Dark Matter Searches – WIMPs

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The Future of Non-Collider-Physics
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with input from K. Eitel, M. Lindner, F. Petricca,
T. Pollmann, S. Schönert, C. Weinheimer

Direct Detection in Germany

CRESST

Edelweiss

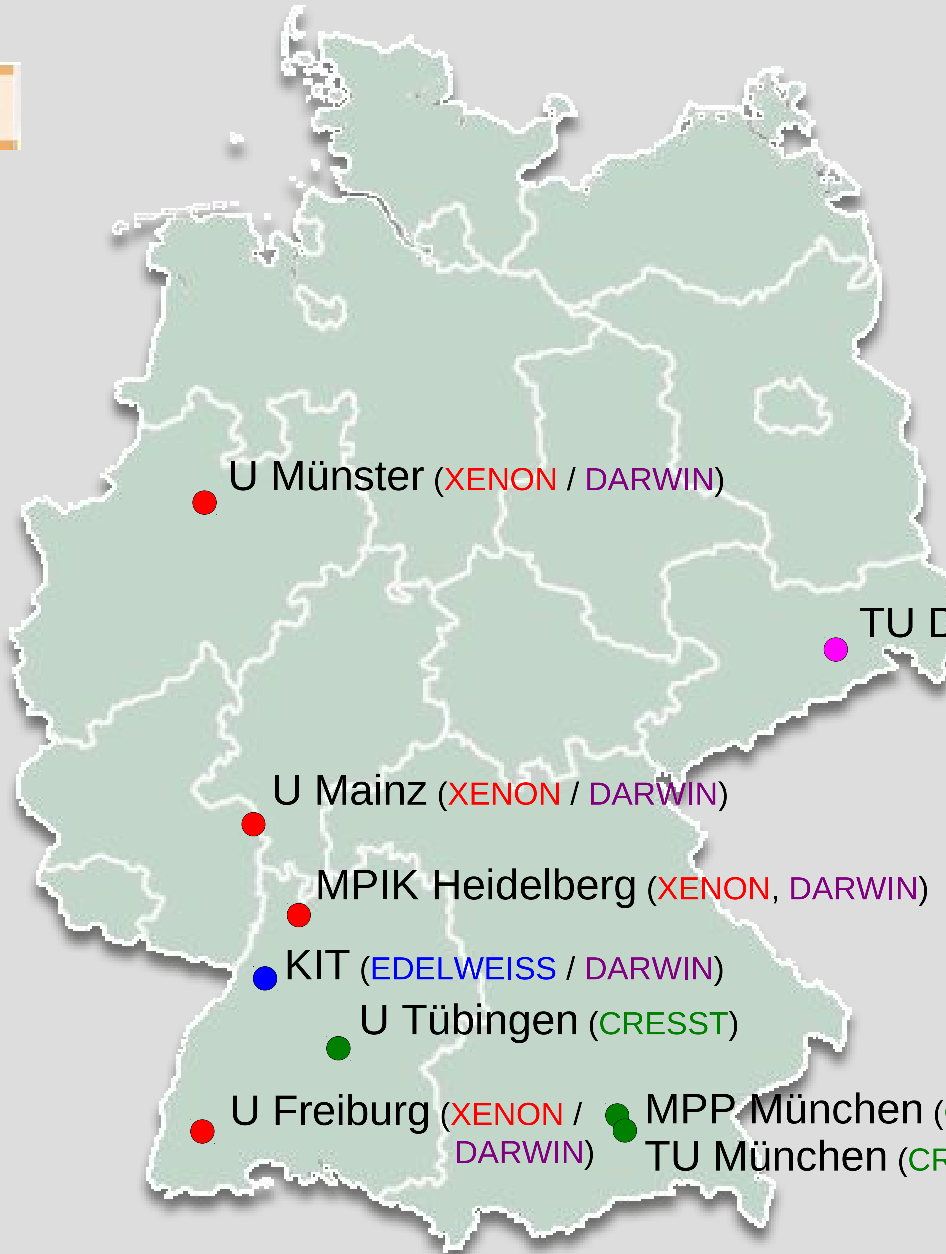
Expérience pour DEtecter Les WIMPs En Site Souterrain

Xe

XENON

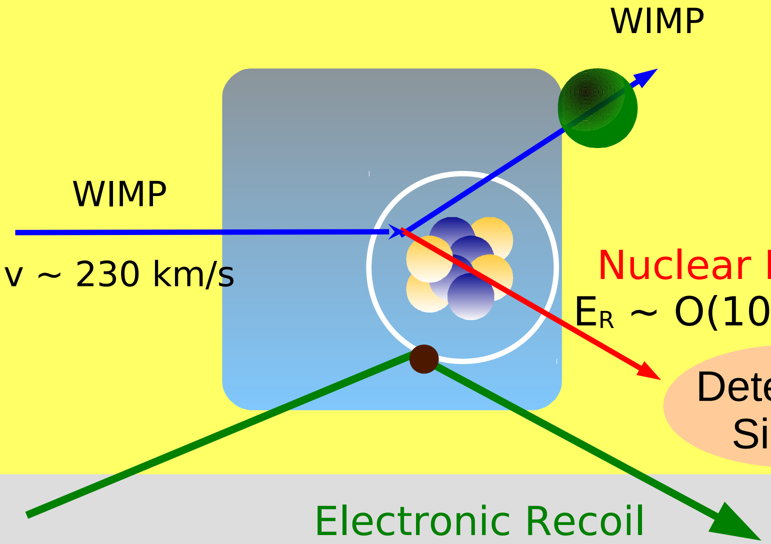
Dark Matter Project

DARWIN

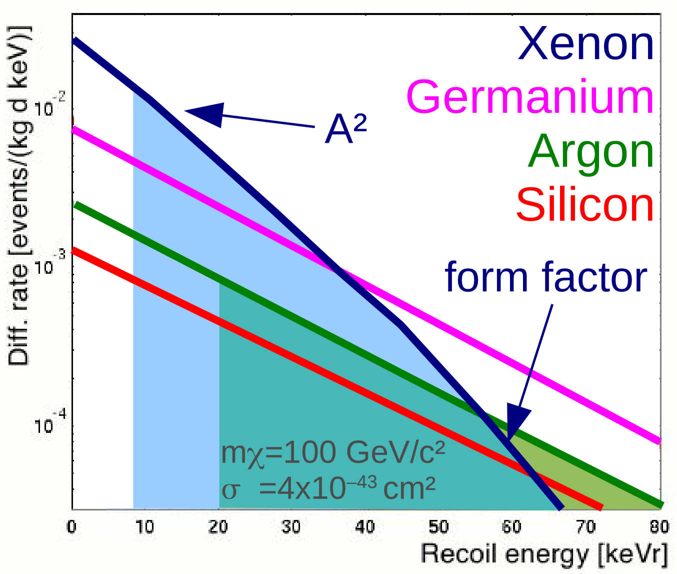


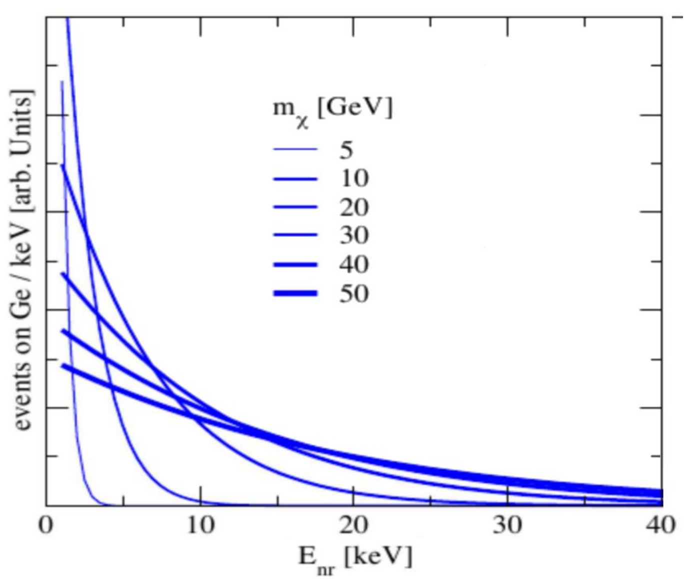
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



Recoil Spectra:



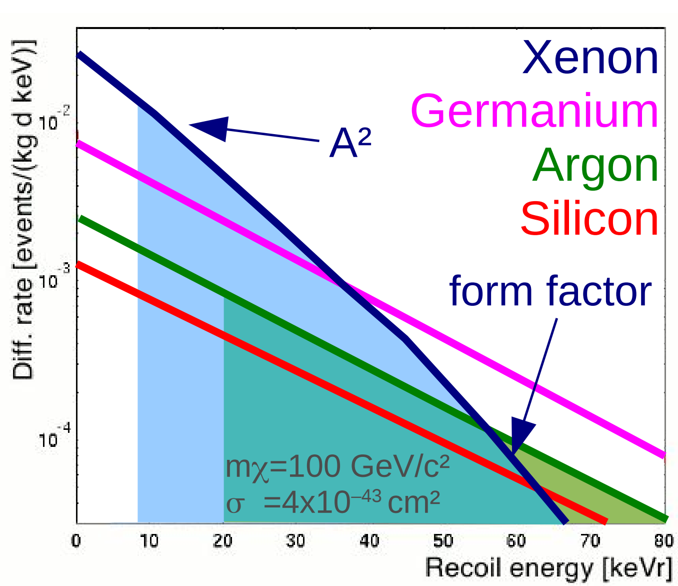


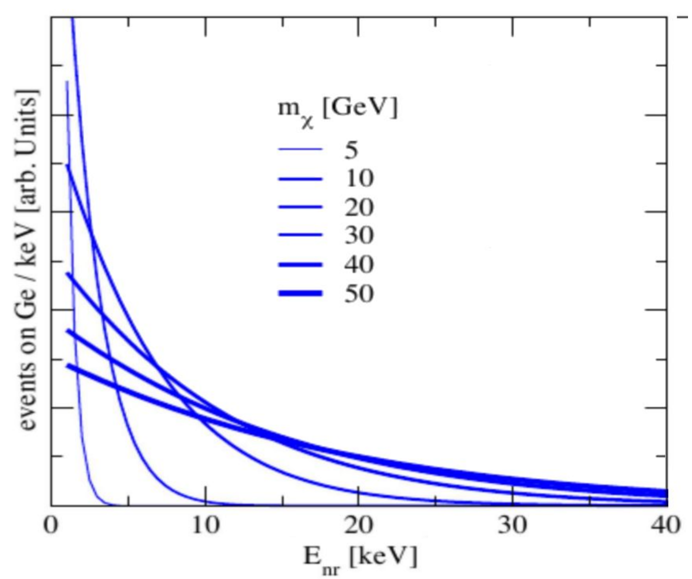
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil

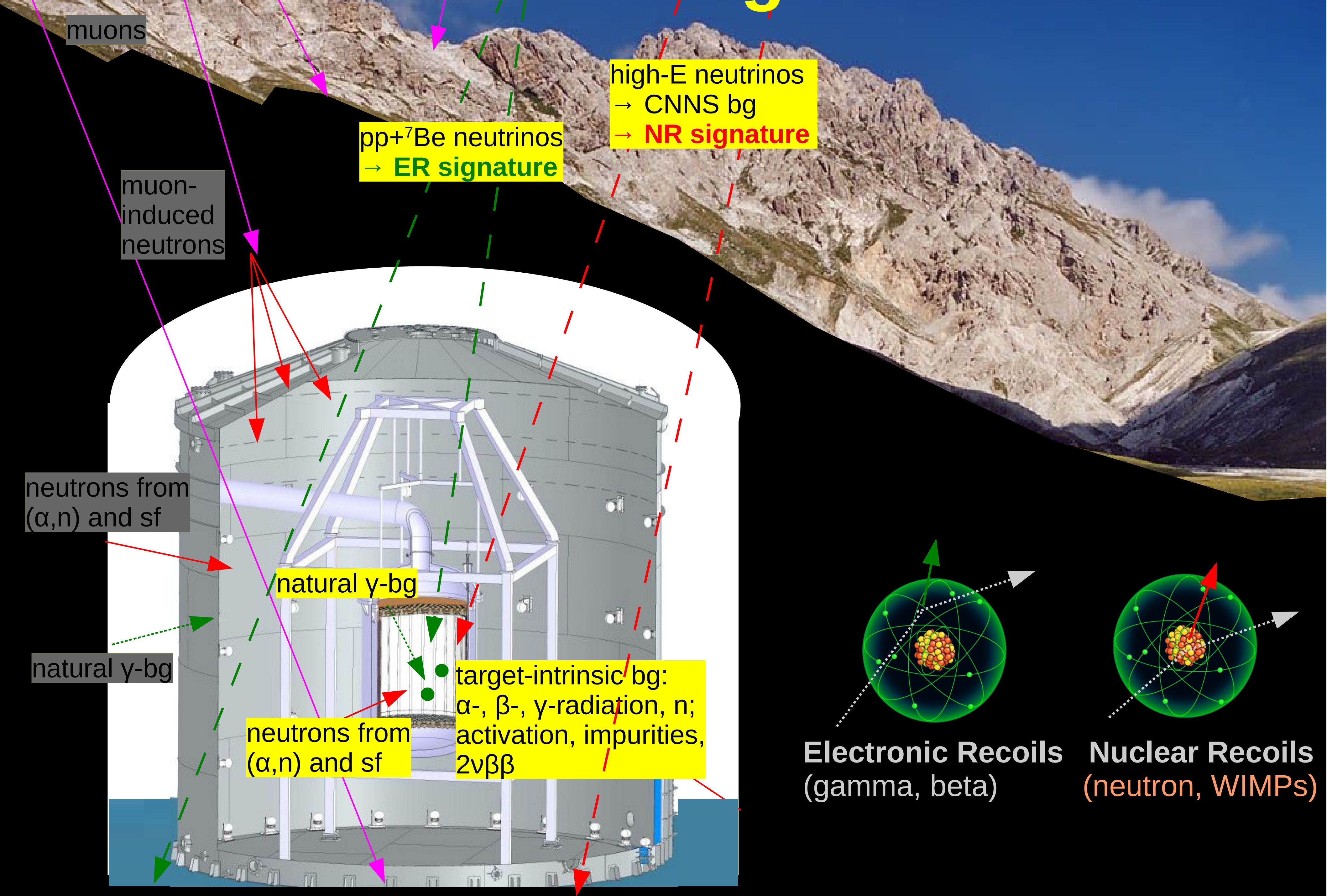
How to build a WIMP detector?
- large total mass, high *A*
- very low energy threshold
- ultra low background
- good signal / background discrimination

Recoil Spectra:





Background Sources



Background Suppression

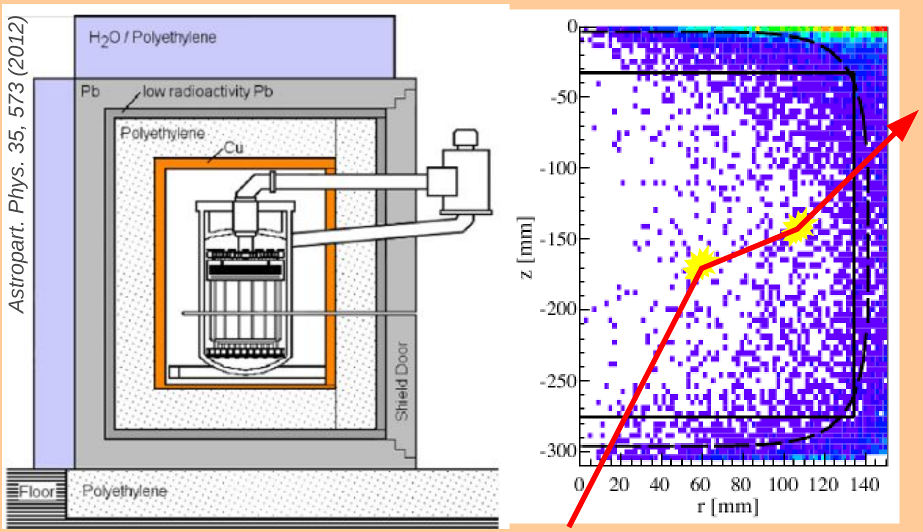
Avoid Backgrounds

Shielding

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

self shielding → fiducialization

Use of radiopure materials



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 d*E*/d*x* from signal and background

Examples:

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

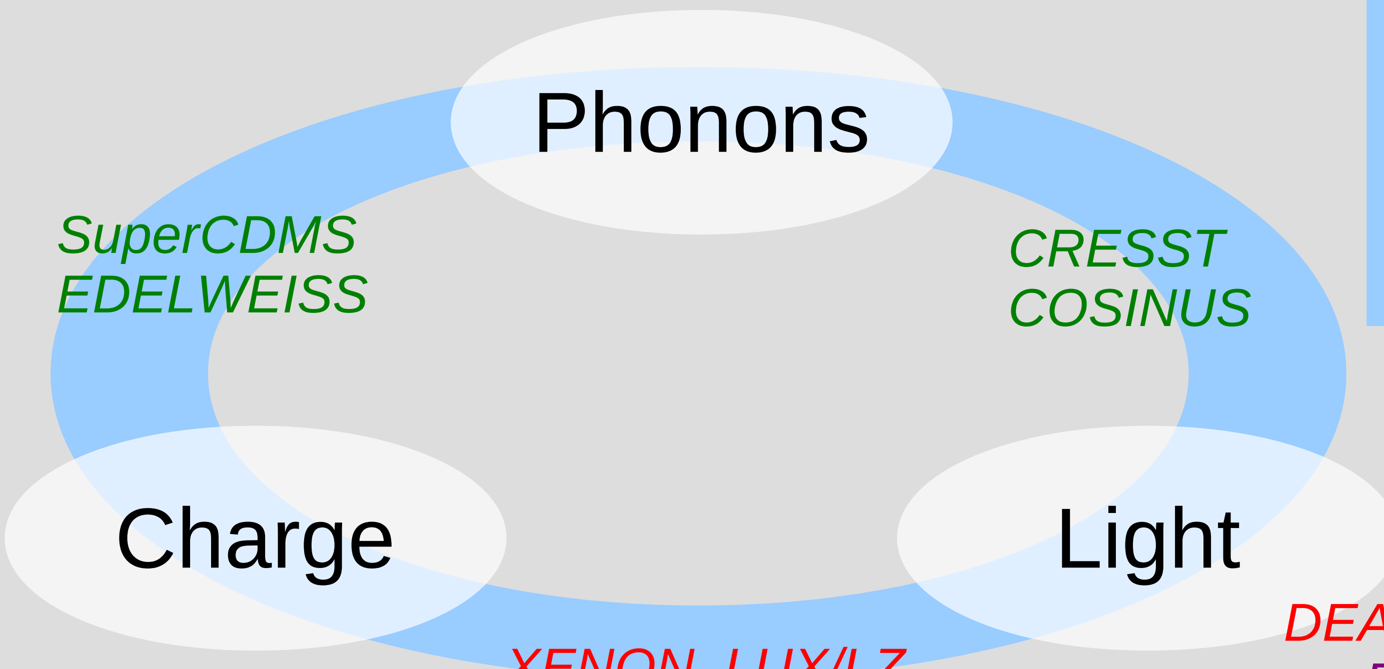
Direct WIMP Detection

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

Tracking:
DRIFT, DMTPC
MIMAC, NEWS
NEWAGE

Superheated Liquids:
PICO
SIMPLE

CUORE



SuperCDMS
EDELWEISS

CRESST
COSINUS

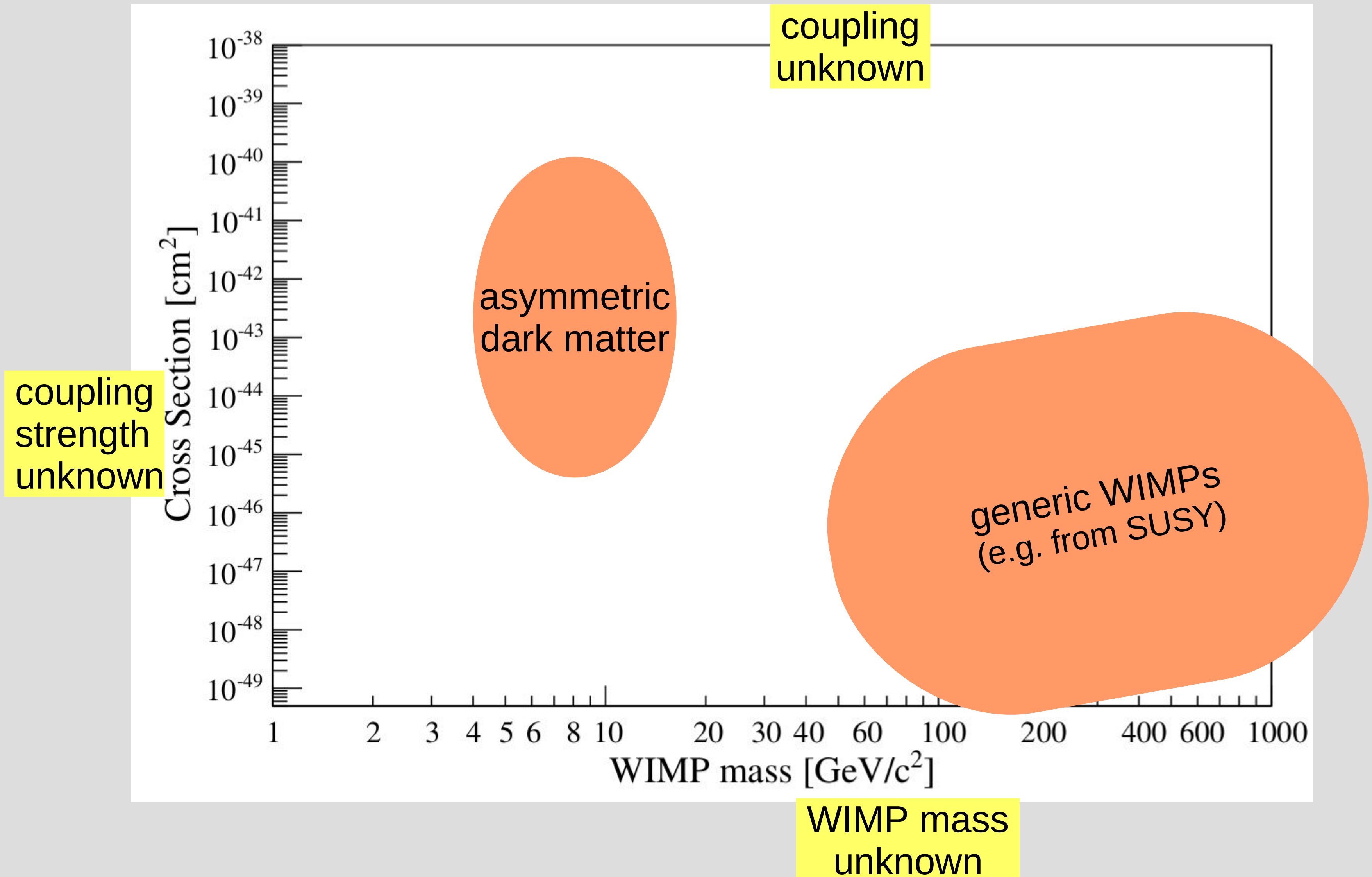
CoGeNT
CDEX
Malbek
DAMIC
NEWS (gas)

XENON, LUX/LZ
ArDM, Panda-X
DarkSide, DARWIN

DEAP-3600, CLEAN
DAMA, KIMS
XMASS, COSINE
ANAIS, SABRE

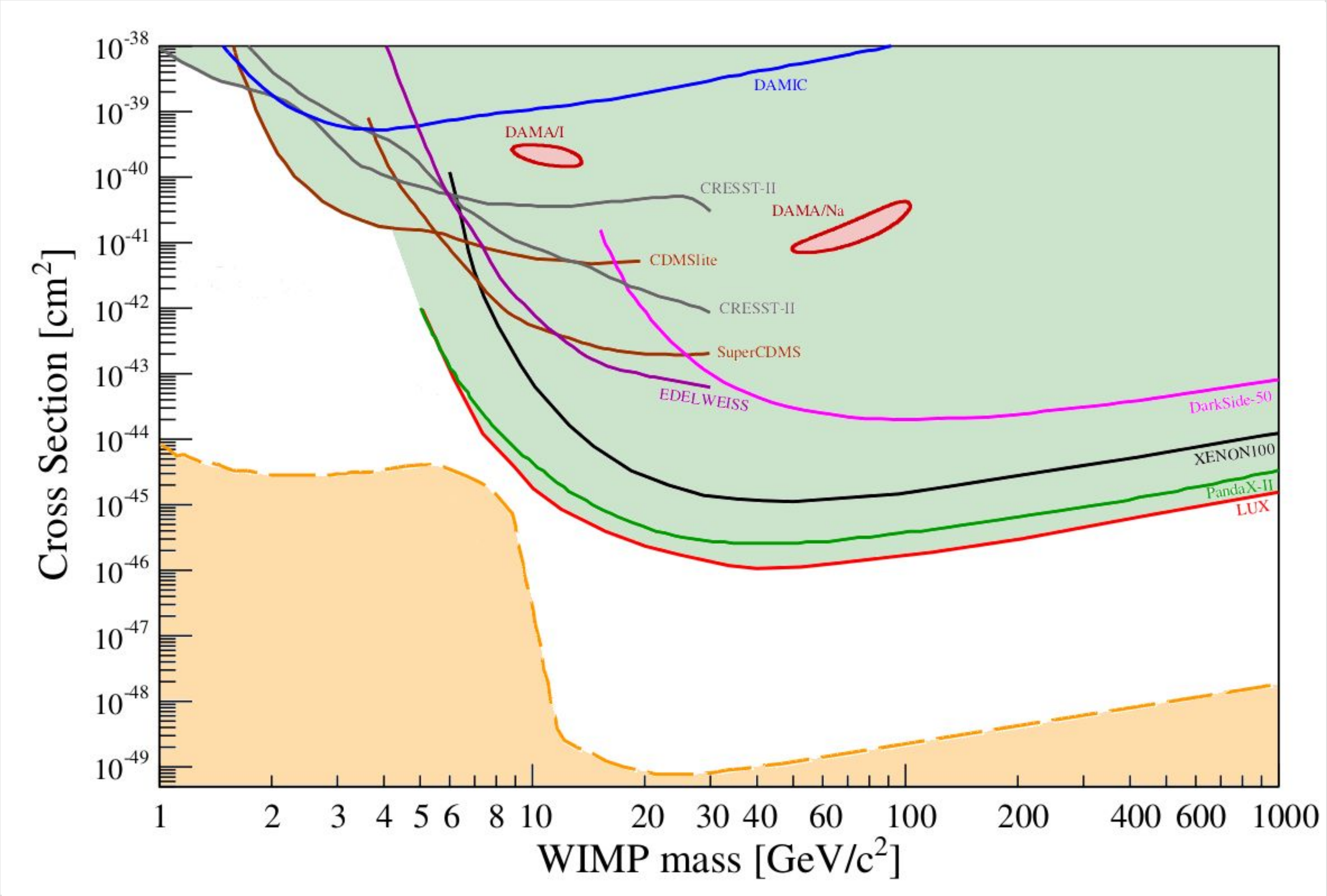
The WIMP Parameter Space

spin-independent WIMP-nucleon interactions



Current Status

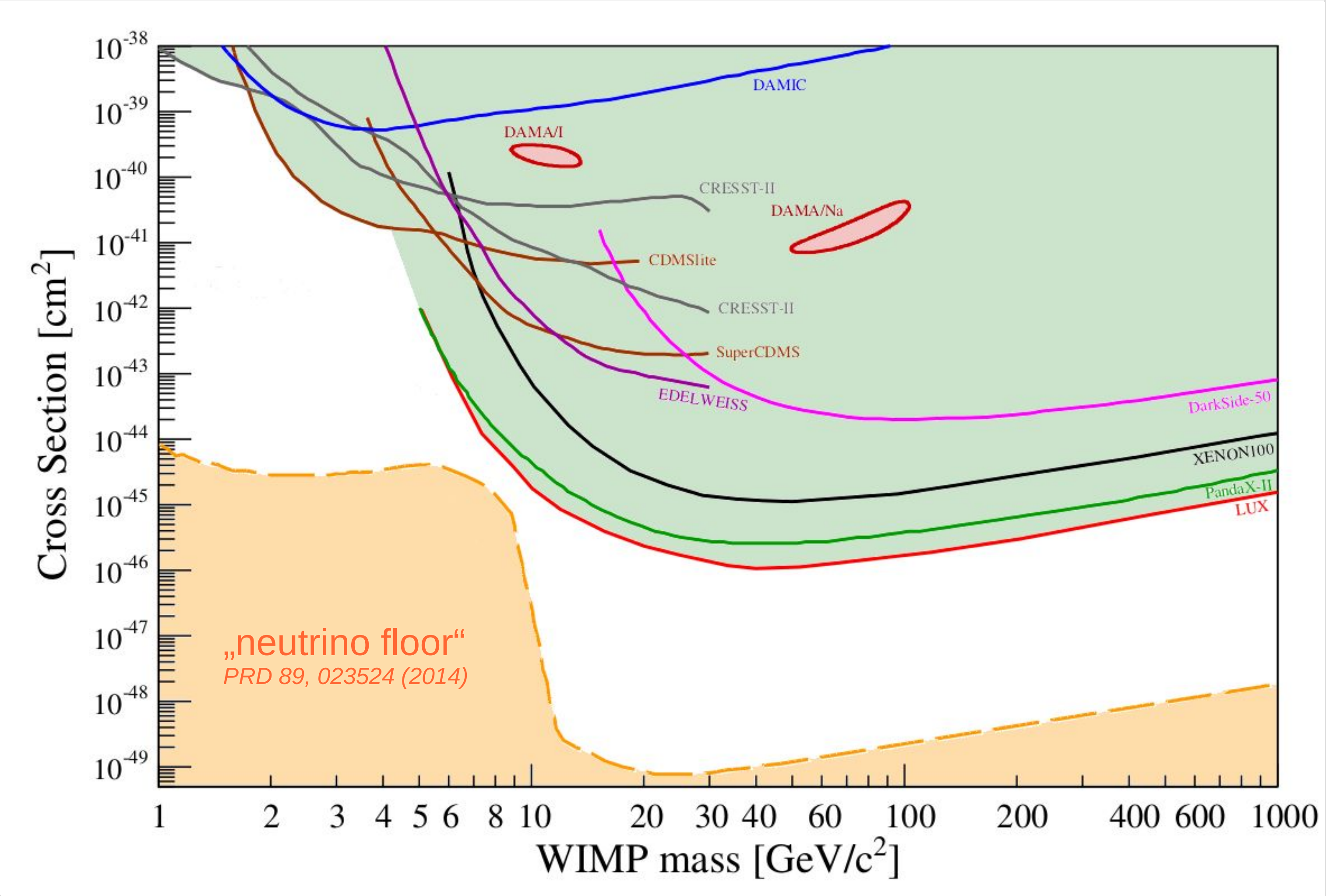
spin-independent WIMP-nucleon interactions



some results are missing...

Neutrino Floor

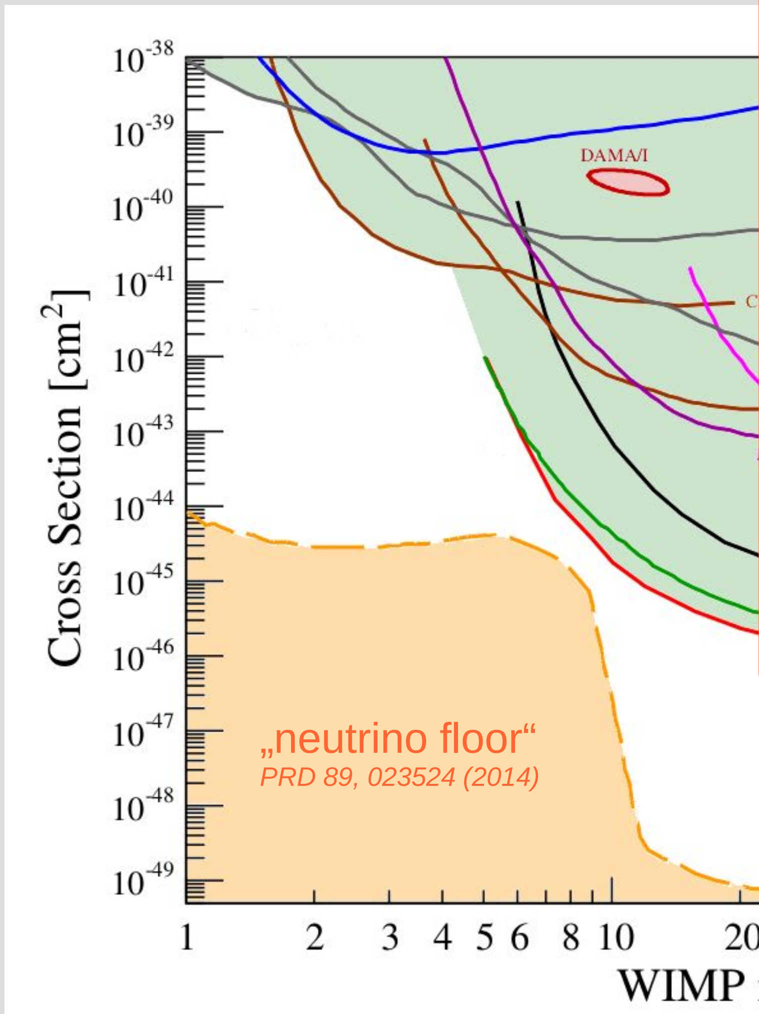
spin-independent WIMP-nucleon interactions

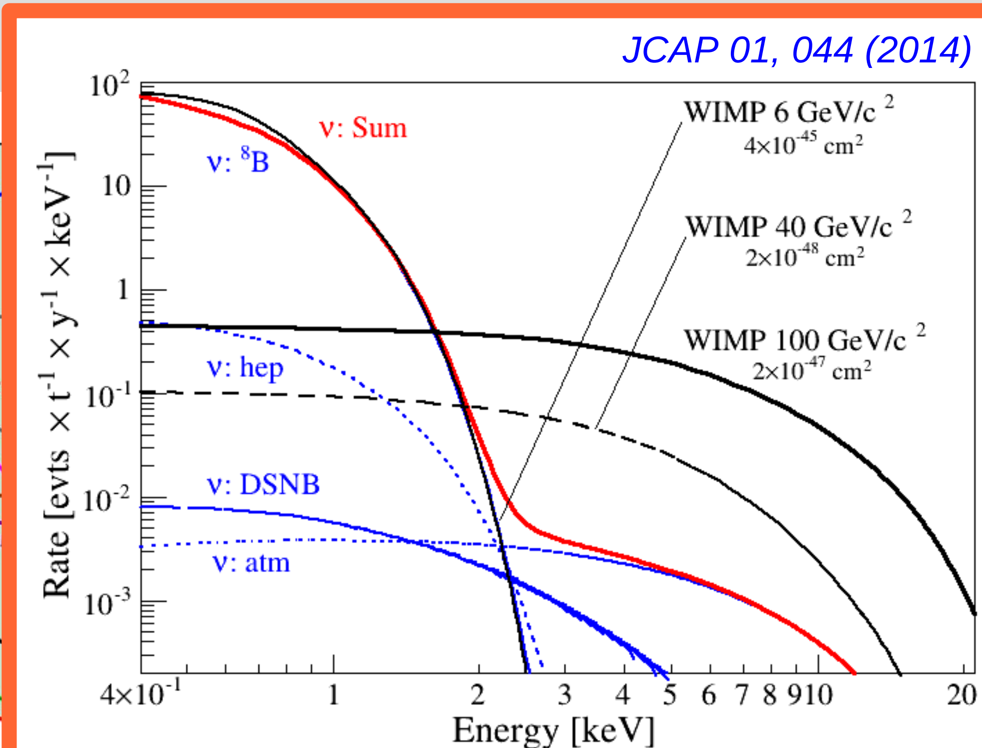


some results are missing...

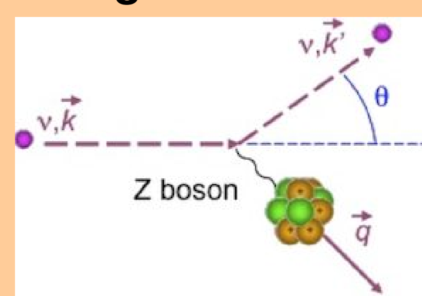
Neutrino Floor

spin-i



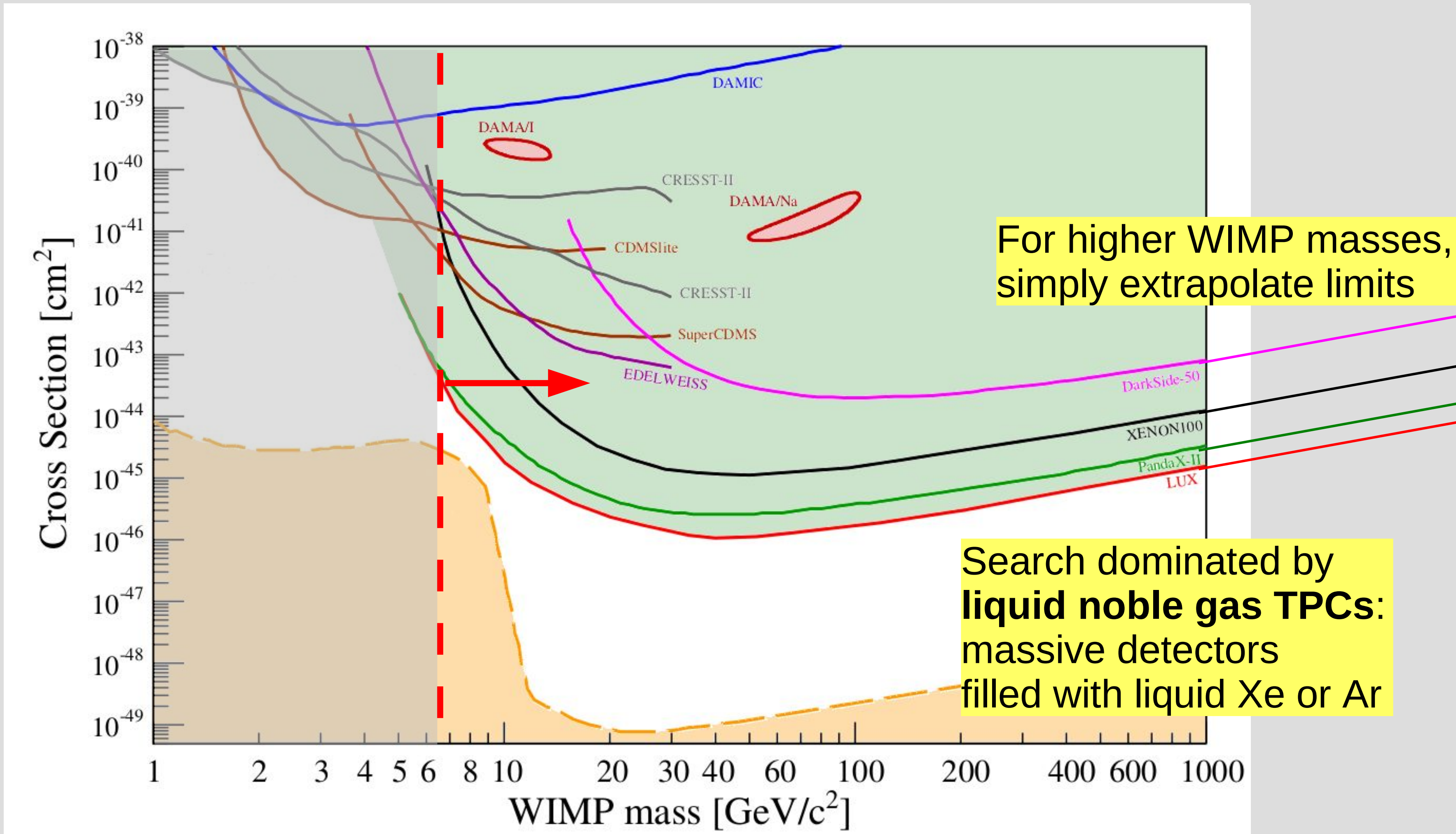


Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection



High WIMP Masses

spin-independent WIMP-nucleon interactions



For higher WIMP masses, simply extrapolate limits

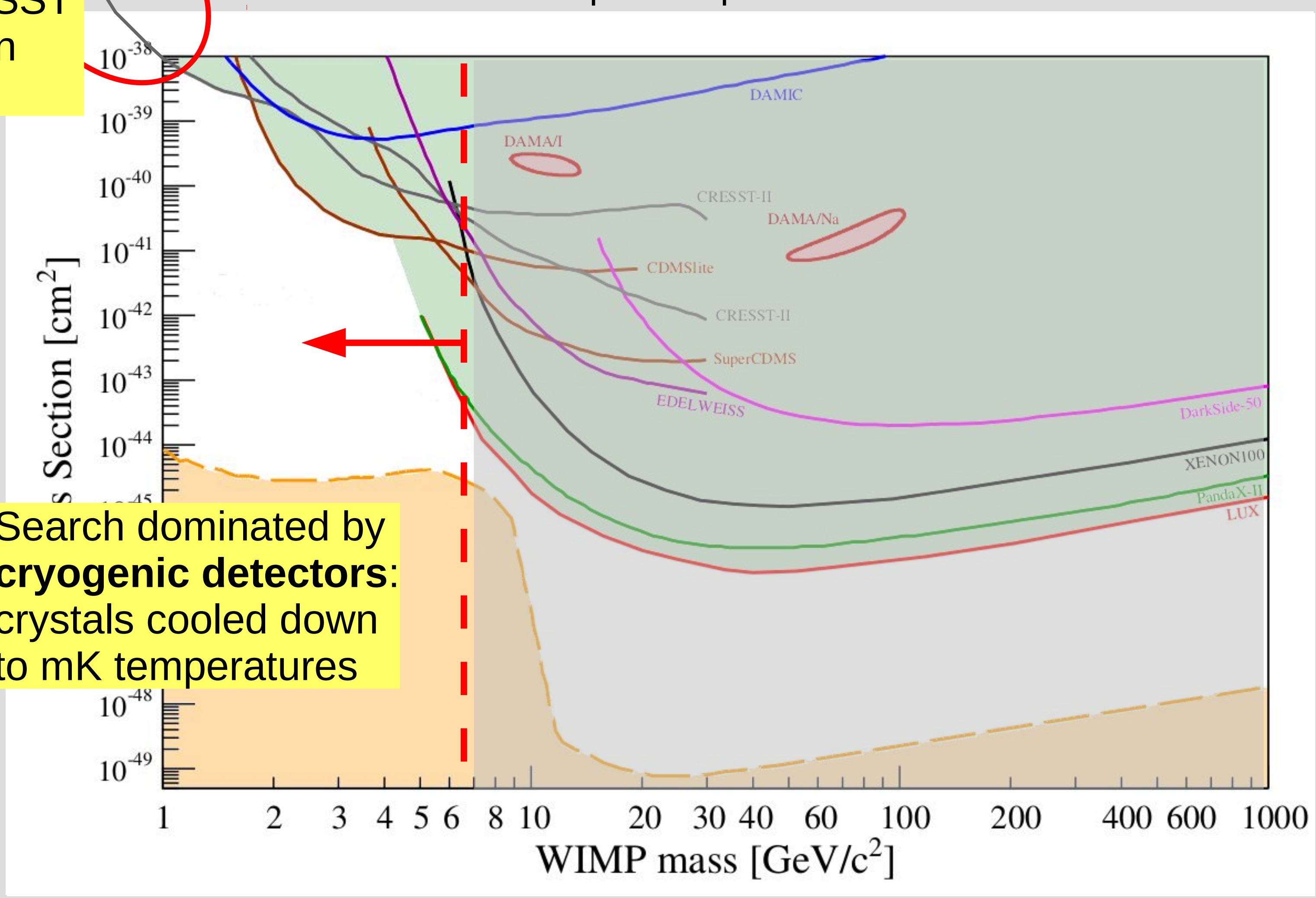
Search dominated by **liquid noble gas TPCs**: massive detectors filled with liquid Xe or Ar

some results are missing...

Low WIMP Masses

Current CRESST limits go down to 500 keV/c²

spin-independent WIMP-nucleon interactions



Search dominated by **cryogenic detectors**: crystals cooled down to mK temperatures

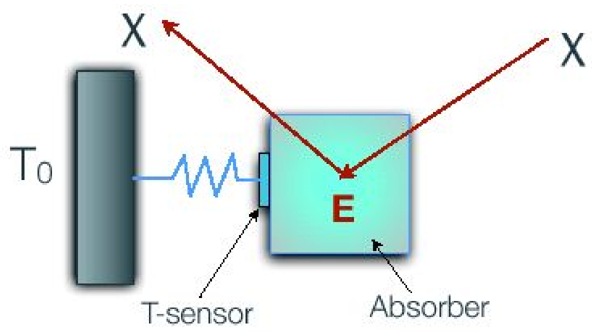
some results are missing...

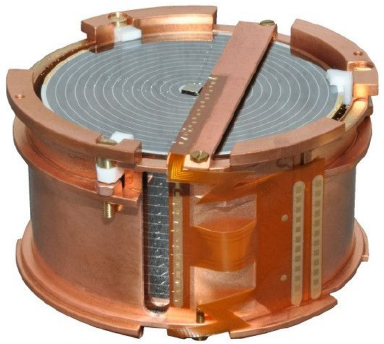
Cryogenic Detectors

measure charge or light and heat (phonons) in crystals: Ge, (Si), $CaWO_4$
E deposition → temperature rise $\Delta T \sim \mu K$ *(→ TES)*

→ requires detecors with low heat capacity at mK temperatures

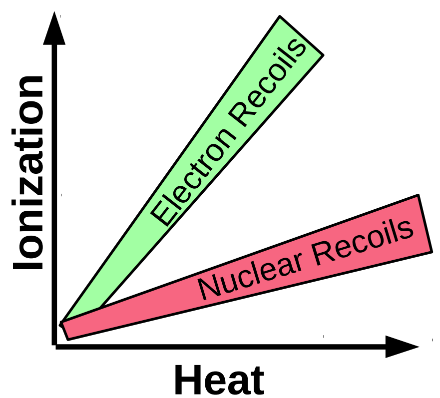
Ge: SuperCDMS, EDELWEISS, CDEX





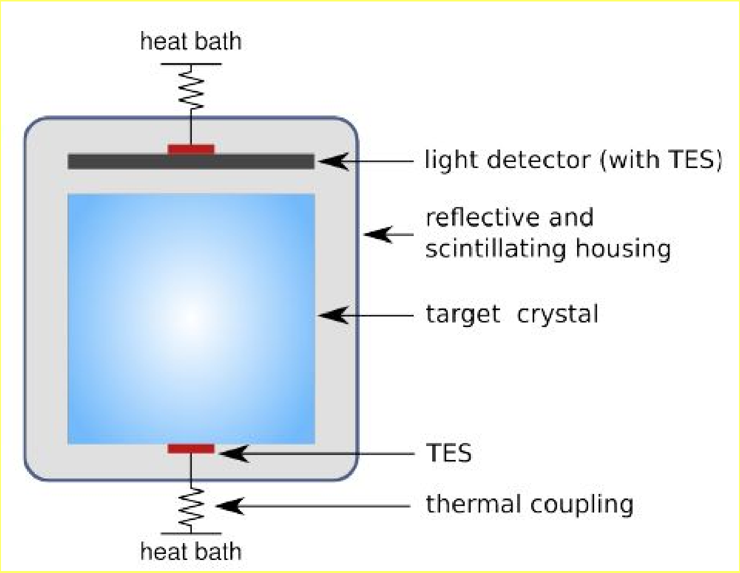
Charge and heat measurement

Very good discrimination
→ BUT: need to reject surface events



very low threshold in „HV mode“

$CaWO_4$: CRESST

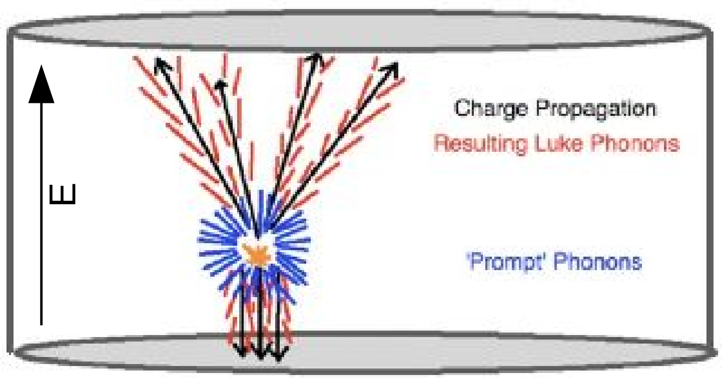


– Light and heat measurement
– very good discrimination
– multi-isotope target

Ge: Very low WIMP masses

very low threshold for sensitivity to very low-mass WIMPs:
amplify signal → HV operation: **Neganov-Luke effect** to amplify charge signal

convert work done by E-field on e⁻-hole pairs to phonons



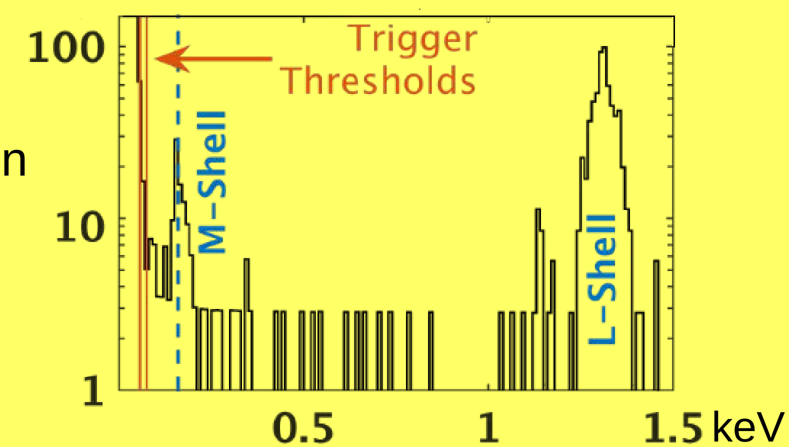
$$\begin{aligned} E_{tot} &= E_r + E_{luke} \\ &= E_r + n_{eh} e V_b \\ &= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right) \end{aligned}$$

bias voltage (V_b)
initial recoil (E_r)
3 eV/pair (ϵ_{eh})

CDMSlite *PRL 116, 071301 (2016)*

- 625 g iZIP detector, 70 kg×d exposure
- V_b=69 V, **56 eV$_{ee}$ threshold!** 14 eV$_{ee}$ resolution
- no ionization measured

→ **no ER rejection**

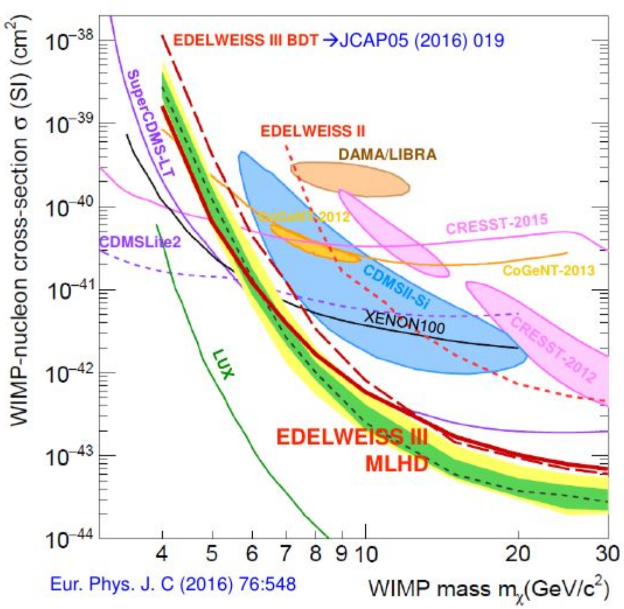


Cryogenic Detectors: Status

EDELWEISS-III @ Modane

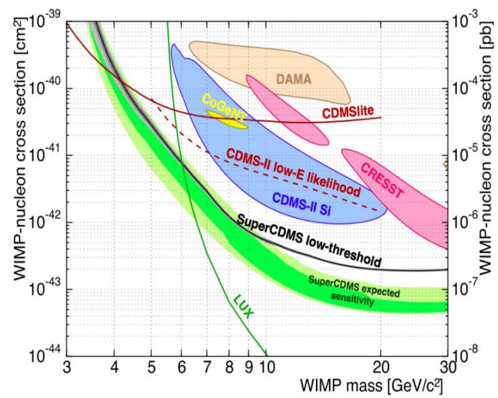
new **low-threshold result**:
- 8 Ge detectors
- lowest thresholds (2.5–20 keVnr)
  - → no significant excess
  - → 40× better than EDW-II @ 5 GeV/c²

BDT: JCAP 05, 019 (2016)
PL: EPJ C 76, 548 (2016)



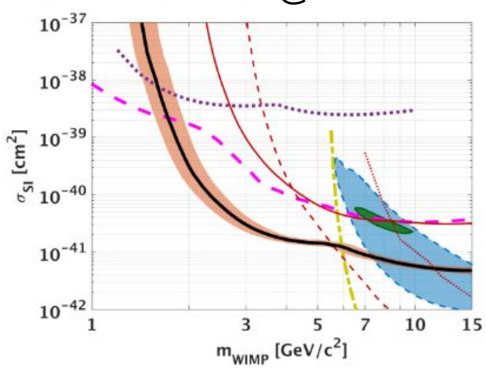
SuperCDMS @ Soudan

- 100×33.3 mm IZPs (1.4 kg Ge)
- results on low-mass WIMPs



PRL 112, 241302 (2014)

CDMSlite @ Soudan



PRL 116, 071301 (2016)

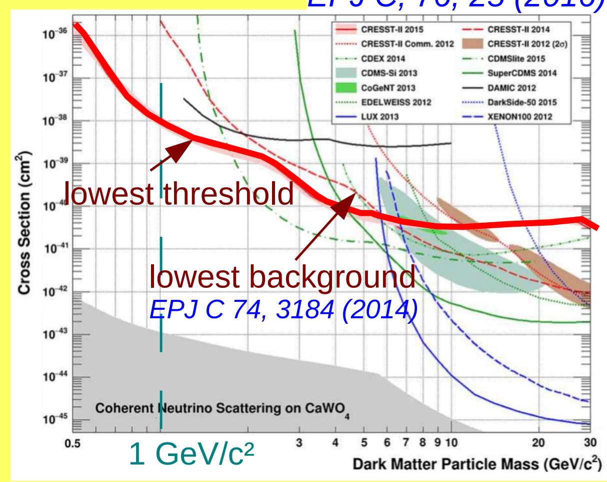
Not operational anymore!

$CaWO_4$: CRESST @ LNGS

The low mass record

- target: $CaWO_4$
  → multi-element material
- bg reduced successfully
  data taking 2013-2015, 52 kg×d
- new result *EPJ C, 76, 25 (2016)*
  300 g crystal with
  307 eVnr threshold

EPJ C, 76, 25 (2016)



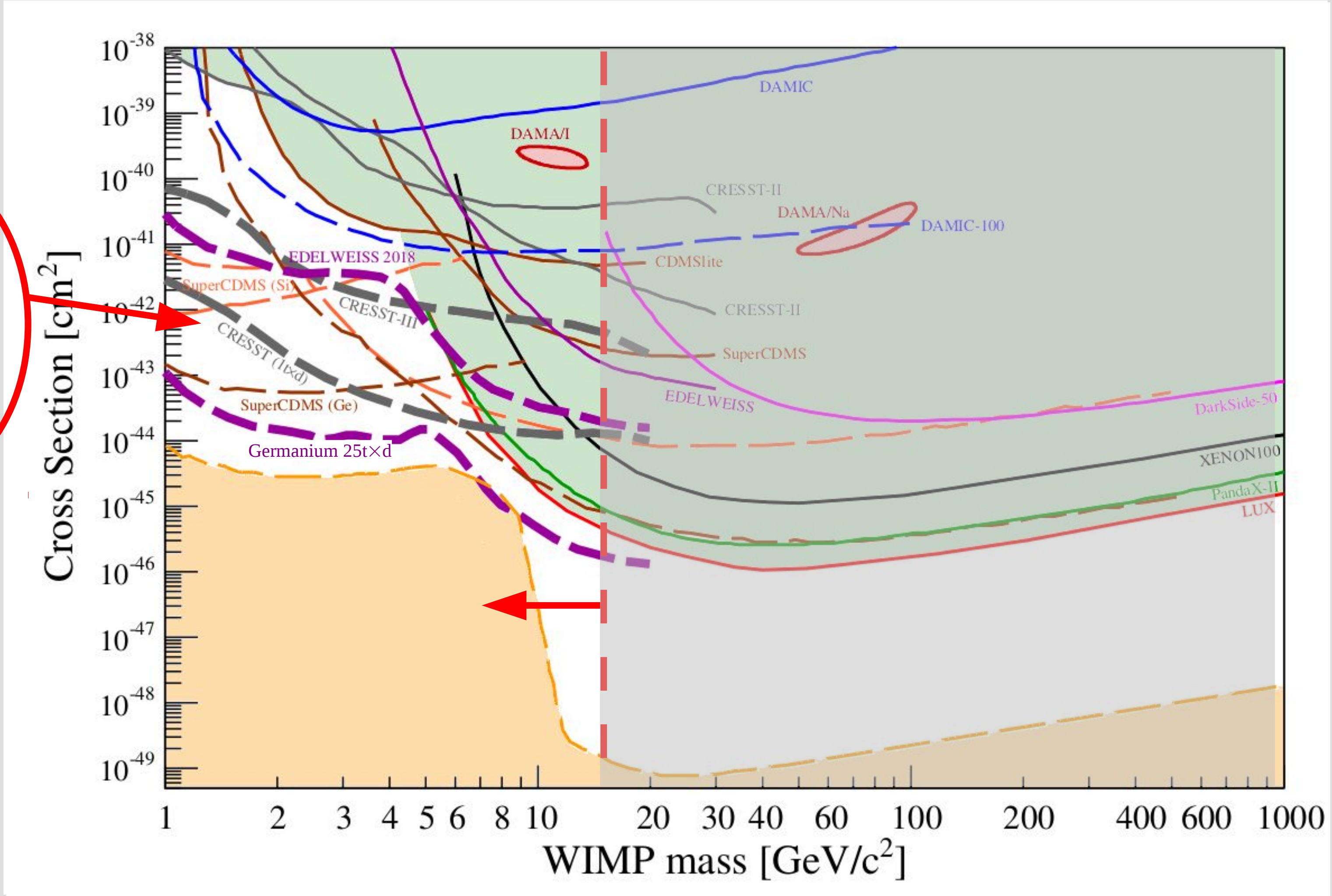
Upcoming Projects

basically funded

CRESST-II

EDELWEISS

SuperCDMS



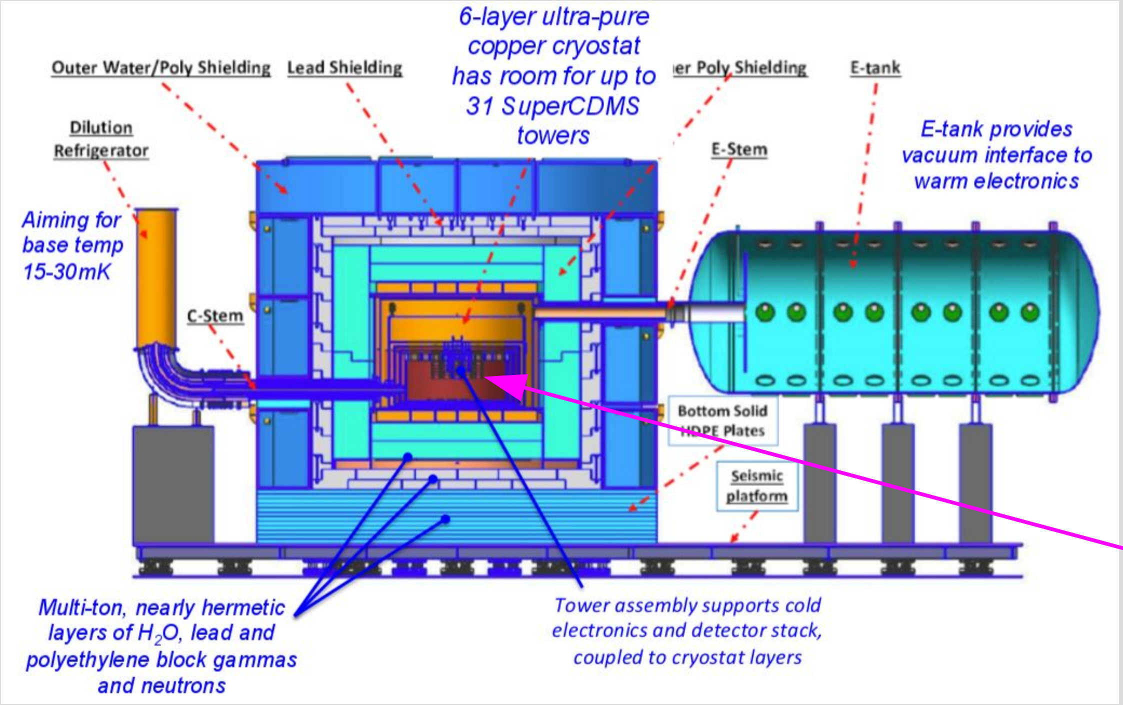
some results are missing...

Ge/Si: SuperCDMS

PRD 95, 082002 (2017)

selected by NSF-DOE downselection

- ~50 kg target (upgrade to 400 kg possible)
- low threshold
  → focus on 1-10 GeV/c² mass range
- Move Soudan → SNOLAB:
  deeper lab, better materials & shield, improved resolution, electronics, ...
- 100×33.3 mm IZPs (1.4 kg Ge, 0.6 kg Si)



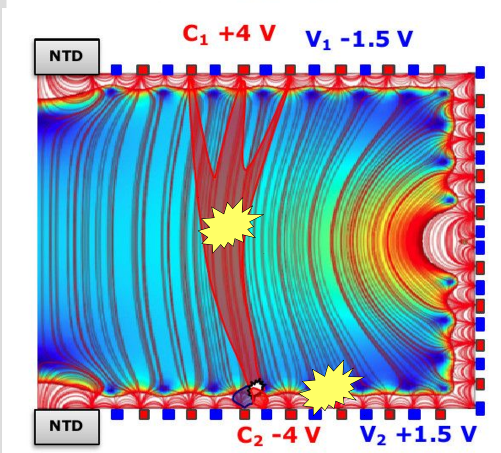
Timeline:
- 2018/19: construction
- comissioning/science by **2020**
- beyond 2024:upgrade mass?

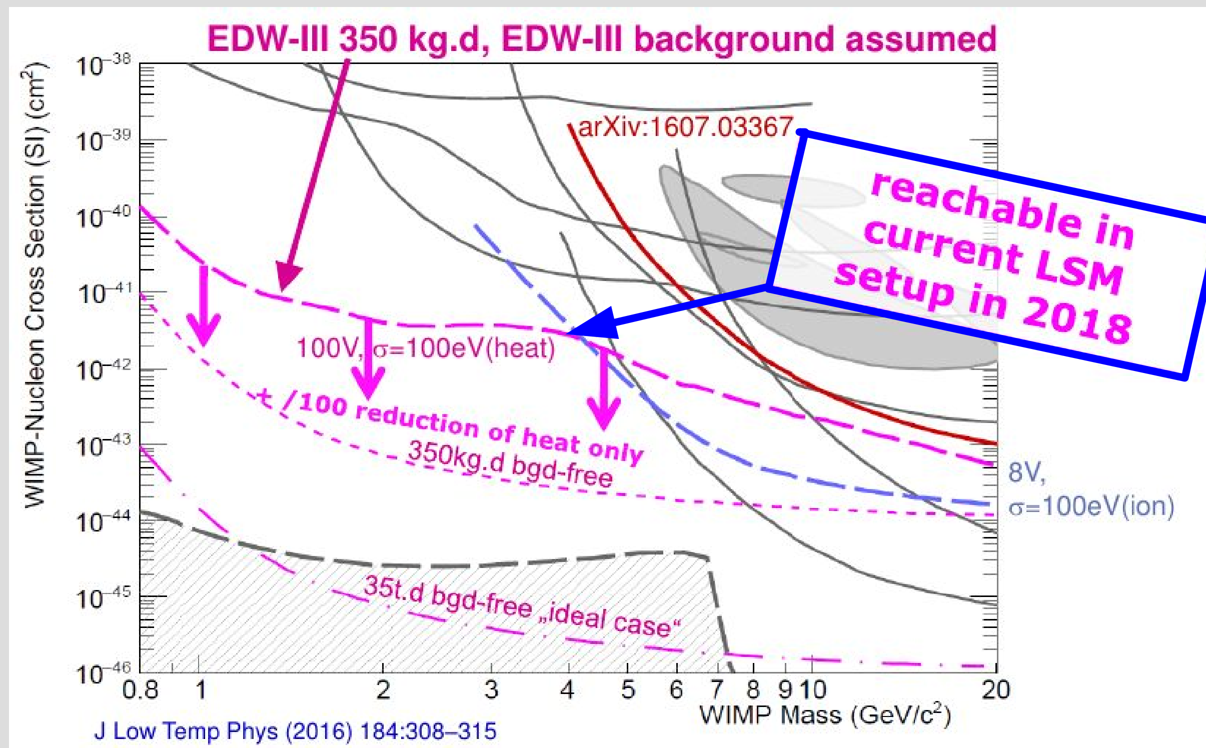
until then:
- CUTE detector R&D
  platform at SNOLAB

cryostat oversized:
offers prime real-estate with
<40 mK, ultra low-noise,
ultra-low background

Ge: EDELWEISS-III

- continue operatation of a few kg of Ge detectors in Modane Lab (F)
- 800 g Ge crystals measure ionization and heat (NTD sensors) interdigitized electrodes: fiducialization (~600 g)
- **focus on low-mass WIMPs (HV or „lite“ mode)**

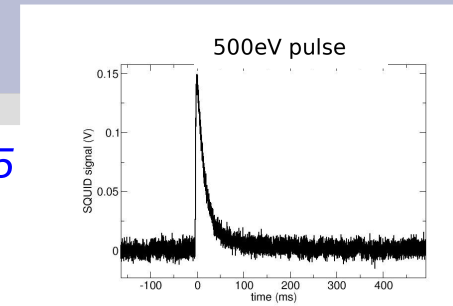




Strategy beyond 2019:
→ potential to cooperate with SuperCDMS @ SNOLAB

CaWO4: CRESST-III

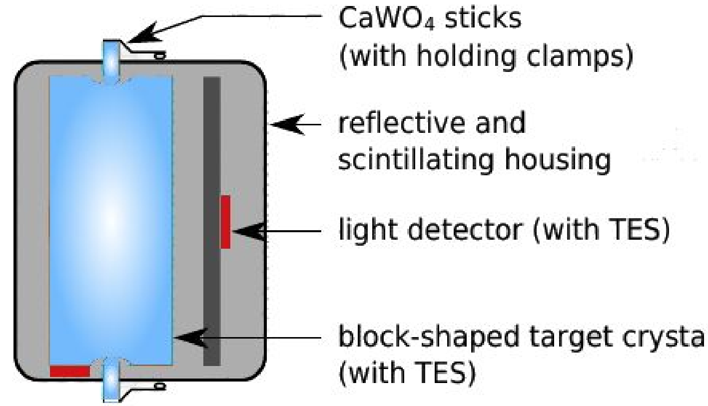
Lead technologies by German groups

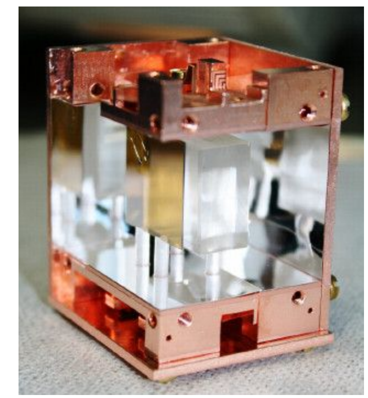


arXiv:1503.08065

CRESST-III: lower threshold to 100 eV_{nr}

- smaller, cleaner, self-grown crystals (300 g → 25 g)
- all-scintillating detector design
  → avoid partial energy depositions
- improve signal-to-noise
- still able to discriminate ER/NR



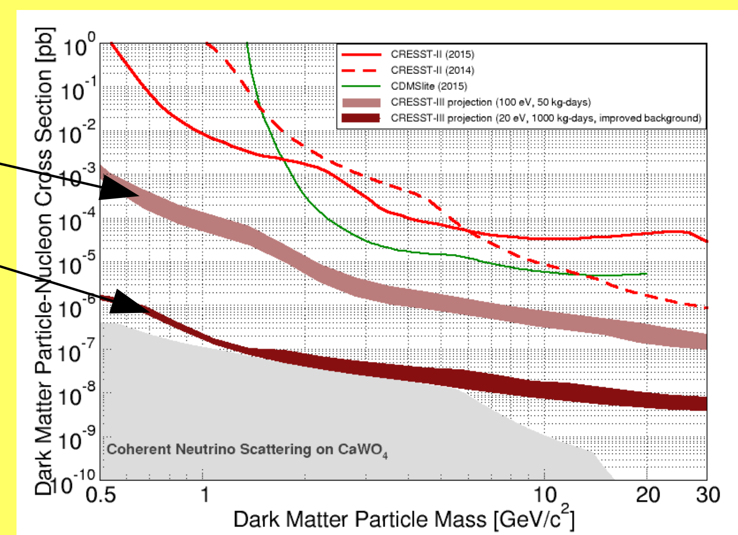


Status:

- Prototype exceeds design goal: 50 eV_{nr} threshold
- 6 modules with <100 eV threshold running @ LNGS

CRESST-III Timeline

- Phase 1 (**2017**): „faster than SuperCDMS“
  50 kg×days (1 y), design goal threshold (100 eV)
- Phase 2 (>**2019**): „approaching the neutrino floor“
  → 1000 kg×days (2 y, 100 detectors)
  → background reduced by factor 100
  → 20 eV_{nr} threshold
- Beyond CRESST-III: depends on WIMP results
  → CRESST detectors sensitive to CNNS etc.



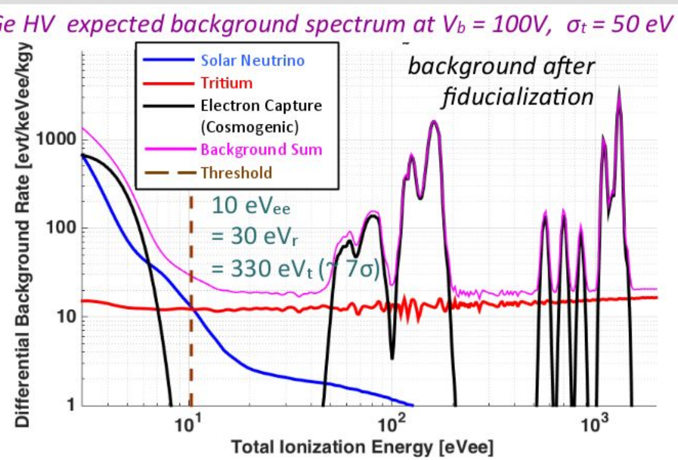
Technical Challenges

CRESST ($CaWO_4$)

– at which energy does ER/NR discrimination not work anymore?
(no photons created in 10 eV regime)

– smaller crystals lower threshold
→ technical challenge to reach required large exposure
→ **radiopurity of crystals** becomes very important

– **background**:
→ many small crystals: small S/V ratio
→ bg from instrumentation/cables etc?



L. Hsu @ ICHEP 2016

EDELWEISS / SuperCDMS (Ge)

– **no ER rejection in HV mode**
→ background challenging
→ detection experiment or always background limited?

– phonon resolution crucial
→ environmental noise reduction

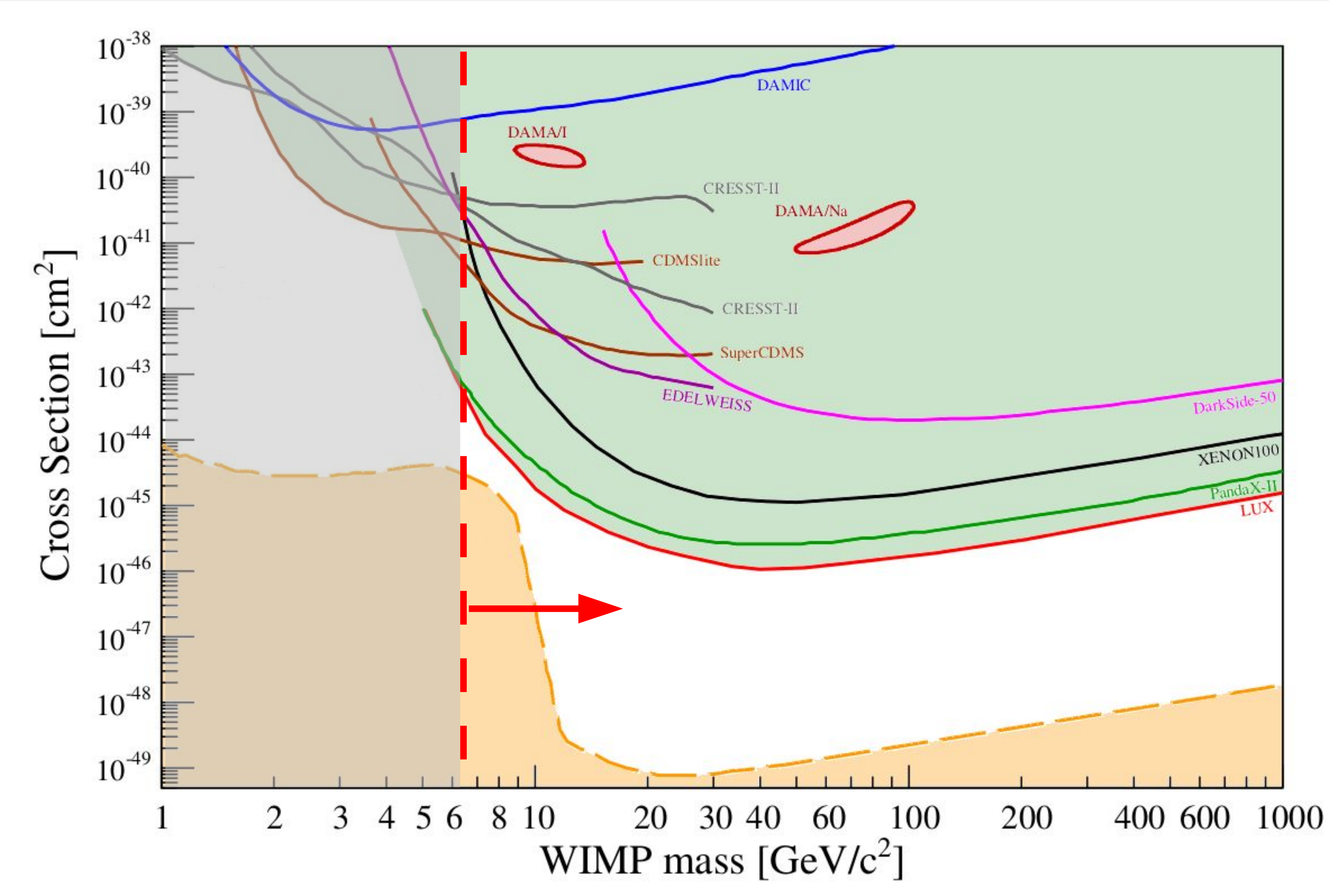
– „heat-only“ events in EDW: dominant and reproducible low-E background
→ currently not fully understood
(stress from gluing?)
→ factor 100 reduction required

– HV detector background dominated by **cosmogenic activation**
→ Ge isotopes
→ ^3H production in Ge/Si

Astropart. Phys. 91, 51 (2017)

High WIMP Masses

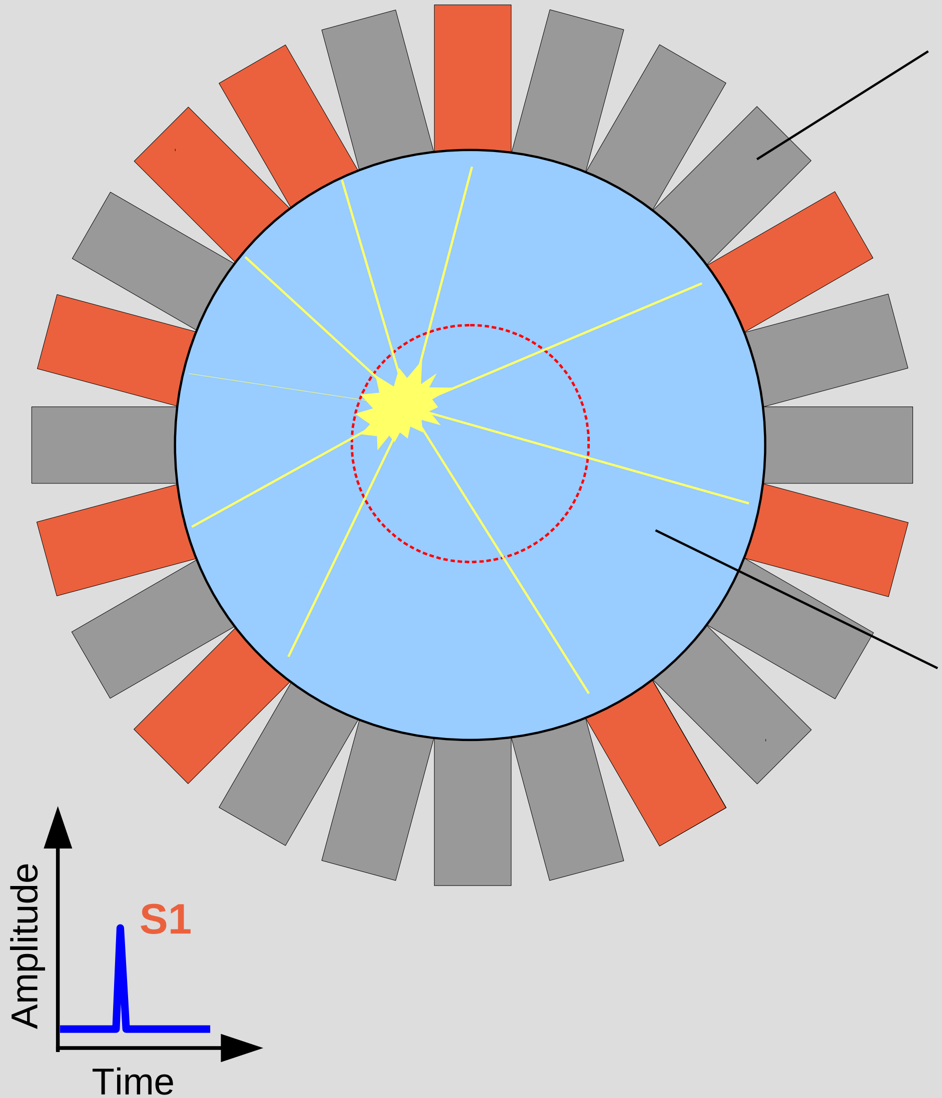
spin-independent WIMP-nucleon interactions



some results are missing...

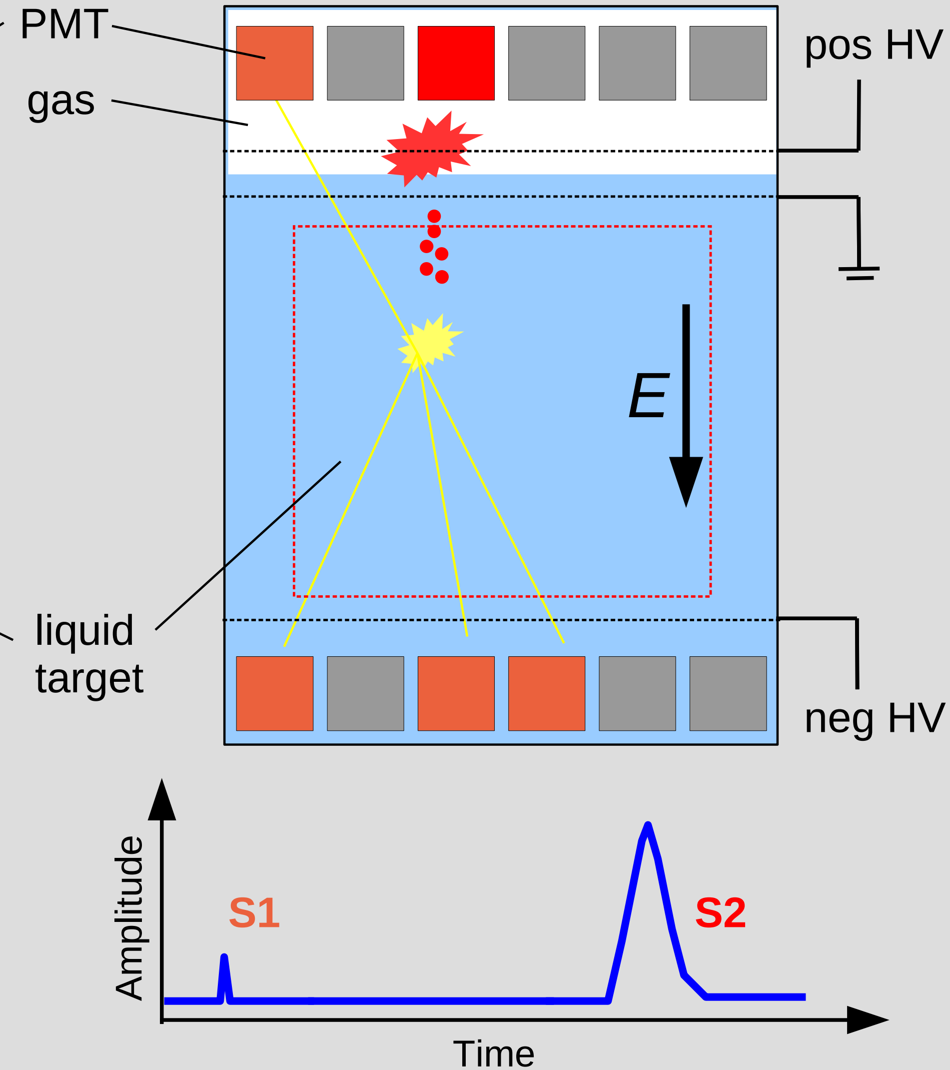
Liquid Noble Gases: Detector Concepts

Single Phase Detector



+ no high voltage, very high light yield
– O(cm) resolution, no double scatter rejection

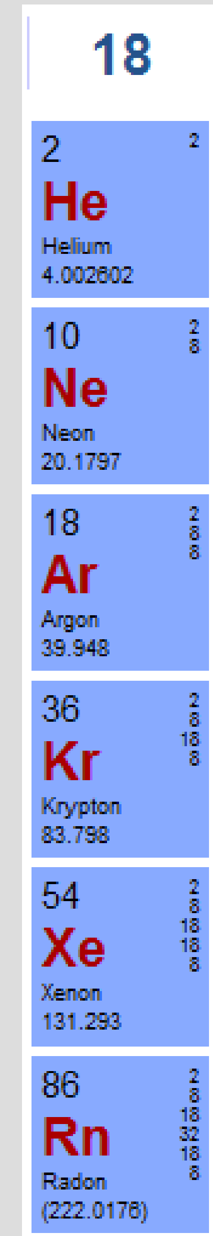
Time Projection Chamber



+ O(mm) resolution, S2/S1 NR rejection
– technical challenges (HV), less light

Noble Liquid Targets

Target	LXe	LAr
Atomic Number	54	18
Atomic mass	131.3	40.0
Boiling Point T_b [K]	165.0	87.3
Liq. Density @ T_b [g/cm³]	2.94	1.40
Fraction in Atmosphere	0.09	9340
Price	$$$ (no consumable; can be re-used)	($) (^{39}Ar-depleted gas: $$$)
Scintillator	✔	✔
Scint. Wavelength [nm]	178	128
Ionizer	✔	✔
W (E to generate e-ion pair) [eV]	15.6	23.6
Radioactive Isotopes	^{136}Xe (2νββ)	^{39}Ar (~1 Bq/kg)
ER Rejection	ok (2-phase only)	great (high-E only)
Odd Isotopes (→ SD couplings)	50% (^{129}Xe, ^{131}Xe)	✘
Scalability	✔	✔
Projects [running, in preparation]	~4	~2½



ER Background Rejection

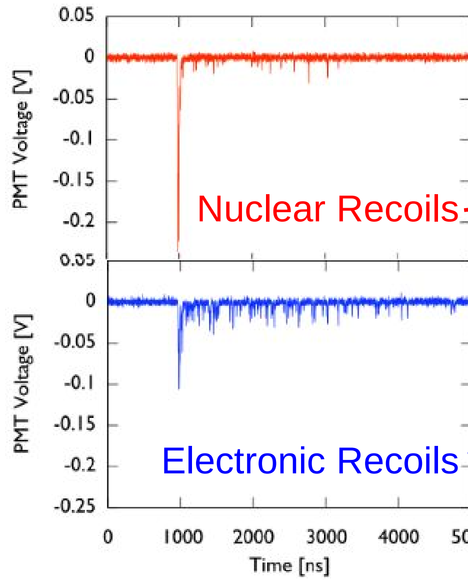
Pulse shape discrimination (PSD):
Lifetimes of singlet and triplet states:

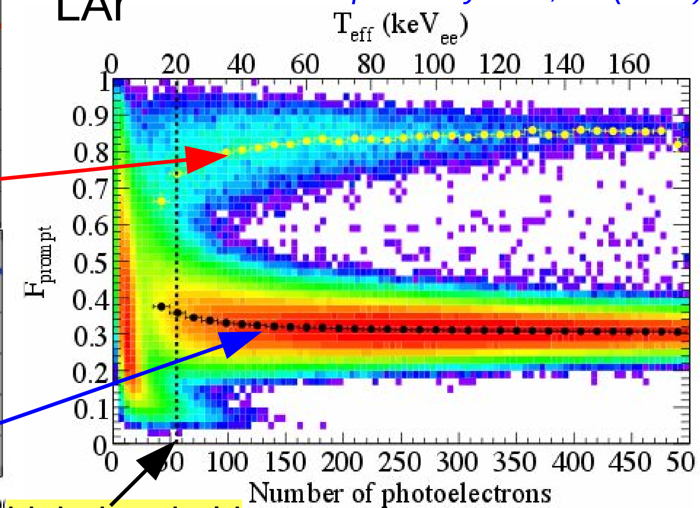
Ar: 5 ns, 1.6 µs
Xe: 4 ns, 22 ns

Ratio N_{trip}/N_{sing} depends on d*E*/d*x*
→ the interaction type

LAr: excellent ~3×10^−8
PRC 78, 035801 (2008)

LXe: irrelevant ~1×10^−1
NIM A 612, 328 (2010)

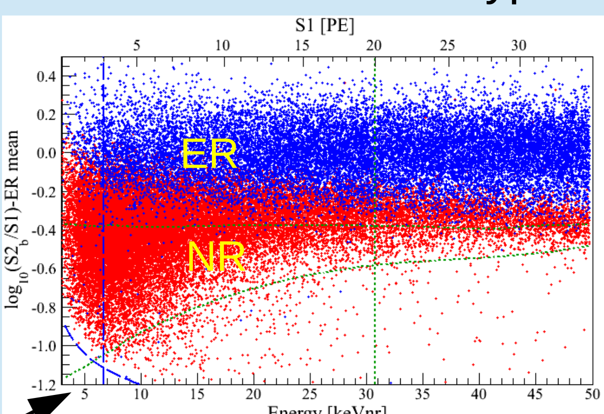




high threshold required

Charge-Light-Ratio (S2/S1):
Signal partition in light/charge depends on d*E*/d*x* → the interaction type

→ works for **LXe** and **LAr**
→ significant loss of acceptance



works down to low-E threshold

	E_{drift} [kV/cm]	LY @ 122 keV [PE/keV]	NR acc [%]	ER rej [%]
XENON100	0.53	3.8	40	2.5×10^−3
XENON100	0.53	3.8	30	1×10^−3
LUX	0.18	8.8	50	1..10×10^−3
ZEPLIN-III	3.4	4.2	50	**1.3×10^−4**
K. Ni *APP14*	0.2-0.7	10	50	**<1×10^−4**

Relevant Backgrounds

	LXe	LAr
Radioactivity Laboratory (ER, NR)	✘	✘
Muon-induced neutrons	✘	✘
Detector materials		
Gamma (ER)	✘	✘
Neutrons (NR)	✔	✔
Target Intrinsic isotopes (ER)		
^{39}Ar	–	✔
^{85}Kr	✔	✘ price: high threshold
^{222}Rn	✔	✘ price: high threshold
Neutrinos		
NR: ^{8}B, atmospheric	✔	✘ threshold too high for ^{8}B
ER: pp, ^{7}Be	✔	✘ ER rejection mandatory
Artefacts	??	??

– all experiments are underground and sufficiently shielded

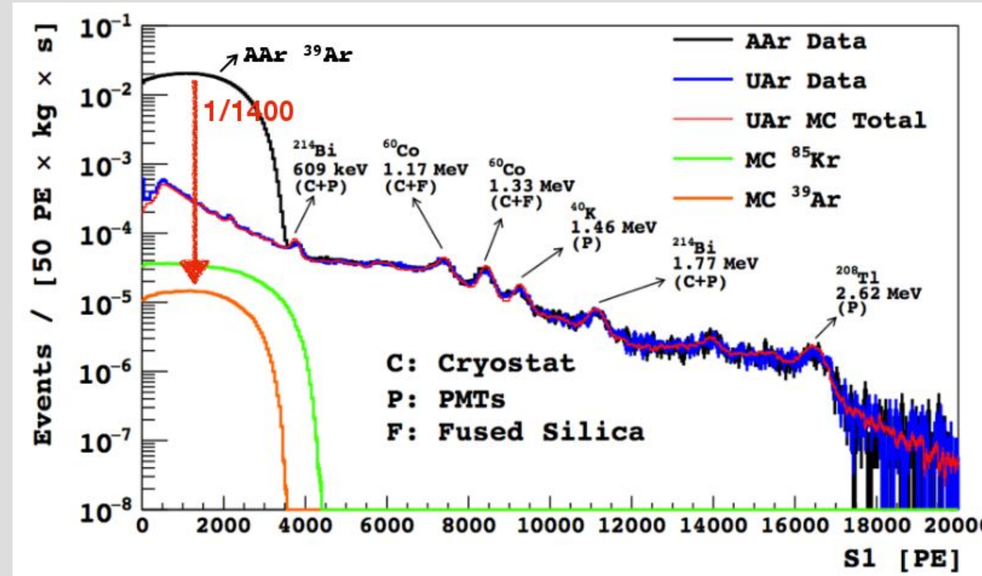
– all TPCs employ fiducialization and multiple-scatter rejection

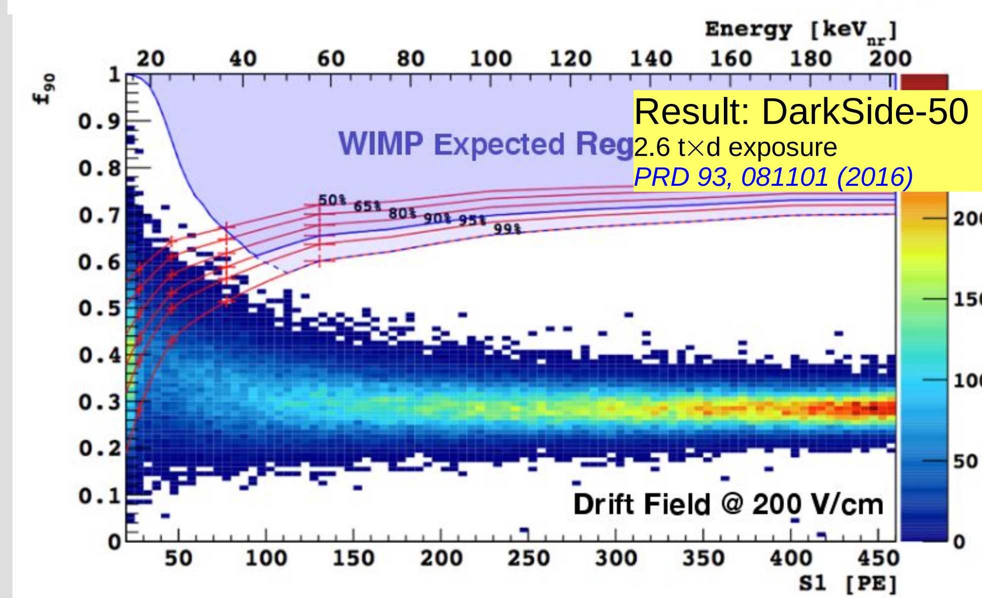
DarkSide: ^{39}Ar-depleted Argon

content: M. Wada, Moriond 2017

– extract underground Ar (UAr) in CO_2 well in Colorado
– cryogenic distillation @ FNAL

→ **^{39}Ar reduced by factor ~1400!**
→ 155 kg UAr produced in 6 years effort

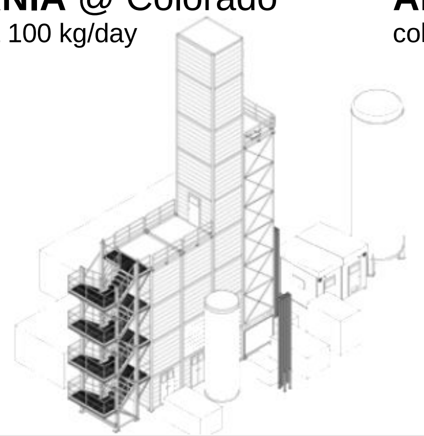




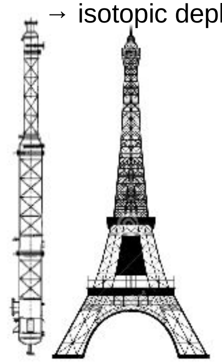
Result: DarkSide-50
2.6 t×d exposure
PRD 93, 081101 (2016)

Future: mass-production planned

URANIA @ Colorado
extract 100 kg/day



Aria @ Sardegna
column: 350m high, 1.5m OD
→ isotopic depletion



LXe: Krypton Removal

Two methods: – cryogenic distillation (XMASS, XENON)
– chromatography (LUX)

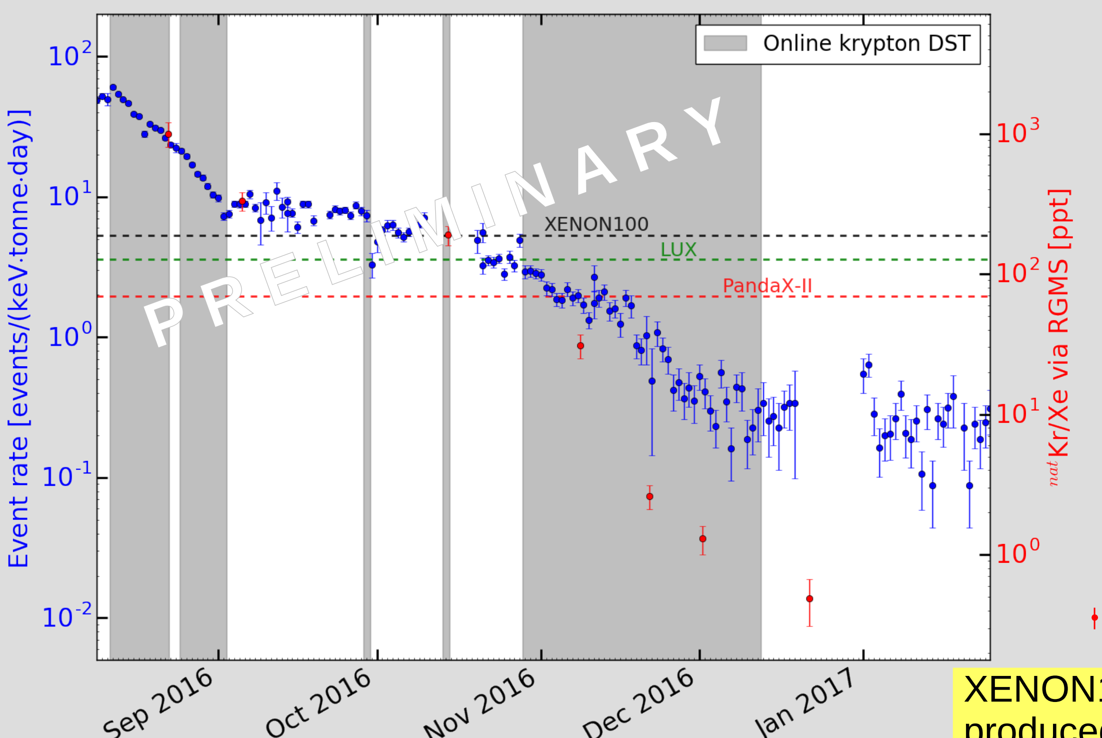
Example: **XENON1T**

goal: ^{nat}Kr/Xe = 0.2 ppt (below level of pp-neutrinos)

achieved by novel online distillation:

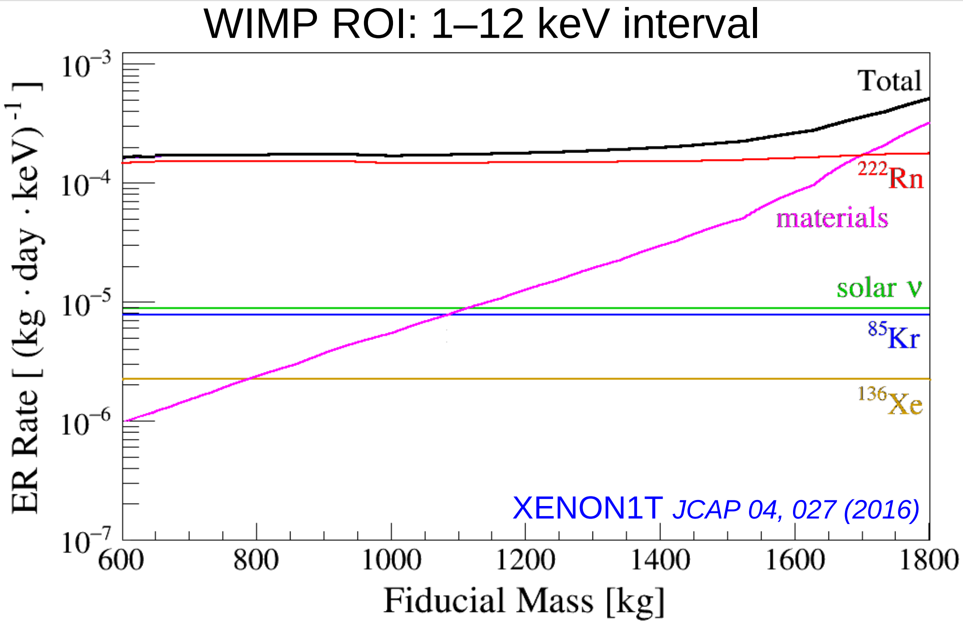
^{nat}Kr/Xe = (0.36±0.06) ppt achieved

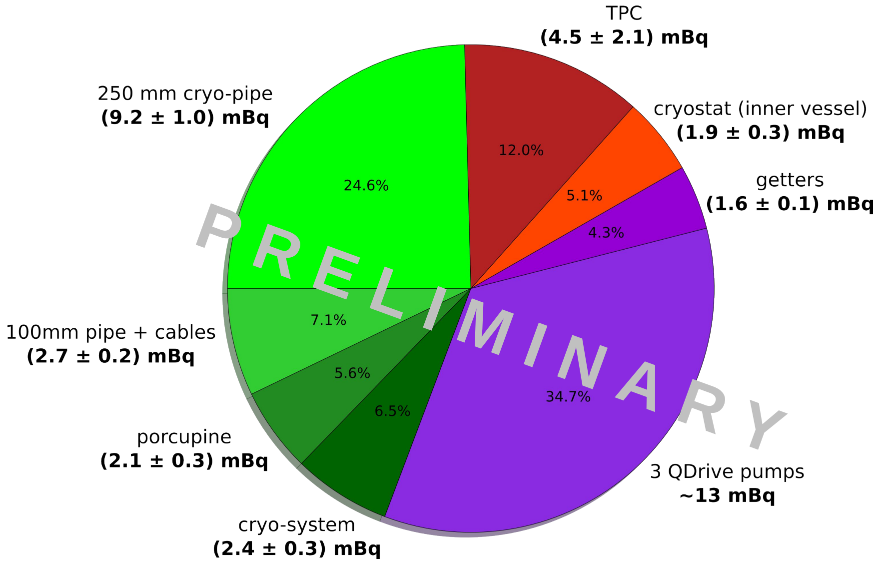
→ lowest value in LXe experiments ever



XENON1T column has produced large gas sample **<0.048 ppt** = 4.8×10^{-14} (90% CL)
→ 4x cleaner than needed
arXiv:1612.04284

LXe: Radon Background





Current Strategy avoid Rn emanation by selecting clean materials

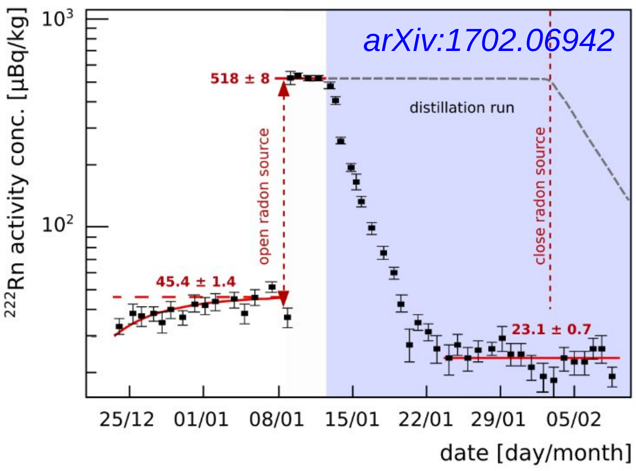
Example: goal 10 µBq/kg

XENON1T measured **(11±2) µBq/kg** *prelim.*

Future Strategy

– active Rn removal

– *Example*: **cryogenic distillation**
XENON1T distillation column installed @ XENON100
→ demonstrated **reduction factor >27** (@ 95% CL)



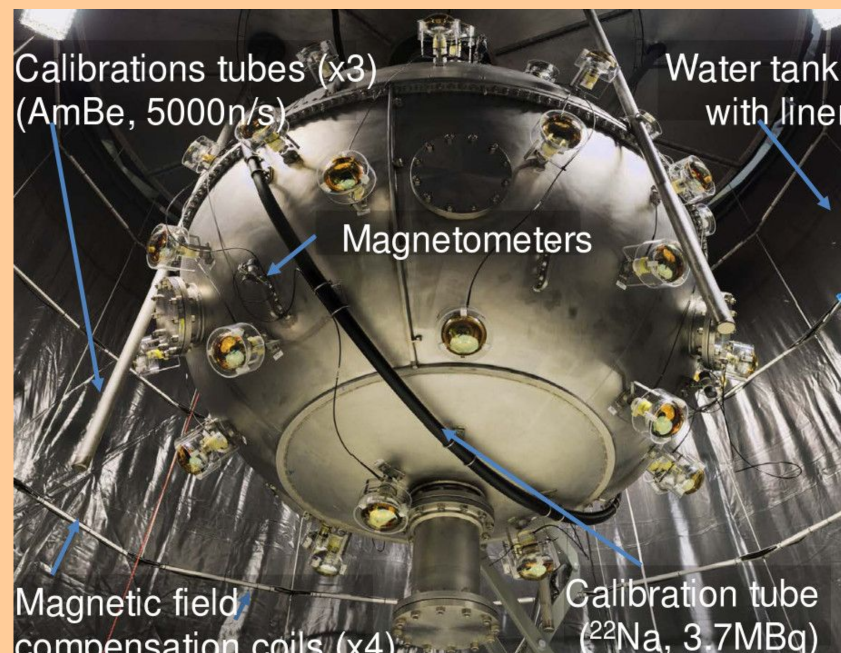
Noble Gas: Single Phase Detectors

XMASS @ Kamioka (JP) **LXe**

– **832 kg** LXe target, 642 PMTs
– very high light yield, low threshold (0.5 keV_{ee})
BUT: **no possibility to reject NRs**
– many results: summary: *arXiv:1506.08939*
→ **background limited!**
– stable data taking since >2 years

DEAP-3600 @ SNOLAB (CA) **LAr**

– **light pulse-shape for discrimination**
– **3.6t** liquid argon target;
high ^{39}Ar background in ^{nat}Ar (~1 Bq/kg)
– data taking right now... high light yield,
→ results expected for TAUP 2017
– sensitivity: 1×10^{-46} cm² @ 100 GeV/c²



F. Retiere (LIDINE 2015)

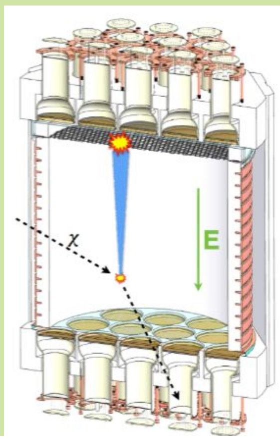
Running dual phase detectors

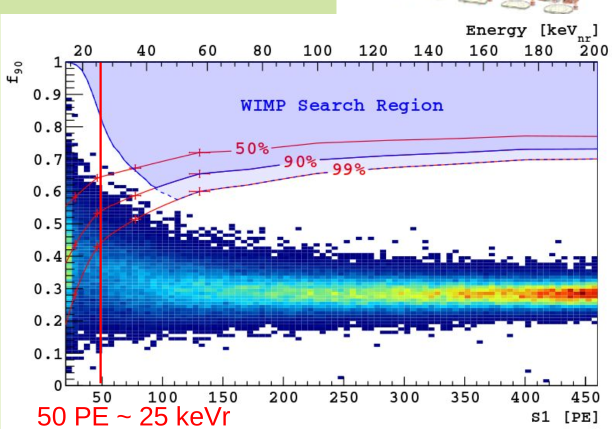
LAr

DarkSide-50 @ LNGS (IT)
PRD 93, 081101 (2016)

- **46 kg** LAr, which is ^{39}Ar-depleted by a factor 1400
- 71d×37kg exposure
- no event in ROI

- still taking data
  (mid March:
  >35 kg×y data)



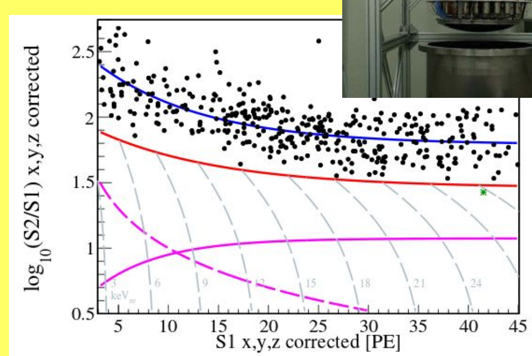


LXe

PandaX-II @ CJPL (CN)
PRL 117, 121303 (2016)

- 60cm×60cm, **500 kg** target
- 2nd largest operational LXe TPC

New result July 2016:
- combines data from 2 runs
  (^{85}Kr differs by factor 10)
- 3.3×10^4 kg×d = 0.1 t×y exposure
- no signal excess
- best limit above ~4.5 GeV/c²
- still taking data
  aim for 2 years
  of data



LXe

XENON1T @ LNGS (IT)
JCAP 04, 027 (2016)

- 96cm×96cm, **2.0 t** target
- largest LXe TPC taking data
- Rn and Kr background goals
  basically achieved

Expect first result soon!

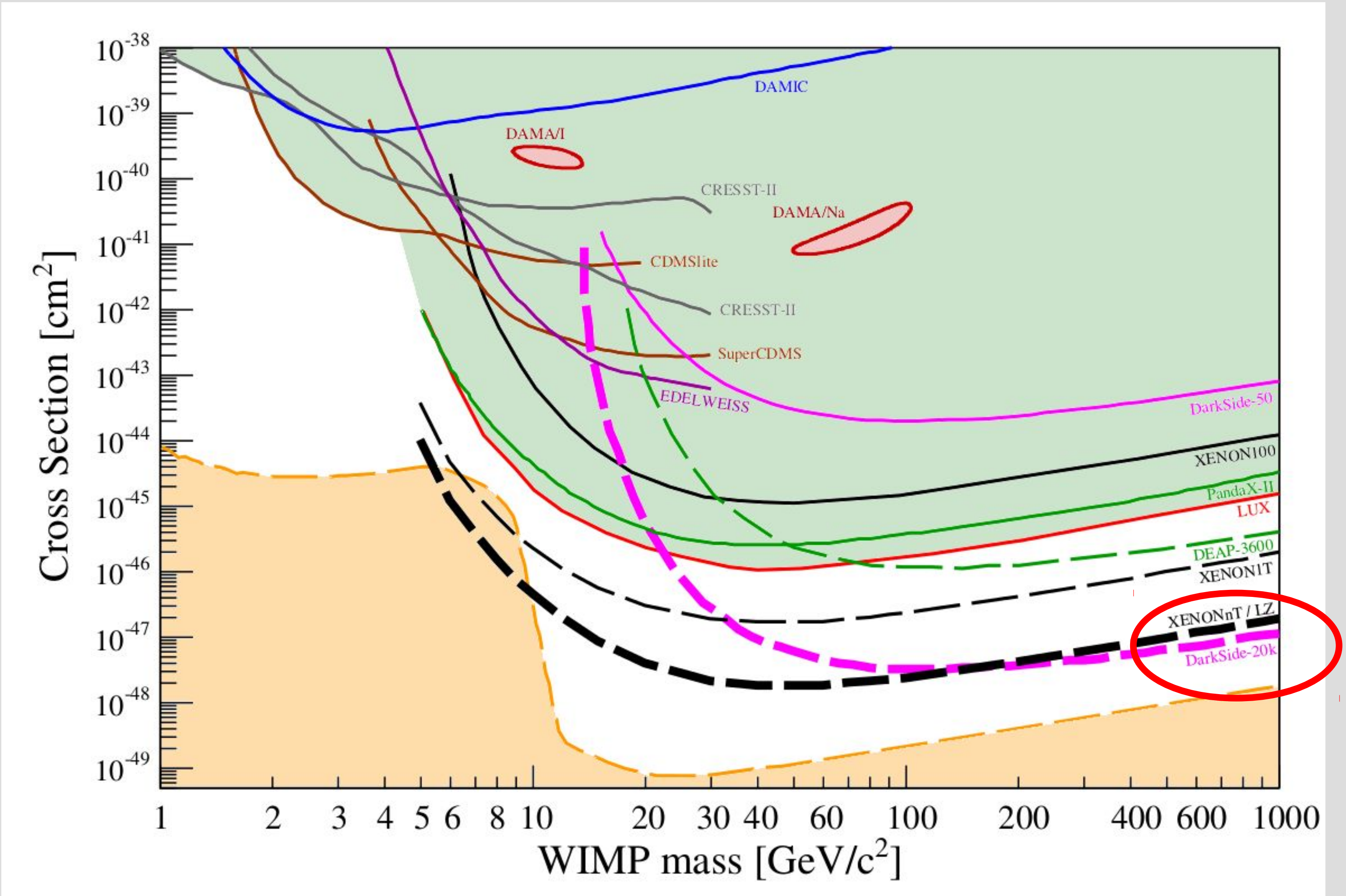
Goal: $<2\times10^{-47}$ cm² @ 50 GeV/c²

LXe

Finished projects: XENON100 @ LNGS (IT), **LUX** @ SURF (USA)

Upcoming Projects

basically funded



some results are missing...

DarkSide-20k

LAr

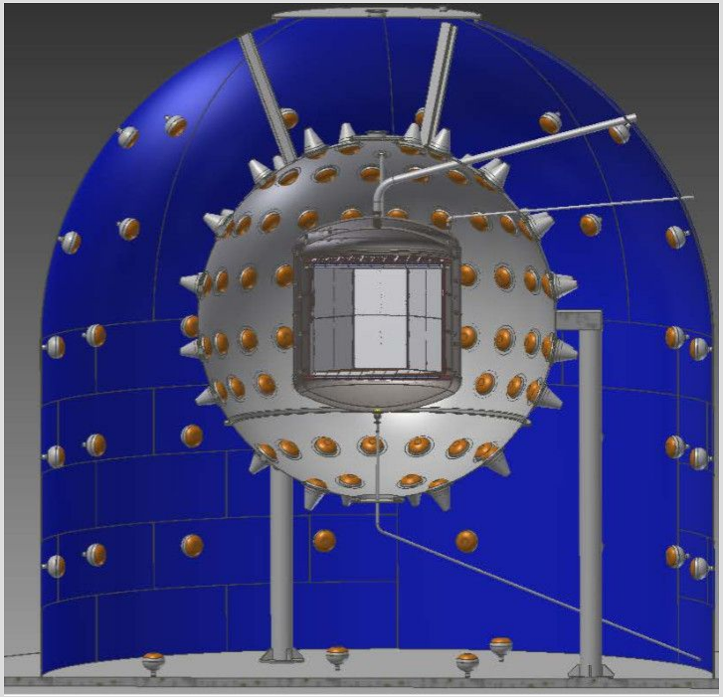
– scale up DS-50 by factor 400:

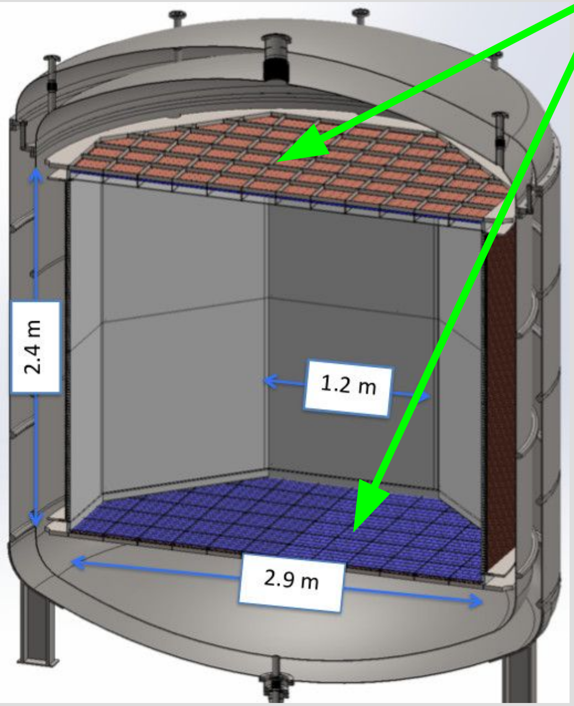
30t LAr total
20t fiducial

– focus on high-mass region >400 GeV/c^2

– keep strategy for background-free search with 100 t×y exposure
  → large amount of underground Ar: URANIA (+ARIA)
  → pulse-shape discrimination → high LY needed
  → liquid scintillator neutron veto

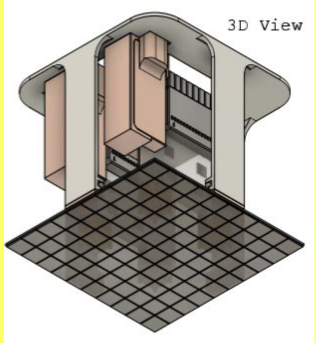
– start operations @ LNGS within 2021





Readout by two arrays of grouped SiPMs:
14 m^2 total

Requirements:
– PDE: 45% ✔
– Dark Count Rate:
0.1 Hz/mm^2 ✔



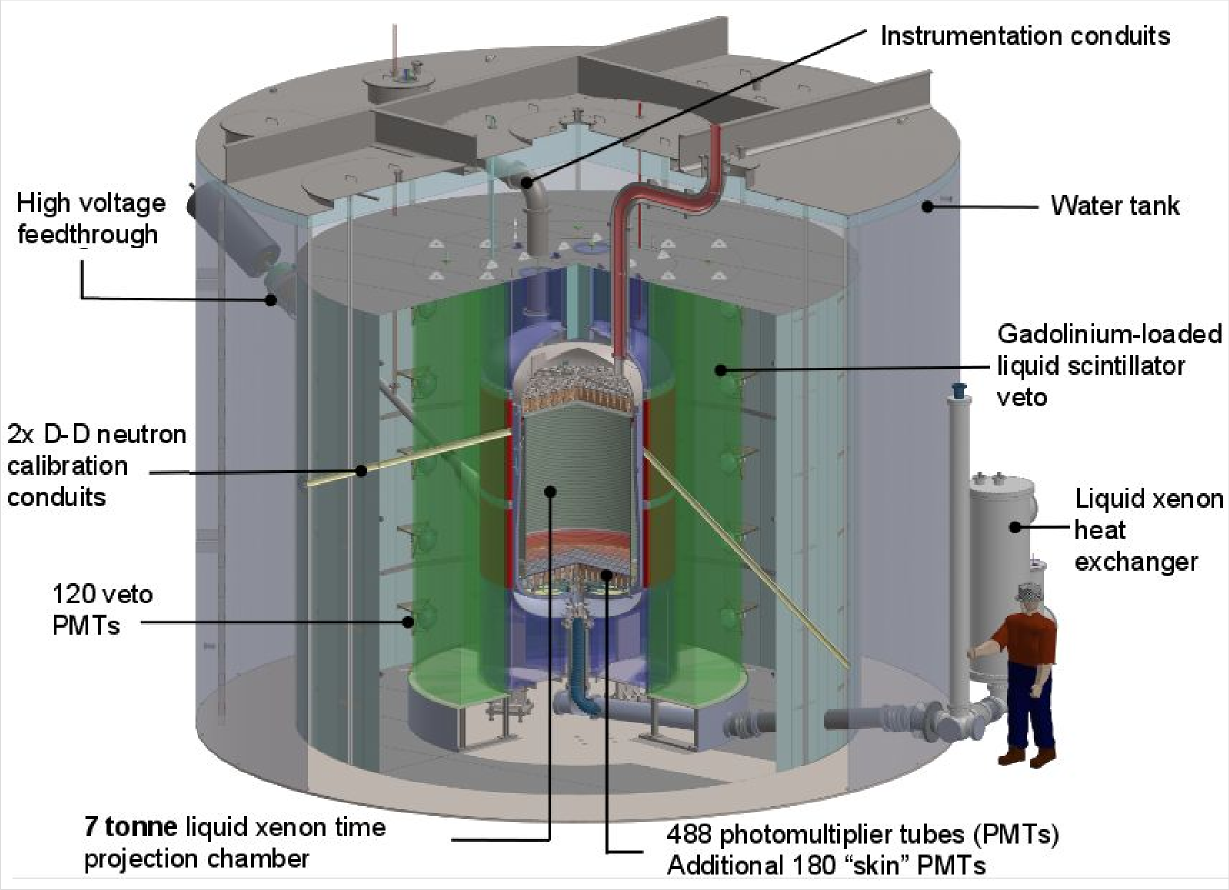
LZ – LUX/ZEPLIN

LXe

arXiv:1509.02910

- **LZ = LUX+ZEPLIN**
  selected by 2014
  US DOE-NSF downselection
- to be installed @ SURF (USA)
- 50× larger than LUX

  10t total LXe mass,
  7t active target,
  5.6t fiducial target
- 488 R11410 PMTs
- *2015*: started procurement of xenon gas, PMTs, ...
  06/2020: start commisioning
- goal: 2×10^{-48} cm² @ ~50 GeV/c² after 15 t×y exposure

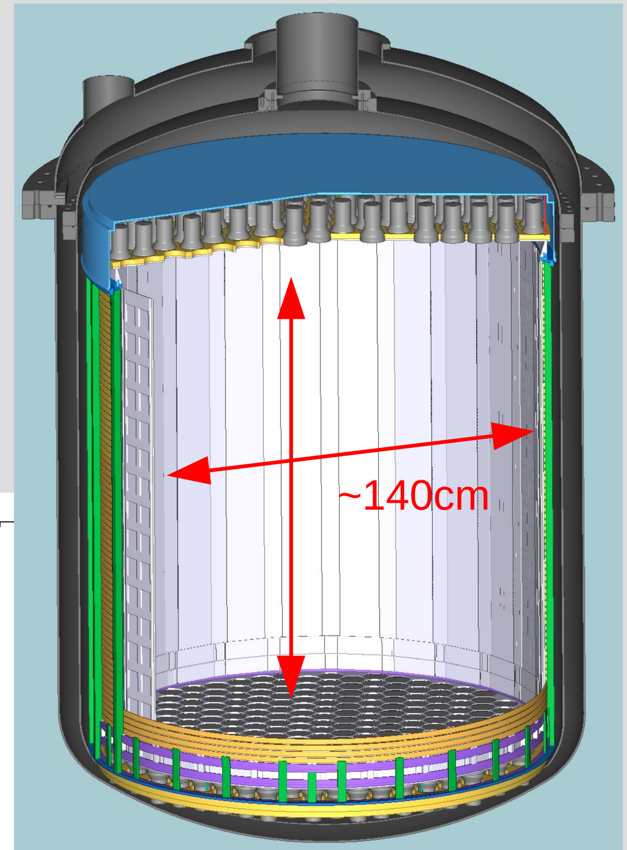


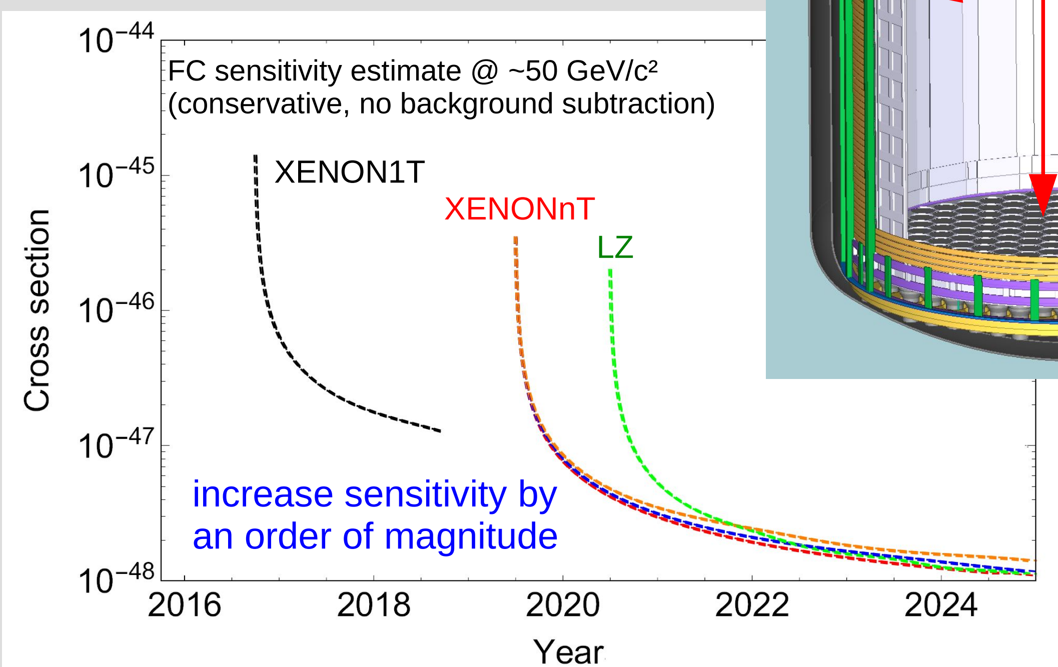
XENONnT

LXe

JCAP 04, 027 (2016)

- @ LNGS using XENON1T systems
- **6.0t** active target
  ~8t total mass
- 476 R11410 PMTs
- projected to start science in 2019
- goal: factor 10 better than XENON1T





LZ information from: https://idm2016.shef.ac.uk/indico/event/0/contribution/69/material/slides/0.pdf

Existing/operational:
- Muon Veto
- Cryostat Support
- Outer Cryostat
- in-LXe Cabling
- LXe storage system
- Cryogenic system
- Purification system
- Kr removal
- DAQ ← responsibility or participation
- 95% of Electronics
- Calibration System
- 260 PMTs
- >8t of LXe
- Screening facilities

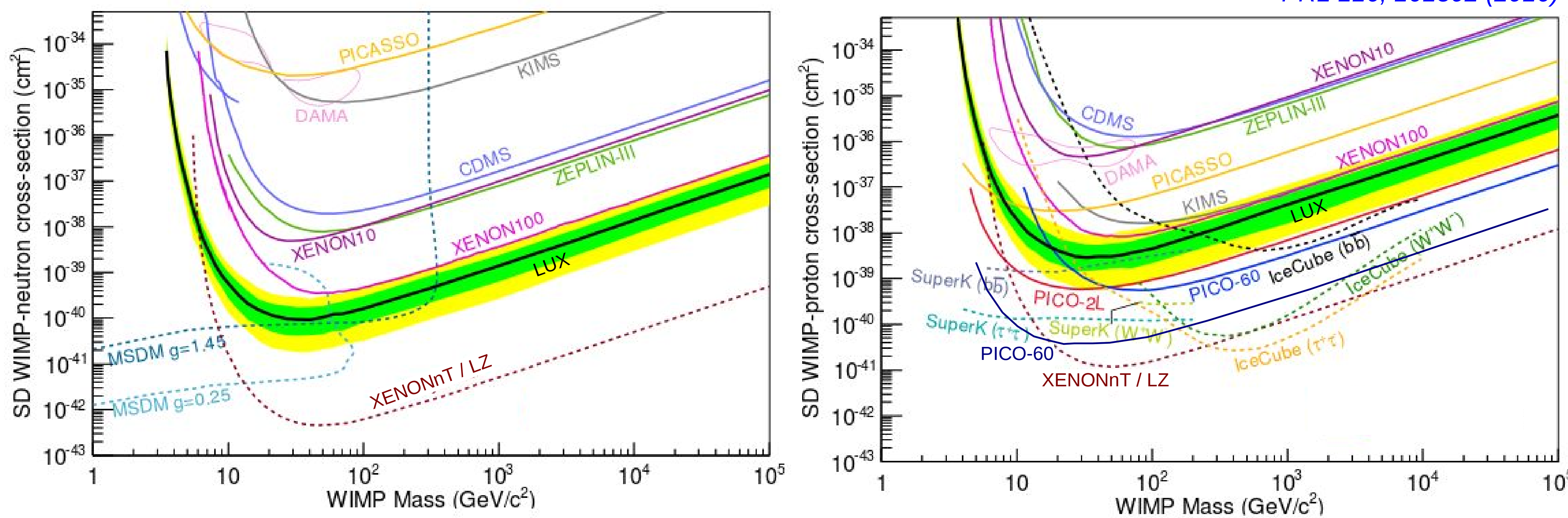
Started:
- 230 new PMTs ordered
- TPC/Cryostat design
- first material orders
- Screening campaign
- Neutron veto studies
- 2nd storage vessel ordered
- Rn reduction system design
- purification improvements
- etc.

Spin-dependent WIMP Couplings

WIMP-neutron scattering:
– dominated by **LXe TPCs**
– also: Ge, NaI, CsI, CF_3I, C_3F_8

WIMP-proton scattering:
– dominated by **bubble chambers** (CF_3I, C_3F_8)
– also: Xe, NaI, CsI

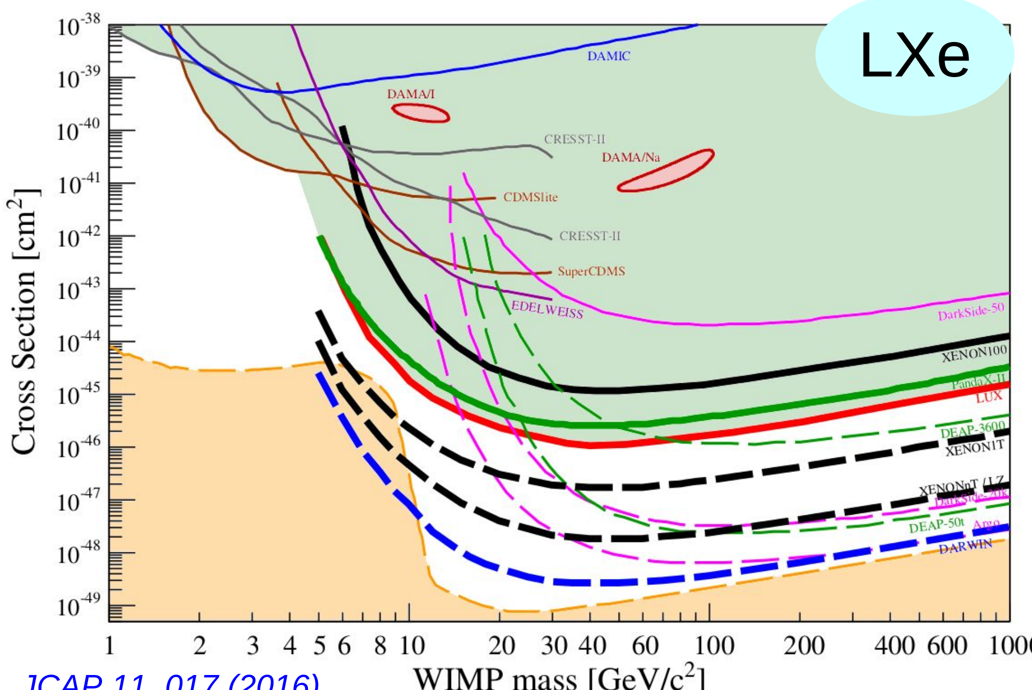
PRL 116, 161302 (2016)



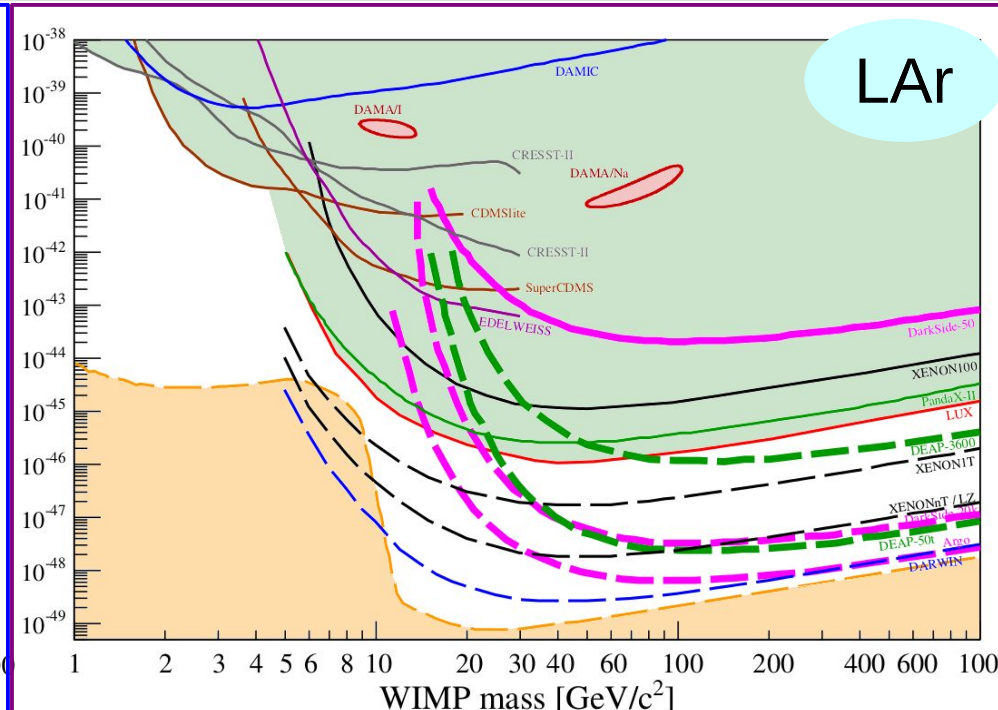
excellent complementarity to **LHC searches** (ATLAS, CMS)

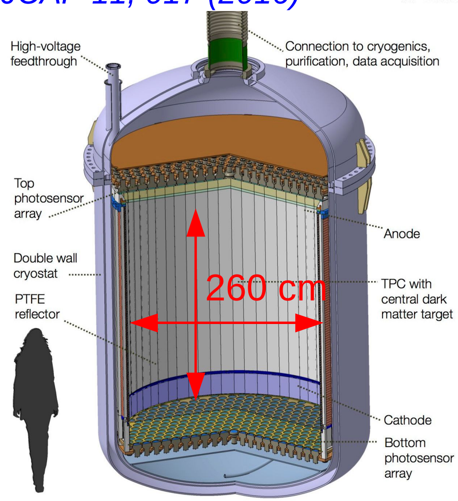
excellent complementarity to **indirect searches** (IceCube, SuperK)

Towards the Neutrino Floor



JCAP 11, 017 (2016)





DARWIN

DARWIN

~50t total LXe

~40 t LXe TPC

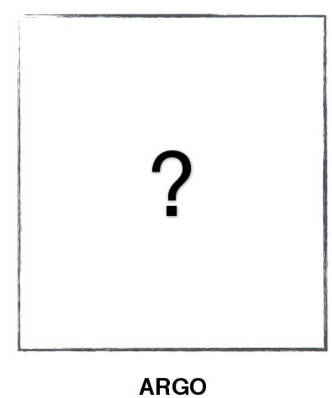
– aim for 200 t×y exposure

– start operations at LNGS by 2026??

– lots of sensitivity studies

darwin-observatory.org

M. Wada @ Moriond 2017



300 tonne (200 tonne fiducial) detector

ARGO

– **~300t depleted Ar** TPC

– aim for 1000 t×y exposure

– „background-free“

– start operations at LNGS by 2027??

Technical Challenges

50 t LXe TPC 🇩🇪 — LXe

– *size*: 2.6m (~2.7× XENON1T, ~2× XENONnT/LZ)
  → procurement of LXe → no consumable!
  → high voltage for drift field
  → gas purification for high e-lifetime

– *photosensors*:
  → long-term stability of PMTs?
  → alternatives? (GPMs, hybrid, etc)

– *backgrounds in WIMP ROI*

JCAP 10, 016 (2015)

Source	Rate [events/(t·y·keVxx)]
γ-rays materials	0.054
neutrons*	3.8×10^{-5}
intrinsic ^{85}Kr	1.44
intrinsic ^{222}Rn	0.35
$2\nu\beta\beta$ of ^{136}Xe	0.73
pp- and ^{7}Be ν	3.25
CNNS*	0.0022

= 0.1 ppt of ^{nat}Kr
0.5× XENON1T goal;
0.03 ppt achieved
EPJ C 74 (2014) 2746

= 0.1 µBq/kg of ^{222}Rn
0.01× XENON1T goal;
→ main challenge

  → challenging Rn background
  → 2×10^{-4} ER rejection is required
    → need high LY
  → challenge: keep large LXe inventory clean
– unexpected artefacts?

300 t LAr TPC — LAr

– *size*: 6.5m (~18× DS-50, ~2.5× DarkSide-20k)
  → DAr: isotopic depletion by cryogenic distillation (never demonstrated for ^{39}Ar)
  → high voltage for drift field
  → gas purification for high e-lifetime
    → single-phase better option?

– *light detection*:
  → PSD requires lots of photons
    → very high LY, high threshold (→6x more gas)
  → attenuation/scatt. length XUV photons?
  → wavelength shifters: long-term stability
  → SiPMs: reduce channels by tiling:
    huge number of channels; large capacitance leads to rapidly decreasing signal-2-noise ratio
    → radiopurity? neutrons?

– *backgrounds in WIMP ROI*
  → ^{39}Ar → PSD; PSD with pile-up?
  → neutrons? Rn plate-out?

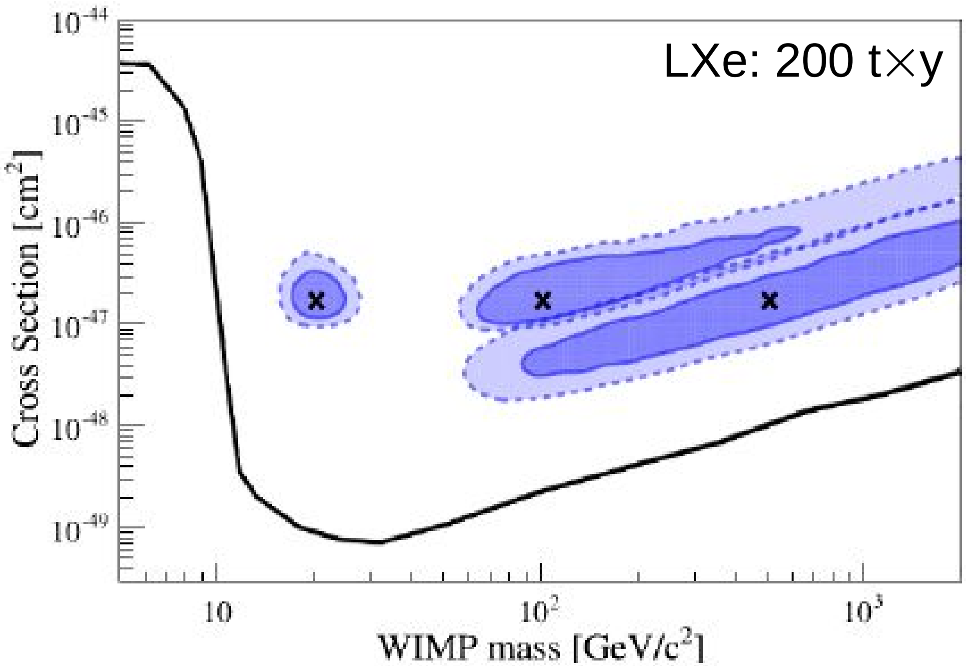
→ challenge: keep large UAr inventory clean
– unexpected artefacts?

Science Channels

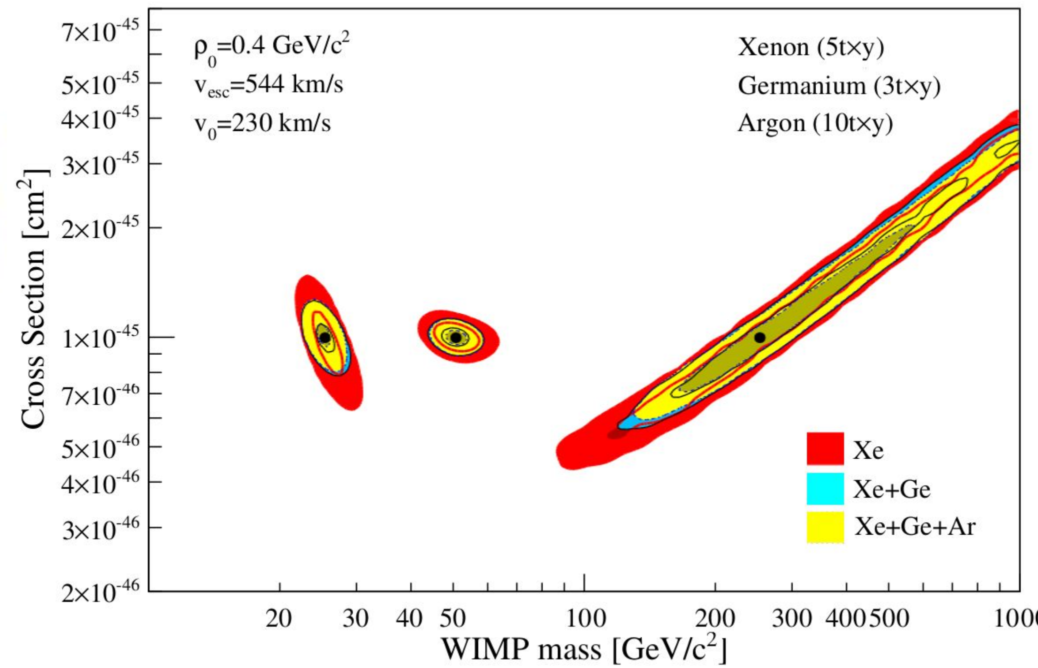
50 t LXe TPC (LXe)	300 t LAr TPC (LAr)
Nuclear Recoil Interactions	
WIMP dark matter	
– spin-independent mid/high mass *JCAP 10, 016 (2015)*	– spin-independent high mass
– spin-dependent *Phys.Dark Univ. 9-10, 51 (2015)* → complementary with LHC, indirect search	
– various inelastic models (χ, n, MiDM, …)	
Coherent neutrino-nucleon scattering (CNNS)	
– ^{8}B neutrinos (low E), atmospheric (high E) *JCAP 1611, 017 (2016)*	– atmospheric (high E)
– supernova neutrinos *PRD 89, 013011 (2014), PRD 94, 103009 (2016)*	
Electronic Recoil Interactions	
Non-WIMP dark matter and neutrino physics	
– axions, ALPs *JCAP 1611, 017 (2016)*	
– sterile neutrinos	
– pp, ^{7}Be: precision flux measurements (pp: <1%) *JCAP 01, 044 (2014)*	– ^{7}Be, pep , CNO flux measurements (2%, 10%, 15%) *JCAP 1608, 017 (2016)*
Rare nuclear events	
– 0νββ (^{136}Xe), 2νEC (^{134}Xe), ... *JCAP 01, 044 (2014)*	

WIMP Spectroscopy

Parameter Reconstruction



Target Complementarity



JCAP 11, 017 (2016)

PRD 83, 083505 (2011)

Capability to reconstruct WIMP parameters

- m_χ=20, 100, 500 GeV/c²
- due to flat WIMP spectra, no target can reconstruct masses >500 GeV/c²

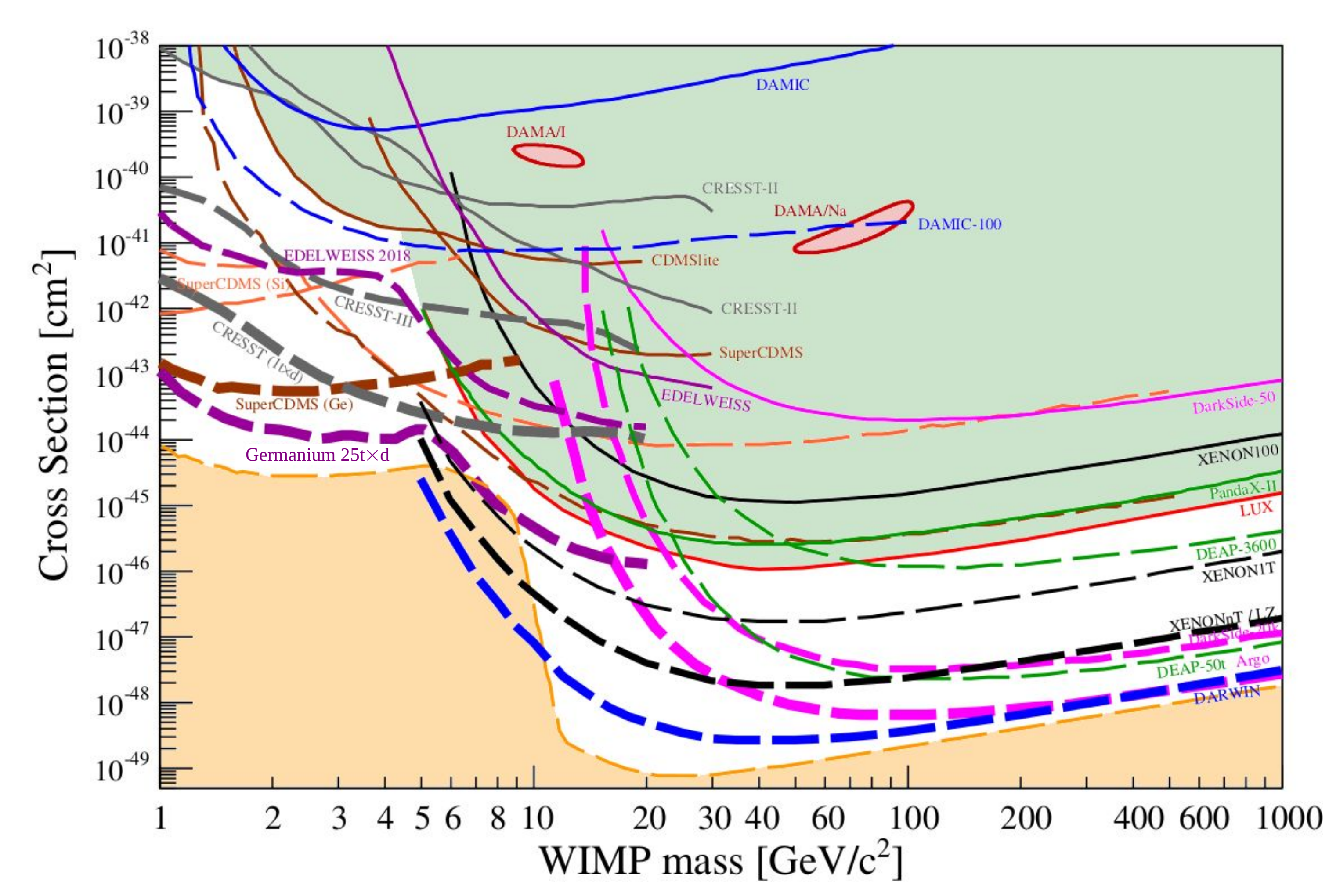
Reconstruction improves considerably by adding Ge-data to Xe.

Only minimal improvement for Ar.

If there is no hint for DM from direct detection + LHC?
Do we proceed with multi-ton scale projects

erc **R&D has to continue to be ready!**

Summary



Cross Section [cm^2]
WIMP mass [GeV/c^2]
DAMIC
DAMA/I
CRESST-II
DAMA/Na
DAMIC-100
EDELWEISS 2018
CDMSlite
SuperCDMS (Si)
CRESST-III
CRESST-II
CRESST (1t×d)
SuperCDMS
SuperCDMS (Ge)
EDELWEISS
Germanium 25t×d
DarkSide-50
XENON100
PandaX-II
LUX
DEAP-3600
XENON1T
XENONnT / LZ
DEAP-50t
Argo
DARWIN

Question 1: Science I

What are the primary scientific questions of the field?

– Direct detection of WIMP dark matter
– What is the nature of the WIMP? (mass, X-section, couplings)?

Which experimental options exist to answer them and when?

– Direct measurement of WIMP-induced nuclear recoils
Different experimental approaches (different targets)
cryogenic detectors @ low mass: lowest threshold, low exposure, mediocre background
noble-liquids @ higher masses: high exposure, low background, mediocre threshold/resolution

– different targets are sensitive to different couplings, WIMP models
(SI: all targets, SD/inelastic: Xe, Ge, F)

– Important **complementarity** with
indirect detection:
mainly spin-dependent (F, Xe, Ge) but also spin-independent (Super-K)
collider searches:
mainly spin-dependent (Xe, F, Ge)

Question 1: Science II

For proposed projects: Important results guaranteed, likely or possible?

WIMP-detection depends on nature's choice.
Future experiments will scan well-motivated parameter space

However: even limits are high-impact results!
→ big impact on validity of models!

Which secondary topics are covered by the project and what are its chances for success?

– CNNS → not yet detected (Ge, $CaWO_4$, Xe)	*yes!*
– Supernova neutrinos (Xe) → complementarity with large detectors	*yes if SN*
– Solar neutrinos: low-E (Xe), high-E (Ar)	*yes!*
– neutrinoless double beta decay (Xe)	*??*
– Axions, ALPs, SuperWIMPs, dark photons, etc. (Xe, Ge, Si, $CaWO_4$ → experiments need ER sensitivity = low ER background)	*??*
– fractional charges (Ge, Si)	*??*
– etc etc etc	

Question 2

Estimate of the time scales, costs (invest) and structures (collaboration size and international composition)

– time scale:
 next generation („basically funded") have results by ~2022–2025
 „ultimate" detectors: TDRs needed in 5-6 years
 operation in mid 2020s

– cost: n/a

– structures:
 → sufficient size (moderate increase) for next generation projects
 → more manpower/funding needed for „ultimate" detectors

Which risks exist?

– see various technical challenges
– unknown and fastly changing Chinese projects → competition
– don't lose European leadership

Which competing projects exist world-wide for the physics question, taking also realistic schedules and progress into account?

– see talk

Question 3

Where is the specific German interest?
Do special strengths of German groups play a role?
Are there enough interested groups/people for a meaningful contribution?

Currently two activities pursued in Germany:

- Low-mass with cryogenic detectors (CRESST: $CaWO_4$, EDELWEISS: Ge)
  - CRESST is a **German** project (75% manpower, expertise)

- High-mass with LXe TPC (XENON, DARWIN)
  - DE groups are largest community (with US), major contributions to project special expertise: **background reduction**
  - DARWIN pushed forward by German PIs
  - Special Opportunity: DARWIN is largely European project! (66% EU, 25% D)
    Unique possibility for leadership!

Will the participation create synergies and international visibility?

It does already.

How does the required funding fit to the German funding structures?

CRESST: *BMBF, SFB, MPG*
XENON: *BMBF, MPG*
DARWIN: *currently: Universities, MPG, ERC → future: BMBF*

Question 4

Where could the project be realized?

- Direct WIMP searches need large underground laboratories, which do not exist in Germany.
- CRESST and XENON are installed at LNGS (IT) and will continue there.
- DARWIN: a LOI/space request has been submitted to LNGS
- SuperCDMS (Ge, Si) will be hosted by SNOLAB (CA)
  → EDELWEISS groups might join
- Argon: DarkSide-20k will be realized at LNGS.
- no concrete proposal for ARGO yet.
  Maybe LNGS? Maybe SNOLAB (merger with DEAP??)
- Unknowns: China (Ge/Xe), Japan (Xe)