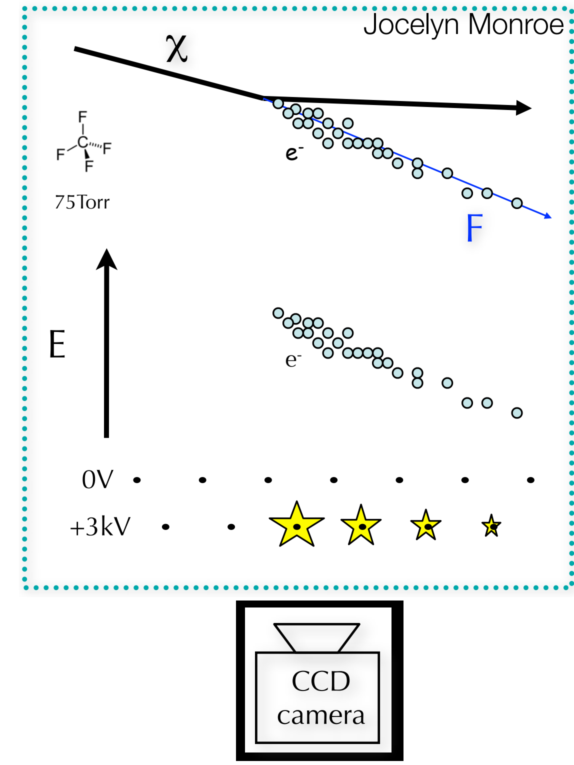
PICO-2L n-calibration

PRD 93, 061101 (2016)

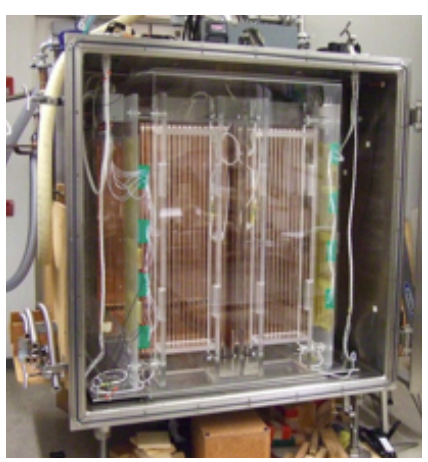


Directional detectors

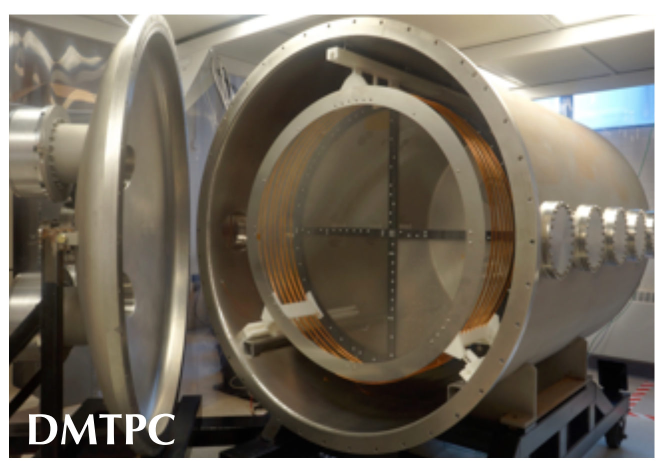
- R&D on low-pressure gas detectors to measure the recoil direction (~30° resolution), correlated to the Galactic motion towards Cygnus
- Challenge: good angular resolution + head/tail at 30-50 keVnr
- **One common technology to be proposed in 2017**



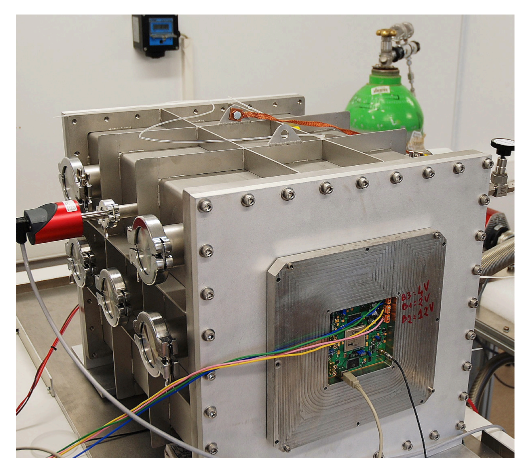
CYGNUS: coordination of directional R&D



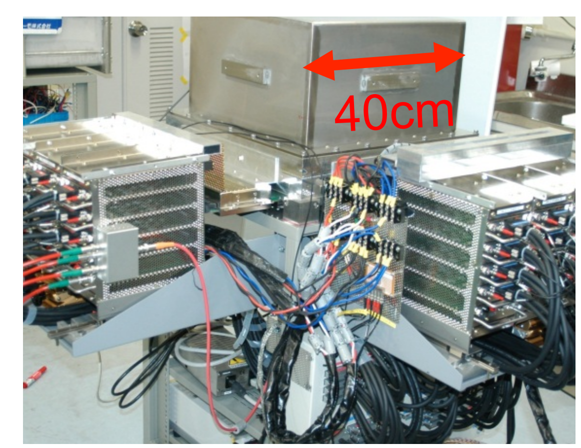
DRIFT, Boulby Mine
1 m^3, negative ion drift
CS_2 +CF_4 gas



DMTPC, MIT
Optical and charge readout
CF_4 gas
commissioning 1 m^3 module



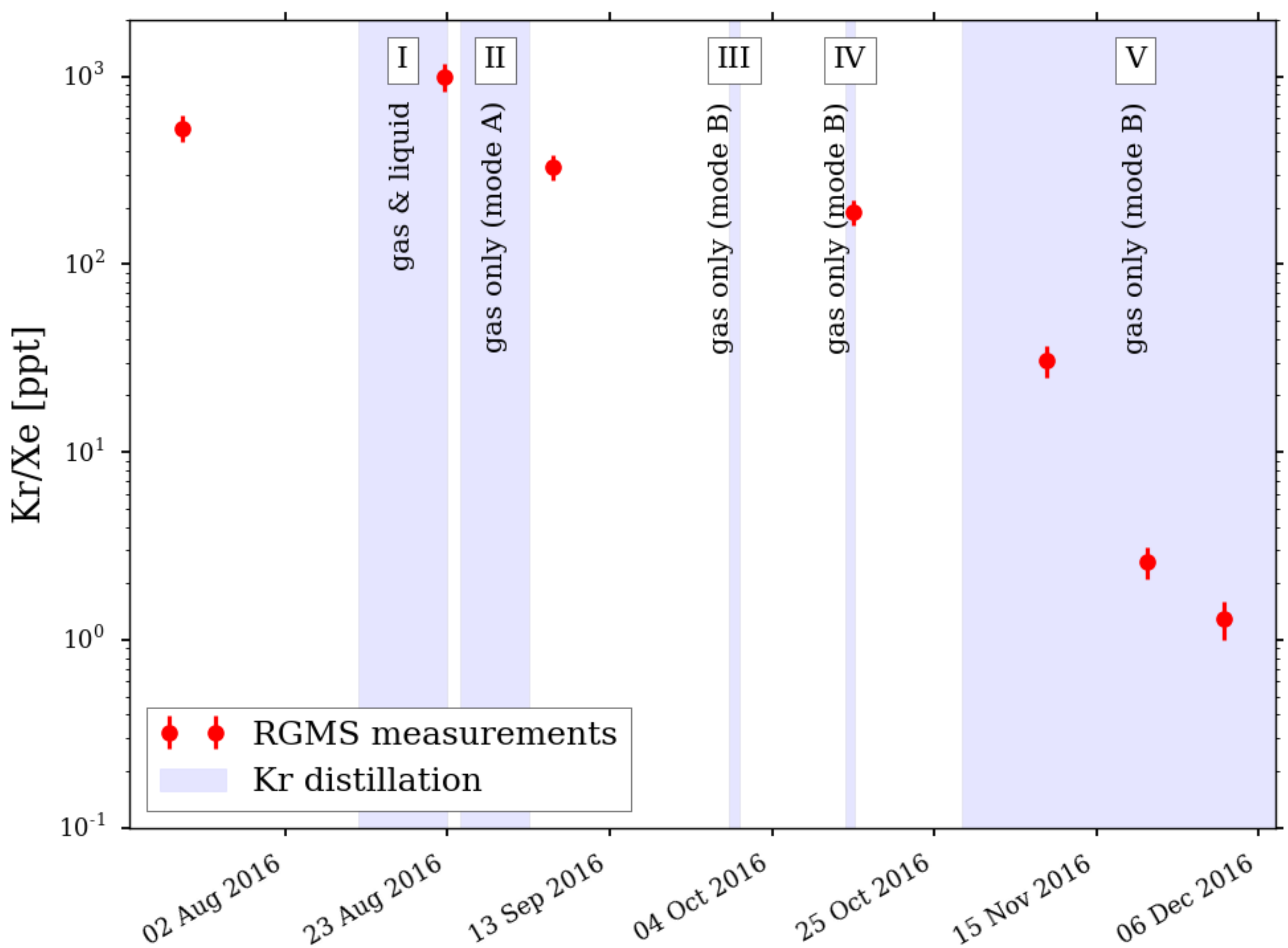
MIMAC 100x100 mm^2
5l chamber at Modane
CF_4 gas



NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

XENON1T: Kr level evolution

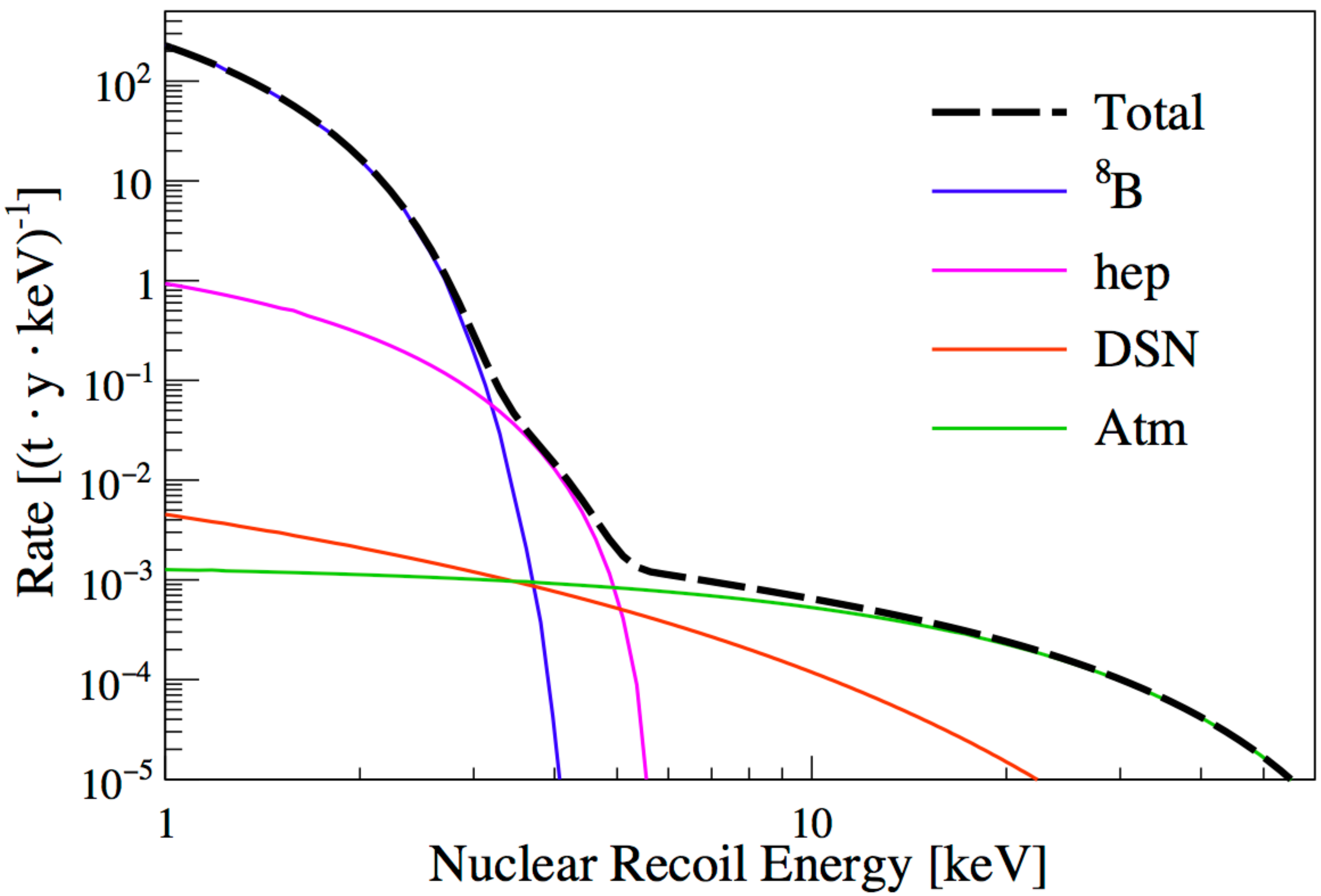
- Evolution of Kr/Xe [ppt, mol/mol] level during online distillation (as measured by RGMS)



Level as of 01.12.2016
1.3 ± 0.3 ppt

New sample being measured

Coherent neutrino-nucleus scatters in XENON1T



- **Total rates:**
- 90 events/(t yr) > 1 keVnr
- 9 x 10^{-2} events/(t y) > 3 keV_{nr}
- 1.8 x 10^{-2} events/(t y) > 4 keV_{nr}
- 1.2 x 10^{-2} events/(t y) > 5 keV_{nr}

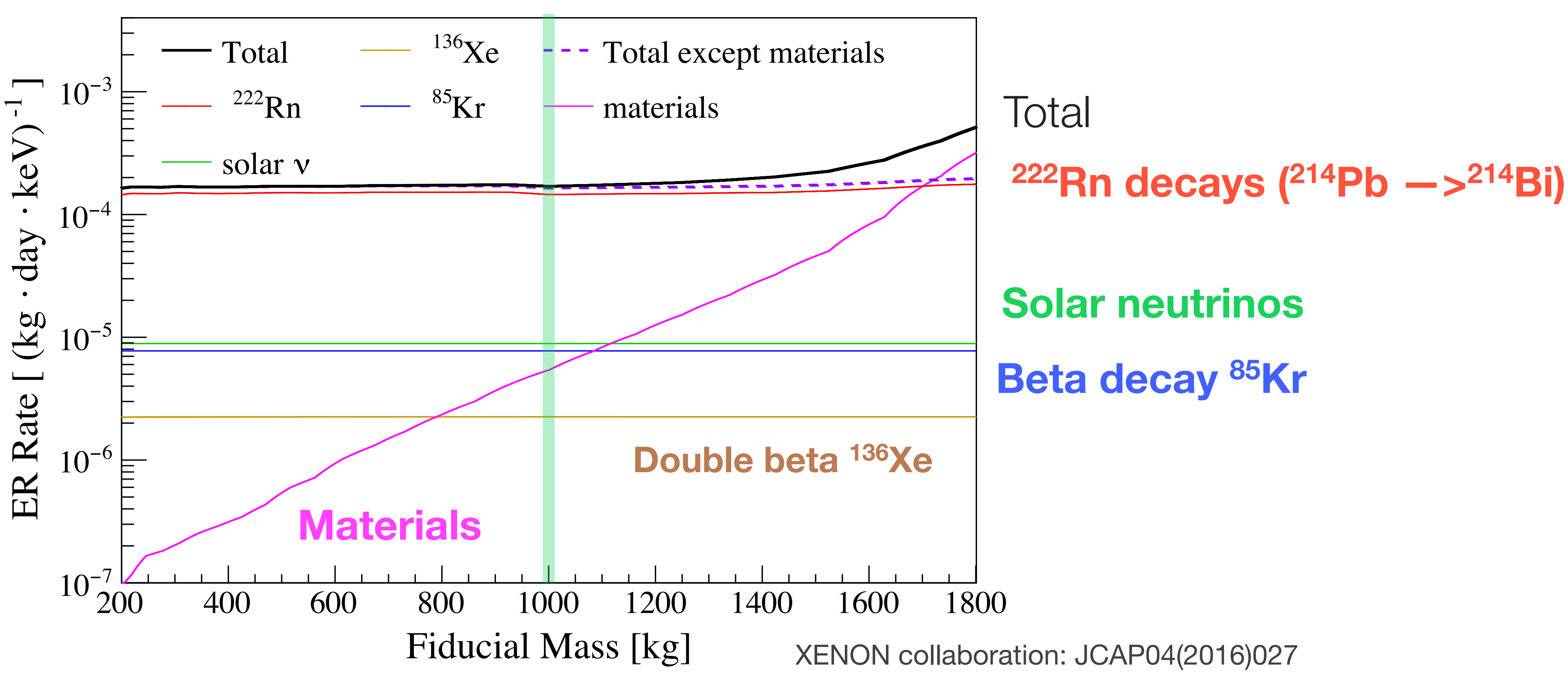
XENON collaboration: JCAP04(2016)027

XENON1T background predictions

- Materials: based on screening results for all detector components
- ^{85}Kr: 0.2 ppt of ^{nat}Kr with 2x10^{-11} ^{85}Kr; ^{222}Rn: 10 µBq/kg; ^{136}Xe double beta: 2.11x10^{21} y
- ER vs NR discrimination level: 99.75%; 40% acceptance for NRs

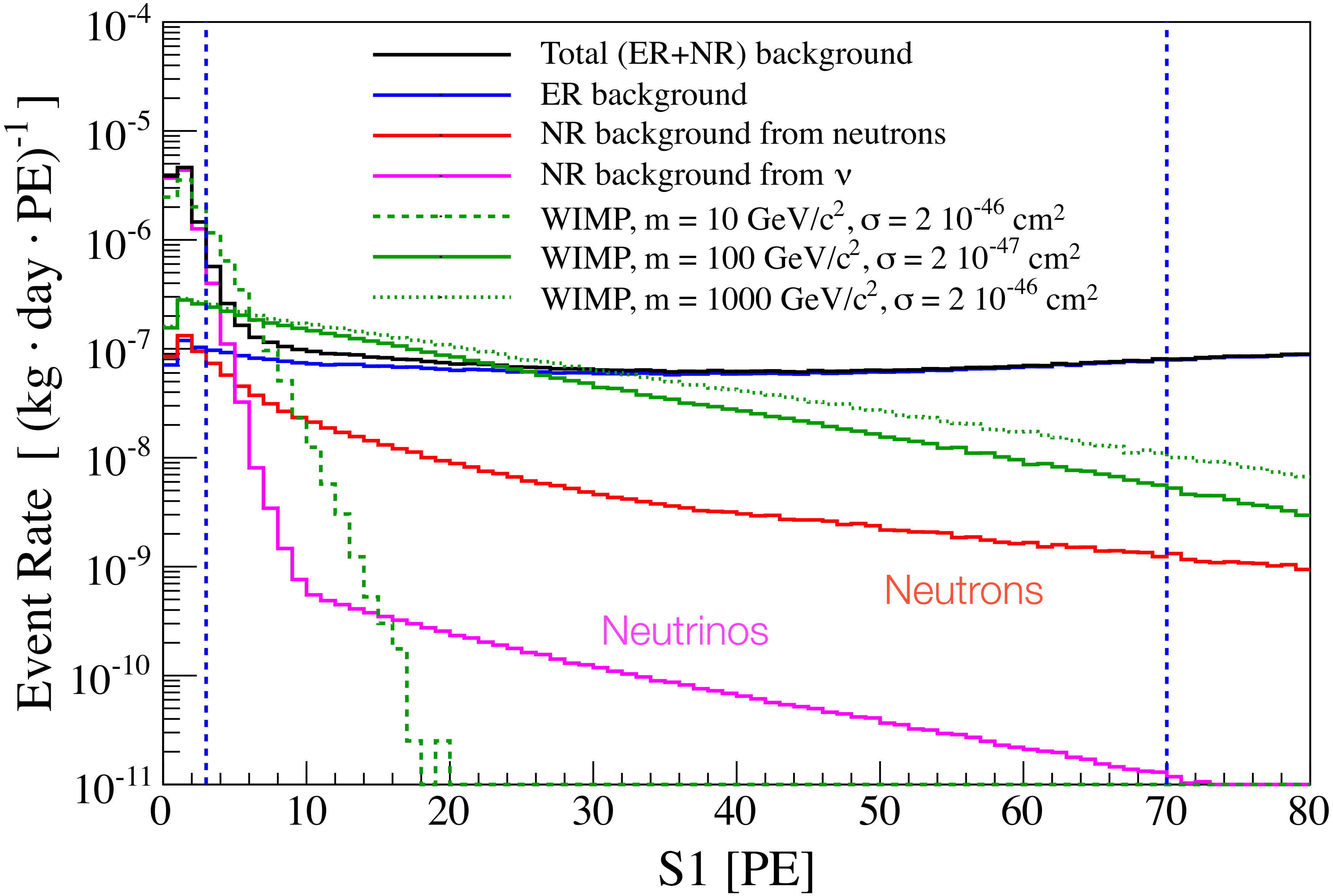
➡ **Total ERs: 0.3 events/year** in 1 ton fiducial volume, [2-12] keV$_{ee}$

➡ **Total NRs: 0.6 events/year in 1 ton**, [5-50] keV$_{nr}$ (muon-induced n-BG < 0.01 ev/year)



XENON collaboration: JCAP04(2016)027

XENON1T backgrounds and WIMP sensitivity



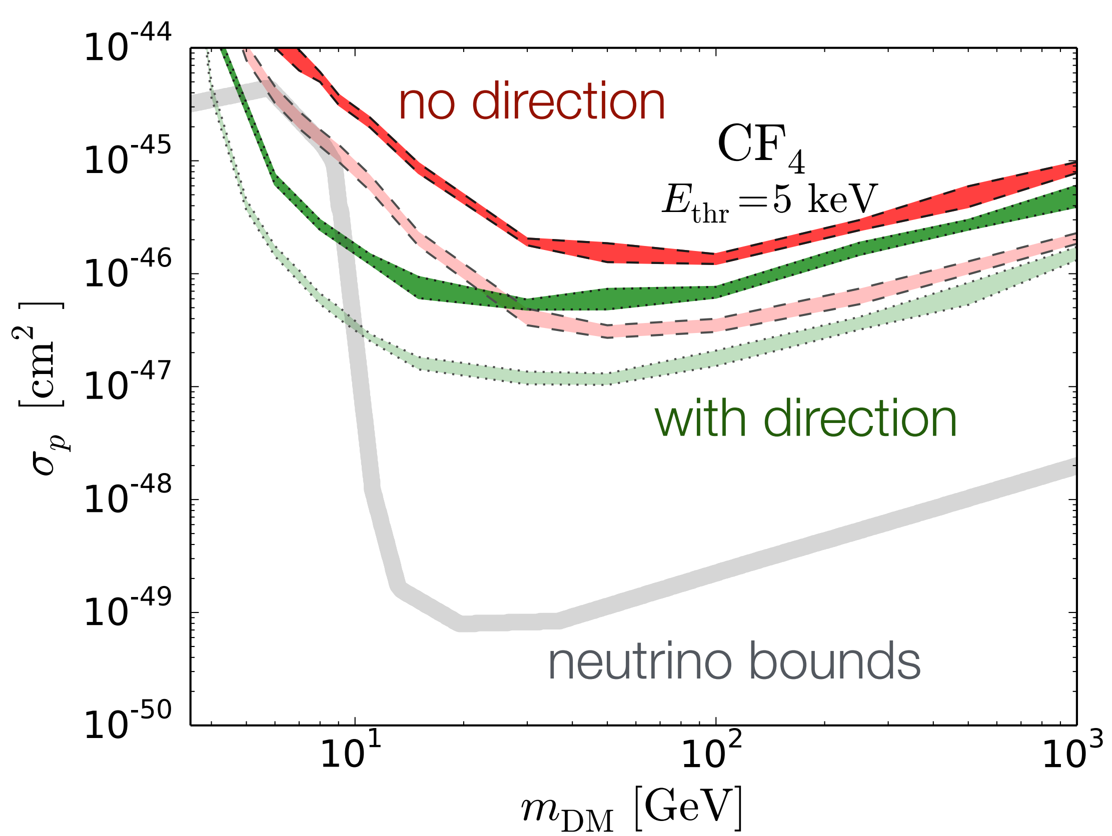
Light yield = 7.7 PE/keV at 0 field
L_{eff} = 0 below 1 keVnr

99.75% S2/S1 discrimination
NR acceptance 40%

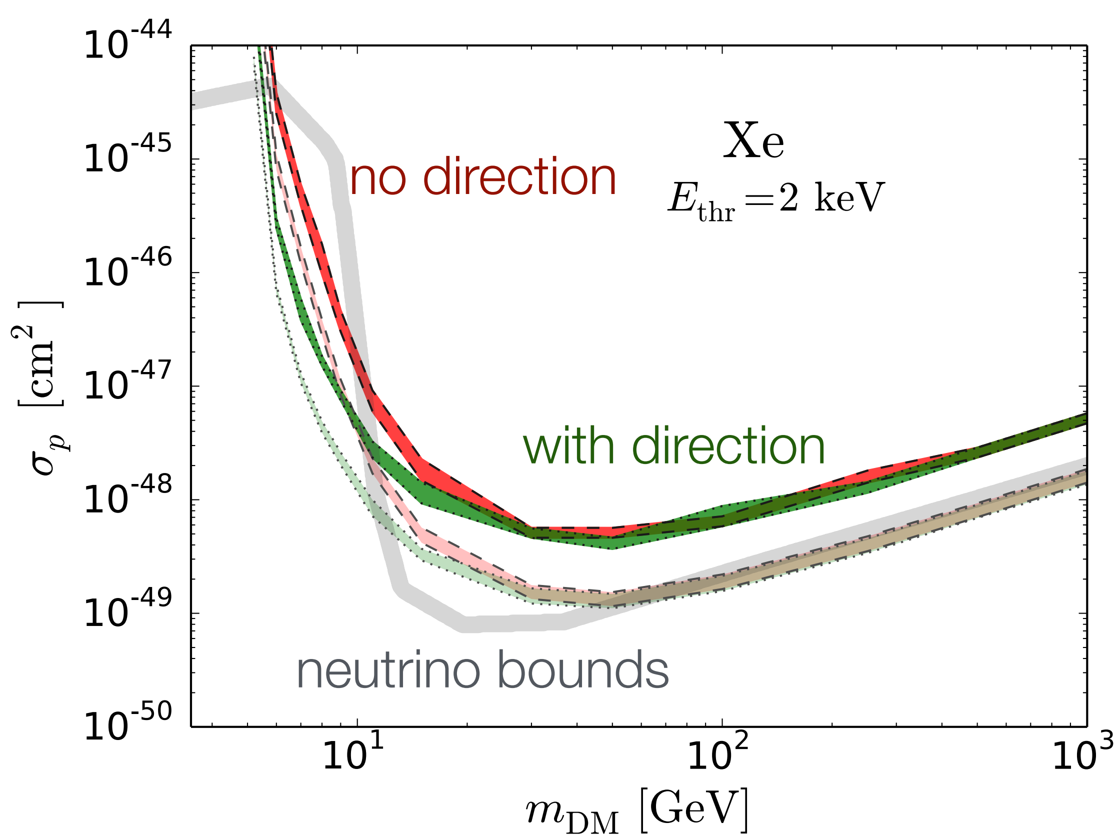
Will directional information help?

- Yes, but mostly at low WIMP masses
- Directional detection techniques currently in R&D phase
- Would be very challenging to reach 10^{-48} - 10^{-49} cm^2 with these techniques

36.6 t yr exposure, 500 (solar) nu events



367 t yr exposure, 500 nu events



P. Grothaus, M. Fairbairn, J. Monroe, arXiv: 1406.5047