



DARK MATTER

Searching for Physics Beyond the Standard Model

Chamkaur Ghag



on behalf of Alex Murphy



Outline

- Evidence for Dark Matter
- How do we search?
- Recent results
- Looking to the future

The Evidence

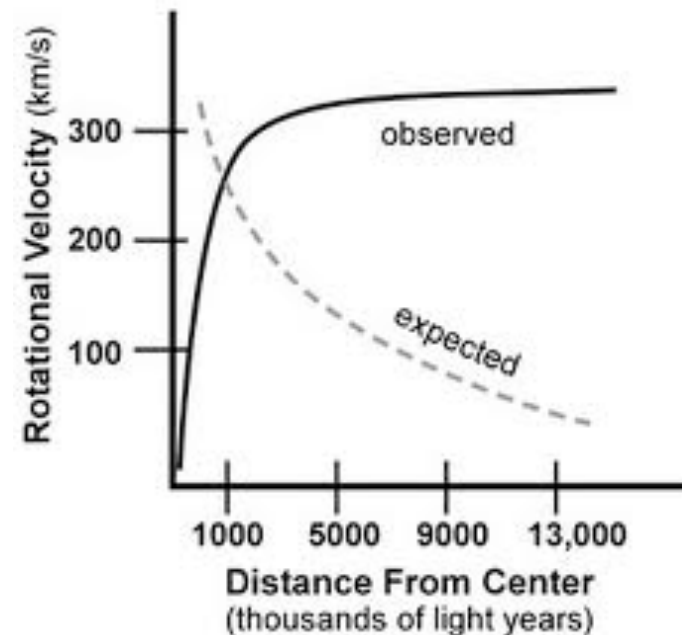
Early evidence

1930's - Fritz Zwicky

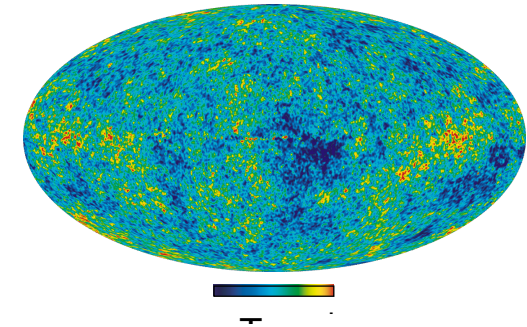
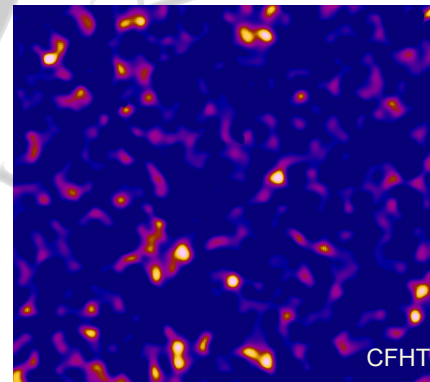
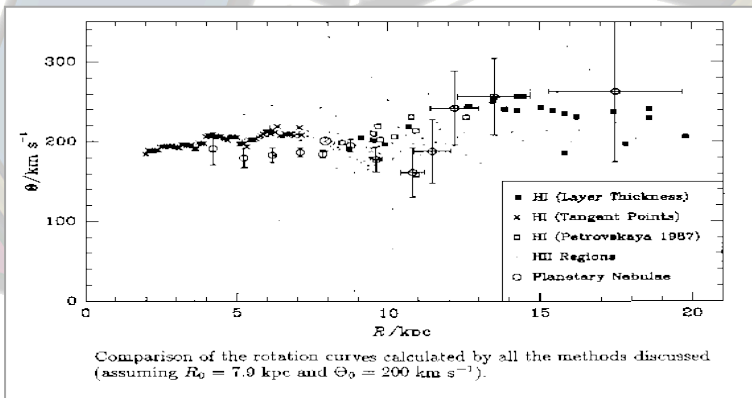
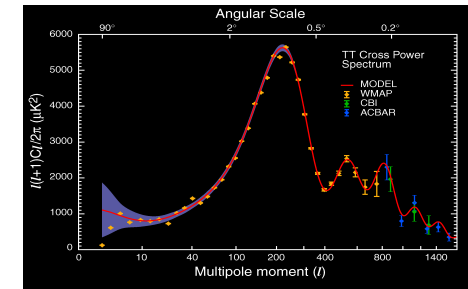
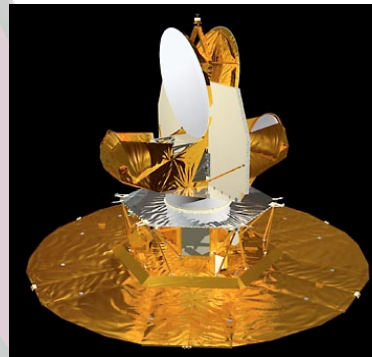
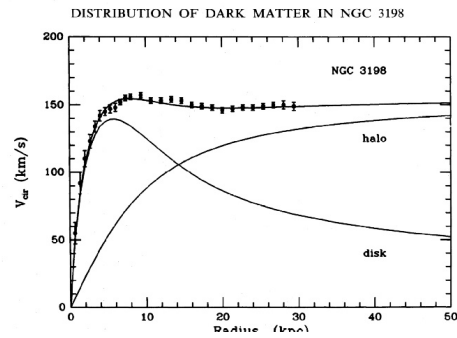
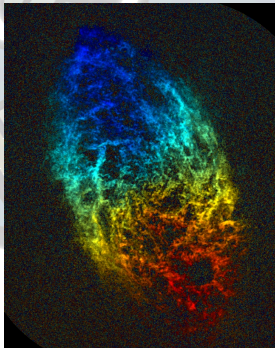
1970's - Vera Ruben

Measured rotational velocity of galaxies and observed flat curves rather than expected Keplerian fall-off with distance from galactic centre

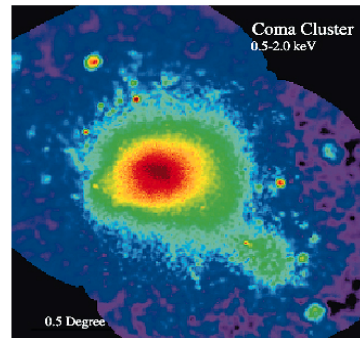
GALAXIES ARE ROTATING TOO FAST!



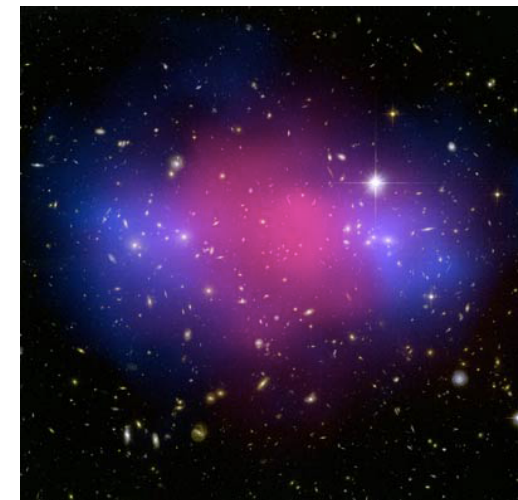
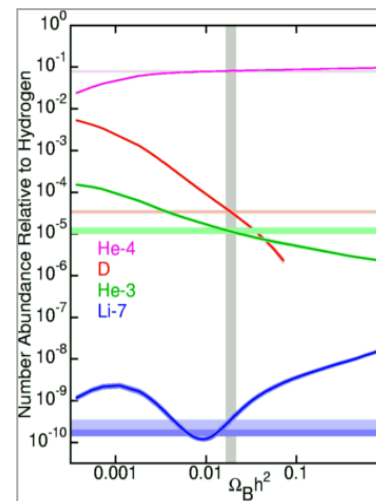
Lots more evidence since then...

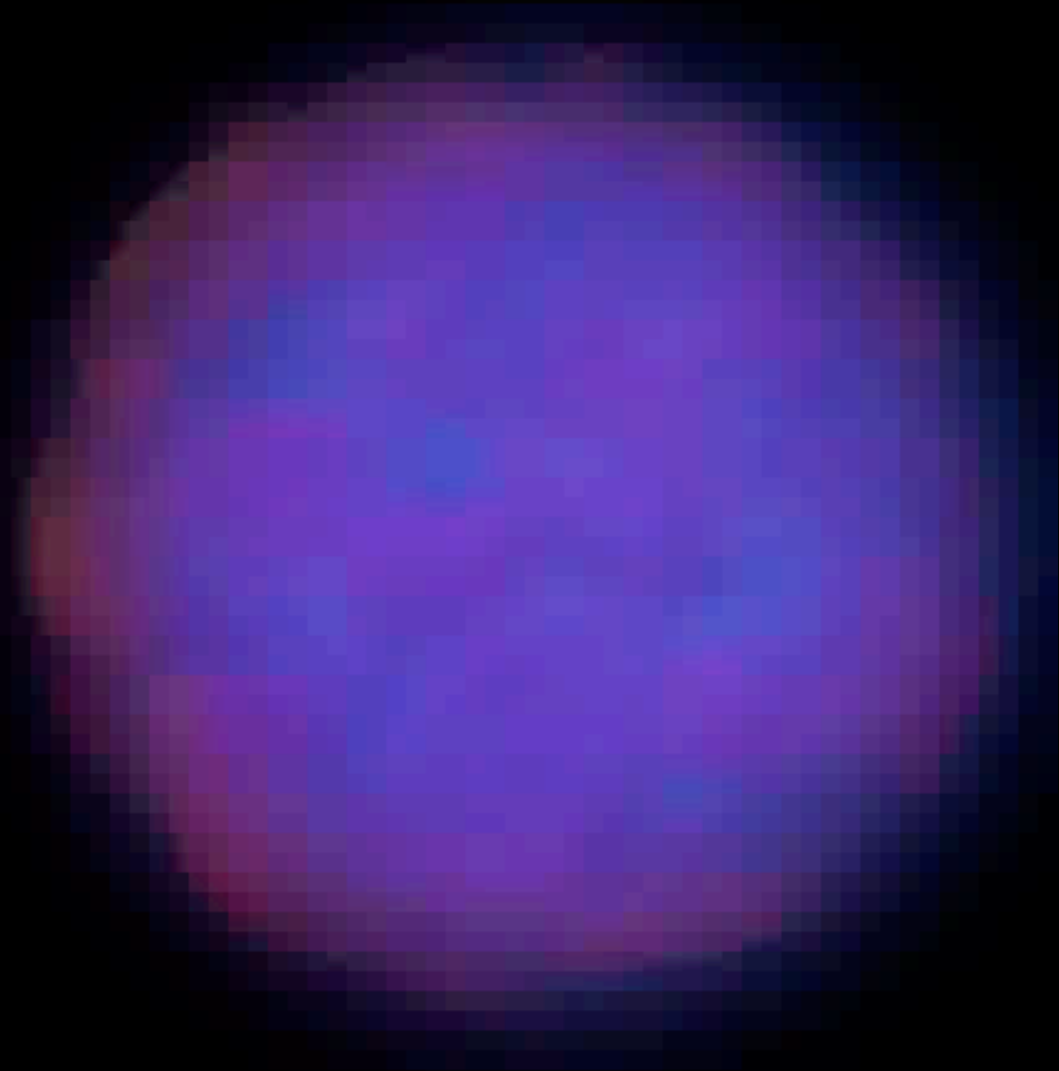
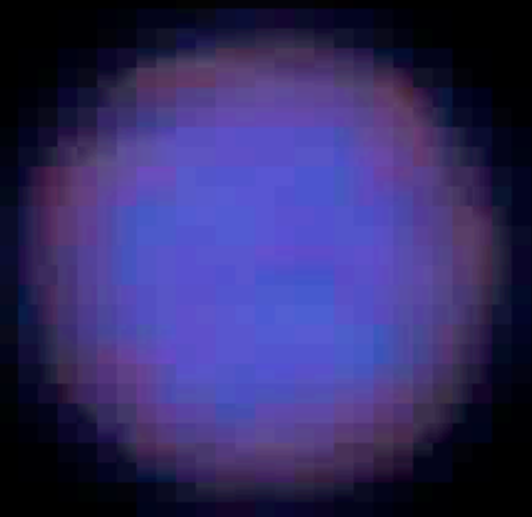


(a)
Copyright © Addison Wesley.



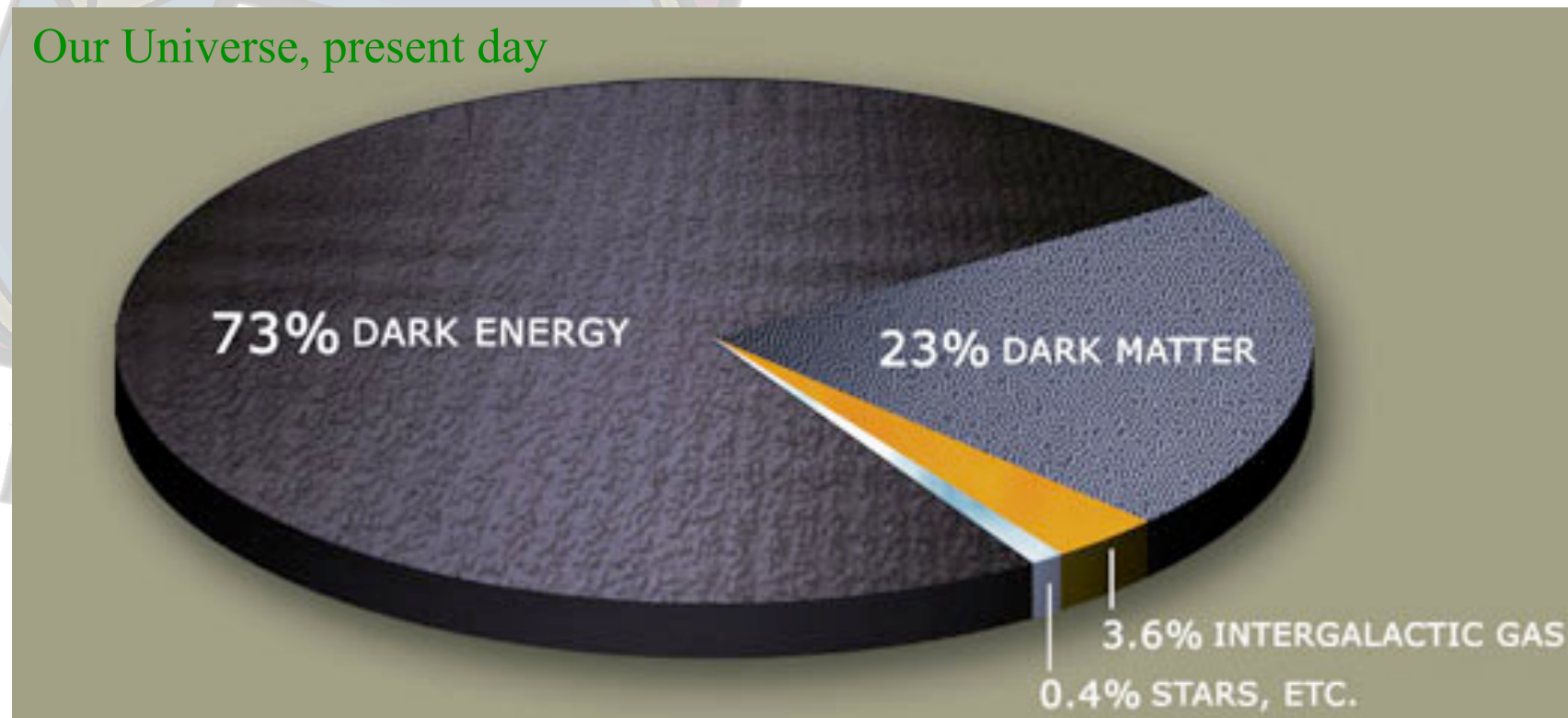
(b)





The conclusion

Our Universe, present day



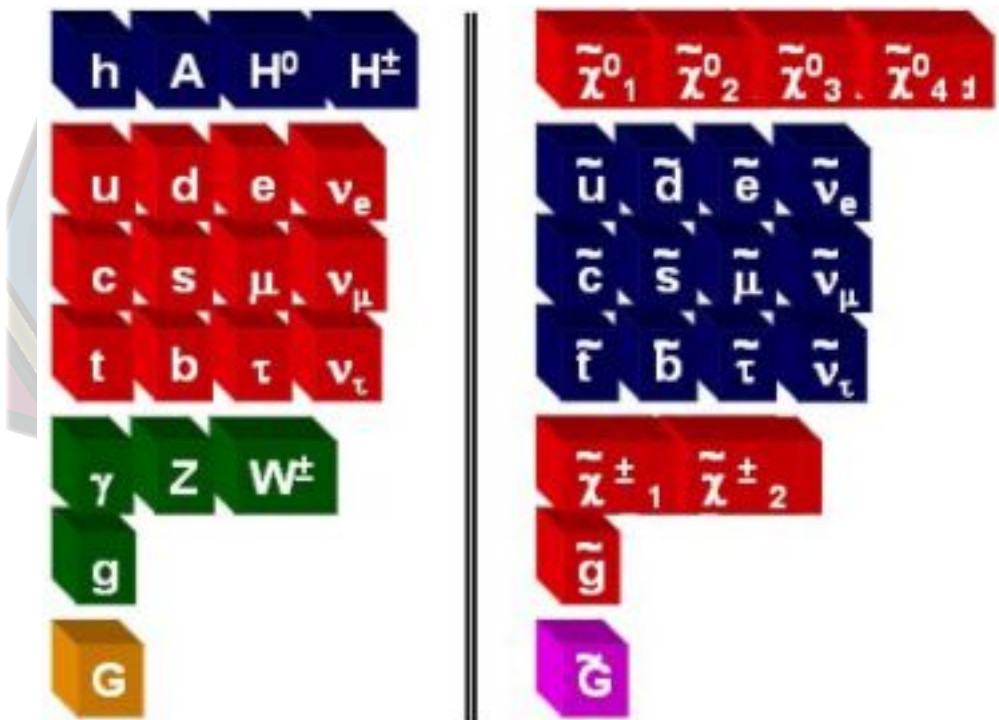
Dark Matter properties

- No electromagnetic interaction
- No strong interaction
- Stable
- Neutrinos are too hot
- Likely weak interaction (WIMPs)



The existence of Dark Matter points to BSM physics

One possibility: LSP of SUSY



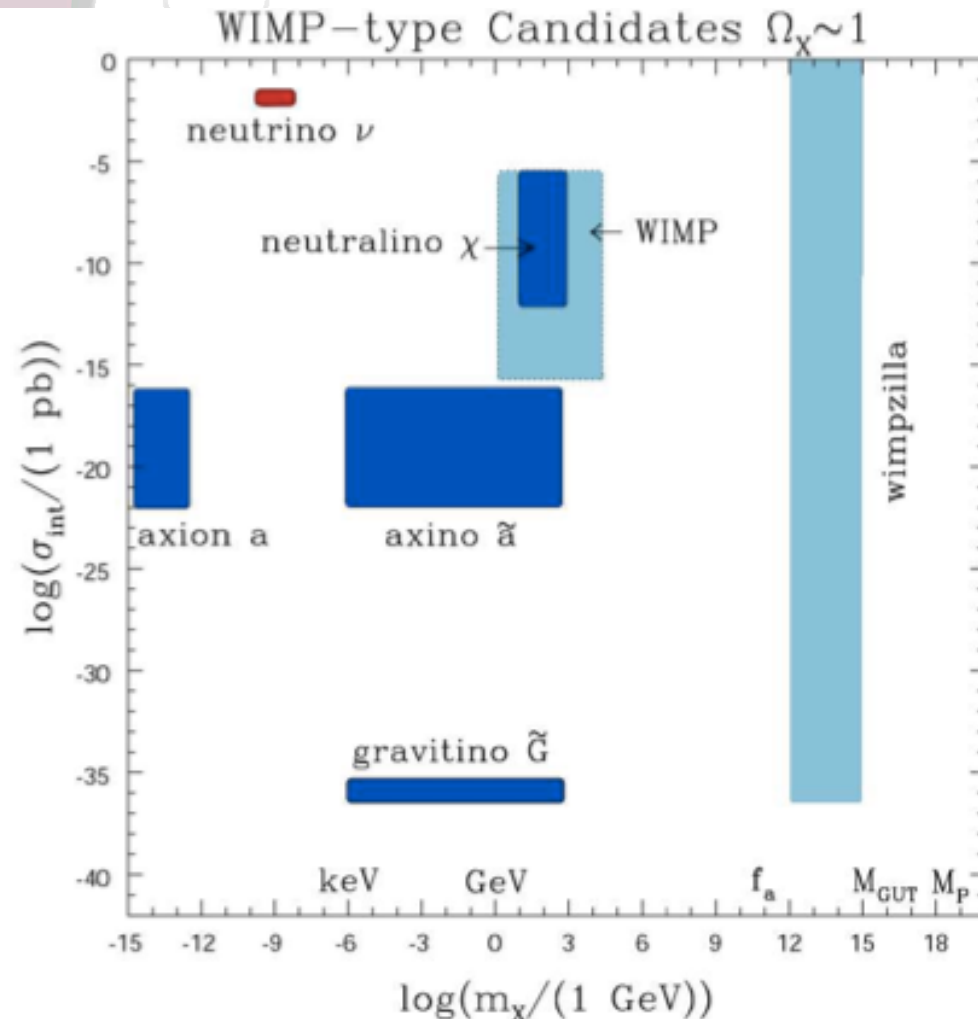
WIMP is the lightest supersymmetric particle ('LSP'), χ , a linear combination of bino, wino and Higgsino fields.

$$\chi = \alpha \tilde{B} + \beta \tilde{W} + \gamma \tilde{H}_1 + \delta \tilde{H}_2$$

A zoo of DM candidates...

If SUSY is wrong, that
doesn't stop galaxies
rotating too fast!

Direct DM searches
are “broadband”
searches



The background of the slide features a large, faint watermark of the Edinburgh University crest. The crest is a shield divided into four quadrants, with a book in the top left, a ship in the top right, a lion in the bottom left, and a unicorn in the bottom right. The word 'EDINBURGH' is written in a semi-circle above the shield, and 'UNIVERSITY' is written in a semi-circle below it.

How do we search?

How to search for dark matter?

Collider



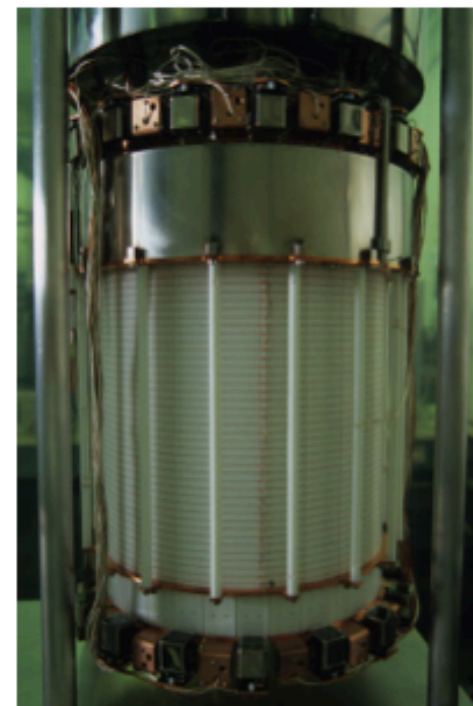
Production

Indirectly



Annihilation

Directly

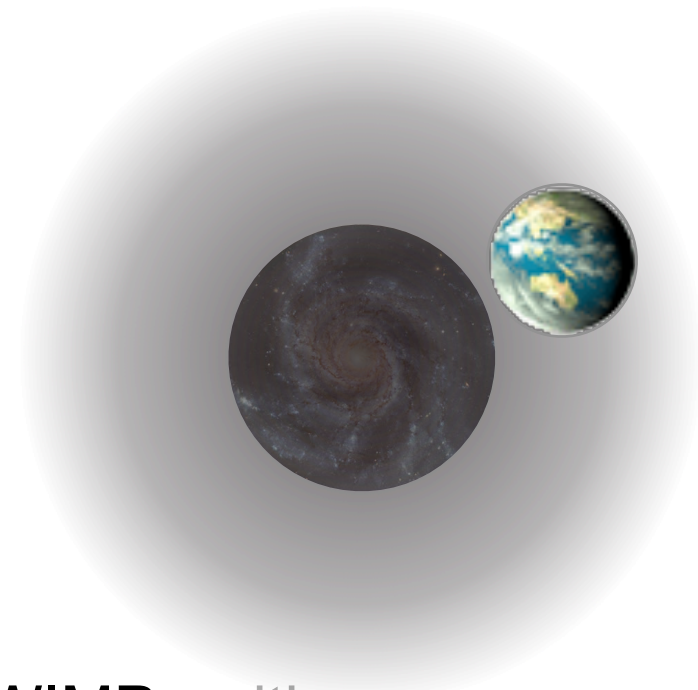


Scattering

The direct detection premise...

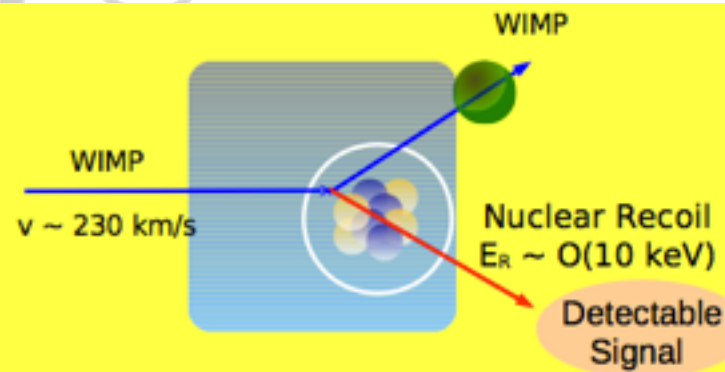
Interact with galactic WIMPs (*our* Dark Matter) in ultra-low background terrestrial detectors

- Earth should be passing through a halo of weakly interacting massive particles
- We search for the rare collisions of WIMPs with normal matter here on Earth.



How to directly detect dark matter

Elastic Scattering of
WIMPs off target nuclei
→ nuclear recoil

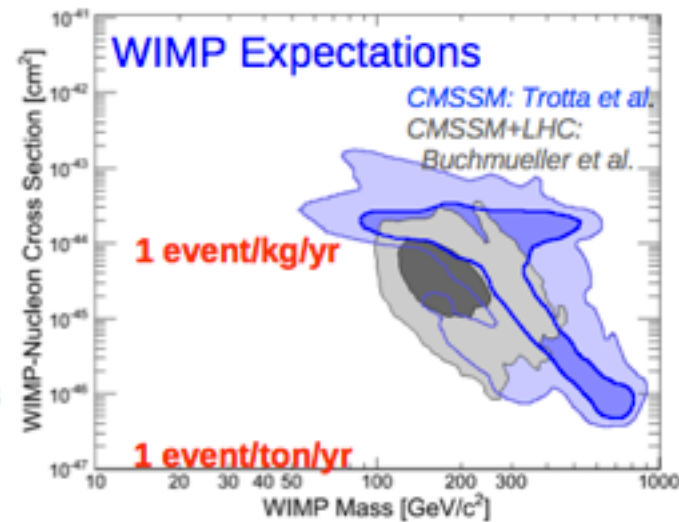


Recoil Energy: $E_R \sim \mathcal{O}(10 \text{ keV})$

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

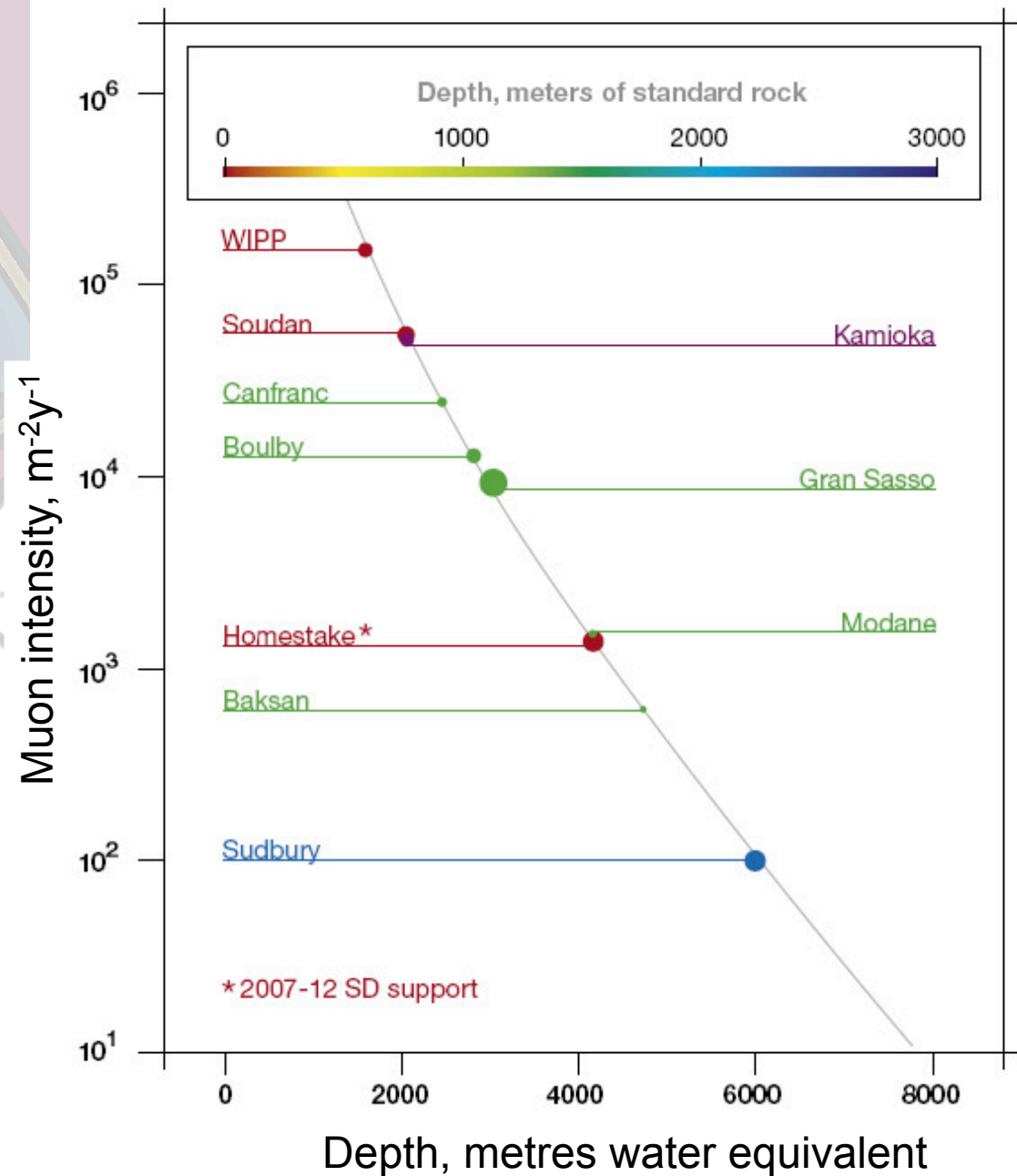
Diagram illustrating the components of the Event Rate equation:

- Detector** (red arrow) points to N .
- Local DM Density** (blue arrow) points to ρ_χ , with the value $\rho_\chi \sim 0.3 \text{ GeV}/c^2$.
- Physics** (green arrow) points to $\langle \sigma_{\chi-N} \rangle$.

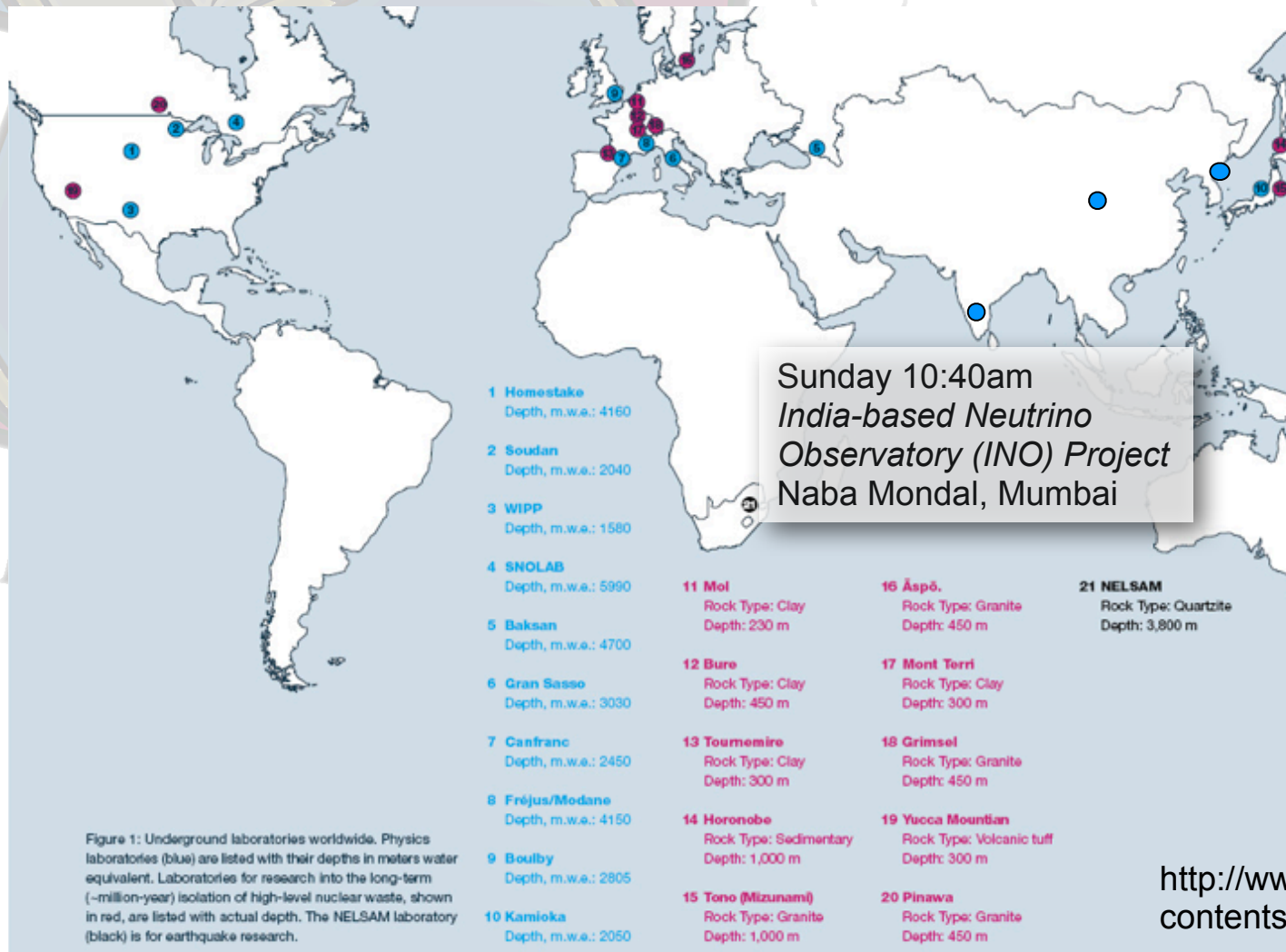


Muons produce secondary neutrons, which can be particularly problematic

Going deep underground significantly reduces cosmic ray muon flux



Deep underground laboratories around the world



Blue -
science
labs

Pink/black -
Rad' waste
storage &
earthquake
research

http://www.deepscience.org/contents/facilities_popup01.shtml

The detector wish-list

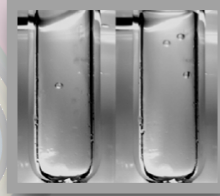
- ☑ Radio-pure (low background)
- ☑ Active Shielding (single elastic scatters)
- ☑ 3D vertex reconstruction (reject surface background)
- ☑ Discrimination (reject SM interactions)
- ☑ Low threshold (recoil spectrum peaked at low E)
- ☑ Good energy resolution (discern WIMP spectrum)
- ☑ High A target, with odd-nucleon isotopes too (S.I./S.D.)
- ☑ High mass (low event rate)
- ☑ Scaleable (for tonne+ scale)

Direct detection techniques

CDMS
EDELWEISS



CUOPP
PICASSO
SIMPLE



CRESST
ROSEBUD

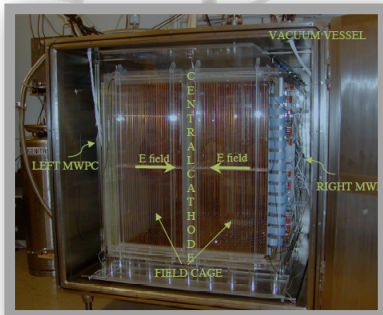


Phonons

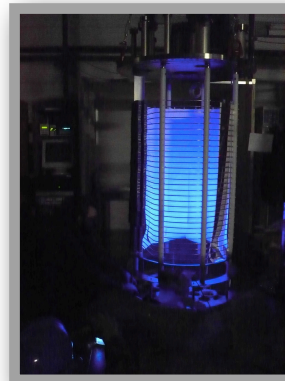
dE/dx

Charge

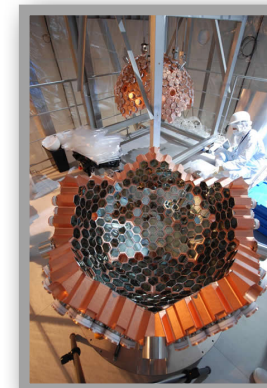
Light



DRIFT
DMTPC
GENIUS
NEWAGE



LUX
XENON
WARP
ArDM
ZEPLIN
DARKSIDE

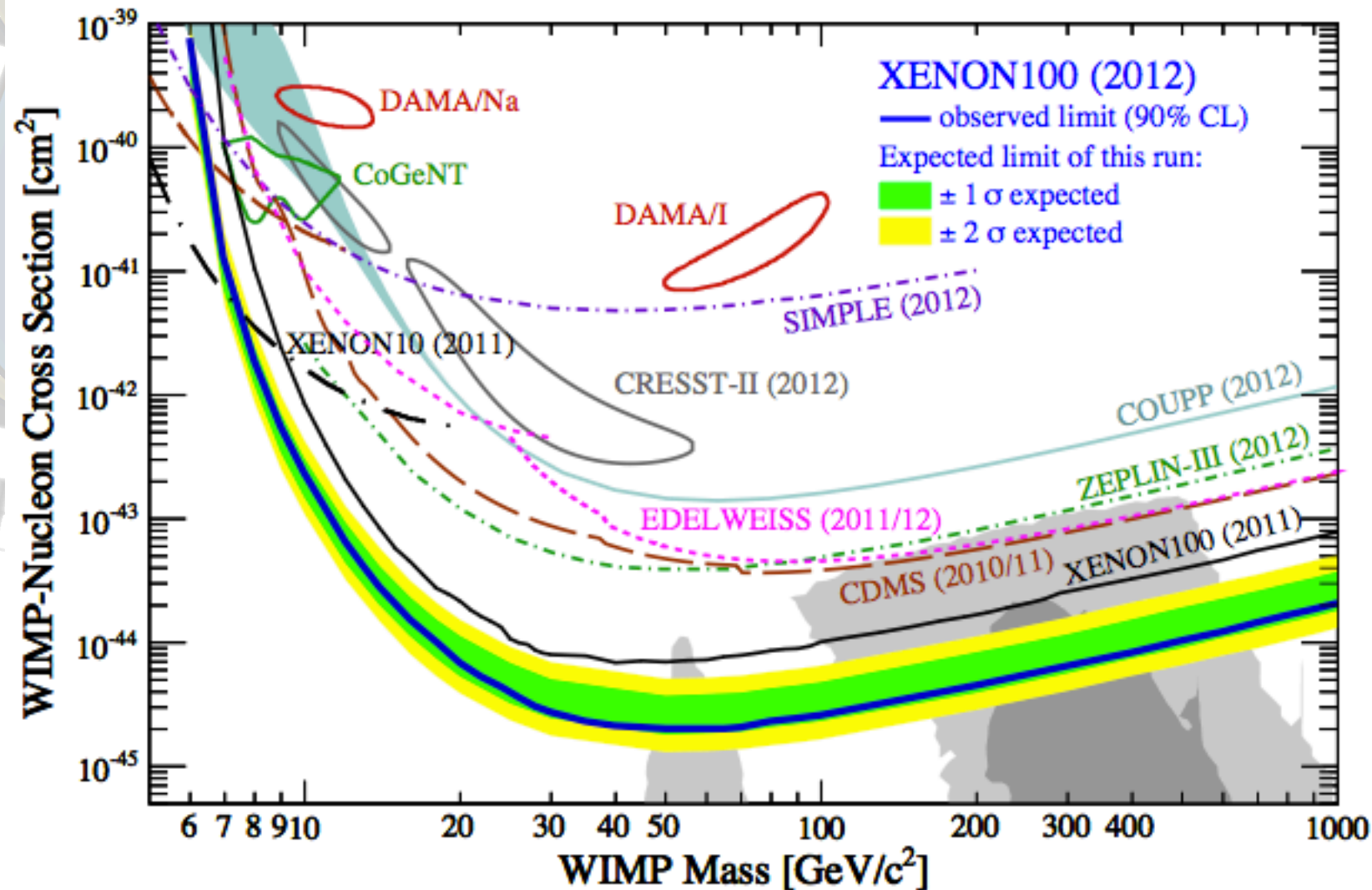


DAMA
LIBRA
XMASS
CLEAN
ANAIS
KIMS
DEAP/CLEAN

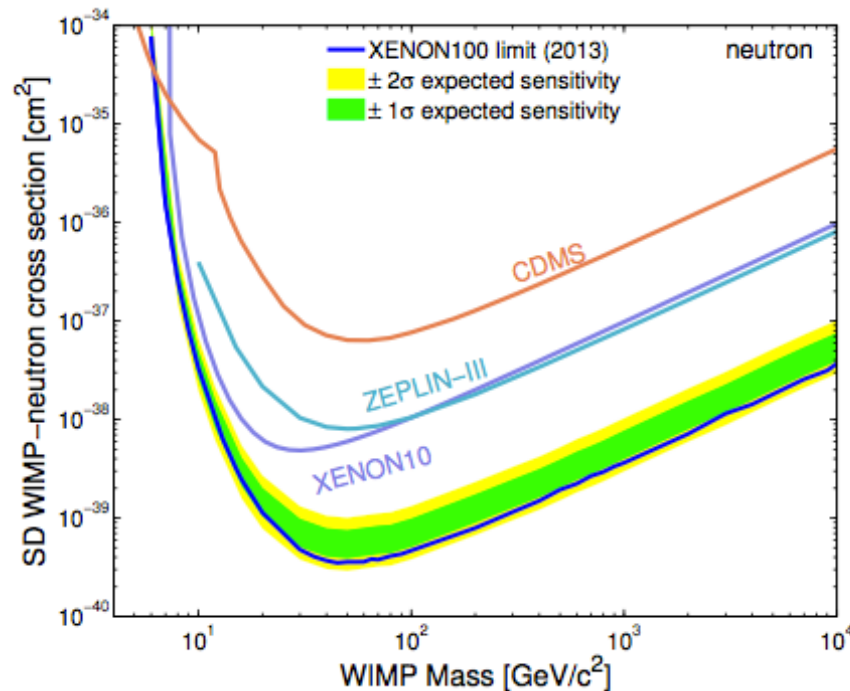


The current state of play

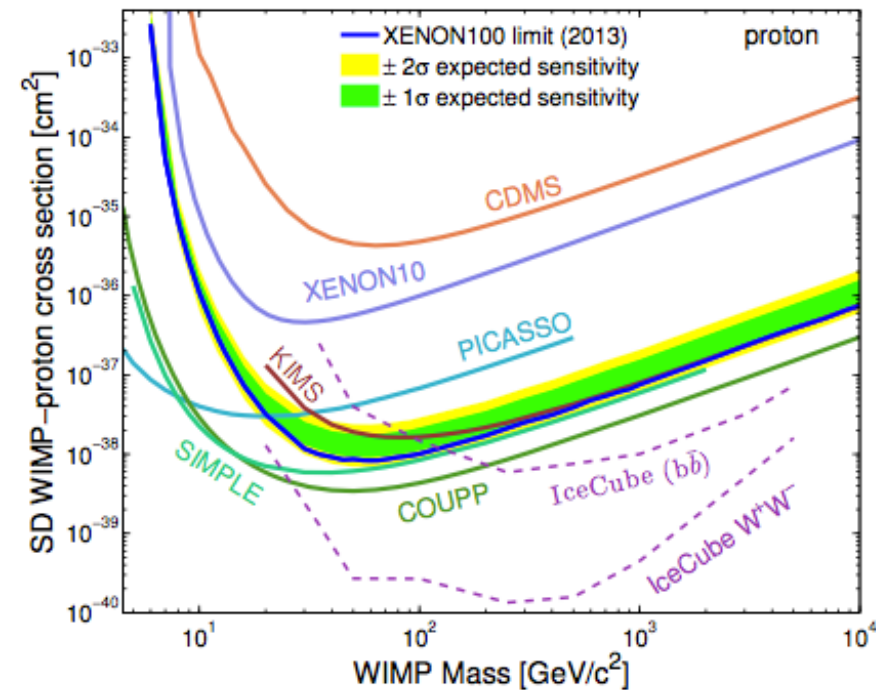
Spin-Independent interaction



Spin-dependent interaction



WIMP-Neutron



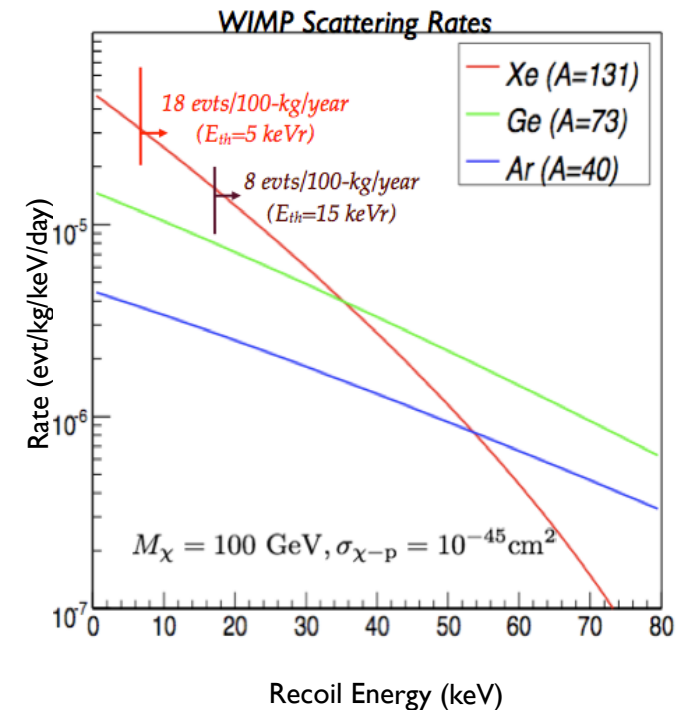
WIMP-Proton

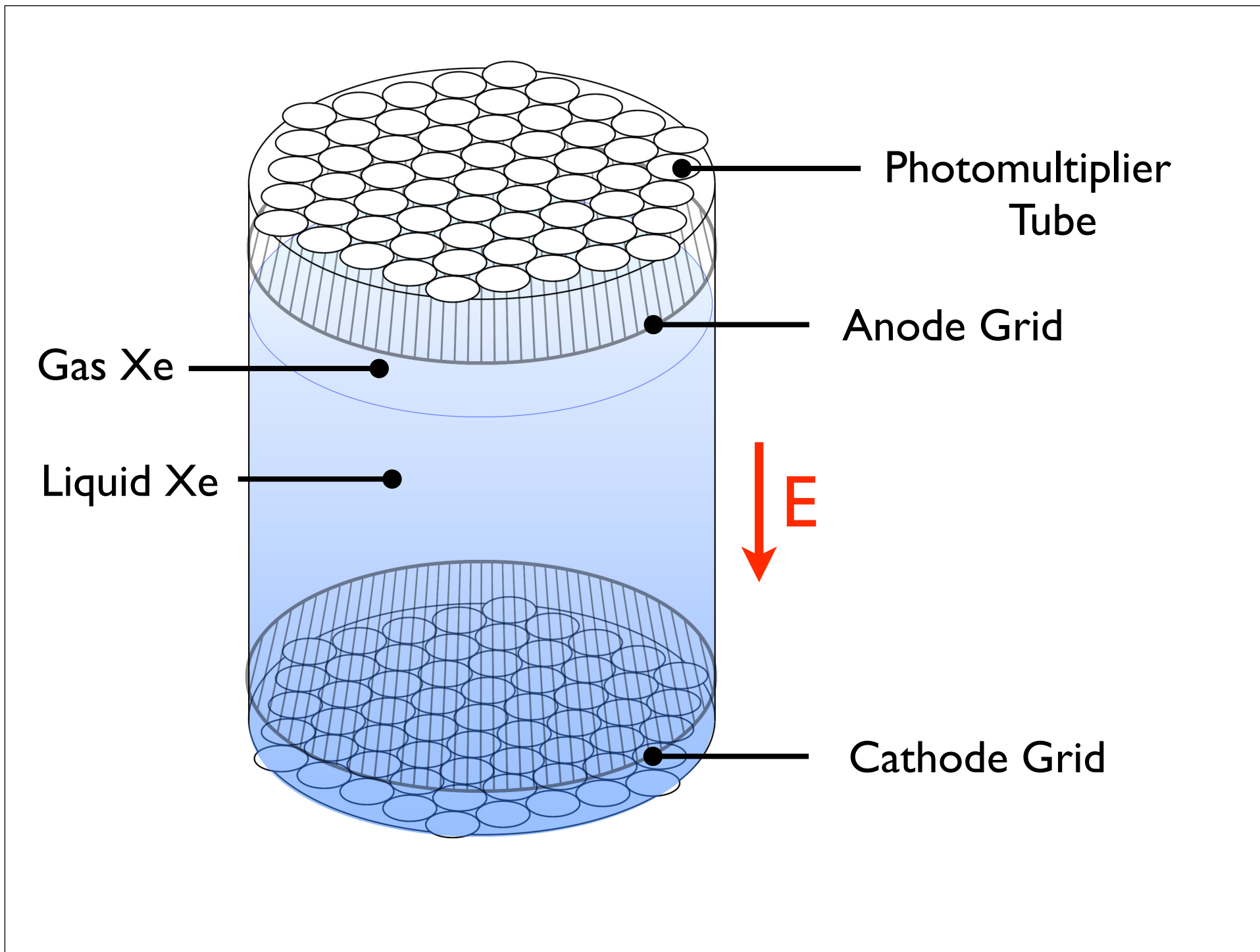
Experiments/Collaborations

- Approximately 30 'serious' Direct DM Searches
- Cannot cover them all
- I'll present a summary of the key players...

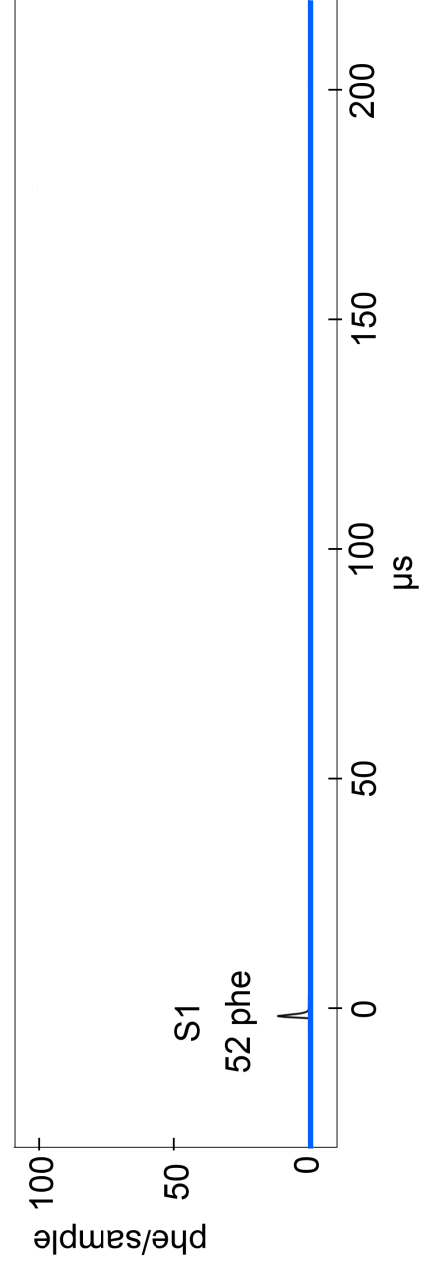
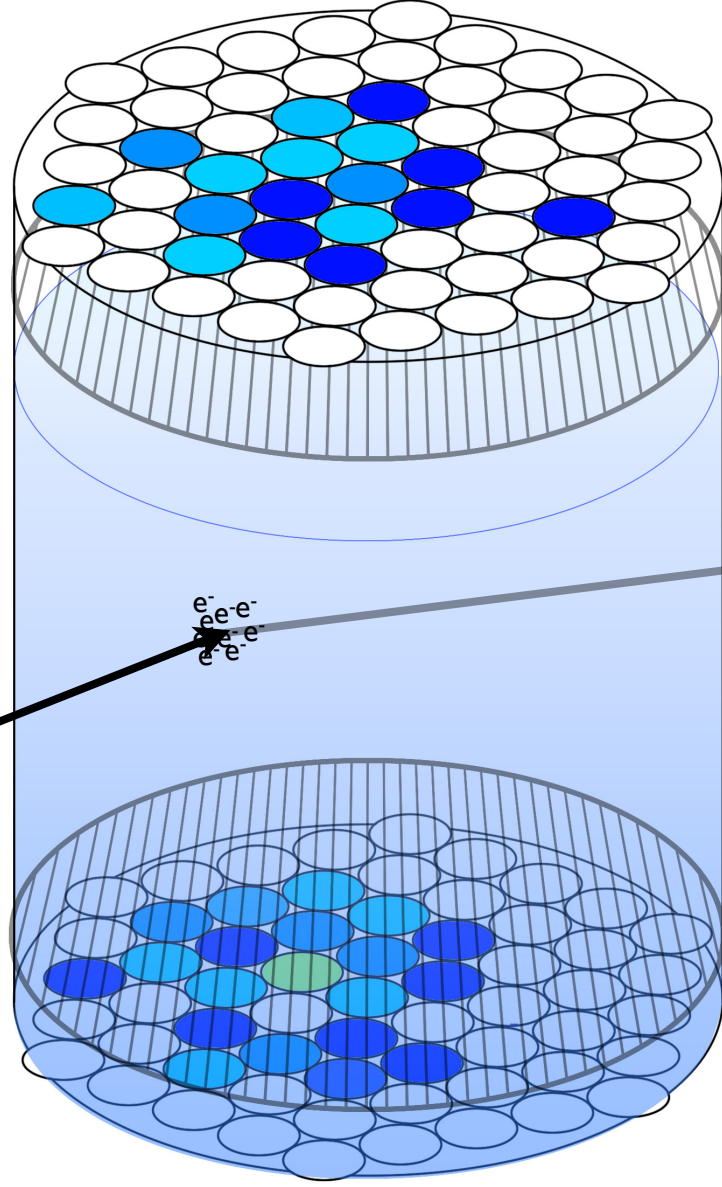
Liquid Xenon TPCs

- **S1: LXe is an excellent scintillator**
 - Density: 3 g/cm³
 - Light yield: >60 ph/keV (0 field)
 - Scintillation light: 178 nm (VUV)
 - **Nuclear recoil threshold ~5-8 keV**
- **S2: Even better ionisation detector**
 - S1+S2 allows mm vertex reconstruction
 - Sensitive to single ionisation electrons
 - **Nuclear recoil threshold ~1 keV**
- **Well suited WIMP target**
 - Scalar WIMP-nucleon scattering rate $dR/dE \sim A^2$
 - Odd-neutron isotopes (¹²⁹Xe, ¹³¹Xe) enable spin-dependent sensitivity
 - Excellent ionisation threshold: 'light WIMP' searches using S2 only
 - No intrinsic backgrounds (⁸⁵Kr can be removed, low rate from ¹³⁶Xe 2νββ)
 - Easily scaled with no loss of performance (actually improves!)



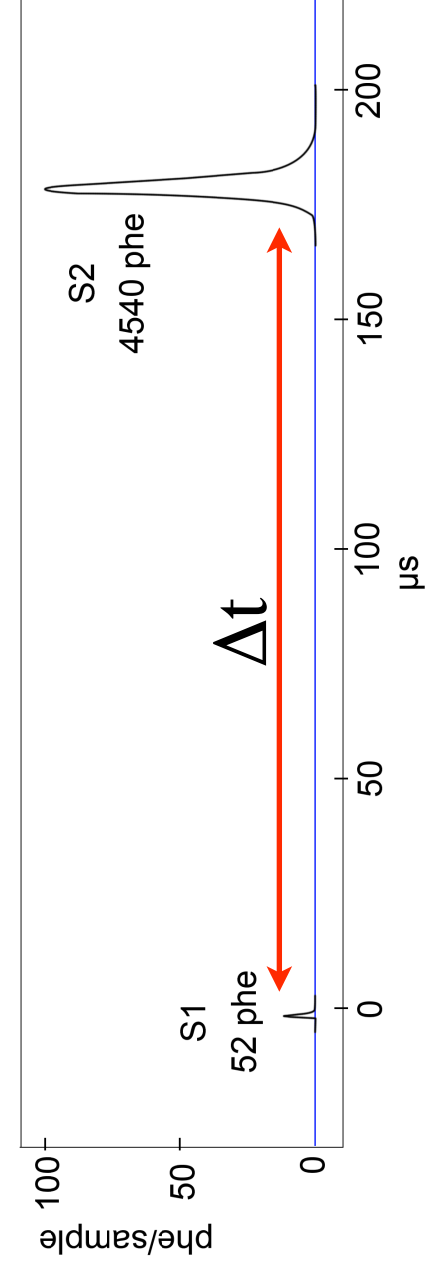
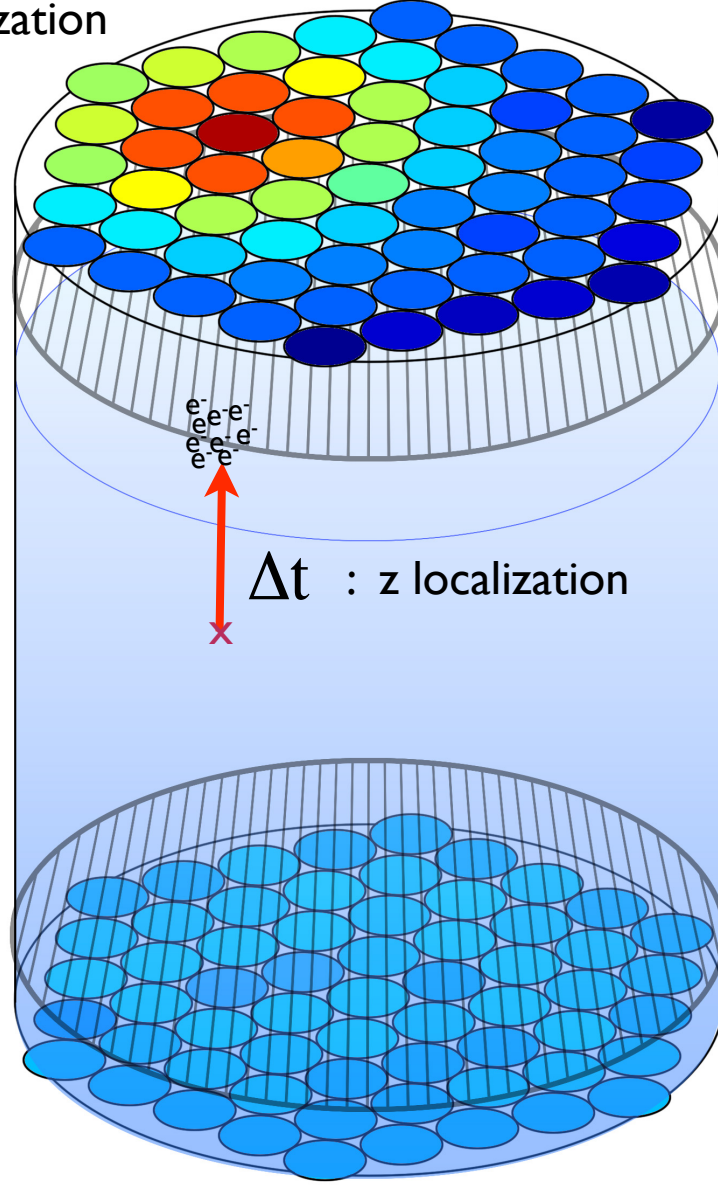


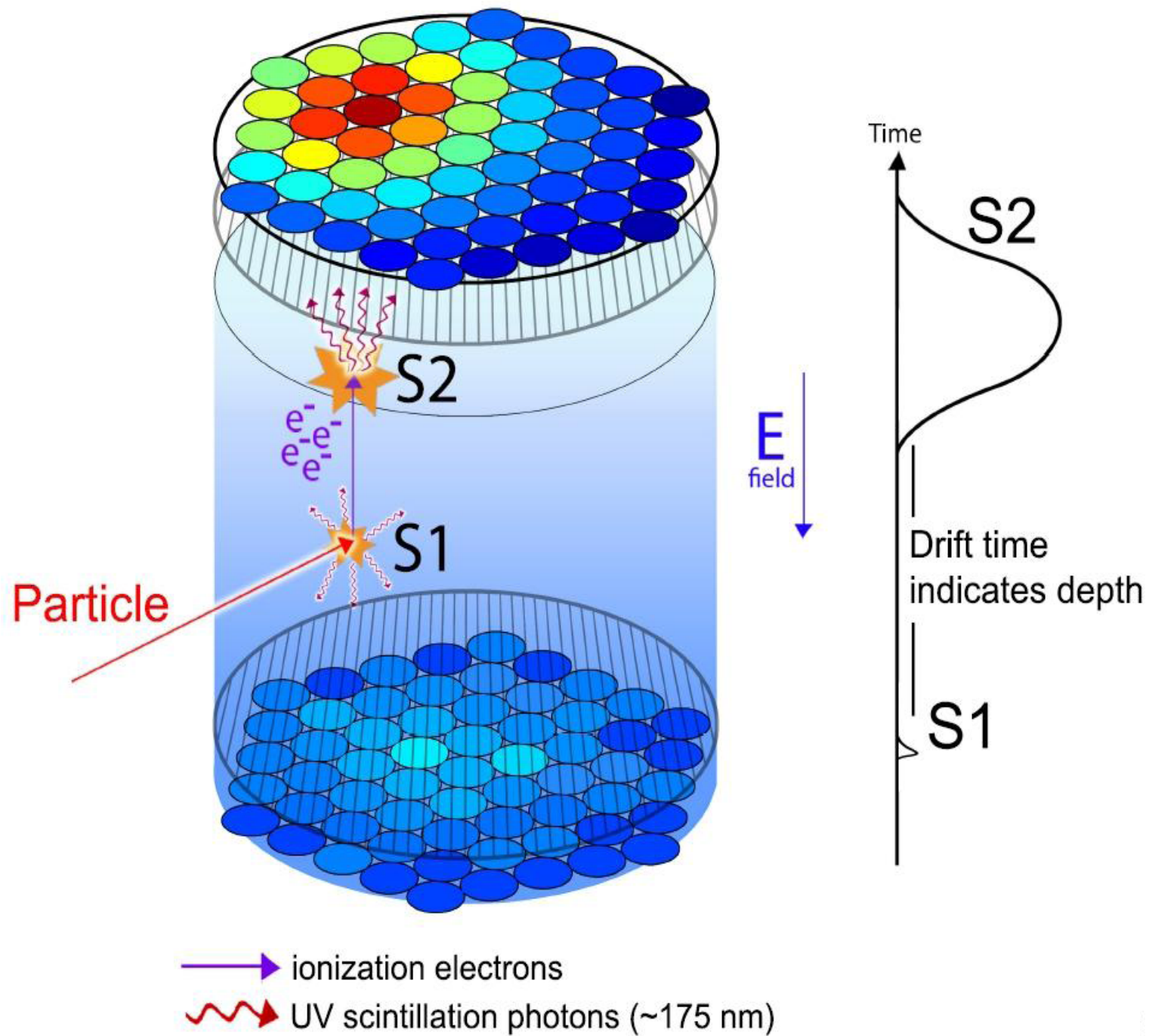
S1



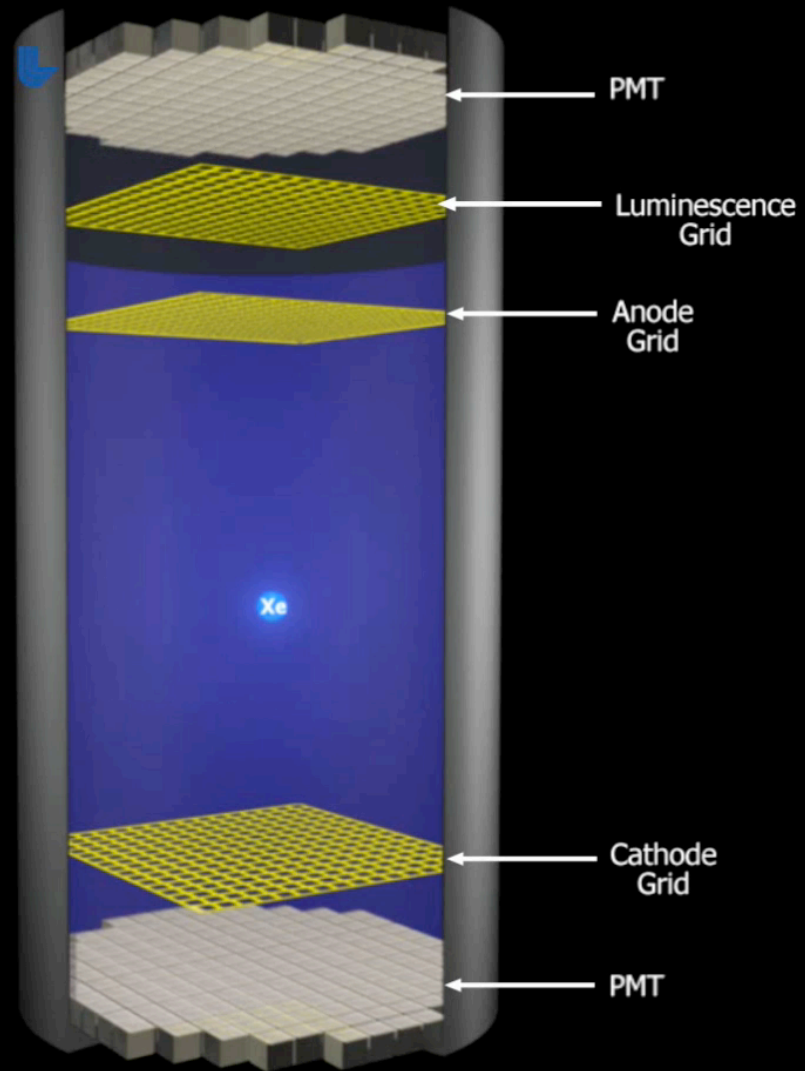
S2

top hit pattern:
x-y localization

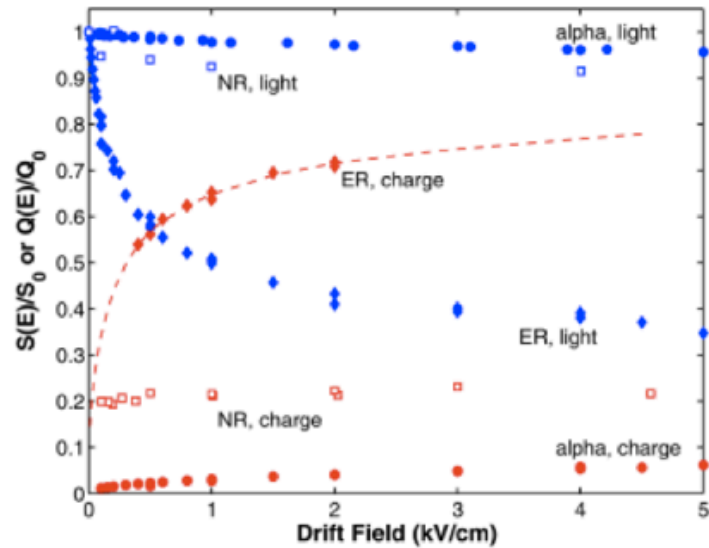




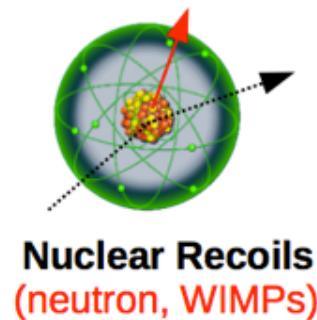
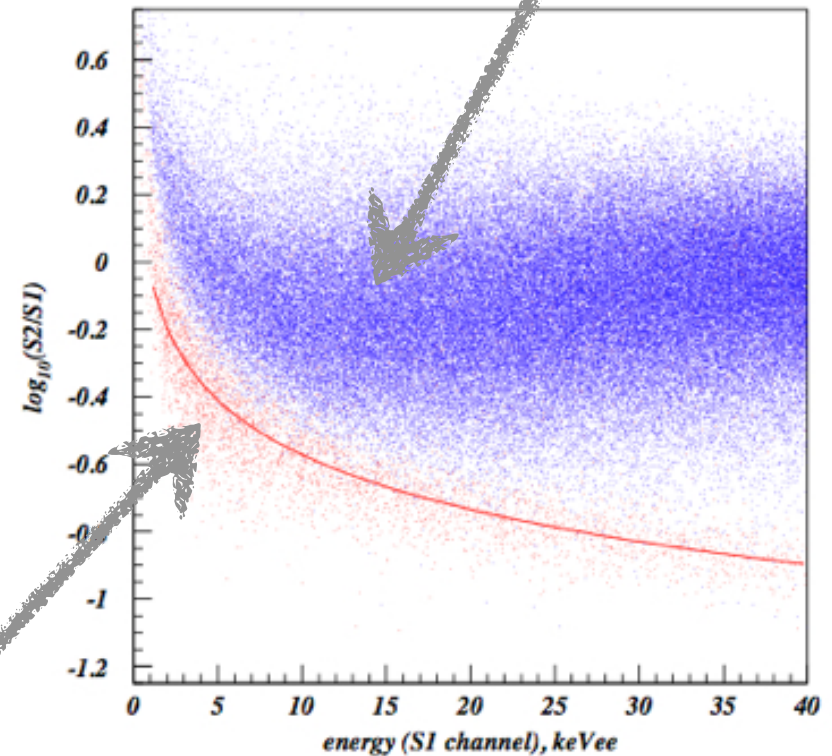
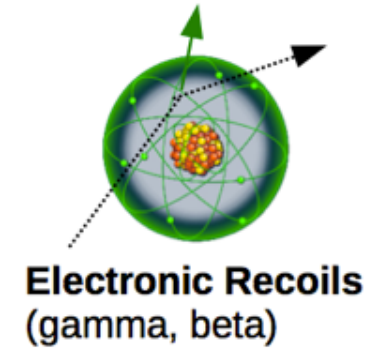
WIMP Signals in a Dual-Phase Xenon Detector



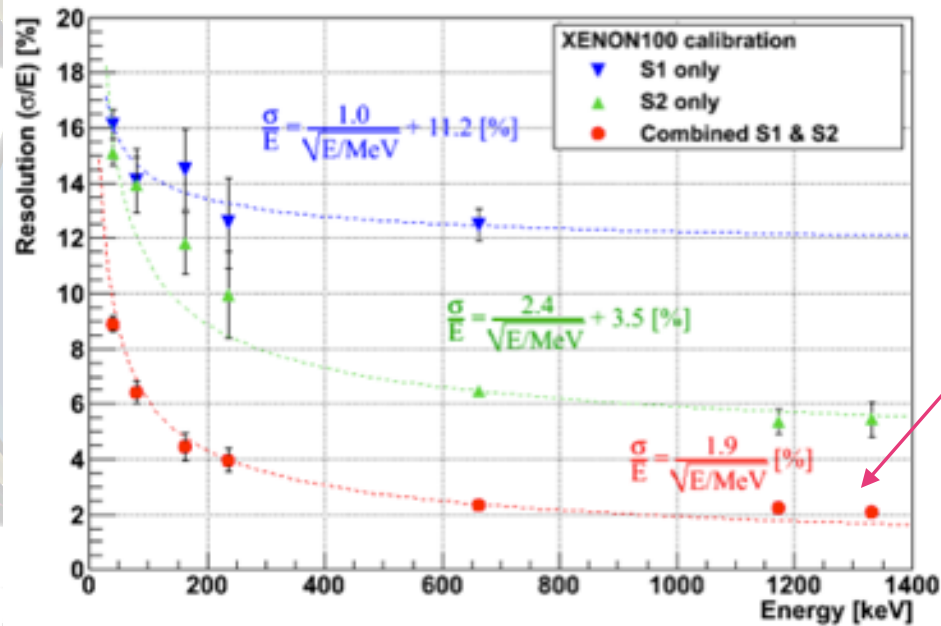
Particle Discrimination



Light (S1) and charge (S2)
depend on recoil dE/dx

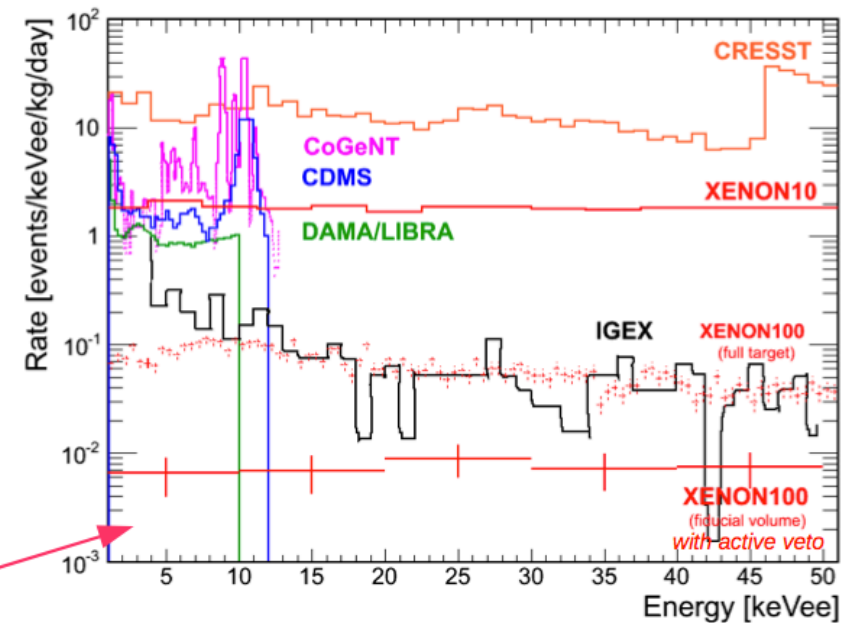


XENON100



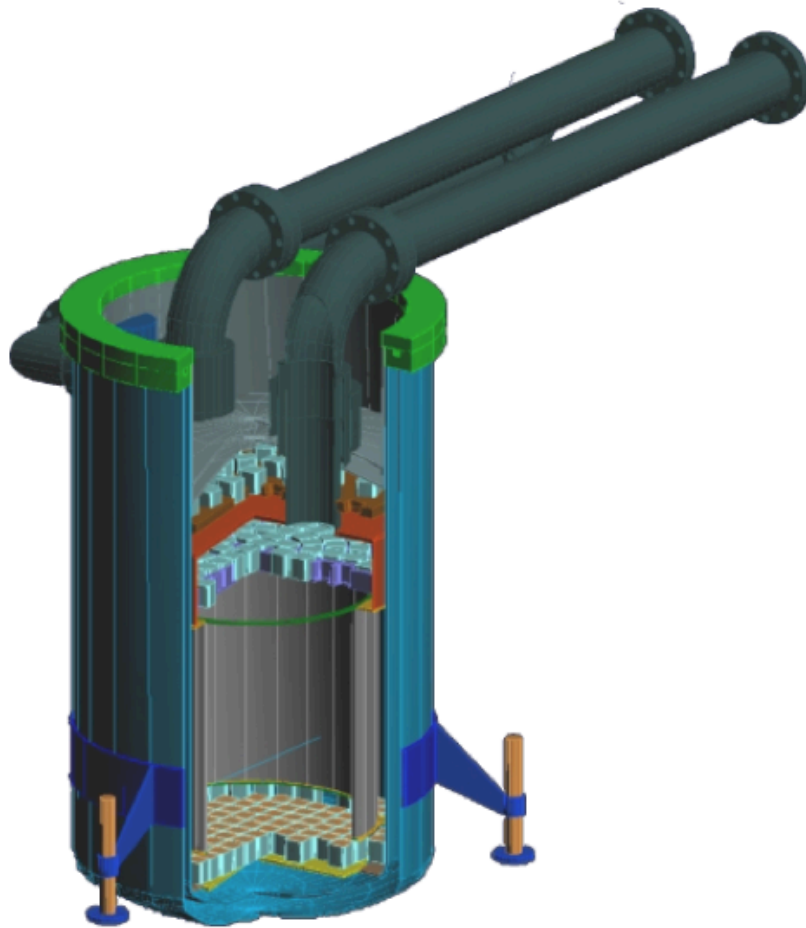
Combined E scale

Fiducialisation



The present world leader

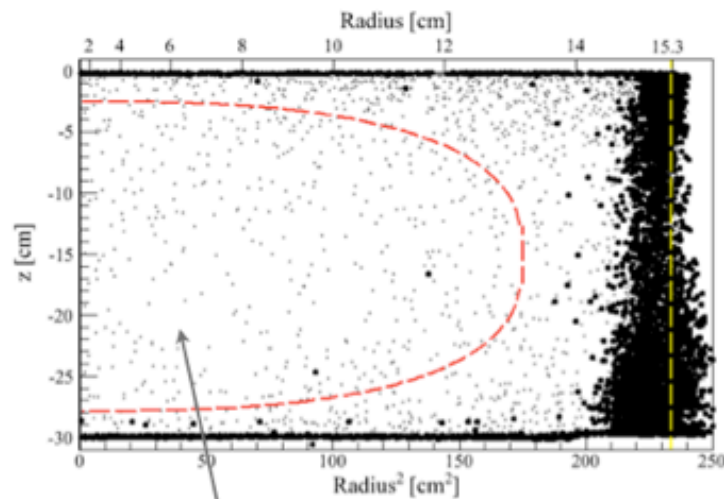
The XENON100 detector overview



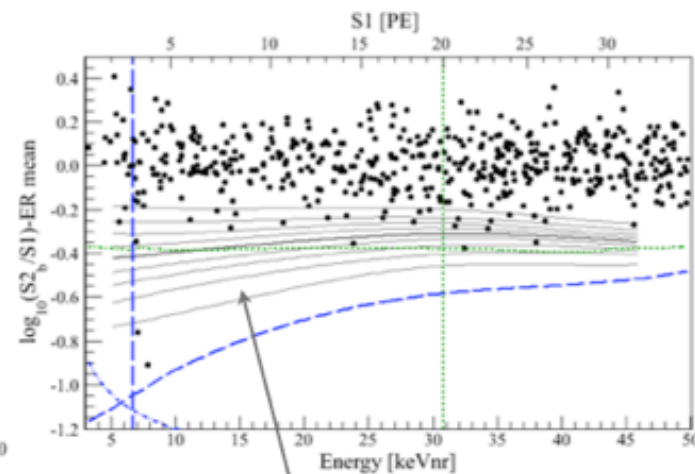
- 100 x less background than XENON10
- 10 x more fiducial mass than XENON10
- Cryocooler and FTs outside shield
- Materials screened for low radioactivity
- LXe scintillator active veto system
- Improved passive shield system
- Dedicated Kr distillation column
- TPC with 30 cm drift x 30 cm diameter
- 161 kg ultra pure LXe - 62 kg as target
- 1" square PMTs with ~ 1 mBq (U/Th)

XENON100

Exposure: 225 days x 34 kg fiducial mass

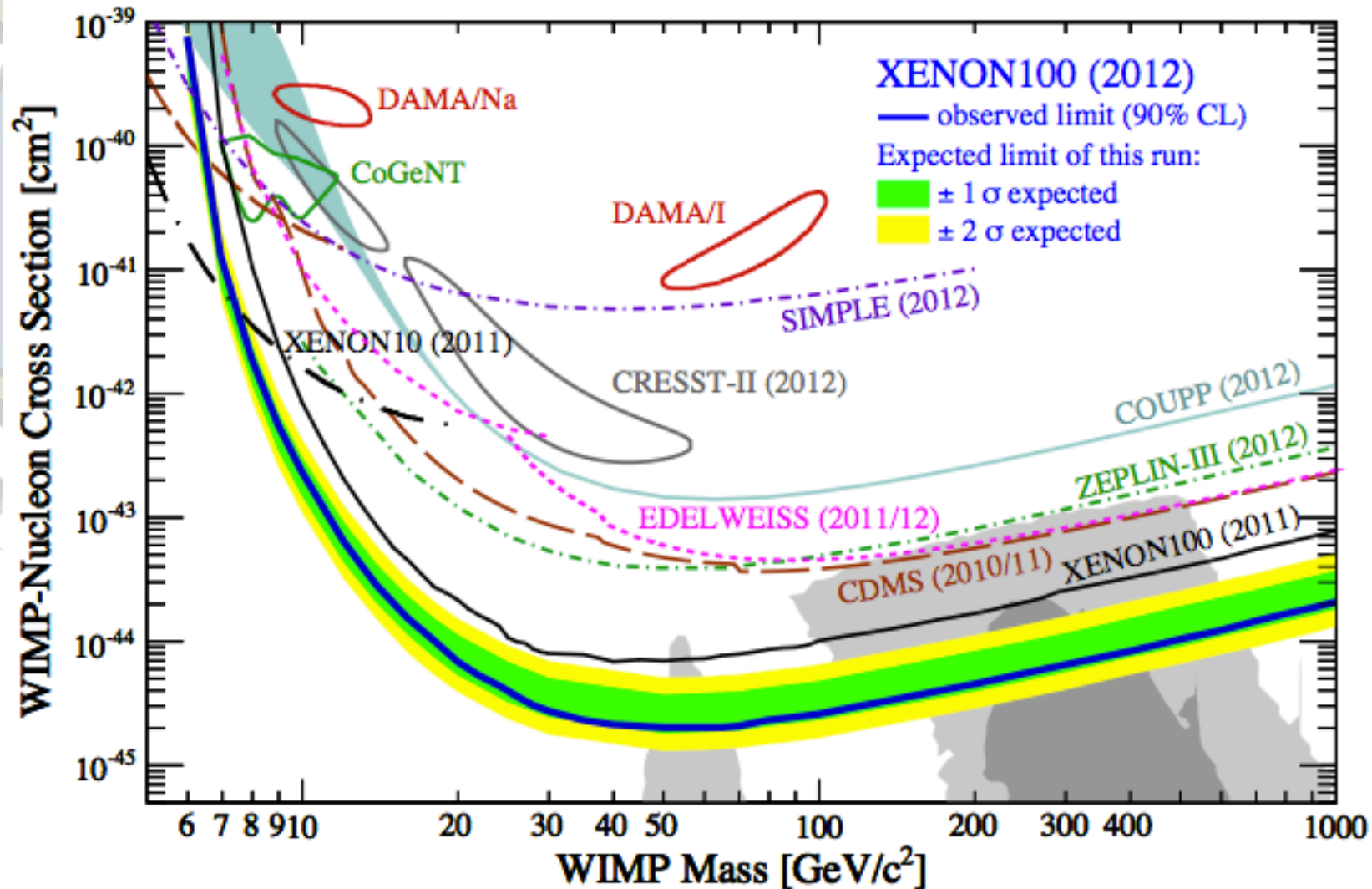


Fiducial mass region:
34 kg of liquid xenon
406 events in total

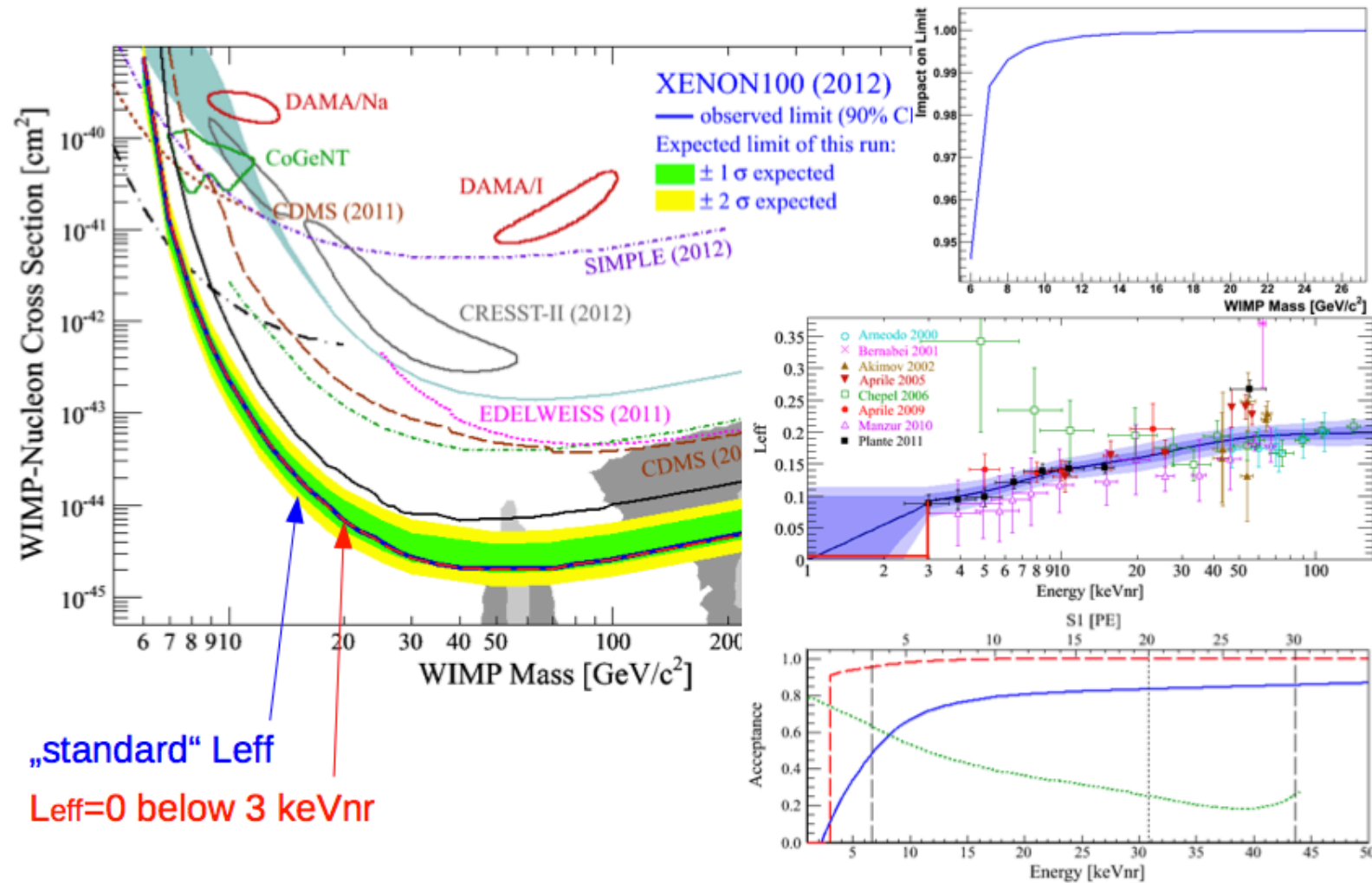


Signal region:
2 events are observed
 0.79 ± 0.16 gamma leakage events expected
 $0.17 +0.12-0.7$ neutron events expected

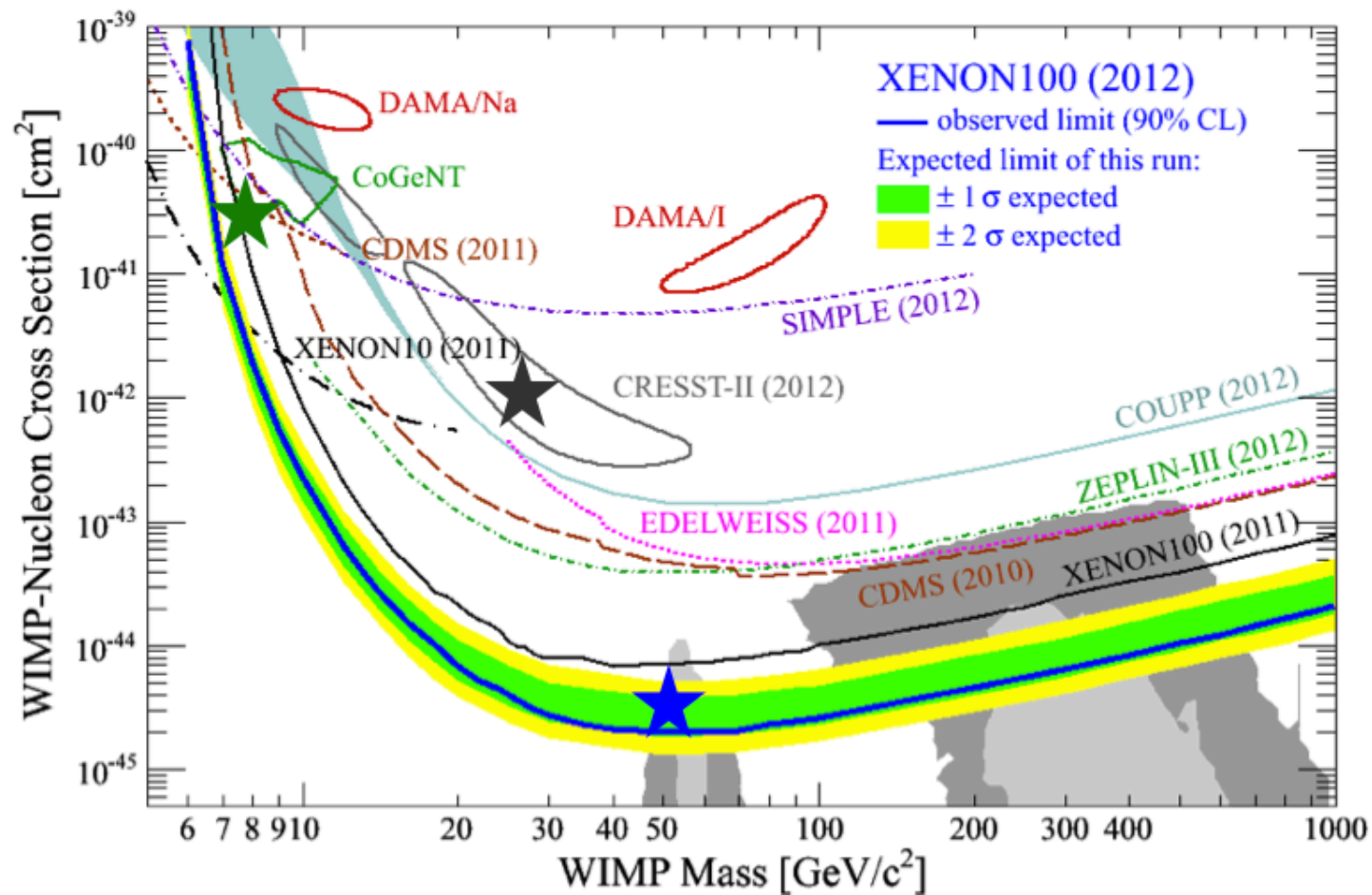
Spin-Independent interaction



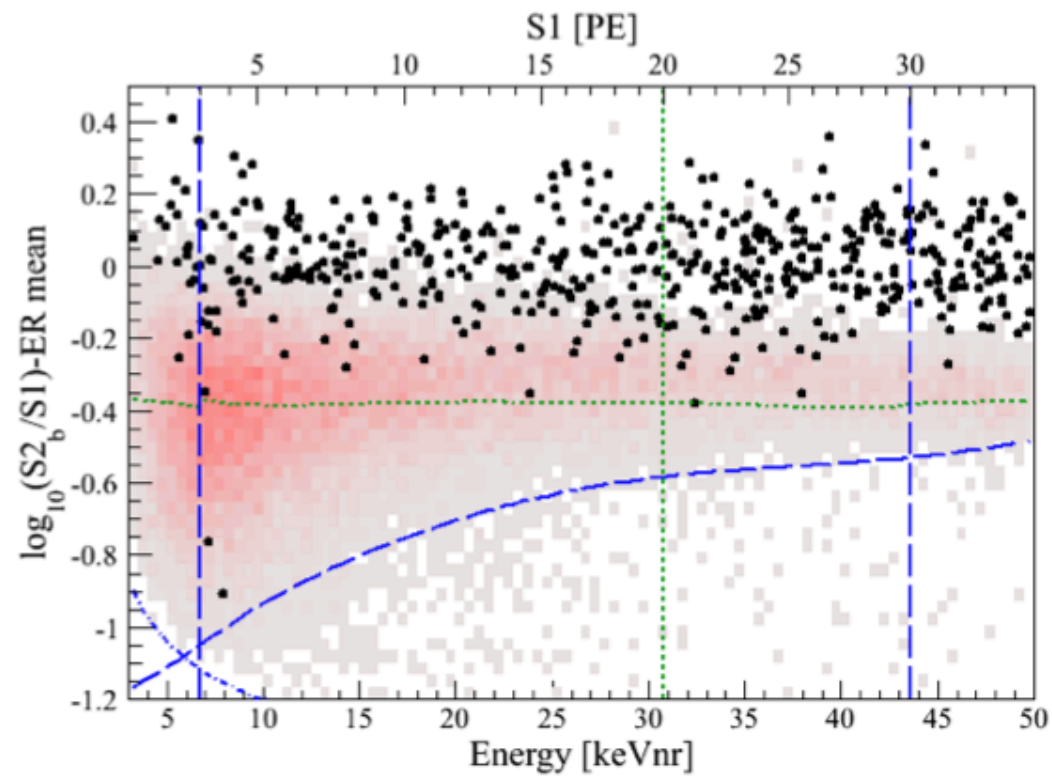
No Impact of L_{eff} below 3 keVr



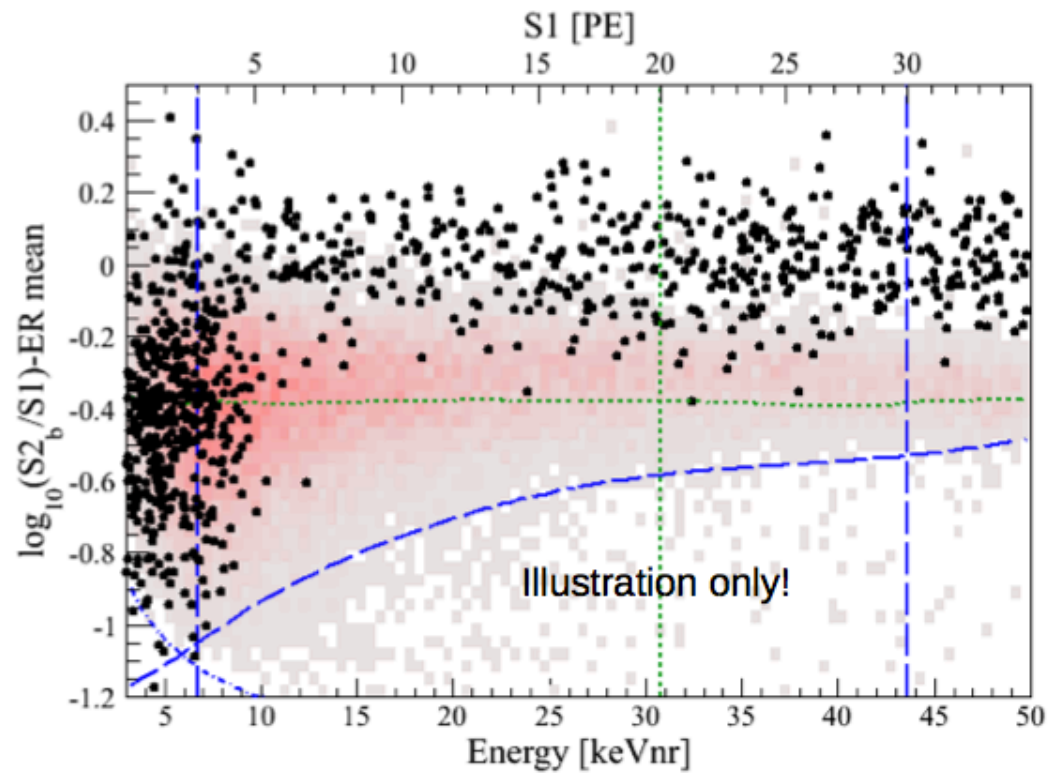
The new XENON100 Limit



What XENON100 sees...

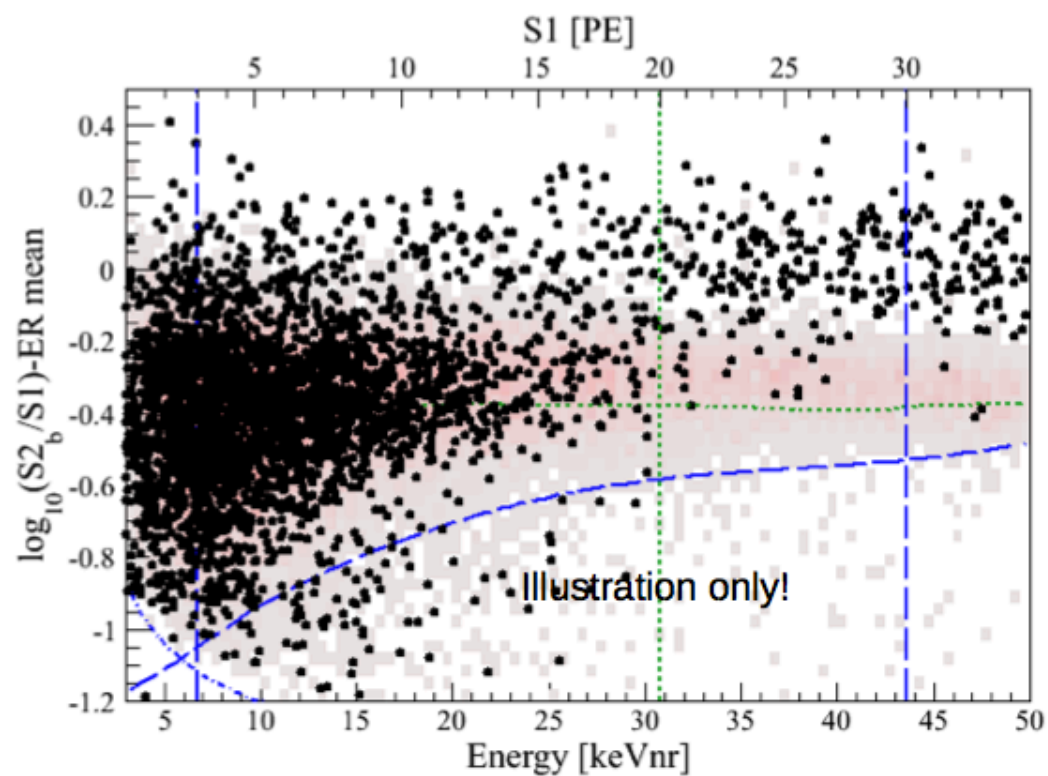


A light mass WIMP...



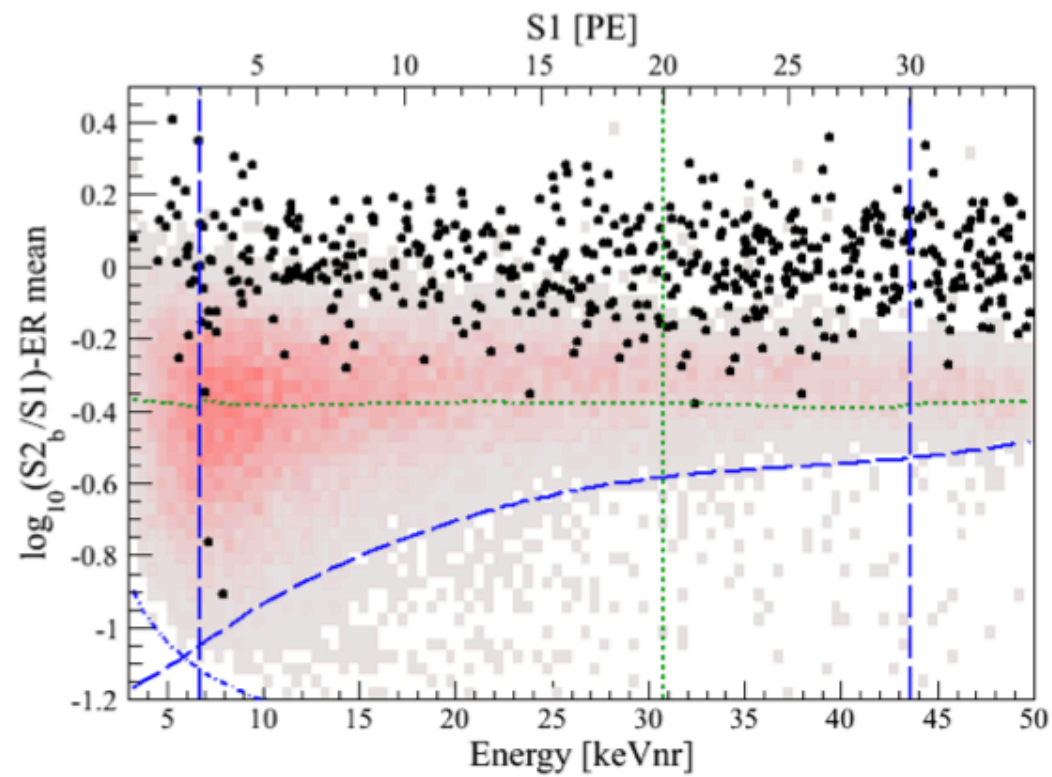
$$m_\chi = 8 \text{ GeV}/c^2 \quad \sigma = 1.0 \times 10^{-40} \text{ cm}^2$$

A CRESST-like signal...

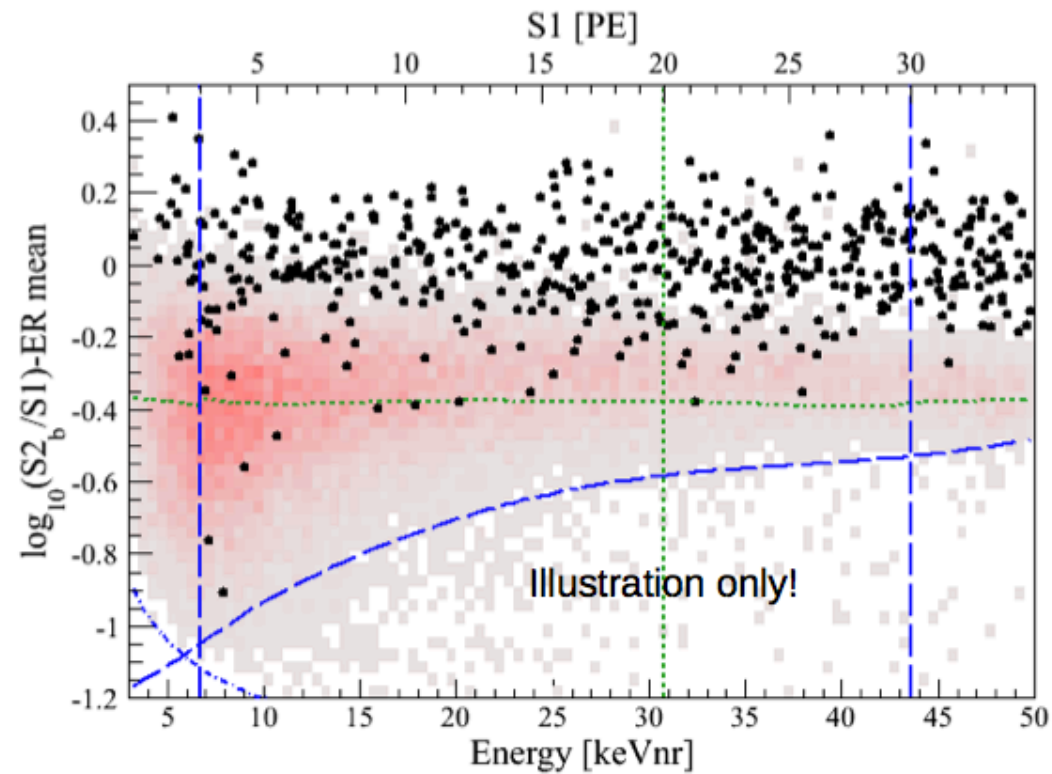


$$m_\chi = 25 \text{ GeV}/c^2 \quad \sigma = 1.6 \times 10^{-40} \text{ cm}^2$$

What XENON100 sees...

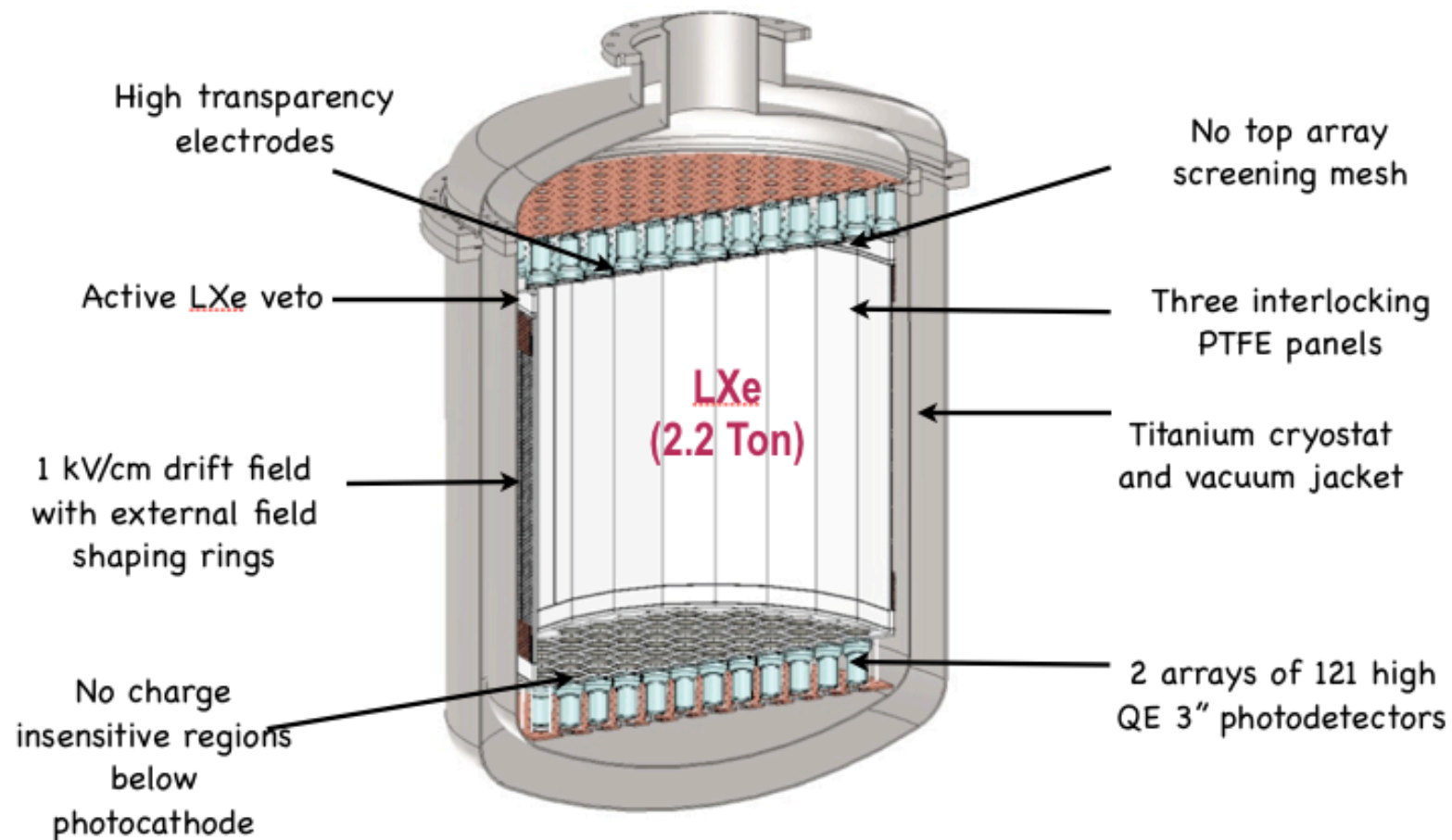


What XENON100 excludes...



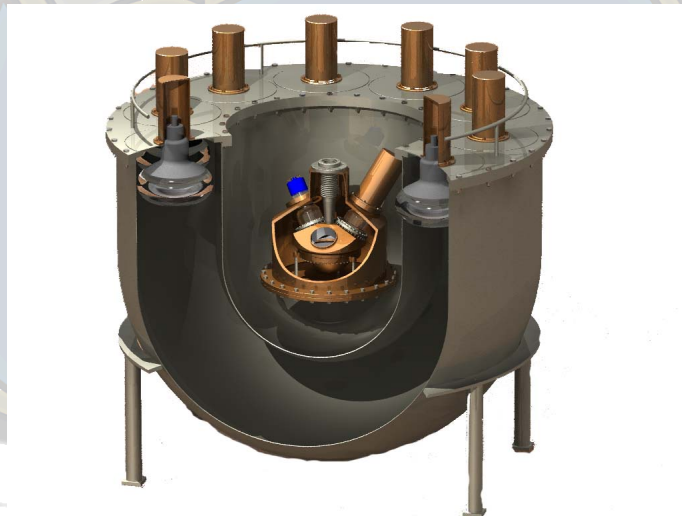
$$m_\chi = 50 \text{ GeV}/c^2 \quad \sigma = 3.0 \times 10^{-45} \text{ cm}^2$$

Future: XENON100 → XENON1T



Operational ~2016

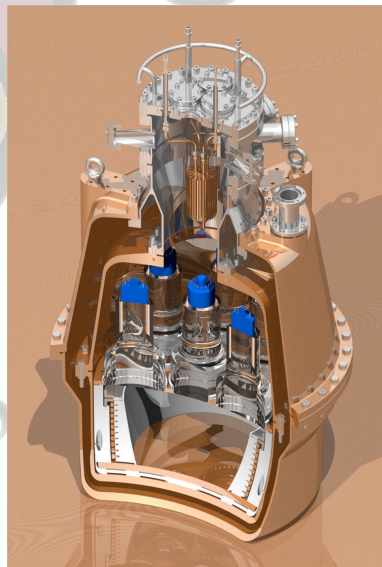
The ZEPLIN programme



ZEPLIN I

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

Single-phase



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!

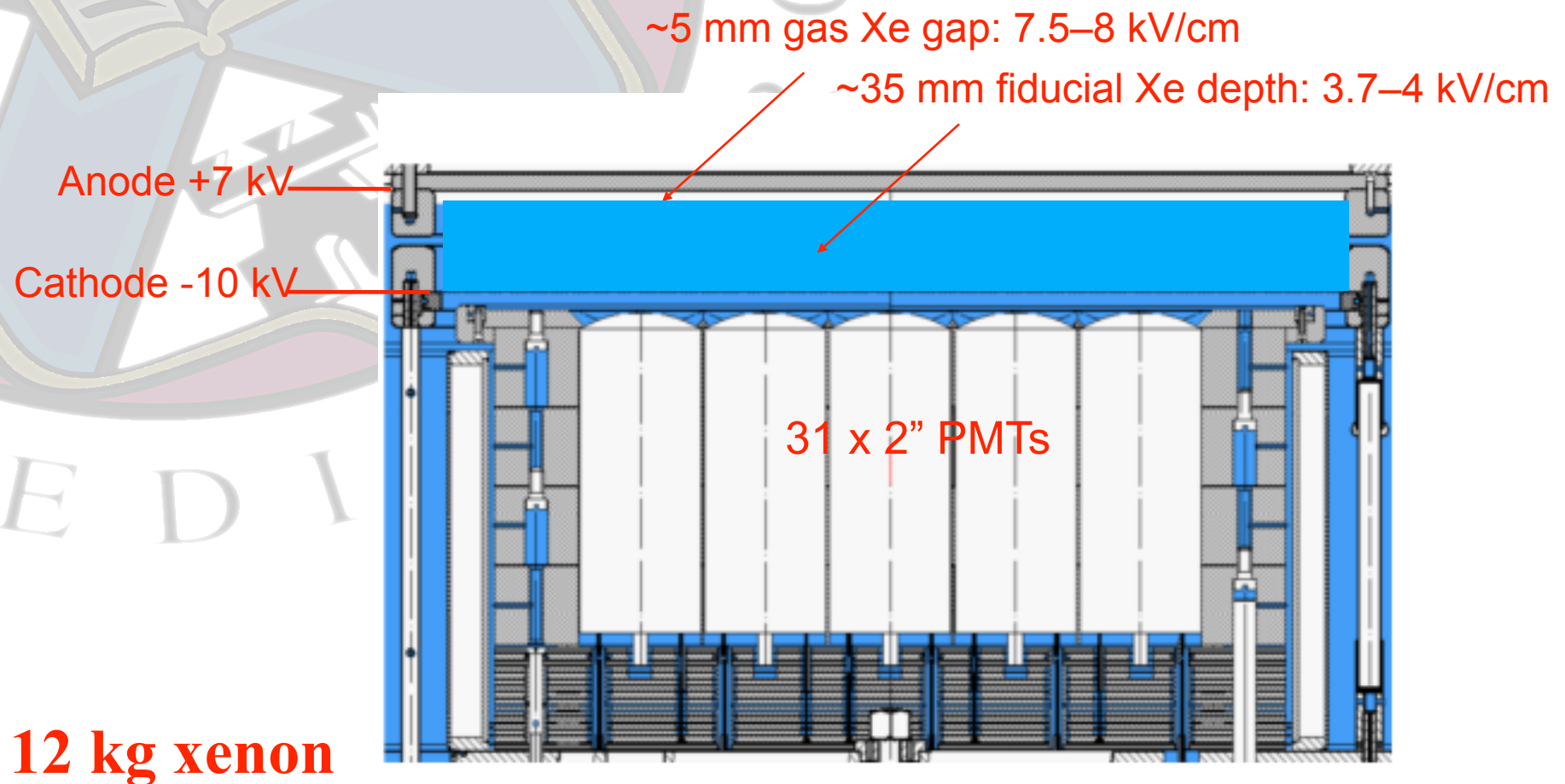


ZEPLIN III

Double phase, 31 PMTs, high E field, 10/6.4 kg
Run 2009-11
Limit: 3.9×10^{-8} pb

Europe's most sensitive SI
World's best WIMP-neutron SD

ZEPLIN-III



ZEPLIN-III Second Science Run Result

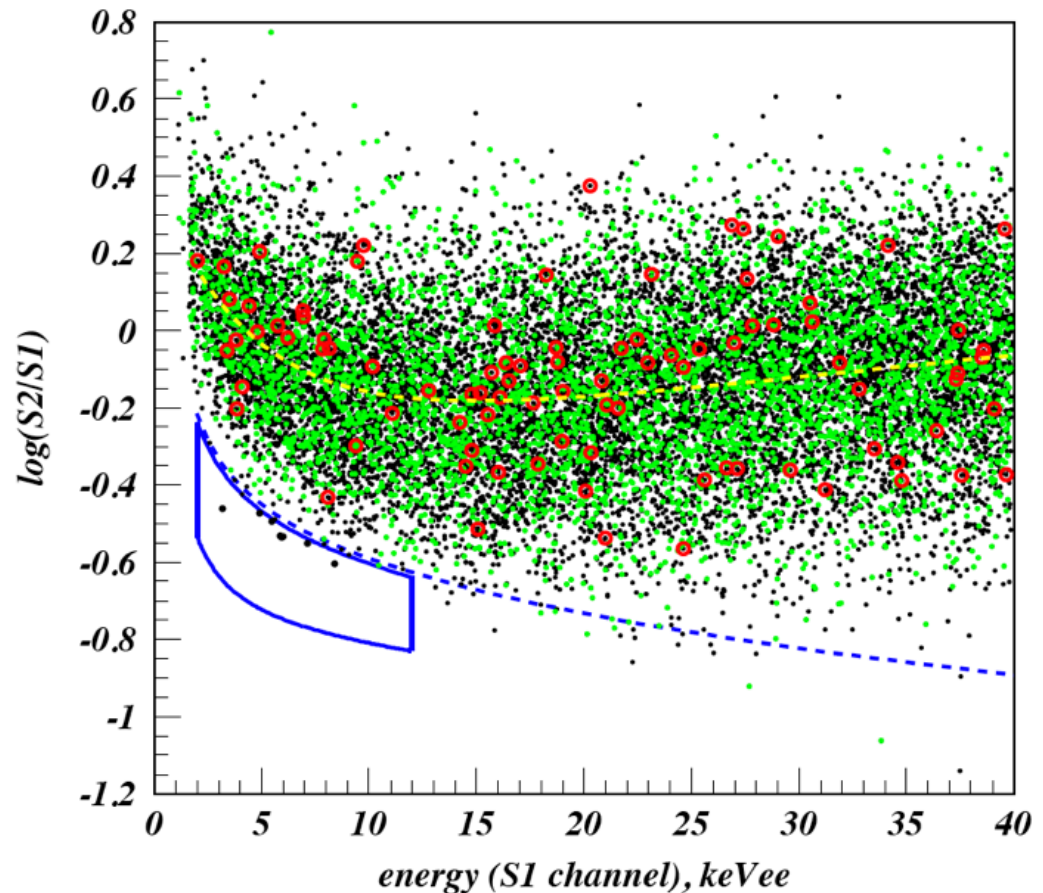
0 neutrons predicted

9 gamma rays predicted

...so what was
seen?

8 events in box

Consistent with γ background
Consistent with zero WIMPs



ZEPLIN Programme

ZEPLIN-I → ZEPLIN-II → ZEPLIN-III



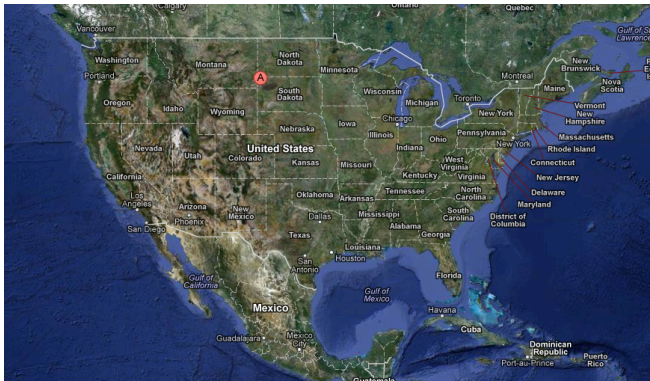
LUX-350

Boulby, UK



Homestake, US

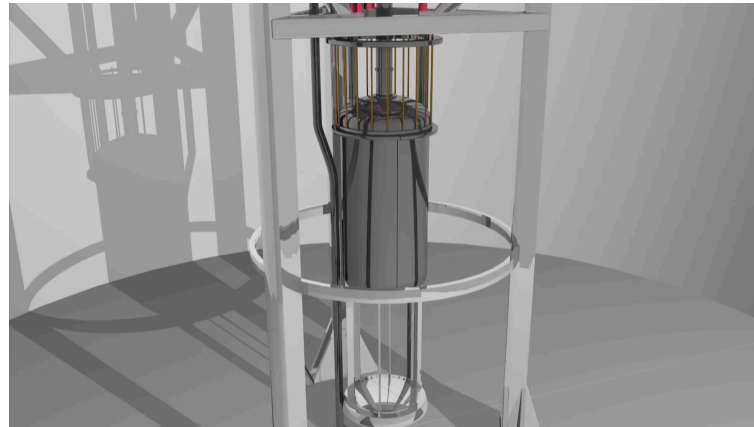




Homestake mine
South Dakota

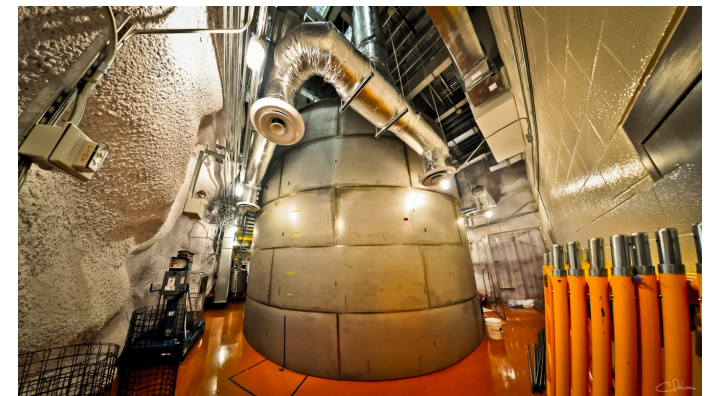


Davis Cavern (5th May 2011)
4850 ft depth



Dec 2011

**World
leader in
2013**



Sept 5th 2012
Water Shield and lab ready for LUX!

LUX Construction

at the Sanford Surface Facility



LUX within the
empty water
tank before
filling (Dec 2012)



Latest news: LUX-350



On track to be **World Leader** in 2013

ZEPLIN Programme

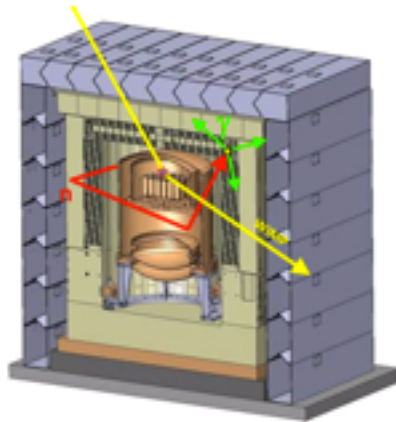
Completed Running Planned

ZEPLIN-II → ZEPLIN-III → LUX-ZEPLIN
LUX-350



Scaling up to LUX-ZEPLIN (LZ)

ZEPLIN-III



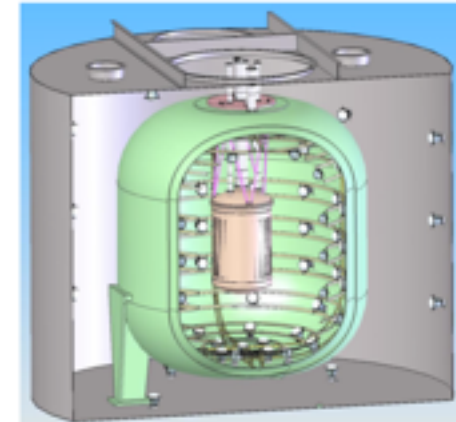
6 kg LXe

LUX



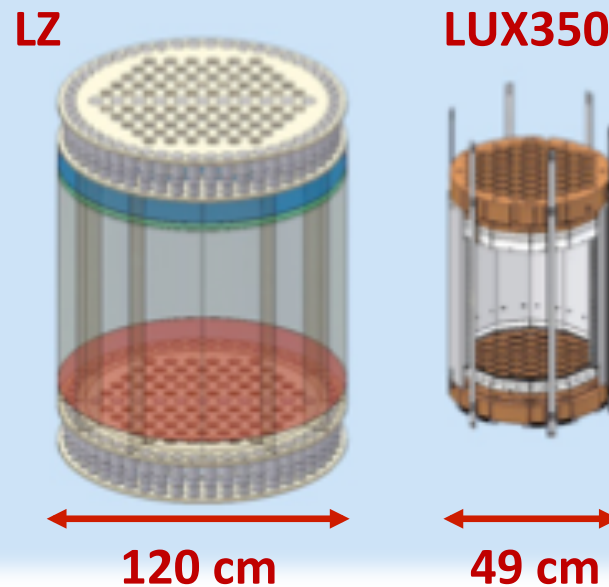
100 kg

LZ



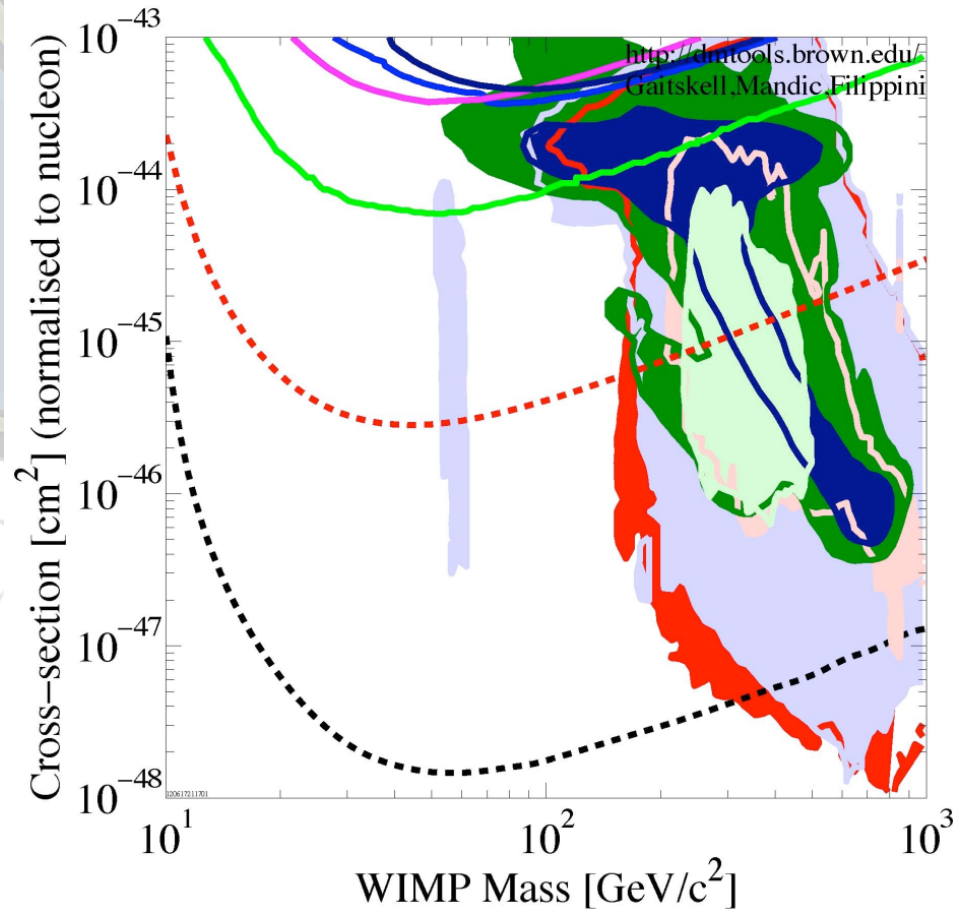
5,000 kg

Multi-tonne: Not so big really



- Modest up-scale from LUX in physical dimensions
- Huge background reduction from self-shielding & vertex reconstruction
- 7T LXeTPC to fit in LUX water tank; inherits much infrastructure

Science reach



Elastic scattering SI cross-section

Results

ZEPLIN-III 2011 (magenta)

XENON100 2011 (green)

XENON100 2012 (grey)

EDELWEISS II 2011 (dark blue)

CDMS-II 2010 (blue)

Projections

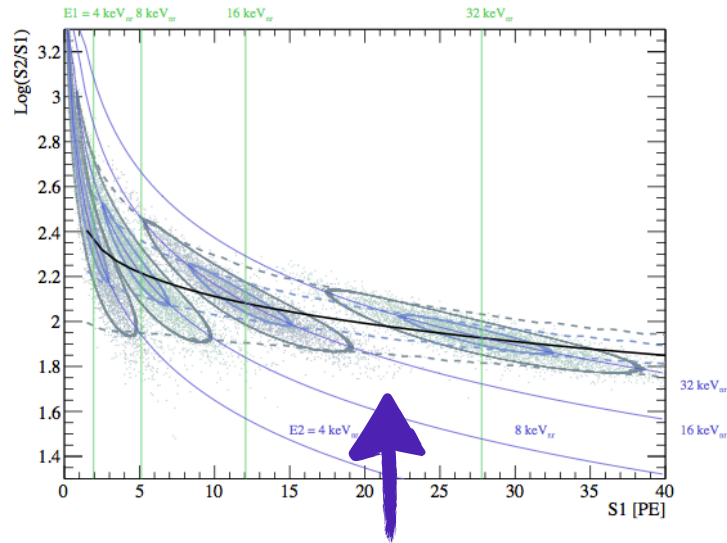
LUX (red dash)

100 kg fiducial x 300 live days

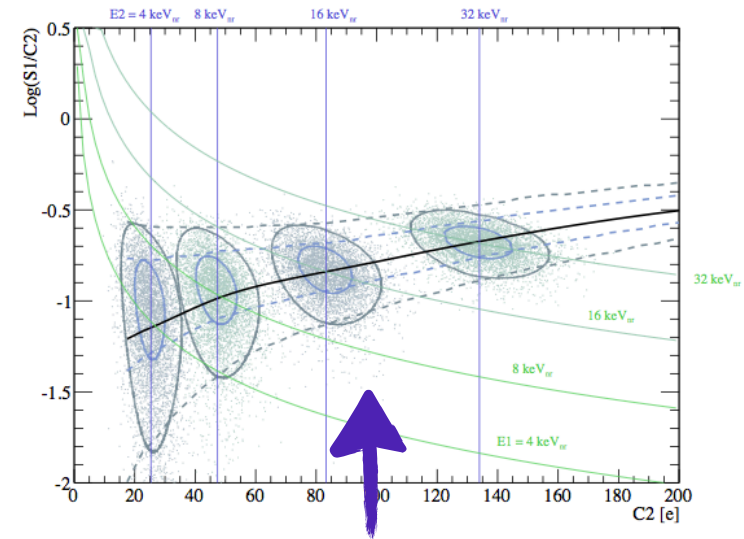
LUX-ZEPLIN (black dash)

5-tonne fiducial x 1,000 live days

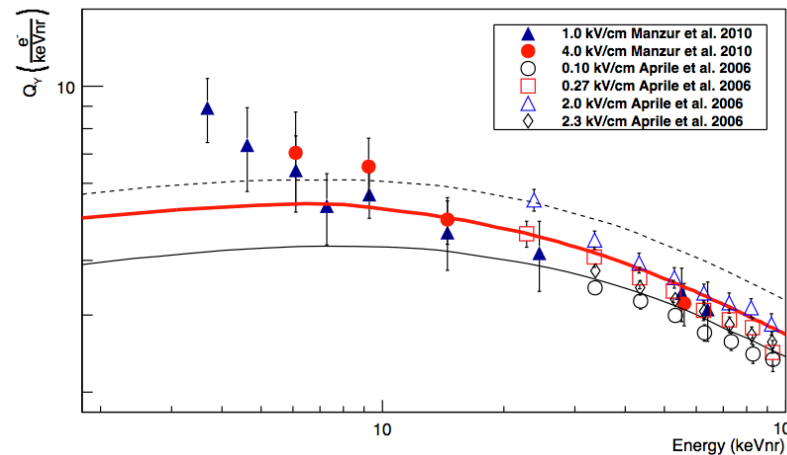
(Further) Exploiting the Ionisation Channel



To go from this...



to this...

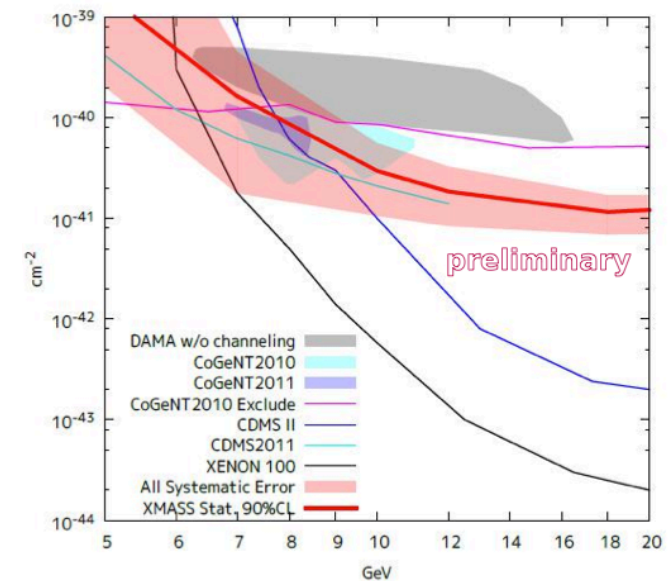
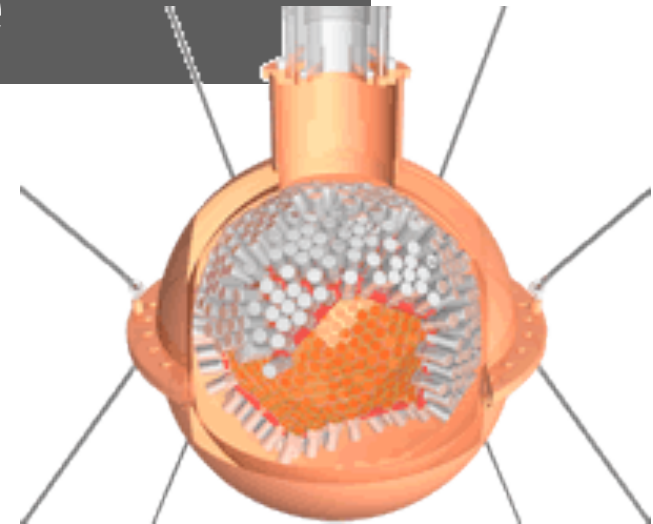


...we need this!

Liquid Xe single-phase

XMASS

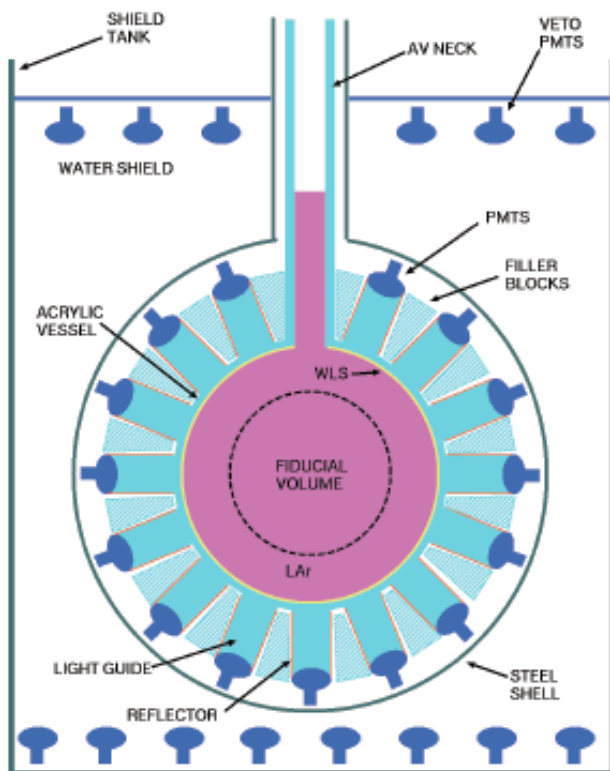
- Based at Kamioka, Japan
- Single phase detector (no S2 signals)
- 100 kg Xe fiducial (800 kg fiducial)
- Unexpected background observed
- Performance severely compromised
- Undergoing refurbishment of PMTs



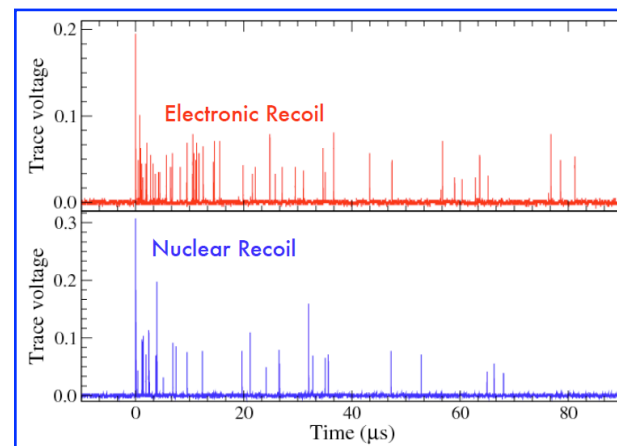
Liquid Ar single-phase

DEAP/CLEAN

SNOlab, Ca



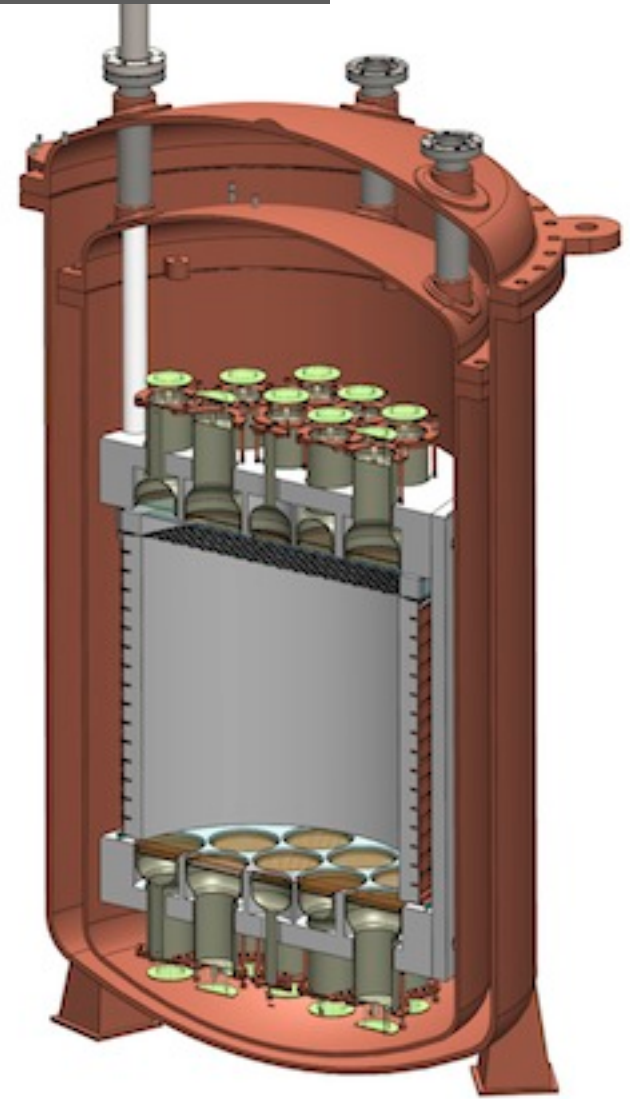
- LAr for powerful PSD
- 2 detectors in parallel development
- miniCLEAN: 150 kg fid. 2013 start
- DEAP3600: 1T fid. 2014-17 run
- Threshold $\sim 40\text{-}50$ keV due to ^{39}Ar
- DEAP/CLEAN 10T fid. successor



Liquid Ar 2-phase TPCs

DARKSIDE-50

- Based at LNGS, under construction
- Neutron veto inside Borexino CTF
- Used underground (depleted) Ar target
- Adopts v. successful Xe technology
- PSD + S2/S1 discrimination
- 3D position reconstruction for surface background rejection (ala LXeTPCs)



Cryogenic bolometers

SuperCDMS

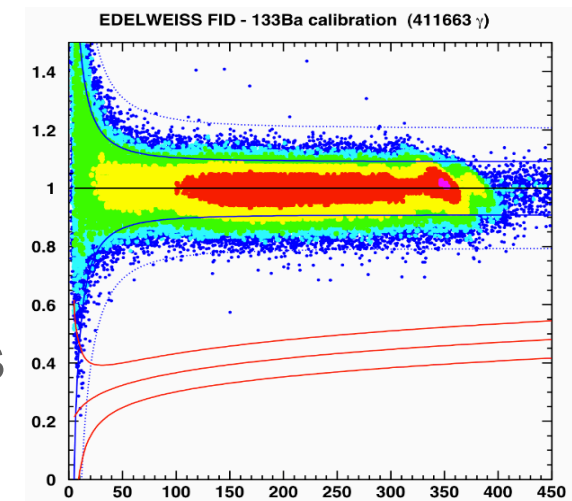
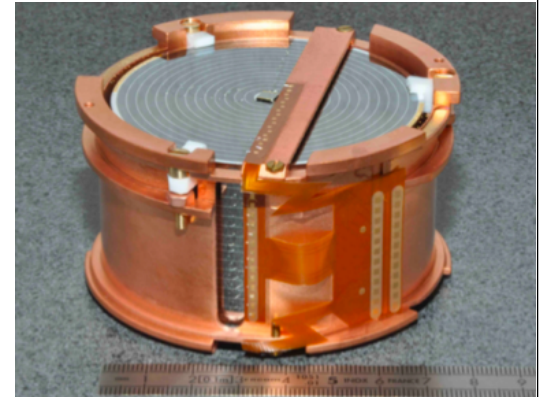
- CDMS (Soudan), world leader before XENON100
- Rules out CoGeNT with same (Ge) target
- Z-sensitive Ionization and Phonon (ZIP) detectors
- Segmented (x,y) with t_0 from phonons
- Excellent discrimination
- Low threshold
- SuperCDMS to be ~400 kg target



Cryogenic bolometers

EDELWEISS-II → EDELWEISS-III → EURECA
CRESST-II

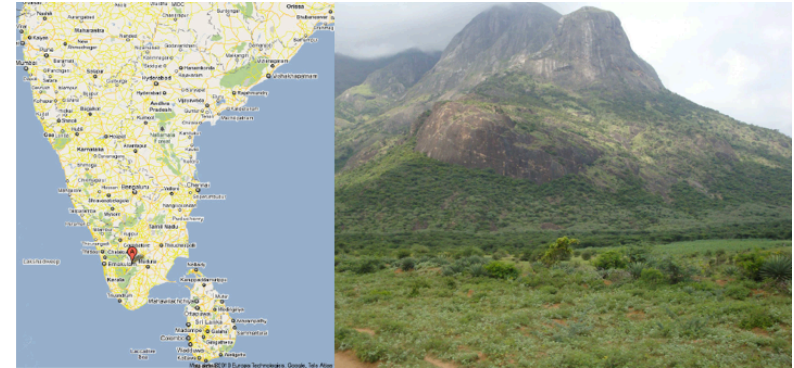
- Similar technology to CDMS
- Based in Modane (EDELWEISS) and LNGS (CRESST)
- Cryogenic Ge and CaWO_4
- Excellent discrimination
- Efficiency to ~ 5 keV for low mass WIMPs
- EURECA will be 1T successor: 2018



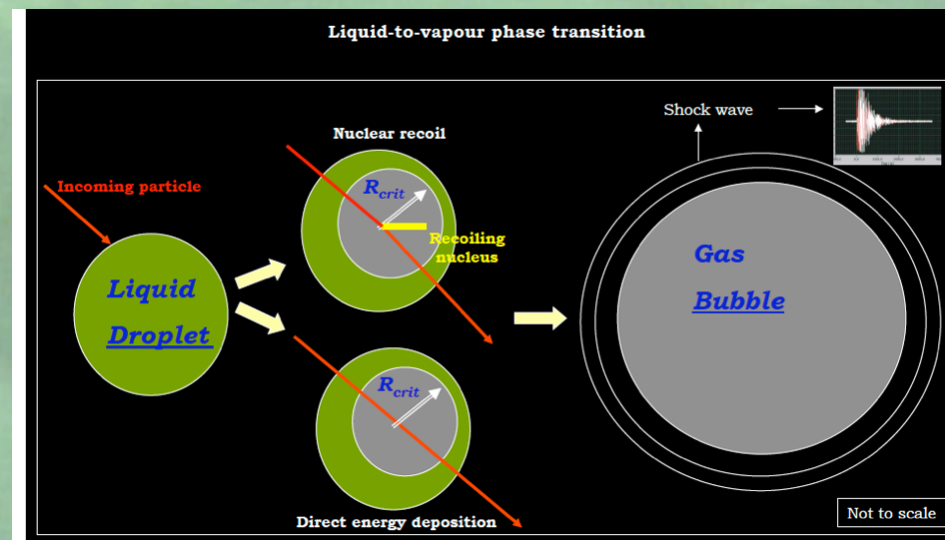
Silicon crystal detectors

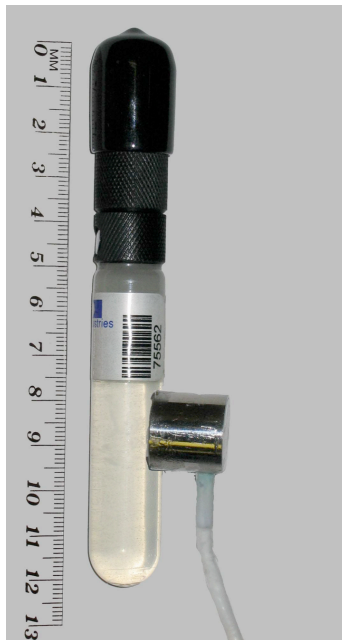
DINO

- Dark Matter at the INO
- Si crystal detectors
- 30 kg prototype at Jaduguda mines near Jamshedpur
- Prototype operational in 1-2 years



Superheated Droplet detectors





1st generation* : 10ml



2nd generation : 1L



3rd generation : 4.5L

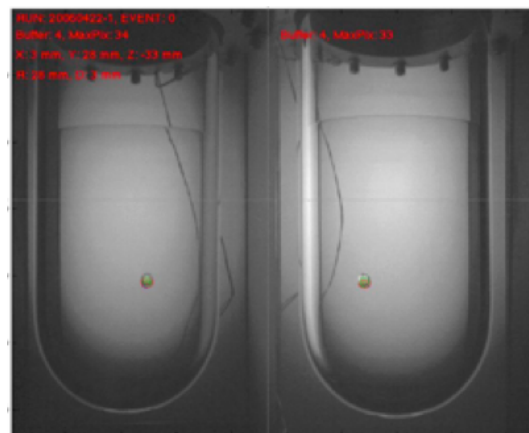
Picasso



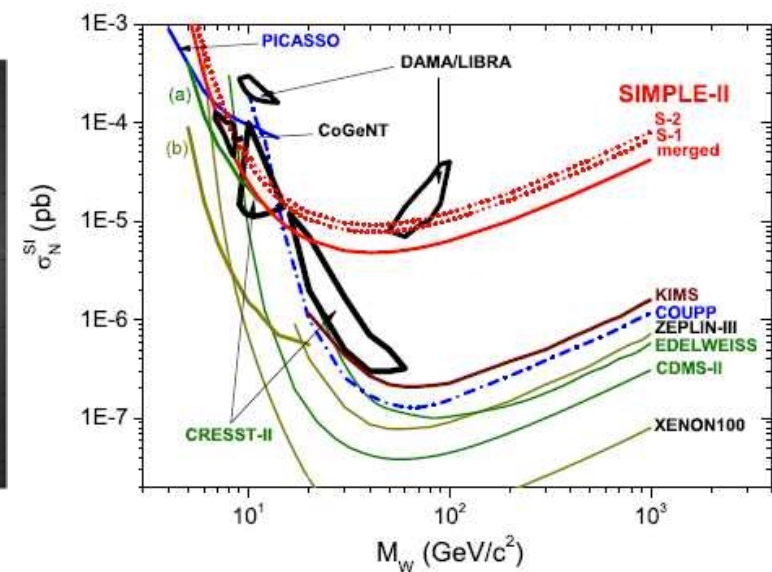
SNOLAB, Ca



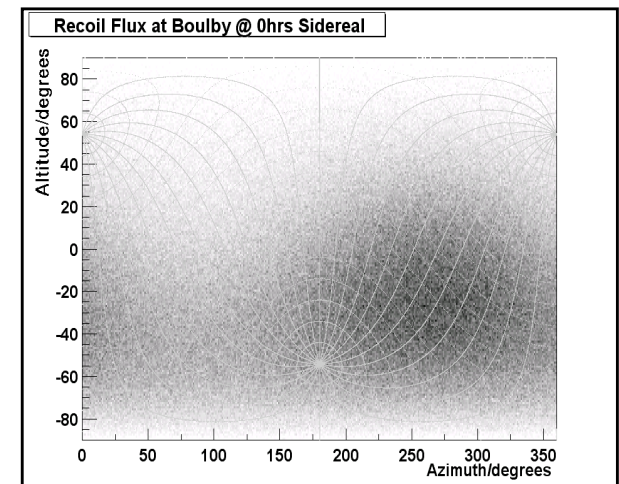
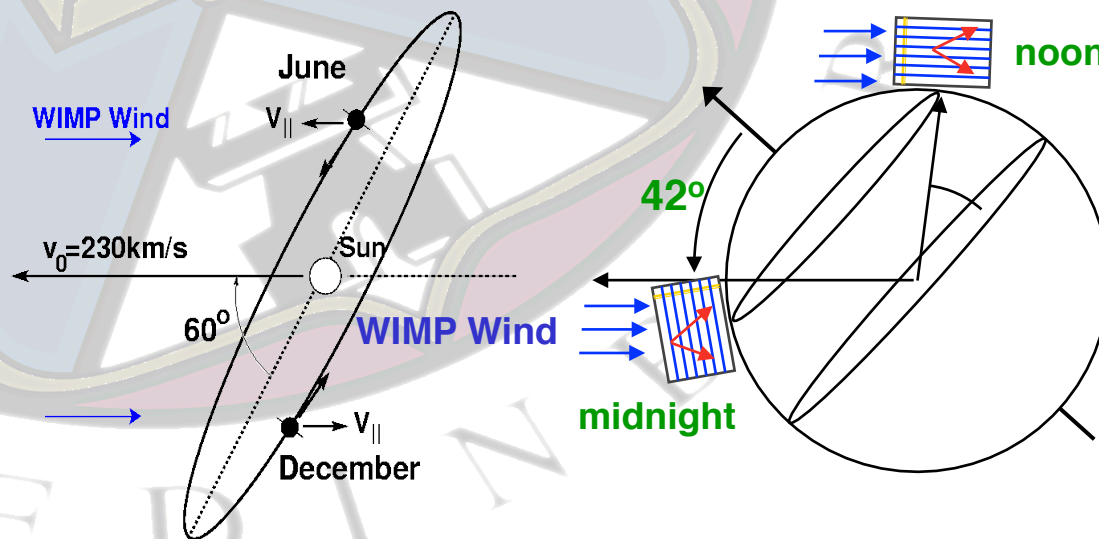
SIMPLE (Freon target)



COUPP (CF₃I)



Directional gas TPCs



- Directionality robustly tests Galactic origin of signal

Annual modulation

~10% variation in signal strength
Small change in energy spectrum

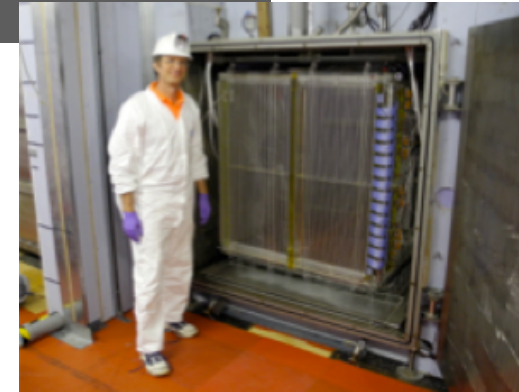
Diurnal signature - goes in and out of phase with solar day-night cycle.

Directional asymmetry ~50%

Directional gas TPCs

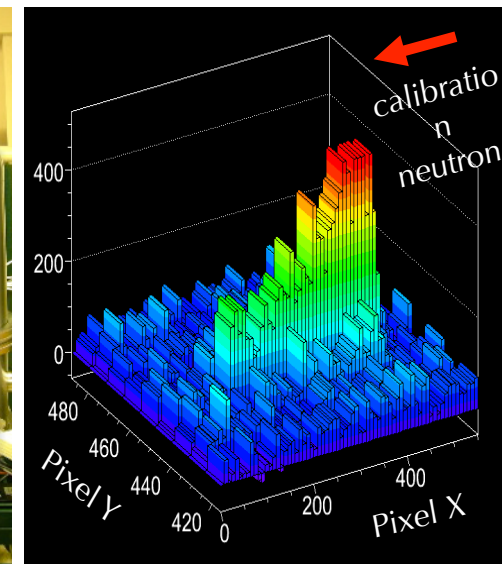
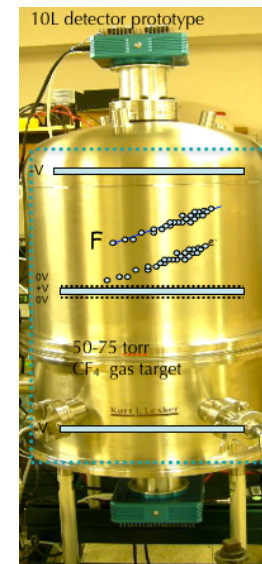
DRIFT-II/III

- $\text{CS}_2:\text{CF}_4$ low pressure target (33 g fid.)
- MWPC readout for 3D track reconstruction
- 1 m³ modules in Boulby Mine, UK
- DRIFT-III plans for 24 m³



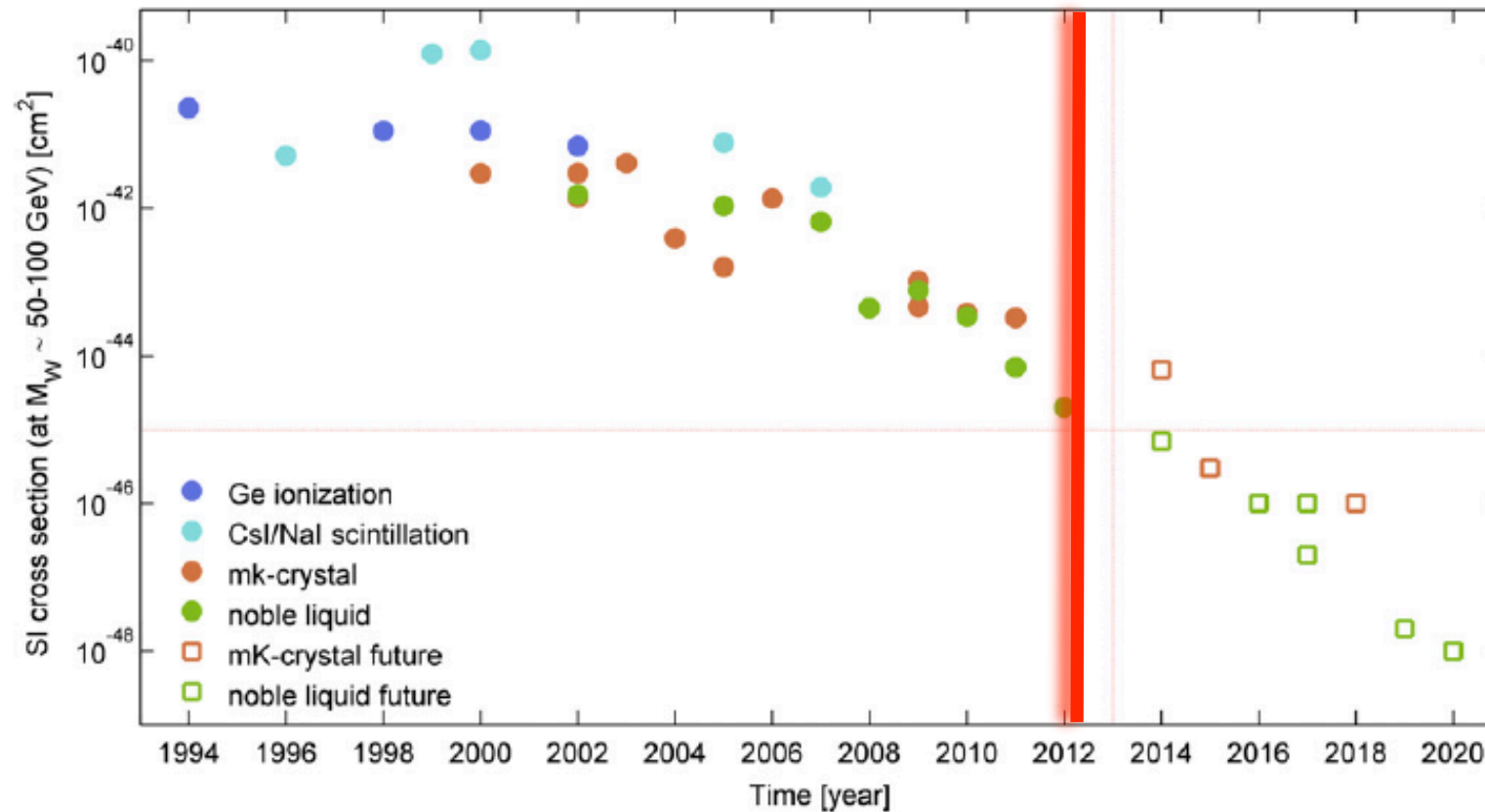
DMTPC

- CF_4 target (10l prototype)
- 1 m³ modules in development
- Charge and optical readout



The future

Stated sensitivity aims



Remarkable technical innovation will drive to further enormous progress

A new collaboration...

- A lot of activity in the UK....!



Imperial College
London



US
University of Sussex

Royal Holloway
University of London

EDELWEISS

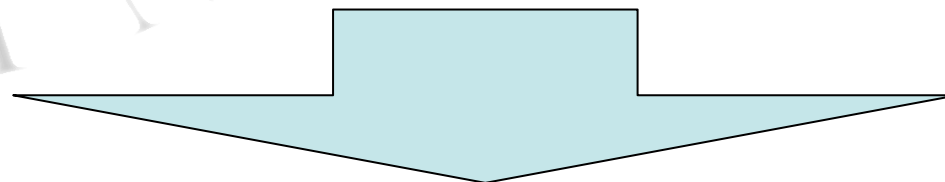
EURECA

DEAP/CLEAN

DRIFT

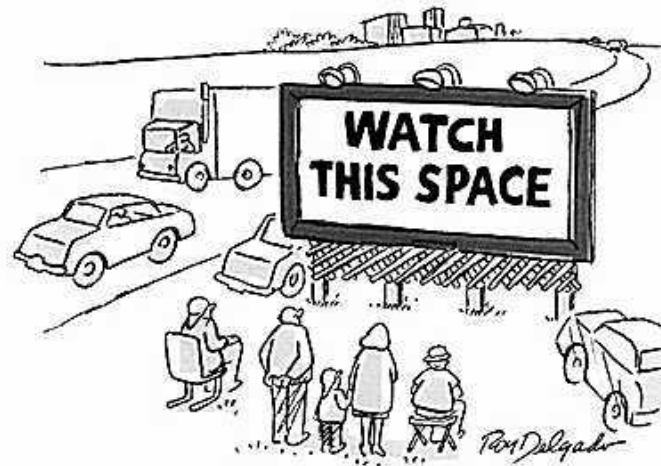
LUX

LZ



DMUK

Exciting times ahead....



Thank you all for listening!