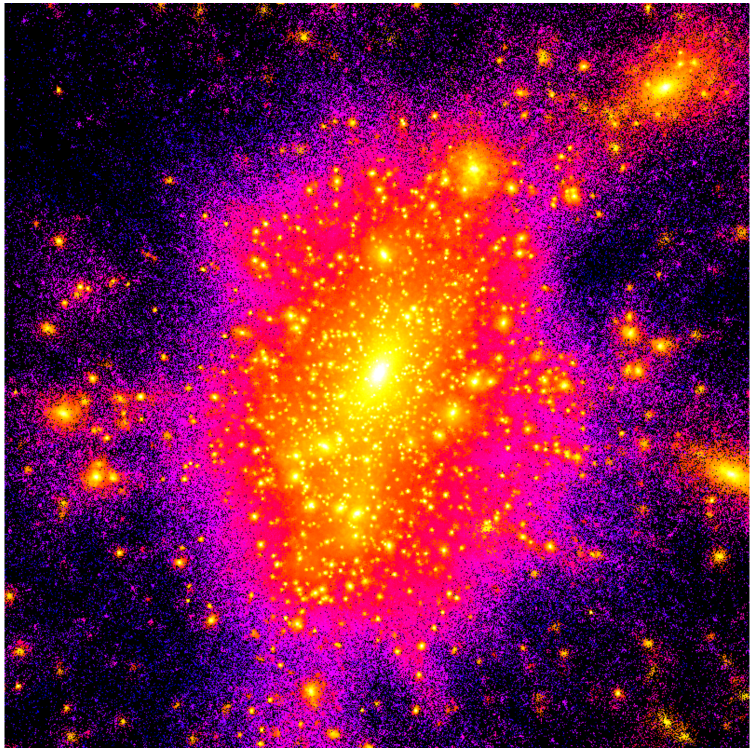
Dark Matter in the Universe ?

A (mostly) Pictorial Introduction



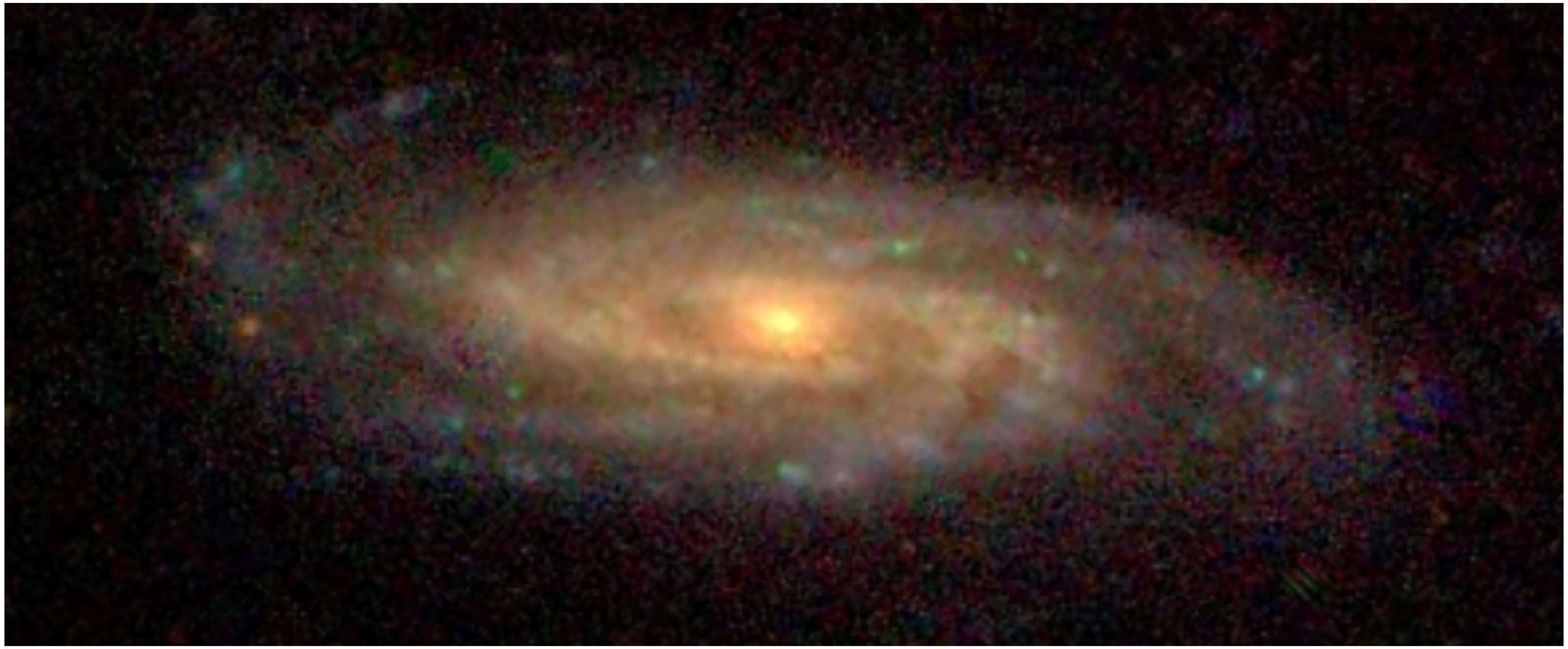
Edward Daw

University of Sheffield

A Spiral Galaxy-NGC3198

In Ursa Major (Great Bear / Plough / Big Dipper) constellation.
Distance is 9.1Mpc, or 30 million light years.

For comparison, distance from Earth to the galactic centre is a factor of ~1000 less, ~ 30 thousand light years



33 thousand light years

Dust, Gas, and Debris

Sombrero Galaxy - NGC 4594, in Virgo. Hubble Space Telescope Image `http://antwrp.gsfc.nasa.gov/apod`

Horsehead Nebula

In Orion, 0.9m telescope, Kitt Peak National Observatory, U.S.A.

Image is 2.7 by 1.8 light years, distance is 1.6 thousand light years

Pink background is hydrogen emmission from IC434 emmission nebula.

http://antwrp.gsfc.nasa.gov/apod

Question:

Is the mass in the universe all observable through emmission or absorbsion of electromagnetic radiation ?

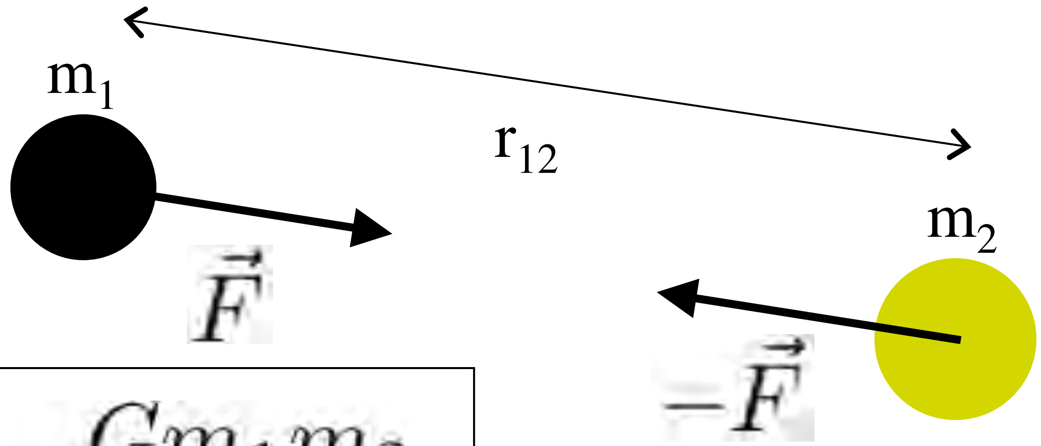
Dark Matter

...is matter that does not shine or absorb light, and has therefore escaped direct detection by electromagnetic transducers like telescopes, radio antennas, x-ray satellites...

It turns out that there is strong experimental evidence that there is more than 4 times as much dark matter as luminous matter in the observable universe

Evidence for Dark Matter

Use the fact that massive objects, even if they emit no light, exert gravitational forces on other massive objects.



$$\left|\vec{F}\right| = \frac{G m_1 m_2}{r_{12}^2}$$

Study the motions (dynamics) of visible objects like stars in galaxies, and look for effects that are not explicable by the mass of the other light emmitting or absorbing objects around them.

Rotation of Stars around Galactic Centres

We can measure how fast stars rotate around galactic centres by looking at the frequency shift of known spectral lines originating in the luminous material in the galaxy using the DOPPLER SHIFT of emission lines..

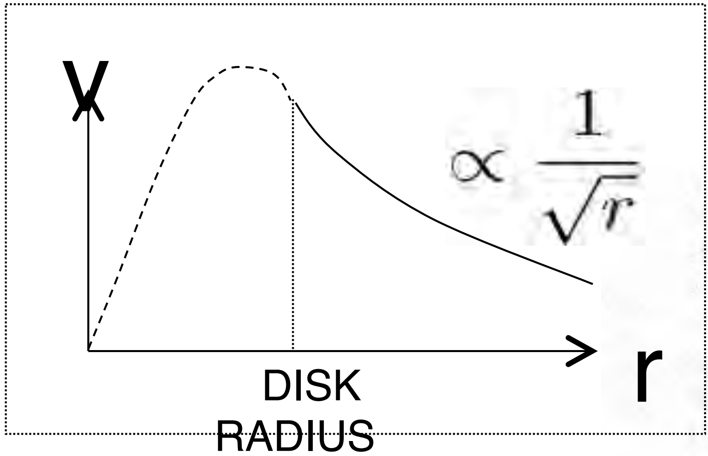
Emitter motion towards you, relative to the galactic centre alters wavelength of light

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

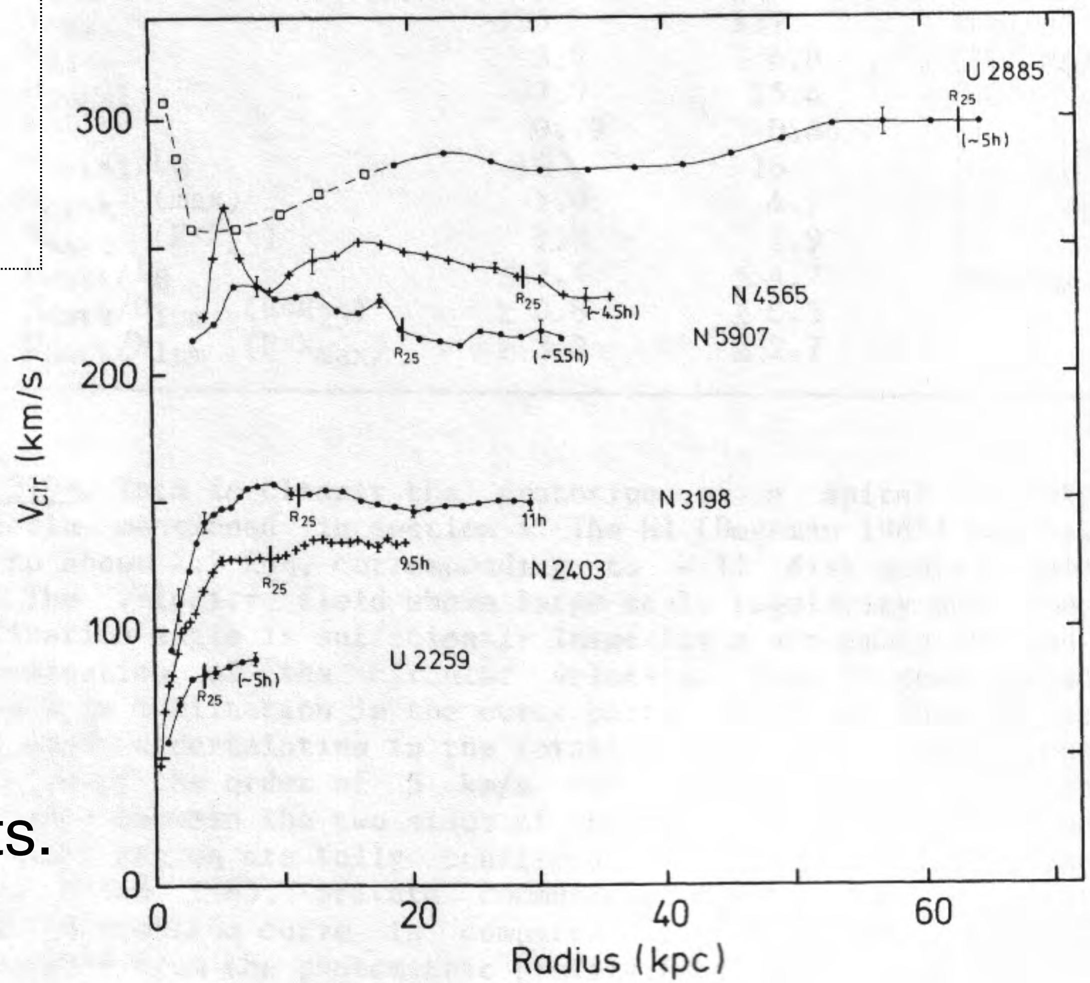
Need World's largest telescope...

Some Results

This is what we expect....why?



...but here are some typical results



Wavelength shifts are about a part in 10^6. These are hard measurements.

Possible Interpretations

-Maybe there is more matter in galaxies that we have not observed.

(WHAT ? Faint stars ? Planets ? Rocks ? Gas ? Dust ? Exotic Particles ?)

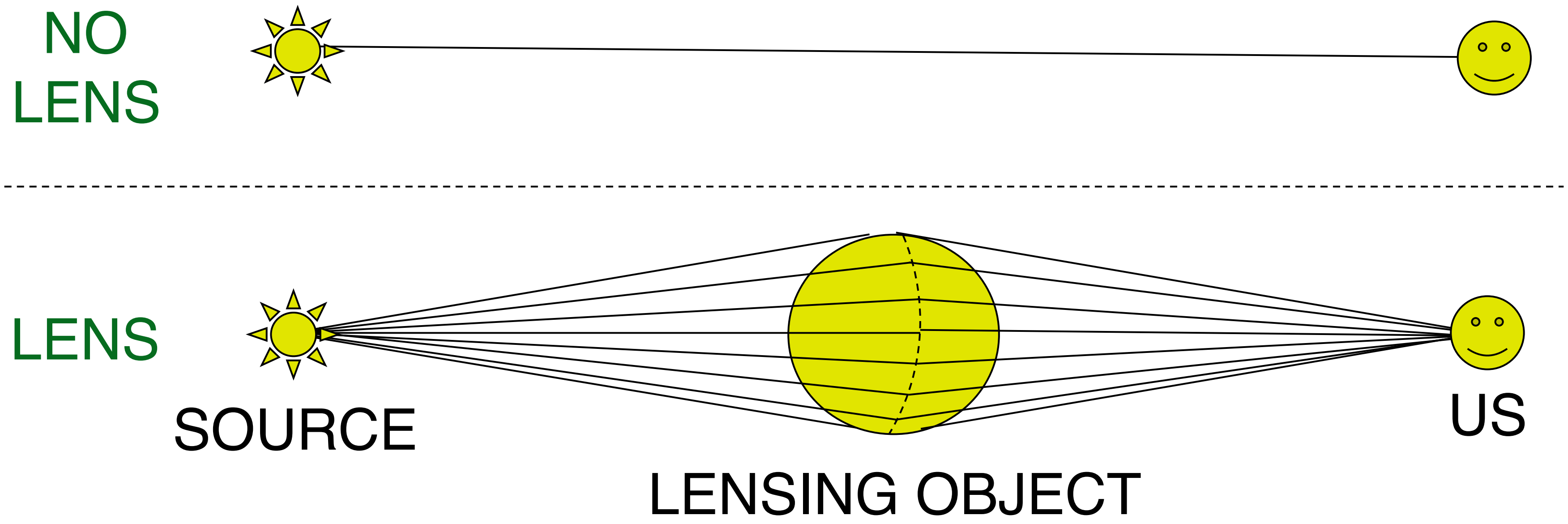
Need about 10 times as much dark matter as visible matter to explain the rotation curve discrepancy !

-Maybe Newton's law of gravitation is wrong for very large distances or very small accelerations.

(A alternative theory (MOND) has been seriously proposed, cannot yet rule this out)

Gravitational Lensing of Light

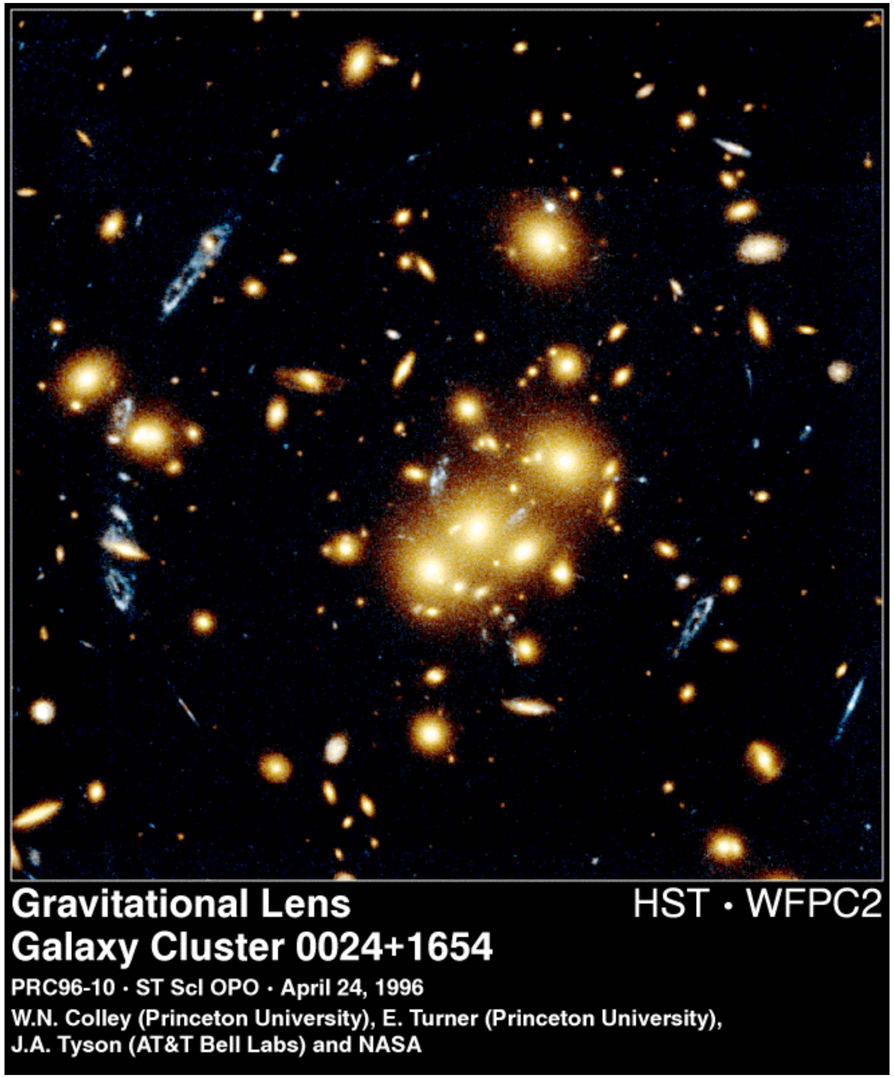
Bending of light in gravitational fields can make lenses out of massive objects



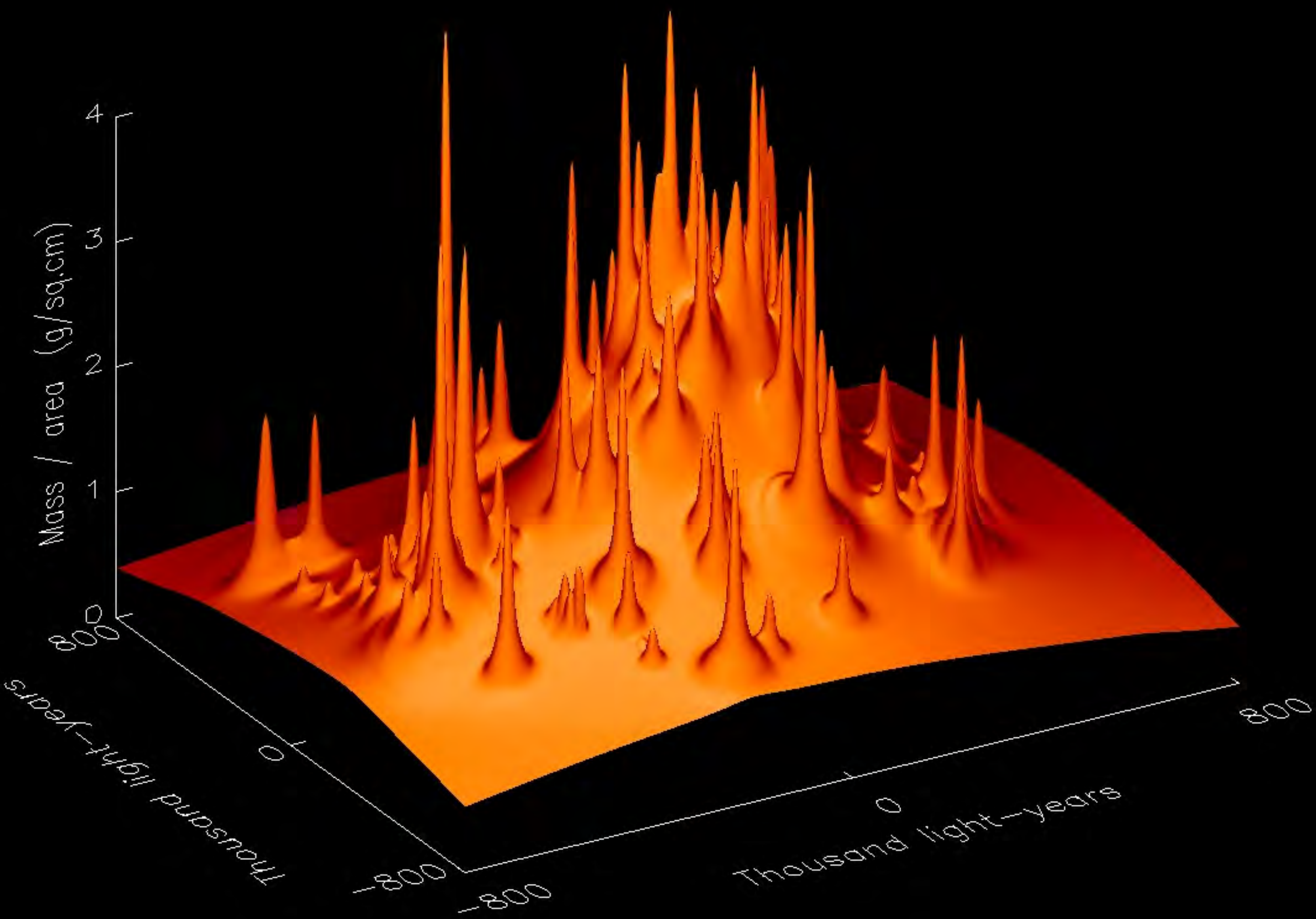
Strong or close lens, expect a ring of light, or a ring of images in the presence of the lens. When not resolved, expect increased intensity.

Galaxy Cluster 0024-1654, Hubble Deep Field

← 1.4 million light years →



Reconstructed Matter Distribution in CL0024-1654



[Tyson et al., Ap. J. **498** L107-110, 1998]

Further evidence from post-collision galaxy clusters

blue : distribution of MASS from gravitational lens analysis

red: distribution of luminous matter from its X-ray emission.

http://www.optcorp.com/edu/articleDetailEDU.aspx?aid=1535

How Much Dark Matter in Clusters ?

Need about 10 times as much dark matter in the overall cluster as observable in the individual galaxies to explain the observed microlensing

Galaxies are made up of about 10 percent visible matter and 90 percent dark matter, whose nature is currently not understood. Galaxy clusters that have been measured are made up of about 10 percent visible matter and 90 percent dark matter, which means that on a galaxy and cluster scale, only a few percent, perhaps lower, of the matter is solidly understood.

...OR you could consider modifying Newton's law of gravitation, but the modifications proposed to explain both rotation curves and cluster lensing are so complicated that nobody except the author claims to understand them !

What Could Constitute the Dark Matter (1)?

IDEA 1 : Rocks

-from pebbles to giant planets like Jupiter.
If there are enough of them, they could make up the dark matter.

Jupiter-size and above planets are a serious contender, and are called MACHOs by the community - MAssive Compact Halo Objects.

IDEA 2: Neutrinos

Light, neutral particles of which at least some have a small mass. Produced in enormous numbers in stars and possibly at the big bang. If there are enough of them, they could (maybe) be the dark matter.

What Could Constitute the Dark Matter (2) ?

IDEA 3: Black Holes

Don't emit significant amounts of light, can be very massive. Would need lots of them.

IDEA 4: Cosmic Strings

Dense filamentary structures that some theorists think could thread the universe, giving rise to its present-day lumpiness. Currently disfavoured by cosmological data, but may come back into vogue sometime.

What Could Constitute the Dark Matter (3) ?

IDEA 5: Axions

Very light particles, mass around 10^{-12} of an electron. Needed for building most realistic models of the neutron from standard model particle physics. Not detected. To be the dark matter, there should be around 10^{13} per cubic centimetre here on Earth.

IDEA 6: WIMPS (for the rest of this talk)

Particles having mass roughly that of an atomic nucleus, could be as light as carbon or as heavy as 7 nuclei of xenon. Need a few per litre to constitute dark matter. Unlike nucleus, only interact WEAKLY with other matter, through the same mechanism that is responsible for nuclear beta-decay.

What do we know about the distribution of dark matter in space?

Two important questions:

Two sources of information:

1. The matter in question is feebly coupled to ordinary matter, so guess its self-coupling is also feeble.

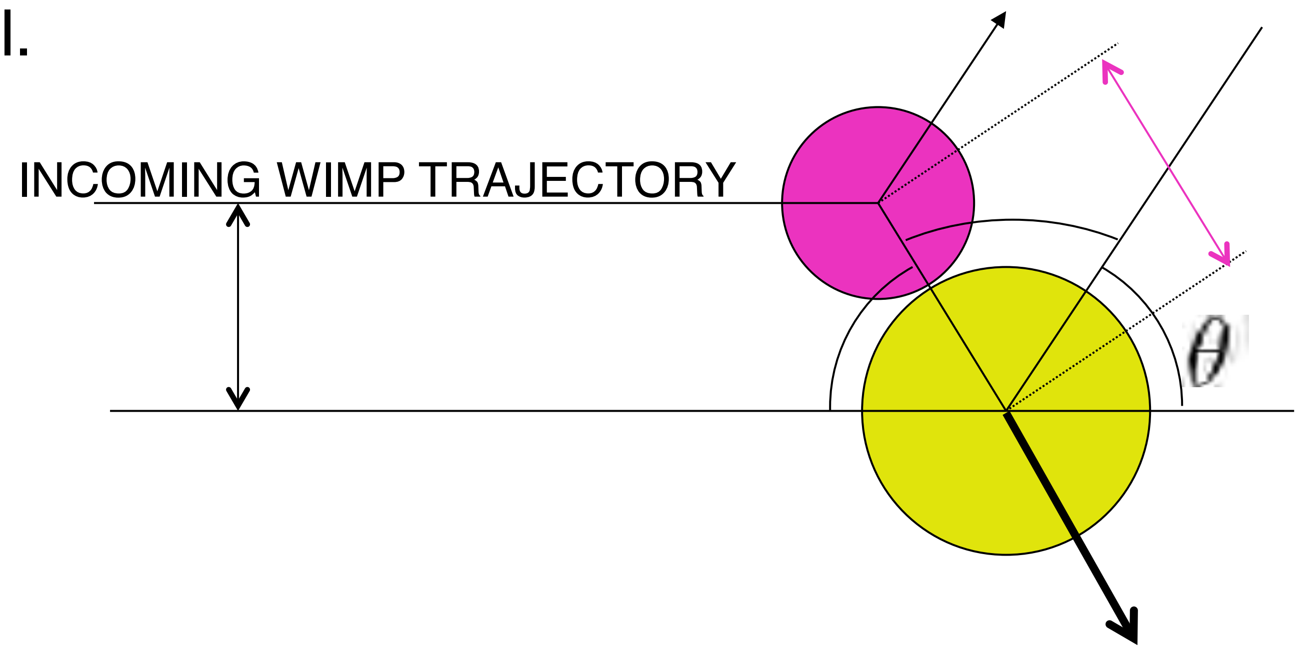
2. N-body simulations try to model the halos of galaxies to see whether the dark matter is clumped.


R = 6.0 Mpc
z = 10.155
a = 0.090
diemand 2003

Detectable WIMP Interactions

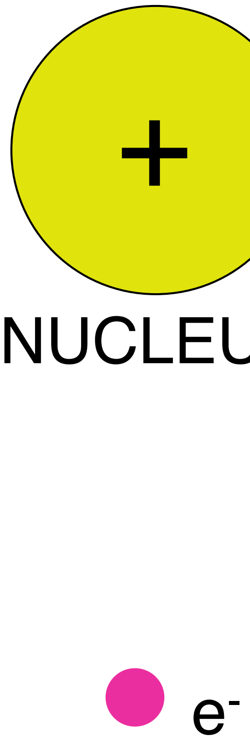
WIMPs interact WEAKLY with ordinary matter. Ordinary matter consists of protons, neutrons, and electrons.

Think of this interaction as classical, 'billiard ball' scattering, except that the probability of scattering occuring is absolutely tiny. The billiard balls are the incoming WIMP and an atomic nucleus. The WIMP collides with the nucleus, causing it to recoil.



Detecting the WIMP Interactions

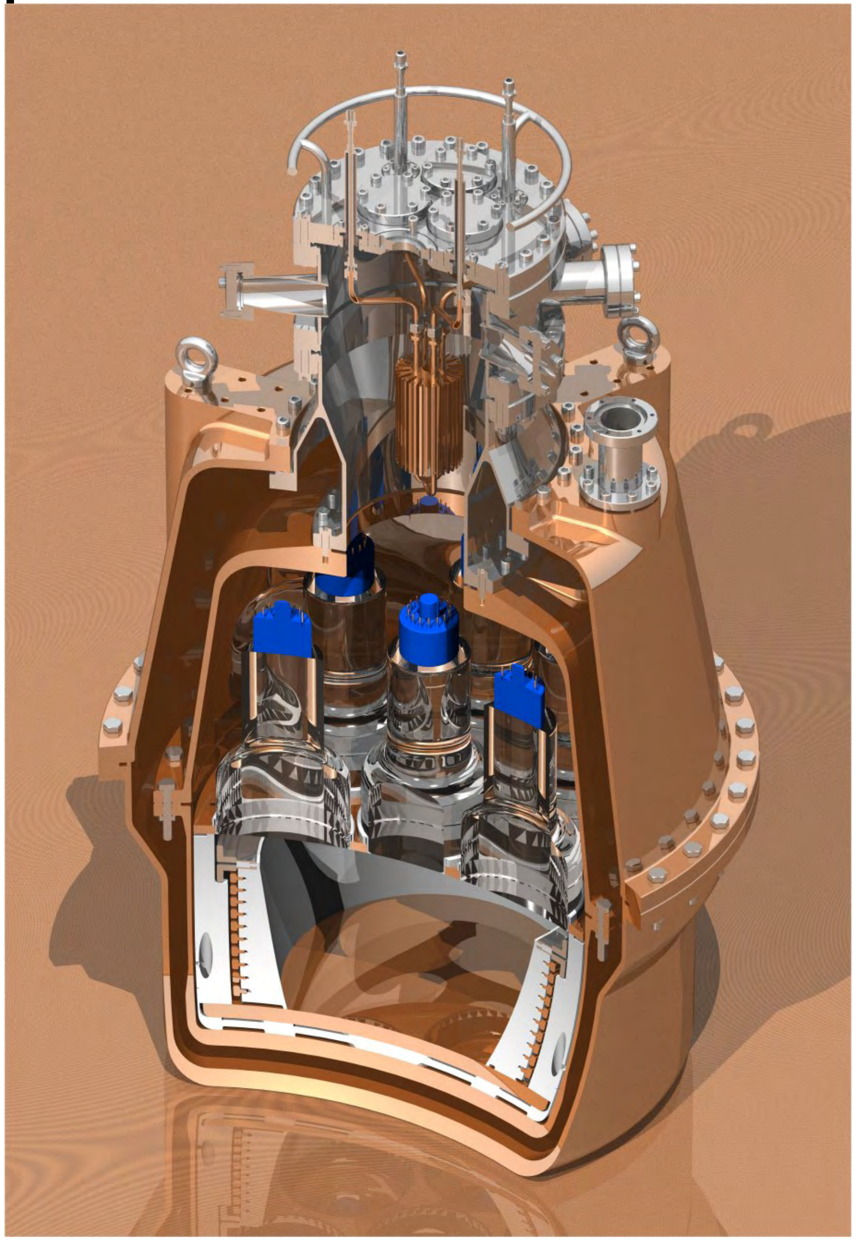
The nucleus recoils after being hit. The kinetic energy it gains is enough to ionize the atom, creating a positively charged nucleus and a free electron.



EXAMPLE DETECTION SCHEME:

The struck nucleus is part of a molecule. The molecule is ionized, but the ionization electron recombines with the other remnant parts of the molecule to form an excited molecular state. This state then decays back to the ground state with the emission of light of a characteristic frequency

Zeplin II - A Scintillator Detector for WIMPs

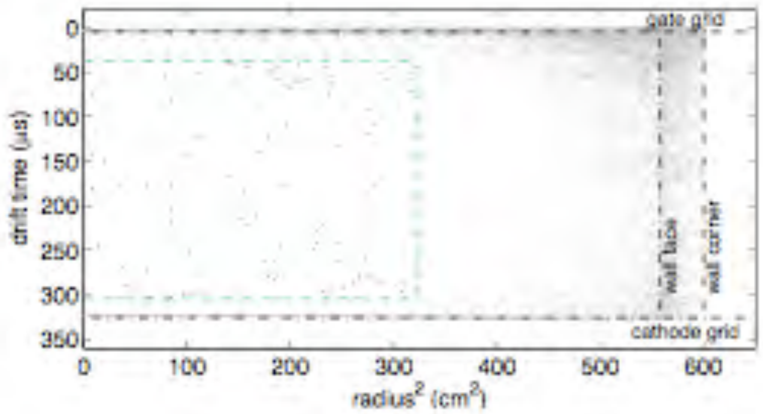


Detector houses 35kg of Liquid Xenon, which is a scintillator.

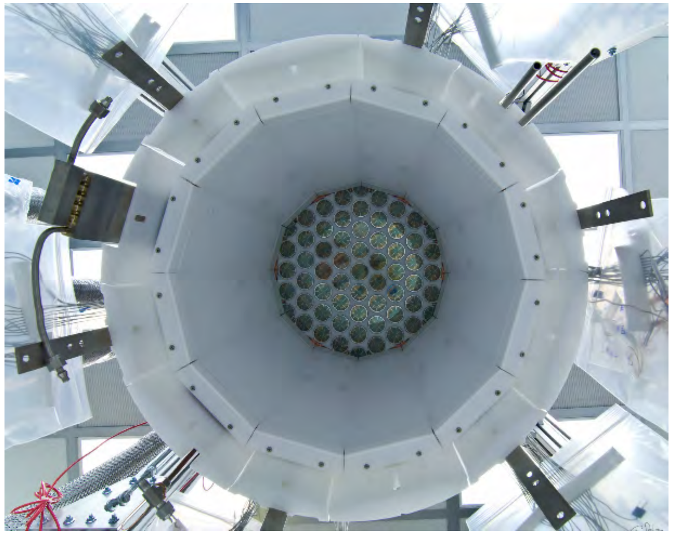
The signal is flashes of 175nm (ultra violet) light on de-excitation of a Xenon molecular excited state after a WIMP collision.

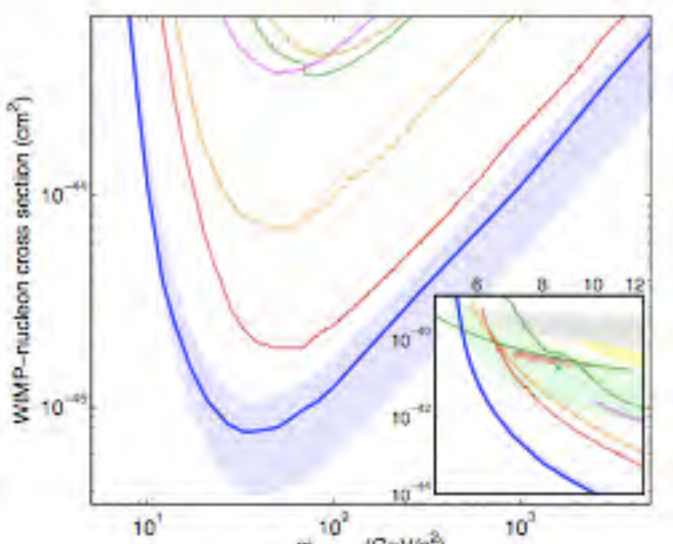
7 Photomultiplier tubes are used to collect the scintillation light.

LUX (Large Underground Xenon dark matter detector)



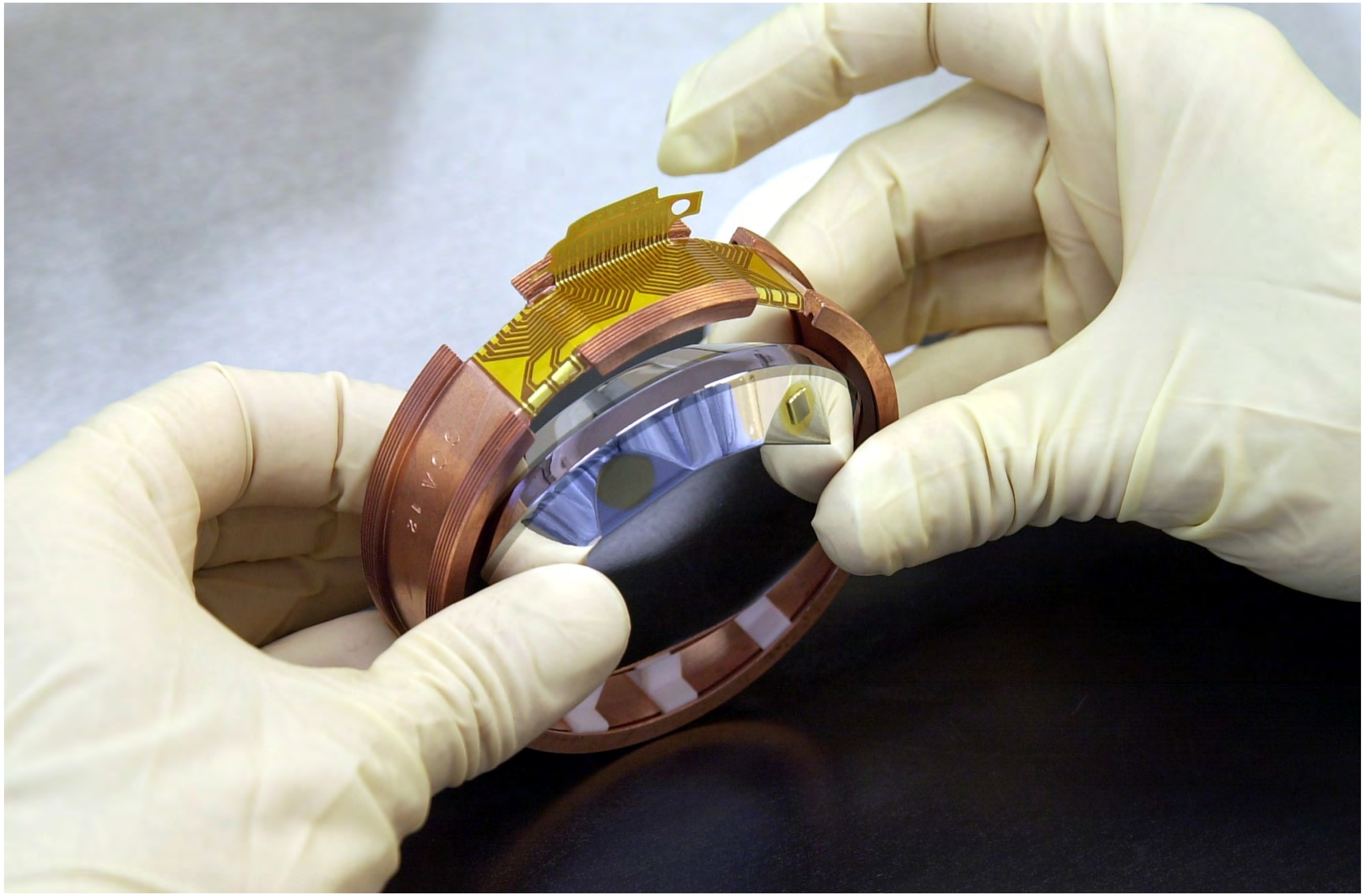
http://www.flickr.com/photos/luxdarkmatter/?share=mail





http://www.symmetrymagazine.org/article/april-2012/dark-matter-search-goes-deep-underground-in-south-dakota

Cryogenic semiconductor detectors



Experiments employing these technologies include Edelweiss (Vitaly Kudravtsev), CDMS

Why These are Hard Experiments

BACKGROUNDS

Lots of other things can cause the xenon to emit scintillation light.

a) Background radiation in the form of gamma rays emmitted by impurities in solids surrounding the detector, or in the detector itself.

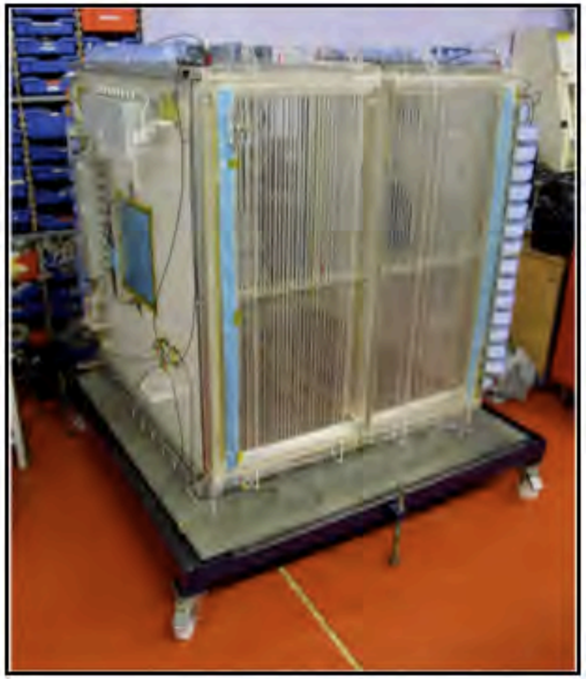
b) Background radiation in the form of neutrons. Neutrons are the most troublesome problem. Some are emmitted by the detector or surrounding material. The rest have their origin in cosmic rays from space.

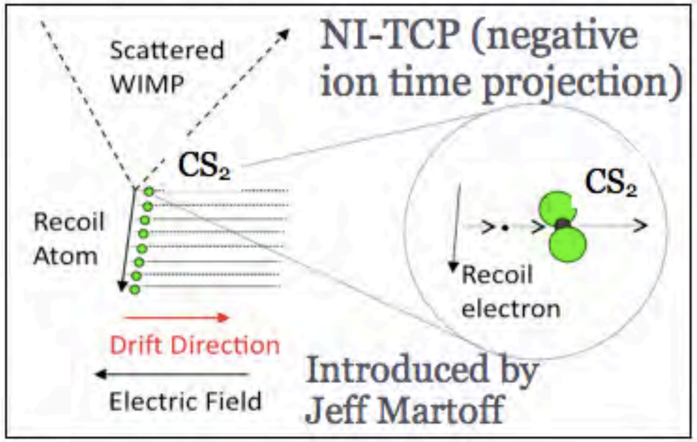
If you DO detect something, how do you know it is not just another low level radioactive background?

DRIFT

(Neil Spooner, Ed Daw)

- Negative ion time projection chambers containing a gas target for directional dark matter detection.
- Operating underground at Boulby since 2001
- DRIFT-IId* is 1m^3 of CS_2 and CF_4 in ratio 3:1 at 40 torr.

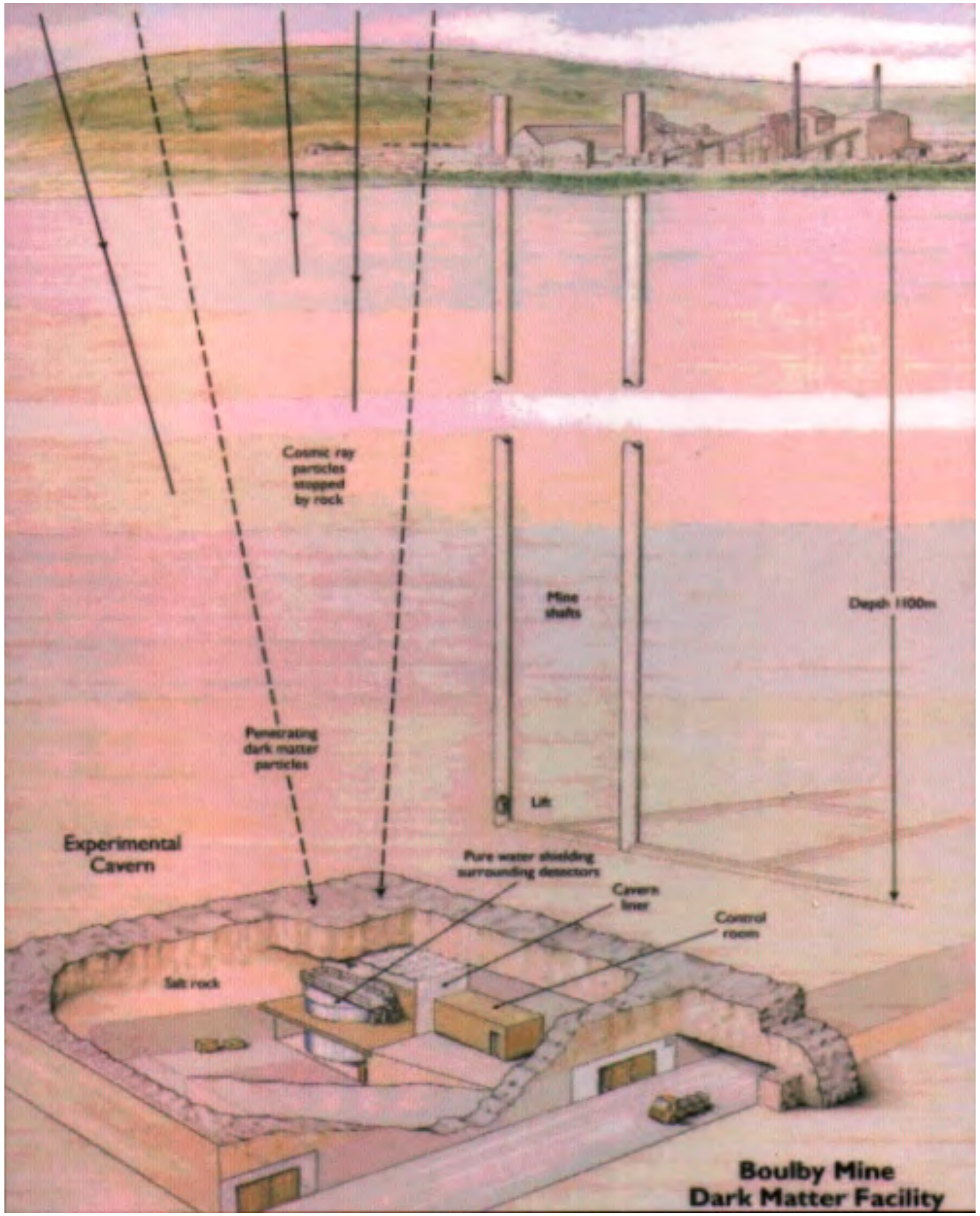




* S. Burgos et al., Nucl. Instr. Meth. A 584, 114 (2008)

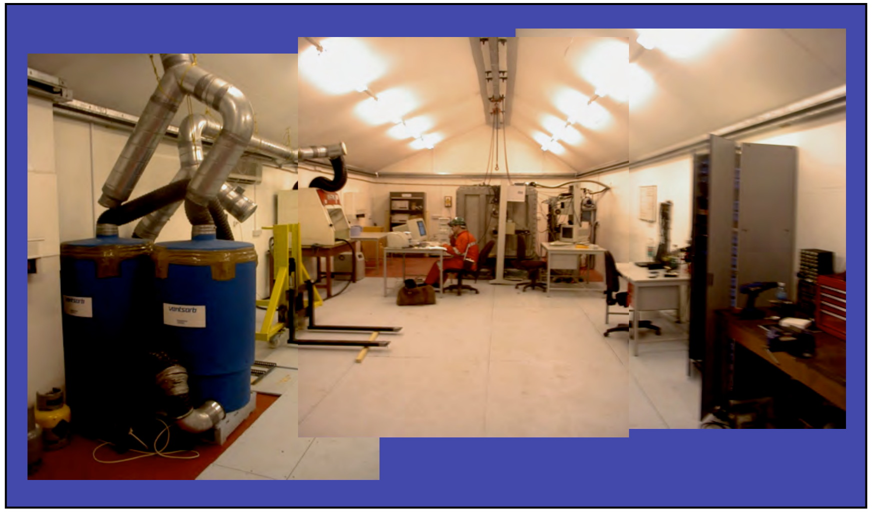
Shielding the Experiment from Cosmic Rays

Boulby Mine, Near Whitby, North Yorkshire. 1.1km deep potash and rock salt mine. Temperature at bottom is between 100 and 130 farenheit. Our lab is now air conditioned.



Laboratory Infrastructure

The UKDMC runs 3 experiments that are now being installed in the underground lab - Zeplin II, Zeplin III (both liquid xenon) and DRIFT (gaseous CS2 gas time projection chamber).



What if there are no WIMPs

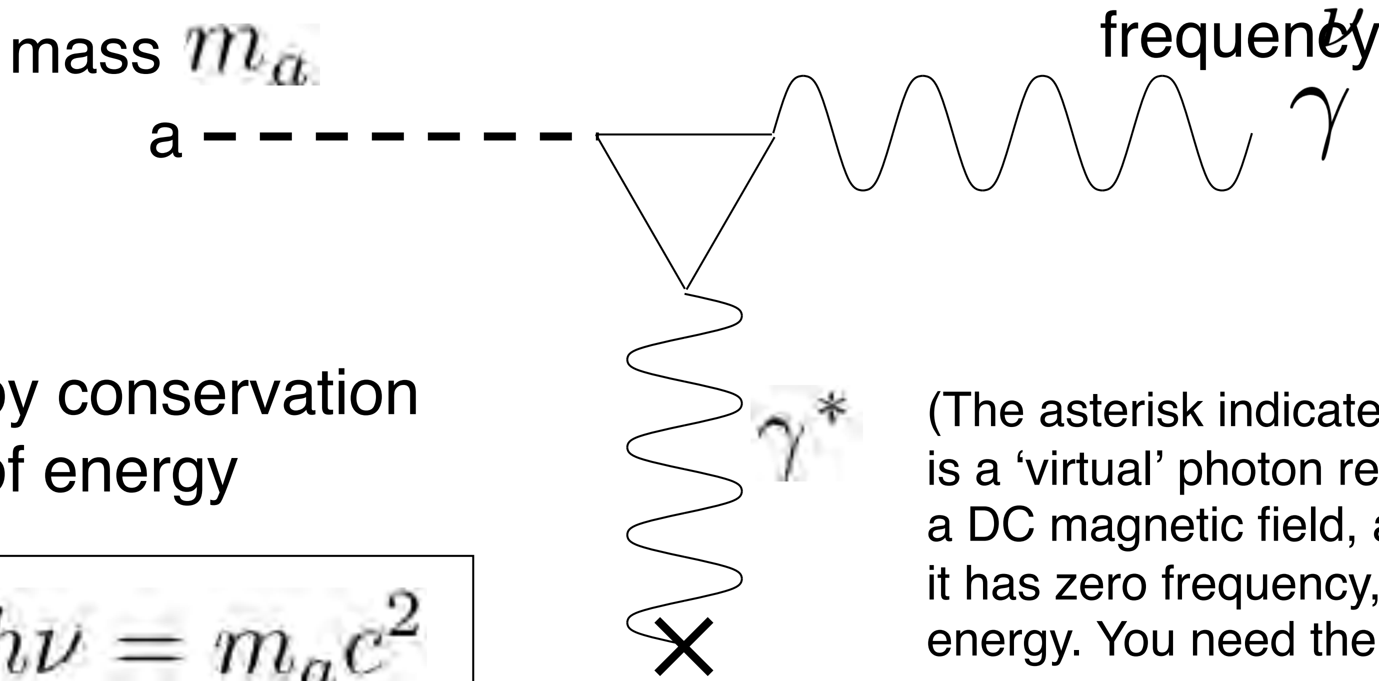
Playing devil's advocate, just for fun, suppose that the ATLAS and CMS experiments at CERN's LHC fail to find any new physics in the mass range 90 GeV/c^2 to 200 GeV/c^2? Maybe the physics of dark matter is NOT at the weak scale.

What are the alternatives to WIMPs for standard model extensions that yield a stable particle that could be dark matter ?

The axion is not weakly interacting, and would not show at LHC. AND, it is produced by spontaneous symmetry breaking, which also leads to the Higgs.

Detecting Axions in Our Galactic Halo

Typical axion velocity is the virial velocity, but with masses typically around $10\,\mu\mathrm{eV}$ they have De-Broglie wavelenths of 10s of metres. Momentum transfer from a single axion to a single nucle essentially zero. However, they do couple to photons, and this allows the following detection scheme:



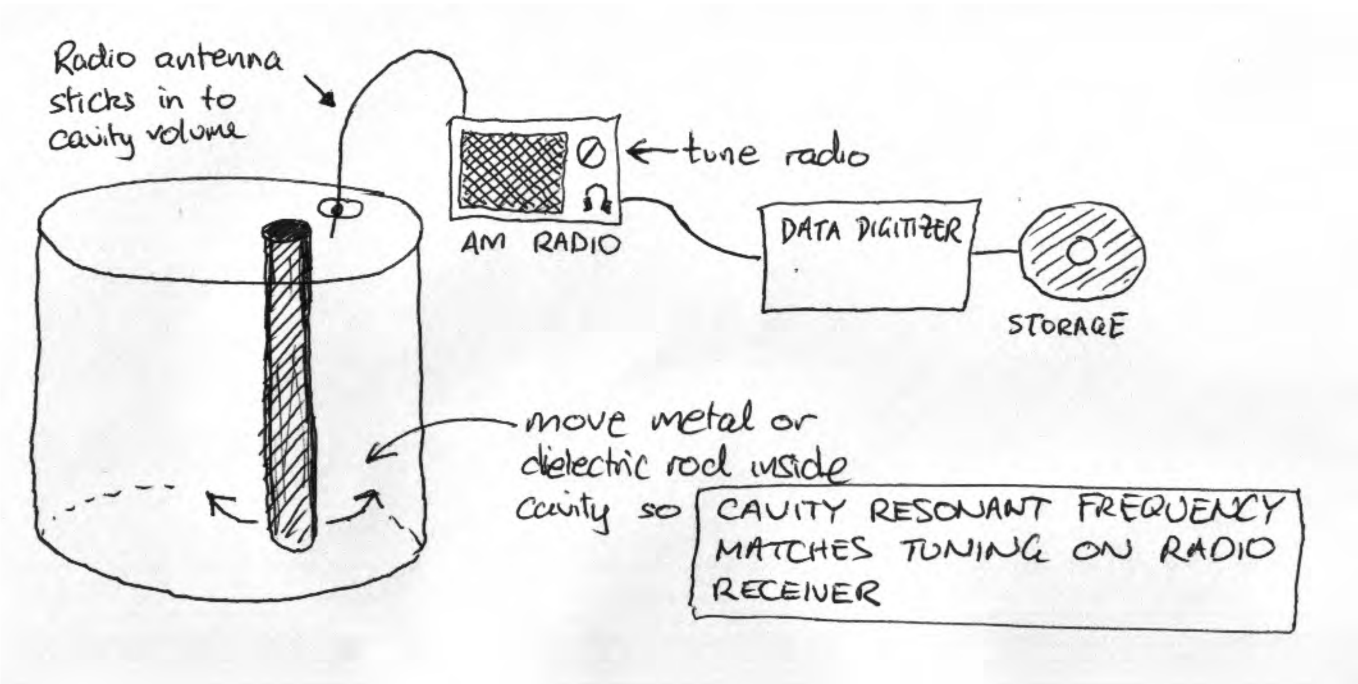
by conservation of energy

$$h\nu = m_a c^2$$

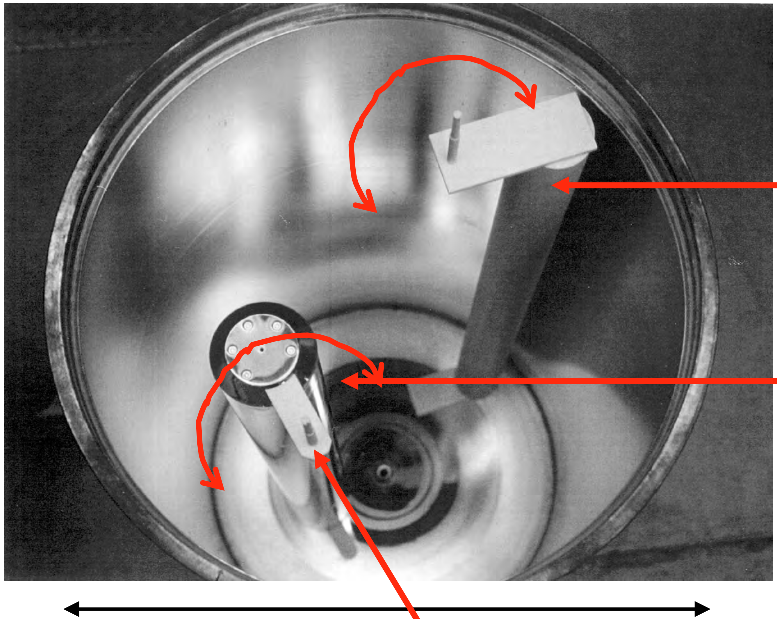
(The asterisk indicates that this is a 'virtual' photon representing a DC magnetic field, and hence it has zero frequency, and zero energy. You need the virtual photon to conserve momentum in the axion to photon conversion.)

Basics of Resonant Cavity Detectors

Cartoon diagram illustrating the resonant cavity, containing a tuning rod, the electric field probe used to measure the power in a cavity mode, and the electronics used to read out this power.



A resonant cavity for axion searches.



50cm

cam

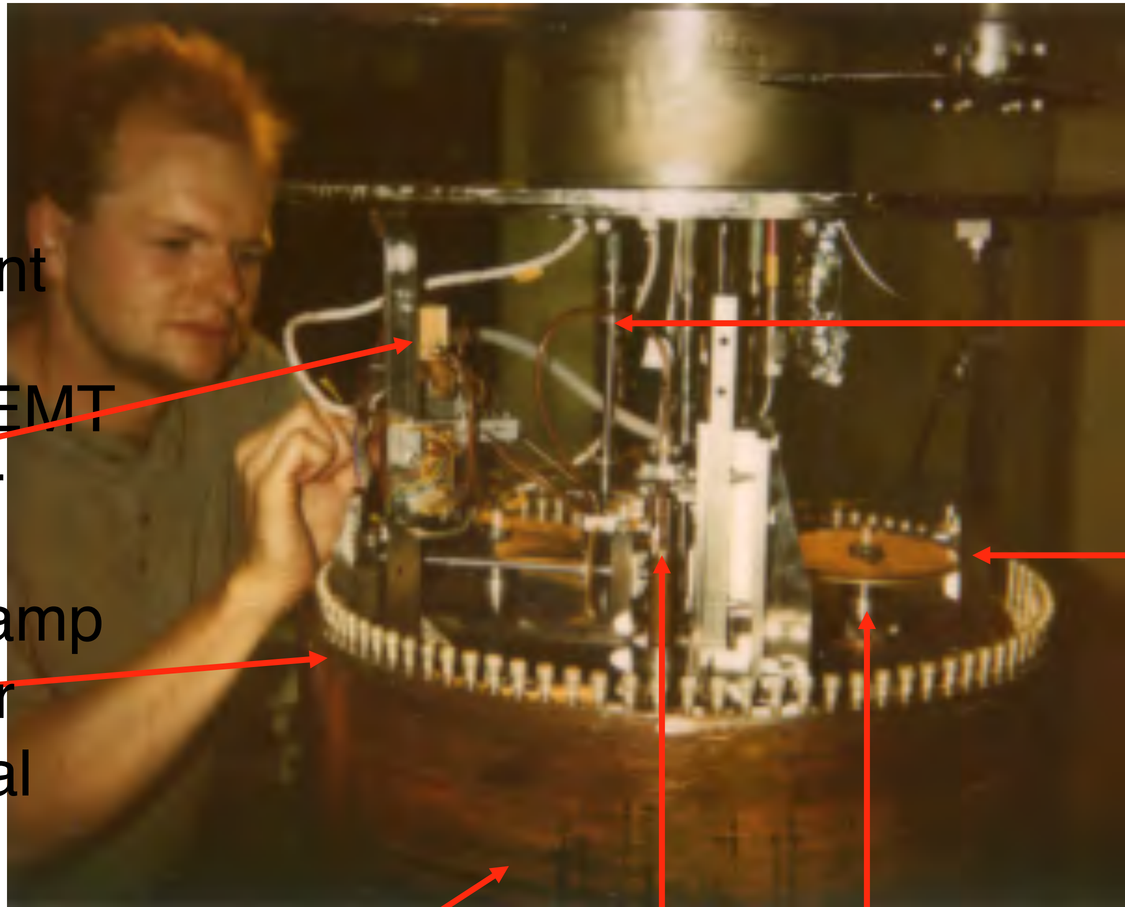
alumina tuning rod
(a dielectric)

copper coated
stainless steel
(a metal)

from above with lid removed.
Depth is 1m.

A resonant cavity is a box with conducting walls. The dimensions of the box dictate a set of RESONANT MODES of the cavity, at which standing electromagnetic waves oscillate at natural frequencies, with the walls imposing boundary conditions (in the same way as a guitar string has natural frequencies imposed by its length).

The axion experiment top plate, 1995



harrassed Ph.D. student

2nd stage HEMT RF amplifier

96 bolts to clamp lid in place for good electrical contact

drive axle from stepper motor above insert

anti-backlash gear

copper resonant cavity

collar for RF antenna insertion hole

axle connected to tuning rod cam.

Conclusions

There is **MUCH MORE** to the Dark Matter problem than I have had time to discuss in this talk.

Other detection methods (solid Gemanium and Silicon crystals, Calcium Tungstate, Sodium Iodide)

There is also **MUCH MORE** to the technology of liquid xenon based detectors - gamma background rejection, scale up to huge detectors with around a tonne of liquid xenon.

There is also **MUCH MORE** to the dark matter problem - axion searches, dark energy and cosmology

Take PHY323 in your 3rd year, or check out the course web site at http://www.shef.ac.uk/physics/teaching/phy323/