Direct Detection of Dark Matter Particles

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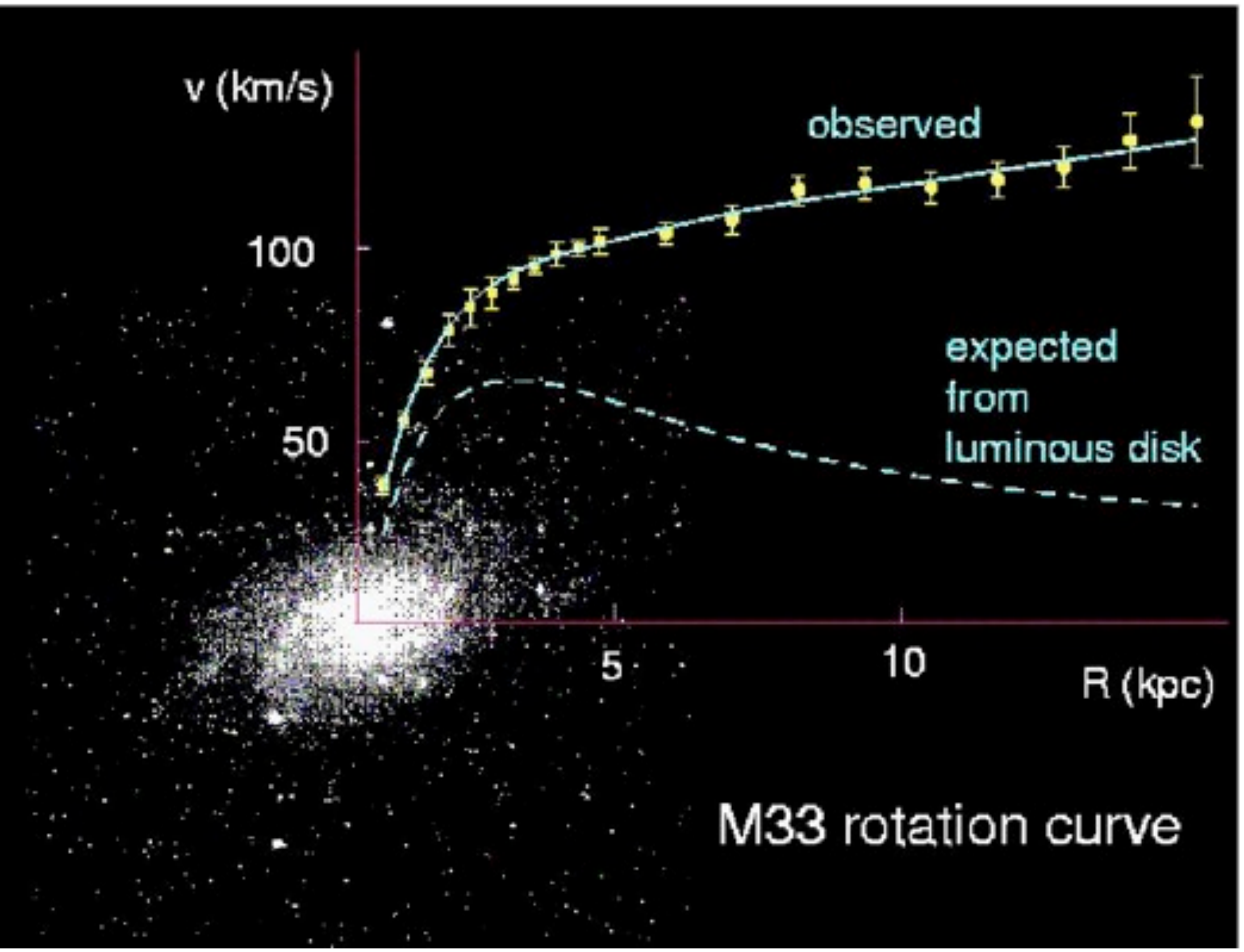
NIKHEF

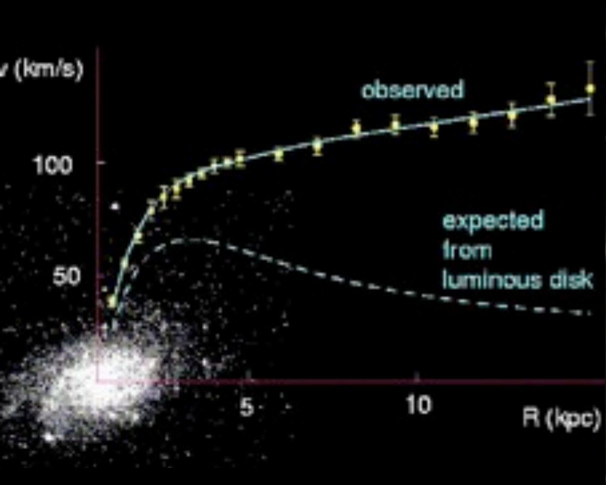
Rotation Curves



- Zwicky in 1933: luminous matter insufficient to describe gravitational binding in clusters of galaxies
- Vera Rubin in early '70: Rotational curves of spiral galaxies do not follow Newtonian expectation based on mass in luminous disk

Need non-luminous "Dark Matter"

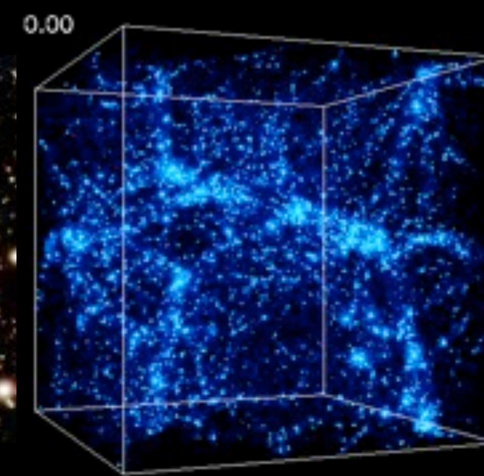
What is the subatomic origin of Dark Matter?



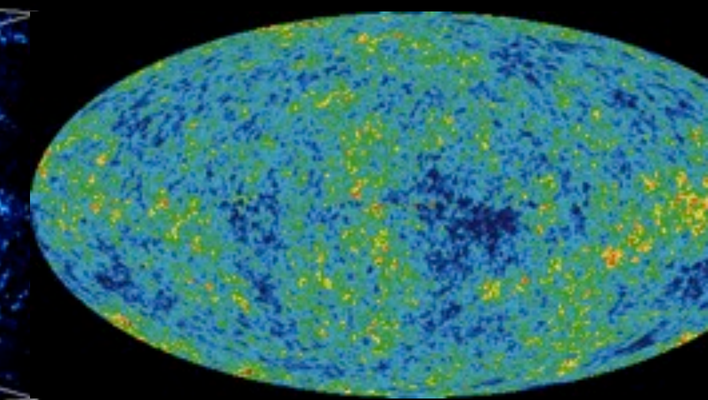
Rotational Curves

Weak Lensing

Galaxy Clusters



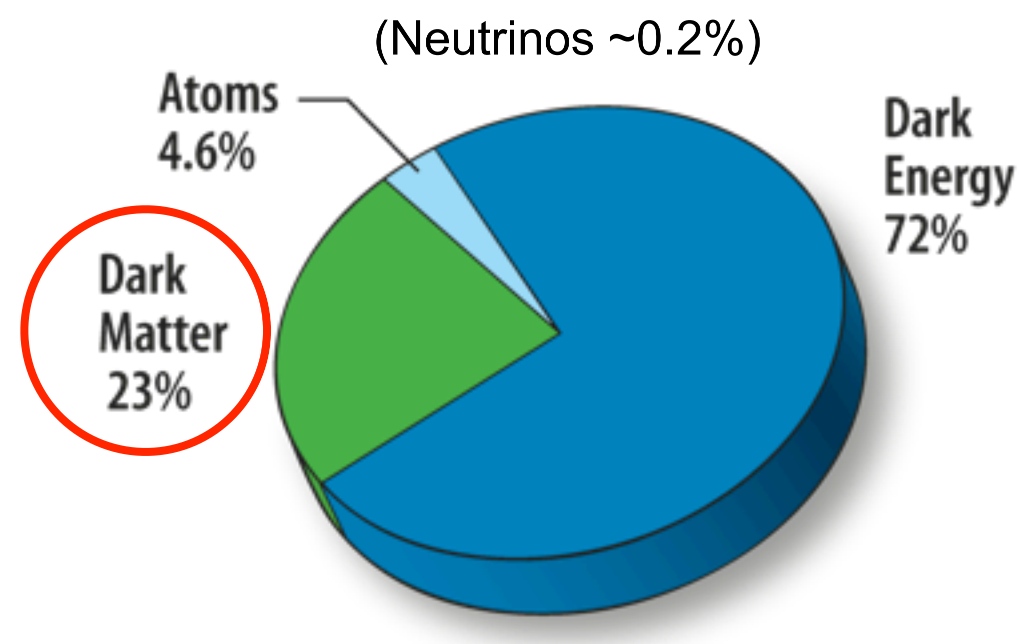
Large Scale Structure



Anisotropy in CMB

Overwhelming **cosmological** evidence for:

Non-luminous "Dark Matter"



But what is the **subatomic** origin?

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Properties of Dark Matter

- Known properties of DM:
  - Gravitationally interacting
  - No EM interactions
  - “Cold” i.e. non-relativistic
  - Non-baryonic
  - Long lived

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

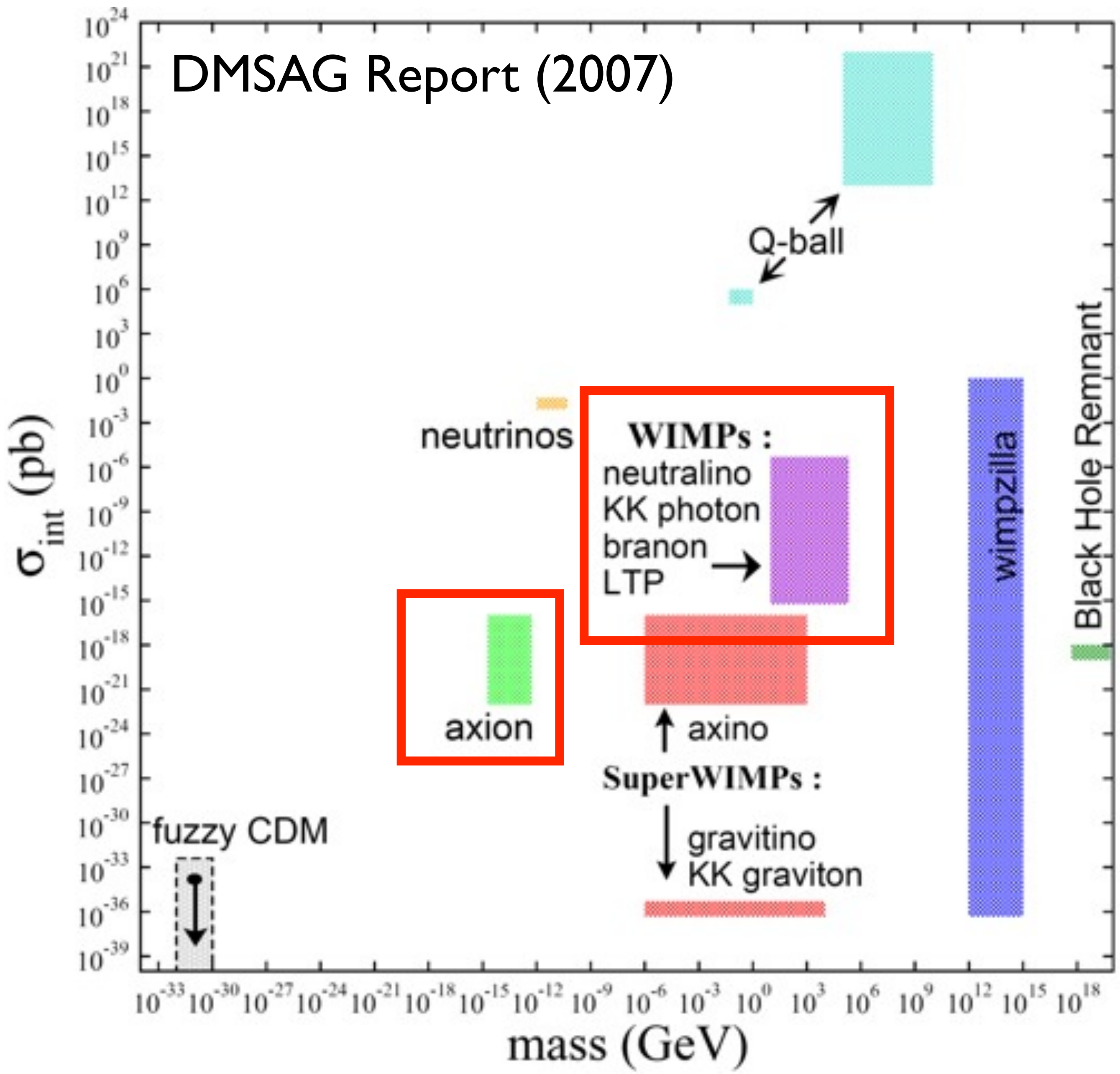
Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Has to be some new, unknown, particle

Some DM Candidates

Many candidates, usually some extension of the Standard Model



“10-point test” of DM candidates

DM candidate	I. Ωh^2 (Appropriate relic density?)	II. Cold (Is it cold?)	III. Neutral (Is it neutral?)	IV. BBN (Consistent with BBN?)	V. Stars (Leaves stellar evol. unchgnd?)	VI. Self (Compat. with self-interactions?)	VII. Direct (Consist. with direct DM searches?)	VIII. γ-rays (Consist. with gamma-ray constr.?)	IX. Astro (Consist. with other astro. constr.?)	X. Probed (Can it be probed exp.?)	Result
SM Neutrinos	×	×	✓	✓	✓	✓	✓	–	–	✓	×
Sterile Neutrinos	~	~	✓	✓	✓	✓	✓	✓	✓!	✓	~
Neutralino	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Gravitino	✓	✓	✓	~	✓	✓	✓	✓	✓	✓	~
Gravitino (broken R-parity)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	~	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	~	–	✓!	✓	✓	✓	~
B^1 **UED**	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
Axion	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
Heavy photon (Little Higgs)	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

M. Taoso, G.Bertone, A.Masiero, JCAP 0803:022,2008

√ =OK | ~ =Still viable | × = NO

What is a WIMP?

- Weakly Interacting Massive Particle miracle

$$\Omega_{DM} h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_a v \rangle}$$

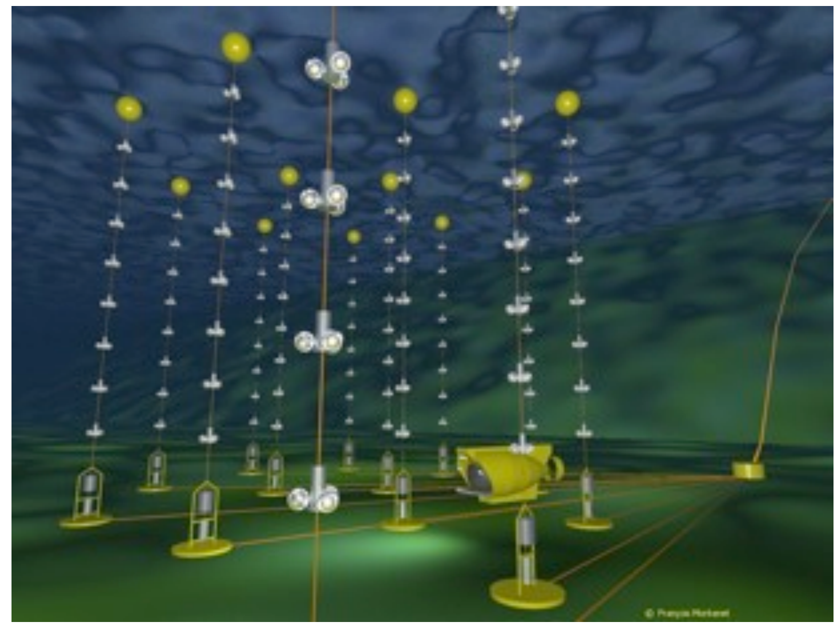
→ particles with annihilation cross sections mediated by weak interactions and mass 100GeV naturally produce right density

- The lightest superpartner (LSP) is stable in R-conserving supersymmetry (SUSY)
  - Neutralino (χ)
    - → Good WIMP candidate
- Mass of 10-1000 GeV
- Cross sections comparable to neutrino cross sections
  - Electroweak scale

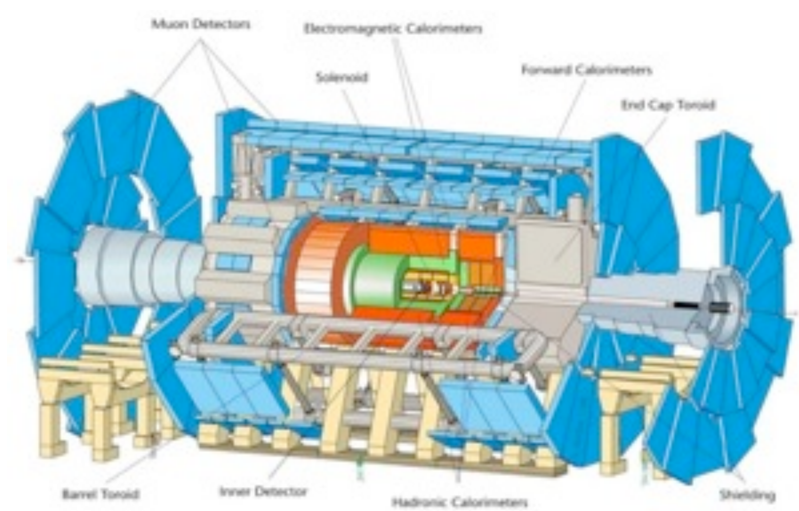
Searching for Dark Matter

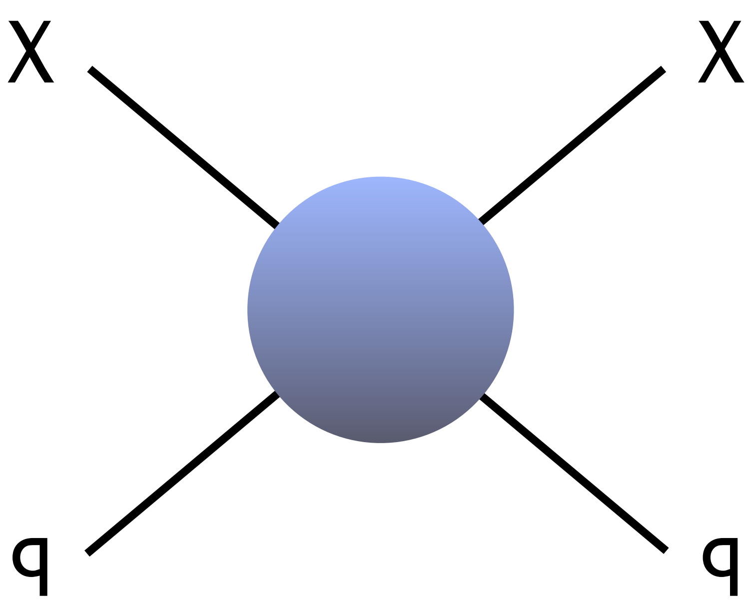
Direct Searches

Indirect Searches

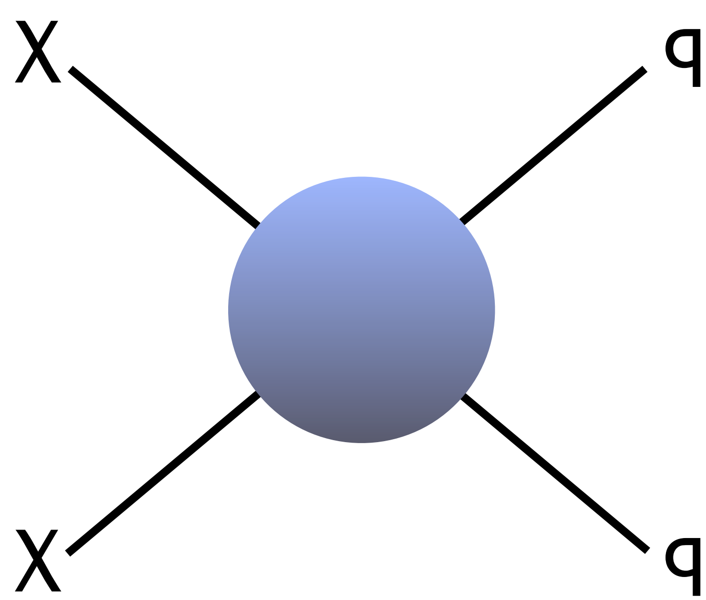


Collider Searches

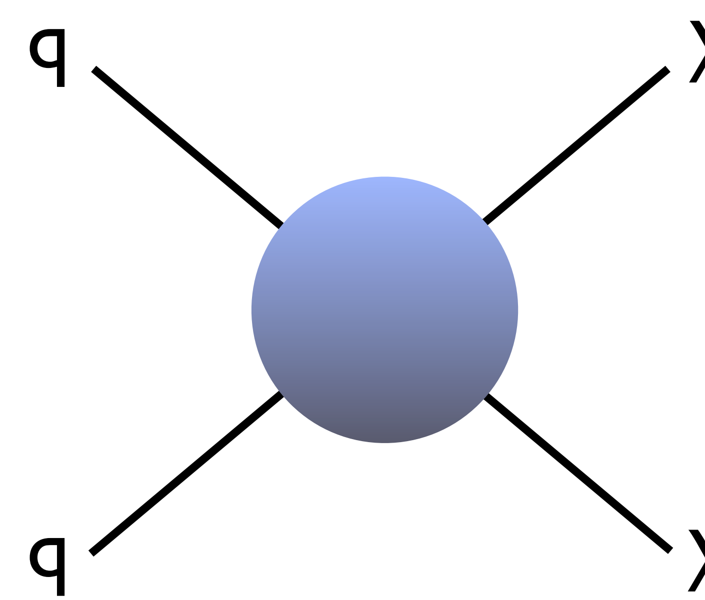




Scattering

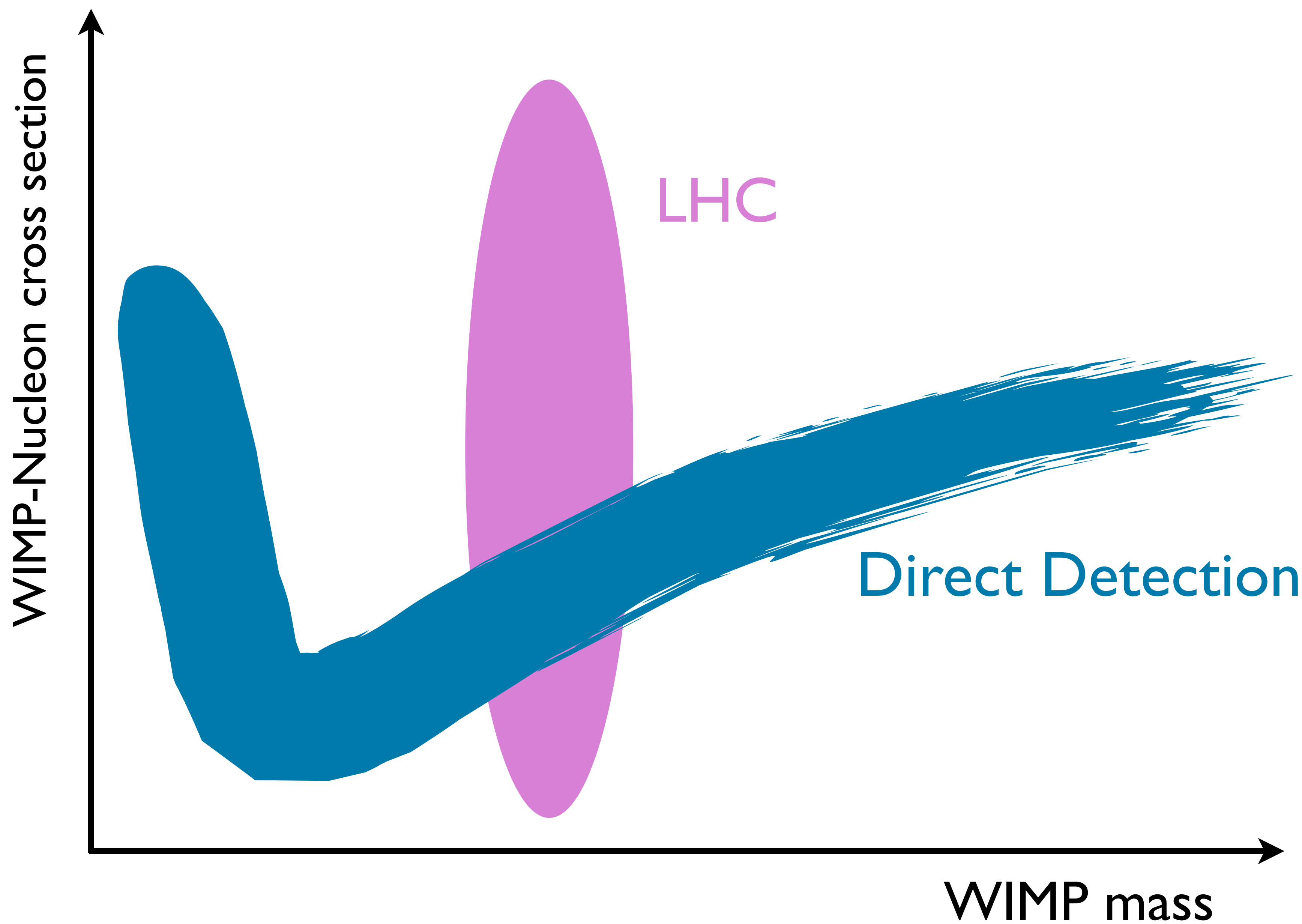


Annihilation



Production

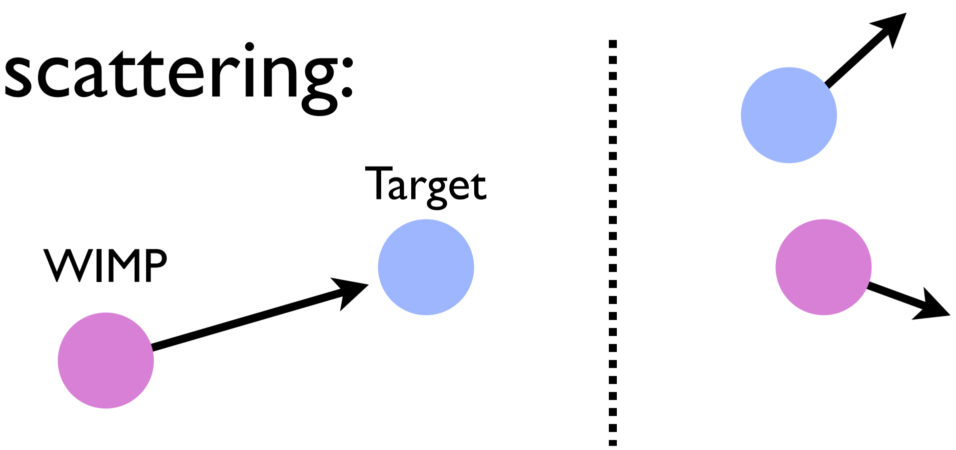
Complementarity between approaches



See, e.g. G.Bertone *et al.*, arXiv:1107.1715

Direct Detection DM Experiments

Elastic scattering:



- Uses the local "WIMP wind" in DM halo of Milky Way :

$$\left.\begin{array}{r}\rho_{DM} \approx 0.3\,\mathrm{GeV/cm^3} \\ v_{solar} \approx 220\mathrm{km/s} \\ M_{WIMP} = 100\mathrm{GeV}\end{array}\right\} \rightarrow \sim\ 10^9\ \mathrm{WIMPs\ m^{-2}s^{-1}}$$

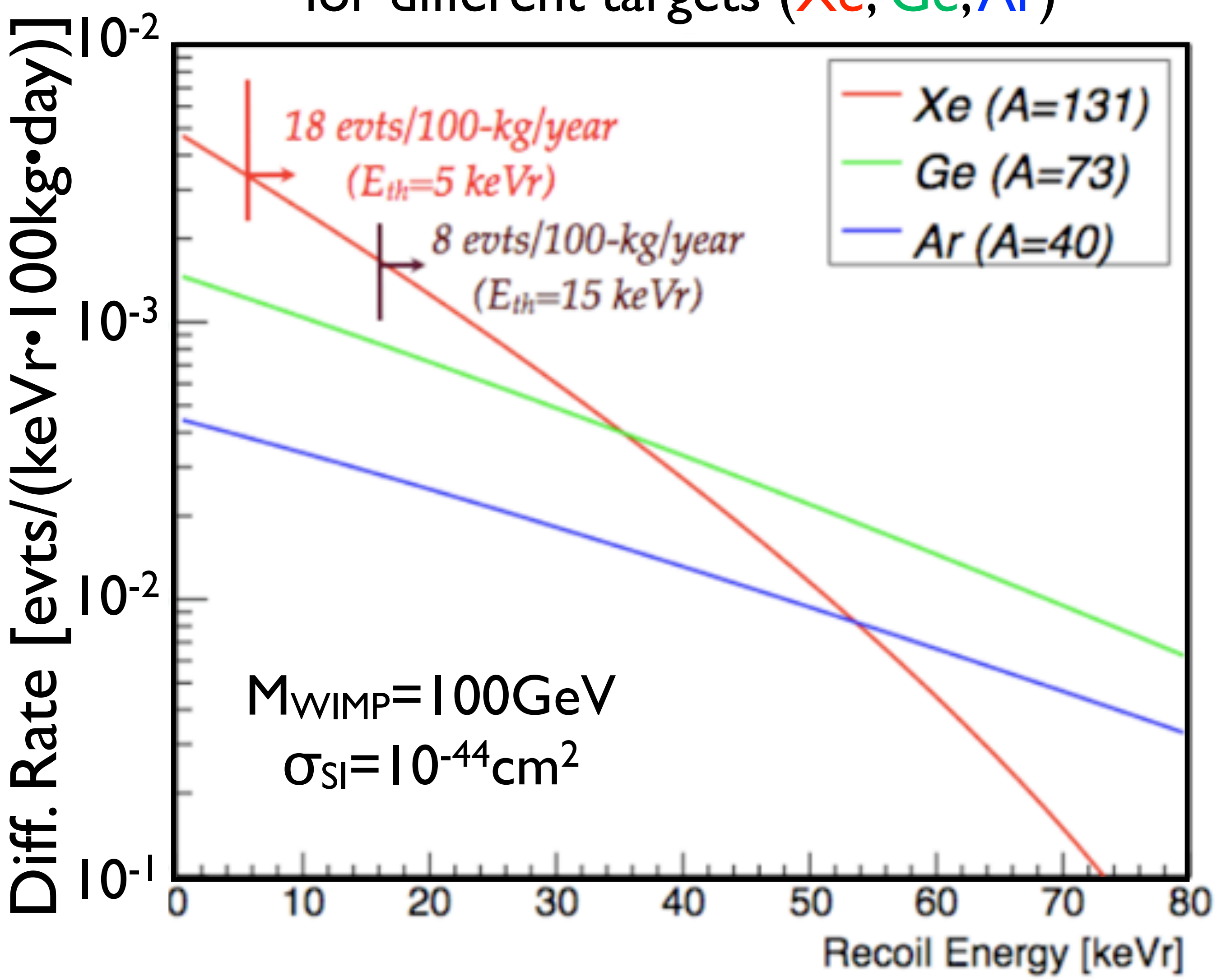
- Elastic scattering off a heavy nucleus
- Most direct method of identifying dark matter

Spin dependence

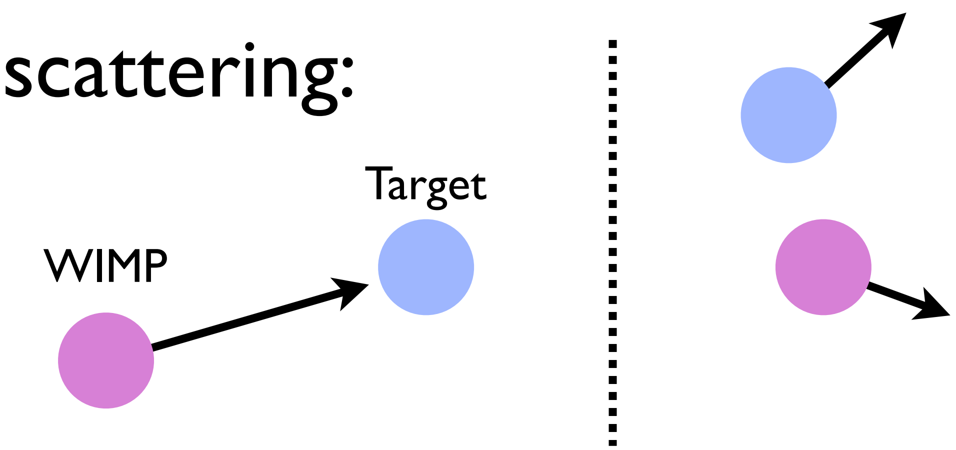
- $\sigma_{\chi N} = \sigma_{SI} + \sigma_{SD}$
- σ_{SI} - **Spin-independent** cross section:
  - Coherent enhancement, cross section grows as A^2 :
- σ_{SD} - **Spin-dependent** cross sections:
  - Axial-vector interactions result in WIMP couplings to the spin of the nucleus J
  - $\sigma_{SD}=0$ for even-even nuclei
- $\sigma_{SI} > \sigma_{SD}$ for A > ~30 and σ_{SD} is typically ignored
  - Important exceptions:
    - ^{19}F, ^{23}Na, ^{73}Ge, ^{127}I, ^{129}Xe, ^{131}Xe, ^{133}Cs

Expected Energy Spectrum

WIMP Scatt. Rates per 100kg per day
for different targets (Xe, Ge, Ar)



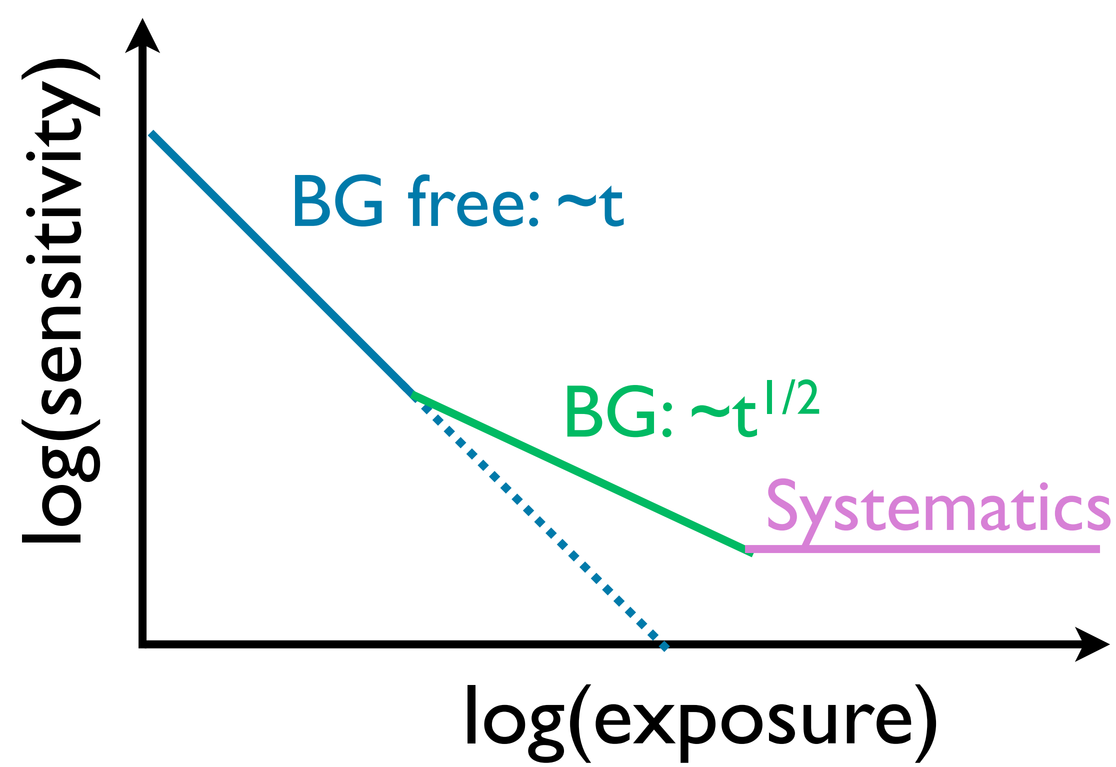
Elastic scattering:



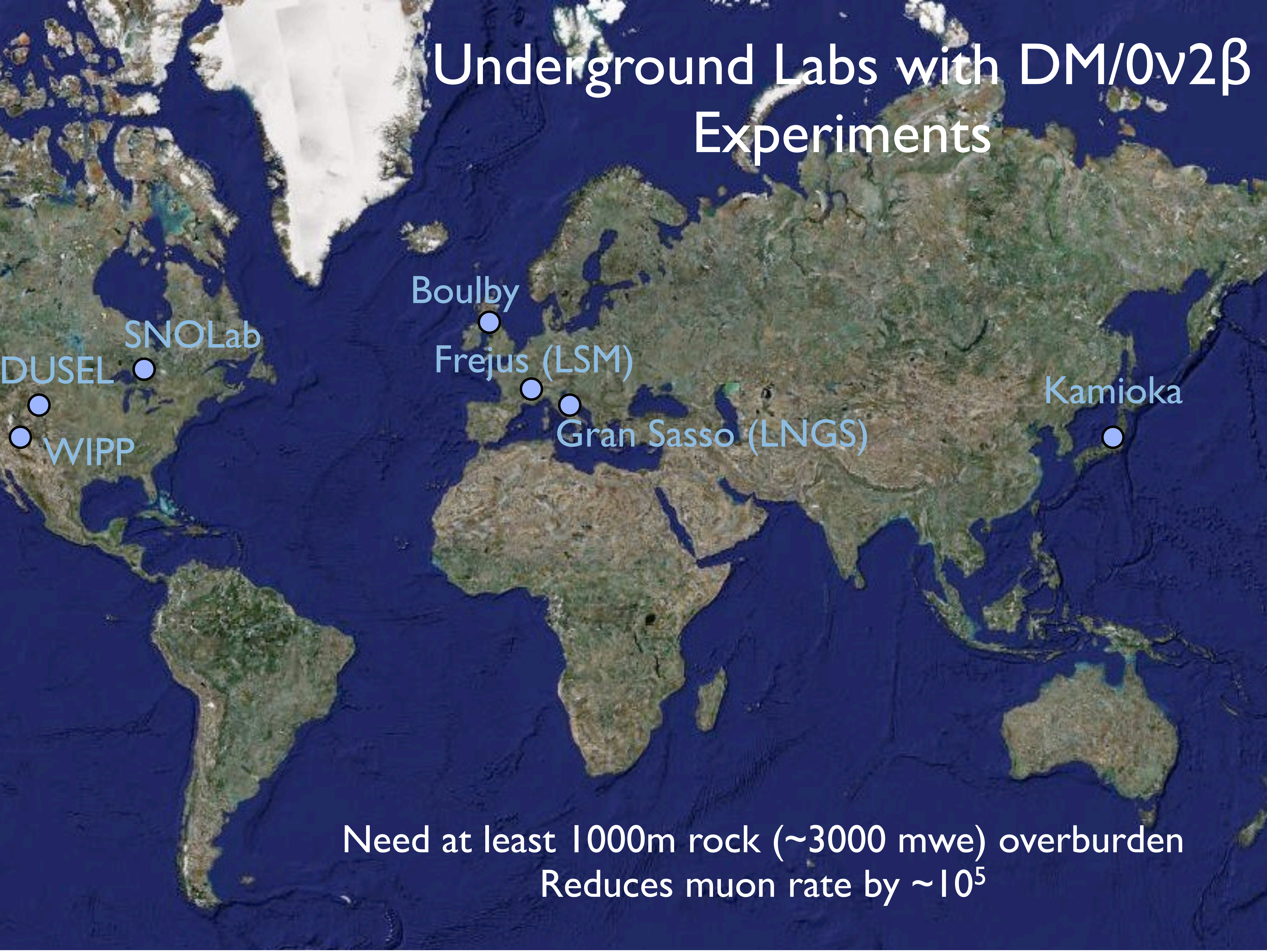
- Elastic collisions with nuclei
  - WIMP velocity ~10^{-3}c
- Energy of recoiling nucleus is tiny : <50 **keV** (!)
- Rates are uncertain, since they depend on model
- Spectrum is featureless (no bumps)

Minimizing Backgrounds

- Critical aspect of any rare event search
- Purity of materials
  - Copper, germanium, neon, xenon among the cleanest with no natural occurring long-lived isotopes
  - Ancient lead, if free of Pb-210
- Shielding
  - External U/Th/K backgrounds
- Krypton and Radon mitigation
- Material handling and assaying
  - Surface preparation, cosmic activation
- Underground siting and active veto
  - Avoid muon-induced neutrons
- Detector-based discrimination



Underground Labs with DM/0ν2β Experiments



Need at least 1000m rock (~3000 mwe) overburden
Reduces muon rate by ~10^5

Direct DM detection techniques

Measuring WIMP recoil energy: detector = target

- Single channel techniques
  - Ionization: Ge-detectors [CoGeNT]
  - Scintillation: NaI [DAMA/Libra], LXe [XMASS]
  - Phonons: [CRESST-I]
- Two-channel techniques: combination of above for better radioactive background rejection
  - Ionization & Phonons: cryogenic Ge&Si [CDMS, Edelweiss]
  - Ionization & Scintillation: LXe [XENON,ZEPLIN] & LAr [WARP]
  - Scintillation & Phonons: cryogenic $CaWO_4$ [CRESST-II]
- Tracking gas detector [DRIFT]
- Bubble chambers - superheated droplets [Picasso, COUPP]

Present Status for direct detection DM

- A number of "claims" out there - light WIMP mass:
  - DAMA: annual modulation "at 8.9σ"
  - CoGeNT: indication of an annual modulation, can't explain it with BG
  - CRESST-II: sees 67 events, not consistent with background
- WIMP parameters from these experiments inconsistent…
- ~10GeV region is experimentally challenging
  - systematic uncertainties on quenching, energy scale, thresholds, backgrounds…
- Astrophysics alone cannot reconcile the differences observed in experiments

Nobel Liquid Detectors

- Target is detection medium
- Target material has to be purified of radioactive contaminants to a high degree
  - → Nobel liquids

	Unit	Neon	Argon	Xenon
Z		10	18	54
A		20	40	~132
Liquid Density	g/cm^3	1.21	1.4	3.06
Energy Loss (dE/dX)	MeV/cm	1.4	2.1	3.8
Radiation Length	cm	24	14	2.8
Boiling Temperature	°K	27.1	87.3	165
Scintillation Wavelength	nm	85	125	175
Scintillation	photon/keV	30	40	46
Ionization	e^-/keV	46	42	64
Background Isotope		No	^{39}Ar (1 Bq/kg)	^{136}Xe
Price	$ /ton	$90k	$20k	~$1.2M

WIMP-nucleon spin-independent cross section grows as A^2
→ Using xenon attractive

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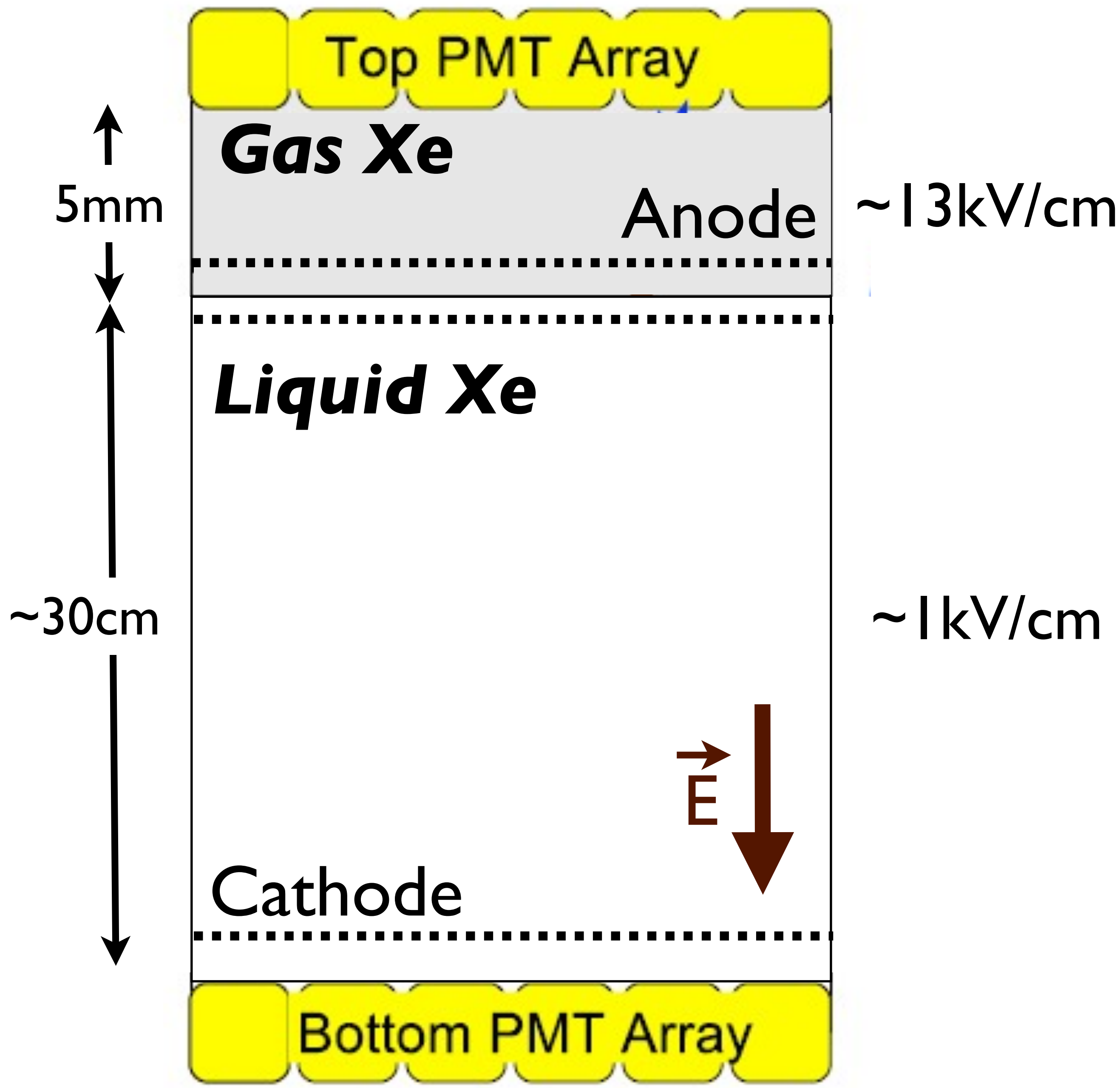
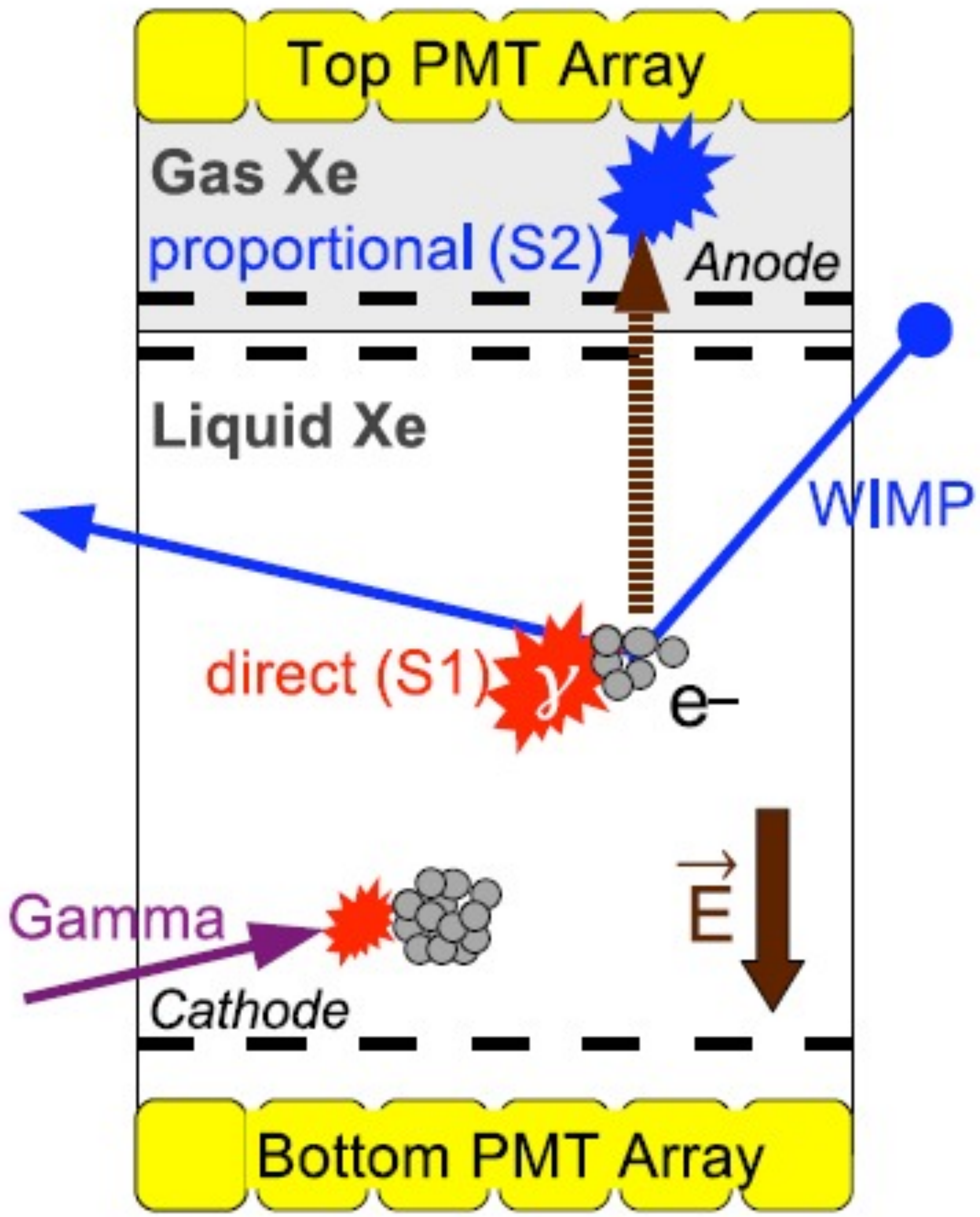
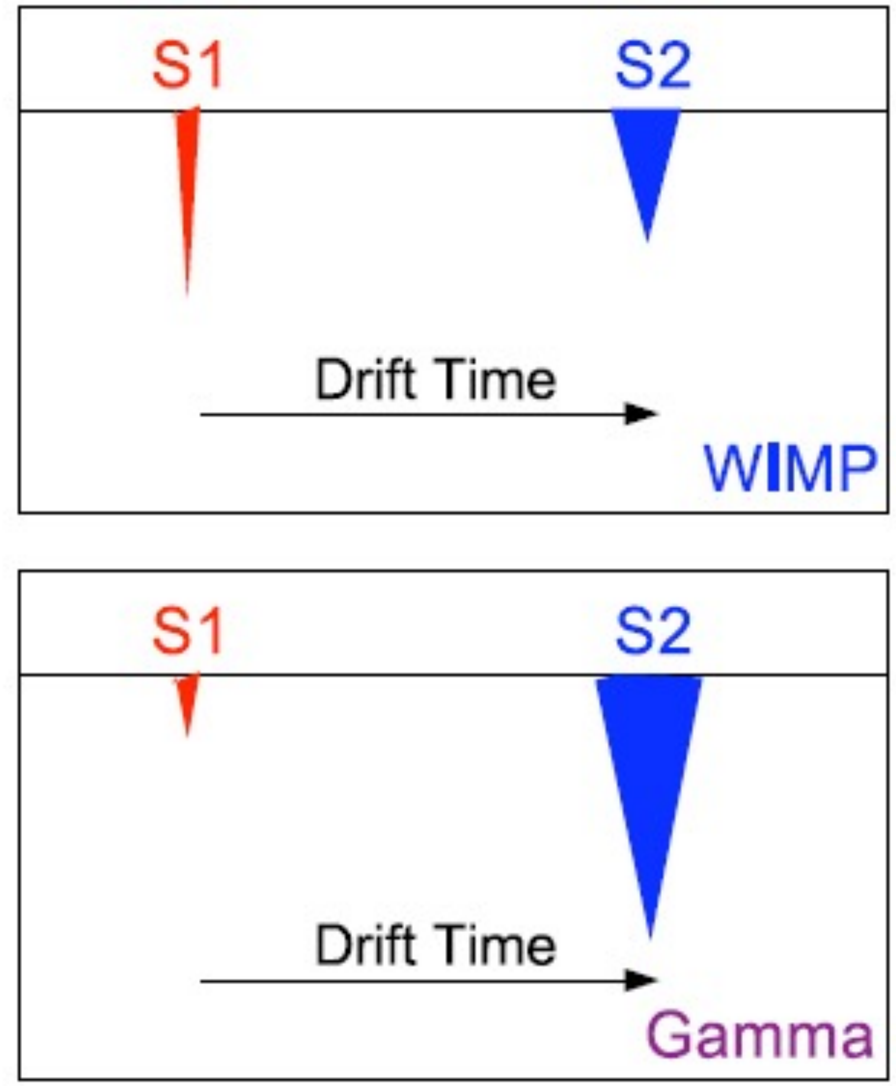
Dual-Phase Xe TPC



Detection Properties



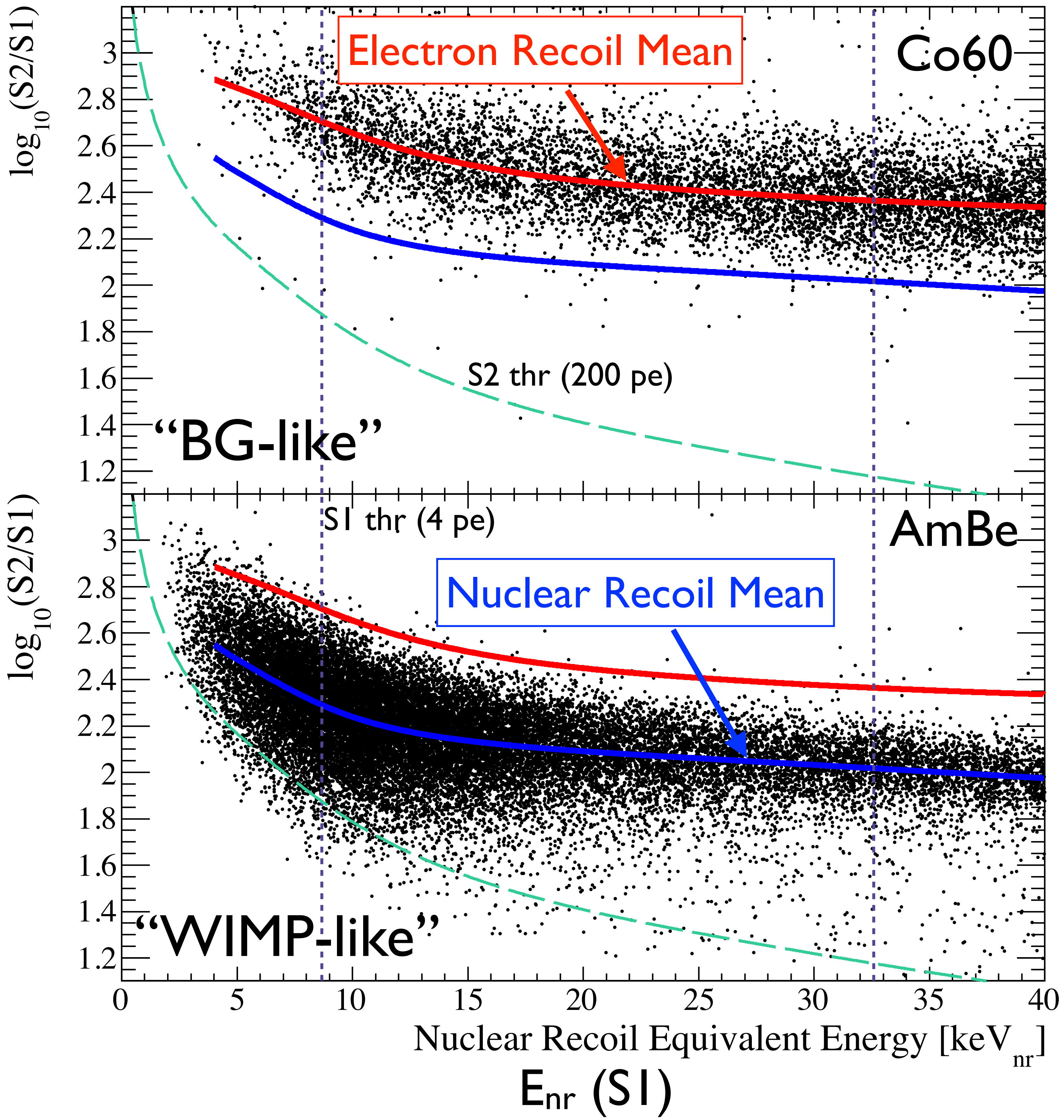


Signal:
nuclear recoil

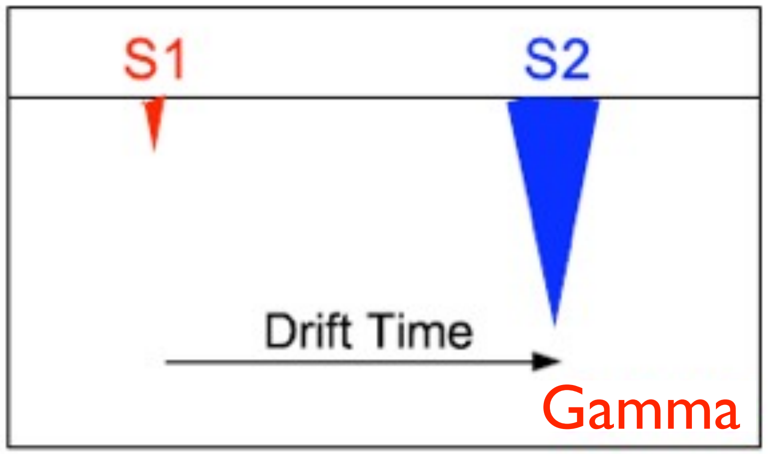
Background:
Electron recoil

$(S2/S1)_{WIMP} \ll (S2/S1)_{Gamma}$

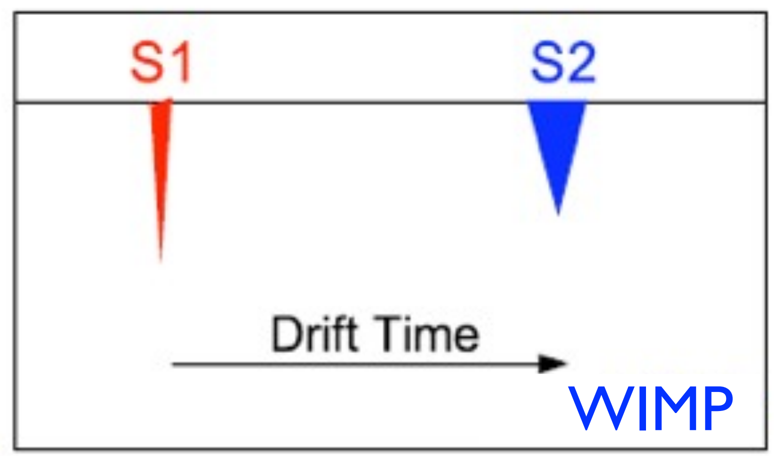
Discrimination through S2/S1



Gamma Source

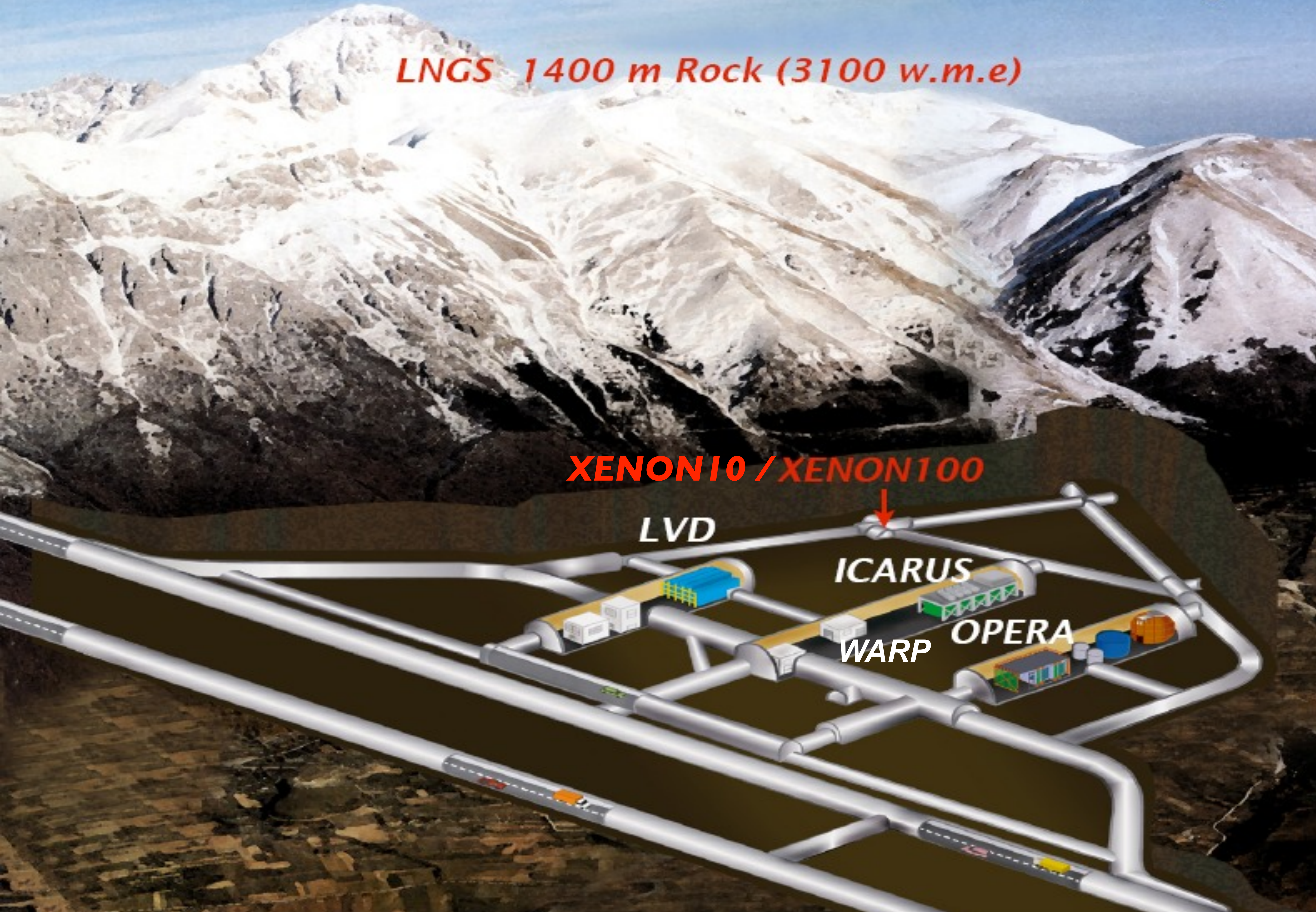


Neutron Source

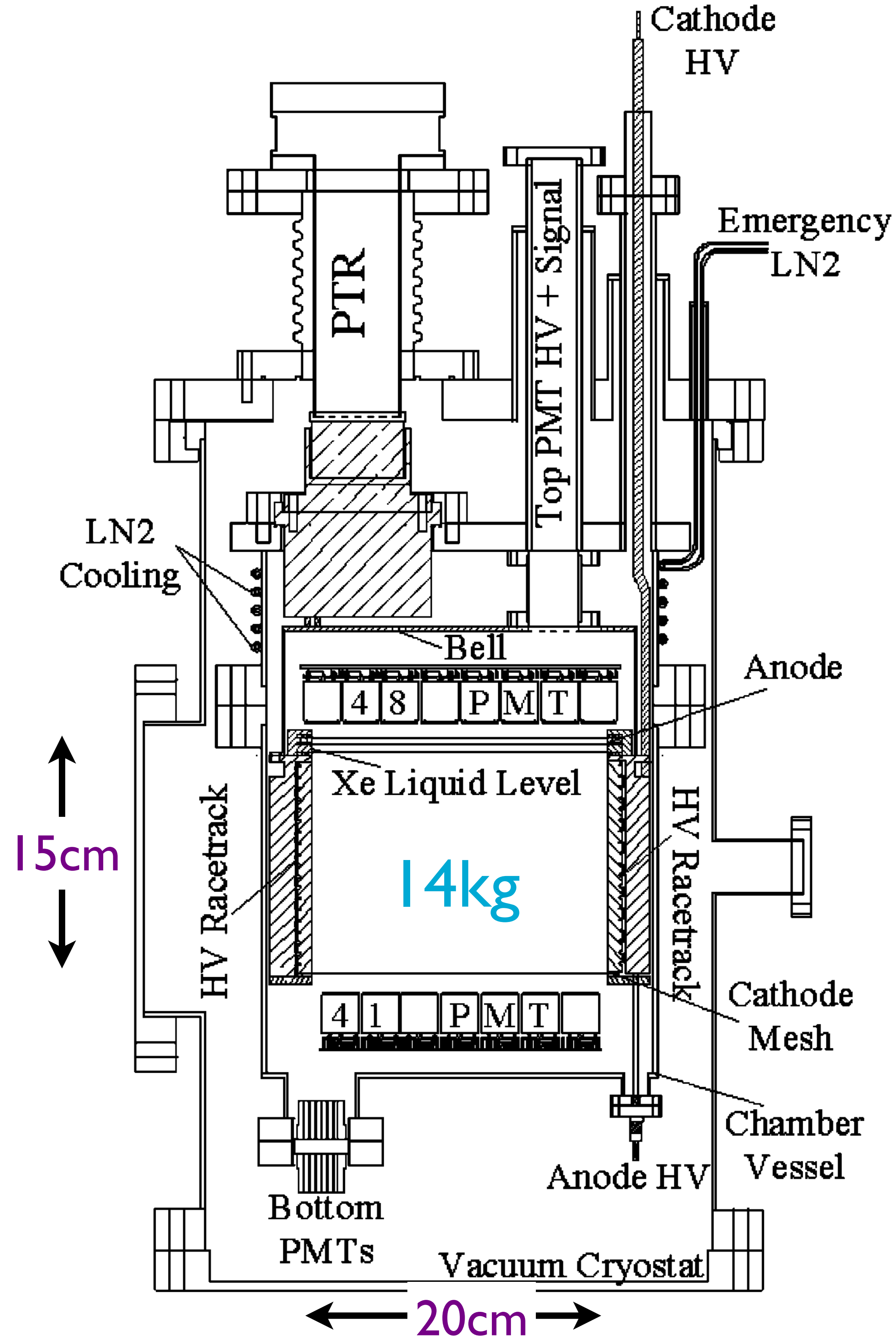


Detector-based background rejection of 99.75% [XENON100]

Laboratori Nazionali del Gran Sasso, Italy

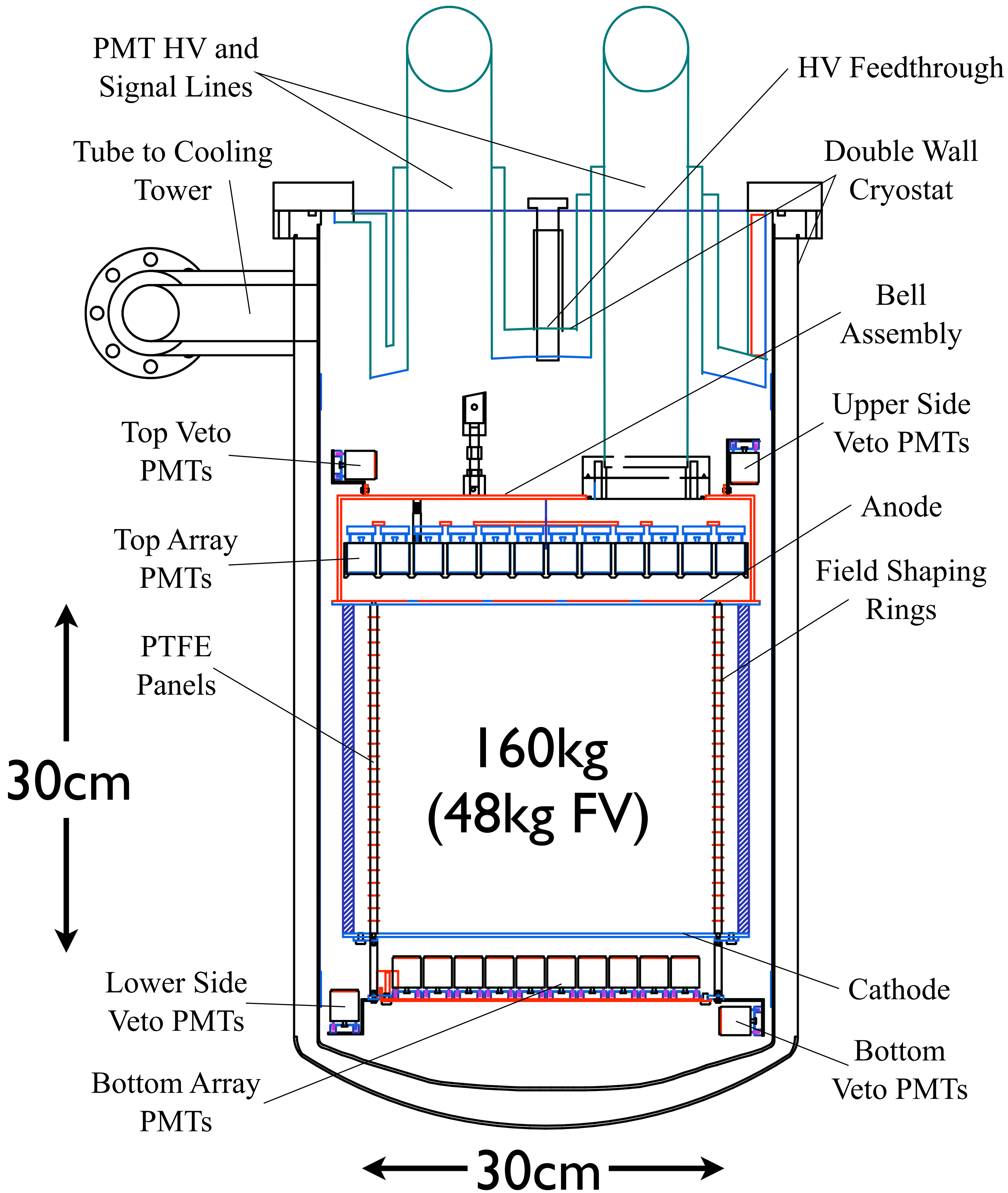


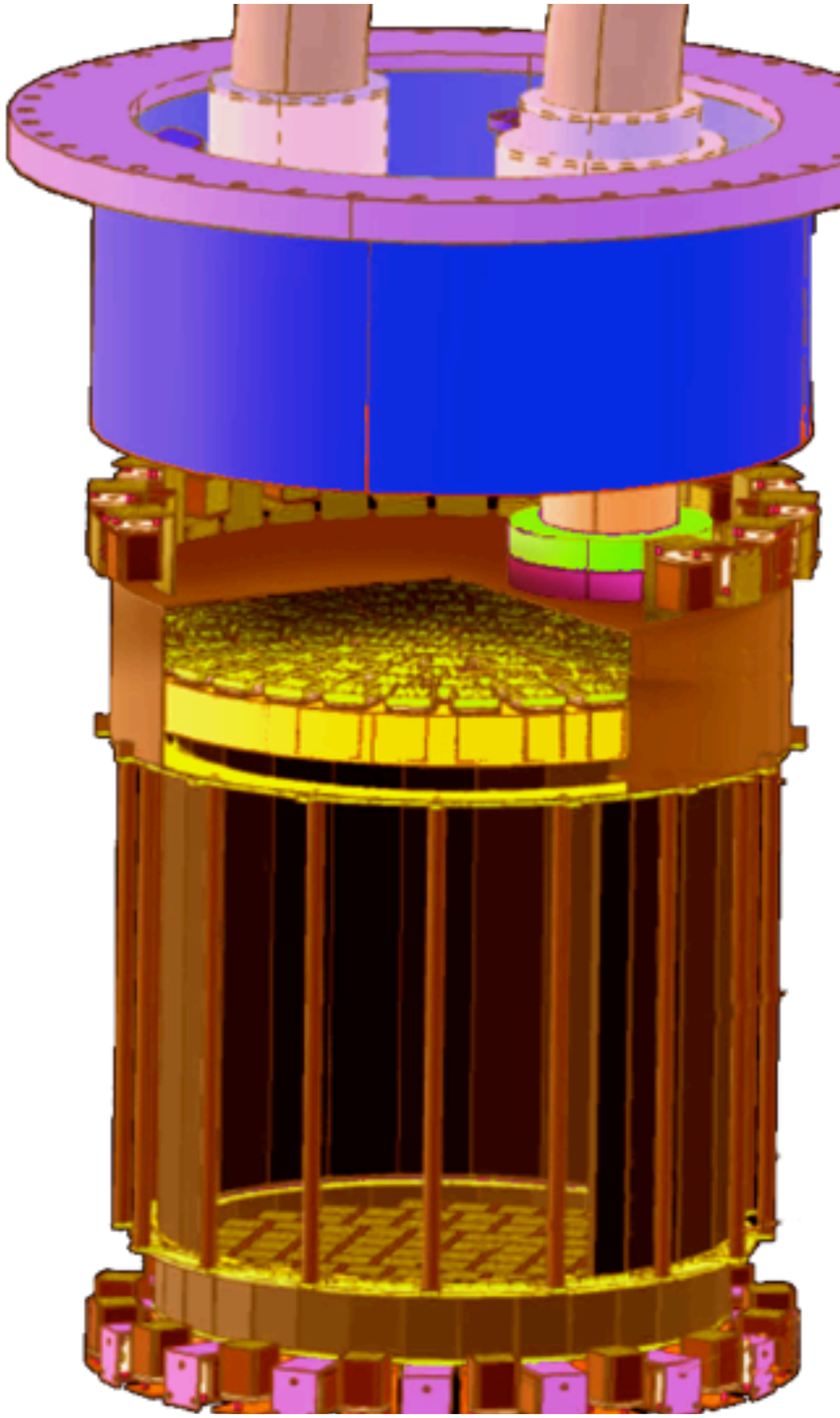
2007: XENON10



XENON10 and ZEPIN-II proved that reliable dual-phase Xe TPCs possible

2009: XENON100





XENON100 started physics run in early 2010

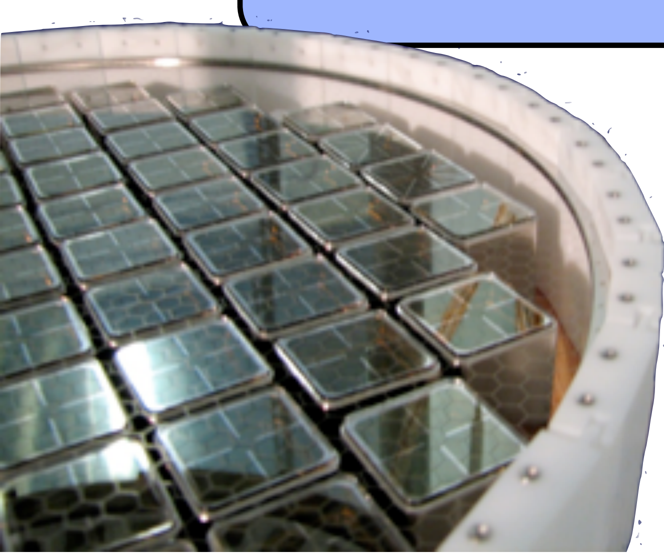
Patrick Decowski - Nikhef

XENON100

Top array: 98 PMTs

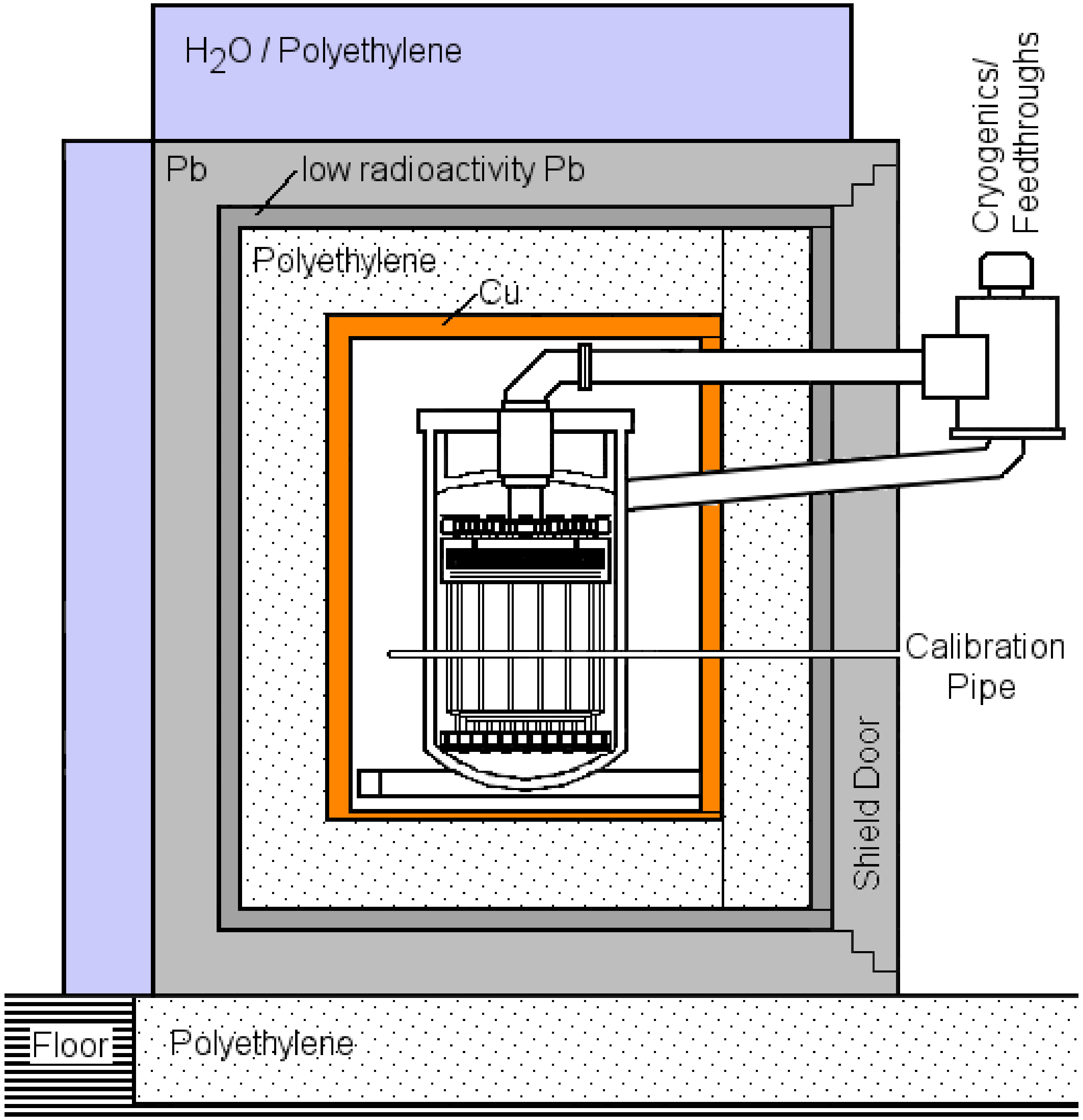
- Goal compared to XENON10
  - 10x more target mass
  - 100x reduction in gamma background
    - Material section & screening
    - Detector design

PTFE TPC,
Field shaping rings



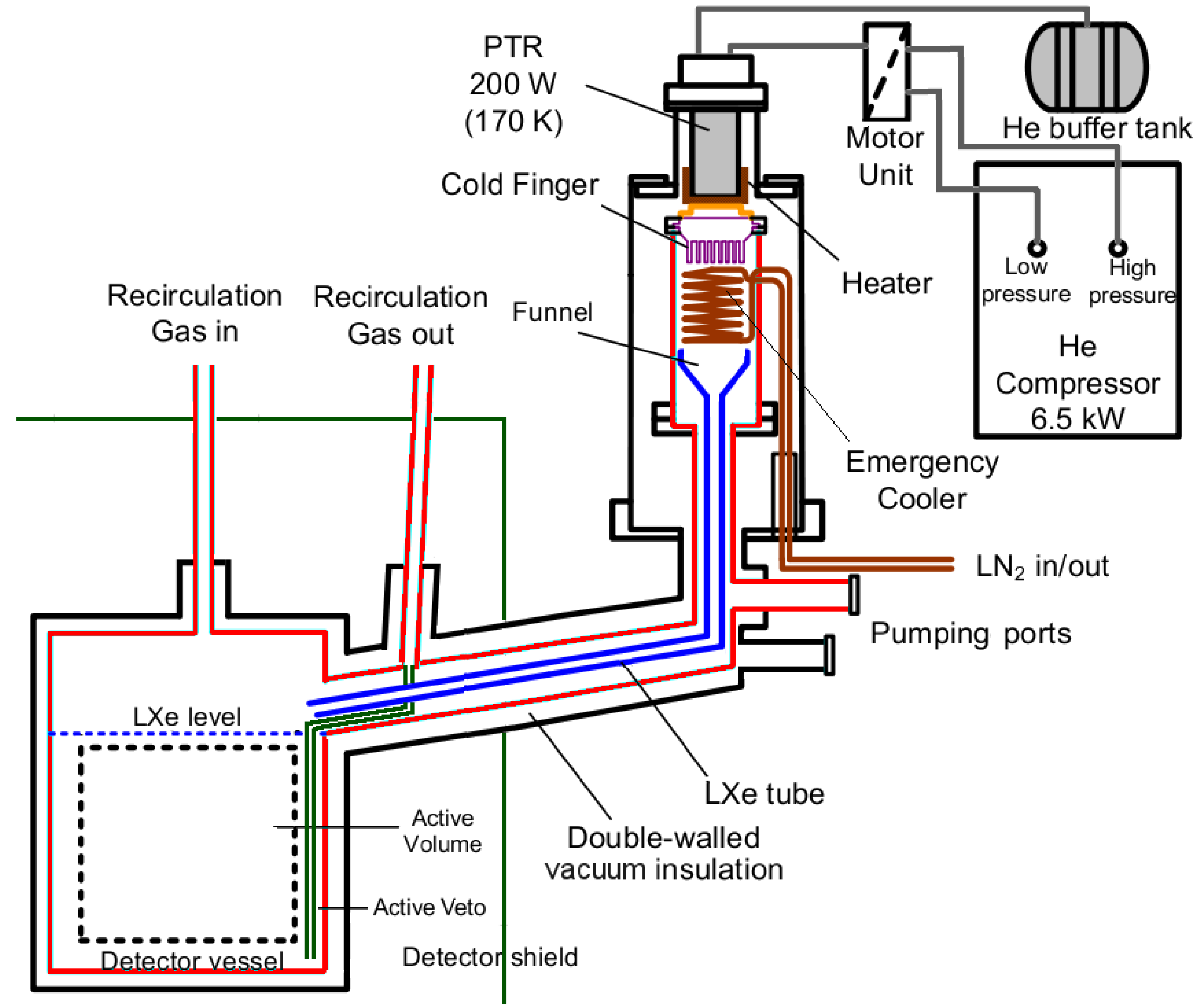
Bottom array: 80 PMTs

Schematic of Detector



Shield for external backgrounds

Use of low-background materials

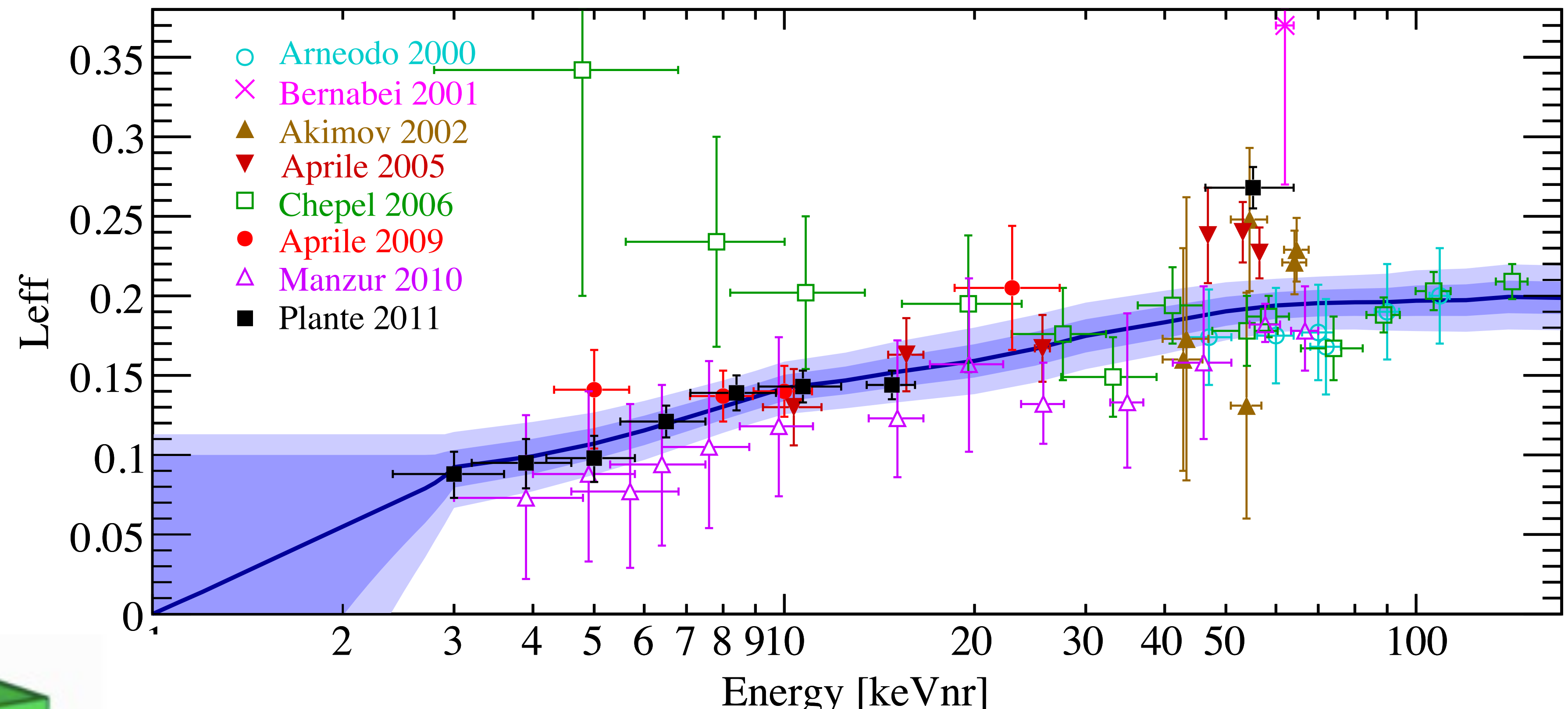


GXe purification system: Continuous recirculation to eliminate impurities

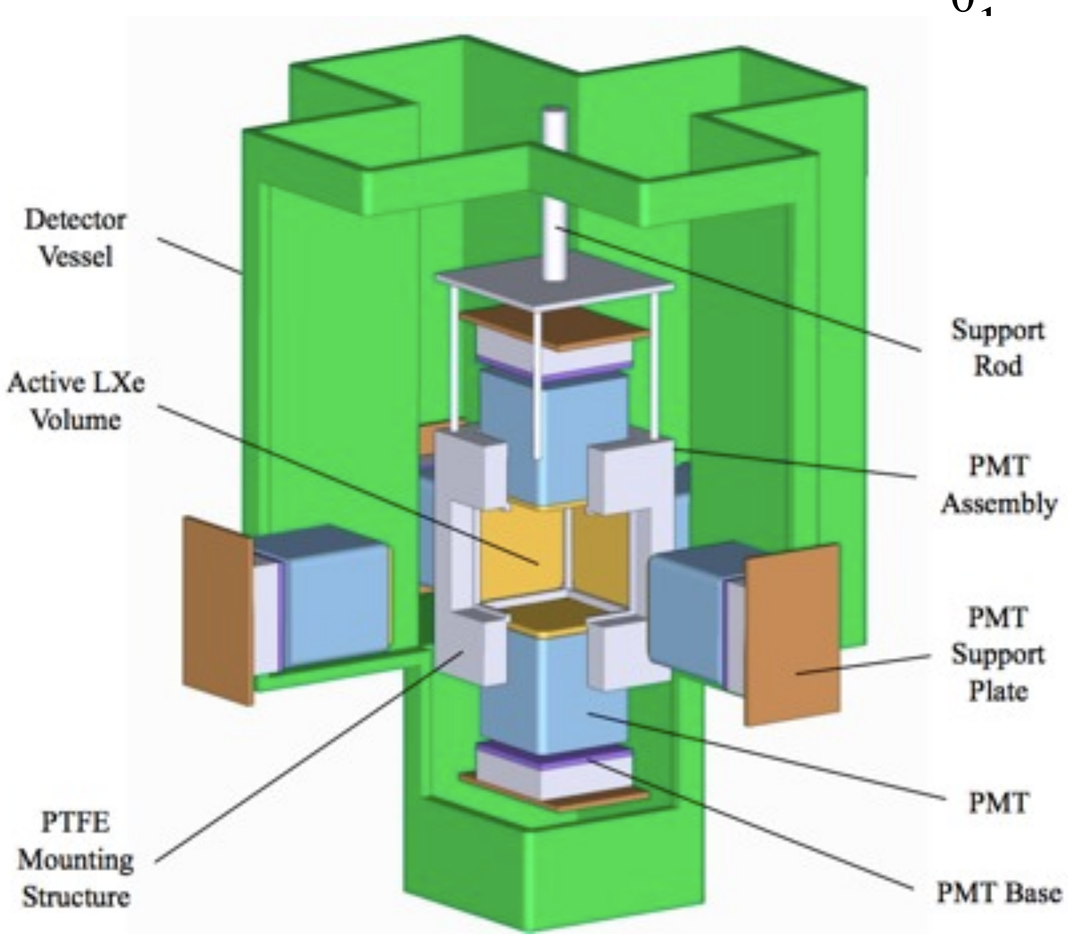
Energy determination

E_{nr} = fcn(S1) → measured in dedicated setups

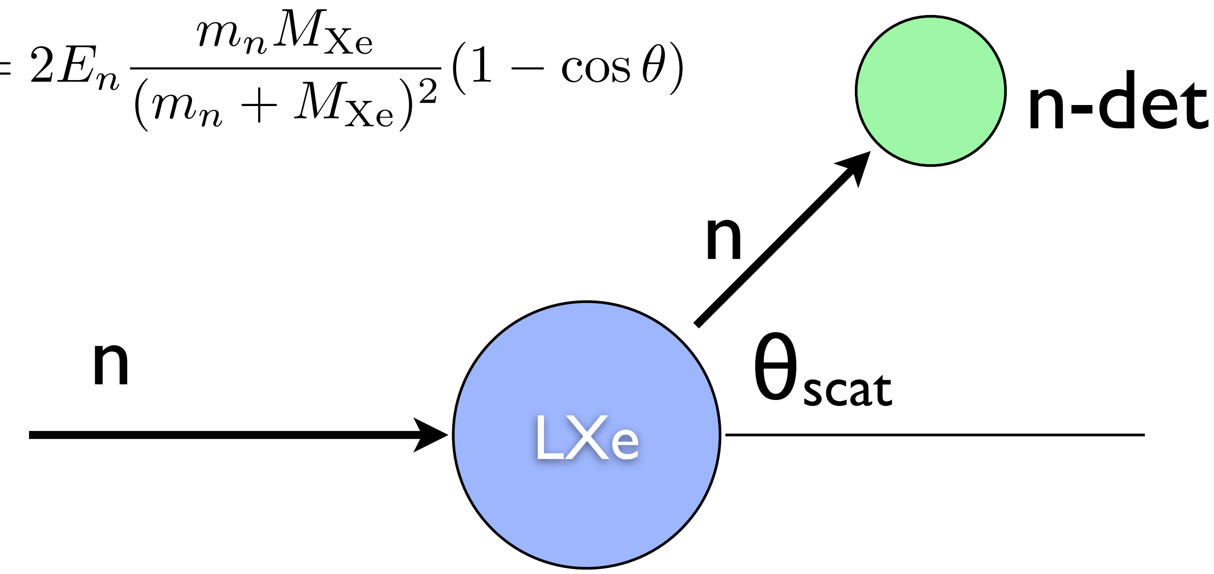
$$\mathcal{L}_{eff} = \frac{\mathrm{LY}(\mathrm{E_{nr}})}{\mathrm{LY}(\mathrm{E_{ee}} = 122\,\mathrm{keV})}$$



G. Plante *et al.*, Phys.Rev. C84 (2011) 045805

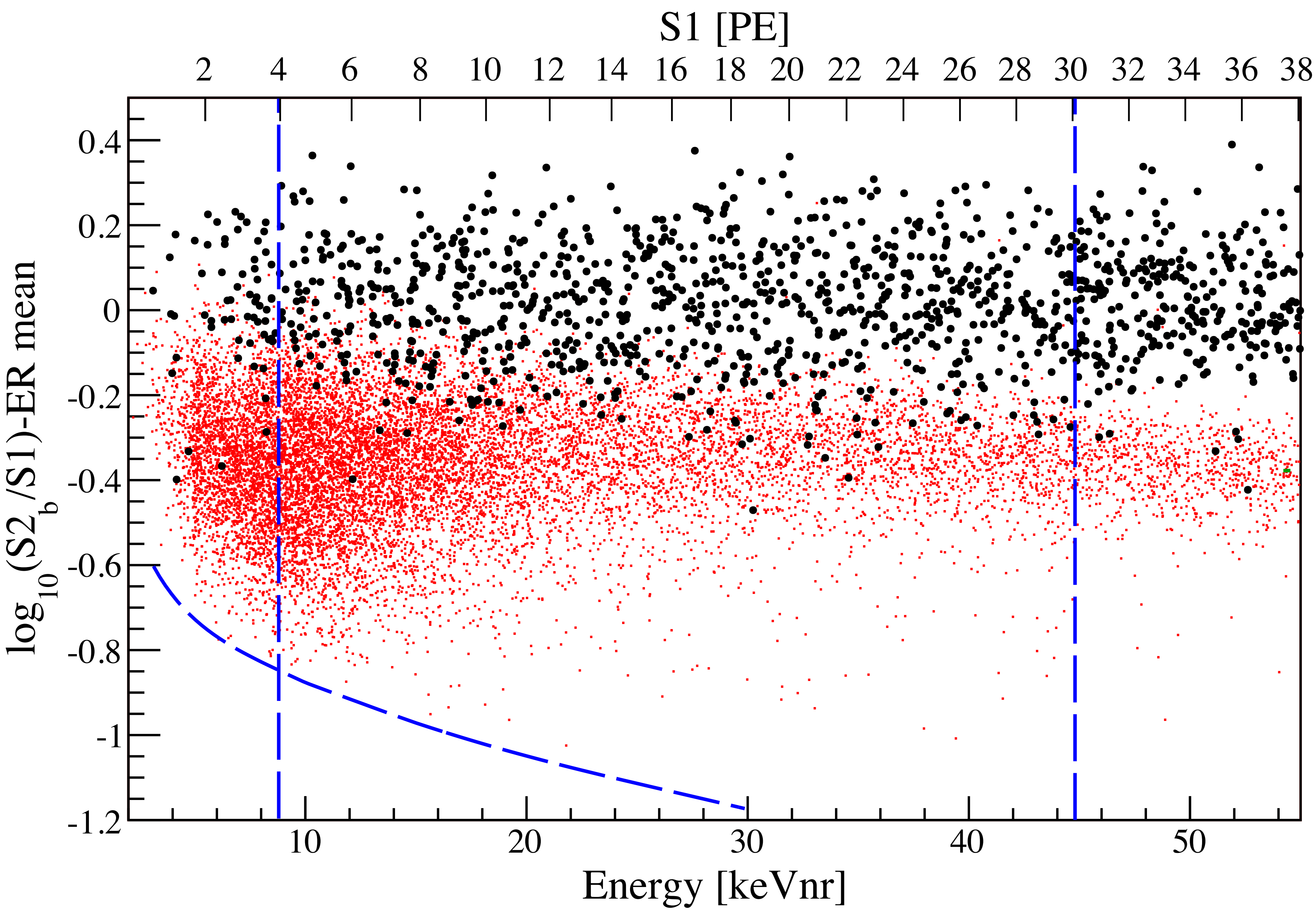


$$E_r = 2E_n \frac{m_n M_{\mathrm{Xe}}}{(m_n + M_{\mathrm{Xe}})^2}(1 - \cos\theta)$$



Recent Results from XENON100

100.9 live days, 48 kg fiducial mass



Data from DM run ("background")

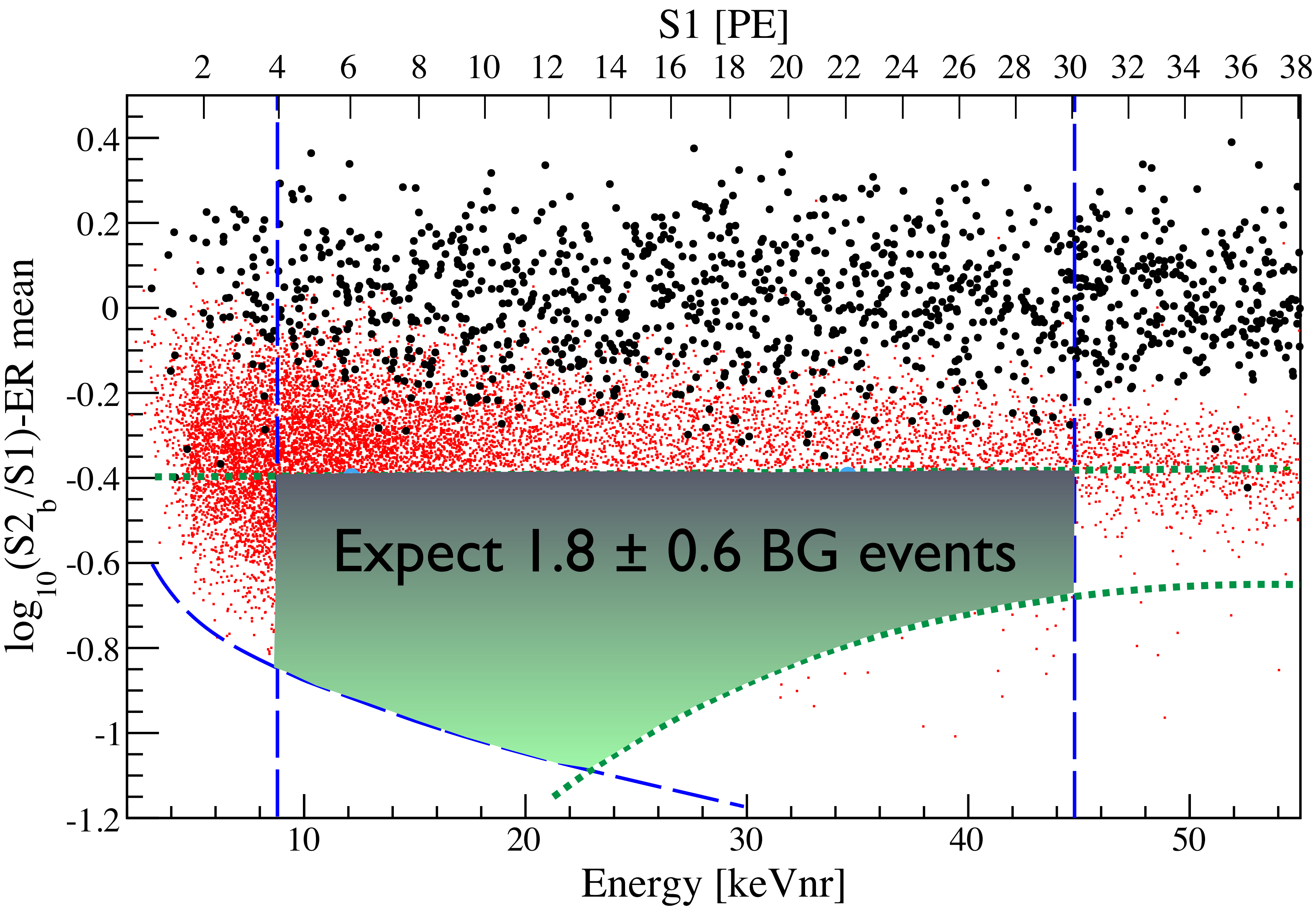
WIMP-like recoils (calibration)

E. Aprile et al, [XENON100], Phys. Rev. Lett. 107, 131302 (2011), arXiv:1104.2549

Profile Likelihood analysis: no WIMP events, BG-only hypothesis has p-value of 31%

Traditional Analysis: Optimal Interval

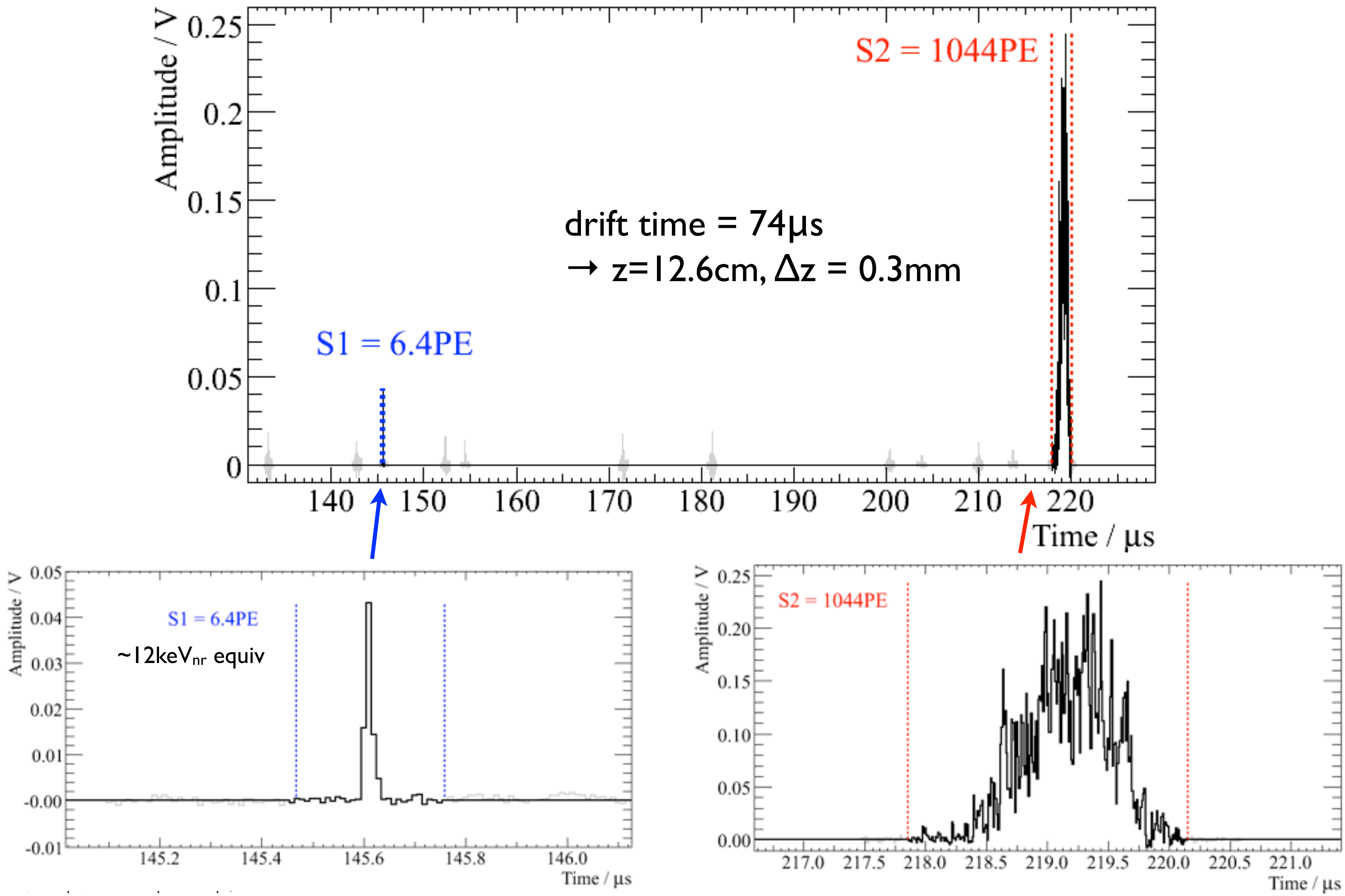
Cuts were determined in a blind fashion



Gaussian Leakage	1.14±0.48
Anomalous Leakage	0.56±0.25
Neutron BG	0.11±0.08

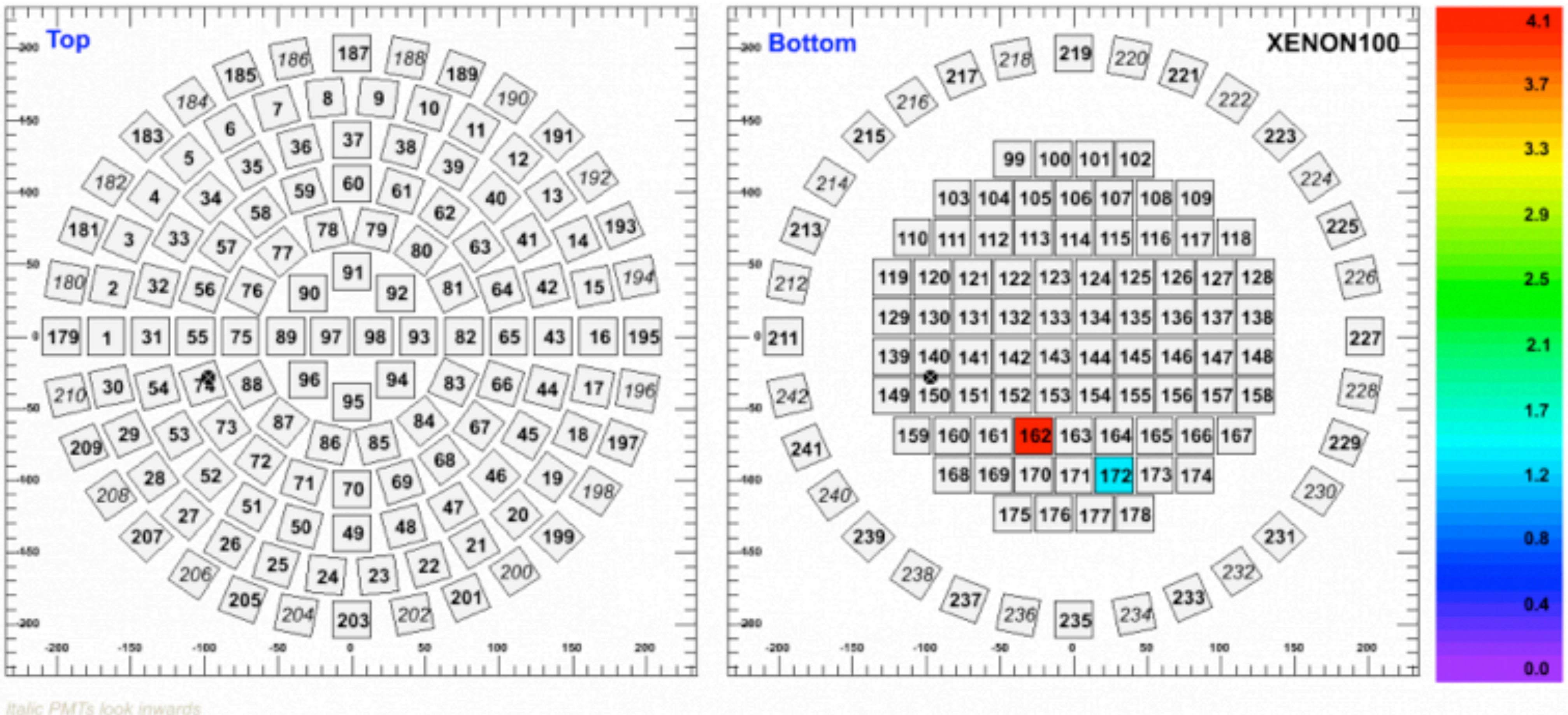
Box cuts: 3 events seen, when 1.8±0.6 expected

One of the Candidates



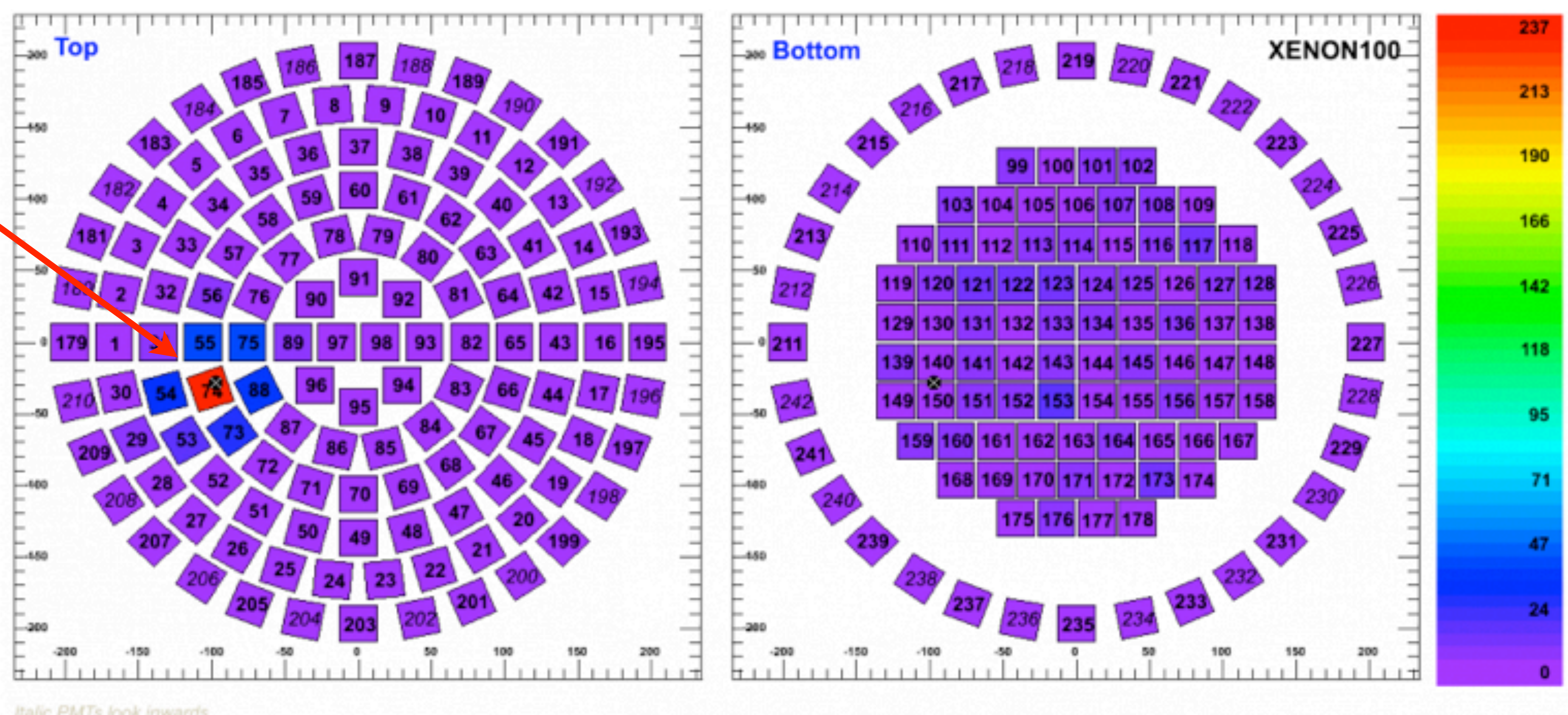
Same low-energy candidate event

S1: Energy determination

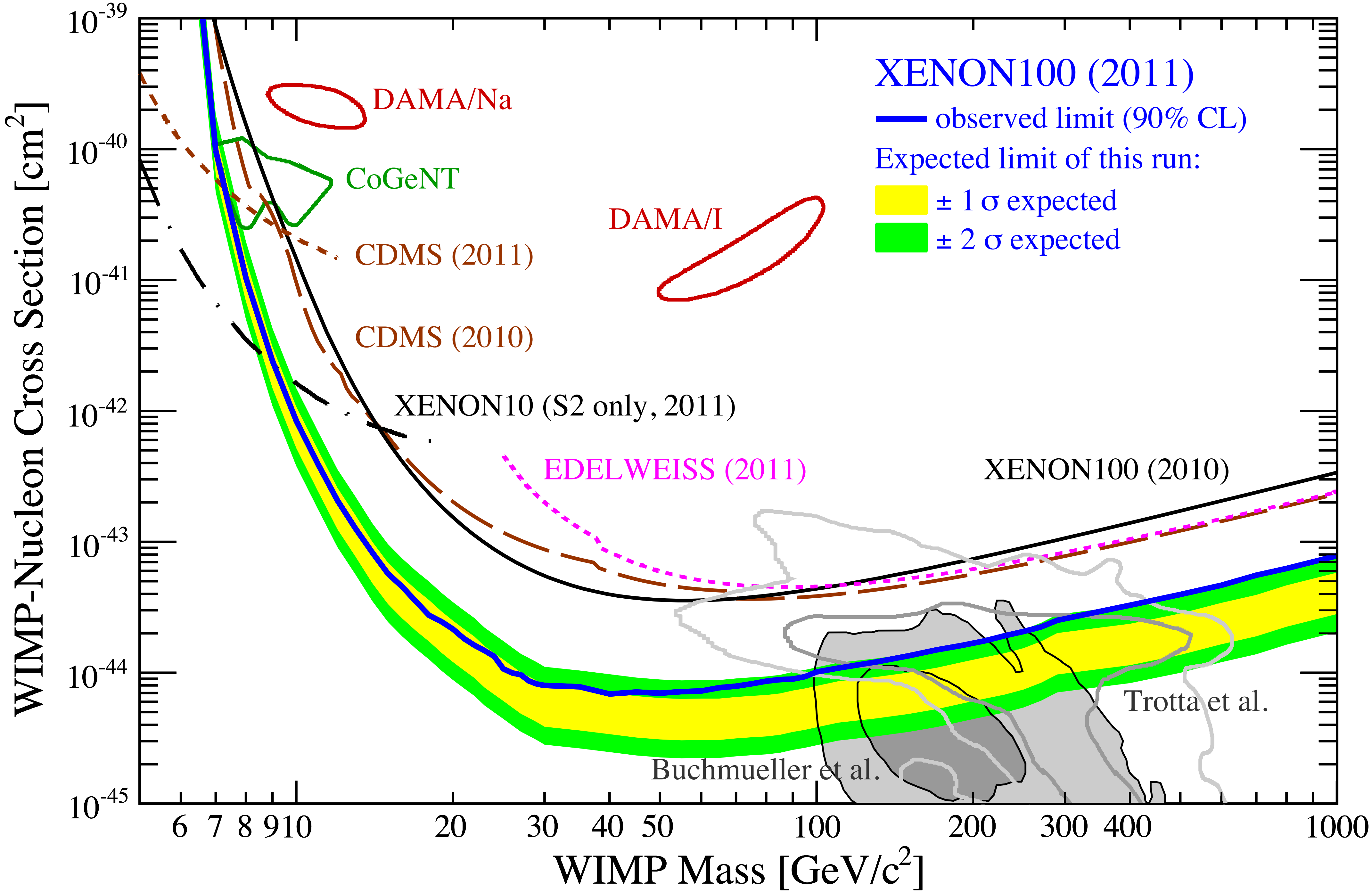


S2: Position determination

Δr ~ 3mm



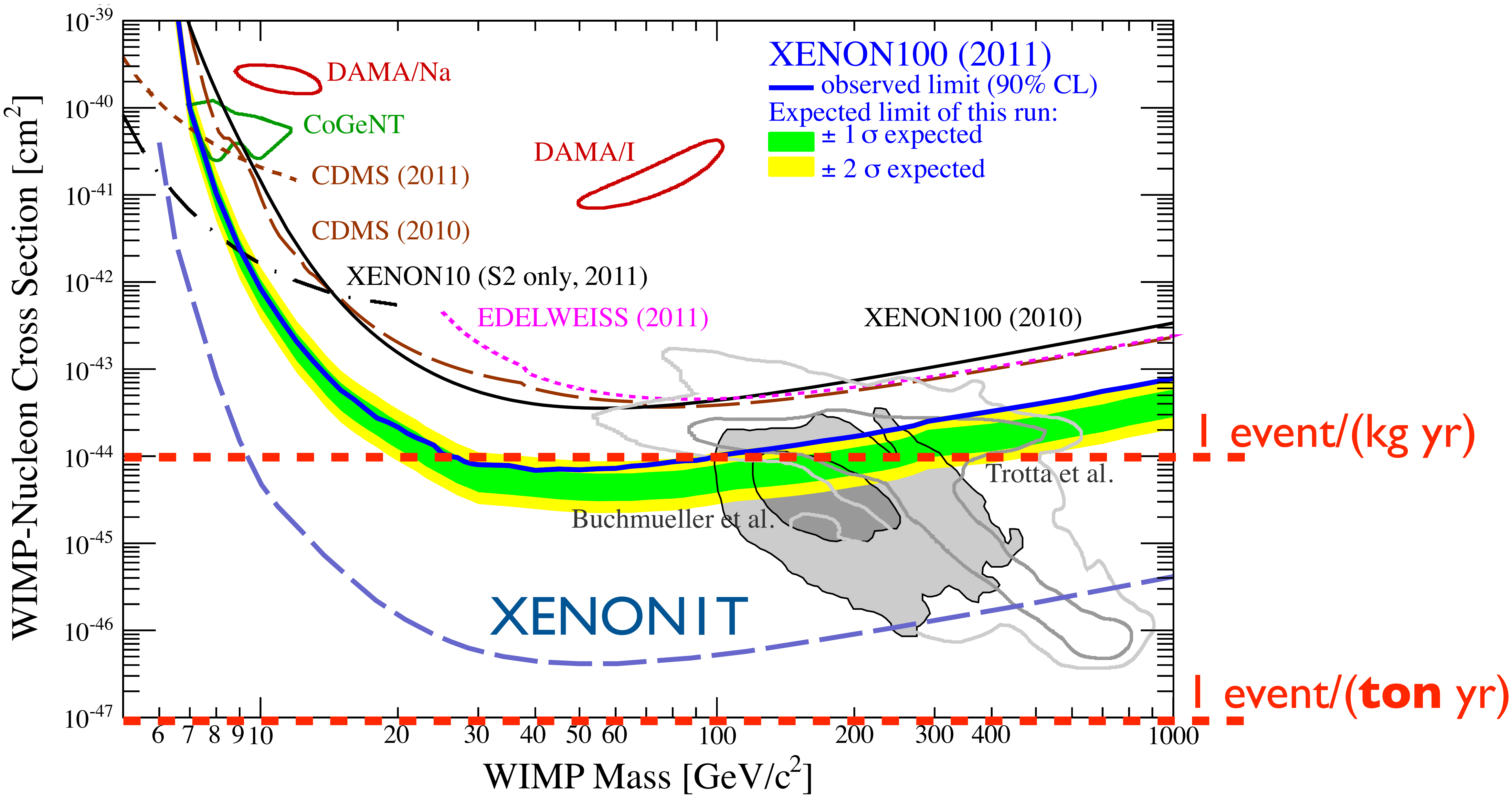
Limits from 4843 kg-day exposure



E. Aprile et al, [XENON100], Phys. Rev. Lett. 107, 131302 (2011), arXiv:1104.2549

SI Sensitivity Curves

Spin-independent WIMP-nucleon cross section



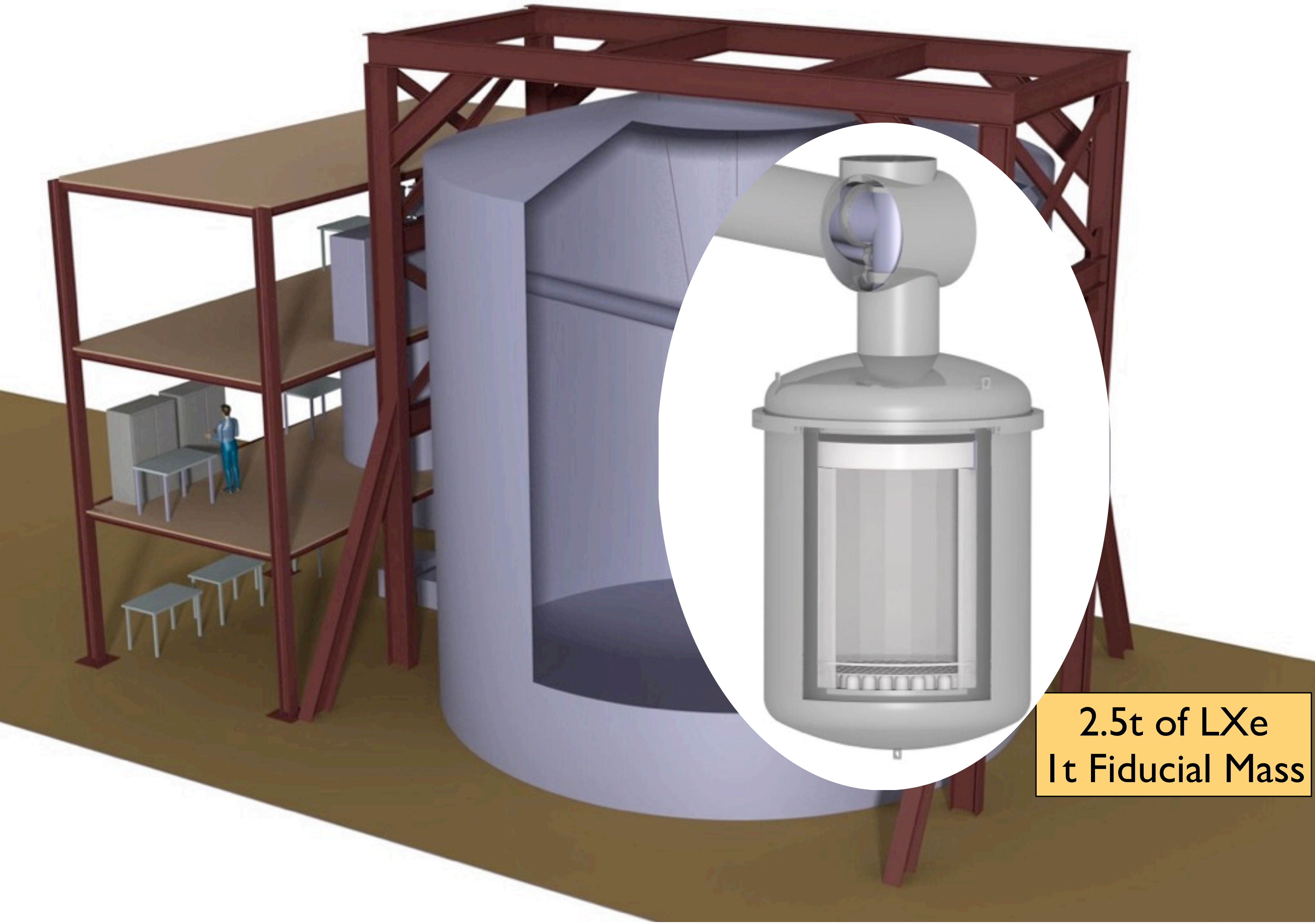
XENON100→ XENON1T:

Improve current sensitivity by ~2 orders of magnitude

XENON Collaboration

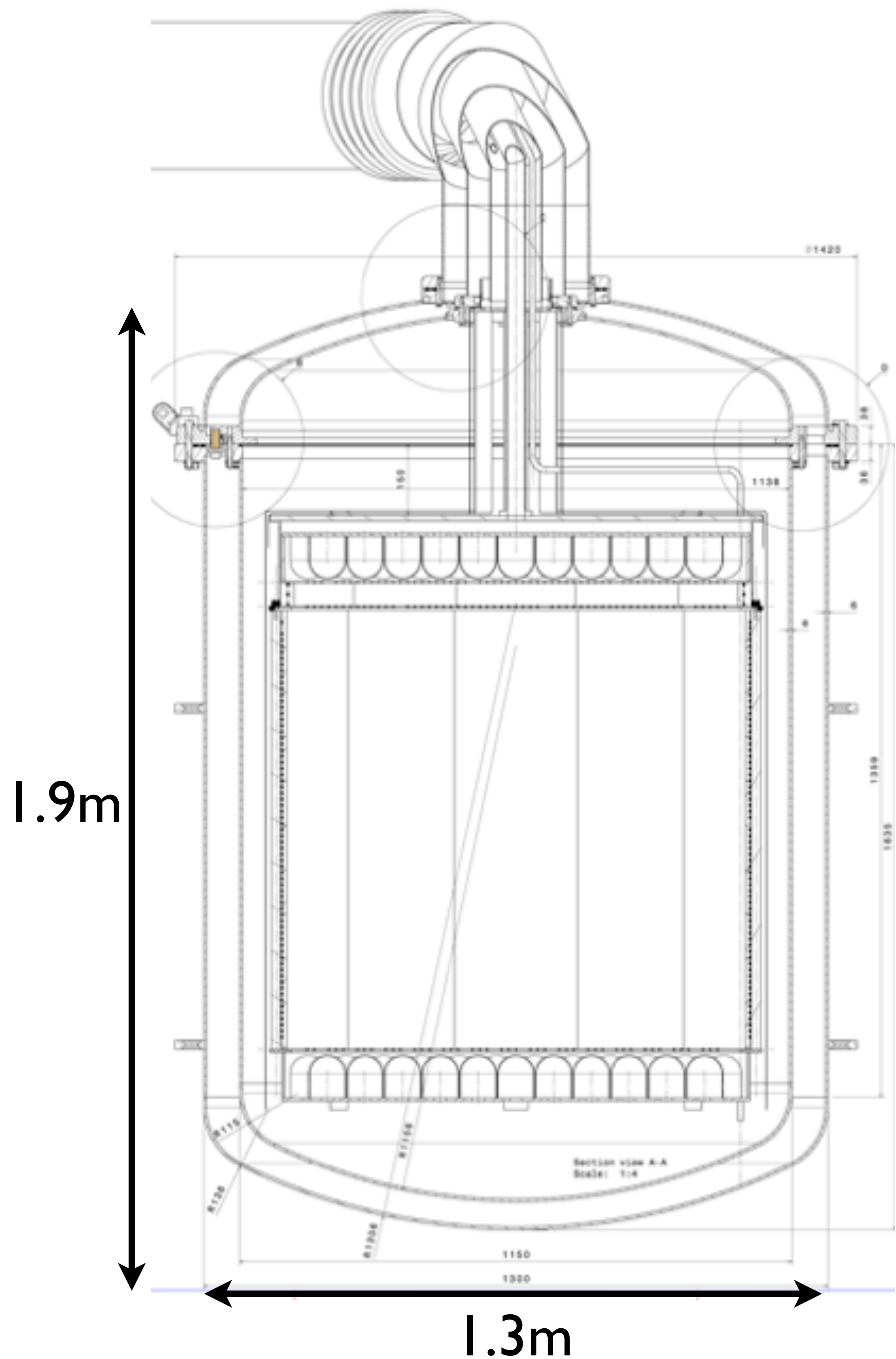
Columbia University
Rice University
UCLA
University of Zürich
Coimbra University
LNGS & INFN
Shanghai Jiao Tong University

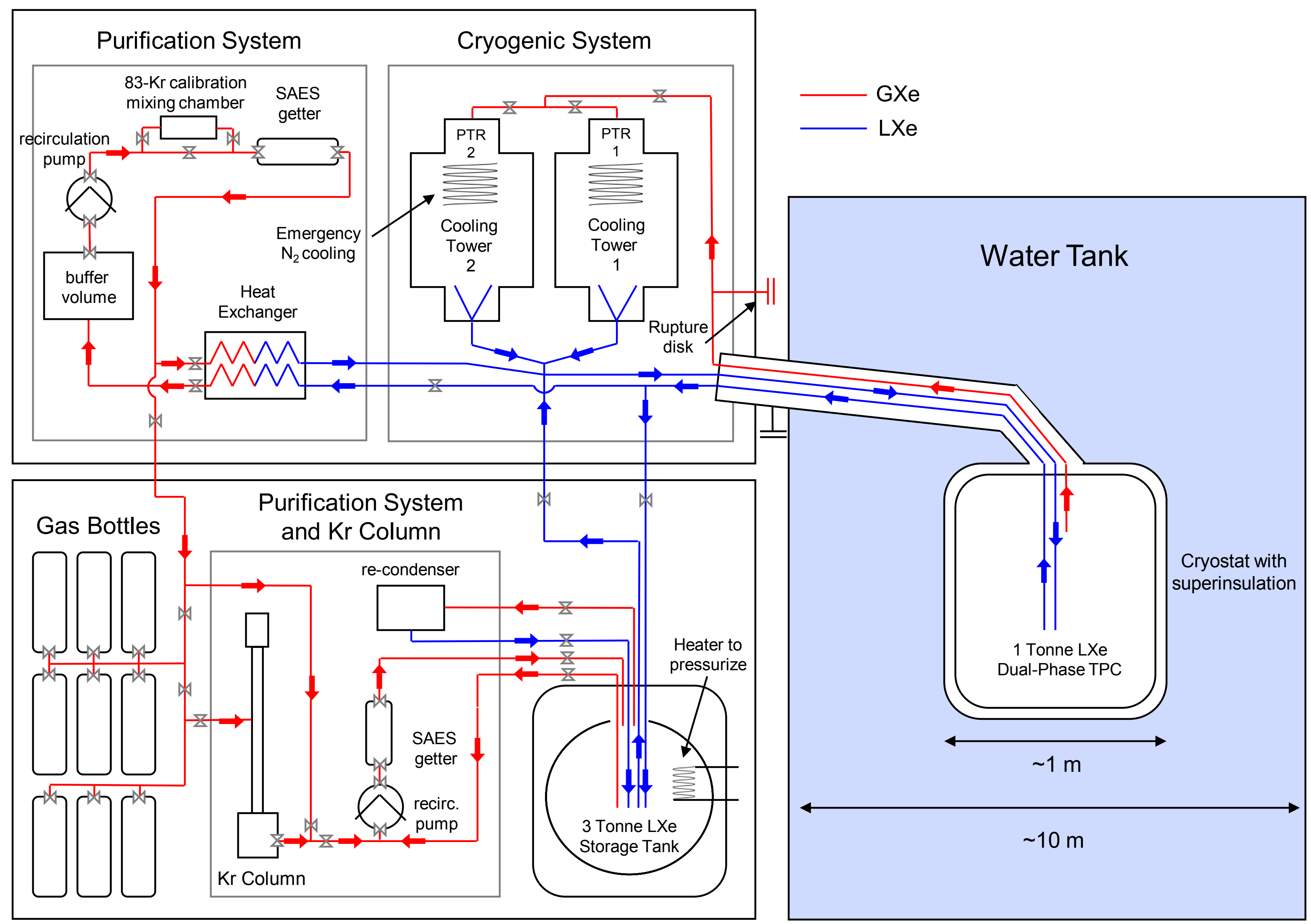
MPIK-Heidelberg
Bologna University
Münster University
Subatech
Nikhef
Weizmann Institute
Mainz University


2.5t of LXe
1t Fiducial Mass

This is what 1.3tons of Xe looks like!

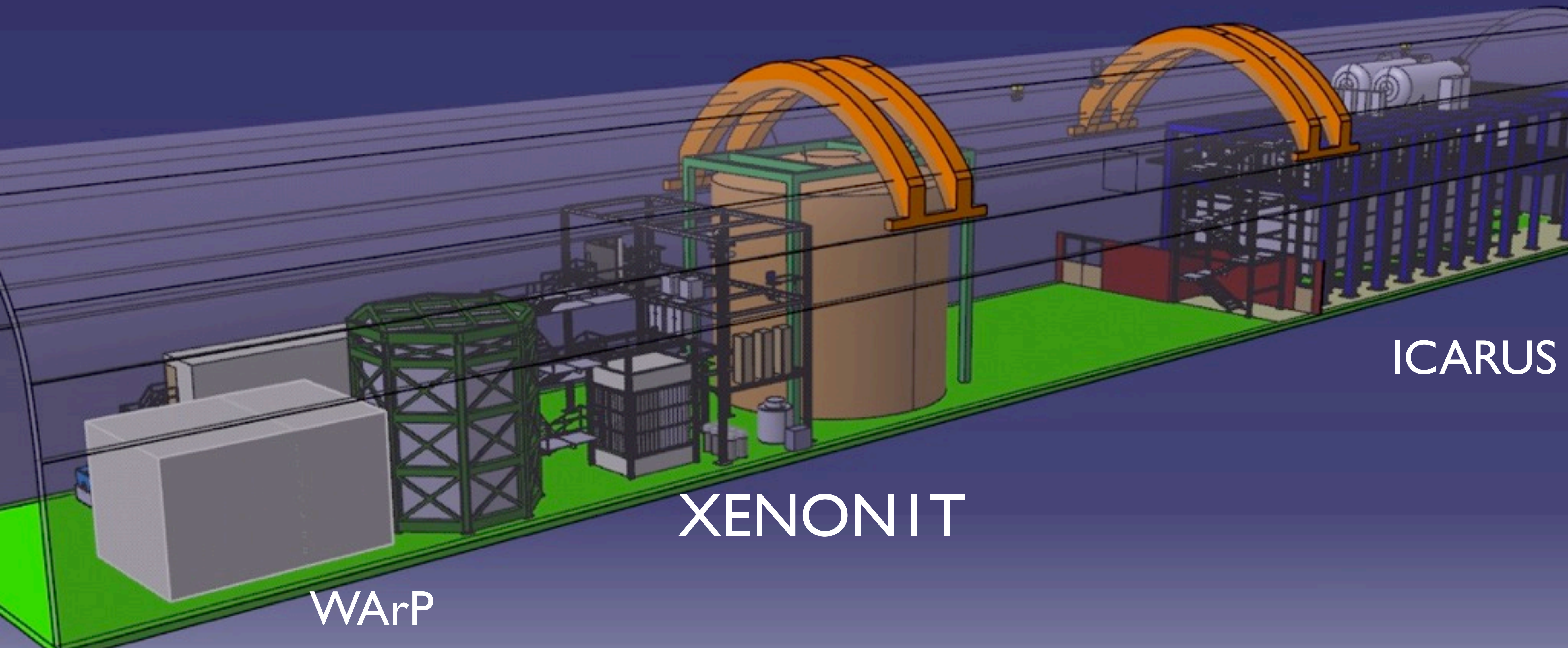
Preliminary Design of Cryostat



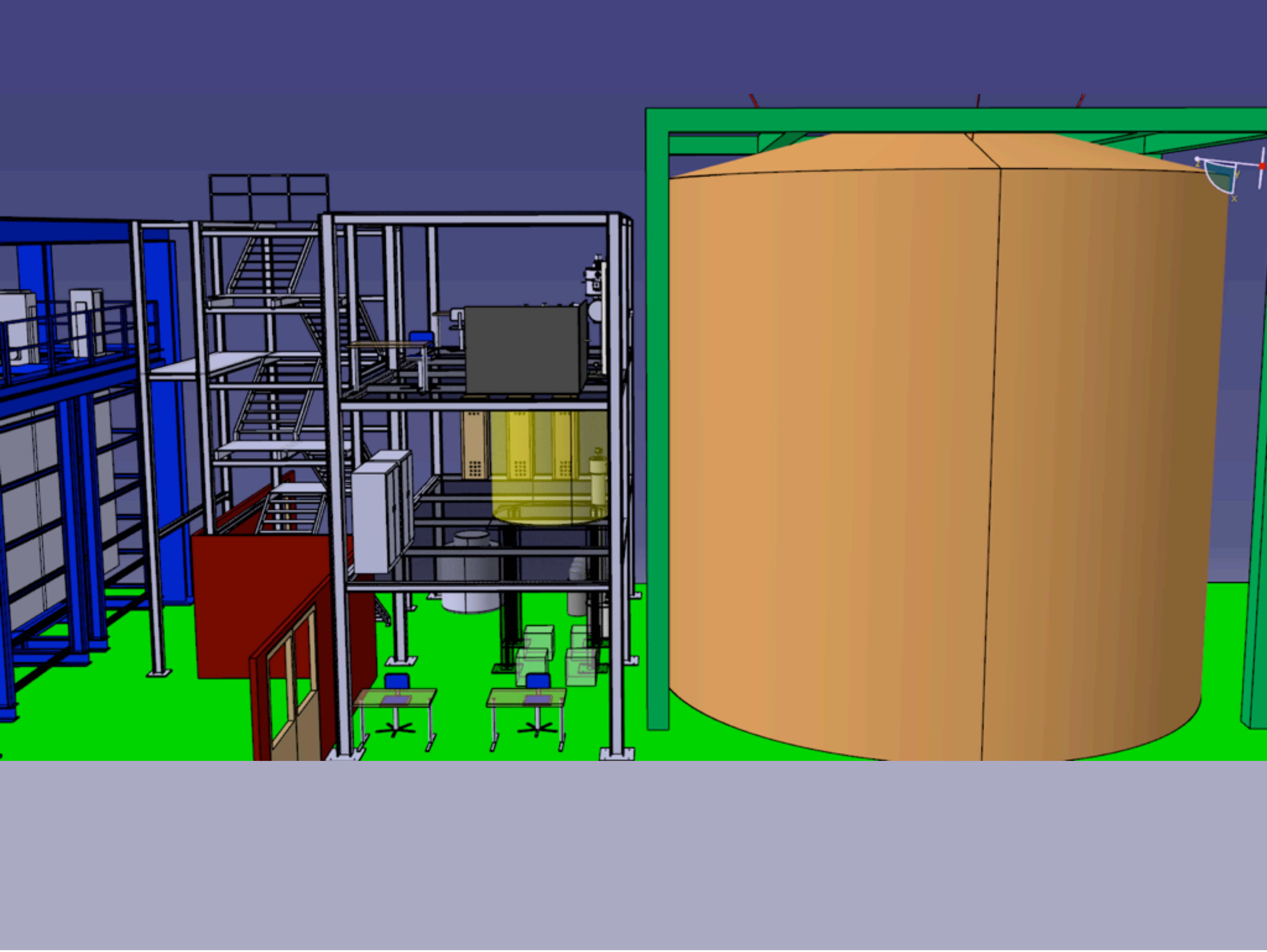


Reduce backgrounds:
Titanium cryostat,
better material screening

Patrick Decowski

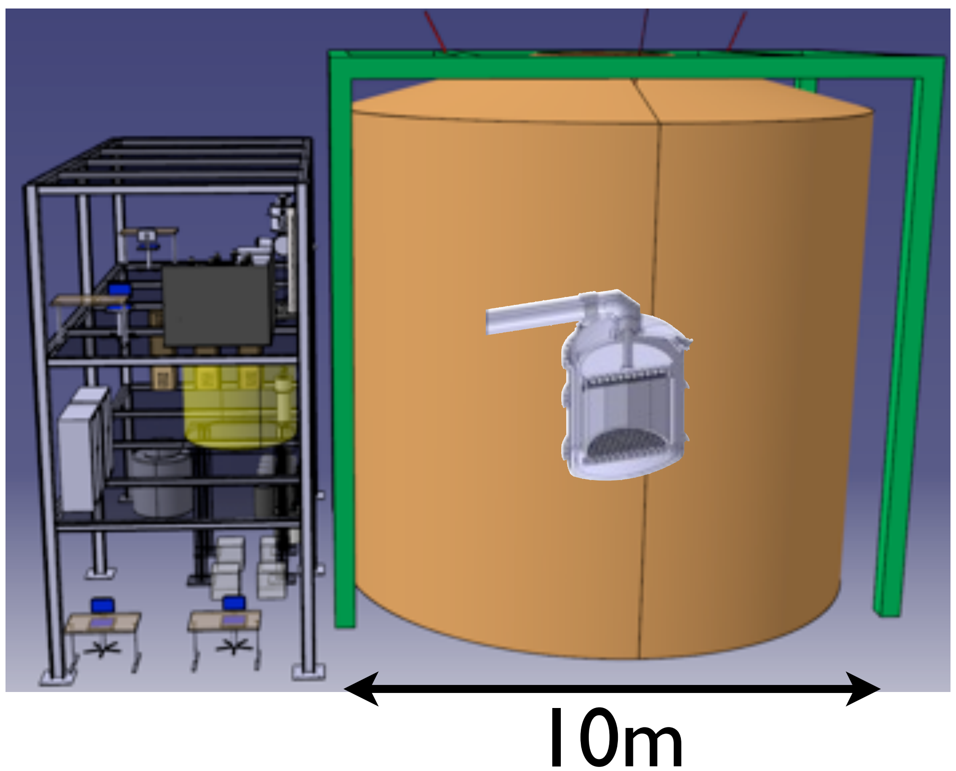


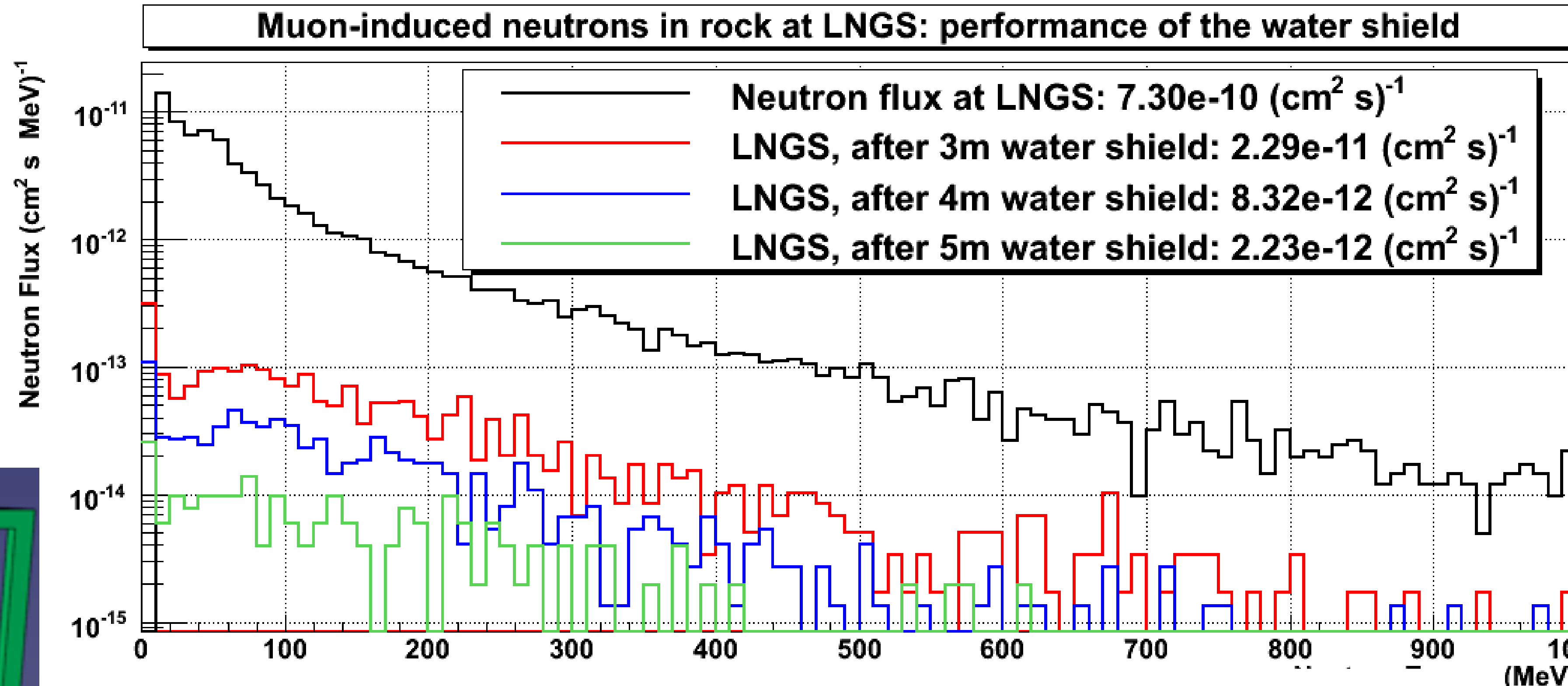
Experiment is approved for Hall B of Gran Sasso
Commissioning in 2014

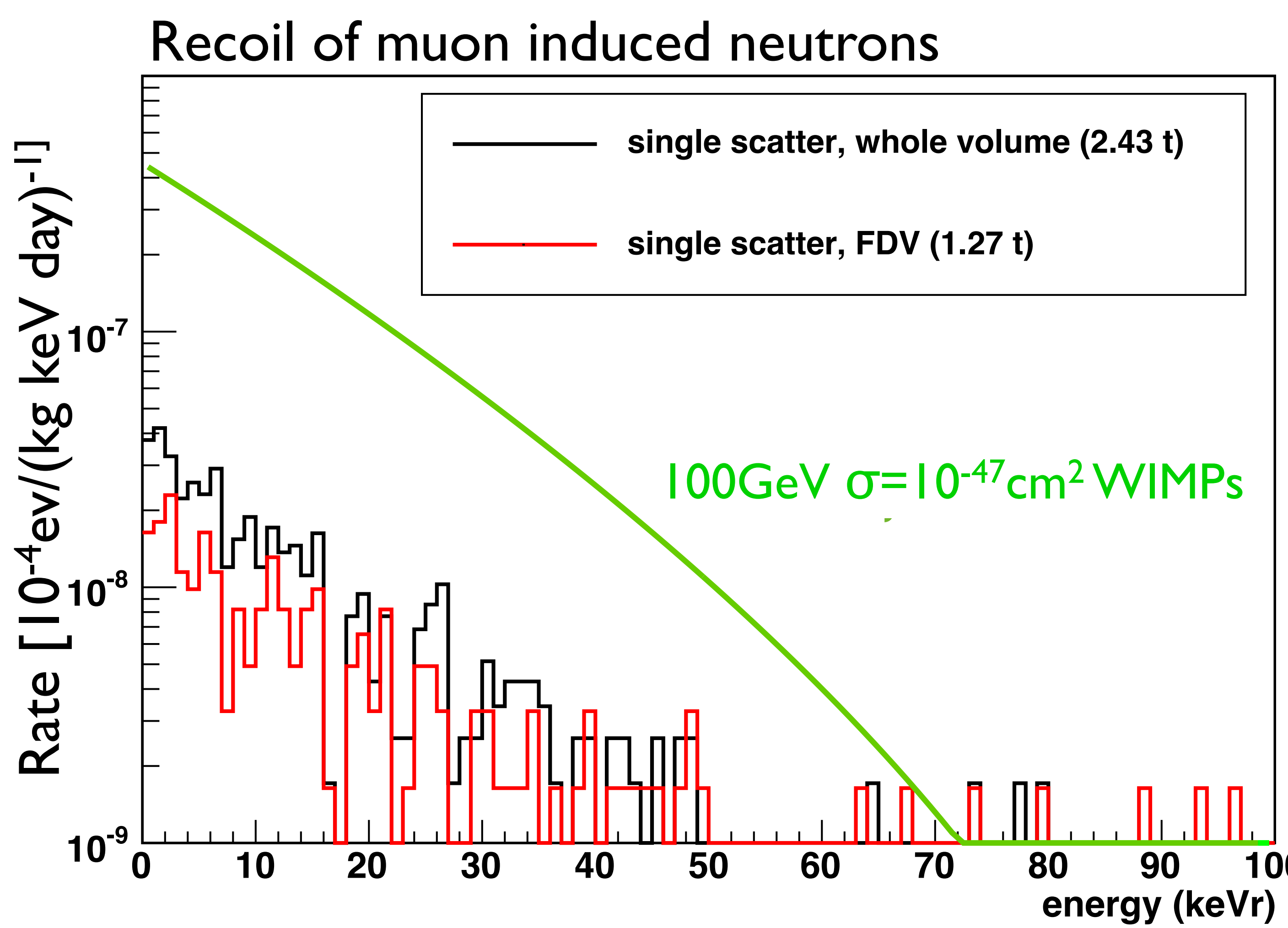


Neutron shielding

Neutrons will leave same recoil signal as WIMPs
→ shielding essential





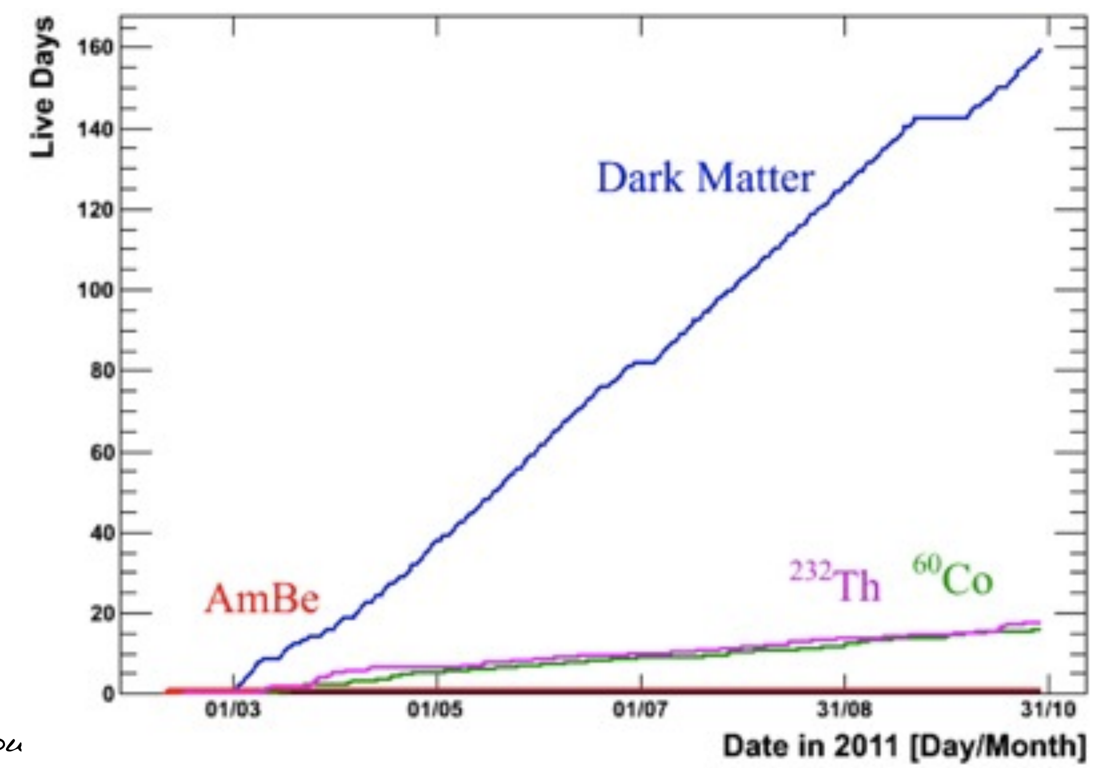


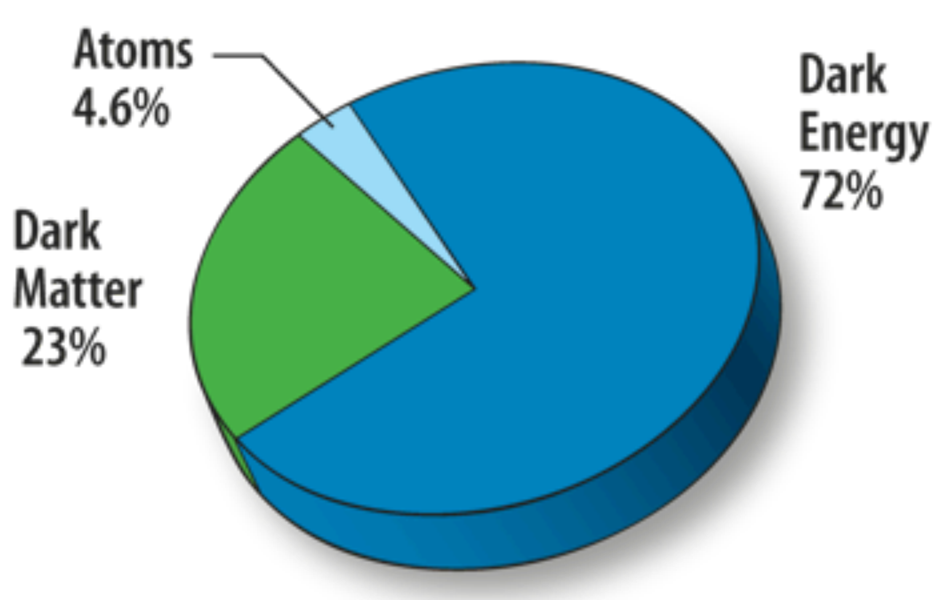
Water tank provides:

- Active μ veto
- Moderates n

Summary

- Much progress in Direct Detection searches for Dark Matter
  - 3 orders of magnitude improvement achieved in last 10 years
- Complementarity of Direct, Indirect and Production DM Searches
  - In particular LHC + Xe100 together have already changed the SUSY-WIMP landscape
- Construction of XENON1T beginning
  - XENON100 will continue taking data for at least the next year





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