# Observational Cosmology and Astroparticles I:

# DARK MATTER

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SCHOOL ON HIGH ENERGY PHYSICS

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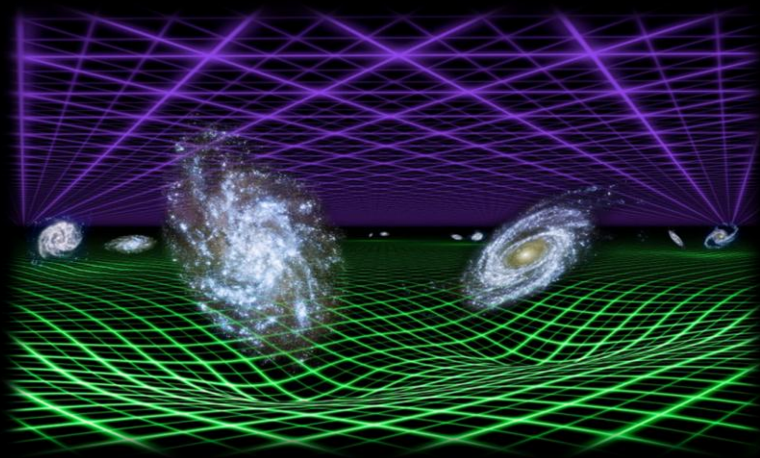
# Outline

## 1.- Introduction: The Dark Side of the Universe

The Standard Cosmological model. Observational basis.

Why we need dark Matter and Dark Energy

Other possibilities?



## 2.- The Dark Matter

Obervational Evidence and Properties

Identification of Dark Matter: Results

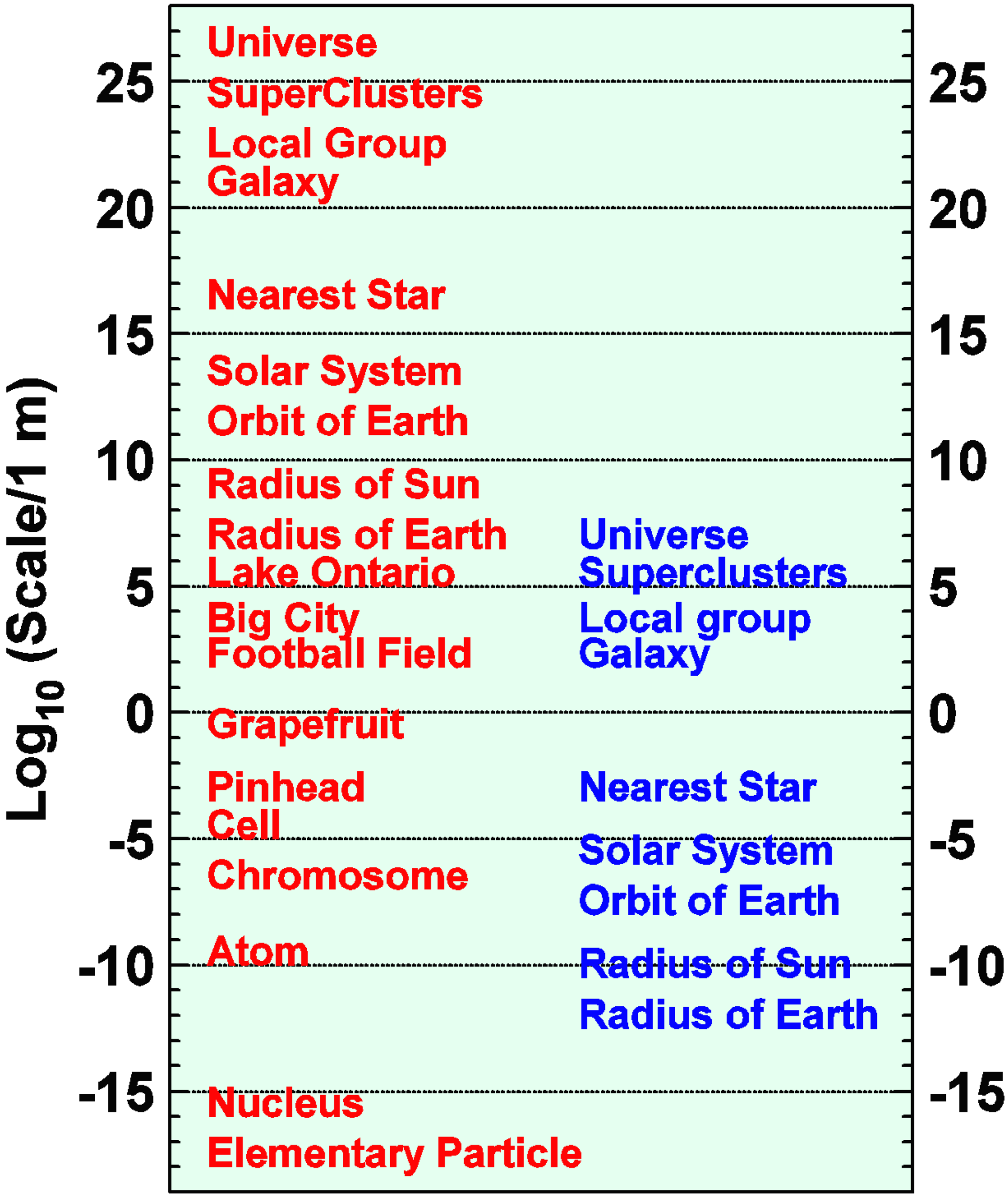
*Production*

*Indirect detection*

*Direct detection*

Summary

# Scales




Cosmology studies the largest spatial scales.

The visible universe as a whole

# Scale Model

**The Solar System to scale $1/10^{12}$ fits within a room, with the Sun being a 100 W lamp**

**The closest star would be another lamp at 40 km**

**Our galaxy would be 100000 millions lamps spread in a disk with a radius like the Moon orbit, and with a width like the Earth diameter (100000 millions of rice grains fill a cathedral)**

**The limit of the visible universe reachs up to 1/30 of the distance to the closest star**

# Universe scales are also huge in time: Observing huge distances means observing remote times also

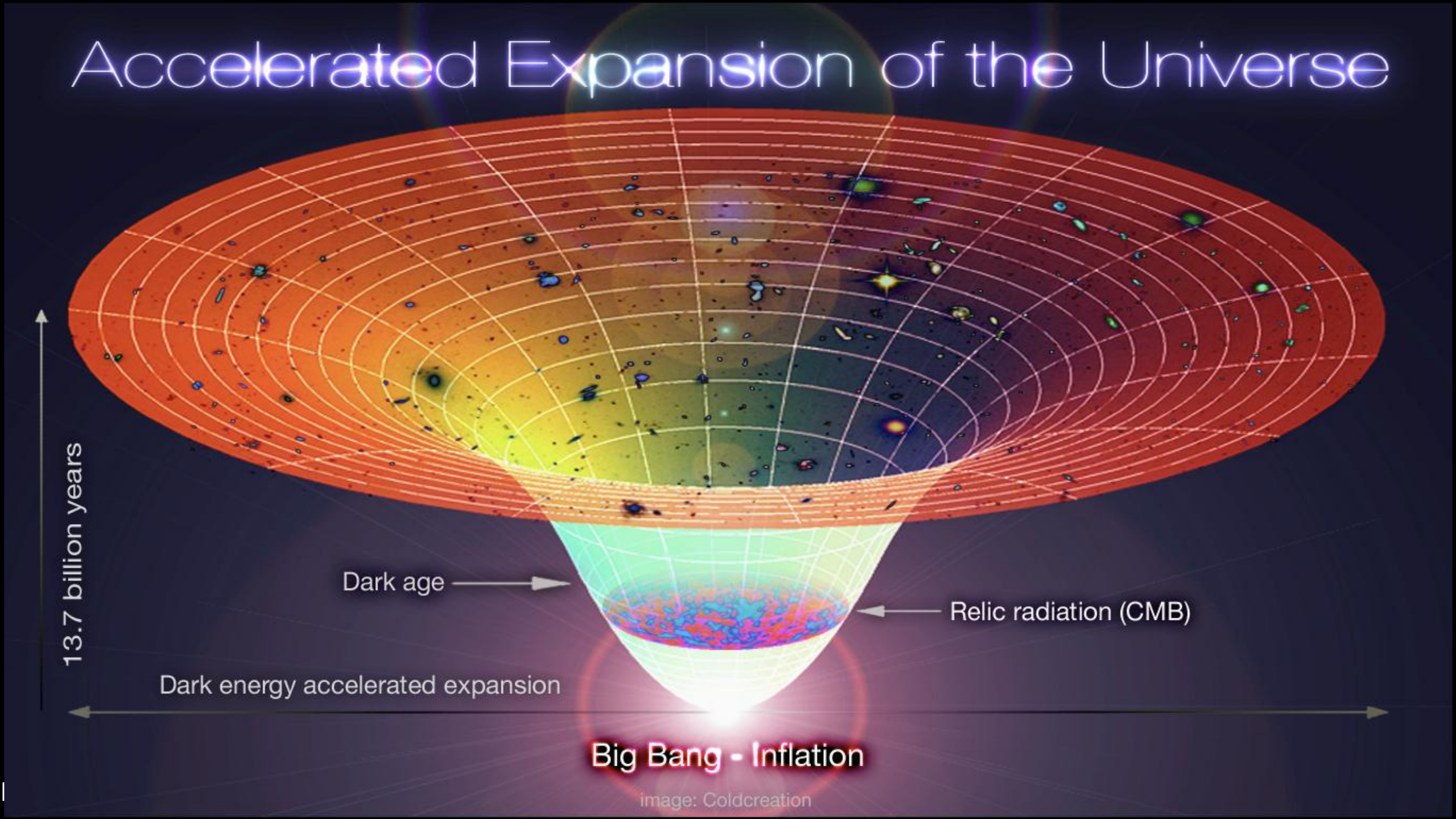

Cosmic calendar Carl Sagan´s style

**Human History; from 23:59:00**

# Introduction

The current standard model of cosmology, LCDM, is based on

- **General Relativity**
- **The Cosmological Principle (homogeneous and isotropic)**
- **Inflation (Particle Physics in the early universe)**



# Large amount of observational evidence

From CMB → $\Omega_{TOT}$ ~1
(Universe is **FLAT**)

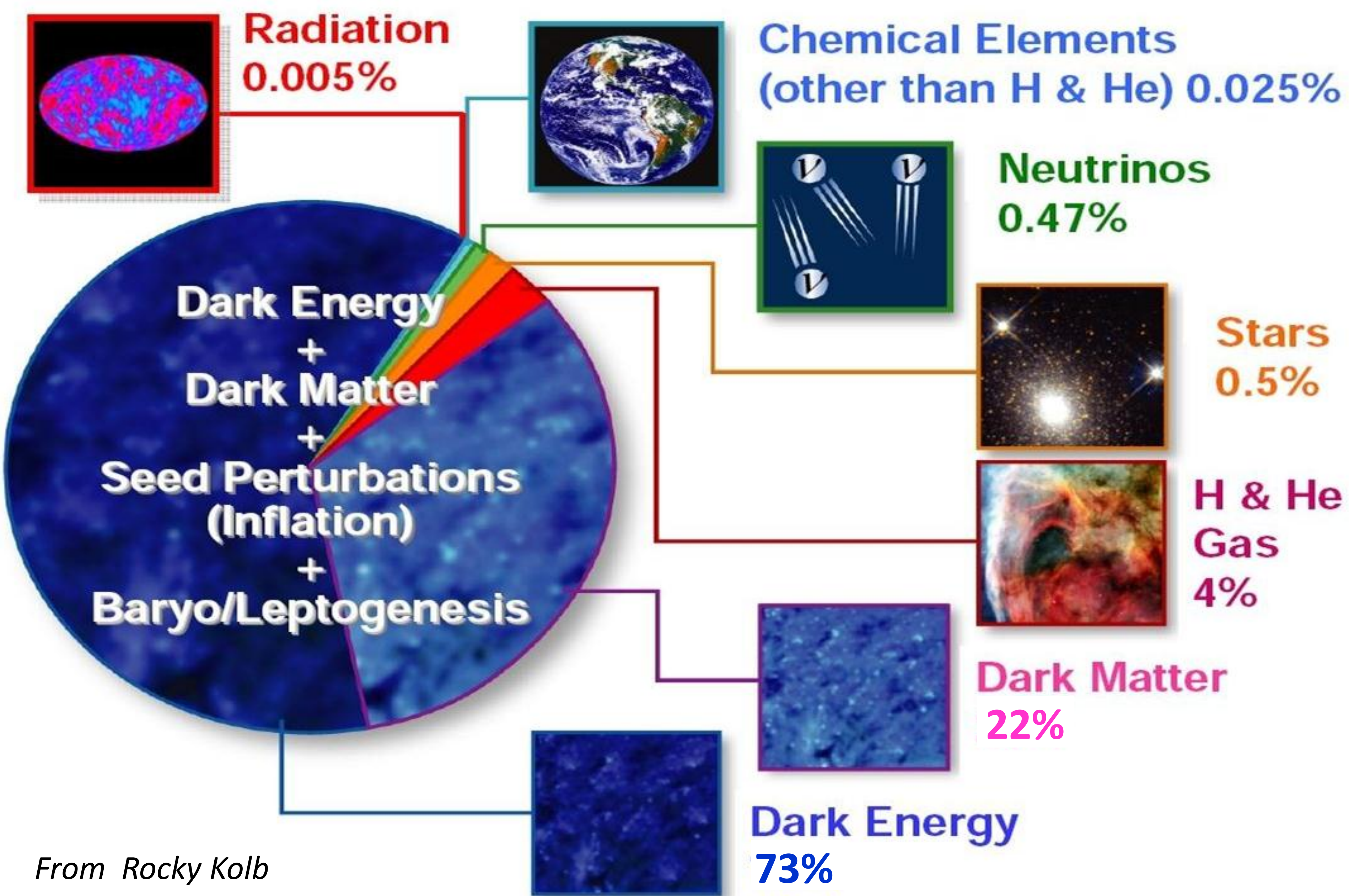
From BBN + CMB → $\Omega_B$ ~ 0.04
→ Most of the universe is **non-baryonic**

LSS (galaxy surveys) + DYNAMICS (rotation curves of galaxies, cluster masses, gravitational lensing) → **DARK MATTER!!!!** ; $\Omega_{DM}$~ 0.22

Supernovae Ia → **DARK ENERGY!!!** ; $\Omega_{DE}$ ~ 0.74

- Large scale homogeneity
- Hubble diagram
- Abundances of light elements (BBN)
- Existence of CMB
- Fluctuations of CMB
- Large Scale Structure
- Age of stars
- Evolution of galaxies
- Time dilation in SN brightness curves
- Temperature vs redshift (Tolman test)
- Gravitational Lensing
- Sunyaev-Zel´ dovich effect
- Integrated Sachs-Wolf effect
- Dark matter (rotation/dispersion velocity)
- Dark energy (accelerated expansion)
- Consistency of all observations

# 96% of the universe remains unexplained




*From Rocky Kolb*

# Other possibilities?

**GR+SM failed several/most/all (*) tests above the astronomical unit:**

*(*) Depending who you are*

1) Galaxies need extra gravity (rotation curves, velocity dispersion)
2) Clusters need extra gravity (velocities, X-ray, mass-to-light)
3) Weak lensing and collision of clusters need extra gravity
4) dT/T ~ few x $10^{-5}$ @ z~1100 → Need extra gravity to create structure
5) Cosmic acceleration
6) Universe acausaly homogeneus but has acoustic structure

1+2 → Invention of dark matter, which explained also 3 and 4

5 → Invention of dark energy

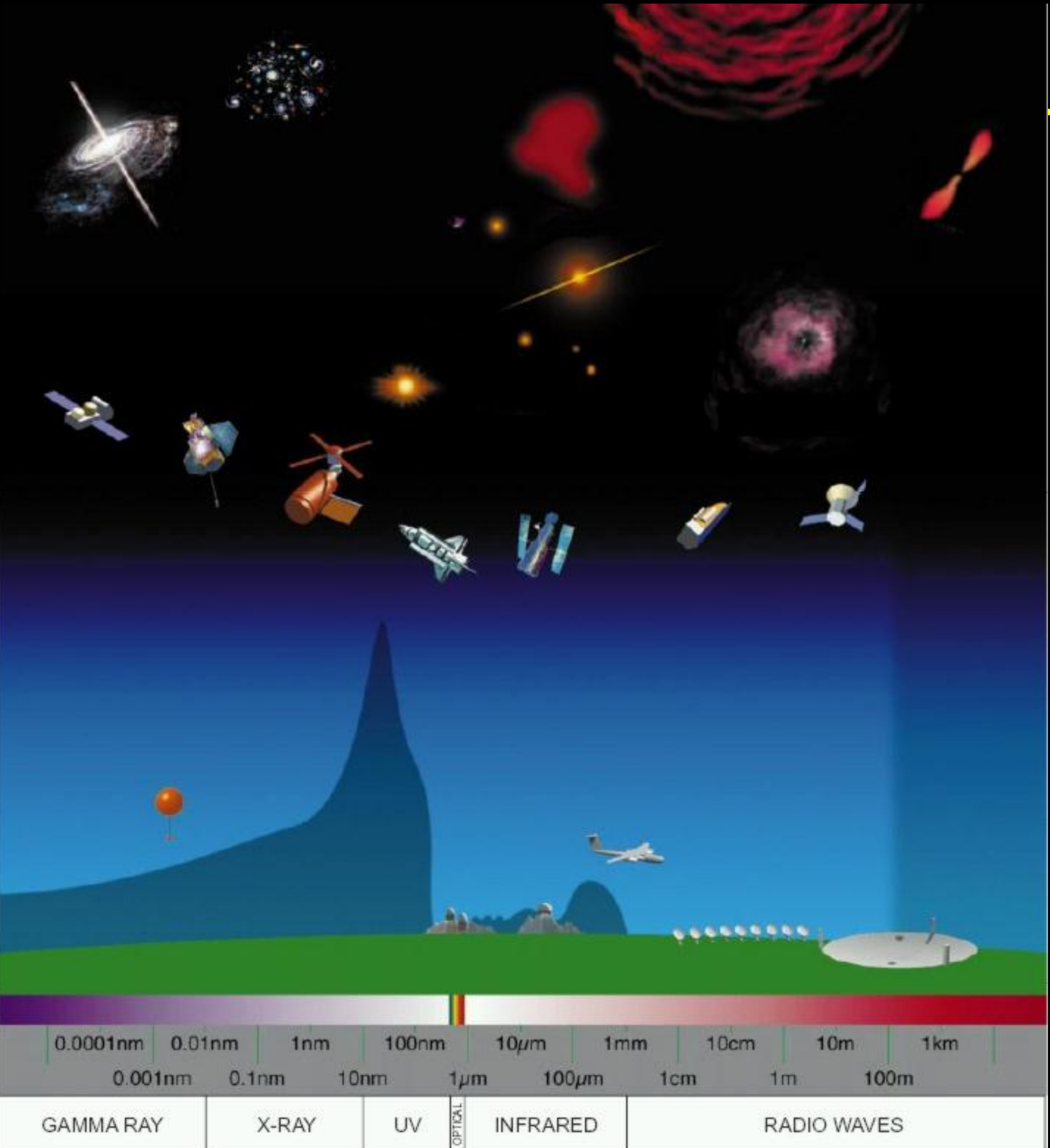
6→ Invention of inflation

**We invented 3 strange things just because we are in love with general relativity. Should we accept a modification of gravity?**

**It is very difficult to formulate an alternative theory...**

**What about other supositions? → Cosmological principle**

LTB models → almost excluded




## How is this observed?

Powerful telescopes and detectors, both on earth and in space

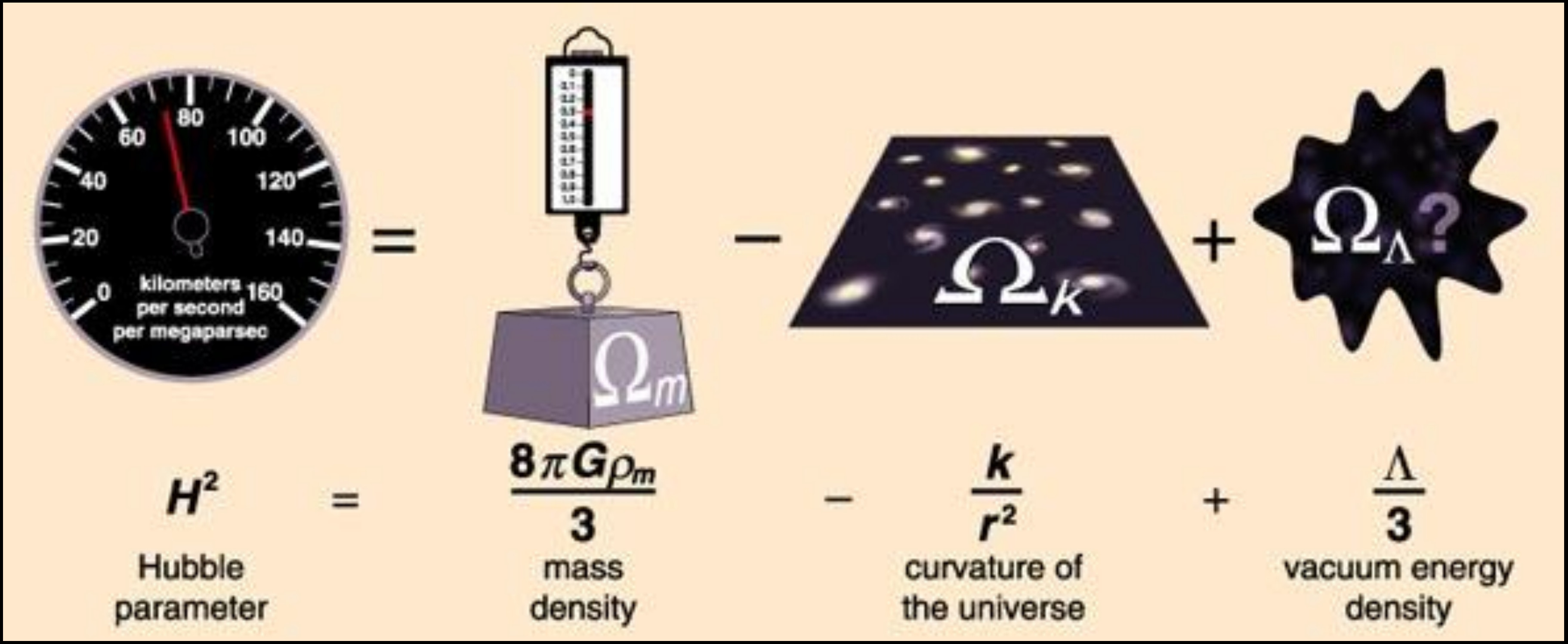
For very different wavelengths (not only visible light)

Other particles coming from space are also observed (cosmic rays, neutrinos… and dark matter??)

# Cosmological Parameters

Using the standard model of cosmology, the universe can be described with a few parameters (energy, matter, radiation densities, curvature, dark energy EoS…)

Measuring the expansion rate of the universe $H^2$, we obtain information about its energy contents



# Dark Matter and Dark Energy

**Understanding the nature of the dark matter and the dark energy is one of the main problems of science today.**

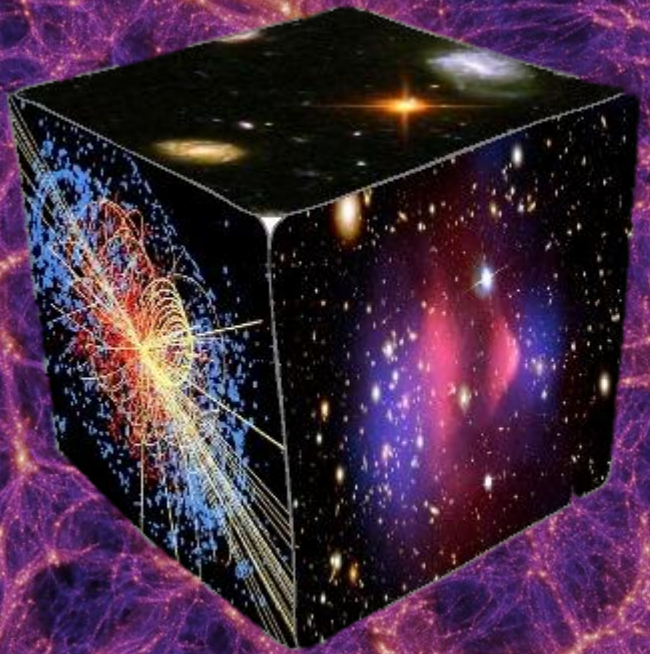
**It is a fundamental problem not only for cosmology, but also for particle physics.**

**The structure, evolution and fate of the universe depend strongly on the properties of the dark side**

***"You don´t know the power of the dark side"***

*Darth Vader, Star wars, episode 6*

# DARK MATTER



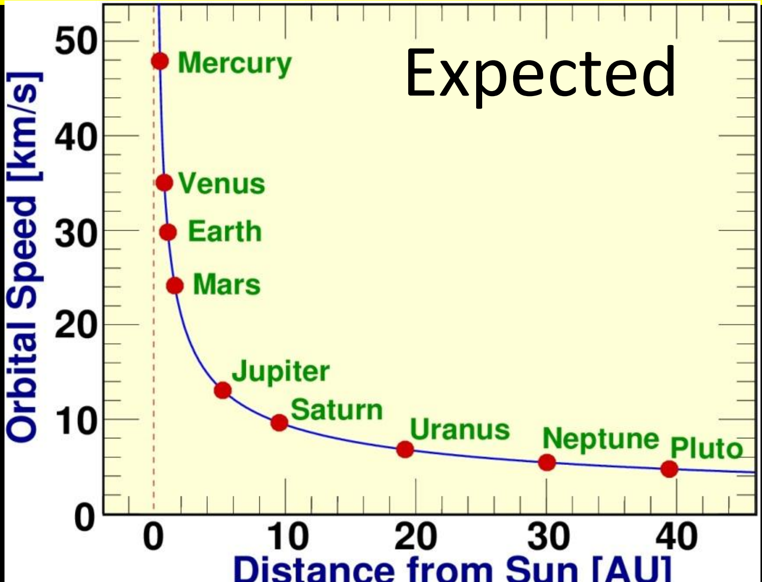
# DM: Observational Evidence

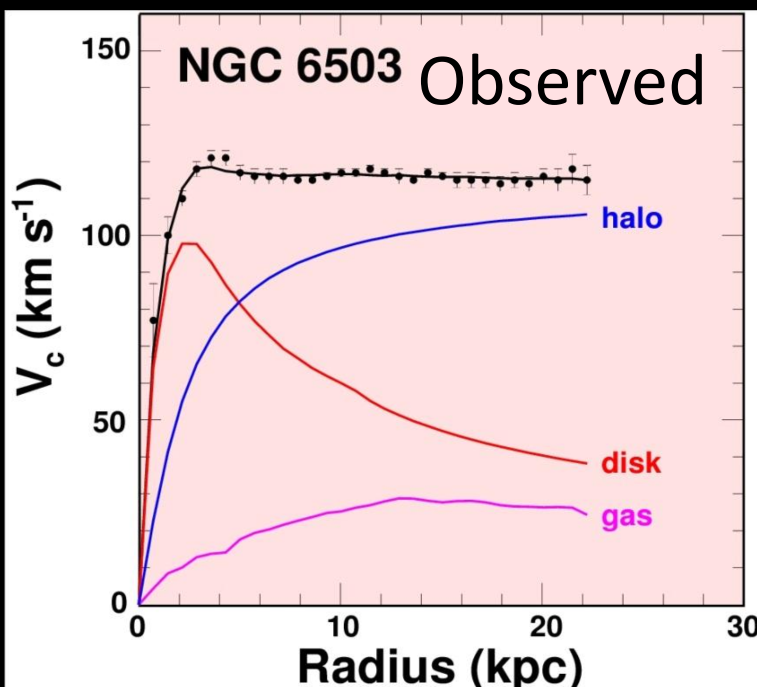
The existence of dark matter is inferred from many different observations

First evidence comes from the 1930´s, and from then to now it has only grown. Some of the main measurements that show the necessity of dark matter are:

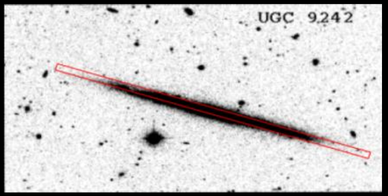
- **Spiral galaxy rotation curves or ellipticals velocity dispersion**
- **Mass-to-luminosity ratio in galaxy clusters**
- **Gravitational lenses**
- **Large scale structure of the universe**
- **Abundances of light elements: Dark Matter is non-baryonic**

# DM Evidence: Rotation Curves




Measure the redshift of the different zones of the galaxy. One side recedes and the other approaches to us. From this behaviour obtain the rotation velocity

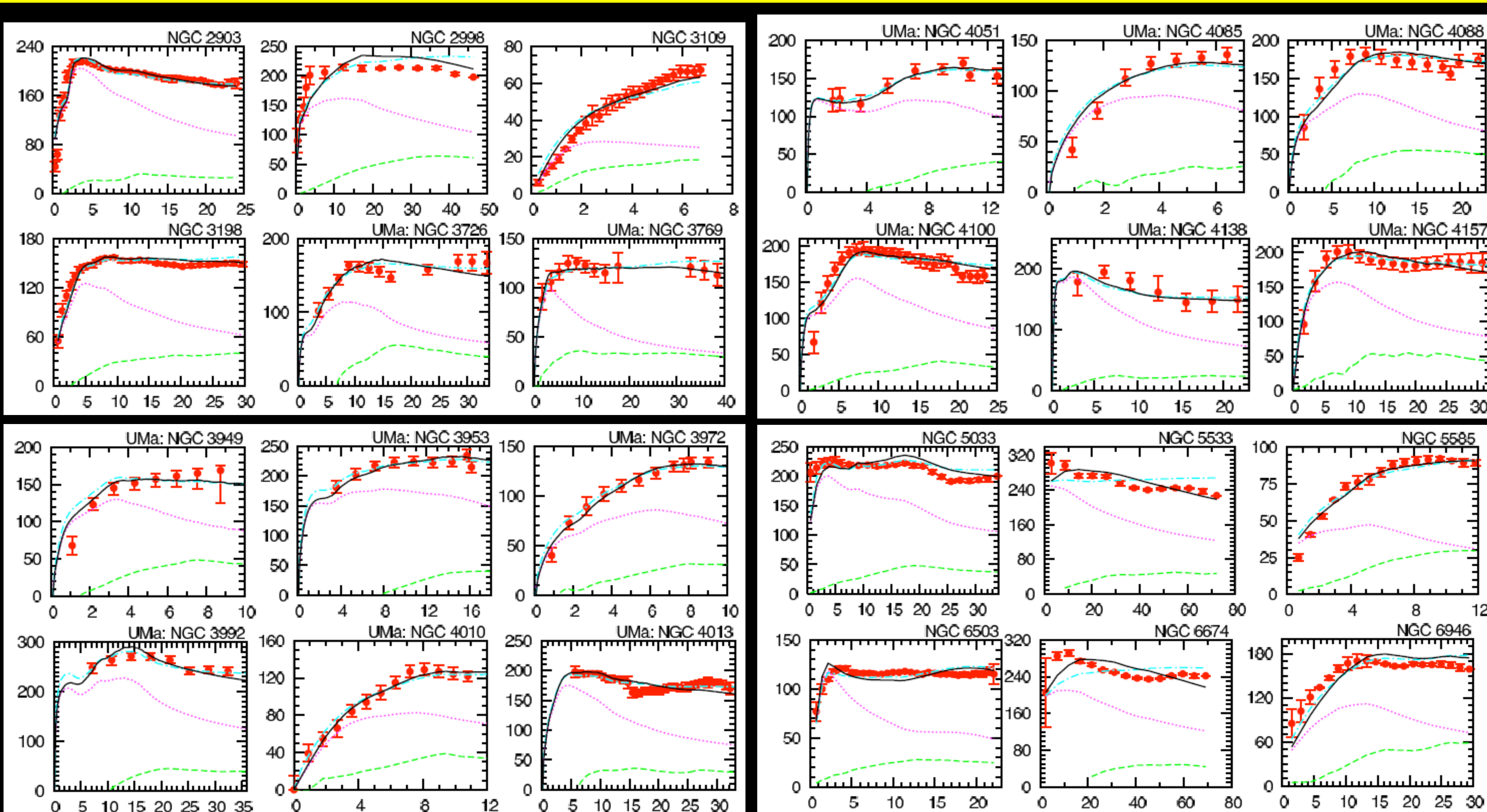



Galaxies do not follow the Newton (or Einstein) gravity prediction naively expected from their stars.

More (not visible) matter is needed to maintain such rotation speed…

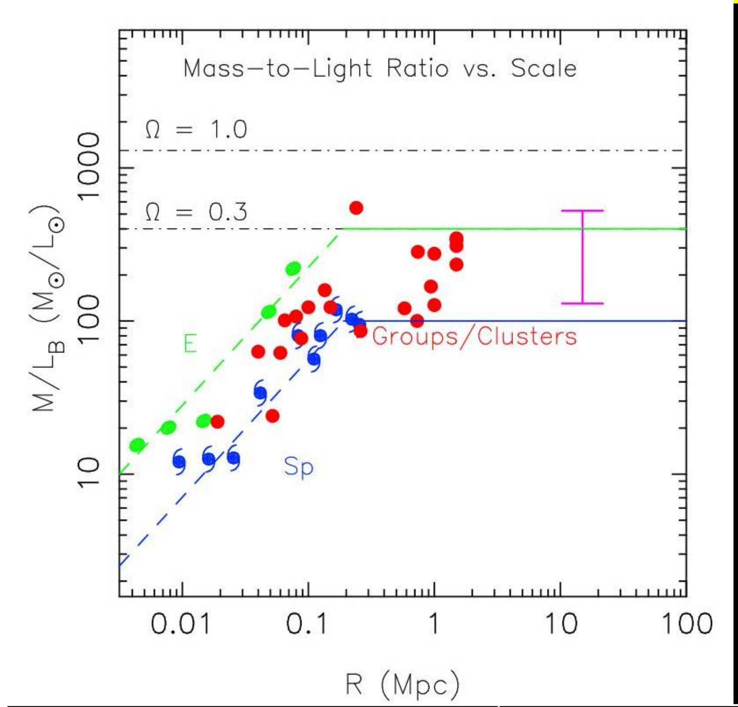
**DARK MATTER!!!!!!!**

# DM Evidence: Rotation Curves



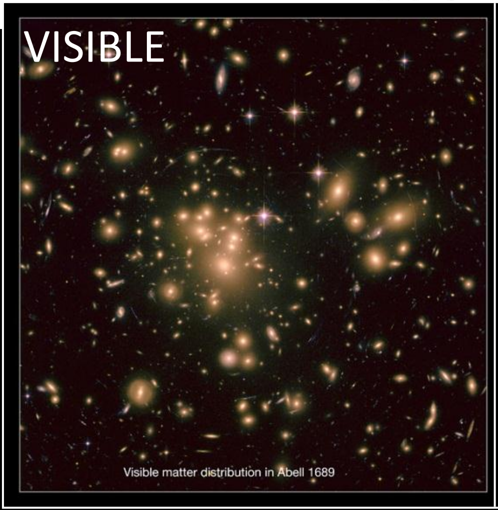

# DARK MATTER!!!!!!!

# DM Evidence: Mass-to-Light Ratio

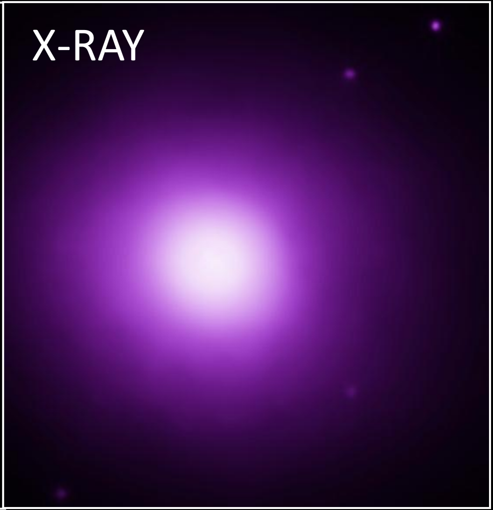



There is much more mass in the galaxy clusters than we see through star light from the galaxies themselves

Total Cluster Mass:
Virial Theorem
Intracluster gas temperature (X-ray)
Gravitational lensing
SZ effect on CMB

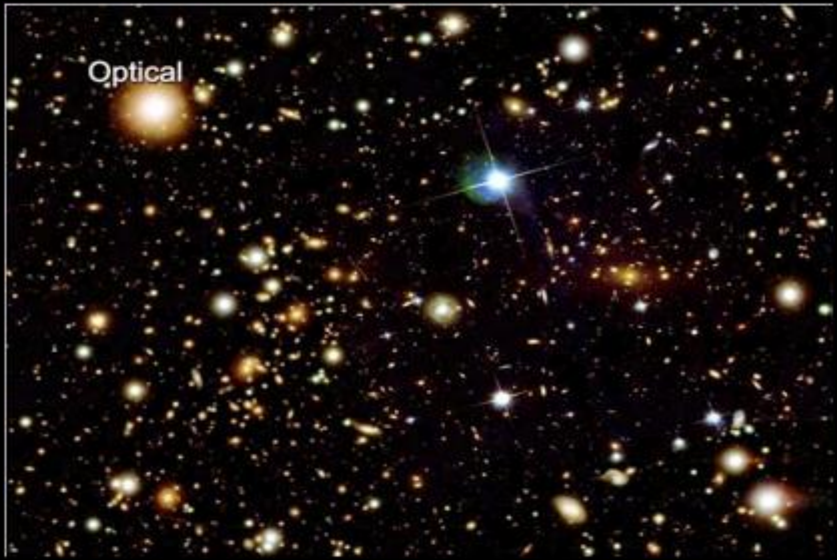


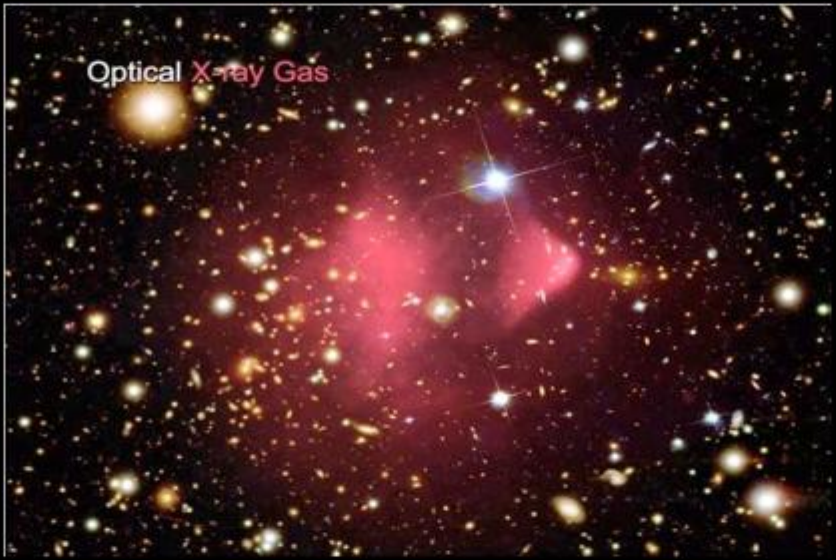


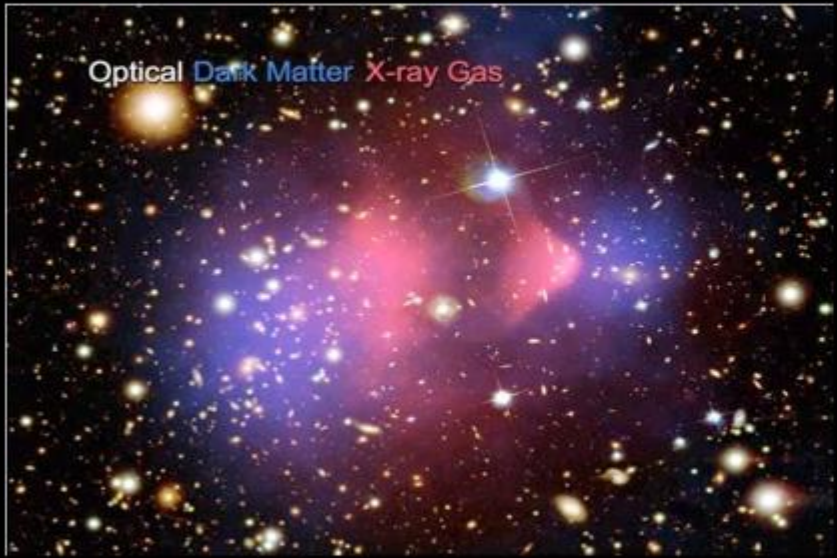



**DARK MATTER!!**

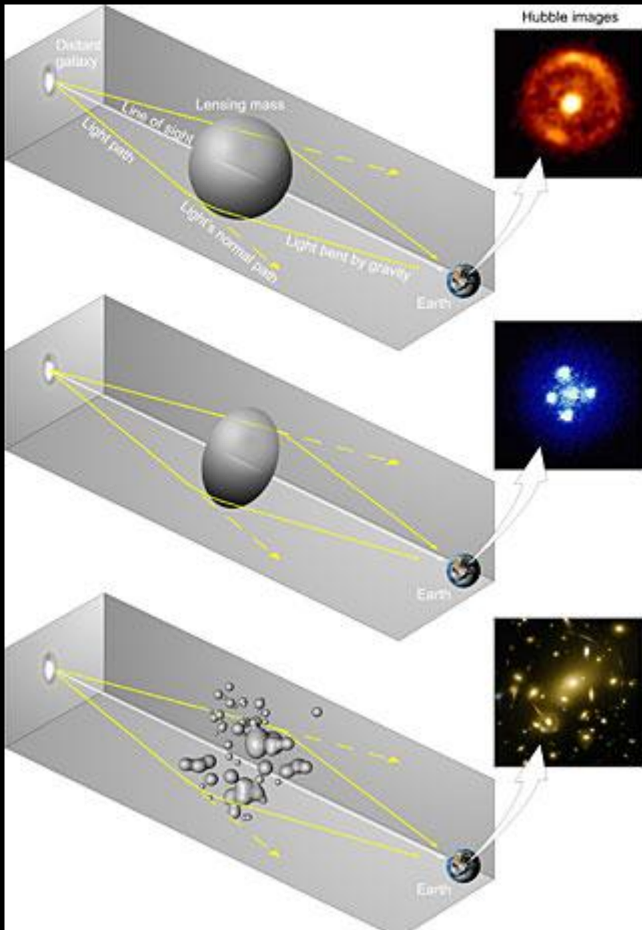
# DM Evidence: Total mass >> Visible mass



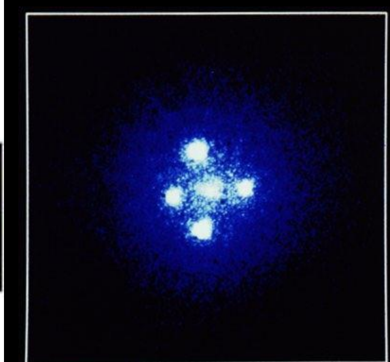



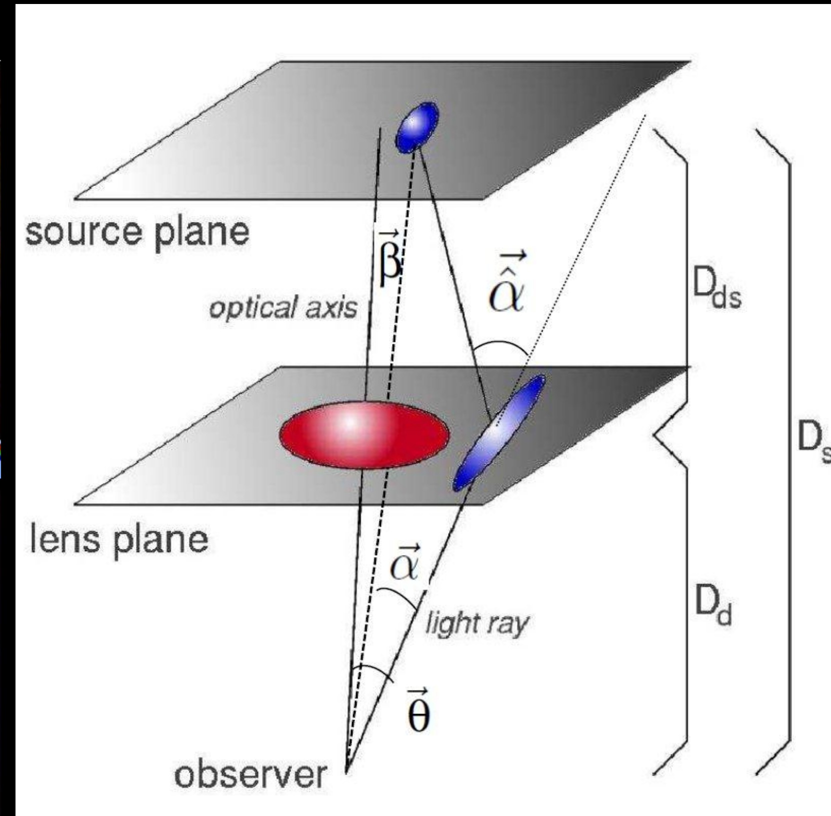




# DM Evidence: Gravitational Lenses






Gravitational Lens G2237+0305




$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta}) = \vec{\theta} - \frac{D_{ds}}{D_s}\hat{\vec{\alpha}}(D_d\vec{\theta})$$

Studying the properties of the images, it is possible to reconstruct the total mass distribution of the lens and compare it to the visible mass

# DM Evidence: Gravitational Lenses

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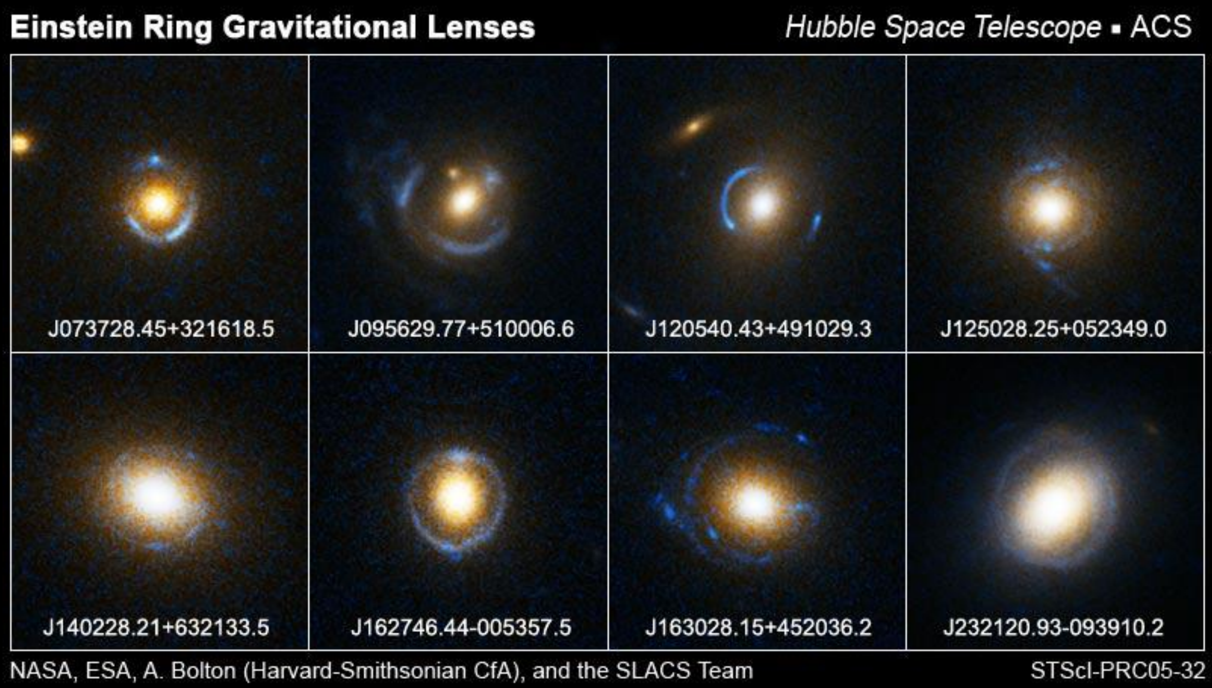
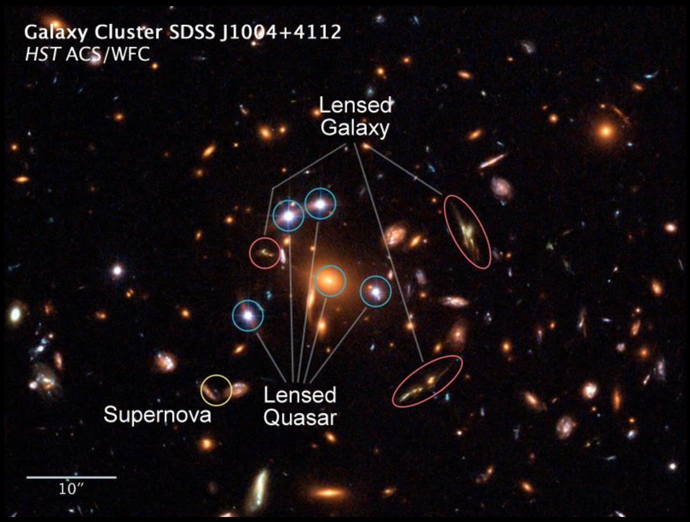
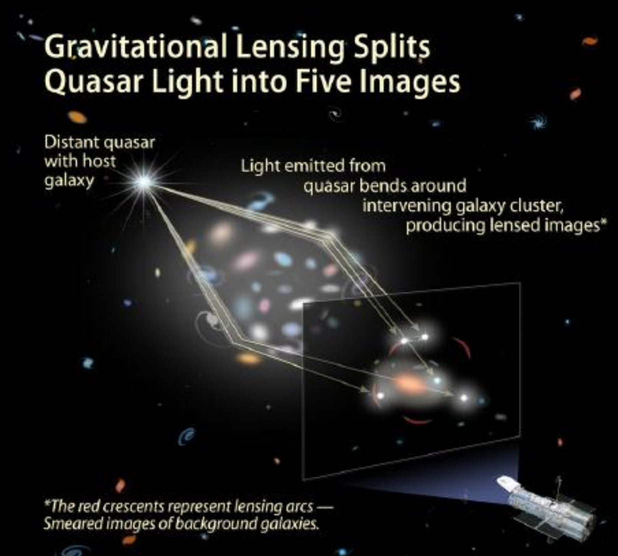
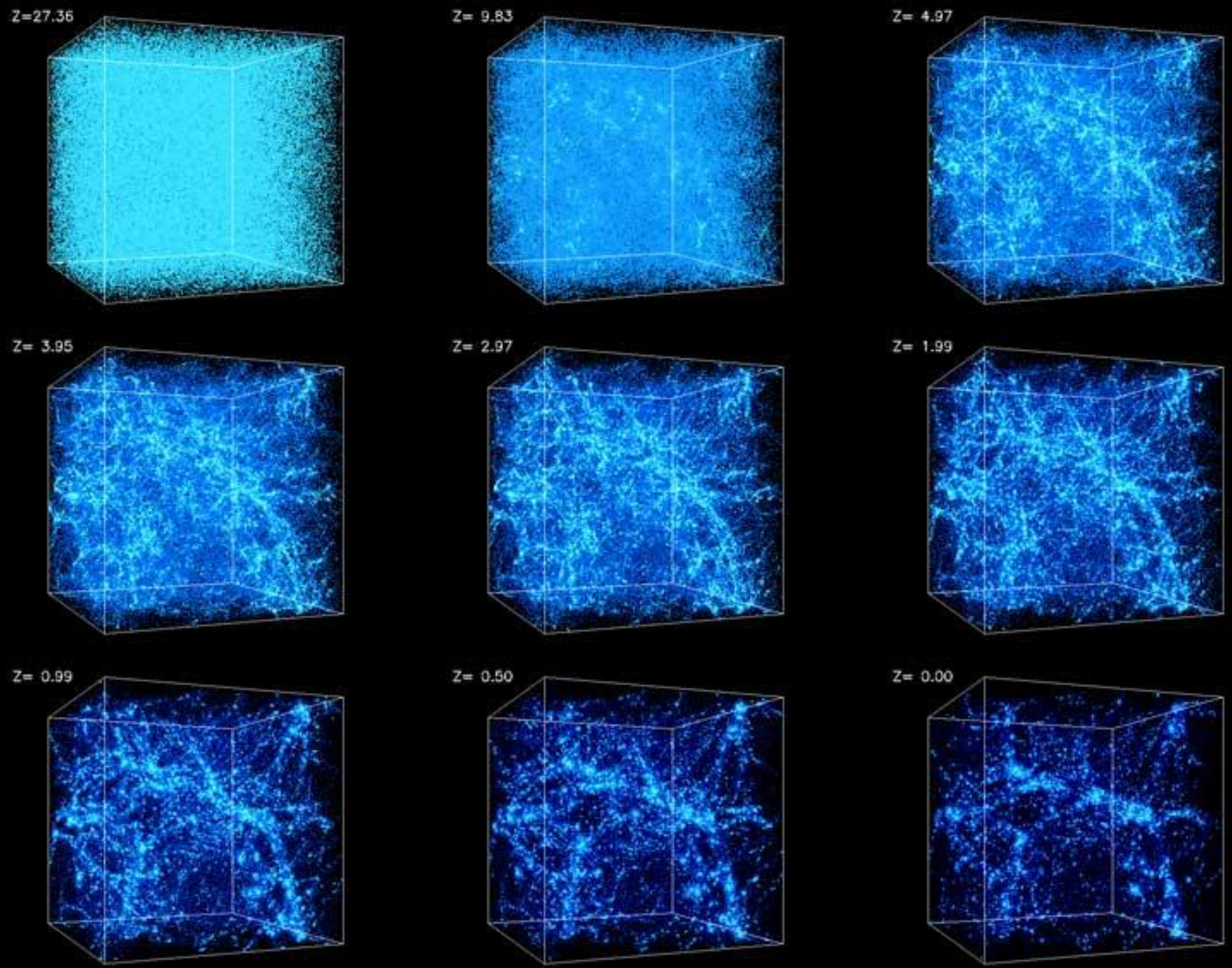


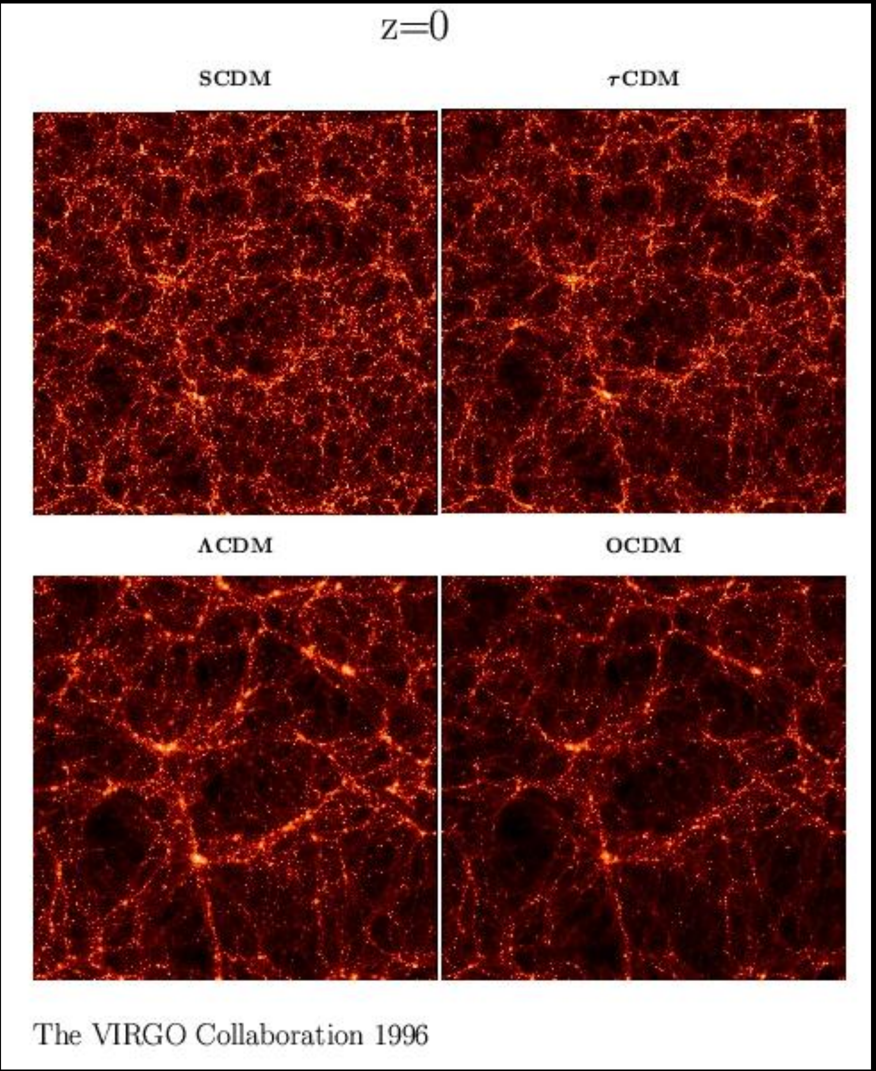



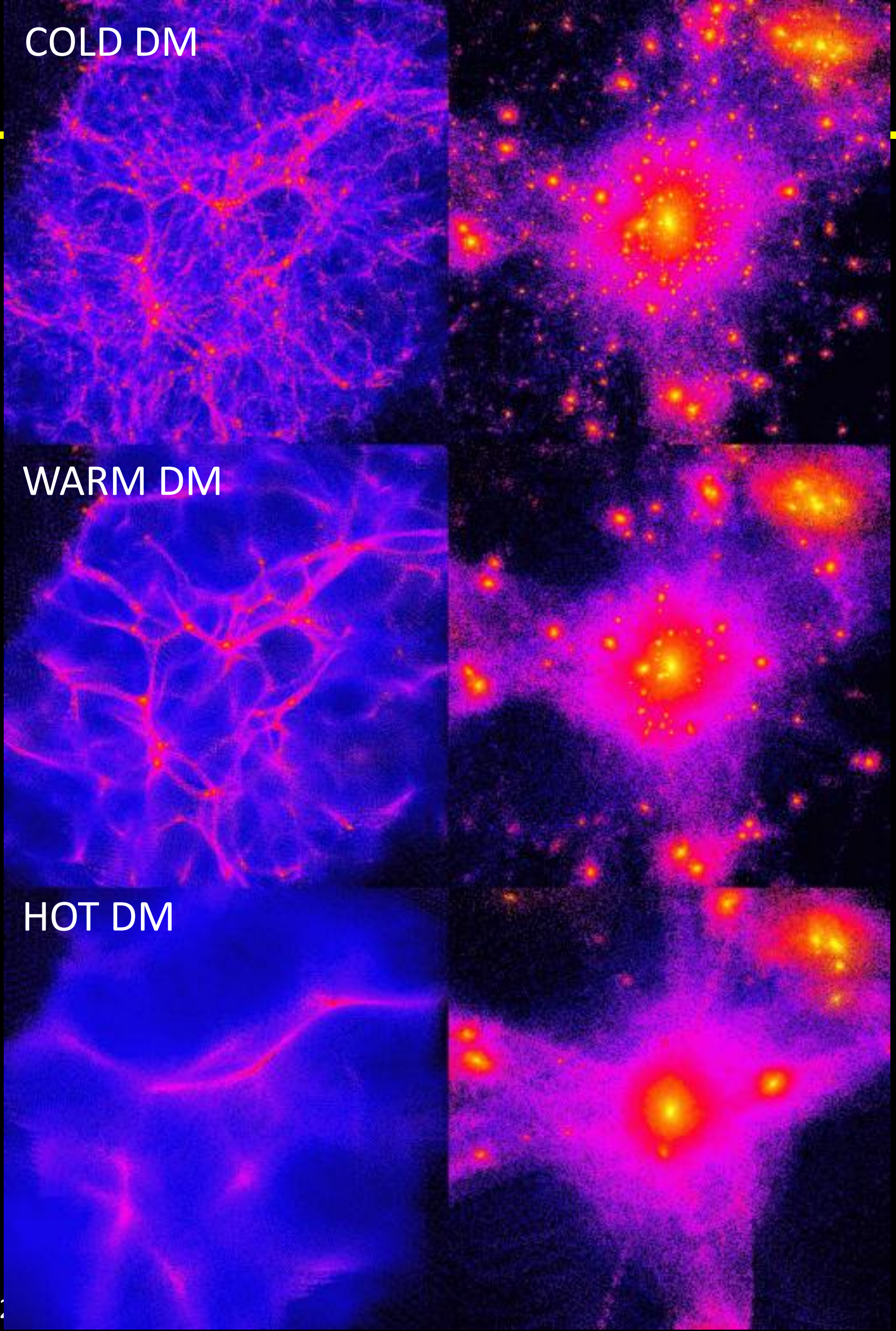
# DM Evidence: Large Scale Structure



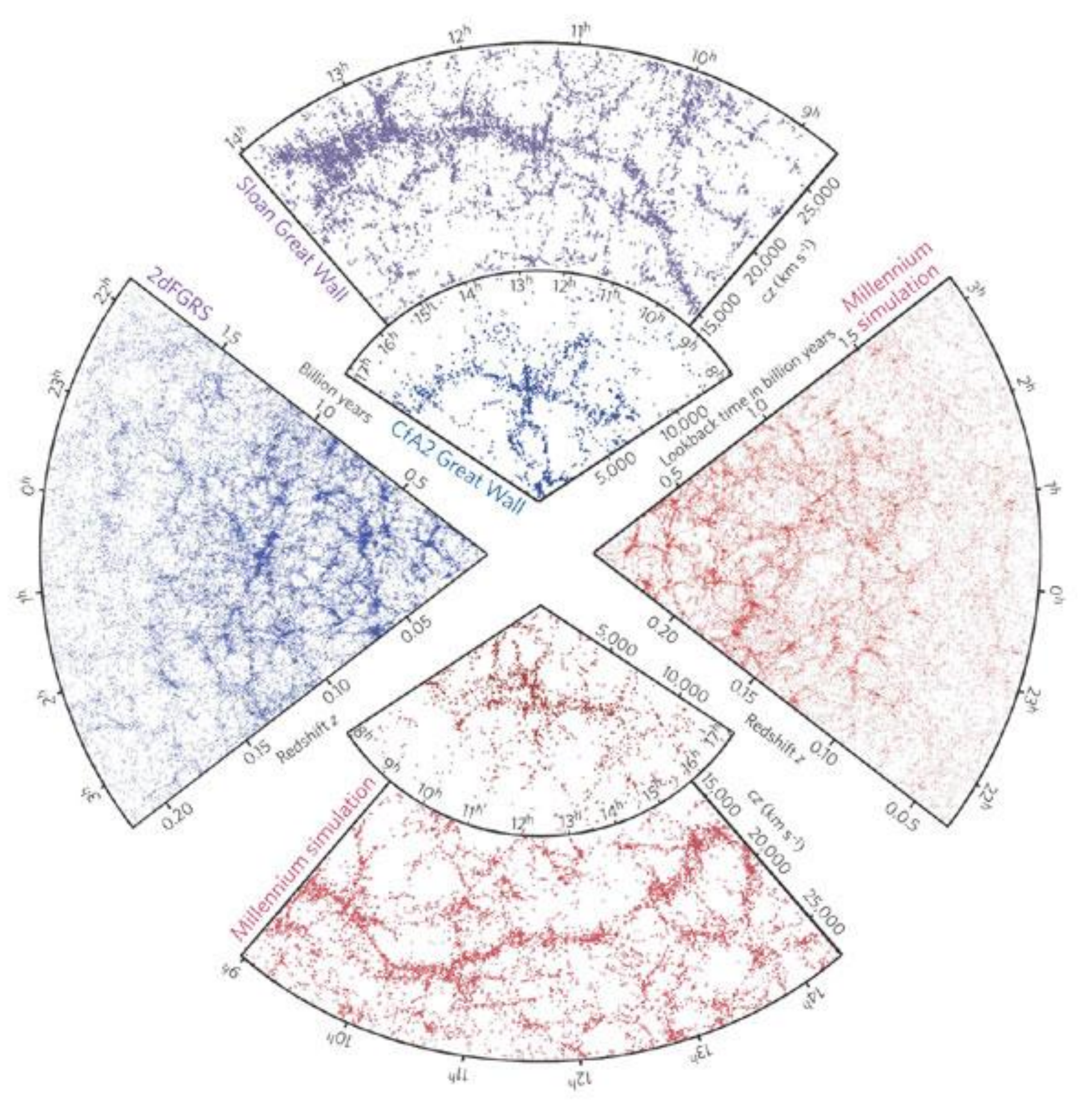
# DM Evidence: LSS

Different matter contents produce different structure levels in the universe



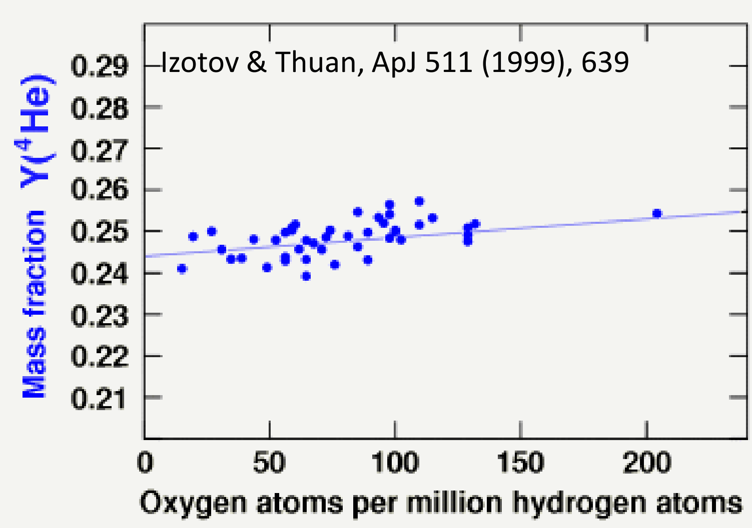
# DM Evidence: Large Scale Structure

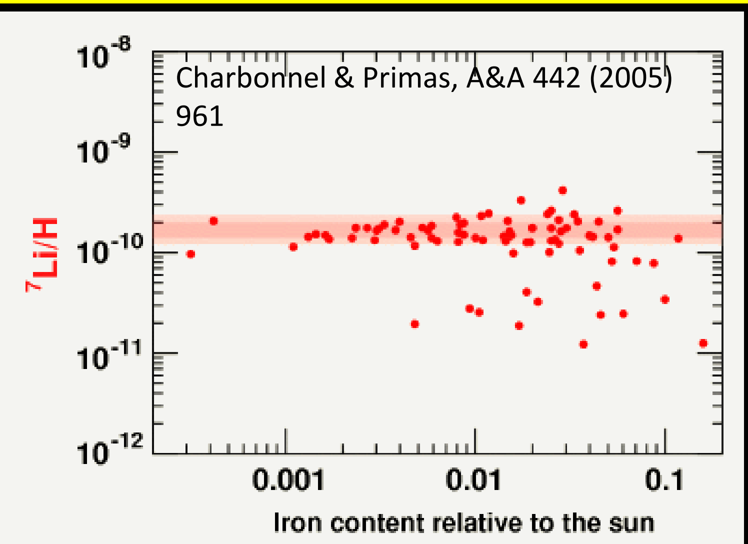


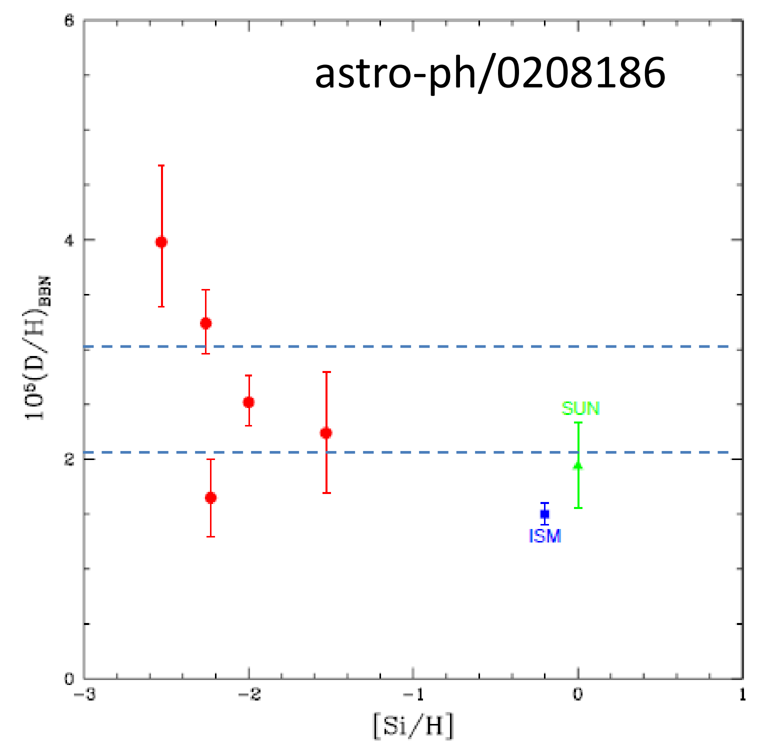

The standard model of cosmology, LCDM, **requires ~75% dark energy and ~25% cold dark matter** to describe the structure formation of the universe

# Non-baryonic DM: Nucleosynthesis

During a bit more than a quarter of hour, the primordial light elements did form (from ~3 minutes to ~20 minutes after BB)



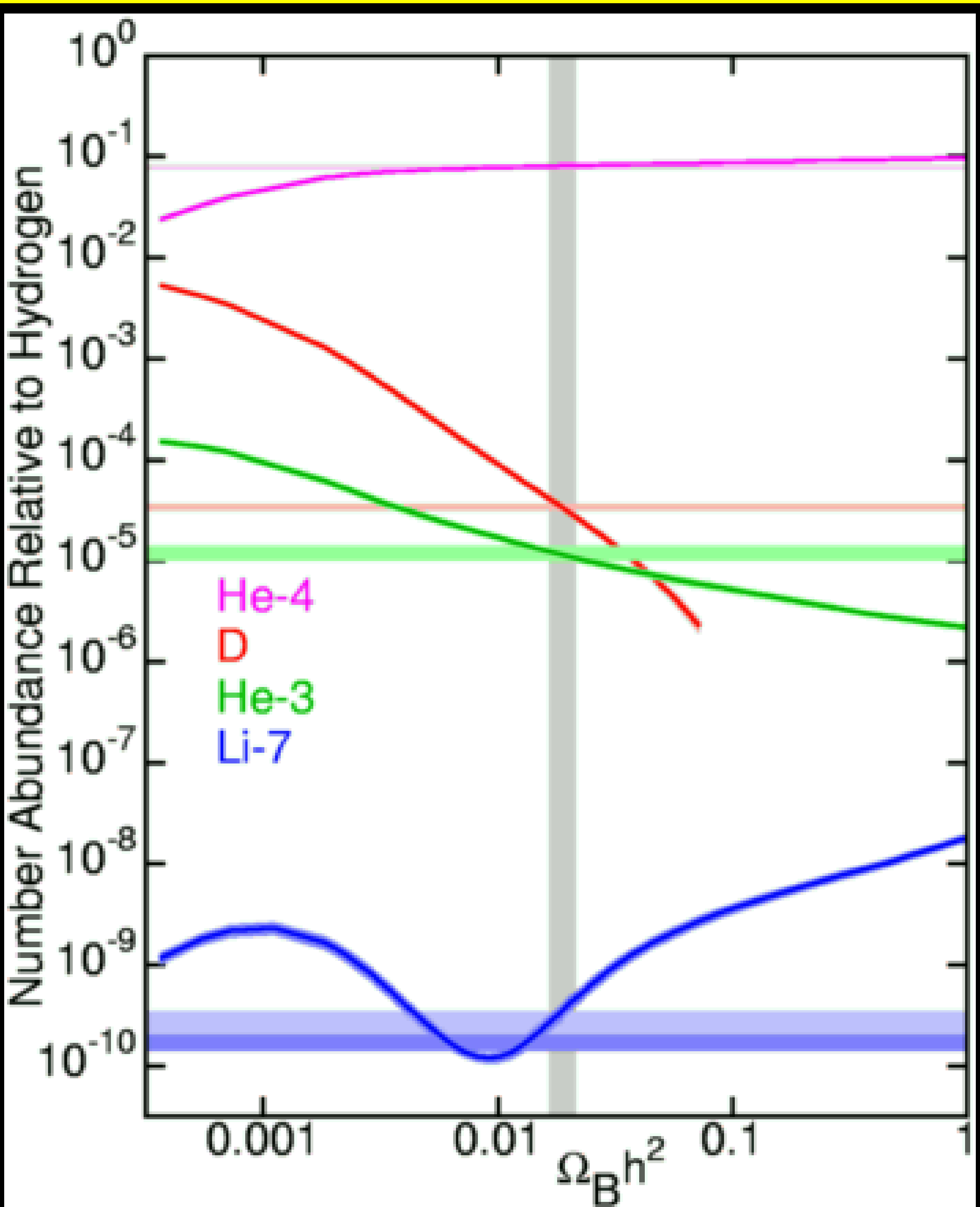




Measure abundances:

- D→ Absorption lines in QSOs
- $^4$He→ Extragalactic HII regions of low metalicity (O/H).
- $^7$Li→ Dwarf stars from the halo.
- Large systematic errors

# Non-baryonic DM: Nucleosynthesis




Controlled by the number of photons per baryon

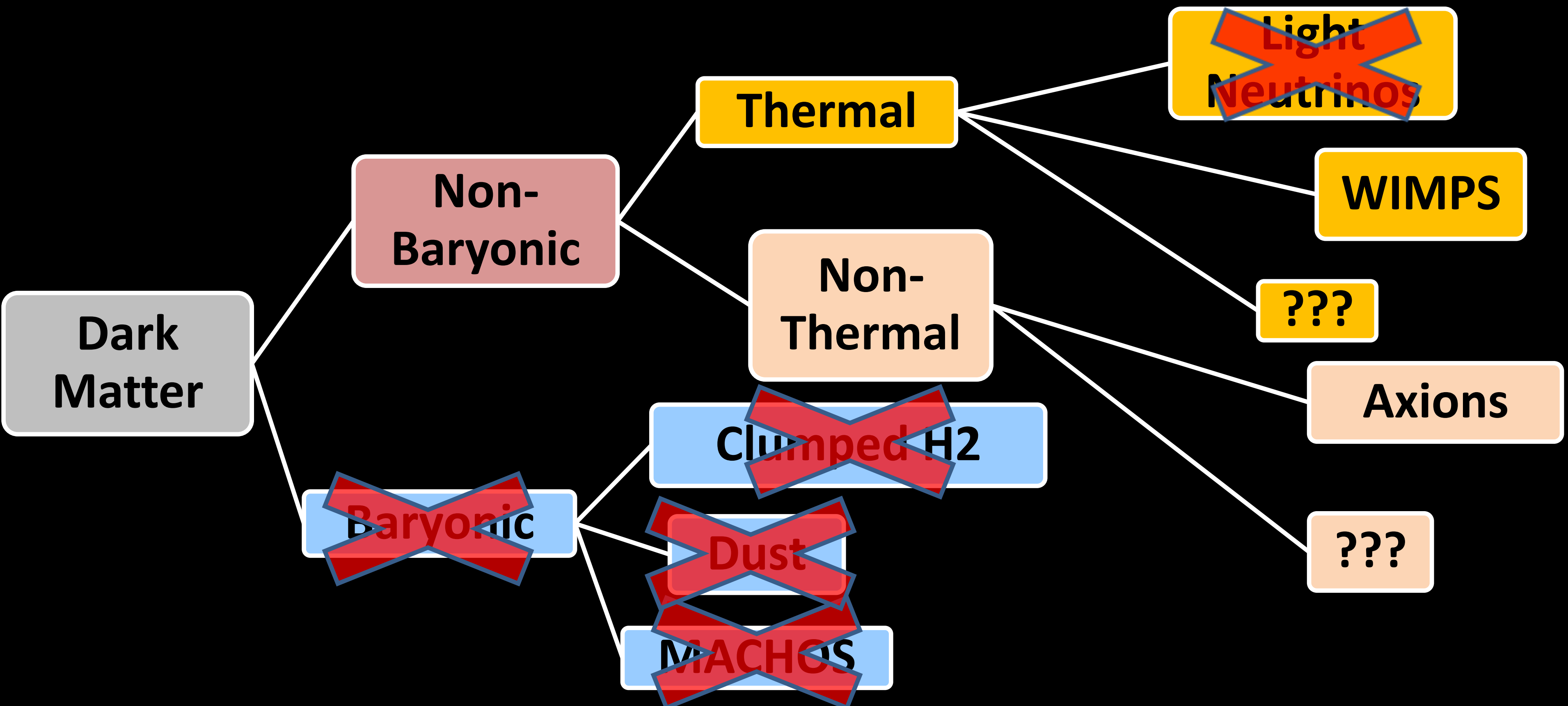
Physics of nucleosynthesis is well-known

Number of photons per baryon from CMB. Perfect match with the measured abundances!!!

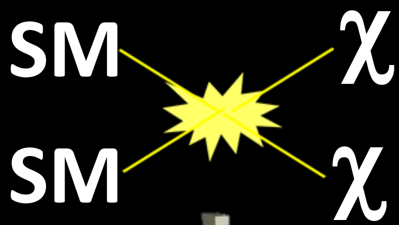
**DARK MATTER IS NON-BARYONIC!!!**

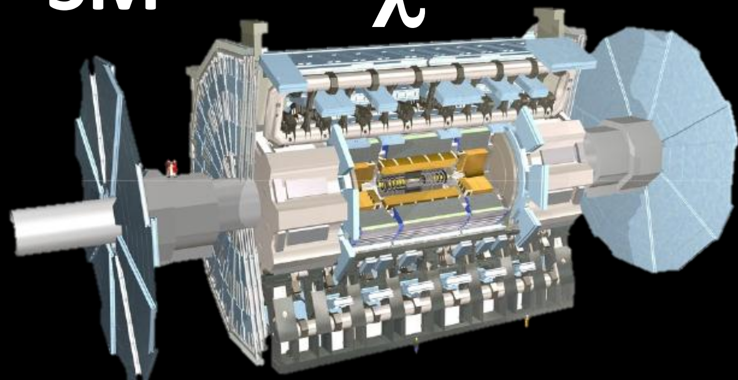
# What have we learnt about DM?

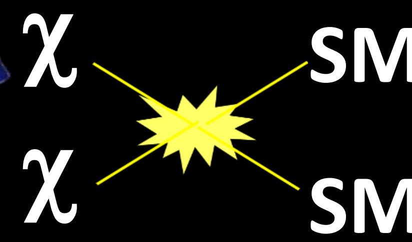
Since the growth of structure in the universe is bottom-up (clusters and superclusters are still forming today), **DARK MATTER IS COLD**: ***Non-relativistic, stable, neutral, weakly interacting particles***



# How to detect Dark Matter






**INDIRECT DETECTION:**

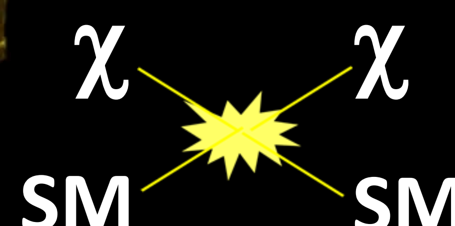
Measure gamma rays, neutrinos, positrons, antiprotons, anti-deuterons, etc from DM annihilation

**PRODUCTION:**

Produce and measure DM from partcle colliders

**DIRECT DETECTION:**

Measure DM scattering off targets in detectors on Earth



# Production of Dark Matter

## NO HINTS of Dark Matter at LHC.

Very difficult to make a model independent search of dark matter particles at LHC. Mainly centered at SUSY models, and simplest SUSY models have been already excluded…

However , LHC can be very important to determine DM properties with precision after the detection.

**Any detection at LHC must be compatible with astrophysical and cosmological measurements** → Strong Consistency test, required to fully determine the DM identity

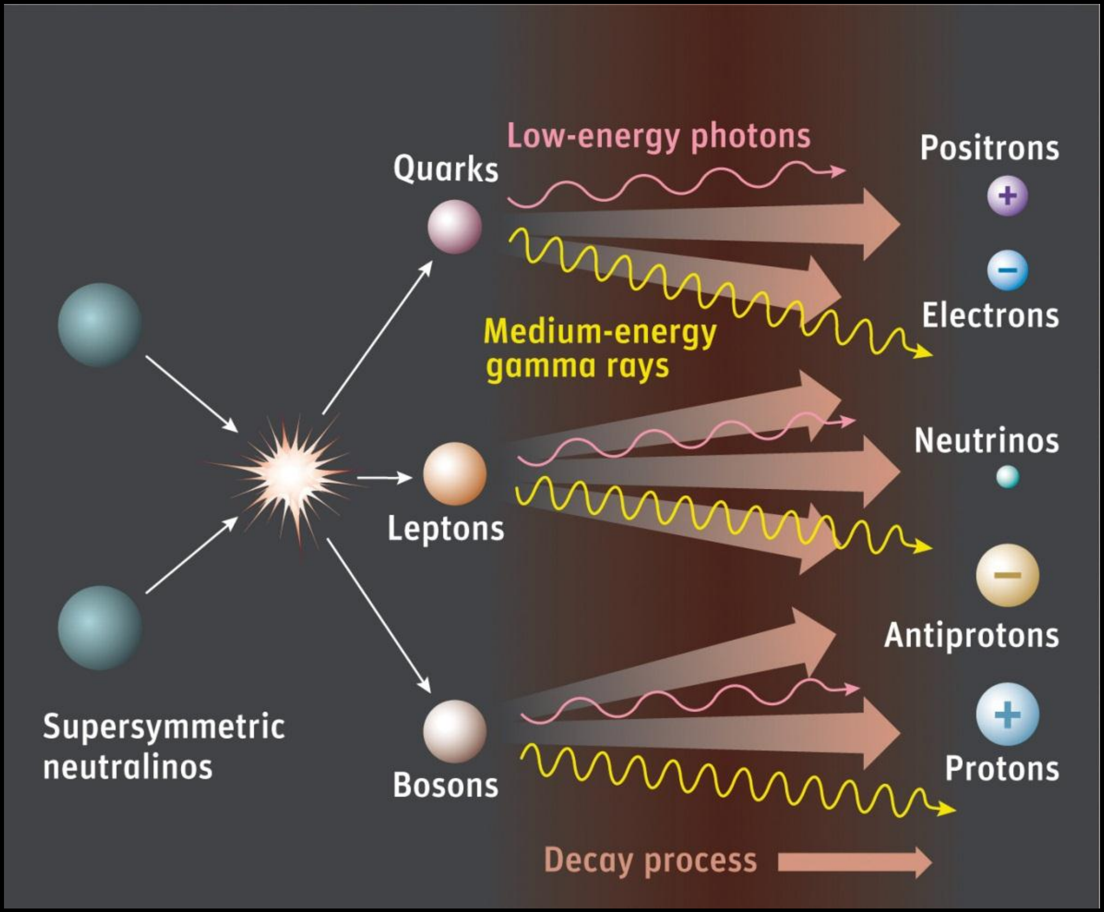
# Indirect Detection of Dark Matter

**At this moment, NO CONFIRMED DETECTION: Set Constraints**

Gamma rays (**Nothing**): Magic, Hess, Veritas, Fermi

Neutrinos (**Nothing**): IceCube, Antares…

Charged Particles (**Some hints, not confirmed…. Yet?**): Pamela, AMS..



# Indirect Detection: Gamma Rays



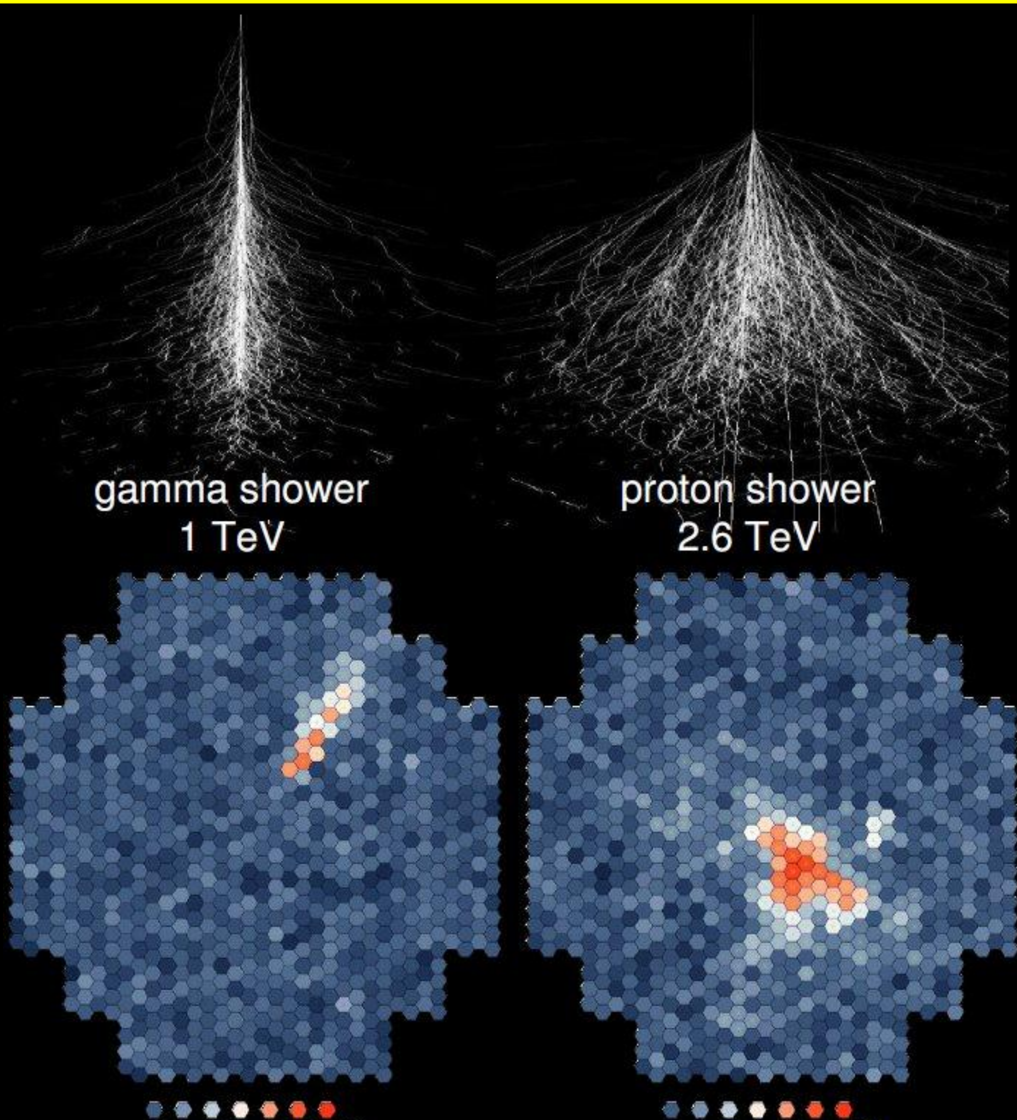

Cerenkov telescopes: detect Gamma rays through Cerenkov light of the atmospheric cascades

Photomultiplier cameras

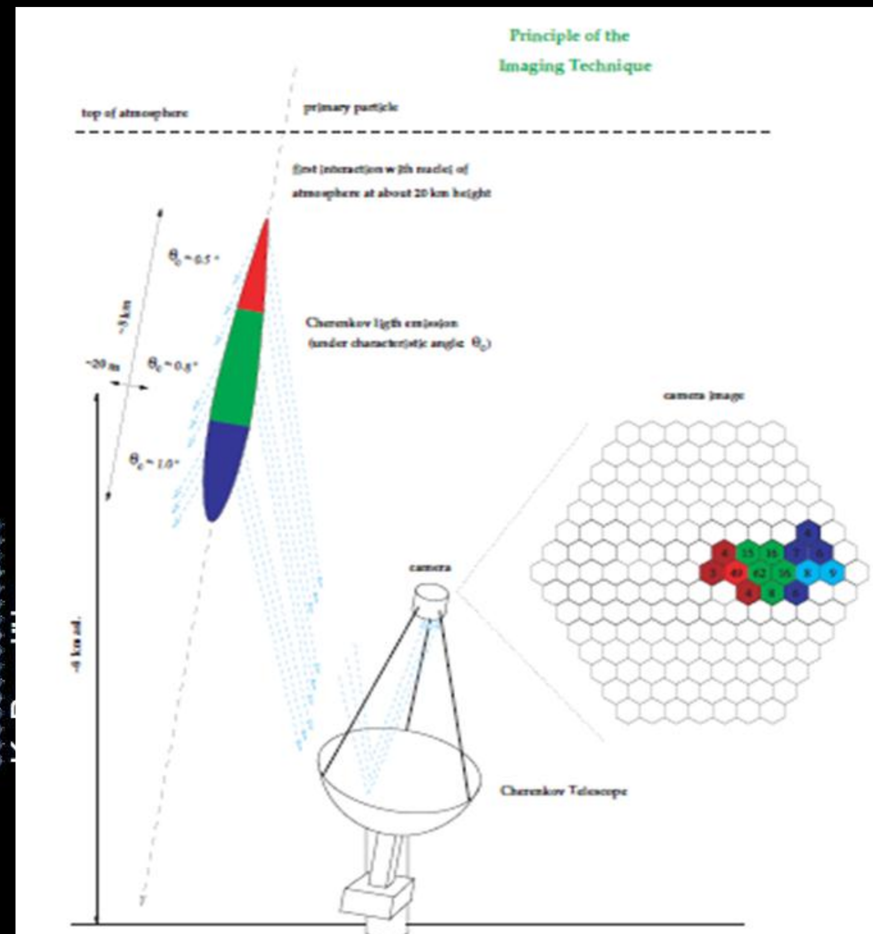
- **E: 50-100 GeV - ~10 TeV**
- **Effective area: ~$10^5$ $m^2$**
- **Angular resolution: <0.1°**
- **Duty cycle: 15%, FoV: 5°**
- **Pointed observations (<10% of sky), ~120 sources**
- **Hadron background**

Detect gamma rays from regions that are candidates to contain a large amount of dark matter: Center of the galaxy, dwarf galaxies…

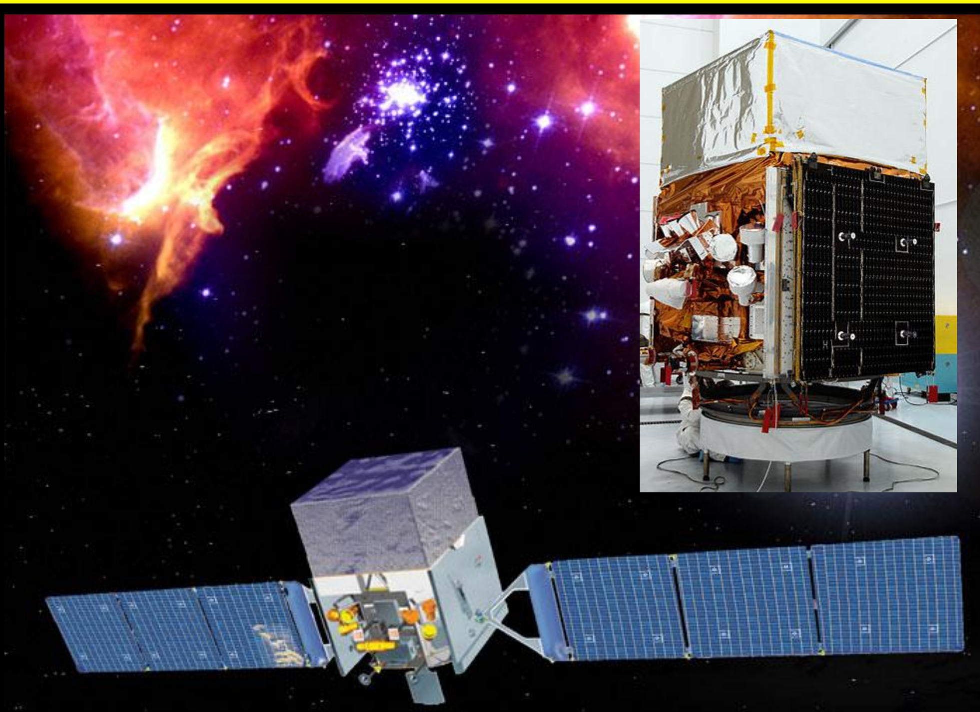
# Indirect Detection: Gamma Rays

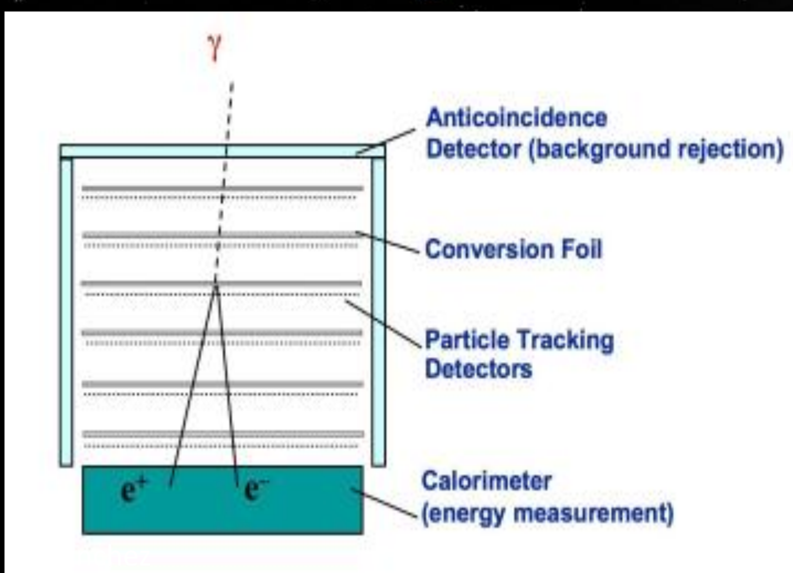



## DETECTION PRINCIPLE



# Indirect Detection: Gamma Rays






The other possibility is to measure gamma rays from space, without atmospheric effects: FERMI TELESCOPE

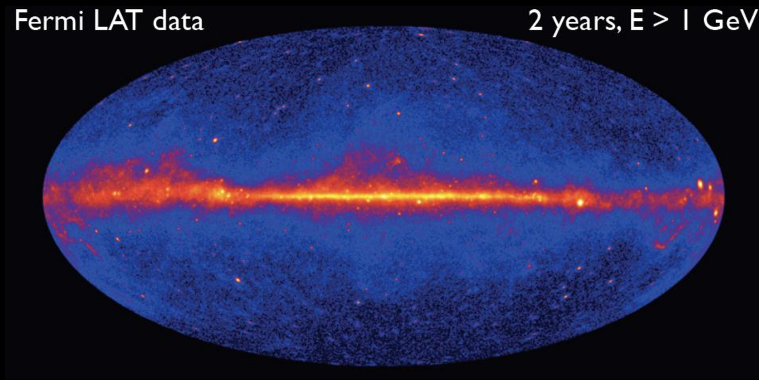
Launched on 11 june 2008, with an initial mission of 5 years

Covers the energy range from 20 MeV to 300 GeV

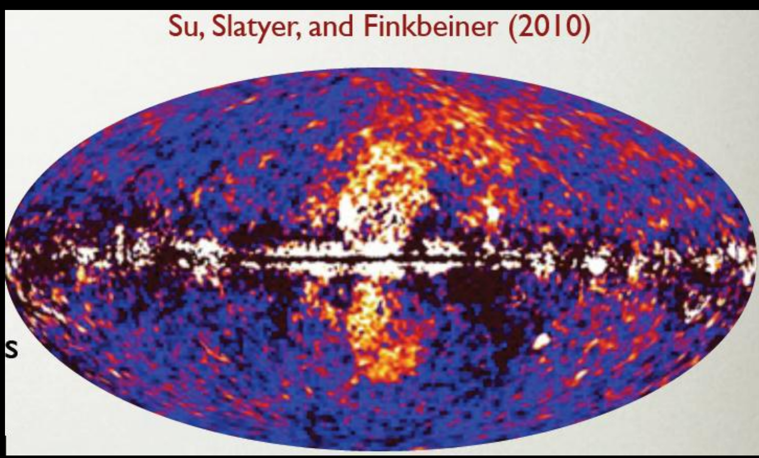
FoV of 20% of th whole sky, and scans continuosly, covering the whole sky every 3 hours

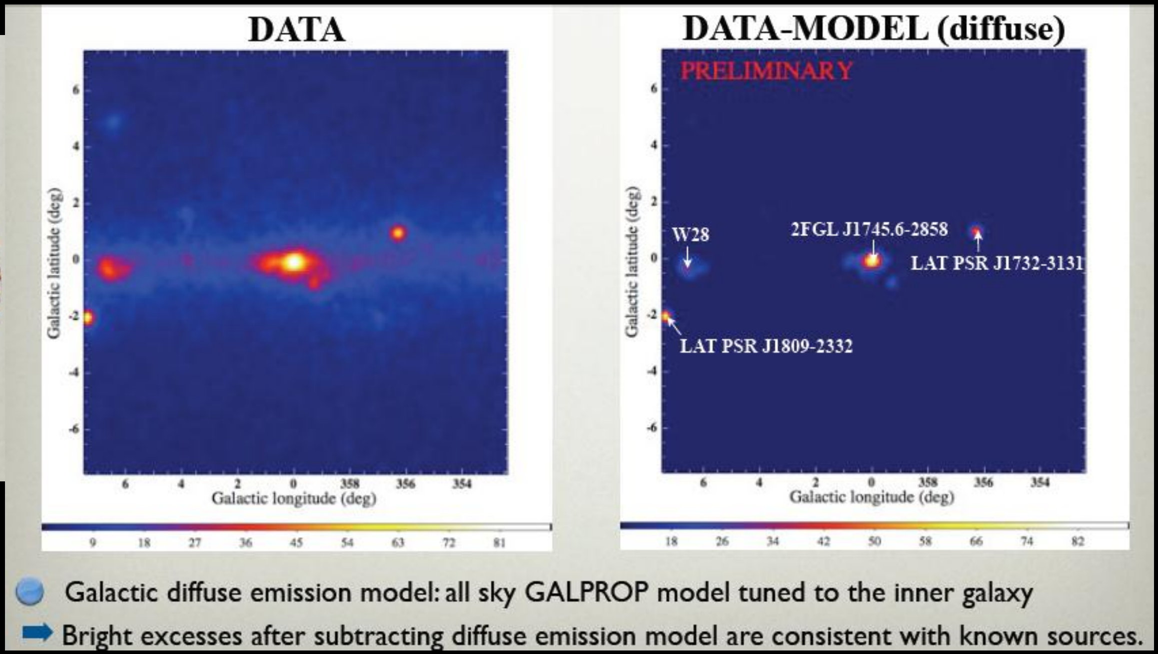
Detects photons by it conversion in pairs within the detector. Angular resolution : 3 degrees at 100 MeV and 0.04 degrees at 100 GeV

# Indirect Detection: Gamma Rays



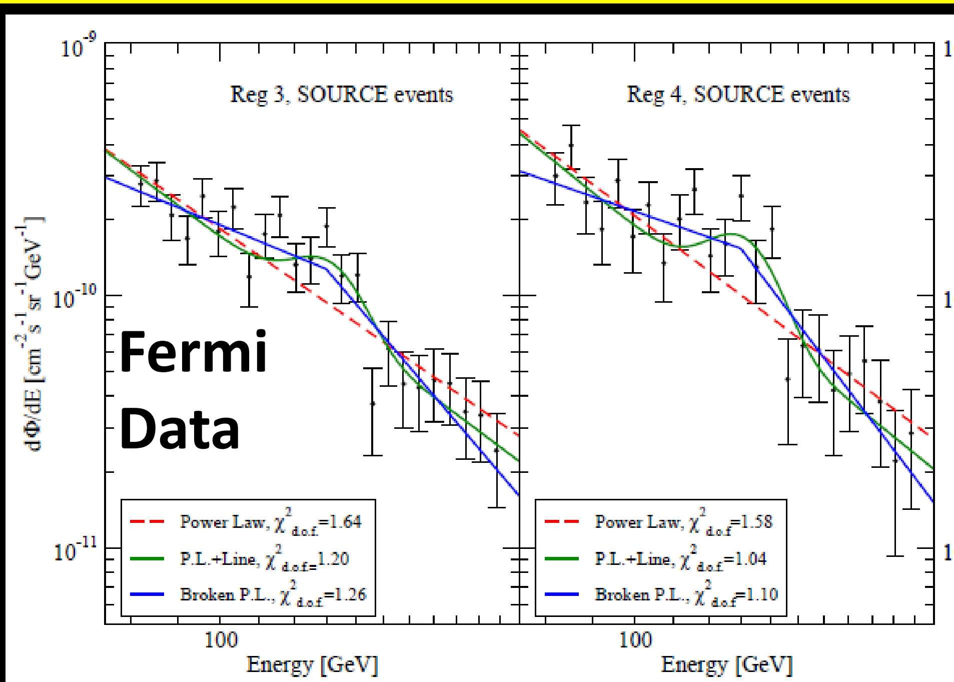

Observations compatible with known sources. No dark matter

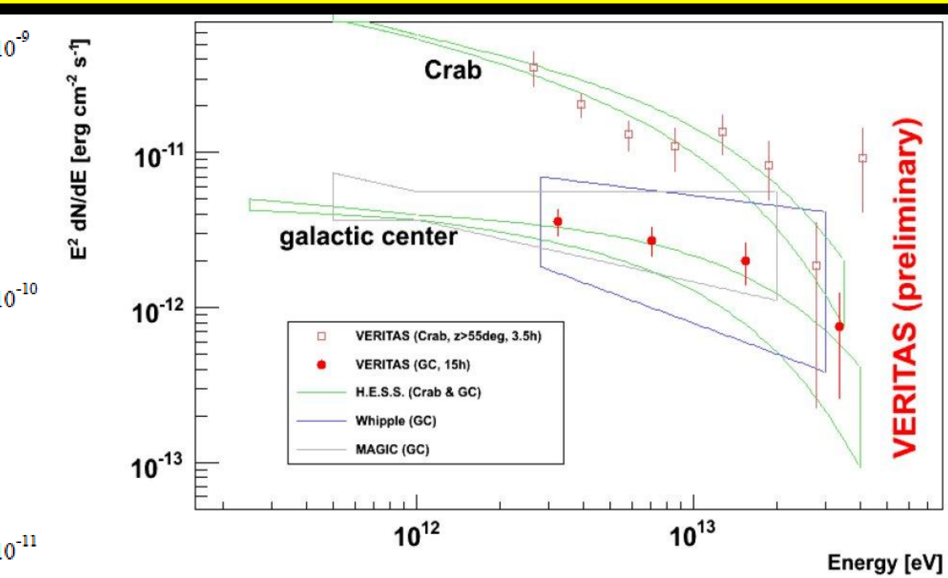


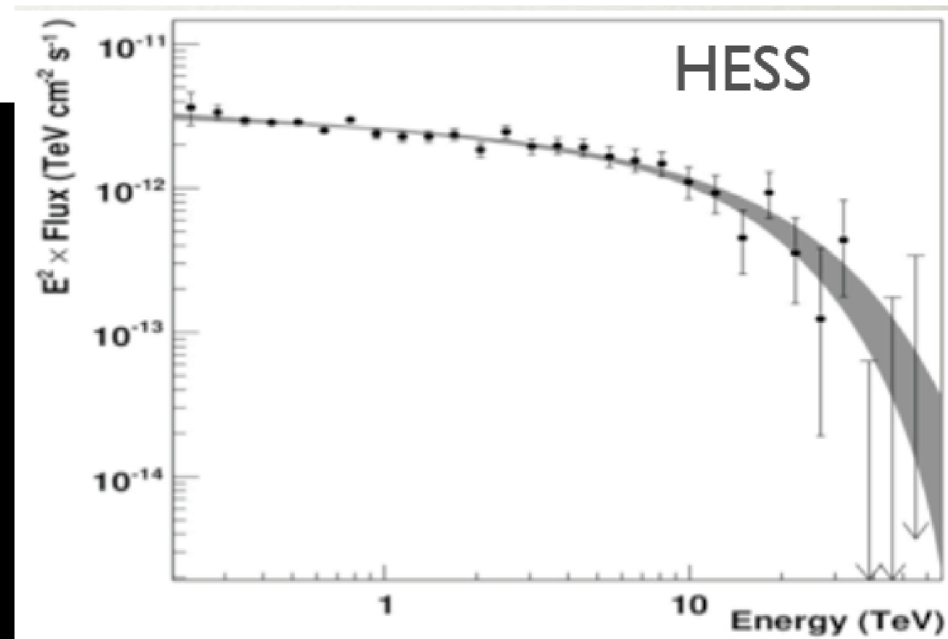




*Gamma Ray lobes in our galaxy discovered by Fermi. Relics of an ancient active galaxy phase??*

# Indirect Detection: Gamma Rays




Some claims of a line at 130 GeV in fermi data.

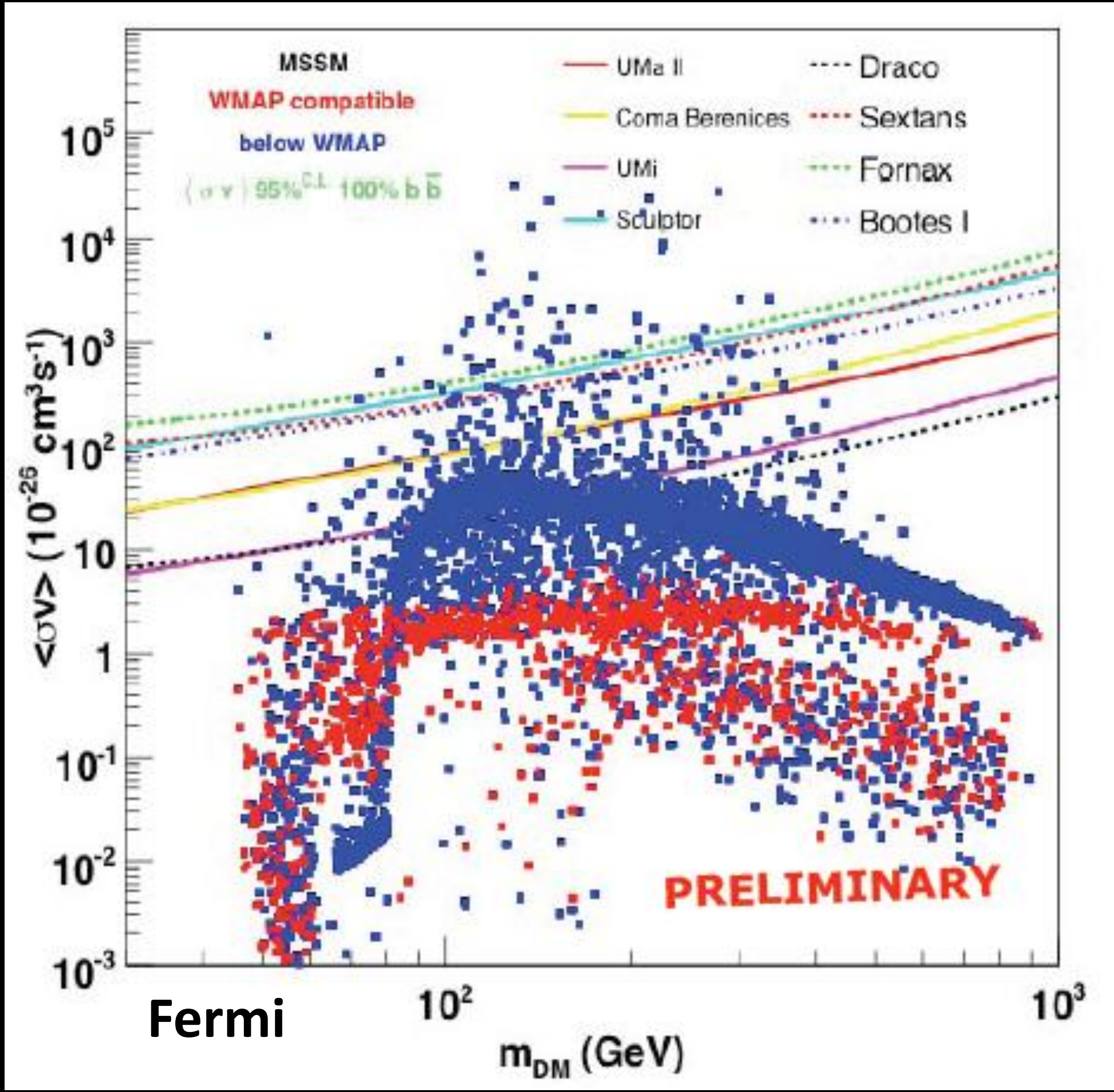
Not confirmed by fermi collaboration.

No dark matter

# Indirect Detection: Gamma Rays

Result observing 10 dwarf galaxies

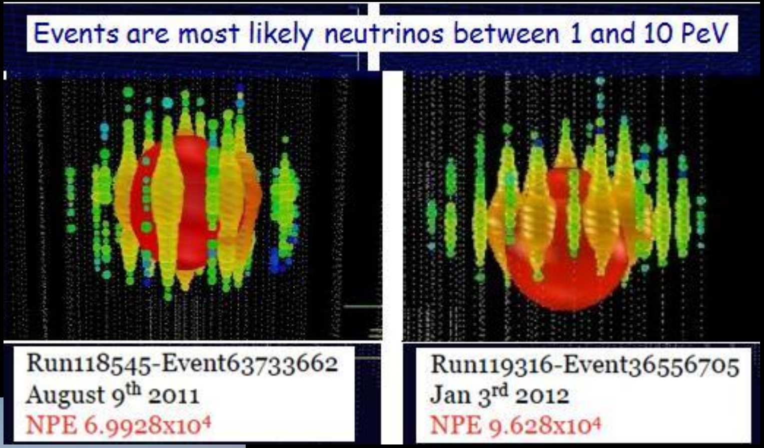
**No excess in any observation. No dark matter**

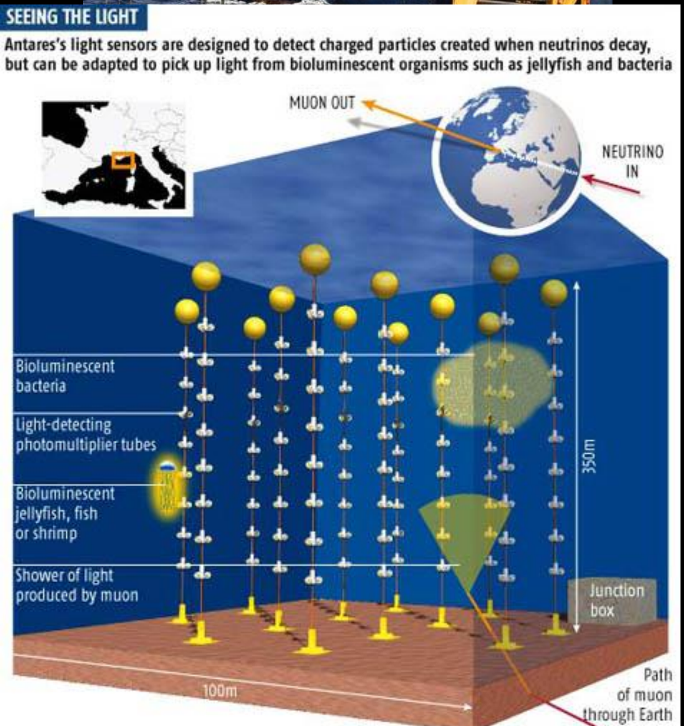


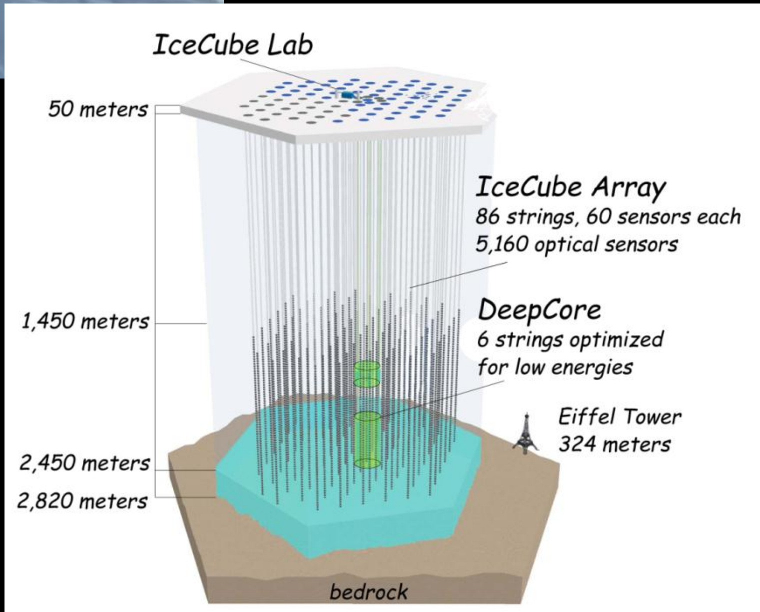
# Indirect Detection : Neutrinos

**NO SIGNAL OF DARK MATTER**

Detect the cerenkov light of neutrinos in ice (IceCube) or water (Antares) Only 2 neutrinos detected coming from space in Icecube .

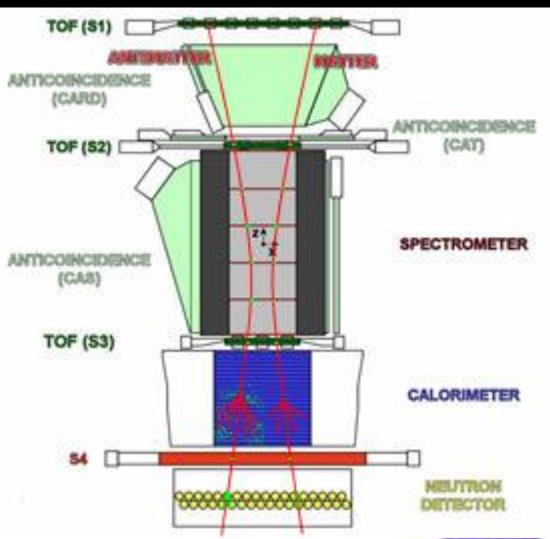


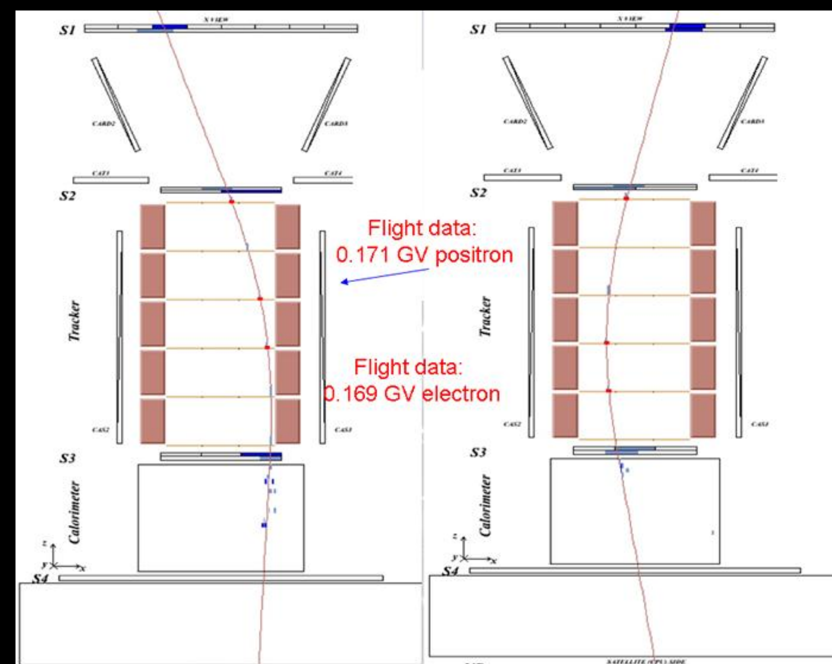



# Indirect Detection: Charged Particles

## PAMELA is a Particle detector in space
## HINTS OF DARK MATTER?

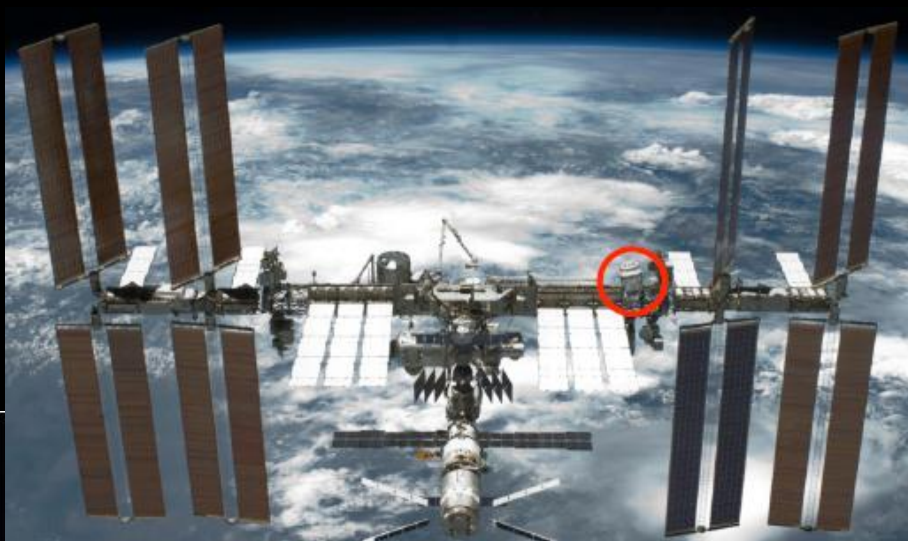


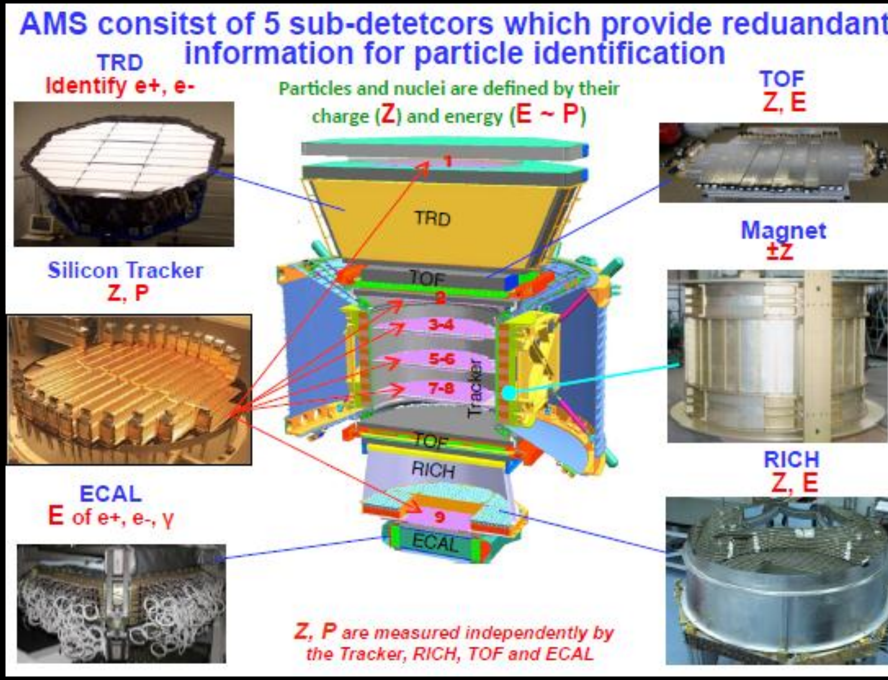

**PAMELA was put in an elliptical orbit at an altitude between 350 and 610 Km, onboard of the Resurs-DK1 Russian satellite by a rocket Soyuz, on the 15th of June 2006.**

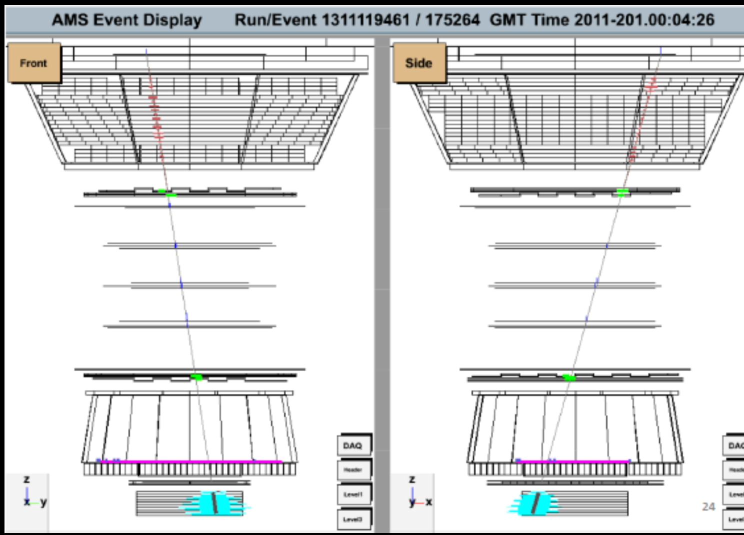


# Indirect Detection: Charged Particles

AMS is the next generation. On the ISS since may 2011, and taking data



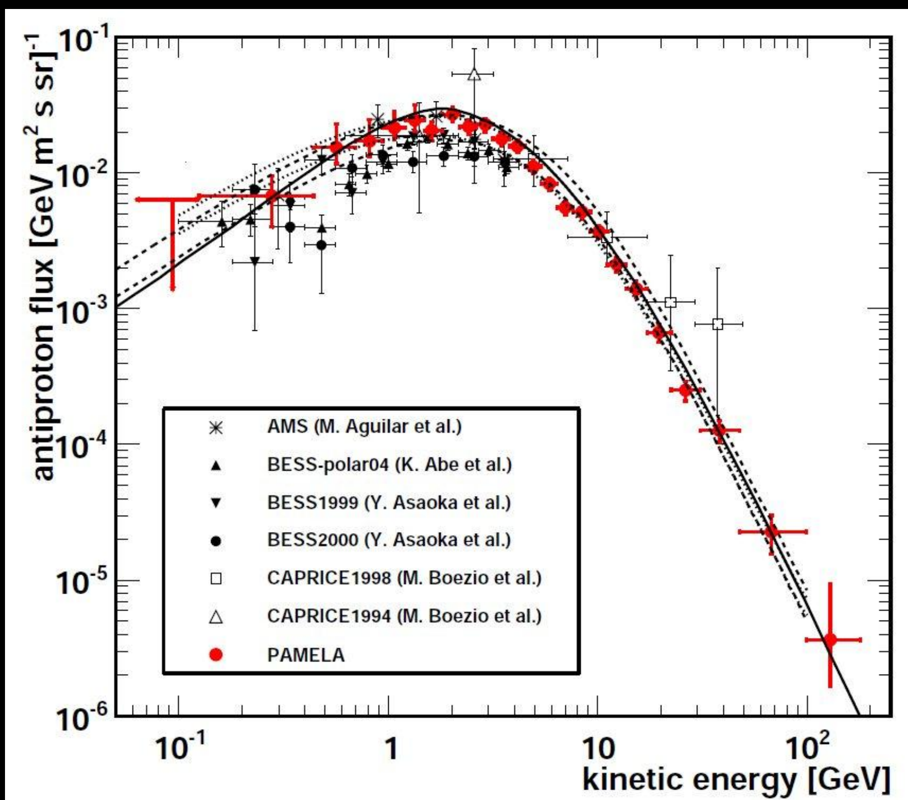



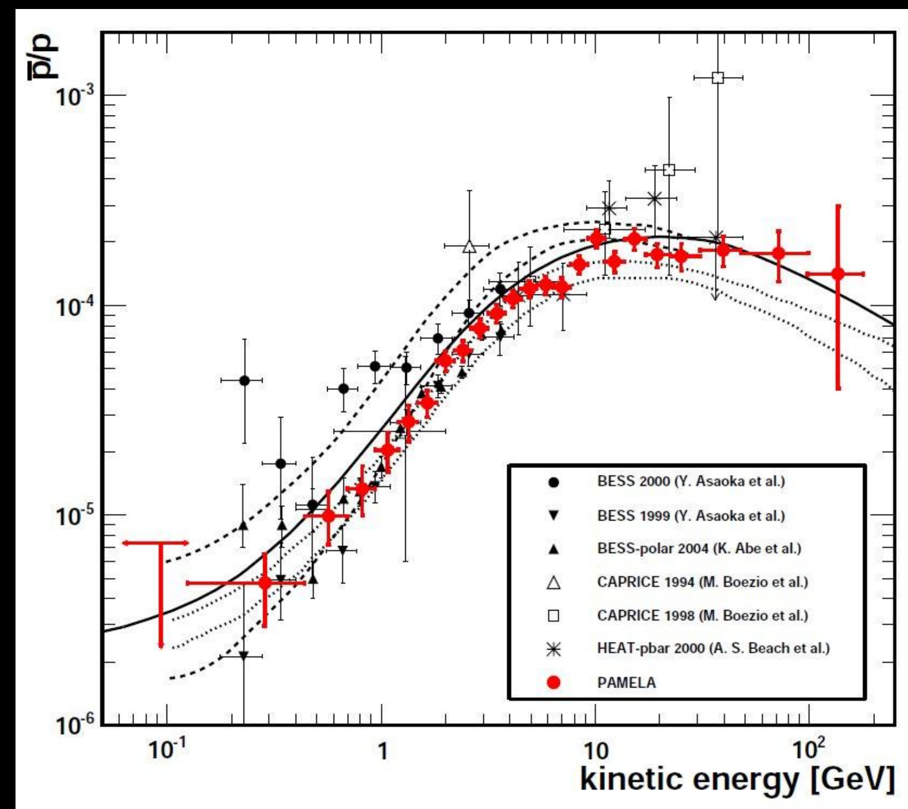



# Indirect Detection: Charged Particles

## Pamela results on antiprotons: No excess

## NO DARK MATTER

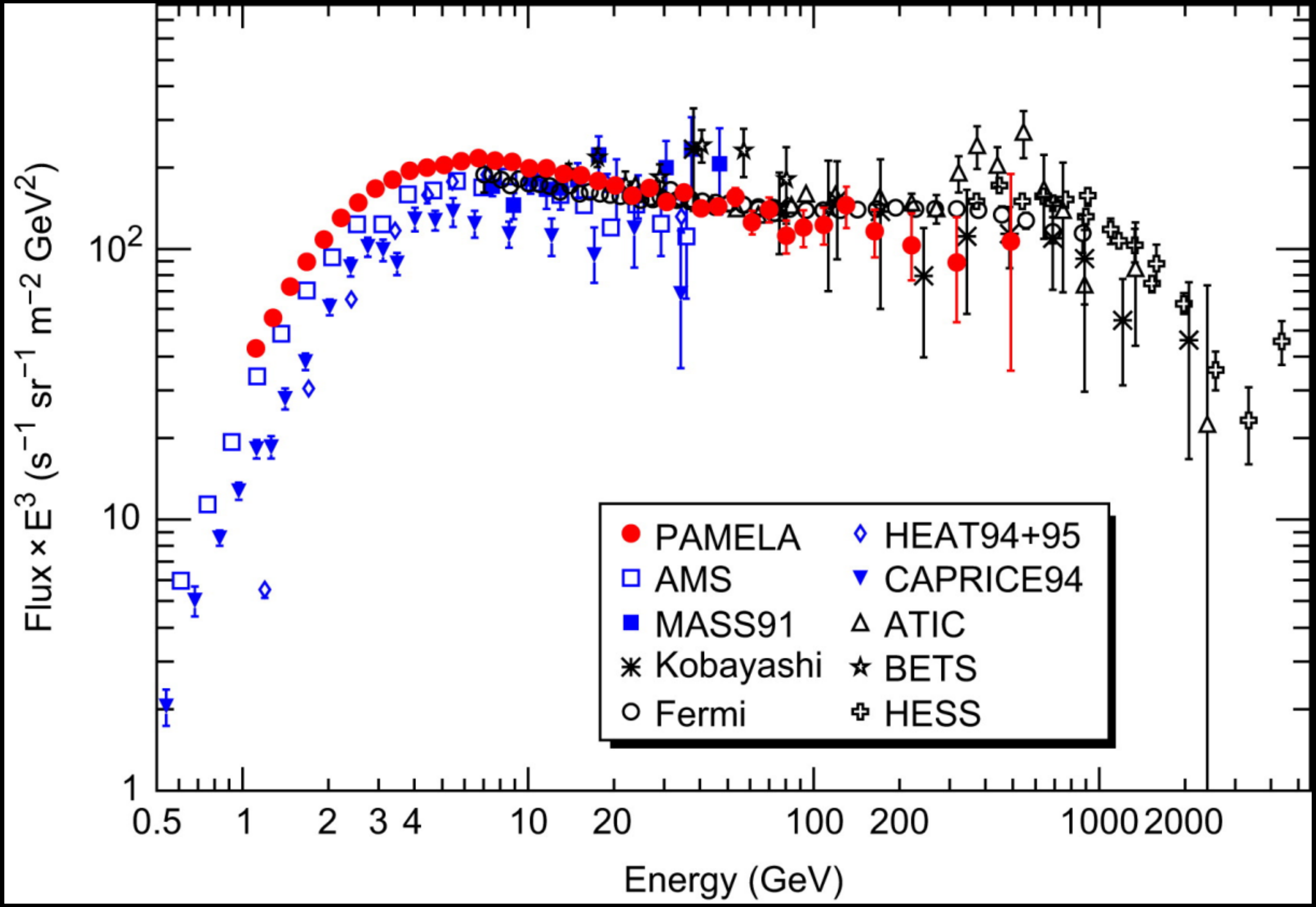


# Indirect Detection: Charged Particles

## Electrons plus positrons. No excess

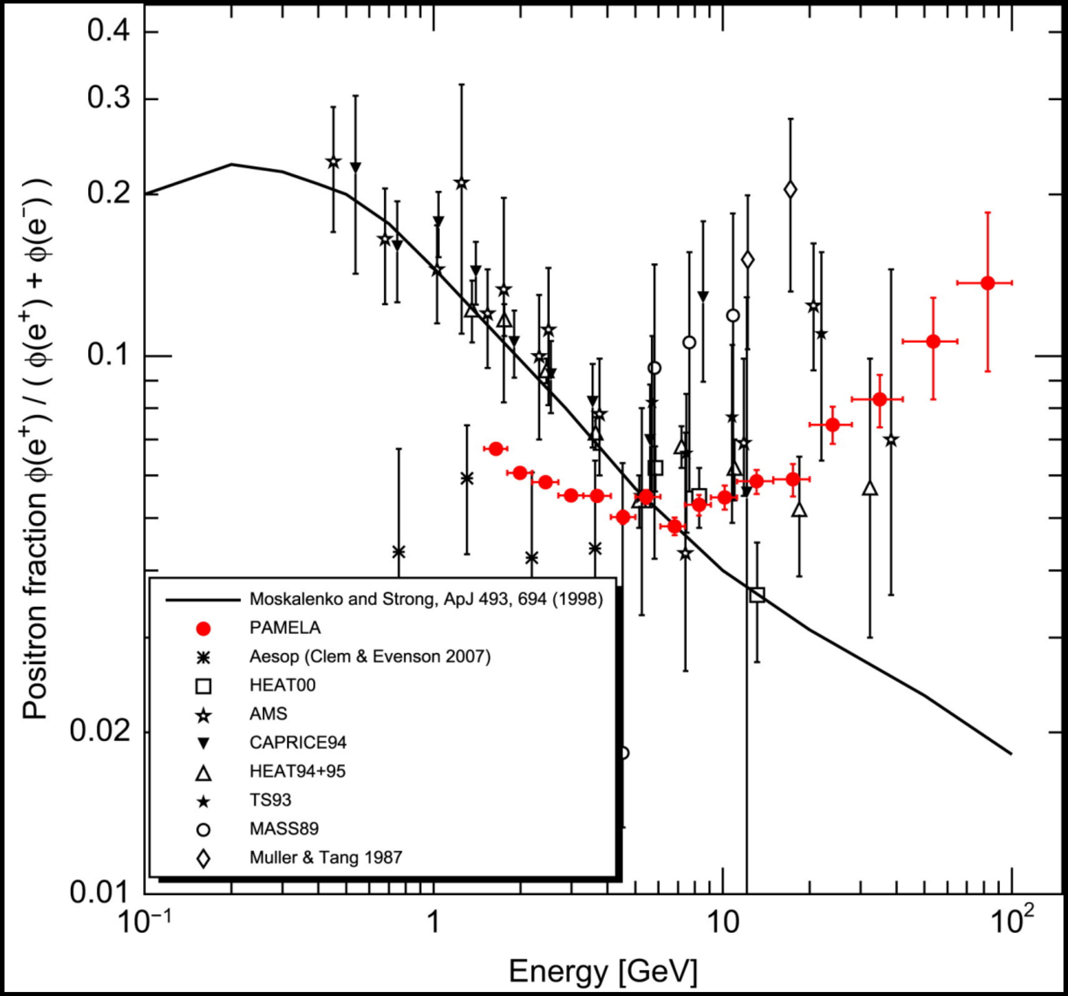
## No Dark Matter



# Indirect Detection: Charged Particles

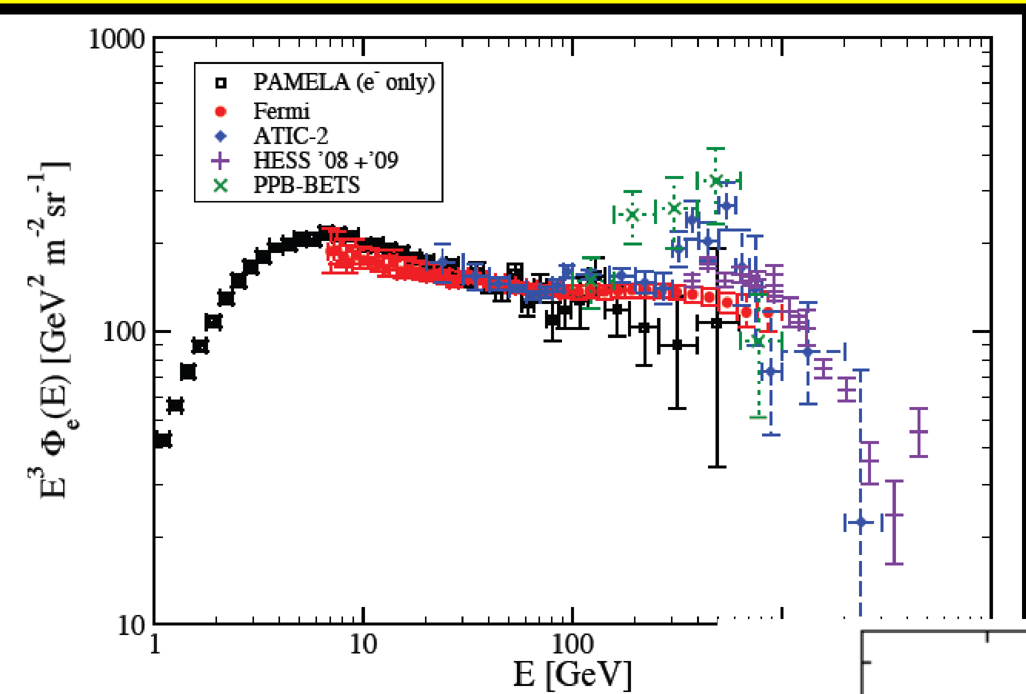
## Positron fraction measured in PAMELA

## Dark Matter hint???



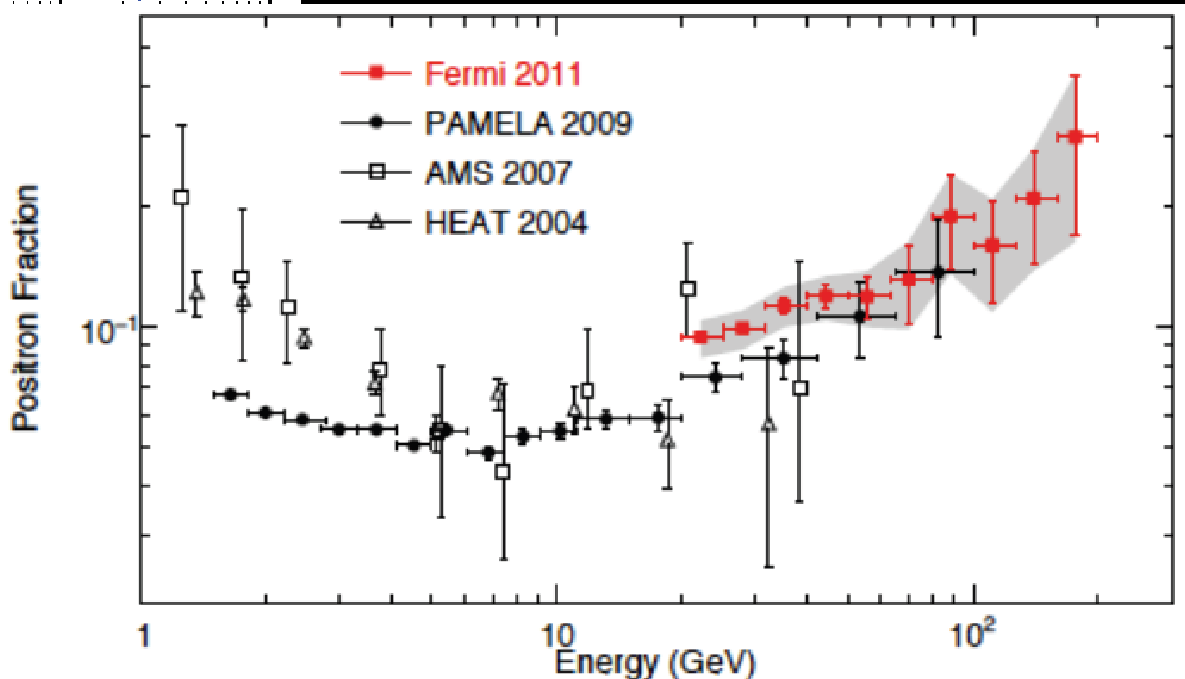

**It´s possible, AND…**

# Indirect Detection: Charged Particles




**Fermi confirms PAMELA´s results !!!**

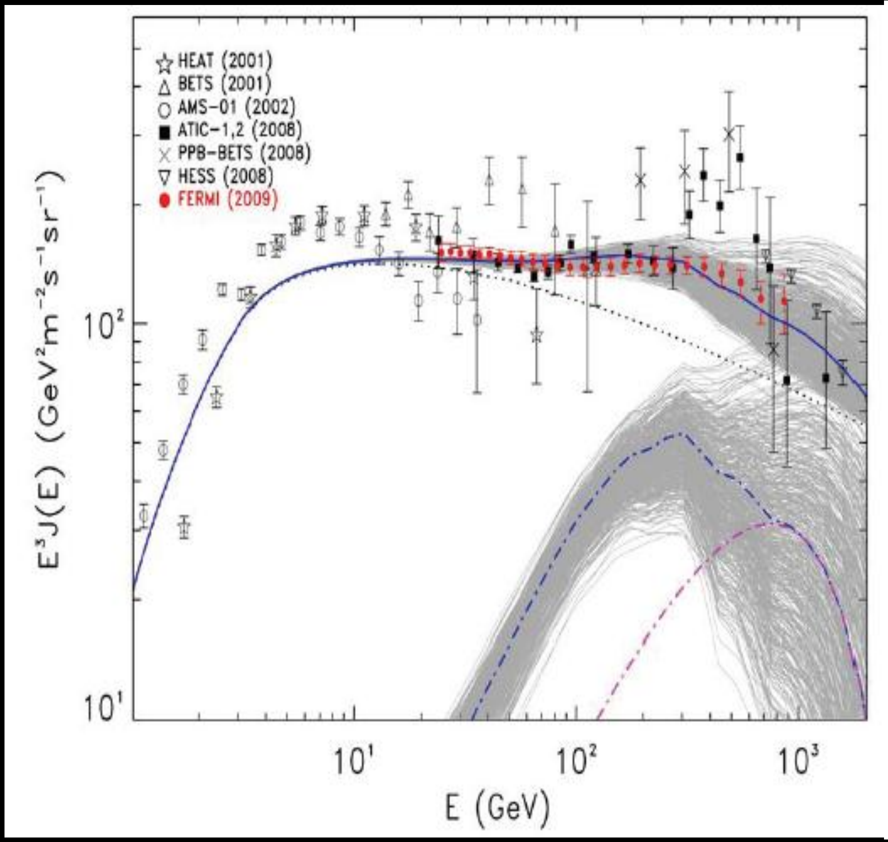
**BUT…**

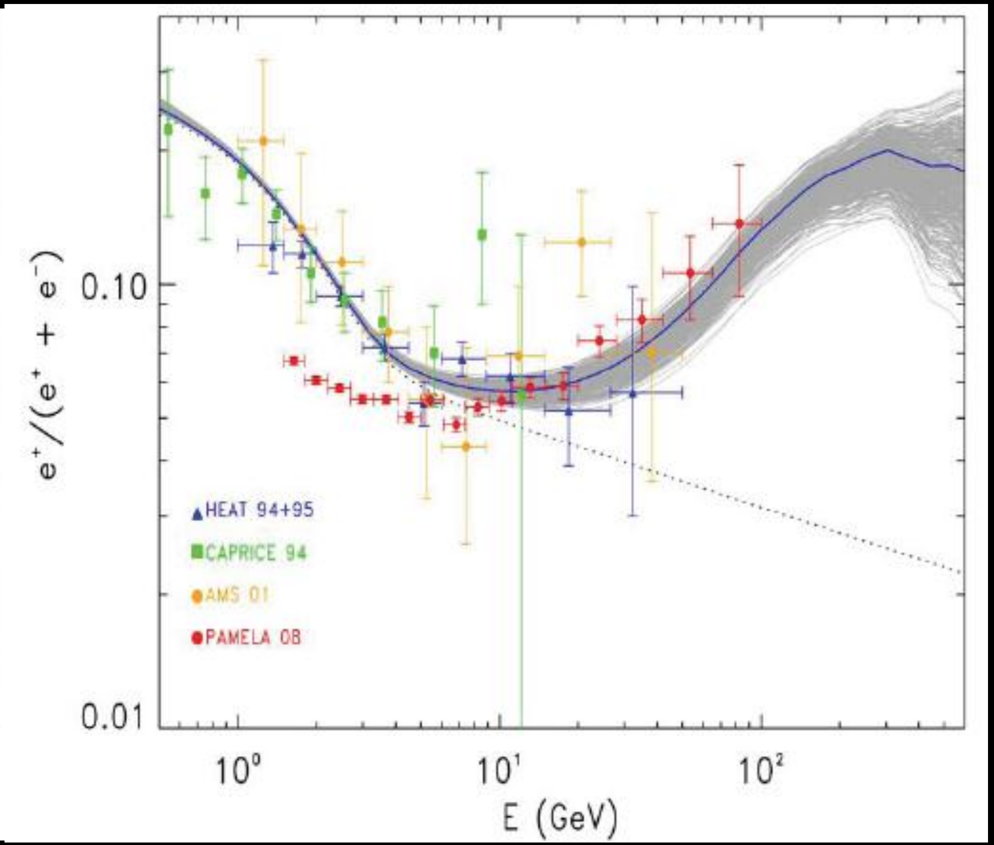



E. Sánchez

# Indirect Detection: Charged Particles

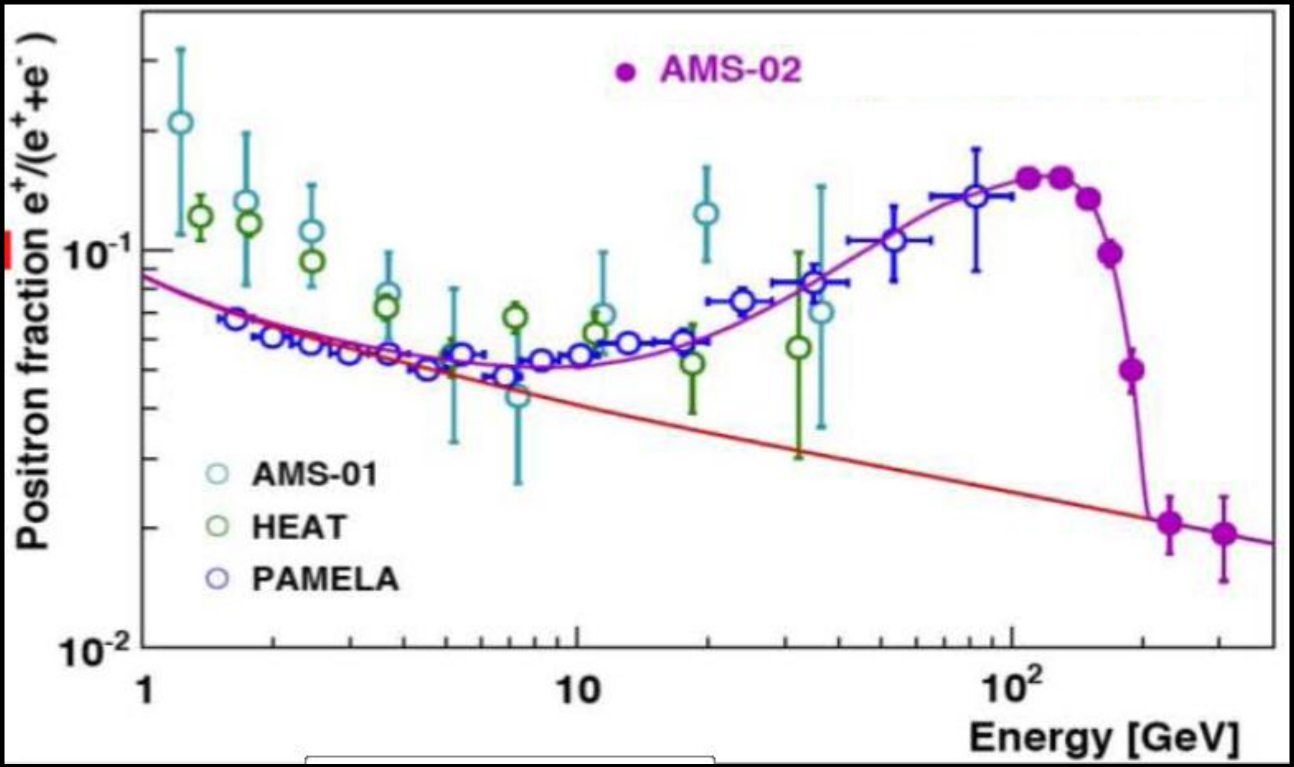
**Fermi confirms the PAMELA result, but**
**Under reasonable assumptions, electron/positron emission from pulsars offers a viable interpretation of data.**



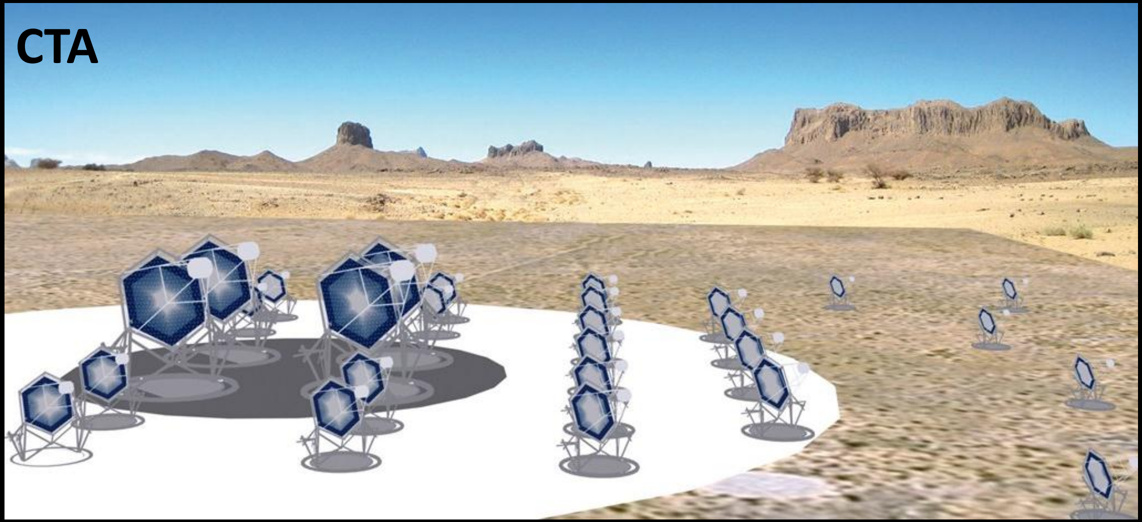



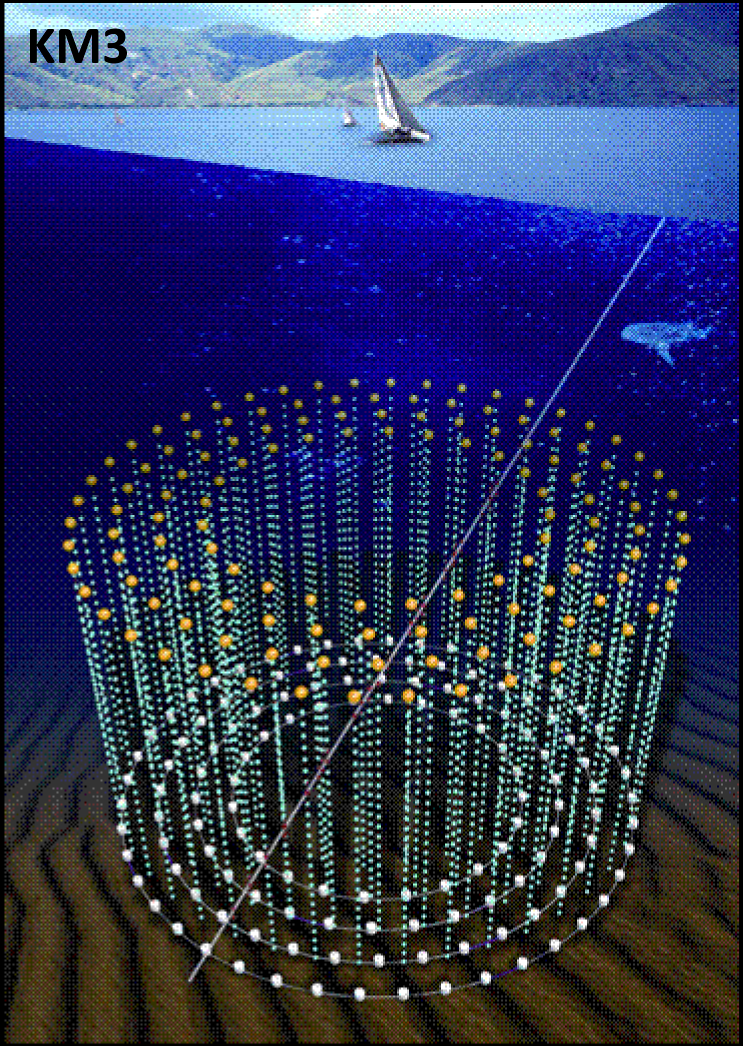
# Indirect Detection: Charged Particles

AMS should be able to confirm or exclude the dark matter signal



# Indirect Detection of DM:Future

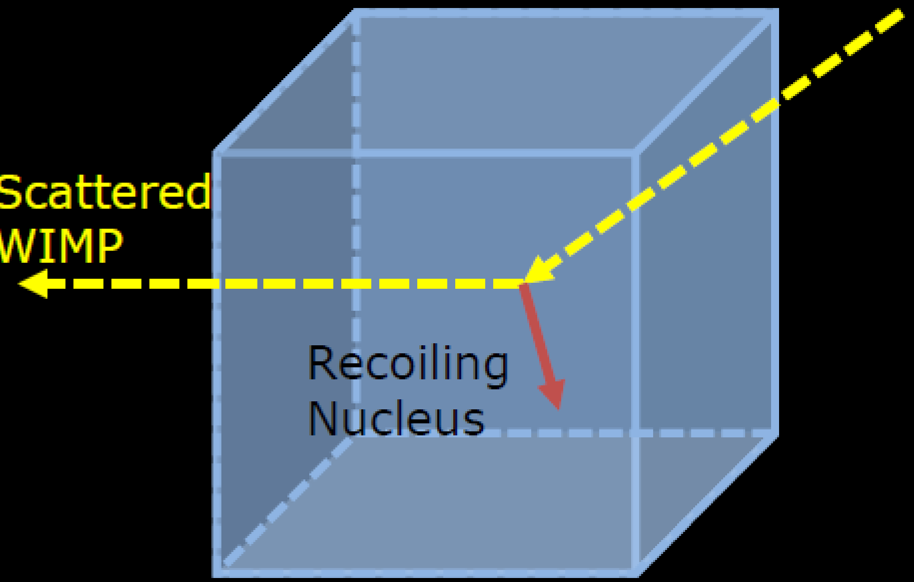



Next projects for indirect detection of dark matter are CTA for gamma rays and the cubic kilometer, KM3, for neutrinos.

# Direct Detection of Dark Matter

Elastic collisions with nuclei deposit a small, but detectable, amount of energy (Nuclear Recoil)




Interaction Rate:

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v\, f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

**EXPERIMENTAL SETUP**

Target Material (sensitivity to spin-dependent and -independent couplings)

Detection threshold

**ASTROPHYSICAL PARAMETERS**

Local DM density

Velocity distribution factor

**THEORETICAL INPUT**

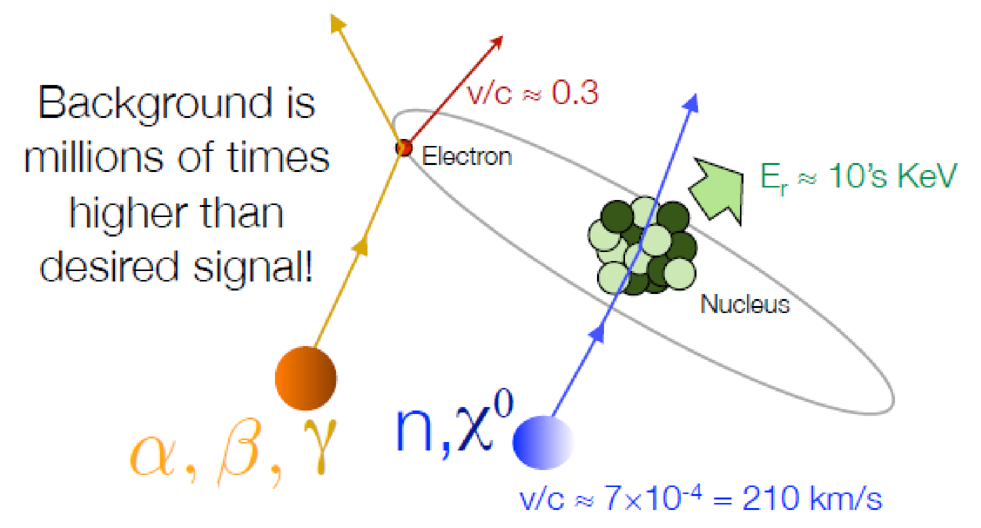
Differential cross-section (WIMP-quark)

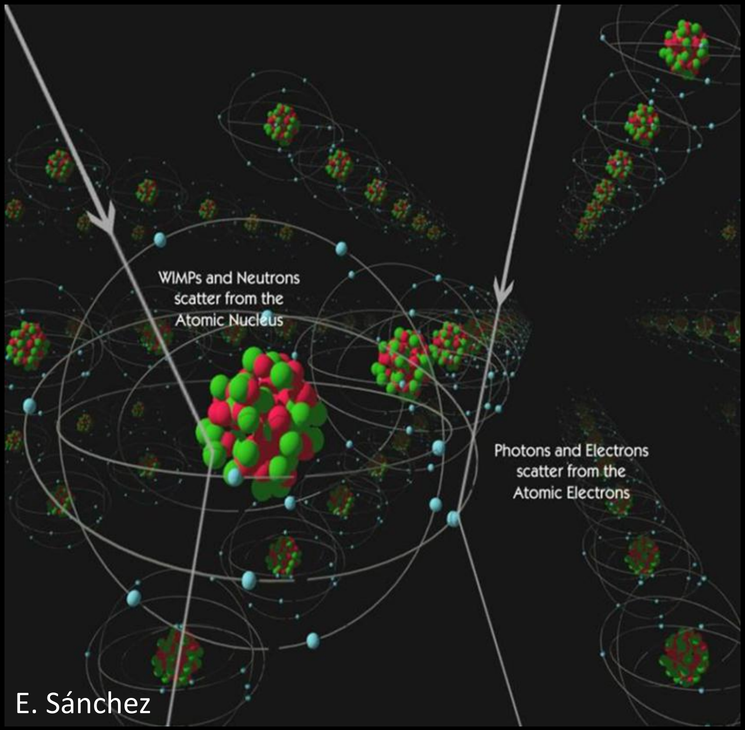
Nuclear uncertainties

# Direct Detection of Dark Matter

WIMPs (and neutrons) scatter off nuclei and many background sources (gammas, electrons) scatter off electrons

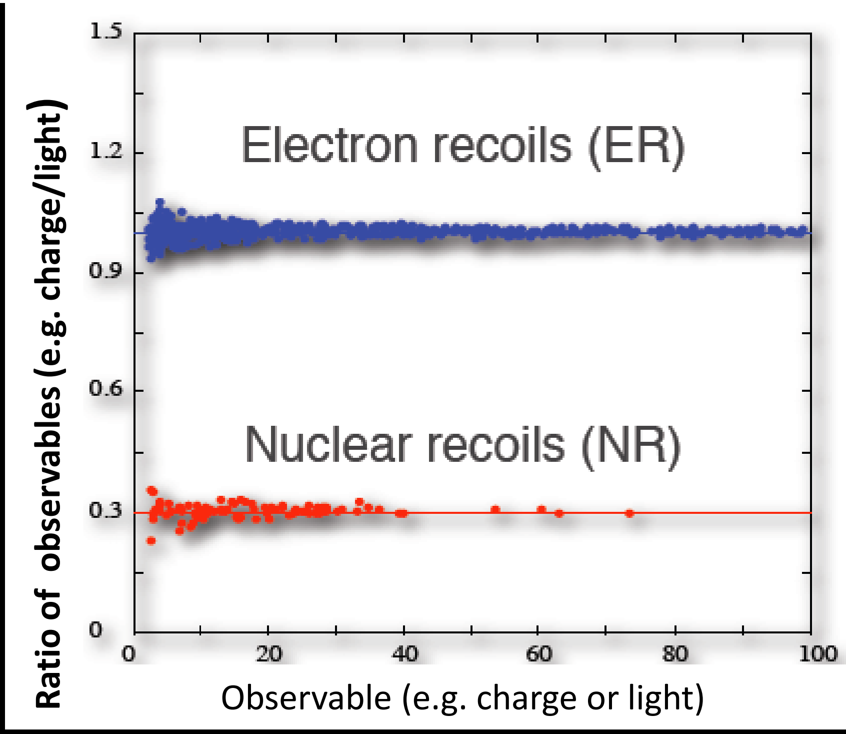
Detectors have a different response to nuclear recoils than to electron recoils




The detector is on Earth, which moves around the Sun, which moves around the galactic centre: **Modulation of the signal**

TAE 2012

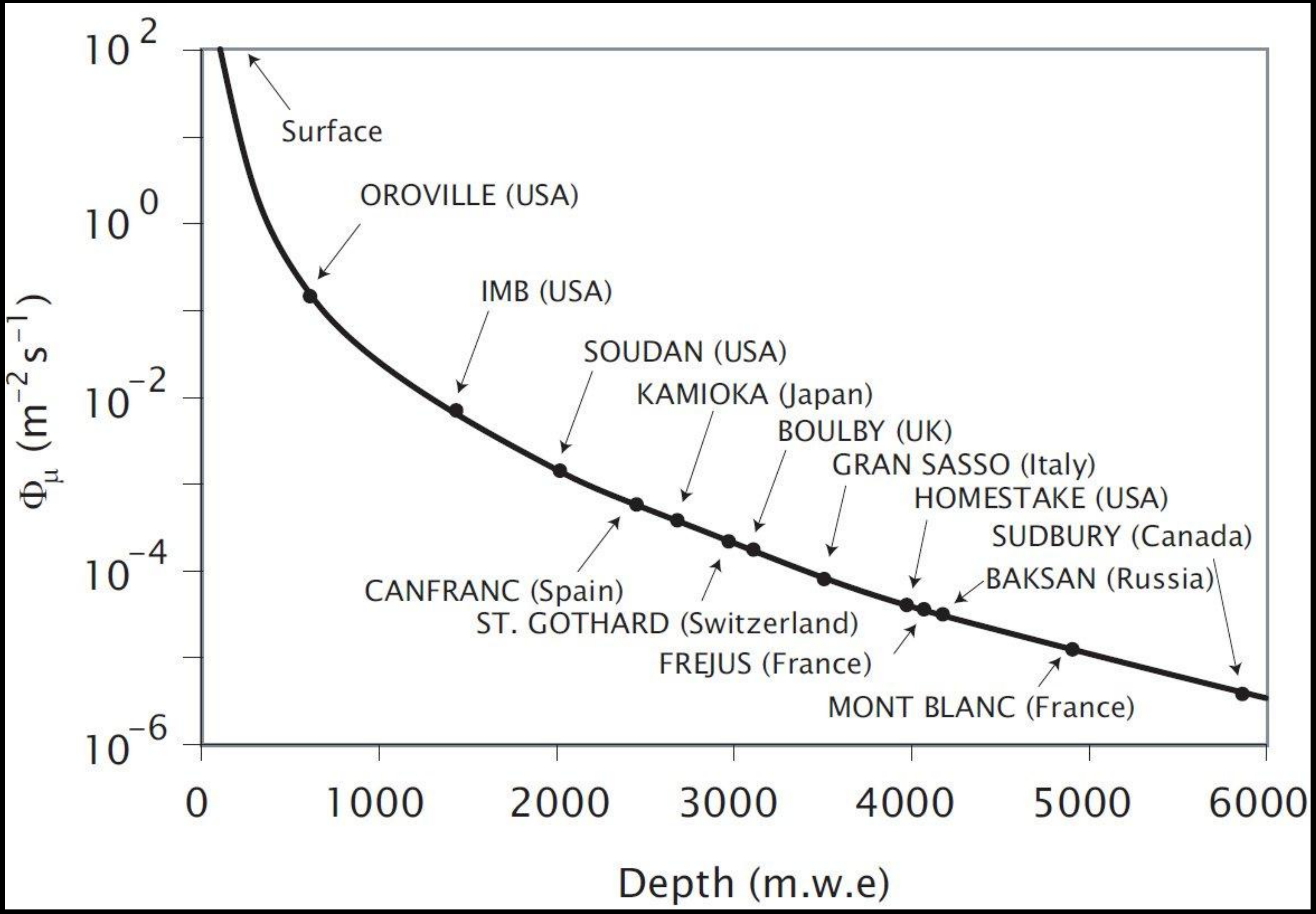


# Minimize background: Underground

Cosmic rays create high-energy muons when they interact with the atmosphere.

Muons release high-energy neutrons when they collide with
things (like rock) near an experiment

Go deep underground and make them penetrate as
much rock as possible



# 2 types of interactions

$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \frac{32 G_F^2 \mu^2}{\pi}\frac{(J+1)}{J}\left[a_p < S_p > + a_n < S_n >\right]^2$$

## Spin-independent

$f_p$ and $f_n$ are the couplings to proton and neutron, but $f_p \sim f_n$ for most models: Add coherently with $A^2$ enhancement

Dominates for heavy nuclei due to $A^2$ enhancement

Form factor can suppress momentum transfer in very large nuclei though

Most studied, most accessible

## Spin-dependent

Scales with spin of nucleus

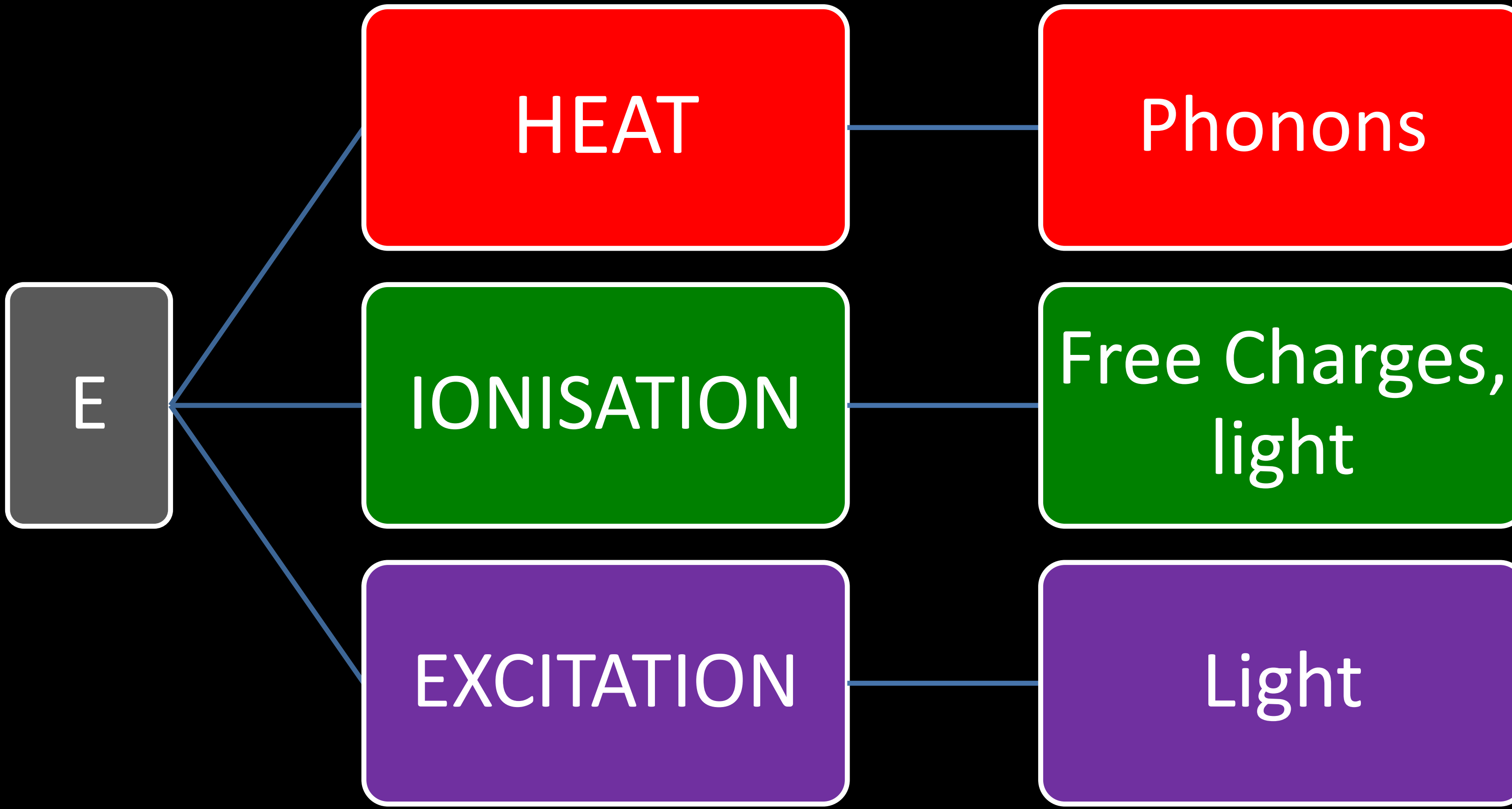
Scattering only off nucleons with net nuclear spin (i.e. whose spins remain unpaired)

Less increase with A than spin-independent cross-section

Important for light nuclei (e.g. in stars!)

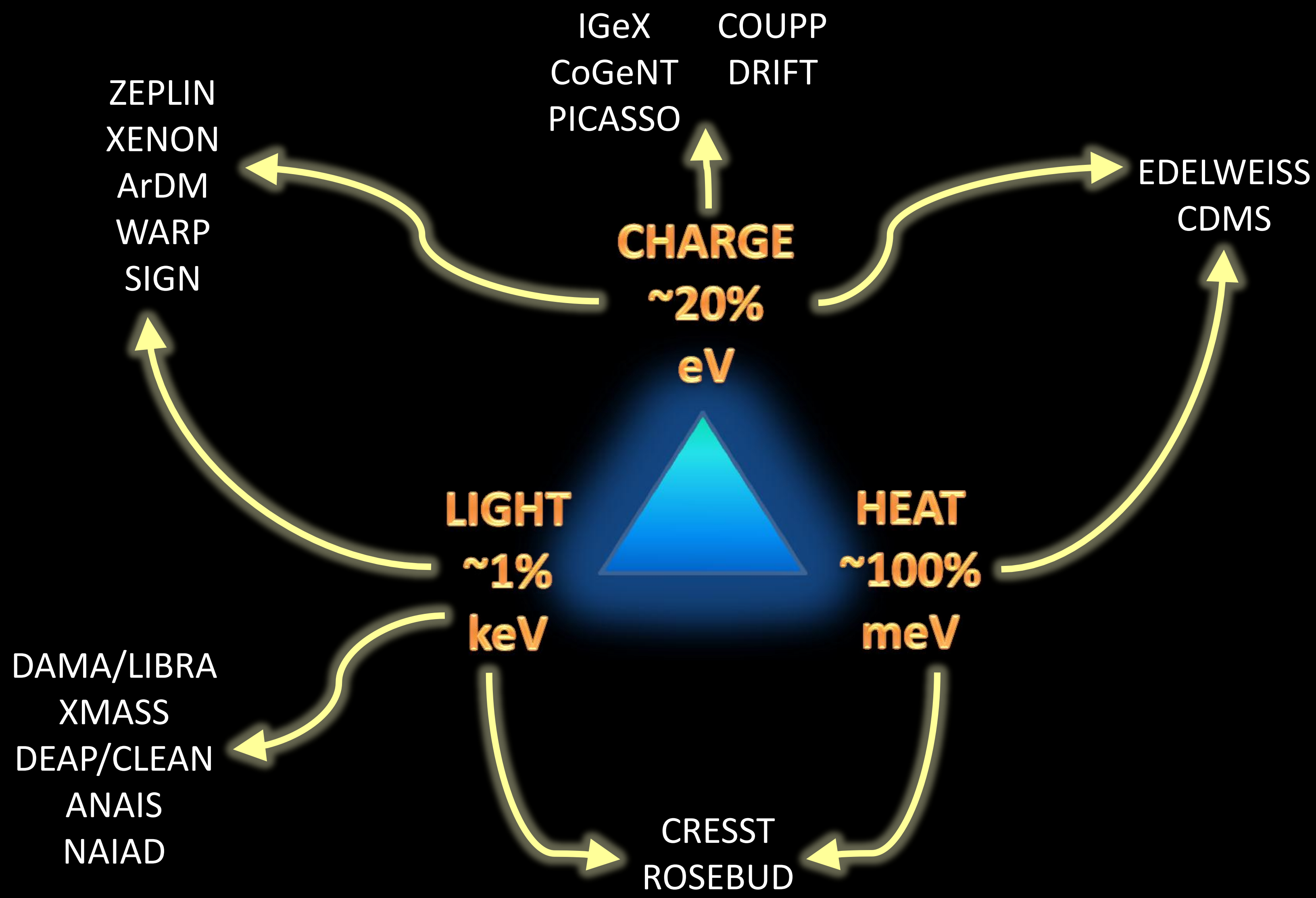
Least studied, trickier

# Recoil energy goes to…




The combination of detection principles allows a better identification of the interaction and helps to suppress background

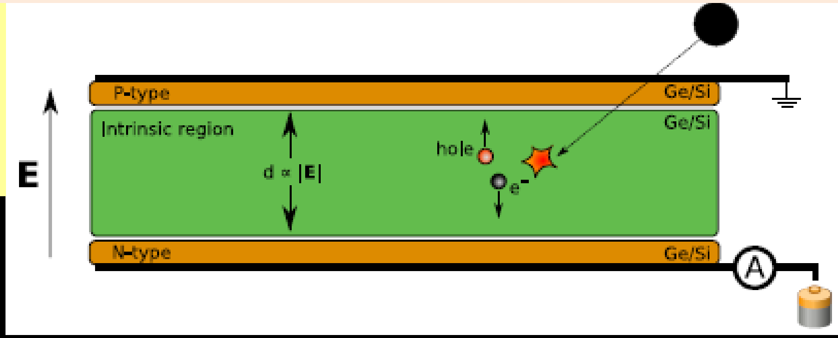
# Direct Detection Techniques



# Detector types

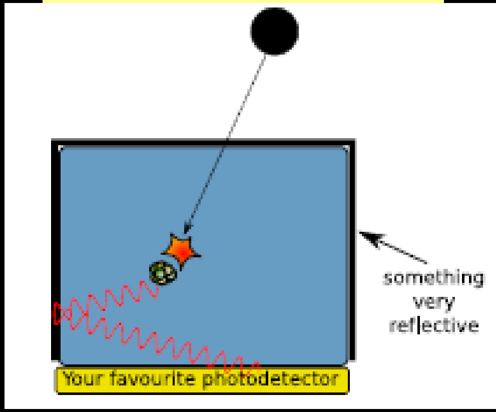
## IONIZATION

| | |
|---|---|
| Ionisation | 🟢 |
| Scintillation | 🔴 |
| Phonons | 🔴 |




## SOLID SCINTILLATORS

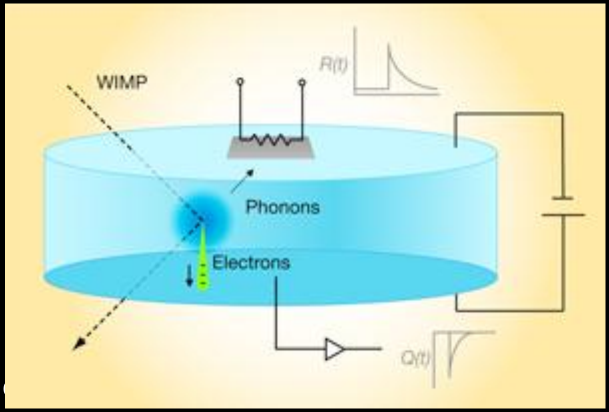
| | |
|---|---|
| Ionisation | 🔴 |
| Scintillation | 🟢 |
| Phonons | 🔴 |




## CRYOGENIC

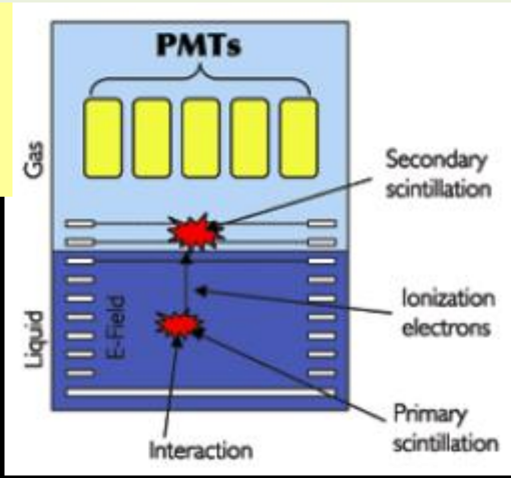
| | | | |
|---|---|---|---|
| Ionisation | 🔴 | Ionisation | 🟢 |
| Scintillation | 🟢 | Scintillation | 🔴 |
| Phonons | 🟢 | Phonons | 🟢 |

Need to make things very cold (10 mK) to see see individual phonons




## NOBLE LIQUID

| | |
|---|---|
| Ionisation | 🟢 |
| Scintillation | 🟢 |
| Phonons | 🔴 |



# Current Situation

**The situation is very exciting… But also very confusing!!!**

**POSITIVE CLAIMS FROM DAMA, CoGeNT and CRESST**

DAMA: 13 annual cycles, claims annual modulation at 8.9 σ C.L.

CoGeNT: 15 months, confirms annual modulation at 2.8 σ C.L., plus excess of events

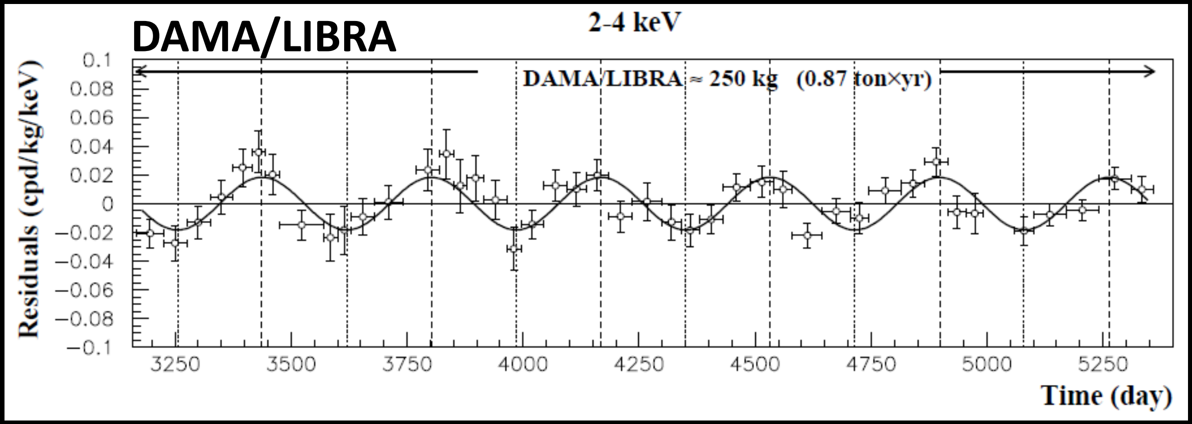
CRESST: Excess of events

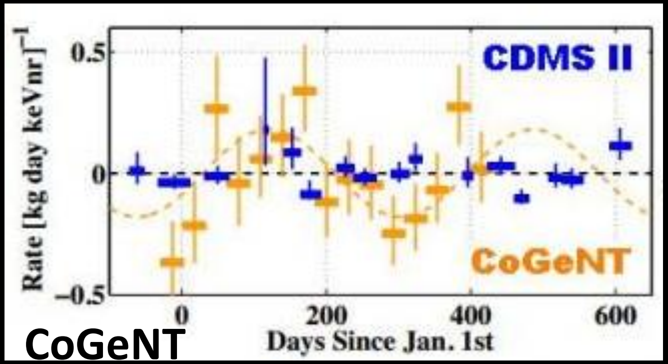
**Compatible with a WIMP of mass ~10 GeV**

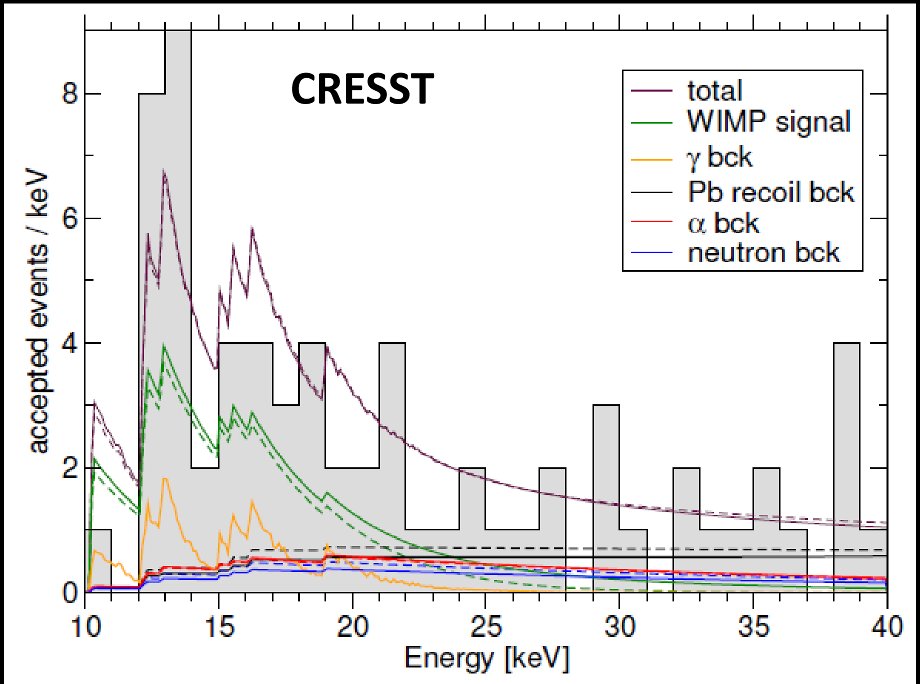
BUT… These signals are

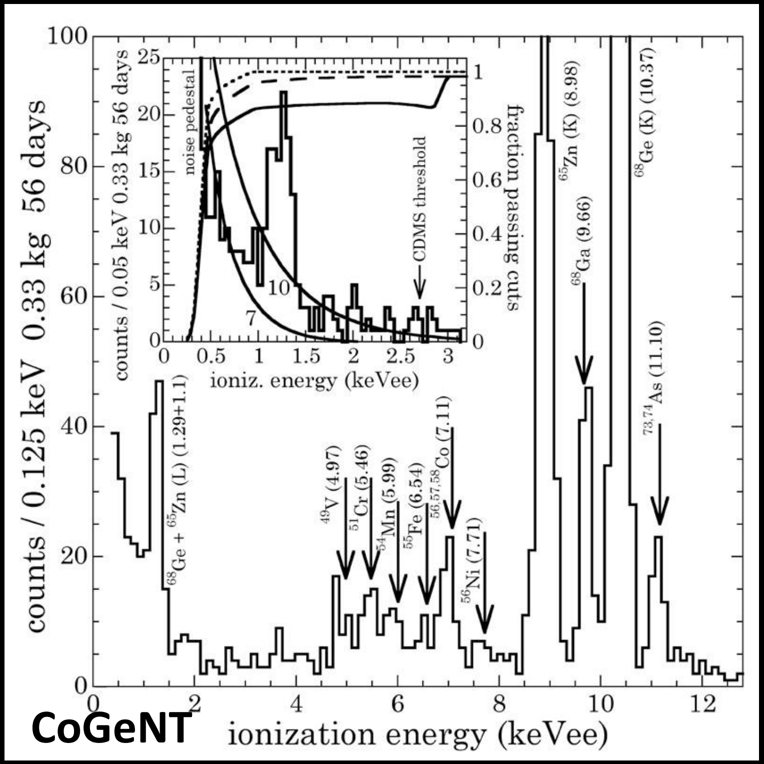
**EXCLUDED BY CDMSII, XENON100, XENON10**

# Current Situation: Positive Claims

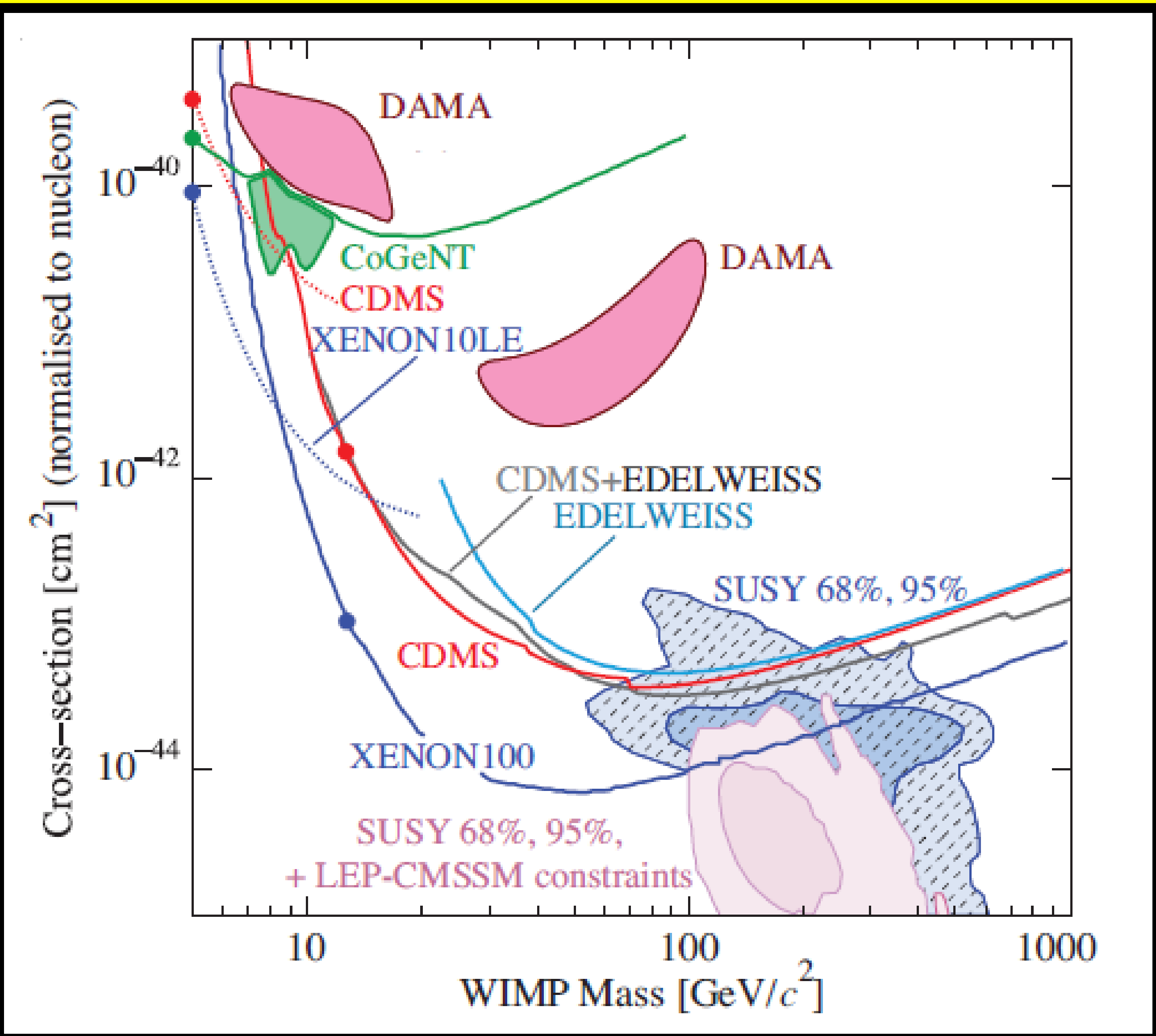


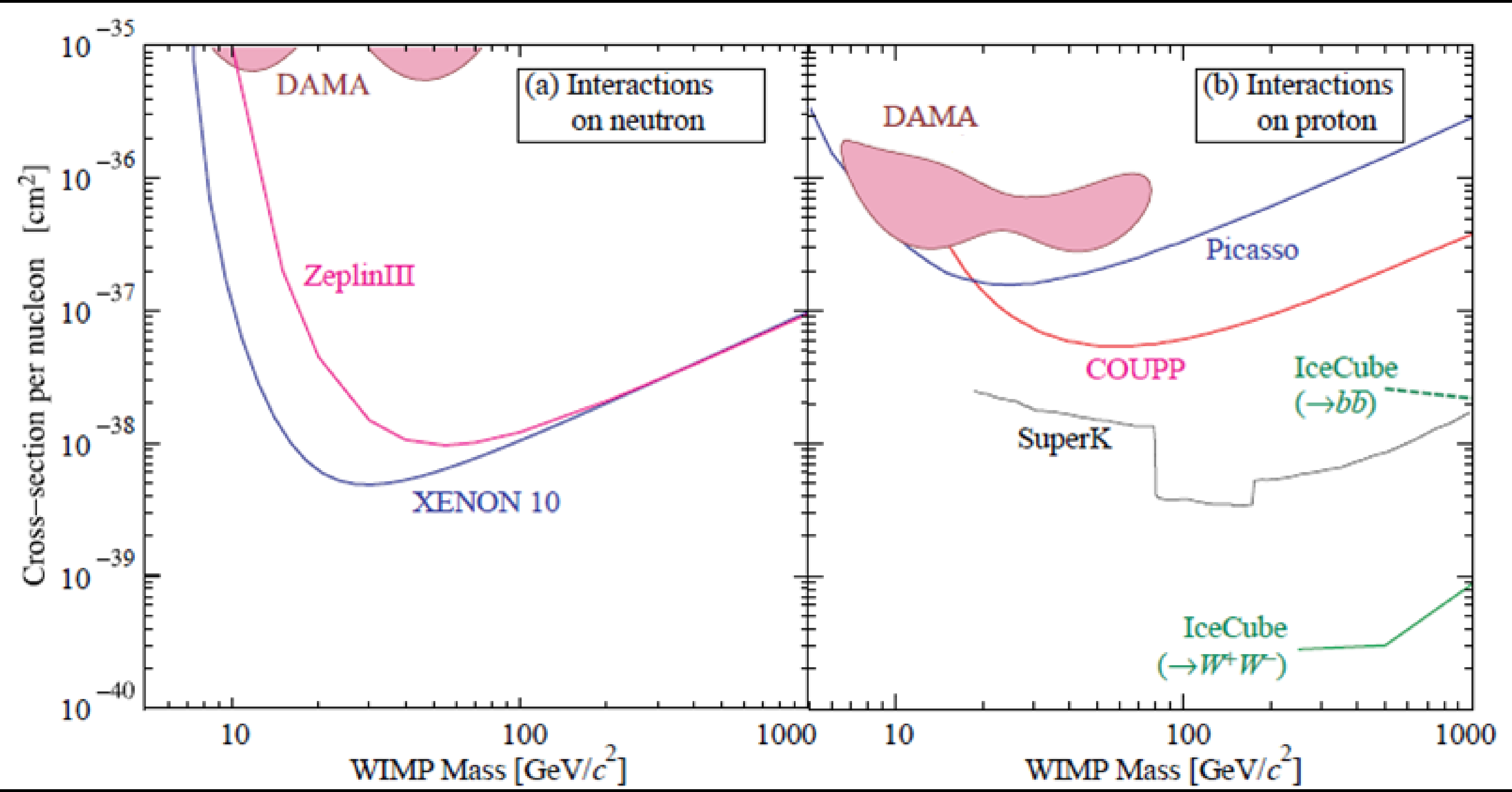



# Current Situation: Spin Independent




**More data are needed to clarify the situation**

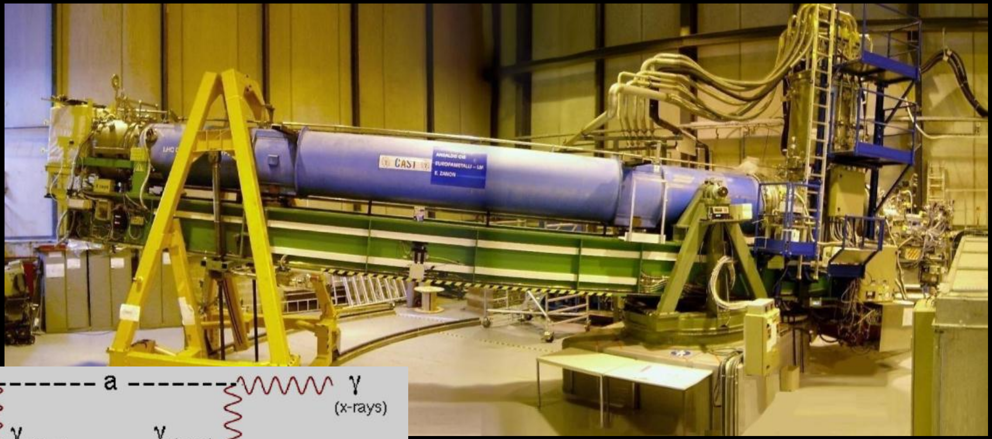
# Current Situation: Spin Dependent

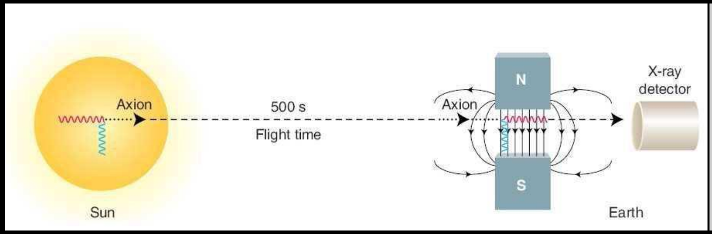


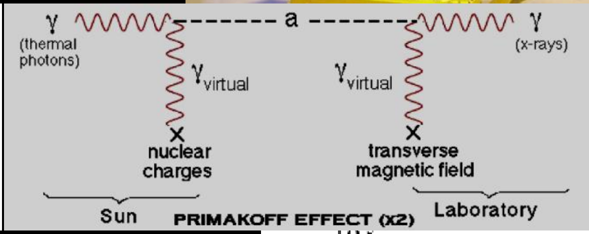

**More data are needed to clarify the situation**

# Axion search

The CERN Axion Solar Telescope (CAST) looks for axions originating from the Sun. Started in 2003 and is still running



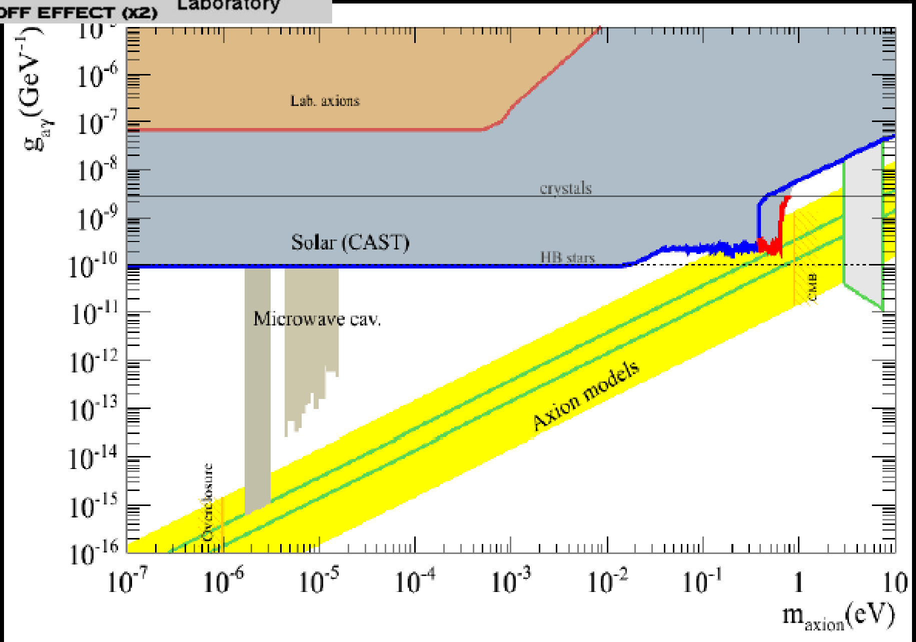




Use a strong magnetic field (old LHC dipole)

Point magnet to the Sun, follow the Sun as long as possible

1.5 **h observation time during sun rise and sun set (** 46 **days/year)**

Signal: excess of x-rays while pointing at the sun . <u>**NO SIGNAL OBSERVED**</u>



# Summary of Dark Matter Results

Huge obervational evidence for **COLD DARK MATTER**:
Stable, neutral, non relativistic particles that form ~22% of the universe density

*If they are WIMPs, the local abundance is ~0.4 GeV/cm$^3$*
*If $m_{WIMP}$~100 GeV, around 10 WIMPs interact with a human body per year*
*If $m_{WIMP}$~10 GeV, around $10^5$ WIMPs interact with a human body per year*

**Dark matter at LHC:**
- **No signal observed**

**Indirect searches of Dark Matter**
- **No signal in gamma rays**
- **No signal in neutrinos**
- **Some hints in positrons. Compatible with pulsars emission**

**Direct search of Dark Matter**
- **Some experiments claim a signal (DAMA, CoGeNT, CRESST)**
- **Which is excluded by the others (CDMS, XENON10/100)**

**Axions Searches**
- **No signal observed**