



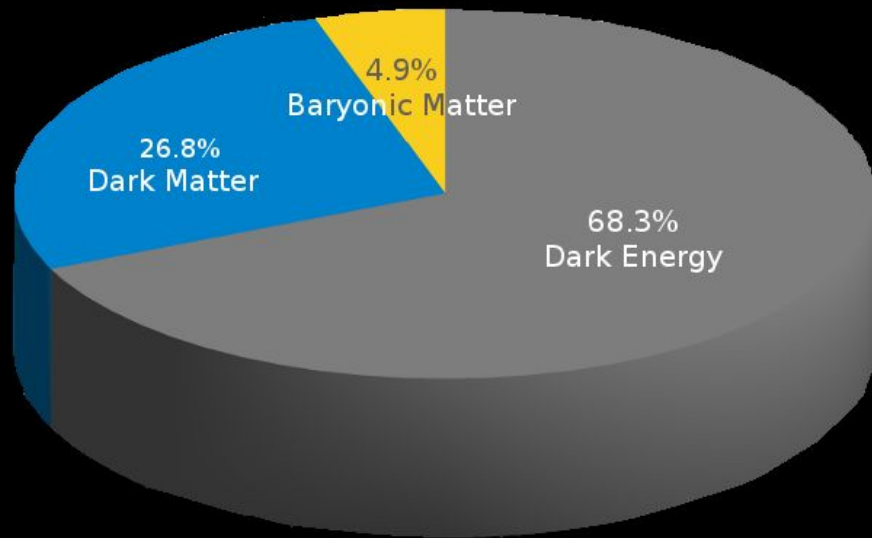
Exploring the Dark Universe

Marc Schumann *University of Freiburg*

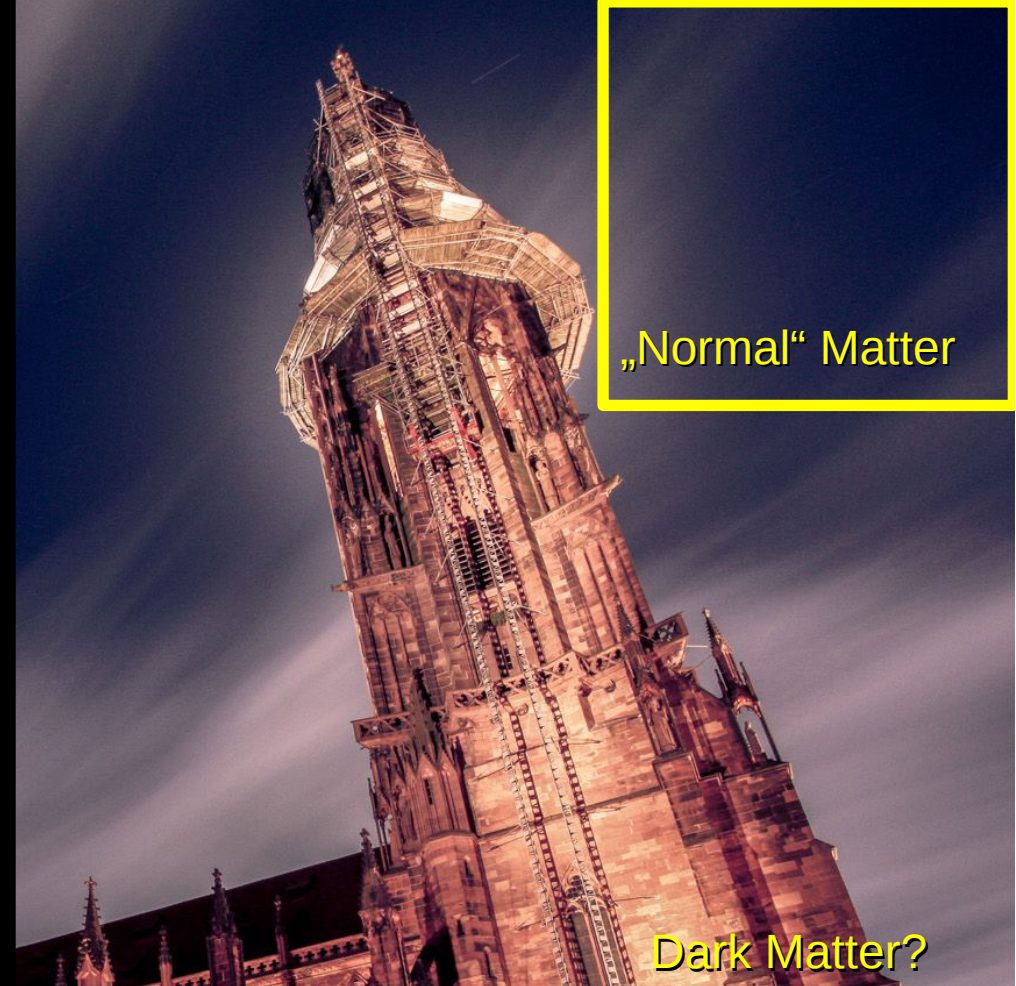
Physics Colloquium Freiburg, 12.06.2017

www.app.uni-freiburg.de

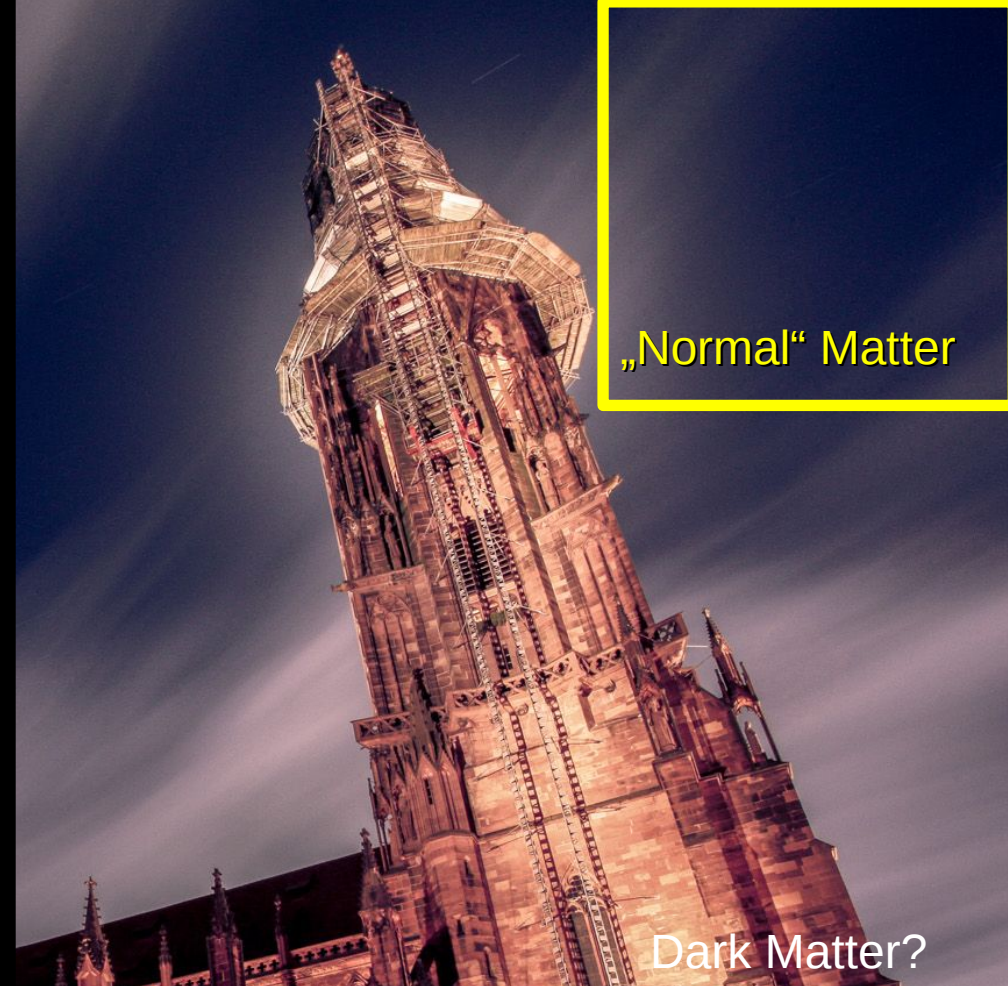
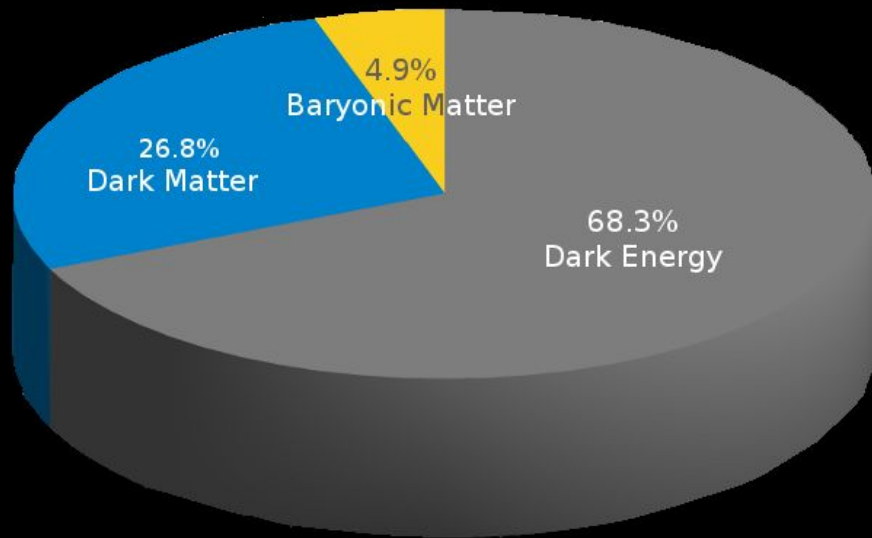




**95% of
the Universe
is dark!**



Dark Energy????



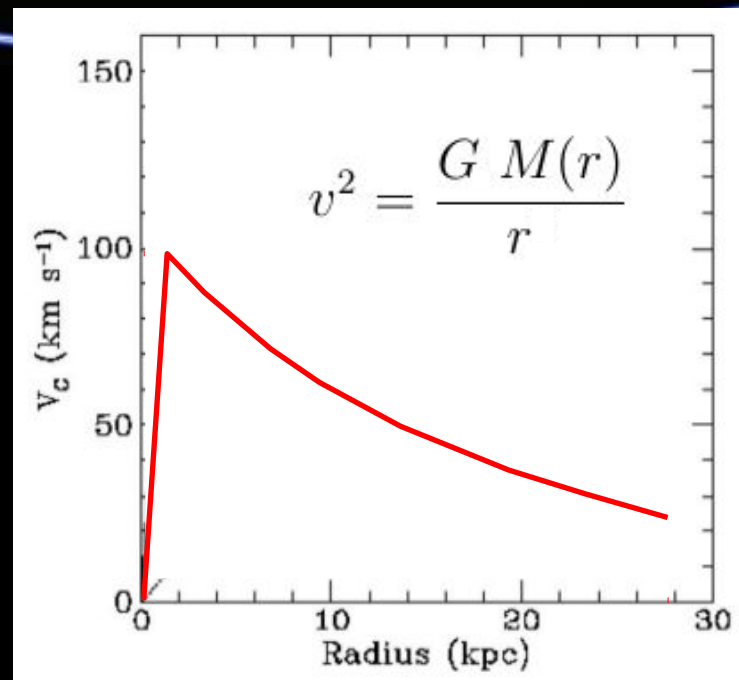
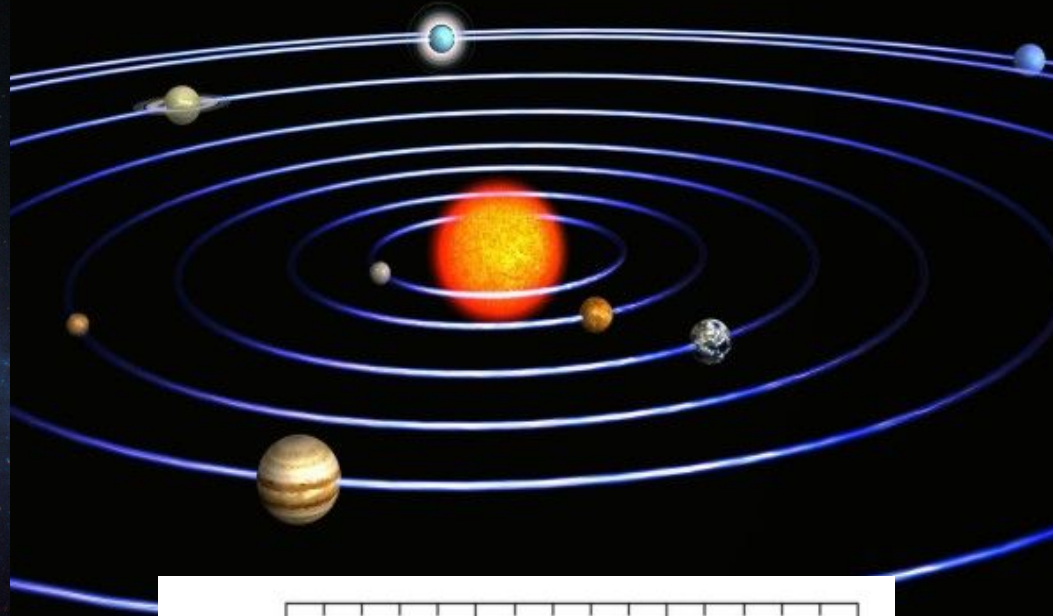
**about 100'00 dark matter particles
cross an area of 1 cm² per second**



**Part 1 –
Evidence for Dark Matter**

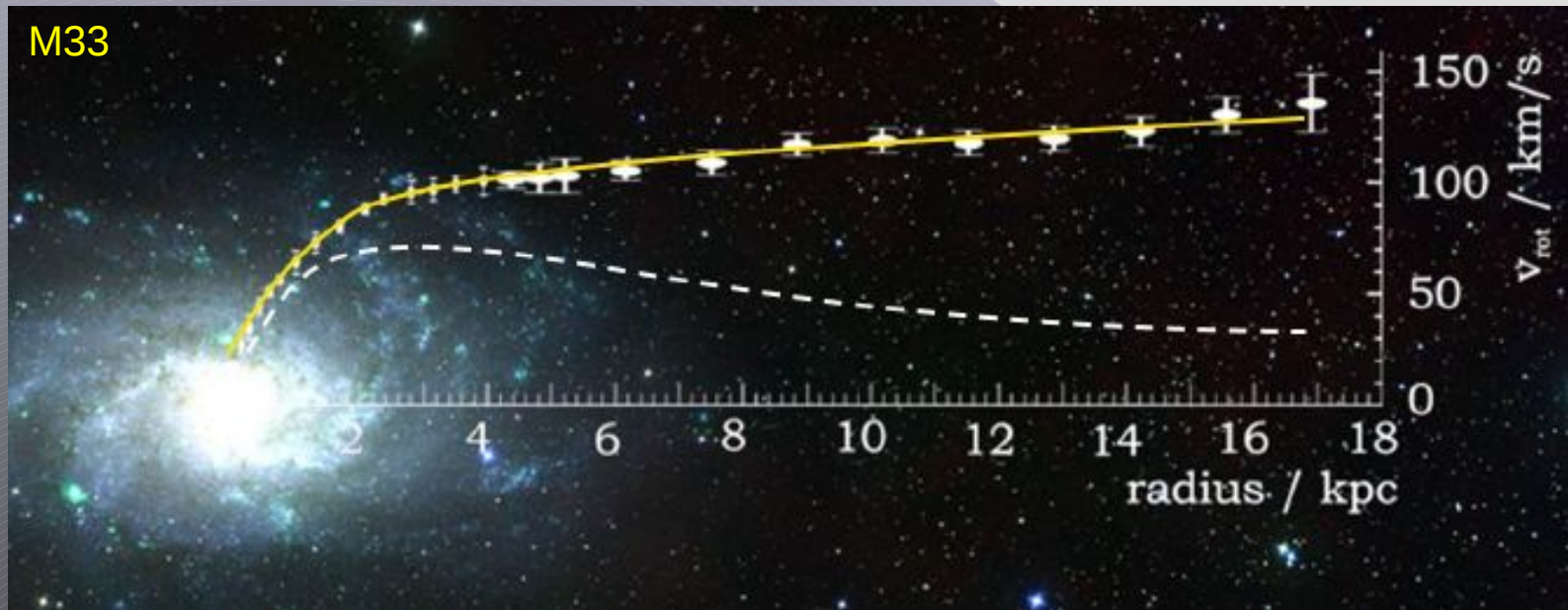


Expect: Kepler Rotation
(as solar system)



Galactic Rotation Curves

Measurement: flat rotation profile ... well beyond visible stars

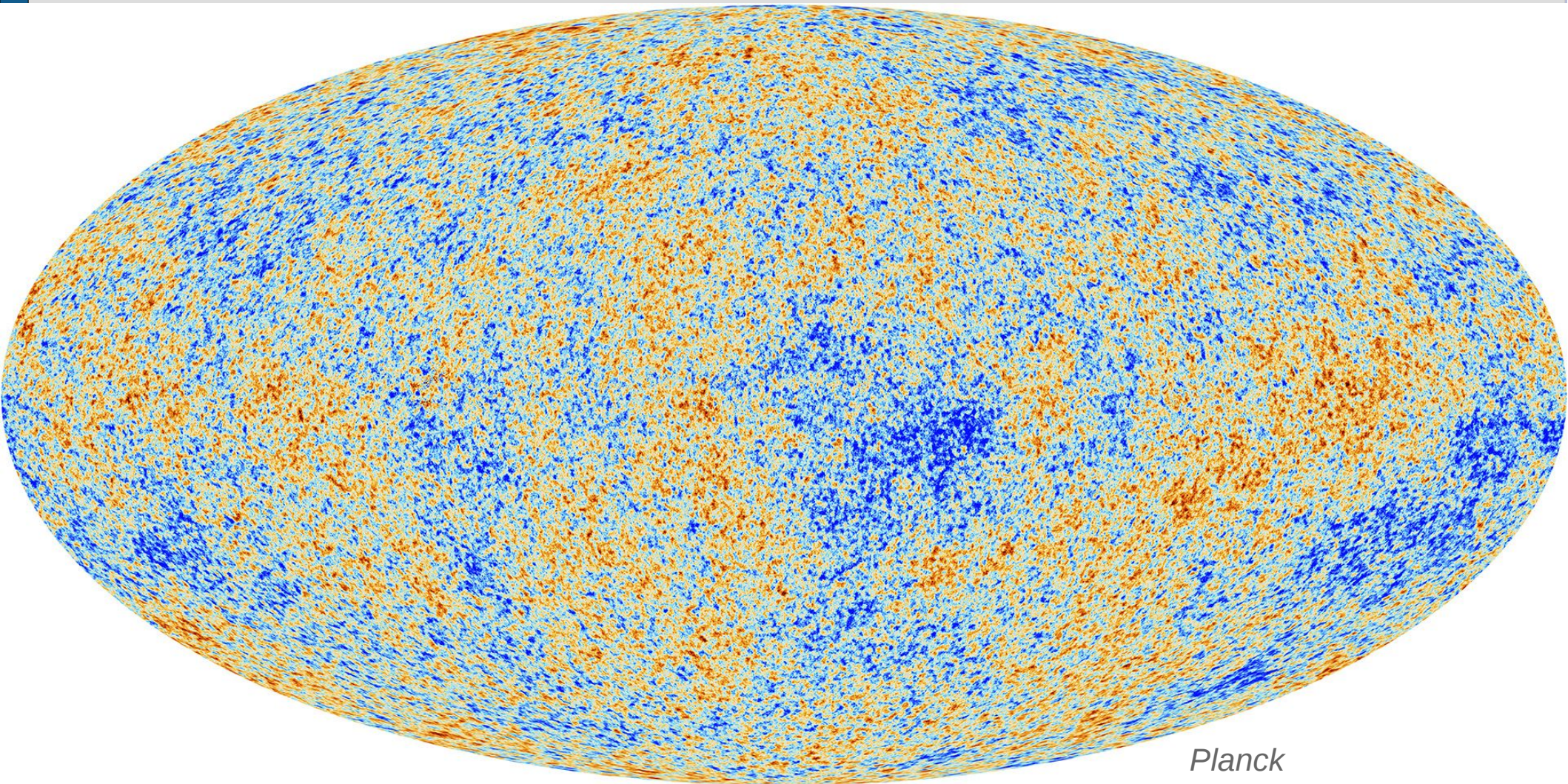


„Halo“ made from Dark Matter
(*isothermal sphere*, $\rho \sim 1/r^2$)



Cosmic Microwave Background

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

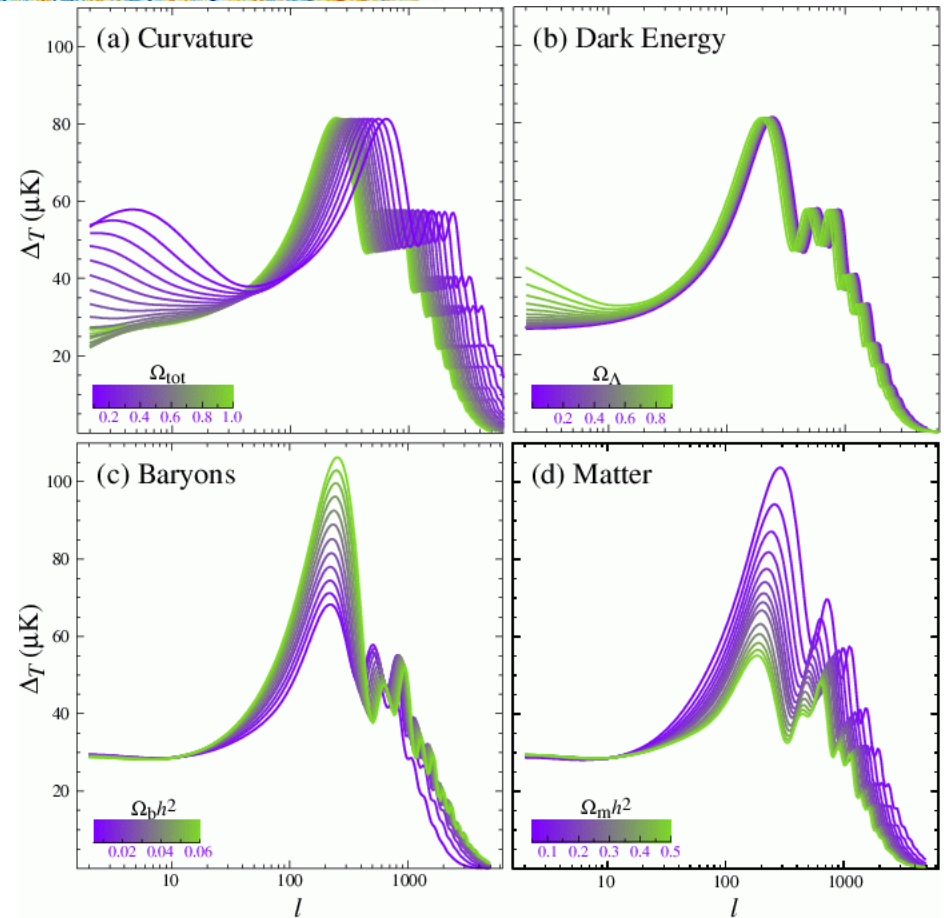
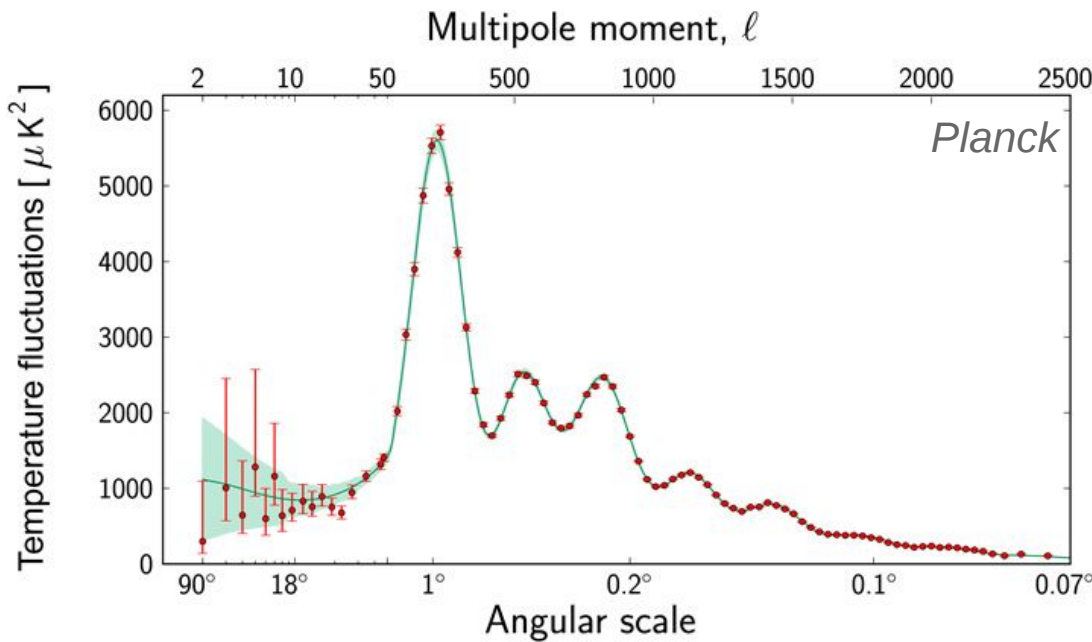


Planck

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“

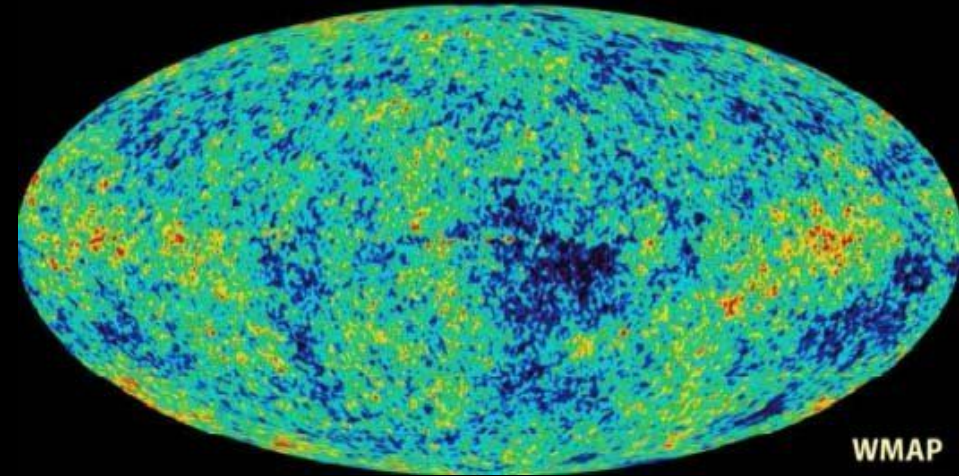
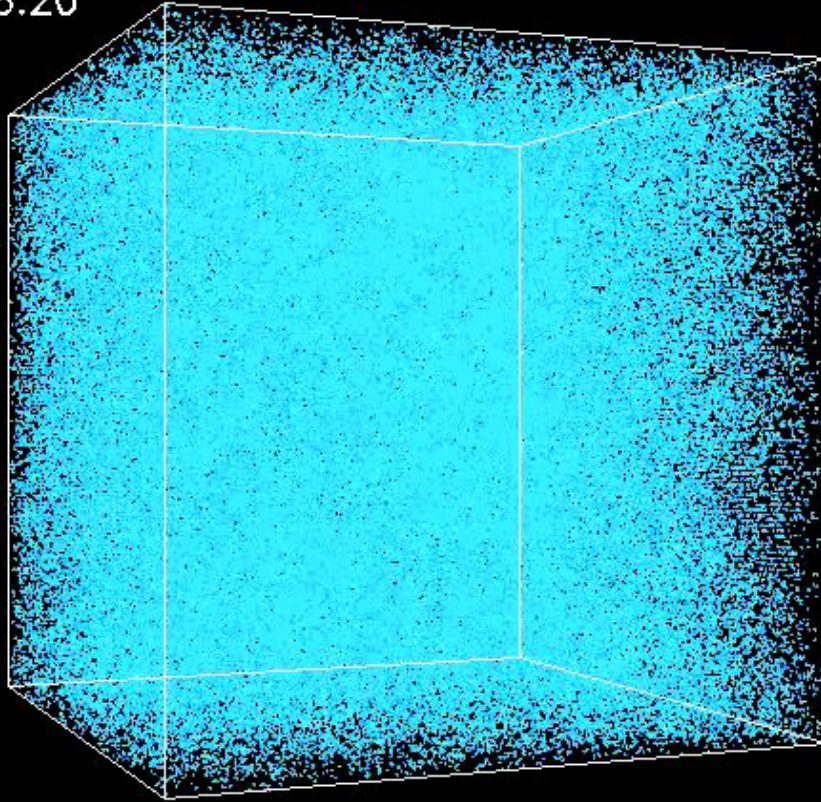


Planck

Dark Matter shapes the Universe

~40M years
after big bang

$Z=26.20$

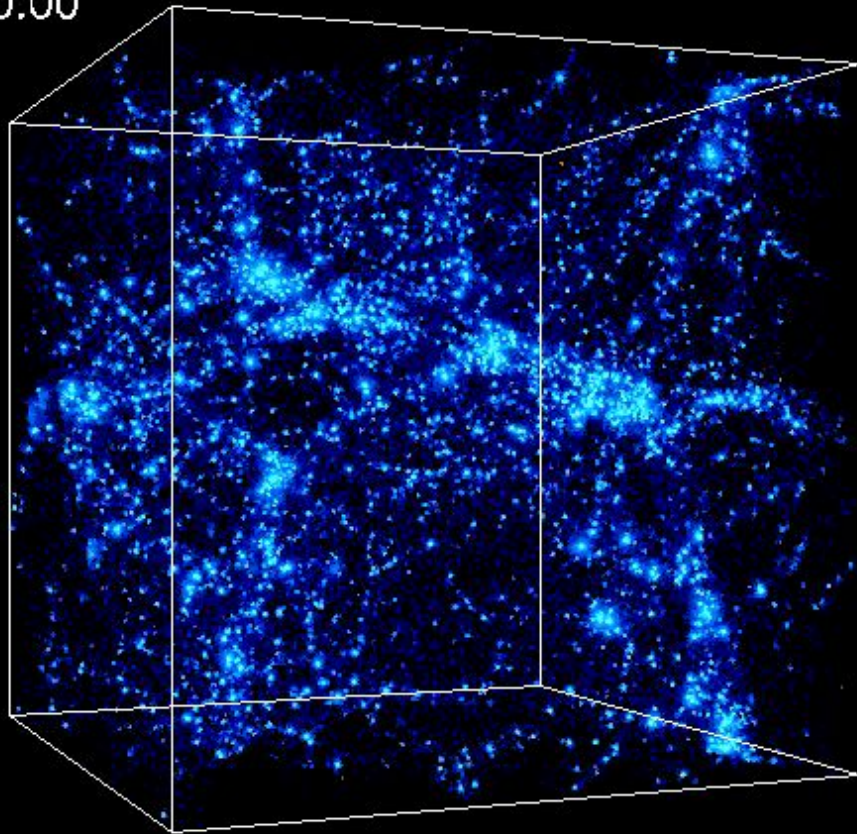


<http://cosmicweb.uchicago.edu>

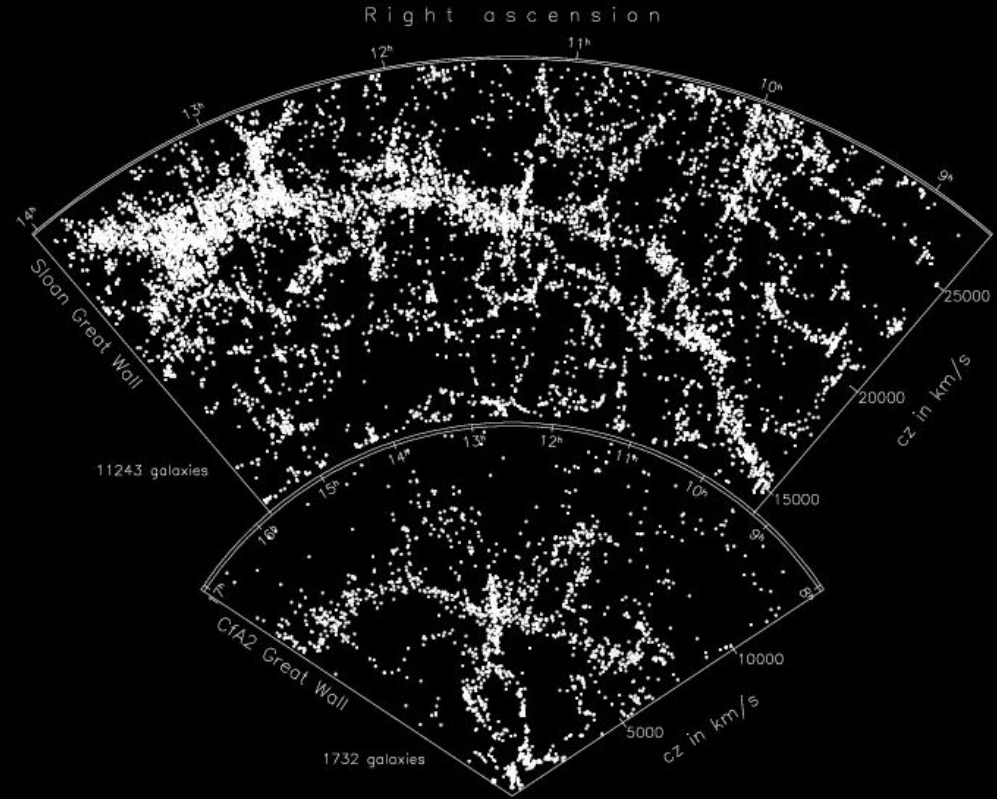
Dark Matter shapes the Universe

now

$Z = 0.00$



Simulation



Observation (SDSS)

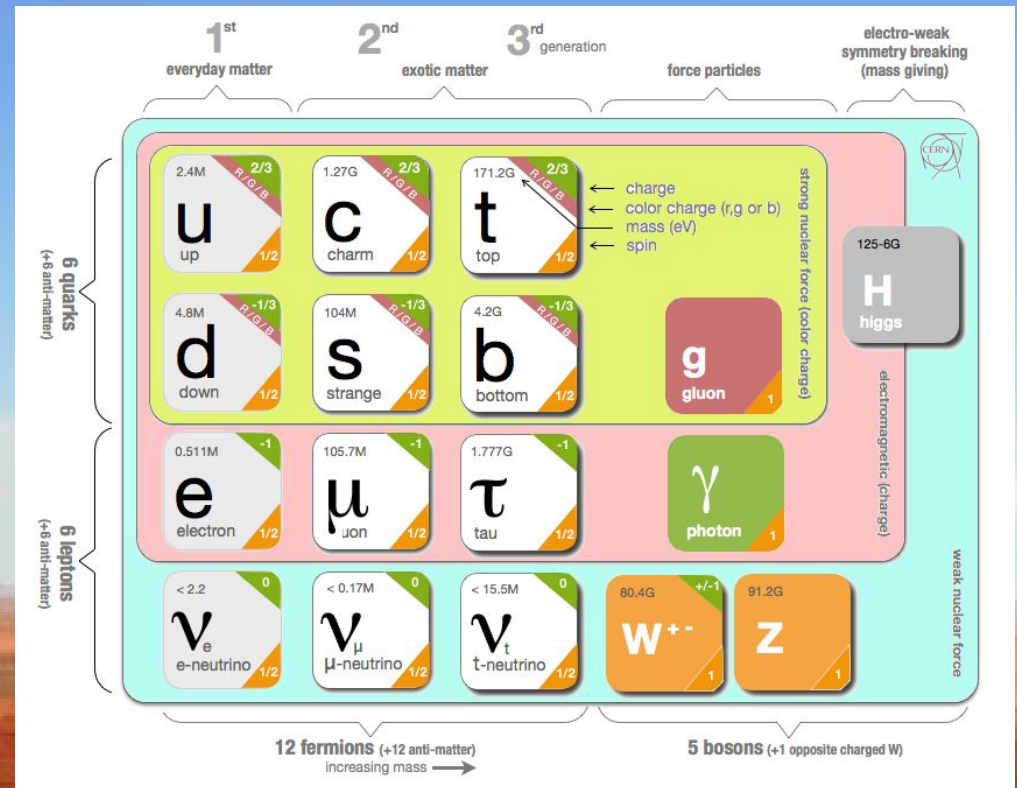
WANTED

FOR MOVING THE UNIVERSE
DARK MATTER

Looking for matter with
the following properties:

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

REWARD: NOBLE PRICE?



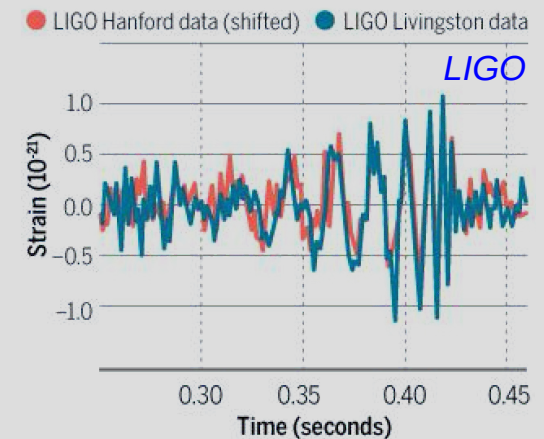
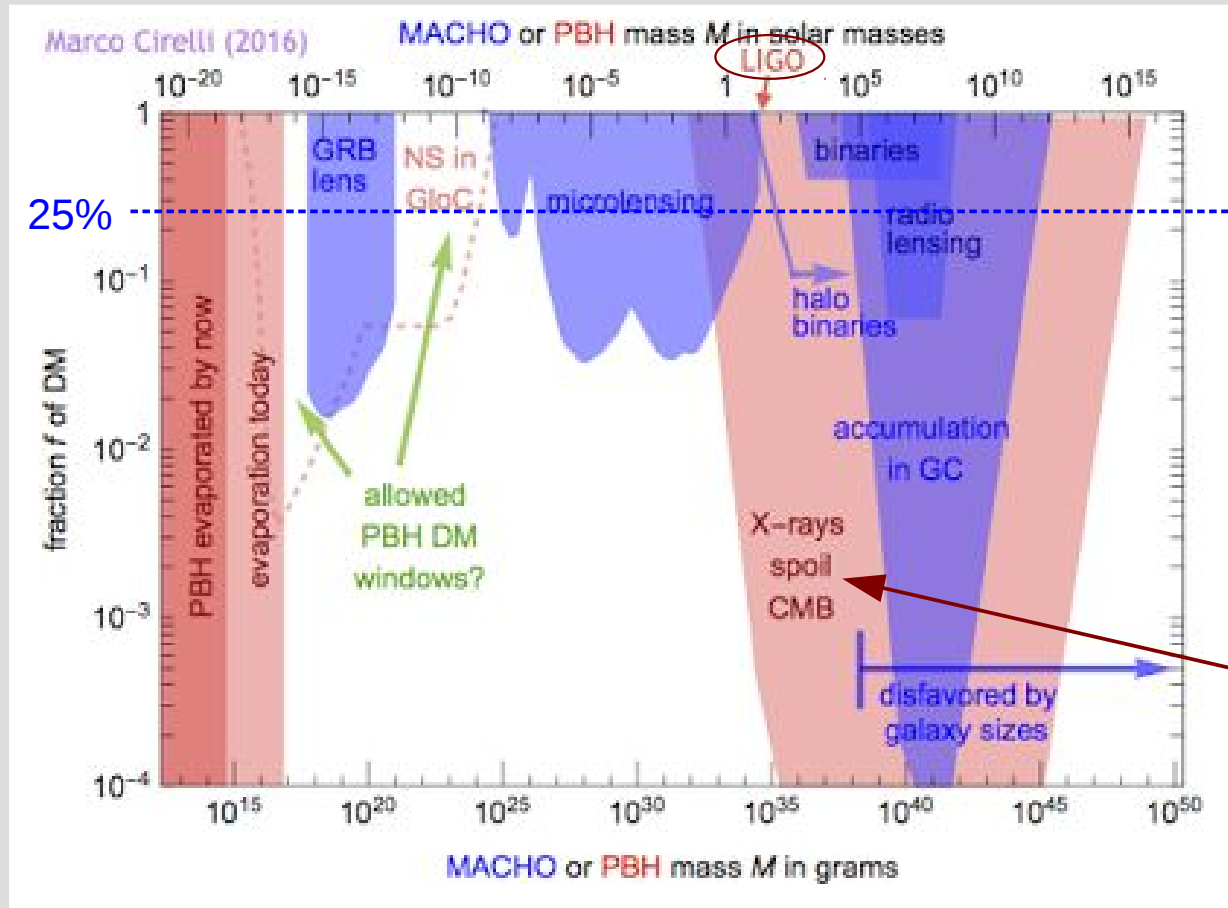
Problem:

no known particle fits the description

→ we need to look for something new
weakly interacting massive particle (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):

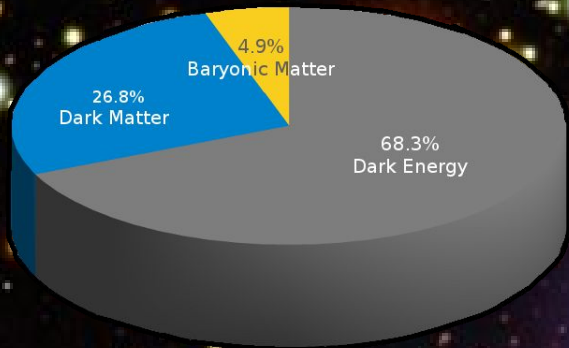
- **PBHs cannot constitute >0.01% of dark matter**
- *but*: new discussion about PBH dark matter started
 maybe PBH not dark matter but faster merger rate

Astrophys.J. 680, 829 (2008)

PRL 116, 201301 (2016)

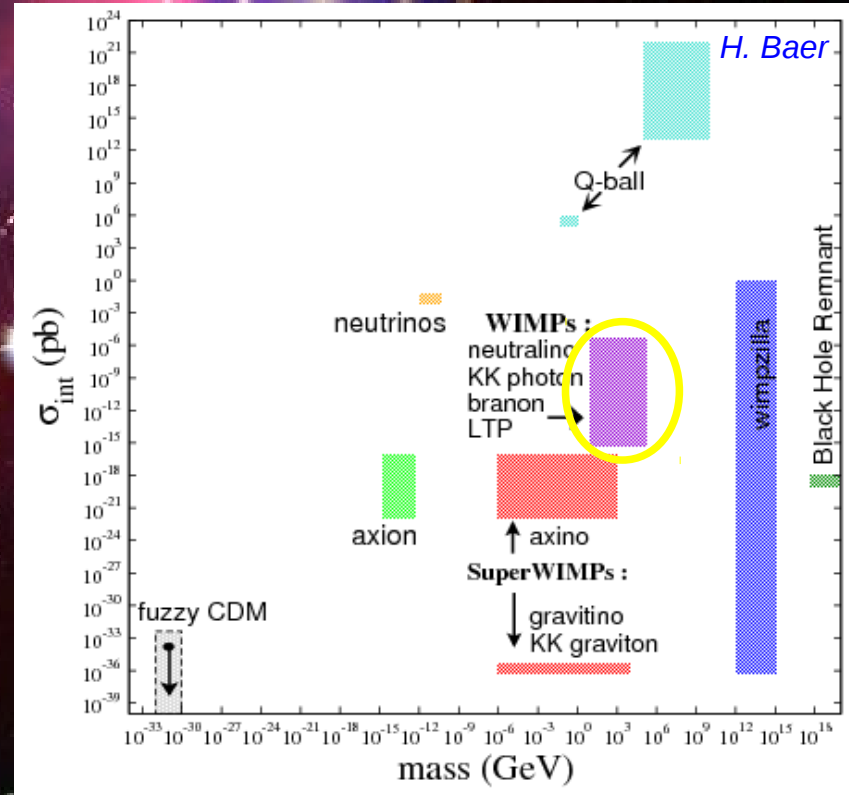
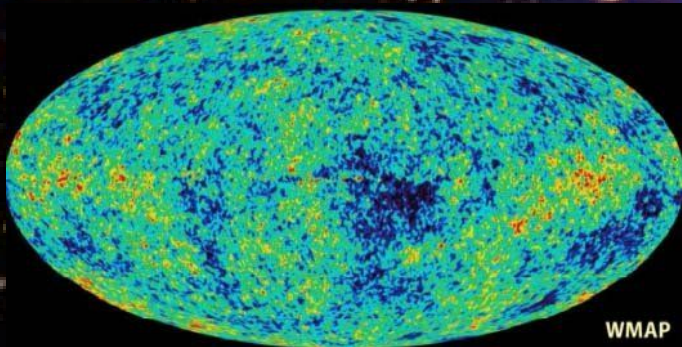
PRL 117, 061101 (2016)

Dark Matter: (indirect) Evidence



Particle Dark Matter Candidates:

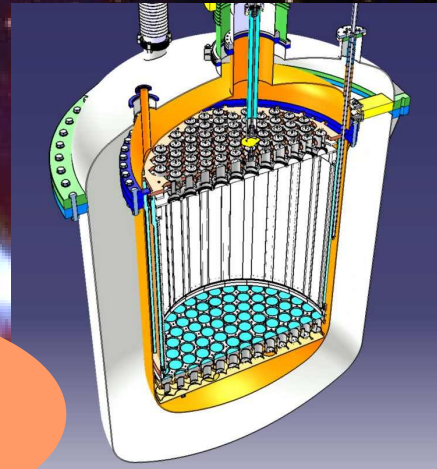
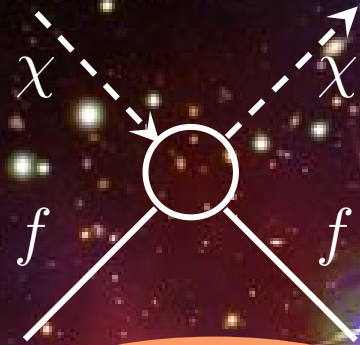
- **WIMP** → „WIMP miracle“
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPlless dark matter
- Gravitino
- ...



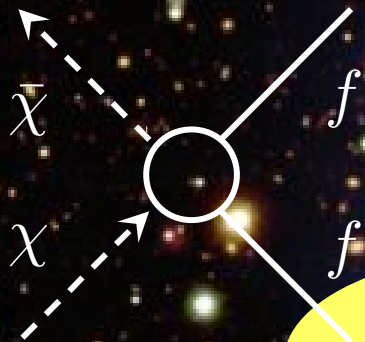


**Part 2 –
Searching for Dark Matter**

Dark Matter Search

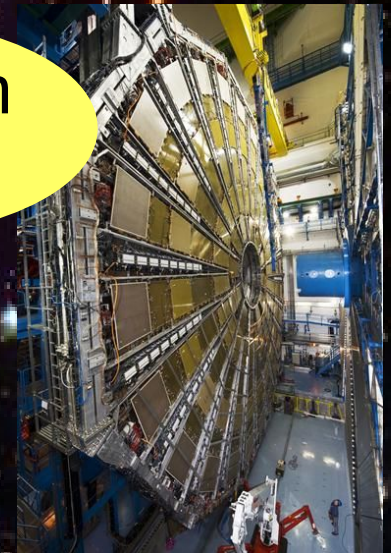
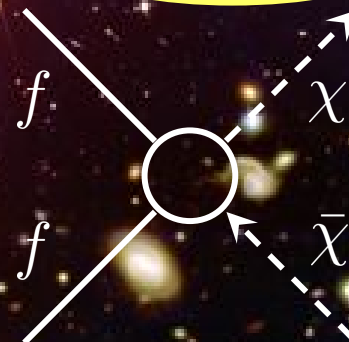
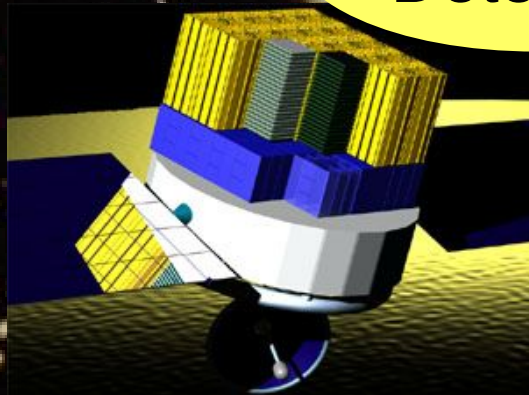


Direct
Detection



Indirect
Detection

Production
@ Collider

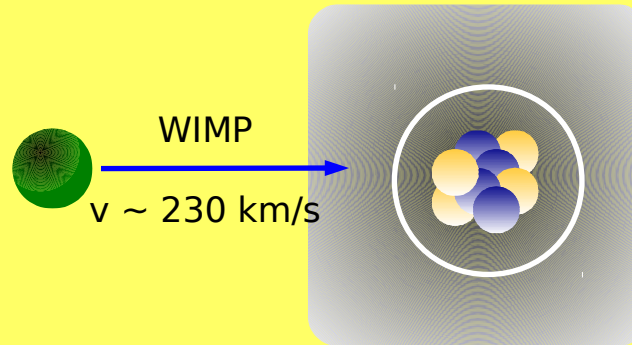


Cygnus Arm

Direct WIMP Search

Carina-Sagittarius Arm

Elastic Scattering of
WIMPs off target nuclei



Perseus Arm

$v \sim 230 \text{ km/s}$

<- Our Solar System

Local or Orion Arm

How much dark matter is here?
canonical value: $\sim 0.3 \text{ GeV/cm}^3$

40 000

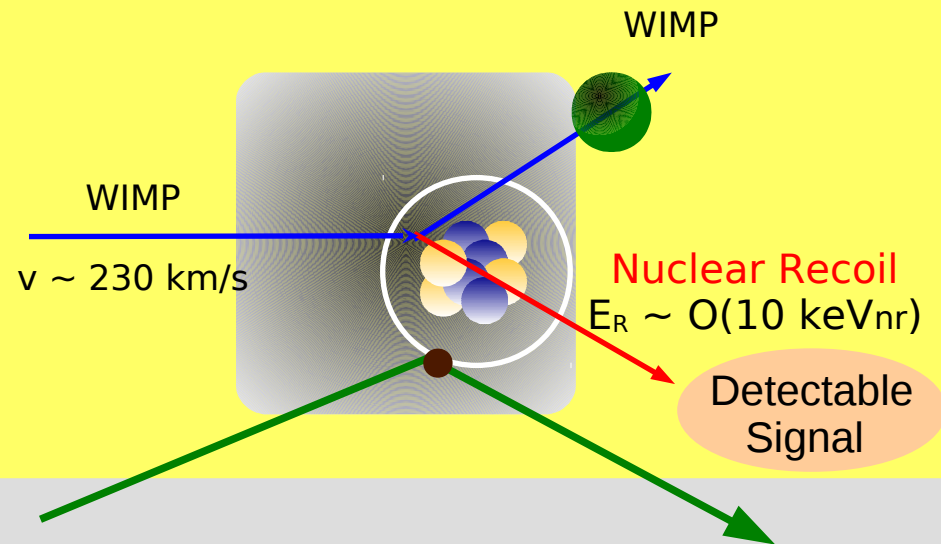
30 000

20 000

10 000

Direct WIMP Search

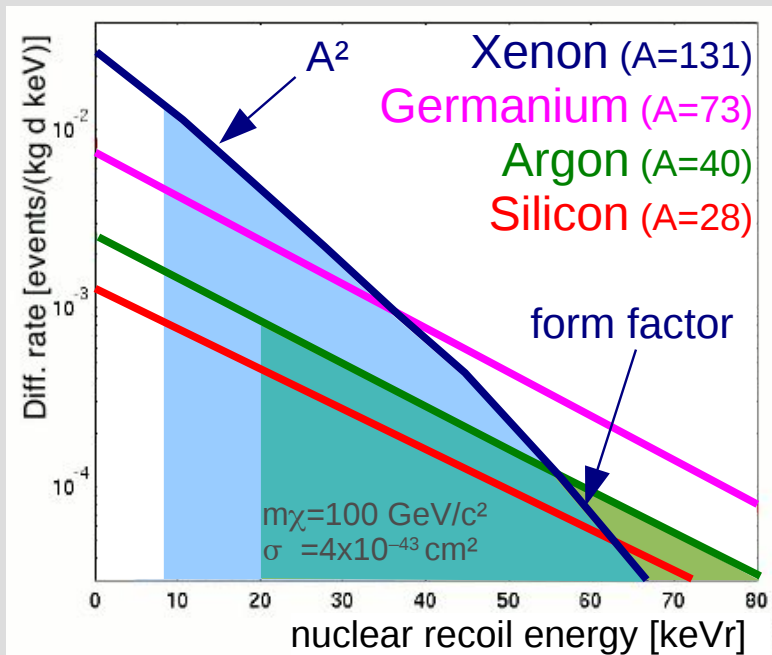
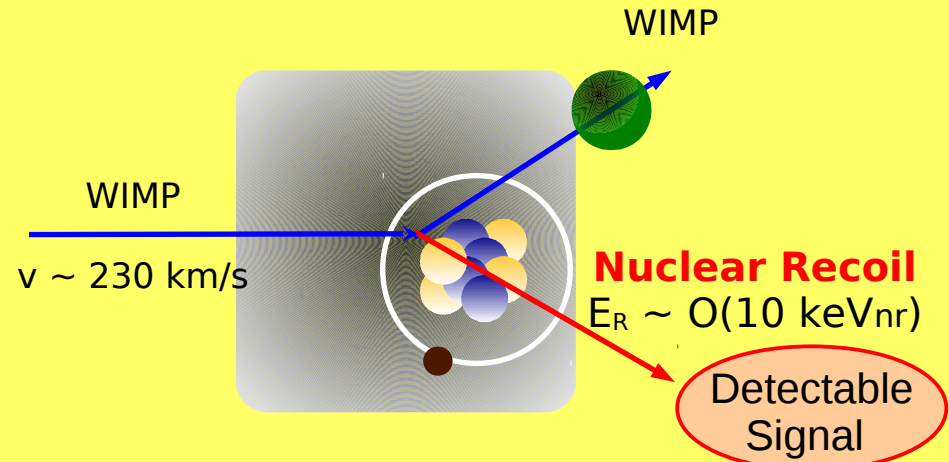
Elastic Scattering of
WIMPs off target nuclei
→ nuclear recoil



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

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

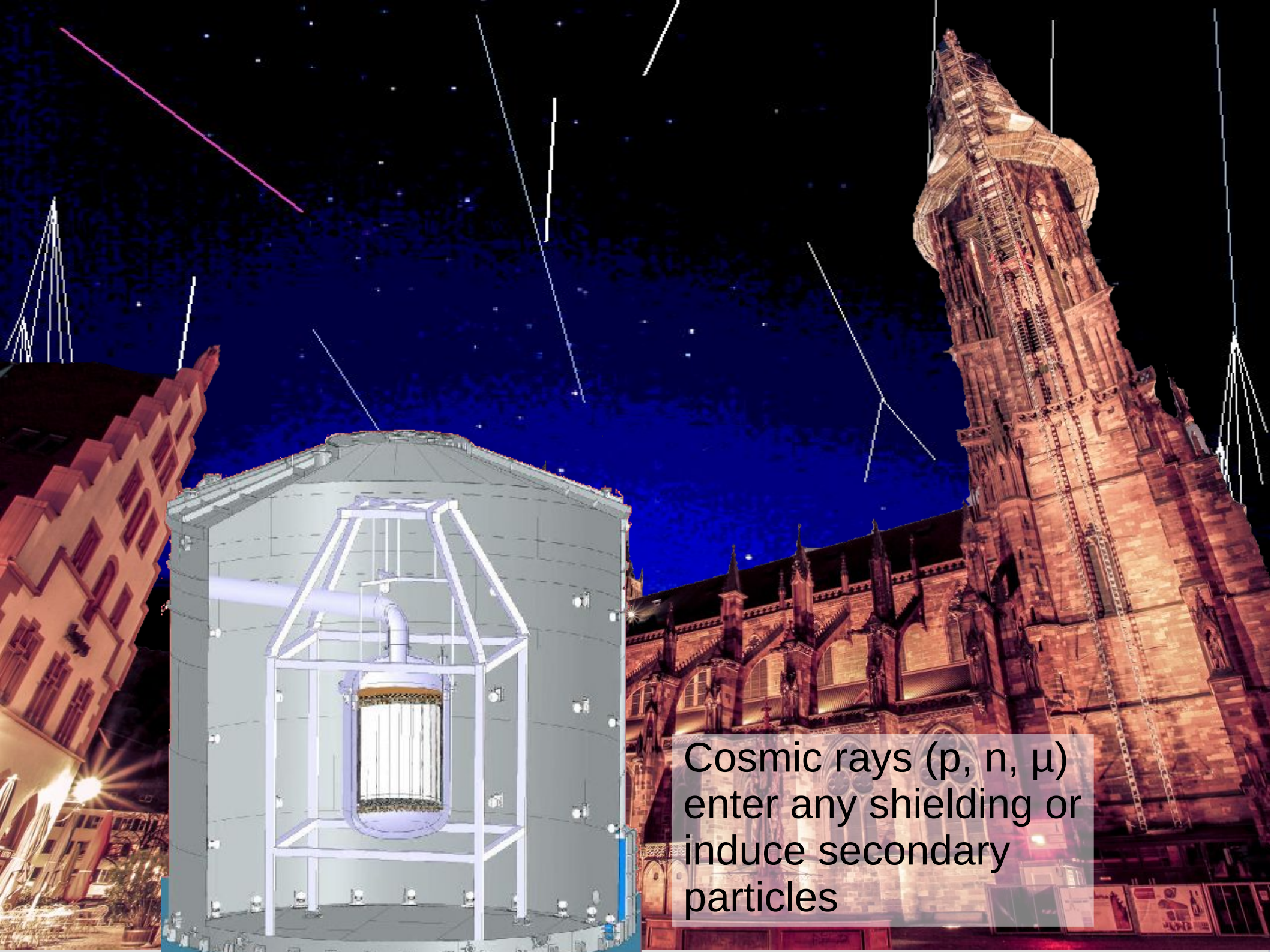
Detector

Local DM
 Density

Physics

$$\rho_\chi \sim 0.3 \text{ GeV}/c^2$$

- very small: $\ll 1 \text{ event/kg/year}$
- search for rare events
- **low-background crucial**



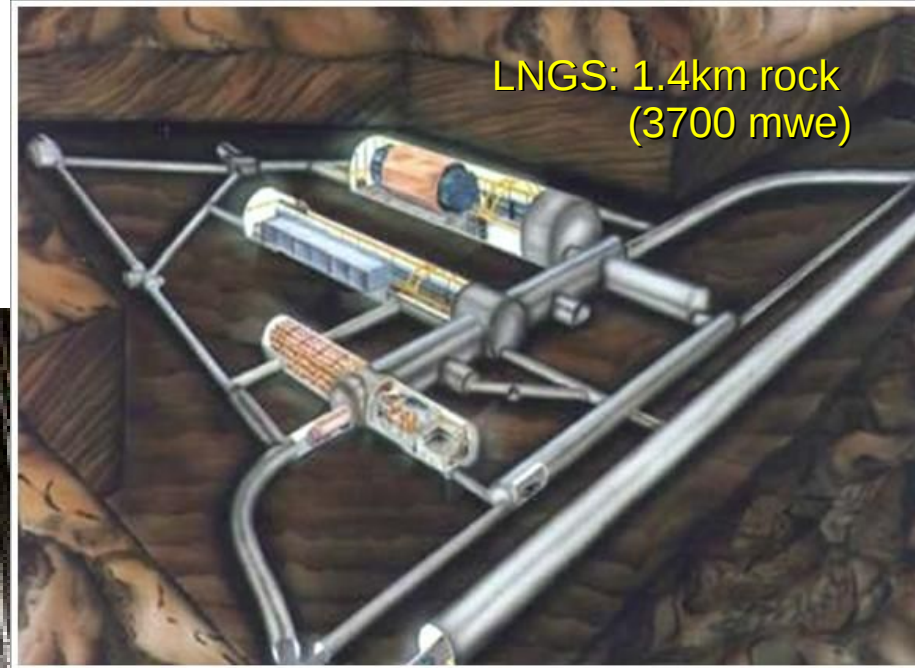
Cosmic rays (p , n , μ)
enter any shielding or
induce secondary
particles





Laboratori Nazionali del Gran Sasso

LNGS: 1.4km rock
(3700 mwe)



Background Sources

muons

muon-induced neutrons

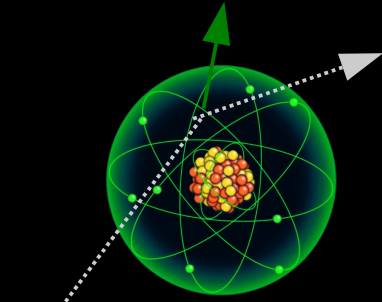
neutrons from (α, n) and sf

natural γ -bg

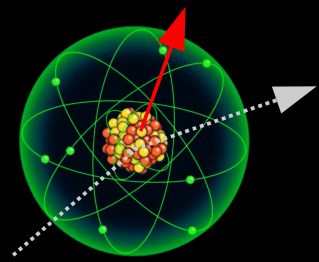
natural γ -bg

neutrons from (α, n) and sf

target-intrinsic bg:
 α -, β -, γ -radiation, n;
activation, impurities,
double-beta decay

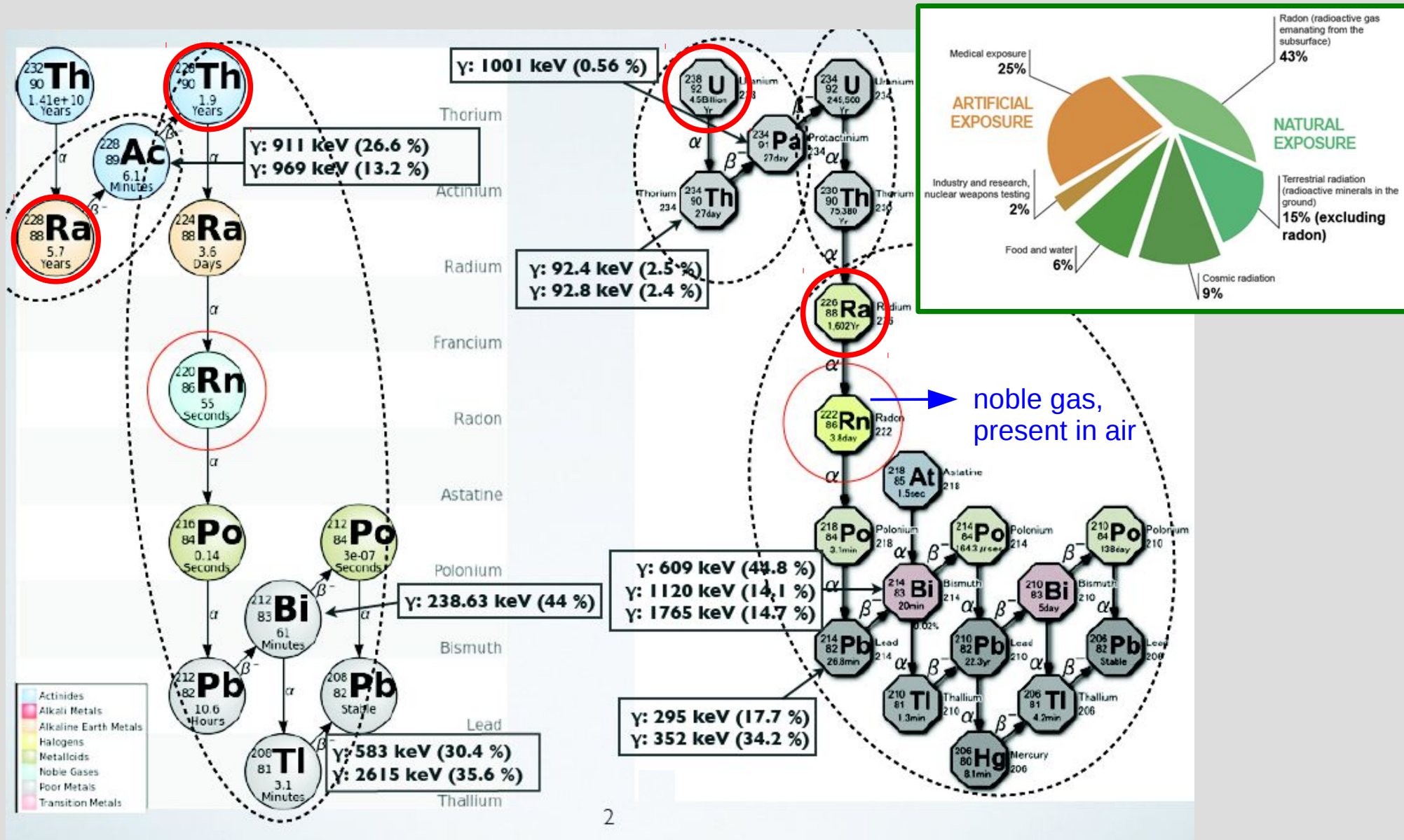


Electronic Recoils
(gamma, beta)



Nuclear Recoils
(neutron, WIMPs)

The U and Th Chains



2



182
SPARE PARTS

NON-MAGNETIC

LHE

100lbs.)

**GeMSE**
Germanium
Material and
Meteorite
Screening
Experiment

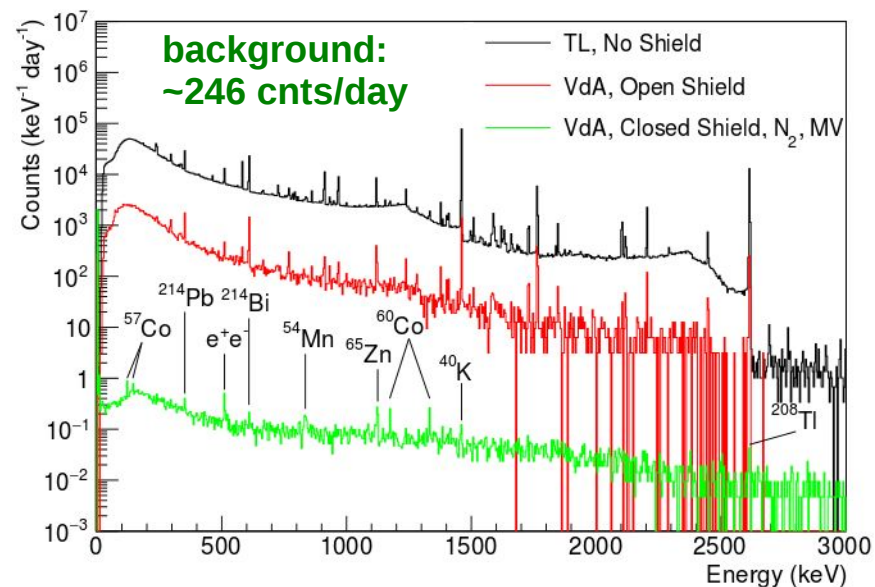
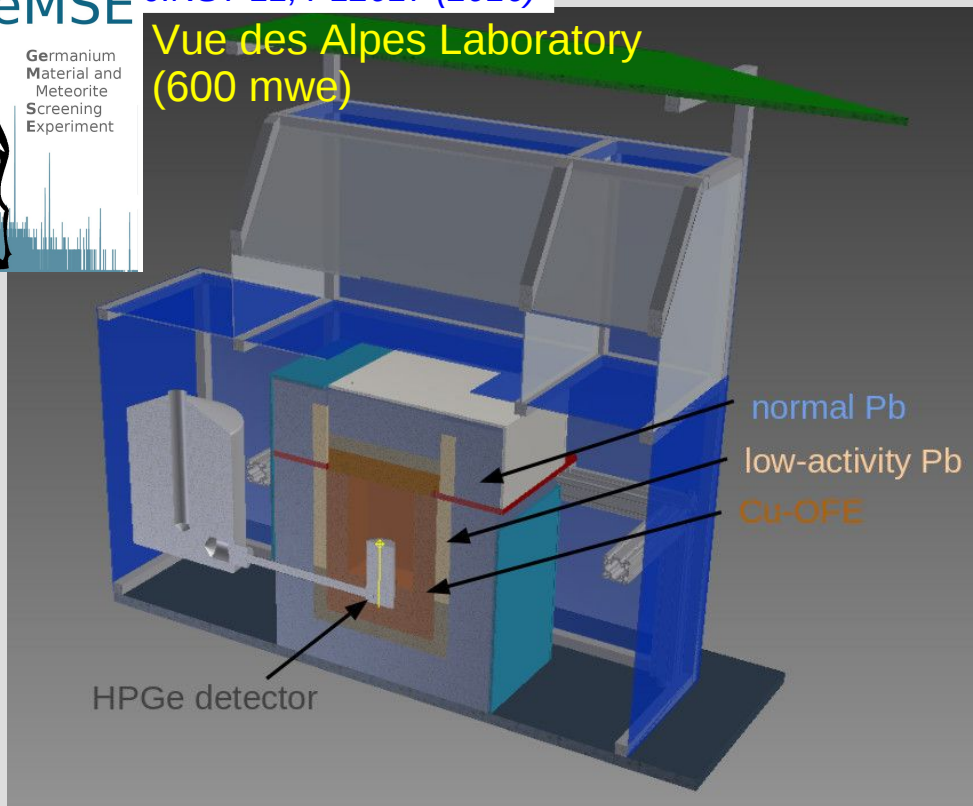
Low-background Screening



GeMSE JINST 11, P12017 (2016)

Germanium Material and Meteorite Screening Experiment

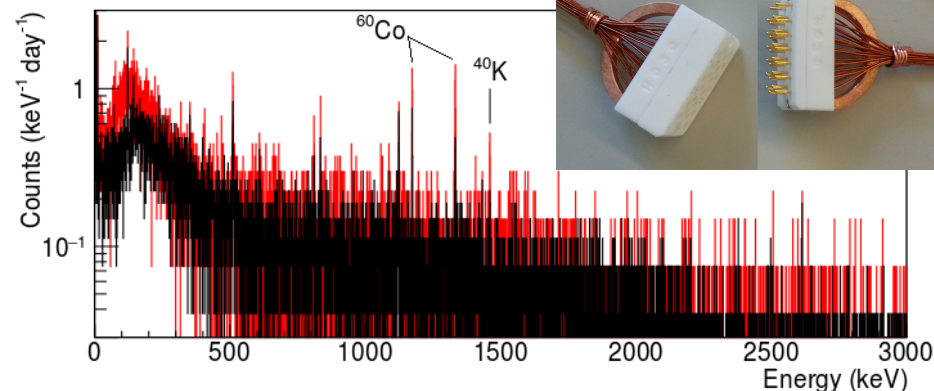
Vue des Alpes Laboratory (600 mwe)



Identify materials with lowest radioactivity:

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

low-background HV connector



Background Sources

solar neutrino flux:
 $\sim 6.4 \times 10^{10} \text{ s}^{-1} \text{ cm}^{-2}$

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

pp+⁷Be neutrinos
→ **ER signature**

muons

muon-induced neutrons

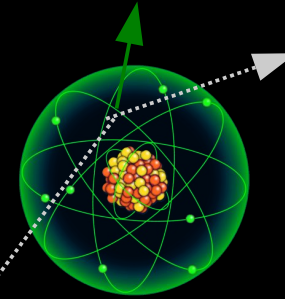
neutrons from (α,n) and sf

natural γ-bg

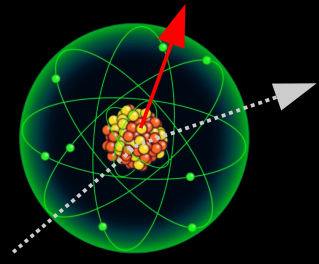
natural γ-bg

neutrons from (α,n) and sf

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



Electronic Recoils
(gamma, beta)



Nuclear Recoils
(neutron, WIMPs)

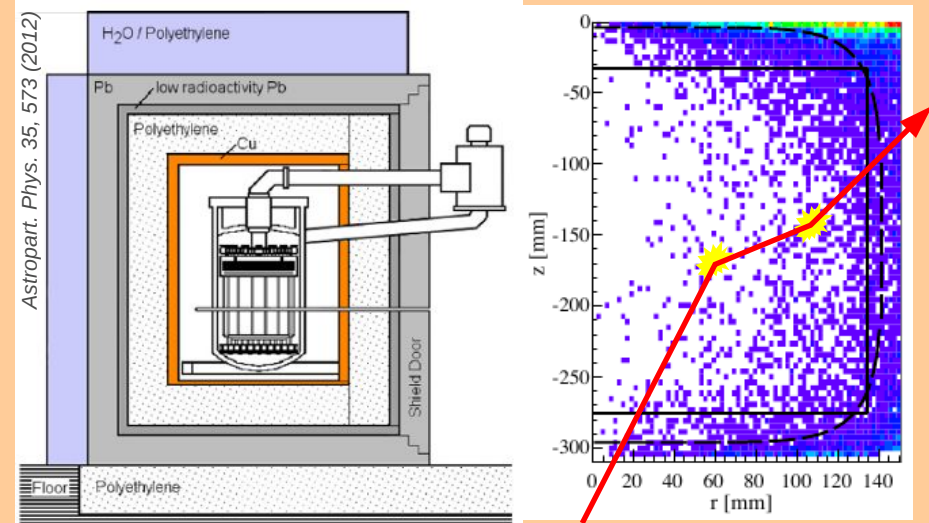
Background Suppression

Avoid Backgrounds

Shielding

- deep underground location
- large shield (Pb, water, PE)
- active veto (μ , γ coincidence)
- self shielding \rightarrow fiducialization

Use of radiopure materials



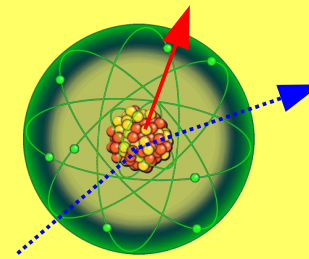
Use knowledge about expected WIMP signal


WIMPs interact only once

- \rightarrow single scatter selection
- requires some position resolution

WIMPs interact with target nuclei

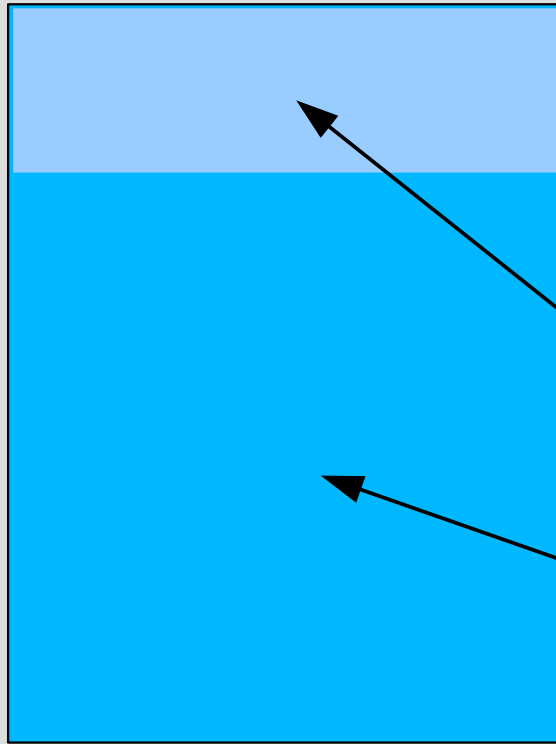
- \rightarrow nuclear recoils
- exploit different dE/dx from signal and background



A photograph showing several technicians in white cleanroom suits and blue gloves working on a large, cylindrical, orange-colored detector assembly inside a cleanroom. The assembly is mounted on a metal frame. One technician is standing on a step ladder, reaching up to adjust a component on the ceiling. Another technician is on a step ladder to the left, looking down at the assembly. A third technician is on the floor to the right, looking at the assembly. The cleanroom has a glass and metal frame with overhead fluorescent lights. The floor is light-colored and polished.

**Part 3 –
The XENON1T Experiment**

Dual Phase liquid xenon TPC

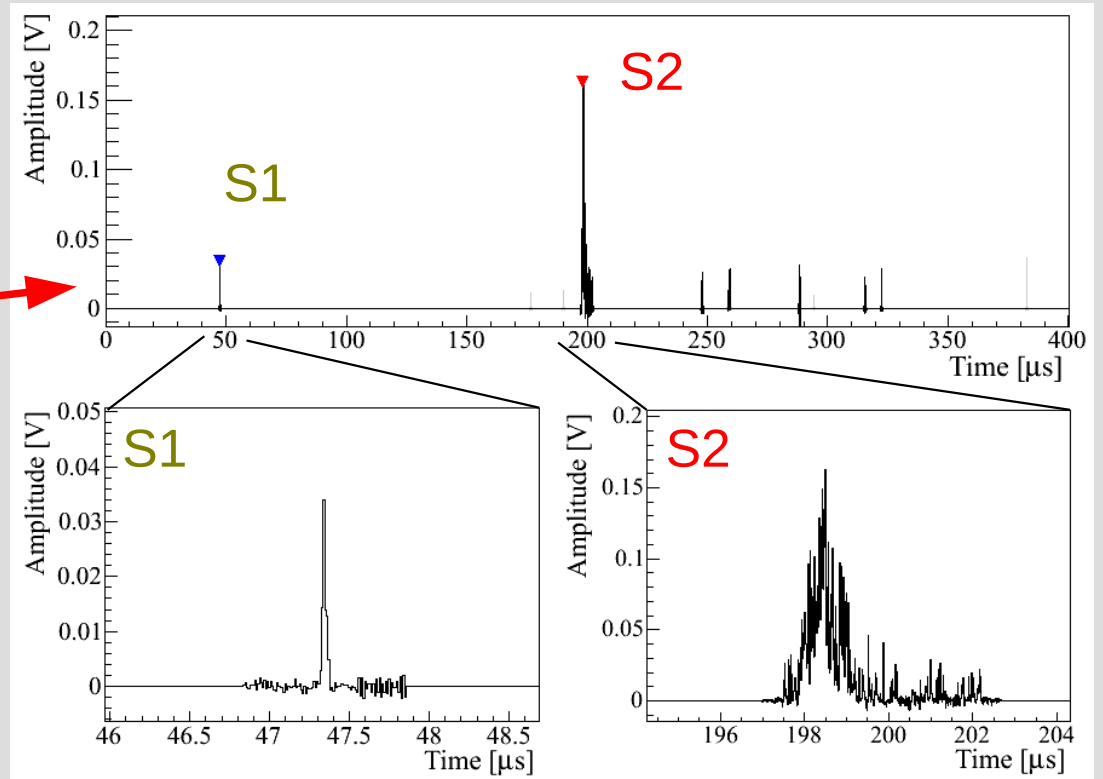
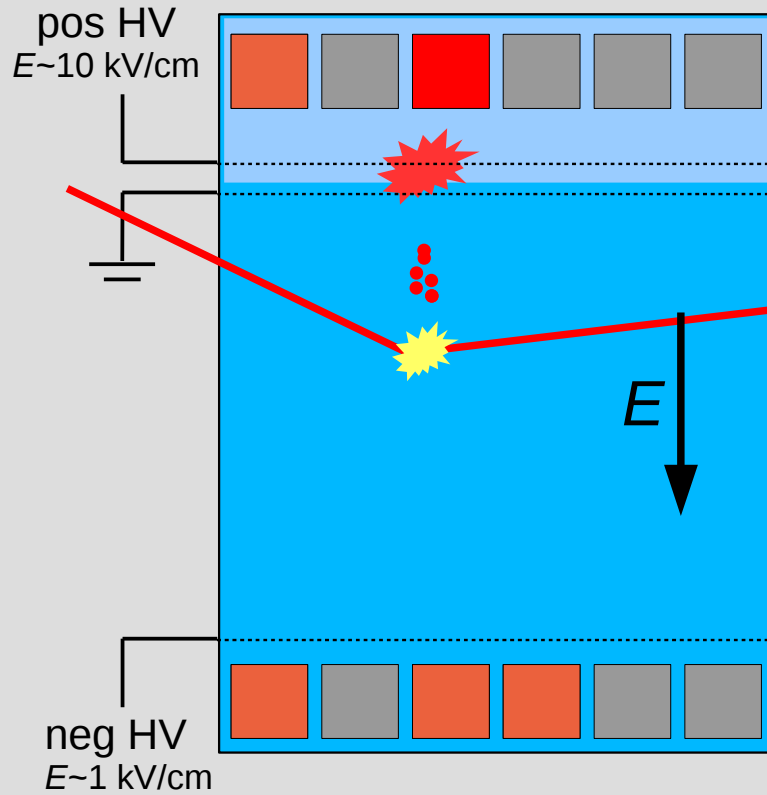


1	New Original																18
1	IA																18
1	IIA																18
3	4											13	14	15	16	17	18
3	4											13	14	15	16	17	18
11	12											13	14	15	16	17	18
11	12											13	14	15	16	17	18
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
55	56	57 to 71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
55	56	57 to 71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
87	88	89 to 103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
87	88	89 to 103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118

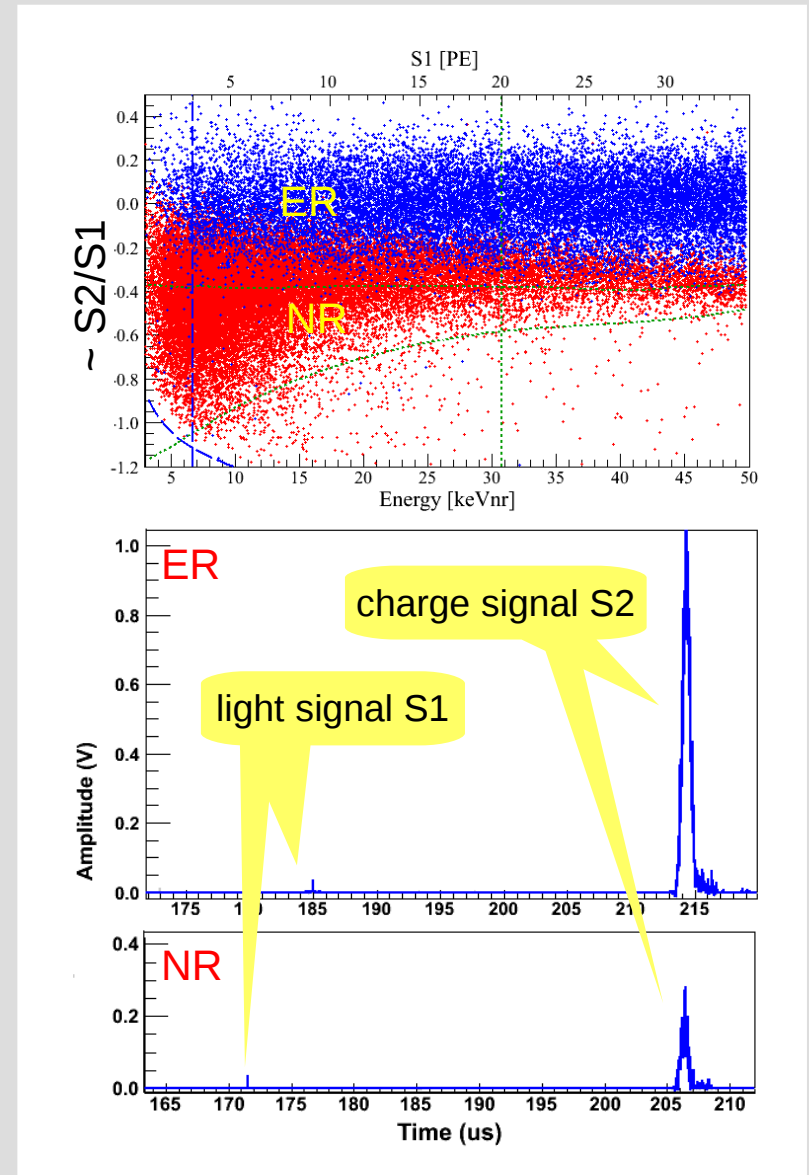
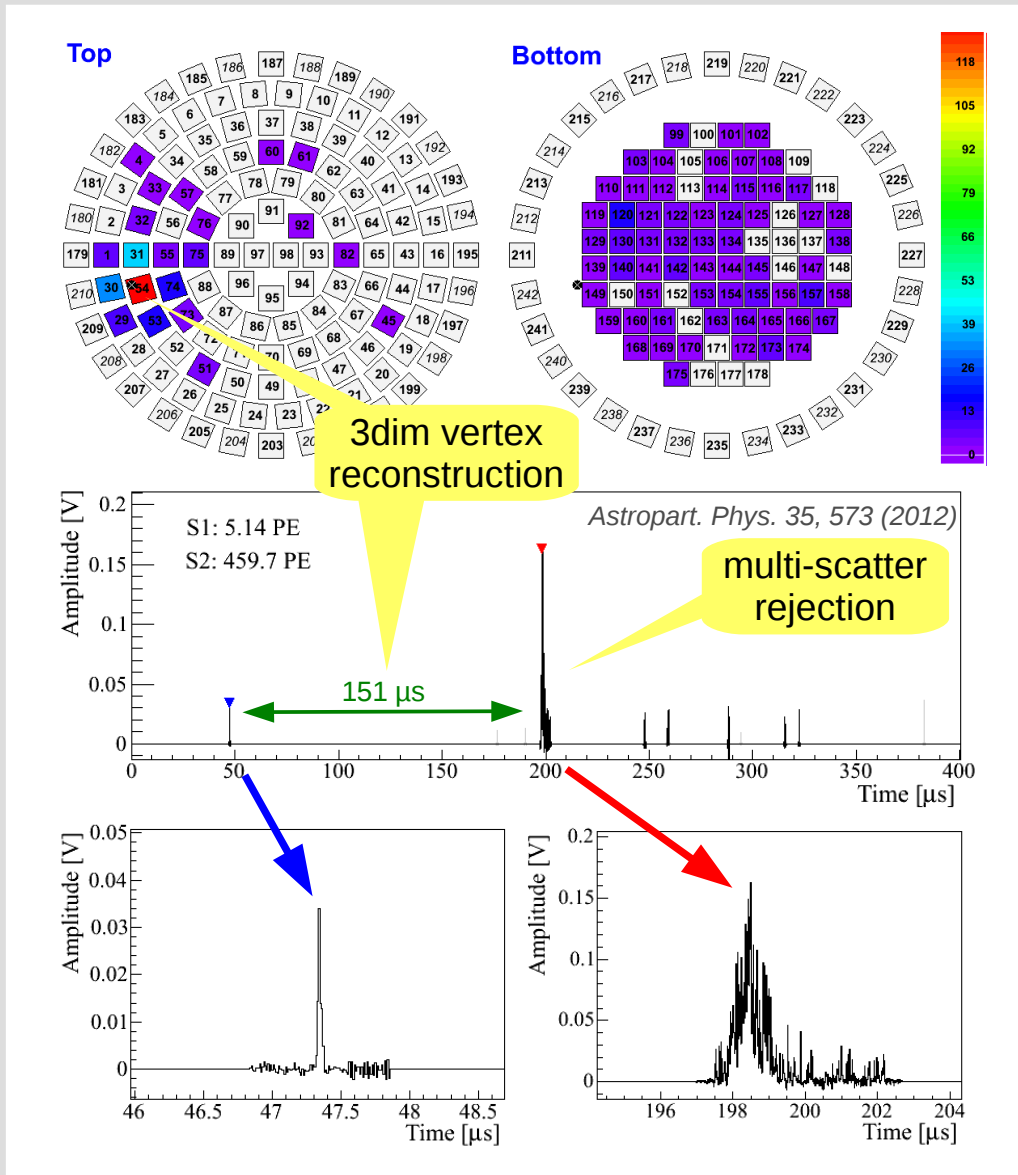
gaseous xenon

liquid xenon (LXe)

Dual Phase TPC



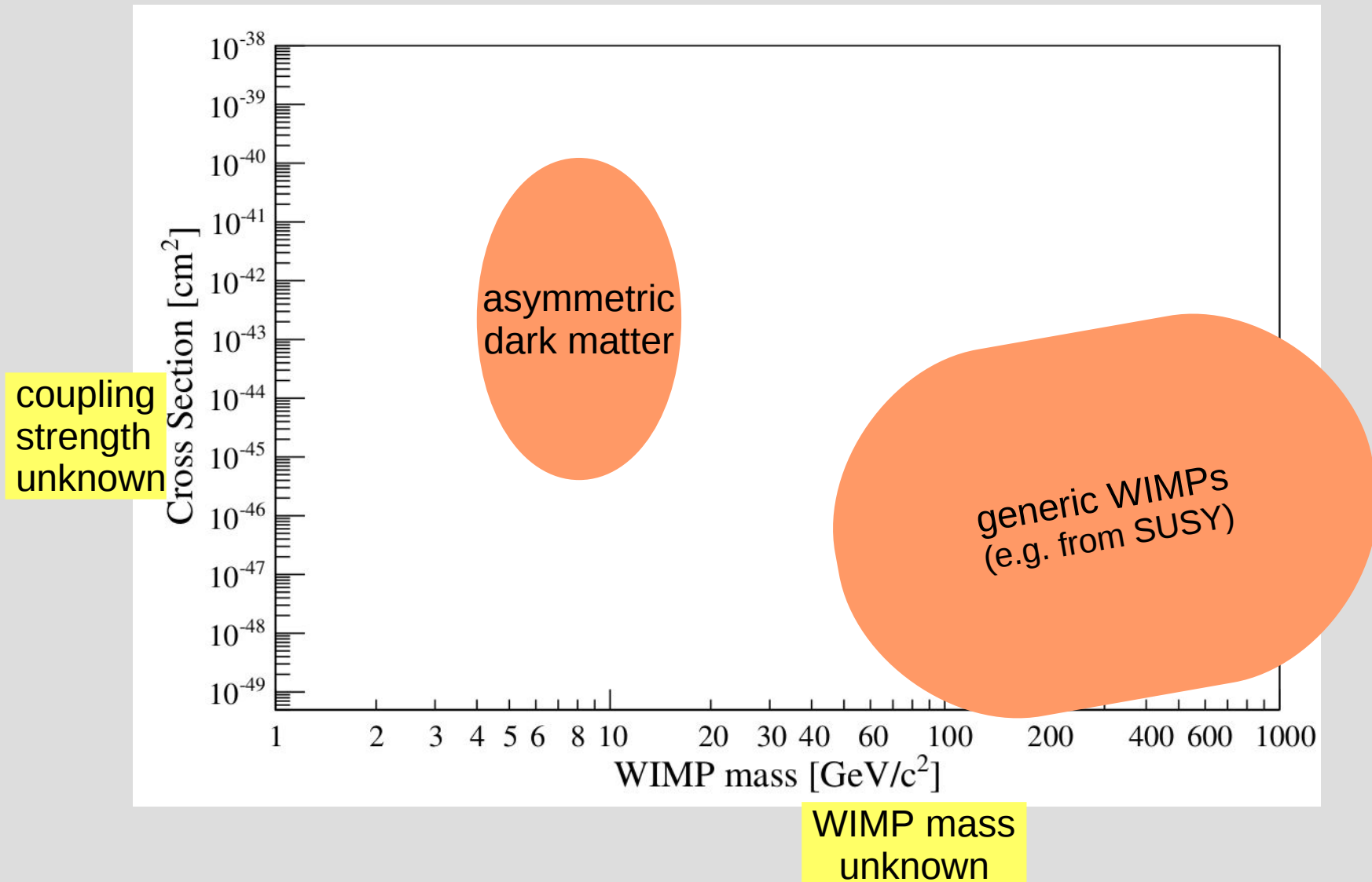
Dual Phase TPC



Figures from XENON100

The WIMP Parameter Space

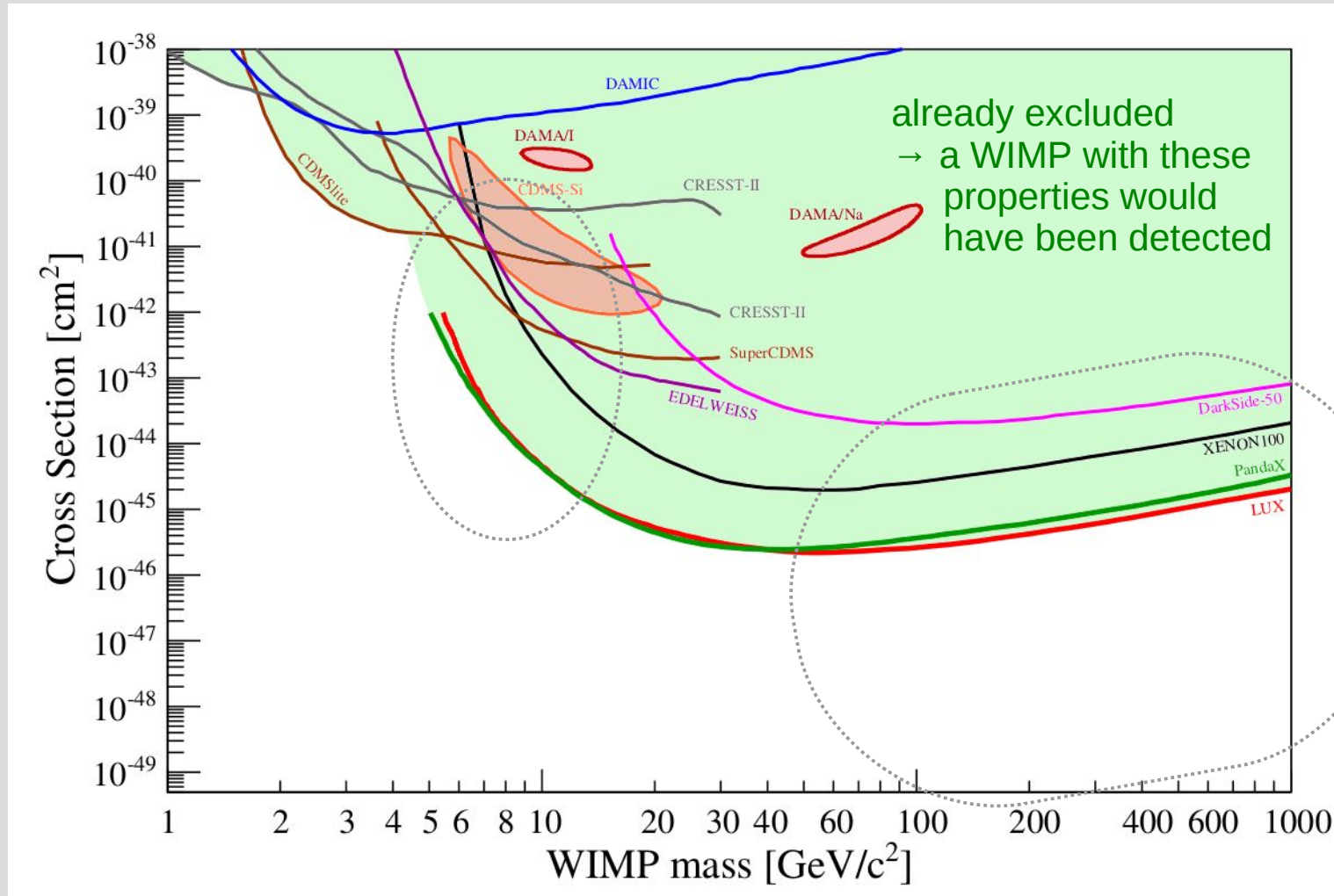
spin-independent WIMP-nucleon interactions



High WIMP-masses TPC dominated

$\geq 4.5 \text{ GeV}/c^2$

spin-independent WIMP-nucleon interactions

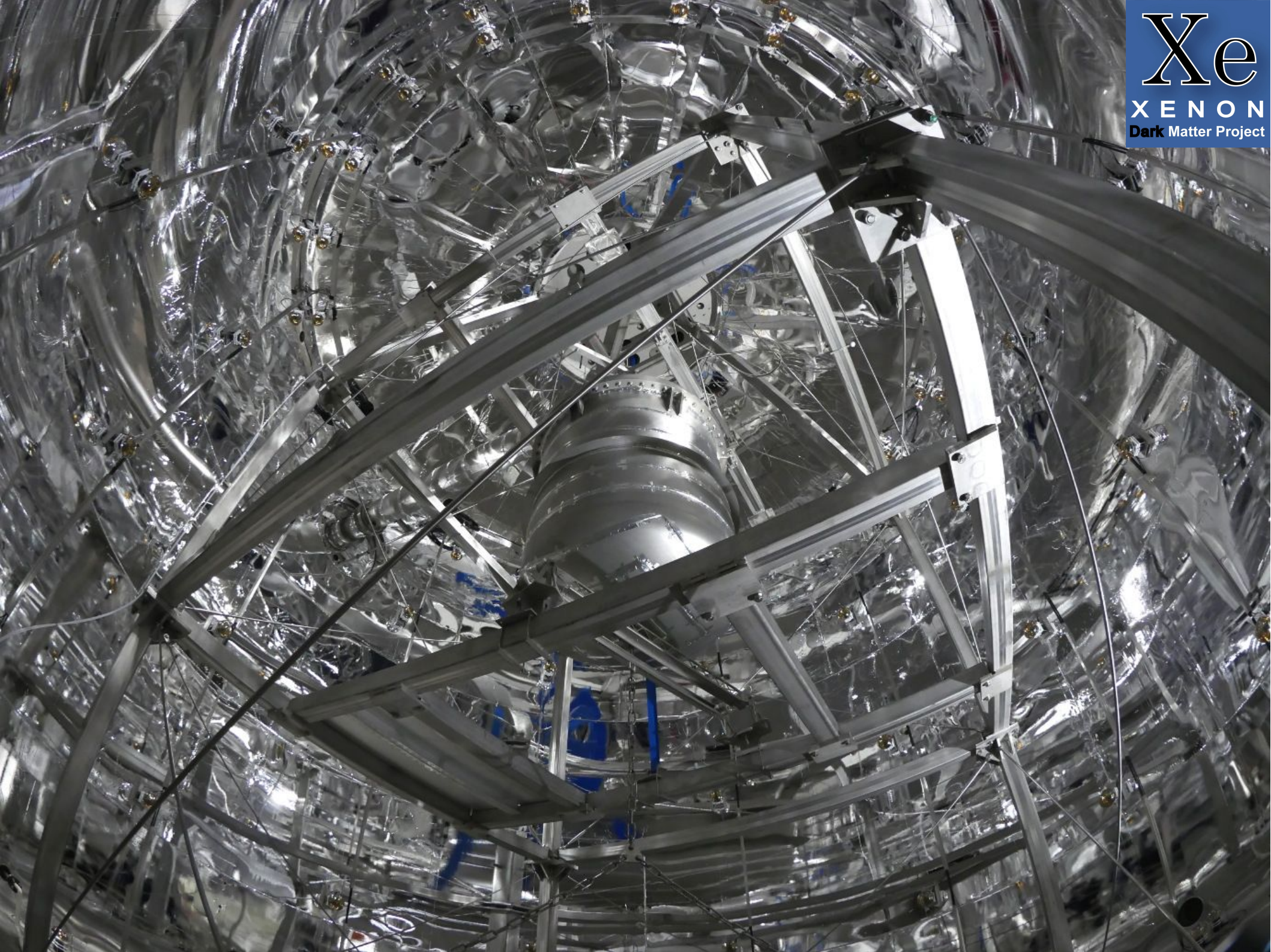


some projects are missing...

XENON1T @ LNGS

Xe
XENON
Dark Matter Project





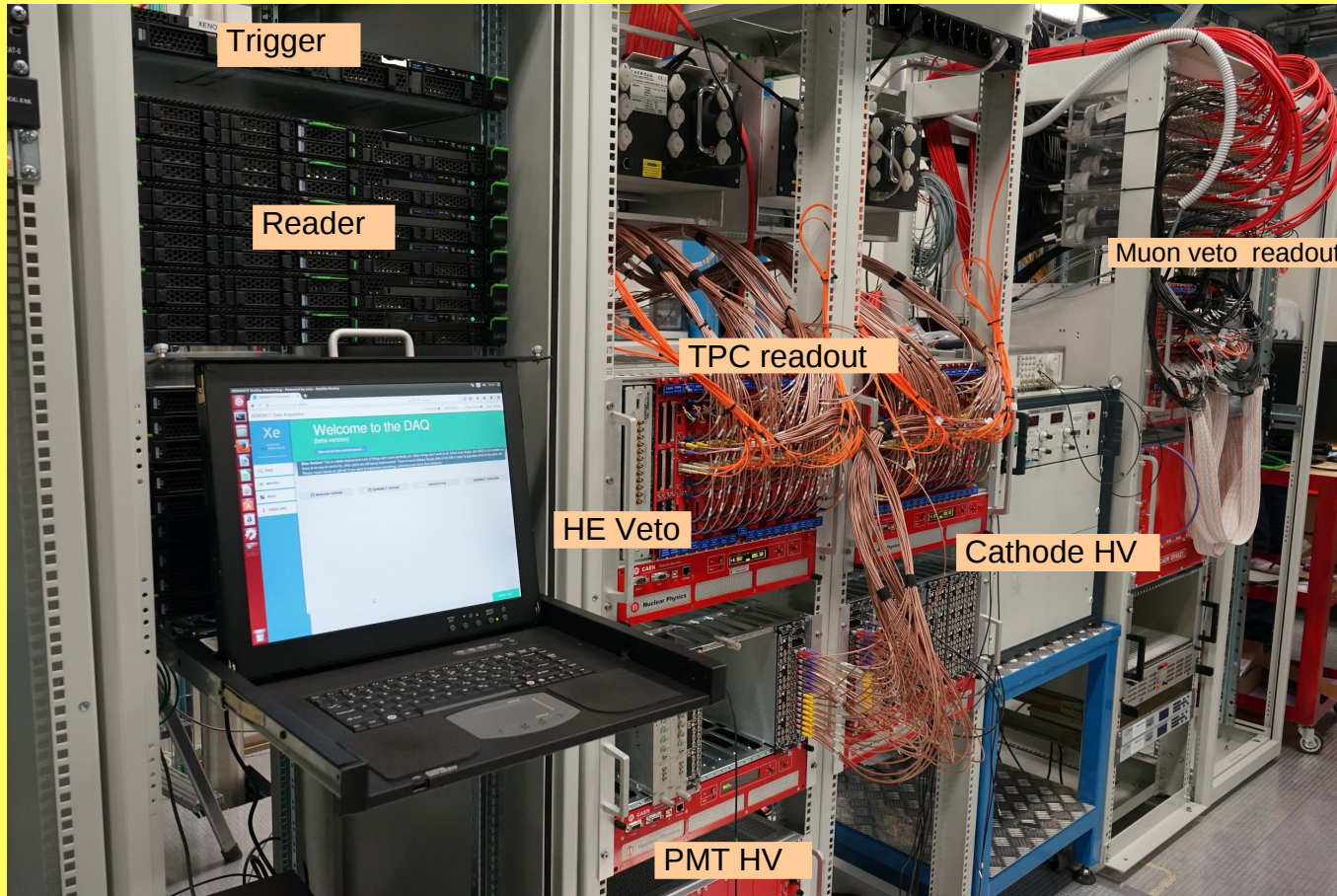






largest LXe TPC ever built
cylinder: 96 cm
active LXe target: 2.0t (3.2t total)
248 PMTs

TPC Data Acquisition, Electronics

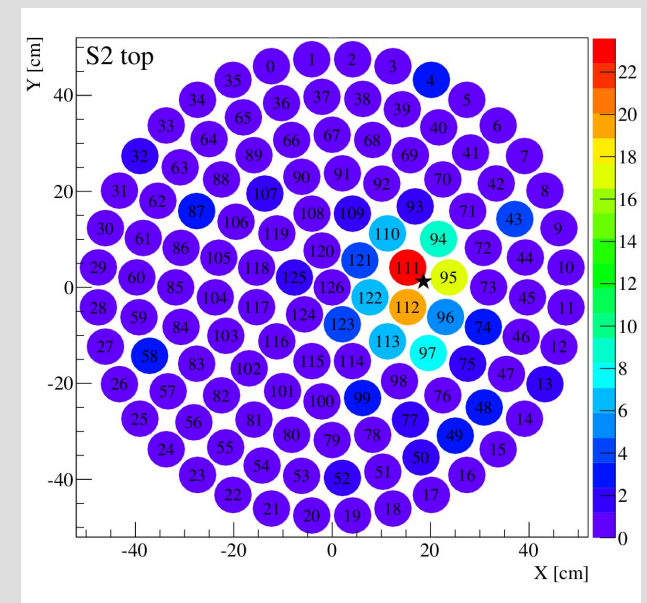
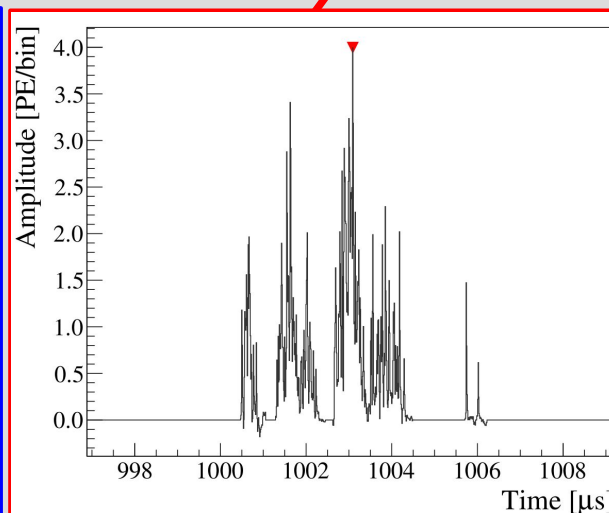
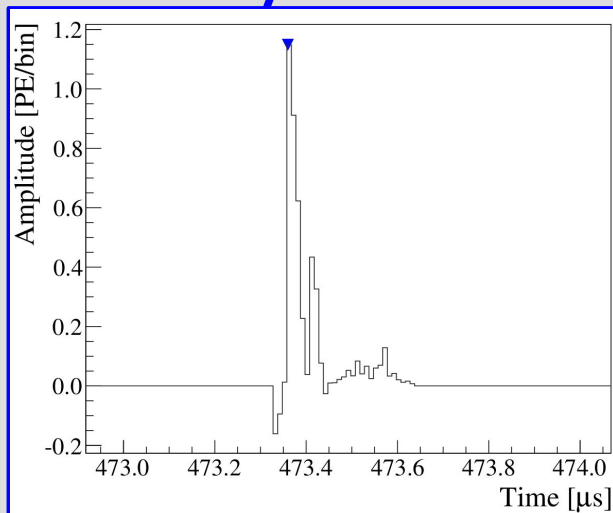
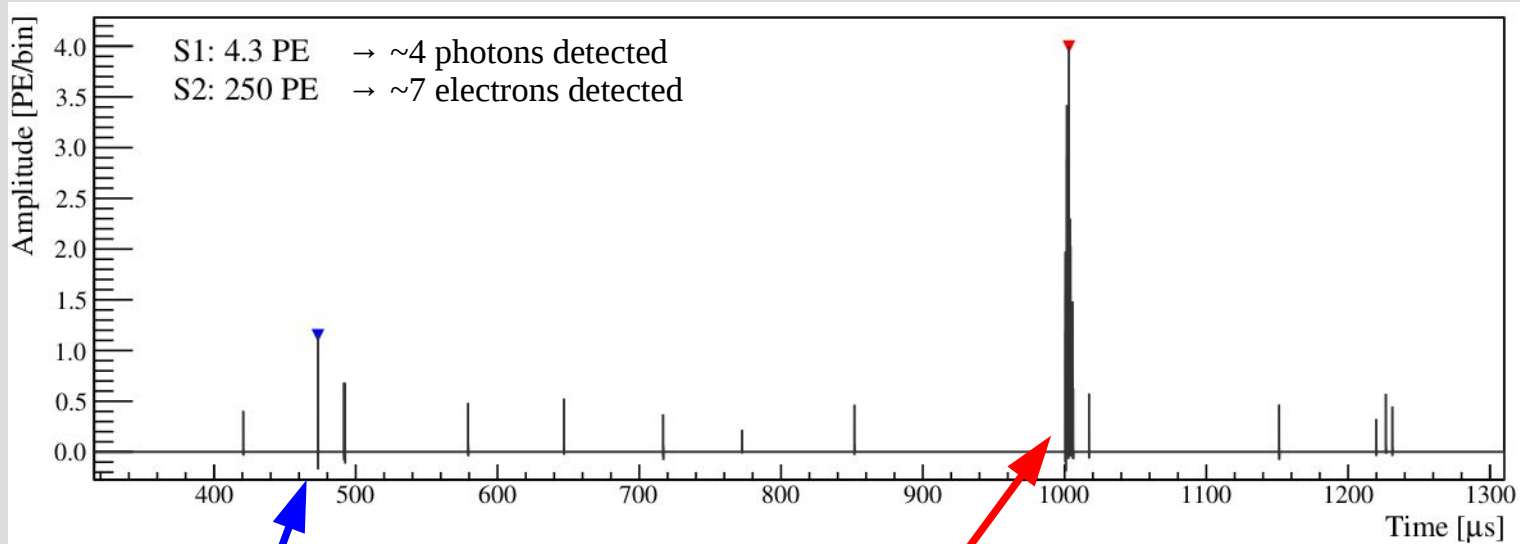


Parallel, trigger-less readout: → low threshold
→ high throughput (>300 MB/s achieved → 0.8 TB/d):



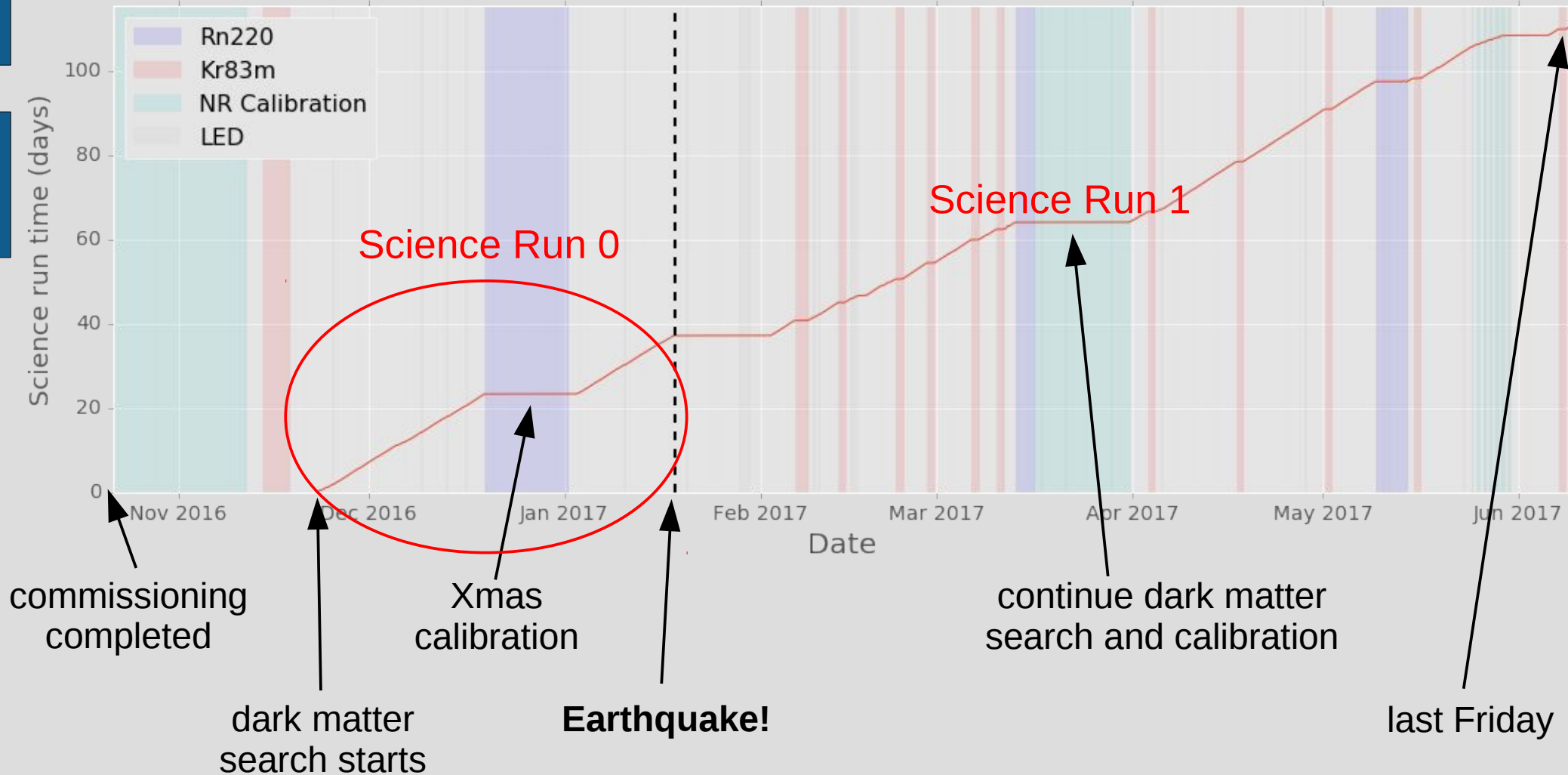
How would dark matter look?

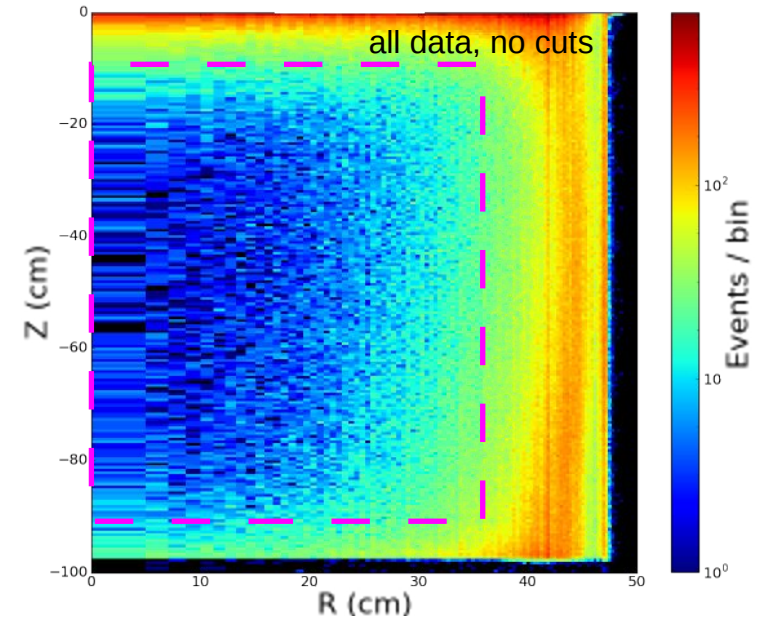
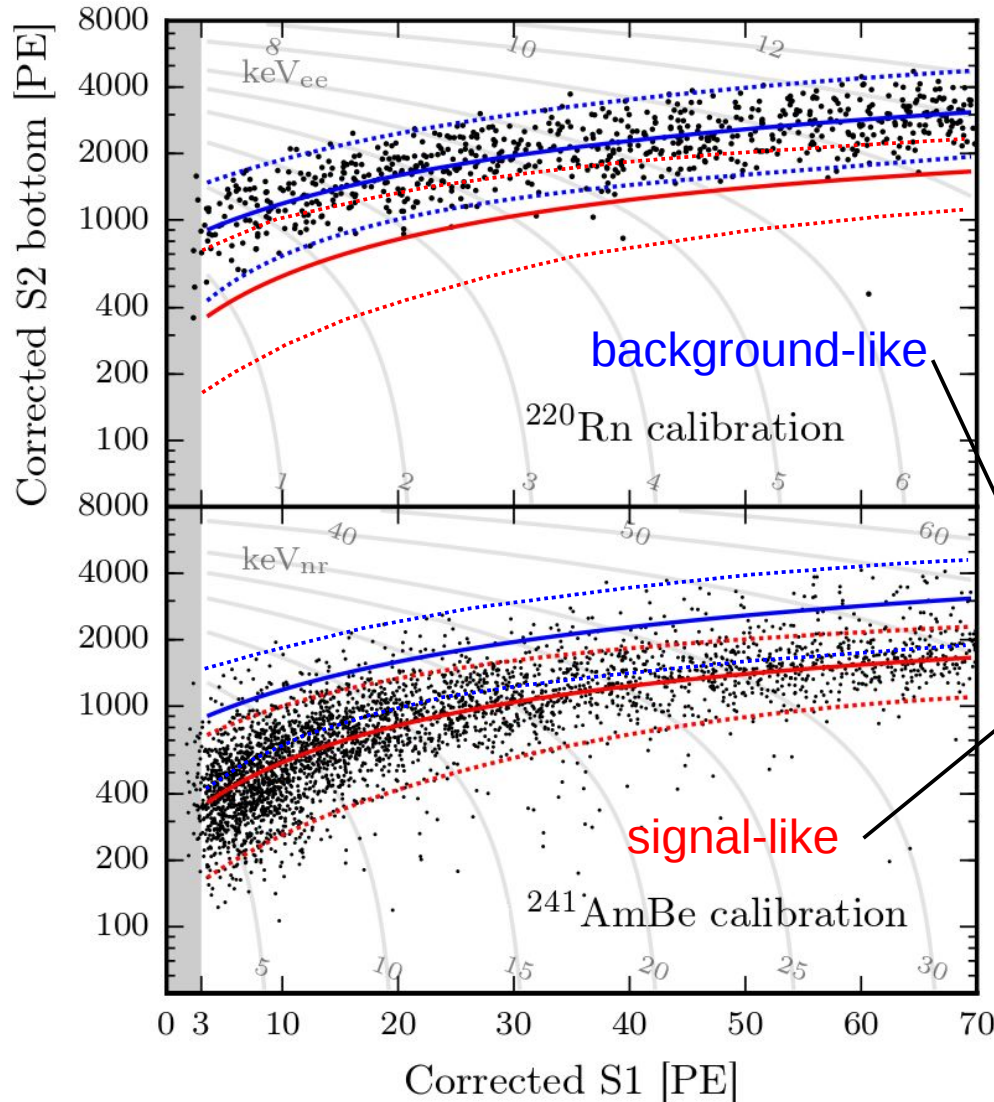
... but it's a low-E neutron interaction from calibration!



Dark Matter Data Taking

arXiv:1705.06655





Used to construct **background** and **signal** models.

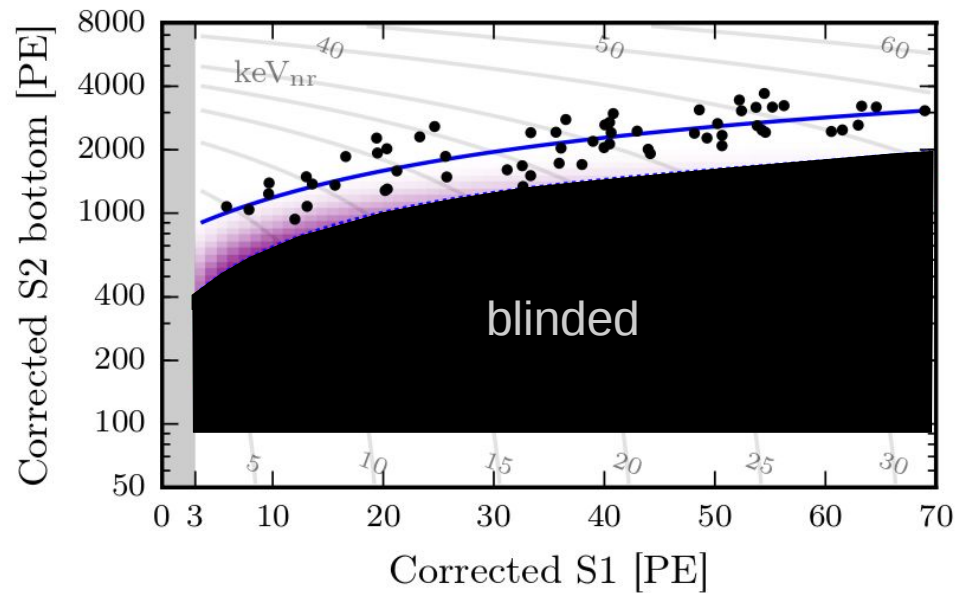
use **central 1000 kg** LXe for analysis

Blind analysis

= region of interest inaccessible during analysis to avoid human bias

Blinded Data

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

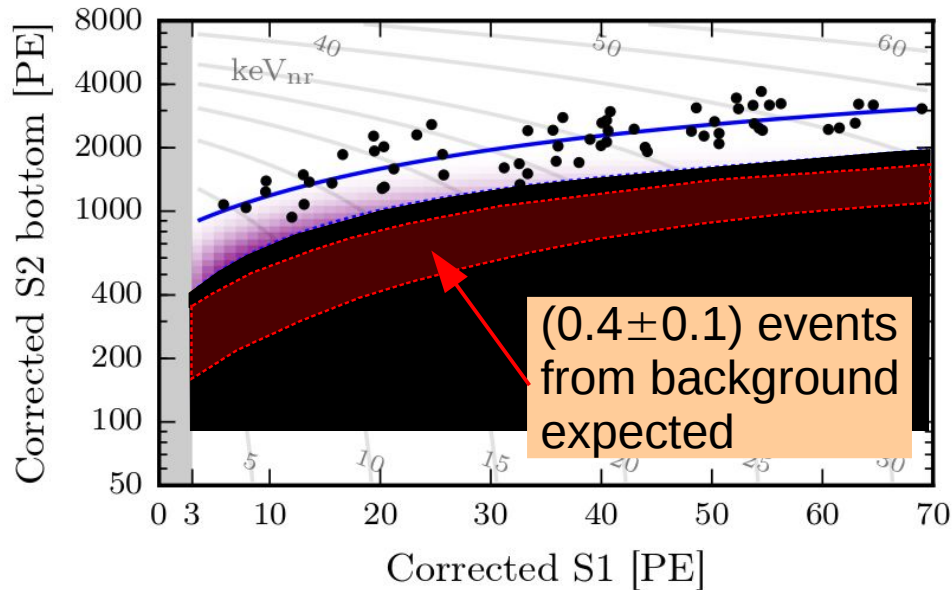


XENON1T: **35.6 t × d**

Background Expectation

arXiv:1705.06655

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



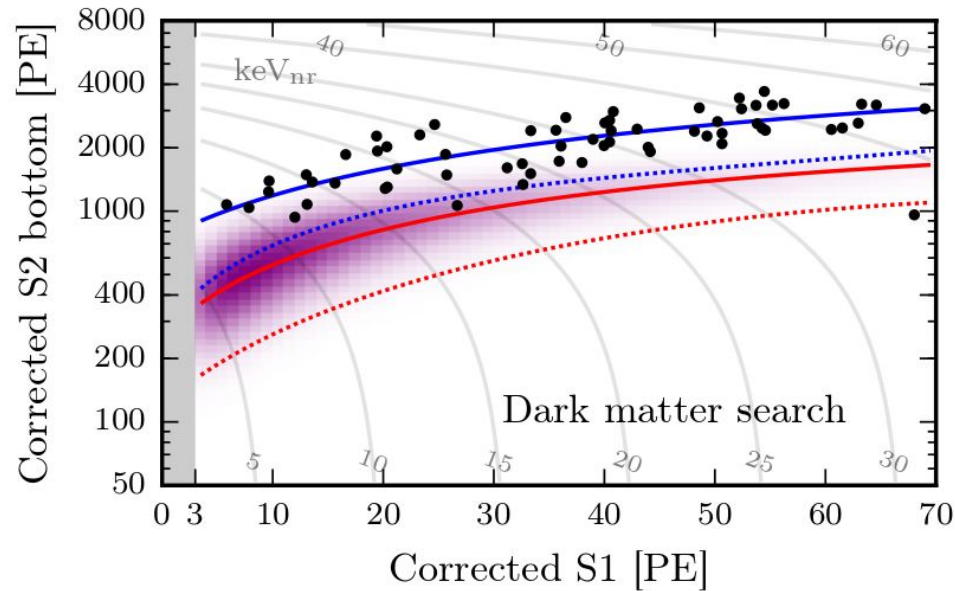
XENON1T: $35.6 \text{ t} \times \text{d}$

note:

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

Unblinding...

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

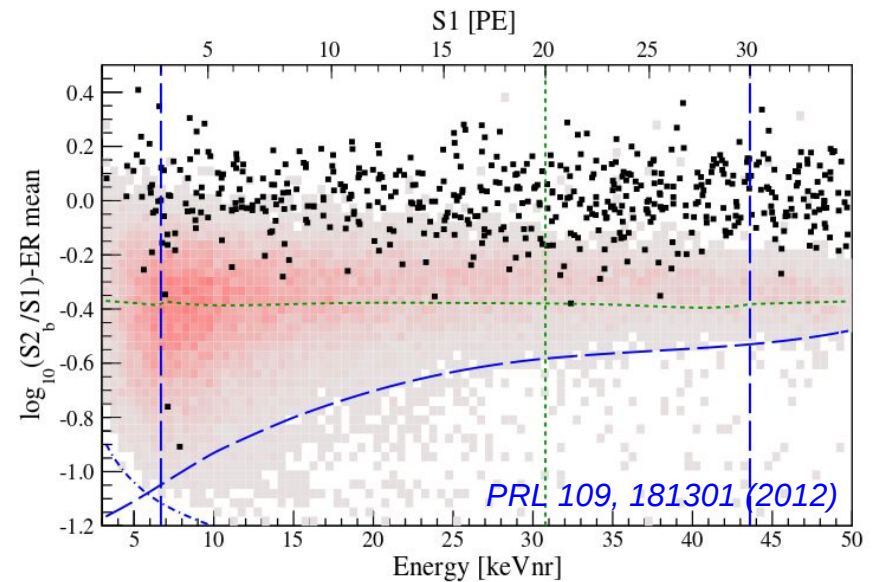
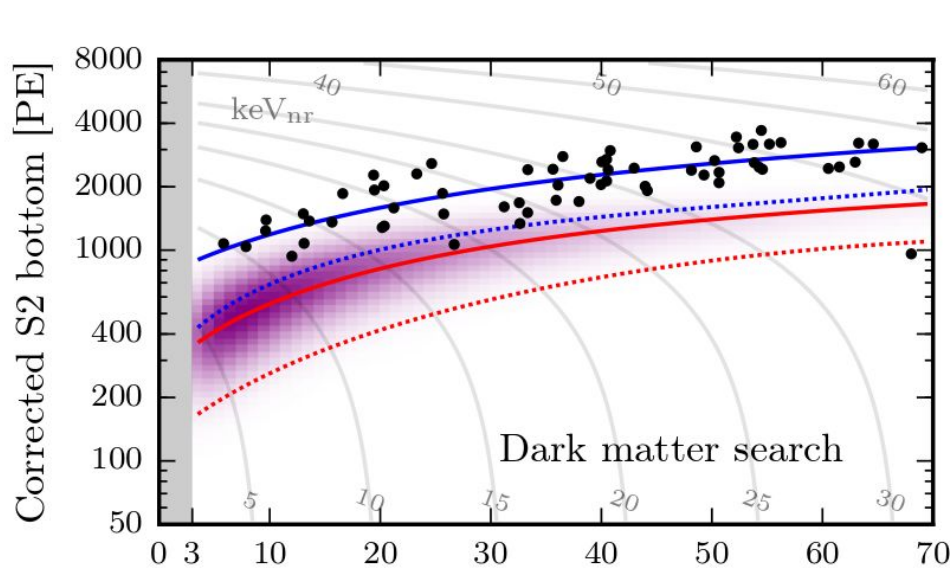


XENON1T: **35.6 t × d**

no dark matter candidate observed!

An ultra-low background

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



Corrected S1 [PE]

XENON1T: 35.6 t × d

XENON100: 7.6 t × d

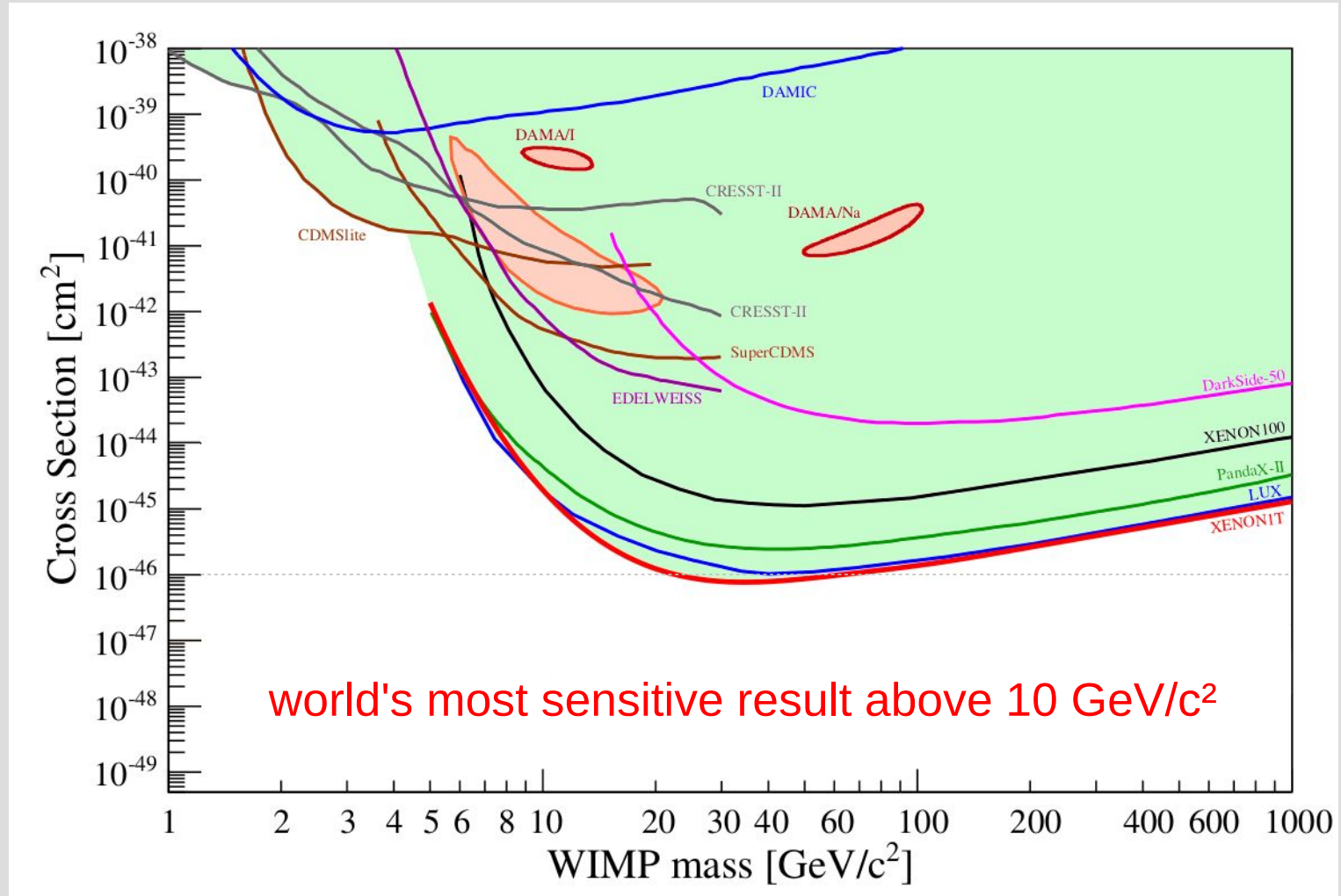
← 5× more data
30× lower background

no dark matter candidate observed!

No Signal \rightarrow Exclusion Limit

arXiv:1705.06655

spin-independent WIMP-nucleon interactions



XENON1T science goal: 5 \times more sensitive than current result

XENON1T → XENONnT

JCAP 04, 027 (2016)

XENON1T

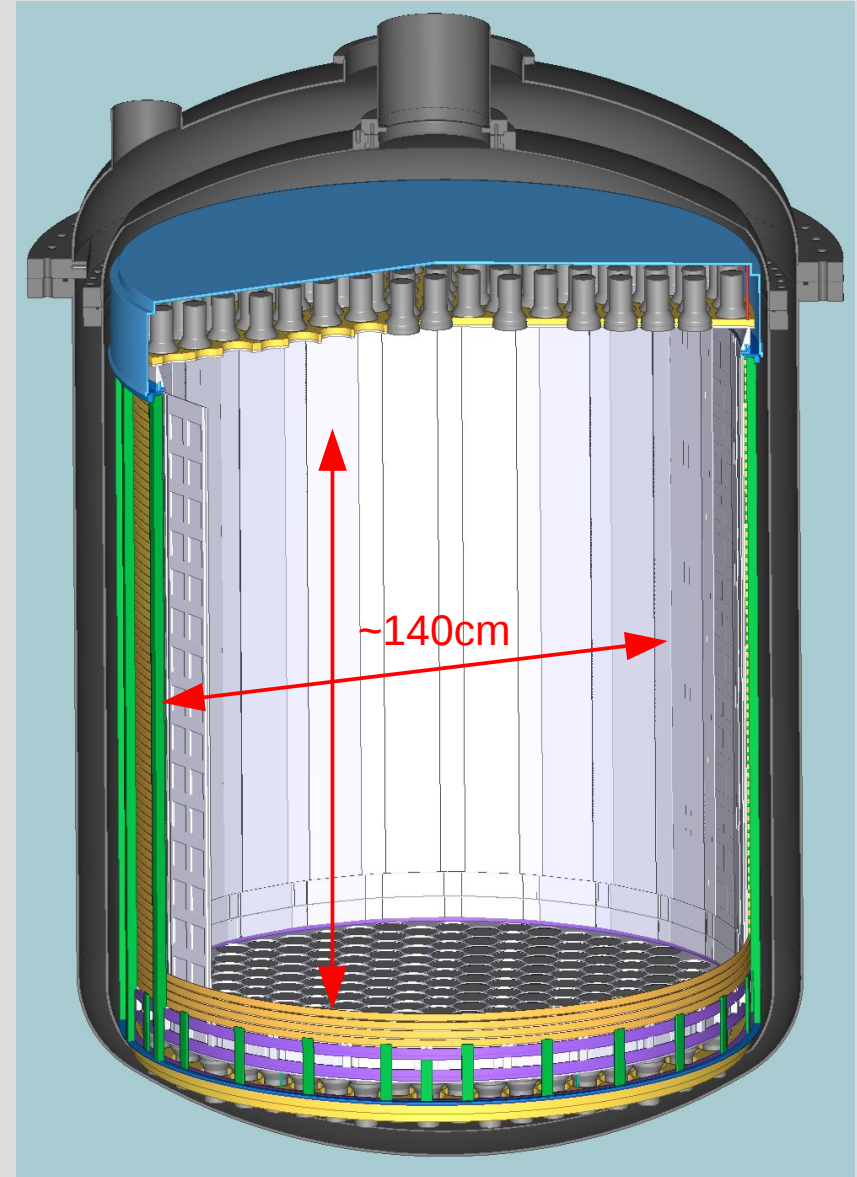
- 2t active LXe target
- taking data

XENONnT

- 6t active target
- science run by 2019

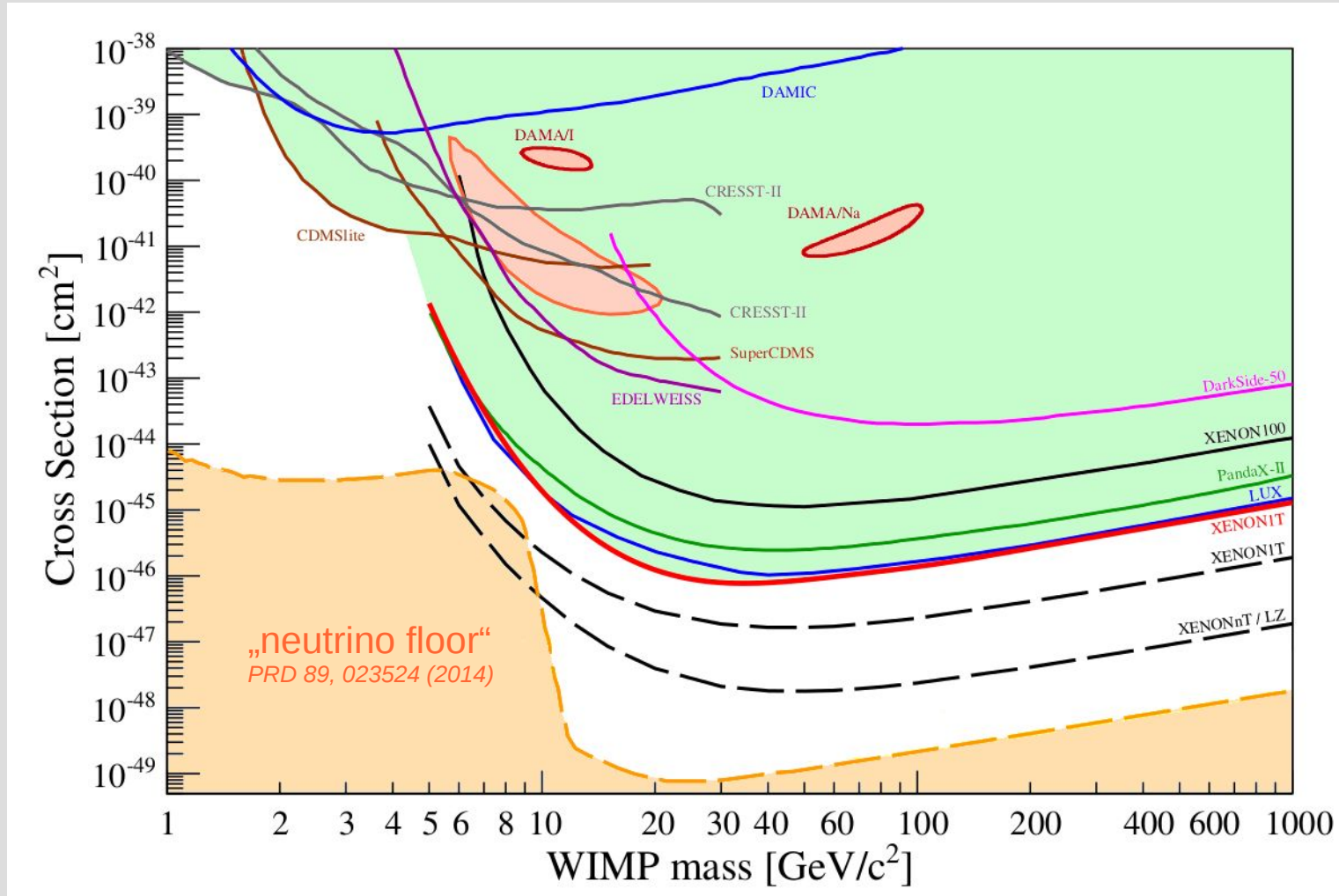


- TPC design
- data acquisition system
- material selection



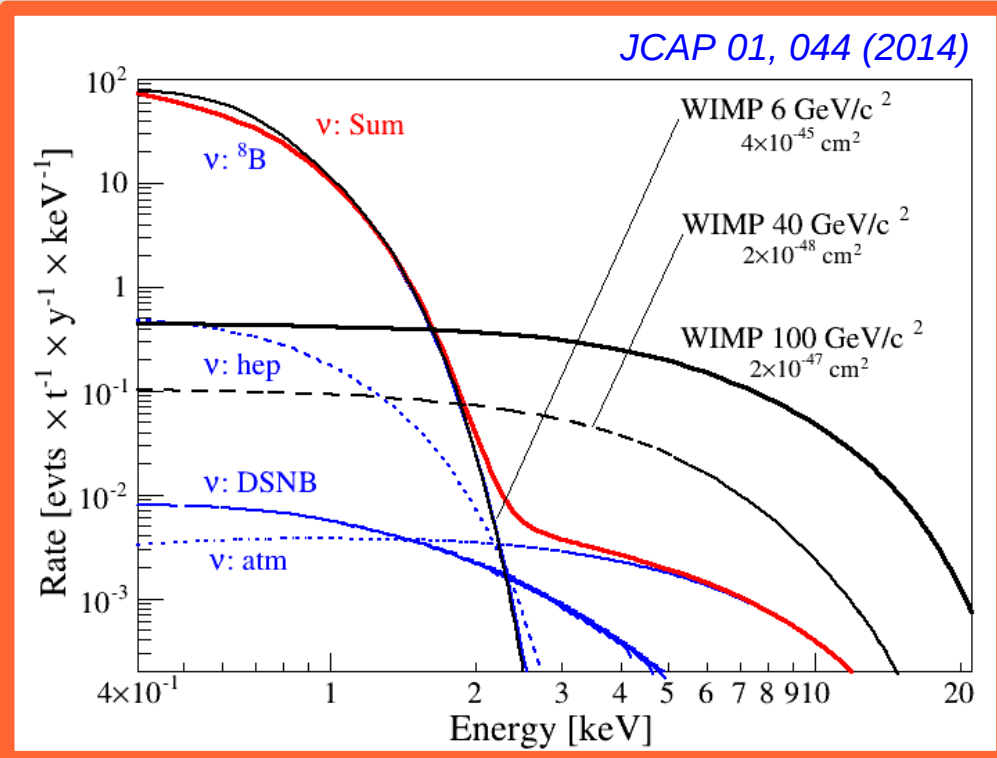
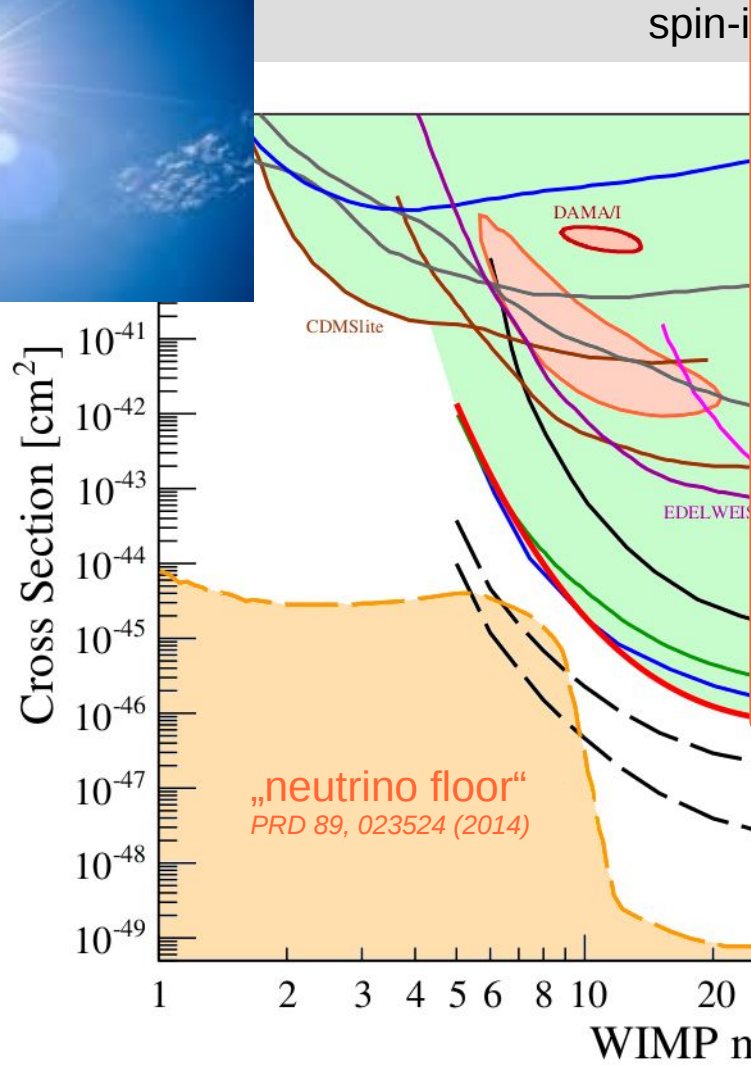
Dark Matter Searches: The Limit

spin-independent WIMP-nucleon interactions

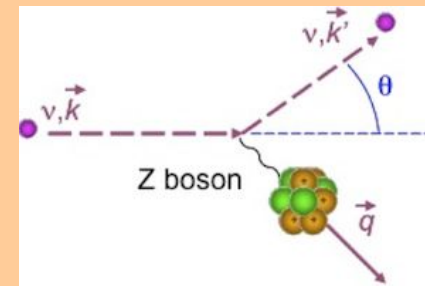


some projects are missing...

Dark Matter Searches: The Limit



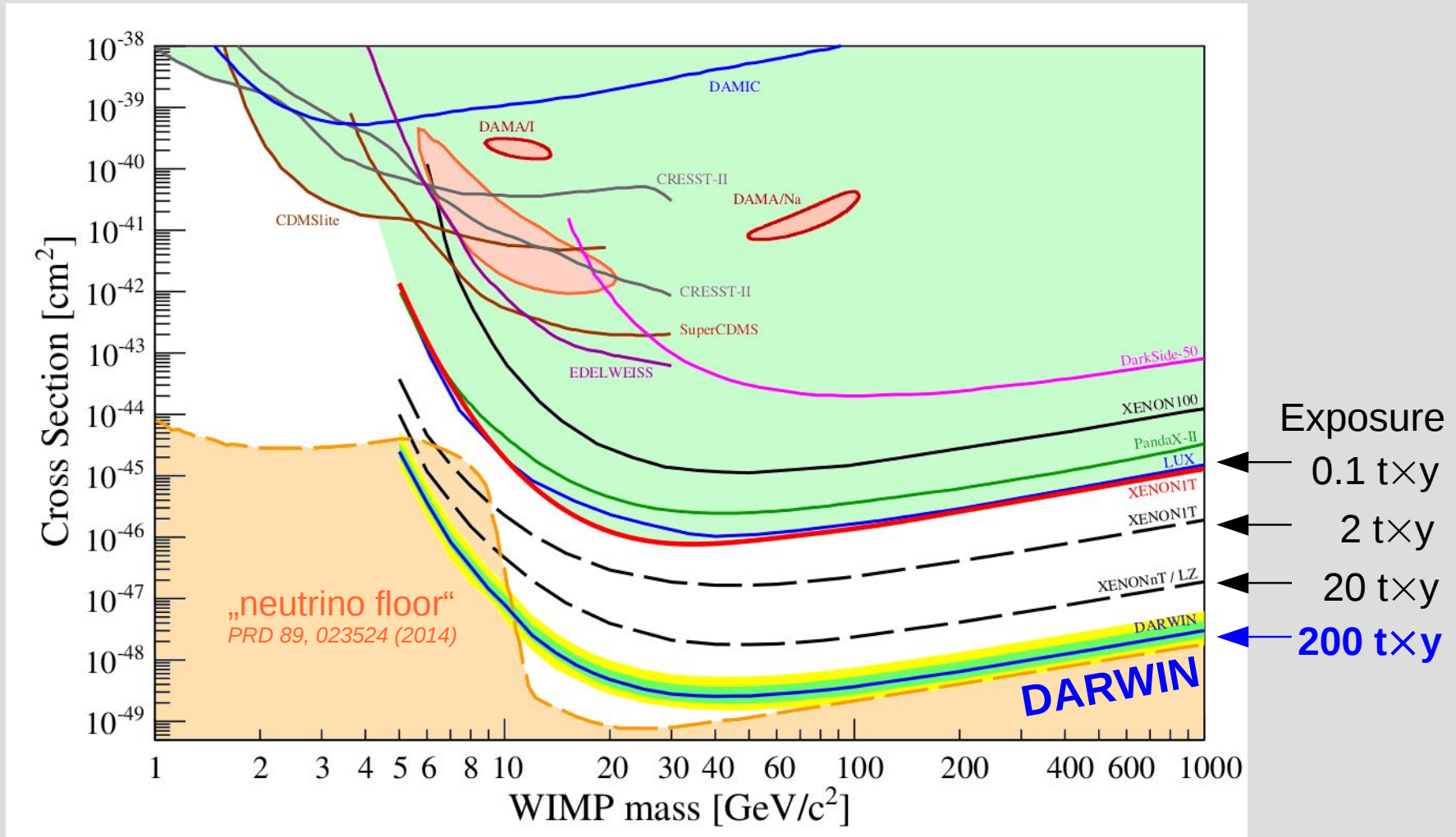
Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
 → **ultimate background** for direct detection



DARWIN The ultimate WIMP Detector



spin-independent WIMP-nucleon interactions



some projects are missing...

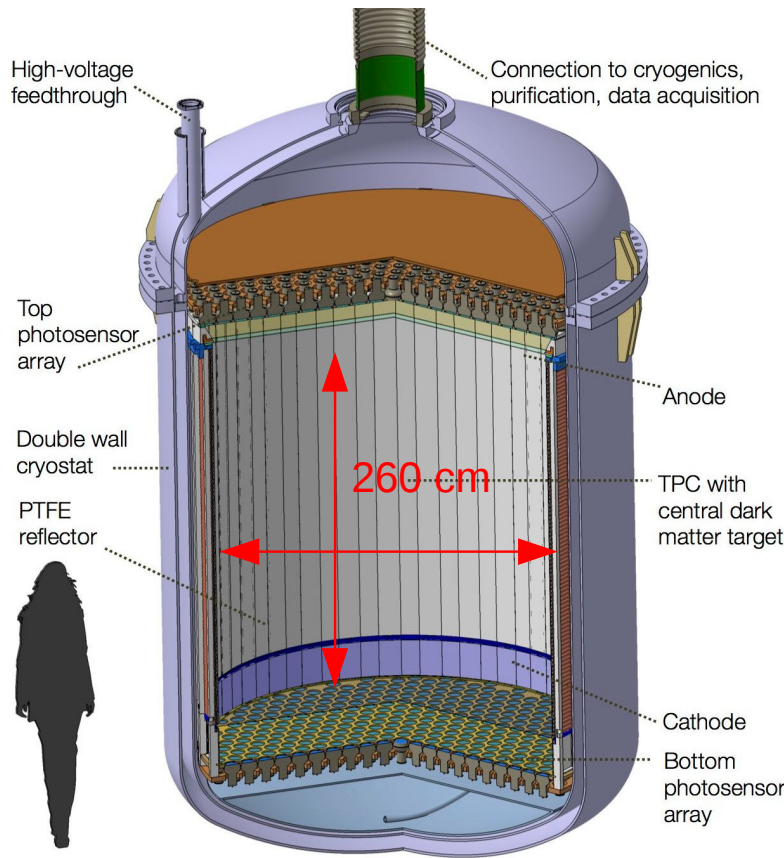
DARWIN The ultimate WIMP Detector

JCAP 11, 017 (2016)

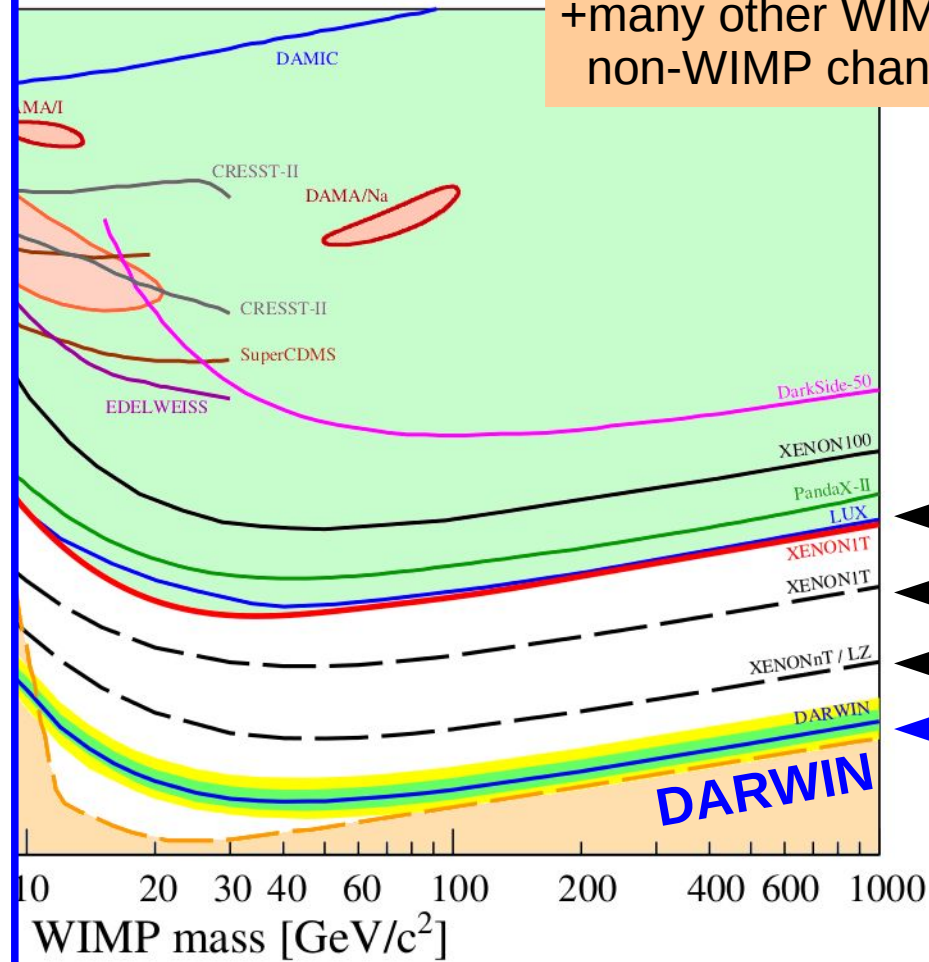


spin-independent WIMP-nucleon interactions

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

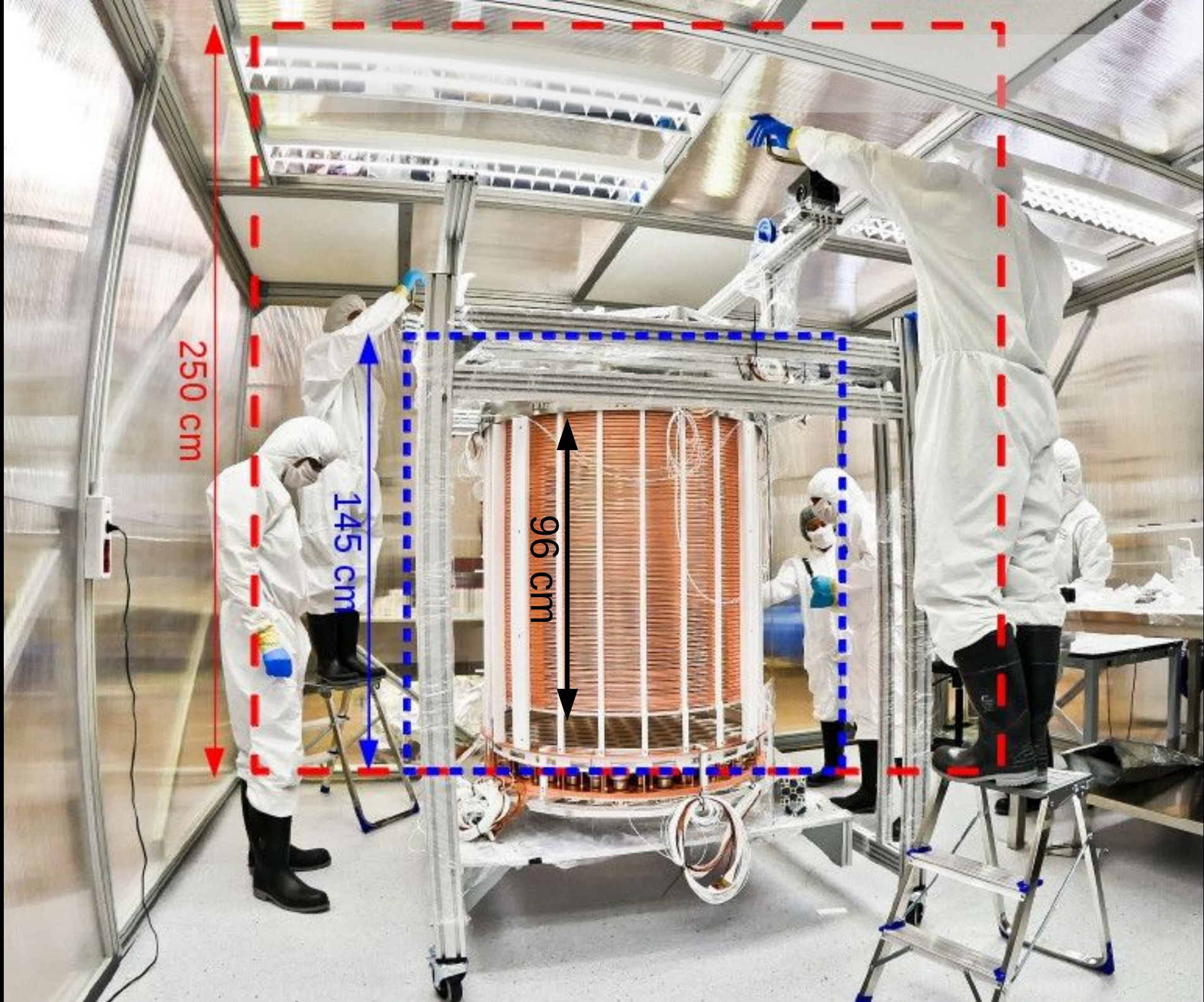


+many other WIMP and non-WIMP channels!



Exposure
 0.1 t×y
 2 t×y
 20 t×y
200 t×y

some projects are missing...



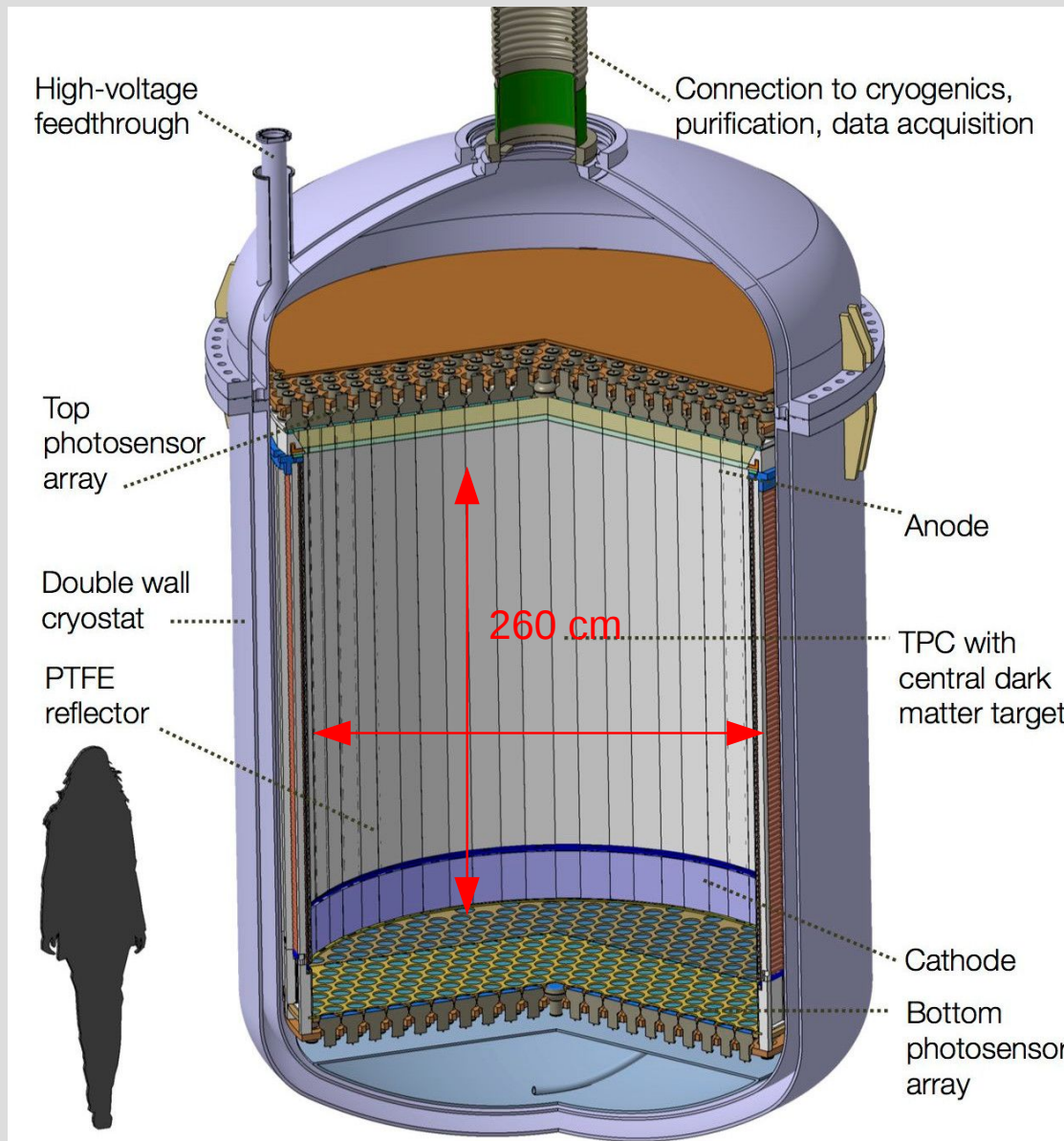
250 cm

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

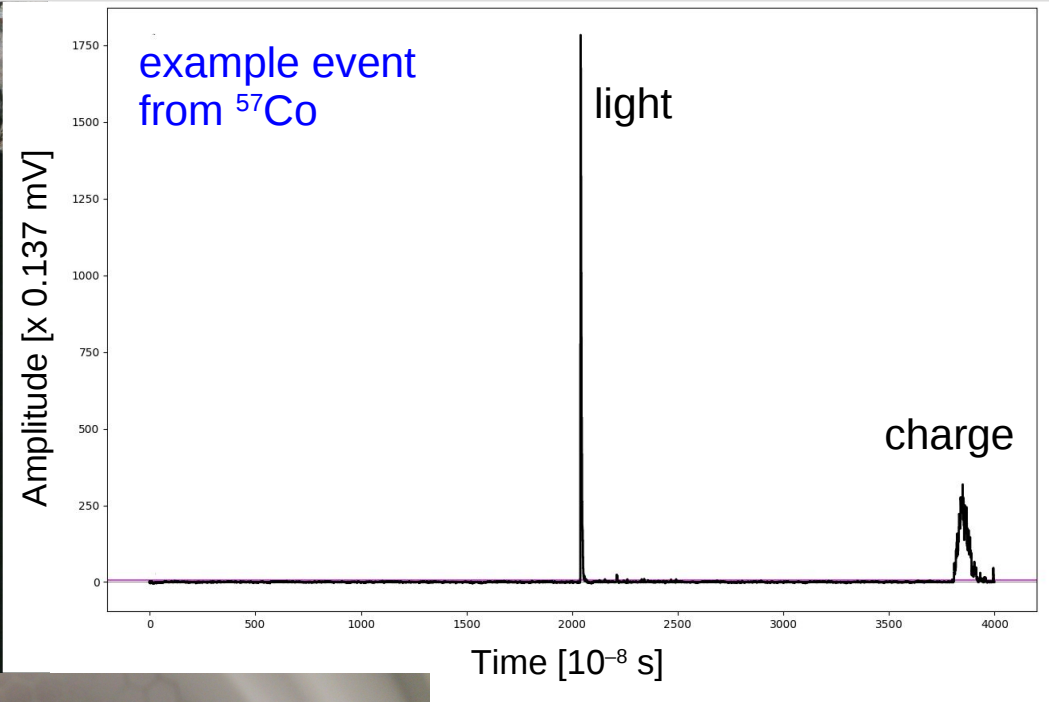
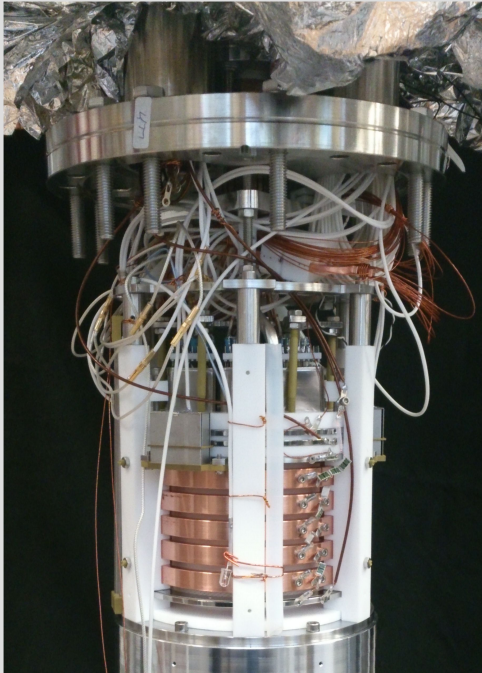
- high light yield (QE)
- low radioactivity
- long-term stability

• etc etc

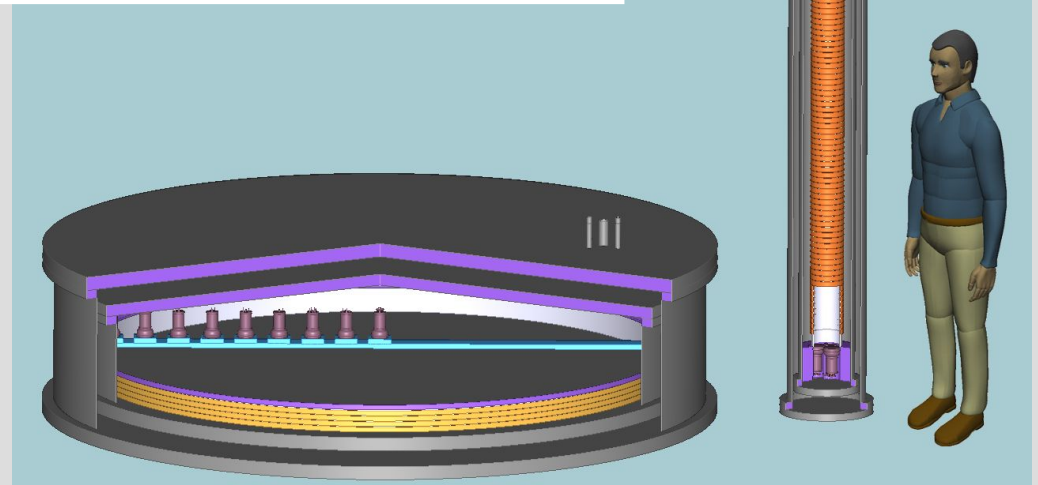
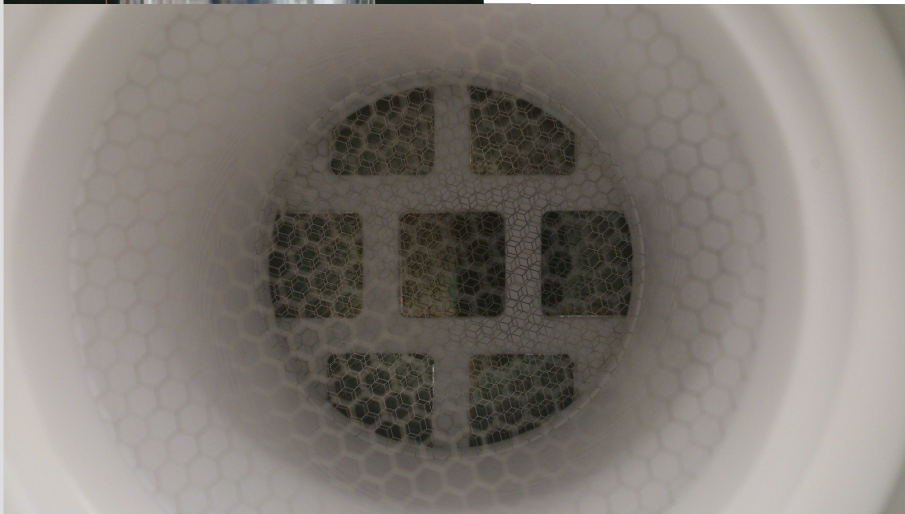
– new ERC project
ULTIMATE
started May 2017



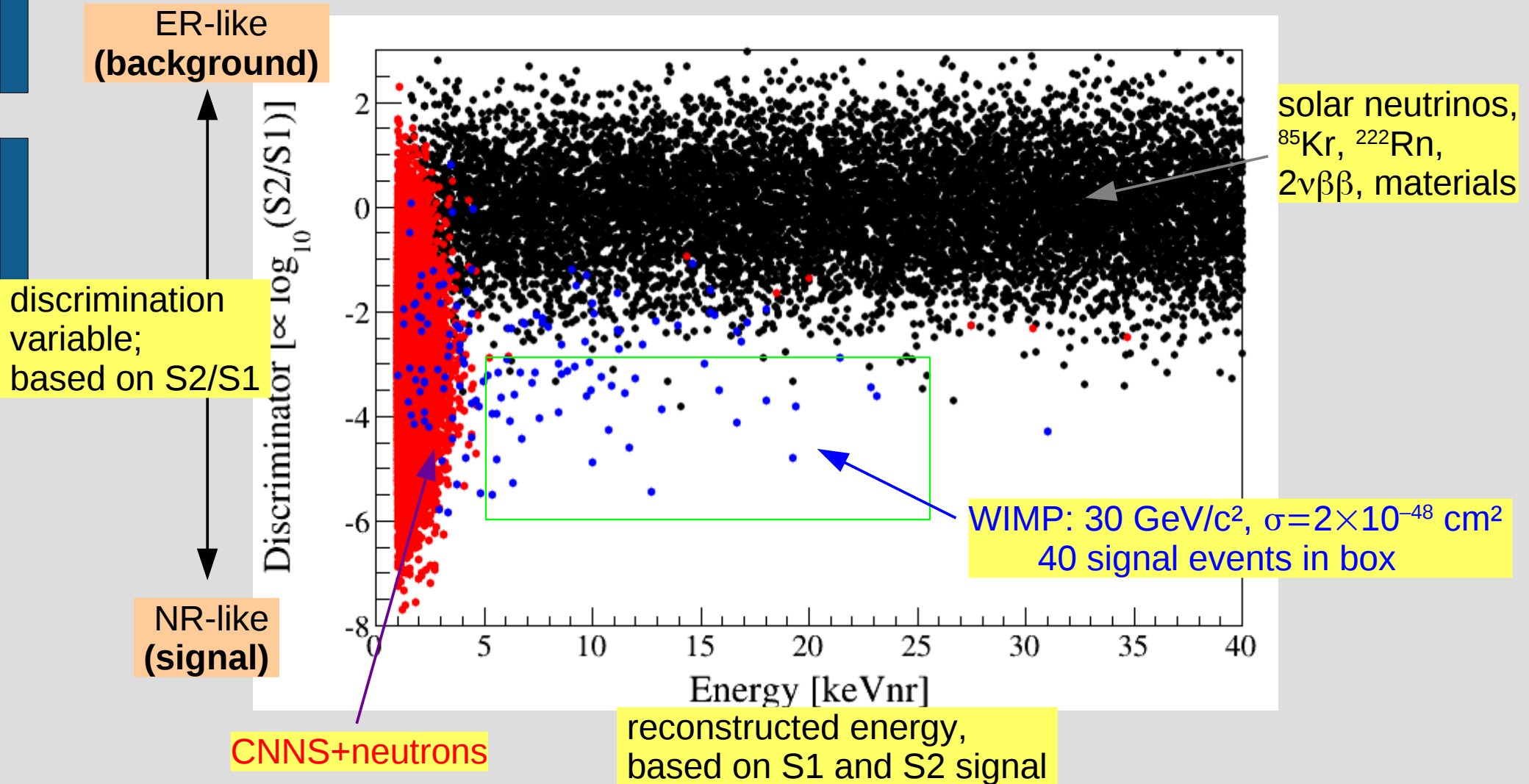
Towards the **ULTIMATE** detector



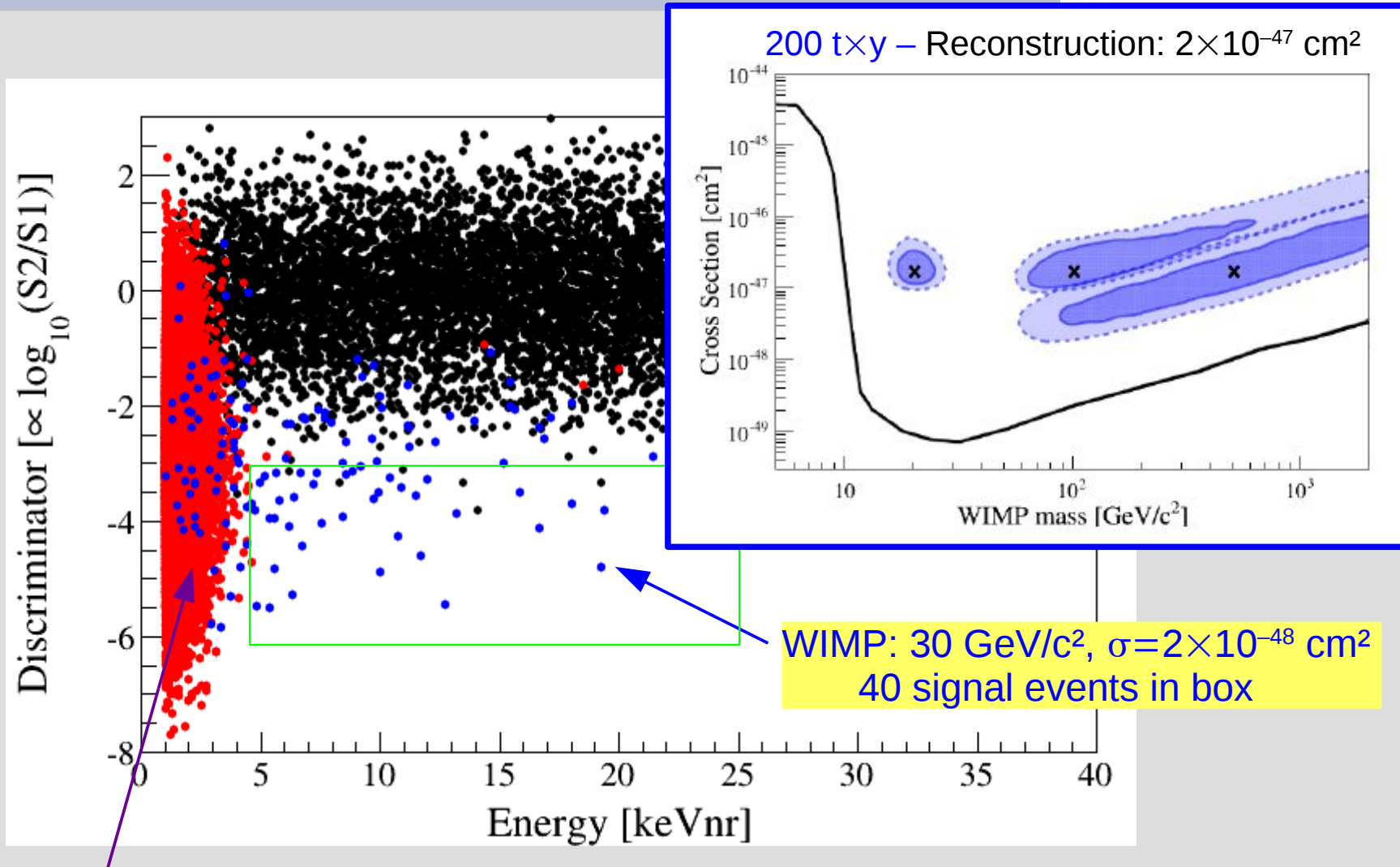
Test platforms for R&D operated in Freiburg



WIMP Detection

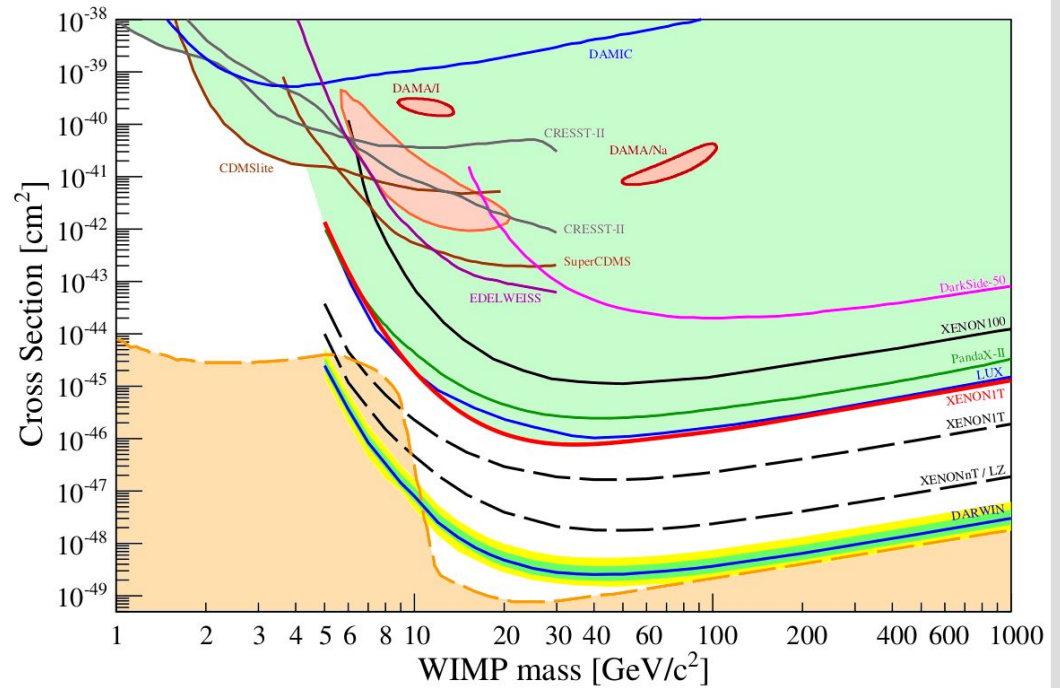
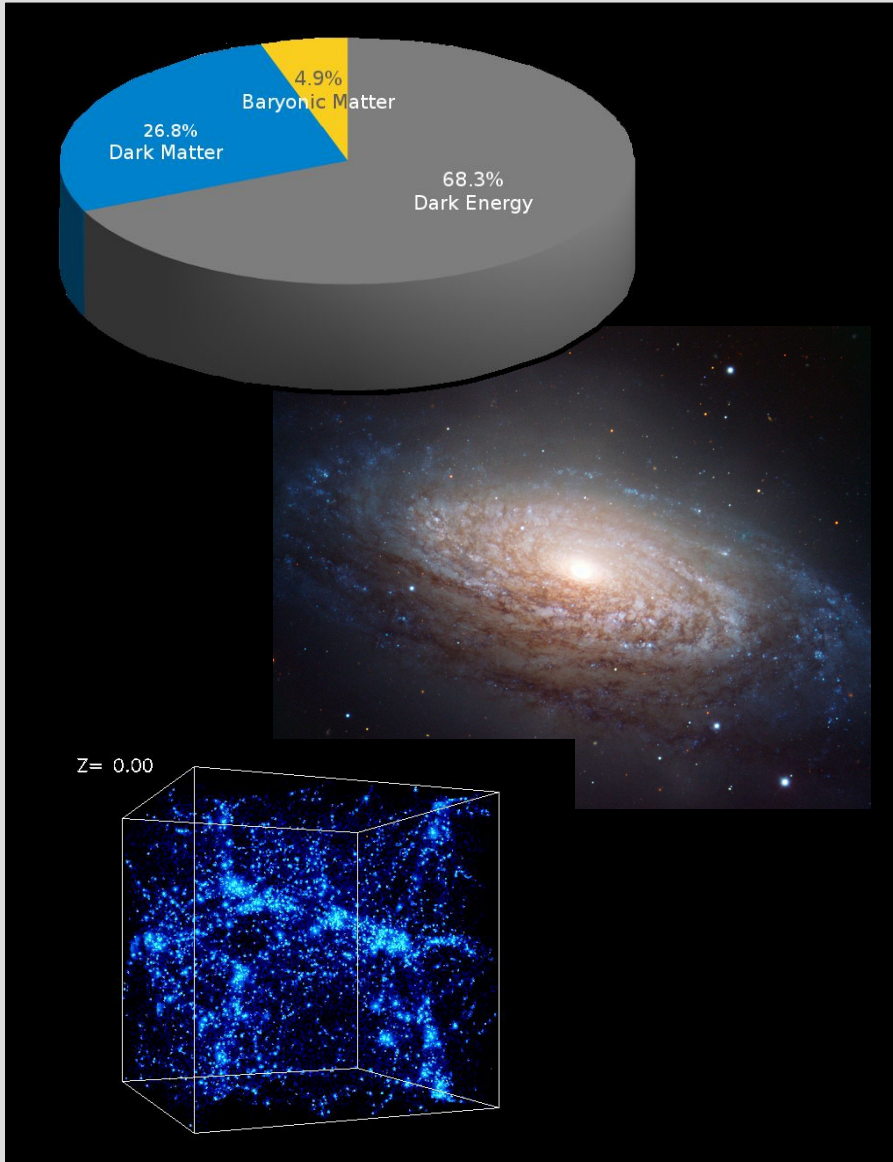


WIMP Spectroscopy



CNNS+neutrons

Exploring the dark with LXe Detectors



www.xenon1t.org



www.darwin-observatory.org