Direct Dark Matter Searches
... in Freiburg

Masse und Symmetrien nach der
GRK 2044
Entdeckung des Higgs-Teilchens am LHC

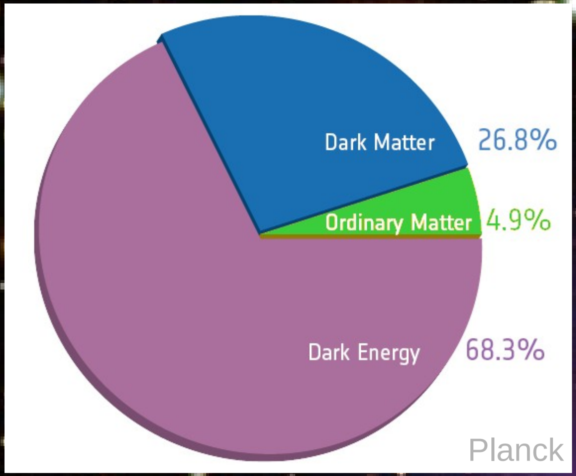
Marc Schumann *Universität Freiburg*

GRK 2044 Seminar, Universität Freiburg, December 7, 2016

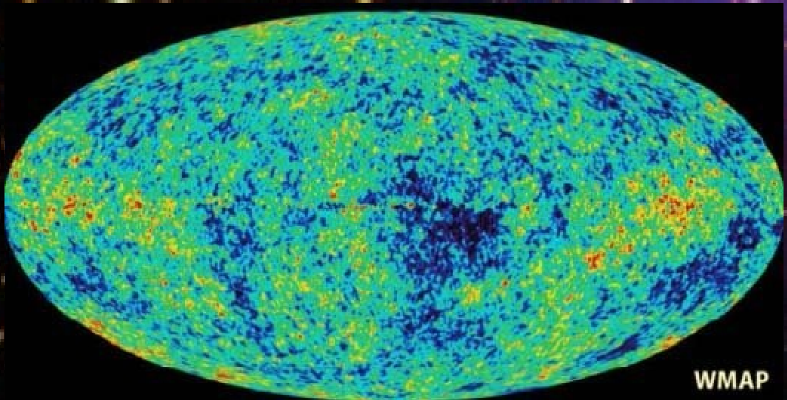
`marc.schumann@physik.uni-freiburg.de`

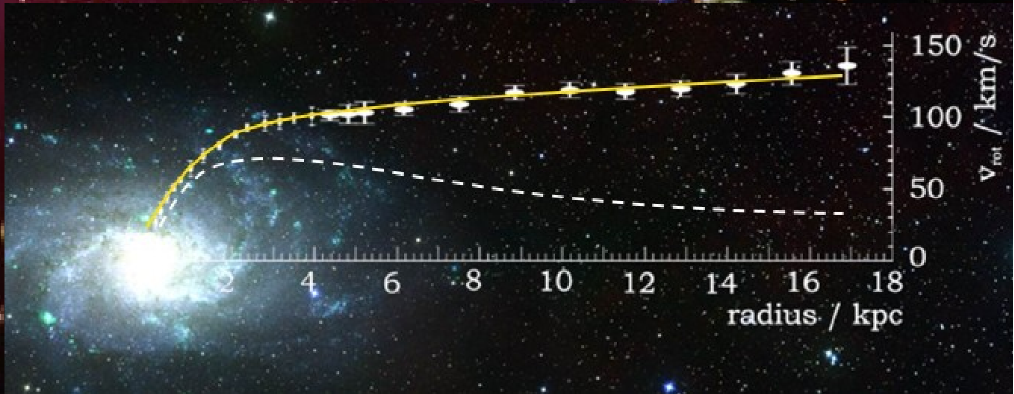
UNI FREIBURG

Dark Matter: (indirect) Evidence



The indirect evidence for the existence of dark matter is a clear indication for physics beyond the Standard Model





THE DM CANDIDATES ZOO

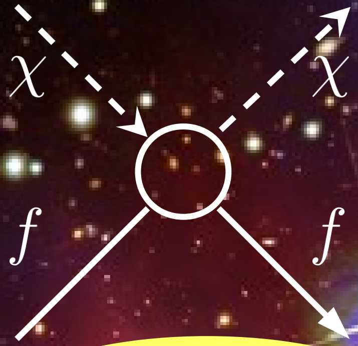
WIMPs

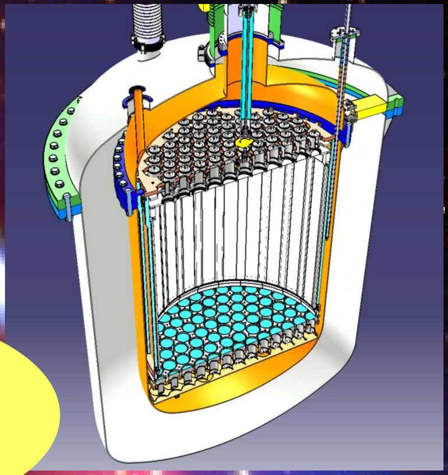
= weakly interacting massive particles

stolen from G. Bertone

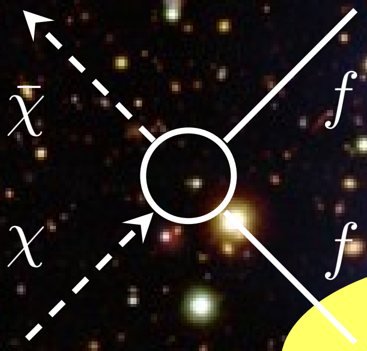
Dark Matter WIMP Search

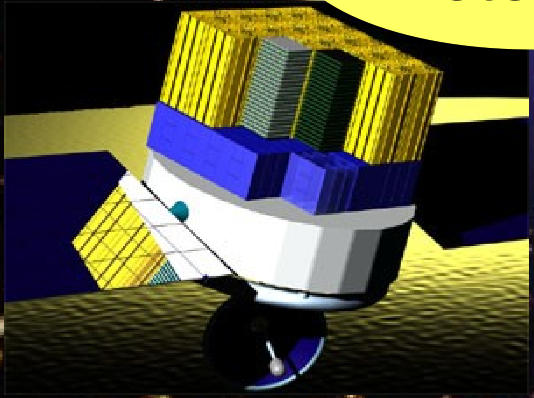
Direct
Detection



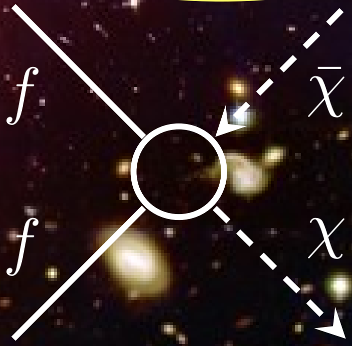


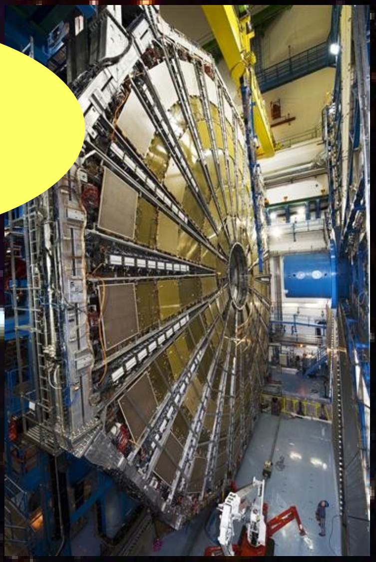
Indirect
Detection



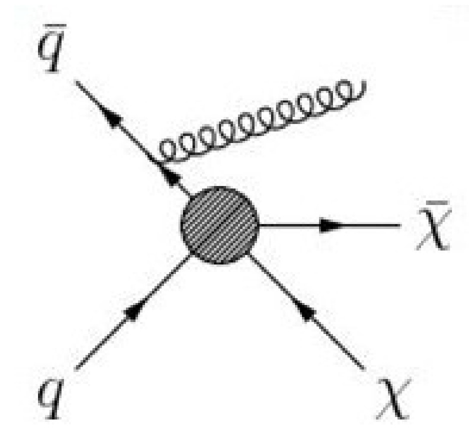


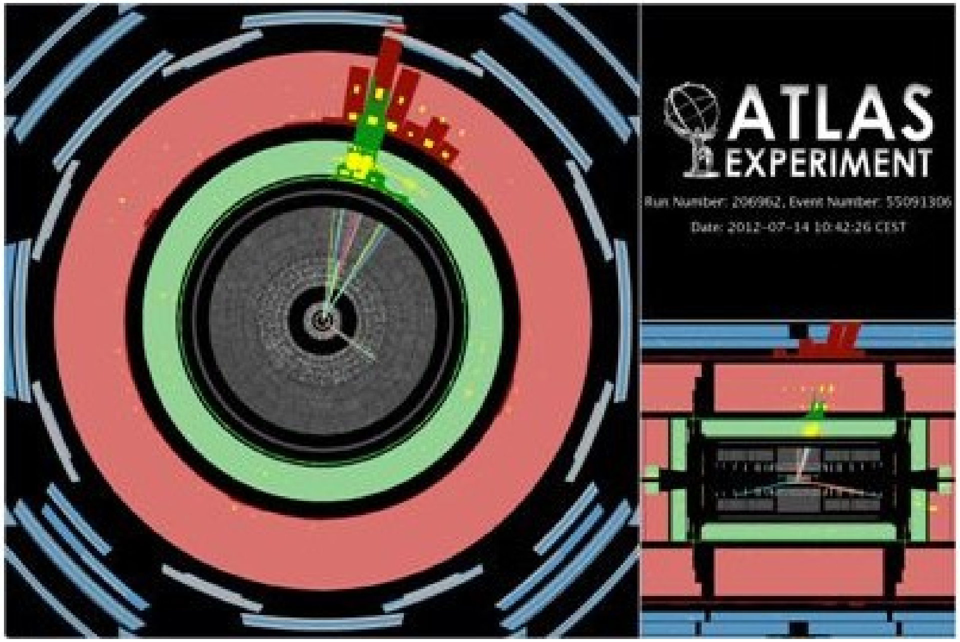
Production
@Collider





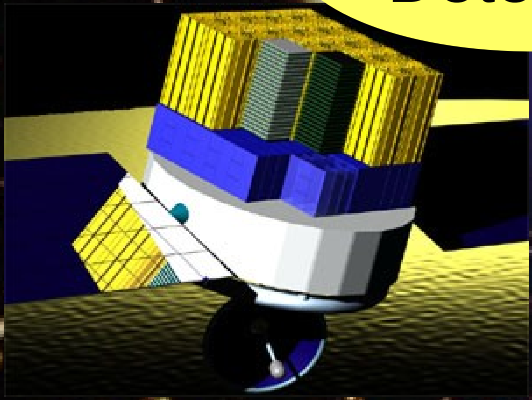
Dark Matter WIMP Search

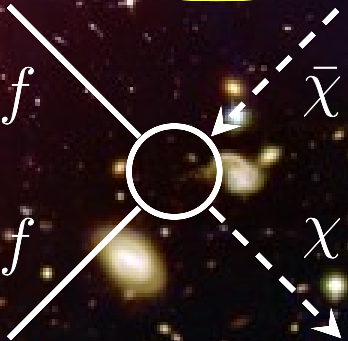


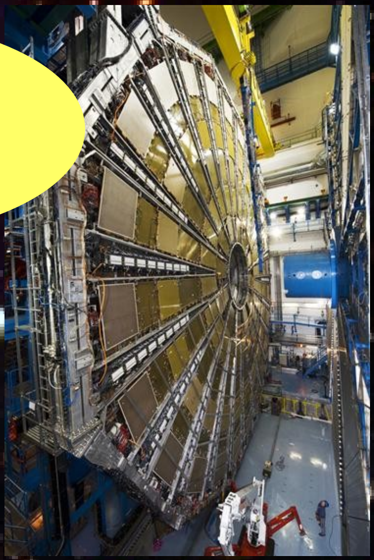


Indirect Detection

Production @Collider



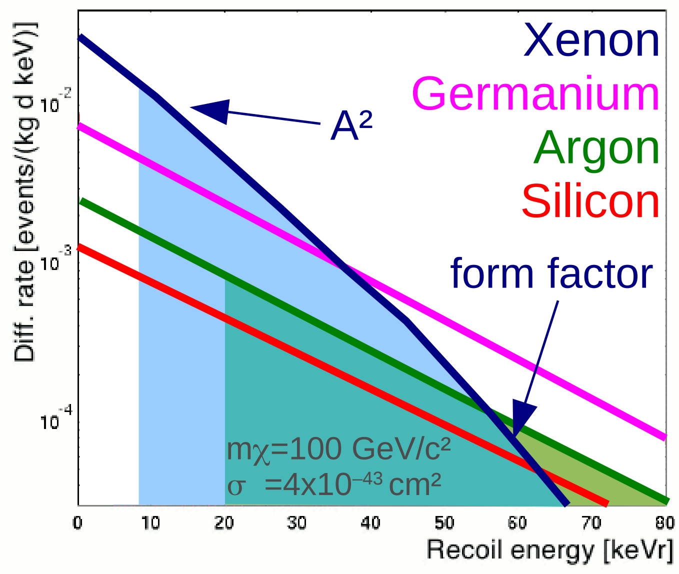




Direct WIMP Search

Direct Detection:

$E_r < 100$ keV
$R < 1$ evt/kg/year



Recoil Energy: $E_r \sim \mathcal{O}(10\ \mathrm{keV})$

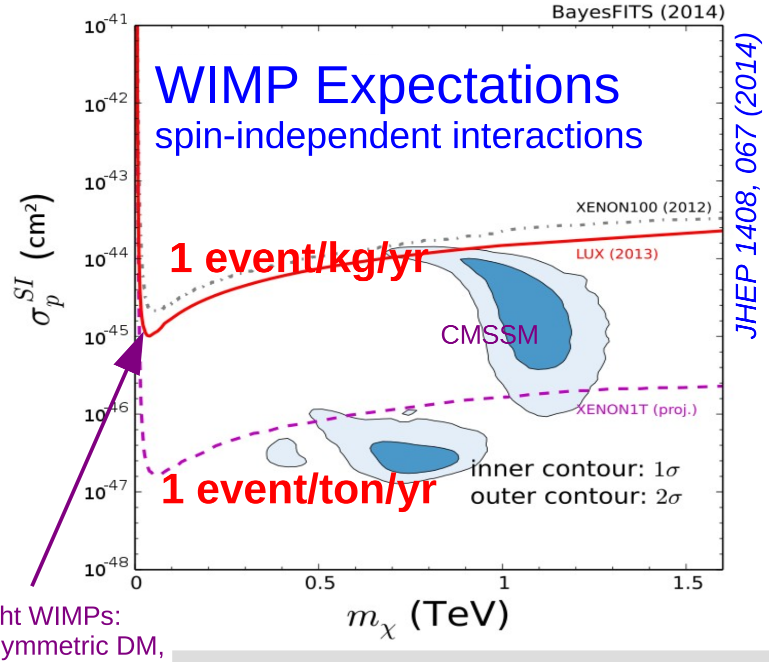
Event Rate: $R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$

Detector

Local DM Density

Physics

$\rho_\chi \sim 0.3$ GeV/c²



light WIMPs:
asymmetric DM,
sneutrinos, ...

Direct WIMP Search

Direct Detection:

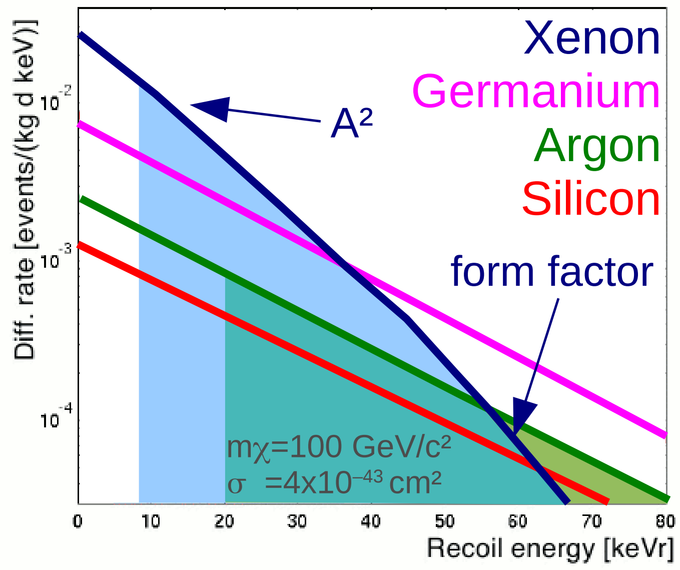
$E_r < 100$ keV
$R < 1$ evt/kg/year

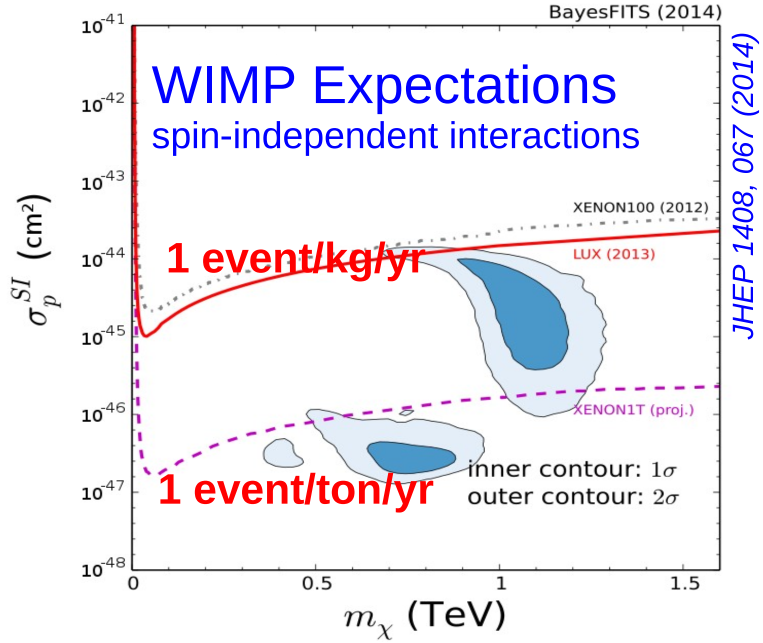
How to build a WIMP detector?

- large total mass, high A ✓
- low energy threshold ✓
- ultra low background ✓
- good signal / background discrimination ✓

for liquid xenon TPCs

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



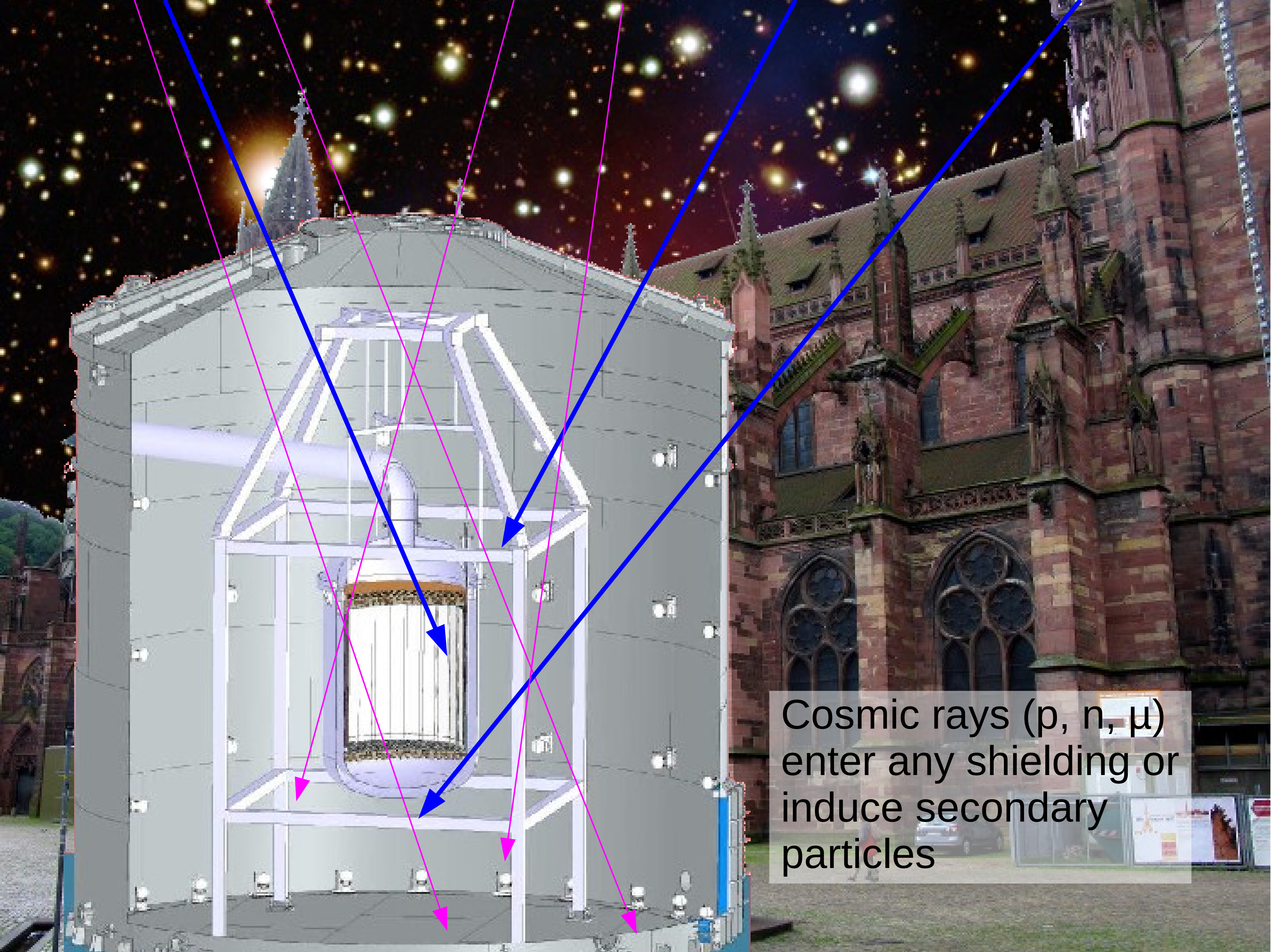


WIMP Expectations
spin-independent interactions

1 event/kg/yr

1 event/ton/yr

JHEP 1408, 067 (2014)

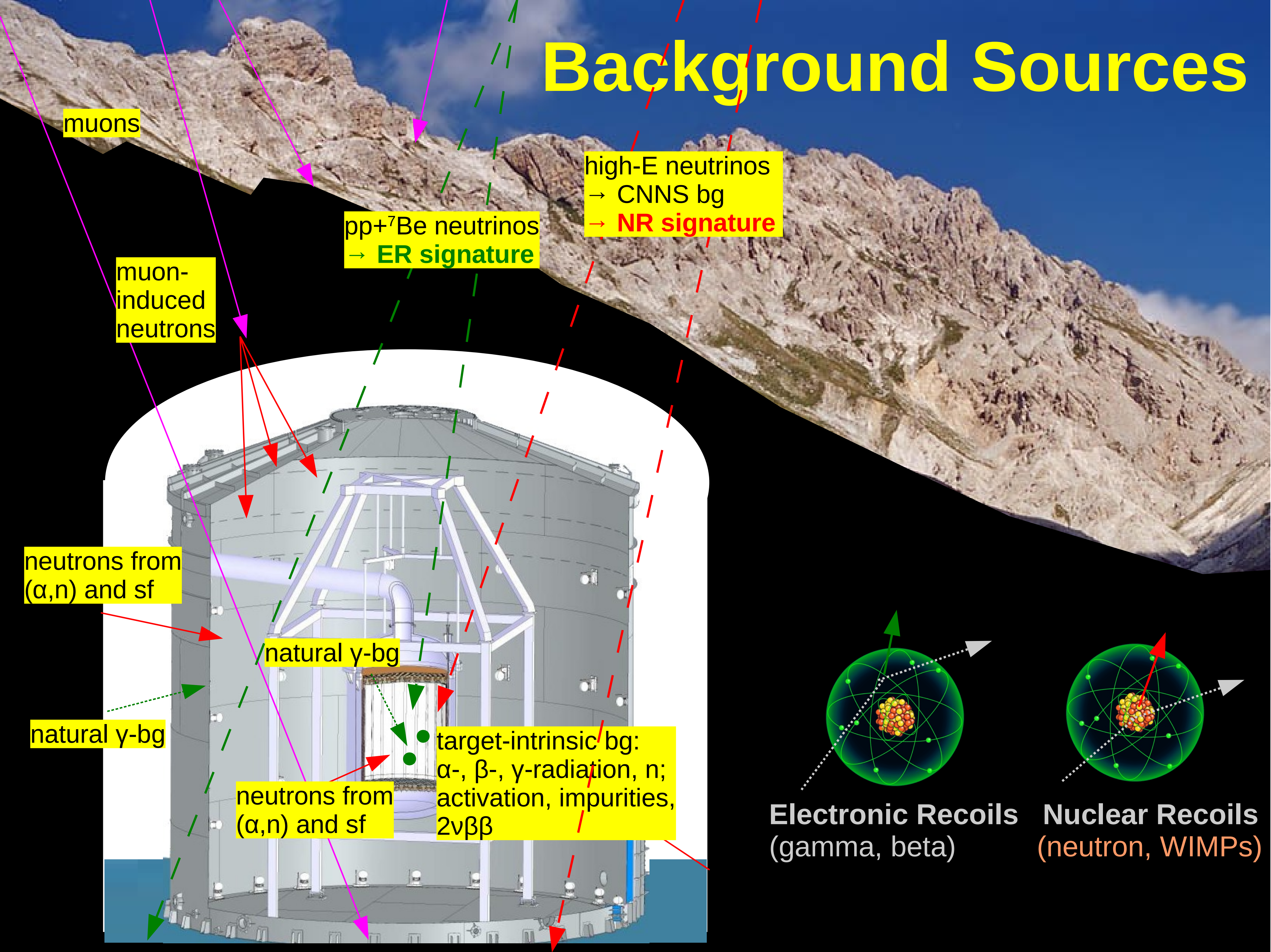


Cosmic rays (p, n, μ) enter any shielding or induce secondary particles

Laboratori Nazionali del Gran Sasso

LNGS: 1.4km rock
(3700 mwe)

Background Sources



muons

muon-induced neutrons

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

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

neutrons from (α,n) and sf

natural γ-bg

natural γ-bg

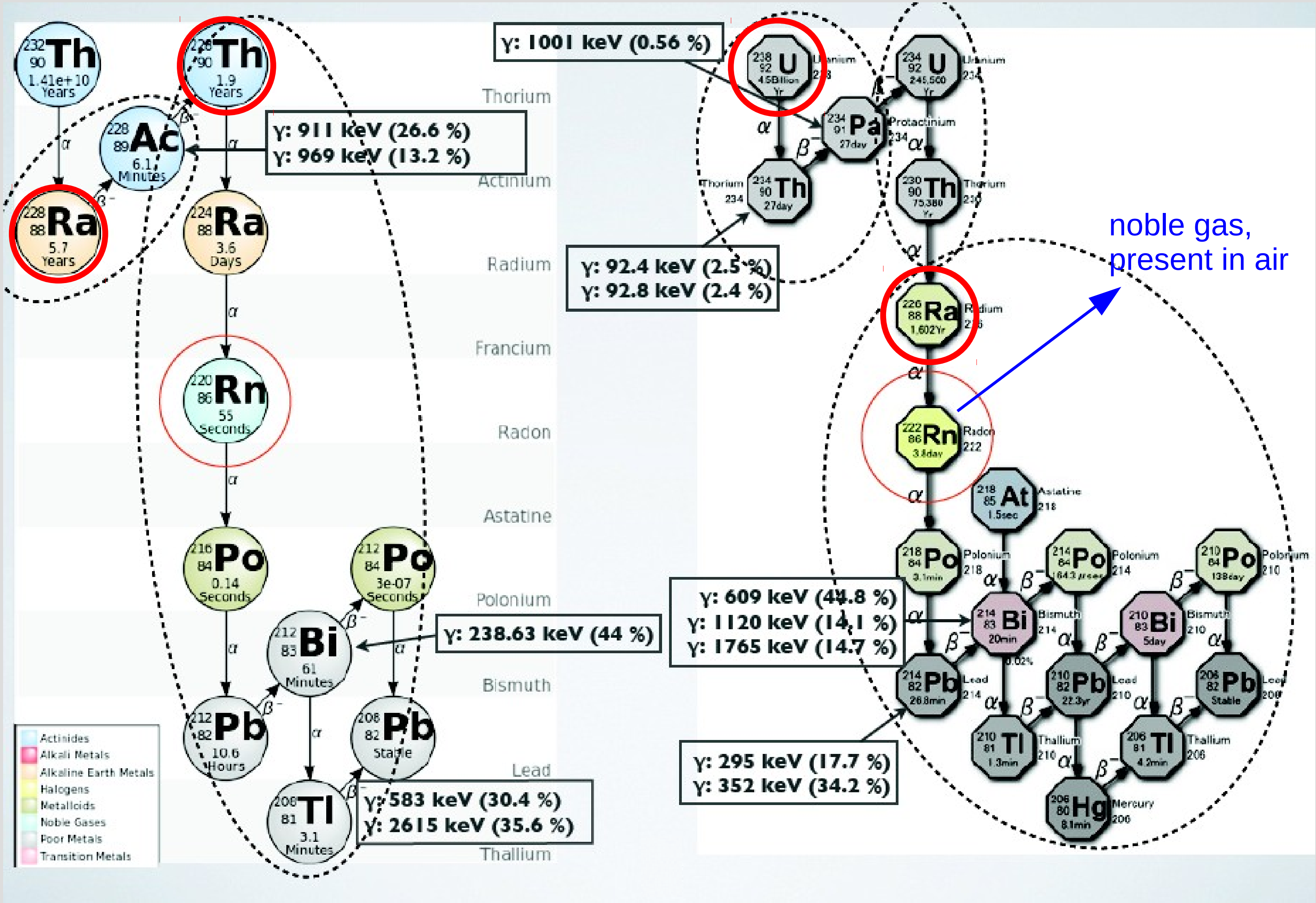
neutrons from (α,n) and sf

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

Electronic Recoils
(gamma, beta)

Nuclear Recoils
(neutron, WIMPs)

The U and Th Chains



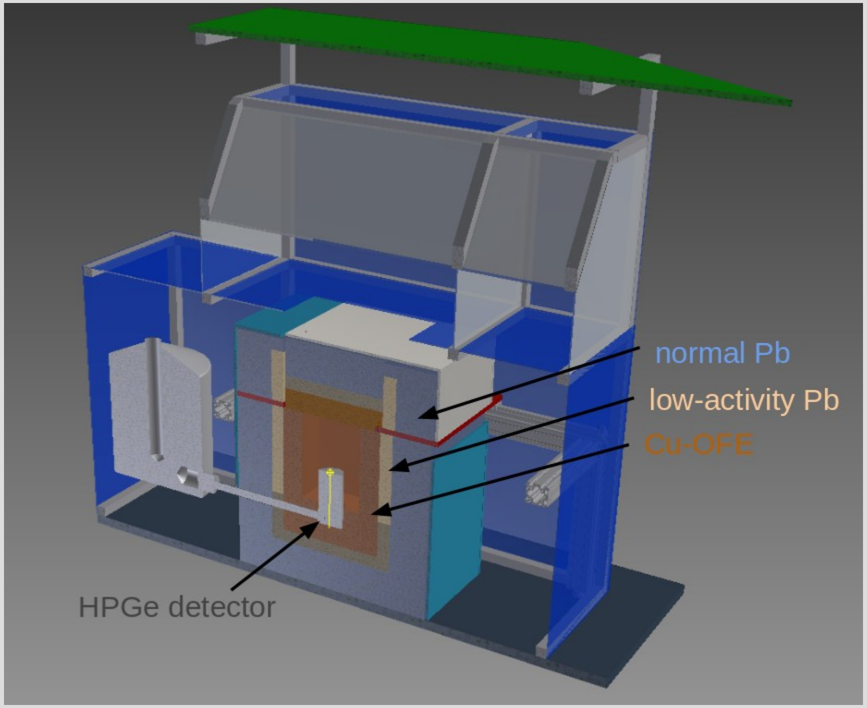
noble gas,
present in air

Low-background Screening

arXiv:1606.03983

GeMSE

Germanium
Material and
Meteorite
Screening
Experiment



Low-background Screening

arXiv:1606.03983

GeMSE
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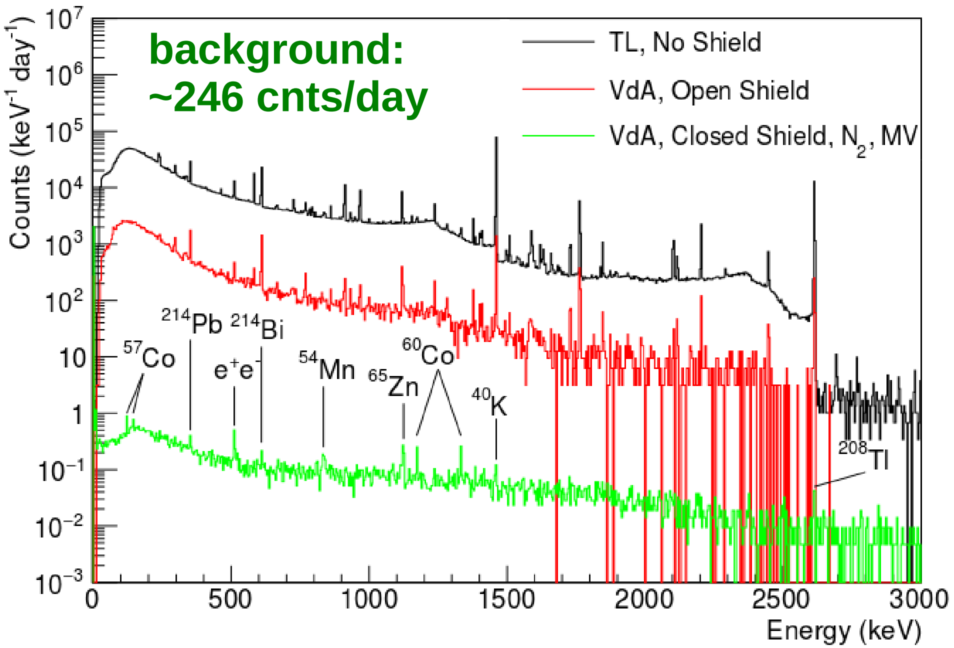
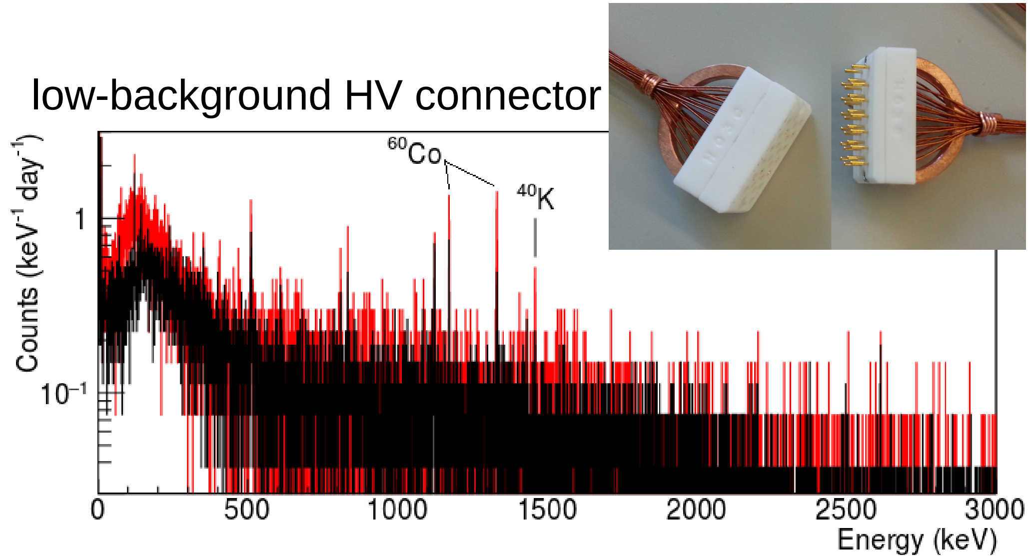
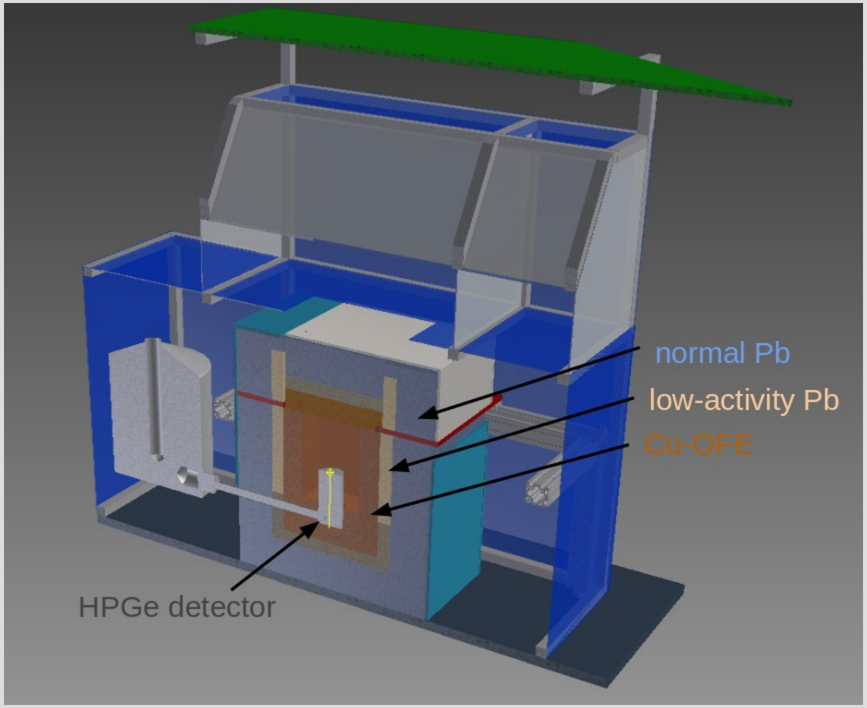

background:
~246 cnts/day


low-background HV connector



Background Suppression

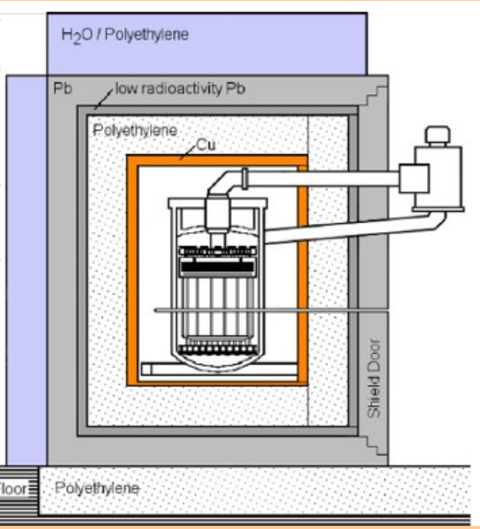
A Avoid Backgrounds

Use of radiopure materials

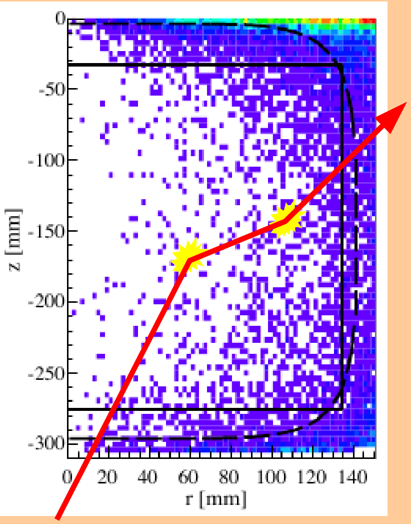
Shielding

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

self shielding → fiducialization



Astropart. Phys. 35, 573 (2012)



B Use knowledge about expected WIMP signal

WIMPs interact only once

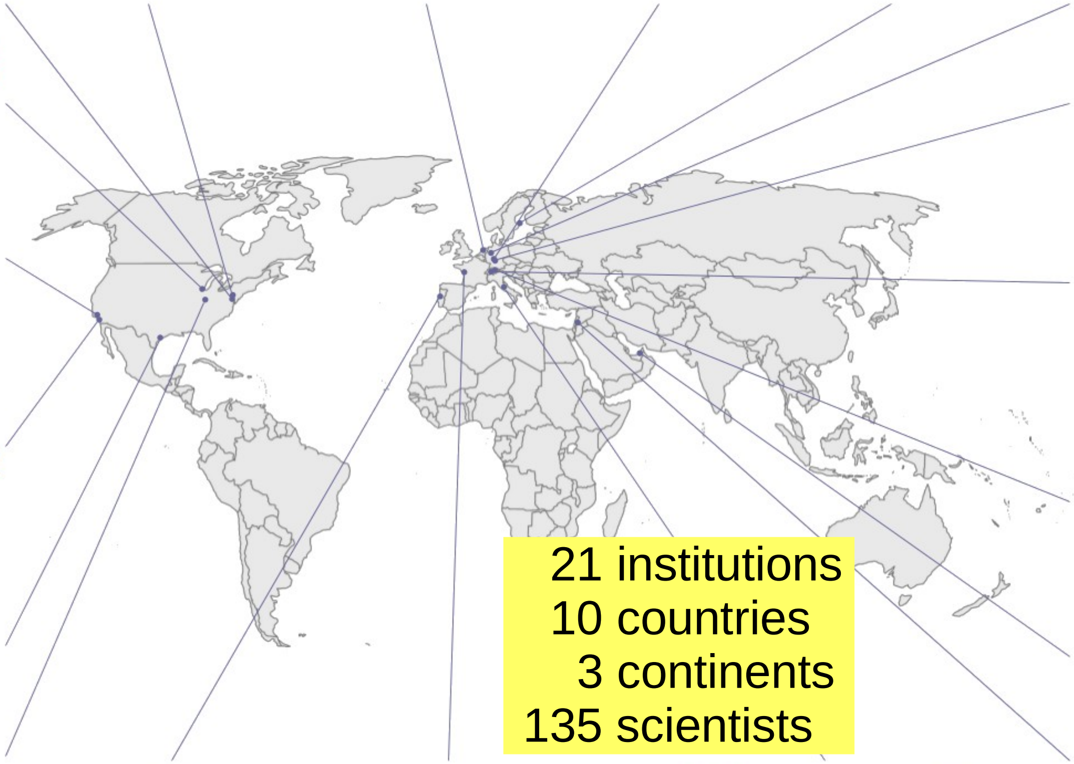
→ single scatter selection
require some position resolution

WIMPs interact with target nuclei

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

The XENON Collaboration

www.xenon1t.org



Columbia

RPI

Nikhef

Mainz

Stockholm

Muenster

Chicago

MPIK

UCLA

Freiburg

UCSD

Zurich

Rice

NYUAD

Purdue

Coimbra

Subatech

Bologna

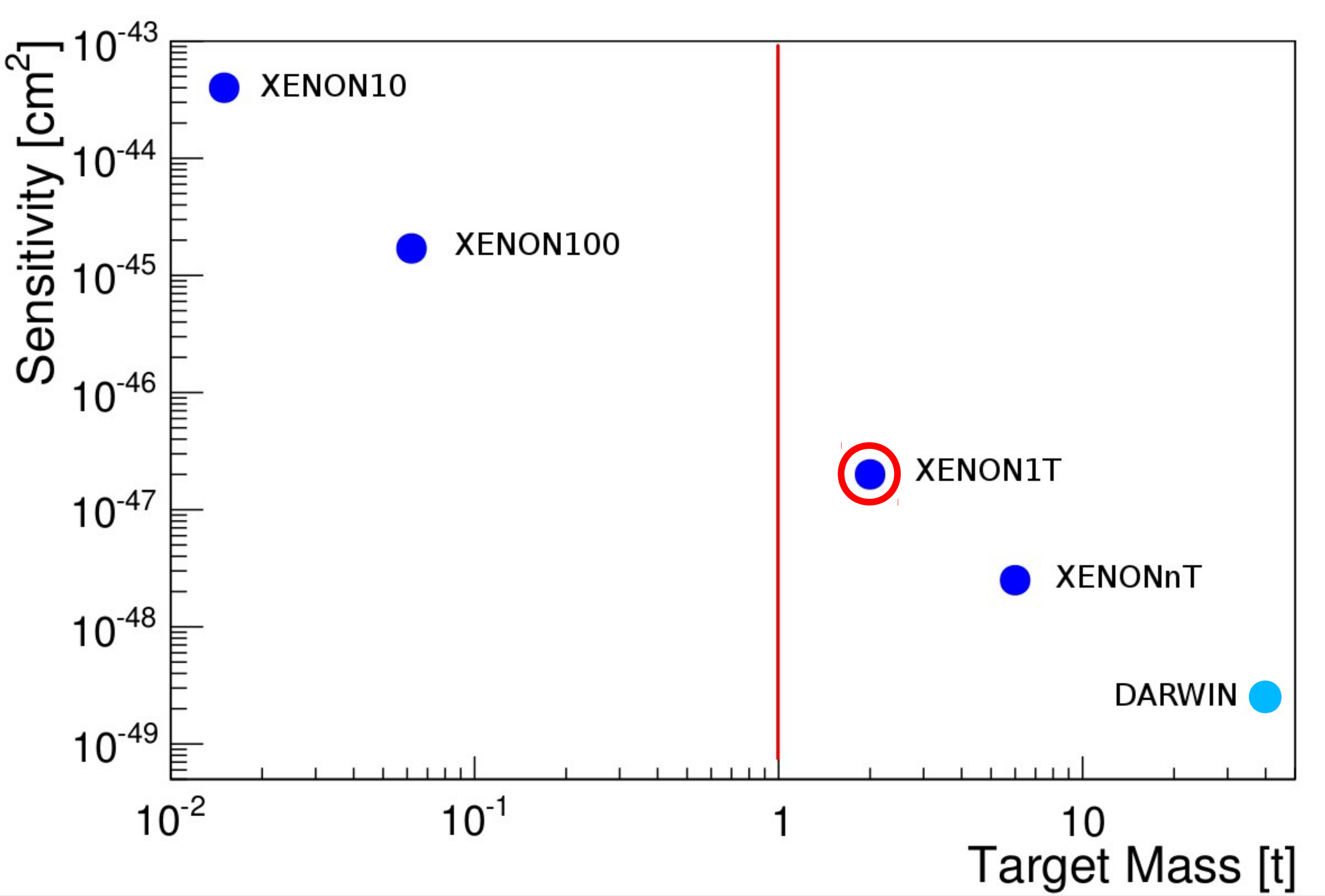
LNGS

Torino

Weizmann

21 institutions
10 countries
3 continents
135 scientists

XENON Instruments

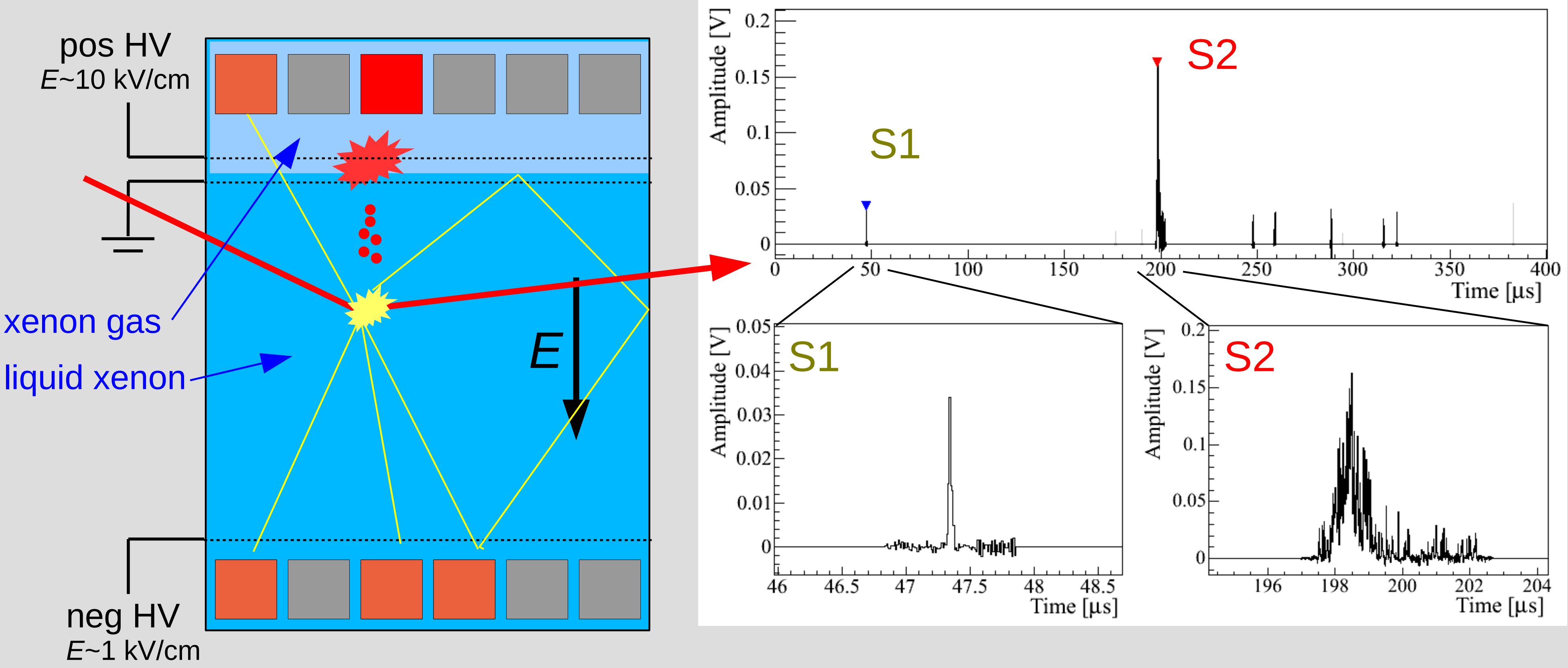


The XENON collaboration develops and operates
dark matter detectors of increasing size and sensitivity

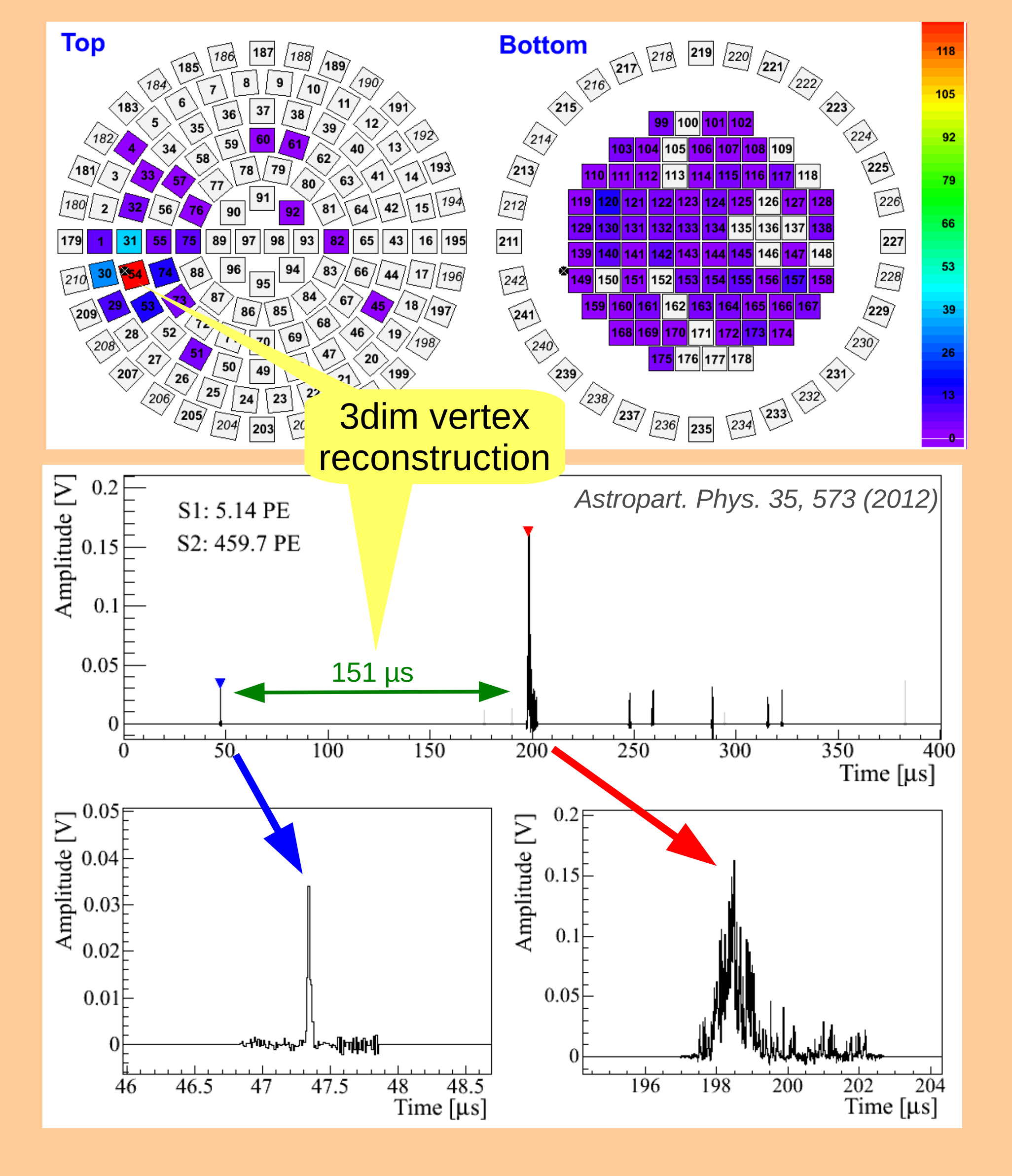
Dual Phase TPC

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

TPC = time projection chamber

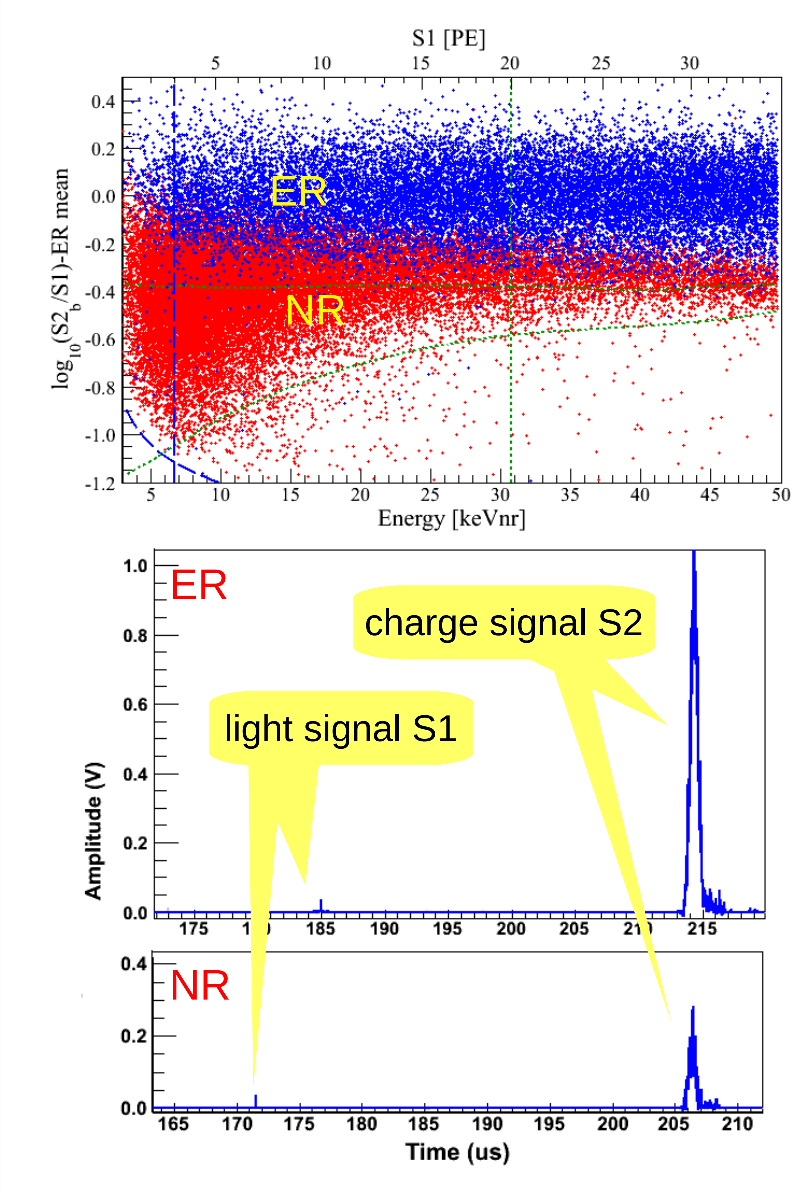


Dual Phase TPC



3dim vertex reconstruction

Astropart. Phys. 35, 573 (2012)



charge signal S2

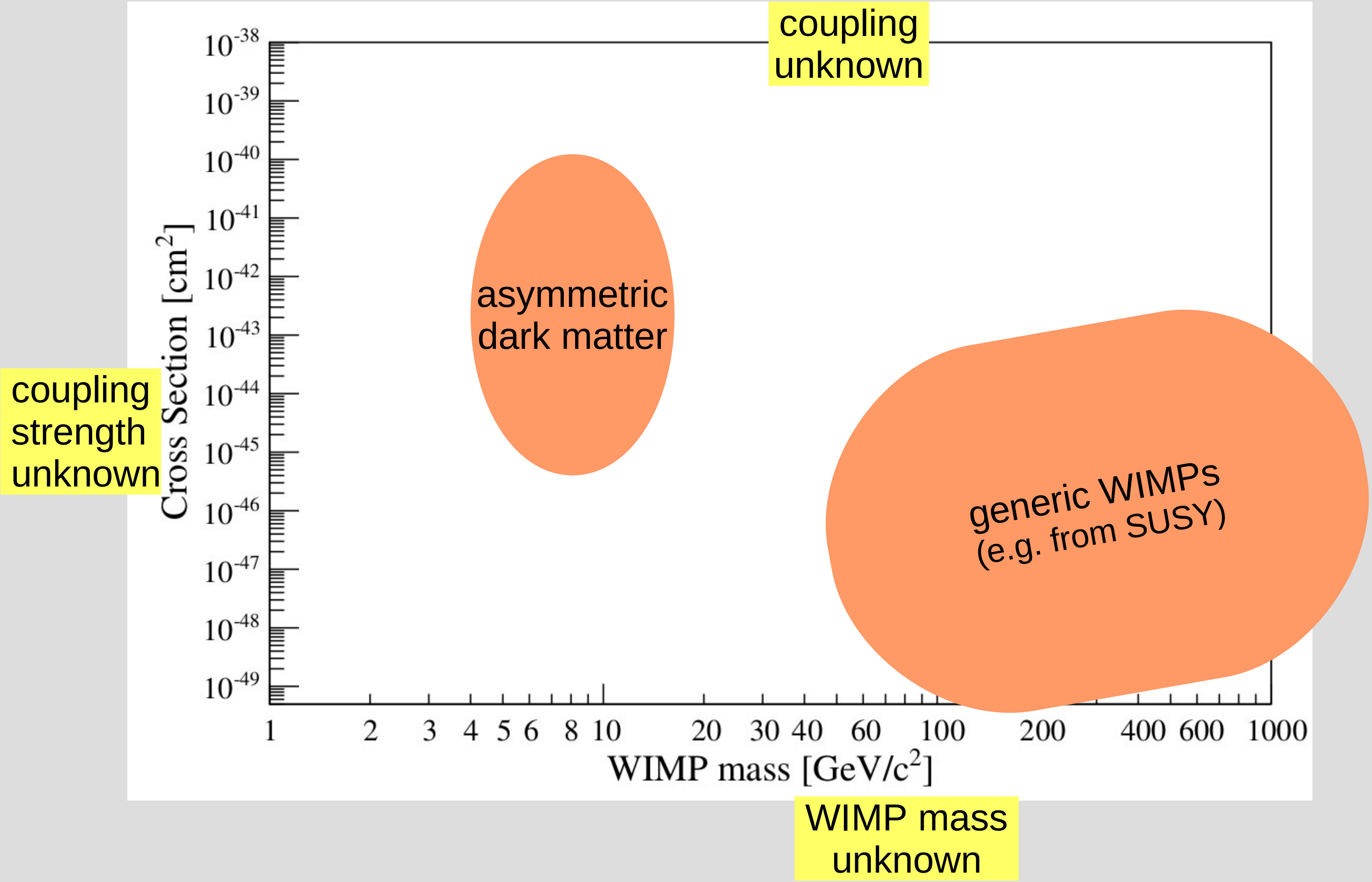
light signal S1

Figures: XENON100

M. Schumann (Freiburg) – Direct Dark Matter Detection

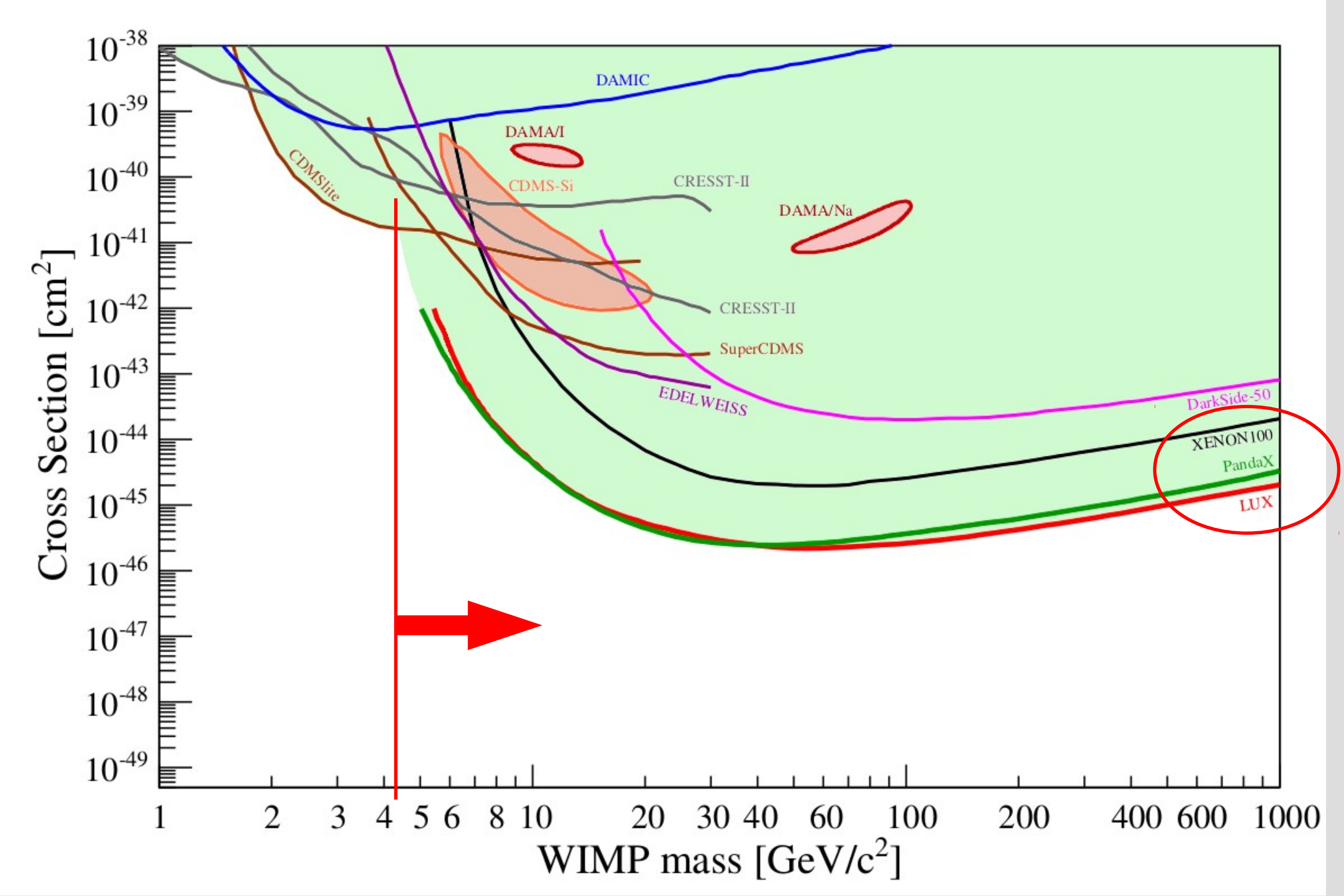
The WIMP Parameter Space

spin-independent WIMP-nucleon interactions



State-of-the-Art

spin-independent WIMP-nucleon interactions



some results are missing...

XENON1T @ LNGS

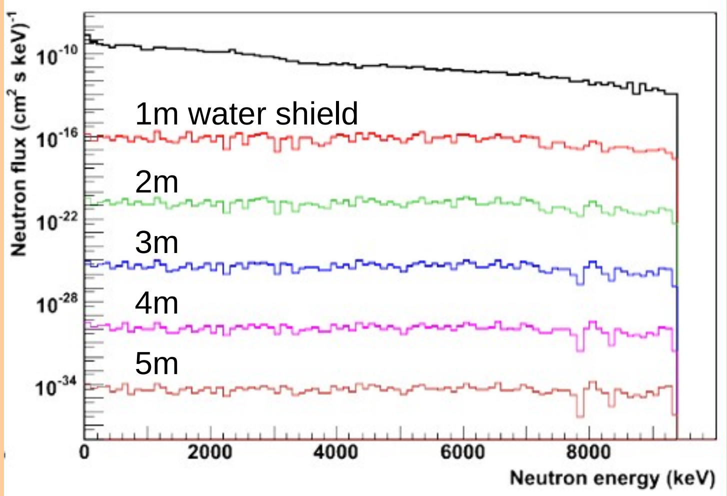
XENON1T @ LNGS

Water Cerenkov Shield

JINST 9, P11006 (2014)

- 9.6m diameter, 10m height
- external γ, neutrons irrelevant
- muon induced NRs irrelevant

→ dominating background of XENON1T will be intrinsic



Xe
XENON
Dark Matter Project

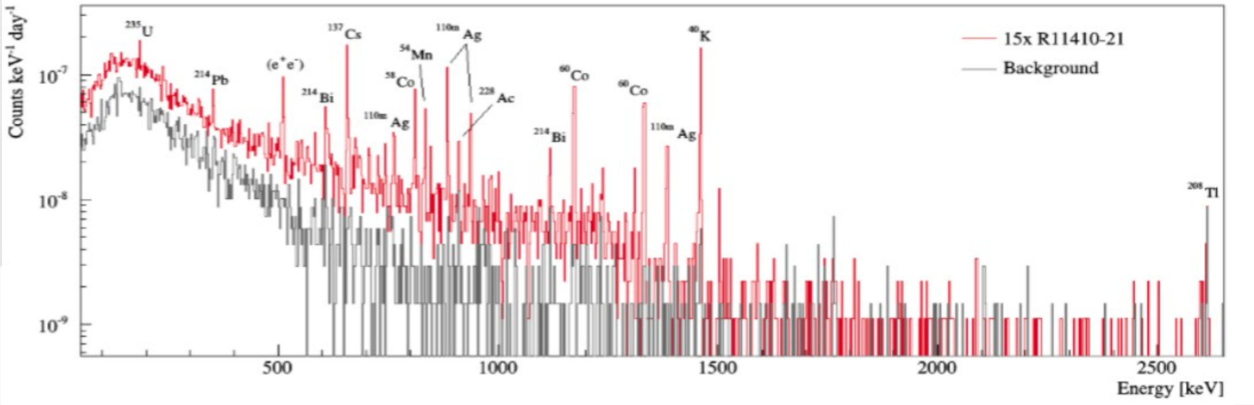
PMTs: Hamamatsu R11410-21

JINST 8, P04026 (2013)
EPJ C 75, 546 (2015)

top array: 121

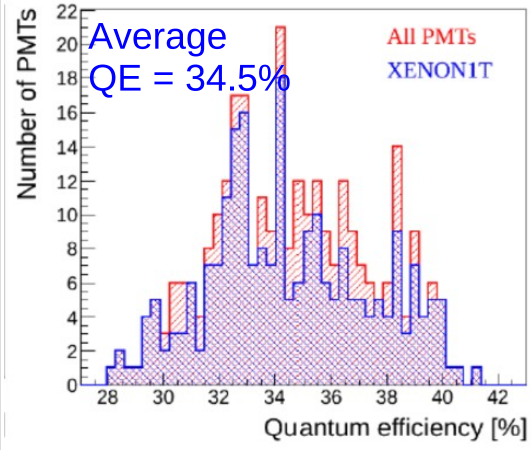
bottom array: 127

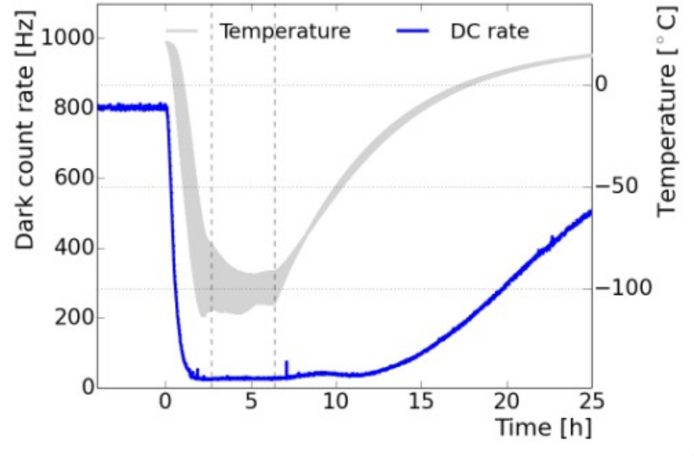
Low-background PMT developed with Hamamatsu



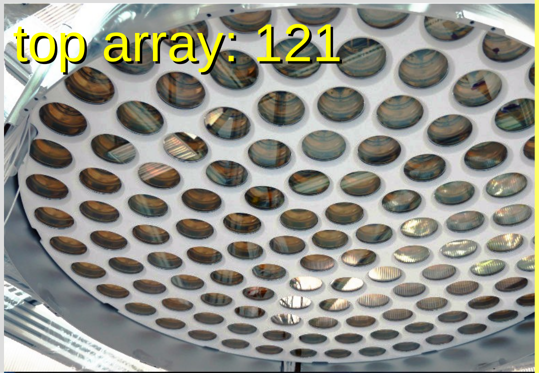
Extensive pre-testing/characterization campaign

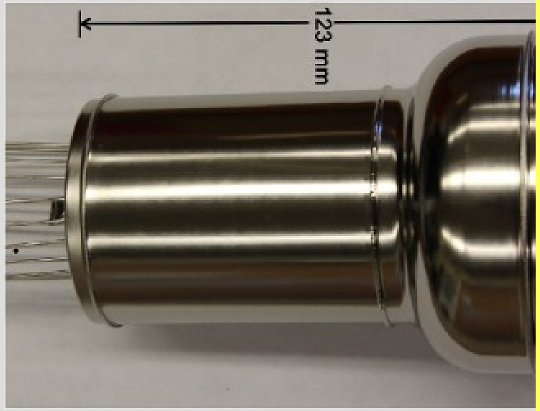
arXiv:1609.01654



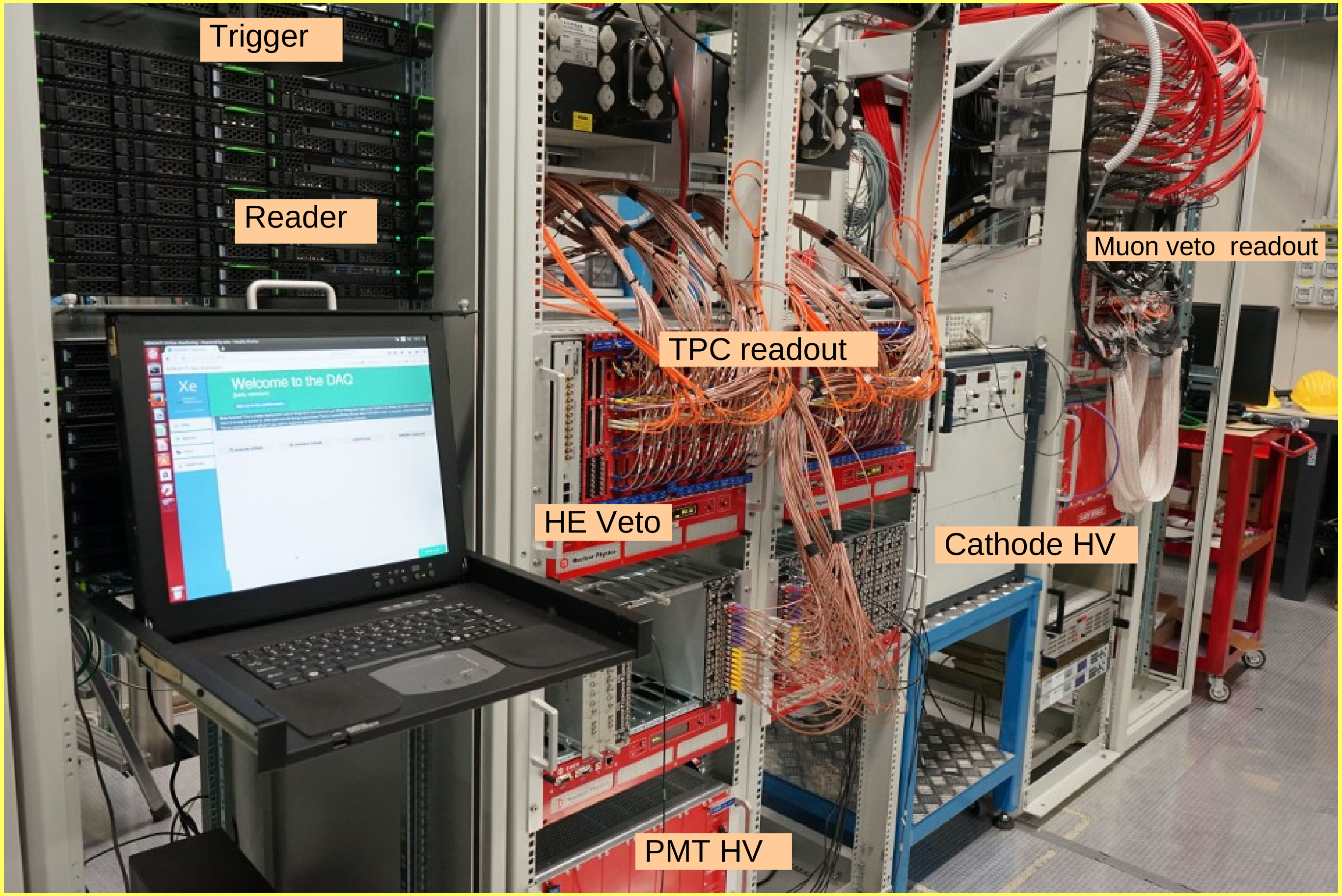


PMTs: Hamamatsu R11410-21



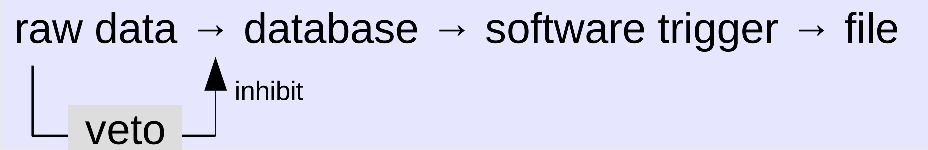


TPC Data Acquisition, Electronics

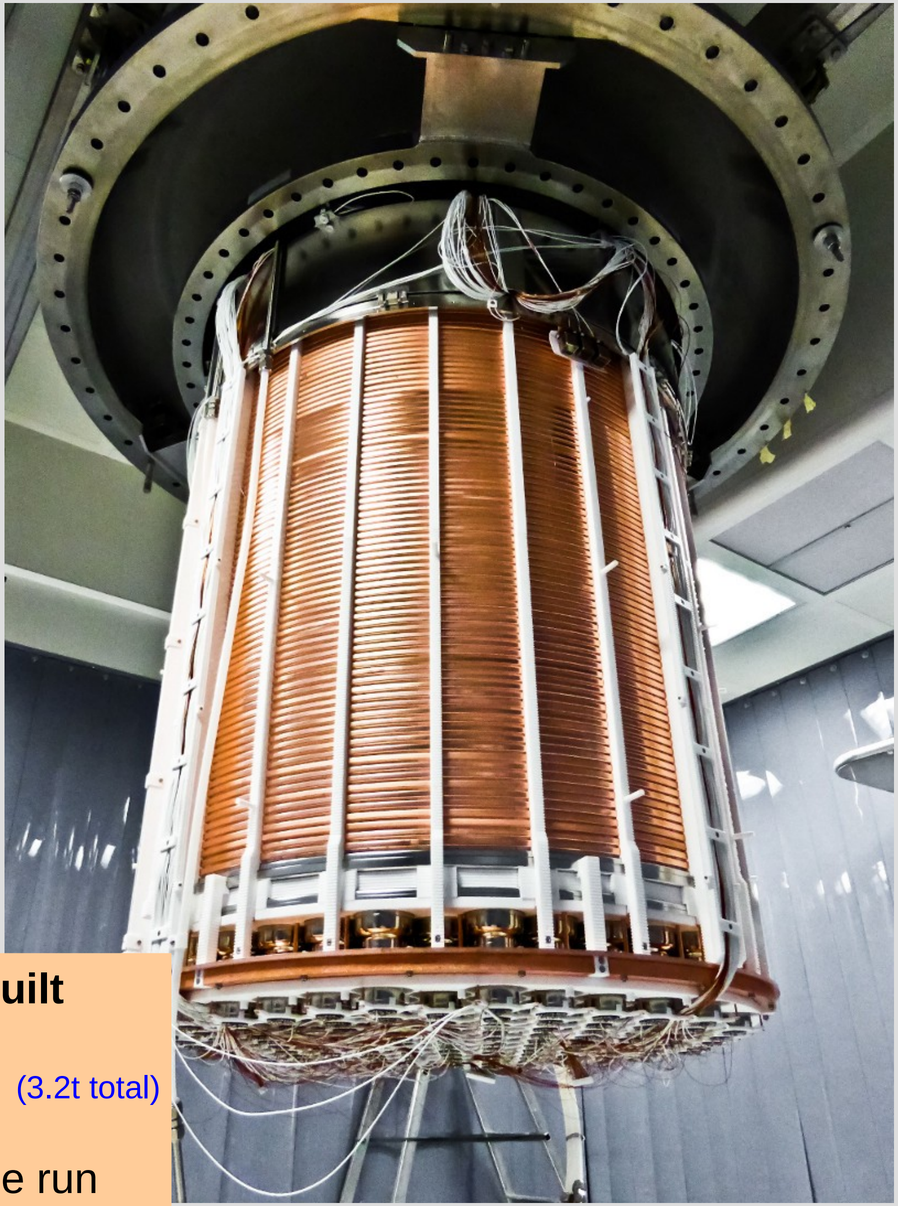


Parallel, trigger-less readout: → low threshold

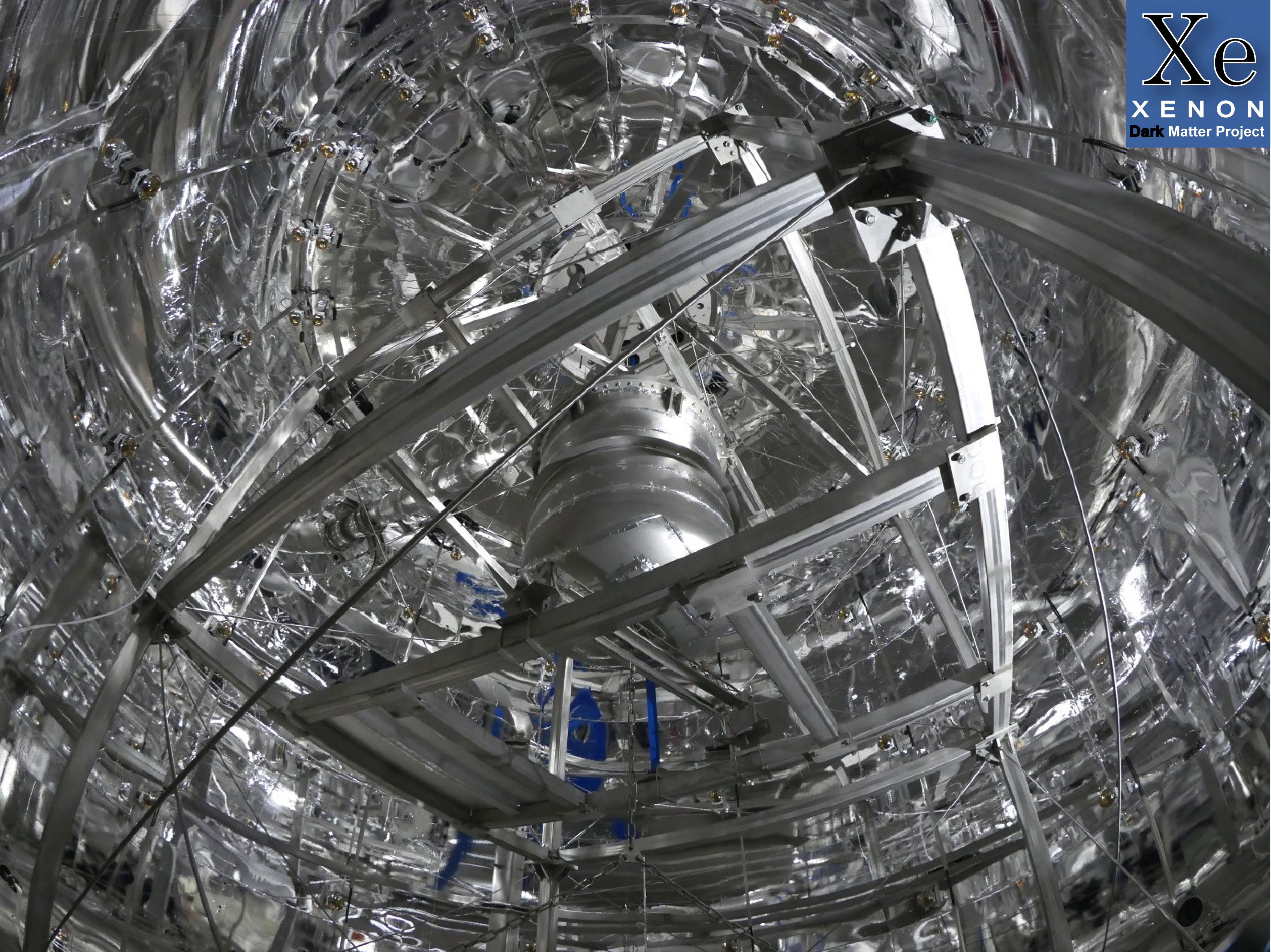
→ high throughput (>300 MB/s achieved → 0.8 TB/d):


raw data → database → software trigger → file

XENON1T

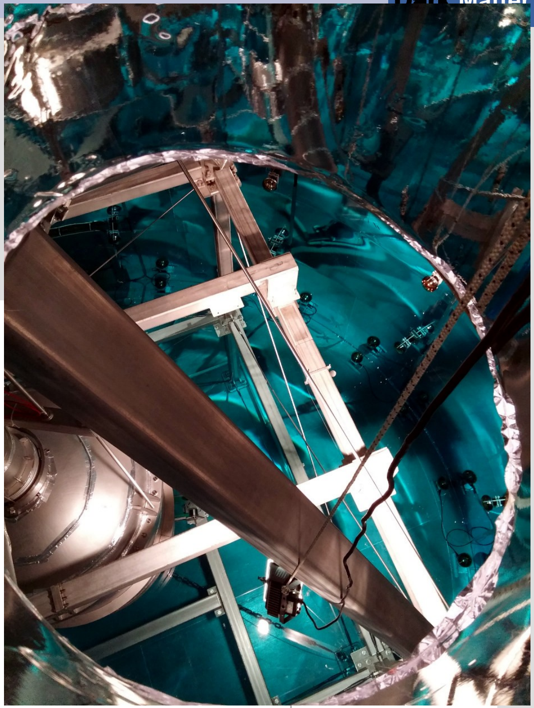


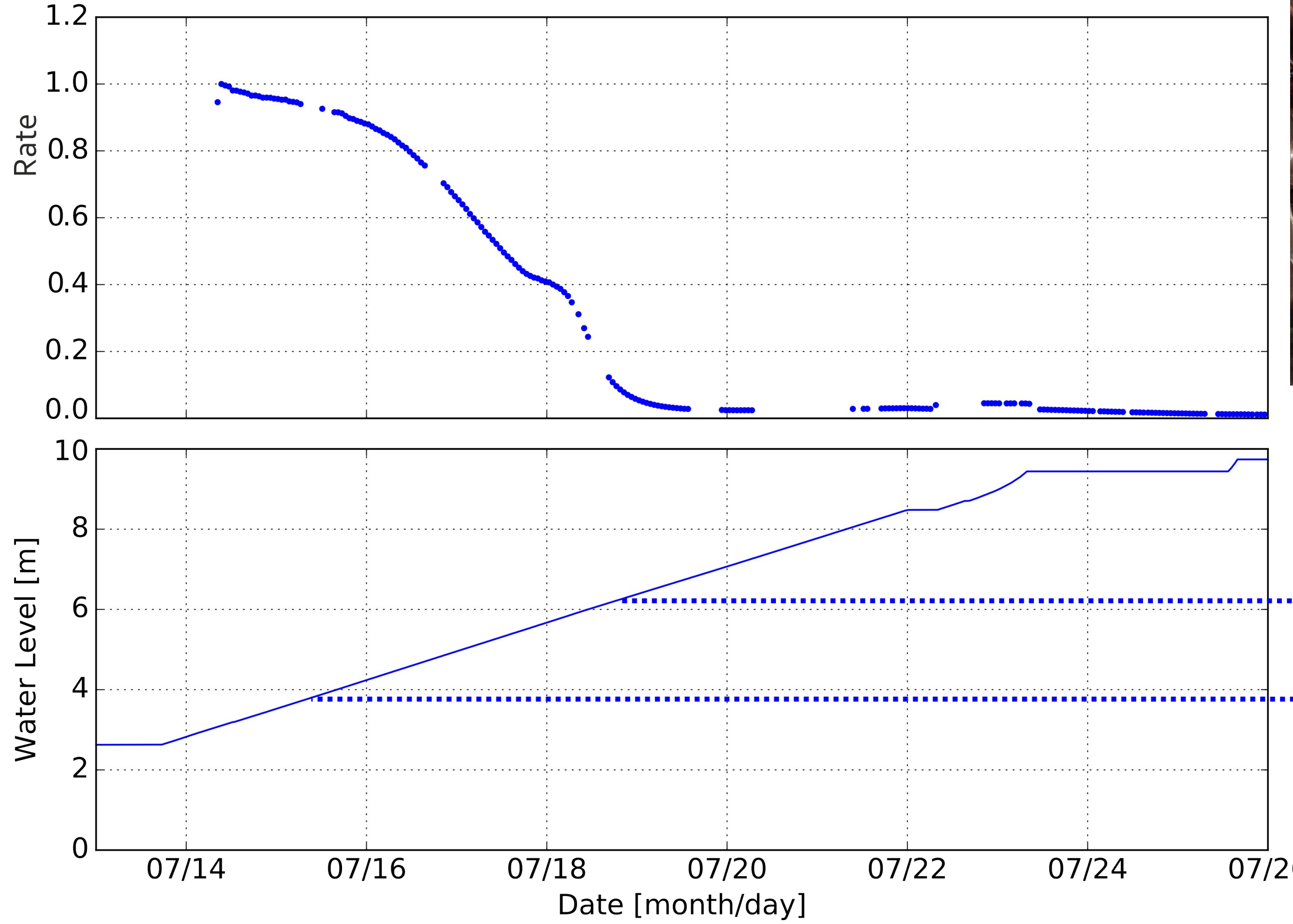
- **largest LXe TPC ever built**
  - **cylinder: 96 cm**
  - **active LXe target: 2.0t** (3.2t total)
  - **248 PMTs**
- operating: started science run

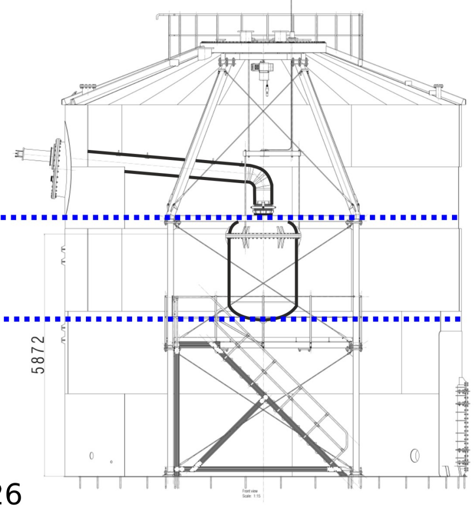

Xe
XENON
Dark Matter Project

XENON1T Performance

Water shield filled since Summer...



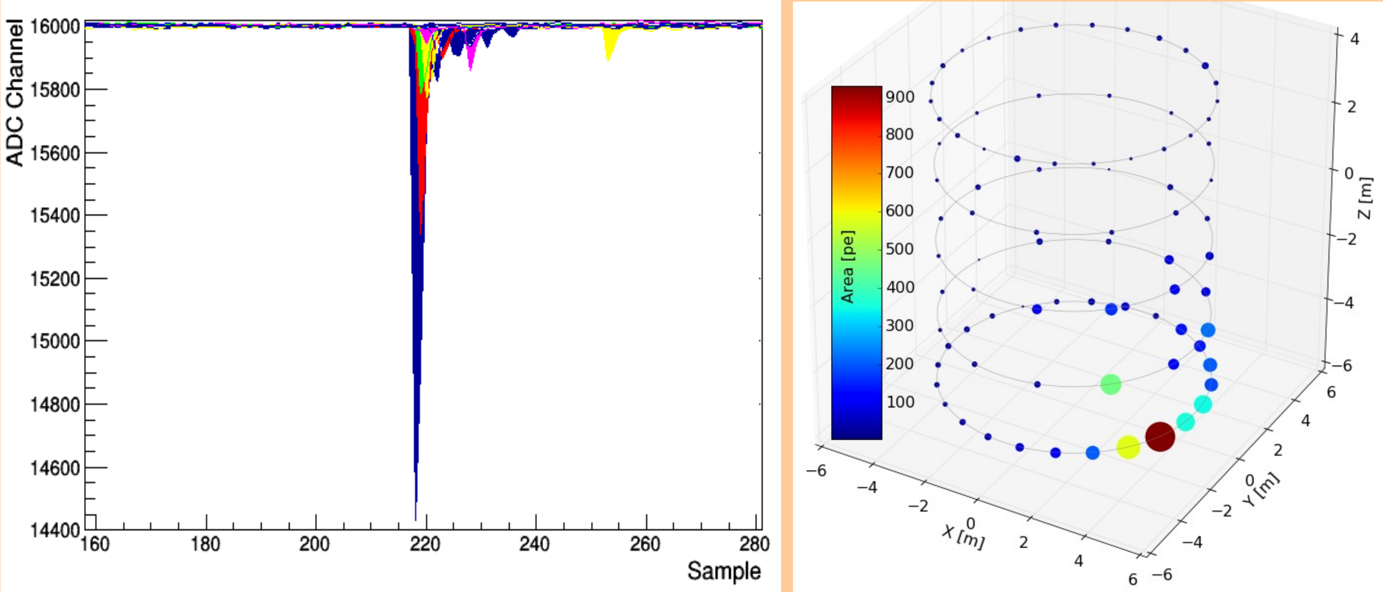


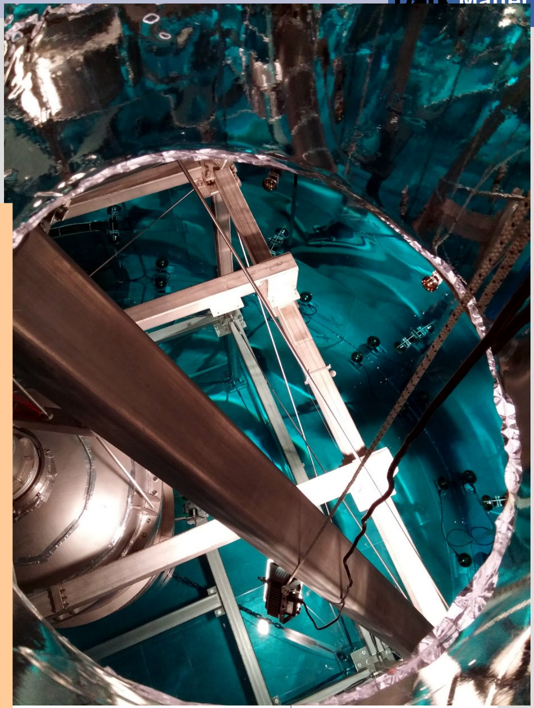


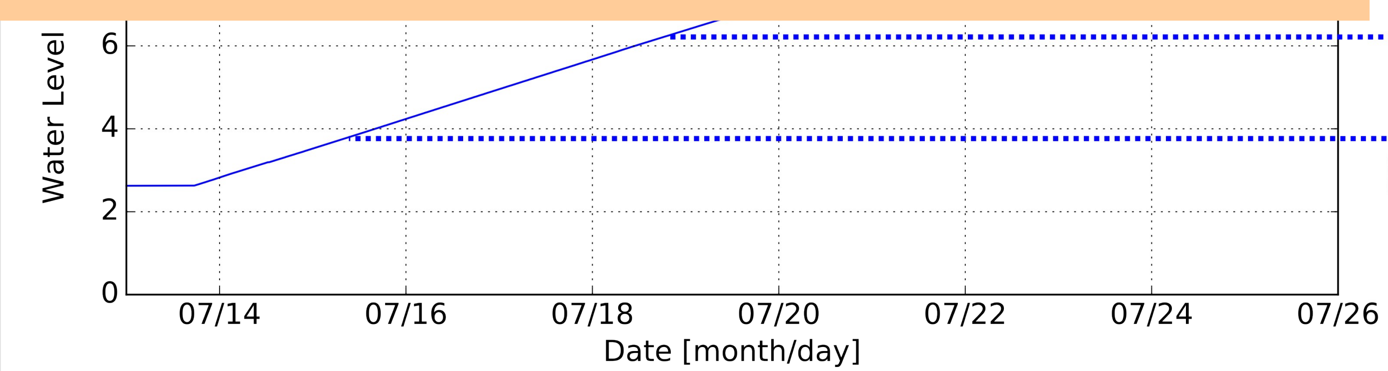
XENON1T Performance

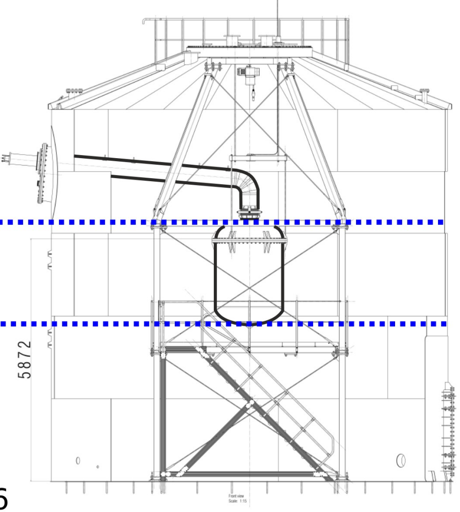
Water shield continuously filled since Summer...

Cerenkov detector sees muons...



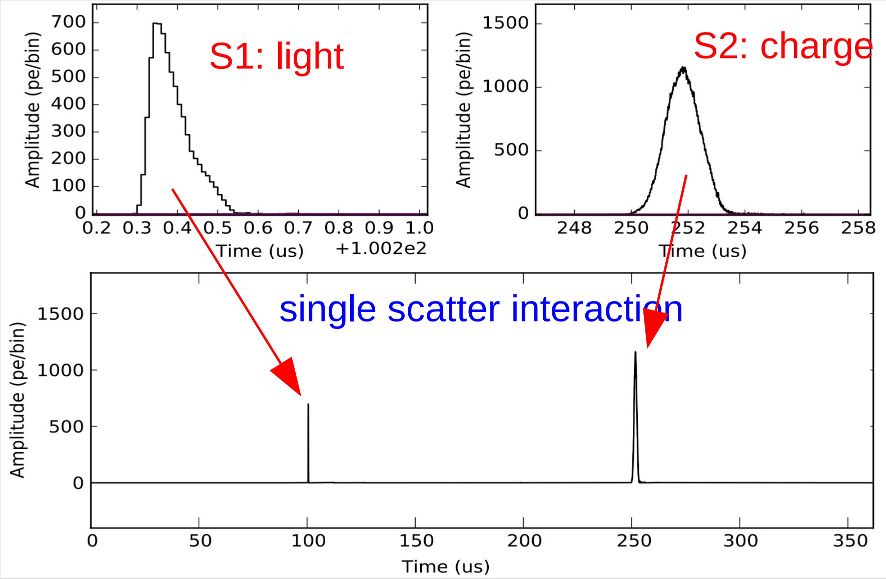


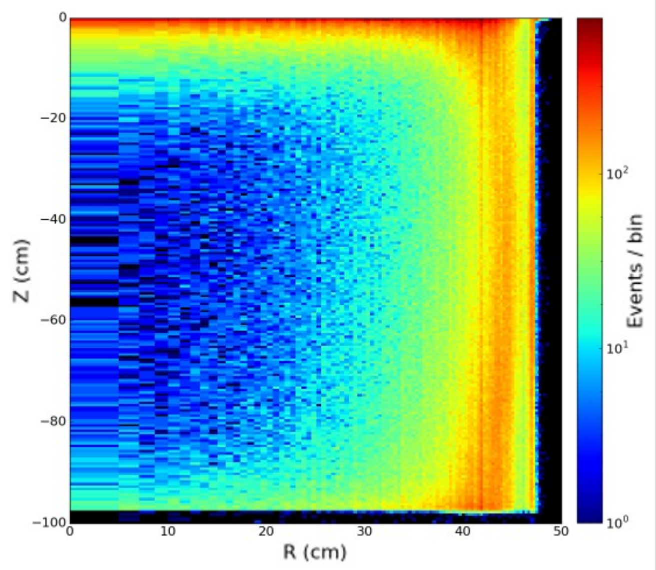




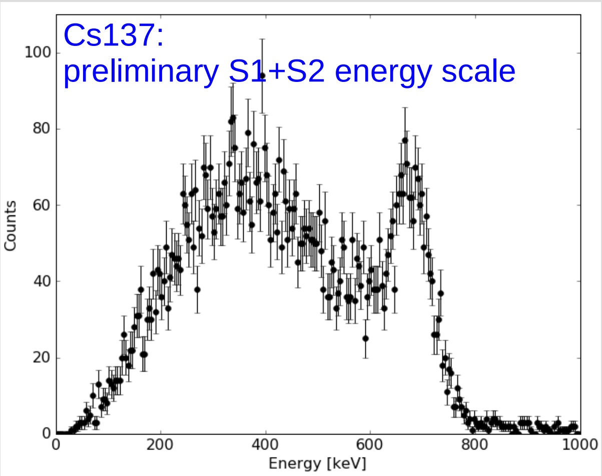
XENON1T Performance

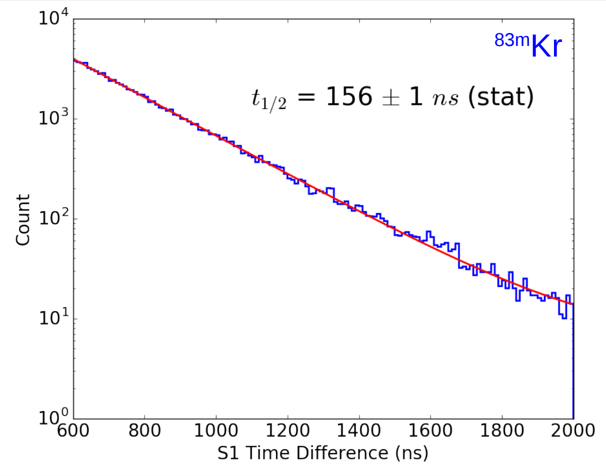
Recording light (S1) and light signals (S2) from the entire detector





Calibration: external (^{137}Cs, AmBe), internal (^{83m}Kr, ^{220}Rn)



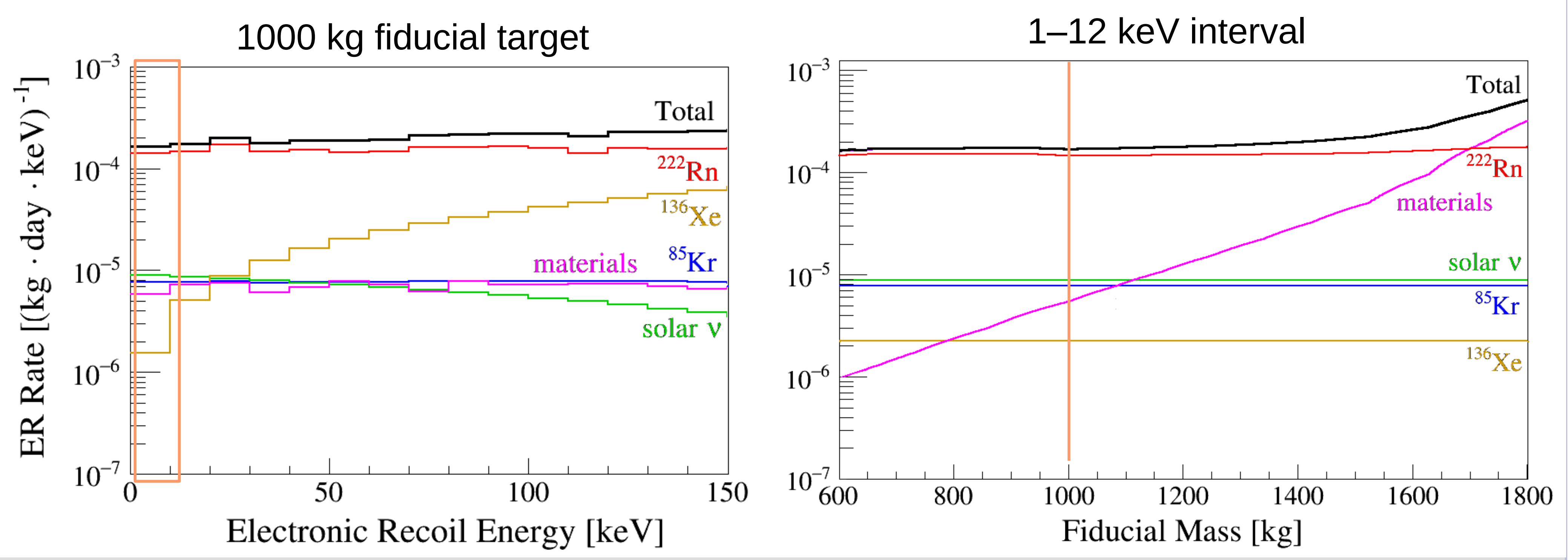


Backgrounds

- material background low, self-shielding effective
- ^{222}Rn background agrees with predictions
- online removal of ^{85}Kr via cryogenic distillation started

Background: Electronic Recoils

JCAP 04, 027 (2016)

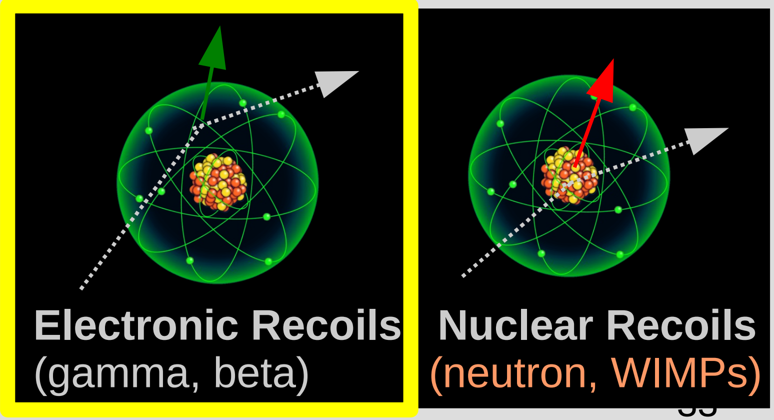


Assumed contamination:

^{222}Rn: 10 µBq/kg

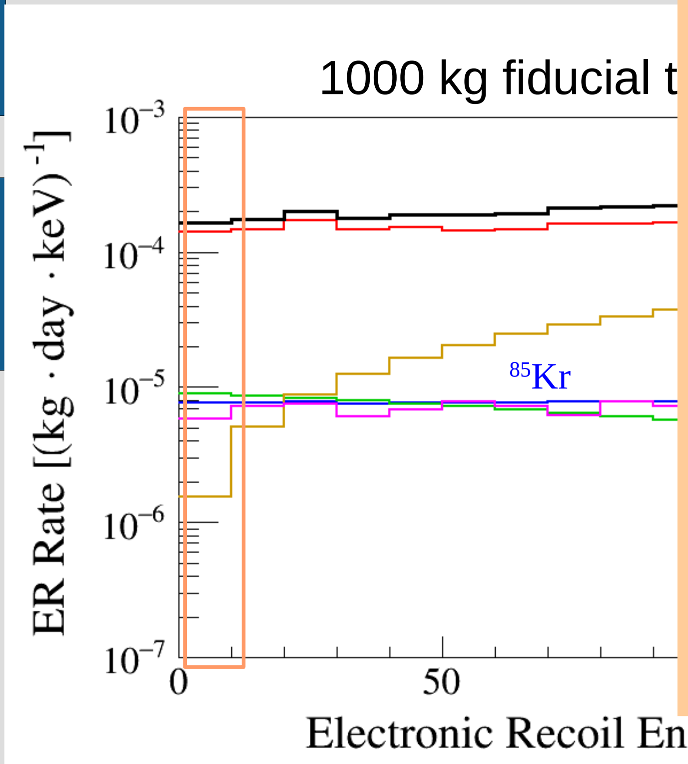
^{nat}Kr: 0.2 ppt

^{136}Xe: 8.9% natural abundance



Background: Electronic Recoils

JCAP 04, 027 (2016)

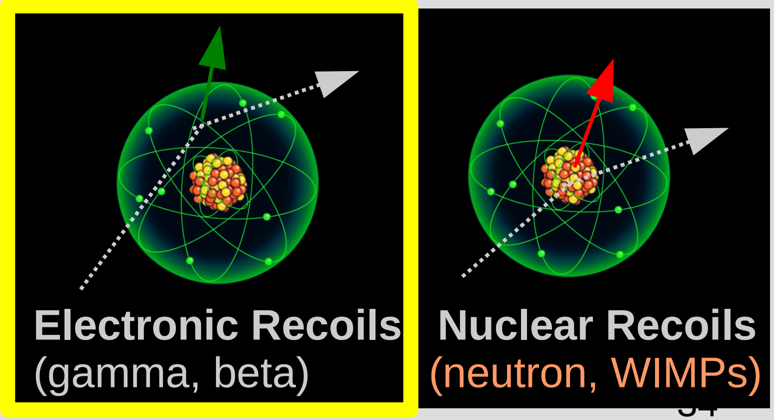


different boiling points of Xe and Kr
→removal of Kr by cryogenic distillation

→ **achieved reduction factor ~5×10^5**
→ exceeds the design goal of 10^4!

column has already delivered a concentration of **<0.026 ppt** = 2.6×10^{-14}
→**better than required for XENON1T**

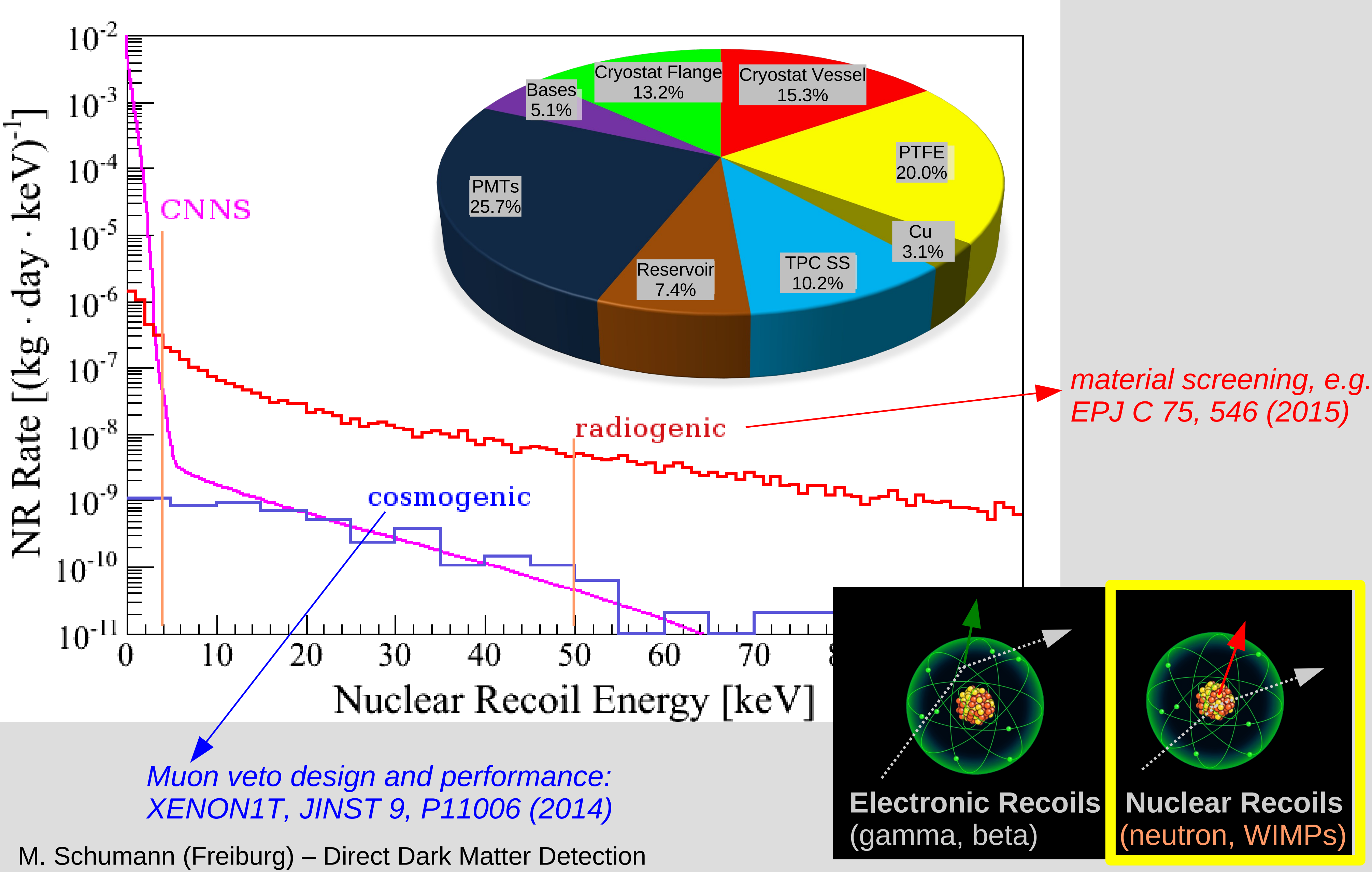
Assumed contamination:
^{222}Rn: 10 µBq/kg
^{nat}Kr: 0.2 ppt
^{136}Xe: 8.9% natural abundance



Background: Nuclear Recoils

JCAP 04, 027 (2016)

XENON Dark Matter Project



Electronic Recoils (gamma, beta)

Nuclear Recoils (neutron, WIMPs)

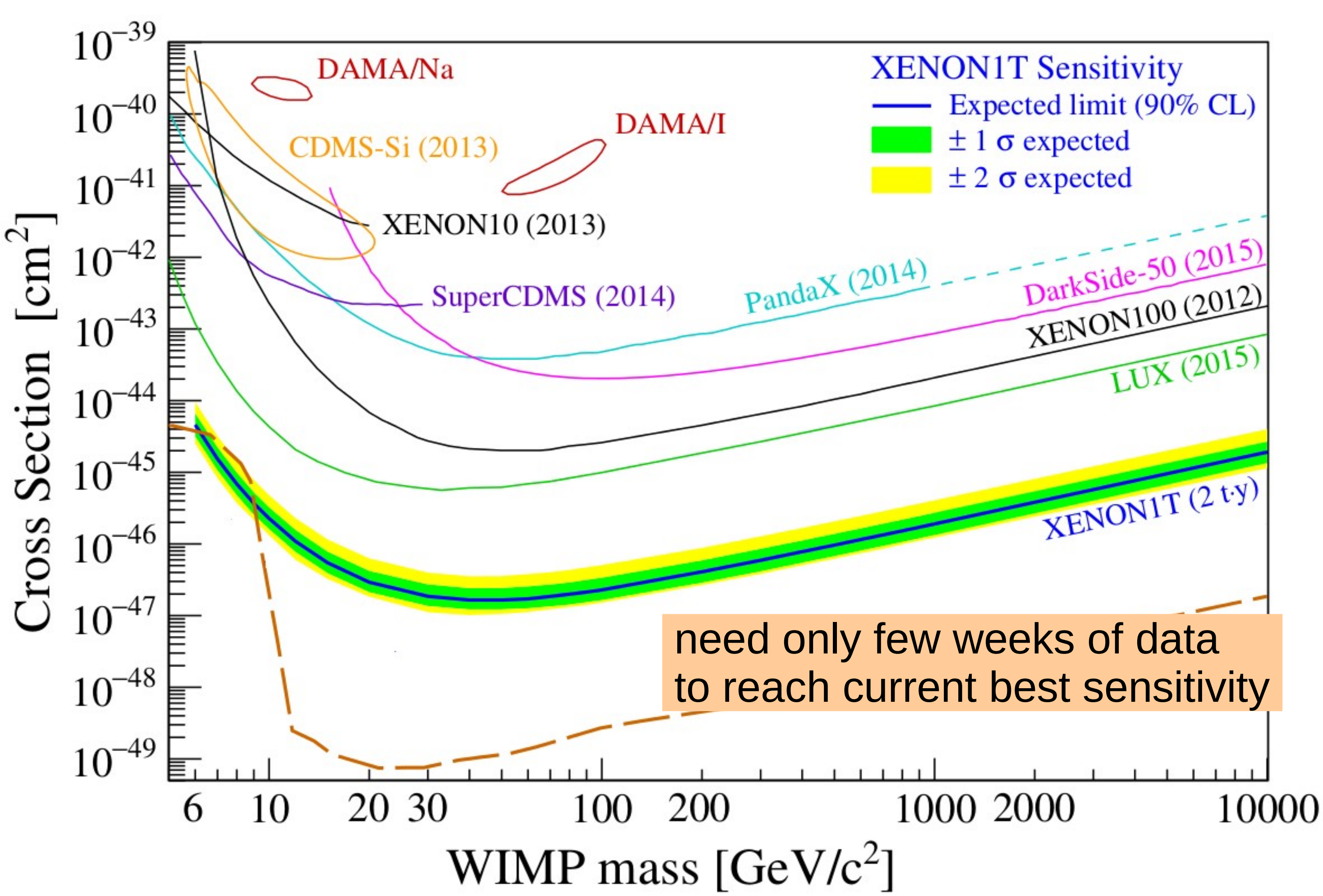
material screening, e.g. EPJ C 75, 546 (2015)

Muon veto design and performance: XENON1T, JINST 9, P11006 (2014)

XENON1T Sensitivity

JCAP 04, 027 (2016)

based on background predictions shown before, 2 t×y exposure:



need only few weeks of data to reach current best sensitivity

assumptions: energy interval: 4 – 50 keVr, ER rejection as XENON100: 99.5% @ 50% NR acc.

→ expected LY is 2x higher than in XENON100!

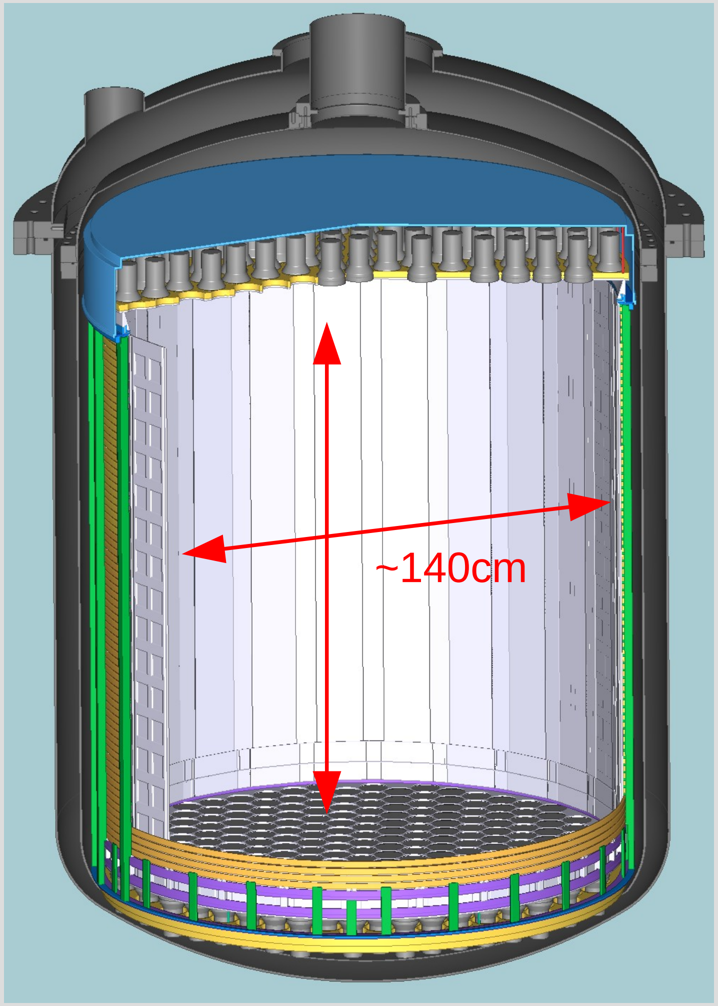
confirmed by measurement!

XENON1T → XENONnT

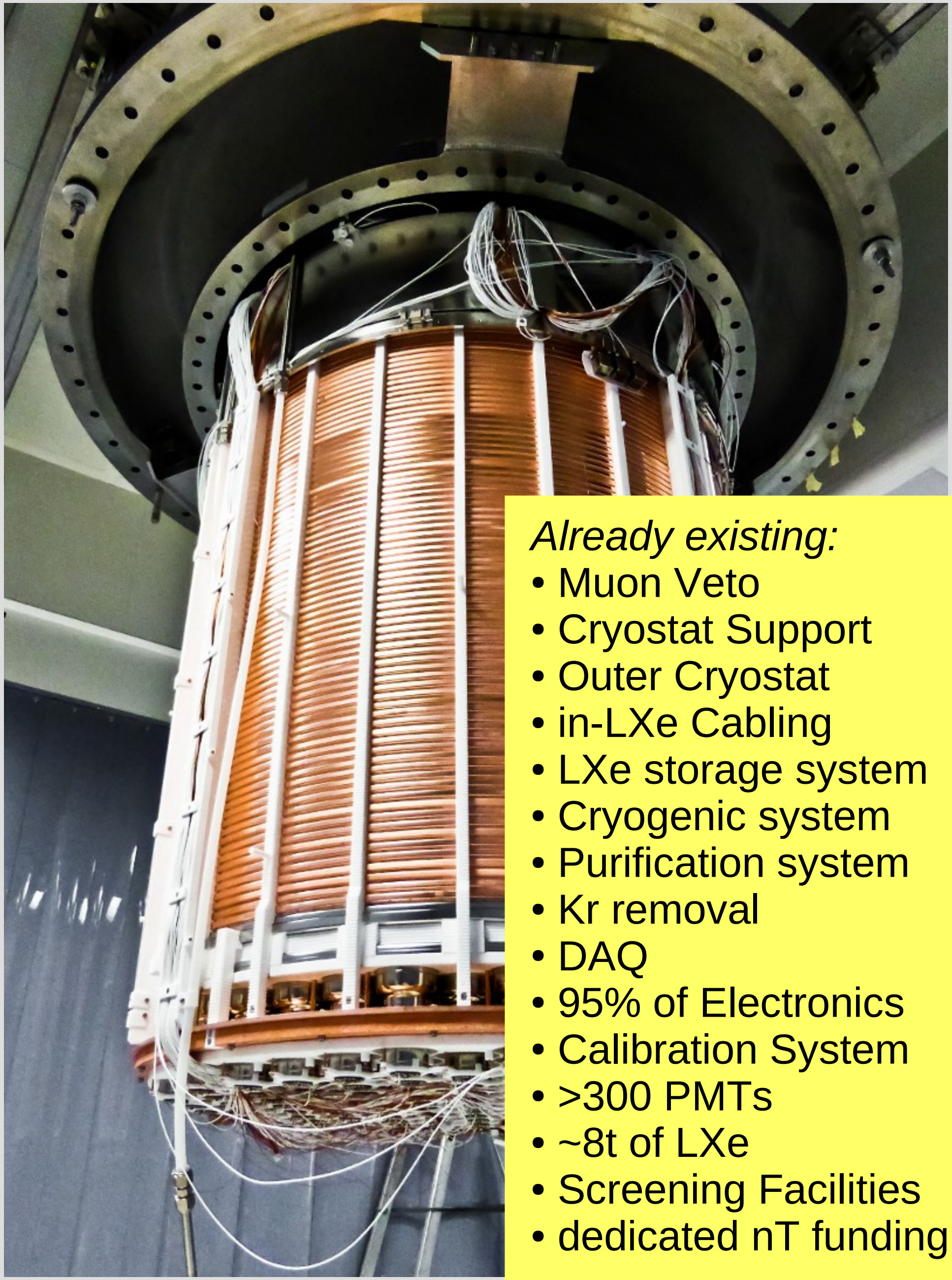
JCAP 04, 027 (2016)

XENON1T
- **2t** active LXe target
- operating
- science run started

XENONnT
- **6t** active target
- projected to start in 2018

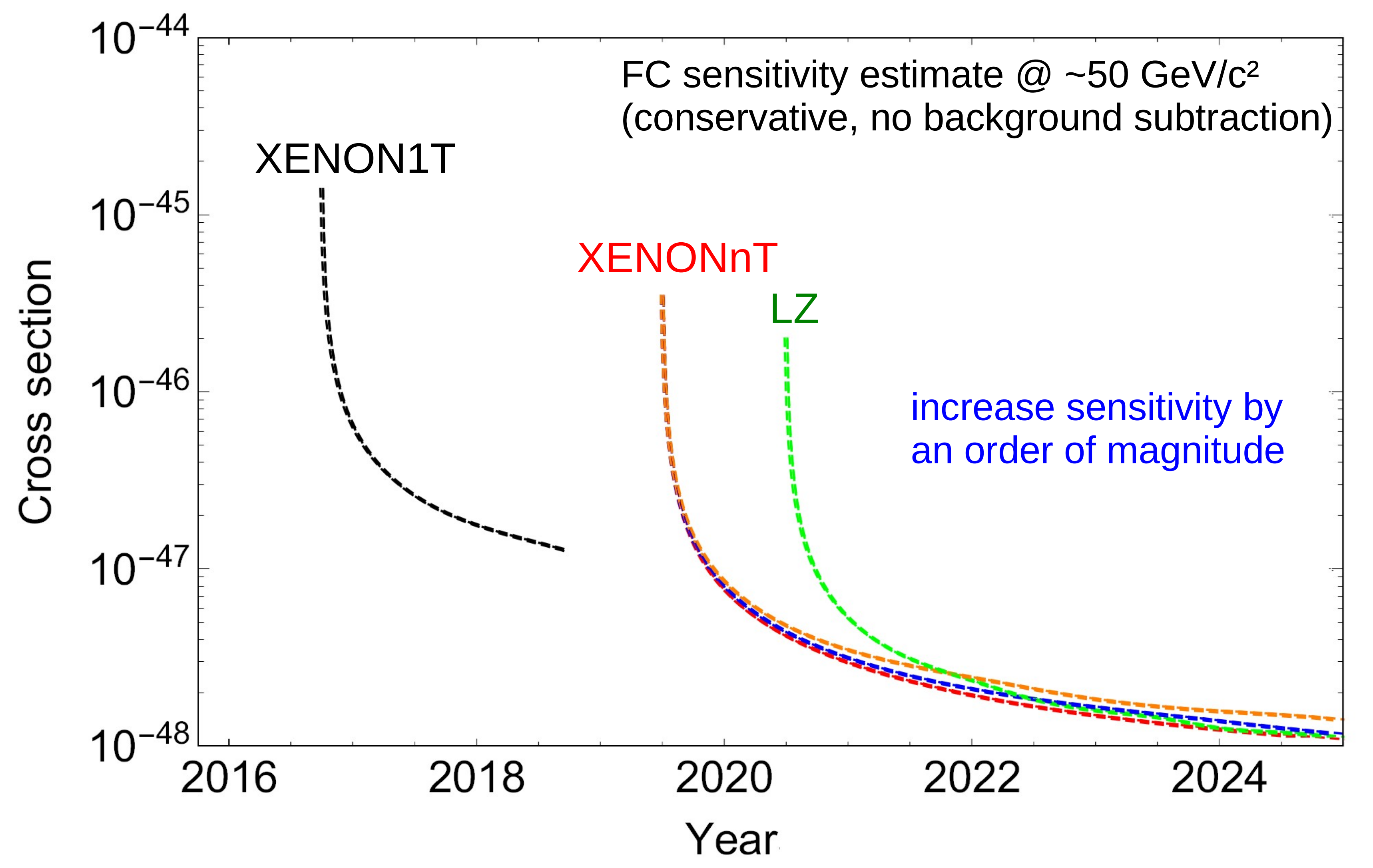


M. Schumann (Freiburg) – Direct Dark Matter Detection



Already existing:
- Muon Veto
- Cryostat Support
- Outer Cryostat
- in-LXe Cabling
- LXe storage system
- Cryogenic system
- Purification system
- Kr removal
- DAQ
- 95% of Electronics
- Calibration System
- >300 PMTs
- ~8t of LXe
- Screening Facilities
- dedicated nT funding

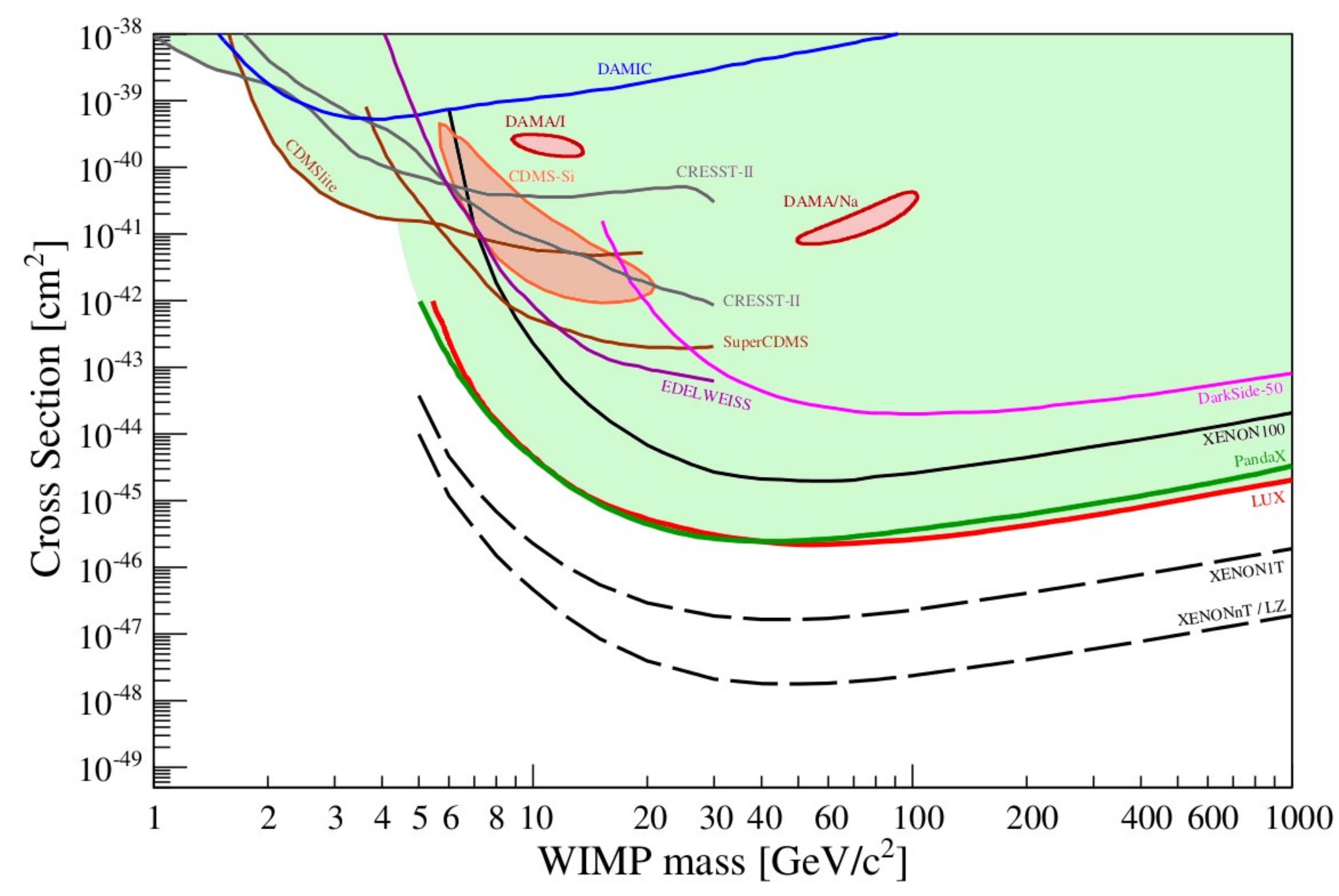
XENONnT: Sensitivity vs. time



LZ information taken from: https://idm2016.shef.ac.uk/indico/event/0/contribution/69/material/slides/0.pdf

XENON Science Goals

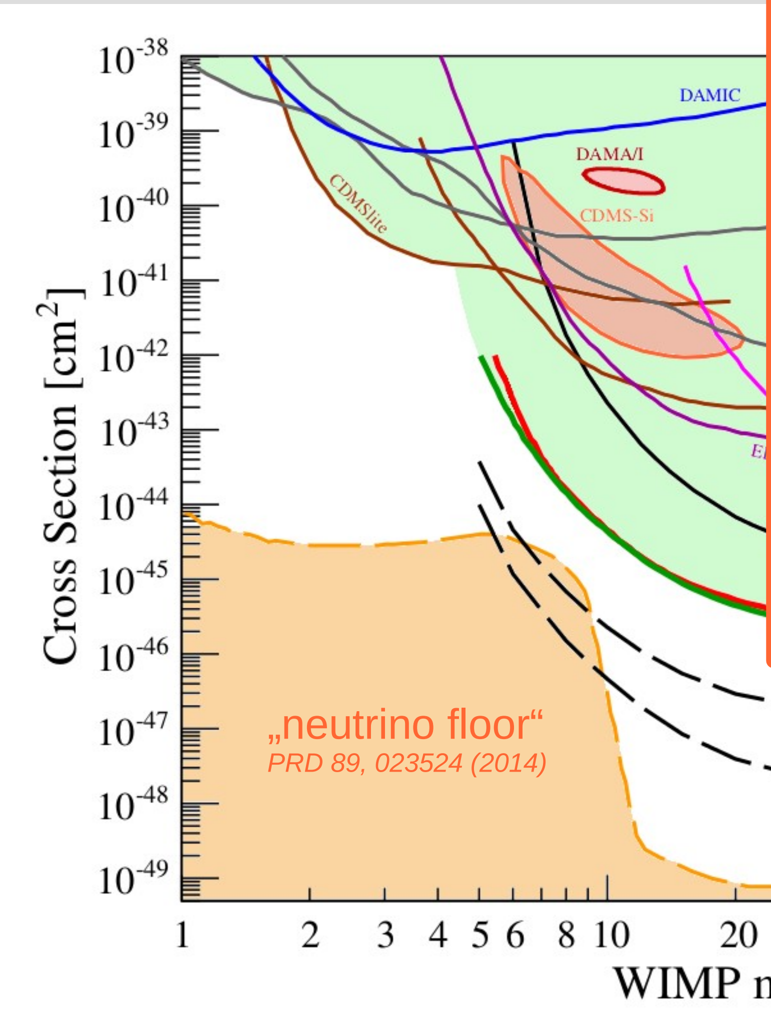
spin-independent WIMP-nucleon interactions



some projects are missing...

Dark Matter Searches: The Limit

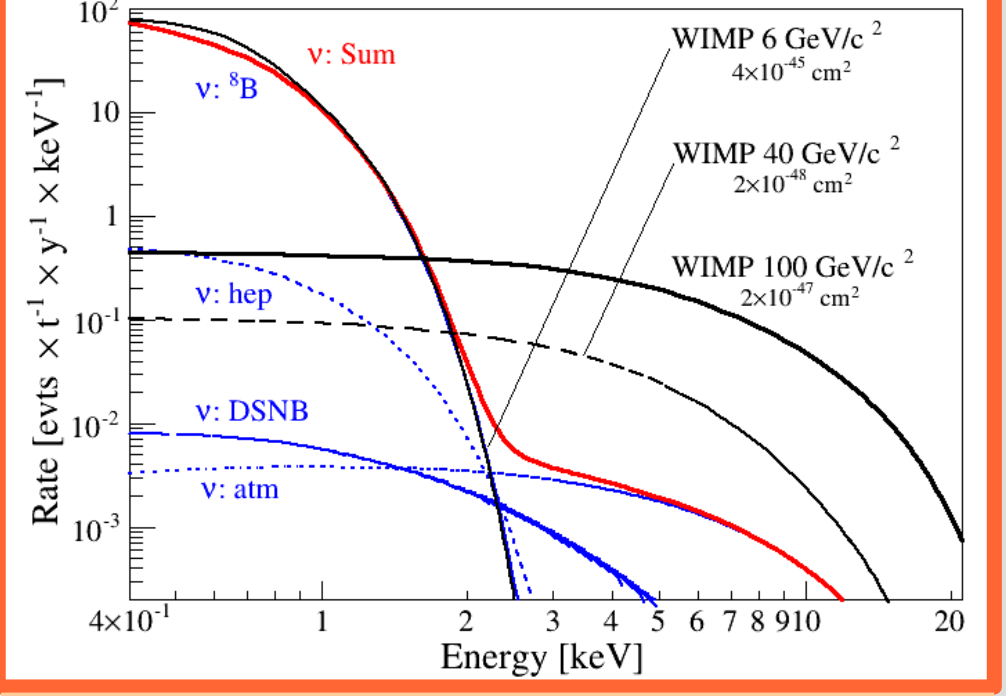
spin-i



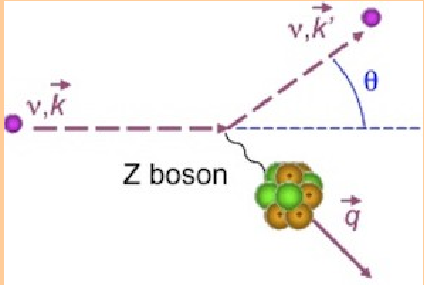
„neutrino floor“

PRD 89, 023524 (2014)

JCAP 01, 044 (2014)

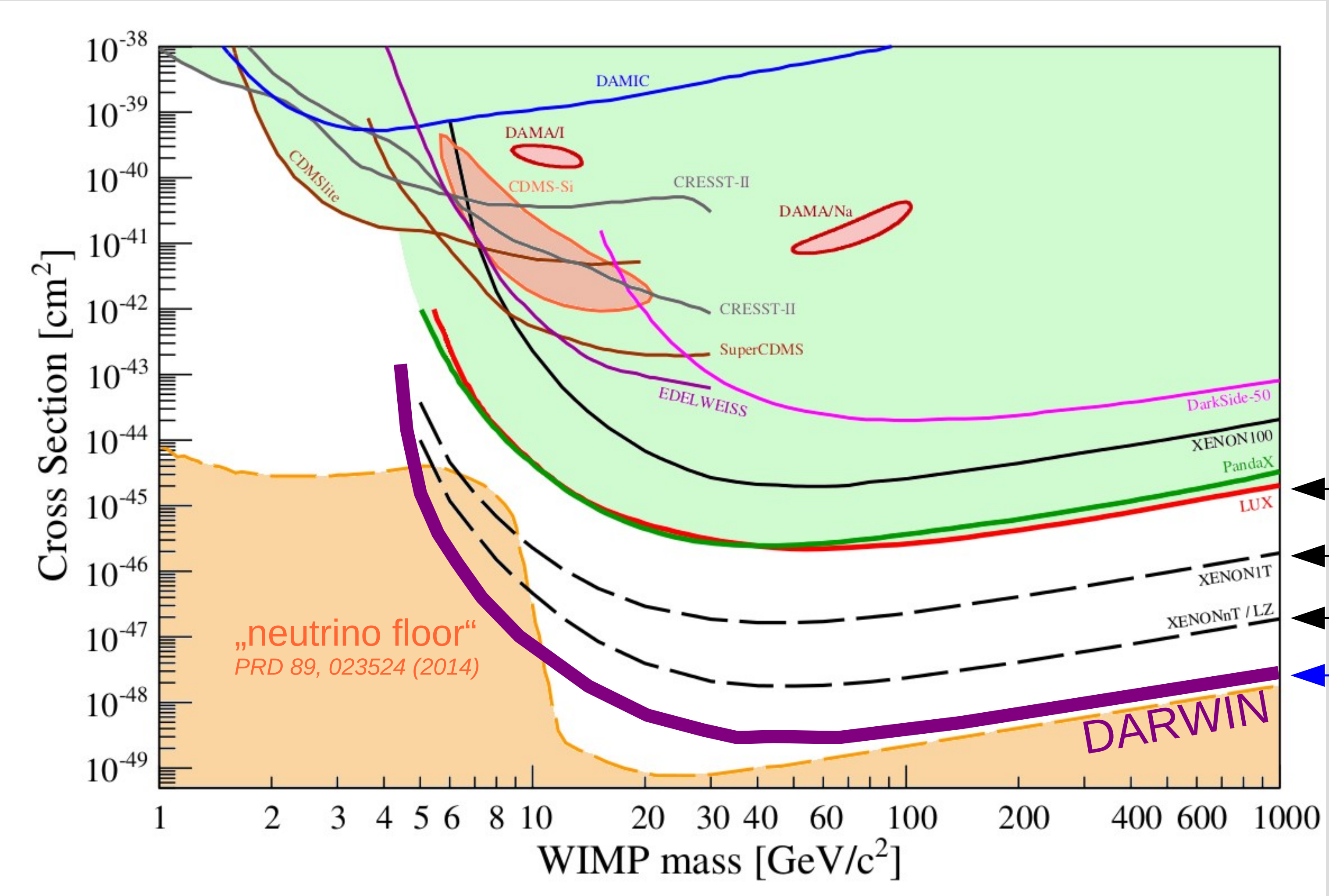


Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection



DARWIN The **ultimate** WIMP Detector

spin-independent WIMP-nucleon interactions



Exposure

0.1 t×y

2 t×y

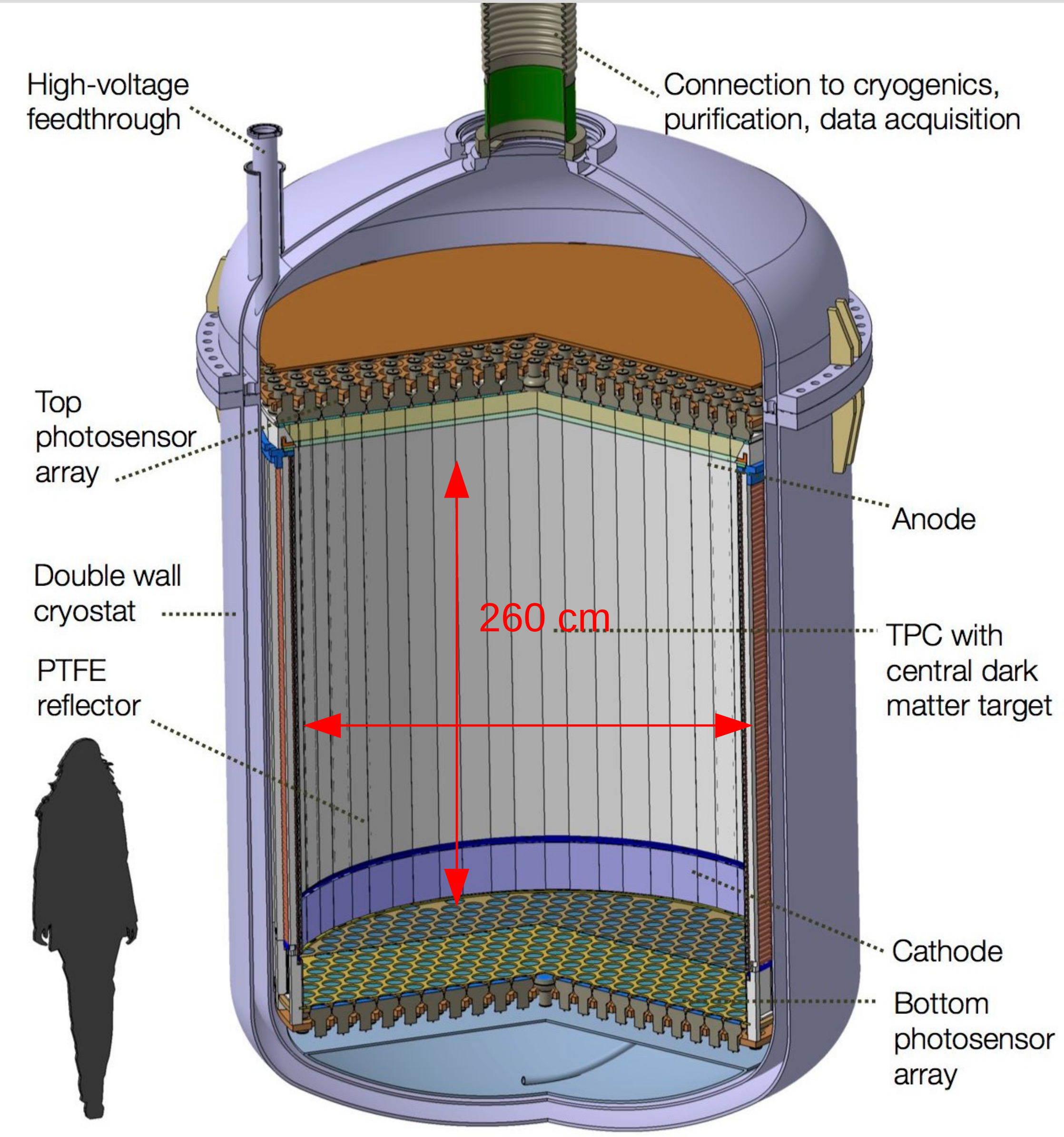
20 t×y

200 t×y

some projects are missing...

DARWIN The ultimate WIMP Detector

JCAP 11, 017 (2016)



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

- international consortium, 21 groups

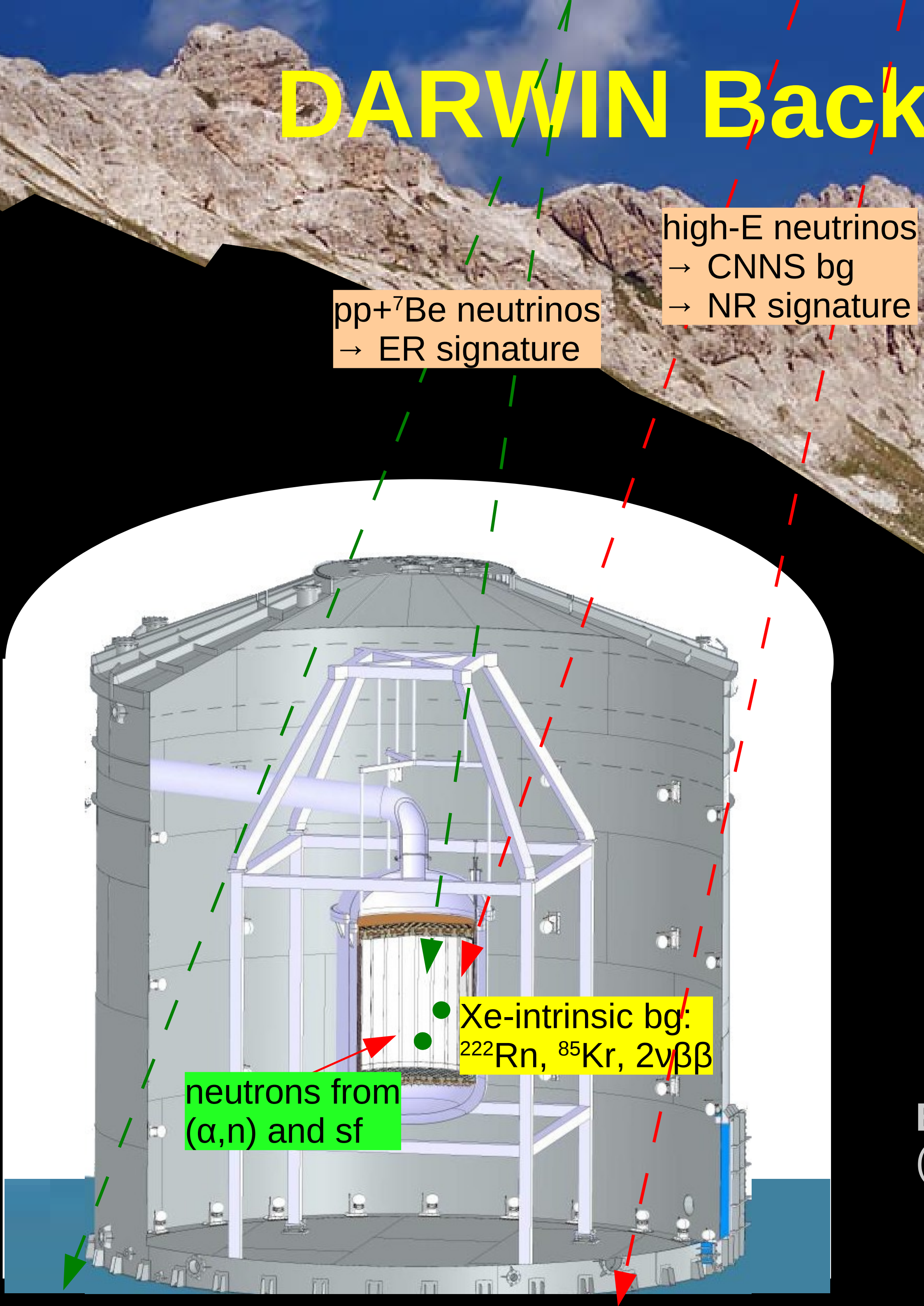
  → R&D ongoing

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

- Timescale: start after XENONnT

`www.darwin-observatory.org`

DARWIN Backgrounds



pp+^{7}Be neutrinos
→ ER signature

high-E neutrinos
→ CNNS bg
→ NR signature

Xe-intrinsic bg:
^{222}Rn, ^{85}Kr, $2\nu\beta\beta$

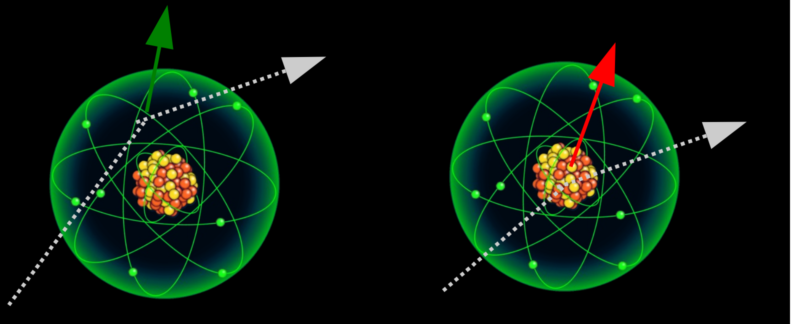
neutrons from
(α,n) and sf

Remaining background sources:

– Neutrinos (→ ERs and NRs)
– Detector materials (→ n)
– Xe-intrinsic isotopes (→ e⁻)

(assume 100% effective shield (~15m) against μ-induced background)

JCAP 10, 016 (2015)



Electronic Recoils
(gamma, beta)

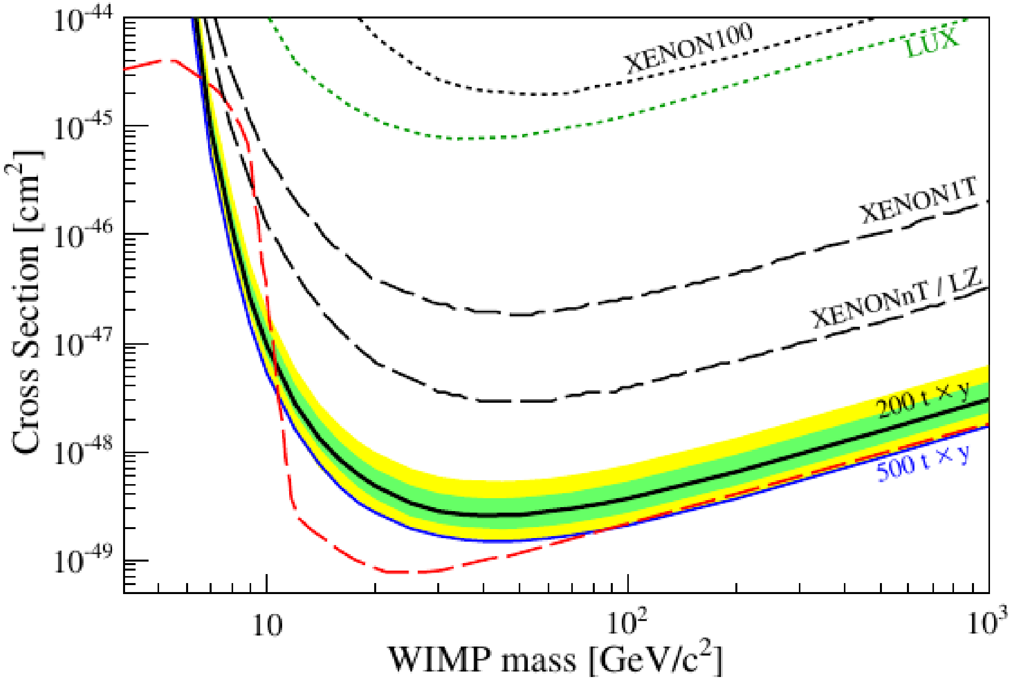
Nuclear Recoils
(neutron, WIMPs)
→ only single scatters

DARWIN WIMP Sensitivity

JCAP 10, 016 (2015)

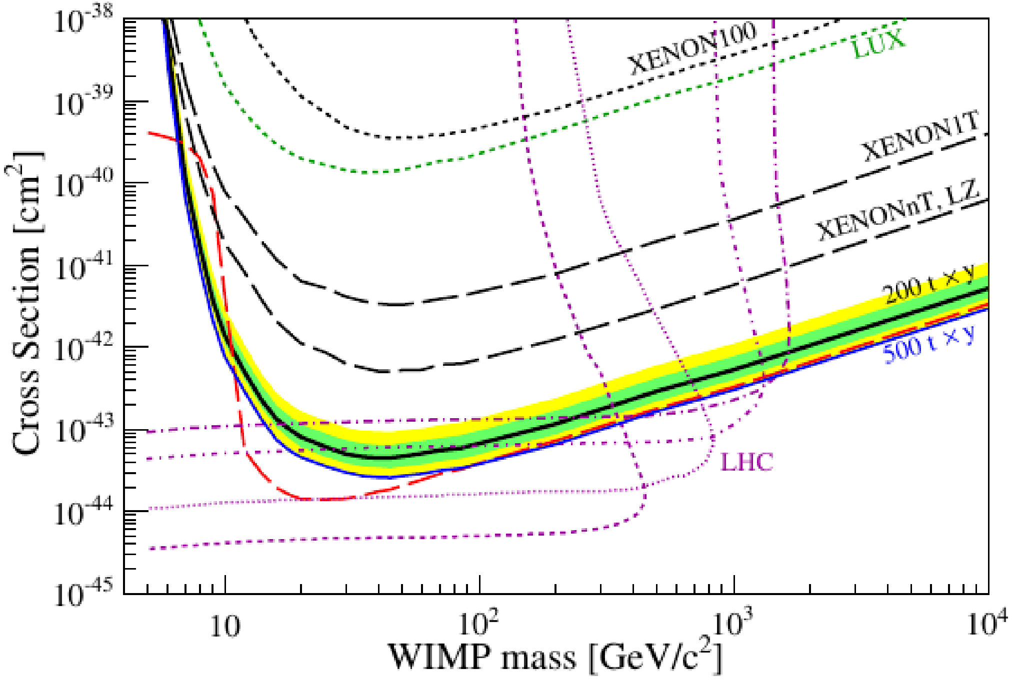
- exposure: 200 t × y; **all backgrounds included**
- likelihood analysis
- 99.98% ER rejection @ 30% NR acceptance,
  S1+S2 combined energy scale, LY=8 PE/keV, 5-35 keV_{nr} energy window

spin-*in*dependent couplings



200 t×y: $\sigma < 2.5 \times 10^{-49}$ cm² @ 40 GeV/c²

spin-*de*pendent couplings (n-only)



excellent complementarity to LHC searches

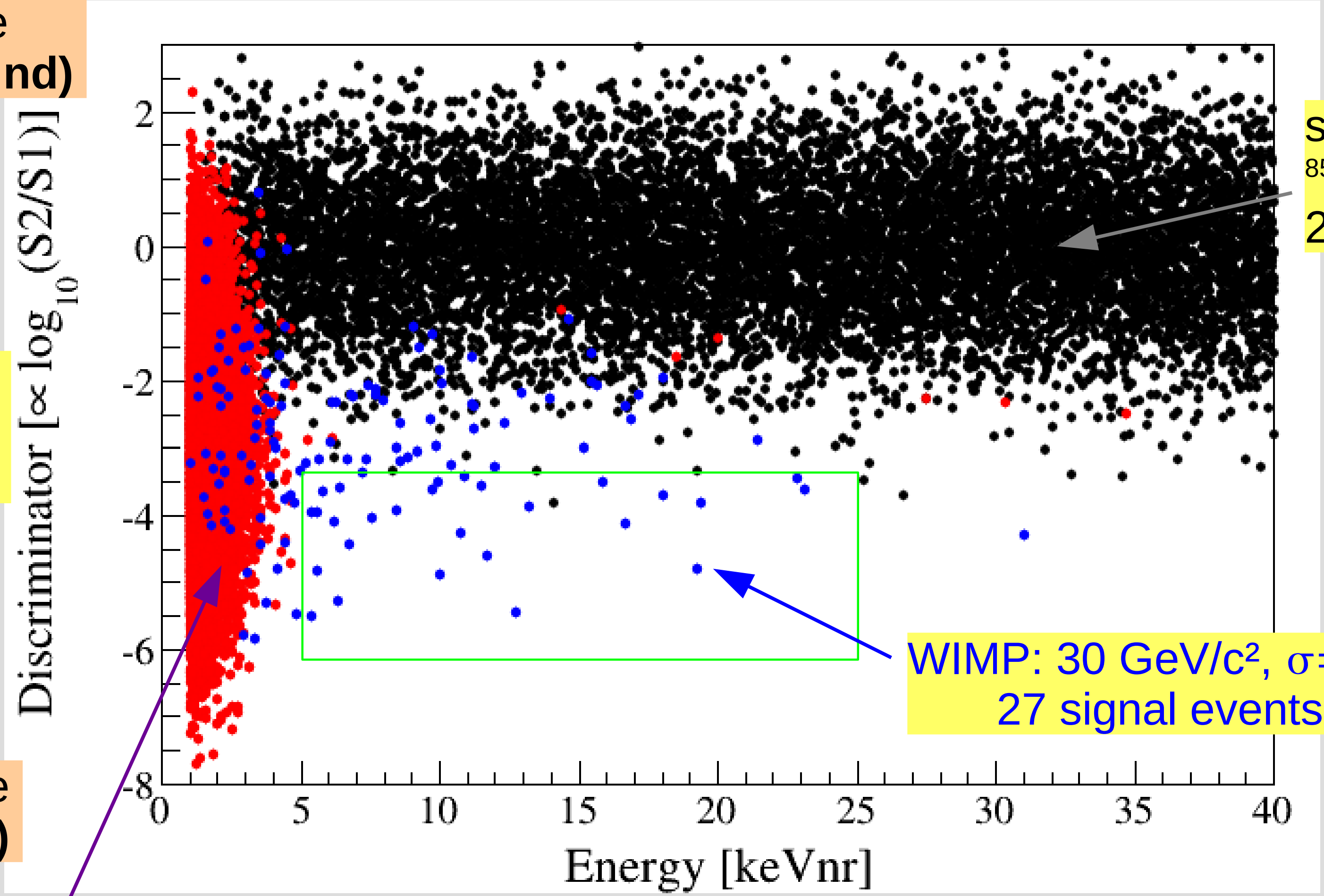
Phys.Dark Univ. 9-10, 51 (2015).

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
27 signal events in box

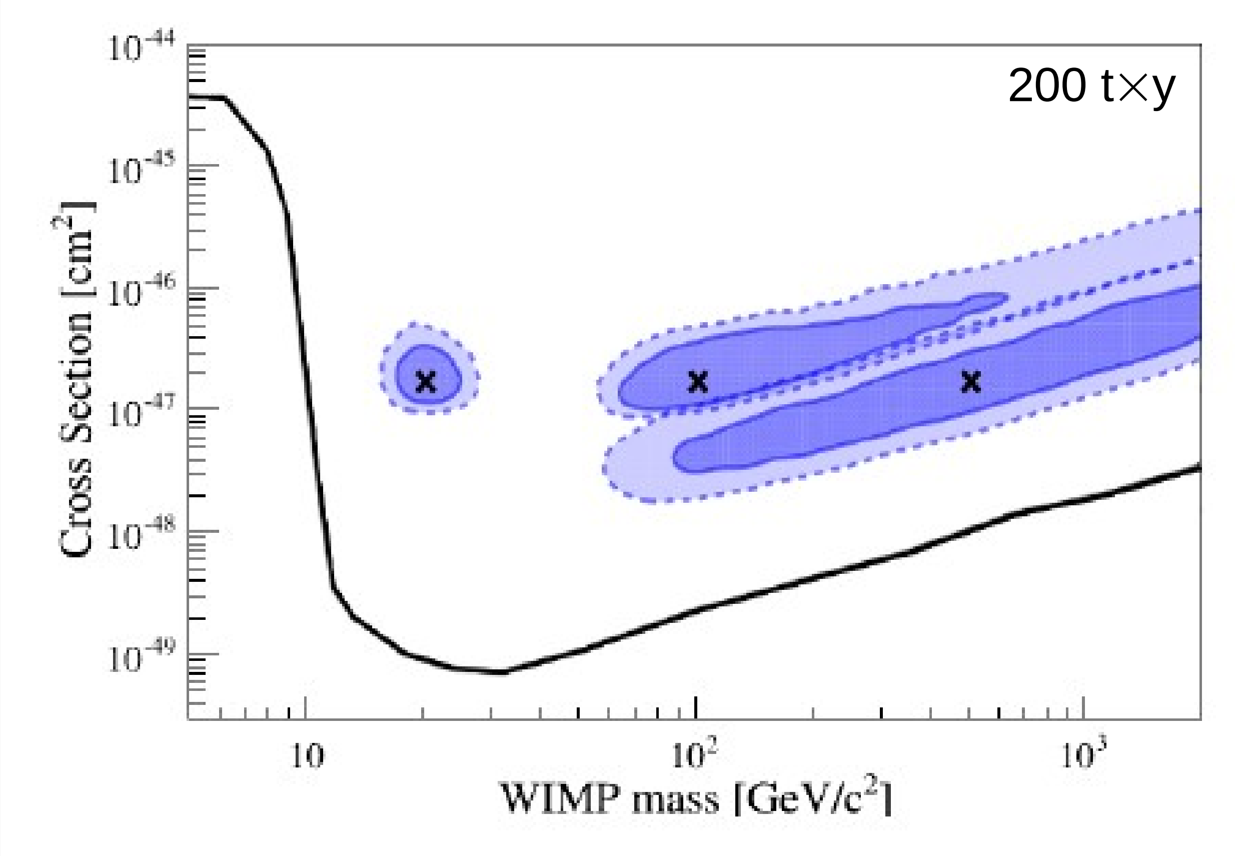
CNNS+neutrons

reconstructed energy, based on S1 and S2 signal

WIMP Spectroscopy

JCAP 11, 017 (2016)

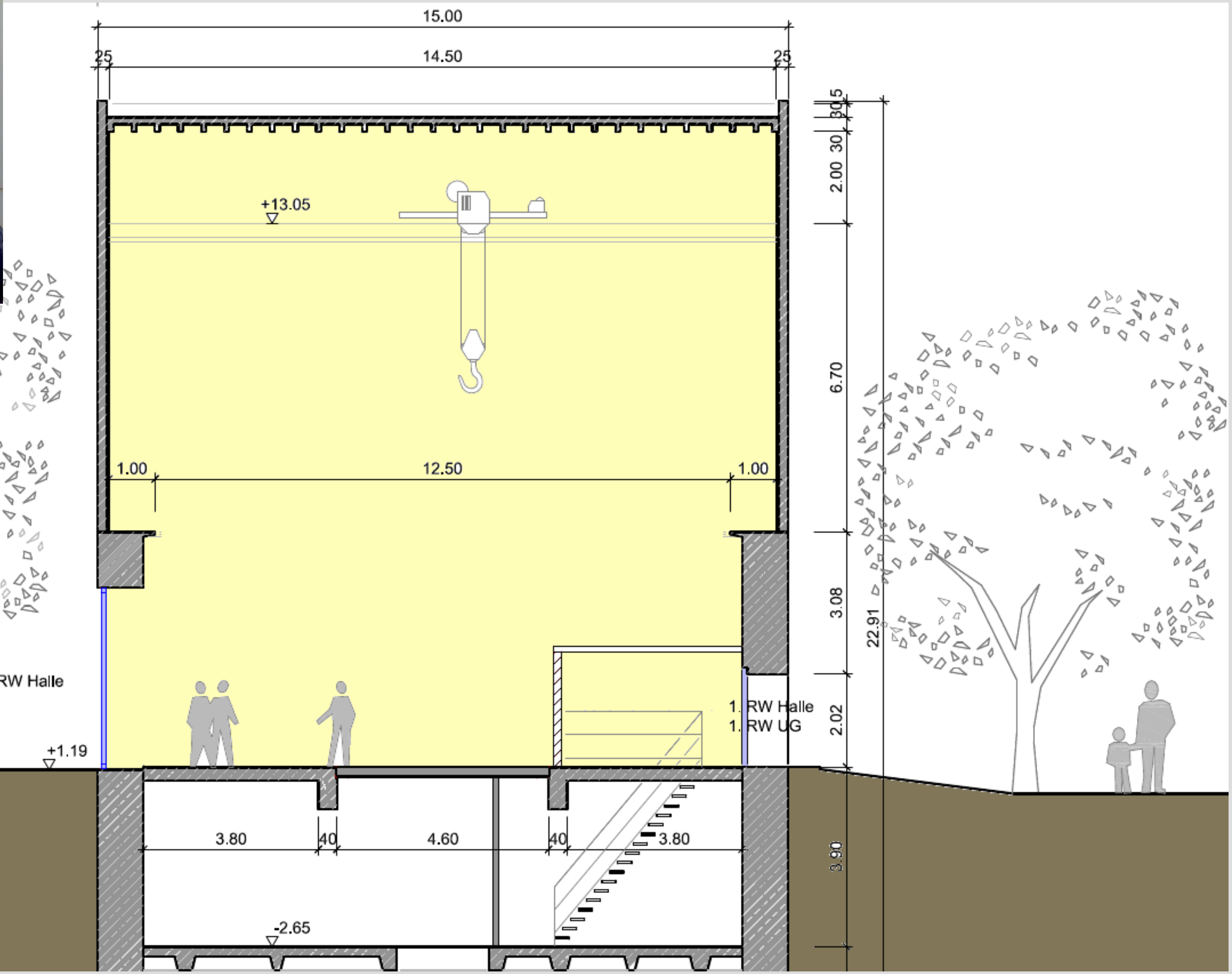
Reconstruction: 2×10^{-47} cm²



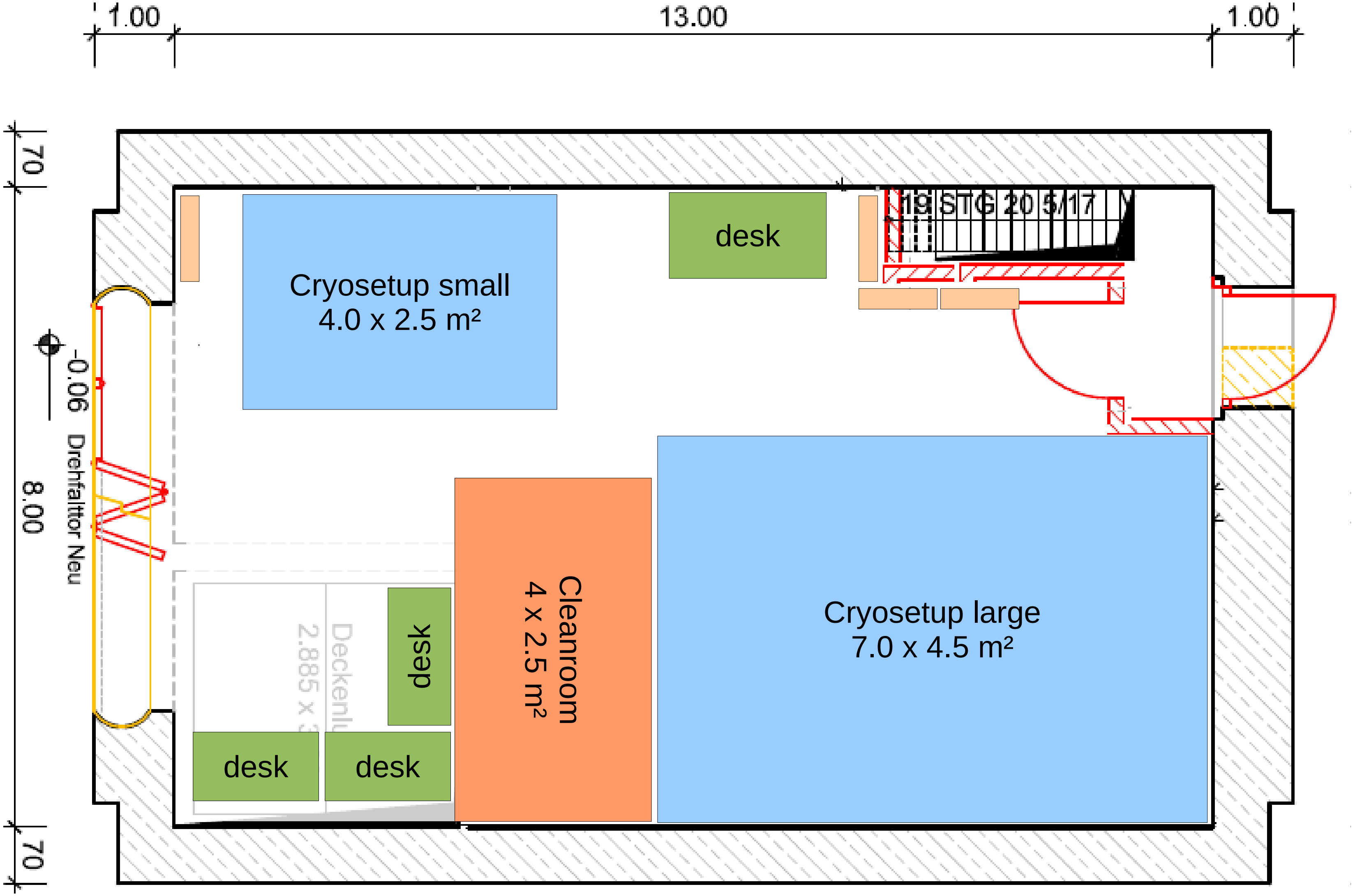
Capability to reconstruct WIMP parameters

- m_χ=20, 100, 500 GeV/c²
- 1σ/2σ CI, marginalized over astrophysical parameters
- due to flat WIMP spectra, no target can reconstruct masses >500 GeV/c²

New: Cryolab @ FR

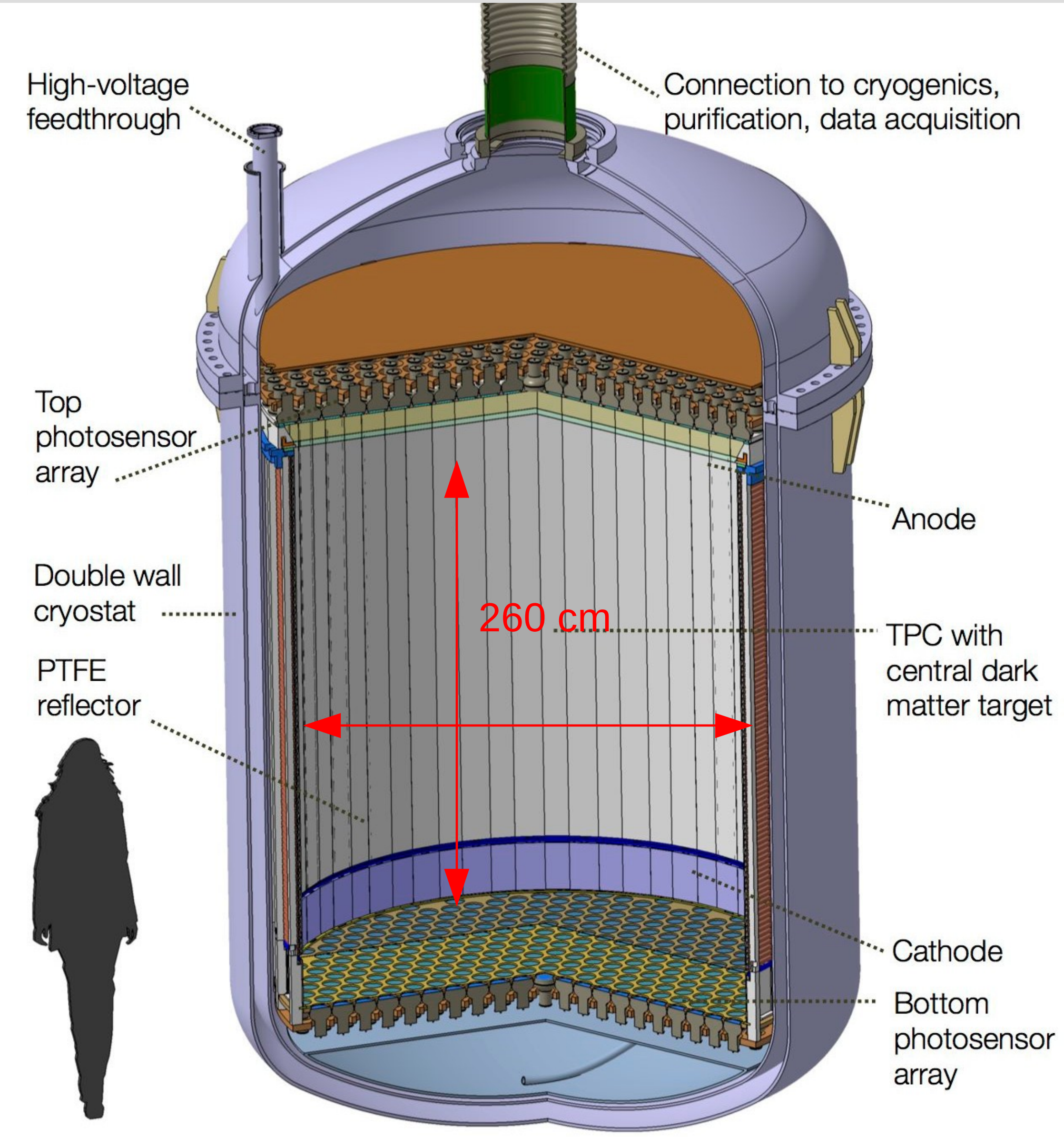


New: Cryolab @ FR



R&D Objective: Solve some of the most critical challenges for the *ultimate* dark matter detector.
→ backgrounds (^{222}Rn, (α,n) neutrons), detector size

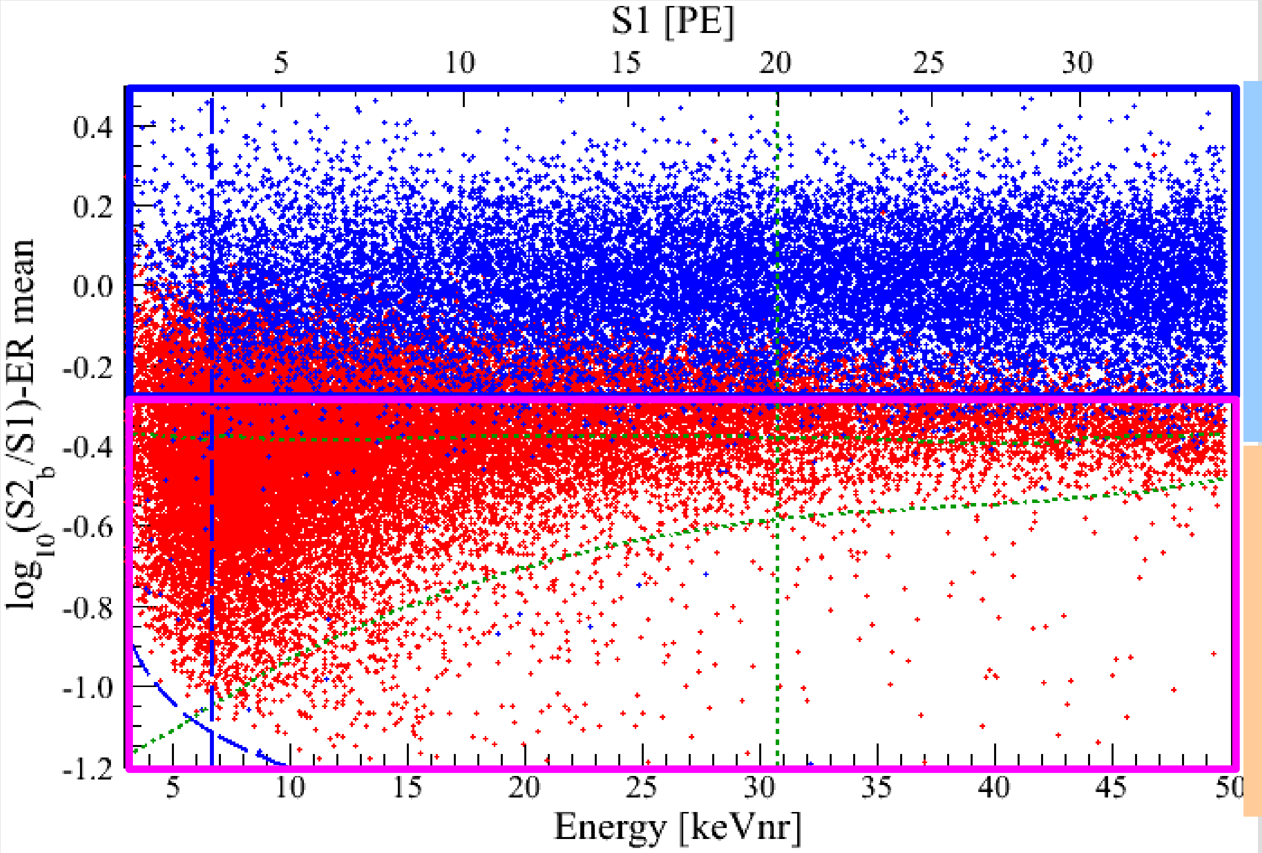
DARWIN The ultimate WIMP Detector



other than WIMPs

What (else) can we do with these instruments?

Interactions in LXe Detectors



scattering off atomic electrons, excitations etc.
→ electronic recoil

- rare processes detectable if ER background is low

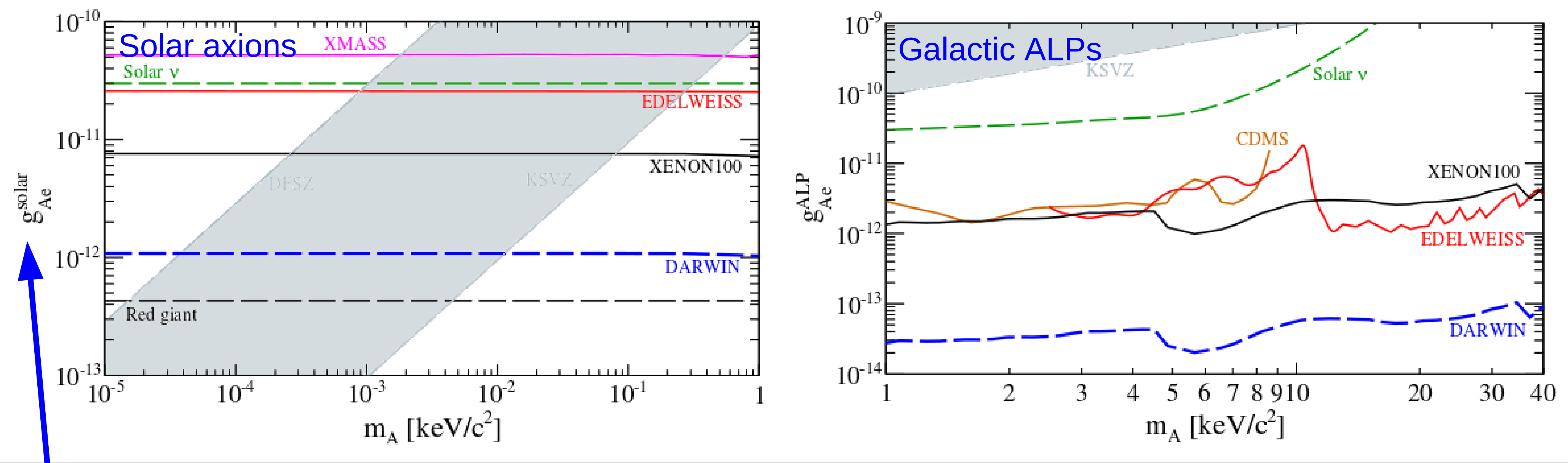
coherent scattering off xenon nucleus
→ nuclear recoil

- Dark Matter
- CNNS

Many **science channels** are accessible with a multi-ton DARWIN detector thanks to its extremly low ER background.

Solar Axions, Dark Matter ALPs

JCAP 11, 017 (2016)



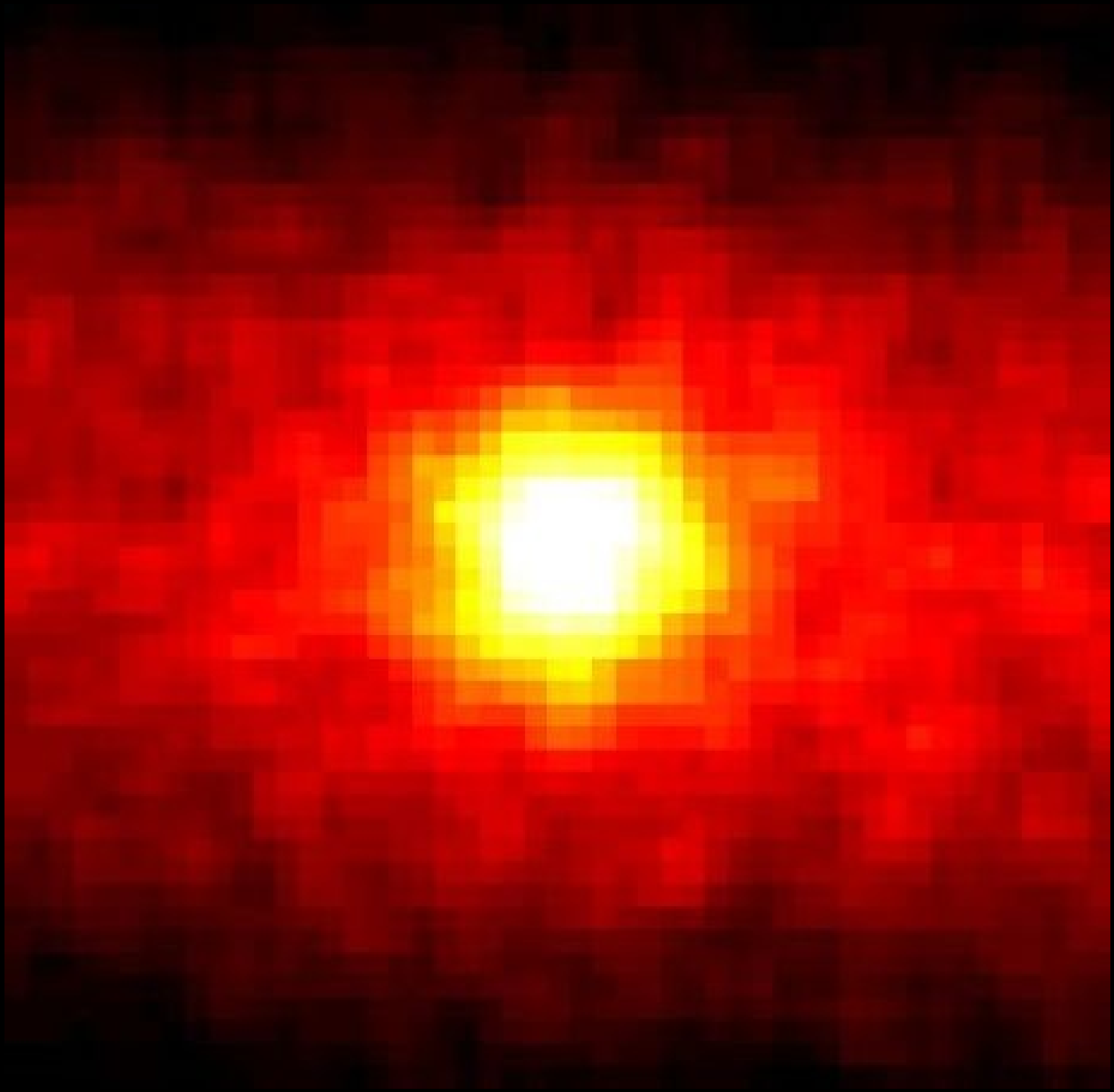
Axions and ALPs couple to xenon via **axio-electric-effect**

$$\sigma_{Ae}(E_A) = \sigma_{pe}(E_A)\frac{{g_{Ae}}^2}{\beta_A}\frac{3{E_A}^2}{16\pi\,\alpha\,{m_e}^2}\left(1-\frac{\beta_A}{3}\right)$$

→ axion ionizes a Xe atom

Axion
arises naturally in the Peccei-Quinn solution of the strong CP-problem
→ well-motivated dark matter candidate

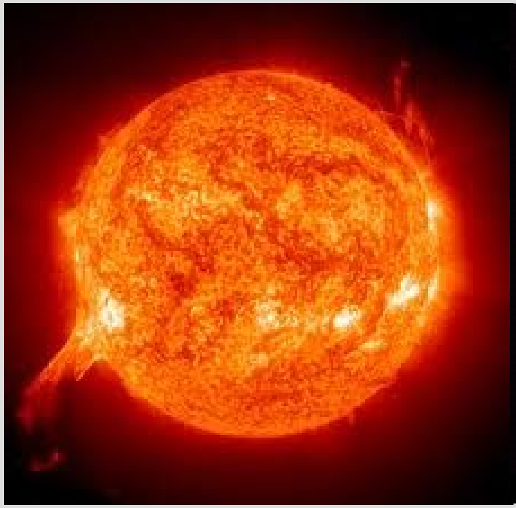
Axion-like particle (ALP)
generalization of the axion concept, but without addressing strong CP problem
(ALPs = Nambu-Goldstone bosons from breaking of some global symmetry)

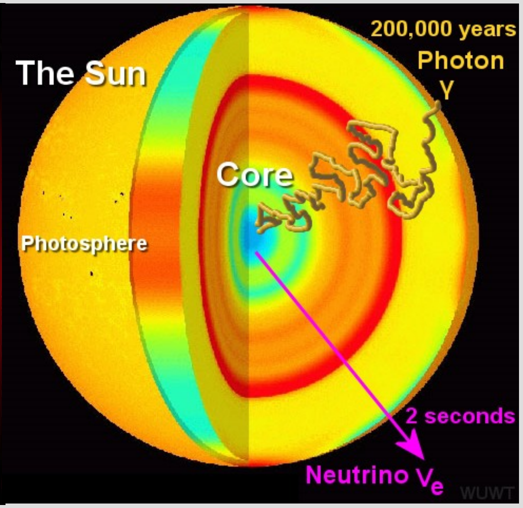


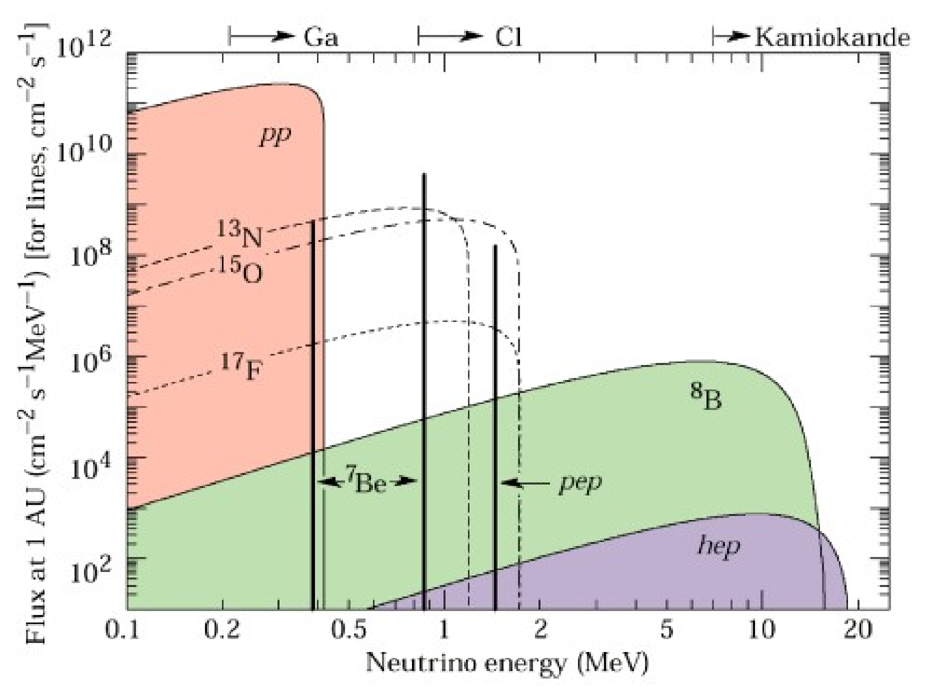
Low-E solar Neutrinos

Low-energy solar Neutrinos: pp, ^{7}Be

→ vast majority of solar neutrinos;
help to understand how the Sun works
→ very low energetic, hard to detect
→ mainly pp-neutrinos







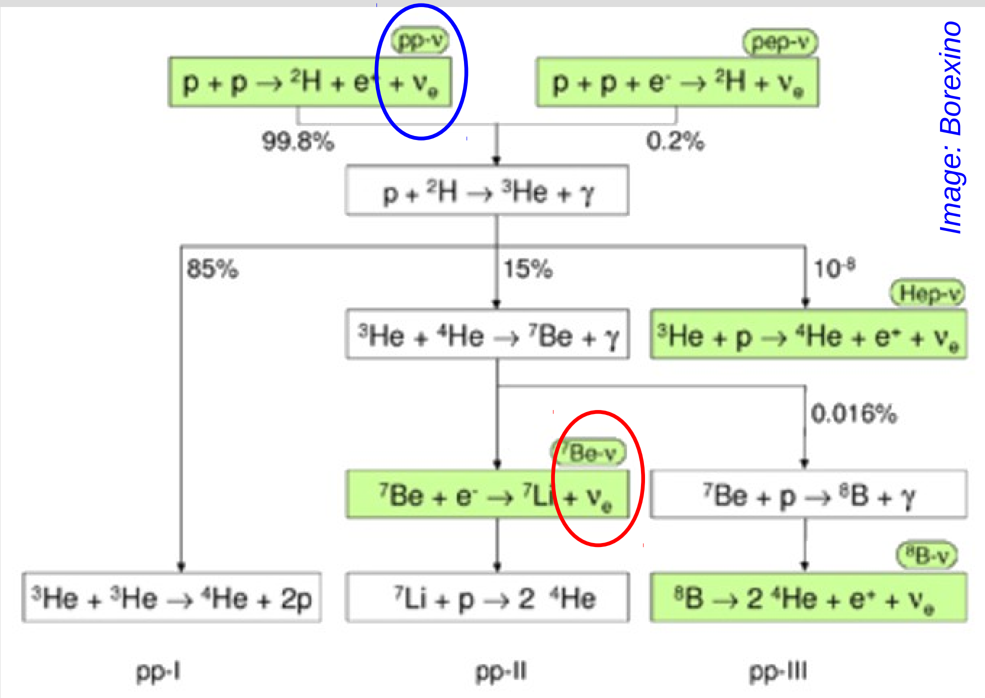


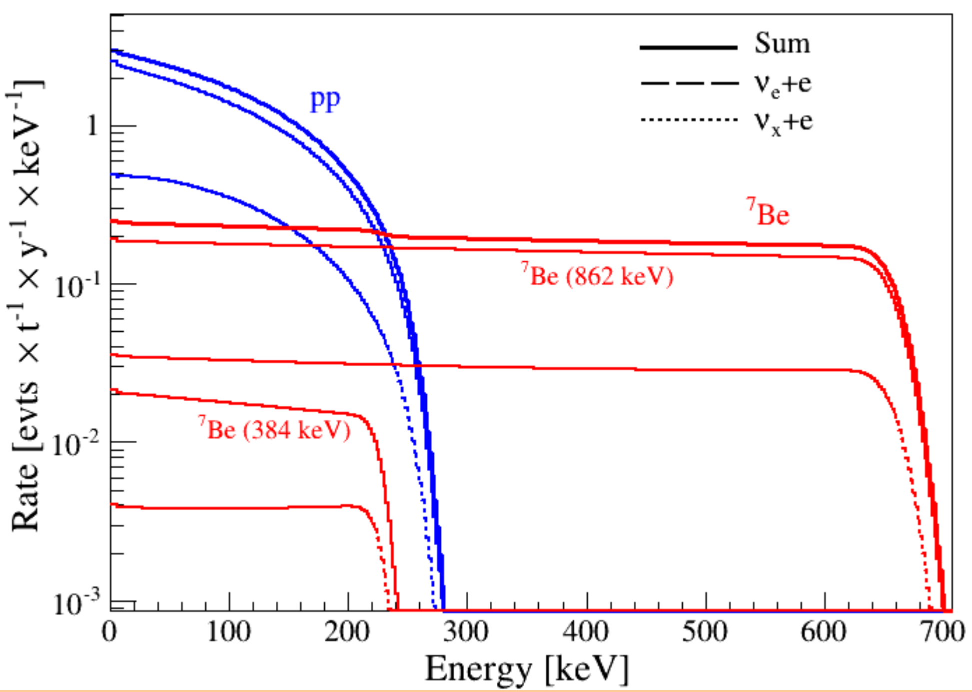
Image: Borexino

pp-Neutrinos in DARWIN

a background for the WIMP search

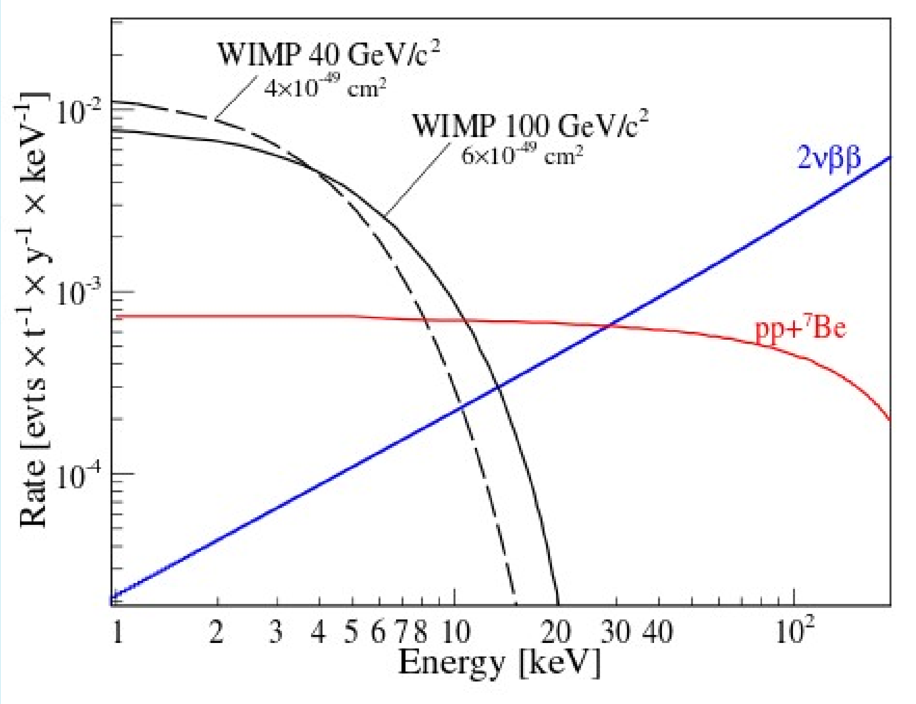
JCAP 11, 017 (2016)

Differential Recoil Spectrum in Xe



- neutrinos interact with Xe electrons
  → electronic recoil signature
- continuous recoil spectrum
  → largest rate at low E

Neutrino interactions



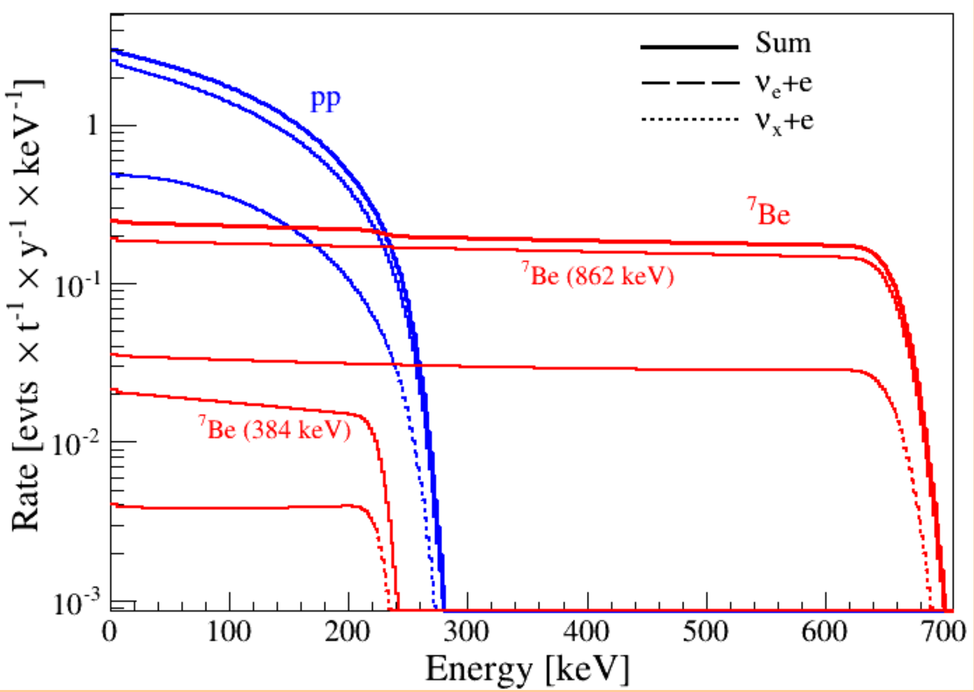
- ER rejection efficiencies ~99.98% at 30% NR efficiency are required to reduce to sub-dominant level

pp-Neutrinos in DARWIN

a new physics channel!

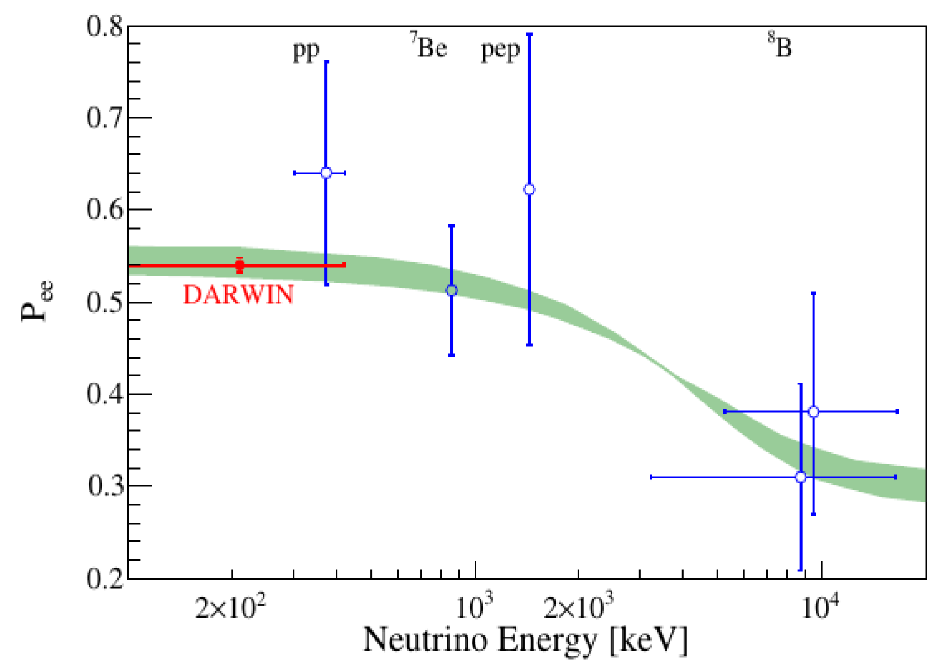
JCAP 11, 017 (2016)

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)

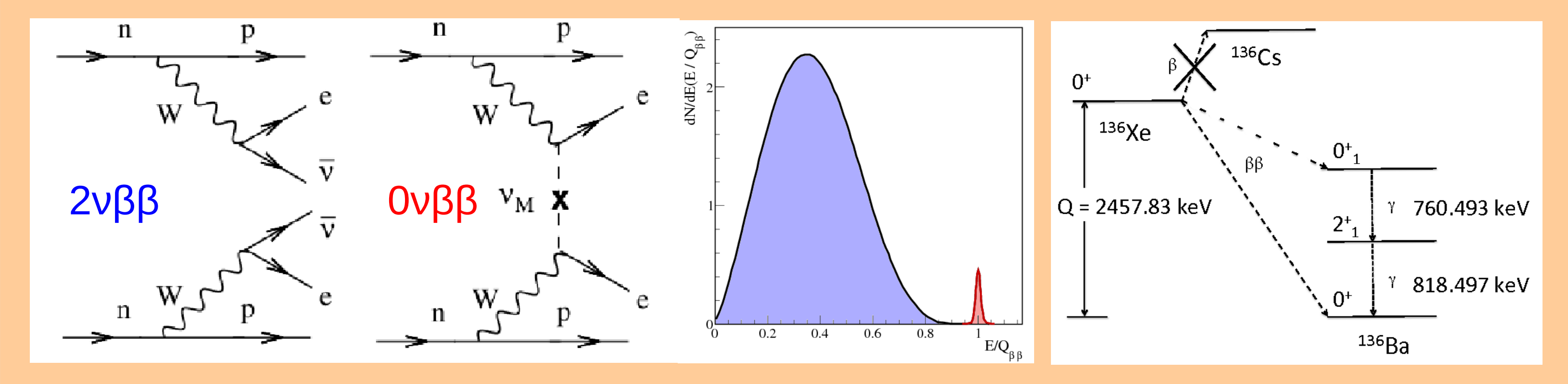
Neutrino interactions

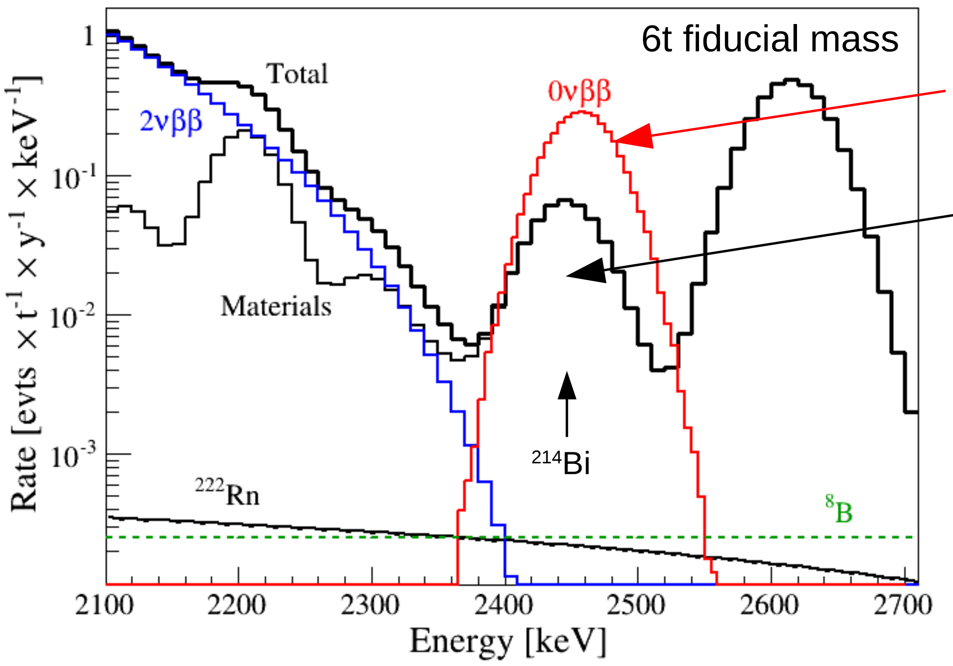


- 30t target mass, 2-30 keV window
  → 2850 neutrinos per year (89% pp)
  → achieve 1% statistical precision on pp-flux (→P_{ee}) with 100 t x y

^{136}Xe: 0ν double-beta Decay

JCAP 01, 044 (2014)





EXO-200 limit

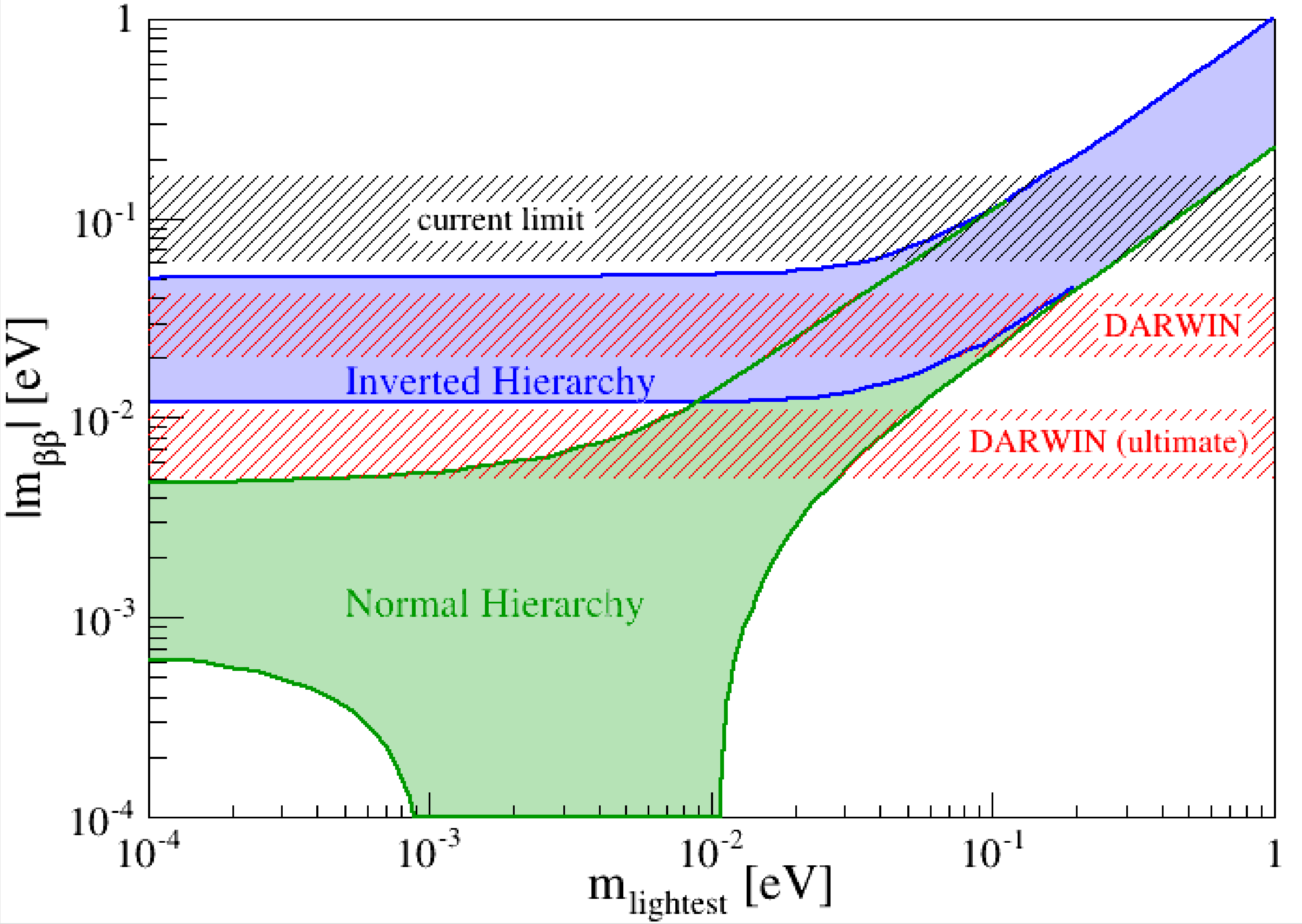
Background (6t): 4.6 evts/t/y in ±3σ

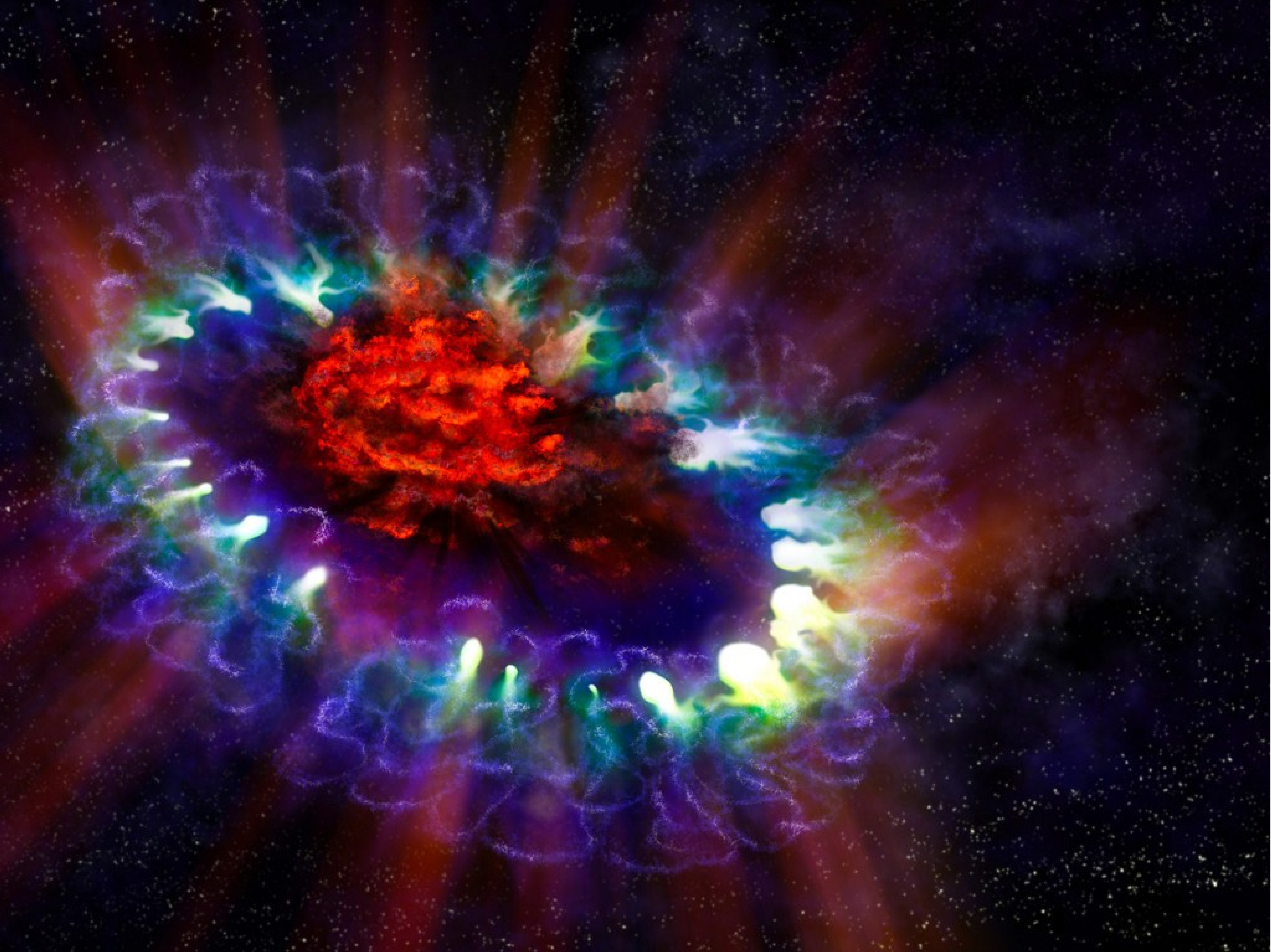
no ^{136}Xe enrichment!

- σ/E~1% at Qββ, combined *E*-scale
- signal in plot assumes $T_{1/2}$=1.6 x 10^{25} y
- sensitivity: $T_{1/2}$=5.6 x 10^{26} y (95% CL, 6t x 5y)

0ν Double-beta Decay

JCAP 11, 017 (2016)

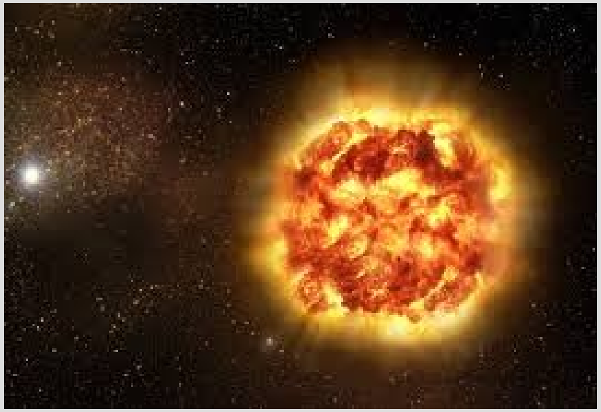


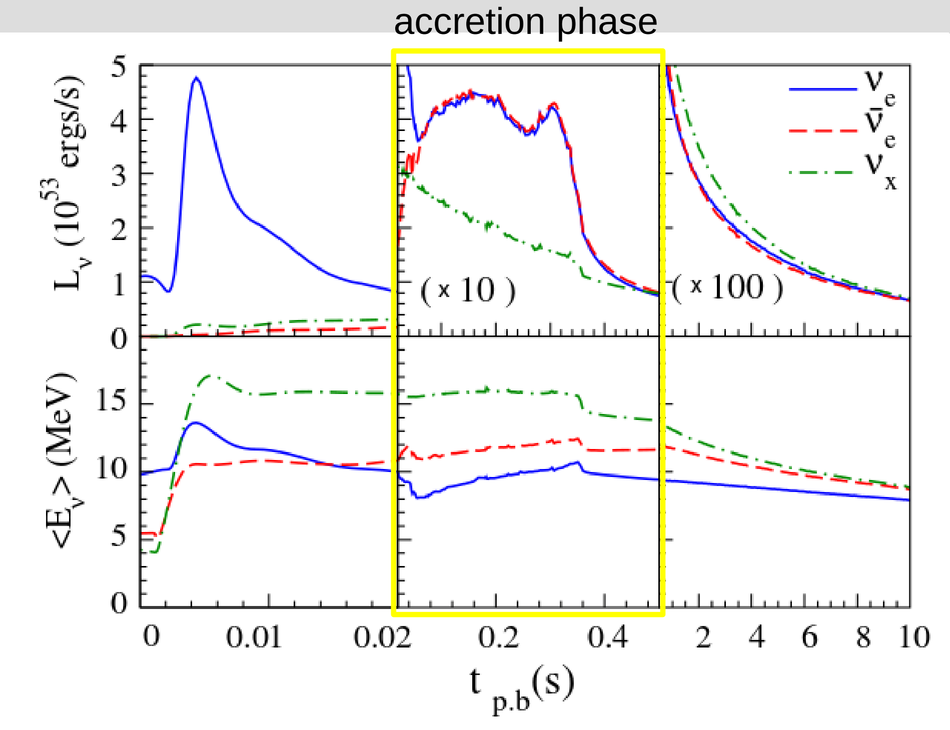


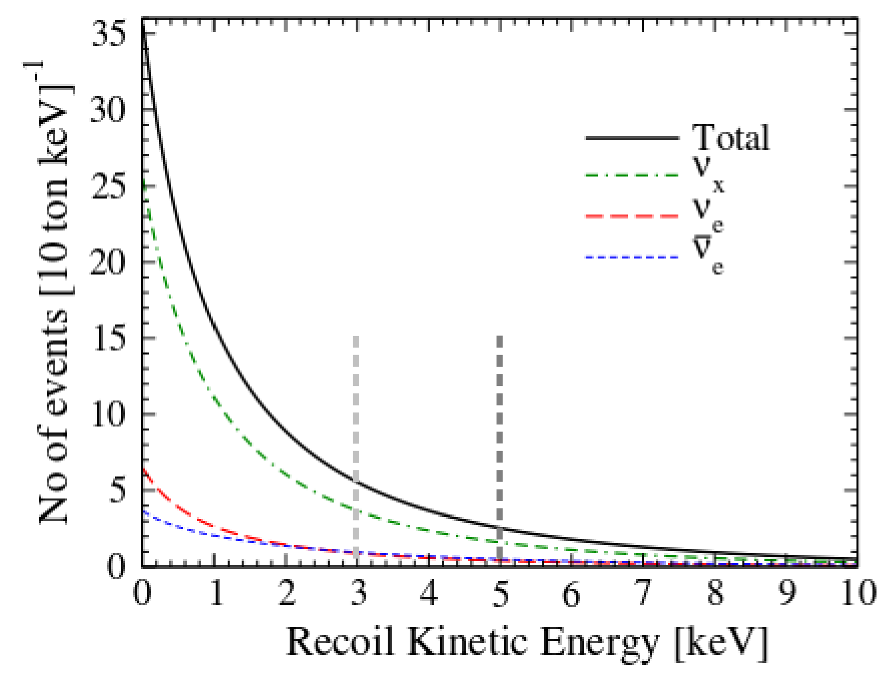
Supernova Neutrinos

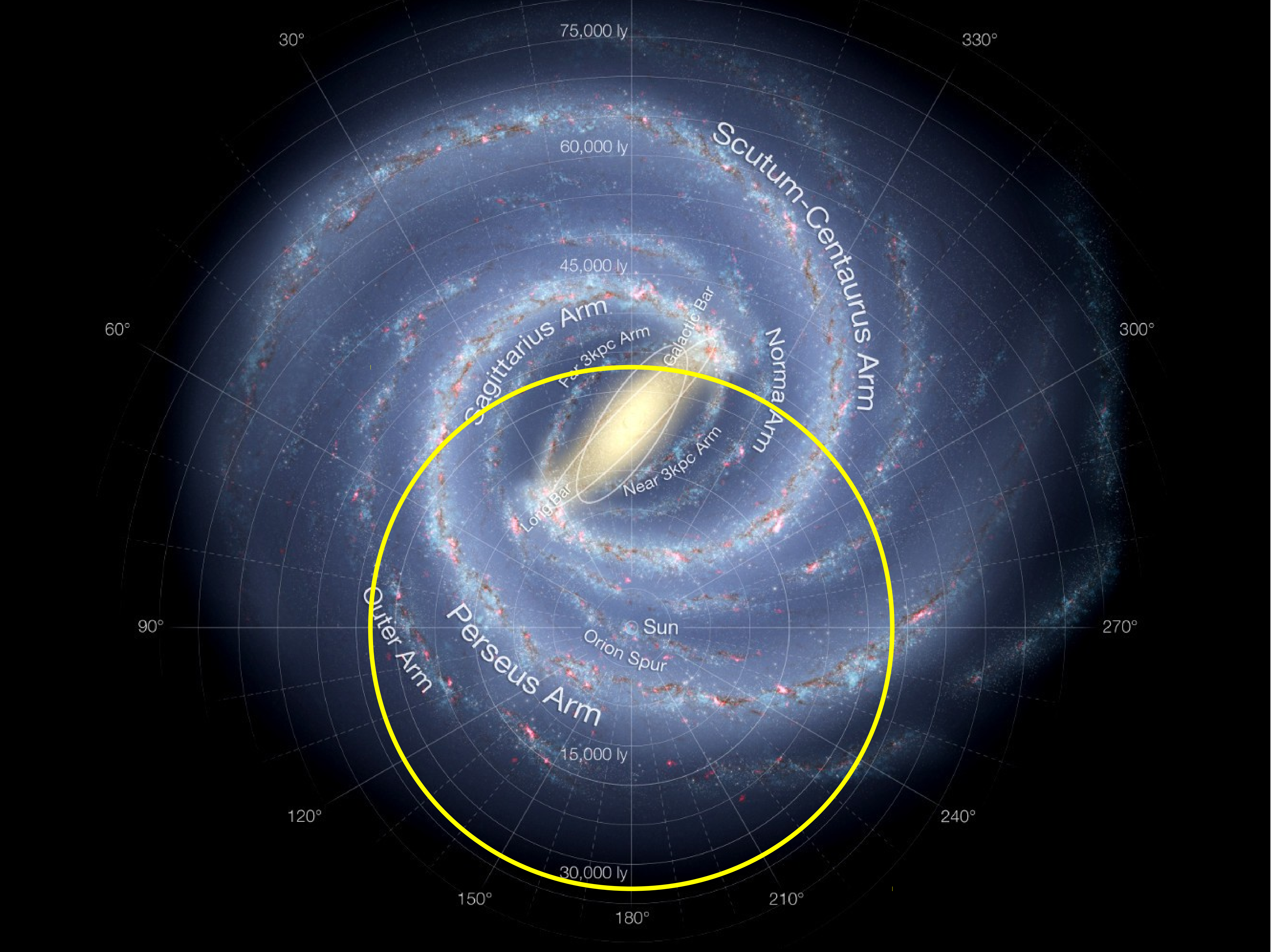
Chakraborty et al., PRD 89, 013011 (2014)
Lang et al., PRD 94, 103009 (2016)

- ν from supernovae could be detected via CNNS as well
- signal fom accretion phase of a ~18 Msun supernova @ 10 kpc is visible in a 10t-LXe detector (=DARWIN)
- signal: NRs plus precise time information
- challenge: theshold

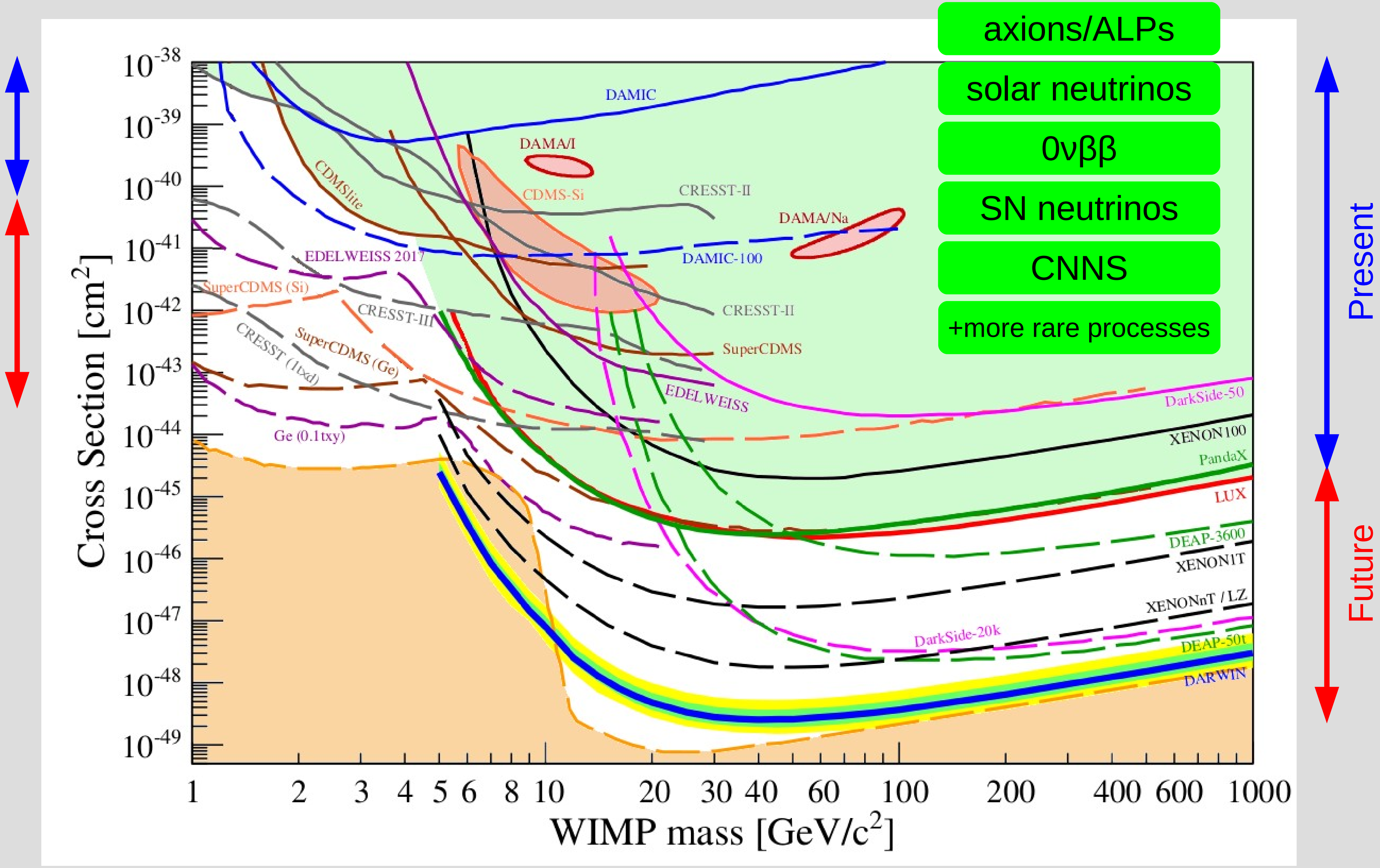



accretion phase




75,000 ly
30°
330°
60,000 ly
Scutum-Centaurus Arm
45,000 ly
Galactic Bar
Sagittarius Arm
Far 3kpc Arm
Norma Arm
60°
300°
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
90°
Sun
270°
Orion Spur
15,000 ly
120°
240°
30,000 ly
150°
210°
180°

Exciting times ahead of us



- axions/ALPs
- solar neutrinos
- 0νββ
- SN neutrinos
- CNNS
- +more rare processes