DARK MATTER

Searching for Physics Beyond the Standard Model

Presented by Chamkaur Ghag

on behalf of Alex Murphy

Outline

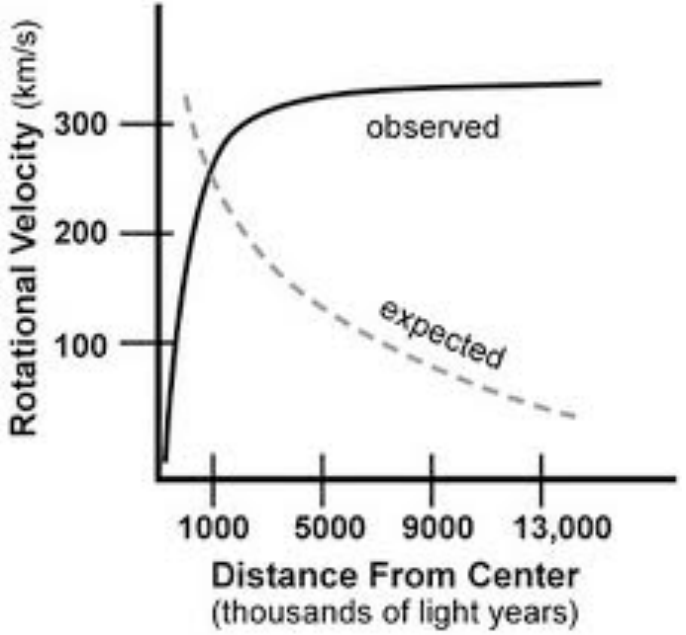
- Evidence for Dark Matter
- How do we search?
- Recent results
- Looking to the future

The Evidence

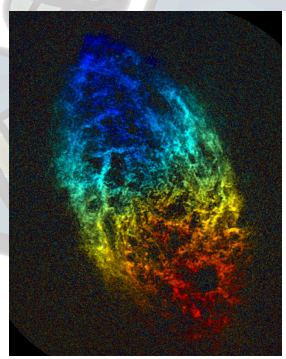
Early evidence

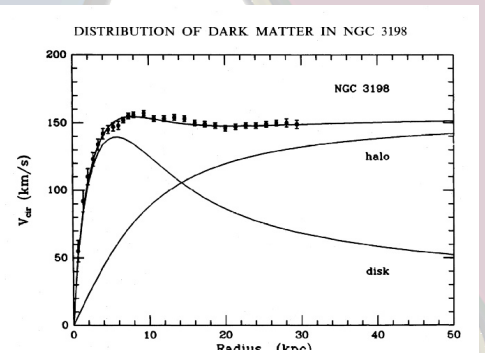
1930's - Fritz Zwicky
1970's - Vera Ruben
Measured rotational velocity of galaxies and observed flat curves rather than expected Keplerian fall-off with distance from galactic centre

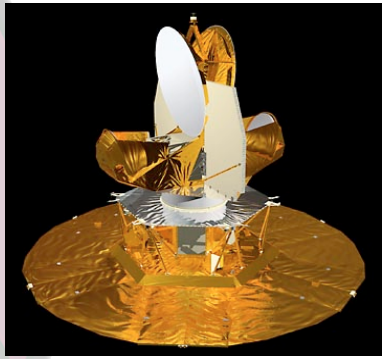
GALAXIES ARE ROTATING TOO FAST!

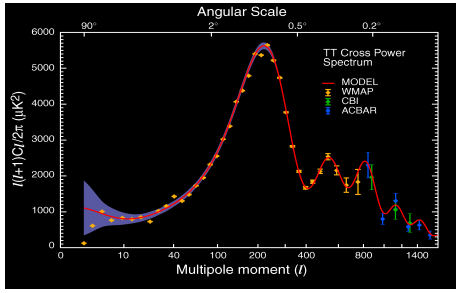


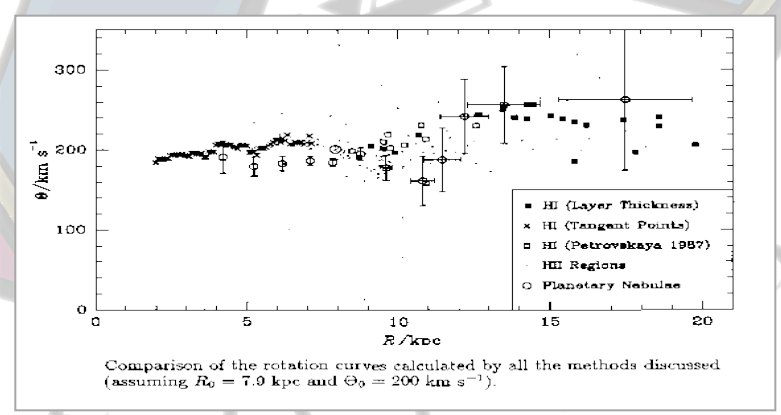
Lots more evidence since then...



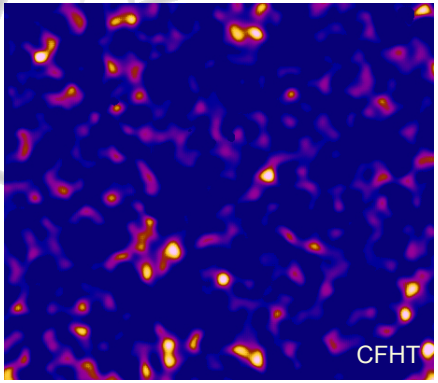


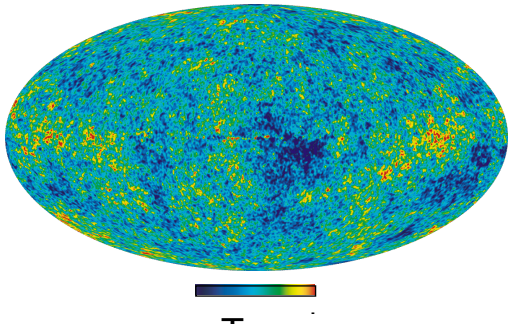


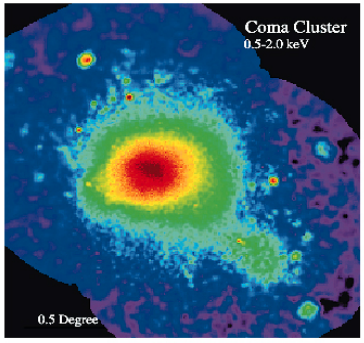




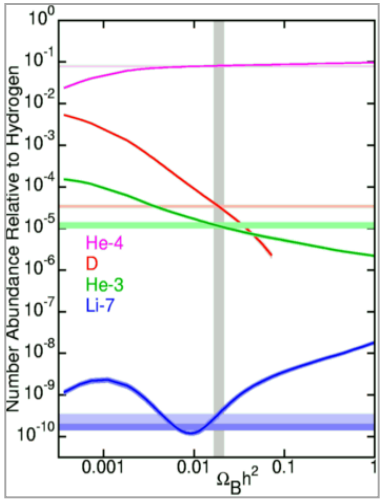
Comparison of the rotation curves calculated by all the methods discussed (assuming $R_0 = 7.9$ kpc and $\Theta_0 = 200$ km s^{-1}).

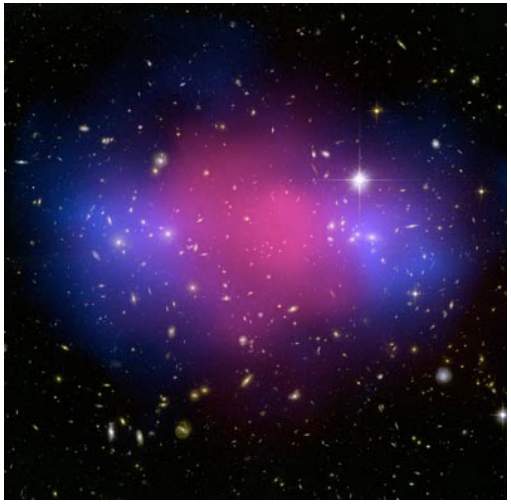


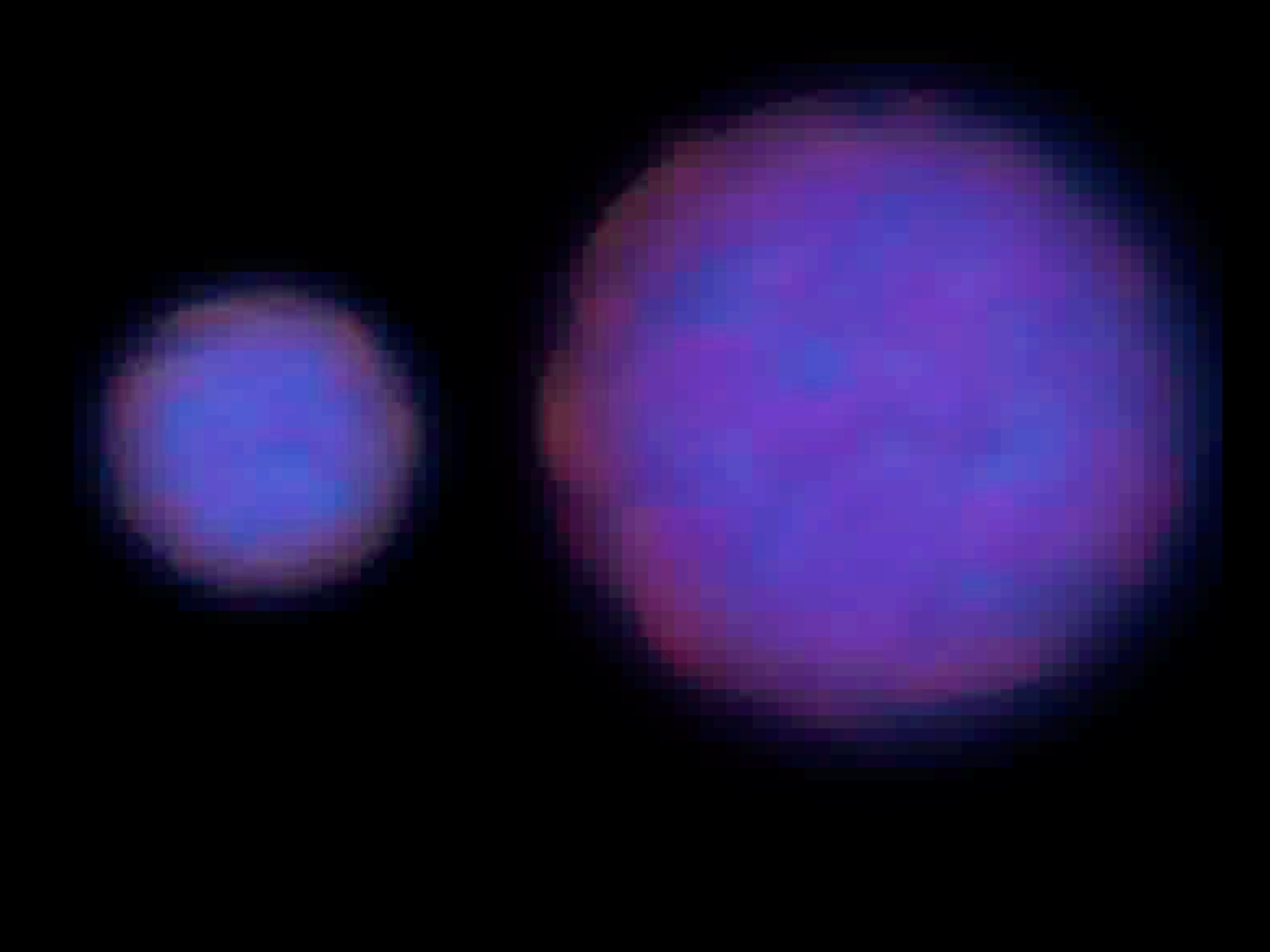




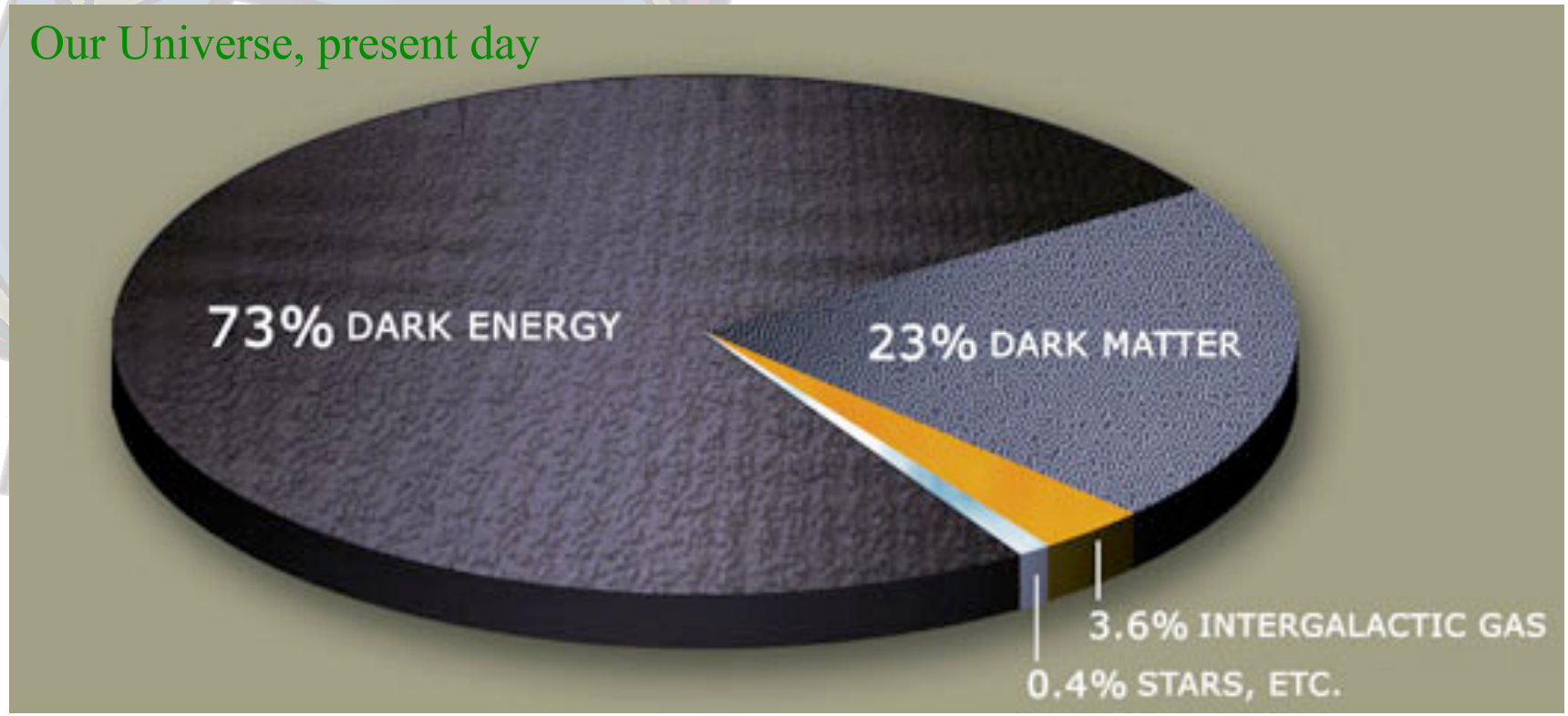
(a) (b)







The conclusion

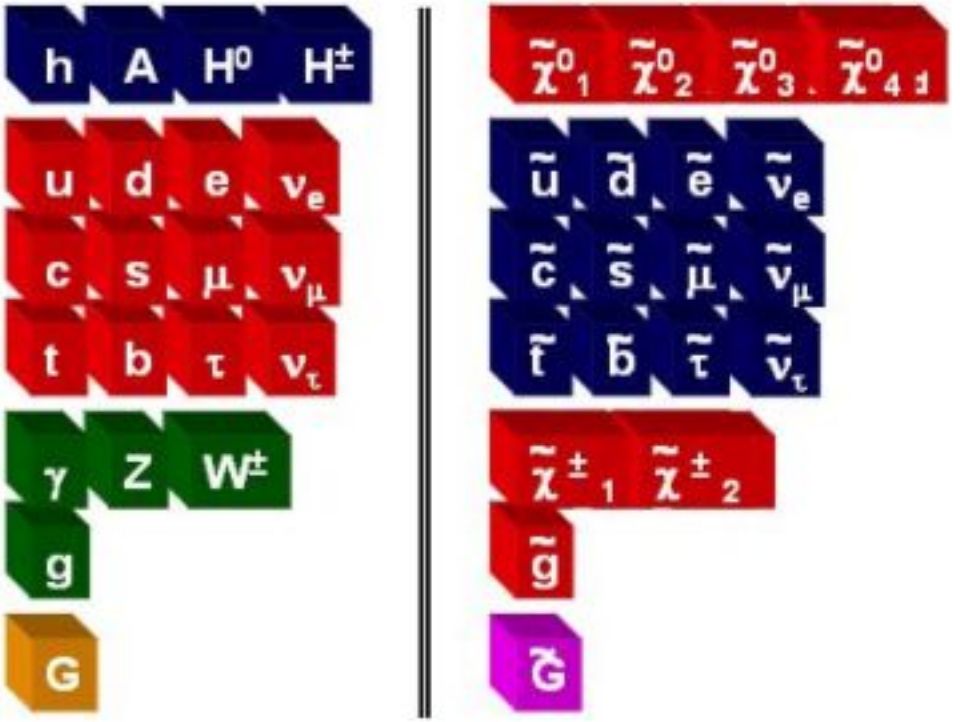


Dark Matter properties

- 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



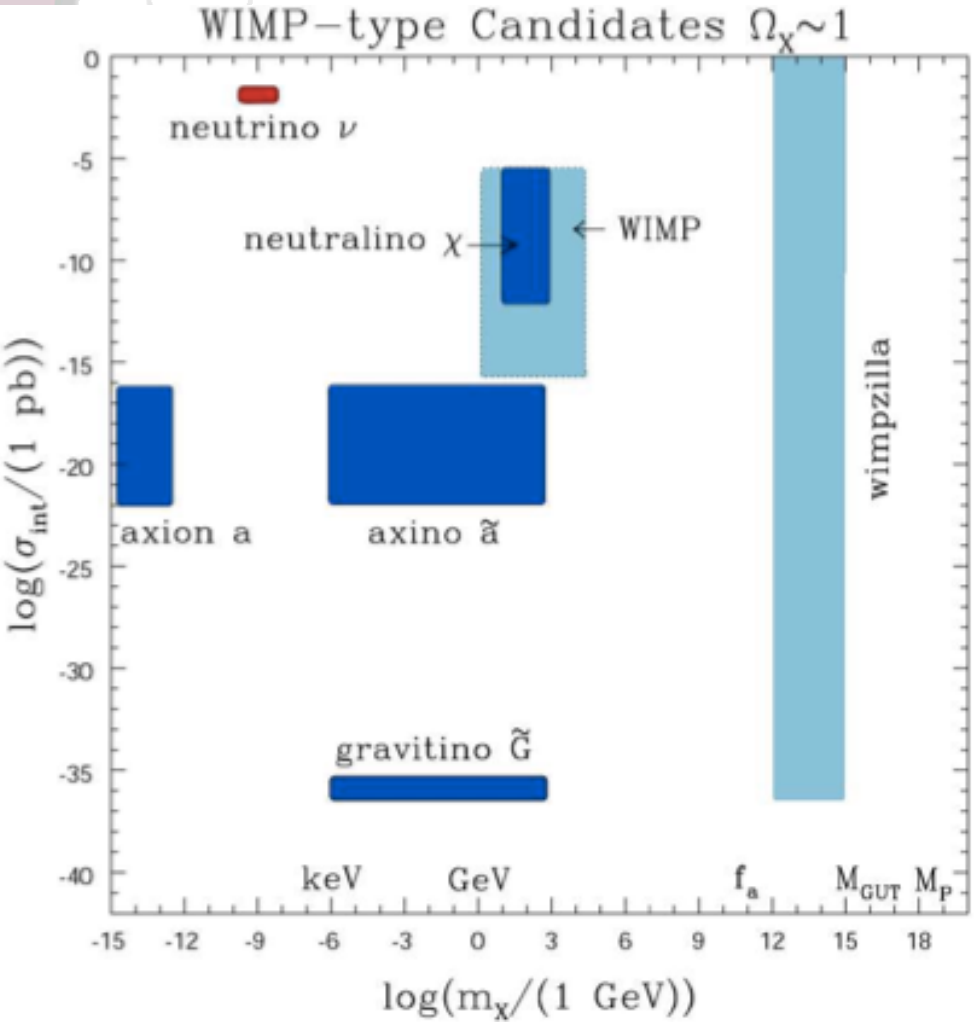
WIMP is the lightest supersymmetric particle ('LSP'), χ, a linear combination of bino, wino and Higgsino fields.

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

A zoo of DM candidates...

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

Direct DM searches are "broadband" searches



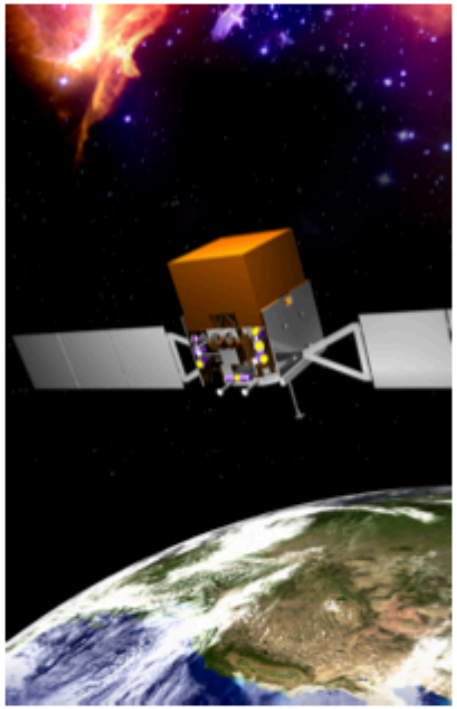
How do we search?

How to search for dark matter?

Collider

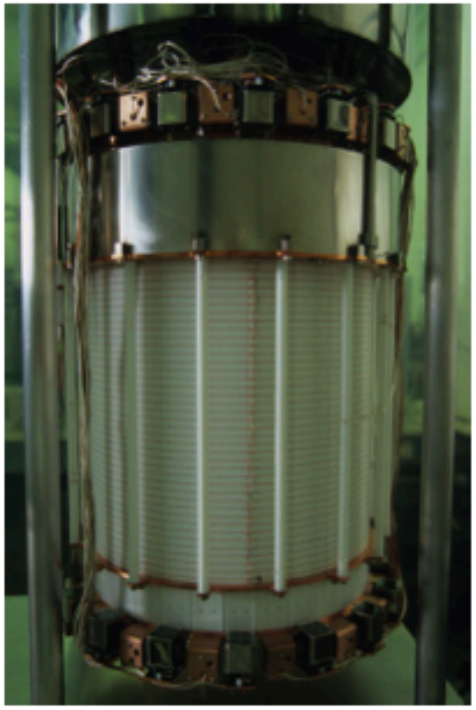
Production

Indirectly



Annihilation

Directly

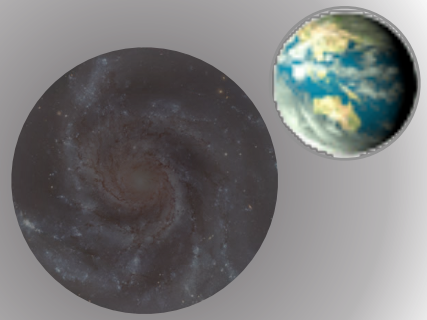


Scattering

The direct detection premise...

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

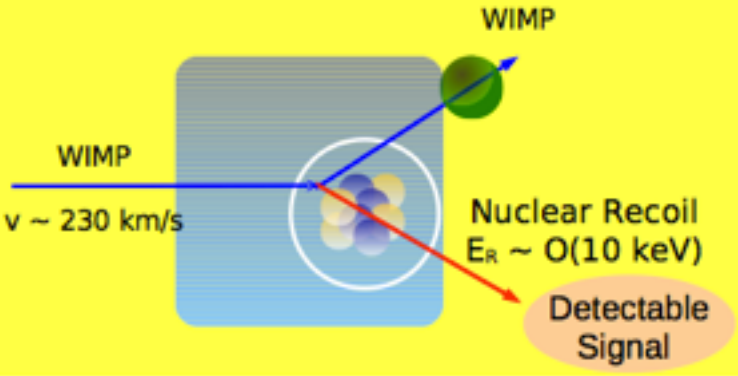
- Earth should be passing through a halo of weakly interacting massive particles



- 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

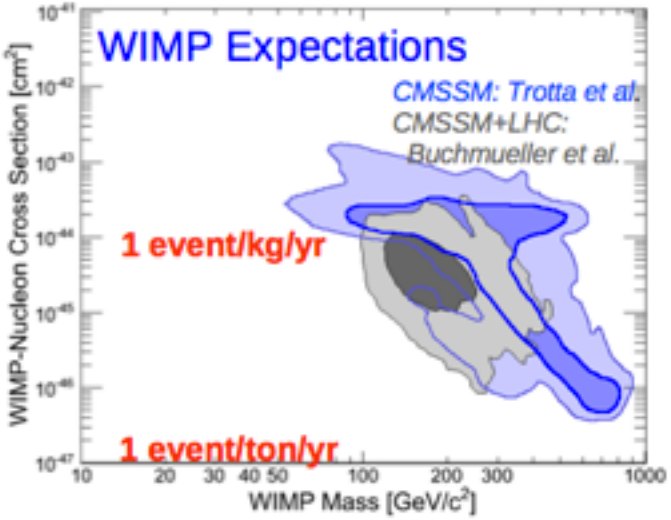


Recoil Energy: $E_r \sim \mathcal{O}(10\ \mathrm{keV})$

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

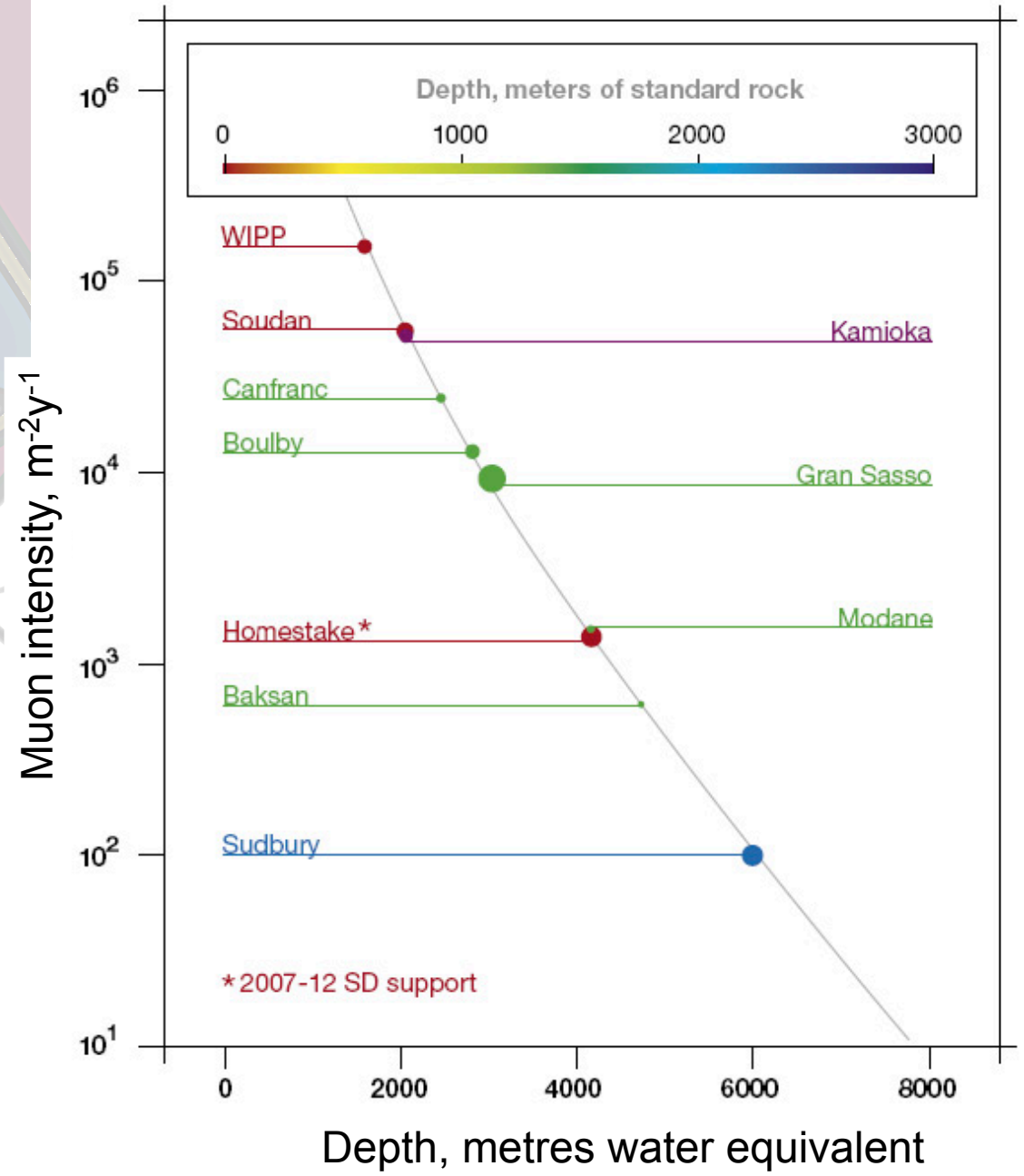
Detector — Local DM Density — Physics

ρ_χ~0.3 GeV/c^2

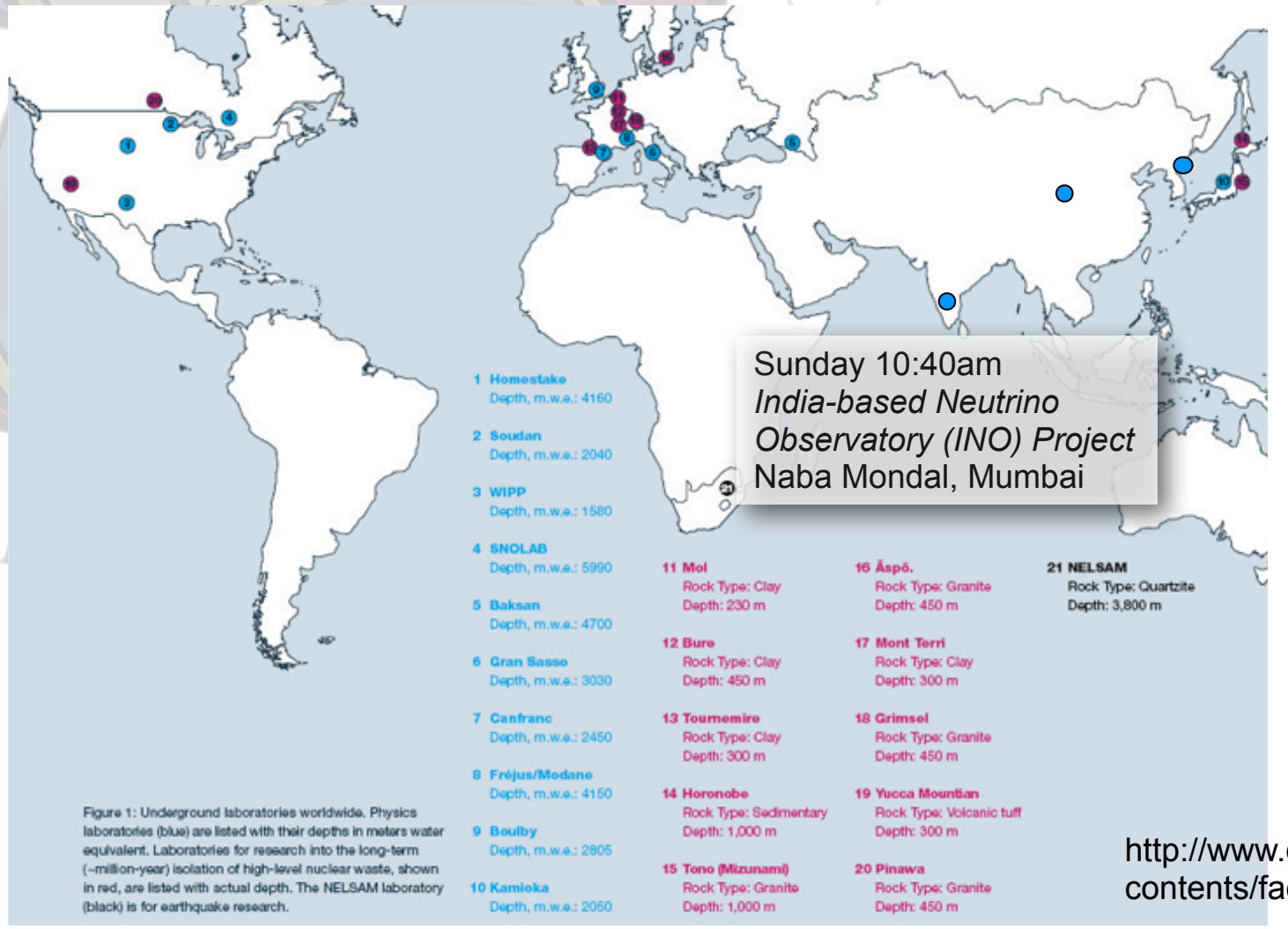


Muons produce secondary neutrons, which can be particularly problematic

Going deep underground significantly reduces cosmic ray muon flux



Deep underground laboratories around the world



Sunday 10:40am
India-based Neutrino Observatory (INO) Project
Naba Mondal, Mumbai

Blue - science labs

Pink/black - Rad' waste storage & earthquake research

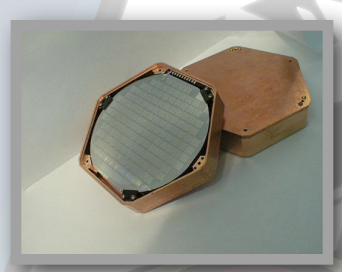
http://www.deepscience.org/contents/facilities_popup01.shtml

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 (need tonne+ scale)

Direct detection techniques

CDMS
EDELWEISS



CUOPP
PICASSO
SIMPLE

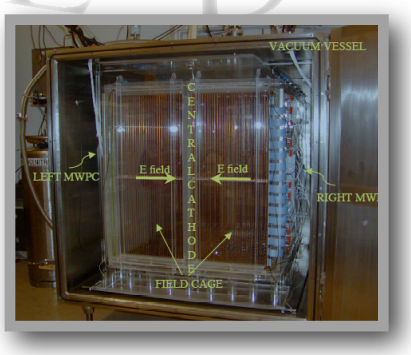
CRESST
ROSEBUD

Phonons

dE/dx

Charge

Light



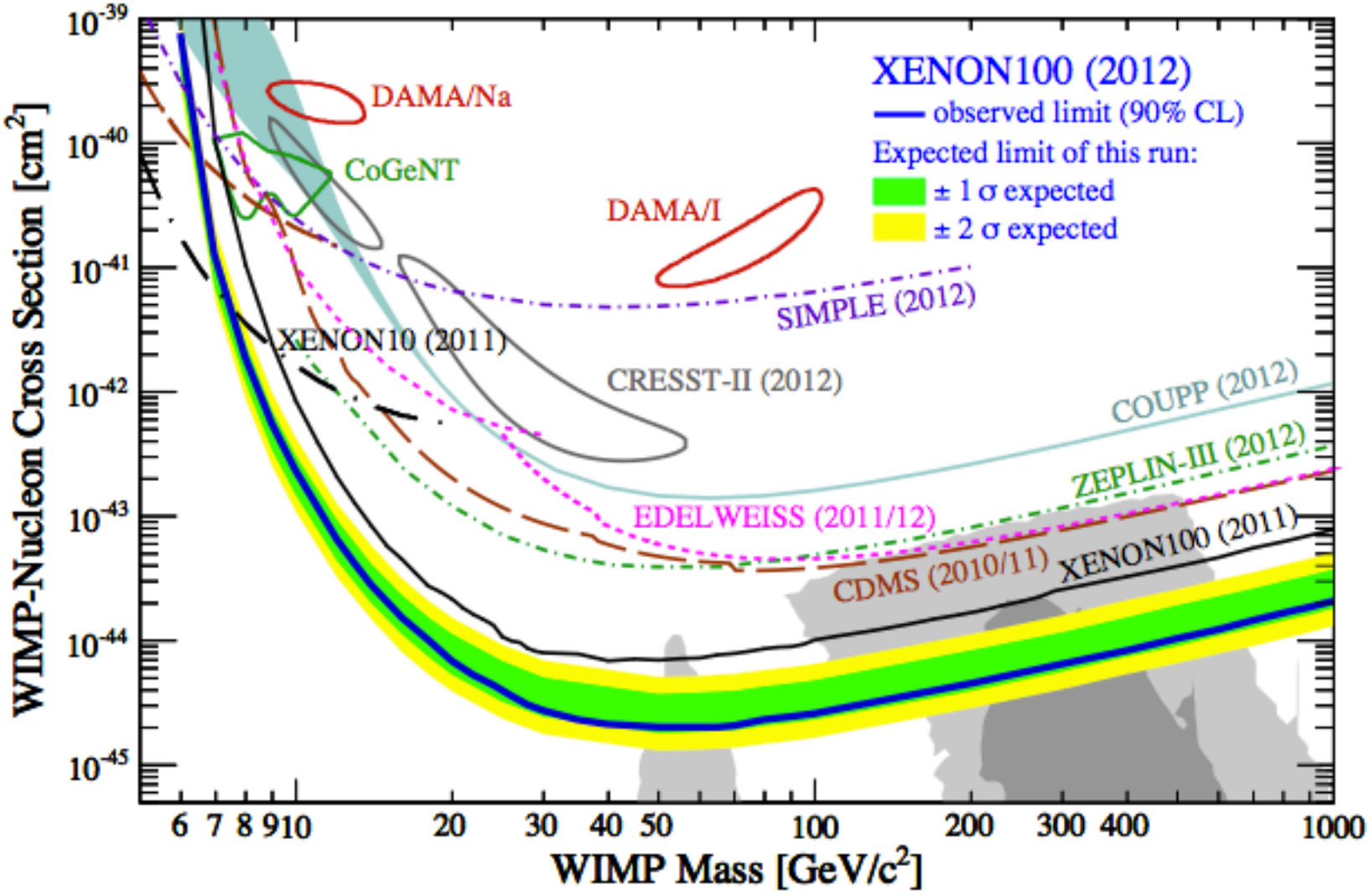
DRIFT
DMTPC
GENIUS
NEWAGE

LUX
XENON
WARP
ArDM
ZEPLIN
DARKSIDE

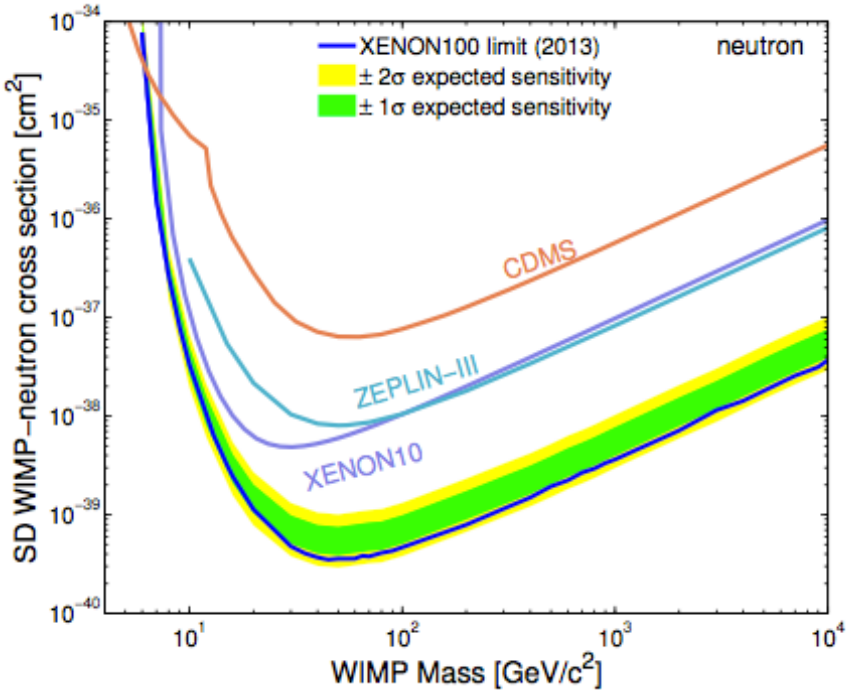
DAMA
LIBRA
XMASS
CLEAN
ANAIS
KIMS
DEAP/CLEAN

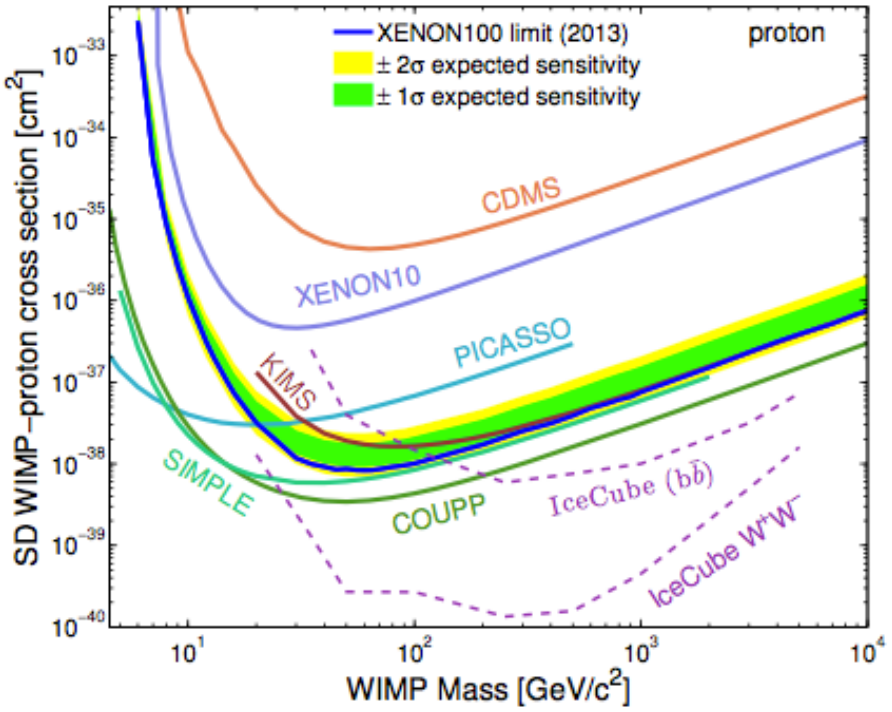
The current state of play

Spin-Independent interaction



Spin-dependent interaction





WIMP-Neutron

WIMP-Proton

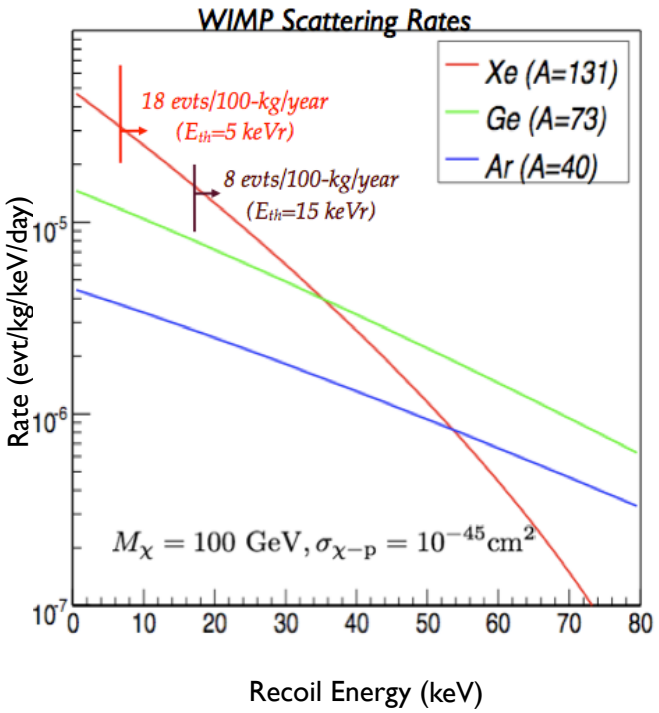
Experiments/Collaborations

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

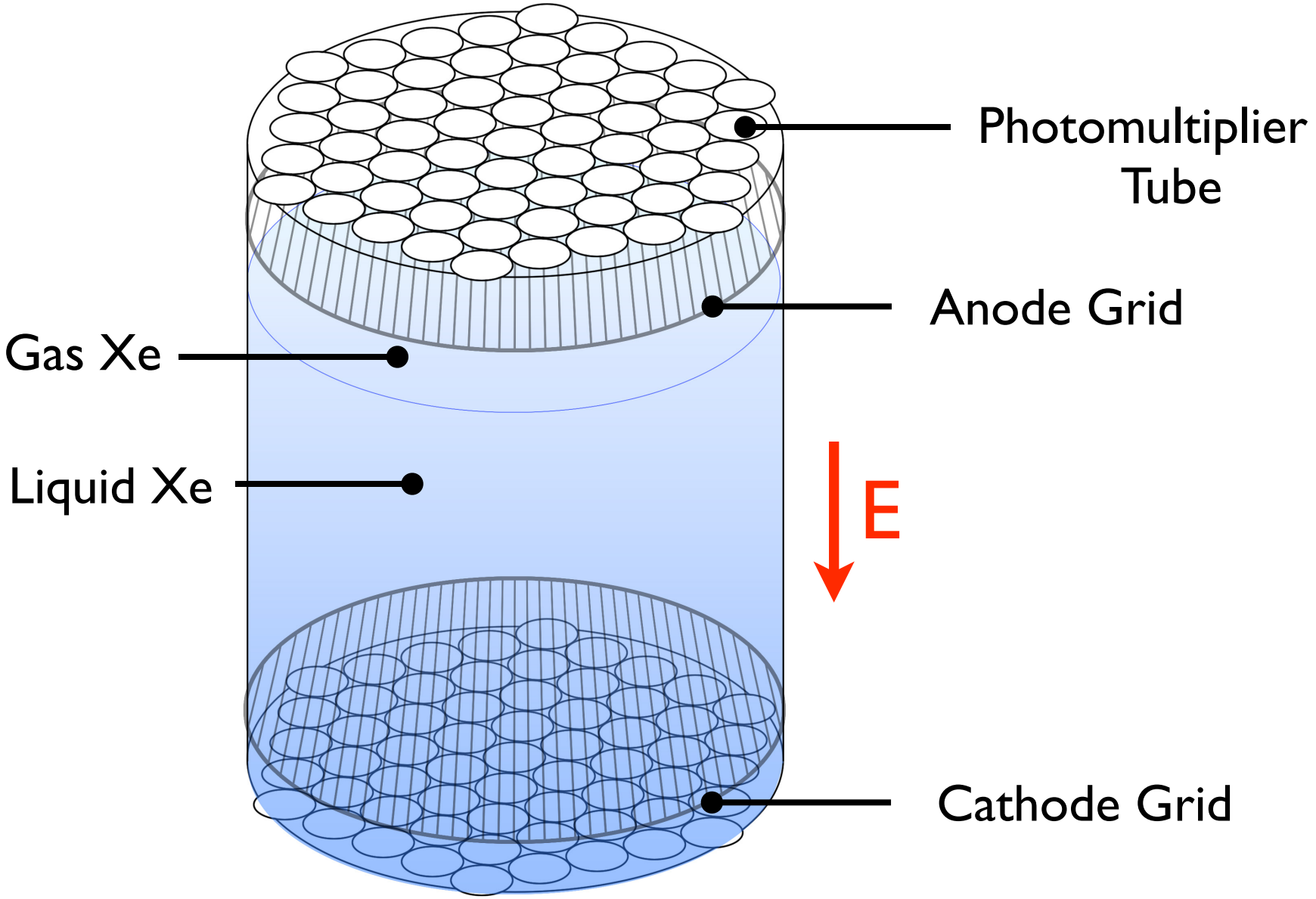
Liquid Xenon TPCs

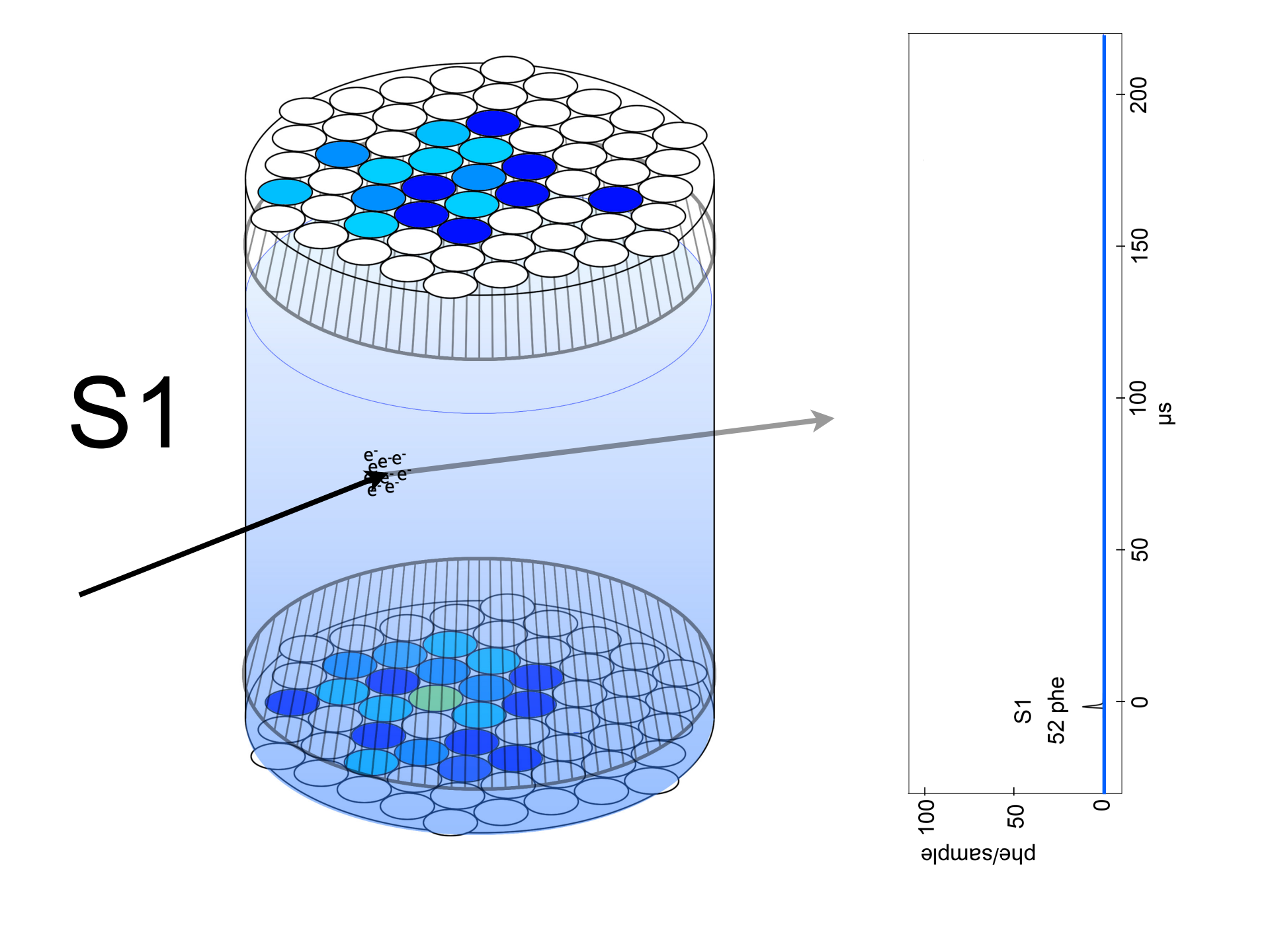
- **S1: LXe is an excellent scintillator**
  - Density: 3 g/cm^3
  - Light yield: >60 ph/keV (0 field)
  - Scintillation light: 178 nm (VUV)
  - **Nuclear recoil threshold ~5-8 keV**

- **S2: Even better ionisation detector**
  - S1+S2 allows mm vertex reconstruction
  - Sensitive to single ionisation electrons
  - **Nuclear recoil threshold ~1 keV**



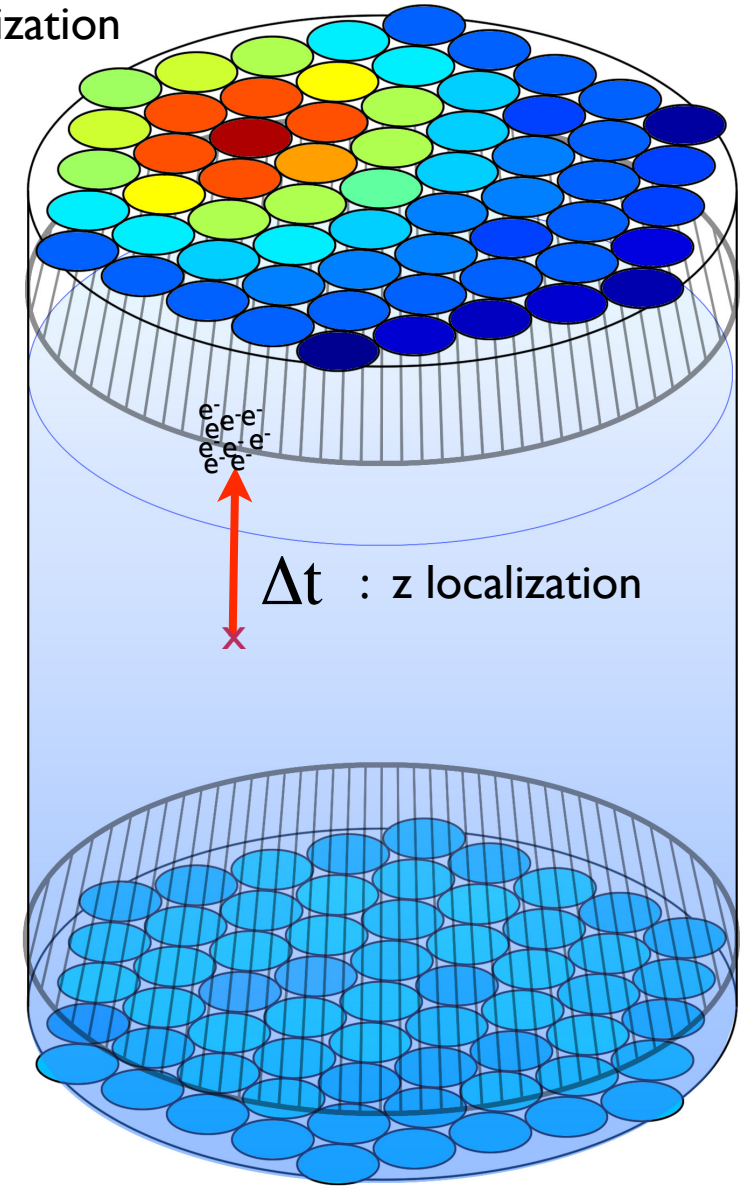
- **Well suited WIMP target**
  - Scalar WIMP-nucleon scattering rate dR/dE~A^2
  - Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable spin-dependent sensitivity
  - Excellent ionisation threshold: 'light WIMP' searches using S2 only
  - No intrinsic backgrounds (^{85}Kr can be removed, low rate from ^{136}Xe 2$\nu\beta\beta$)
  - Easily scaled with no loss of performance (actually improves!)

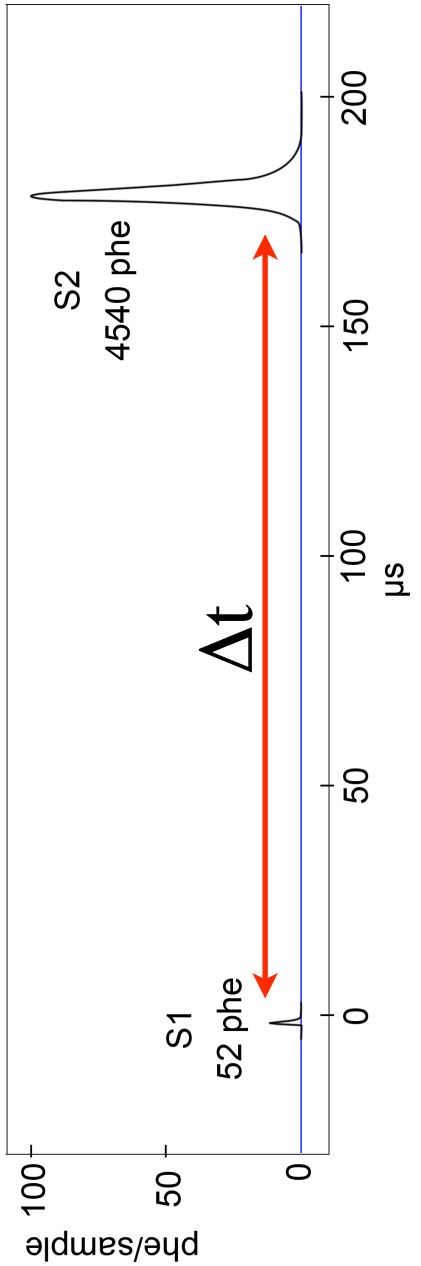

Photomultiplier Tube
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid

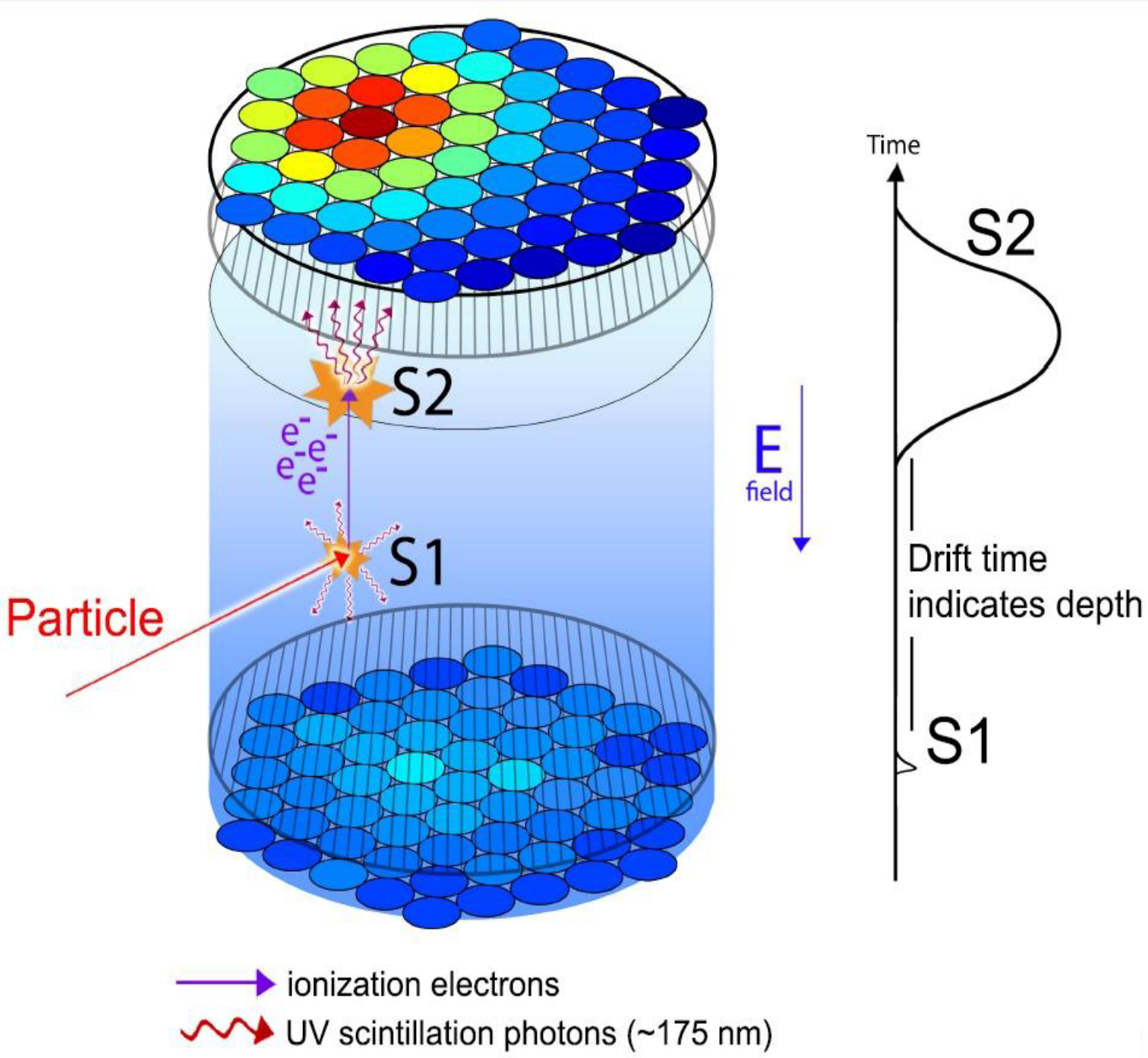

S1
e-
e-
e-
e-
e-
e-
S1
52 phe
phe/sample
0
50
100
0
50
100
150
200
µs

top hit pattern:
x-y localization

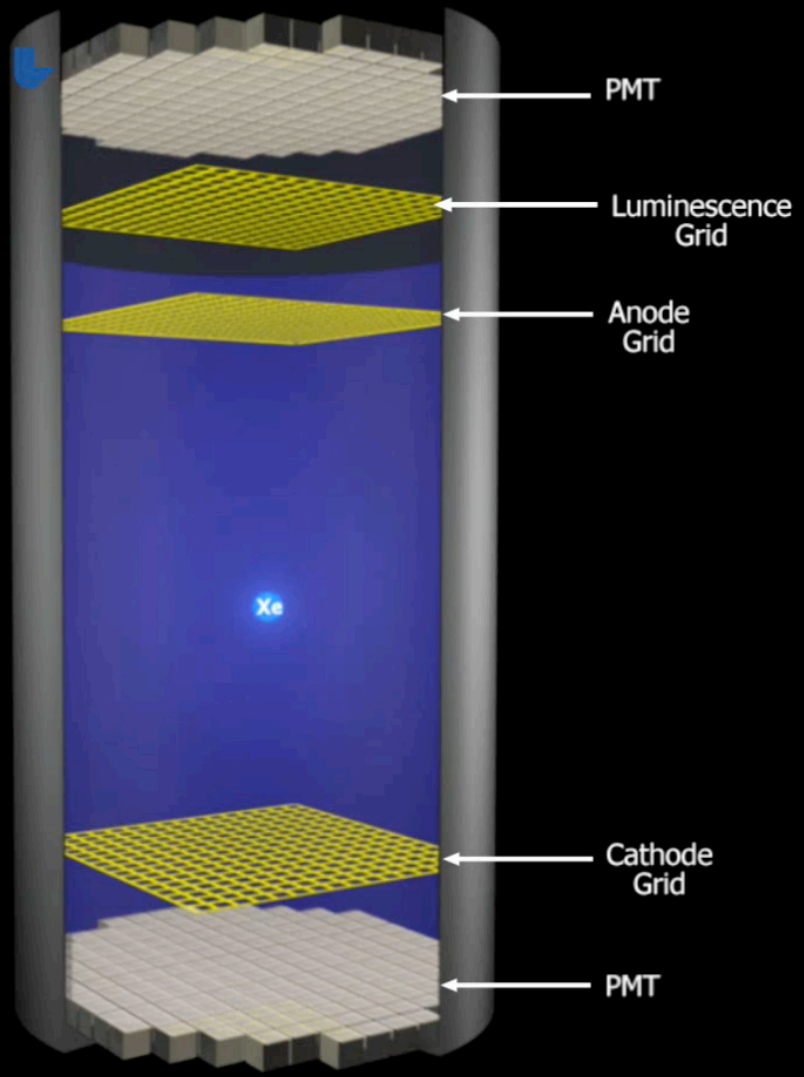
S2



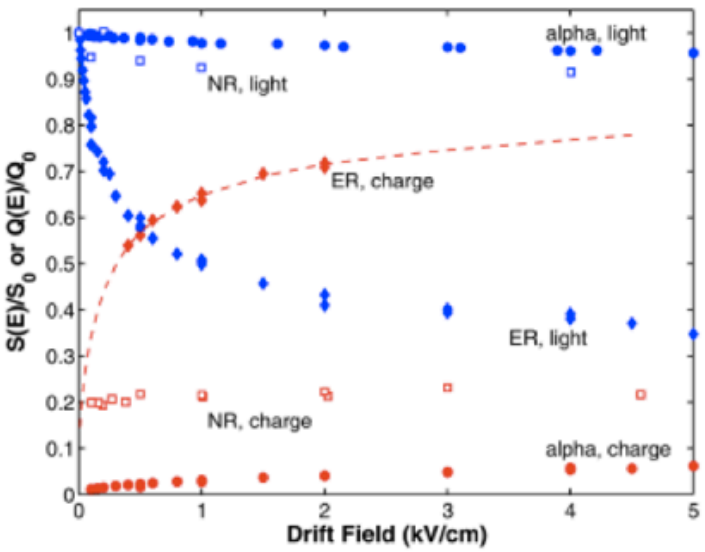



S2
e-
e-e-
e-
S1
Particle
E
field
Time
S2
Drift time
indicates depth
S1
ionization electrons
UV scintillation photons (~175 nm)

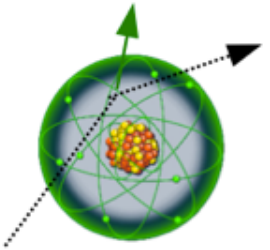
WIMP Signals in a Dual-Phase Xenon Detector



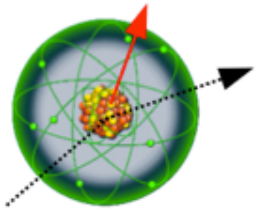
Particle Discrimination



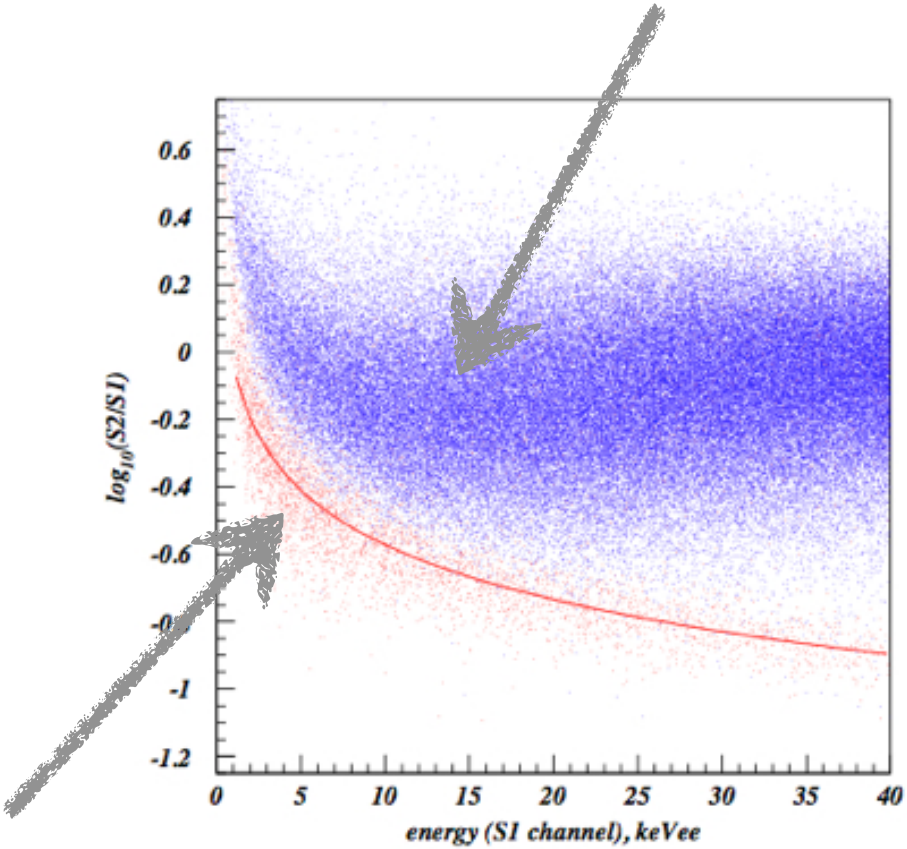
Light (S1) and charge (S2)
depend on recoil dE/dx



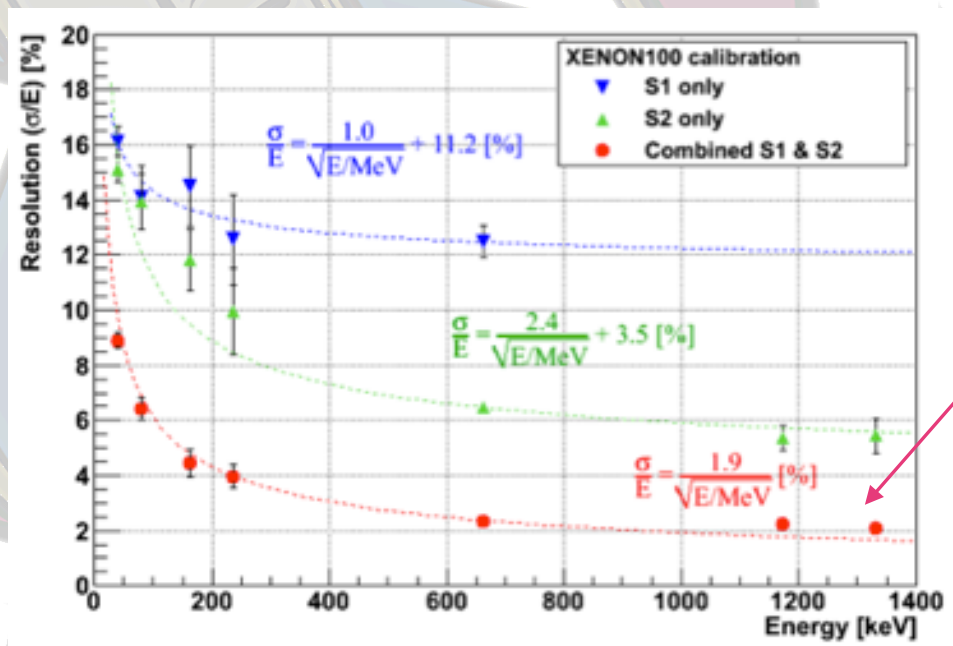
Electronic Recoils
(gamma, beta)



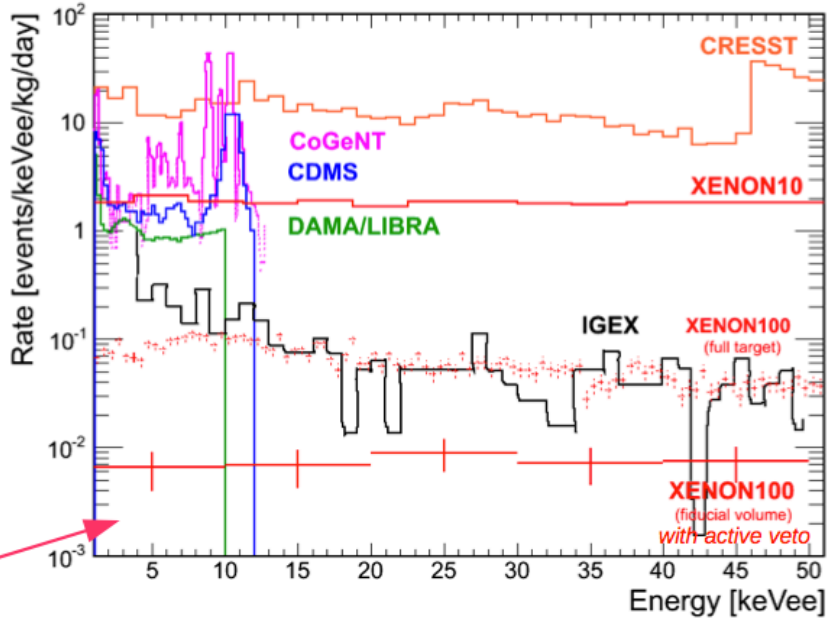
Nuclear Recoils
(neutron, WIMPs)



XENON100



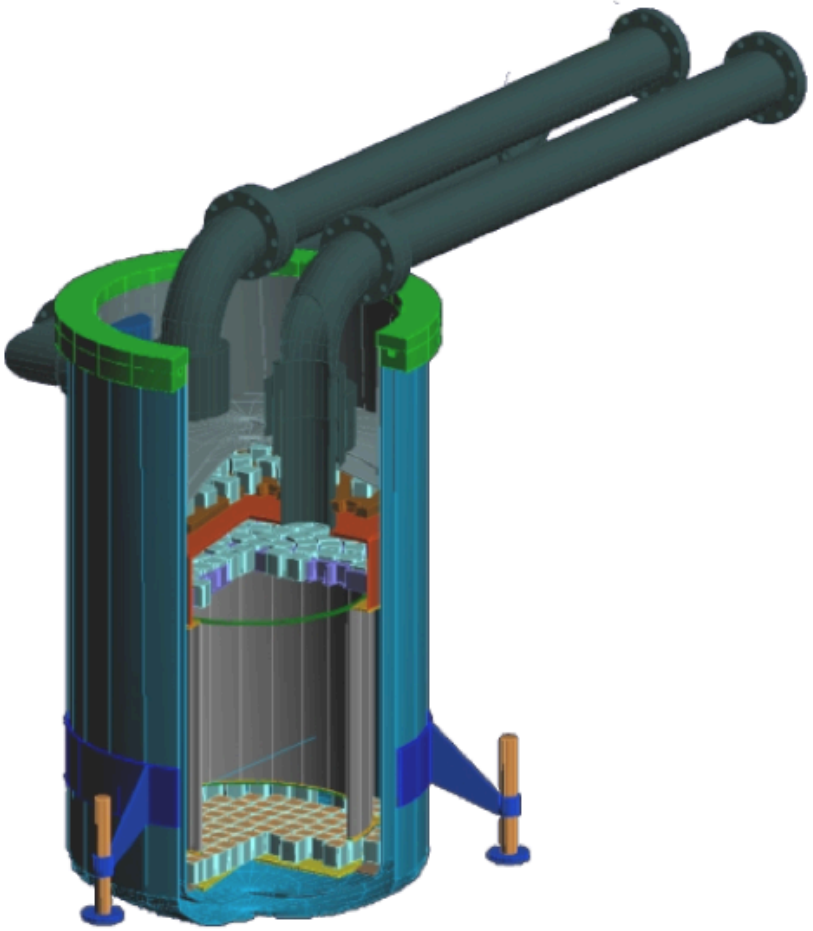
Combined E scale



Fiducialisation

The present world leader

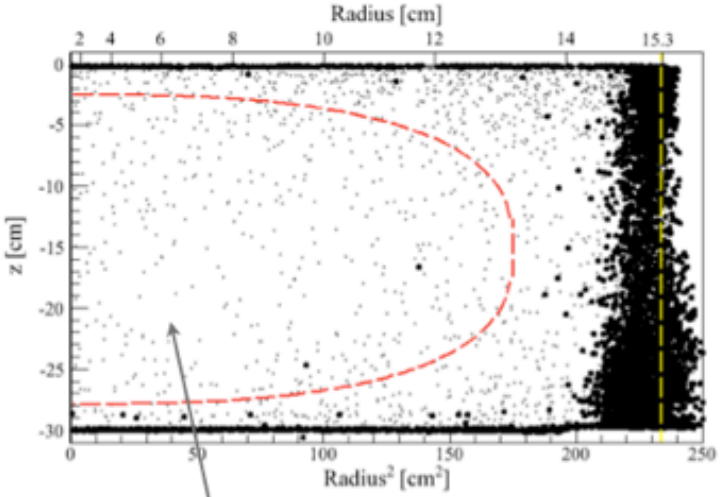
The XENON100 detector overview



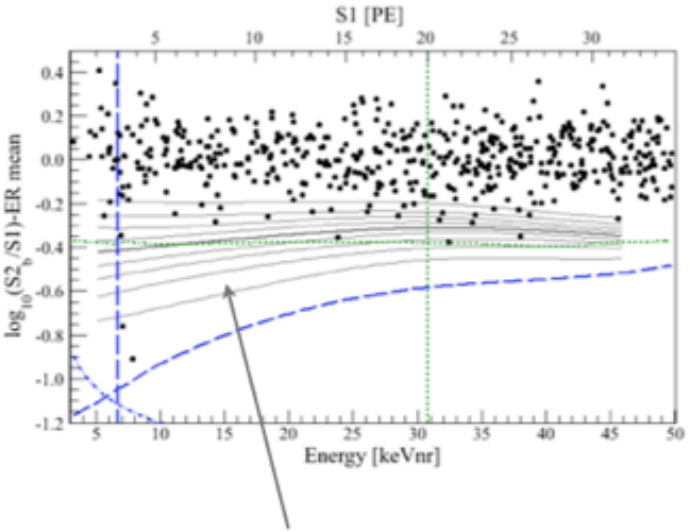
- 100 x less background than XENON10
- 10 x more fiducial mass than XENON10
- Cryocooler and FTs outside shield
- Materials screened for low radioactivity
- LXe scintillator active veto system
- Improved passive shield system
- Dedicated Kr distillation column
- TPC with 30 cm drift x 30 cm diameter
- 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

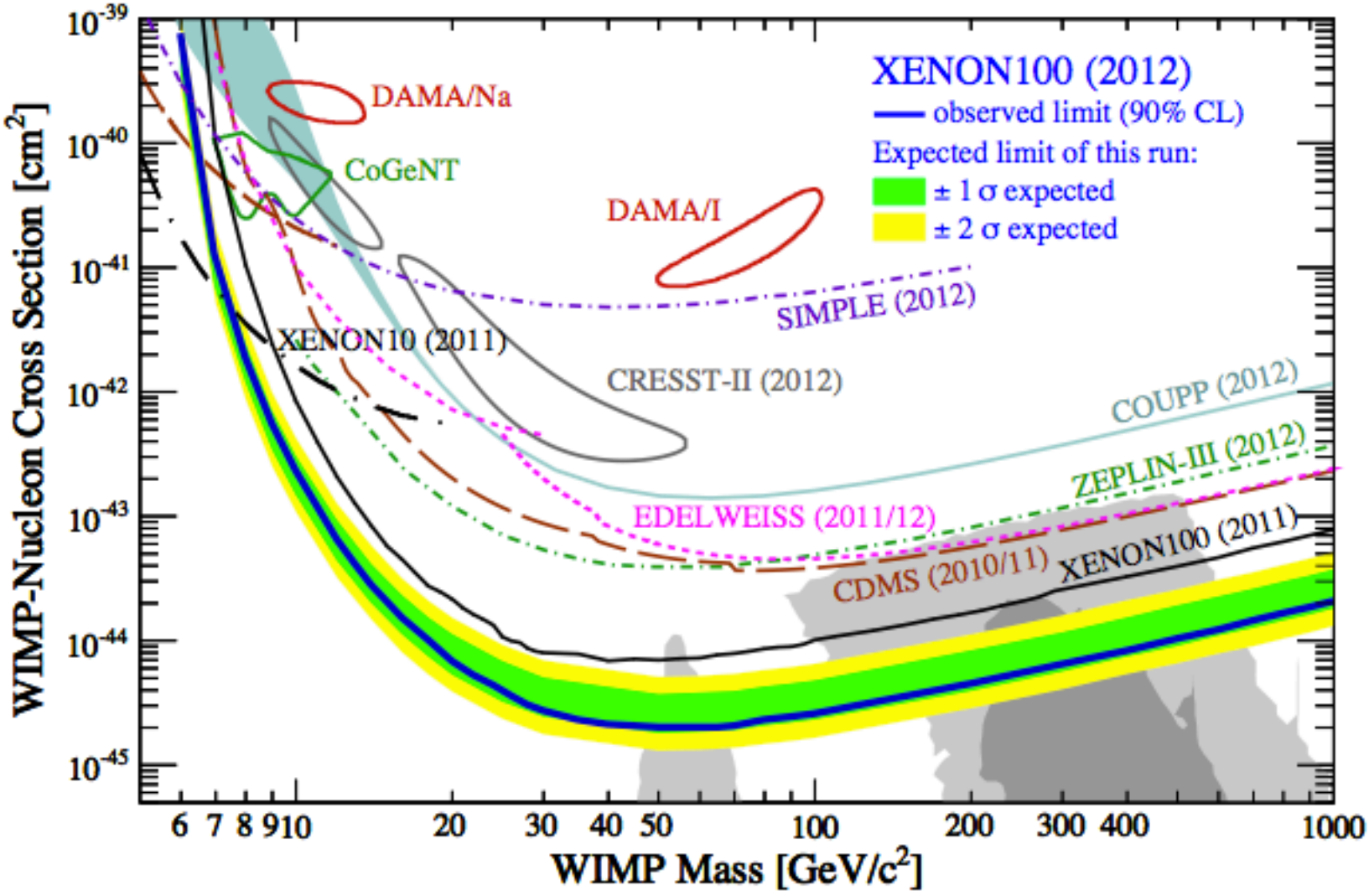


Fiducial mass region:
34 kg of liquid xenon
406 events in total

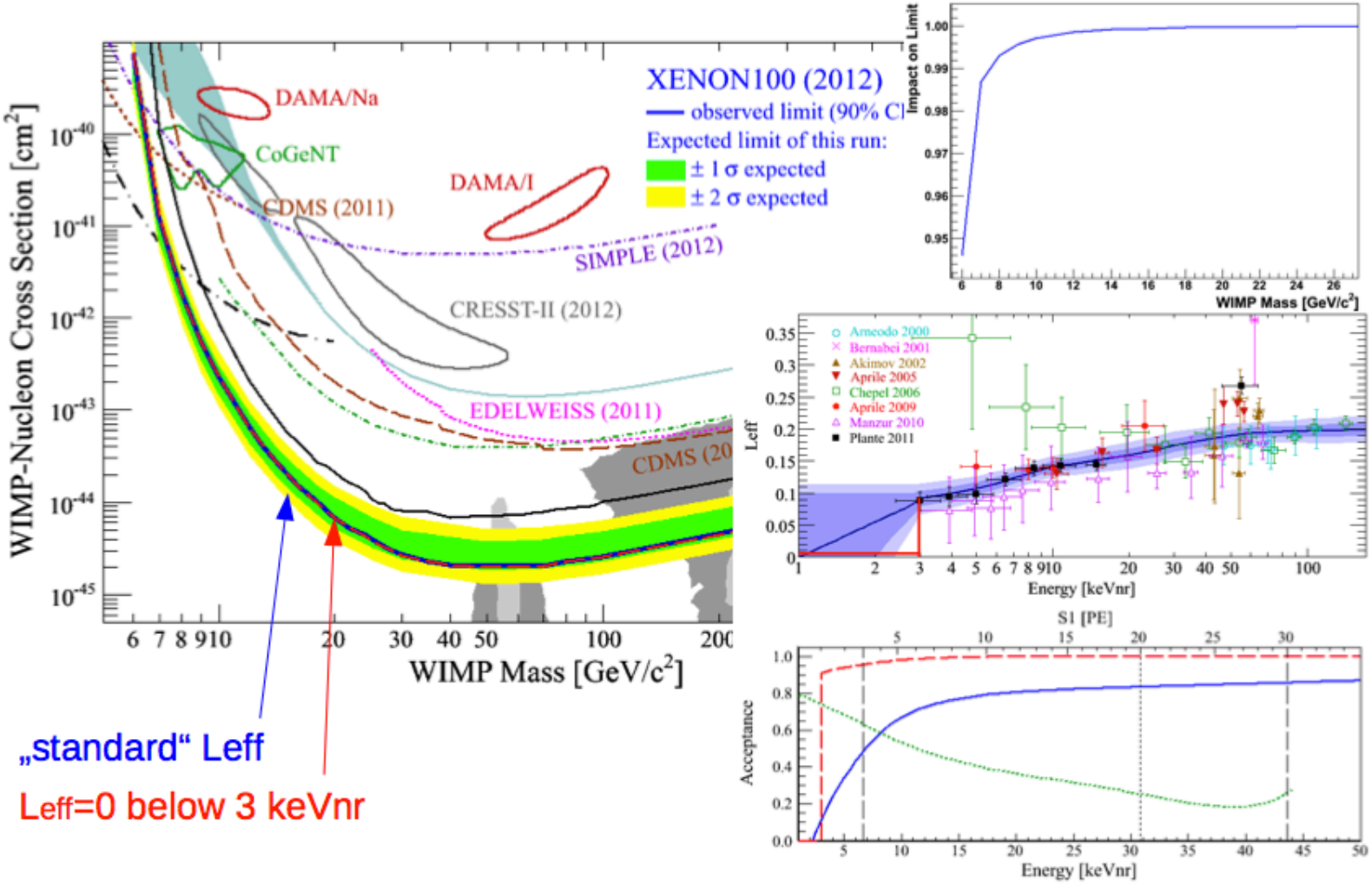


Signal region:
2 events are observed
0.79 ± 0.16 gamma leakage events expected
0.17 +0.12-0.7 neutron events expected

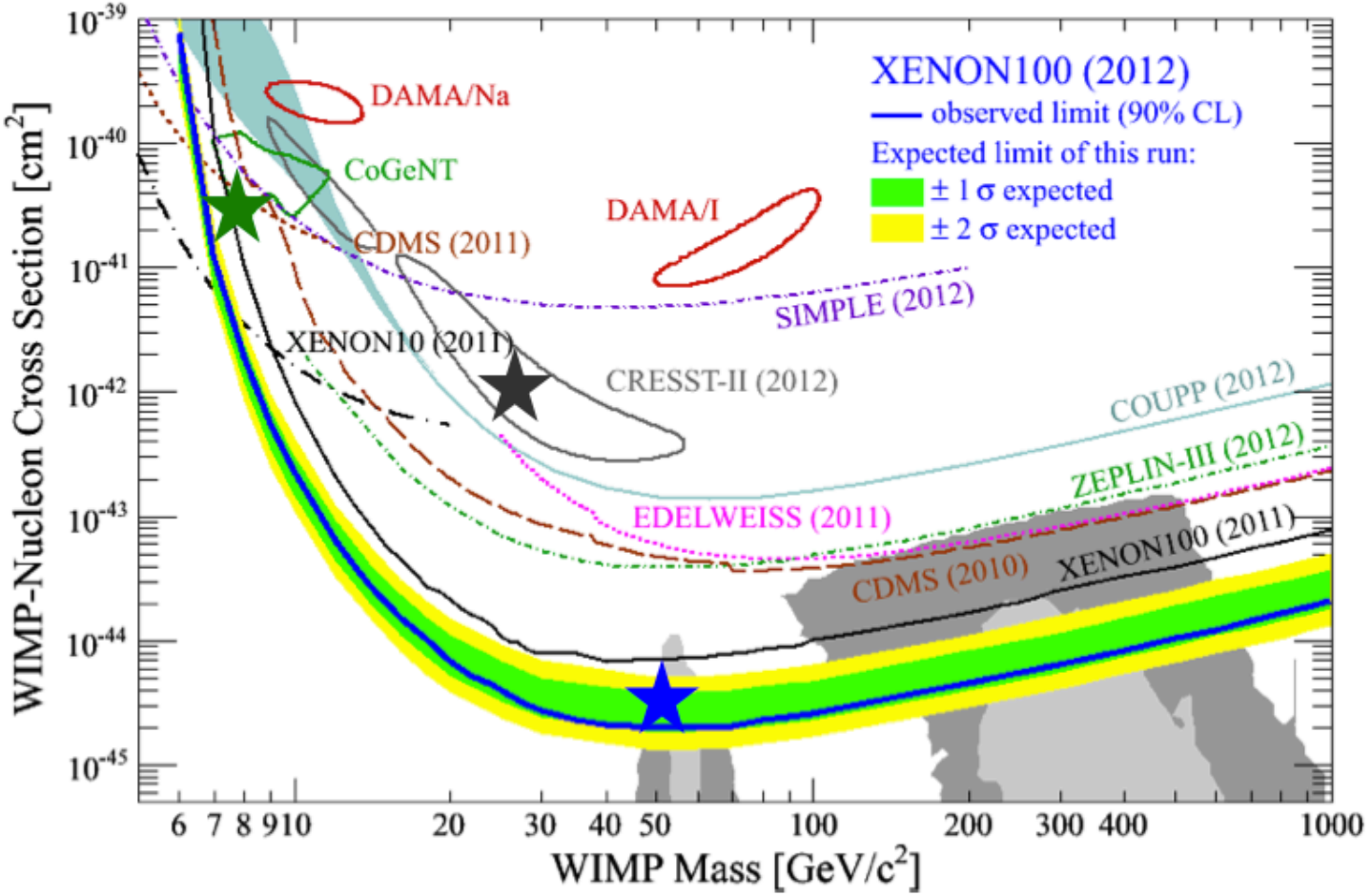
Spin-Independent interaction



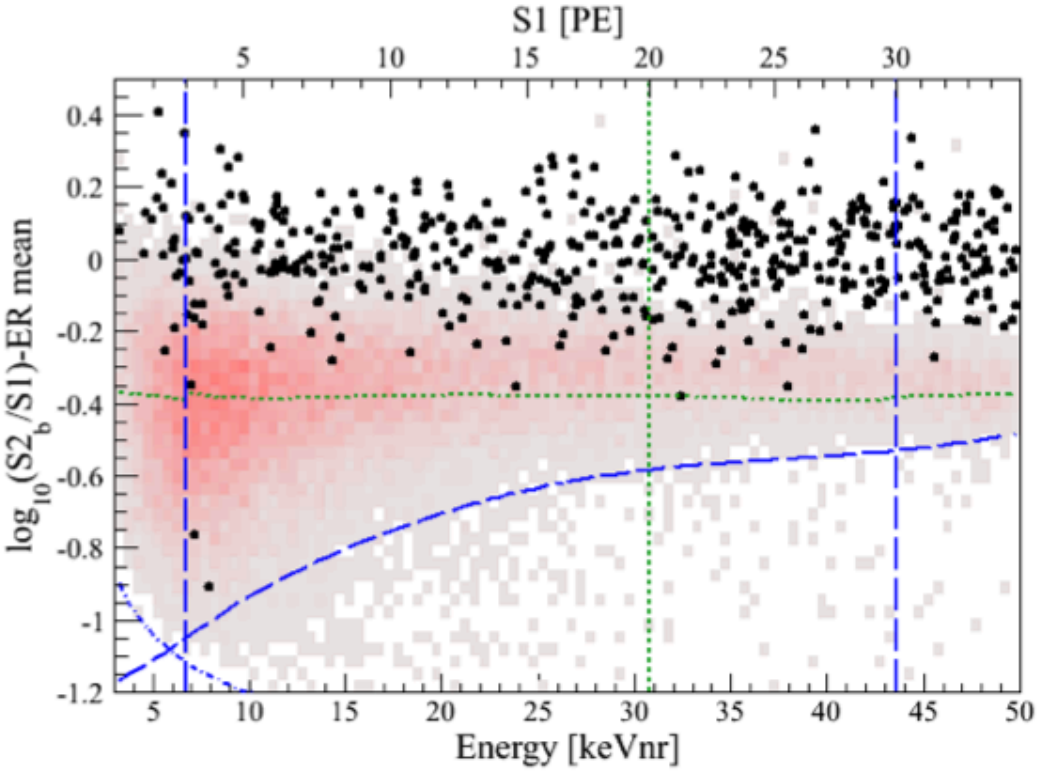
No Impact of L_{eff} below 3 keVr



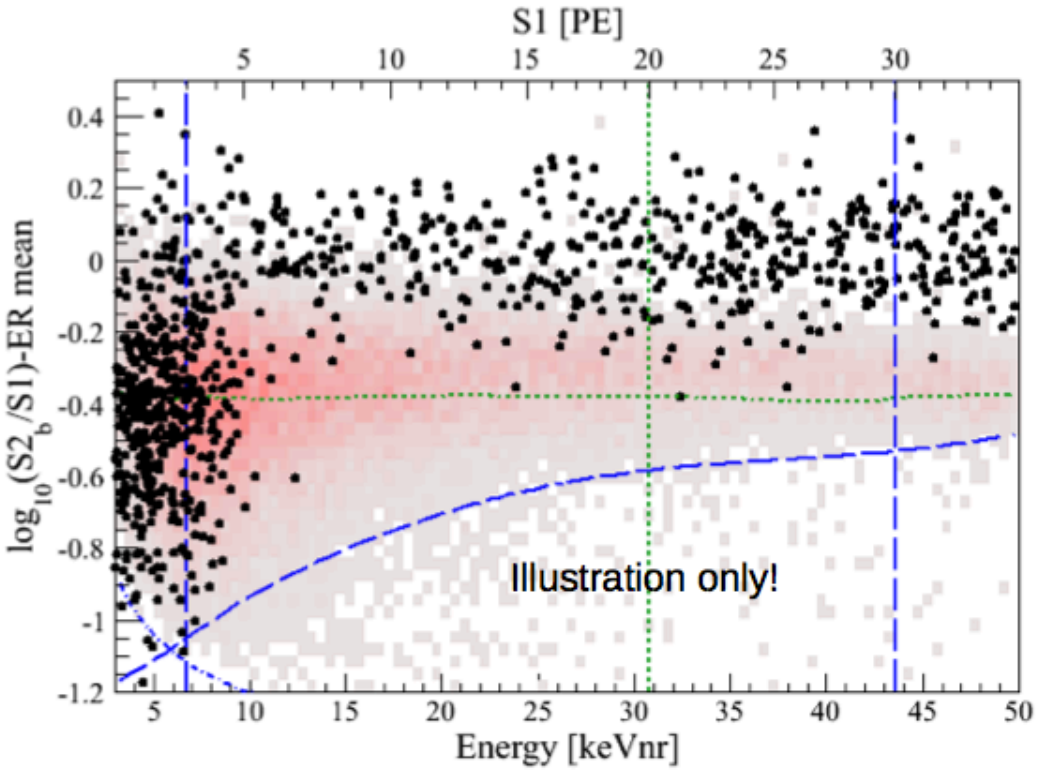
The new XENON100 Limit



What XENON100 sees...

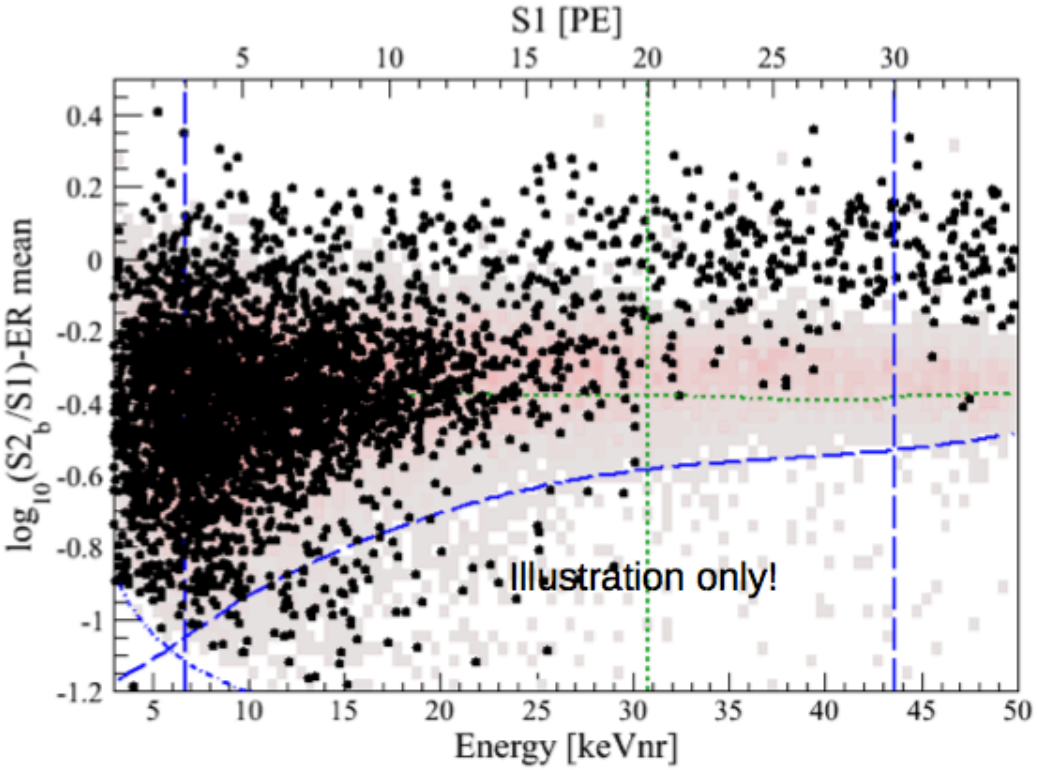


A light mass WIMP...



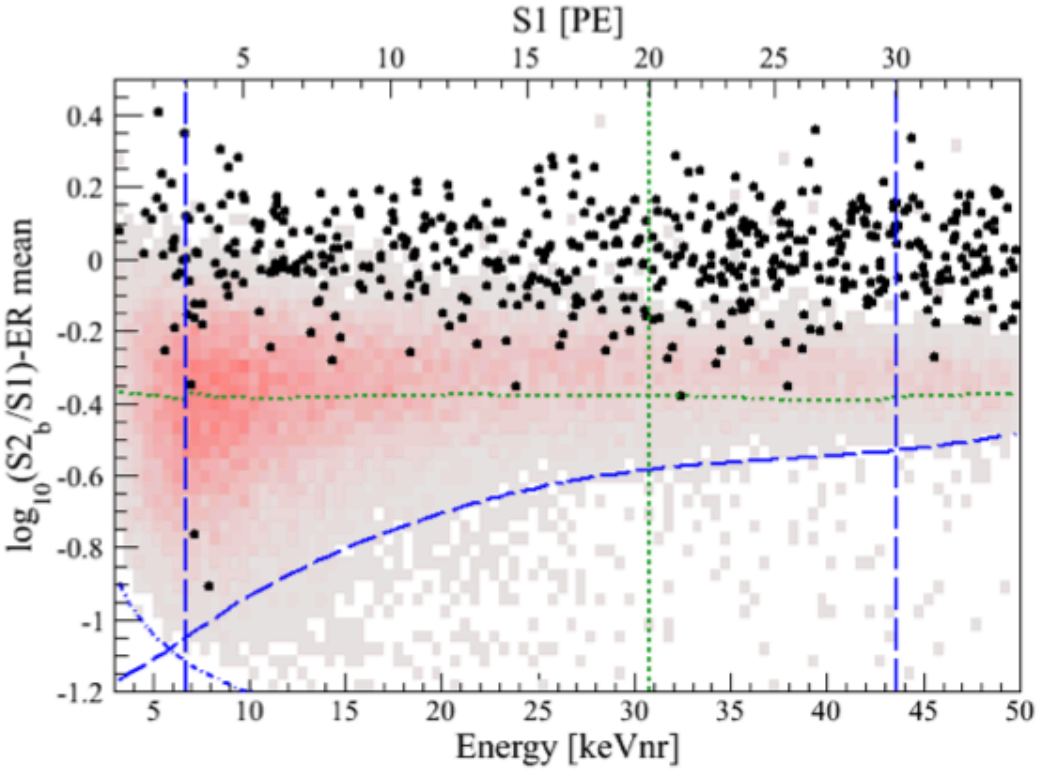
m_X= 8 GeV/c² σ=1.0x10^{-40}cm²

A CRESST-like signal...

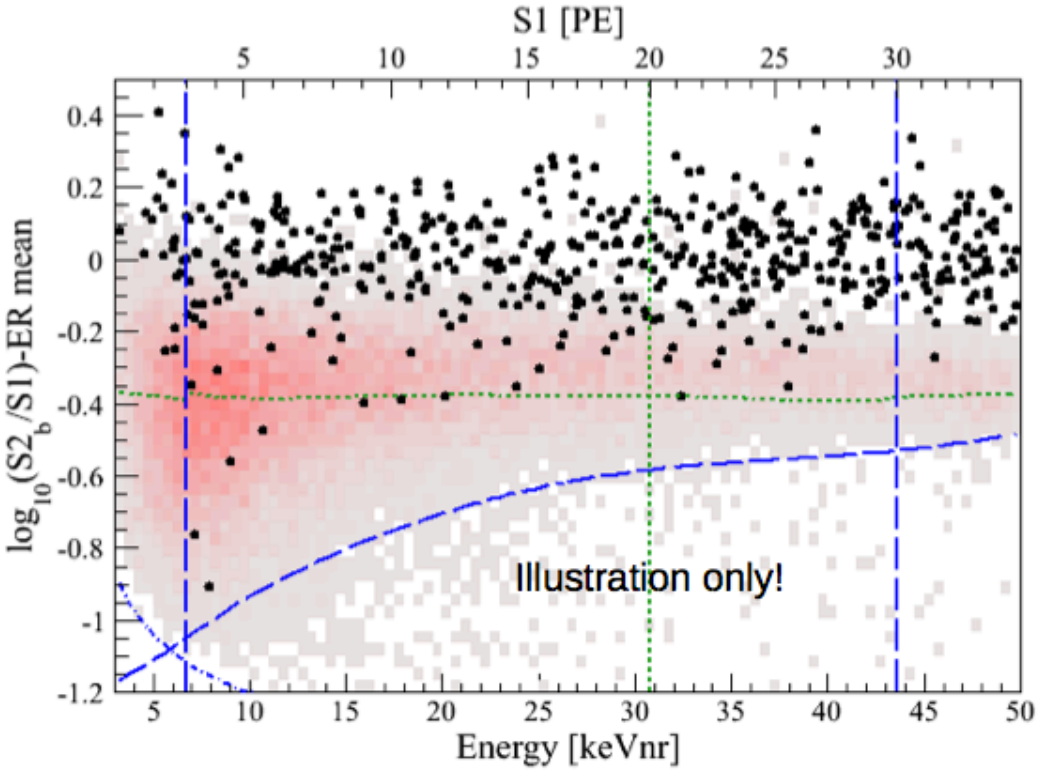


m_χ= 25 GeV/c² σ=1.6 x10^{-40} cm²

What XENON100 sees...

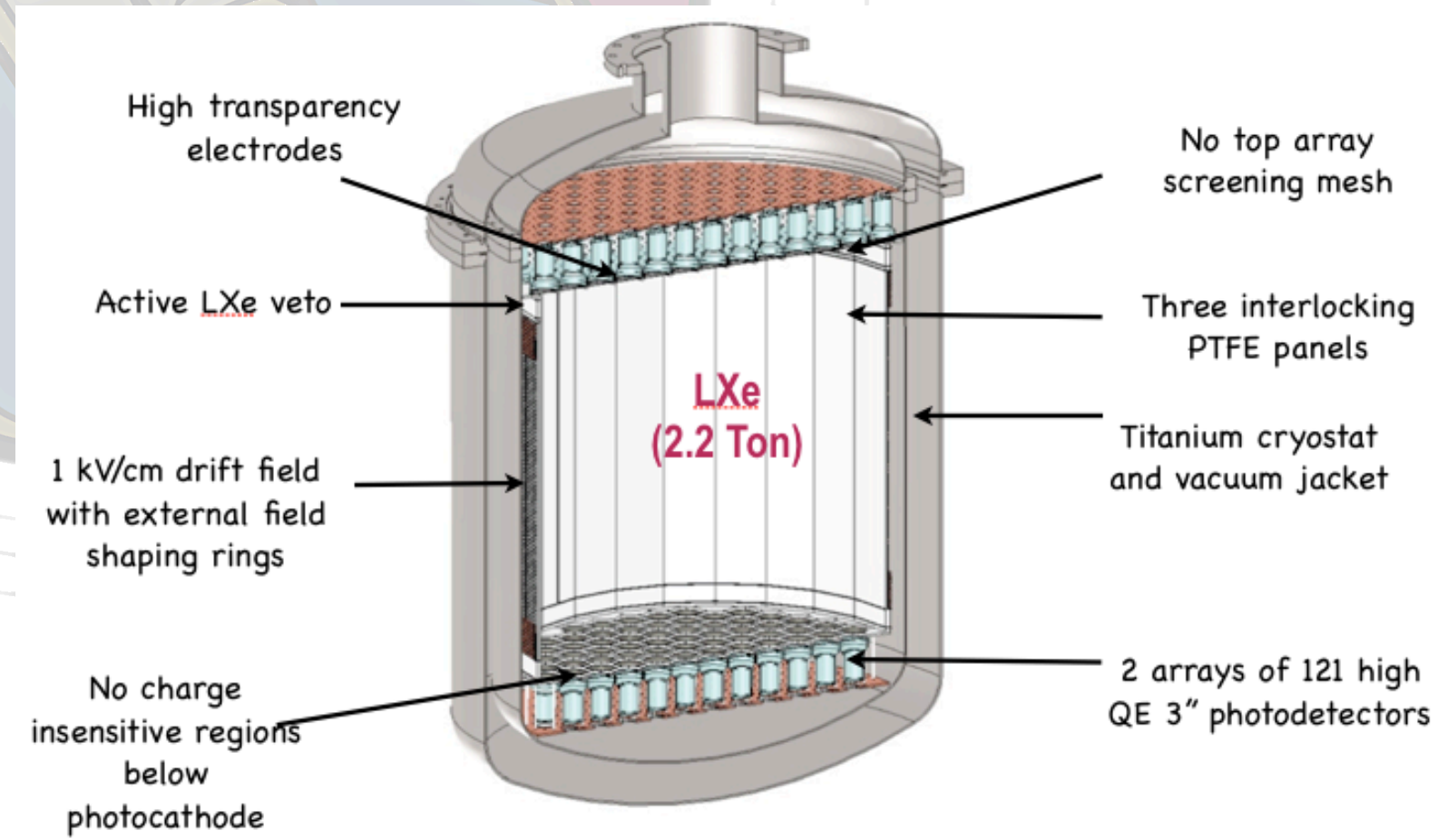


What XENON100 excludes...

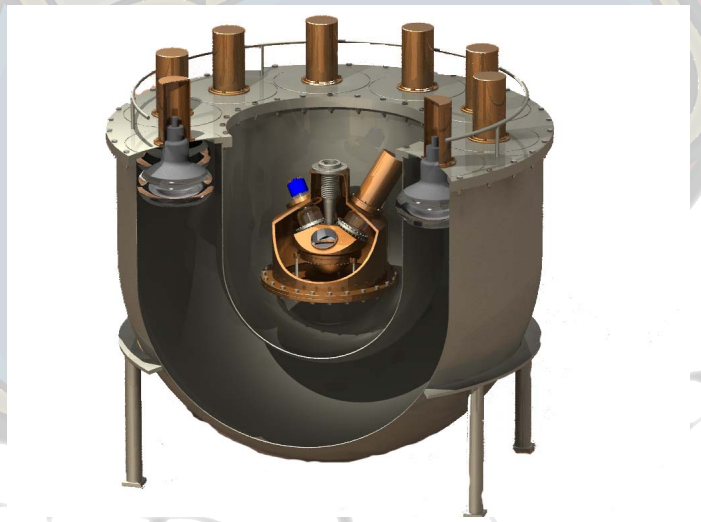


m_X= 50 GeV/c² σ=3.0 x10^{-45} cm²

Future: XENON100 → XENON1T

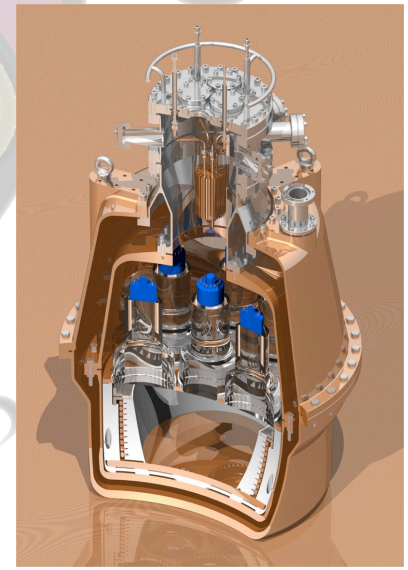


The ZEPLIN programme



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

Single-phase



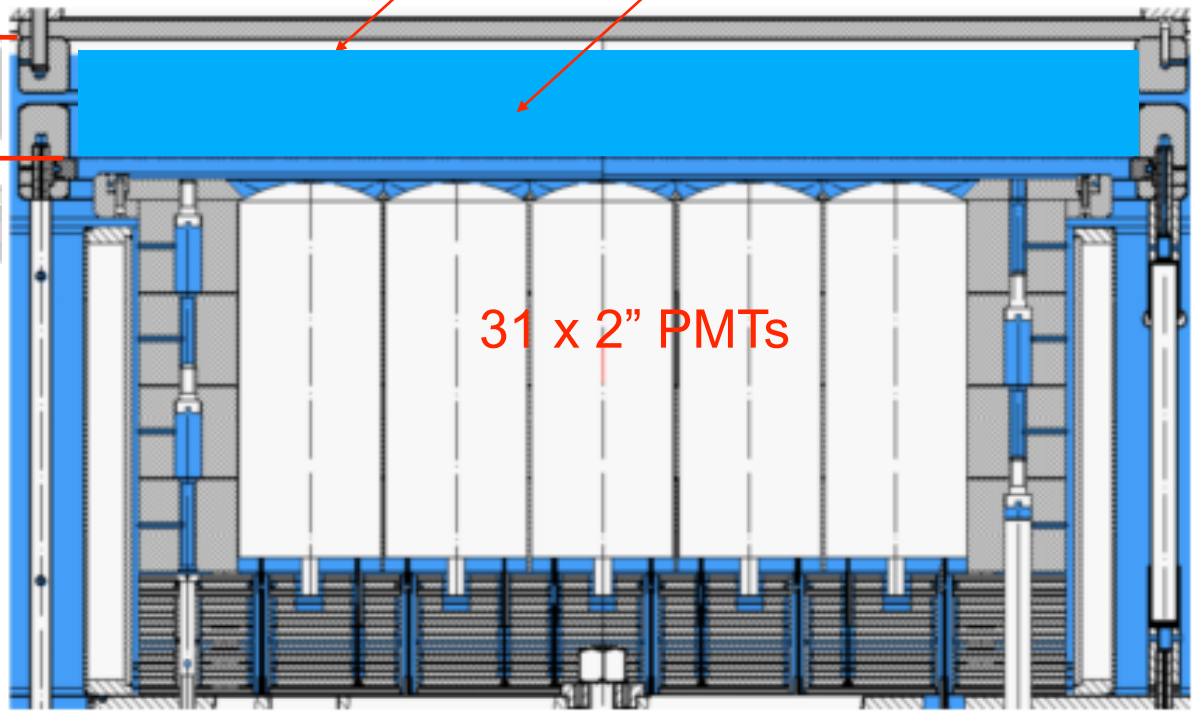
ZEPLIN II
Double phase, 7 PMTs,
moderate E field, 31/7.2 kg
Run 2005-06
Limit: $6.6*10^{-7}$ pb

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



12 kg xenon

ZEPLIN-III
Second Science Run Result

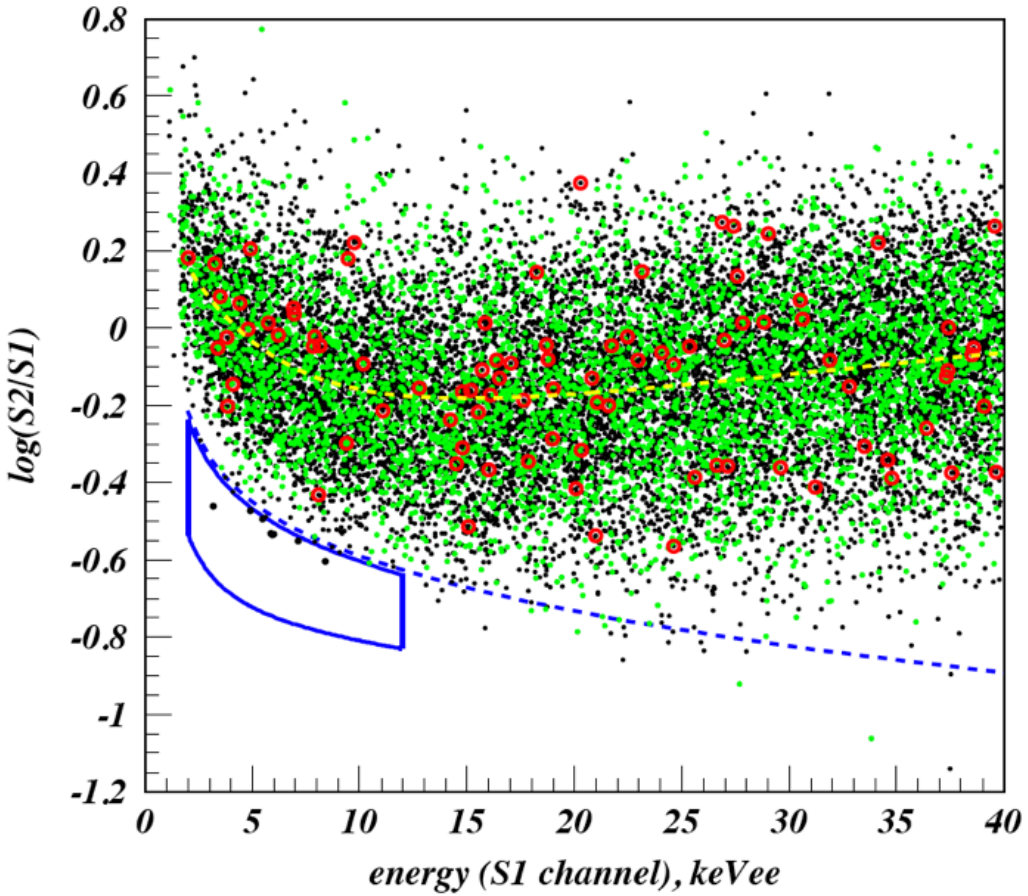
0 neutrons predicted

9 gamma rays predicted

...so what was seen?

8 events in box

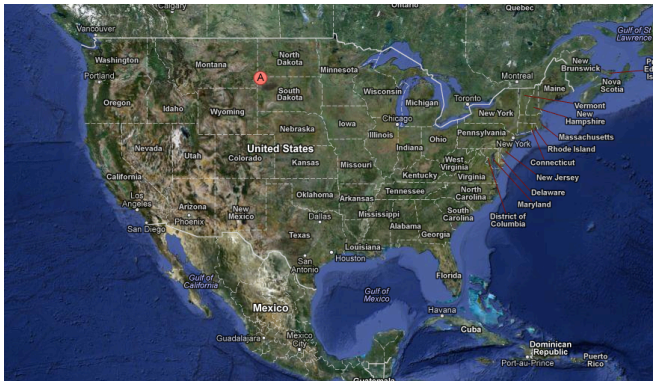
Consistent with γ background
Consistent with zero WIMPs



ZEPLIN Programme

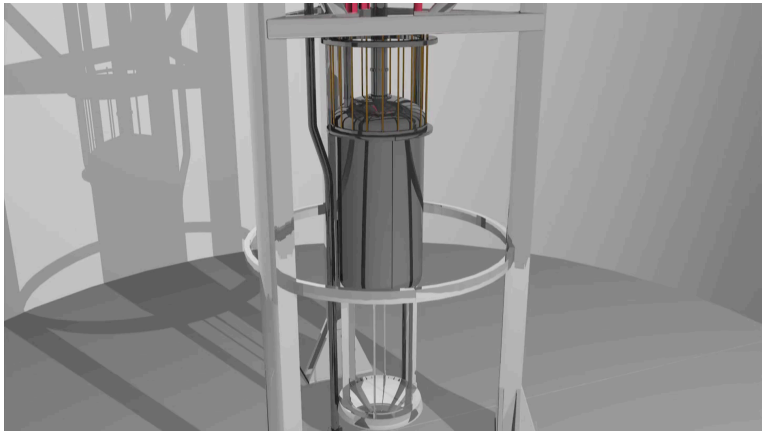
ZEPLIN-I ➜ ZEPLIN-II ➜ ZEPLIN-III ↘

LUX-350



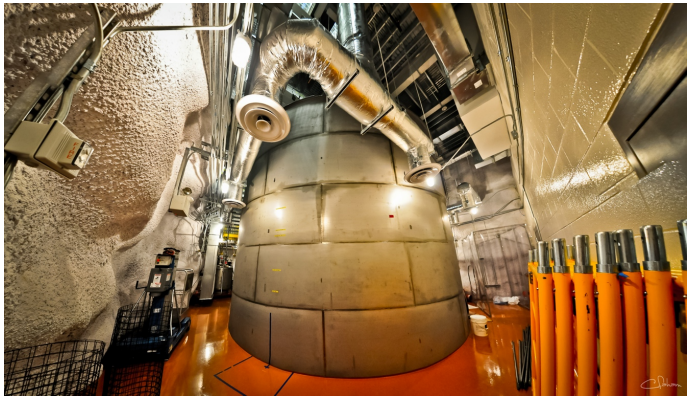
Homestake mine
South Dakota

Davis Cavern (5th May 2011)
4850 ft depth



Dec 2011

World leader in 2013



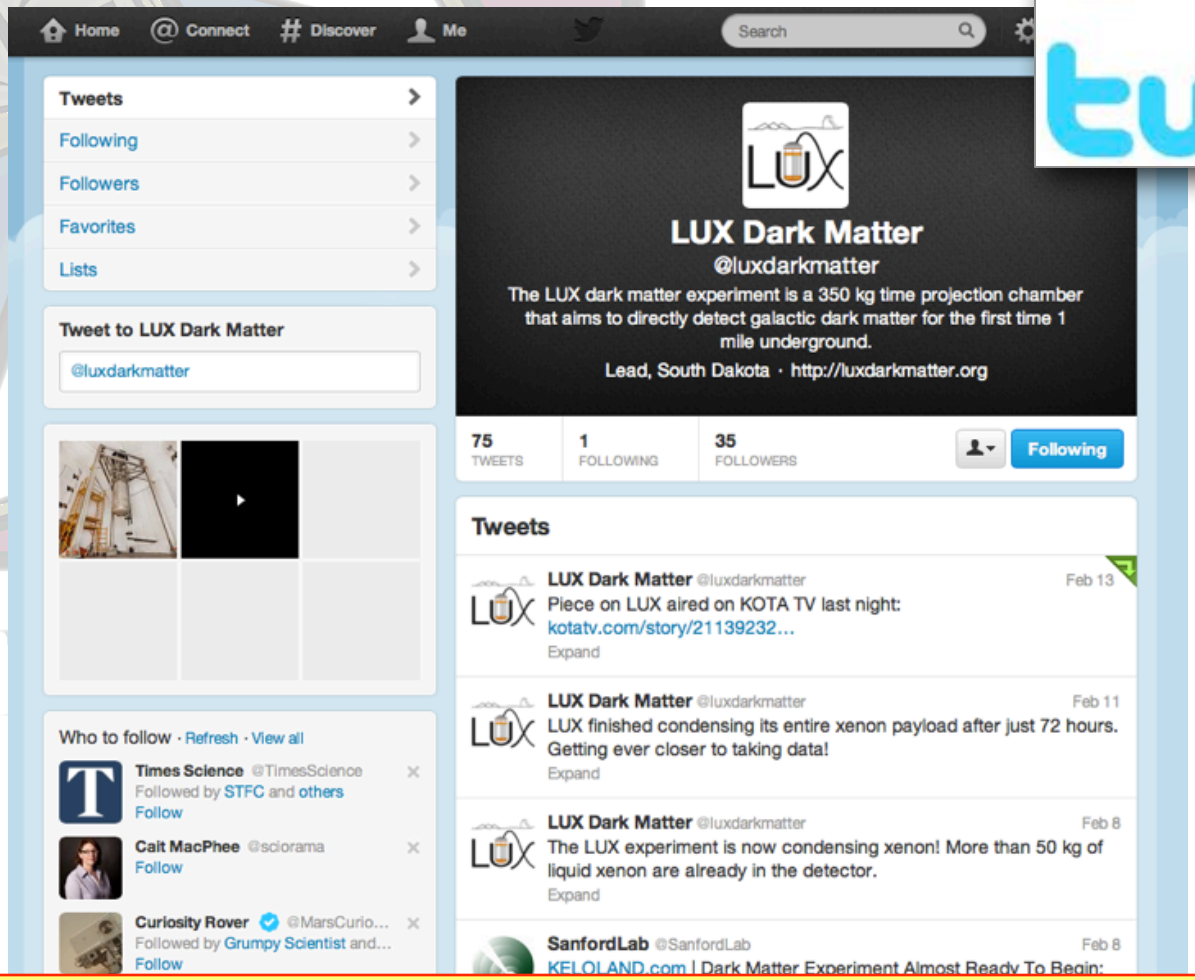
Sept 5th 2012
Water Shield and lab ready for LUX!

LUX Construction

at the Sanford Surface Facility

LUX within the empty water tank before filling

Latest news: LUX-350



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

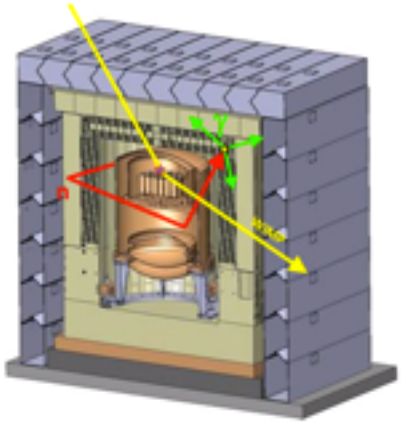
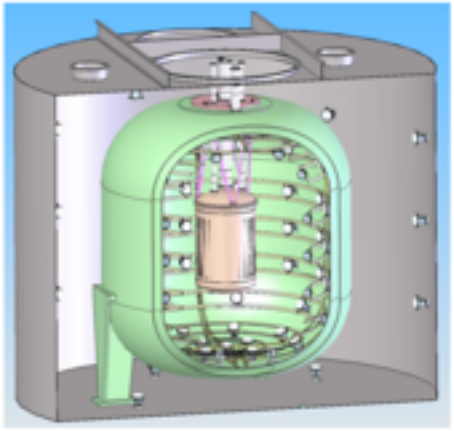
ZEPLIN Programme

Completed Running Planned

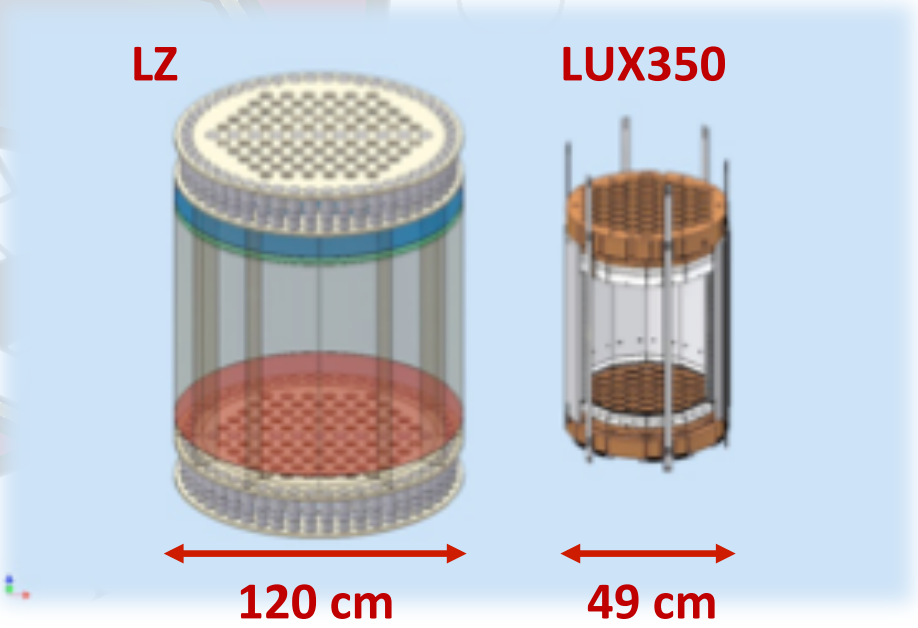
ZEPLIN-II ➜ ZEPLIN-III ➜ LUX-ZEPLIN

LUX-350

Scaling up to LUX-ZEPLIN (LZ)

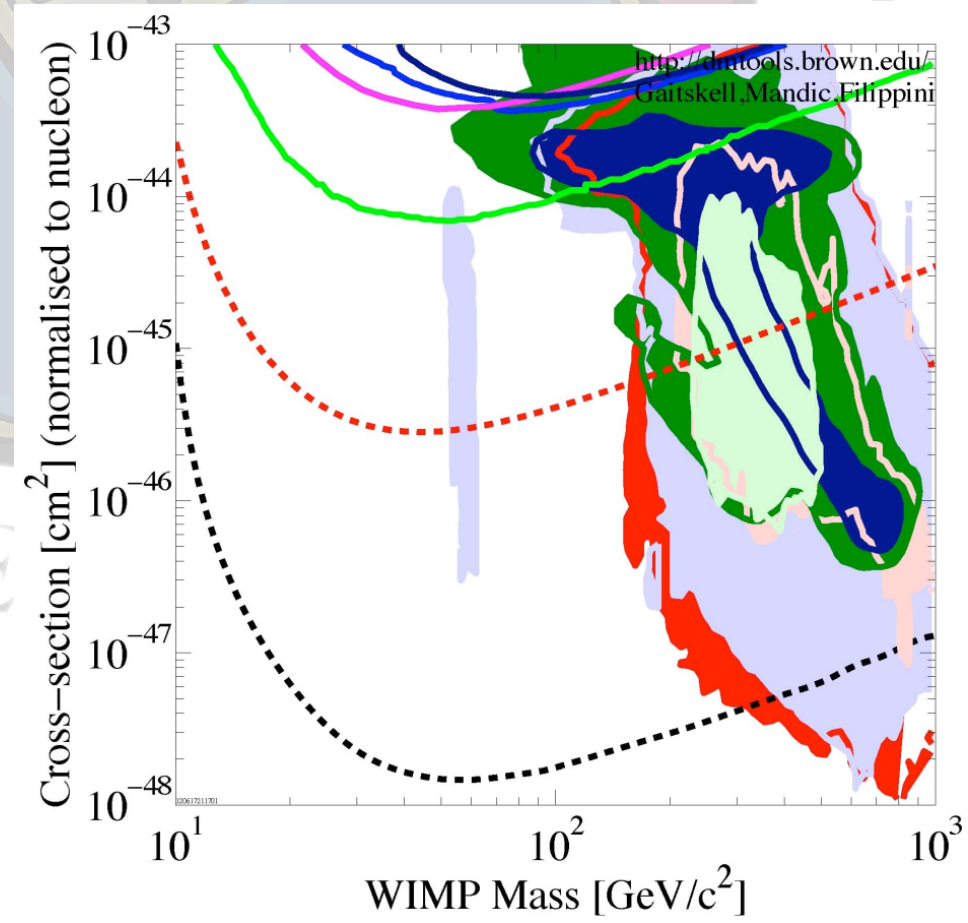
ZEPLIN-III	LUX	LZ
		
6 kg LXe	100 kg	5,000 kg

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

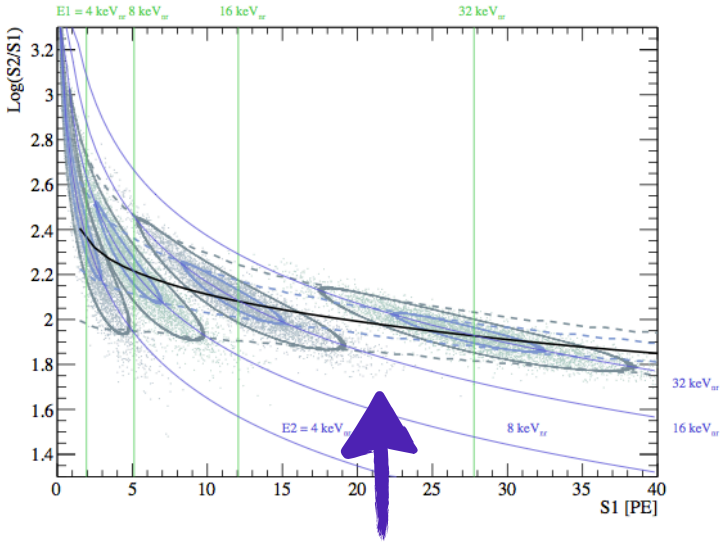
LUX (red dash)

100 kg fiducial x 300 live days

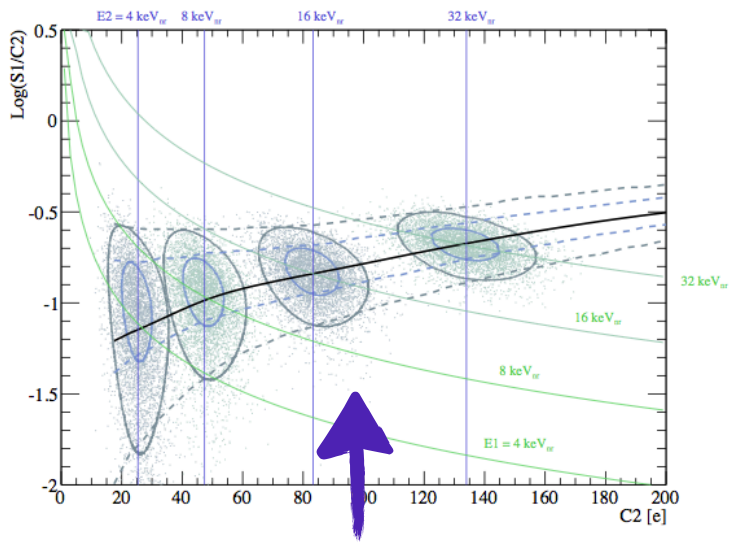
LUX-ZEPLIN (black dash)

5-tonne fiducial x 1,000 live days

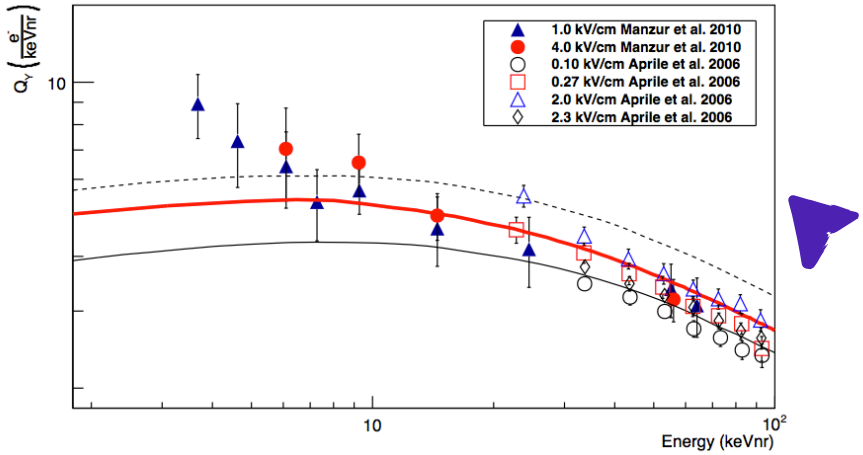
(Further) Exploiting the Ionisation Channel



To go from this...



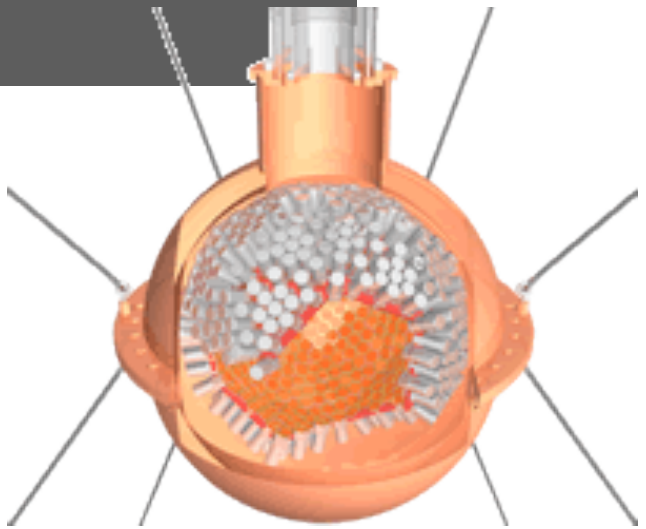
to this...



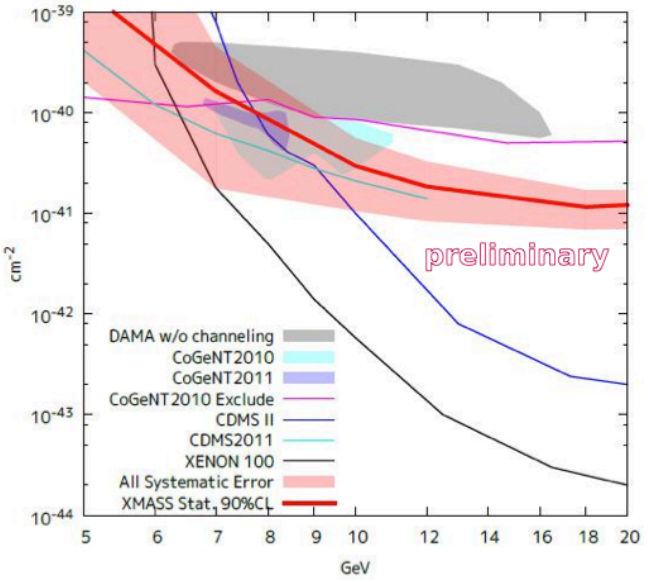
...we need this!

Liquid Xe single-phase

XMASS

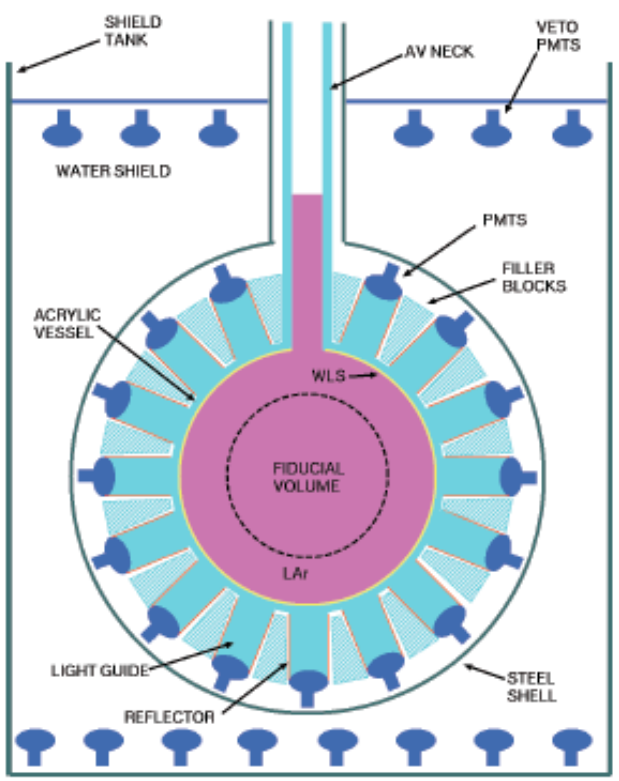


- Based at Kamioka, Japan
- Single phase detector (no S2 signals)
- 100 kg Xe fiducial (800 kg fiducial)
- Unexpected background observed
- Performance severely compromised
- Undergoing refurbishment of PMTs

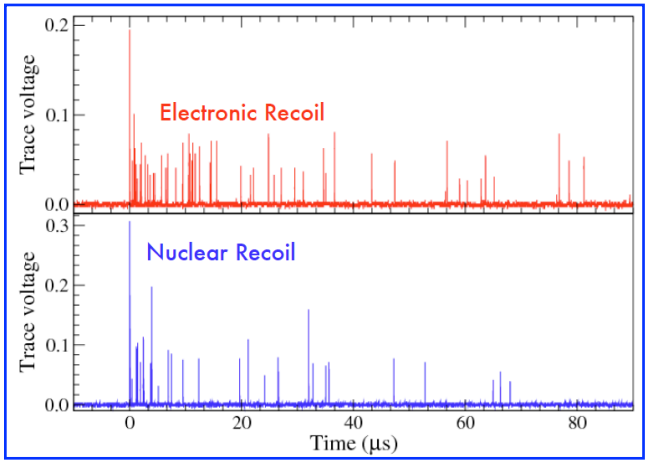


Liquid Ar single-phase

DEAP/CLEAN



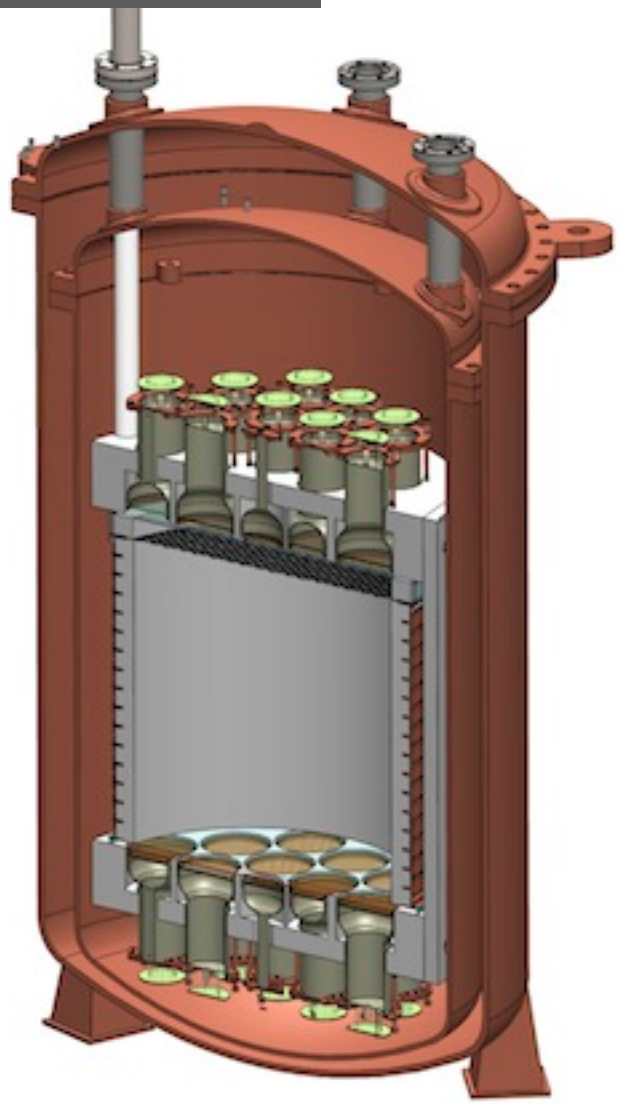
- LAr for powerful PSD
- 2 detectors in parallel development
- miniCLEAN: 150 kg fid. 2013 start
- DEAP3600: 1T fid. 2014-17 run
- Threshold ~40-50 keV due to ^{39}Ar
- DEAP/CLEAN 10T fid. successor



Liquid Argon 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

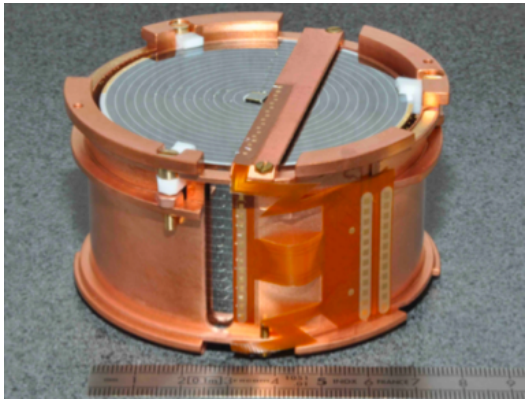
SuperCDMS

- 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

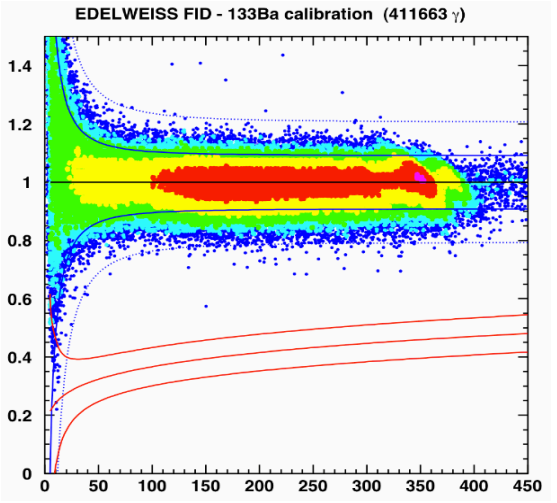
Cryogenic bolometers

EDELWEISS-II ➜ EDELWEISS-III ➜ EURECA

CRESST-II

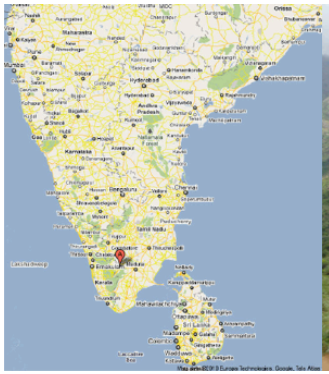


- Similar technology to CDMS
- Based in Modane (EDELWEISS) and LNGS (CRESST)
- Cryogenic Ge and $CaWO_4$
- Excellent discrimination
- Efficiency to ~5 keV for low mass WIMPs
- EURECA will be 1T successor: 2018



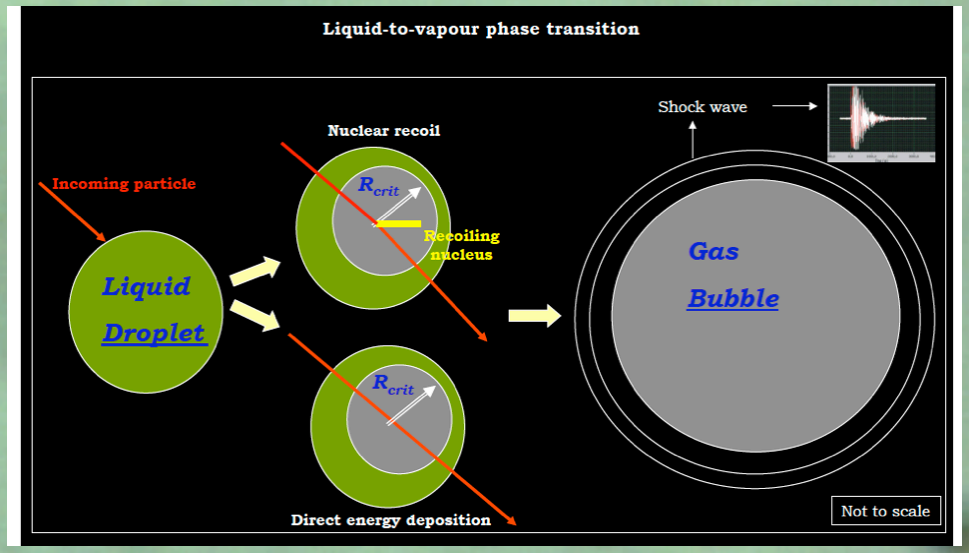
Silicon crystal detectors

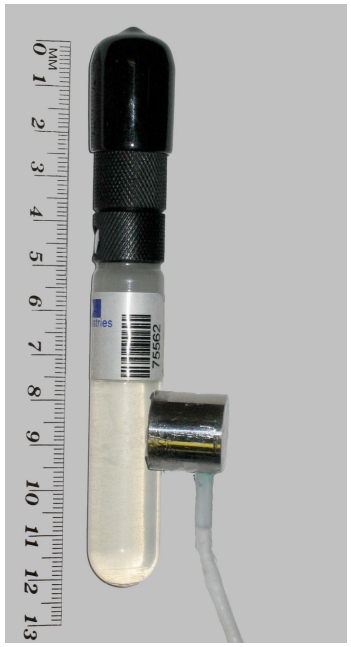
DINO



- 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

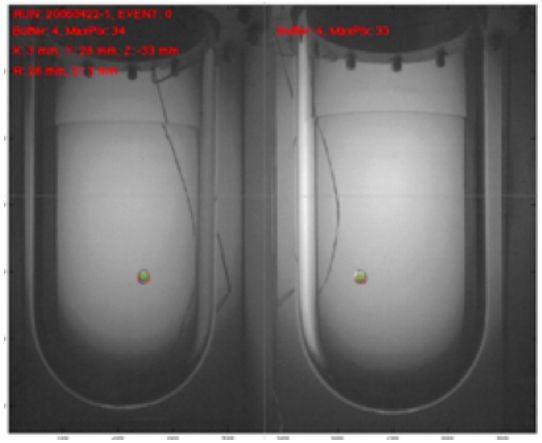
2nd generation : 1L

3rd generation : 4.5L

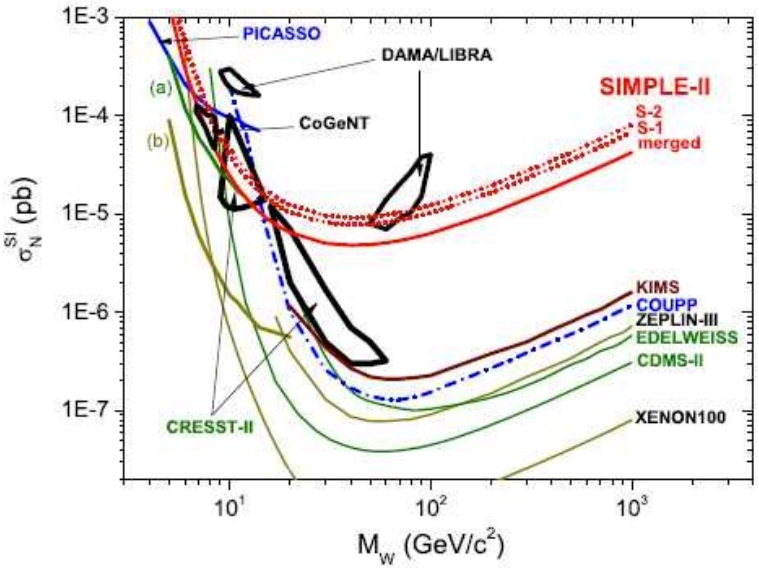
Picasso

SNOLAB, Ca

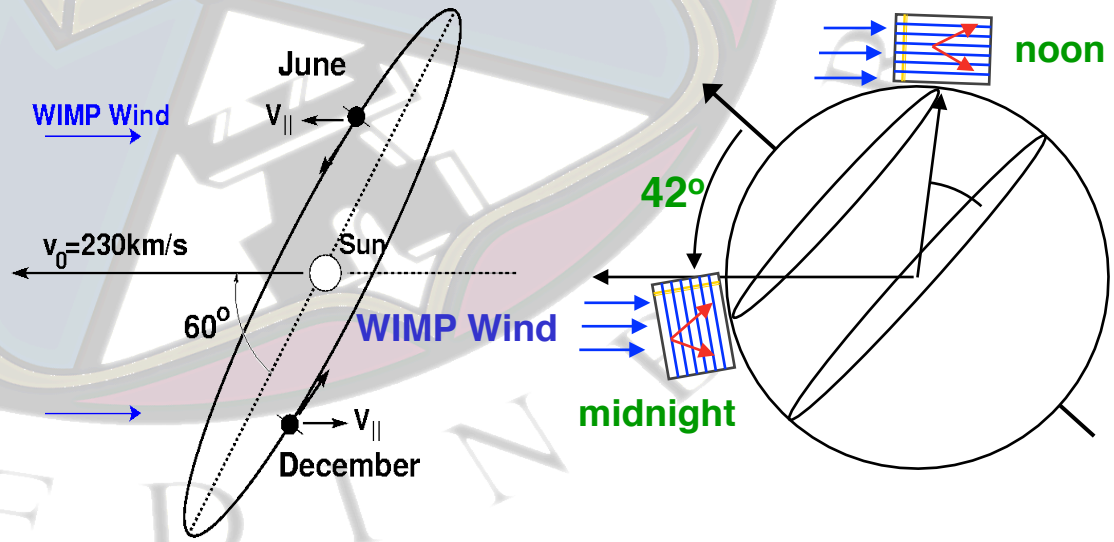
SIMPLE (Freon target)

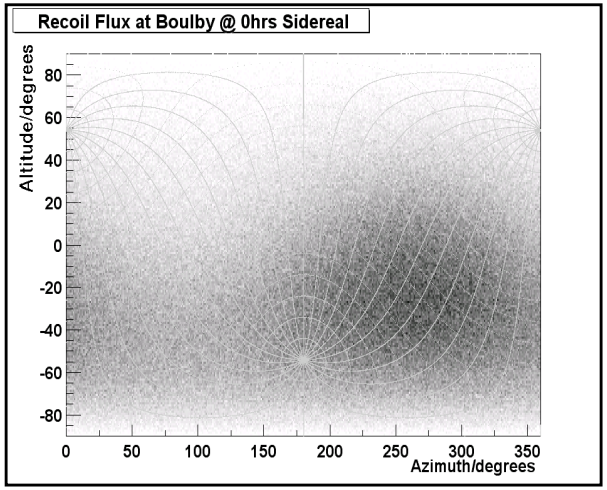


COUPP (CF_3I)



Directional gas TPCs





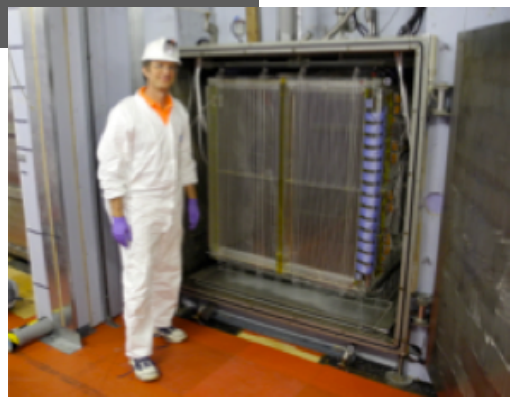
- Directionality robustly tests Galactic origin of signal

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%

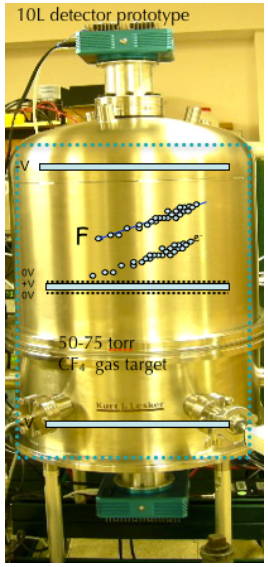
Directional gas TPCs

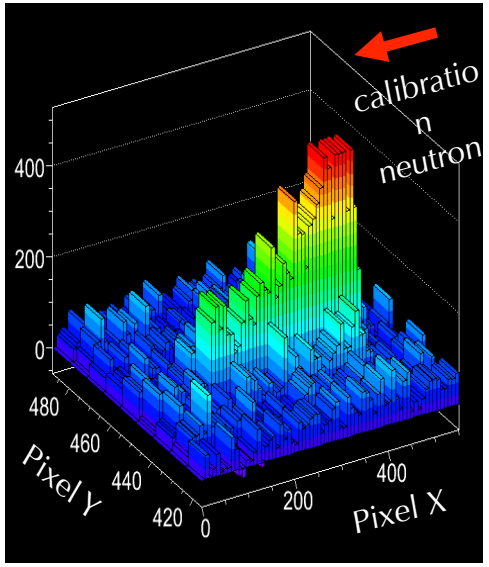
DRIFT-II/III



- CS_2:CF_4 low pressure target (33 g fid.)
- MWPC readout for 3D track reconstruction
- 1 m^3 modules in Boulby Mine, UK
- DRIFT-III plans for 24 m^3

DMTPC

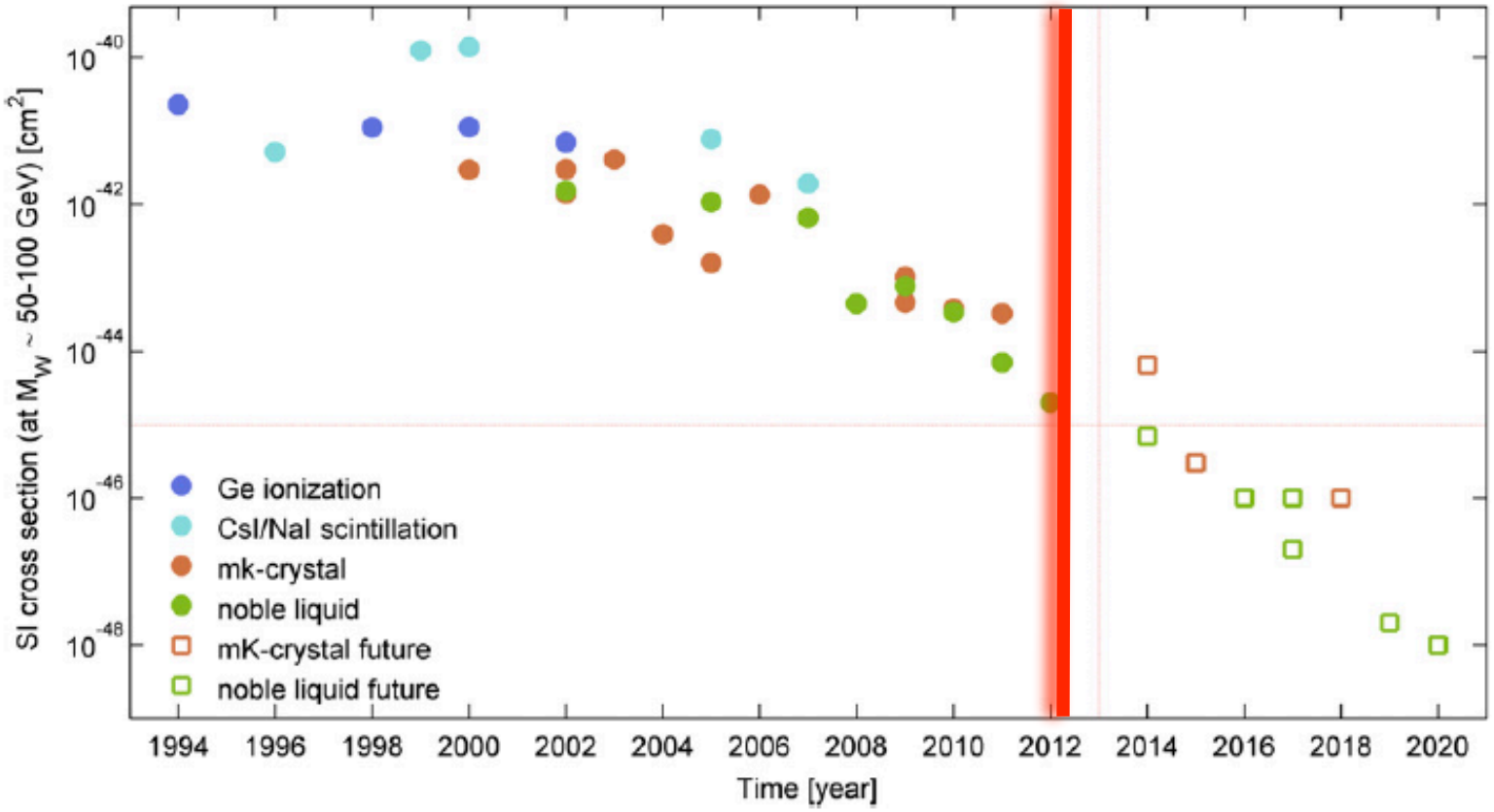




- CF_4 target (10l prototype)
- 1 m^3 modules in
- Charge **and** optical readout

The future

Stated sensitivity aims

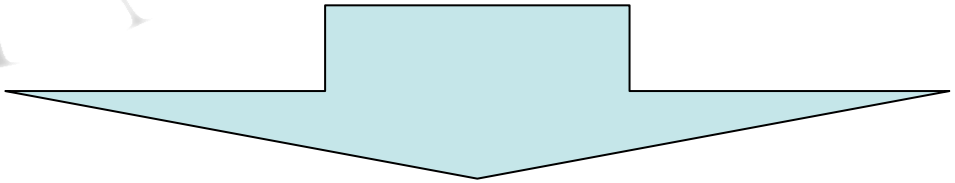


Remarkable technical innovation will drive to further enormous progress

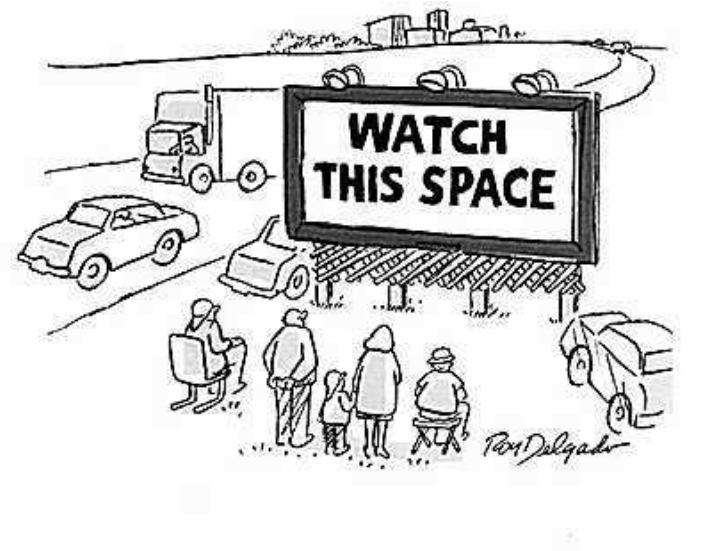
A new collaboration...

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

EDELWEISS | EURECA | DARKSIDE | DEAP/CLEAN | DMTPC | DRIFT | LUX | LZ



Exciting times ahead....



Thank you all for listening!