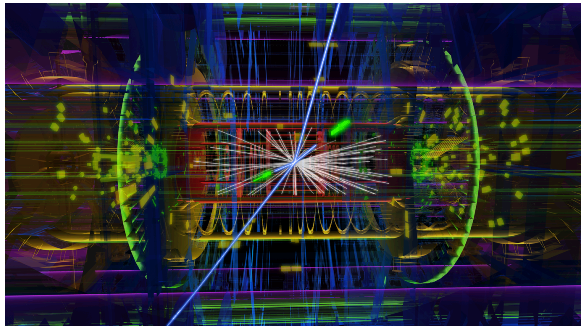
CERN

European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

Particle physics today

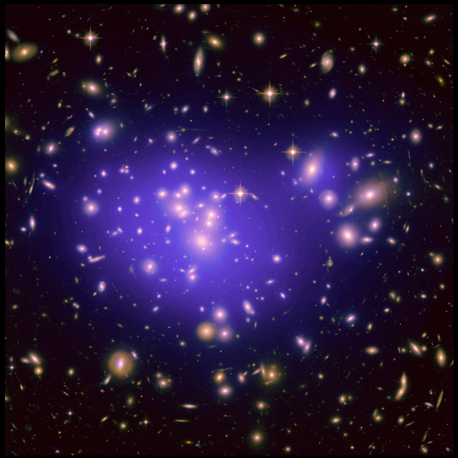


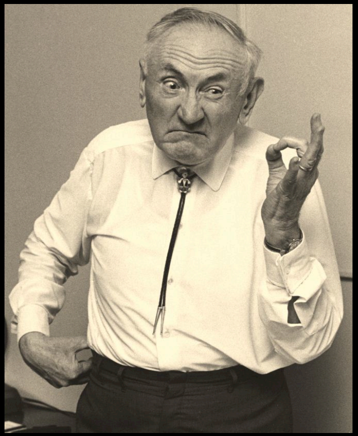
Giulia Zanderighi (CERN & University of Oxford)

Evidence for Dark Matter

Zwicky (1933):

mass of luminous matter = 10% of gravitation mass





The galaxy cluster Abell 1689, with the mass distribution of the dark matter overlaid in purple

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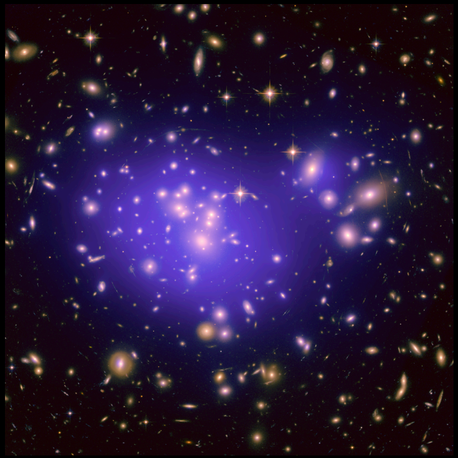
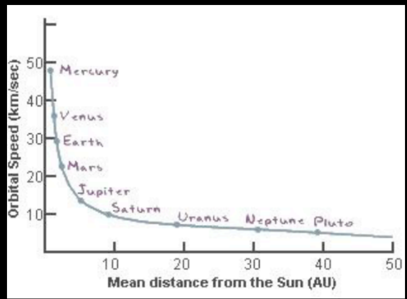


The galaxy cluster Abell 1689, with the mass distribution of the dark matter overlaid in purple

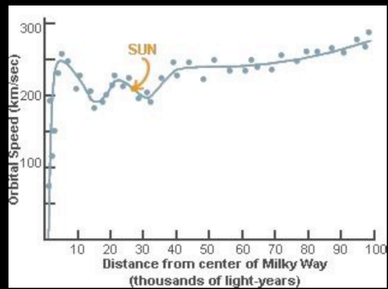
More evidence for DM

According to Kepler's law: orbital speed from the central ~ $1/r^{1/2}$

✓ Planets around the sun



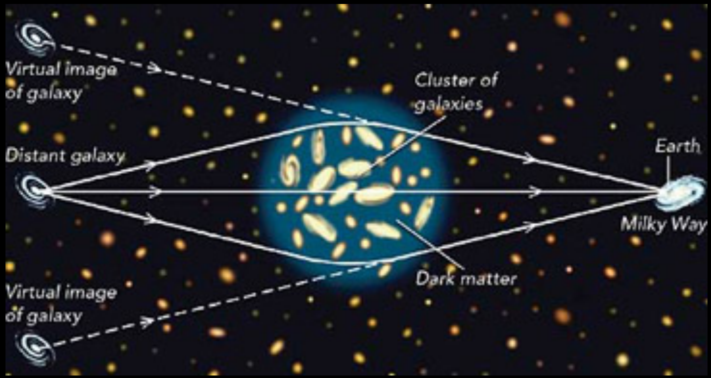
× Milky way



This was as if the stars were not rotating around the visible centre of the galaxy but around many unknown centers, all providing additional gravitational attraction. This could only happen if huge amounts of invisible matter filled the entire galaxy and beyond.

Even more evidence for DM

Gravitations lensing

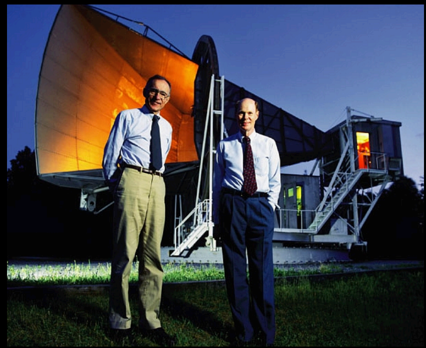


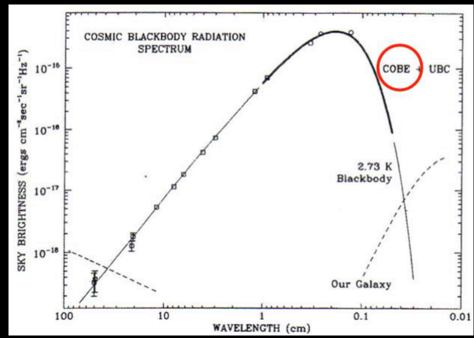
Gravitational lensing can occur when light from a distant galaxy, center left, passes through a dark-matter halo around a cluster of galaxies

CMB from Big Bang

- In the 60s, some supported a flat steady-state theory of the universe, in which the universe always existed and will always continue to exist
- Others believed in a Big Bang theory, according to which the universe was created in a massive explosion-like event (later to be determined to be about 13.7 billions years ago)
- Penzias and Wilson were building a super-sensitive antenna to detect radio waves bounces off balloon satellites
- After removing all the "background noise" they found a mysterious persisting noise (100 times the expected residual noise)
- At the same time Dicke, Peebles, Wilkinson realized that a Big Bang should have released a blast of radiation that could still be detectable
- The radiation detected by Penzias and Wilson was suggested to be the cosmic microwave background (CMB) from the primordial Big Bang

Discovery of CMB



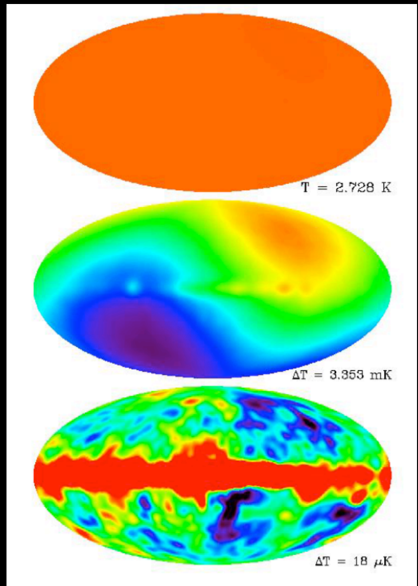


Penzias and Wilson

(Nobel prize 1978)

1964 discovery of Cosmic Microwave Background: universe behaves like a perfect black body with T = 2.73 K

First studies of CMB



T= 2.7 K

Δελτα–T= 3.3 mK
(after subtraction of constant emission)

Δελτα–T= 18 μK
(after correcting for motion of Earth)

2nd CMB Nobel Prize

COBE was launched by NASA in 1989. Its mission was to measure the spectrum of the CMB and find possible anisotropies. It was a success, followed by similar experiments (e.g. BOOMERanG, WMAP, Planck)

Two of COBE's principal investigators

The Nobel Prize in Physics 2006

Photo: P. Izzo
John C. Mather
Prize share: 1/2

Photo: J. Bauer
George F. Smoot
Prize share: 1/2

The Nobel Prize in Physics 2006 was awarded jointly to John C. Mather and George F. Smoot *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*

According to the Nobel Prize committee, "the COBE-project can also be regarded as the starting point for cosmology as a precision science"

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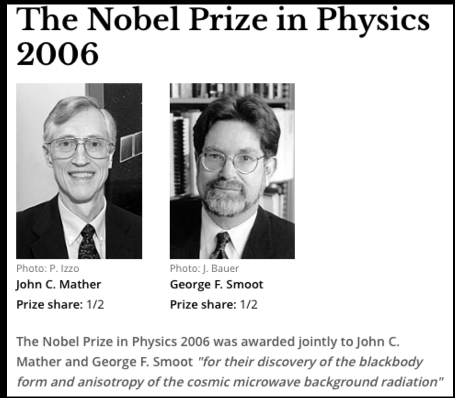
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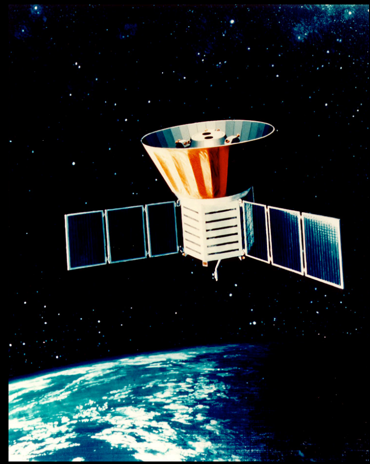

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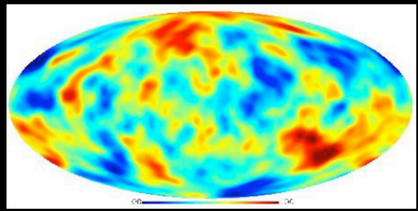
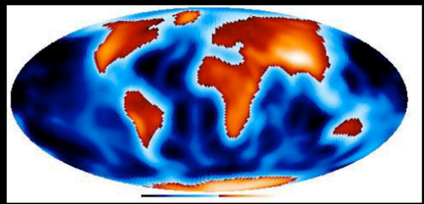
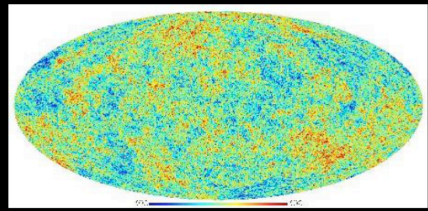
More CMB studies

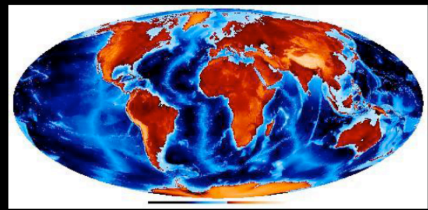
COBE
(7 degree resolution)





WMAP
(0.25 degree resolution)

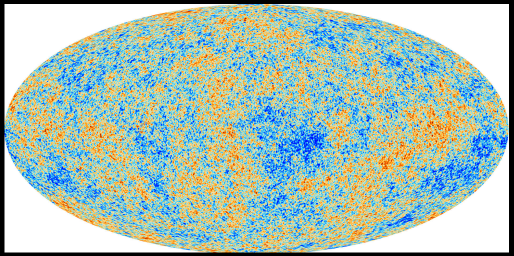


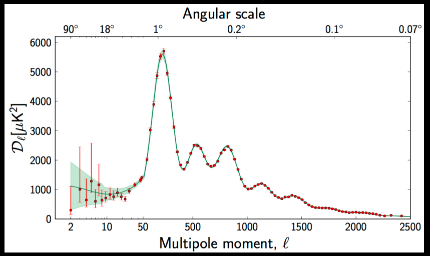


Todays CMB map

Precision CMB measurements from European Planck satellite

launched in 2009, has been taking impressive data since





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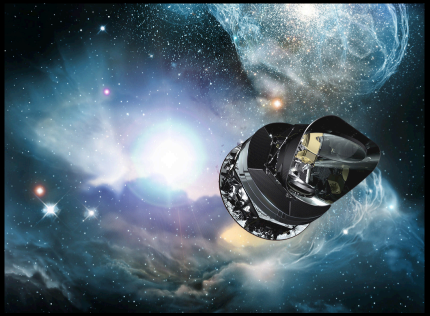
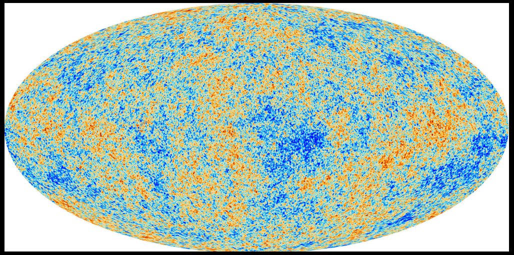
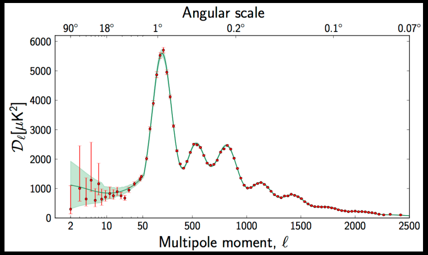
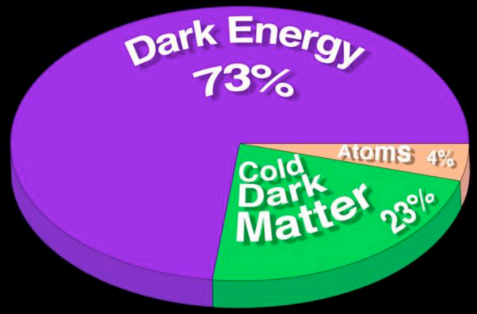






Composition of the universe



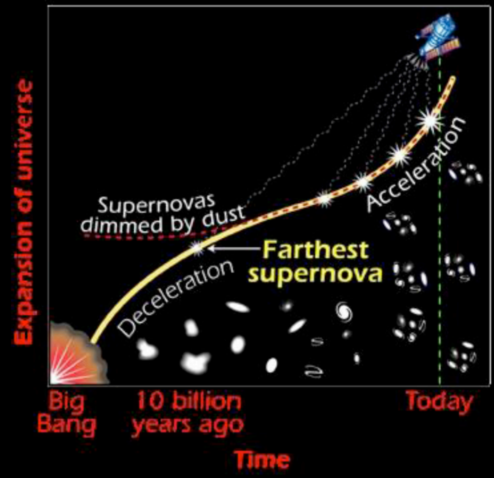
FAQ: what is the difference between Dark Matter and Dark Energy?

DM behaves like matter, it dilutes as the volume expands, it clusters gravitationally on small scales

DE behaves like a constant, it does not dilute, it does not cluster, it is probably homogeneous, fluid with negative pressure that forces the universe to expand

Composition of the universe

Evidence for Dark Energy

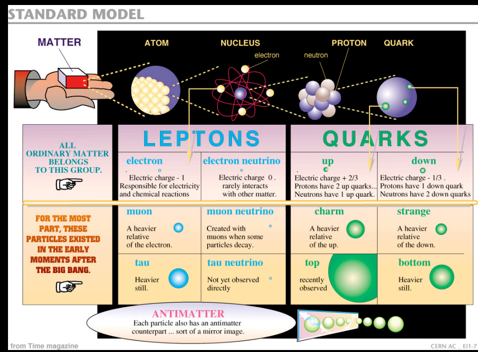


Properties of DM

- does not emit light, it is neutral
- there since the beginning of the Universe: stable
- none, or very weak interactions
- more abundant than ordinary matter

What about neutrinos?

they are neutral, interact only very weakly ...



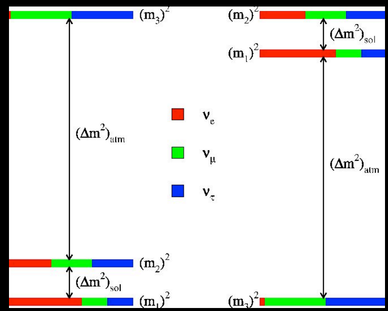
Neutrinos as DM?

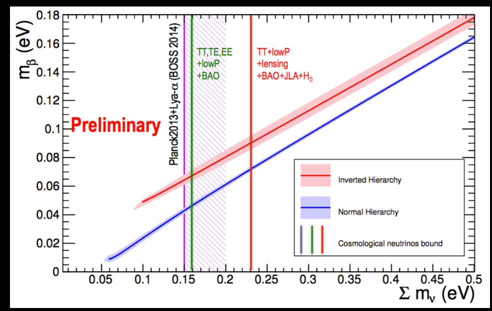
Problem: neutrinos are light. In fact, we do not even know how light!

We know that $m_2 - m_1 \approx 0.009$ eV and $m_3 - m_2 \approx 0.05$ eV

And we have a bound on the sum of all neutrino masses (from Planck):

$m_1+m_2+m_3 < 0.3$ eV





Neutrinos as DM?

Three types of possible DM:

Hot: relativistic, kinetic energy of the order of the rest mass, or higher

Cold: non-relativistic, kinetic energy much smaller than the rest mass

Warm: in between the two

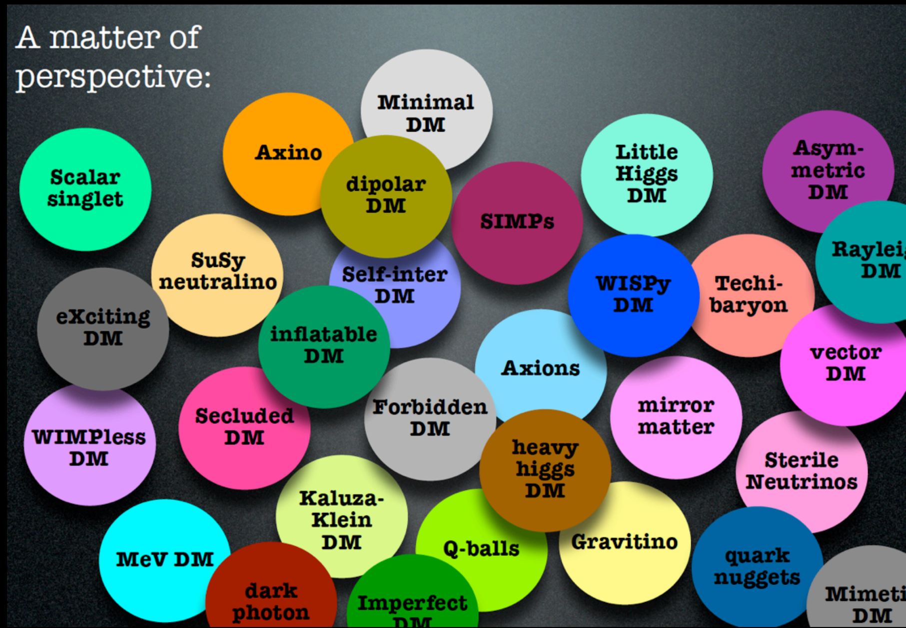
Cold dark matter must be a significant component of the universe to explain the growth of structures such as galaxies $m_{DM} \sim$ 10-1000 GeV

Hence, neutrinos excluded as a main component of DM

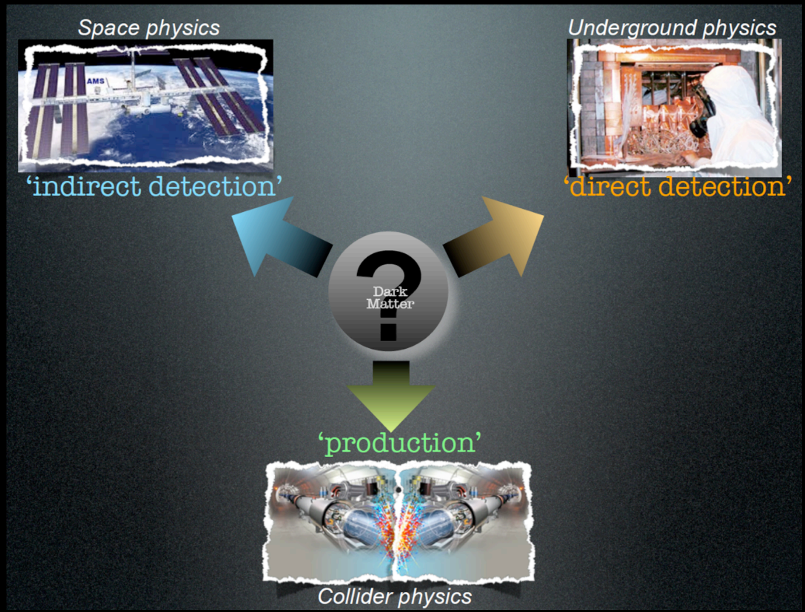
The observation of DM points to (at least) a new, still unknown particle

Candidates for DM

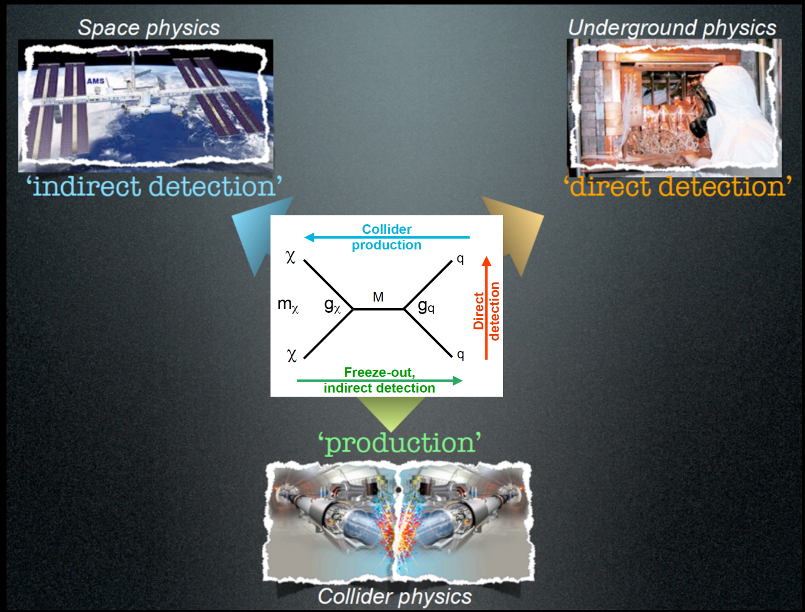
Candidates for DM



The DM hunt

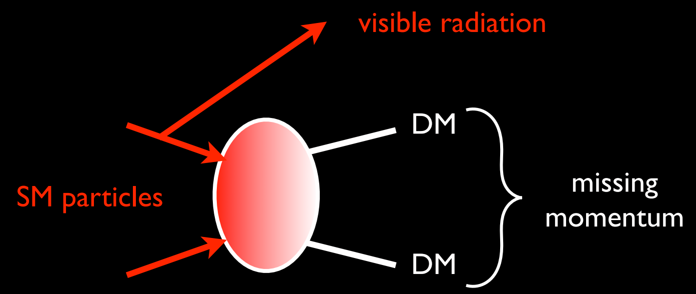

Space physics
Underground physics
'indirect detection'
'direct detection'
Dark Matter
'production'
Collider physics

The DM hunt

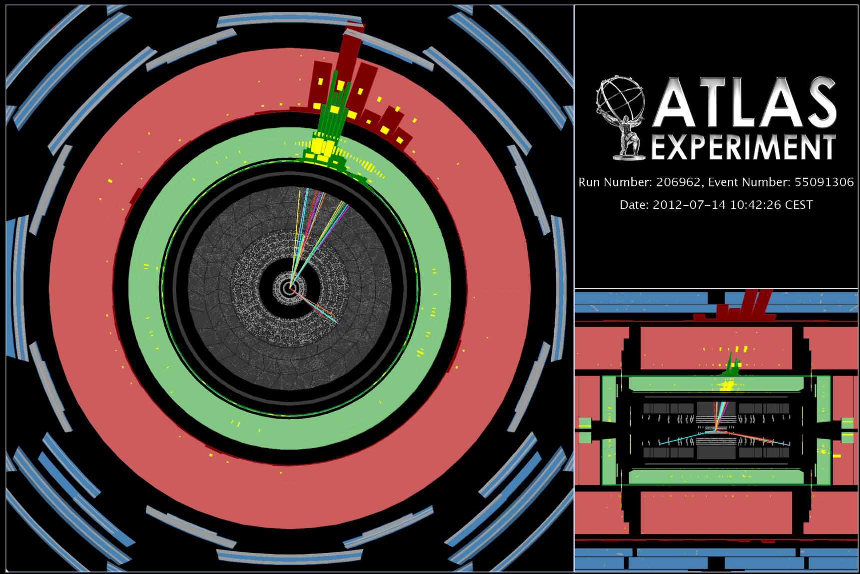

Space physics
Underground physics
'indirect detection'
'direct detection'
Collider production
χ
χ
m_χ
g_χ
M
g_q
q
q
Direct detection
Freeze-out, indirect detection
'production'
Collider physics

How to see the invisible?

- Dark matter (DM) particles interact so weakly that they are expected to pass out of detector components without any significant interaction, making them effectively invisible (much like neutrinos)
- One way to see DM particles nonetheless, works by looking for missing momentum & additional SM radiation



How to see the invisible?



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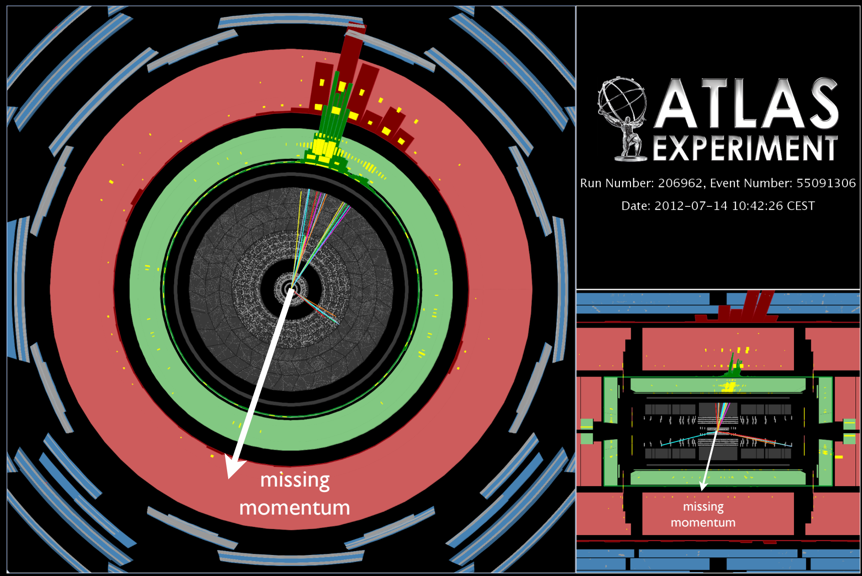
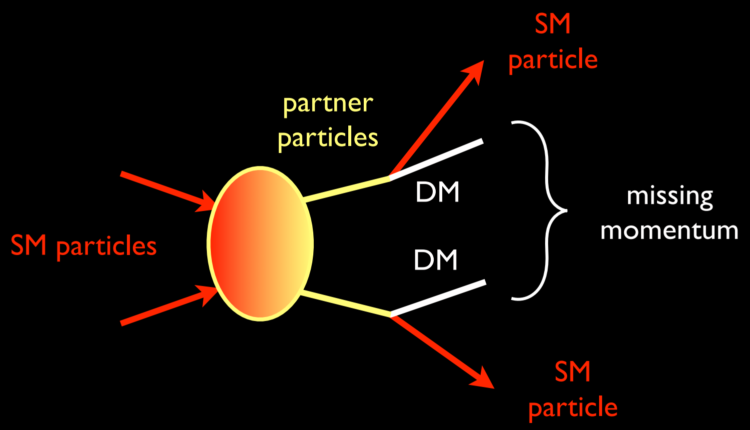
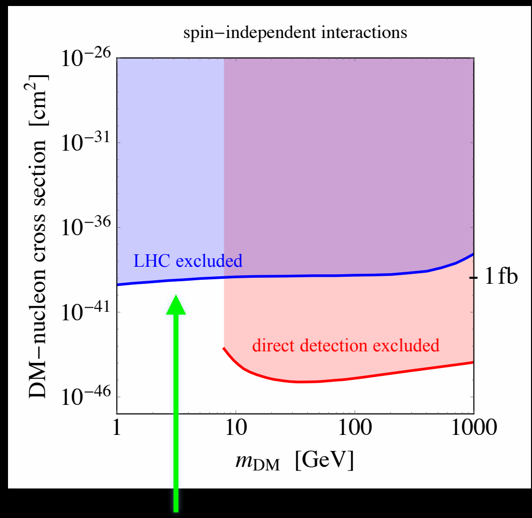


How to see the invisible?

- Second way to detect DM, based on production of partner particles that decay to DM & SM particles (prime example supersymmetry with conserved R-parity)

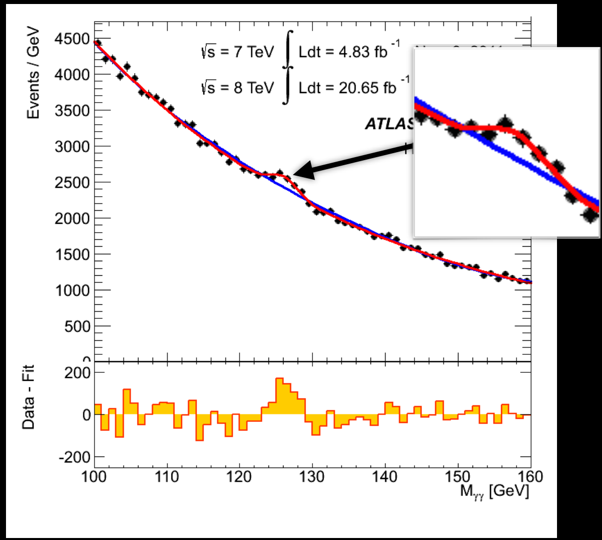


LHC vs. DM direct detection



The LHC constraints are strongest at low DM mass, where direct detection is challenging due to the small nuclear recoil

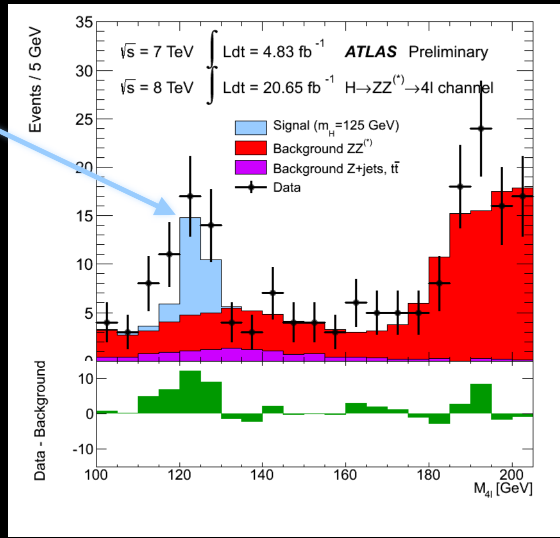
Bump hunting for the Higgs



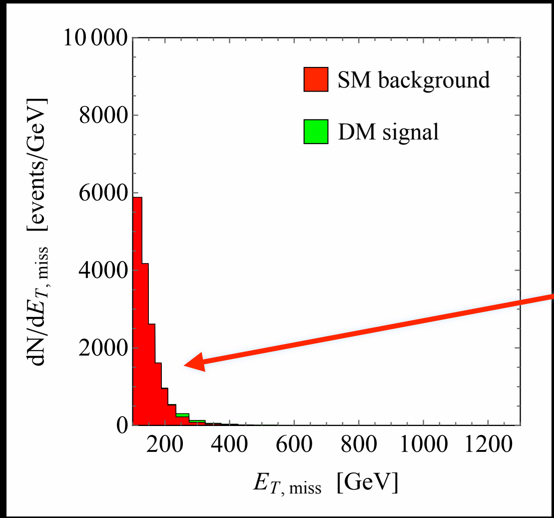
The di-photon decay of the Higgs leads to a nice bump in the invariant mass distribution

Bump hunting for the Higgs

To see the bump for the Higgs decaying to two Z bosons, one does not even have to zoom in

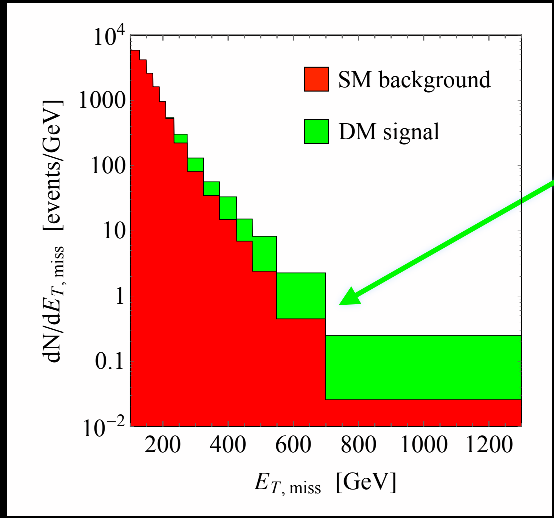


Tail surgery to find DM



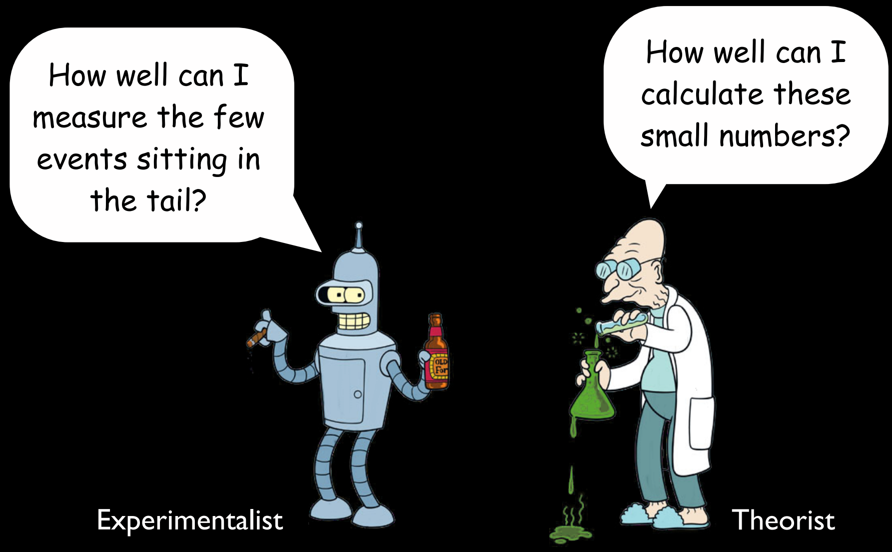
Overwhelming SM background, that arises in the case of mono-jet searches from Z + jet production with the Z boson decaying to neutrinos

Tail surgery to find DM

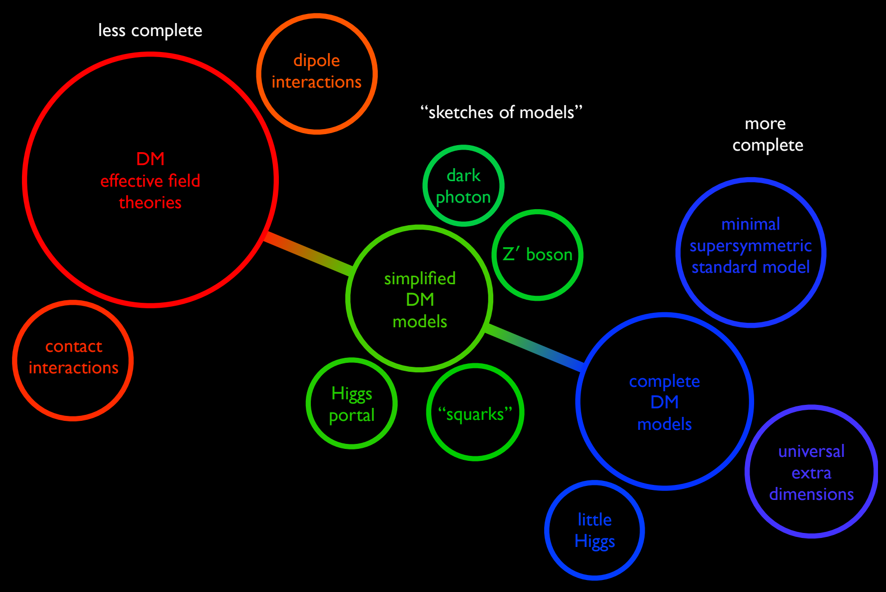


The presence of DM manifests itself in a small enhancement in the tail of the missing energy distribution

A big challenge indeed



DM theory space



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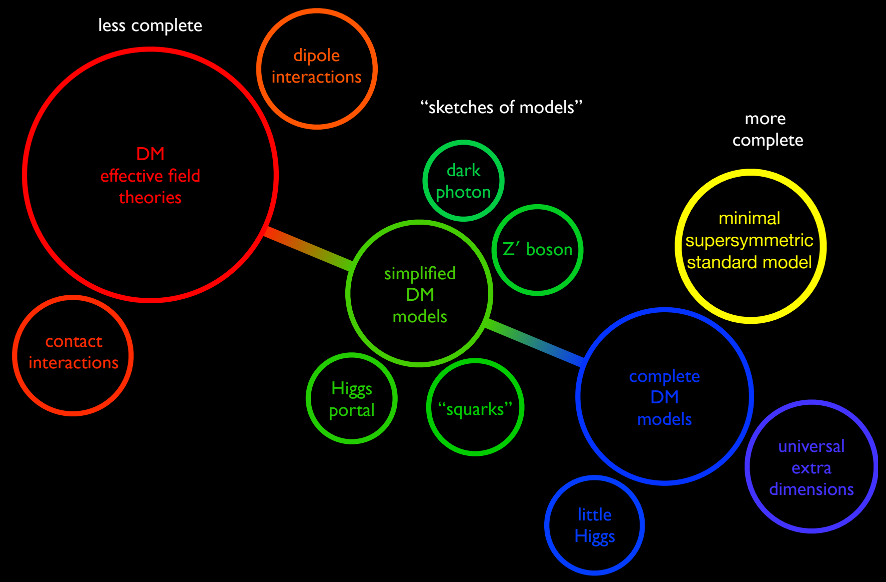
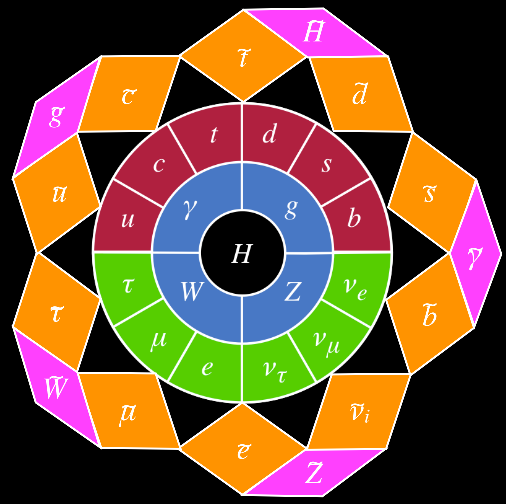


MSSM

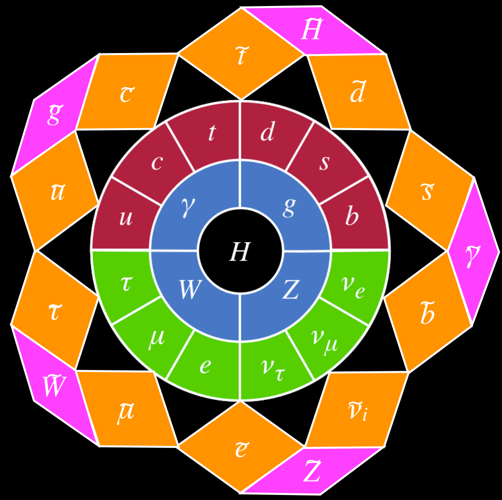
- All complete DM models add more particles to the SM, most of which are not viable DM candidates
- The classical example is the MSSM in which each SM particle gets its own superpartner
- In the case of the MSSM there are 20 additional parameters that can be relevant for DM physics



Minimal supersymmetric SM (MSSM)

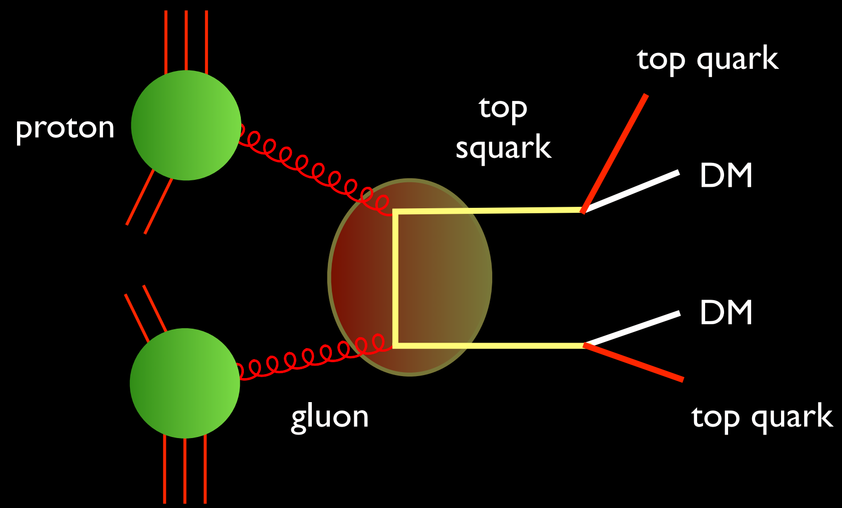
MSSM

- In the MSSM baryon (B) and lepton (L) number are no longer conserved
- Since B and L conservation have been tested precisely, the B/L violating interactions must be very smal
- R-parity is a symmetry that forbids these couplings. It is defined as $(-1)^{3(B-L)+2spin}$
- All SM particles have R = 1, all MSSM particles have R=-1

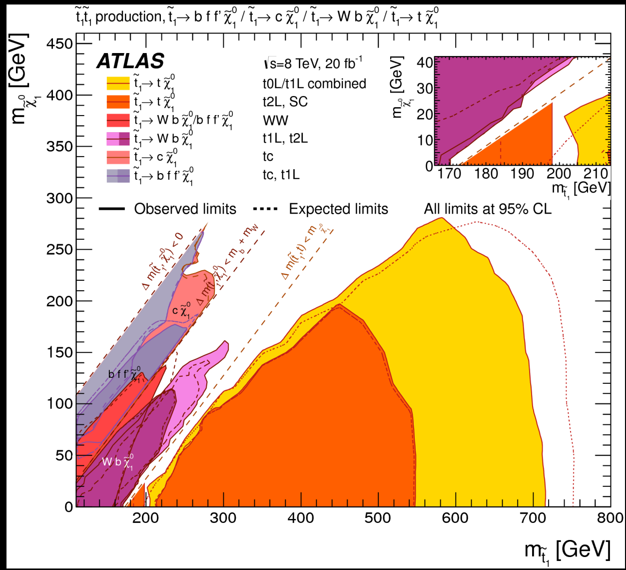


This implies that the lightest SUSY particle can not decay to SM particles. It is stable and provides naturally a DM candidate

One way to produce DM in MSSM



LHC limits on DM mass in MSSM



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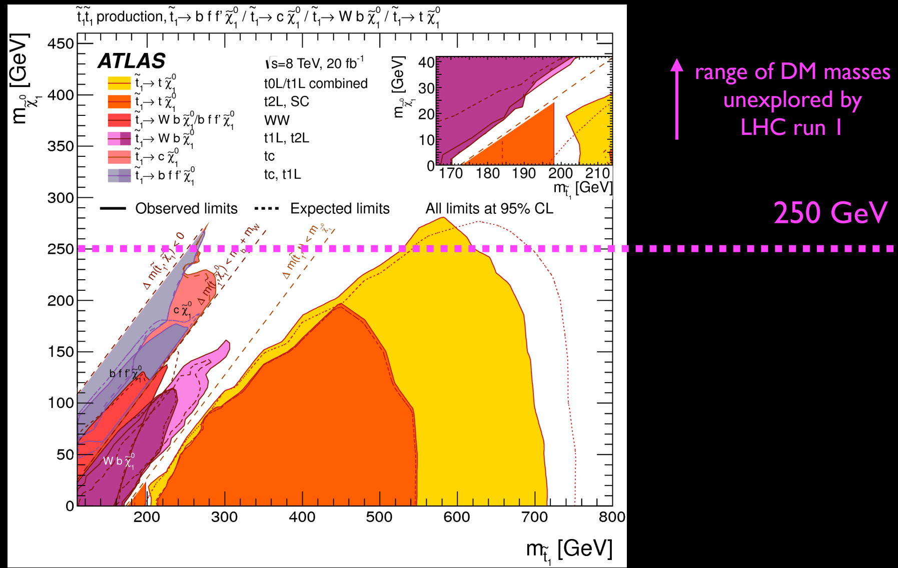

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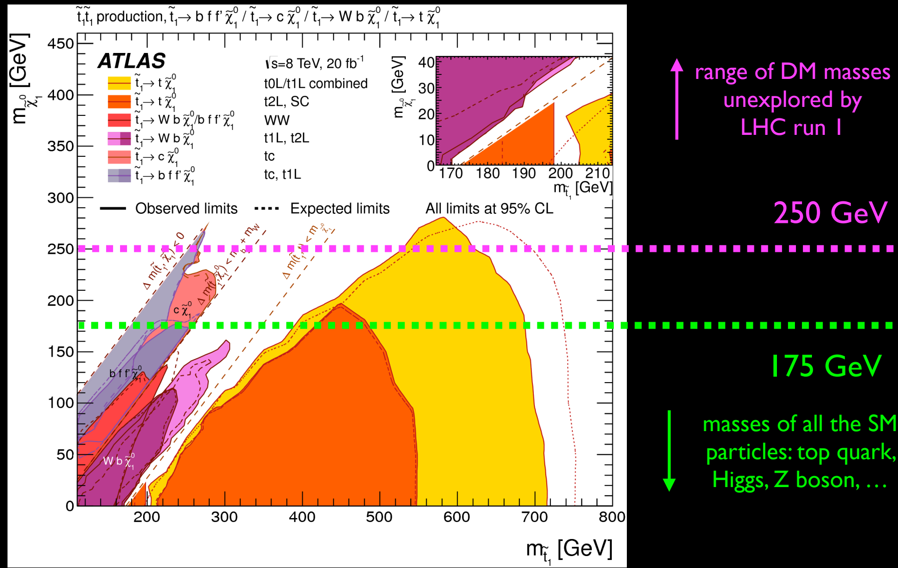
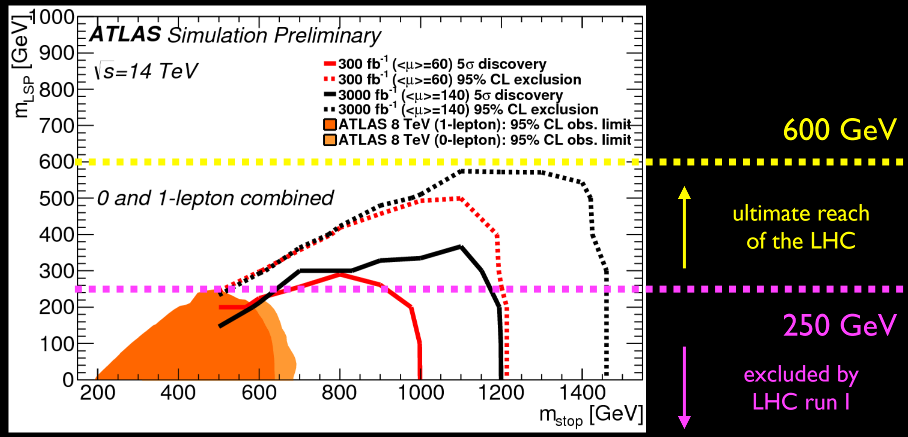


range of DM masses unexplored by LHC run 1

masses of all the SM particles: top quark, Higgs, Z boson, …

LHC limits on DM mass in MSSM



Conclusions

- We have a Standard Model that works fabulously at colliders (somehow frustrating...)
- Dark matter is (to me) the most compelling argument in support of physics beyond the Standard Model
- Dark matter also provides a link between the particle physics at colliders (study of the smallest scales) and cosmology (study of the largest scales)
- Many big mysteries to solve

The big open questions

- why three generations?
- what explains the hierarchy of fermion masses and mixings?
- what created the matter anti-matter asymmetry of the universe?
- what protects the Higgs mass from large corrections (hierarchy problem)?
- what is the nature of Dark Matter?
- how does gravity enter the picture?
- what is Dark Energy?
- are these the right questions to ask?