Photosensors development and Monte Carlo simulation for direct Dark Matter search

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

MC - PAD
CLOSING NETWORK EVENT
19-22 SEPTEMBER 2012

MC PAD

MARIE CURIE ACTIONS

Paolo Beltrame
Weizmann Institute of Science
XENON Collaboration

Xe
XENON
Dark Matter Project

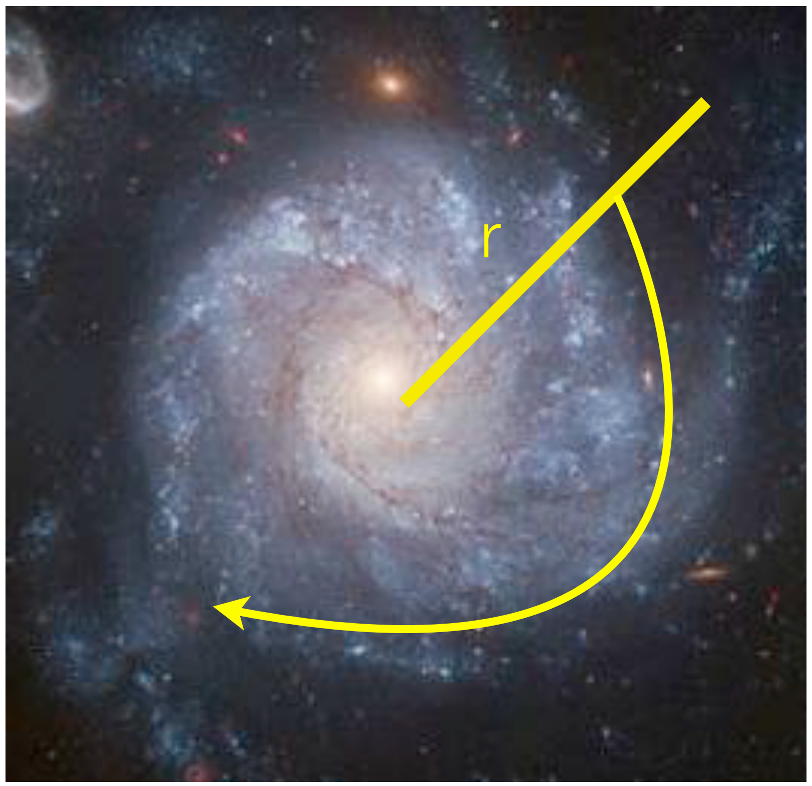
Brief introduction

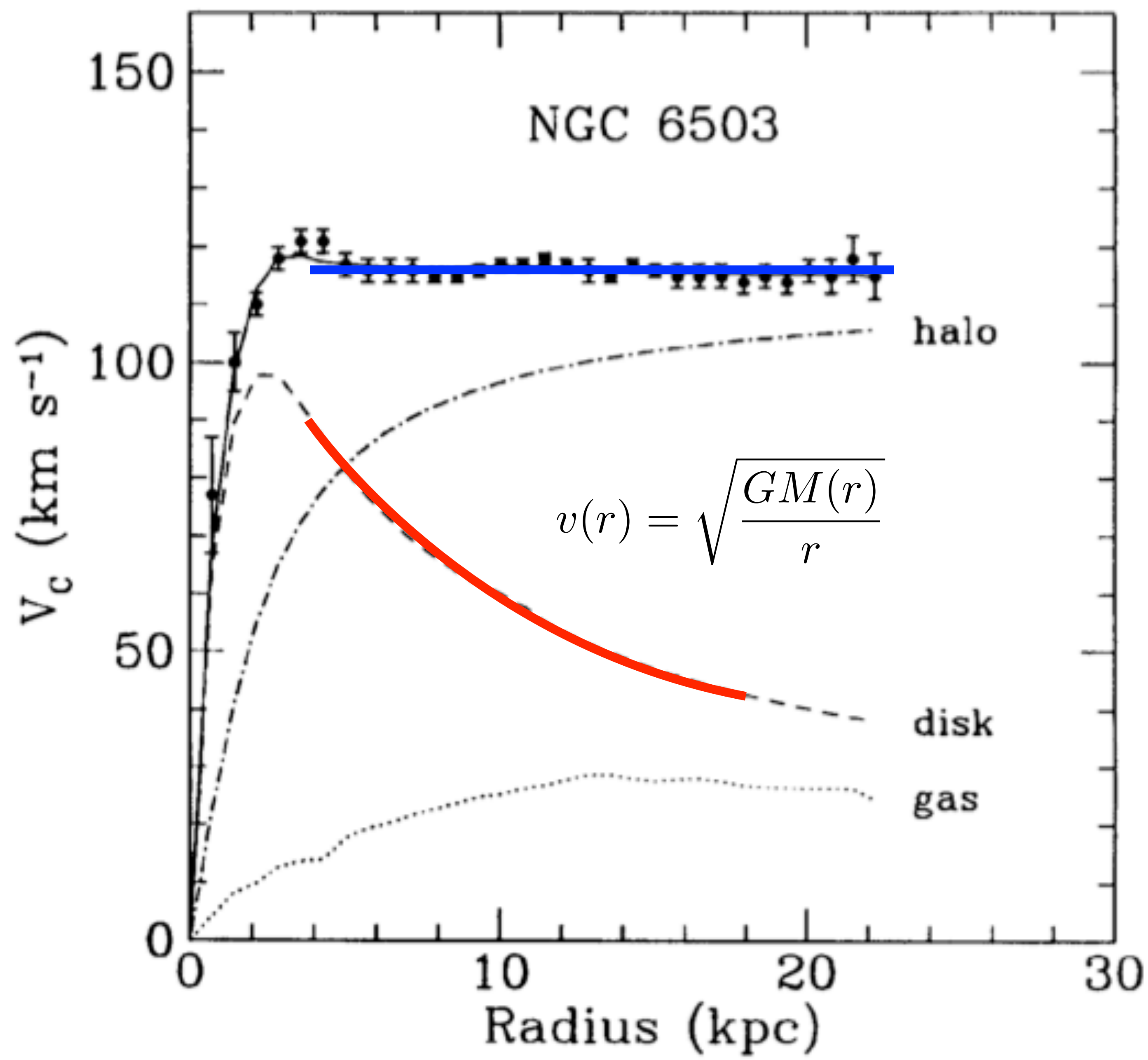
After PhD at the KIT on hadronic cross section data analysis using KLOE data

- MC-PAD
  - ER at CERN April 2009 - April 2011
  - P7 Advanced Photodetectors
  - AX-PET & ATLAS-ALFA
  - Supervisor: Christian Joram
- PostDoc at UCLA
  - Moving to dark matter direct search XENON and DarkSide collaborations
- Fellowship at WIS
  - Continue dark matter search within the XENON100 and XENON1T experiment... מזל טוב

Scientific framework and (some of the) tasks

What is the Dark Matter? Hints of its existence:
1. Rotational curves of stars in galaxies





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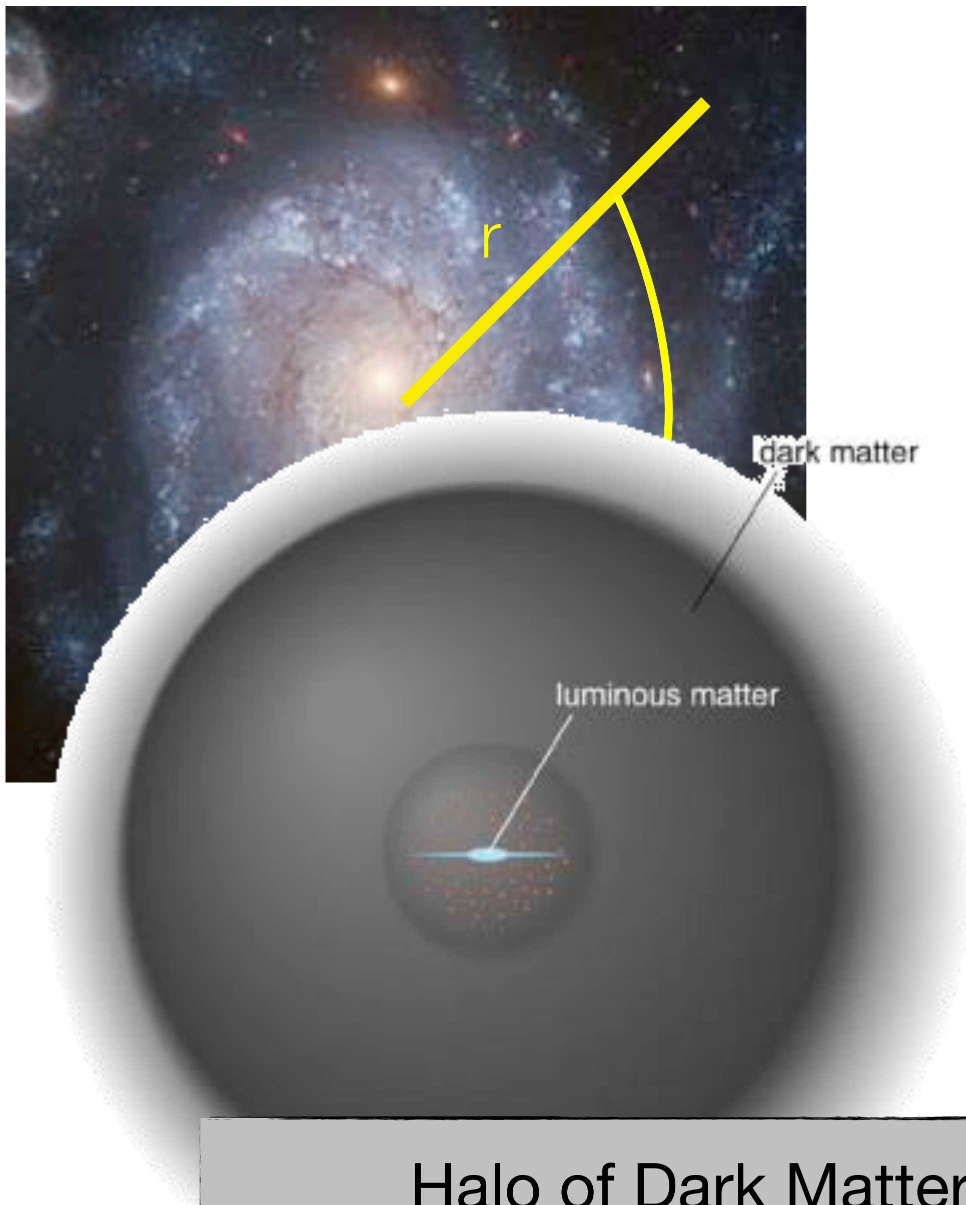
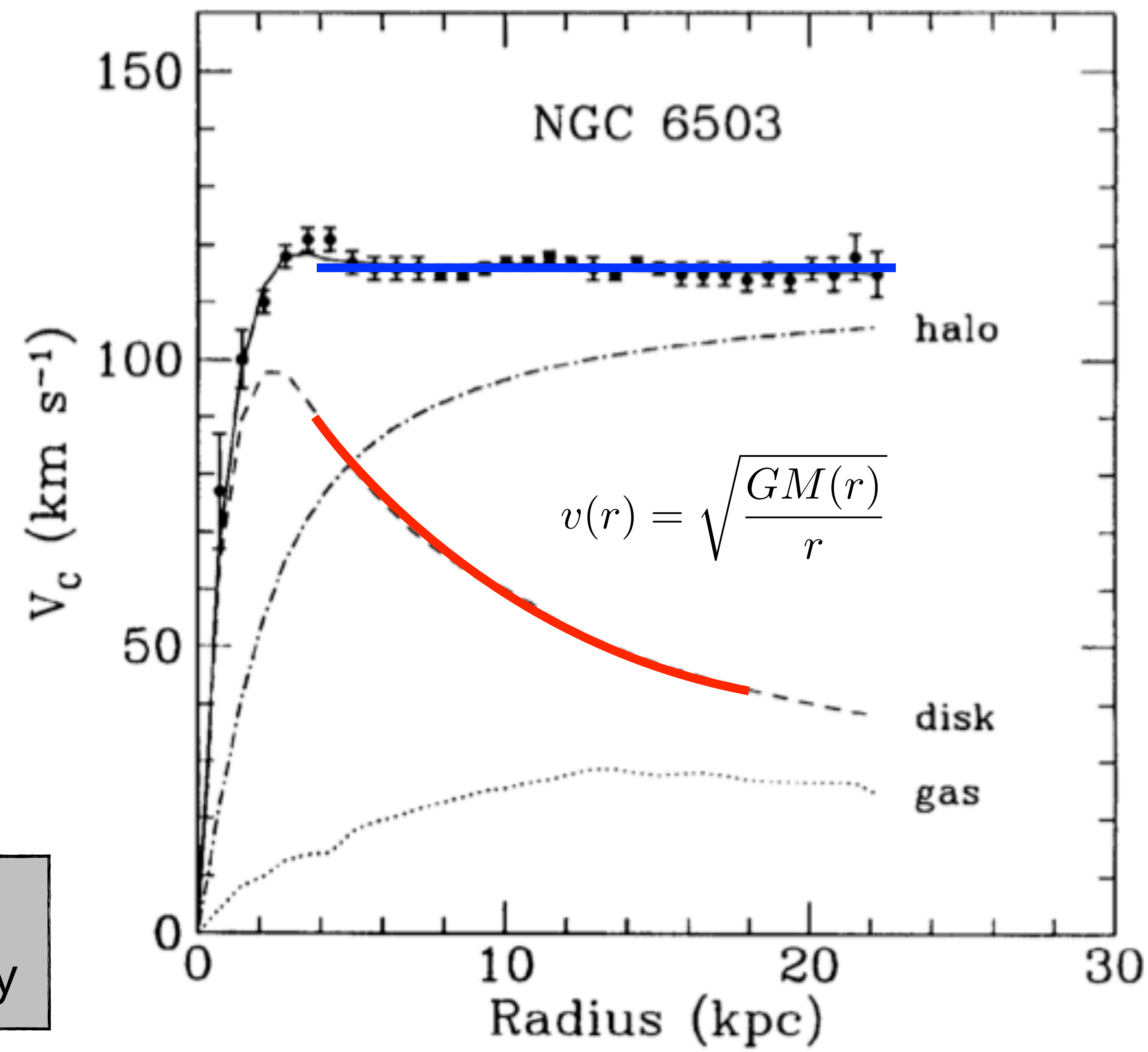
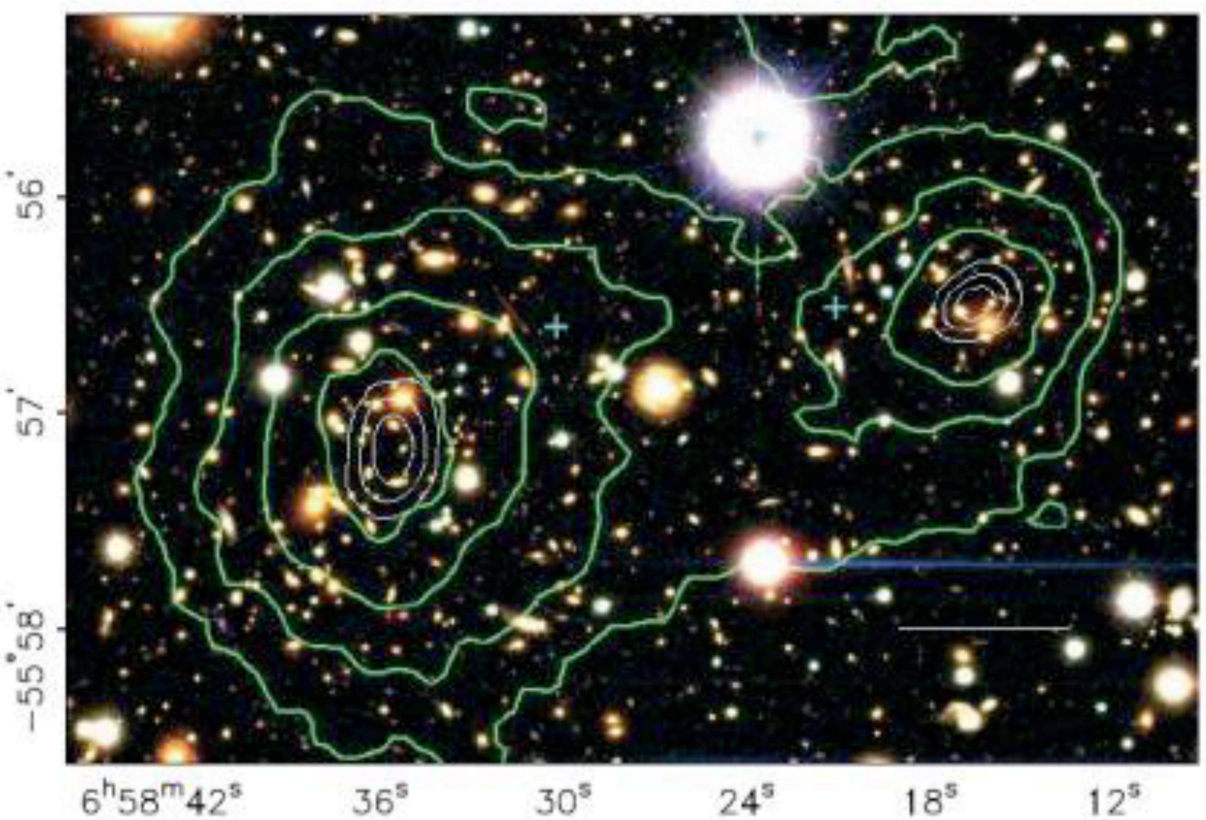


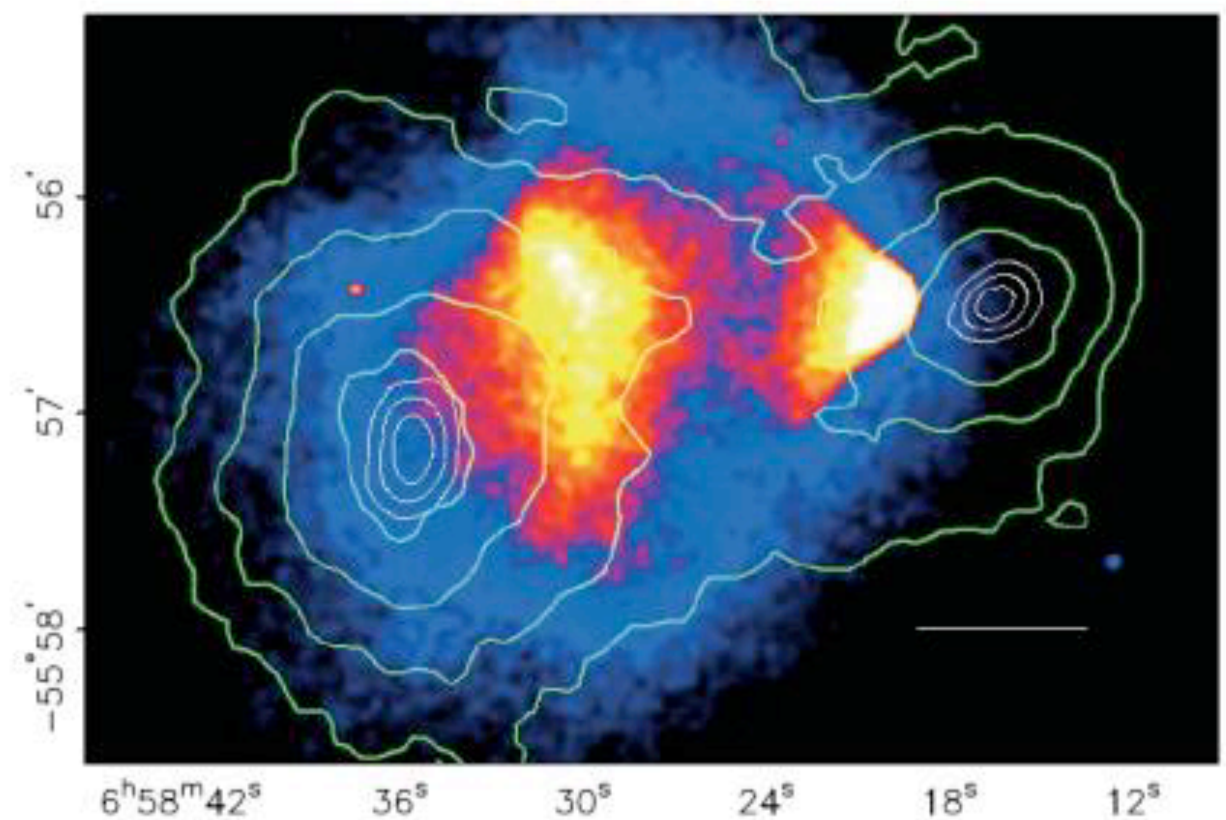
Halo of Dark Matter
surrounding the “visible” galaxy



What is the Dark Matter? Hints of its existence: 2. Bullet cluster



Map of gravitational potential from weak gravitational lensing



Superimposed X-ray plasma image

Gravitational potential
does not follow the plasma distribution
(main baryonic mass component)
but rather traces the galaxies distribution…

What is the Dark Matter?
What do we think to know of it

(PDG) JP G 37, 075021 (2010) , updated in 2012

From observation

73% Dark energy (Ω_Λ: Dark Energy density)
27% Matter (Ω_m: Matter density)
  22,5 % non-baryonic matter
  4,5 % baryonic matter

Dark Matter candidate characteristics

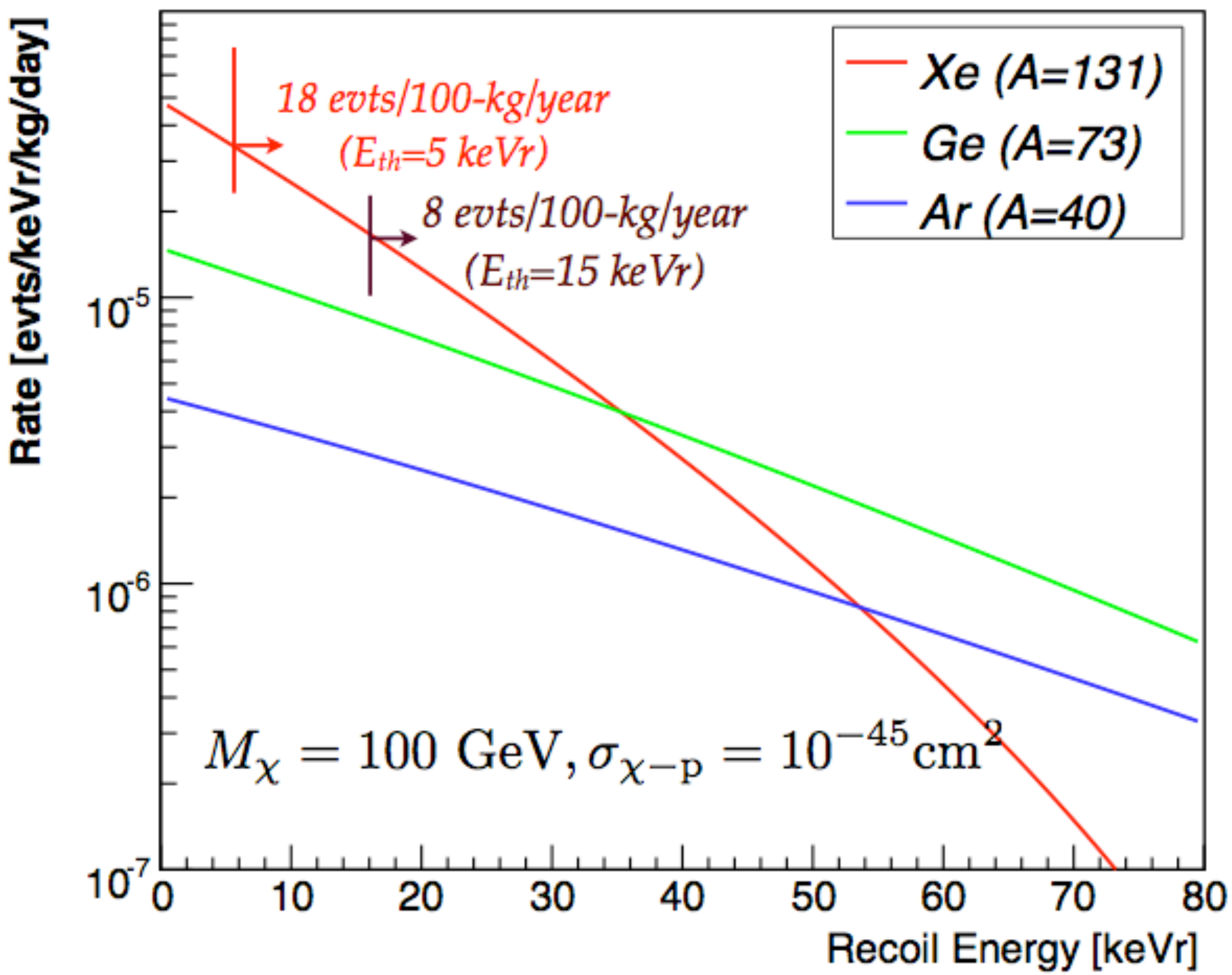
Low interaction rate with electromagnetic radiation and baryonic matter
Stable (relic density) and non-relativistic (structures)

Weakly Interactive Massive Particle

Supersymmetric extension of the SM ⇒ lightest neutralino (χ)

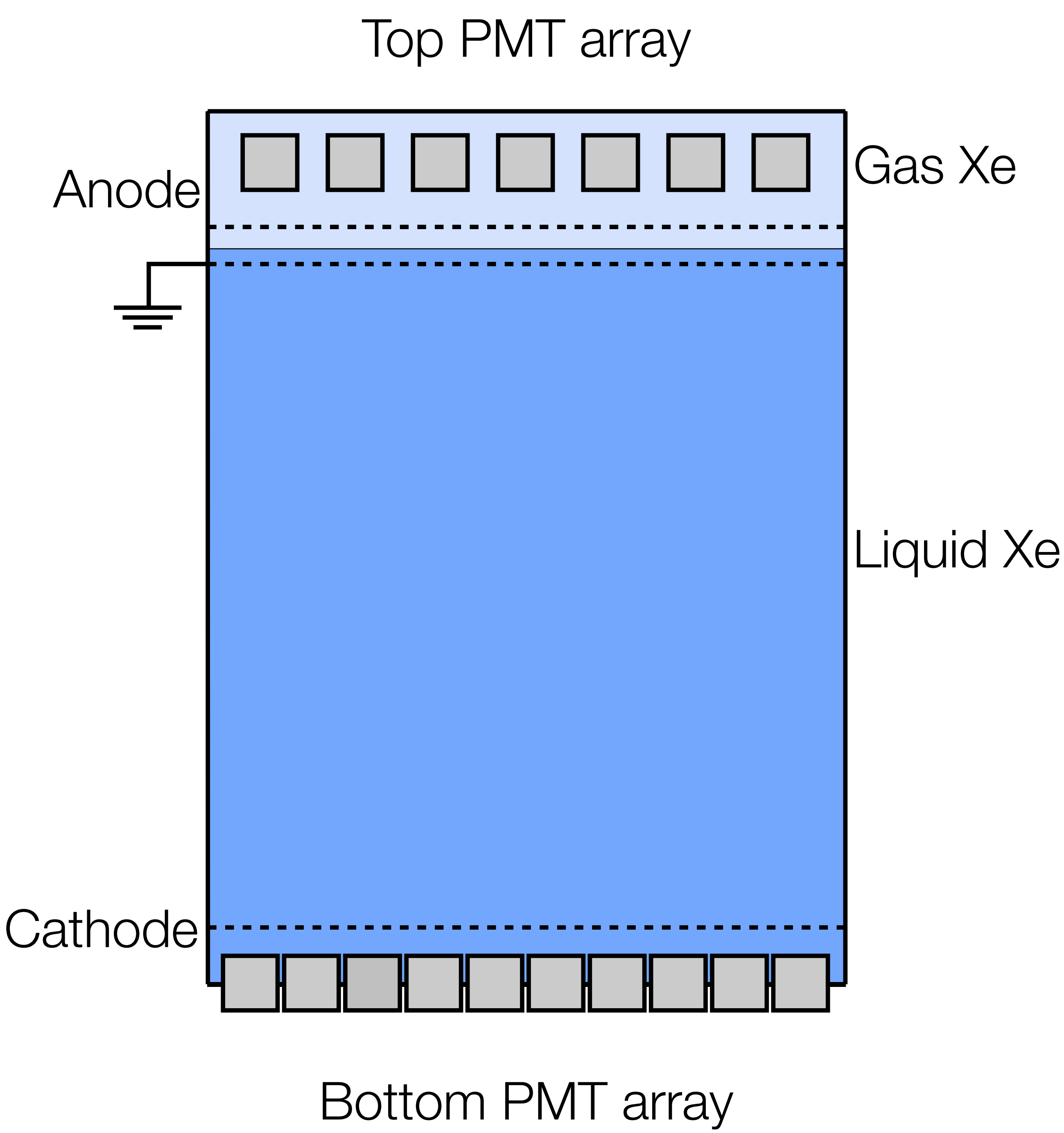
Dark Matter rate and Xe as detection medium

$$\frac{dR}{dE_{nr}} \propto N \frac{\rho_\chi}{2 m_\chi \mu^2} \sigma_N |F^2(E_{nr})| \int_{v_{min}}^{v_{esc}} \frac{f(\vec{v})}{v} d^3 v$$

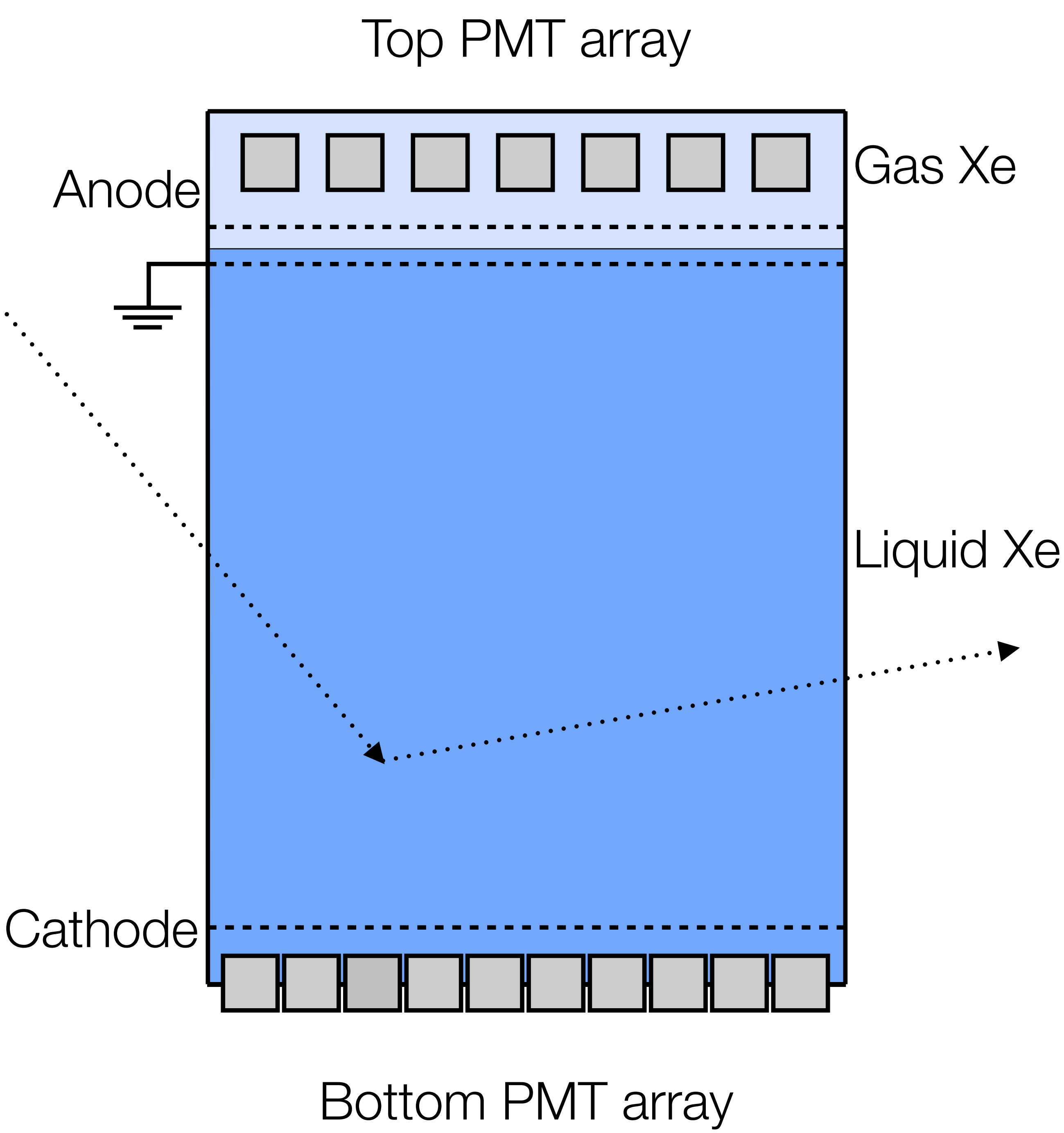


- Scalability
- Simple cryogenic: ~ -100 ºC
- High atomic mass: A~131
- Self shielding: high atomic number and density (Z = 54 and 2.8 kg/l)
- Intrinsically pure: no long-lived radioactive isotopes, Kr/Xe reduction to ppt level
- Low energy threshold
- Light (S1) and charge (S2) signals: background identification and reduction (charge-to-light ratio, 3D localization)

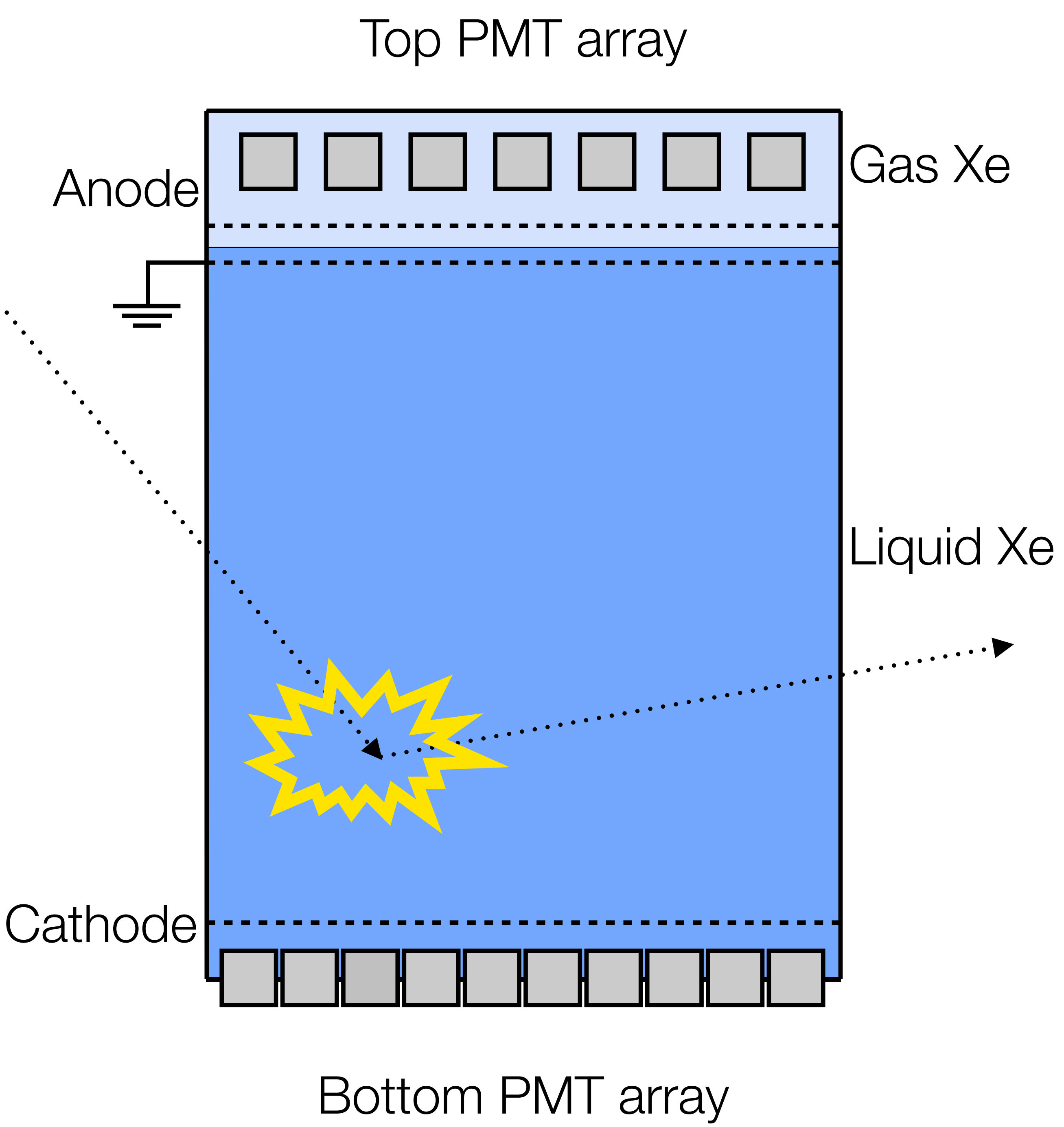
Dual-Phase Xenon TPC



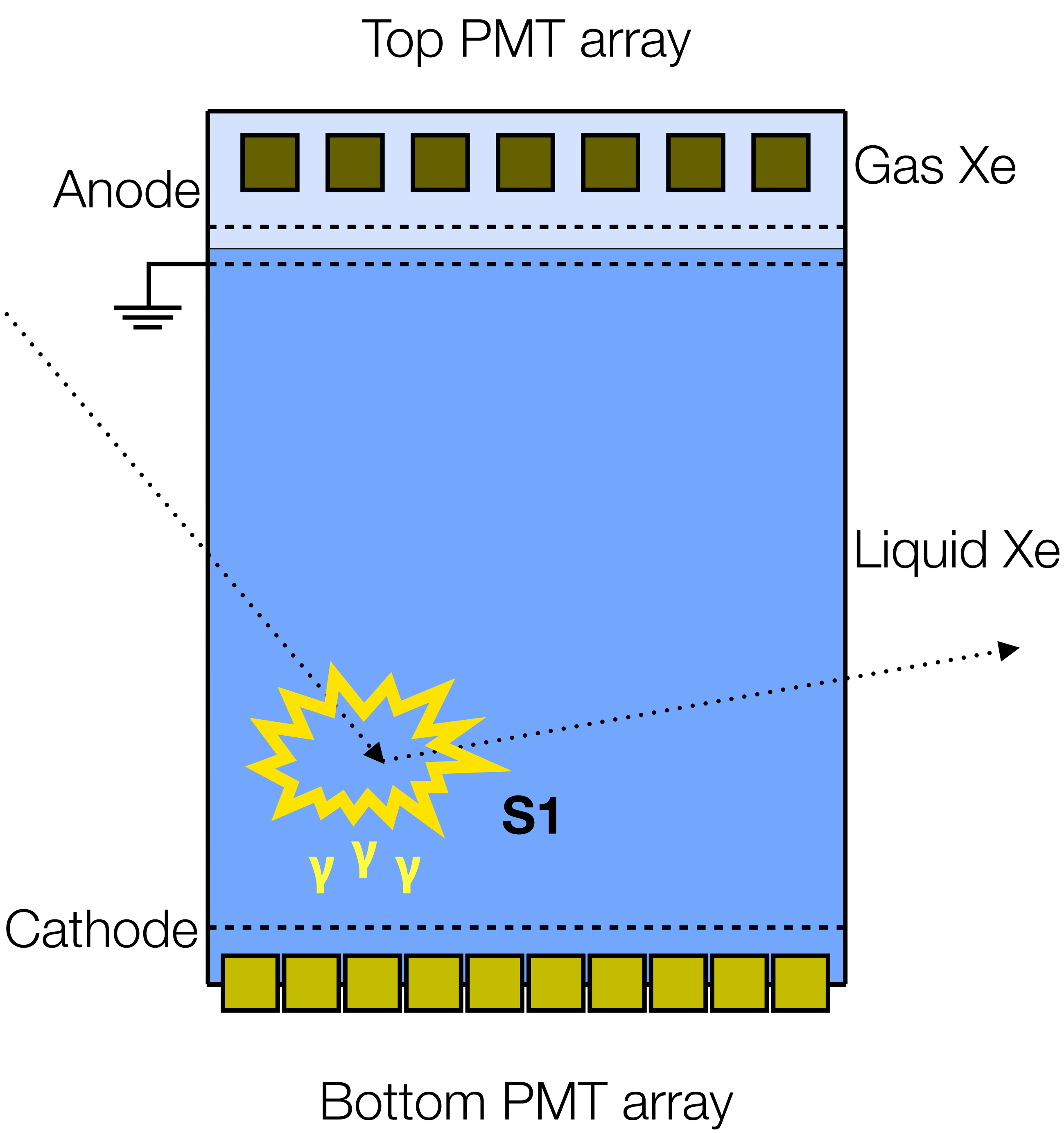
Dual-Phase Xenon TPC



Dual-Phase Xenon TPC



Dual-Phase Xenon TPC



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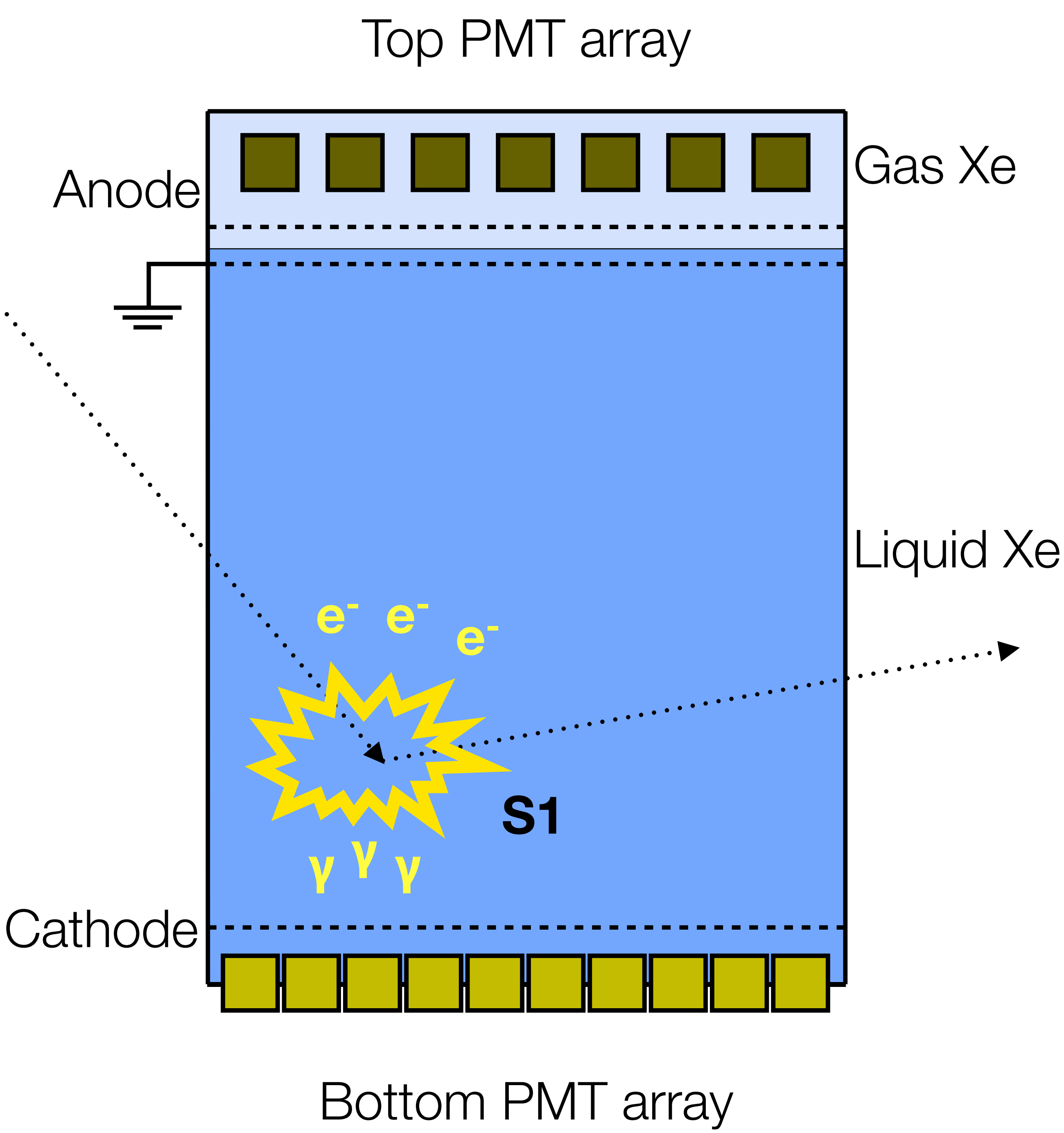
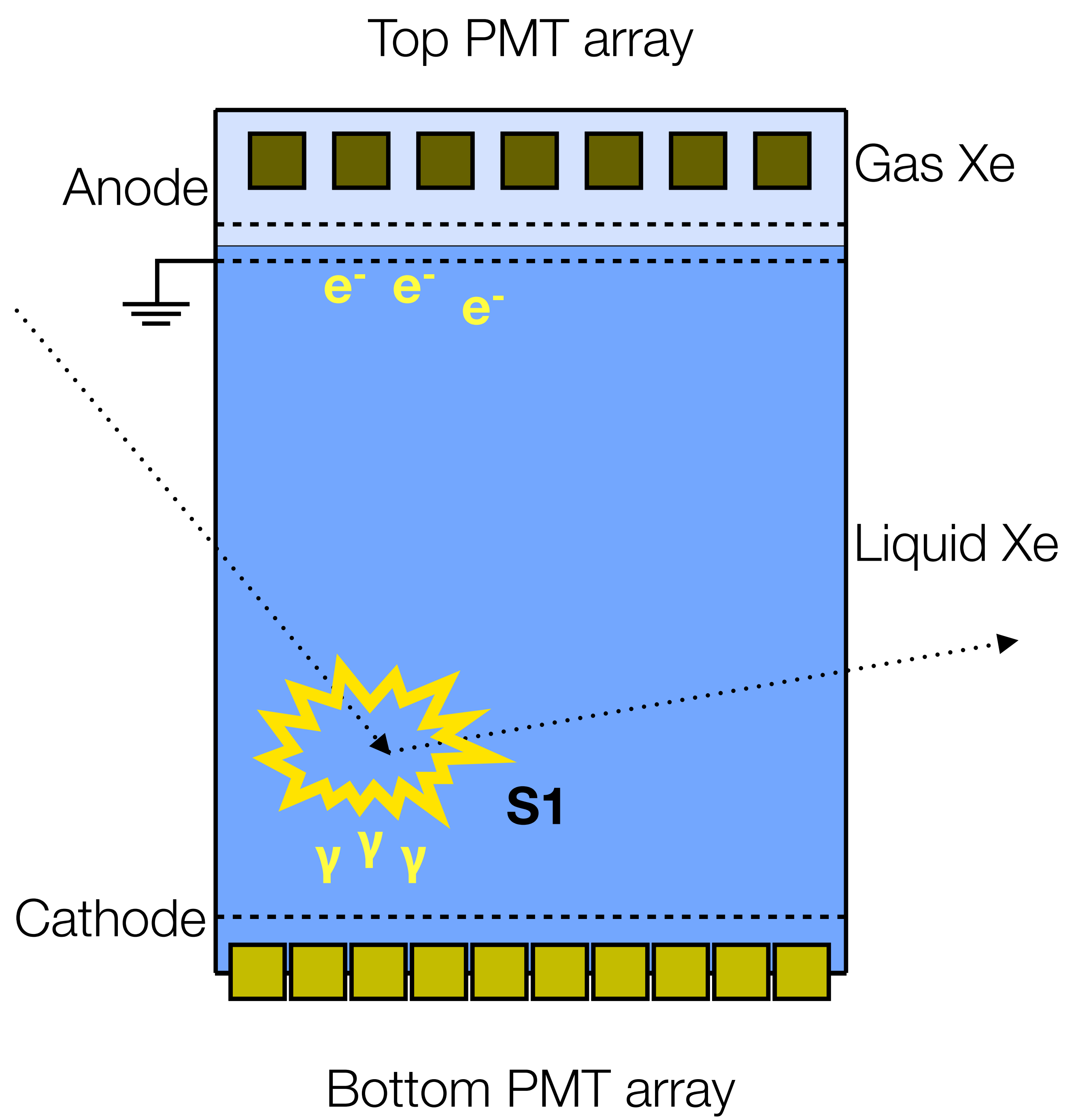
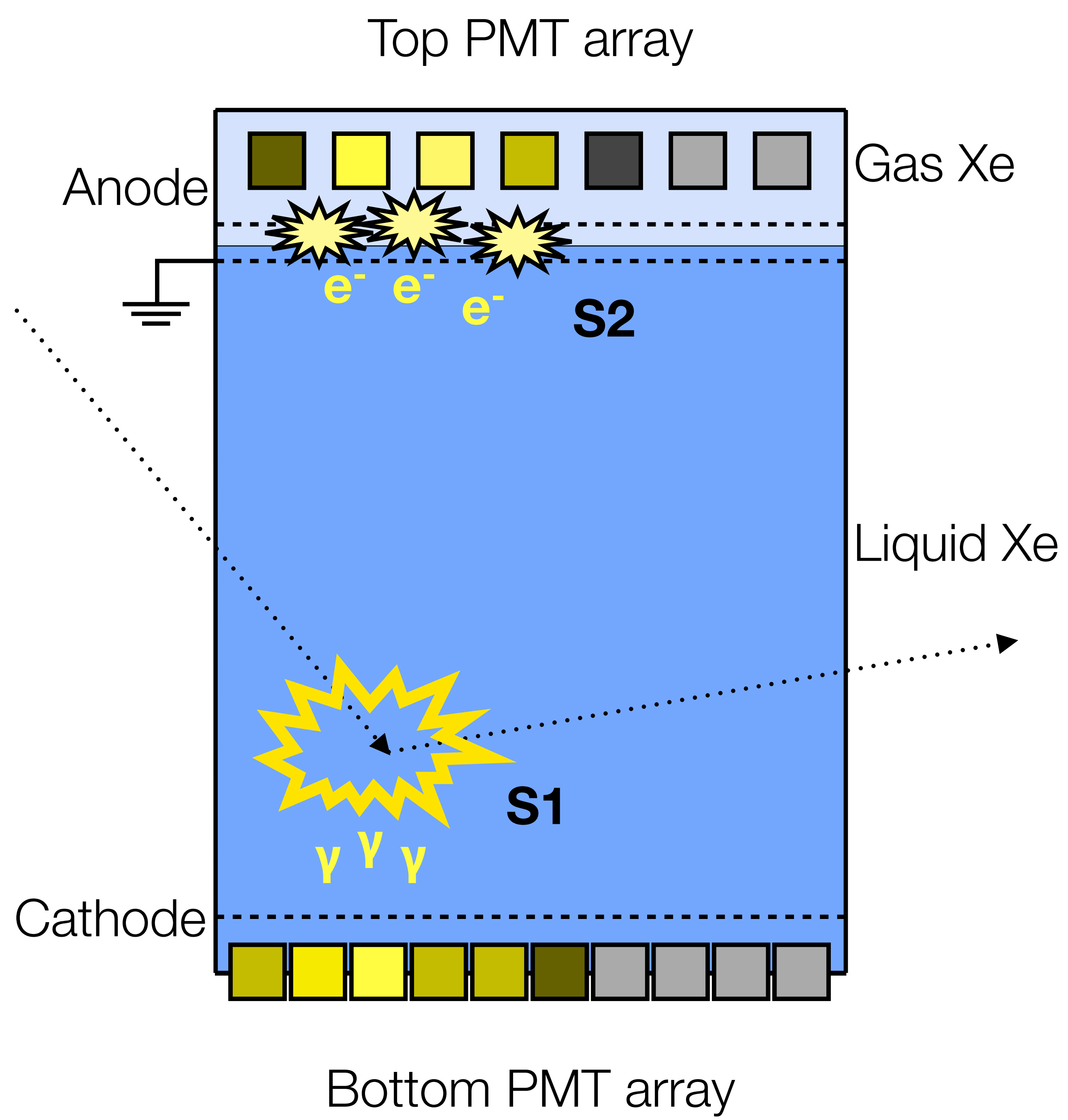


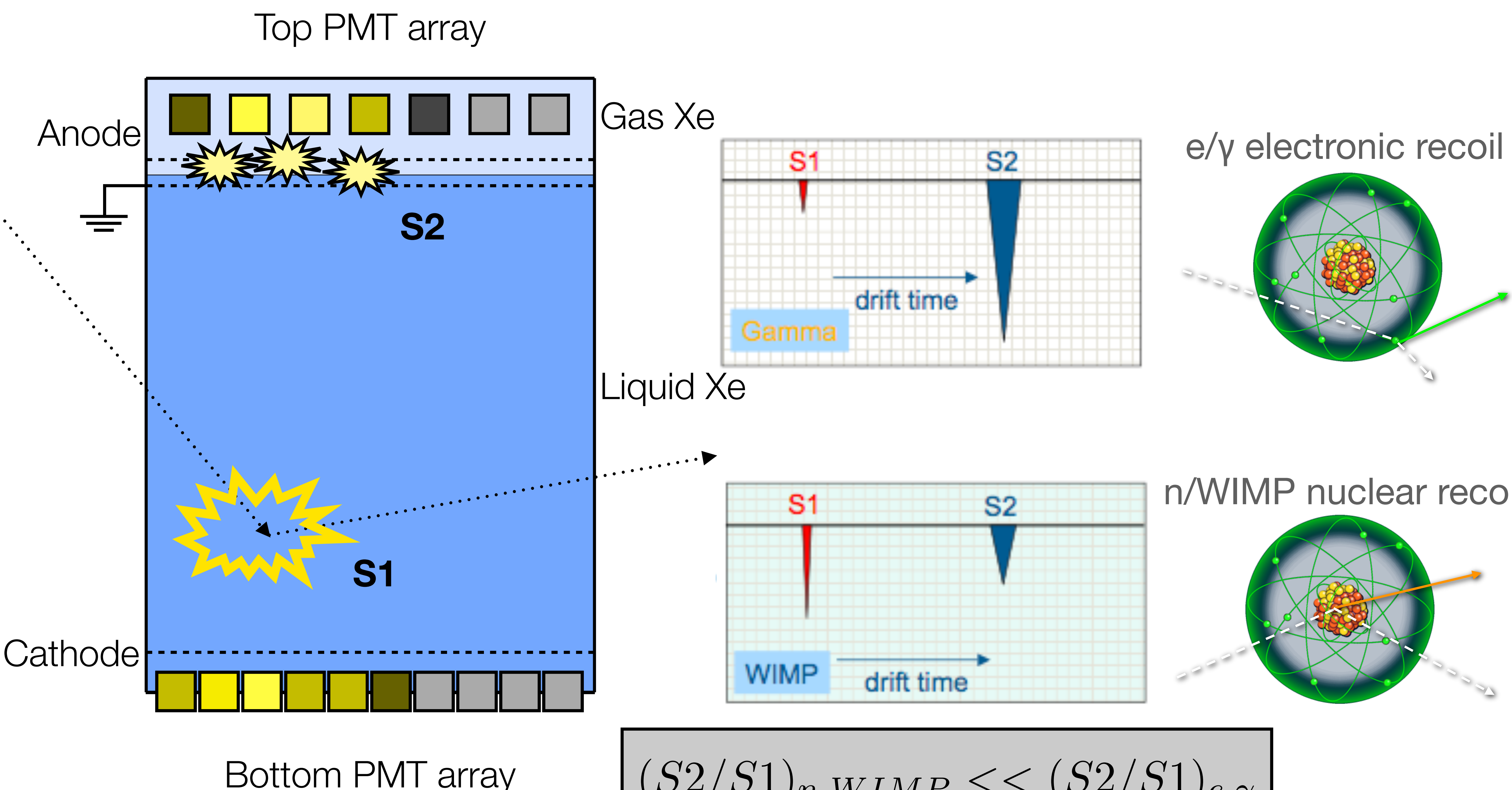
Dual-Phase Xenon TPC



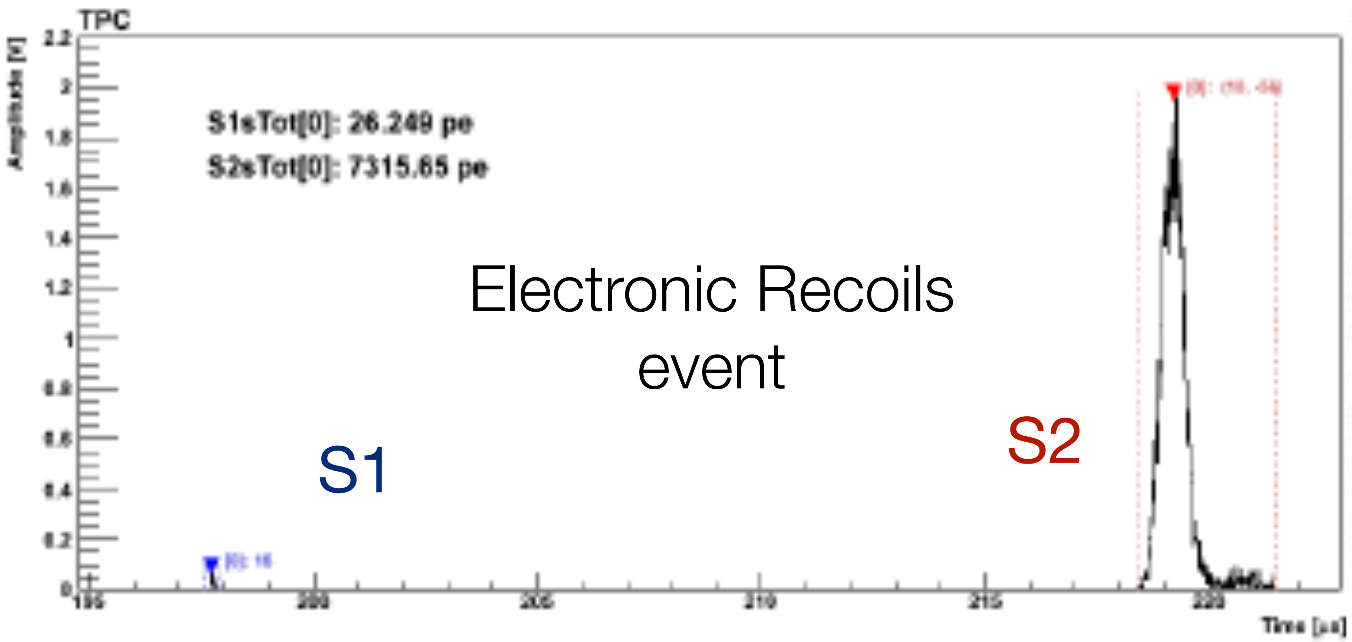
Dual-Phase Xenon TPC

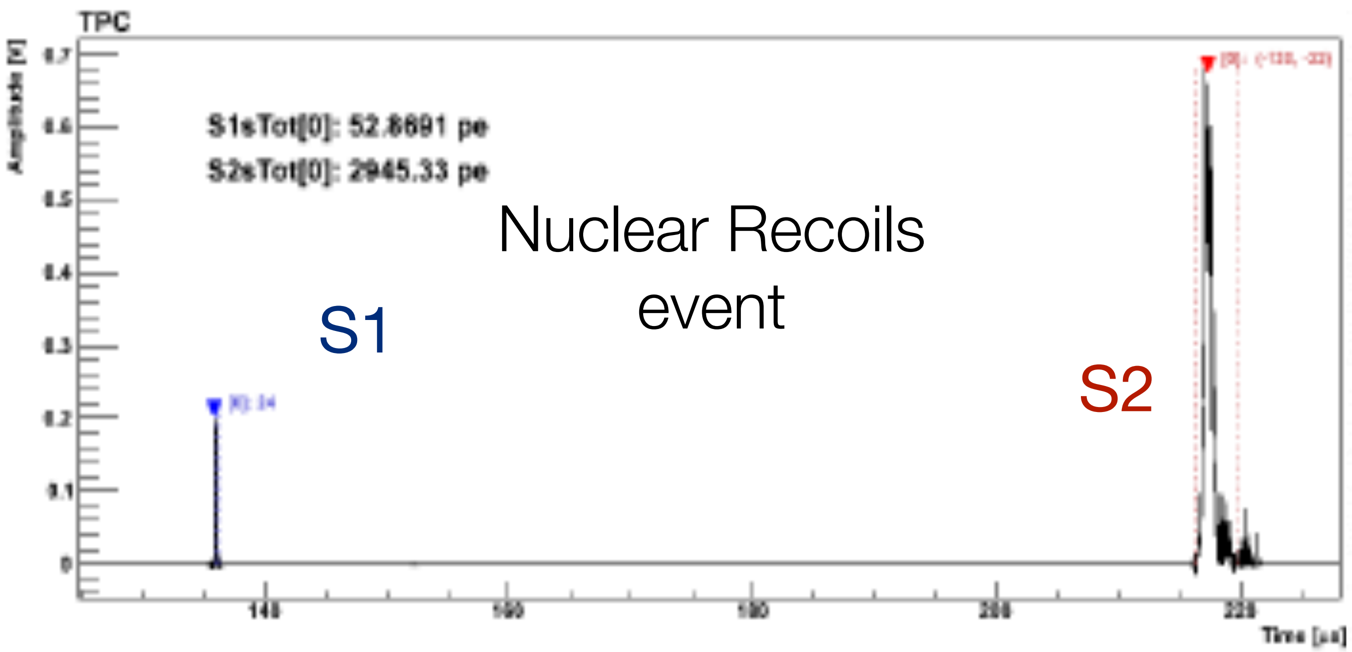


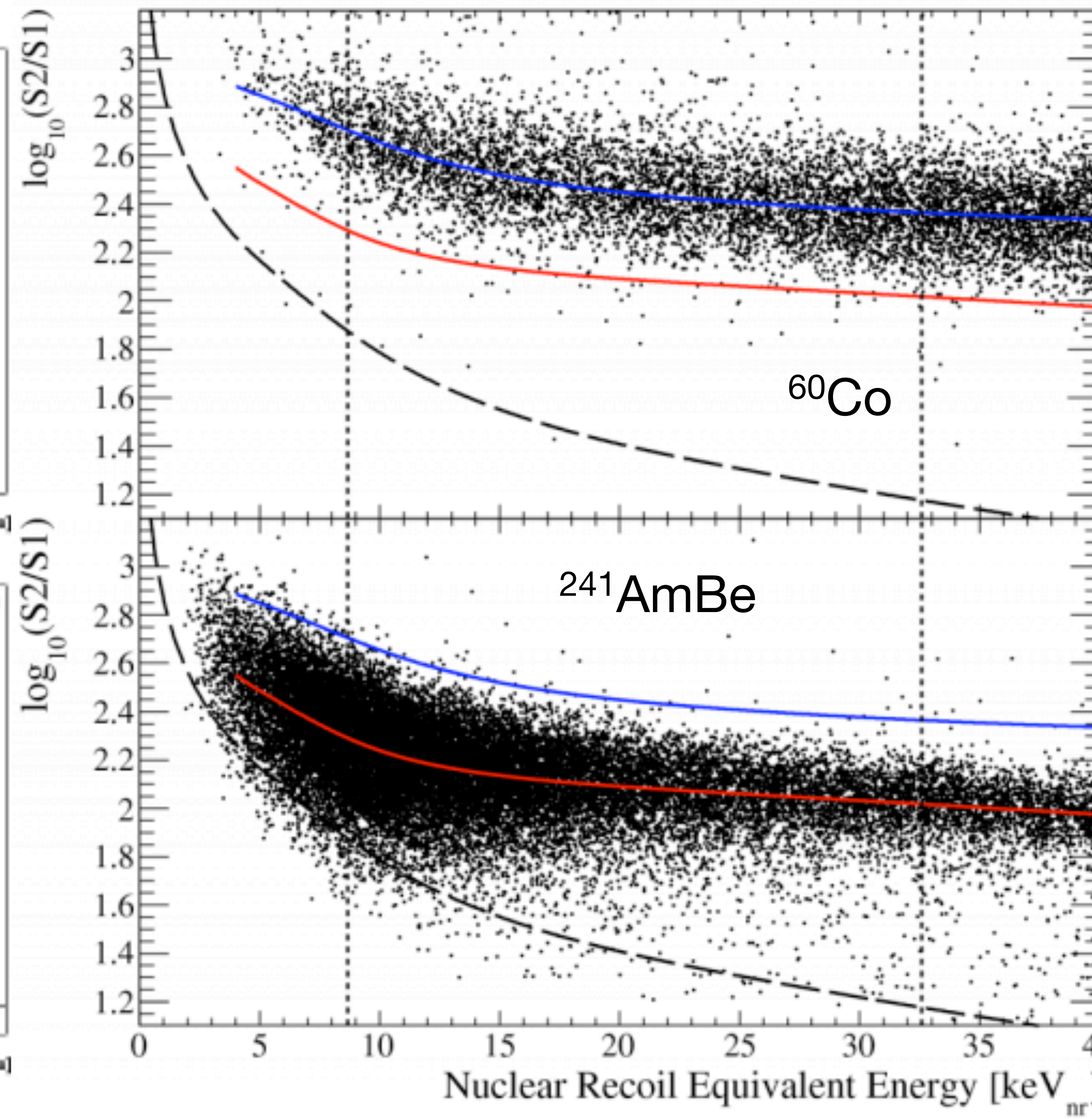
Dual-Phase Xenon TPC
Electronic and nuclear recoils discrimination



$$(S2/S1)_{n,WIMP} << (S2/S1)_{e,\gamma}$$

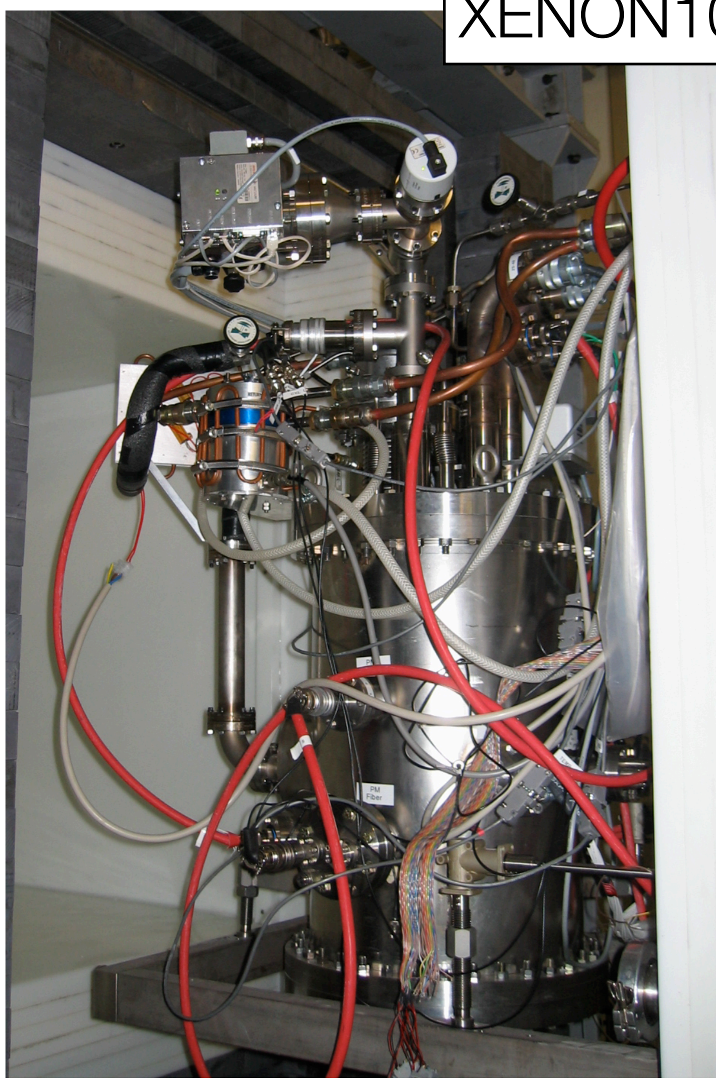

TPC
S1sTot[0]: 26.249 pe
S2sTot[0]: 7315.65 pe
Electronic Recoils event
S1
S2
Time [µs]


TPC
S1sTot[0]: 52.8691 pe
S2sTot[0]: 2945.33 pe
Nuclear Recoils event
S1
S2
Time [µs]


$log_{10}(S2/S1)$
^{60}Co
$^{241}AmBe$
Nuclear Recoil Equivalent Energy [keV_{nr}]

The XENON program

XENON10

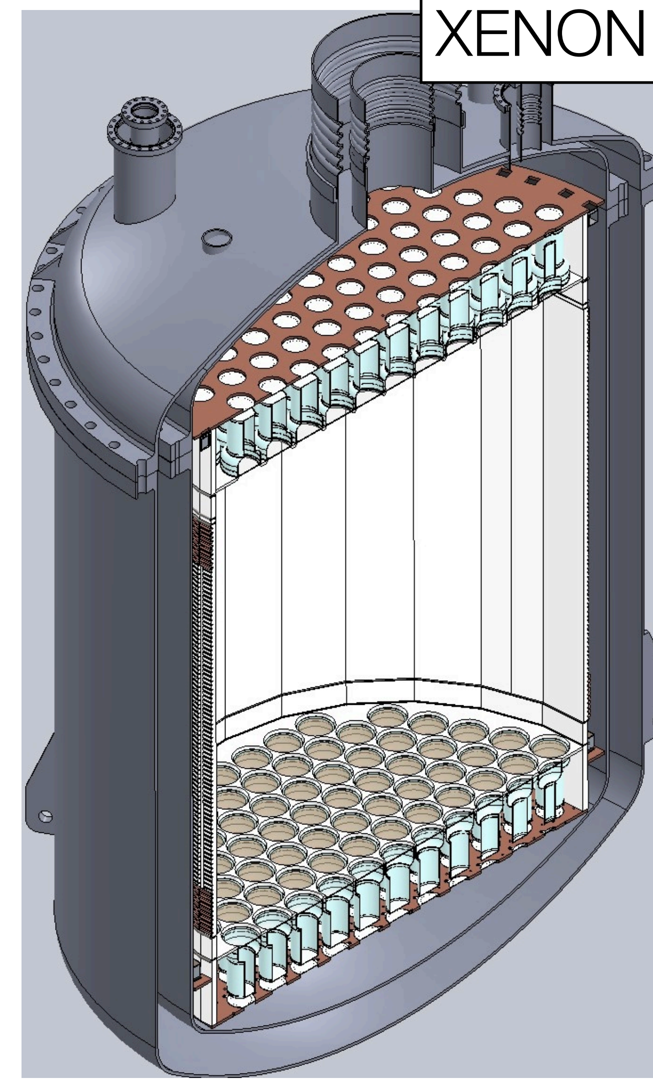


2005 - 2007
R&D demonstrator
and proof of concept

XENON100

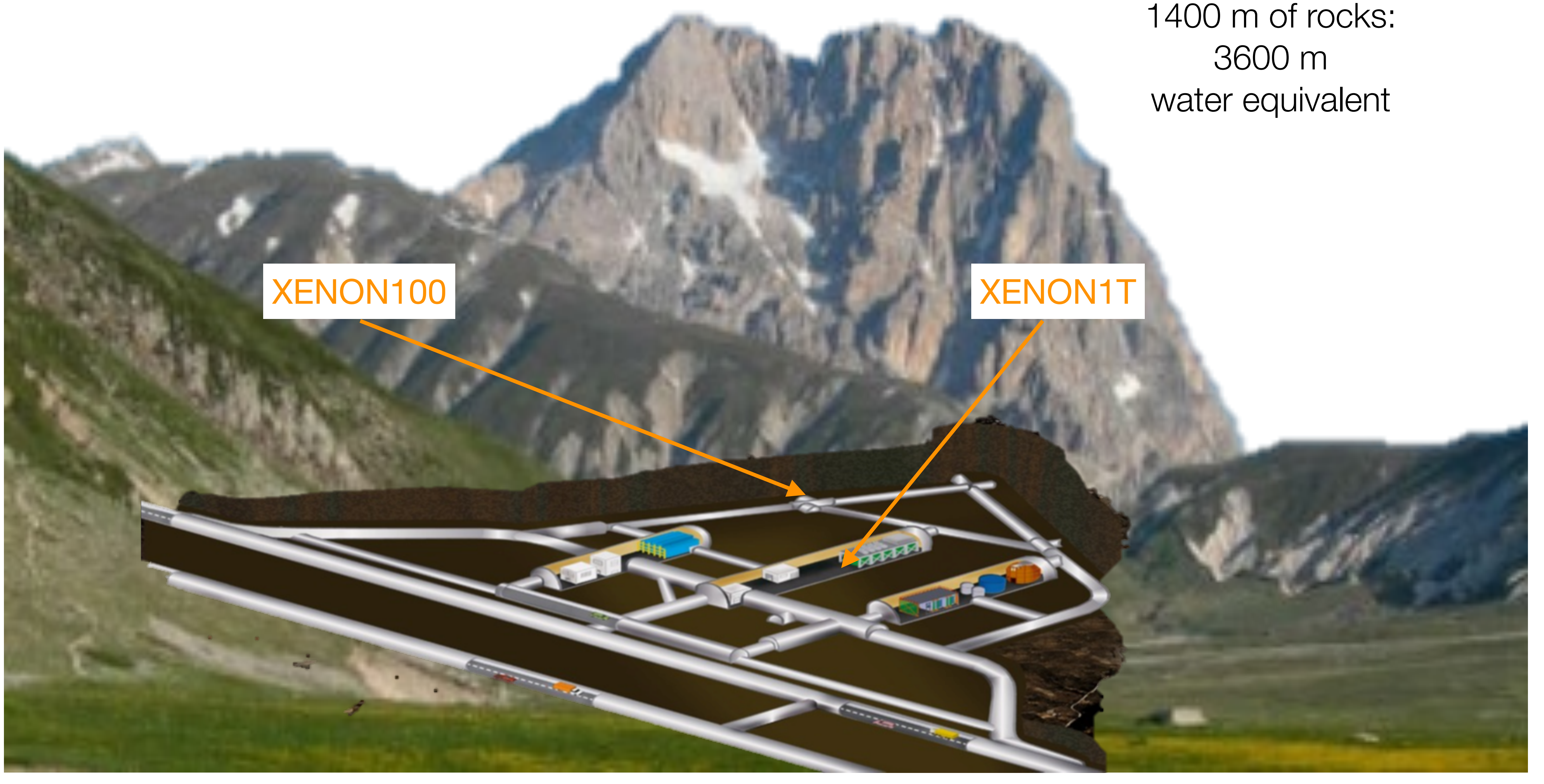
2007 - 2012
Post R&D and first
scientific results

XENON1T



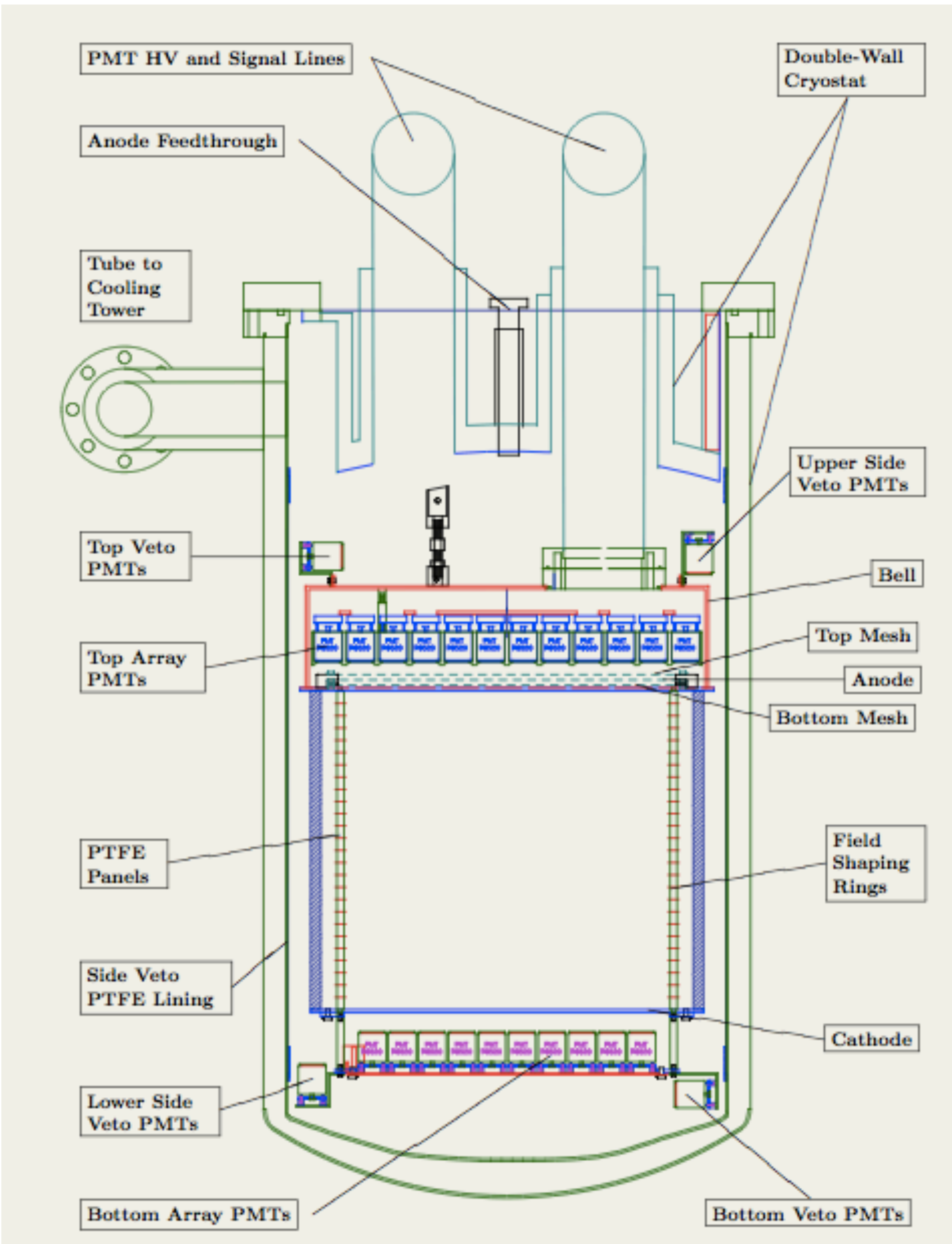
2012 - 2017
First Ton scale
detector and
discovery chance

XENON @ LNGS



1400 m of rocks:
3600 m
water equivalent

The XENON100 detector



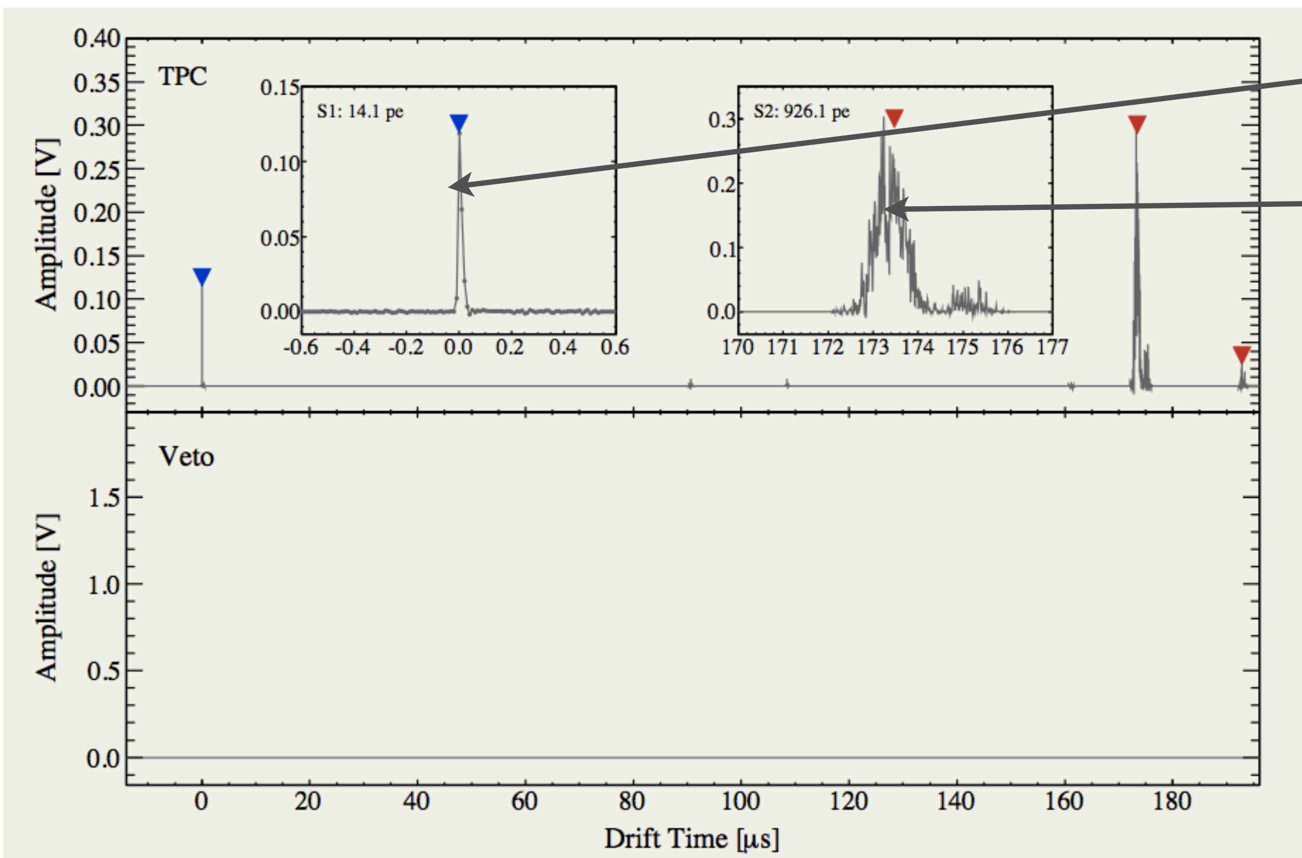
- 161 kg LXe total, 62 kg target volume,
  99 kg LXe veto.
  15 cm Radius, 30 cm drift

- Cathode at -16 kV, drift field of 0.533 kV/cm.
  Proportional scintillation region with field ~12 kV/cm.

- All components screened at dedicated screening facilities at LNGS.

- Custom-made low radioactivity HV feedthroughs.

The XENON100 waveforms

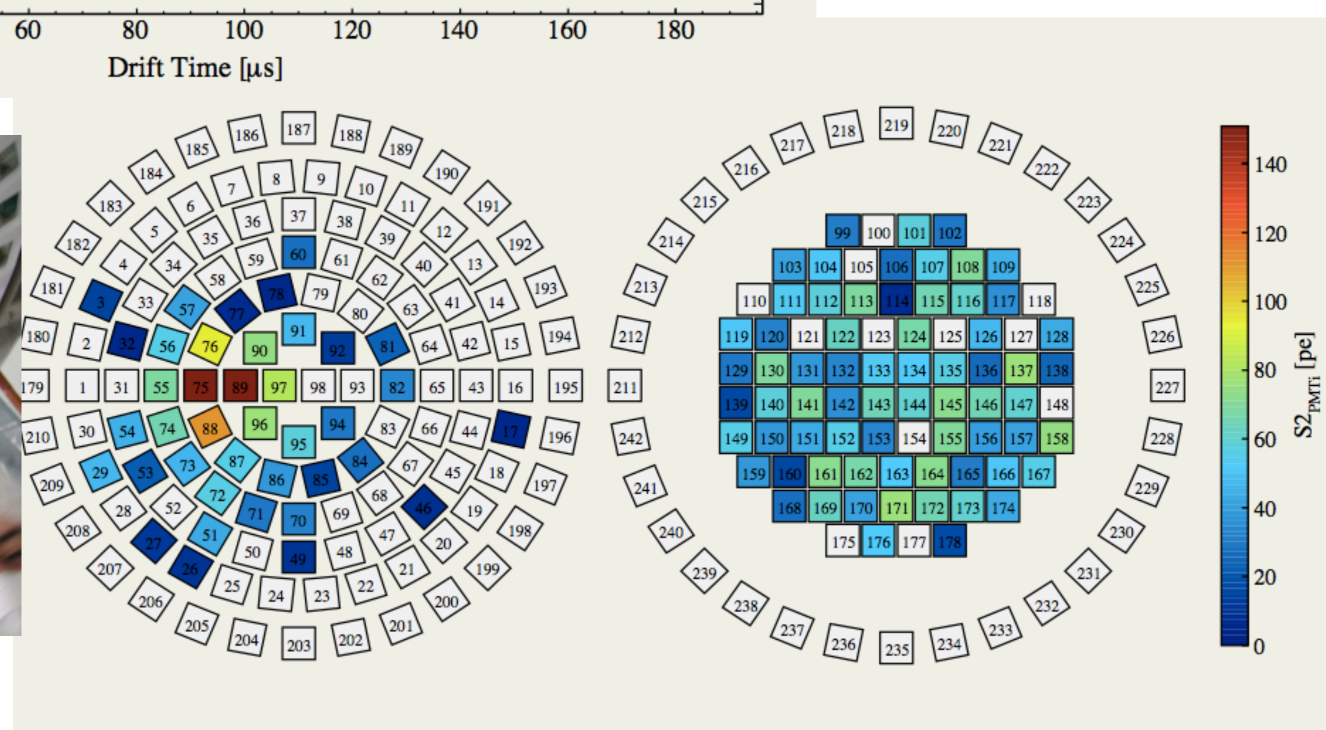


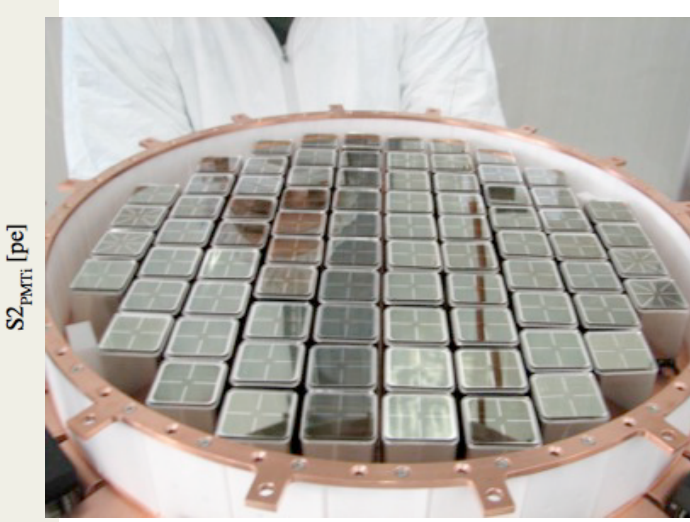
Primary (S1)

Secondary (S2)

Position determined by top array.
Checks performed using bottom array

242 total PMTs.
178 in active TPC volume





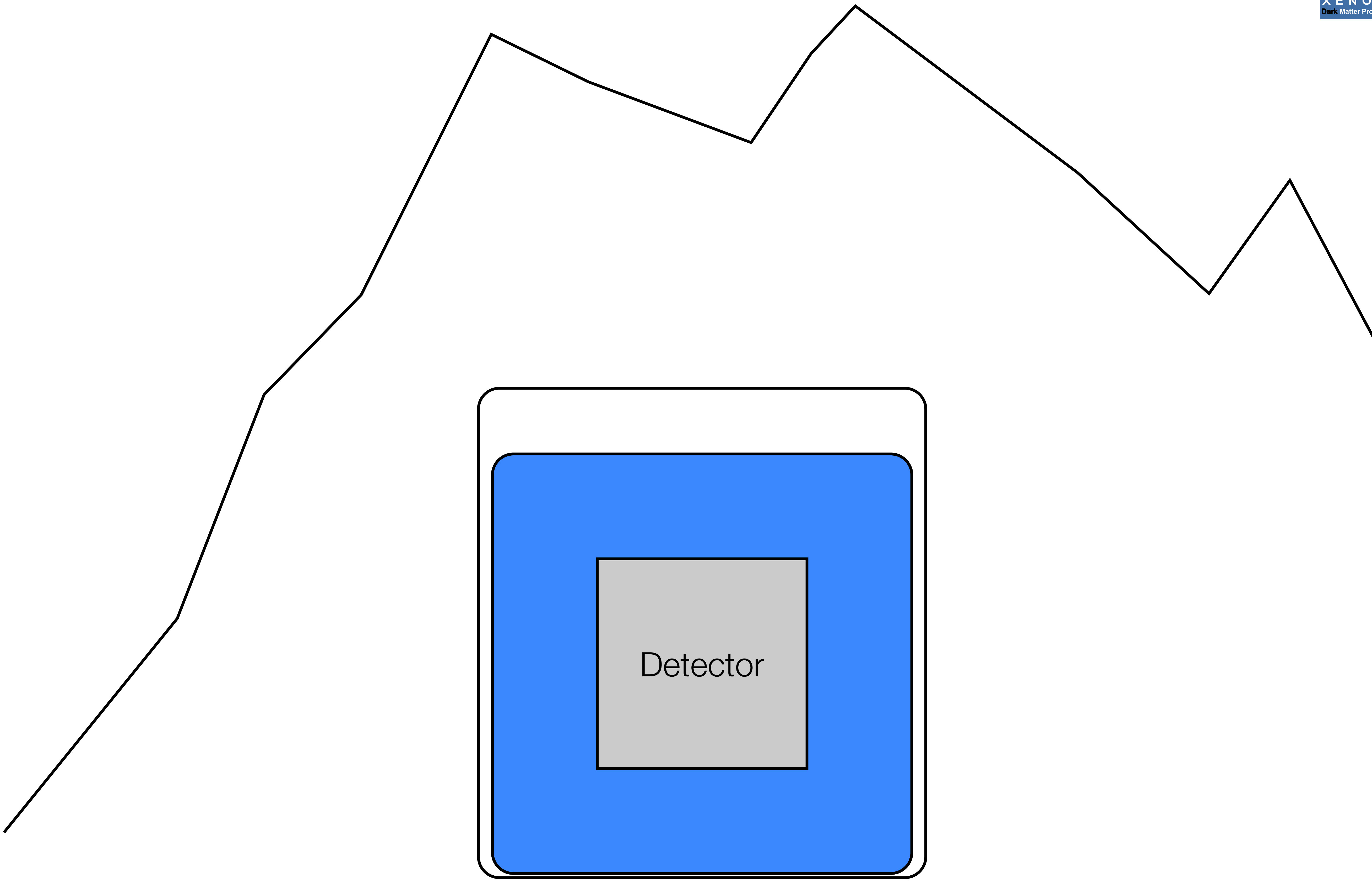
Addressing some of the main challenges of the present and future experiment

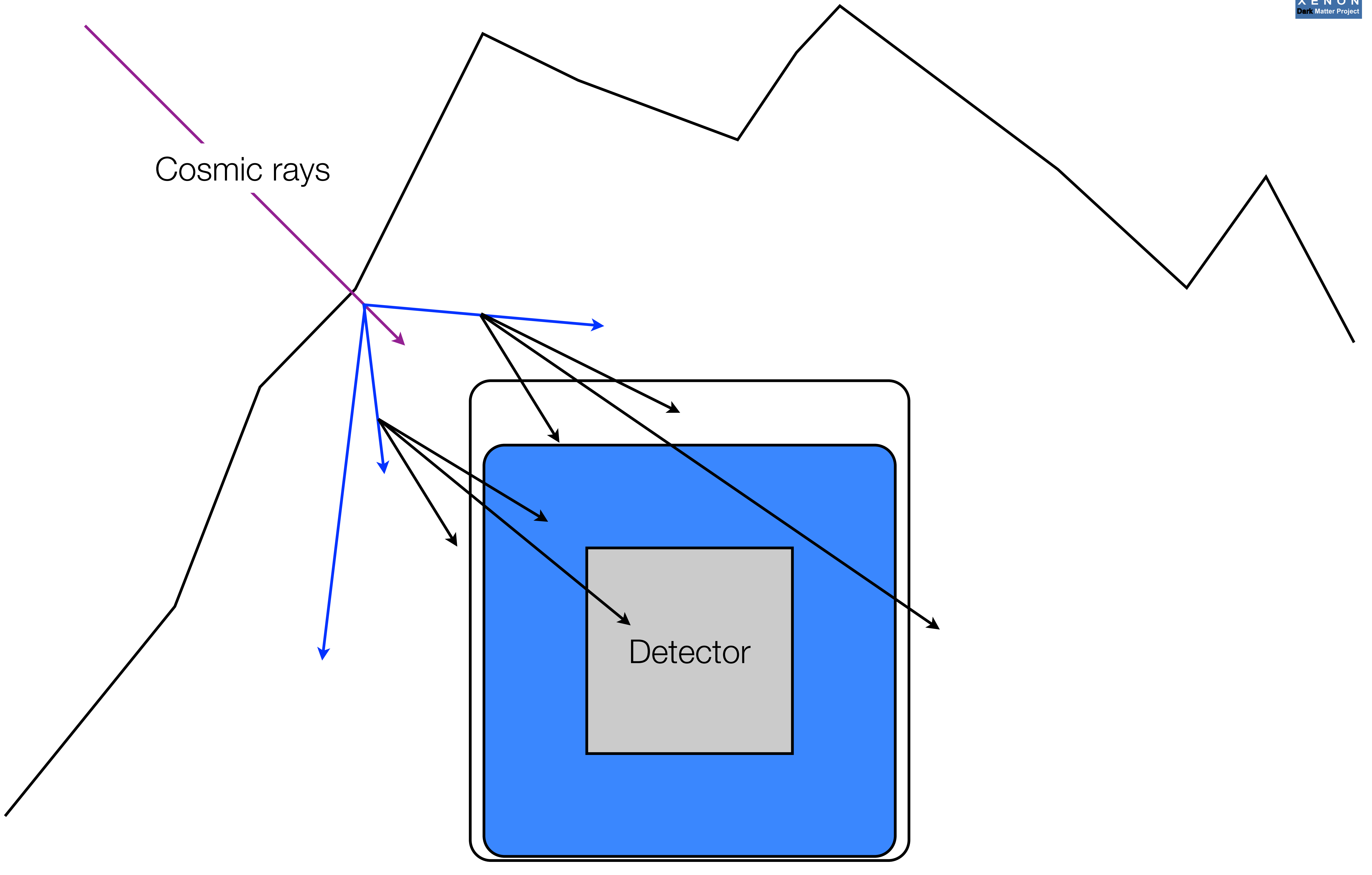
- Hardware and software: fighting against the radioactive background
  - Photosensors R&D and characterization
  - Detector material screening campaigns (especially for photosensors)
  - Detailed Monte Carlo simulation

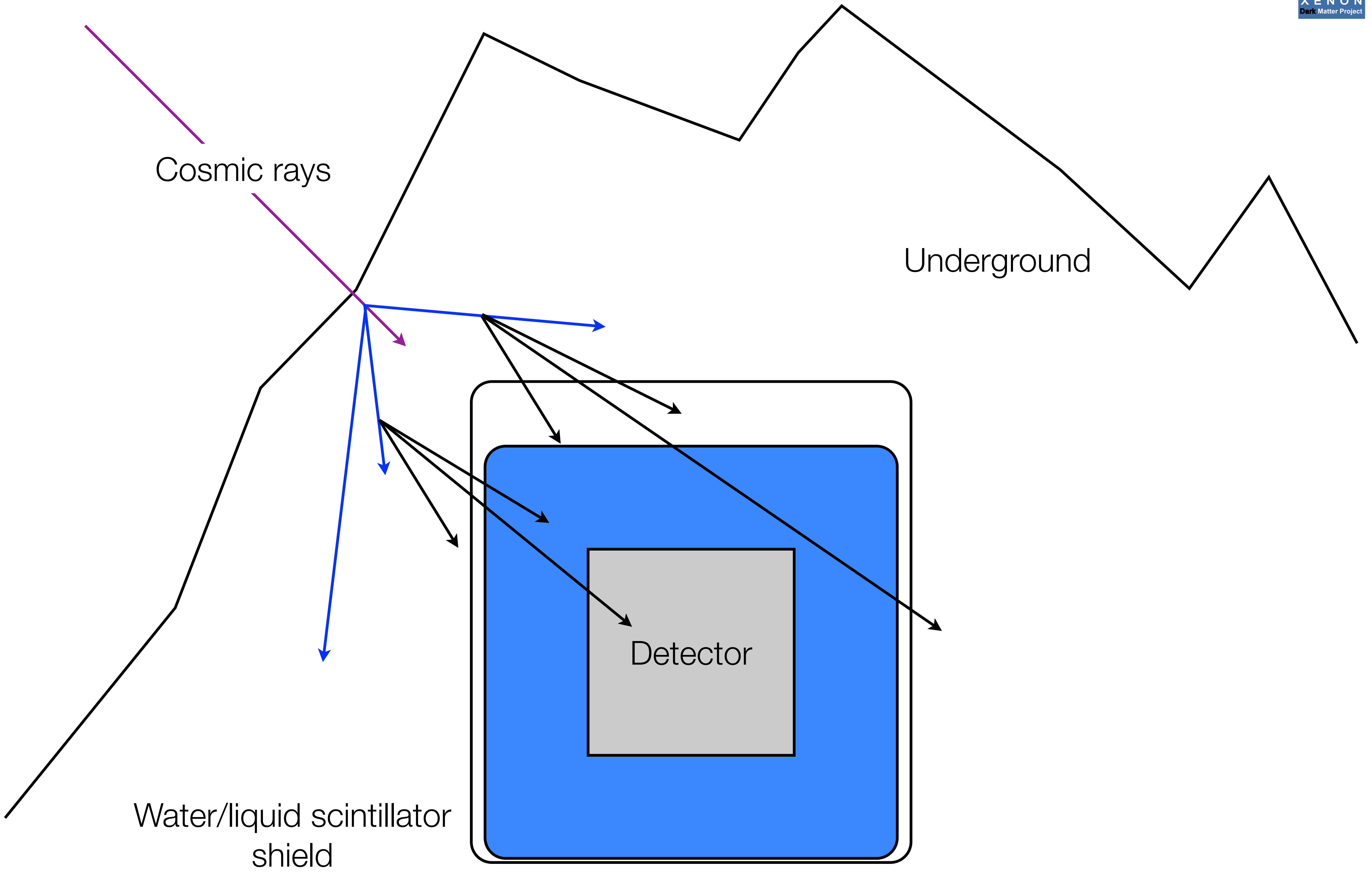
⇒ Running experiment (XENON100) background prediction

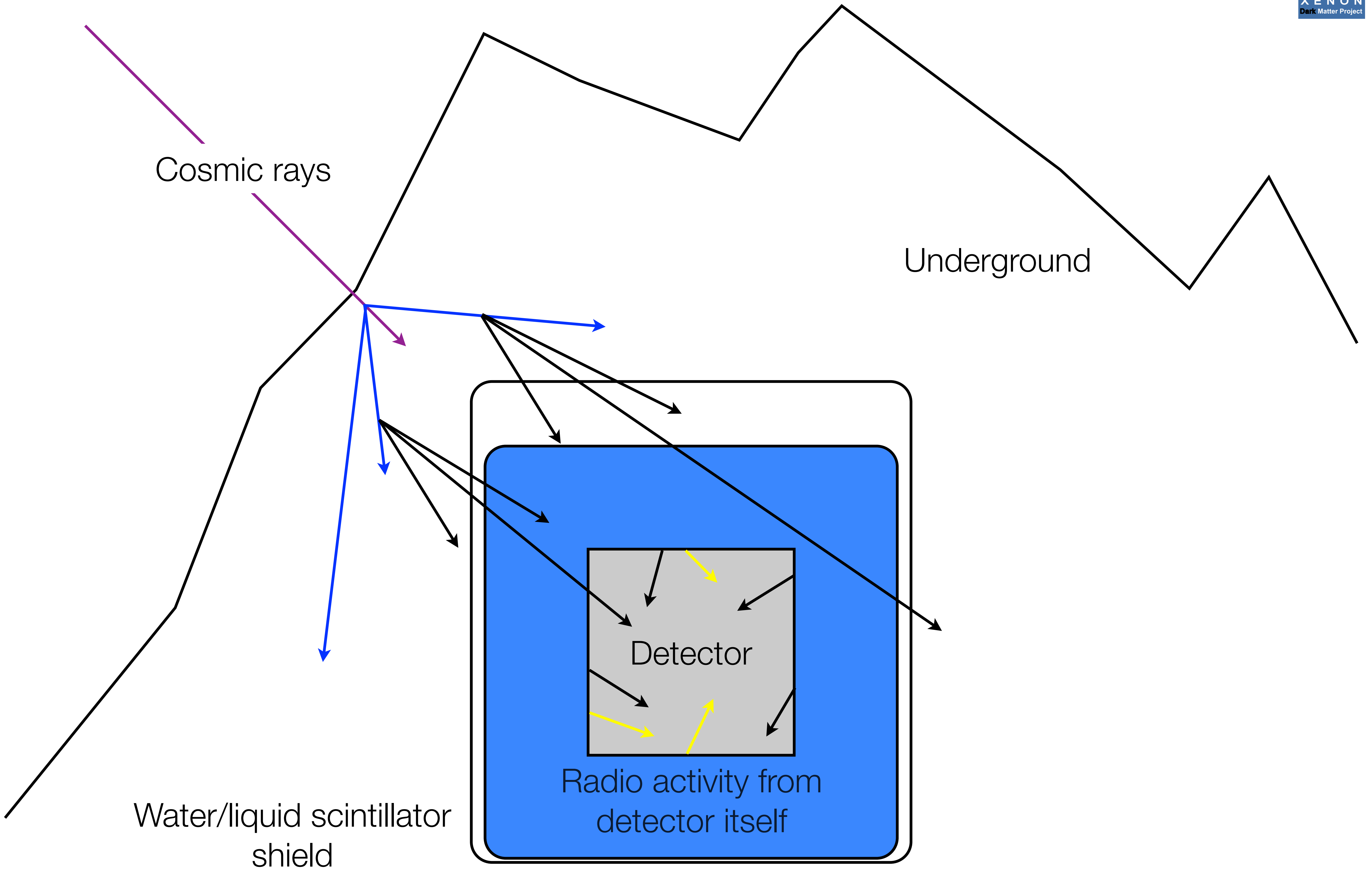
⇒ Future experiment (XENON1T) design, preparation and proposals

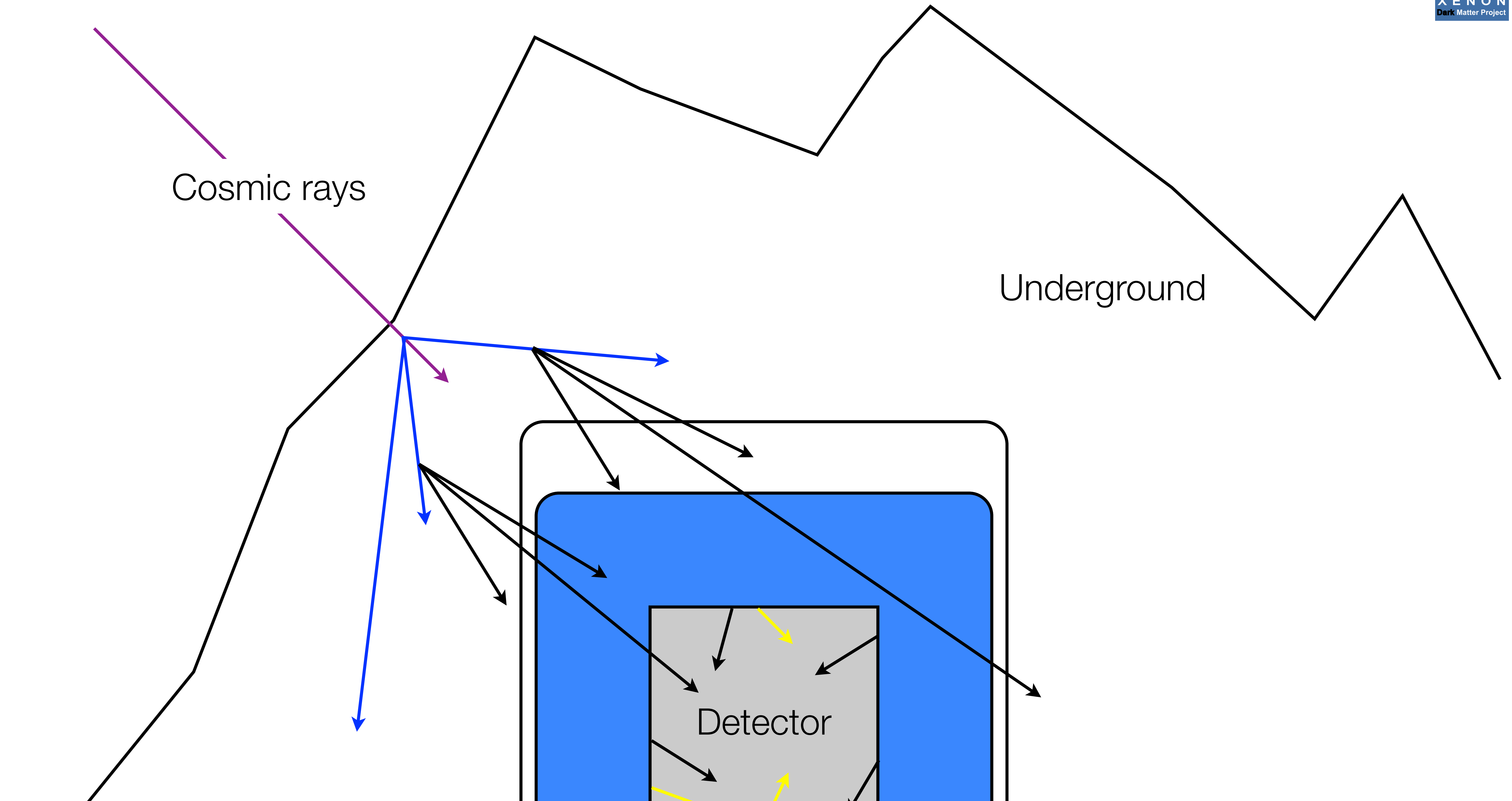
- Data analysis: New calibration approach and data analysis method
  - AmBe data/MC matching
  - E2-based analysis

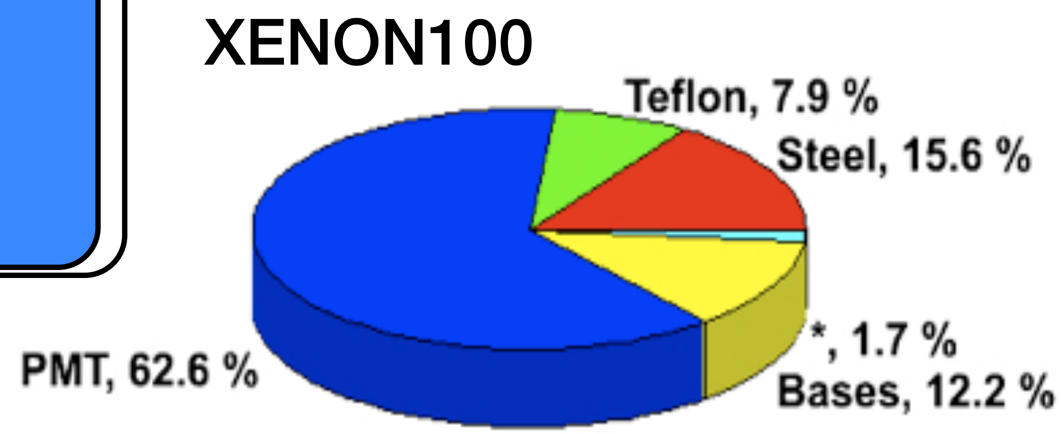

Detector


Cosmic rays
Detector


Cosmic rays
Underground
Detector
Water/liquid scintillator
shield

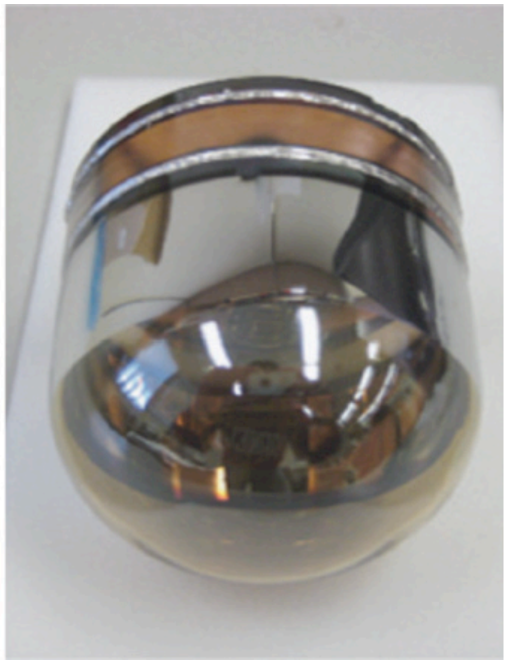

Cosmic rays
Underground
Detector
Radio activity from
detector itself
Water/liquid scintillator
shield

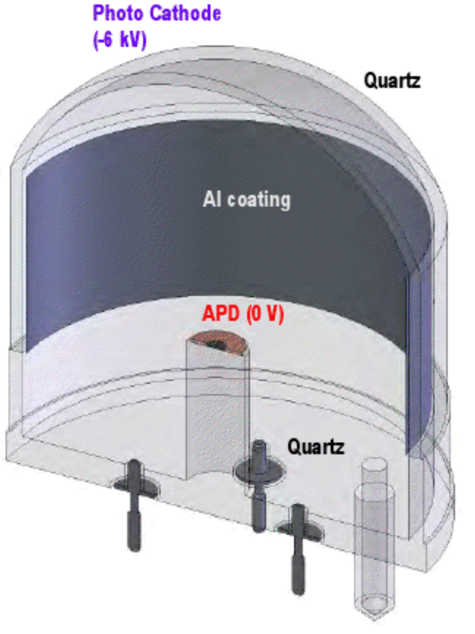

Cosmic rays
Underground
Detector
Radio activity from
detector itself
Water/liquid scintillator
shield

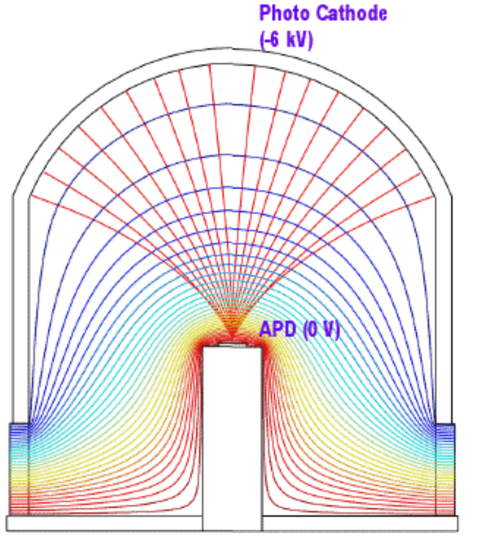

XENON100
Teflon, 7.9 %
Steel, 15.6 %
*, 1.7 %
Bases, 12.2 %
PMT, 62.6 %

QUPID (QUartz Photon Intensifying Detector)

Nucl. Instr. and Meth., A 654 (2011) 184-195





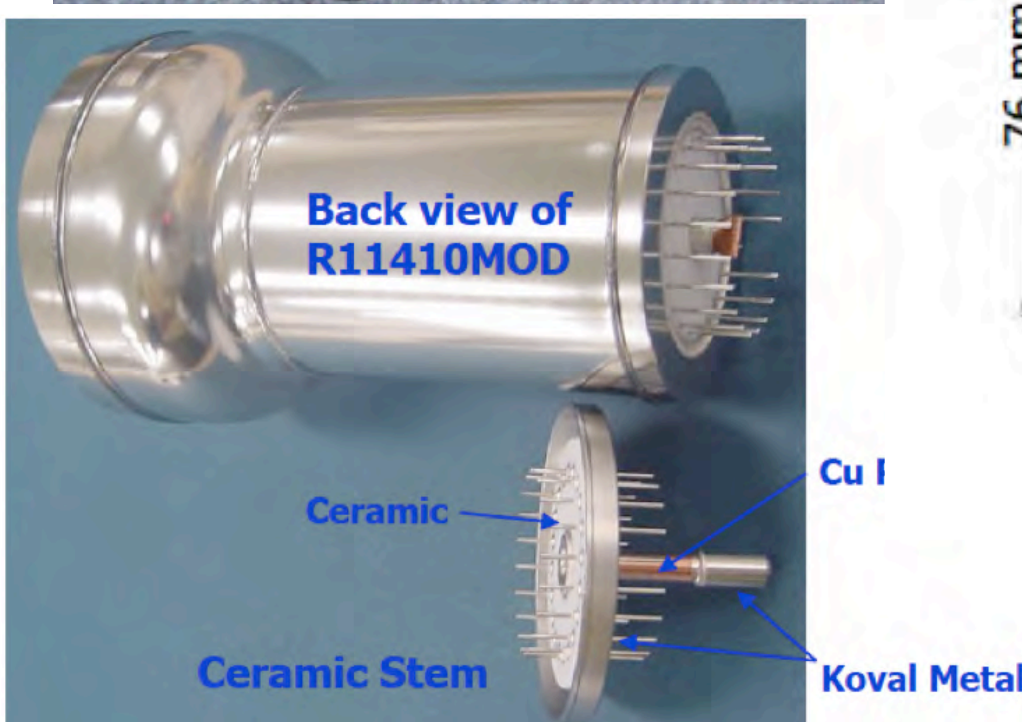


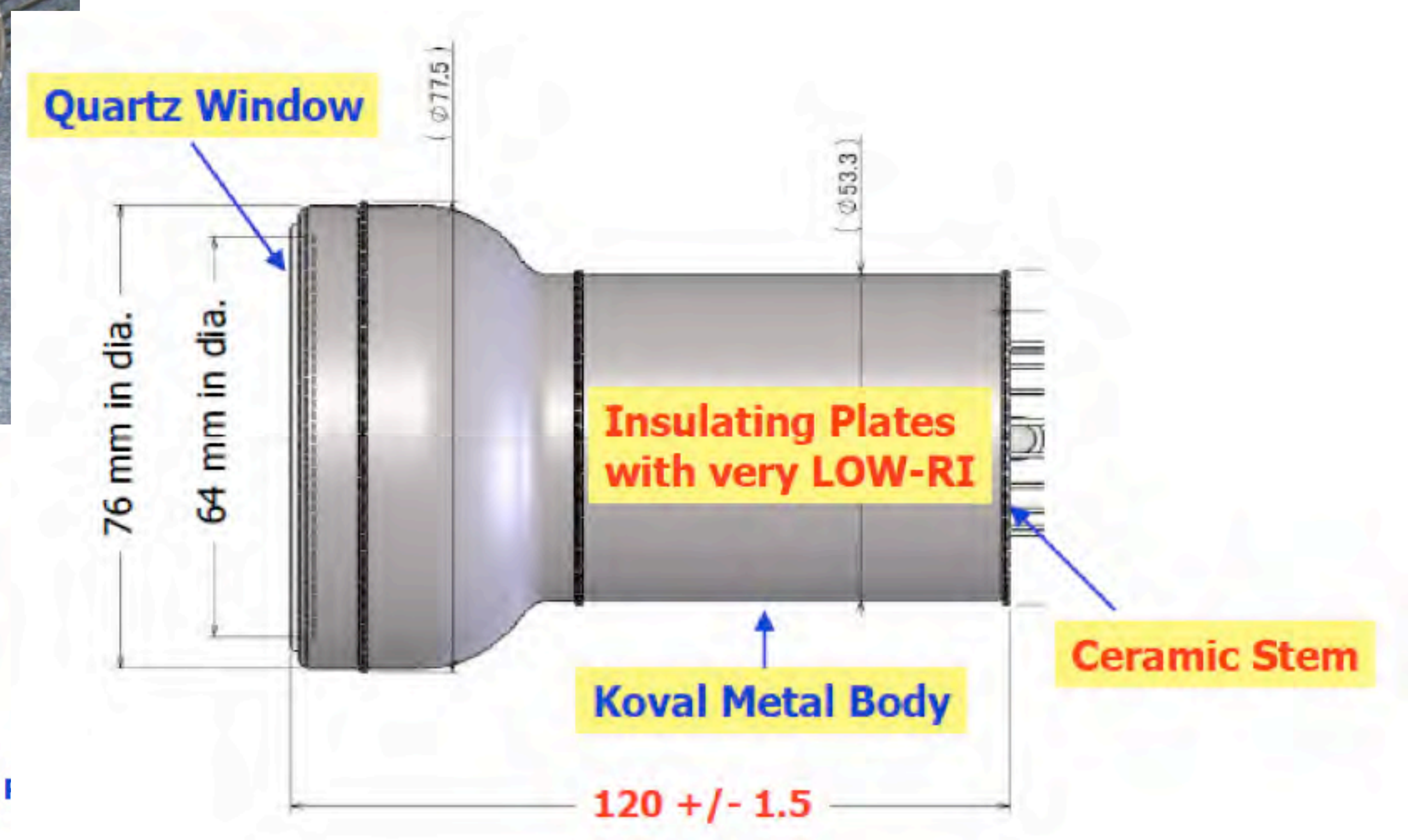
Made by Synthetic Silica only.
US Patent pending.

Contaminant	Activity (mBq/QUPID)	Events/year in fiducial cut, target mass (after fiducial cut), energy [2–18] keV		
		0 cm, 2.3 ton	5 cm, 1.6 ton	10 cm, 1.1 ton
^{238}U	< 17.3	< 560	< 0.5	0
^{226}Ra	0.3 ± 0.1	23	0.14	0.01
^{232}Th	0.4 ± 0.2	35	0.24	0.02
^{40}K	5.5 ± 0.6	55	0.32	0.02
^{60}Co	< 0.18	< 4.9	< 0.21	< 0.02
Total	< 23.7	< 678	< 1.41	< 0.07

R11410-MOD (MOD, 20, 21) PMT

arXiv:1202.2628 submitted to NIM A





Detector material screening campaign
Mass spectrometry radioactivity measurements R11410-21
Samples

No.	Part Name	Material Name	Density	to MPI	to UCLA
1	Faceplate 	Quartz plate	2.2	70.5 dai. x 3.5 mm 7 pcs (210 g)	25 x 12 x 3.5 mm (2.9g)
2	Aluminum ring 	Pure alminum sheet	2.7	100 x 90 x 0.5 mm 42 sheets (510 g)	100 x 90 x 0.5 mm (12g)
3	Metal bulb 	Cobalt free metal sheet	8	100 x 50 x 0.5 mm 25 sheets (500 g)	100 x 50 x 0.5 mm (20g)
4	Electrode (DISK) 	Stainless steel sheet (gloss surface)	7.93	100 x 50 x 1 mm 14 sheets (555 g)	100 x 50 x 1 mm (40g)
5	Other electrodes 1 	Stainless steel sheet (mat surface)	7.93	100 x 60 x 0.2 mm 54 sheets (514 g)	100 x 60 x 0.2 mm (9.5g)
6	Other electrodes 2 (Shield Plate) 	Stainless steel sheet (mat surface)	7.93	100 x 60 x 0.3 mm 36 sheets (514 g)	100 x 60 x 0.3 mm (14.3g)
7	Insulator plate 	Quartz insulator	2.2	50 x 28 x 1.4 mm 48 pcs (206 g)	50 x 28 x 1.4 mm (4.3g)

Detector material screening campaign
Mass spectrometry radioactivity measurements R11410-21
Results

- Inductively coupled plasma mass spectrometry (ICP-MS) @ LNGS, UC-Davis and EAG
- Glow Discharge MS @ EAG

R11410 3" PMT ICP-MS Results UC-Davis

Item	Description	Material	Mass	Thorium						Uranium						item total	
			g	ppb	<	ug	<	mBq	<	ppb	<	ug	<	mBq	<	mBq	<
1	Face plate	Quartz (4)	30	4.0E-03	4.0E-03	1.2E-04	1.2E-04	5.0E-04	5.0E-04	2.0E-03	2.0E-03	6.0E-05	6.0E-05	7.3E-04	7.3E-04	1.2E-03	1.2E-03
2	Aluminium ring	Aluminium	0.6	6.6E+00	6.6E+00	4.0E-03	4.0E-03	1.7E-02	1.7E-02	4.9E+01	4.9E+01	2.9E-02	2.9E-02	3.5E-01	3.5E-01	3.7E-01	3.7E-01
3	Kovar flange	Kovar (1)	18	1.6E+01	1.6E+01	3.0E-01	3.0E-01	1.2E+00	1.2E+00	6.0E-01	6.0E-01	1.1E-02	1.1E-02	1.3E-01	1.3E-01	1.4E+00	1.4E+00
4	Kovar funnel side plate	Kovar (2)	36	1.1E+01	1.1E+01	3.9E-01	3.9E-01	1.6E+00	1.6E+00	4.0E-01	4.0E-01	1.4E-02	1.4E-02	1.8E-01	1.8E-01	1.8E+00	1.8E+00
5	Kovar side pipe	Kovar (3)	49	3.8E+00	3.8E+00	1.9E-01	1.9E-01	7.8E-01	7.8E-01	2.0E-01	2.0E-01	9.8E-03	9.8E-03	1.2E-01	1.2E-01	9.0E-01	9.0E-01
6	Ceramic stem*	Ceramic	28	1.0E+00	1.0E+00	2.8E-02	2.8E-02	1.2E-01	1.2E-01	1.0E+00	1.0E+00	2.8E-02	2.8E-02	3.4E-01	3.4E-01	4.6E-01	4.6E-01
9	Substrate	Quartz (1)	8.9	2.2E-01	2.2E-01	2.0E-03	2.0E-03	8.3E-03	8.3E-03	6.8E+00	6.8E+00	6.1E-02	6.1E-02	7.4E-01	7.4E-01	7.4E-01	7.4E-01
10	Spacer	Quartz (2)	0.8	1.1E-02	1.1E-02	8.6E-06	8.6E-06	3.6E-05	3.6E-05	8.2E-02	8.2E-02	6.4E-05	6.4E-05	7.8E-04	7.8E-04	8.1E-04	8.1E-04
12-25	Electrodes	SUS (1)-14	24.4	1.0E+00	1.0E+00	2.4E-02	2.4E-02	1.0E-01	1.0E-01	3.0E-01	3.0E-01	7.3E-03	7.3E-03	8.9E-02	8.9E-02	1.9E-01	1.9E-01
7-8	Electrodes	Nickel	0.06	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	Getter	Getter	0.06	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	SUM		196	4.7	4.7	0.9	0.9	3.9	3.9	0.8	0.8	0.2	0.2	1.9	1.9	5.8	5.8

Lanthanum	
ppb	<
1.4E-02	1.4E-02
2.9E+01	2.9E+01
6.4E+00	6.4E+00
6.7E+00	6.7E+00
3.0E+00	3.0E+00
6.0E+00	6.0E+00
9.0E+00	9.0E+00
5.7E+00	5.7E+00
6.0E+00	6.0E+00

PMT TOTAL (U+Th)		
	5.8	mBq
	5.8	<

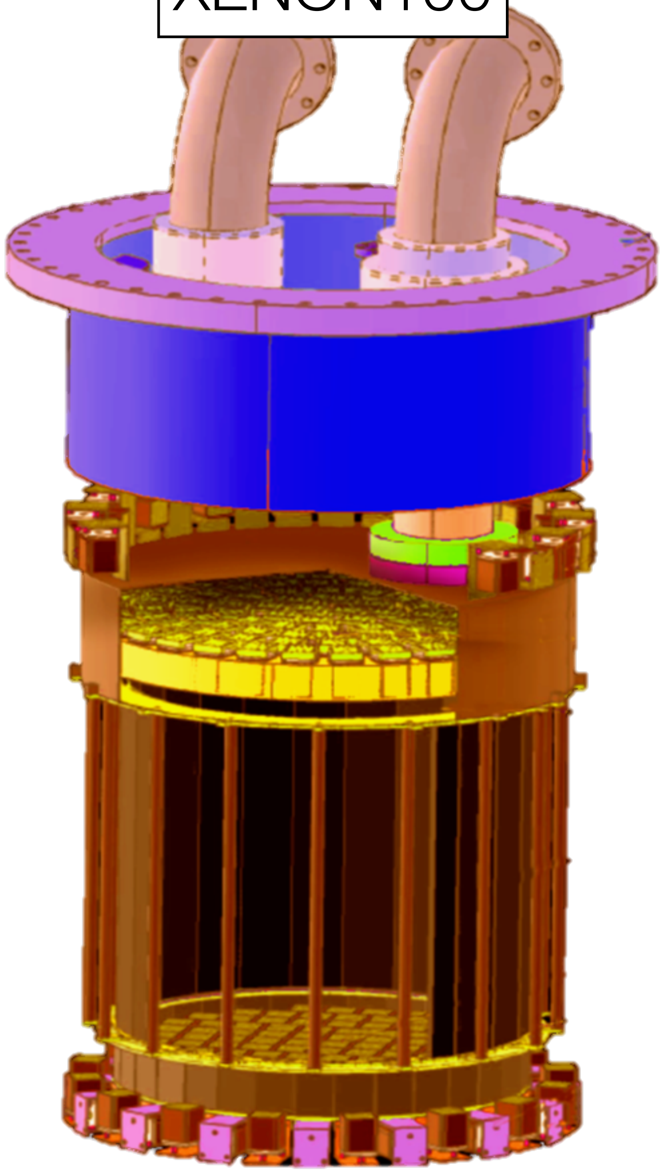
First pass analysis for ceramics (<1ppb U & Th limits; need to verify solution). Currently trying heat, pressure and microwave vessel. Will also try HCl.

R11410 3" PMT ICP-MS Results with GDMS for ceramic, aluminium ring, and kovar from EAG

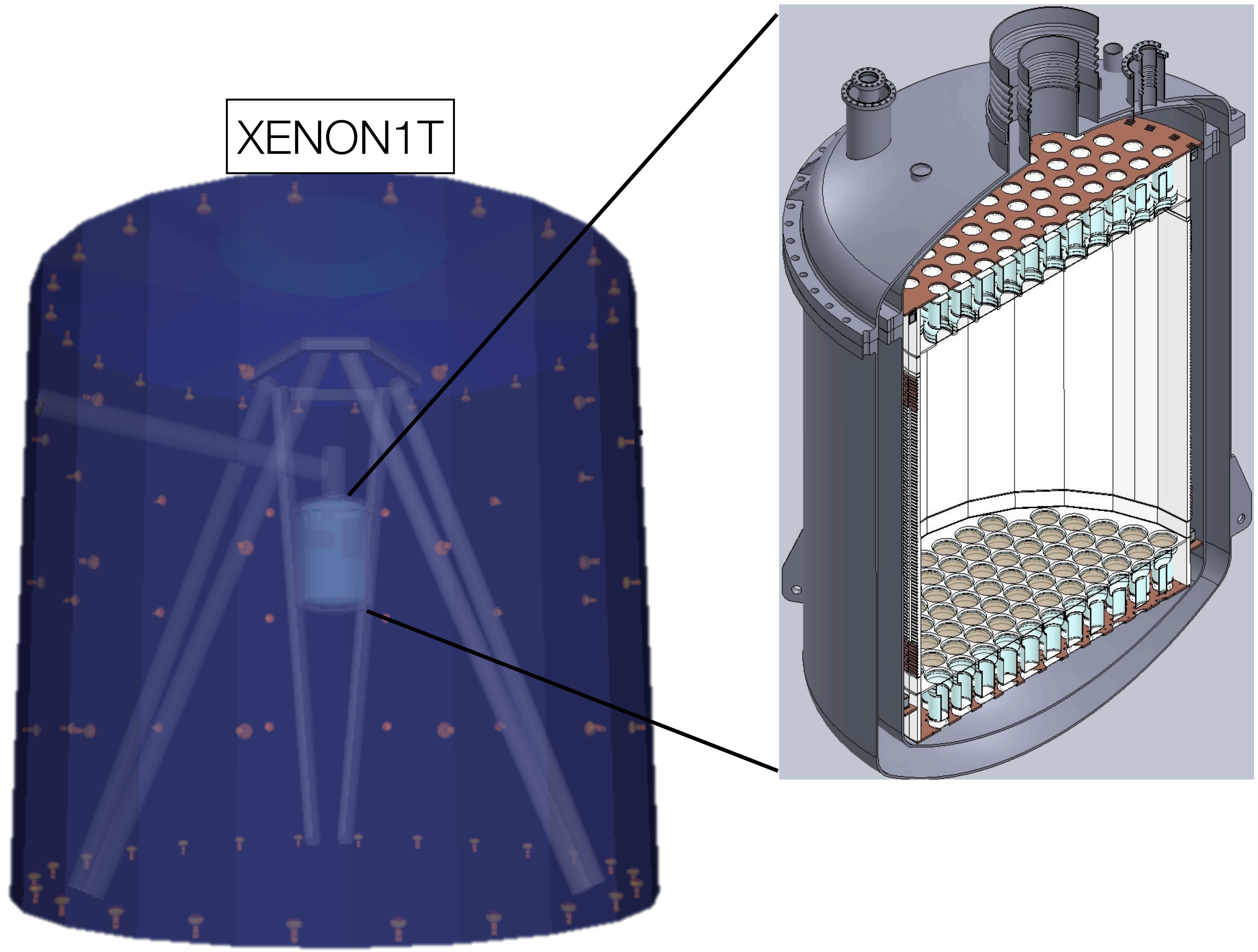
Item	Description	Material	Mass	Thorium						Uranium						item total	
			g	ppb	<	ug	<	mBq	<	ppb	<	ug	<	mBq	<	mBq	<
1	Face plate	Quartz (4)	30	4.0E-03	4.0E-03	1.2E-04	1.2E-04	5.0E-04	5.0E-04	2.0E-03	2.0E-03	6.0E-05	6.0E-05	7.3E-04	7.3E-04	1.2E-03	1.2E-03
2	Aluminium ring	Aluminium	0.6	6.0E+01	6.0E+01	3.6E-02	3.6E-02	1.5E-01	1.5E-01	9.0E+01	9.0E+01	5.4E-02	5.4E-02	6.6E-01	6.6E-01	8.1E-01	8.1E-01
3	Kovar flange	Kovar (1)	18	1.0E-02	1.0E-02	1.8E-04	1.8E-04	7.5E-04	7.5E-04	2.0E-01	2.0E-01	3.6E-03	3.6E-03	4.4E-02	4.4E-02	4.5E-02	4.5E-02
4	Kovar funnel side plate	Kovar (2)	36	1.0E-02	1.0E-02	3.6E-04	3.6E-04	1.5E-03	1.5E-03	2.0E-01	2.0E-01	7.2E-03	7.2E-03	8.8E-02	8.8E-02	8.9E-02	8.9E-02
5	Kovar side pipe	Kovar (3)	49	1.0E-02	1.0E-02	4.9E-04	4.9E-04	2.0E-03	2.0E-03	2.0E-01	2.0E-01	9.8E-03	9.8E-03	1.2E-01	1.2E-01	1.2E-01	1.2E-01
6	Ceramic stem**	Ceramic	16	4.0E+00	4.0E+00	6.4E-02	6.4E-02	2.7E-01	2.7E-01	8.0E+00	8.0E+00	1.3E-01	1.3E-01	1.6E+00	1.6E+00	1.8E+00	1.8E+00
9	Substrate	Quartz (1)	8.9	2.2E-01	2.2E-01	2.0E-03	2.0E-03	8.3E-03	8.3E-03	6.8E+00	6.8E+00	6.1E-02	6.1E-02	7.4E-01	7.4E-01	7.4E-01	7.4E-01
10	Spacer	Quartz (2)	0.8	1.1E-02	1.1E-02	8.6E-06	8.6E-06	3.6E-05	3.6E-05	8.2E-02	8.2E-02	6.4E-05	6.4E-05	7.8E-04	7.8E-04	8.1E-04	8.1E-04
12-25	Electrodes	SUS (1)-14	24.4	1.0E+00	1.0E+00	2.4E-02	2.4E-02	1.0E-01	1.0E-01	3.0E-01	3.0E-01	7.3E-03	7.3E-03	8.9E-02	8.9E-02	1.9E-01	1.9E-01
7-8	Electrodes	Nickel	0.06	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	Getter	Getter	0.06	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	SUM		184	0.7	0.7	0.1	0.1	0.5	0.5	1.5	1.5	0.3	0.3	3.3	3.3	3.8	3.8
	PMT TOTAL (U+Th)	3.8 mBq															
		3.8 <															
	**Princeton measurement	Ceramic	16	1.0E+01	1.0E+01	1.6E-01	1.6E-01	6.7E-01	6.7E-01	1.0E+01	1.0E+01	1.6E-01	1.6E-01	1.9E+00	1.9E+00	2.6E+00	2.6E+00
	UCLA measurement	Ceramic	16	4.3E+00	4.3E+00	6.9E-02	6.9E-02	2.9E-01	2.9E-01	8.0E+00	8.0E+00	1.3E-01	1.3E-01	1.6E+00	1.6E+00	1.8E+00	1.8E+00

Detailed Monte Carlo simulation (Background understanding & minimization)

XENON100



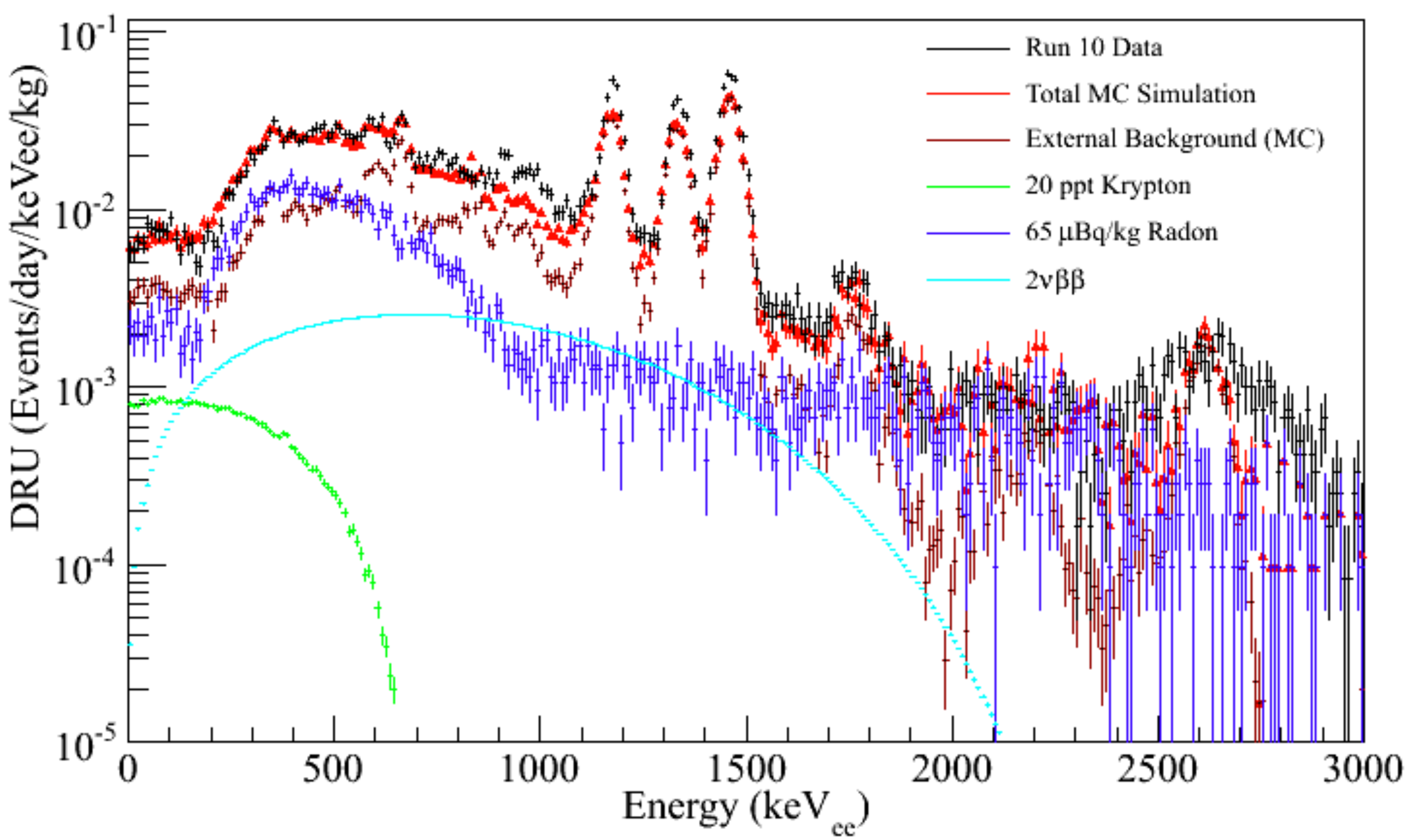
XENON1T



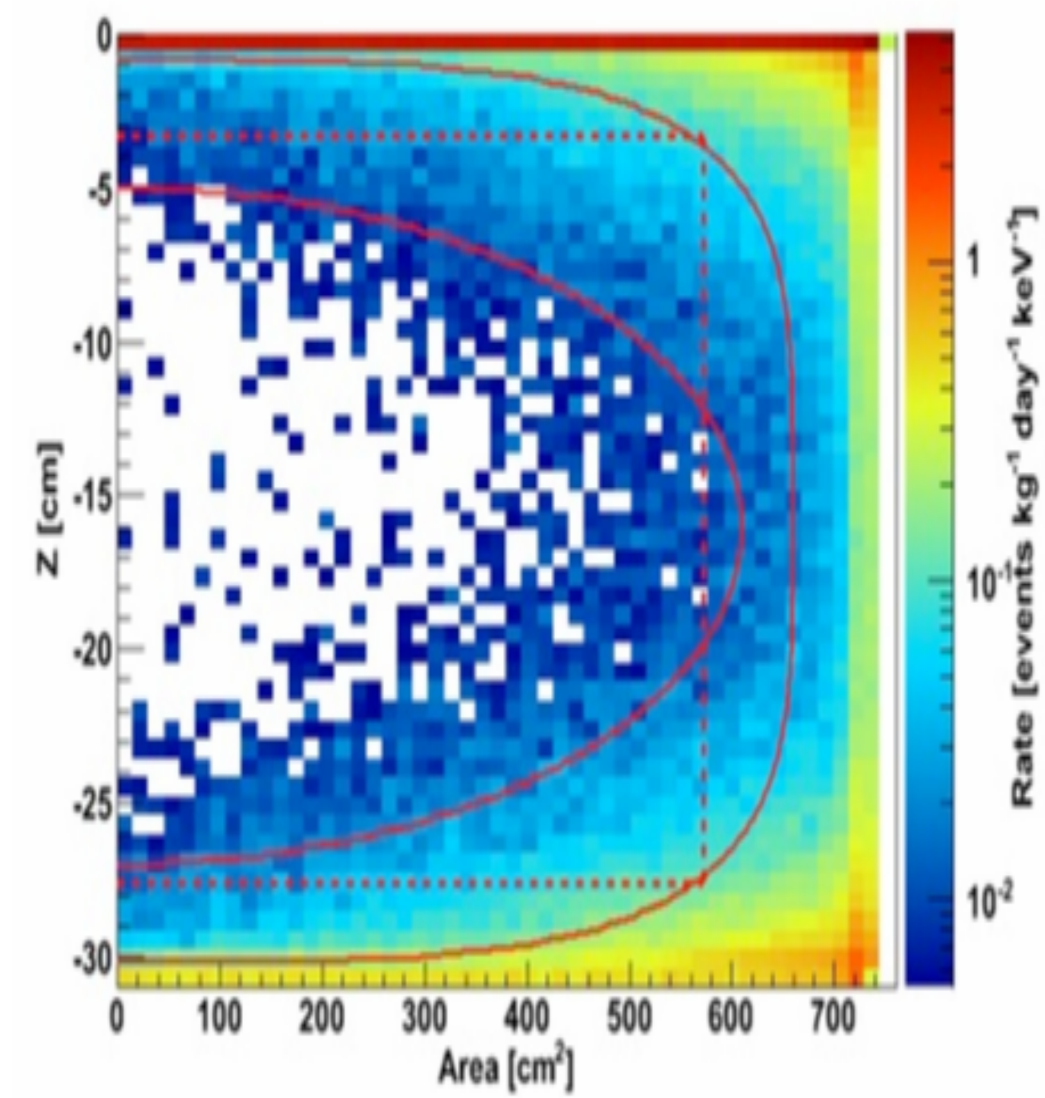
XENON100

Phys. Rev. D 83, 082001 (2011) & Astropart. Phys.35:43-49 (2011)

Electronic recoils background



Nuclear recoils background

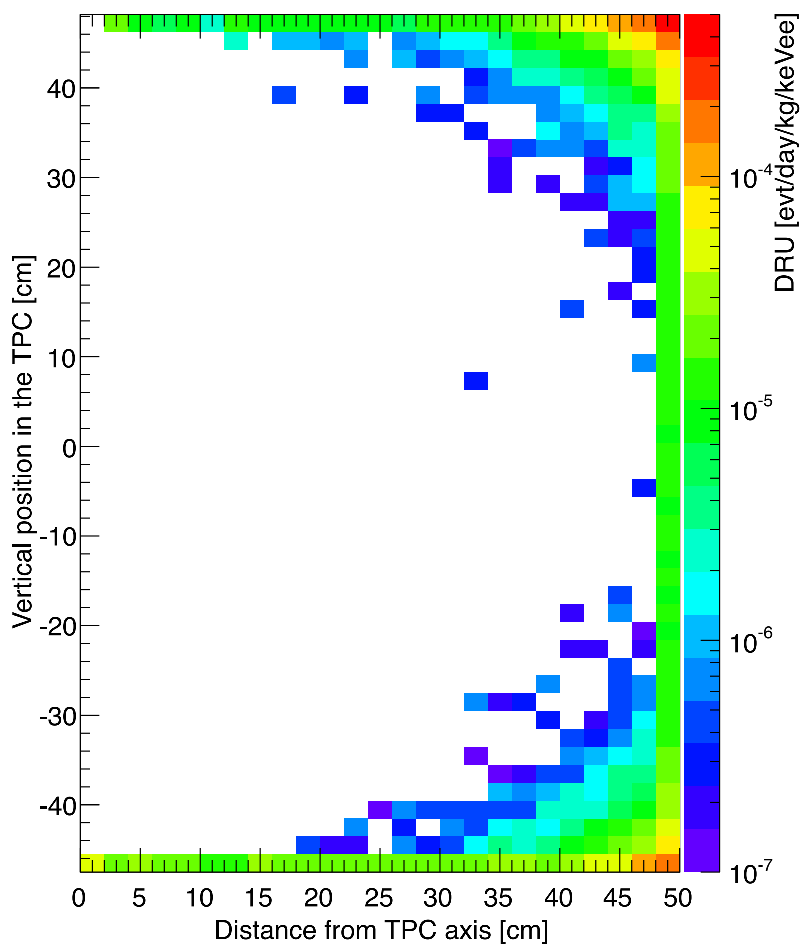


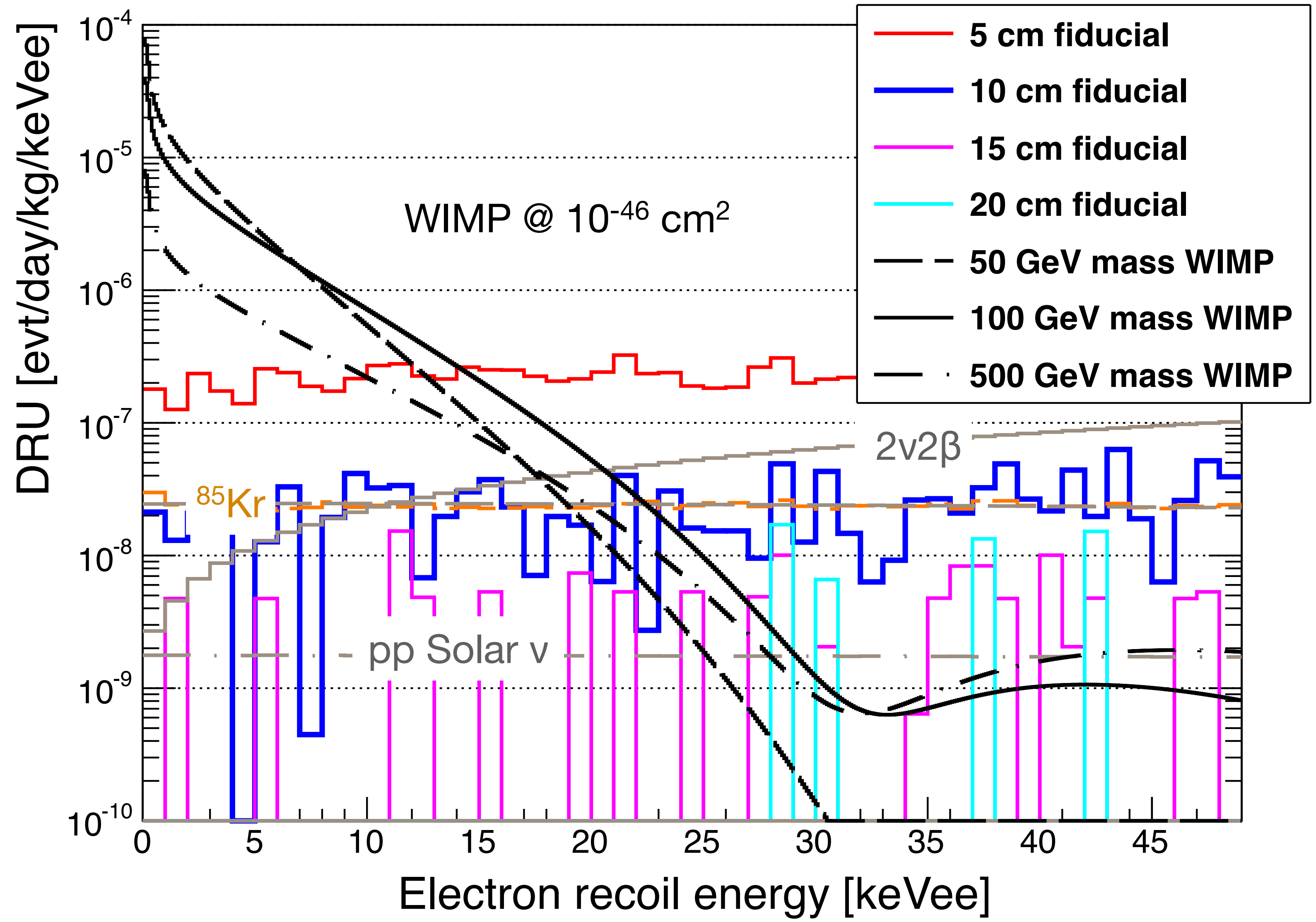
In 30 kg fiducial volume, in WIMP-search energy region

⇒ ~10 mdru (even before applying the LXe veto cut and the S2/S1 discrimination)

XENON1T
Electronic recoils background

Several proposals for NSF and DOE

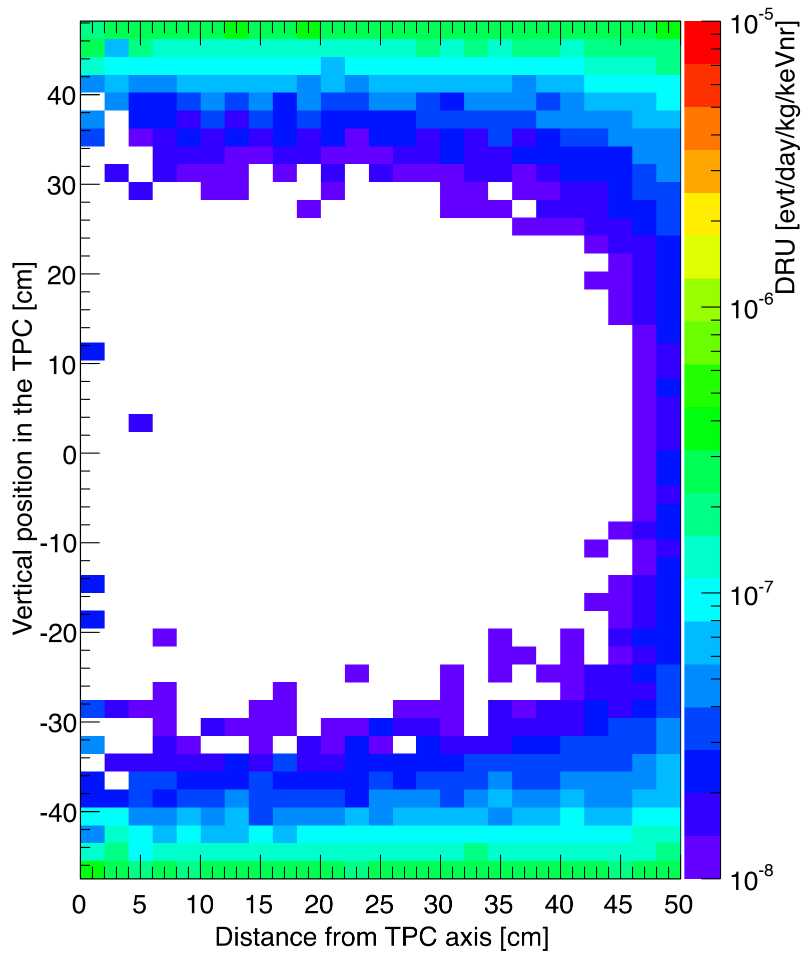


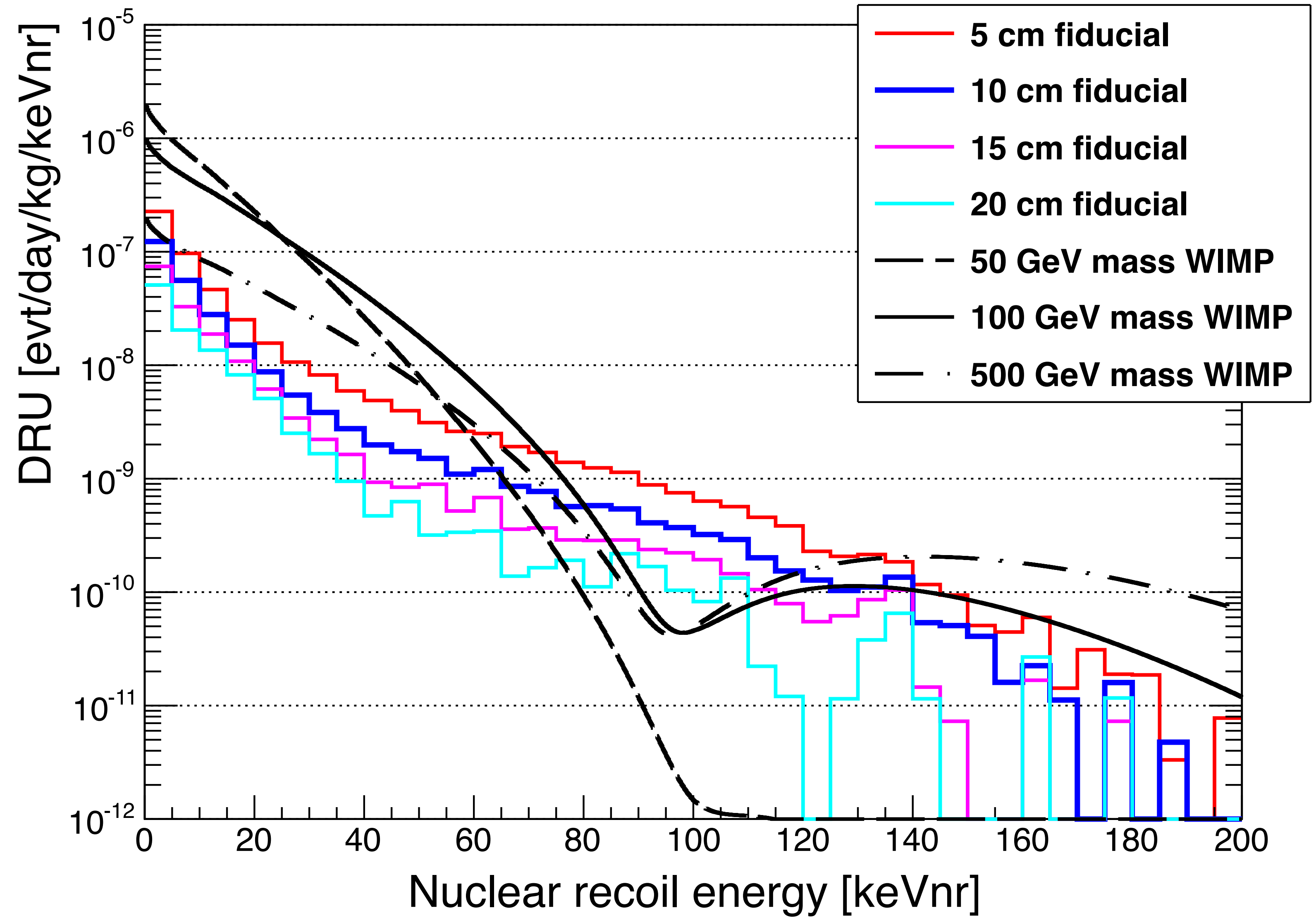


Gamma background:
< 0.2 evt/y in 1 ton
Main contribution from the PMTs

XENON1T
Nuclear recoils background

Several proposals for NSF and DOE





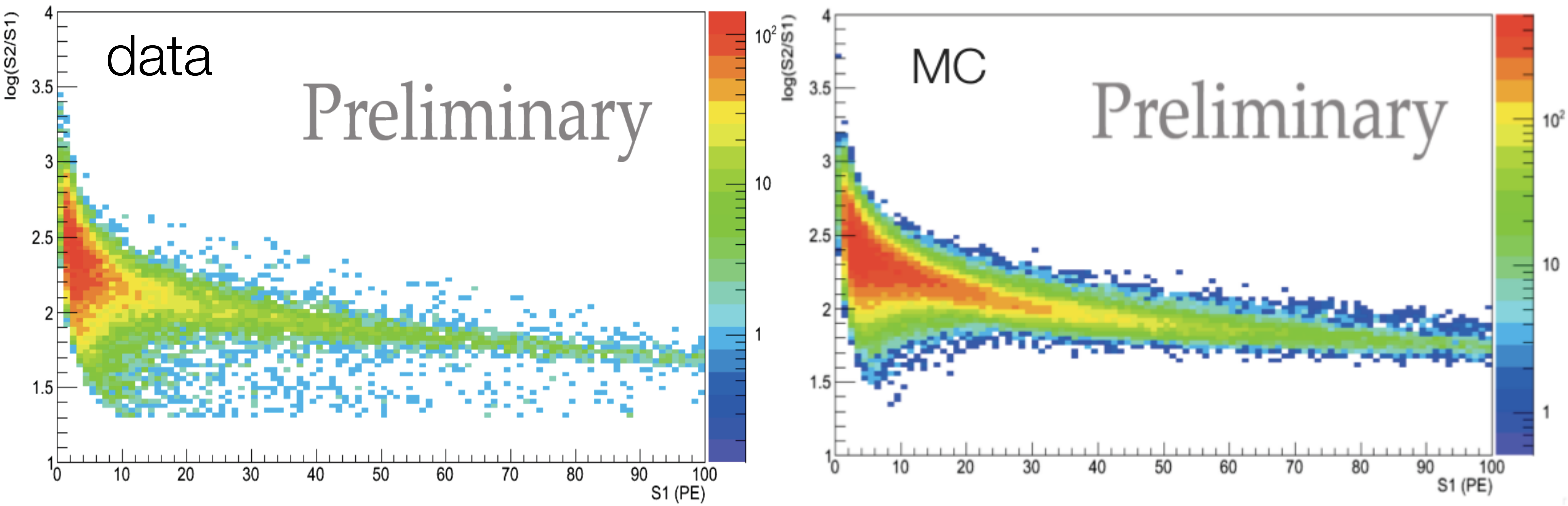
Neutron background from (α,n):
0.6 evt/y in 1 ton.
Main contribution from cryostat and ceramics of the PMTs

New detector response estimation approach

Publication under consideration

Energy deposited in the LXe by nuclear recoils looking at S1 ⇒ $E_{nr} = \frac{S1}{L_y}\frac{S_{ee}}{S_{nr}}\frac{1}{\mathcal{L}_{eff}}$

- Instead of dedicated experiments, running under different condition w.r.t. the dark matter detector, extracting $\mathcal{L}_{eff}$ directly from XENON100
- Reliable and robust data/MC matching necessary



New data analysis method (E2 based analysis)

Astroparticle Physics 37 (2012) 51–59

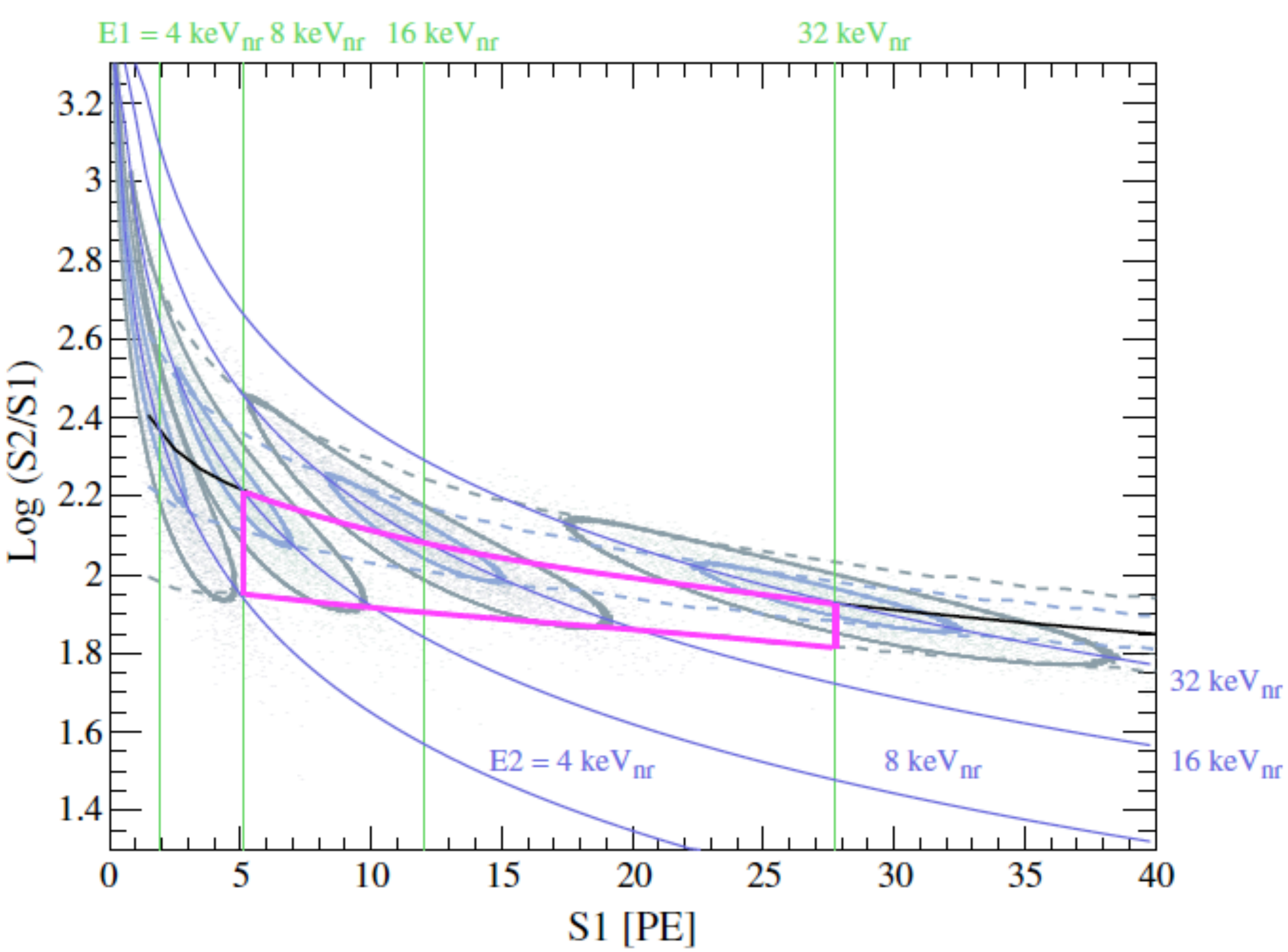
S1 as energy estimator (⇒ E1)

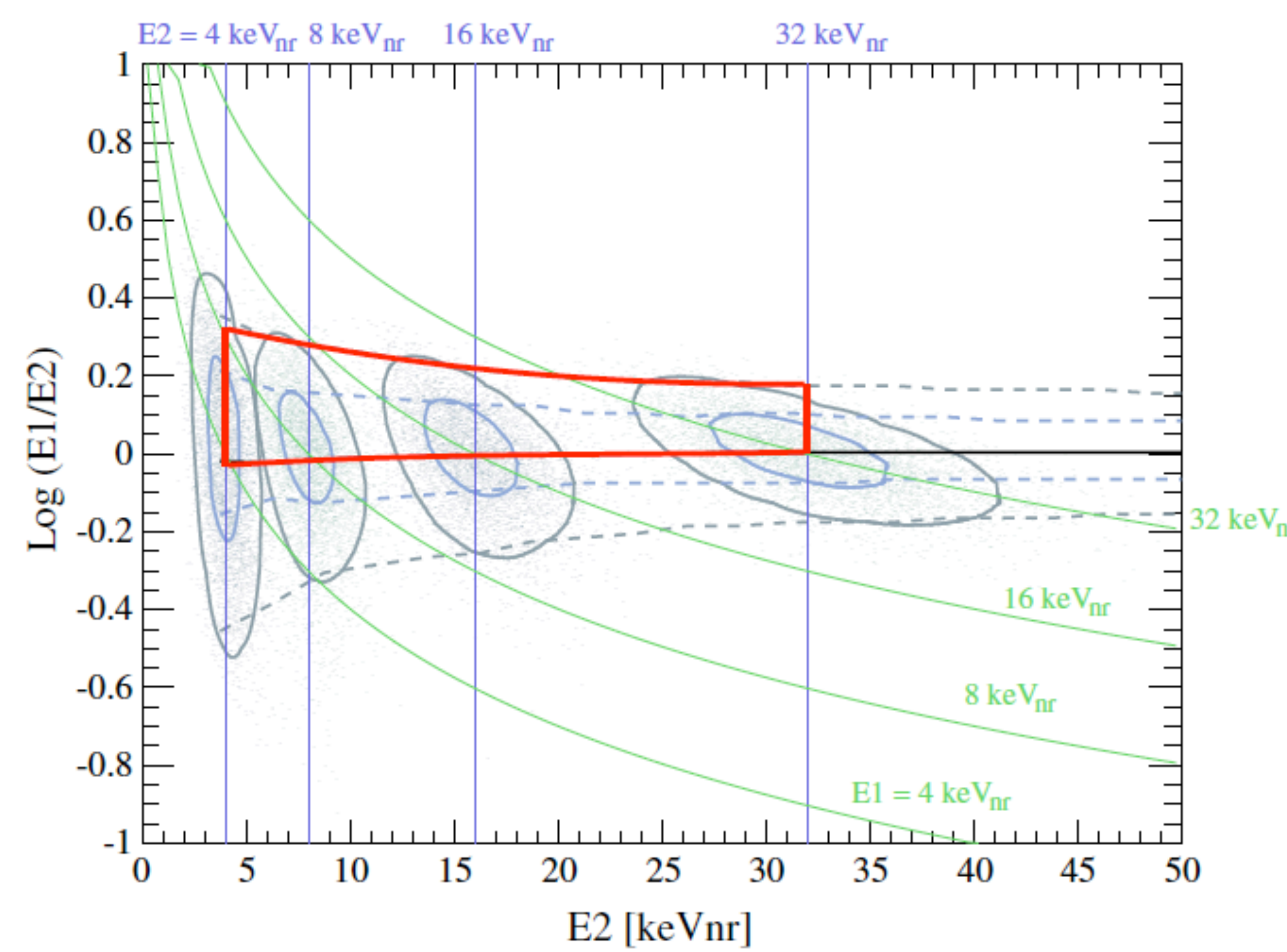
Because of Poisson statistics in photon detection the PhotoElectrons - keV conversion is distorted

S2 as energy estimator (⇒ E2)

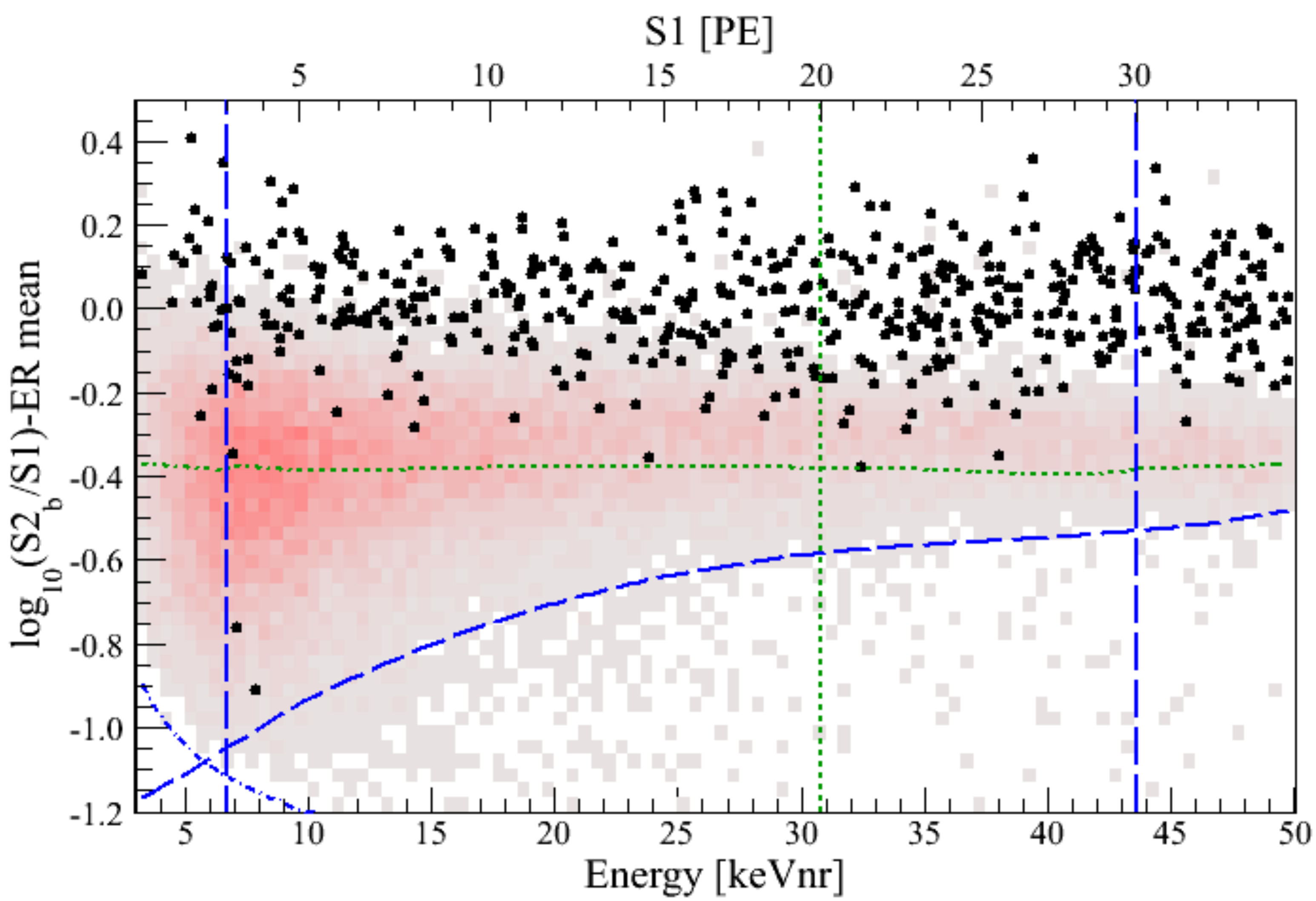
Proposing E2 (energy based on S2 signal) Poisson fluctuation affects the signal much lesser

⇒ More accurate energy estimation



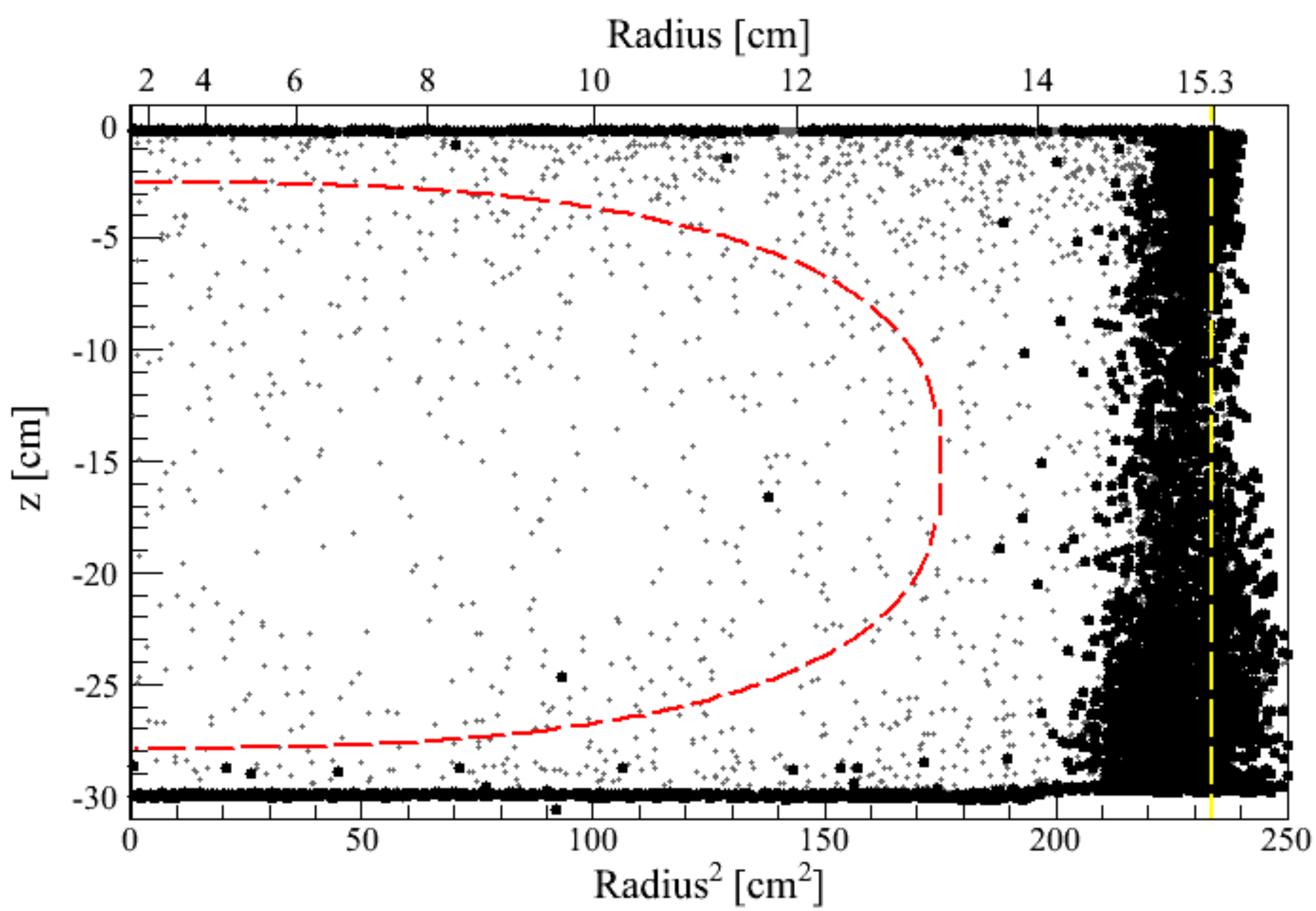


XENON100 Run10 results

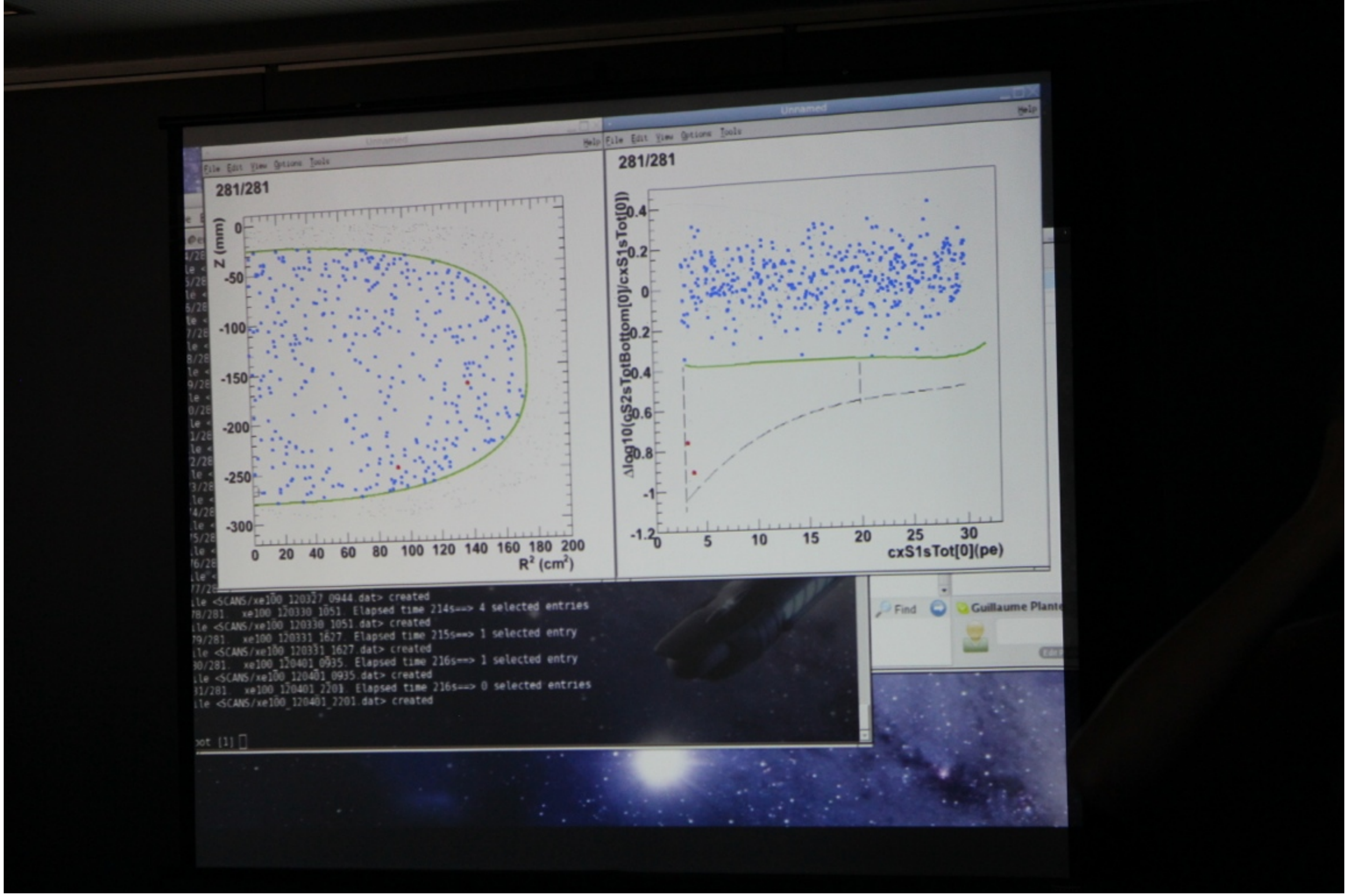


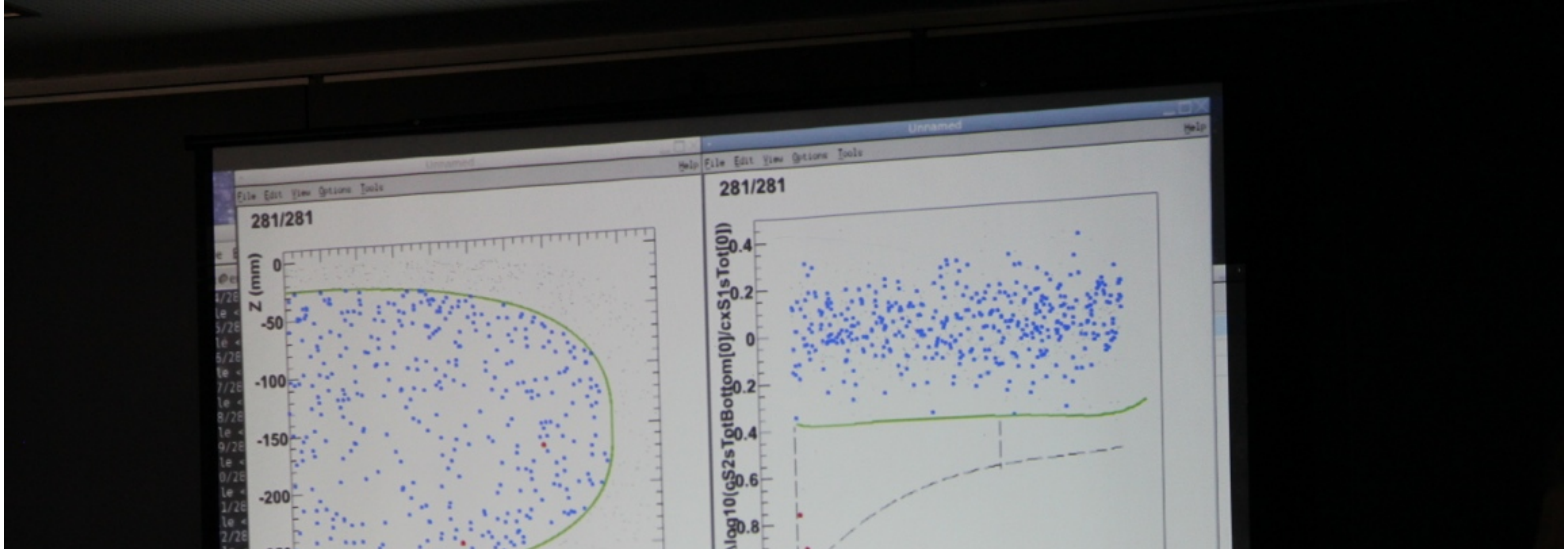
2 events observed in the signal region with (1±0.2) expected background
No events below the signal threshold

XENON100 Run10 results



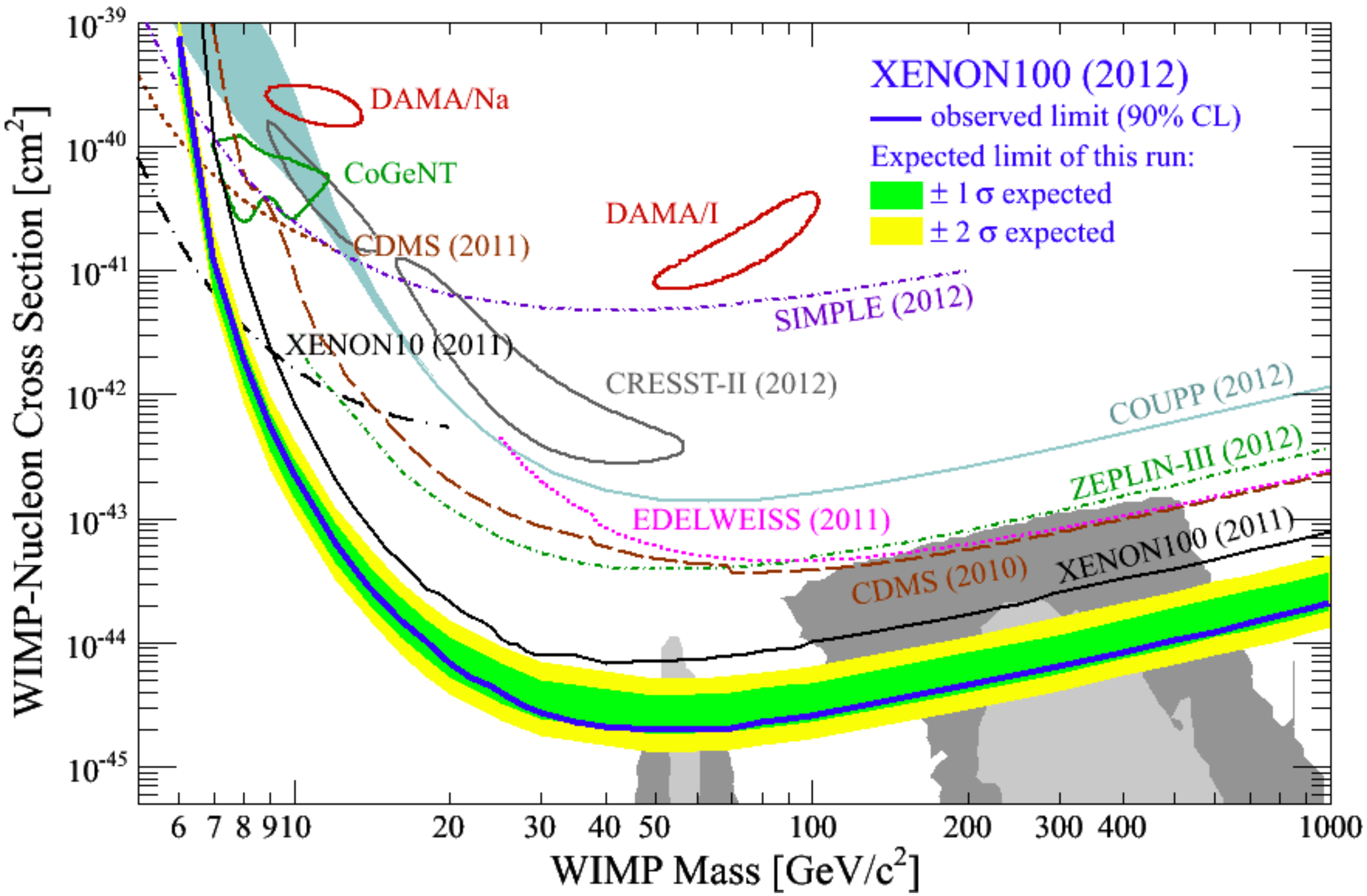
2 events observed in the signal region with (1±0.2) expected background
No events below the signal threshold


281/281
Z (mm)
R² (cm²)
281/281
cxS1sTot[0](pe)


281/281
Z (mm)
281/281
log10(cS2sTotBottom[0]/cxS1sTot[0])

XENON100 Run10 results

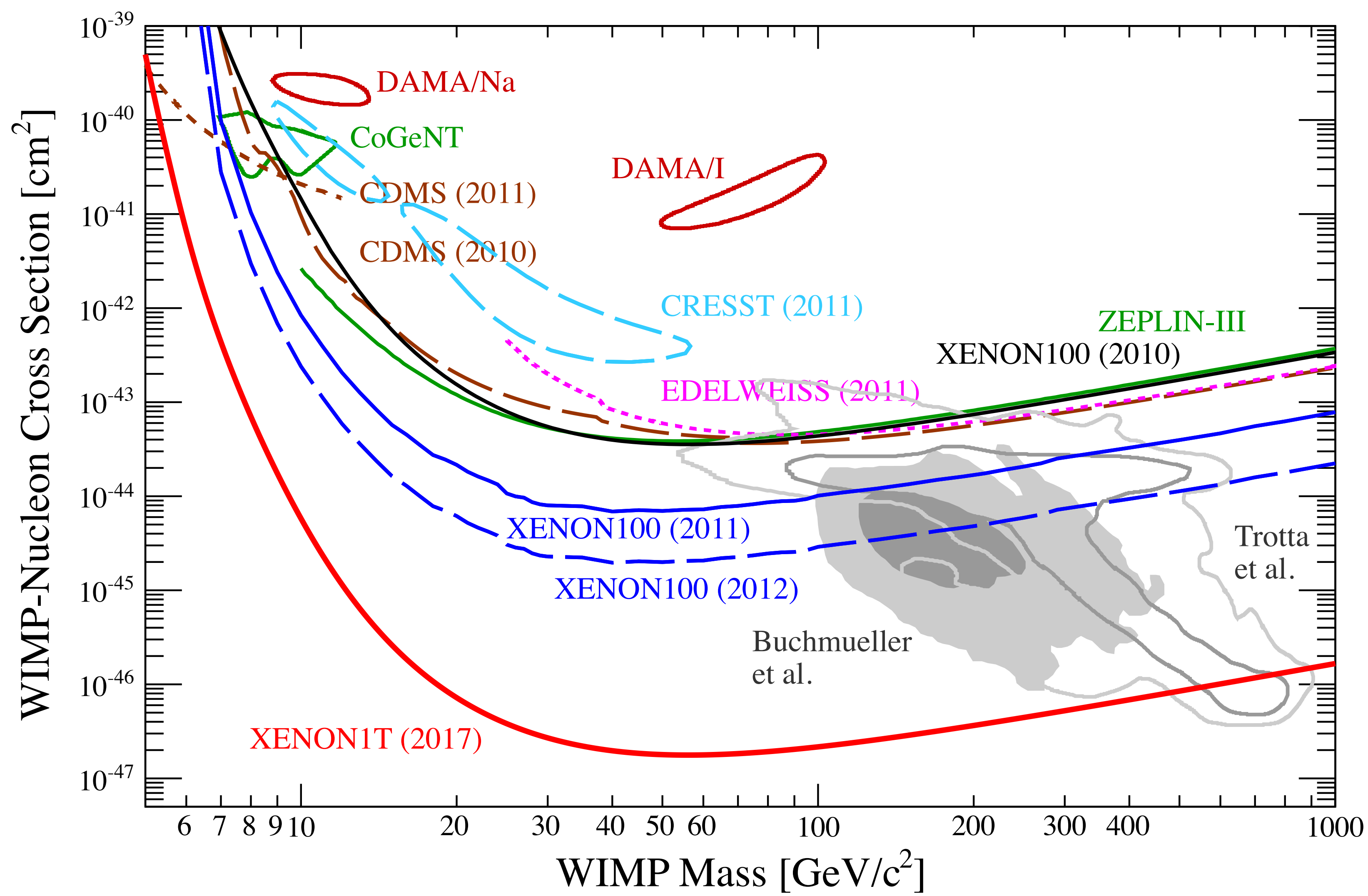
arXiv:1207.5988 submitted to PLB



2 events observed with background expectation of 1±0.2

⇒ 90% CL limit in the WIMP-nucleon cross section of 2.0×10^{-45} cm² for a 50 GeV/c² WIMP

XENON1T projected sensitivity



2 x 10^{-47} cm^2 for 50 GeV/c^2 WIMP in 2.2 ton-year
Two orders of magnitude improvement
w/r to XENON100

MC-PAD and beyond

MC-PAD fellowship and training

- Projects:
  - AX-PET and ATLAS-ALFA (under supervision of Christian Joram)
- Trainings:
  - LabView, C++ and ROOT (@ CERN)
  - French (... I should learn Hebrew now)
  - MC-PAD network trainings

Very positive!

- Broad overview, especially on how perform detector R&D, focusing on the issue and hunting for the solutions
- Most important training has been the way of thinking more than the specific notions
- For me as mostly "data analysis guy" the MC-PAD experience has been extremely educative and useful

Moving to Dark Matter

- Simulation software packages
- Low background detectors (photosensors) and material screening measurements
- Cryogenic detectors (UCLA shifter curse)
- Dealing with companies, industries and services (photosensors, cryogenic products, screenings...)
- Supervisions of PhD students and summer students
- Publication within the XENON100 collaboration:
  - *Dark Matter Results from 225 Live Days of XENON100 Data* (arXiv:1207.5988)
- Publications within the UCLA Dark Matter group:
  - *A new analysis method for WIMP searches with dual-phase liquid Xe TPCs* (Astropart. Phys. 37 (2012) 51–59)
  - *Studies of a three-stage dark matter and neutrino observatory based on multi-ton combinations of liquid xenon and liquid argon detectors* (Astropart. Phys. 36 (2012) 93–122)
  - *Characterization of the Hamamatsu R11410-10 3-Inch Photomultiplier Tube for Dark Matter Direct Detection Experiments* (arXiv:1202.2628)
  - *Characterization of the QUartz Photon Intensifying Detector (QUPID) for noble liquid detectors* (NIM A 654 (2011) 184-195)

Future perspectives

Moving to Weizmann Institute of Science in Tel-Aviv
keep working on dark matter direct search within the XENON collaboration

- Job possibilities:
  - Large chances after the MC-PAD fellowship
  - Risk of "lowering" the career after the Marie Curie fellowship (if one wants to change field, how I have done)... standard PostDoc is somehow less prestigious than a Marie Curie

... but that's all for Science's sake

- Bit more far future job:
  - Staying in research (either academia or research center)... proceeding in dark matter search (*Mazel Tov*)... getting a tenure (***Mazel Tov***)

Thanks to ALL the people who made this possible

Thanks to ALL the people who made this possible

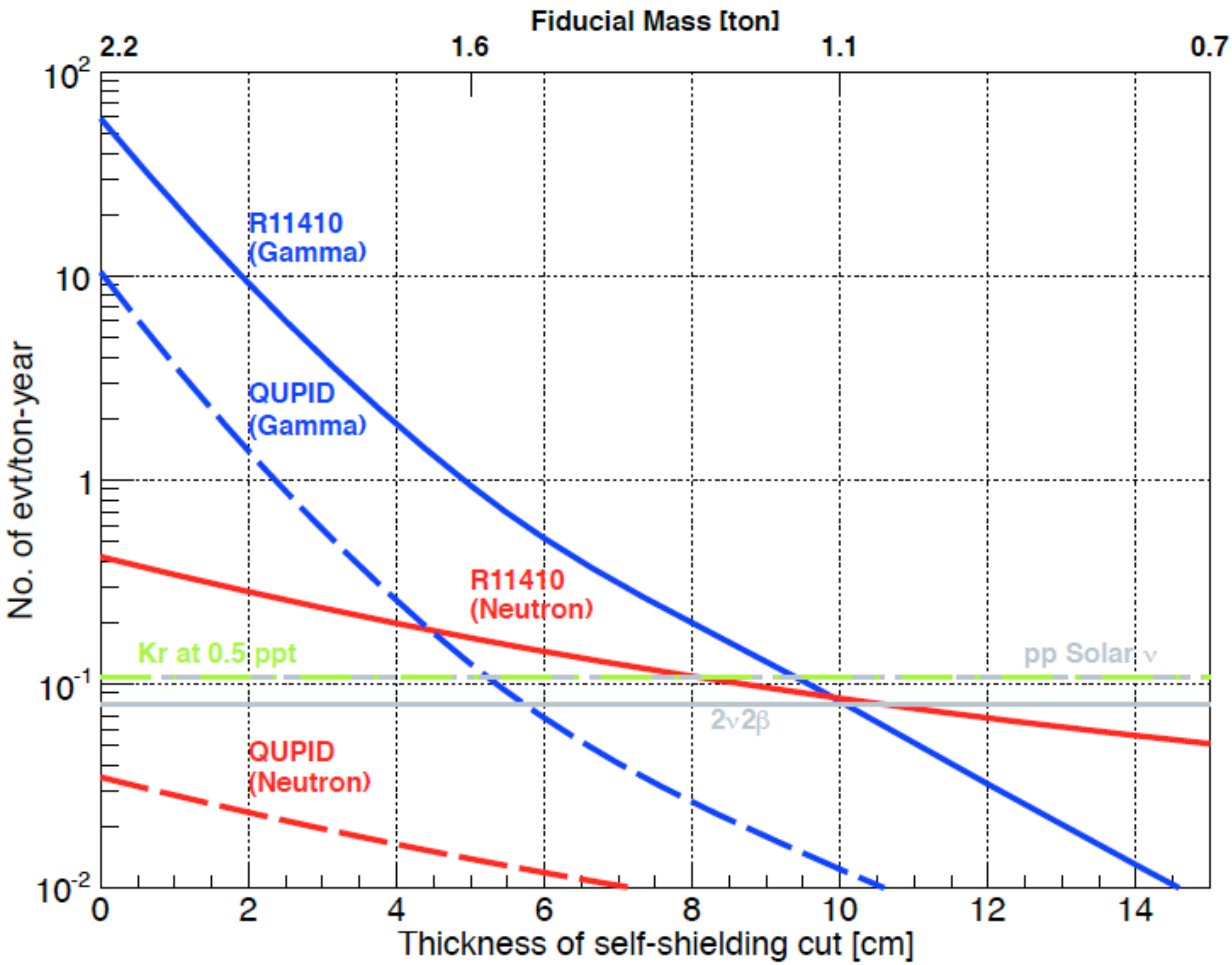
Wonder & Wander

Spare slides

Screening techniques

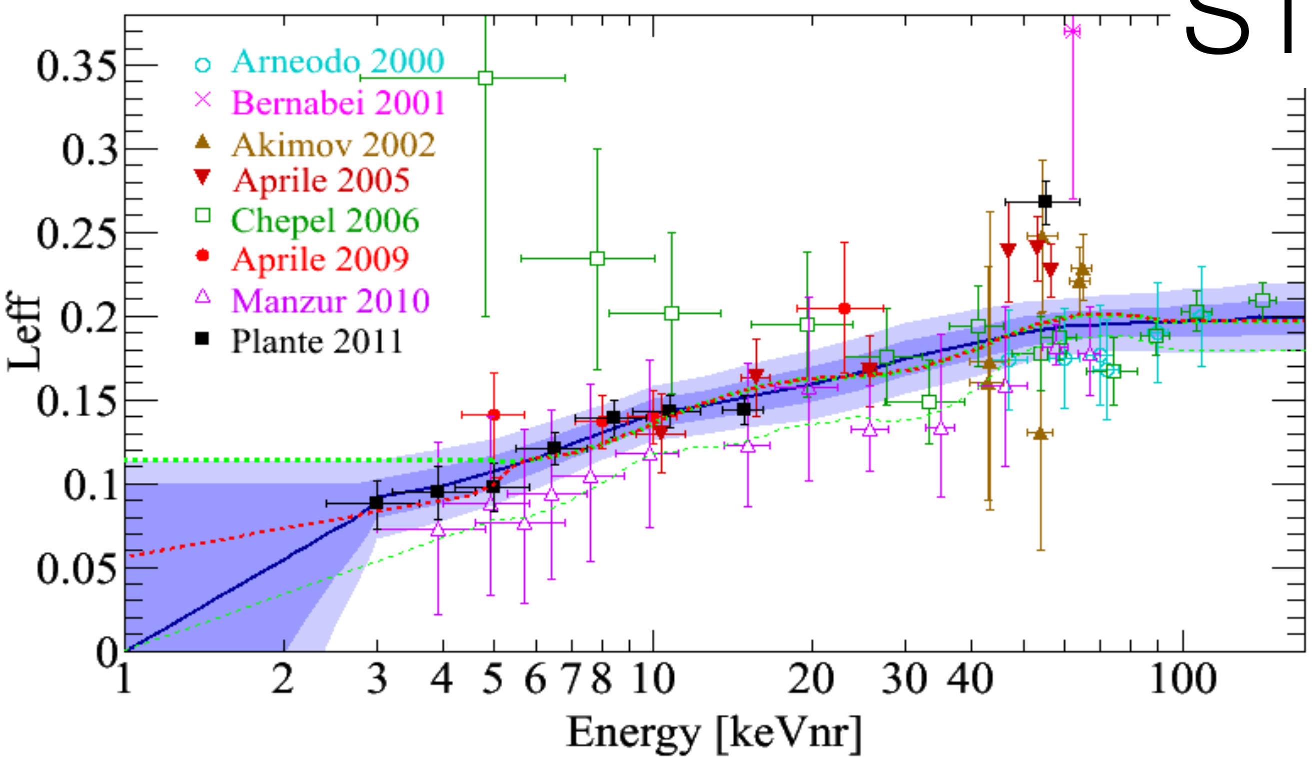
Method	Suited for	Sensitivity
γ spectroscopy	γ emitting nuclei	10 - 100 μBq/kg
NAA	primordial parents	0.01 - 100 μBq/kg
Rn emanation	^{226}Ra - ^{228}Th	0.1 - 10 μBq/kg
ICP-MS	primordial parents	1 - 100 μBq/kg

Self shielding on background from photosensors

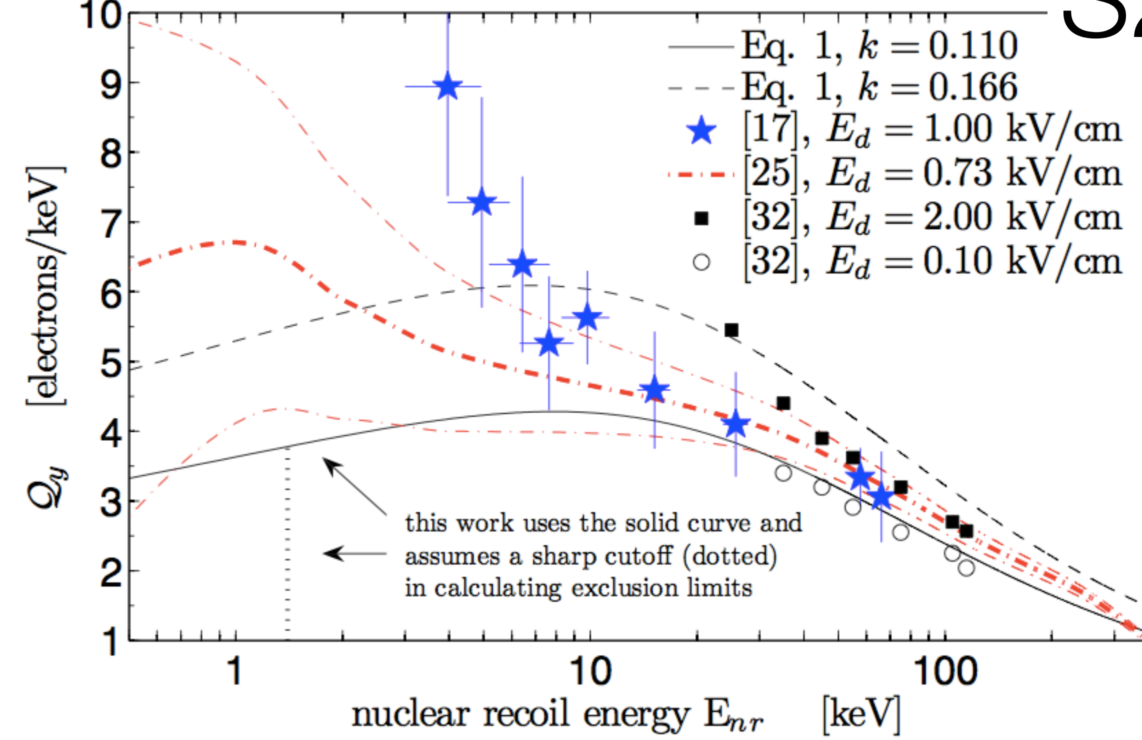


$\mathcal{L}_{eff}$ & Q_y

S1



S2



$$E_{nr} = \frac{S1}{L_y} \frac{S_{ee}}{S_{nr}} \frac{1}{\mathcal{L}_{eff}}$$

S1: Measured number of PE

L_y: light yield for gamma @ 122 keV

S_{ee}: Light quenching due to electric field for gammas @ 122 keV

S_{nr}: Light quenching due to electric field for nuclear recoils