Dark Matter

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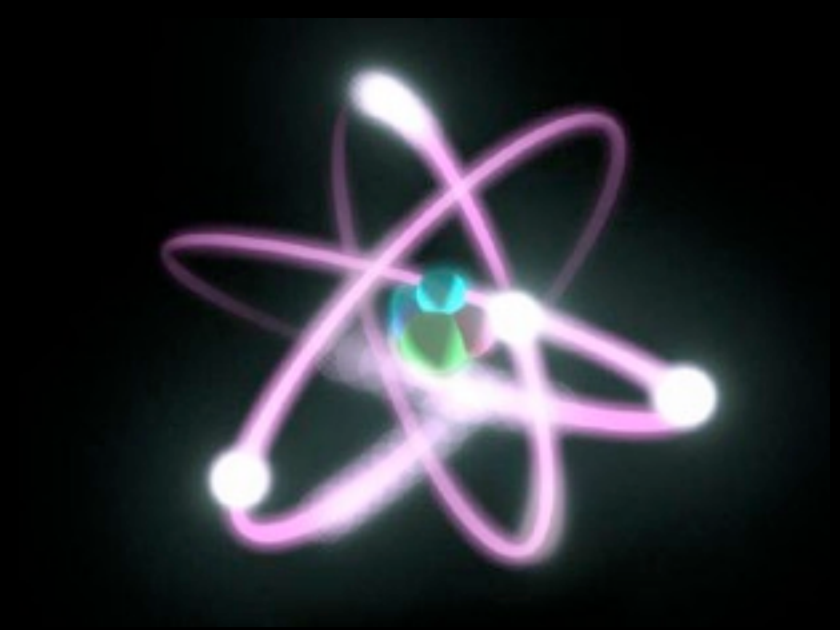
Content

- ***What do we know about DM ?***
  - Observation - galaxy rotation curves
  - Observation - gravitational lensing
- ***What do we imagine DM can be ?***
  - DM origin
  - Supersymmetry
- ***How can we measure DM ?***
  - Detection methods
  - DM at the LHC

From the very big

To the very small



What do we know about Dark Matter ?

The composition of the Universe


The Milky Way Galaxy

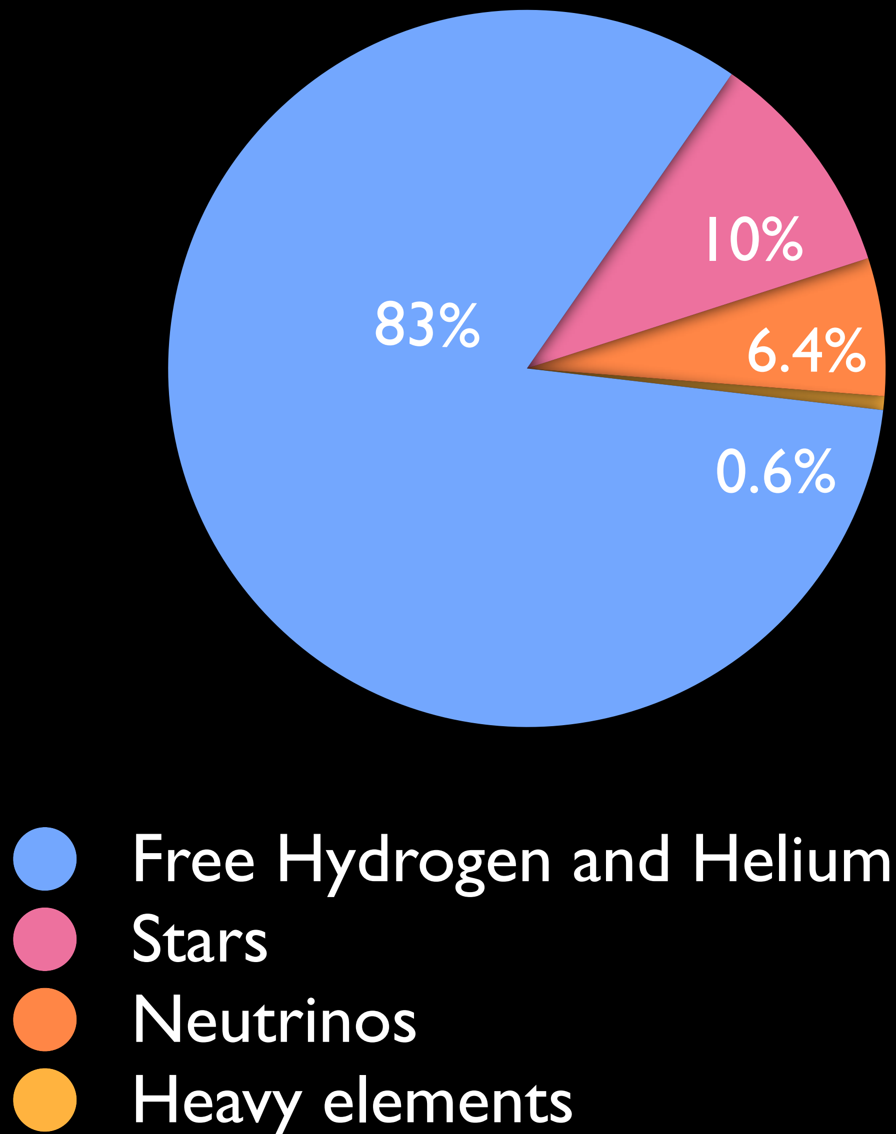
Studied quantitatively since the ancient Greek

- The age of the universe is **13.7 billion** years
- The observable universe (visible from Earth) has a radius of about **46 billion light years**
- Diameter of a typical galaxy is **30.000 light years in diameter** (Milky way about 100.000 light years)
- Our nearest galaxy, Andromeda, is about **2.5 million light years away**
- Possibly about **10^{11}** galaxies in the observable universe
- The Universe is made up of filaments, voids, superclusters, galaxy groups and clusters

Looking closer The visible Universe is made of ....

The composition of the Universe

THE VISIBLE UNIVERSE CONSIST OF :



The Milky Way Galaxy

STUDIED QUANTITATIVELY SINCE THE ANCIENT GREEK

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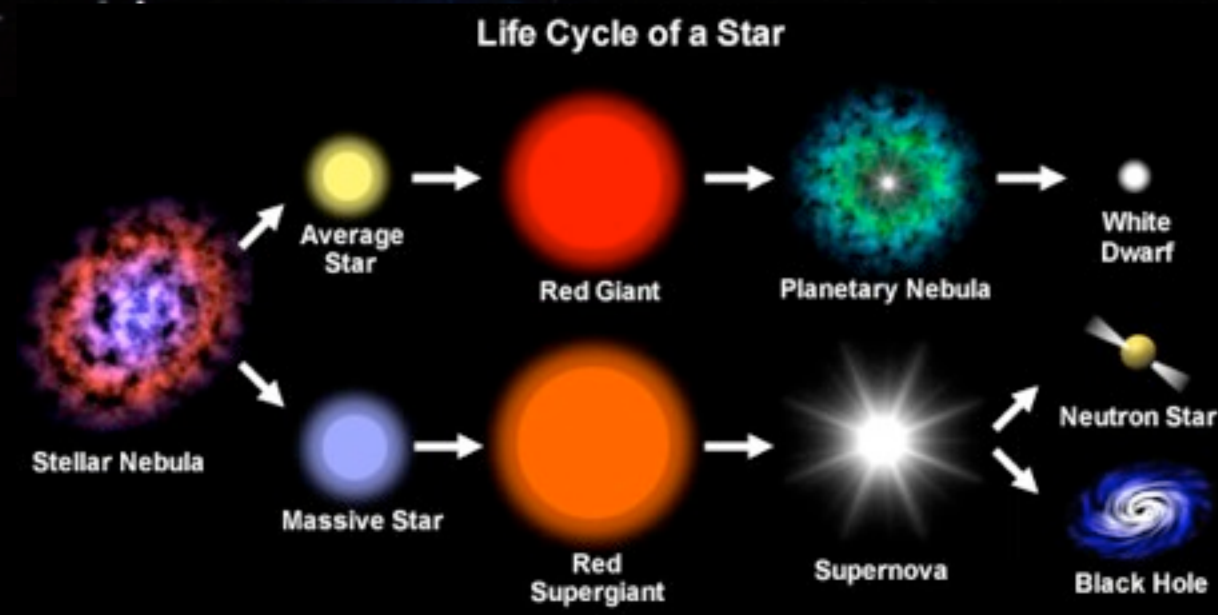
LOOKING CLOSER THE VISIBLE UNIVERSE IS MADE OF ....

The visible universe



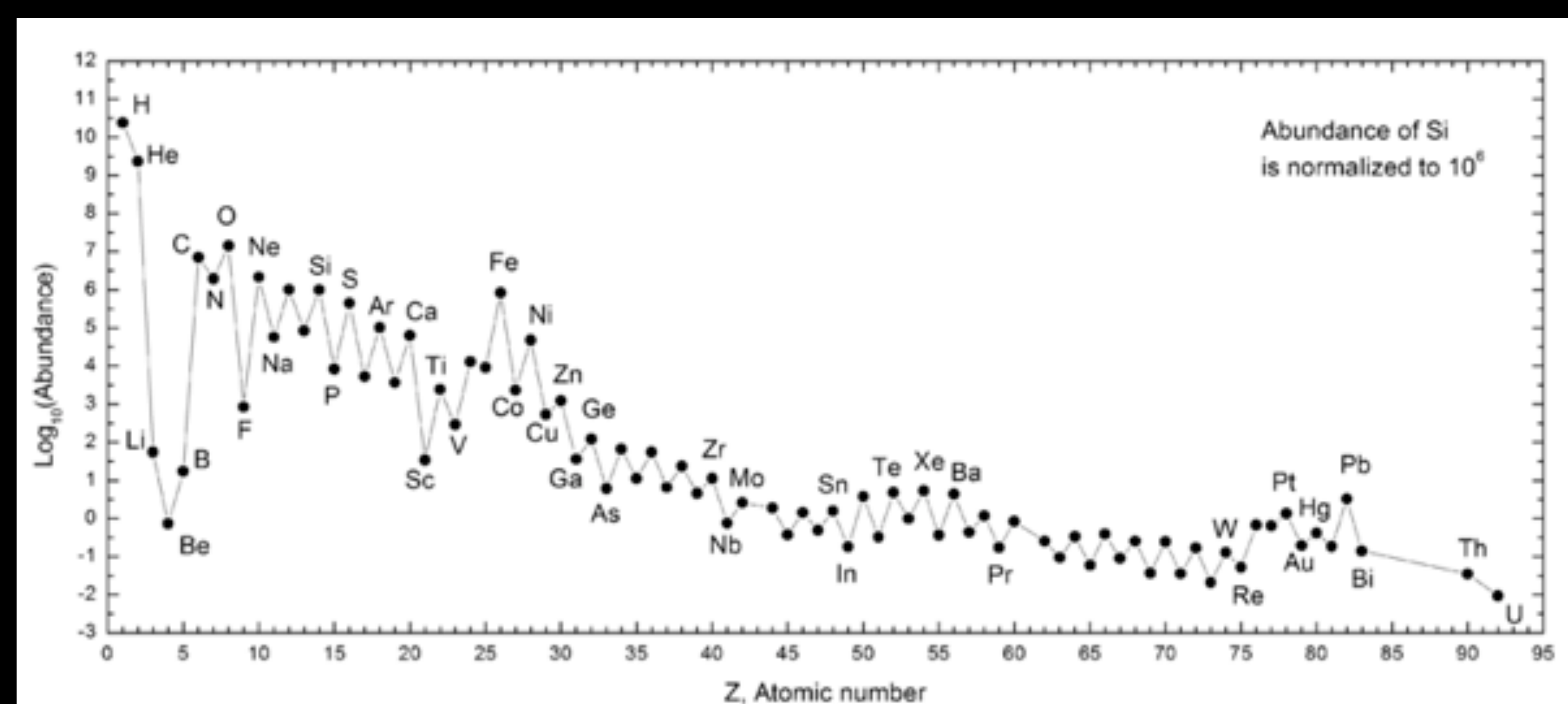
We know quite a bit about stars !

- A star is a massive, luminous ball of plasma hold together by gravity
- We know about the birth and life, movement, nuclear fusion, magnetic fields, clustering, ...

We know a lot about heavy elements !

- Fractions (lithium, beryllium, boron?) produced in the big bang, the rest a result of stellar activity - fusion !
- Planets, the Earth, Atomic physics,Chemistry, Geology

Estimated abundance of chemical elements in the solar system



The visible universe

The Cat's eye nebula

We do know something about gaseous systems

- Hydrogen and Helium are the most abundant elements in the universe (Hydrogen is about 75 % of normal matter)
- Found in abundance in stars and gas giant planets and as nebula - an interstellar cloud of dust, hydrogen gas, helium gas or other ionised gases
- In solar winds they interact with the Earths magnetosphere and give rise to Birkeland currents and Aurora

We are discovering the properties of the neutrinos

- When a star explodes in a supernova it ejects neutrinos that travel through space at almost the speed of light
- Neutrinos are created in certain radioactive decays, nuclear reactions (e.g. sun) or in cosmic ray collisions with atoms
- Three types exists, **electron-, muon- and tau-neutrino**, as well as its anti-neutrinos
- About 65 billion solar neutrinos per second pass through every square centimeter of the Earth

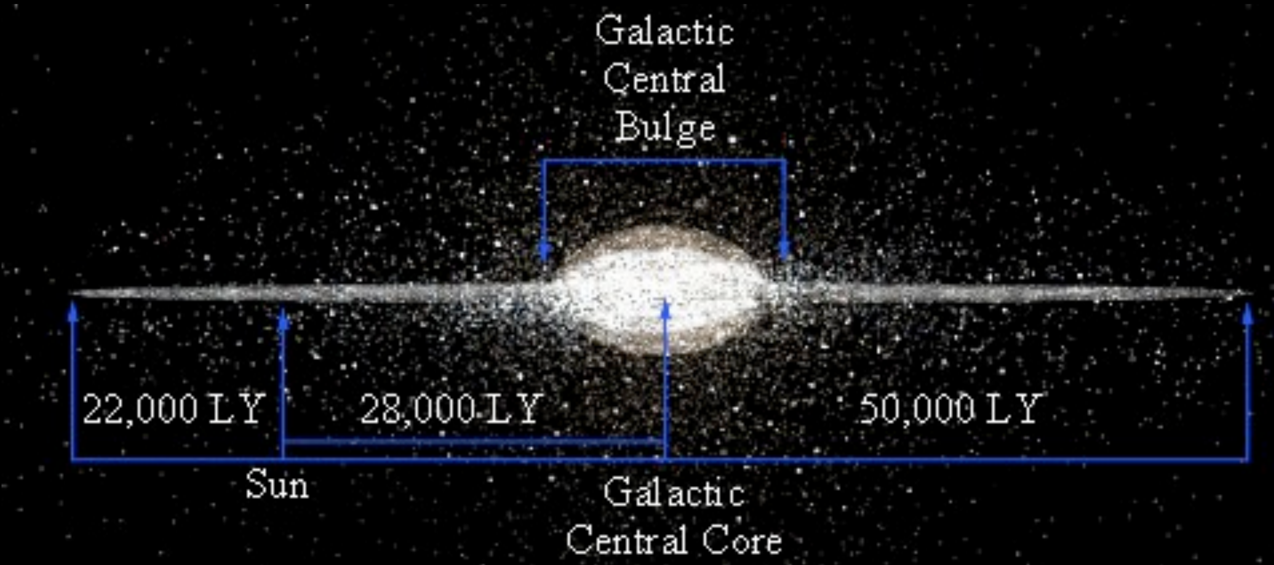
Is this all ?

No there is more ...

First indications already in the 30's

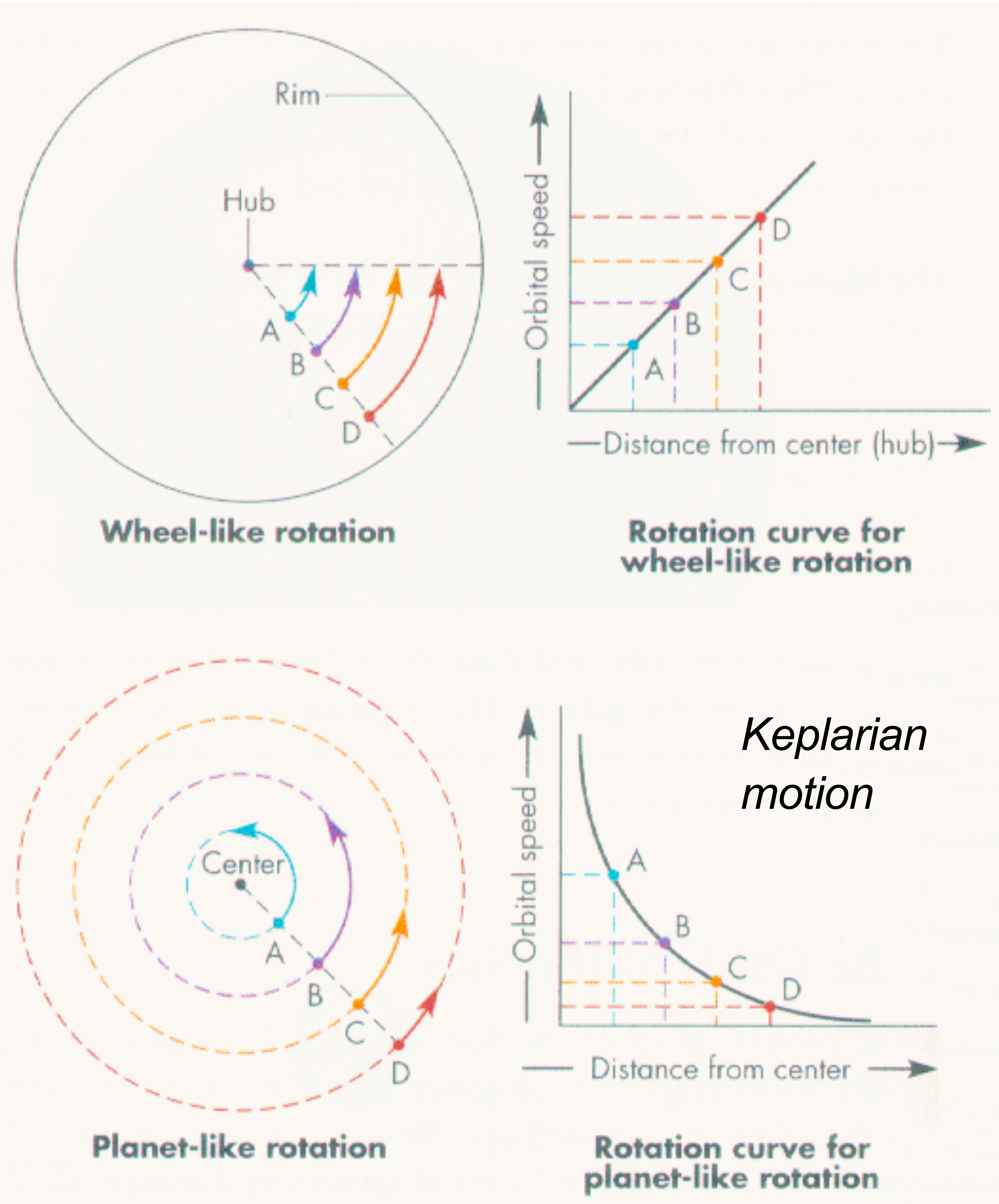
- **Fritz Zwicky** was the first to point out that the rotation curves for galaxies where not quite right - proposed the idea of **Dark Matter**
- In the 50's astronomers started to study the internal motions of galaxies (rotation for disk galaxies) and their interaction with each others in clusters
- Early 60's there was an indication that the brightest galaxies was not always the most massive - the missing mass problem
- Soon they started to wonder if we were observing the mass or the light in the Universe, most of what we see in galaxies is starlight.
- One of the first studies was the rotation of our own galaxy:

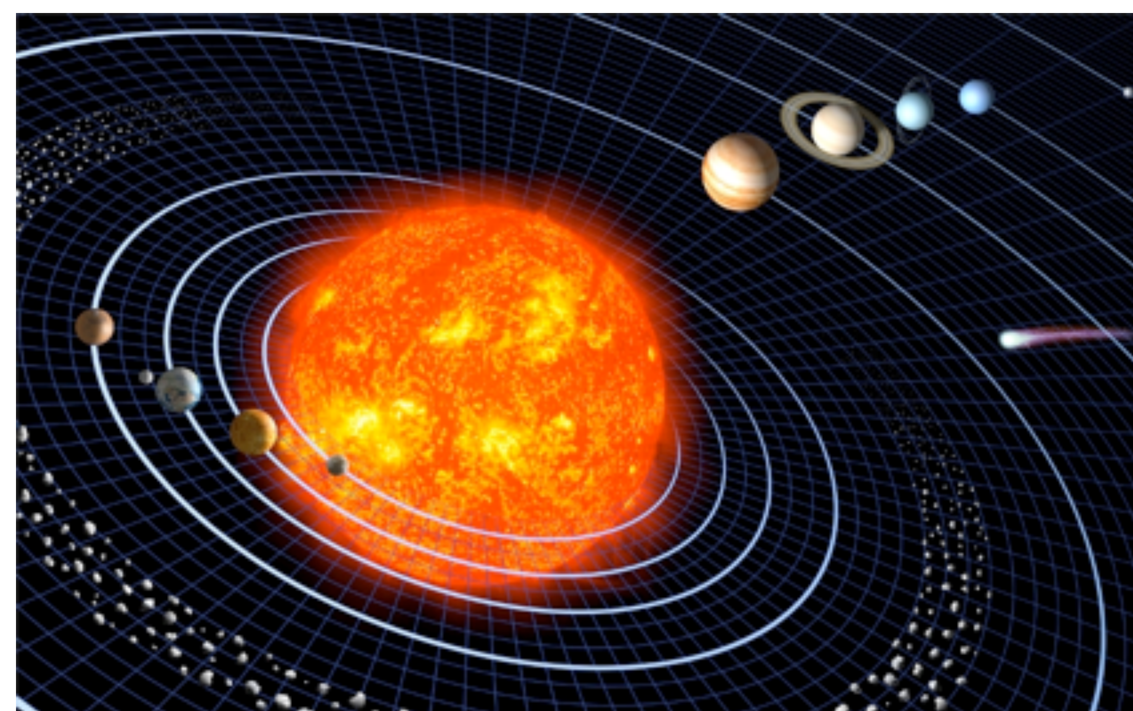
Fritz Zwicky



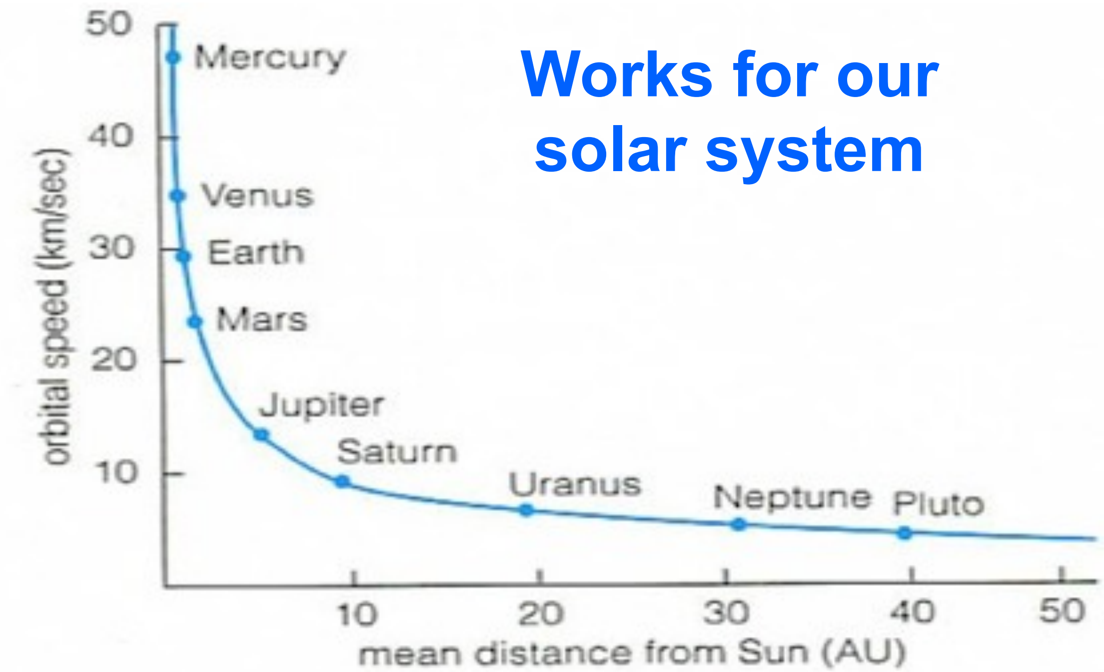
The Milky Way

Orbital movements





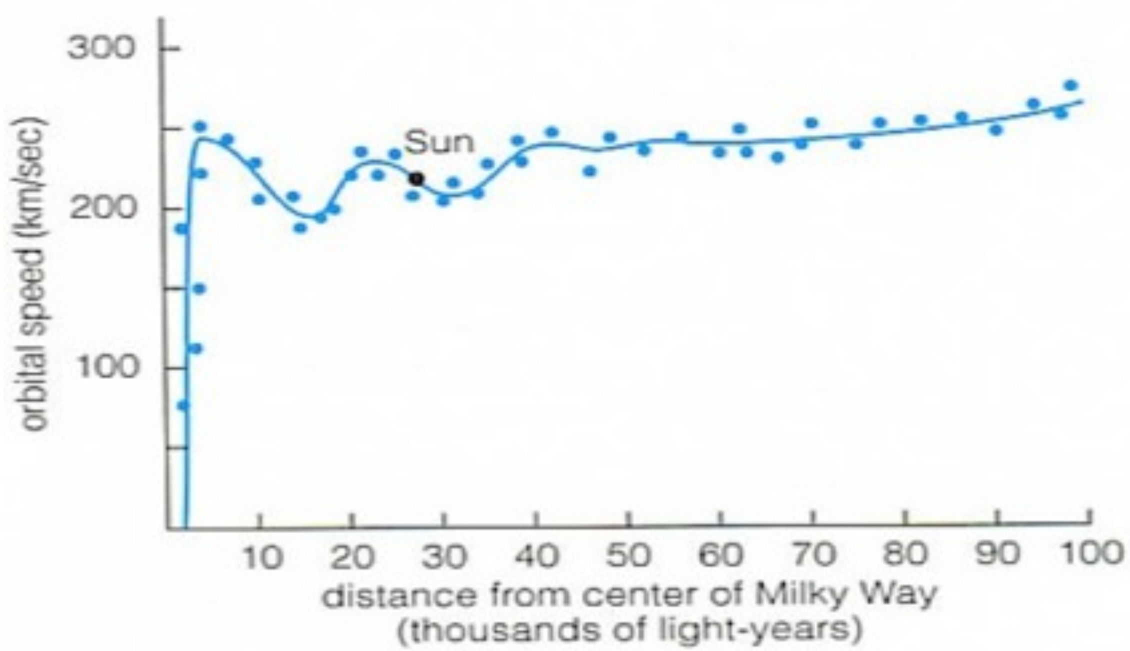
Rotation curves



The rotation curve for the planets in our solar system.

Works for our solar system

Not for our galaxy



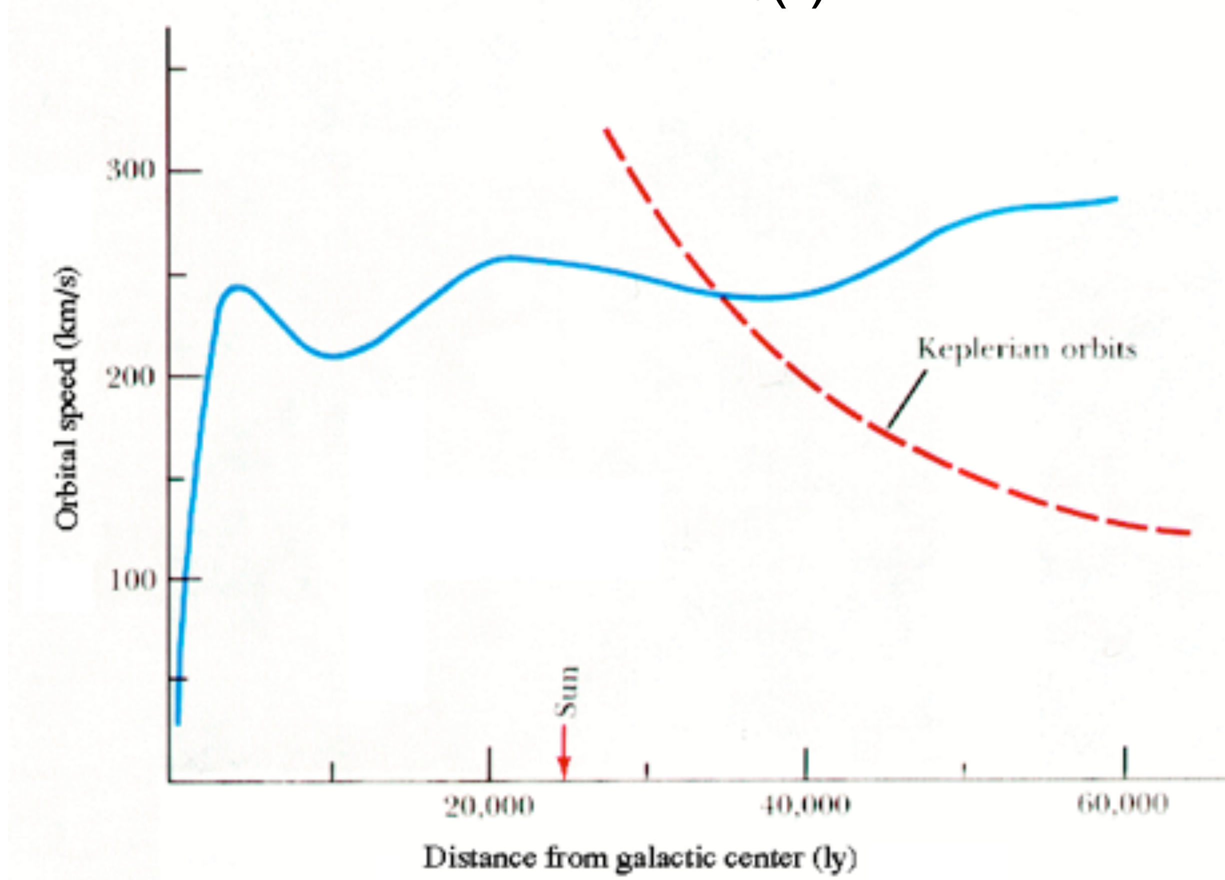
The rotation curve for the Milky Way Galaxy.

- From Newtons equations we know that the circular velocity of stars around the galactic centre is:

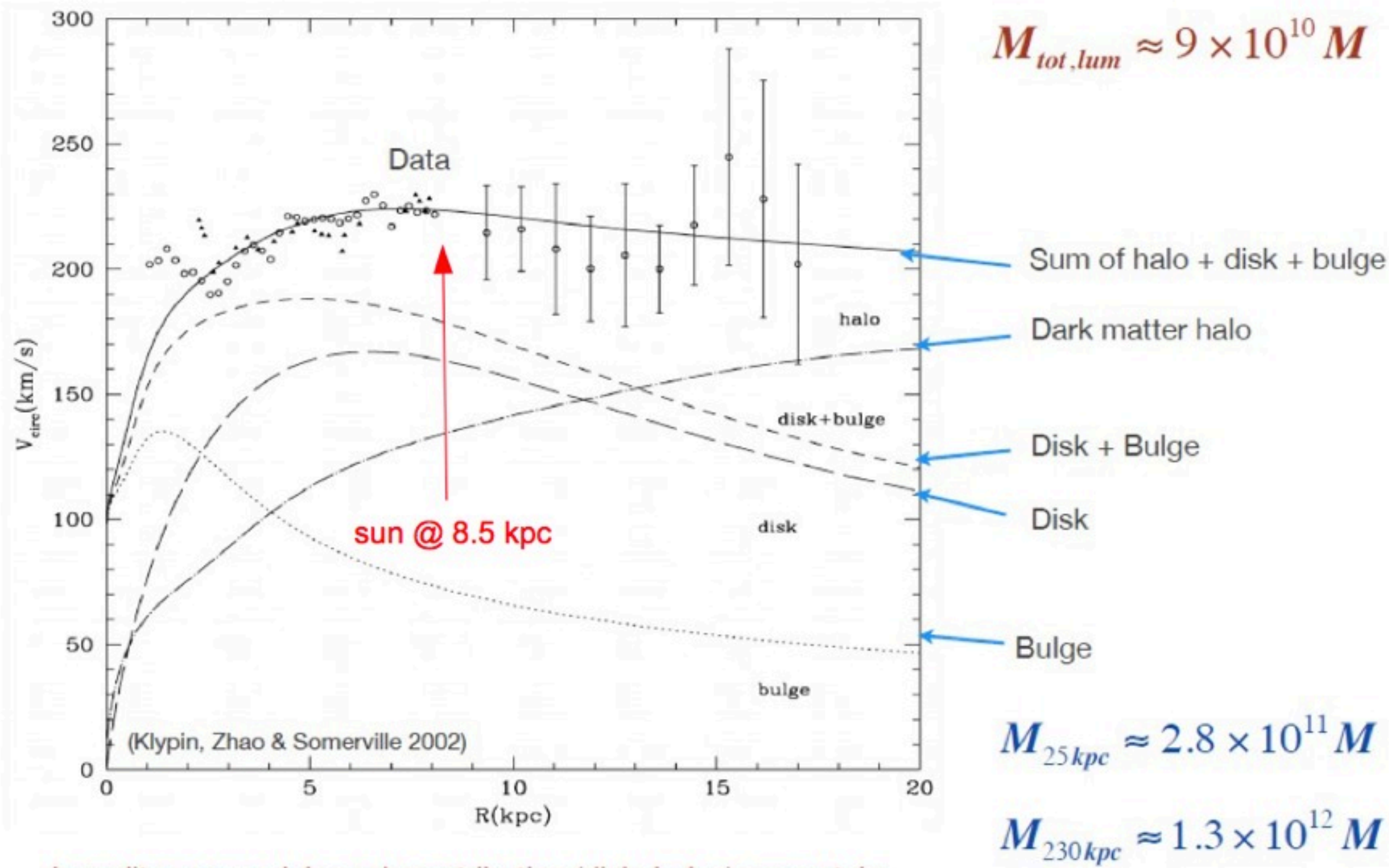
$$v_c(r) = \sqrt{\frac{GM(r)}{r}}$$

- M(r) is the total mass inside the galactio-centric distance r
- We expect the velocity to fall proportional to:

$v_c(r) \sim 1 / \sqrt{r}$



Rotation curves - Milky way components



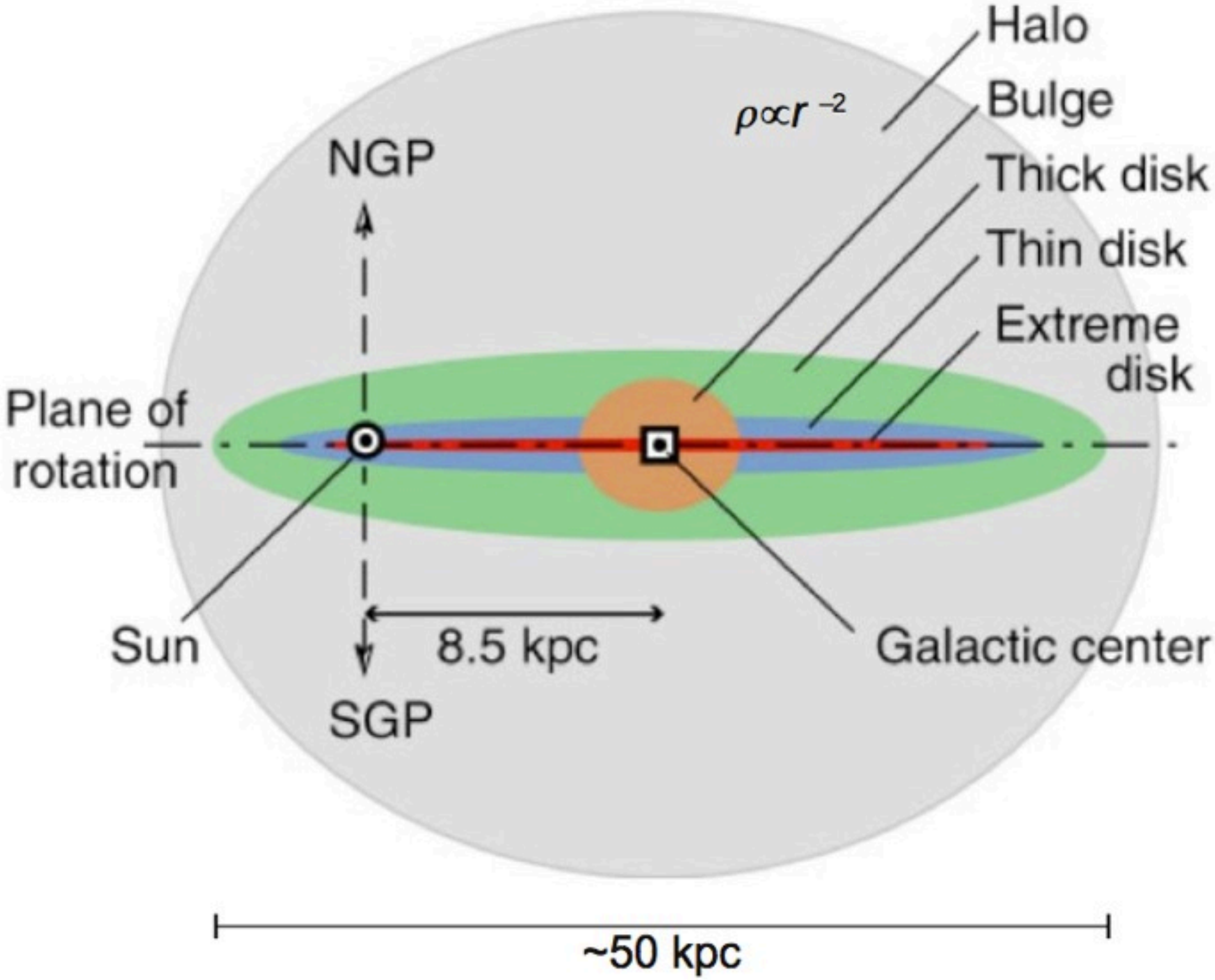
$M_{tot,lum} \approx 9 \times 10^{10} M$

$M_{25kpc} \approx 2.8 \times 10^{11} M$

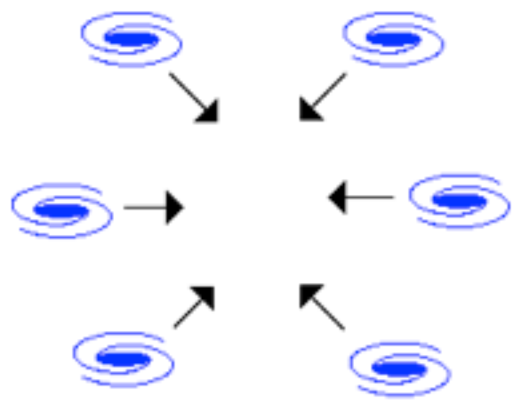
$M_{230kpc} \approx 1.3 \times 10^{12} M$

In reality one models each contribution (disk, bulge) separately

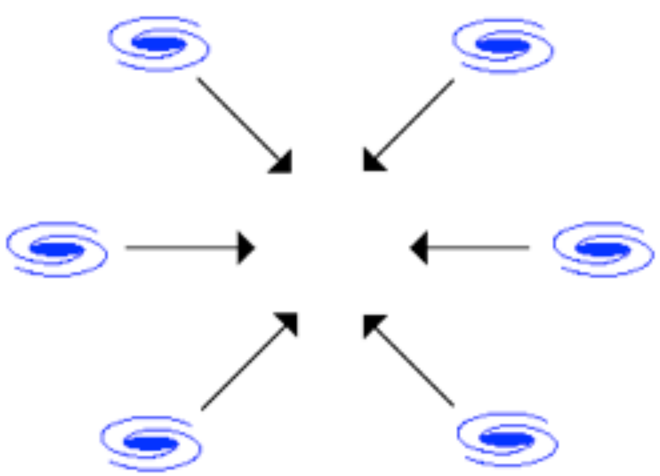
Rotation curves - Milky way components



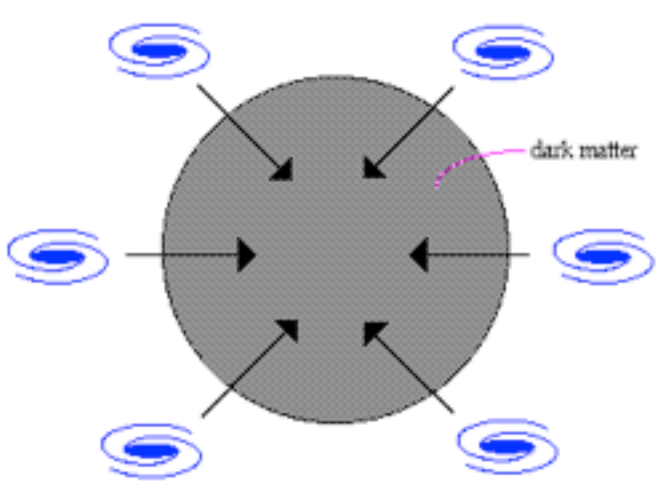
Cluster velocities



The members of a cluster of galaxies move because of their mutual gravitational attraction.



In most clusters, the velocity of the cluster galaxies is much higher than can be accounted for from the individual galaxy masses.



The result is there must be an unseen core of dark matter attracting the galaxies with more gravity and, therefore, more velocity.

- One can also look at clusters of stars which are hold together by gravitational forces between the galaxies
- Clusters can have from around 10-100 galaxies
- The more mass, the higher the velocity - test for unseen matter
- The measurement showed that up to 95% of the mass in clusters is not seen, but dark
- Our “normal” matter is special, and what there is most of we can not see
- What is this dark matter?

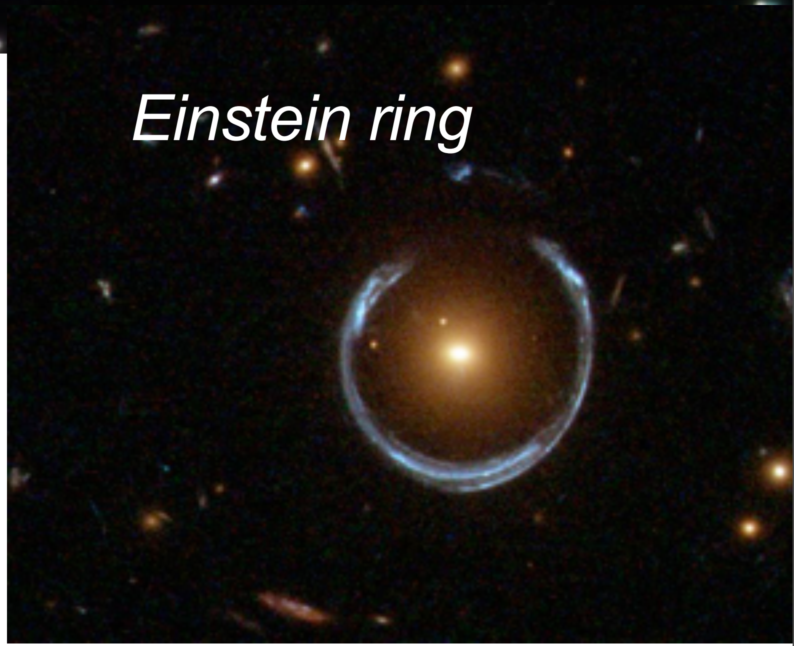
Observational evidence for dark matter

Picture of the galaxy cluster ZwCI0024+1652, 5 billion light years away, showing one of the strongest evidence of dark matter !

Pictures from the Hubble telescope

Gravitational lensing makes the galaxies appear as disks

Gravitational lensing



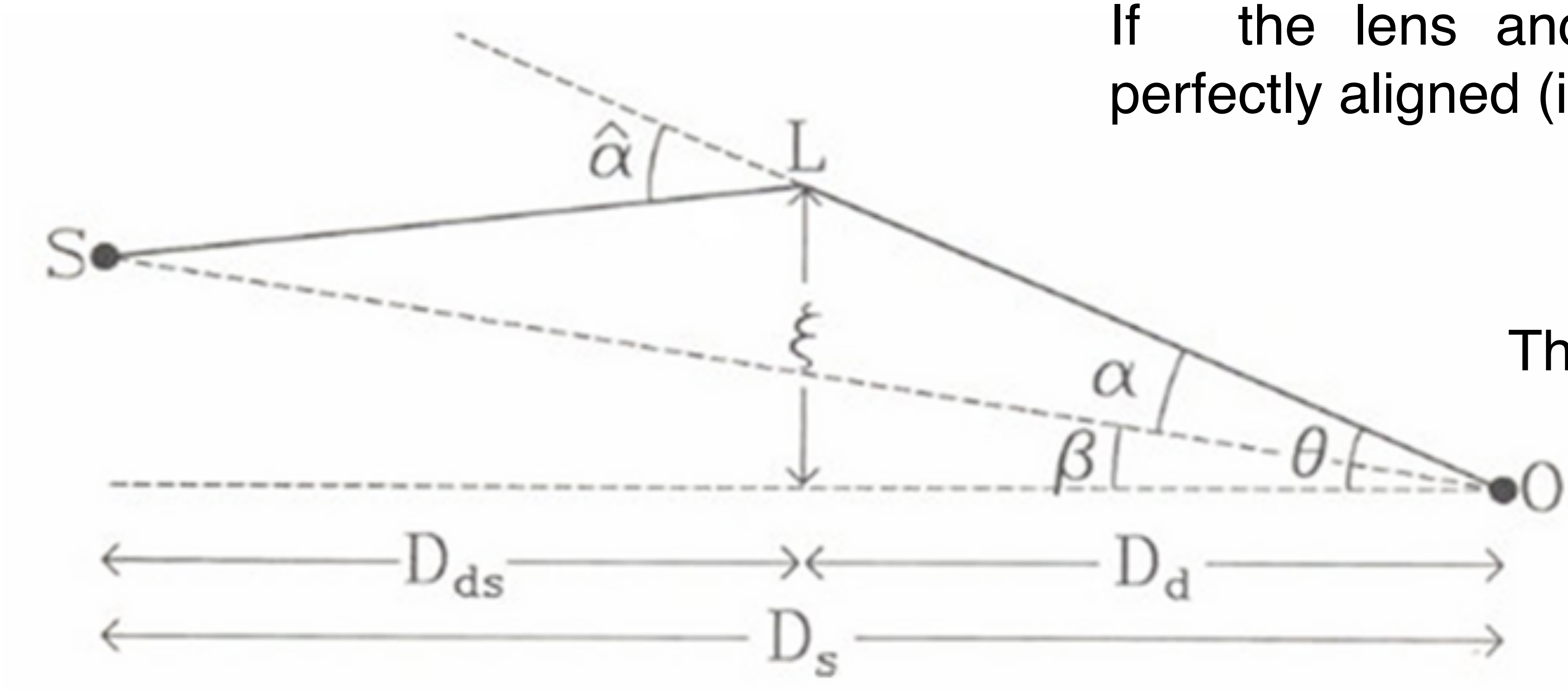
- Einsteins equivalence principle: The forces of gravitation and acceleration are equivalent
- This means that photons also are under the influence of gravitation and bends when passing a massive object
- The angle by which the light bended can be calculated in the context of Einsteins theory of general relativity:

$$\hat{\alpha} = \frac{4GM}{c^2 \xi},$$

G is the Gravitational constant, M the mass of the deflecting object and c the speed of light

ξ → impact parameter of the light ray

- Observer O sees the image L of the source S at a position on the plane of the sky



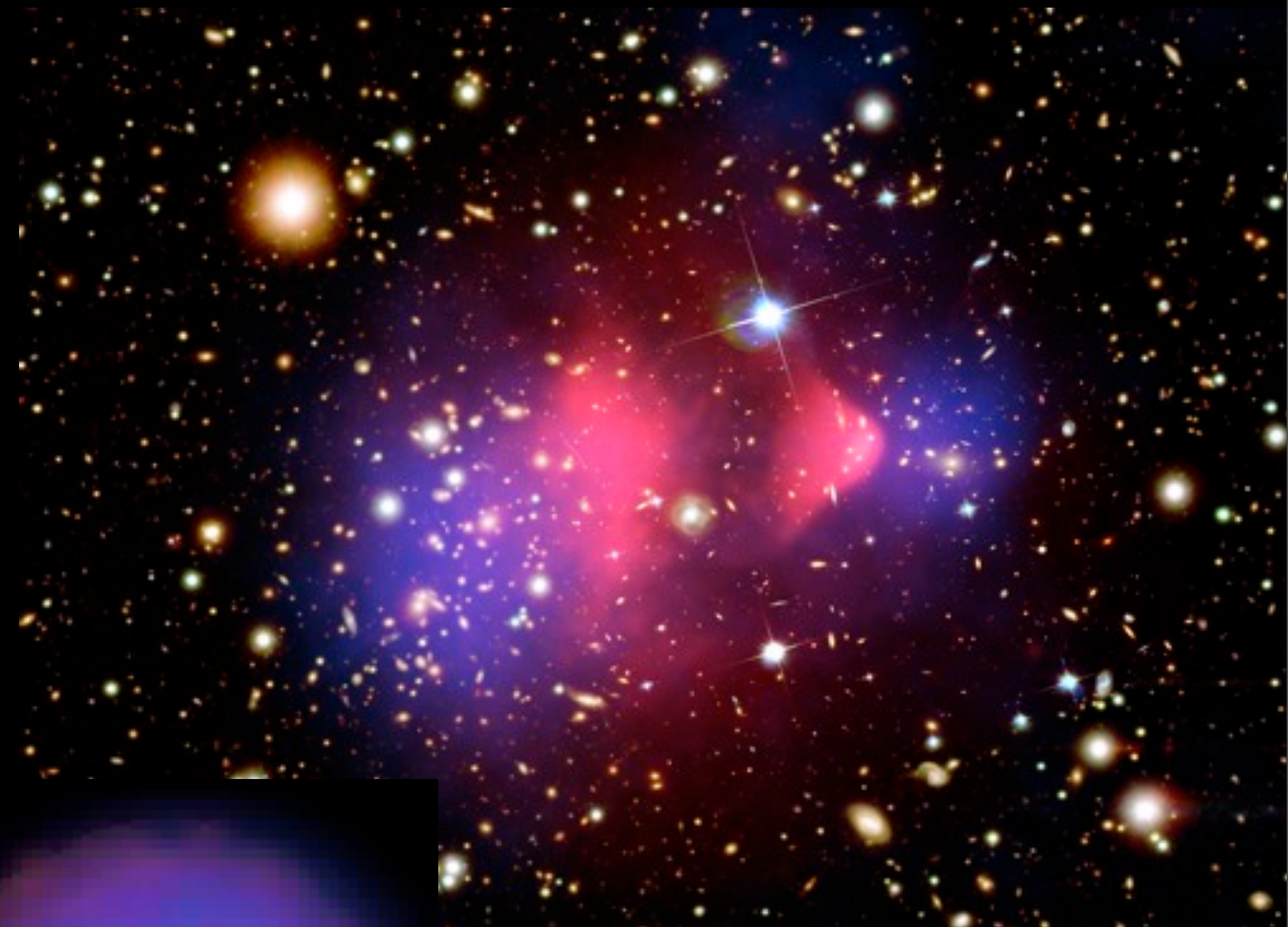
If the lens and the observer are almost perfectly aligned (i.e., beta = 0):

$$\alpha = \hat{\alpha} \cdot \frac{D_{ds}}{D_s}$$

The Einstein radius is (beta = 0) :

$$\theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s}}$$

Observational evidence for dark matter



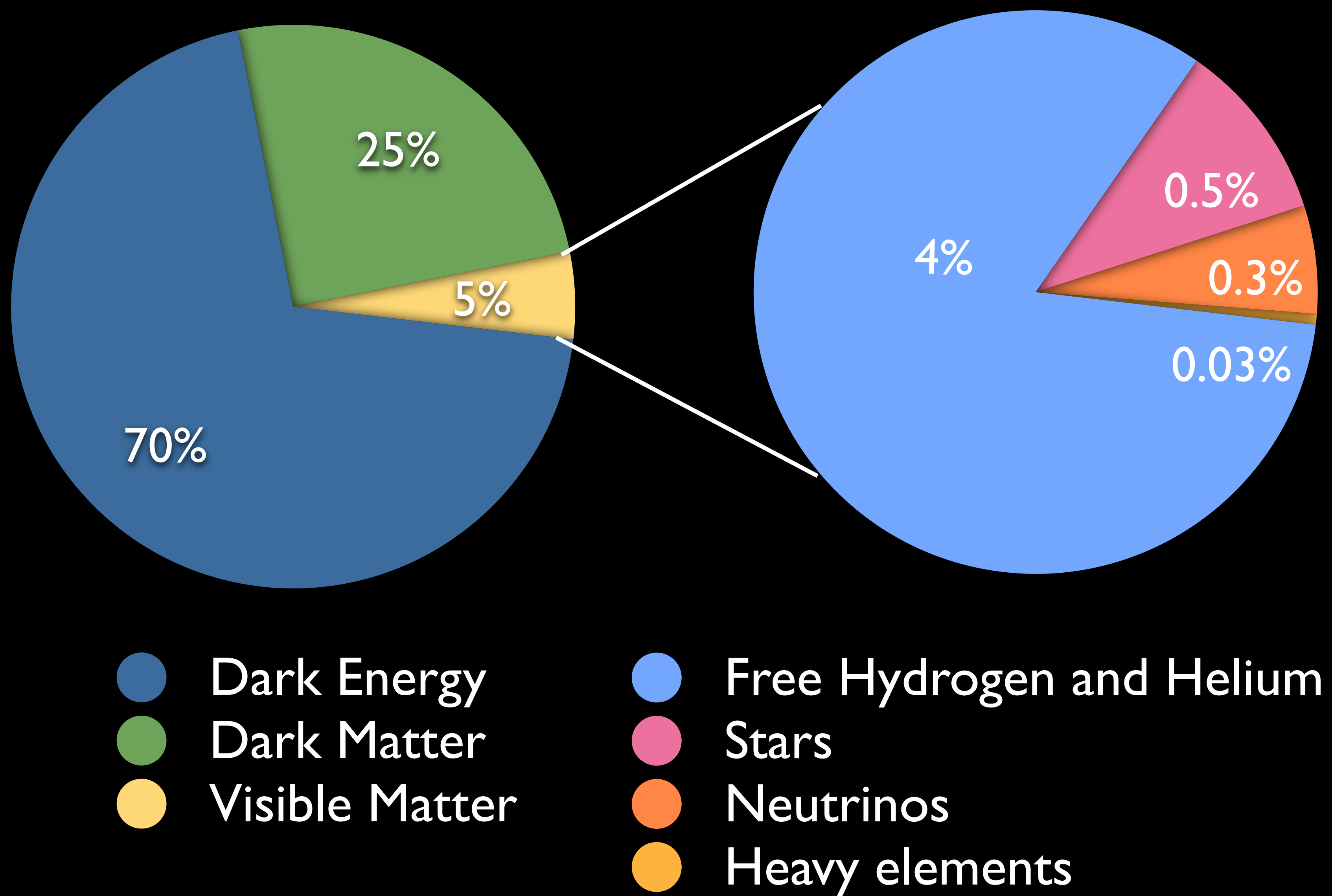
Hot gas (pink) detected in two galaxy clusters, one with a particular bullet shape. Other telescopes detected the bulk matter in the clusters which turns out to be dark matter (blue)

Dark Matter no deformation

Weakly interacting

CREDIT: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Composition of the Universe



About 95 % of the Universe is unknown !

What do we imagine Dark Matter can be?

What do we know about Dark Matter ?

DARK MATTER IS PROPOSED TO EXPLAIN THE EXTRA MASS SEEN IN THE UNIVERSE ASSUMING THAT OUR ASSUMPTIONS ABOUT GRAVITY ARE CORRECT

No doubt that dark matter exists - there is a multitude of direct observational evidence (since the 1930s):

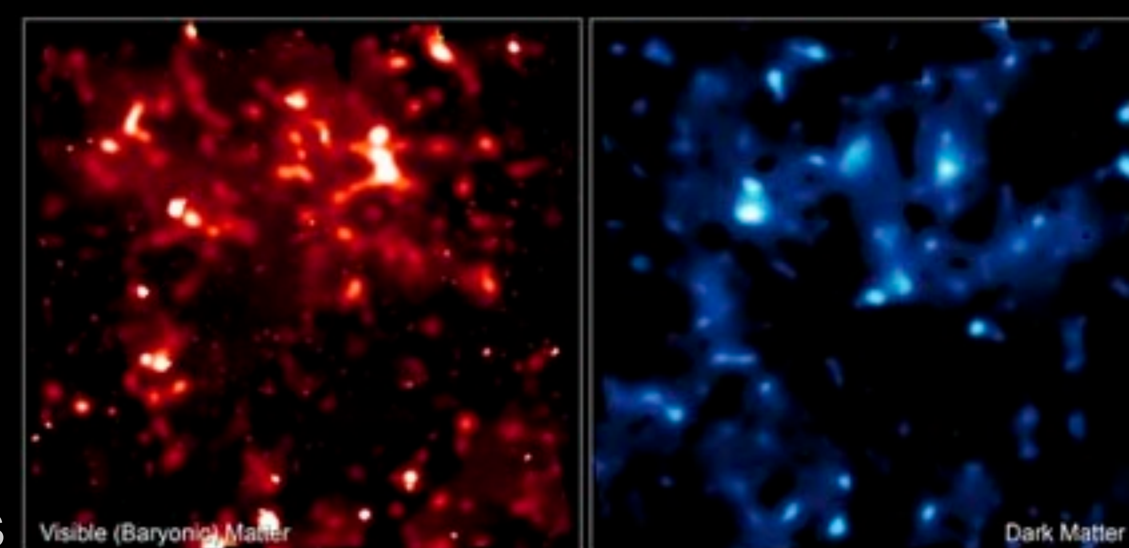
- Galactic rotational curves
- Velocity dispersion of galaxies
- Galaxy clusters and gravitational lensing
- Cosmic microwave background
- Sky surveys and baryon acoustic oscillations

Fritz Zwicky

Vera Rubin

What do we know about Dark Matter

- Can only be observed through gravitational effects on visible matter
- It interacts only weakly with regular matter (not by electromagnetic radiation)
- It also interact with other dark matter particles only through gravity



Distribution of Visible and Dark Matter • Cosmic Evolution Survey
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, and R. Massey (California Institute of Technology) STScI-PRC07-01b

What can dark matter be?

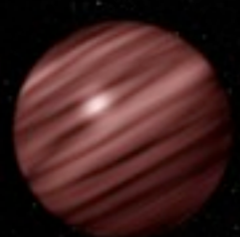
Different theories

Multitude of models providing candidates as to what dark matter could be,
from astrophysics, cosmology and particle physics

MACHOS

Massive, Compact Halo Objects

Brown dwarfs Neutron stars Black holes



→ not likely to account for more than a small fraction

WIMPS

Weakly Interactive Massive Particles

Known particle

Neutrino

→ not likely to clump as DM do

Unknown particle !

Supersymmetry → DM candidates !

... → DM candidates

We need to look for new physics beyond the standard model !

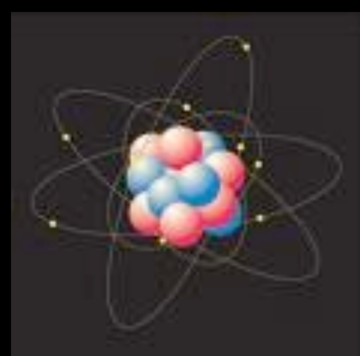
Possible new physics

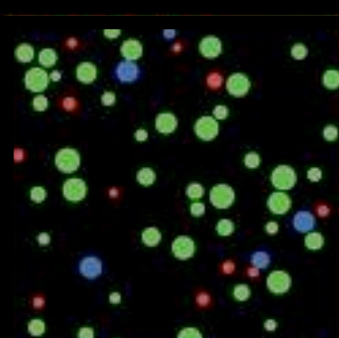
New states and new symmetries could have existed just after the Big Bang

Today

t

time = 0





Low energy

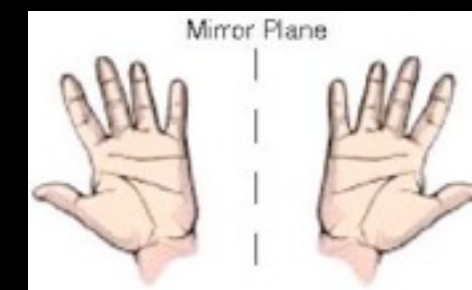
E

High energy

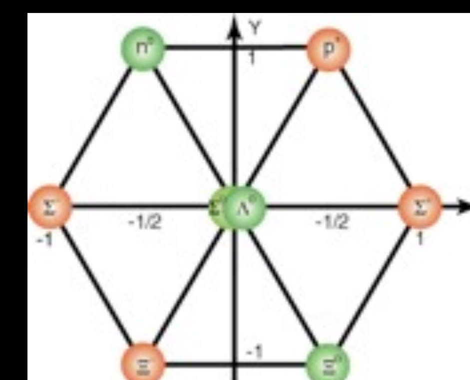
Cold

T

Warm



Left-Right symmetry



8-fold symmetry

Supersymmetry ?

Maybe supersymmetry ?

Supersymmetry

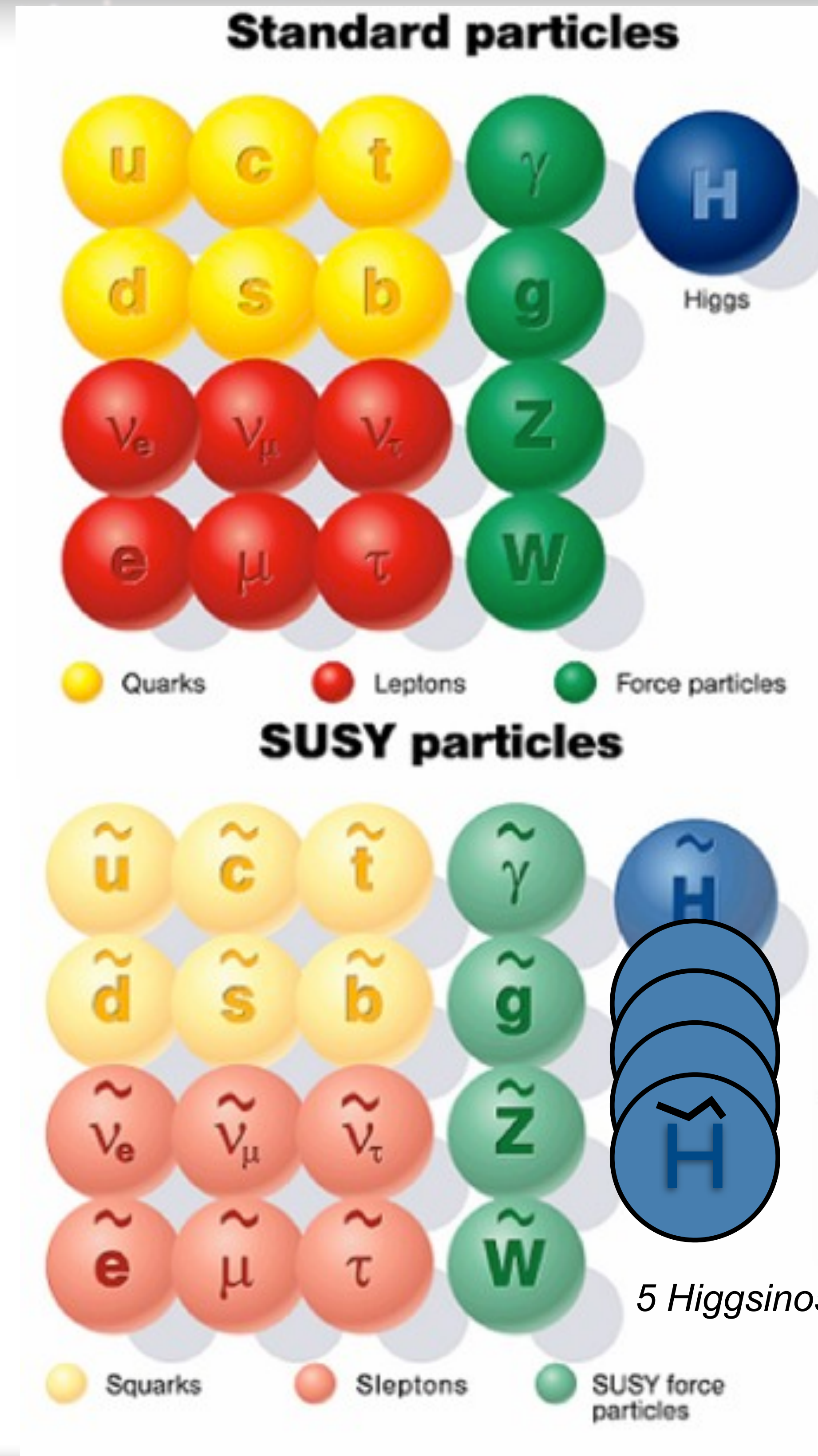
A very attractive model to explain the caveats of the SM

- ➡ Hierarchy problem is solved
- ➡ Natural cancellations of corrections to the Higgs mass
- ➡ Unification of the three gauge couplings at the GUT scale
- ➡ ***And it provides three Dark Matter candidates !***
  - **Sneutrino** - spin 0 (largely excluded)
  - Lightest **neutralino** - spin 1/2 (WIMP candidate)
  - **Gravitino** - spin 3/2 (Gravitationally interacting)

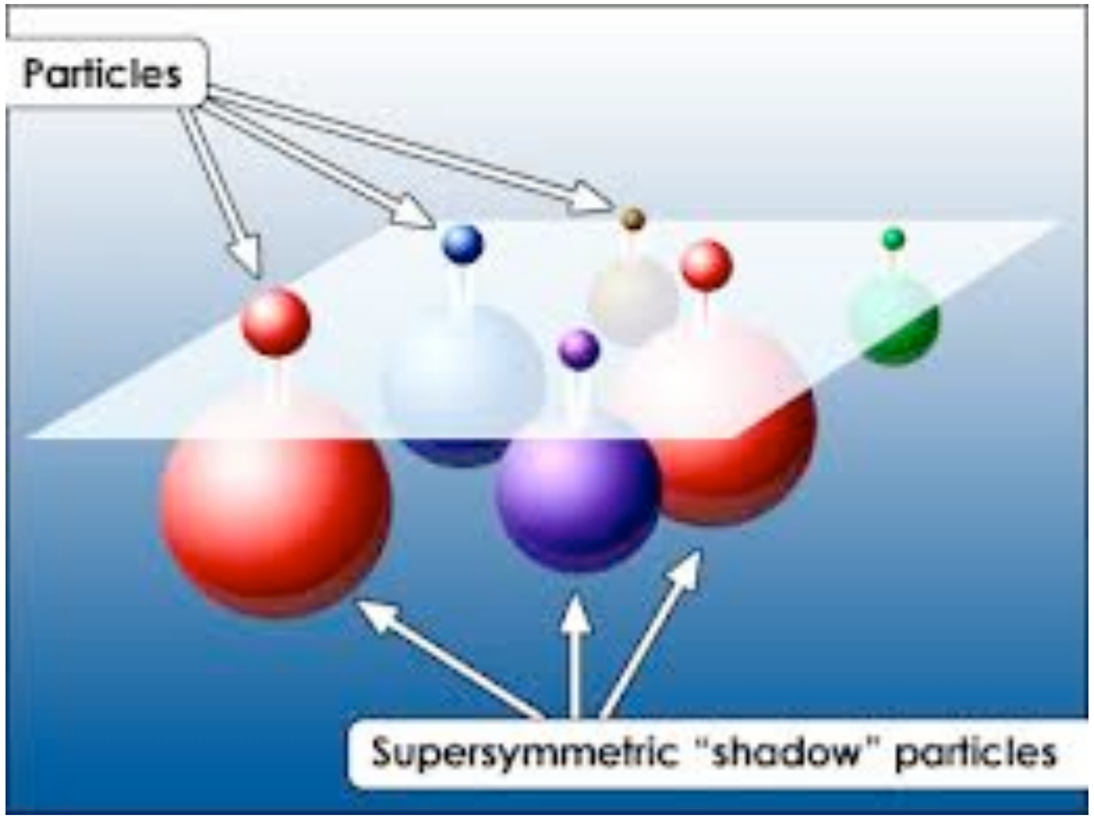
What is Supersymmetry

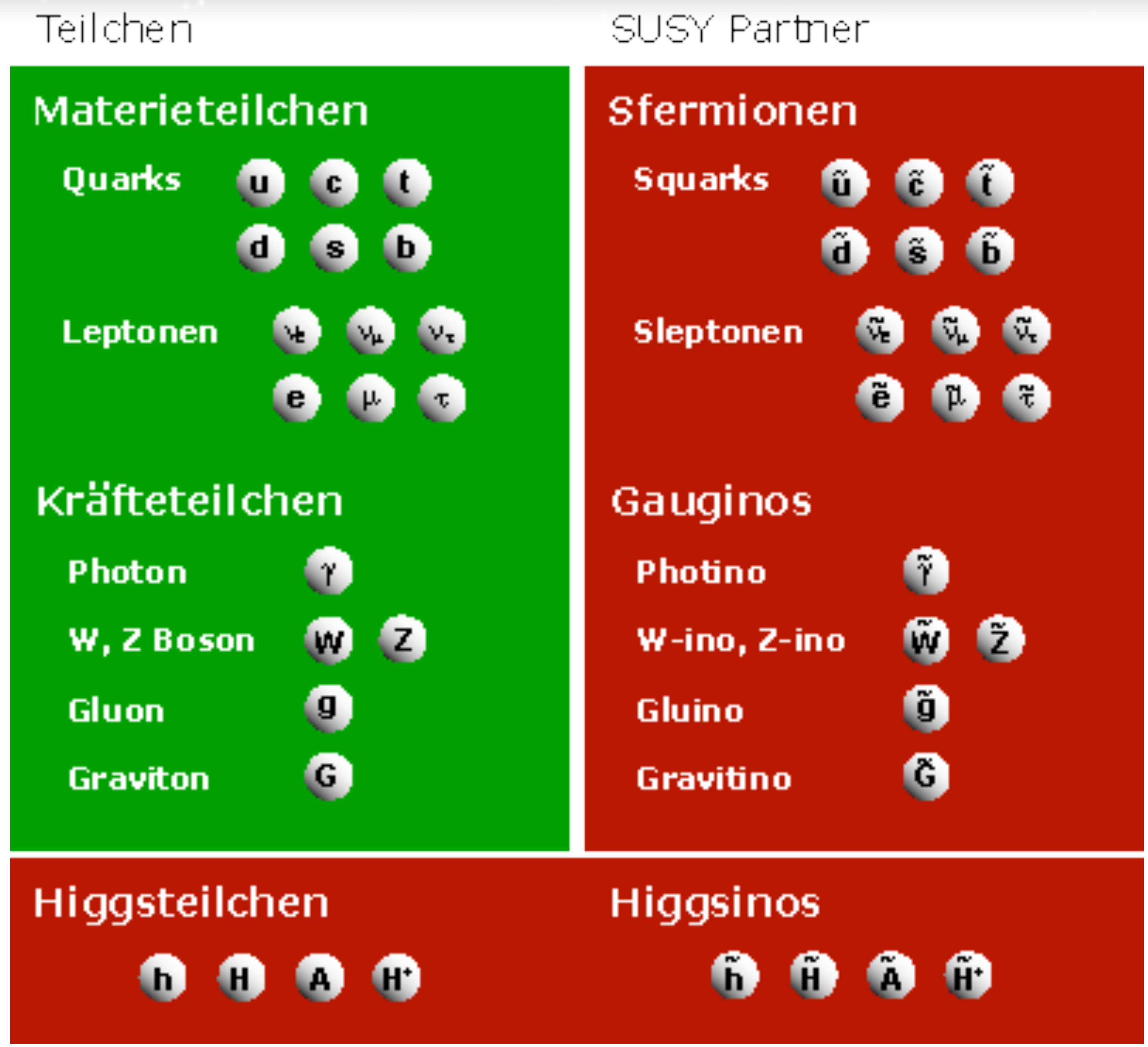
- Each SM particle has a superpartner providing boson ↔ fermion symmetry
- All internal quantum numbers are the same but with different spin (differs by 1/2 unit)
- No SUSY particles observed so far → SUSY must be broken and sparticle masses high

  → breaking mechanism determines phenomenology

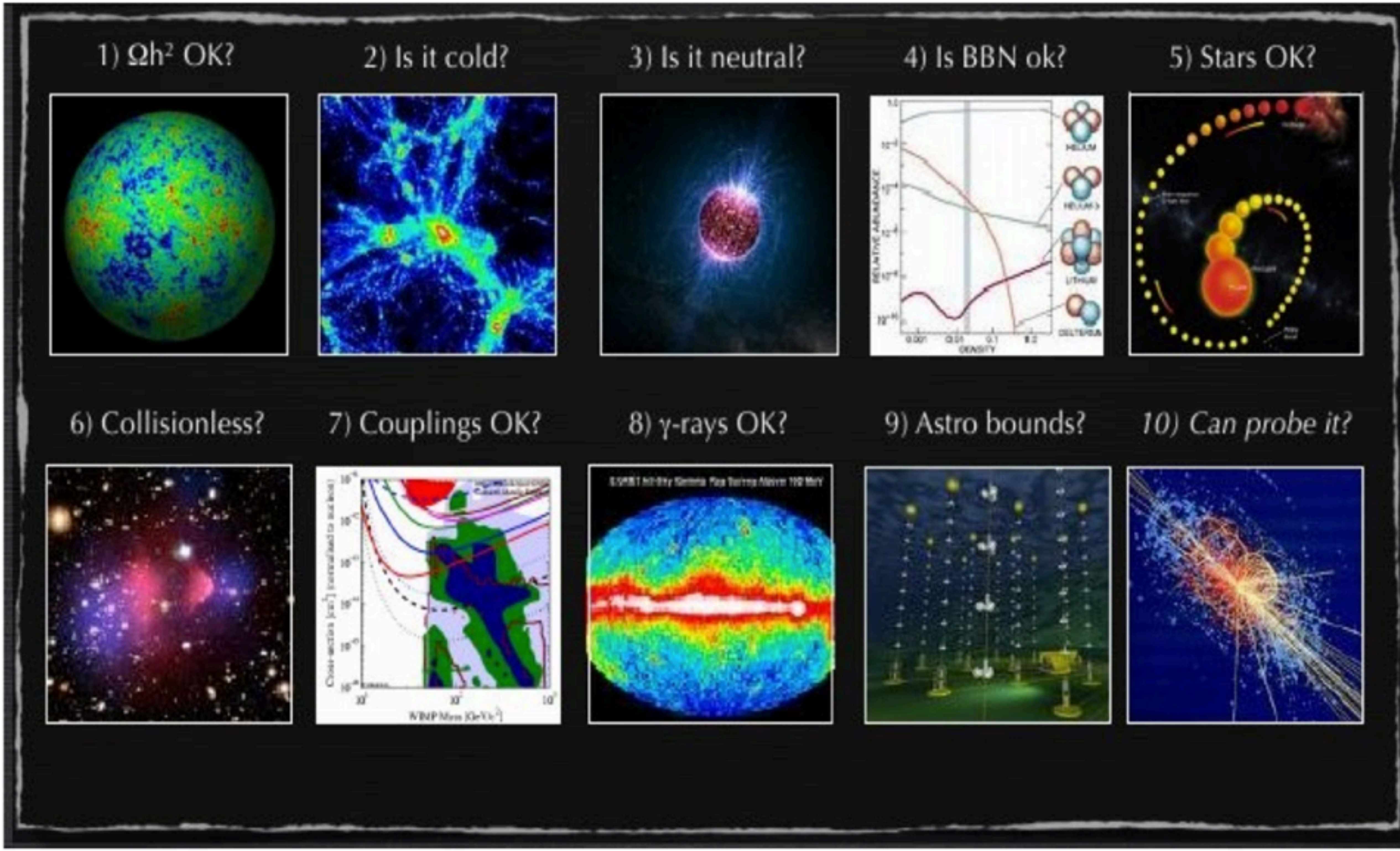


Supersymmetry





The 10 Points Test for new Particles



stolen from Gianfranco Bertone, arXiv:0711.4996
and Marc Schumann


How can we measure Dark Matter ?

Basically two places to look !

The Hubble telescope

Observations of the universe

- The best place to look !
- A large range of phenomena to study
- But the universe is **big** and you may not look at the right place
- It may take a long **time** for what you are looking for to happen

(astrophysics, astroparticle physics)

Laboratory studies

- It is much more difficult to reproduce the phenomena of the universe in the laboratory
- But if successful we can do **detailed** studies
- And we can **reproduce** one phenomena several times

(particle physics)

The example of Dark Matter

Dark Matter detection

Dark matter very hard to detect and study since it is not visible

- Indirect searches for the products of dark matter particle annihilation (e.g. Amanda, IceCube, GLAST-FERMI, EGRET)

- Direct searches for the atom recoil energy when a WIMP is passing (e.g. DAMA, CDMS, Xenon-10)

- Direct production made in high energy laboratories on earth (e.g. CERN, LHC, Tevatron)

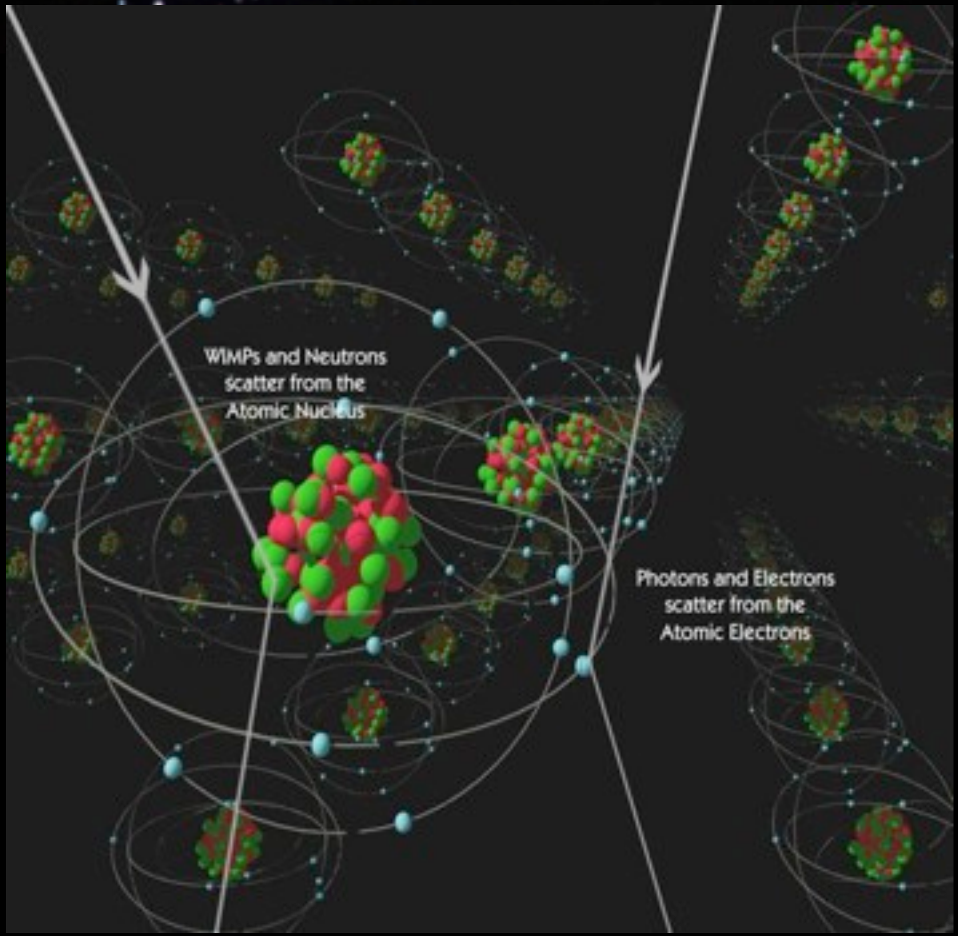
  Starting in 2009 LHC could be the first dark matter factory

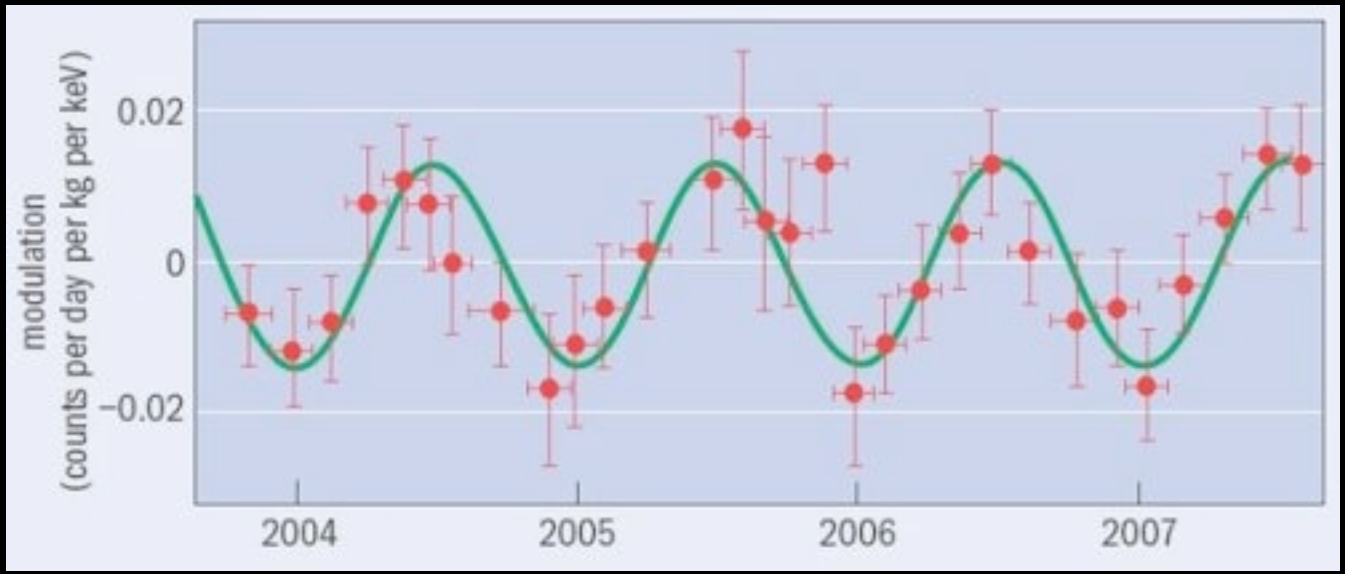
Example of direct detection of Dark Matter

It may be possible to measure the atom recoil energy when dark matter scatter from the atomic nucleus

DAMA/LIBRA (Large sodium Iodide Bulk for RAre processes)

- 250 kg scintillation thallium-doped sodium ionide NaI(Tl) radioactivity pure crystals
- The nuclei recoiling causes emissions of photons which are detected using photomultiplier tubes
- The measurements shows an modulation from the annual revolution of the Earth around the sun
- If this is a Dark Matter signal it is incompatible with other results from other experiments



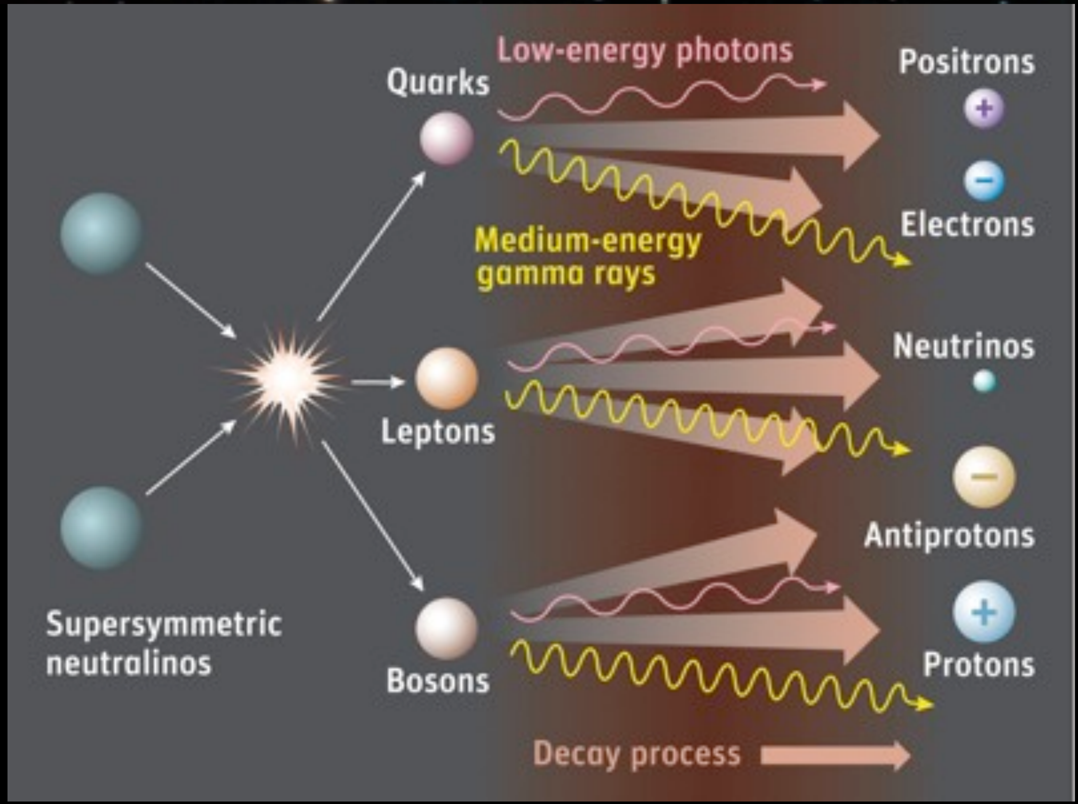


Measurement from DAMA/LIBRA

DAMA/LIBRA underground in Grand Sasso

Example of Indirect detection of Dark Matter

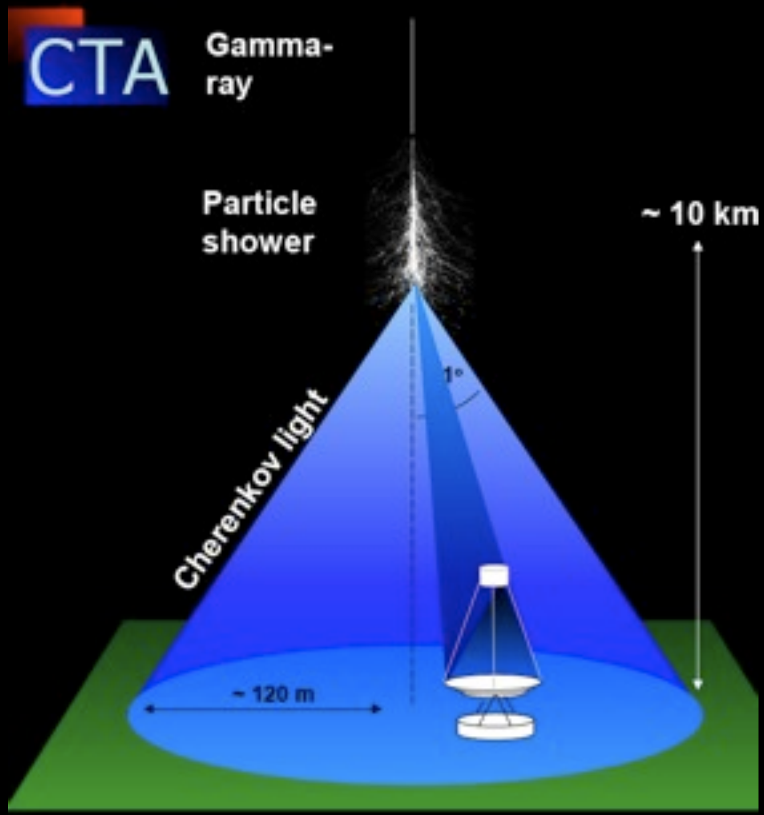
IF DARK MATTER IS A WIMP IT MAY PRODUCE OBSERVABLE SIGNALS WHEN IT SELF ANNIHILATES



Gamma ray telescopes (H.E.S.S, CTA)

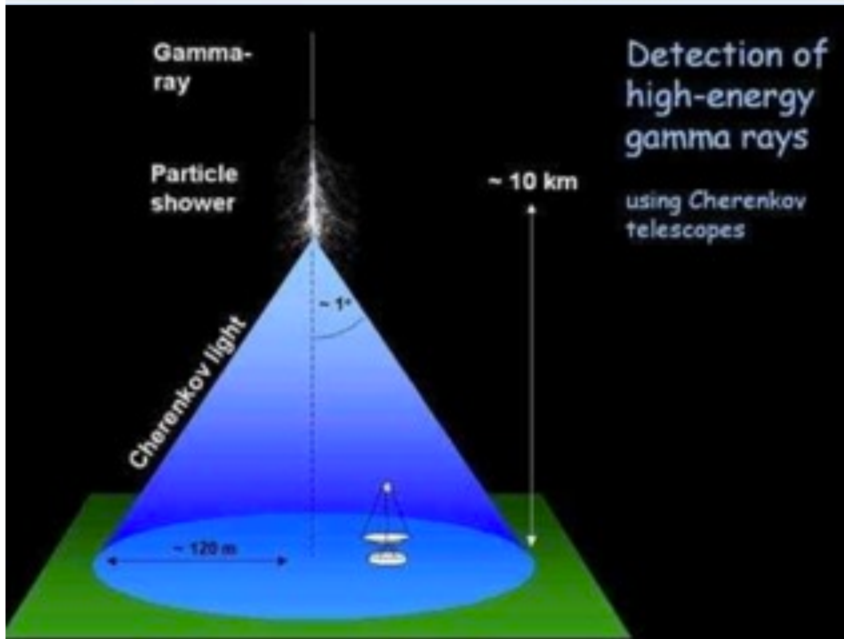
- HESS is one of the operating ground based gamma-ray instruments
- Observes the Cherenkov light from high energy cosmic radiation
- In the future the Cherenkov Telescope Array will be built (Construction phase 2014-2018)
- Two observatories operating as one covering both hemispheres and a large energy range

H.E.S.S in Namibia



Conceptual drawing of CTA (to be built)

The most advanced : H.E.S.S. 2



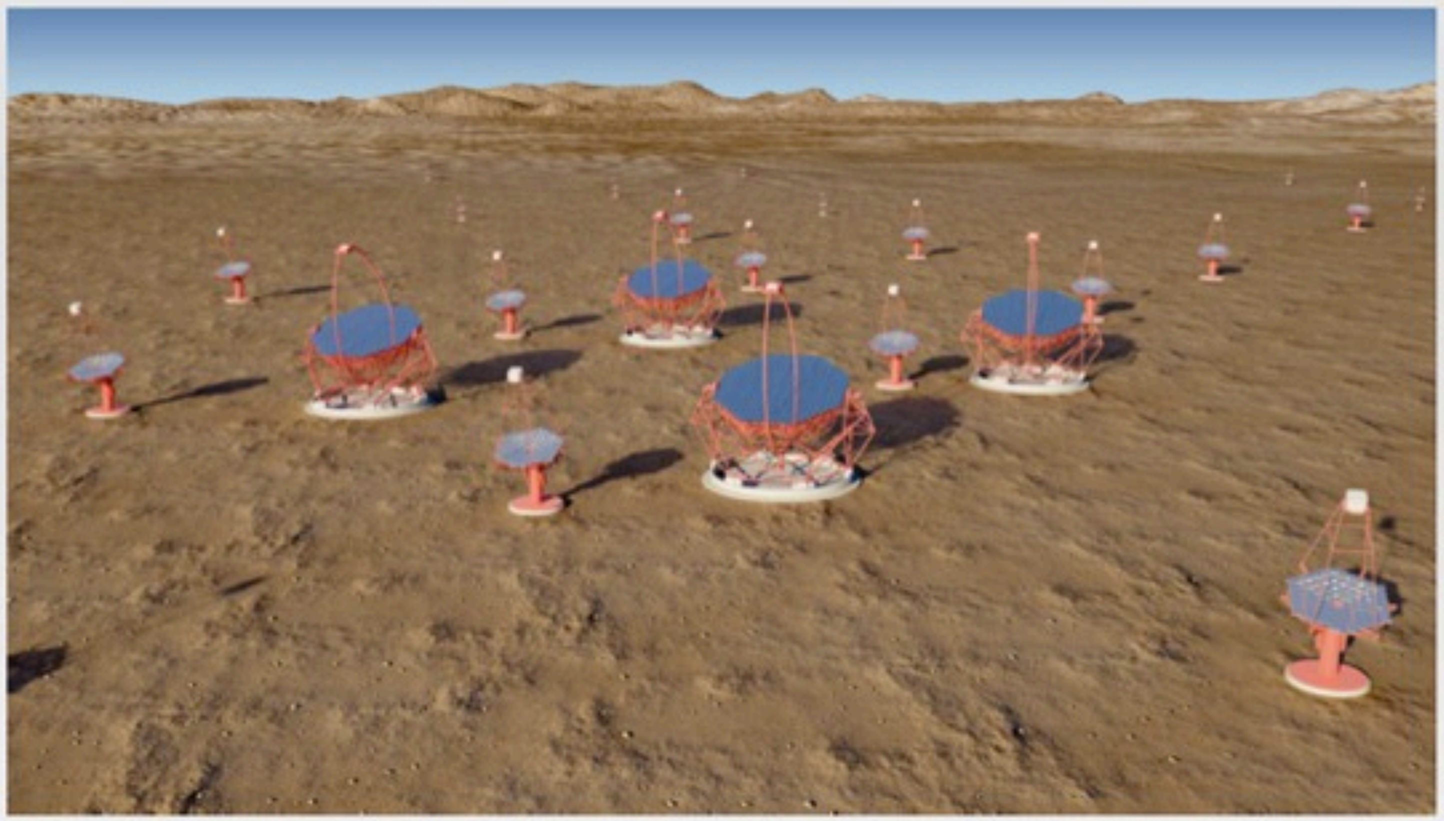
IACT experiments have entered into a new era

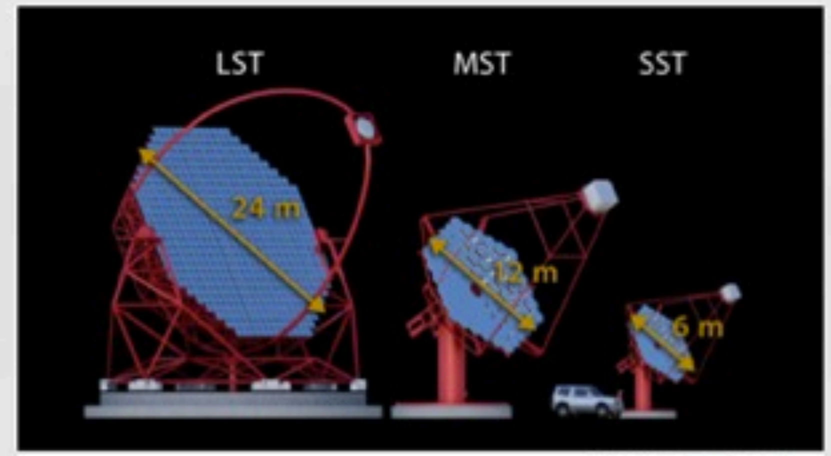
- Already >140 sources detected @ VHE
- HESS-II inaugurated a year ago - new results soon

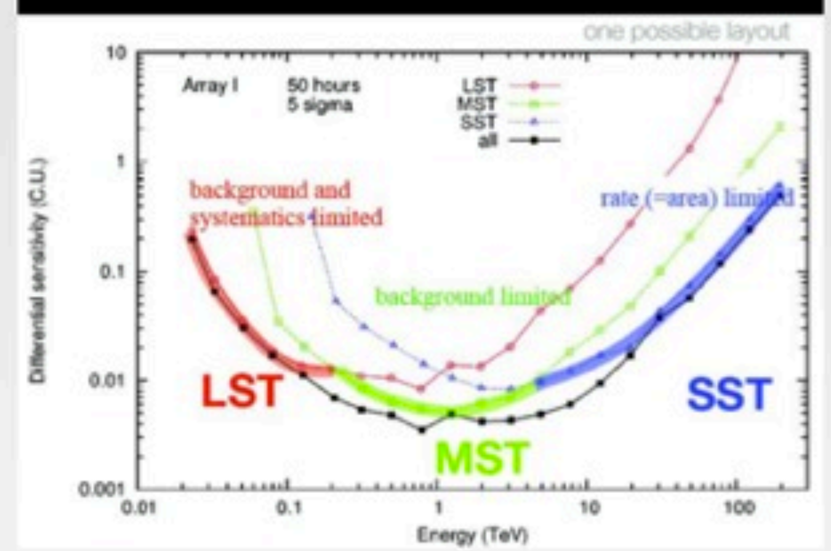
Phase 1 : 4x Ø: 13m
Camera :1 ton, 960 PMTs
Begining of operation : 2004

Phase 2 : + 1 Ø: 28m
Camera :2 ton, >2000 PMTs
Begining of operation : 09/2012

CTA - Cherenkov Telescope Array







- The CTA observatory, will enlarge this window recently opened and allow to discovered ~10 times more sources

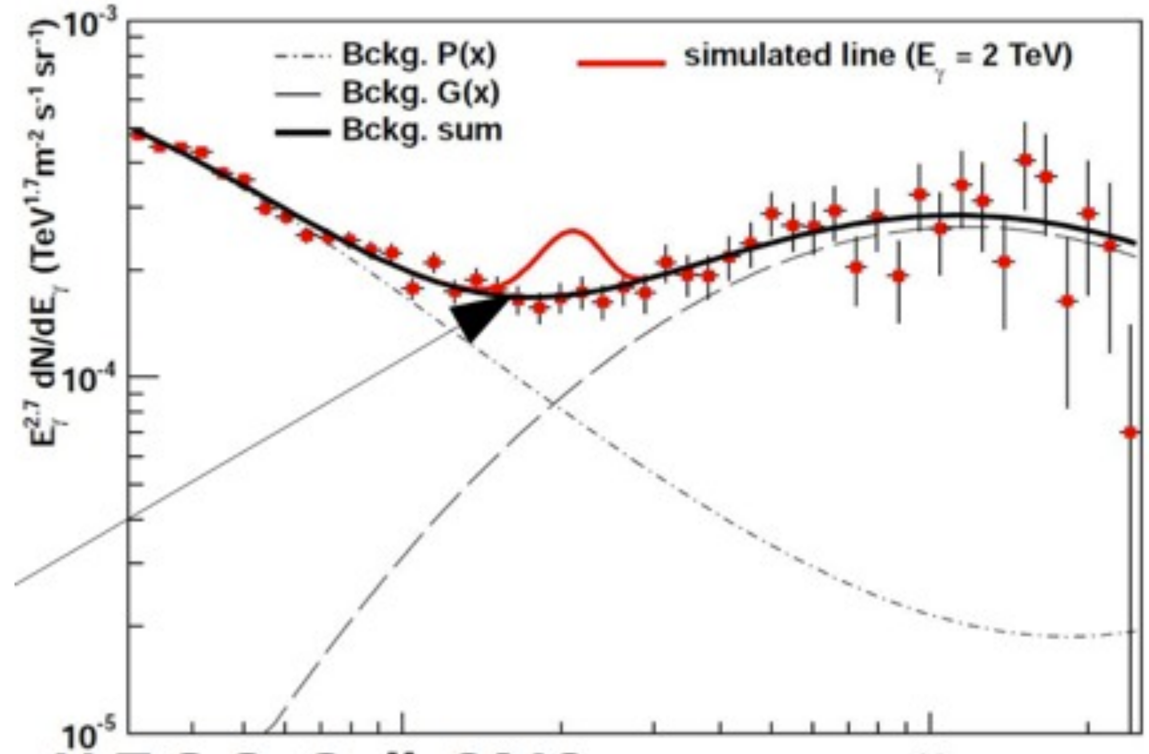
- 27 countries
- > 1000 scientists
- 2 arrays
- 3 types of telescopes

- Currently in the preparatory phase
- Construction phase will start in 2014
- >1000 sources expected
- ~ 1000h obs/y

Example analysis: Line searches

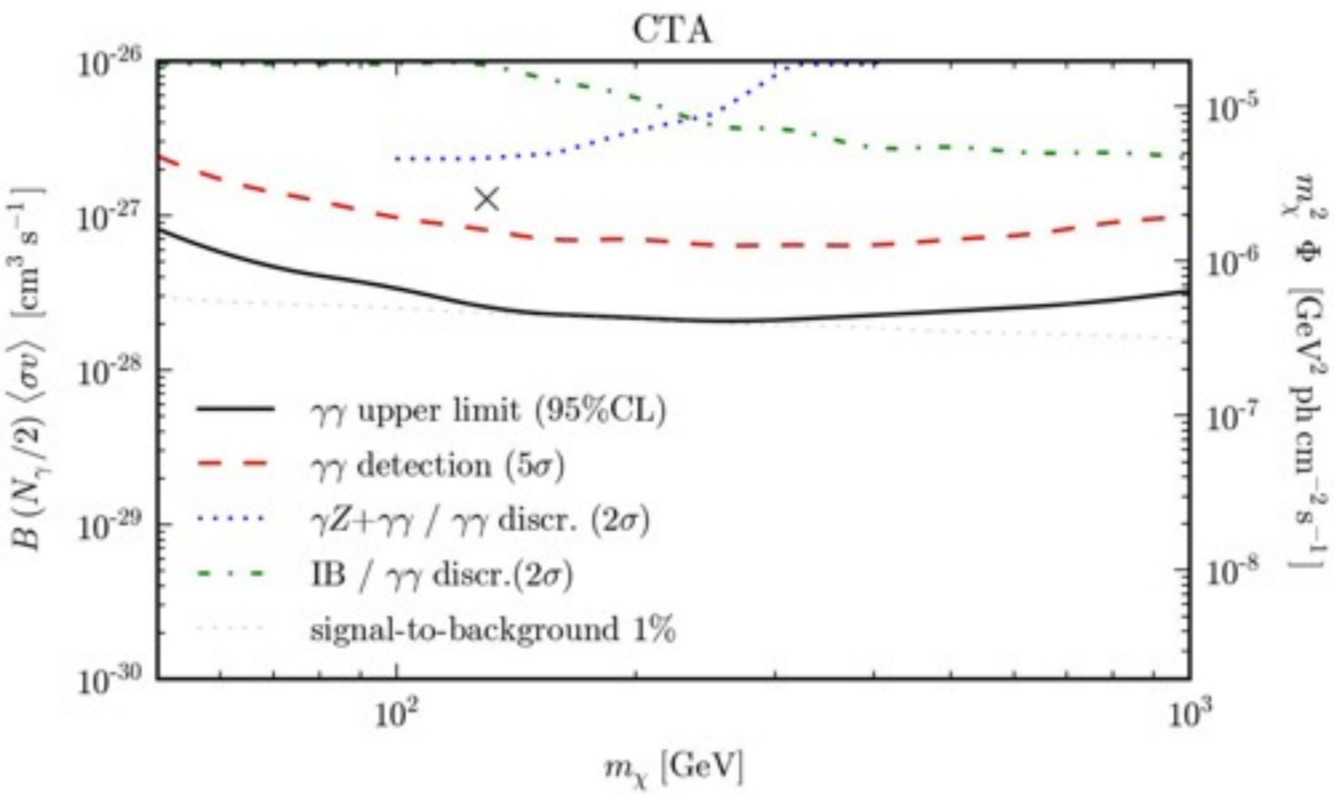
Christian Farnier

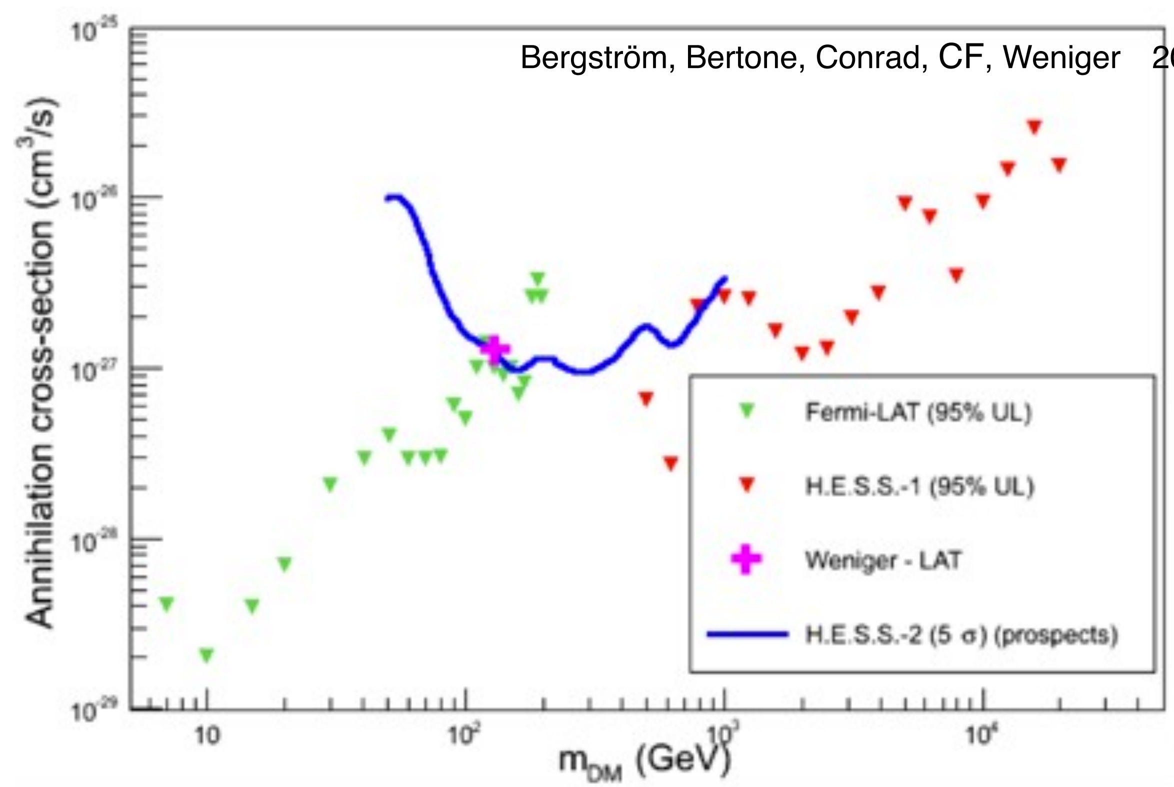
- Integration region similar to halo analysis
- Data set :
  - 4-tel. events (ΔE/E), 2004-2007 [112h] (E_{th})
- No OFF subtraction
  - Bckg (« g-like » CRs) spectrum fitted
- Profile likelihood search of a line-like signal on top of background
- H.E.S.S. II prospects



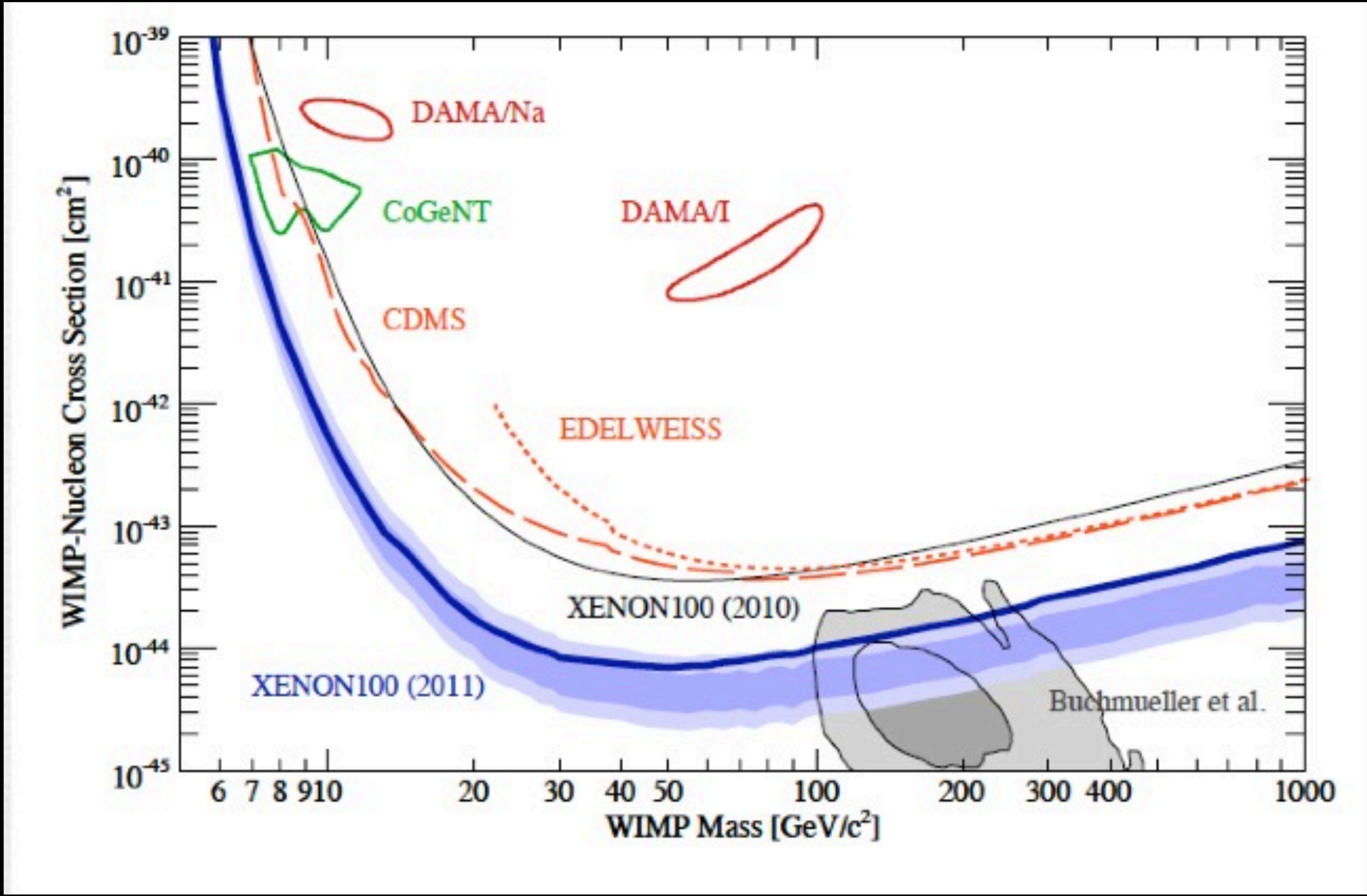
H.E.S.S. Coll. 2013

- CTA expectations : Confirmation of Weniger (2012) line >5σ in 5h [syst. uncertainties] & 1 vs 2 lines distinction reachable with additional time and refined analysis





Indirect and direct Dark Matter measurements



Exclusion limits for different experiments
- not agreeing !

Direct production - Large Hadron Collider

7 TeV

5 LHC

450 GeV

4 SPS

26 GeV

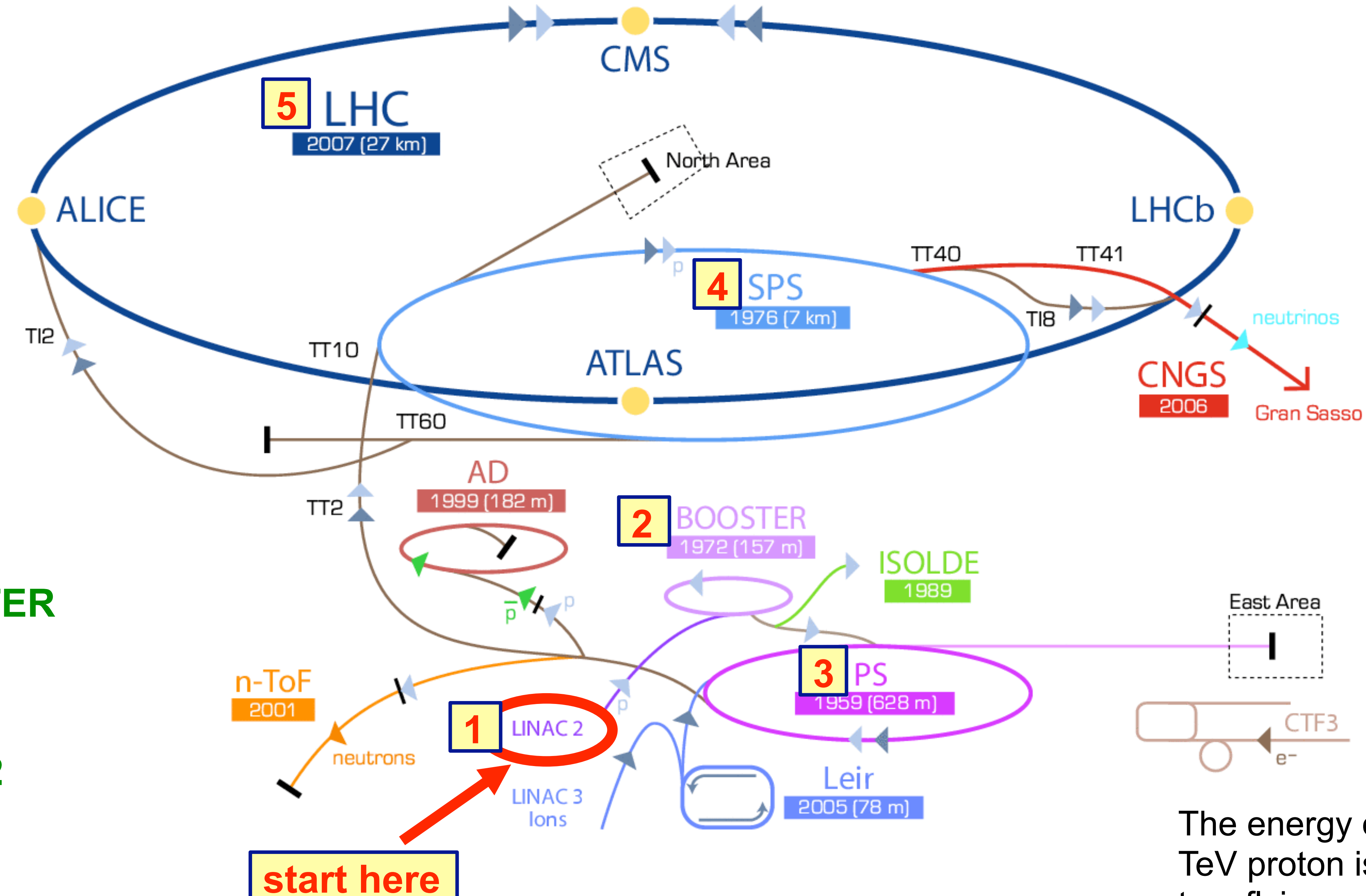
3 PS

1.4 GeV

2 BOOSTER

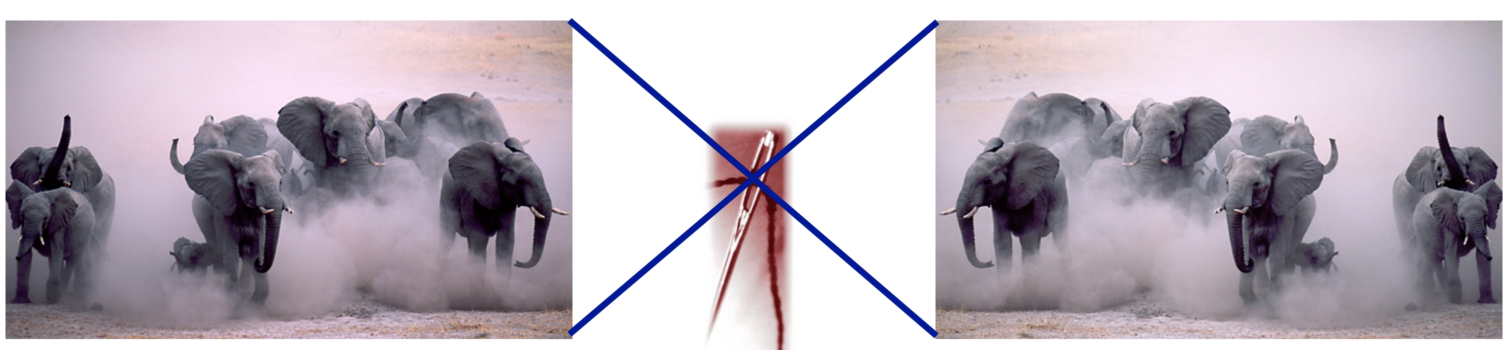
50 MeV

1 LINAC2



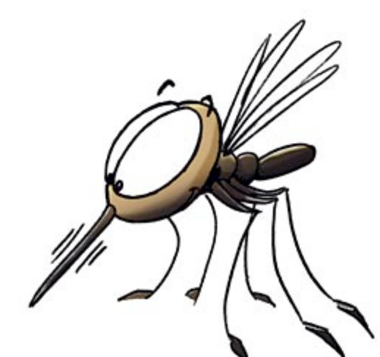
The energy of a single 7 TeV proton is equivalent to a flying mosquito 1 μJ

350 MJ stored energy per proton beam

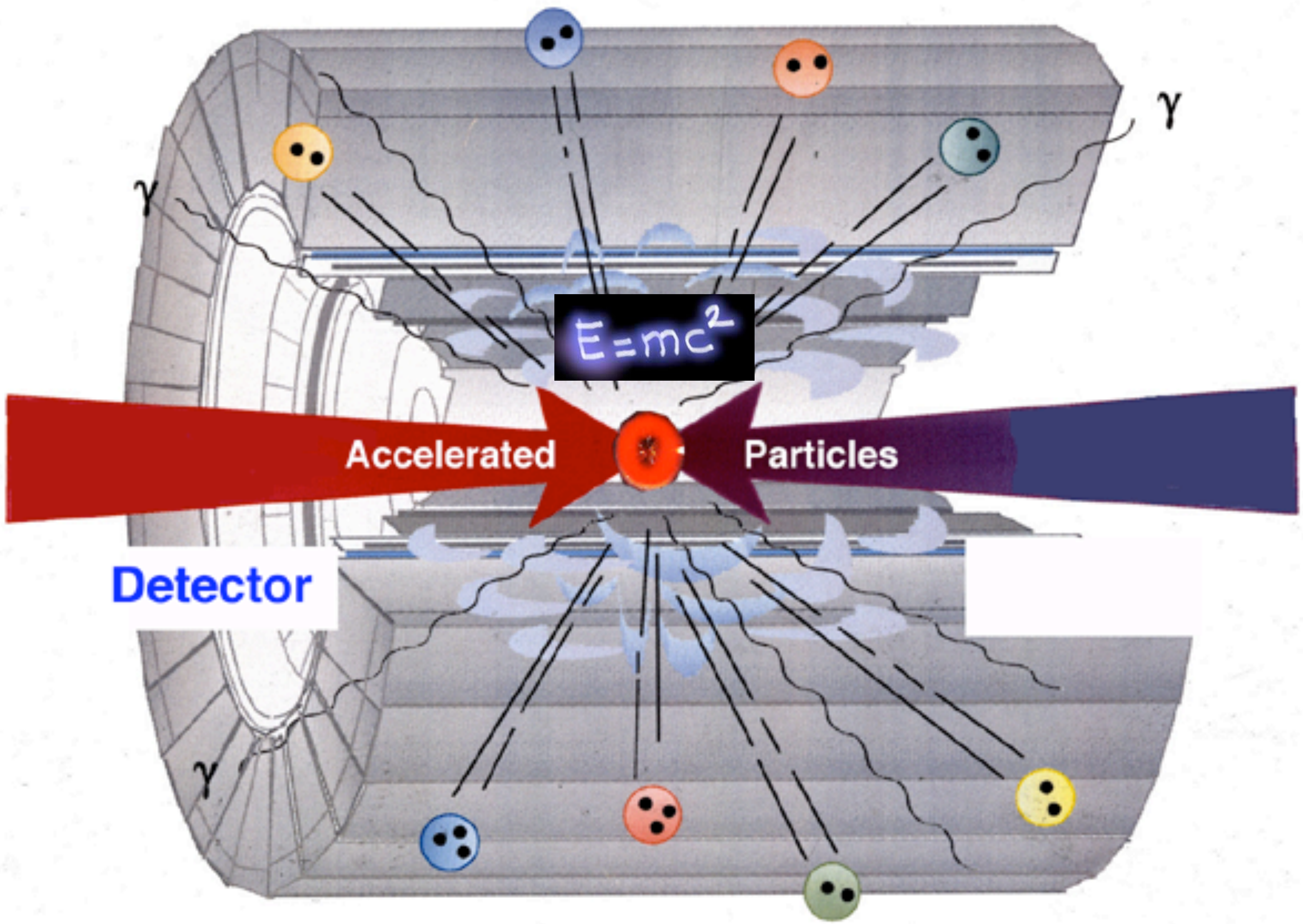


120 elephants running at 40 km / h

120 elephants running at 40 km / h



Einstein's equation

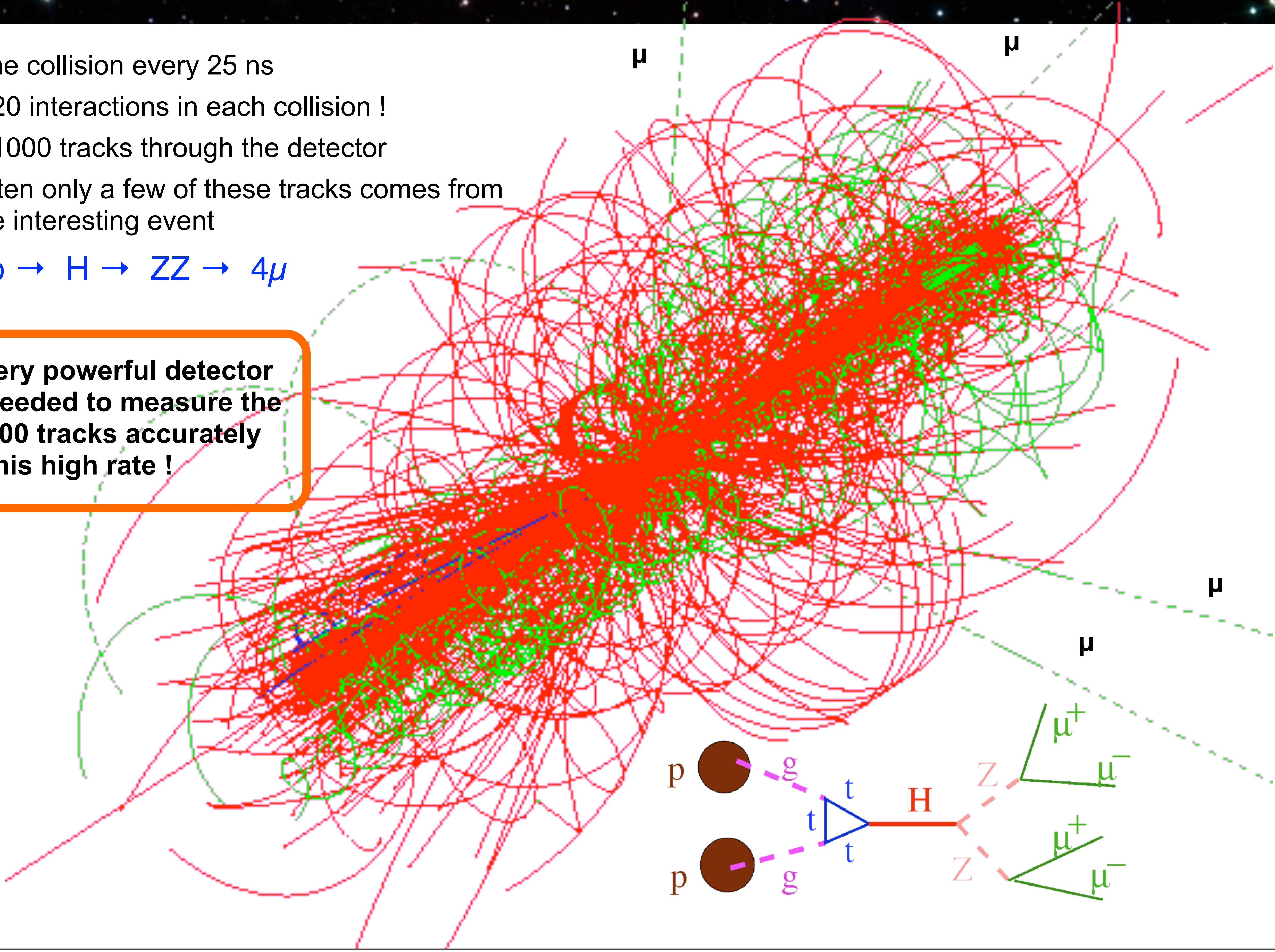


Large Hadron Collider (LHC)

- One collision every 25 ns
- < 20 interactions in each collision !
- ~ 1000 tracks through the detector
- Often only a few of these tracks comes from the interesting event

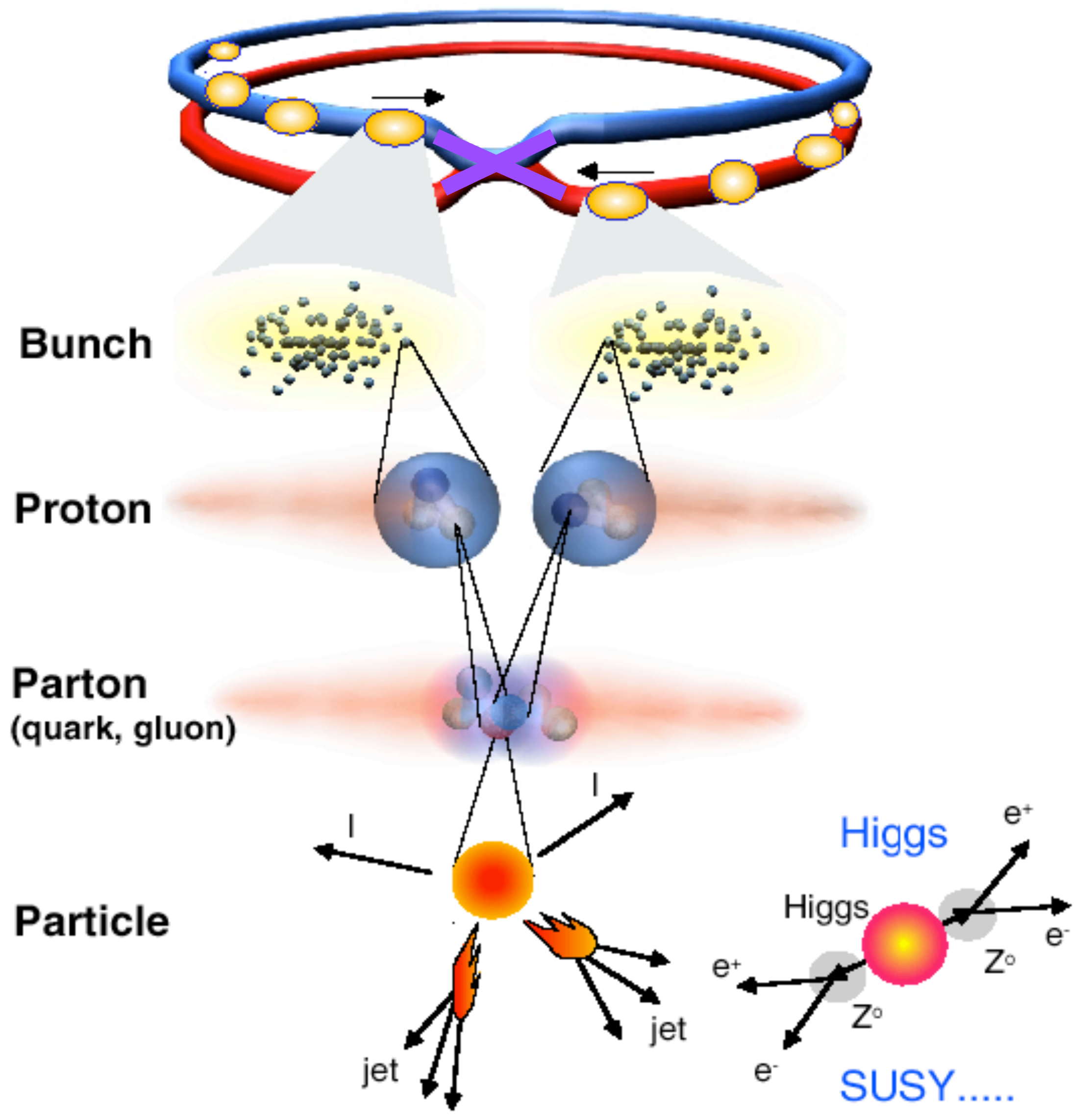
$pp \rightarrow H \rightarrow ZZ \rightarrow 4\mu$

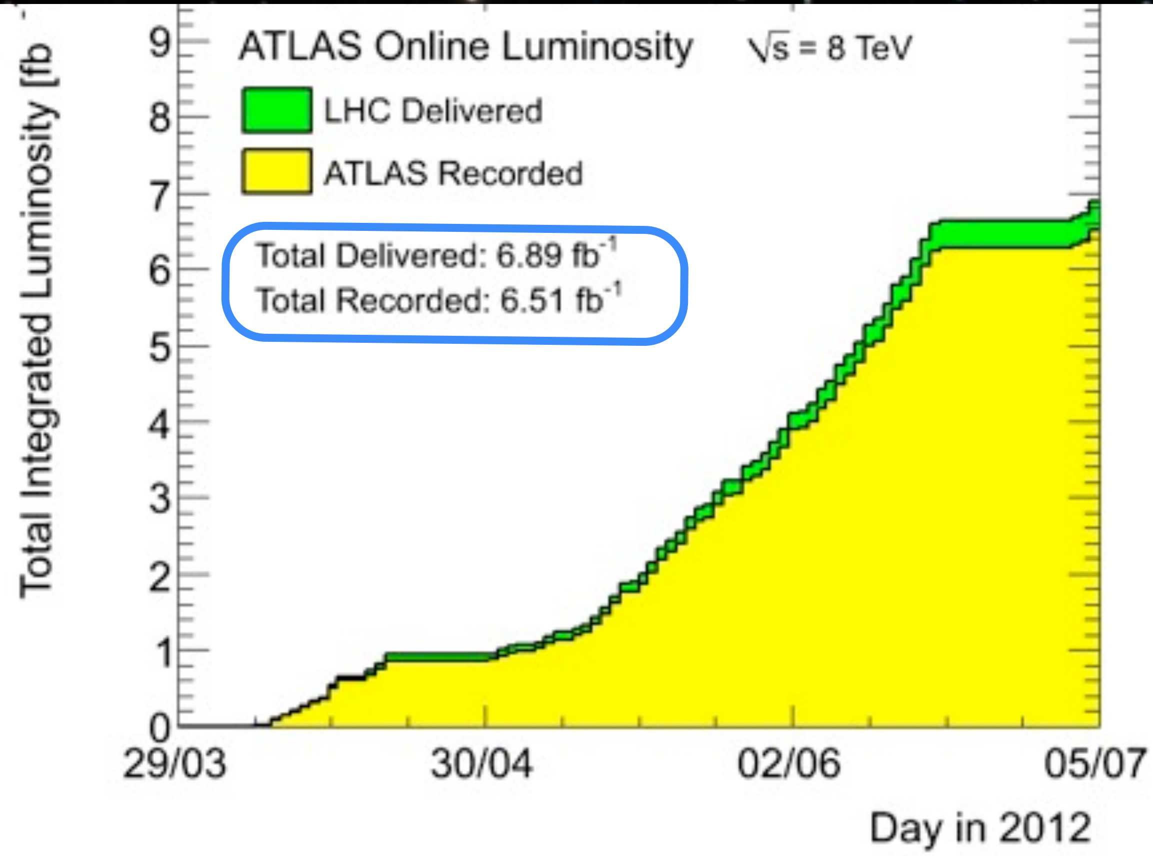
A very powerful detector is needed to measure the ~1000 tracks accurately at this high rate !

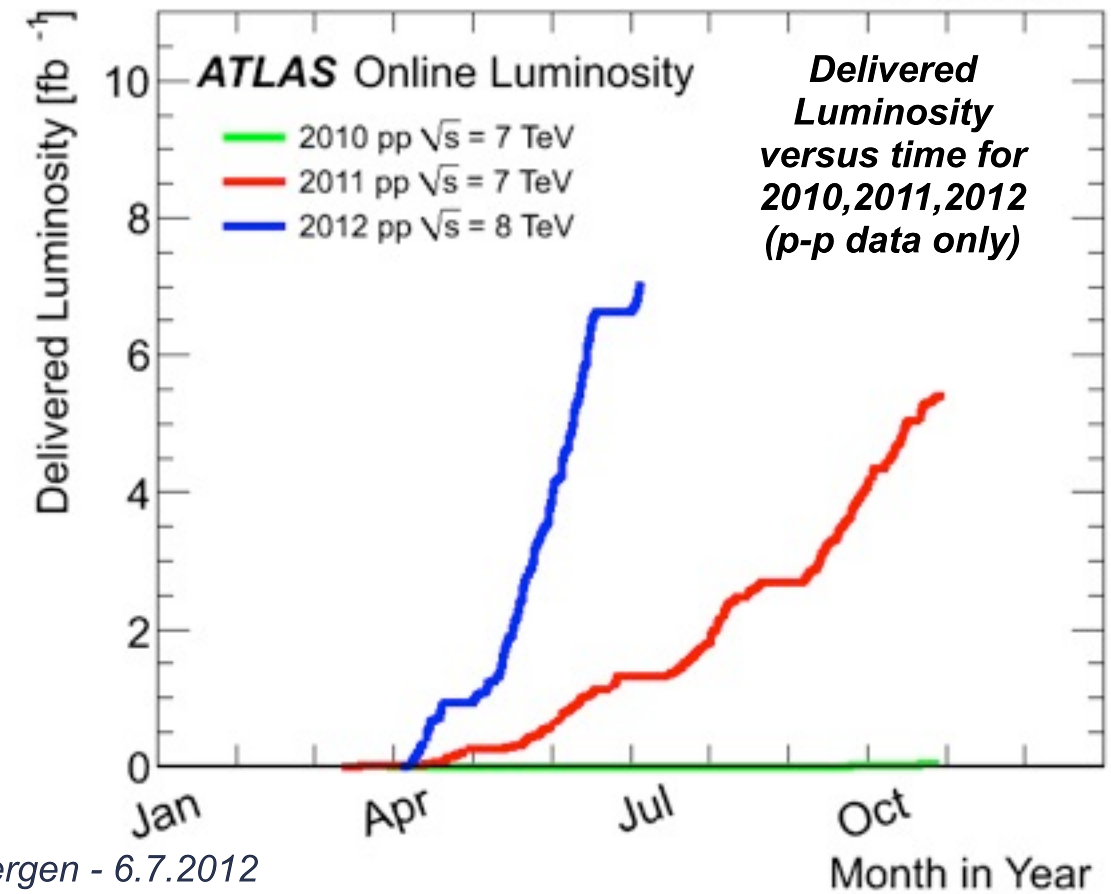


Proton-proton collisions

- 3.5 - 4 TeV beam energy (design energy = 7 TeV)
- 10^{11} protons per bunch
- Mostly soft (low p_T) events, interesting hard (high p_T) events are rare
- N = 1 000 000 000 interactions/s (design)
- Data recorded in July 2012 = 6.51 fb^{-1} at 8 TeV !







ATLAS searches for supersymmetry

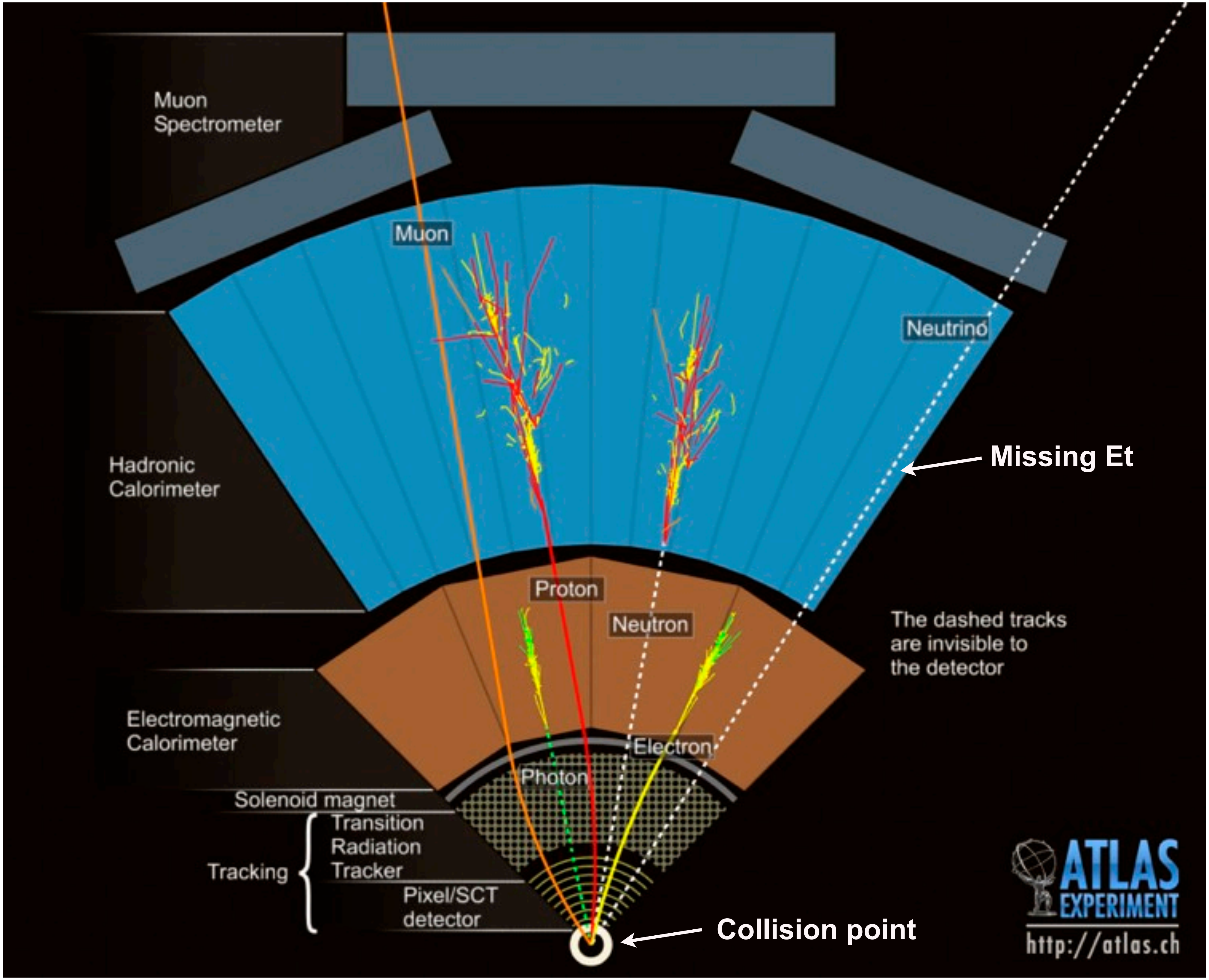
Slice of ATLAS

Detector closes hermetically around the collision point

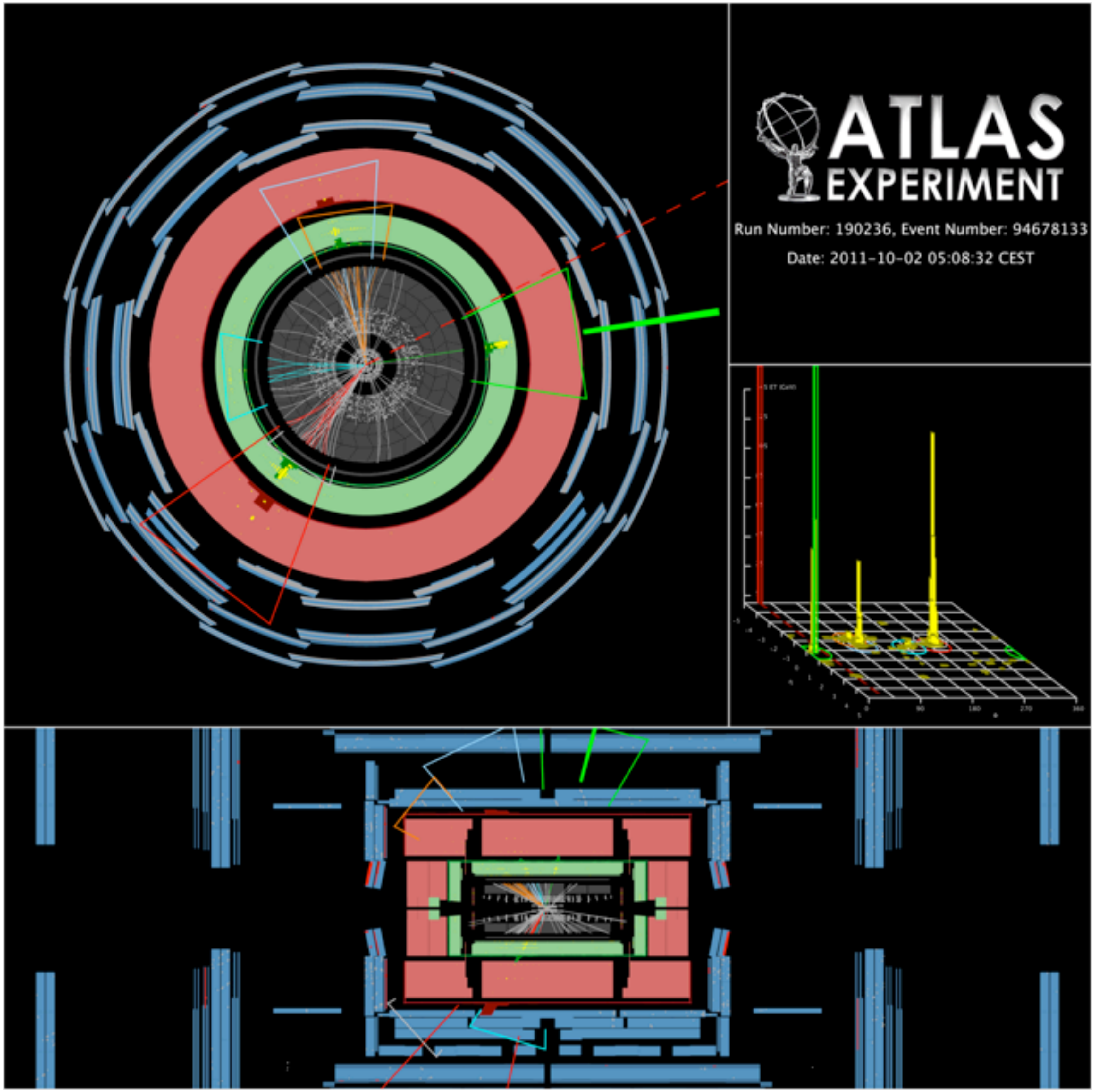
No escaping particles except neutrinos ...

Or new physics particles not interacting with the detector !

Dark Matter particles would be seen as an excess in missing energy (Etmiss)



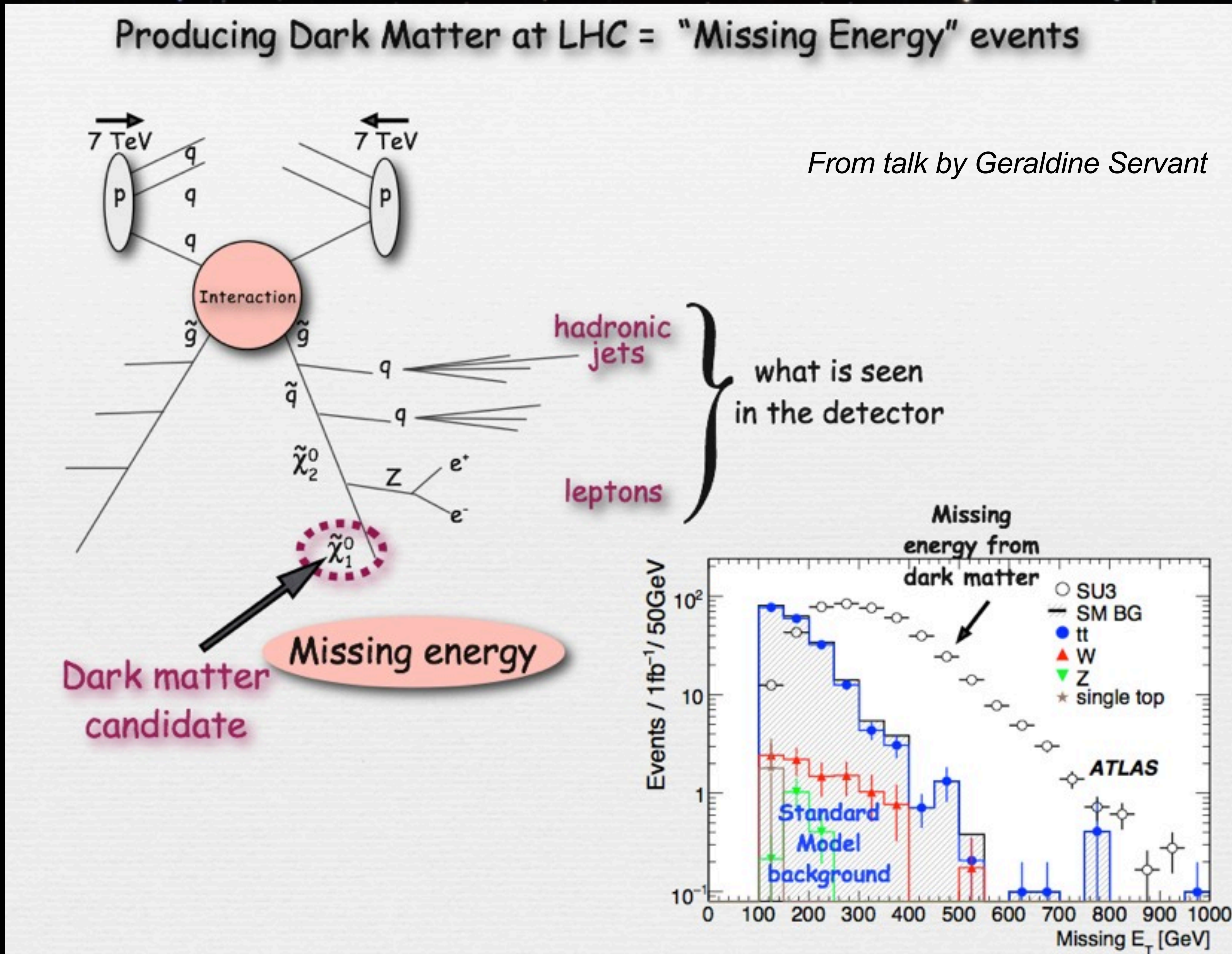
Supersymmetric signatures



Example of event with high energy jets and missing Et

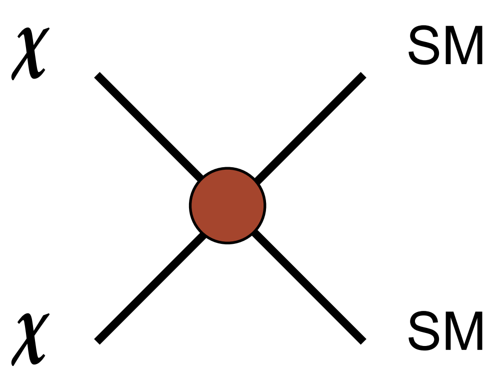
- Passing 4 jet selection (5 jets)
- Jet Pt = (690, 254, 117, 84 and 36 GeV)
- Electron Pt = 265 GeV
- Etmiss = 381 GeV
- Inclusive effective mass =1827 GeV

Dark Matter production

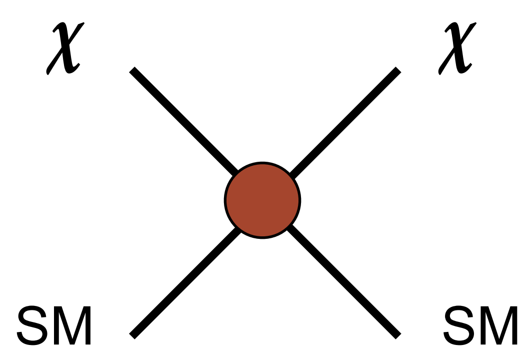


Dark Matter searches

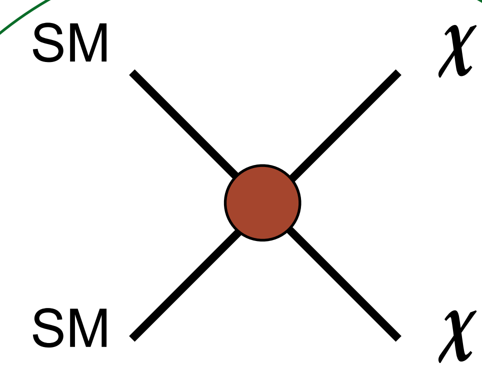
Different types of experiments (above and under ground, in accelerators) :



Indirect searches

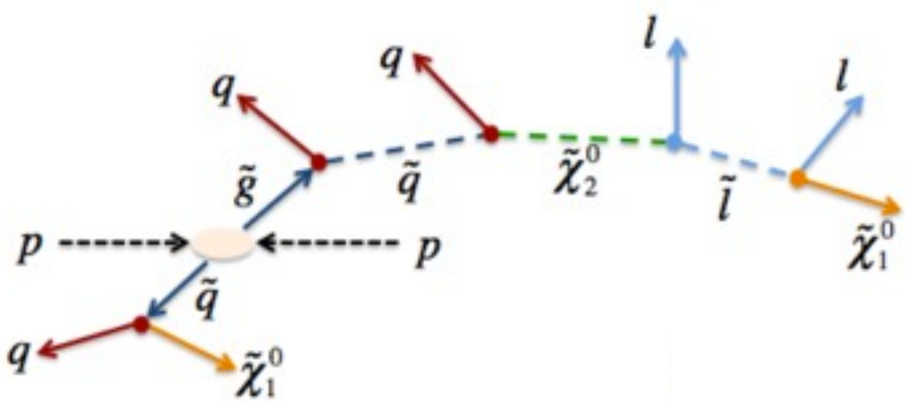


Direct searches



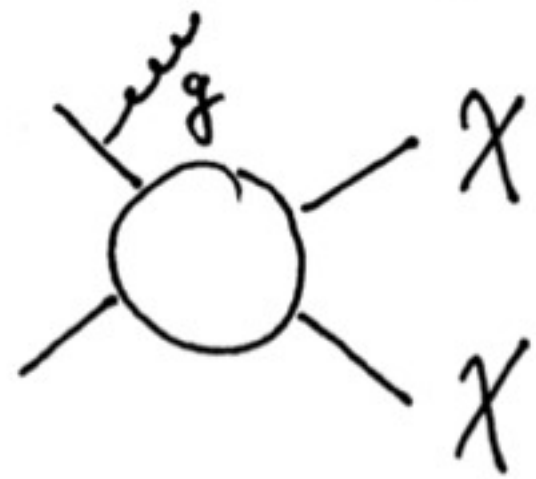
Collider searches

In LHC two different search modes (model dependent, model independent):



Cascade decades

Typical for supersymmetric searches



Pair production

Assume WIMPs produced in pairs and tagged by a jet or photon

hep-ph/1002.4137

hep-ph/0403004

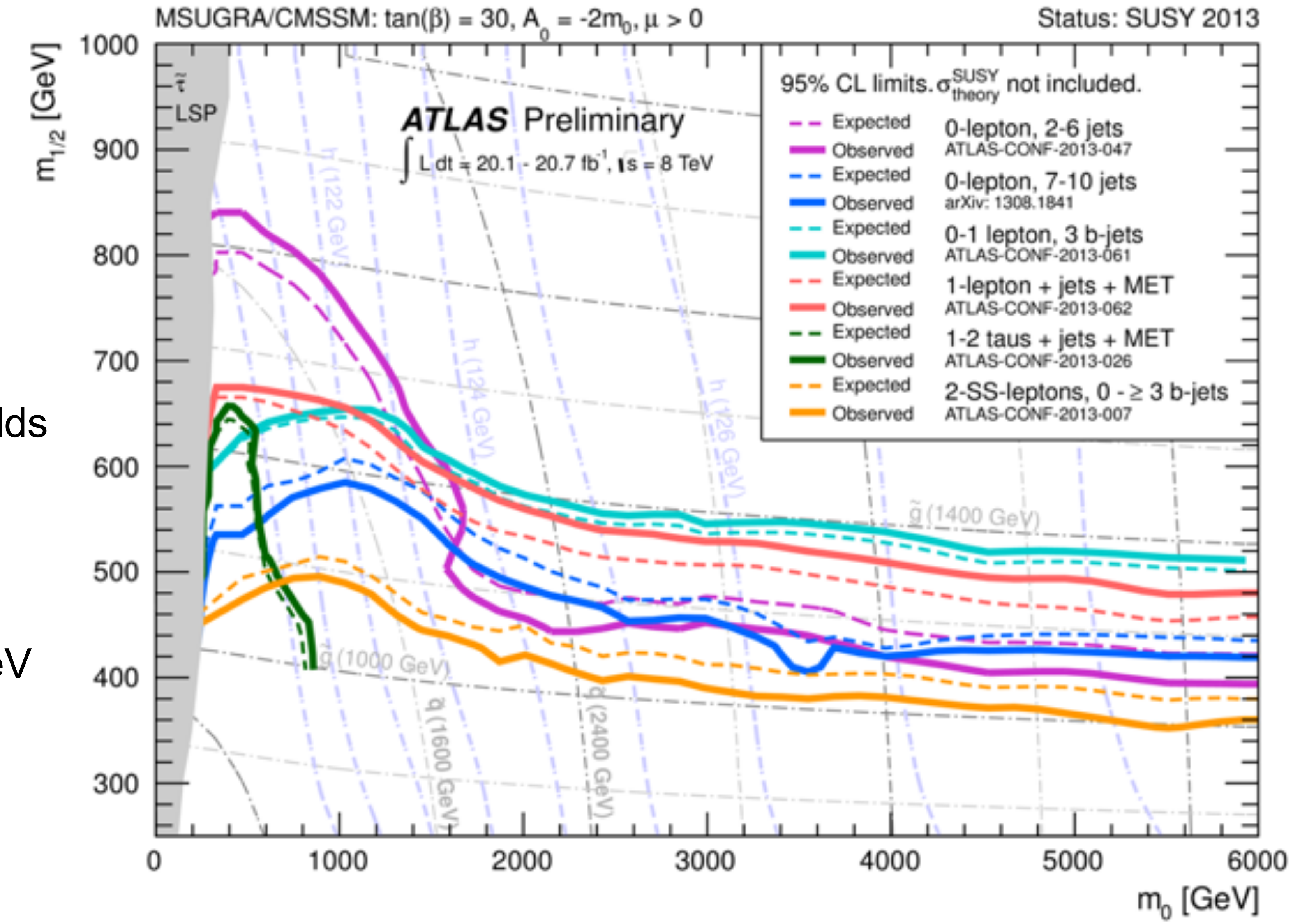
David Berge

Model dependent searches - SUPERSYMMETRY

Interpretation of ATLAS results for neutralino masses

Exclusion plot from mSUGRA

- 0 lepton, ≥ 2-6 jets
- 0 lepton, ≥ 6-9 jets
- 1 lepton, ≥ 3,4 jets



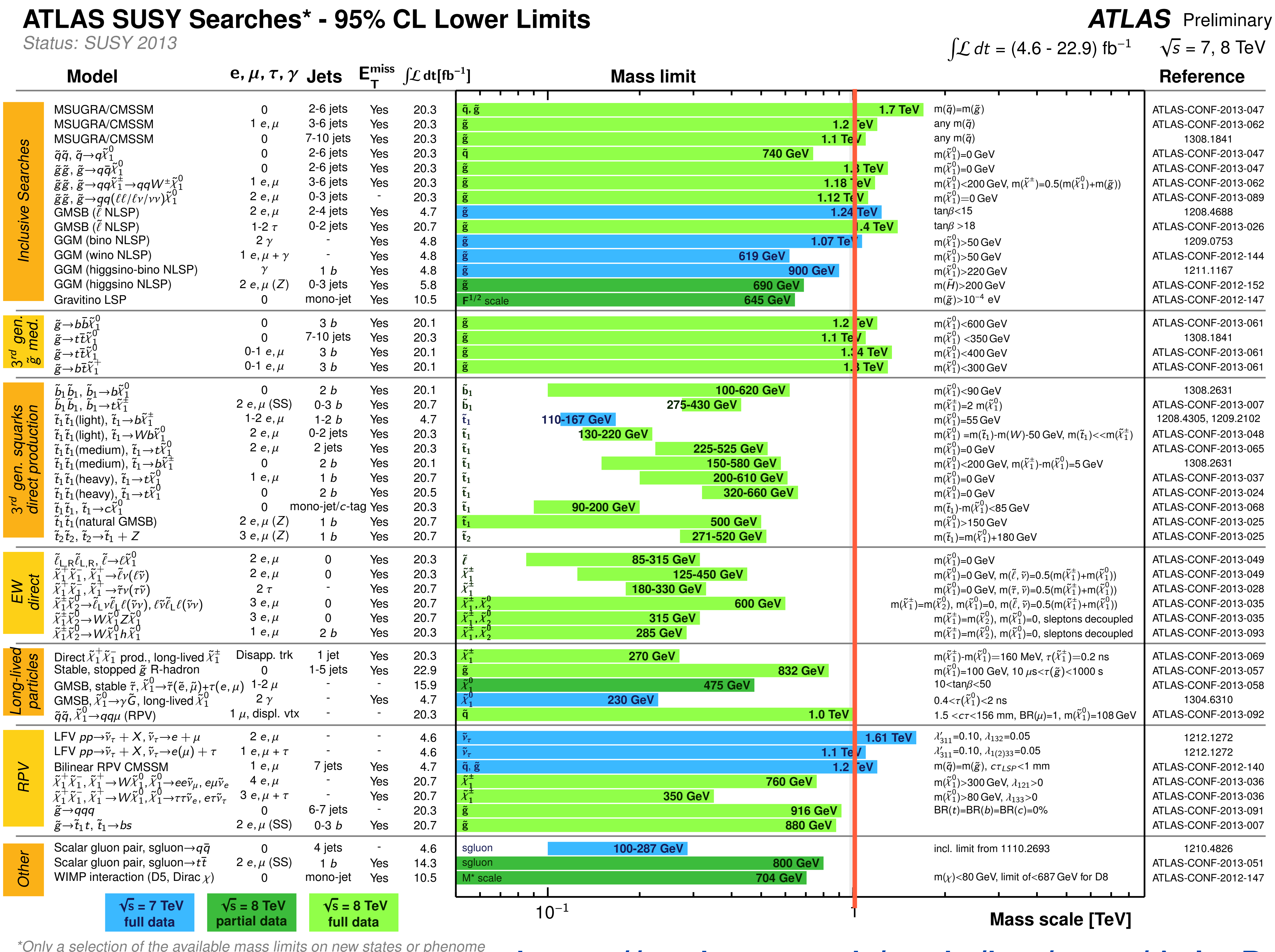
- For mSUGRA/CMSSM, the relation between the gluino mass and the neutralino mass is approximately (holds in the gaugino region) :

  $m_{gluino} \approx 6.4\, m_{\chi}$

- For a gluino mass of 1400 GeV this means that a mass of around 200 GeV for the neutralino is excluded (2013 data)

➡ Very model dependent !

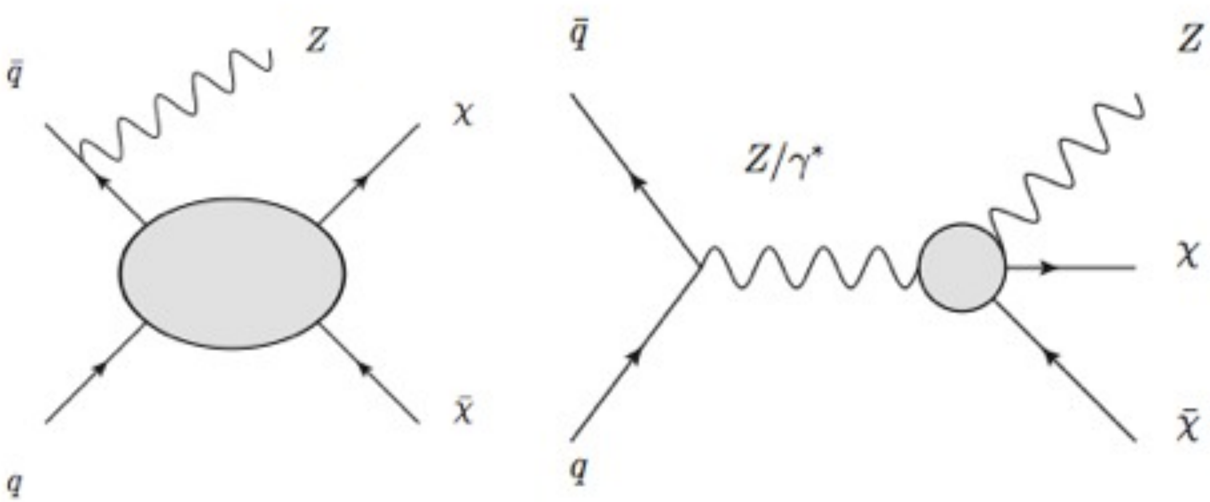
LHC results - SUSY ATLAS results

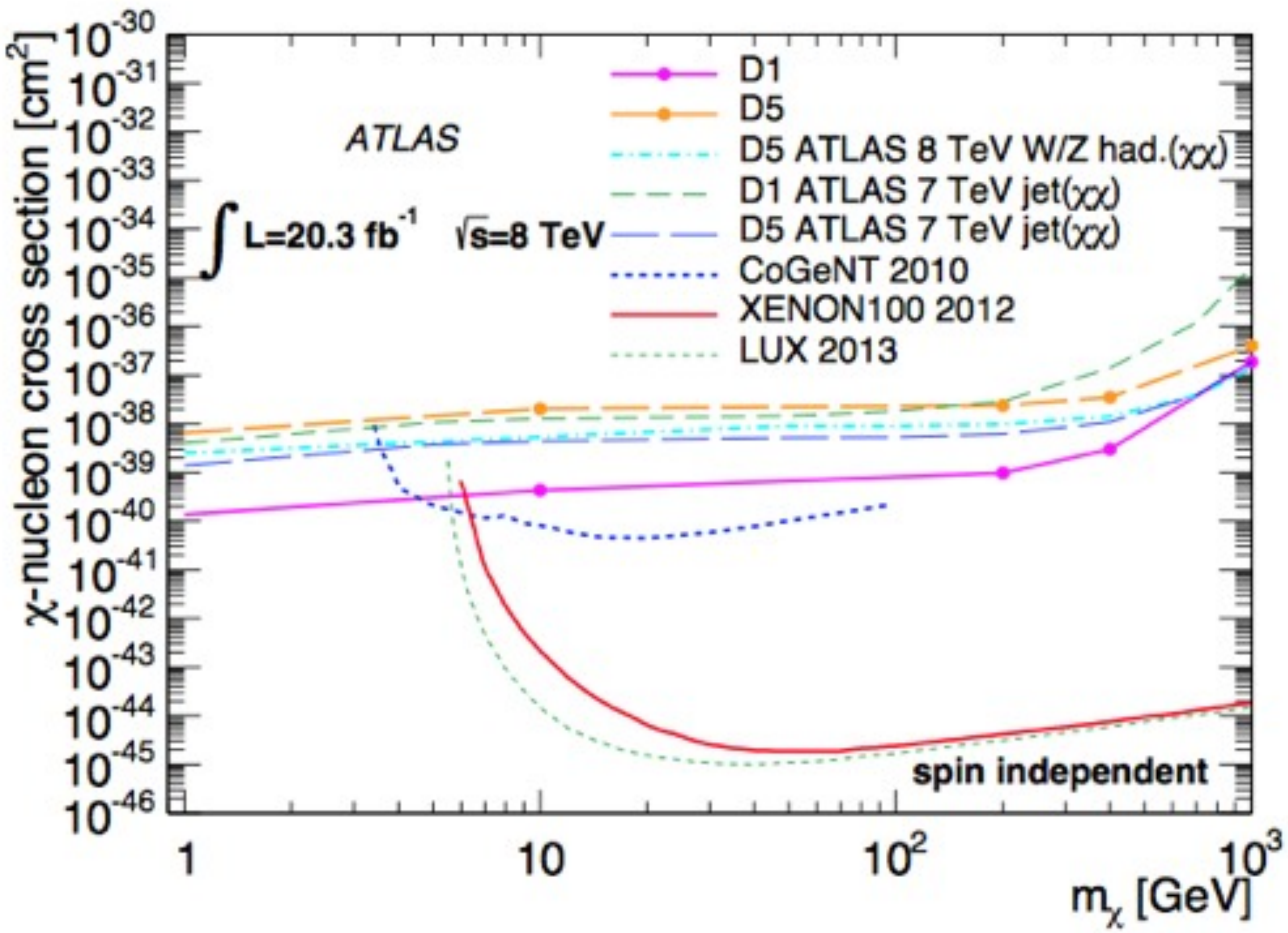


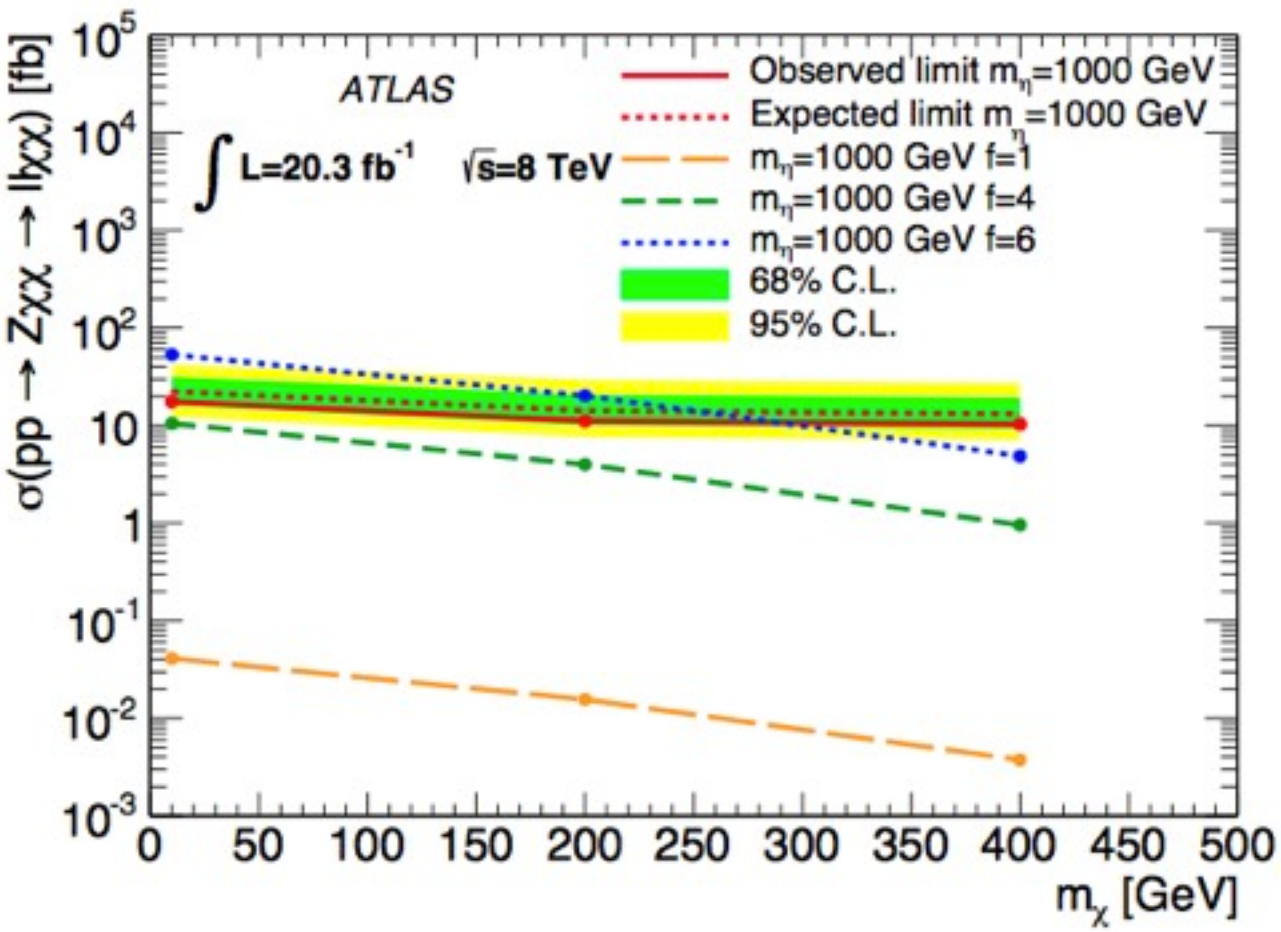
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

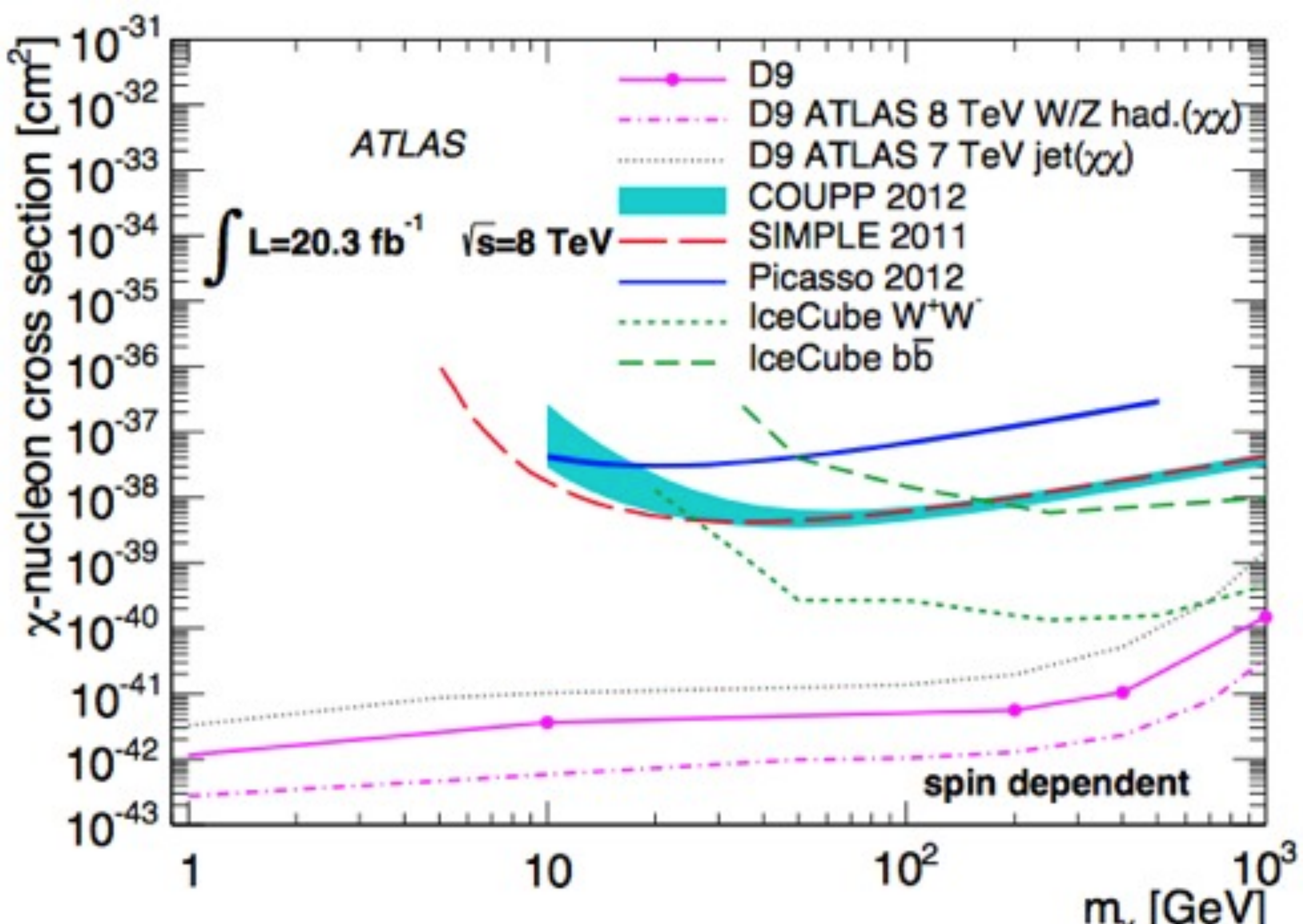
http://arxiv.org/pdf/1404.0051v1.pdf

Search for dark matter in events with a Z boson and missing transverse momentum in pp collisions at \sqrt s = 8 TeV with the ATLAS detector



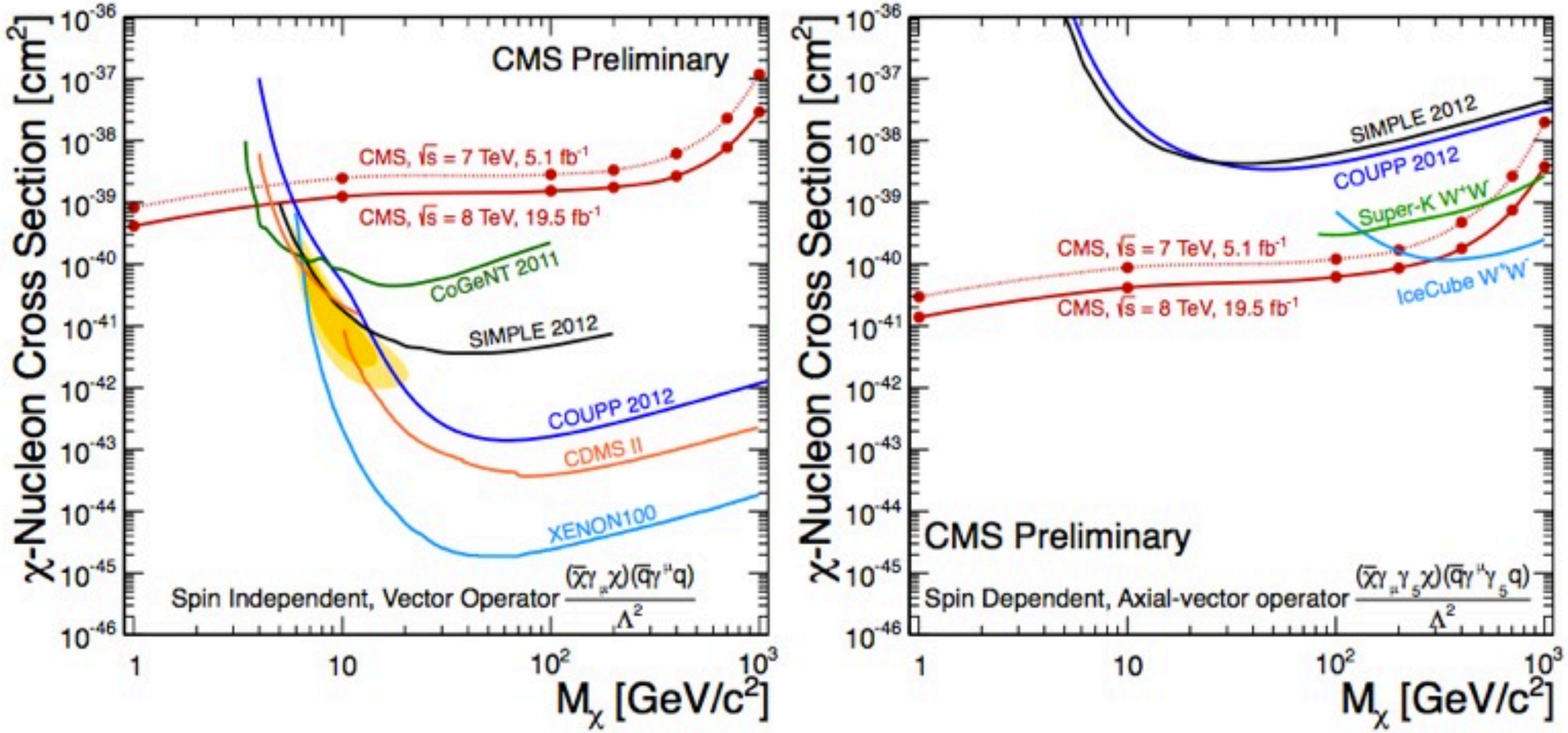






LHC results - Example Mono-Jet

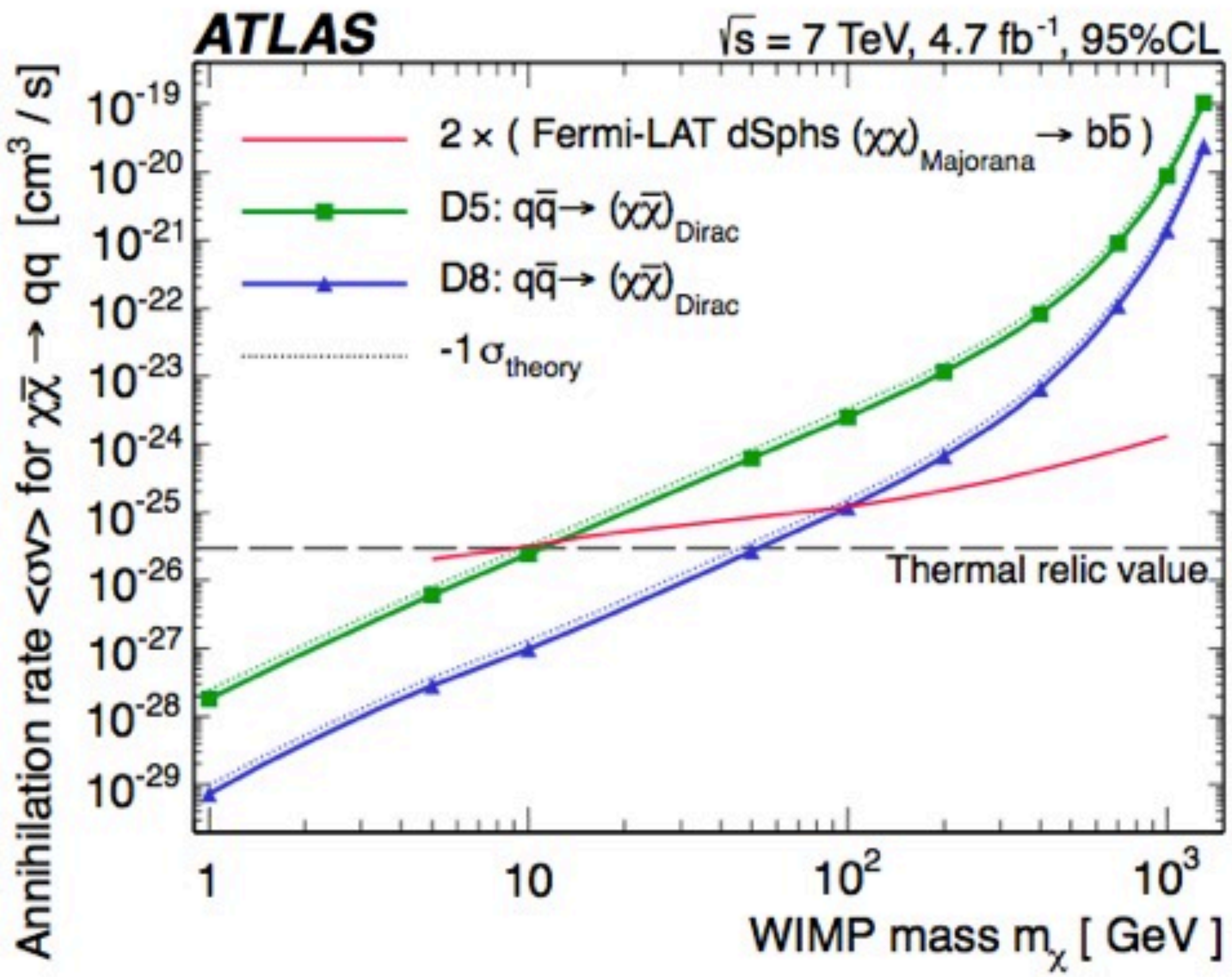
WIMP-Nucleon Scattering Limits



- Cross sections above observed are excluded.
- Assumption is that DM interacts with SM particles solely by a given operator: SI = D5, SD = D8
- Yellow contours show candidate events from CDMS: arXiv:1304.4279

LHC results - Example Mono-Jet

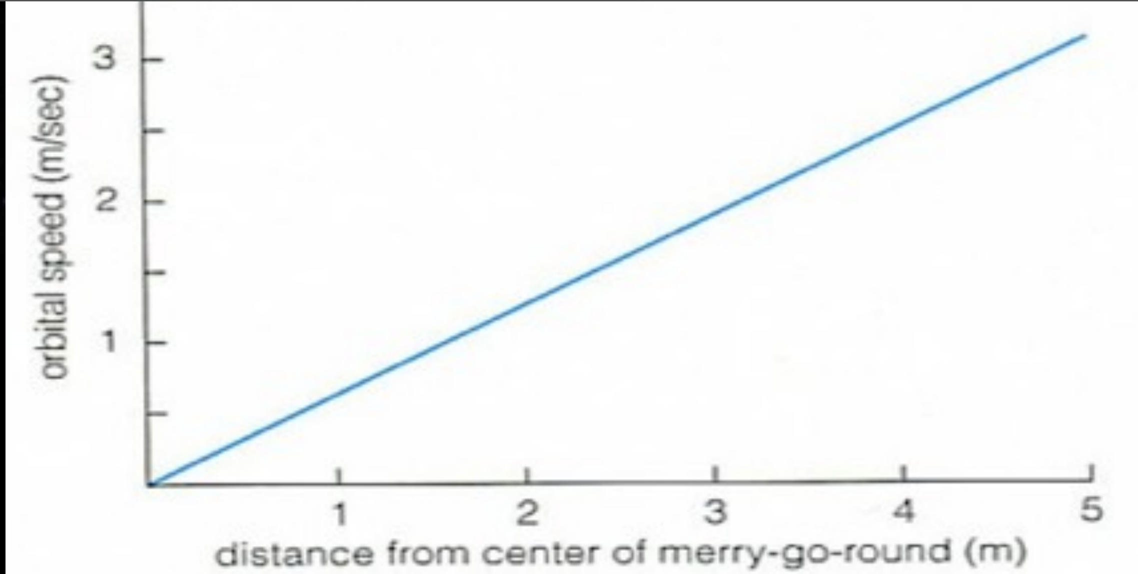
WIMP Annihilation Limits



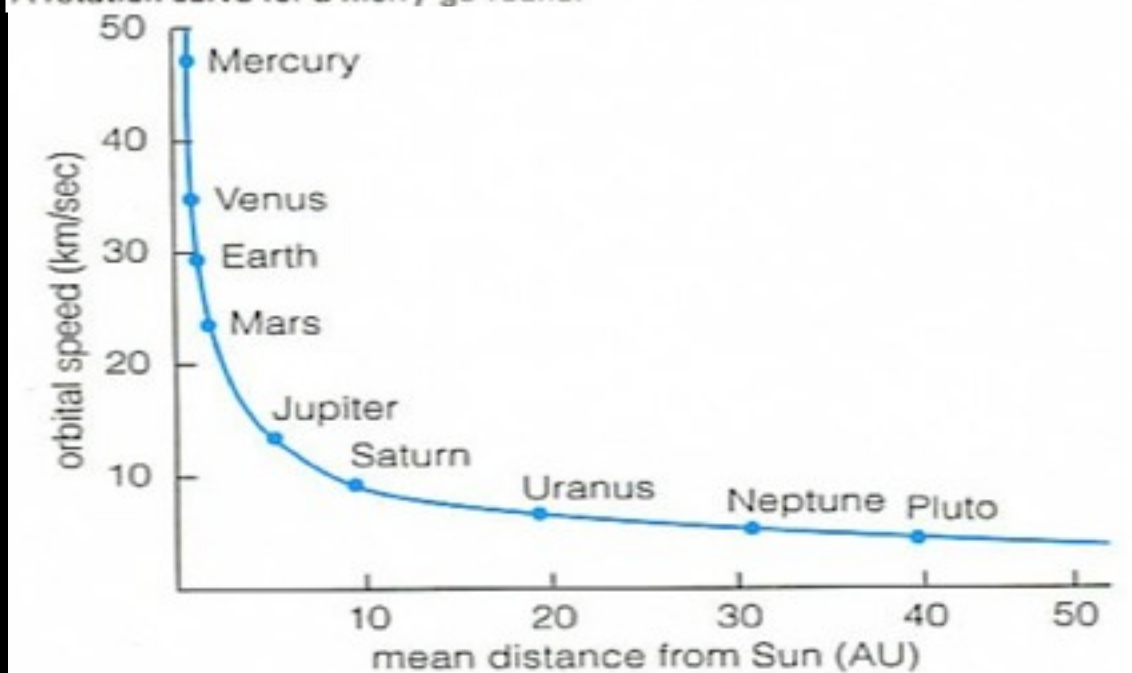
- Comparison with FERMI-LAT is possible through our EFT

- The results can also be interpreted in terms of limits on WIMPs annihilating to light quarks
- All limits shown here assume 100% branching fractions of WIMPs annihilating to quarks
- Below 10 GeV for D5 and 70 GeV for D8 the ATLAS limits are below the values needed for WIMPs to make up the DM relic abundance

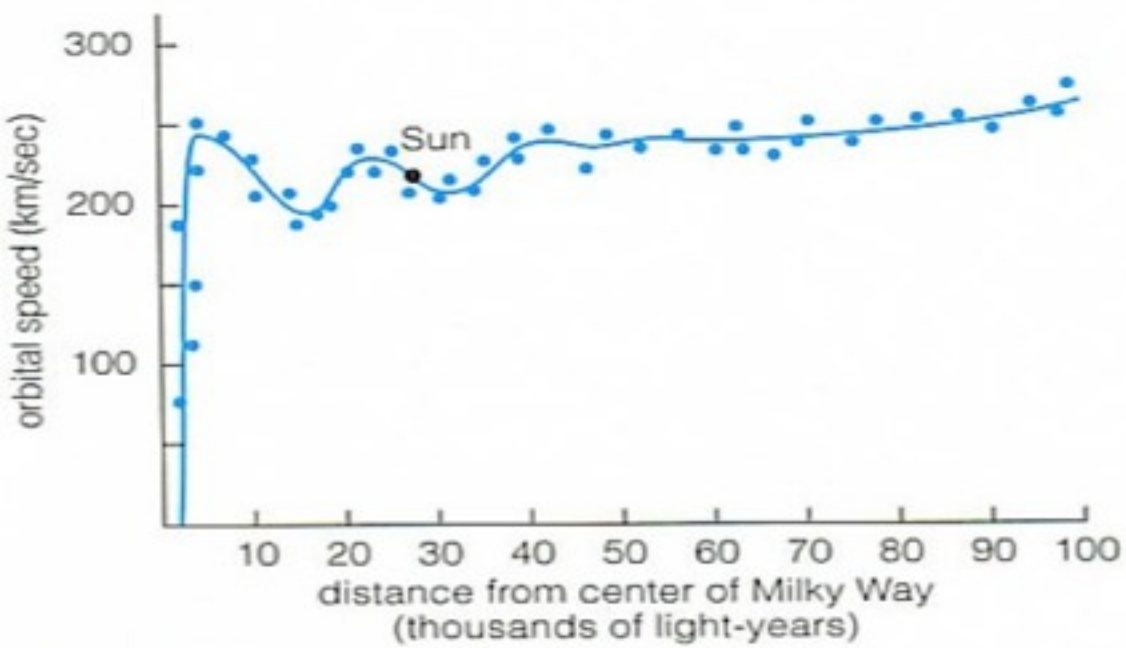
Not the end but the beginning of lots of new research !



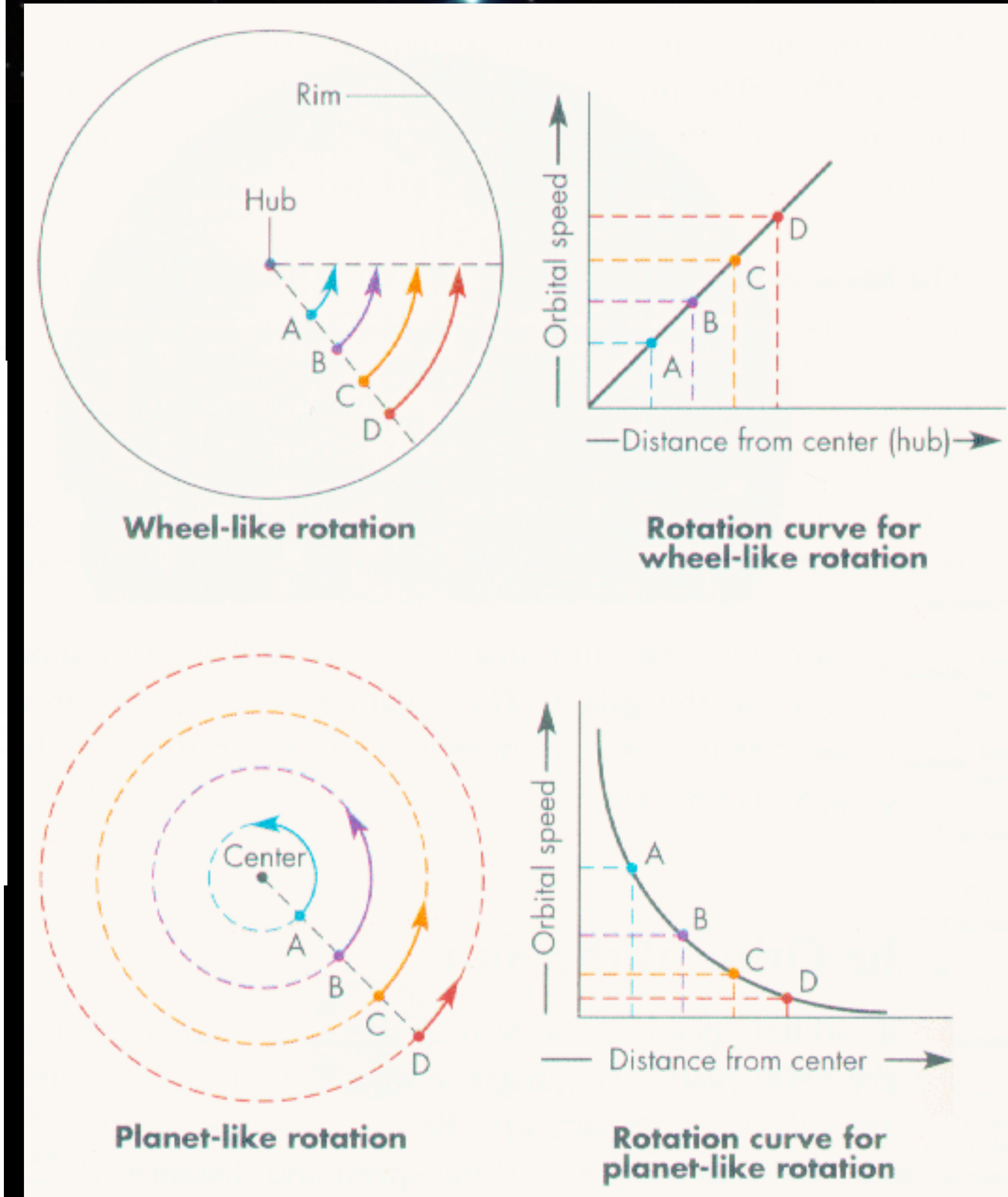
A rotation curve for a merry-go-round.



The rotation curve for the planets in our solar system.

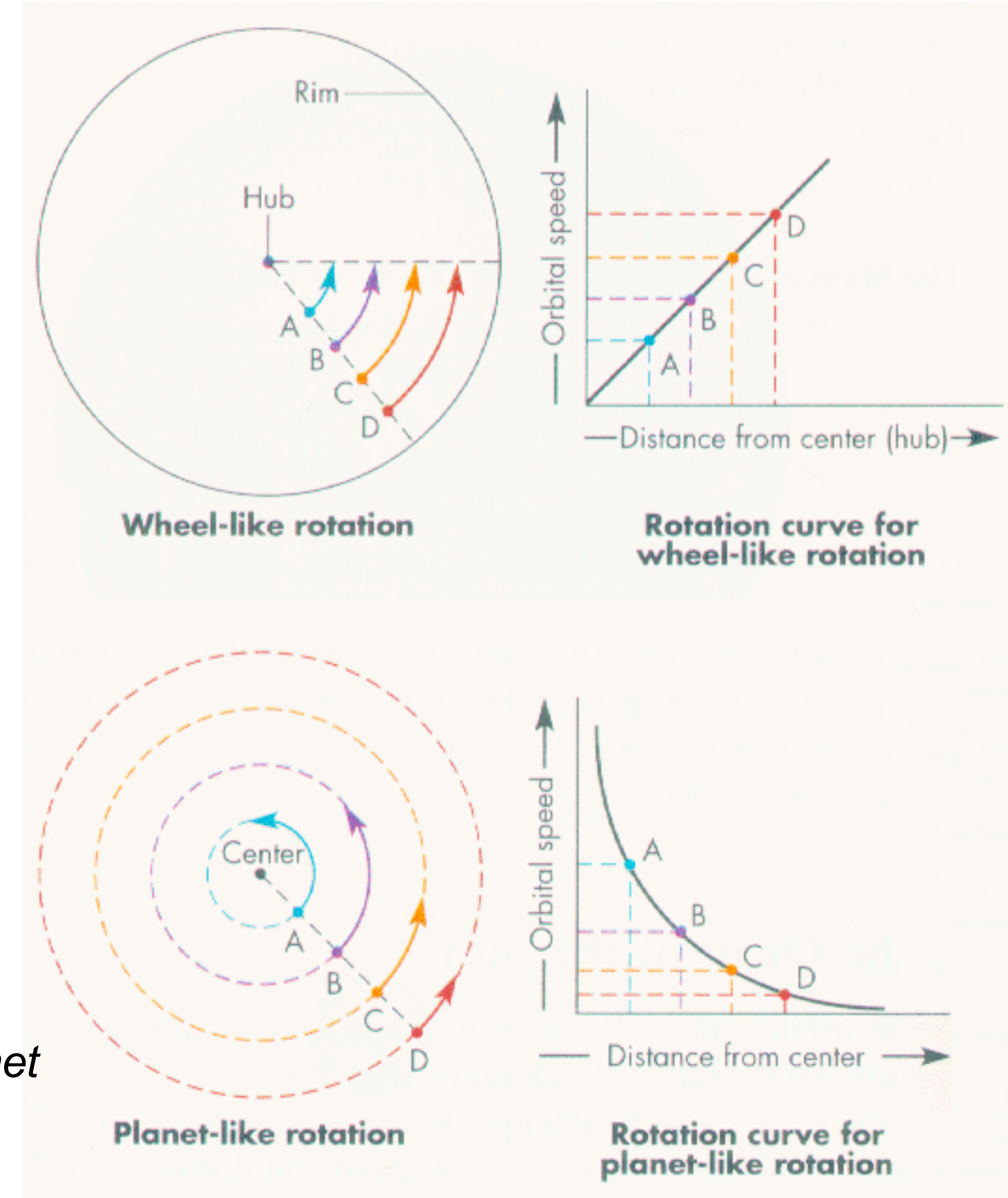


The rotation curve for the Milky Way Galaxy.

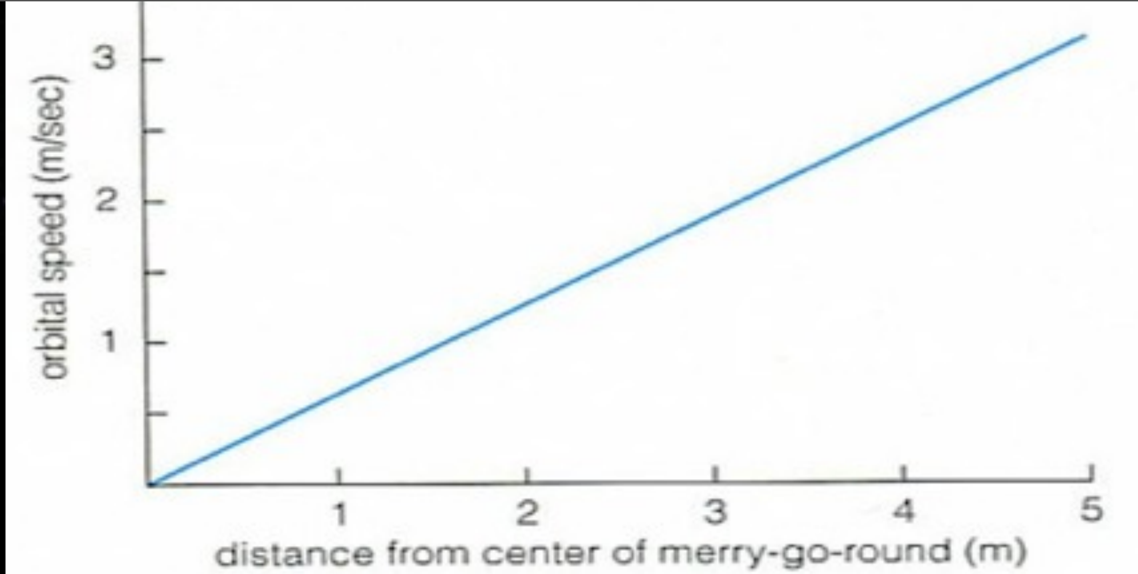


Rotation curves

- In the 50's astronomers started to study the internal motions of galaxies (rotation for disk galaxies) and their interaction with each other as in clusters
- Soon they started to wonder if we were observing the mass or the light in the Universe, most of what we see in galaxies is starlight.
- Early 60's there were the indication that the brightest galaxies was not always also the most massive - the missing mass problem
- One of the first studies was the rotation of our own galaxy:



Examples of simple rotation curves. Planet like rotation follows Keplers 3rd law :



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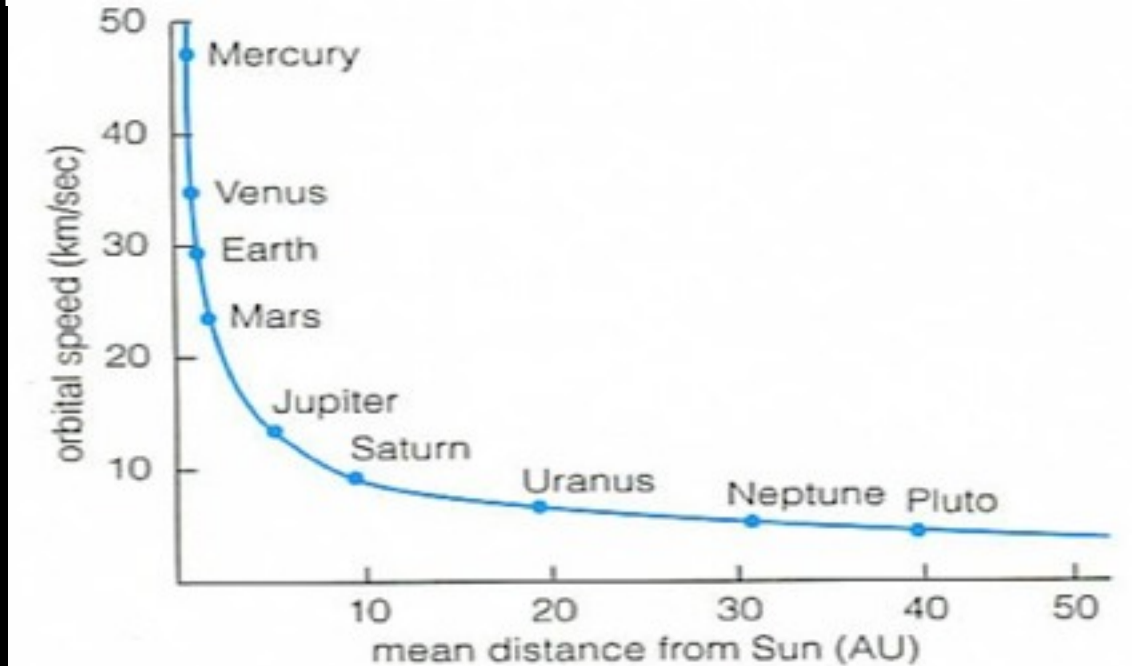

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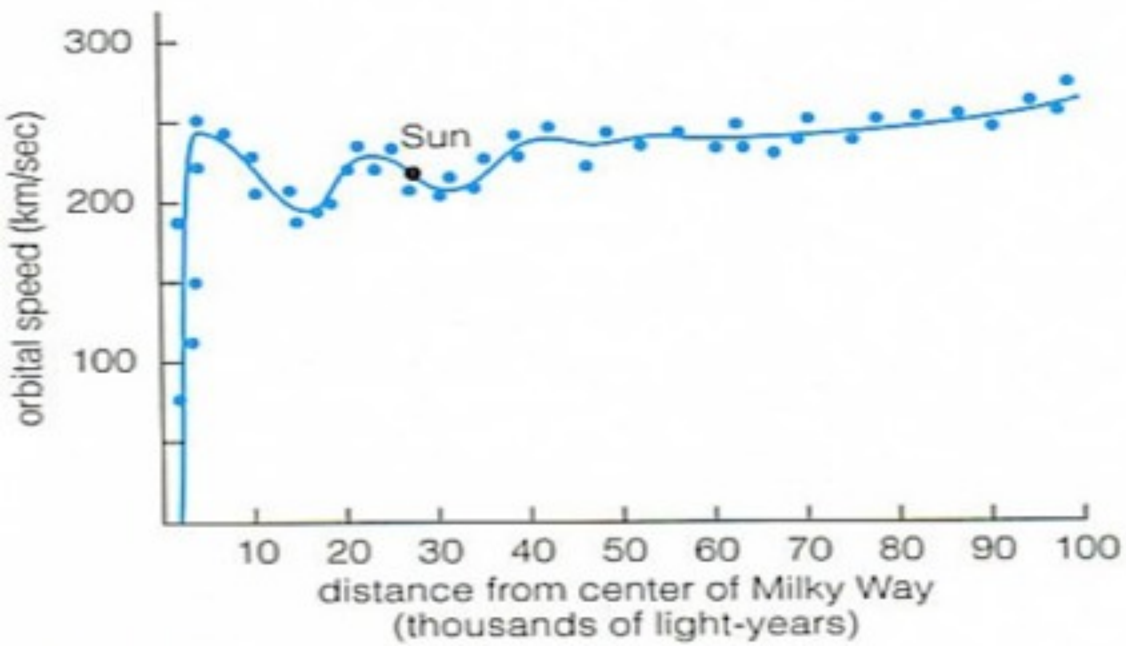

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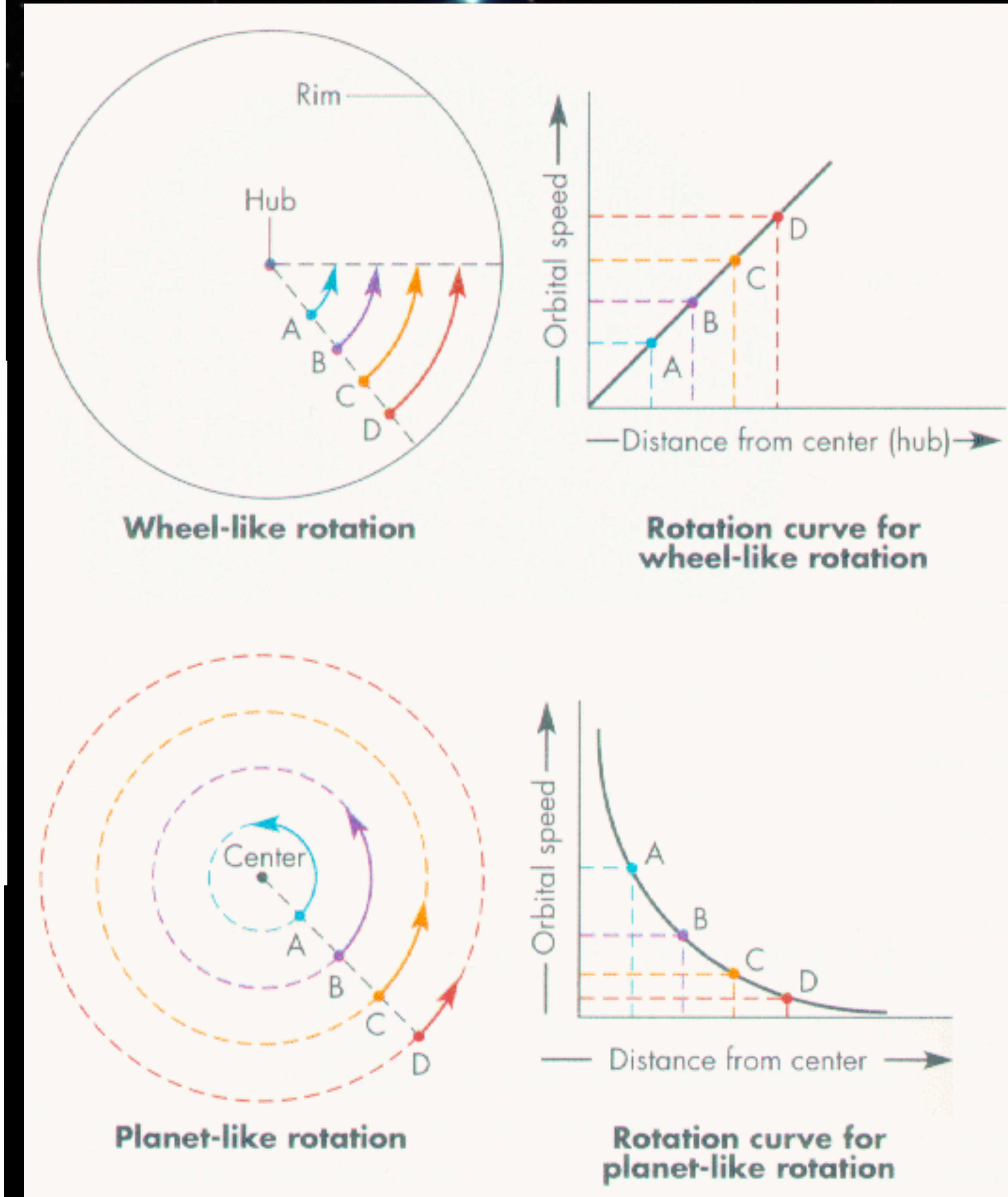

Rotation curves

- To determine the rotation curve of the Galaxy, stars are not used due to interstellar extinction. Instead, 21-cm maps of neutral hydrogen are used. When this is done, one finds that the rotation curve of the Galaxy stays flat out to large distances, instead of falling off as in the figure above. This means that the mass of the Galaxy increases with increasing distance from the center.
- Soon they started to wonder if we

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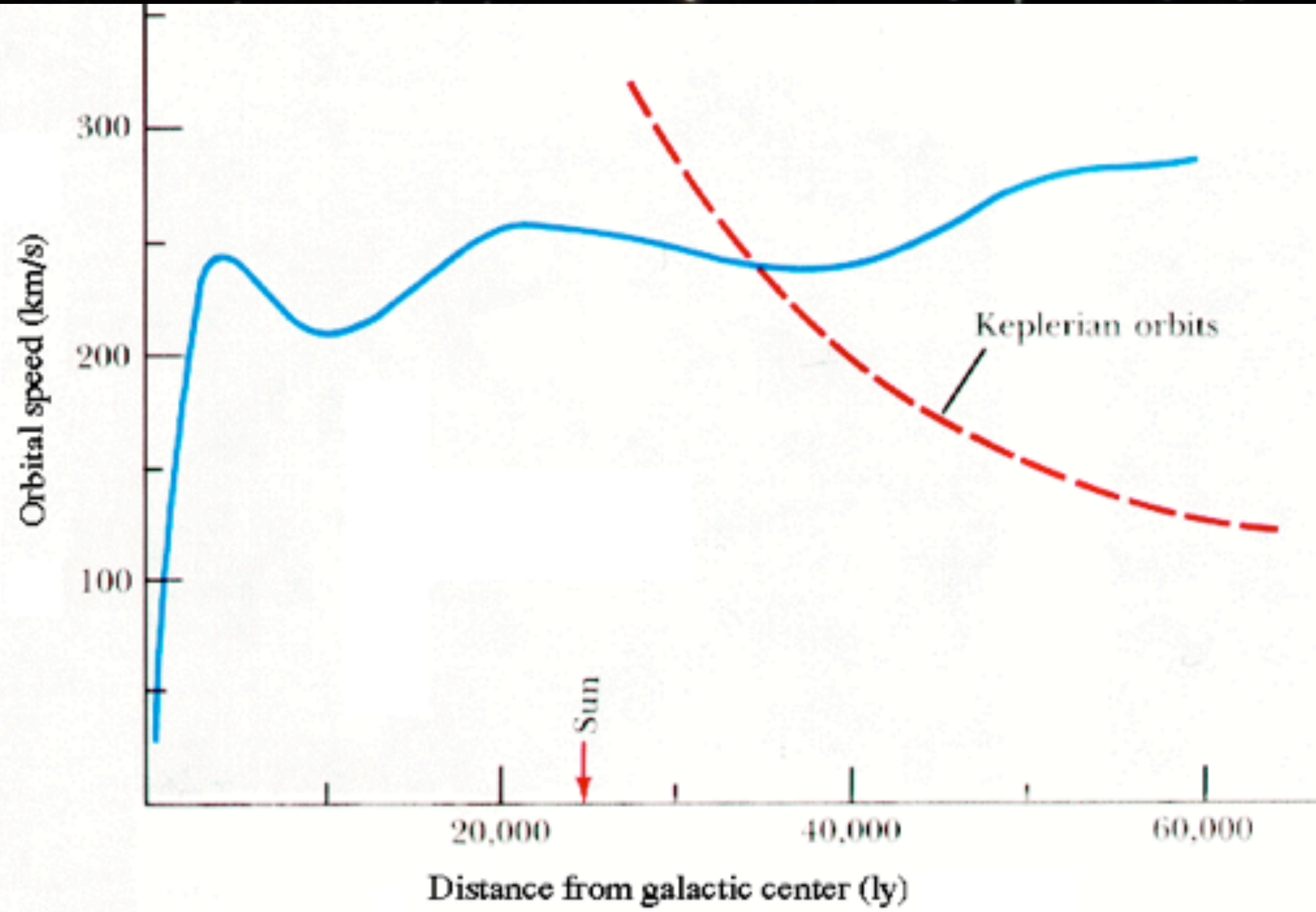
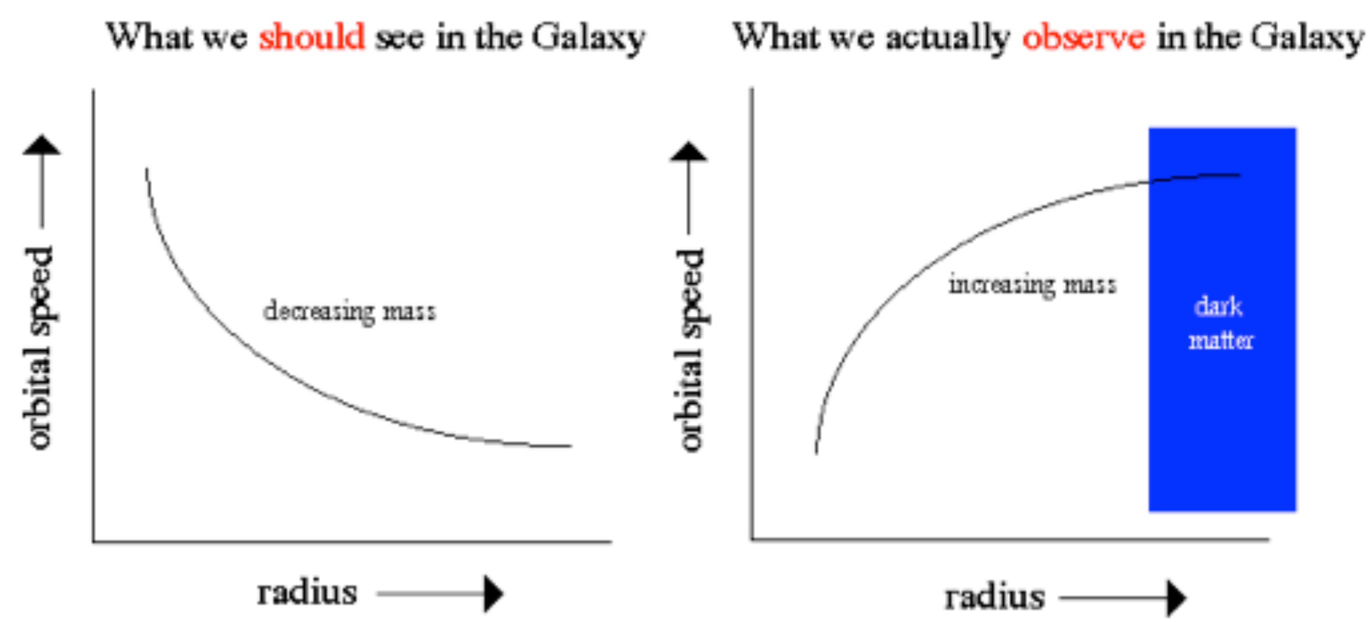


Rotation Curve of the Galaxy

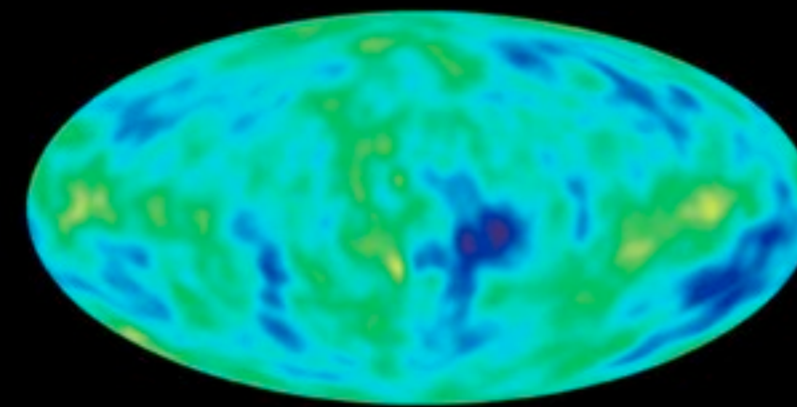


The surprising thing is there is very little visible matter beyond the Sun's orbital distance from the center of the Galaxy. So, the rotation curve of the Galaxy indicates a great deal of mass, but there is no light out there. In other words, the halo of our Galaxy is filled with a mysterious dark matter of unknown composition and type.

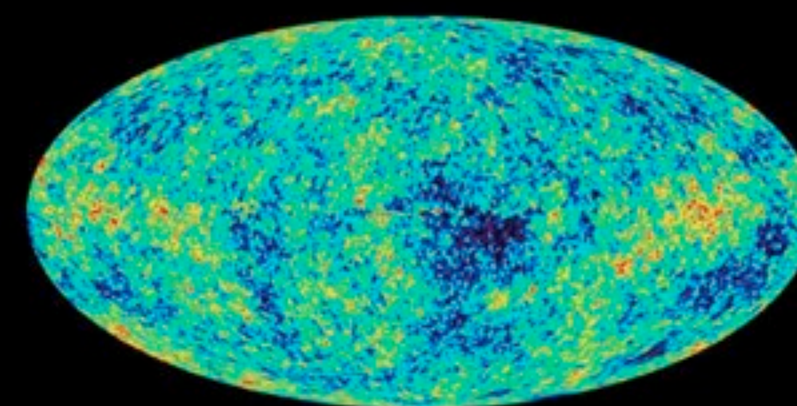
The geometry of the universe

Both dark energy and dark matter important ingredients

- The amount of dark matter and dark energy in the universe is crucial to determine the geometry of space
  - Open : density less than critical density
  - Flat : density equal to critical density
  - Closed: density more than the critical density
- Gives information on the evolution of the universe (eternal expansion, in equilibrium, or stop and collapse)
- The spacial geometry have been measured by WMAP to be nearly flat

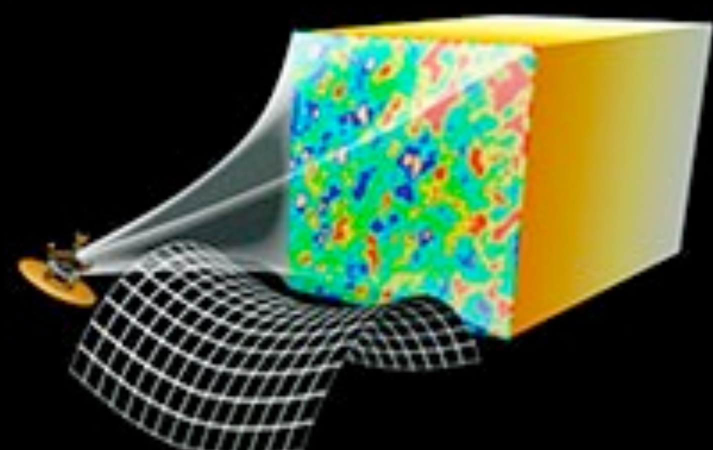


COBE

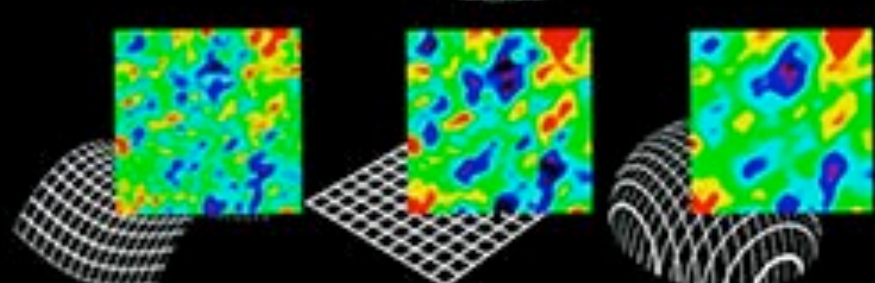


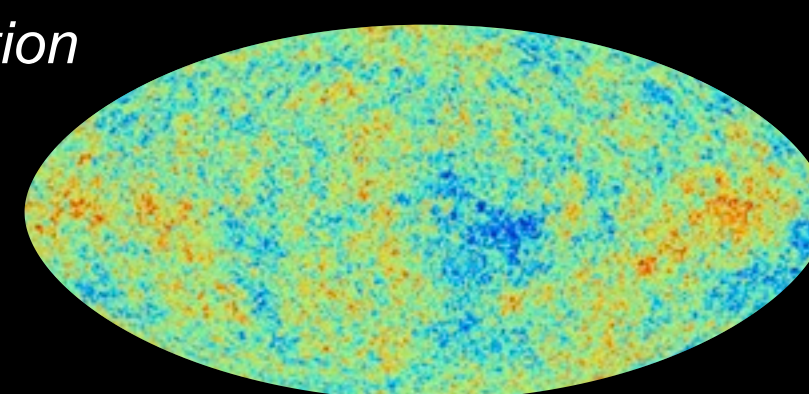
MAP

WMAP



Cosmic microwave background radiation





PLANCK (simulated)

Open Flat Closed

ESA/NASA