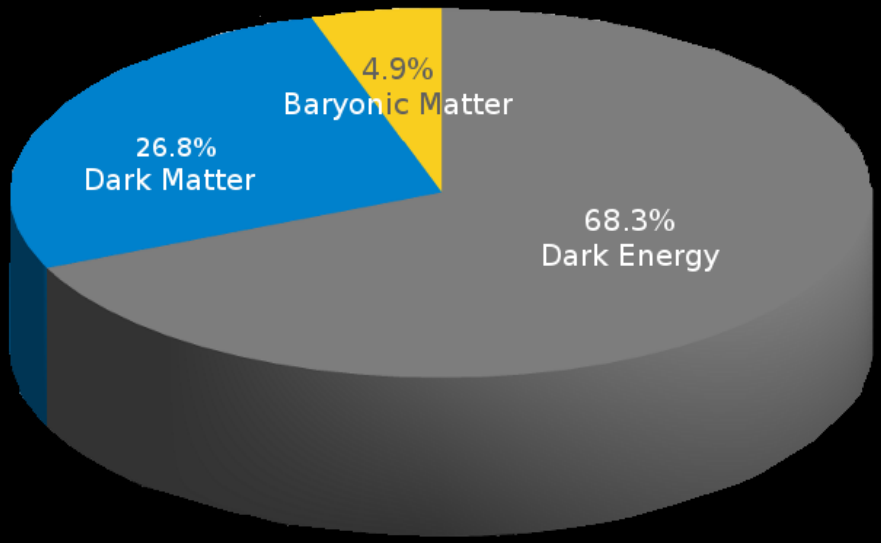
Exploring the Dark Universe with XENON

Marc Schumann *University of Freiburg*

KIS Colloquium, Freiburg, 20.02.2020

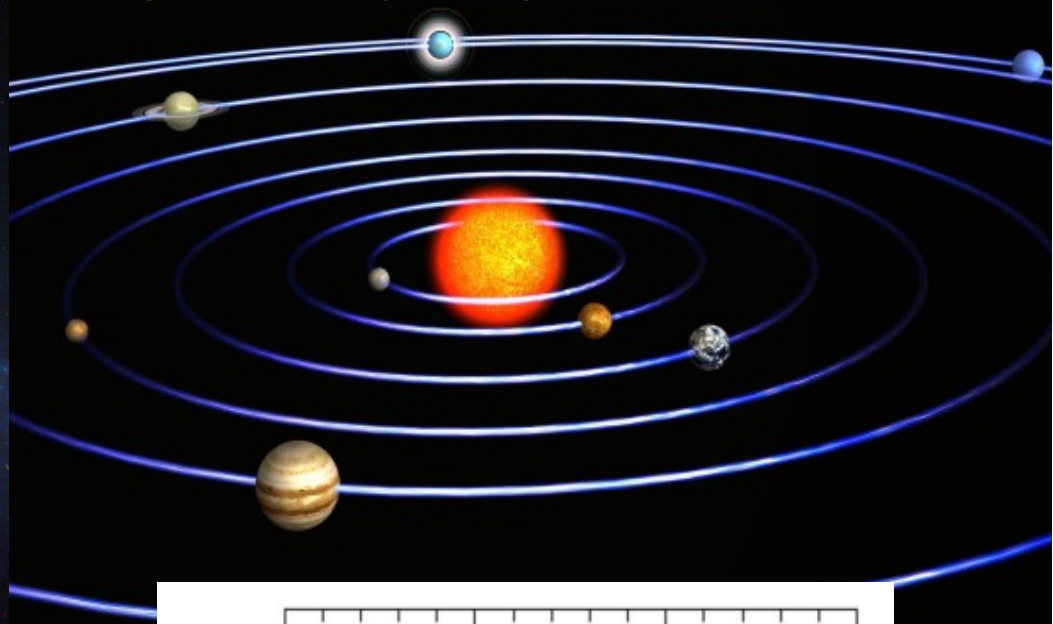
www.app.uni-freiburg.de

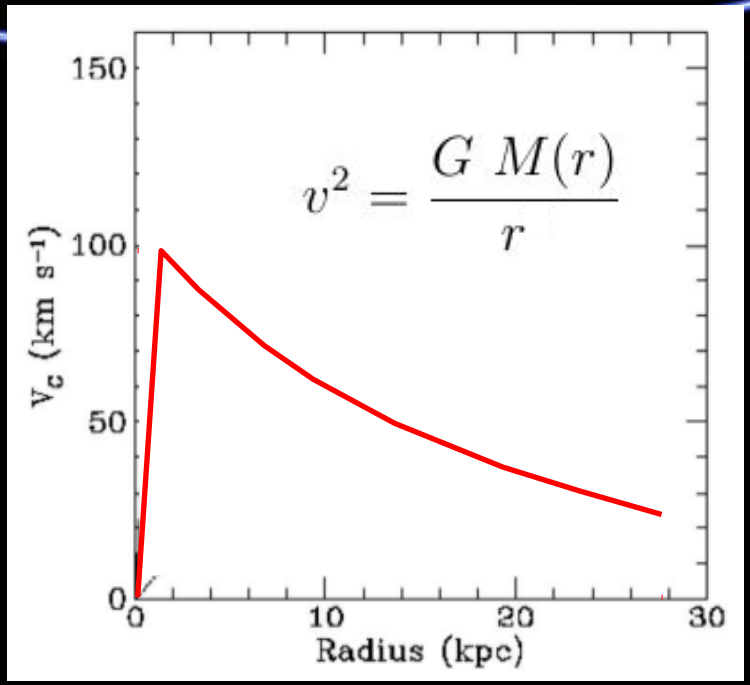


about 100'00 dark matter particles cross an area of 1 cm² per second

Part 1 – Evidence for Dark Matter

Expect: Kepler Rotation
(as solar system)



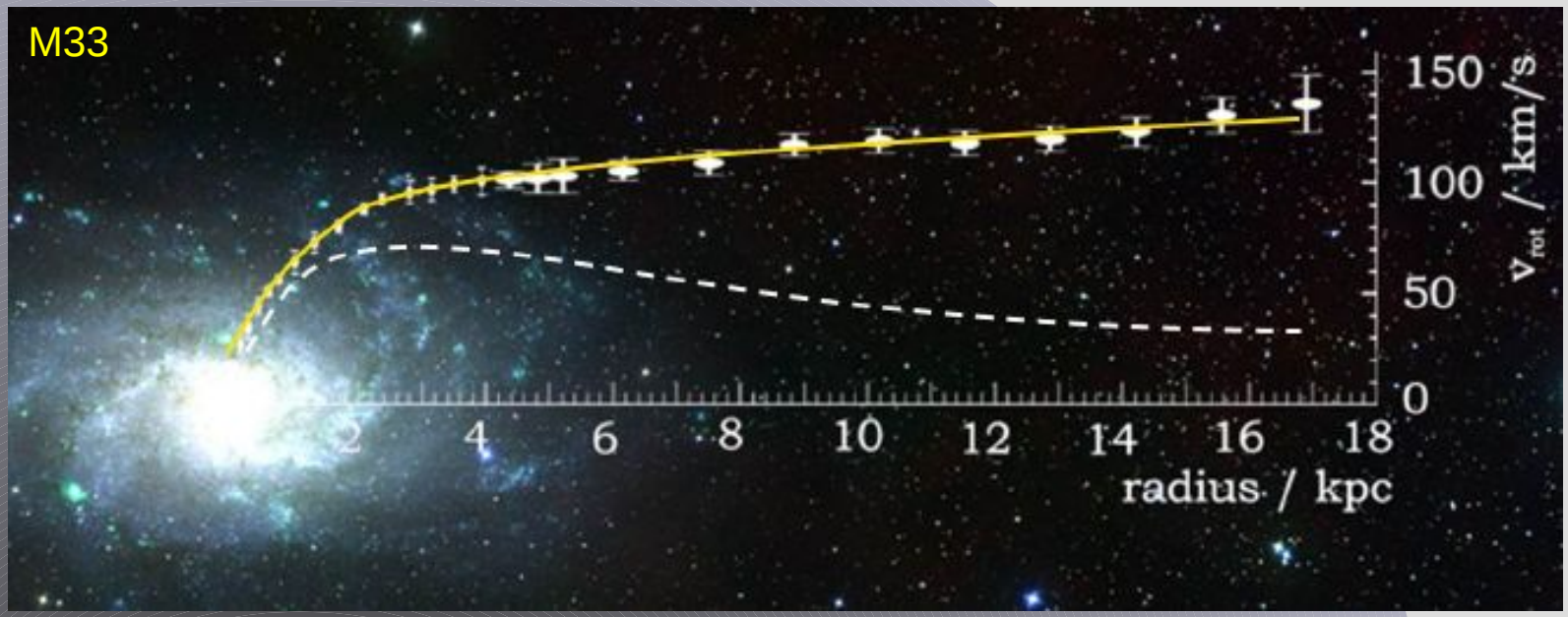


Expectation

Observation

Galactic Rotation Curves

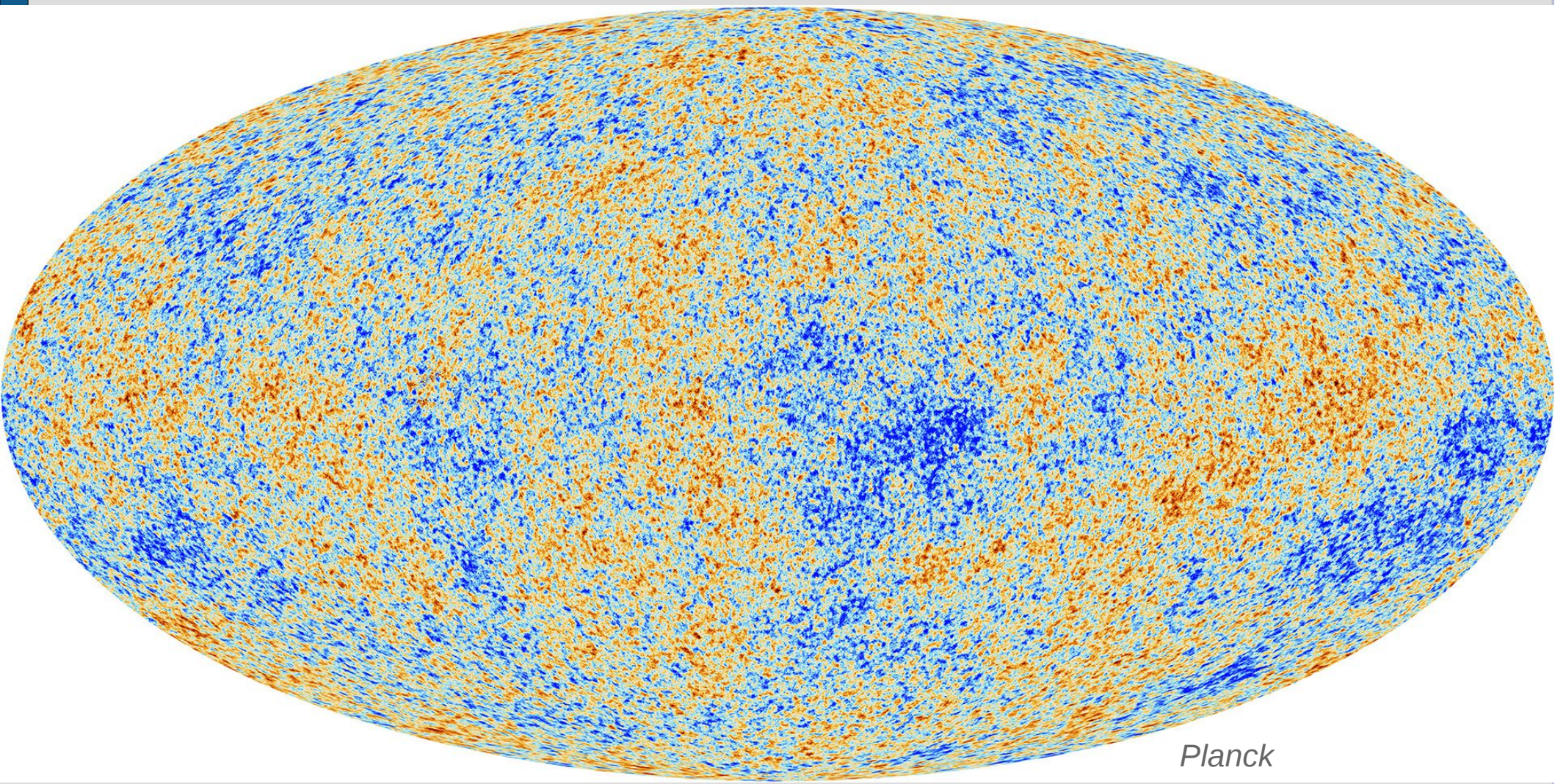
Measurement: flat rotation profile … well beyond visible stars



„Halo“ made from Dark Matter
(isothermal sphere, $\rho \sim 1/r^2$)

Cosmic Microwave Background

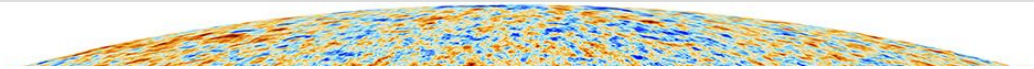
= afterglow of the hot big bang; variations at $\Delta T/T \sim 10^{-5}$ level



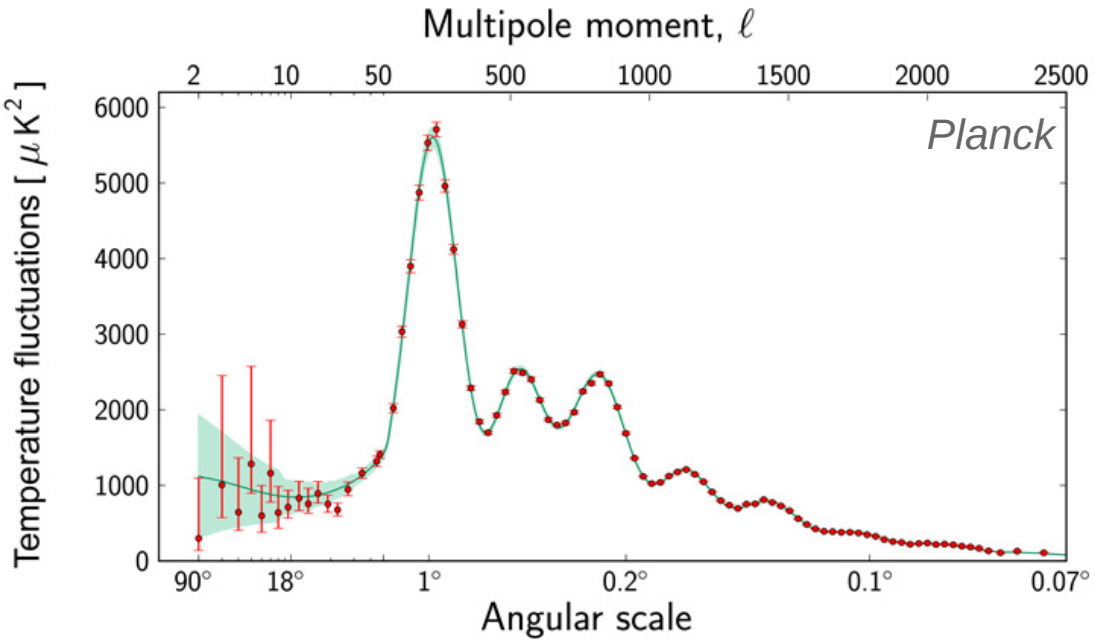
Planck

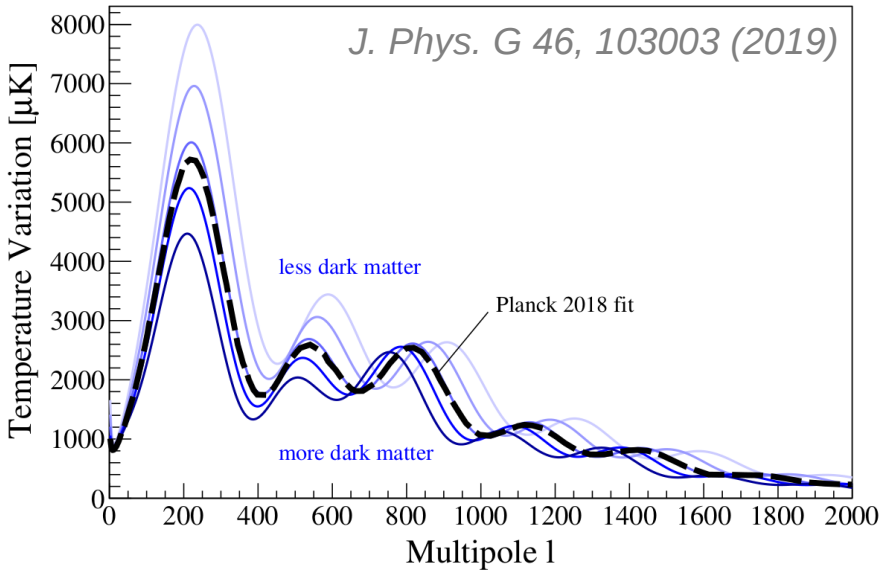
Cosmic Microwave Background

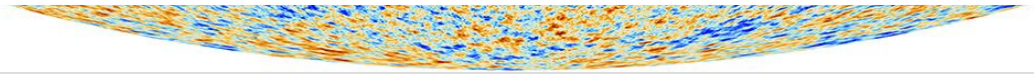
= afterglow of the hot big bang; variations at $\Delta T/T \sim 10^{-5}$ level



Correlation Analysis:
„typical *T* variation at typical angular scale“

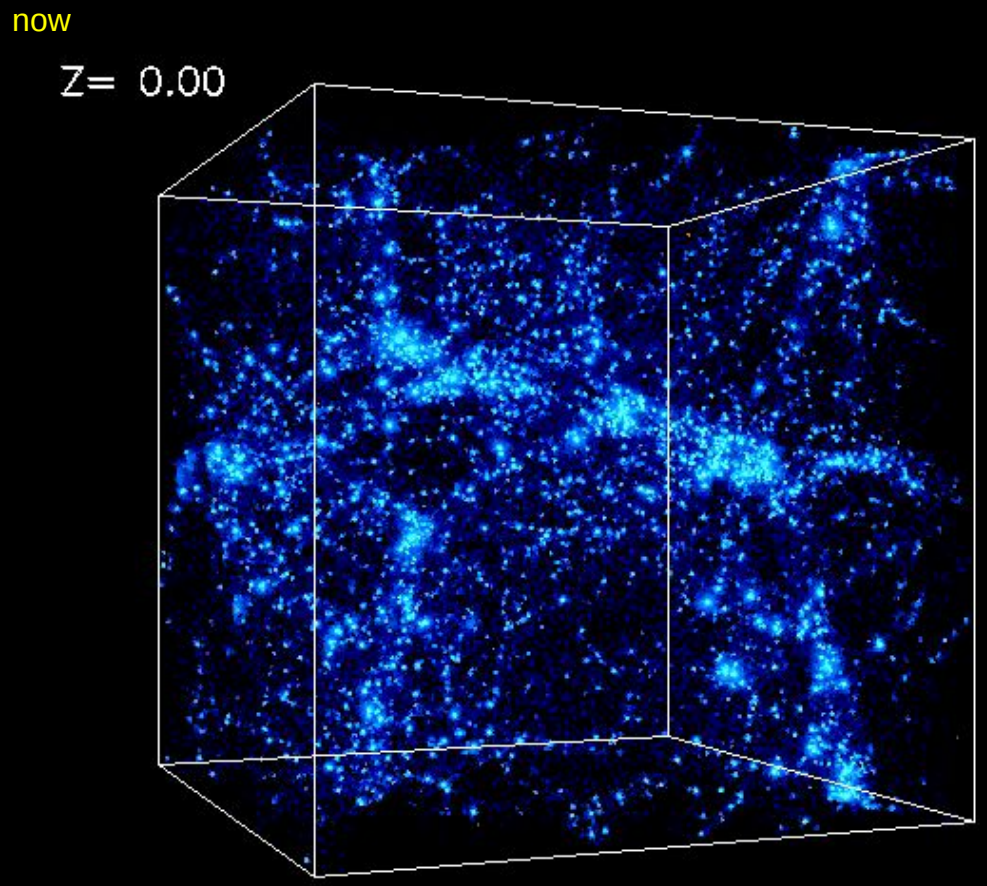


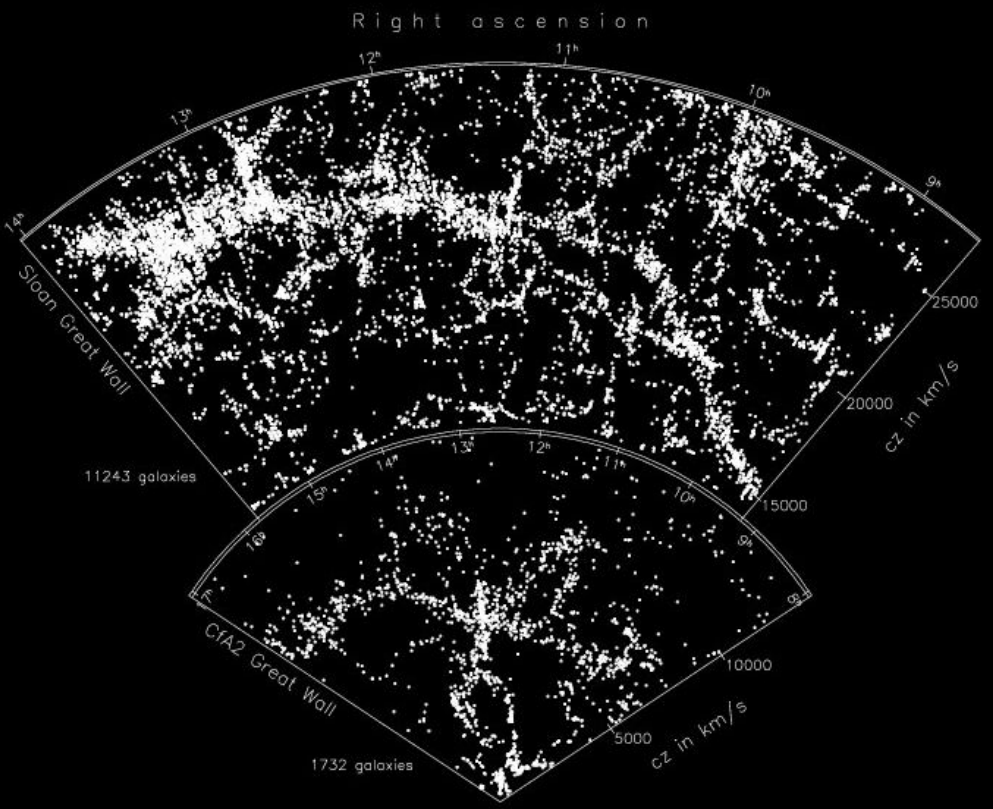




Planck

Dark Matter shapes the Universe





http://cosmicweb.uchicago.edu

Simulation

Observation (SDSS)

WANTED

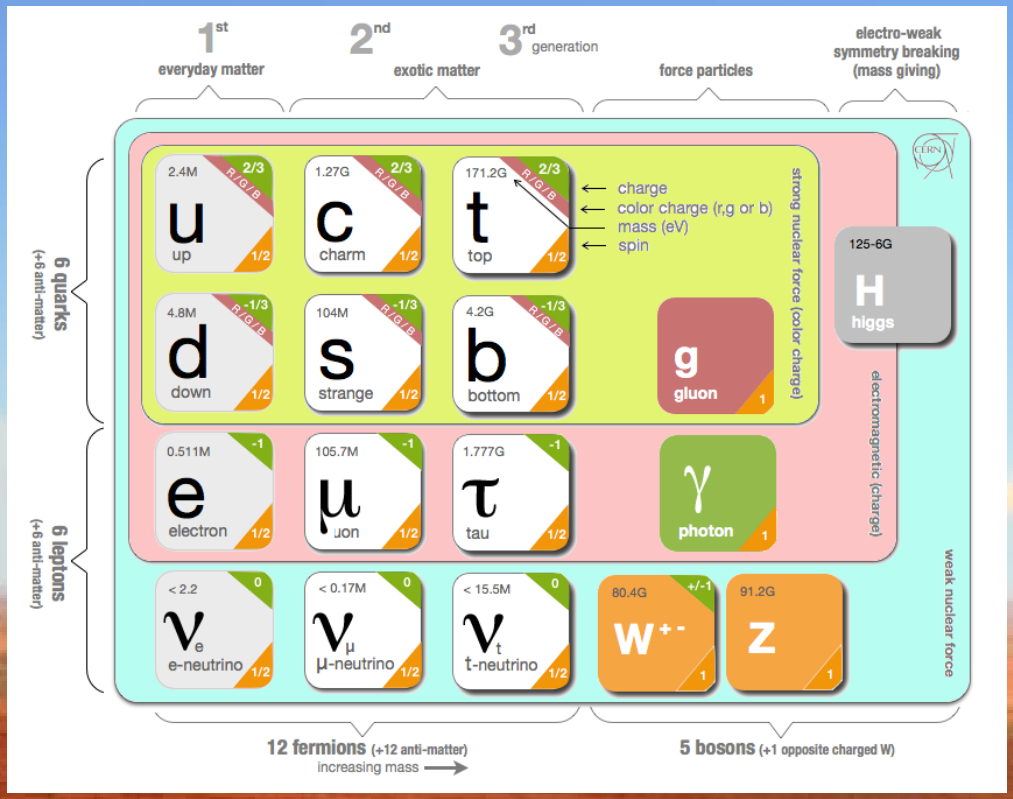
FOR MOVING THE UNIVERSE

DARK MATTER

Looking for matter with the following properties:

- „invisible“
- „cold“ (= „slow“)
- almost collisionless
- stable

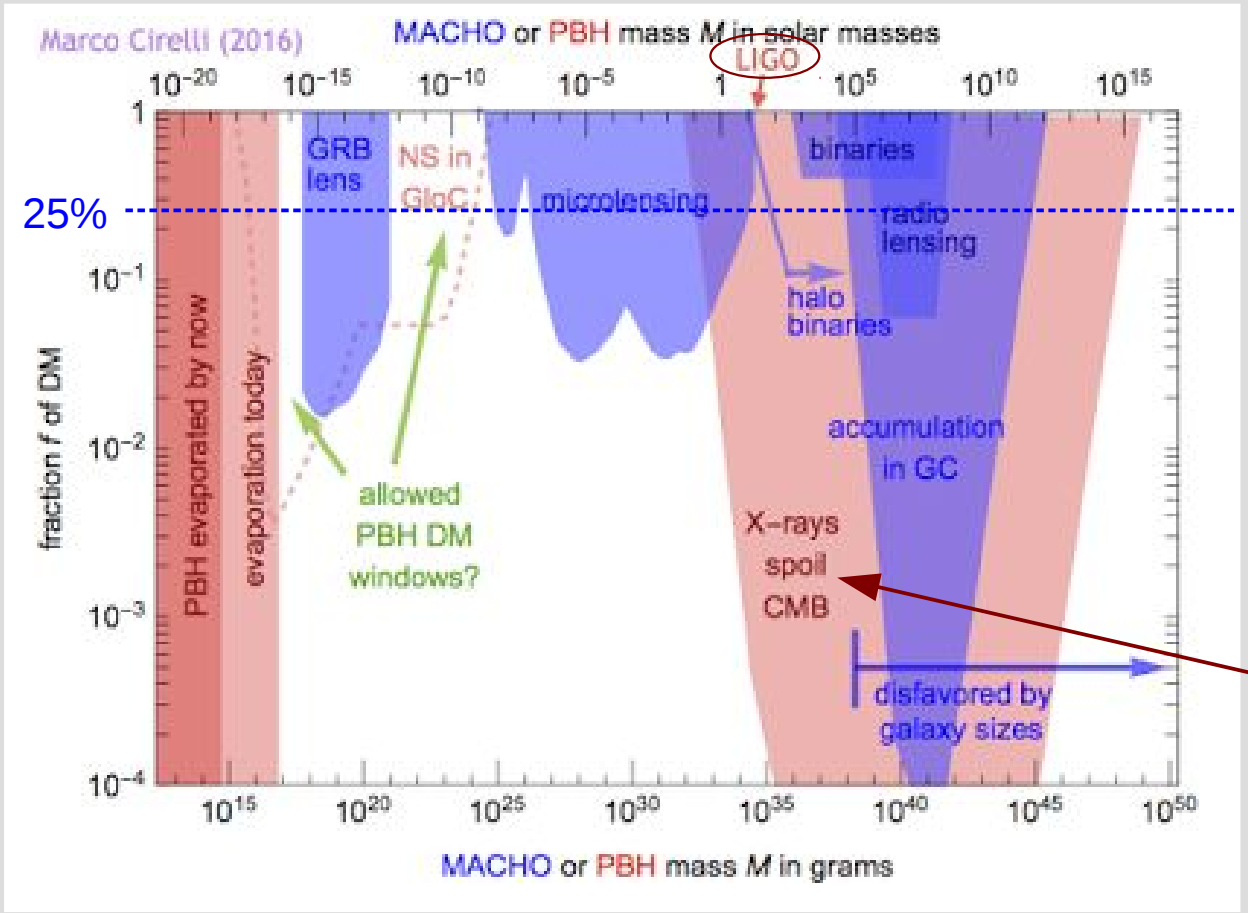
REWARD: NOBLE PRICE?

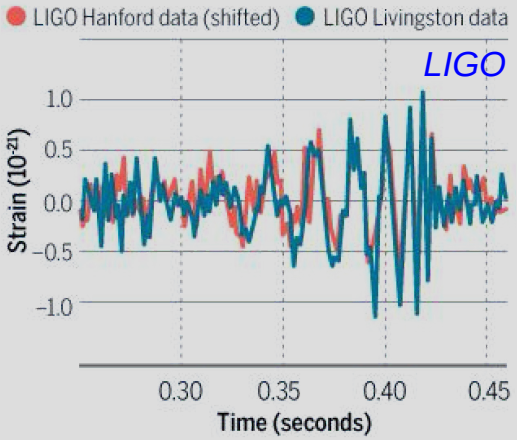


Problem:
no known particle fits the description
→ **we need to look for something new**
weakly **i**nteracting **m**assive **p**article (WIMP)

Primordial Black Holes?

Can primordial black holes (PBH) formed in the big bang be the dark matter?





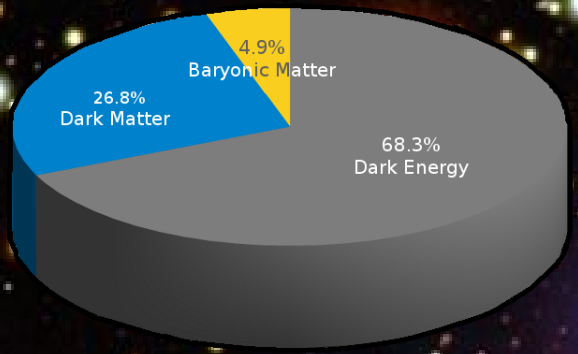
Black holes moving in early dense universe accrete matter and produce X-rays
→ ionize atoms
→ affect CMB

constraints in 10-100 M_{sun} range (LIGO):

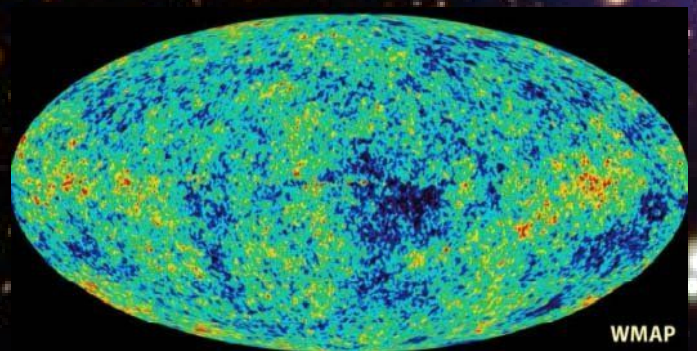
– **PBHs cannot constitute >0.01% of dark matter** *Astrophys.J. 680, 829 (2008)*

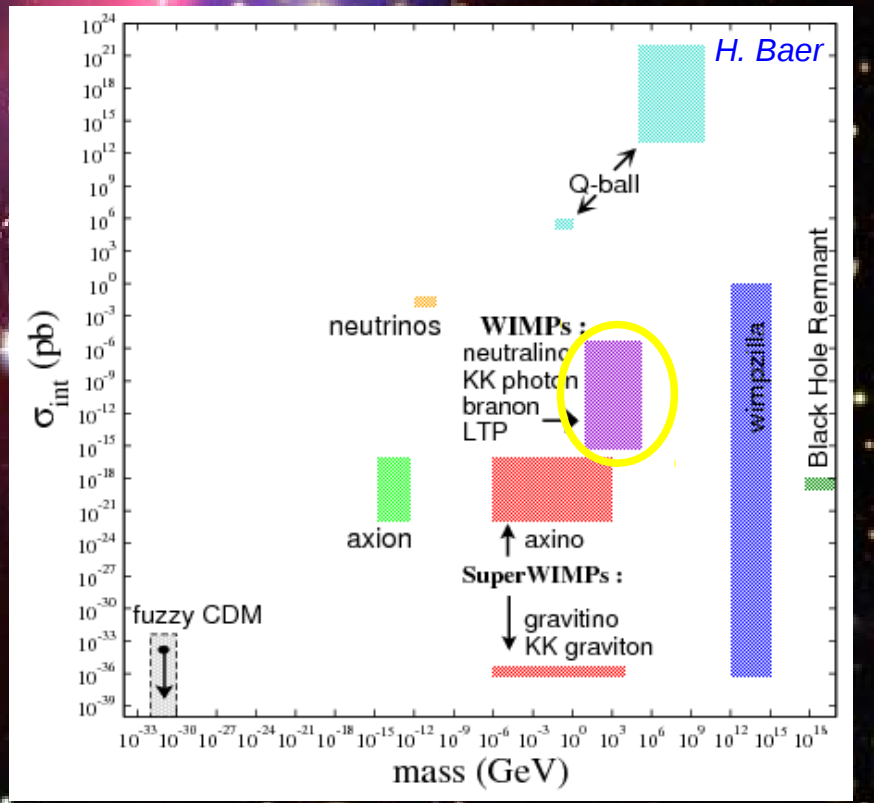
– *but*: new discussion about PBH dark matter started *PRL 116, 201301 (2016)*
maybe PBH not dark matter but faster merger rate *PRL 117, 061101 (2016)*

Dark Matter: (indirect) Evidence



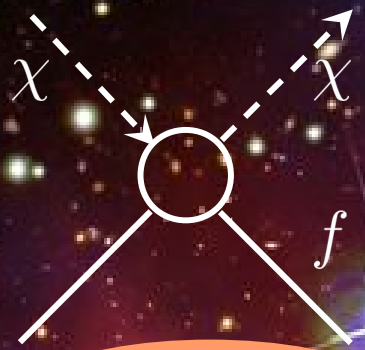
Particle Dark Matter Candidates:
- **WIMP** → *„WIMP miracle“*
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...

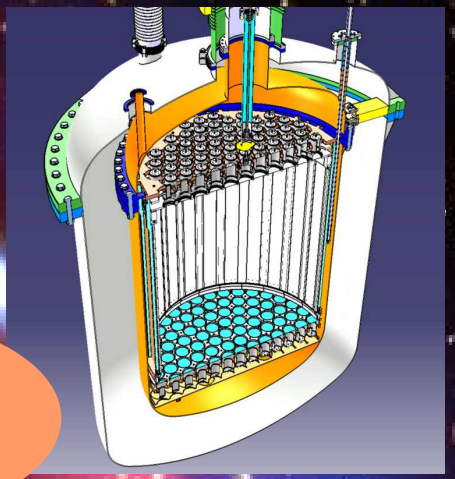




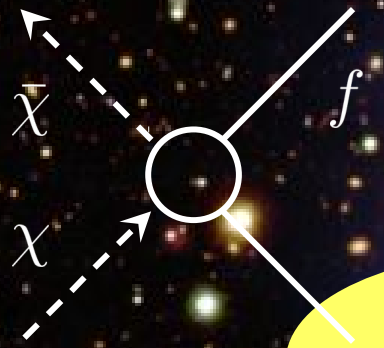
Part 2 – Searching for Dark Matter

Dark Matter Search

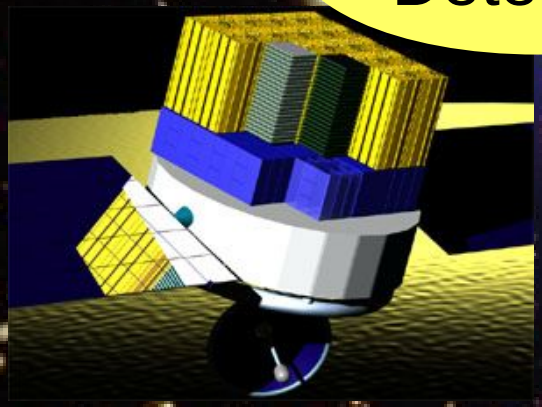




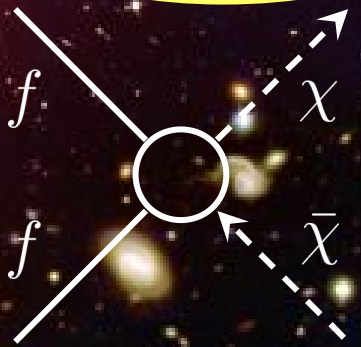
Direct Detection

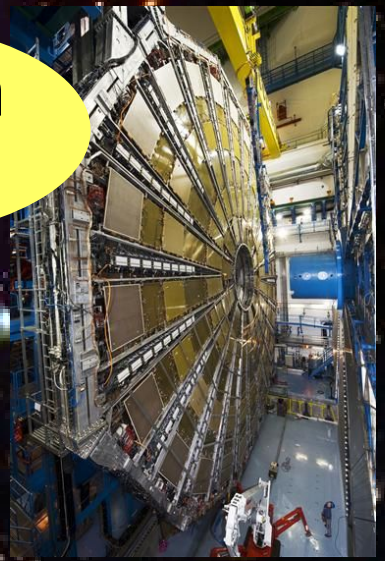


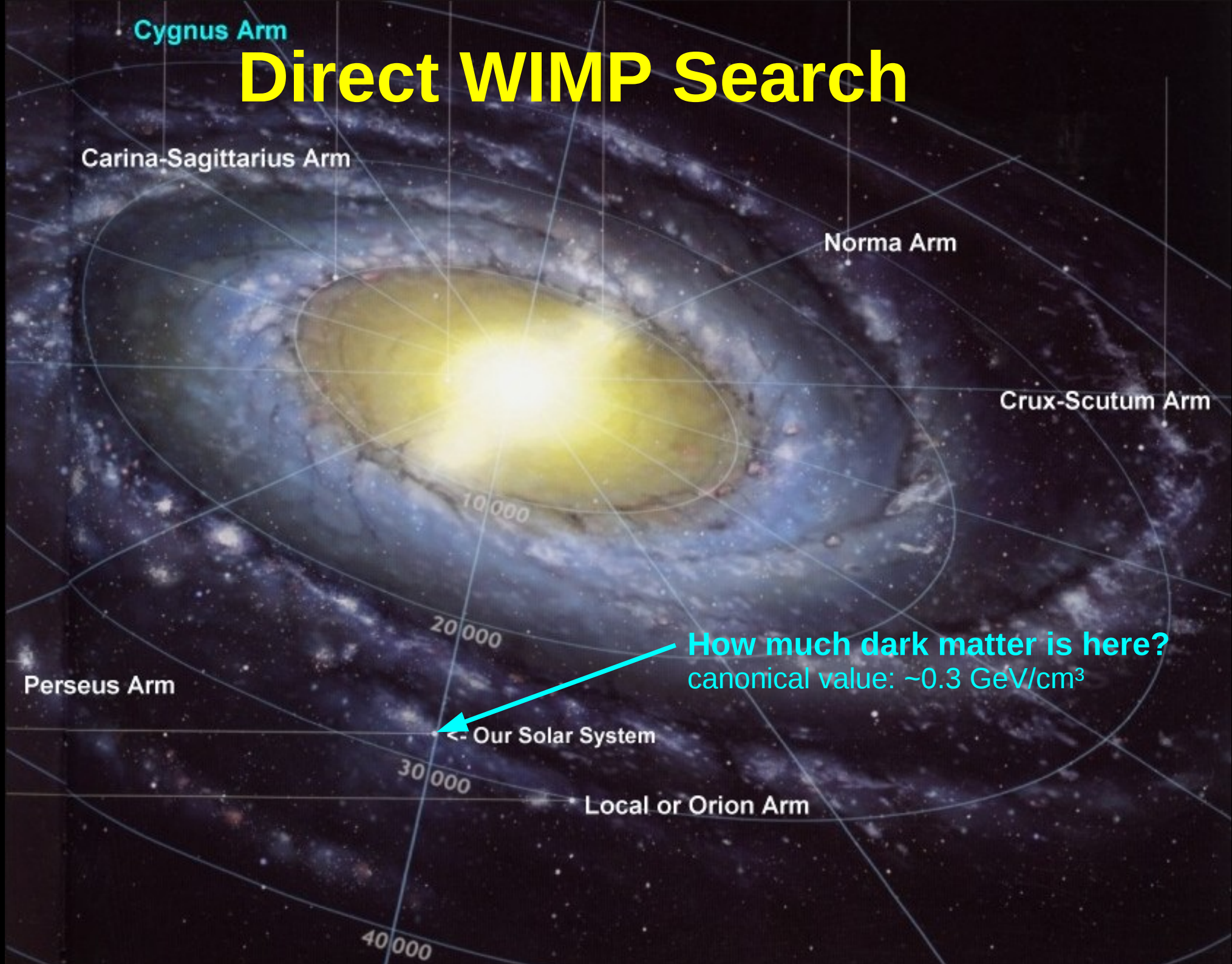
Indirect Detection



Production @Collider

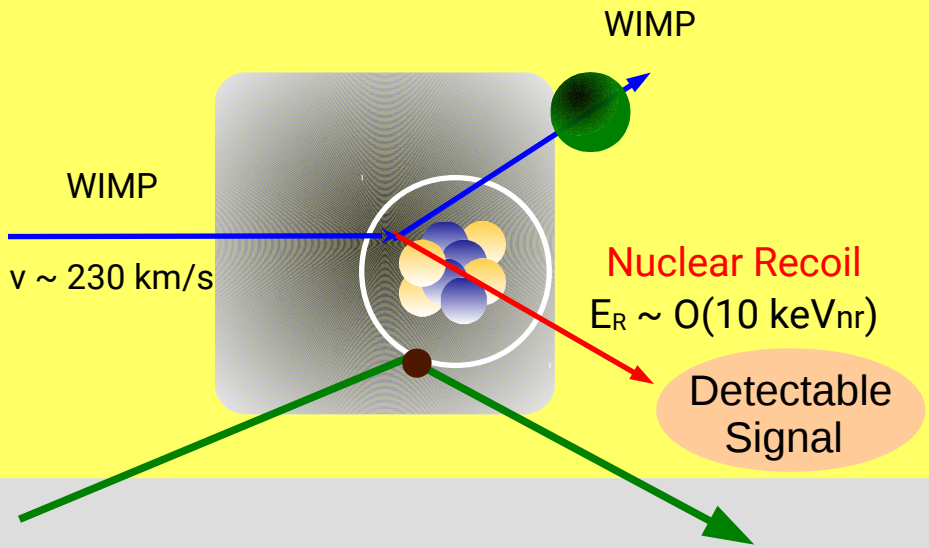


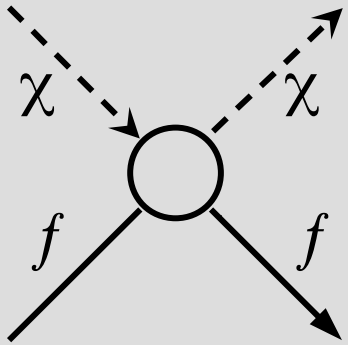



Cygnus Arm
Direct WIMP Search
Carina-Sagittarius Arm
Norma Arm
Crux-Scutum Arm
10 000
20 000
How much dark matter is here?
canonical value: ~0.3 GeV/cm³
Perseus Arm
<- Our Solar System
30 000
Local or Orion Arm
40 000

Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil

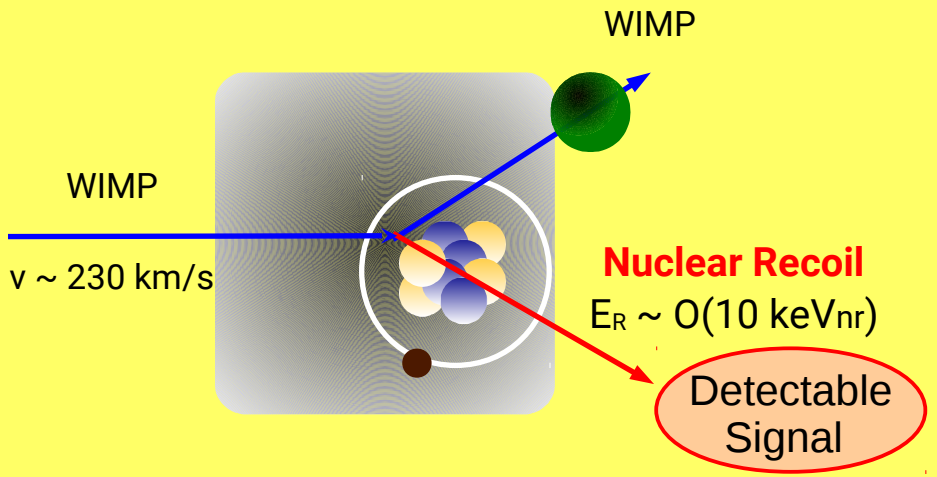


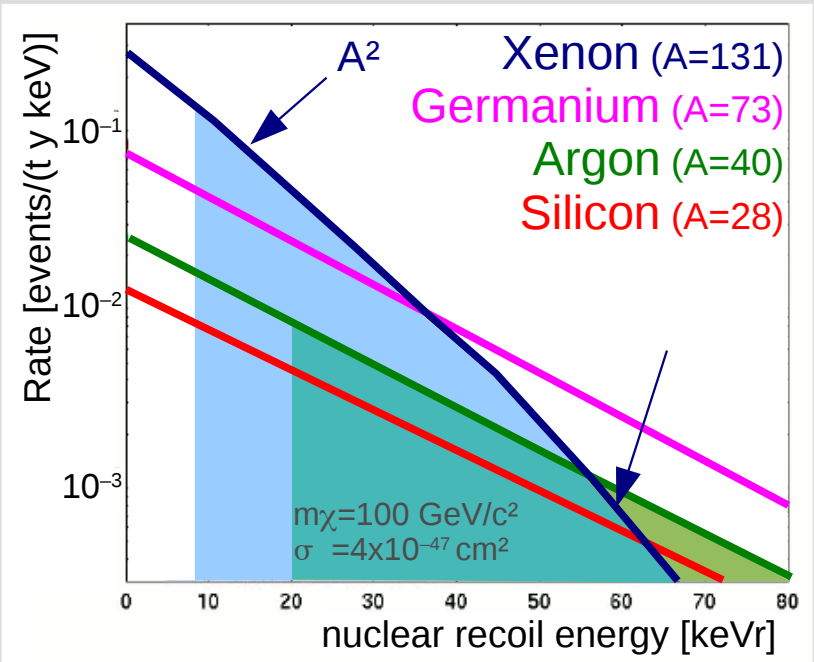


gamma- and beta-particles (background) interact with the atomic electrons
→ **electronic recoil** [in keVee]

Direct WIMP Search

Elastic Scattering of
WIMPs off target nuclei
➡ nuclear recoil





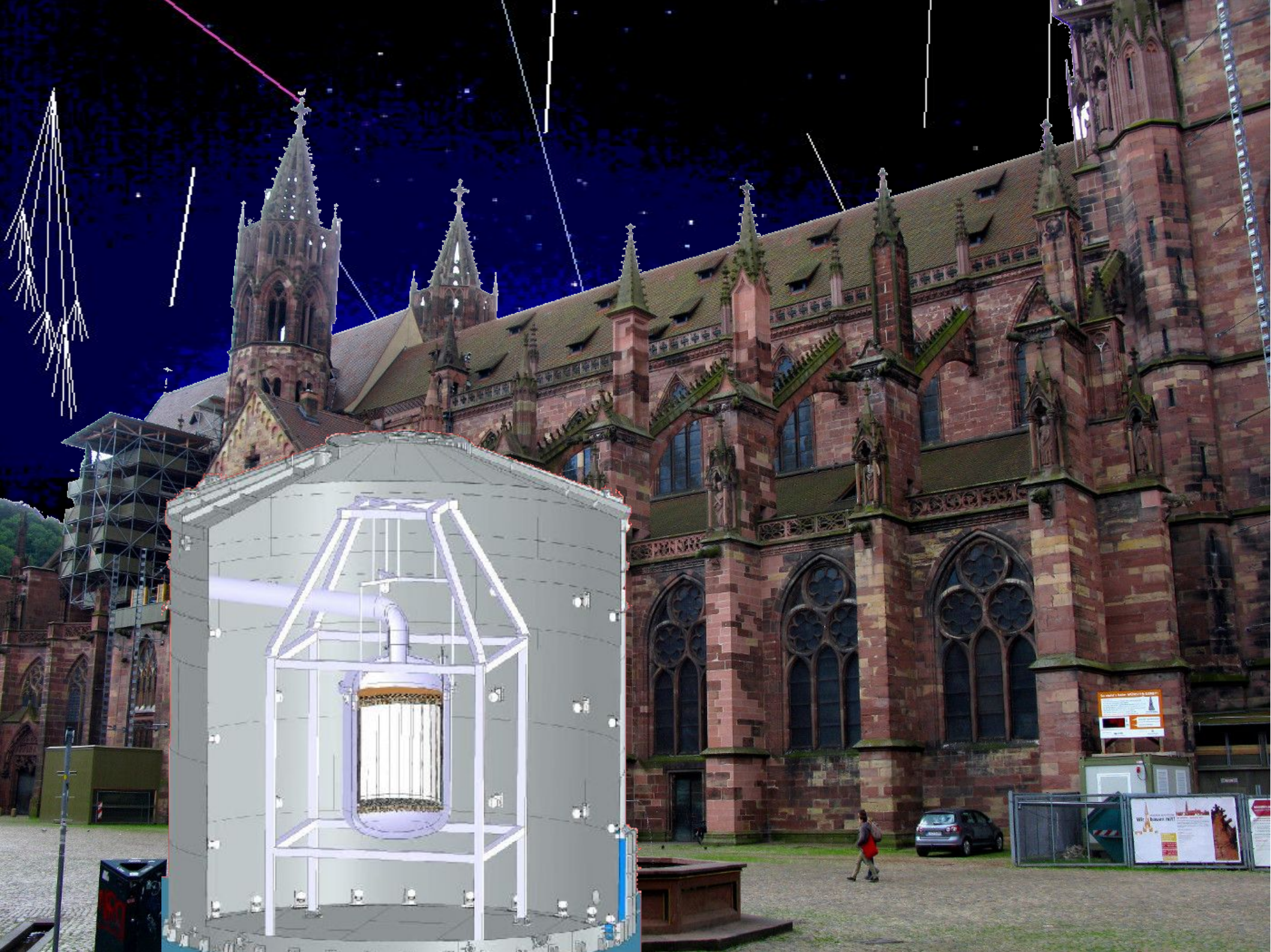
Event rate

$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$$

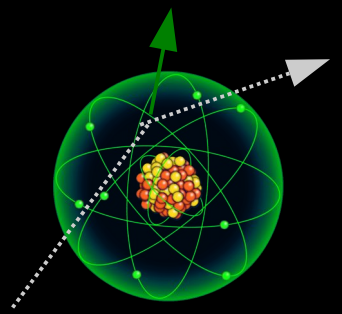
Detector — Local DM Density — Physics

ρ_χ~0.3 GeV/c^2

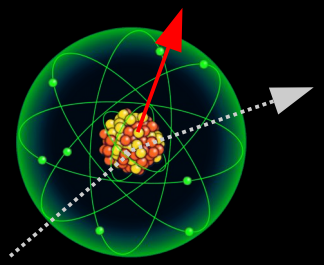
→ very small: ≪1 event/kg/year
→ search for rare events
→ **low-background crucial**



Background Sources

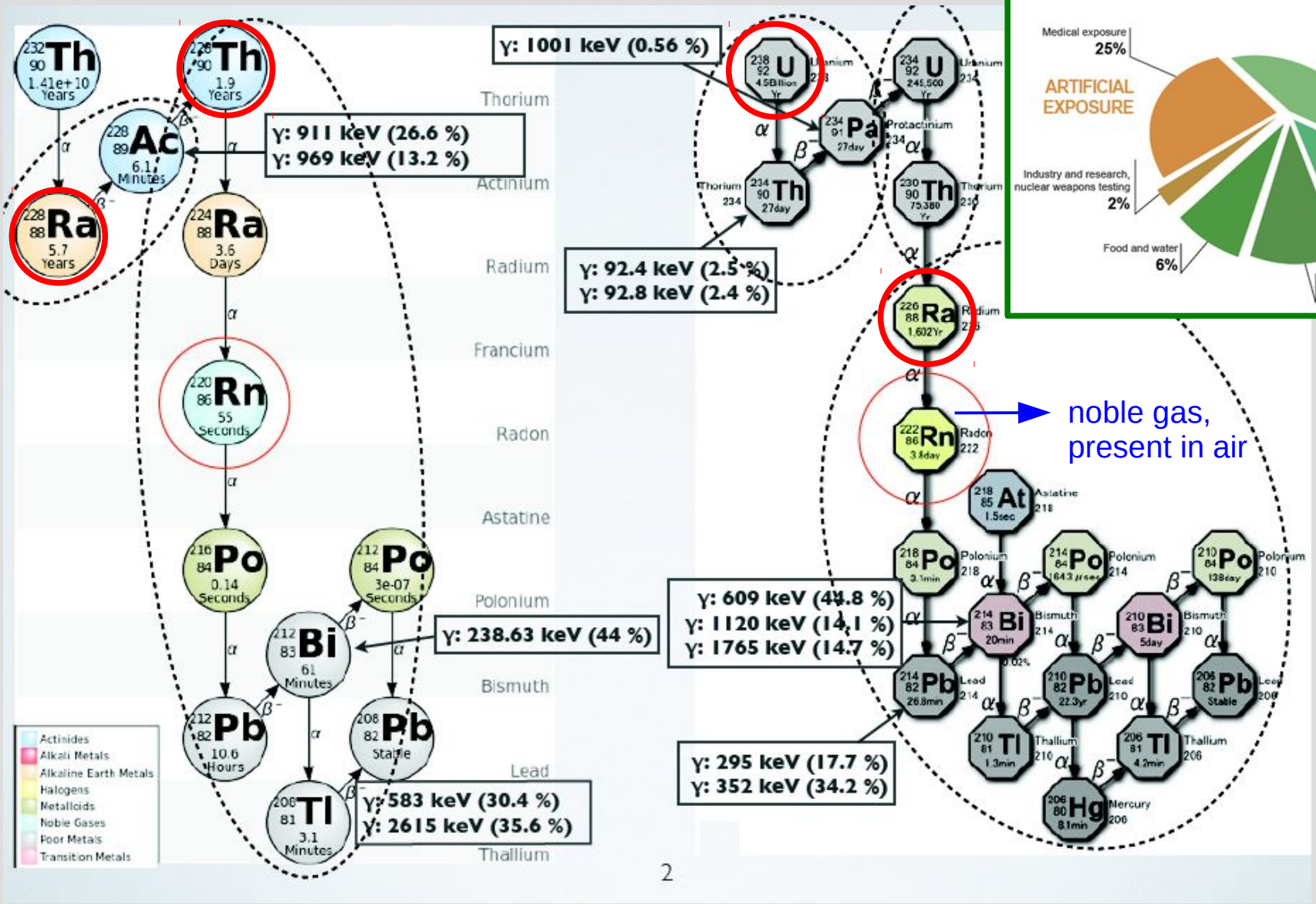


Electronic Recoils (gamma, beta)



Nuclear Recoils (neutron, WIMPs)

The U and Th Chains



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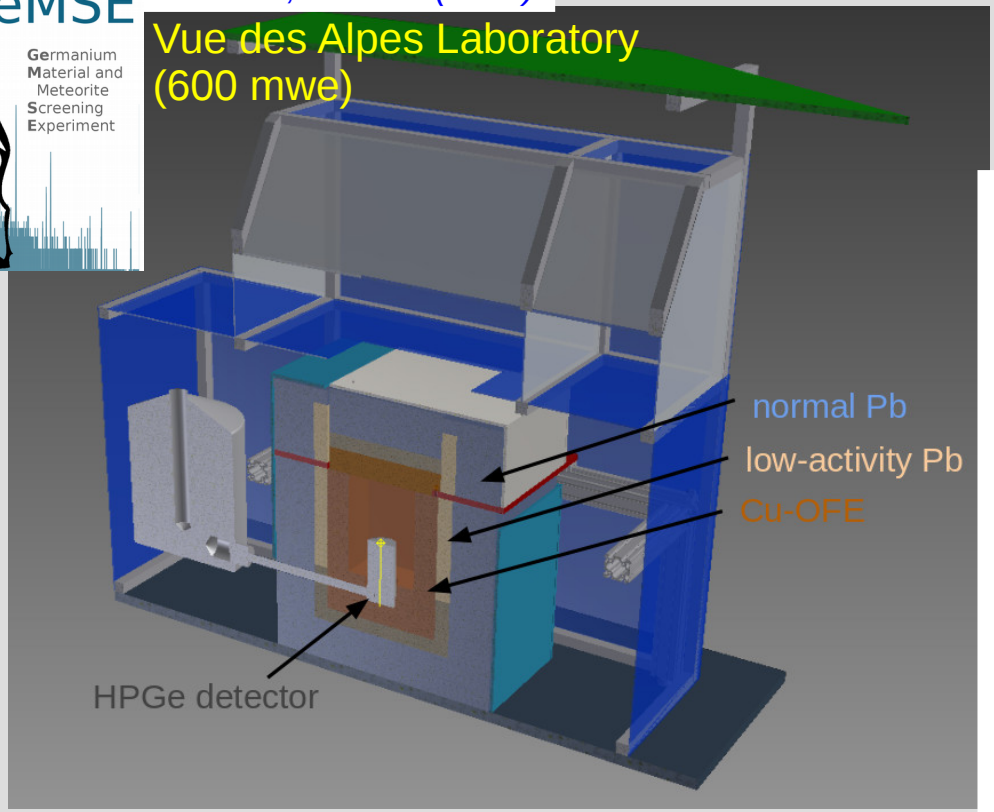
UNIVERSITÄT
BERN

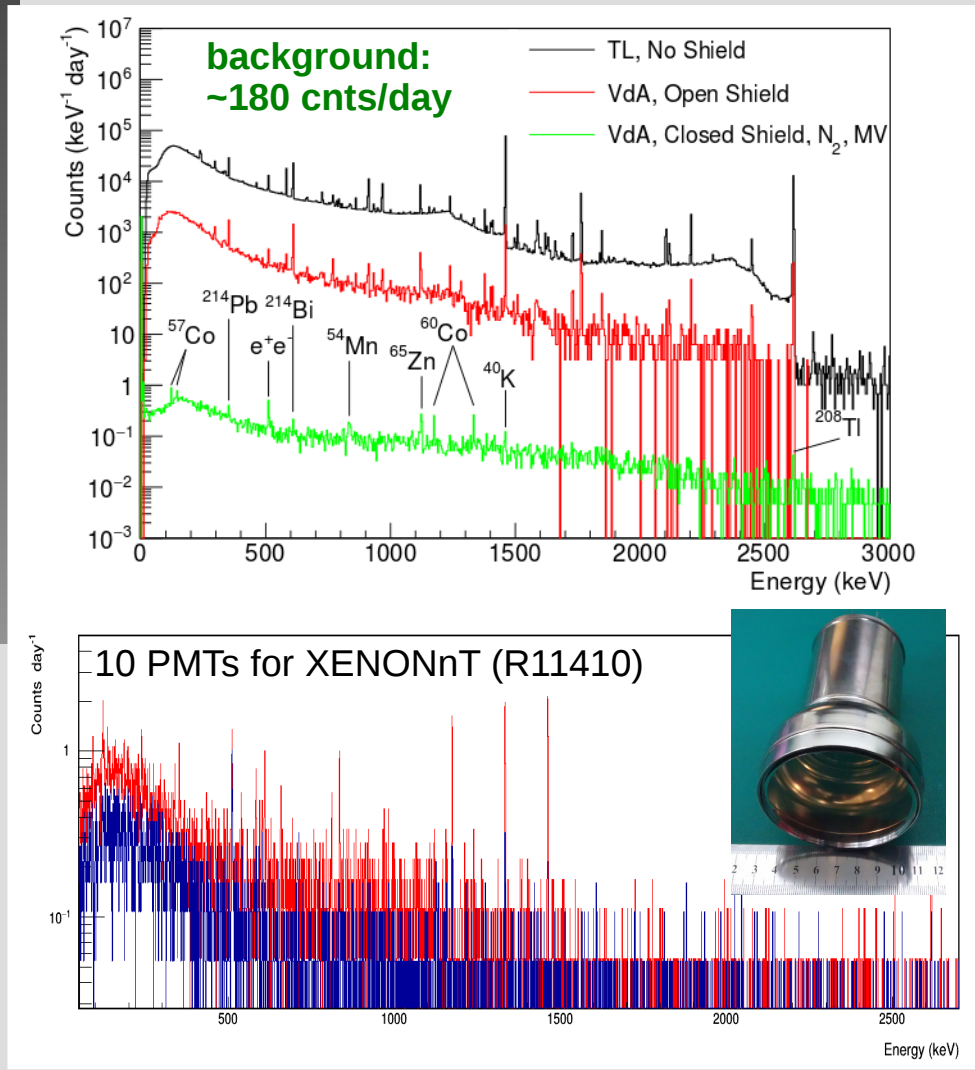
AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

Low-background Screening

GeMSE
Germanium Material and Meteorite Screening Experiment

JINST 11, P12017 (2016)





Identify materials with lowest radioactivity:

- γ-spectrometry using HPGe Detectors
- mass spectroscopy: ICP-MS, GDMS
- neutron activation analysis
- ^{222}Rn emanation

Background Sources

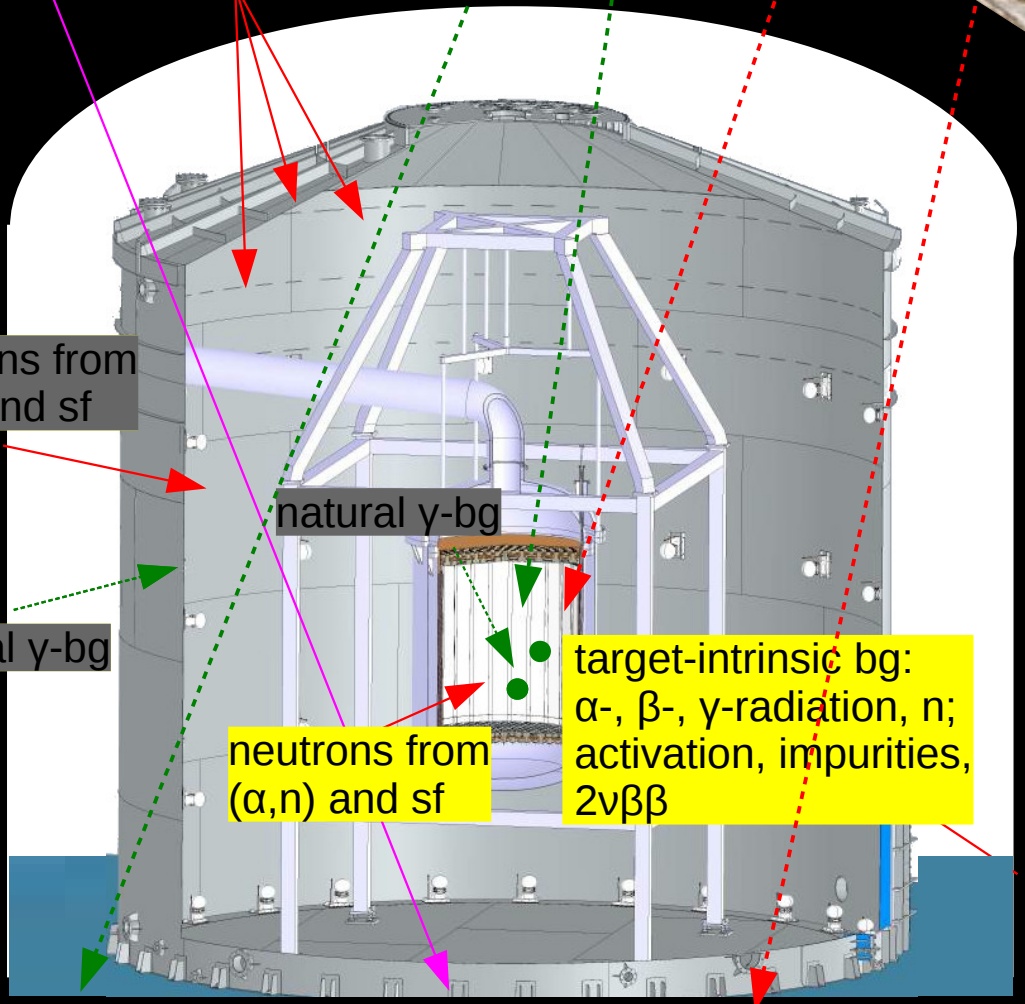
solar neutrino flux:
~6.4 x 10^{10} $s^{-1}cm^{-2}$

muons

high-E neutrinos
→ CNNS bg
→ **NR signature**

pp+^{7}Be neutrinos
→ **ER signature**

muon-induced neutrons



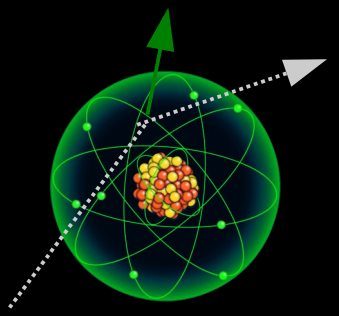
neutrons from (α,n) and sf

natural γ-bg

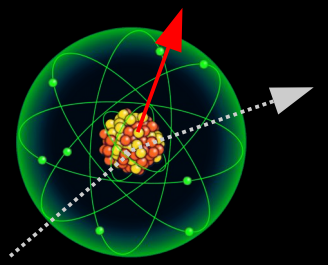
natural γ-bg

target-intrinsic bg:
α-, β-, γ-radiation, n;
activation, impurities,
2νββ

neutrons from (α,n) and sf



Electronic Recoils
(gamma, beta)



Nuclear Recoils
(neutron, WIMPs)

Background Suppression

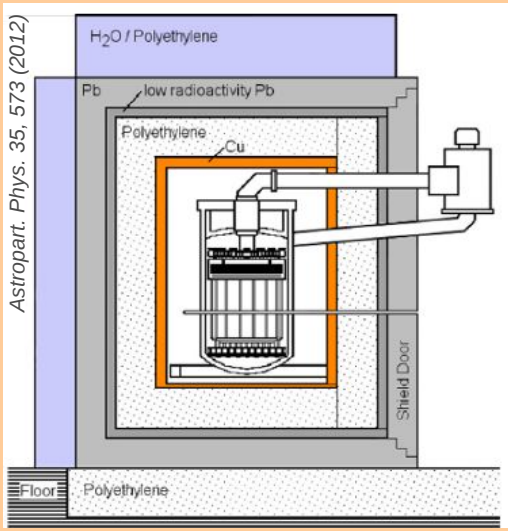
Avoid Backgrounds

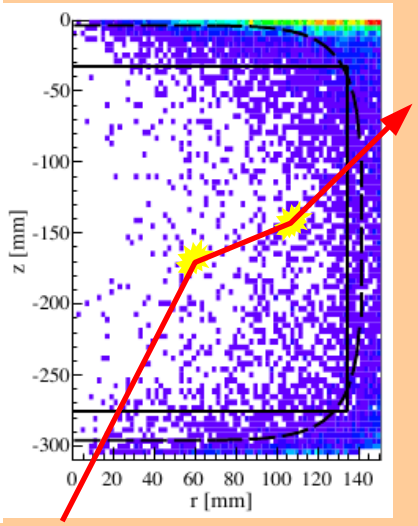
Shielding

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

self shielding → fiducialization

Use of radiopure materials





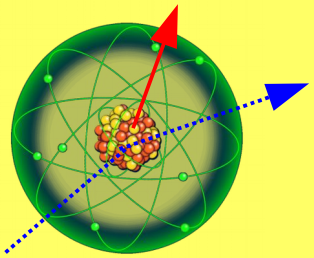
Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection
requires some position resolution

WIMPs interact with target nuclei

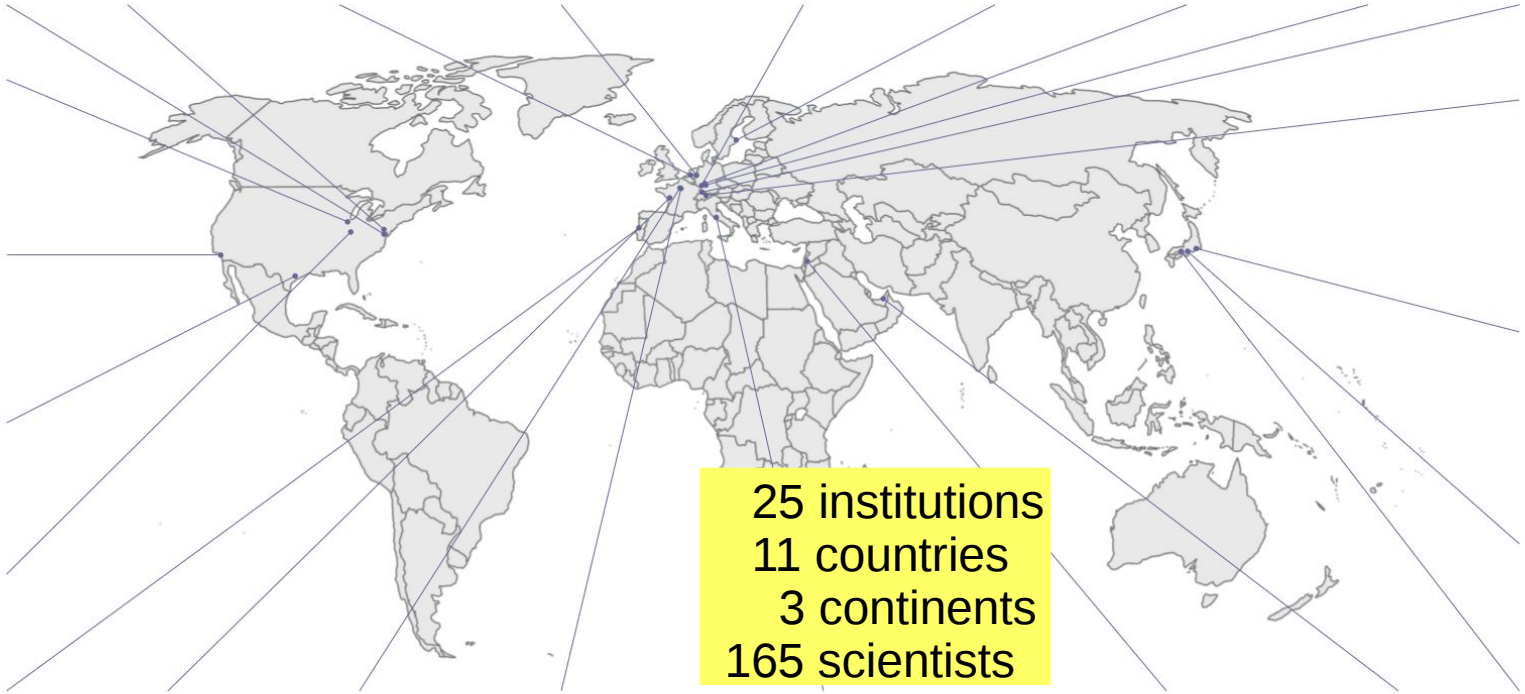
→ nuclear recoils
exploit different d*E*/d*x* from
signal and background



Part 3 – The XENON Experiment

Die XENON Kollaboration

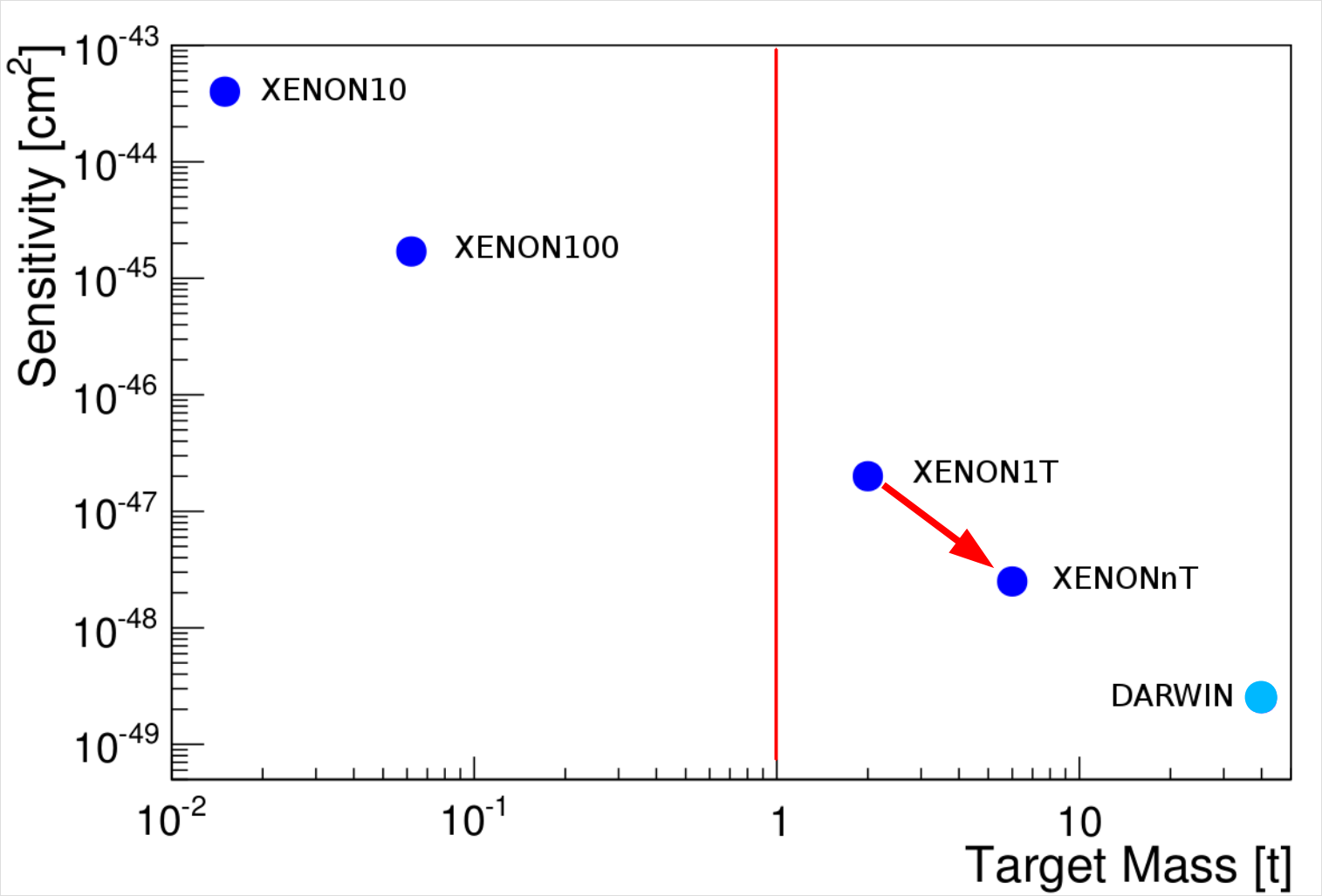
www.xenon1t.org



25 institutions
11 countries
3 continents
165 scientists

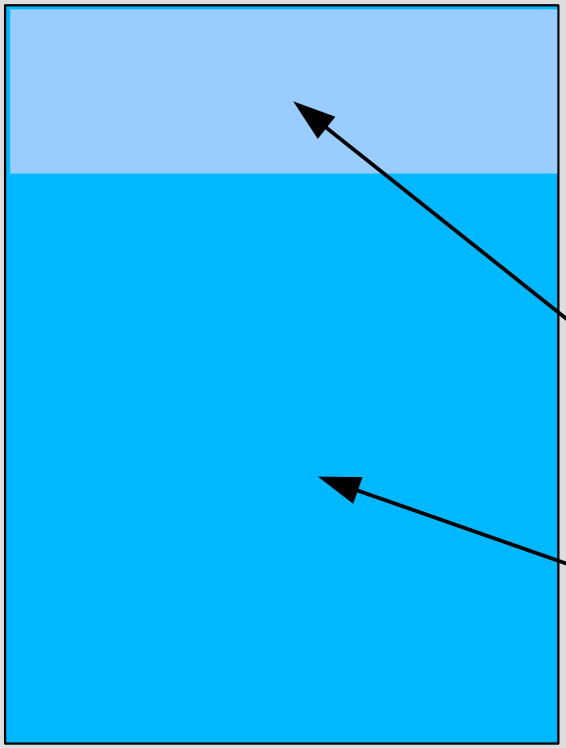
Columbia, RPI, Nikhef, Muenster, KIT, Stockholm, Mainz, MPIK, Heidelberg, Freiburg, Chicago, UCSD, Rice, Purdue, Zurich, Tokyo, Nagoya, Coimbra, Subatech, LPNHE, LAL, Bologna, LNGS, Torino, Napoli, Weizmann, NYUAD, Kobe

XENON Detektoren



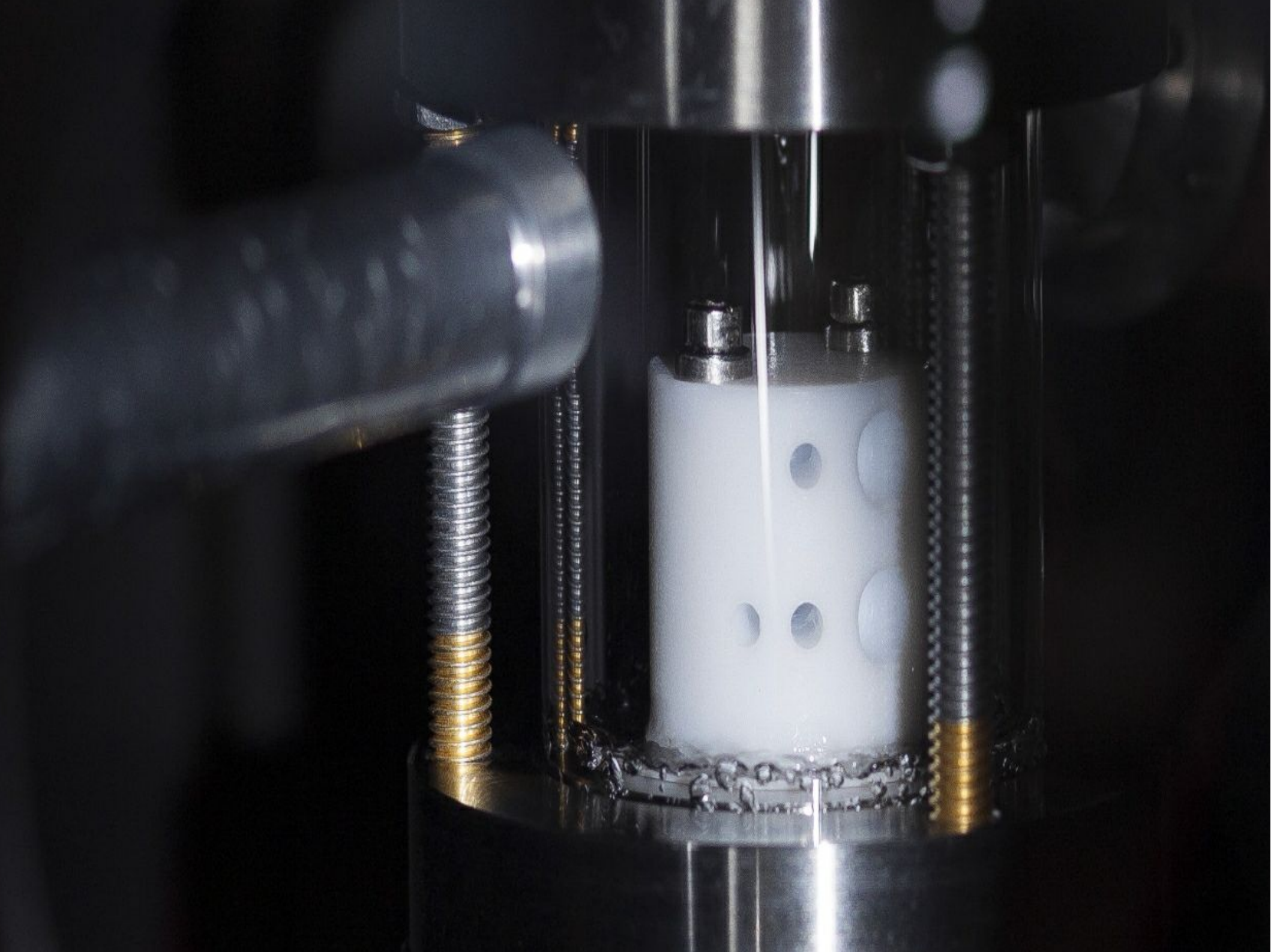
Die XENON Kollaboration entwickelt und betreibt
immer größere und empfindlichere Dunkle Materie Detektoren.

Dual Phase liquid xenon TPC

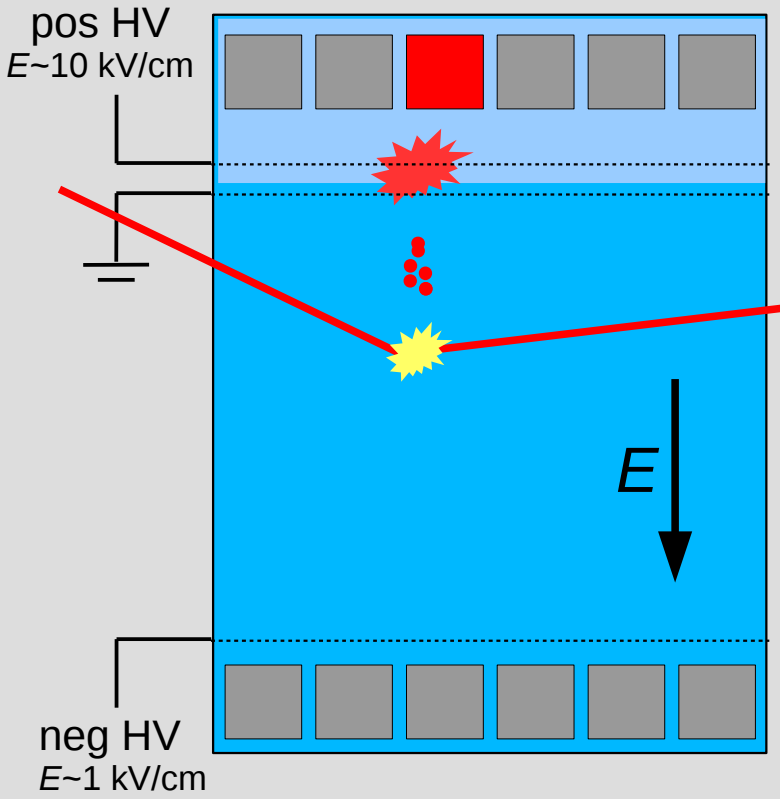


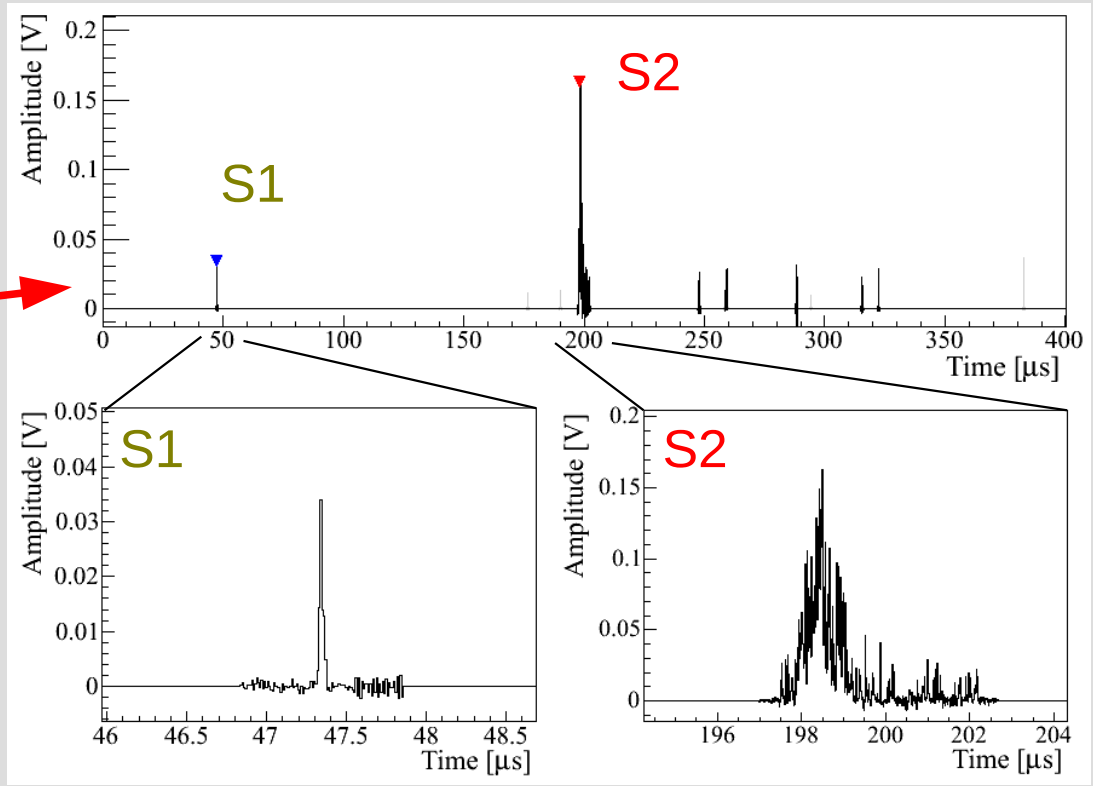
gaseous xenon

liquid xenon (**LXe**)

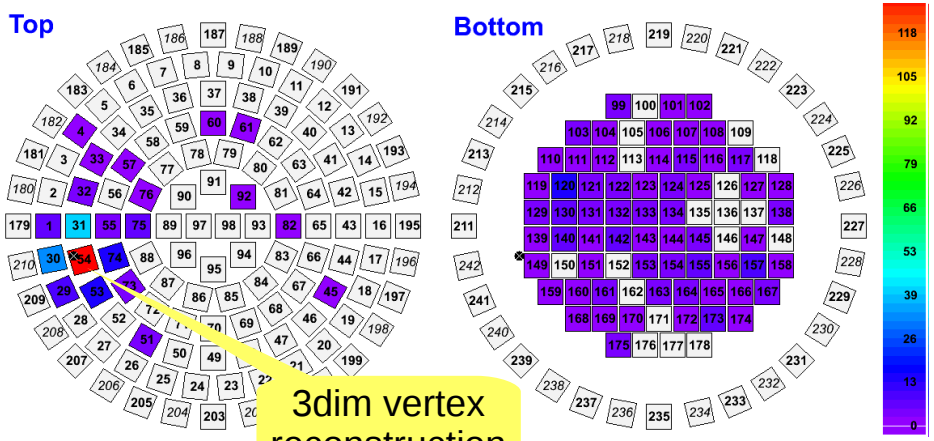


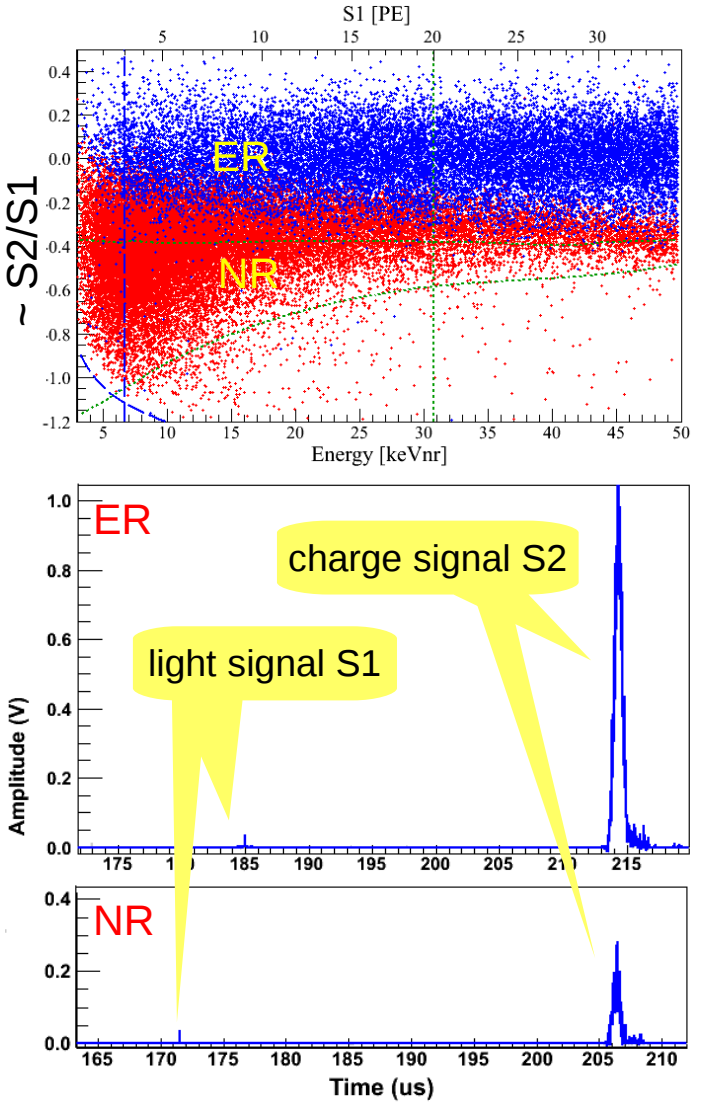
Dual Phase TPC





Dual Phase TPC

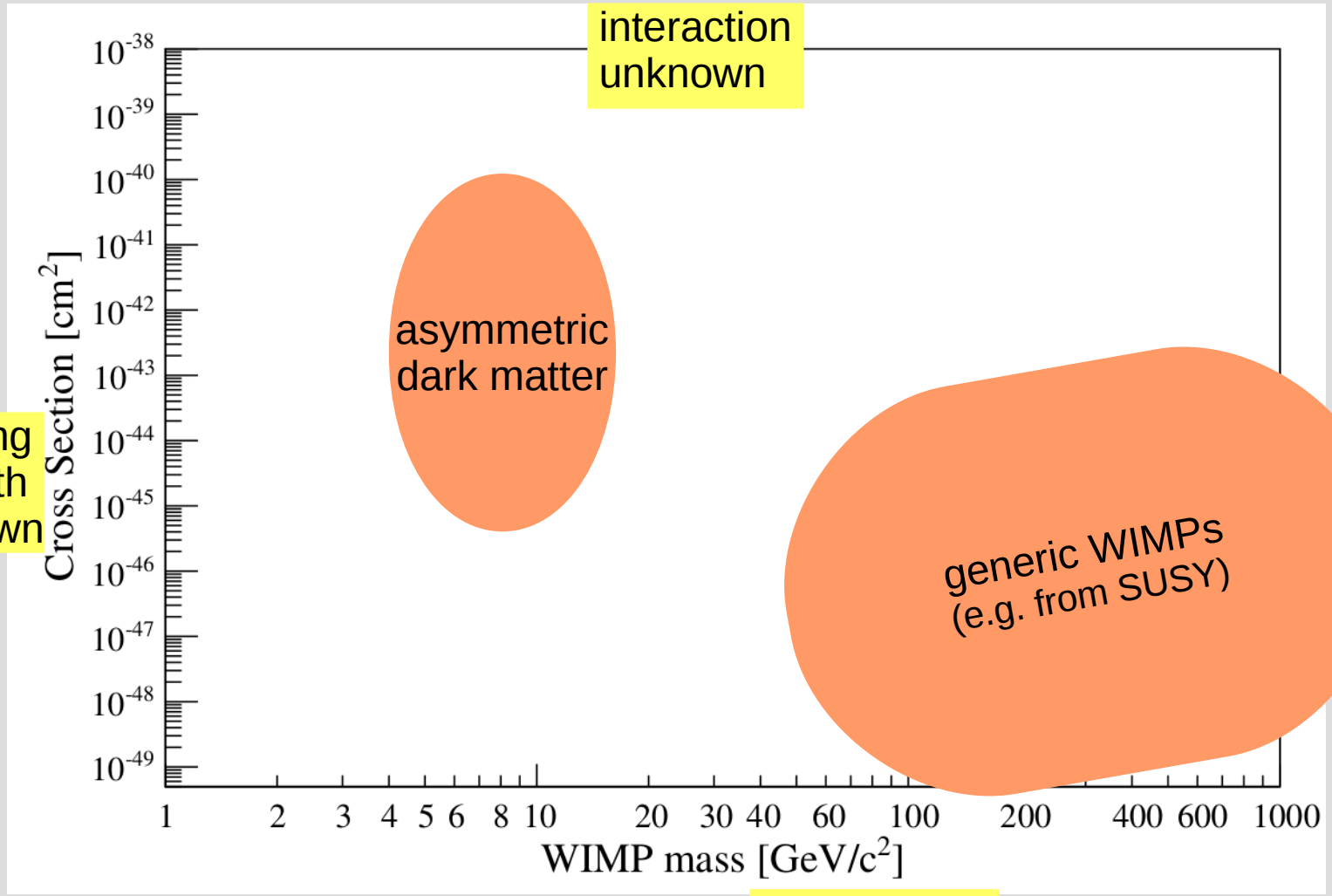




Figures from XENON100

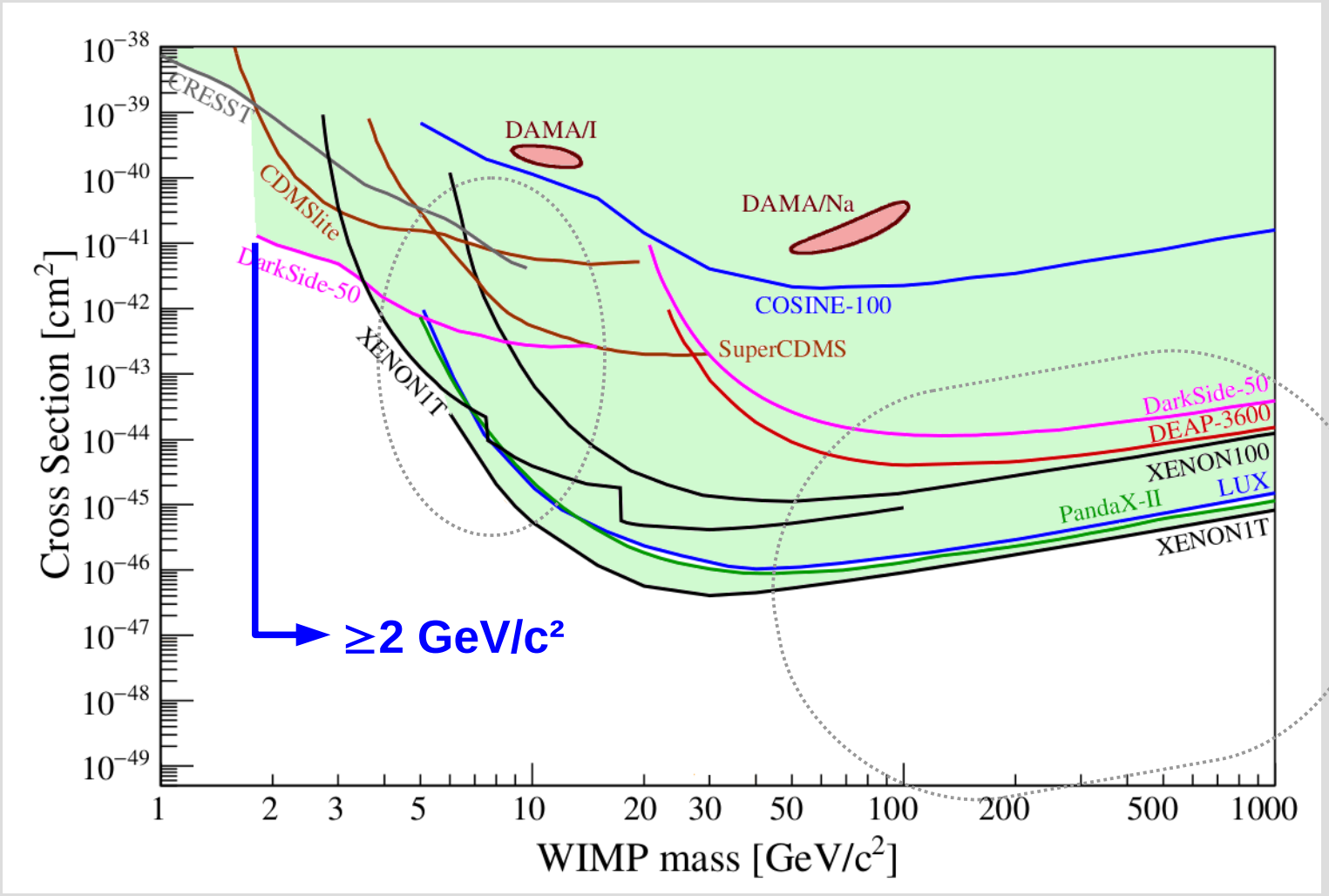
The WIMP Parameter Space

spin-independent WIMP-nucleon interactions



High WIMP-masses TPC dominated

spin-independent WIMP-nucleon interactions



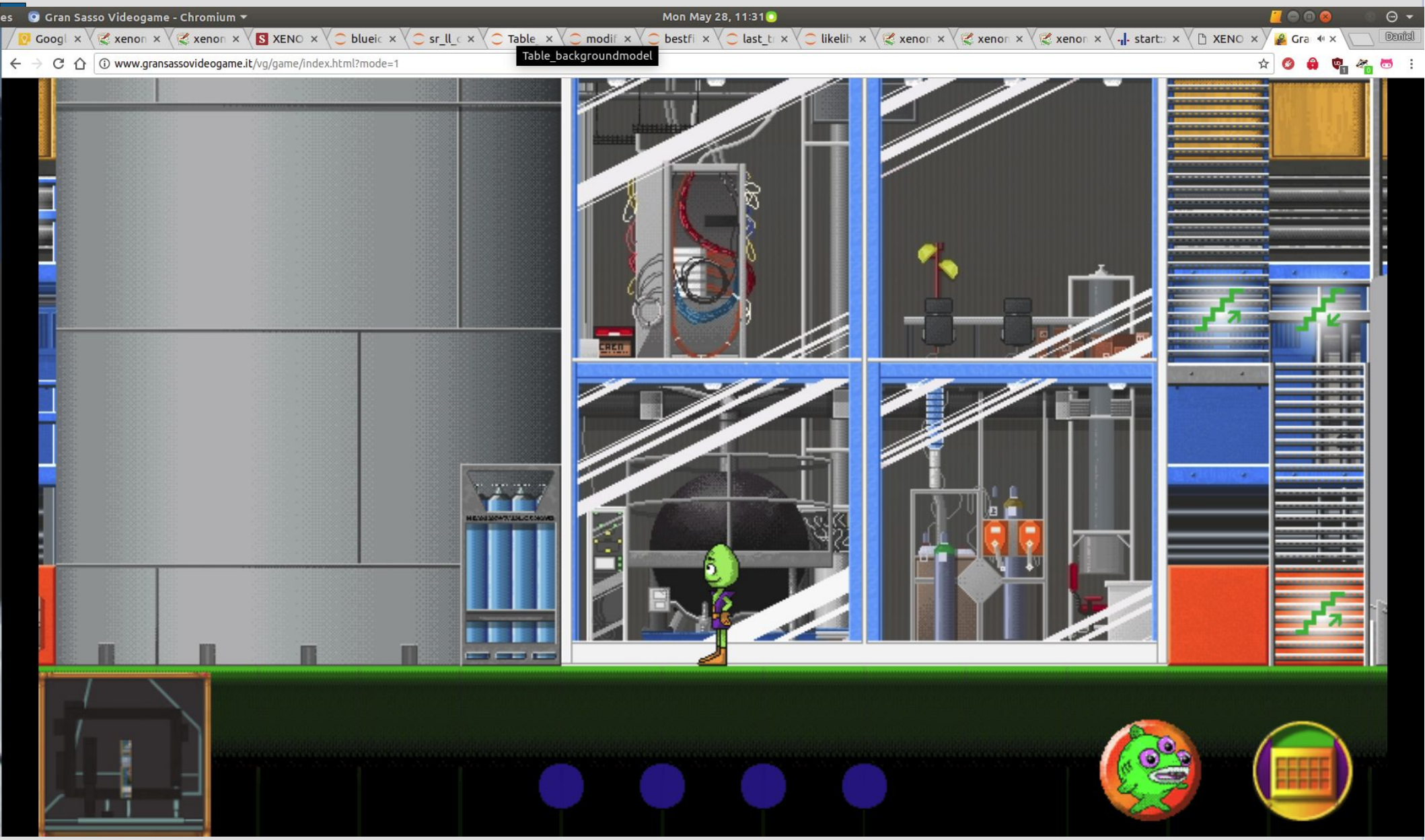
some projects are missing...

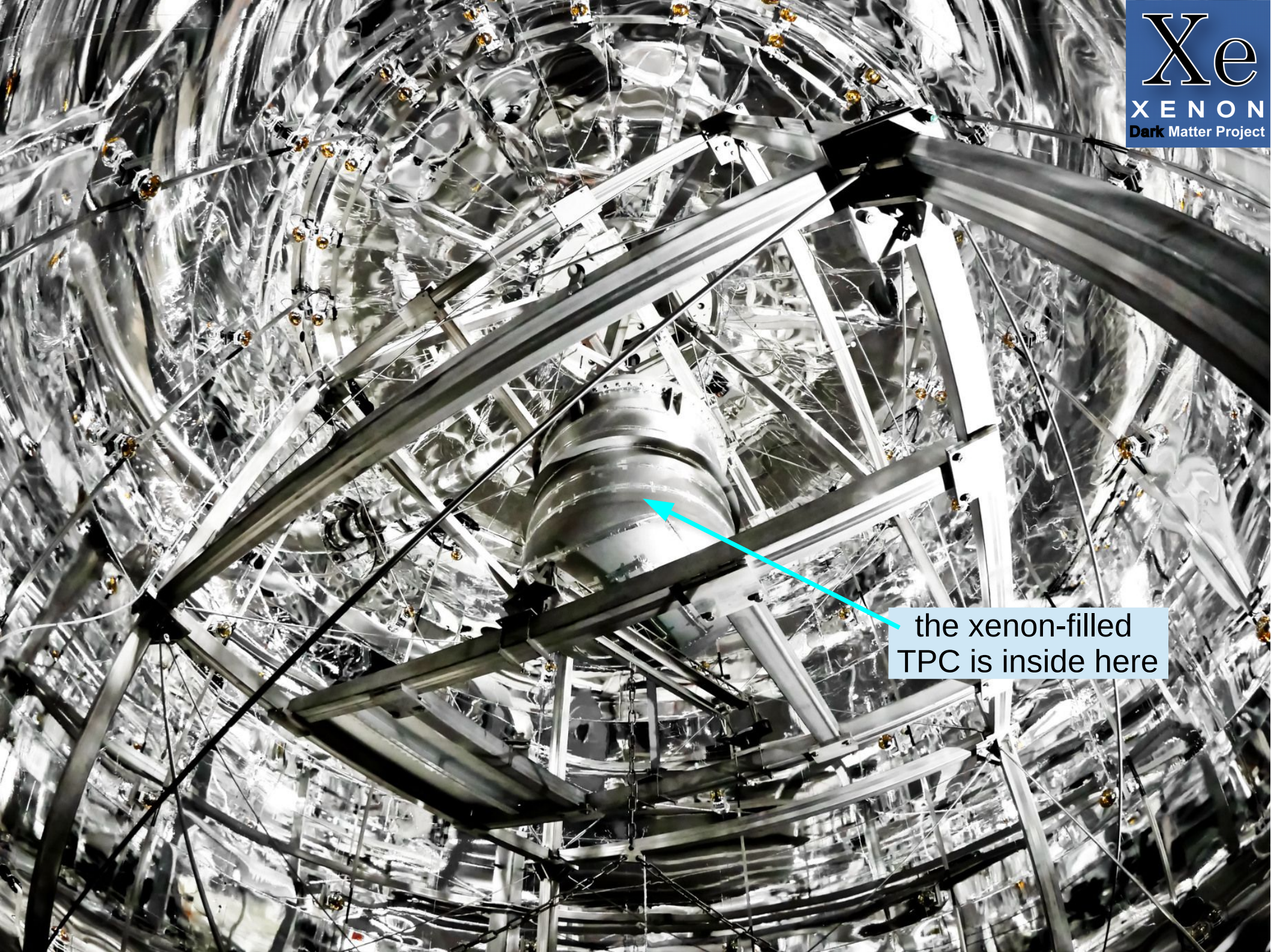
XENON @ LNGS

XENON
Dark Matter Project

EPJ C 77, 881 (2017)

XENON1T @ www.gransassovideogame.it




Xe
XENON
Dark Matter Project
the xenon-filled
TPC is inside here

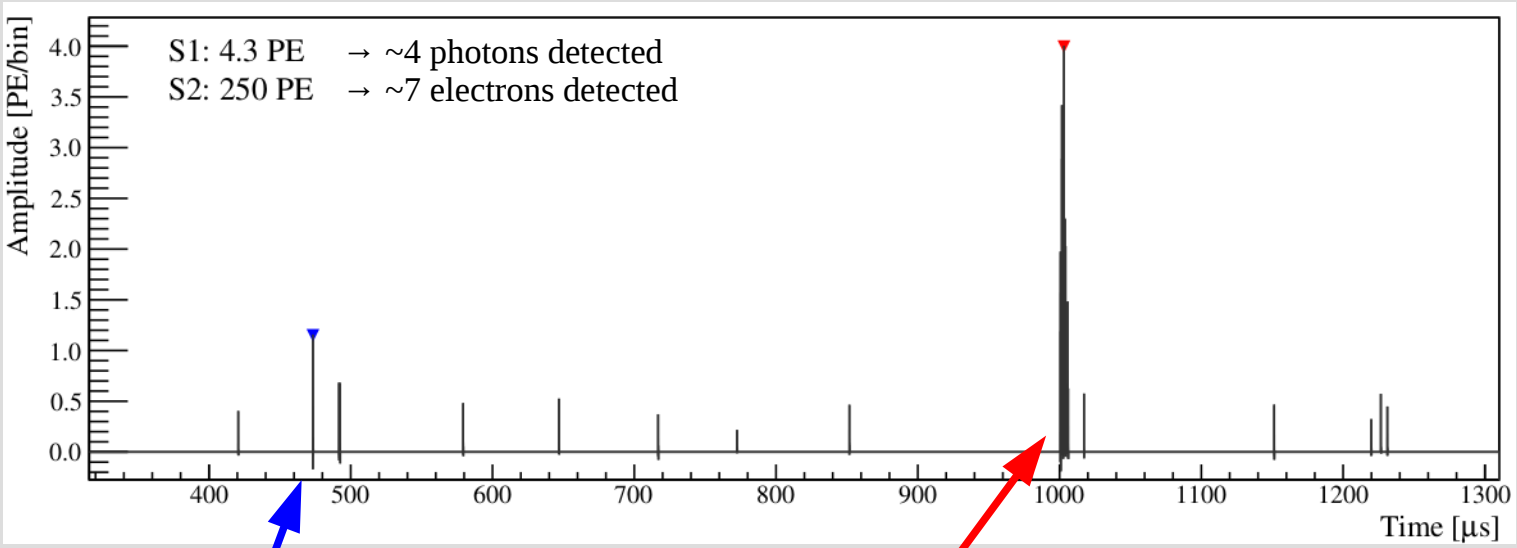
XENON
Dark Matter Project

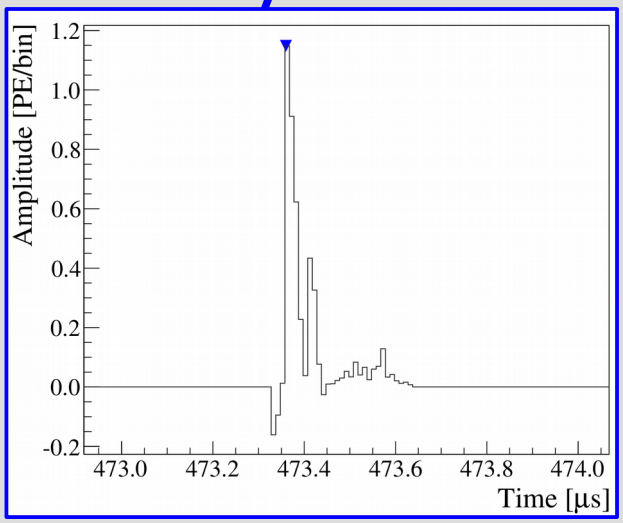
largest LXe TPC built so far...

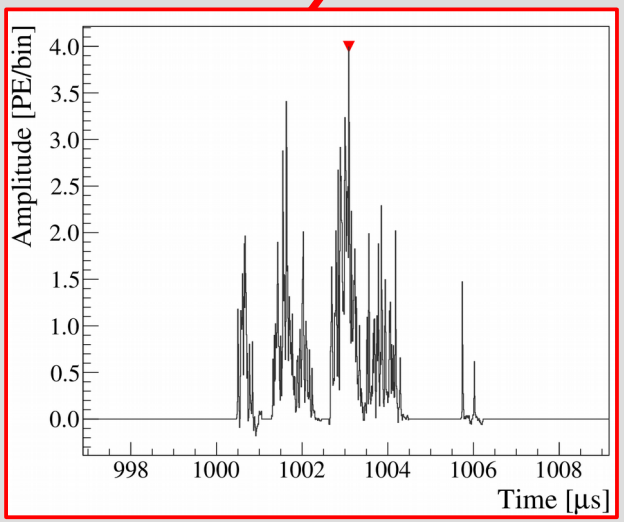
- **cylinder: 96 cm**
- **active LXe target: 2.0t** (3.2t total)
- **248 PMTs**

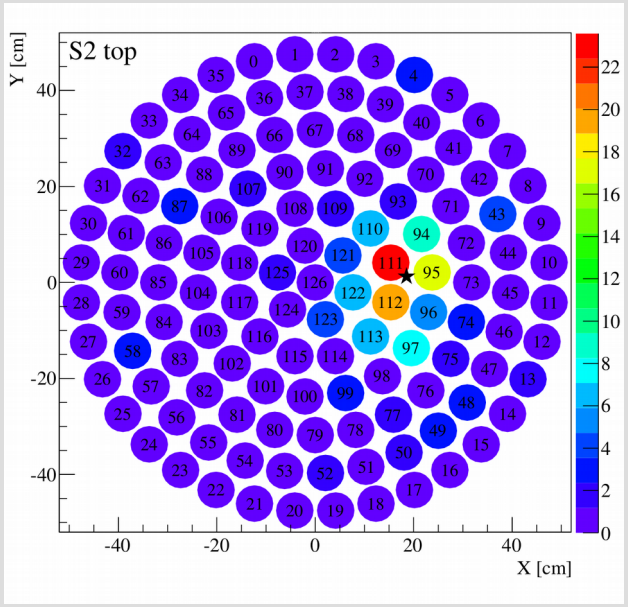
How would dark matter look?

… but it's a low-E neutron interaction from calibration!

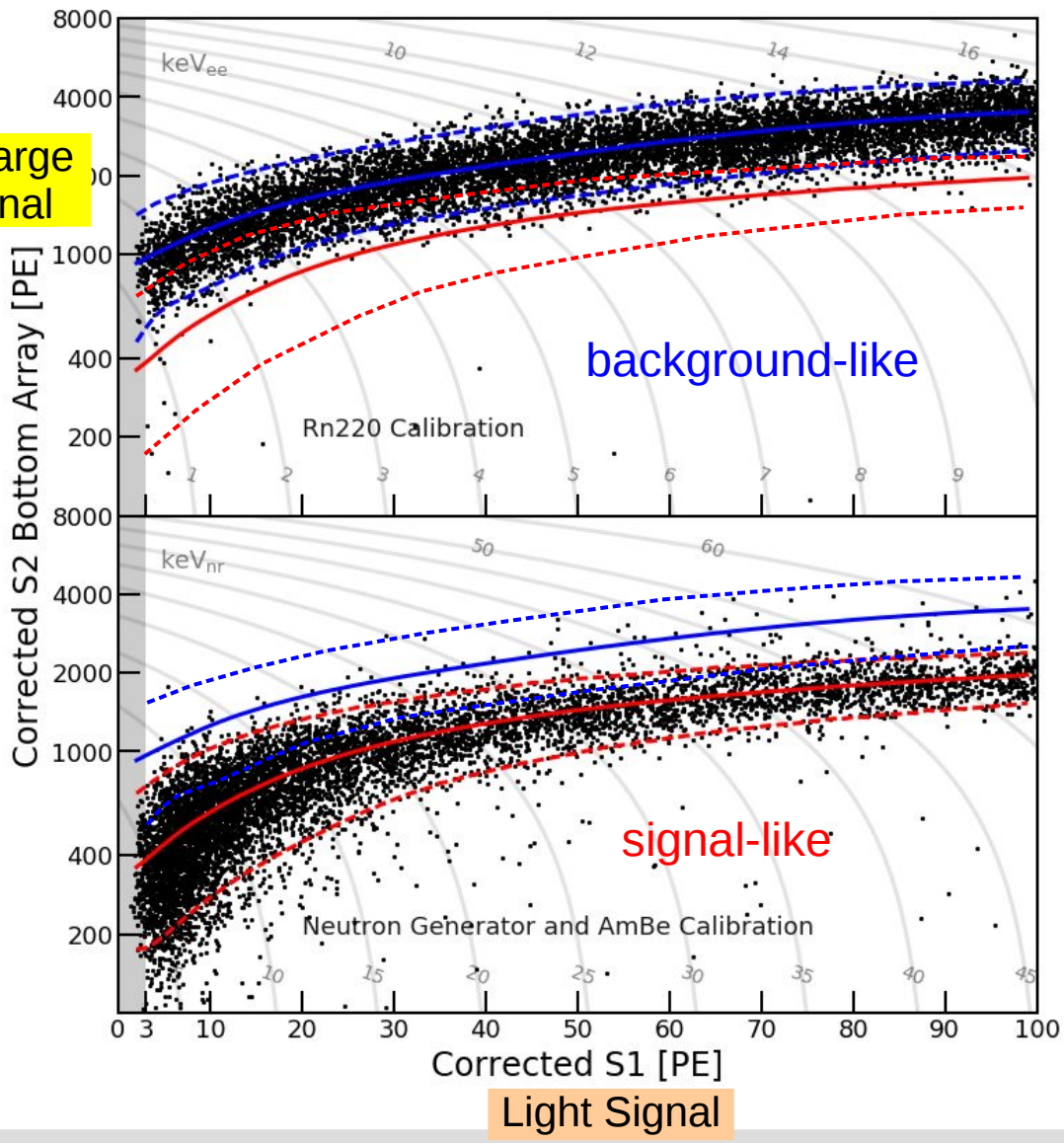


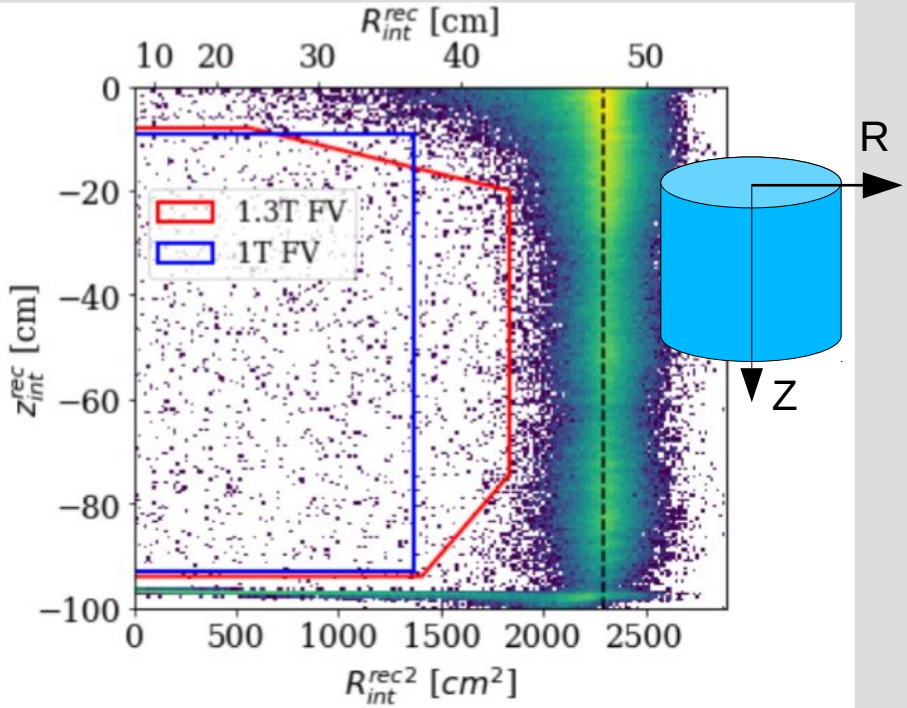






Calibration and Analysis



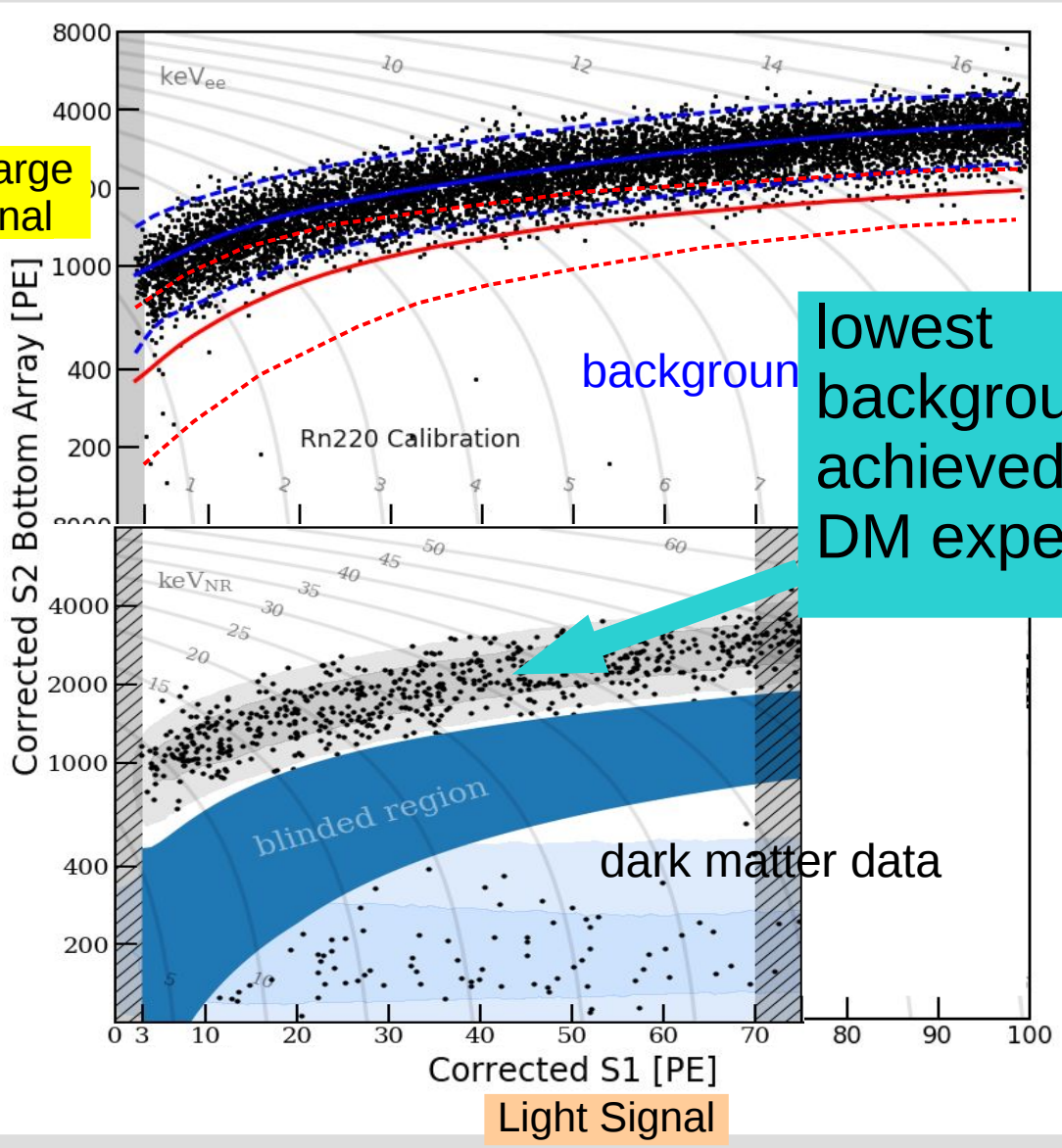


Used to construct background and signal models.

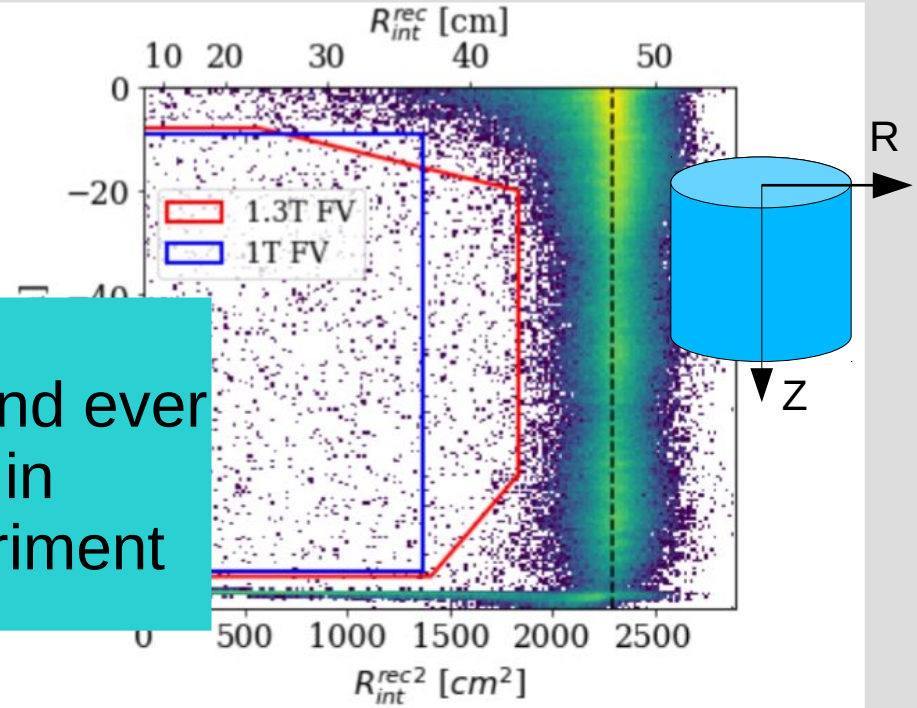
use **central 1.3 t** LXe for analysis

Exposure: 1.3 t × 278.8 d = 1.0 t×y
→ **largest low-bg exposure ever**

Blind WIMP Search



lowest background ever achieved in DM experiment

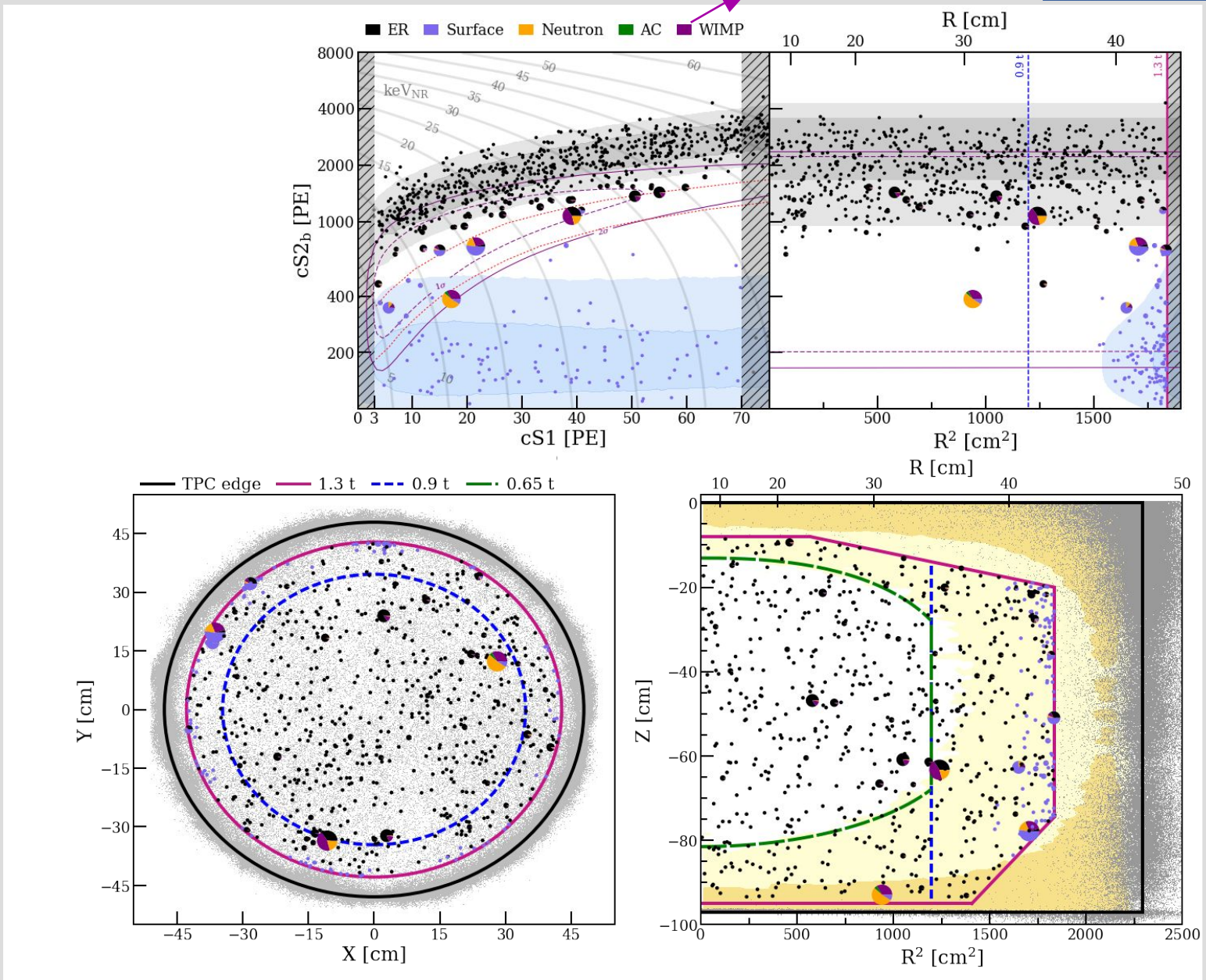


Used to construct background and signal models.

use **central 1.3 t** LXe for analysis

Blind analysis
= region of interest inaccessible during analysis to avoid human bias

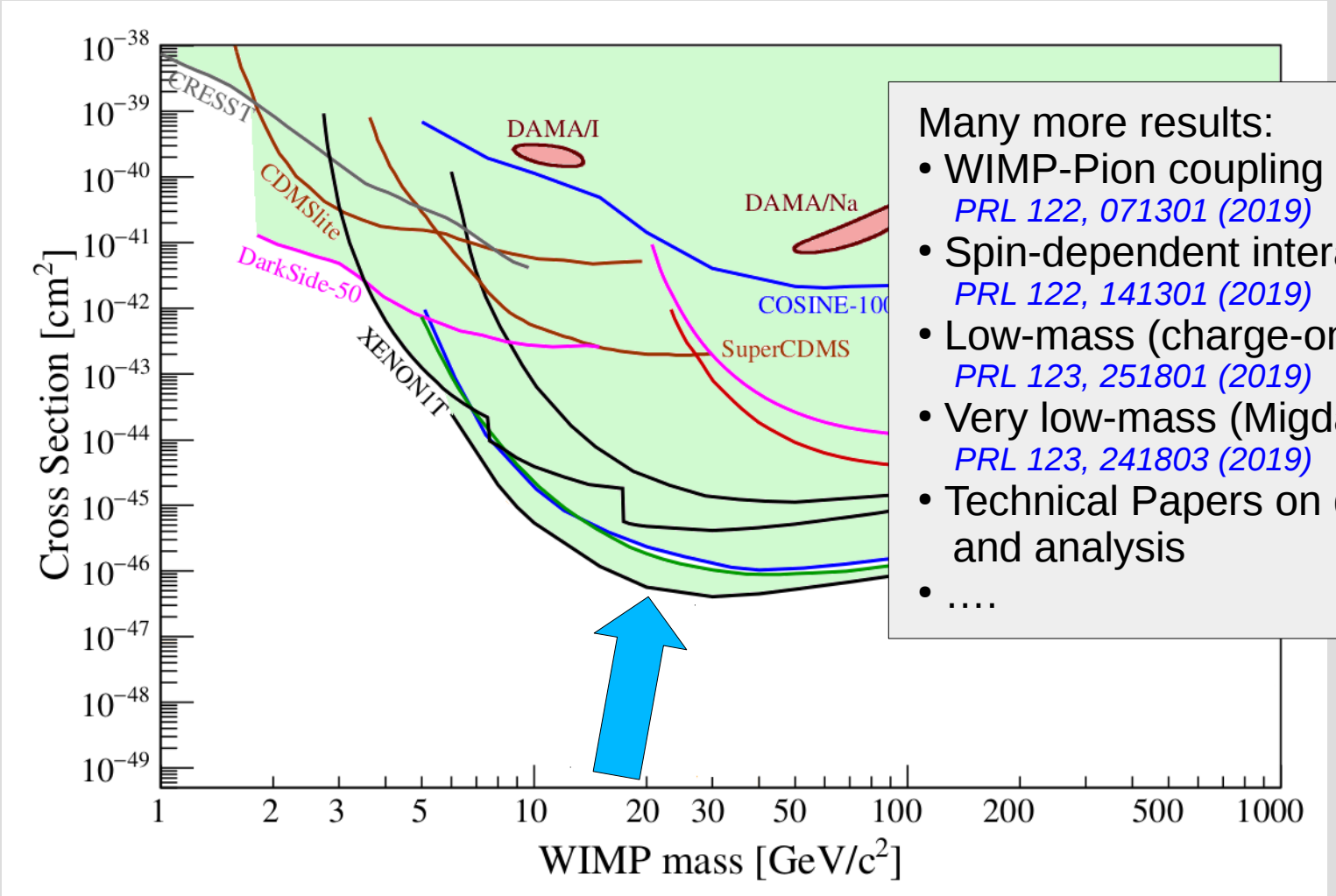
Unblinding



→ no statistically significant excess observed

No Signal → Exclusion Limit

PRL 121, 111302 (2018)

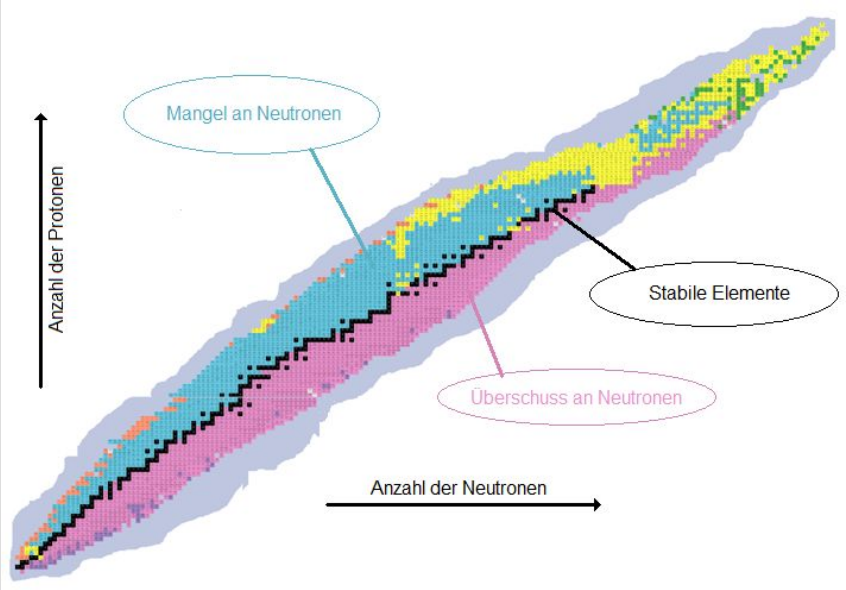


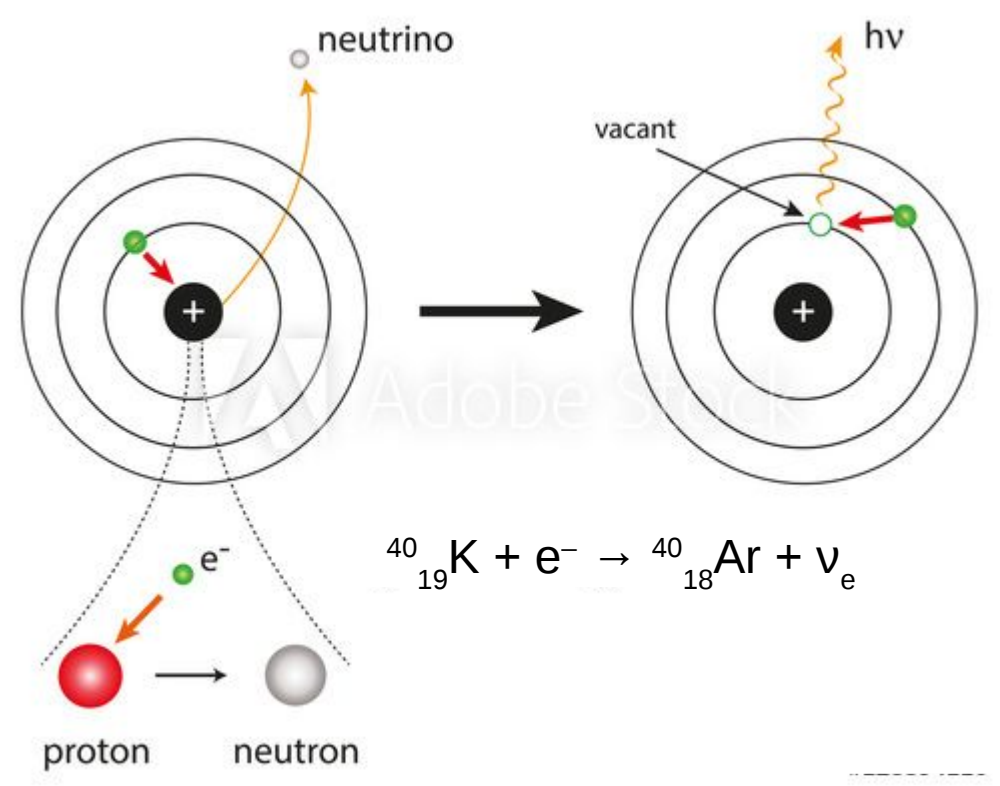
Many more results:

- WIMP-Pion coupling
  PRL 122, 071301 (2019)
- Spin-dependent interactions
  PRL 122, 141301 (2019)
- Low-mass (charge-only)
  PRL 123, 251801 (2019)
- Very low-mass (Migdal effect)
  PRL 123, 241803 (2019)
- Technical Papers on detector and analysis
- ….

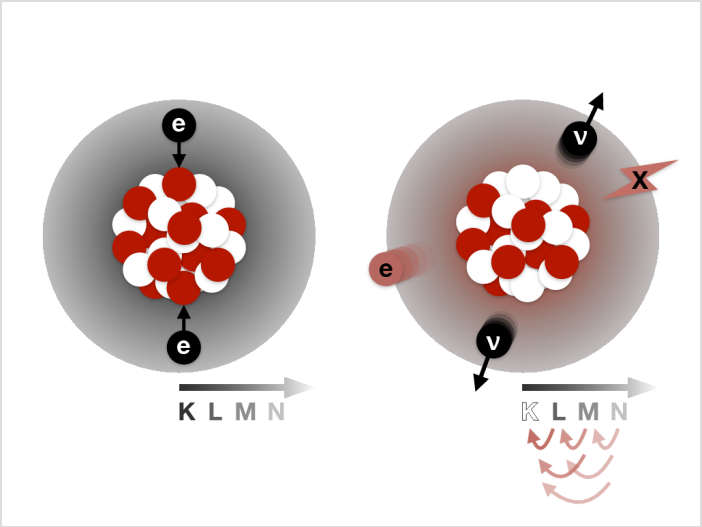
Electron Capture (EC)

Competing process to β^+ decay





Double Electron Capture of ^{124}Xe

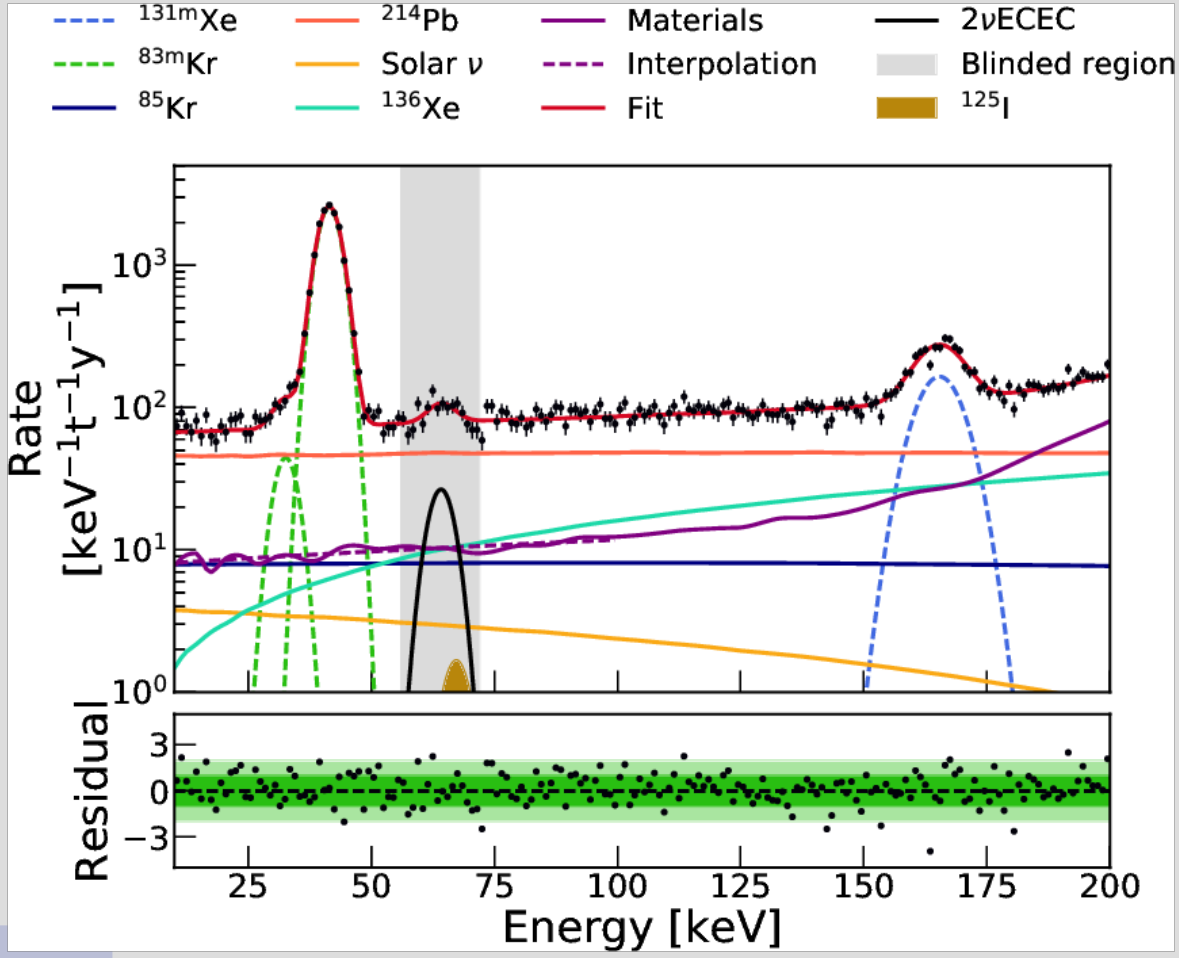


- 2nd order weak process with very long half life $T_{1/2}$

- so far observed in ^{78}Kr, ^{130}Ba

- $^{124}Xe + 2\ e^- \rightarrow {}^{124}Te^{**} + 2\ \nu_e$

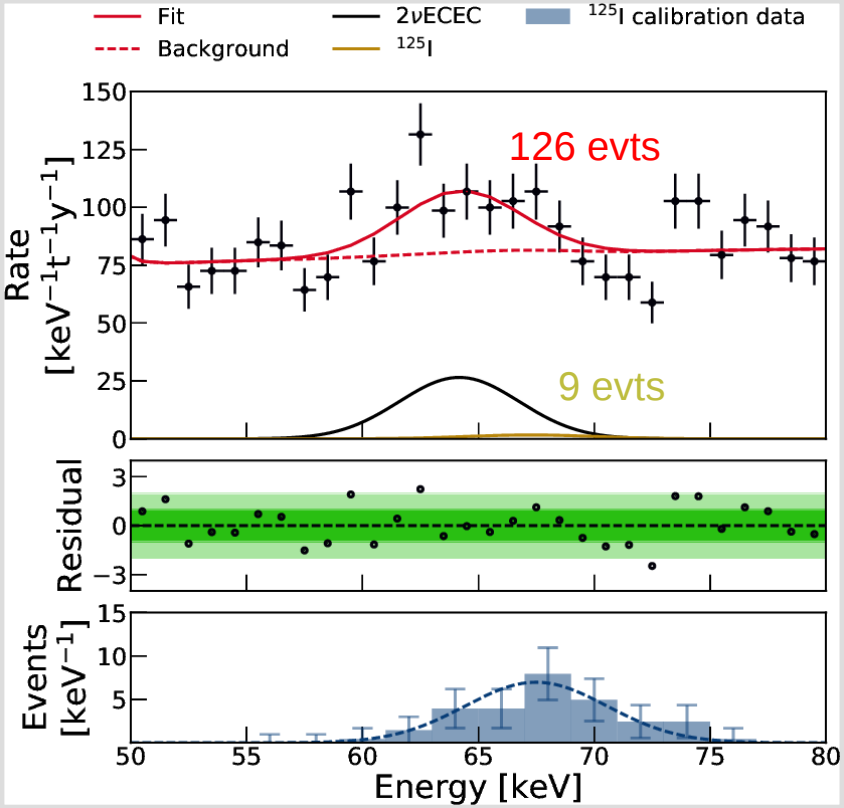
mono-energetic line at 64.33 keV



^{nat}Xe contains ~1 kg ^{124}Xe per ton

Double Electron Capture of ^{124}Xe

Nature 568, 532 (2019)



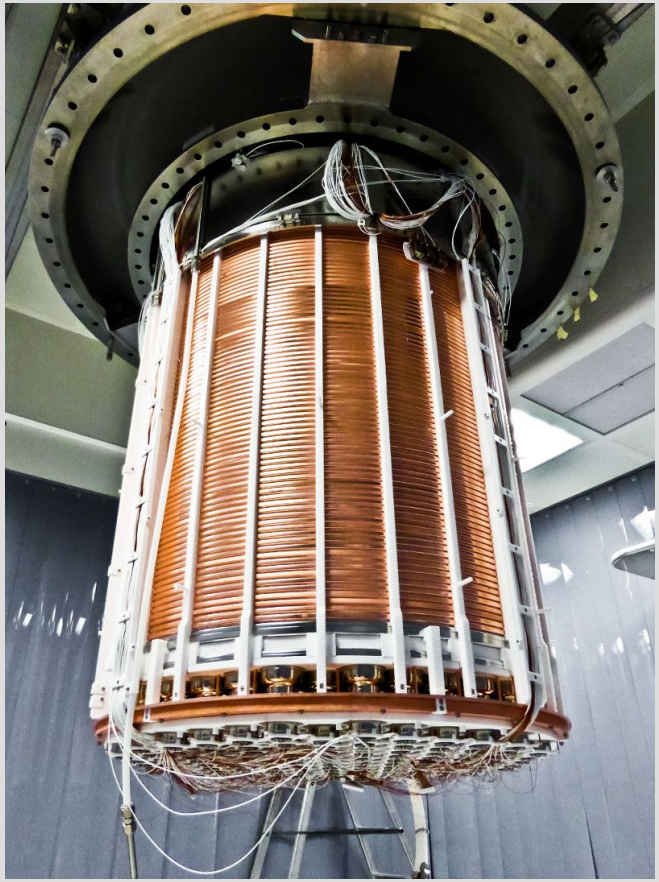
- 126 Events above Background in 1.5 t xenon
- $T^{2\nu ECEC}_{1/2} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$y
- **longest half life ever measured directly**

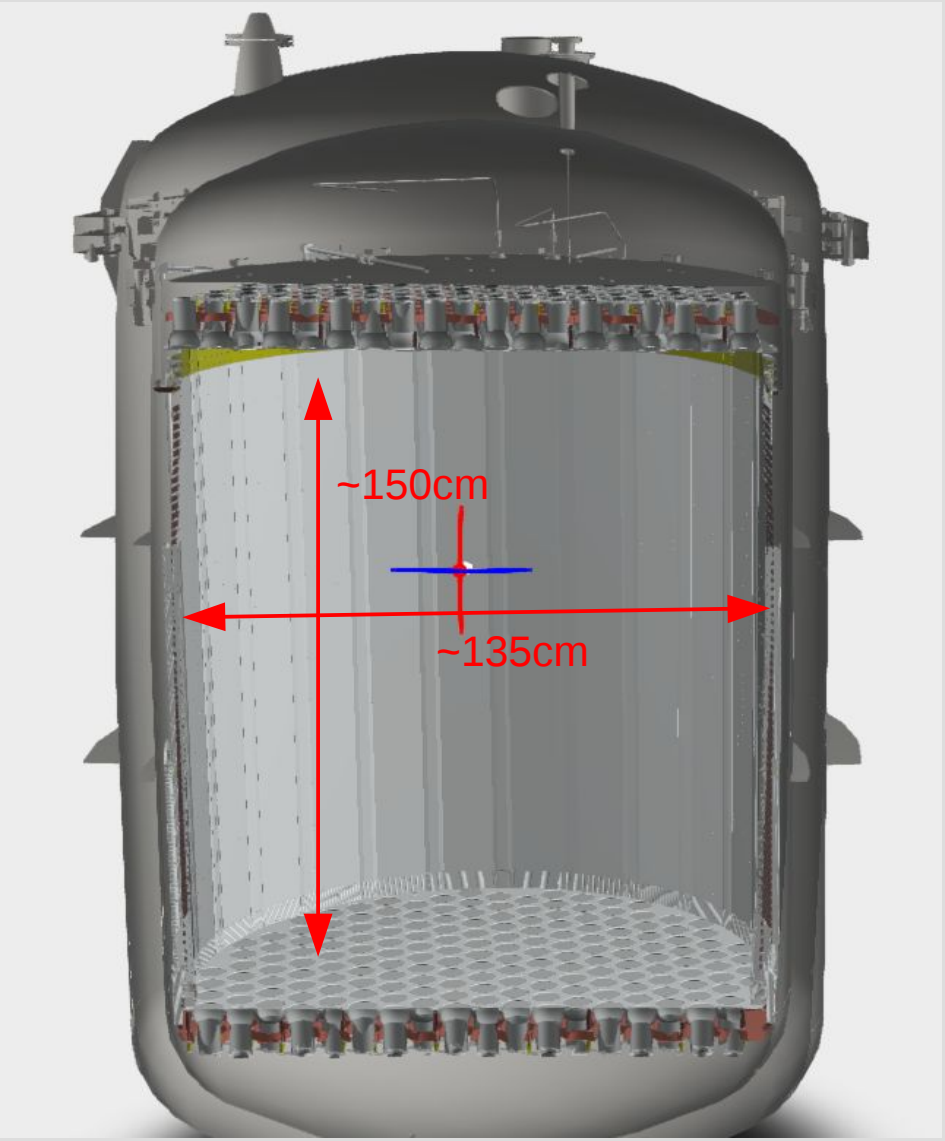
XENON1T → XENONnT

JCAP 04, 027 (2016)

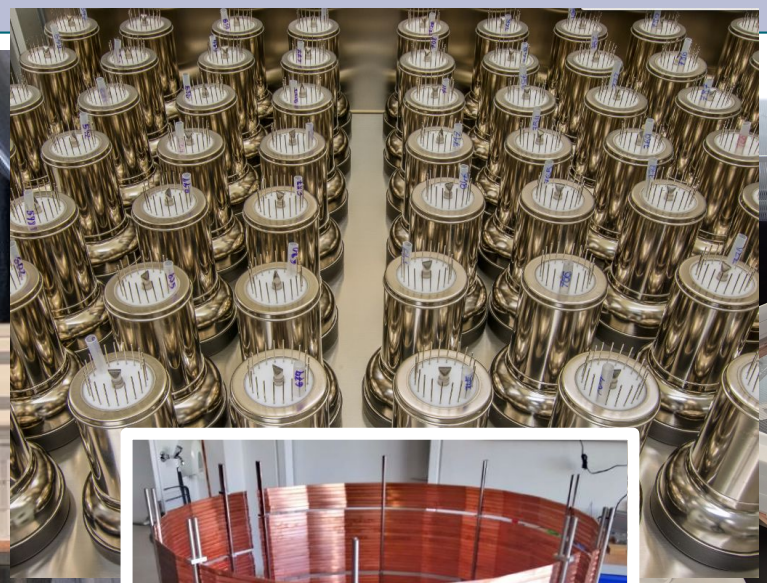
XENON1T
- **2t** active LXe target
- stopped Dec 2018

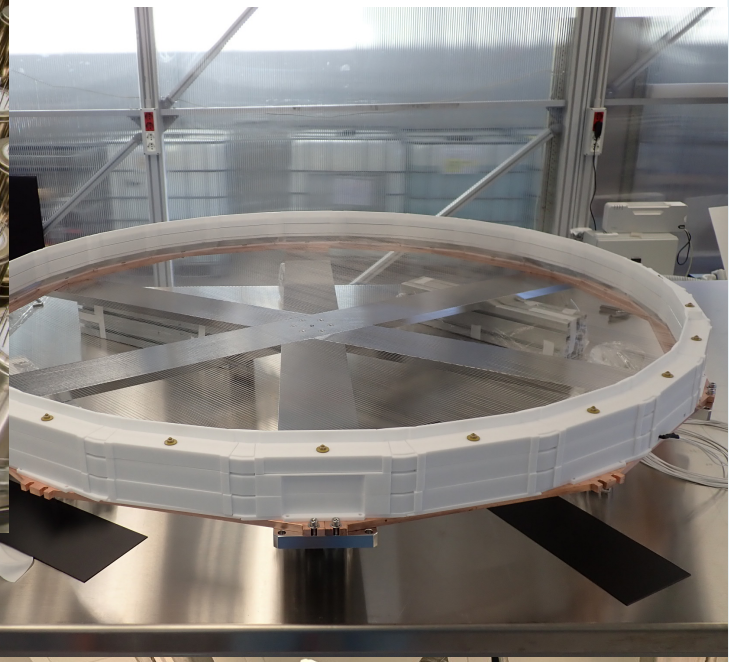
XENONnT
- **5.9t** active target
- science run by 2020

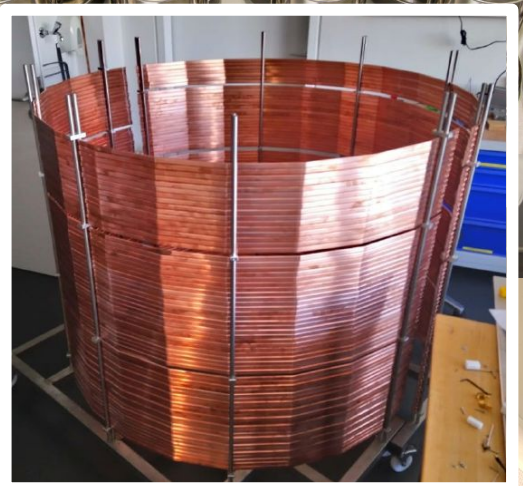




XENONnT: under construction...

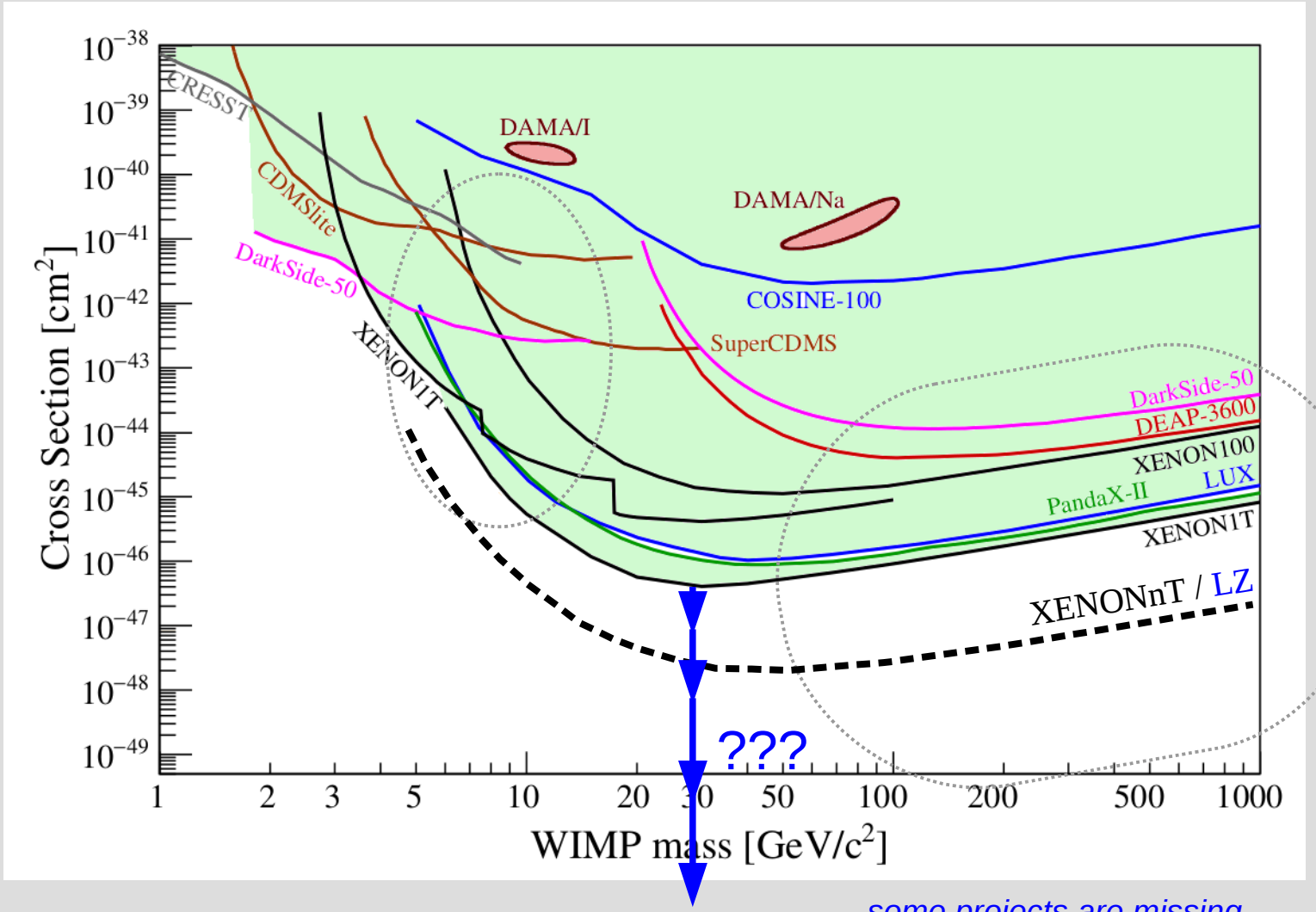






XENON: The Future

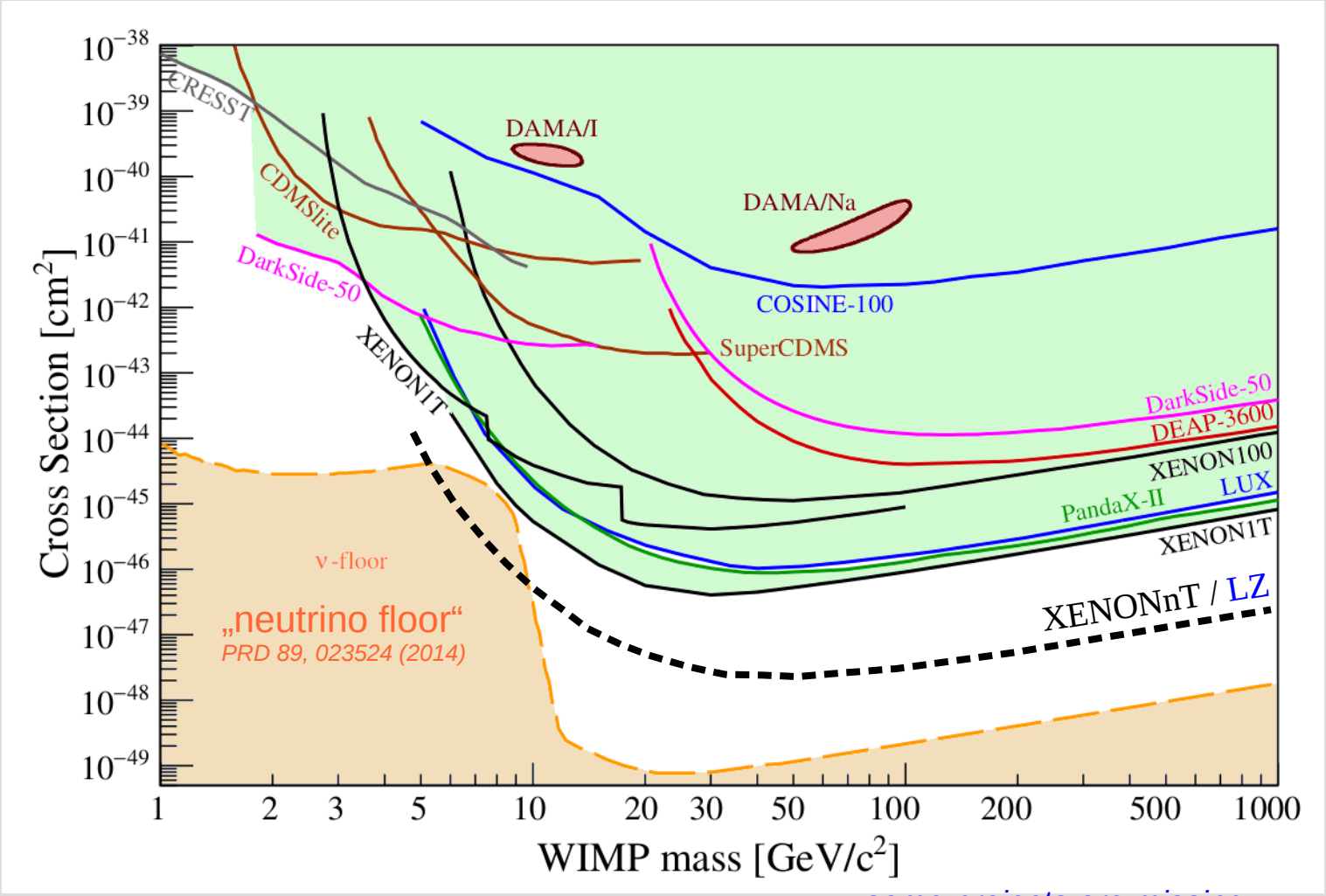
spin-independent WIMP-nucleon interactions



some projects are missing...

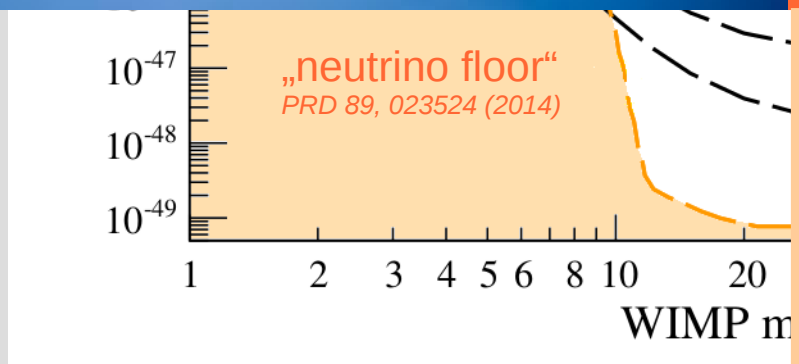
Dark Matter Searches: The Limit

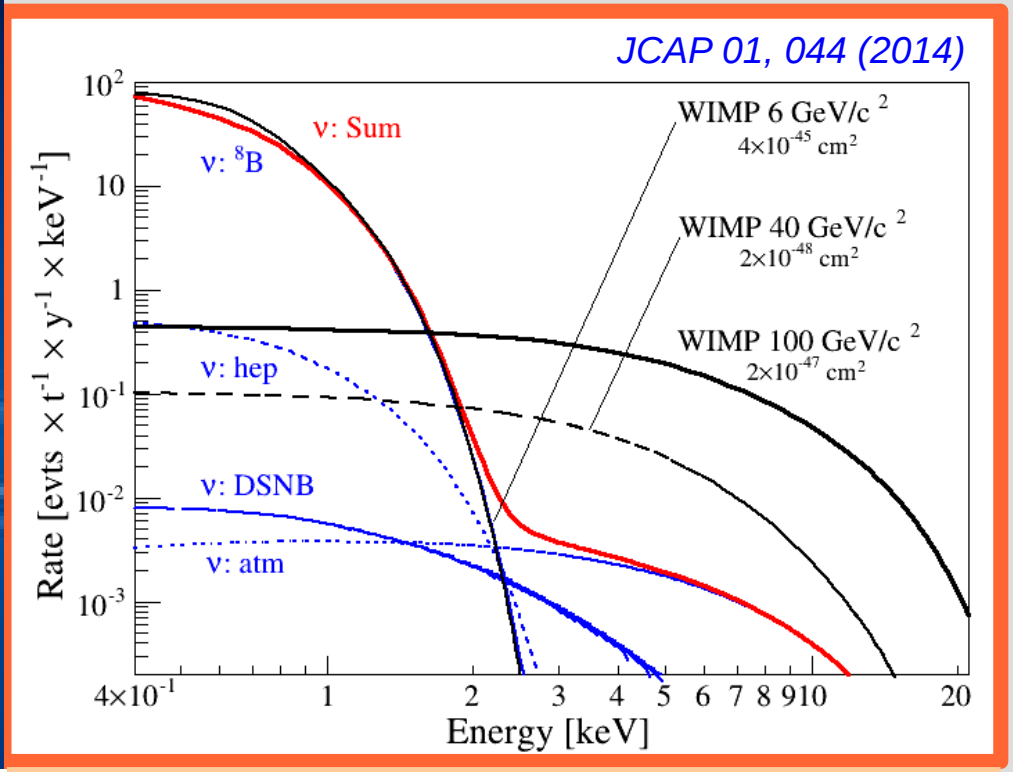
spin-independent WIMP-nucleon interactions



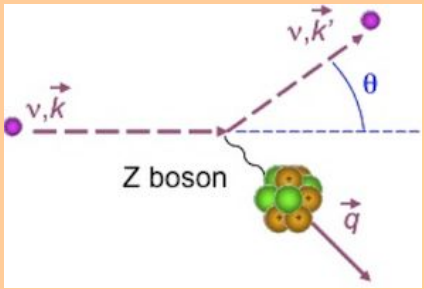
some projects are missing...

Dark Matter Searches: The Limit



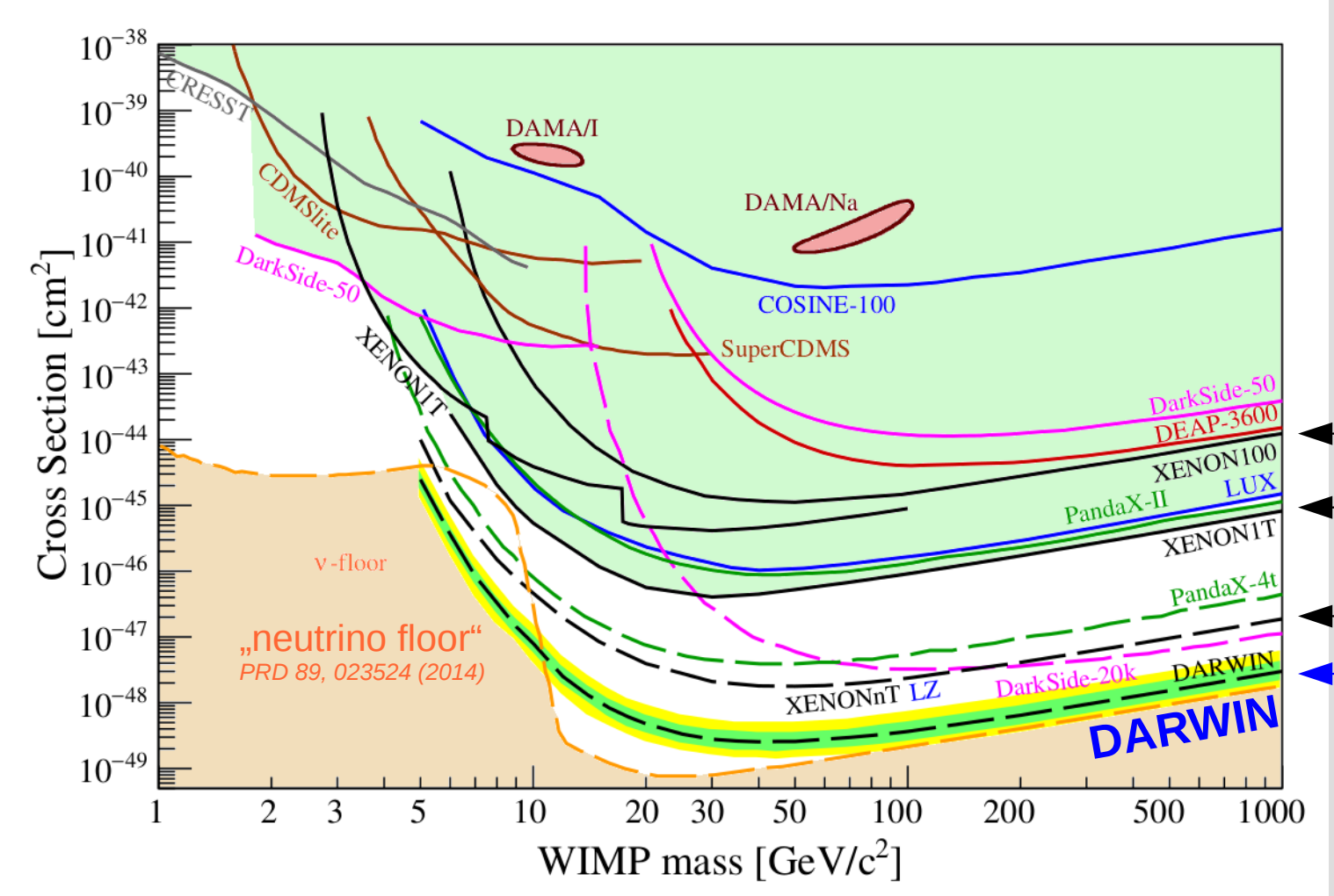


Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection



DARWIN The ultimative WIMP Detector

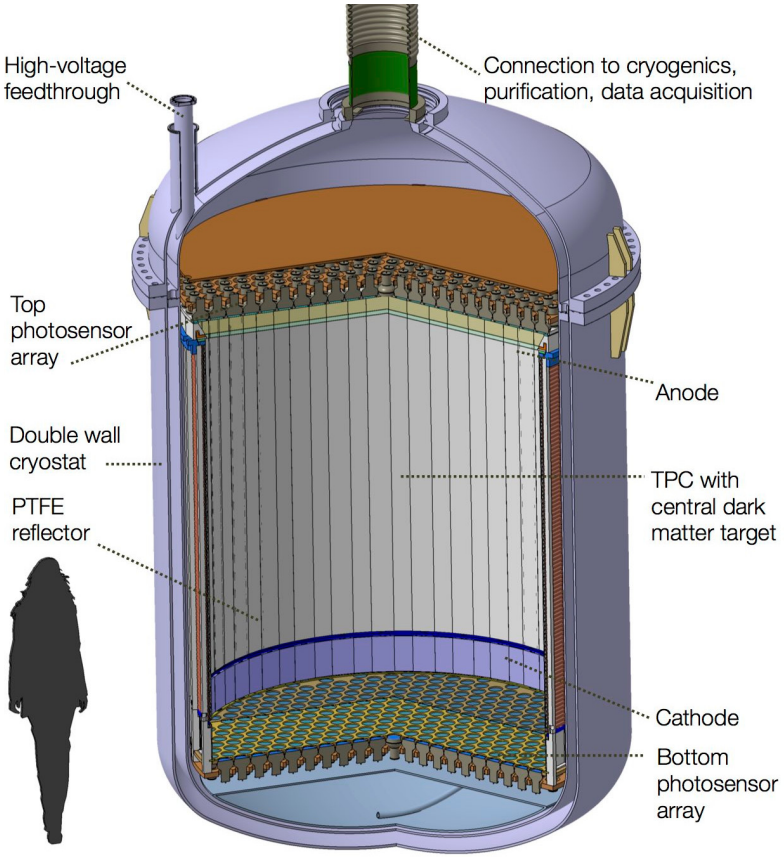
spin-independent WIMP-nucleon interactions



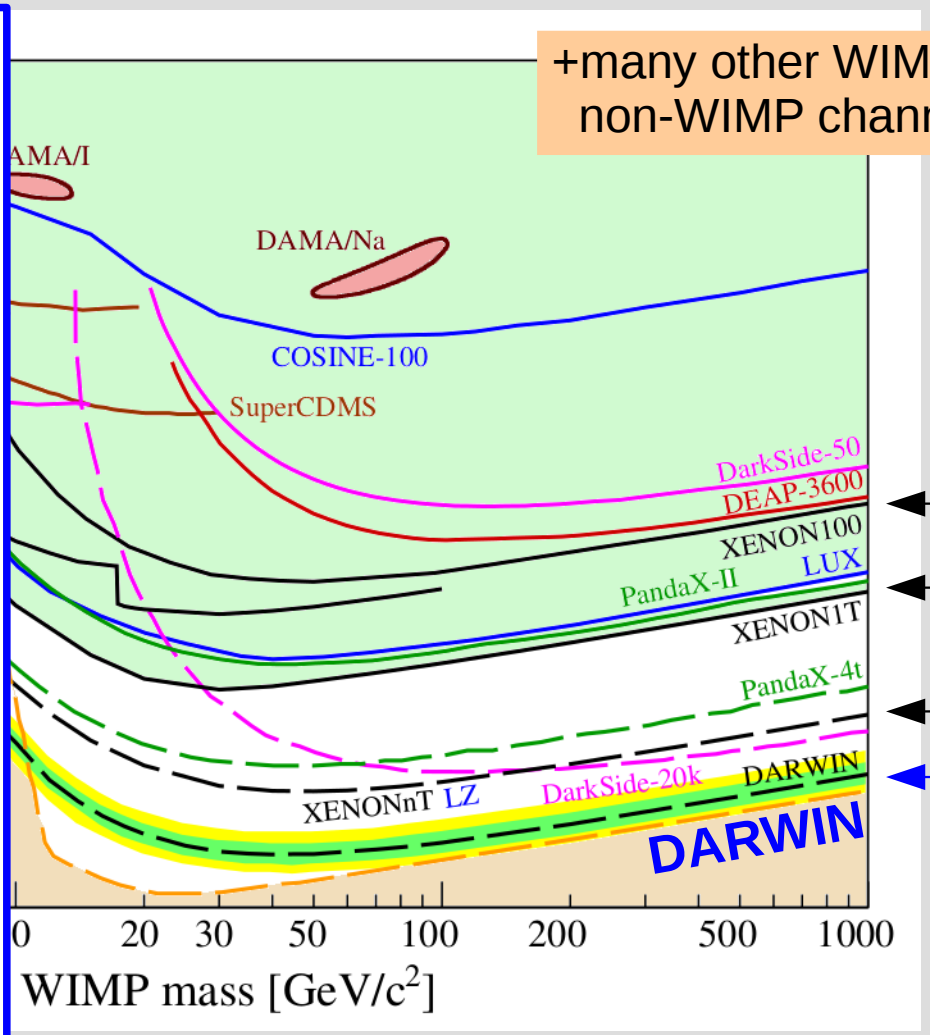
some projects are missing...

DARWIN The ultimative WIMP Detector

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

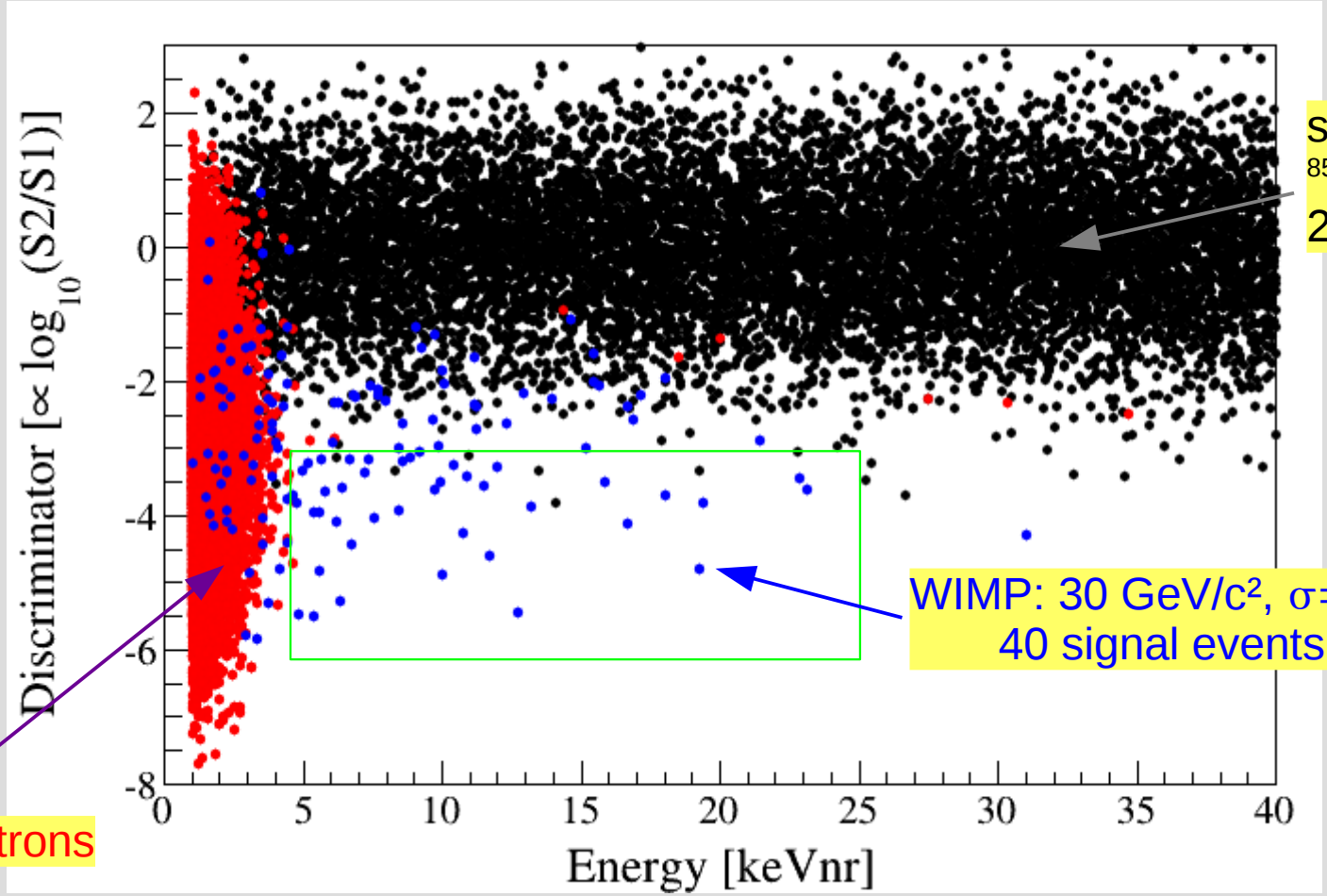


spin-independent WIMP-nucleon interactions



some projects are missing...

WIMP Detection

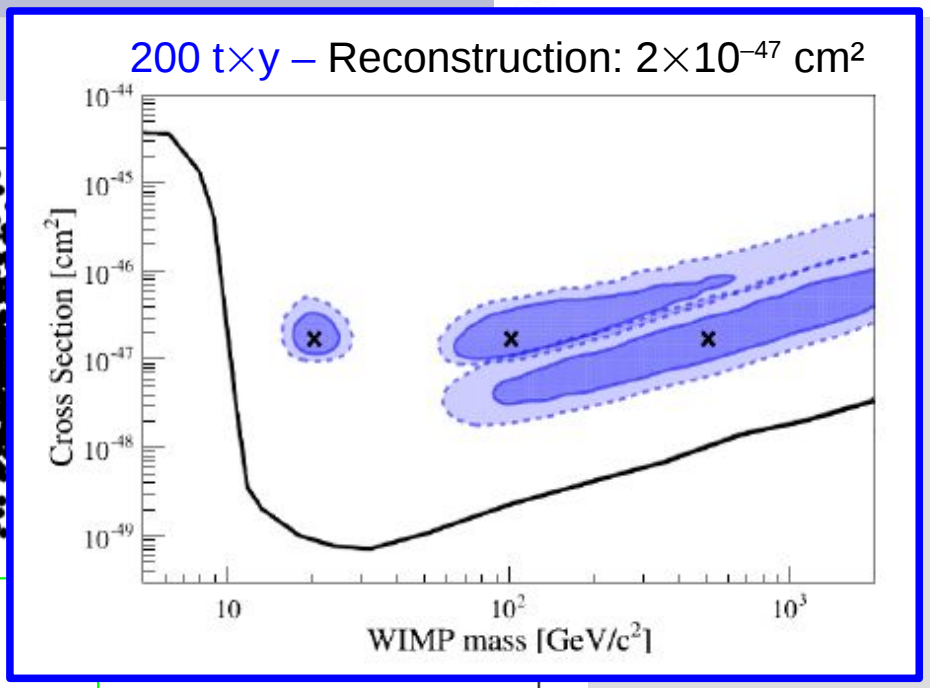


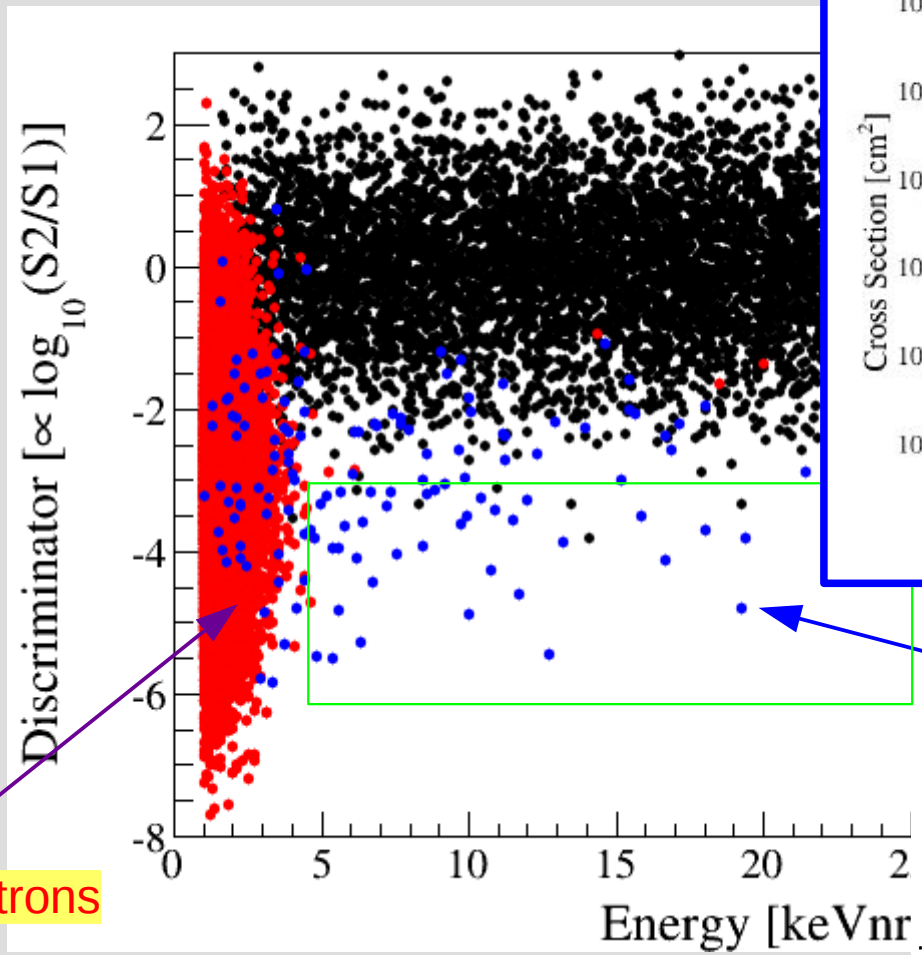
solar neutrinos, ^{85}Kr, ^{222}Rn, $2\nu\beta\beta$, materials

WIMP: 30 GeV/c², $\sigma = 2 \times 10^{-48}$ cm²
40 signal events in box

CNNS+neutrons

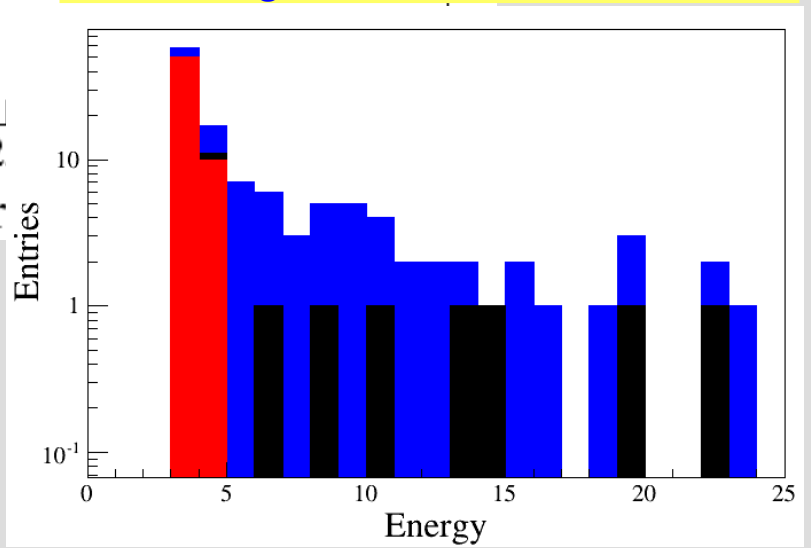
WIMP Spectroscopy





CNNS+neutrons

WIMP: 30 GeV/c², σ=2×10⁻⁴⁸ cm²
40 signal events in box

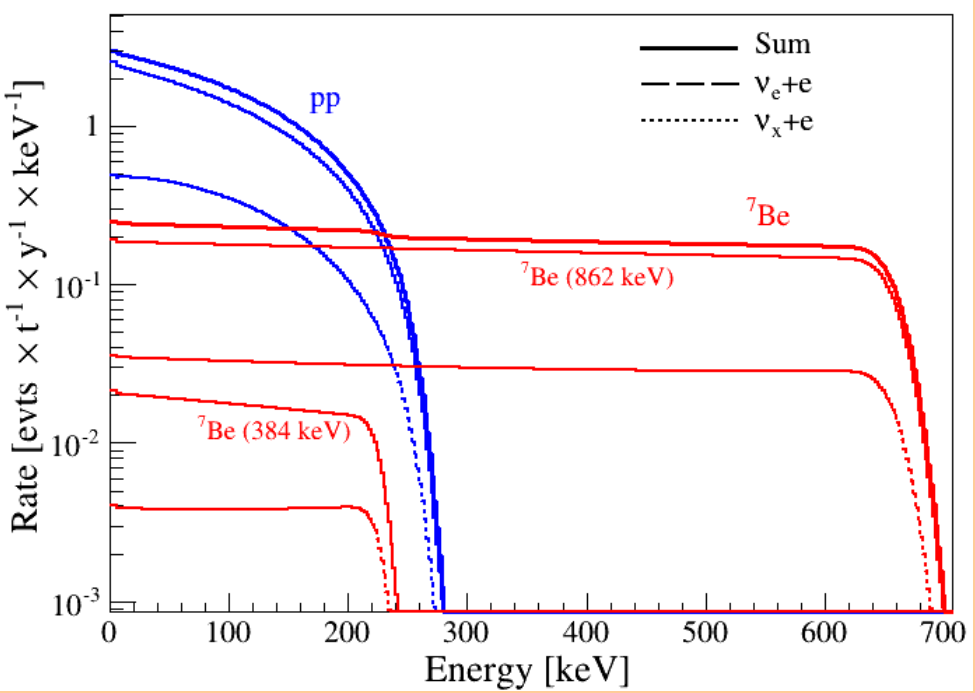


pp-Neutrinos in DARWIN

a new physics channel!

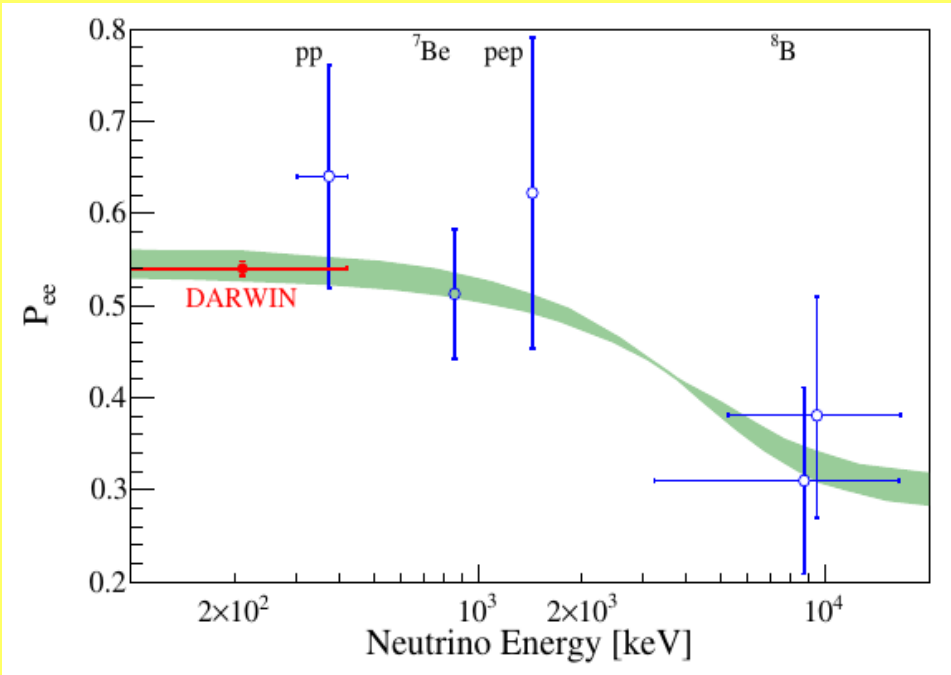
JCAP 11, 017 (2016)

Differential Recoil Spectrum in Xe



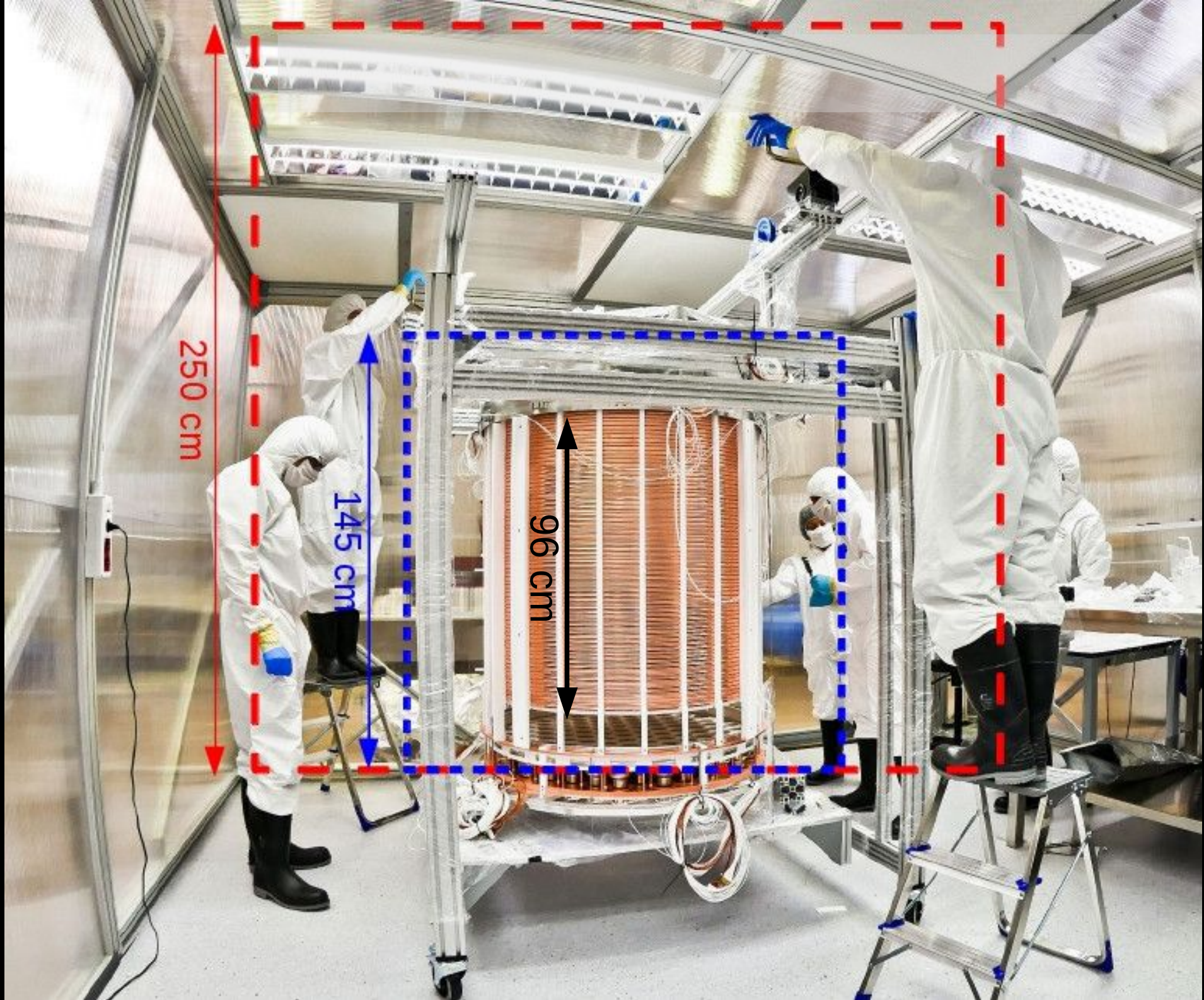
- neutrinos interact with Xe electrons
  → electronic recoil signature
- continuous recoil spectrum
  → largest rate at low E
  ~0.26 ν evts/t/d in low-E region (2-30 keV)

Neutrino interactions



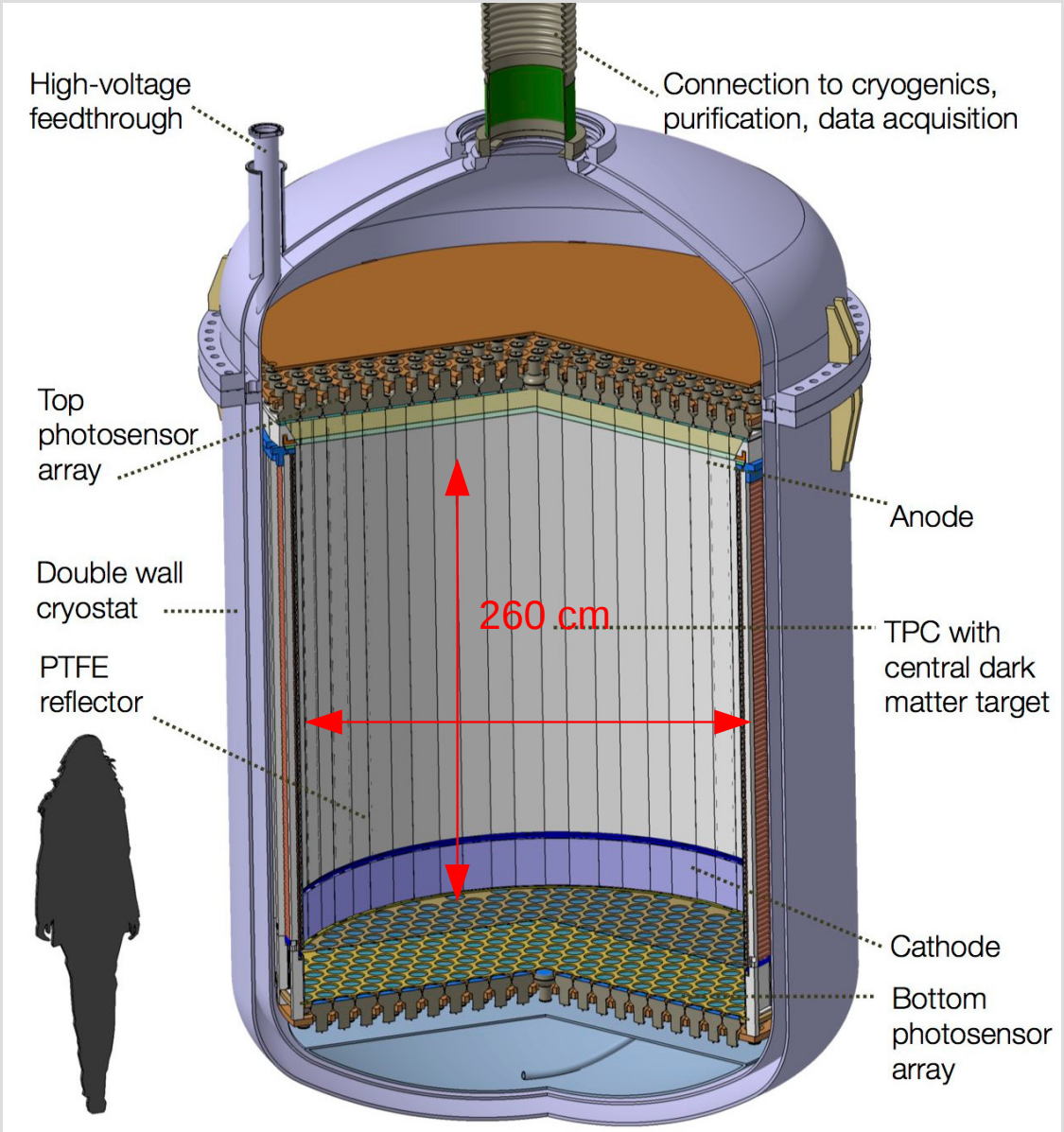
- 30t target mass, 2-30 keV window
  → 2850 neutrinos per year (89% pp)
  → achieve 1% statistical precision on pp-flux (→P_{ee}) with 100 t x y


PROJETMAN - cmi
PORTATA t. 5


250 cm
145 cm
96 cm

DARWIN The ultimate WIMP Detector

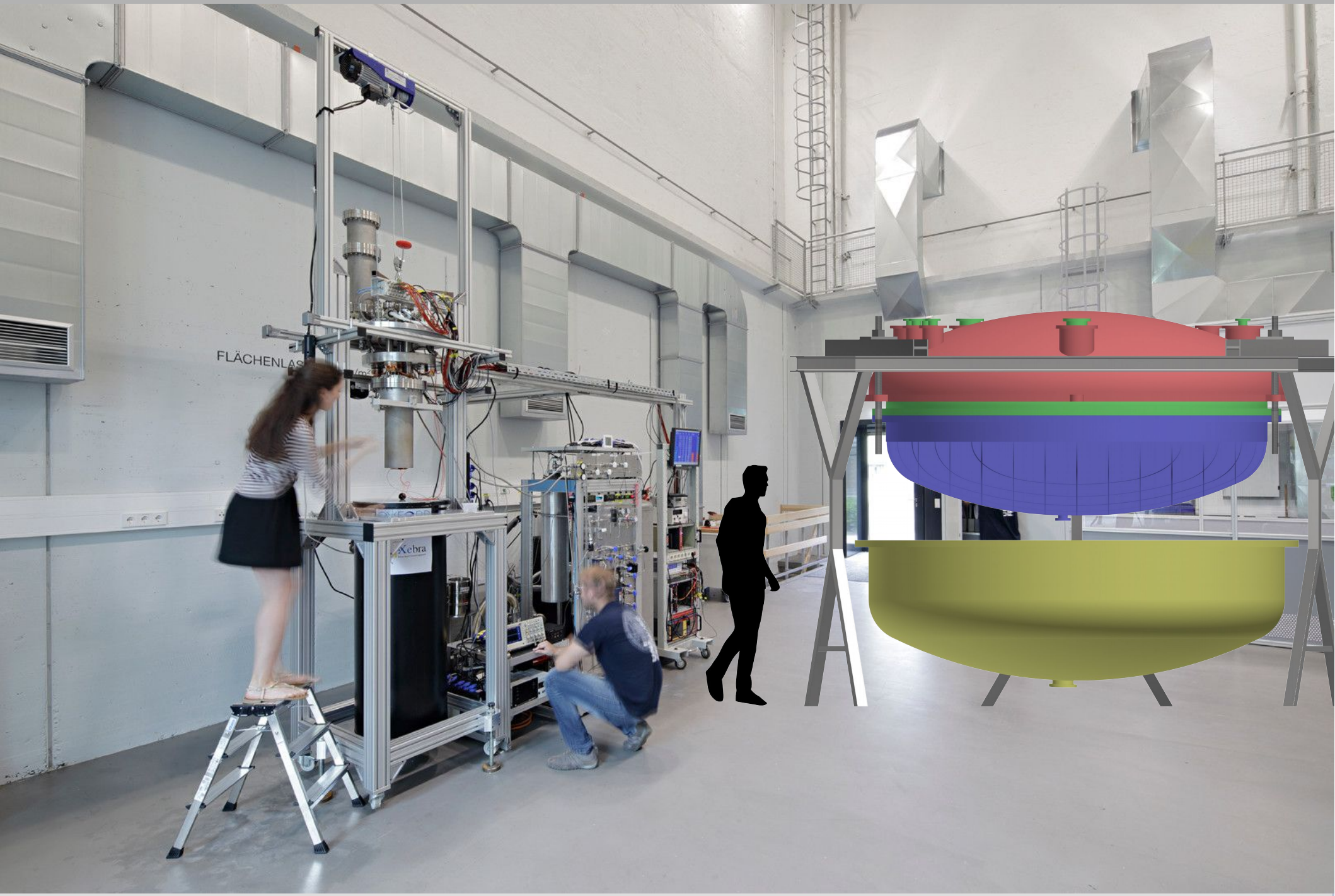
JCAP 11, 017 (2016)

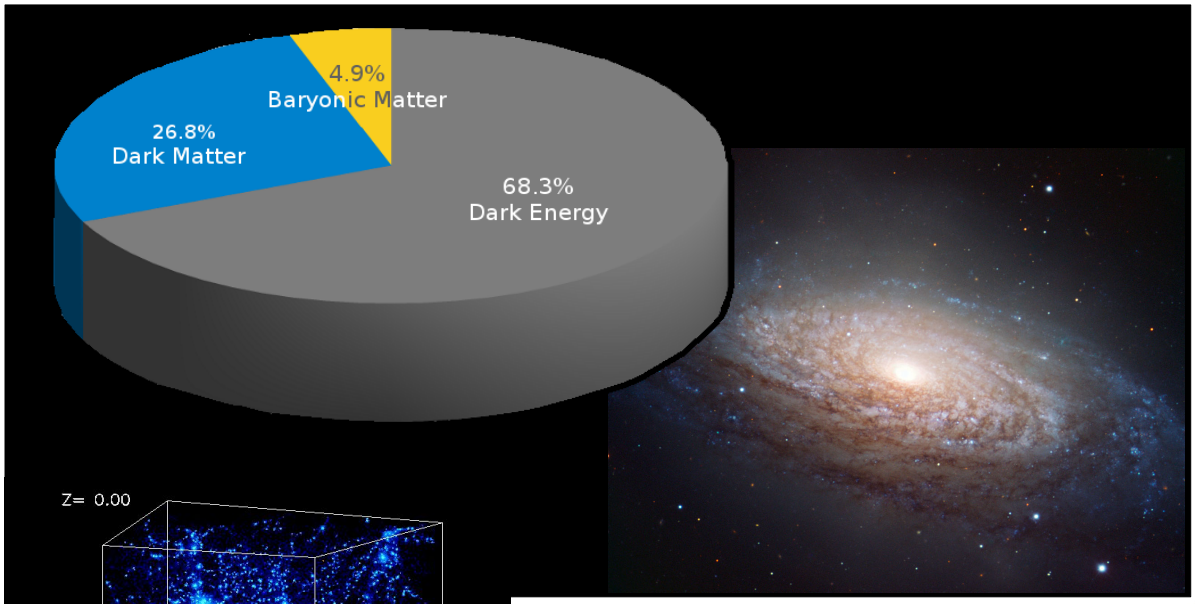


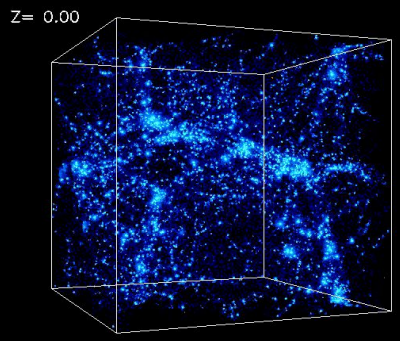
Challenges

- Size
  - → electron drift (HV)
  - → diameter (TPC electrodes)
  - → mass (LXe purification)
  - → dimensions (radioactivity)
  - → detector response (calibration, corrections)
- Backgrounds
  - → ^{222}Rn: factor 100 required
  - → (α,n) neutrons (from PTFE)
- Photosensors
  - → high light yield (QE)
  - → low radioactivity
  - → long-term stability
- etc etc

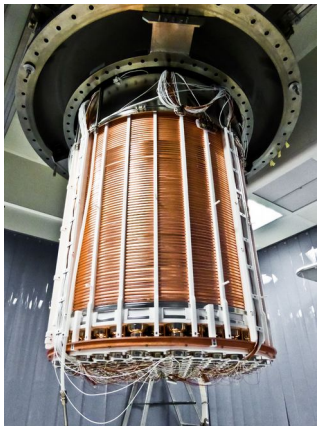
erc ULTIMATE


FLÄCHENLAS
Xebra



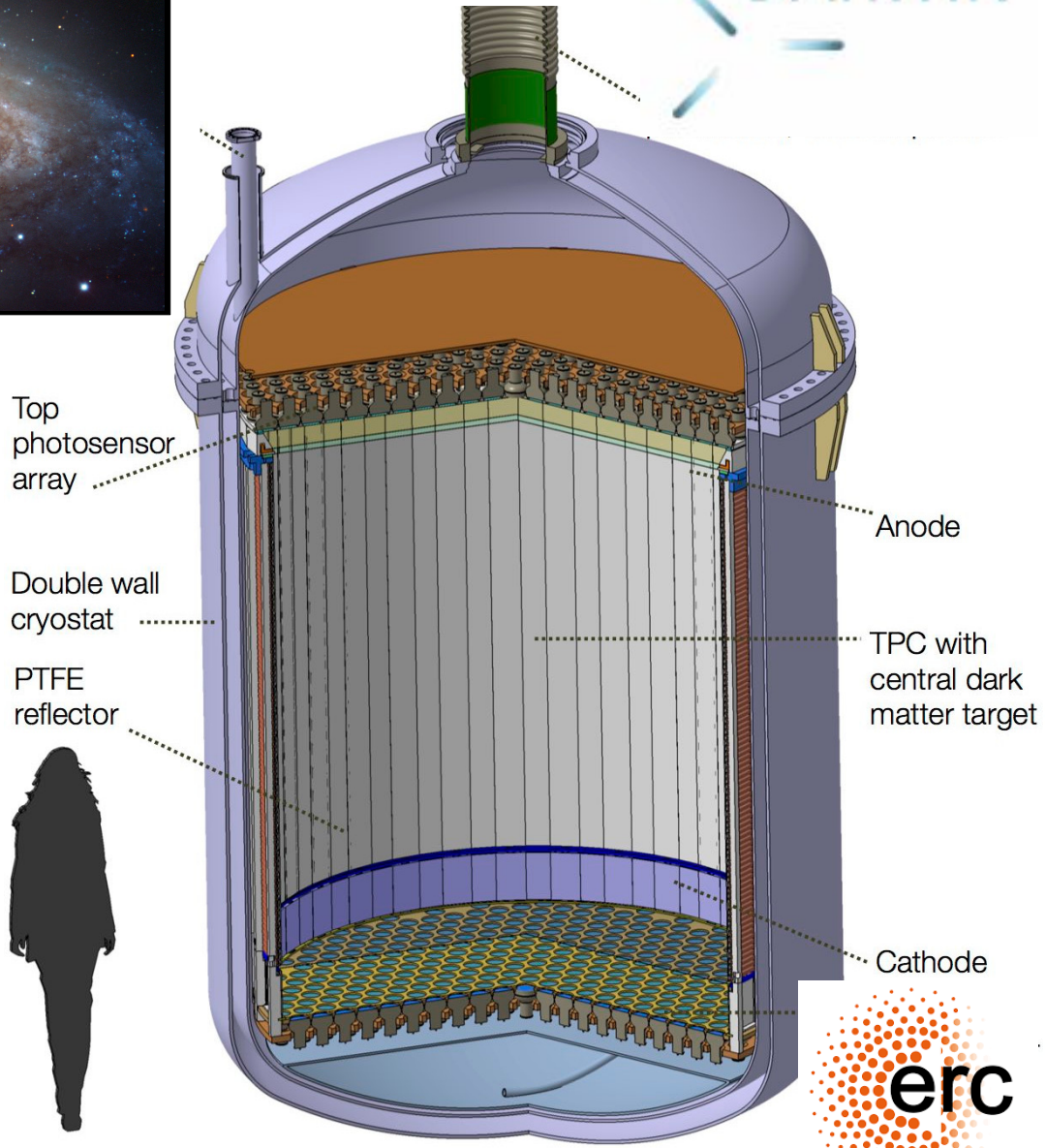


XENON1T
- **2t** active Xe target
- decommissioned



XENONnT
- **5.9t** active Xe target
- science run in 2020

DARWIN
- **40t** active Xe target
- science run in 2025+



www.xenon1t.org

www.darwin-observatory.org