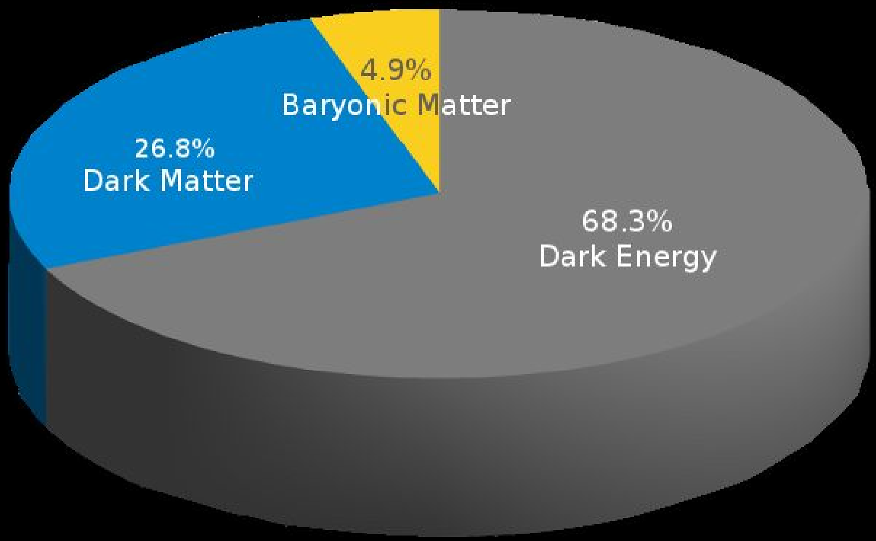
Exploring the Dark Universe

Marc Schumann *University of Freiburg*

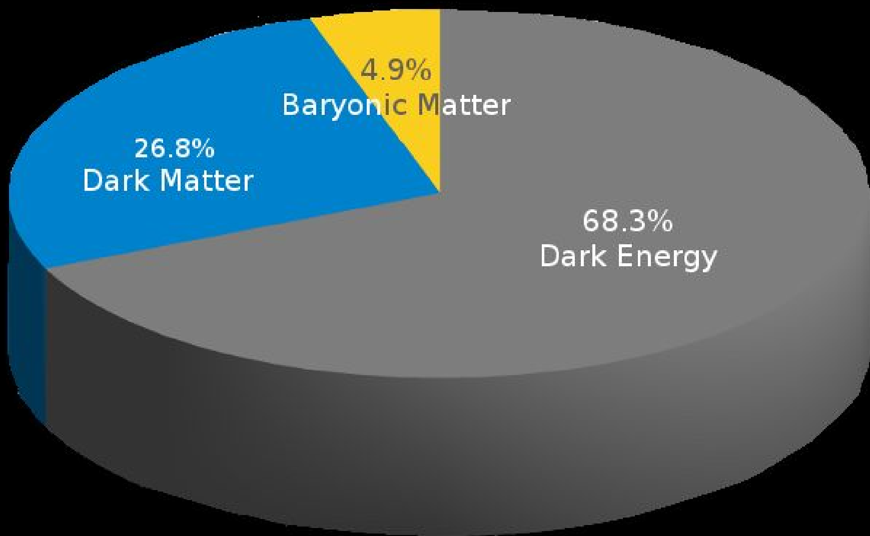
Physics Colloquium Freiburg, 12.06.2017

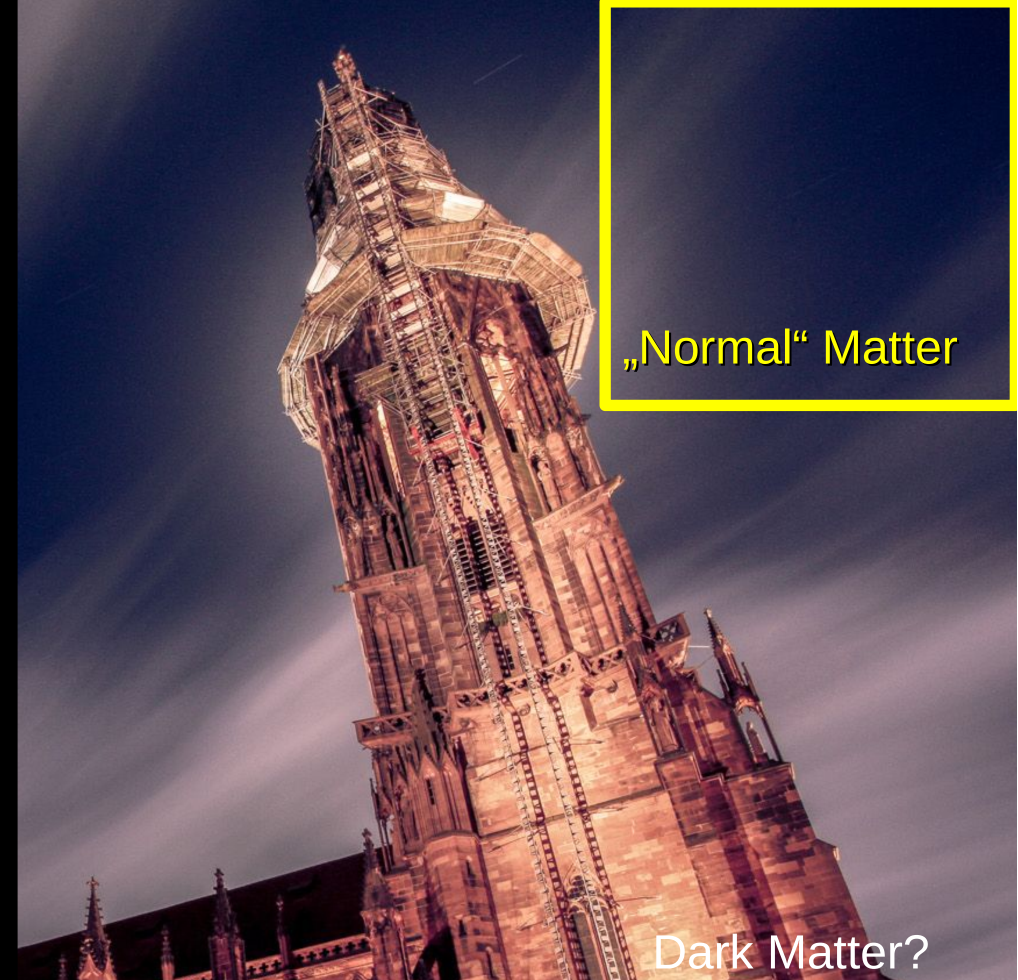
www.app.uni-freiburg.de



95% of the Universe is dark!

Dark Energy????

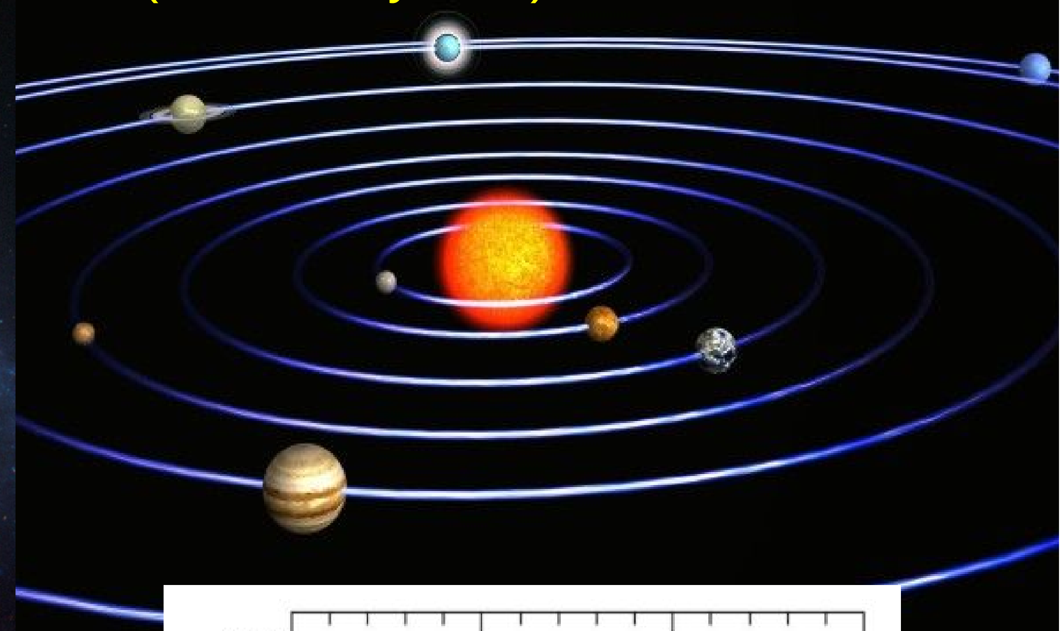


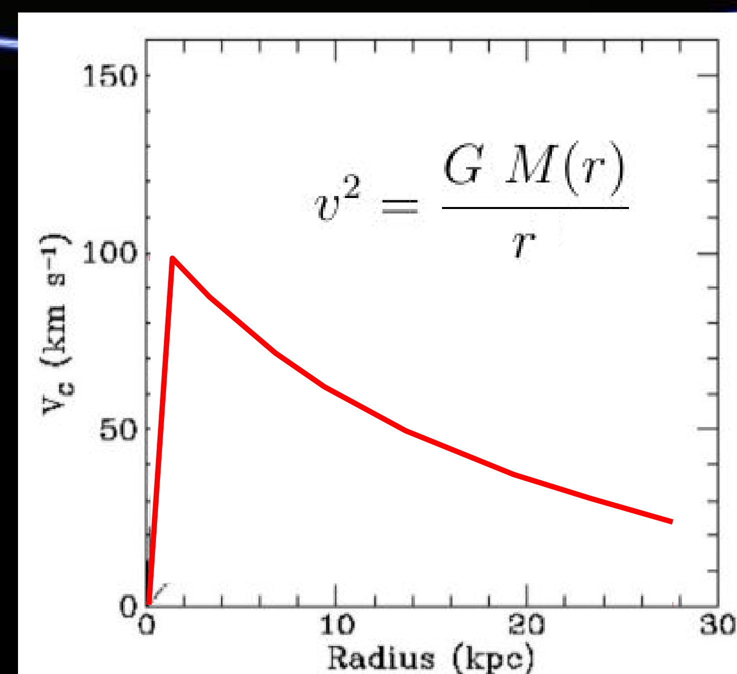


about 100'00 dark matter particles cross an area of 1 cm² per second


Part 1 –
Evidence for Dark Matter

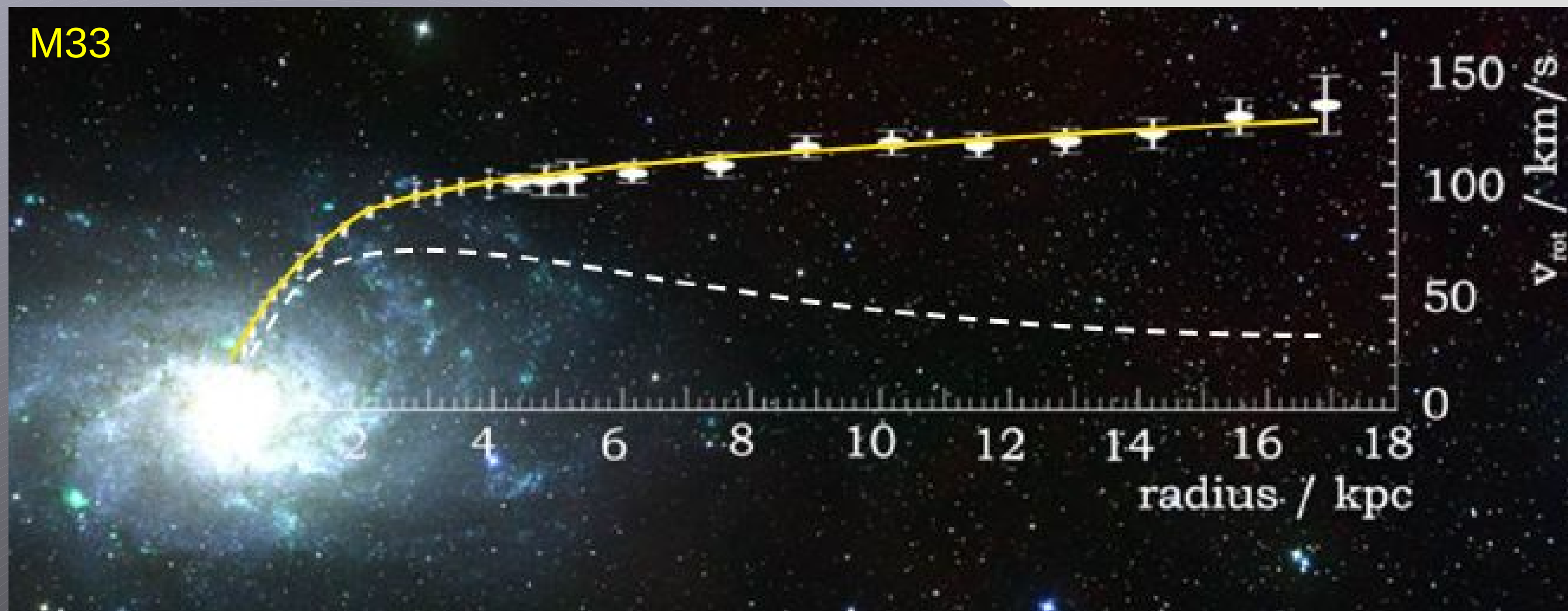
Expect: Kepler Rotation
(as solar system)





Galactic Rotation Curves

Measurement: flat rotation profile … well beyond visible stars

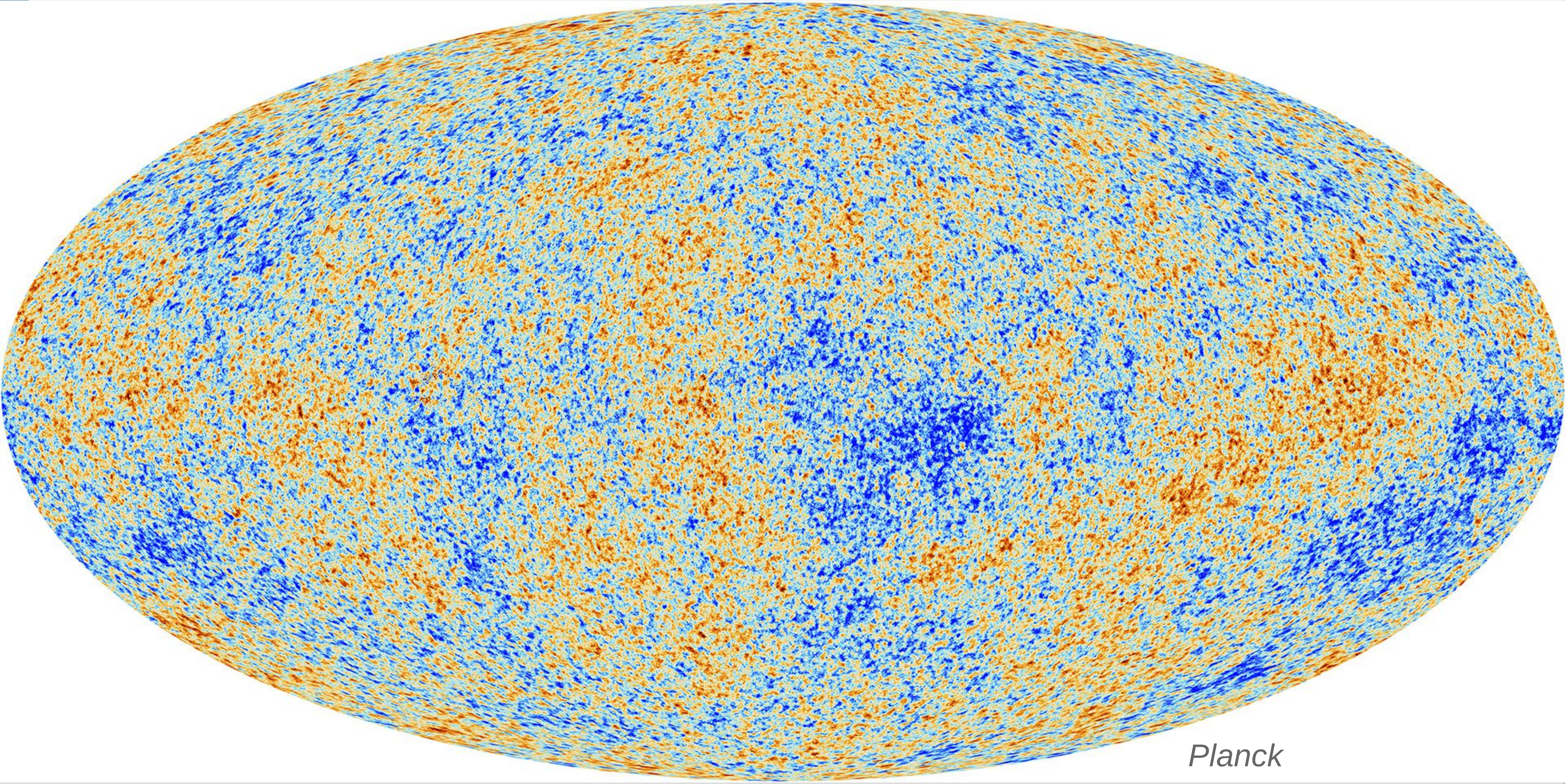


„Halo“ made from Dark Matter

(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

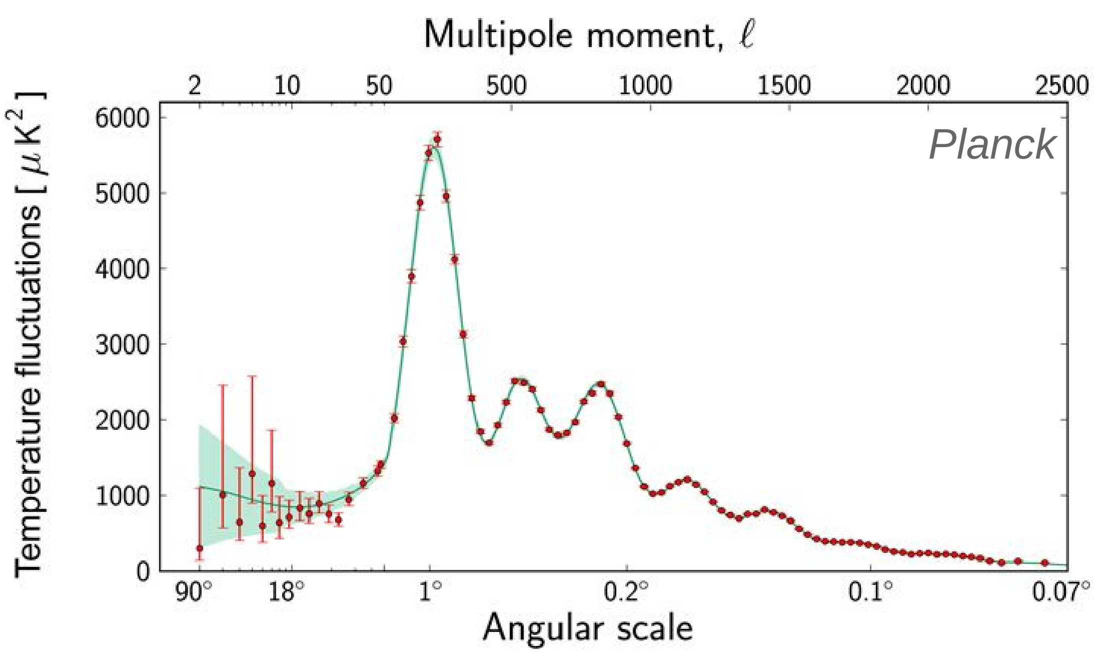


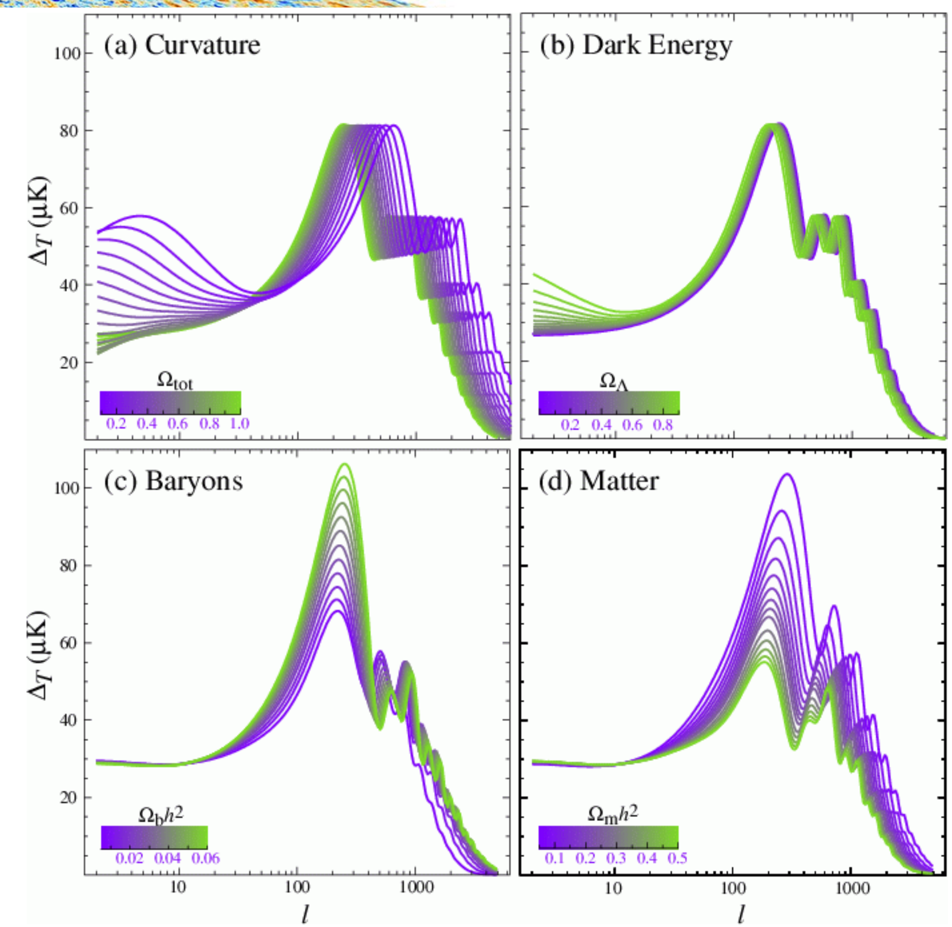
Planck

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“

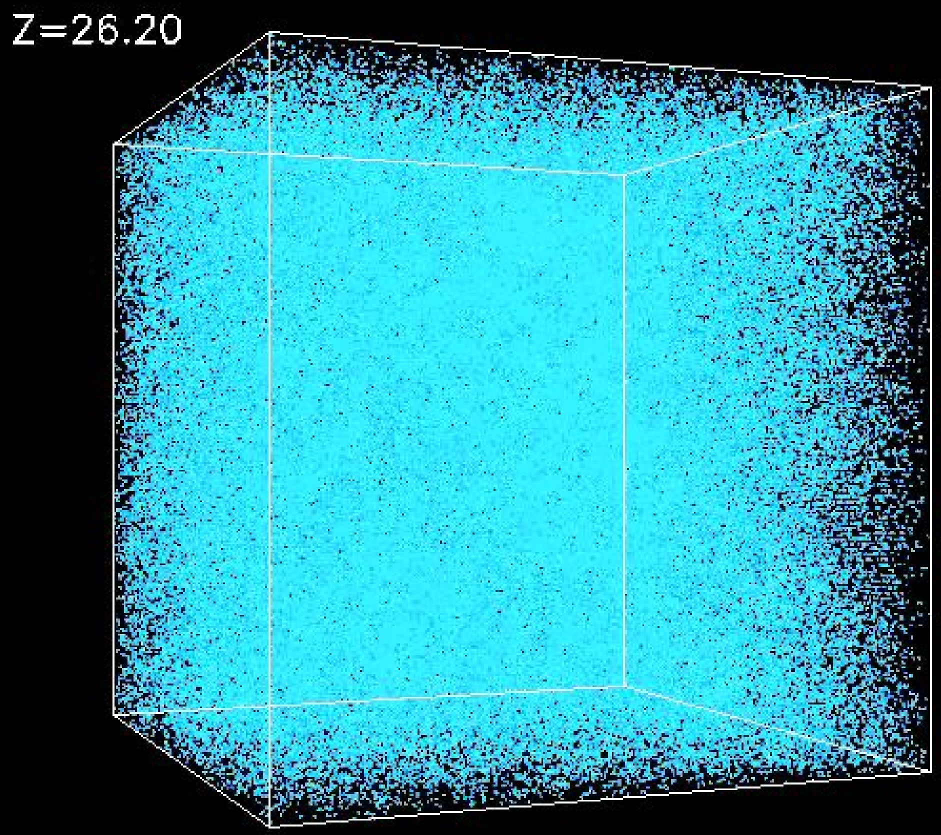


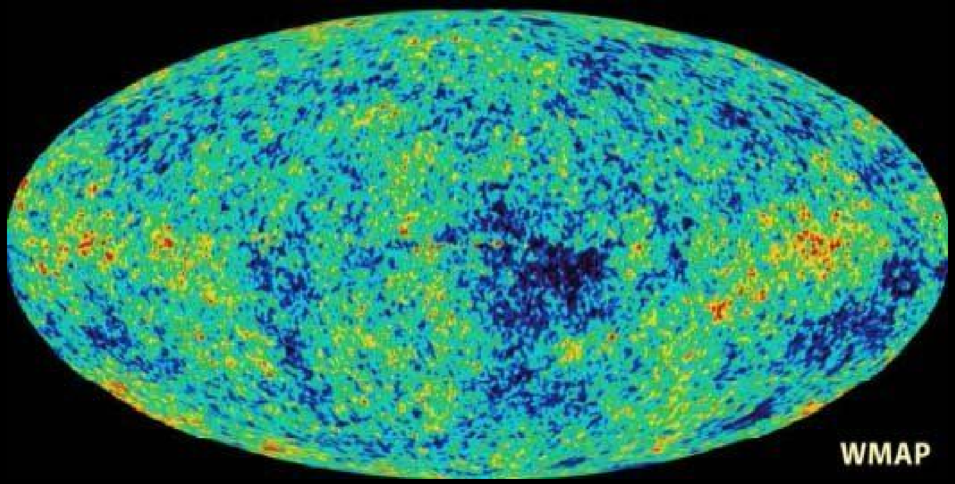


Planck

Dark Matter shapes the Universe

~40M years
after big bang

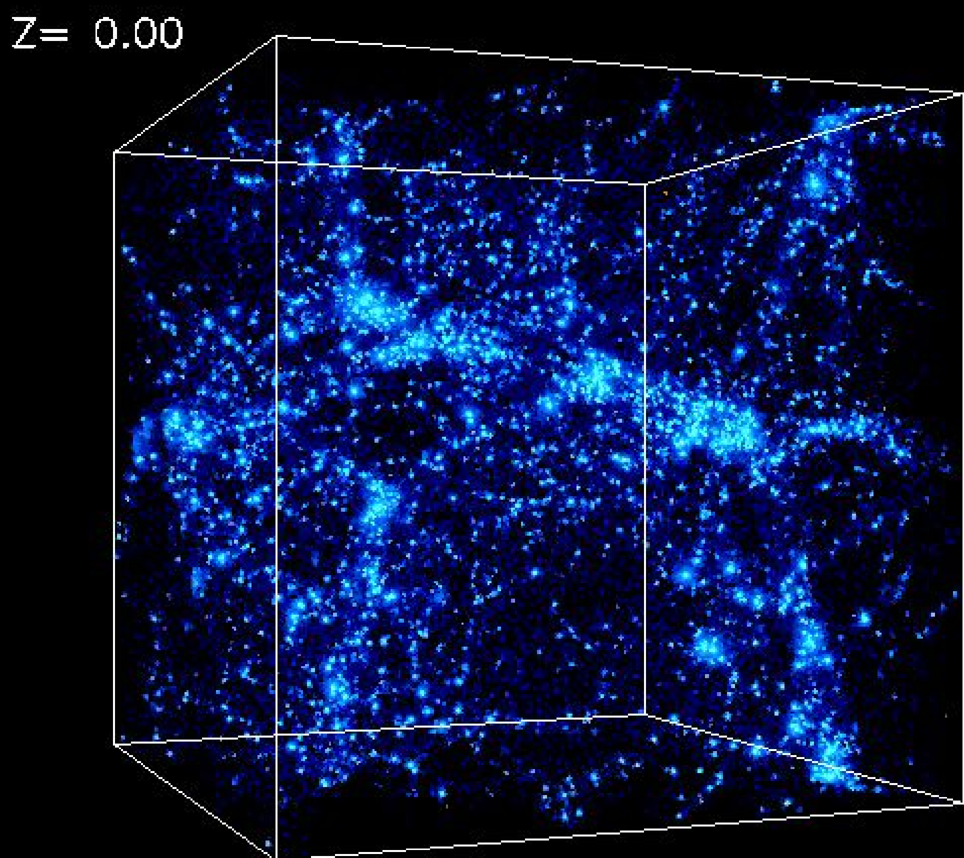


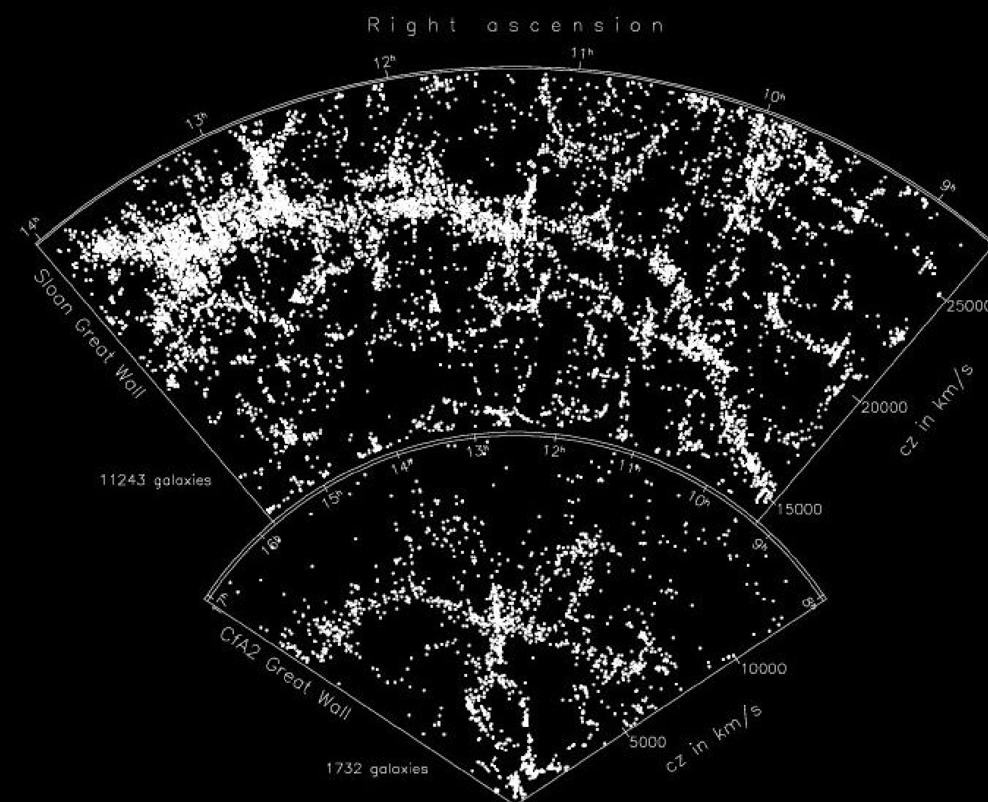


http://cosmicweb.uchicago.edu

Dark Matter shapes the Universe

now



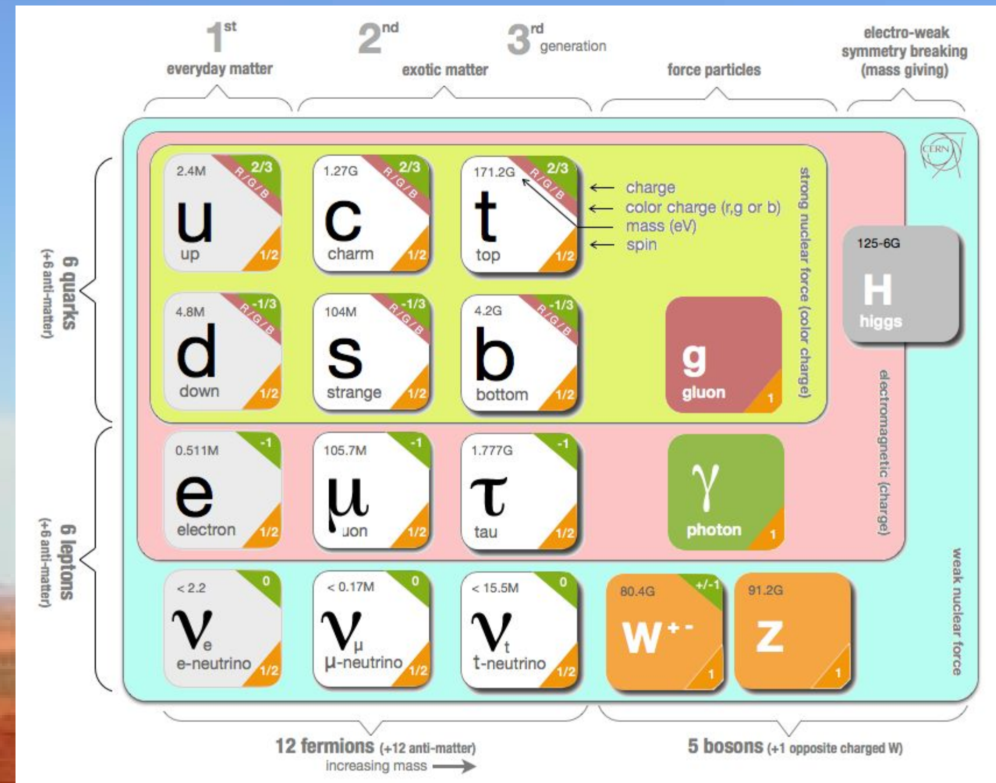


Simulation

Observation (SDSS)

Looking for matter with the following properties:

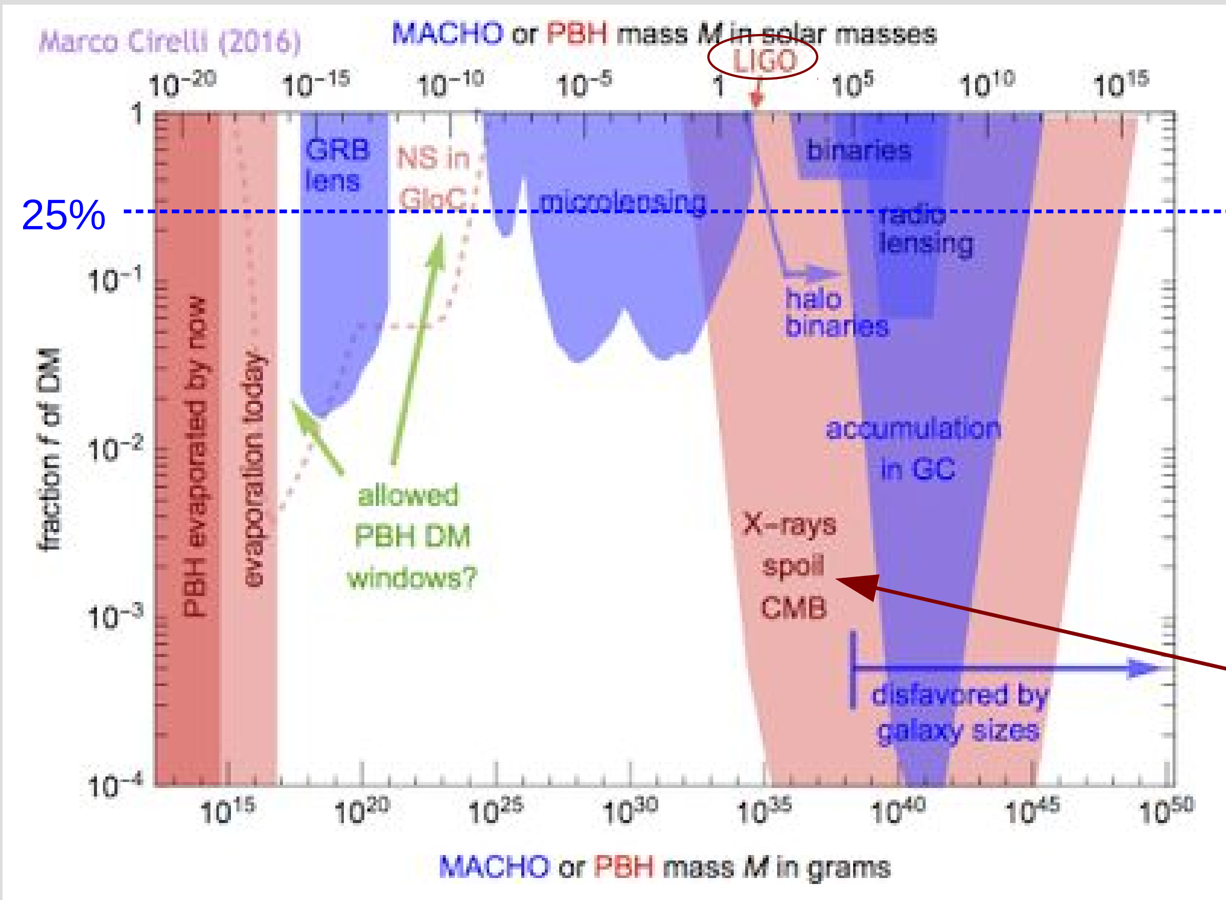
- „invisible“
- „cold“ (= „slow“)
- almost collisionless
- stable

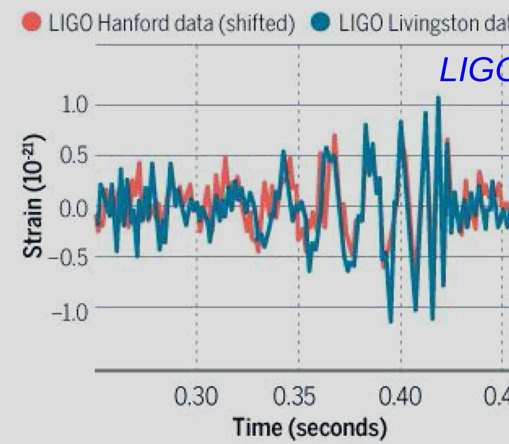


Problem:
no known particle fits the description
→ **we need to look for something new**
weakly **i**nteracting **m**assive **p**article (WIMP)

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

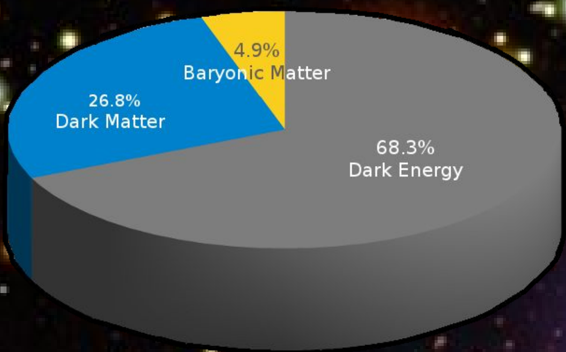
constraints in 10-100 M_{sun} range (LIGO):

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

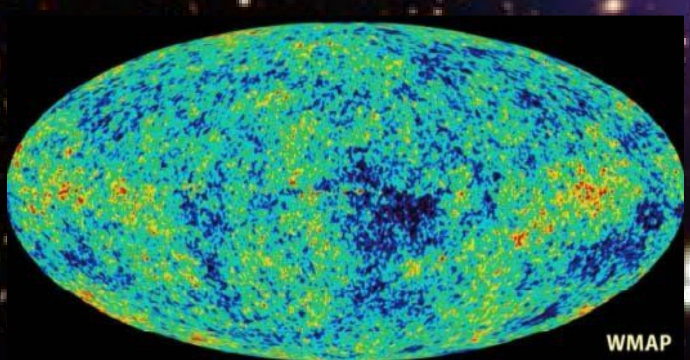
– *but*: new discussion about PBH dark matter started *PRL 116, 201301 (2016)*

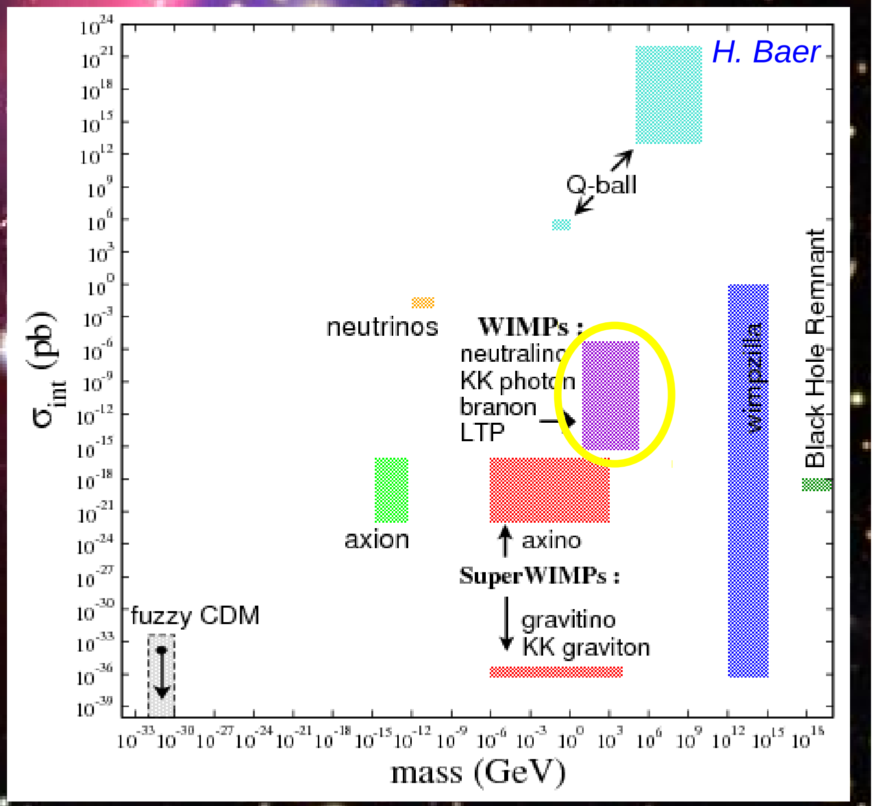
maybe PBH not dark matter but faster merger rate *PRL 117, 061101 (2016)*

Dark Matter: (indirect) Evidence



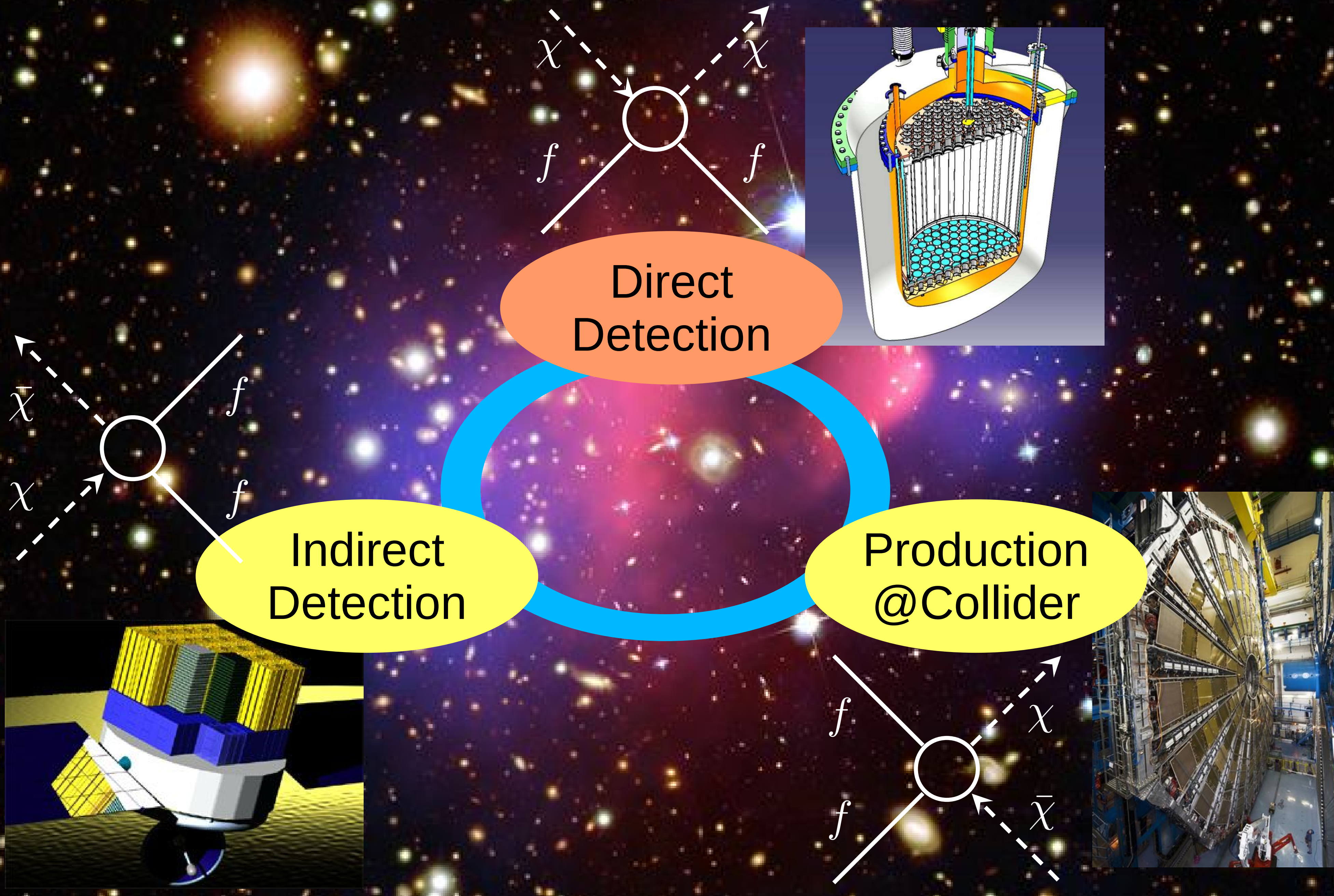
Particle Dark Matter Candidates:
- **WIMP** → *„WIMP miracle“*
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...





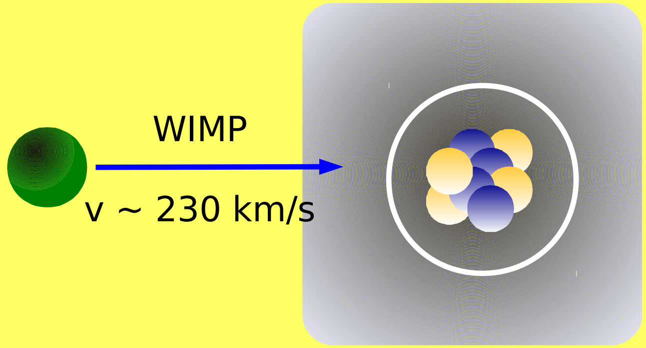
Part 2 –
Searching for Dark Matter

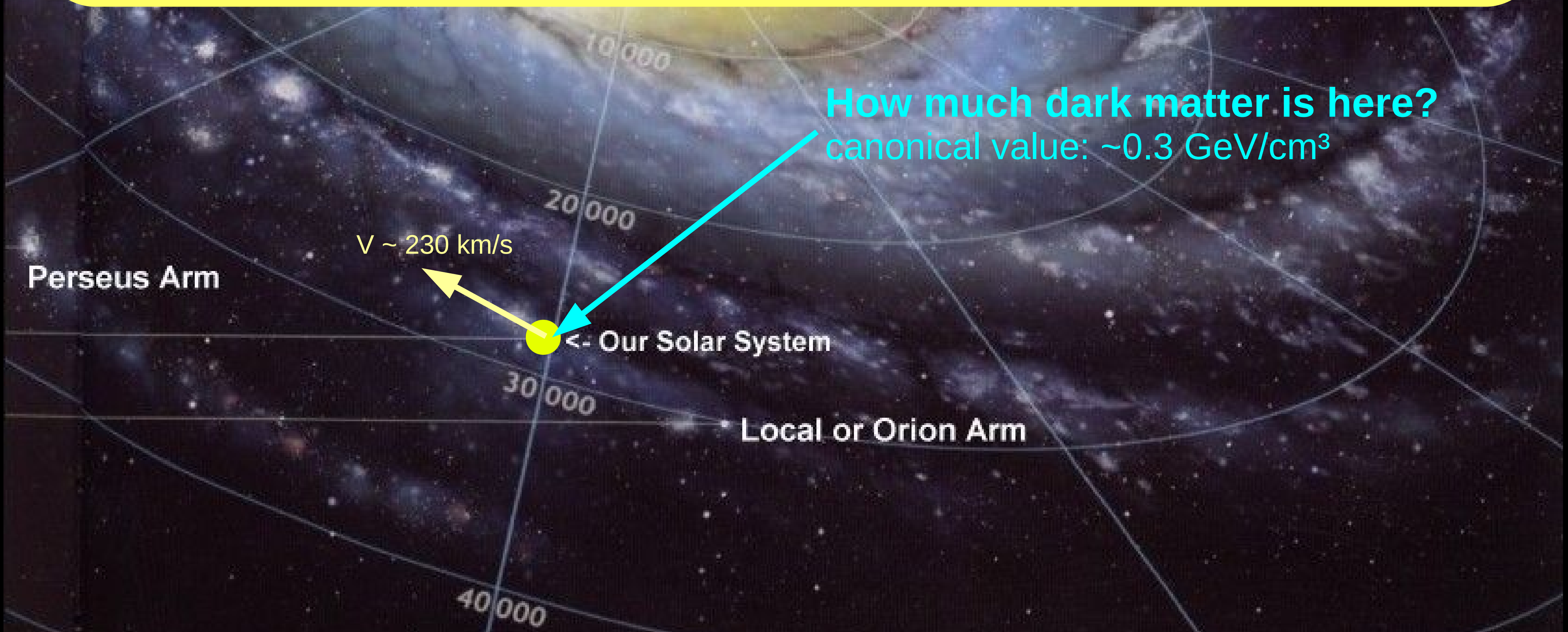
Dark Matter Search



Direct WIMP Search

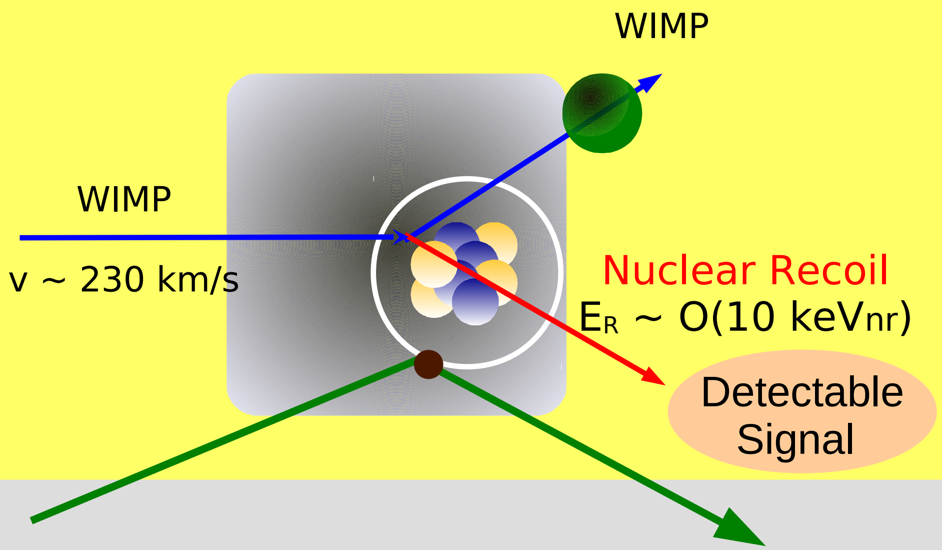
Elastic Scattering of WIMPs off target nuclei





Direct WIMP Search

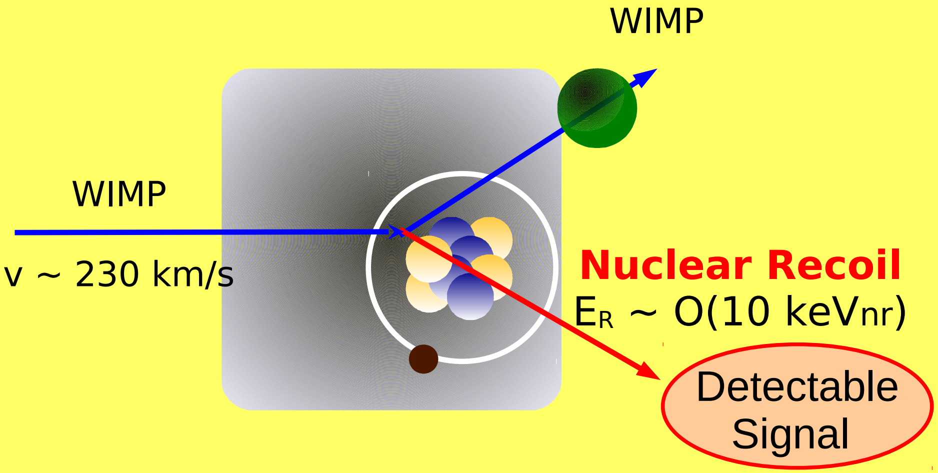
Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil

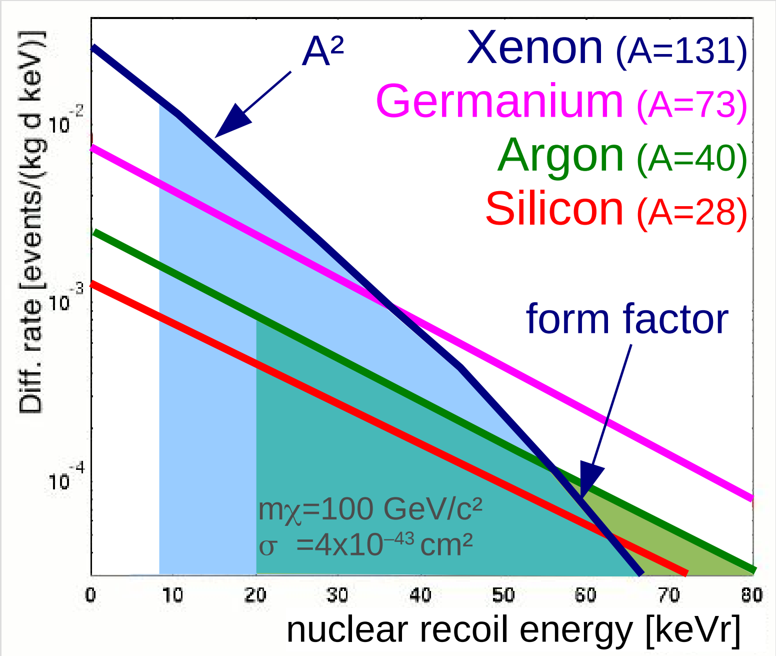


gamma- and beta-particles (background) interact with the atomic electrons
→ **electronic recoil** [in keVee]

Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



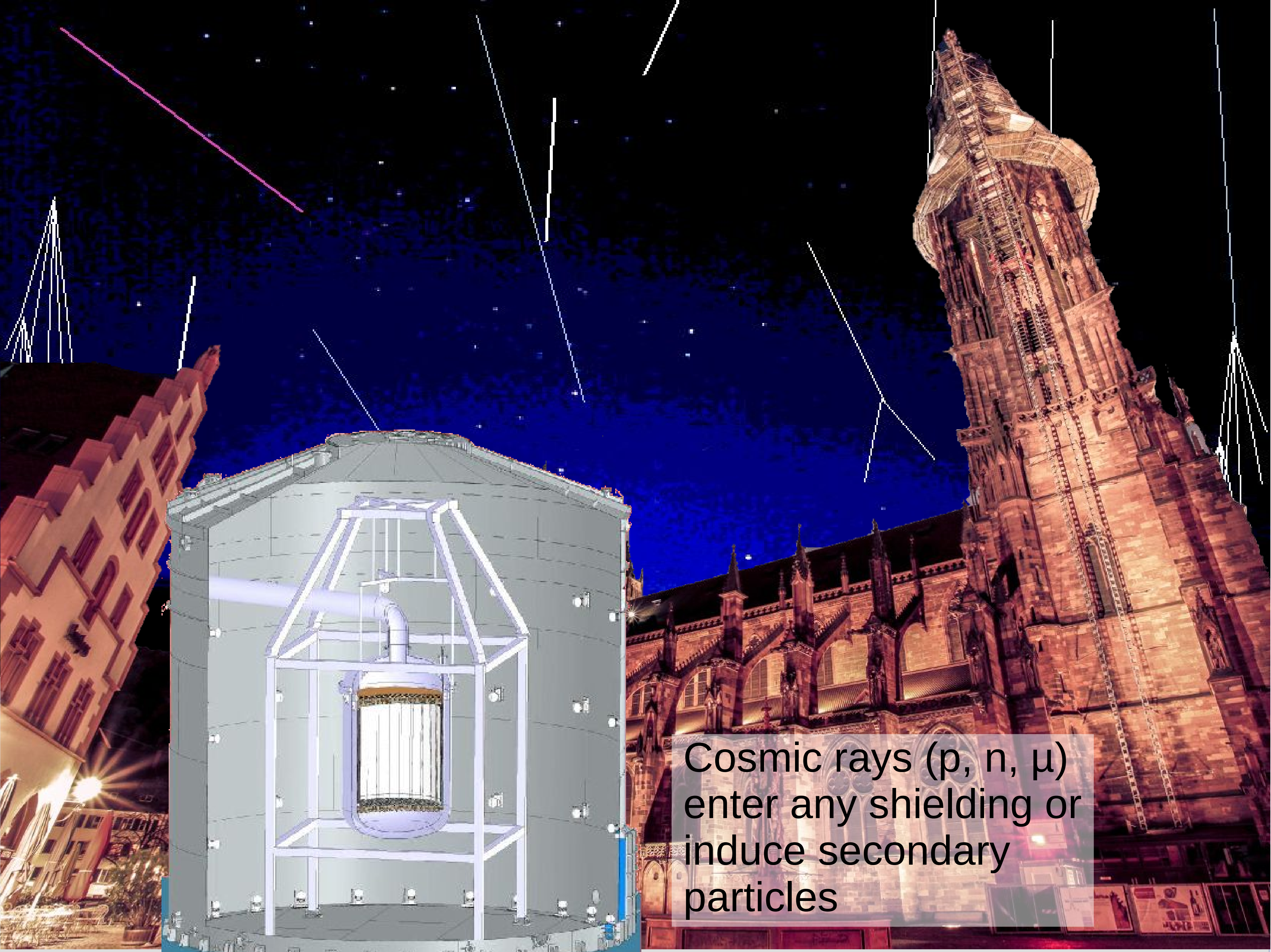


Event rate $R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$

Detector — Local DM Density — Physics

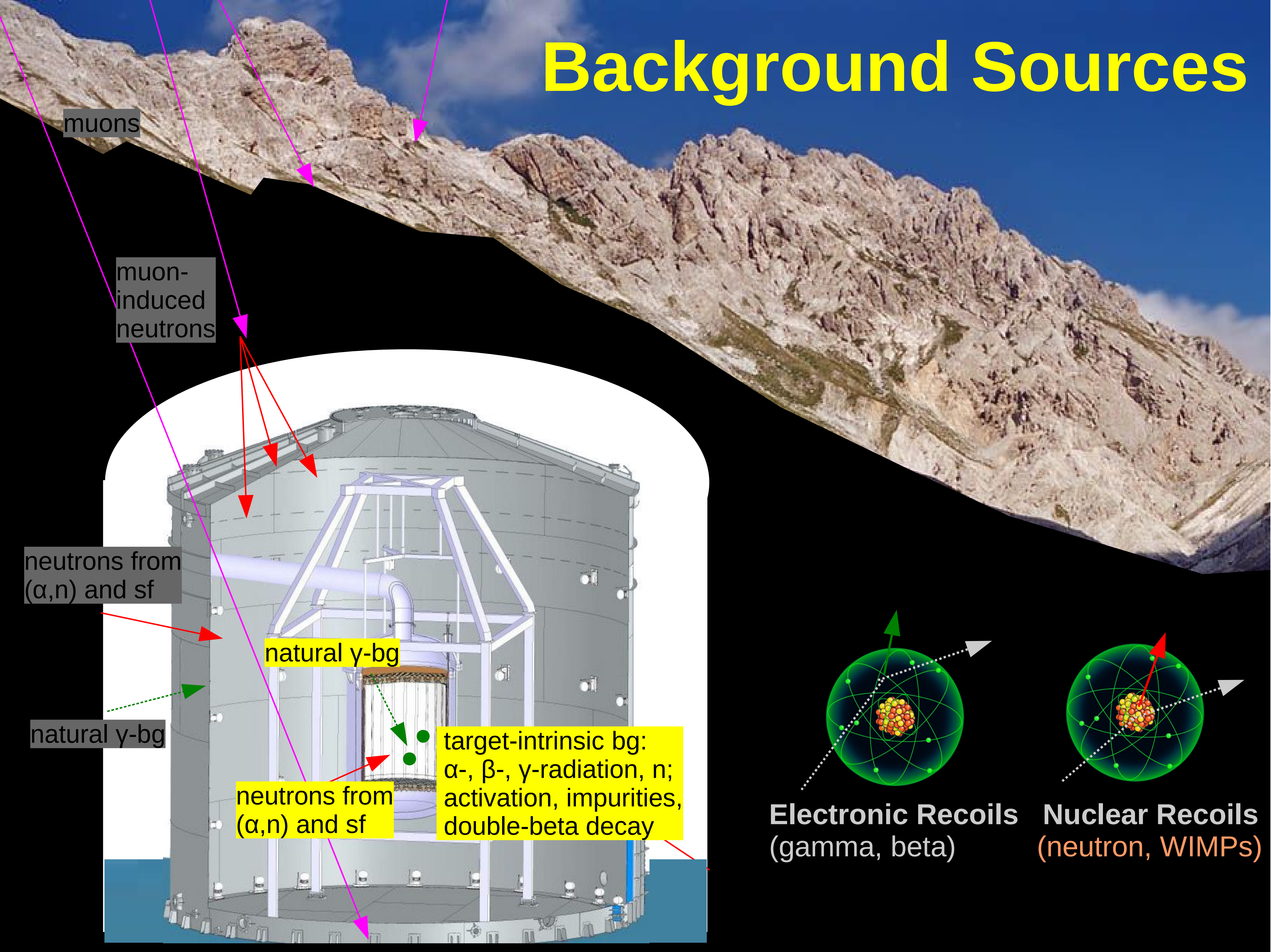
$\rho_\chi \sim 0.3$ GeV/c^2

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

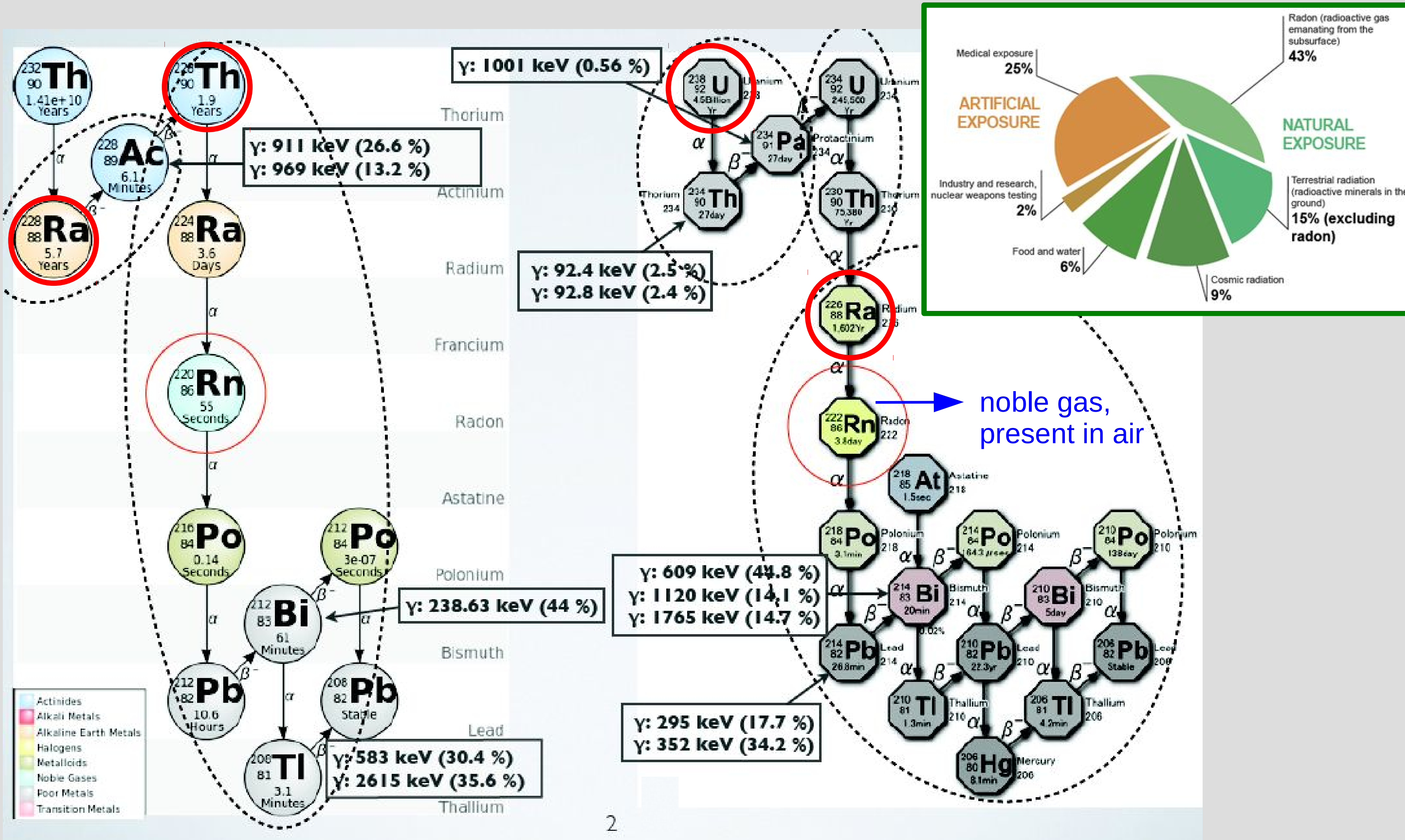

Cosmic rays (p, n, μ) enter any shielding or induce secondary particles

Laboratori Nazionali del Gran Sasso

Background Sources



The U and Th Chains

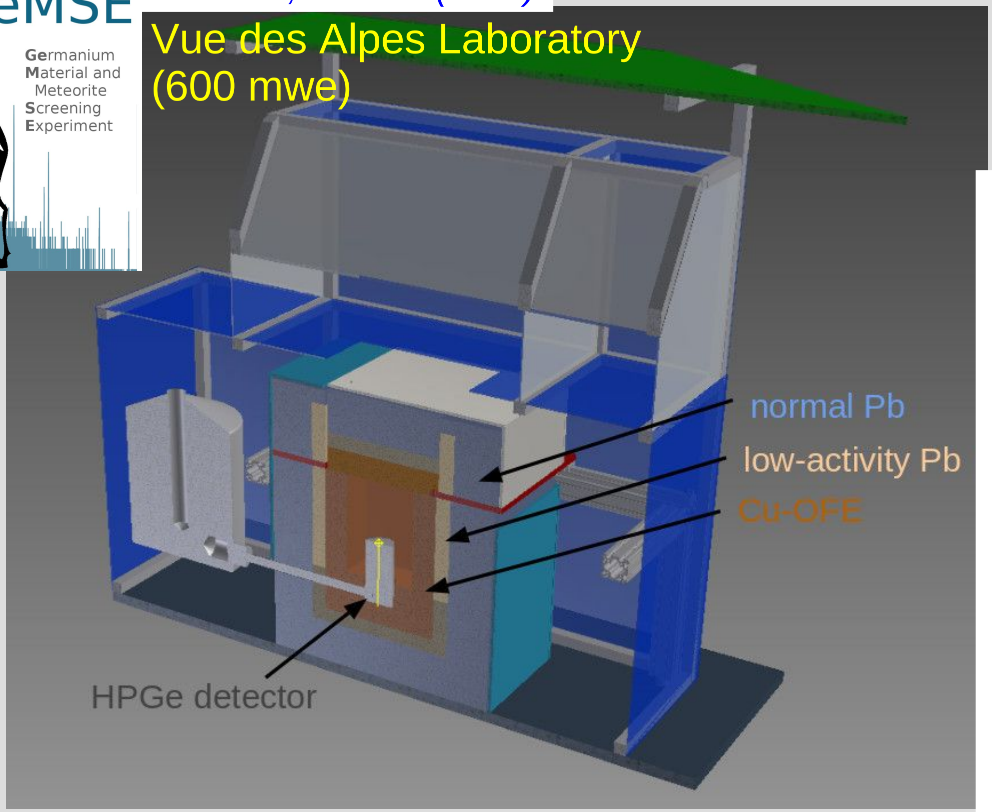


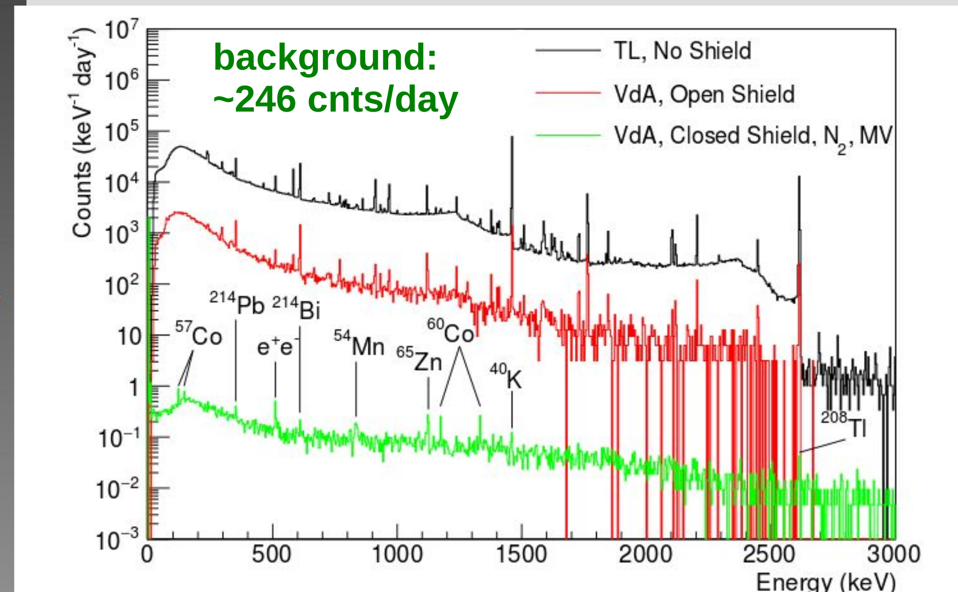

GeMSE
Germanium
Material and
Meteorite
Screening
Experiment
NON-MAGNETIC
LHE
100lbs.)

Low-background Screening

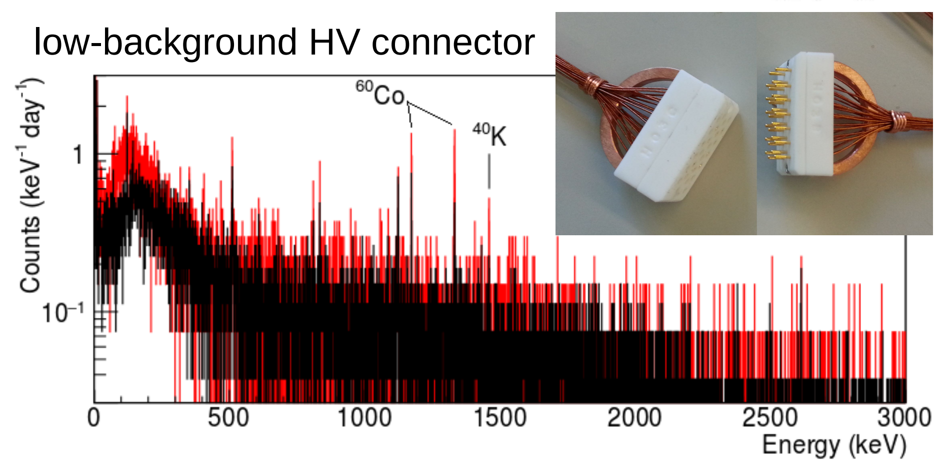
GeMSE
Germanium Material and Meteorite Screening Experiment

JINST 11, P12017 (2016)





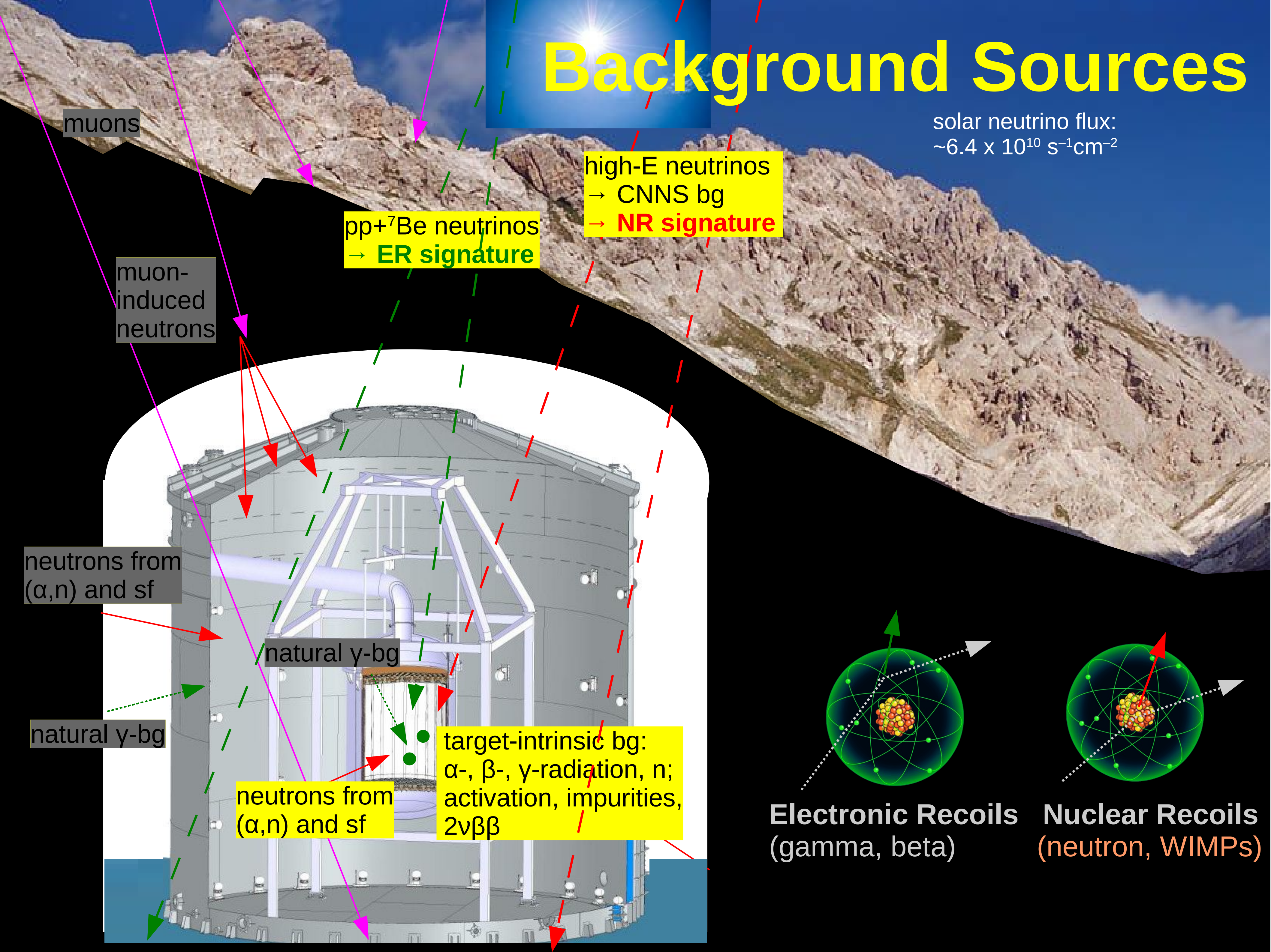
low-background HV connector



Identify materials with lowest radioactivity:

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

Background Sources



Background Suppression

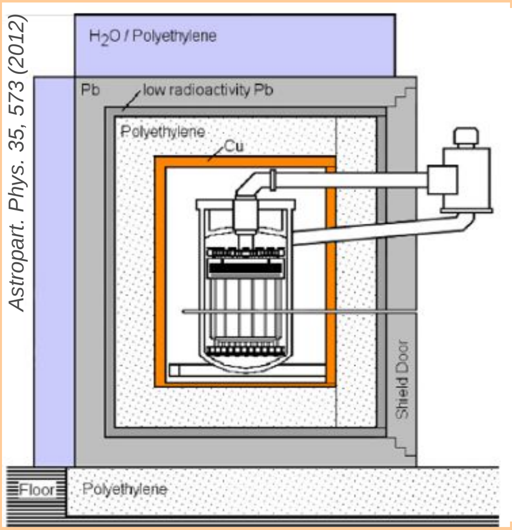
Avoid Backgrounds

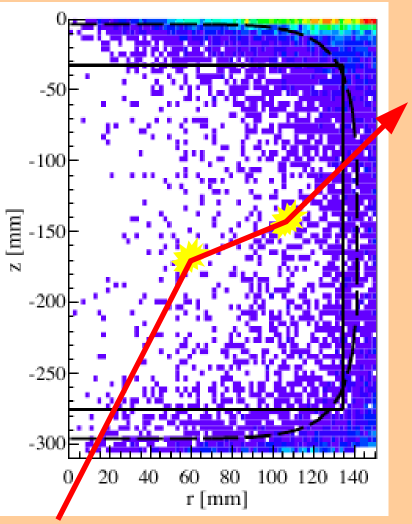
Shielding

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

self shielding → fiducialization

Use of radiopure materials





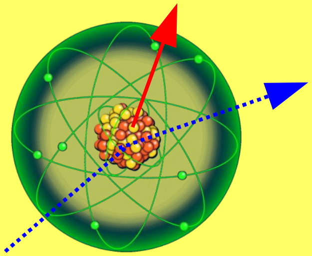
Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection
requires some position resolution

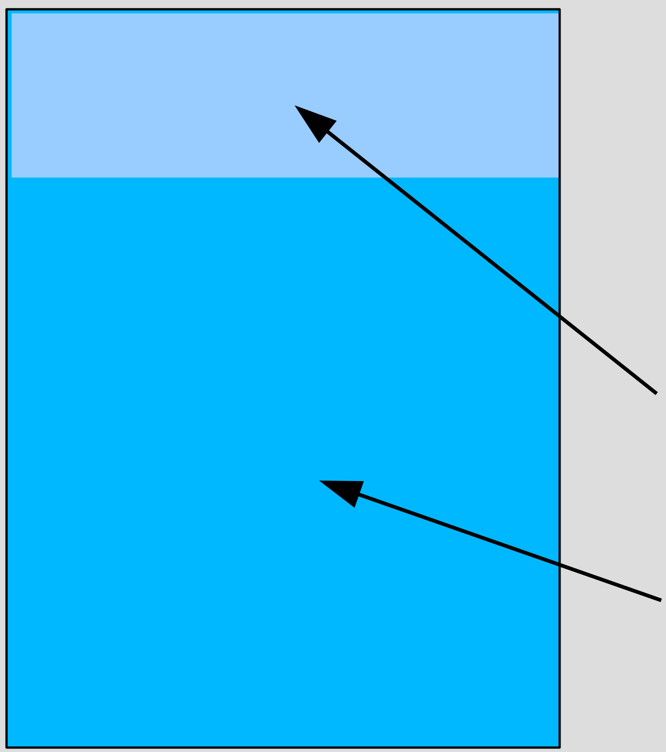
WIMPs interact with target nuclei

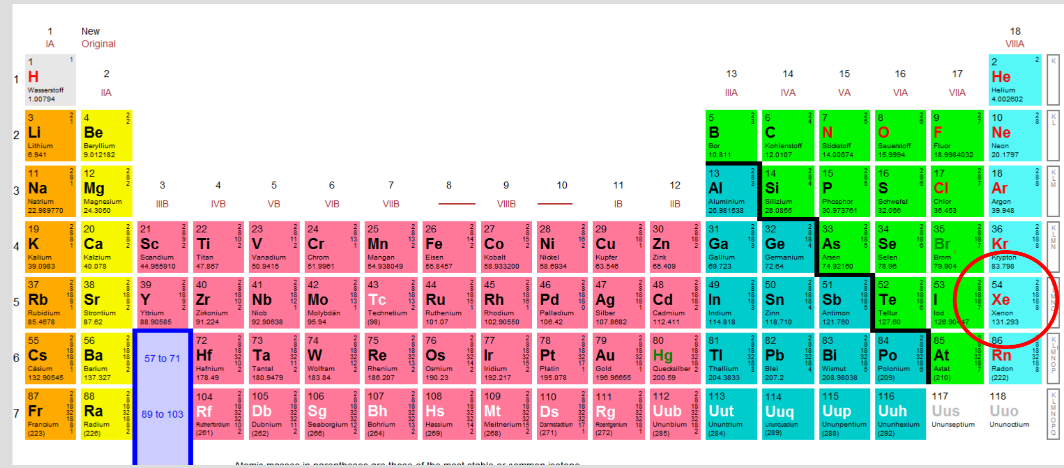
→ nuclear recoils
exploit different d*E*/d*x* from
signal and background



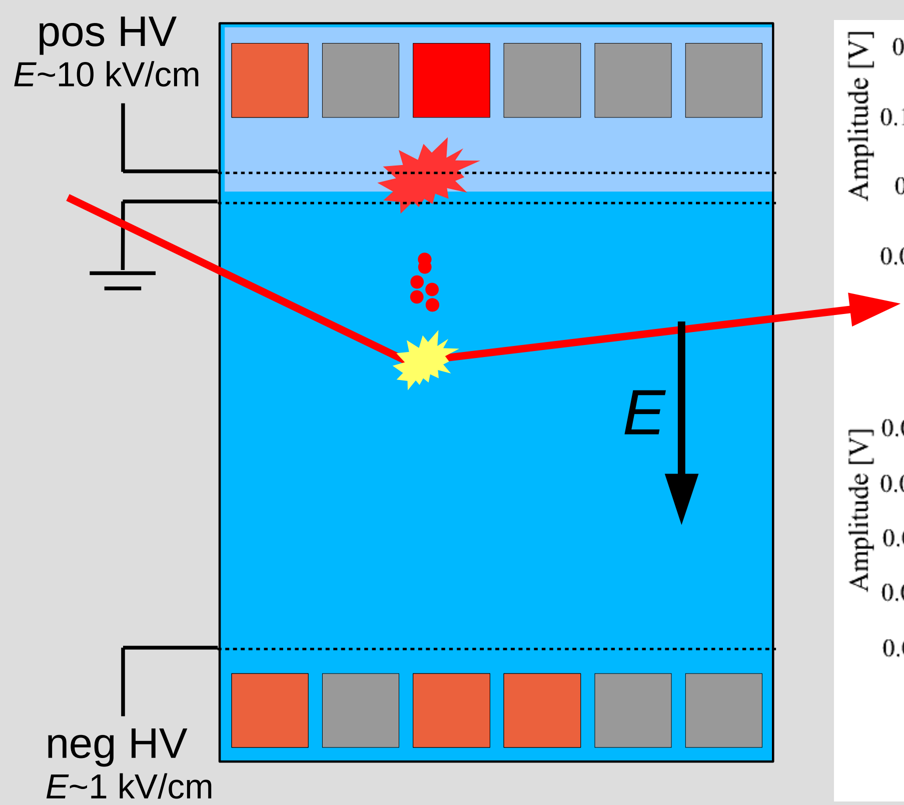
Part 3 –
The XENON1T Experiment

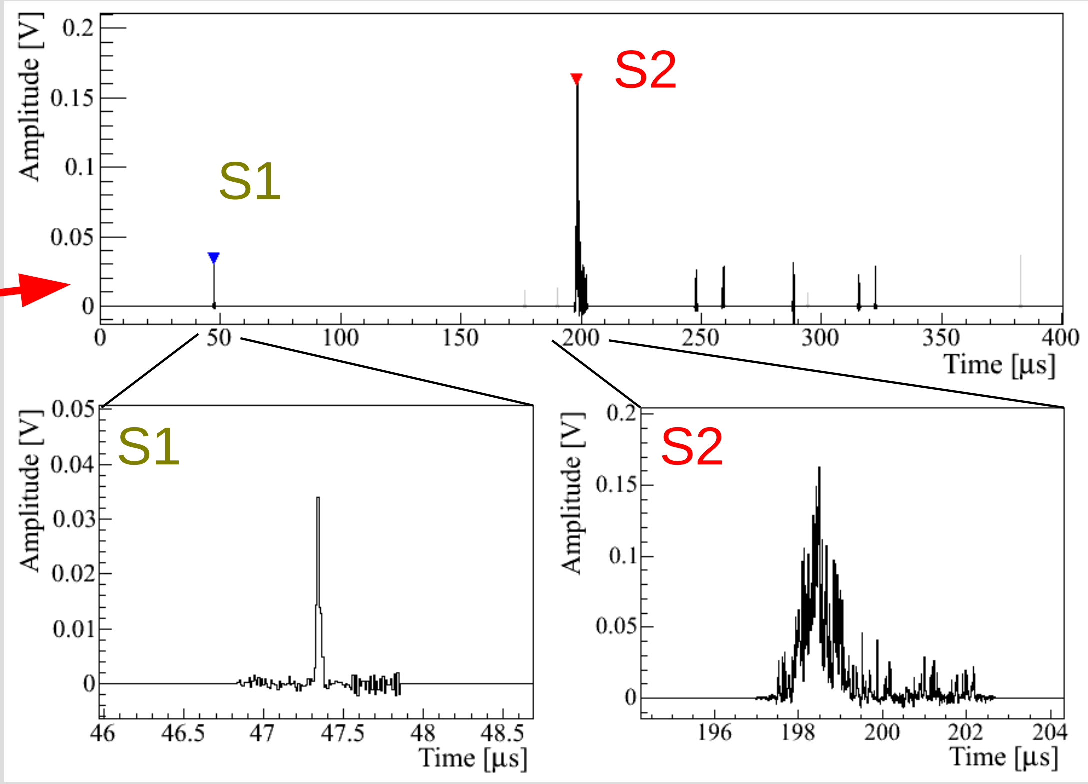
Dual Phase **liquid xenon** TPC

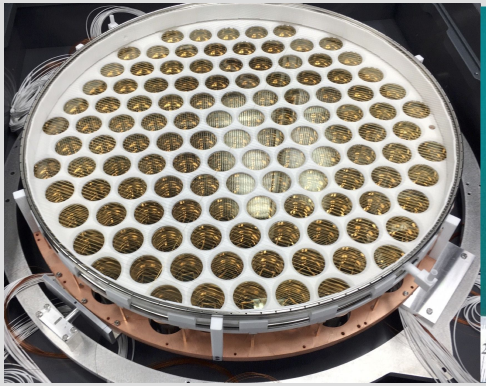




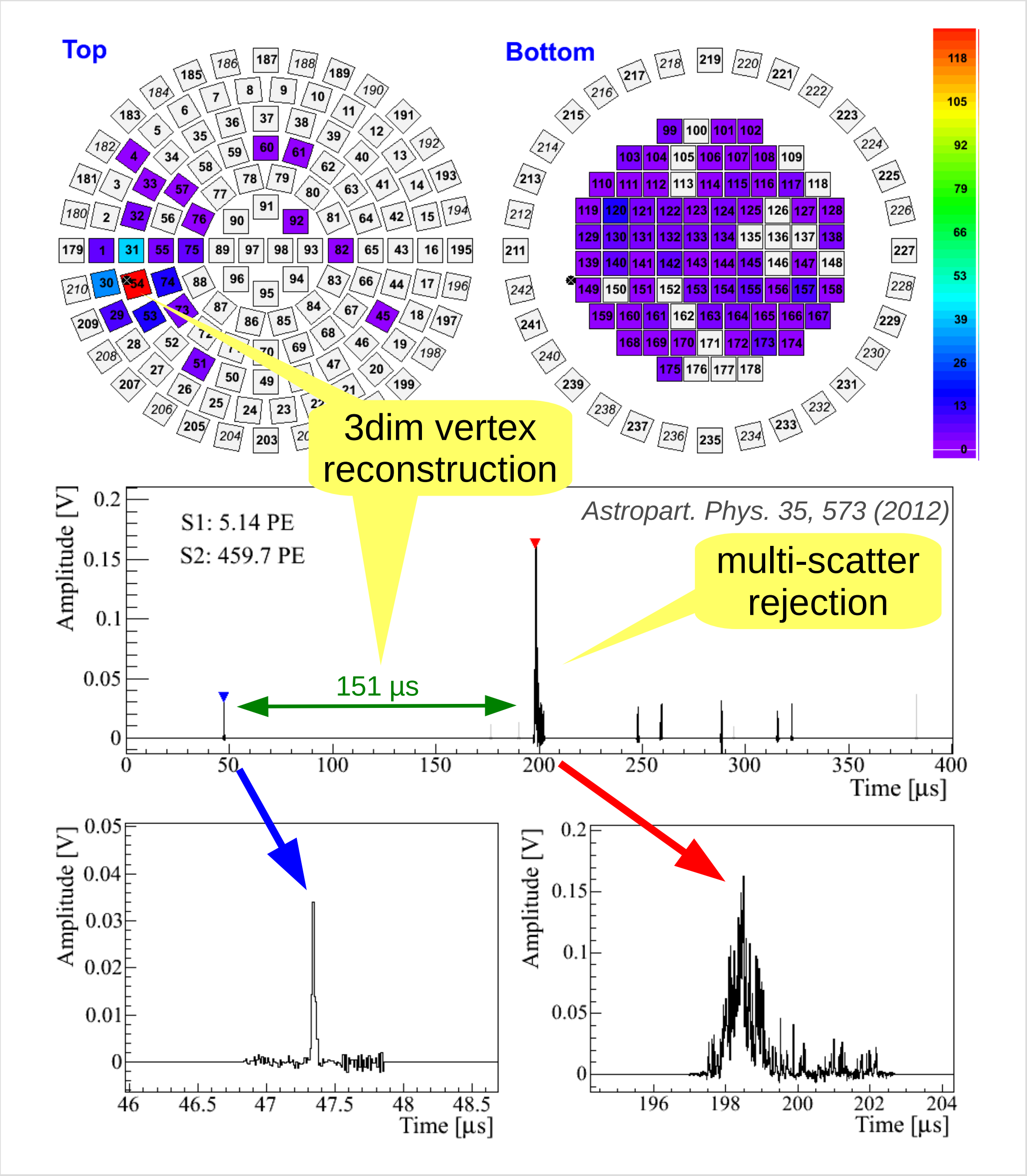
Dual Phase TPC

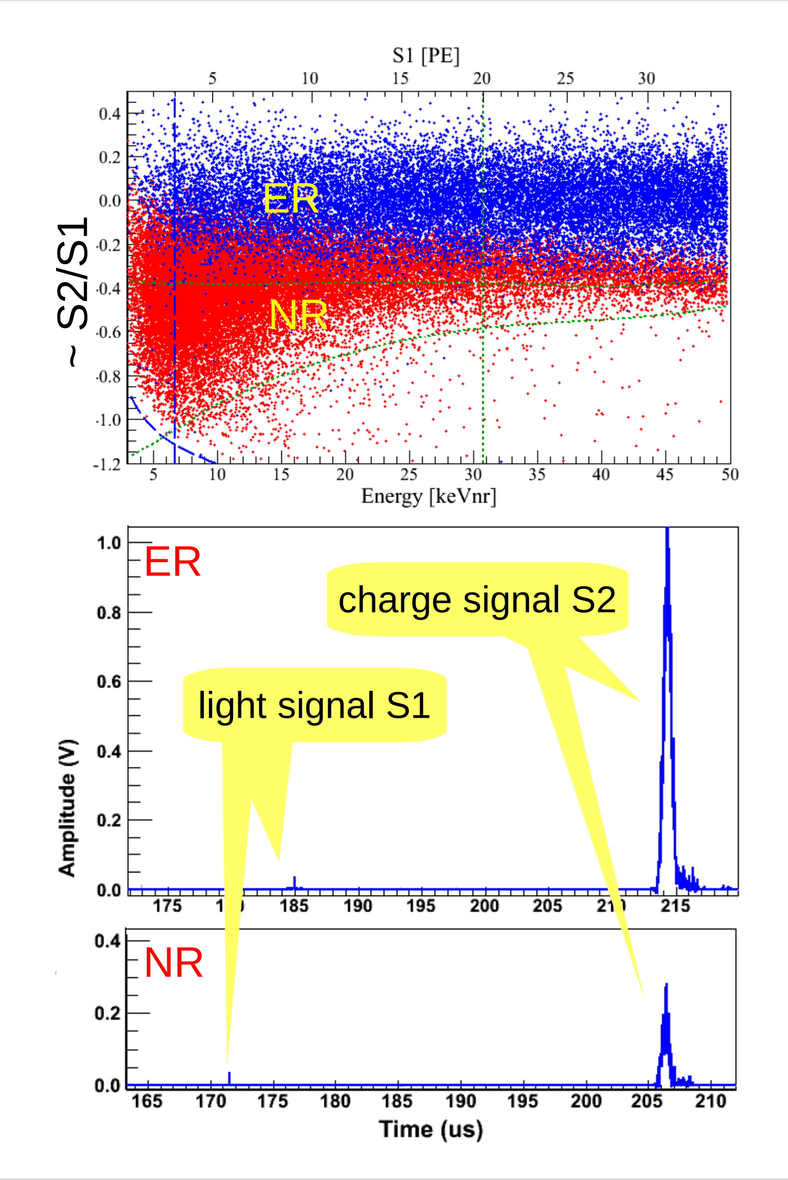






Dual Phase TPC

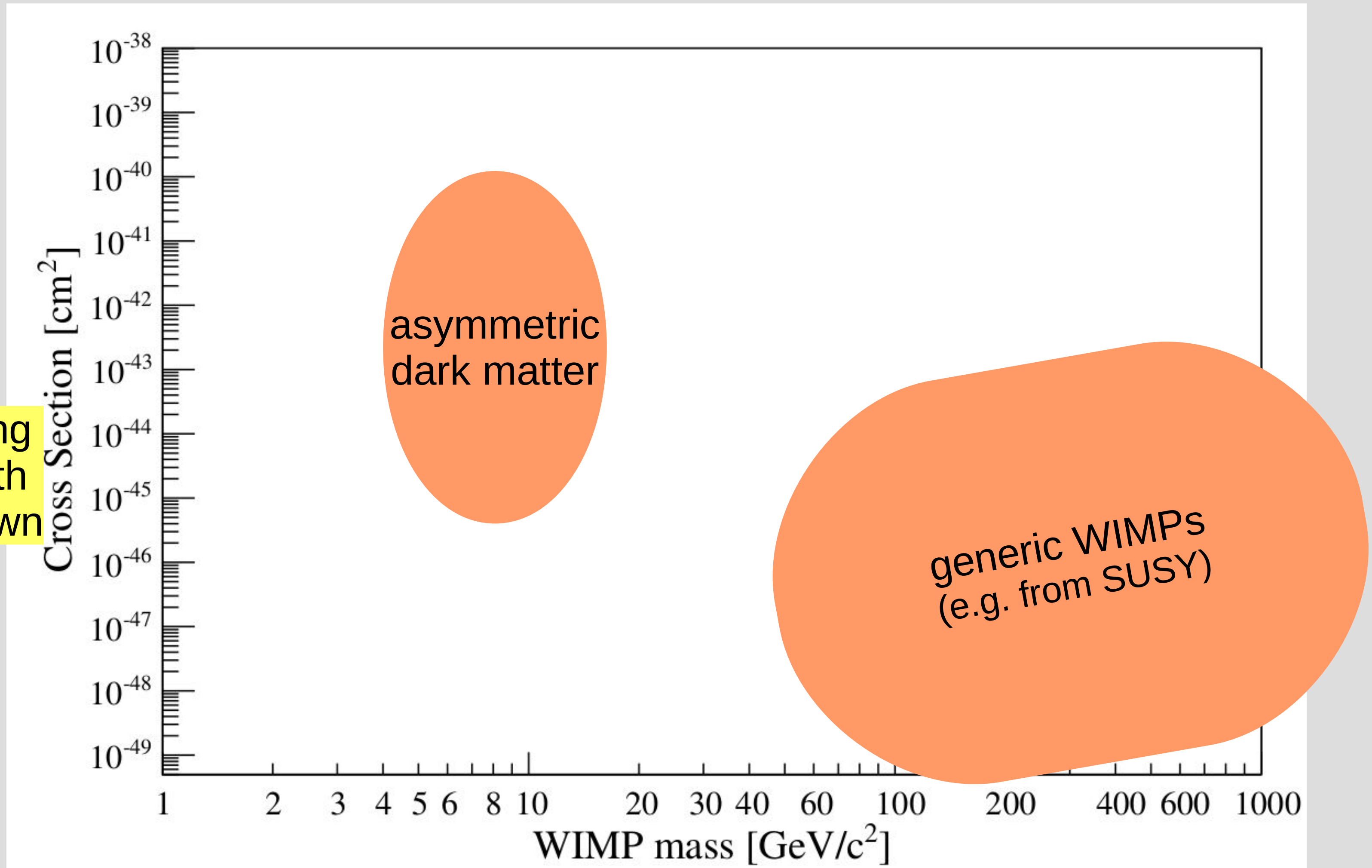




Figures from XENON100

The WIMP Parameter Space

spin-independent WIMP-nucleon interactions



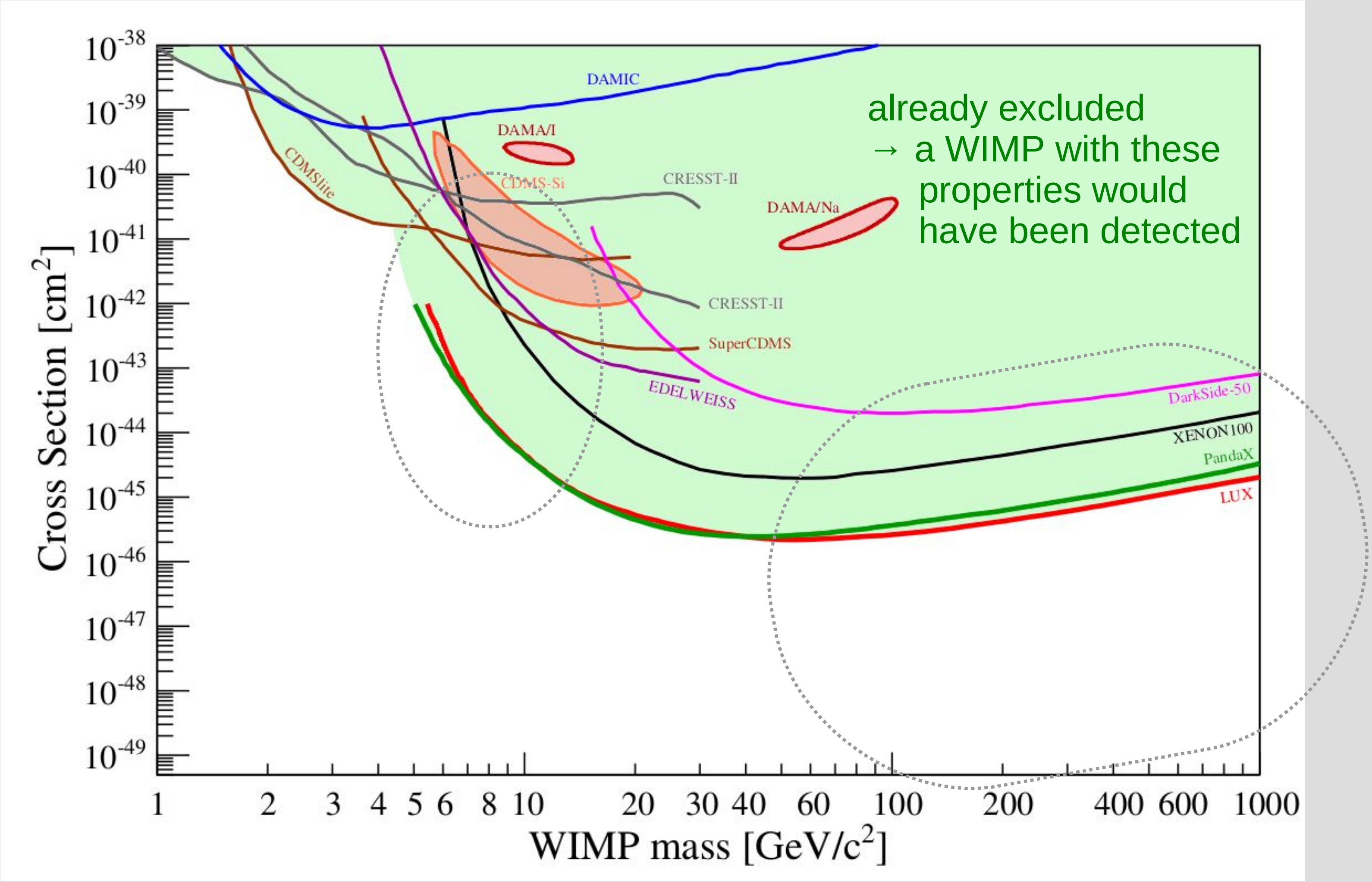
coupling strength unknown

WIMP mass unknown

High WIMP-masses TPC dominated

→ **≥4.5 GeV/c²**

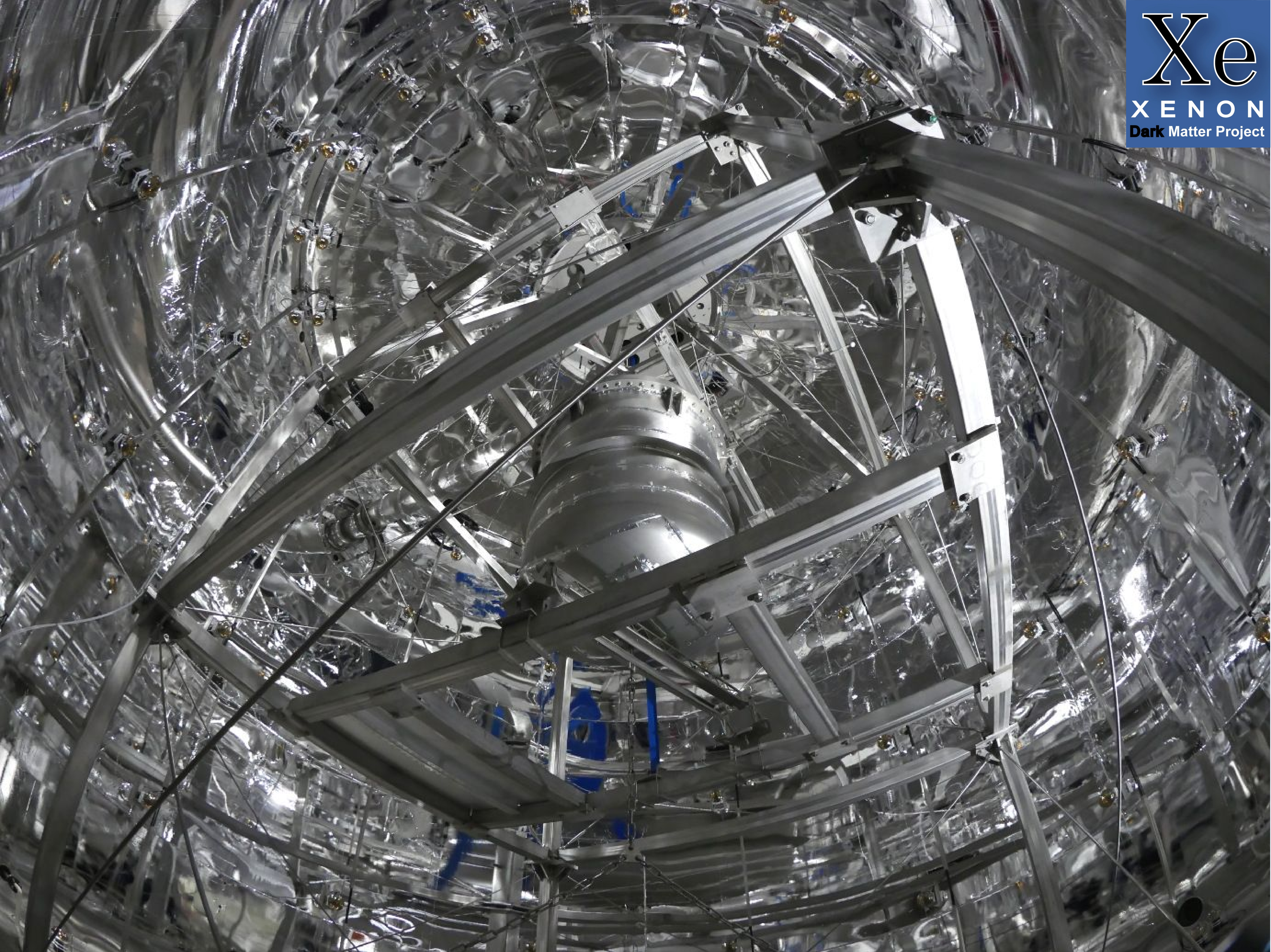
spin-independent WIMP-nucleon interactions



some projects are missing...

XENON1T @ LNGS

Xe
XENON
Dark Matter Project


Xe
XENON
Dark Matter Project


Xe
XENON
Dark Matter Project

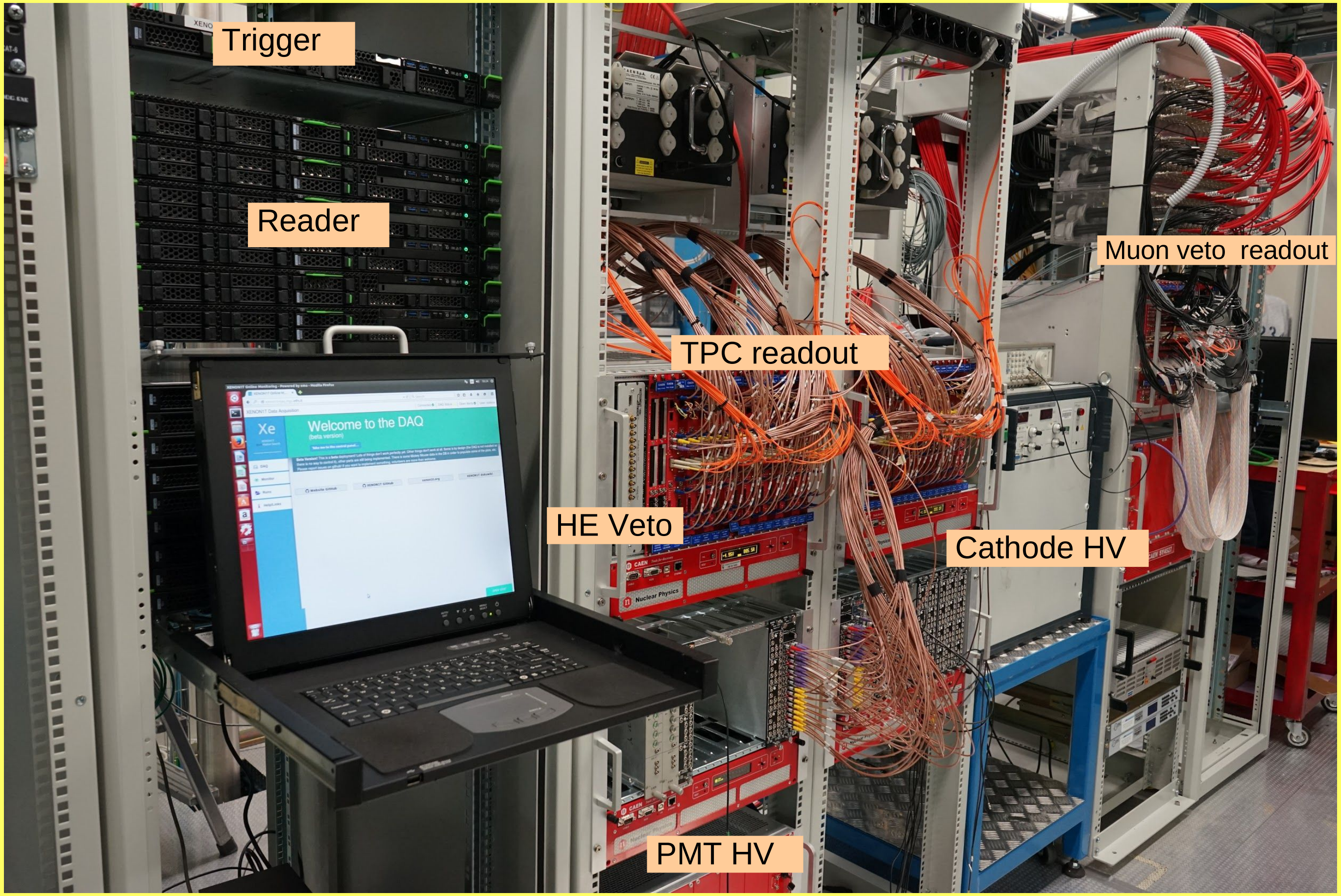

Xe
XENON
Dark Matter Project

Xe XENON Dark Matter Project

largest LXe TPC ever built

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

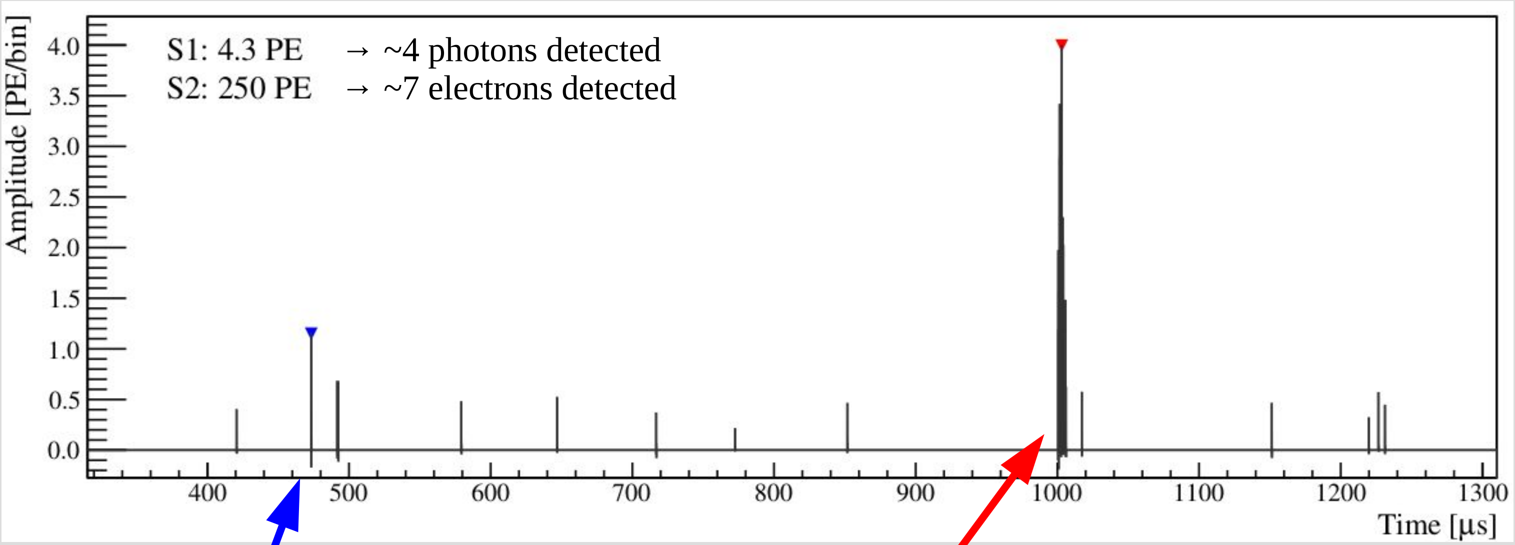
TPC Data Acquisition, Electronics

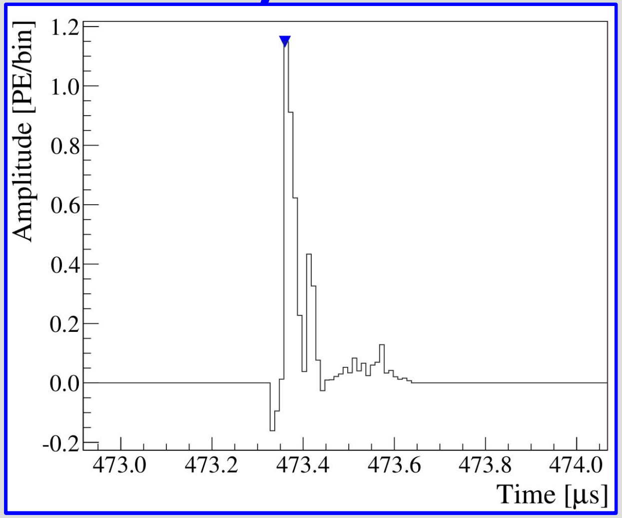


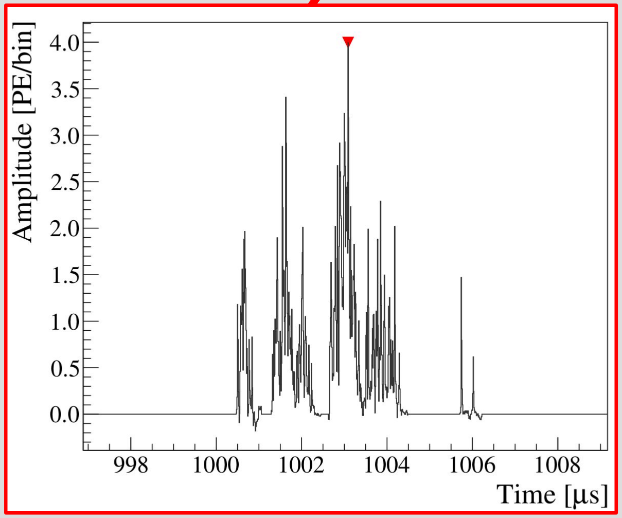
Parallel, trigger-less readout: → low threshold
→ high throughput (>300 MB/s achieved → 0.8 TB/d):

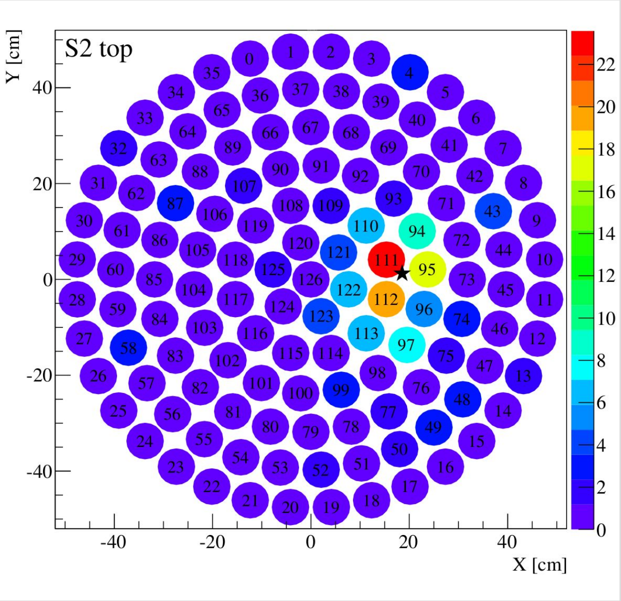
How would dark matter look?

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



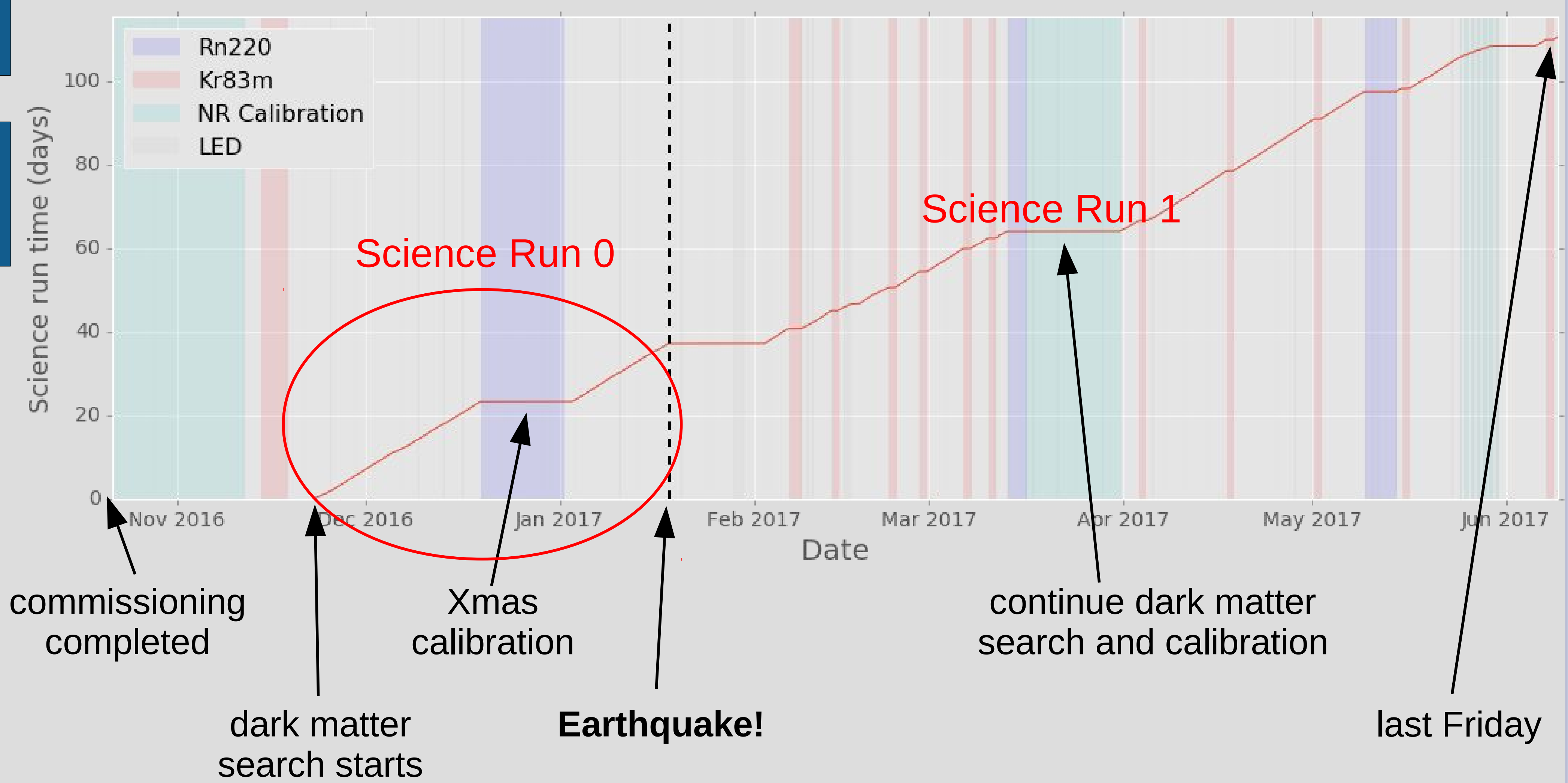






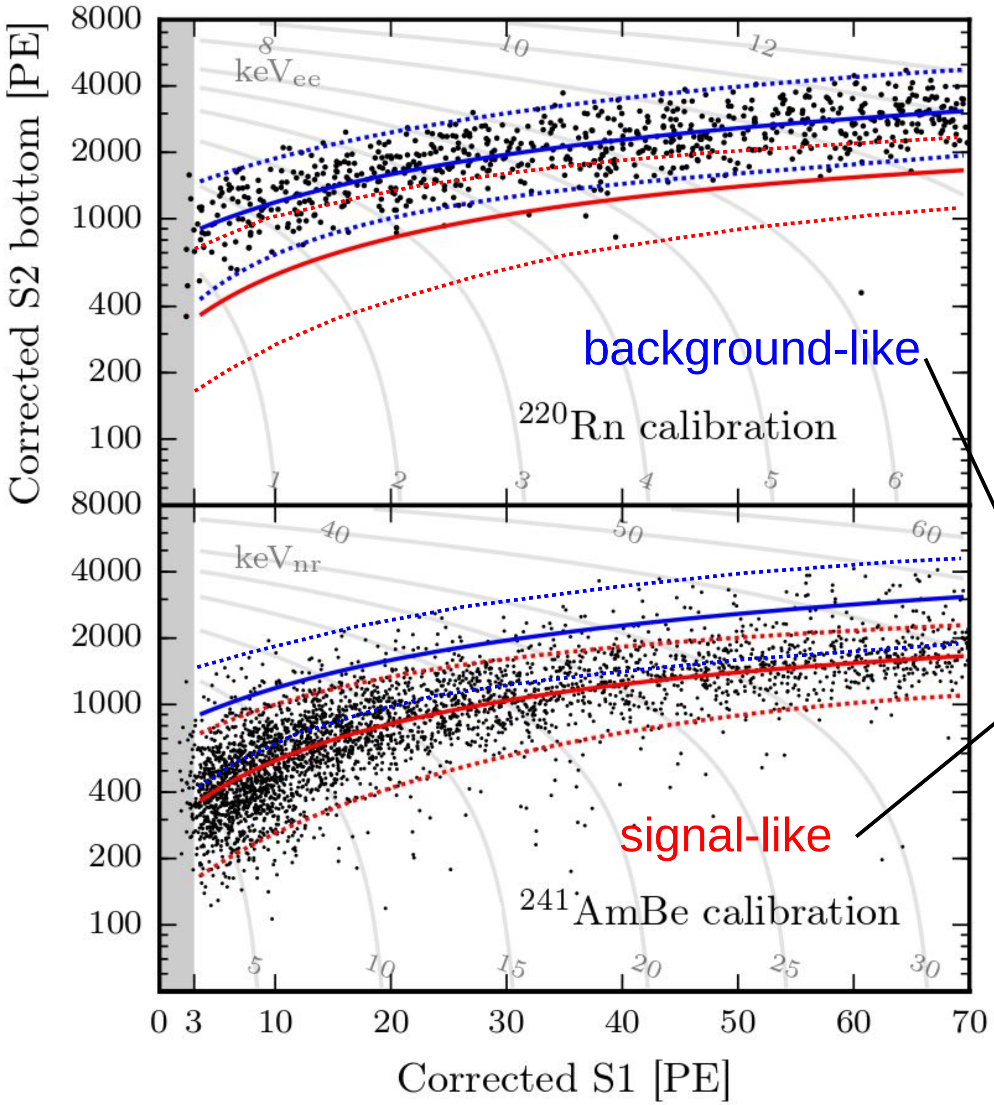
Dark Matter Data Taking

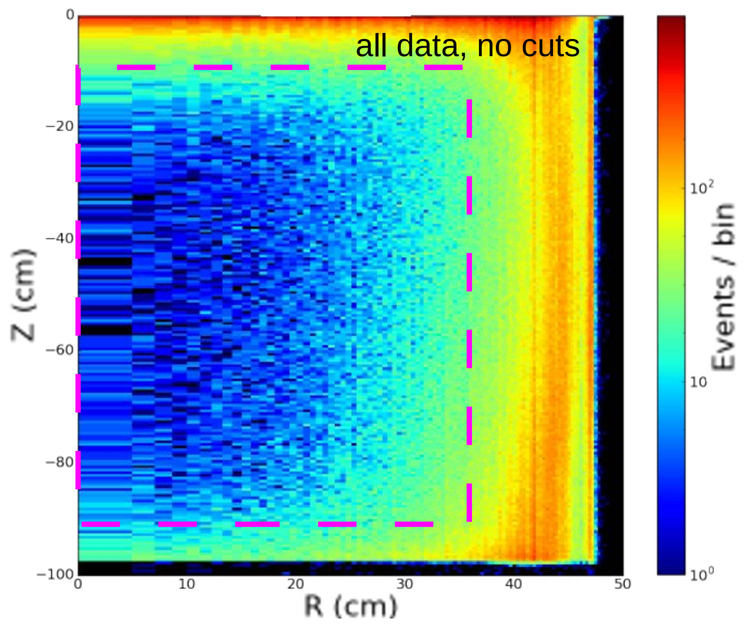
arXiv:1705.06655



Calibration and Analysis

arXiv:1705.06655





Used to construct background and signal models.

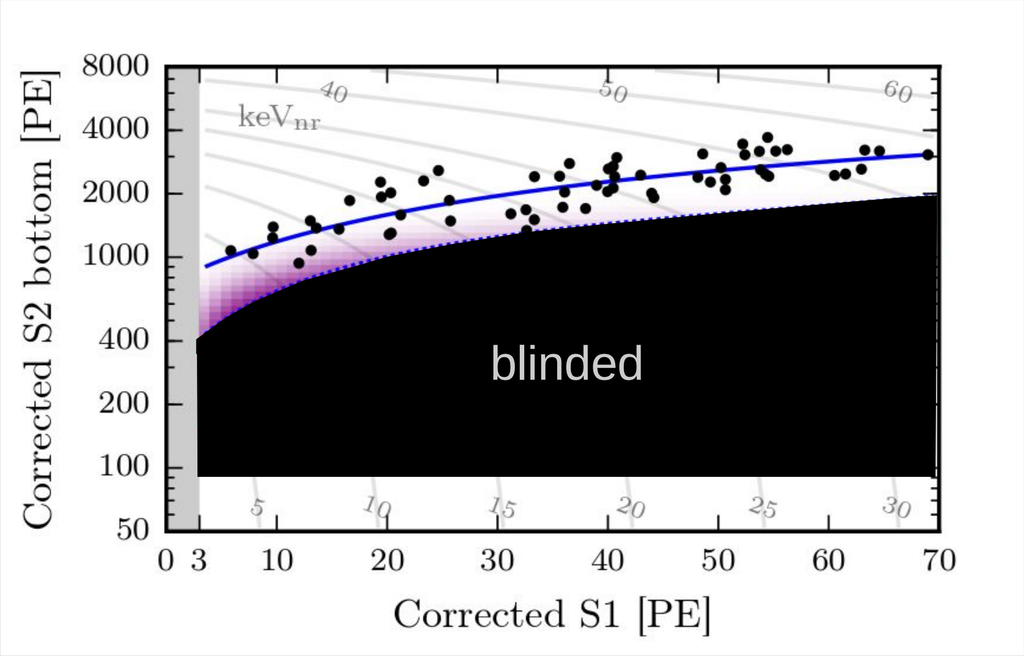
use **central 1000 kg** LXe for analysis

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

Blinded Data

arXiv:1705.06655

figure of merit: exposure E = target mass [t] $\times$ measuring time [d]

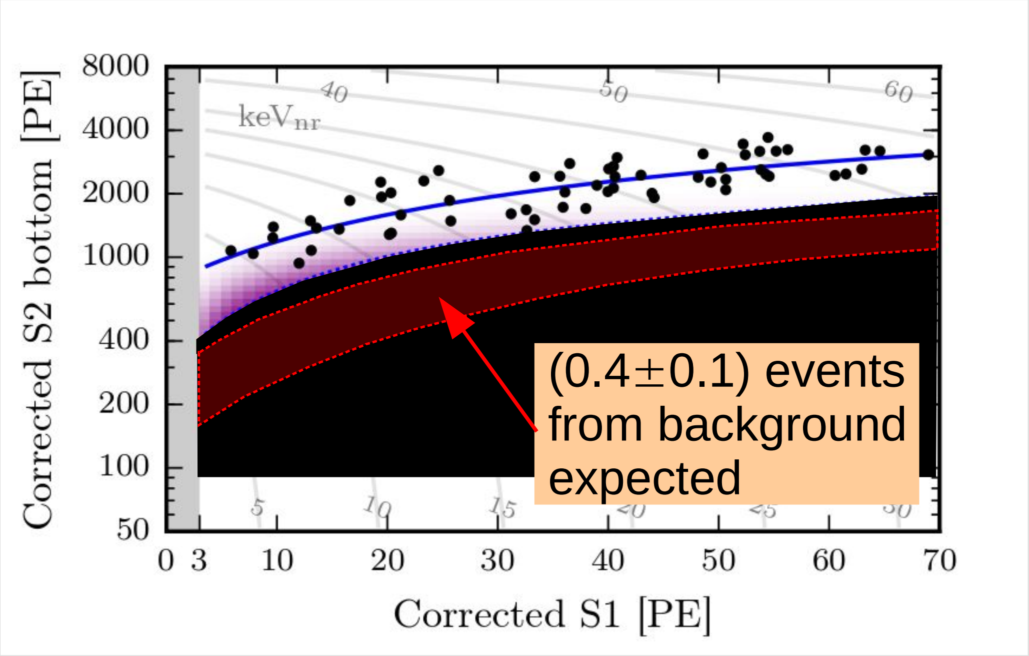


XENON1T: **35.6 t $\times$ d**

Background Expectation

arXiv:1705.06655

figure of merit: exposure E = target mass [t] $\times$ measuring time [d]



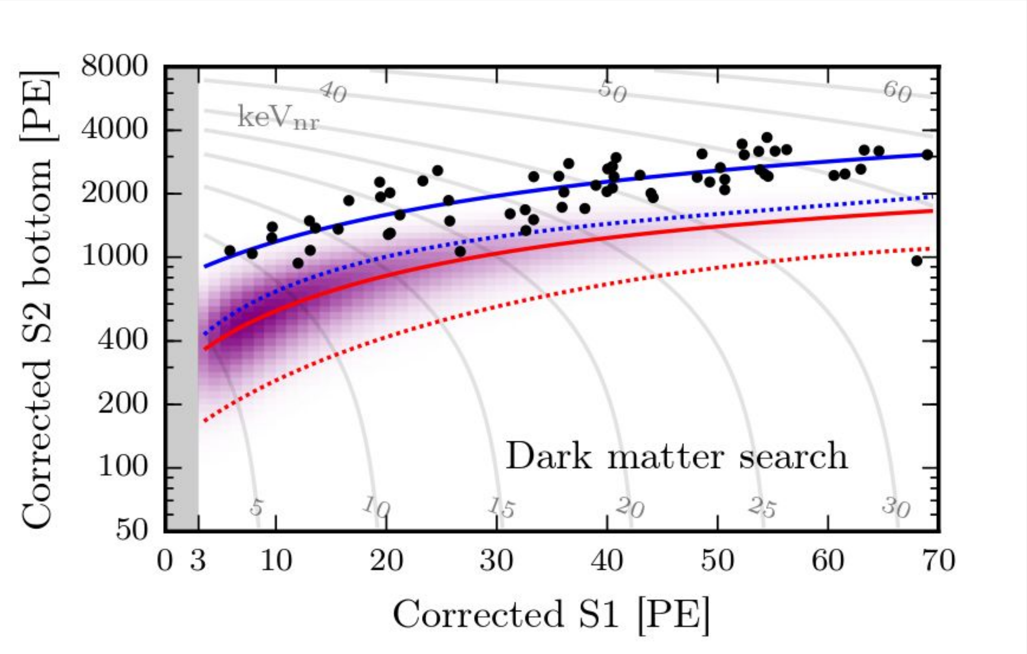
XENON1T: **35.6 t × d**

note:
final **unbinned profile likelihood** analysis takes into account
- full signal and background distributions
- full parameter space

Unblinding...

arXiv:1705.06655

figure of merit: exposure E = target mass [t] $\times$ measuring time [d]



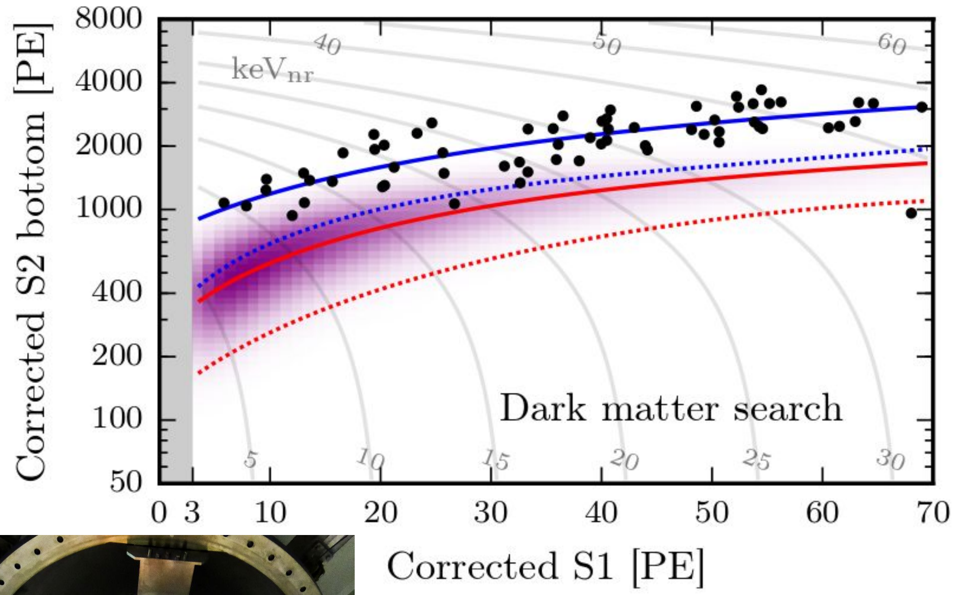
XENON1T: **35.6 t × d**

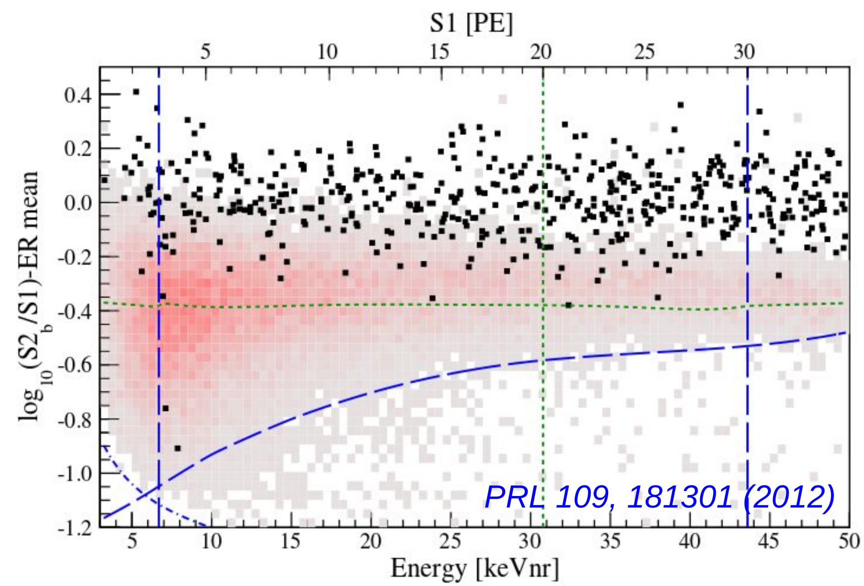
no dark matter candidate observed!

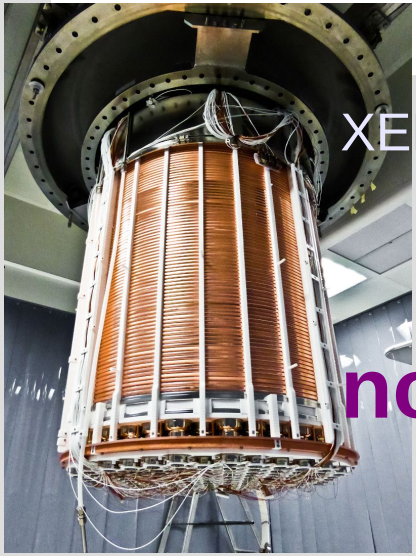
An ultra-low background

arXiv:1705.06655

figure of merit: exposure E = target mass [t] $\times$ measuring time [d]







XENON1T: **35.6 t × d** ← XENON100: **7.6 t × d**

5× more data

30× lower background

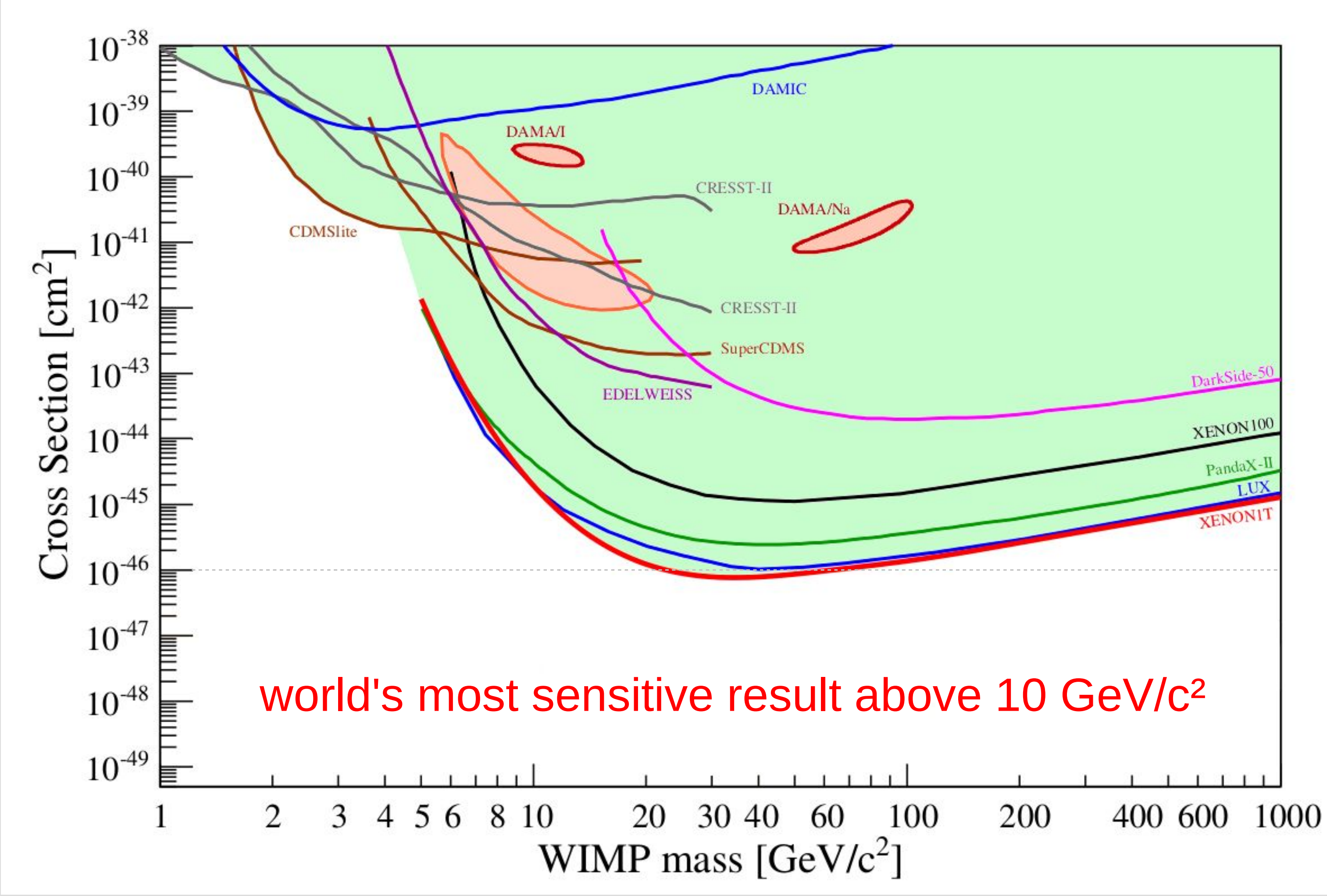
no dark matter candidate observed!

No Signal → Exclusion Limit

arXiv:1705.06655

XENON Dark Matter Project

spin-independent WIMP-nucleon interactions



XENON1T science goal: 5× more sensitive than current result

XENON1T → XENONnT

JCAP 04, 027 (2016)

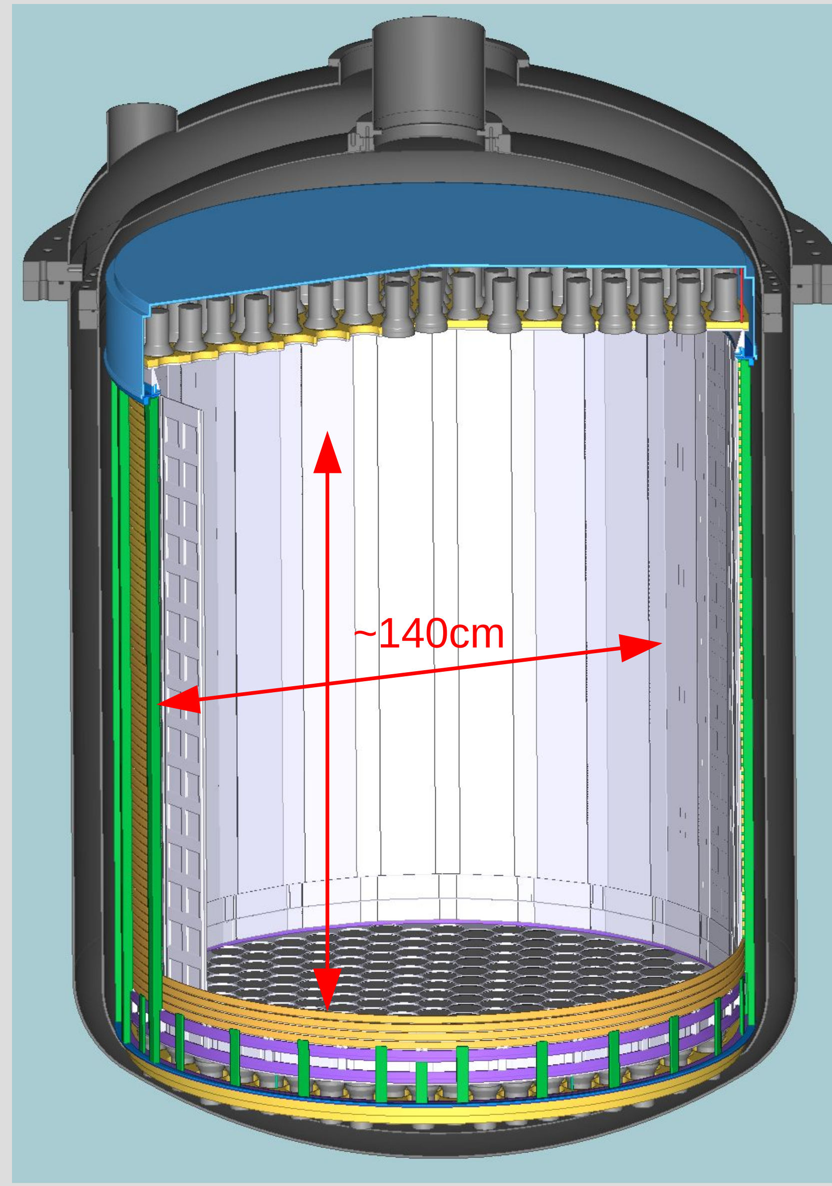
XENON
Dark Matter Project

XENON1T
- **2t** active LXe target
- taking data

XENONnT
- **6t** active target
- science run by 2019

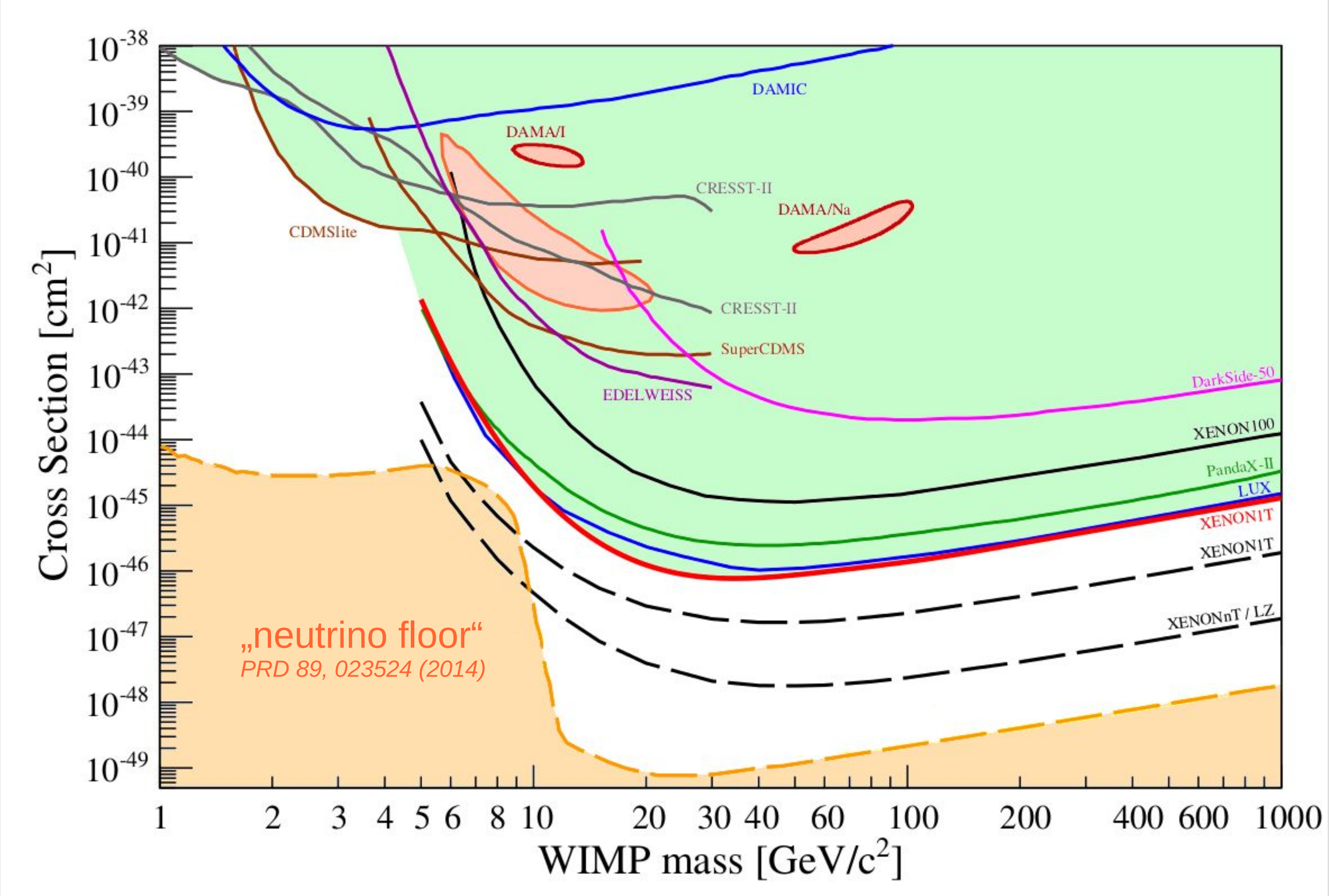
UNI FREIBURG

– TPC design
– data acquisition system
– material selection



Dark Matter Searches: The Limit

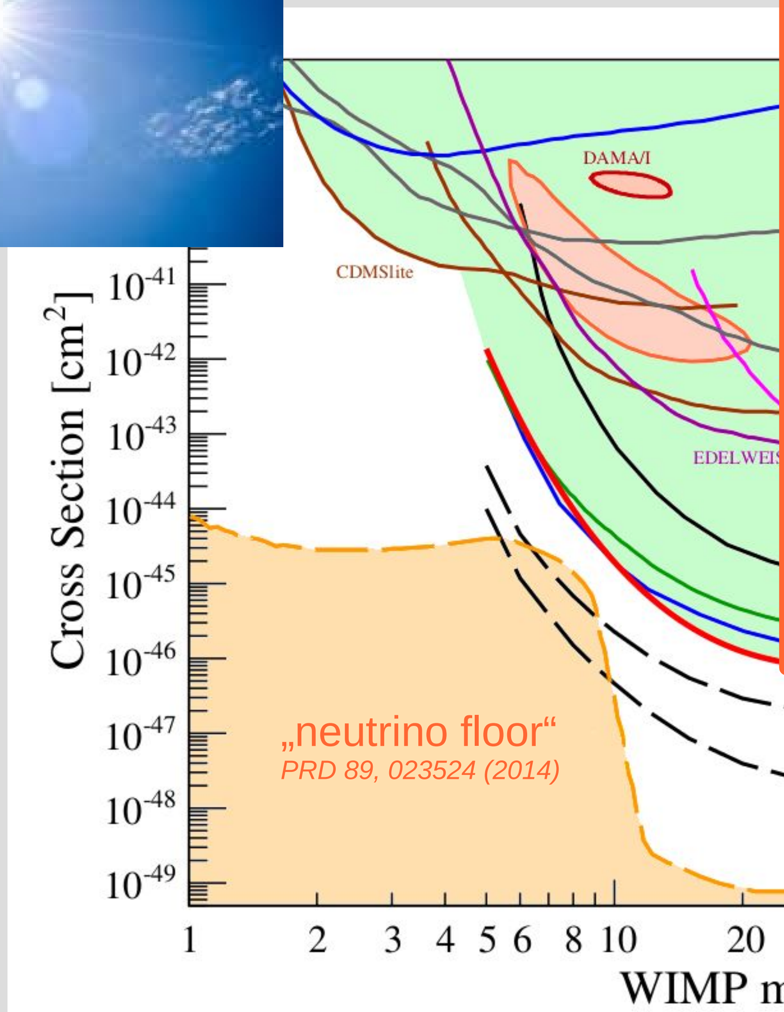
spin-independent WIMP-nucleon interactions

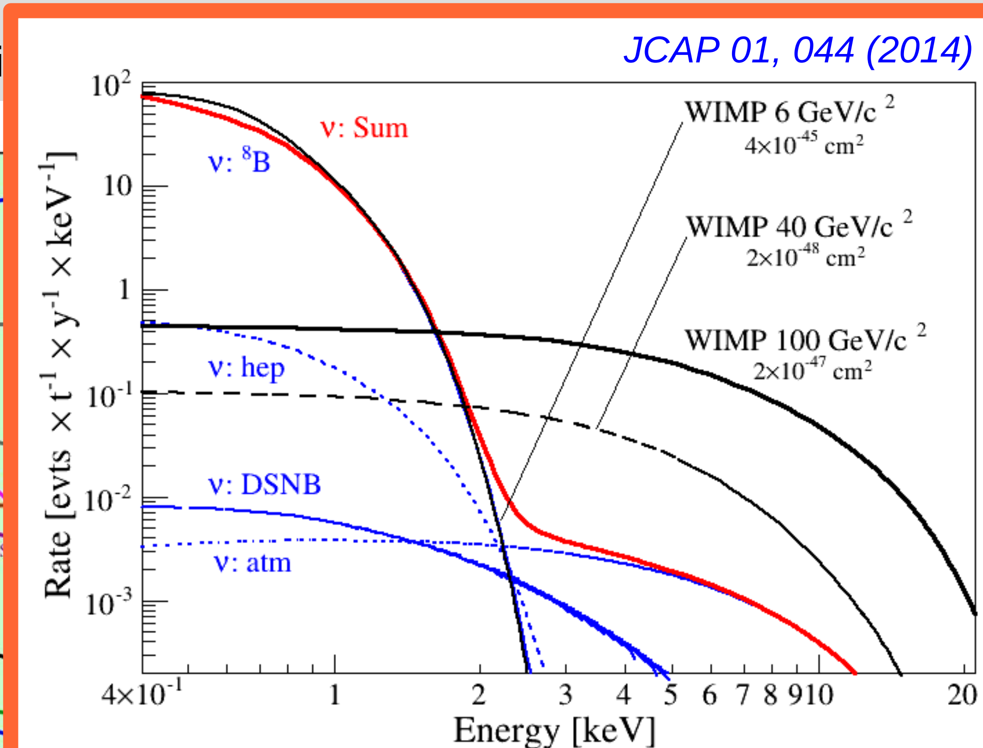


some projects are missing...

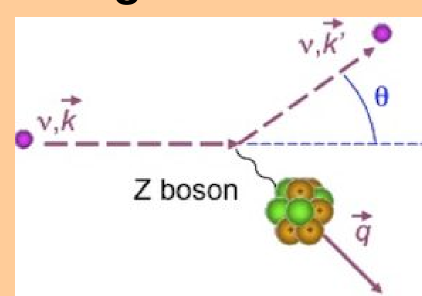
Dark Matter Searches: The Limit

spin-i



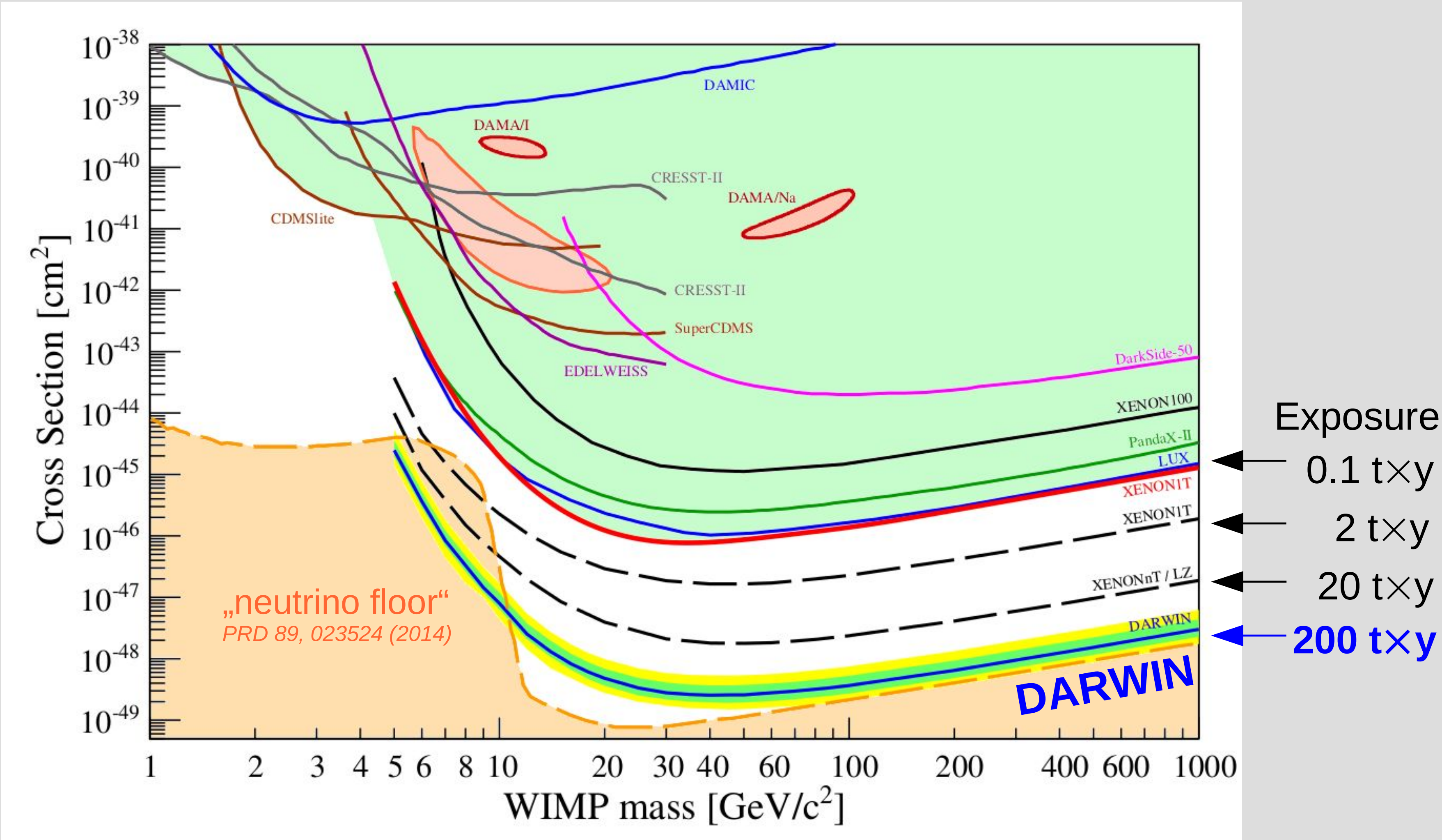


Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection



DARWIN The **ultimate** WIMP Detector

spin-independent WIMP-nucleon interactions



some projects are missing...

DARWIN The **ultimate** WIMP Detector

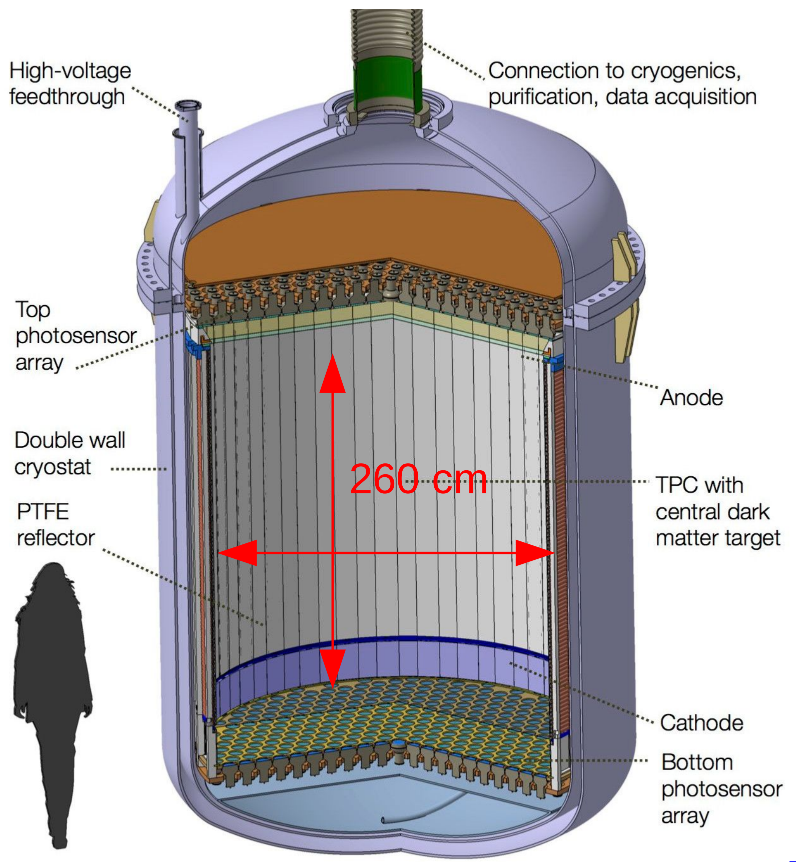
JCAP 11, 017 (2016)

Baseline scenario

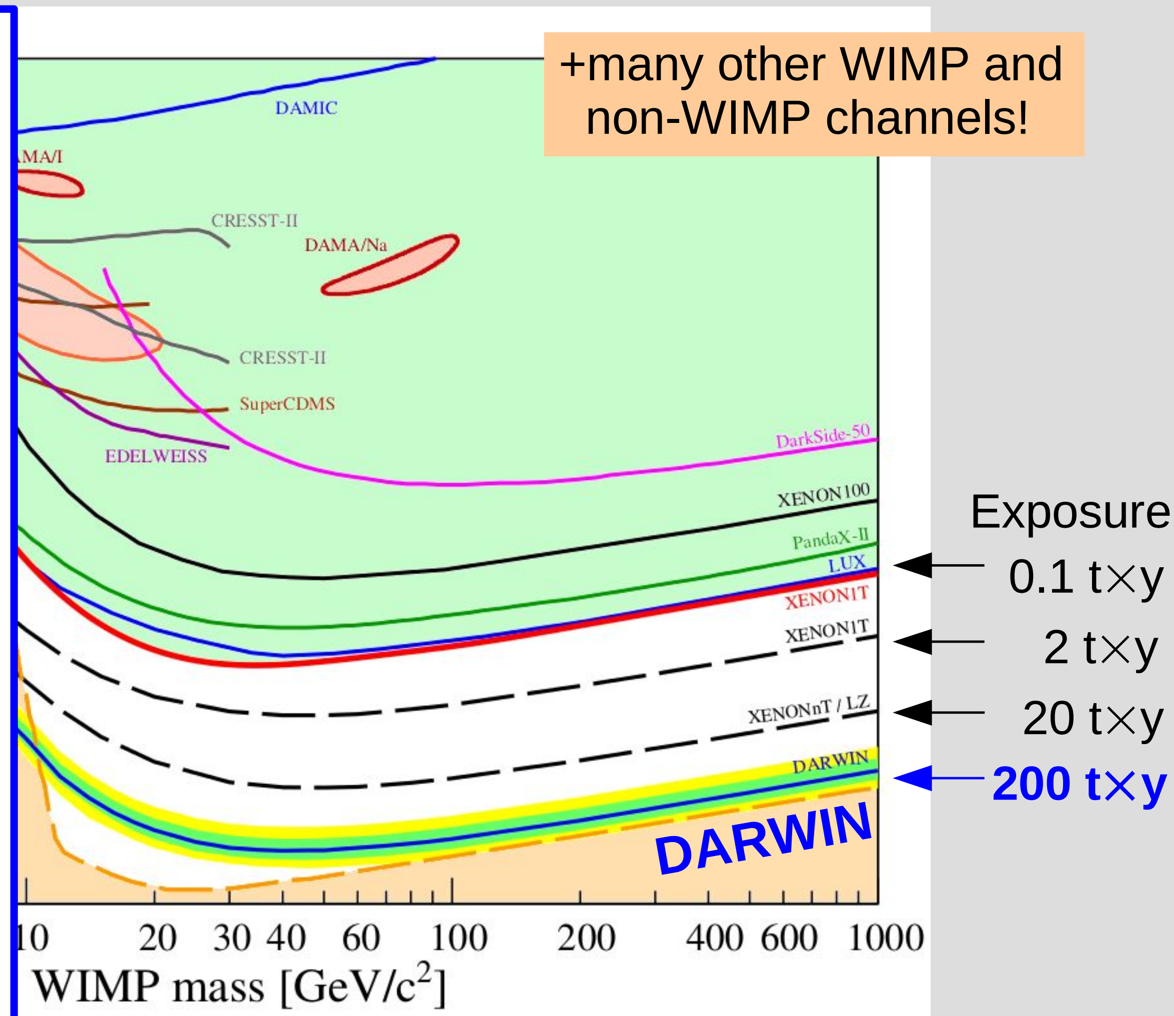
~50t total LXe mass

~40 t LXe TPC

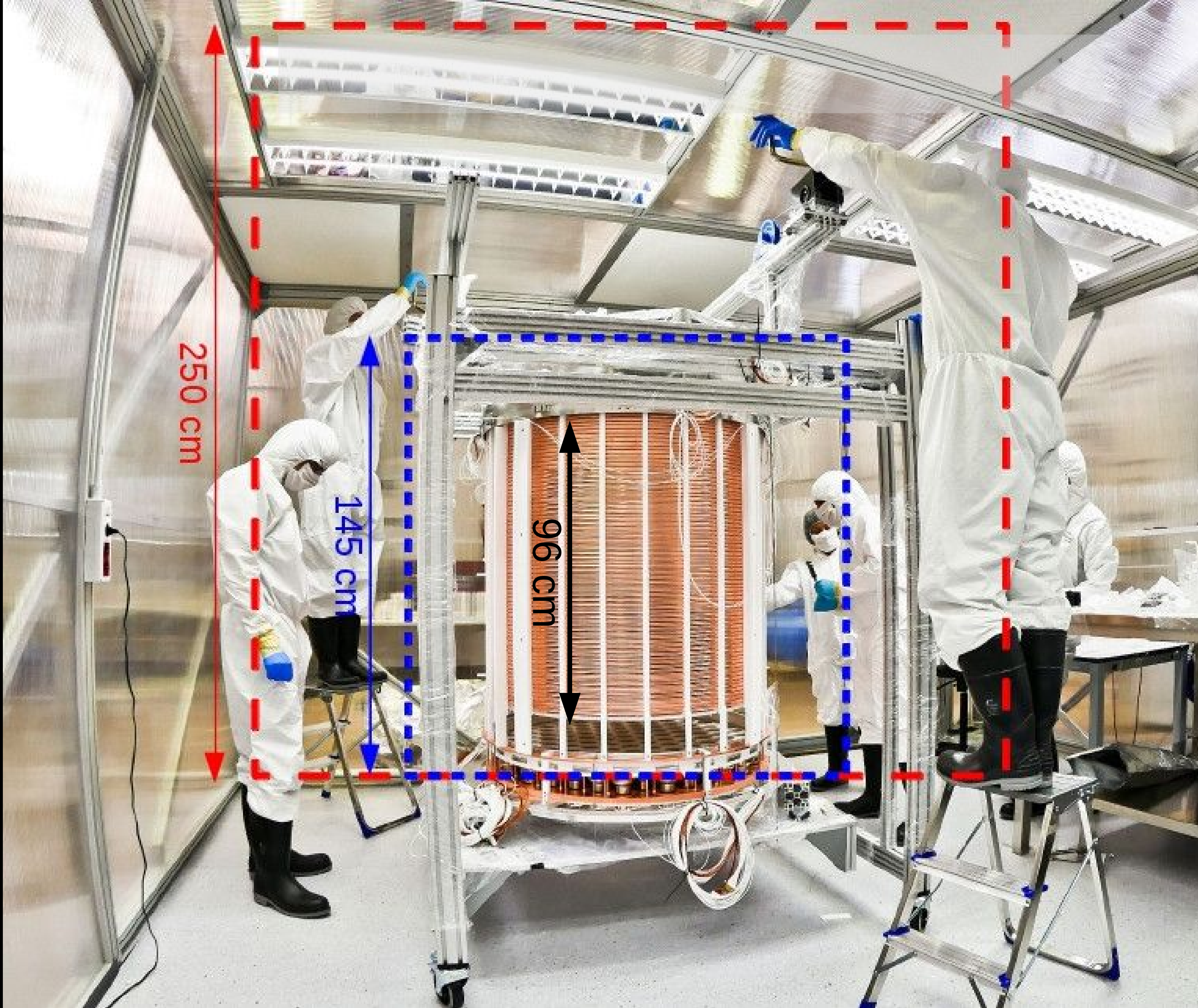
~30 t fiducial mass



spin-independent WIMP-nucleon interactions

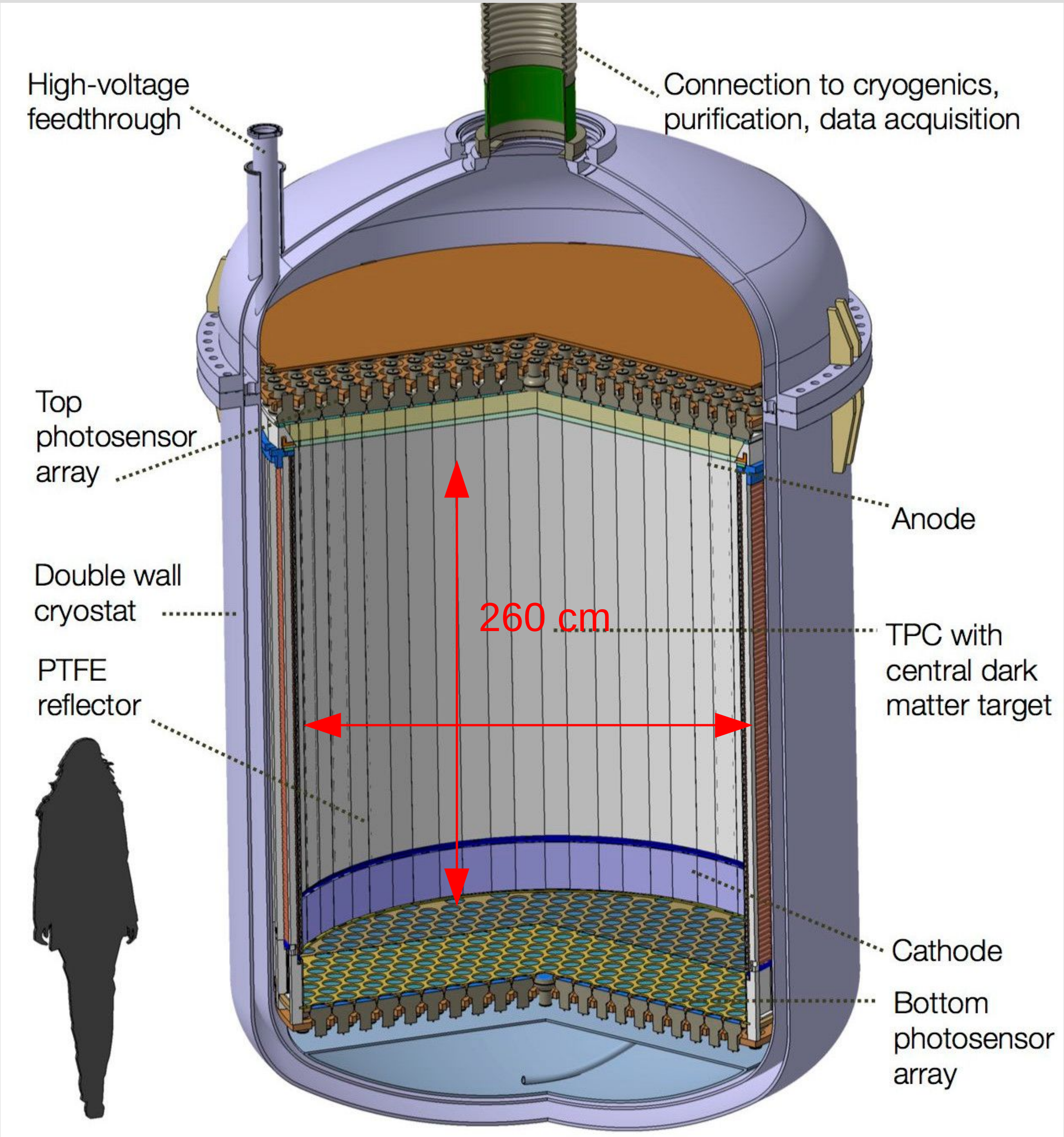


some projects are missing...


250 cm
145 cm
96 cm

DARWIN The **ultimate** WIMP Detector

JCAP 11, 017 (2016)

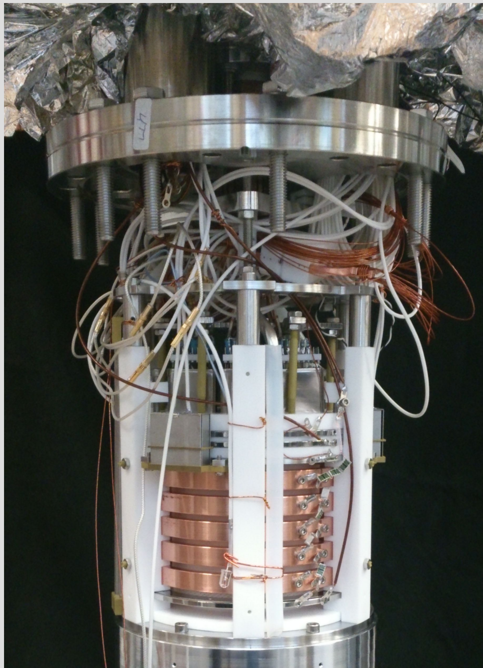


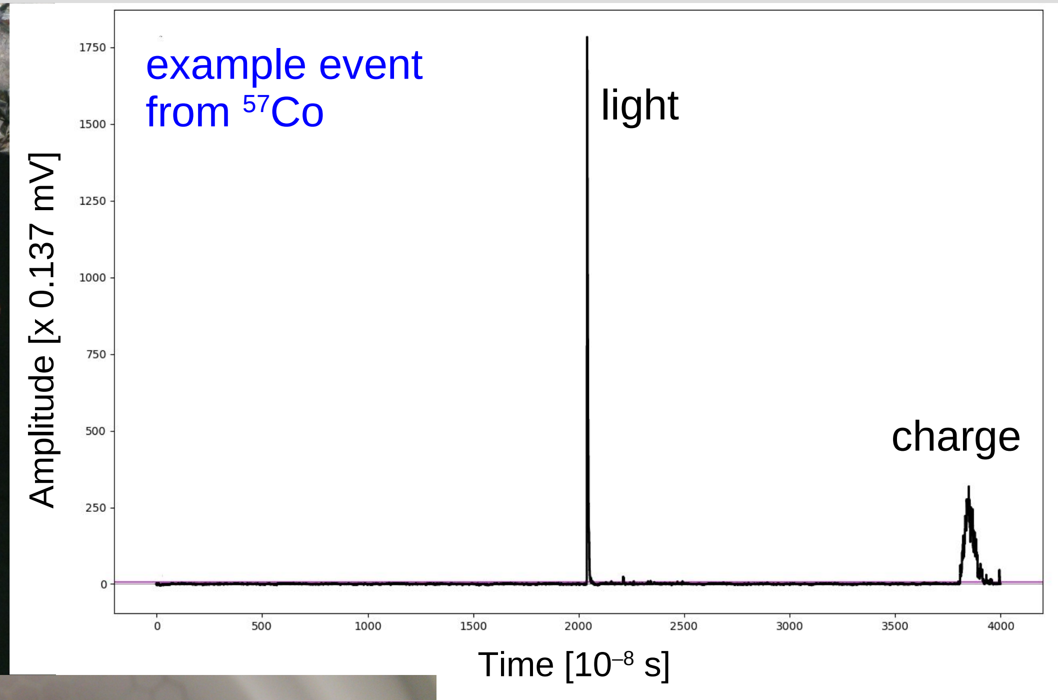
Challenges

- **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

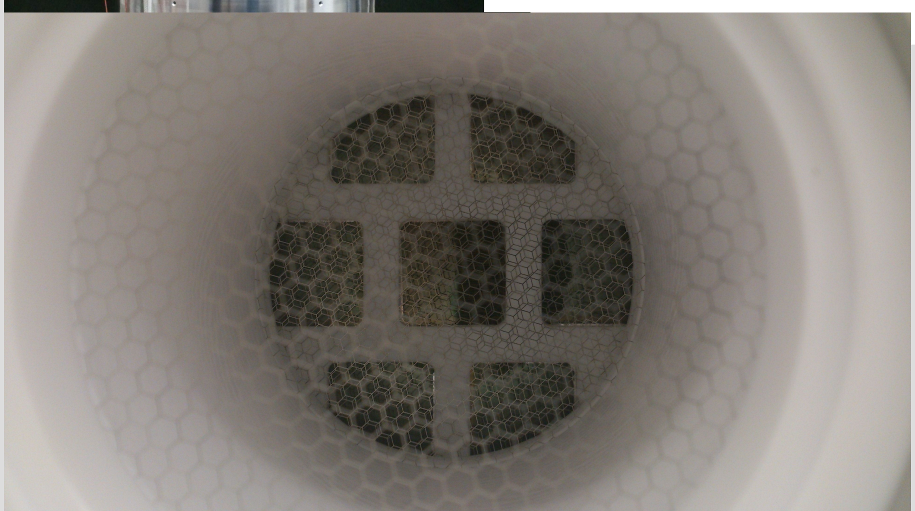
– new ERC project **ULTIMATE** started May 2017

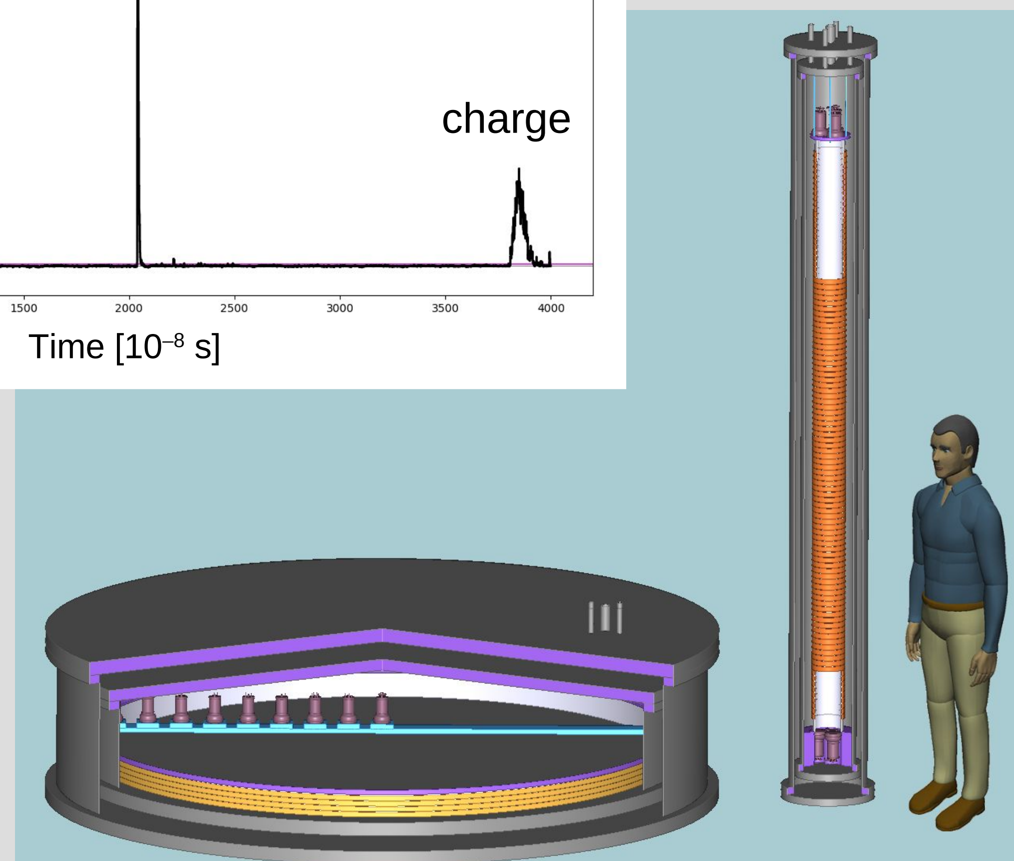
Towards the ULTIMATE detector





Test platforms for R&D operated in Freiburg



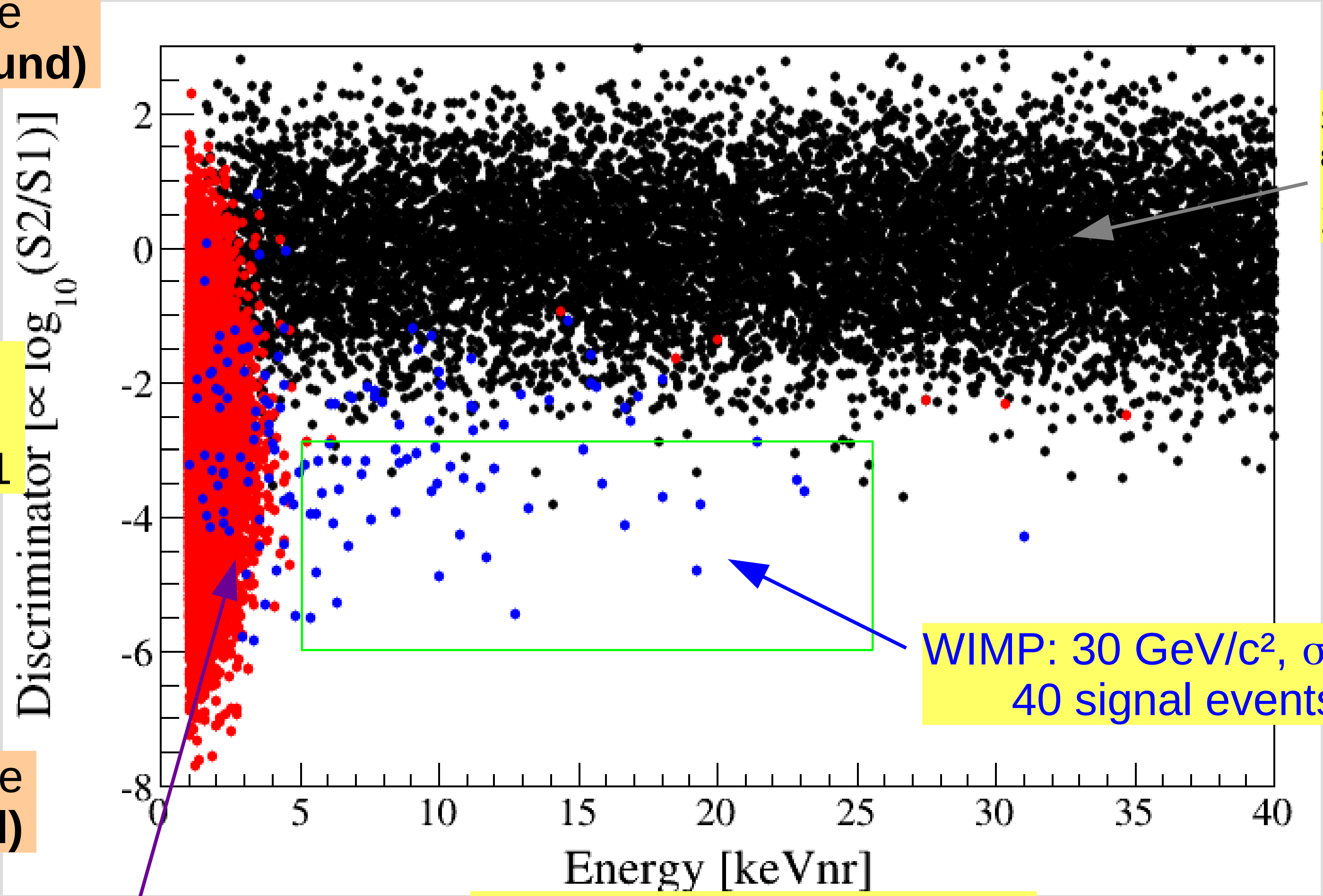


WIMP Detection

ER-like
(background)

discrimination variable;
based on S2/S1

NR-like
(signal)



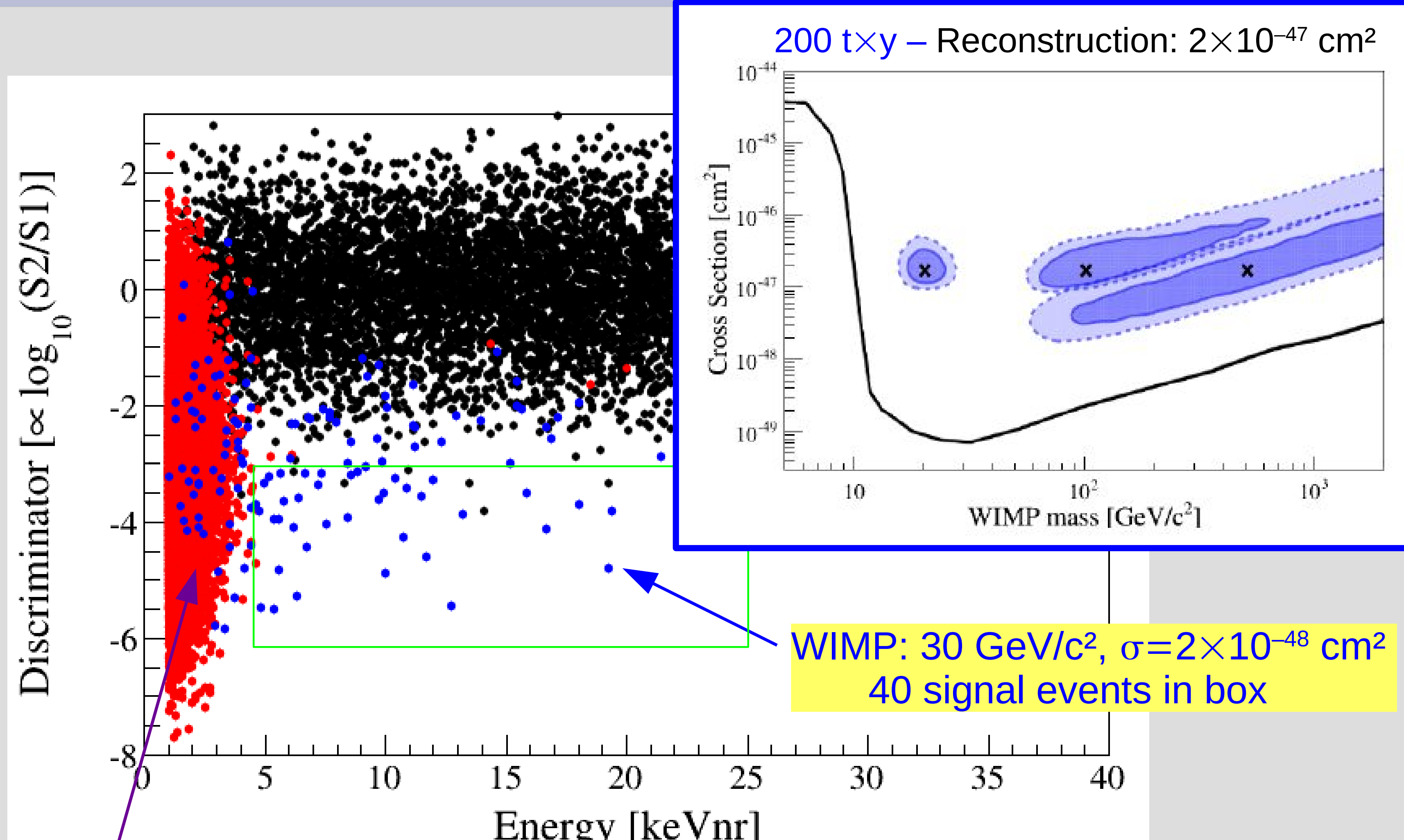
solar neutrinos, ^{85}Kr, ^{222}Rn, $2\nu\beta\beta$, materials

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

CNNS+neutrons

reconstructed energy, based on S1 and S2 signal

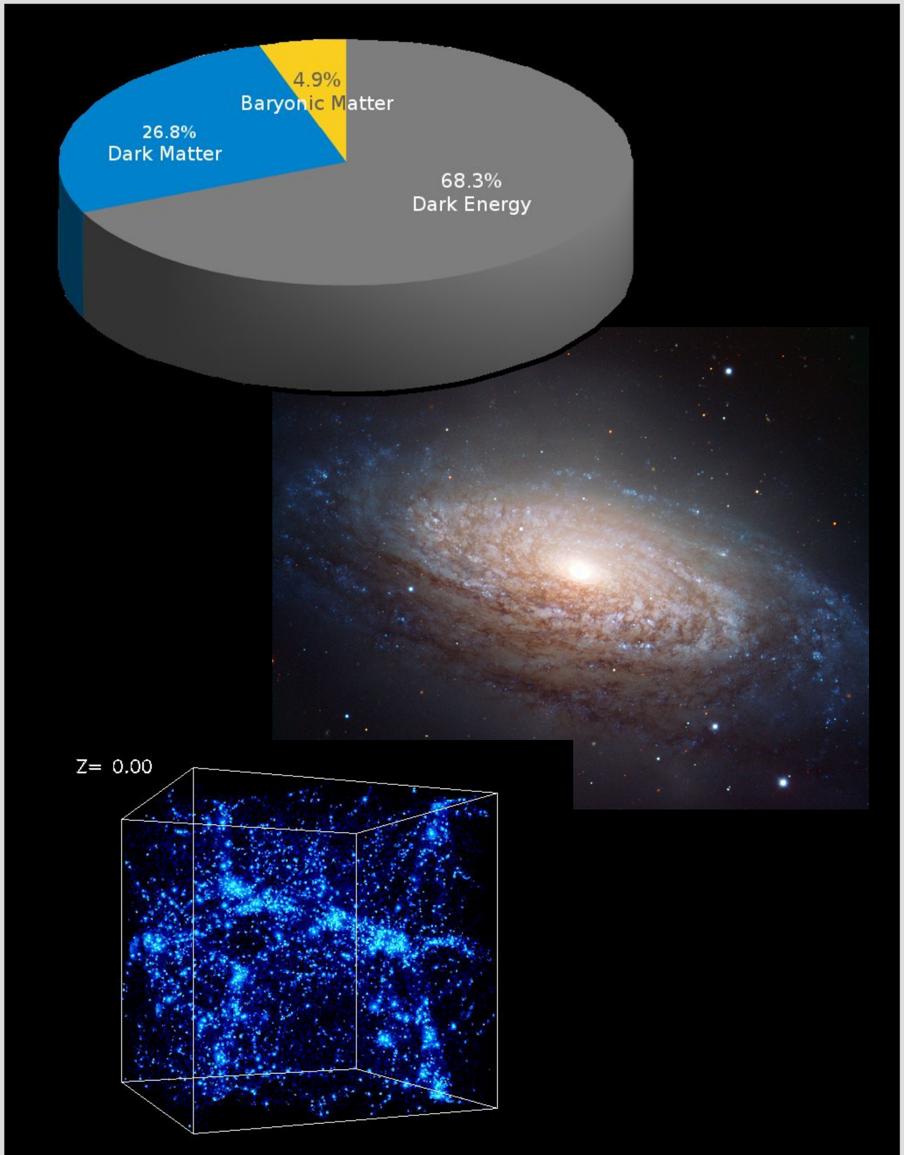
WIMP Spectroscopy

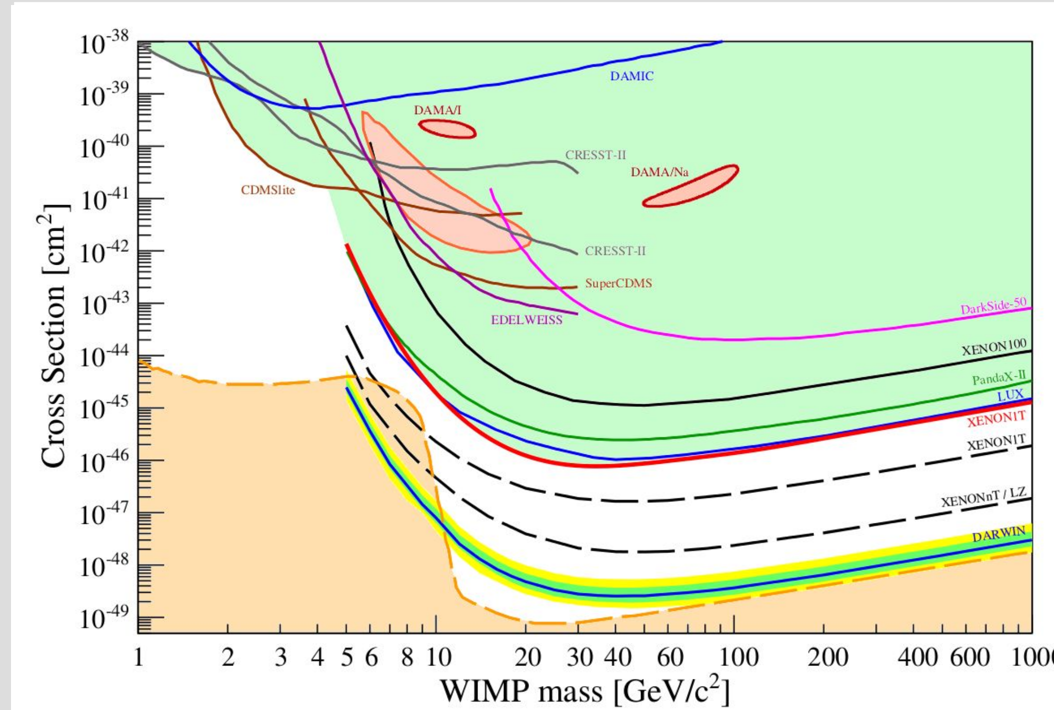


WIMP: 30 GeV/c², σ=2×10^{-48} cm²
40 signal events in box

CNNS+neutrons

Exploring the dark with LXe Detectors





www.xenon1t.org

www.darwin-observatory.org