Direct Detection of Dark Matter

Marc Schumann *AEC, Universität Bern*

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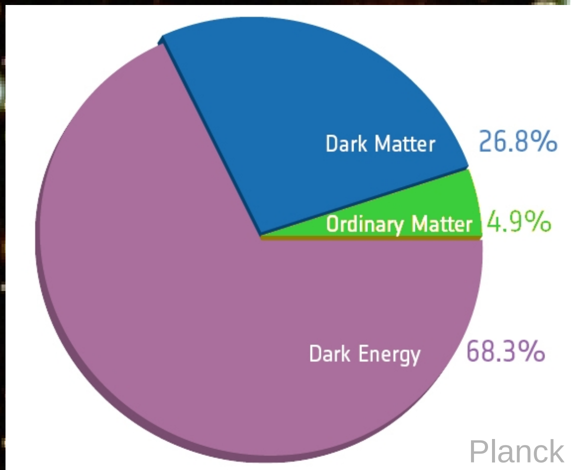
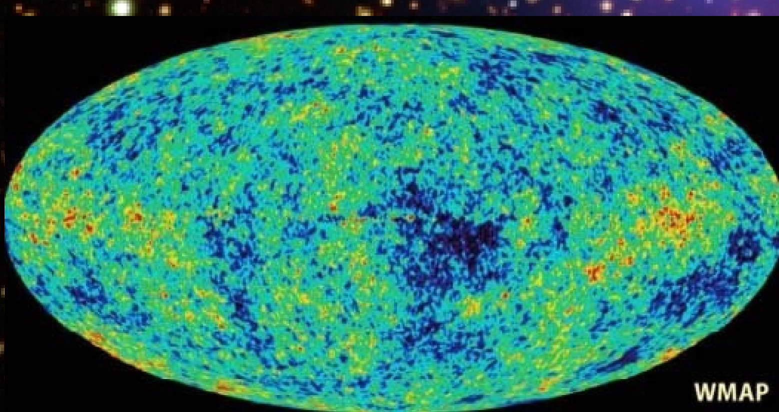
marc.schumann@lhep.unibe.ch
www.lhep.unibe.ch/darkmatter

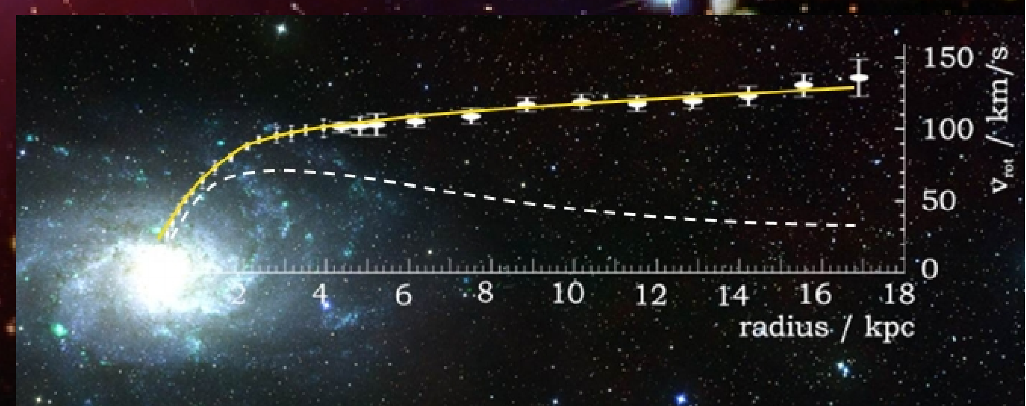
UNIVERSITÄT BERN
AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

Dark Matter: (indirect) **Evidence**

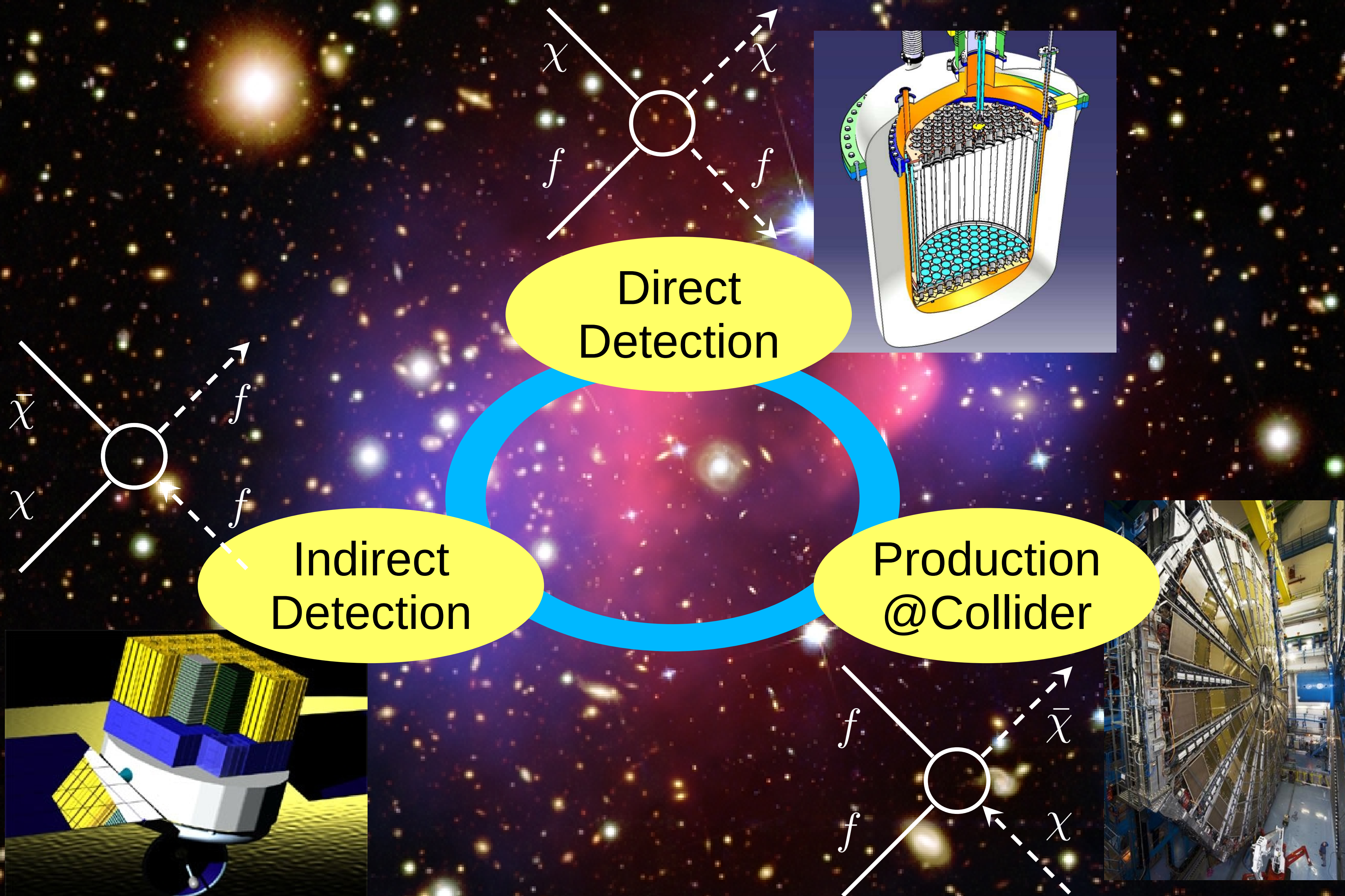


Particle Dark Matter Candidates:
- **WIMP** → *„WIMP miracle“*
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...

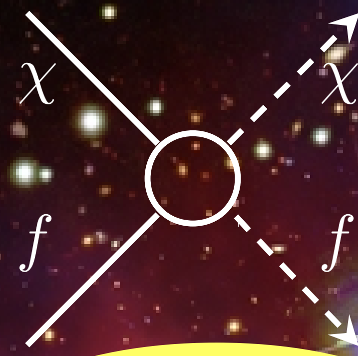


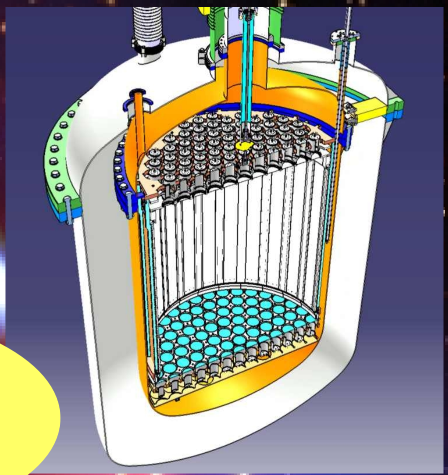


Dark Matter Search



Dark Matter Search





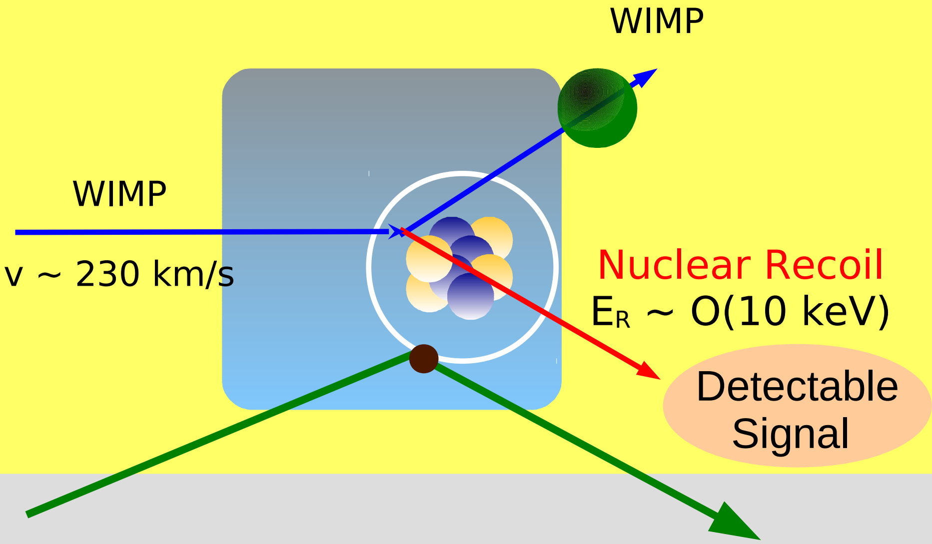
Direct Detection

Xe	XENON, DARWIN	*UZH, Bern*
Ar	ArDM → G2/G3 LAr	*ETHZ*
Si	DAMIC	*UZH*

information/slides
C. Regenfus
information/slides
B. Kilminster

Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



gamma- and beta-particles (background) interact with the atomic electrons
→ **electronic recoil**

Direct WIMP Search

Tiny Rates, small energies

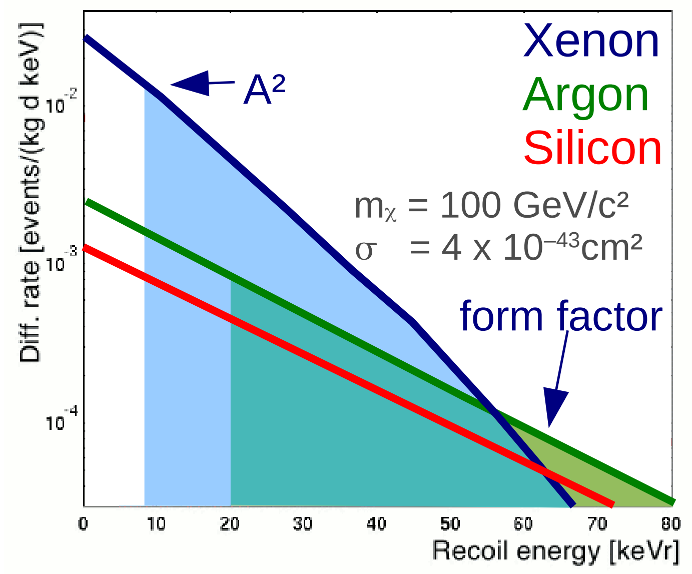
$R < 0.01$ evt/kg/day

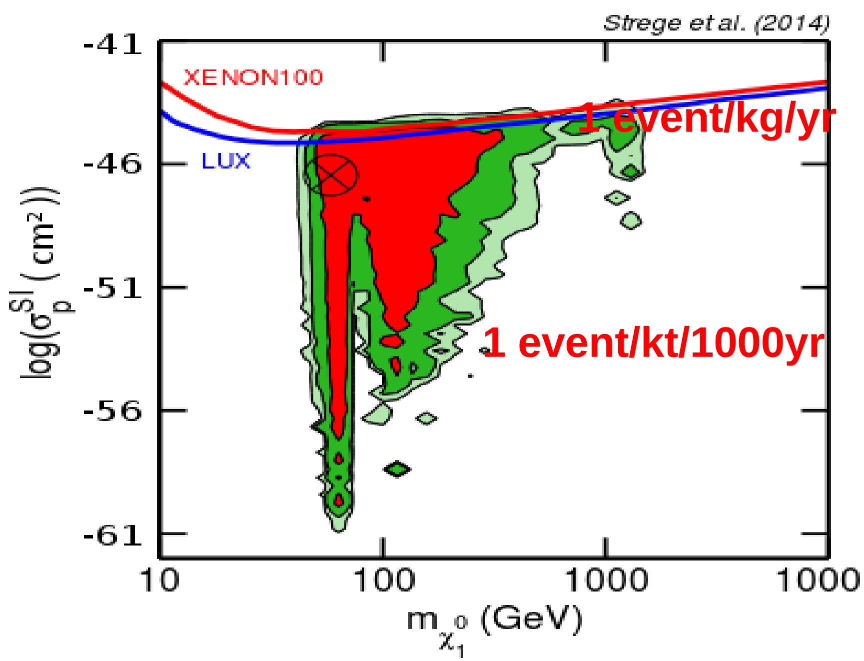
$E_R < 50$ keV

How to build a WIMP detector?

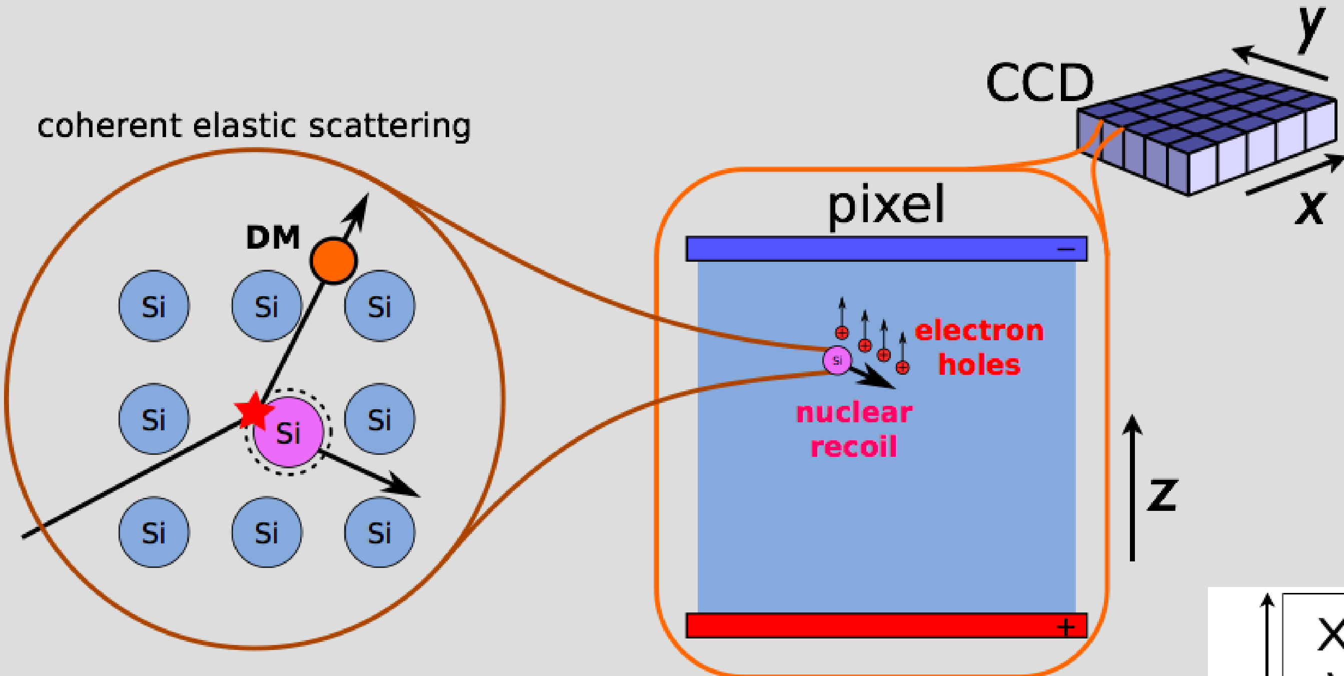
- large total mass, high *A*
- low energy threshold
- ultra low background
- good background discrimination

We are dealing with
- extremely **low rates** (1 – 1000 Hz)
- extremely **low thresholds** (~2 keV)
- extremely **low radioactive** backgrounds



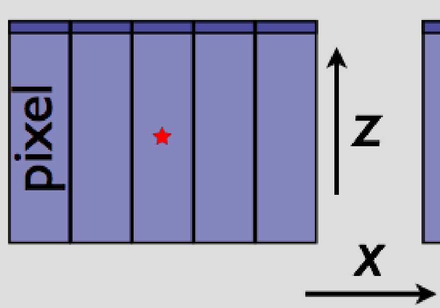


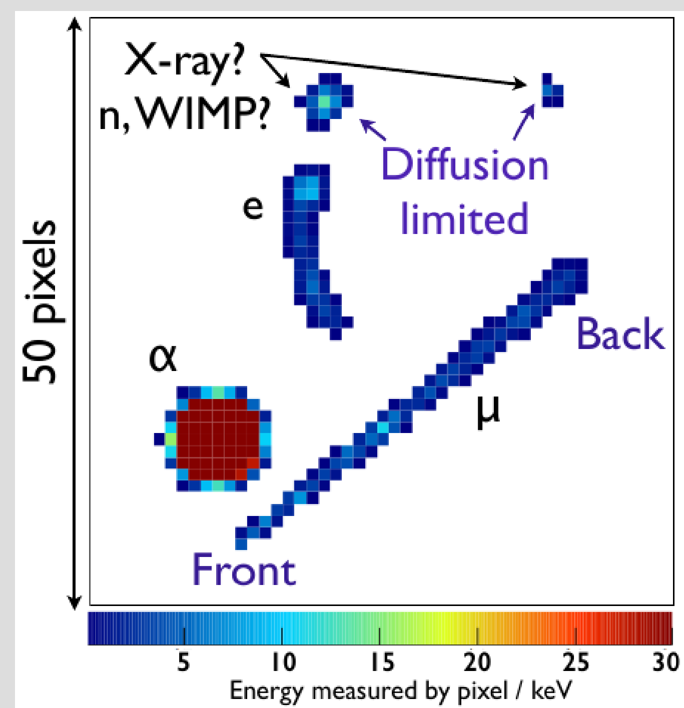
DAMIC – Dark Matter with CCDs



- Target: **Si – thick CCDs**
- need only 3.6 eV to create e^--hole pair
- measure charge collected in CCD pixels
- low target mass but very low threshold (readout noise only 2 e^- RMS)
  → **low-mass WIMPs**
- use tracks for particle ID

Charge drifted up and held at gates.





DAMIC – R&D

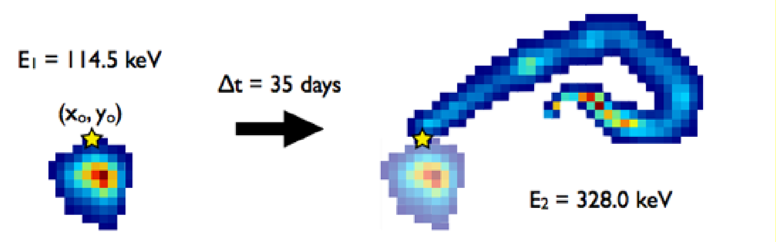
Background measurements of CCDs

- Measure intrinsic radioactive contamination in silicon bulk of CCD of ^{238}U, ^{232}Th, ^{32}Si, ^{210}Pb
  → ultimate limitations of the detector technology

- search for ^{32}Si-^{32}P or ^{210}Pb-^{210}Bi delayed β-coincidence signatures
  → time separation is tens of days!

arXiv:1506.02562

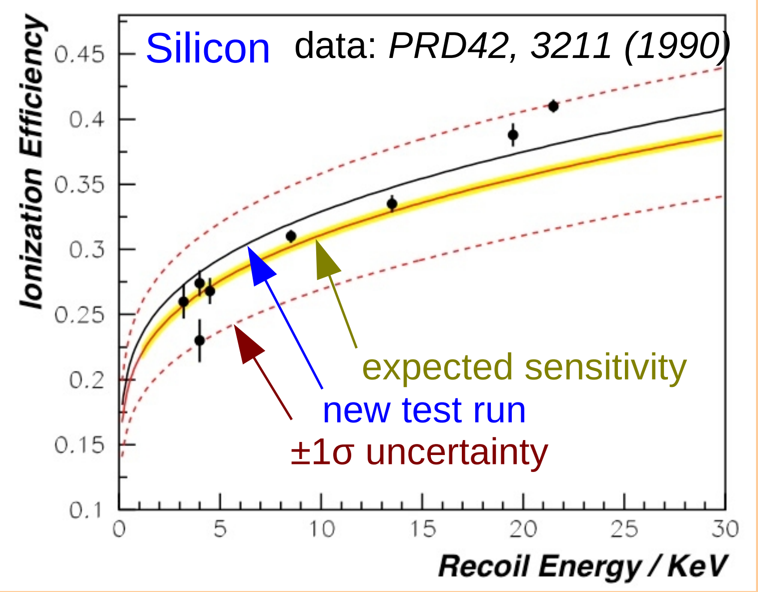
Analysis method	Isotope(s)	Tracer for	Bulk rate kg^{-1} d^{-1}
α spectroscopy	^{210}Po	^{210}Pb	<37
	^{234}U + ^{230}Th + ^{226}Ra	^{238}U	<5 (4 ppt)
	^{224}Ra–^{220}Ra–^{216}Po	^{232}Th	<15 (43 ppt)
β spatial coincidence	^{32}Si–^{32}P	^{32}Si	80^{+110}_{-65}
	^{210}Pb–^{210}Bi	^{210}Pb	<33



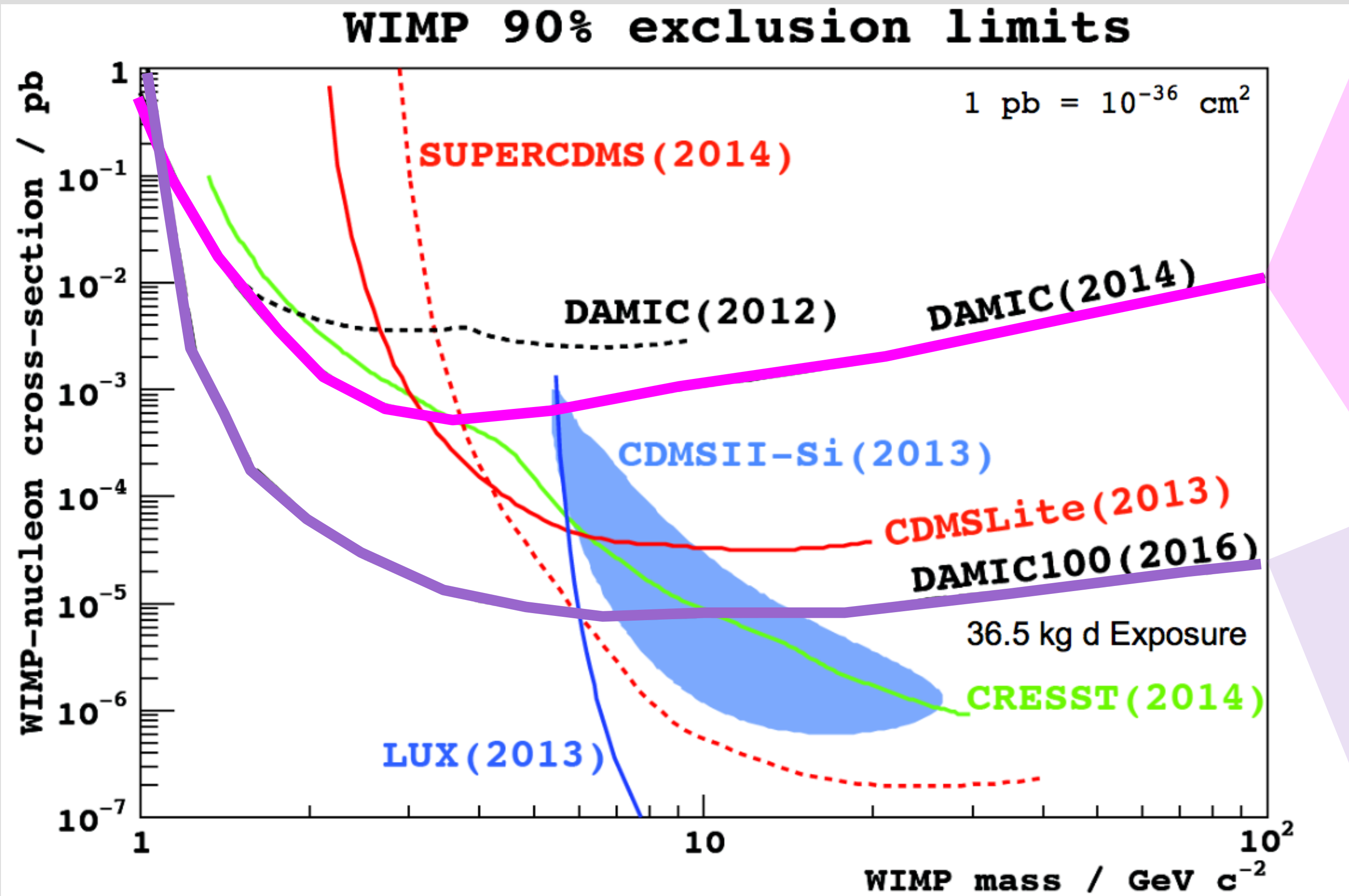
Quenching factor measurements for low-E recoils

- Scattering experiment in ~100 keV neutron beam
  → measure ionization efficiency

- UZH contributions: PMT characterization, detector design and GEANT simulation,



DAMIC – Results and Prospects



preliminary result
36 days of 3 CCDs up to 675 µm thick (2.9 g) in SNOLAB
→ better than CRESST at low WIMP masses
→ @ 3 GeV/c²: 10x better than DAMIC (2012)

DAMIC100
start data taking in 2015
→ explore new regions which are not covered by big experiments

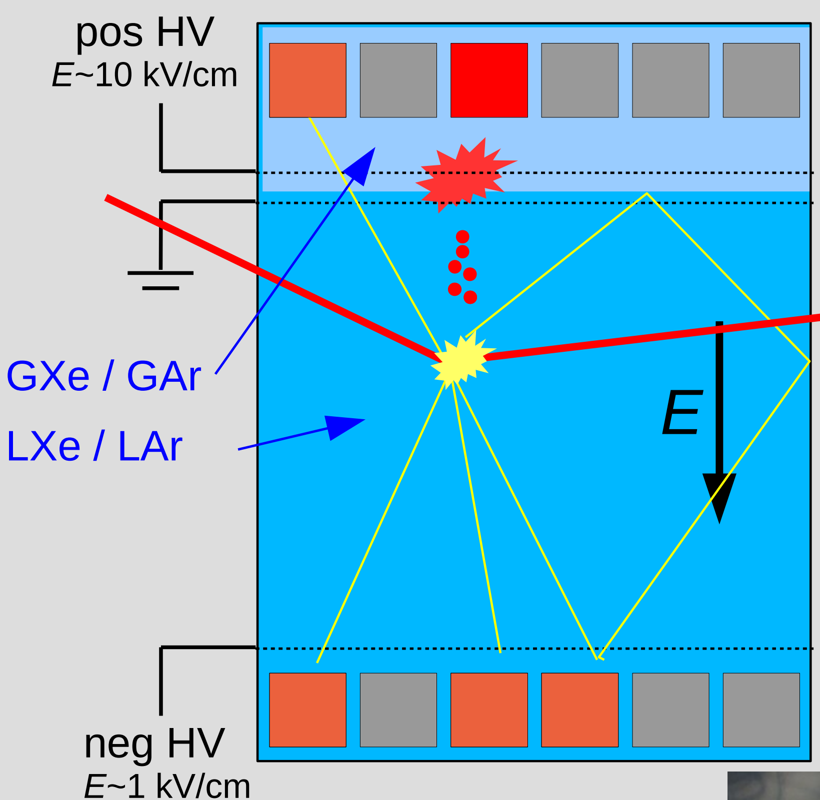
Towards the „neutrino-floor“: DAMIC-1kg will improve by another factor 100.
Skipper-CCDs: 3.6 eV energy threshold will cover region down to ~300 MeV

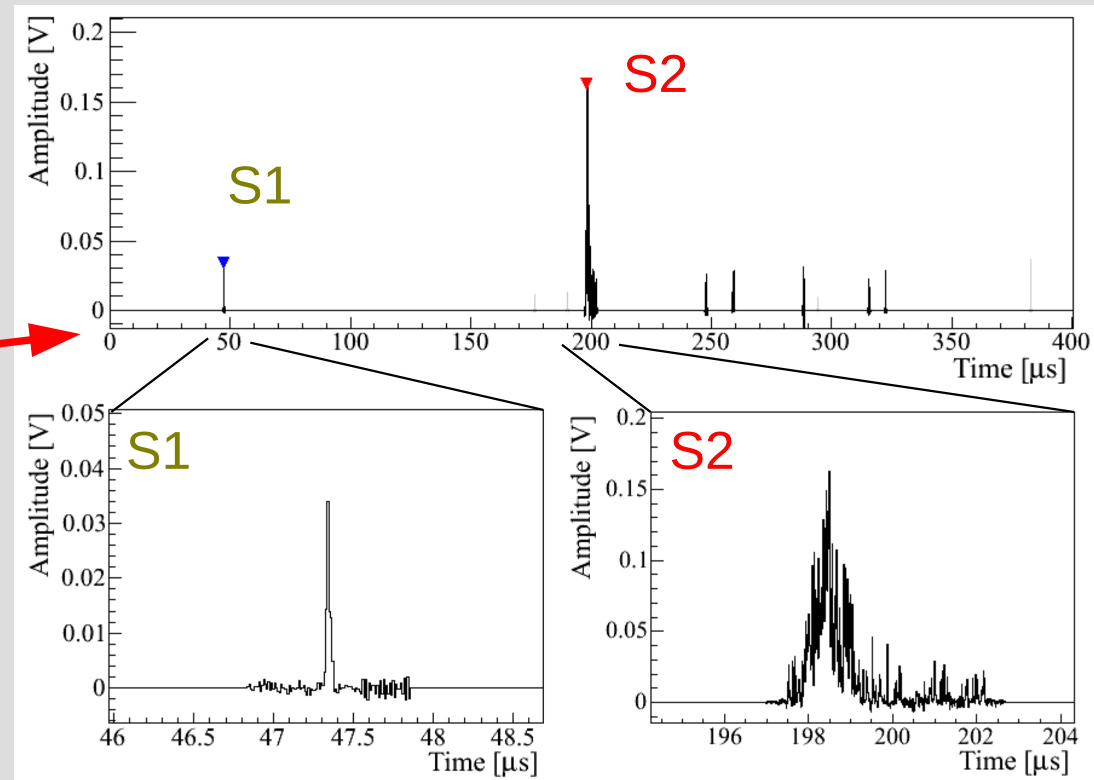
arXiv:1106.1839

Dual Phase TPC

Dolgoshein, Lebedenko, Rodionov, JETP Lett. 11, 513 (1970)

TPC = time projection chamber





LAr Activities: ArDM and Upgrades

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

– ArDM - first ton-scale LAr DM detector
– Now fully operational in single phase physics mode
– First data available from ArDM phase Run I
– Charge readout to be added later this year

- The LAr technology seems to provide a very promising concept for large future DM facilities of highest sensitivity
  → Mainly due to PSD background suppression (>10^8 ?)
- ArDM is a **prototype facility towards G2 and G3 developments**
- Reconfirmed as a **CERN Recognized Experiment** (RE18) - 2018
  - access to CERN infrastructure (e.g. PLC, data storage - defined in MoU)
- Starting collaboration with **Princeton**, **APC Paris**, **LNGS**
  - access to **depleted argon** for ArDM (in the future)
  - common developments towards G2 and G3
  - mutual exchange of technologies

LNGS

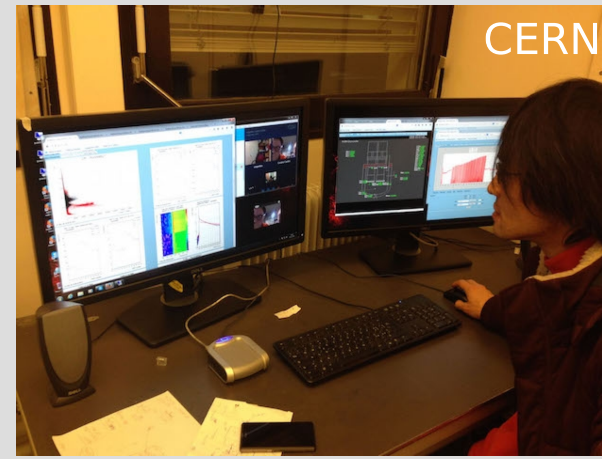
ArDM – Strategy and Reach

– Experiment developed in synergy with R&D for large LAr facilities (e.g. neutrino detectors)
– Installation at LSC 2012/2013 – safety approvals, commissioning 2014
– Operation of ArDM is fully remotely controlled (CERN)

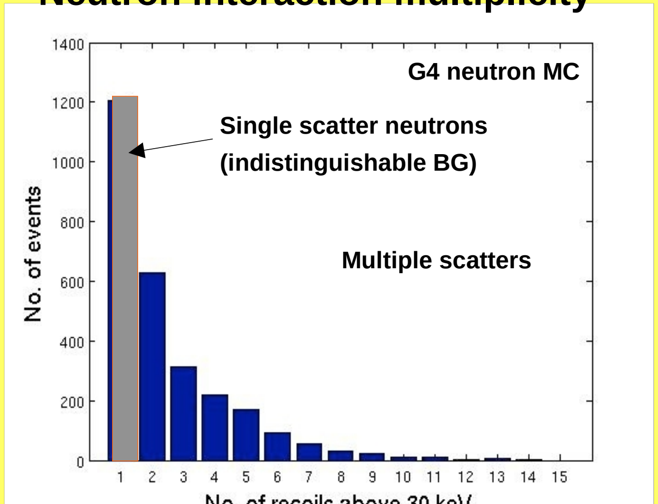
LAr technology: promising for searches of **higher mass WIMPs,** difficult or inaccessible for present colliders.

ArDM will deliver design parameters for **LAr G2 and G3** future facilities

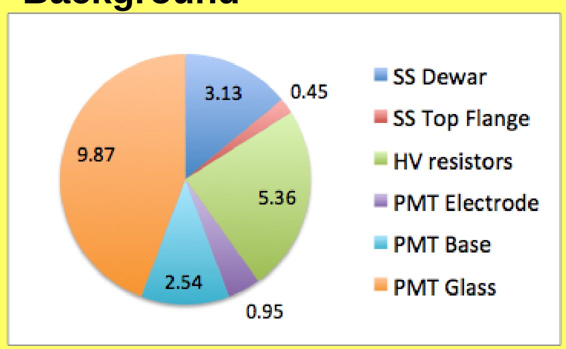
<u>Research focus of ArDM</u>
PSD - neutron interaction - γ background - VUV Rayleigh scattering - light collection - attenuation length - LAr purity



Neutron interaction multiplicity

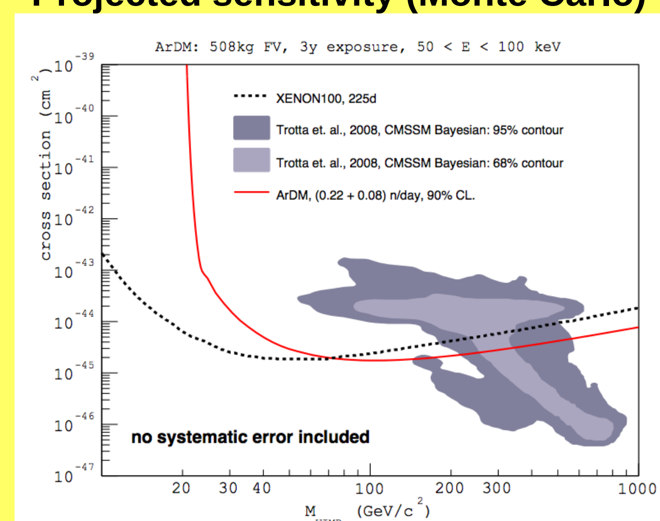


Background

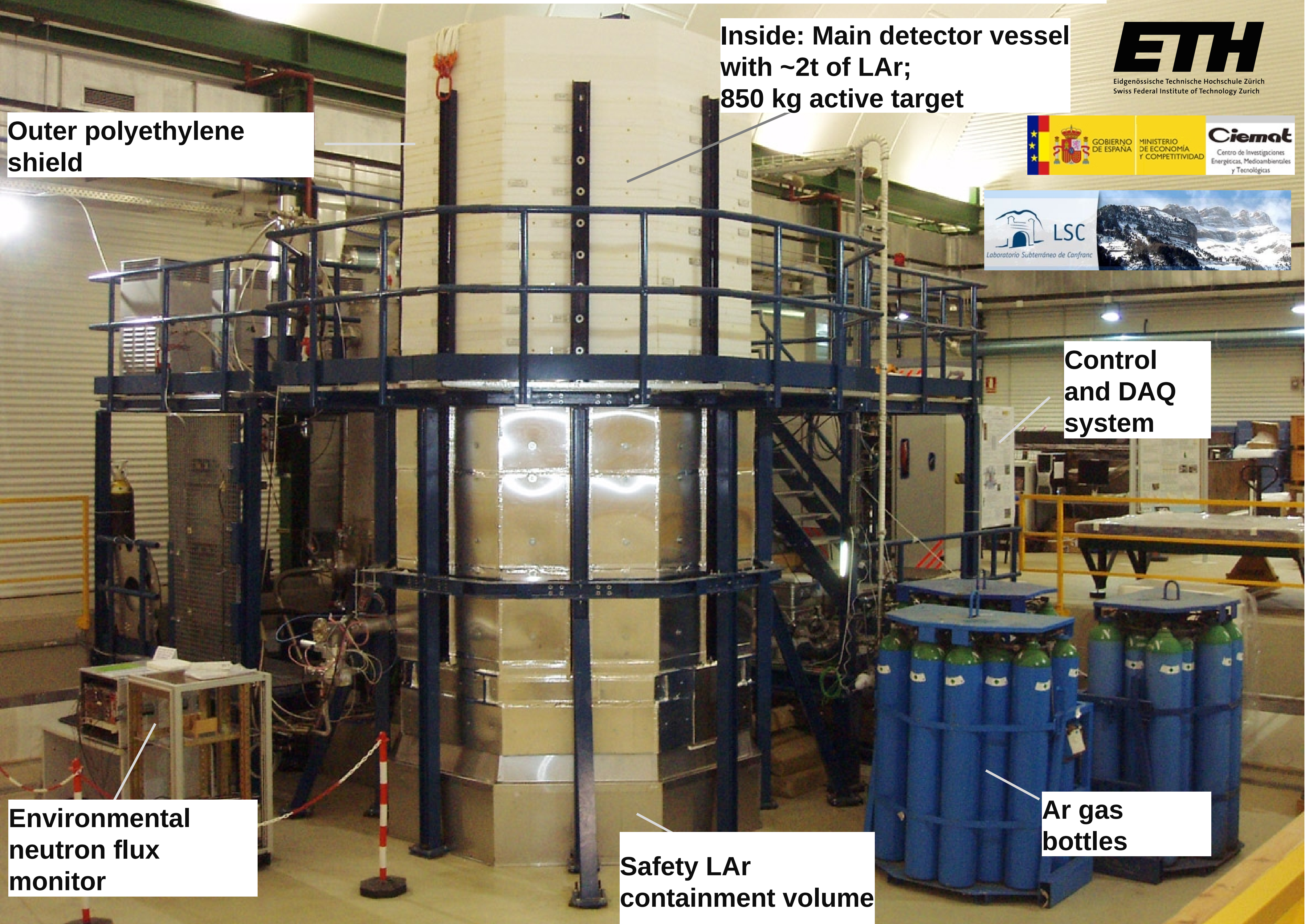


84% of neutron BG from replaceable parts (mainly PMTs)

Projected sensitivity (Monte Carlo)

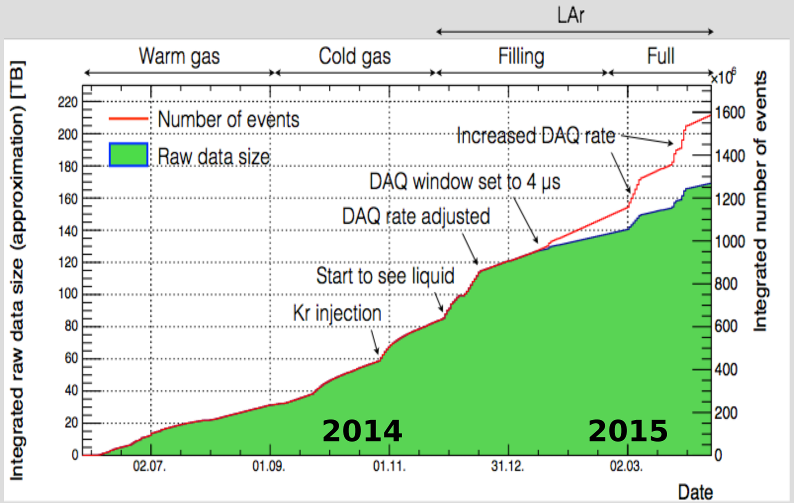


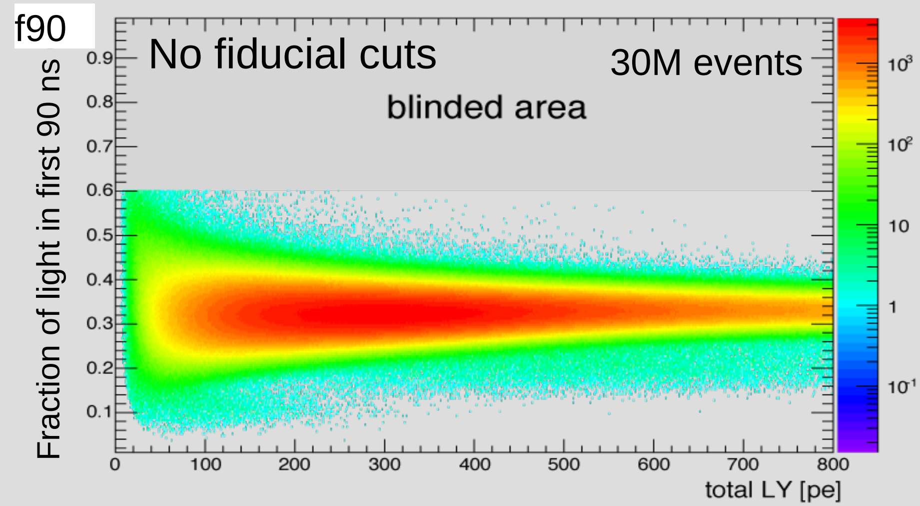
ArDM at LSC hall A - taking data - Run I



Status and preliminary Results

Total accumulated data >10^9

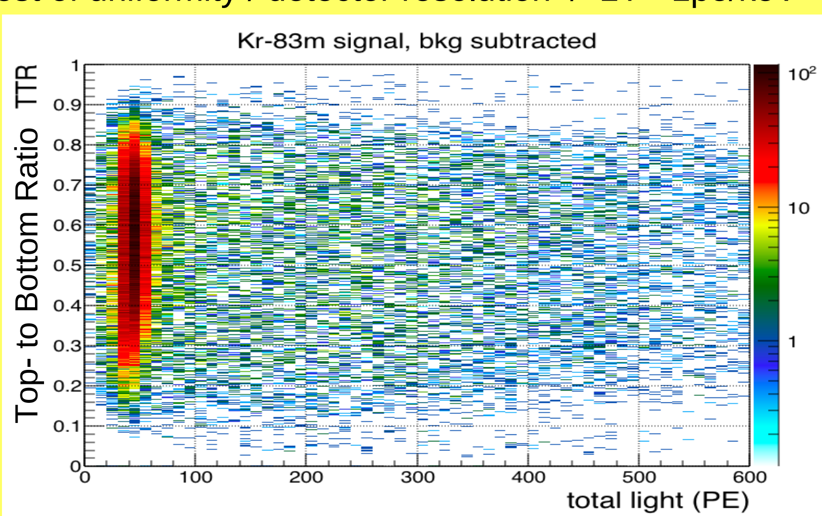


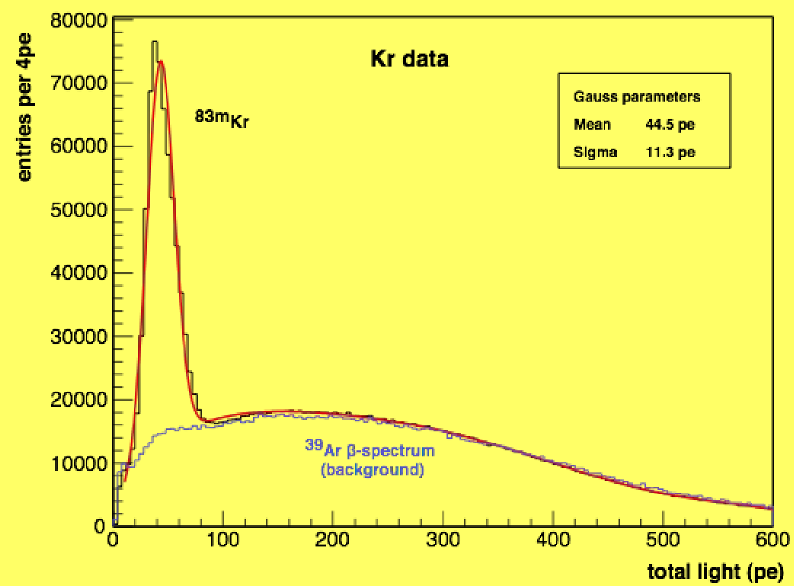


Background separation by PSD only
→ very promising

Calibration data with internal ^{83m}Kr source (41 keV)

→ test of uniformity / detector resolution / LY ~1pe/keV



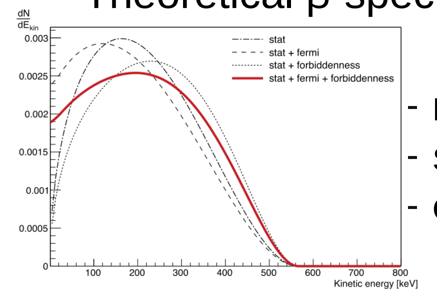


Background Studies

Main background is produced by ^{39}Ar (β-emitter)

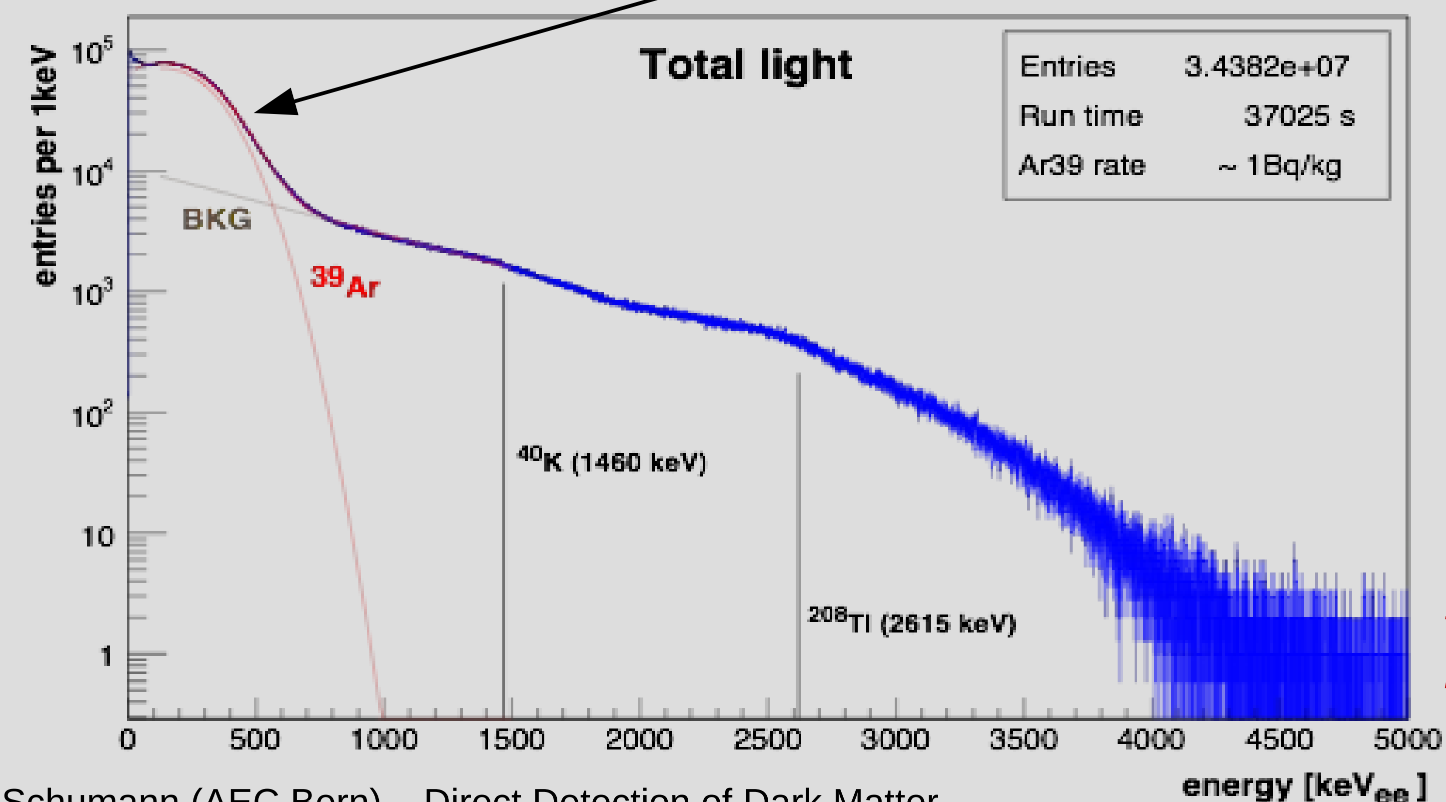
- first data (34M events) analysed
- comparison to screening results and MC ongoing
- promising data quality and detector performance

Theoretical β-spectrum of ^{39}Ar



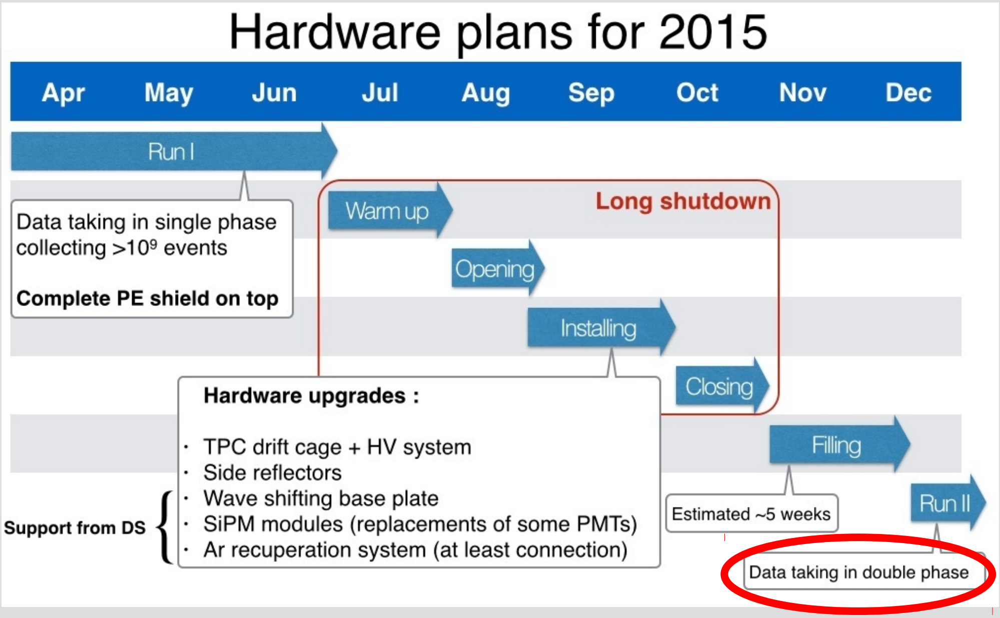
- F(Z,w) Fermi corr.
- S(w) Forbiddenness corr.
- Q-value : 565 keV.

$$\frac{dN}{dw} \sim pw(w_0 - w)^2 F(Z,w) S(w)$$



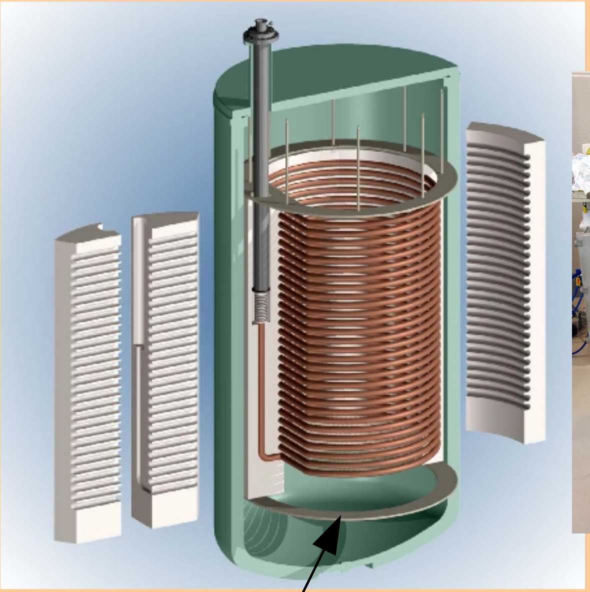
Thesis Khoi Nguyen in preparation (2015)

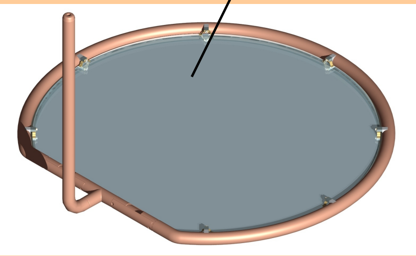
Planned Upgrades 2015



- Improved HV FT location
- Boronated PE shields
- Components ready to be installed

New TPC drift cage and cathode



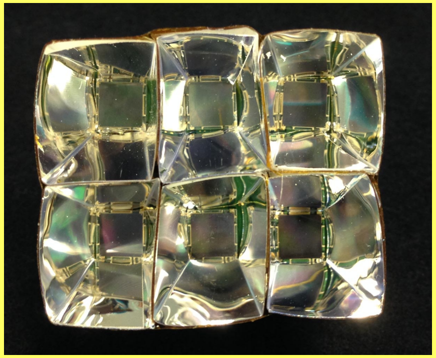


New window cathode

Conductive transparent coating + TPB

Better LY and exact fiducialisation

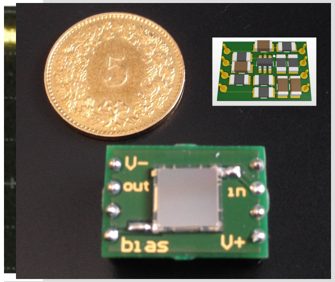
Evaluation of prototype SiPM array



Preparation for upgrade in 2016

R&D on large area fast SiPM @ 87K

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



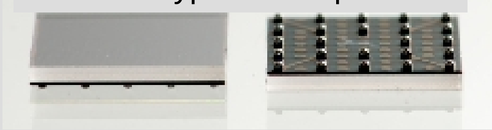
Single channel protoype
Excellent photon counting
6x6 mm² sensor ~40% PDE
Cryogenic electronics
Low power ~0.5mW/ch

SiPMs love low temperatures

New sensors - 3rd generation

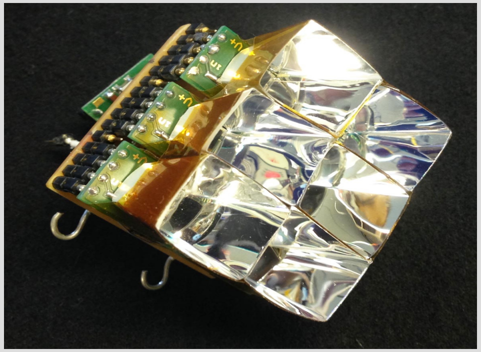
- Improved dark count rates / after pulsing
- PDE > 50%
- Tiling with less 100µm gaps
- Very radio pure
- Spice / G4 simulations ongoing

7x7 mm² type - bump bonds

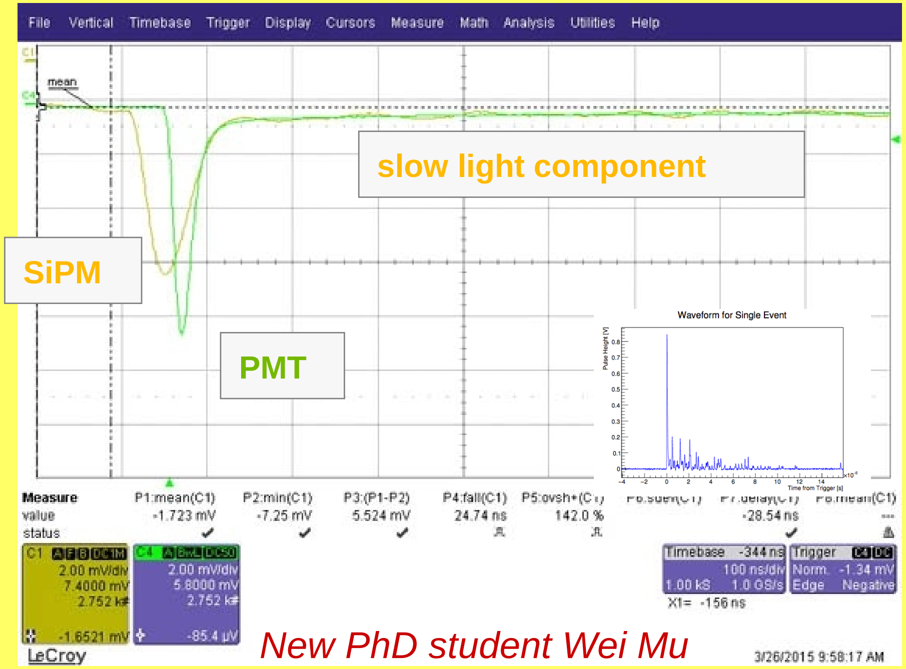


Towards large surfaces - first array tests

- Large capacitance - multiplexing
- Testing light concentration possibilities

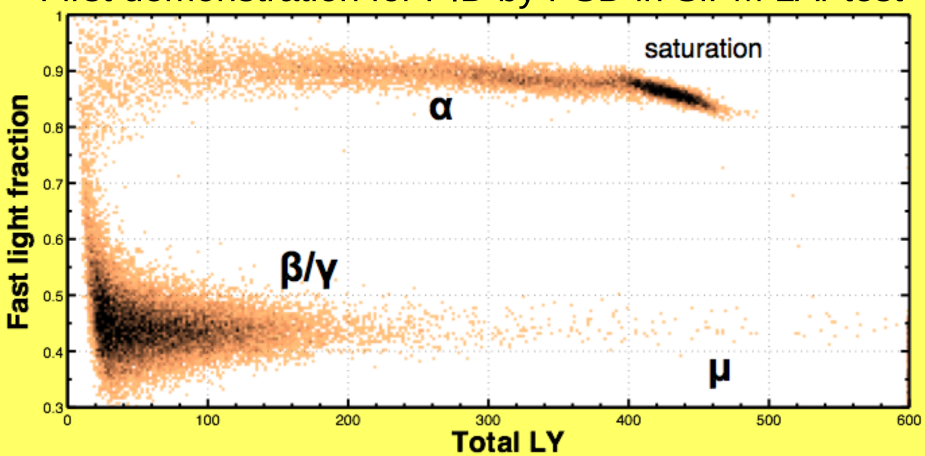


Ar PS reconstruction (SiPM vs PMT mean trace)

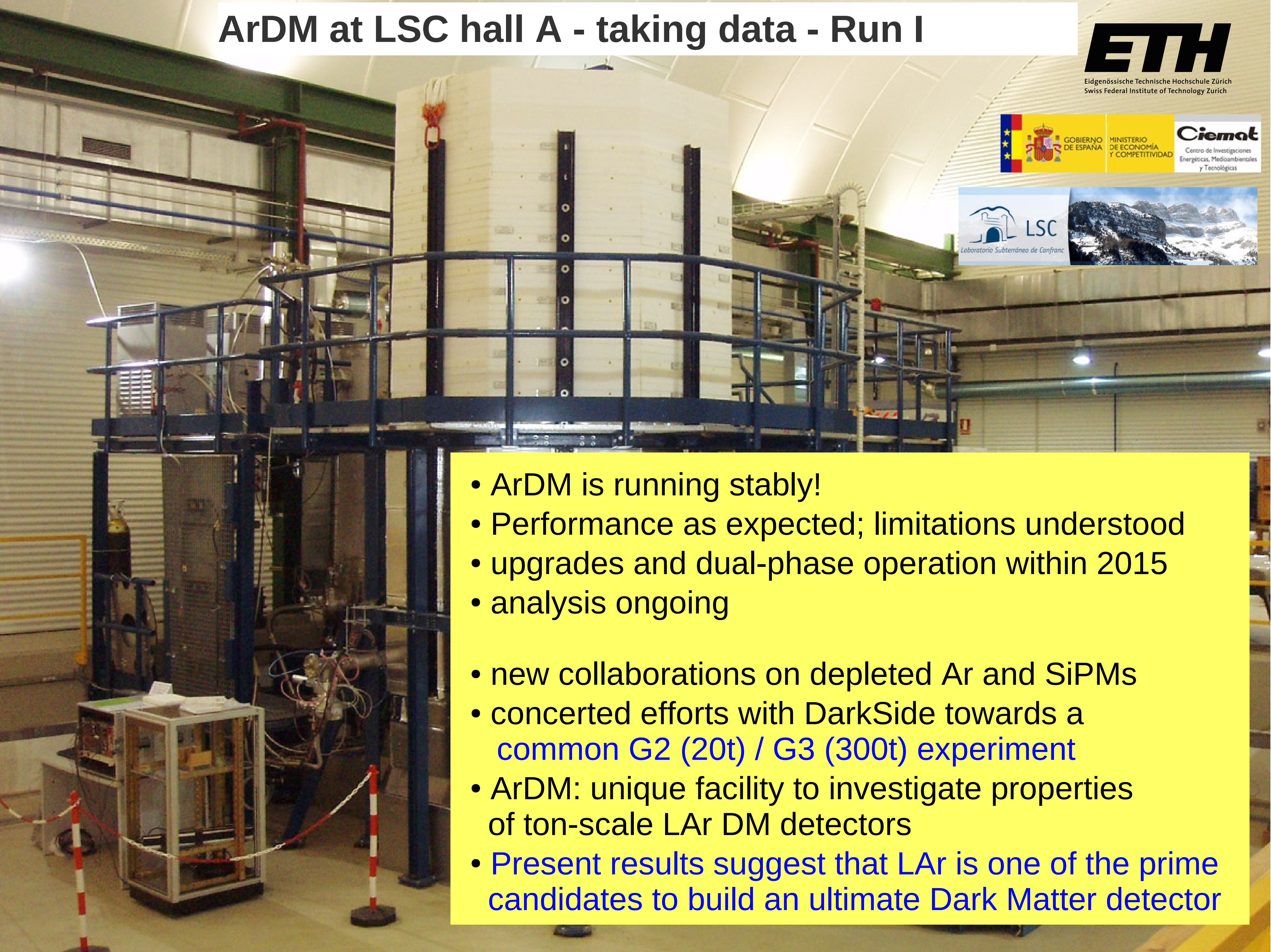


New PhD student Wei Mu

First demonstration for PID by PSD in SiPM LAr test



ArDM at LSC hall A - taking data - Run I

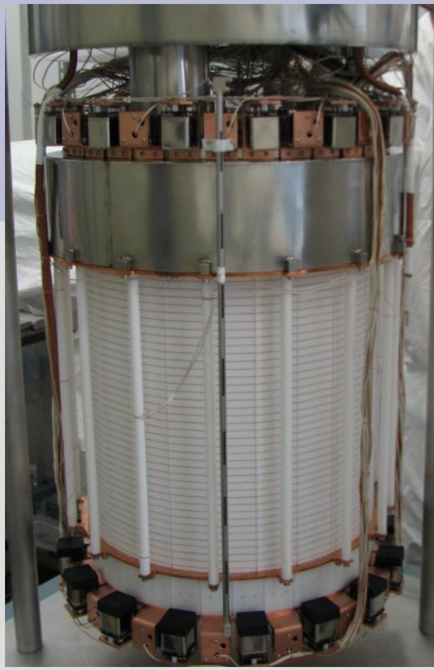


- ArDM is running stably!
- Performance as expected; limitations understood
- upgrades and dual-phase operation within 2015
- analysis ongoing

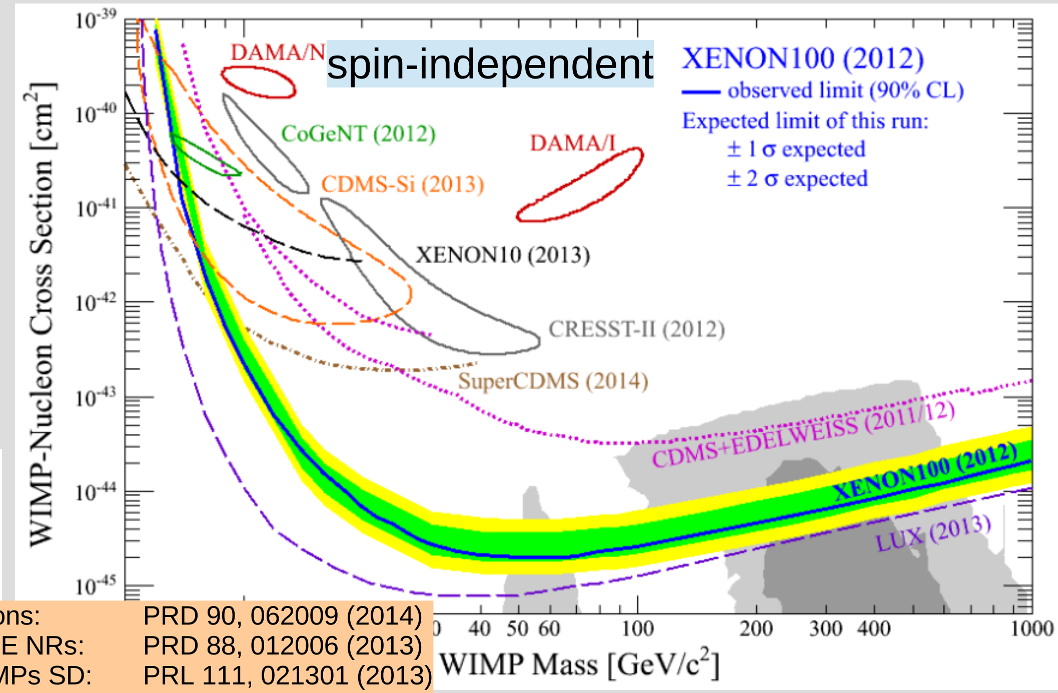
- new collaborations on depleted Ar and SiPMs
- concerted efforts with DarkSide towards a common G2 (20t) / G3 (300t) experiment
- ArDM: unique facility to investigate properties of ton-scale LAr DM detectors
- Present results suggest that LAr is one of the prime candidates to build an ultimate Dark Matter detector

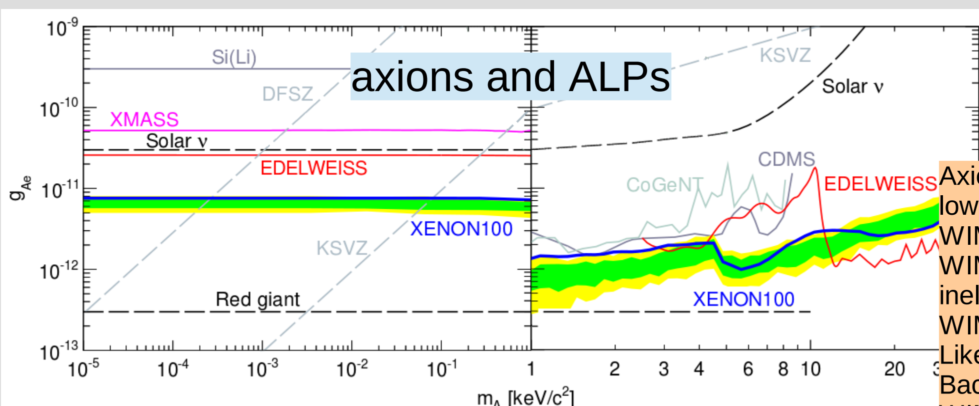
XENON100

Astropart. Phys. 35, 573 (2012)

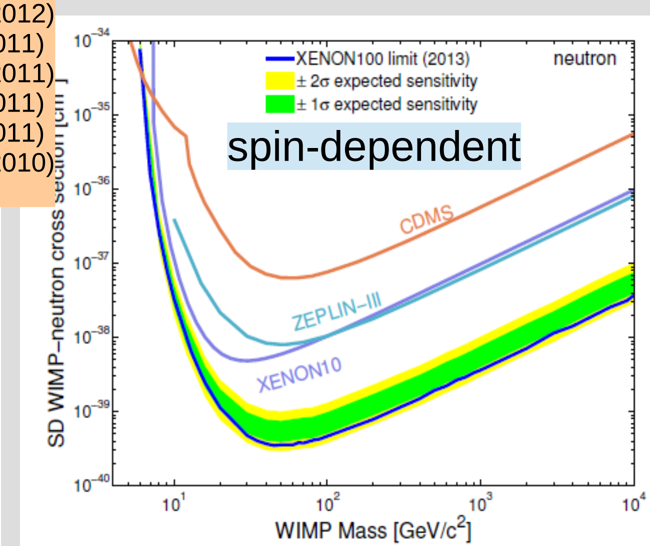


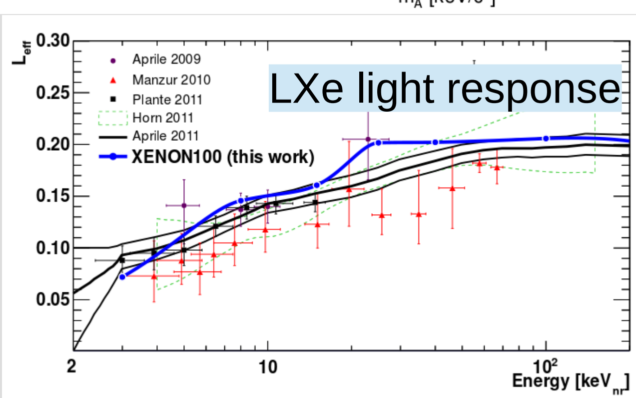
- many results on a plethora of channels
- design goal reached
- running @ LNGS from 2008 to now

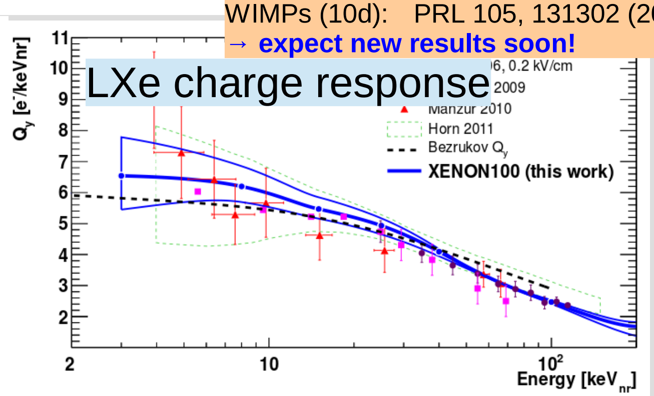




Axions: PRD 90, 062009 (2014)
low E NRs: PRD 88, 012006 (2013)
WIMPs SD: PRL 111, 021301 (2013)
WIMPs (225d): PRL 109, 181301 (2012)
inelastic DM: PRD 84, 061101 (2011)
WIMPs (100d): PRL 107, 131302 (2011)
Likelihood: PRD 84, 052003 (2011)
Background: PRD 83, 082001 (2011)
WIMPs (10d): PRL 105, 131302 (2010)
→ **expect new results soon!**

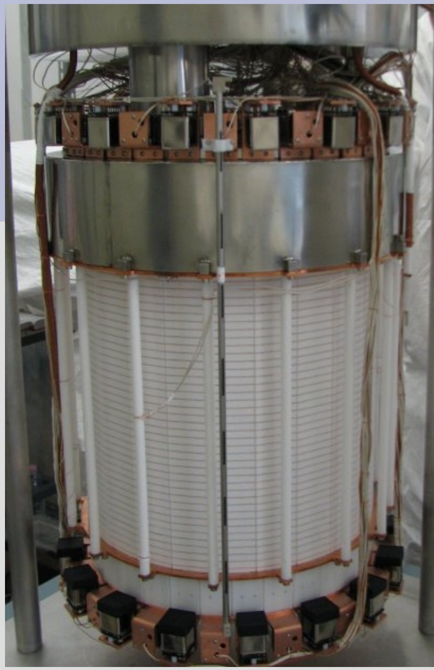






XENON100

Astropart. Phys. 35, 573 (2012)



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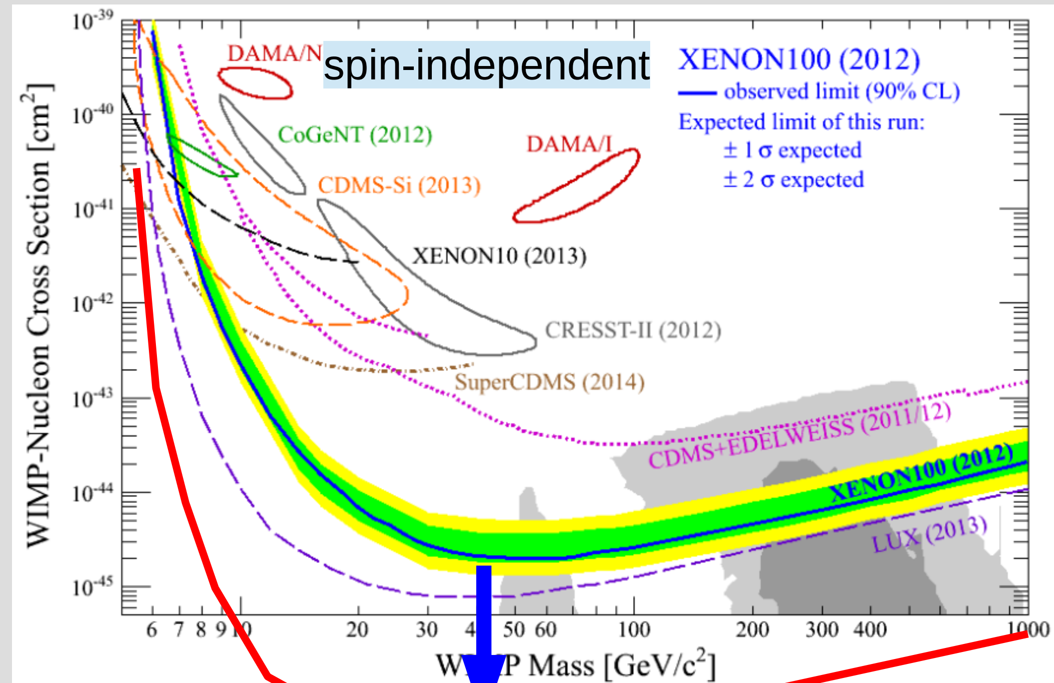
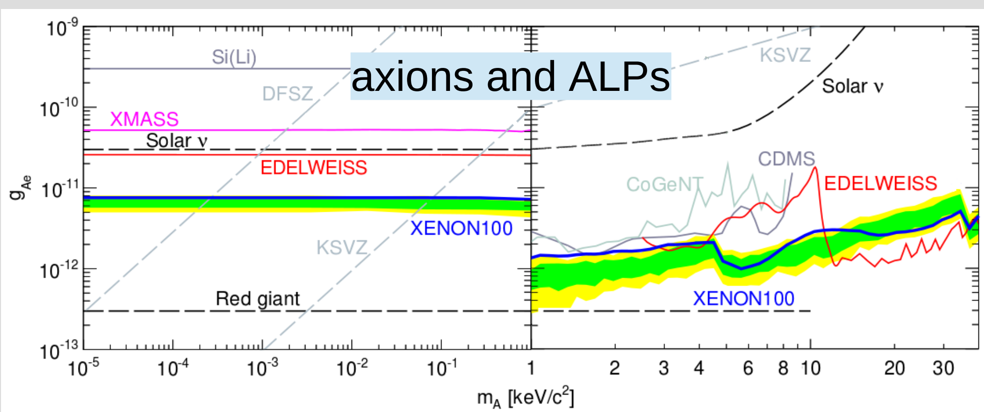
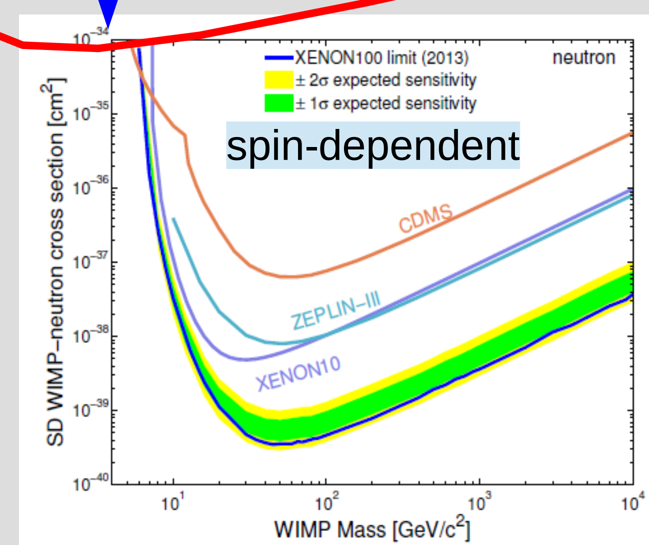
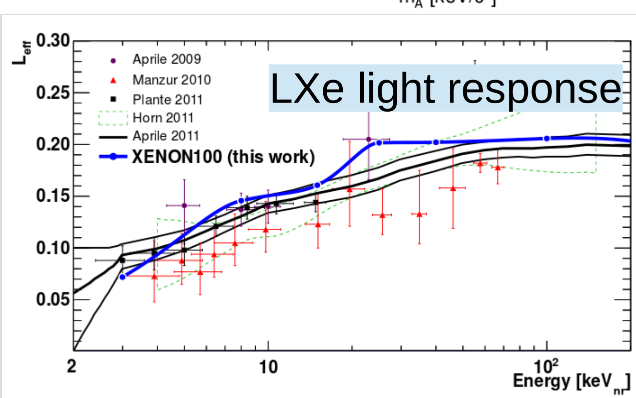
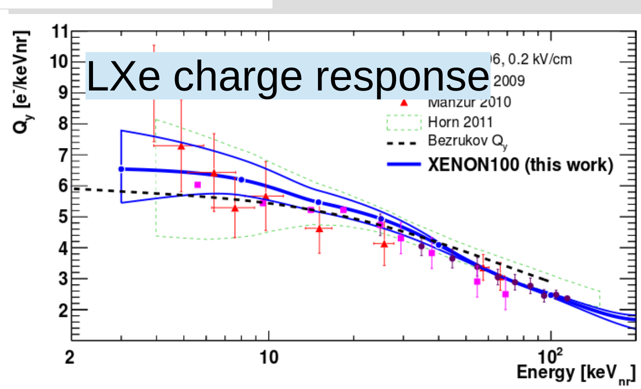




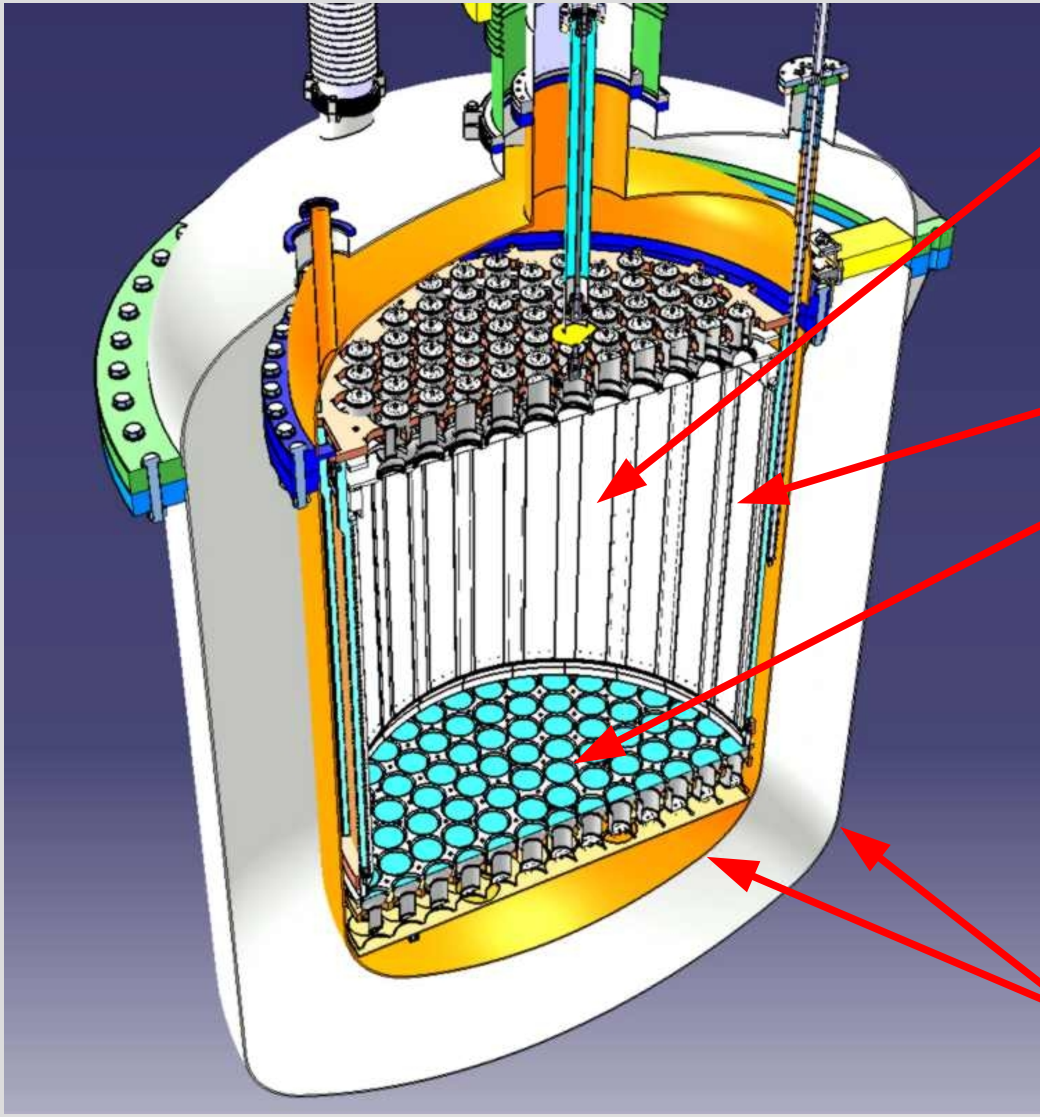






XENON1T @ LNGS

XENON1T



dual-phase LXe TPC
- total mass ~3.2 t
- active mass ~2.0 t
- fiducial mass: ~1.0 t

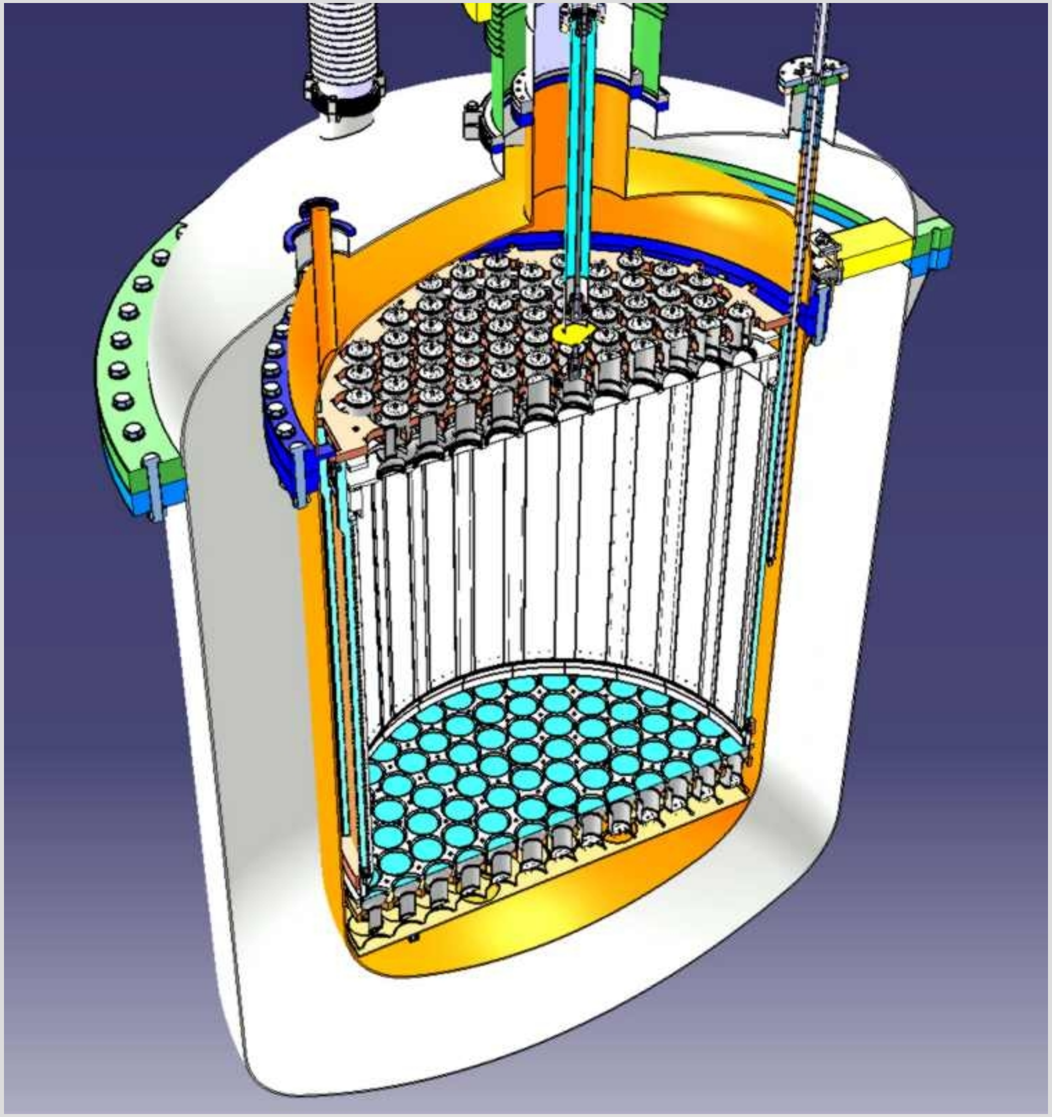
TPC made from OFHC and PTFE

248 photomultipliers
- Hamamatsu R11410-21
- low background
- high QE (36% @ 178nm)
- extensive testing in cryogenic environments *JINST 8, P04026 (2013)*

Low-background stainless steel cryostats

→ **will start taking data end of 2015**

XENON1T

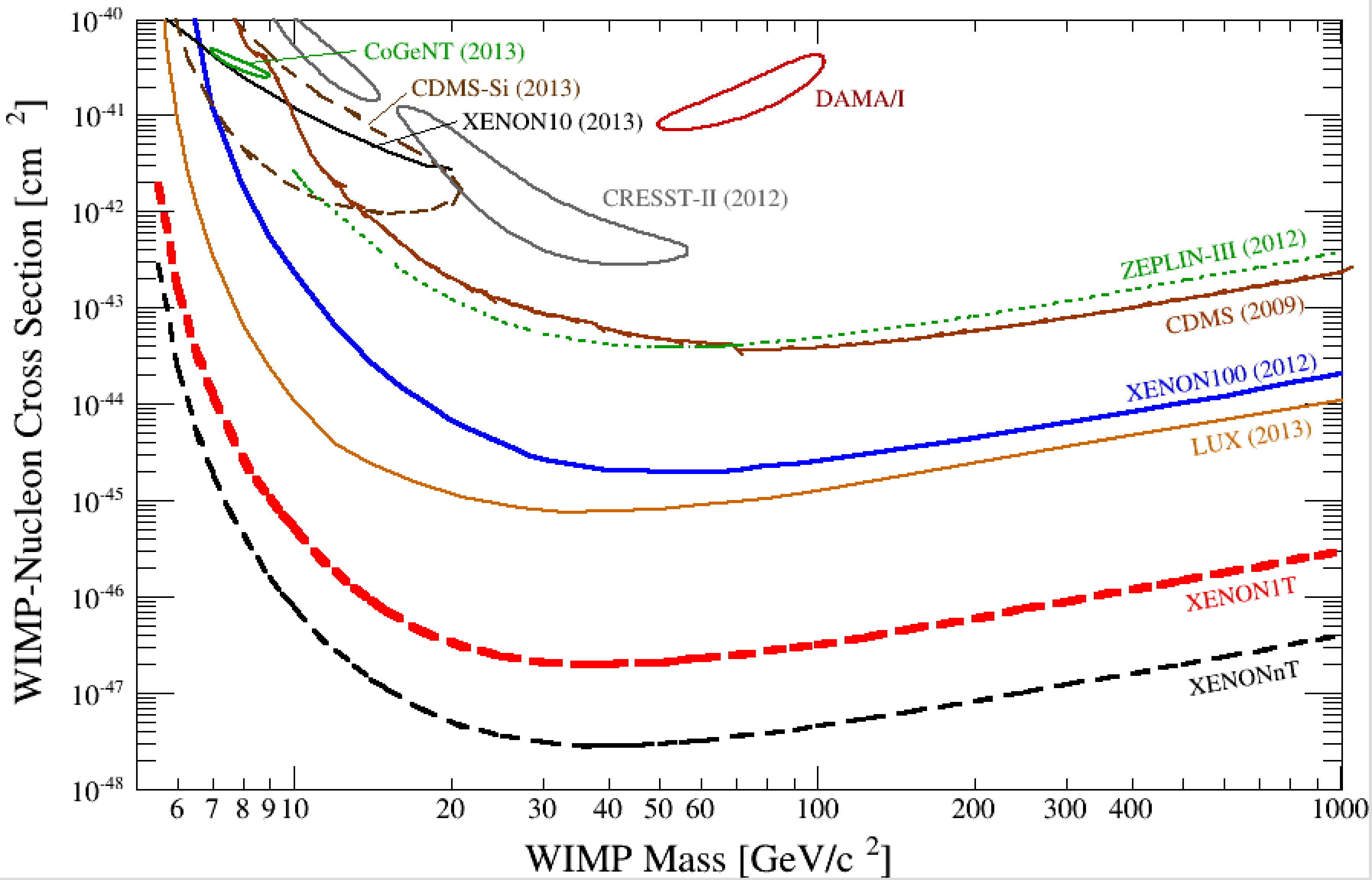


dual-phase LXe TPC
- total mass ~3.2 t
- active mass ~2.0 t
- fiducial mass: ~1.0 t

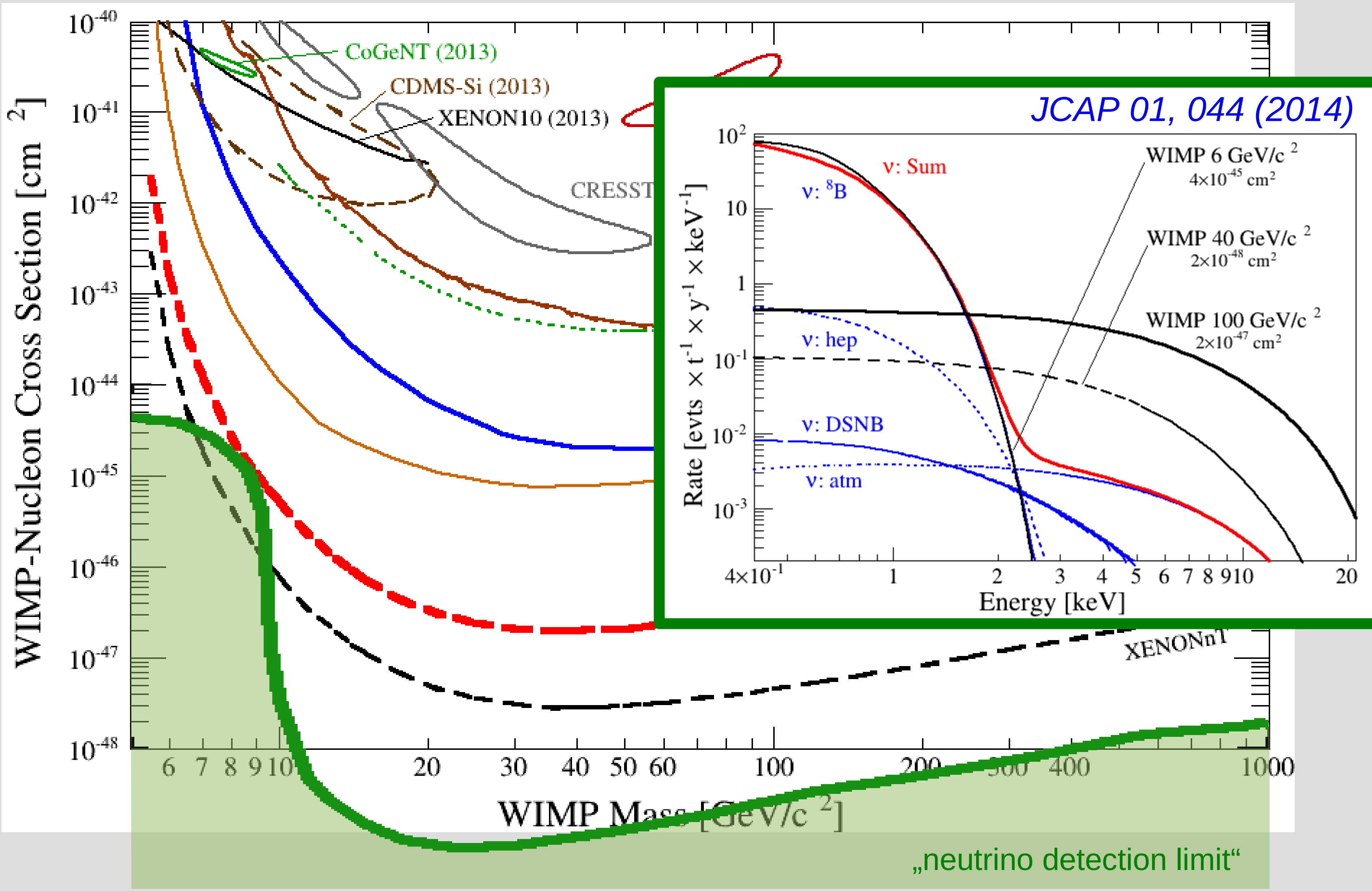
Strong Swiss Involvement
– Deputy spokesperson (Baudis)
– UZH and Bern lead 4 working groups

Main contributions
– TPC design, construction, installation
– PMT procurement and testing
– Material Screening
– Data Acquisition
– Calibration
– Monte Carlo
– Analysis XENON100 → XENON1T

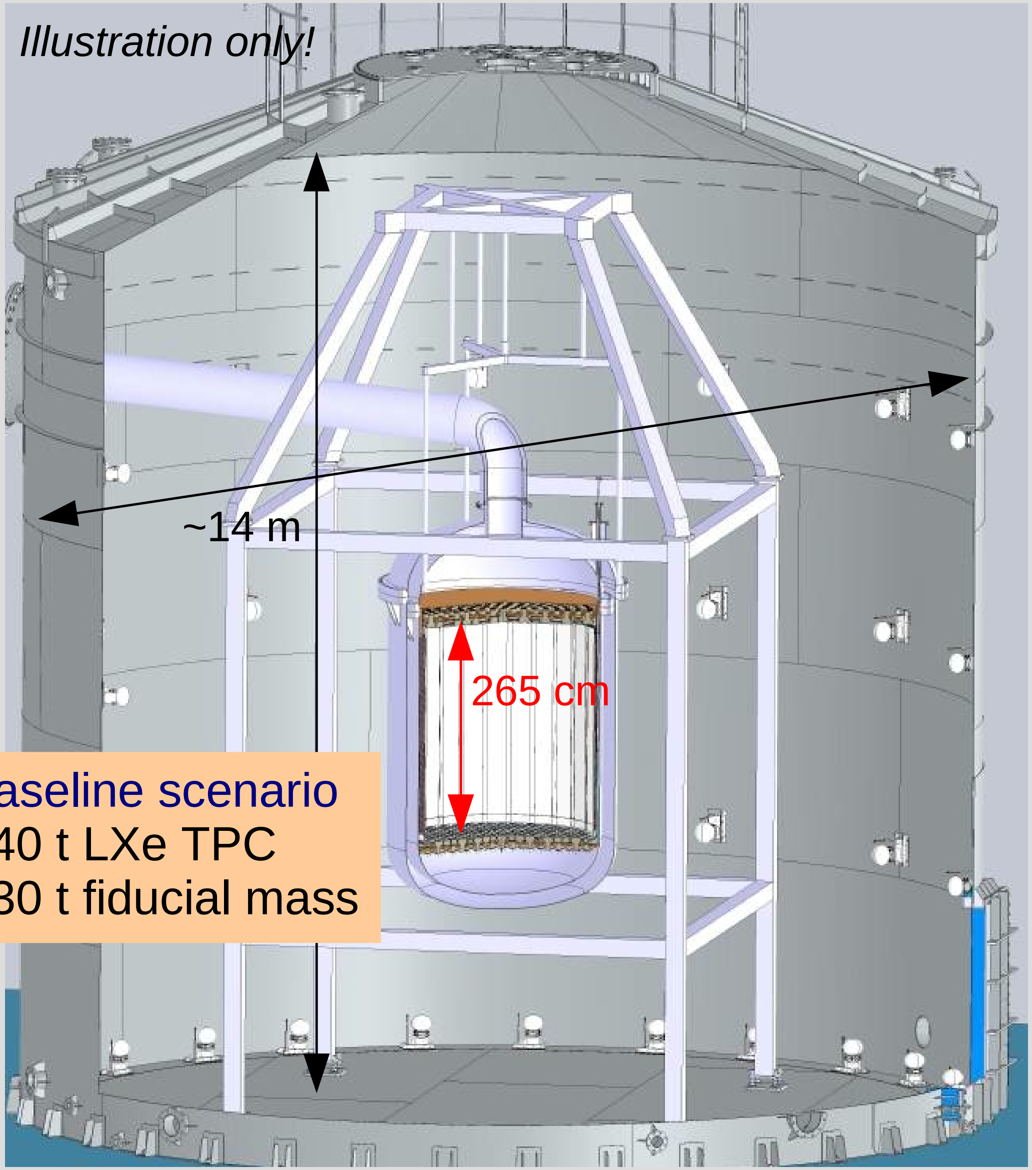
The XENON Future



The XENON Future



DARWIN The ultimate WIMP Detector



Baseline scenario
~40 t LXe TPC
~30 t fiducial mass

- aim at sensitivity of a few 10^{-49} cm², limited by **irreducible ν-backgrounds**

- R&D ongoing
  - challenges include
    - background rejection
    - HV stability (–150..200 kV)
    - target purity, electron drift
    - intrinsic radiactivity (^{85}Kr, ^{222}Rn)
    - calibration, stability

- 2014: LoI to SERI: „*The future of dark matter detection with liquid xenon: XENONnT and DARWIN*“ → rated „A“ in evaluation

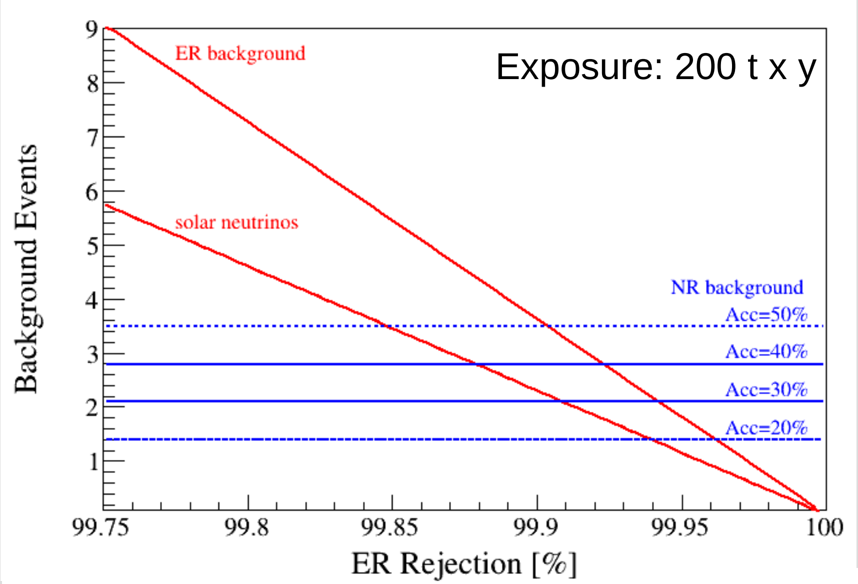
Timescale: start after XENONnT

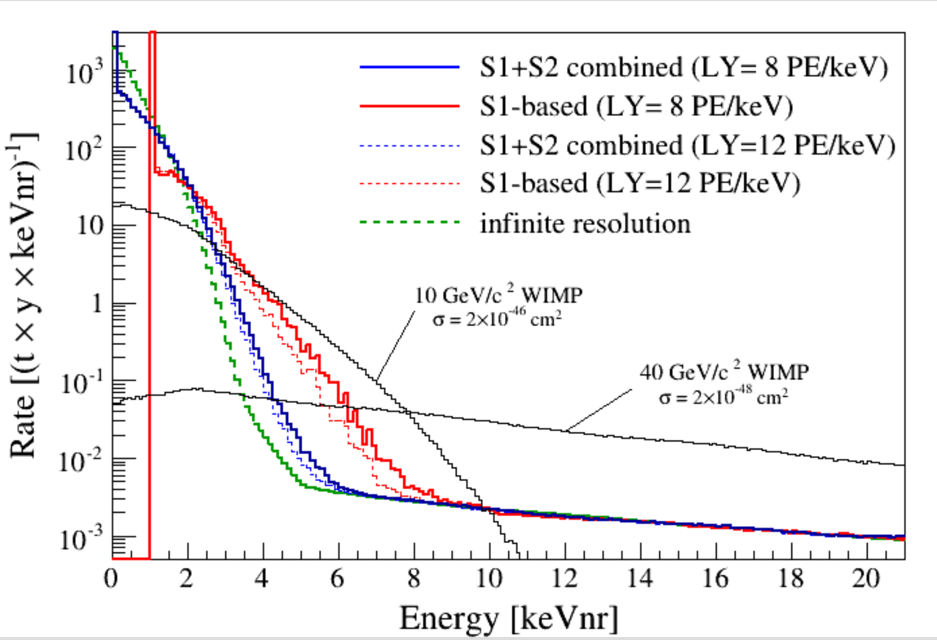
`www.darwin-observatory.org`

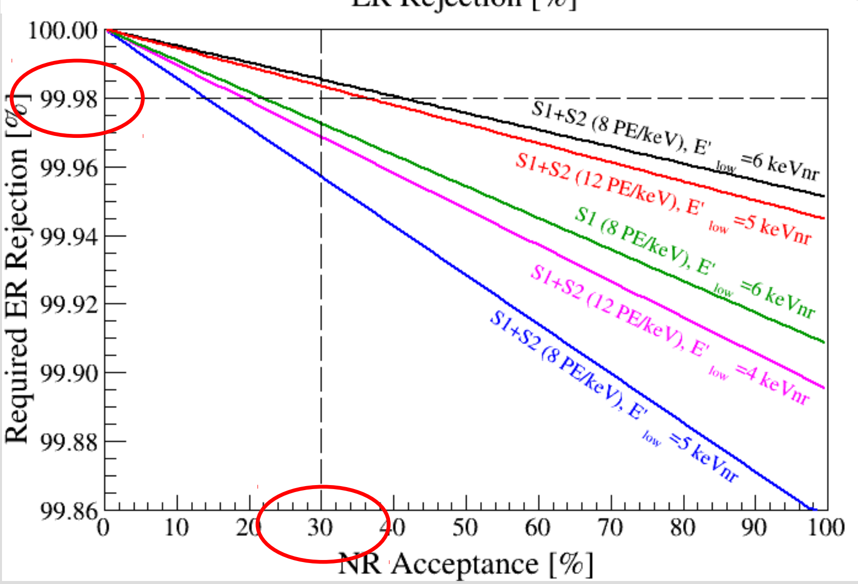
DARWIN Sensitivity

arXiv:1506.08309

- consider all backgrounds:
  - neutrinos (pp, 7Be)
  - external (γ, neutrons)
  - intrinsic (0.1 μBq/kg 222Rn, 0.1 ppt Kr)
  - CNNS (mainly 8B at low E)
- study different E-scales (S1, S1+S2, LY)
- study threshold, exposure, ER rejection



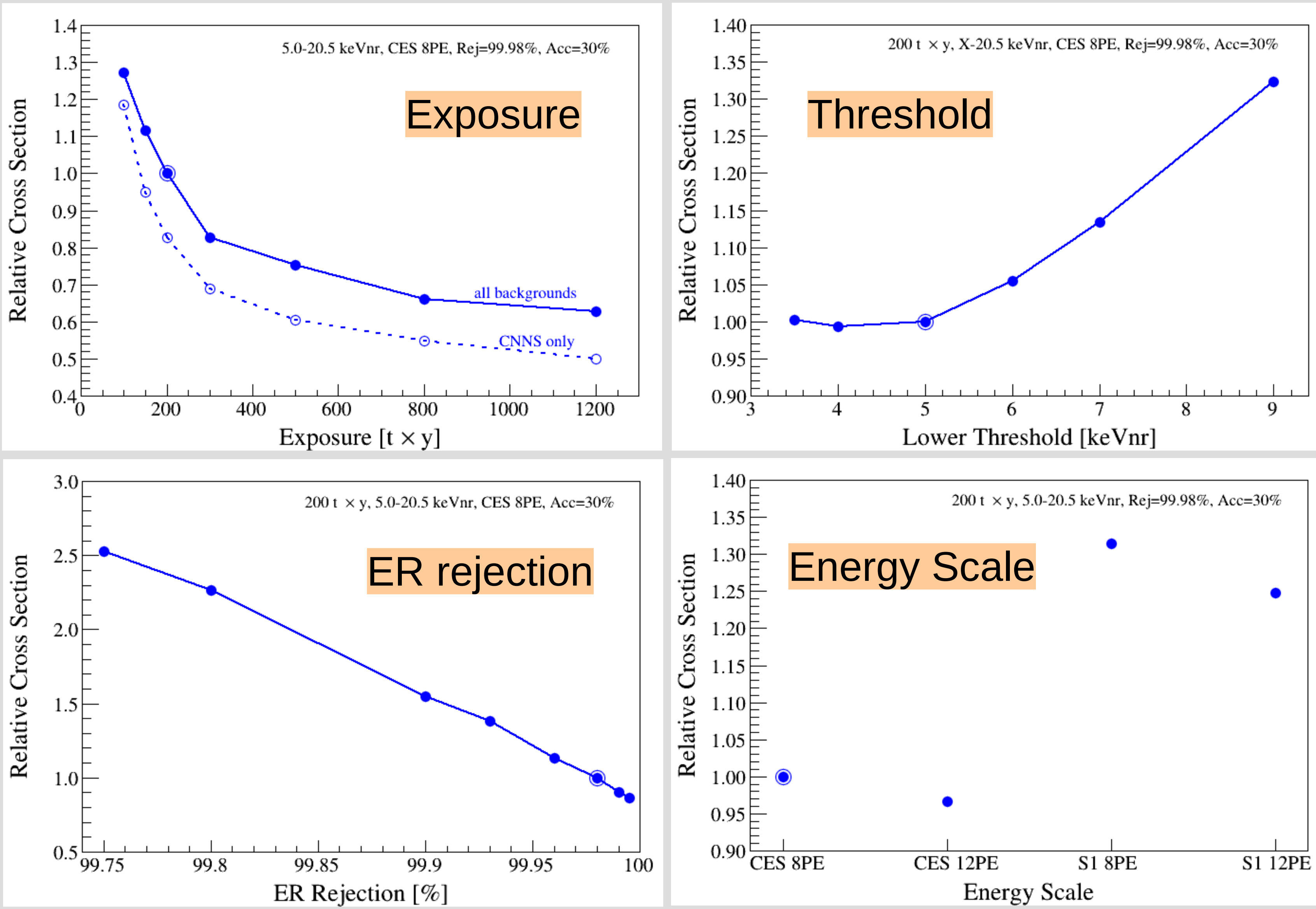




DARWIN Sensitivity

Reference WIMP mass = 40 GeV/c²

arXiv:1506.08309



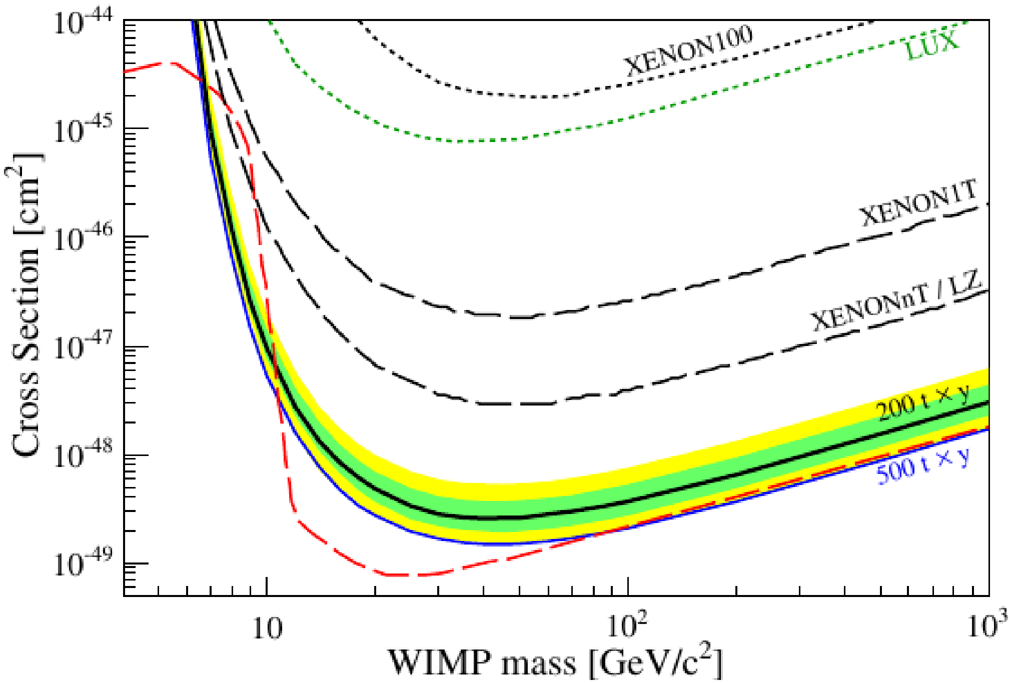
DARWIN Sensitivity

DARWIN

arXiv:1506.08309

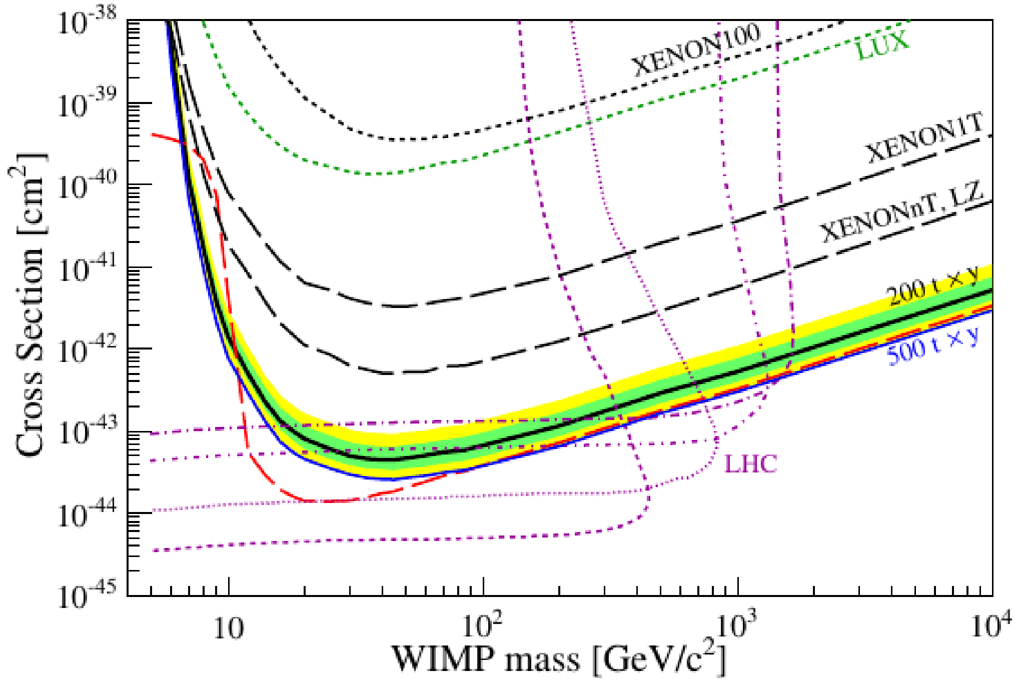
- exposure: 200 t x y; **all backgrounds included**
- likelihood analysis (~99.98% ER rejection @ 30% NR acceptance)
- S1+S2 combined energy scale, LY=8 PE/keV, 5-35 keVnr energy window

spin-independent couplings



best sensitivity: 2.5 x 10^{-49} cm^2 @ 40 GeV/c^2

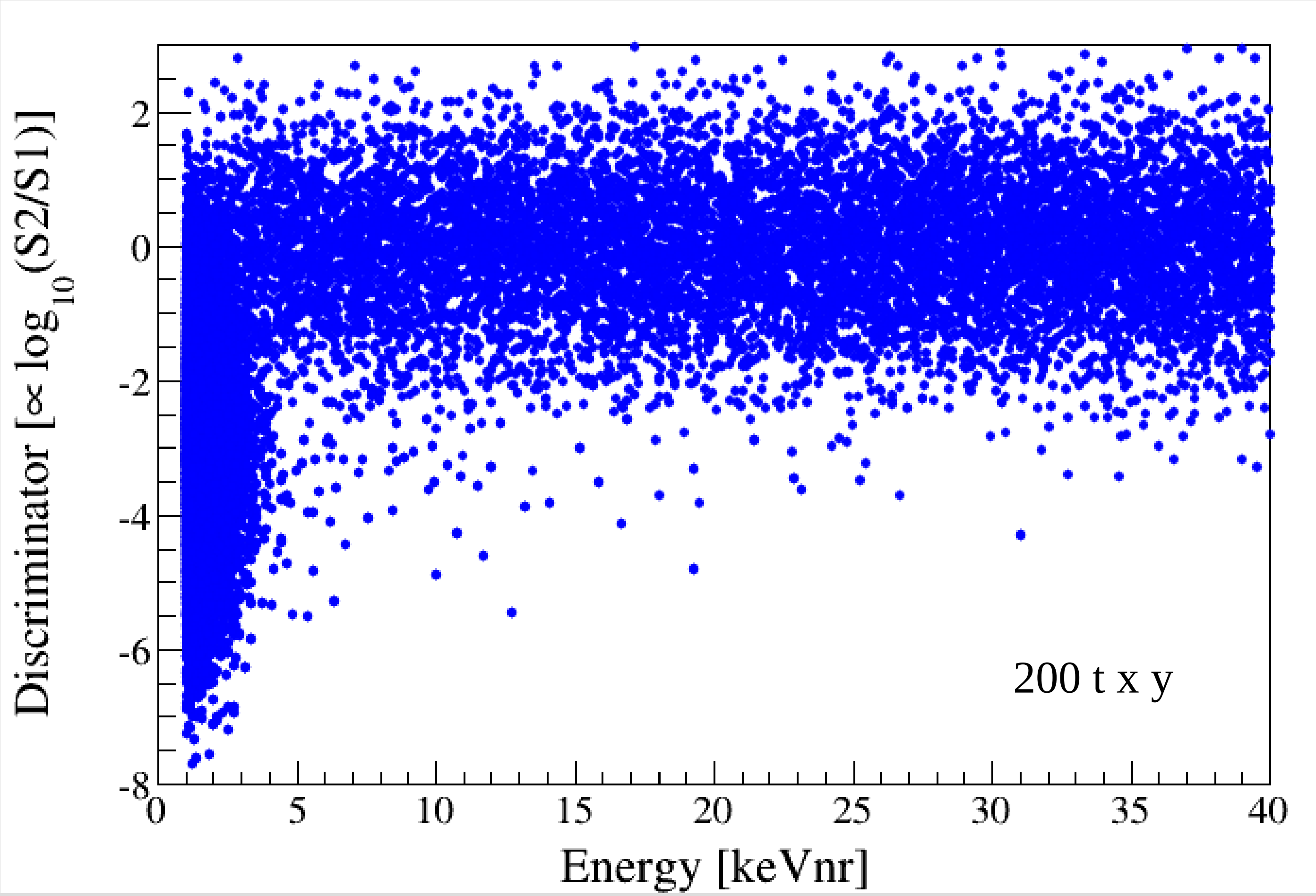
spin-dependent couplings (n-only)



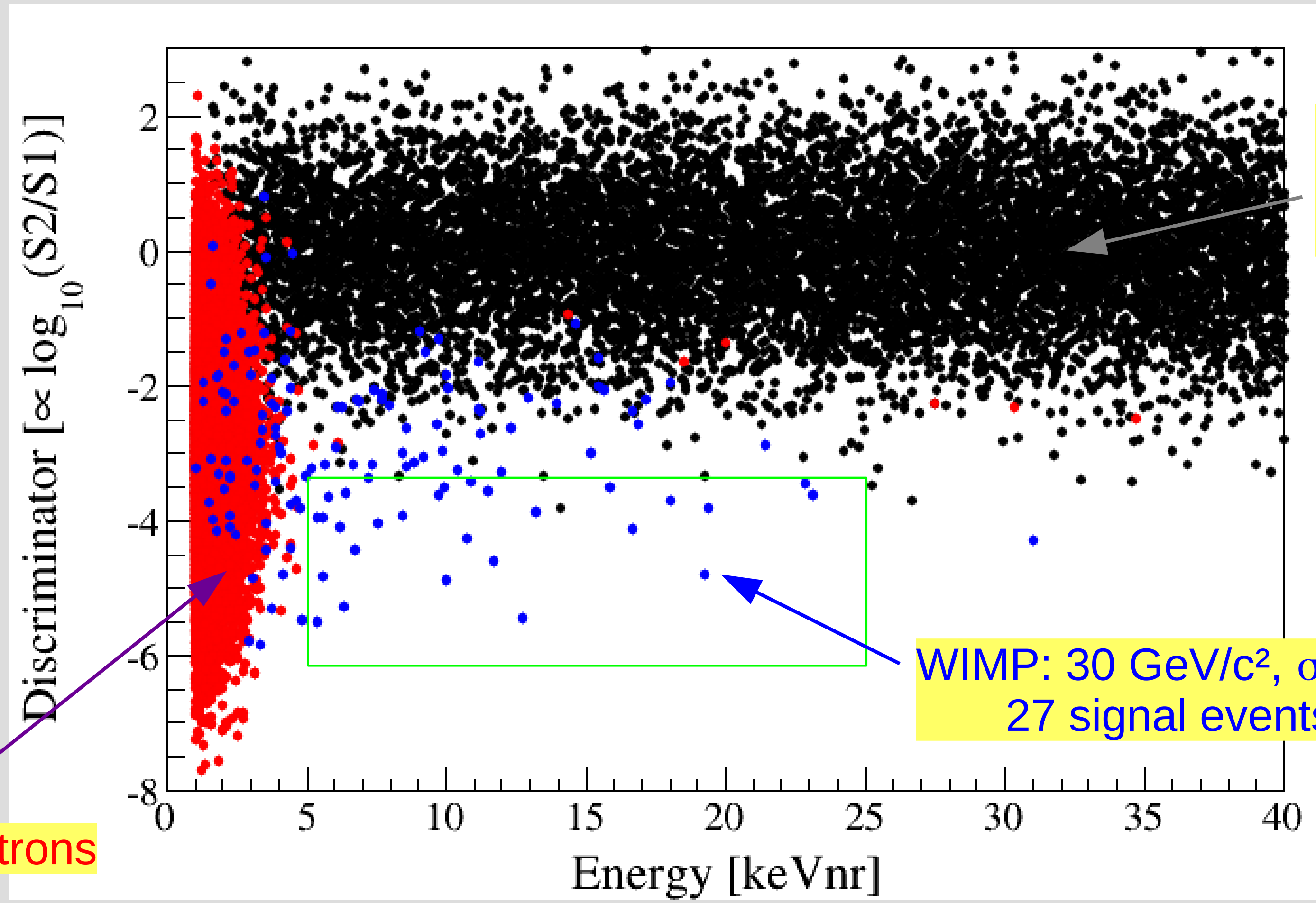
excellent complementarity to LHC searches

→ also sensitive to inelastic WIMP interactions

WIMP Detection



WIMP Detection



solar neutrinos, ^{85}Kr, ^{222}Rn, $2\nu\beta\beta$, materials

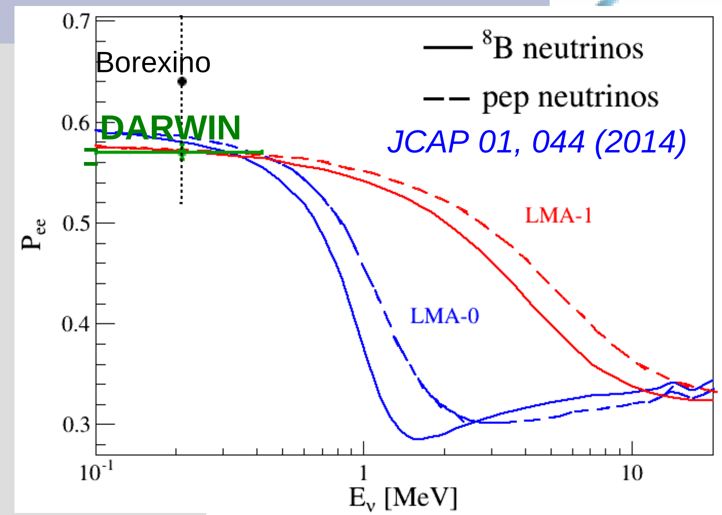
WIMP: 30 GeV/c², $\sigma=2\times10^{-48}$ cm²
27 signal events

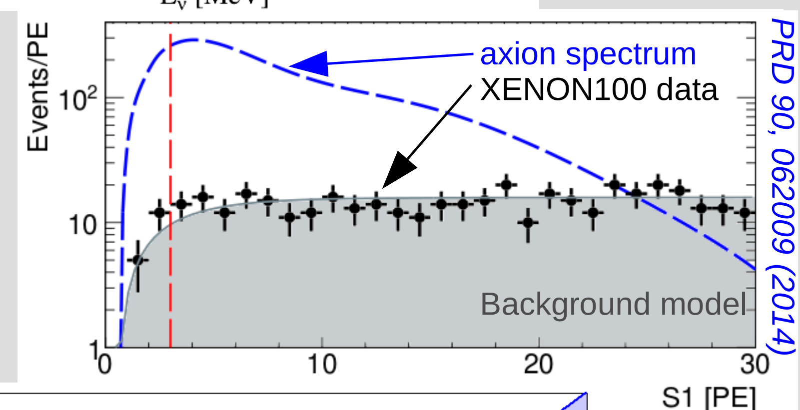
CNNS+neutrons

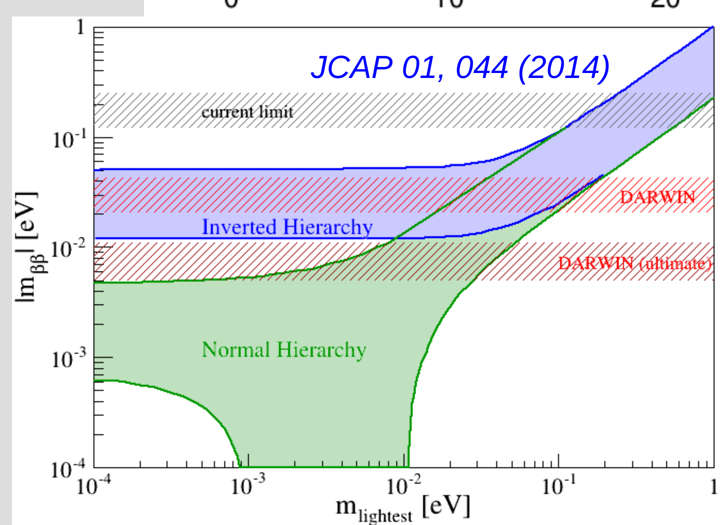
LXe: Non-WIMP Channels

DARWIN

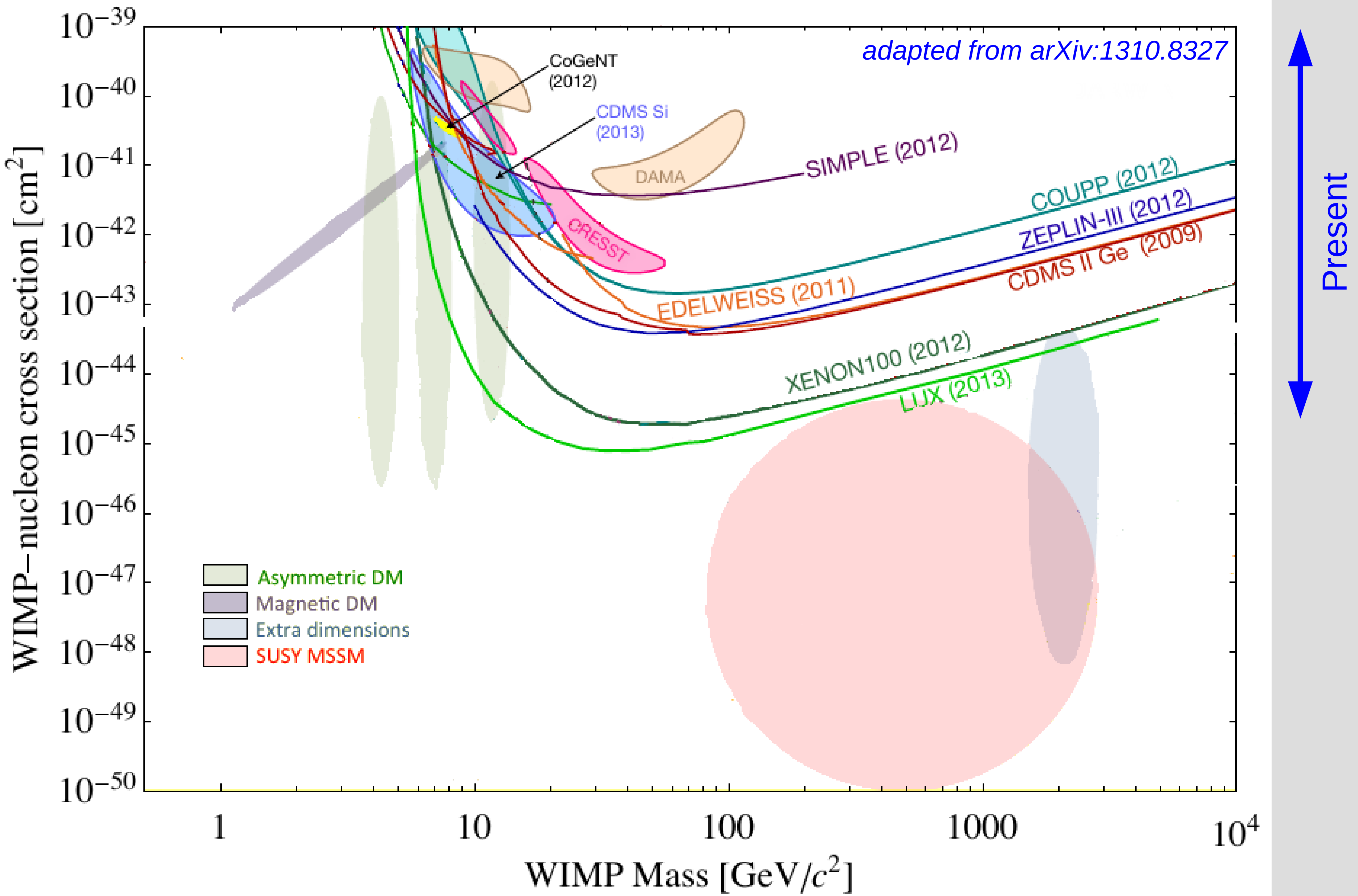
- **Low E solar neutrinos: pp, ^{7}Be**
  → test solar model; test neutrino models
  → 1% stat. precision in 100 t x y
- **Coherent Neutrino Nucleus Scattering**
  → not observed yet
  → 200 txy: ~200 evts > 3 keVnr
  ~25 evts > 4 keVnr
- **Solar axions and dark matter ALPs**
  → alternative dark matter candidates
  → couple to electrons via axio-electric effect
- **Supernova Neutrinos**
  → sensitive to all neutrino species (CNNS)
  (→ complementary information to large-scale neutrino detectors)
  → O(10) events for ~18 Msun SN @ 10 kpc
- **Neutrinoless Double-Beta Decay**
  → Leption number violating process
  → access to neutrino mass, neutrino hierarchy
  → no ^{136}Xe enrichment required







The WIMP Landscape today



Exciting times ahead of us