Theoretical Physics

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February 15, 2011

Theoretical Particle Physics

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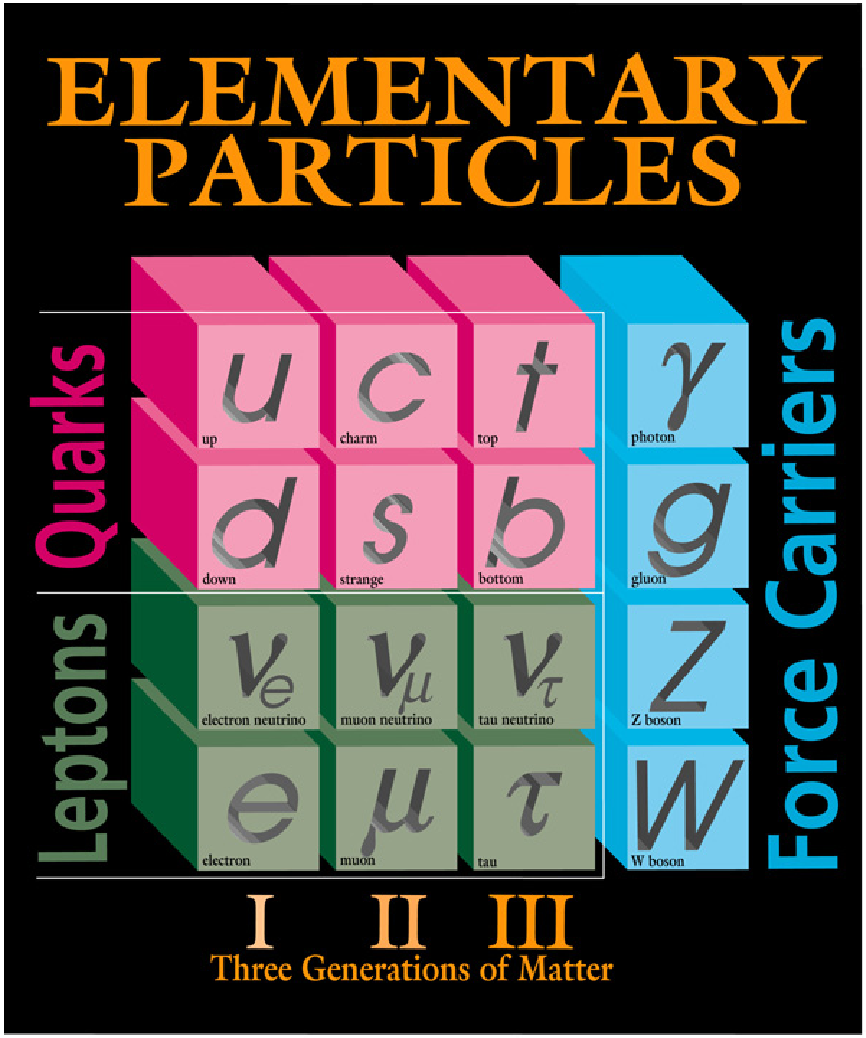
We know a lot about the structure of matter.



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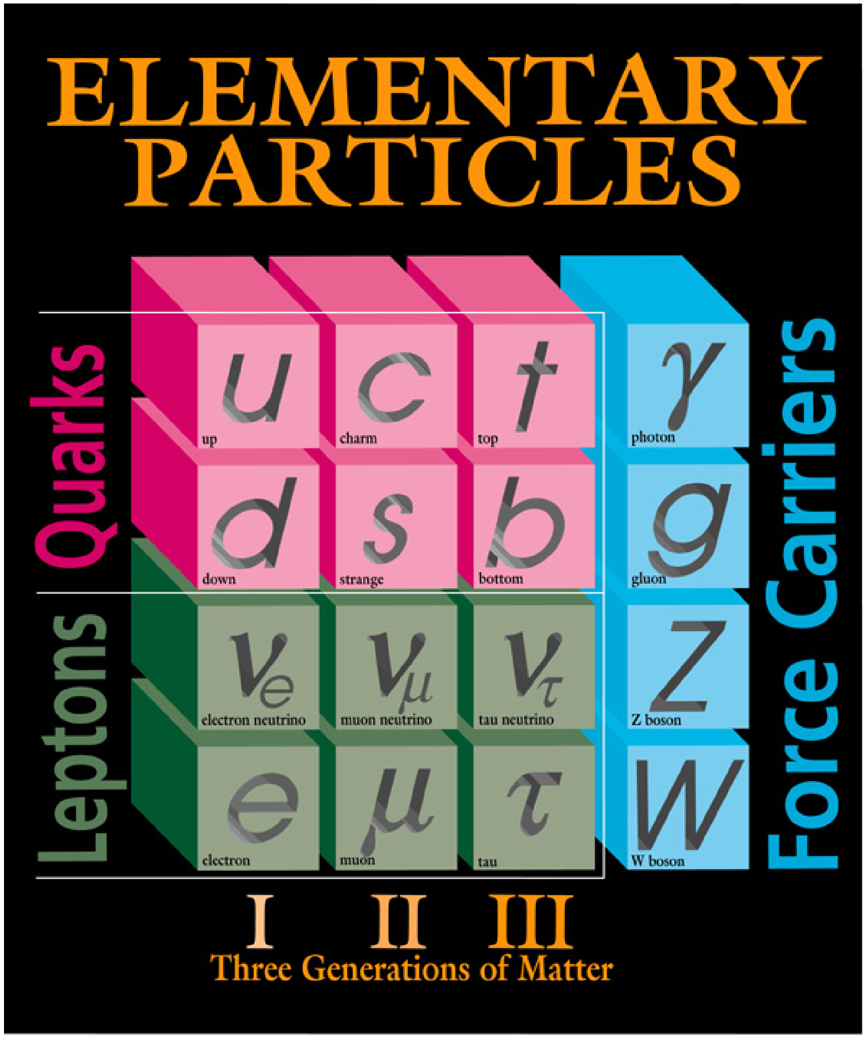

	I	II	III	
Quarks	u up	c charm	t top	γ photon
Quarks	d down	s strange	b bottom	g gluon
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
Leptons	e electron	μ muon	τ tau	W W boson

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u and d quarks make up the proton and neutron, held together by strong force (gluons).

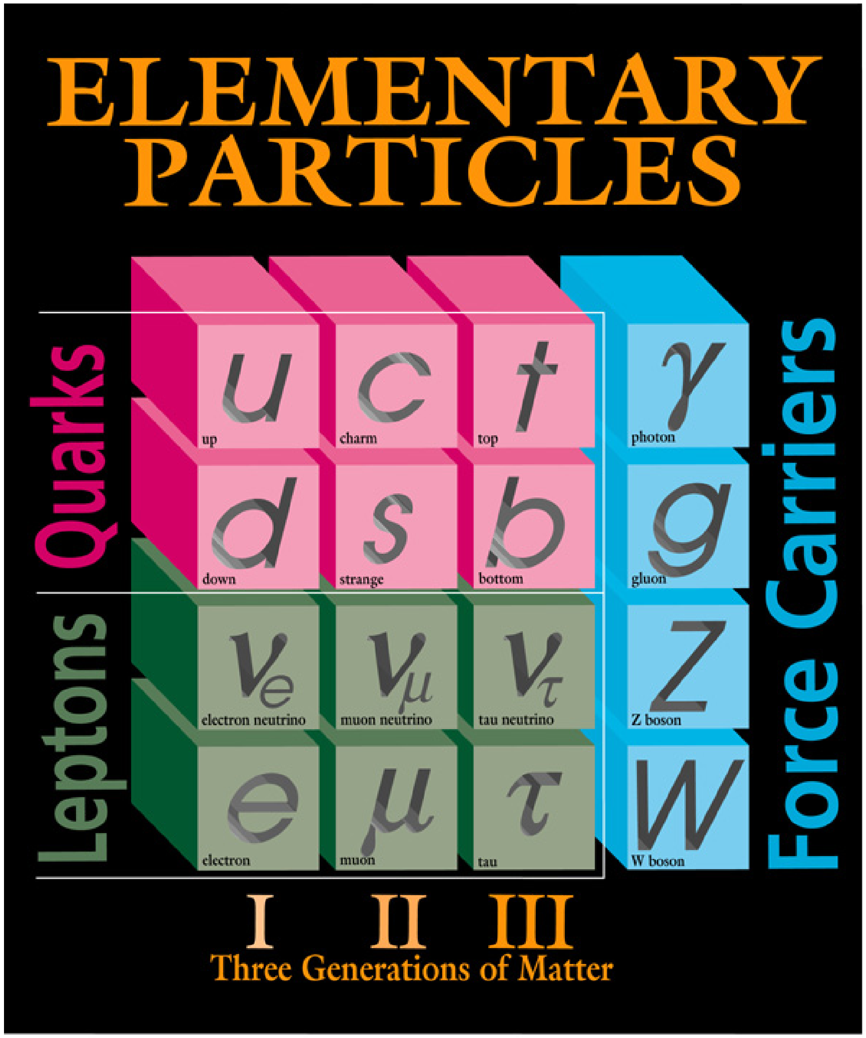
Protons and neutrons make up atomic nuclei.

Nuclei plus electrons make up atoms, held together by electromagnetic force (photons).

Weak interactions (W boson) change $u \leftrightarrow d$ and $e \leftrightarrow \nu_e$; Z boson is "partner" of W.

Each of these matter particles has two heavier "siblings".

We know a lot about the structure of matter.



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I want to talk about:

- what we know we don't know,

- what we think might be out there,

- how we're trying to find out,

- and why theory and experiment go hand-in-hand.

This will be an incomplete sampling of topics that I am fond of.

Outline:

The origin of mass

why we worry, and how we can find out

Dark matter

evidence from gravity, searches for particles

Particle physics phenomenology

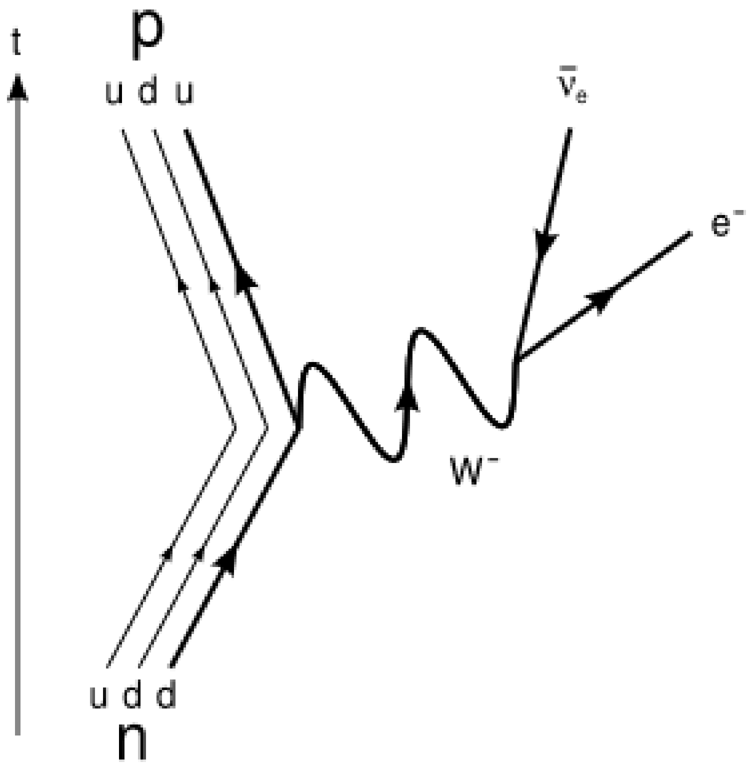
what it is and what it's good for

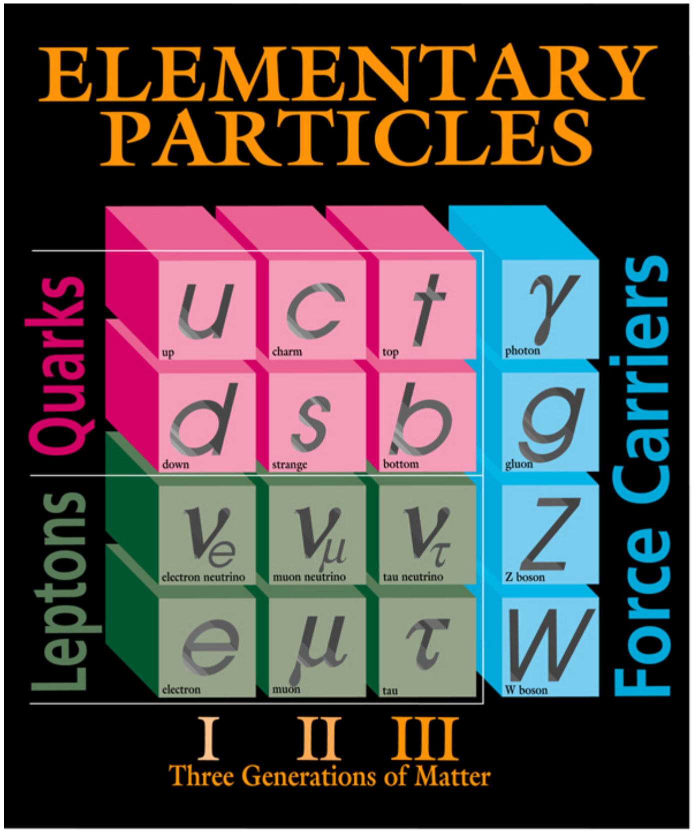
The origin of mass

Despite what you may have heard, there is nothing intrinsically “wrong” with particles just having mass by themselves.

The reason we have a “mystery of mass” in the Standard Model is because of a weird feature of the weak interactions.

Weak interactions are responsible, e.g., for nuclear beta decay.





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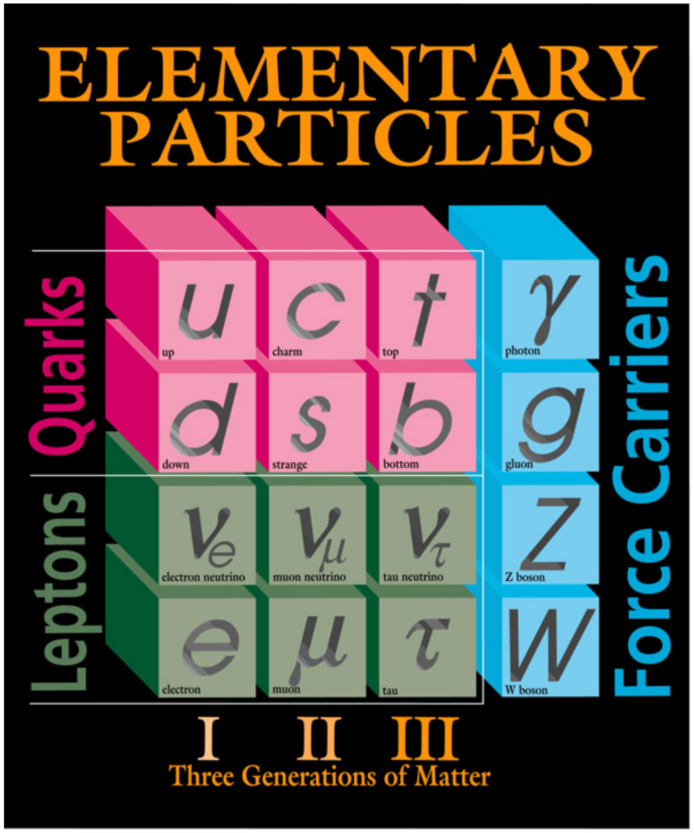
The force carriers are the charged W^+ and W^- bosons and the neutral Z boson.

To describe the problem with weak interactions, I need to introduce the spin of quarks and leptons, and what we know from experiment about how the weak interaction talks to them.



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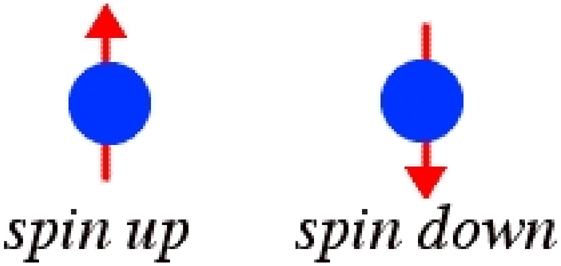
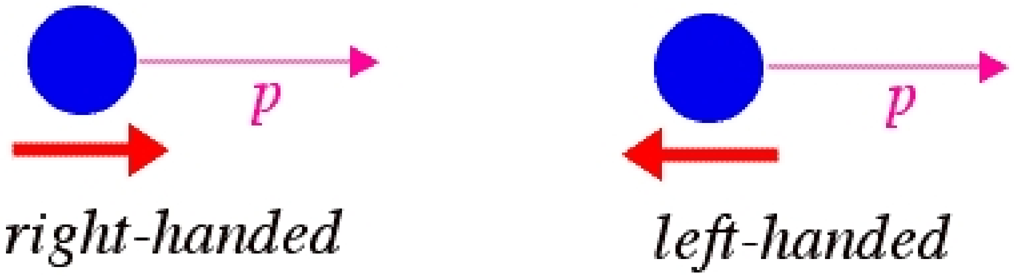
Standard Model matter particles are fermions: spin-1/2.



For fast-moving particles, it's convenient to quantize spin along direction of motion: these are called helicity states.



Can transform a right-handed particle into a left-handed particle (in your reference frame) by running faster than it:

(This is only possible for particles with nonzero mass. Massless particles move at the speed of light: can't run faster than them, so the two helicity states are physically distinct.)

So what's the problem?

Weak interactions treat left-handed and right-handed particles differently!

- $W^{\pm}$ bosons couple only to left-handed fermions
- Z bosons couple with different strengths to left- and right-handed fermions

This "handedness" is called parity violation (discovered in the weak interactions in 1957).

This would be like the charge of the electron being different depending on which reference frame you look at it from—impossible!

The only solution is for the quarks and leptons to be massless, so that the left- and right-handed fermions are distinct particles.

How can we account for the measured masses of the quarks and leptons?

Need to find a way for a fermion to “dump its excess weak charge” when you boost past it.

This is actually possible if the vacuum is filled with a sea of weak-charged stuff: we call this the Higgs field.

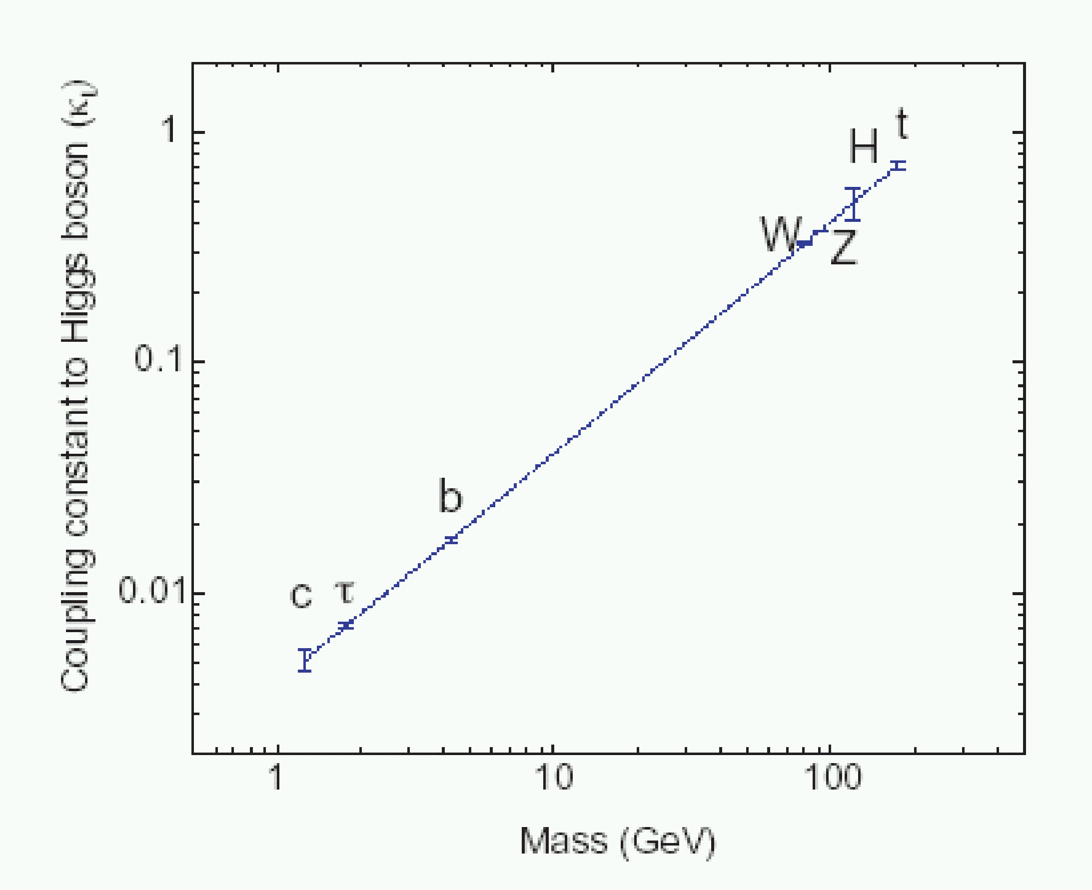
Can write down a mathematically-concrete theory involving this new “Higgs field” that accounts for the masses of the quarks and leptons and the W and Z bosons while still preserving weak interactions as a proper theory.

So how do we test it?

The Higgs mechanism makes two big predictions:

1) Vibrations of the Higgs field correspond to a physical particle: the Higgs boson.

2) The mass of a quark or lepton or W or Z is proportional to how strongly it interacts with the Higgs field, and hence with the Higgs boson.



Test the Higgs mechanism by:

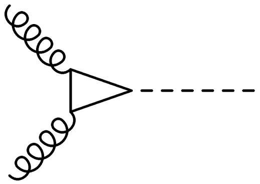
1) discovering the Higgs

and

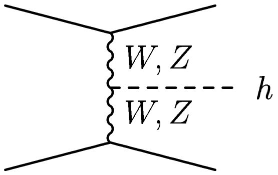
2) measuring its couplings to other particles.

Higgs production rates are controlled by Higgs couplings to Standard Model particles.

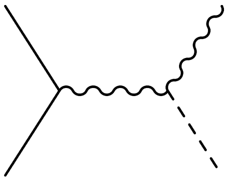
- Gluon fusion, $gg \to H$



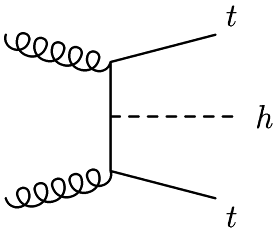
- Weak boson fusion, $qq \to Hqq$

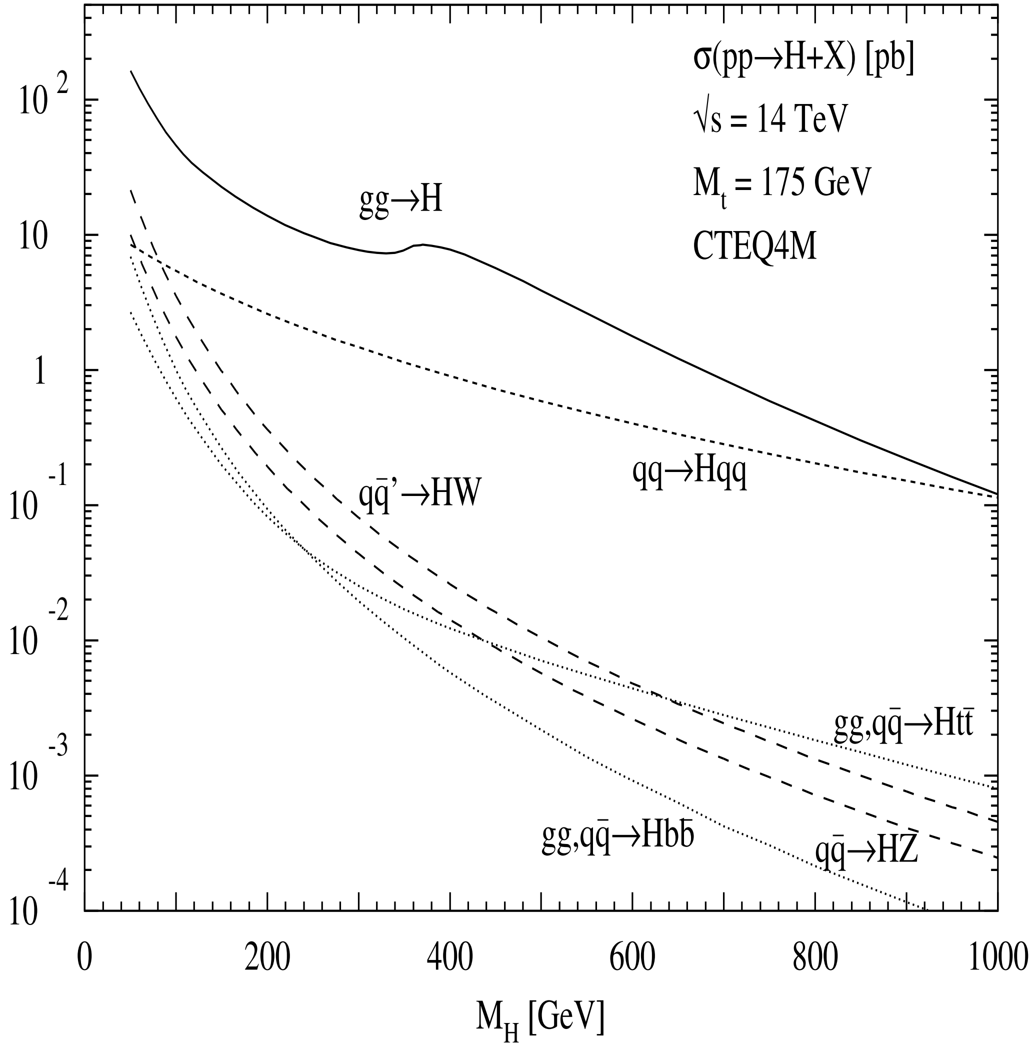


- WH, ZH associated production



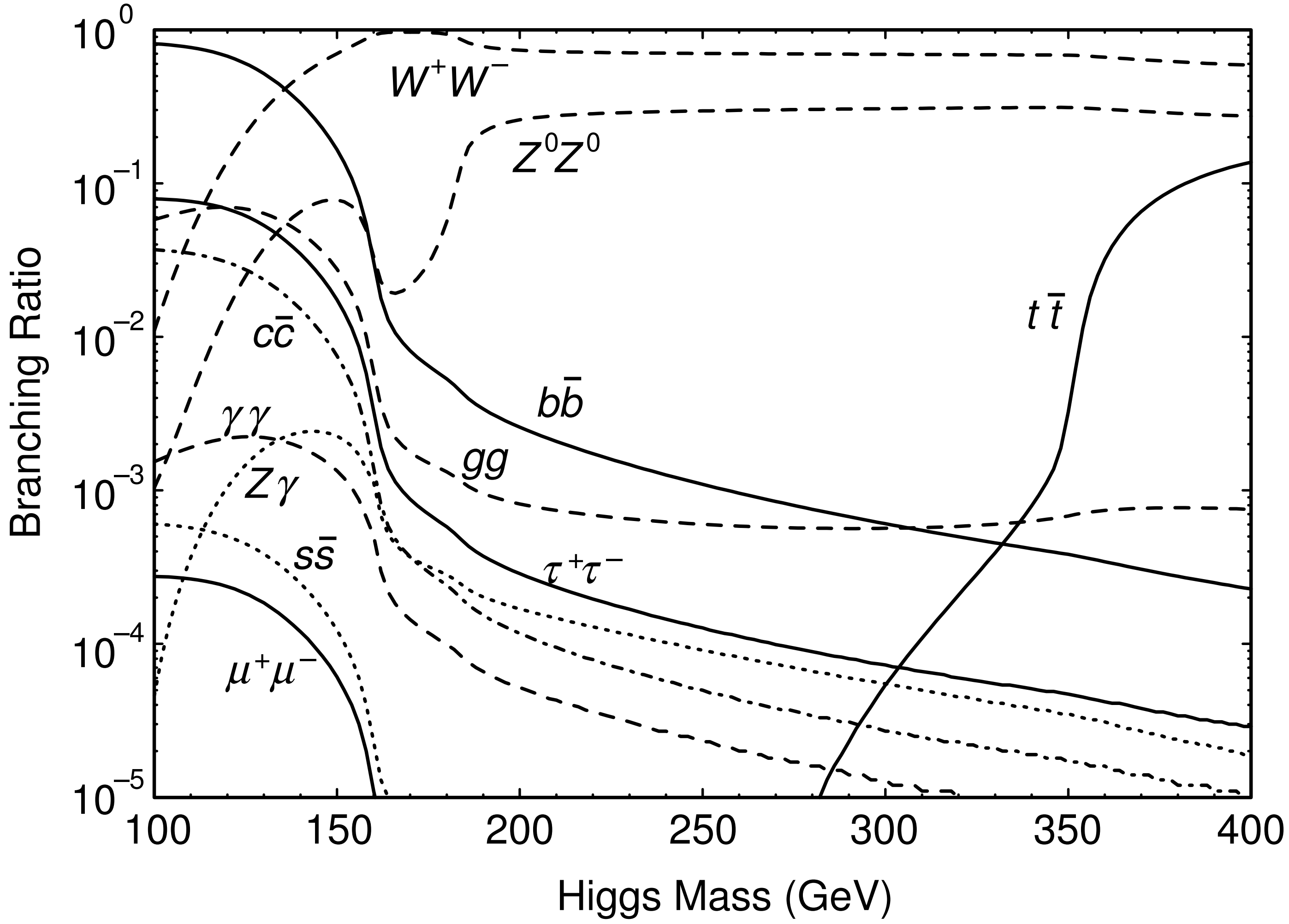
- ttH associated production





M. Spira, Fortsch. Phys. 46, 203 (1998)

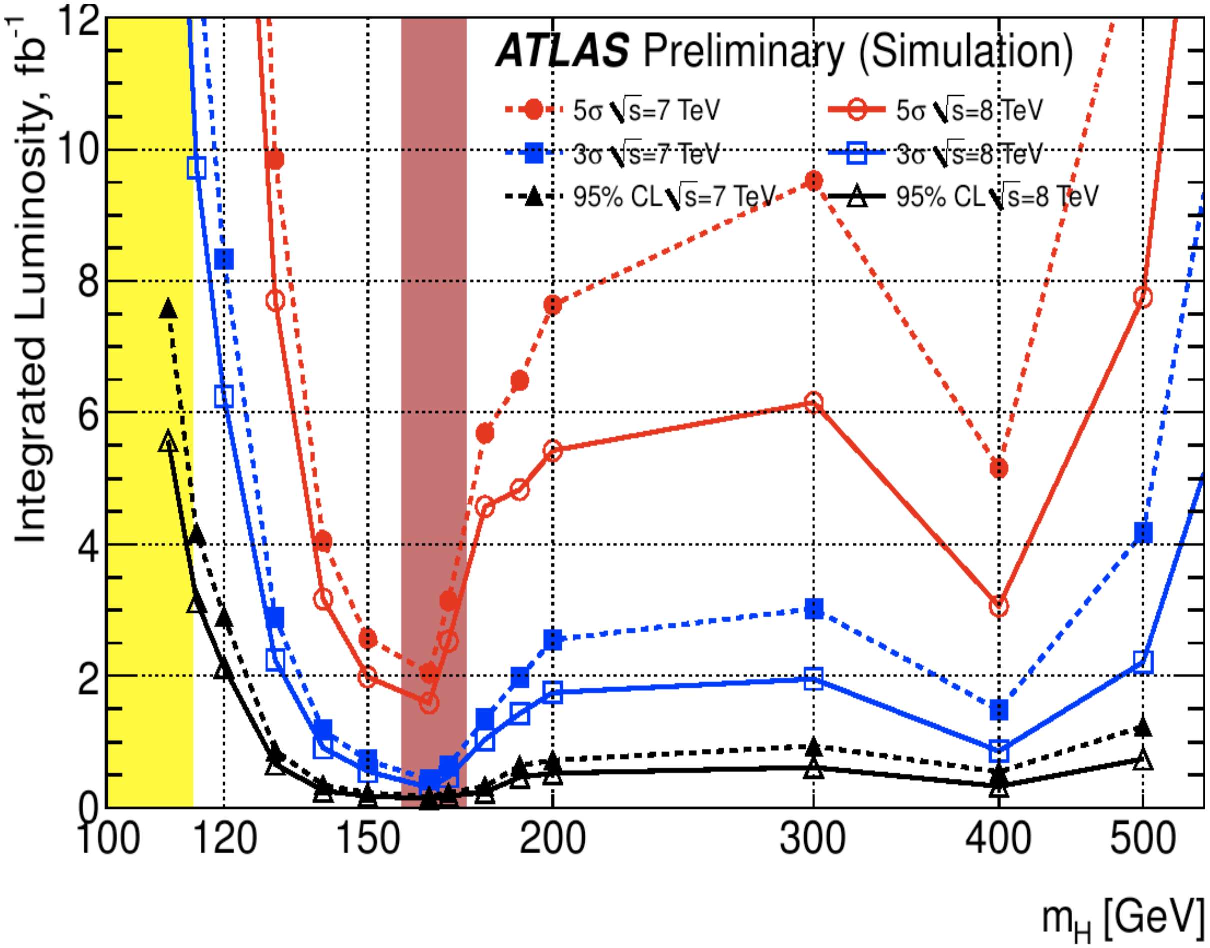
Higgs decay rates are controlled by Higgs couplings to Standard Model particles.



HDECAY

Decay modes depend on Higgs mass.

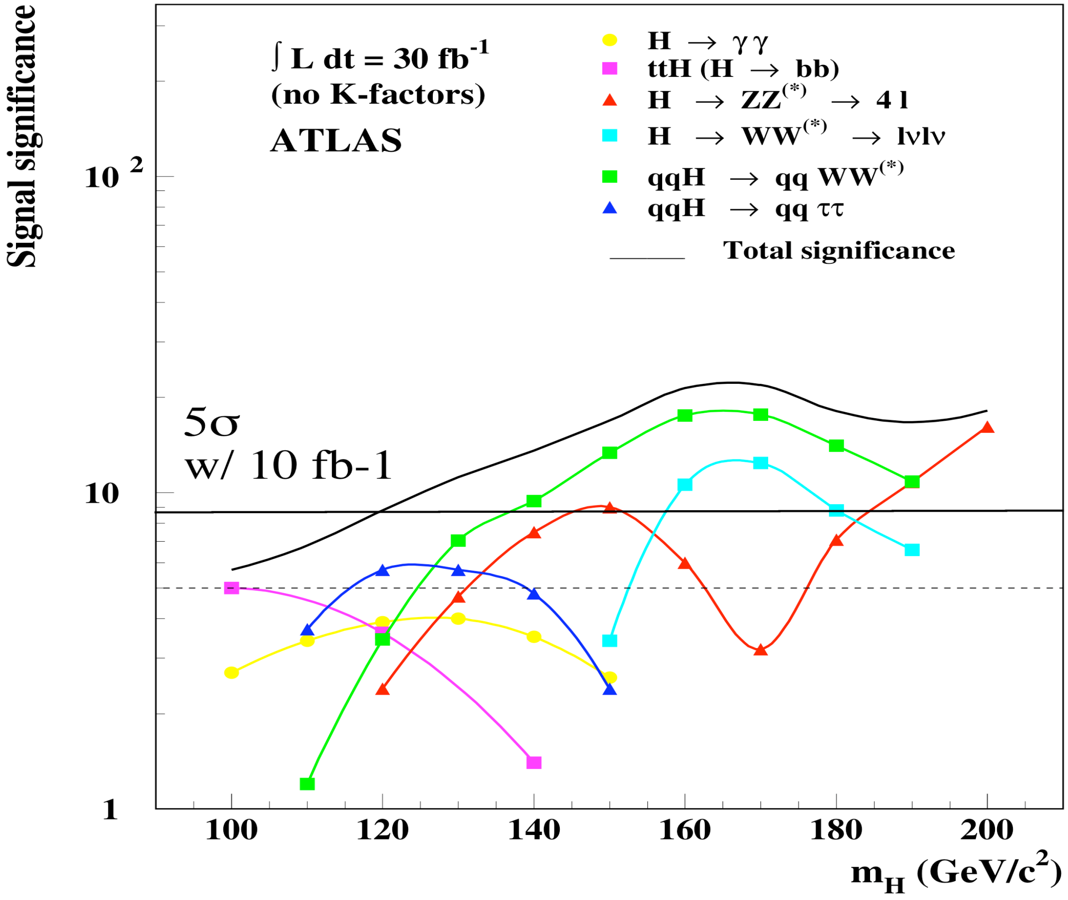
The LHC was built to do this (among other things)!



ATLAS collaboration, Jan 2011

2011-12 run: 7 TeV (dashed lines); hope to collect as much as 5 fb^{-1}. Good prospects for discovery or at least 3σ evidence over much of the allowed mass range!

Production rate × decay branching fraction = signal rate.



(Warning: old plot)

Dashed line is 5-sigma discovery after first 3 years of LHC running.

Already know that $m_H > 114$ GeV.

S. Asai et al., Eur. Phys. J. C 32S2, 19 (2004)

LHC will discover the Higgs if its couplings are as predicted.
Measure signal rates → test the pattern of Higgs couplings.

Dark matter

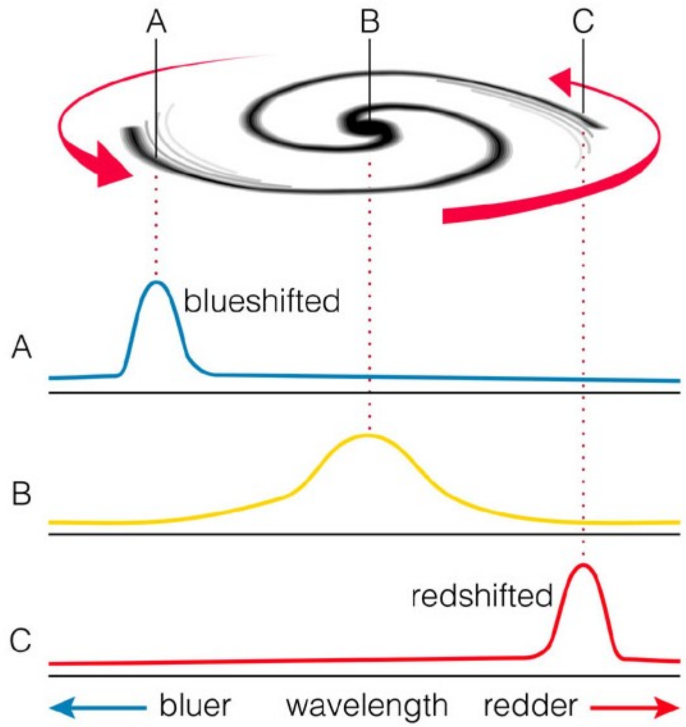
The observational evidence for dark matter dates back to the 1930s(!!).

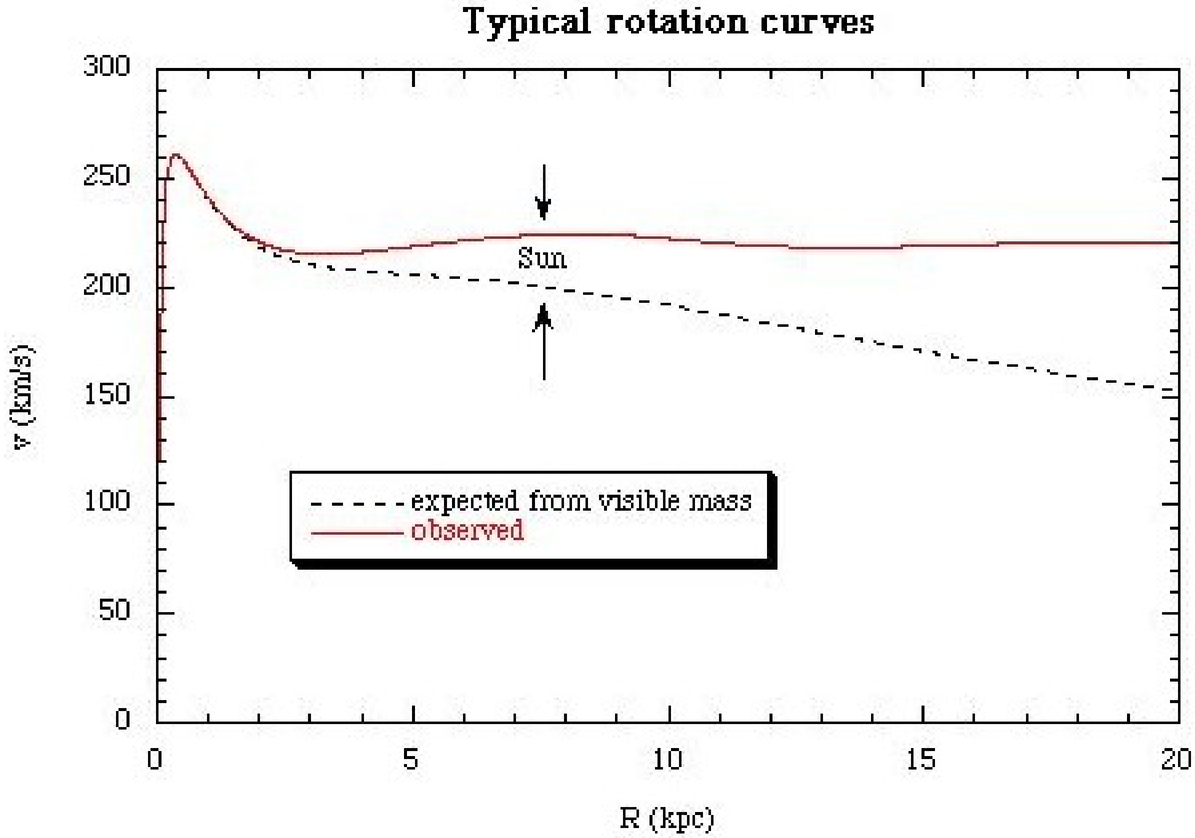
But it was only recently that the evidence sharpened enough to tell us that new particle physics is needed.

Zwicky 1933

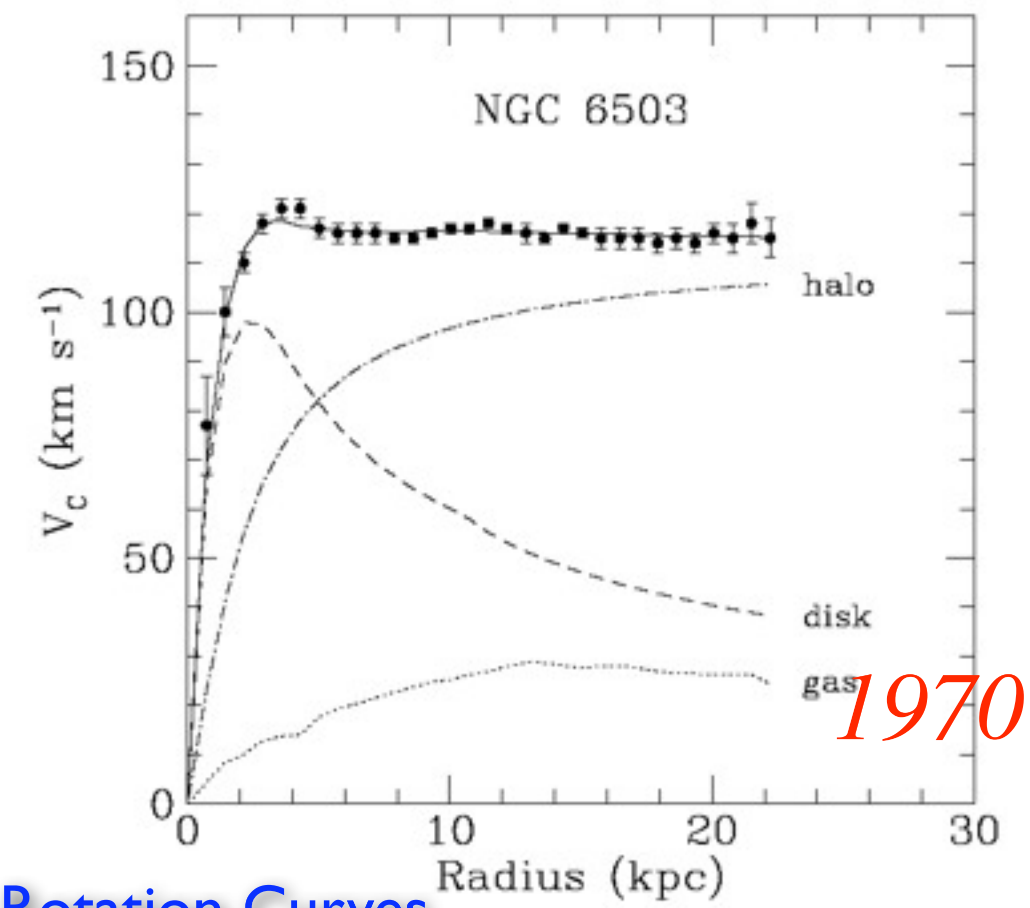
Galaxies in clusters moving too fast to be gravitationally bound if the only mass is what you extrapolate from the starlight.

Speed of outer stars orbiting a galaxy should be like outer planets orbiting the sun: depends on total mass “inward” from the star.





Rotation Curves

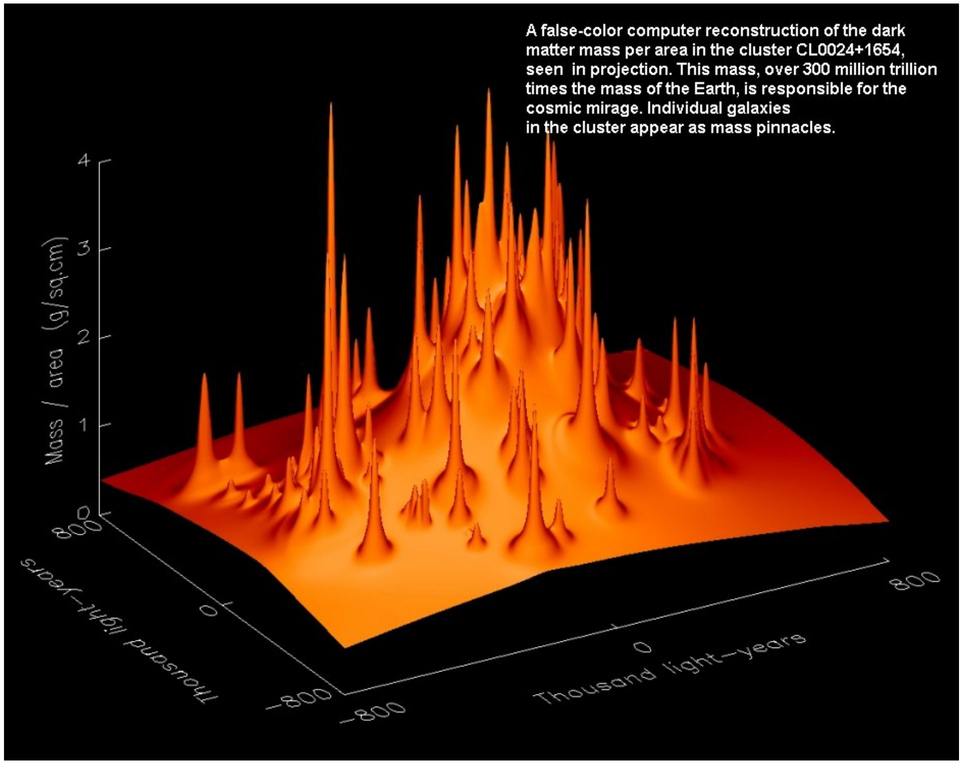


1970

Rubin 1970

Have to hypothesize an unseen “halo” of extra matter (so called because it should be spherical, not disc-shaped) in each galaxy.

Modern techniques allow for more precise measurements of mass distribution in galaxy clusters.



A false-color computer reconstruction of the dark matter mass per area in the cluster CL0024+1654, seen in projection. This mass, over 300 million trillion times the mass of the Earth, is responsible for the cosmic mirage. Individual galaxies in the cluster appear as mass pinnacles.

Weak gravitational lensing (of light from farther-away galaxies) allows reconstruction of actual gravitating matter profile.

Looks like there's something extra out there. What could it be?

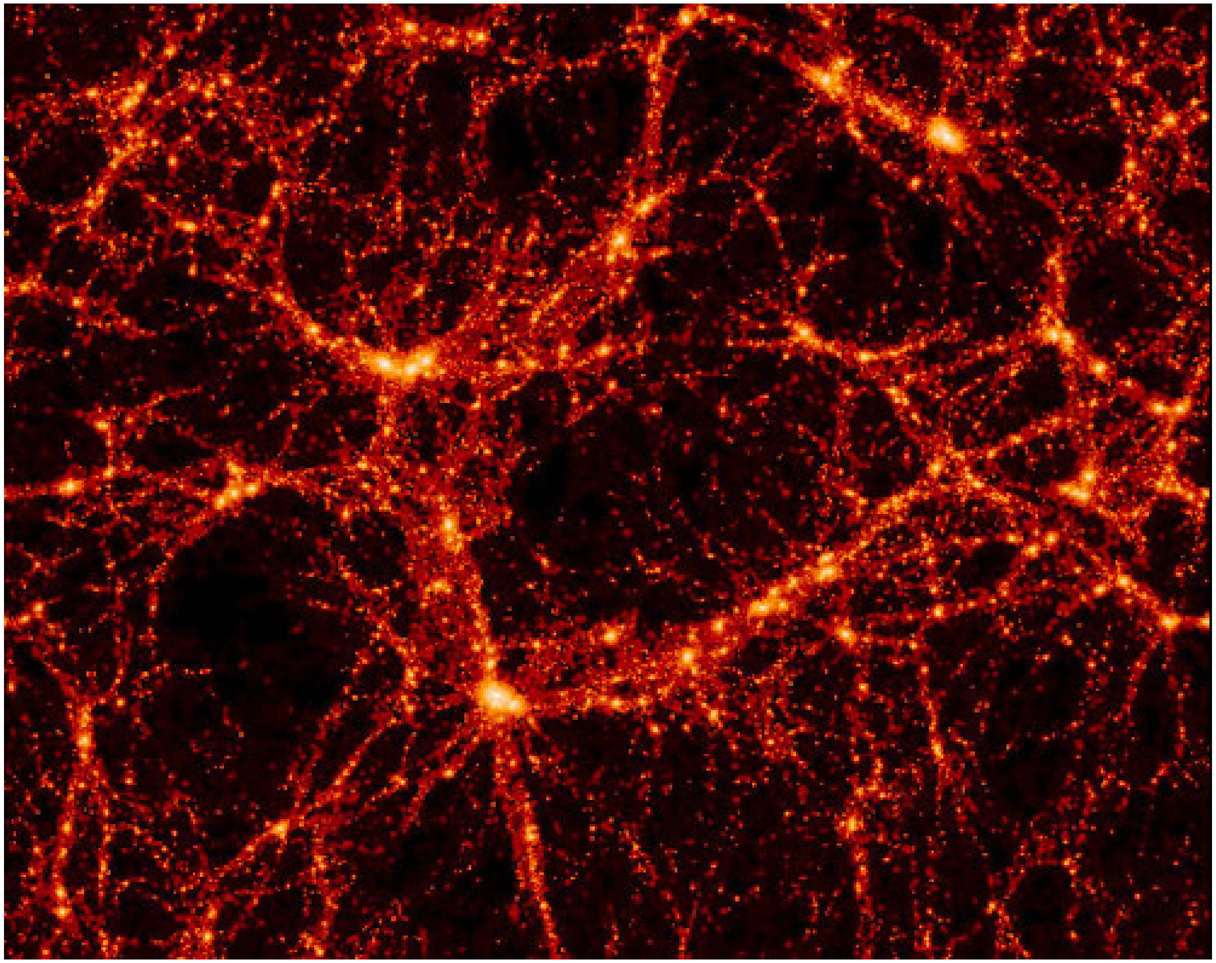
- Neutrinos?

- Brown-dwarf stars or large gas-giant planets?

- A modification of gravity at very low accelerations?

- A brand new kind of particle?

Neutrinos are quite light; they would be moving very fast. Inconsistent with observed clumpiness of the universe at very large scales.



Virgo Consortium, 1998

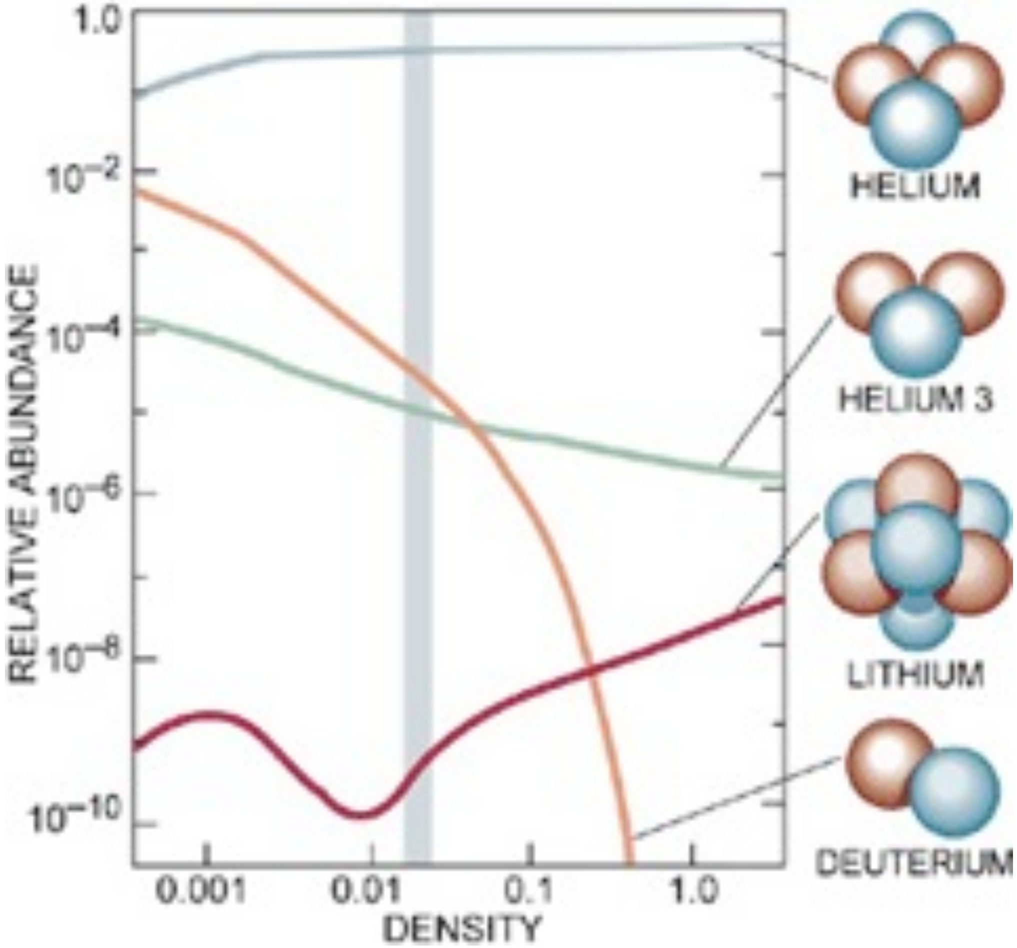
Can search for brown-dwarf stars / large gas-giant planets in our galactic halo:

- stare at the stars in one of our small satellite galaxies

- look for transitory brightening due to gravitational microlensing by a brown-dwarf star

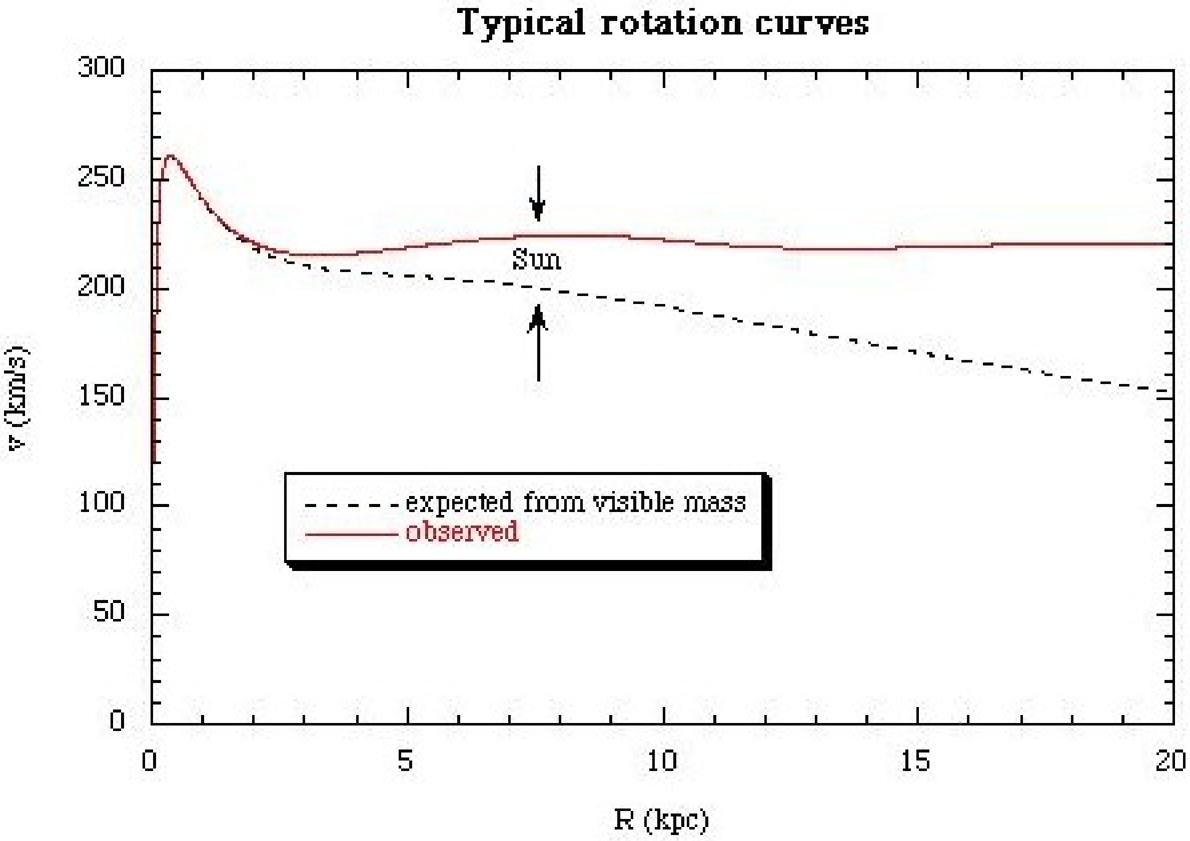
Search done in the early '90s: found a few, but far too few to make up the dark matter.

Also, we now know from the elements produced in the Big Bang that there cannot have been enough baryons (protons + neutrons) around to make up the dark matter.



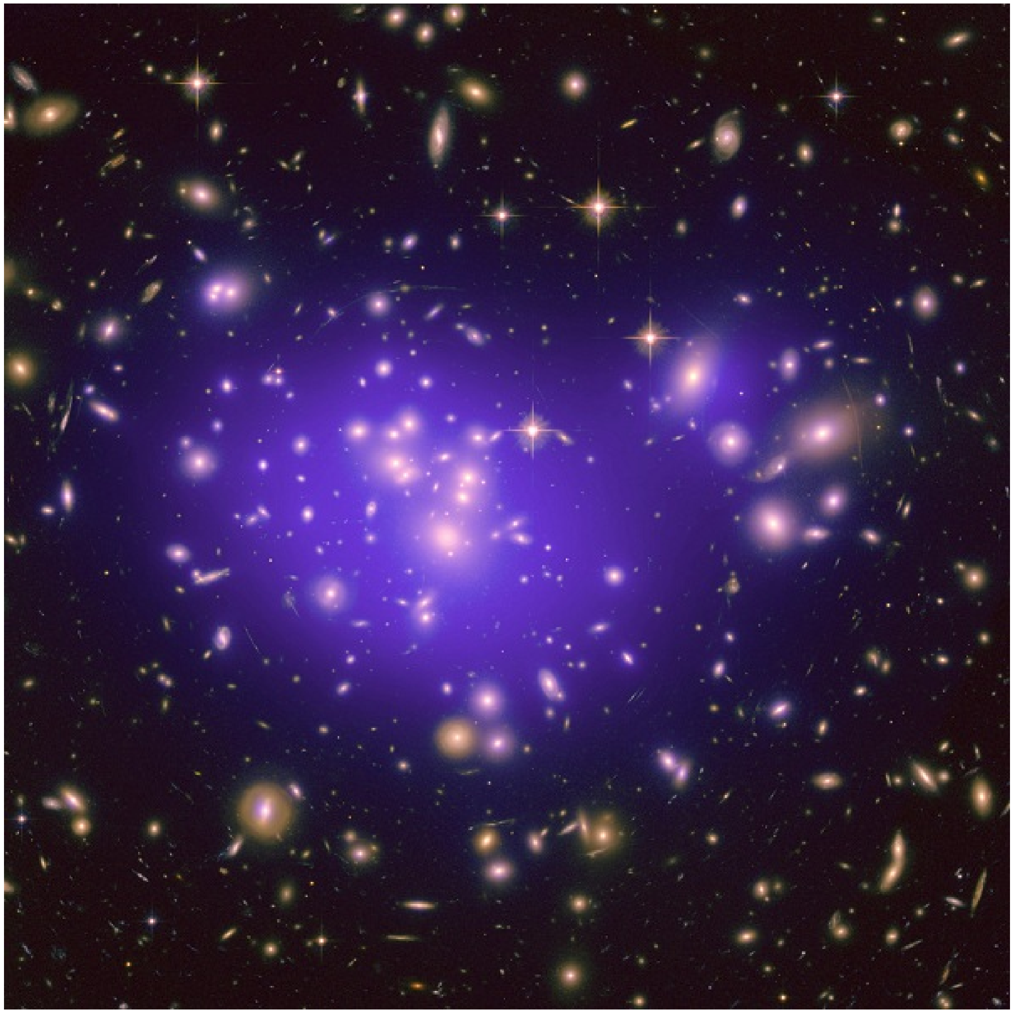
Need about 6 times as much mass in dark matter as there is in baryons.

What about a modification of gravity?



Gravitational force law never before tested in these environments.
This would be spectacular new physics!

Idea: the ordinary matter gravitates stronger than expected at very large distances.

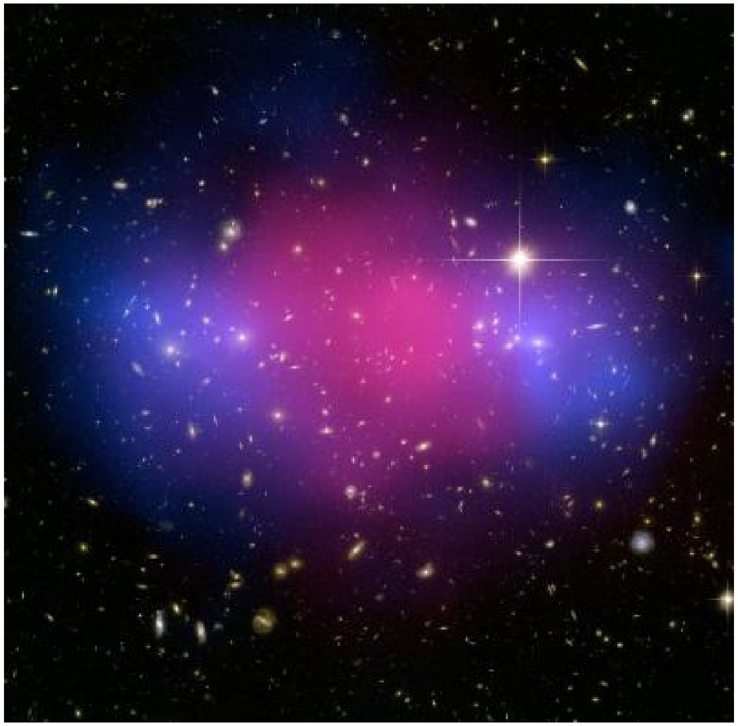


Get "dark matter" effect from ordinary baryonic matter in galaxy, cluster, etc.

How can we distinguish this possibility from extra new mass?

Answer: displace most of the mass of the cluster by smashing it into another cluster!

Bullet cluster



MACS J0025

Pink – hot gas via x-ray emission (Chandra)

Blue – mass density as reconstructed from gravitational lensing (Hubble)

Modified gravity is basically dead (as a dark matter explanation).

Looks like there's something extra out there. What could it be?

- Neutrinos? ✗

- Brown-dwarf stars or large gas-giant planets? ✗

- A modification of gravity at very low accelerations? ✗

- A brand new kind of particle? ← !!

If the dark matter is a new kind of particle, it has to have the following properties:

- Electrically neutral

otherwise it would scatter light, and would not be “dark”

- Stable

has to have stuck around since the birth of the universe

We also need it to be:

- “Cold”

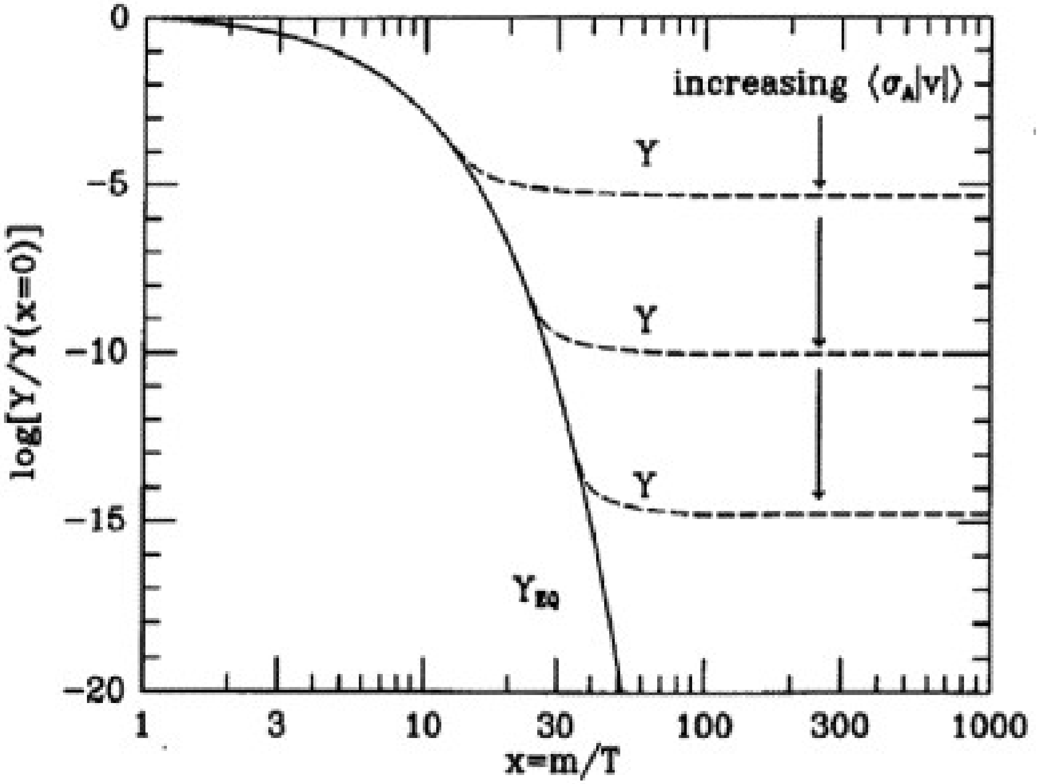
must be non-relativistic—requirement from the large-scale structure of the universe

- Must have the right “relic density”

we know there is about 6 times as much mass density in dark matter as in ordinary matter

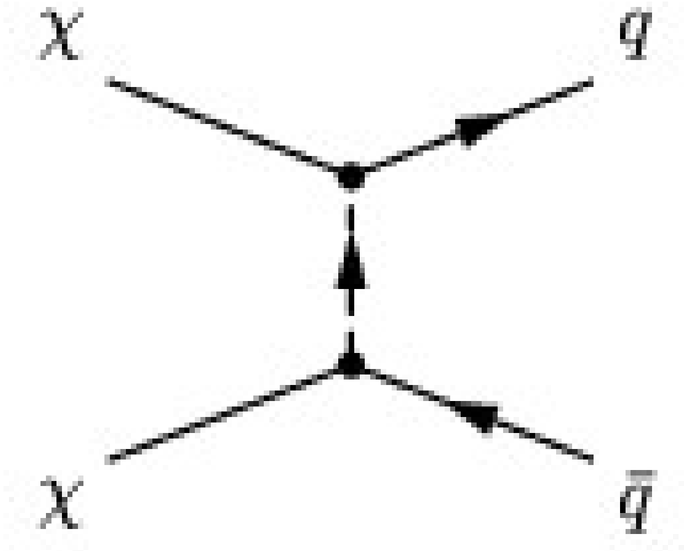
If the dark matter interacts with ordinary matter, it would have been produced in the hot soup of the Big Bang.

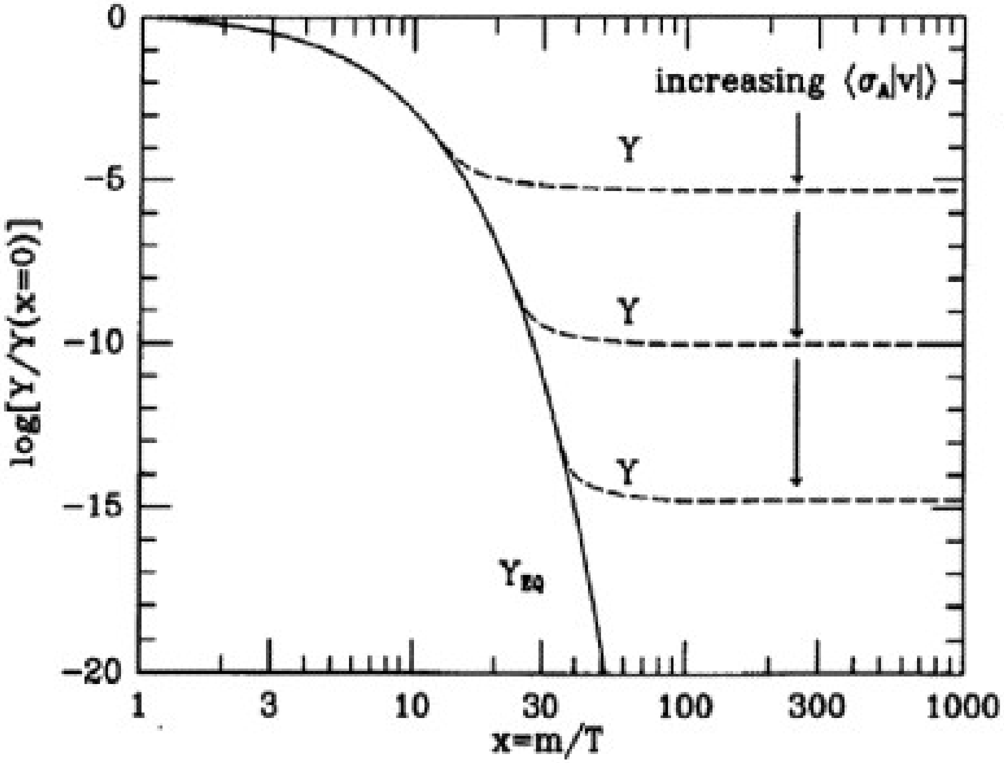
As the temperature dropped, dark matter particles would annihilate away... till they became too sparse to find one another!



The left-over "relic density" depends on how strongly they interact with each other.

Dark matter annihilation process:





Annihilation strength comes out about right if the interaction is about as strong as weak interactions and the mass is about as heavy as the W or Z boson.

Weakly Interacting Massive Particle (WIMP) dark matter!

Caveat: this is not the only possibility.

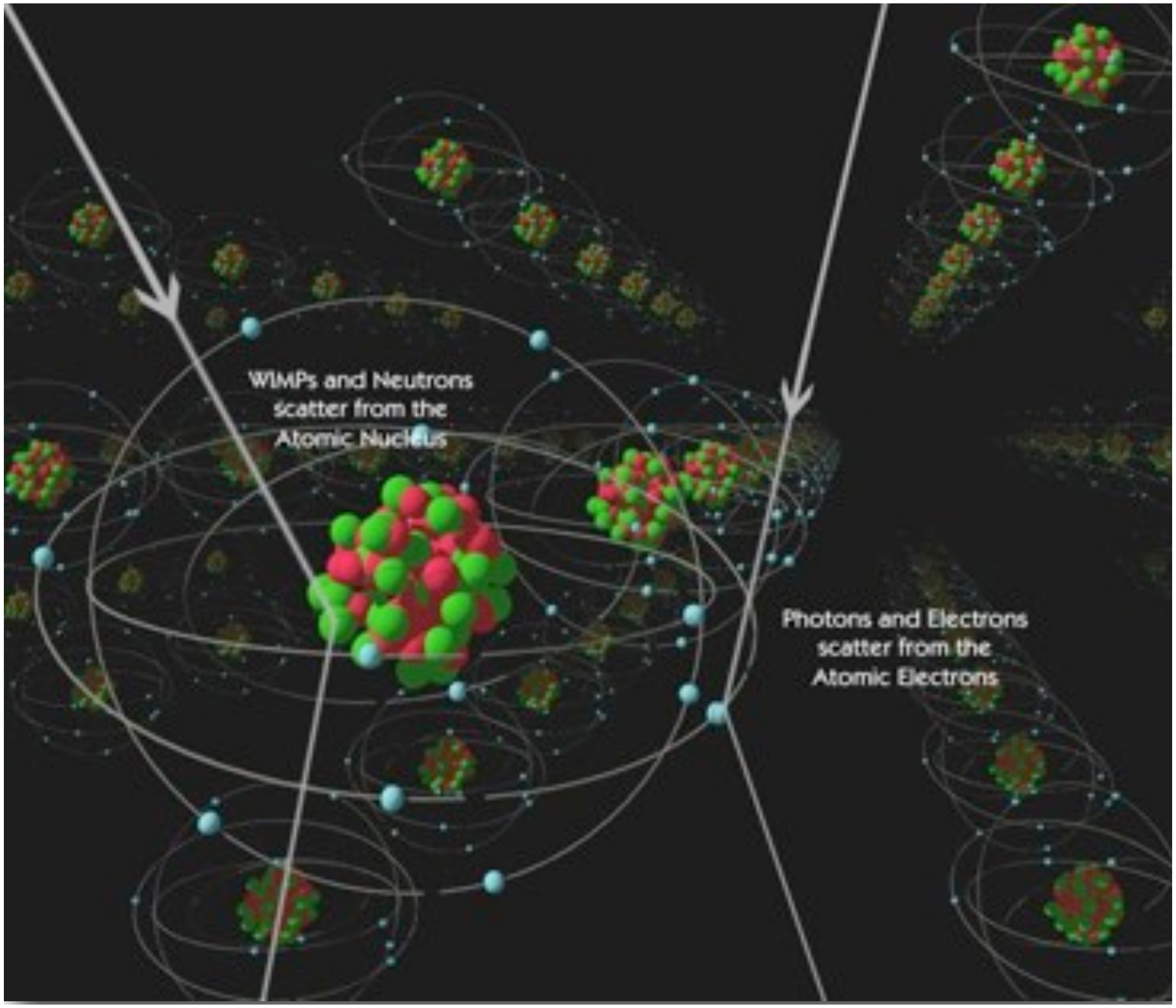
How can we detect the dark matter?

Direct: dark matter hitting a detector
- detect the recoil of the atoms in the detector

Indirect: dark matter annihilates into visible particles
- Gamma rays from the galactic centre
- Neutrinos from the sun

Collider: produce the dark matter particles in the lab
- LHC!

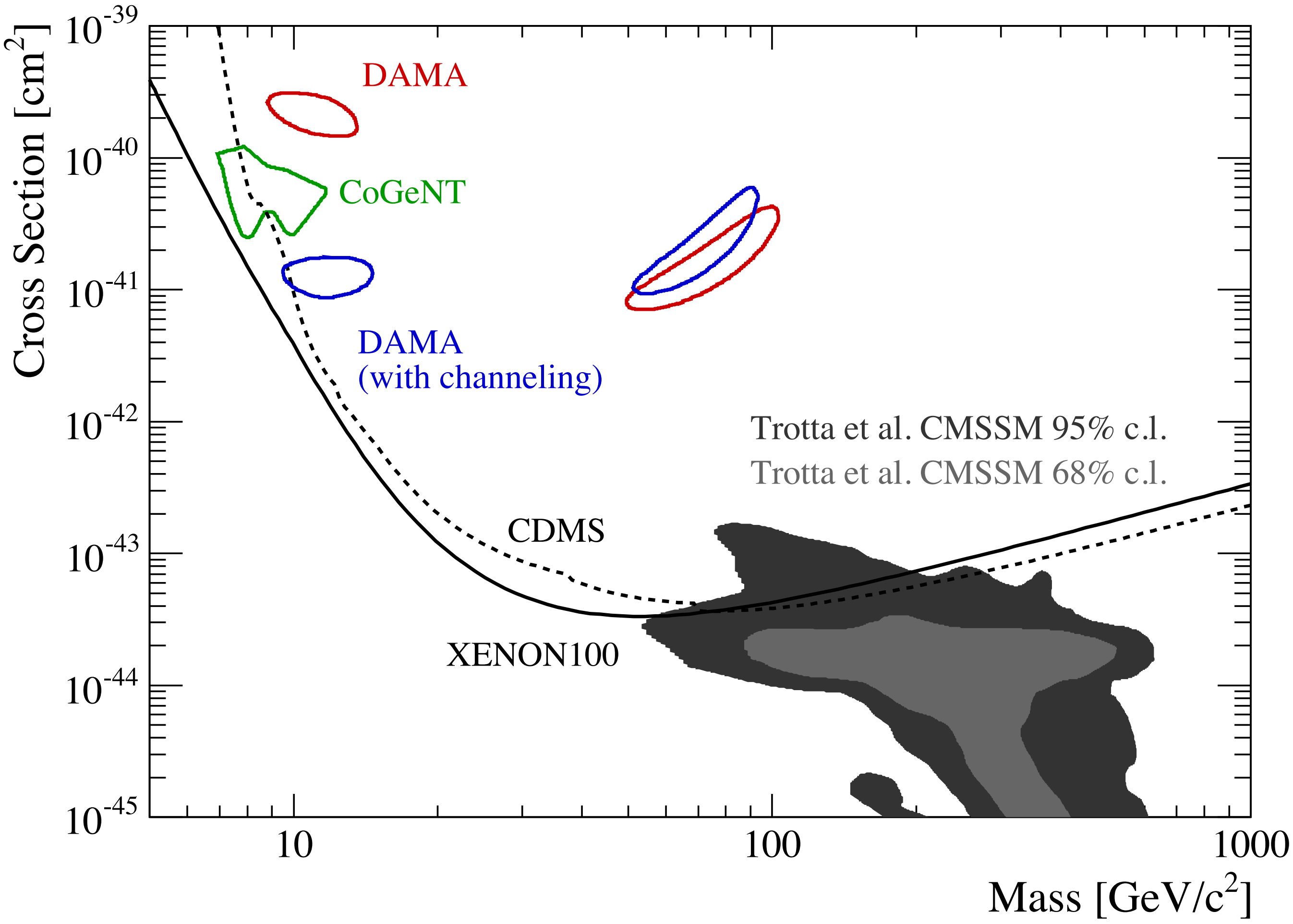
Direct detection of WIMPs: look for the recoil of an atomic nucleus struck by a WIMP



One experiment: Cryogenic Dark Matter Search (there are many others)

CDMS detector. Operates at 40 mK

So far no (unequivocal) discovery; only exclusion limits.



But cutting more and more into the “favoured” parameter space of popular models like supersymmetry.

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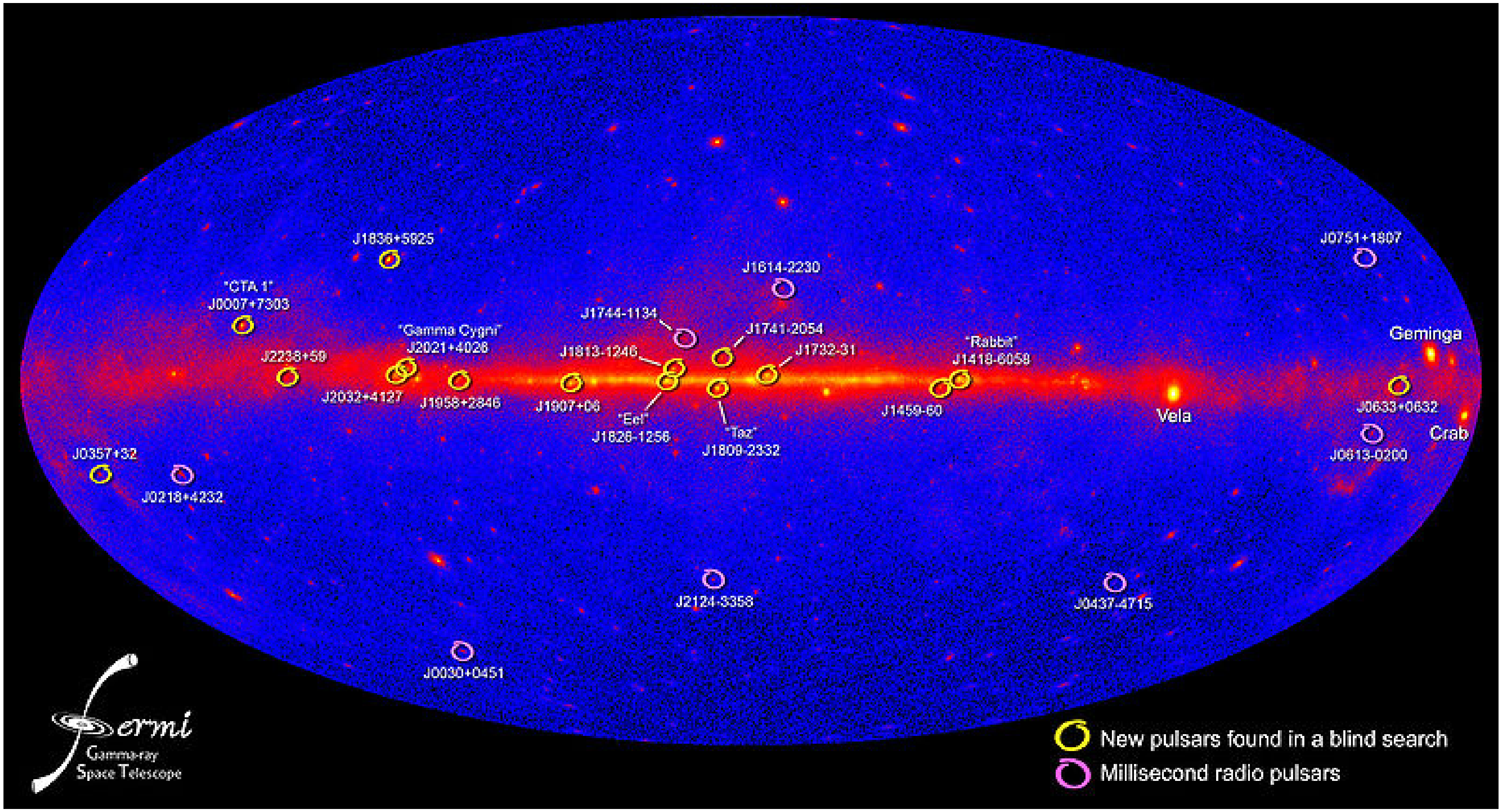
Where the density of dark matter particles is high, they can meet each other and annihilate into more-easily-detected particles.

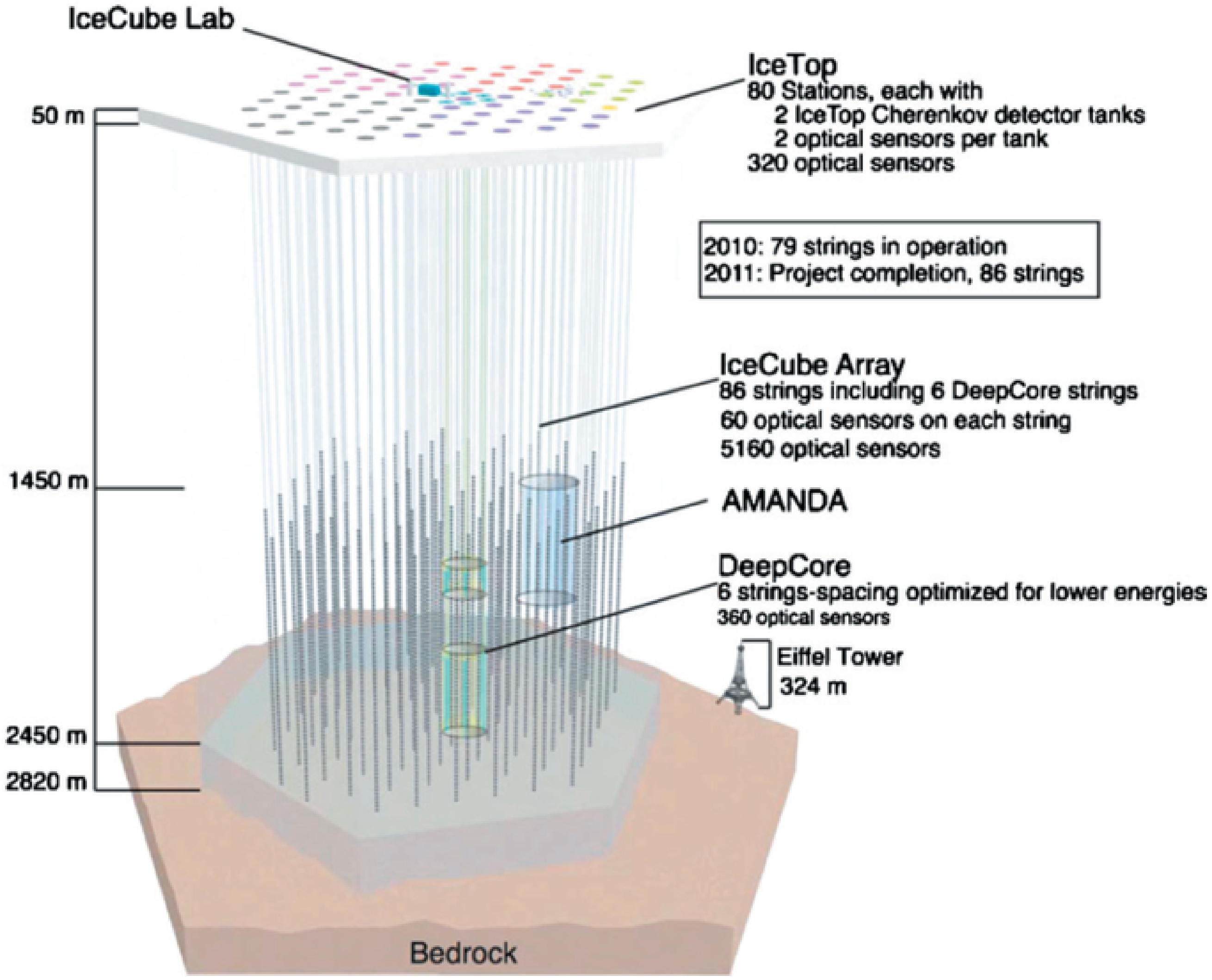
- Galactic centre: look for gamma rays

- WIMPs gravitationally captured in the sun: look for neutrinos

Fermi Gamma-ray Space Telescope (in orbit since 2008) looking at gamma rays from space.
Need a “long exposure” to try to see dark-matter annihilation gamma rays from galactic centre, other neighbouring galaxies.



IceCube Neutrino Observatory, at the South Pole.
Look for high energy neutrinos from dark matter annihilation inside the sun.



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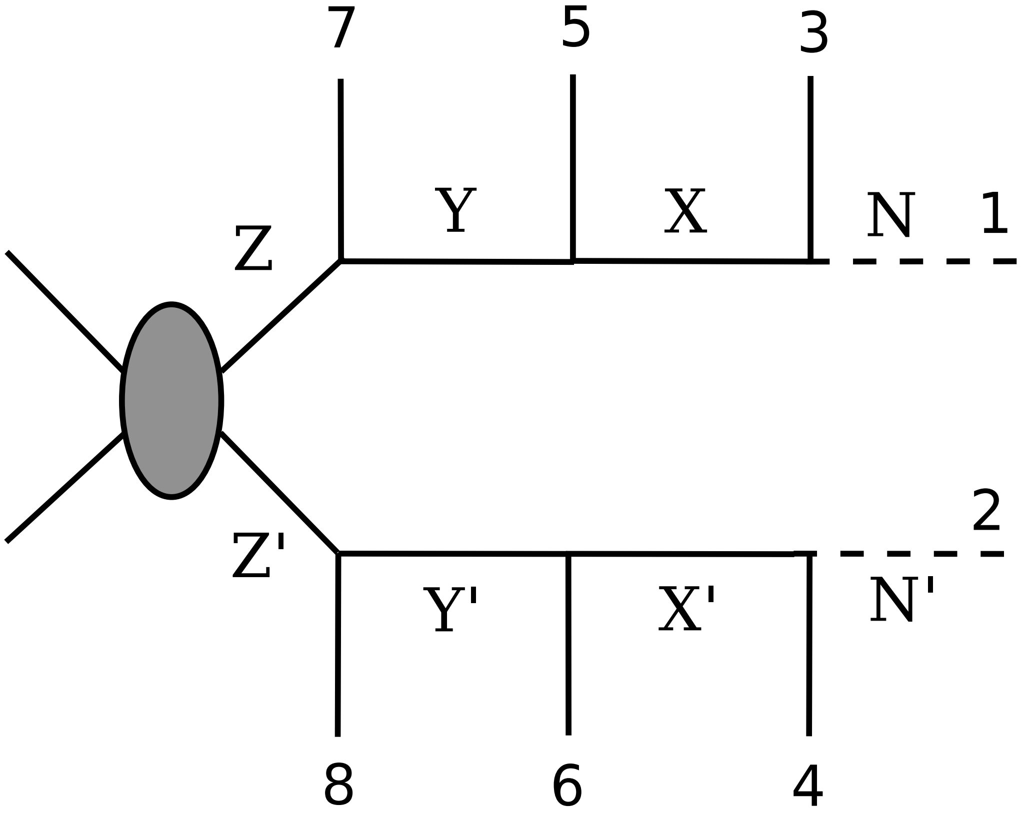
Collider: produce the dark matter particles in the lab

- LHC!

When we try to construct a coherent theory for dark matter, there are usually other particles involved.

- Produce new particles at the LHC
- They decay into familiar particles plus WIMPs
- Detect the WIMPs by seeing a momentum imbalance



This is a major part of the LHC physics program.

Ultimate aim: measure properties of WIMP in the lab and match them to production rate in early universe and direct/indirect detection processes!

Particle physics phenomenology

What is phenomenology?

Philosophy:
the study of what we experience subjectively as consciousness

Disclaimer: I am not a philosopher

Particle physics:
the analyses or calculations that connect theory to concrete experimental predictions

Particle interactions are fundamentally quantum-mechanical.

Cannot predict what will come out from any particular particle collision.

But, can predict probabilities with great precision.

- Probability distribution is randomly populated by each collision: subject to statistical uncertainties

- Collect enough data to test probabilistic prediction

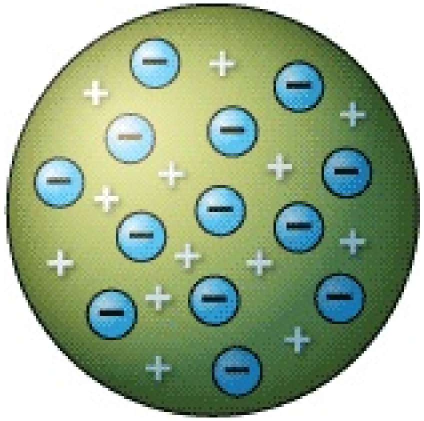
An early example: learning about the structure of the atom

- Atoms have (negatively charged) electrons in them

- Atoms are net neutral

- There must be some positively charged stuff in the atom too.

Plum pudding model (Thomson)

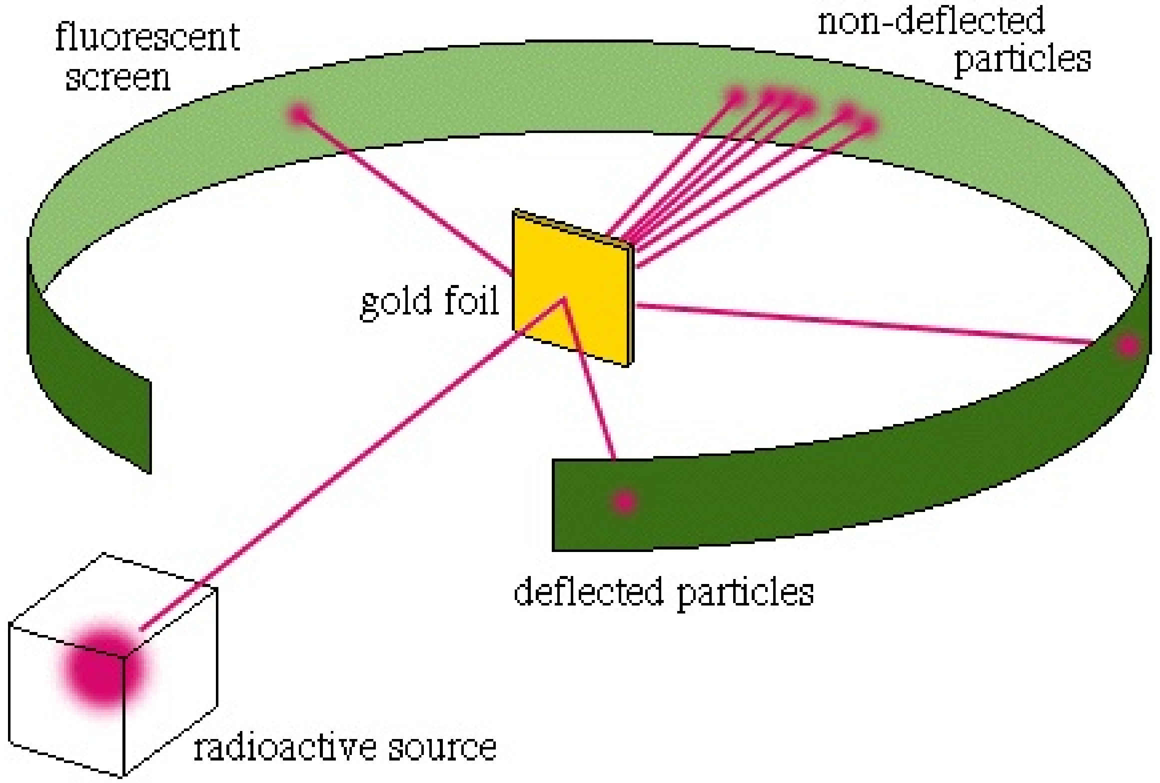


But how do you test this? Atoms are too small to see.

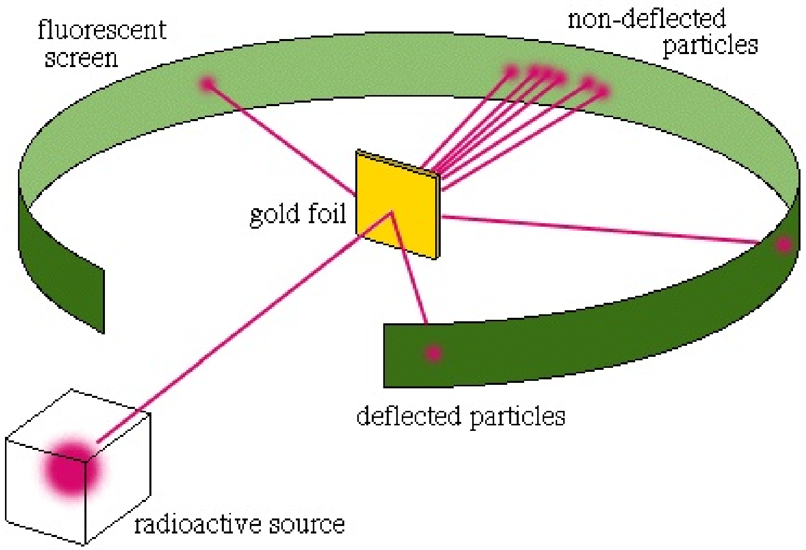
Answer: shoot stuff at it!

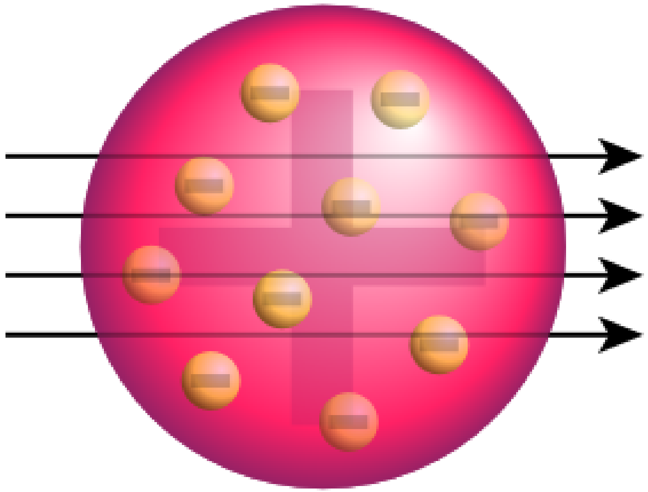
Radioactive elements had been discovered by then: use a source that emits alpha particles.

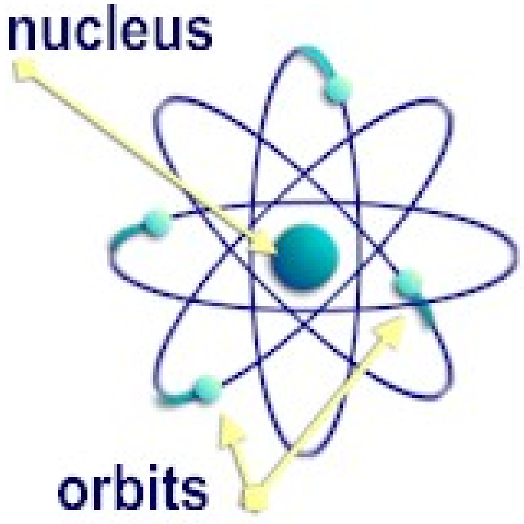
“Rutherford scattering” experiment (done 1909 by Geiger & Marsden, working under Rutherford’s direction)

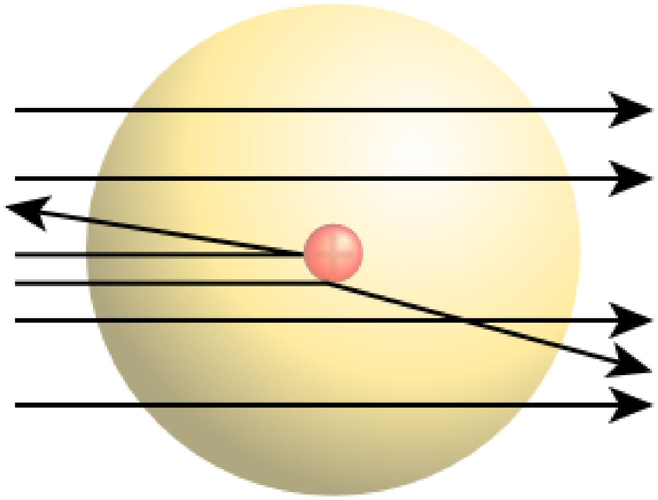


Surprising thing was the large-angle deflections.



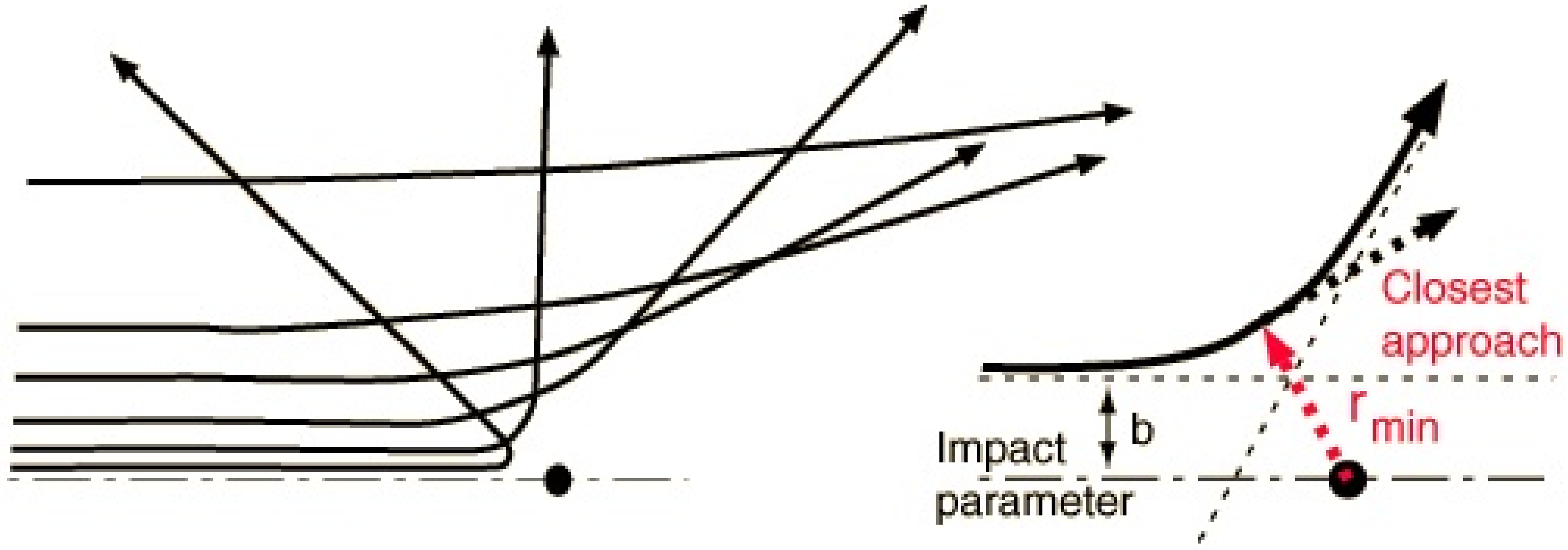


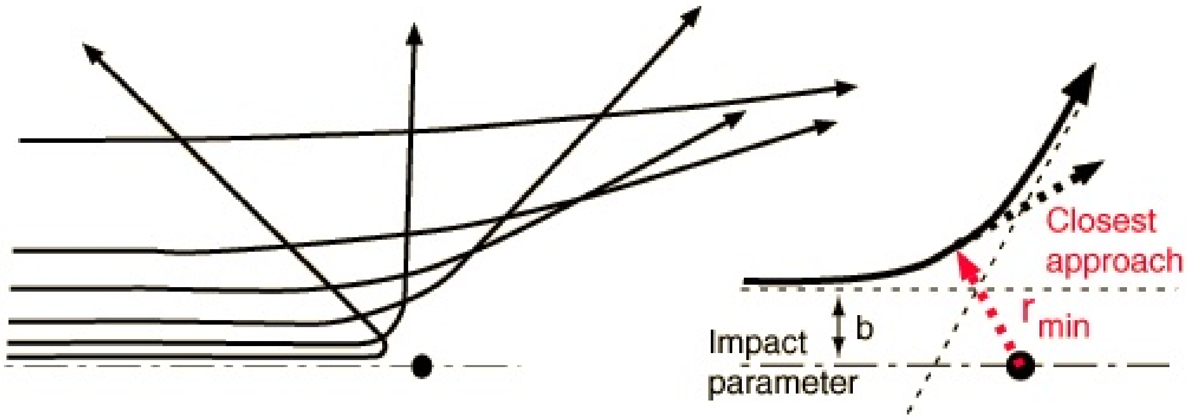




Experiment done 1909, but theoretical interpretation only worked out by Rutherford in 1911.

Understand this using scattering theory: an established idea in classical mechanics.





- Hypothesize the force law from the target:
  Coulomb force in this case, $\vec{F} = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}\hat{r}$
- Pick a value for the "impact parameter"
- Figure out projectile motion using $\vec{F} = m\vec{a}$
- Predict the scattering angle θ

- Average over the impact parameter: gives a "count density" as a function of angle.

- Compare to experiment to test the force law hypothesis!

To make things more general, divide out the number of projectiles per square centimetre per second.

This gives what's called a differential cross section (a function of scattering angle in this case): expected number of events per unit angle per unit incoming beam flux.

- Predicted by the underlying interaction hypothesis
- Can be tested quantitatively in a scattering experiment

This concept is absolutely central in modern particle physics experiments.

Example:
proton + antiproton → W boson → electron + neutrino

- See the electron in the detector

- See a momentum-conservation mismatch from the neutrino (it does not leave a signal in the detector)

- Want to use this to measure the W boson mass

Difficulty: don't know how fast the W is going along the beam direction when it's produced.

Measure a rather esoteric quantity called the "transverse mass" in each event, made up just of the energy/momentum perpendicular (transverse) to the colliding beams:

$$M_T = \sqrt{(E_T^e + E_T^\nu)^2 - (\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu})^2}$$

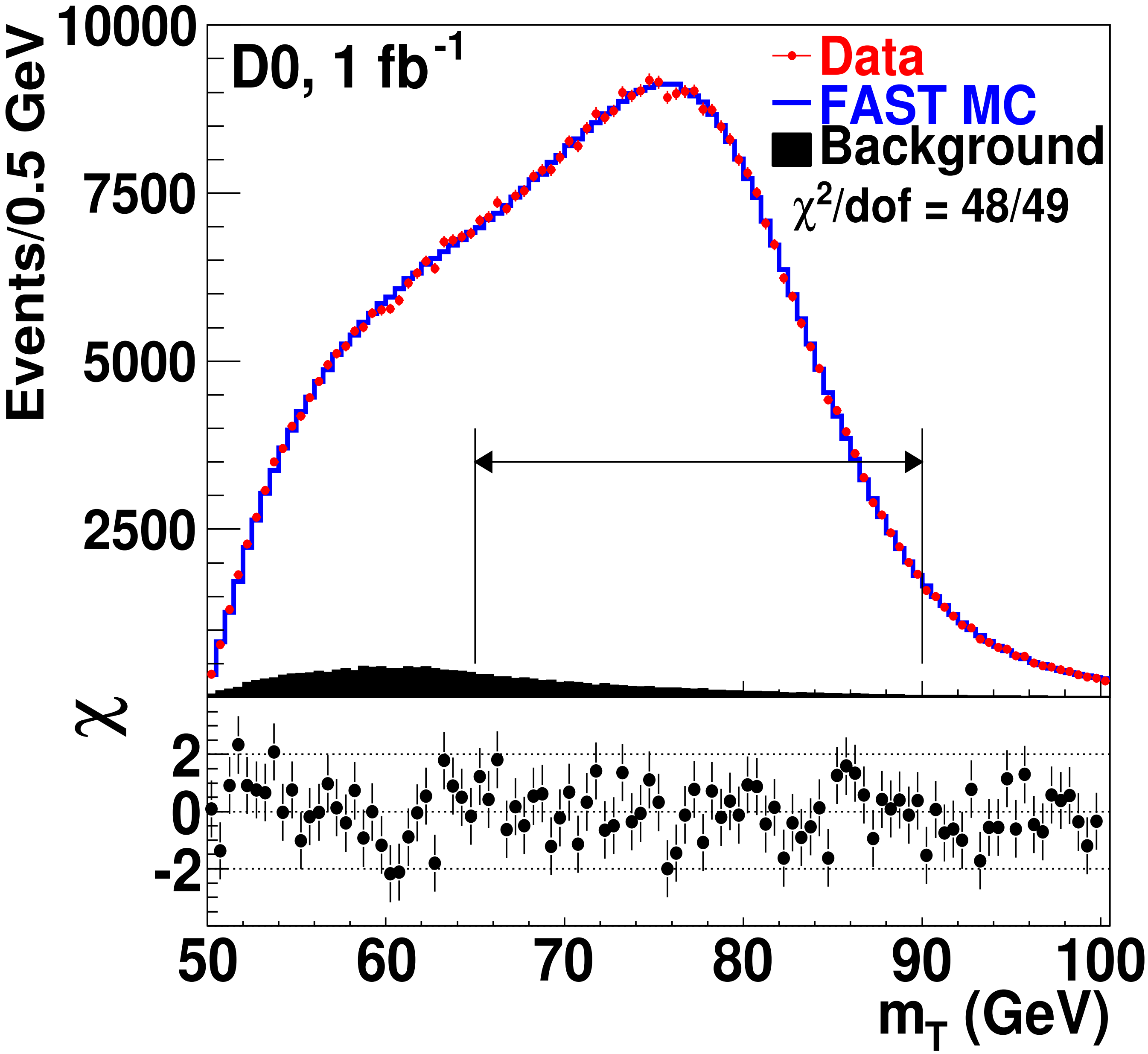
M_T is not the same in each event
- depends on which direction the W decay products come out

But we (theorists :) can predict the probability distribution for M_T very precisely if we know the W boson's mass.

- Make the prediction for a bunch of different mass guesses
  need to calculate the M_T probability distribution for each guess

- Collect a lot of data
  need enough events to statistically populate the distribution

- Check how well each mass hypothesis fits the data
  find the mass value that gives the best fit to the data



Just under 500,000 $W \to e\nu$ candidates from the D0 detector at the Tevatron collider at Fermilab

Fitted W mass:

80.401 ± 0.043 GeV

(precision of 1 part in 2000!)

see, e.g., PoS EPS-HEP2009, 361 (2009) The hard work here is the detector calibration!

MC = Monte Carlo:

Physicists' name for a computer program that simulates events based on a probability distribution. A reference to "rolling the dice" :)

Lets us produce "simulated events" with the same features that you would measure in an actual detector:

- do a dry run, develop good analysis techniques

- see what "backgrounds" (known processes) will look like

- figure out what the "signal" we're looking for will look like, depending on the underlying physics

- use this to work backwards to figure out the underlying physics

Why have specialists in phenomenology?

- large-scale, complicated calculations often needed for precise predictions: particularly processes involving strong interactions

- figure out how to search for new models for “new physics”: Start with some “elegant” symmetry structure, proposed to solve some problem of the Standard Model.
Have to work out what the particles are, how they would be produced, how they would decay, how all this depends on free parameters of model, and how to tell this model apart from competing models.

- invent new data-analysis methods to search for particles or make desired measurements

- gather experience with many “new physics” models:
Develop “intuition” to guess type of underlying physics based on characteristics of new signatures

Outlook

Right now particle physicists are tremendously excited about the potential for new discoveries at the LHC.

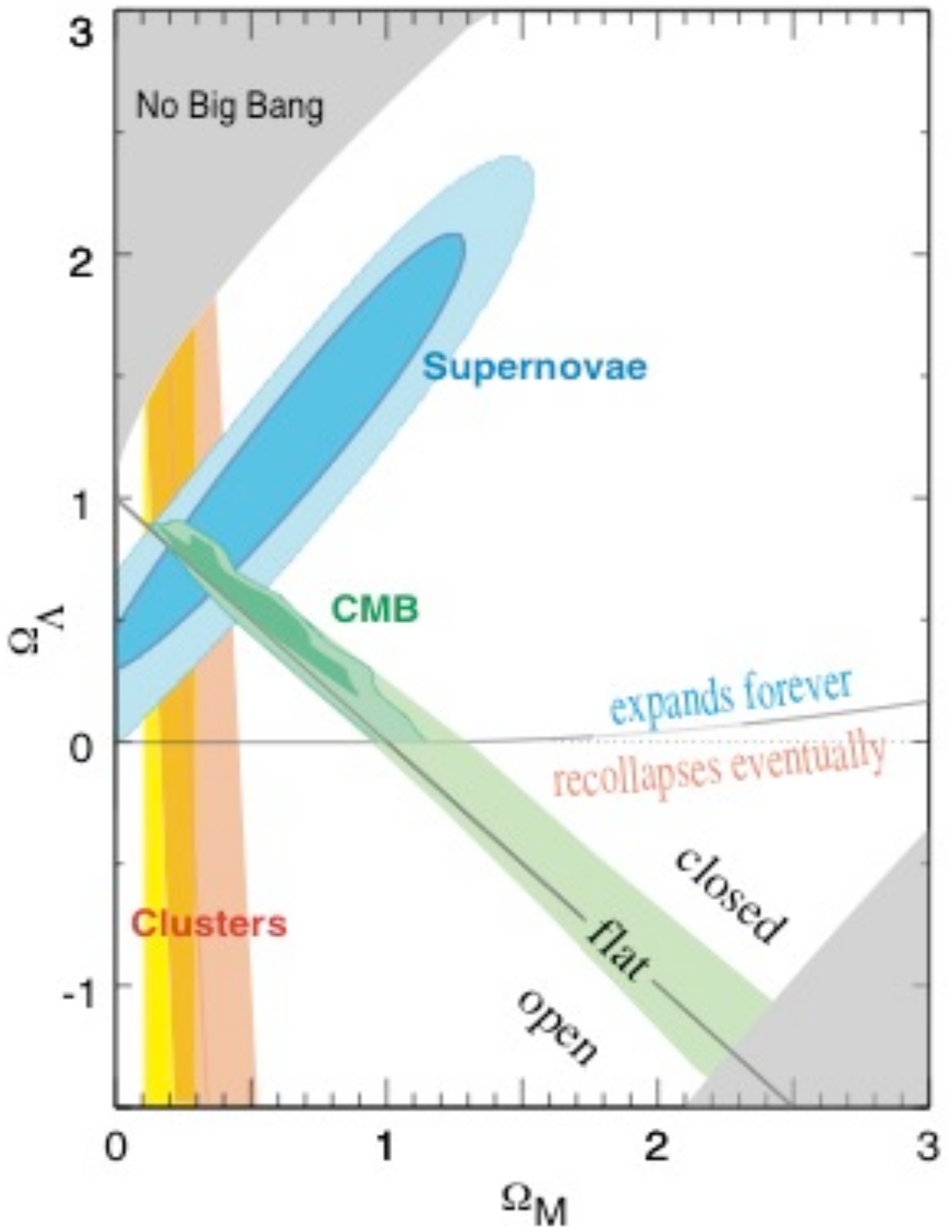
The next 3 - 12 - 24 months could revolutionize our understanding of physics at the smallest scales.

- February-March-April 2011: analyses of the first LHC data collected last year will be finishing

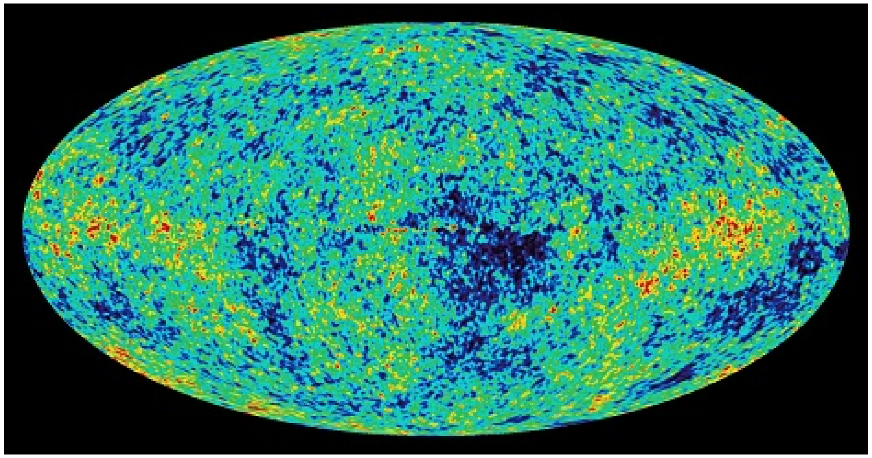
- LHC will run all this year and 2012, then shut down for $\sim$1 year for installation of new parts that will let it run at higher energy

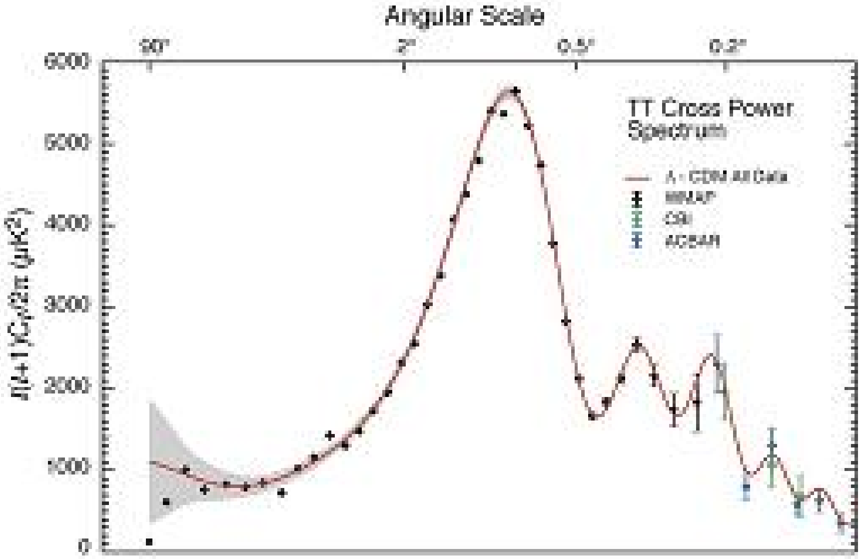
Stay tuned for brand new results!

Backup slides


3
2
1
0
-1
No Big Bang
Supernovae
CMB
expands forever
recollapses eventually
closed
flat
open
Clusters
Ω_Λ
0
1
2
3
Ω_M

Temperature fluctuations in the Cosmic Microwave Background





- Baryons 4%
- Nonbaryonic dark matter 23% ⟵ known to ±10% precision!
- Dark energy 73%