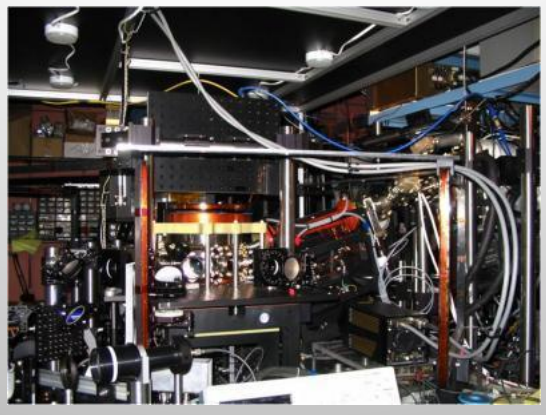
Gravity and the Universe

Test general relativity via:

- Solar System / lab tests
- Binary pulsars
- Black hole mergers (future)
- Cosmology – evolution of the Universe



Gravitational time dilation observable directly by changing the height of best atomic clocks by as little as a foot!

Gravity and the Universe

Universe is expanding (*Hubble's Law*):

- is the evolution of the expansion rate consistent with known contents of the Universe and predictions of GR?
- does structure form in the Universe under action of gravity as predicted by GR?

Dark Matter

Directly observed matter in the Universe (stars, gas) is **not** consistent with the observed motions in galaxies and clusters of galaxies if general relativity (*) is correct theory of gravity

(*) Newtonian gravity does not work either, and the differences between Newton and Einstein on these scales are insignificant

Dark Matter

In a spherically symmetric mass distribution, the velocity of a circular orbit traces the amount of mass interior to the orbit

$$v = \sqrt{\frac{GM}{r}} \Rightarrow M(r) = \frac{rv^2}{G}$$

…measure the *rotation curve* v(r) and we get the mass interior

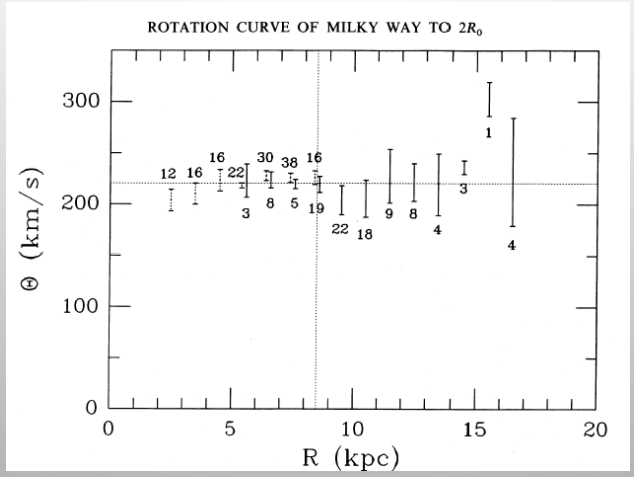
Spiral galaxies are good places to measure mass:

- disk rotates in nearly circular orbits
- can measure gas clouds at greater radii than almost all of the light

Expectations: beyond the radius where we see light, mass *interior* is constant:

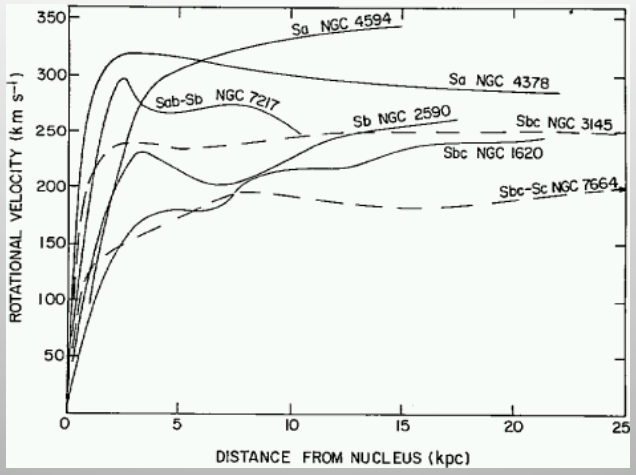
$$v = \sqrt{\frac{GM}{r}} \propto r^{-1/2}$$

…velocity should decrease with distance further out



Instead observe a **flat rotation curve**

More gravity than accounted for by known stars and gas – evidence for **dark matter**



Dynamical evidence for dark matter also seen in clusters of galaxies: galaxies are moving faster than expected if just the known gas and galaxies are present

What is the dark matter?

All we know for certain is that it cannot be any luminous object (e.g. stars)

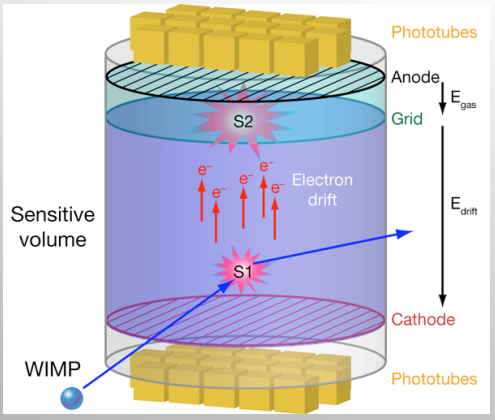
Strong arguments that it is not made of ordinary ("baryonic") matter – can infer how much was produced in the first minutes after the Big Bang and not enough

Consistent with being an *undiscovered* elementary particle massive enough to move at v << c as galaxies form – **"cold dark matter"**

Structure of the Universe on large scales is consistent with there being ~5 times as much dark matter as visible matter

Dark matter particles could be detected:

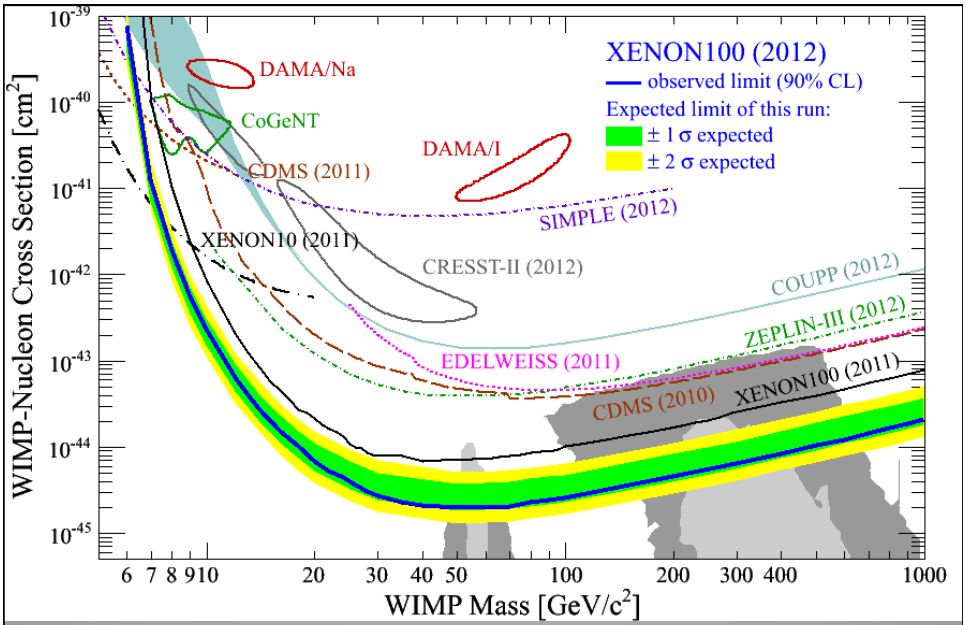
- produced in high energy particle collisions
- detected when they collide with nuclei in sensitive detectors
- if they annihilate into observable particles



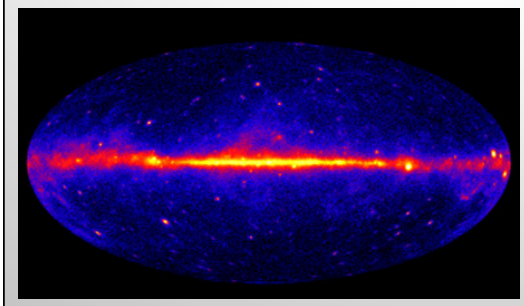
Xenon100 experiment

Try to detect dark matter collisions with xenon atoms

- situated deep underground (shielded from cosmic rays)
- sensitive to cold dark matter particles that interact weakly (via weak nuclear force) with matter



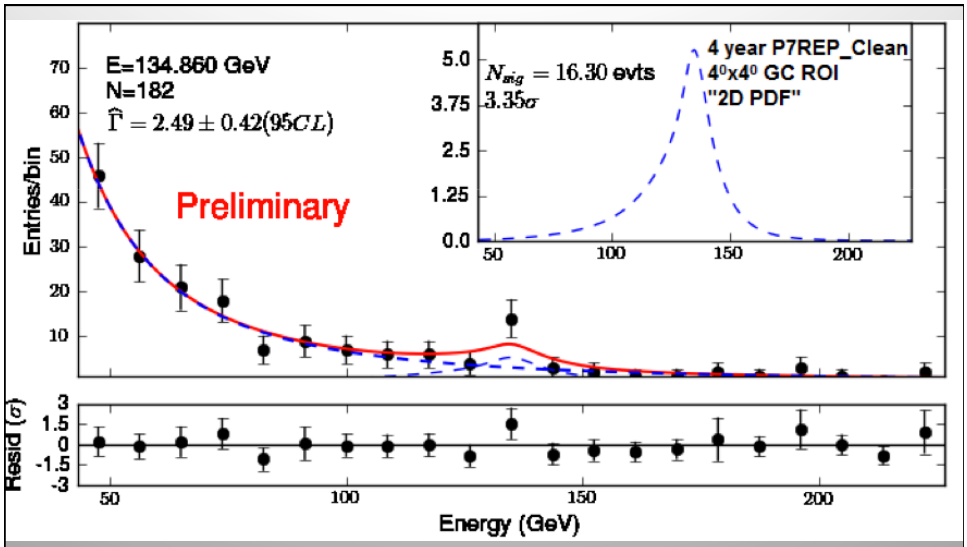
No clear evidence for dark matter so far…



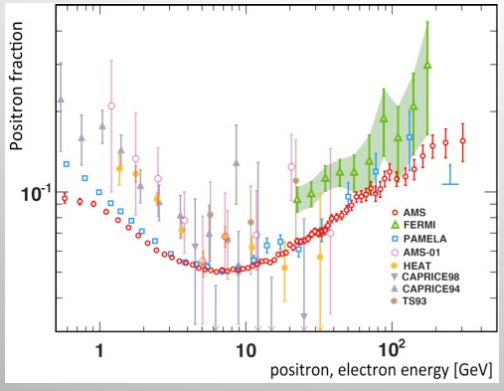
Collisions between dark matter particles might lead to annihilation into photons

Observable in regions where the dark matter density is highest – e.g. center of Milky Way

Signature: flux of high energy photons (gamma rays) with energies set by the mass of the dark matter particles



Data from *Fermi* satellite shows apparent excess of ~135 GeV gamma-rays from Galactic Center – not (yet?) convincing evidence for dark matter detection



AMS experiment on the Space Station sees increase in the fraction of high energy positrons in cosmic rays

Could be consequence of dark matter particles annihilating into positrons near Earth

BUT could also be due to production of positrons at nearby pulsars…

Very strong evidence that dark matter exists if Newtonian gravity / GR works on galactic scales and beyond

BUT direct evidence from detection of the dark matter particle is lacking

Could gravity be misbehaving on large scales?

Possible to modify gravity so that the *observed* sources of matter yield flat rotation curves

Newton $a = \frac{GM}{r^2} \Rightarrow \frac{a^2}{a_0} = \frac{GM}{r^2}$ **Modified Newtonian Dynamics (MOND)**

a_0 would be new constant describing when ordinary gravity transitions to different law in limit of large scales / low accelerations

Could gravity be misbehaving on large scales?

MOND "works" for spiral galaxy rotation curves

Very hard to explain the full range of astronomical observations that favor the dark matter hypothesis

X-ray / lensing observations of colliding galaxy clusters suggest dark matter is spatially separate from luminous hot gas – not just gas gravitates