DARK MATTER

The Experimental Search

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Dark Matter at Boulby Mine

What *is* 'Dark Matter'?

What are we doing to find it?

What are the results so far?

So what is Dark Matter...?

We don't know!

We know it is there, and we know what it isn't...

We have an excellent hypothesis that solves a lot of problems

Non-trivial to prove but that is what we're testing!

Let's start with some history and why we think it exists at all...

The Story Begins

Fritz Zwicky
1933

Early evidence for Dark Matter

1: Looked at
Galaxy clusters

2. Observed their motion

3: Applied the laws of physics that we know

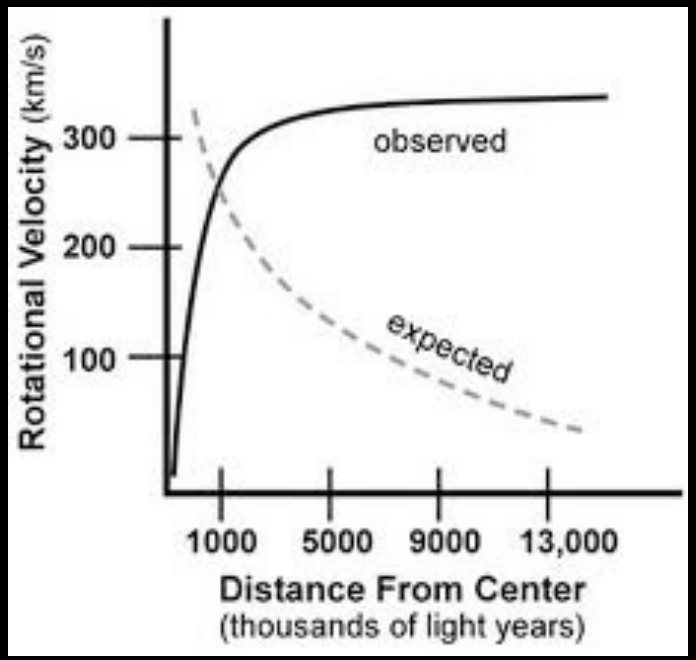
4: Deduced that there must be more mass present than is seen

Early evidence for Dark Matter

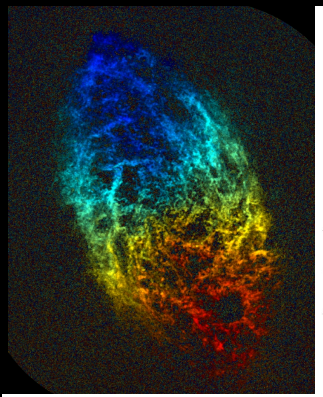
In the 1970s Vera Ruben used the Doppler Shift to look at how fast galaxies were rotating – expecting to see agreement with Newton's Laws, but reproduced Zwicky's results...

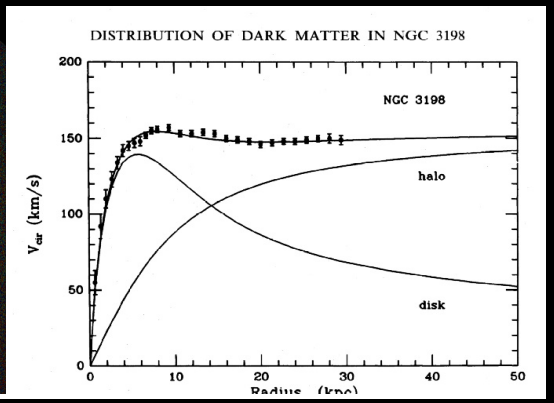
Andromeda

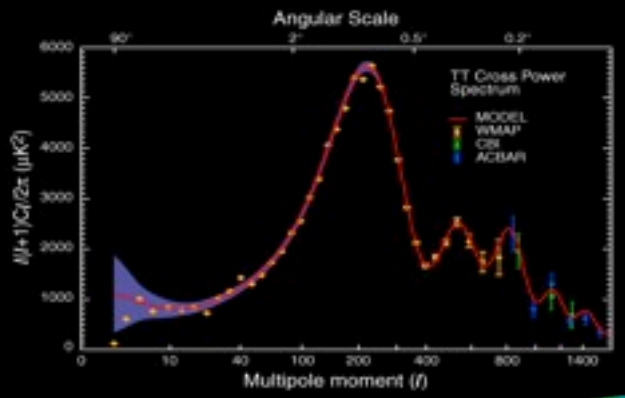
GALAXIES ARE ROTATING TOO FAST!

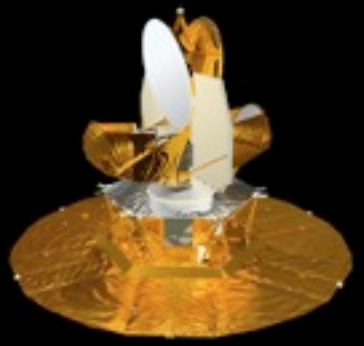


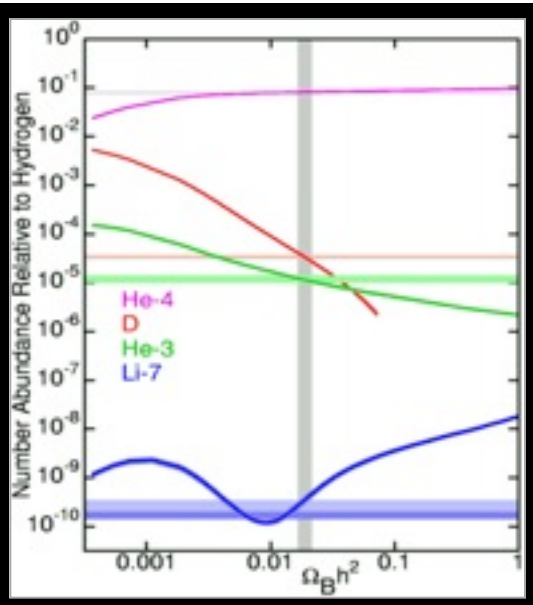
Lots more evidence since then - with little against...

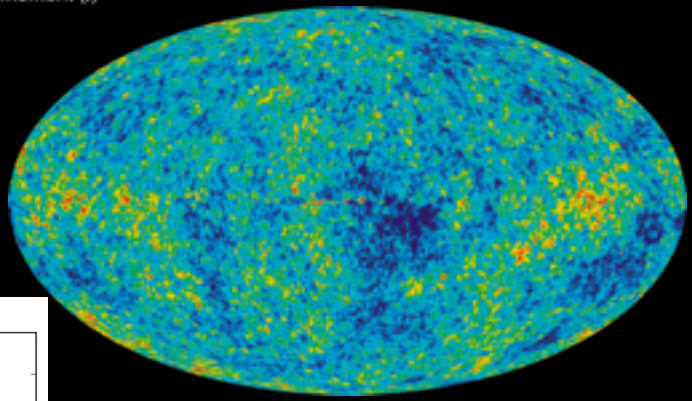


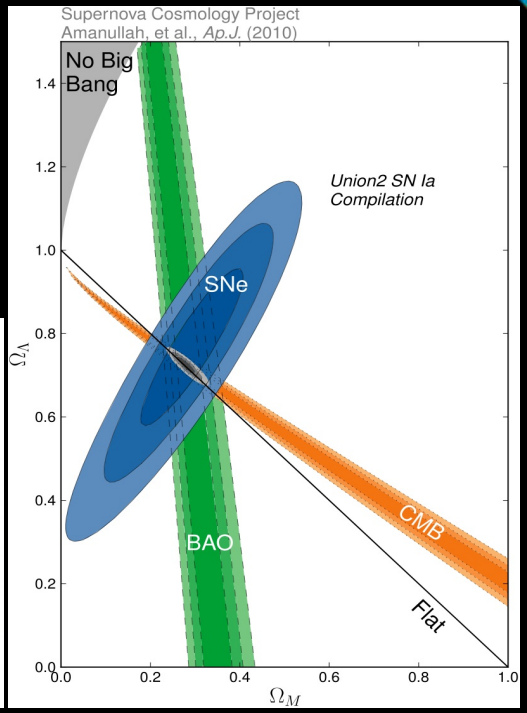

DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)

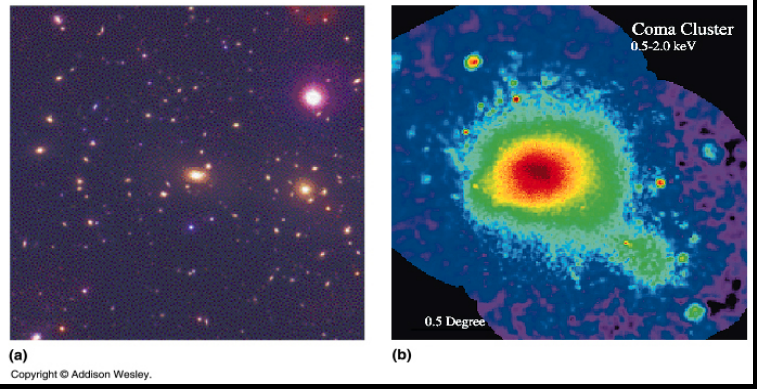

Angular Scale
TT Cross Power Spectrum
MODEL
WMAP
CBI
ACBAR
Multipole moment (l)

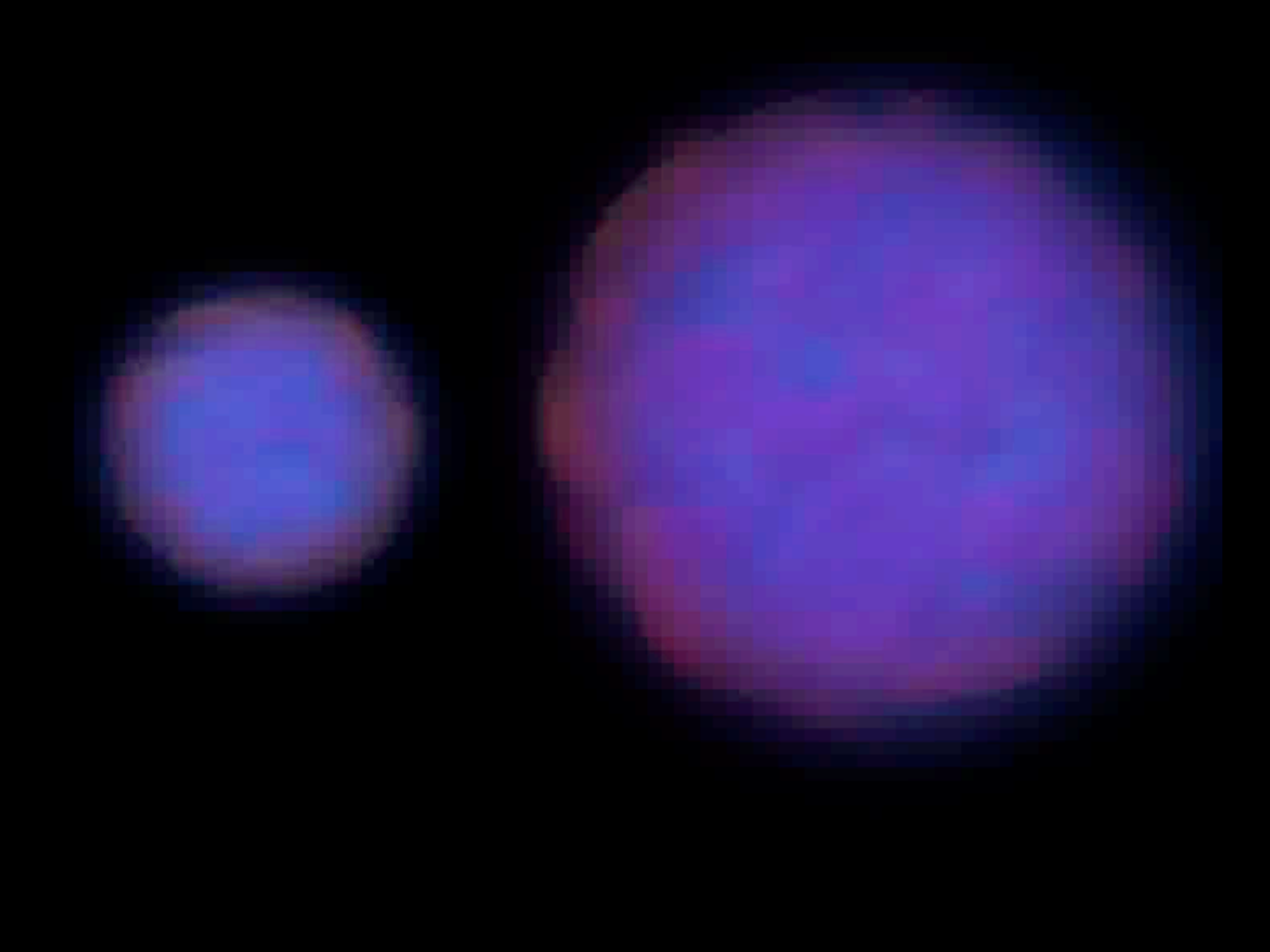


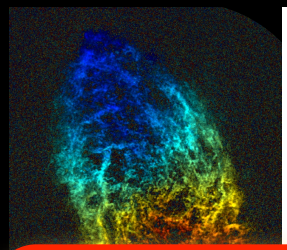

Number Abundance Relative to Hydrogen
He-4
D
He-3
Li-7
$\Omega_B h^2$

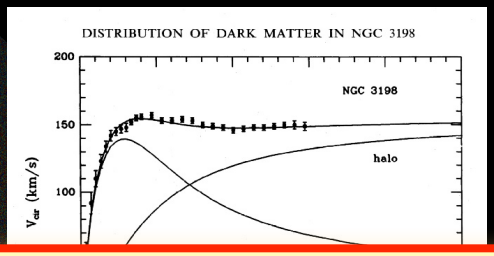


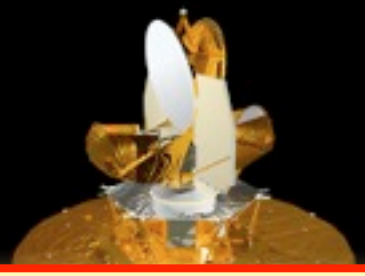

Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)
No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M

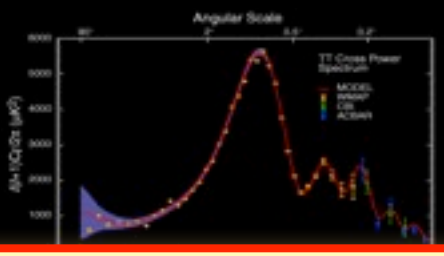

Coma Cluster
0.5-2.0 keV
0.5 Degree
(a)
(b)
Copyright © Addison Wesley.





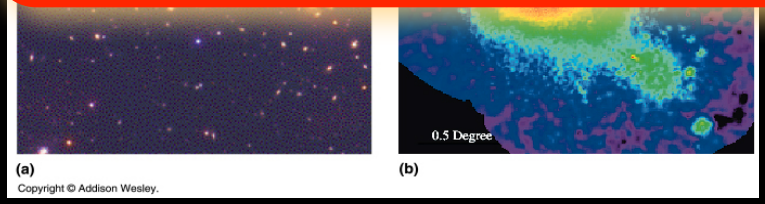


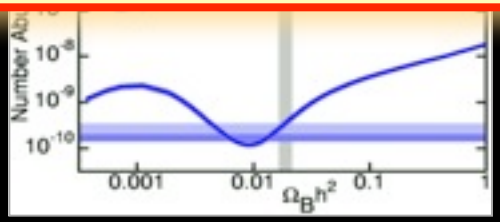




We have a ‘Missing Mass’ Problem!

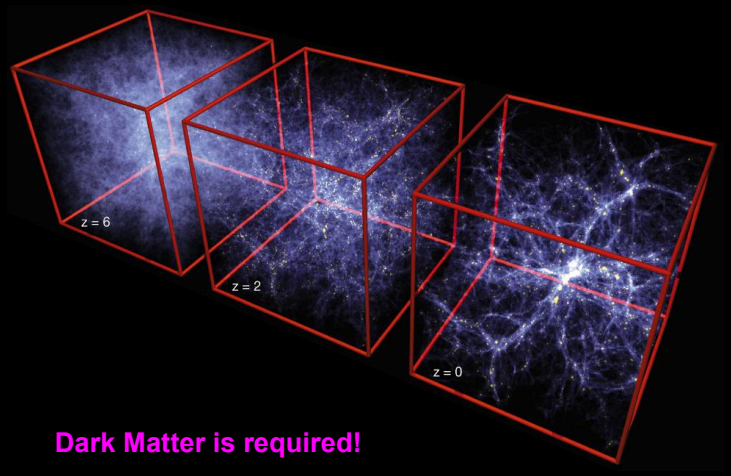
90% of the mass of the Universe is **DARK!**





Does it matter?

Formation of Structure in the Universe



Dark Matter is required!

YES!

- It holds galaxies together
- Without it we and the structures around us wouldn't have formed
- Without an understanding of it, we cannot piece together the past or predict the future fate of the Universe

What could Dark Matter be?

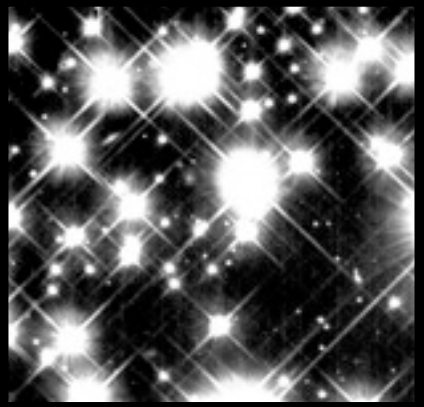
Astronomical objects?

- Gas or dust?
- Small faint stars or big planets?
  - white dwarfs
  - brown dwarfs
  - red giants
  - Jupiters
- Black holes?

'Gas or Dust'

The horse head nebula

Planets

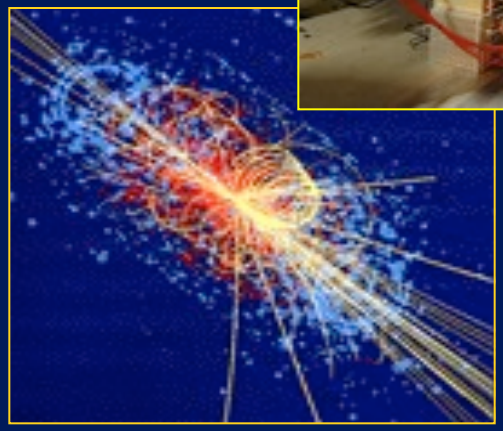


White dwarfs

No... 'Normal Matter' makes up less than **20%** of the matter in the Universe

Could it be particles?

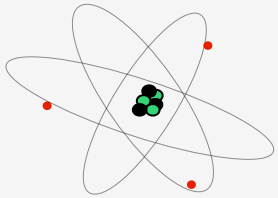
Particle physics @ CERN



The 'Standard Model' of particle physics

Particle physics tells us...

Everything is made of particles...



Electrons

Neutrons

Protons

Quarks (up, down +4 more)
Leptons (electrons, μ, ν, τ)
Bosons (photons, W, Z, gluons)
4 forces (EM, Gravity, Strong, Weak)

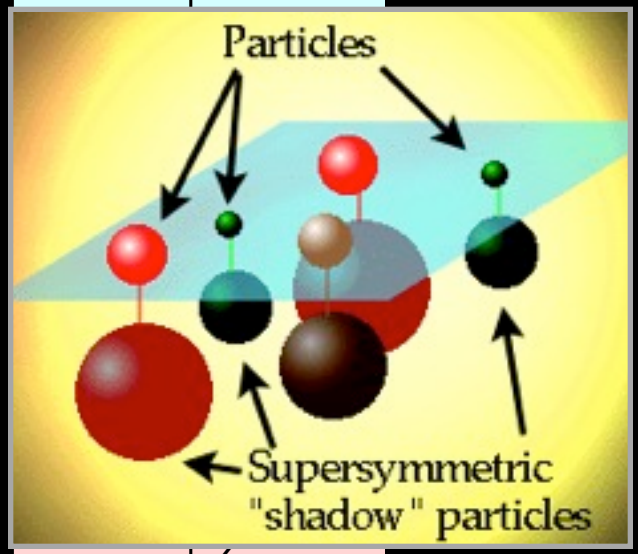
Problems with the standard model makes us think there must be more particles & rules out there...

SUPERSYMMETRY to the rescue!

SUPERSYMMETRY

- Explains why we see the range of particles and forces that we do
- Predicts that there are more particles we have yet to see
- The lightest of these, the **WIMP**, has just the right properties to be dark matter
- An *independent* prediction of the existence of a particle that matches the DM requirement!

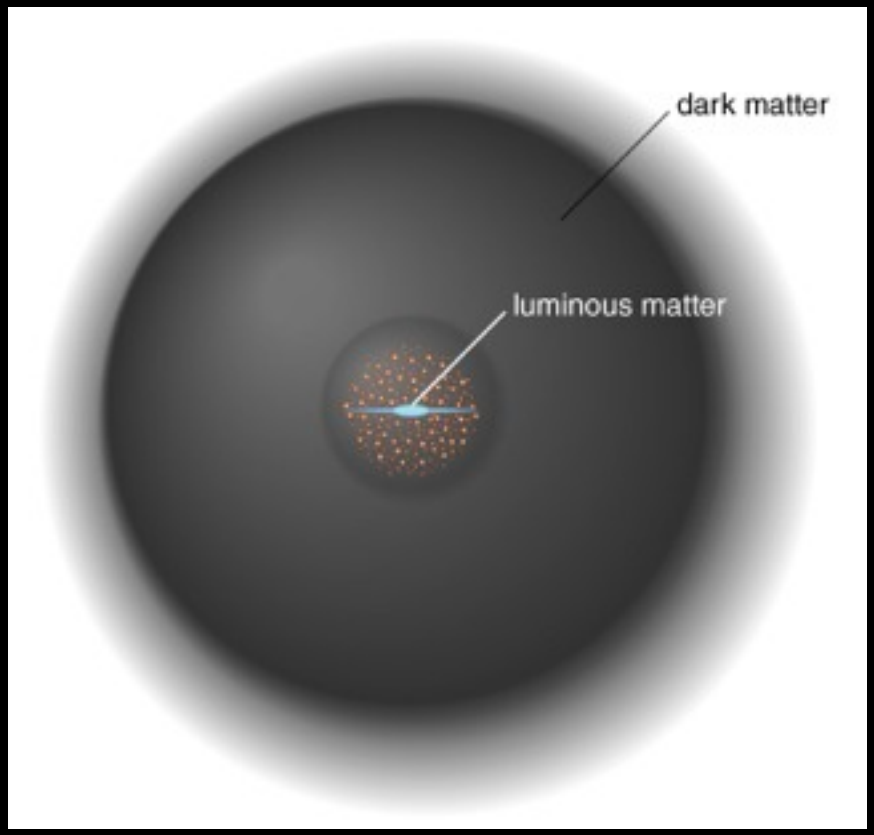
Particle type	Particle
	Z
	Photon
	Gluon
	Higgs



WIMPs

Weakly Interacting Massive Particles

Lots of Tiny Particles



Origin?

Produced after the BIG BANG

(14 billion years ago)

Mass?

Between 50-1000 times mass of a hydrogen atom

Interactability?

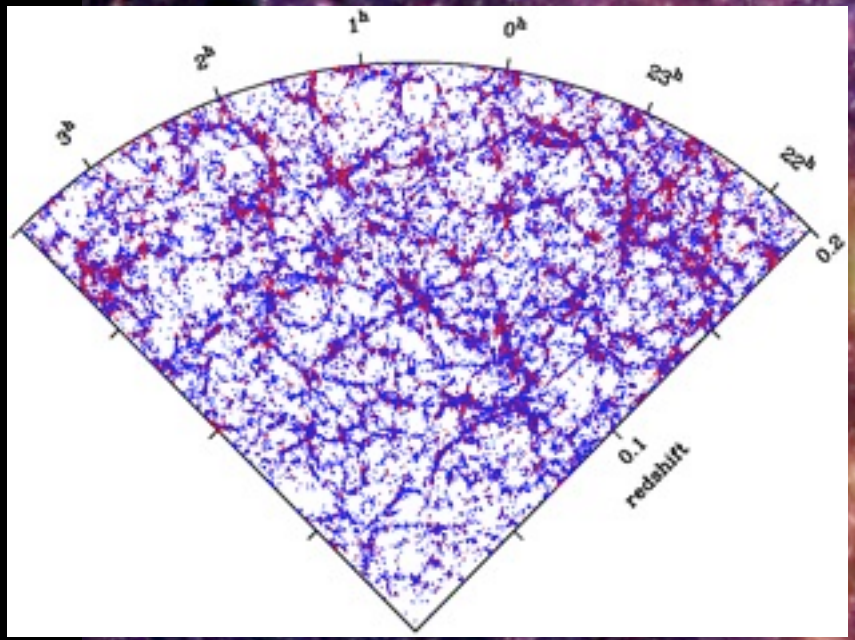
1 billion pass through our bodies every day

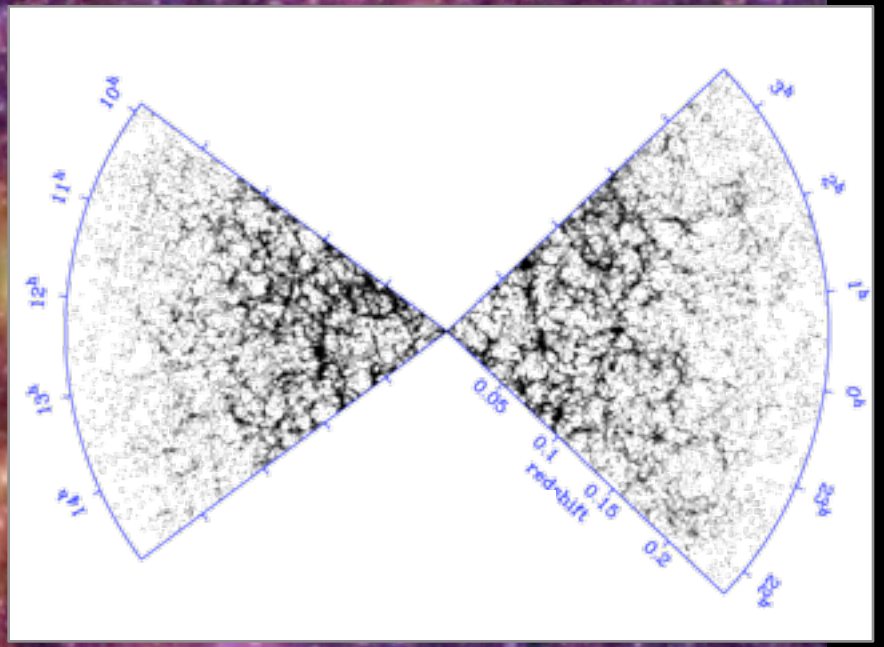
Distribution?

Extended halos around galaxies

Just how well does this model work?

Let's compare this simulation using the WIMP model with observation...





It all works, beautifully!

Conclusion: There is more matter out there than we can see in stars, planets, etc.

This ‘dark matter’ is *fundamentally* different to normal matter

We have an excellent theory for what this stuff might be, but its never been seen

So let’s get cracking!

Three ways to find Dark Matter:

1. Look for secondary products (indirect)

2. Make it afresh (accelerator)

3. Interact directly with ***our*** galactic Dark Matter

DIRECT DETECTION OF GALACTIC WIMPS!

The Direct Detection Challenge

The 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

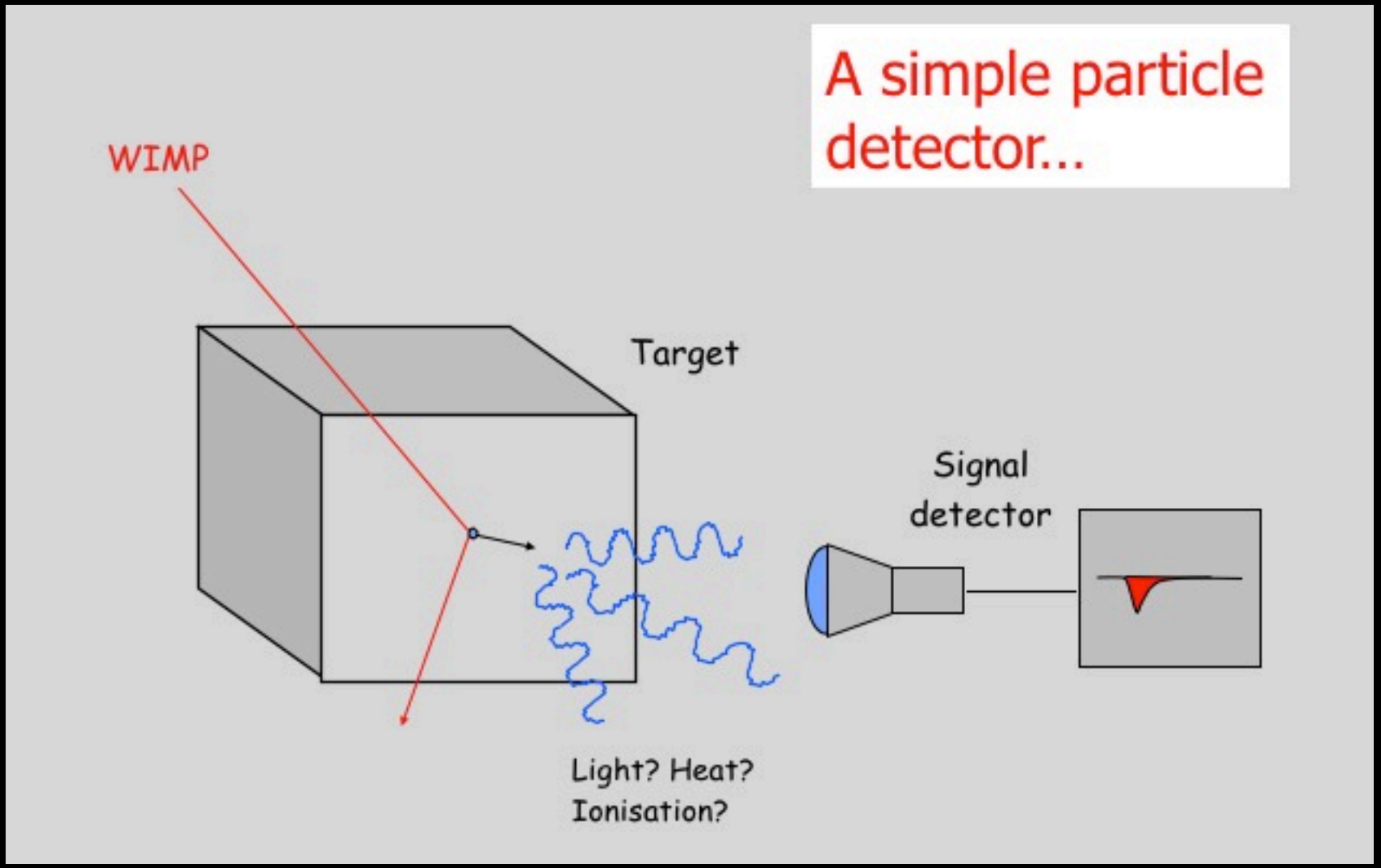
Definitive detection is internationally recognised as one of THE highest priorities in science!

Basic method

Make a device that should see *NOTHING* from ‘normal’ (Standard Model) physics

And see if there’s anything still there...

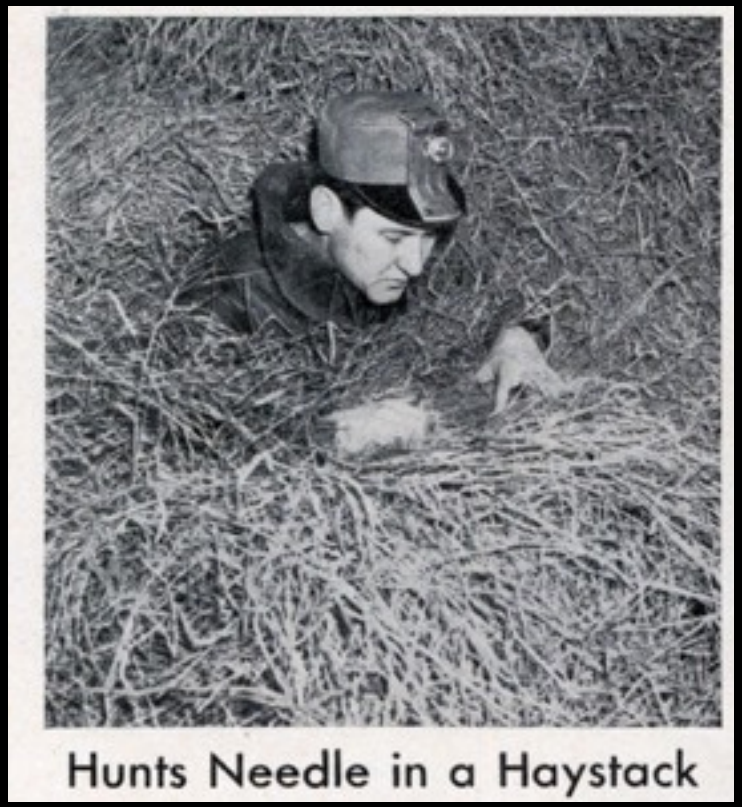
How to detect a WIMP - step 1



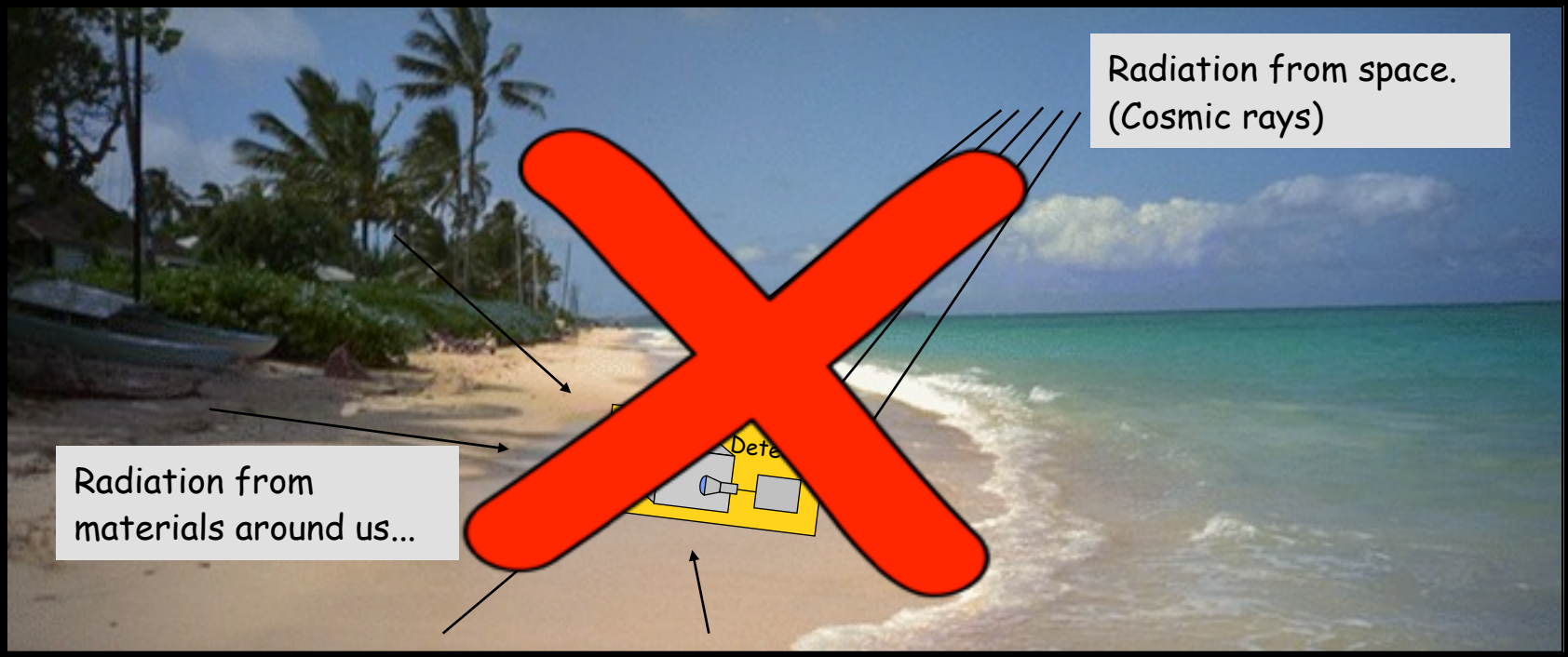
How to detect a WIMP - step 2

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!)



How to detect a WIMP - step 3

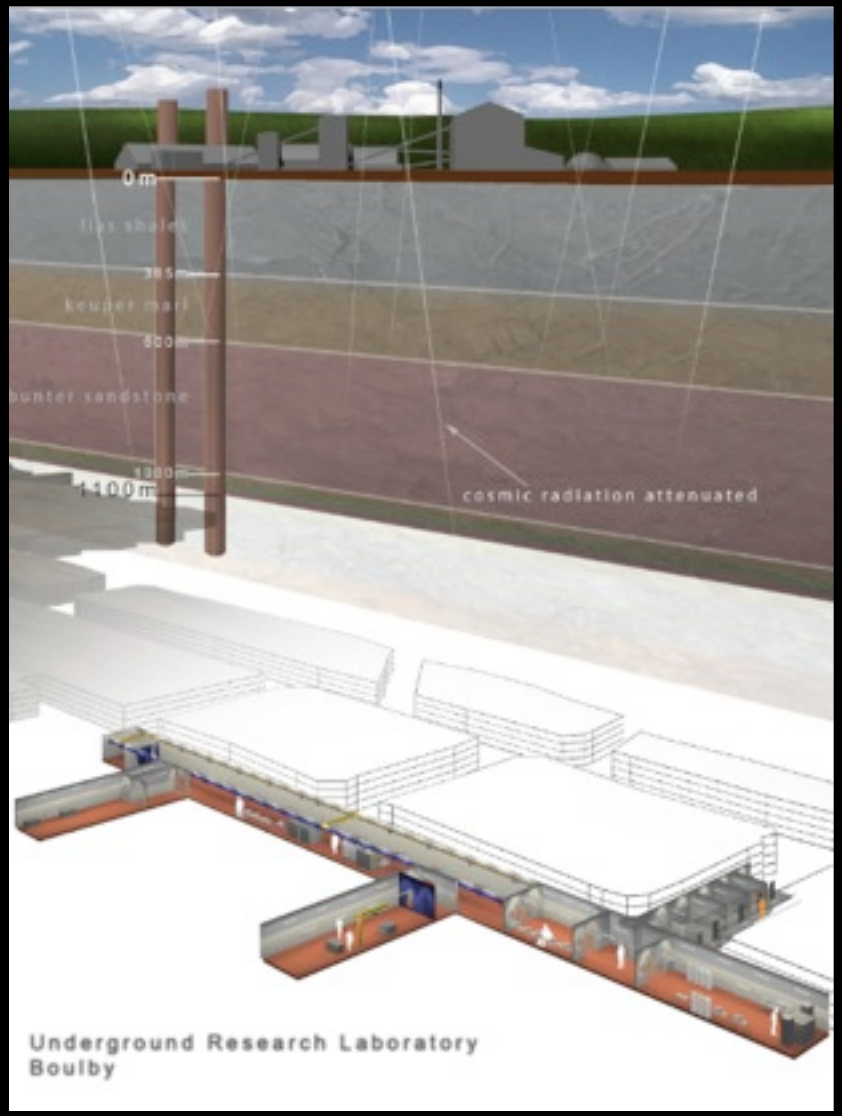


Need to go deep underground!

The Boulby Mine

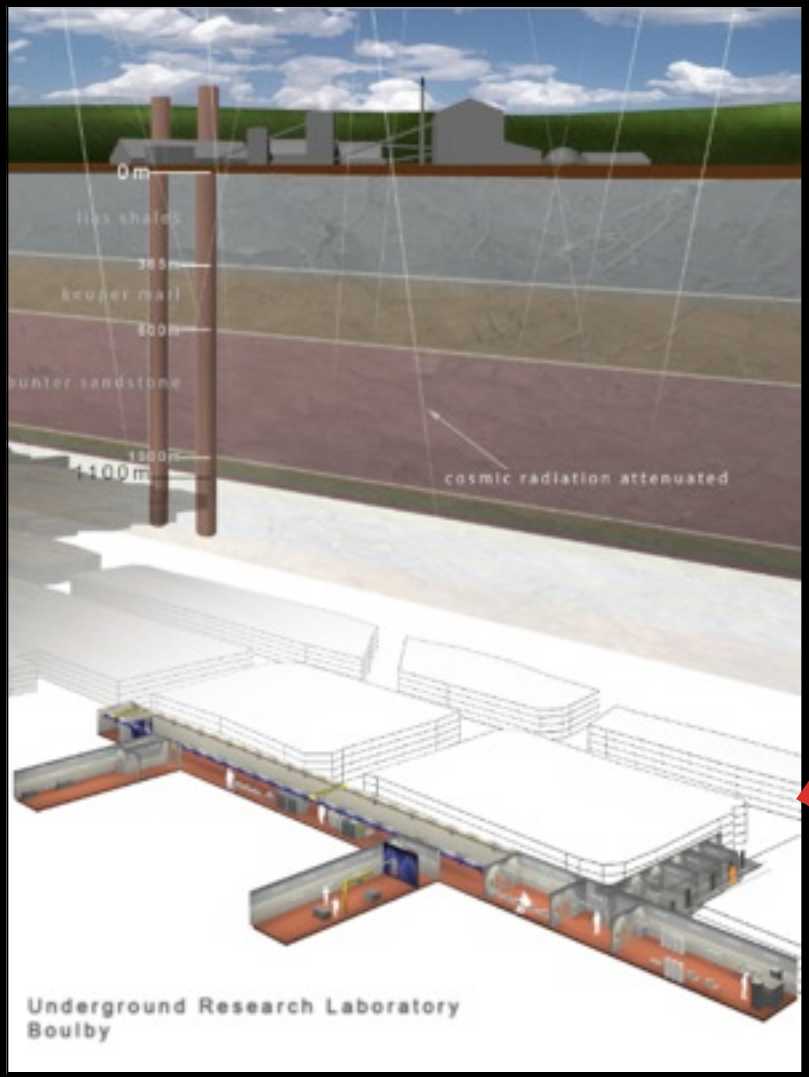
Boulby Mine

- A working potash and rock-salt mine operated by Cleveland Potash Ltd
- On the Cleveland / North Yorkshire border - 12 miles north of Whitby
- Major local employer - ~1000 direct and 4000 indirect employment
- Over 40 kms of tunnel mined each year (now >1,000 kms in total)
- Deepest mine in Britain – 1100m deep (2805mwe) – **Cosmic rays reduced by a factor 1 million**
- Boulby salt is **very low in natural radioactive backgrounds**



Underground

The Palmer laboratory



The Underground Laboratory

The World Dark Matter Search Race

Boulby, UK
ZEPLIN-III,
DRIFT-II

Modane, France
EDELWEISS

Minnesota,
USA
CDMS

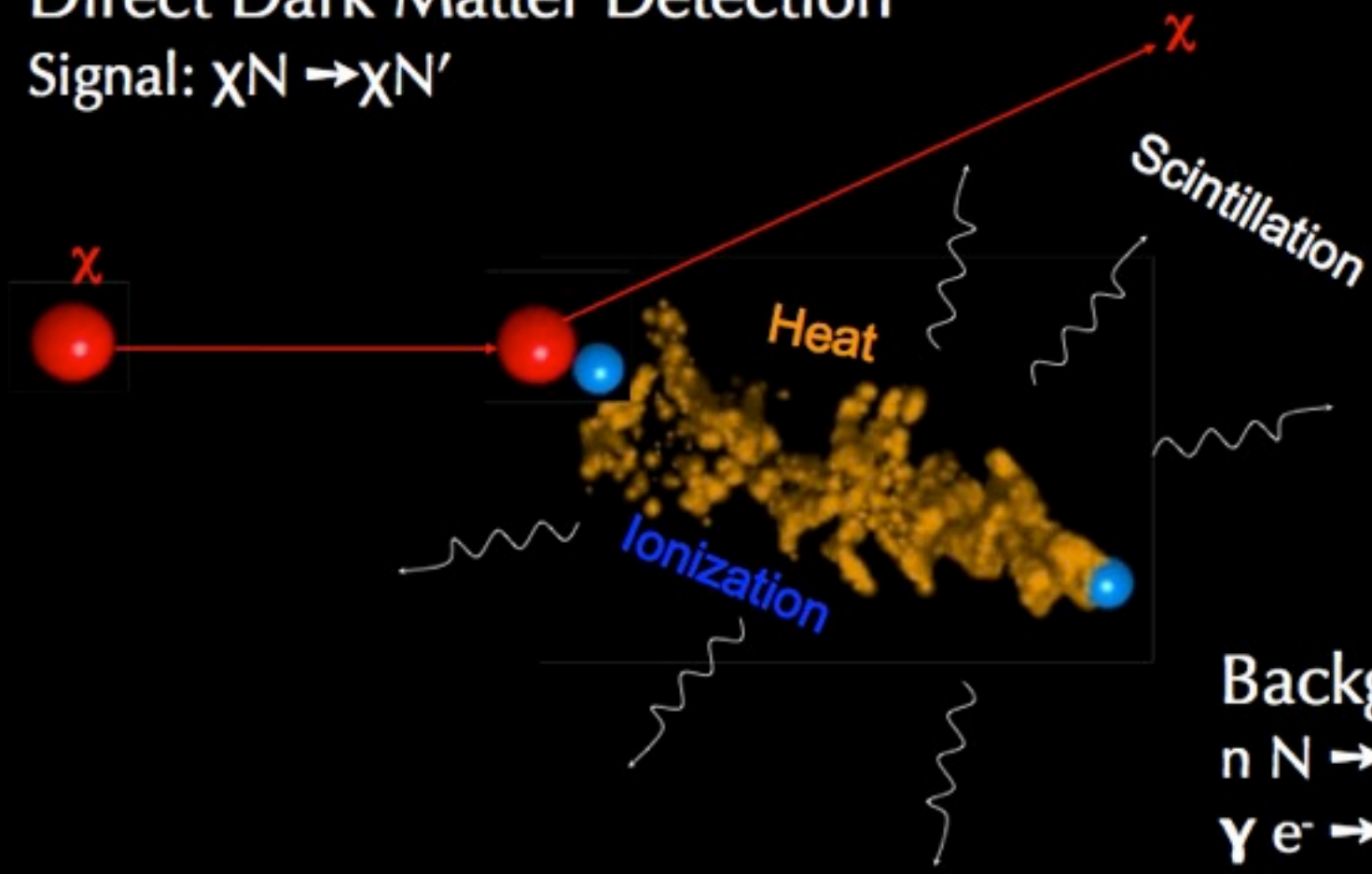
Homestake,
USA
LUX

Gran Sasso, Italy
XENON, DAMA, CRESST

Kamioka, Japan
XMASS

Direct Dark Matter Detection

Signal: $\chi N \rightarrow \chi N'$



Backgrounds:

$n\ N \rightarrow n\ N'$

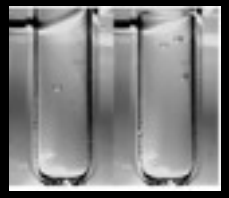
$\gamma\ e^- \rightarrow \gamma\ e^{-\prime}$

$N \rightarrow N' + \alpha, e^-$

$\nu\ N \rightarrow \nu\ N'$

WIMP Detection Techniques

Heat and ionisation bolometers: CDMS
EDELWEISS



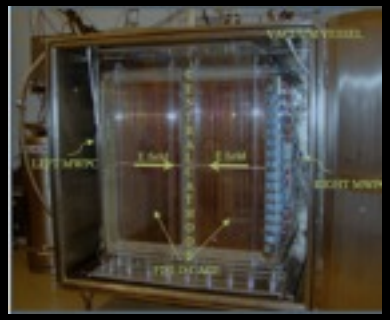
Bubbles and Droplets:
CUOPP
PICASSO

Light and heat Bolometers:
CRESST
ROSEBUD

Phonons

Charge

Light



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

Scintillation and ionisation charge detectors:
XENON
WARP
ArDM
ZEPLIN
LUX

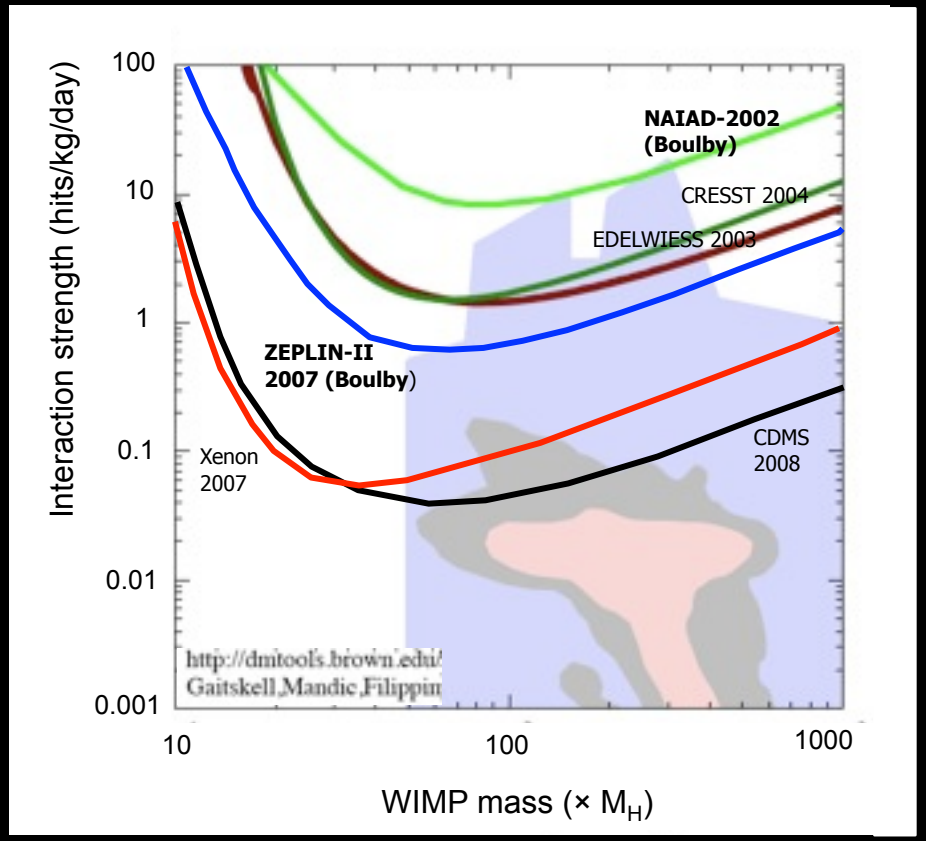
Scintillators:
DAMA
LIBRA
XMASS
CLEAN
ANAIS
KIMS

The World Dark Matter Search Race

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'

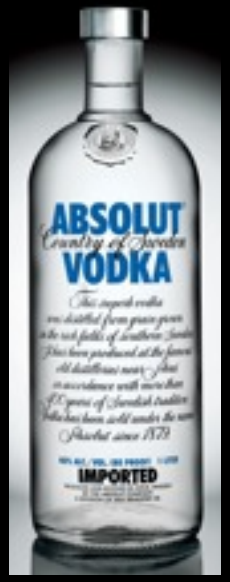
'Exclusion plots' let us keep track of who is in the lead and how we stack up against the competition



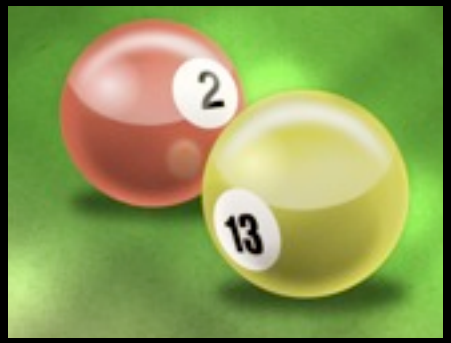
Let the games begin!

Why xenon?

Excellent light output



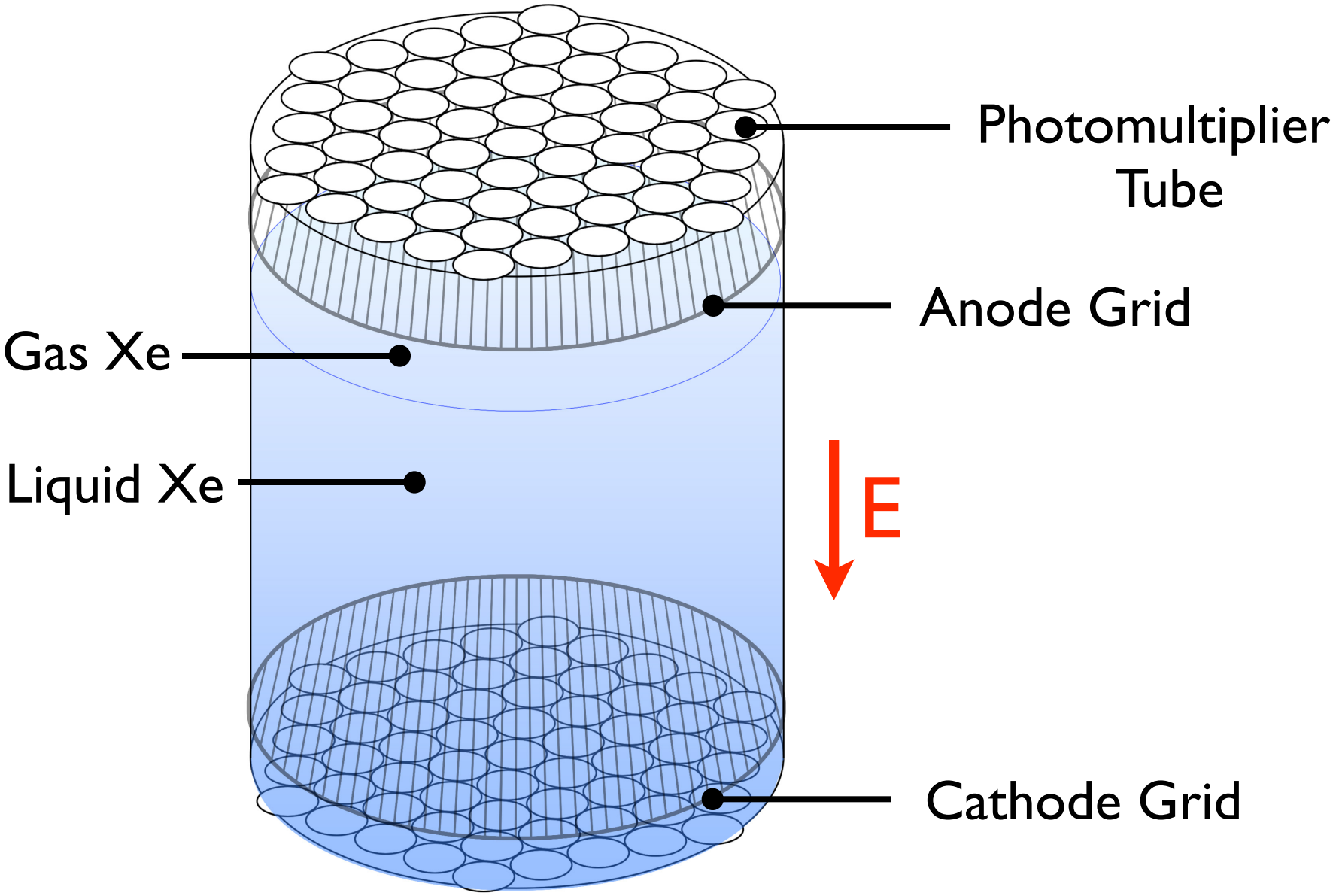
Very high purity

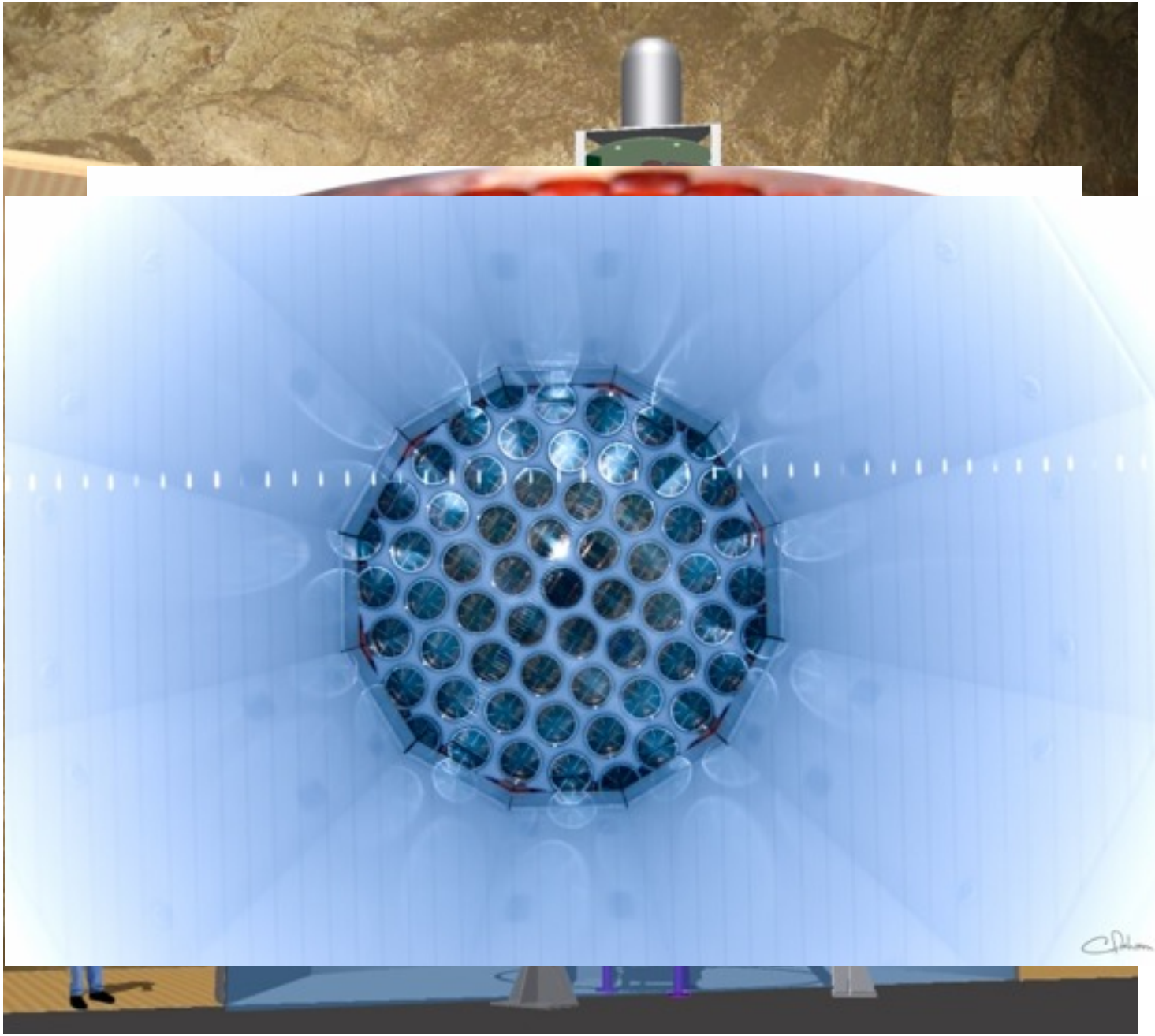


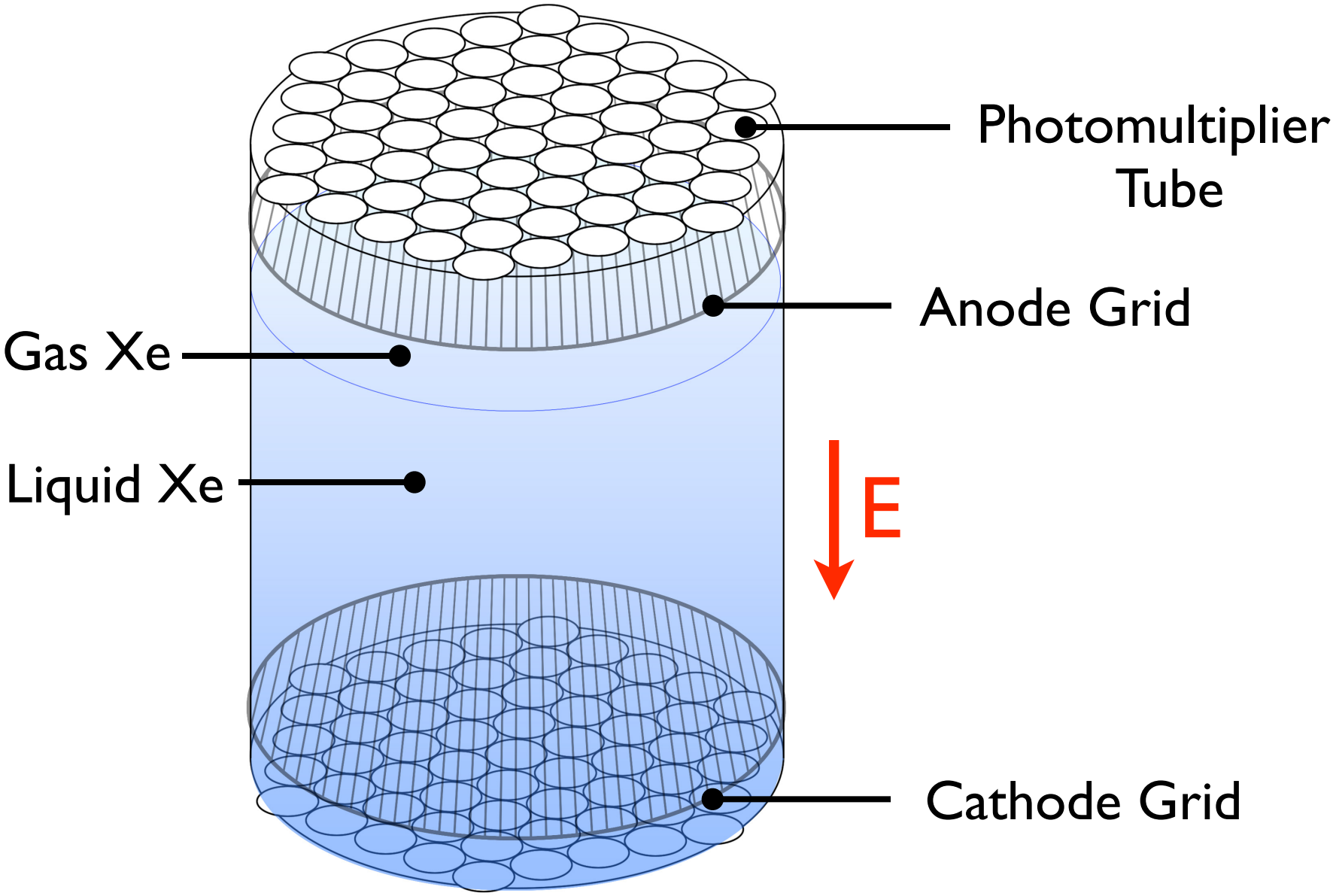
Mass Xe ~ Mass WIMP

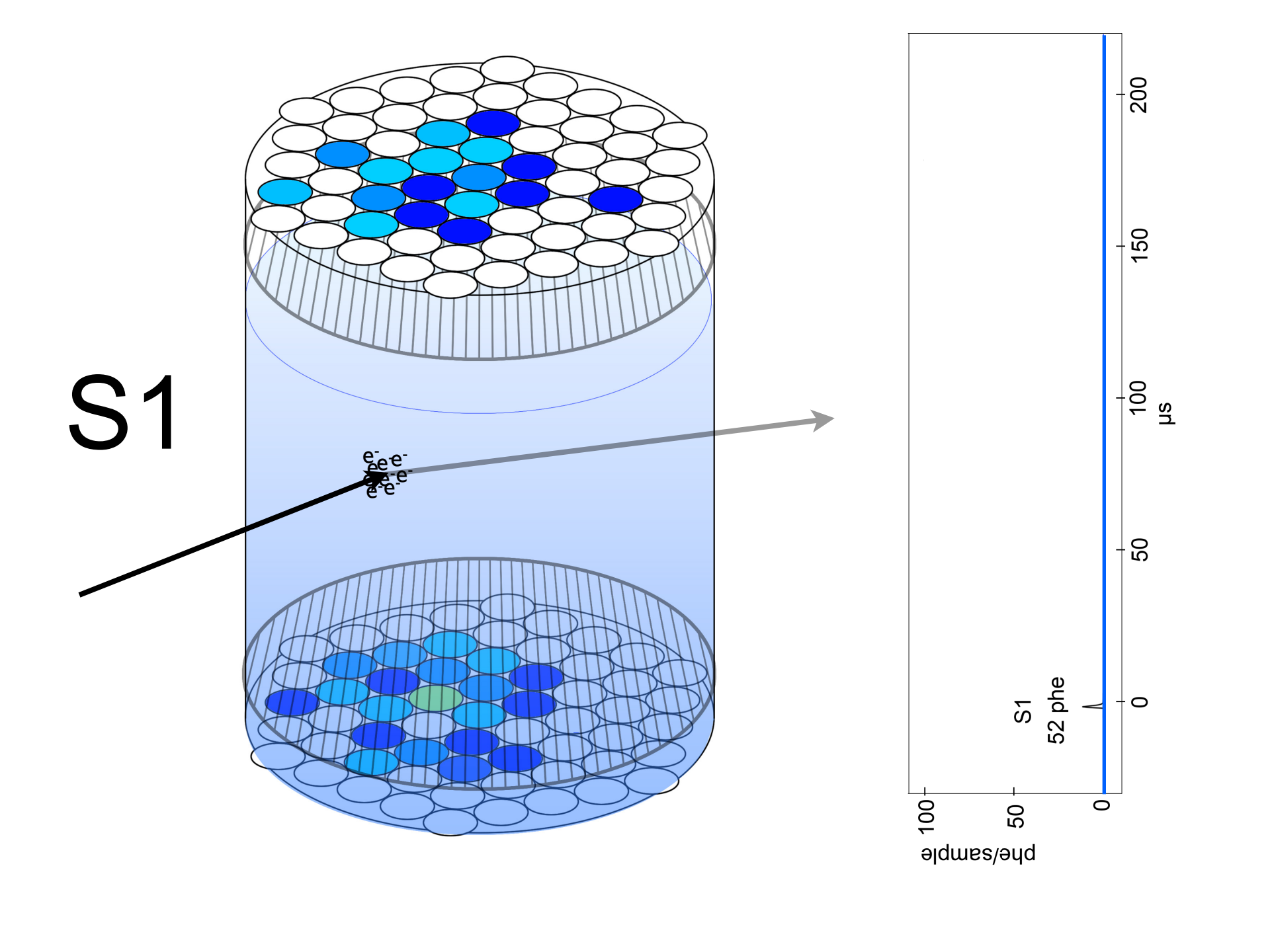
1 tonne

70 cm


Photomultiplier Tube
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid

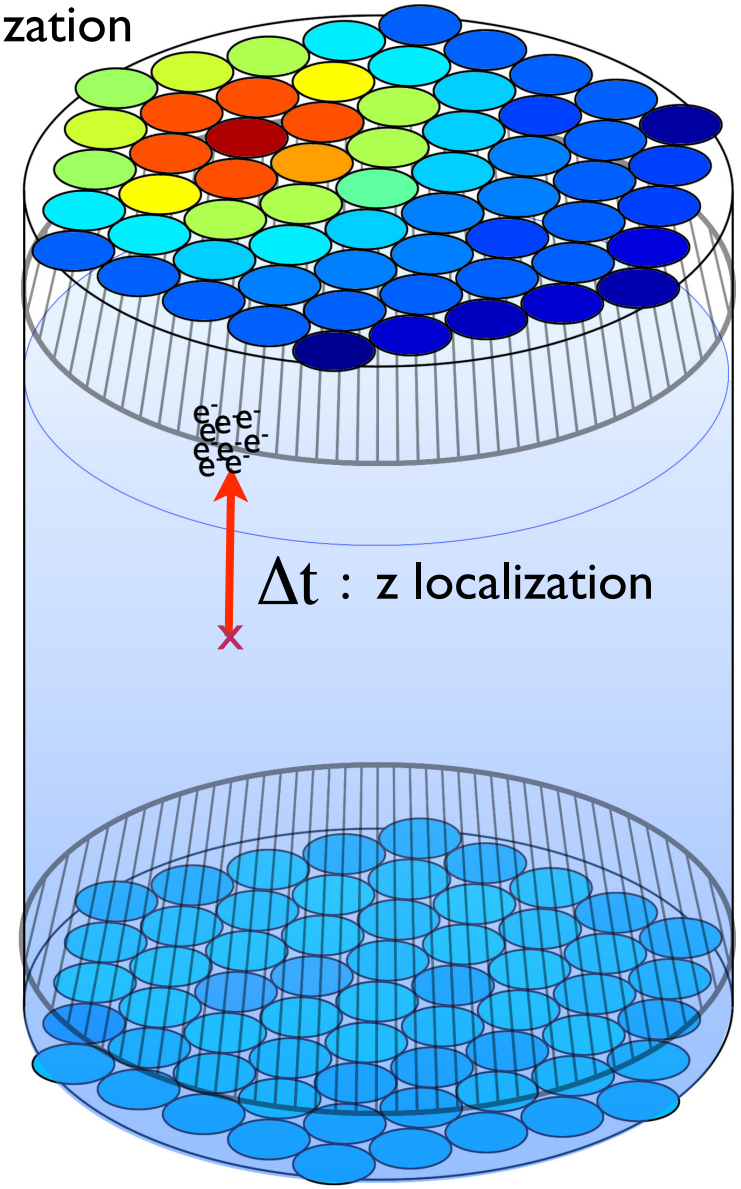


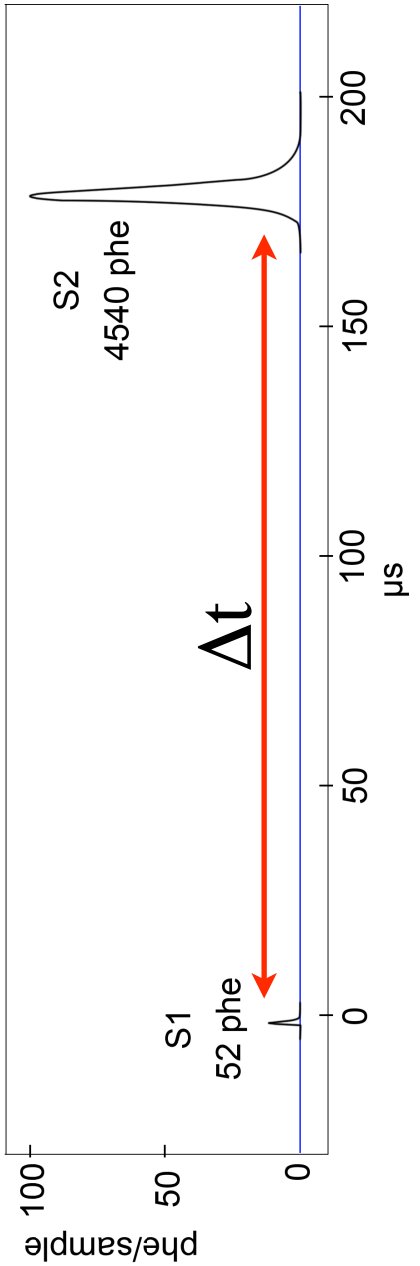

Photomultiplier Tube
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid

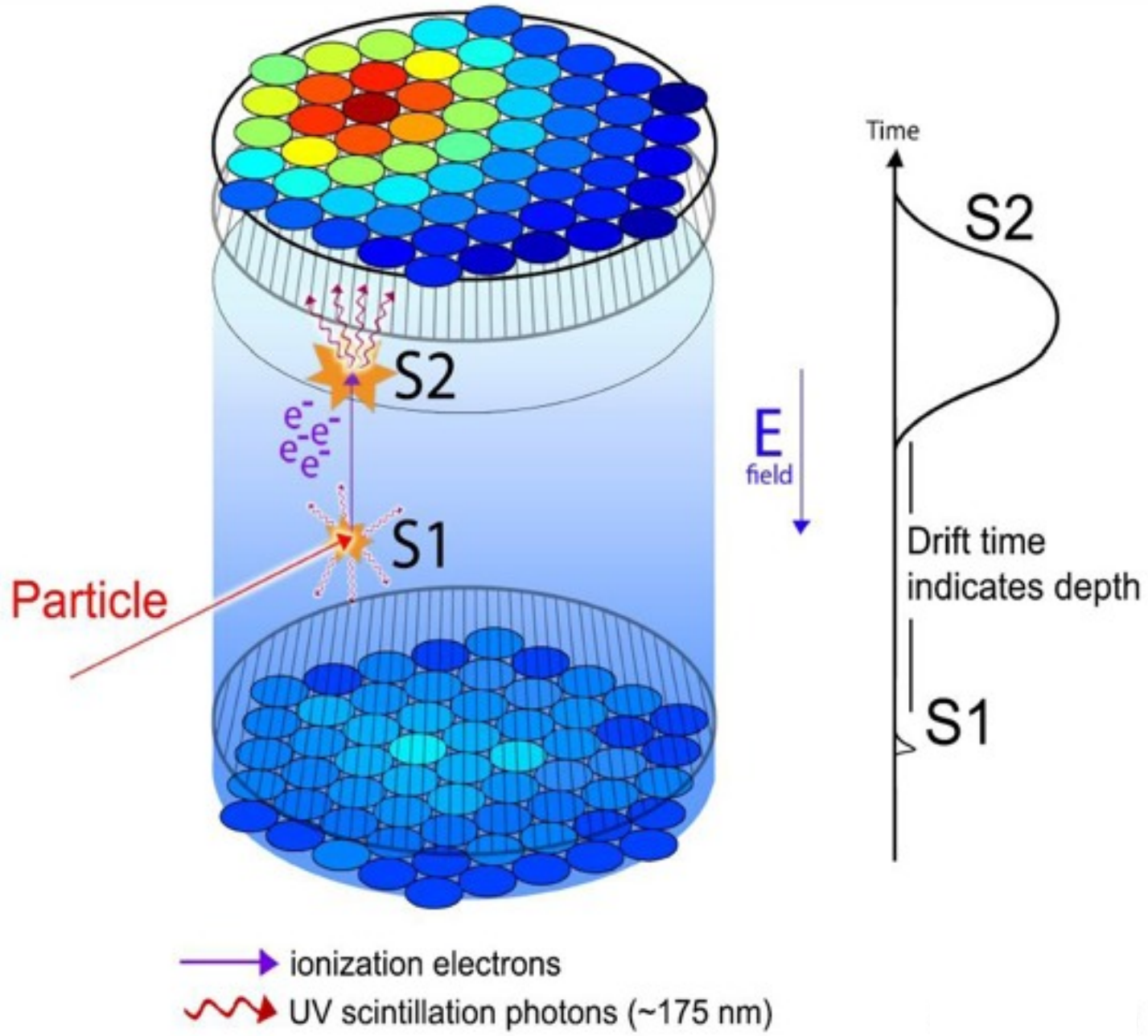

S1
e-
e-
e-
e-
e-
e-
e-
e-
S1
52 phe
0
50
100
phe/sample
0
50
100
150
200
µs

top hit pattern:
x-y localization

S2





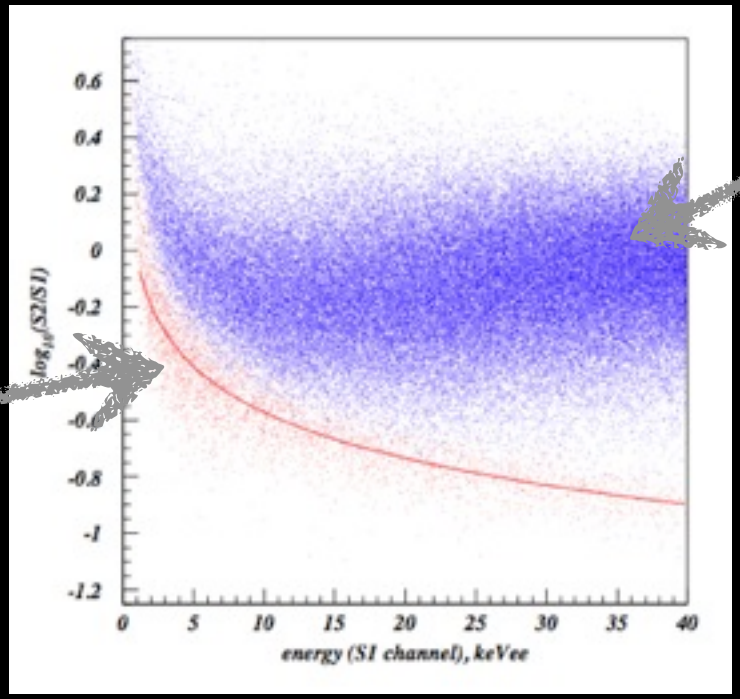

S2
e-
e-e-
e-
S1
Particle
E
field
Time
S2
Drift time
indicates depth
S1
ionization electrons
UV scintillation photons (~175 nm)

WIMP Signals in a Dual-Phase Xenon Detector

Calibration

How do we know what WIMPs will look like...?

We calibrate with neutrons....



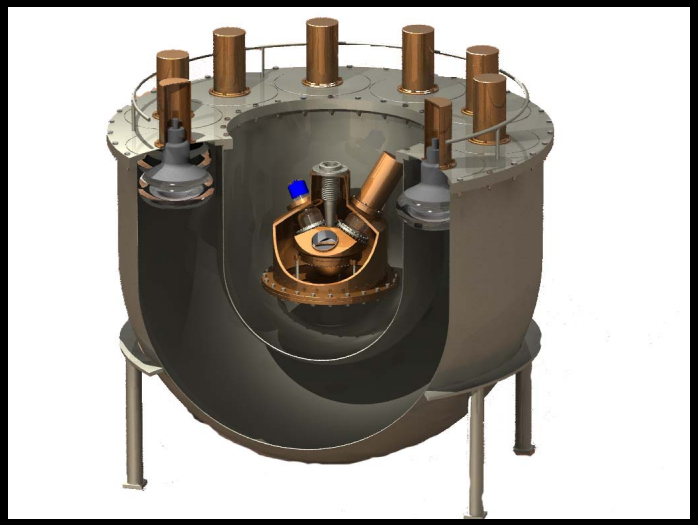
Gamma-ray background

Neutrons & WIMPs

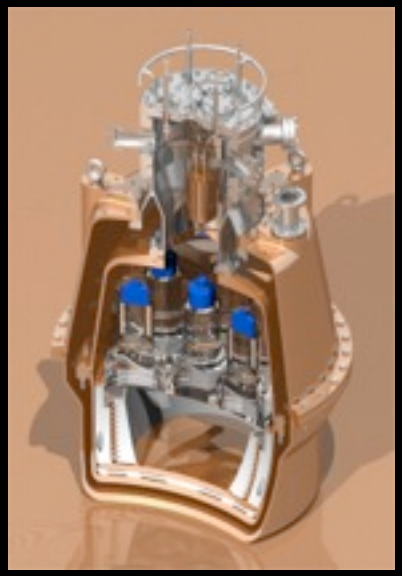
➡ Clear separation between ‘background’ and neutrons (or WIMPs!)

➡ We’re ready to start a Dark Matter search!

The ZEPLIN Programme 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!

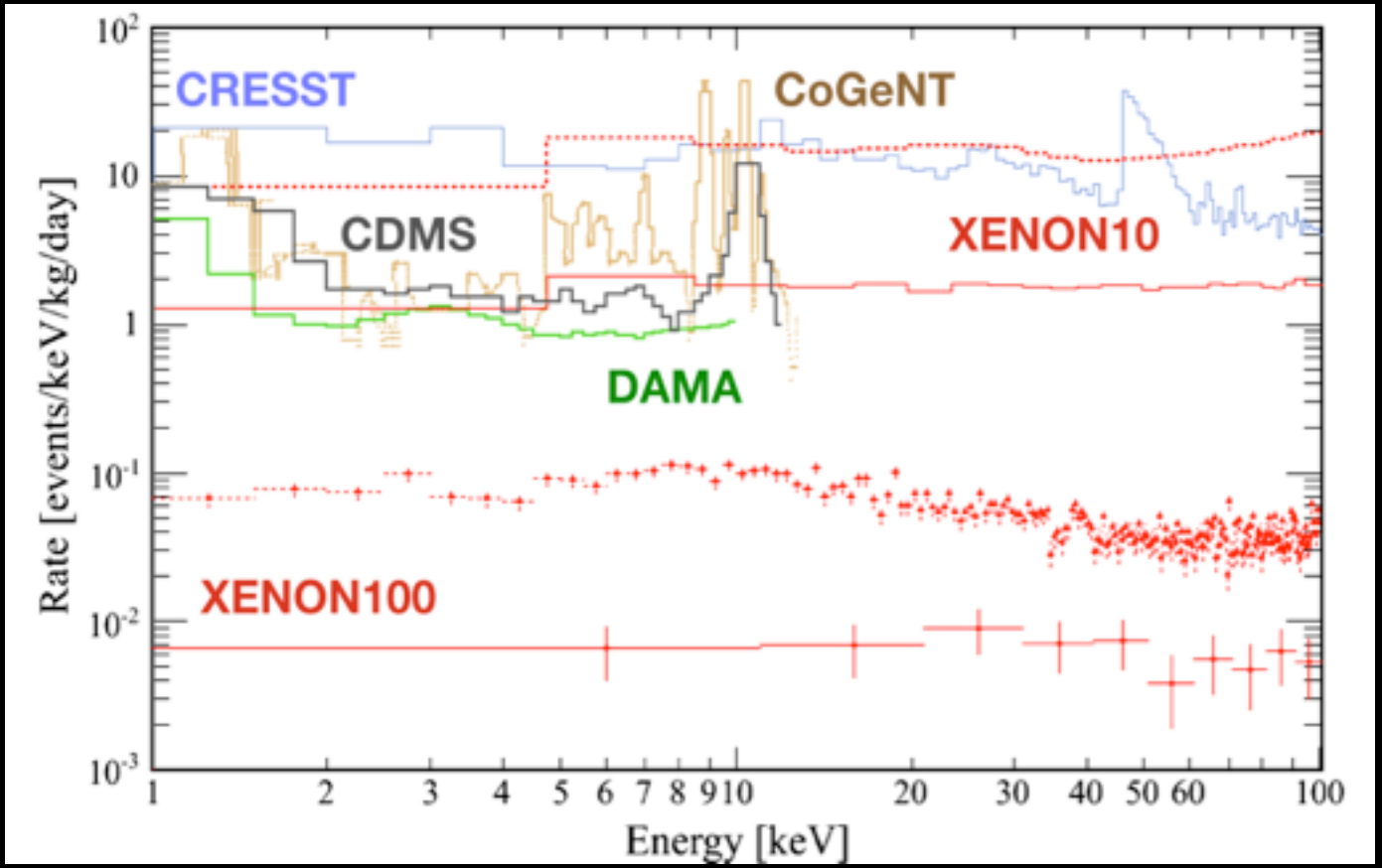
ZEPLIN III
Double phase, 31 PMTs,
high E field, 10/6.4 kg
Run 2009-11
Limit: $3.9*10^{-8}$ pb

Europe's most sensitive!

XENON100

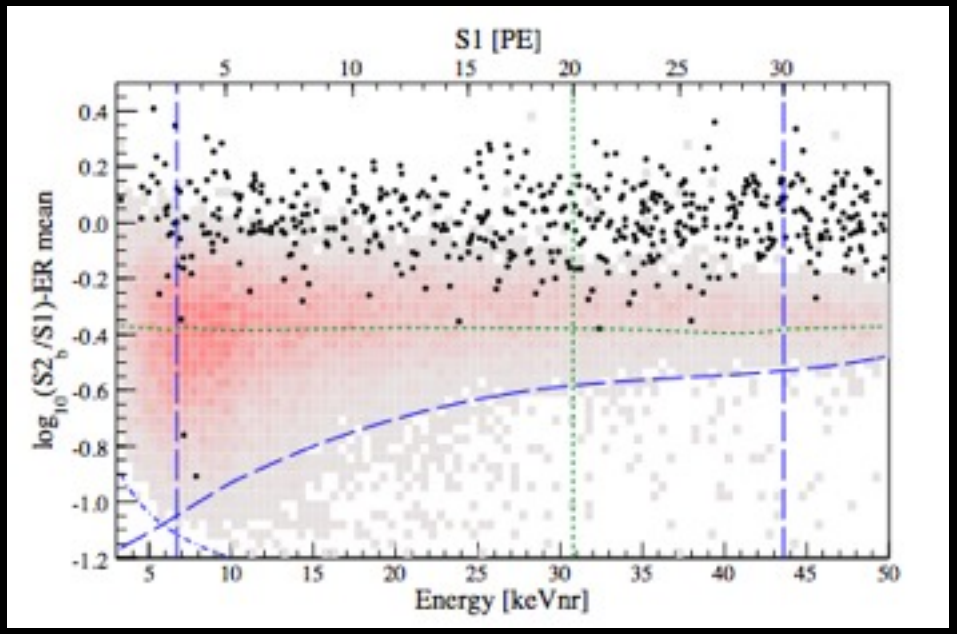

Laboratori Nazionali del Gran Sasso
LNGS
LNGS: 1.4km rock
(3700 mwe)

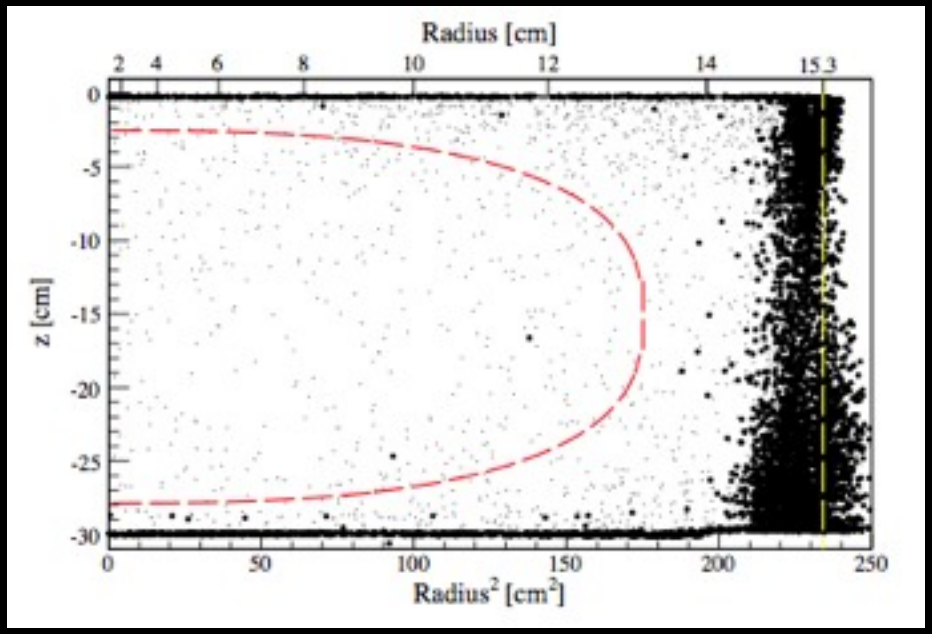
XENON100



- Powerful self-shielding and position reconstruction of LXe TPCs - bigger is better!
- Event rate orders of magnitude lower than the competition

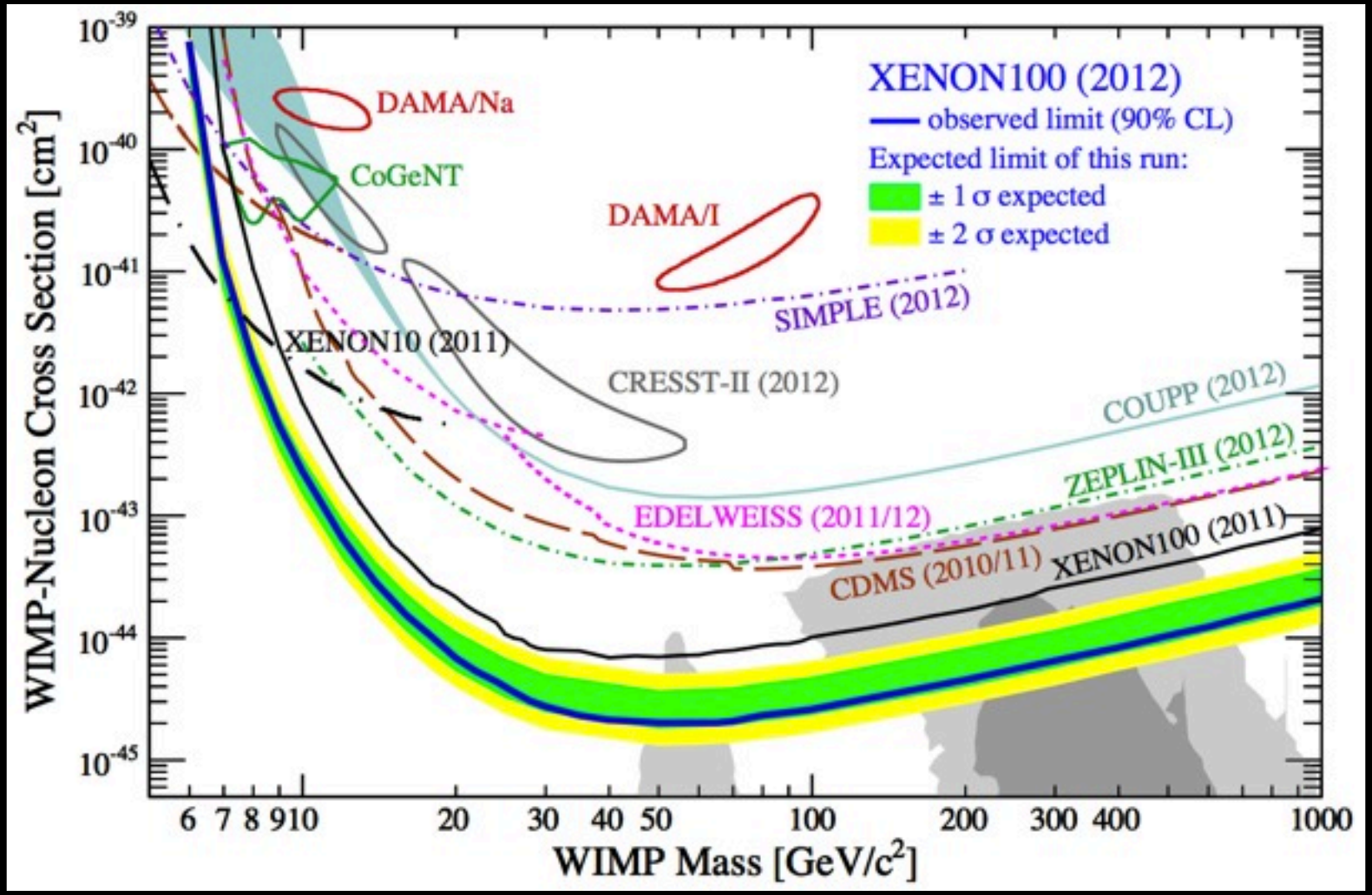
Latest Results (August 2012)



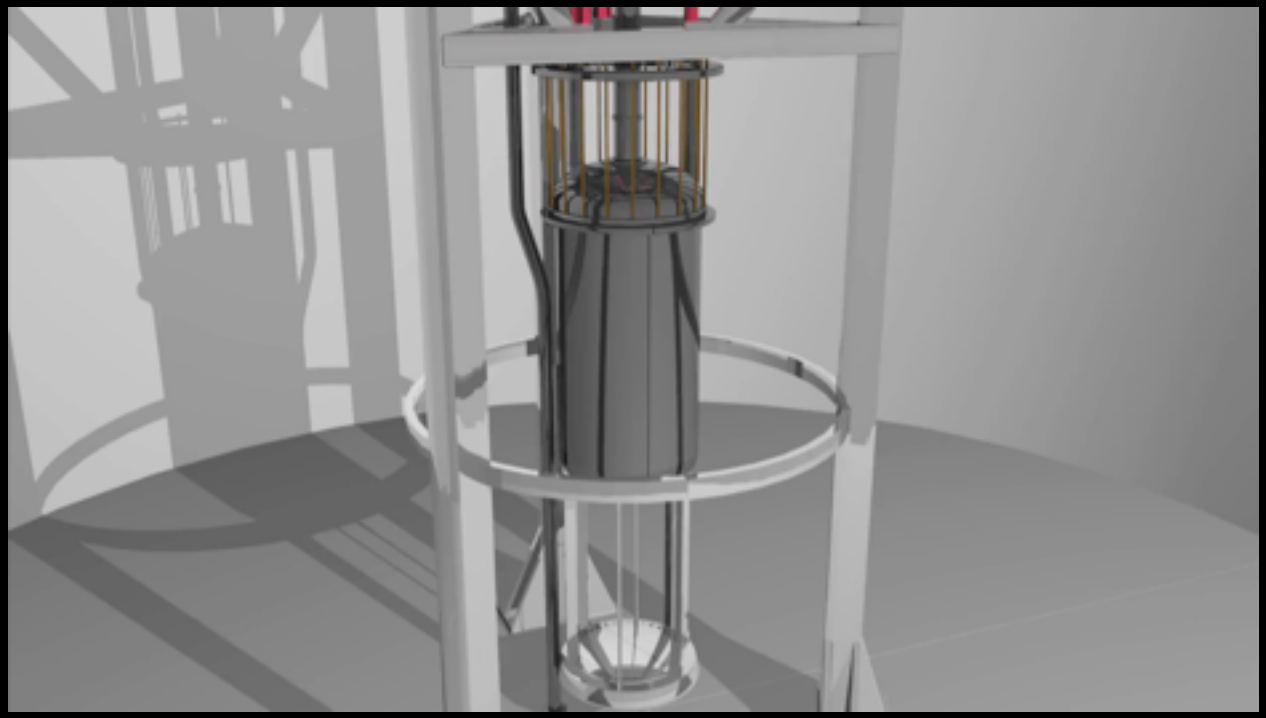


Two Events - No WIMPs!*

The Current State-of-Play



The Next Big Thing....



Homestake mine
South Dakota

Davis Cavern (5th May 2011)
4850 ft depth

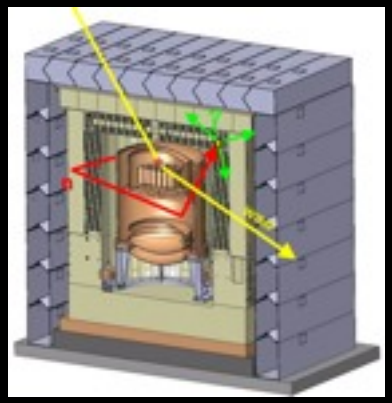
Dec 2011

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

Oct 2012

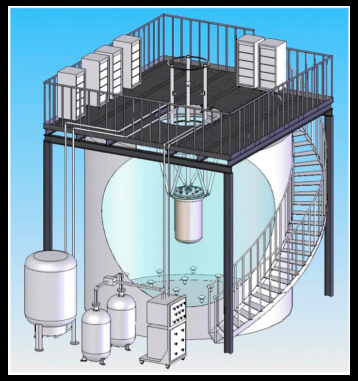
LUX-ZEPLIN (LZ)

ZEPLIN-III



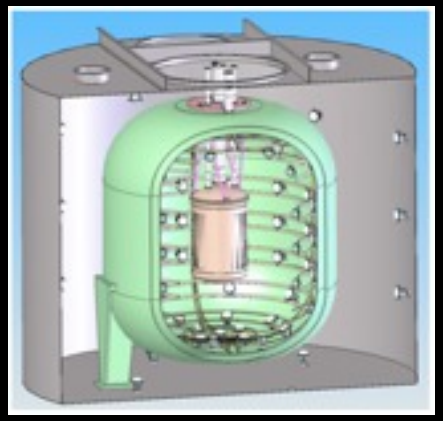
6 kg LXe

LUX



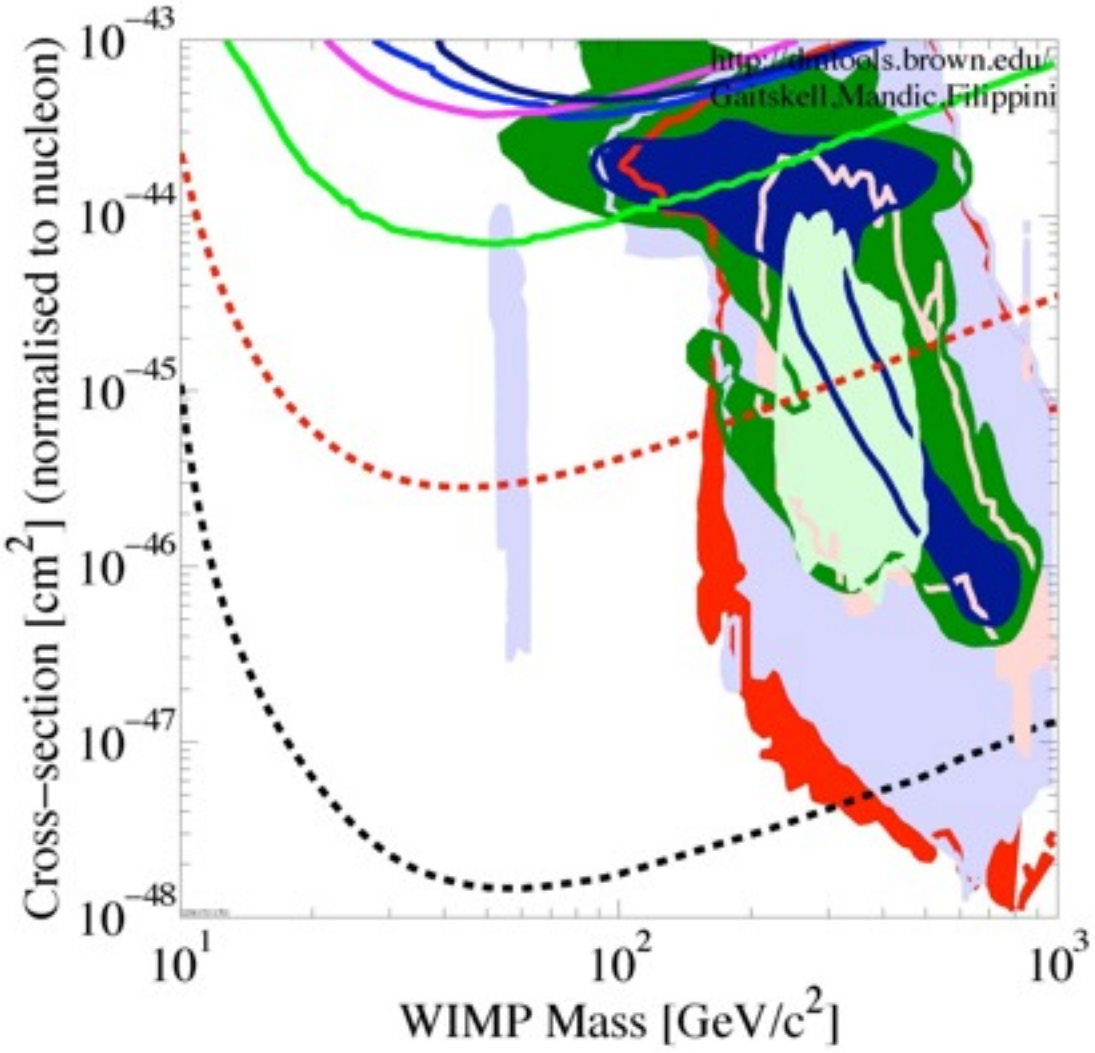
100 kg

LZ



5,000 kg

Next-generation LXe experiment building on progressive LUX (ongoing) and ZEPLIN (completed) programmes



Elastic scattering SI cross-section

Results

ZEPLIN-III 2012 (magenta)

XENON100 2011 (green)

EDELWEISS II 2011 (dark blue)

CDMS-II 2010 (blue)

Projections

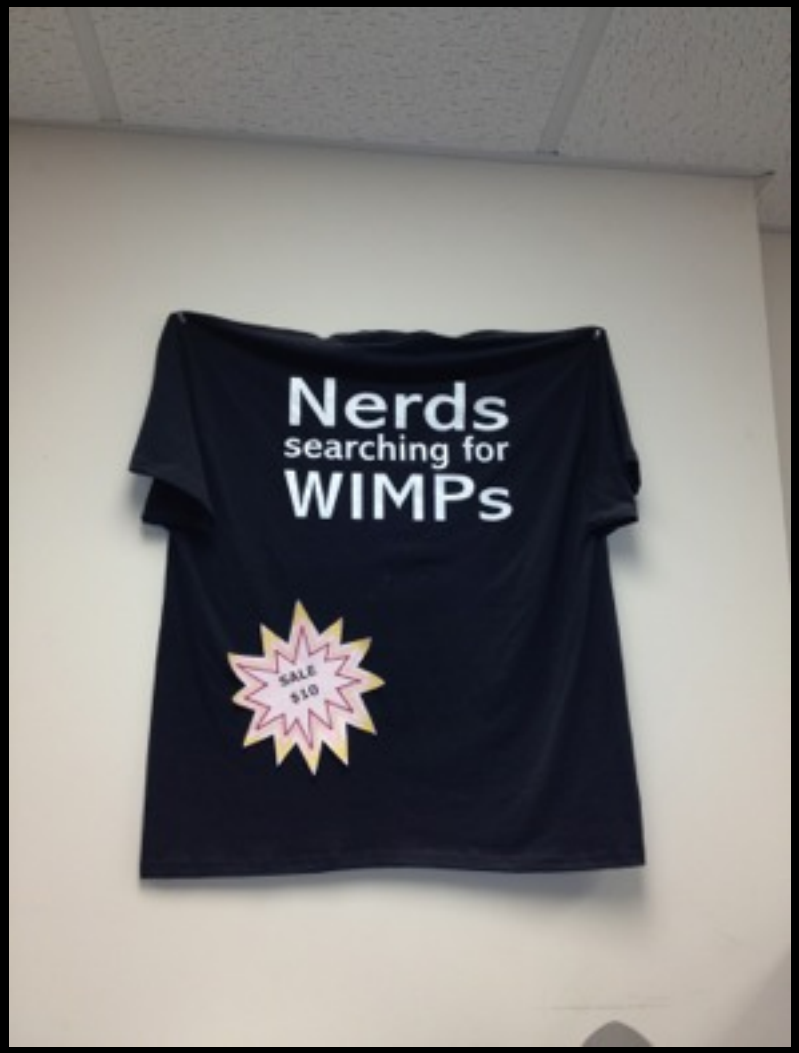
LUX (red dash)

100 kg fiducial x 300 live days

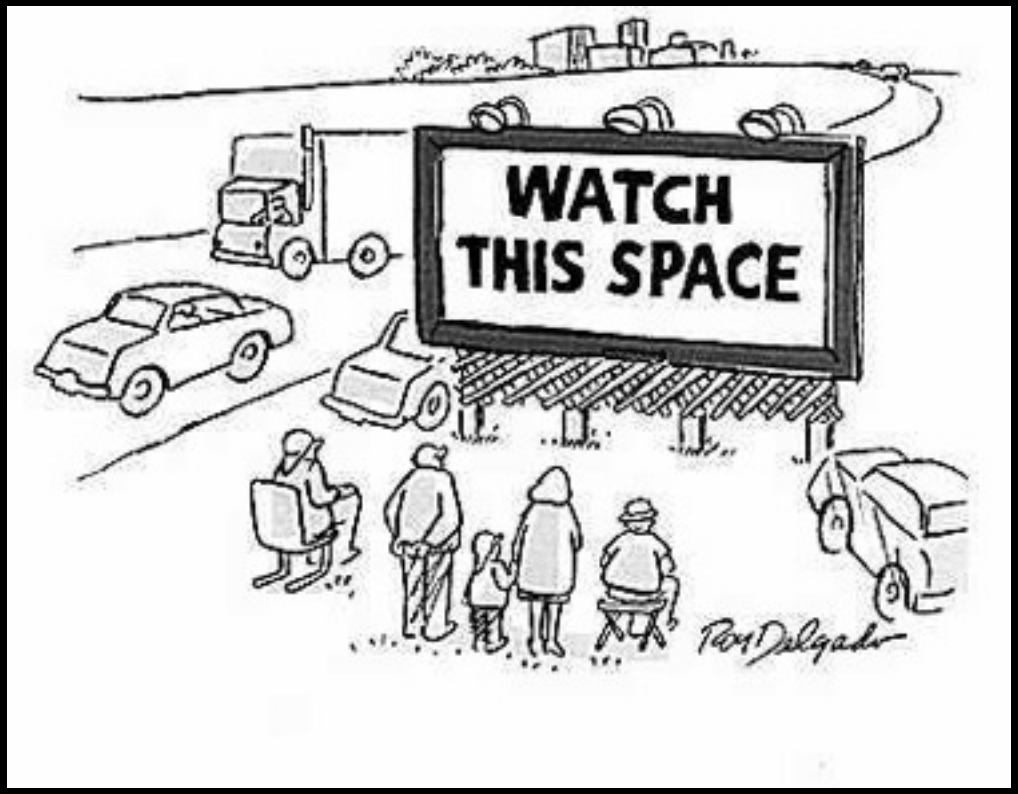
LUX-ZEPLIN (black dash)

5-tonne fiducial x 1,000 live days

Nobel Prize aside, you could get one of these...



Exciting times ahead....



Thank you all for listening!