Search for Dark Matter at the LHC

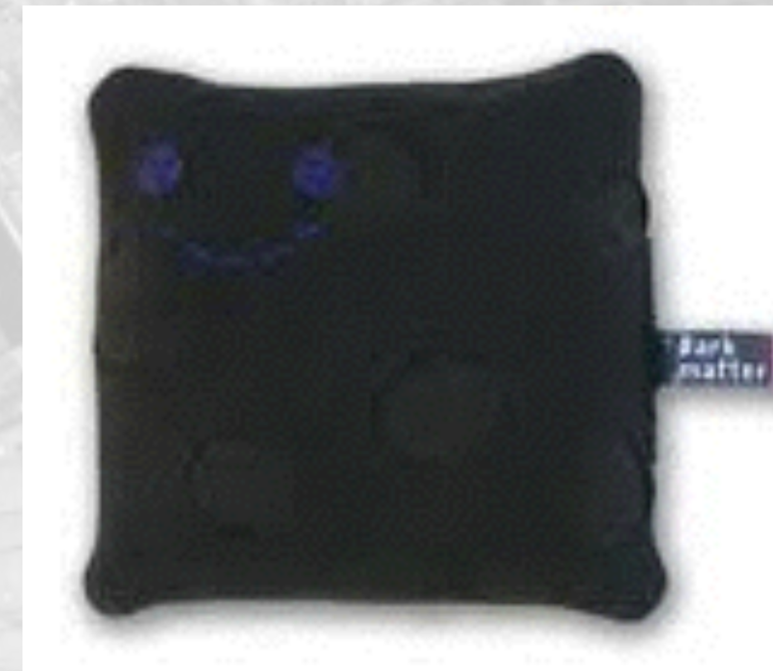
Maurizio Pierini
CERN

Outline

- What is Dark Matter
- Evidence for Dark Matter from Space
  - Galaxy rotation curves
  - Gravitational Lenses
  - The CMB spectrum
  - Bullet Cluster
  - The ΛCDM model of cosmology
- The WIMP paradigm
- Search for Dark Matter with space detectors
- Search for Dark Matter underground
- Search for Dark Matter at the LHC
  - Missing transverse energy
  - SM background
  - Results
- Conclusions

What is Dark Matter

- The majority of Matter in the universe is protons in H and He atoms in burning stars
- We can see this matter, as stars emit light burning
- Dark matter is a form of matter that we cannot see directly (no light emitted)…



- … but through the distortions it causes on the motion of visible matter (through gravitation effects). For instance, the mass of the black hole at the centre of our Galaxy is known from the trajectories around it)

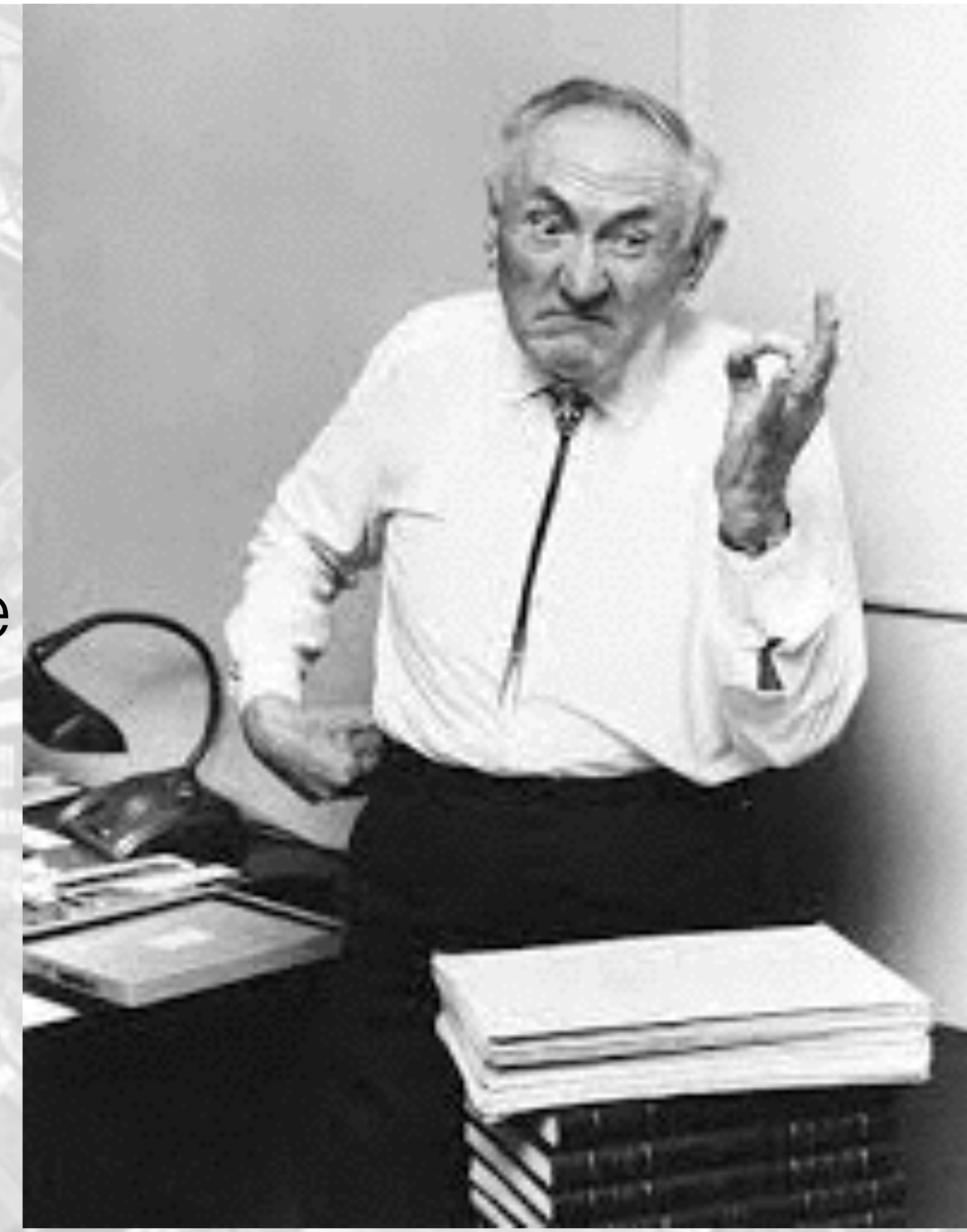

Dark Matter
Observation in Space

’30:The Coma Cluster

- In 1933, studying the Coma galaxy cluster, Fritz Zwicky observed a violation of the viral theorem

- For a power-law potential, one can connect the average kinetic energy to the total potential energy

$$V(r) \sim \frac{1}{r} \Rightarrow 2\langle T \rangle = -\langle V_{TOT} \rangle$$



- As an explanation, he proposed the existence of a dark matter in the galaxy, whose gravitational effect was affecting the distribution of stars

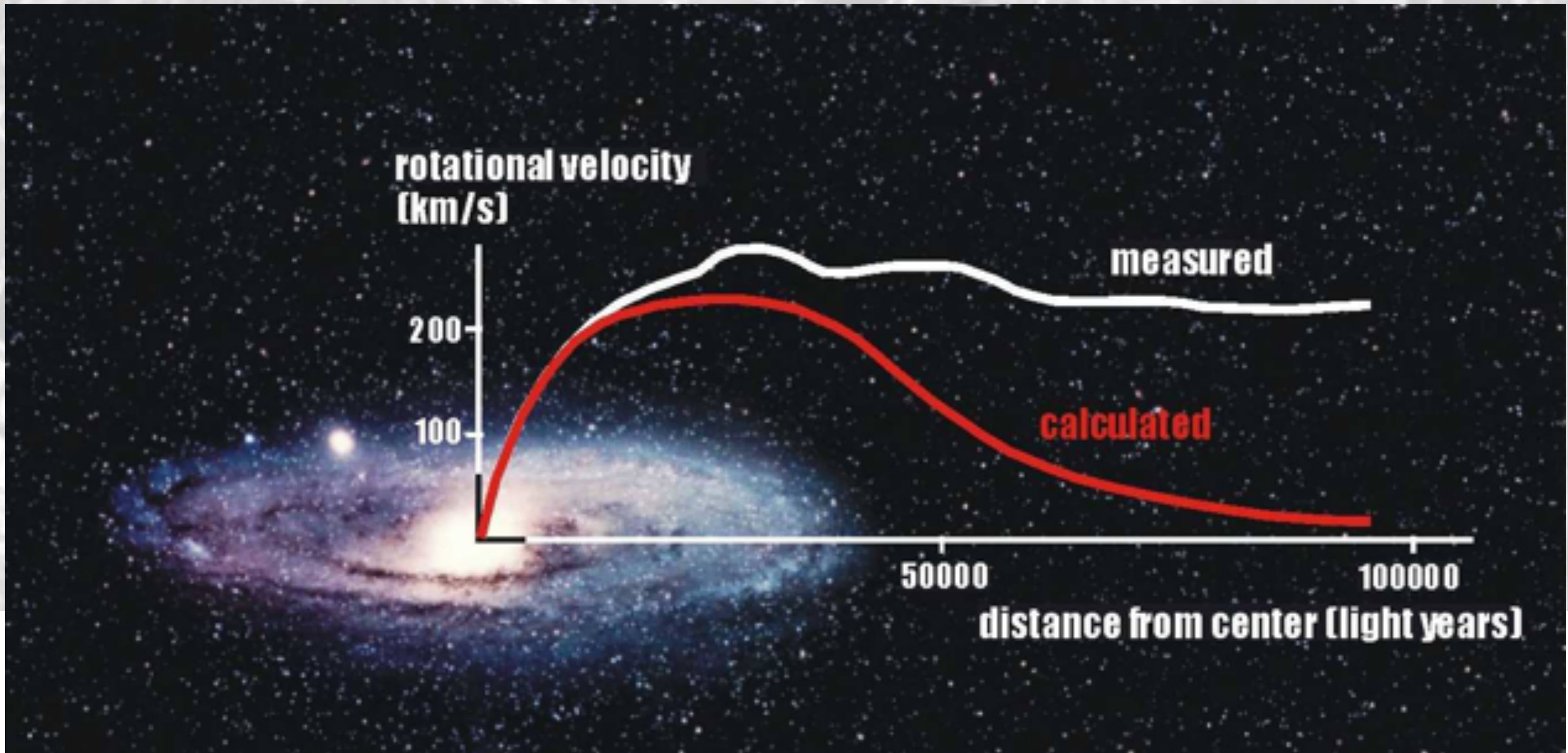
‘70: Galaxy Rotation Curve

- An object in a circular orbit around heavy objects has a circular velocity which depends on the mass inside the orbit

$$\frac{v_{circ}^2}{R} = \frac{GM(R)}{R^2} \qquad M(R) = \frac{v_{circ}^2 R}{G}$$

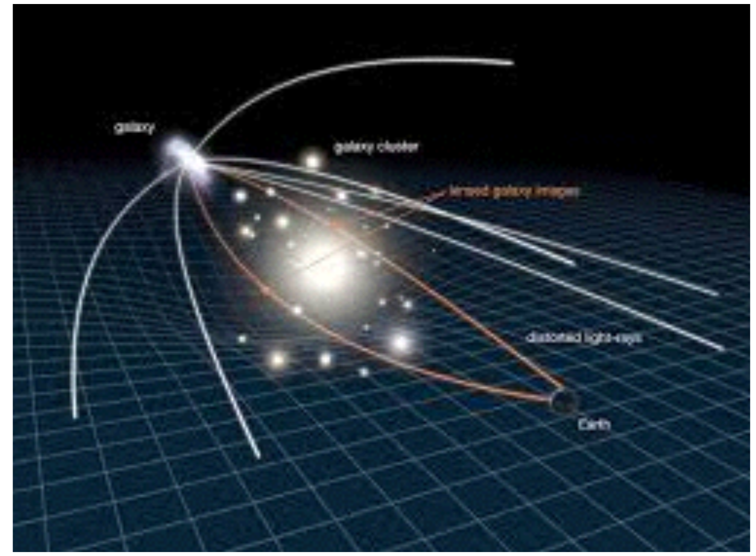
- At the boundary of a galaxy, at large distances the mass does not increase. Hence the velocity should drop

- Instead, Vera Rubin (and others) observed a velocity constant with *R*. Hence the mass is increasing with *R*. There should be a halo of obscure mass (dark matter) to compensate the expected drop (or gravitation is failing)

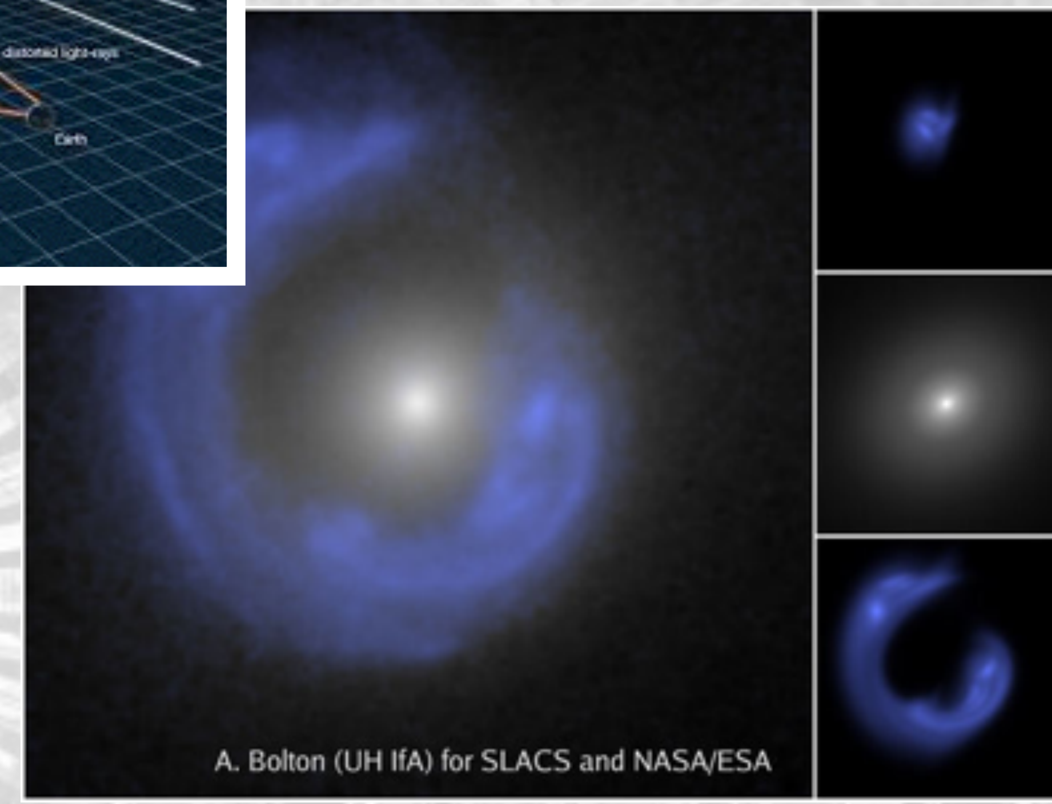


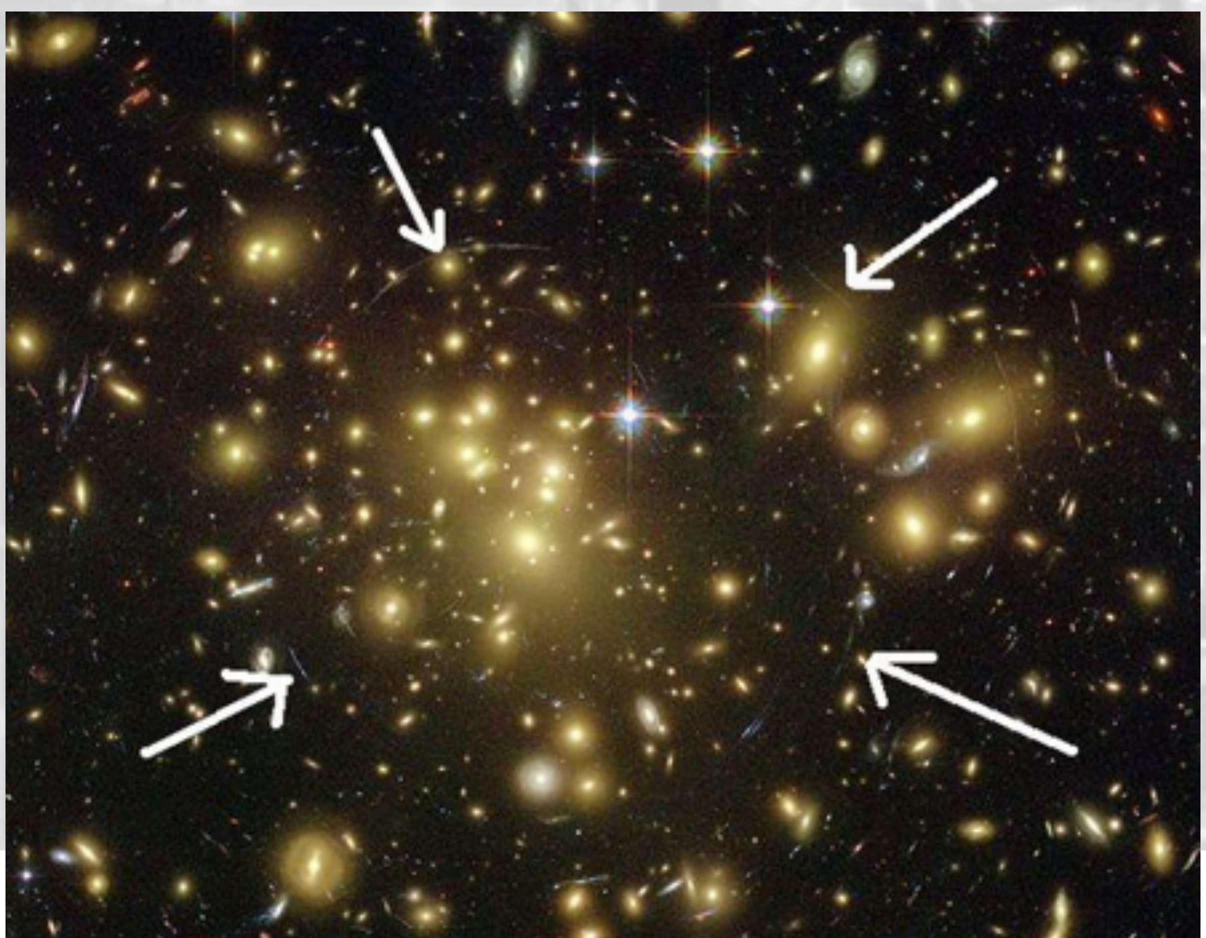
Gravitational Lenses

- Matter and Energy concentration curves space and time (Einstein's General Relativity)



- As a consequence, one can observe arcs around starts, due to the distorted path of light coming from a source behind the star



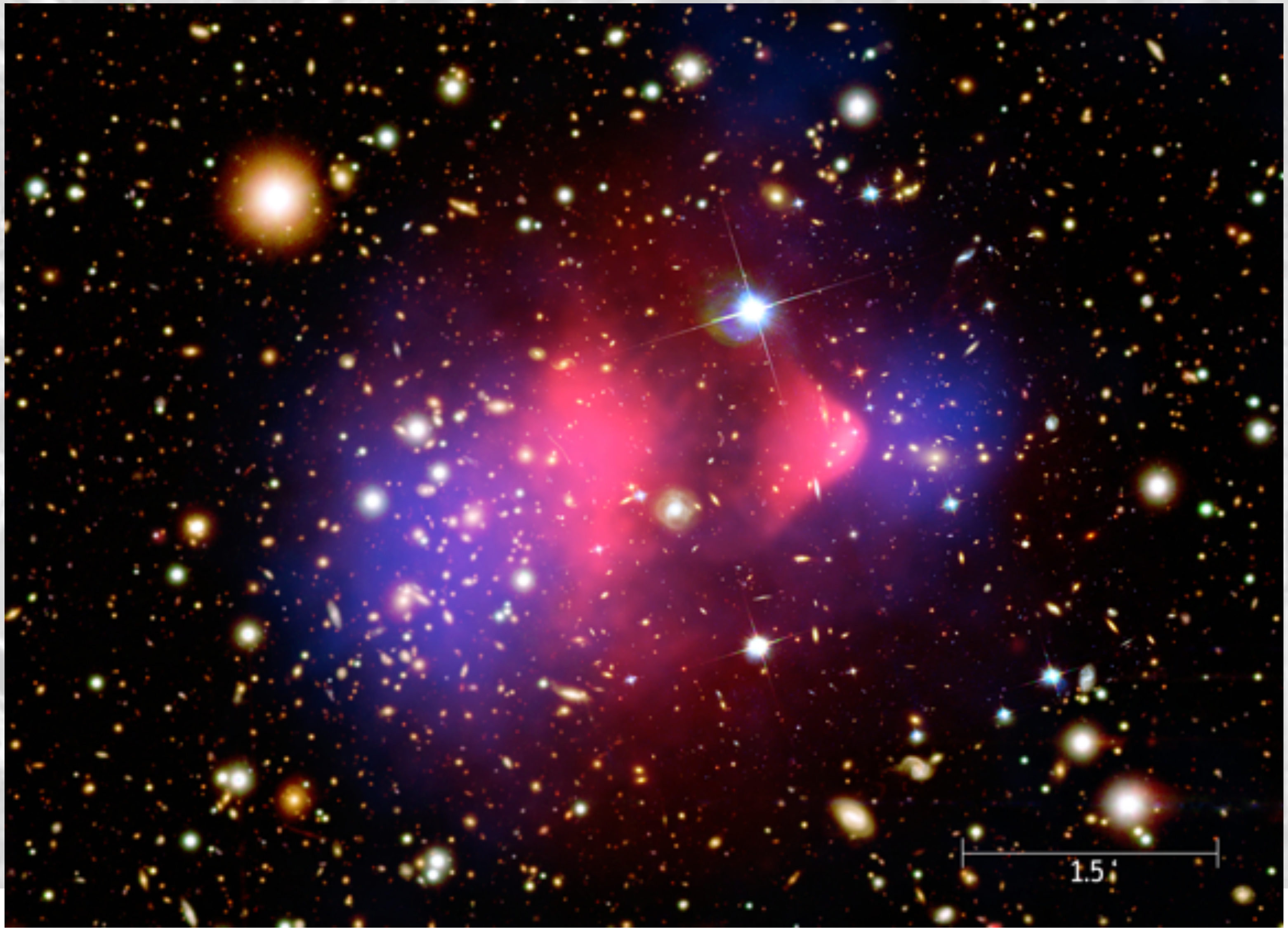


- This effect is observed w/o seeing a large-enough mass at the centre of the arcs

- Some unseen matter has to be there, or gravitation is failing

Dark Particles: Bullet Cluster

- The collision of two clusters of galaxies was observed
- The shock caused a displacement of stars and intergalactic gasses
- The centre of the baryonic mass (blue) was observed looking at stars
- The interstellar gas (observed from X-ray emission) was found to lag behind (red)
- This could be explained assuming that the majority of the mass is included in some invisible halo of particles (more similar to the gas)
- The galaxies behave like stones inside two colliding cotton balls: the stones emerge from the collisions, while the cotton balls are stuck in the collision point



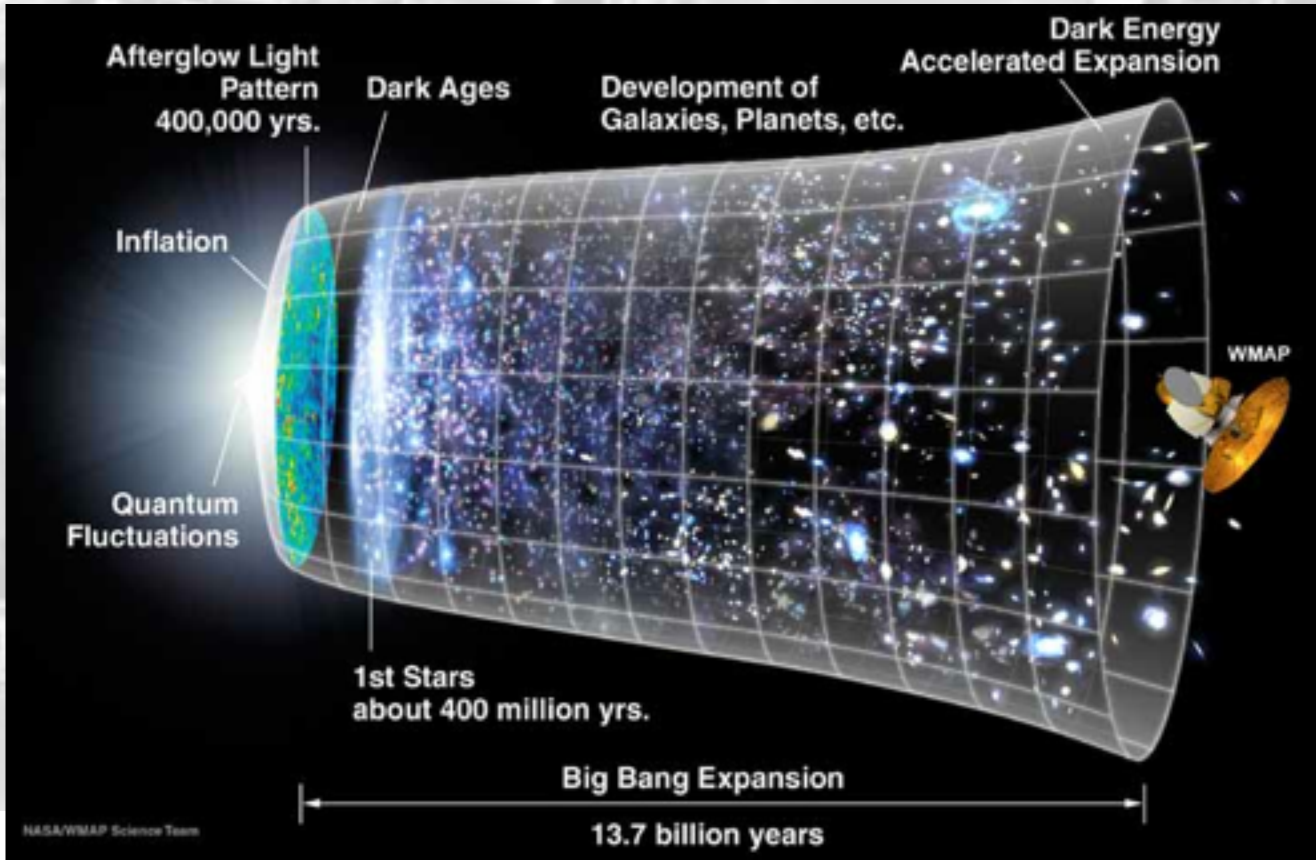
The CMB spectrum

- Big Bang Theory predicted the existence of a isotropic radiation, remnant of the explosion

- The radiation was discovered accidentally by Penzias&Wilson at Bell lab in 1964

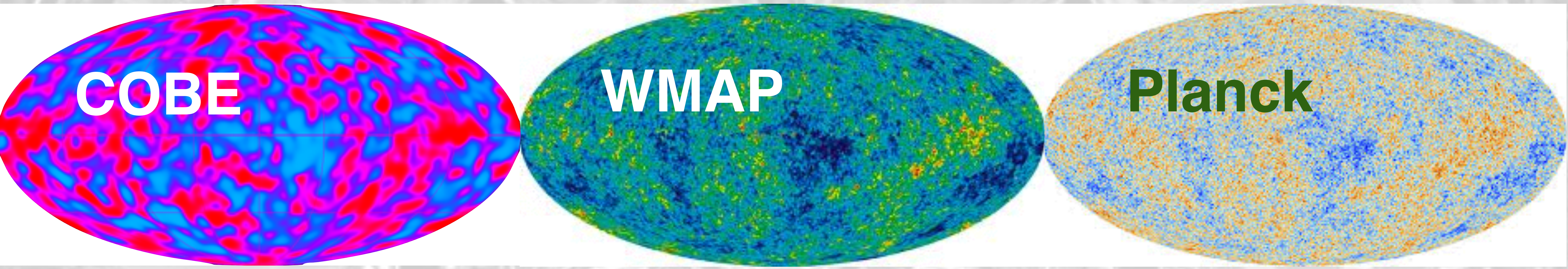
- The radiation corresponds to (small) temperature of the Universe now, consequence of the cooling of the Universe with the expansion

- It was then realised that detecting the fluctuations of this temperature one could see the footprint of visible & dark matter at some early moment of the Universe evolution



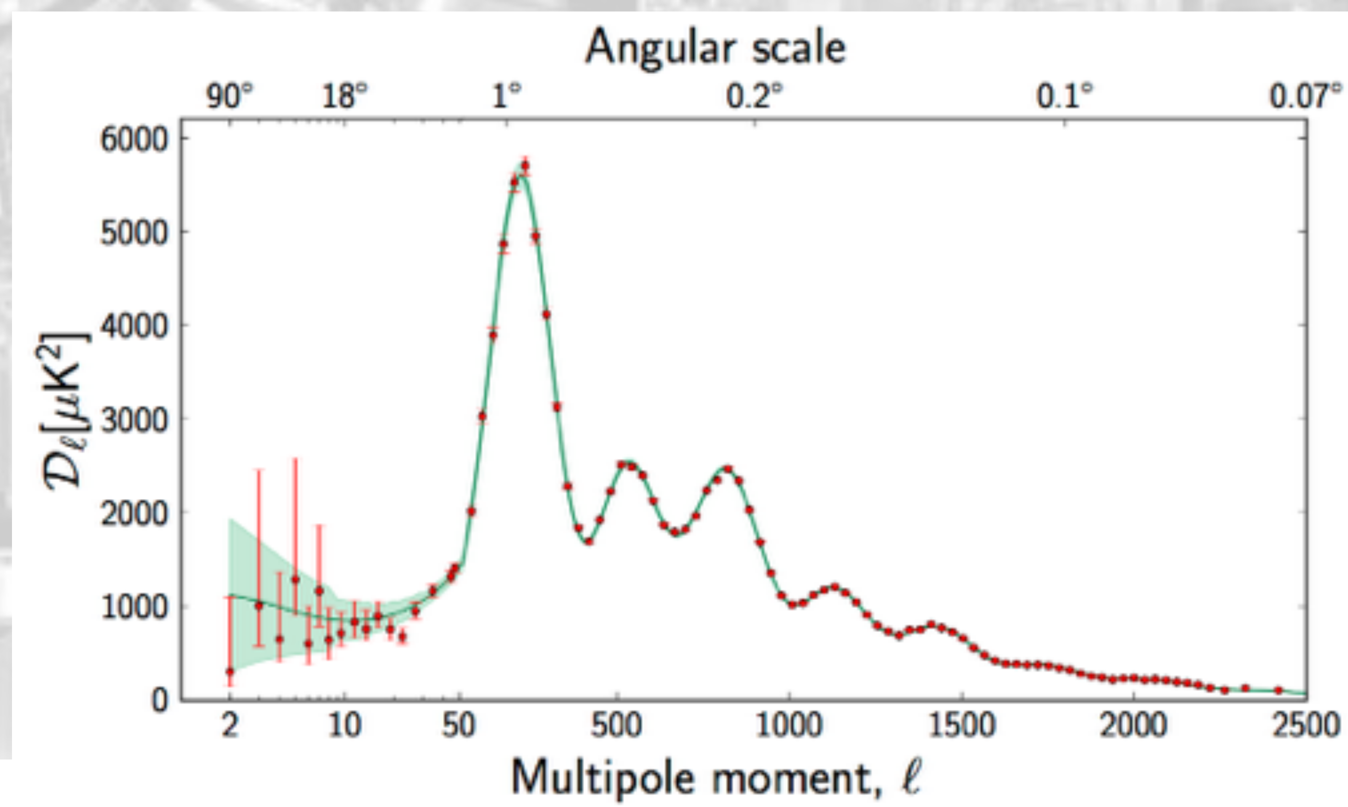
The CMB spectrum

- Fluctuations are small (10^{-5}, 10^{-6})
- Using satellite, map was made with increasing accurate prediction
- The radiation is consistent with a black body



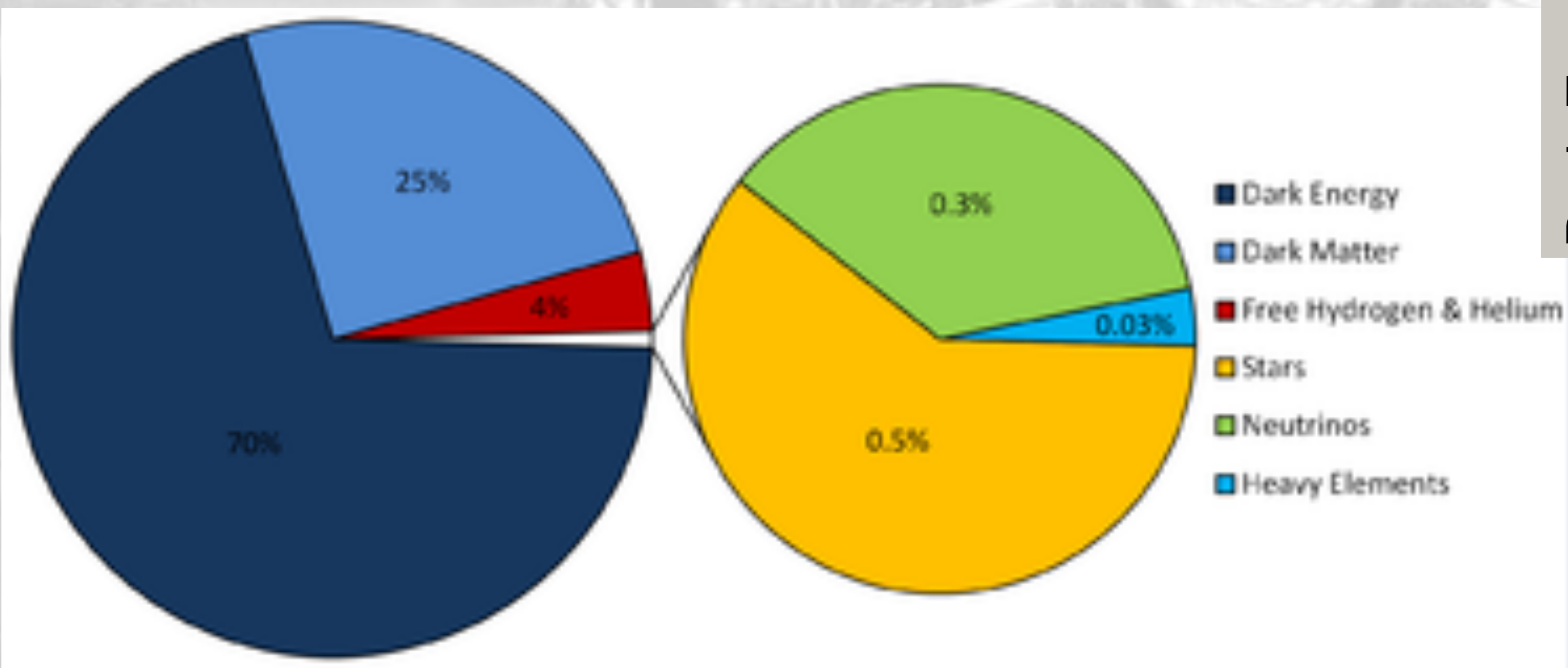
- From the position and the height of the peak one can learn about the composition of the universe

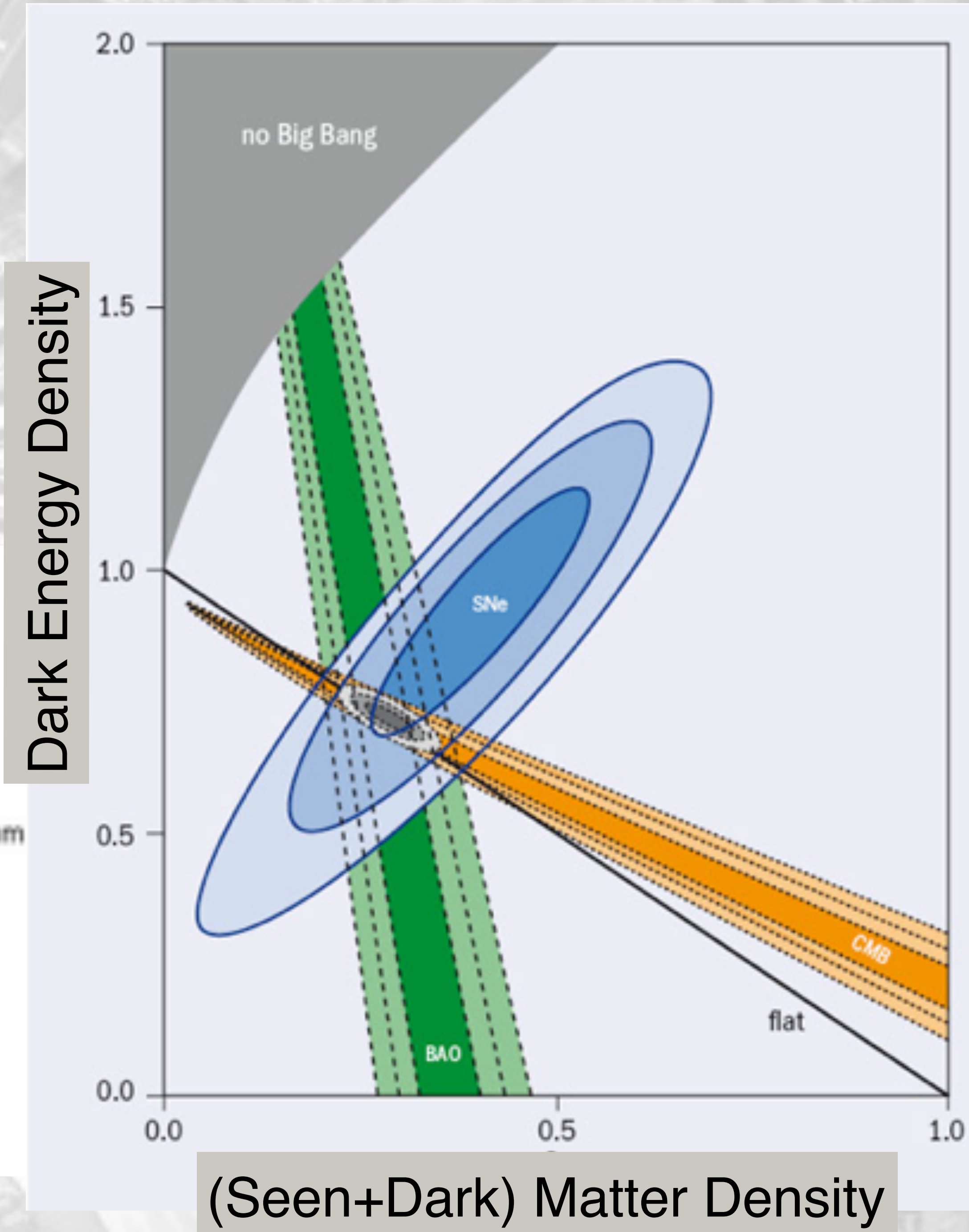
- For instance, the first peak position tells us that the Universe is flat



The ΛCMD Model of Cosmology

- The measurements converge in a globally consistent picture: an isotropic and homogeneous Universe on large scale
- The Universe as we know (and see) is only 5% of the total, as seen from gravitation
- Different measurements (CMB, supernovae redshift, etc) converge to one region of the parameter space





The Wimp "Miracle"

- Dark matter would be a particle with small interactions with SM particles

- The probability of DM particle pairs to annihilate has to be small

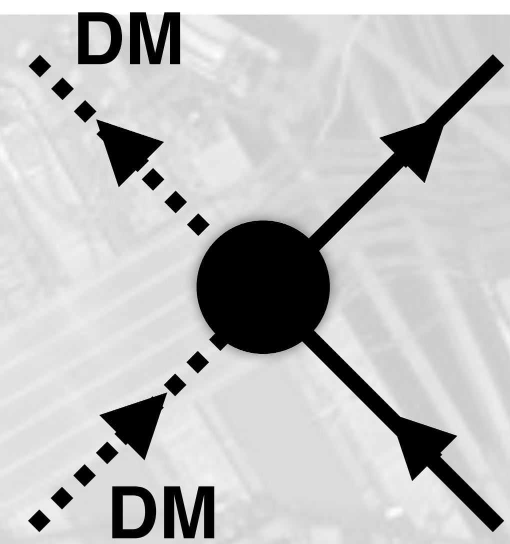
$$\langle \sigma v \rangle \simeq 3 \cdot 10^{-26}\,\mathrm{cm}^3/s$$

- It has to be massive, to explain the observed effect and not to break cosmology constraints (cold dark matter)

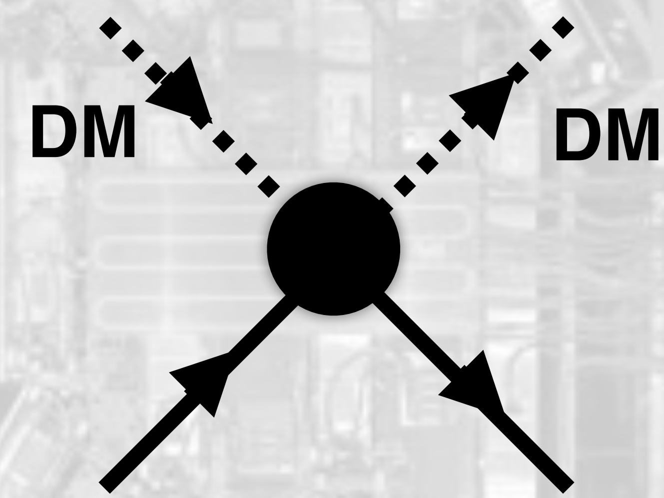
- A **W**eakly **I**nteracting **M**assive **P**article ~ 100 GeV fits quite well the DM picture and it is expected in many scenarios of physics beyond the SM

- This connection between Cosmology and Particle Physics (not directly connected) is called the WIMP miracle

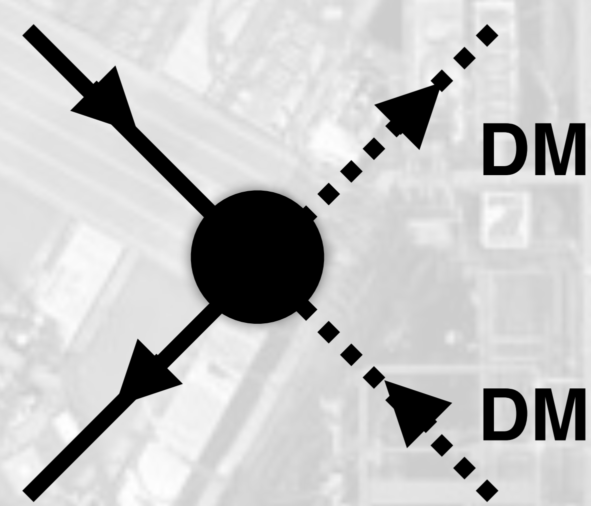
- Annihilation in Space:
  - two DM particles annihilate and two observables particles are produced
  - easier to happen in the centre of the galaxy, where more matter is attracted
  - produced particles detected by satellite experiments (AMS, FermiLAT, etc)

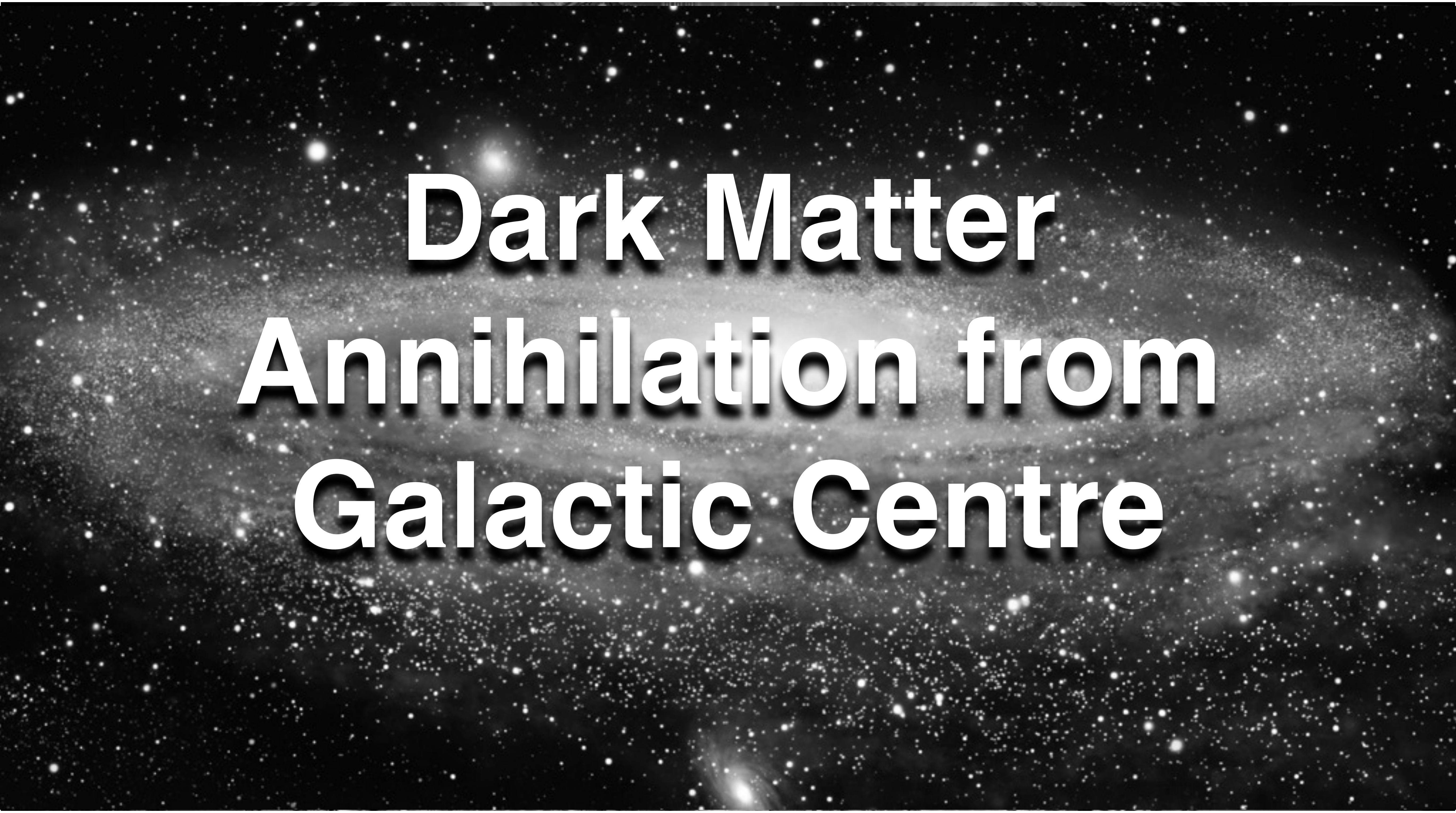


- Underground Detection:
  - one DM particle scatters on a nucleon, transferring momentum
  - nucleon recoil detected in low-background detector
  - detectors operated underground, to remove natural background (e.g., cosmic rays)



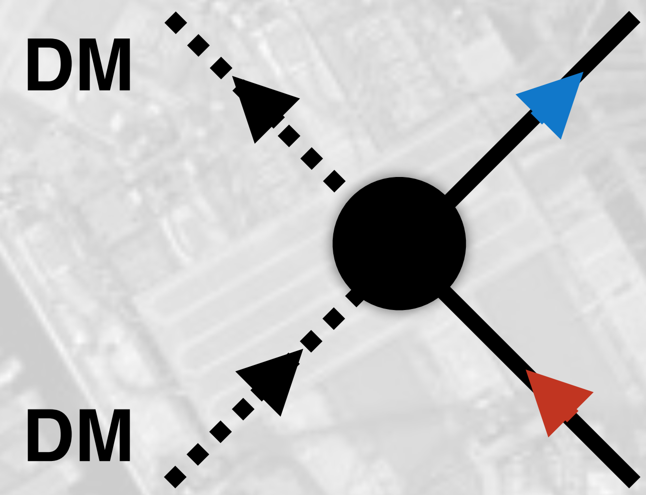
- LHC collisions:
  - Two protons collide producing DM particles
  - DM particles cannot be detected and escape the detector
  - Still, there is something one can do, as we will see

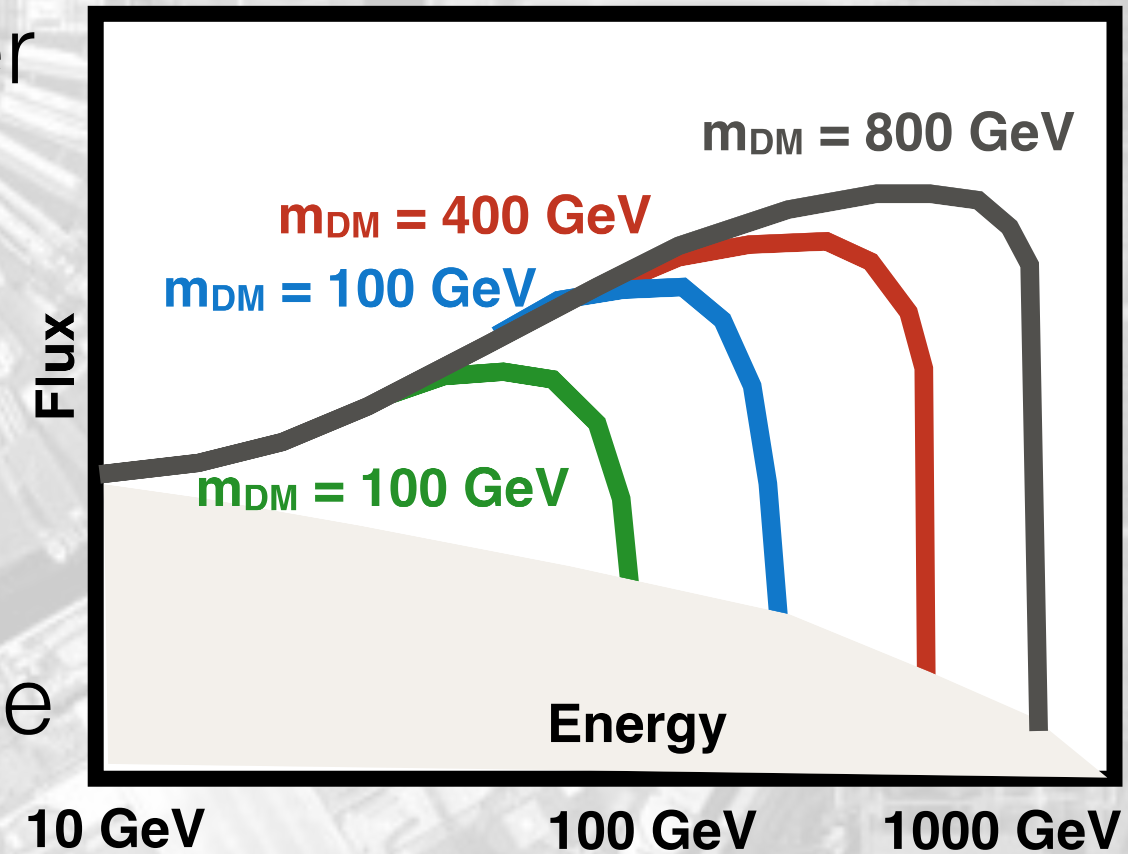



Dark Matter
Annihilation from
Galactic Centre

Detection Strategy

- In the annihilation, a **particle** and an **antiparticle** are produced
- The universe is filled with matter (e & p) while antimatter disappeared
- DM annihilation could be seen as a flux of anti-matter or a flux of matter +antimatter > expected matter
- The result would be a raise and drop of the spectrum
- The typical problem is to control the backgrounds

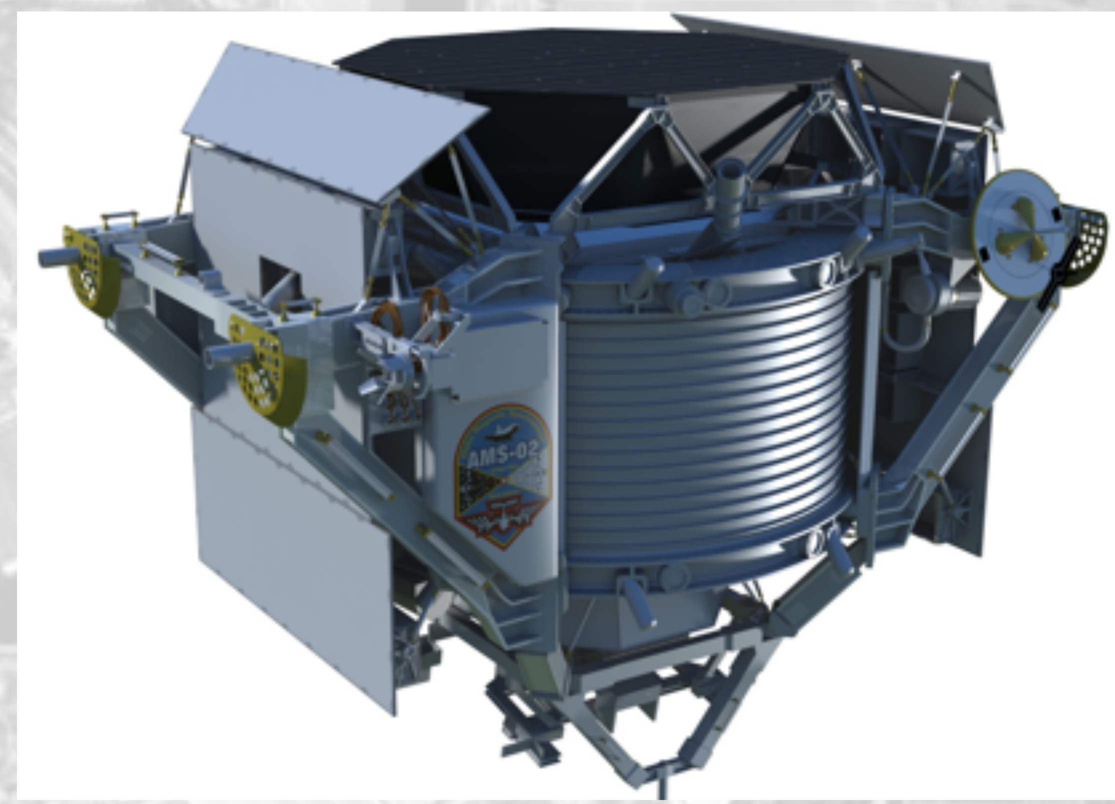




Particle Detectors in Space

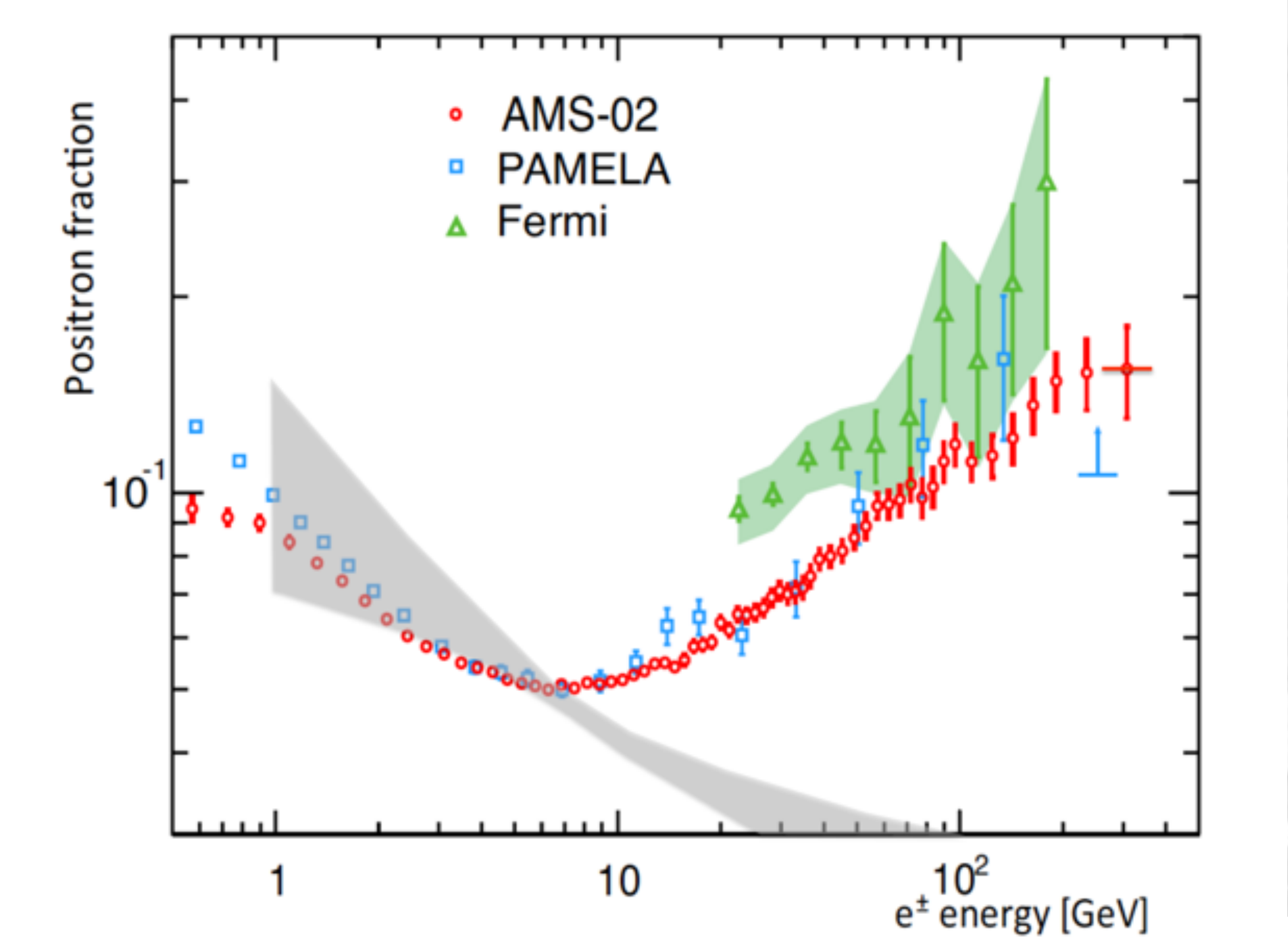
- **FERMI-LAT**
  - designed to detect photons, can be used to detect electrons and positrons
  - no magnetic field, so not possible to distinguish

- **AMS II**
  - detector operating on the inter nation space station
  - magnetic field operating in space (very challenging) allows to distinguish particles from antiparticles (opposite charge)
  - Can measure directly the spectrum of electrons and antiprotons



Dark Matter Detected?

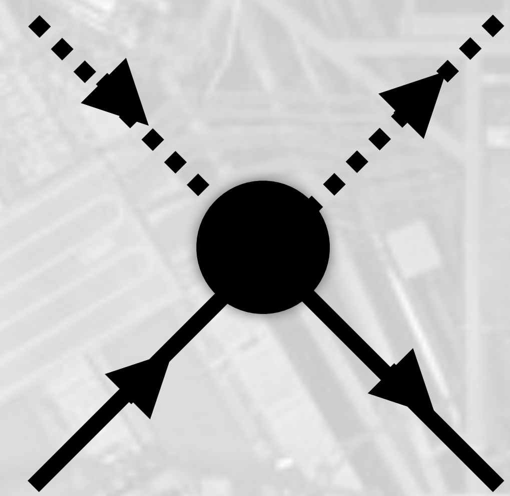
- Three experiments see the spectrum raising, but the drop was not yet observed
- The background is estimated with uncertainty
- News expected from AMS soon (extending the plot at higher energies)



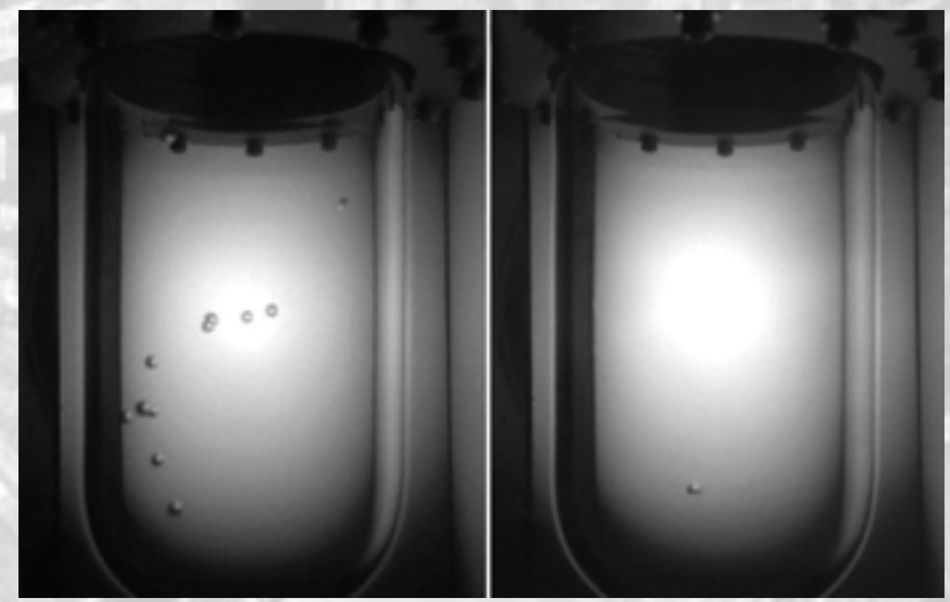
Dark Matter Search Underground

Detection Strategy

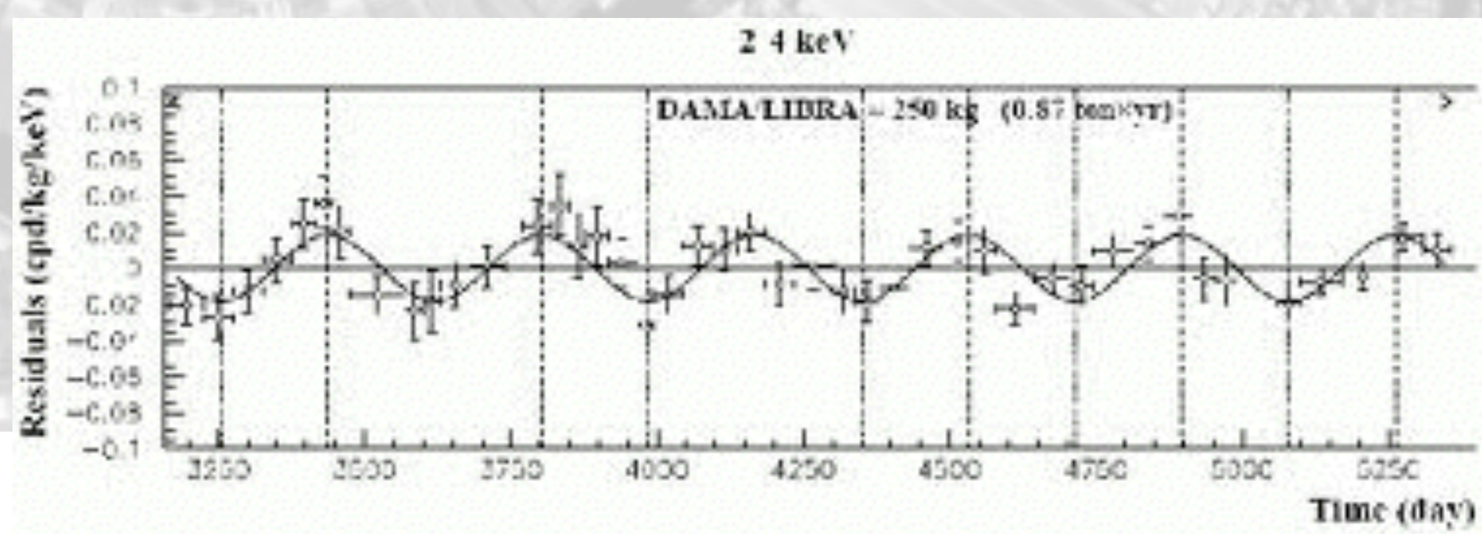
- According to the LCDM model, the Earth travels through a cloud of DM during revolution around the Earth



- Nucleons (in atoms) can collide with DM particles from this “wind”
- The energy transferred in the recoil can be detected in several ways
  - ionization
  - scintillation
  - phase transition (i.e., bubble formation)

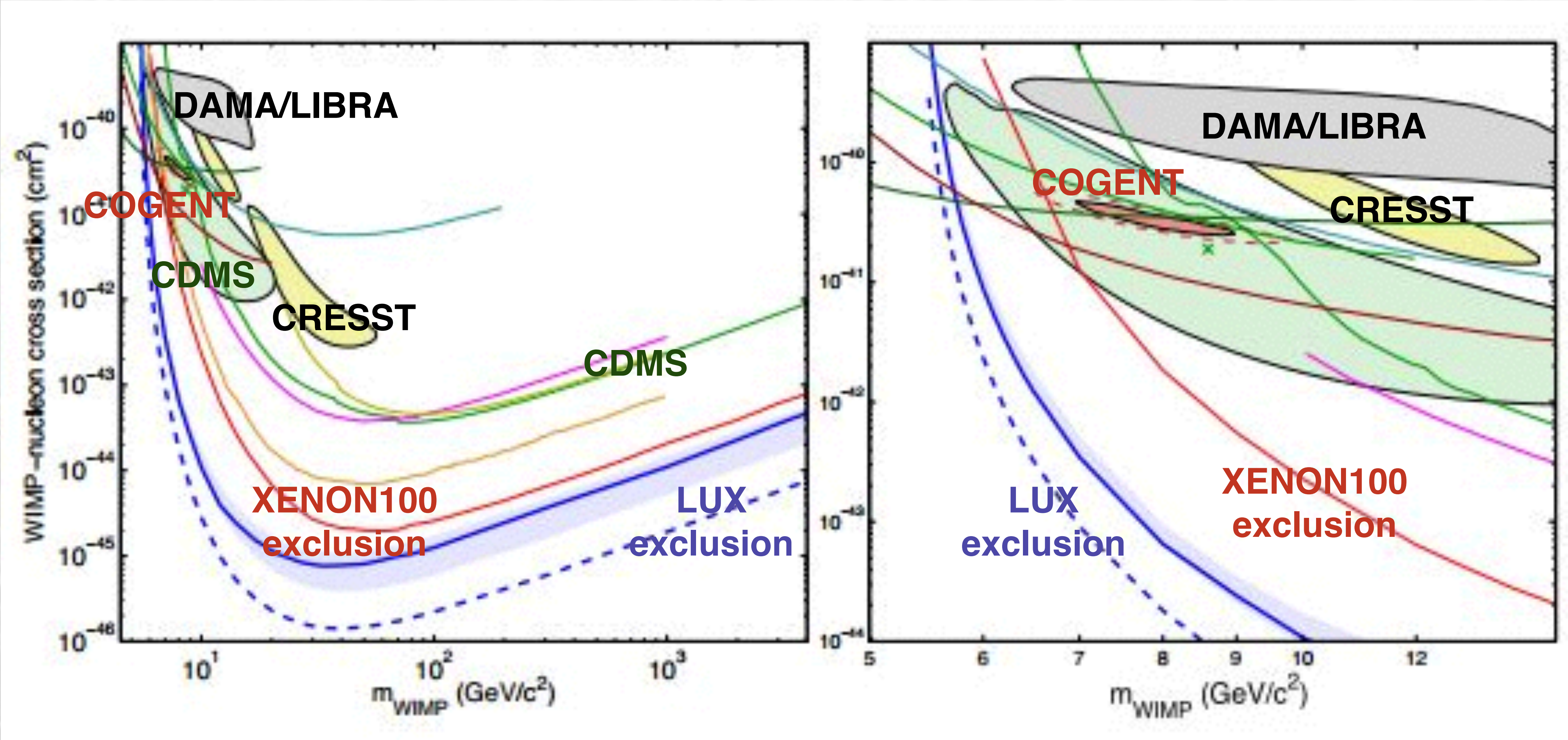


- In addition, year modulation in the signals could be observed (different direction of the earth wrt the wind)



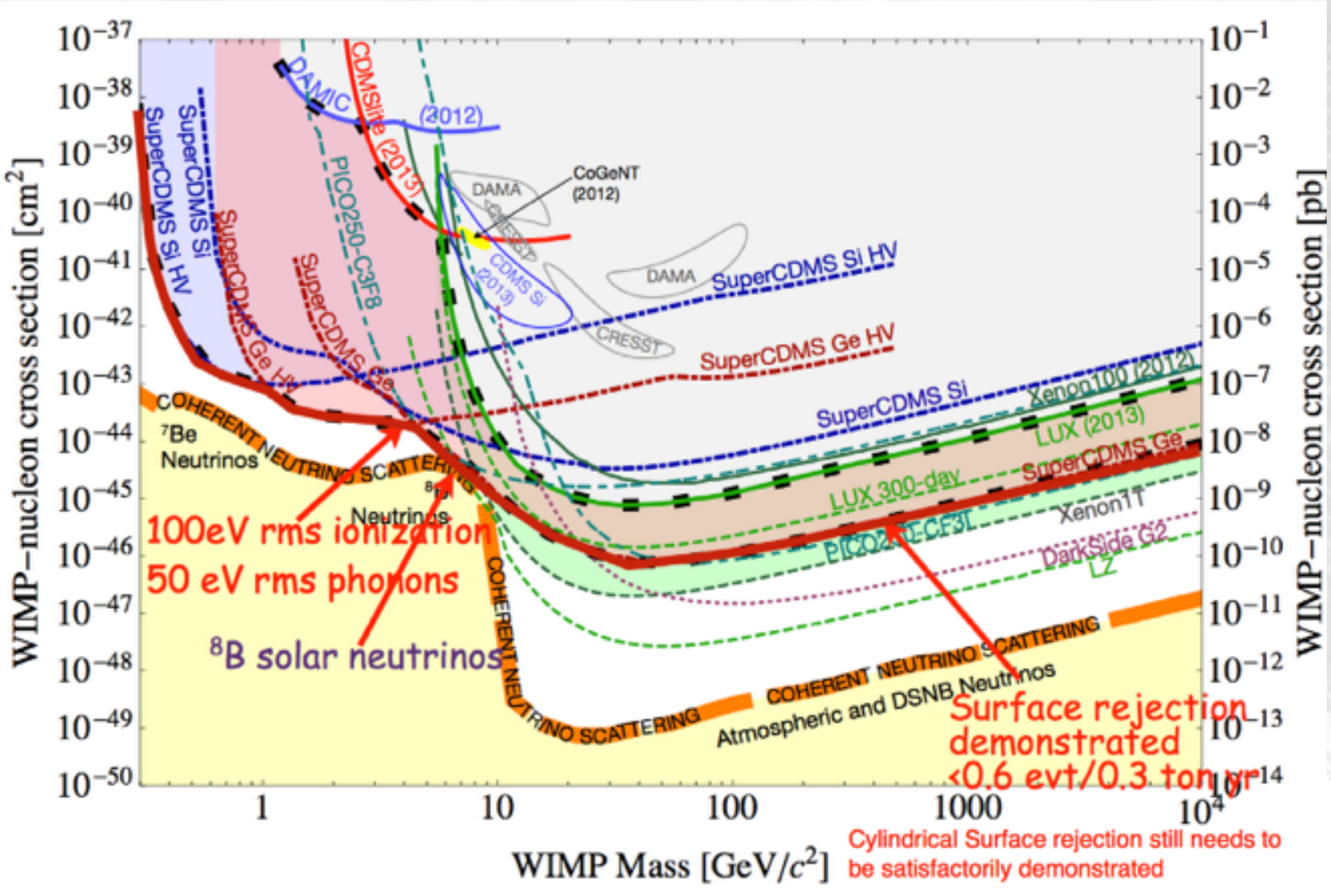
A confusing Situation

- Four experiments claim to see a signal
- The (dis)agreement between them depends on the theory model
- Two experiments have strong exclusion limits



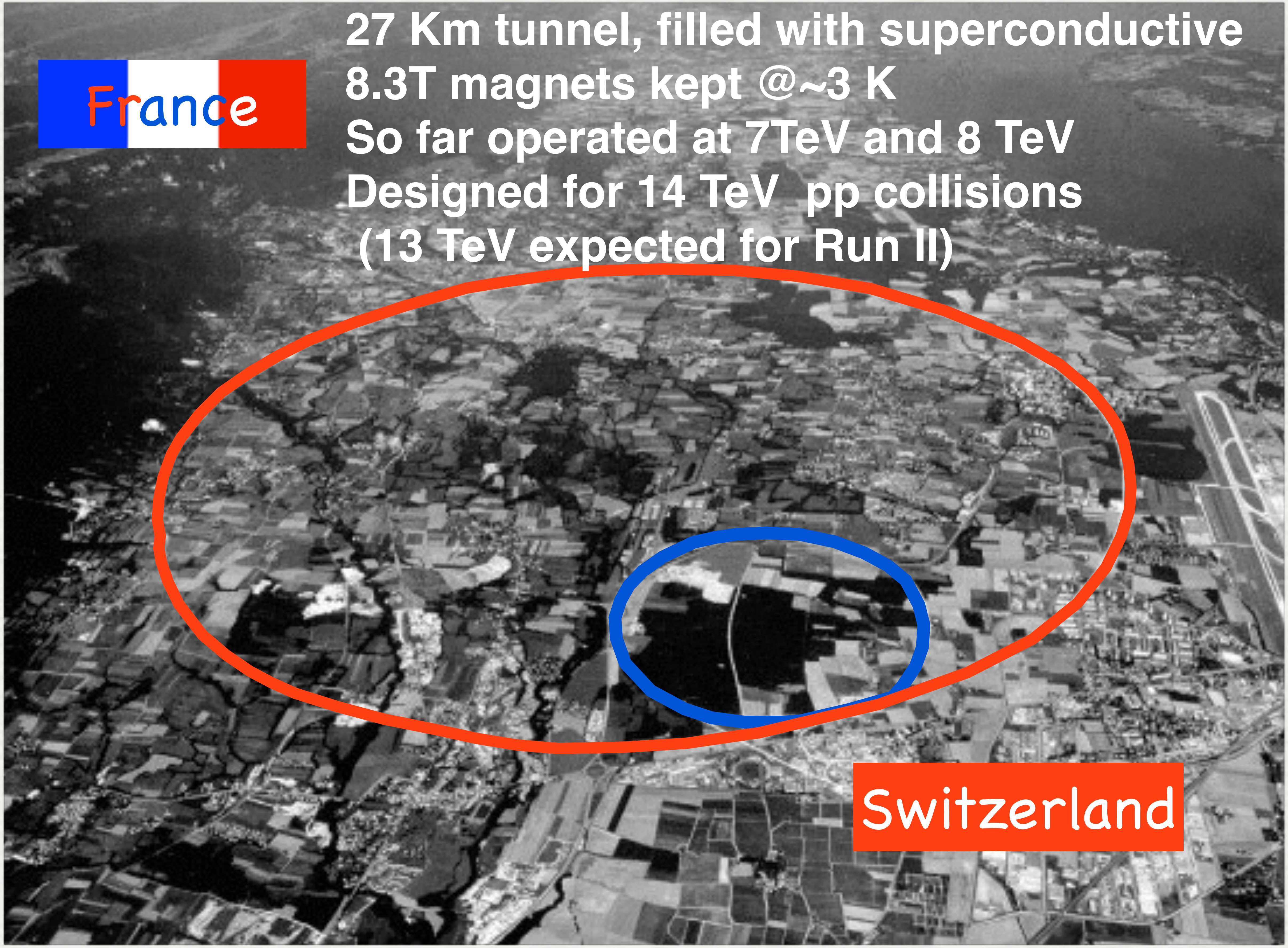
Future Perspectives

- New, more sensitive experiments are under construction
- They will push the sensitivity well beyond the current experiments
- Experiments will eventually confront with irreducible background from neutrinos
- New technology (e.g., directional detection) will have to be designed

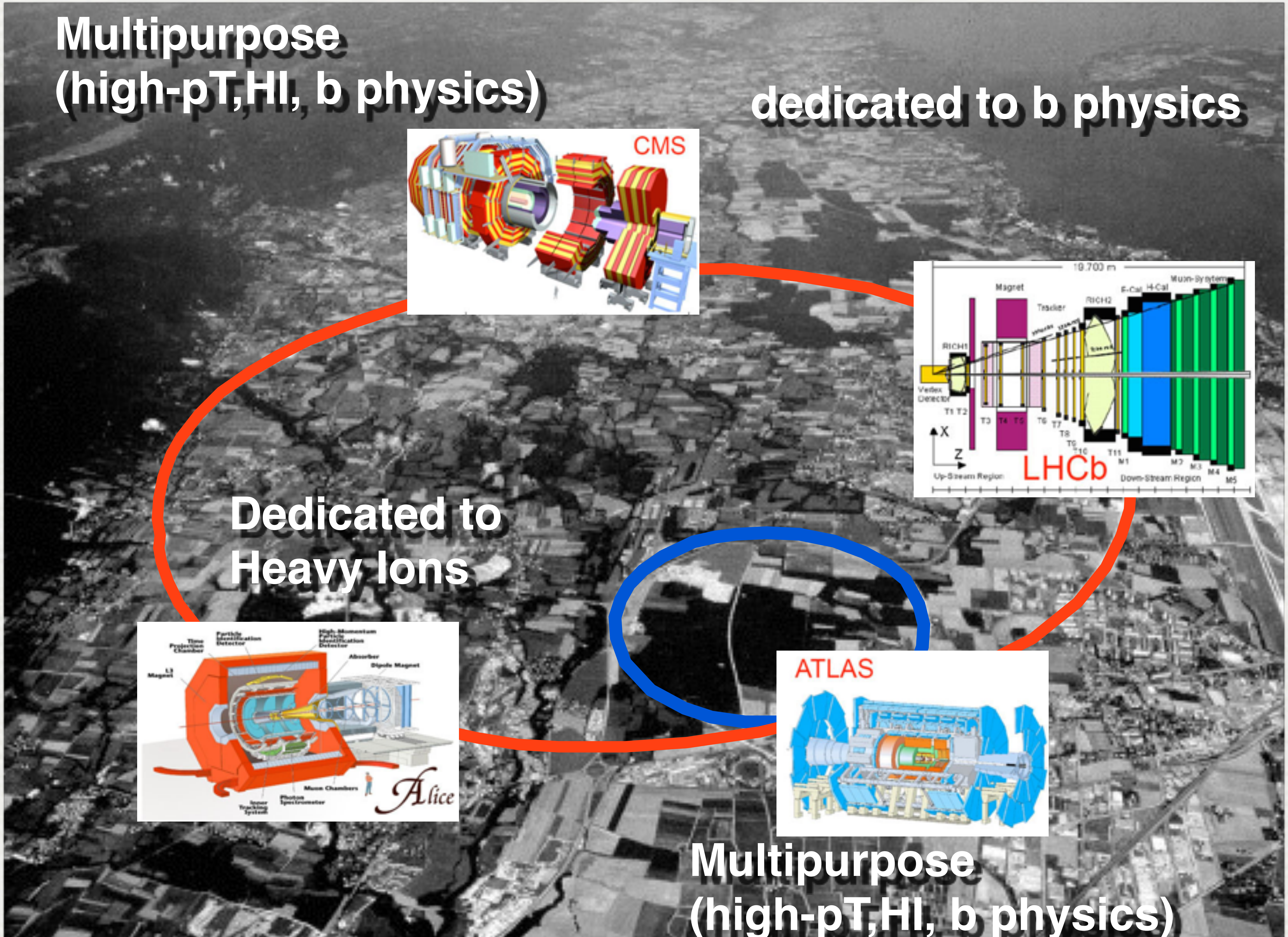


Search for Dark Matter at the LHC

The Large Hadron Collider



THE LHC EXPERIMENTS

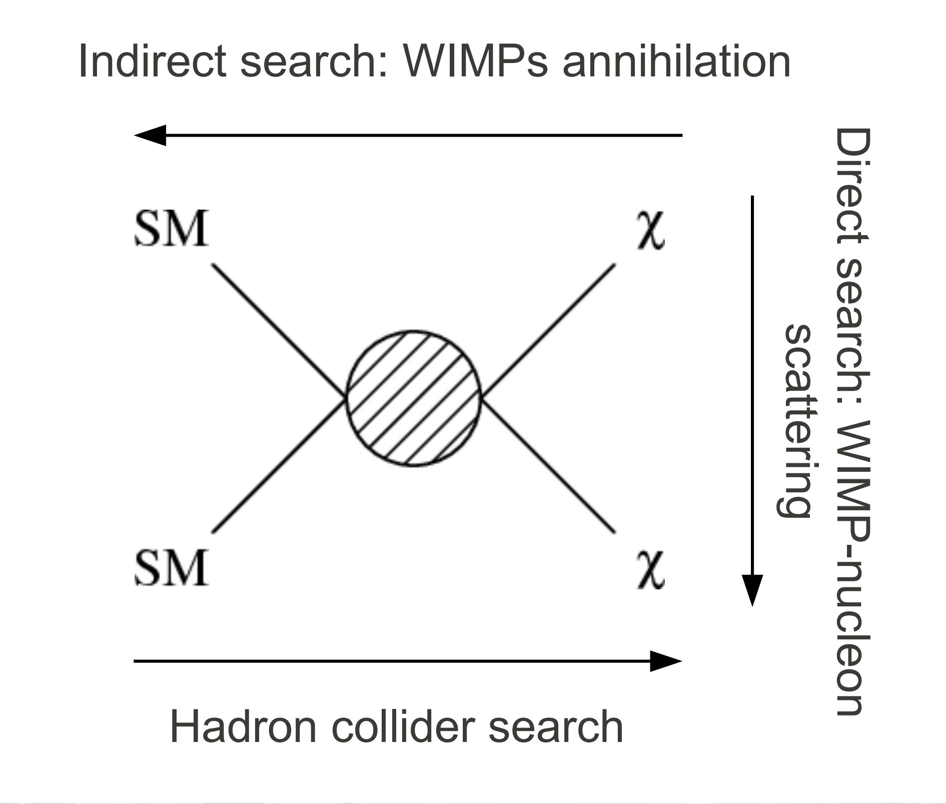


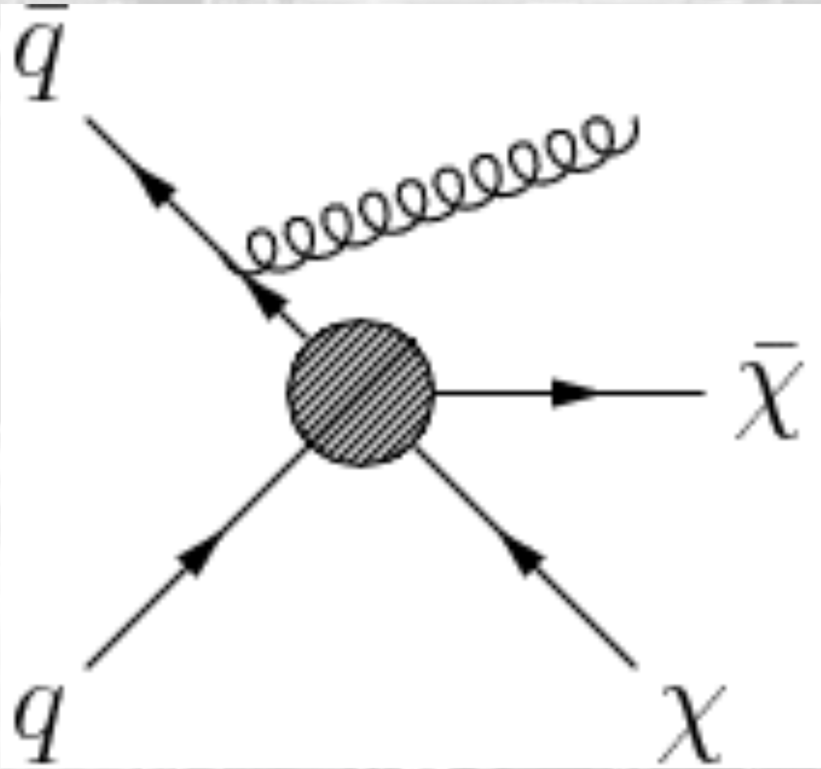
Atlas&CMS physics Goal

- Search for the Higgs boson
- Fully characterise EW symmetry breaking
- Test SM with precision measurements (perturbative QCD, parton density functions, …)
- Improve precision on SM parameters (e.g., masses of W, Z, and top)
- Explore the TeV scale, searching for new phenomena
- The production of Dark Matter particles is one of the new phenomena that we could detect

Invisible and monojet

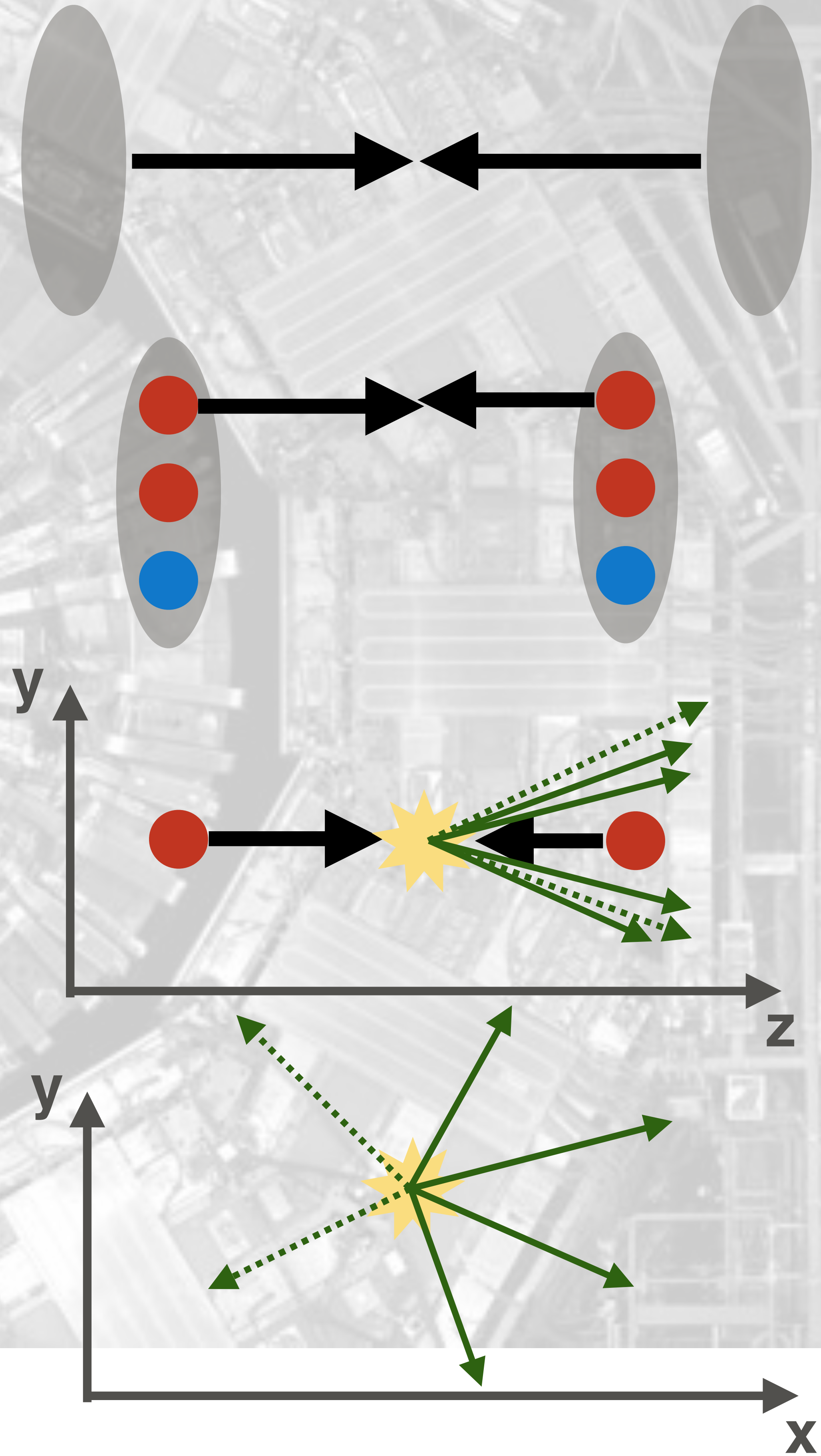
- DM can be produced at the LHC with a process similar to scattering in underground experiments
- But DM is invisible to our detectors, unless something else is produced with DM
- For example, a quark/gluon can be radiated before the collision
- These events look like a single high-pT jet of particles
- Events like this can happen also in the Standard Model. One needs to measure the background



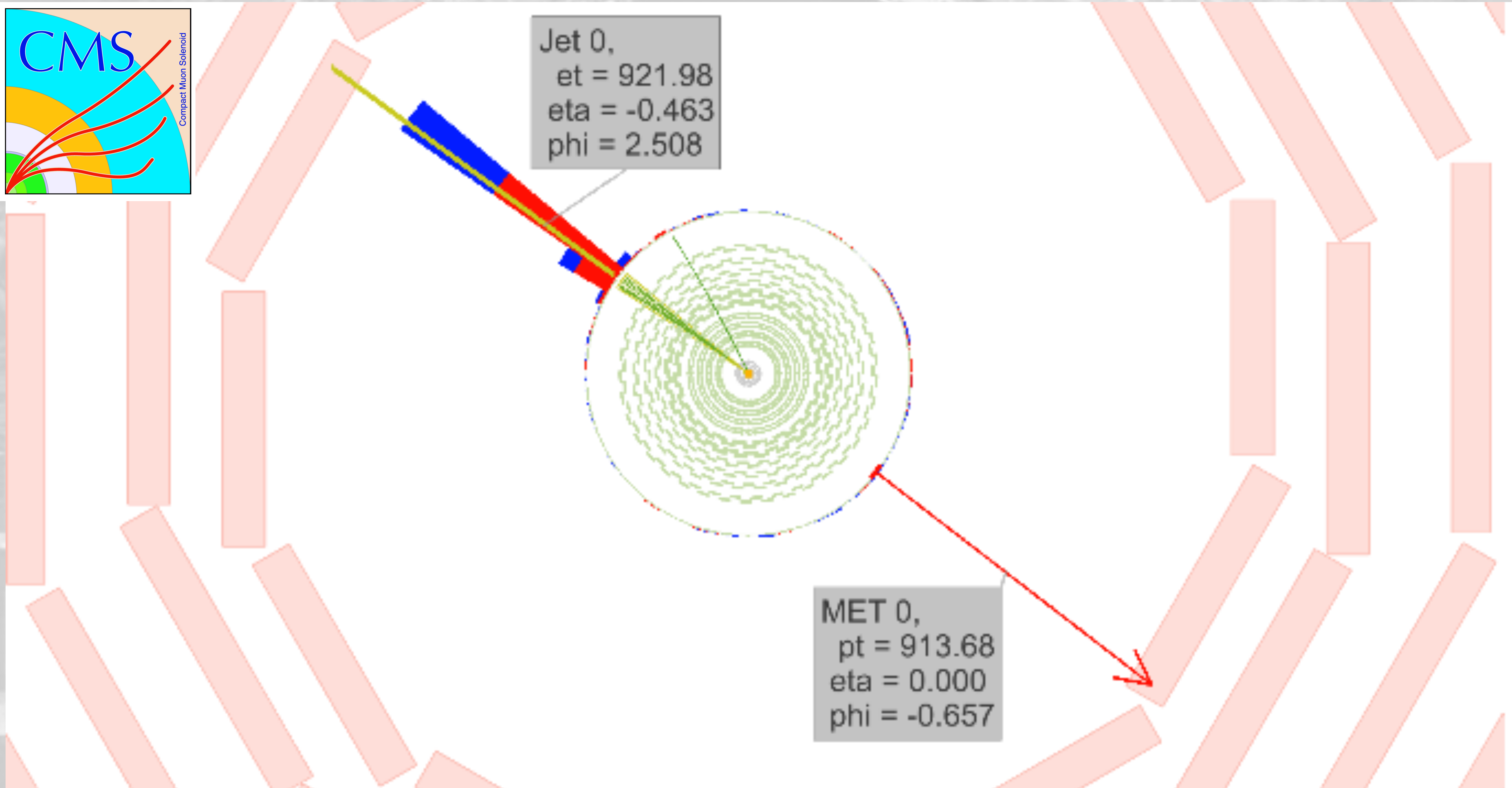


Missing Transverse Energy

- In LHC collisions, as anywhere else, conservation of energy and momentum holds
- Two protons collide with same energy
- What actually collide is quarks/gluons in the proton, which have different momenta
- As a result, there is a momentum imbalance along the beam axes, but not in the transverse plane
- The momenta balance in the transverse plane. If it does not look like, some particle escaped undetected
- This is the concept of **Missing Transverse Energy**

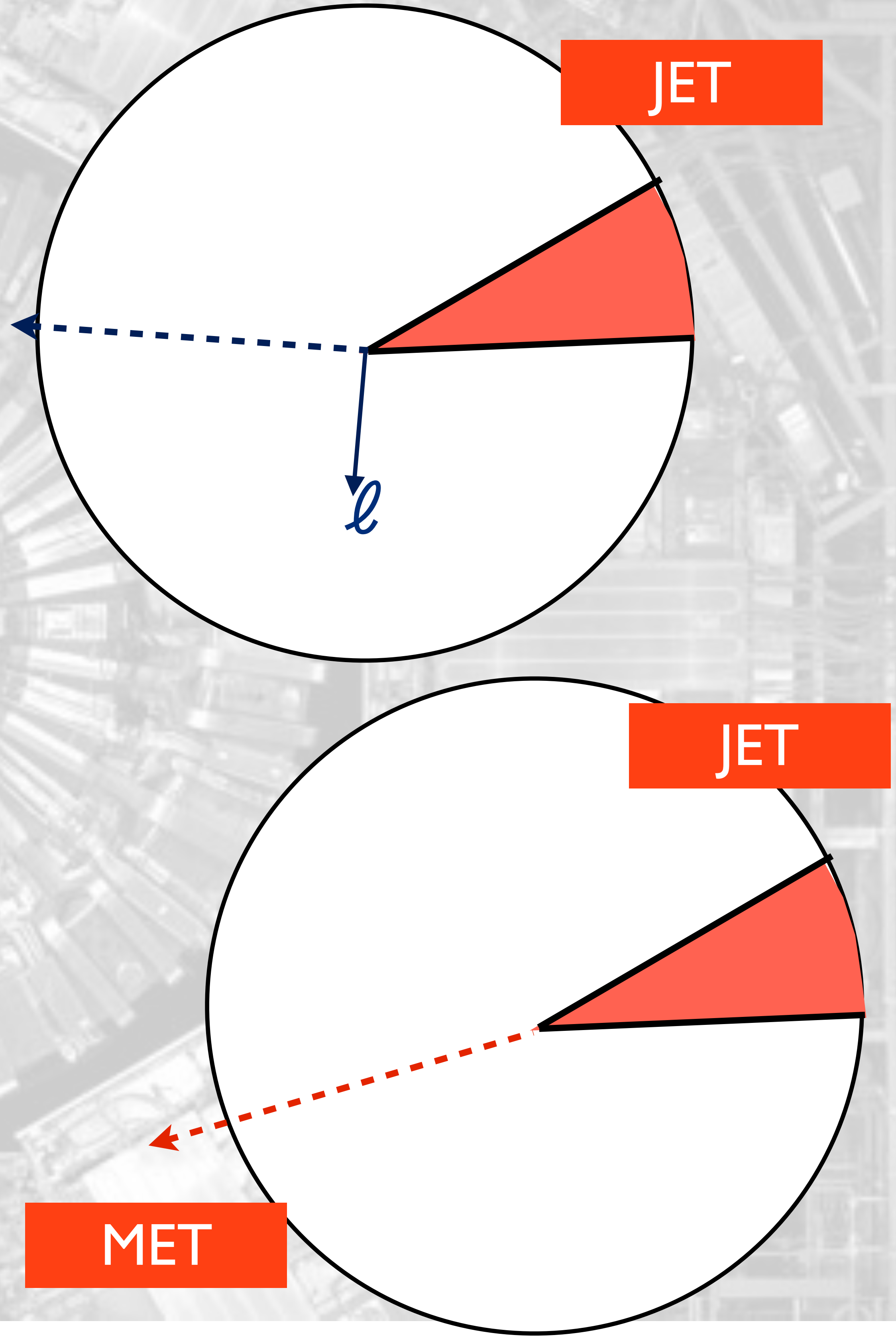


MET AND DM PRODUCTION



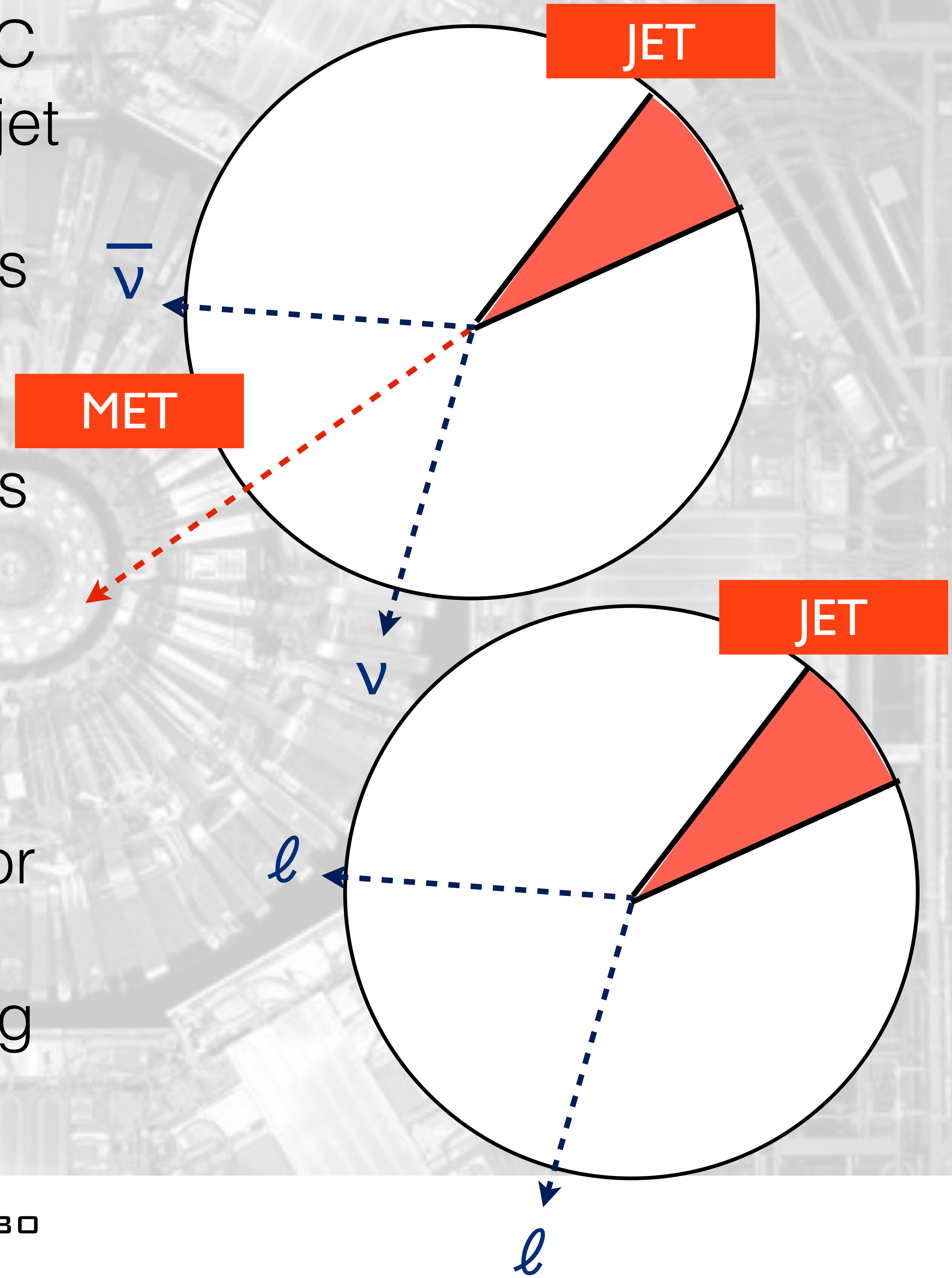
The Background: W+Jets

- W bosons are produced in LHC collisions, recoiling against a jet
- 30% of the time the W decays to a lepton and a neutrino
- Sometimes the lepton is not reconstructed. The event looks like monojet
- We can predict how many events like this we expect, counting the events for which we see the leptons (we know the probability of missing the lepton)



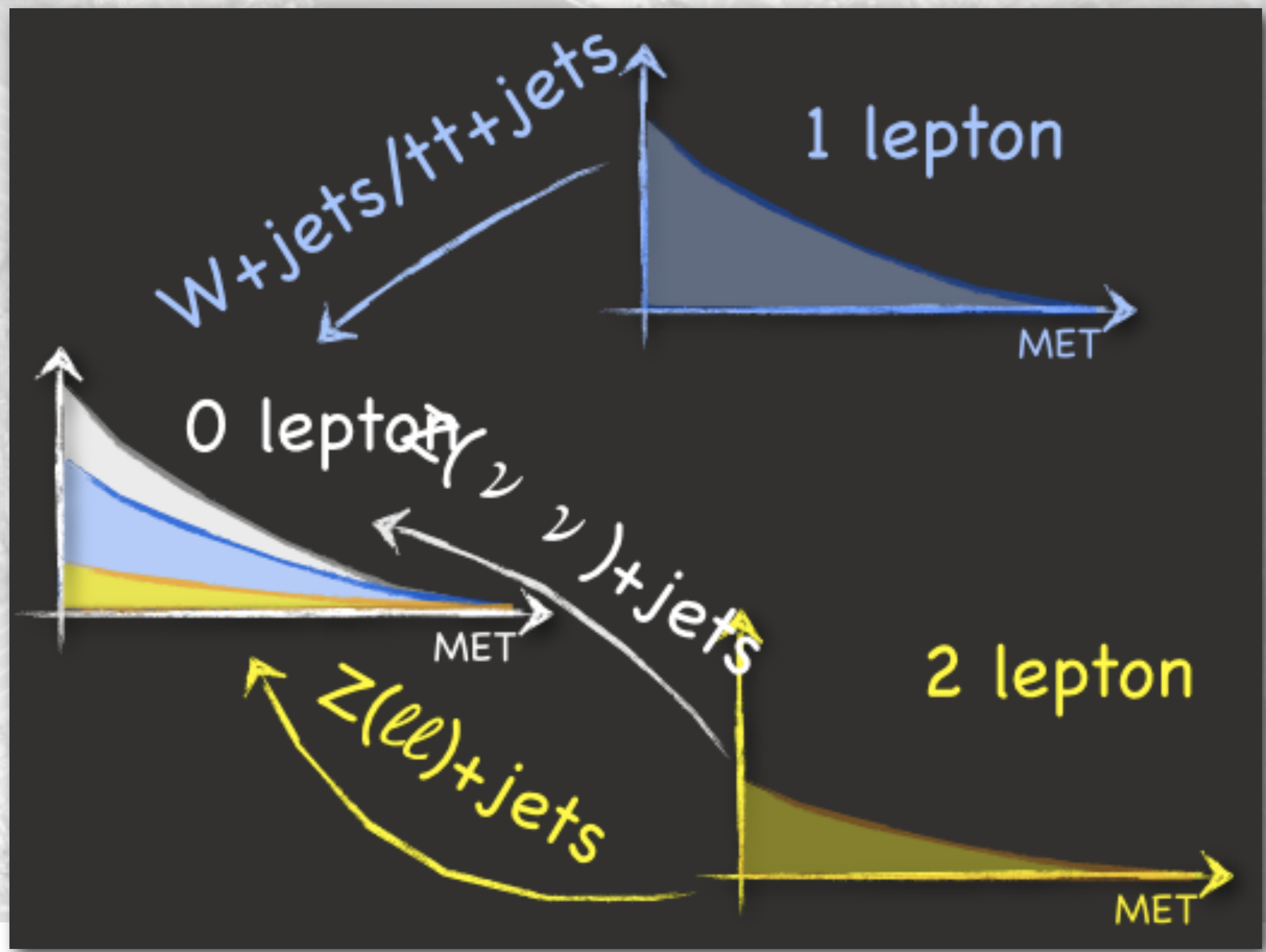
The Background: Z+Jets

- Z bosons are produced in LHC collisions, recoiling against a jet
- ~20% of the time the Z decays to a neutrino pair
- ~10% of the time the Z decays to a lepton pair
- We can predict how many events with neutrinos we expect, counting the events for which we see the leptons (we know the probability of missing the lepton)



Search Strategy

- Events are selected requiring a high-energy jet and large missing transverse energy
- The same selection is applied to events with 1 or 2 leptons
- Simulation is use to connect the samples



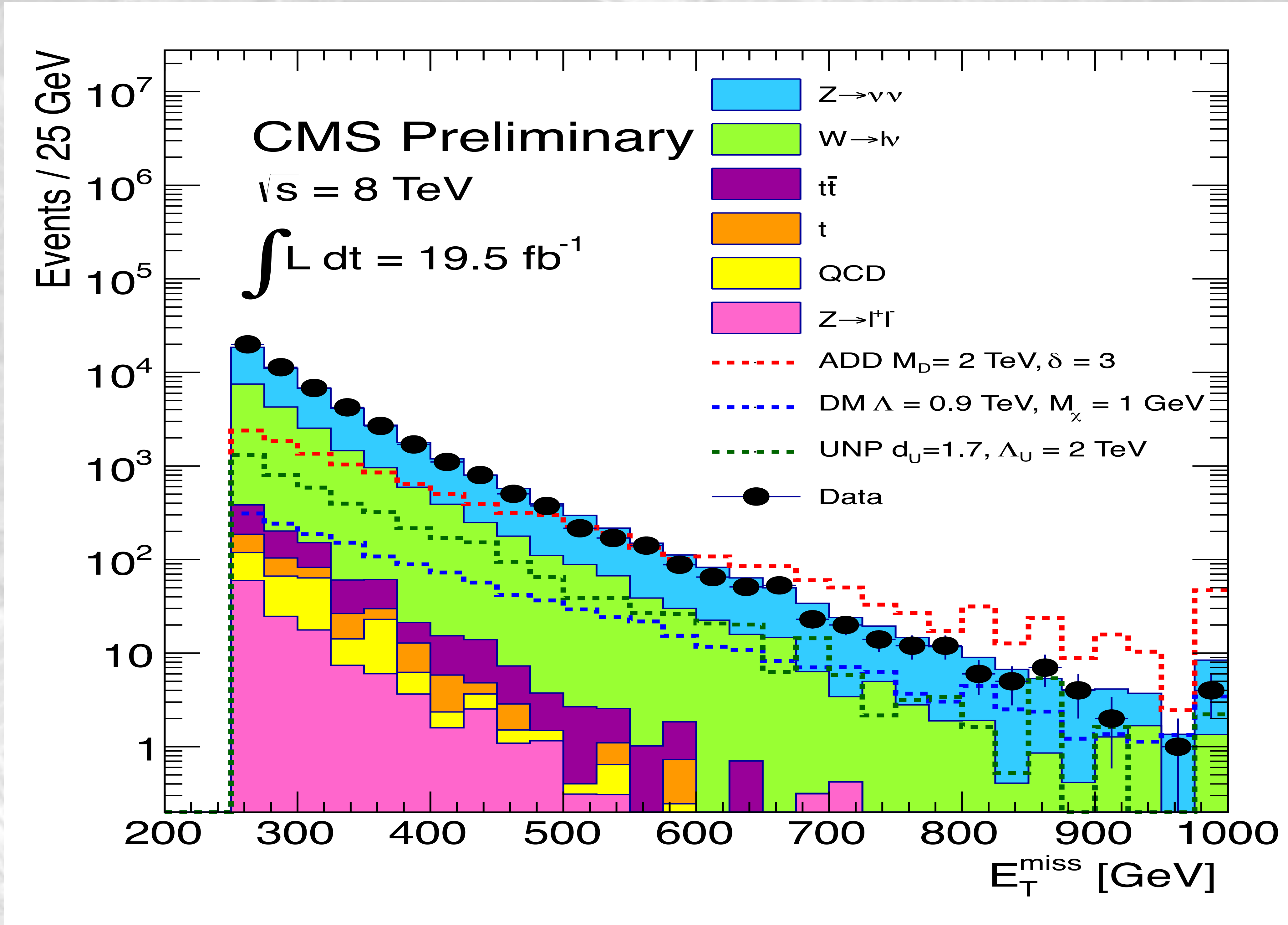
Search Strategy

- Events are selected requiring a high-energy jet and large missing transverse energy

- The same selection is applied to events with 1 or 2 leptons

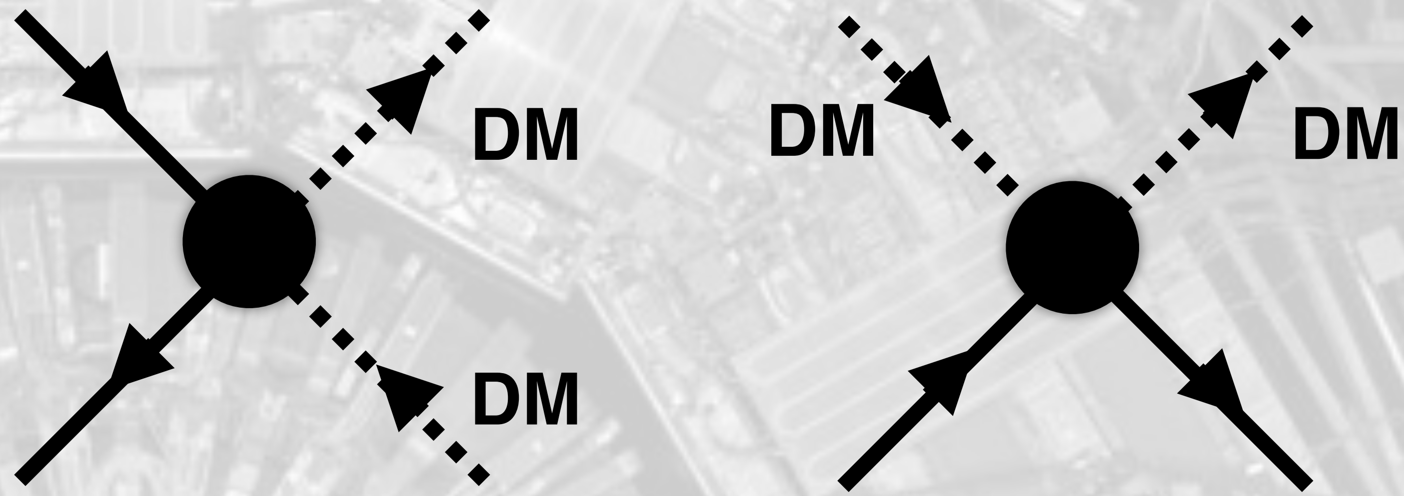
- Simulation is use to connect the samples

- The prediction agrees with the expectation, ie. no signal is found

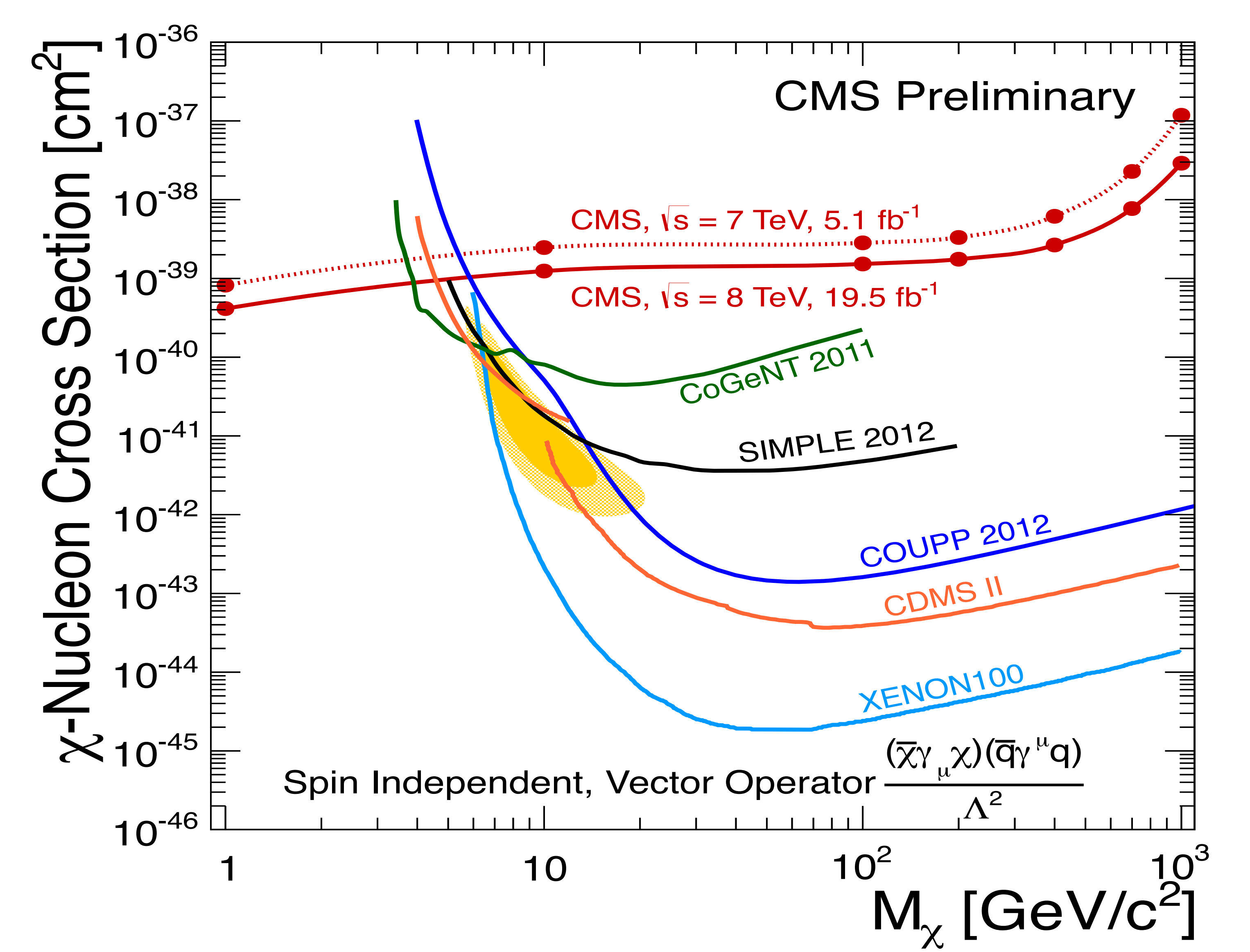


Interpretation

- In absence of a signal, the result is interpreted as an exclusion limit (at 95% confidence level) on the existence of Dark Matter



- The limit is computed as a function of DM mass and the strength of the coupling
- The same coupling enters the scattering processes searched for underground
- We can then derive a similar limit with the LHC data
- Interestingly, sensitivity at low masses

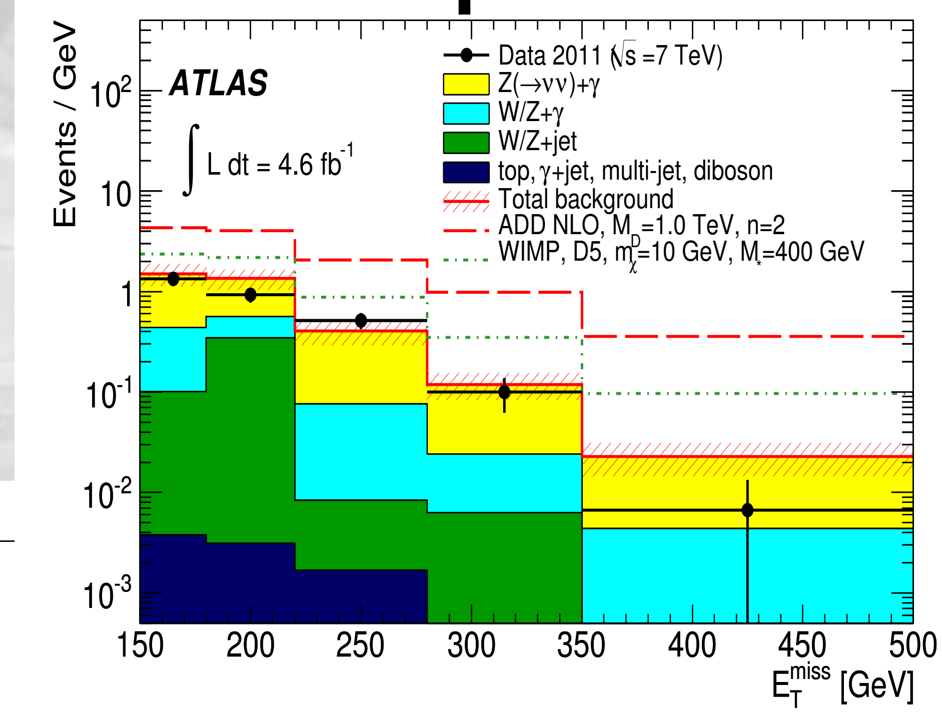


More than Monojet

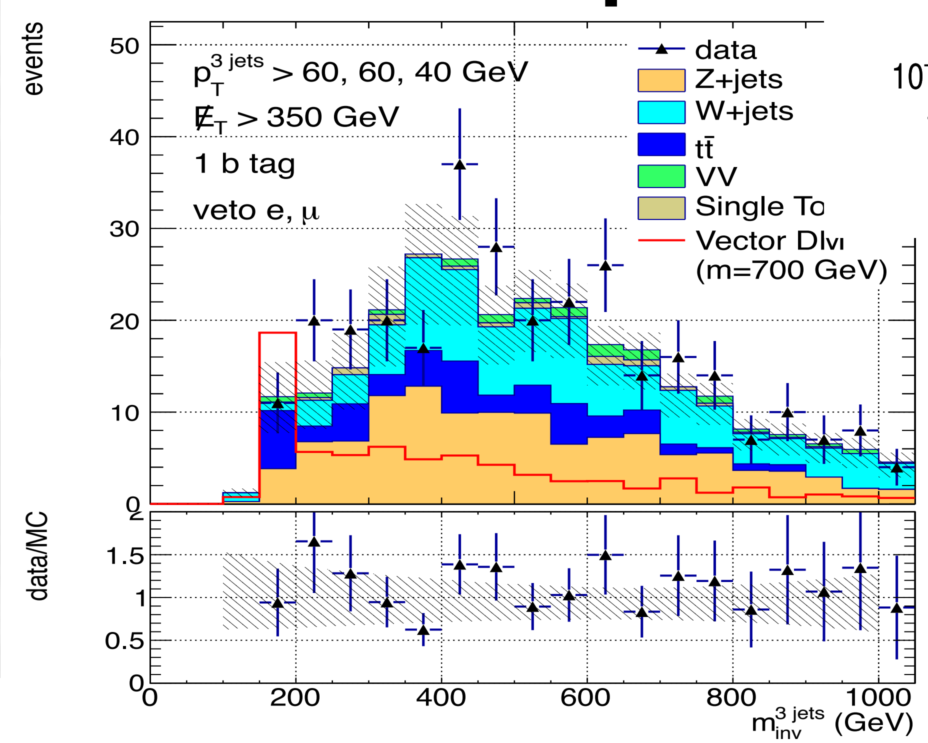
More rare objects than a jet could be radiated (i.e., less background)

Depending on the object, one could be sensitive to different models (e.g. DM coupling more to 3rd generation quarks, etc)

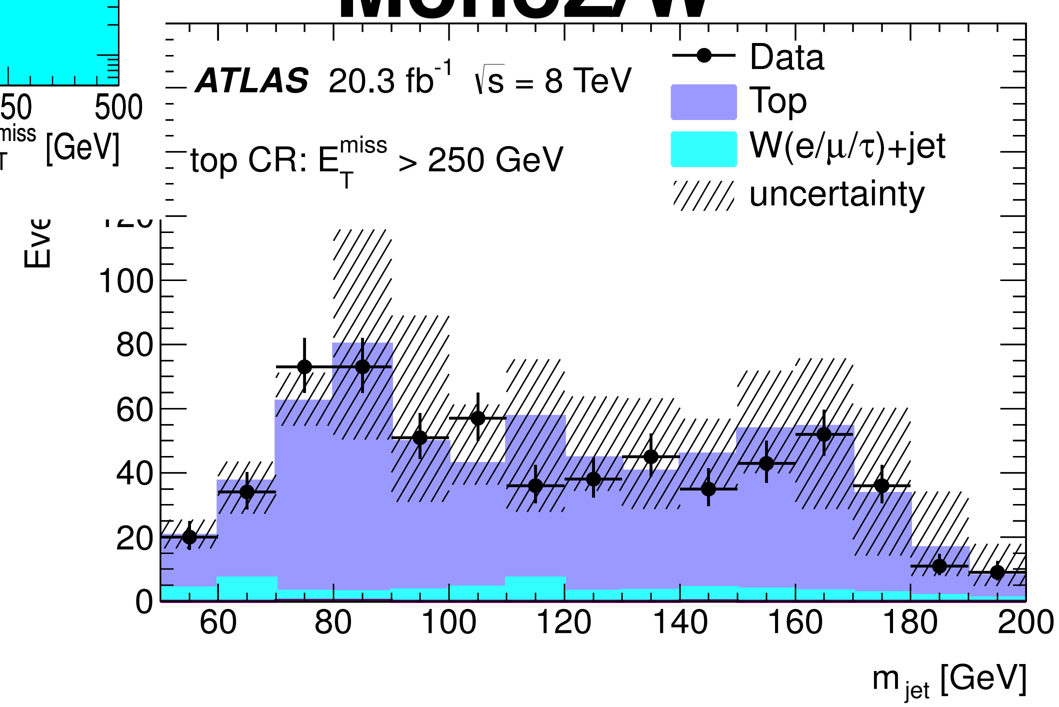
Monophoton



Monotop

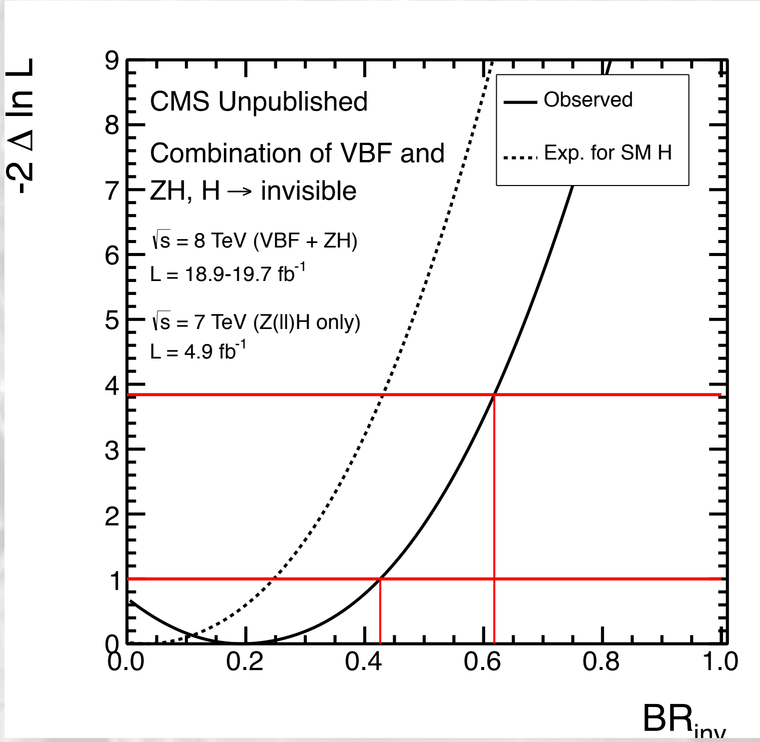


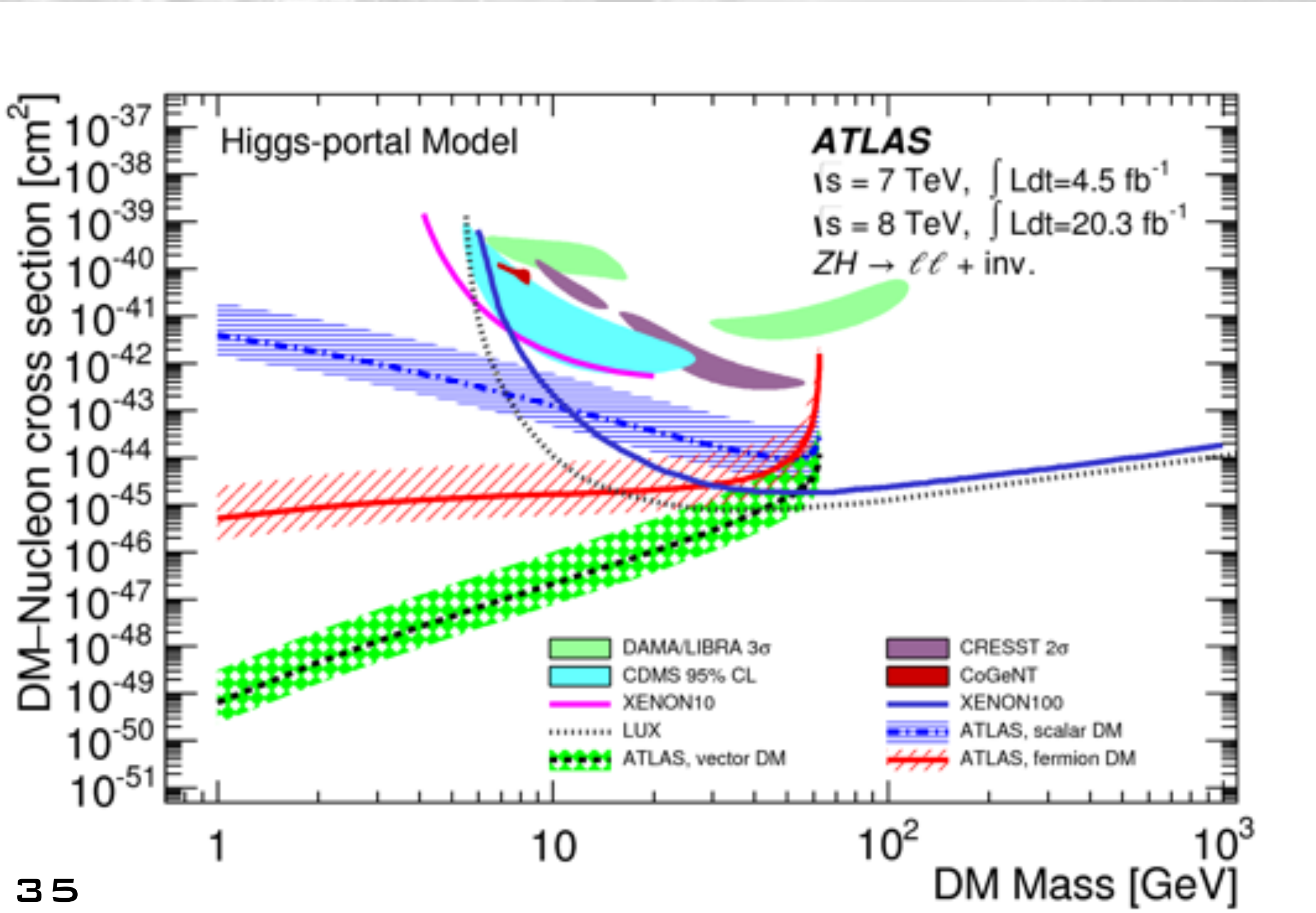
MonoZ/W

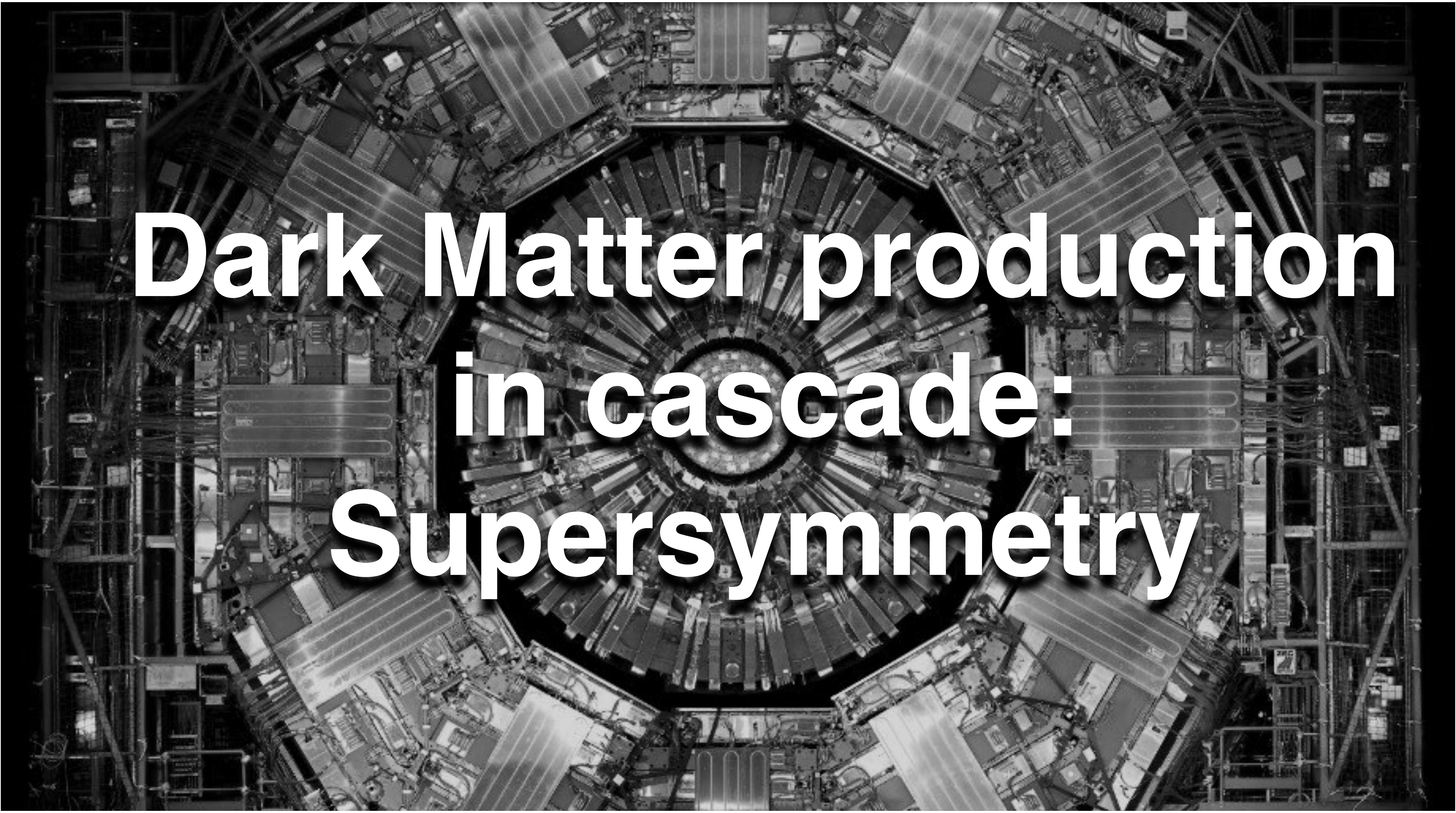


...And monoHiggs

- The Higgs boson could give us access to new particles in the decay (being the less known particle so far)
- In particular, if the Higgs boson gives mass to DM (as it does with SM particles) it could decay to two DM particles
- This is searched for, in the so-called portal model (for which the sensitivity of the LHC becomes even more relevant)
- Again, there is some model dependence (less general than the underground experiments)



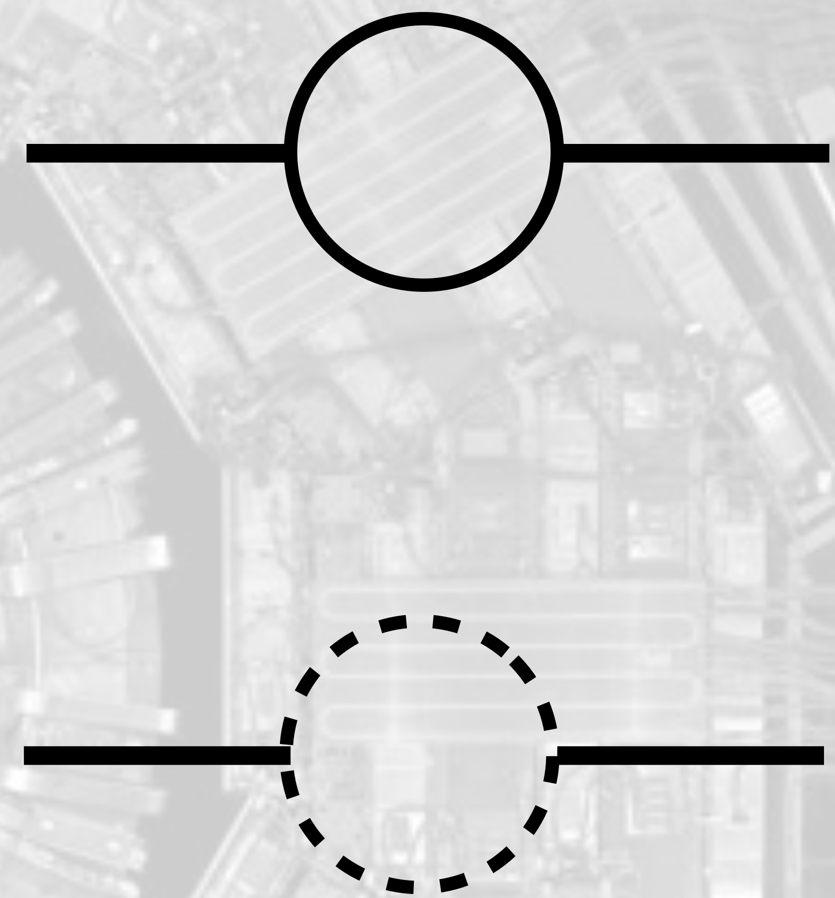



Dark Matter production
in cascade:
Supersymmetry

Problems with Higgs Mass

- The Standard Model cannot be the ultimate theory. It does not introduce gravity. It is an effective theory up to some (large) energy scale Λ_{NP}

- The computation of the Higgs mass receives contributions ~Λ_{NP} from quantum effects but we measured m_H ~ 125 GeV
  - New physics should exist to cancel these divergent contributions



or, in other words,

  - New physics should exist at Λ_{NP} ~ 125 GeV

NOTE from QUANTUM FIELD THEORY:
replacing a boson with a fermion one gets a minus sign

Supersymmetry

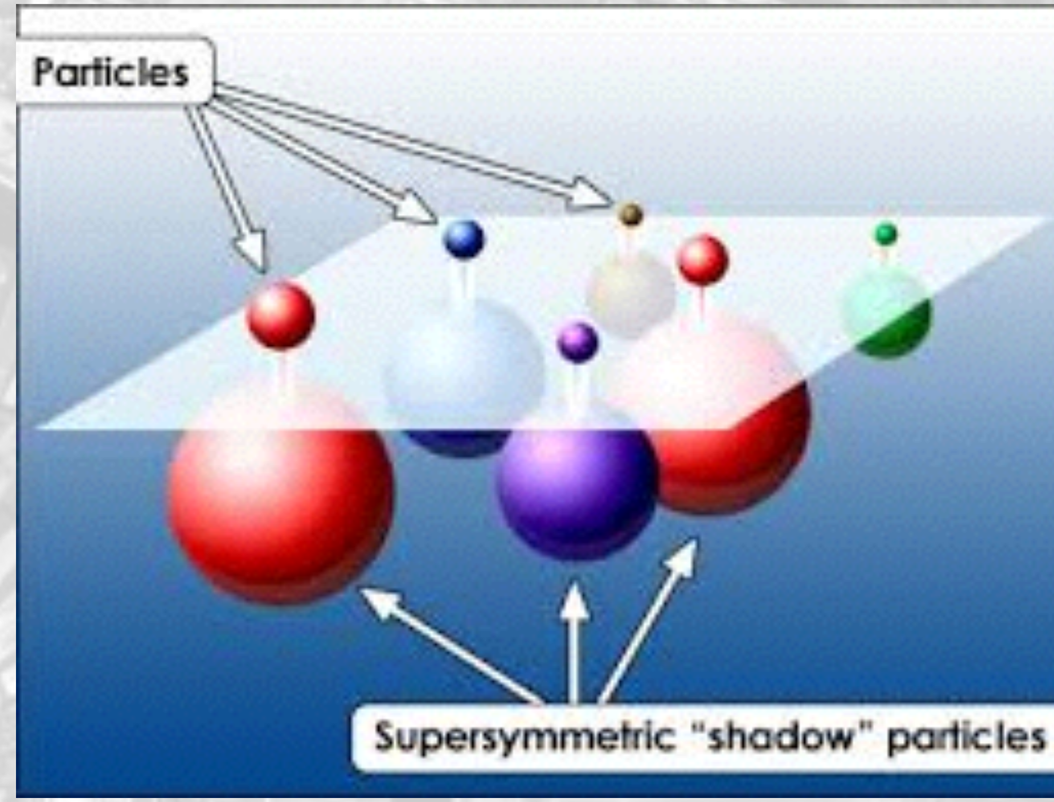
- A symmetry in nature could exist between bosons (spin =0,1,..) and fermions (spin = 1/2, 3/2, …): for each fermion, a boson with same properties (mass, charge, etc) could be there

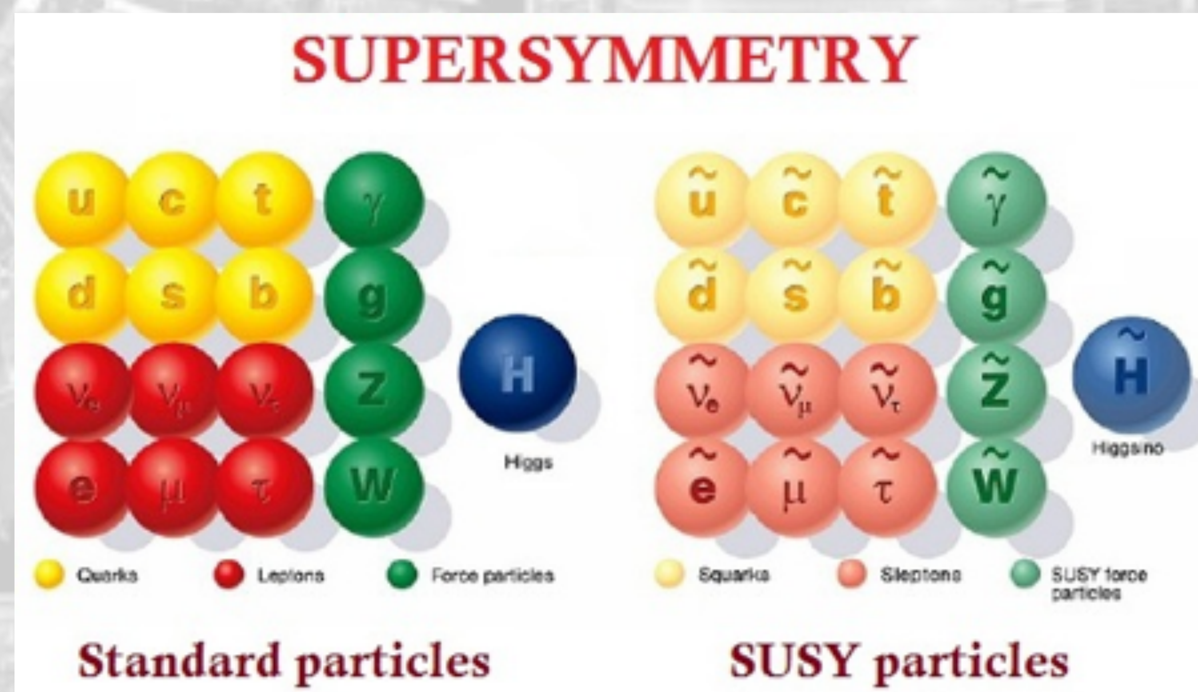
- If SUSY is exact, SUSY partners have same mass

- So electron bosons would exist.

- This is not the case, so SUSY has to be a broken symmetry: it would hold at large energy scale (early phase of the Universe) and it stop holding at lower energies (expanded Universe)

- We live in a non-supersymmetric world. But this could come from the cooling of a supersymmetric one



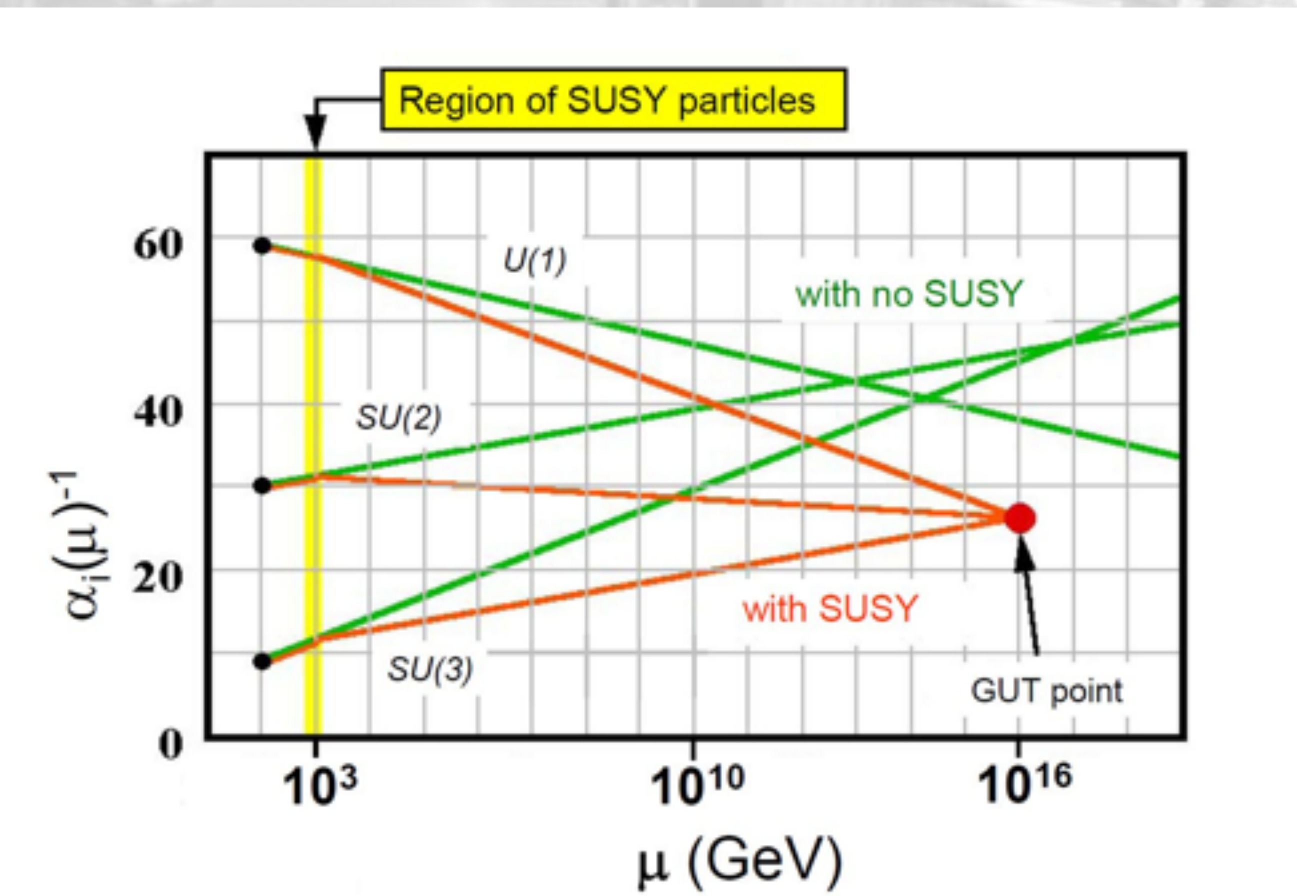


Why Supersymmetry?

- Each contribution to the Higgs mass is cancelled by the similar term from the supersymmetric partner

- The cancellation is not exact, as SUSY is broken. The residual term is ~ the difference of SUSY mass terms and it is $m_H \sim 125$ GeV.

- Hence SUSY particle masses should be around m_H.



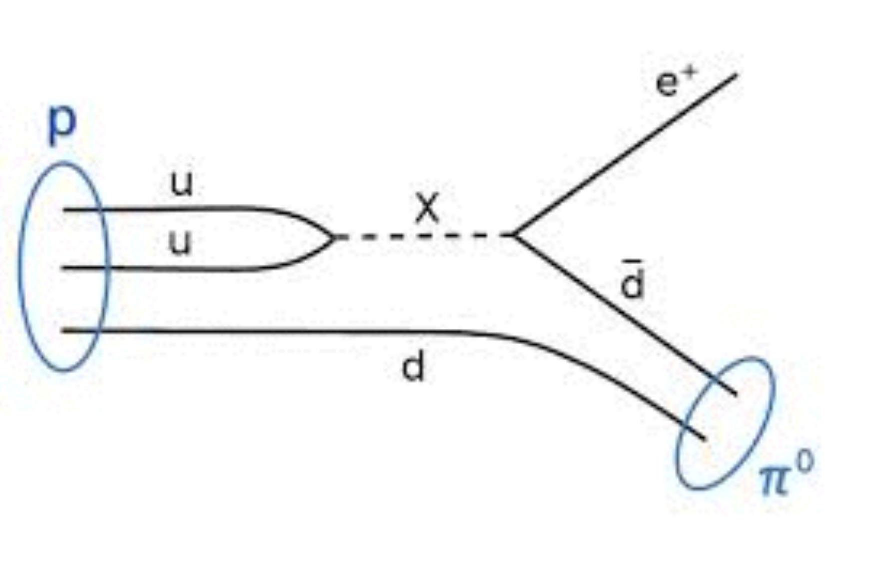
SUSY has also an unexpected nice feature

- It changes the strength of forces, such that at some high scale the strength of the three particle forces we know about is the same
- Without SUSY this does not happen
- Gravity is not in the picture yet

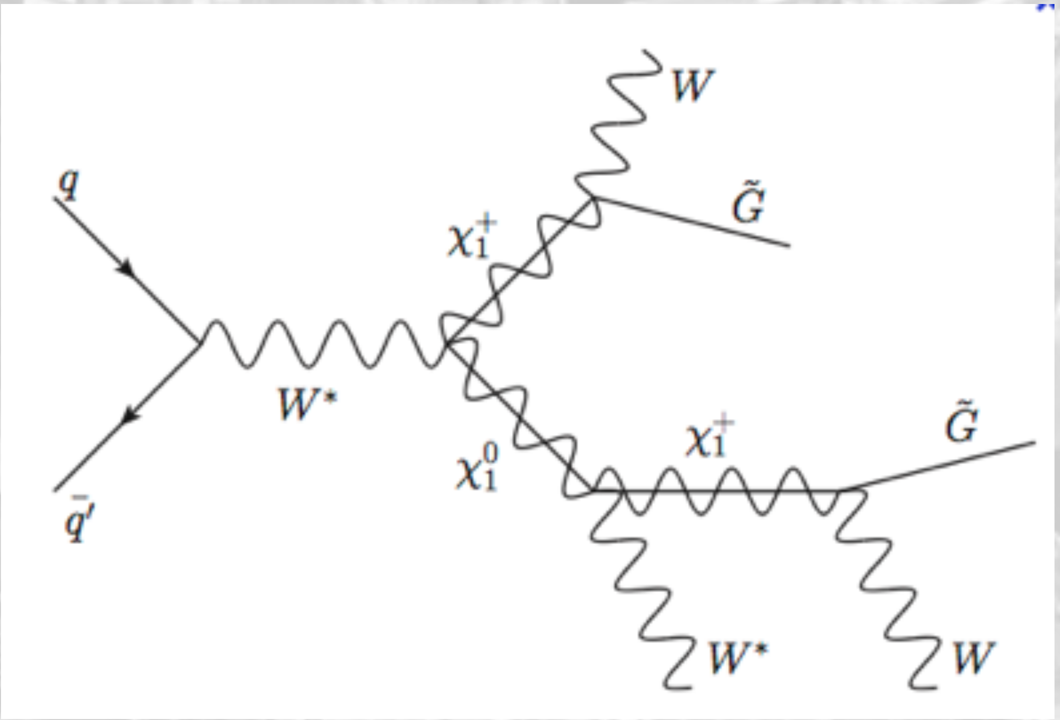
SUSY & Dark Matter

- The problem with SUSY is that it predict proton to decay

- No proton decay was ever observed, so this cannot work



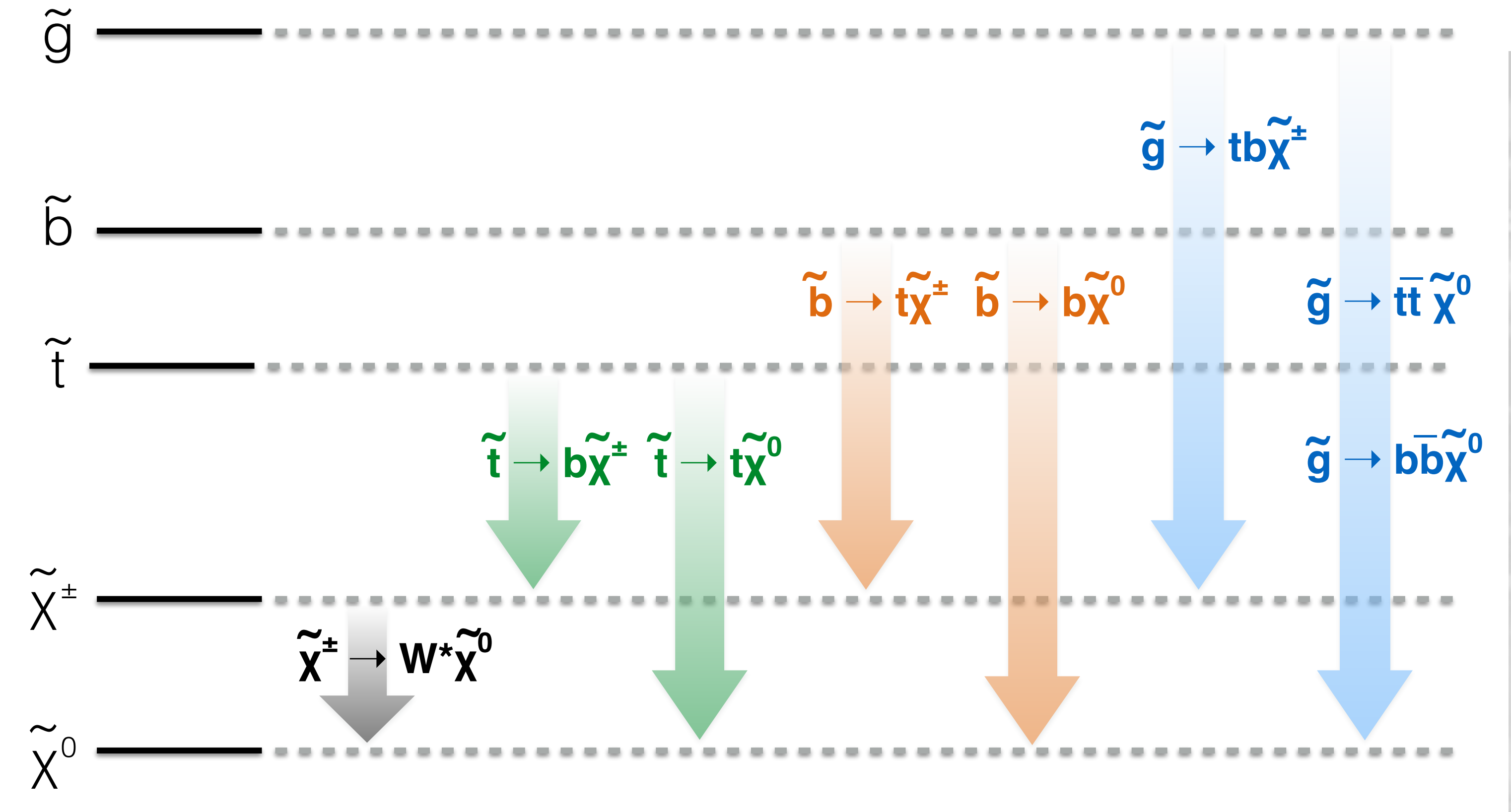
- This is not a problem for a special kind of SUSY (R-Parity conserving), for which SUSY particles can only be produced in even number from SM particles, or in odd number from a SUSY decay



- As a consequence, the lightest SUSY particle cannot decay. It is a stable particle, and it could be the explanation of Dark Matter

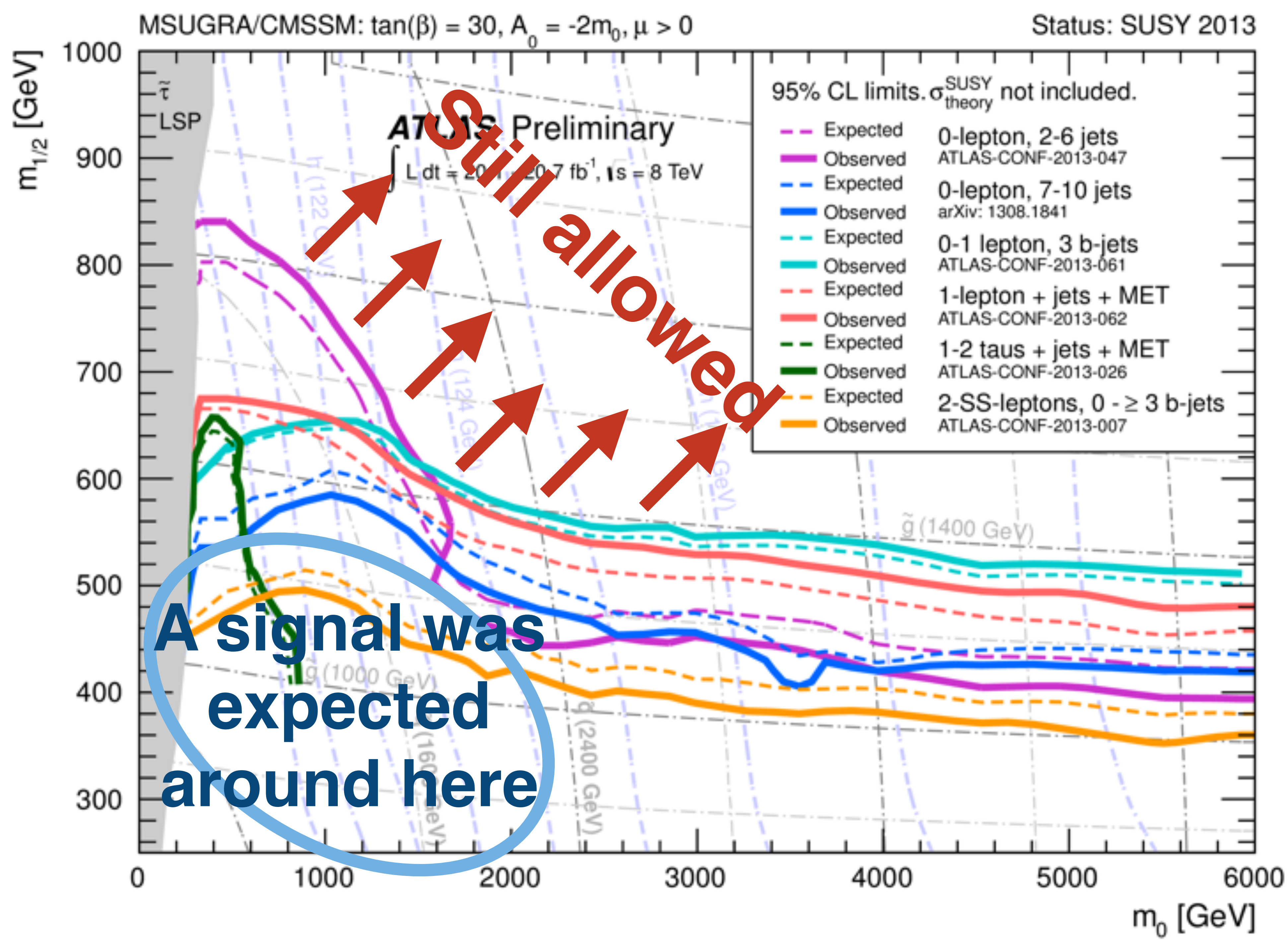
SUSY Phenomenology

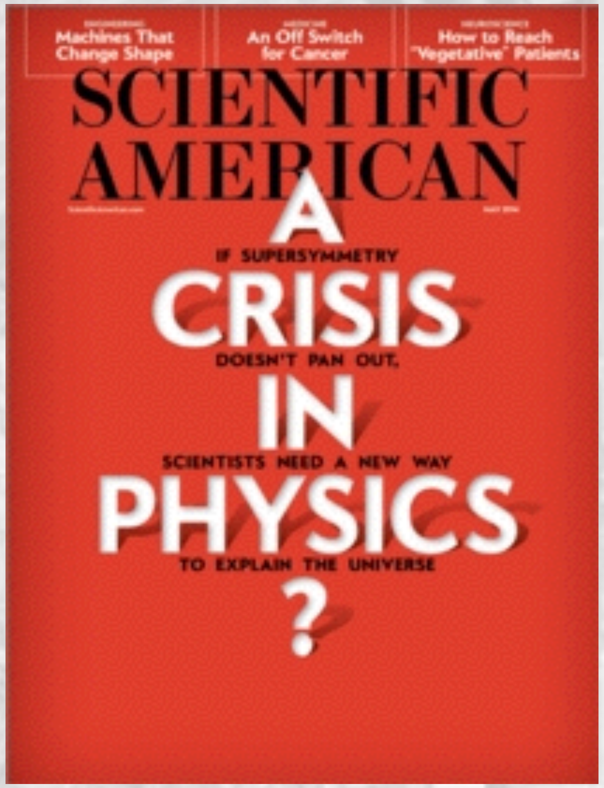
- SUSY particles are produced in pair
- They decay to observable + unobservable particles



- A lightest SUSY particle is produced for each cascade, and it cannot decay
- Missing transverse energy is the key (e.g. analysis similar to Monojet)
- But the final state has more than one jet
- More assumptions behind the search (not only DM, but other new particles also needed)
- Richer phenomenology

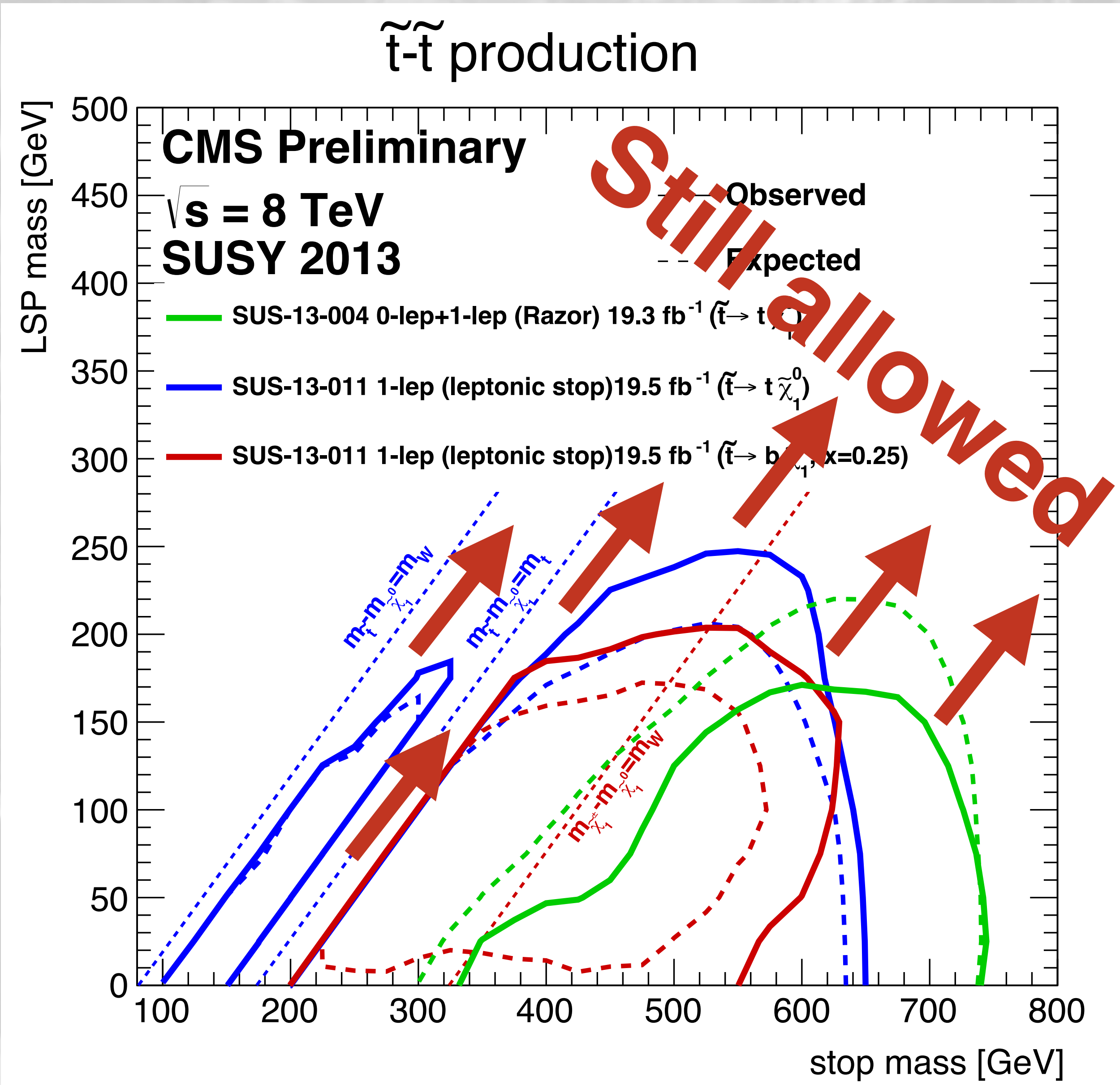
No Sign of SUSY Yet

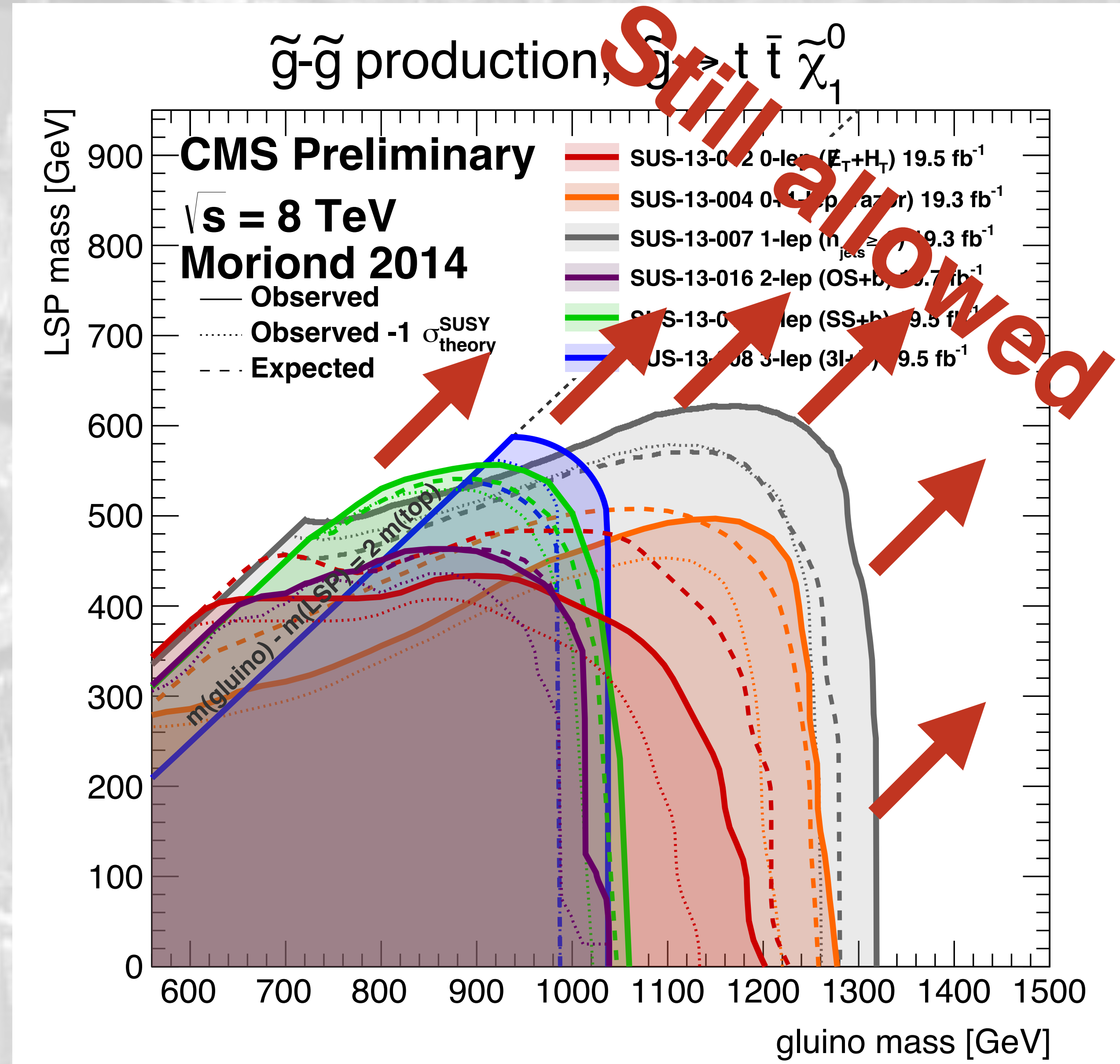




The allowed mass range pushed at the limi of what is acceptable
Next run will be crucial for SUSY

No Sign of SUSY Yet





The allowed mass range pushed at the limi of what is acceptable

Next run will be crucial for SUSY

Conclusions

- Dark Matter is an appealing explanation of several puzzling observations in astrophysics and cosmology
- The WIMP paradigm quantitatively fits the data, and has several positive implications for particle physics
- DM detection is looked for in space, underground, and in LHC collisions
- Several signals from space and underground. None from LHC (both for DM particles or heavier partners, e.g. SUSY particles)
- Still missing a definitive proof
- The next LHC run might say important things on Dark Matter and show the way to follow in our journey