Astrophysics and Nuclear Astrophysics (LPHY2263)

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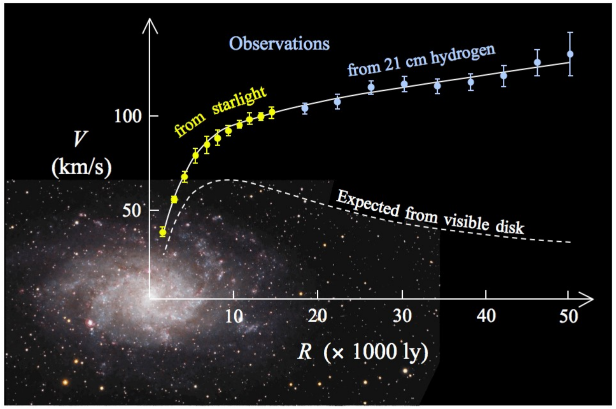
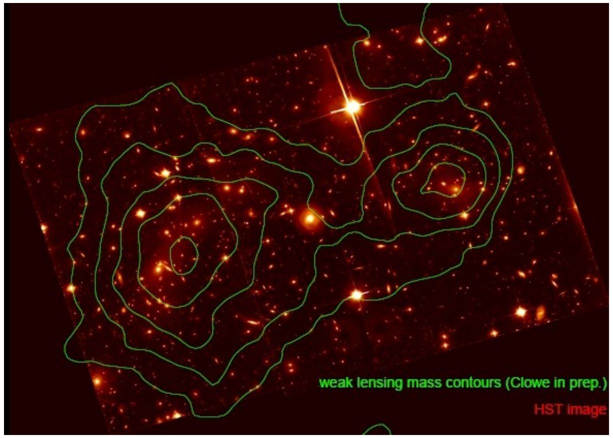
Chapter #8

- Dark Matter
  - Measuring galactic rotation
  - Evidences for Dark Matter
  - Possible types of Dark Matter
  - Searches for Dark Matter

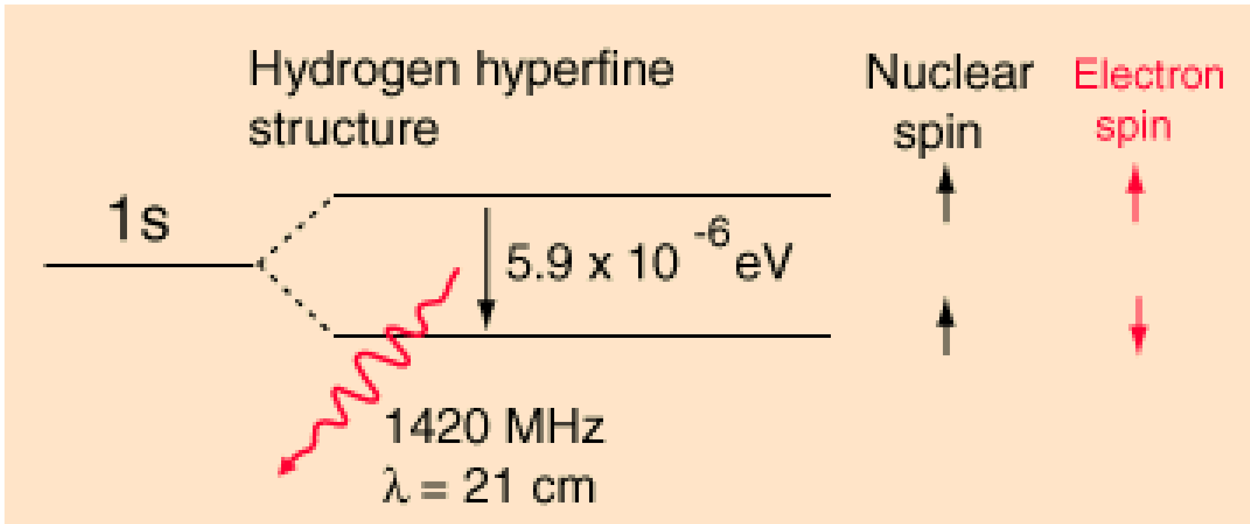


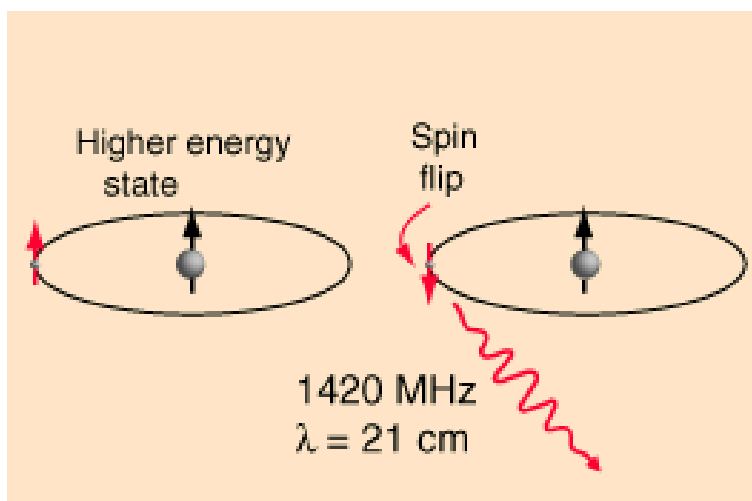


Measuring rotation speed

- We use Doppler effect on reference lines
  - Stars: we use the absorption lines
  - Ionized gas: we use the emission lines
  - *Q: why one or the other?*
- Atomic hydrogen gas: emission line at the radio wavelength of 21 cm (5.9×10^{-6} eV)
  - This is particularly useful for the regions where there are very few stars (gas extends way beyond the volume made visible by stars)
  - *Q: do you know what causes that line?*

The 21 cm line





More here

From rotation speed to mass profile

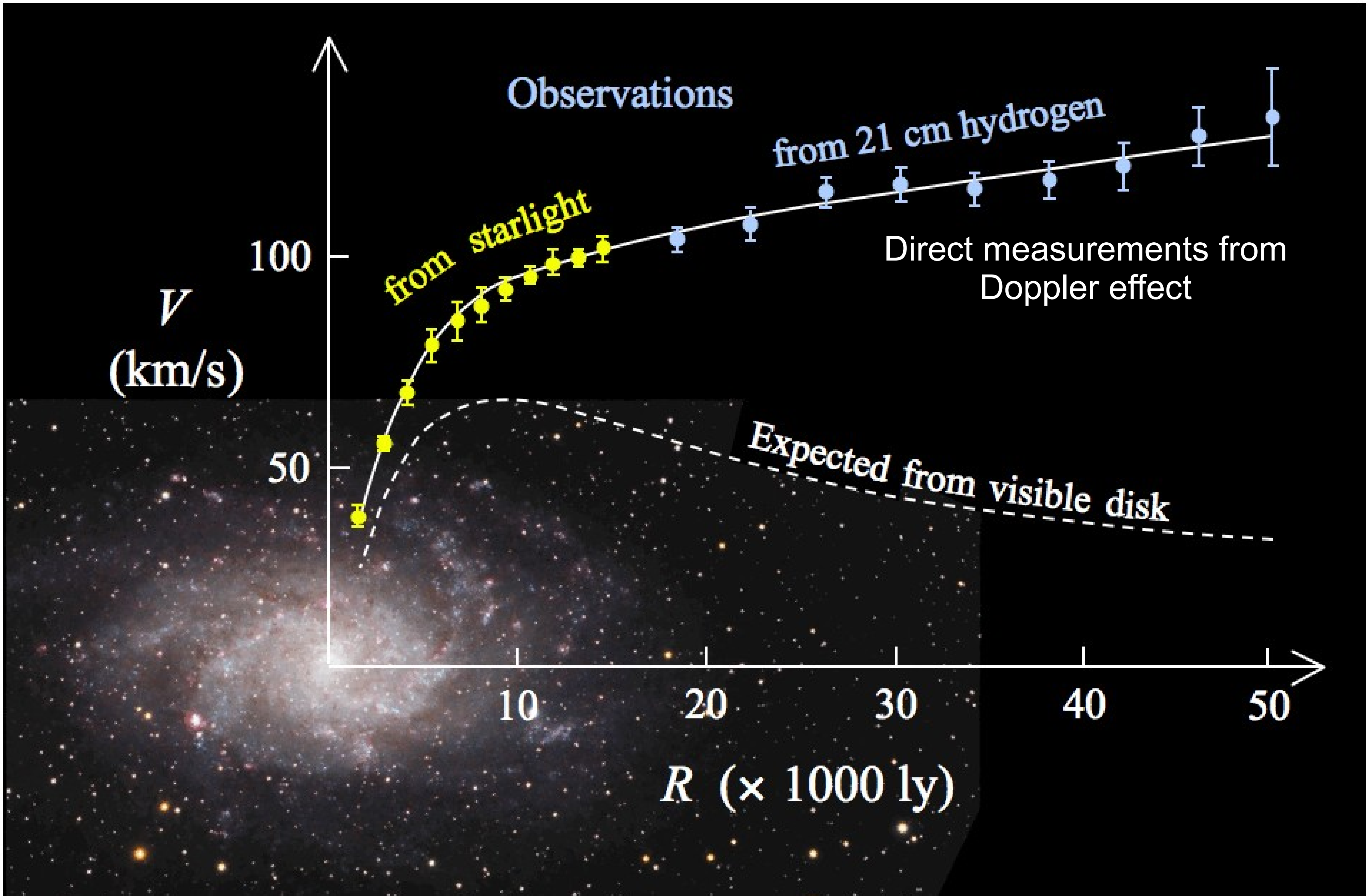
- Every star or gas cloud is affected by the gravity of the mass distribution interior to its distance R from the center of gravity of the galaxy
- Once you know rotation speed (from Doppler effect) you can derive the mass from 0 to R:

$$M(R) = \frac{V_{rot}^2 R}{G}$$

Homework: derive this equation (e.g., from virial theorem)

- If you derive M(R) from the observation of the distribution of stars, you can invert this equation and derive a corresponding $v_{rot}(R)$; and viceversa

Evidence for Dark Matter (DM)



Dark Matter (DM)

- "Dark" because it doesn't emit light
  - Therefore it is invisible to us
  - And it doesn't absorb light either: fully transparent
- It is not a small component: currently estimated as 84% of the mass of the Universe; there are even indications (from gravitational lensing, see later) of the existence of starless galaxies!
- Its composition is still a mystery
- The study of DM is a very intense research field at the boundary between particle physics and astrophysics

Distribution of DM in galaxies

$$M(R) = \frac{V_{rot}^2 R}{G}$$

- Exercise: show that if v(R) is ~ constant, then $\rho(R) \sim R^{-2}$
- In reality, this is true only at large values of R
- Unphysical, because $\rho(0)=\infty$, but useful for its simplicity
- This is called "Singular Isothermal Sphere" (SIS); can be derived from hydrodynamics assuming hydrostatic balance

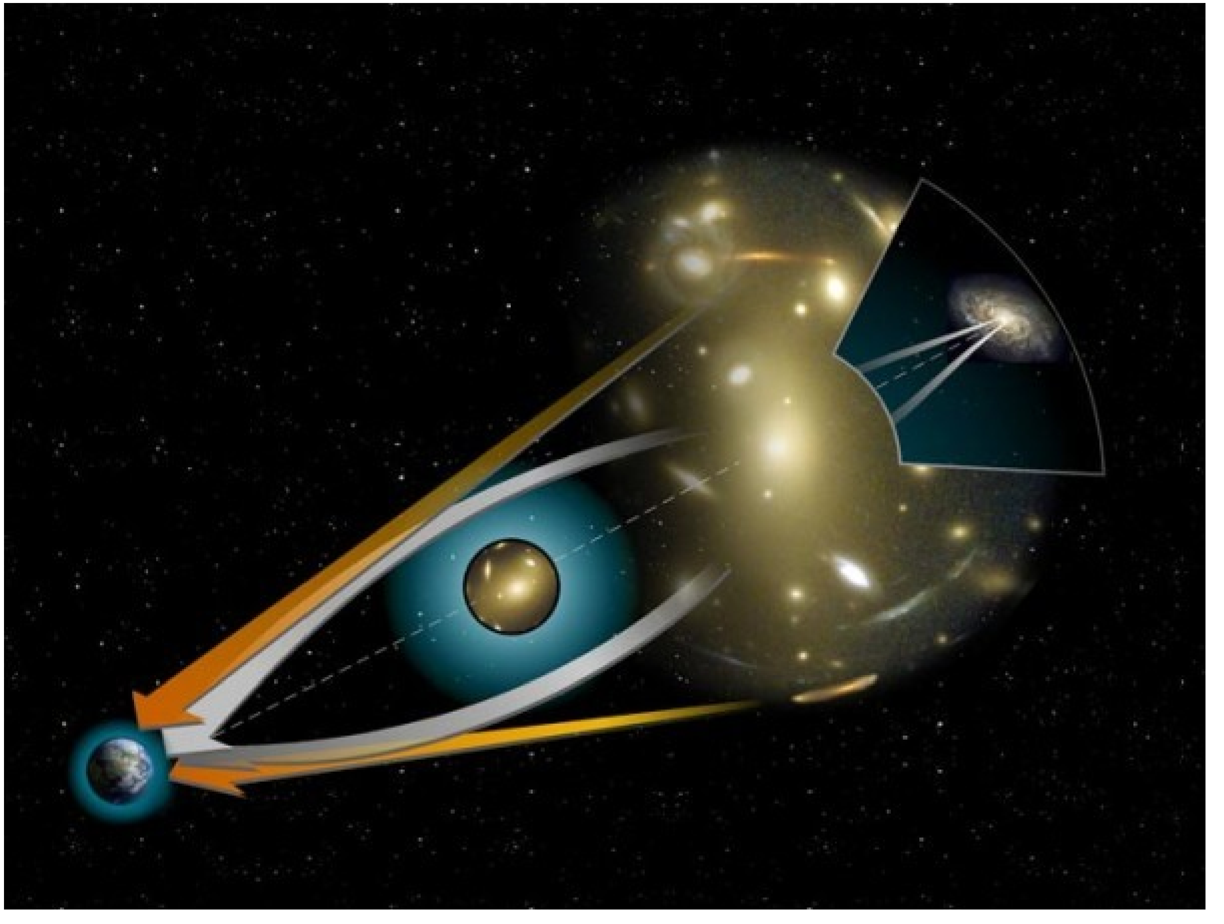
$$\rho(r) = \frac{K}{2\pi G r^2}$$

- A better curve is:

$$\rho = \frac{\rho_c}{1 + (r/r_0)^2}$$

Exercise: consider the limits for $r \to 0$, $r \to \infty$, $r \to r_0$

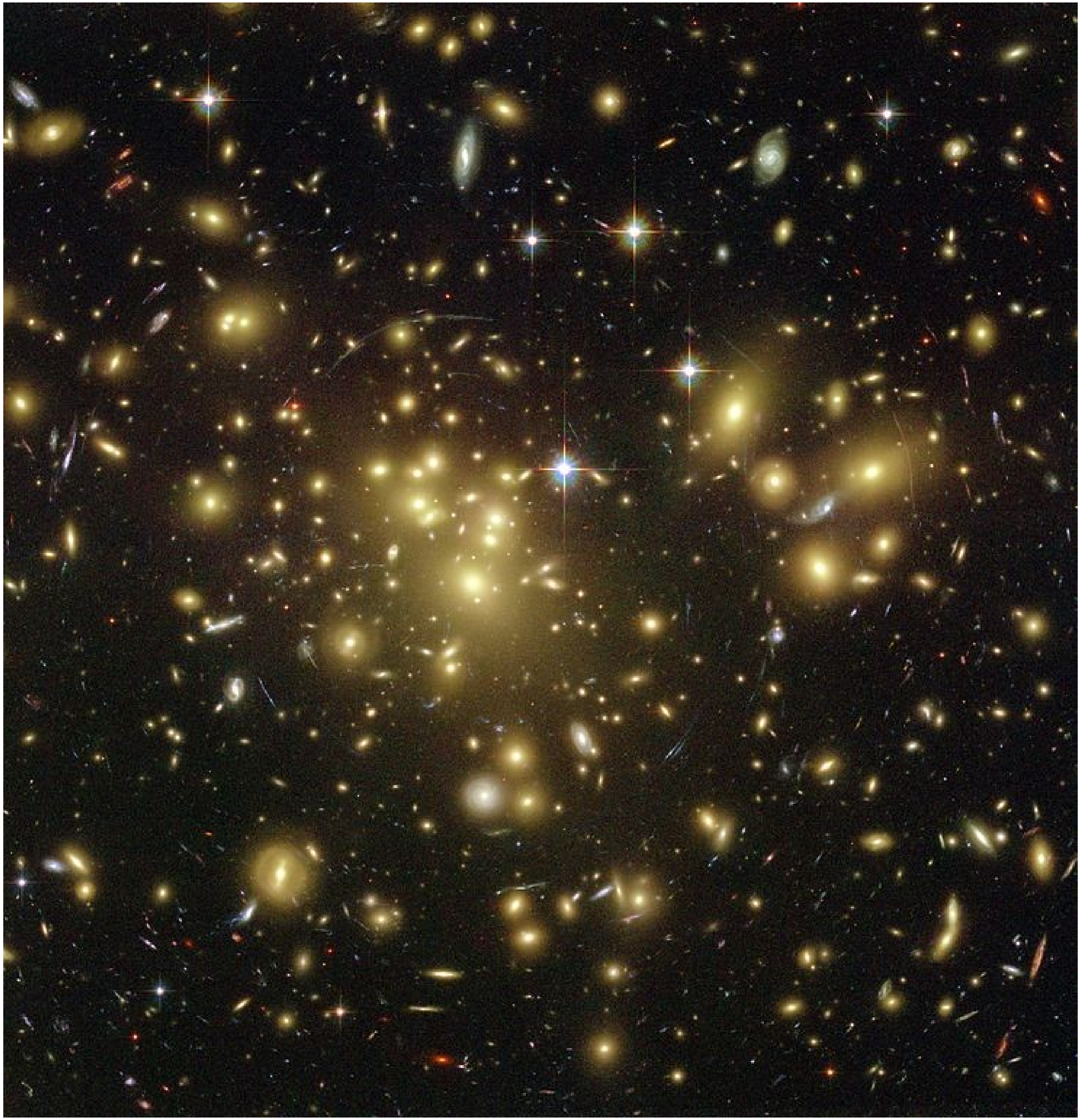
Gravitational lensing



Picture from here

This method allows to measure the mass of galaxies or clusters directly, exploiting bright galaxies just behind

Picture from wikipedia

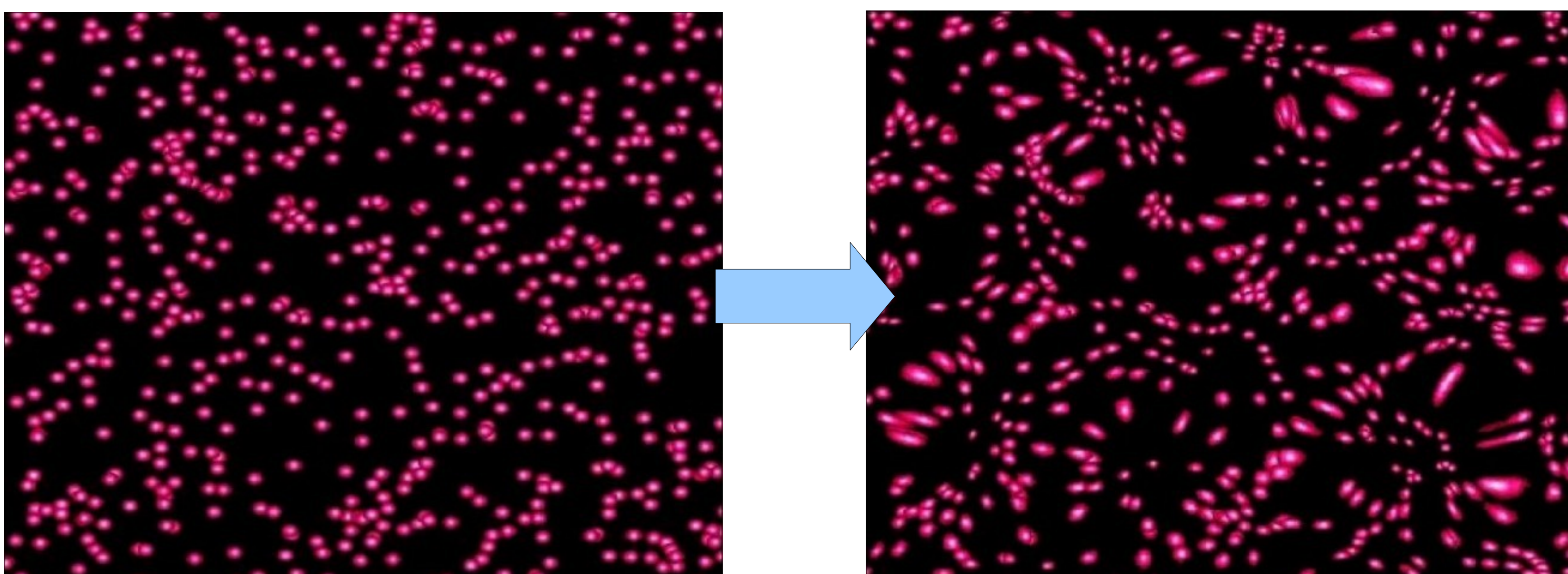


Abell 1689 Cluster, picture from the Hubble Space Telescope
Notice the arcs: those are lensed galaxies behind

Weak gravitational lensing

Unfortunately, spectacular lensing effects as in the previous slide can be visible only in a dozen of very lucky cases (you need a cluster of galaxies perfectly aligned with a bright galaxy in its background!)

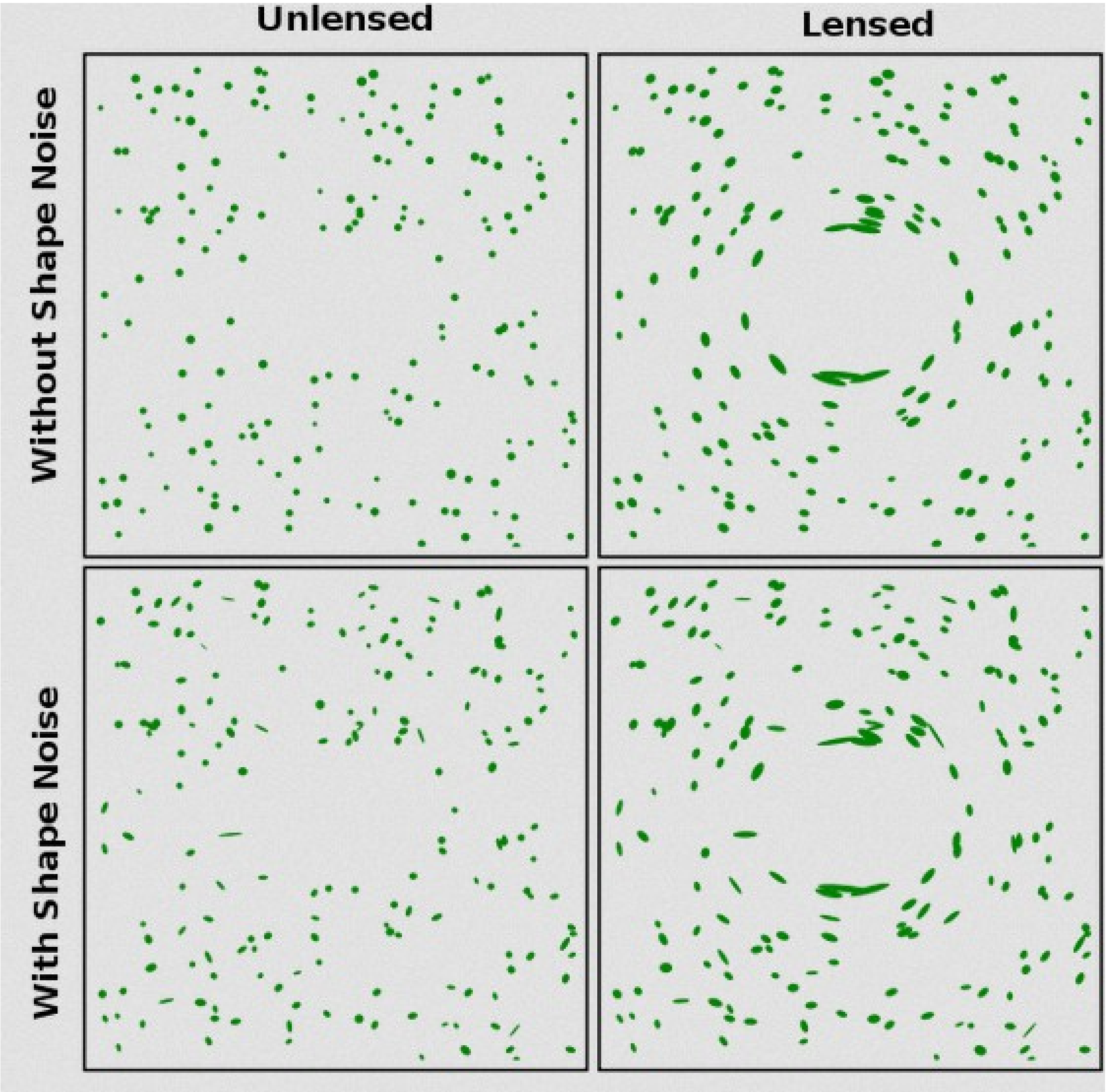
But we are able to learn about the matter distribution in an entire slice of sky by searching for distorsions:



Pictures from here

"Shape noise"

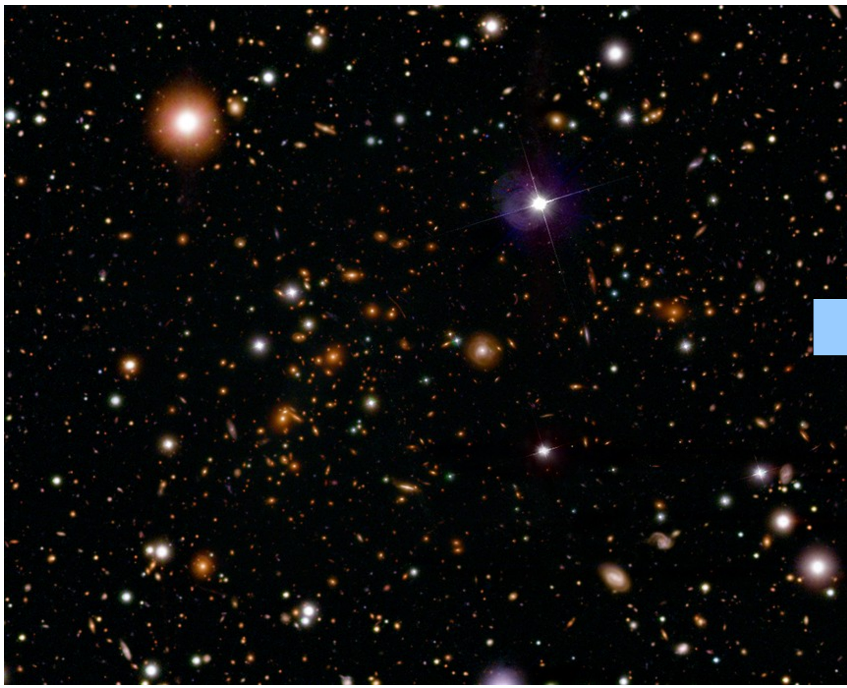
Picture from here

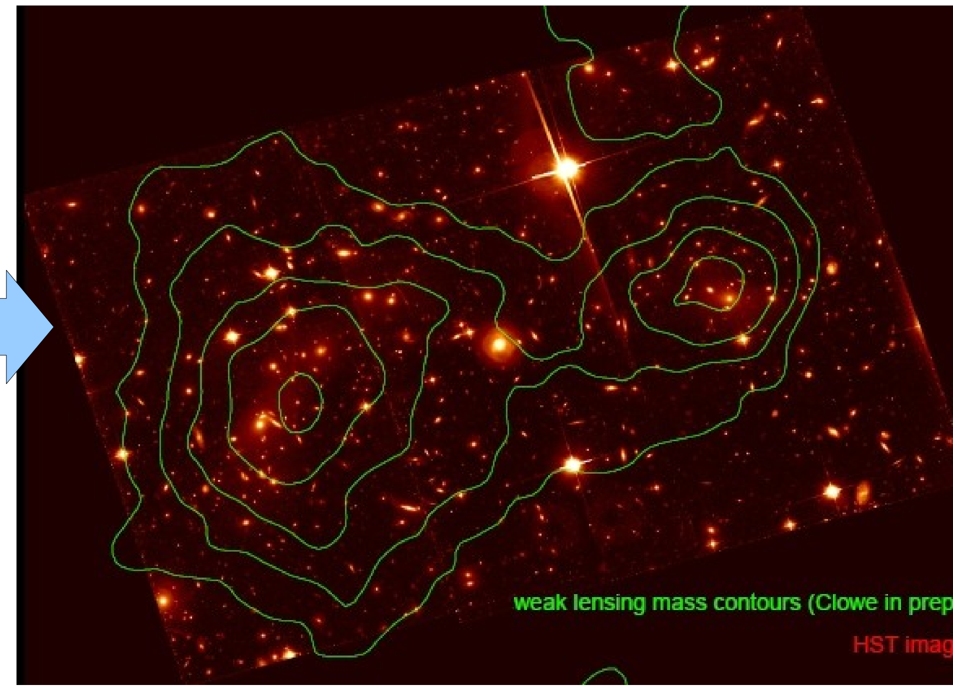


In practice we have to take into account that galaxies come in all kind of shapes

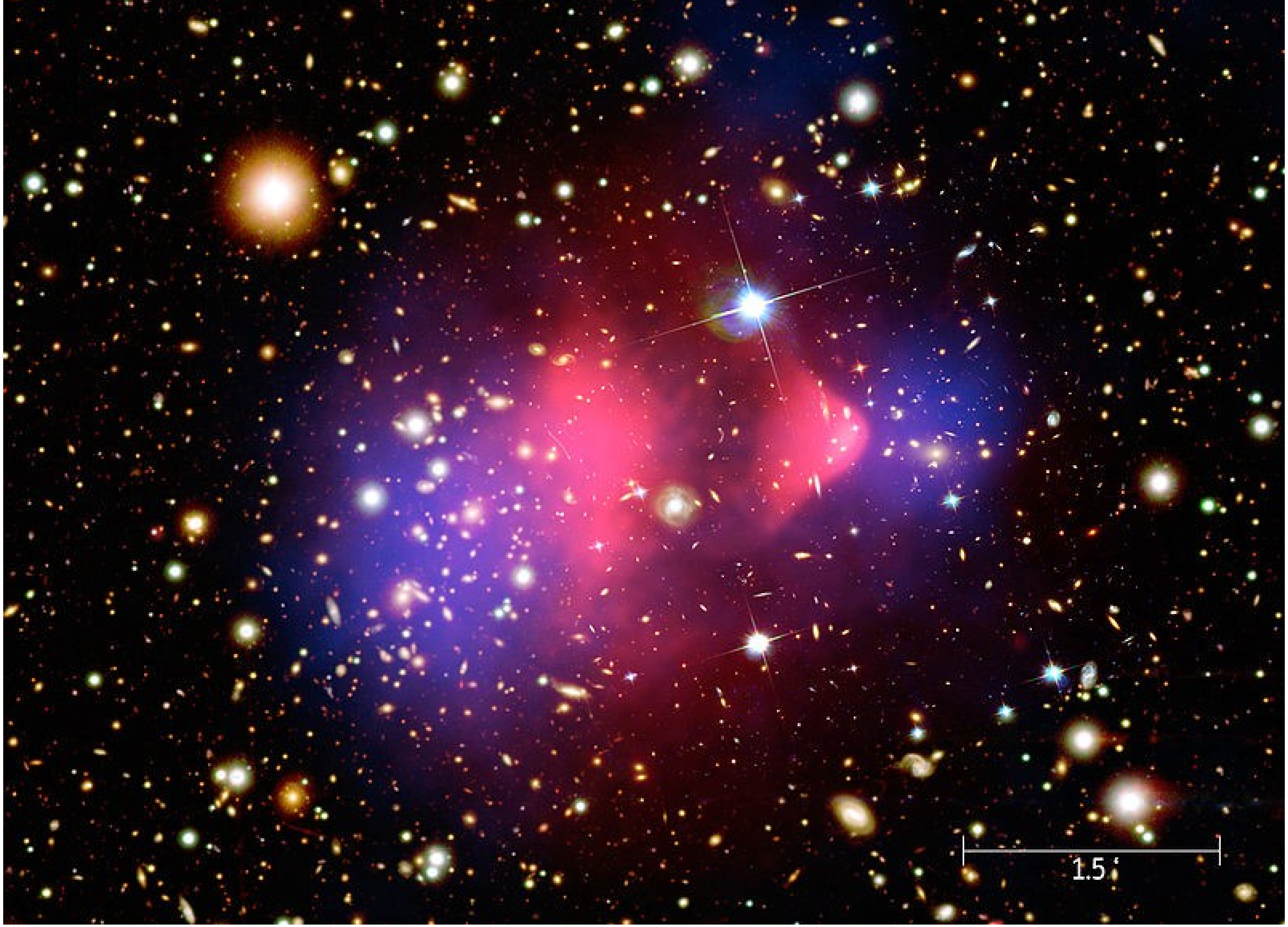
Weak lensing result

Pictures from here





Studies with lensing (strong and weak) confirm that there is much more mass in the Universe than accounted by the visible matter, and distributed differently



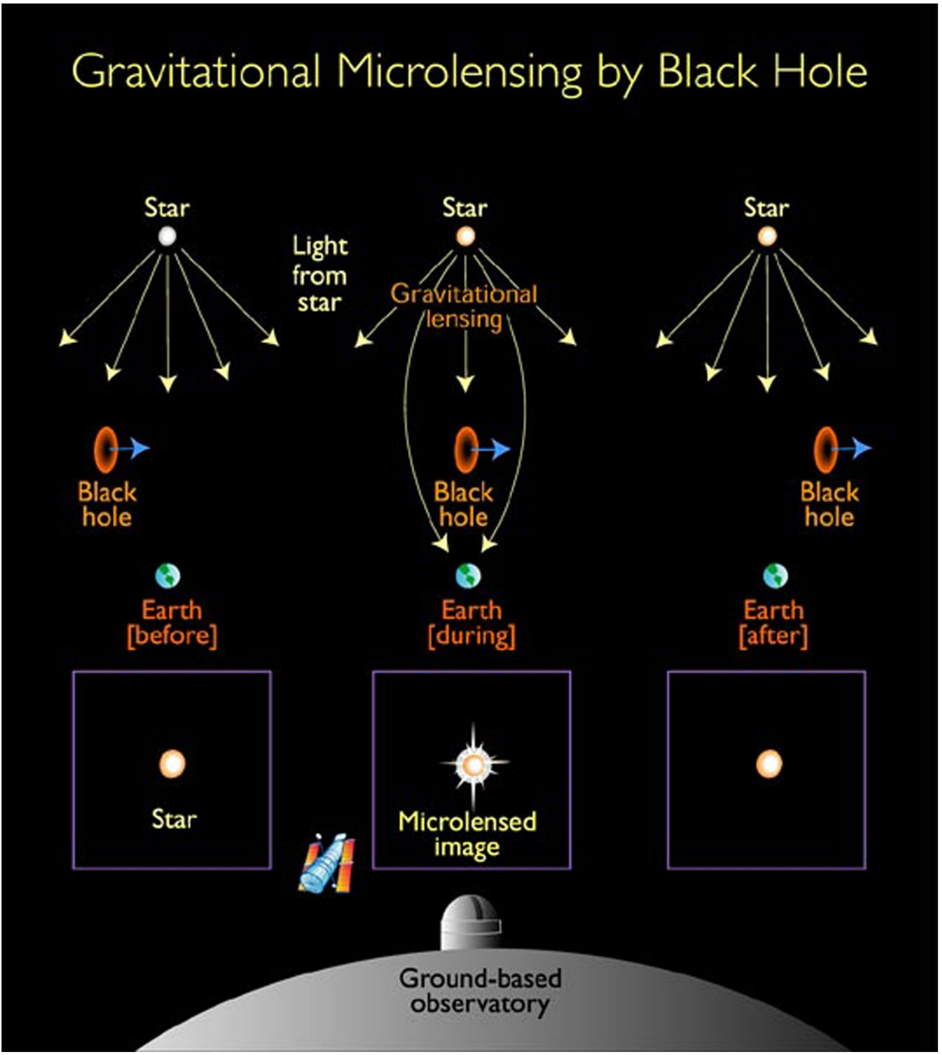
Bullet Cluster. Blue areas: mass distribution reconstructed from strong and weak lensing. Red areas: profile of X-ray emissions (from hot gas).

Interpretation: two clusters collided, EM interactions slowed down the gas, but DM passed through.

Possible composition of DM

- Several hypotheses have been made
  - The most standard: faint stars, brown dwarfs, dust, black holes... (MACHOs)
  - Neutrinos (after all, we know that they have mass)
  - Supersymmetric particles or other Weakly Interacting Massive Particles (WIMPs)
  - Axions
  - Particles from "Hidden Valleys"
  - DM does not exist, but the law of gravity is wrong

Invisible but normal matter?



- Of course, part of normal matter is also invisible (black holes, cold gas) or emits too little to be seen (faint stars, brown dwarfs)
- We call them "MACHOs" (MAssive Compact Halo Objects)
- Estimated by extrapolation, but all extrapolations rely on models
- A recent way to test these models has been offered by gravitational micro-lensing: same principle as before, but looking at temporary increase of brightness of distant stars when a massive object passes in front

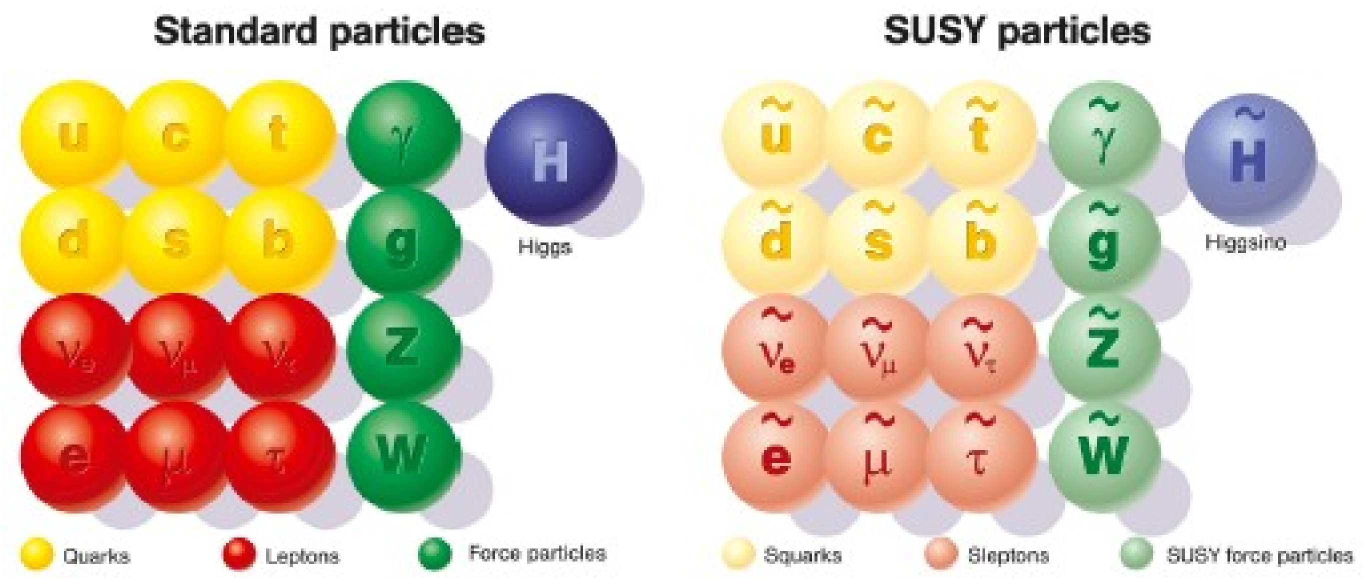
Neutrinos?

- Obviously they contribute to dark matter, but how much?
- It is an example of "hot" DM (i.e., $E_{kin} >> mc^2$)
- Galaxies formed very soon ⇒ most DM is cold
  - Cold DM amplifies local density fluctuations ⇒ bottom-up structure formation
  - Hot DM equalizes density over large scales ⇒ top-down structure formation ⇒ superclusters should have formed first, and then fragmented into clusters, and then galaxies
  - Estimated hot-DM fraction of the Universe: O(0.1%) - O(1%)
- Another possibility: some unknown "heavy neutrino" (it would be "cold" DM), but I will not talk about that

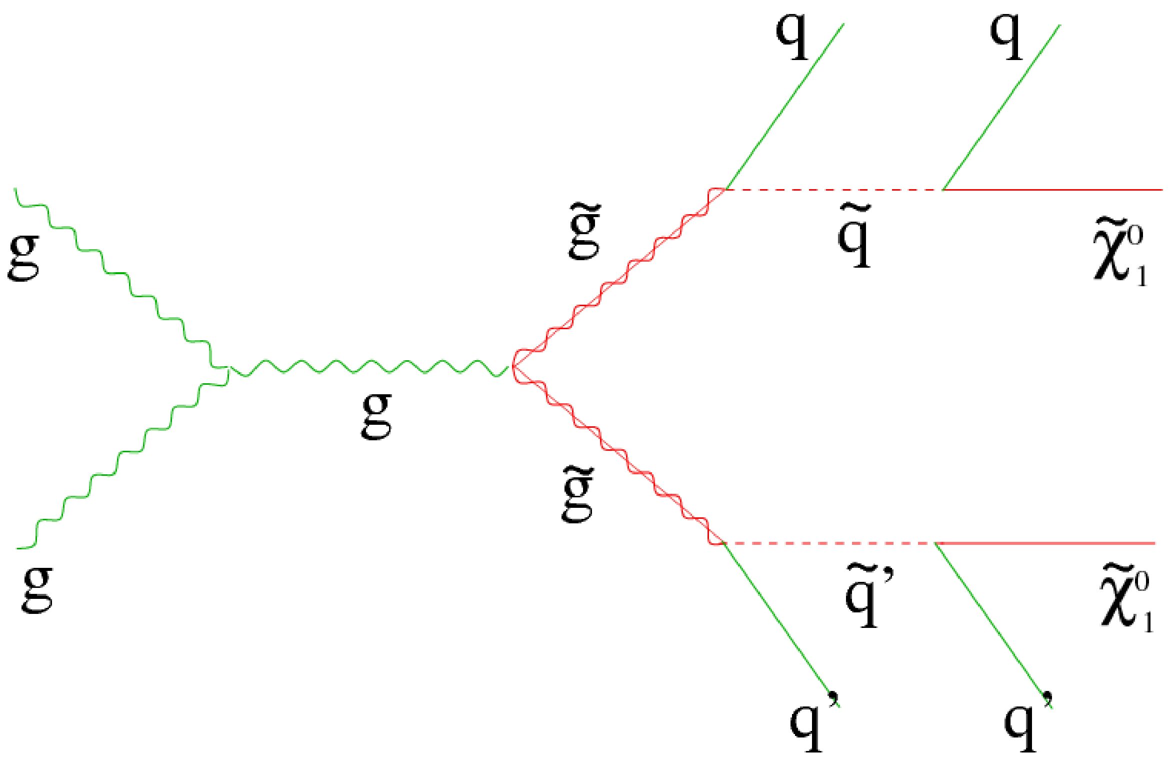
WIMPs
(Weakly Interacting Massive Particles)

- Predicted by many "new physics" models
- Most popular is SUSY (SUper SYmmetry); it postulates that for each fermion there is a boson, and viceversa
    - This theory was formulated for other reasons (because it is elegant, and because it explains why the Higgs boson is several orders of magnitude lighter than its "natural" mass)
    - It must be a "broken symmetry", otherwise we would see the partner of the electron with the same mass of the electron
    - New quantum number R: +1 for normal particles and -1 for their SUSY partners; multiplicative, i.e., **R(A&B) = R(A)R(B)**
    - If heavy SUSY particles were produced in the Big Bang, they decayed to the lightest possible SUSY particle (LSP), but could not decay to normal particles
    - If LSP is neutral, it is a good cold-DM candidate

Minimal SuperSymmetric Model



Example of a "SUSY cascade"



<u>Exercise</u>: show that the R quantum number is conserved in this process

MOND
(MOdified Newtonian Dynamics)

- Basic idea:

$$\mathbf{F_N} = m\mu\left(\frac{a}{a_0}\right)\mathbf{a}$$

- Empirical function $\mu(x)$ must be such that $\mu(x)\rightarrow 1$ for $x>>1$ (i.e., Newton's Law) and $\mu(x)\rightarrow x$ (i.e., $F\sim a^2$) for $x<<1$
- To make this work, you have to choose $\mu(x)$ "smooth" (but the exact functional form is of little importance) and a_0 such to have a negligible effect on "small" scales (e.g., solar system) but large on galactic scales, where accelerations are small
- In the extreme regime $a<<a_0$ (as at large r in galaxies):

$$F_N = ma^2/a_0 \qquad \frac{GMm}{r^2} = m\frac{\left(\frac{v^2}{r}\right)^2}{a_0} \Rightarrow v^4 = GMa_0$$

- So rotation speed would be independent of r, as observed!

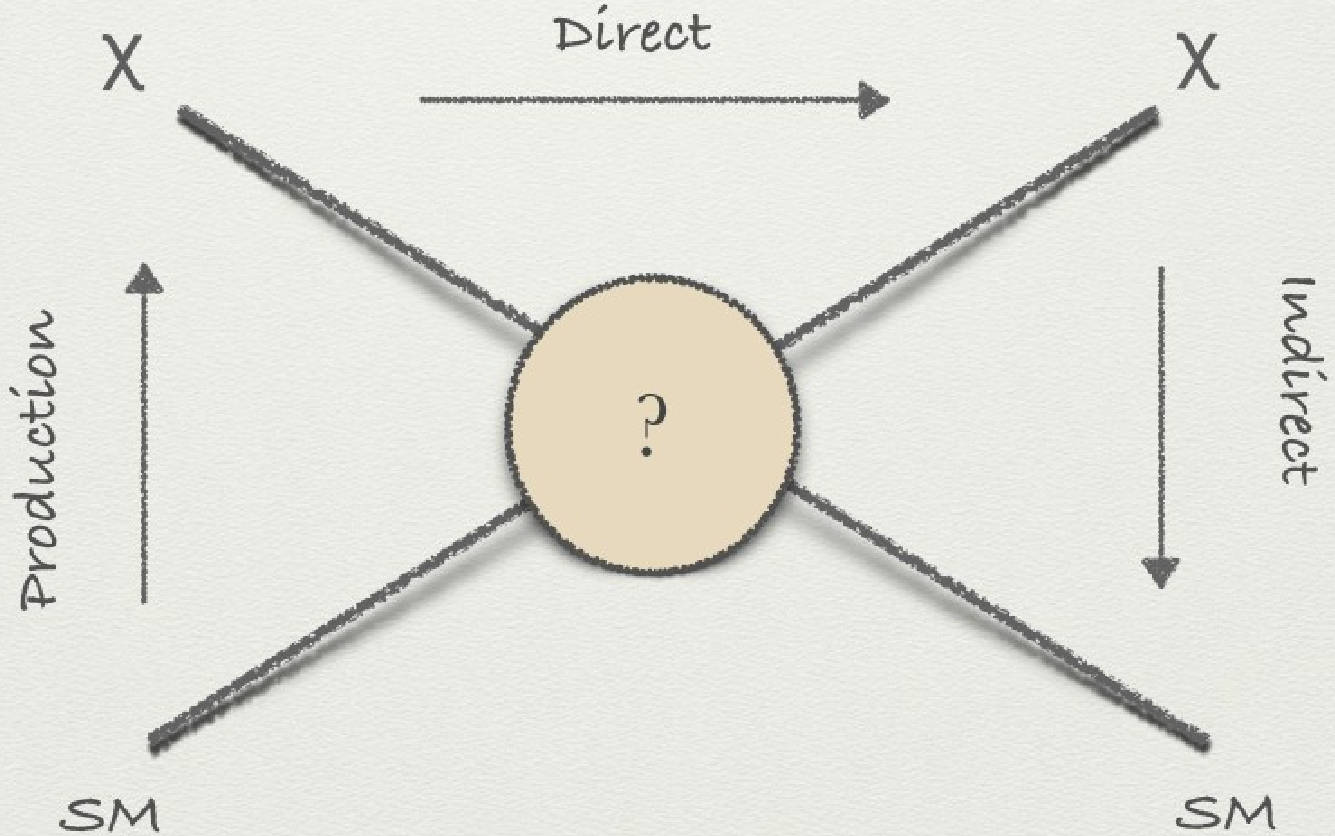
How to search for WIMPs

- Direct detection
  - Similarly to neutrino detectors, try to see them interact despite their weak interaction
  - Experiments must be underground (for the same reason as neutrino experiments)
- Indirect detection
  - Assume that also SUSY partners (or other WIMPs) come as particles and antiparticles; then, in the cosmos, sometimes they must meet and annihilate
  - Energy would convert to high-energy photons
- Production at particle colliders
  - If we provide sufficient energy, we should be able to create the WIMPs, whatever they are

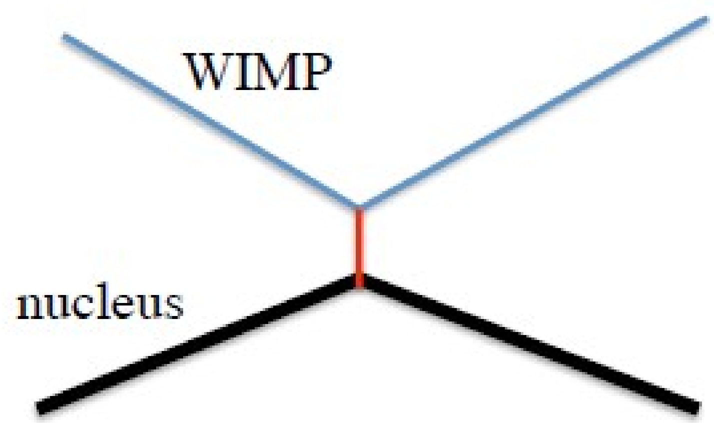
Production $p + \bar{p} \rightarrow \chi + \chi$

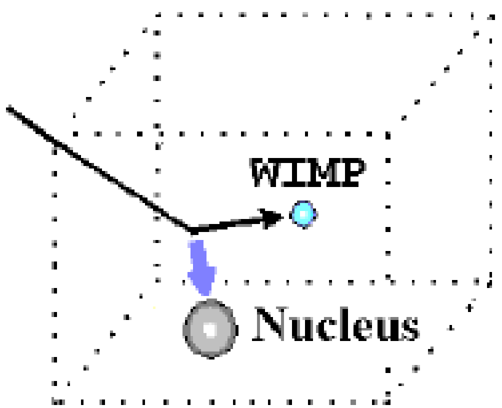
Indirect $\chi + \chi \rightarrow p + \bar{p}$

Direct $\chi + p \rightarrow \chi + p$



Direct detection experiments





<u>Exercise</u>: show that the R quantum number is conserved in this process

Signal modulation with time

$$\frac{dR}{dE_R} = N_T \, n_{\rm DM} \int_{v \geq v_{min}} d^3\mathbf{v} \, v \, f_{\rm LAB}(\mathbf{v}) \frac{d\sigma}{dE_R} \qquad [\text{cpd/kg/keV}]$$

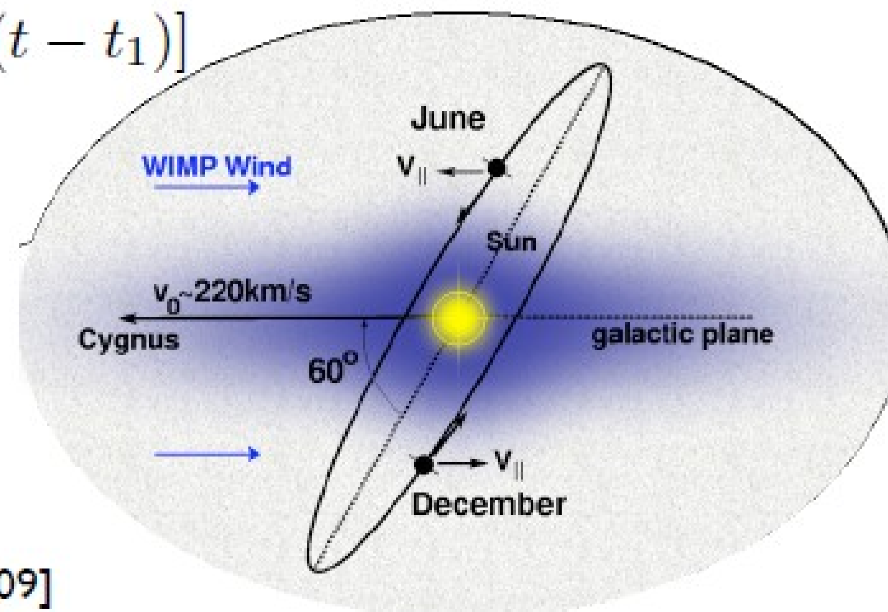
$$\downarrow$$

$$f_{\rm GAL}(\mathbf{v}_{\rm obs} + \mathbf{v})$$

$$\mathbf{v}_{\rm obs} = \mathbf{v}_{\odot} + V_{\oplus} \left[\varepsilon_1 \cos\omega\,(t - t_1) + \varepsilon_2 \sin\omega\,(t - t_1) \right]$$

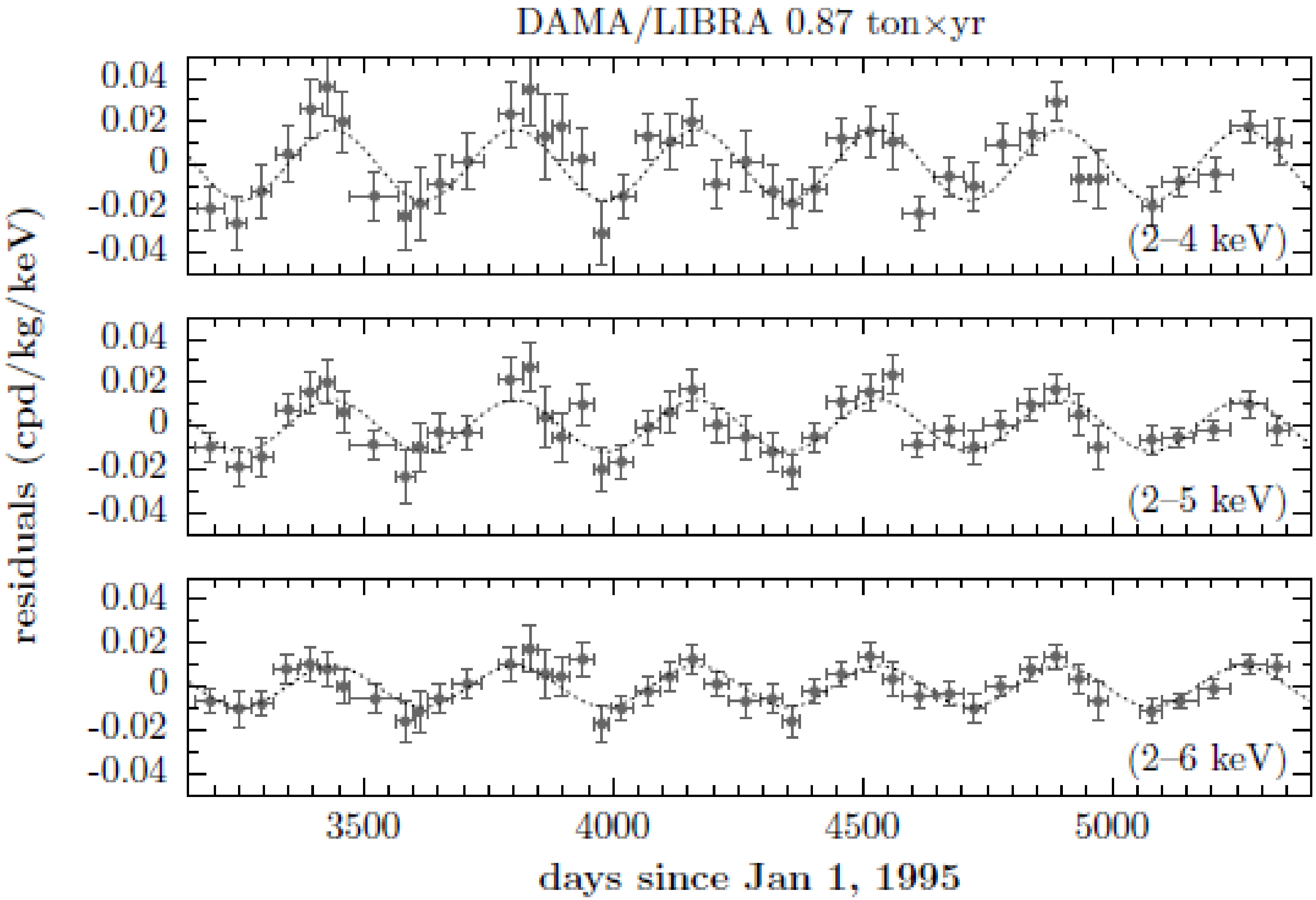
$$|\mathbf{v}_{\rm obs}| = |\mathbf{v}_{\odot}| + \frac{1}{2} V_{\oplus} \cos\omega(t - t_0)$$

$t_0 \simeq 152\,\text{days} \quad (\text{June 2nd})$



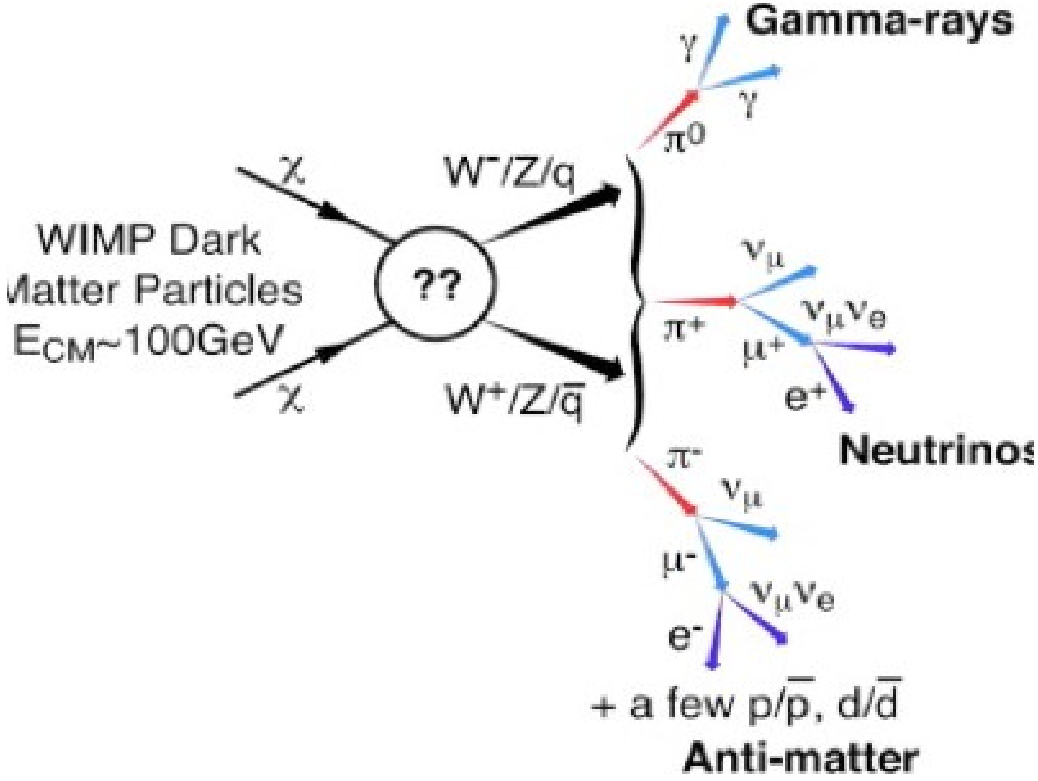
see e.g. [Druiker et al, 1986; Freese et al, 1988; Savage et al, 2009]

The DAMA experiment result



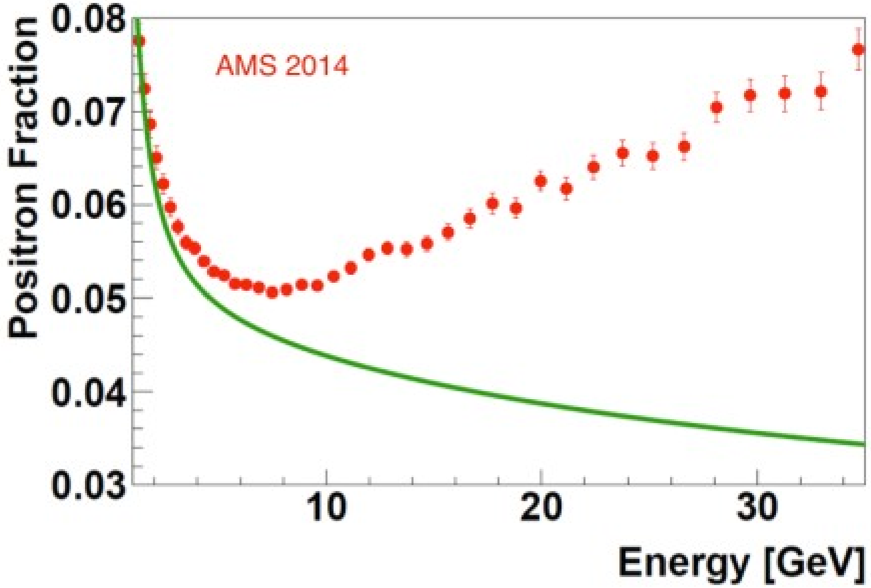
Unfortunately, never confirmed (and in fact, even excluded) by other similar experiments.
But reason for this modulation has never been found.

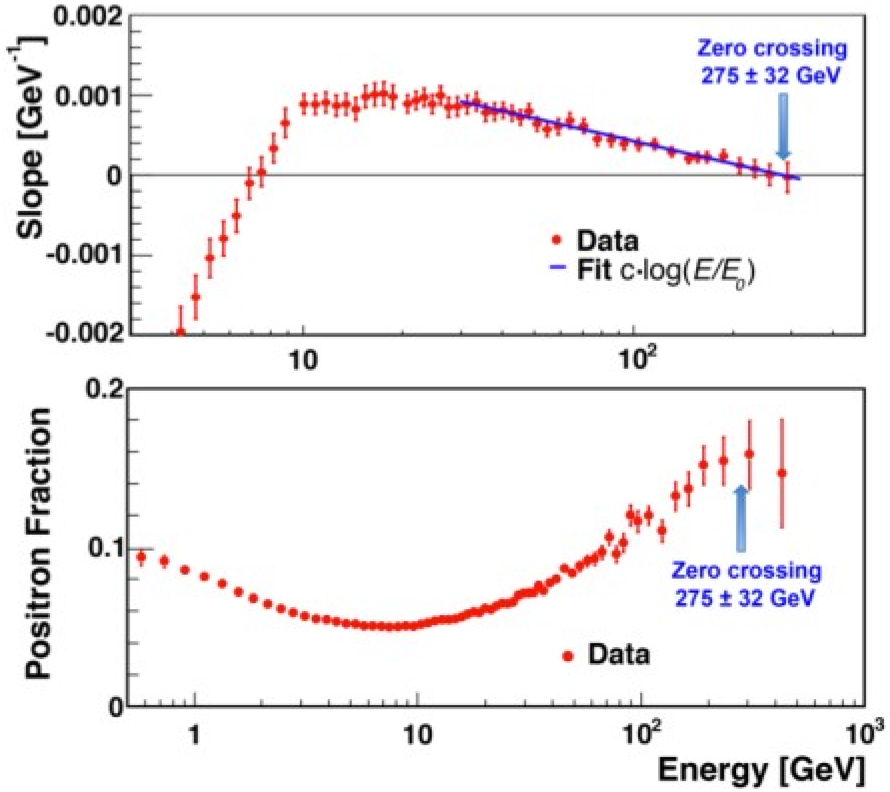
Decay products from space



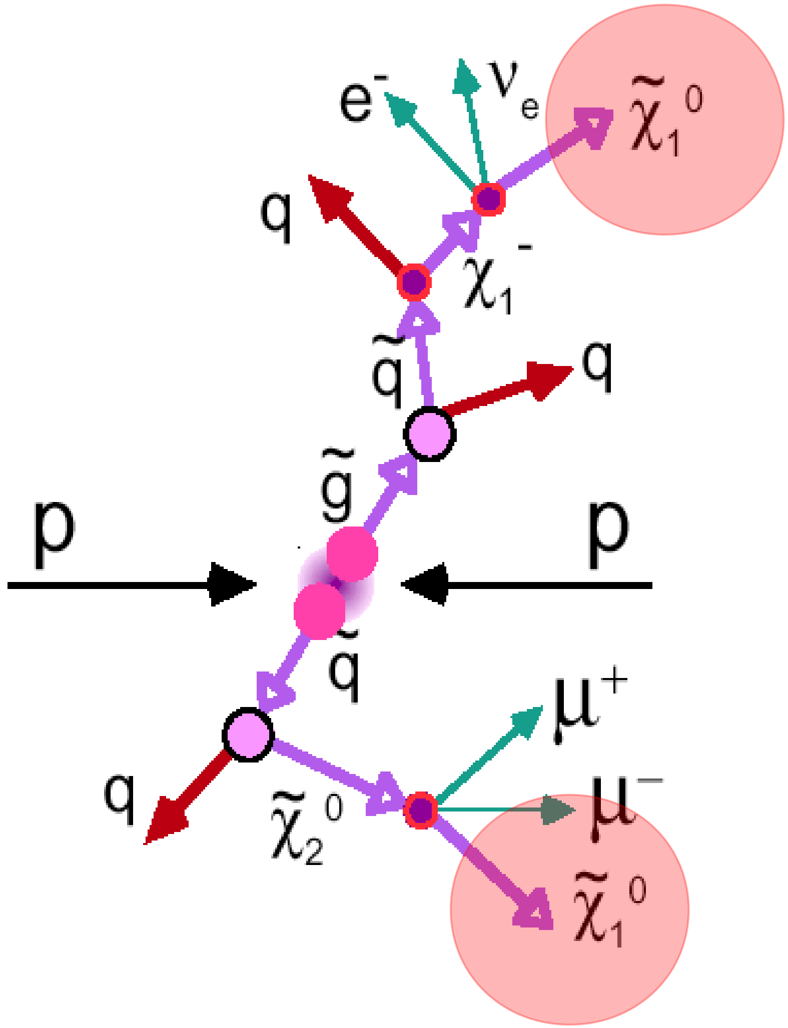
Exercise: show that the R quantum number is conserved in this process

Recent result from AMS
(see chapter 6)





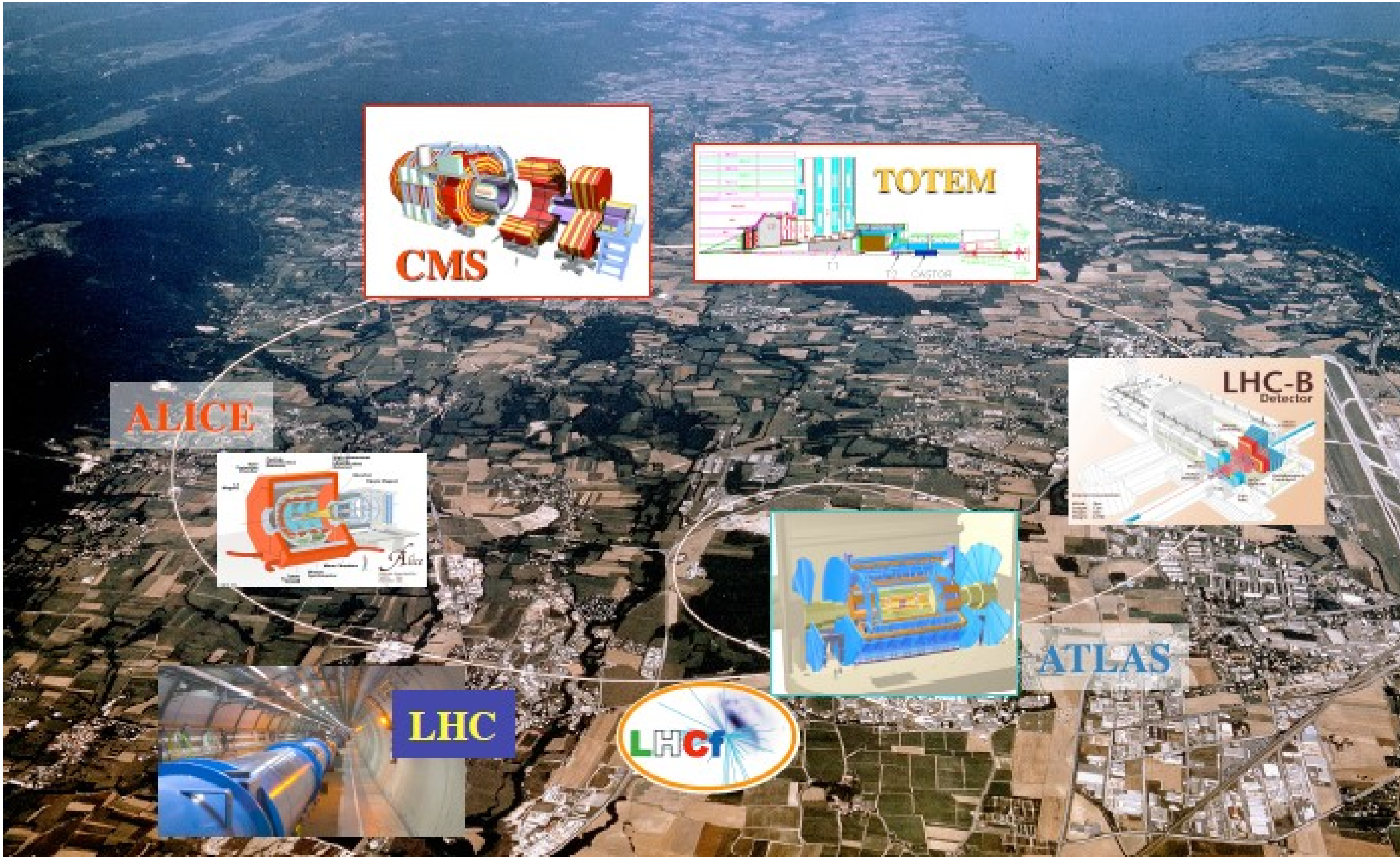
Searches at particle colliders



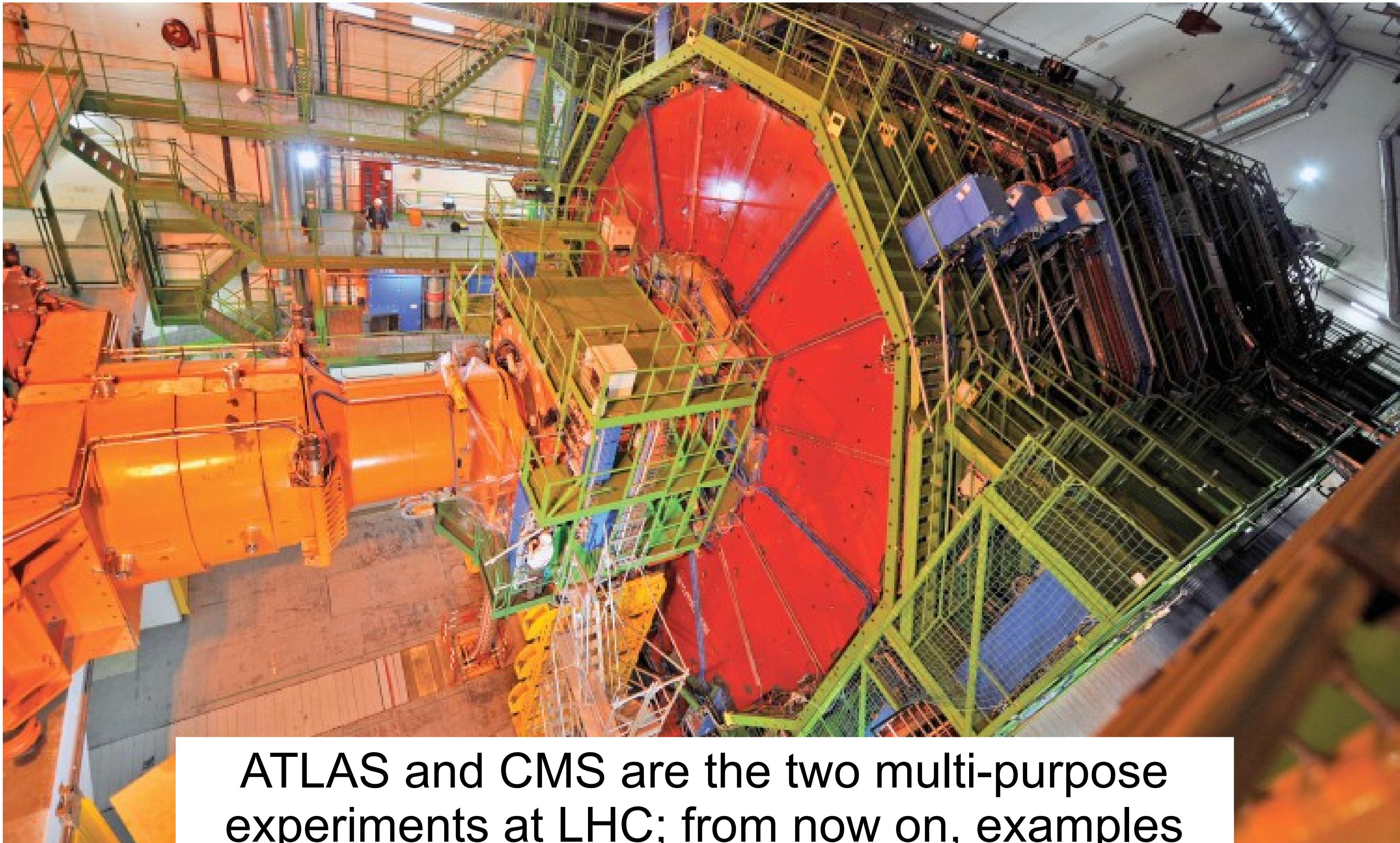
<u>Exercise</u>: show that the R quantum number is conserved in this process

This is just another example of a SUSY cascade; there are many more that one can exploit to search for SUSY evidences

Large Hadron Collider (LHC)

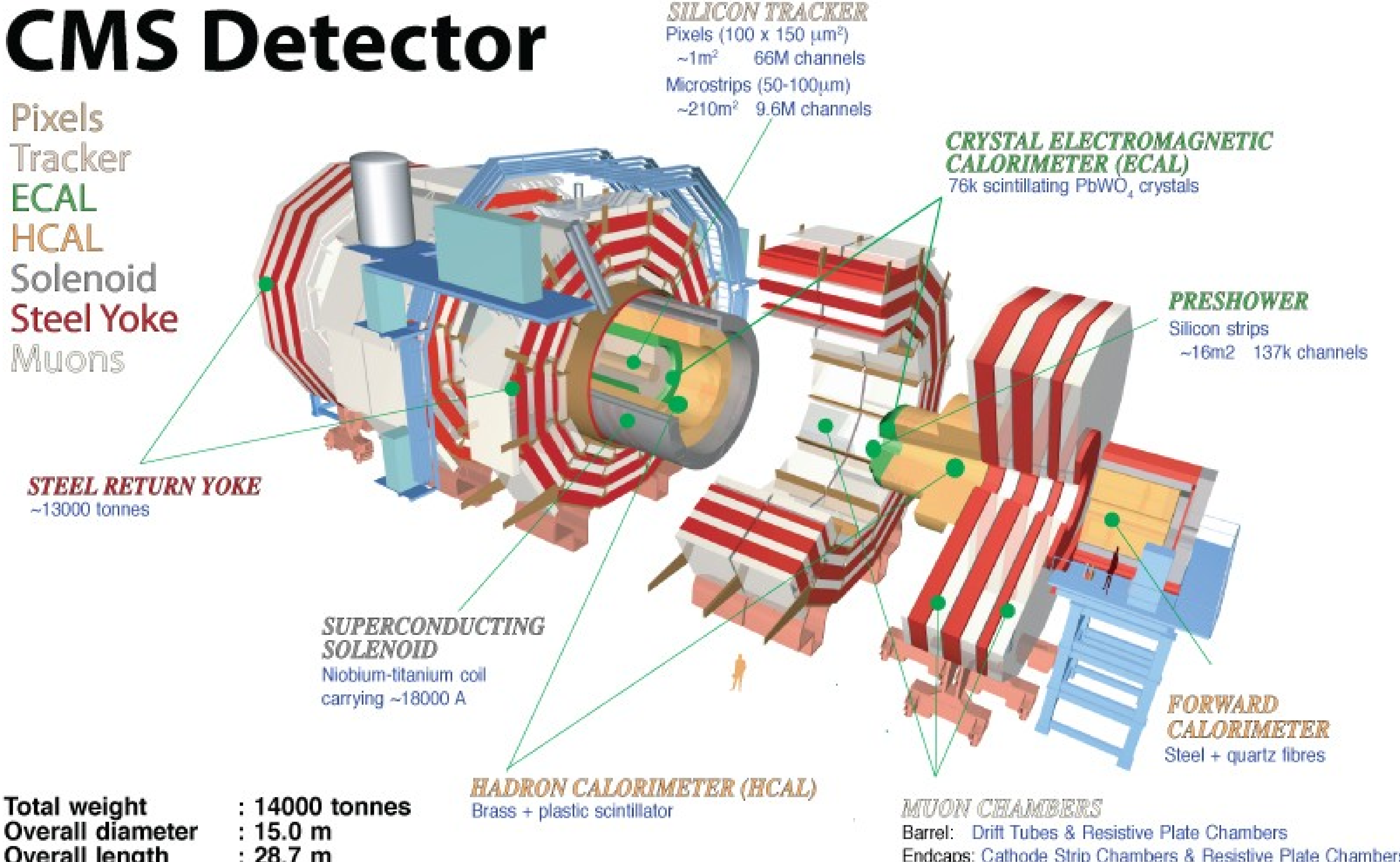


CMS detector

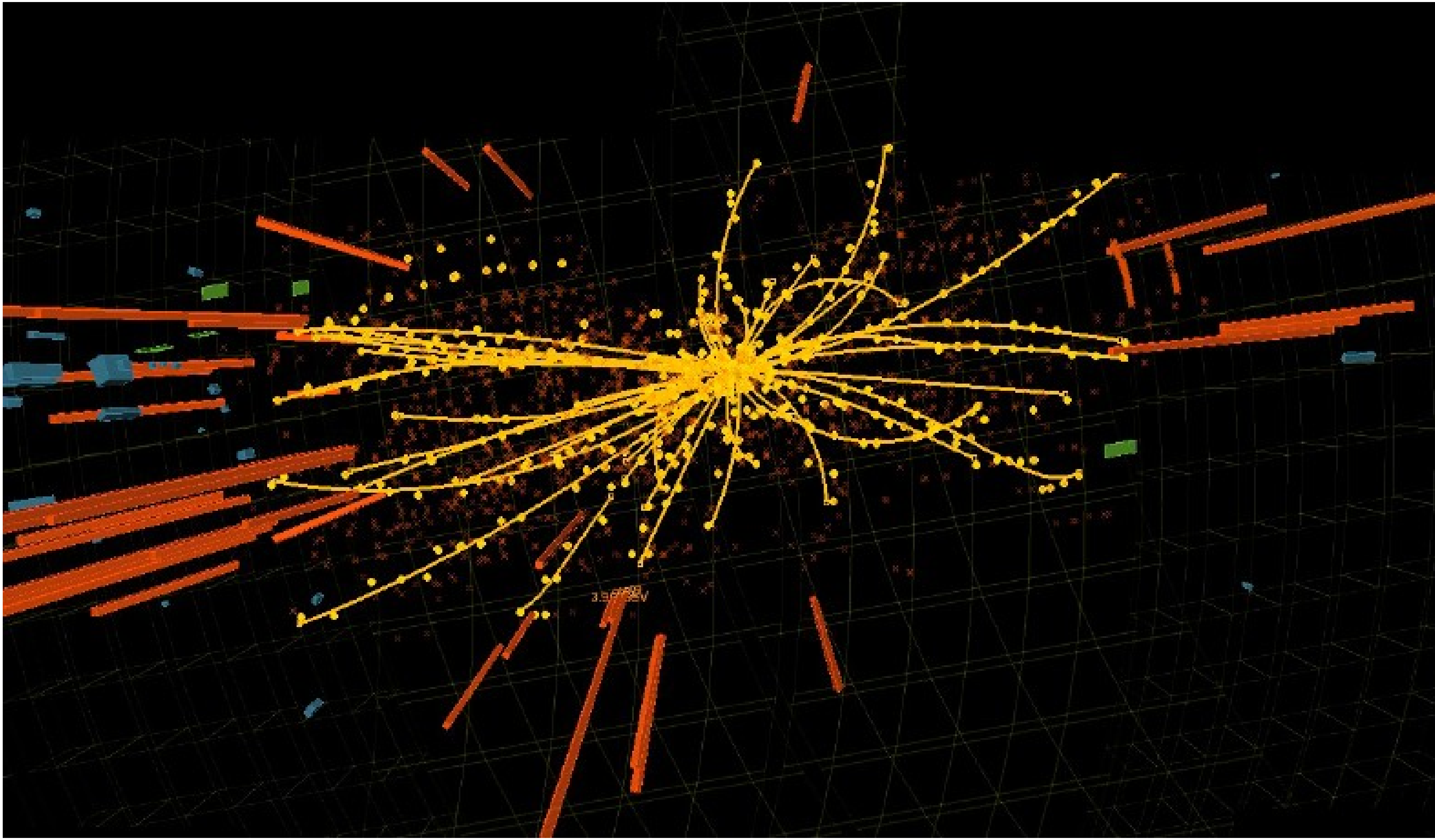


ATLAS and CMS are the two multi-purpose experiments at LHC; from now on, examples from CMS (just because it is what I work on)

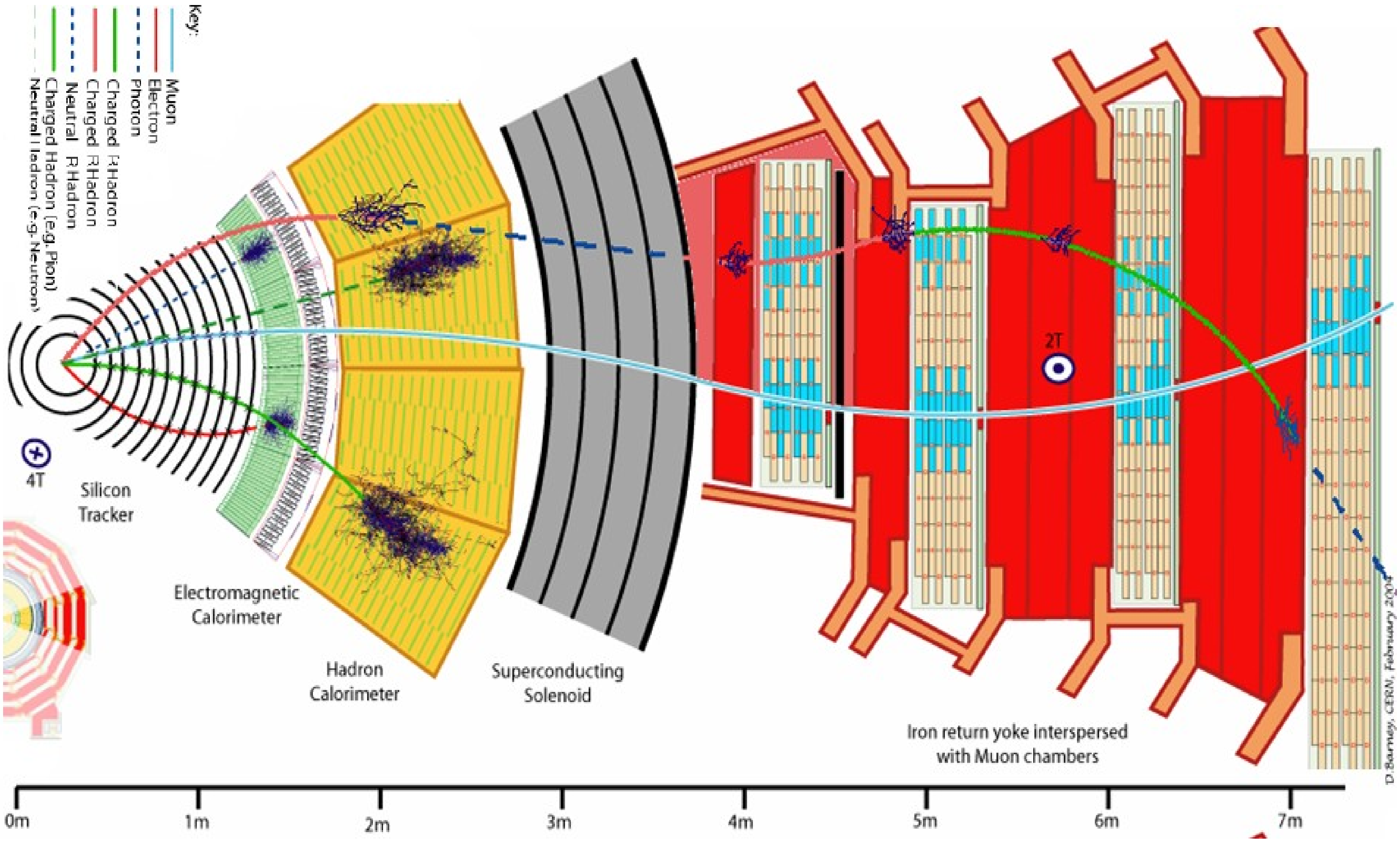
CMS Detector



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

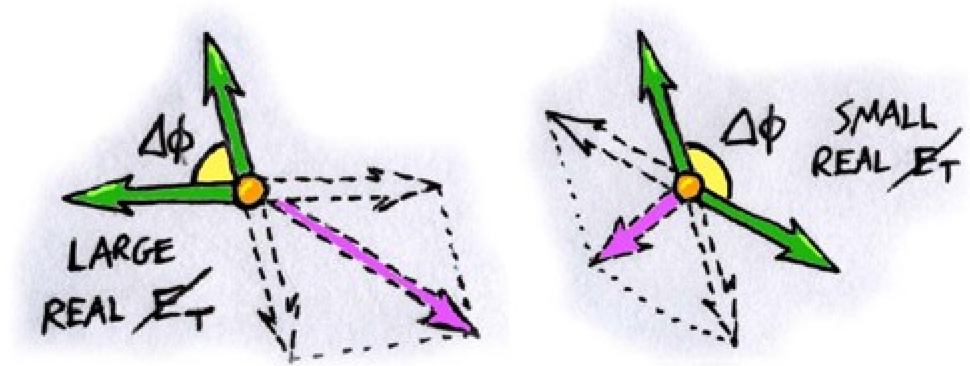


Particle detection in CMS



But neutrinos and WIMPs
don't leave any signal in our detector...

How to see WIMPs (e.g., LSP) with CMS or ATLAS



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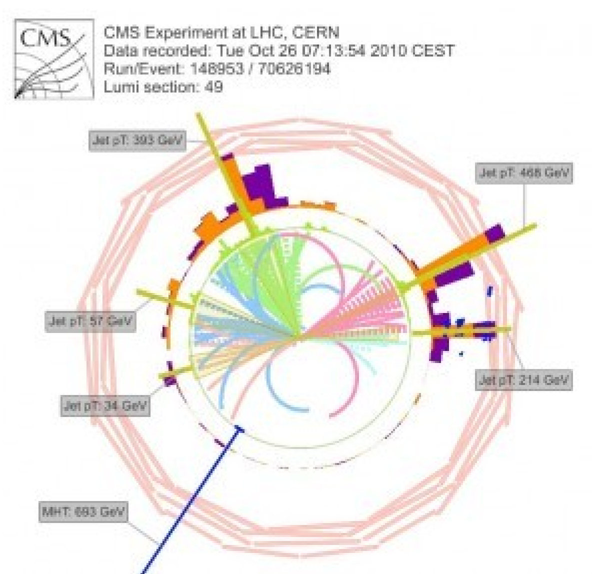
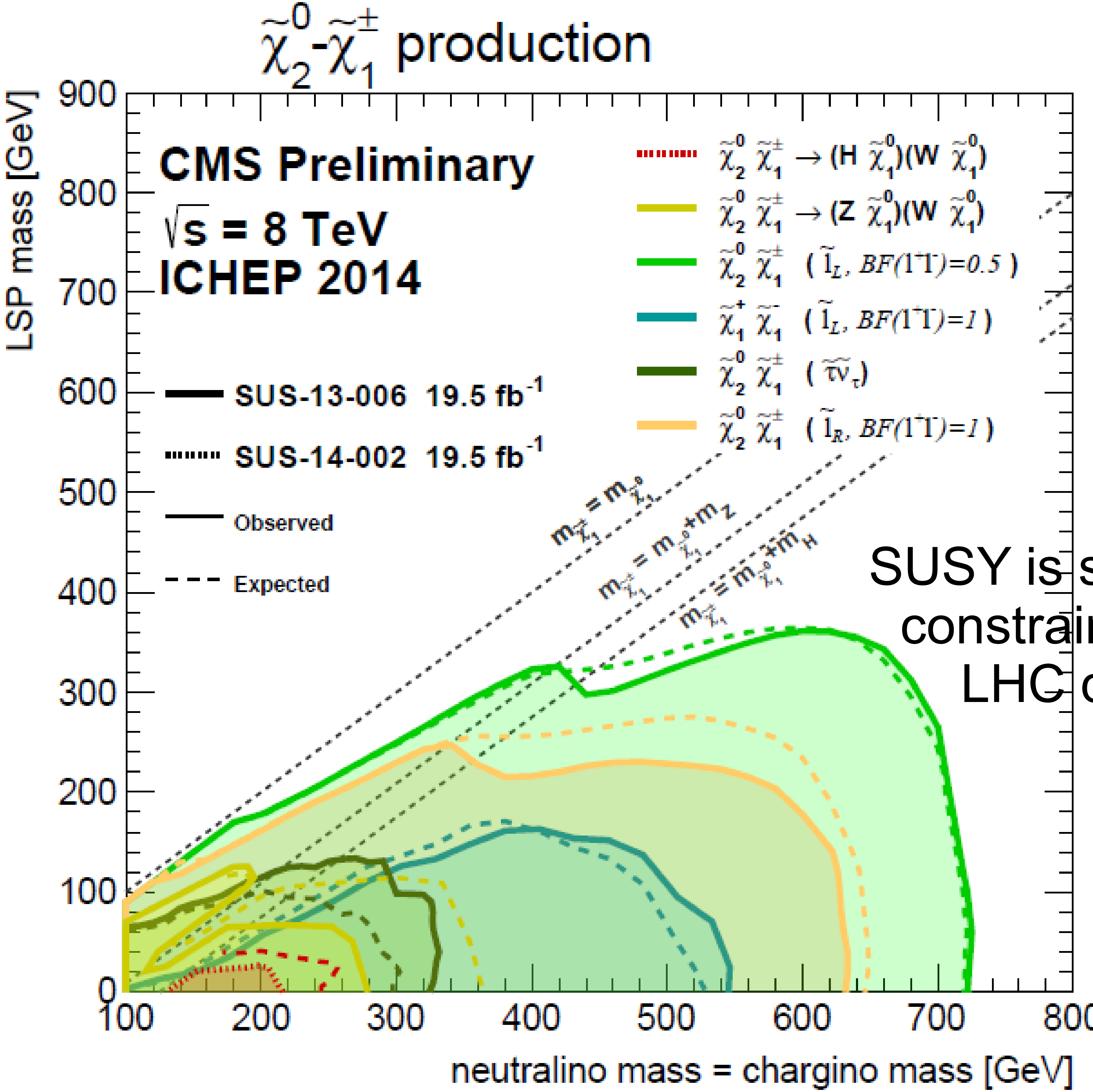
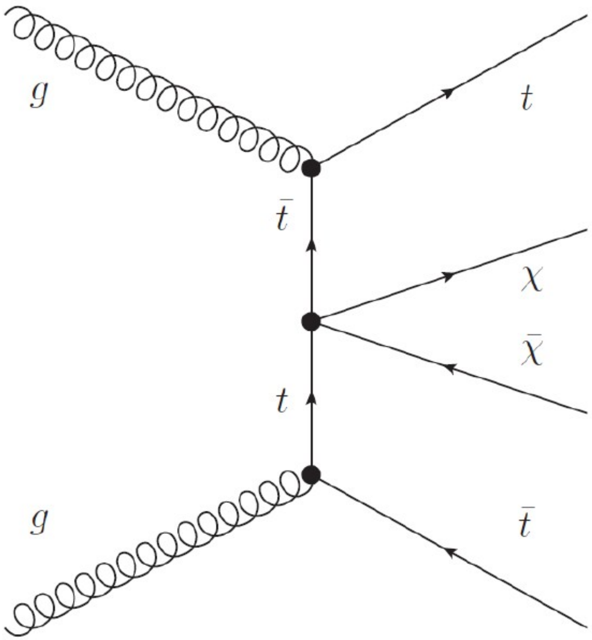
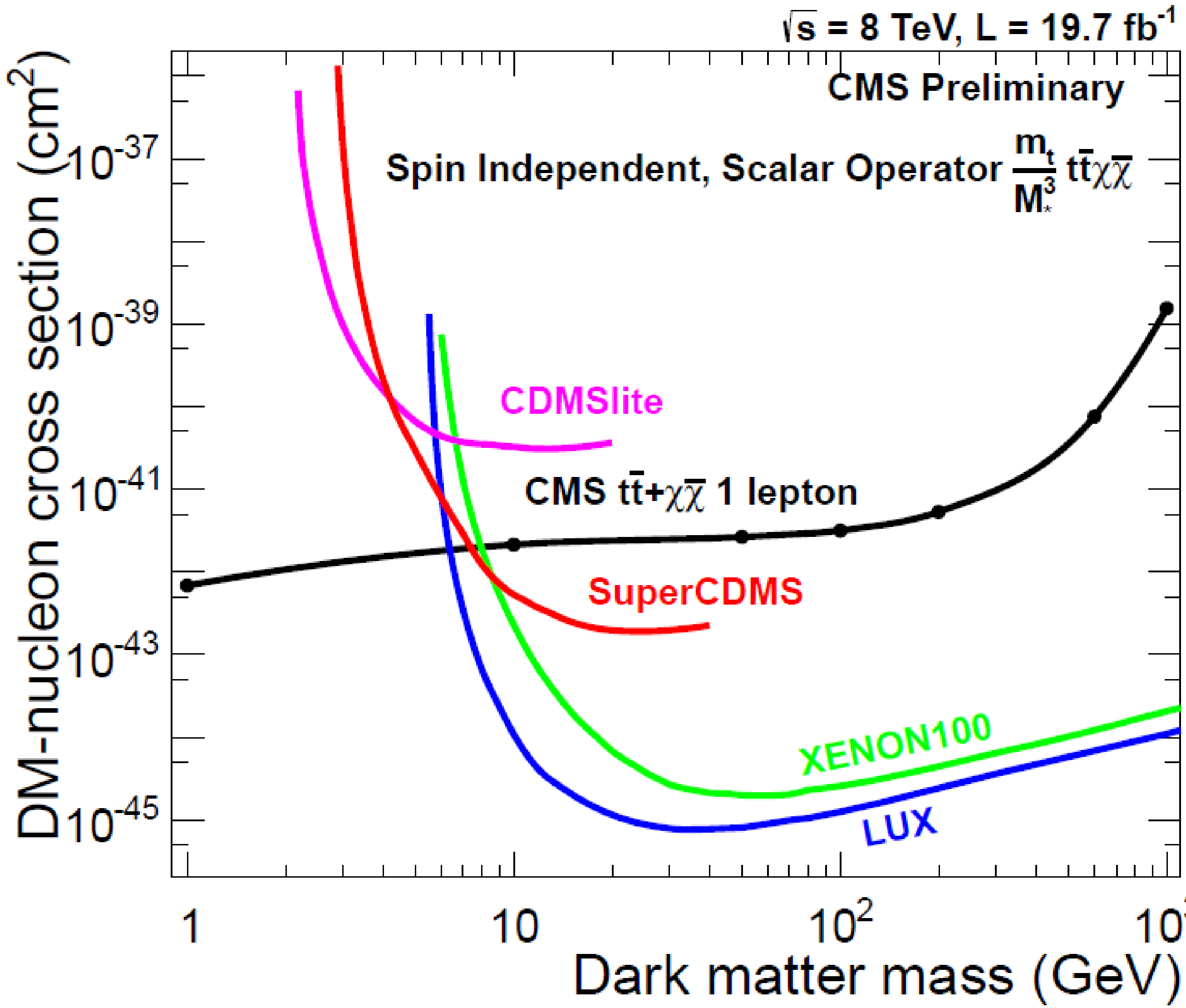
Missing momentum (or missing energy) method





SUSY is severely constrained by LHC data





LHC searches are complementary to direct detection experiments