Direct Searches for Dark Matter

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A long List of Evidences…

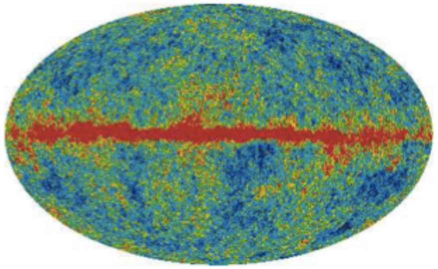
+ Galactic rotation curves
+ Galaxy clusters & GR lensing
+ Bullet Cluster
+ Velocity dispersions of galaxies
+ Cosmic microwave background
+ Sky Surveys and Baryon Acoustic Oscillations
+ Type Ia supernovae distance measurements
+ Big Bang Nucleosynthesis (BBN)
+ Lyman-alpha forest
+ Structure formation
+ …

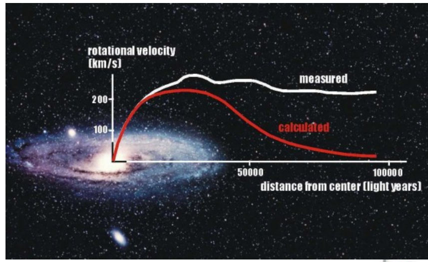
➔ **strong indirect evidence for a large dark sector**

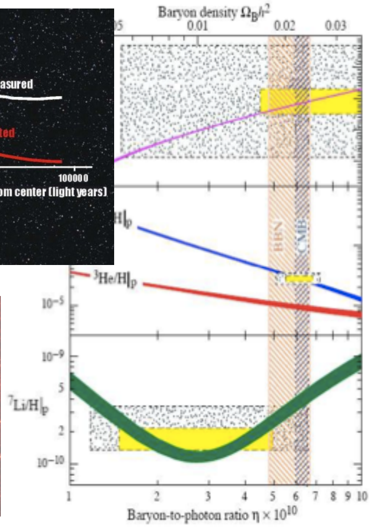
➔ **dynamic, static, radiation, …**

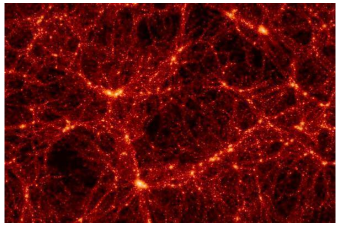
➔ **cannot be explained by ordinary matter**

CMB (WMAP)

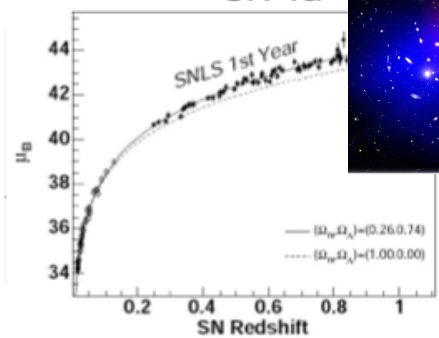




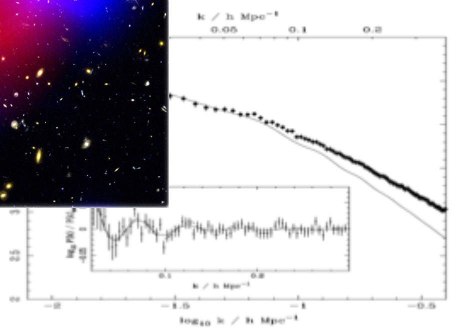


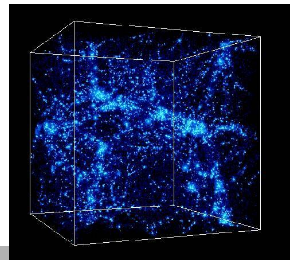


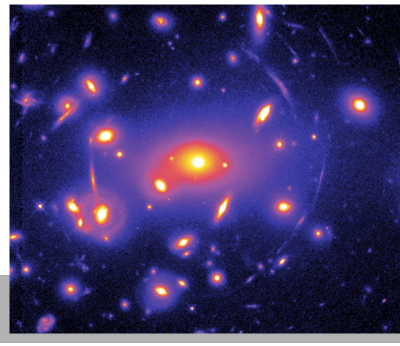
SN 1a



BAO







Dark Matter Directions

Gravity

MOND
simple one scale modification
→ fails badly

Other GR
Other GR modifications

or

a suitable population (mass, number) of black holes

Matter = new Particles

BSM motivated
(SM problems)
- ν's: 0,7% DM
- axions
- sterile ν's
- many other particles

Abundance or model motivated
- various candidates
- ...

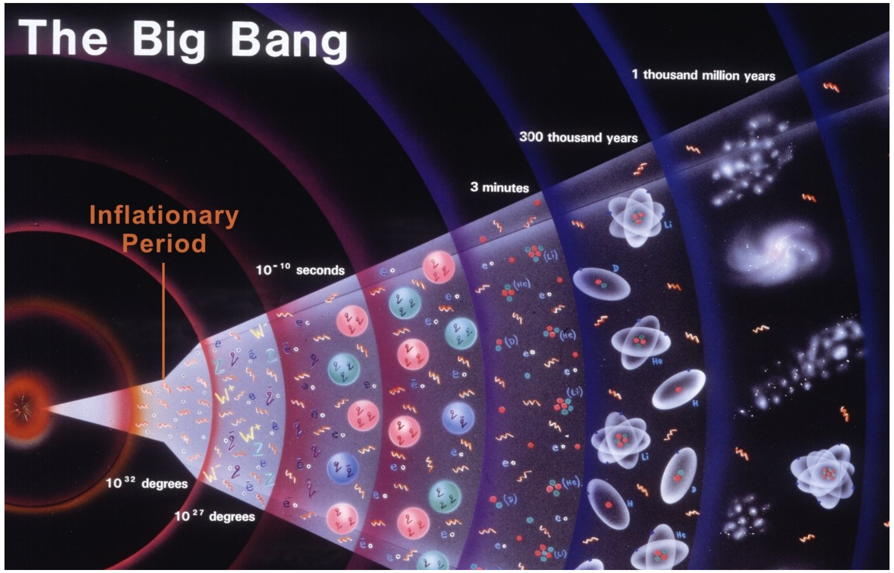
WIMPs combine both aspects in an attractive way + WIMP miracle

The WIMP Miracle

inflation ➔ many e-folds

Reheating ➔ all particle types produced

Evolution of original plasma by:
- **expansion (dilution)**
- **decays**
- **interactions → conversion processes**



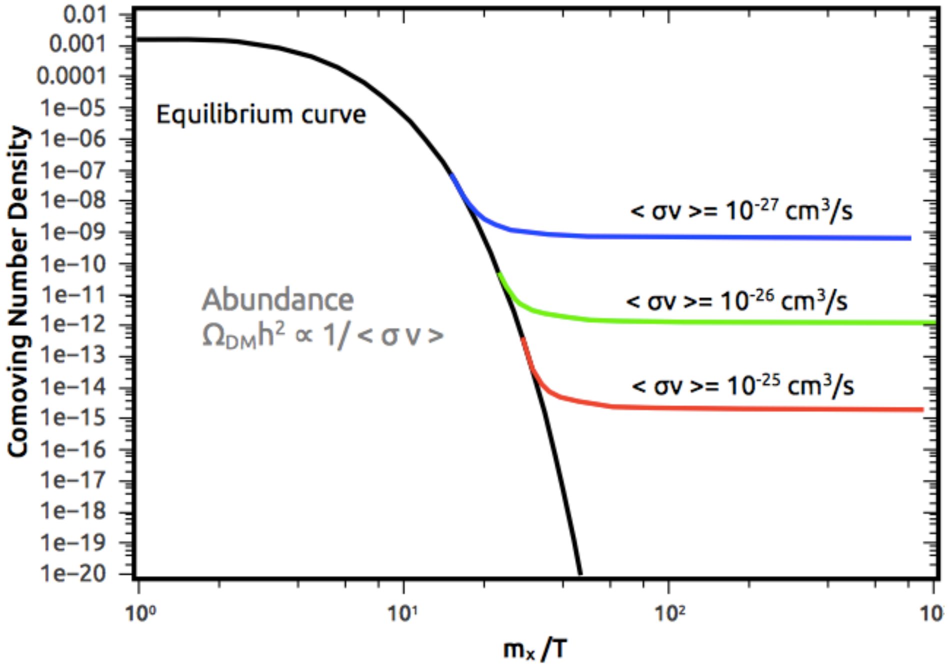
Evolution of original DM density:

➔ Boltzmann equation

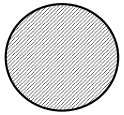
$$\frac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle \sigma v \rangle (n_\chi^2 - n_{\chi,eq}^2)$$

➔ thermal freeze-out

BSM motivated new physics @TeV:
➔ automatically ~ correct abundance
➔ typical WIMP mass O(EW scale)



Generic WIMP Cross Section

- Quantum mechanics: wavelength $\lambda \sim 1/\text{mass}$
-  "size/area" of a particle: $\pi\lambda^2 = \pi/m^2$
- scattering crossection = area times coupling strength
- $\sigma \sim O(0.001\text{-}1.0)^2 \; g_2^{\,2} \; \pi/m^2$ or tuning, symmetry, …

model parameters — weak coupling — area ⟷ abundance

➔ the natural / expected range for a 50GeV WIMP:
$\sigma \sim 10^{-42} - 10^{-48}\ \text{cm}^2$

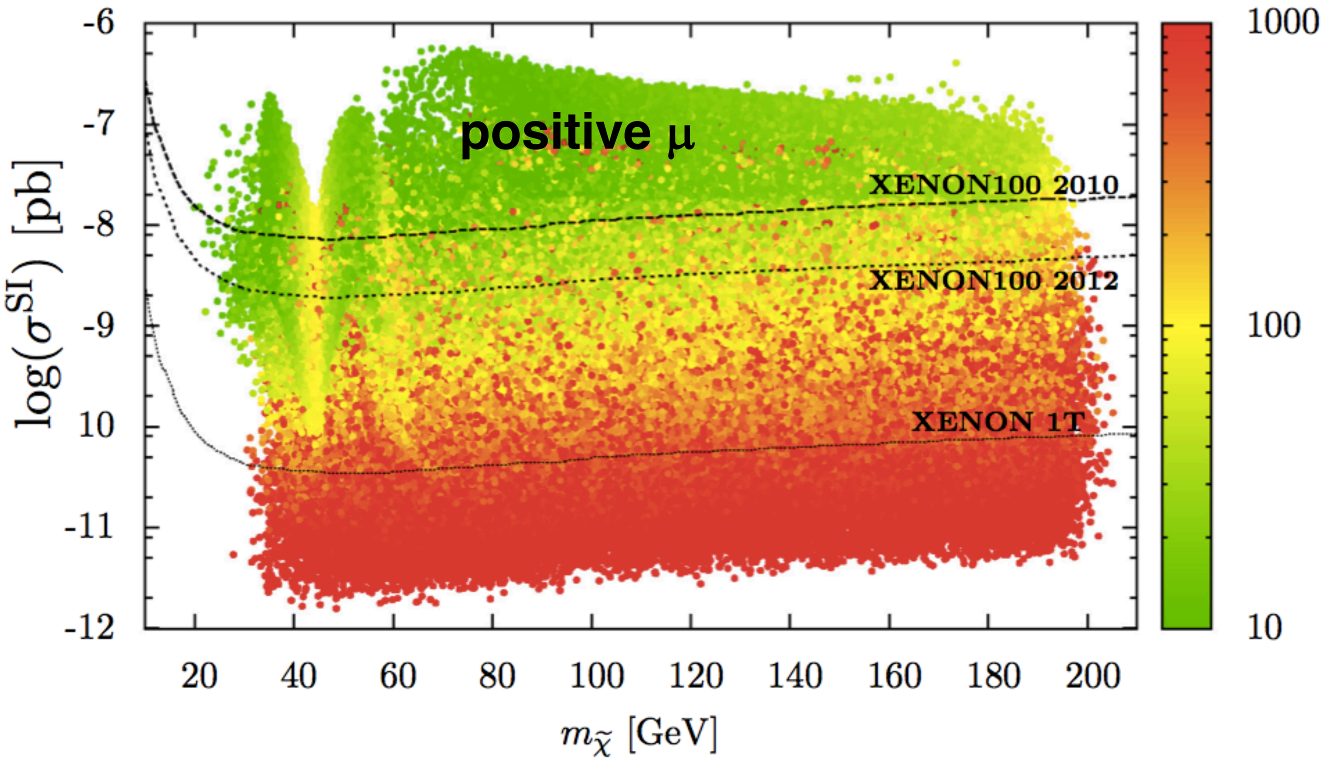
known amount of DM ➔ ~WIMP flux ➔ event rate

➔ we know size/sensitivity of a detector which can cover the most interesting natural WIMP space

A specific Example: MSSM neutralino

- **Level of fine-tuning → Δ_{tot}**

$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right| \qquad \Delta_{\rm tot} \equiv \sqrt{\sum\nolimits_{p_i=\mu^2,b,m_{H_u}^2,m_{H_d}^2} \{\Delta p_i\}^2}$$



- **current experiments cut already into expected space**
- **two options**
  - **good discovery potential**
  - **… or tension**

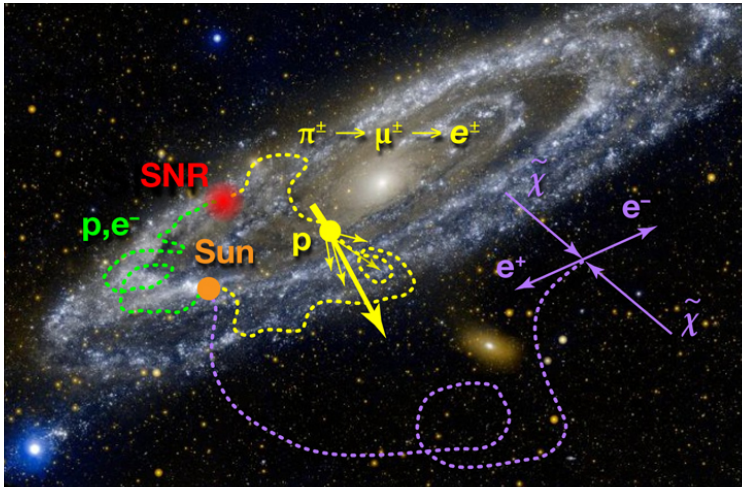
X-MSSM: x-section down ⇔ WIMP miracle?

Grothaus, ML, Takanishi: full MSSM, not cMSSM, pMSSM, NMSSM…

Hunting WIMPS in different Ways

Standard Model particles interact with WIMPs: assumptions…

indirect detection

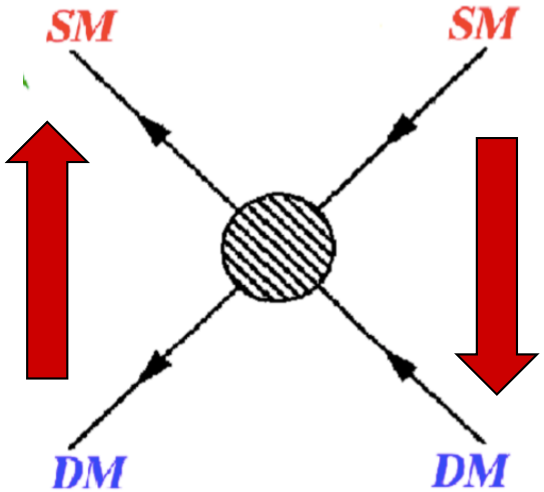


FERMI, PAMELA, AMS, HESS, IceCube, …

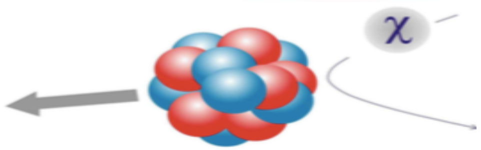
astro. uncertainties...

→ DM signal w/o doubt?

Example: keV lines and charge exchange reactions

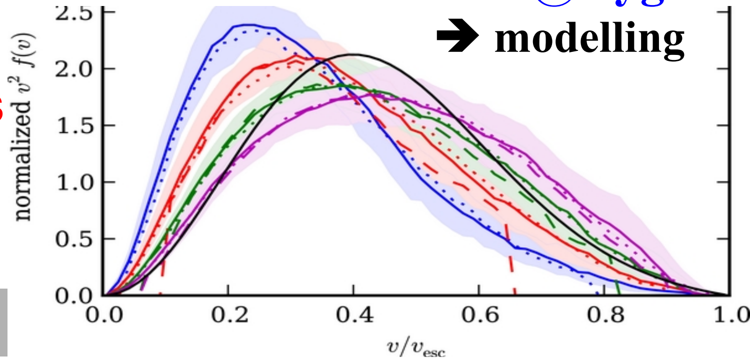


direct detection

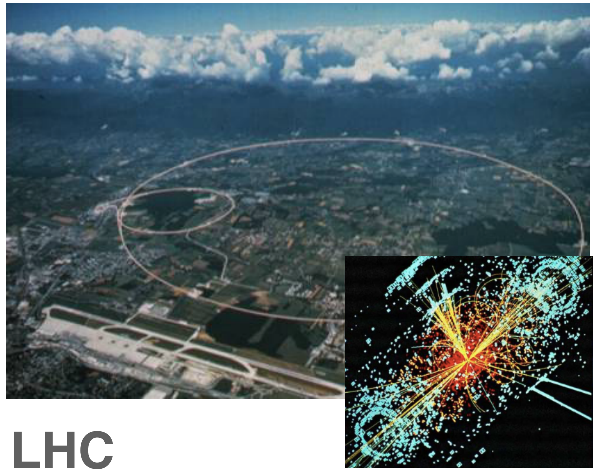


WIMP wind : 220km/s @Cygnus

➔ modelling



colliders



LHC

may detect new particles, DM? (lifetime, abundance)

So far nothing seen…
- → impact on theory…
- → SUSY → higher scale
- → new ideas/candidates

Hunting WIMPS in different Ways

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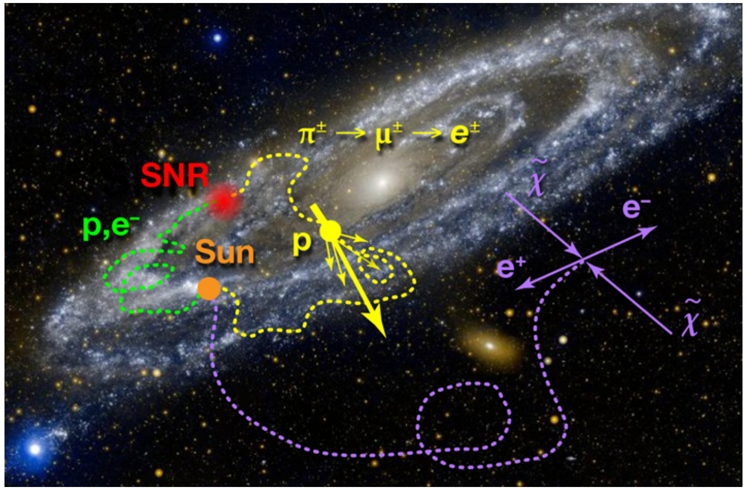

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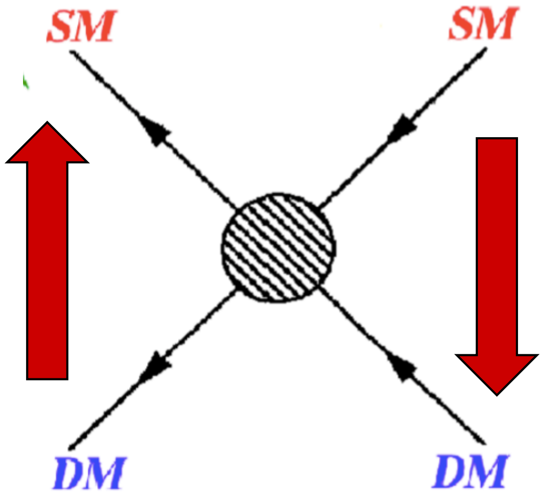
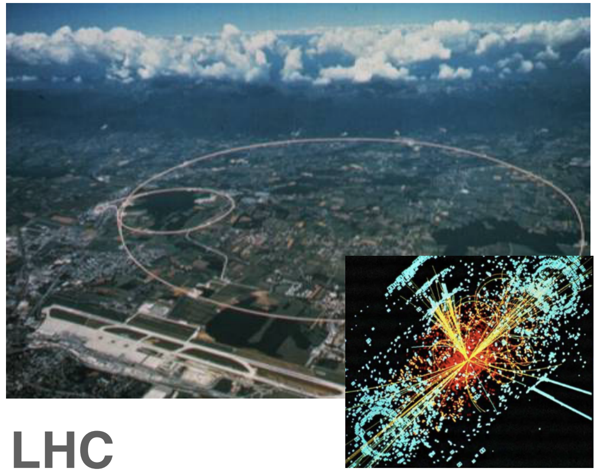


direct detection

colliders



LHC

may detect new particles, DM? (lifetime, abundance)

…ar nothing seen…
…impact on theory…
SUSY → higher scale
new ideas/candidates

- Normal ν's are ~ 0.7% of DM
- Black holes are DM

Questions:

→ one dominant component?

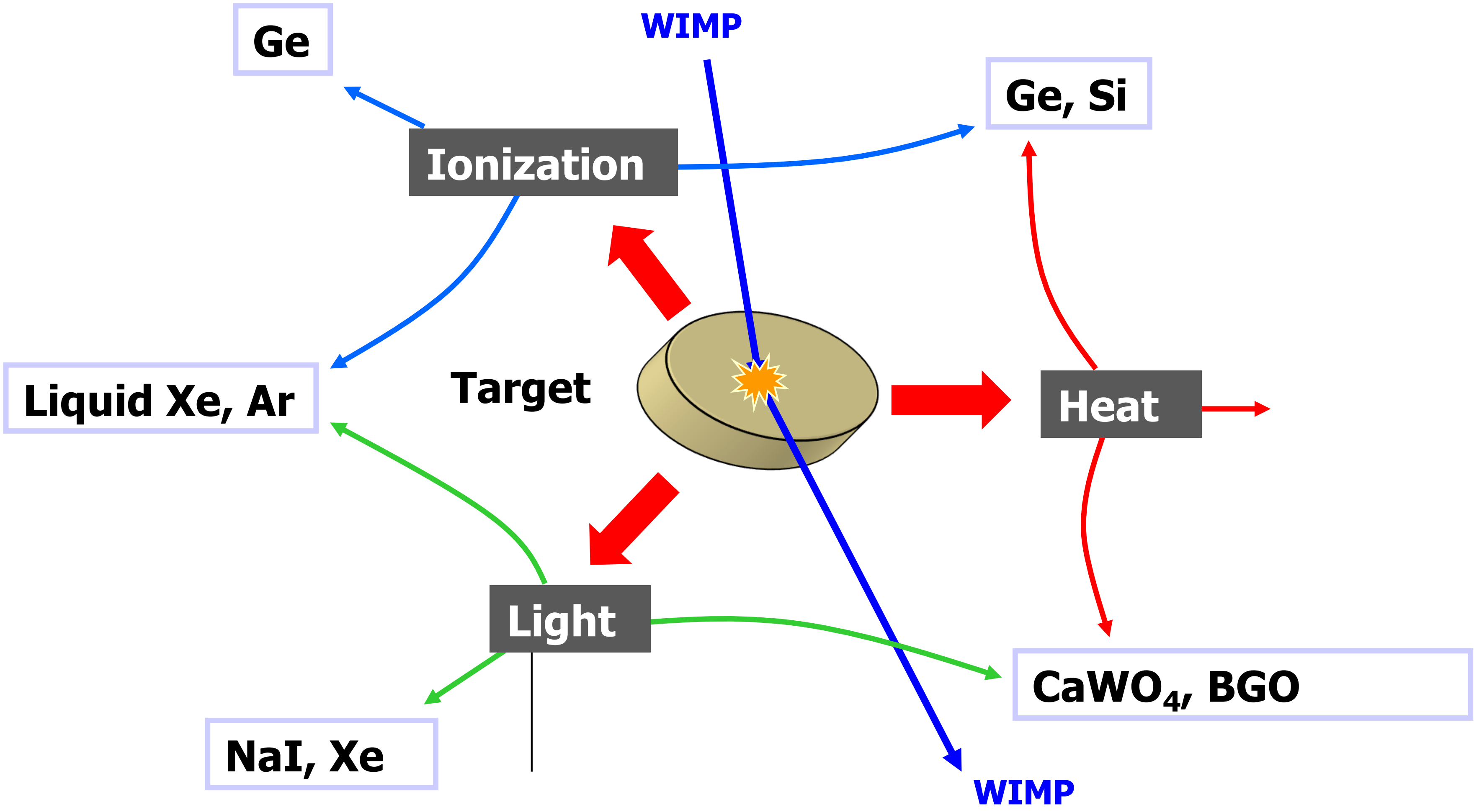
→ a cocktail?

→ is a suitable particle enough?

→ direct detection of DM to see what the universe is made of!

Direct Detection Techniques

- **Detection of DM = see what the Universe is made of**
  ➔ WIMP wind (known flux) scatters on target atoms ➔ signal…

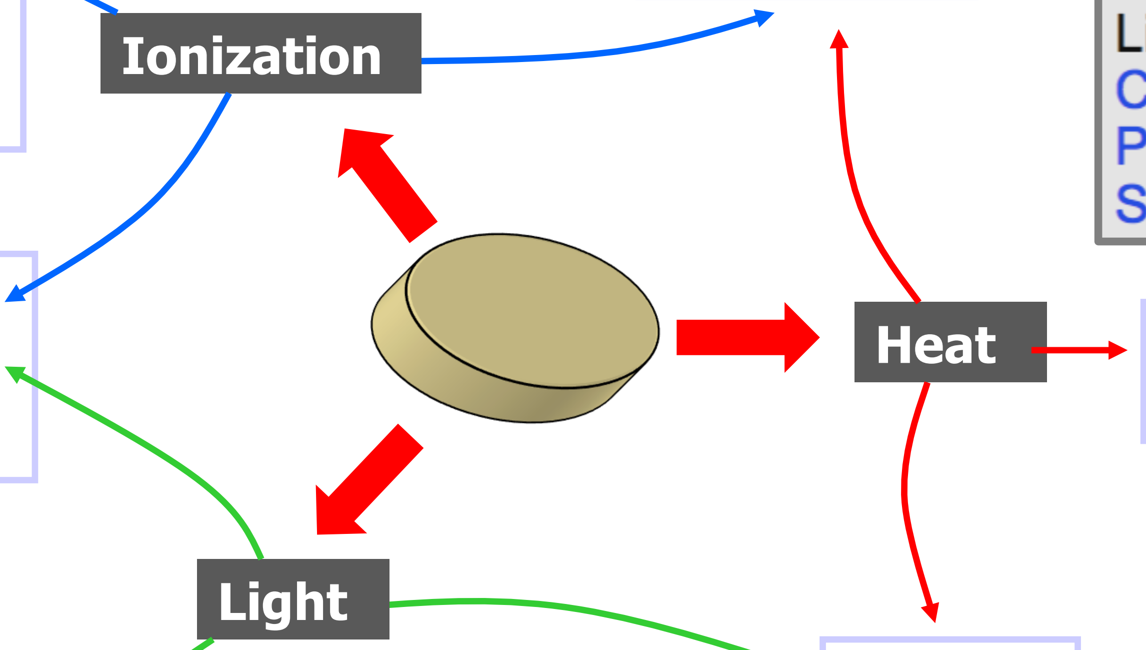


Direct Detection Experiments

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

Tracking:
DRIFT, DMTPC
MIMAC
NEWAGE

Superheated Liquids:
COUPP → PICO
PICASSO → PICO
SIMPLE



Ionization:
- CoGeNT, CDEX, Texono, Malbek, DAMIC
- SuperCDMS, EDELWEISS
- XENON, LUX/LZ, ArDM, PandaX, Darkside,DARWIN

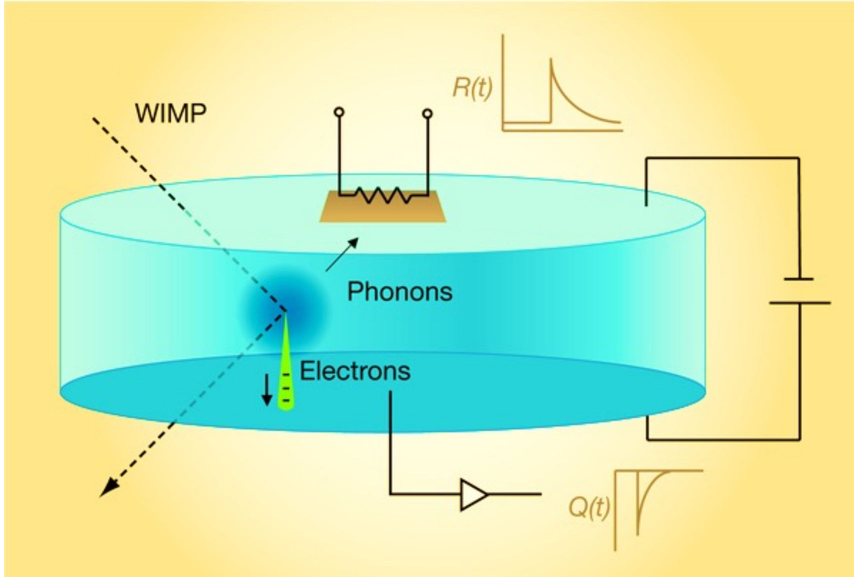
Heat:
- SuperCDMS, EDELWEISS
- CRESST-I, CUORE
- CRESST

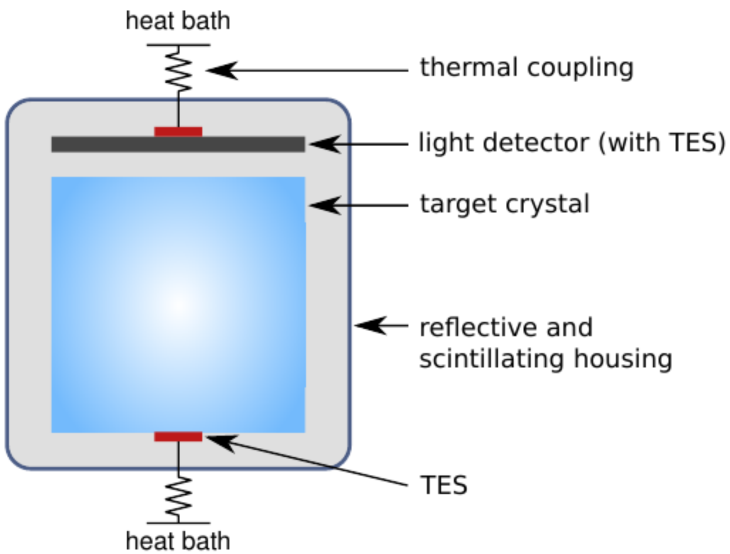
Light:
- XENON, LUX/LZ, ArDM, PandaX, Darkside,DARWIN
- DEAP3600, CLEAN, DAMA, KIMS, XMASS, DM-Ice, ANAIS, SABRE
- CRESST

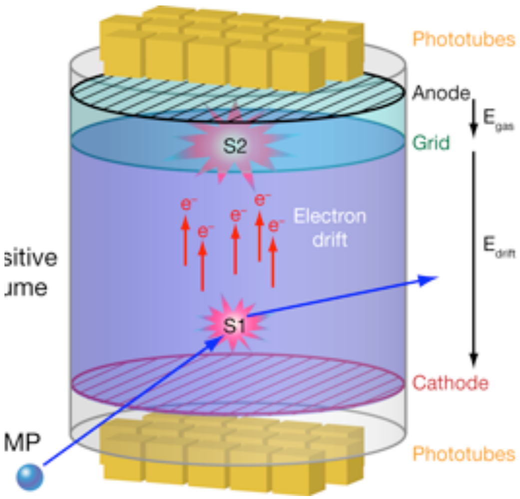
Converting WIMP Scattering into Signals

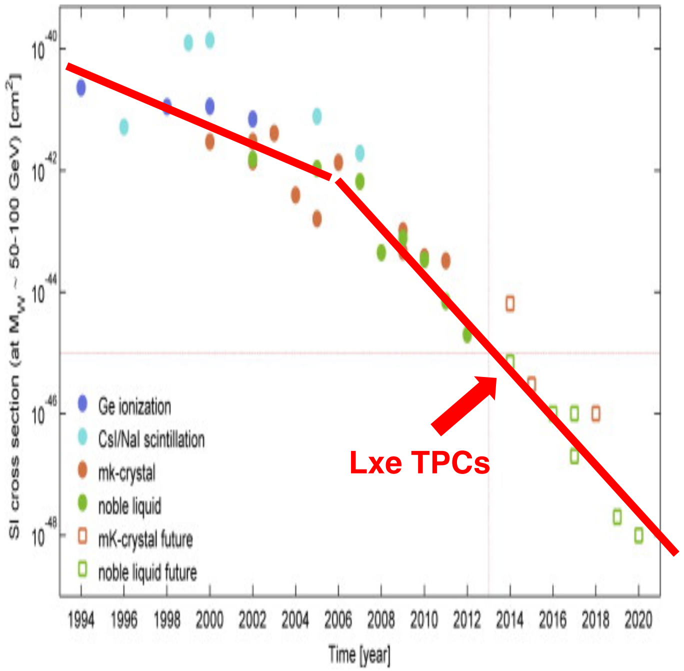
Light – ionization – heat: 3 examples

- **semiconductor Crystals (Ge)**
  → pulses
- **in crystals (e.g. $CaWO_4$) →**
  heat +light signal
- **liquid noble gases**
  → light and ionization@TPC









WIMP Event Rates

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

detector (mass, threshold, ...) astrophysics particle physics

axial-vector

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

$\frac{(J+1)}{J}$

Spin-Dependent (SD) Angular mom)

scalar

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q$$

A^2

Spin-Independent (SI) (Nucleon #)

vector

$$\mathcal{L} \supset \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

A^2

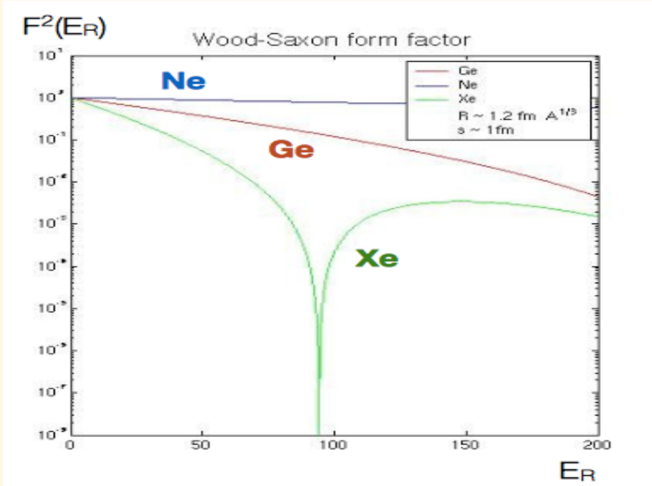
Only for non-Majorana WIMPs

Spin-Independent (SI)

SI is coherently enhanced

$$F(qr_n) = \frac{3[\sin(qr_n) - qr_n\cos(qr_n)]}{(qr_n)^3} e^{-(qs)^2/2}$$

form factor = FT of nucleus

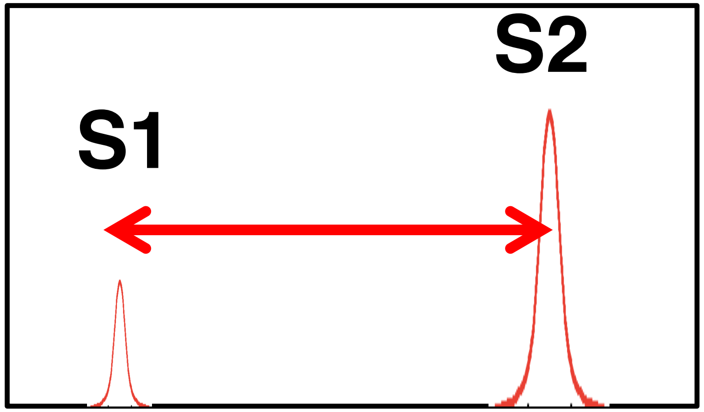


larger momentum transfer probes smaller scales
➔ loss of coherence

Powerful Devices: Dual-Phase TPCs

WIMP-scattering:

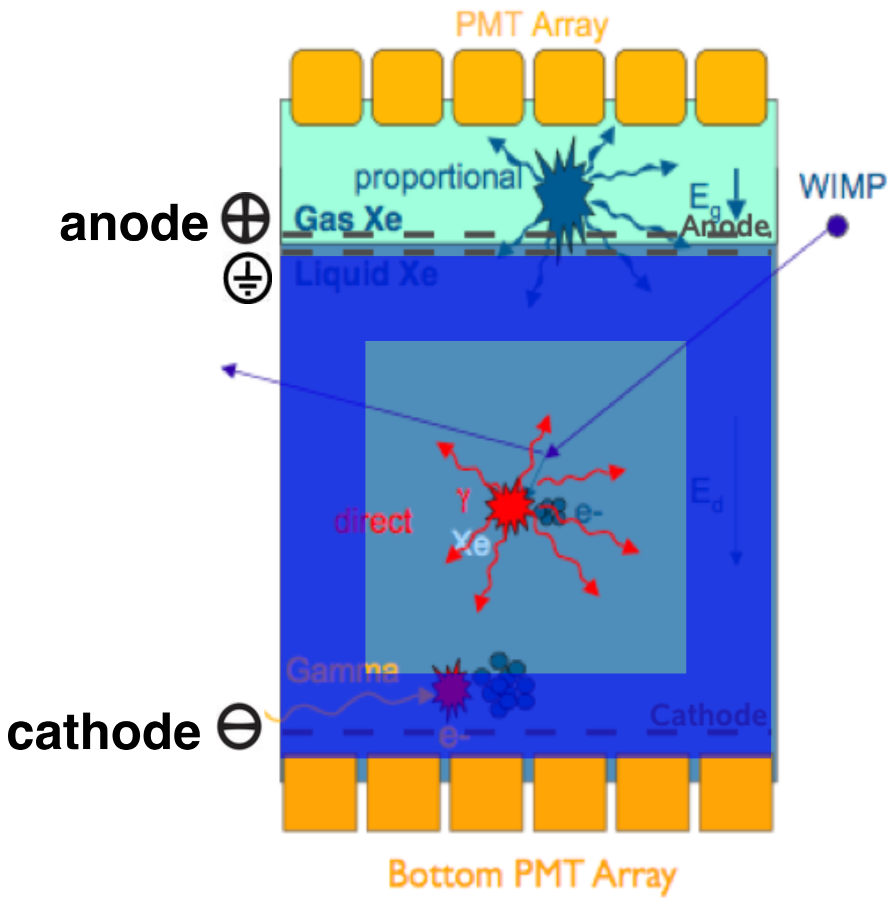
1) direct light singal → **S1**
2) drift of electrons to gas phase
3) 2nd light signal → **S2**

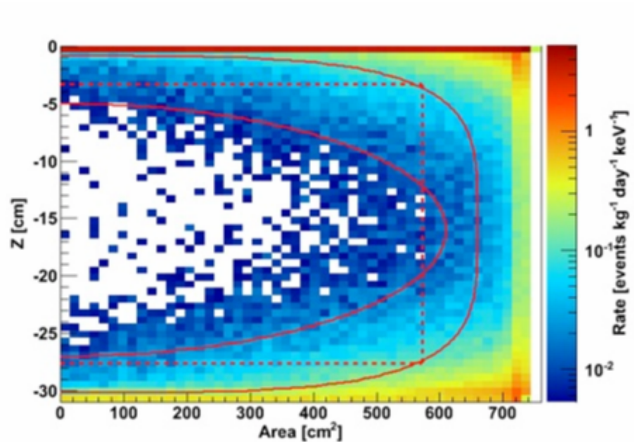


- **Drift-time → z**
- **PMT-signal distribution → x,y**
- **Puls hight, shape, …**

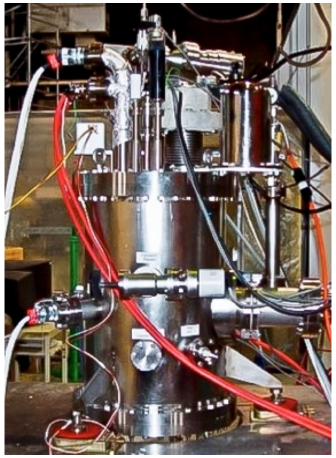
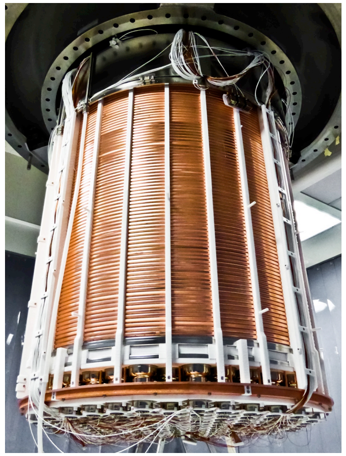
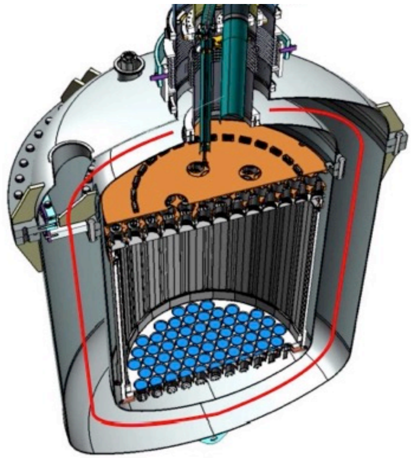
→ excellent 3D position reconstruction
Δr < 3 mm; Δz < 0.3 mm

→ fiducialization = exclude known backgrounds from 'dirty' surfaces





The XENON-Program @ LNGS

	XENON10	XENON100	XENON1T	XENONnT
				
Period	2005-2007	2008-2016	2012-2018	2019-2023
Mass	25 kg	161 kg	3200 kg	~8000 kg
Drift	15 cm	30 cm	100 cm	144 cm
Status	Completed (2007)	Completed (2016)	Running	Construction
σ_{SI} Limit (@50 GeV/c²)	8.8×10^{-44} cm²	1.1×10^{-45} cm²	1.6×10^{-47} cm² (2018)	1.6×10^{-48} cm²(2023)

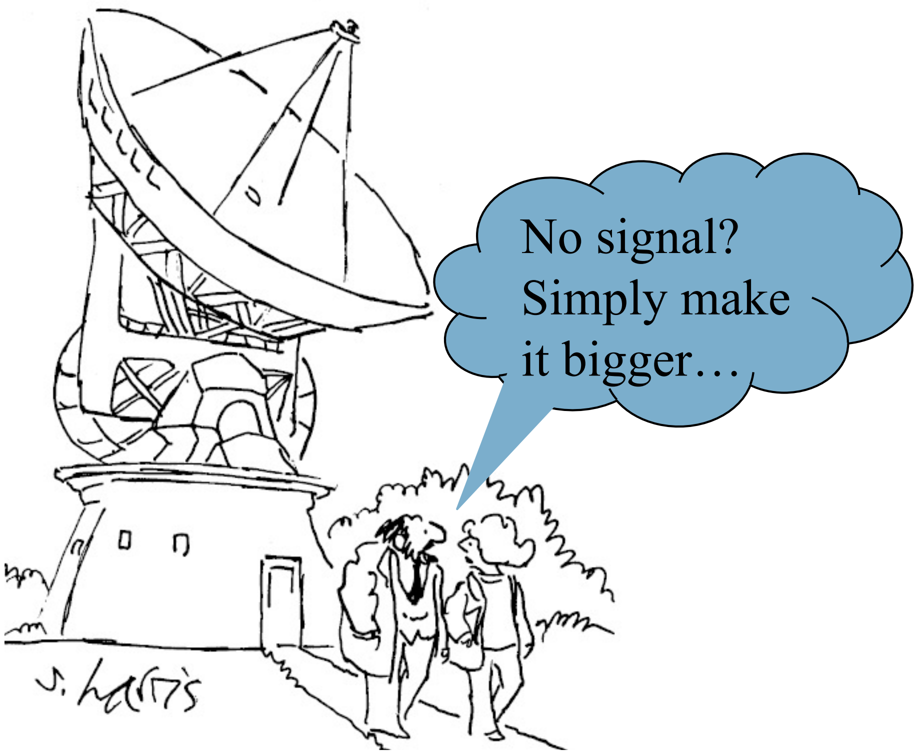
Scaling Considerations

larger WIMP mass:

- higher momentum transfer ➔ lowest threshold less critical
- smaller WIMP flux & reduced cross-section ➔ larger detector

smaller WIMP mass:

- lowest possible threshold
- higher WIMP flux helps



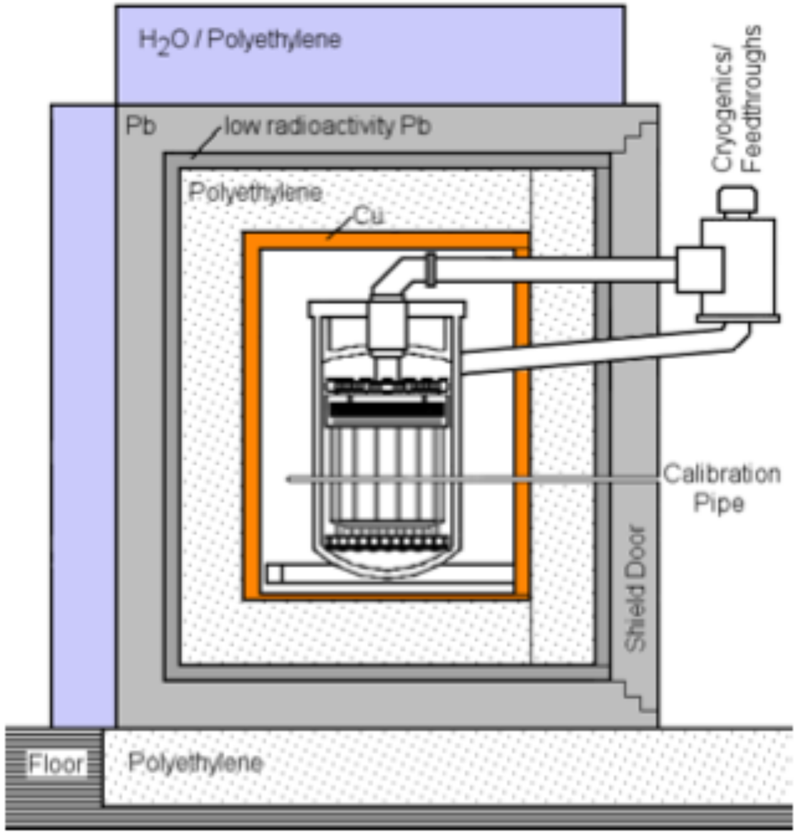
Improving sensitivity

- **bigger detectors**
  - increased technical challenges
  - …
- **more background suppression**
  - UG lab, better μ-veto, n-shielding
  - extremely radio-pure materials
  - Kr reduction
  - Rn emanation
  - outgassing
  - …

Ultra Low Background Requirements

underground laboratory = shielding from cosmic rays

- **remaining μ-flux**
- **neutrons from rock**
  → shields of PE, lead copper
- **Radon** (^{222}Rn is an α-decaying isotope)
  → from UG air: purging with clean nitrogen
  → emanation: screening of detector materials
- **unstable isotopes in detector material (U, Th, K, Tl, …)**
  → "γ screening" of construction material
- **online cleaning: E.g. Xenon gas (both radiopurity and e-lifetime)**
  → distillation
  → extreme precise instruments for the measurements of Rn, Kr, … (ppq)



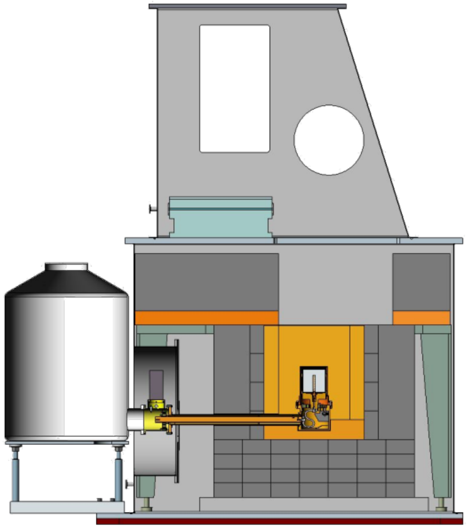
Material γ-Screening Facilities

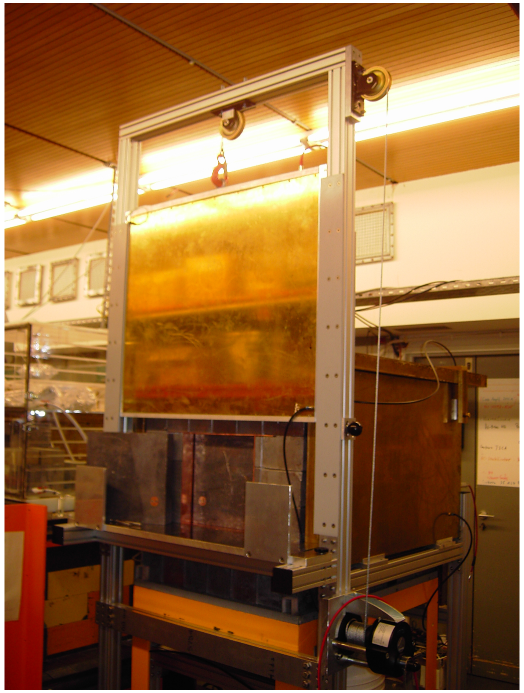
- Different screening stations@MPIK underground lab (1mBq/kg)

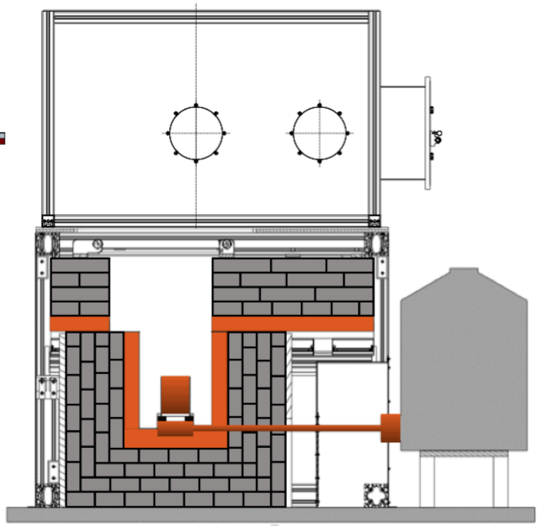
- GEMPIs @LNGS (10μBq/kg)

- GIOVE @MPIK (50μBq/kg)

➔ extensively used for GERDA, XENON and other experiments



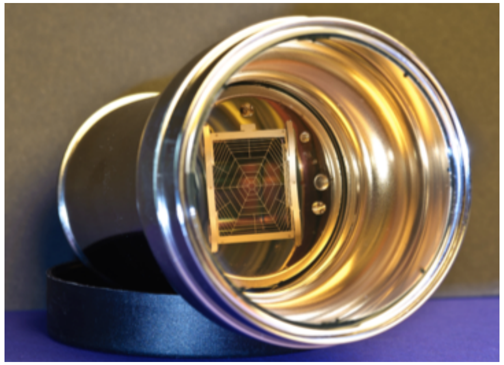




An Example: PMTs for XENON1T

XENON1T:

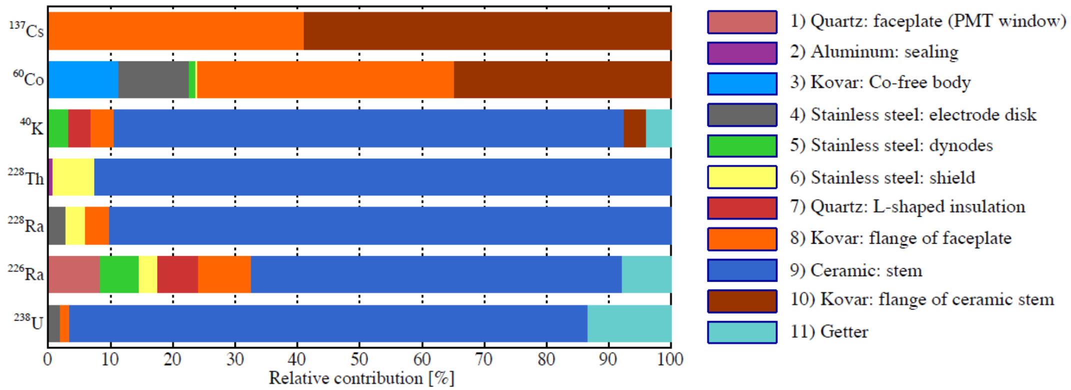
248, 3”
Hamamatsu
R11410-21

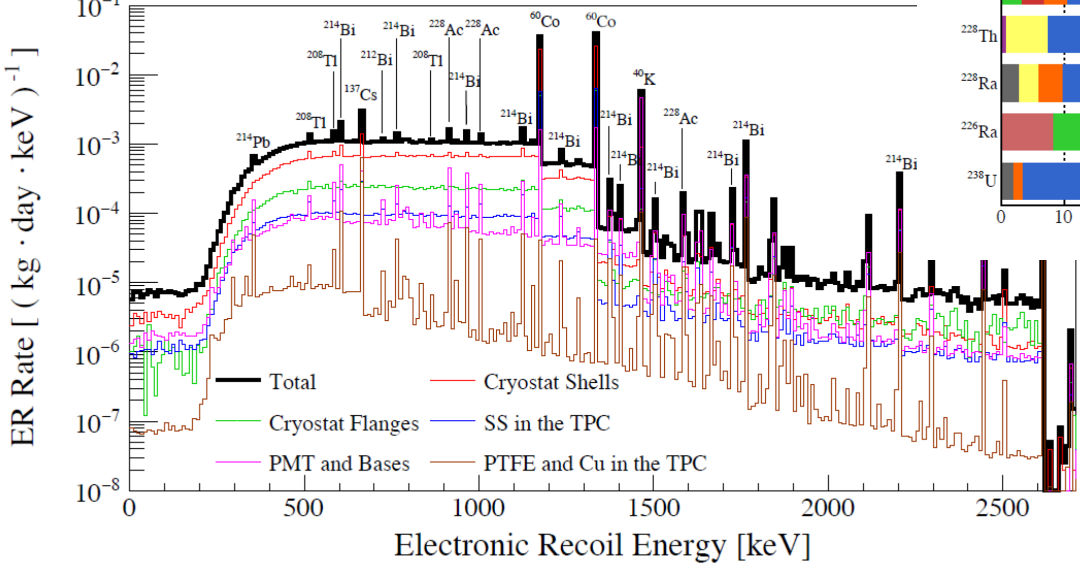


development & optimization together with Hamamatsu

Material selection & screening

< 1mBq/PMT in U/Th





Electronic recoil BG from materials
arXiv:1512.07501, JCAP04(2016)027

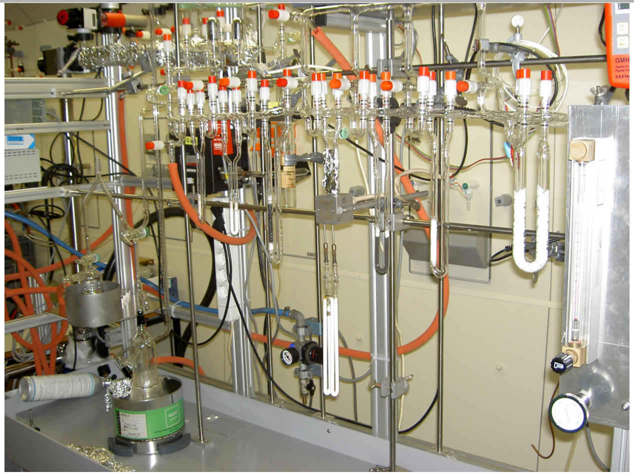
Extensive testing at room temperature and cryogen

high QE: 35% @ 175nm

stability, tightness, …

30% single PE resolution

Rn Screening Facilities



Based on MPIK gas counting systems @LNGS and @MPIK

- sensitivity = few atoms/probe

^{222}Rn emanation measurments

- samples → collect emanated gas
- non-trivial; not commonly available; routine @MPIK
- established numbers:

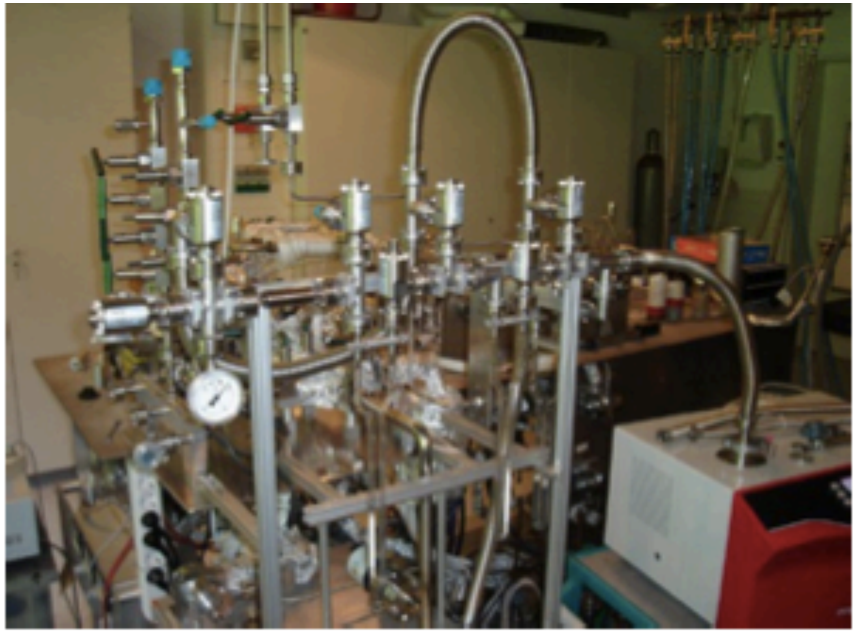
  Nylon (Borexino) < 1μBq/m²
  Copper (Gerda): 2μBq/m²
  stainless steel (Borexino): 5μBq/m²
  Titanium: (100 ± 30) μBq/m²

- Auto-Ema: new automated Rn screening facility at MPIK → many samples
- GeRn data base: more than 2800 samples

Krypton Analysis

^{85}Kr in Xenon: β-decays...
- must control of Kr level

MPIK RGMS (Rare Gas Mass Spectroscopy)
- measure ^{nat}Kr to ppt level
- extrapolation to ^{85}Kr abundance
- ppq sensitivity achieved

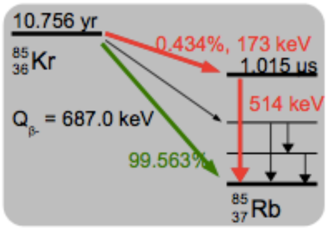


Active Kr and Rn Removal

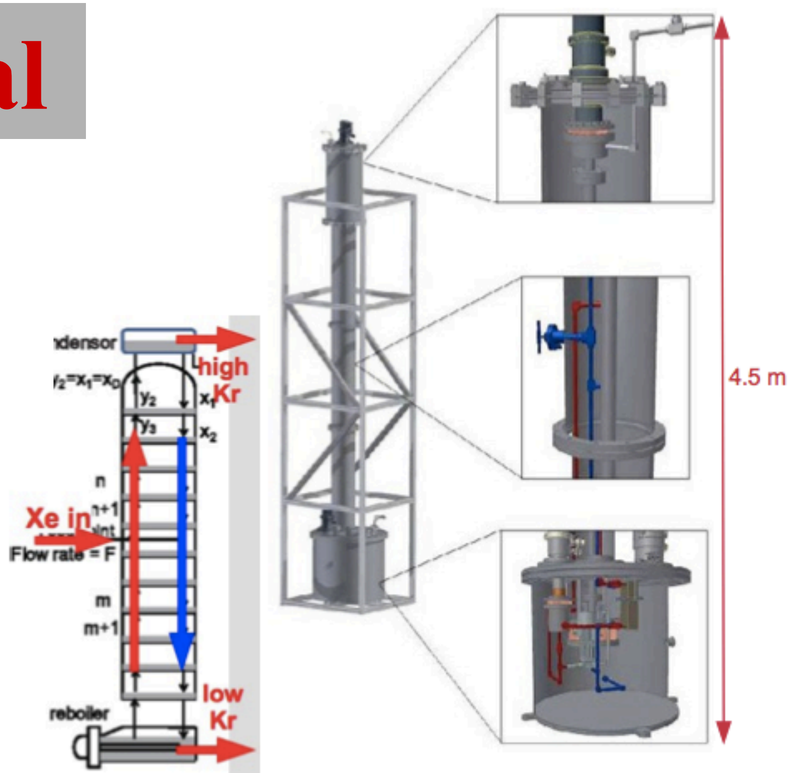
cryogenic distillation:
- established technique
- XENON100: (19 ± 1) ppt

design parameters for XENON1T
- thru-put 3kg/hr
- separation power 10^5
- final Kr/Xe < 1ppt – achieved

Rn distillation…

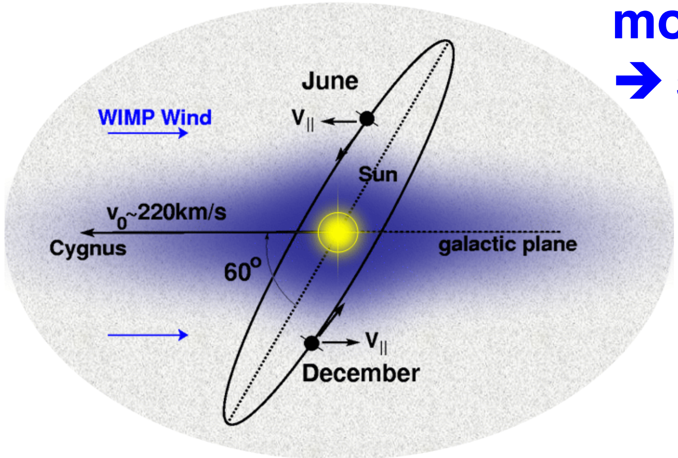


Münster



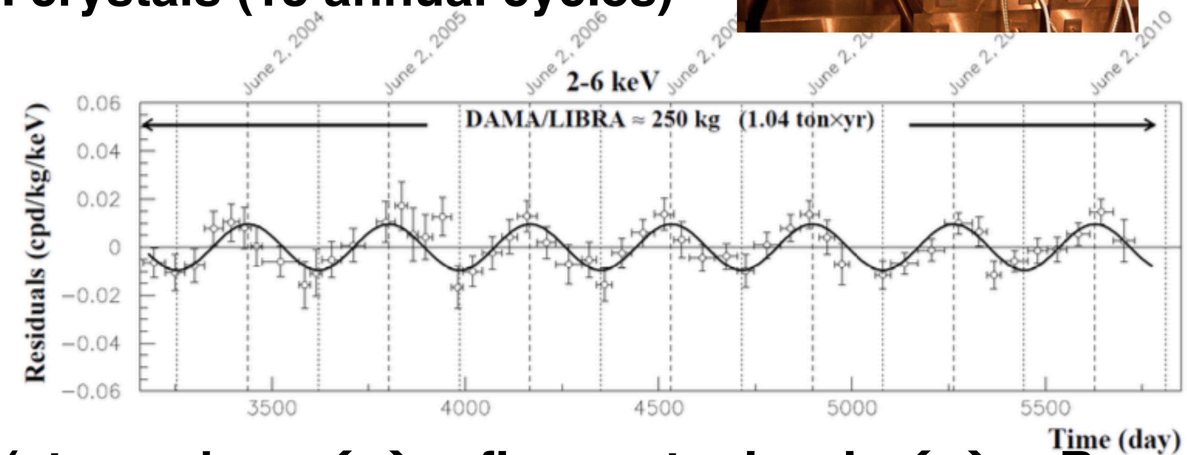
WIMP Results

The DAMA/LIBRA annual Modulation



moving thru the WIMP wind around the sun
➔ small annual modulation

DAMA/LIBRA
1.33 t*year exposure of
NaI crystals (13 annual cycles)



- 9.2σ signal for modulation
- frequency and phase match DM expectation

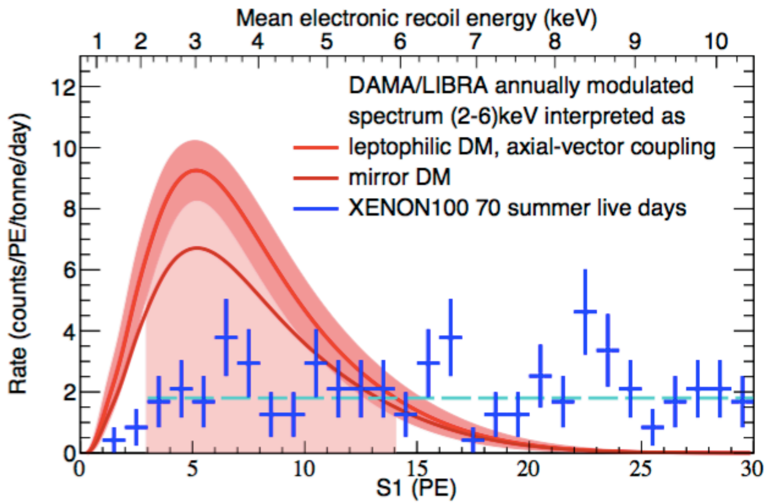
Various periodic backgrounds (atmosphere ←→ μ flux, water levels ←→n, Rn, …)

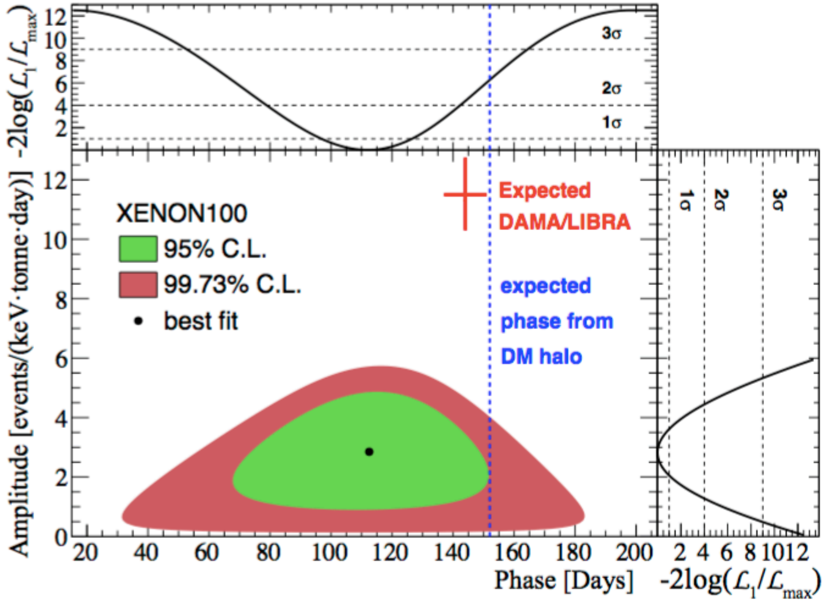
Problem:
- Backgrounds: So far no accepted explanation
- Signal: Other detectors (direct detection, indirect detection, LHC) do not see the corresponding overall signal which matches to the modulation

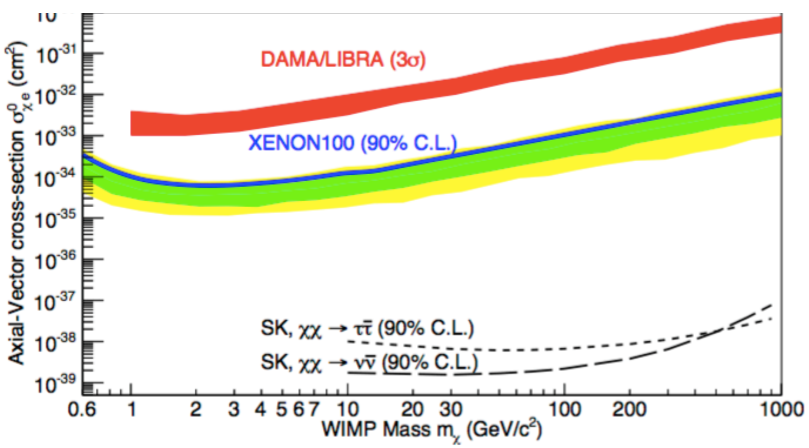
Proposed solution: DM particles which scatter on electrons (leptophilic DM…)
➔ would be seen by DAMA/LIBRA, but not by others

Modulation of Electronic Recoils in XENON100

477 life days (48kg*year); improved signal & bckg. modelling







➔ **DAMA signal excluded @5.7σ**

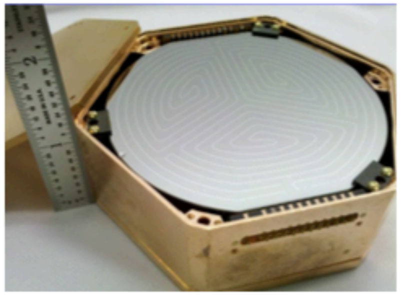
➔ **leptophilic models excluded**

➔ **modulation not understood**

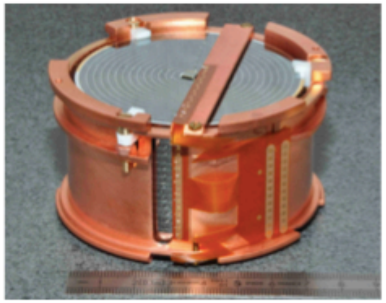
Future: New NaI Projects to directly check DAMA ➔ clarify modulation

➔ new projects: SABRE, COSINUS, COSINE-100, ANAIS, KIMS-NaI, DM-Ice

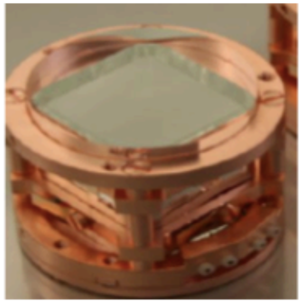
Spin Independet (SI) limits for low M_{WIMP}



SuperCDMS: Ge, Si



EDELWEISS-III (Ge)



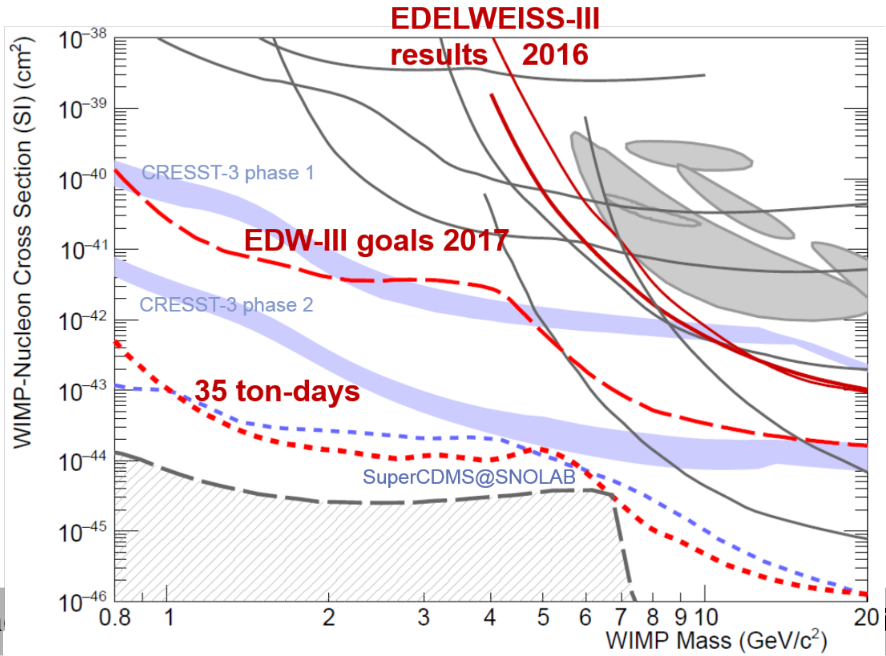
CRESST ($CaWO_4$)

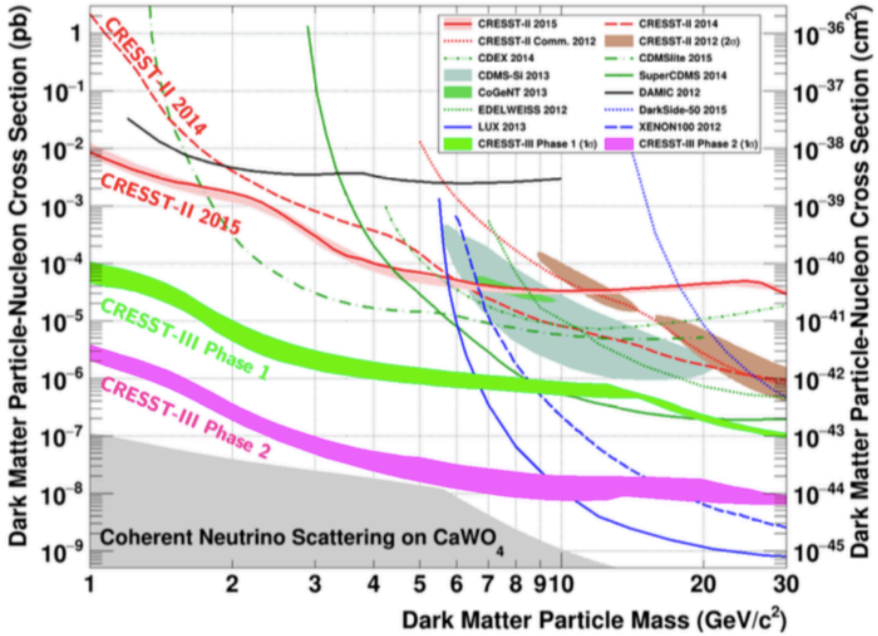
phonons (heat) + ionization | **heat + light**

SuperCDMS @SNOLAB
Aim: 50 kg-scale (cryostat up to 400kg)
low threshold, less bg: deeper, cleaner,
upgraded electronics, data taking 2020+

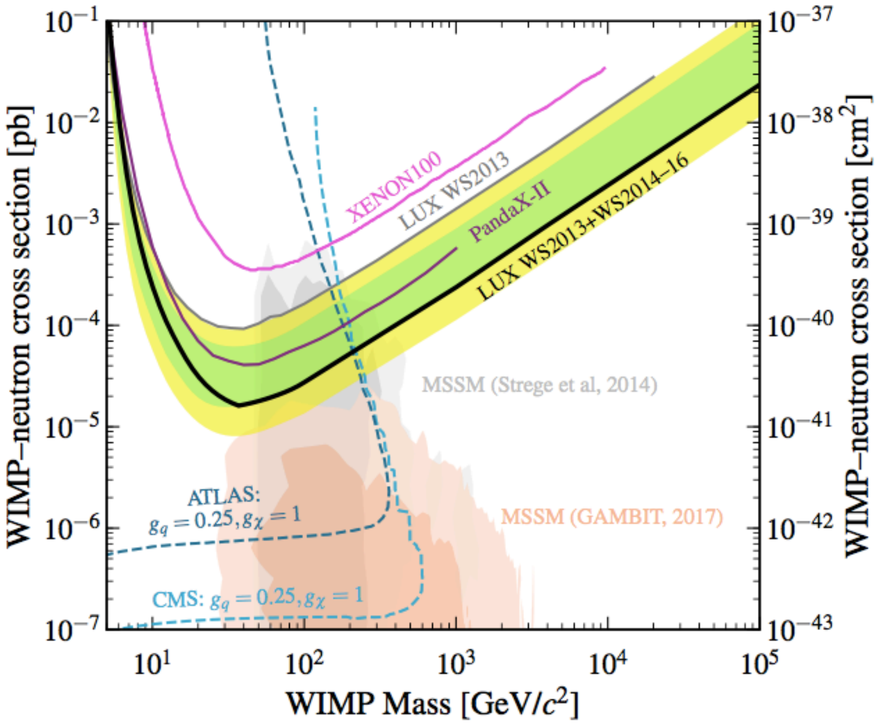
EDELWEISS @LSM
2016: 20 kg Ge array
2017: 350 kgd in HV mode
optimize 1-10 GeV sensitivity
➔ **EDELWEISS-III**

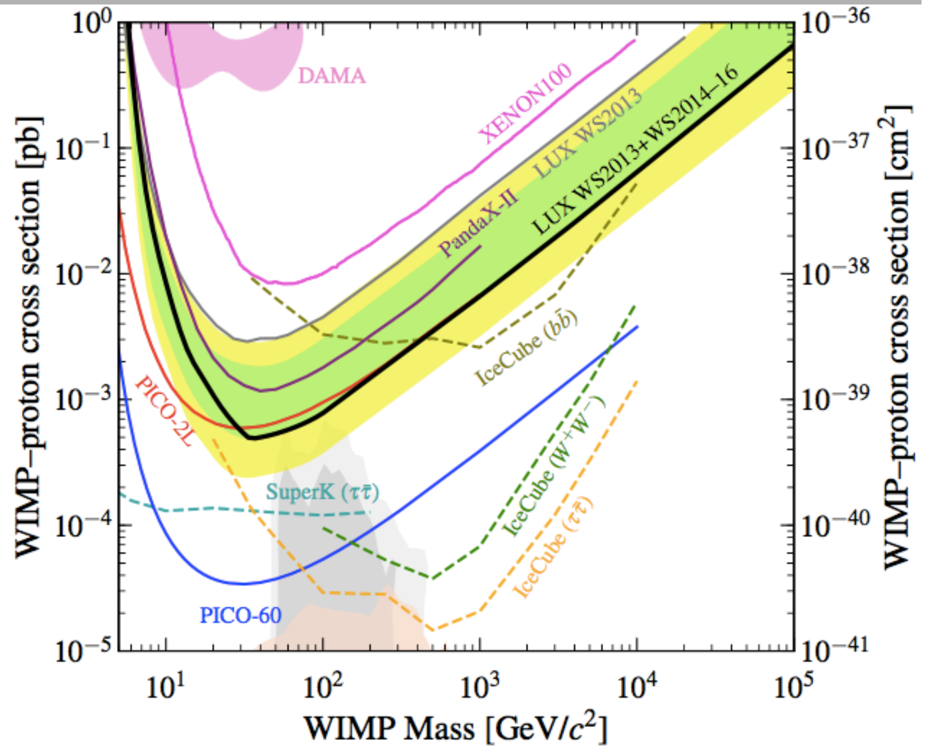
CRESST @LNGS
2013-2015, 52 kg × d
now: best threshold 300 eV_{nr}
excellent for small WIMP mass
➔ **CRESST-III**





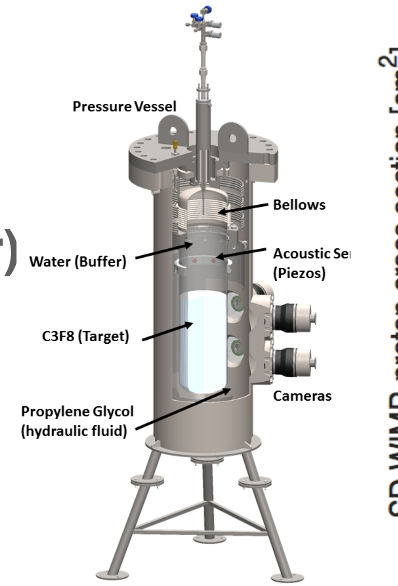
SD Limits for Neutron and Proton

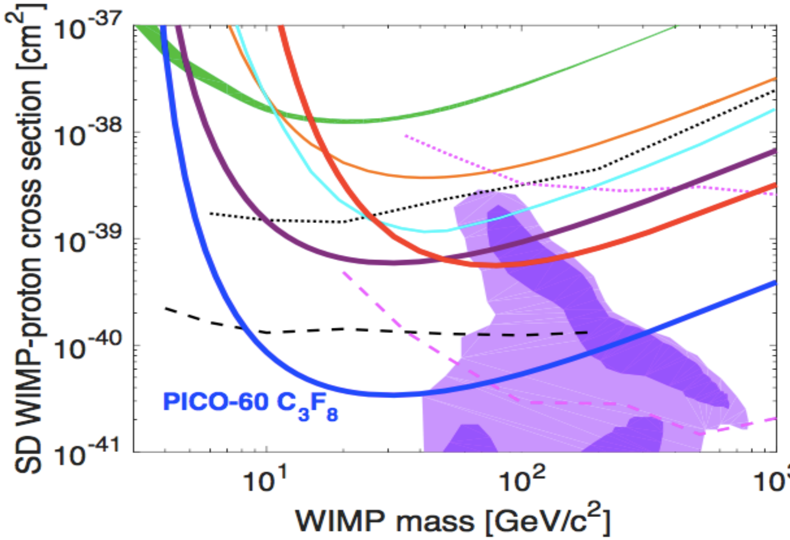




Recently new results from
- LUX (complete exposure)
- PICO-60 (C_3F_8 bubble chamber)

LHC limits depend on couplings
theory ~ rough areas
➔ part of expected area covered

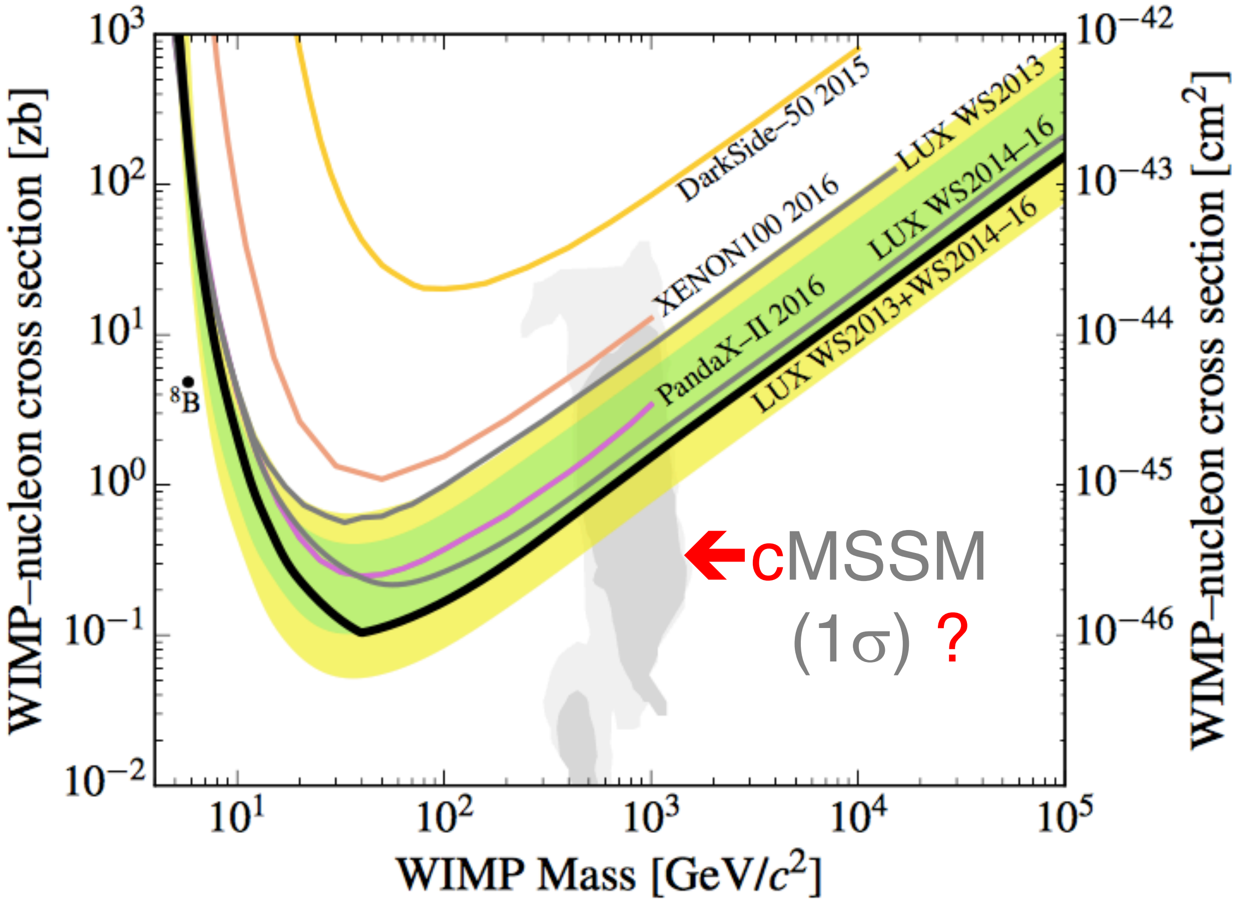




SI Limits for High M_{WIMP}

Limits until recently:

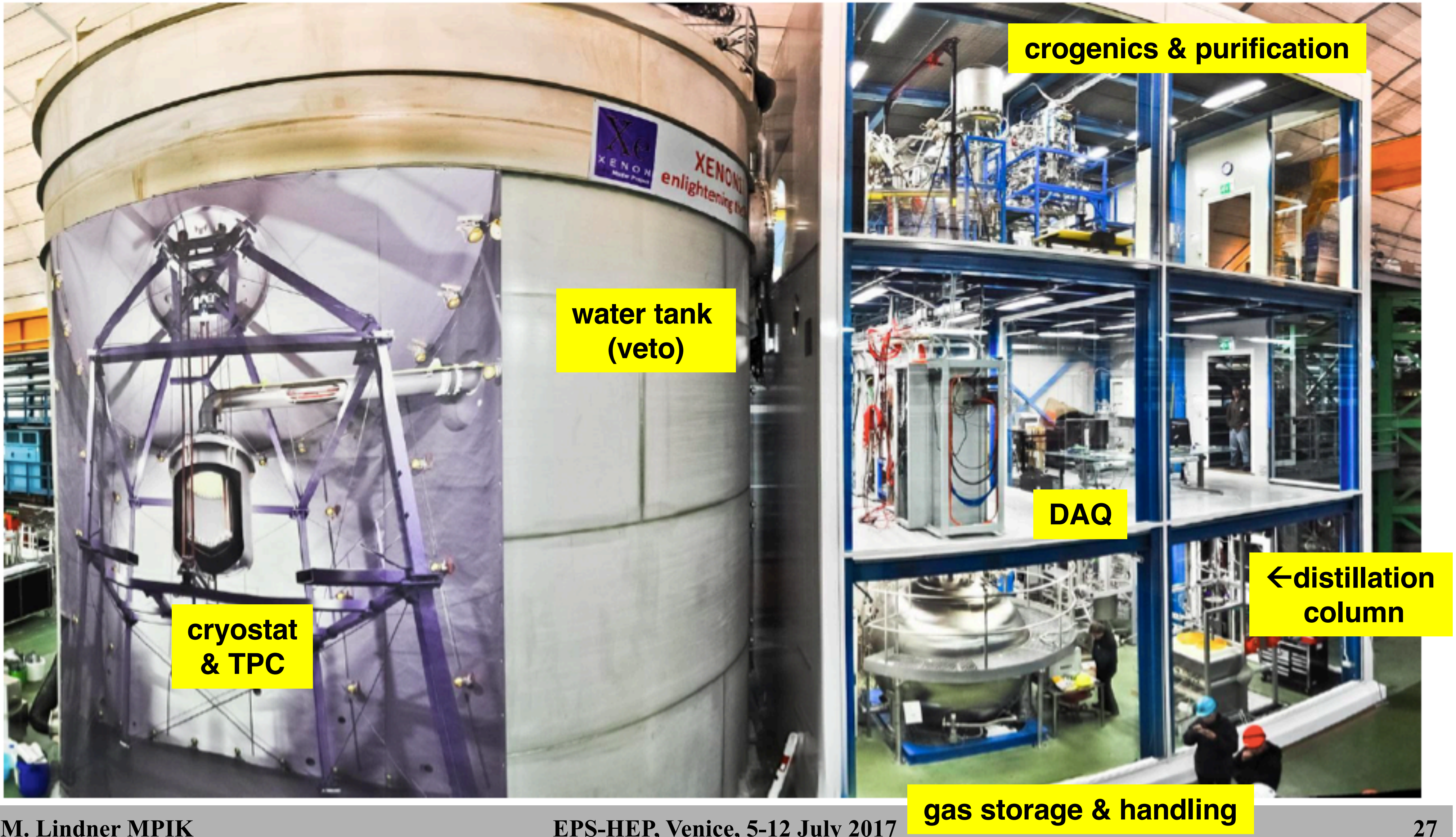
- **XENON100**
  (until 2016)
- **PandaX-II**
- **LUX**



➔ cuts into generic SUSY parameter space!

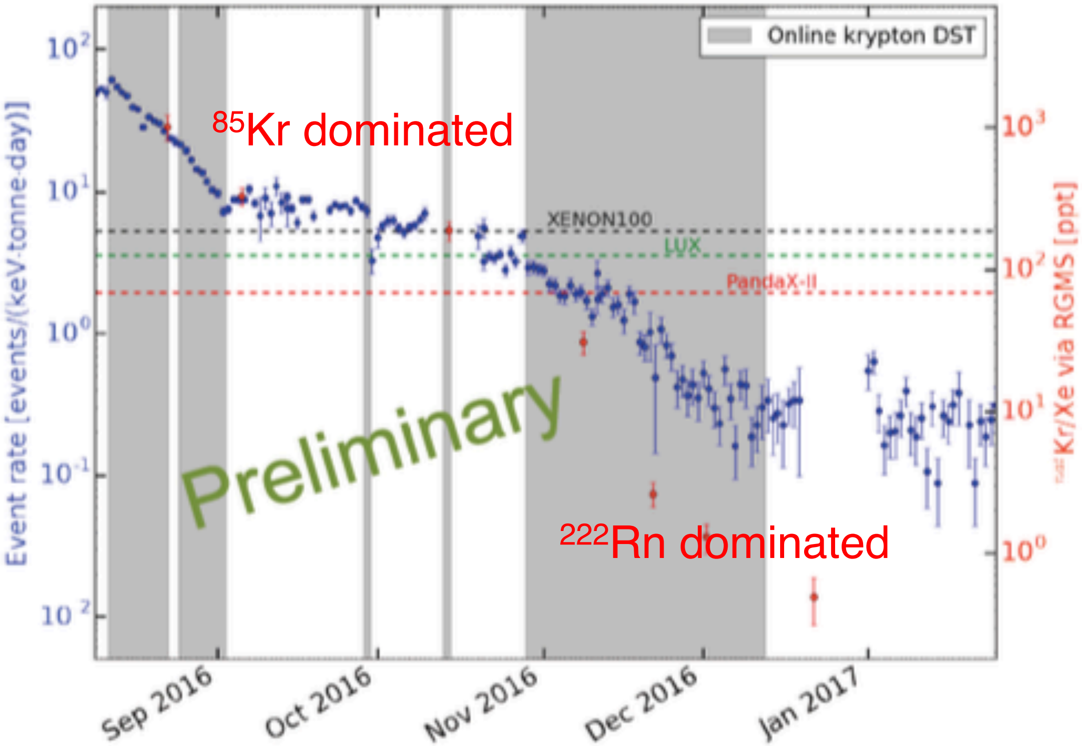
New: XENON1T

→ Goal: two orders of magnitude improvement in sensitivity with respect to XENON100 → commissioning in 2016 → data taking

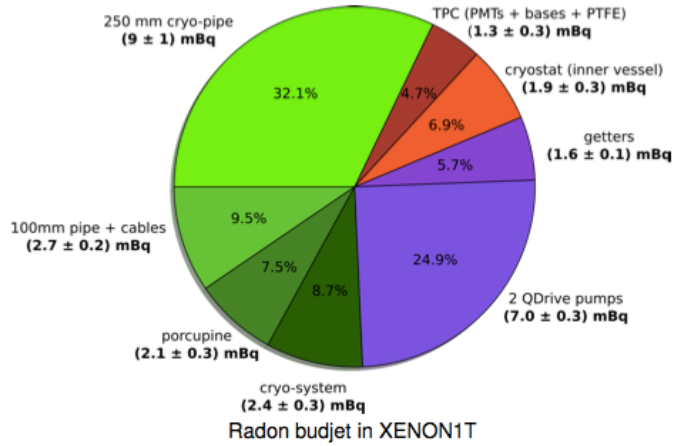


XENON1T Operation

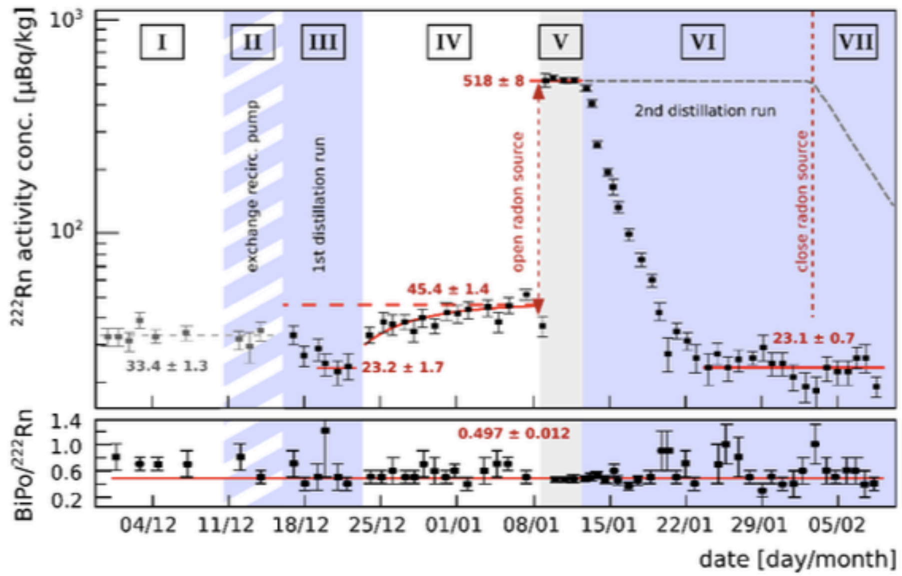
- Lowest background level of all LXe experiments
- Krypton background reduced by cryogenic distillation XENON1T, arXiv:1612.04284
- Krypton level measured independently by RGMS
  Eur. Phys. J. C 74 (2014) 2746



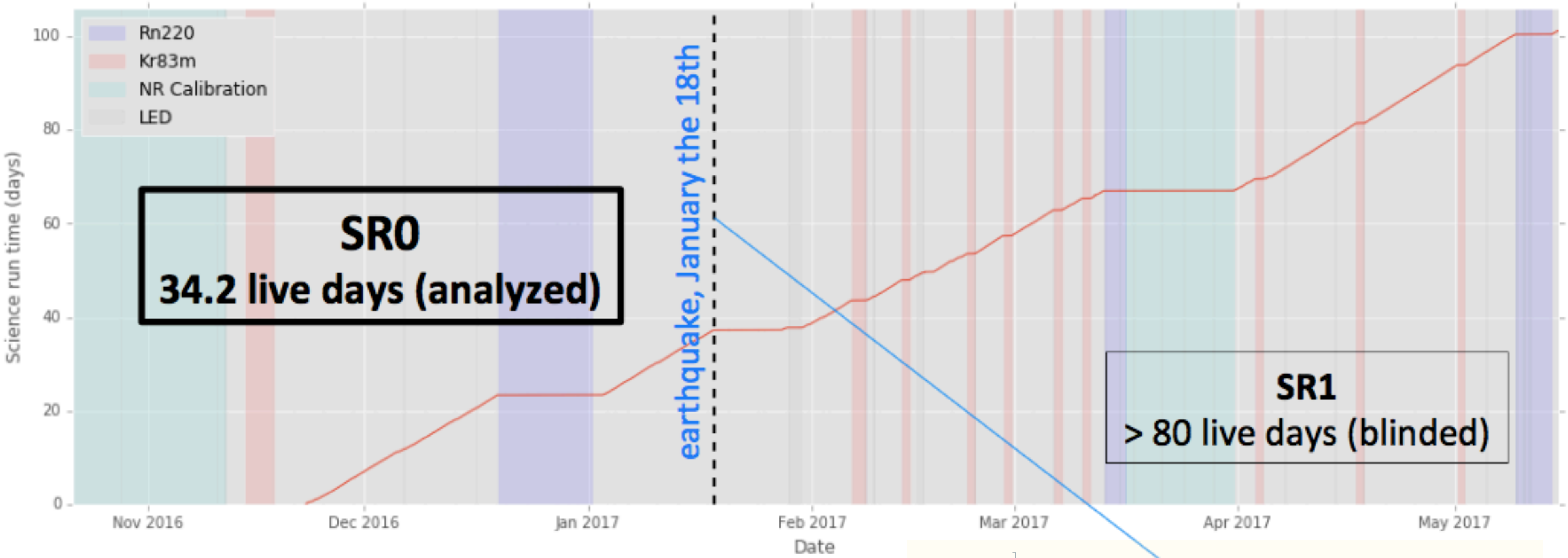
Rn budget well understood



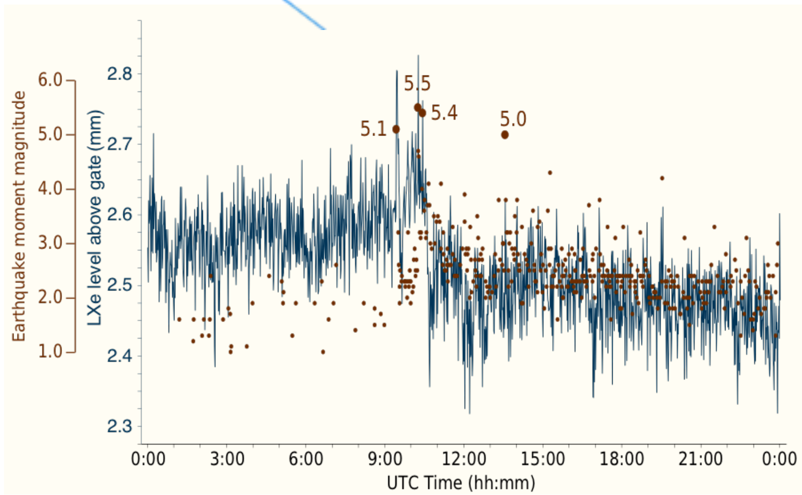
demonstration of Rn distillation



Science Run: Exposure



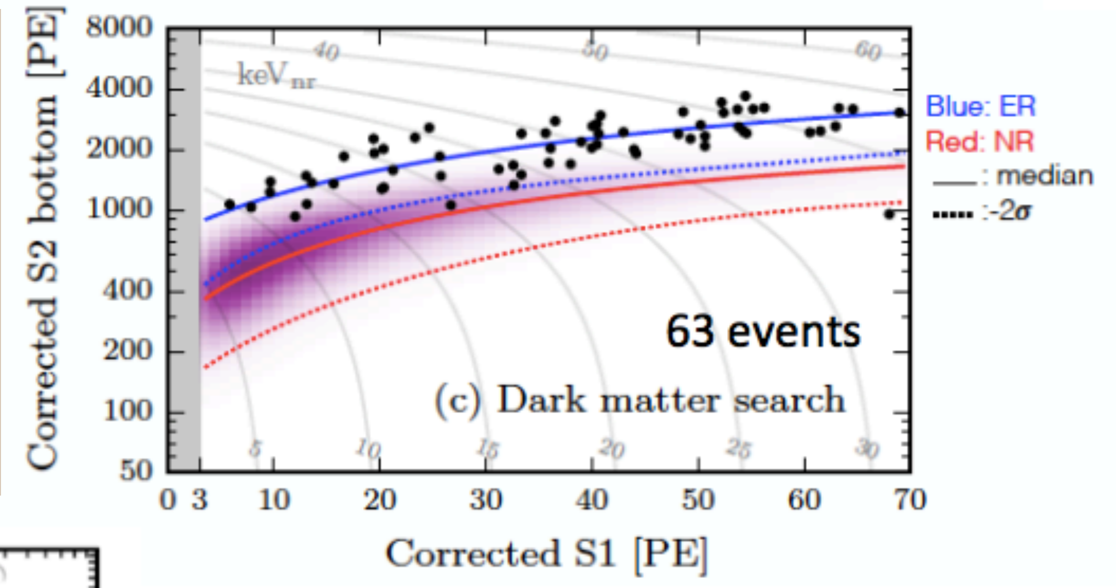
- **SR0: Data up to earthquake in January 2017…**
  ➔ 34.2 live days analyzed
  ➔ 1st results

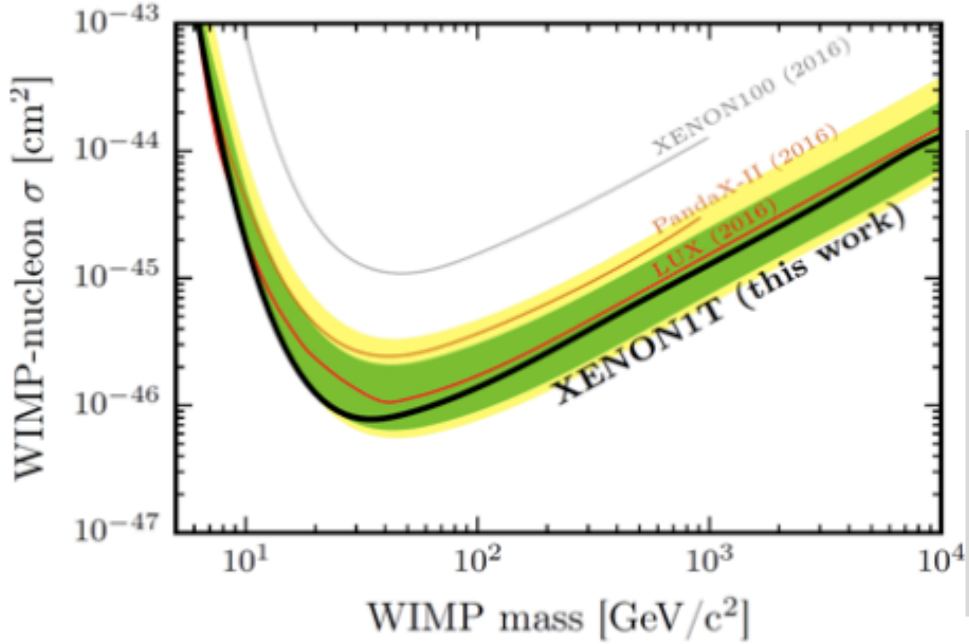


magnitude 5.6 earthquake ~20 km away

XENON1T 1st SI Limits for High M_{WIMP}

- ER and NR shape largely determined from calibration fits
- Unbinned profile likelihood analysis
- Uncertainties from background components included





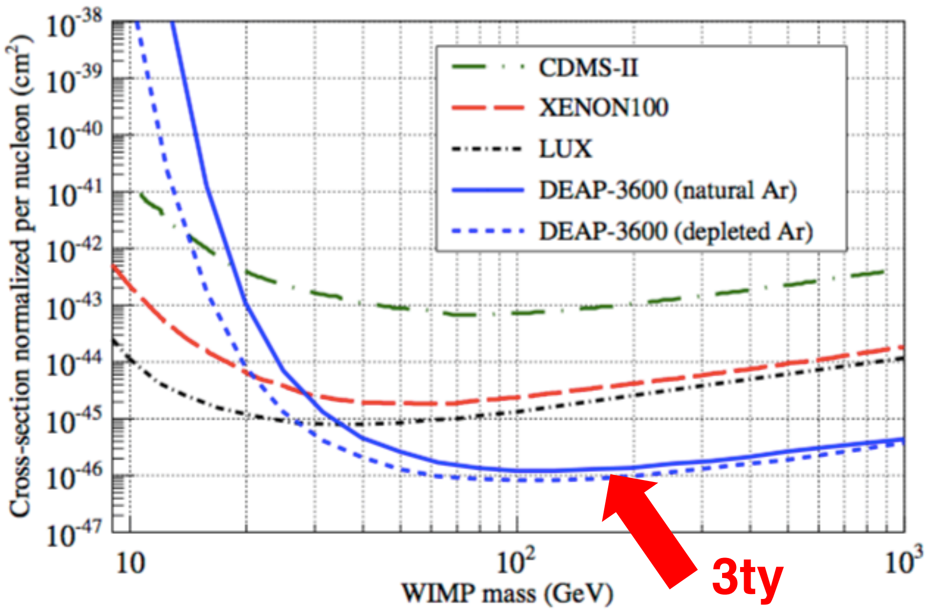
- **Strongest SI limit 1705.06655:** **7.7×10^{47} cm^2 @ 35 GeV/c^2**
- **data taking continues: SR1**

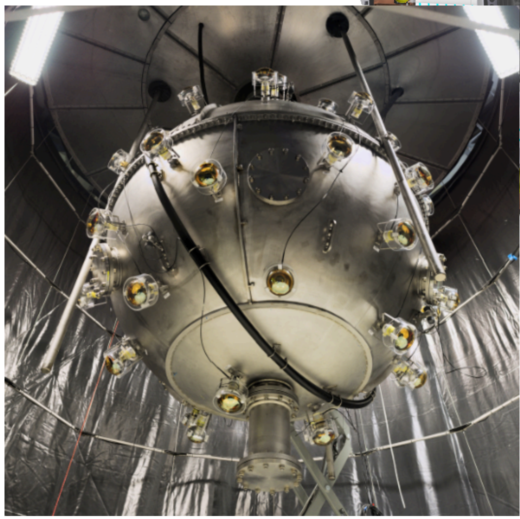
➔ by now > 90 more days of data

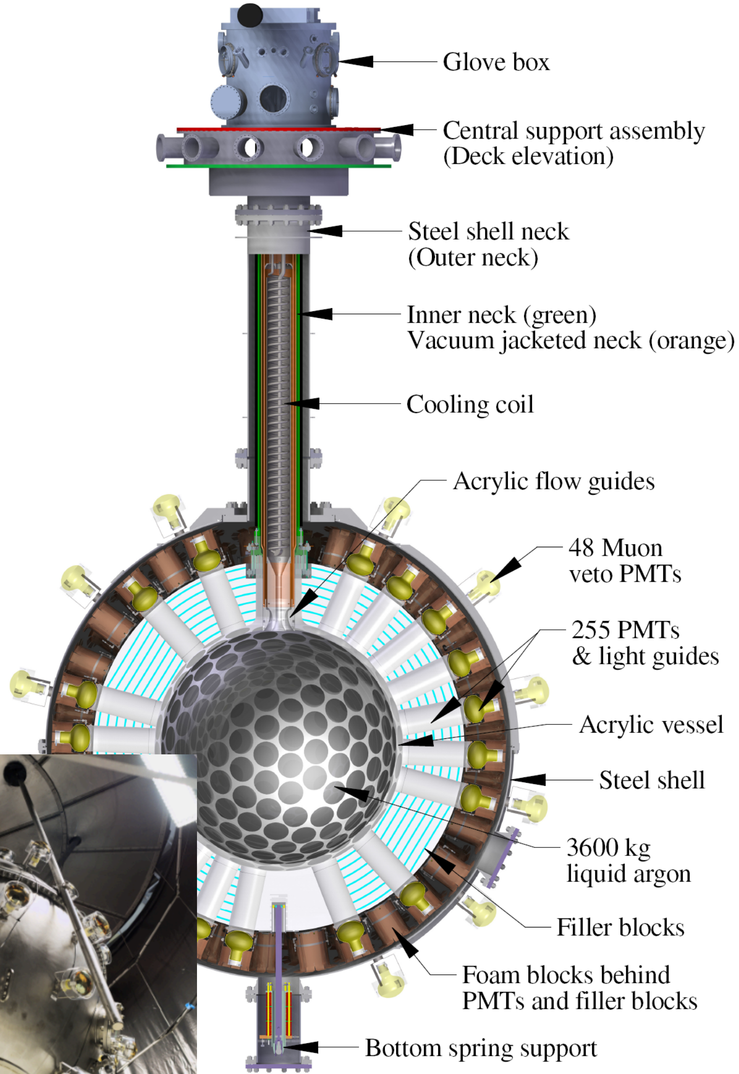
➔ keep running - expect more in 2017!

Expected soon: DEAP-3600 @ SNOLAB

- Single phase LAr TPC, 3.6t (1t fiducial)
- Spherical ultra pure acrylic vessel
- 255 PMTs, extra shielding (foam, PE)
- TPB wavelength shifter
  ➔ 128nm scintillation light into visible light
- Water tank + veto PMTs
- **Physics run ➔ 1st results very soon**







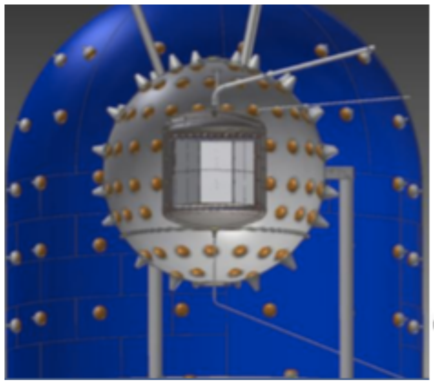
Liquid Argon Projects

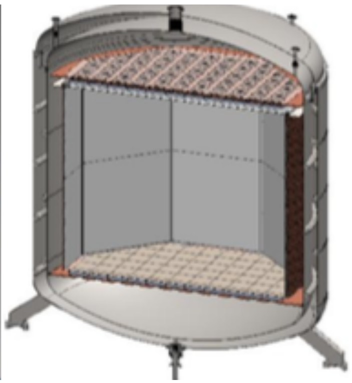
Other targets are important: **different backgrounds, physics, consistency**
Liquid Argon: Excellent target – avoid ^{39}Ar by production from oil/gas wells

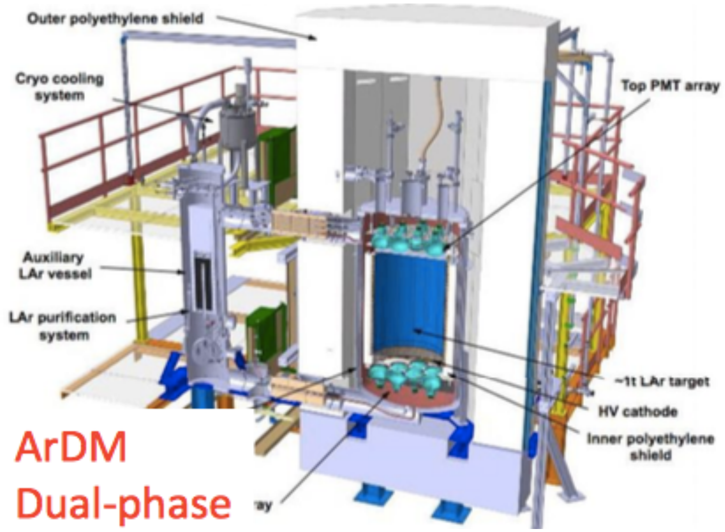
Running:
- DEAP-3600: see previous slides
- DarkSide-50:
- ArDM
- Mini-CLEAN

Plans: DarkSide-20k
20 t fiducial aiming at 100 t*yr
➔ 10^{-47} cm² at 1 TeV/c²

Next: Argo ➔ **1kton*yr exposure**

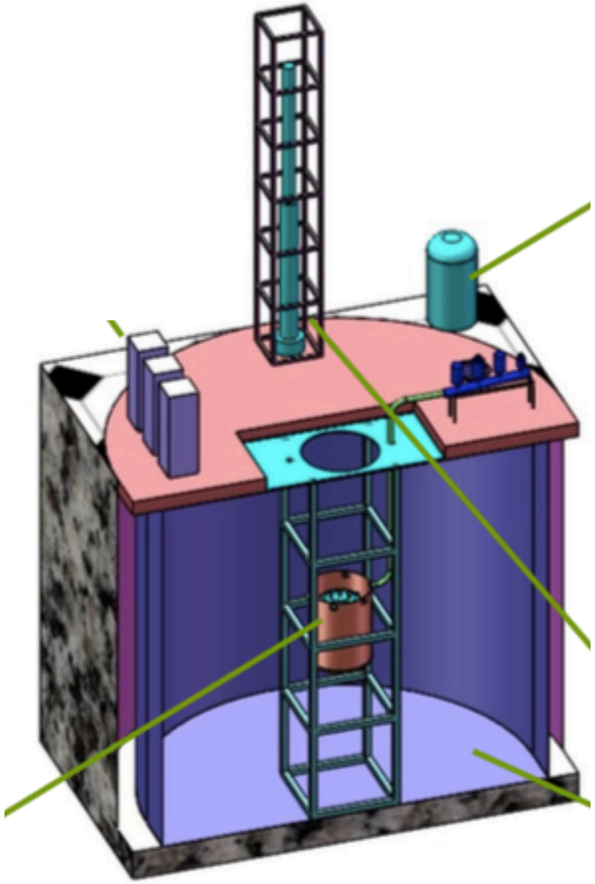


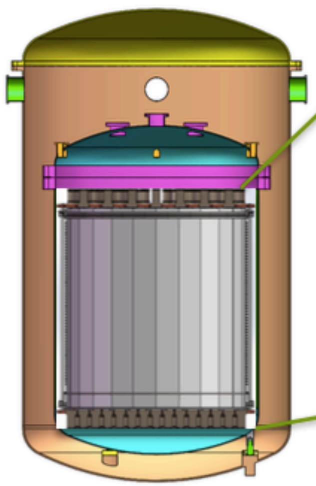


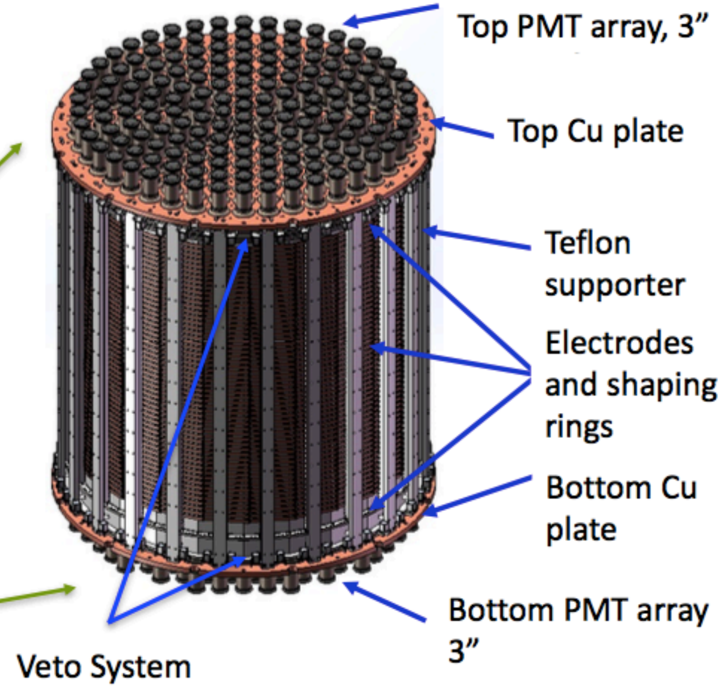


PandaX-4T at CJPL

- Drift region: Φ~1.2m， H~1.2m
  - Xenon in sensitive region～4ton
- Design goal:
  - High signal efficiency
  - Large and uniform electric field
  - Veto ability



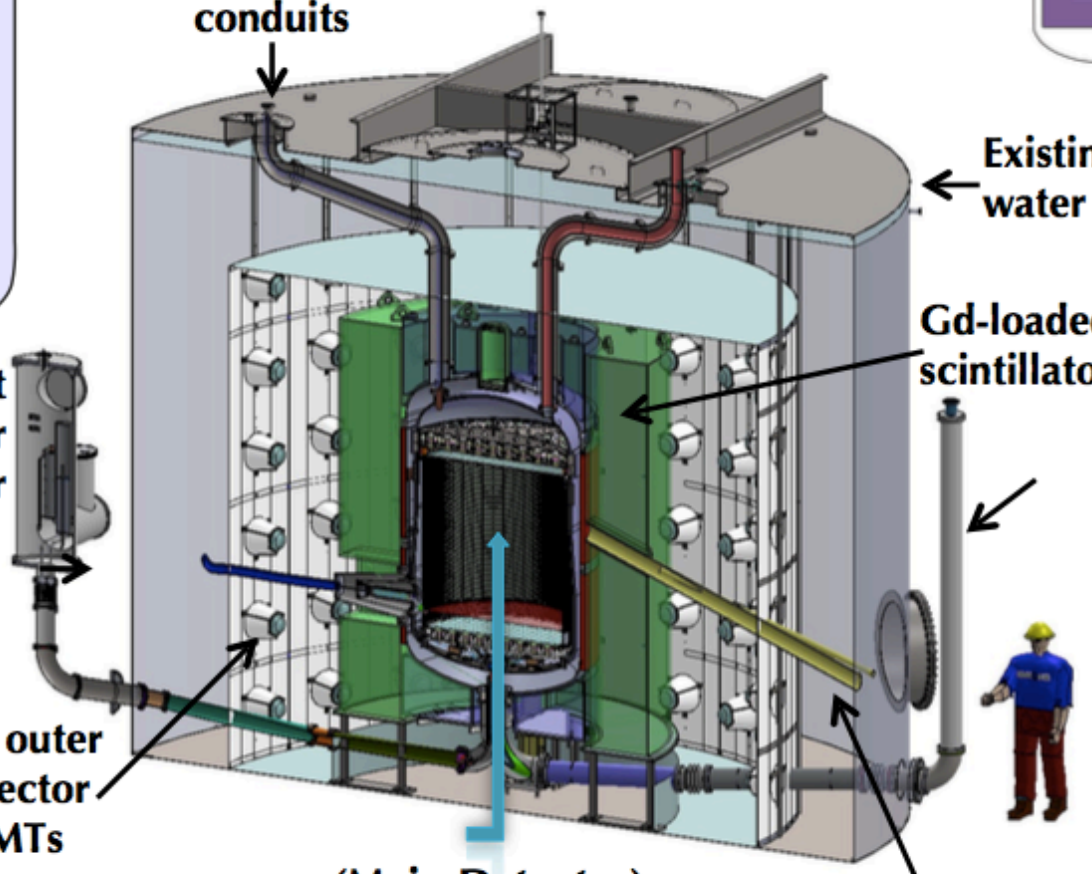




- 2017-2018:Produce all components and test
- 2019-2020:On-site assembling and commissioning
- 2021-2022:Data-taking
- eventual goal: ~30 t at CJPL to reach neutrino floor sensitivity

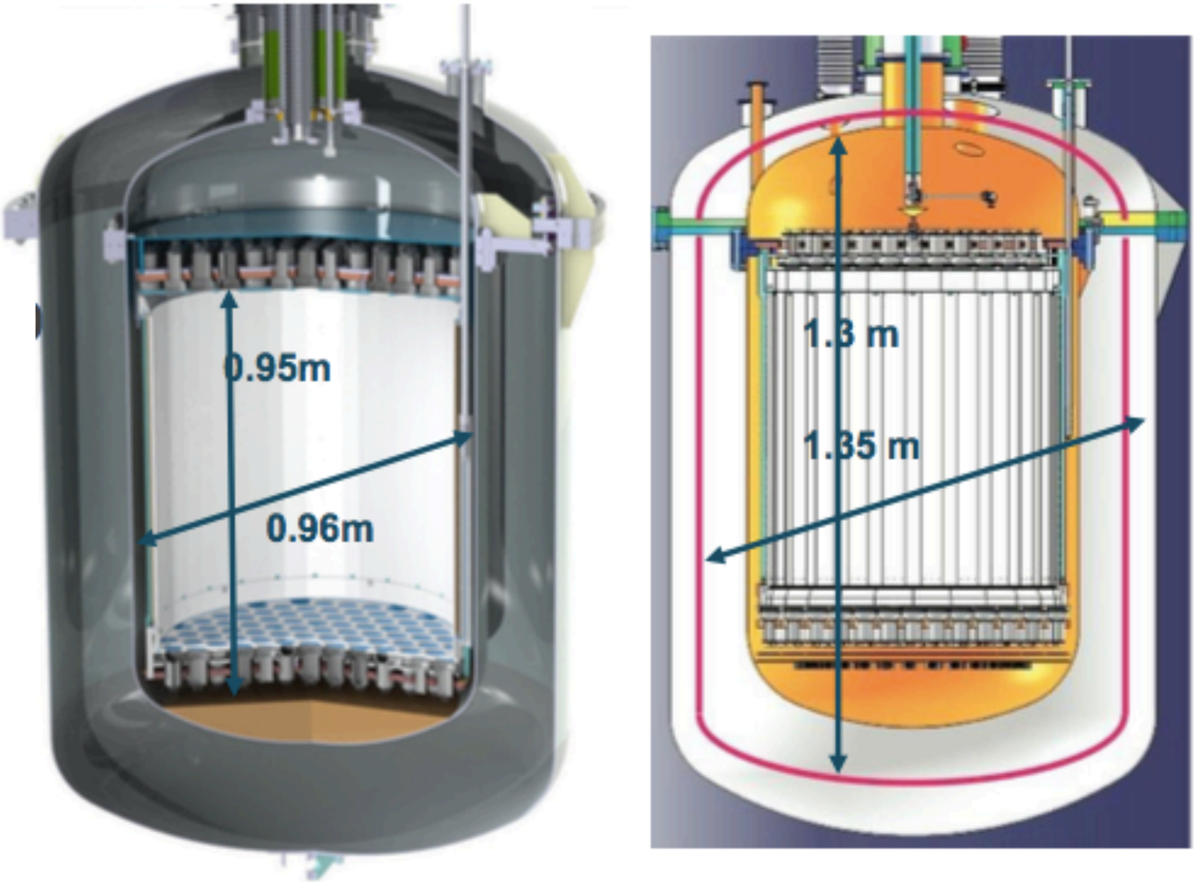
LUX-ZEPLIN (LZ)

- Turning on by 2019 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial
- Unique triple veto
- GOALS: < 2 x 10^{-48} cm^2, at 40 GeV ~100 times better than LUX



The XENONnT Upgrade

XENON1T | **XENONnT**



2013-2018 | **2018-2020**

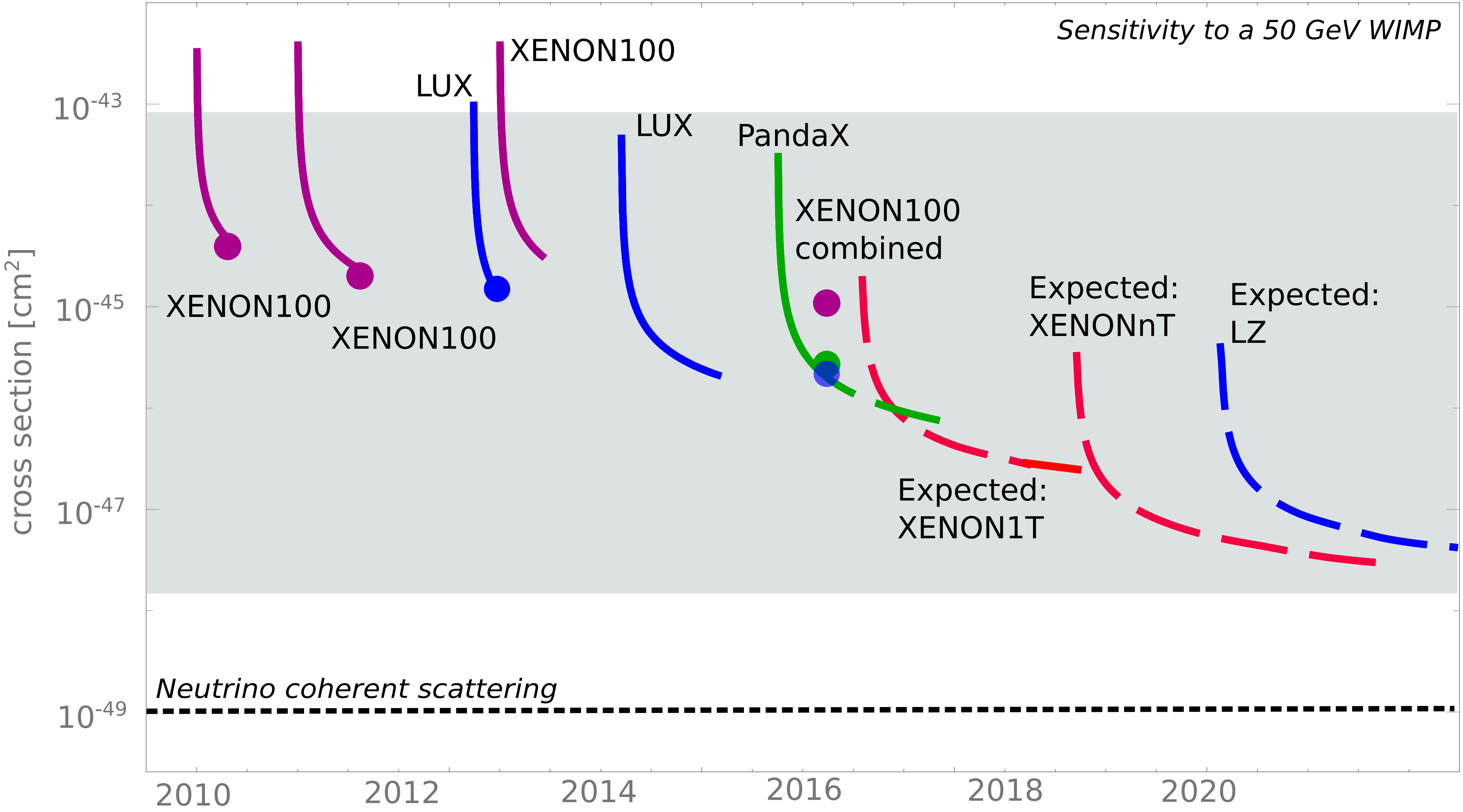
3.2 t LXe
running

ca. 8t LXe
design & preparations

Already existing/operational:
- Muon Veto
- Cryostat Support
- Outer Cryostat
- in-LXe Cabling
- LXe storage system
- Cryogenic system
- Purification system
- Kr removal
- DAQ
- 95% of Electronics
- Calibration System
- 260 PMTs
- >8t of LXe
  (was 4.5t one year ago!)
- Screening facilities
- dedicated nT funding

Already 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.

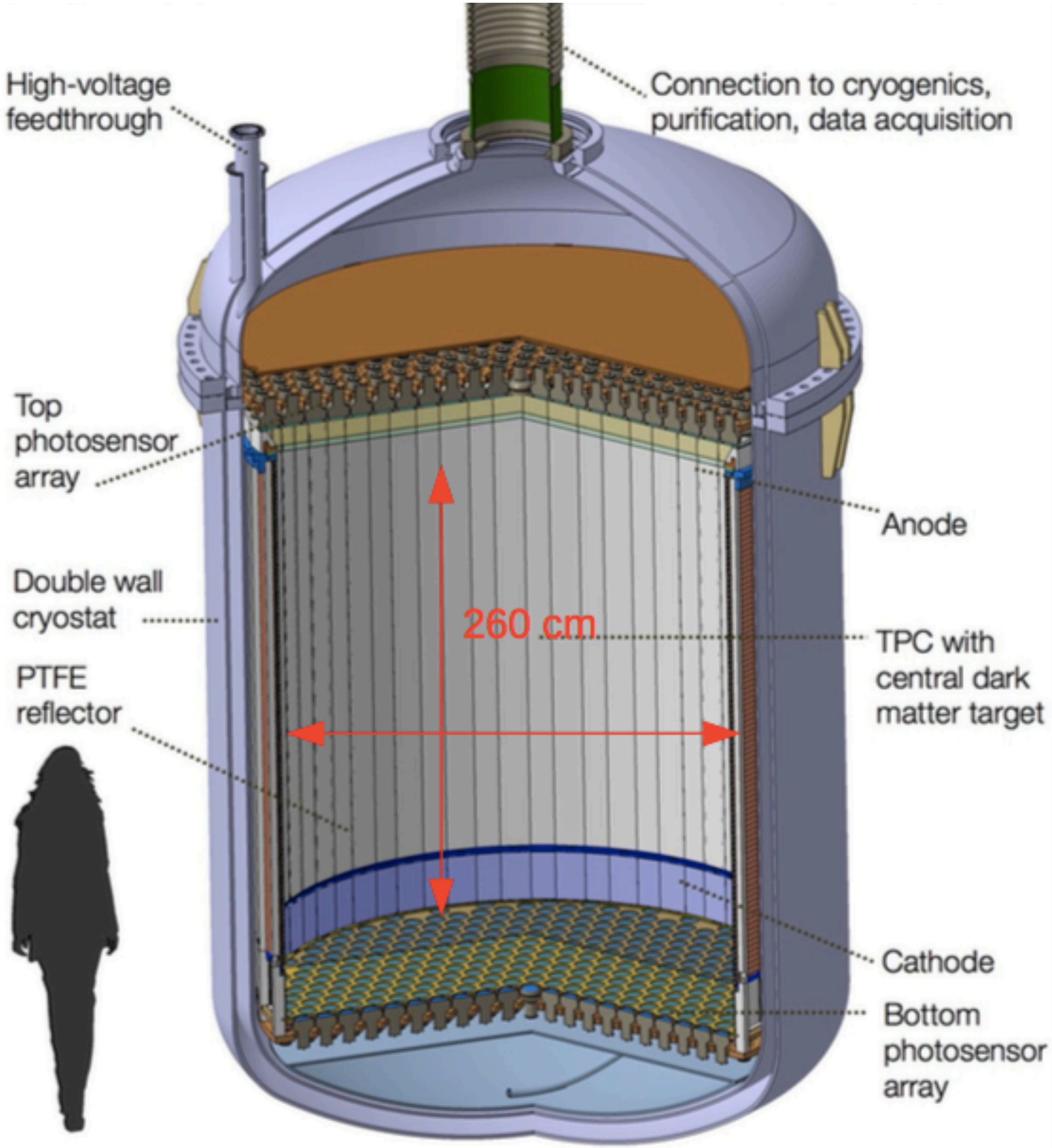
Direct WIMP Search Timeline (Xe)



Generic WIMP parameter space will be covered in the next years

Systematically lowering the x-section (symmetry, tuning,…)? ←→ WIMP miracle?

DARWIN: The ultimate WIMP Detector



- aim at sensitivity of a few 10^{-49} cm², limited by **irreducible ν-backgrounds**
- international consortium, 21 groups
  → R&D ongoing

Baseline scenario
~50t total LXe mass
~40 t LXe TPC
~30 t fiducial mass

- depends on outcome until then
- timeline ~ from ca. 2022 (after XENONnT)
- includes other physics:
  - neutrinos (ν floor)
  - 0νββ – ^{136}Xe in Lxe ~ 4 t

Summary

- **There is clear evidence for DM in the Universe**

Direct detection of Dark Matter is the crucial test to prove that the Universe is full of new particles

- **Different options/candidates:**

➔ **WIMPs seem best motivated**

➔ **Excellent opportunity to find or exclude WIMPs in the next years in the natural parameter space**

➔ **Axions, sterile neutrinos and ... other candidates**

➔ **Interplay of indirect & direct detection & LHC**

➔ **Exciting perspectives for the next few years!**