WIMP Dark Matter Detection with Liquid Xenon

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Overview

- Brief intro to the Dark Matter Problem
- The direct detection technique
- Liquid xenon detectors
- The ZEPLIN-III Experiment & final results
- XENON100 and current results
- The next phase: XENON1T
- Outlook

Early evidence for Dark Matter

1: Zwicky looked at galaxy clusters

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Early evidence for Dark Matter

1: Zwicky looked at galaxy clusters

2. Observed their motion

3: Applied the known laws of physics

4: Deduced that there must be more mass present than is seen

Early evidence for Dark Matter

1970s: Vera Ruben used the Doppler Shift to look at how fast galaxies were rotating – expecting to see agreement with Newton's Laws, but reproduced Zwicky's results...

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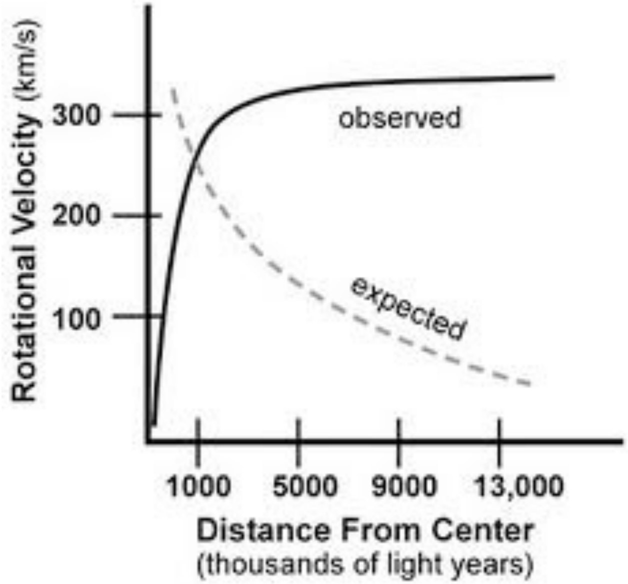
GALAXIES ARE ROTATING TOO FAST!



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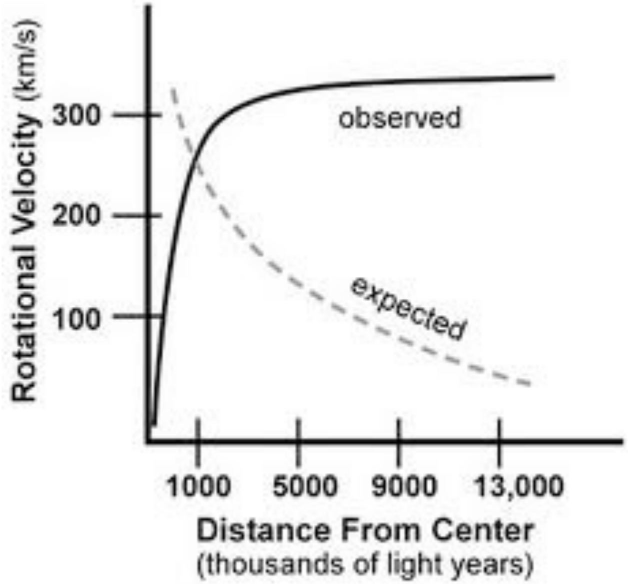
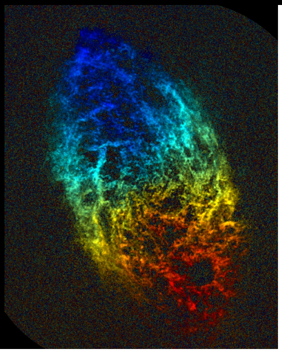
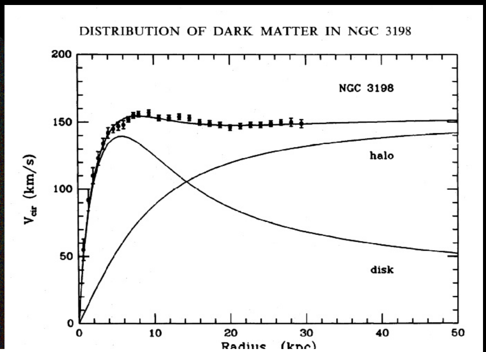
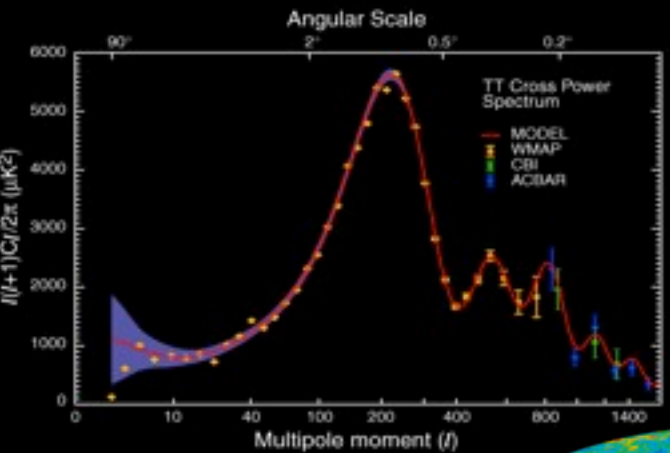


Lots more evidence since then...

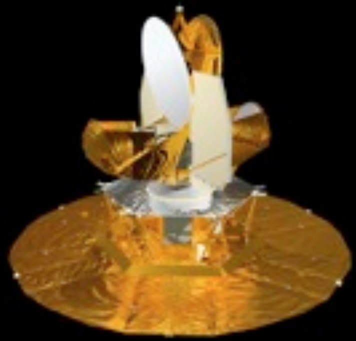


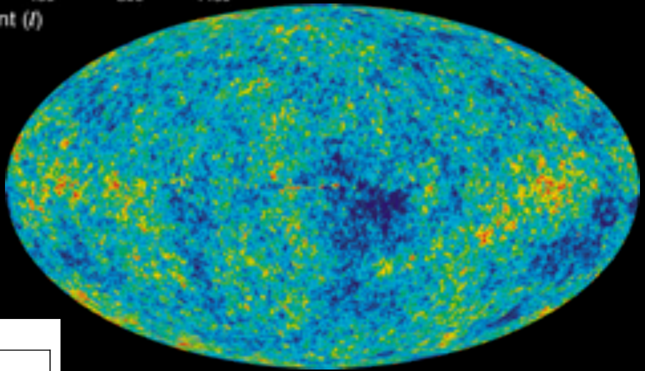


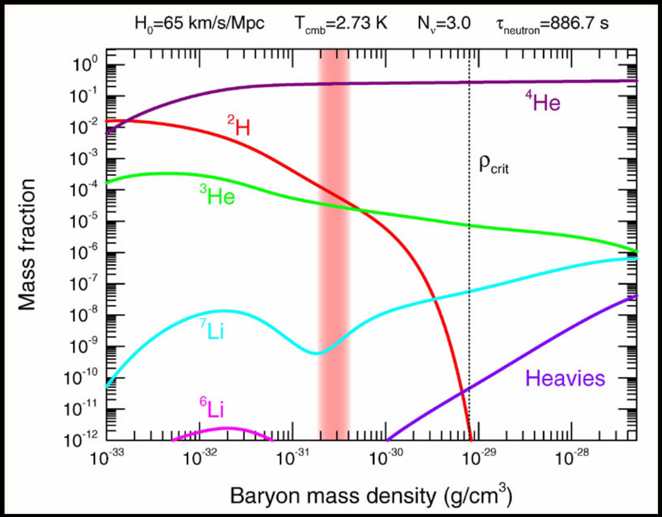
DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)



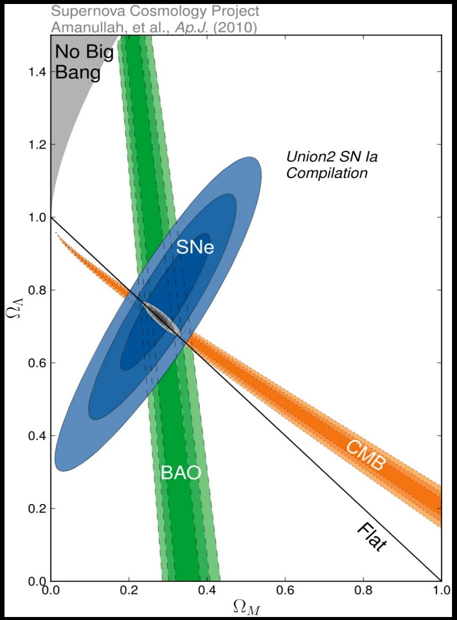
Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
MODEL
WMAP
CBI
ACBAR
$l(l+1)C_l/2\pi$ (μK^2)
Multipole moment (l)



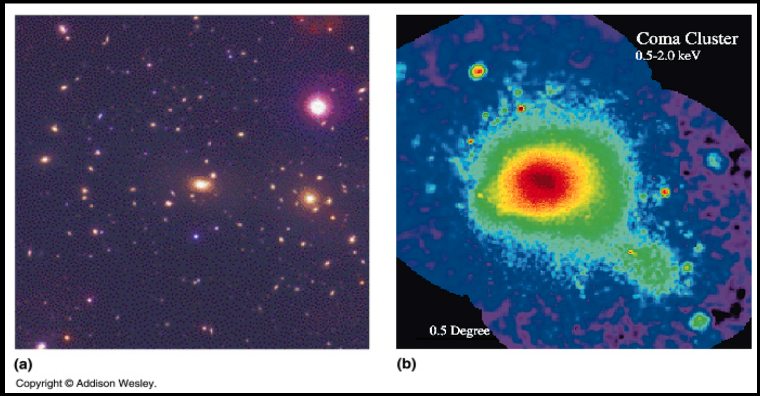




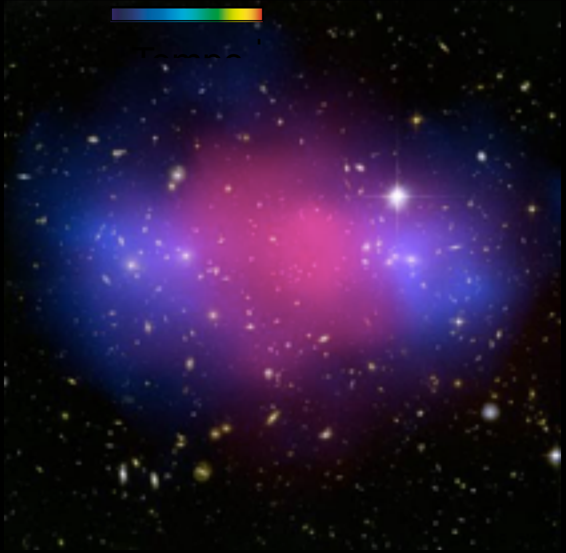
H_0=65 km/s/Mpc
T_{cmb}=2.73 K
N_ν=3.0
$\tau_{neutron}$=886.7 s
^{4}He
^{2}H
^{3}He
ρ_{crit}
^{7}Li
^{6}Li
Heavies
Mass fraction
Baryon mass density (g/cm^3)

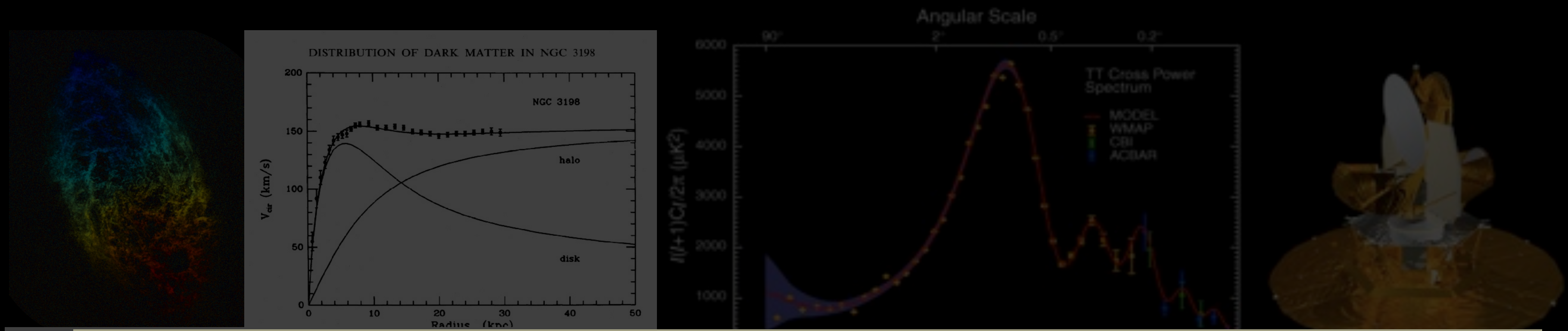


Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)
No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M

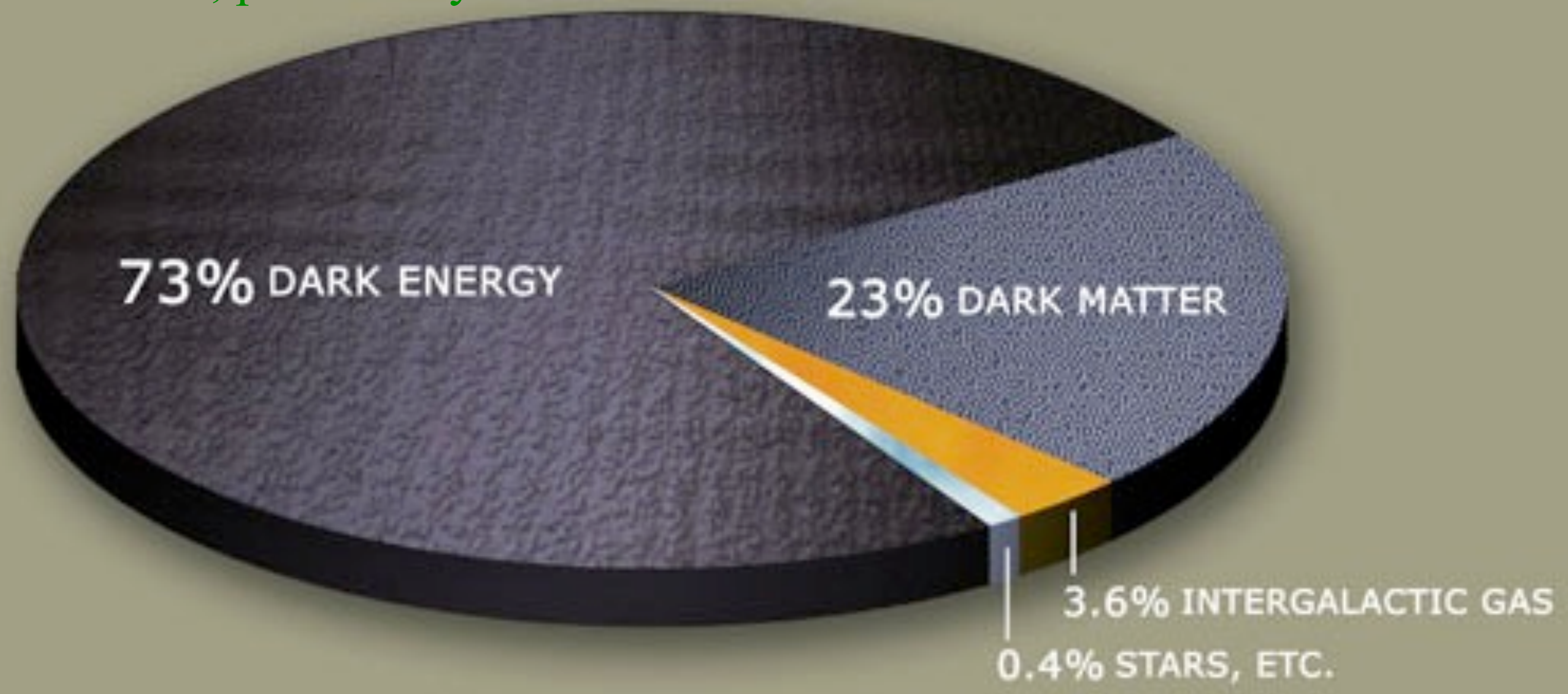


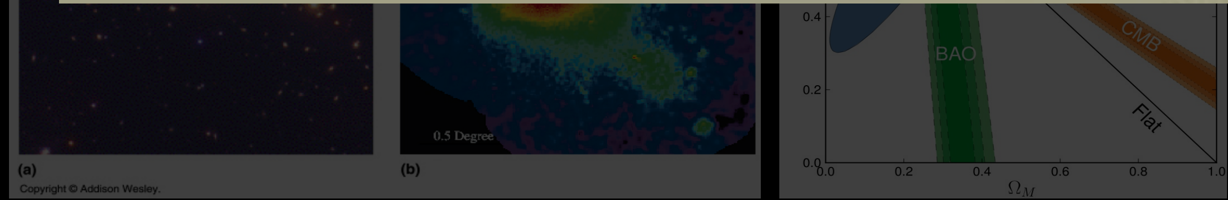
Coma Cluster
0.5-2.0 keV
0.5 Degree
(a)
(b)
Copyright © Addison Wesley.



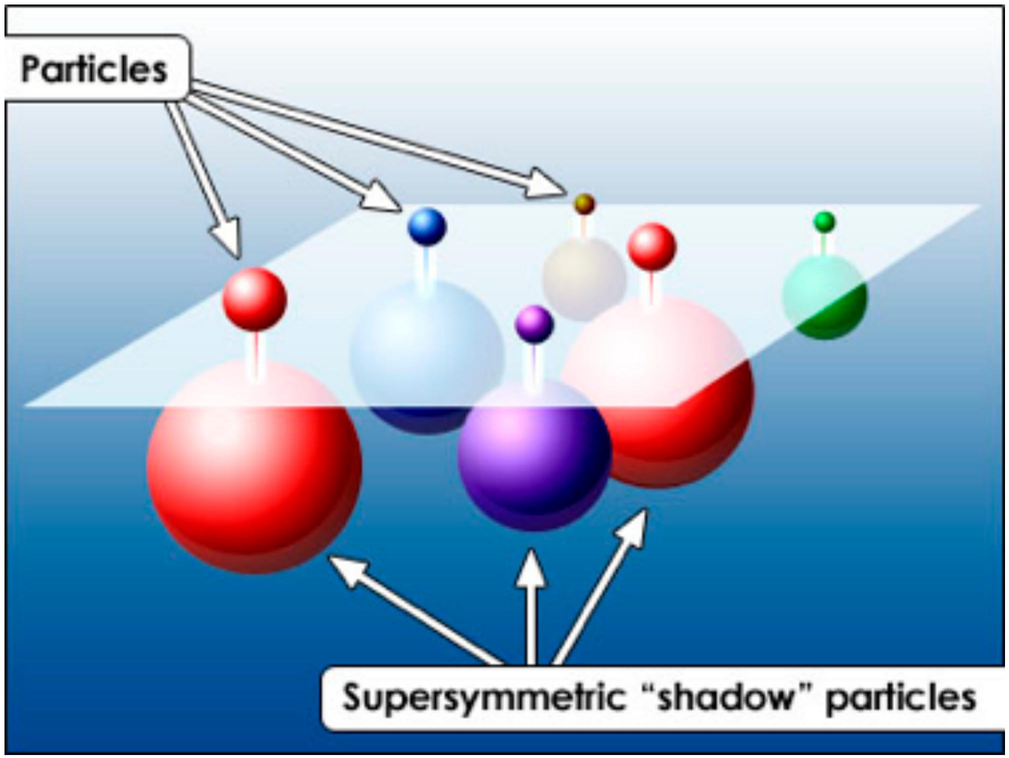


Our Universe, present day

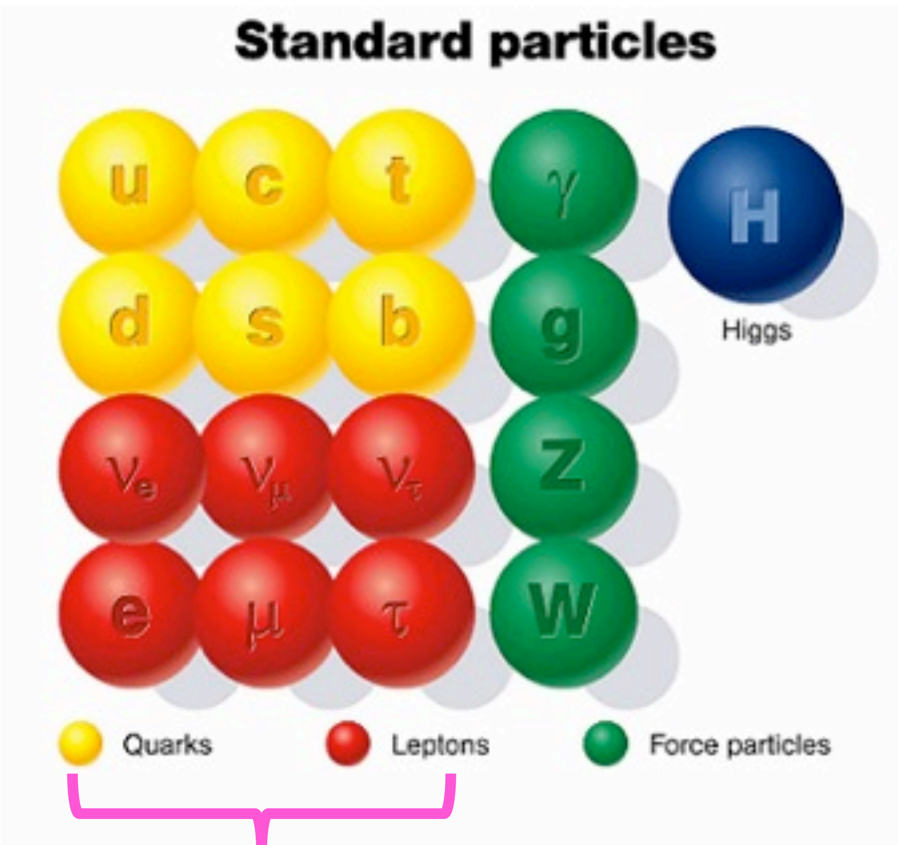




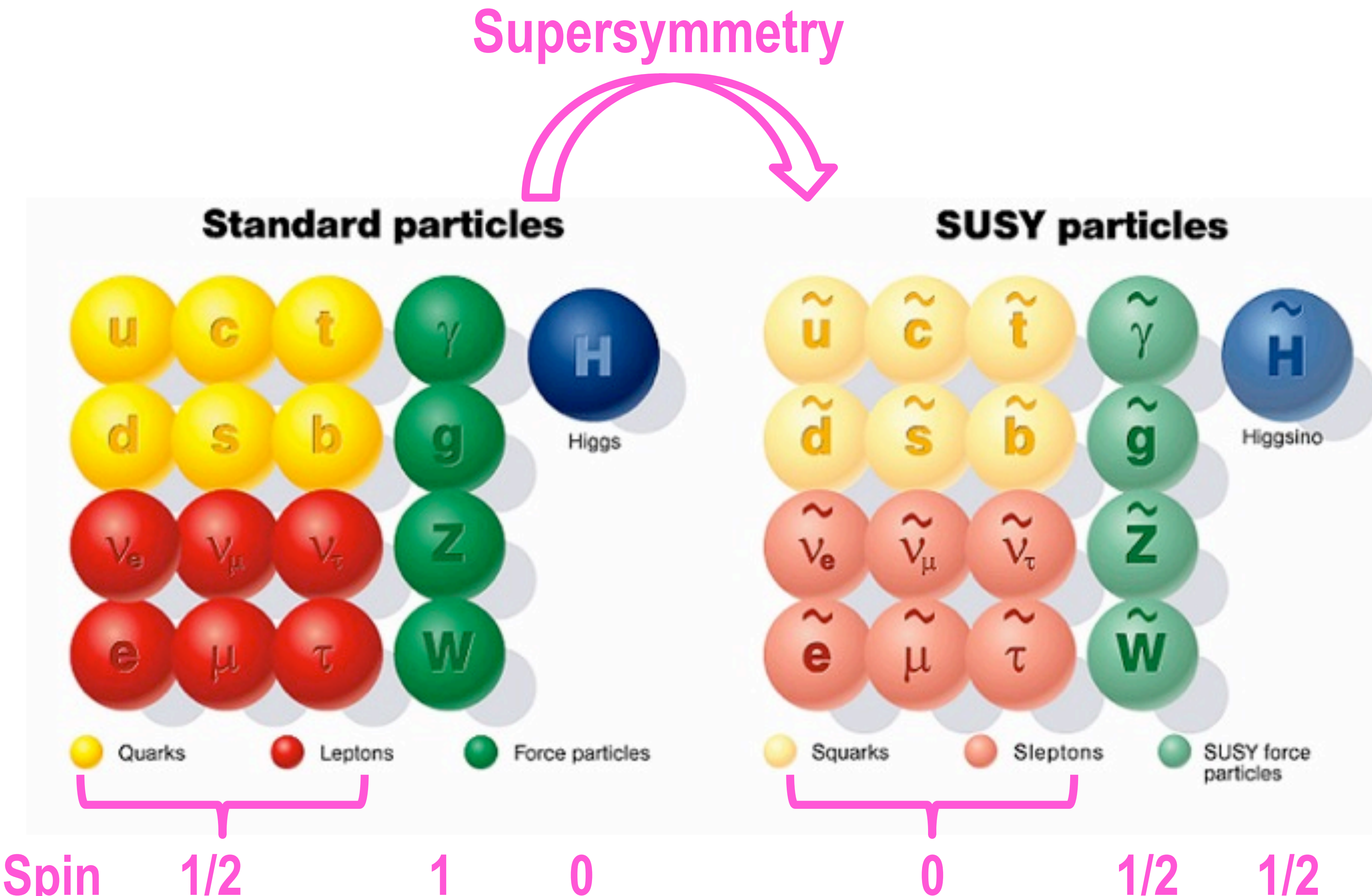
SUPERSYMMETRY



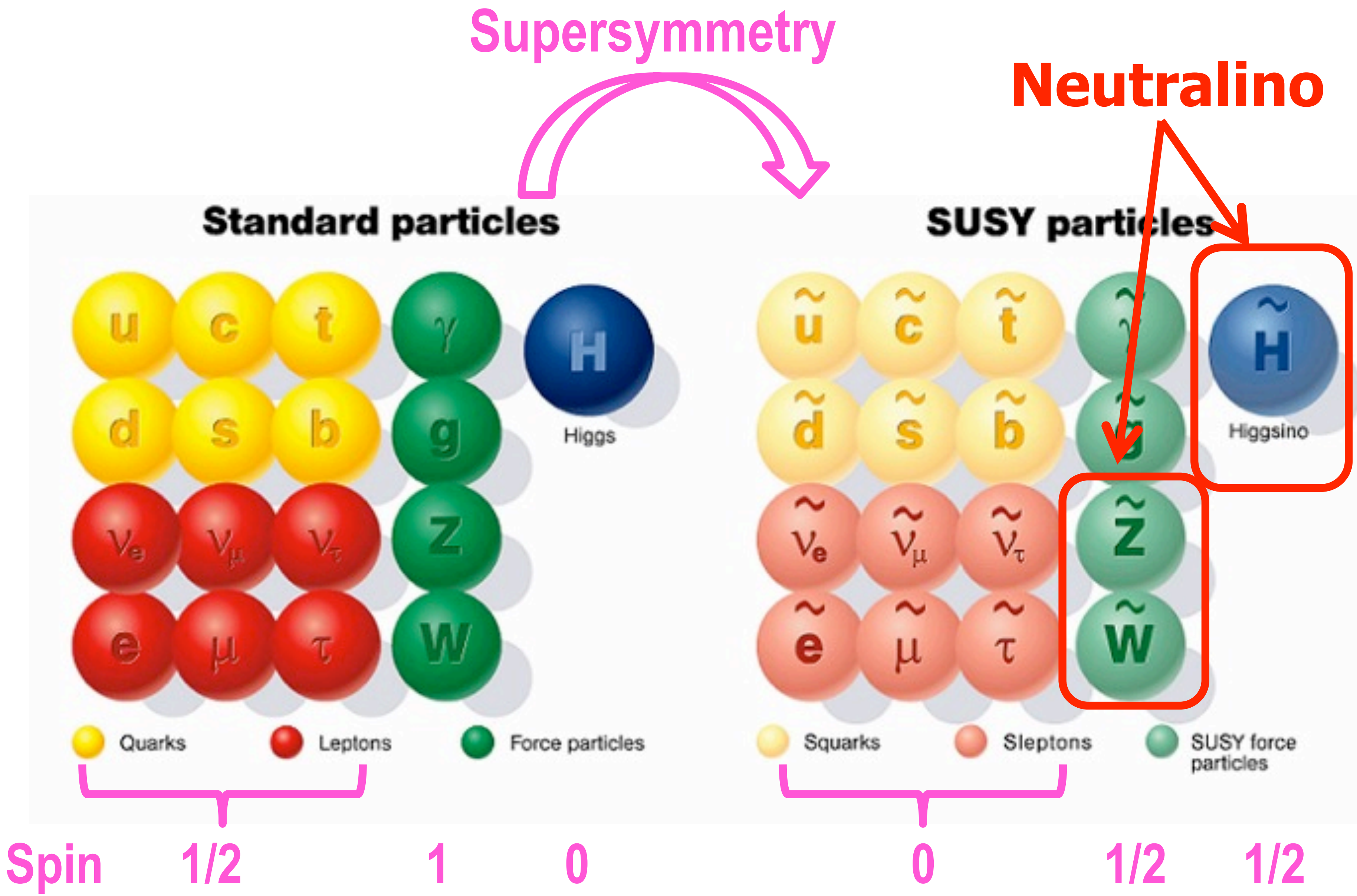
- Extension of the Standard Model of Particle Physics


Standard particles
u
c
t
γ
H
Higgs
d
s
b
g
νe
νμ
ντ
Z
e
μ
τ
W
Quarks
Leptons
Force particles

Spin 1/2 1 0



Supersymmetry
Standard particles
SUSY particles
u c t d s b
ν_e ν_μ ν_τ
e μ τ
γ g Z W
H
Higgs
$\tilde{u}$ $\tilde{c}$ $\tilde{t}$ $\tilde{d}$ $\tilde{s}$ $\tilde{b}$
$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$
$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$
$\tilde{\gamma}$ $\tilde{g}$ $\tilde{Z}$ $\tilde{W}$
$\tilde{H}$
Higgsino
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles
Spin 1/2 1 0
0 1/2 1/2

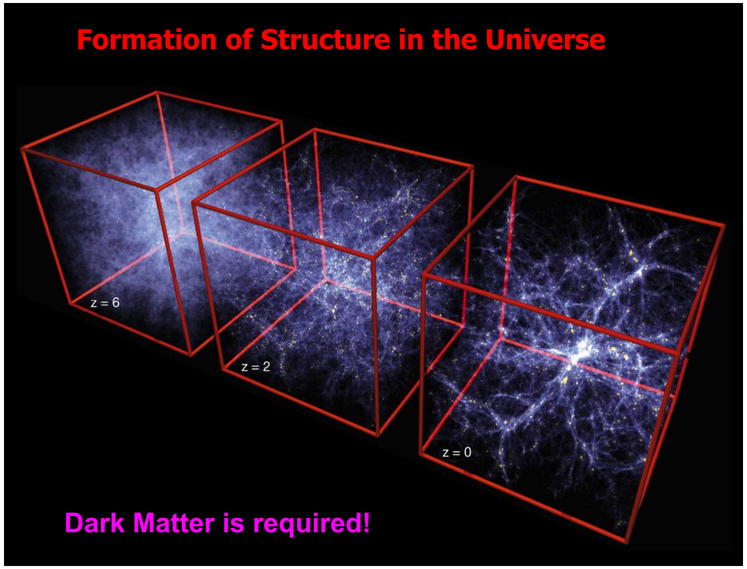

Supersymmetry
Neutralino
Standard particles
SUSY particles
u c t
d s b
γ g Z W
H
Higgs
Higgsino
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles
Spin 1/2 1 0 0 1/2 1/2

SUPERSYMMETRY

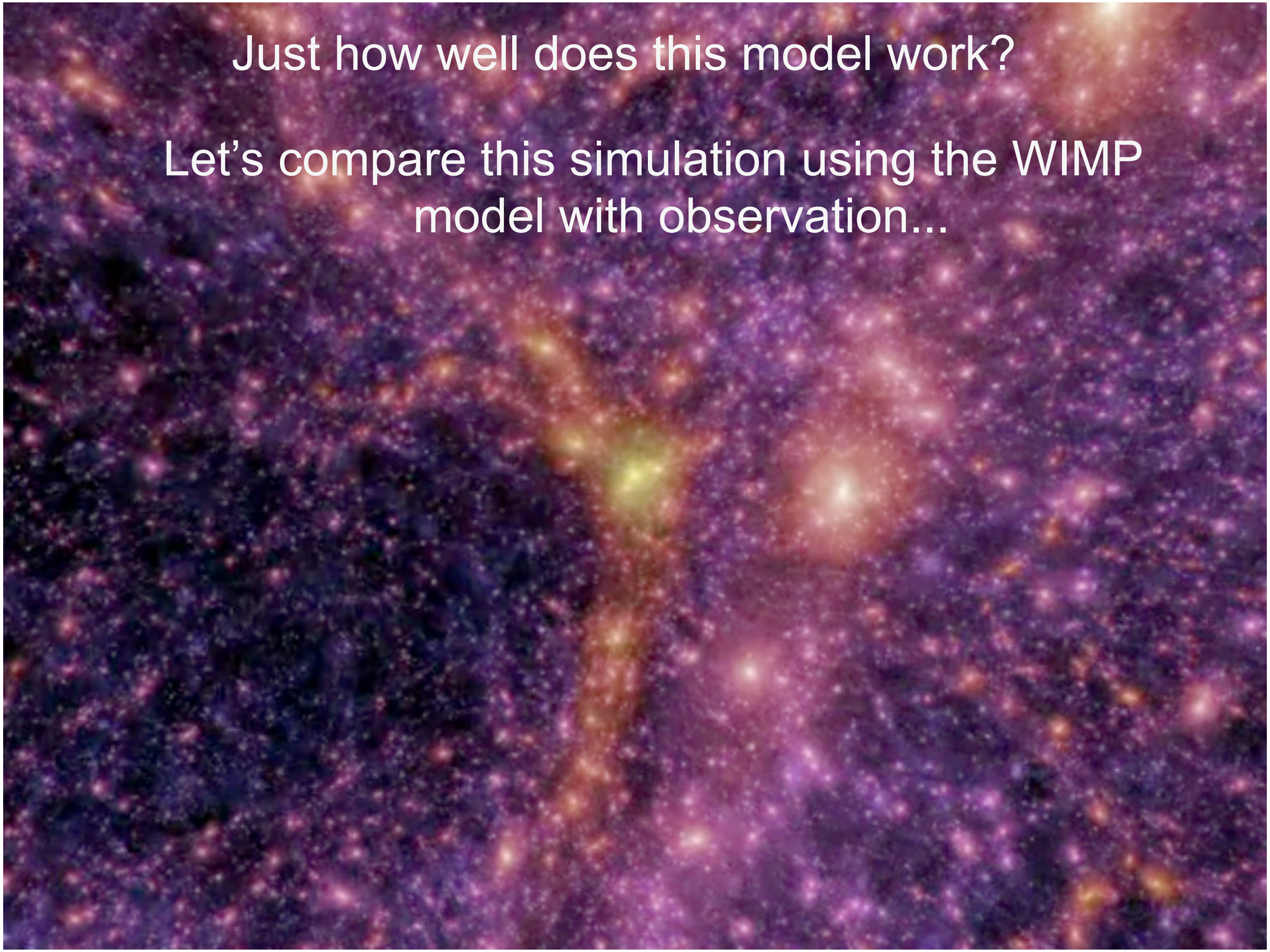
- Predicts more particles we have yet to see
- The lightest of these, the **LSP**, a very promising candidate for dark matter (*stable though R-parity)*
- As a result of the thermal freeze-out process, relic density of dark matter remains
- For GeV-TeV mass particles to have a thermal abundance equal to observed dark matter density, annihilation cross-section must be at the pb level
(similar to generic weak interaction yield)
- An *independent* prediction of the existence of a particle that matches the DM requirement (neutralinos)

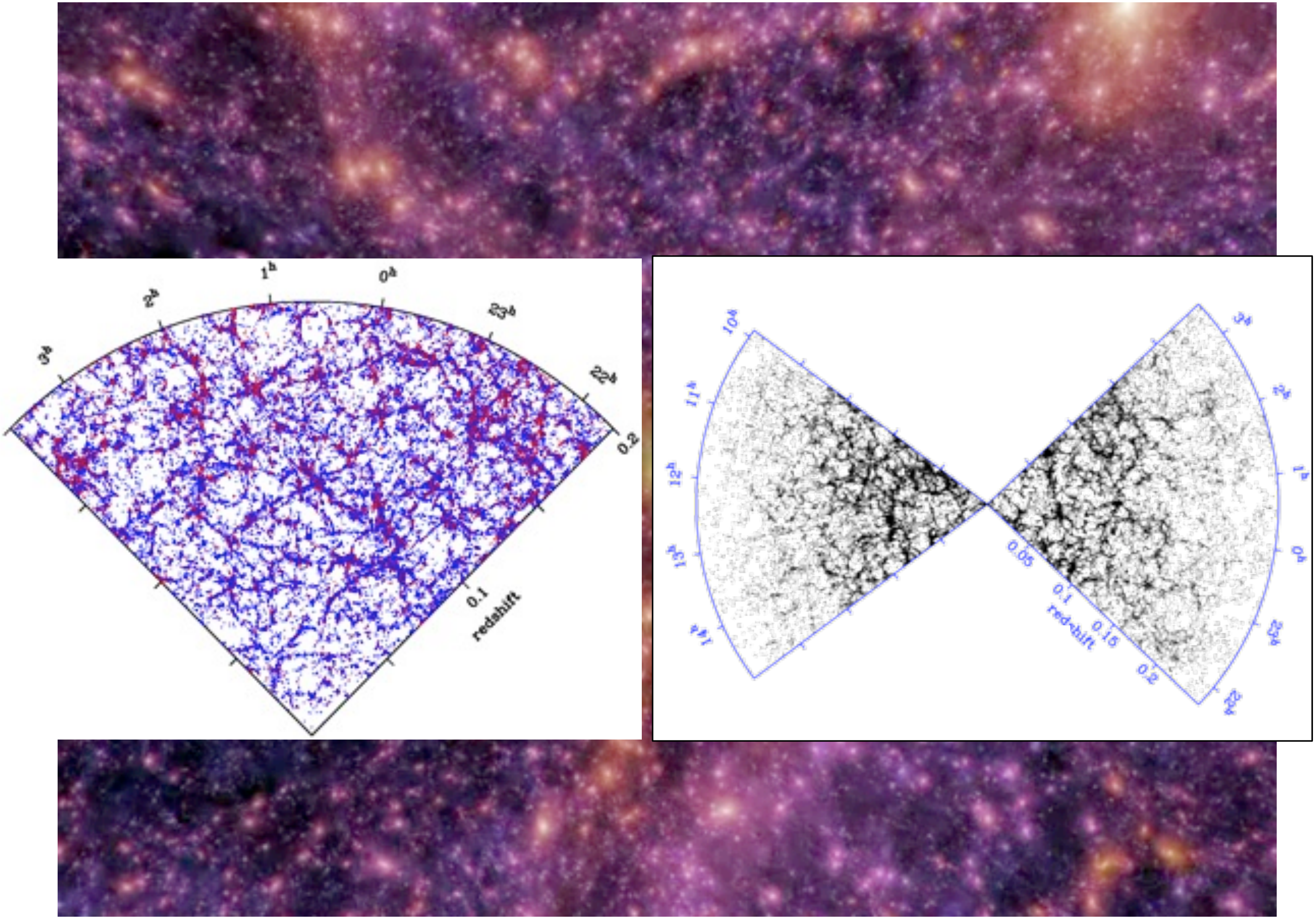
Weakly Interacting Massive Particles

The Need for Dark Matter



- It dominates the evolution of the visible Universe
- It holds the galaxies together! Without it we wouldn't have formed large scale structures


Just how well does this model work?
Let’s compare this simulation using the WIMP model with observation...


3^h
2^h
1^h
0^h
23^h
22^h
0.2
0.1
redshift
10^h
11^h
12^h
13^h
14^h
3^h
2^h
1^h
0^h
23^h
22^h
0.05
0.1
0.15
0.2
red-shift

The Direct Detection Challenge

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The simple WIMP DM hypothesis...

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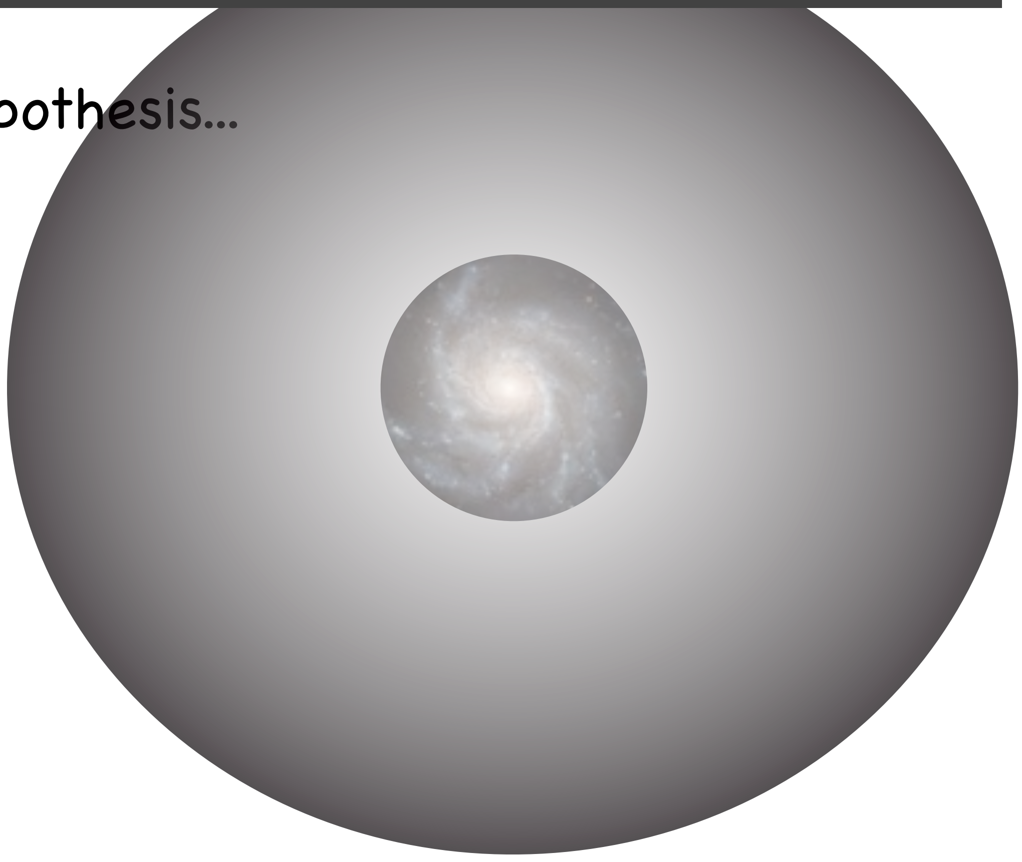
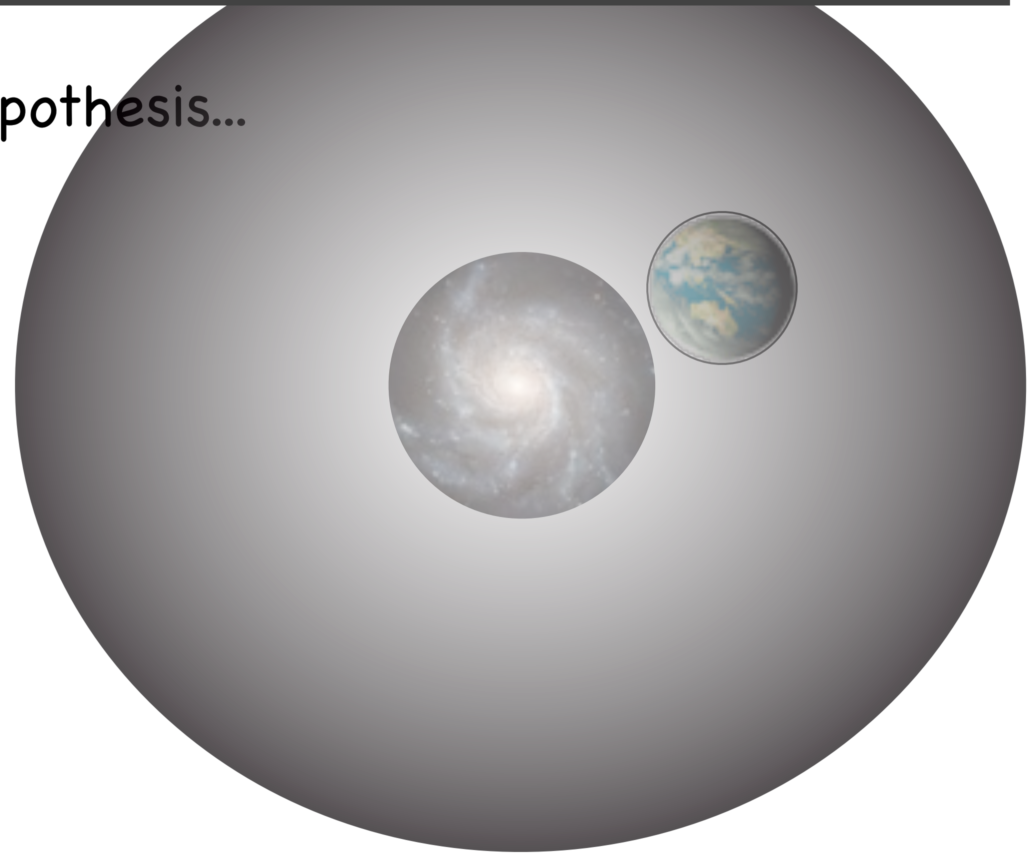
The simple WIMP DM hypothesis…



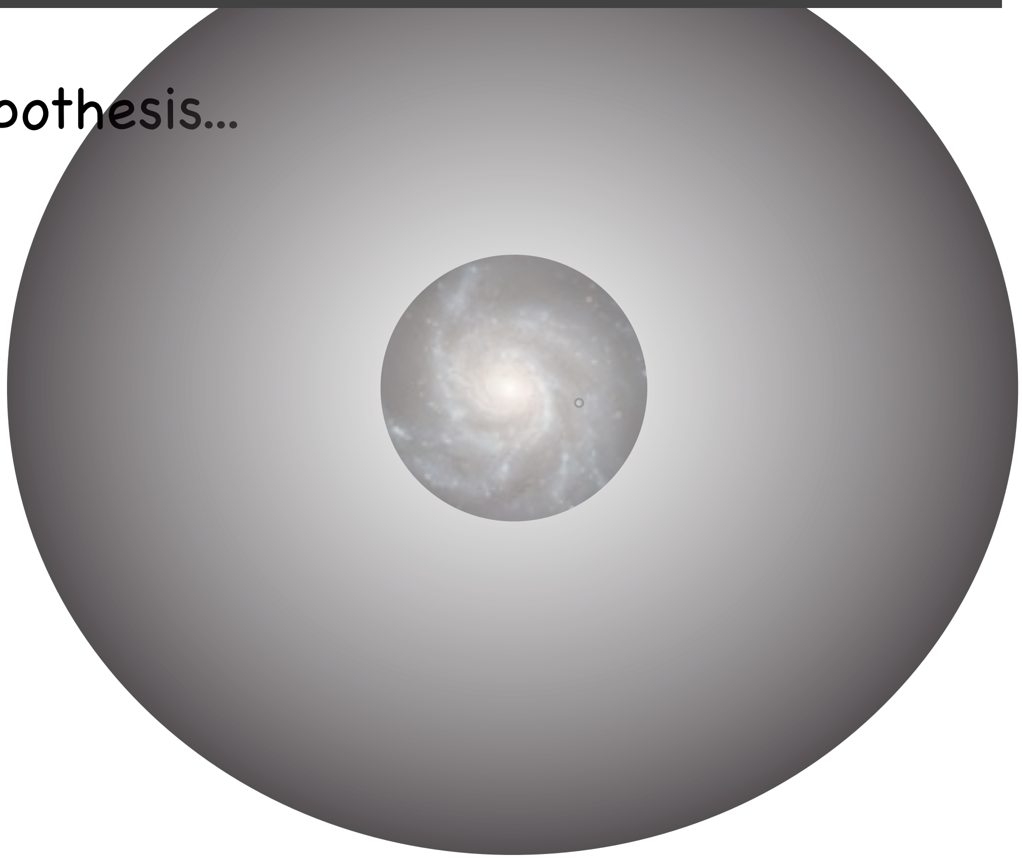
The Direct Detection Challenge

The simple WIMP DM hypothesis…



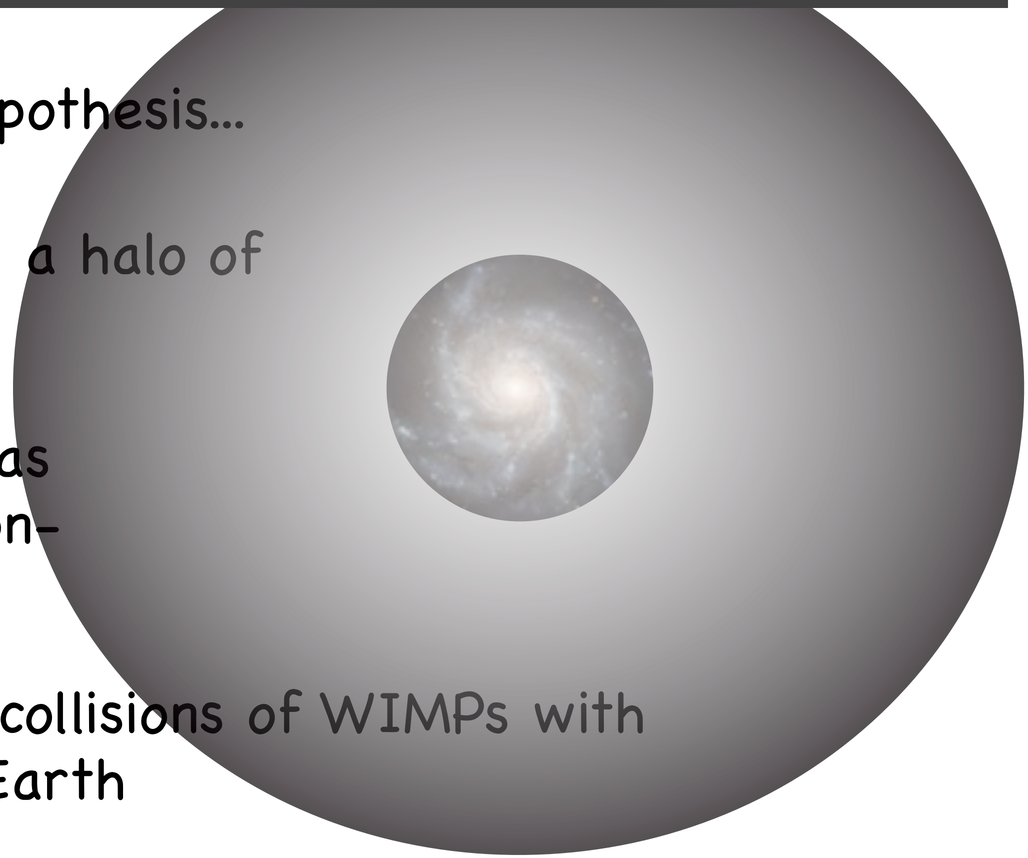
The Direct Detection Challenge

The simple WIMP DM hypothesis...



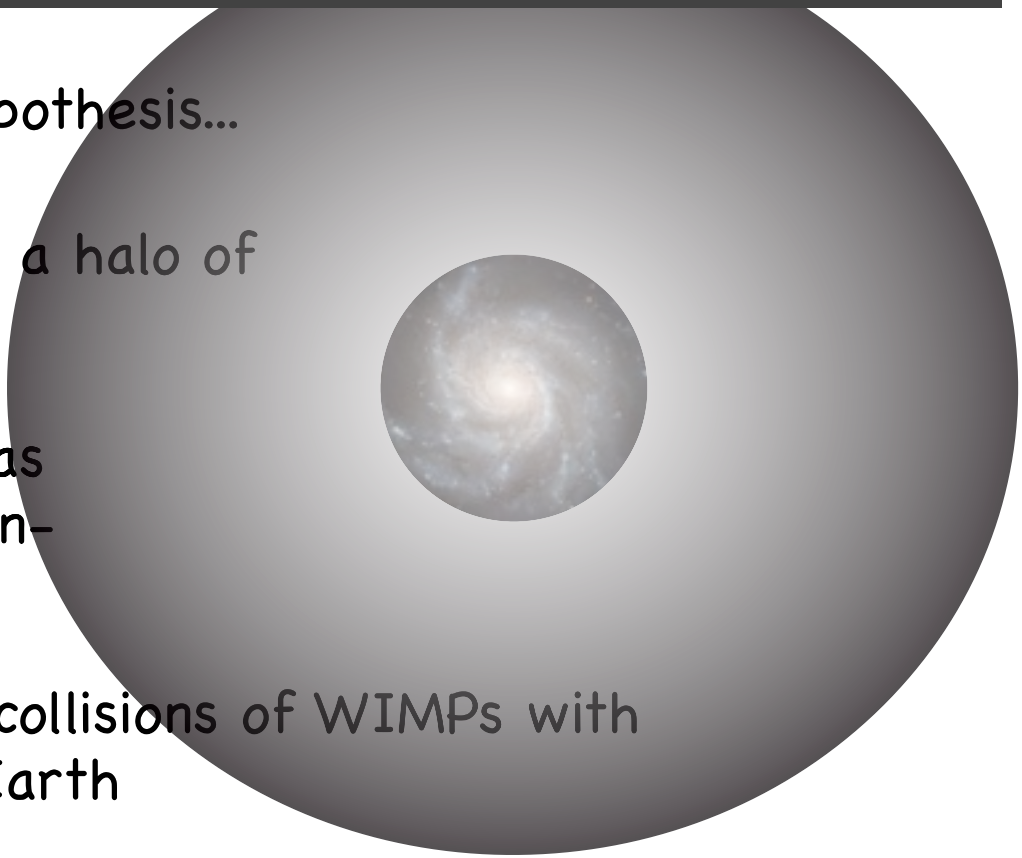
The Direct Detection Challenge

The simple WIMP DM hypothesis…



- Earth is passing through a halo of WIMPs
- We feel a WIMP 'wind' as we move through the non-rotating WIMP halo
- We search for the rare collisions of WIMPs with normal matter here on Earth

The Direct Detection Challenge



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Definitive detection is internationally recognised as one of THE highest priorities in science!

Direct Detection: Basic Method

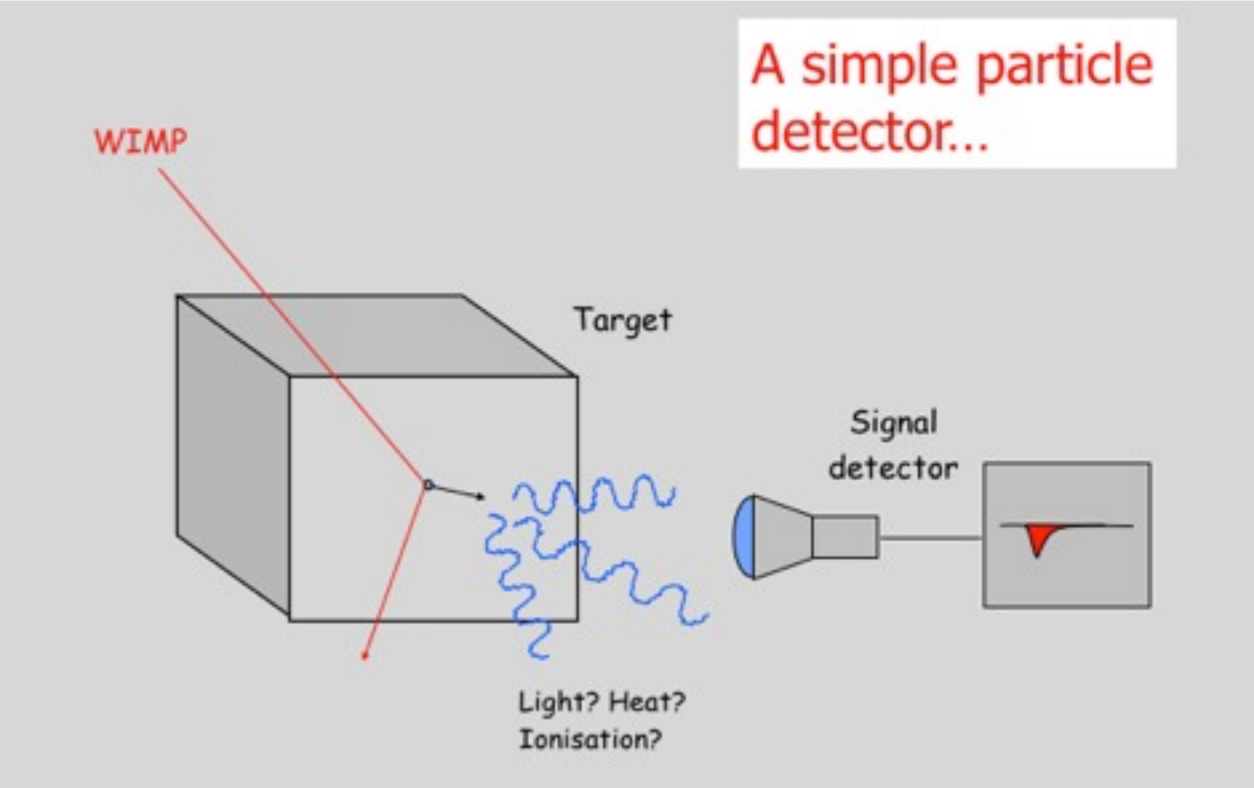
Make a device that should see **NOTHING** from 'standard' physics…

Direct Detection: Basic Method

Make a device that should see **NOTHING** from ‘standard’ physics…

…and see if there’s anything still there!

How to detect a WIMP - Step 1



WIMP will elastically scatter off nuclei and the nuclear recoil may be detected as scintillation, phonons, ionisation, or some combination

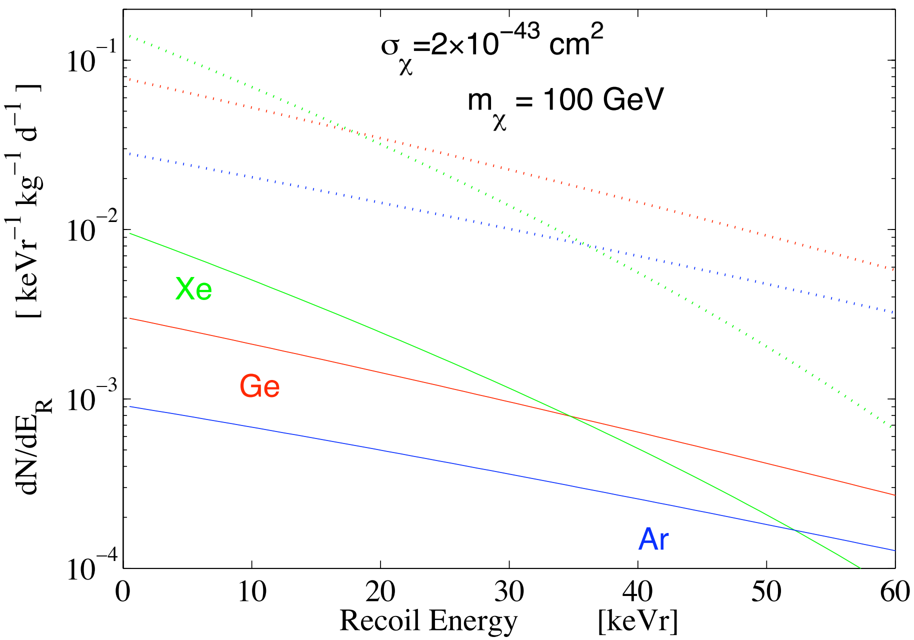
How to detect a WIMP - Step 2

Your detector needs:

- ☑ incredible sensitivity for very low energy signals
- ☑ to be able to discriminate backgrounds
- ☑ to be low-background
- ☑ to have a lot of mass
- ☑ to be able to pick out extremely rare signals (~1 per month!)

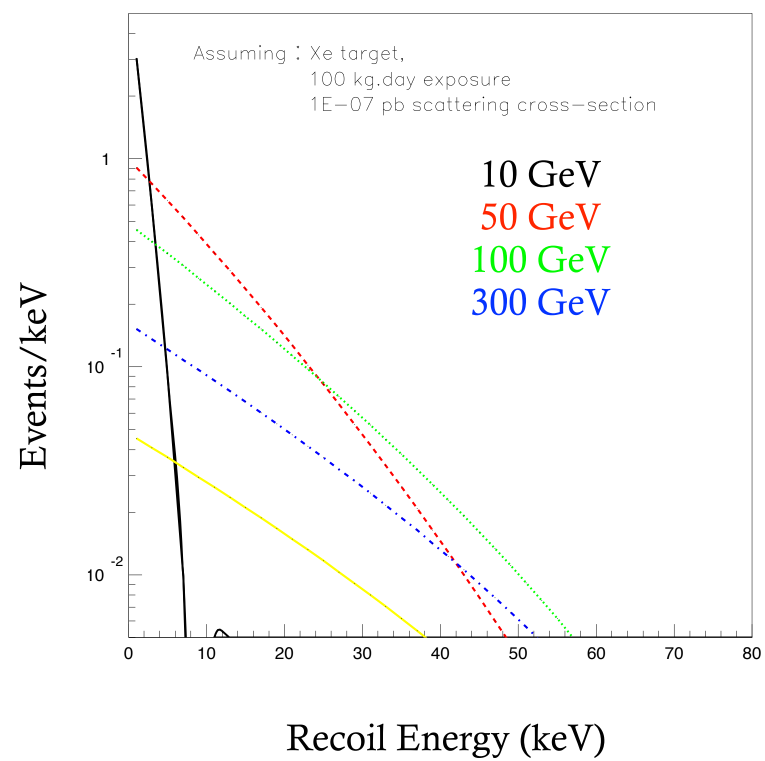
Hunts Needle in a Haystack

How to detect a WIMP - Step 2

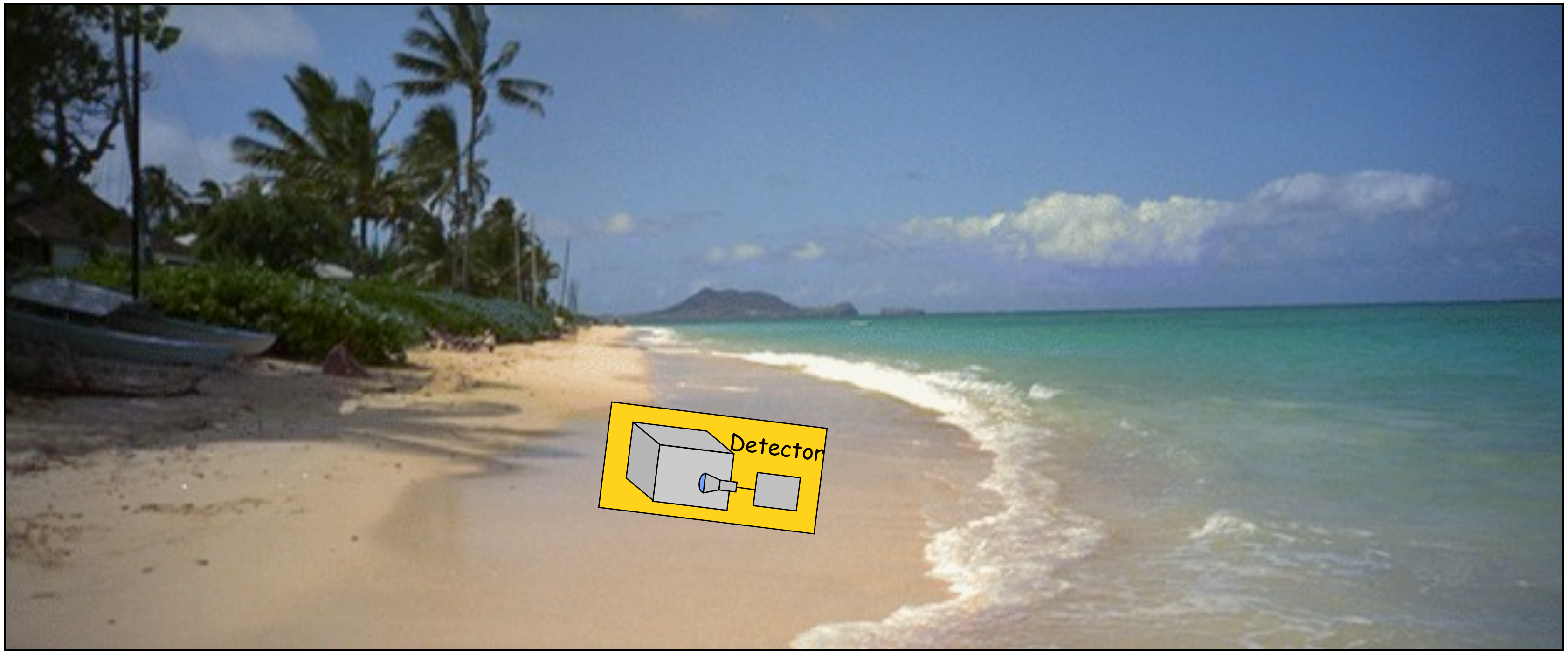


Rare signal

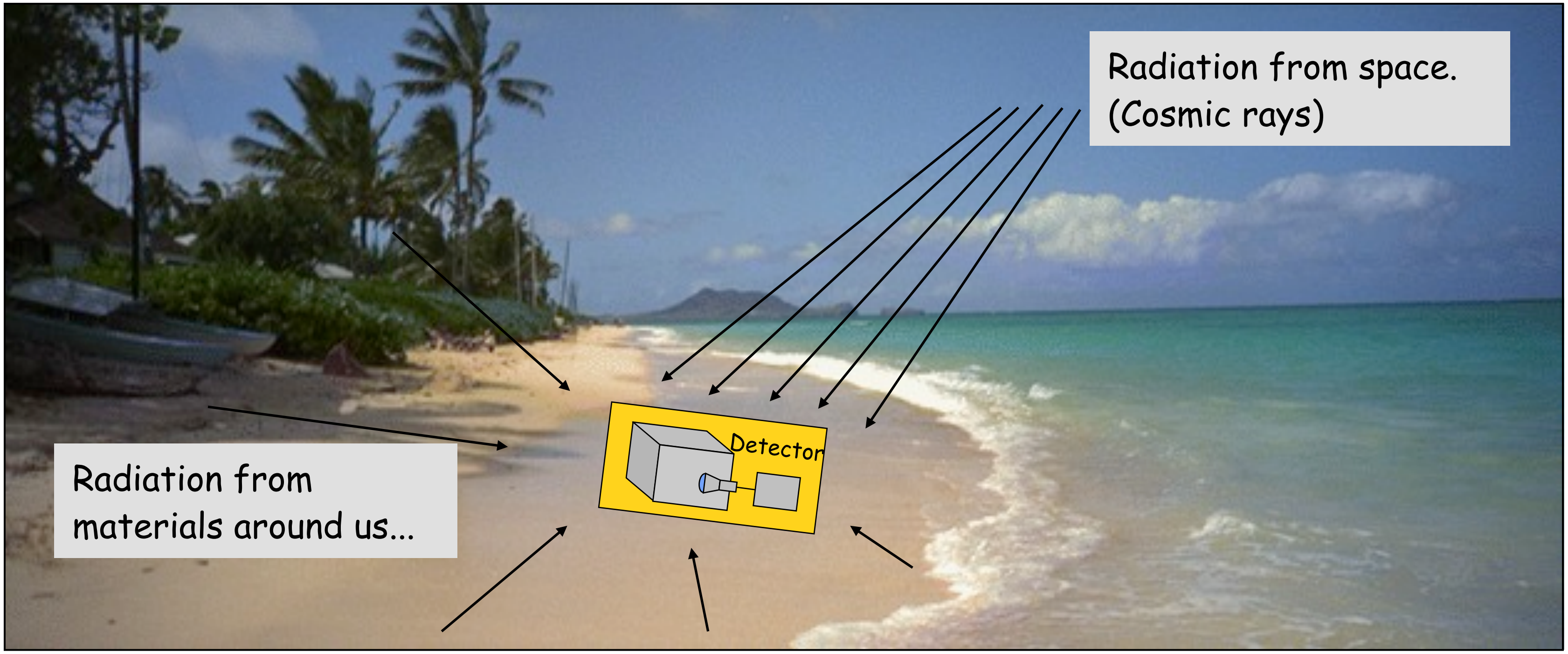
Weak signal



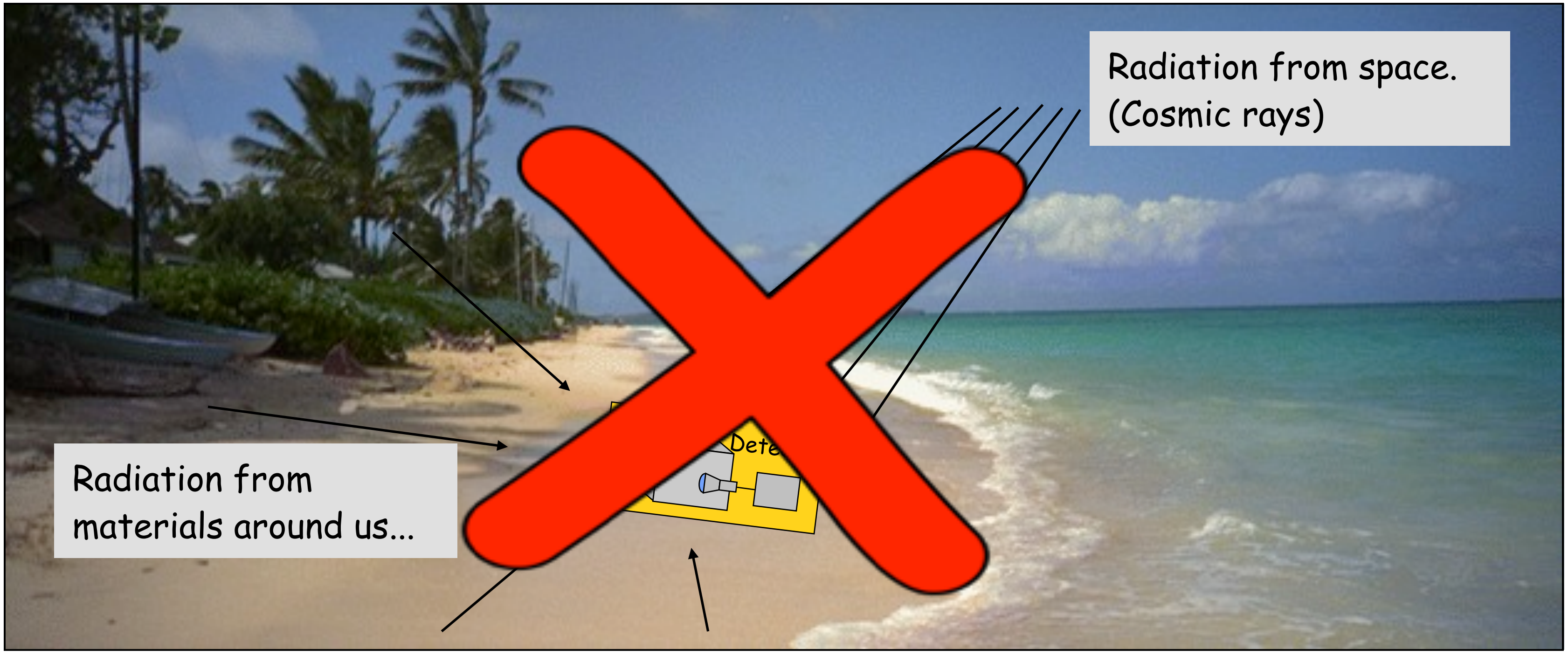
How to detect a WIMP - Step 3



How to detect a WIMP - Step 3



How to detect a WIMP - Step 3



Need to go deep underground!

The Boulby Mine

The Boulby Mine

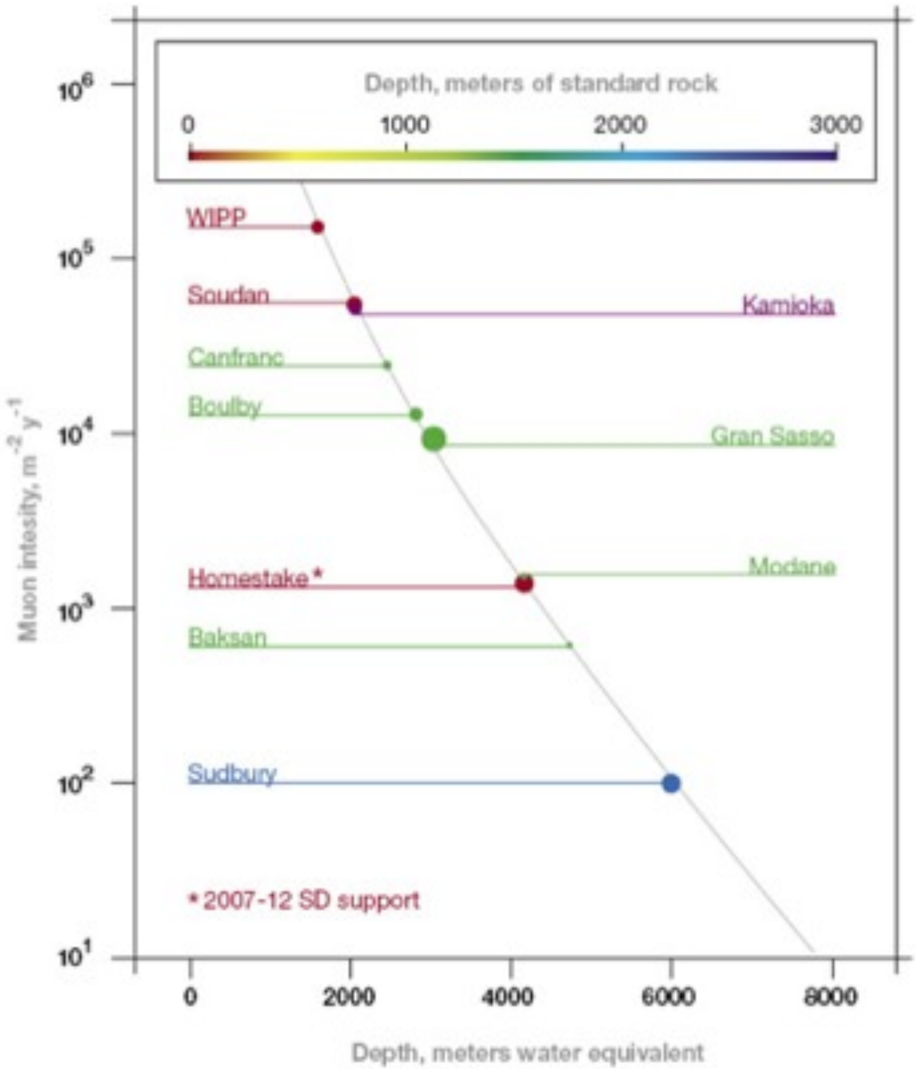
The Boulby Mine

Underground

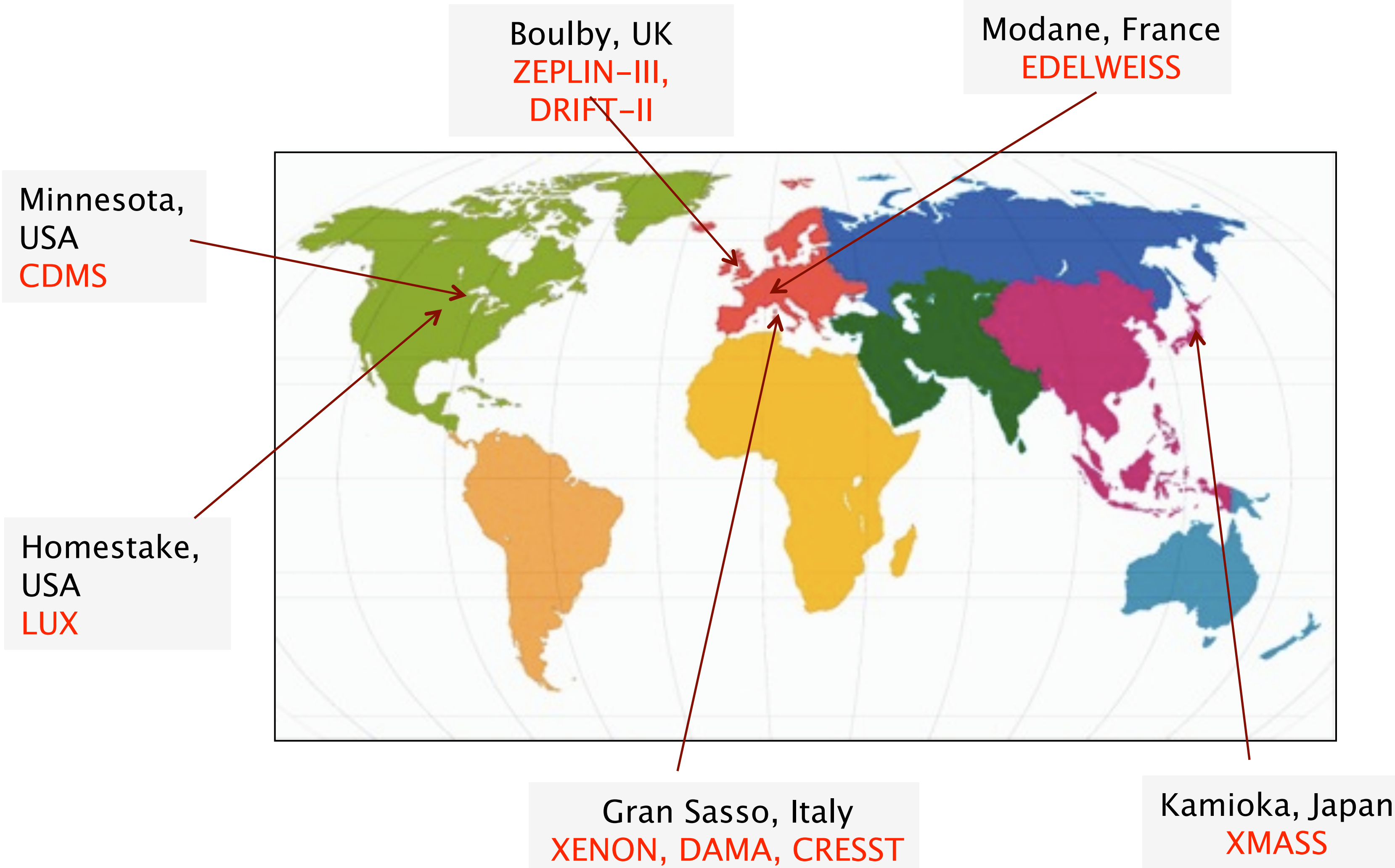
The Boulby Underground Laboratory

The Boulby Mine

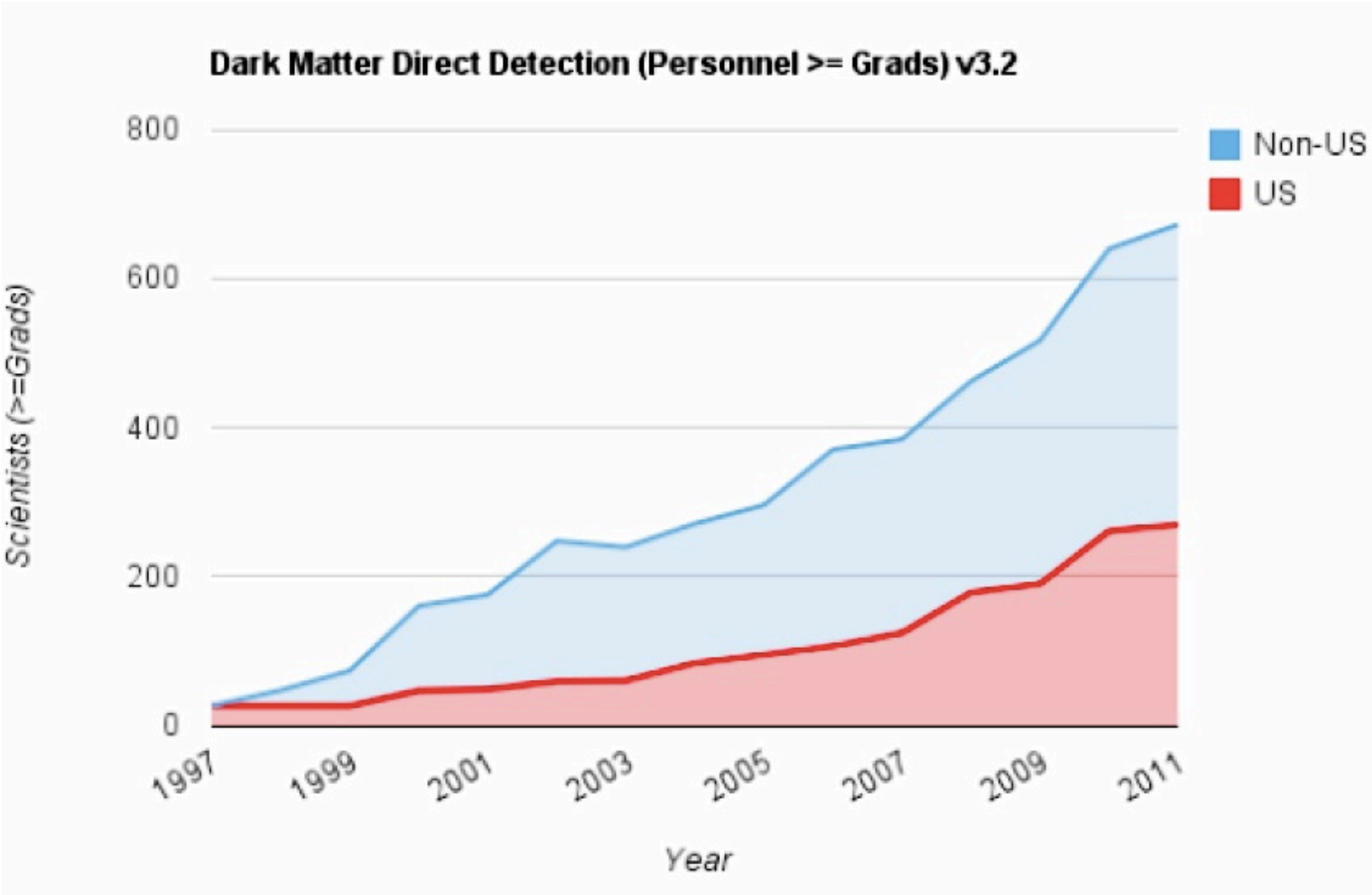
- A working potash and salt mine in the north of England
- 1100m deep (2805mwe) – **Cosmic rays reduced by a factor ~1 million** $(3.79 \pm 0.15) \times 10^{-8}$ muons $cm^{-2}s^{-1}$
- Boulby salt is **very low in natural radioactive backgrounds** (65ppb U, 130ppb Th, 1130ppm K)



The World Dark Matter Search



The World Dark Matter Search

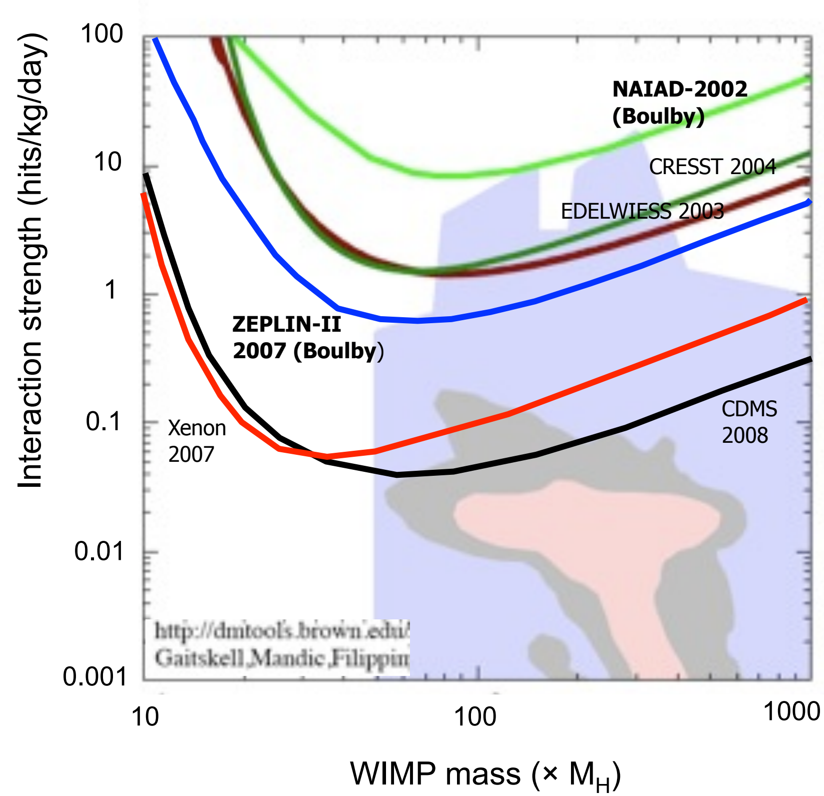


The World Dark Matter Search

A highly competitive field - everybody want to be the first to detect Dark Matter!

The aim of all Dark Matter search experiments is to either detect Dark Matter - or to 'rule it out' by setting the lowest 'WIMP limits'

'Exclusion plots' let us compare progress towards a detection



WIMP Detection Techniques

Heat and ionisation bolometers: CDMS
EDELWEISS

Bubbles and Droplets:
CUOPP
PICASSO

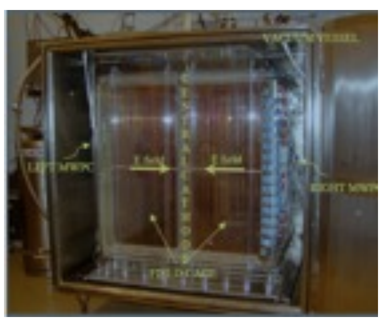
Light and heat Bolometers:
CRESST
ROSEBUD

Phonons

dE/dx

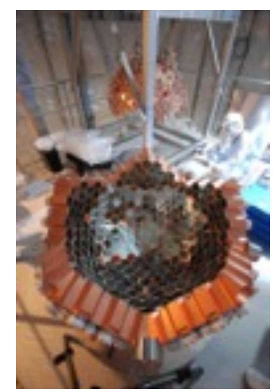
Charge

Light



Ionisation detectors: DMTPC
DRIFT, GENIUS, NEWAGE,
HDMS, IGEX

Scintillation and ionisation charge detectors:
XENON
WARP
ArDM
ZEPLIN
LUX



Scintillators:
DAMA
LIBRA
XMASS
CLEAN
ANAIS
KIMS

Why Xenon?

Excellent light output

Very high purity,
easy cryogenics

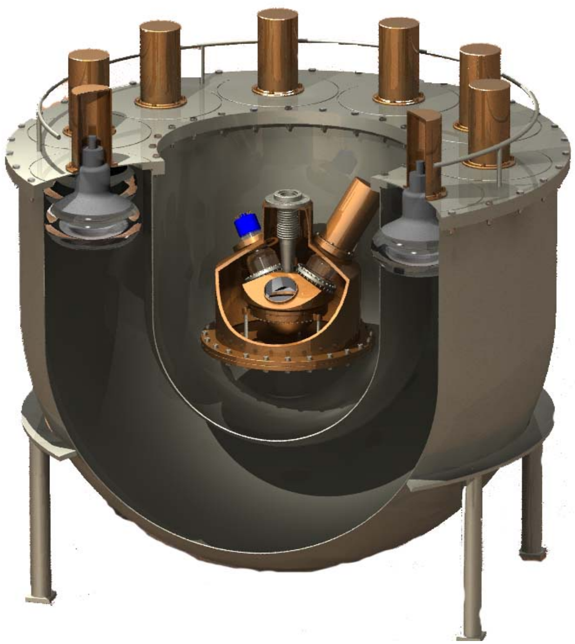
Mass Xe ~ Mass WIMP

1 tonne

70 cm

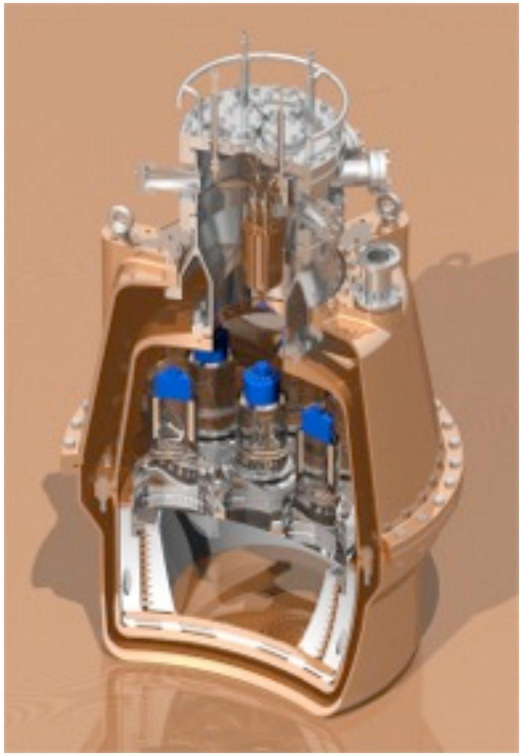
Easily scaled;
Self-shielding

The ZEPLIN Program at Boulby



ZEPLIN I

Single phase, 3 PMTs, 5/3.1 kg
Run 2001/04
Limit: 1.1*10^{-6} pb

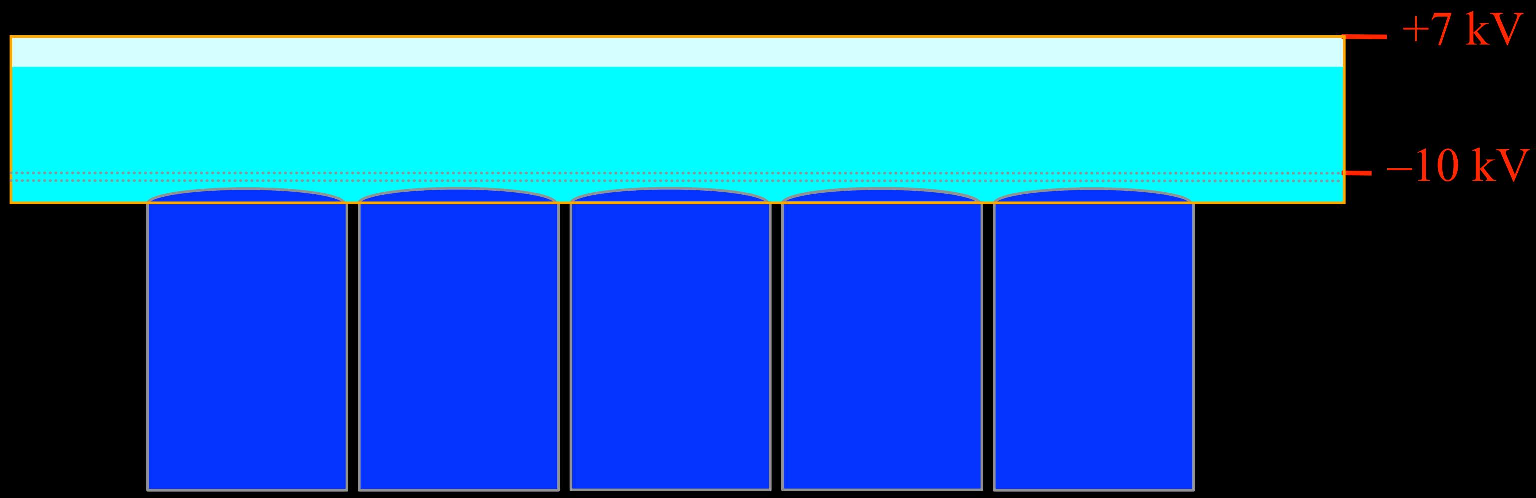


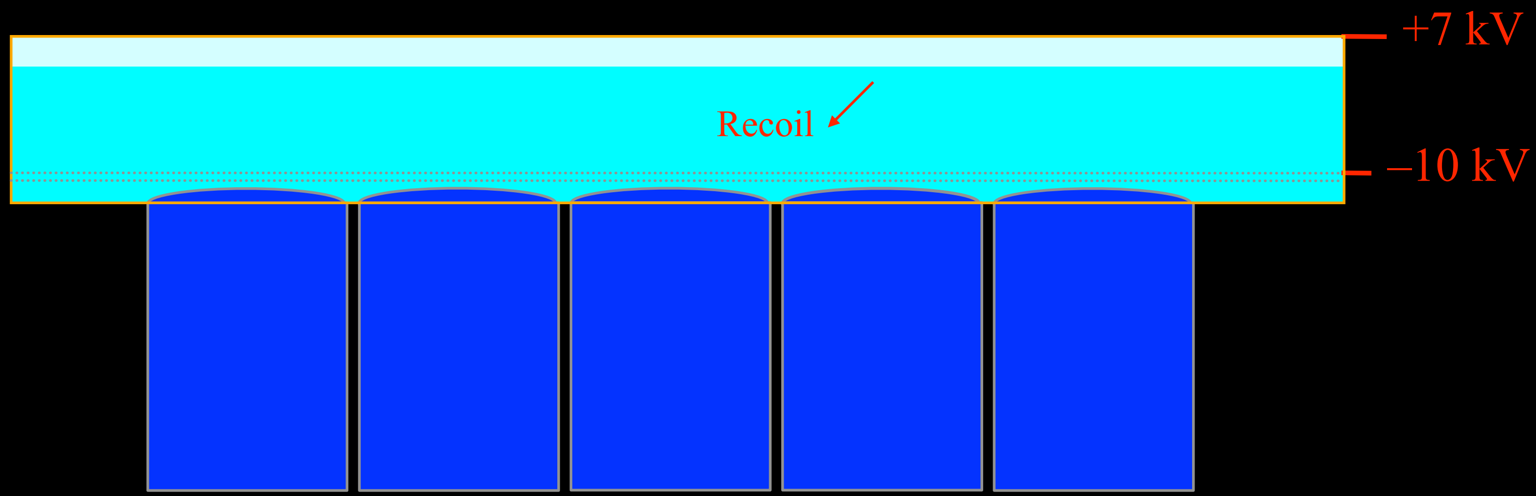
ZEPLIN II

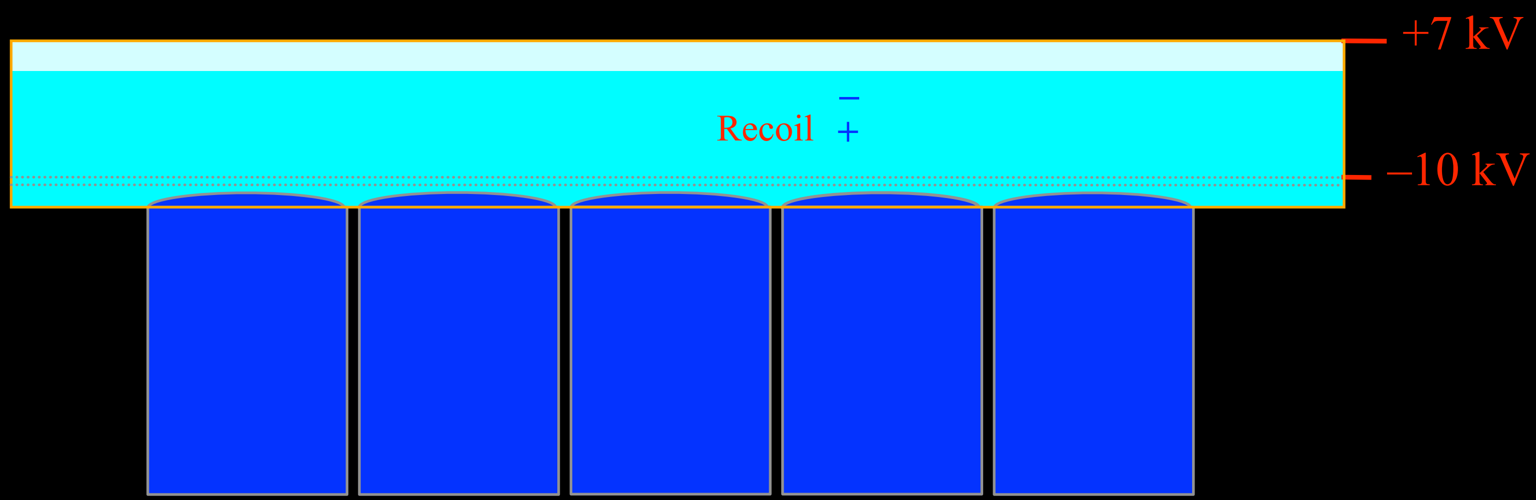
Double phase, 7 PMTs, moderate E field, 31/7.2 kg
Run 2005/06
Limit: 6.6*10^{-7} pb

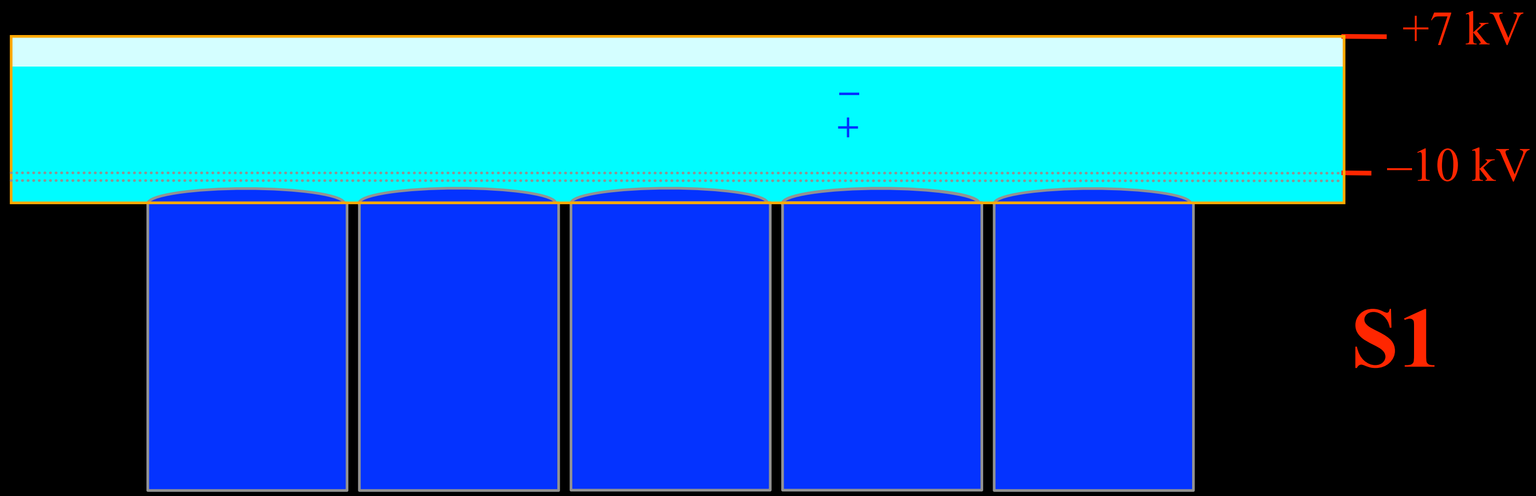
The first 2-phase LXe Dark Matter detector!

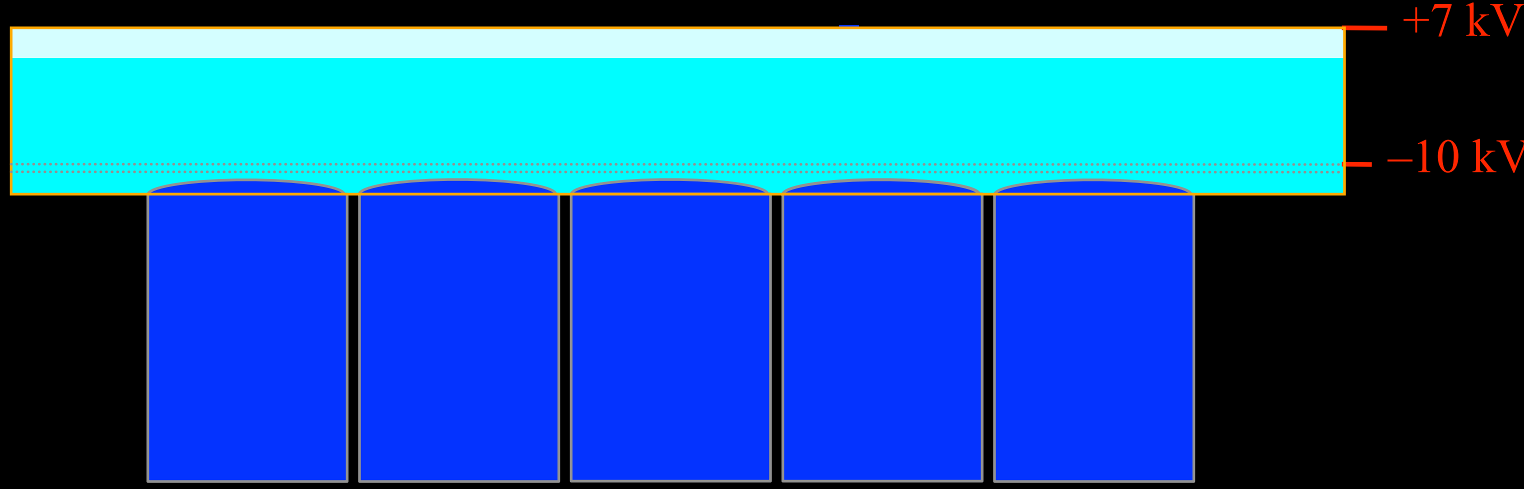
The LXe TPC Technique

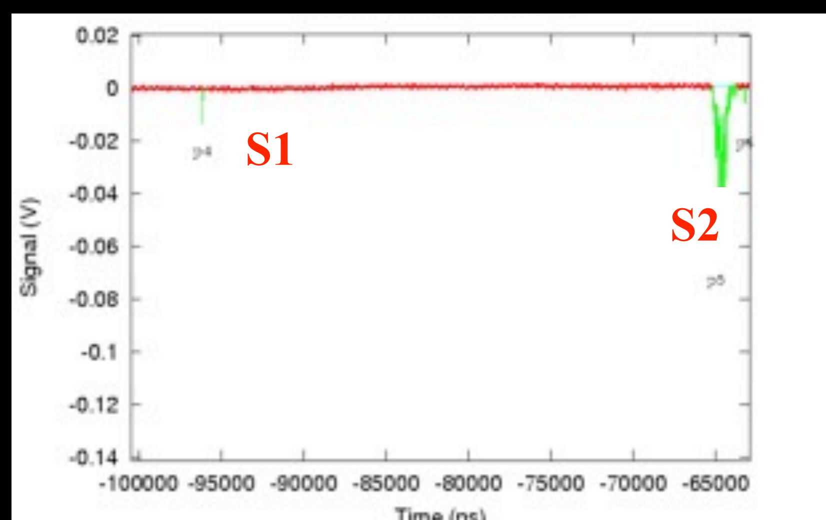



+7 kV
Recoil
–10 kV

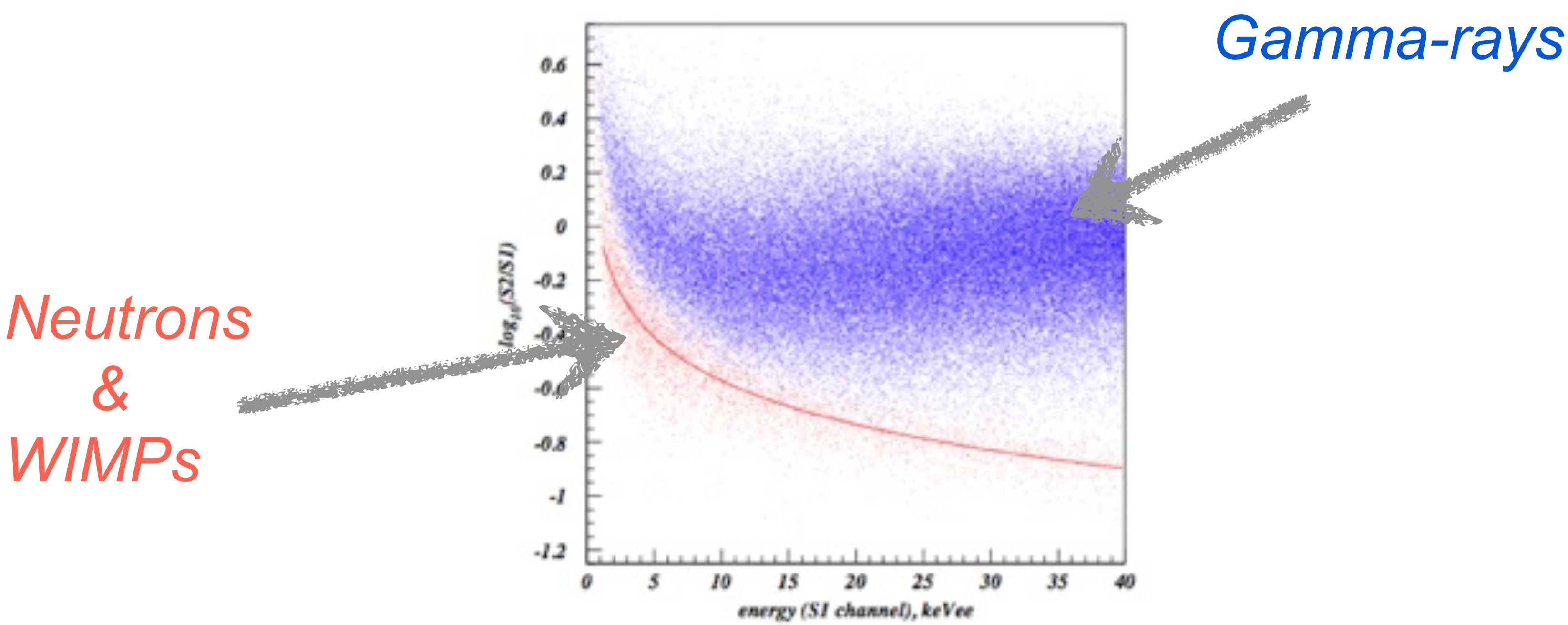

+7 kV
Recoil
–
+
–10 kV


+7 kV
−
+
−10 kV
S1


+7 kV
−10 kV

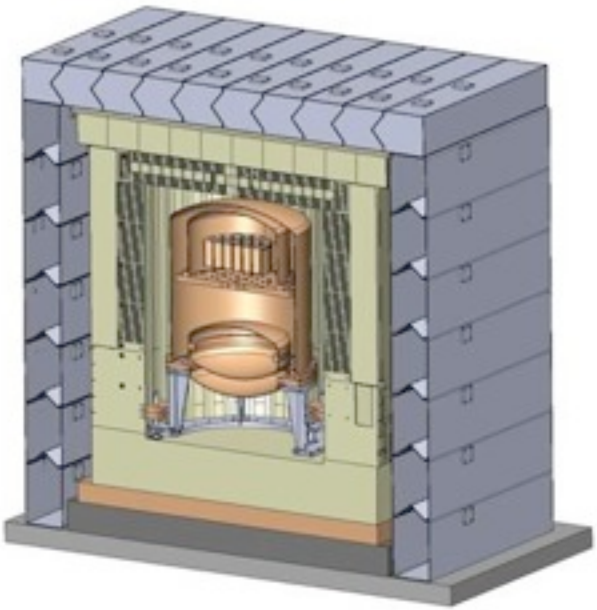

S1
S2
Signal (V)
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-100000
-95000
-90000
-85000
-80000
-75000
-70000
-65000
Time (ns)

Discrimination

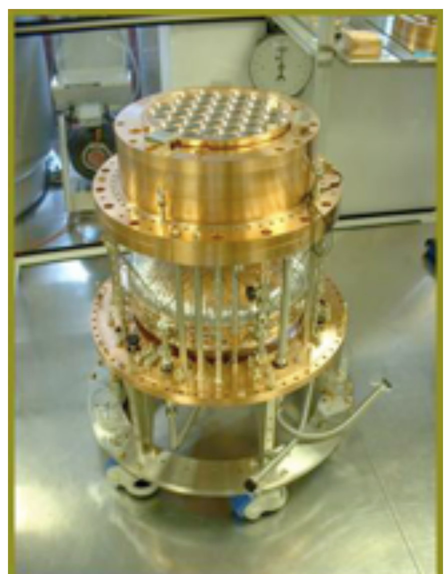


- Clear separation between 'background' and neutrons (or WIMPs!)
- The stronger the E-field the better the discrimination
- 3D TPC allows fiducial volume definition and single scatter selection

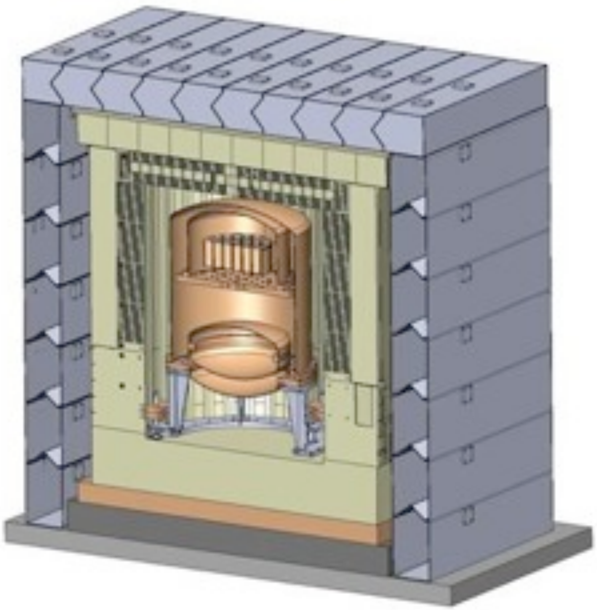
The ZEPLIN-III Detector



- 31 PMTs in liquid to improve light collection
- 12 kg active target mass (pancake) open geometry
- High uniform E-field with no extraction electrodes
- Clean copper construction
- LN_2 used for cooling - no polycolds/compressors, etc
- 3D position reconstruction with 2mm (xy) and micrometer (z) resolution (@122 keV)



The ZEPLIN-III Detector



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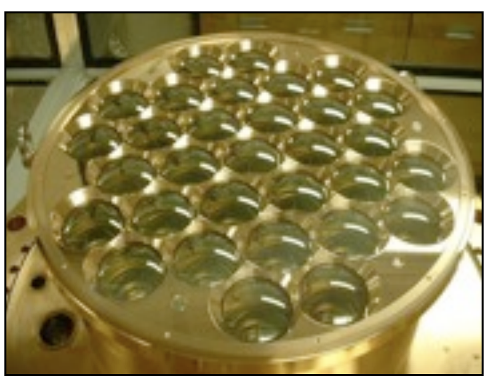
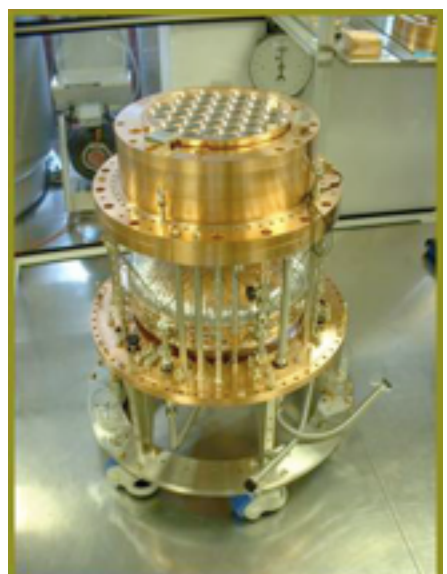
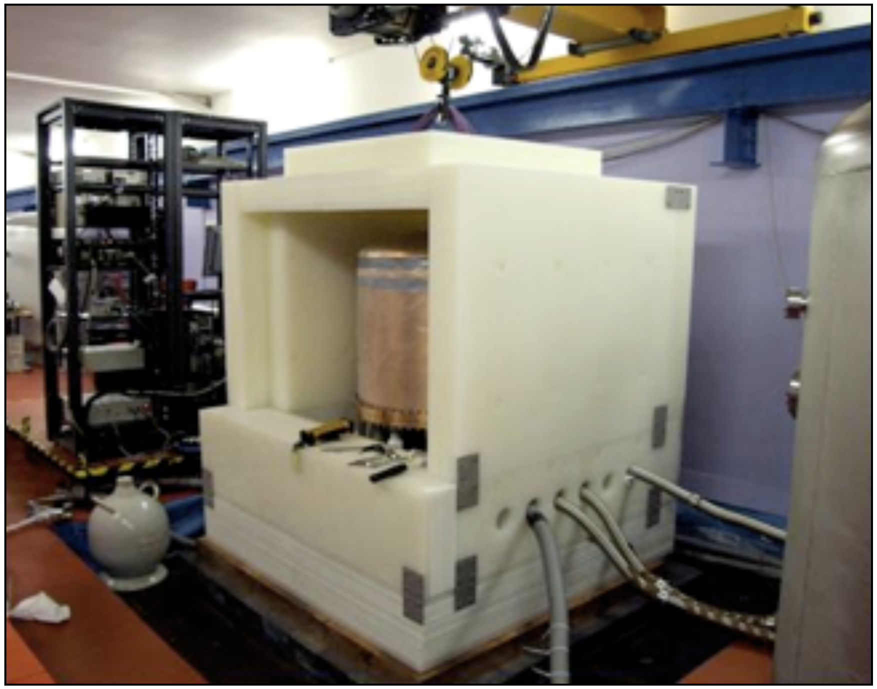
- Clean copper construction
- LN_2 used for cooling - no polycolds/compressors, etc
- 3D position reconstruction with 2mm (xy) and micrometer (z) resolution (@122 keV)





The ZEPLIN-III Detector



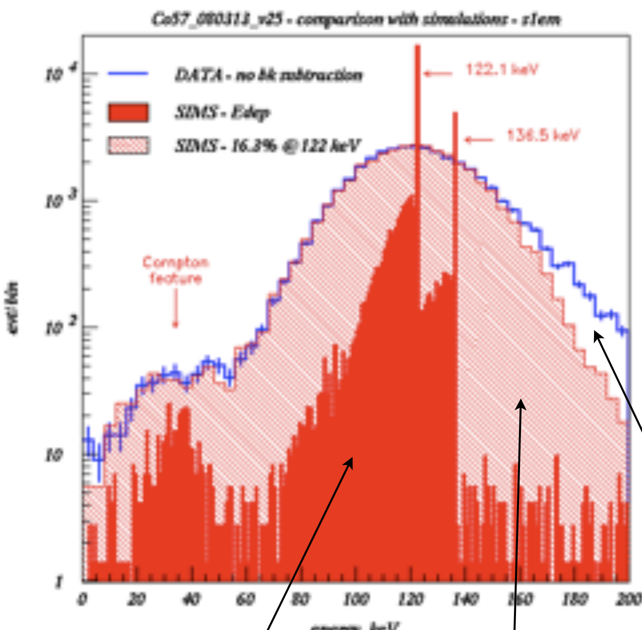
Hydrocarbon passive shielding to moderate external neutrons

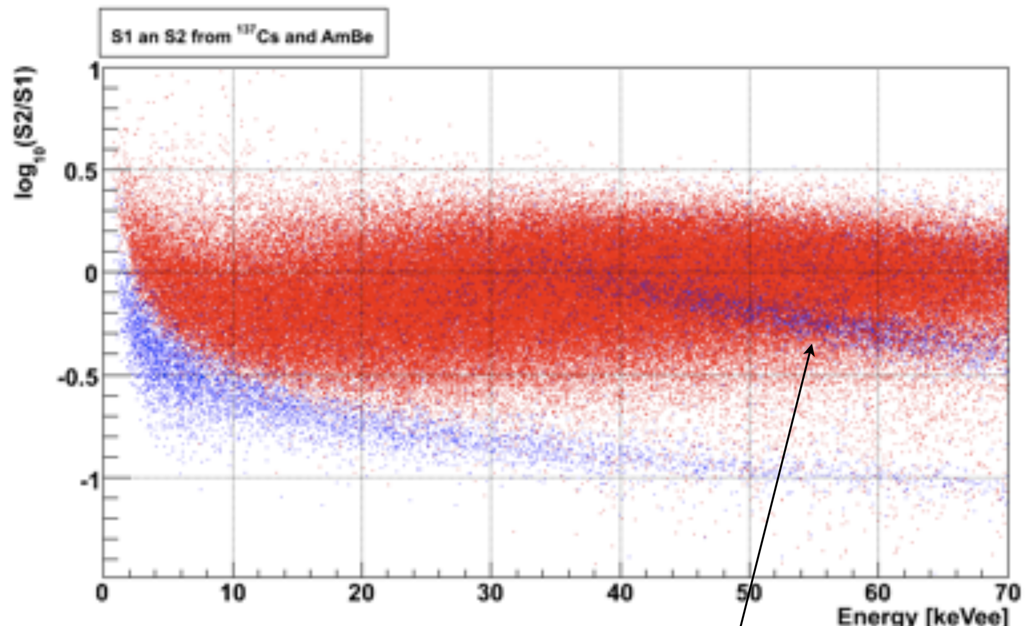
Lead castle to attenuate external gamma-rays

Detector Calibration

Energy resolution @ 122 keV
S1 16.3%, S2 8.8%, E* 5.4%

Data from ^{137}Cs gamma-ray (red)
and AmBe neutron (blue) sources





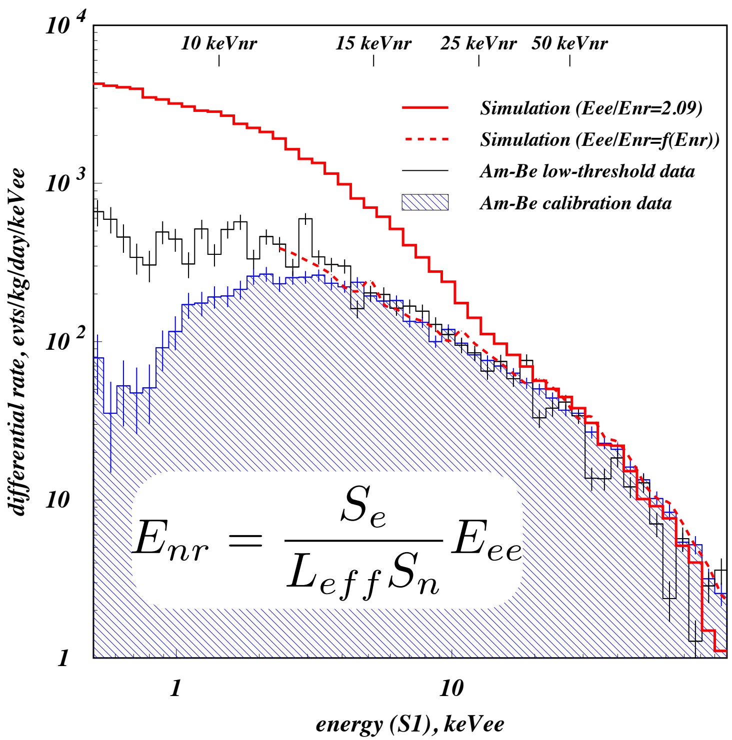
40 keV inelastic scatters

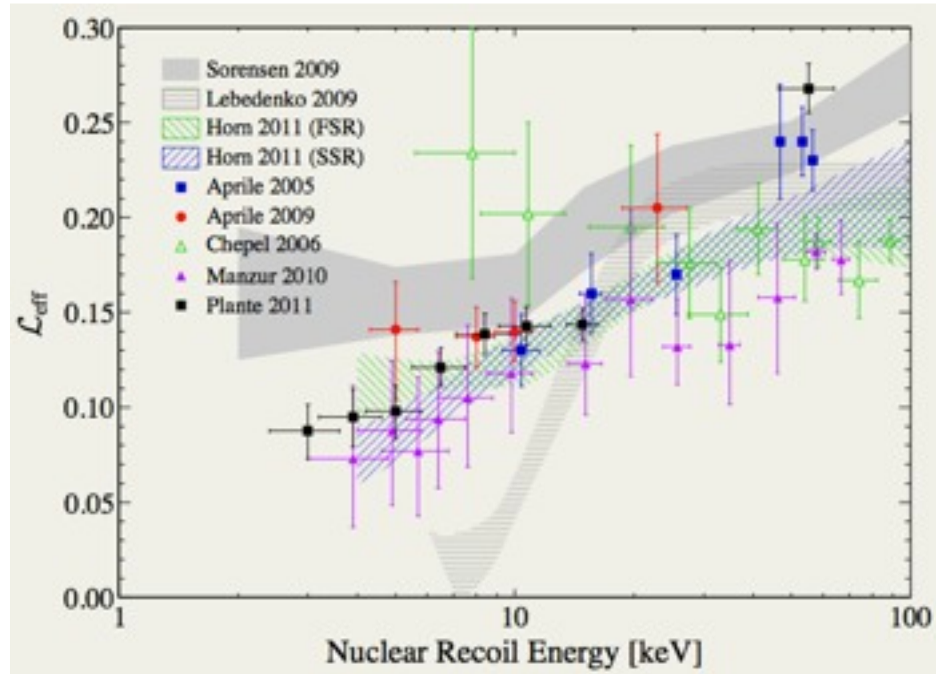
Simulated energy deposition

Smeared simulated energy deposition

Difference for E>160 keV due to
single scatter event selection in
data and saturation

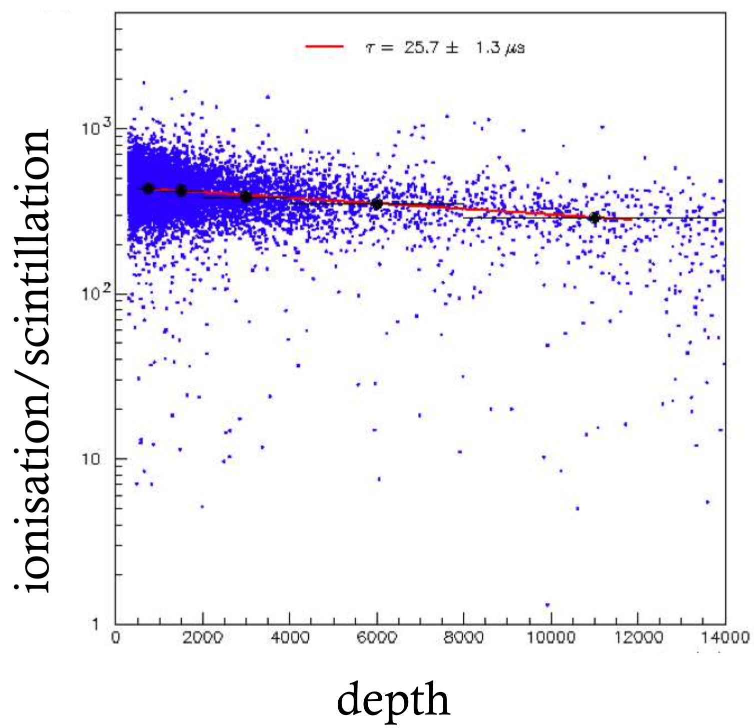
Nuclear Recoil Energy Scale

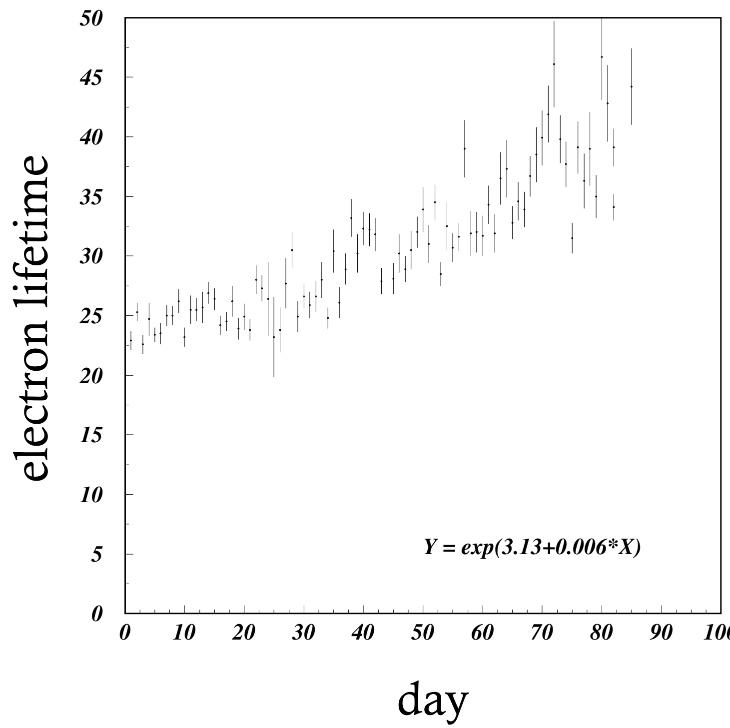




- Energy scale defined in 'keVee' with reference to response from 122 keV gamma-rays
- Nuclear recoil response for equivalent energy deposition is not the same!
- When converting to nuclear recoil energy scale 'keVnr' we must account for any energy dependence in this quenching - a strong effect at low energies

Corrections: e- lifetime





- Depth dependent corrections are required for LXe TPCs
- Daily ^{57}Co calibrations used to measure electron lifetime over the duration of the run
- No recirculation used - system isolated - clean construction: lifetime increases!
- Other corrections include tilt (for Boulby!) and position dependence (for larger systems)

Dark Matter Run - FSR

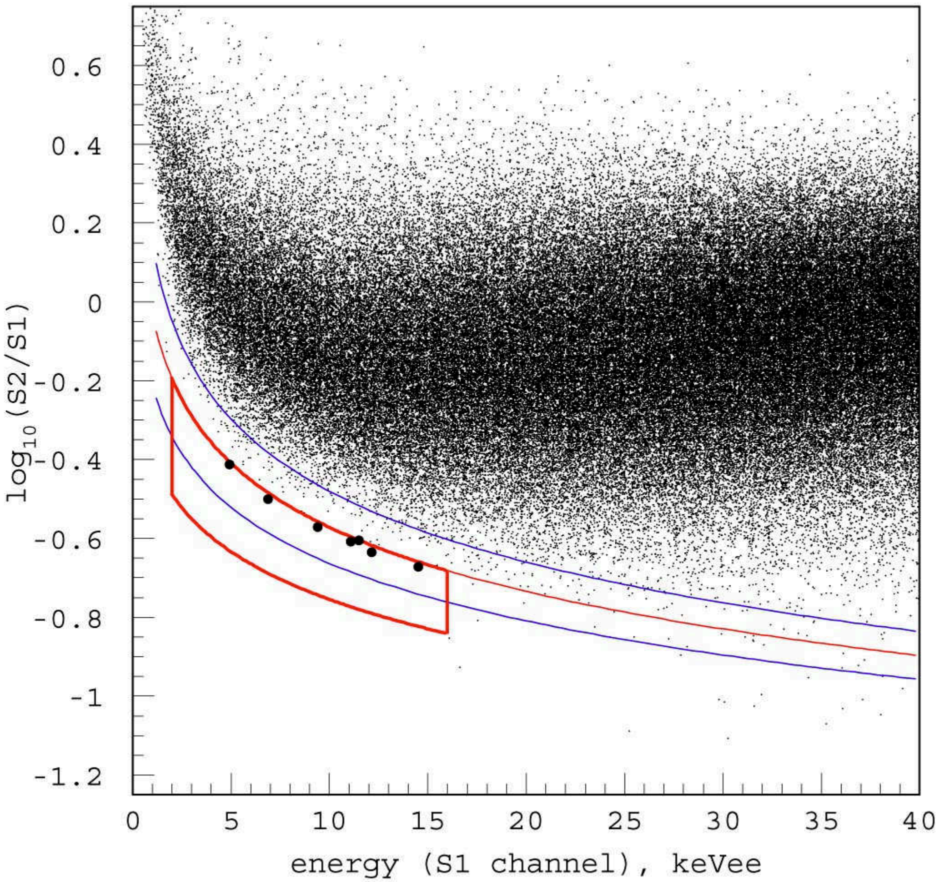
- First Science Run of ZEPLIN-III was a proof of concept for the high E-field and discrimination power - achieved approx. 1:8000 (the highest of any LXe TPC)

- With the detector assembled, shielded, calibrated and corrections tracked, the Dark Matter WIMP search can begin!

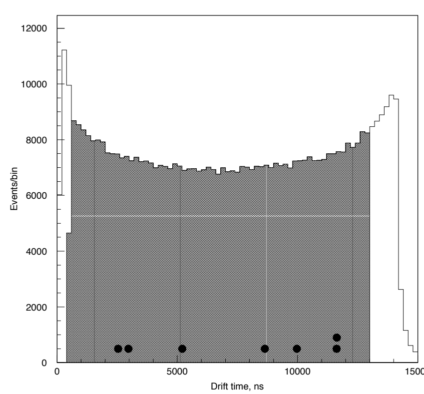
- 3 months data acquired

- Data are BLINDED - quality cuts are tuned on calibration data, background expectation in signal region estimated by calibration, and background extrapolation; only single scatter events selected

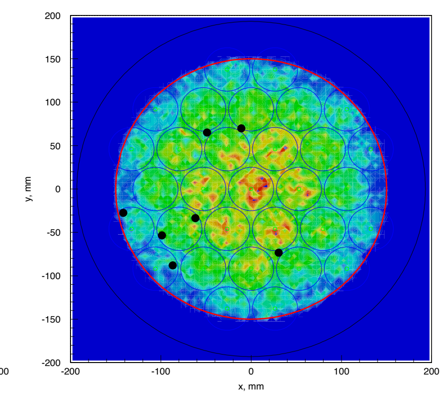
First Science Run Results



7 events observed in signal region, but not in excess of expected background!

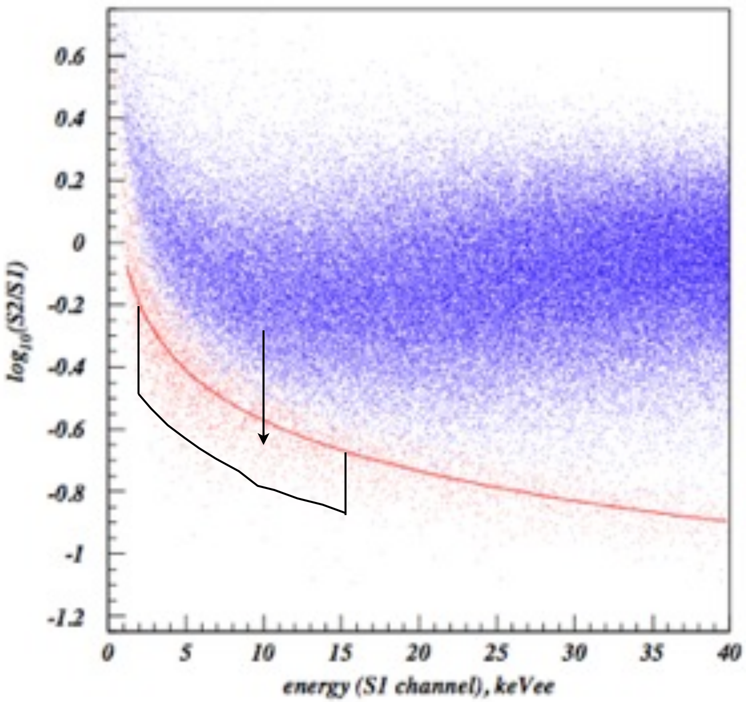


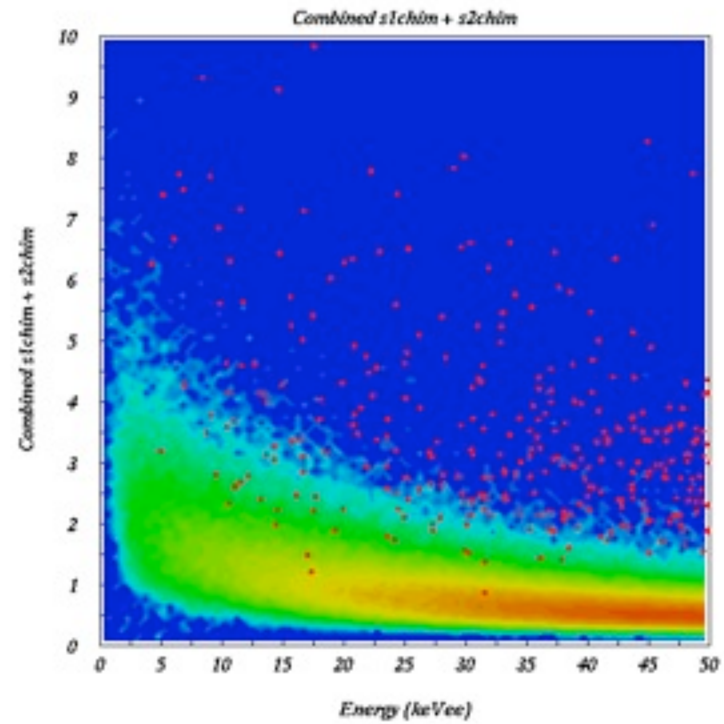
z: drift time (ns)

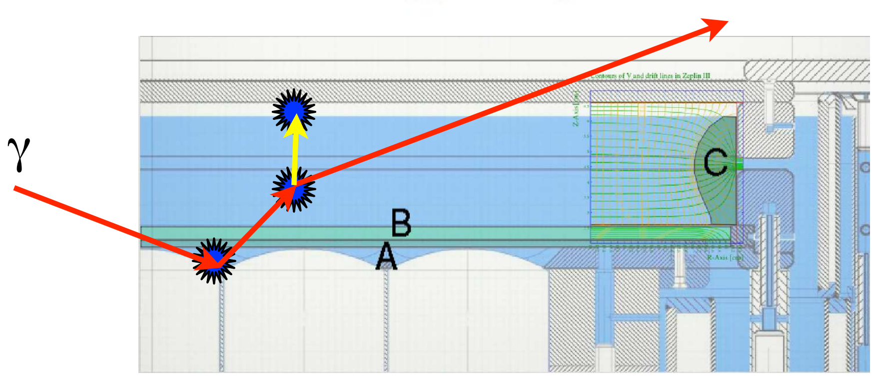


x V y (mm)

The Curse of the Living Dead

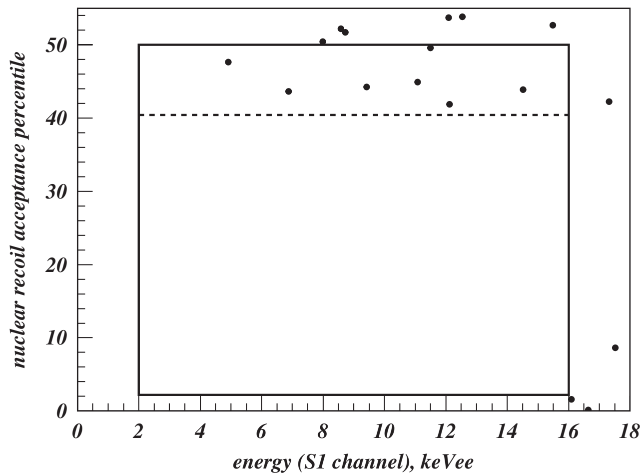


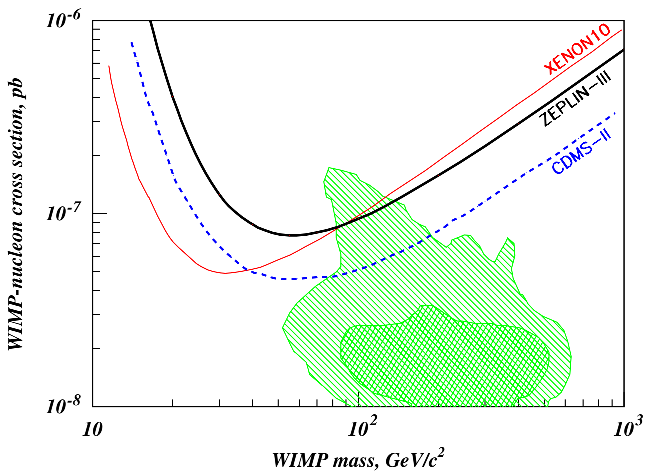




- Multiple scatters with partial energy in charge insensitive regions
- Chi^2 cut on energy reconstruction powerful, but not quite good enough

First Science Run Results





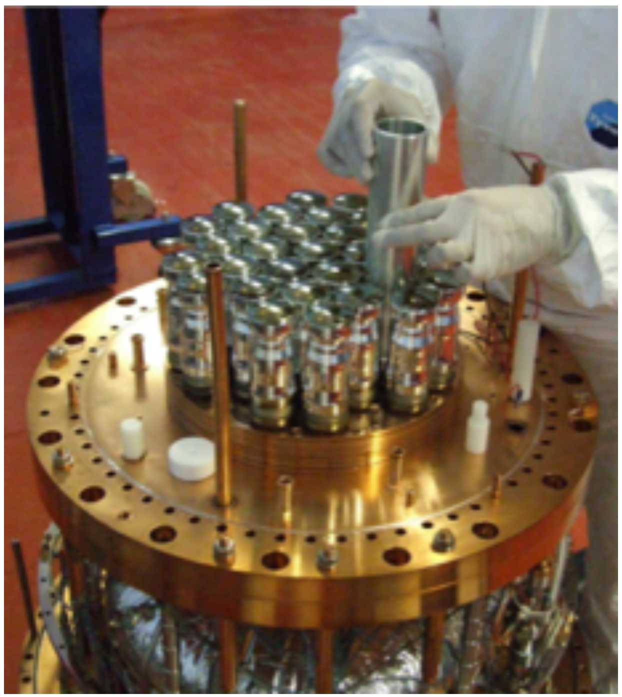
- Maximum patch analysis
  - events mapped to plane of S1, S2 signal acceptance with 80% boundary line
- 90% CL upper limit of 2.44 events from 80% box, 3.05 from full box

- **SI: $8.1*10^{-8}$ pb** @ 60 GeV/c^2, 90% C.L.

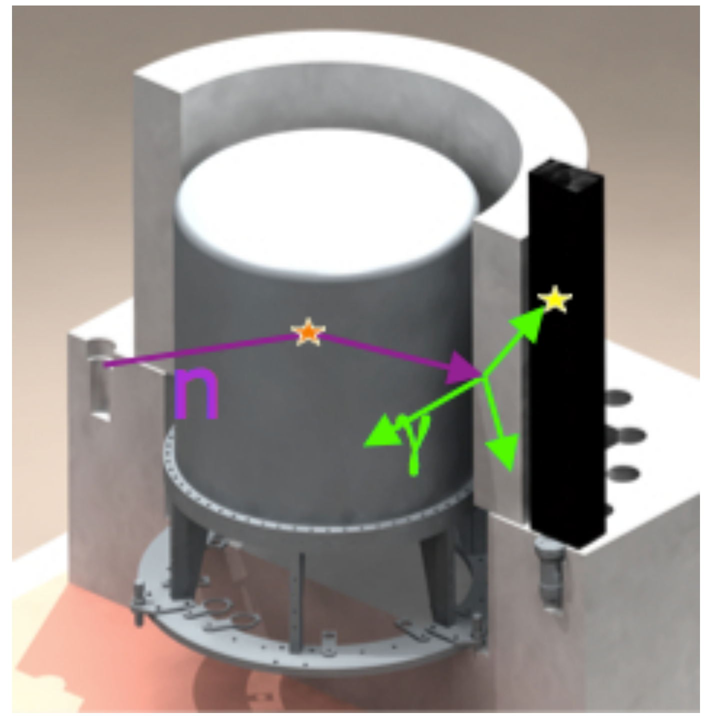
- **SD**: ^{129}Xe and ^{131}Xe (^{136}Xe depleted!)
  - **$\sigma_n < 1.8 \times 10^{-2}$ pb**
  - **$\sigma_p < 7.2 \times 10^{-1}$ pb**

The Second Science Run

31 Lower background PMTs



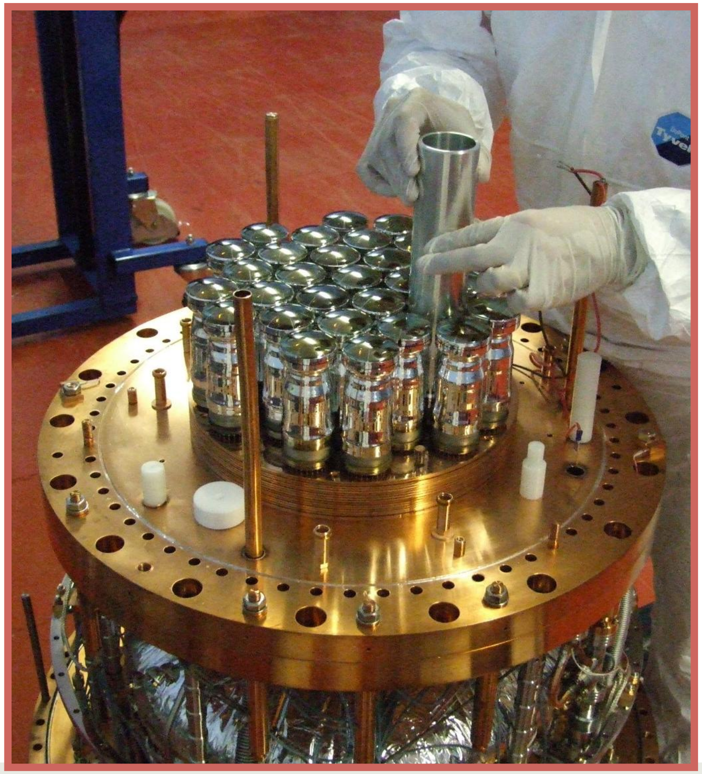
Active VETO detector



- Remote operations and complete automation to reduce systematics
- `Phantom grid' for improved position reconstruction and living dead rejection

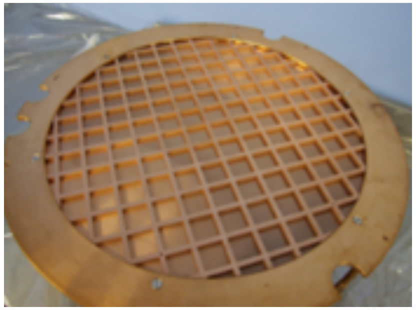
SSR Upgrades - PMTs

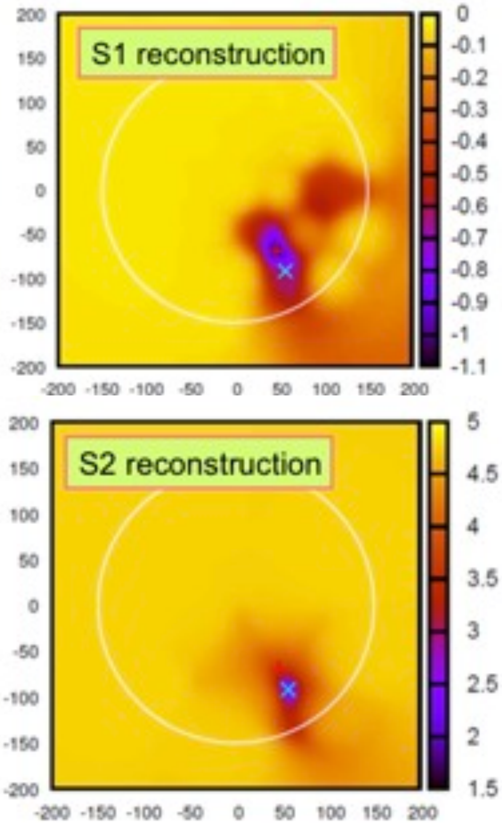
- PMT gamma-rays limited sensitivity of first run (10 d.r.u)
- Custom design for ultra low-background tubes, pin-by-pin compatible
- Aimed for >20x reduction in PMT radioactivity to <50 mBq/PMT; achieved 30mBq through dedicated screening and material selection with ETEL

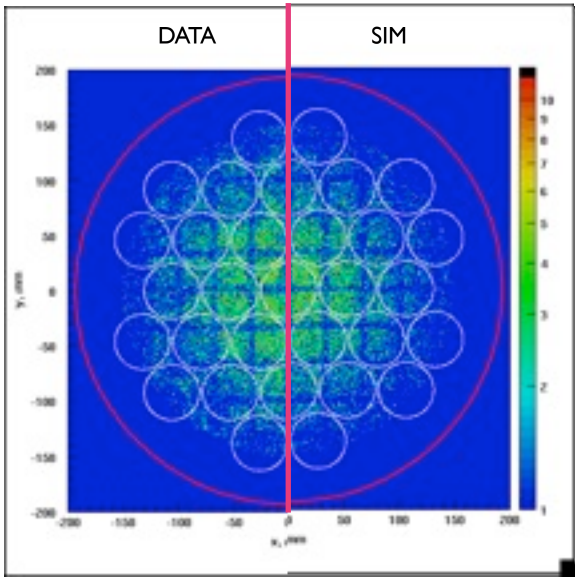


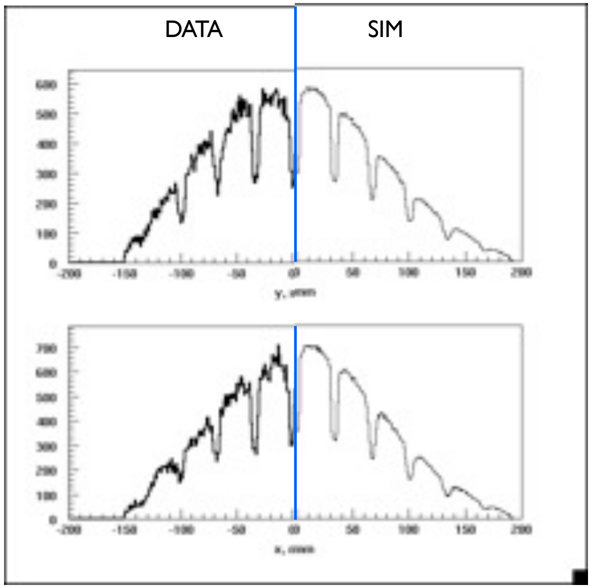
SSR Upgrades - Calibration

- Daily ^{57}Co calibration fully automated for reproducibility
- Weekly PMT calibration with fibre-coupled LED light gun
- Calibrated AmBe neutron source for new L_{eff} measurements
- New "phantom" grid added above anode plate and Development of spatial chi^2 maps in LS and ML reconstructions
- Automation of ancillary systems



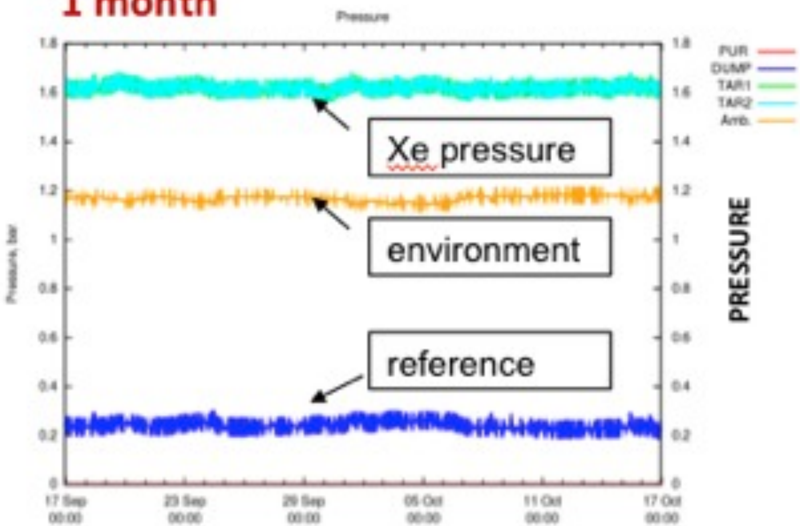


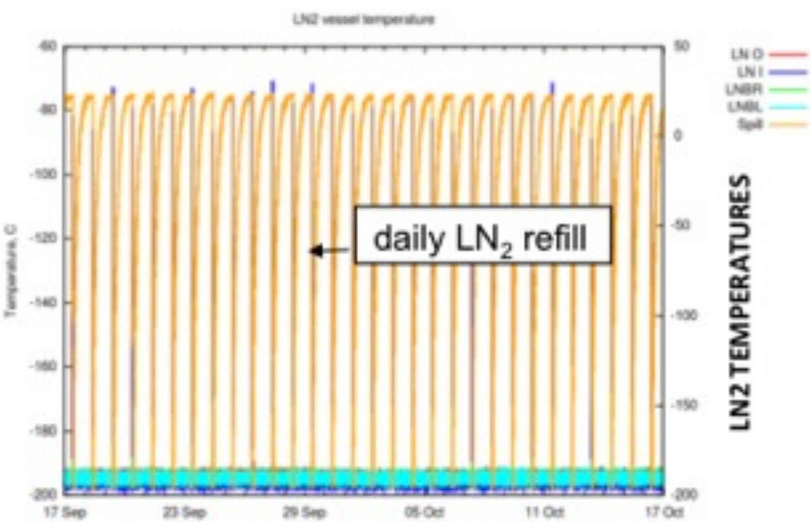




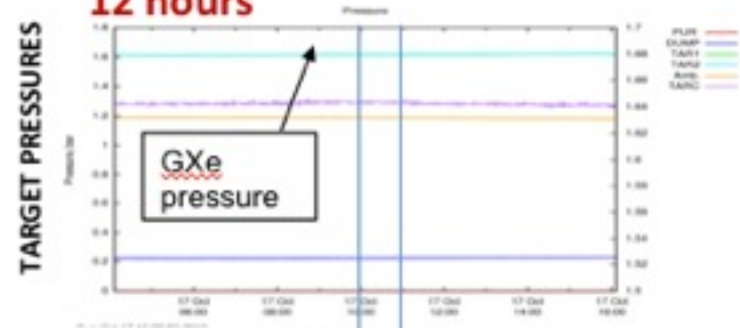
SSR Upgrades - Stability

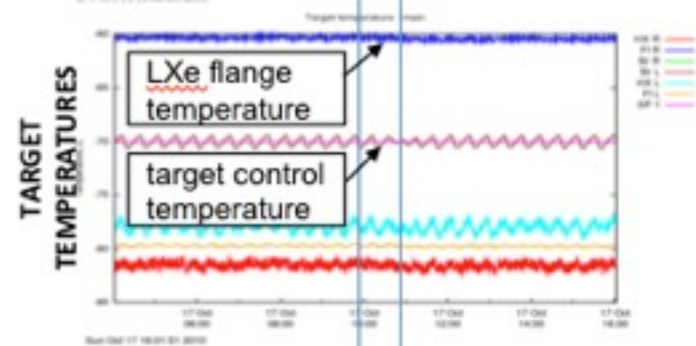
1 month

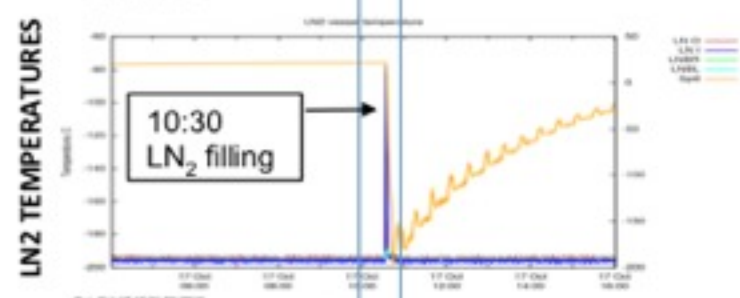


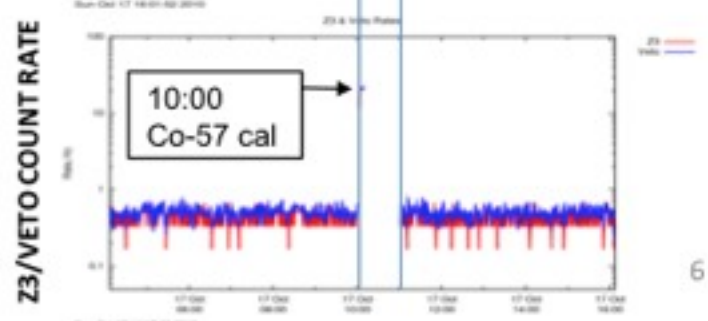


12 hours



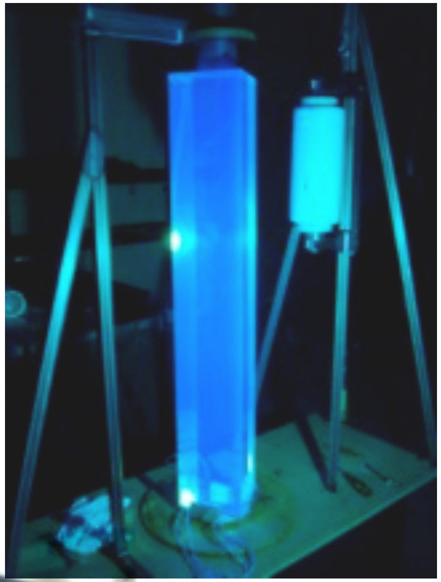


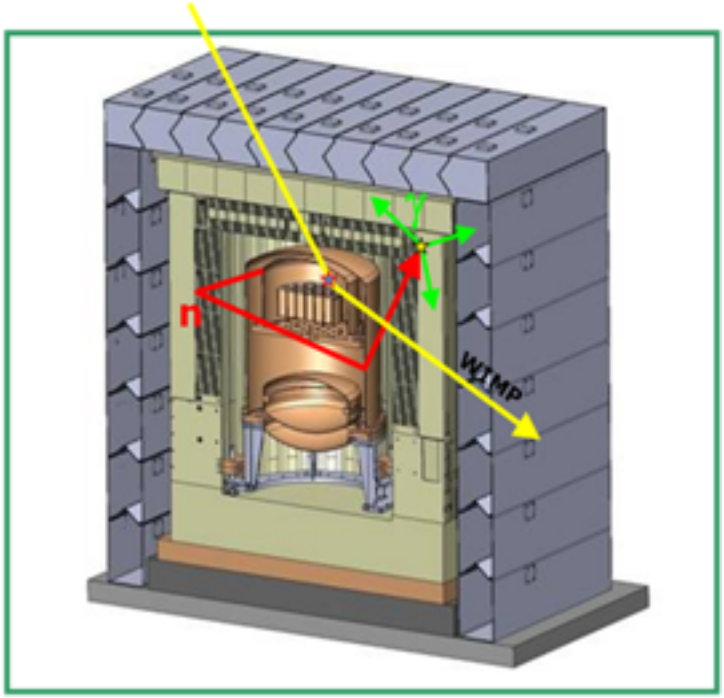


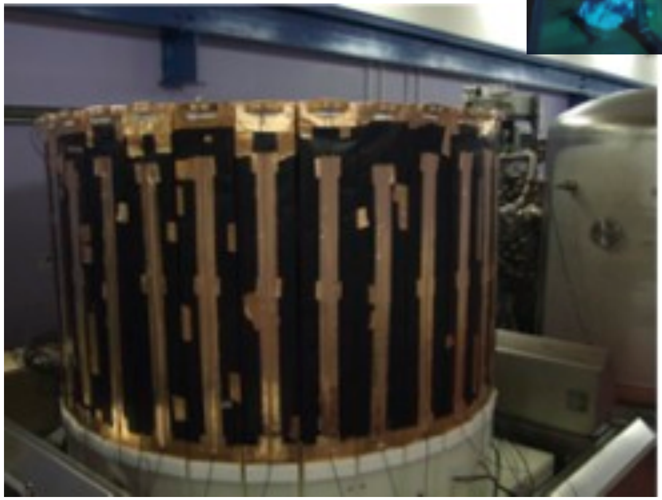


SSR Upgrades - Veto Detector

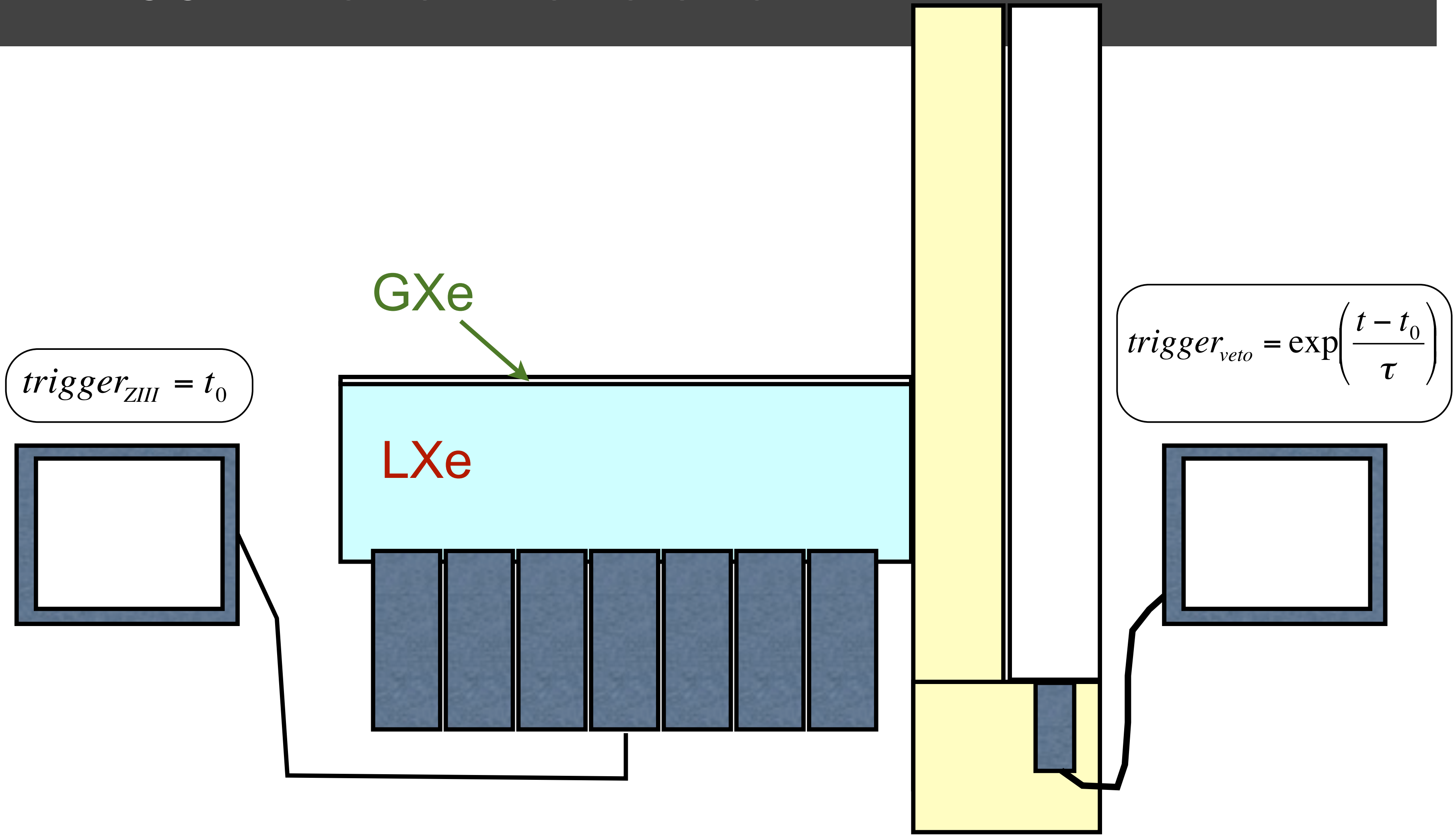
- WIMPs should not multiply scatter!
- 1 tonne plastic scintillator in 52 modules (UPS-923A)
- Scintillator 15cm thick, Gd loaded polypropylene 15cm thick
- Dedicated DAq and monitoring systems, automated calibration
- Radiation budget extremely low



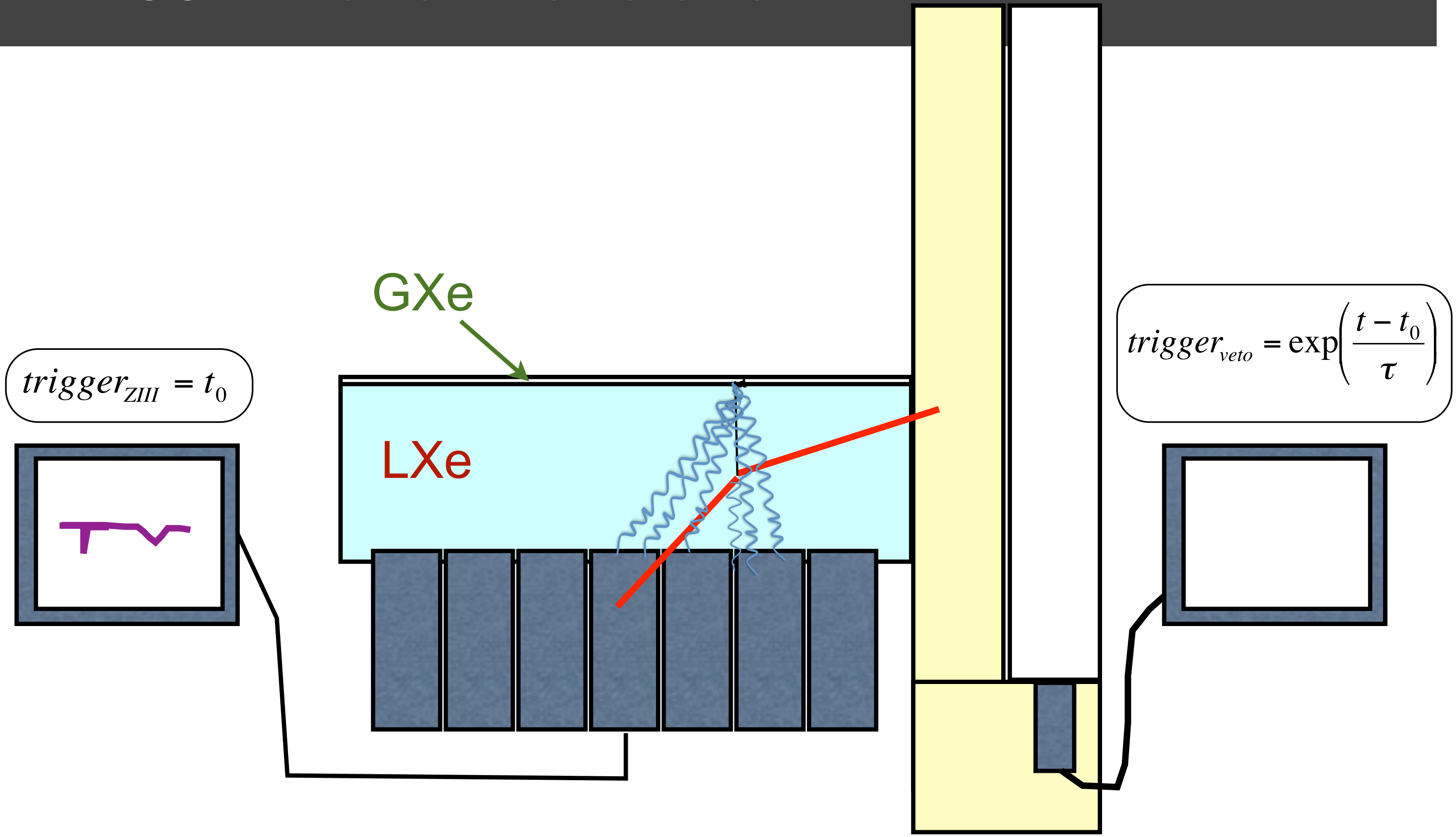




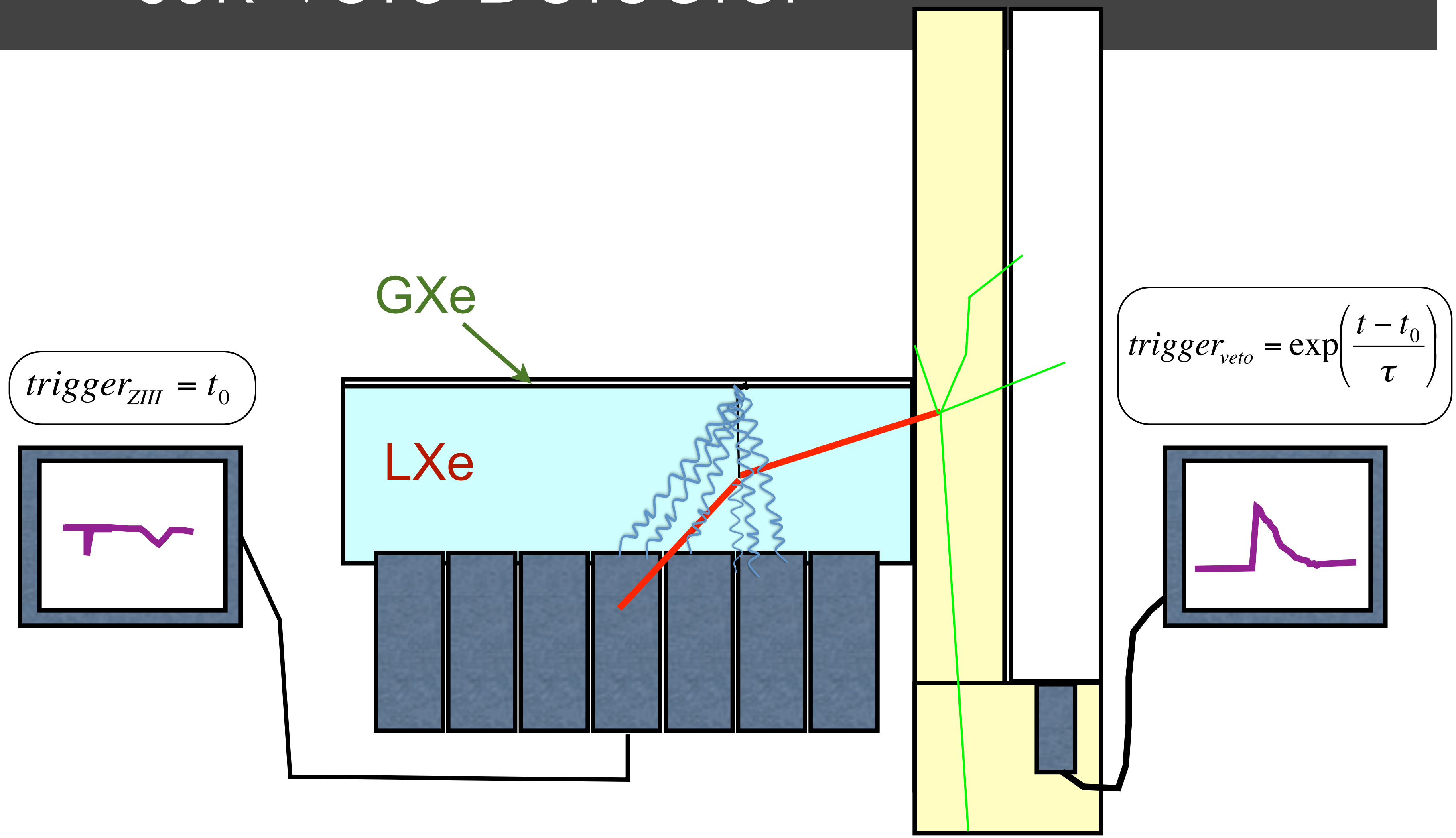
SSR Veto Detector



SSR Veto Detector

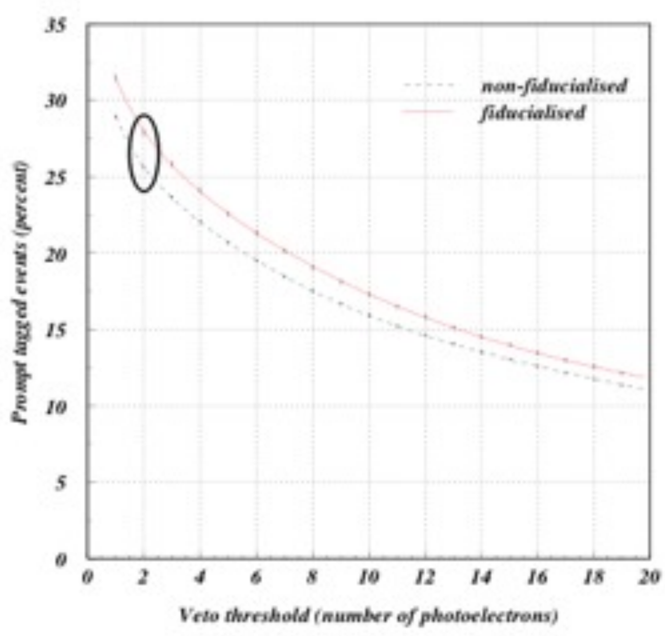


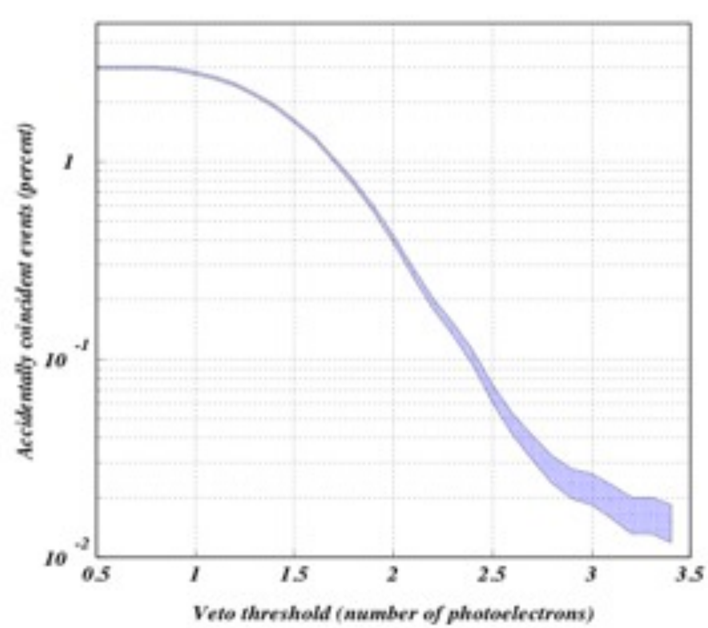
SSR Veto Detector



Veto Performance

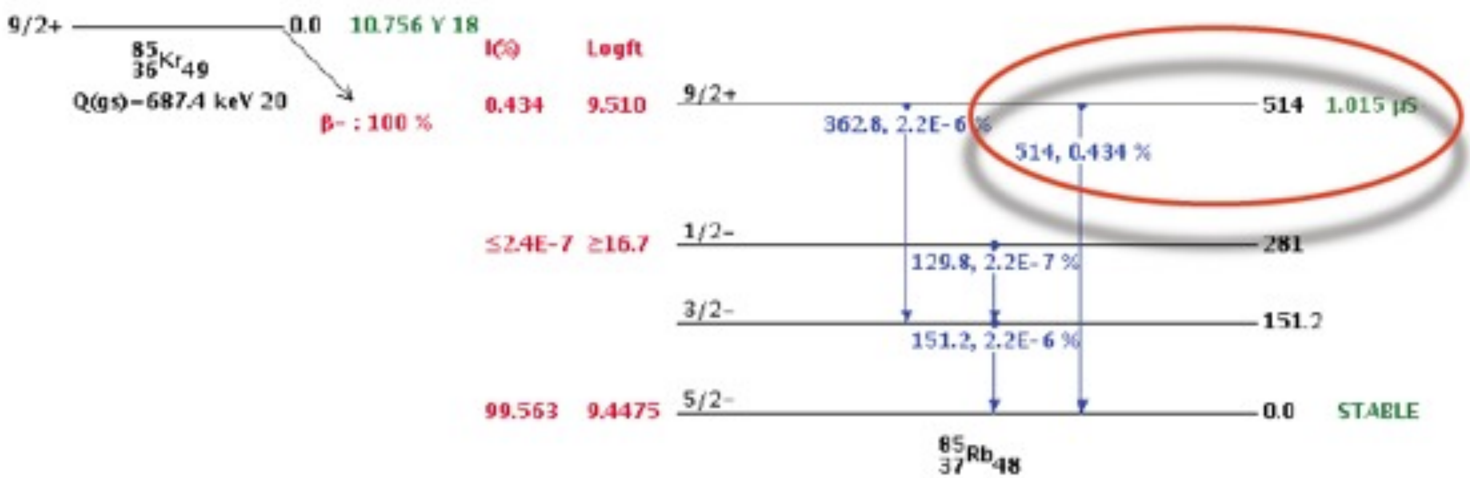
- 61% Neutron Tagging (59% 'delayed' tag + 2% 'prompt' tag)
  -> constant with recoil energy in LXe
- 0.8% accidental tagging for neutrons
- 28% gamma-ray tagging at 2p.e. veto threshold; <0.4% accidental tagging
- Allows (blind!) characterisation of background in WIMP search region with background in addition to calibration – **extremely useful!**



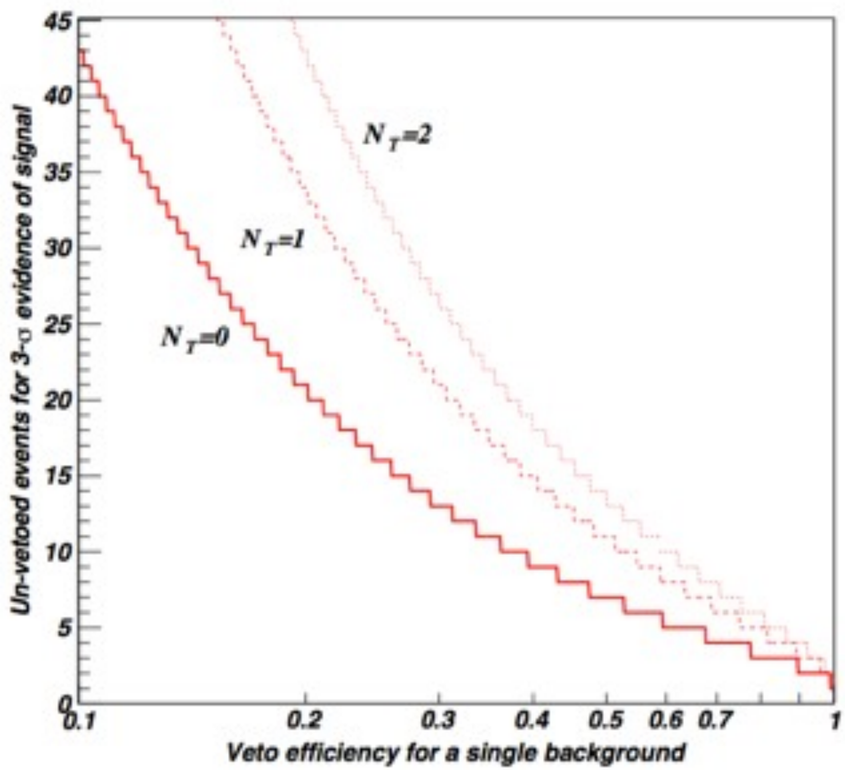


Veto Diagnostics - internal background

- ^{85}Kr measurements: indirect & direct - **150 ppt**
- Long timeline measurement of, for e.g., Bi-Po decays

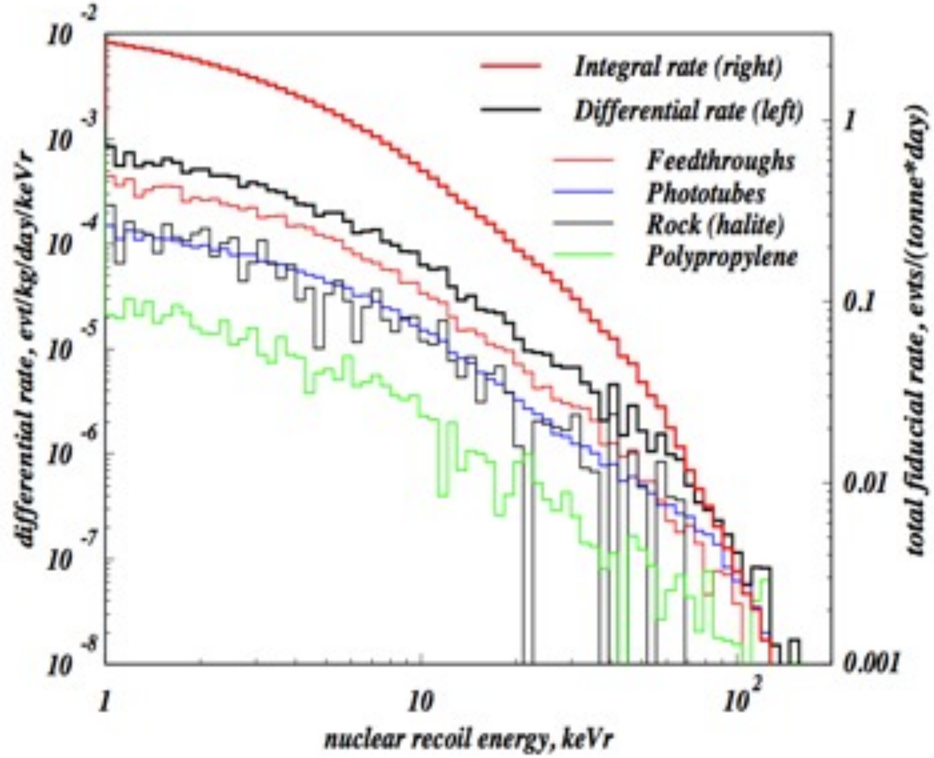


Implications for signal limits



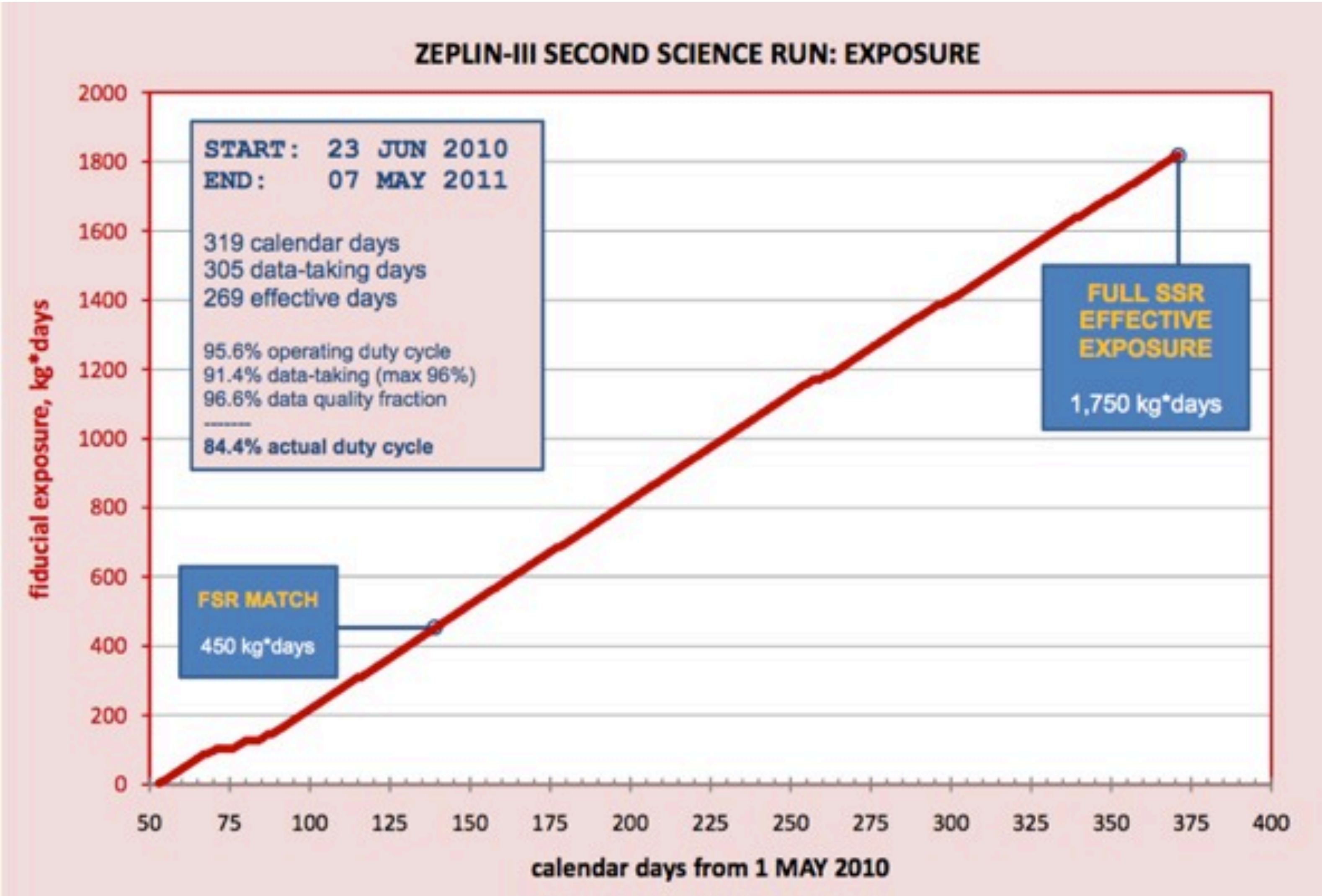
- Consider vetoed events as a measurement of the rate of un-vetoed background events with Poisson uncertainty
- Confidence interval for signal can be set using profile likelihood ratio

ZEPLIN-III Backgrounds

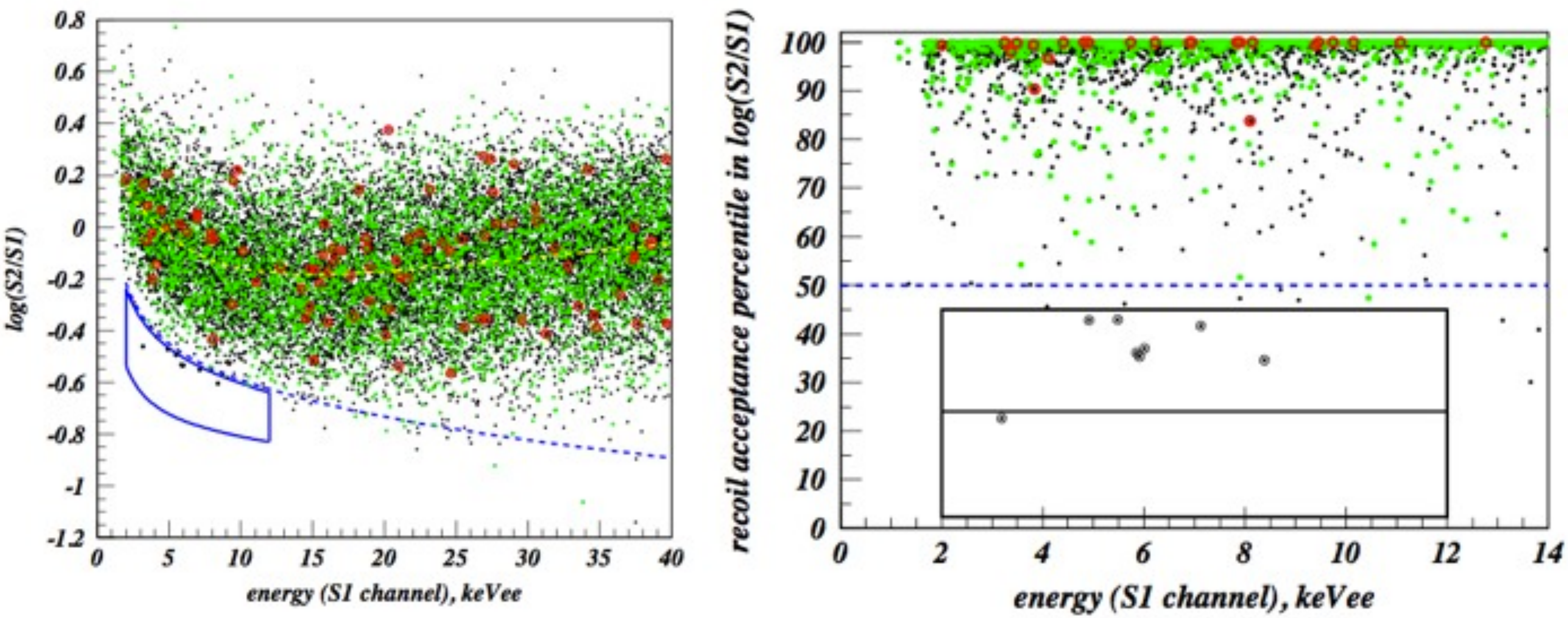


- 20-fold reduction in electron-recoil background to 0.75 dru as predicted
- 0.4 Hz trigger rate (stable for >1 year)
- Excellent background energy spectrum matching with Monte Carlo; 0.3 n/y expected
- Use veto tagging fractions from Monte Carlo to cross check component radioactivity

SSR Complete!

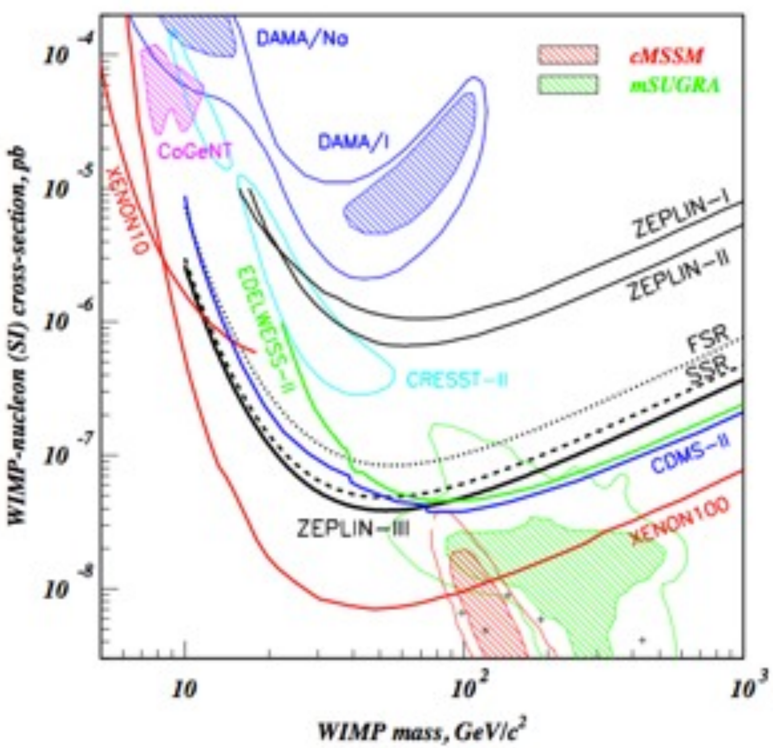


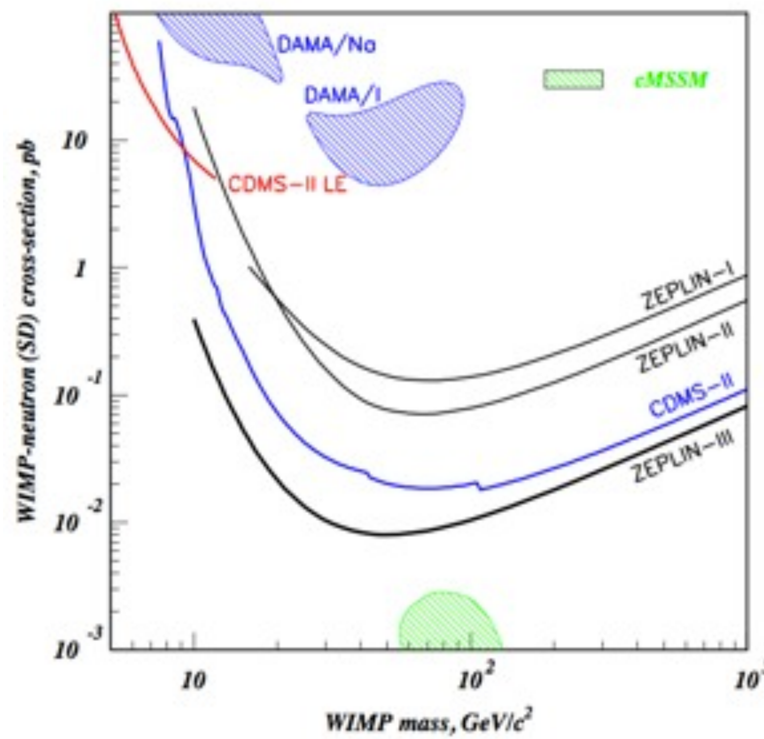
Final Results



- Background distribution, vetoed events in box, and calibration data used for background expectation
- Discrimination very seriously compromised by poor performance of SSR PMTs!
- No evidence of signal in excess of background expectation

ZEPLIN-III Final Results





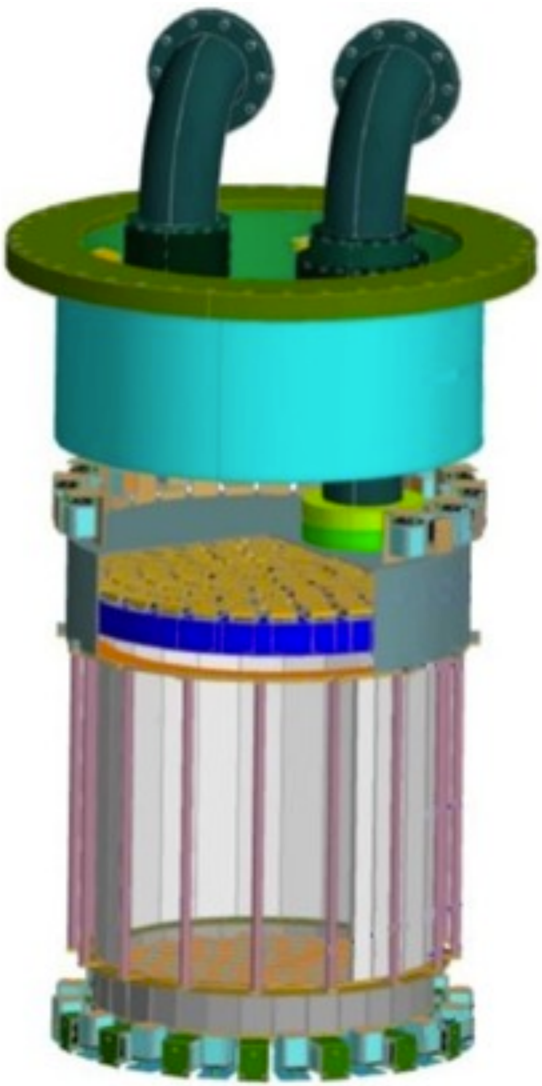
SI: $3.9*10^{-8}$ pb
@ 50 GeV/c^2, 90% C.L.

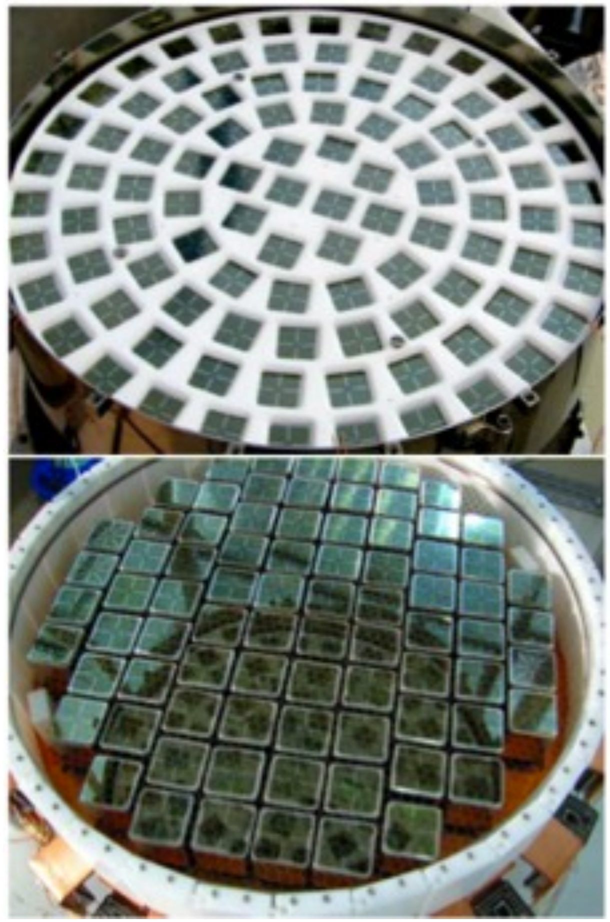
SD: $8.0*10^{-3}$ pb
@ 50 GeV/c^2, 90% C.L.

XENON100


Laboratori Nazionali del Gran Sasso
LNGS
LNGS: 1.4km rock
(3700 mwe)

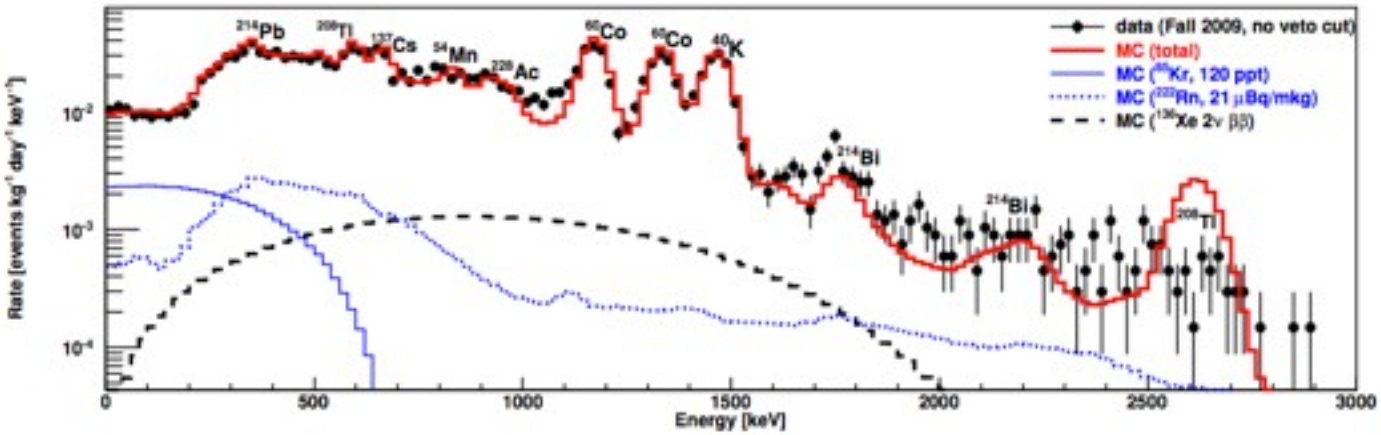
XENON100

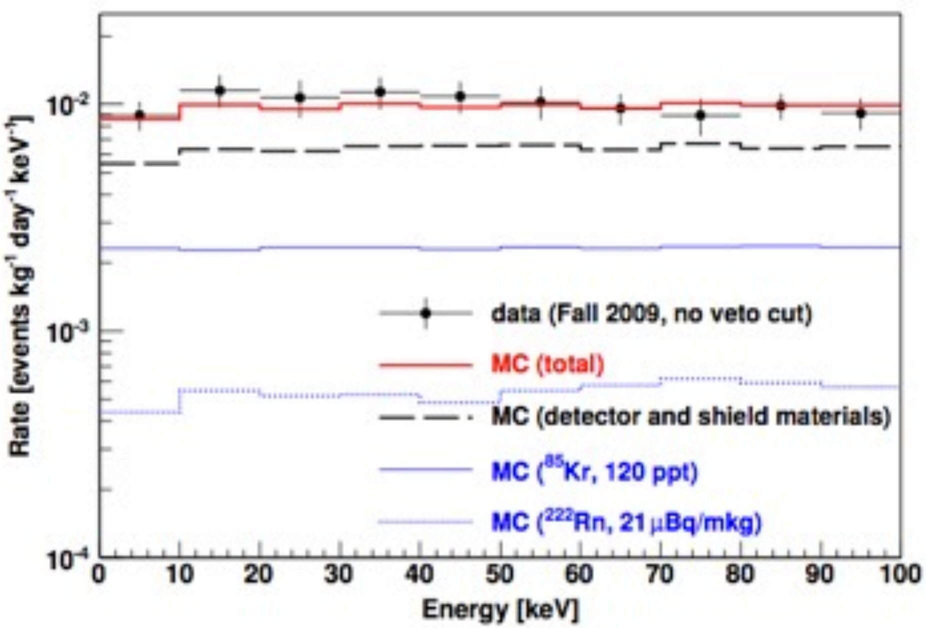




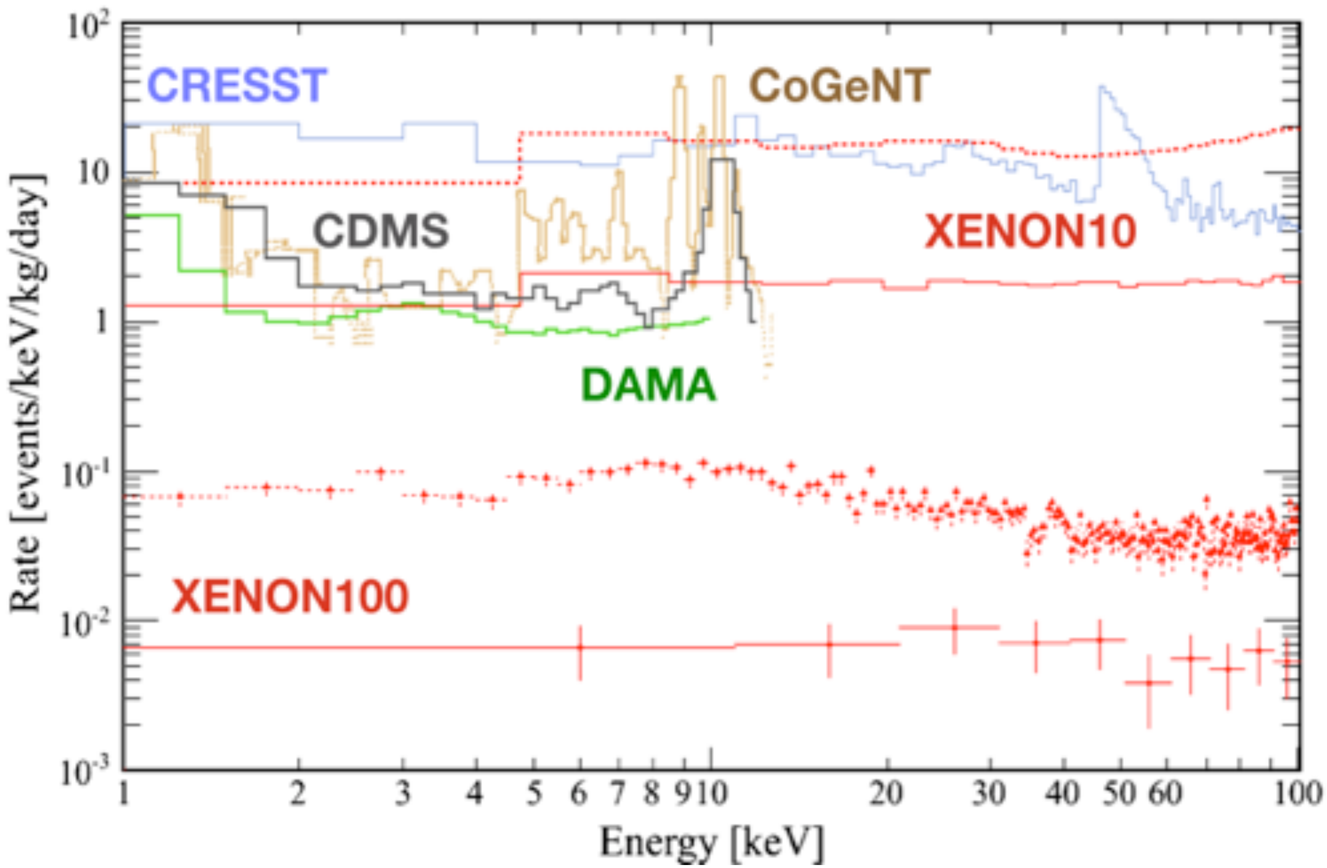
XENON100

XENON100 Background



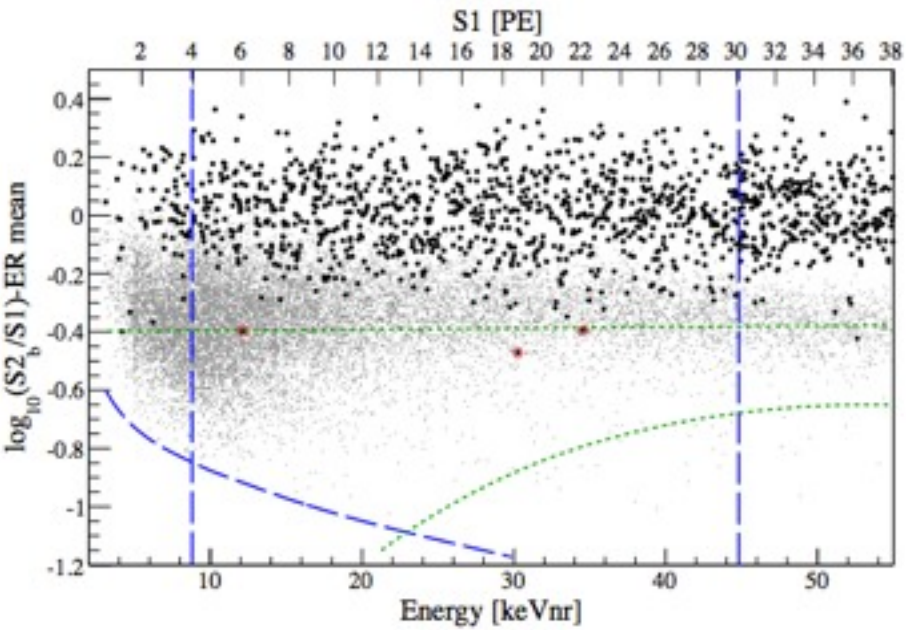


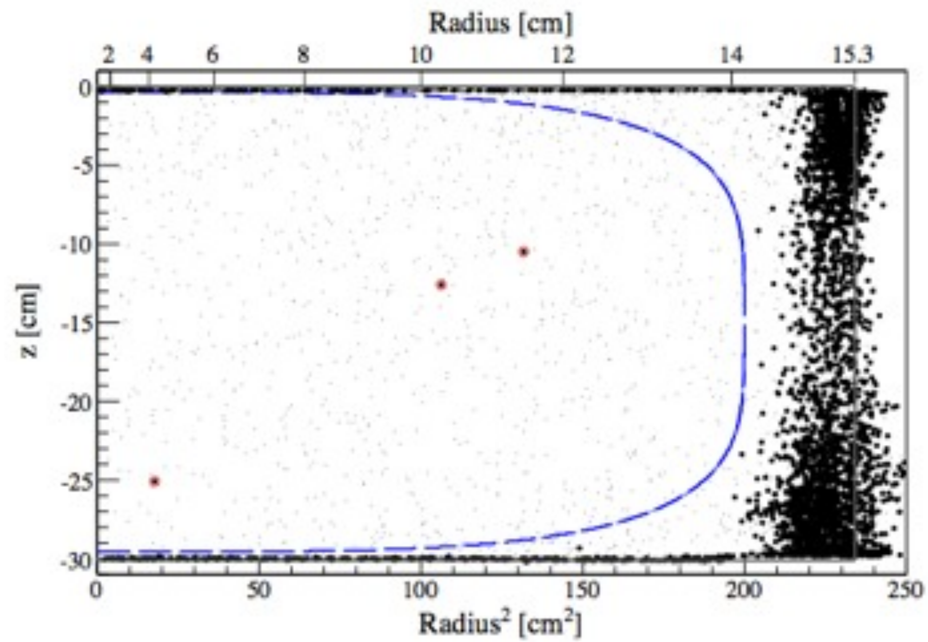
XENON100 Background



- Powerful self-shielding and position reconstruction of LXe TPCs
- Event rate orders of magnitude lower than XENON10 predecessor

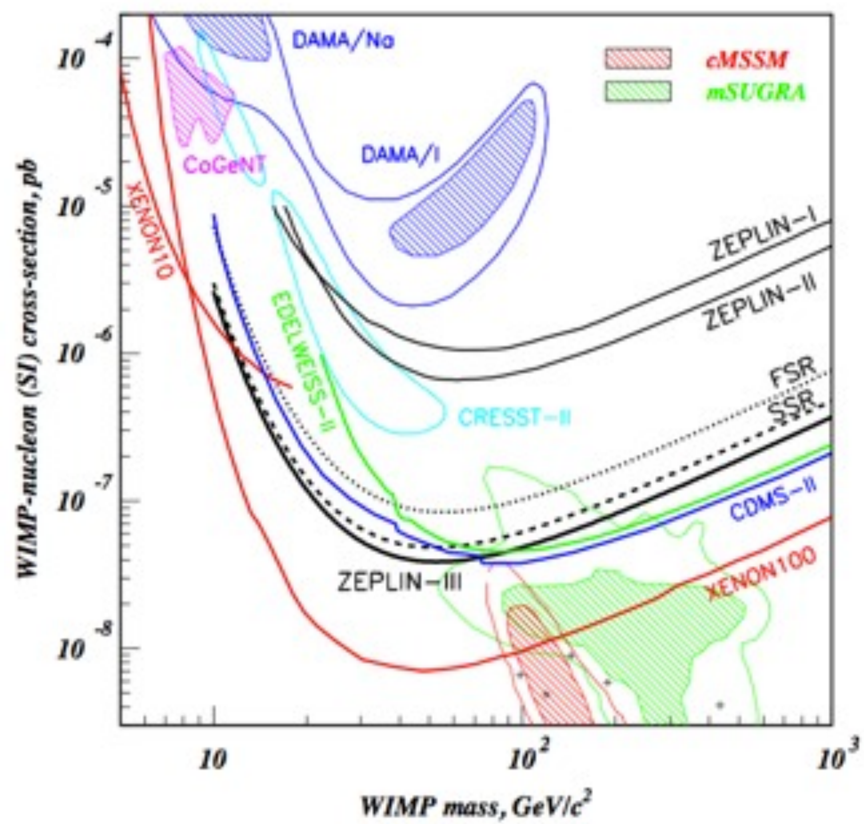
XENON100 Results





- 100.9 day exposure
- Three events observes with 1.8+/-0.6 expected
- No evidence of signal, 200 day run with lower Kr background ongoing

XENON100 Results

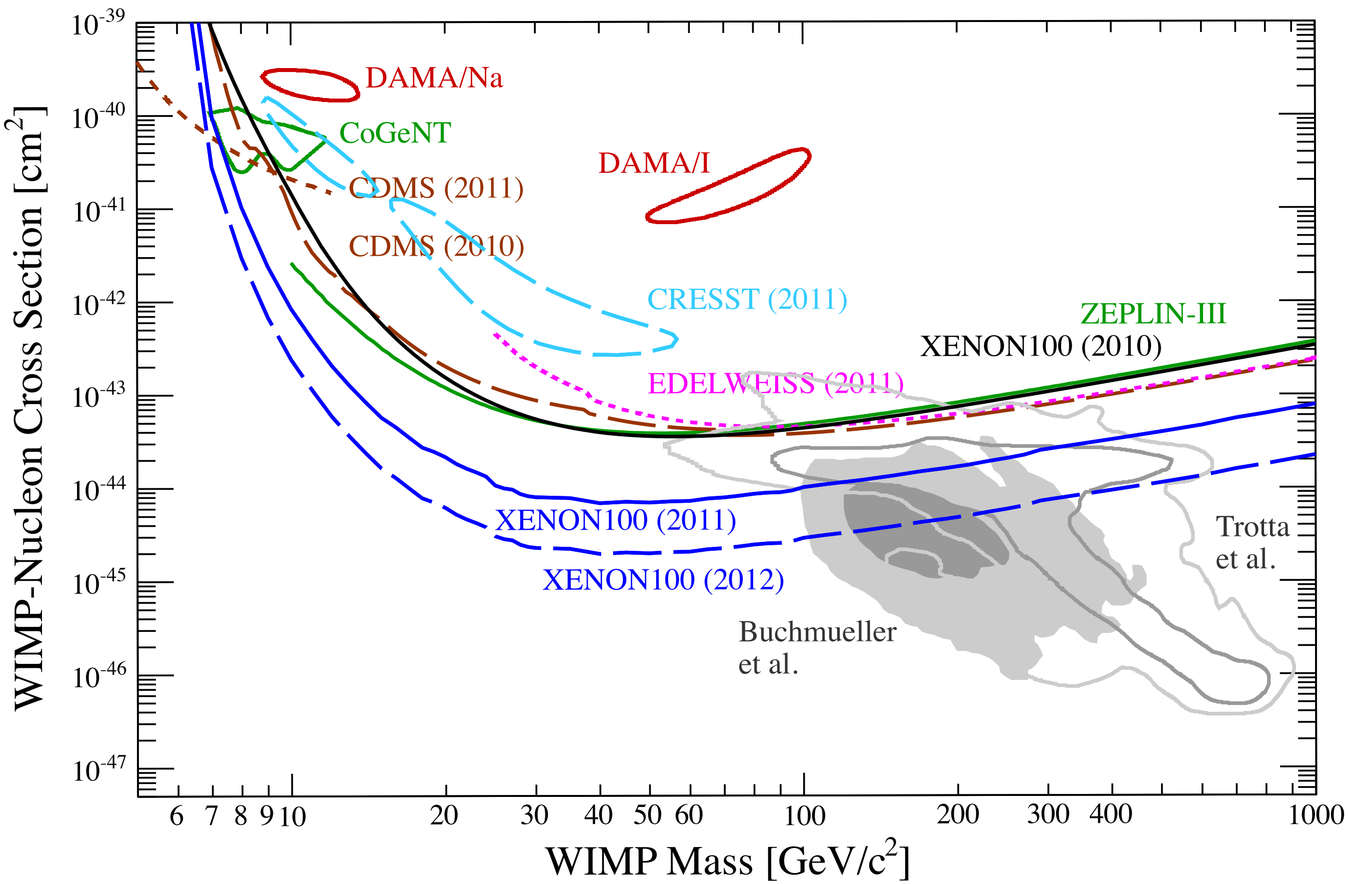


- WIMP-nucleon cross sections above $7\text{x}10^{-8}$ cm^2 at 50 GeV/c^2 excluded
- Ongoing exposure aims to achieve sensitivity of 2×10^{-8}cm^2

Next Generation Detectors

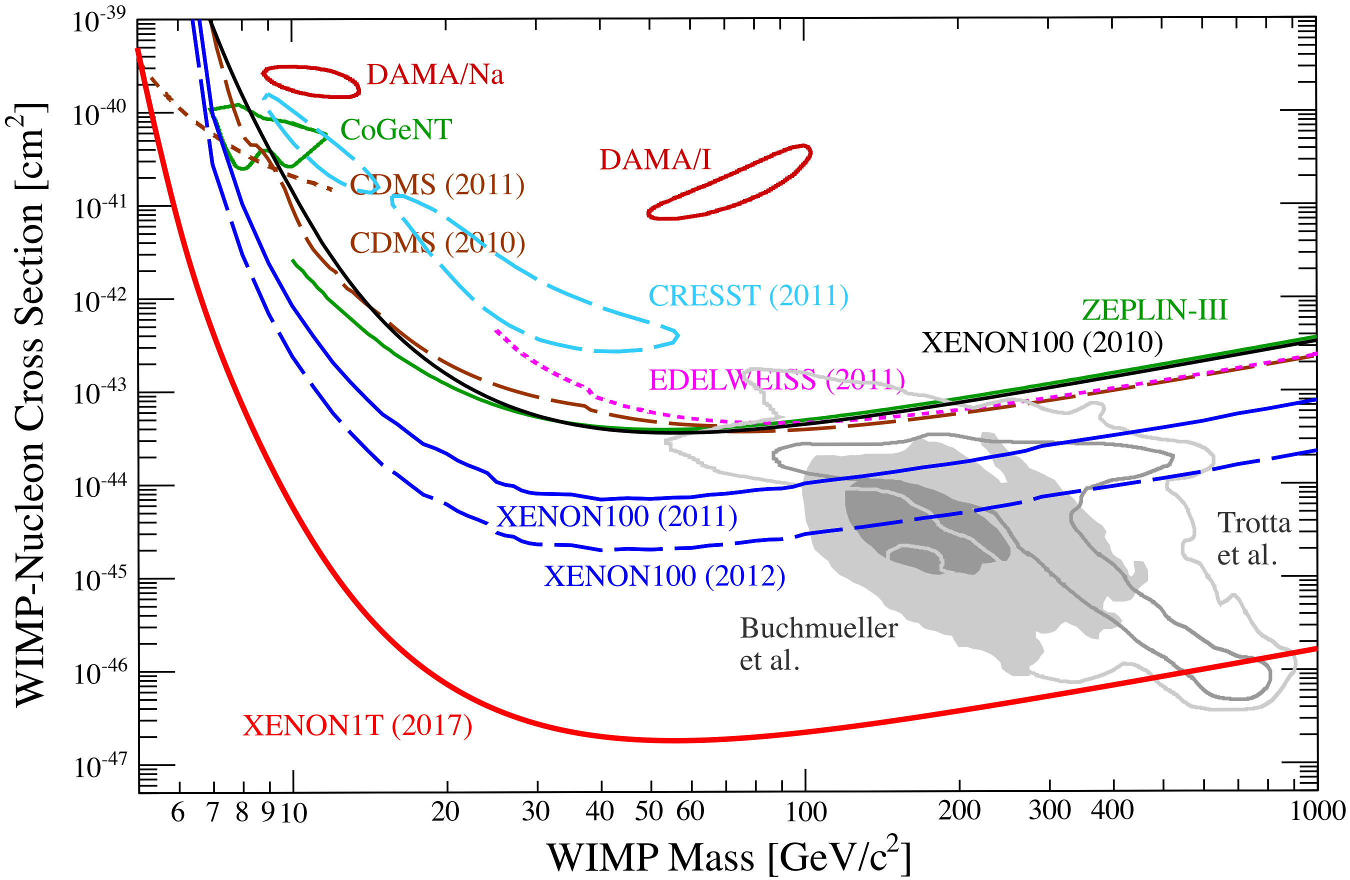
- Current generation experiments beginning to explore promising region of EW scale physics
- LXe detectors are leading the way!
- Demonstrated scaleability with orders of magnitude increases in sensitivity
- BUT - current generation (all - not just LXe) are also approaching limits of sensitivity
- Next generation (G2) detector required!
- LXe TPCs have dramatically accelerated the race for WIMPs and offer the most promising prospects for a discovery
- Ton-scale G2 LXe detector could exclude the bulk of the current favoured parameter space!

XENON1T



DAMA/Na
CoGeNT
DAMA/I
CDMS (2011)
CDMS (2010)
CRESST (2011)
ZEPLIN-III
XENON100 (2010)
EDELWEISS (2011)
XENON100 (2011)
XENON100 (2012)
Trotta et al.
Buchmueller et al.
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
6 7 8 9 10 20 30 40 50 60 100 200 300 400 1000

XENON1T



DAMA/Na
CoGeNT
DAMA/I
CDMS (2011)
CDMS (2010)
CRESST (2011)
ZEPLIN-III
XENON100 (2010)
EDELWEISS (2011)
XENON100 (2011)
XENON100 (2012)
Trotta et al.
Buchmueller et al.
XENON1T (2017)
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
6 7 8 9 10 20 30 40 50 60 100 200 300 400 1000

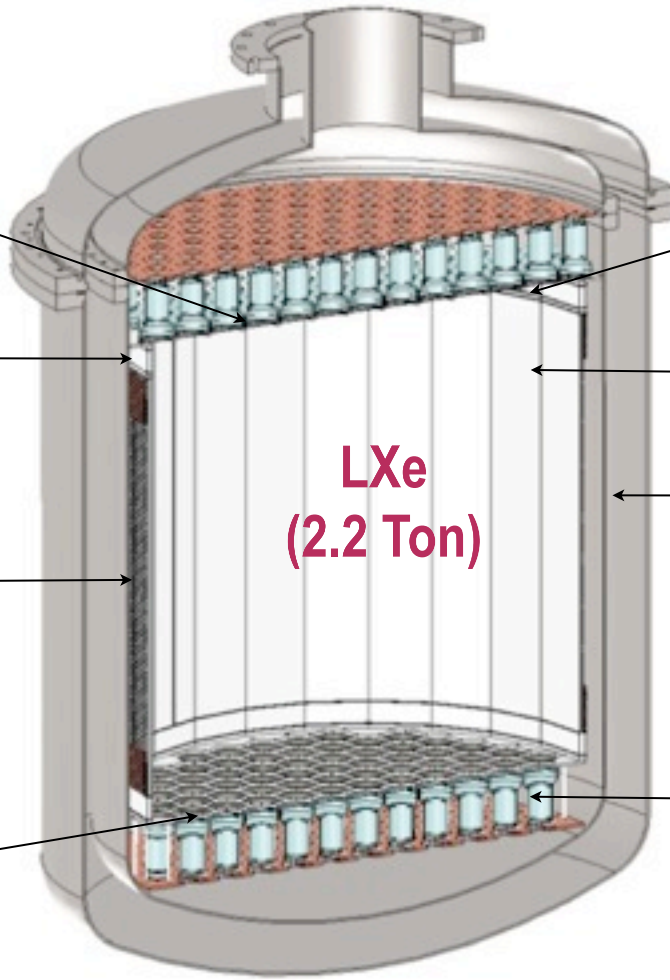
XENON1T - Cryostat and TPC

High transparency electrodes

Active LXe veto

1 kV/cm drift field with external field shaping rings

No charge insensitive regions below photocathode



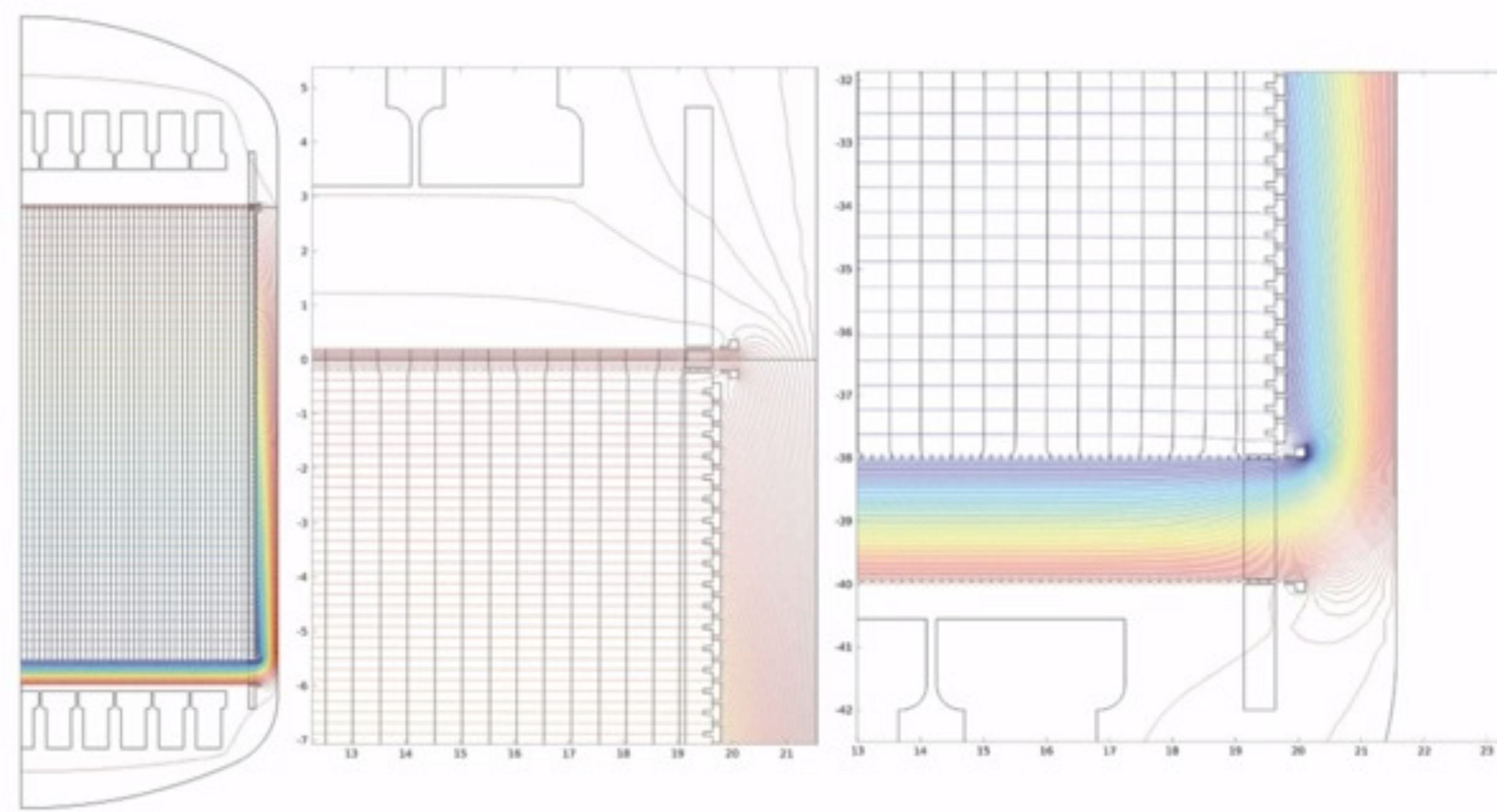
No top array screening mesh

Three interlocking PTFE panels

Titanium cryostat and vacuum jacket

2 arrays of 121 high QE 3″ photodetectors

XENON1T - E-field simulations

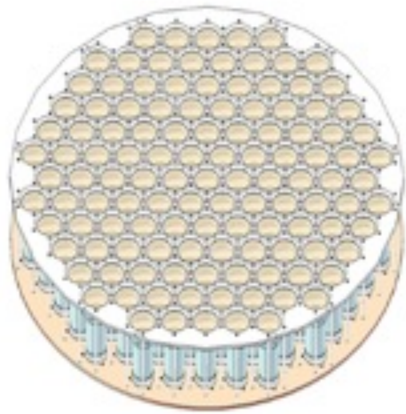


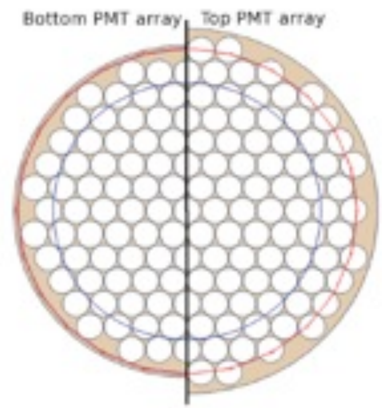
Uniformity in the drift region is key to position reconstruction and multiple scatter rejection, and fiducial volume definition

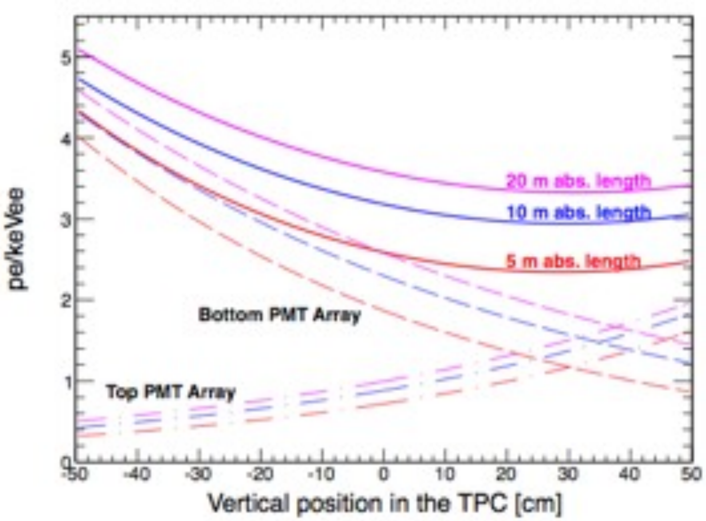
XENON1T is designed for uniformity out to the TPC walls with optimized Cu shaping rings and resistor chain configuration, with ~95% transparent electrodes

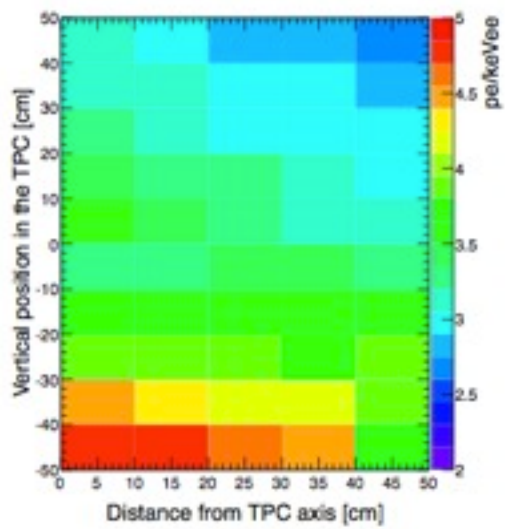
XENON1T - Photodetector Configuration

- PMTs are densely packed in both top and bottom arrays
- Charge insensitive regions optically decoupled to remove living dead events
- Modular PTFE reflectors obscure all surfaces bar photocathode



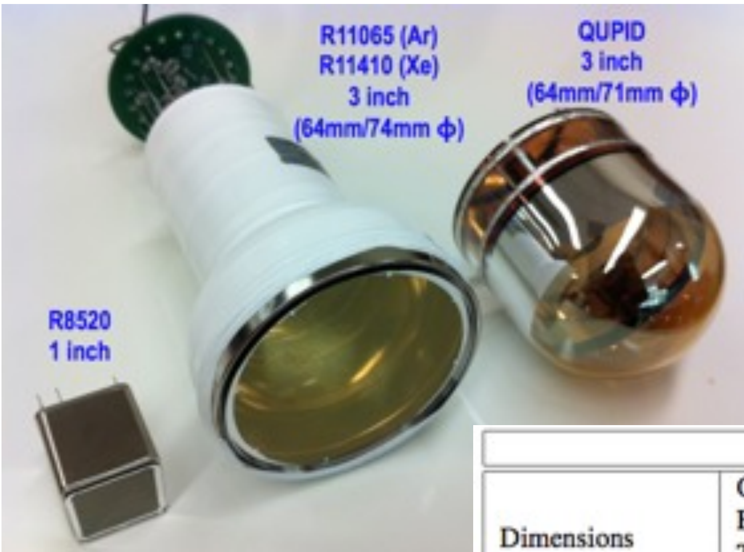






- Light collection efficiency vastly improved relative to XENON100
- Light yield is greater than XENON100 despite larger size
- Energy threshold will be lower than XENON100

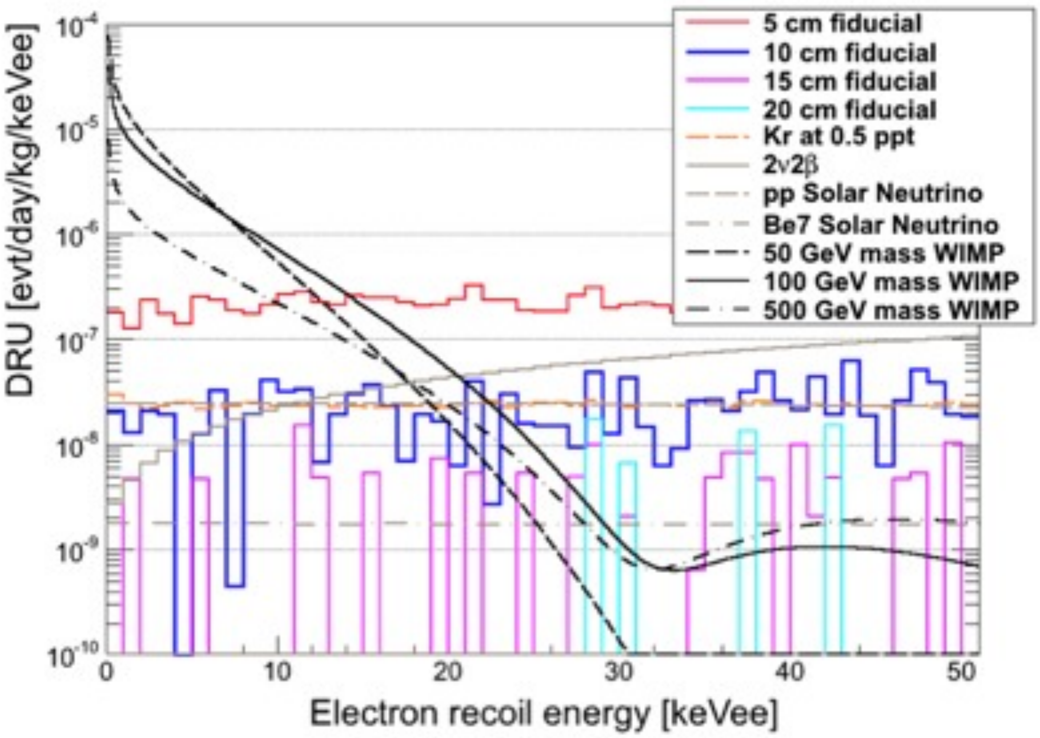
XENON1T - Photodetectors

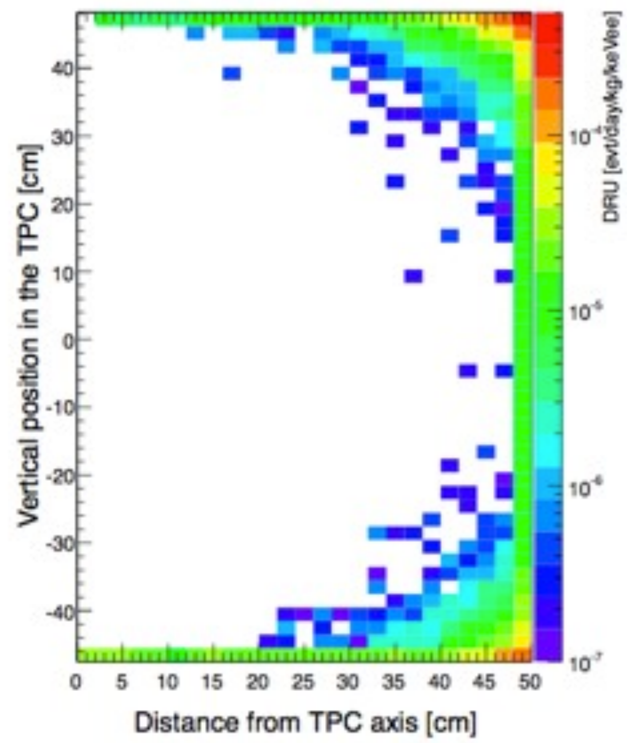


- Choosing the correct photodetector is crucial!
- Development of QUPIDs and improvements in R11410 PMT ongoing at UCLA in partnership with Hamamatsu
- Although higher background, sensitivity goals of XENON1T satisfied with R11410

		R8520		R11410		QUPID	
Dimensions	Outer Diameter	25.7 mm		76 mm		71 mm	
	Eff. Photocathode Diameter	21 mm		64 mm		64 mm	
	Total Height	29 mm		123 mm		76 mm	
Radioactivity	^{238}U	0.25 mBq		3.3 mBq		0.39 mBq	
	^{232}Th	0.46 mBq		2.3 mBq		0.23 mBq	
	^{40}K	8.15 mBq		5.7 mBq		6 mBq	
	^{60}Co	0.75 mBq		9.1 mBq		0.15 mBq	
Performance		$25°C$	$-100°C$	$25°C$	$-100°C$	$25°C$	$-100°C$
Photocathode	Material	Bialkali		Bialkali-LT		Bialkali-LT	
	QE at 178 nm	30%	-	35%	-	35%	-
	Linearity	-	-	1 μA	50 nA	>10 μA	>1 μA
Anode Output	Typical Total Gain	2×10^6		5×10^6		1.5×10^5	
	Maximum Total Gain	5×10^6		1×10^7		2.4×10^5	
	Linearity	10 mA		50 mA		3 mA	
Timing Properties	Rise Time	1.9±0.2 ns		4.2±1.1 ns		1.8±0.1 ns	
	Fall Time	2.9±0.2 ns		10.0±1.0 ns		2.5±0.2 ns	
	Pulse Width	4.4±0.1 ns		8.0±0.6 ns		4.20±0.05 ns	
	Transit Time Spread	1.1±0.1 ns		7.4±0.5 ns		160±30 ps	

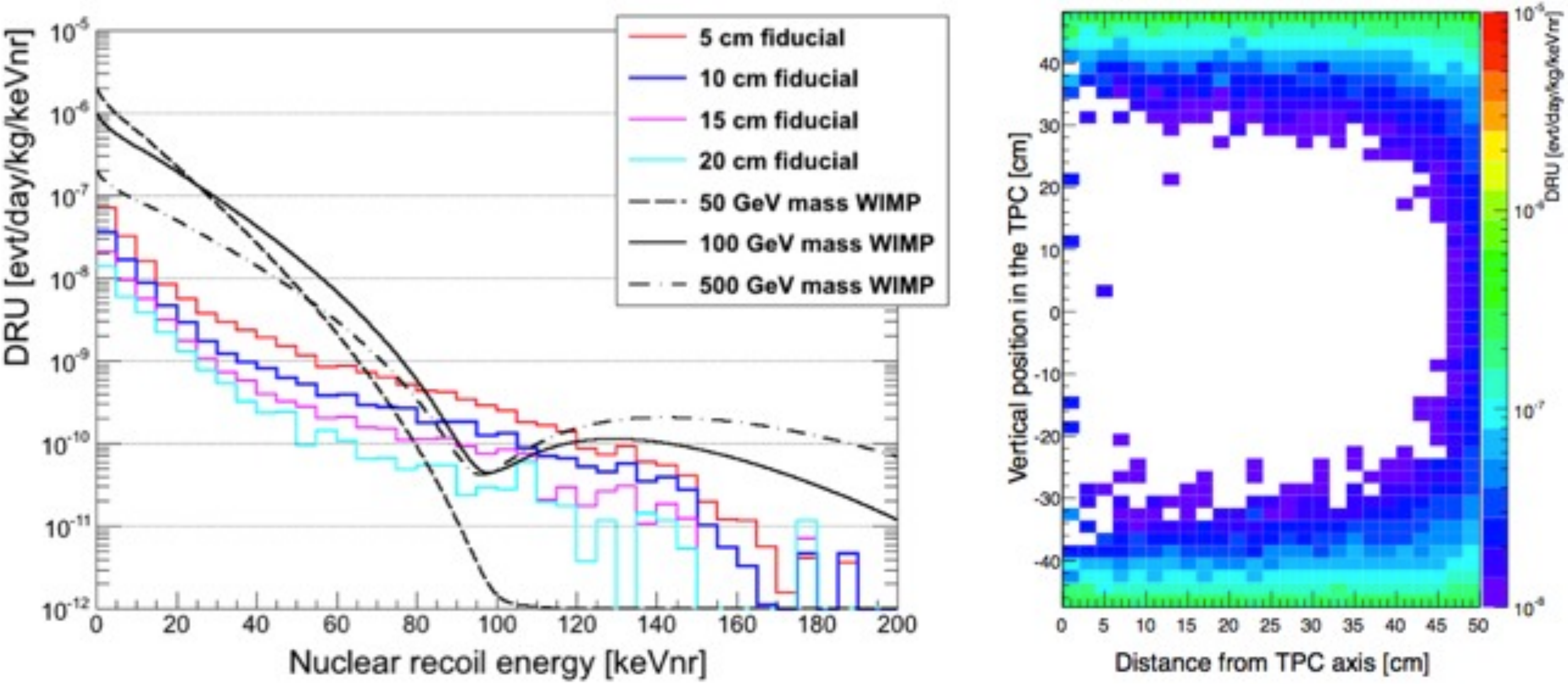
XENON1T - ER Backgrounds





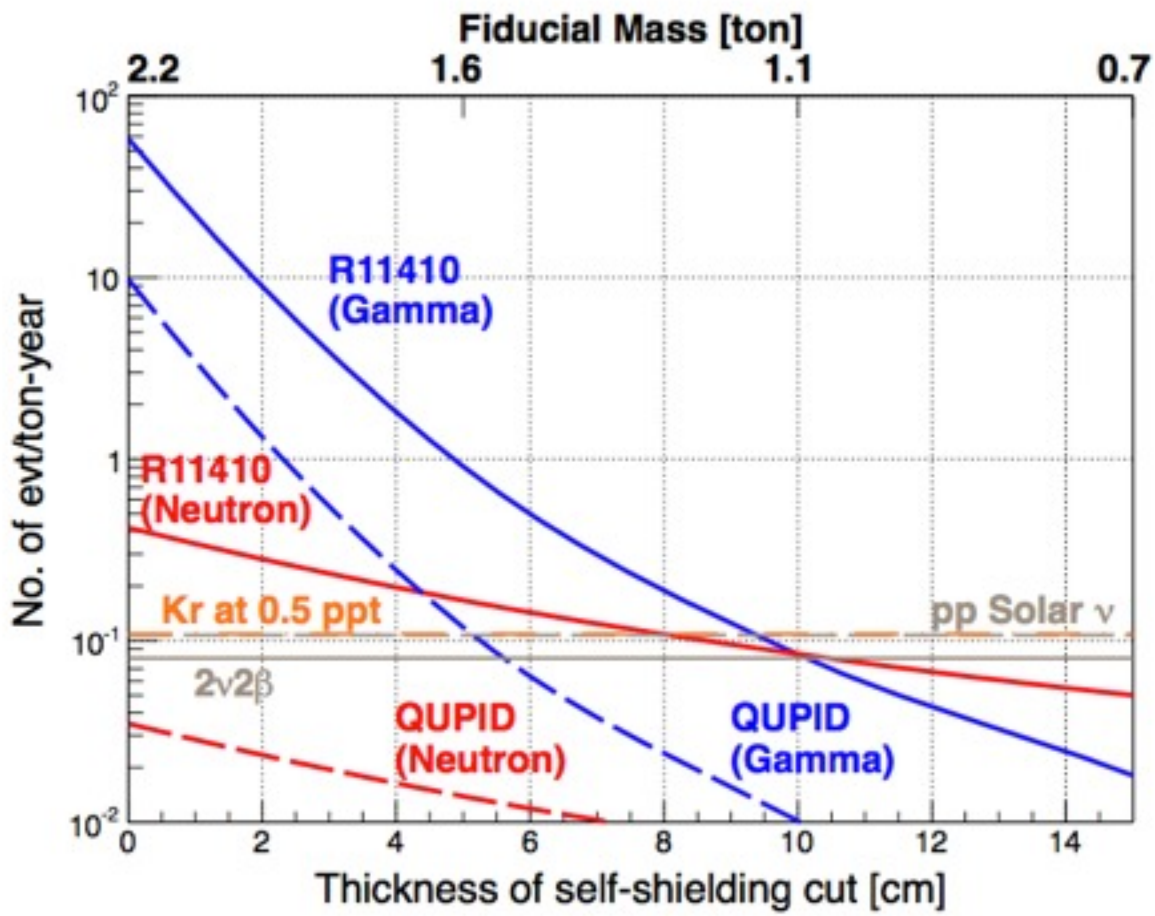
Single scatter events with 99.75% discrimination, WIMP-nucleon interaction cross-section at 10^{-46}cm^2

XENON1T - NR Backgrounds



Single scatter events with 99.75% discrimination, WIMP-nucleon interaction cross-section at 10^{46}cm^2

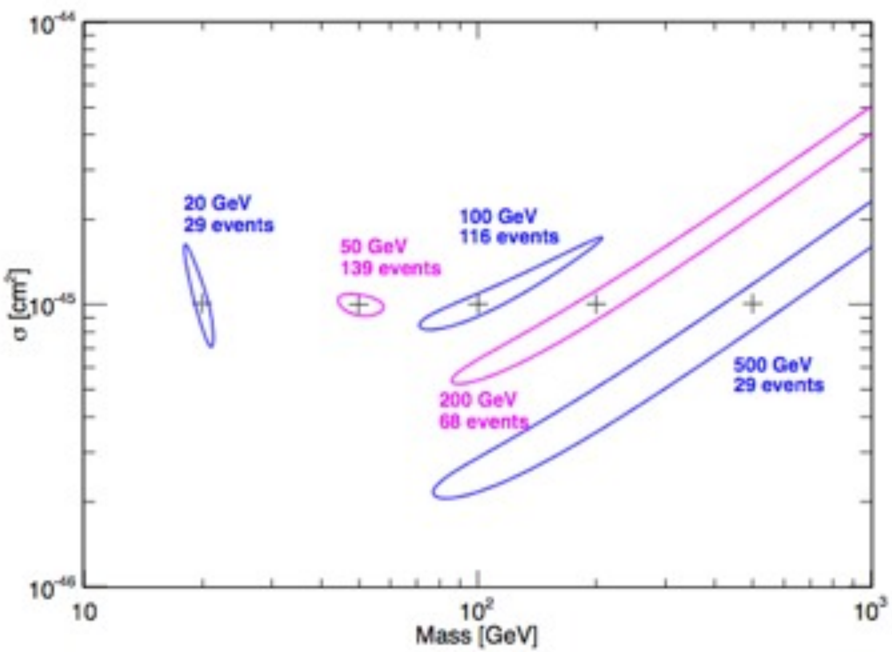
XENON1T - Self-shielding



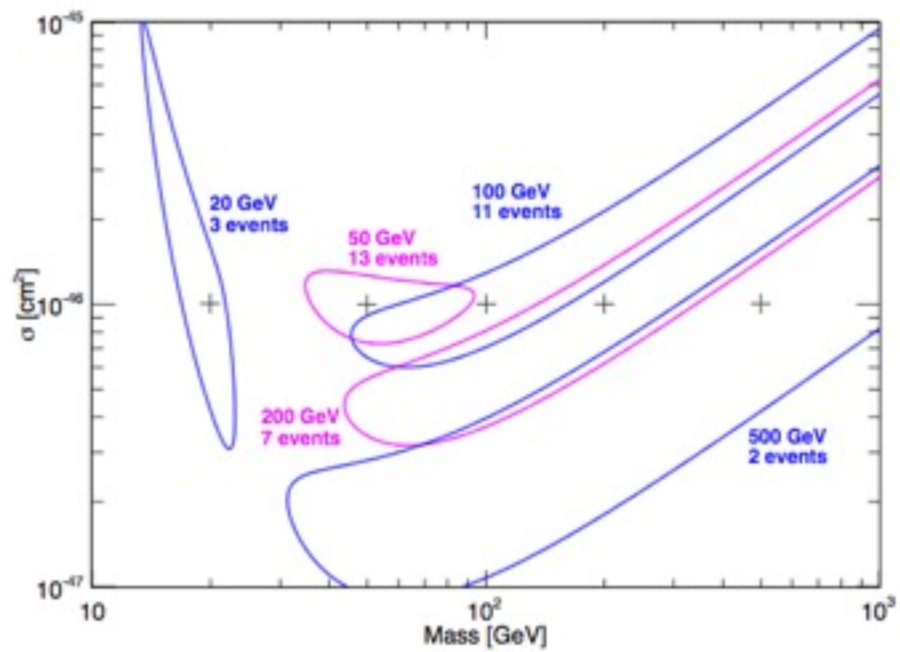
XENON1T - WIMP Detection

For 2 years livetime with 10cm self shielding, 1-sigma uncertainty bounds in determining WIMP mass:

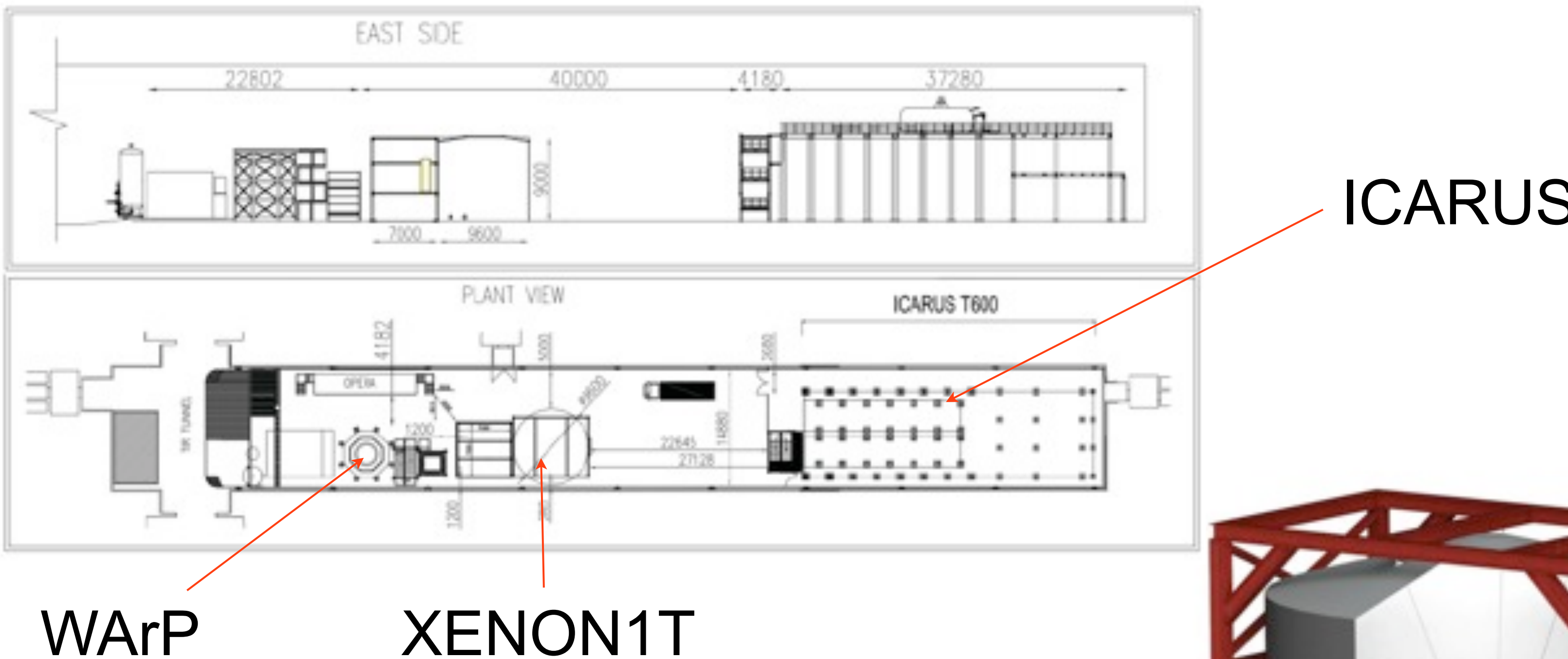
WIMP-nucleon XS~$10^{-45}cm^2$



WIMP-nucleon XS~$10^{-46}cm^2$

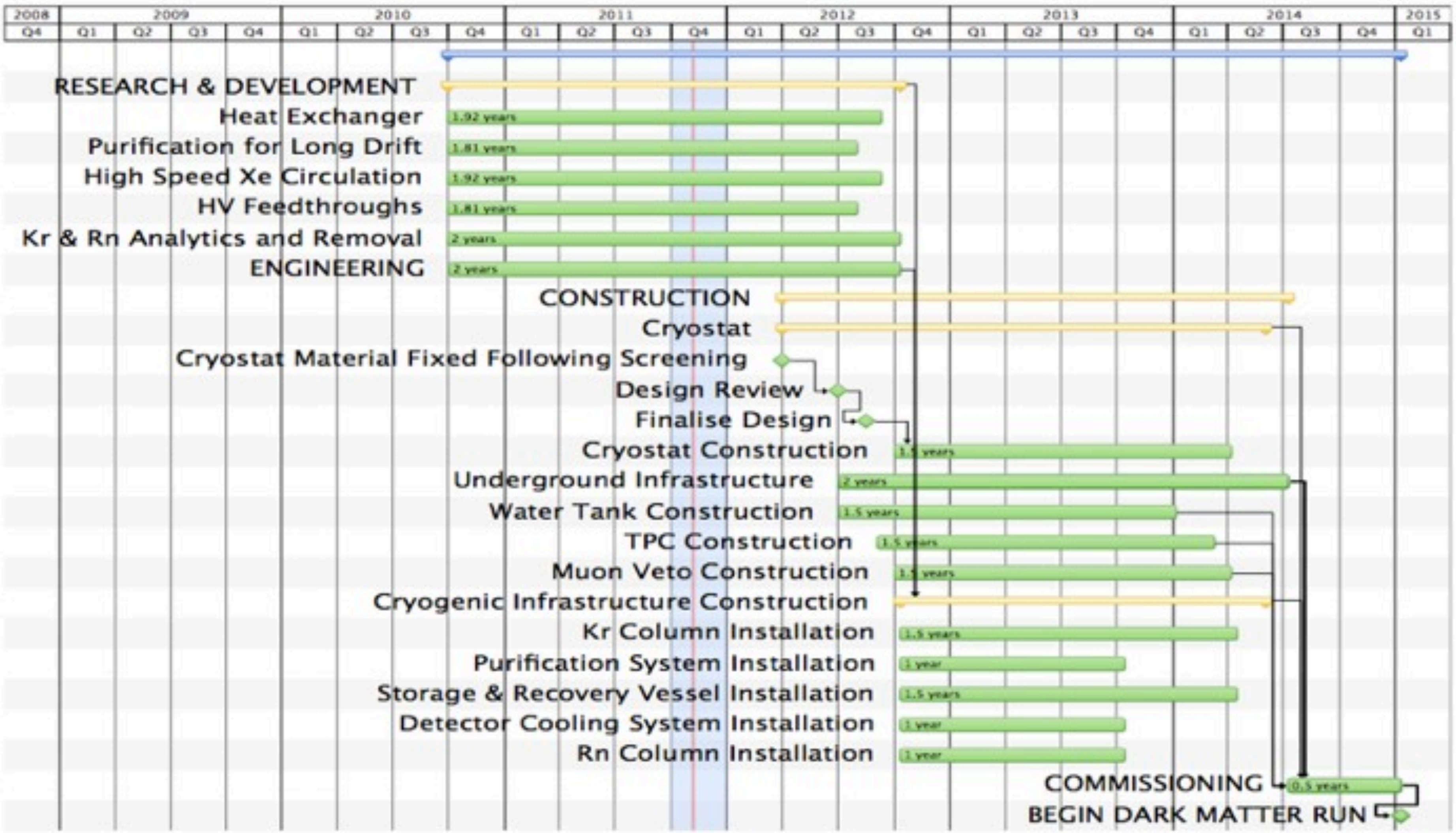


XENON1T - Hall B at LNGS

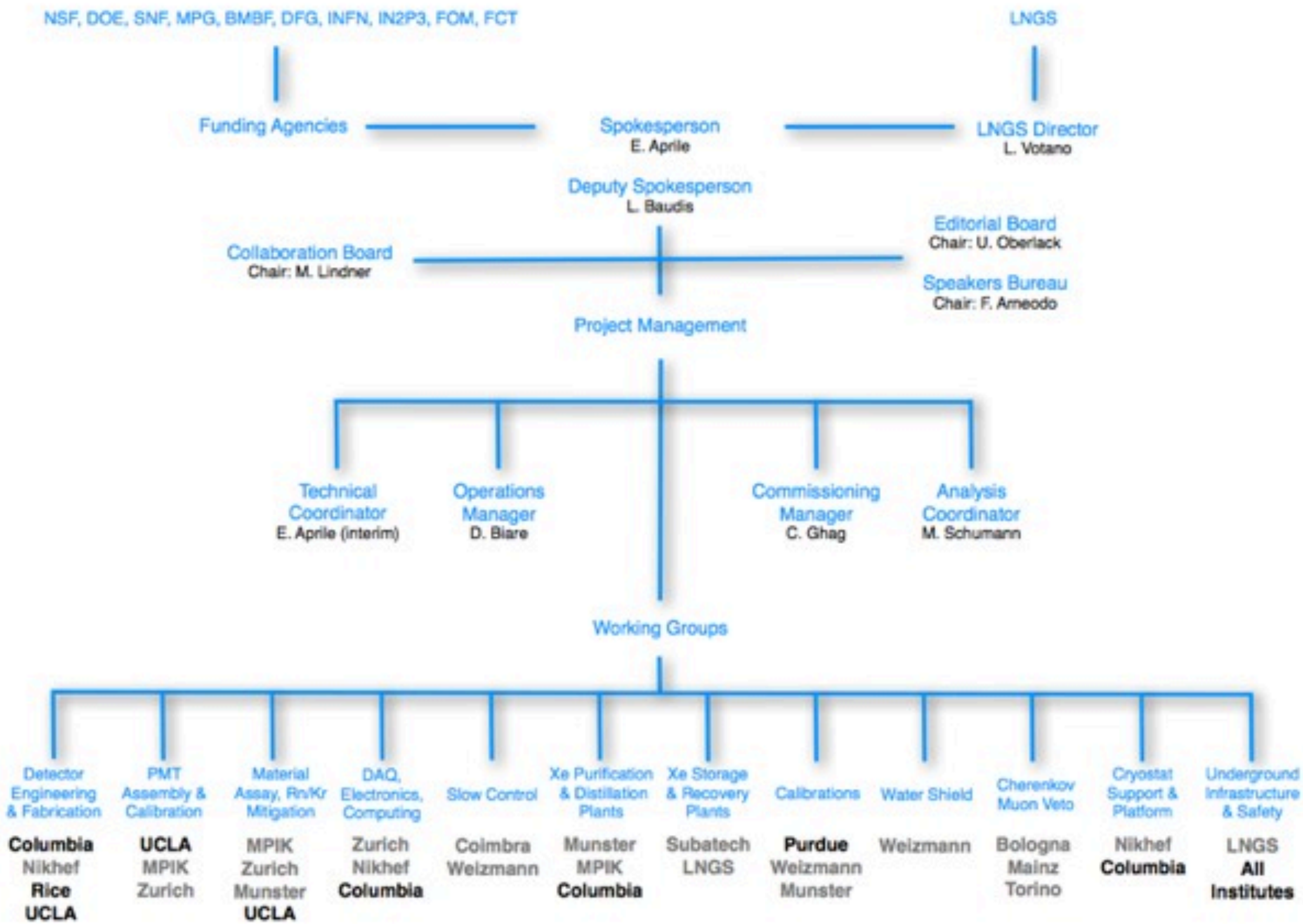


- Location in Hall B at LNGS approved by LNGS Scientific Committee
- Space allocated earlier this month
- Shielding will be a 10m diameter water Cerenkov active muon veto

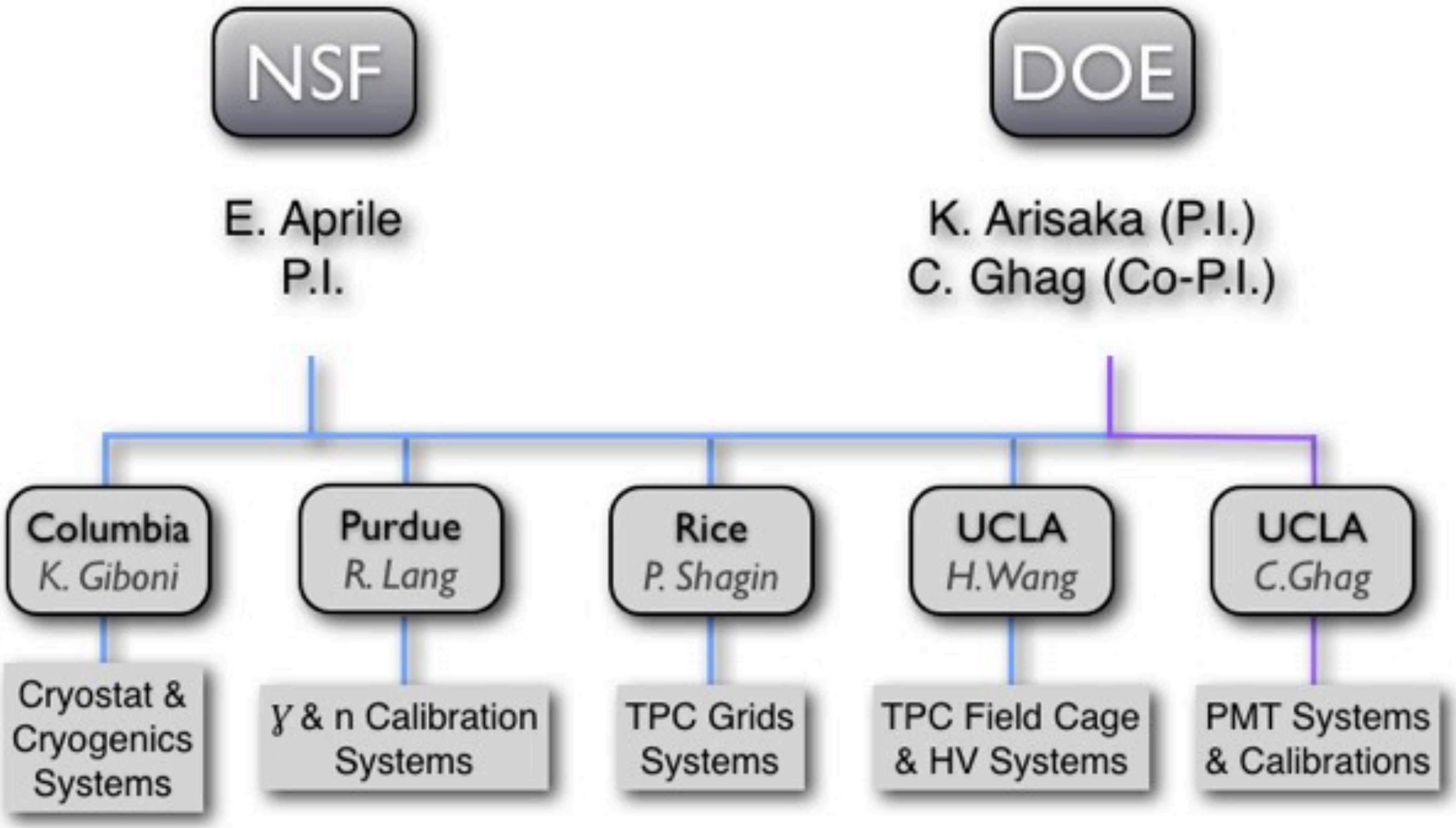
XENON1T - Schedule



XENON1T - Responsibilities



XENON1T - US Responsibilities

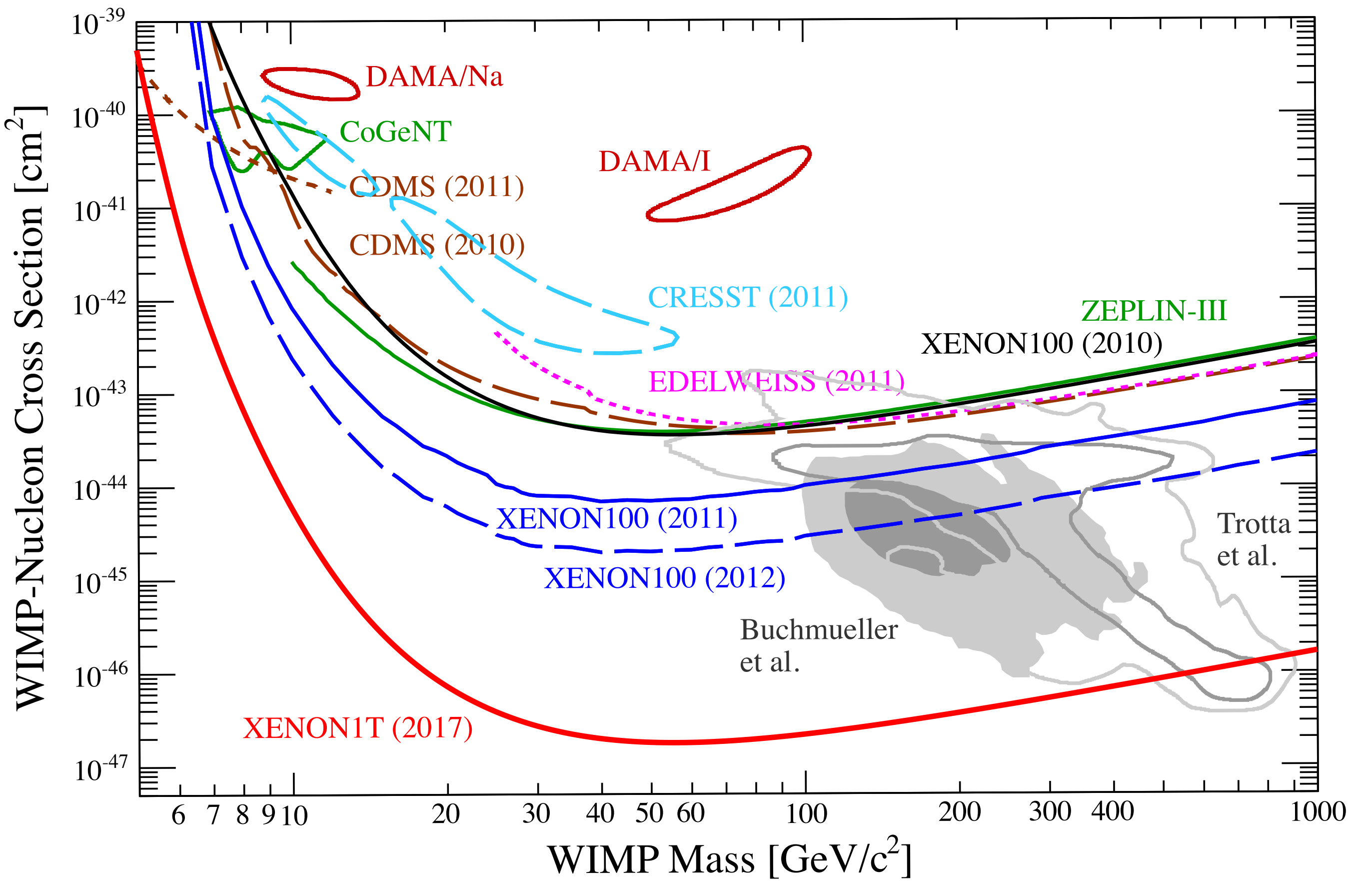


Outlook

- The direct Dark Matter race may be approaching the home straight!
- LXe detectors have proven remarkably successful over recent years, pushing ahead of the pack
- The leading technology for discovery at the G2 level
- Building on experience and expertise gained from world-leading instruments, XENON1T is being designed, and infrastructure built already, to address the bulk of remaining favoured phase-space
- With an aggressive schedule, data taking could start in 2015
- In 2 years, for a 100 GeV/c2 WIMP mass and cross section at the 10^{-45}cm^2 level, XENON1T would detect of order 100 WIMP events
- Multi-ton targets (LXe & LAr) as G3 devices for confirmation of signal under discussion (e.g., MAX, DARWIN, LZD, DarkSide). Liquid noble gas targets at a great advantage with scaleable, shared technologies (possibly even shared detectors) to exploit A^2 dependence

Outlook

We're entering a very exciting period! Dark Matter could be just around the corner...



Outlook

...but I suppose we could always just go and buy some if we don't find it underground!

Thanks for listening!

BACKUPS

XENON1T - Challenges

- For recirculation, need 100 slpm - proved in X1T Demonstrator
- Need 0.5ppt approximately - XMASS already achieved few ppt level (Abe et. al.)
- Need 100 kV HV delivery - T600 feedthrough at ICARUS achieved this
- Need approximately 90% CE and 35% QE - R11410-10 PMT and QUPID achieve this
- Need to reduce Rn levels with column with $V_{RN}/V_{XE} \sim 10^{-3}$ - XMASS achieve this already
- Need 95% reflectivity for PTFE - XENON100 and EXO achieve this
- Need very uniform E-field and reduced electrodes - ZEPLIN-III achieve this
- Need ~5m LXe absorption lengths - XENON100 achieves >2m already

ZEPLIN-III Backgrounds

Material	mass, kg	e-recoil, dru[†]	ptag	n/year[‡]	dtag
Krypton-85	12.5	(<0.1)	~0	–	–
Ceramic feedthroughs	0.9	0.08	0.30	1.35	0.58
Photomultipliers	4.2	0.40	0.26	0.74	0.58
Rock (halite)	–	~0	~0	0.53	0.58
Polypropylene shield	1,266	0.25	0.04	0.10	0.58
Scintillator modules	1,057	0.09	~1	0.03	~1
Copperware	~400	(<0.1)	0.10	(<0.15)	0.58
Lead castle	~60,000	0.01	0.54	~0	0.58
Radon-222	(1 m^3?)	0.03	0.19	~0	–
Muon-induced	–	–		~0.3	~1
SSR total		0.86±0.05	0.28	3.05±0.5	0.58
SSR data		0.75±0.05	0.28	n/a	–
(FSR [6]		14.5±0.5	–	(36±18)*	–)

† events/kg/day/keVee at 10 keVee
‡ single scatters in 2,370 kg·days over 5–50 keVnr (unity detection efficiency)
* FSR dataset expectation was 1.2±0.6 in 454 kg·days; most likely observation was 0 events.

- ☑ **Different tagging efficiencies for components weighted by contribution in Xe predict prompt tagging of 27.4+/-0.6% with 28.2+/-0.6 observed**

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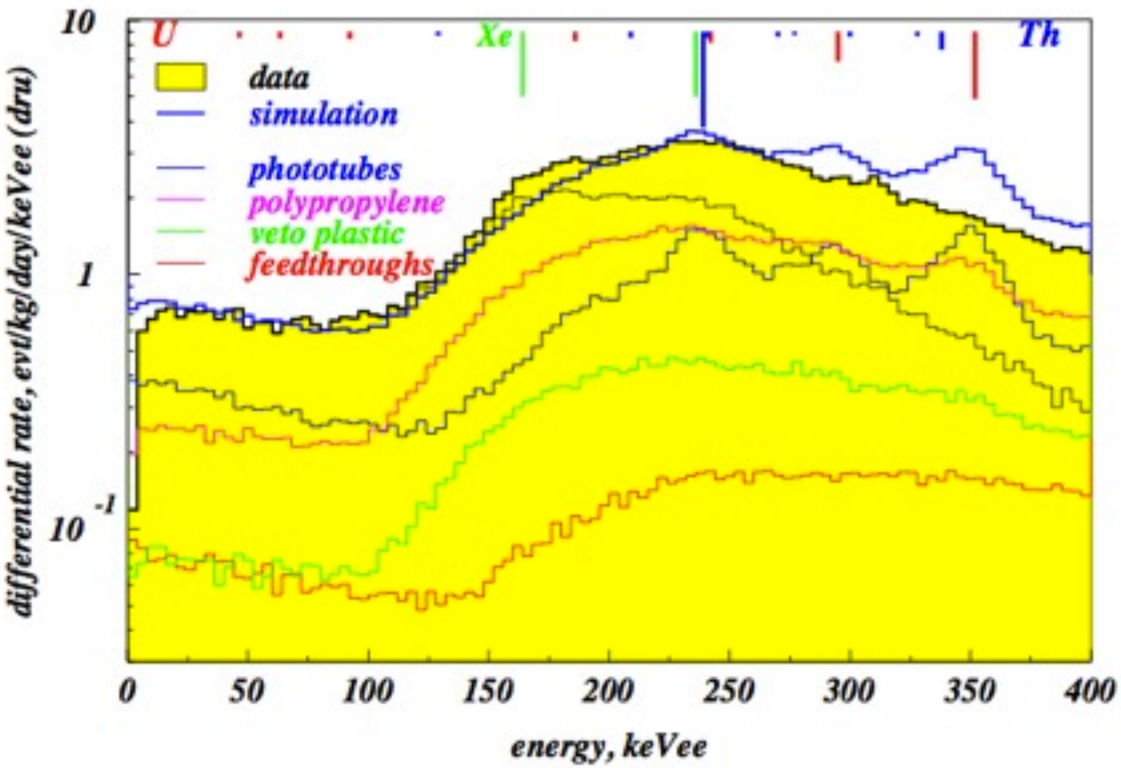
Only possible by simulating SUB-COMPONENTS

☑ **Different tagging efficiencies for components weighted by contribution in Xe predict prompt tagging of 27.4+/-0.6% with 28.2+/-0.6 observed**

Electron recoil backgrounds



Material	mass, kg	e-recoil, dru†
Krypton-85	–	0.007
Ceramic feedthroughs	0.9	0.08
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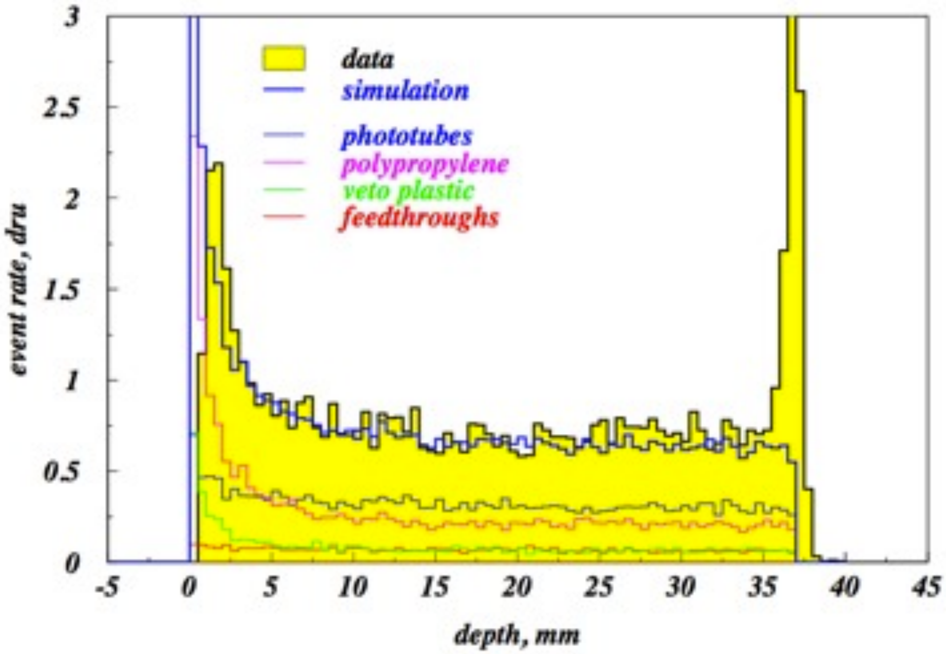
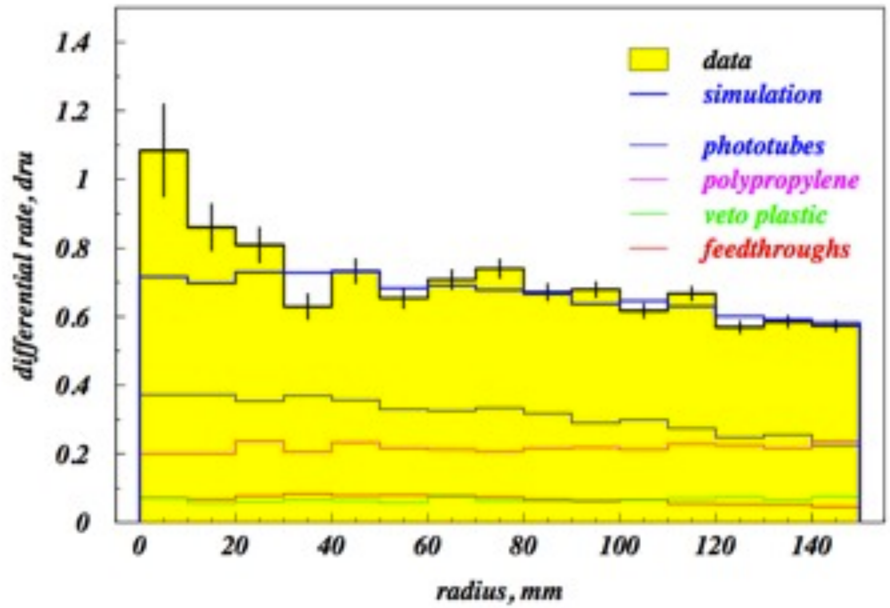
Rock (halite)	–	~0
Polypropylene shield	1,266	0.25
Scintillator modules	1,057	0.09
Copperware	~400	(<0.1)
Lead castle	~60,000	0.01
Radon-222	1 m^3	0.03
Muon-induced	–	–
SSR total		0.86±0.05
SSR data		0.75±0.05
(FSR [6]		14.5±0.5

- Data follows neutron cal. so isometric transition gamma-rays from activation visible (^{129m}Xe $T_{1/2}$ 8.88 days; ^{131m}Xe $T_{1/2}$ 11.8 days)
- 6.5kg fiducial (150mm radial, 32mm deep); no cuts; E* dynamic range loss >200 keV (8-bit digitisers)

Electron recoil backgrounds

Depth distribution

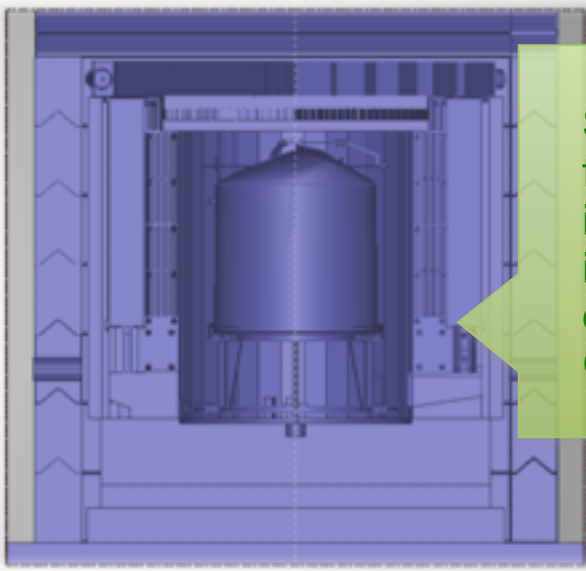




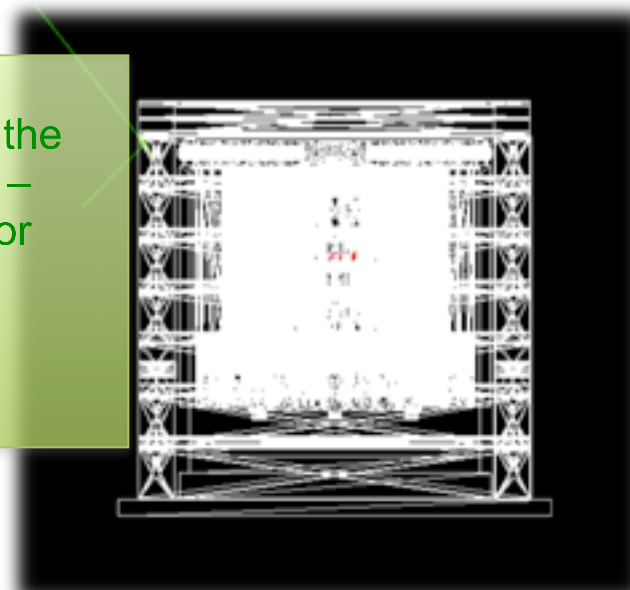
Radial distribution

Simulations & Systematics

…xerces-c 2.7.0, an additional package for GEANT 4 is needed to read in gdml files...

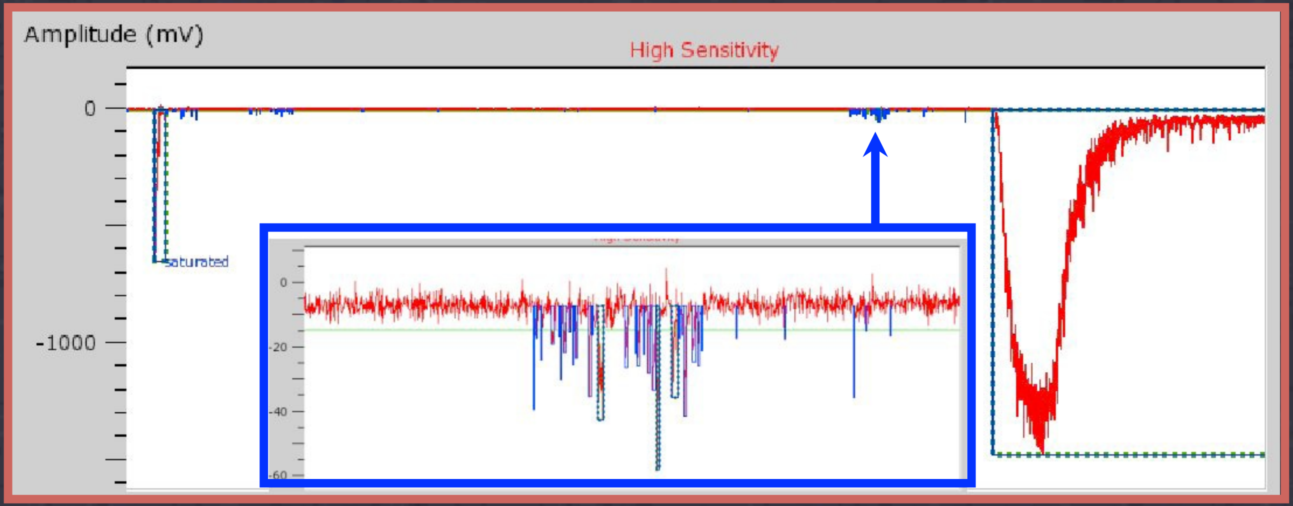


Snapshot of gdml part of the full ZEPLIN-III simulation – incl. shielding and detector in gdml – merged with detectors internals in GEANT 4 C++ code

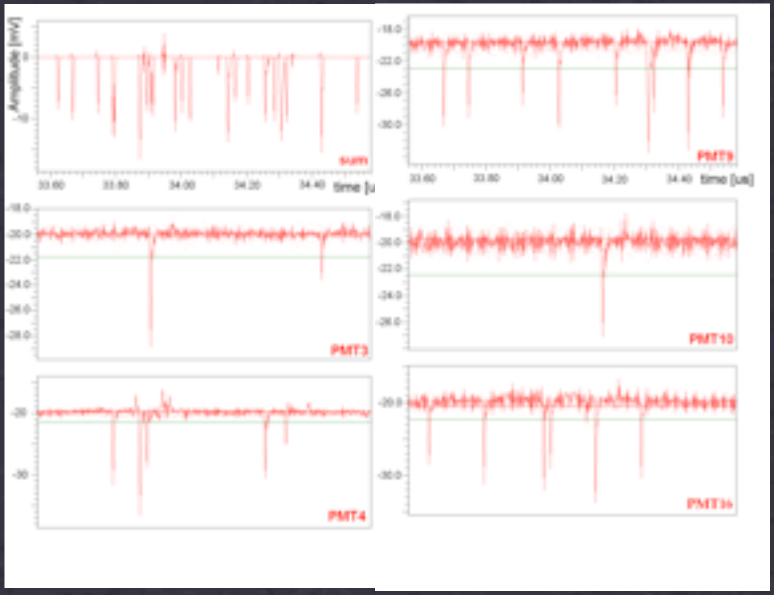


Fastrad → → → gdml → → GEANT4

Single electron detection

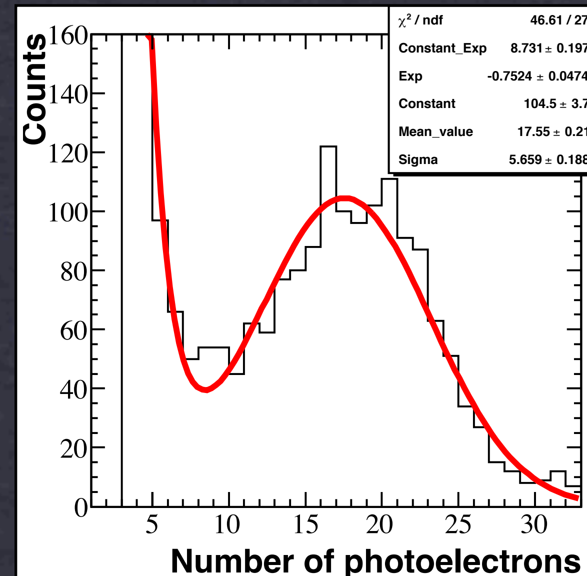


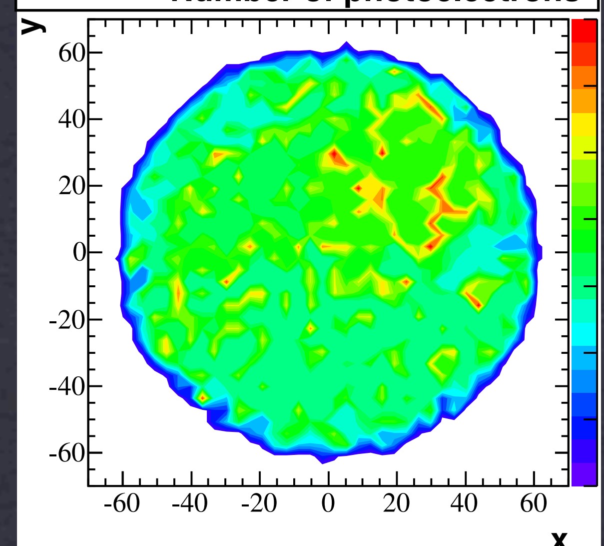
- SE detection within 36 µs timeline
- dedicated SE run (external trigger)



Single electron in ZEPLIN-III

- Origin
  - photon induced (post-S1)
    - photoionisation
    - emission from cathode
  - ‘spontaneous’ emission
    - background related
- Applications
    - electron lifetime measurement
    - low WIMP masses
    - neutrino signal





CNNS Coherent Neutrino Nucleus Scattering

- SM prediction, but not observed yet

$$\frac{d\sigma}{dE_{rec}} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{ME_{rec}}{2E_\nu^2}\right) F^2(Q^2)$$

- Coherence: 3 MeV < E_ν < 50 MeV
- Small nuclear recoil (< 4keV)

$$E_{rec}^{max} = \frac{2E_\nu^2}{M + 2E_\nu}$$

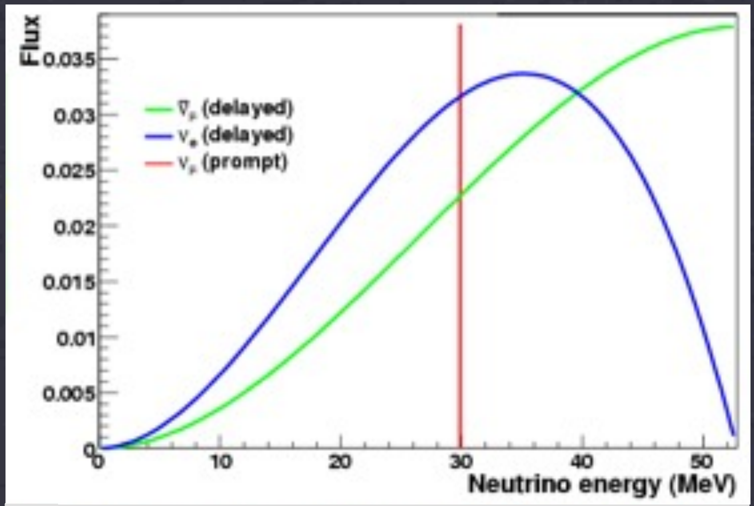
- Rate calculation:

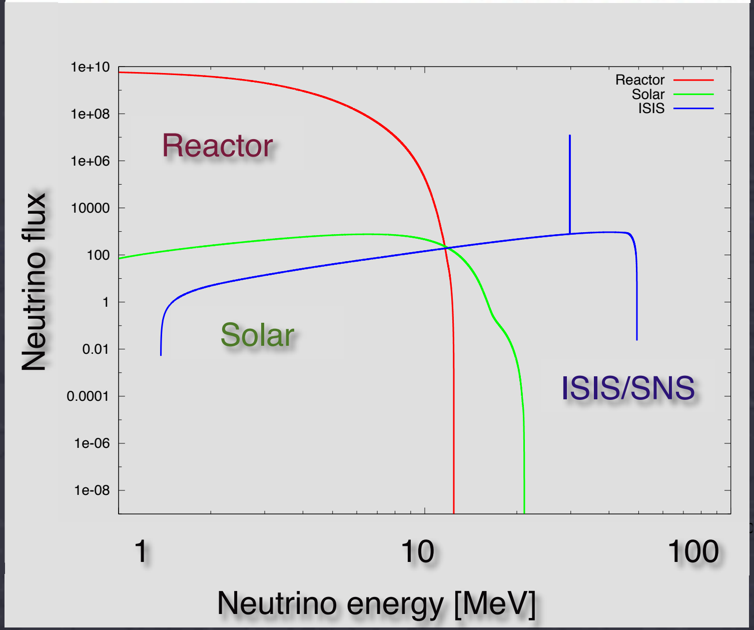
$$R = N_t \int_0^\infty dE_\nu \Phi(E_\nu) \int_{E_{th}}^{E_{rec}^{max}} dE_{rec} \frac{d\sigma(E_\nu, E_{rec})}{dE_{rec}}$$

Neutrino sources

- solar neutrinos
  - pep, ^{8}B, hep
- reactor neutrinos
  - $E_{max} \sim 10$ MeV
- neutrino beam (stopped pion sources)
  - ISIS/SNS

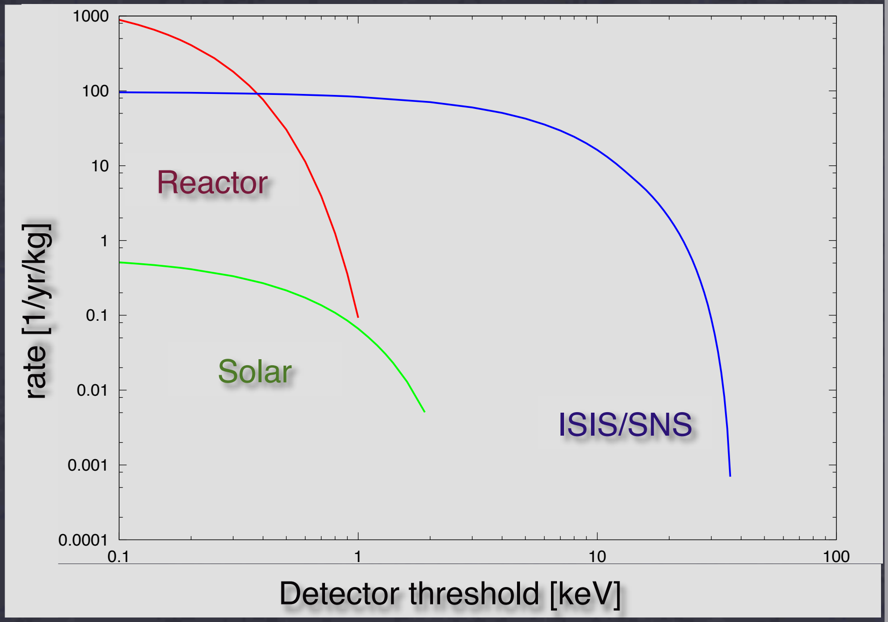
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

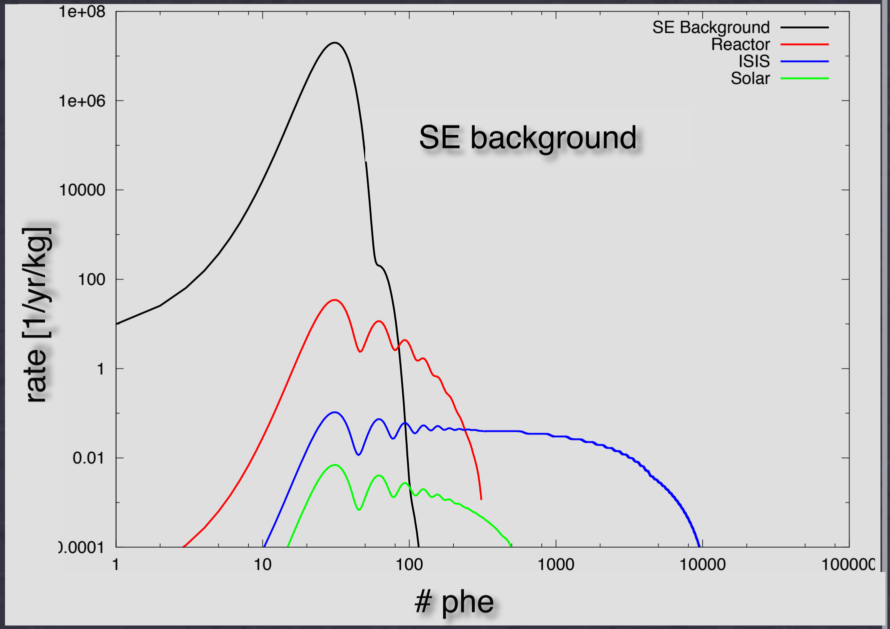




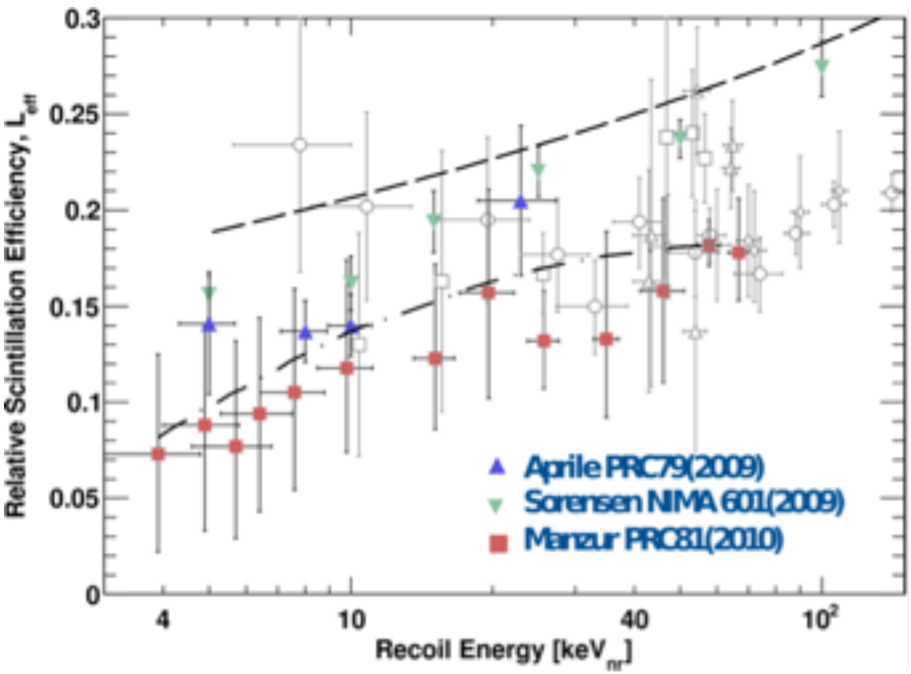
CNNS signal

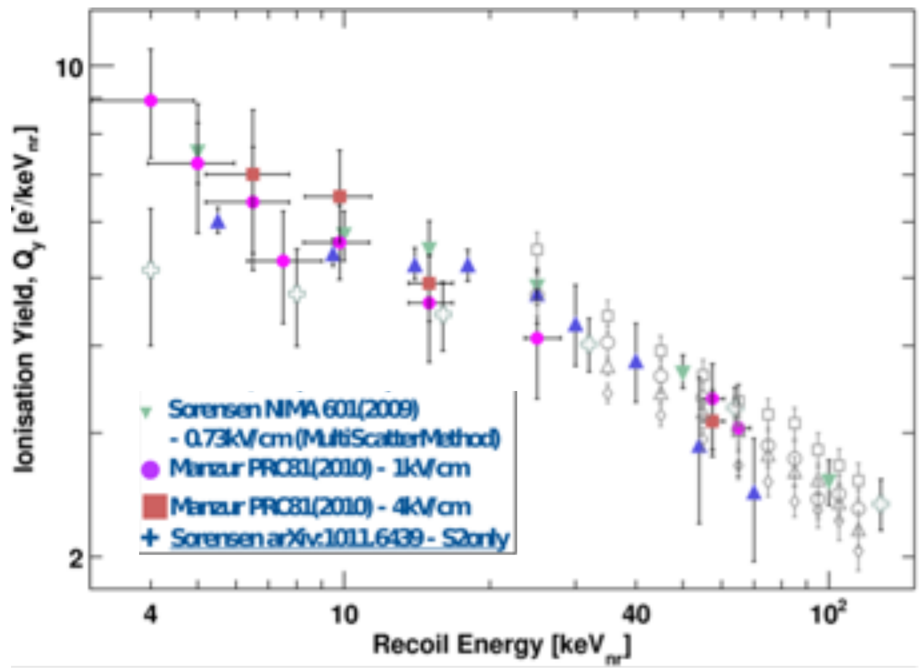
- detectable rates
- solar neutrino
  - large target mass necessary
- reactor neutrinos
  - high rates (10m distance to core)
- beam neutrinos
  - clean signal above 3 SE





Existing yield measurements

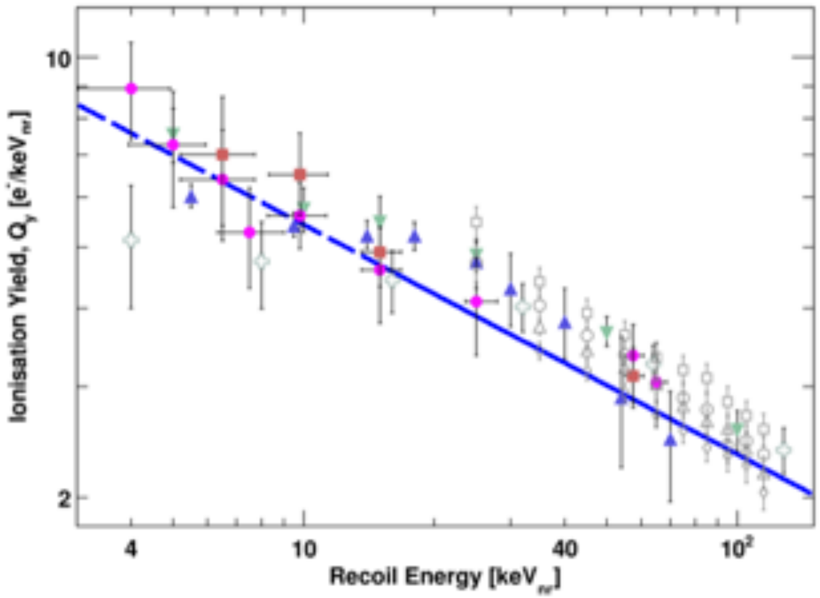




- Mainly neutron beam measurements
  - Tag outgoing neutron: known E_{recoil}

Charge yield results

- Similar approach to L_{eff}, with
  - Power law to parametrise Q_y.
  - Efficiency now η(S1(S2)).
- Recover median S2/S1, consistency with beam measurements



DRIFT-II

- The world's only DIRECTIONAL Dark Matter detector (a 'Dark Matter Telescope')
- Target = low pressure gas (1/20th atm)
- Discrimination: track length and DIRECTIONALITY
- Status: 1m^3 prototype – awaiting scale up