DARK MATTER

What has it ever done for medicine?

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UCL

Dark Matter

What *is* ‘Dark Matter’?

What are we doing to find it?

What has this got to do with medicine?

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

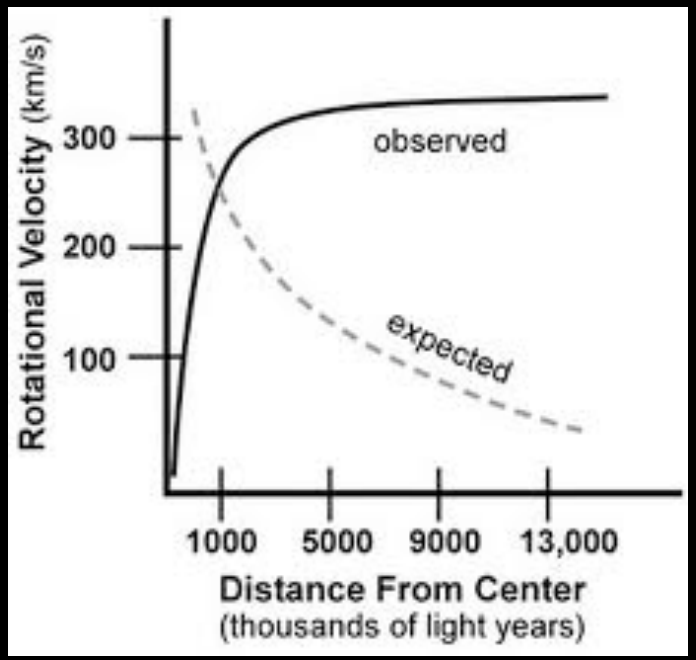
4: Deduced that there must be more mass present than is seen

Early evidence for Dark Matter

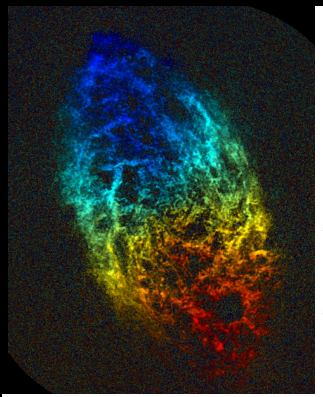
In the 1970s Vera Ruben used the Doppler Shift to look at how fast galaxies were rotating – expecting to see agreement with Newton's Laws, but reproduced Zwicky's results...

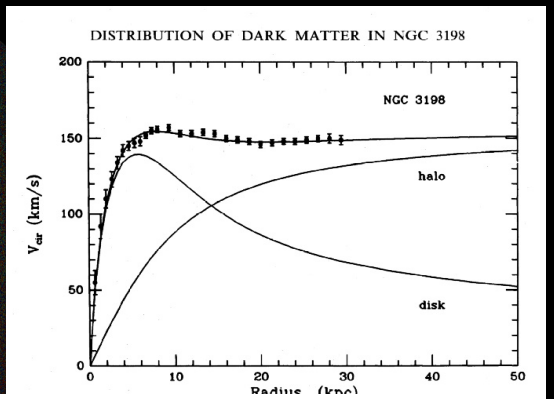
Andromeda

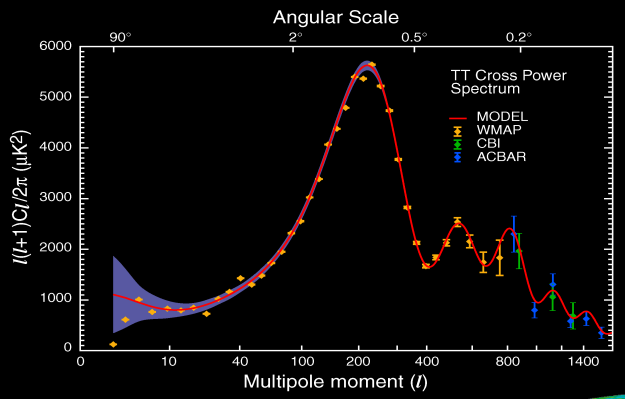
GALAXIES ARE ROTATING TOO FAST!

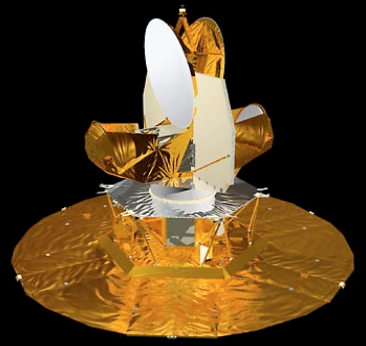


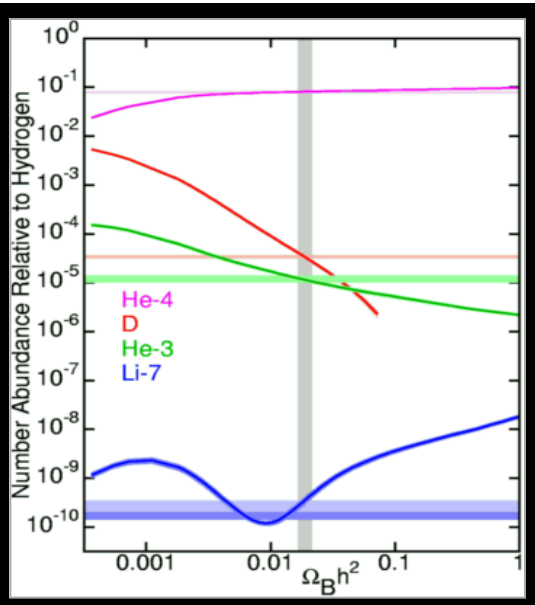
Lots more evidence since then - with little against...

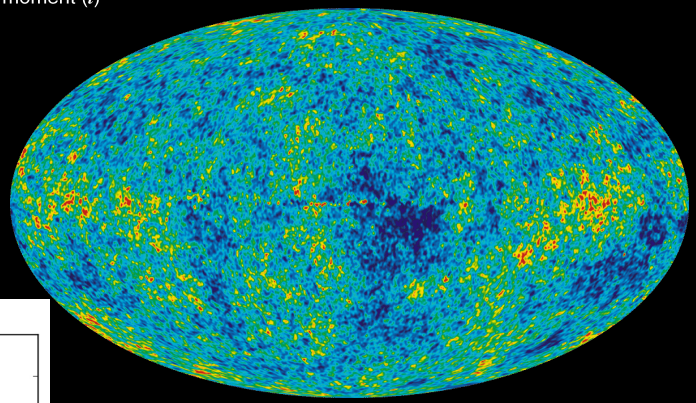


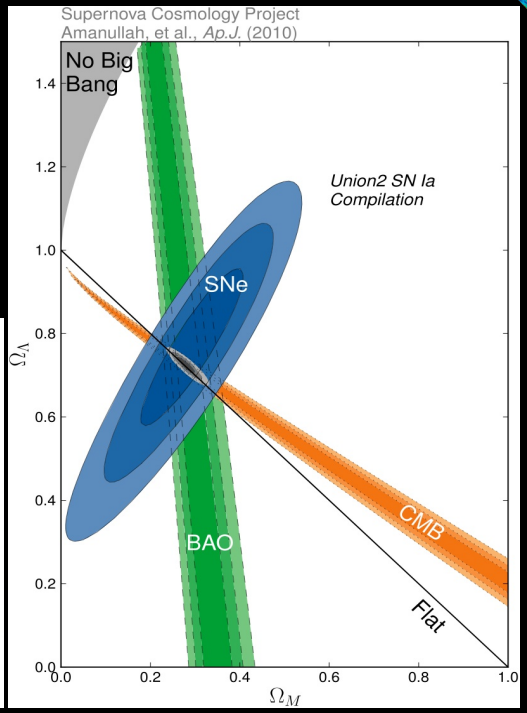

DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)

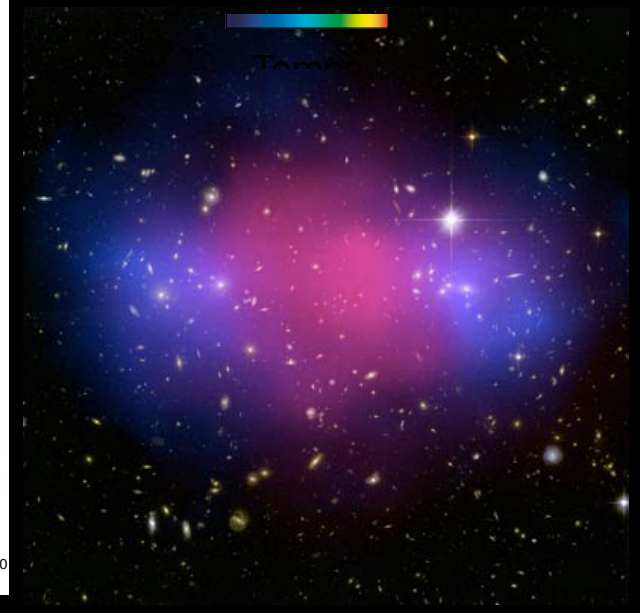

Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
MODEL
WMAP
CBI
ACBAR
$l(l+1)C_l/2\pi$ (μK^2)
Multipole moment (l)

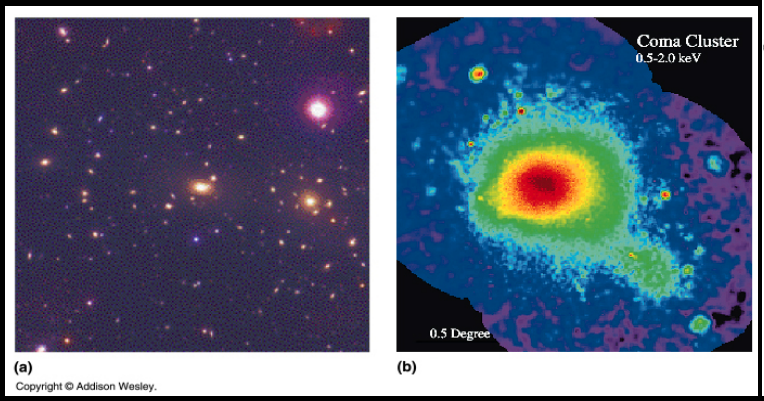


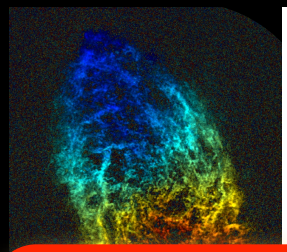

Number Abundance Relative to Hydrogen
He-4
D
He-3
Li-7
$\Omega_B h^2$

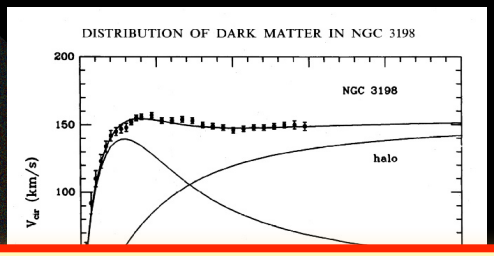


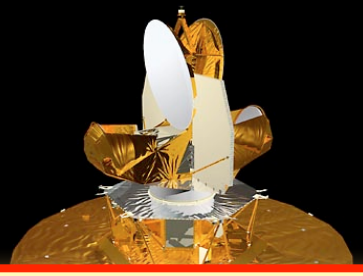

Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)
No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M

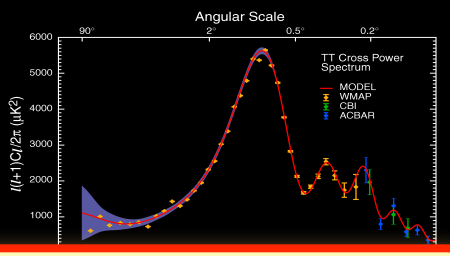



Coma Cluster
0.5-2.0 keV
0.5 Degree
(a)
(b)
Copyright © Addison Wesley.



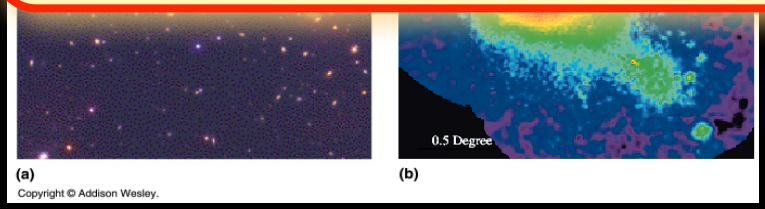


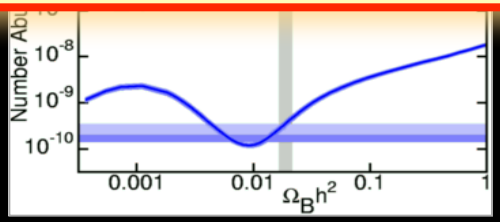


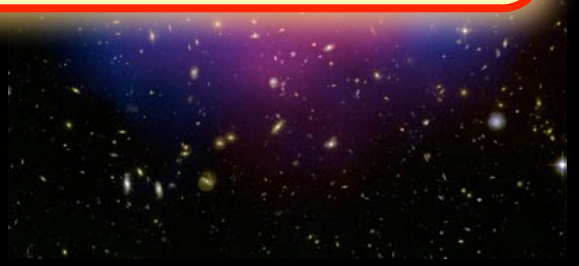


We have a ‘Missing Mass’ Problem!

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

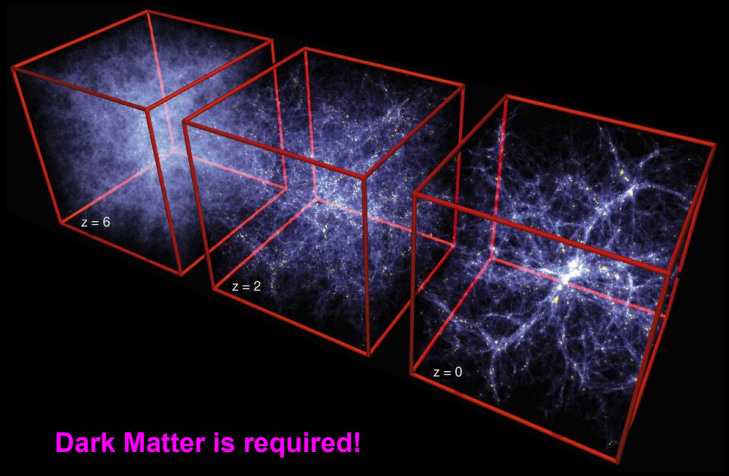






Does it matter?

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

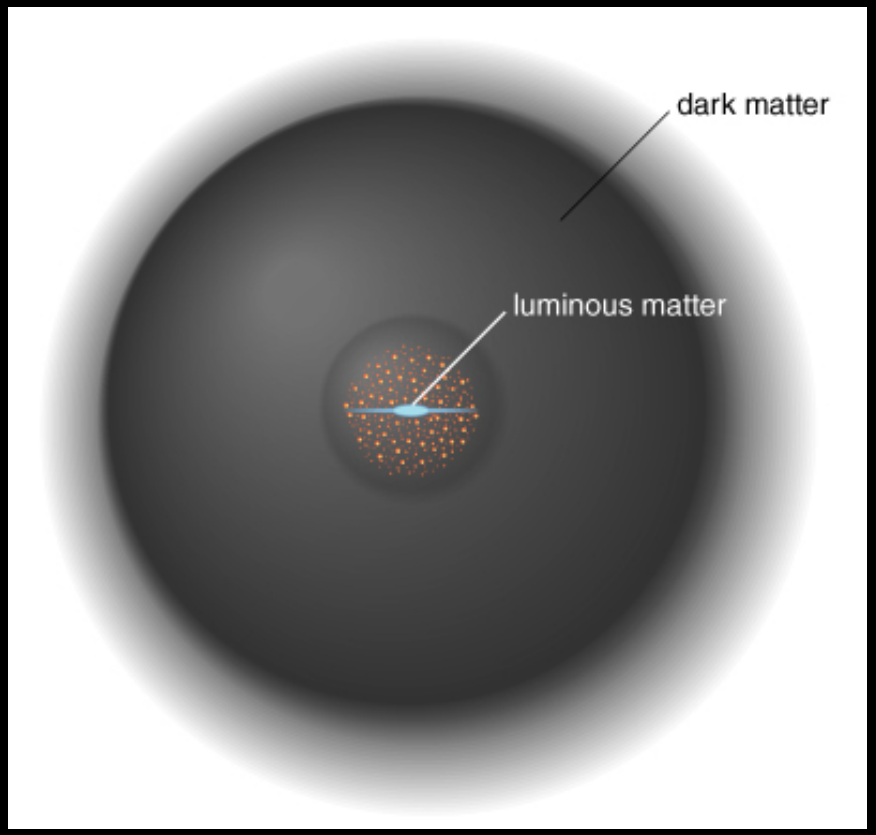
White dwarfs

No... 'Normal Matter' makes up less only **4%** of the Universe!

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?

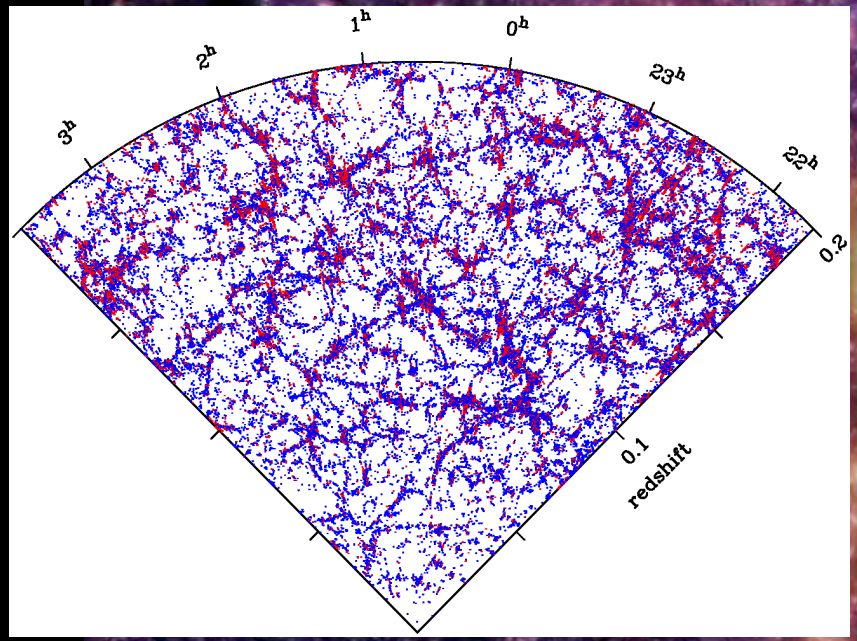
1 billion pass through our bodies every day

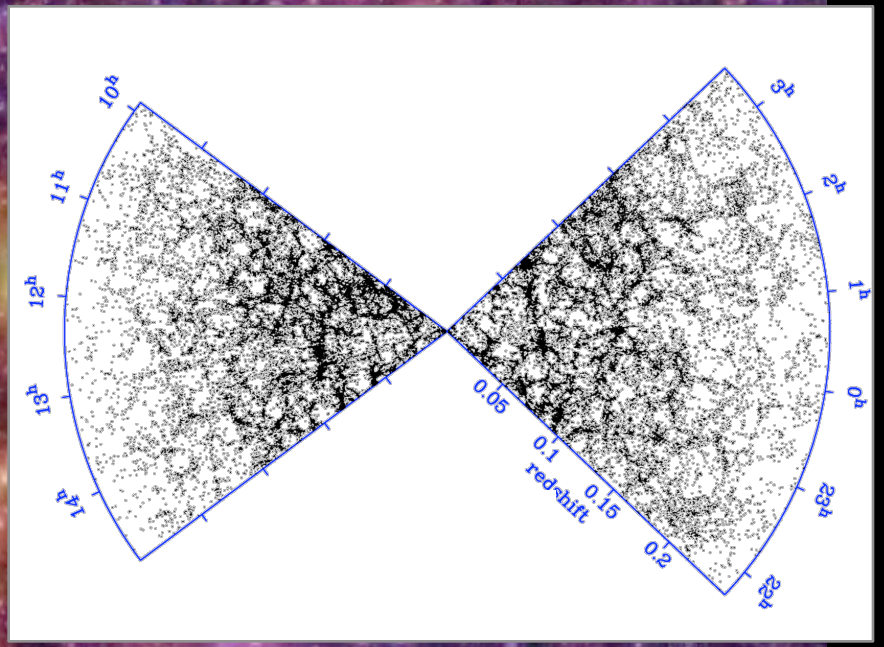
Distribution?

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!

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

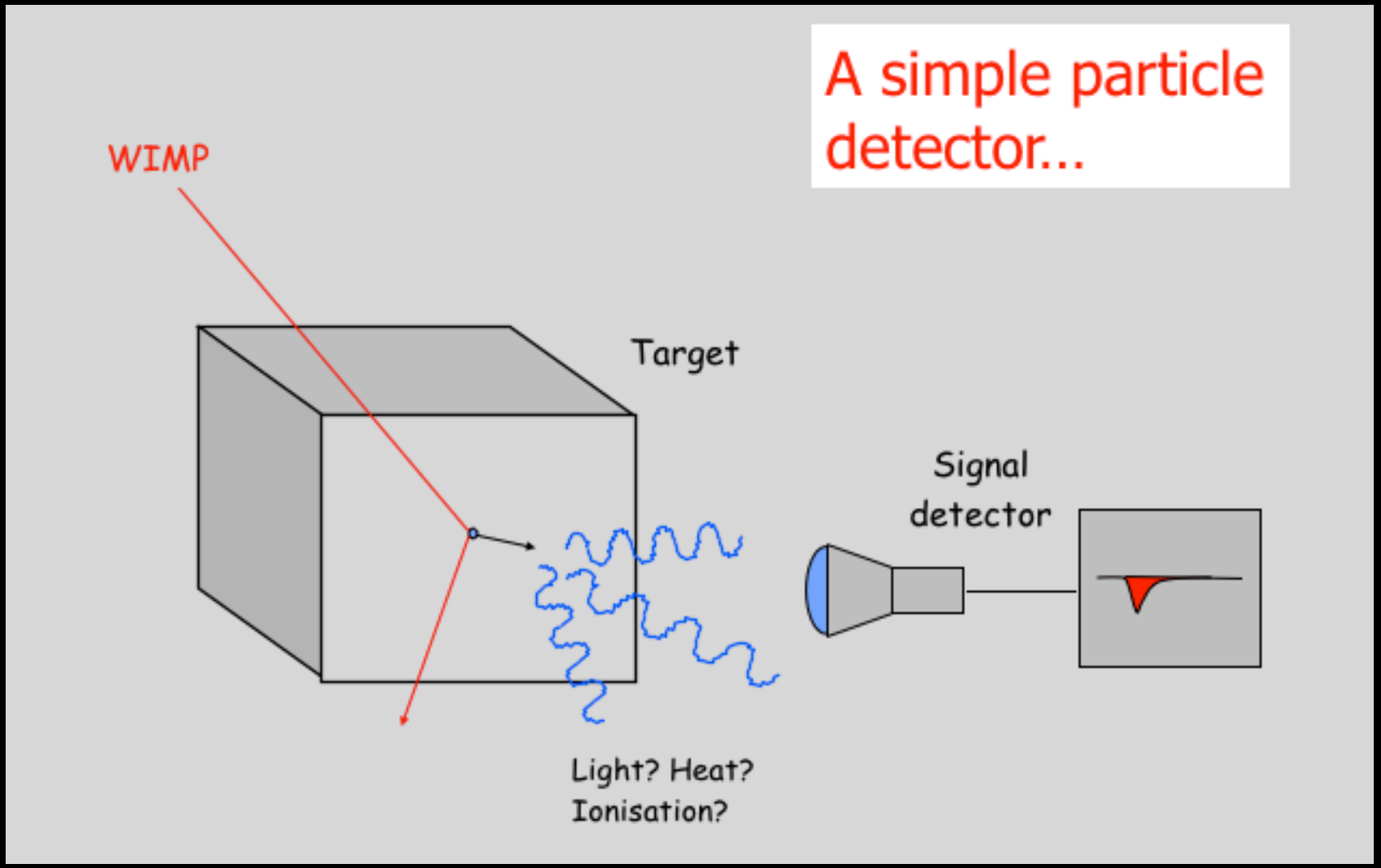
Definitive detection is internationally recognised as one of THE highest priorities in science!

Basic method

Make a device that should see *NOTHING* from ‘normal’ particles

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

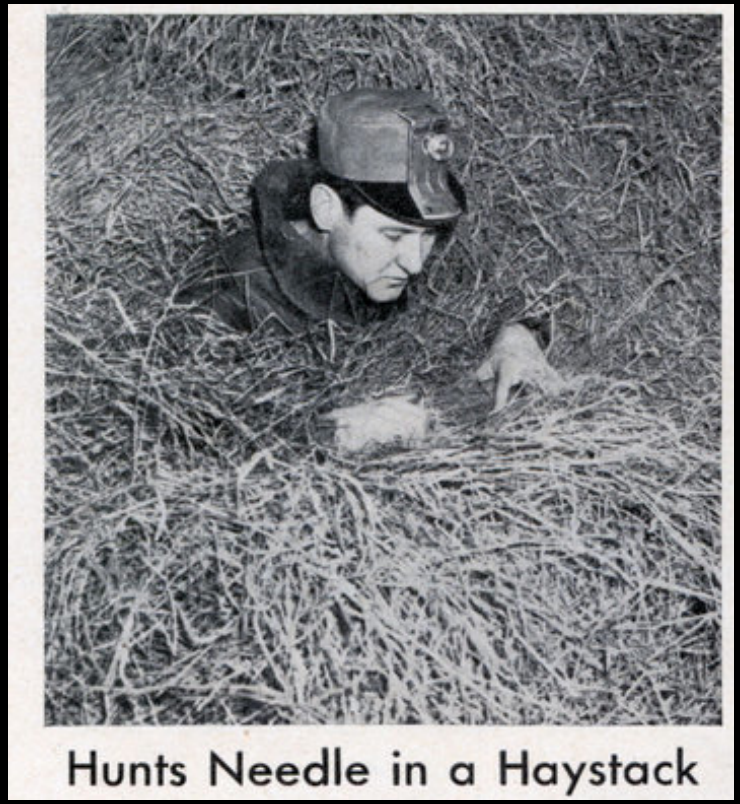
How to detect a WIMP - step 1



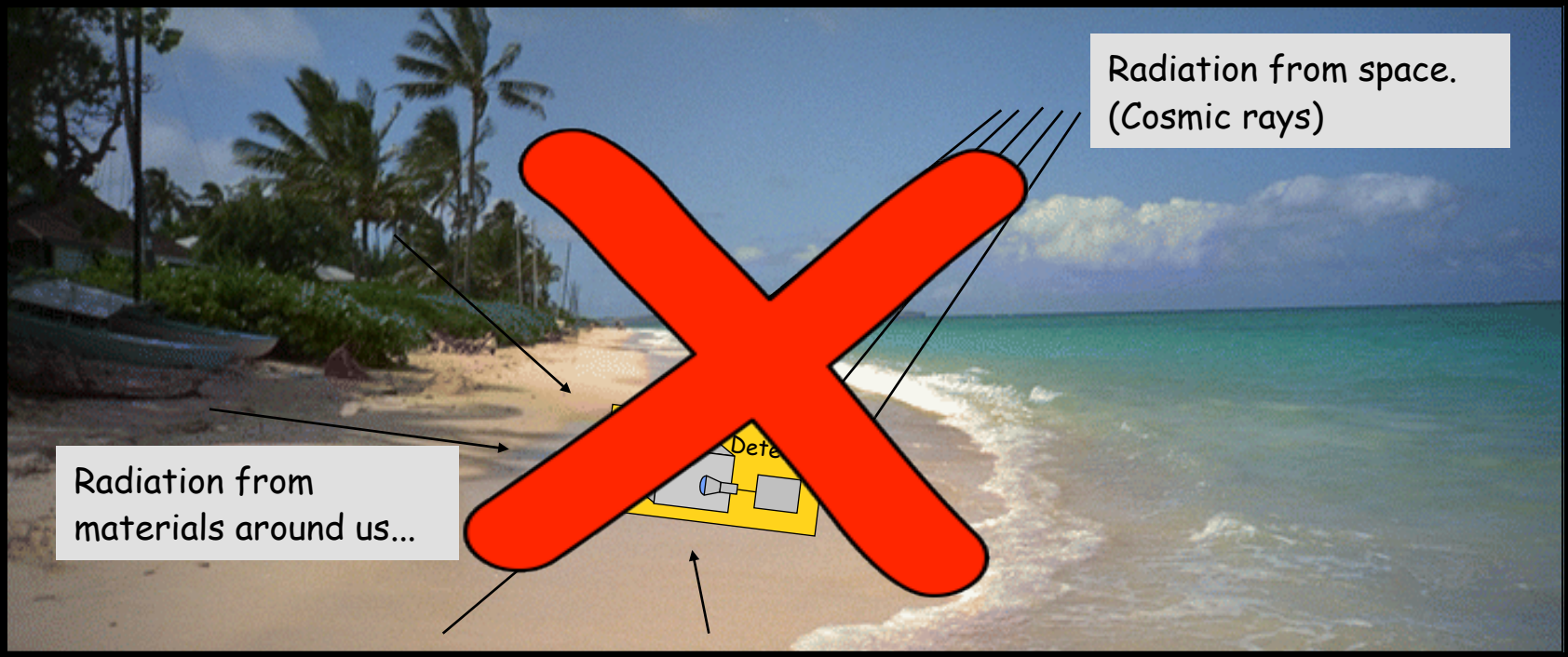
How to detect a WIMP - step 2

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

Underground

The Underground Laboratory

The World Dark Matter Search Race

Boulby, UK
ZEPLIN-III,
DRIFT-II

Modane, France
EDELWEISS

Minnesota,
USA
CDMS

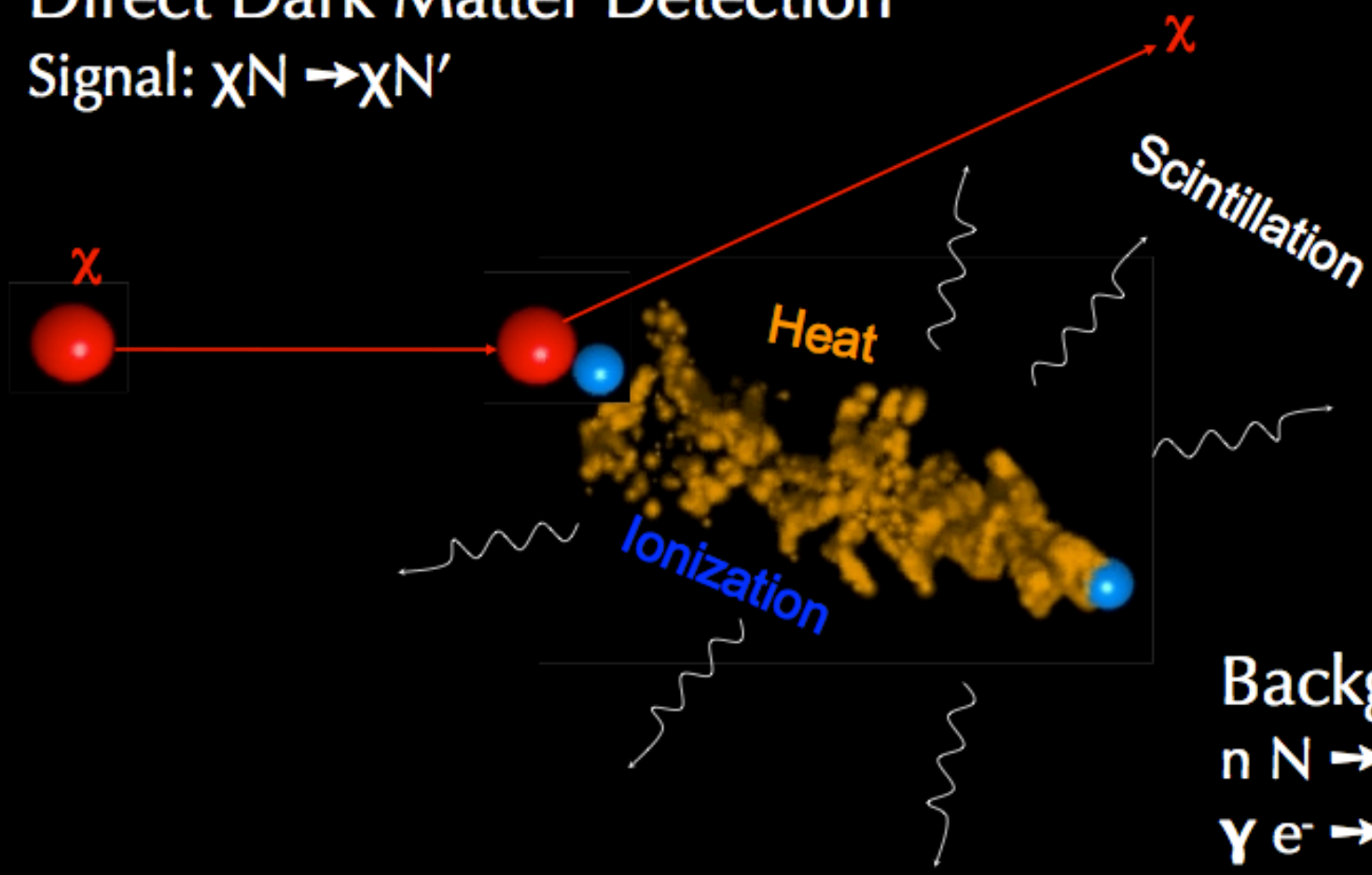
Homestake,
USA
LUX

Gran Sasso, Italy
XENON, DAMA, CRESST

Kamioka, Japan
XMASS

Direct Dark Matter Detection

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



Backgrounds:

$n\ N \rightarrow n\ N'$

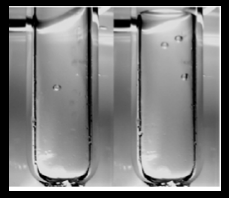
$\gamma\ e^- \rightarrow \gamma\ e^{-\prime}$

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

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

WIMP Detection Techniques

Heat and ionisation bolometers: CDMS EDELWEISS



Bubbles and Droplets:
CUOPP
PICASSO

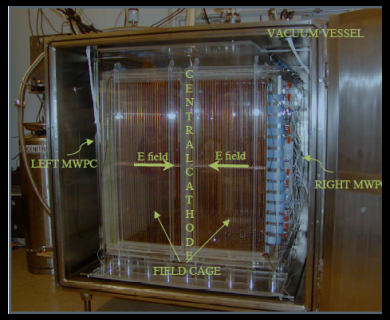
Light and heat Bolometers:
CRESST
ROSEBUD

Phonons

dE/dx

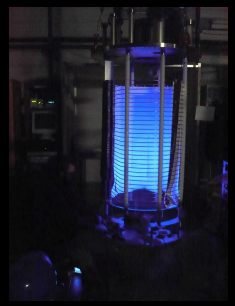
Charge

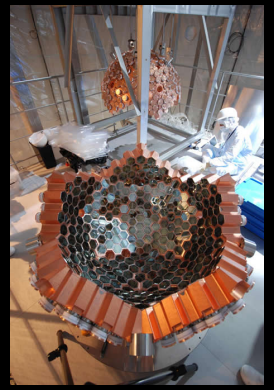
Light



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

Scintillation and ionisation charge detectors:
XENON
WARP
ArDM
ZEPLIN
LUX





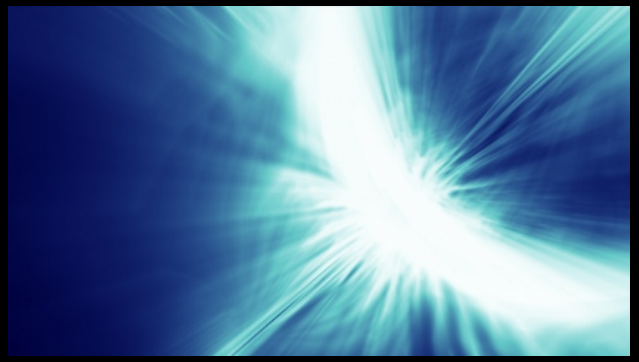
Scintillators:
DAMA
LIBRA
XMASS
CLEAN
ANAIS
KIMS

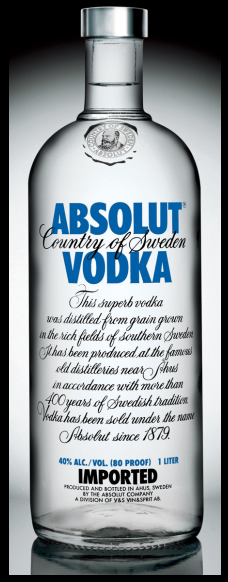
The Leading Detectors are LXeTPCs

- Liquid/gas xenon scintillation/ionisation detectors
- Pioneered by two collaborations: **UK-led ZEPLIN** (at Boulby) and **XENON** (Gran Sasso, Italy)
- Over the last 10 years, have swept 3 orders of magnitude in sensitivity to dominate the field and lead the race

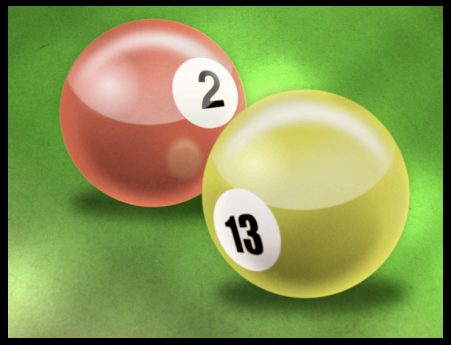
Why xenon?

Excellent light output





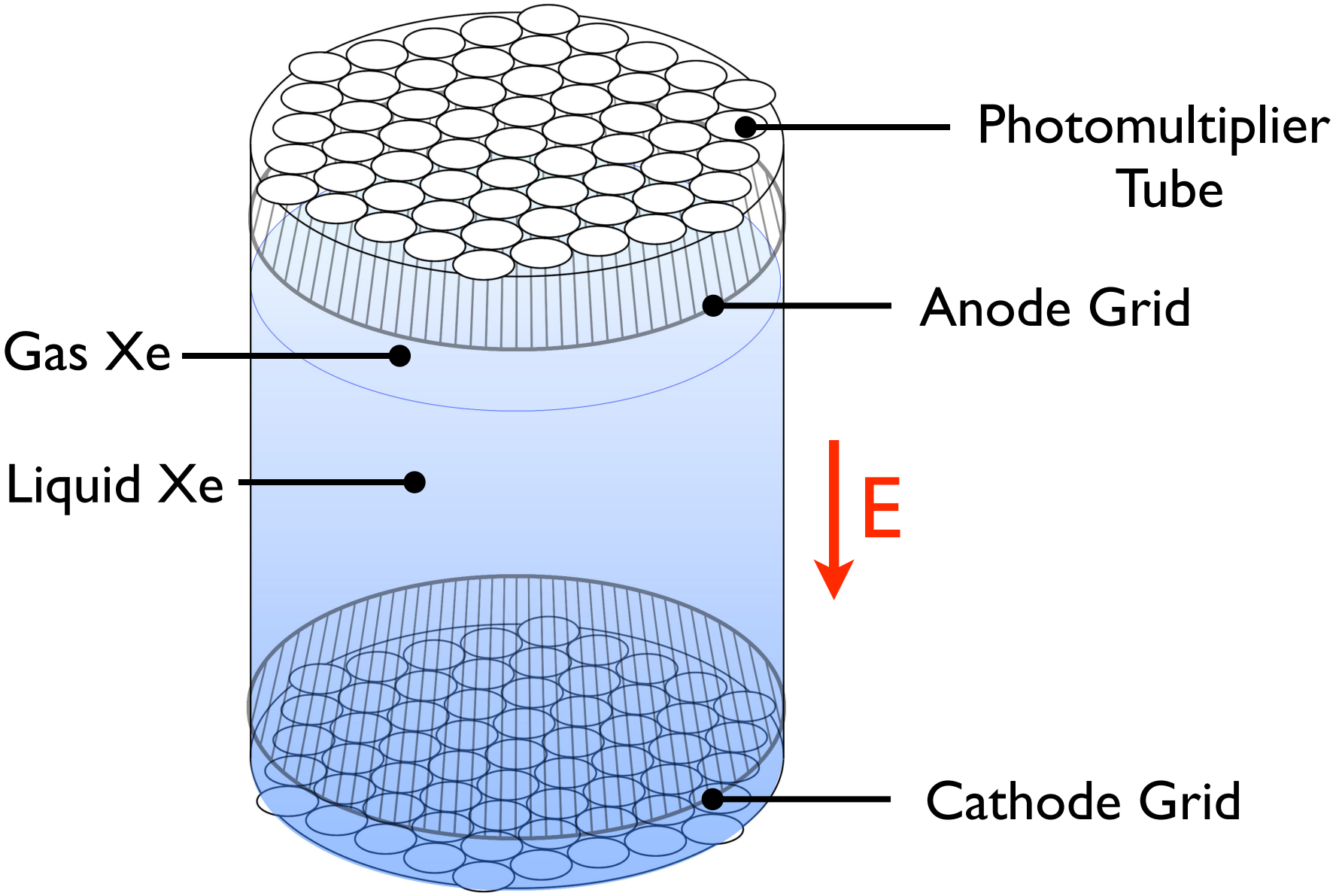
Very high purity

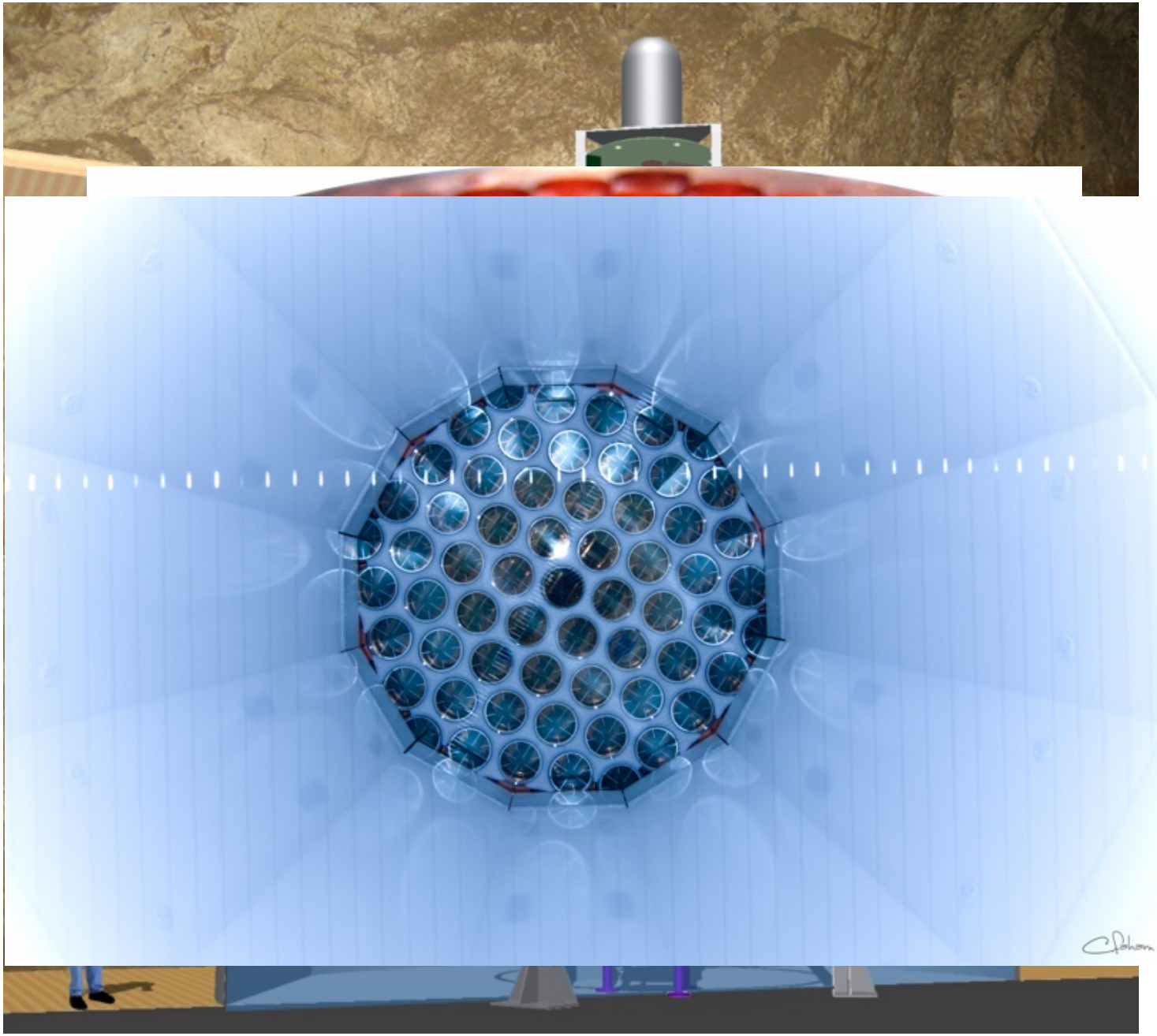


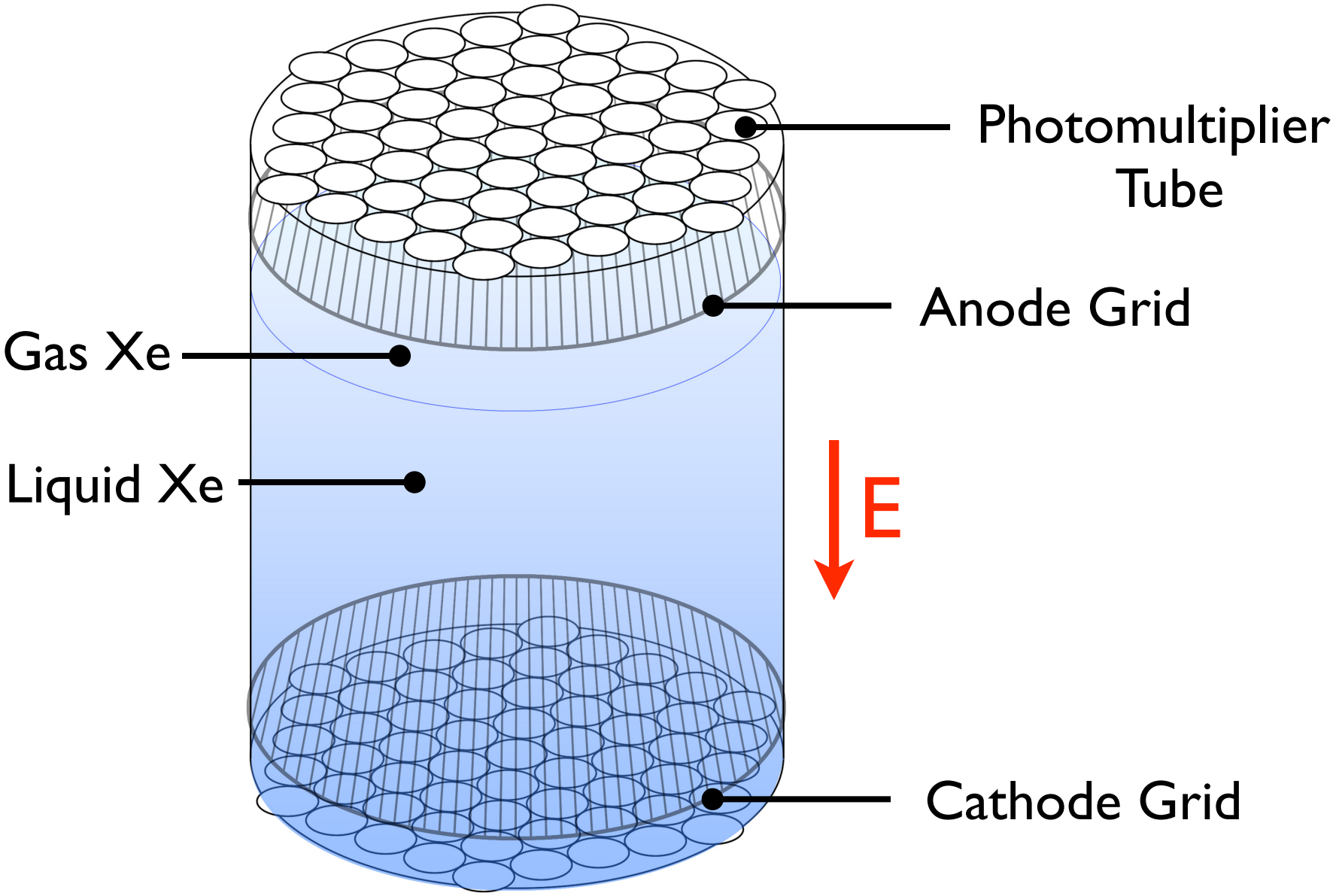
Mass Xe ~ Mass WIMP

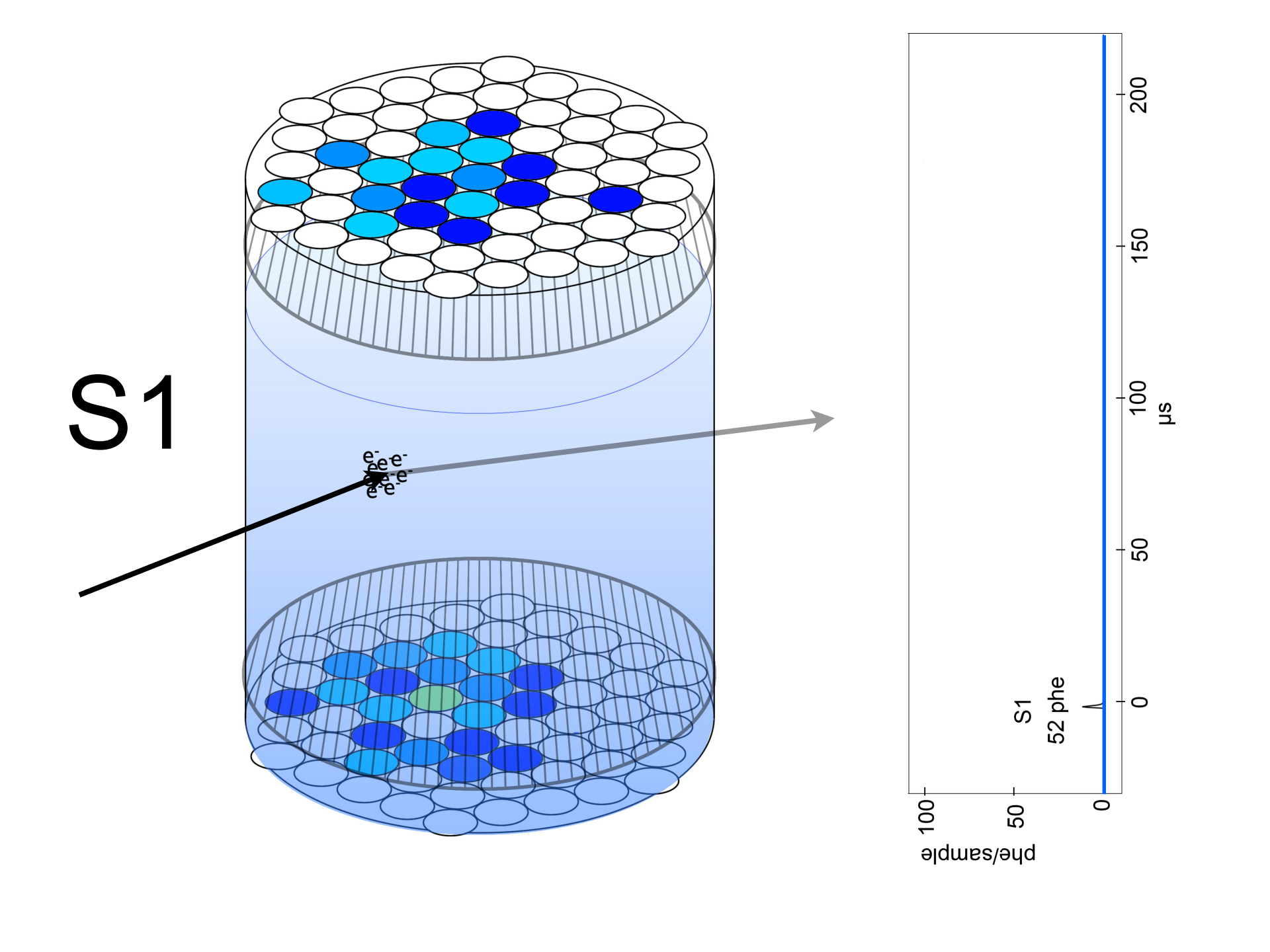
1 tonne

70 cm


Photomultiplier Tube
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid

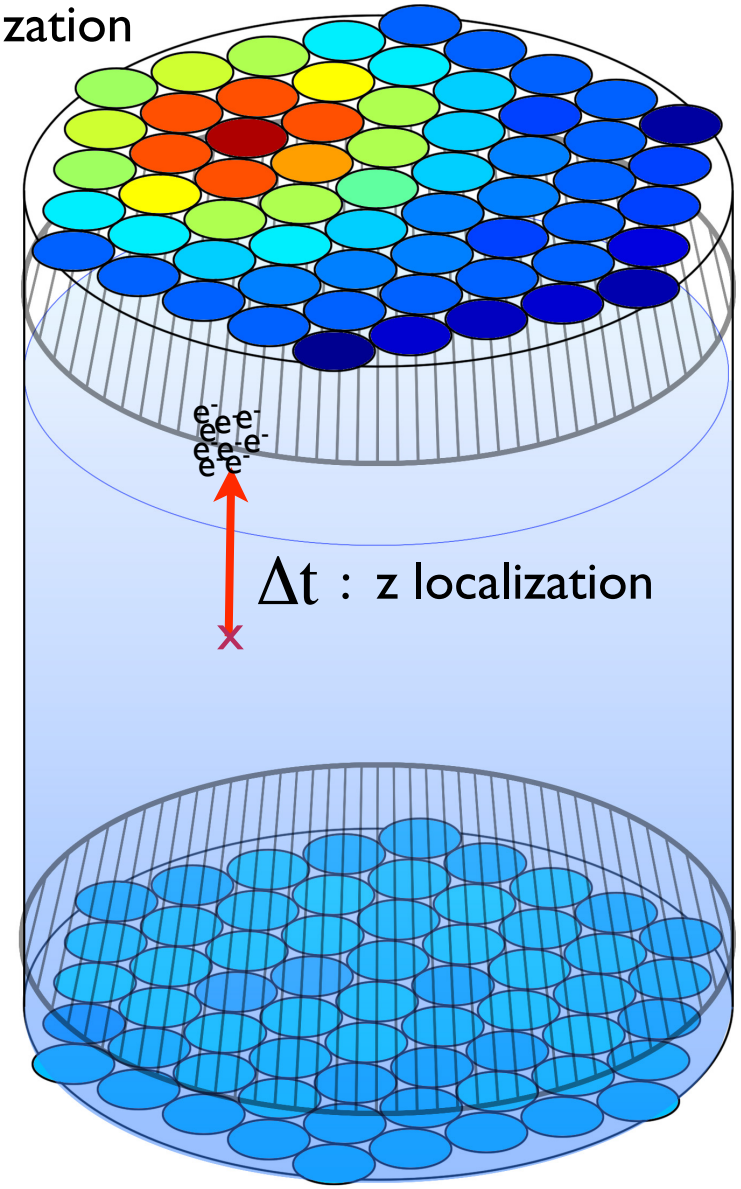


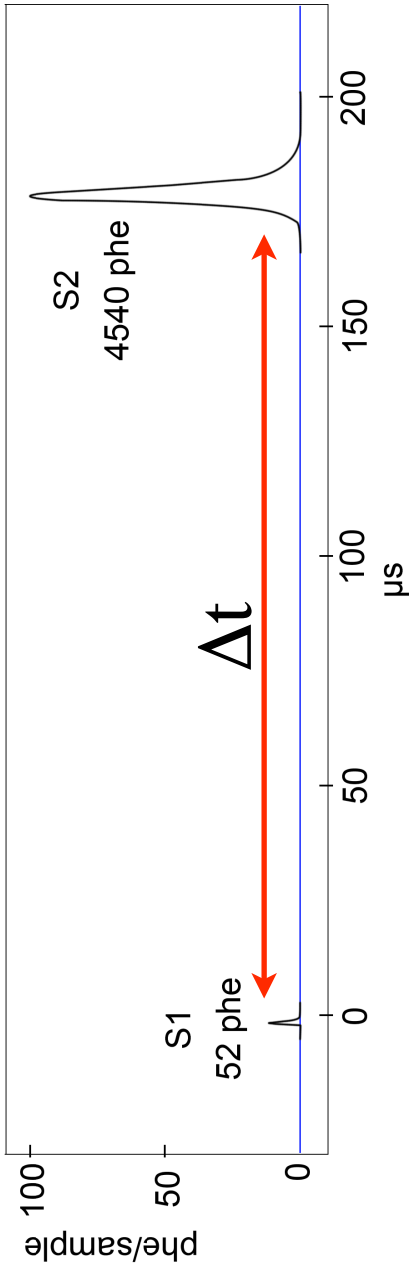

Photomultiplier Tube
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid

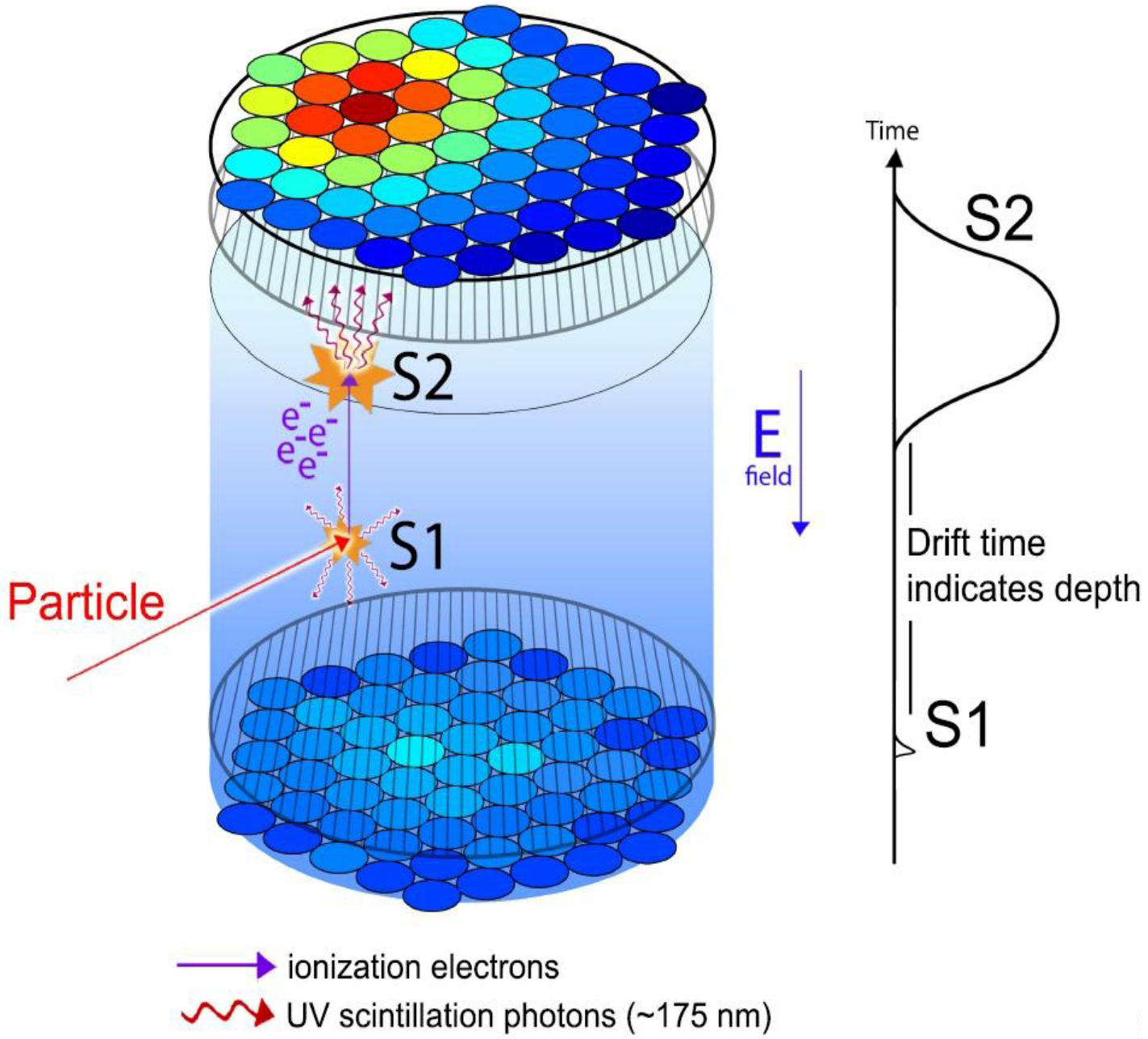

S1
e-
e-
e-
e-
e-
e-
e-
e-
S1
52 phe
0
50
100
phe/sample
0
50
100
150
200
µs

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

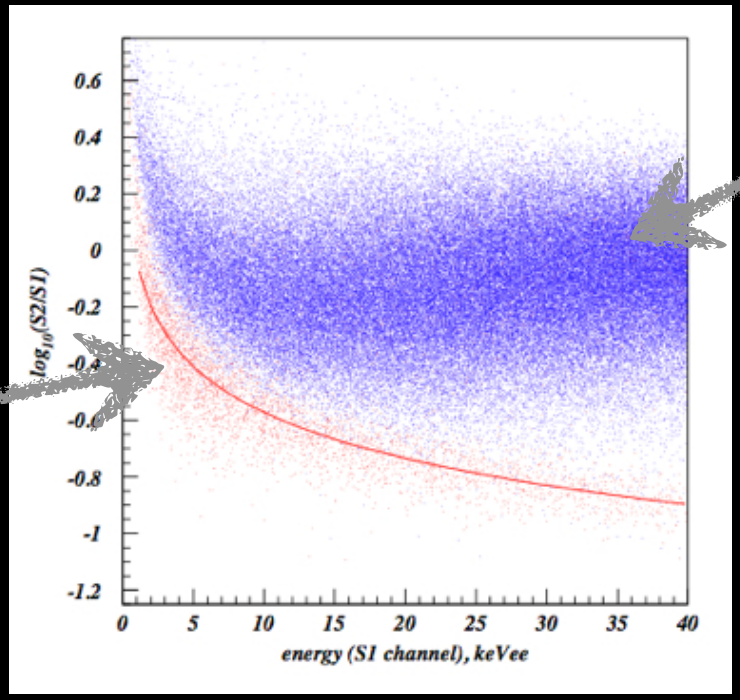
Calibration

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

We calibrate with neutrons....

Gamma-ray background

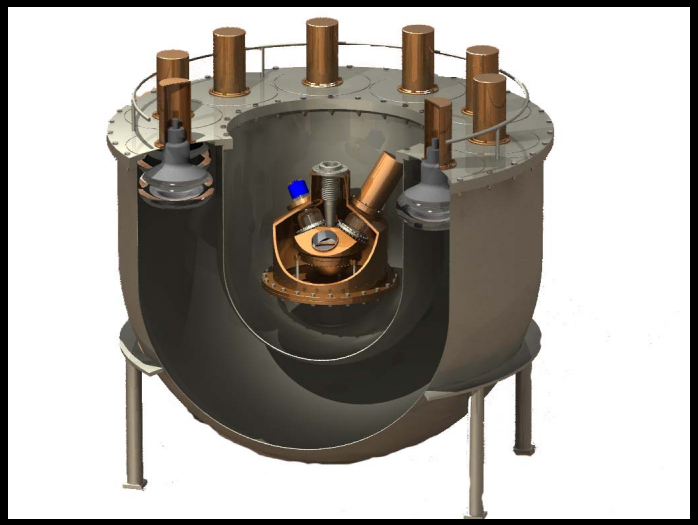
Neutrons & WIMPs



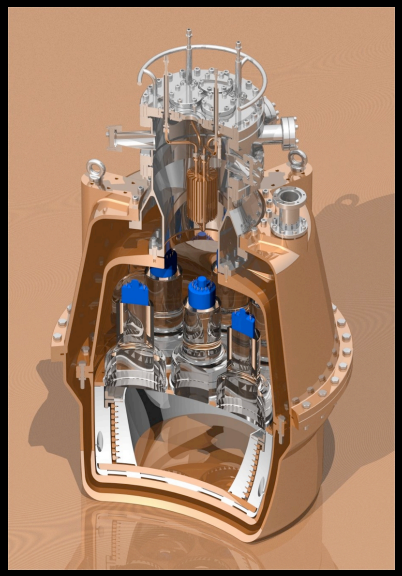
➡ Clear separation between ‘background’ and neutrons (or WIMPs!)

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

The ZEPLIN Programme at Boulby



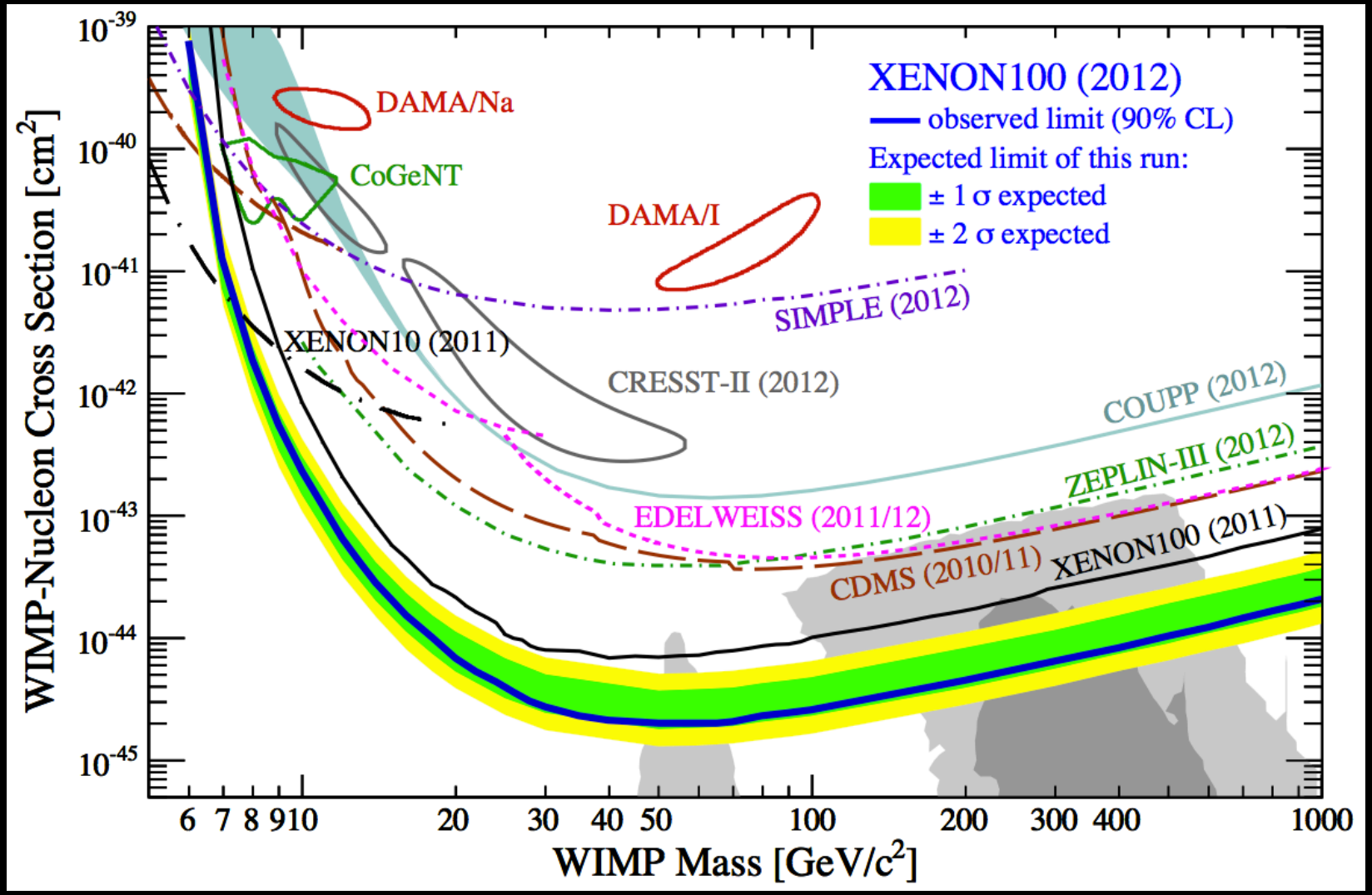
ZEPLIN I
Single phase, 3 PMTs, 5/3.1 kg
Run 2001-04
Limit: $1.1*10^{-6}$ pb



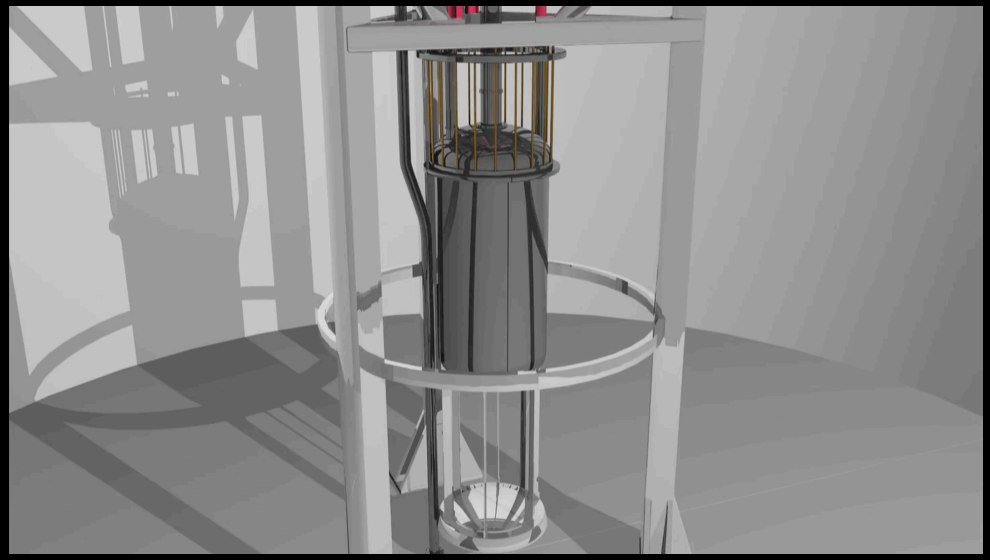
ZEPLIN II
Double phase, 7 PMTs,
moderate E field, 31/7.2 kg
Run 2005-06
Limit: $6.6*10^{-7}$ pb

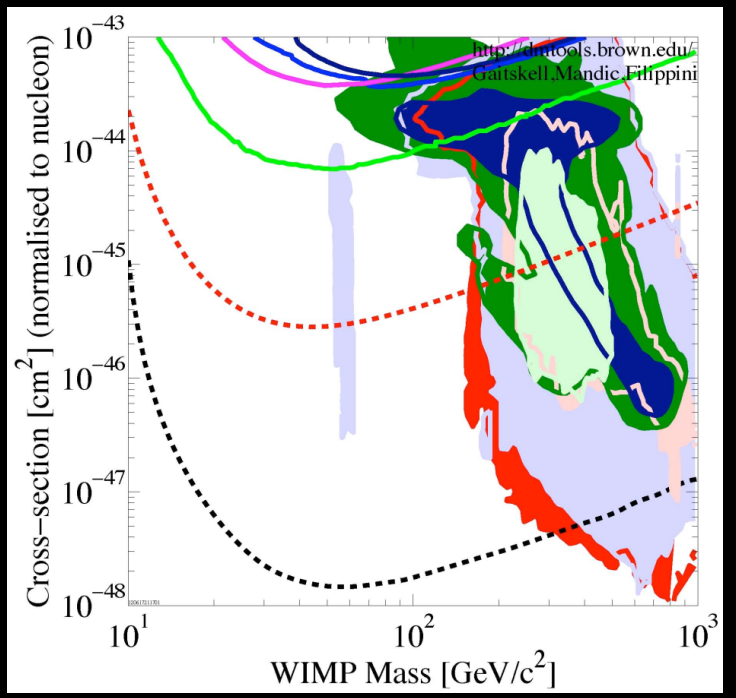
ZEPLIN III
Double phase, 31 PMTs,
high E field, 10/6.4 kg
Run 2009-11
Limit: $3.9*10^{-8}$ pb

The Current State-of-Play

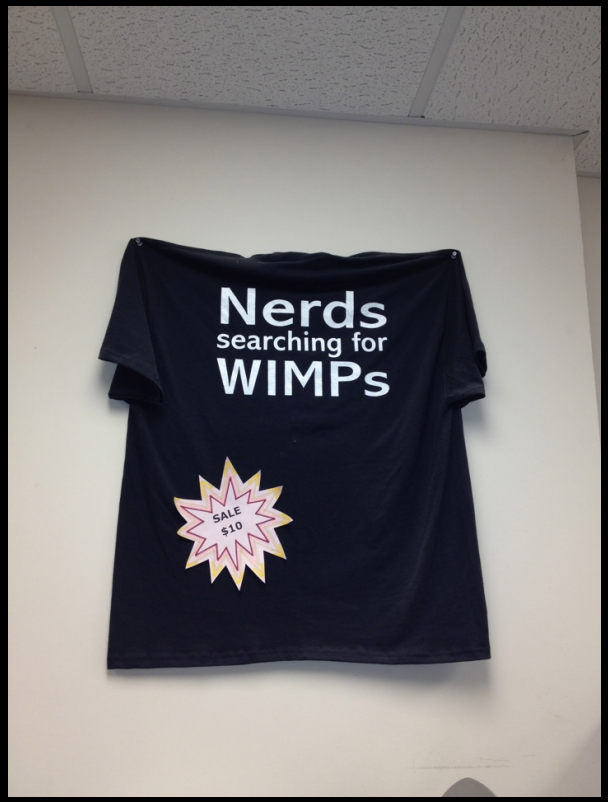


The Next Big Thing....





But it is not all about unravelling the Universe,
Nobel Prizes, or even to get your hands on this...



This technology is proving very useful in other areas
such as SNM and the medical physics domain.

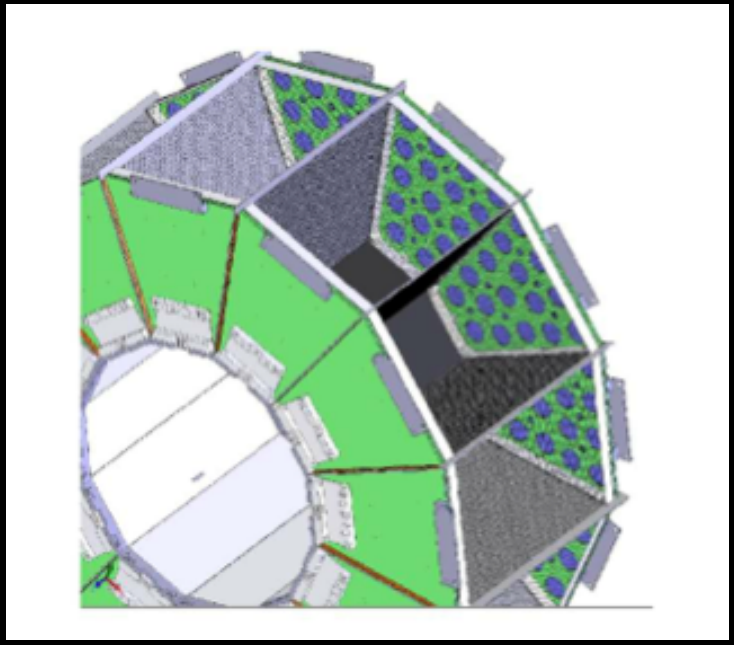
Medical Imaging

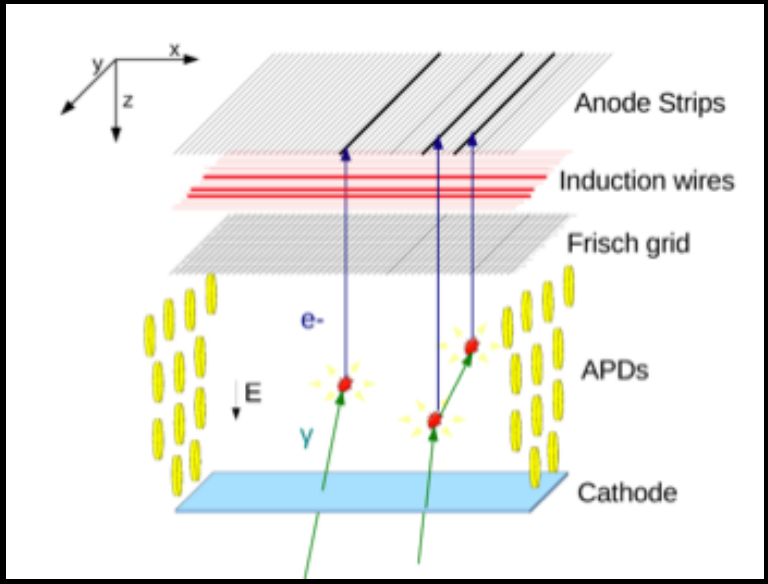
- These LXeTPCs are some of the most sensitive radiation detectors in existence!

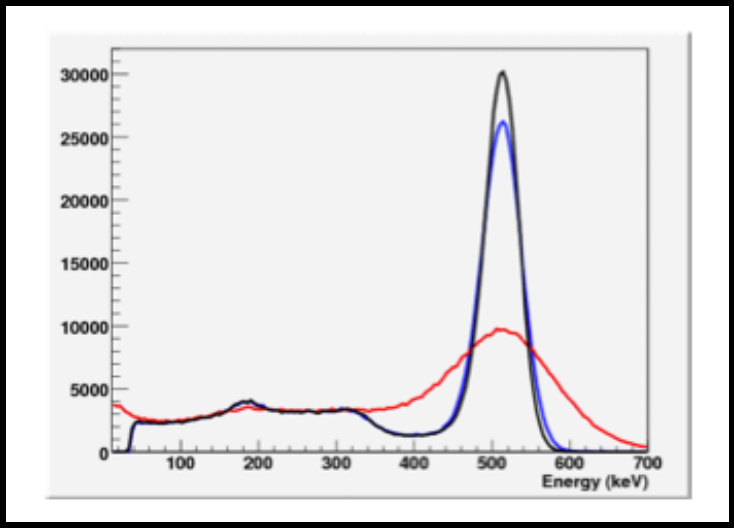
- The most obvious application is for medical imaging. They have excellent resolution and low energy thresholds (much lower than any competing technology!)

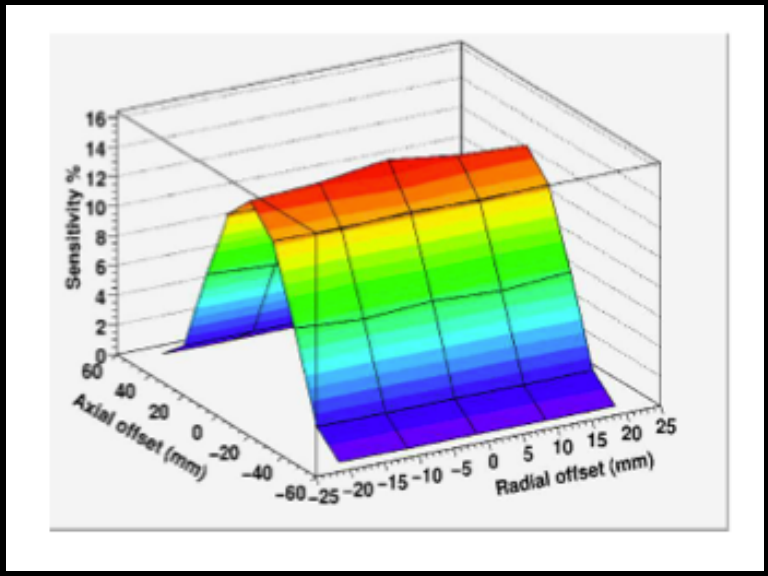
- In particular, LXe PET scanners are in development:
  - ~5 keV FWHM at 122 keV
  - Sub-mm 3D position resolution
  - Scaleable
  - Simultaneous detection of both scintillation and ionisation
  - Background rejection and discrimination
  - Rejection of random coincidences and pile-up

Medical Imaging









Proton Therapy

>50% of cancer patients receive 1+ course of radiation therapy; intense amounts of energy are directed at cancer cells to destroy the genetic material that controls cell growth.

X-rays (photons) are the energy source in conventional radiation therapy, but X-rays radiate everything in their path, in front of and behind the target, damaging good tissue!

In proton therapy, energy comes from protons, the positively charged parts of an atom. Unlike an X-ray, the proton stops after striking the target and the beam can be very finely controlled.

Proton therapy has been shown to be beneficial in the treatment of many kinds of tumours, including head and neck, eye, central nervous system, lung, sarcomas, gastrointestinal, prostate, and many paediatric cancers where fine control is needed.

The precision of pencil beam scanning makes it especially beneficial in treating tumours adjacent to critical and sensitive organs, such as the brain, eye and spinal cord.

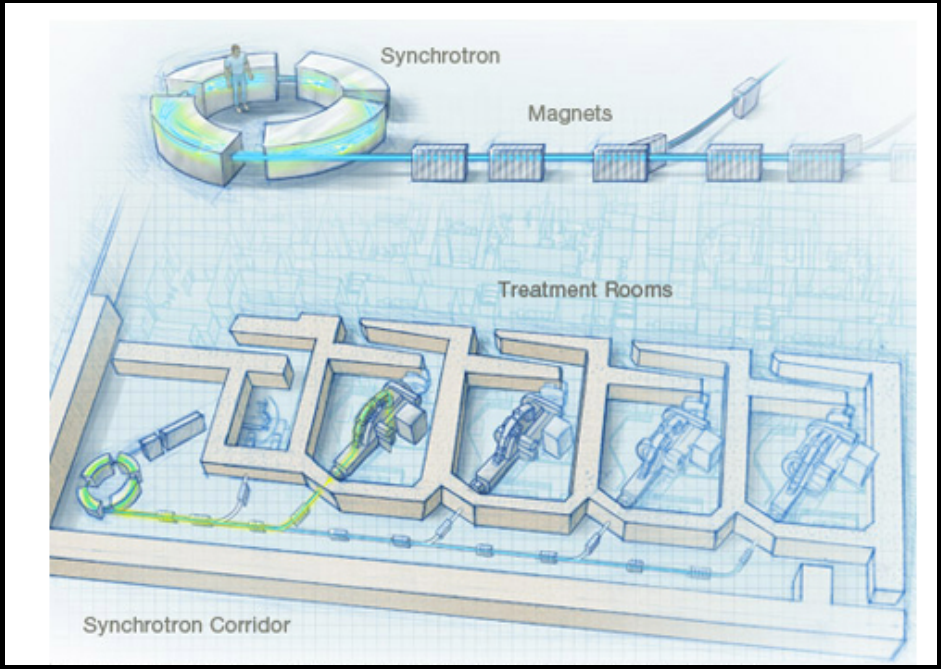
Text/images from Mayo Clinic Website

Proton Therapy

Proton Therapy

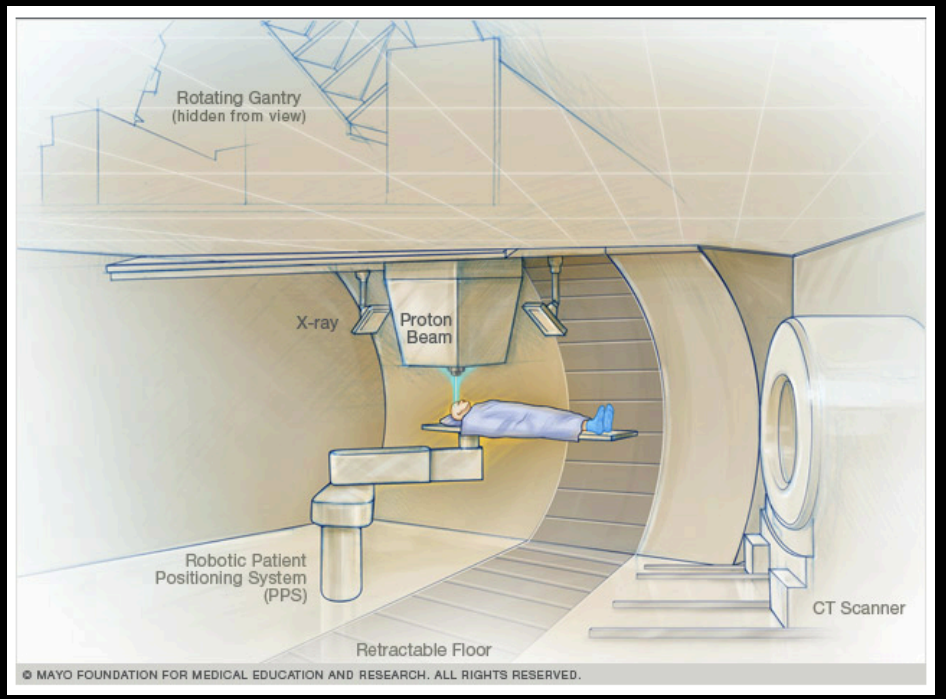
Cyclotron/Synchroton accelerators produce the protons

Proton Therapy

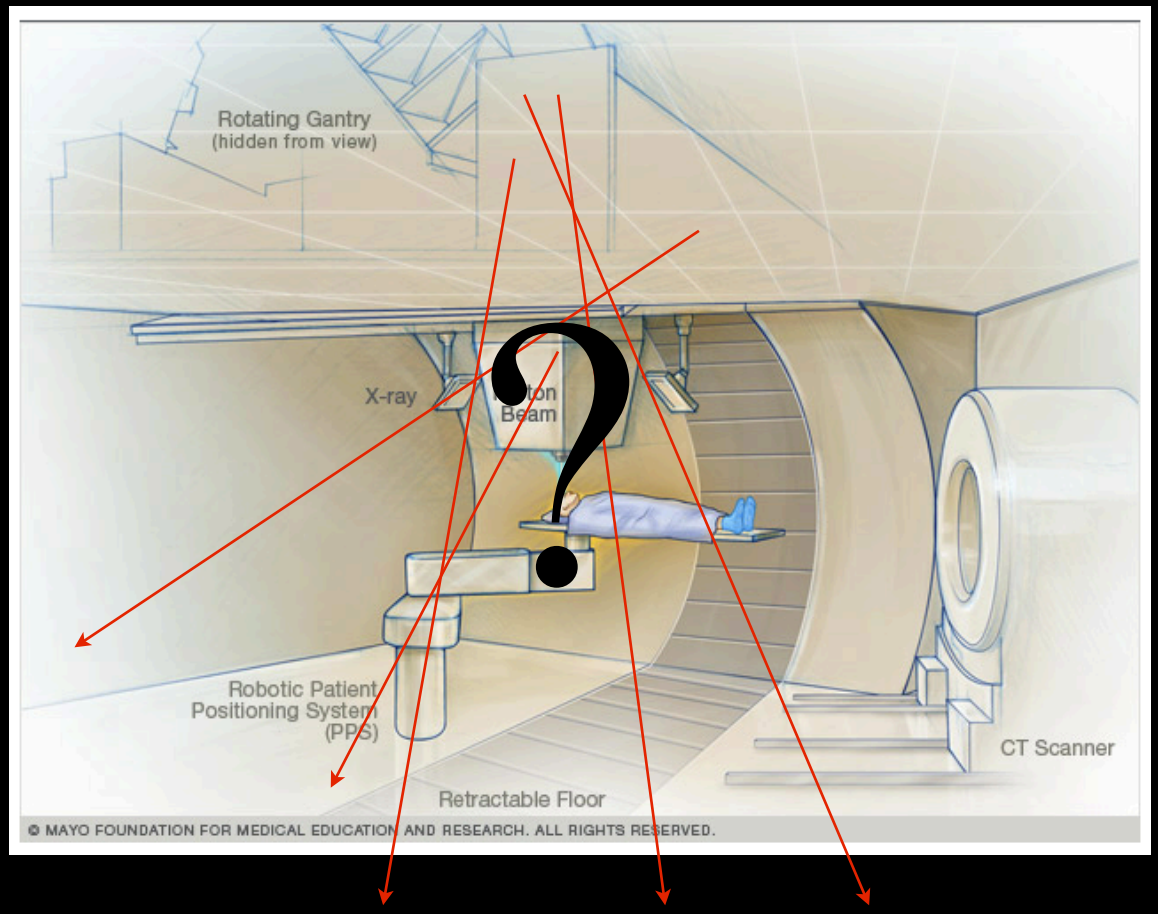


Facility

Treatment Room



Proton Therapy



But what about the neutrons!?!

With the protons come neutrons - we can't stop that.

But we don't (yet) know how many, what energies, or how damaging they would be!

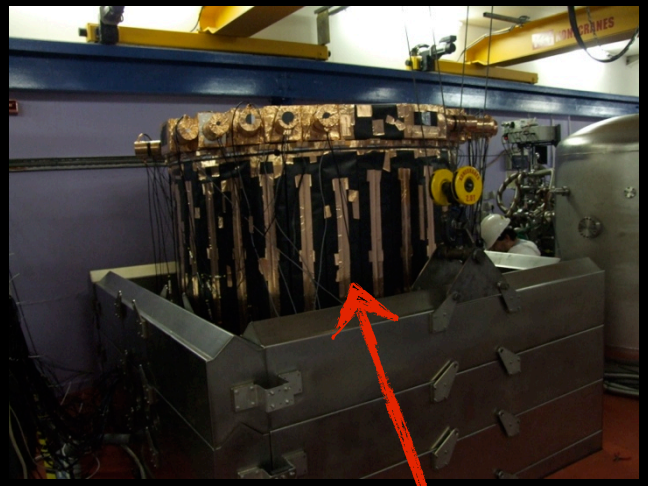
Neutrons are the most penetrating of radiation (= very bad!!)

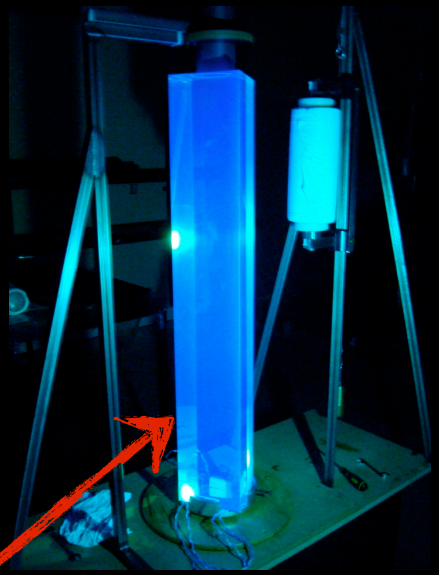
If only we had some excellent neutron detectors...

Proton Therapy

- High Efficiency
- Sensitive to slow and fast n's
- Spectral mapping (not just integrated flux)
- Direction Sensitive
- High resolution
- Particle discrimination

Proton Therapy





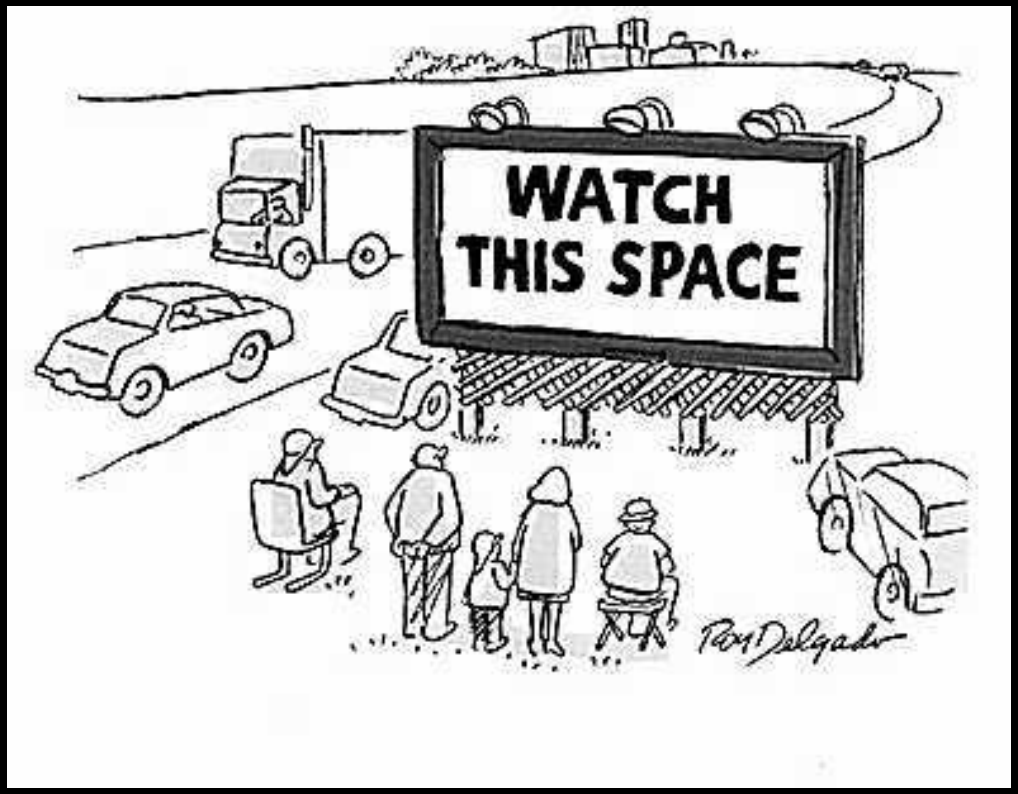
Plastic scintillator
(Gd doped)

Gas directional
TPCs

Summary

- Dark Matter is out there!
- LXeTPCs, pioneered in the UK, lead the race to find it
- The international LUX and LUX-ZEPLIN experiments have significant UK involvement and will eat into the favoured parameter space for a first discovery
- The same technology is being applied to a number of areas, including, SNM, medical imaging and development of cancer therapy centres
- We need to understand the neutron rates for proton therapy and then mitigate against any threats - particle physics detectors can provide the solution!

Exciting times ahead....



Thank you all for listening!