Experimental Astroparticle Physics (a short introduction)

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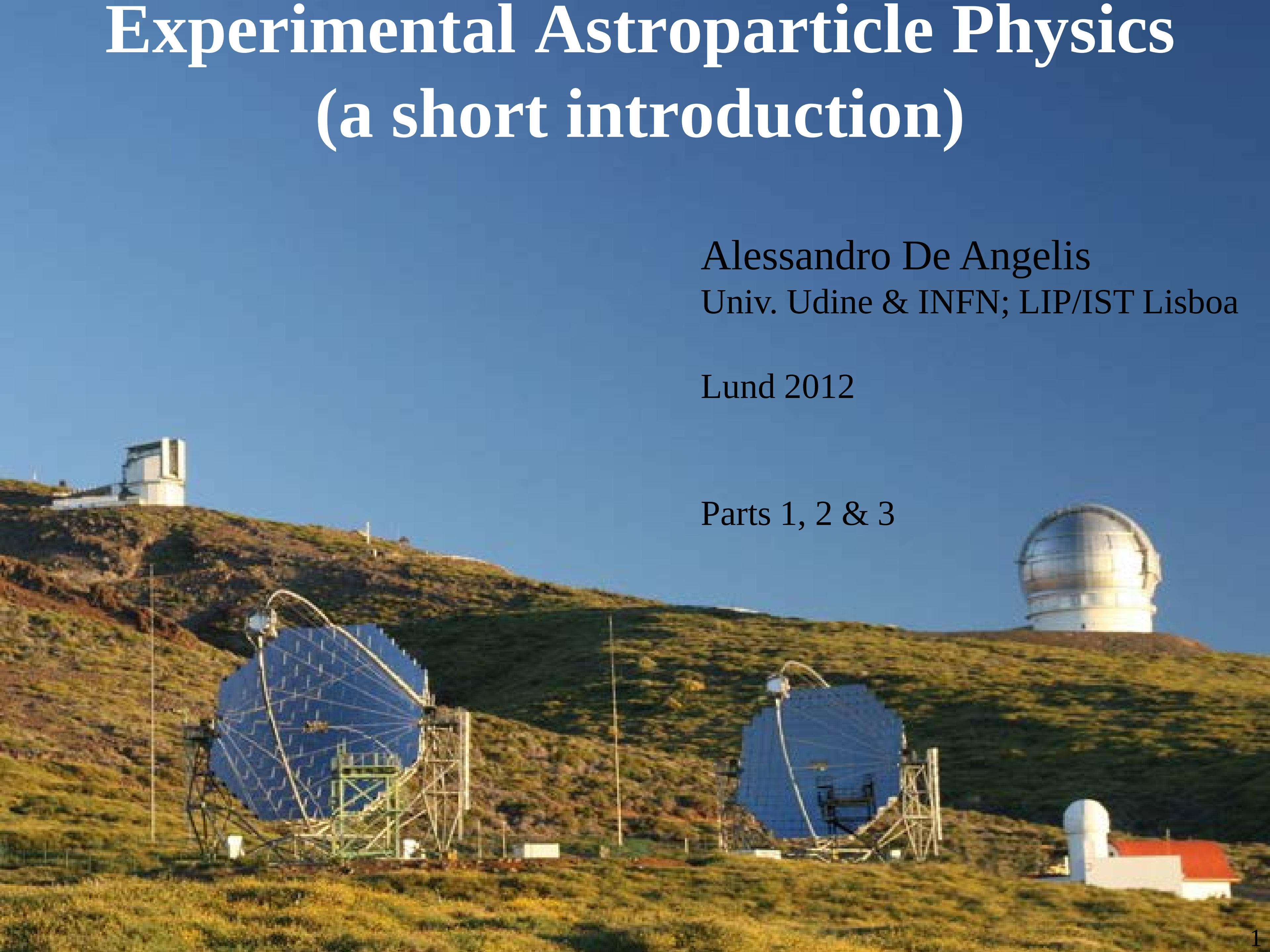
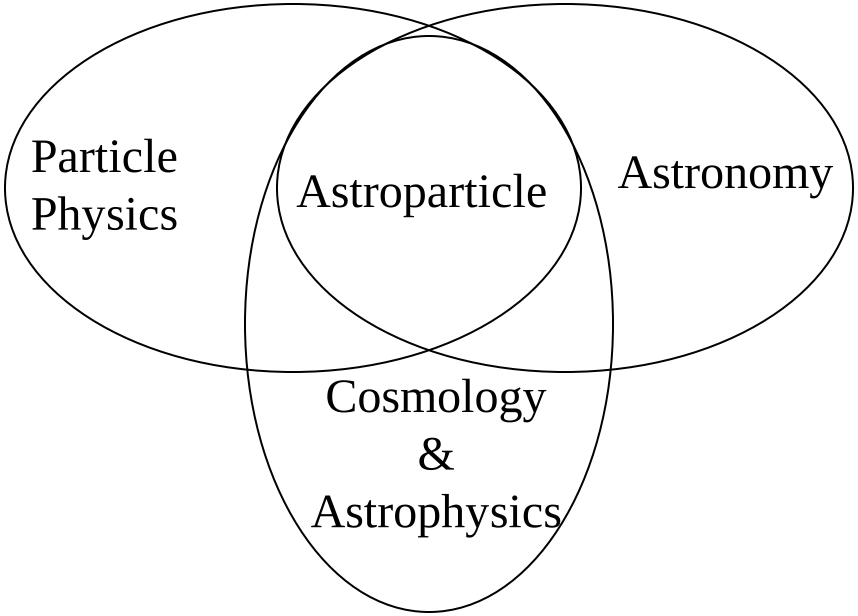
Parts 1, 2 & 3



What is Astroparticle Physics (Particle Astrophysics?)



1) Use techniques from Particle Physics to advance Astronomy

2) Use input from Particle Physics to explain our Universe, and particles from outer space to advance Particle Physics

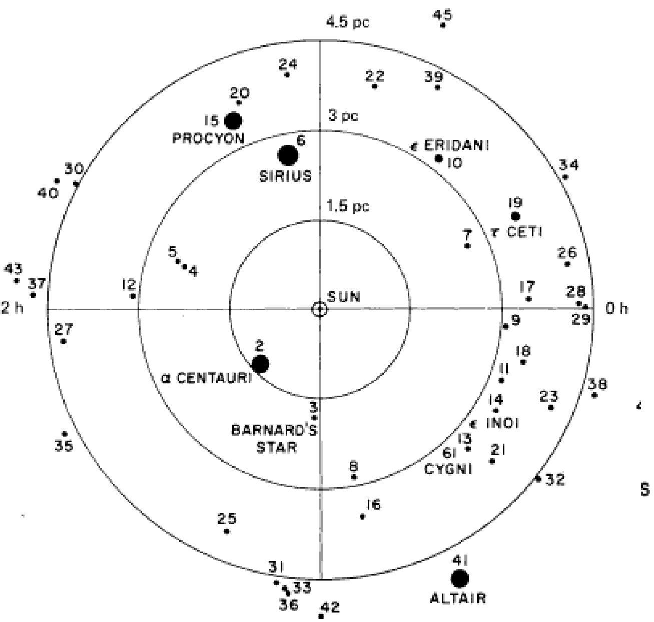
In this lecture I'll concentrate on the 2nd topic

I

A quick look to our Universe

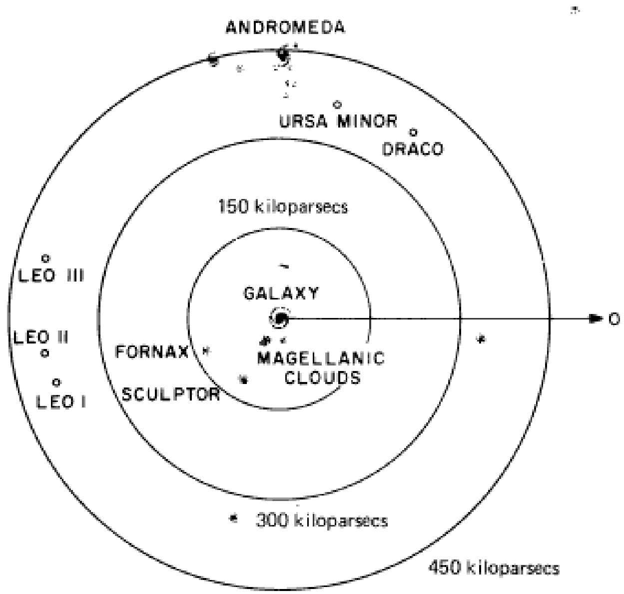
Astronomy Scales

Nearest Stars



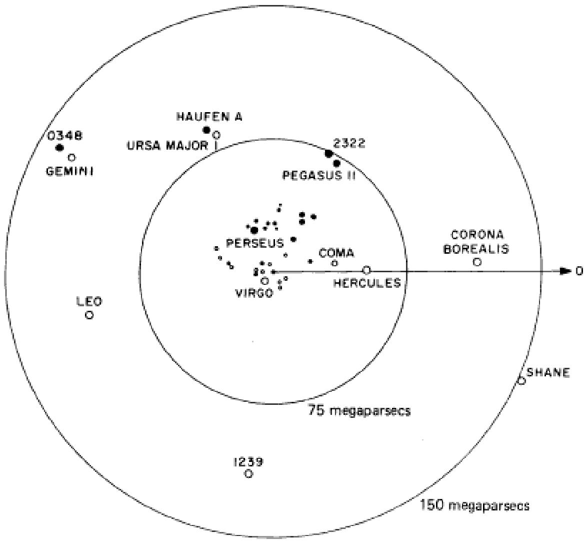
4.5 pc

Nearest Galaxies



450 kpc

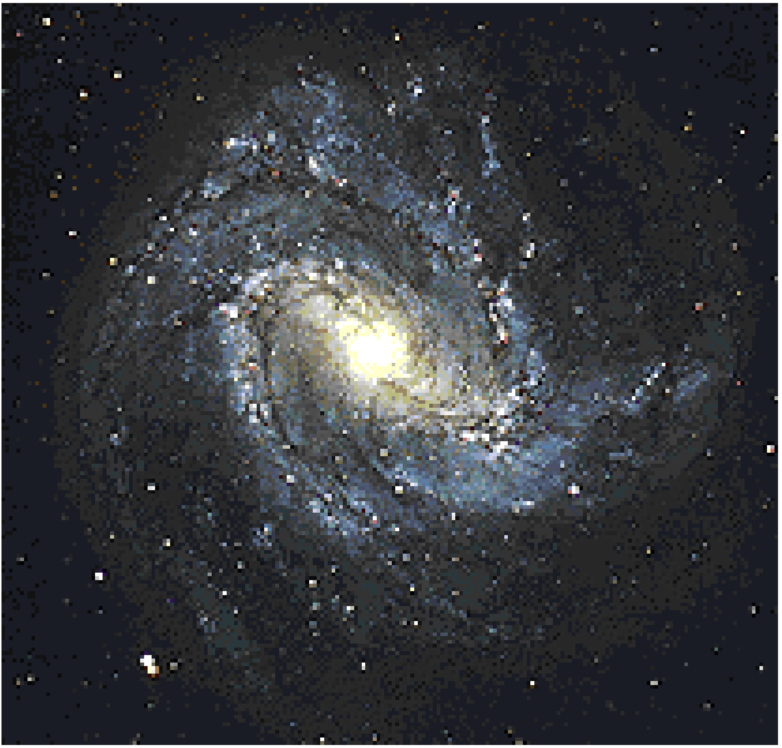
Nearest Galaxy Clusters

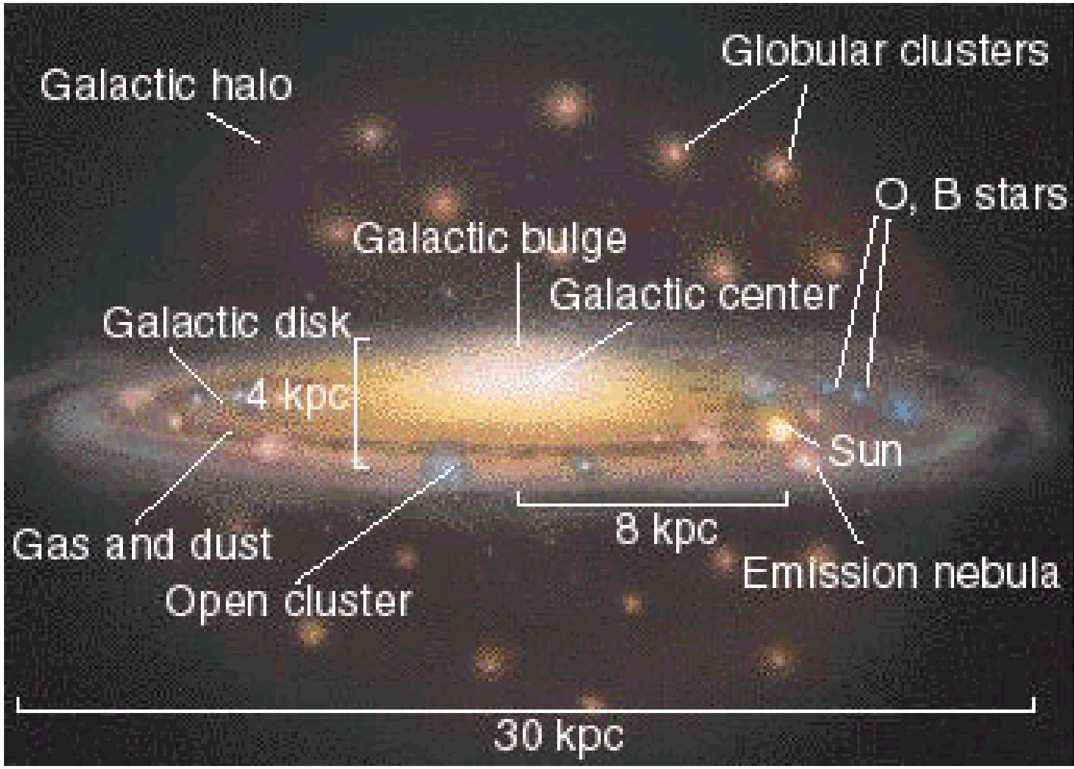


150 Mpc

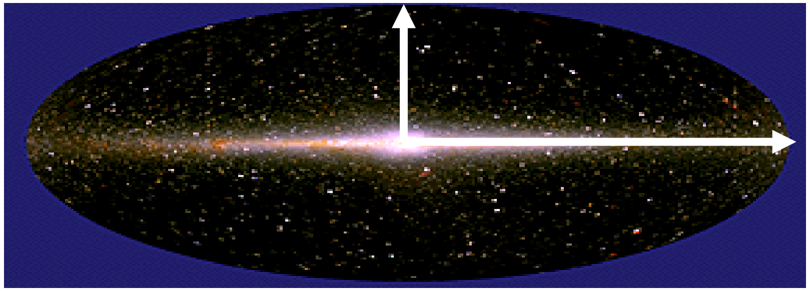
1 pc ~ 3.3 ly

Our Galaxy: The Milky Way



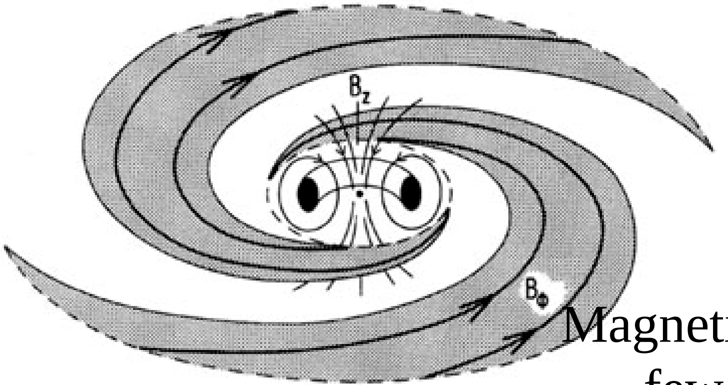


+90°



+180°

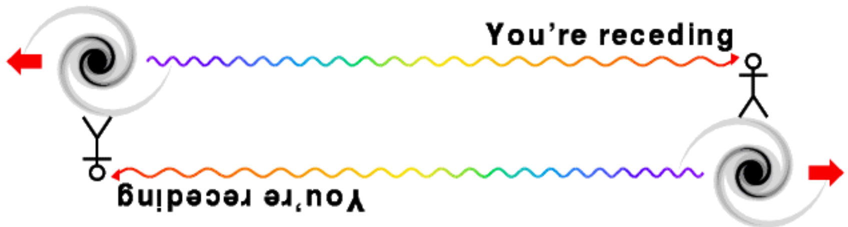
–90°



Magnetic field
~ few μG

What do we know about our Universe ?

- Many things, including the facts that…
  - Particles are coming on Earth at energies 10^8 times larger than we are able to produce…
  - The Universe expands (Hubble ~1920): galaxies are getting far with a simple relationship between distance & recession speed



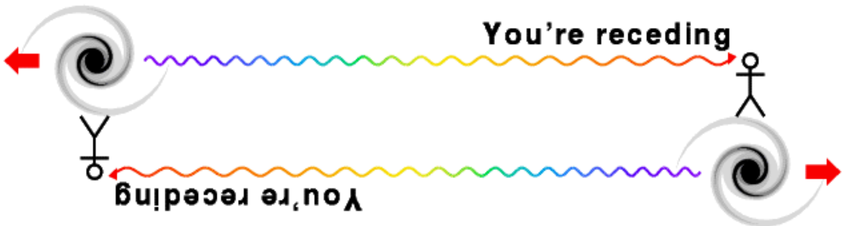
Hubble's constant (km/s/Mpc)

$$V = H_0 r$$

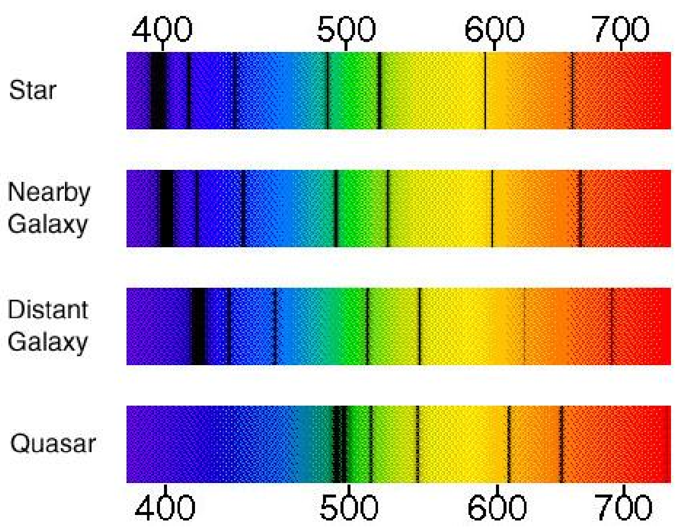
recession speed (km/s)

distance (Mpc

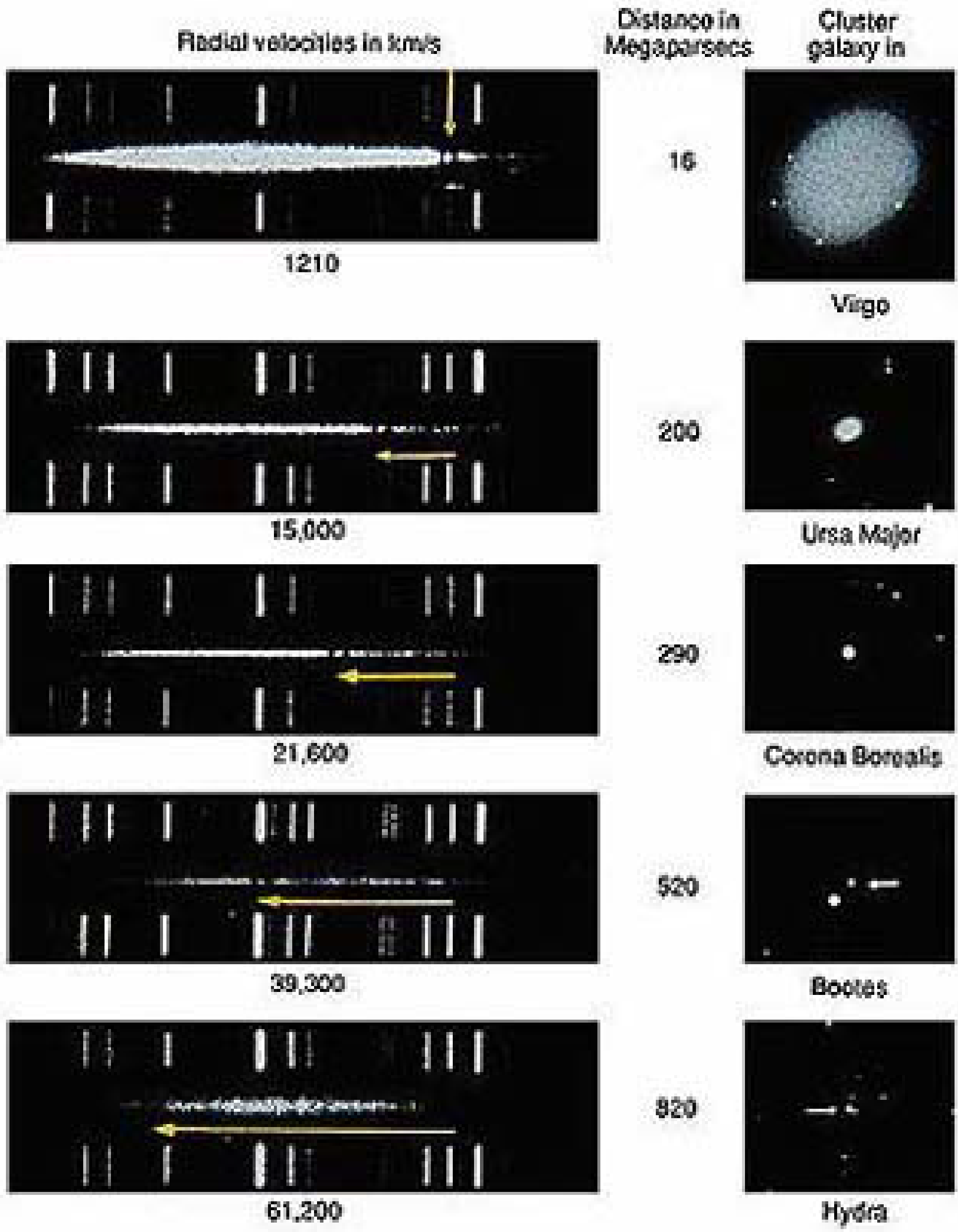
Redshift



You're receding
You're receding



400
500
600
700
Star
Nearby Galaxy
Distant Galaxy
Quasar
400
500
600
700

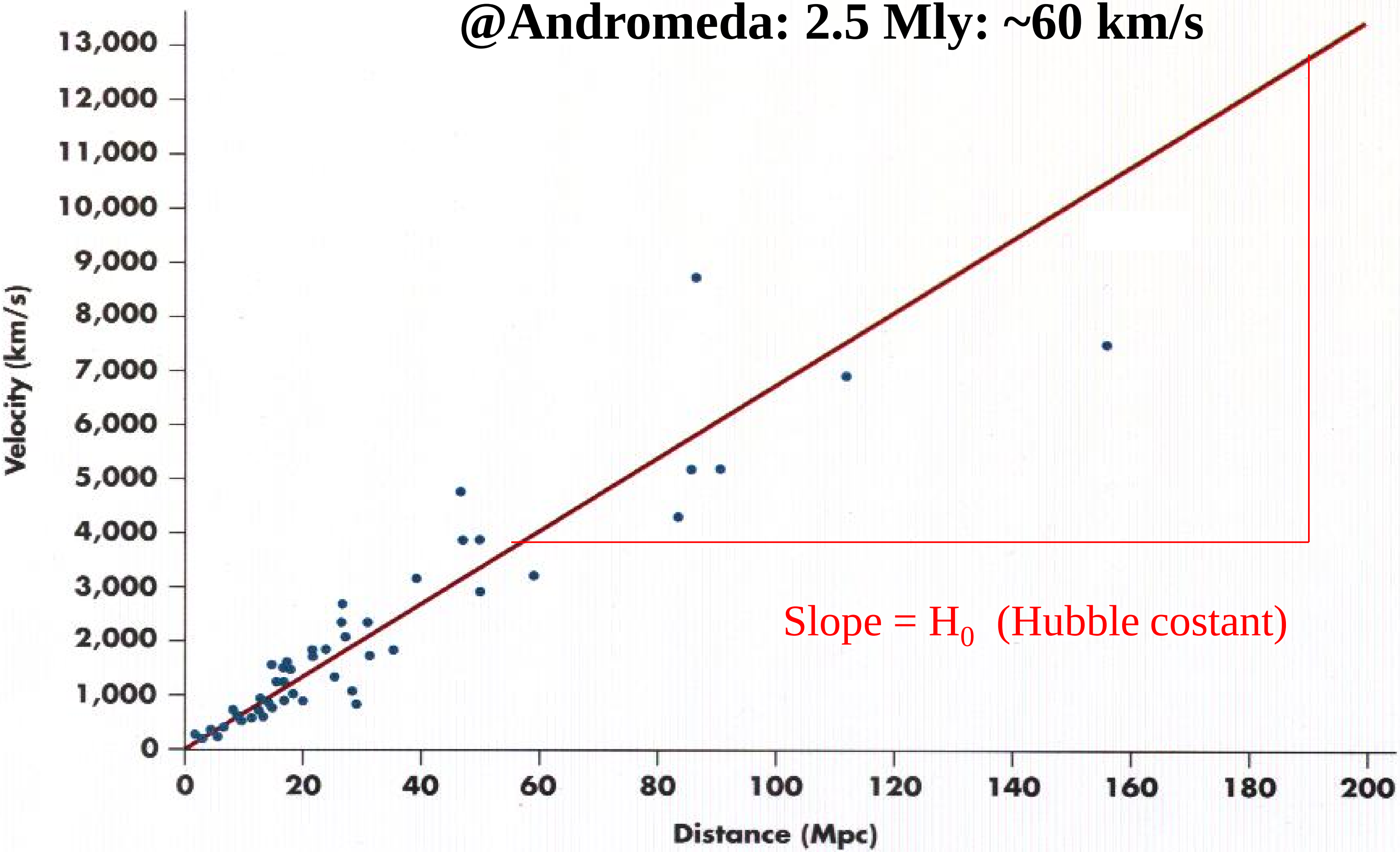


Radial velocities in km/s
Distance in Megaparsecs
Cluster galaxy in
16
1210
Virgo
200
15,000
Ursa Major
290
21,600
Corona Borealis
520
39,300
Bootes
820
61,200
Hydra

Hubble's law

Today: H_0 = (72 ± 3) km/s / Mpc

@Andromeda: 2.5 Mly: ~60 km/s

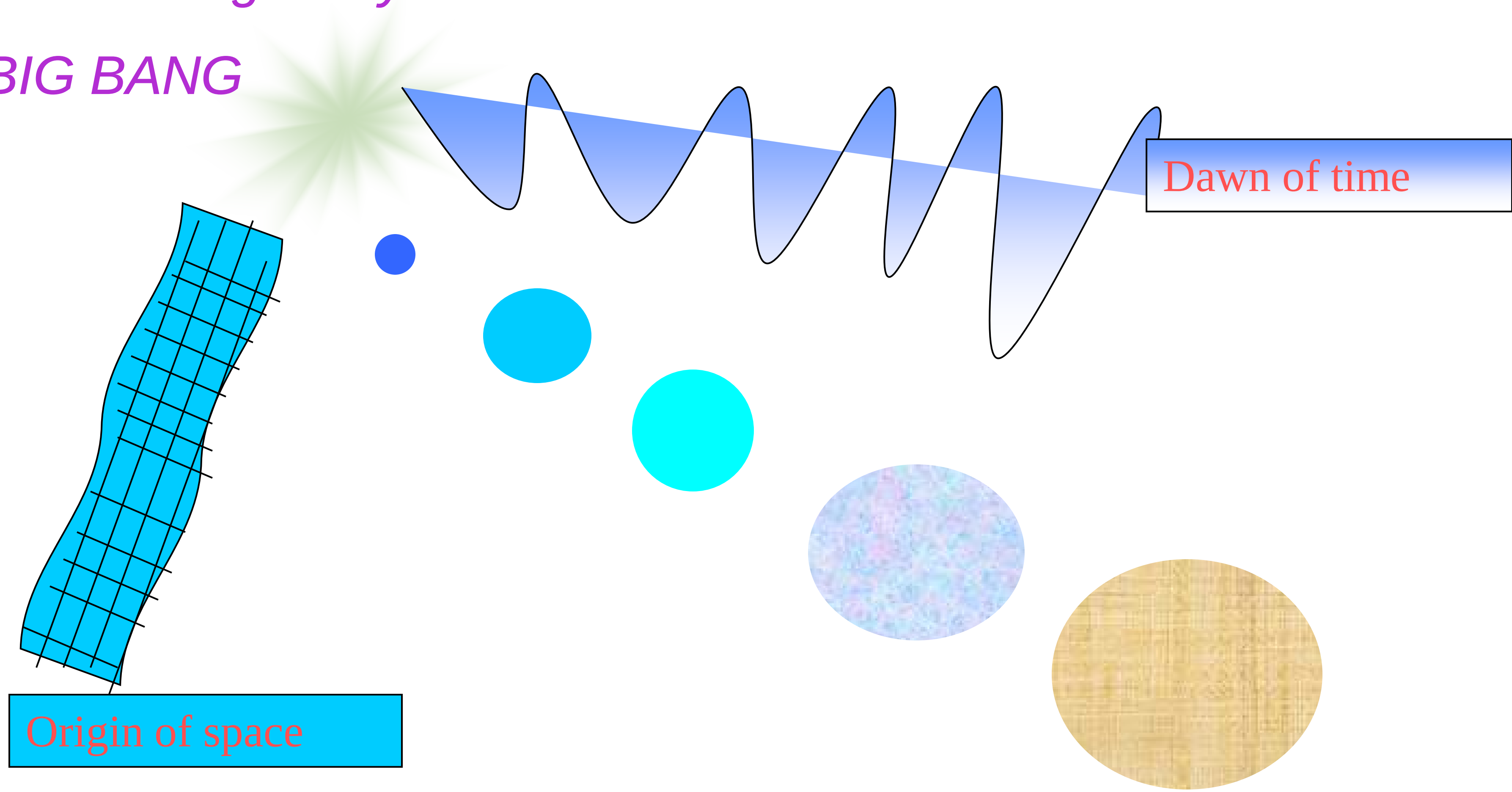


Slope = H_0 (Hubble costant)

Once upon a time...
our Universe was smaller

Primordial singularity !!!

=> BIG BANG



How far in time ?

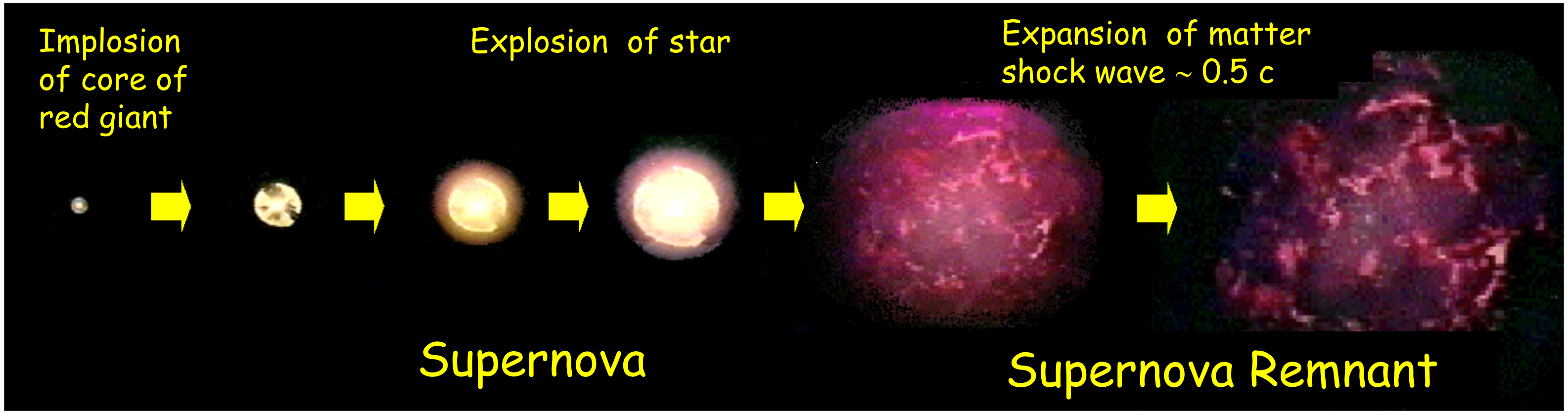
- Extrapolating backwards the present expansion speed towards the big bang

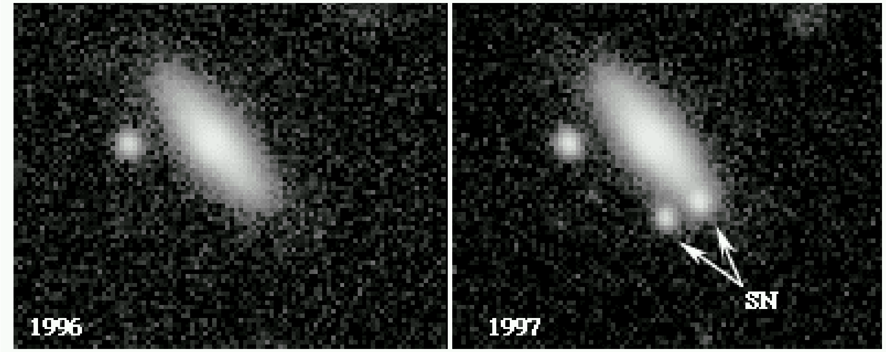
$$T \sim 1/H_0 \sim 14 \text{ billion years}$$

(note that the present best estimate, with a lot of complicated physics inside, is $T = 13.7 \pm 0.2$ Gyr)

- Consistent with the age of the oldest stars

Hubble law in 2009: supernovae





SNIa occurs at Chandra mass, 1.4 M_{sun} ⇒ 'Standard Candle'

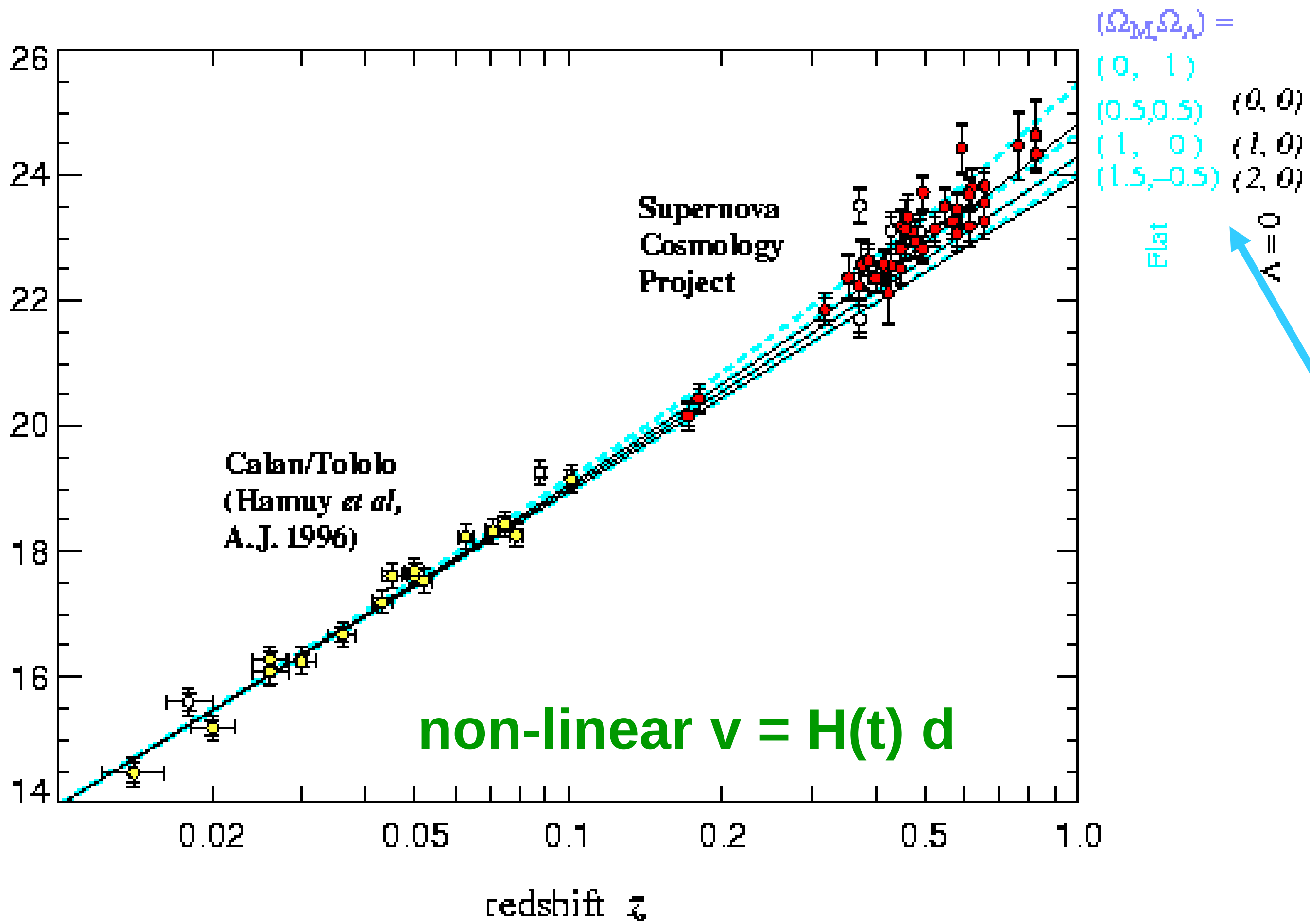
measure brightness → distance: $B = L / 4\pi d^2$

measure host galaxy redshift → get recession velocity

test Hubble's Law: v = H d, at large distances

Expansion with Supernovae Ia

effective magnitude → brightness → distance



Acceleration of universe expansion

redshift → recession velocity

Deviation from Hubble's law
The expansion accelerates
$\Omega_\Lambda \sim 0.7$

Time & temperature (=energy)

- Once upon a time, our Universe was hotter
  - Expansion requires work (and this is the most adiabatic expansion one can imagine, so the work comes from internal energy)

$$T \sim \frac{15}{\sqrt{t}} 10^9 K$$

$$E \cong k_B T$$

Time

Decoupling

$\gamma \leftrightarrow$ particles+antiparticles

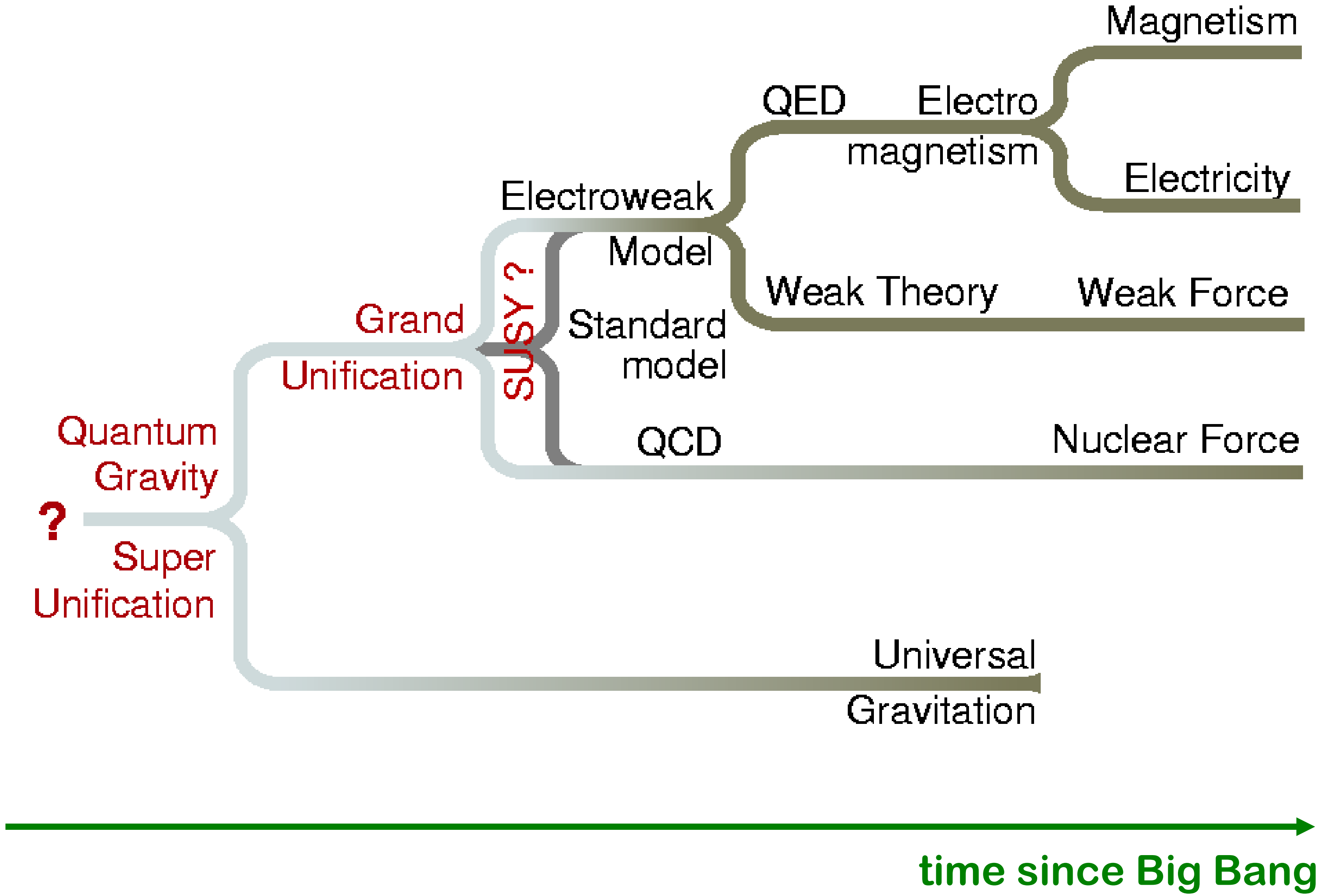
$\gamma \leftrightarrow$ proton-antiproton

$\gamma \leftrightarrow$ electron-positron

(…)

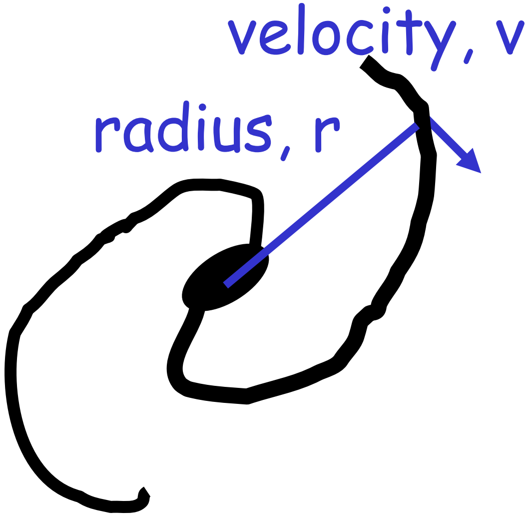
then matter became stable

Particle Physics after the Big Bang

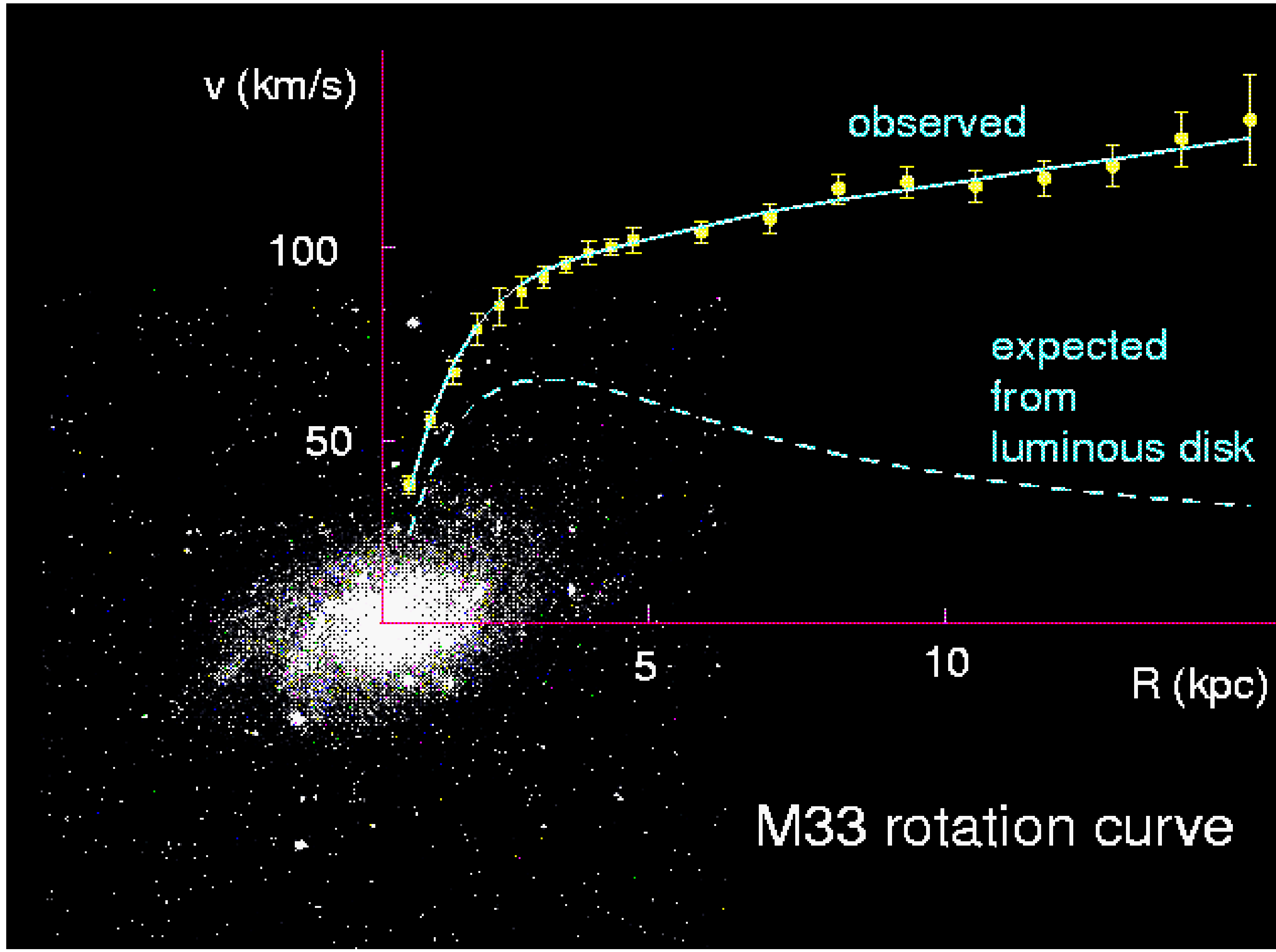


THE QUEST FOR HIGHER ENERGIES IS ALSO A TIME TRAVEL

The Universe today: what we see is not everything



Gravity:
$G\,M(r) / r^2 = v^2 / r$
enclosed mass:
$M(r) = v^2 r / G$

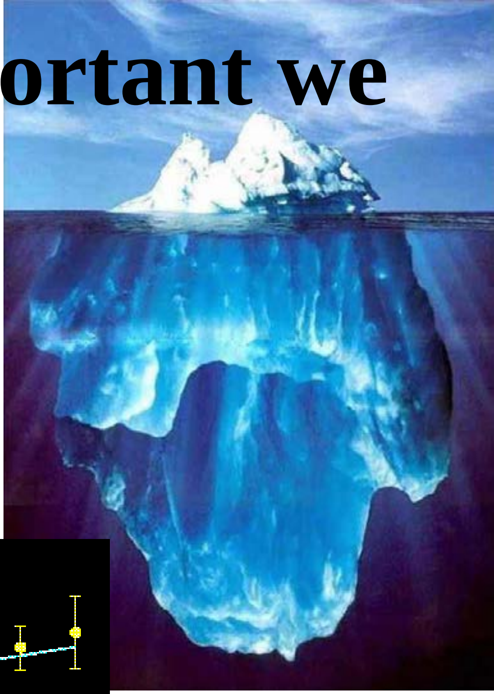


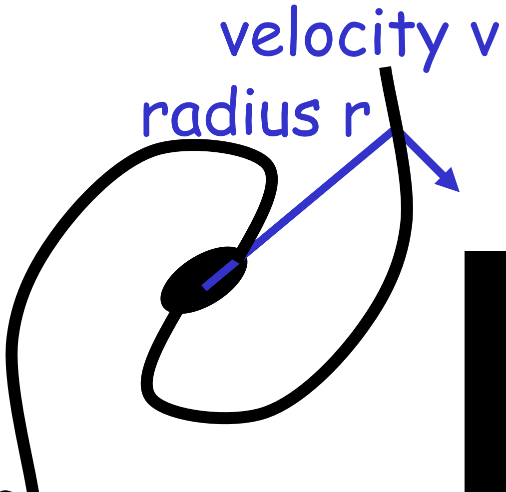
Luminous stars only small fraction of mass of galaxy

II

Dark matter searches

We think there’s something important we don’t see





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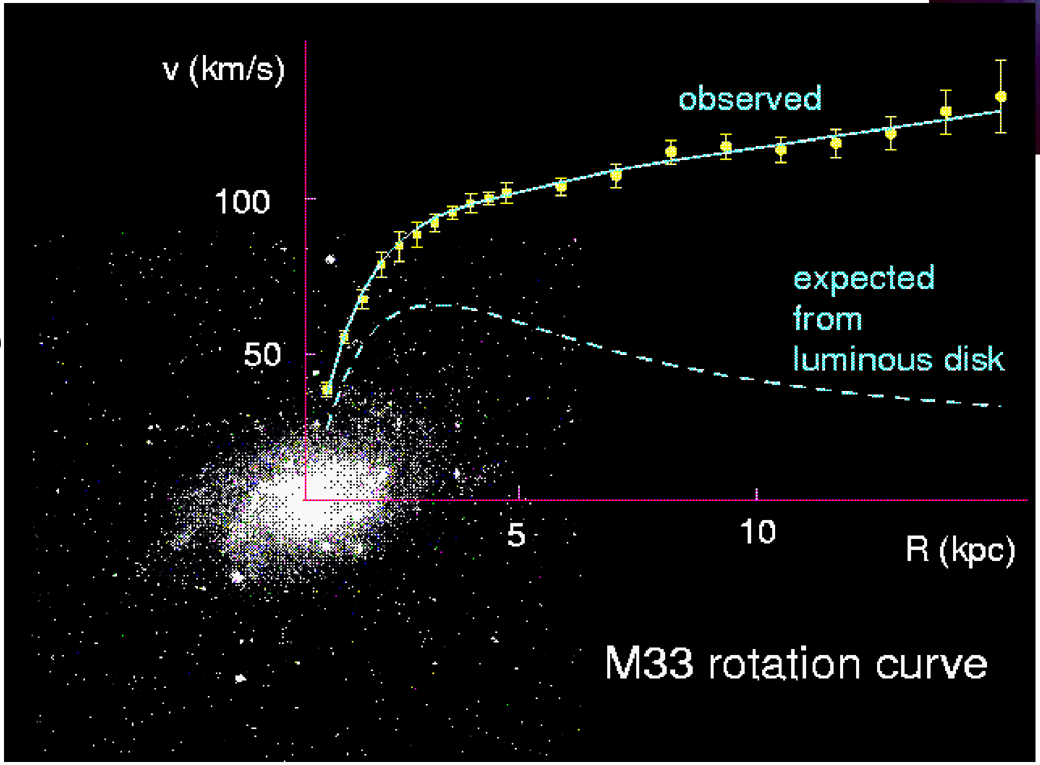
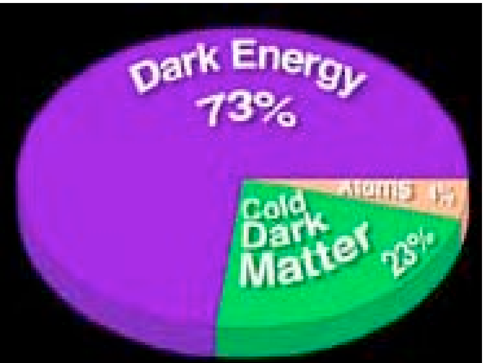
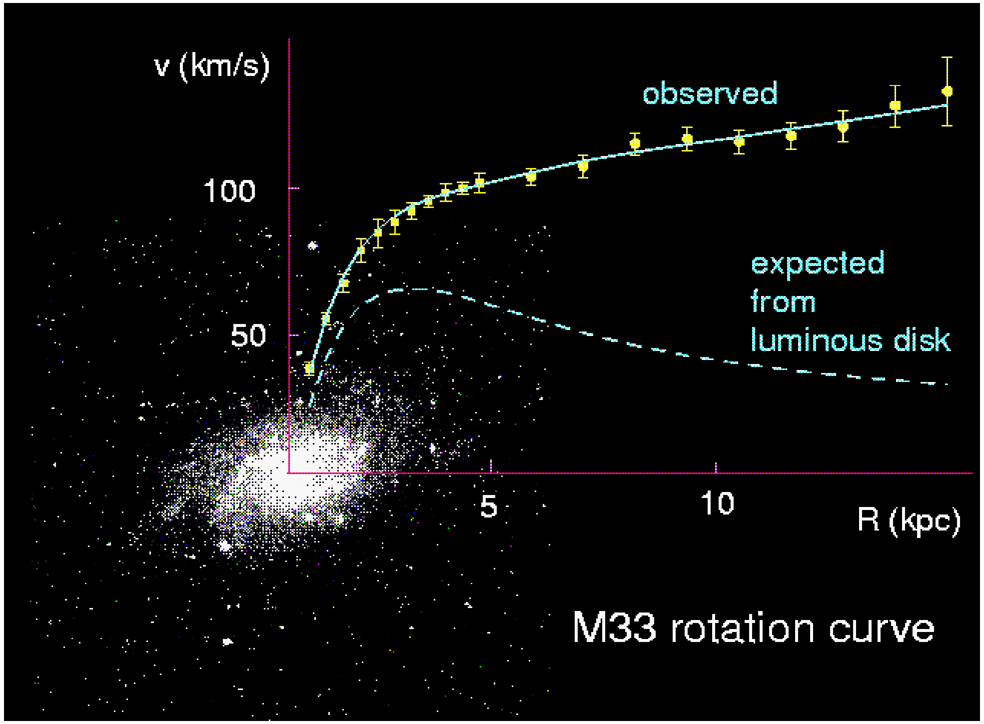




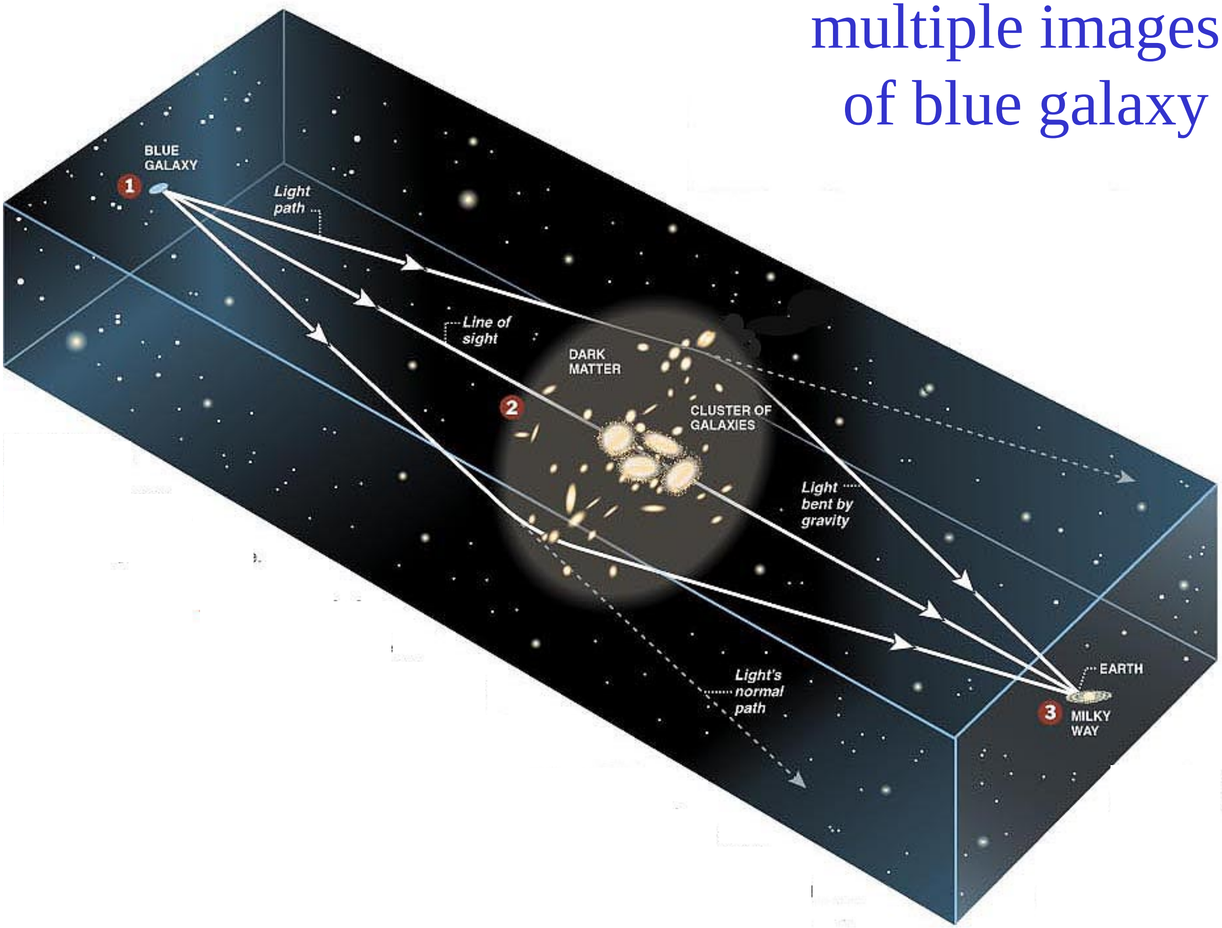
Luminous stars only small fraction of mass of galaxy

Dark matter searches

- Astronomy Dark Matter Candidates
  - Invisible macroscopic objects
    - Non-luminous objects (MACHOs)
    - Black Holes
- Particle Dark Matter Candidates
  - Neutrinos
  - WIMPs

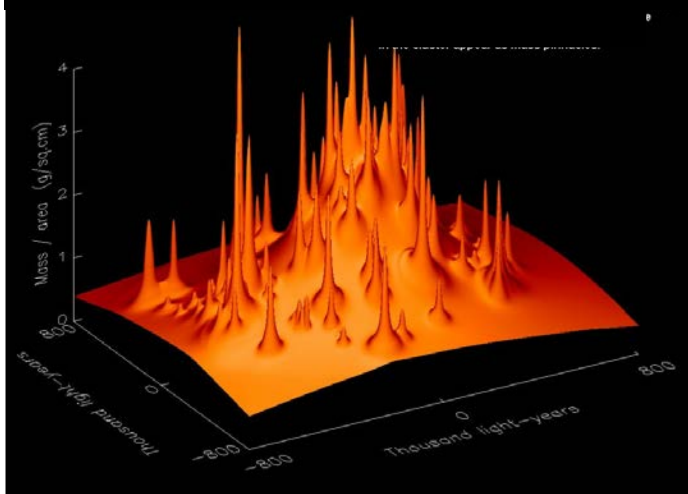


Gravitational Lensing by Dark Matter



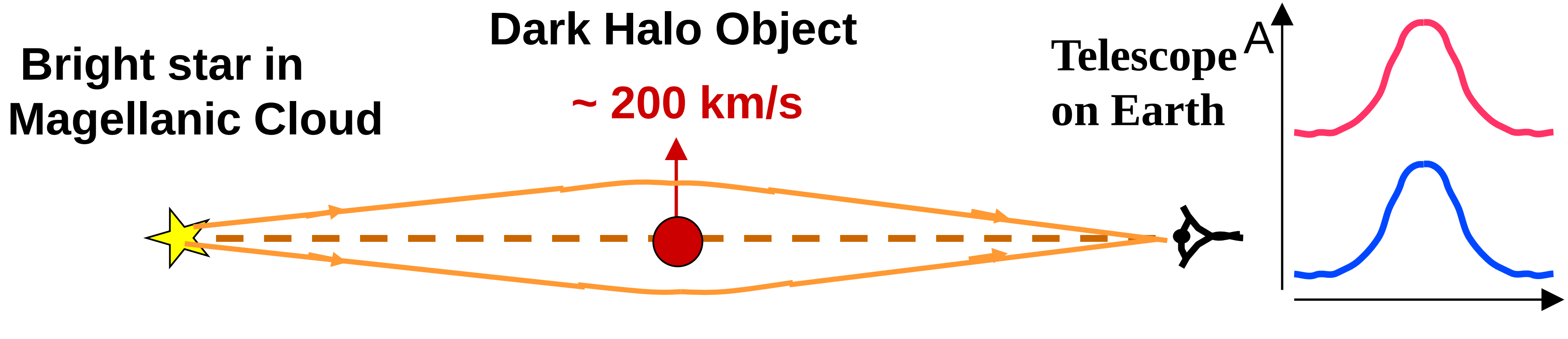
Hubble Space Telescope
multiple images
of blue galaxy

Reconstructed matter distribution



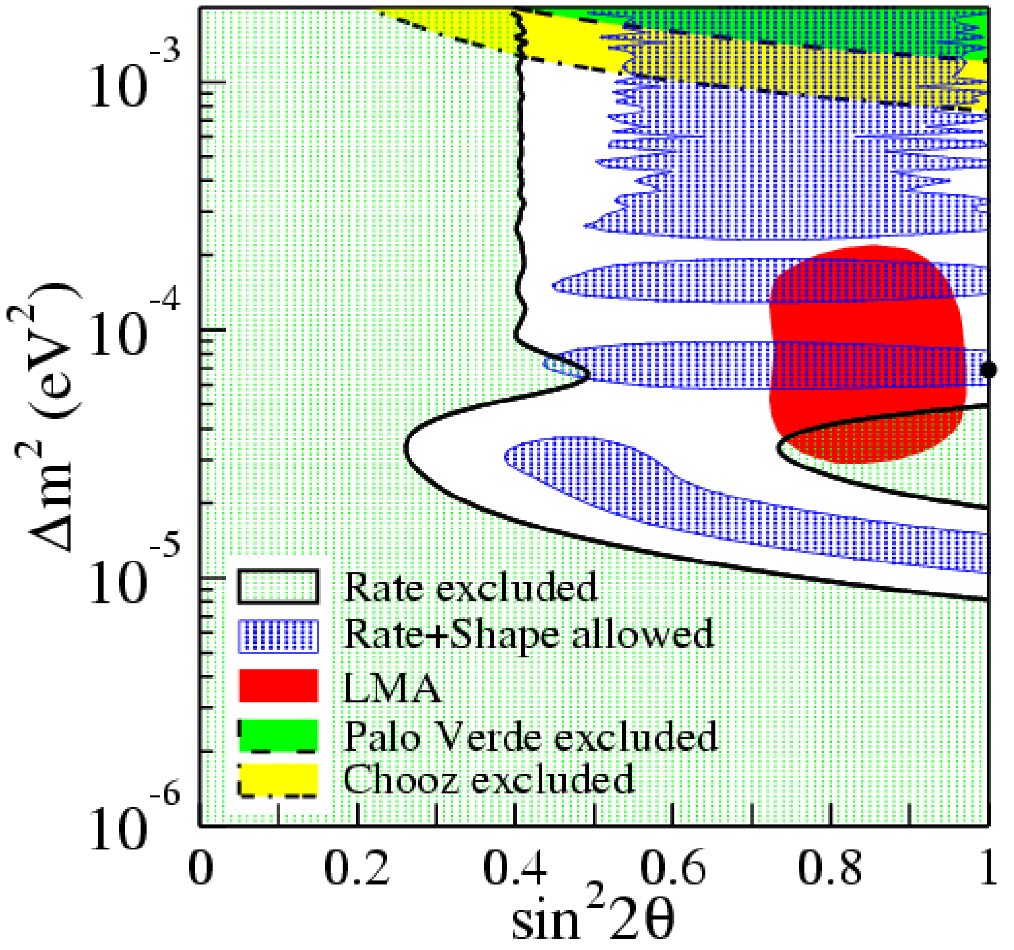
Black holes, etc.

Gravitational Lensing Searches for MACHOs



Neutrino Mass is not enough

$P_{dis} = \sin^2 2\theta \sin^2(1.27\ \Delta m^2 L/E)$,
Δm mass difference, θ mixing angle, E energy of ν, L oscillation length

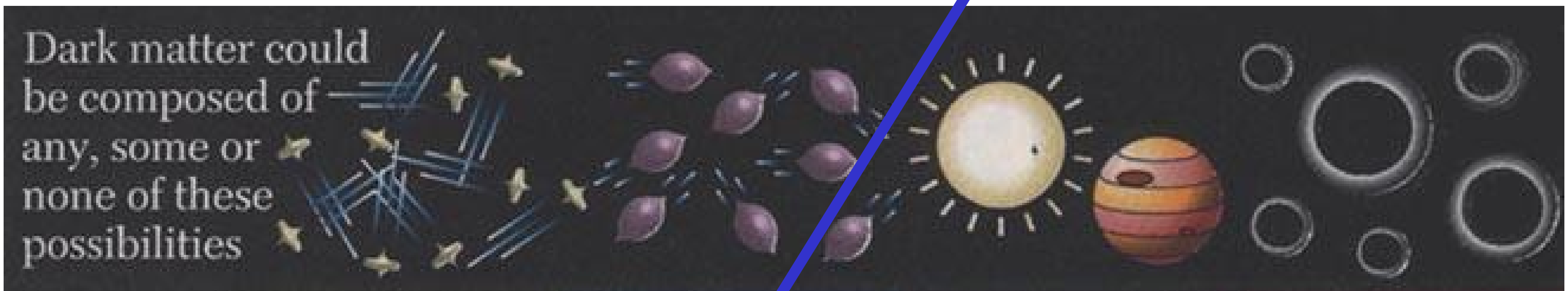


Recent evidence of m>0 from
- SuperKamiokande
- SNO
- K2K
- KamLAND

$\Delta M \sim 0.01$ eV
Mixing ~ maximal

Candidates: only WIMPS are left

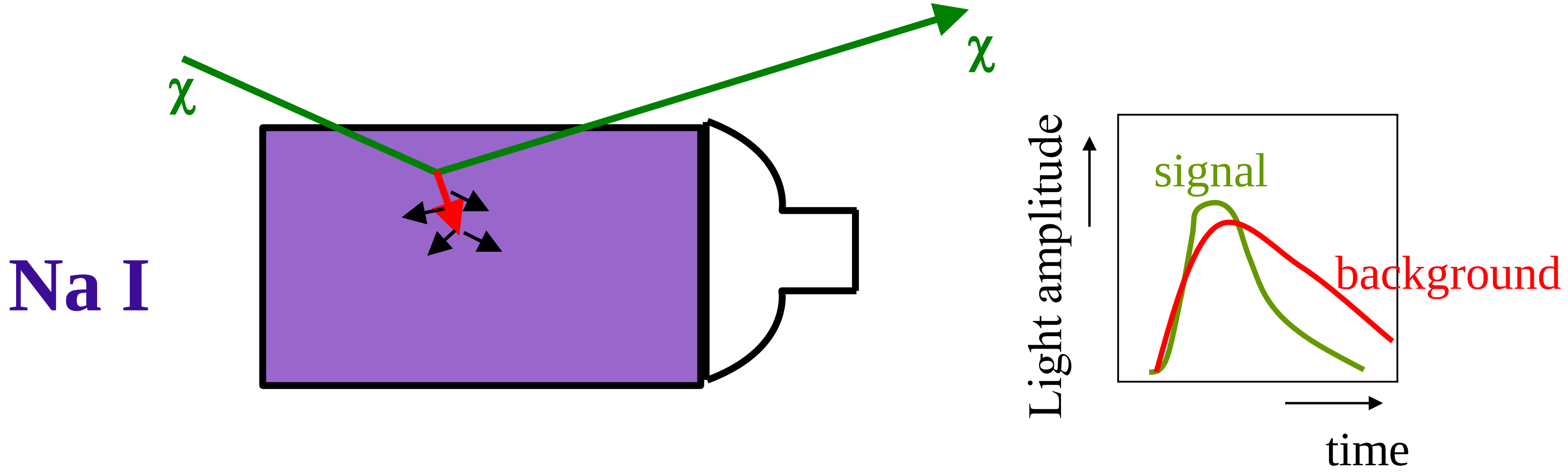
M > ~ 40 GeV
if SUSY (LEP)

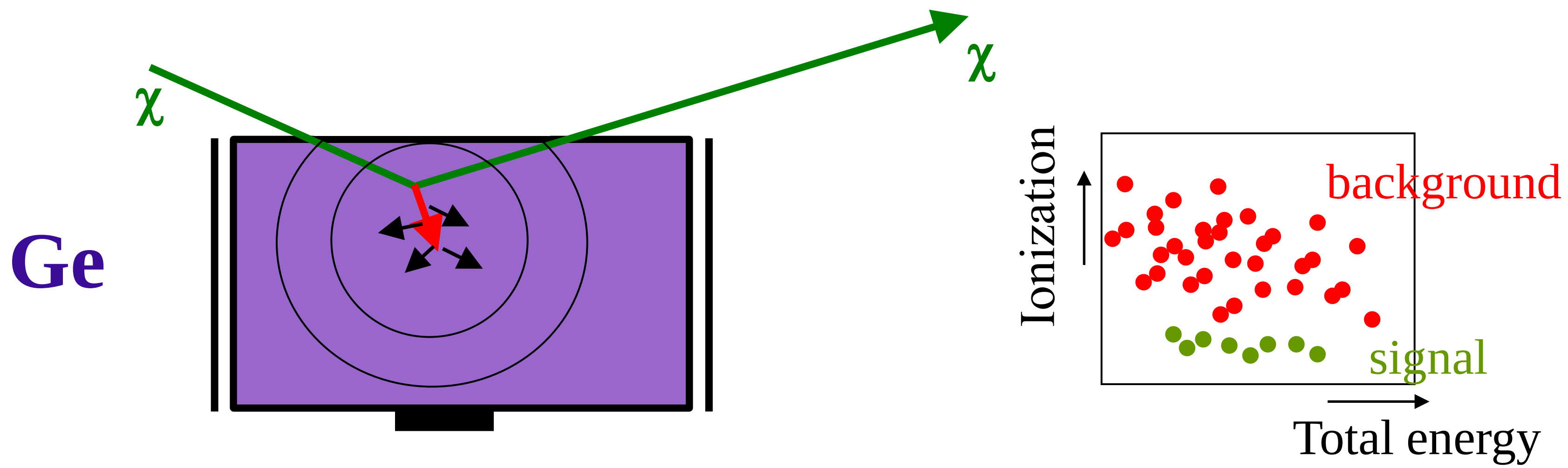


Name	Neutrinos	WIMPs	MACHOs	Black holes
What they are	Subatomic relatives of the electron that have no electrical charge and interact only weakly with ordinary matter	(Weakly interacting massive particles) Also known as cold dark matter	(Massive compact halo objects) Dim Jupiter-size planets or white dwarf stars made of ordinary matter	Objects with gravitational fields so intense that light cannot escape from them
Pros	Known to exist in great numbers	Existence is predicted by theories	The simplest theory	Strongly predicted by general relativity
Cons	[illegible] cannot account for existing cosmic structure	Are hypothetical	So many would be required that it seems unlikely that all the dark matter could be made of them	Their presence in such abundance should have been detected already

Direct WIMP Detection

Rejection of background is the critical issue



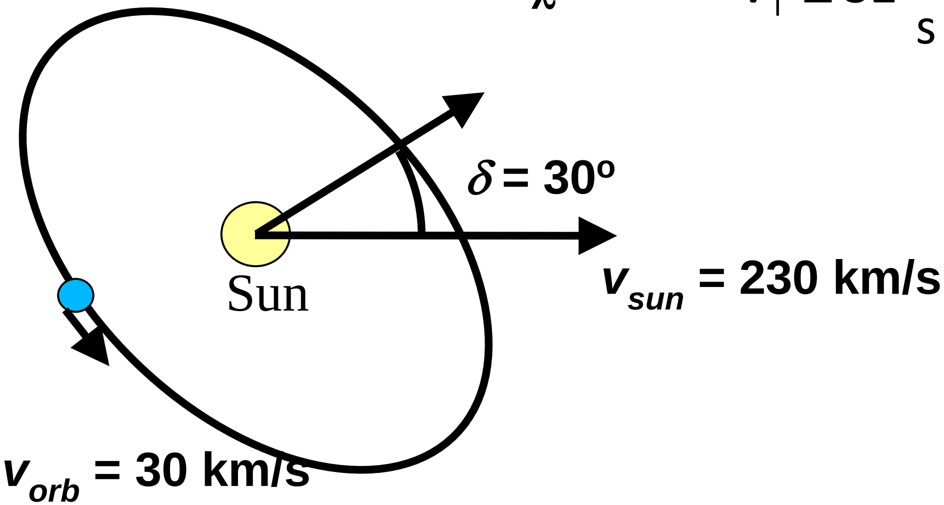


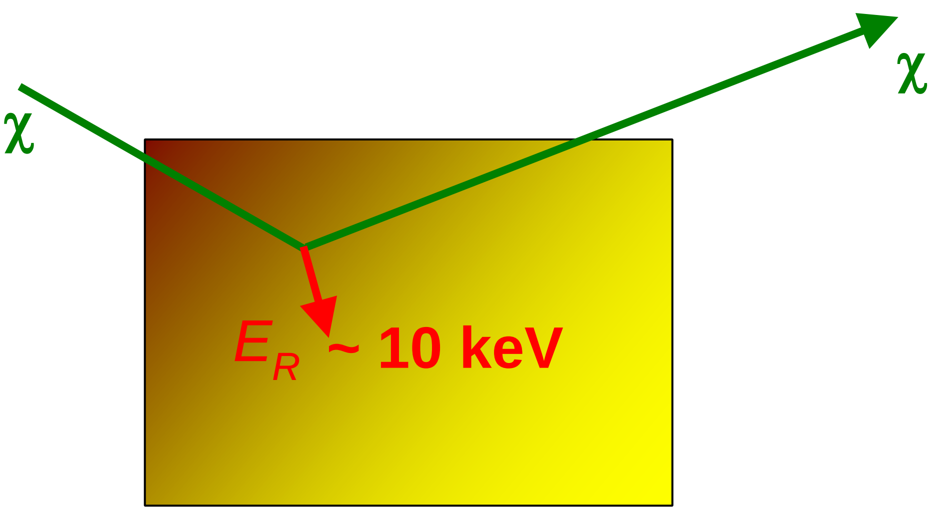
WIMP Direct Detection: modulation

Elastic interaction on nucleus, typical χ velocity ~ 250 km/s (β ~ 10^{-3})

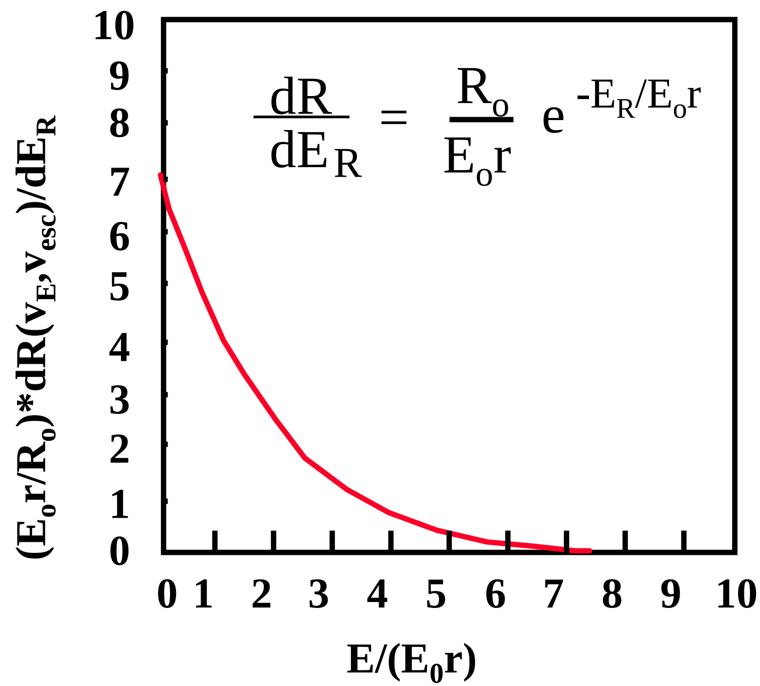
Motion of Earth in the χ wind

$$v_T \cong 32 \frac{m}{s} \sqrt{\frac{50\,\text{GeV}}{m_\chi}}$$





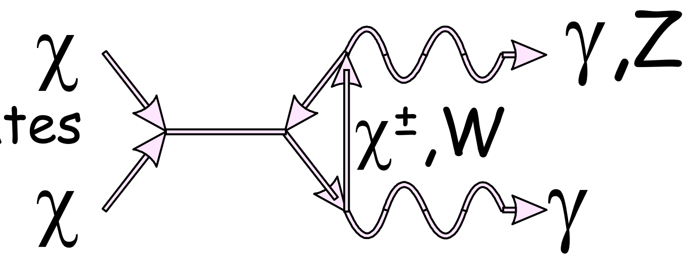
Recoil Spectrum



Featureless recoil energy spectrum
---> looks like electron background

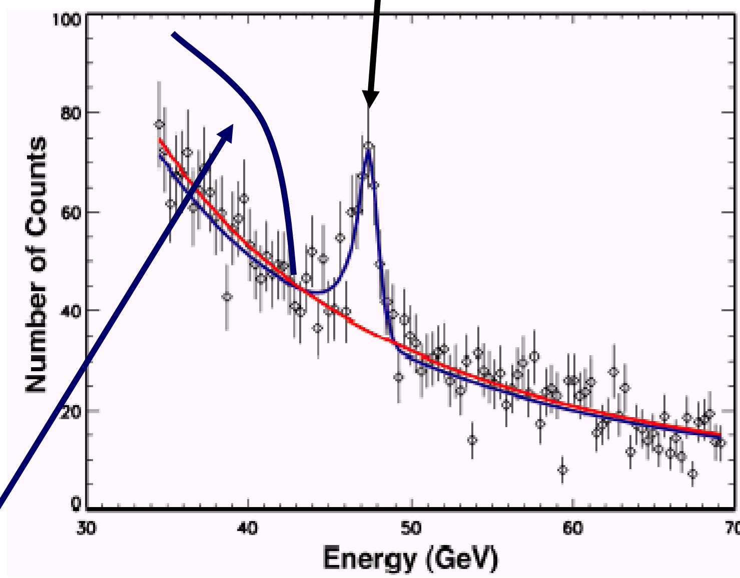
But… Annual modulation

WIMPS & gamma emission

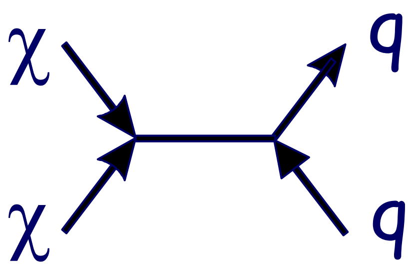


- Some DM candidates (e.g. SUSY particles) would lead to mono-energetic γ lines through annihilation into $\gamma\gamma$ or γZ:
  $E_\gamma = m_\chi \; / \; m_\chi - m_Z^2/4 m_\chi$
  => clear signature at high energies
  but: loop suppressed

Good energy resolution in the few % range is needed



- annihilation into qq -> jets -> n γ's
  => continuum of low energy gammas
  difficult signature but large flux



$$\chi\chi \to q\bar{q} \to n \times \gamma$$

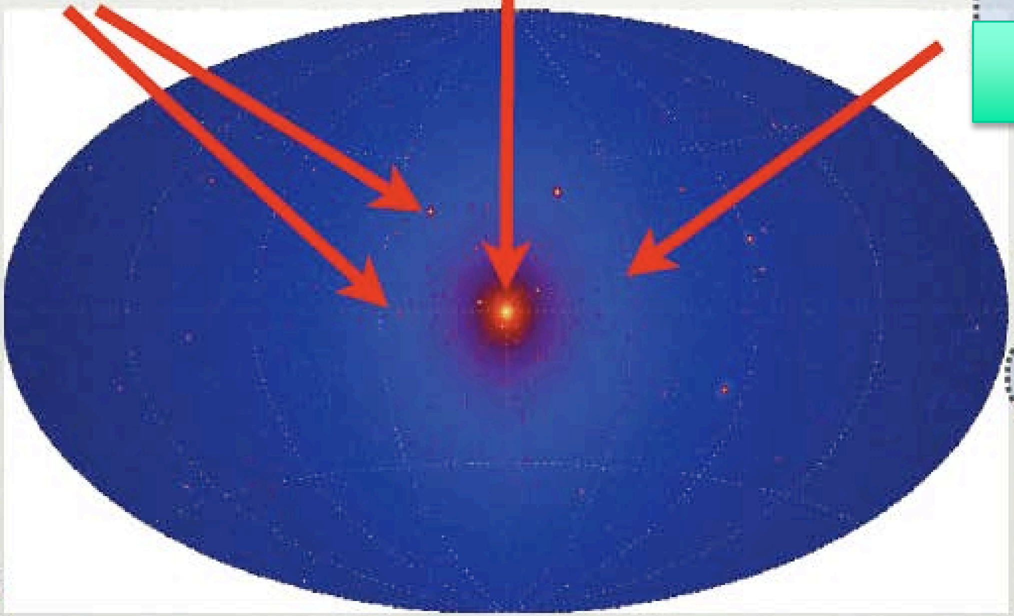
$$\chi\chi \to \gamma\gamma(Z)$$

Search Strategies

Galactic center:
Good statistics but source confusion/diffuse background

Satellites:
Low background and good source id, but low statistics

Milky Way halo:
Large statistics but diffuse background



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

And electrons!

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

Galaxy clusters:
Low background but low statistics

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

DM search
(Majorana WIMPs)

$$\chi\chi \to q\bar{q} \to n\times\gamma$$

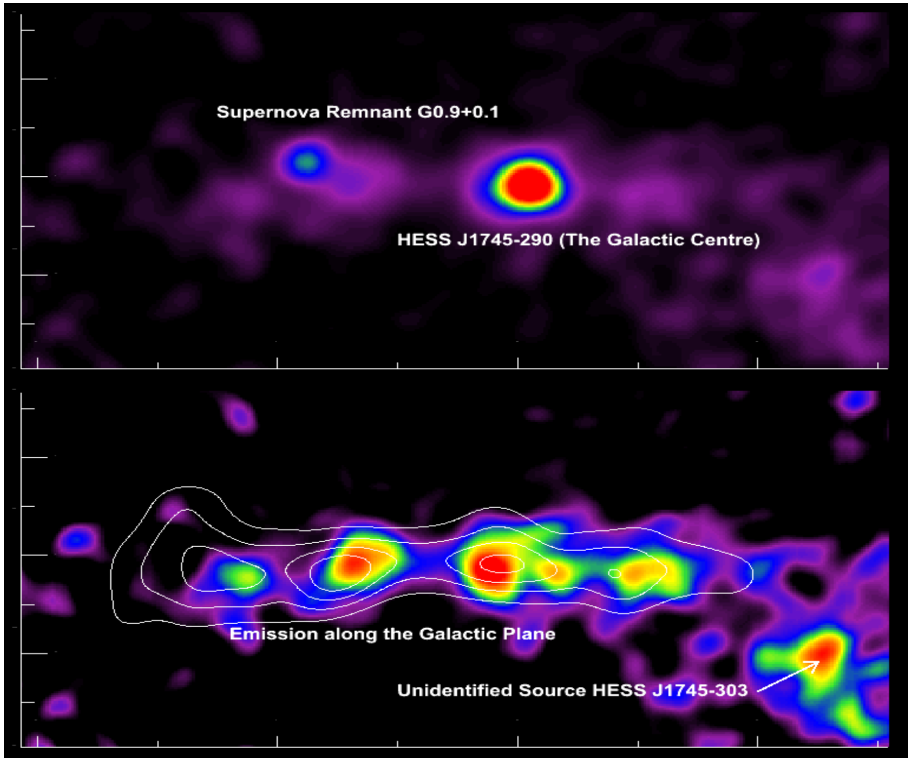
$$\chi\chi \to \gamma\gamma(Z)$$

$$\frac{dN}{dE} = \frac{1}{4\pi} \underbrace{\frac{\langle\sigma v\rangle}{m_{DM}^2}\frac{dN_\gamma}{dE}}_{Particle\ Physics} \times \underbrace{\int_{\Delta\Omega - los} dl(\Omega)\rho_{DM}^2}_{Astrophysics}$$

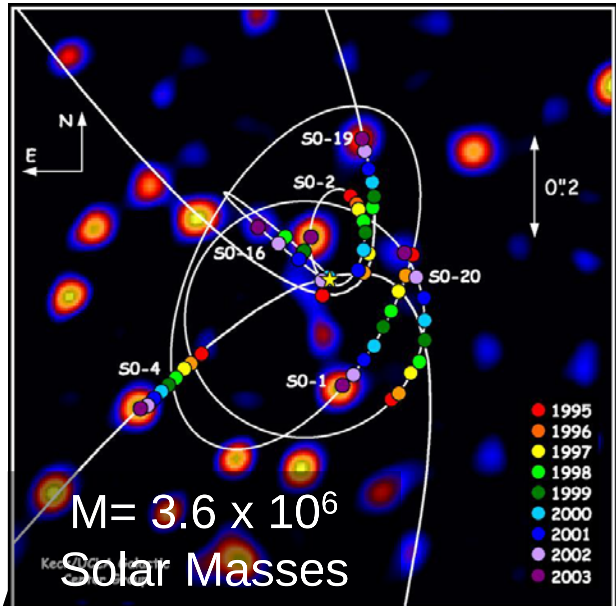
Highest DM density candidate:
Galactic Center?
Close by (7.5 kpc)
Not extended

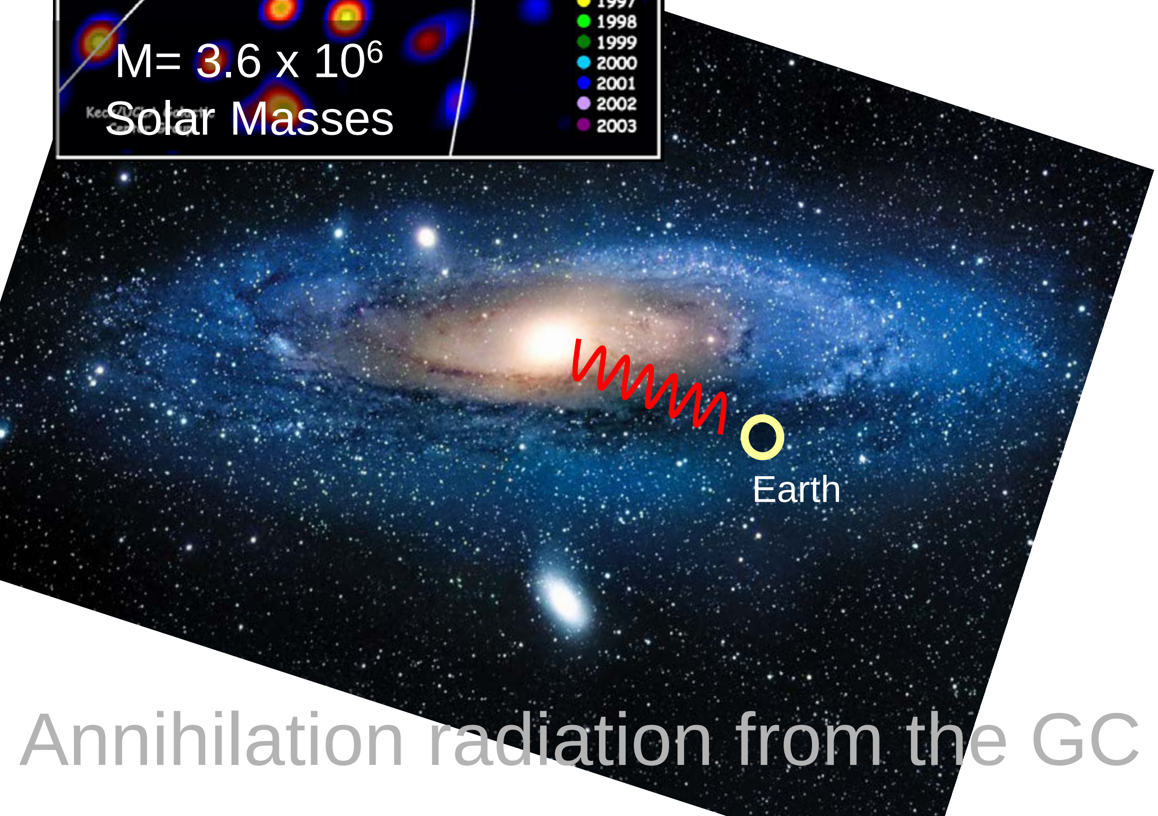
BUT:

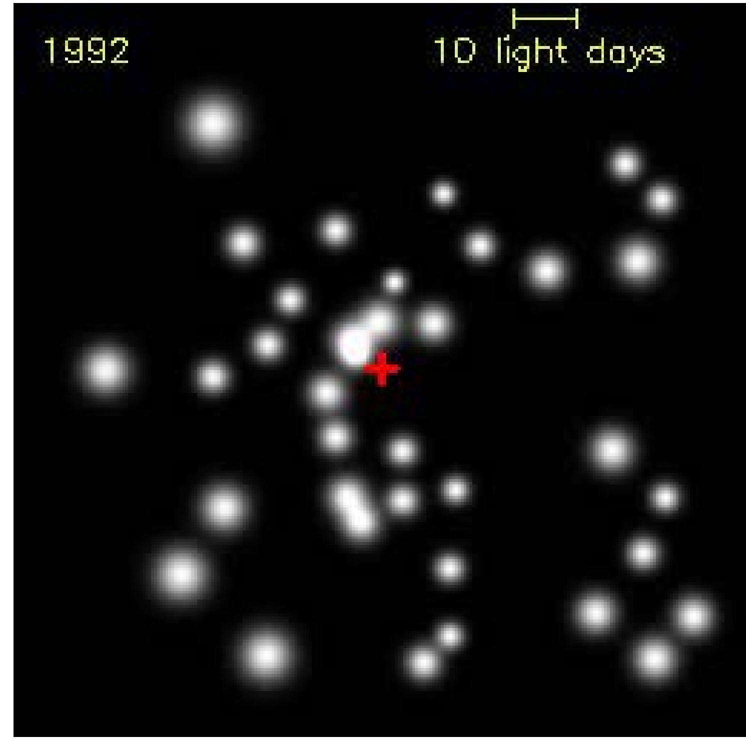
- other γ-ray sources in the FoV
=> competing plausible scenarios



A look to the GC…







X emission (variable)

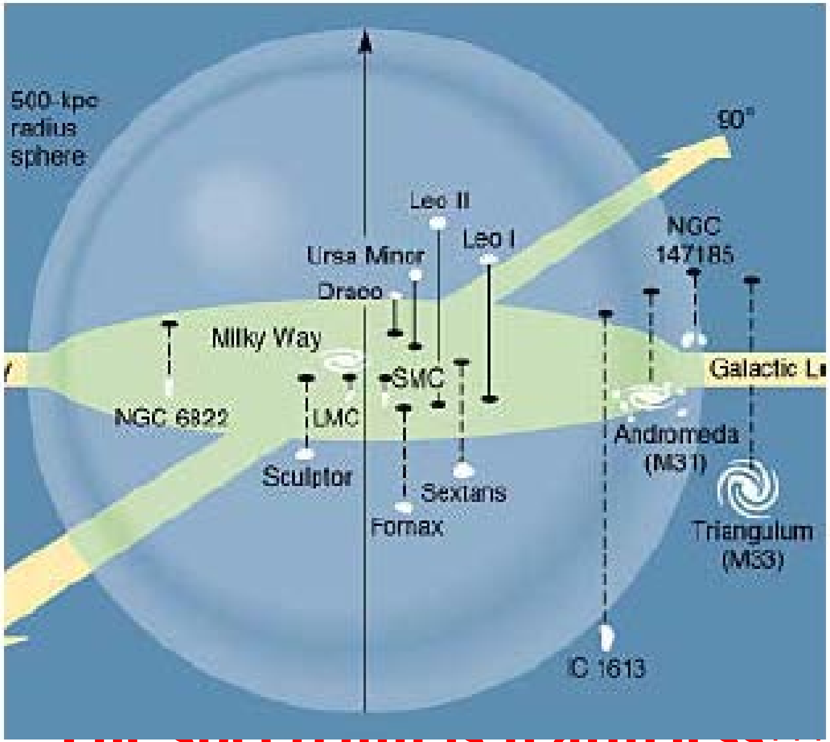
γ emission

Annihilation radiation from the GC

γ-ray detection from the Galactic Center

…and satellite galaxies

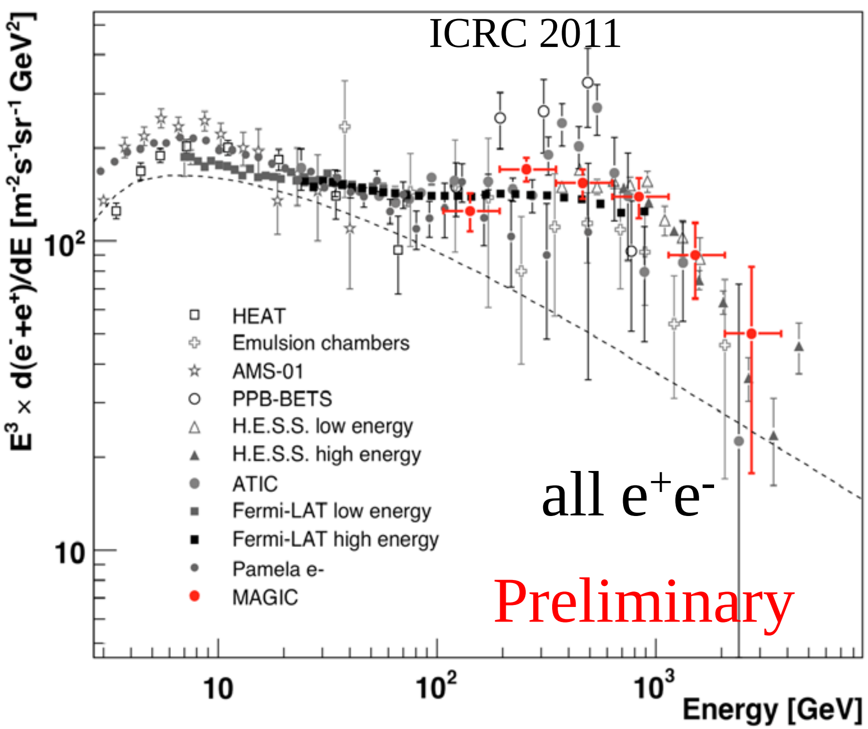
- detection of γ-rays from GC by Cangaroo, Whipple, HESS, MAGIC
- σ_{source} < 3' (< 7 pc at GC)
  - hard $E^{-2.21\pm0.09}$ spectrum fit to χ-annihilation continuum spectrum leads to: M_χ > 14 TeV
  - other interpretations possible (probable)



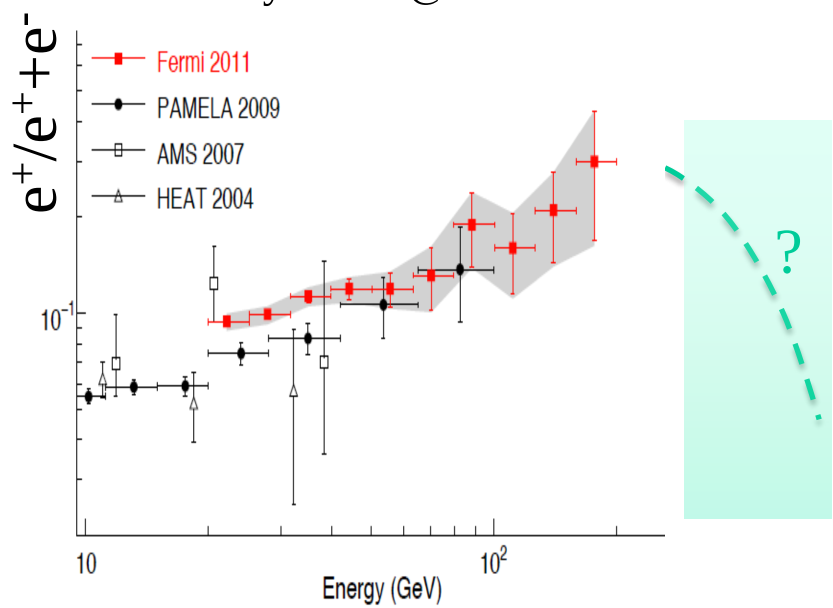
Milky Way satellites Sagittarius, Draco, Segue, Willman1, Perseus, …

- proximity (< 100 kpc)
- low baryonic content, no central BH (which may change the DM cusp)
- large M/L ratio
- No signal now…

Cosmic rays: the ATIC and PAMELA anomalies



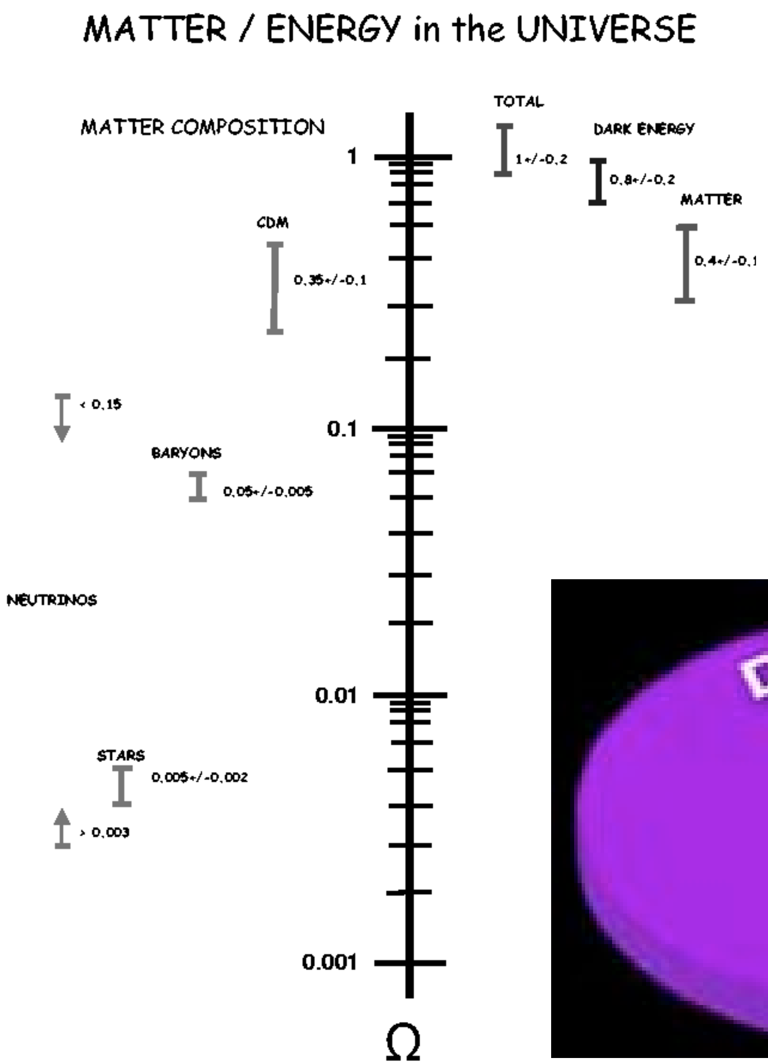
Unexpected increase in e^+/e^- ratio (PAMELA) confirmed by Fermi @ ICRC 2011:



Could be the signature of decays of new heavy unstable particles (or be explained by new astrophysical sources?)

Matter/Energy in the Universe: Conclusion

<u>**Must be something new**</u>



$$\Omega_{total} = \Omega_M + \Omega_\Lambda \sim 1$$

matter dark energy

Matter:

$$\Omega_M = \Omega_b + \Omega_\nu + \Omega_{CDM} \sim 0.3$$

baryons neutrinos cold dark matter

Baryonic matter :

$\Omega_b \sim 0.04$

stars, gas, brown dwarfs, white dwarfs

Neutrinos:

$\Omega_\nu \sim 0.003$

Dark Matter :

$\Omega_{CDM} \sim 0.23$

WIMPS/neutralinos, axions

III

High Energy Particles from space

***** 100 years! *****

Why does an electroscope spontaneously discharge?

- 1785: Coulomb found that electroscopes can spontaneously discharge by the action of the air and not by defective insulation
- 1835: Faraday confirms the observation by Coulomb, with better isolation technology
- 1879: Crookes measures that the speed of discharge of an electroscope decreased when pressure was reduced (conclusion: direct agent is the ionized air)

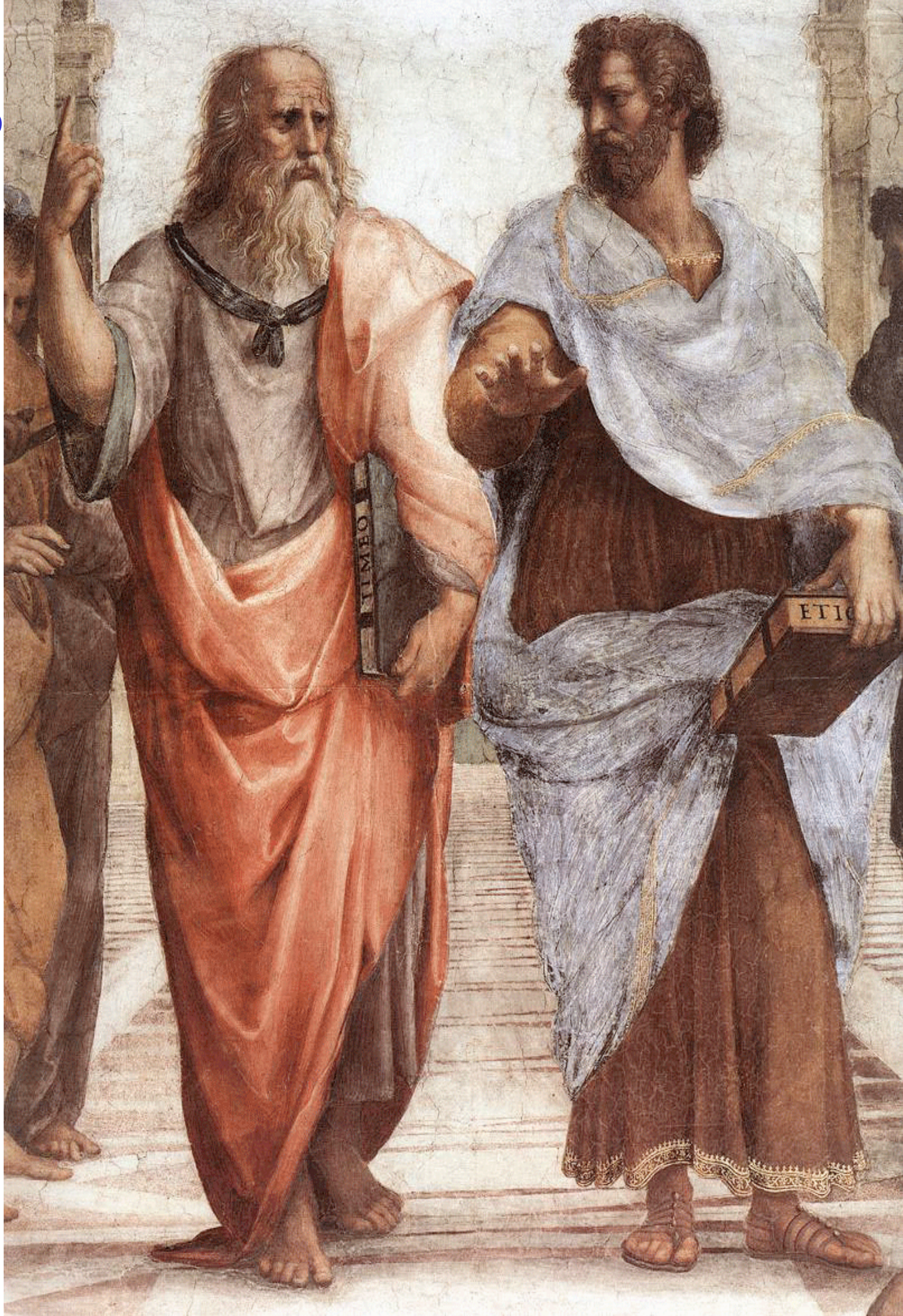
100 years later: cause might be radioactivity

- 1896: spontaneous radioactivity discovered by Becquerel
- 1898: Marie (31) & Pierre Curie discover that the Polonium and Radium undergo transmutations generating radioactivity (radioactive decays)
  - Nobel prize for the discovery of the radioactive elements Radium and Polonium: the 2nd Nobel prize to M. Curie, in 1911
  - In the presence of a radioactive material, a charged electroscope promptly discharges
  - Some elements are able to emit charged particles, that in turn can cause the discharge of the electroscopes.
  - The discharge rate of an electroscope was then used to gauge the level of radioactivity

Where does natural radioactivity come from?

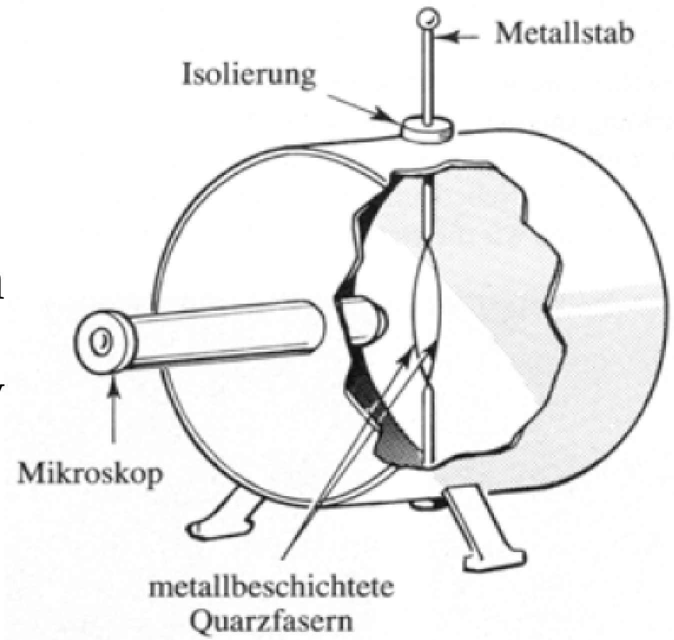
- For sure in part from the soil
- For sure in part from the Sun
- From the atmosphere?
- Is this the full story?

- In the beginning, the dominant opinion was that (almost) all the high energy radiation was coming from the soil



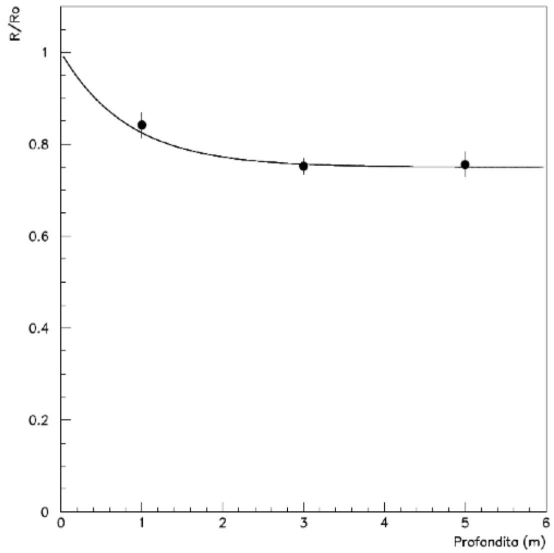
Father Wulf: a true experimentalist

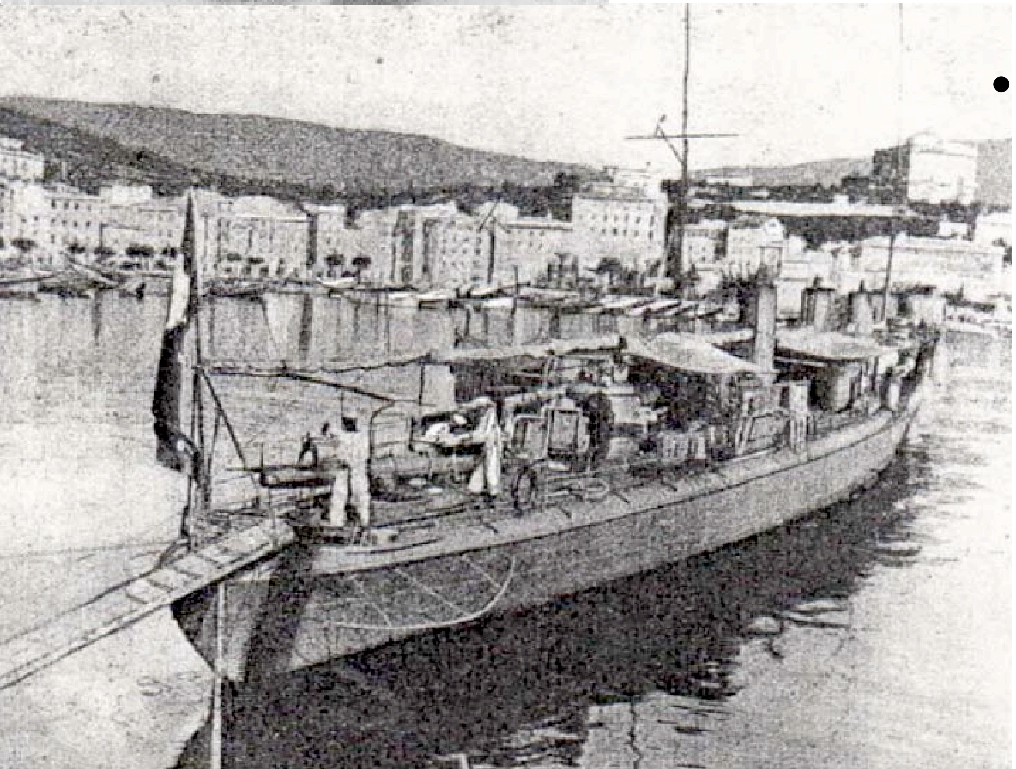
- Theodor Wulf, German Jesuit, professor in Holland and in Rome, perfected the electroscope in 1908-09, up to a sensitivity of 1 volt, making it transportable; he had the idea if measuring radioactivity on top of the Eiffel tower (~300 m) and compare to ground, at day and night
  – The decisive measurement: Wulf was on a Easter holiday trip to Paris and brought a few electroscopes with him
- If most of the radioactivity was coming from the soil, an exponential decrease $e^{-h/\lambda}$ was expected
- Results were not completely consistent, but interpreted as a confirmation of the dominant opinion: radioactivity came from the soil



Domenico Pacini's break-through

- Domenico Pacini, meteorologist in Roma and then professor in Bari, compares the rate of ionization on mountains, over a lake, and over the sea

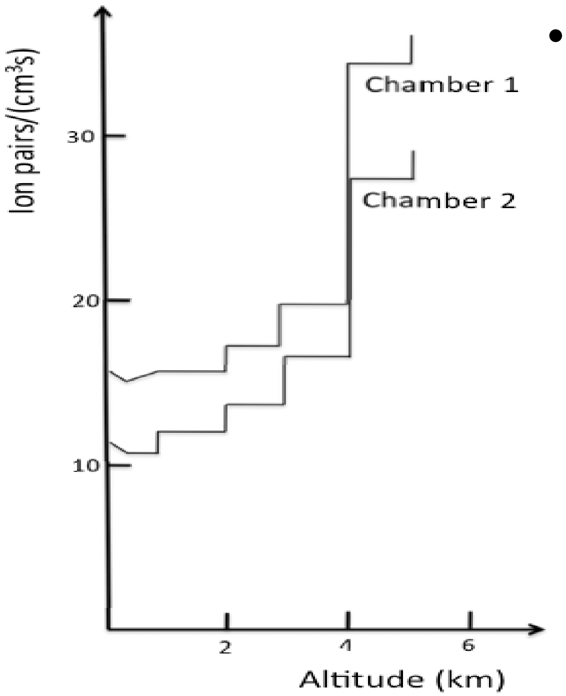




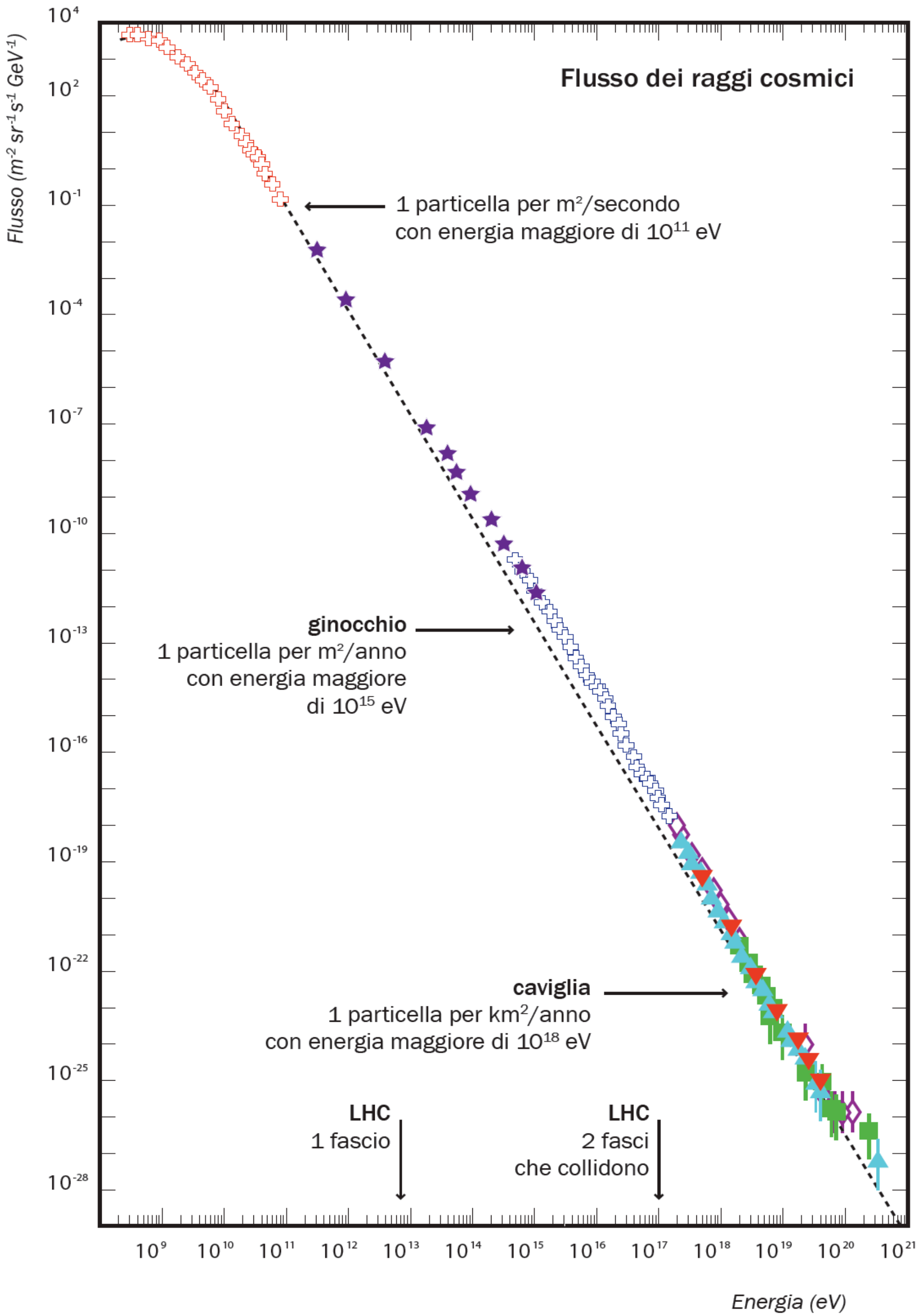
- In June 1911, a great idea: immersing an electroscope 3m deep in the sea (at Livorno and later in Bracciano) Pacini, 33-y-old, finds a significant (20% at 4.3σ) reduction of the radioactivity
  - He publishes in Nuovo Cimento that *a sizable cause of ionization exists in the atmosphere, originating from penetrating radiation, independent of the direct action of radioactive substances in the soil*

The definitive proof: Hess

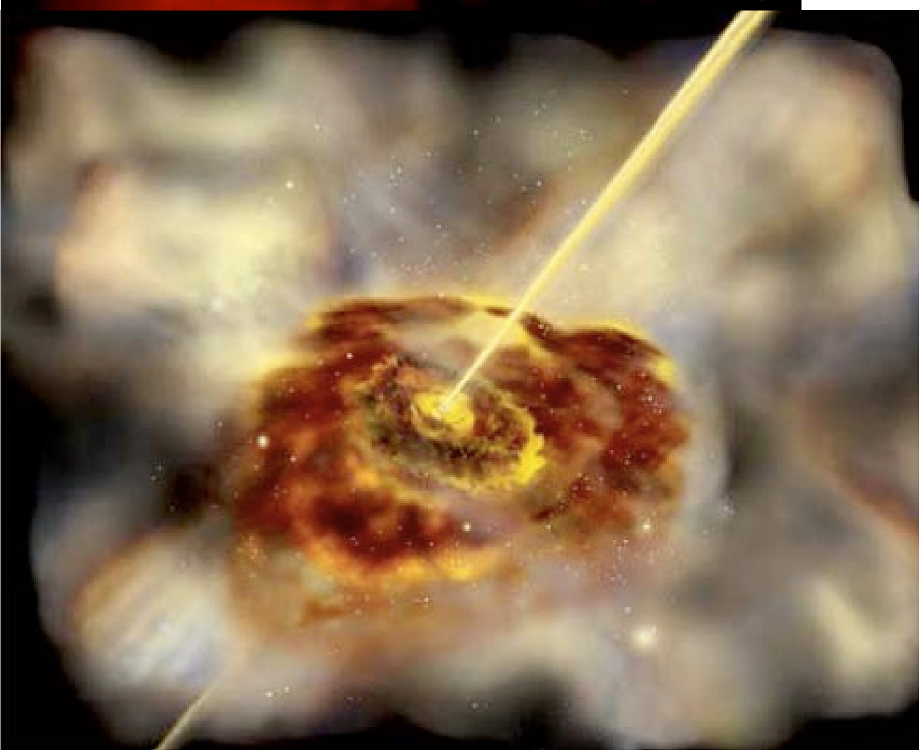
- The Austrian Victor Hess, at that time working in Wien, started studying Wulf's electroscope, and measuring carefully the absorption coefficients of radioactivity in air
- In 1911, he continued his studies with balloon observations: he made 2 ascensions at ~1300 m, measuring possible variations of radioactivity, and found no effect. He had 3 Wulf electroscopes in Zn boxes of different thicknesses
- From April 1912 to August 1912 Hess had the opportunity to fly 7 times. In the final flight, on August 7, Hess, 29-y-old, reached 5200 m
  - His results showed that the ionization, after passing a minimum, increased considerably with height
  - He concluded that the increase of the ionization with height is due to a radiation coming from above, and thought that this radiation had extra-terrestrial origin



Phenomenology of Cosmic Rays - I



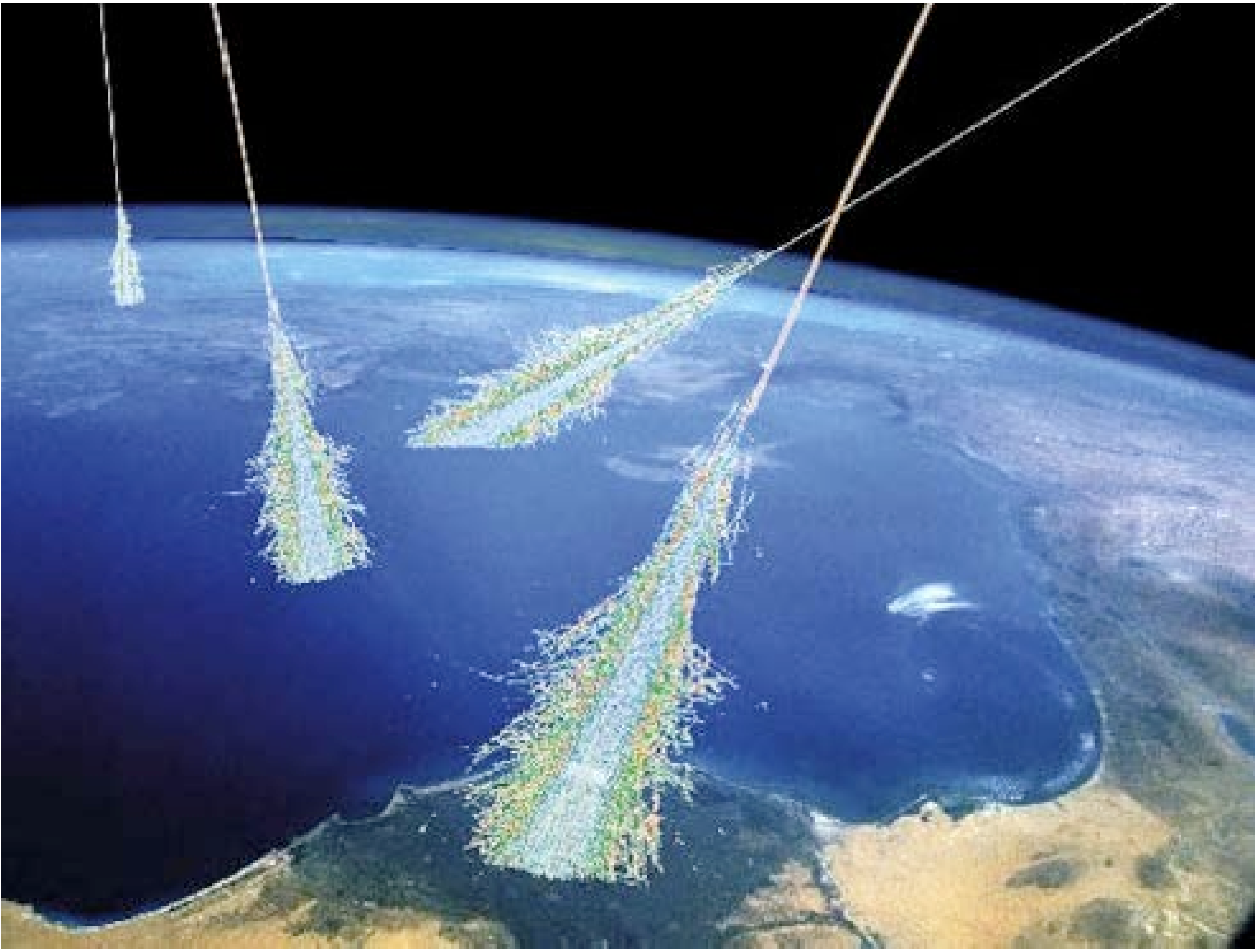
- Cosmic rays (CR) are subatomic particles reaching the Earth from outside
- The flux depends strongly on energy
  - Once per second, a single subatomic particle with the energy of a tennis ball (10 J) hits the atmosphere
  - 100 million times the energy we can produce on Earth (LHC)



Phenomenology of Cosmic Rays - II

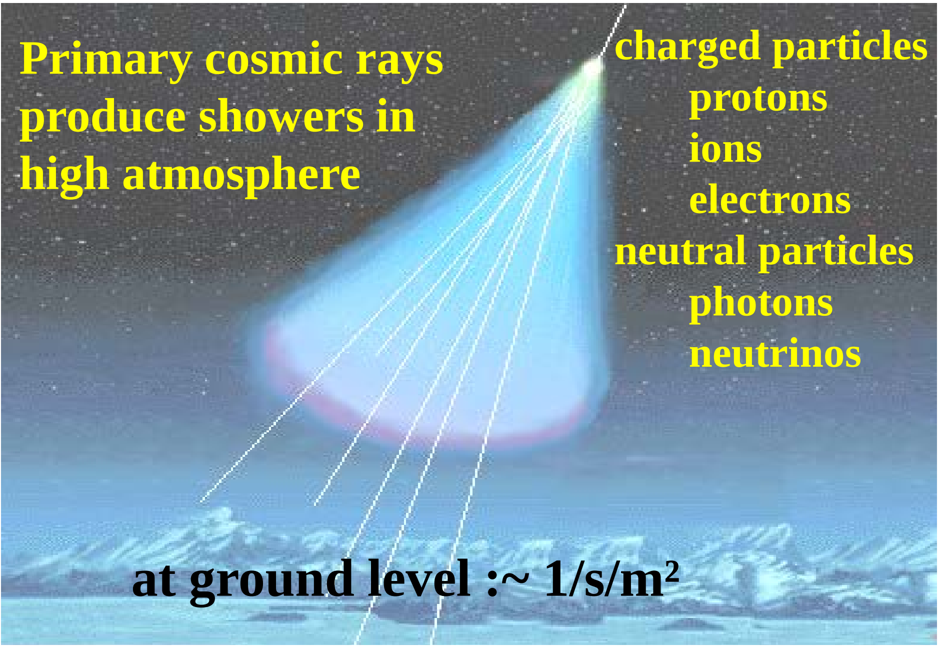
- Cosmic rays appear to be more or less isotropical
  - Once correcting for geomagnetic effects, since they are mostly charged
- Kinetic energy is likely to come from potential gravitational energy (cosmic collapses)
  - Below ~10 PeV: likely to be Galactic (supernova remnants)
  - Above: likely to be extragalactic (accreting supermassive black holes)

Phenomenology of Cosmic Rays - III



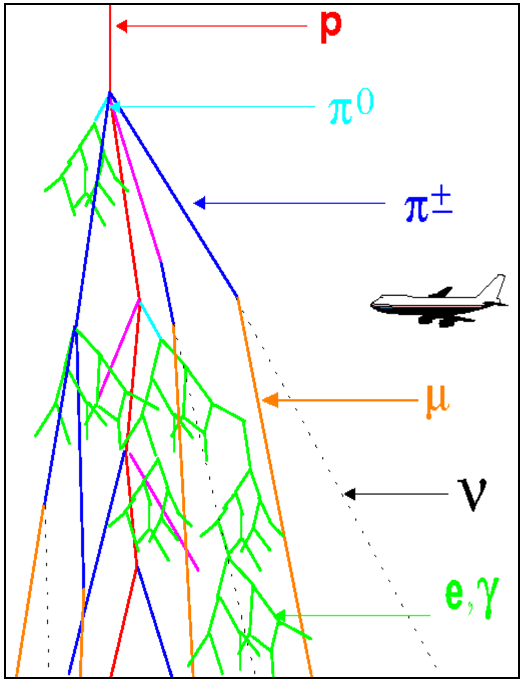
- Once cosmic rays hit the atmosphere, they are absorbed generating showers of particles
- The atmosphere protects us from this radioactivity (which affects people living on top of the mountains and airplane crews)

Phenomenology of Cosmic Rays - IV



Primary:

p 80 %, α 9 %, n 8 %
e 2 %, heavy nuclei 1 %
γ 0.1 %, ν 0.1 % ?

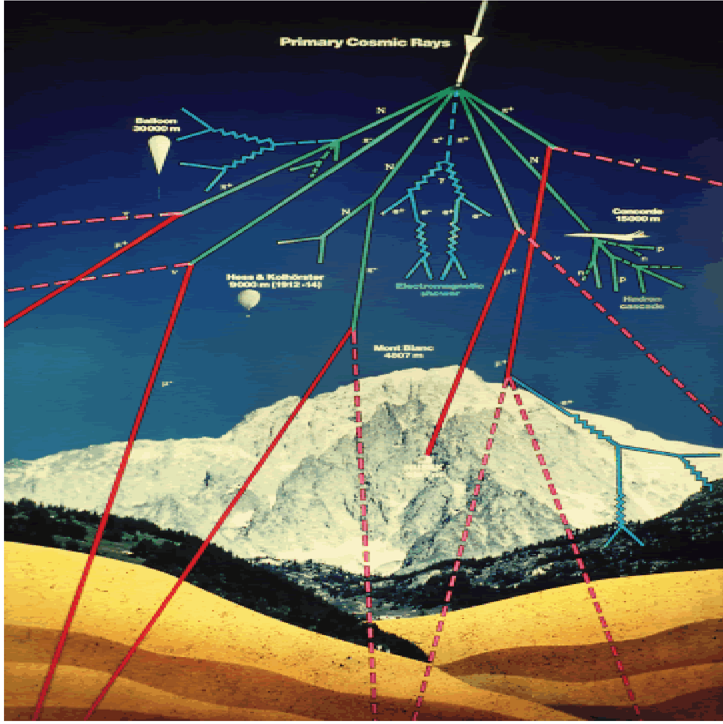


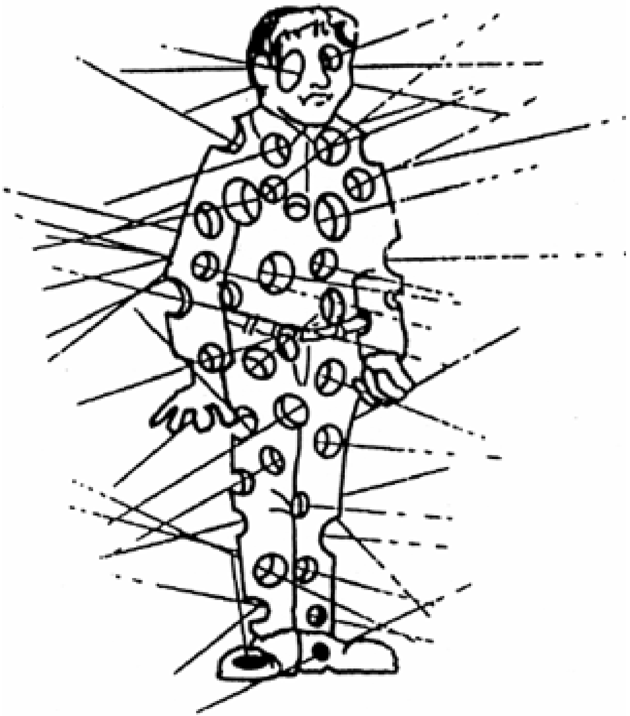
Secondary at ground level:

ν 68 %
μ 30 %
p, n, ... 2 %

Cosmic Rays on Earth

- CR hit frequently the Earth: about 100 000 particles originated by CR cross in an hour the body of each of us
  - And approaching Northern Scandinavia the situation gets worse…

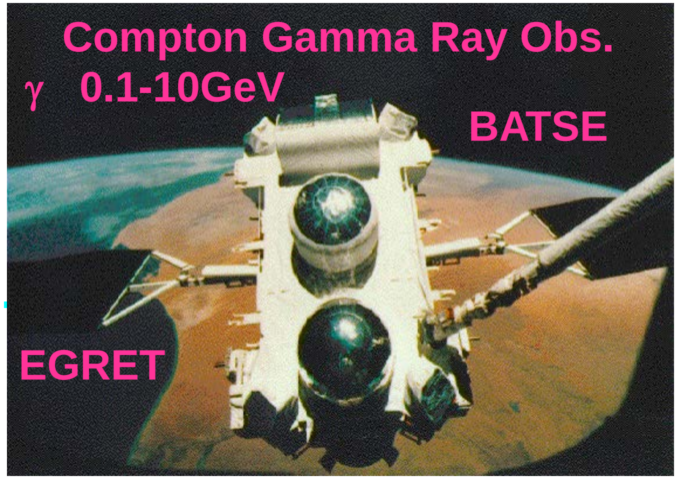




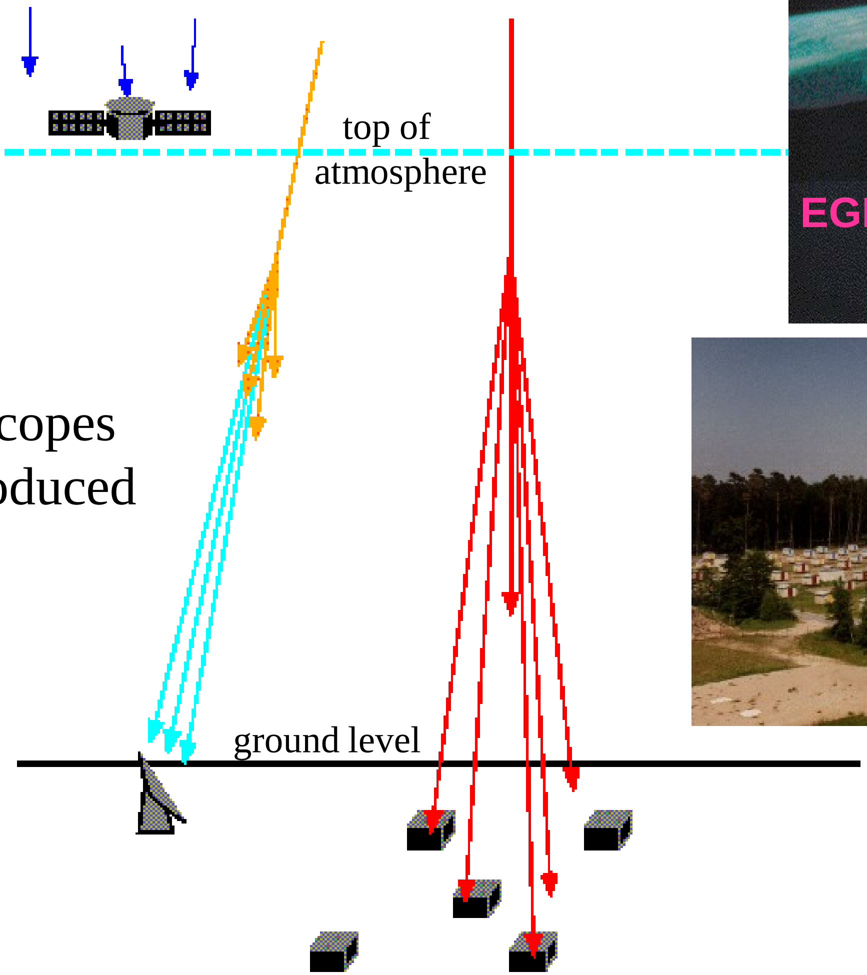
- This is an important contribution to the dose of ambiental radioactivity to which we are exposed

- *Underground* experiments for the penetrating component (muons, neutrinos)

Types of Cosmic Ray Detectors

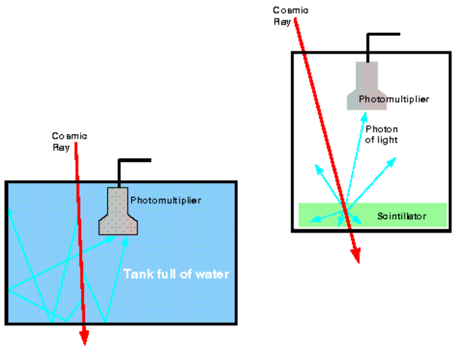


Satellites

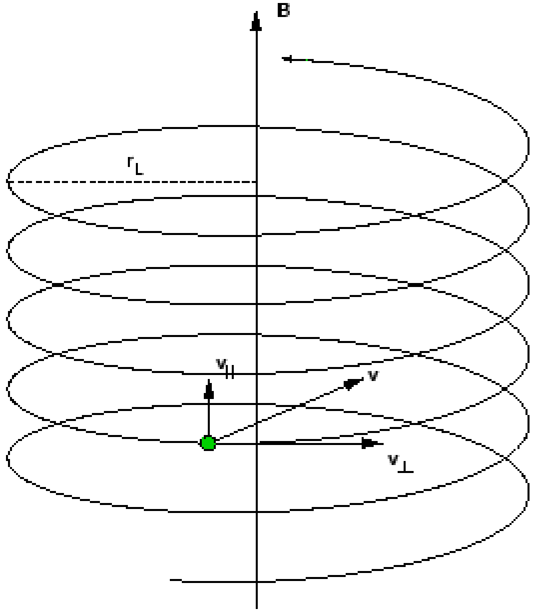


Ground based telescopes
looking at light produced
in atmosphere

Arrays of particle detectors



Curvature radius of a charged particle moving in a magnetic field



- **Larmor radius:**

$$m\frac{v^2}{r} = \frac{pv}{r} \overset{Lorentz}{=} Ze \cdot \frac{v}{c} \cdot B$$

$$r = \frac{pc}{ZeB} \cong \frac{E}{ZeB}$$

$$r_{Larmoor} = \frac{1.6\times10^{-12}(erg/ev)\cdot E(eV)}{Z\cdot(4.8\times10^{-10}u.e.s.)B(Gauss)} = \frac{1}{300}\frac{E}{ZB}(eV/Gauss)$$

Confinement

$$r_{Larmor} = \frac{1}{300}\frac{E}{ZB}(eV / Gauss)$$

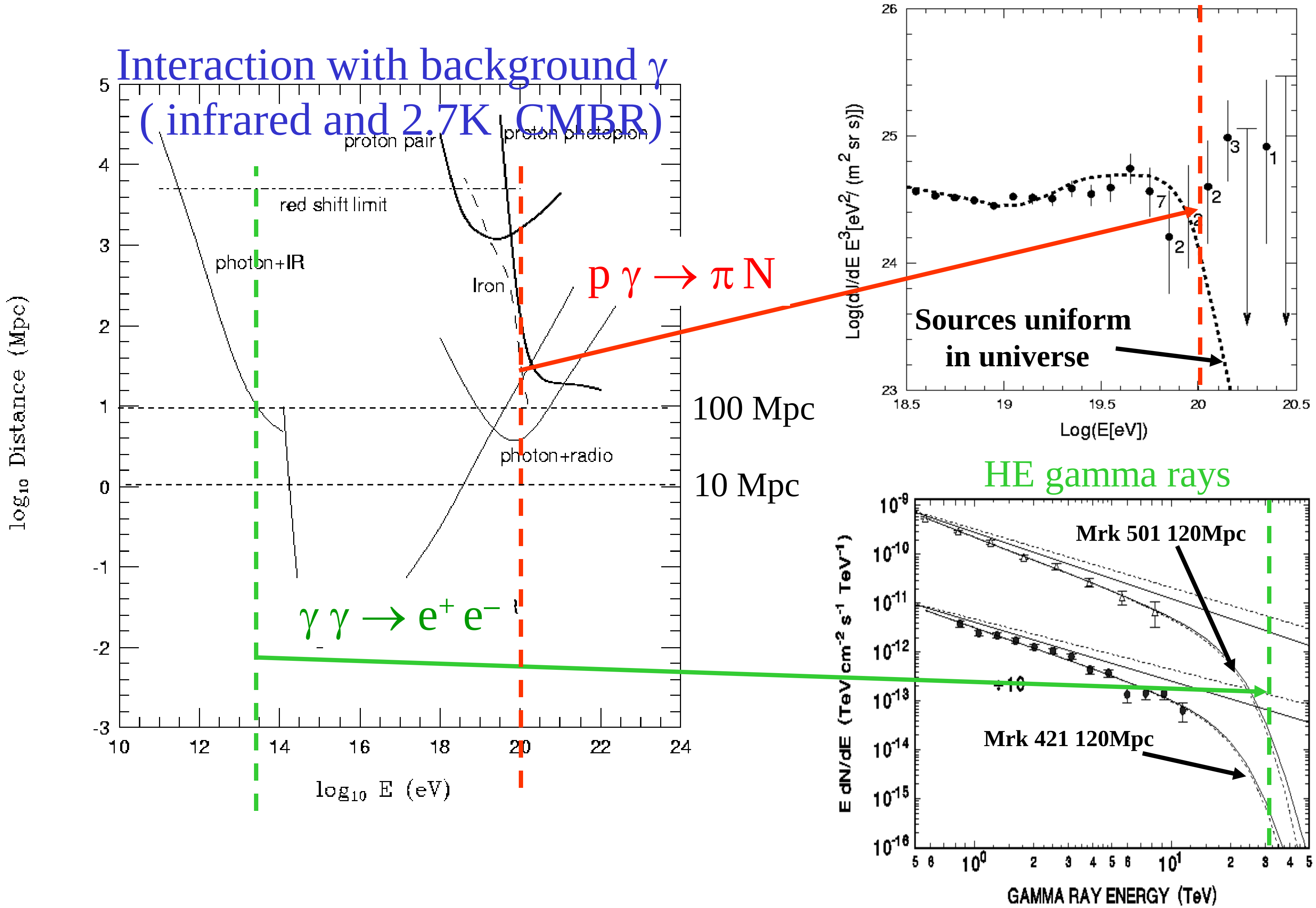
- For protons (Z=1) in the galactic field B ~ 3×10^{-6} G

$$r_L = \begin{cases} (E = 10^{12} eV) & = 10^{15} cm = 3\cdot10^{-4}\ pc \\ (E = 10^{15} eV) & = 10^{18} cm = 0.3\ \ pc \\ (E = 10^{18} eV) & = 10^{21} cm = 300\ \ pc \end{cases}$$

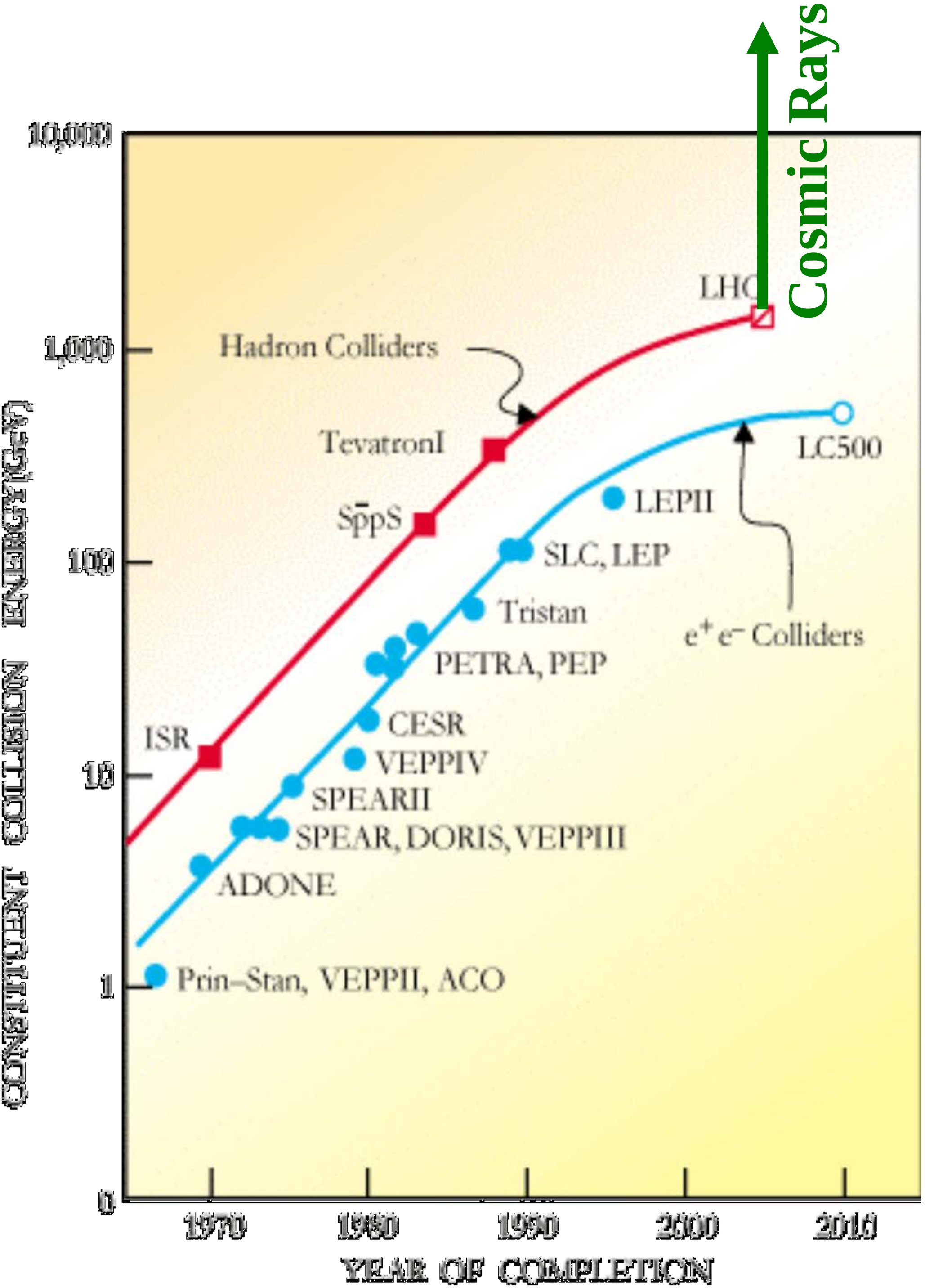
- Protons with E<10^{18} eV have a Larmor radius < the galactic radius (300 pc).

=> Cosmic Rays below E<10^{18} eV are ***confined*** in the Galactic Plane

‘GZK cutoff ’



HE cosmic rays
Interaction with background γ
(infrared and 2.7K CMBR)
proton pair
proton photopion
red shift limit
photon+IR
Iron
photon+radio
p γ → π N
γ γ → e⁺ e⁻
100 Mpc
10 Mpc
log₁₀ Distance (Mpc)
log₁₀ E (eV)
Log(dI/dE E³[eV²/ (m² sr s)])
Log(E[eV])
Sources uniform
in universe
HE gamma rays
Mrk 501 120Mpc
Mrk 421 120Mpc
E dN/dE (TeV cm⁻² s⁻¹ TeV⁻¹)
GAMMA RAY ENERGY (TeV)



The future of HEP?

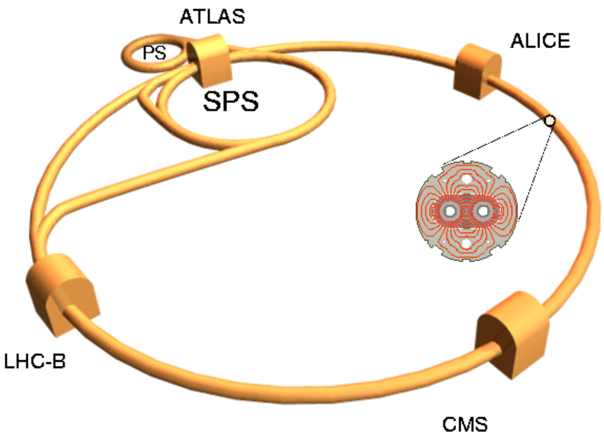
- Higher energies are not the full story…

  Also small x (lost in the beam pipes for collider detectors)

Particle Acceleration

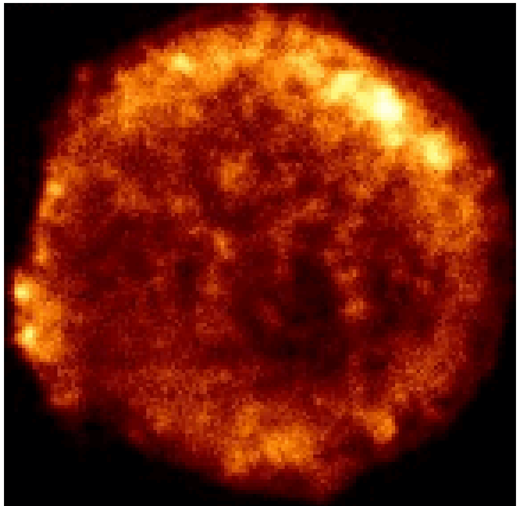
$E \propto BR$

Large Hadron Collider



$R \sim 10\,\text{km},\ B \sim 10\,\text{T} \quad \Rightarrow E \sim 10\,\text{TeV}$

Tycho SuperNova Remnant



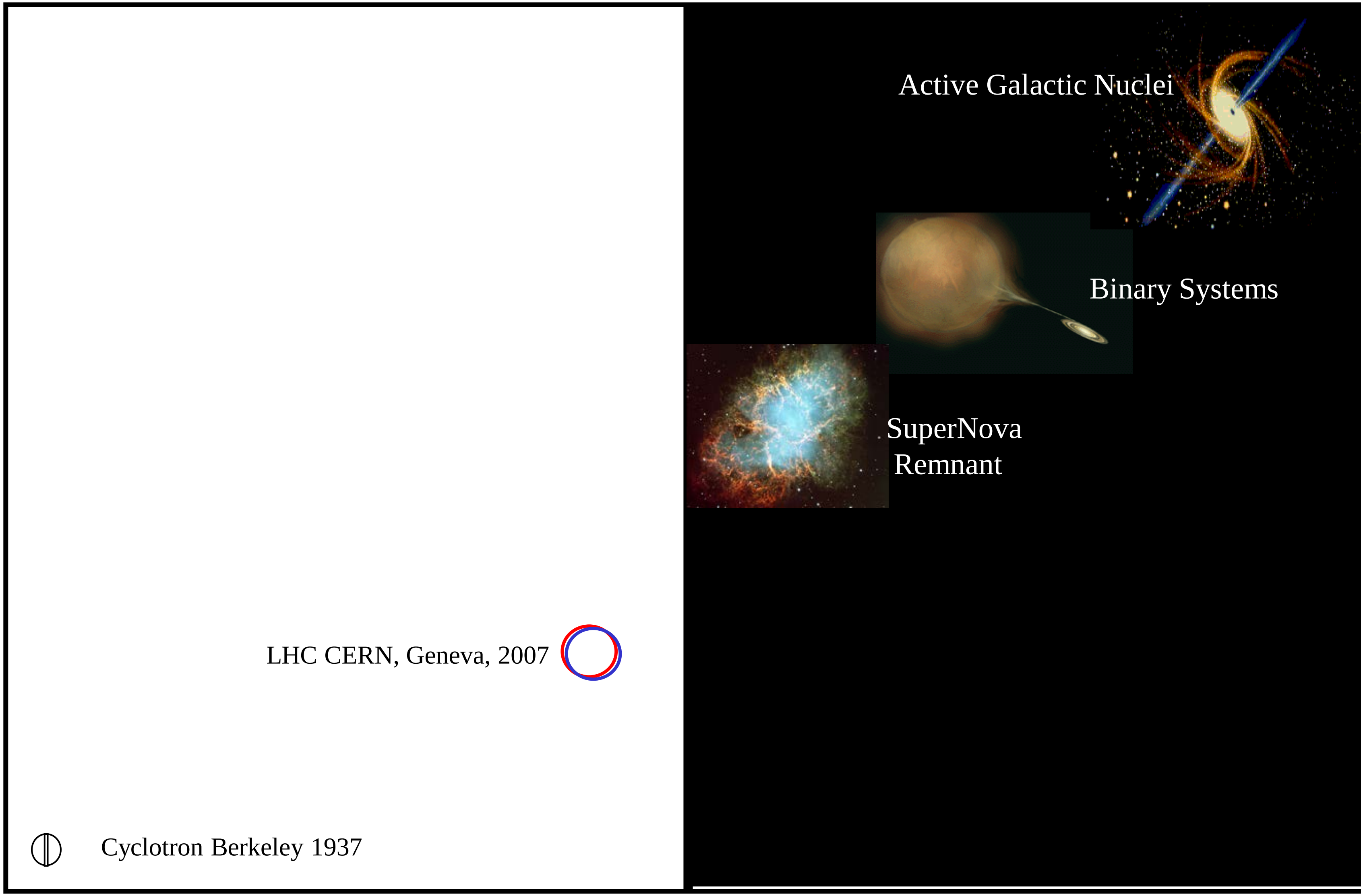
$R \sim 10^{15}\text{km},\ B \sim 10^{-10}\text{T} \quad \Rightarrow E \sim 1000\,\text{TeV}$

(NB. $E \propto Z \rightarrow$ Pb/Fe higher energy)

Particle Physics ⇒ Particle Astrophysics

Terrestrial Accelerators | Cosmic Accelerators

Diameter of collider



Energy of accelerated particles

How are they produced? (Possible acceleration sites)

- Wherever you have gravitational collapses, you can convert gravitational potential energy into kinetic energy of particles
  - Galactic sources (supernova remnants, binaries…) certainly able to produce particles up to ~ 100 TeV
    - Below the knee?
    - Galactic magnetic field ~1-3 μG can trap protons up to the knee
  - Beyond this energy? Active Galactic Nuclei (supermassive black holes, ~10^9 solar masses, accreting at the expense of local matter – with big flares)

AUGER

2 sites each 3000km^2, E > 5.10^{18}eV

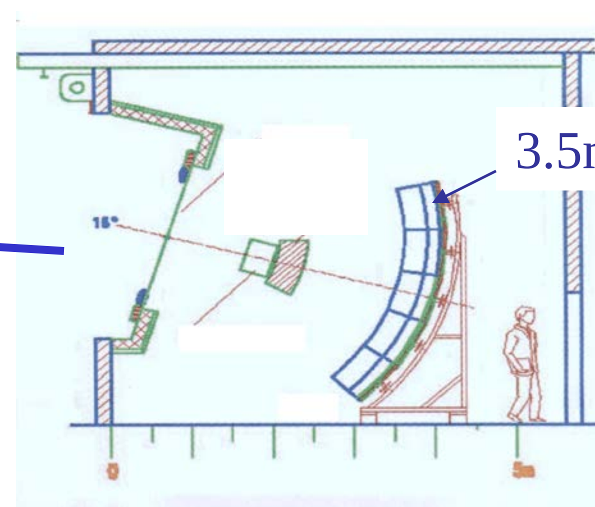
Southern site,
Mendoza Province,
Argentina

Water Cherenkov

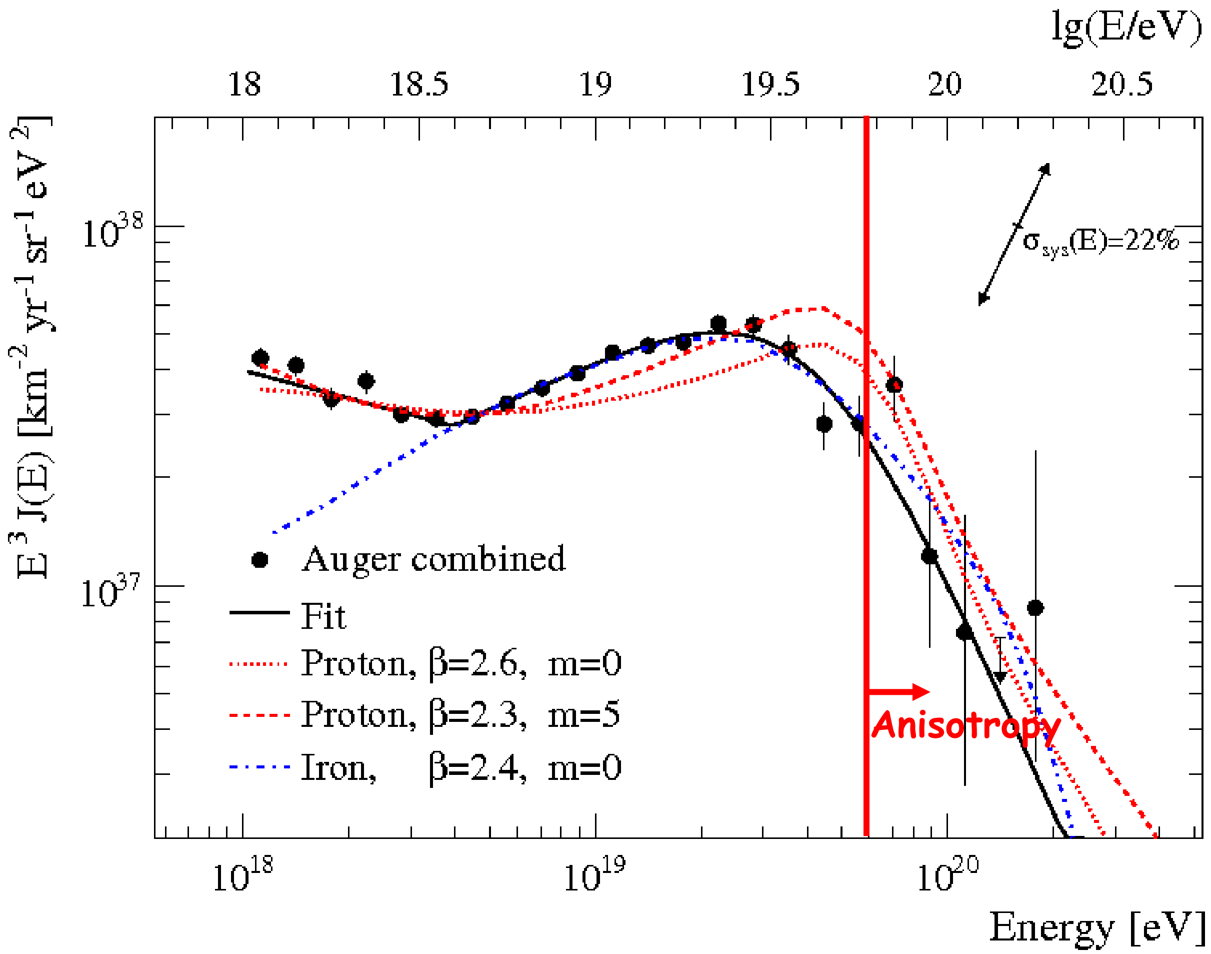
Tanks

(1600 each 10m^2)

Fluorescence Telescopes (6 telescopes each 30° ×30° at 4 sites)

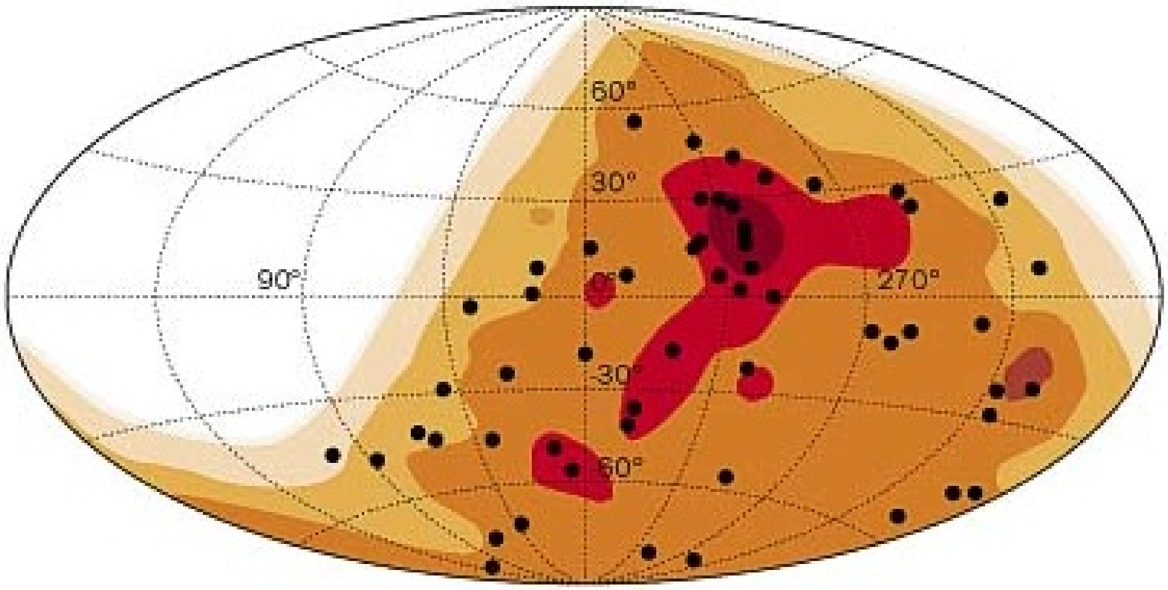


AUGER and GZK

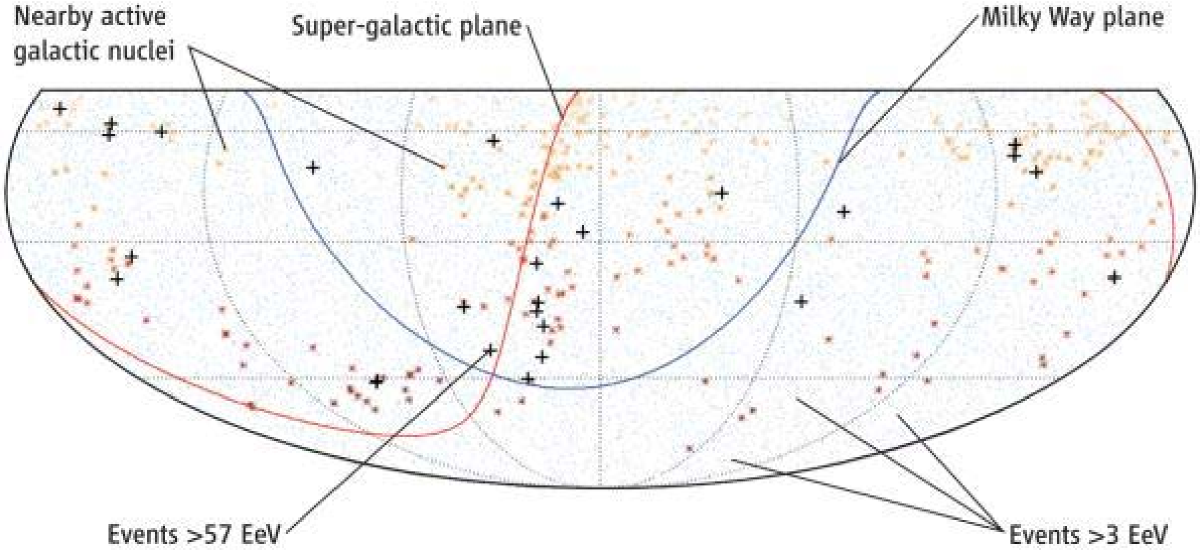


The origin of cosmic rays at VHE

- On Nov 9, 2007, the Pierre Auger Collaboration (J. Cronin, A. Watson et al.) published in Science an article saying that 12/15 events above 10 J were located within 3.1° of AGN closer than 75 Mpc from Earth
  - Three years later, correlation still there…



Conclusion form the Auger result



– Active Galactic Nuclei are the main source of VHE cosmic rays
– First measurement of the extragalactic magnetic field in the local group:

$$B \sim 0.1 - 1 \text{ nG}$$

(dA, Roncadelli and Persic 2007)