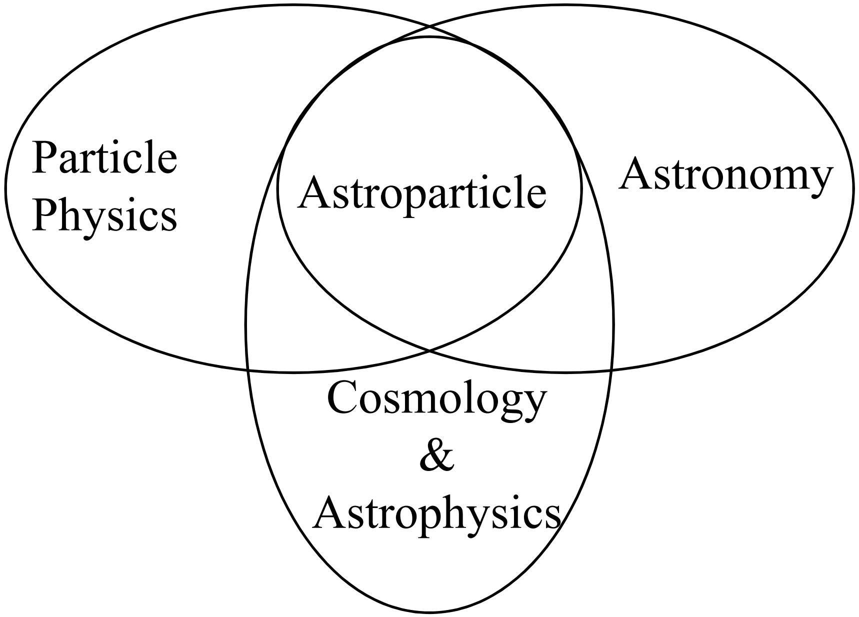
Experimental Astroparticle Physics
(a short introduction)

Alessandro De Angelis
INFN & Univ. Udine; IST Lisboa

Lund 2009

Lectures 1, 2 & 3

What is Astroparticle Physics (Particle Astrophysics?)



Particle Physics

Astroparticle

Astronomy

Cosmology & 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

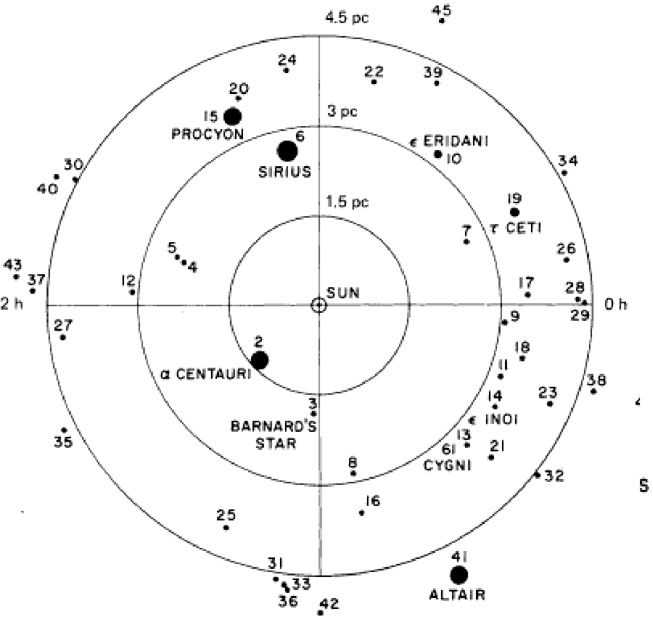
In this lecture I’ll concentrate on the 2nd topic

I

A quick look to our Universe

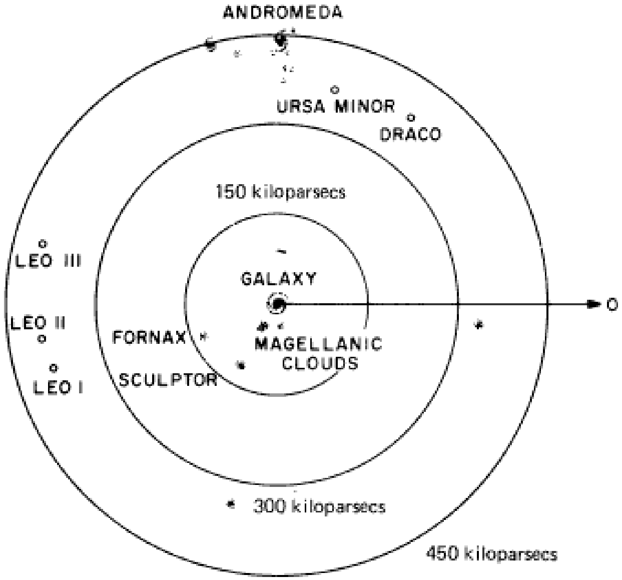
Astronomy Scales

Nearest Stars



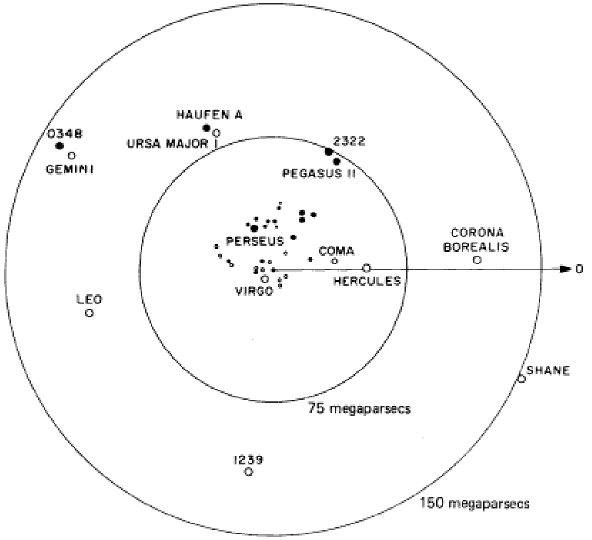
4.5 pc

Nearest Galaxies



450 kpc

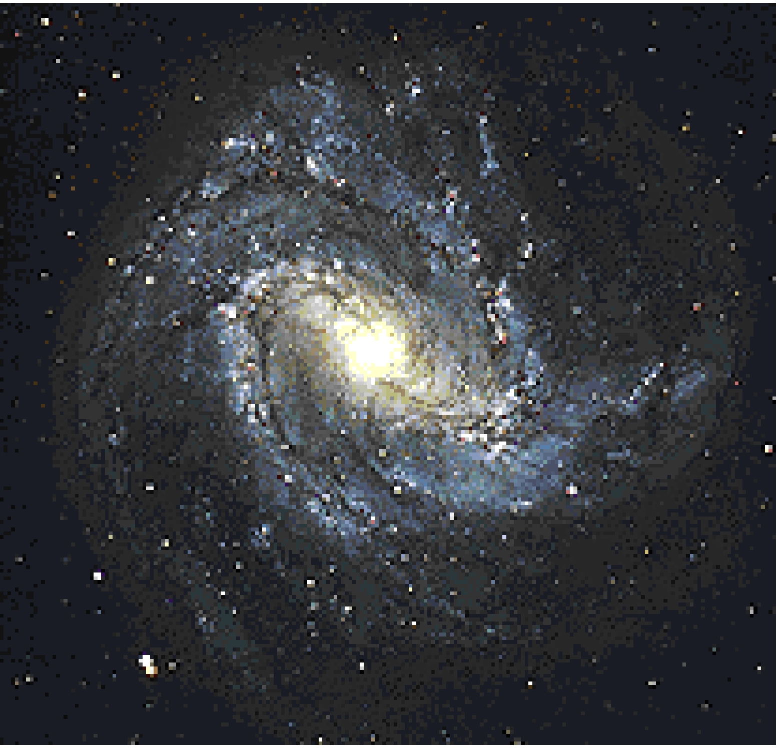
Nearest Galaxy Clusters

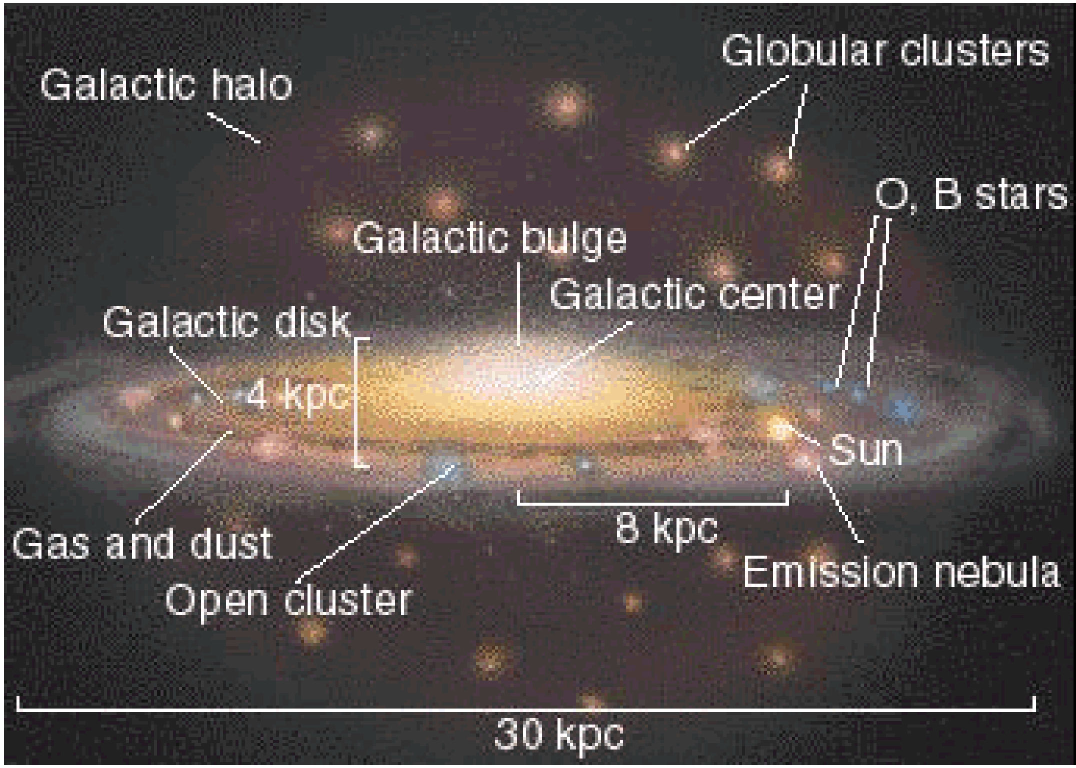


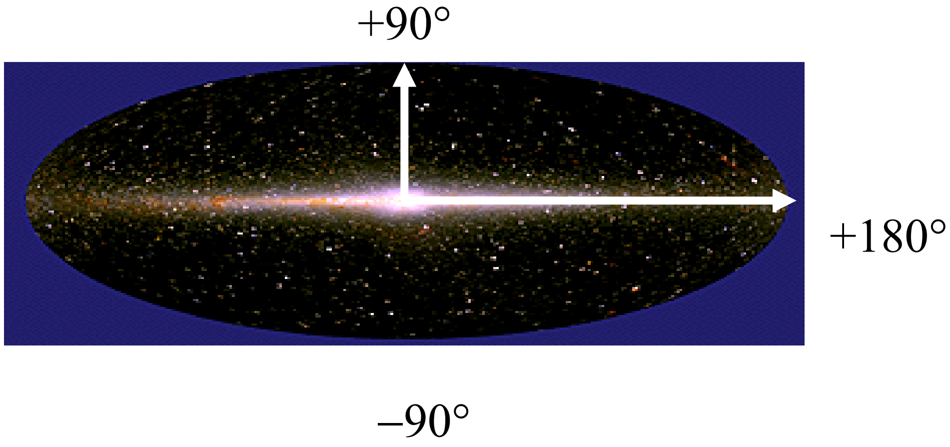
150 Mpc

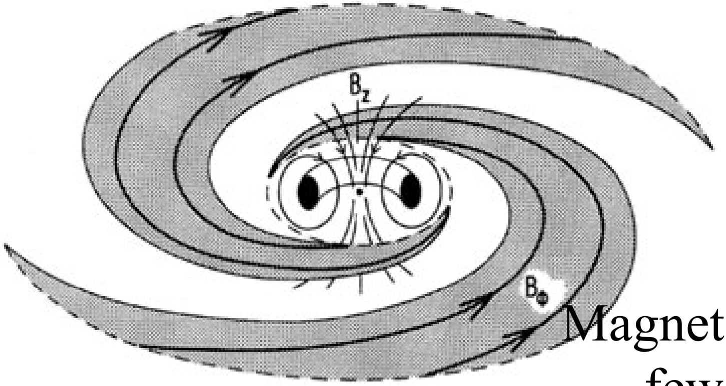
1 pc ~ 3.3 ly

Our Galaxy: The Milky Way





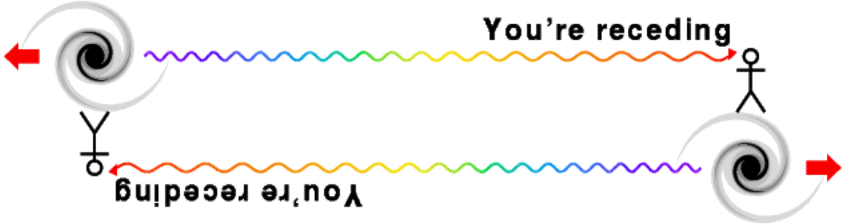




Magnetic field
~ few μG

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



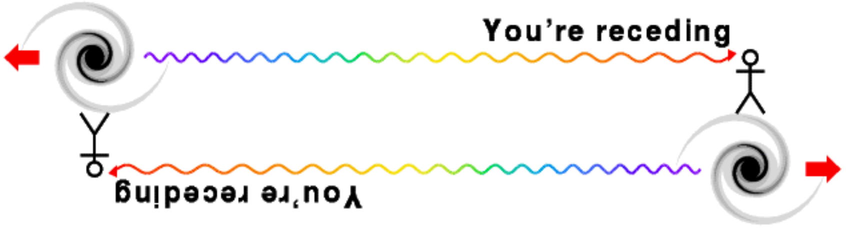
Hubble's constant (km/s/Mpc)

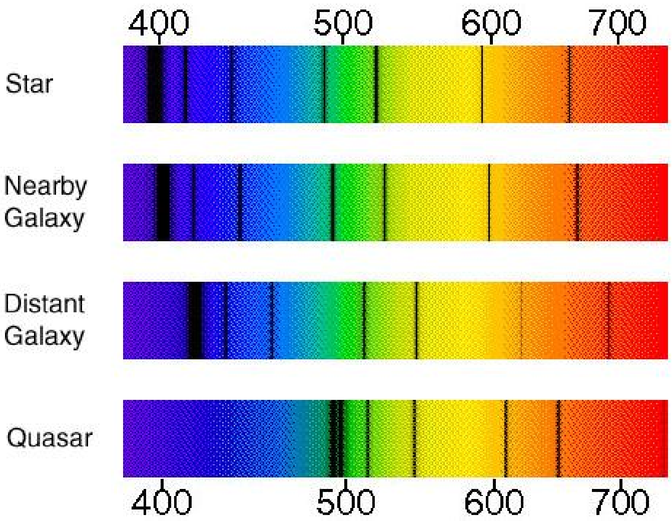
$$V = H_0 r$$

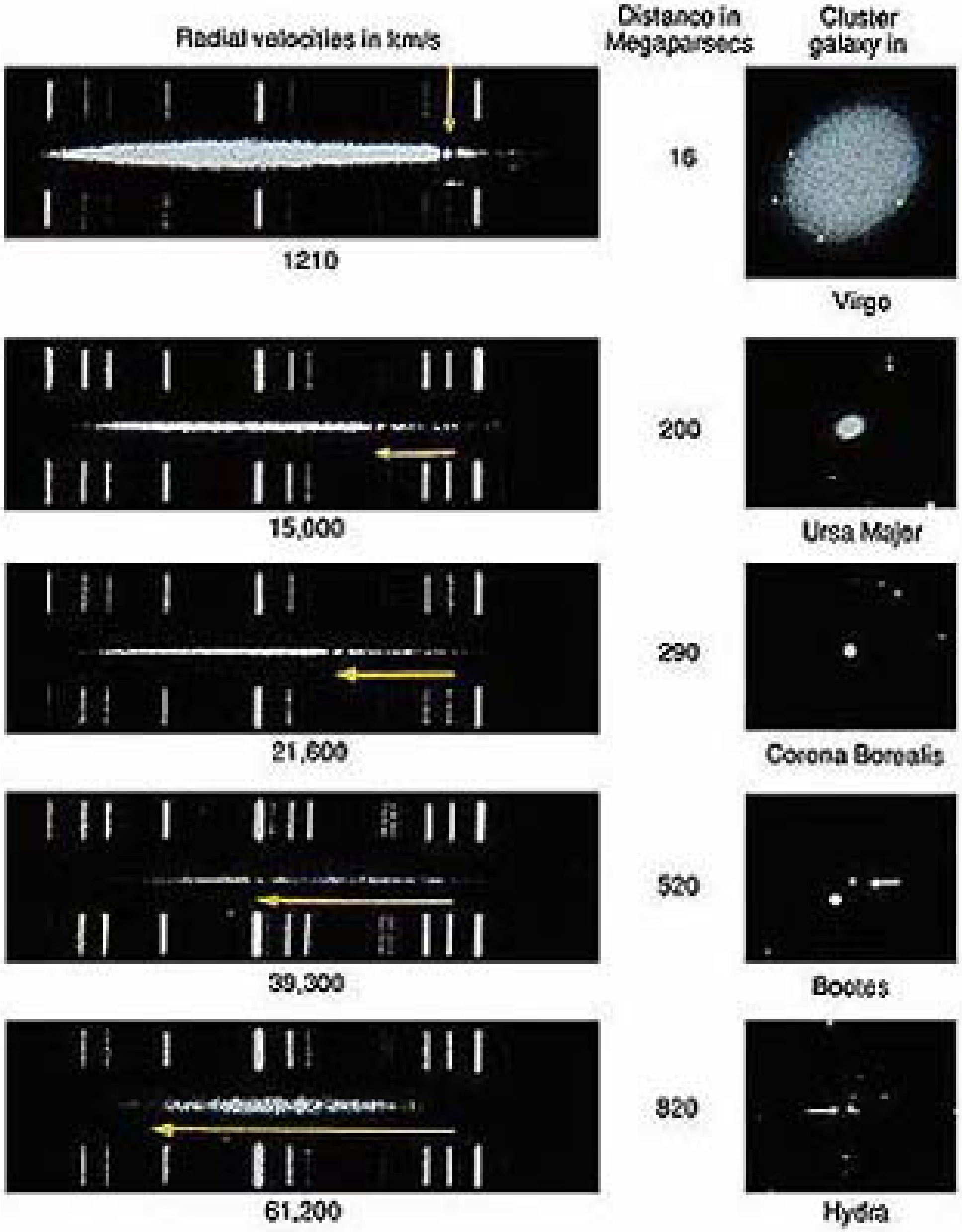
recession speed (km/s)

distance (Mpc

Redshift


You're receding
You're receding

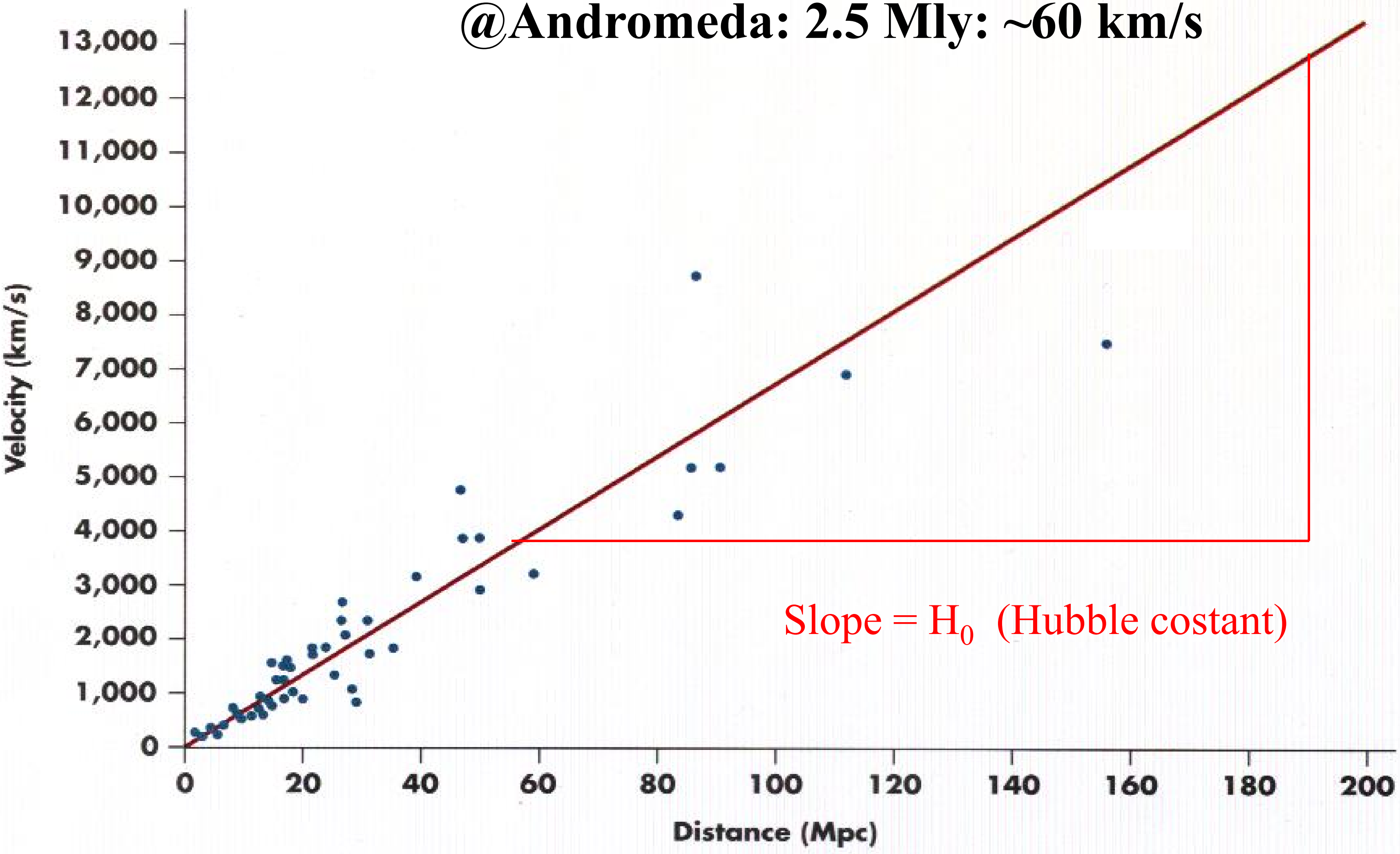

400
500
600
700
Star
Nearby Galaxy
Distant Galaxy
Quasar
400
500
600
700


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

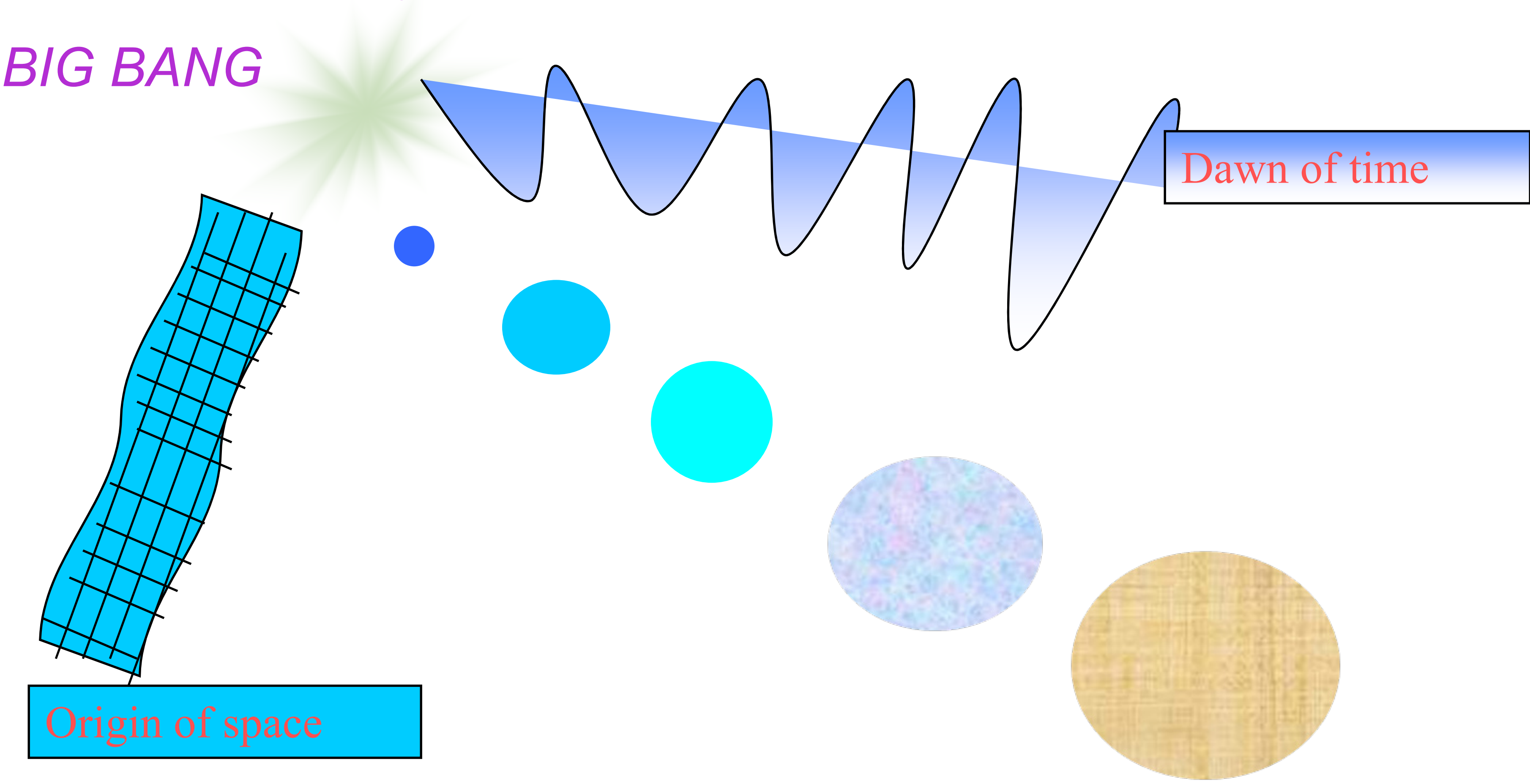


Slope = H_0 (Hubble costant)

Once upon a time...
our Universe was smaller

Primordial singularity !!!

=> BIG BANG



Dawn of time

Origin of space

How far in time ?

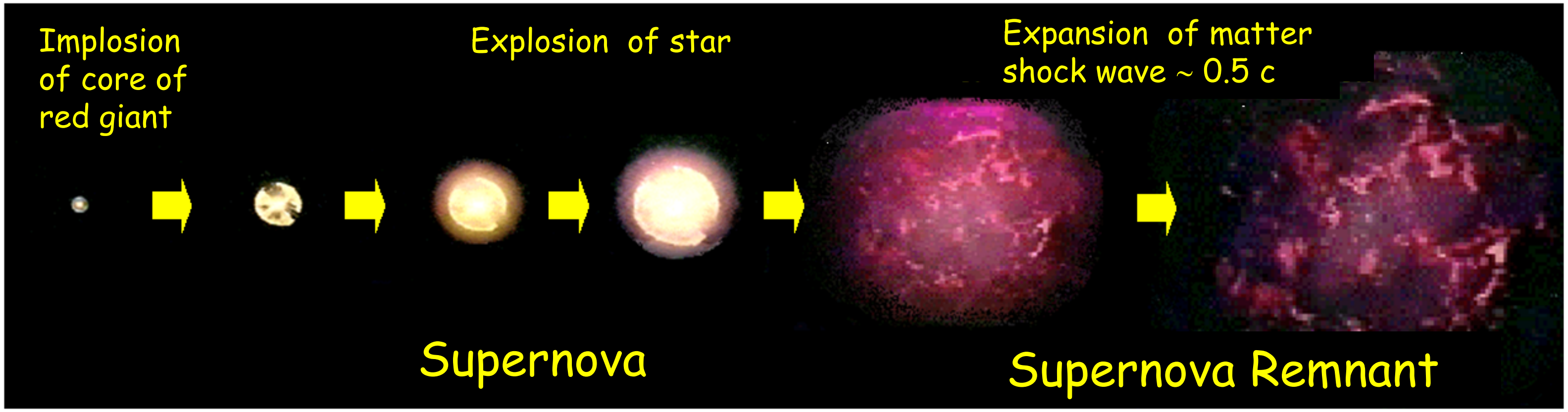
- Extrapolating backwards the present expansion speed towards the big bang

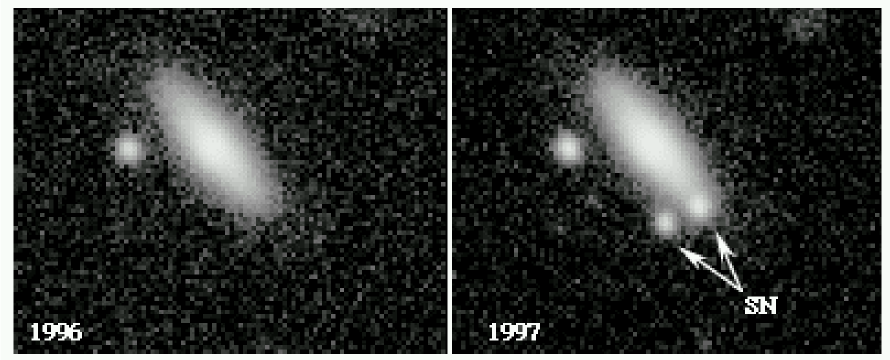
  $$T \sim 1/H_0 \sim 14 \text{ billion years}$$

  (note that the present best estimate, with a lot of complicated physics inside, is T = 13.7 ± 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

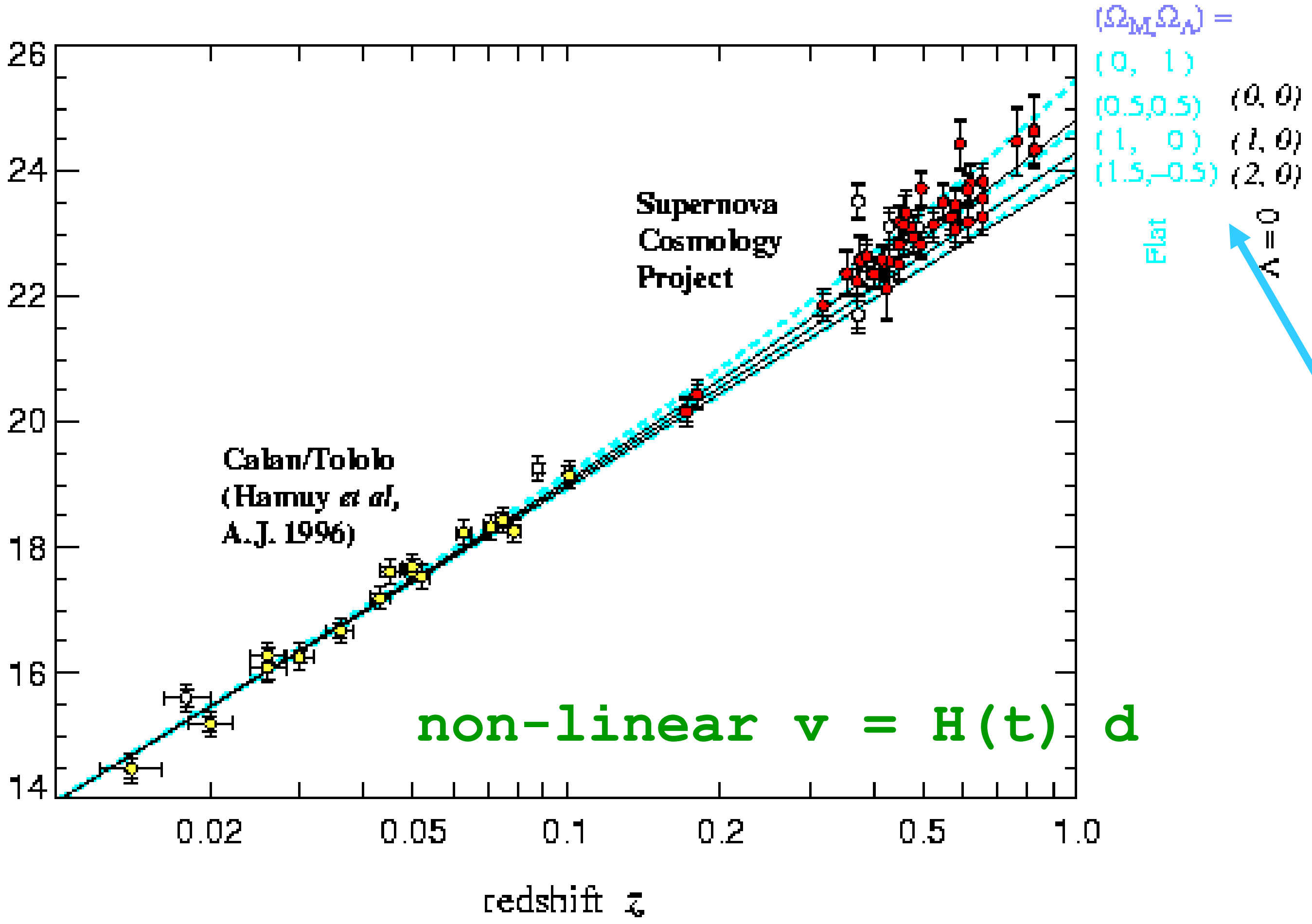
measure brightness

measure host galaxy redshift → get

test Hubble's Law: v = H

Expansion with Supernovae Ia

effective magnitude → brightness → distance



non-linear v = H(t) d

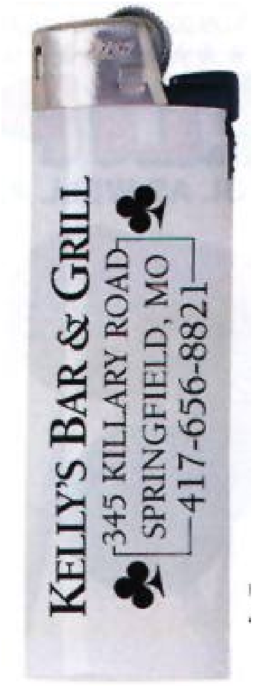
Acceleration of universe expansion

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)



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

Decoupling

$\gamma \leftrightarrow$ particles+antiparticles

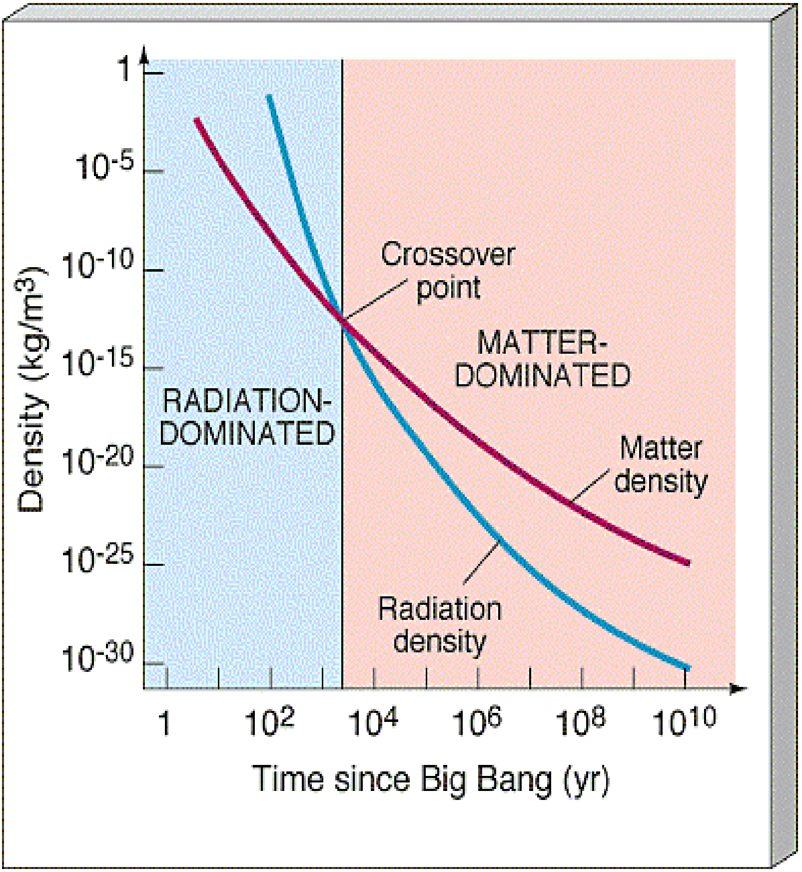
$\gamma \leftrightarrow$ proton-antiproton

$\gamma \leftrightarrow$ electron-positron

(…)

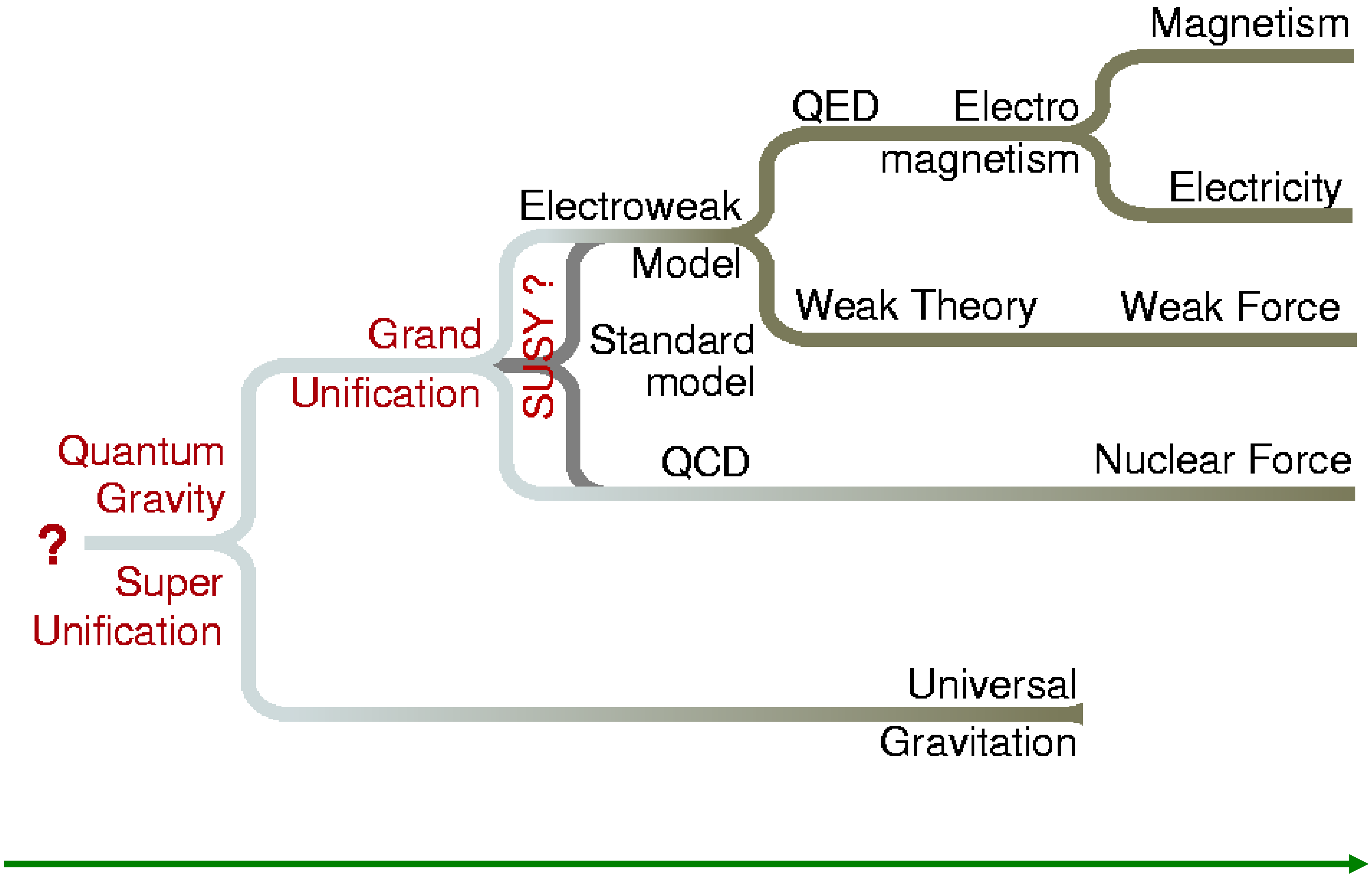
then matter became stable

Time



Two epochs

Particle Physics after Big Bang



?

Quantum Gravity

Super Unification

Grand Unification

SUSY ?

Electroweak

Standard model

Model

QED

Electro magnetism

Magnetism

Electricity

Weak Theory

Weak Force

QCD

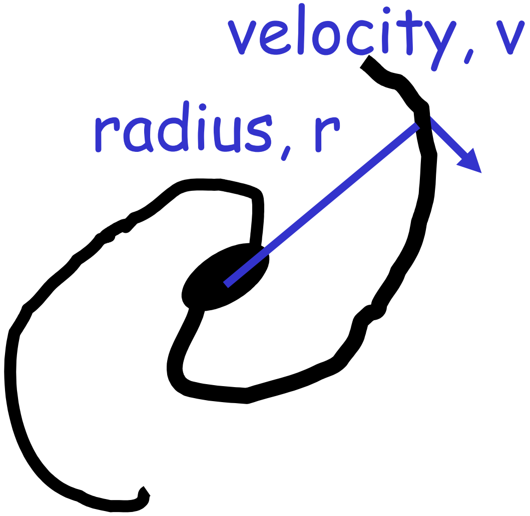
Nuclear Force

Universal Gravitation

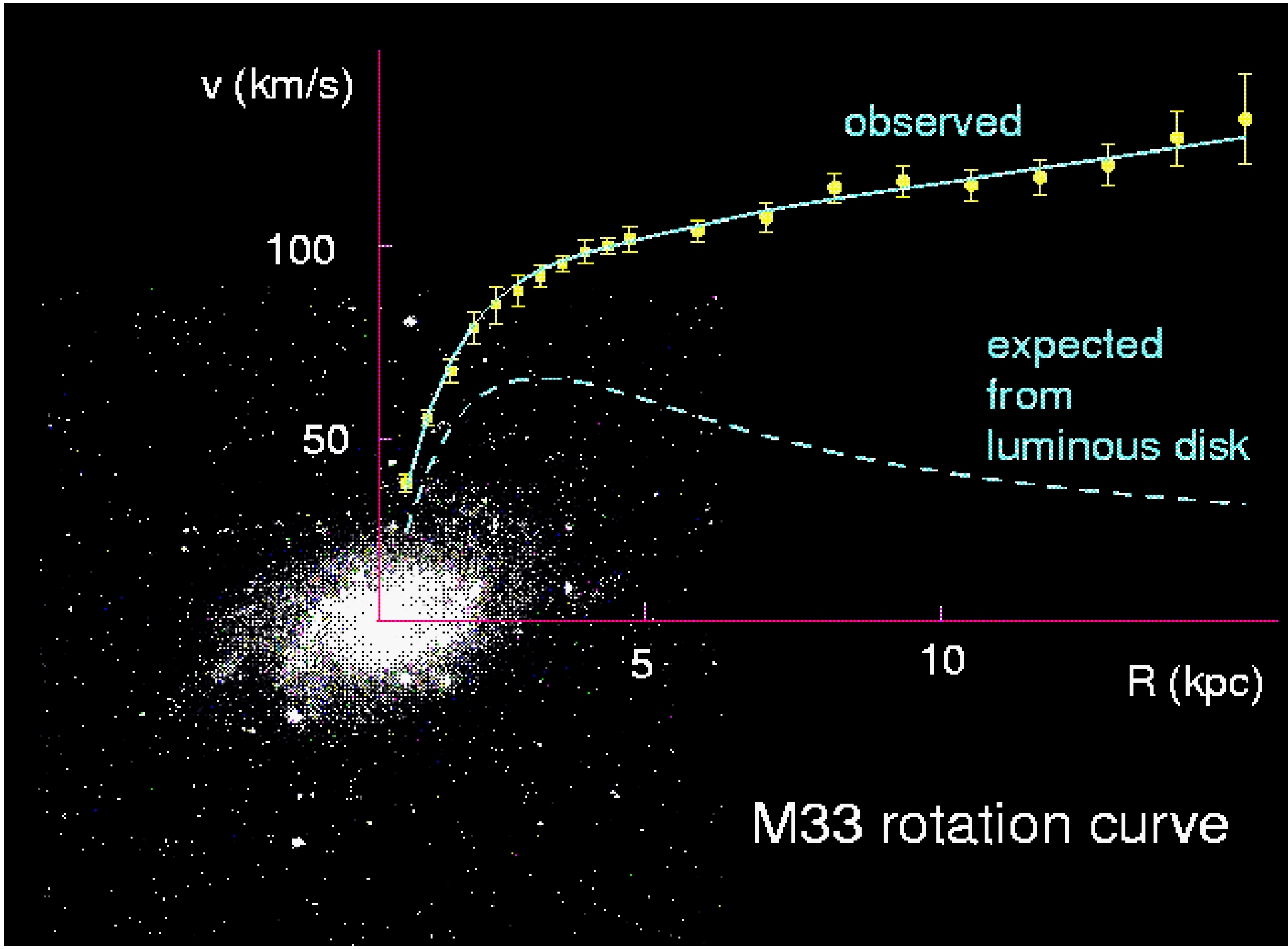
time since Big Bang

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:
$M(r) = v^2 r / G$

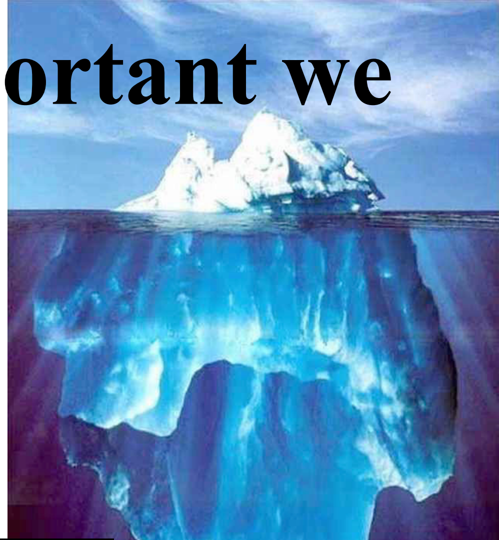


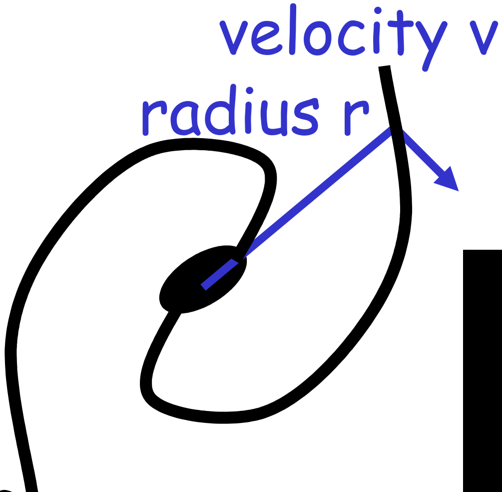
Luminous stars only small fraction of mass of galaxy

II

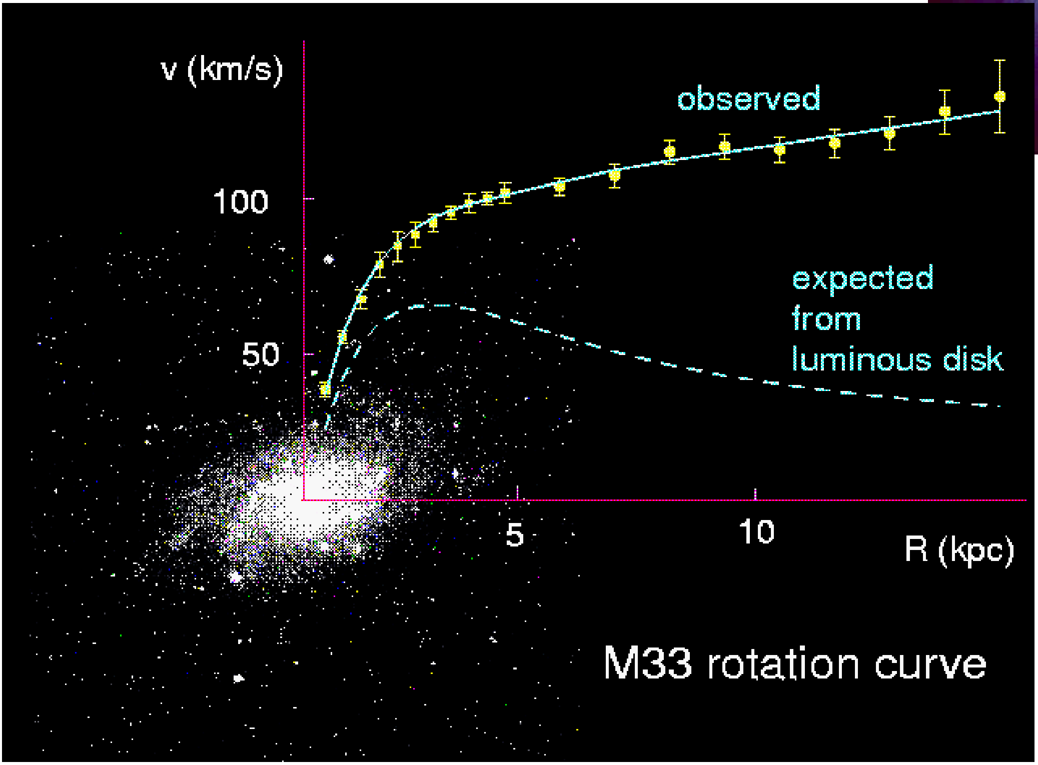
Dark matter searches

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





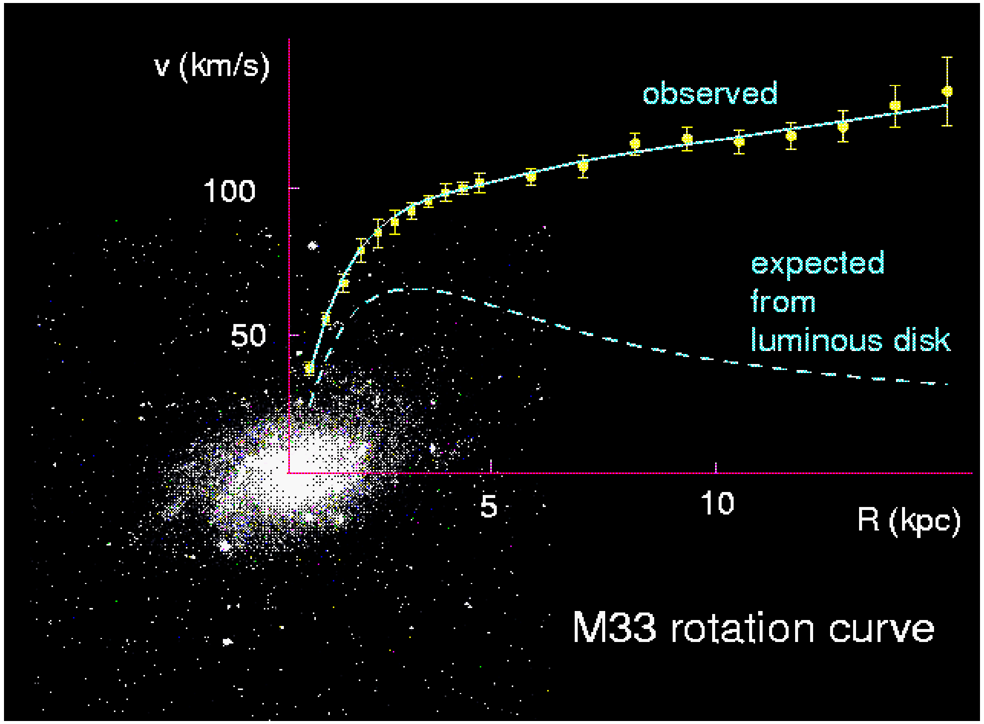
Gravity:
$G\,M(r)/r^2 = v^2/r$
enclosed mass:
$M(r) = v^2\,r\,/\,G$



Luminous stars only small fraction of mass of galaxy

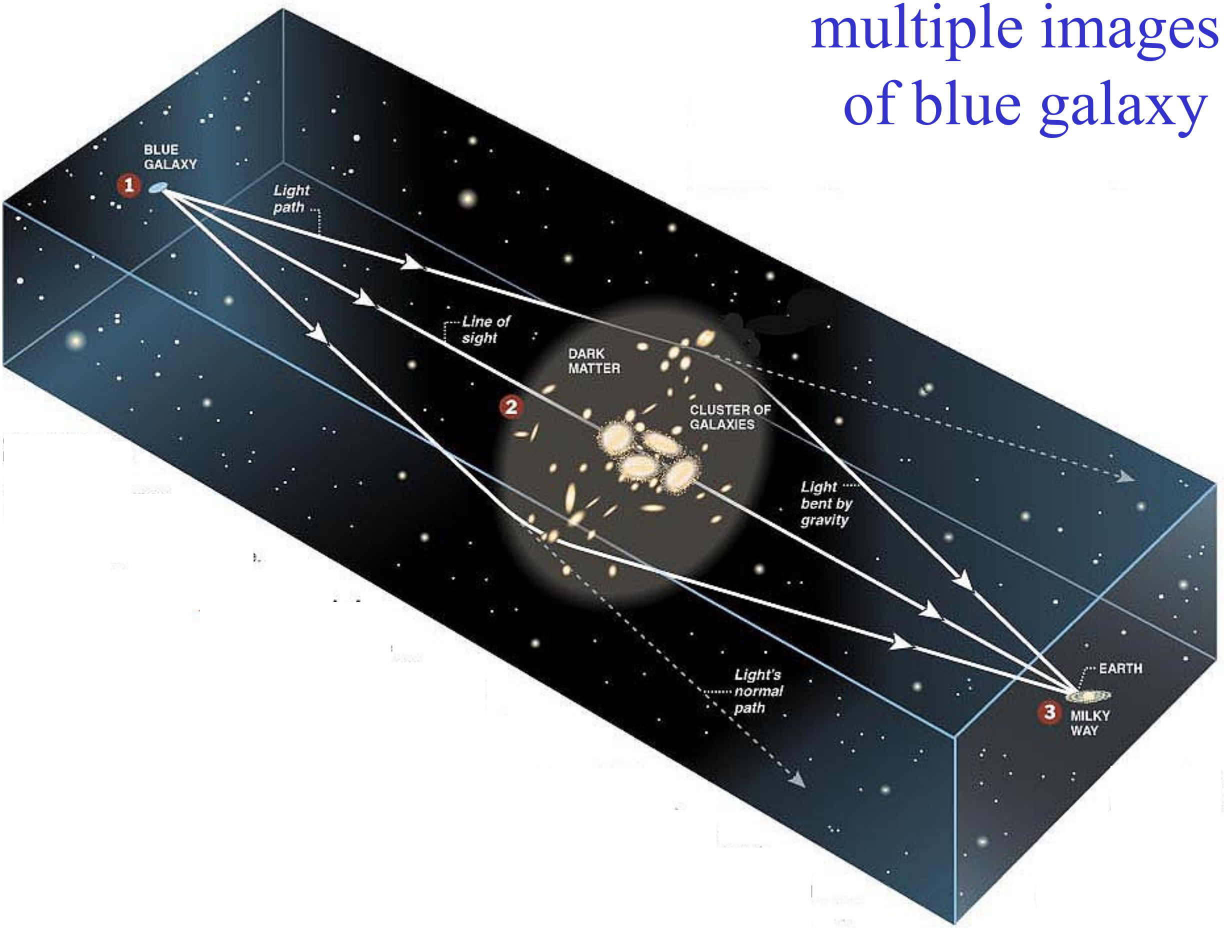
Dark matter searches

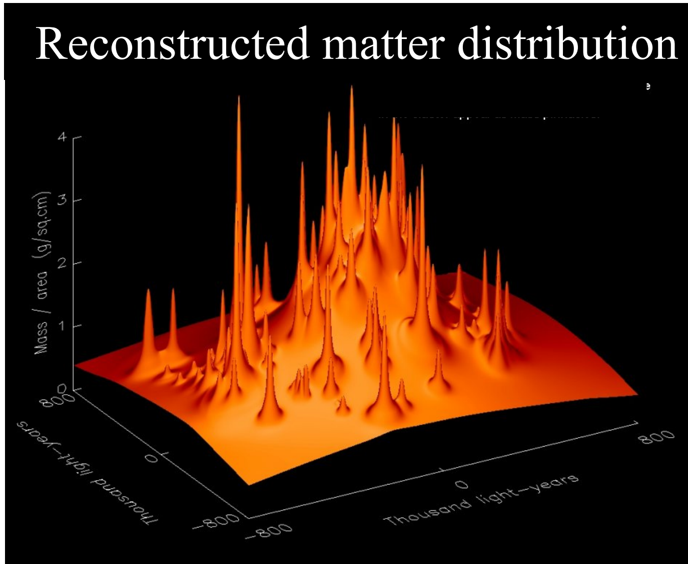
- Astronomy Dark Matter Candidates
  - Invisible macroscopic objects
    - Non-luminous objects
    - Black Holes
- Particle Dark Matter Candidates
  - Neutrinos
  - WIMPs



Gravitational Lensing by Dark Matter

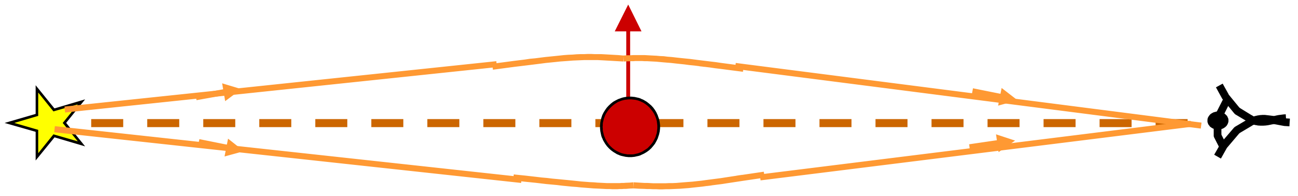
Hubble Space Telescope
multiple images
of blue galaxy




Reconstructed matter distribution

Black holes, etc.

Gravitational Lensing Searches for MACHOs

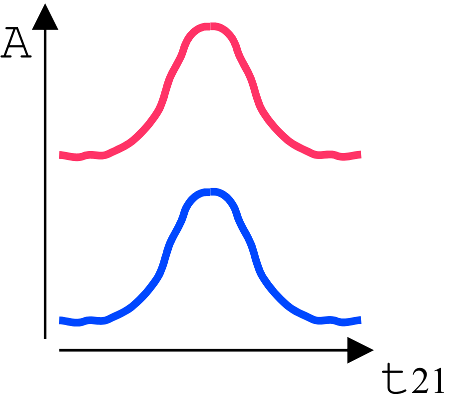


Bright star in Magellanic Cloud

Dark Halo Object

~ 200 km/s

Telescope on Earth



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

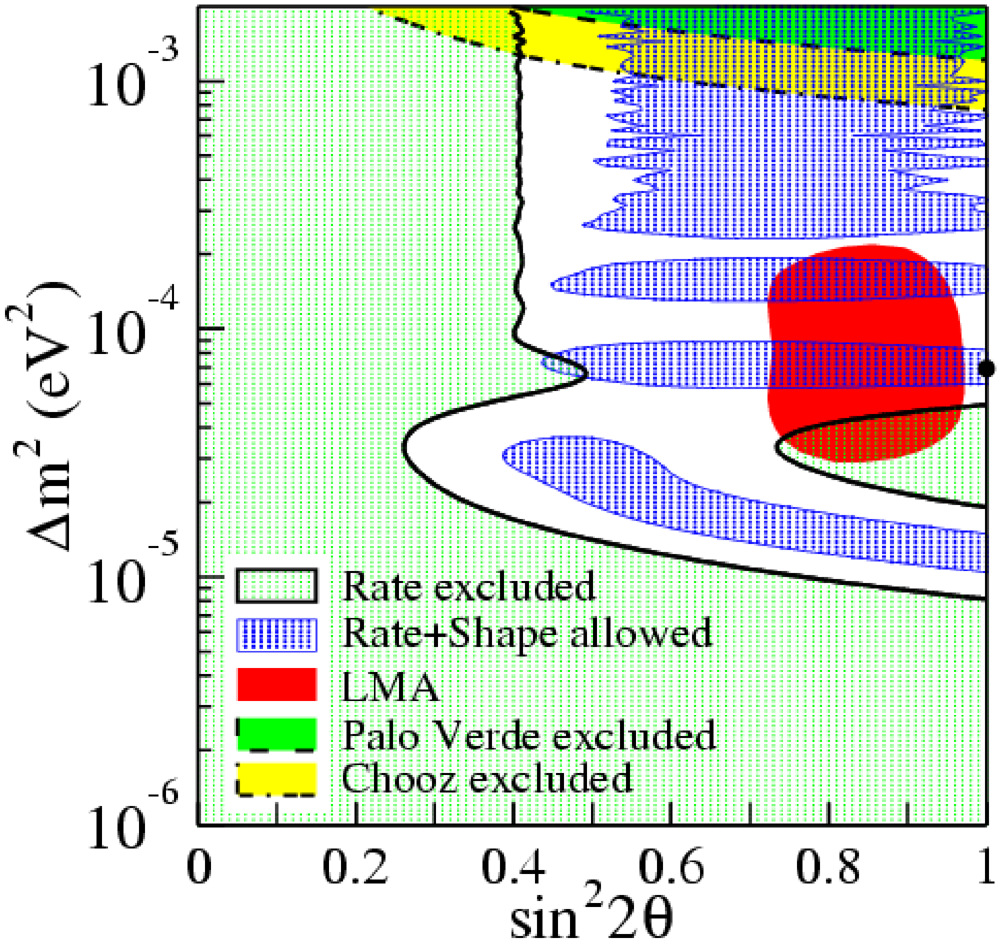
Recent evidence of m>0 from

-SuperKamiokande

-SNO

-K2K

-KamLAND

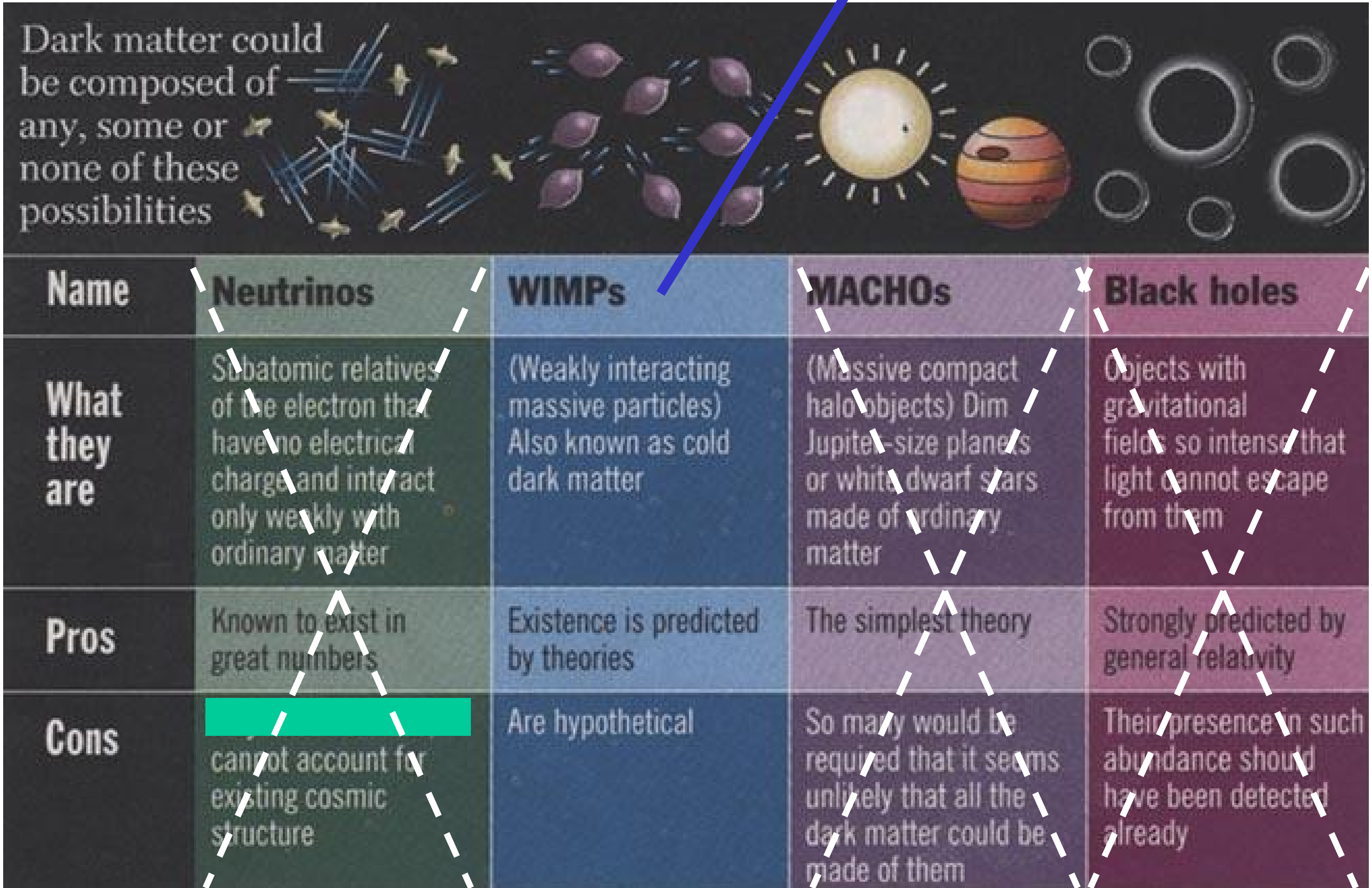


ΔM~ 0.01 eV

Mixing ~ maximal

Candidates: only WIMPS are left

M > ~ 40 GeV
if SUSY (LEP)



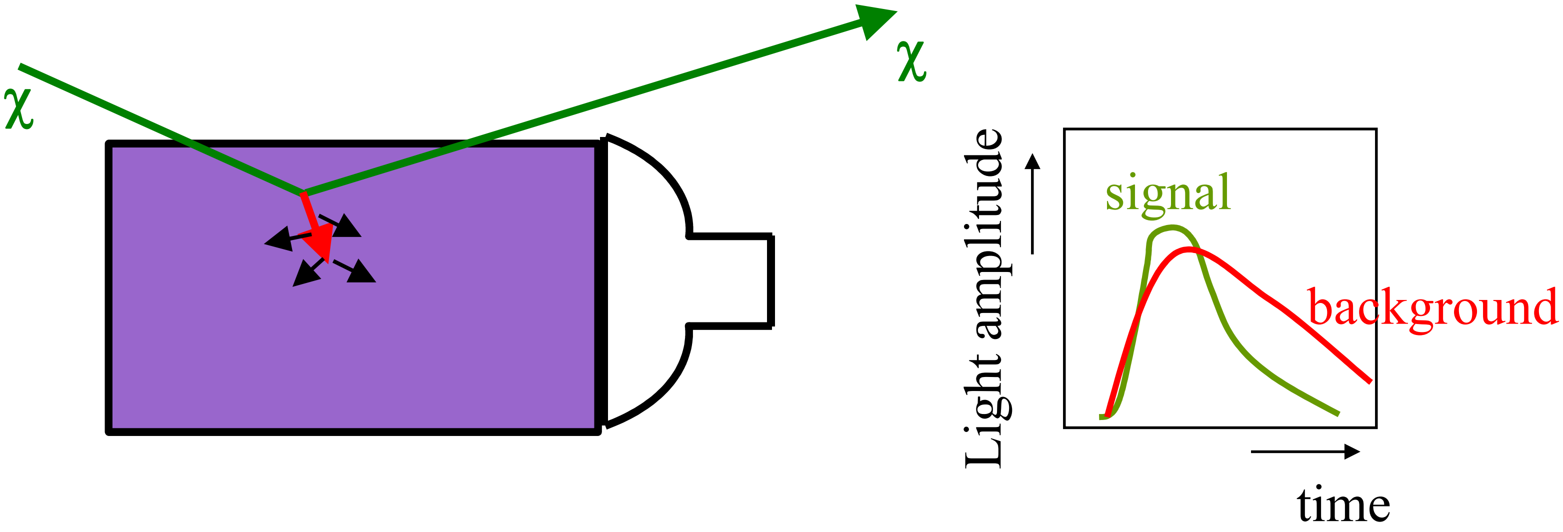
Dark matter could be composed of any, some or none of these possibilities

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	[redacted] ~~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~~

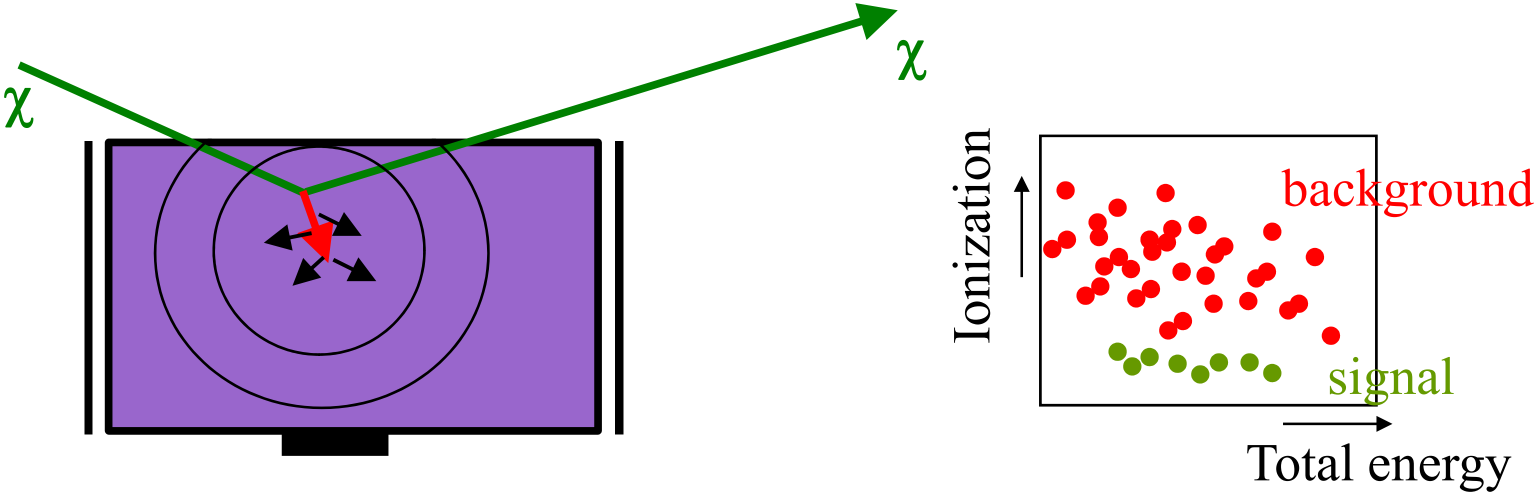
Direct WIMP Detection

Rejection of background is the critical issue

Na I



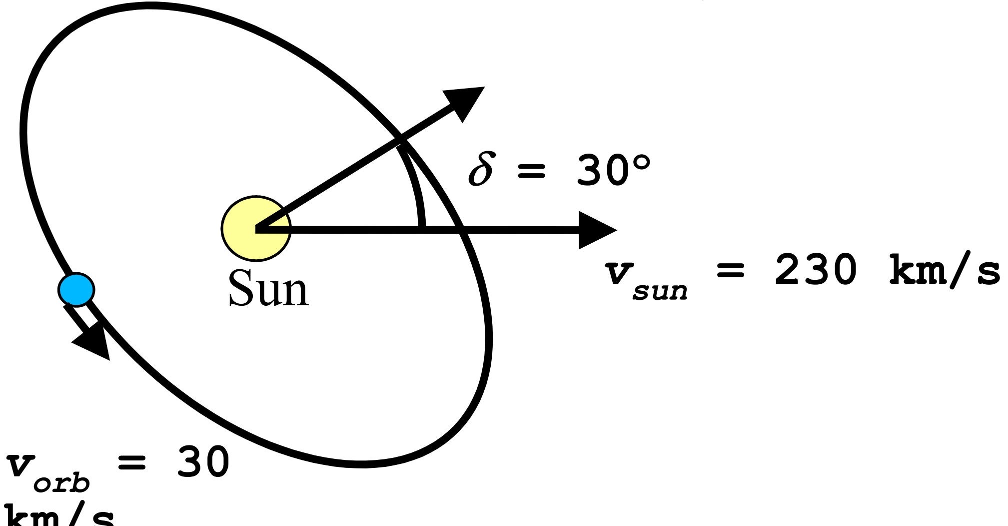
Ge

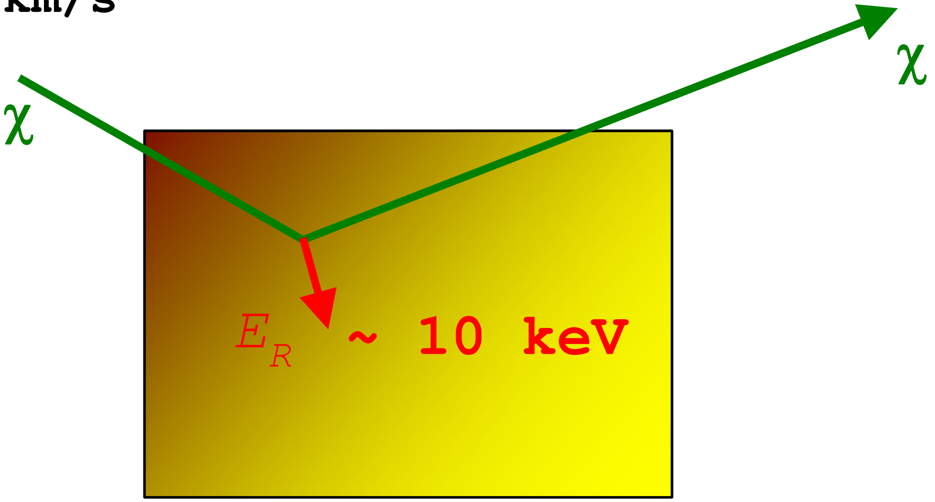


WIMP Direct Detection: modulation

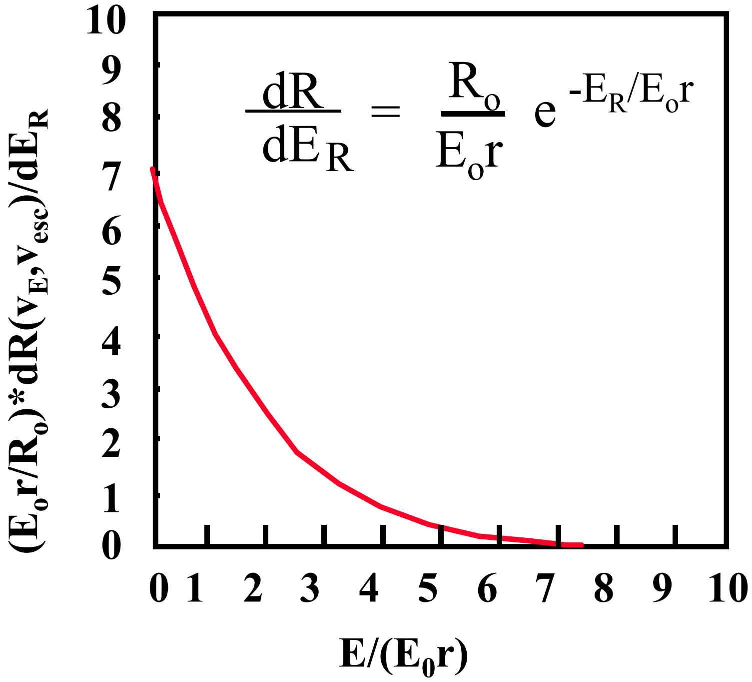
Elastic interaction on nucleus, typical χ velocity ~ 25

Motion of Earth in the χ wind





Recoil Spectrum

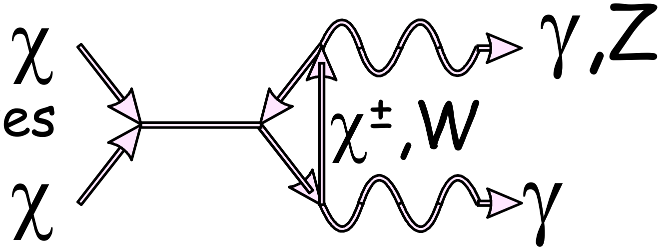


$$\frac{dR}{dE_R} = \frac{R_o}{E_o r} e^{-E_R/E_o r}$$

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

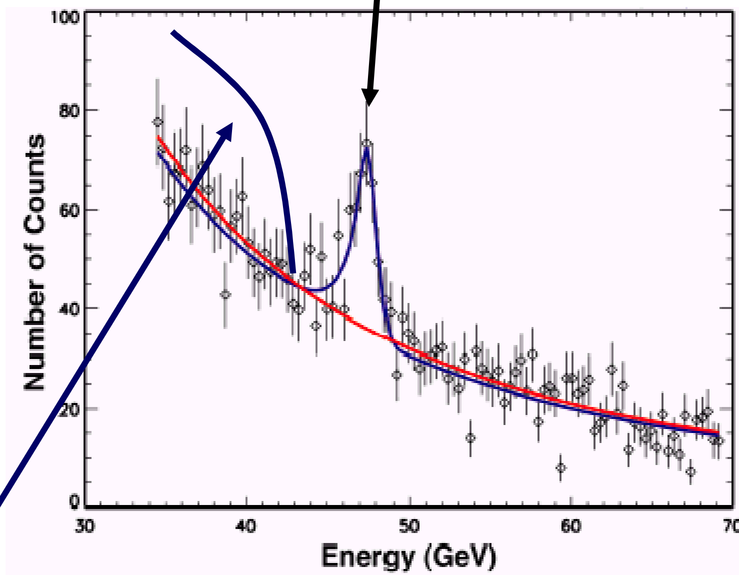
But… Annual modulation

WIMPS & gamma emission

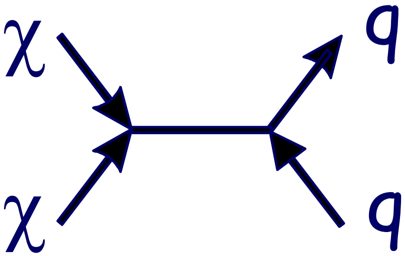


- Some DM candidates (e.g. SUSY particles) would lead to mono-energetic γ lines through annihilation into $\gamma\gamma$ or γZ:
  $E_\gamma = m_\chi \;/\; m_\chi - m_Z^2/4\, m_\chi$
  => clear signature at high energies
  but: loop suppressed

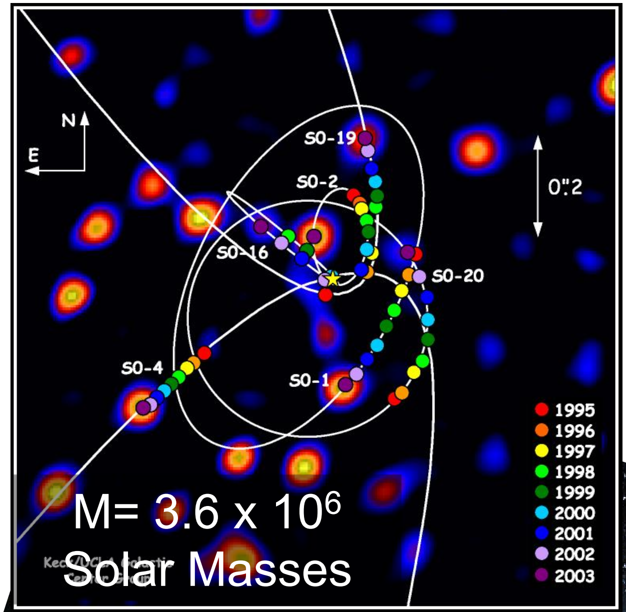
Good energy resolution in the few % range is needed



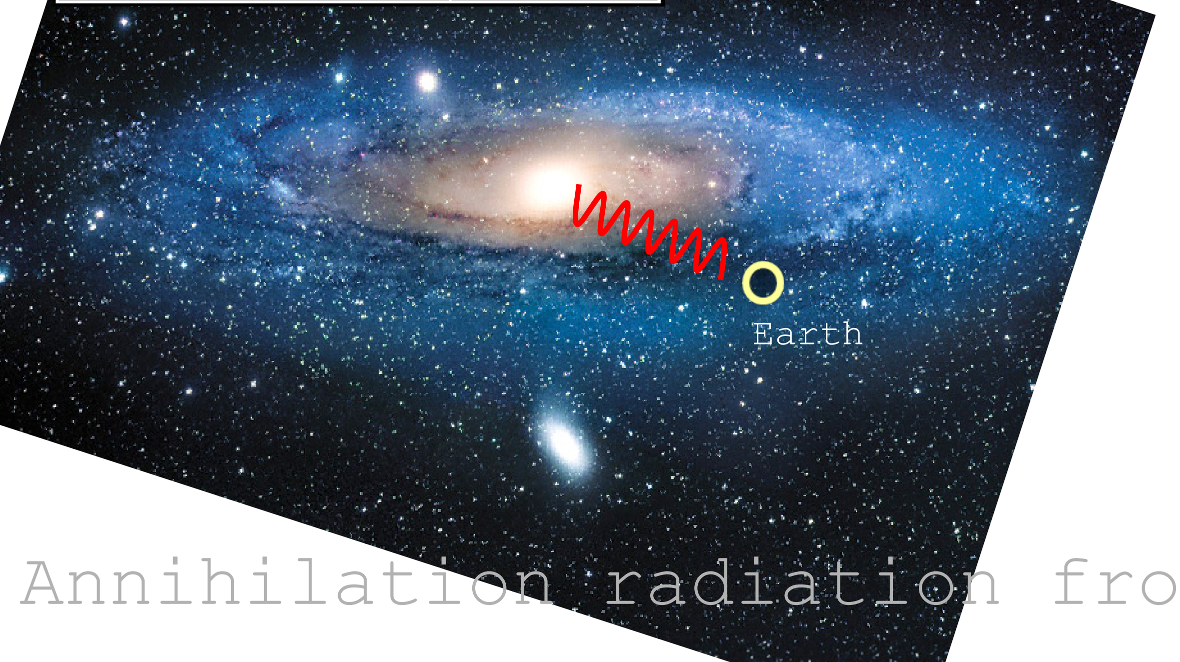
- annihilation into qq -> jets -> n γ's
  => continuum of low energy gammas
  difficult signature but large flux

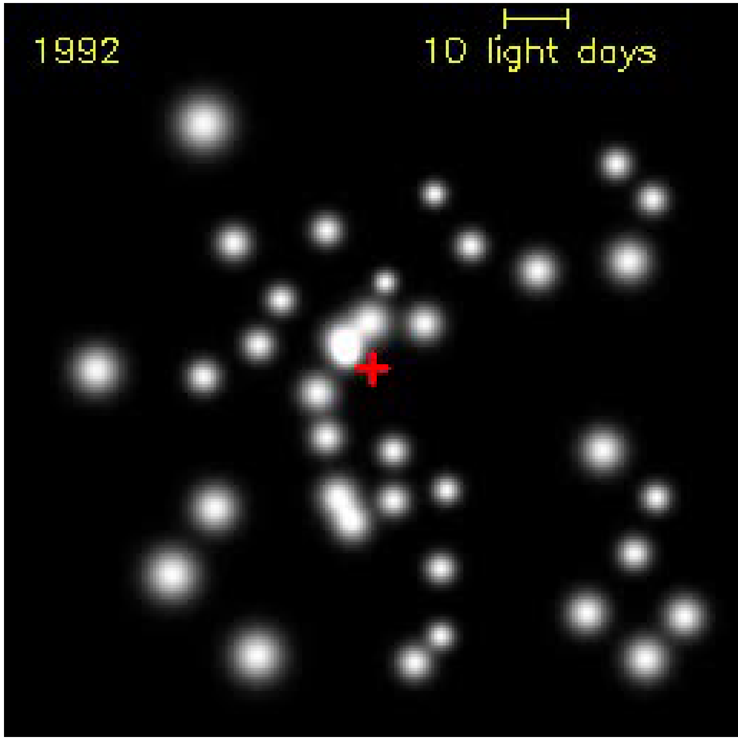


Results: common sense suggests a look @the GC…



M= 3.6 x 10^6 Solar Masses





X emission (variable)

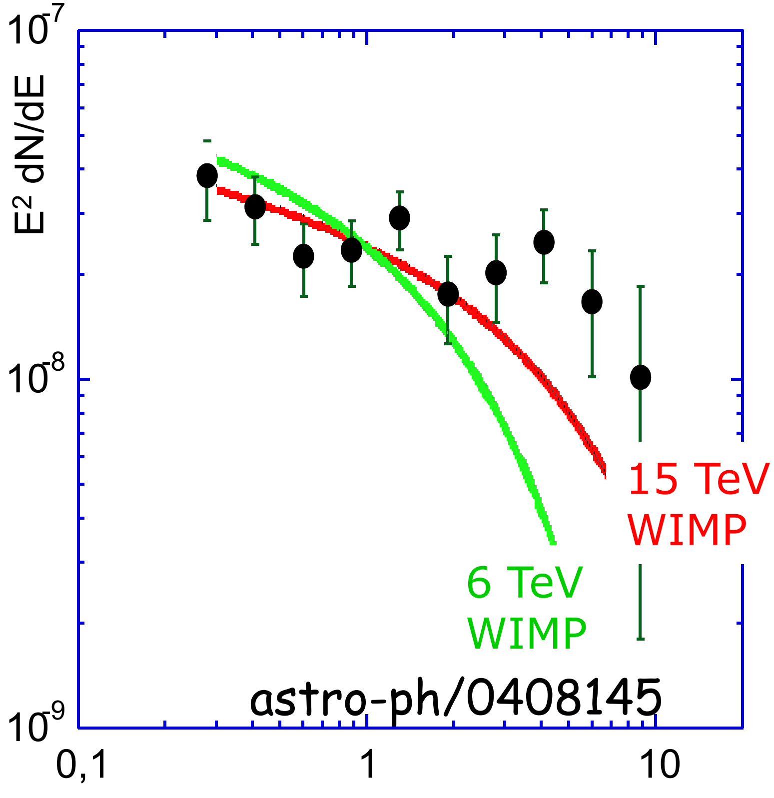
γ emission

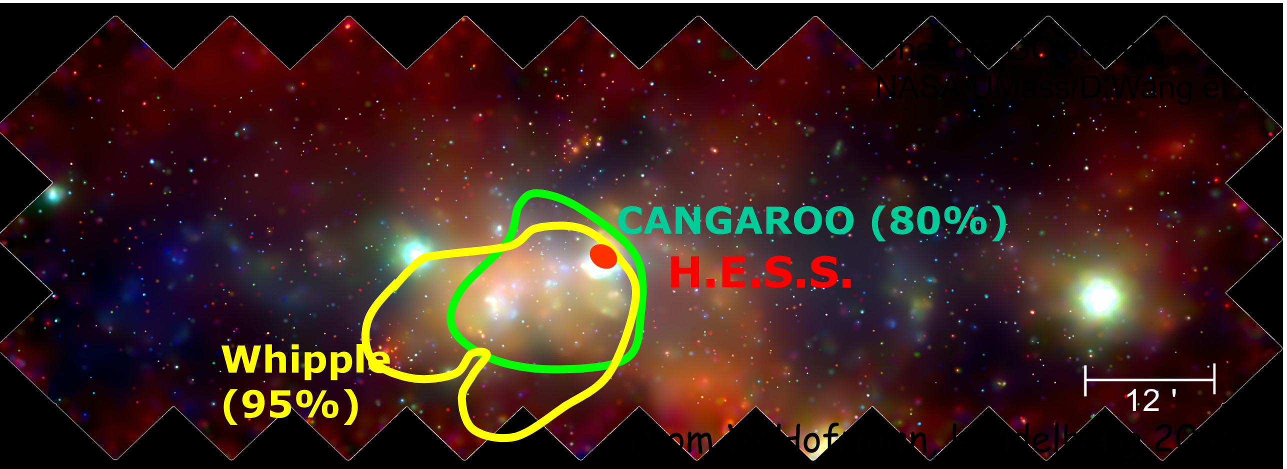
Annihilation radiation from the GC

γ-ray detection from the Galactic Center

- 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 > 12 TeV
  - other interpretations possible (probable)

Galactic Center: very crowded sky region, strong exp. evidence against cuspy profile => not optimal target





Milky Way satellites (Sagittarius, Draco, …)

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

Matter/Energy in the Universe: Conclusion

Must be something new

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

matter dark energy

Matter:

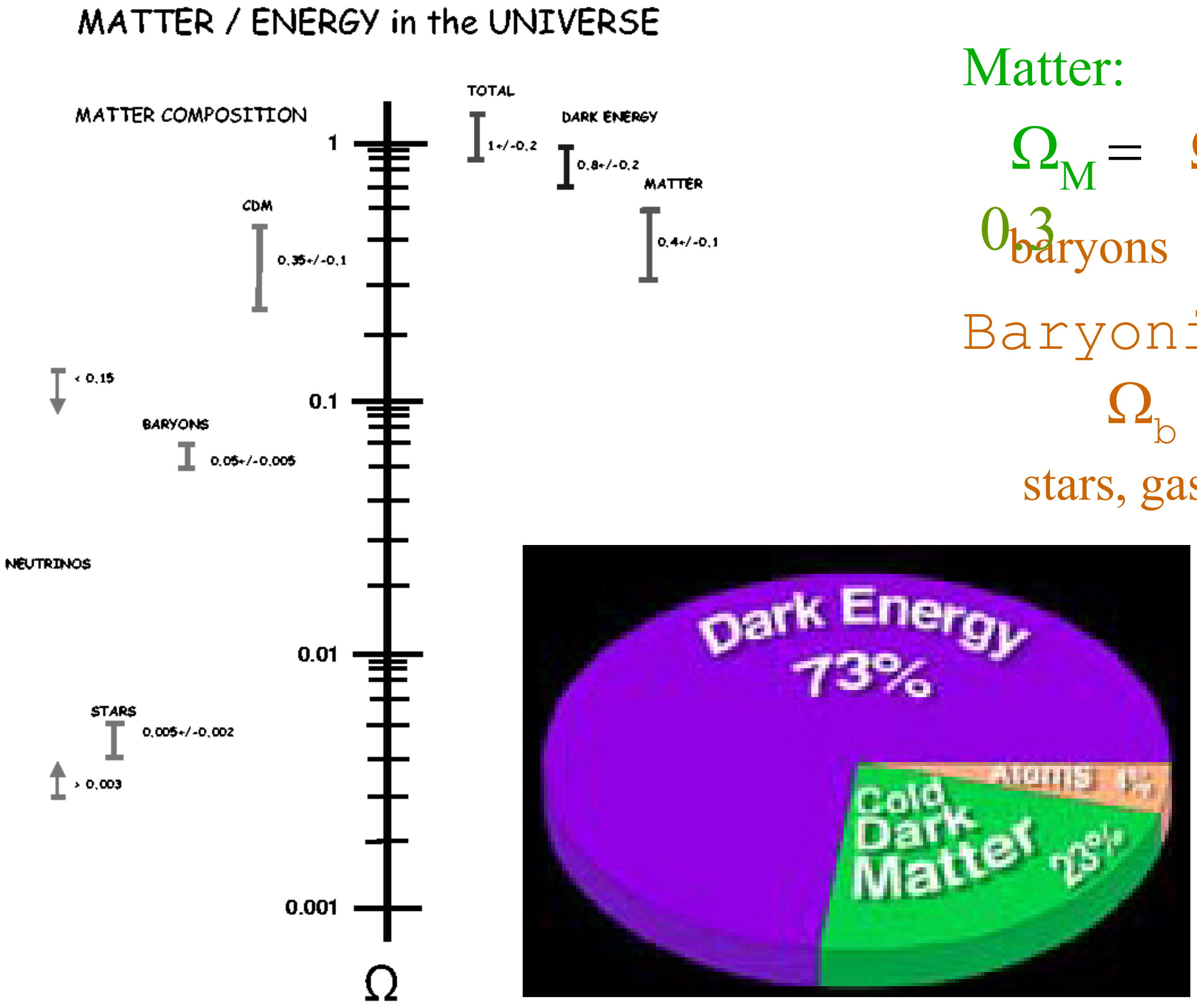
$\Omega_M = \Omega_b + \Omega_\nu + \Omega_{CDM} \sim 0.3$

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 :

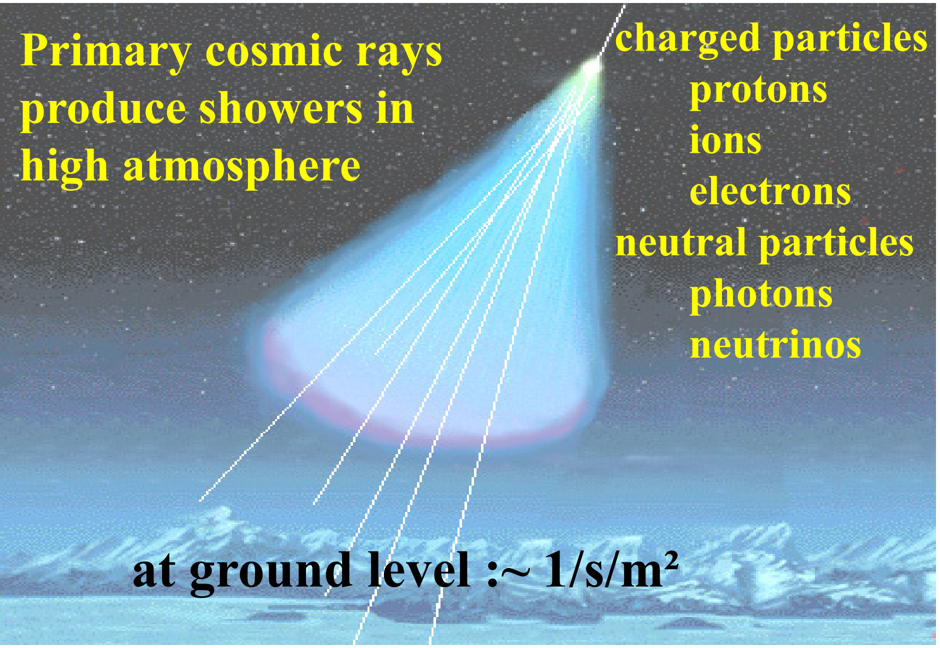
$\Omega_{CDM} \sim 0.23$

`WIMPS/neutralinos, a`

III

High Energy Particles from space

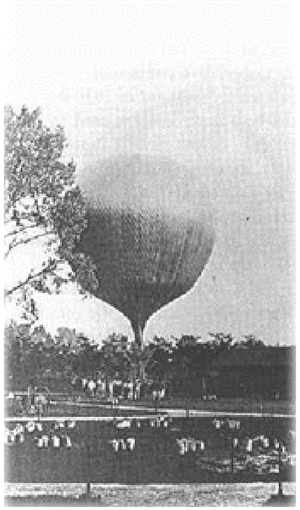
Cosmic Rays



Primary cosmic rays produce showers in high atmosphere

charged particles
protons
ions
electrons
neutral particles
photons
neutrinos

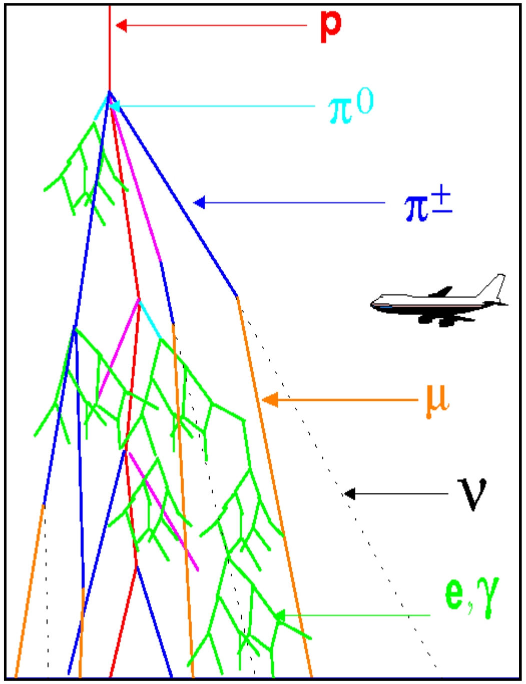
at ground level :~ 1/s/m²



100 years after discovery by Hess origin still uncertain

Primary:

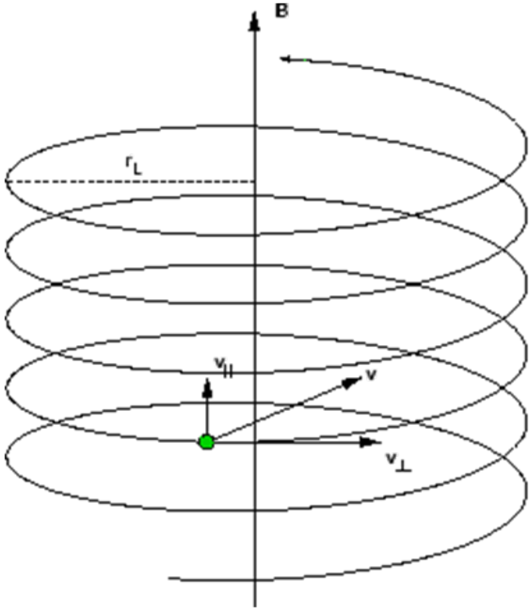
p 80 %, α 9 %, n 8 %
e 2 %, heavy nuclei 1 %
γ 0.1 %, ν 0.1 % ?



Secondary at ground level:

ν 68 %
μ 30 %
p, n, ... 2 %

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

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

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

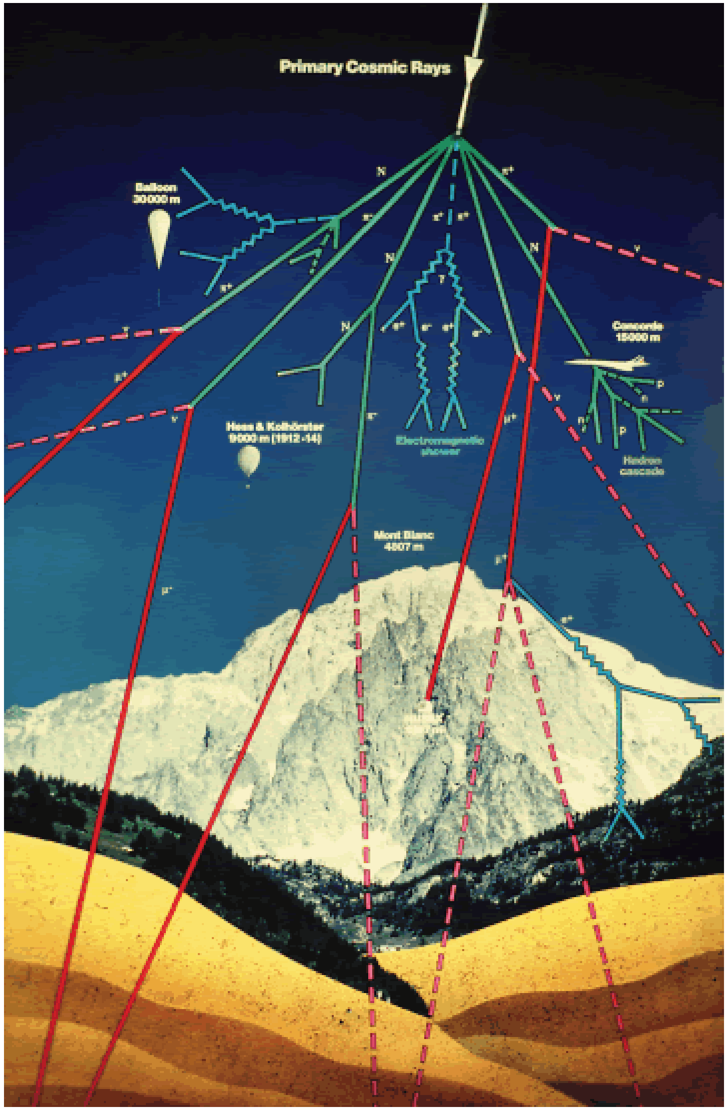
$$\boxed{r_L = \begin{cases} (E = 10^{12}\,eV) & = 10^{15}\,cm = 3\cdot10^{-4}\ pc \\ (E = 10^{15}\,eV) & = 10^{18}\,cm = 0.3\quad pc \\ (E = 10^{18}\,eV) & = 10^{21}\,cm = 300\ \ pc \end{cases}}$$

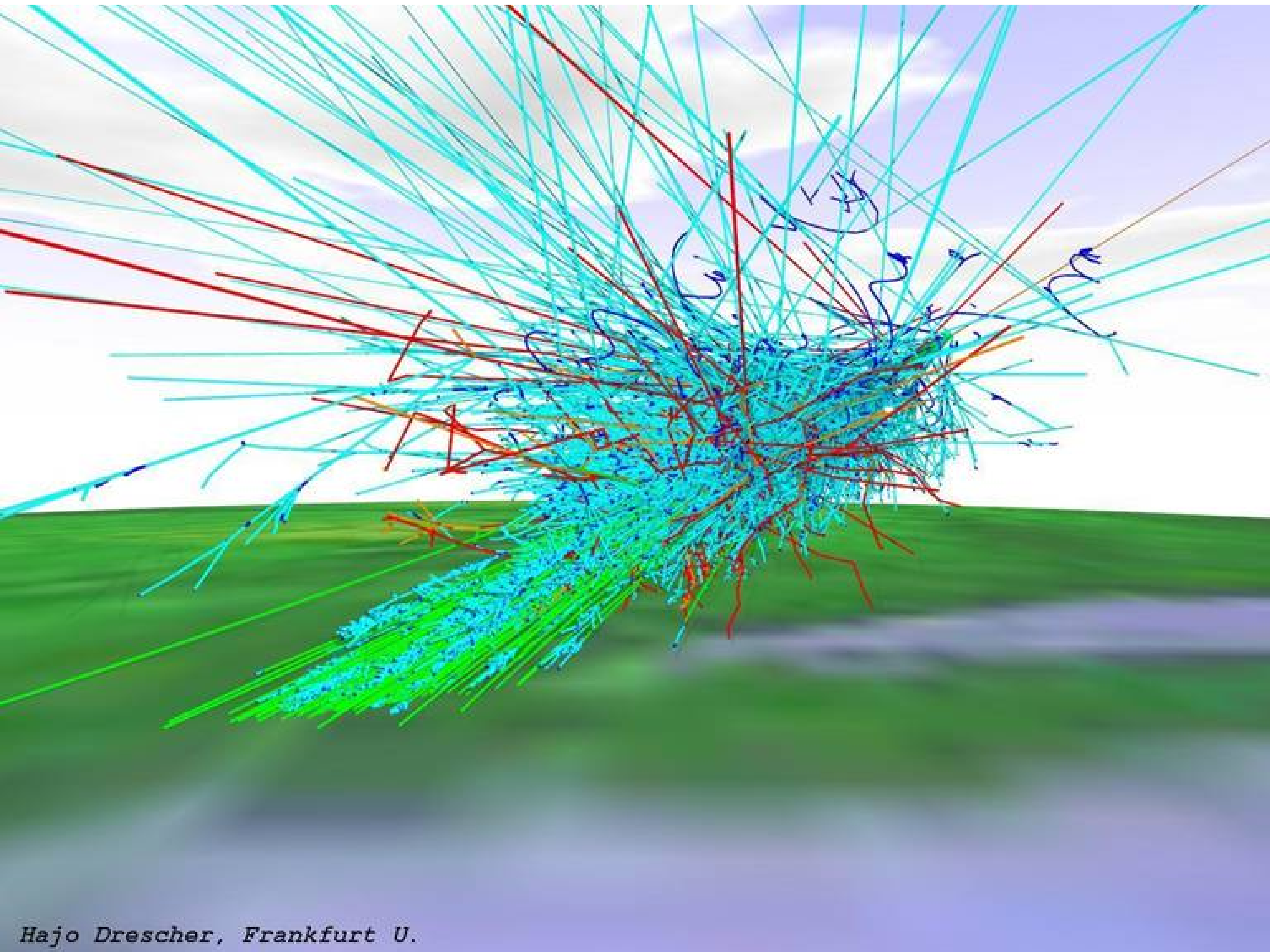
- Protons with E<10^{18} eV have a Larmor radius < the galactic radius (300 pc).

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

Secondary CR

- Interaction of CR with atmospheric nuclei → particle showers → **secondary CR**
- Atmosphere acts as a *converter*
- Primary radiation can be studied only outside the atmosphere
- Radiation at ground can be studied by means of shower detectors
  - With possibly an inference about the nature of the primaries
- *Underground* experiments for the penetrating component (muons, neutrinos)

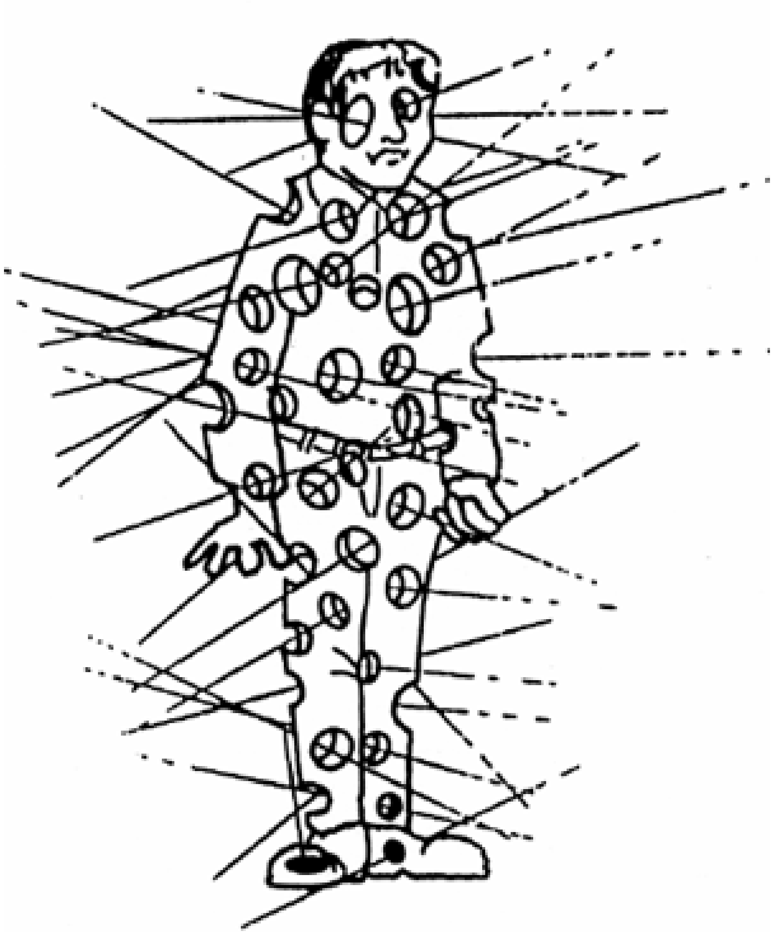




Hajo Drescher, Frankfurt U.

Cosmic Rays on the 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



The flux of secondary CR

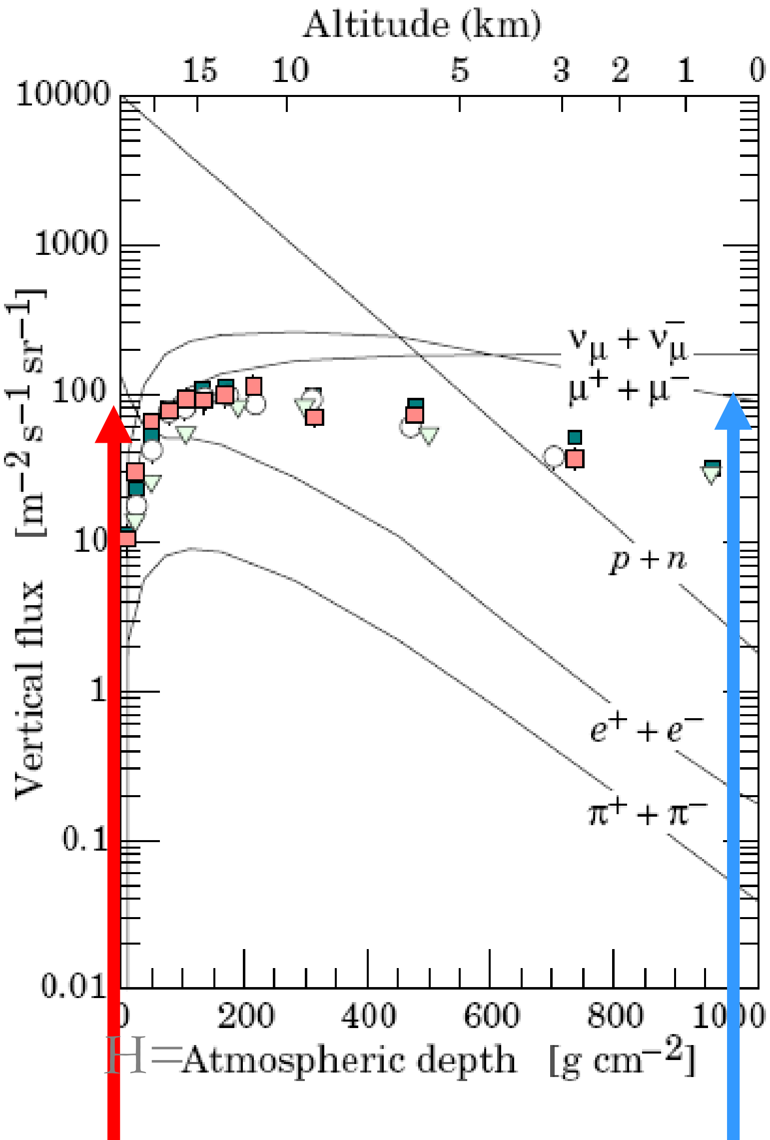
- Atmospheric depth: ~ 10 m of water

$$H_o = \int_{h=0}^{h=\infty} \rho(h)\cdot dh = 10000\,(kg\cdot m^{-2})$$

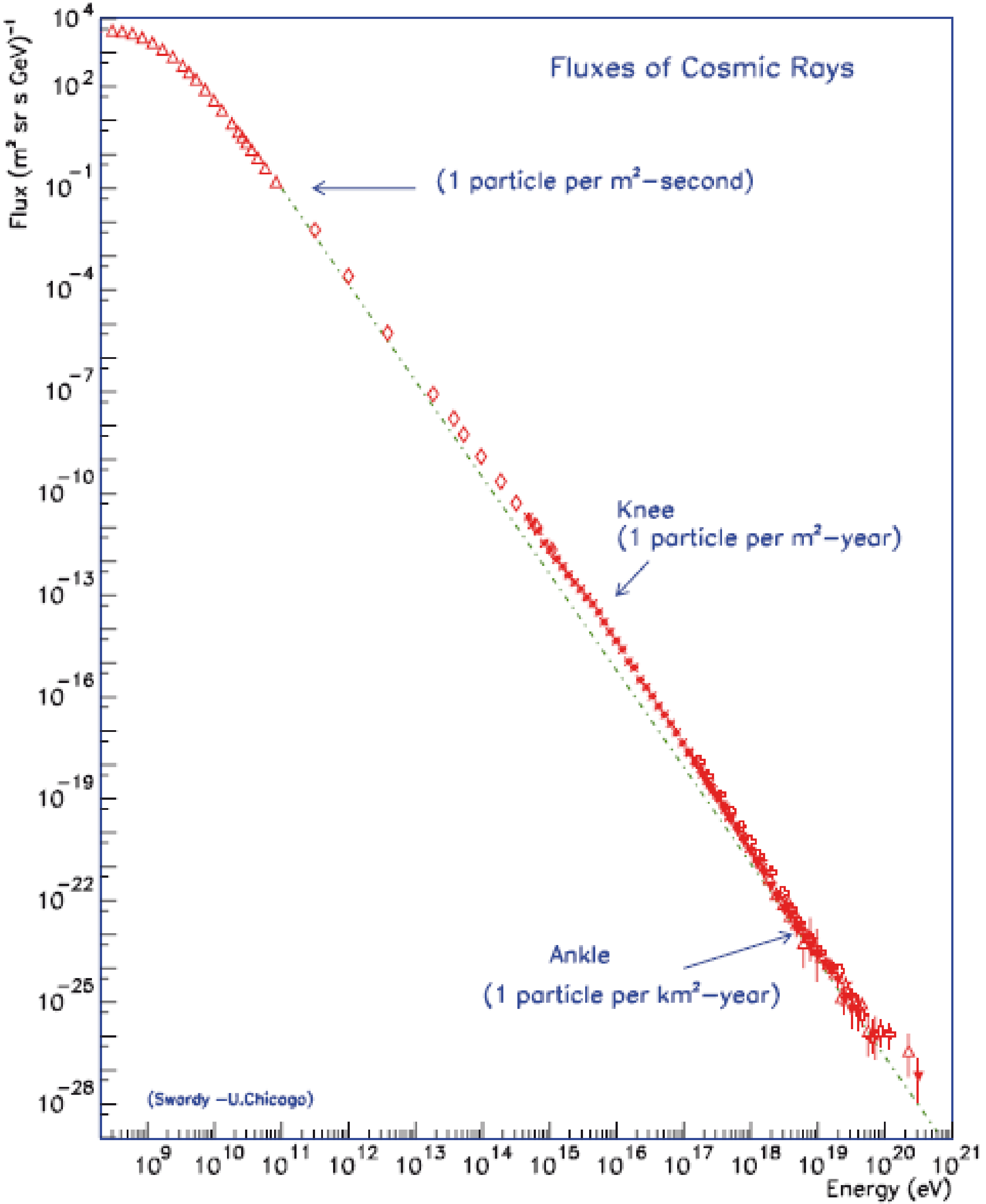
$$= 1000 \qquad (gcm^{-2})$$

1. Flux on top (H=0 g cm^{-2}):
   - 10000 m^{-2} s^{-1}sr^{-1}
   - p (90%), He (9%), A (1%)

2. Flux at sl (H=1000 g cm^{-2}):
   - 200 m^{-2} s^{-1}sr^{-1}
   - Muoni, neutrini, e+e-, γ

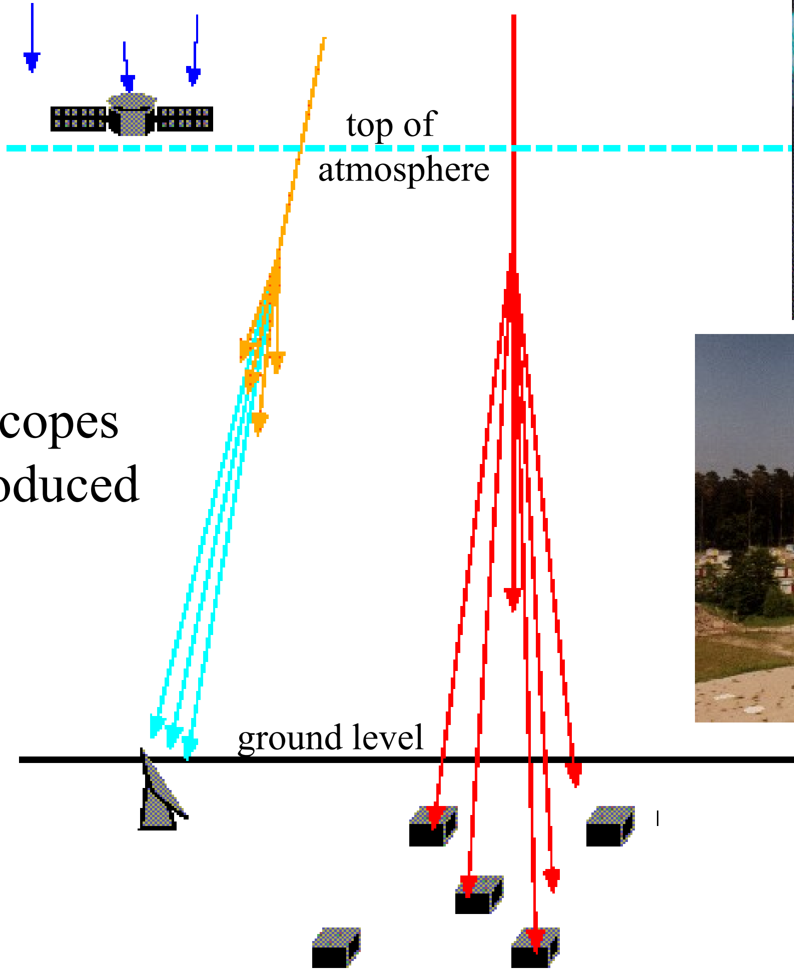


The spectrum of Cosmic Rays



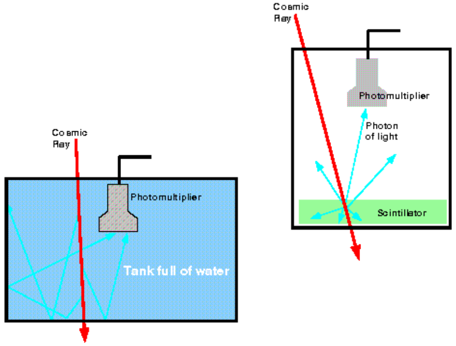
Types of Cosmic Ray Detectors

Satellites

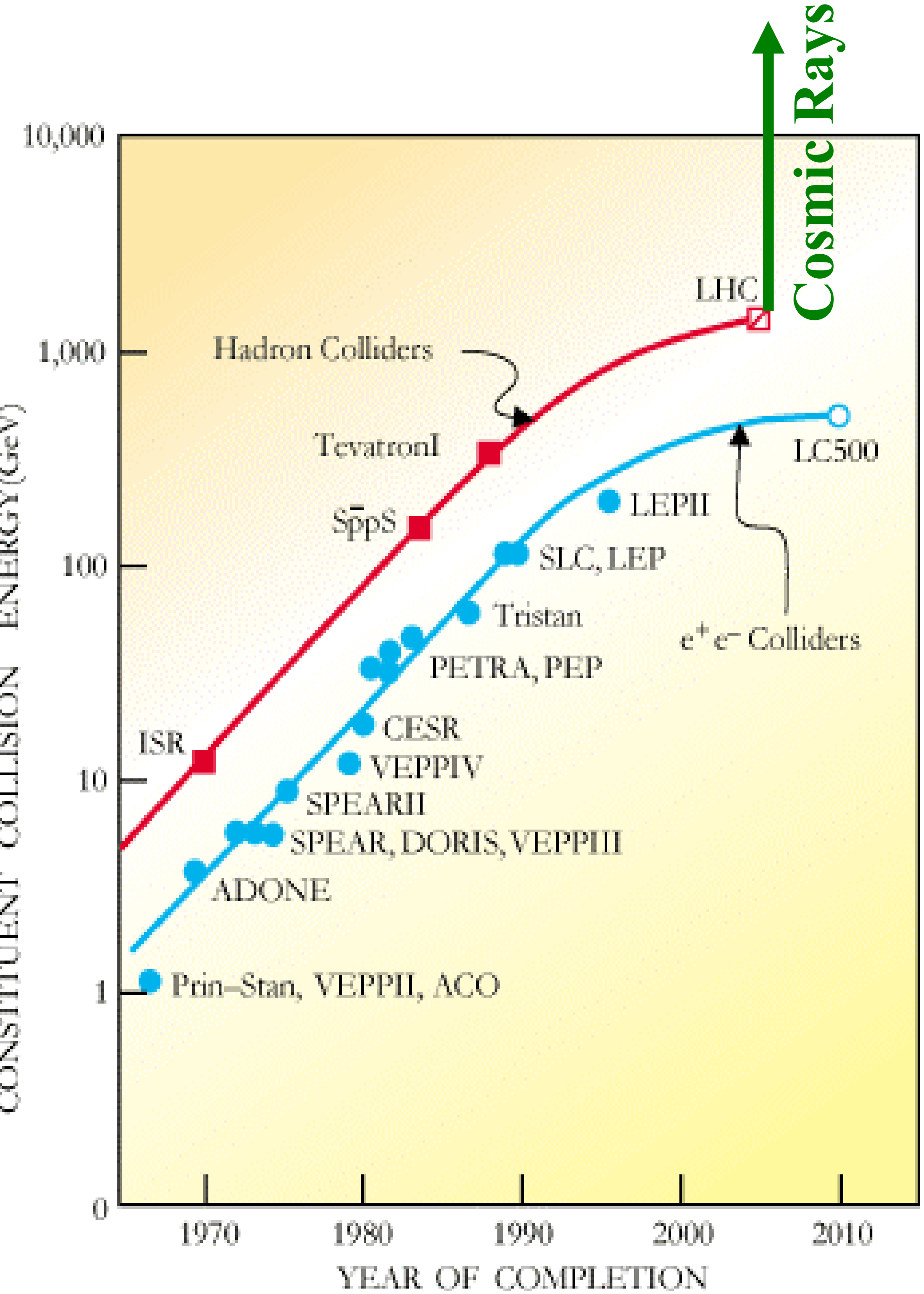


Ground based telescopes looking at light produced in atmosphere

Arrays of particle detectors



The future of HEP?



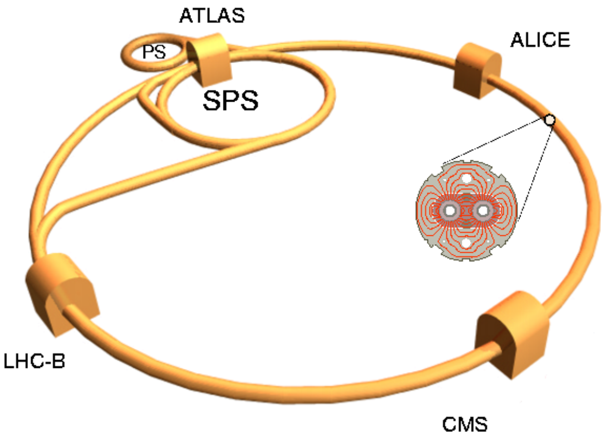
- Higher energies are not the full story…

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

Particle Acceleration

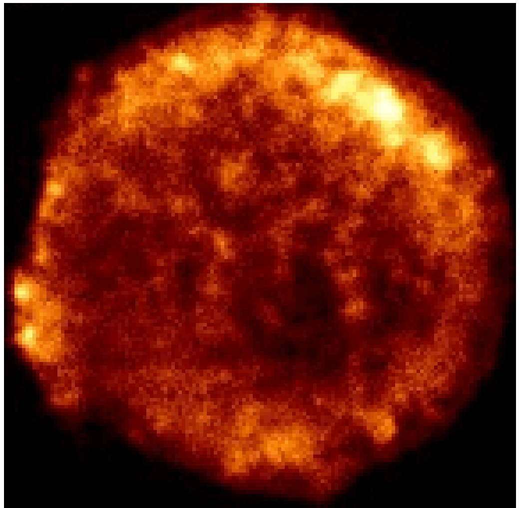
$E \propto BR$

Large Hadron Collider



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

Tycho SuperNova Remnant



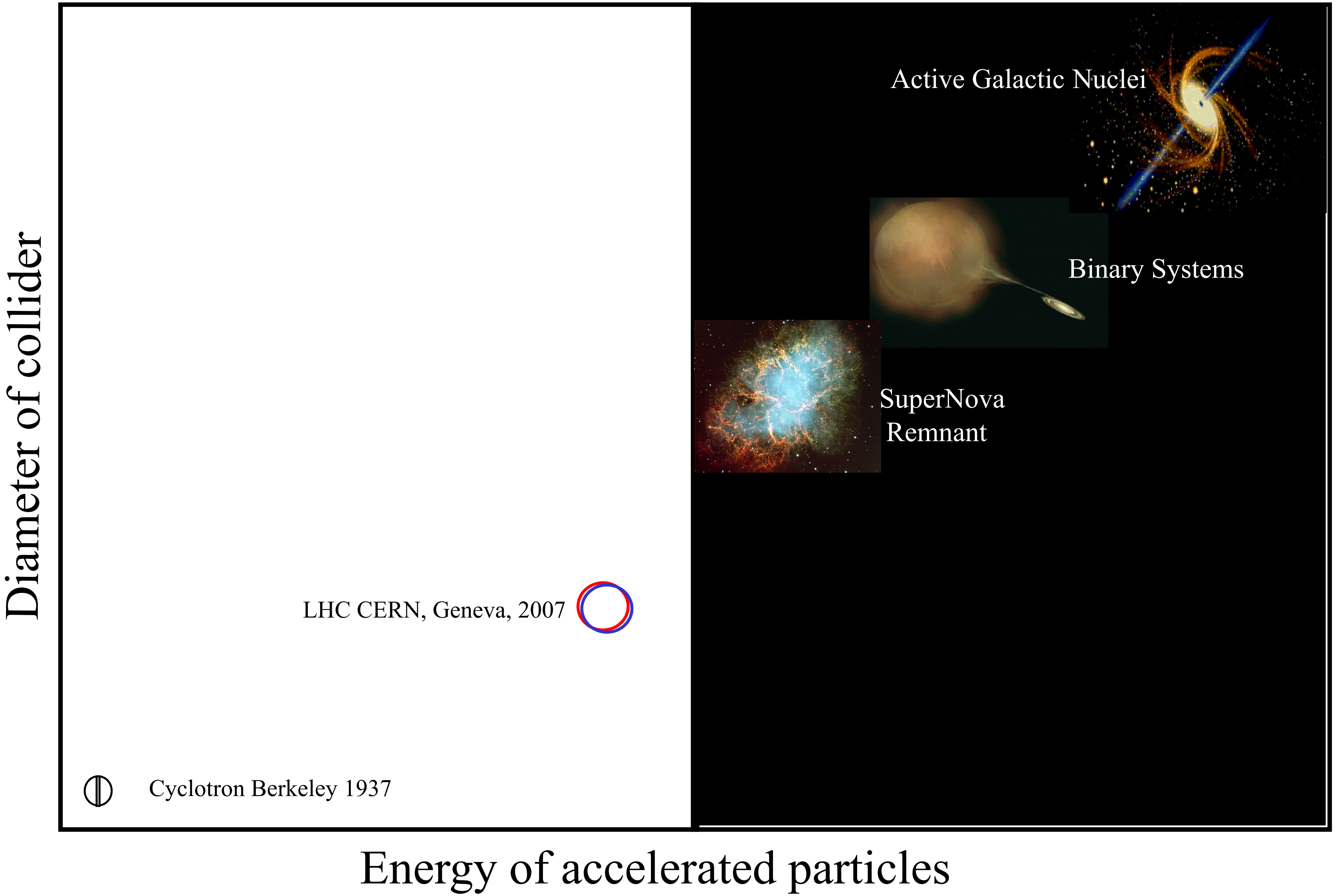
$R \sim 10^{15}\text{km},\ B \sim 10^{-10}\text{T} \quad \Rightarrow E \sim 1000\,\text{TeV}$

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

Particle Physics ⇒ Particle Astrophysics

Terrestrial Accelerators

Cosmic Accelerators



Active Galactic Nuclei

Binary Systems

SuperNova
Remnant

LHC CERN, Geneva, 2007

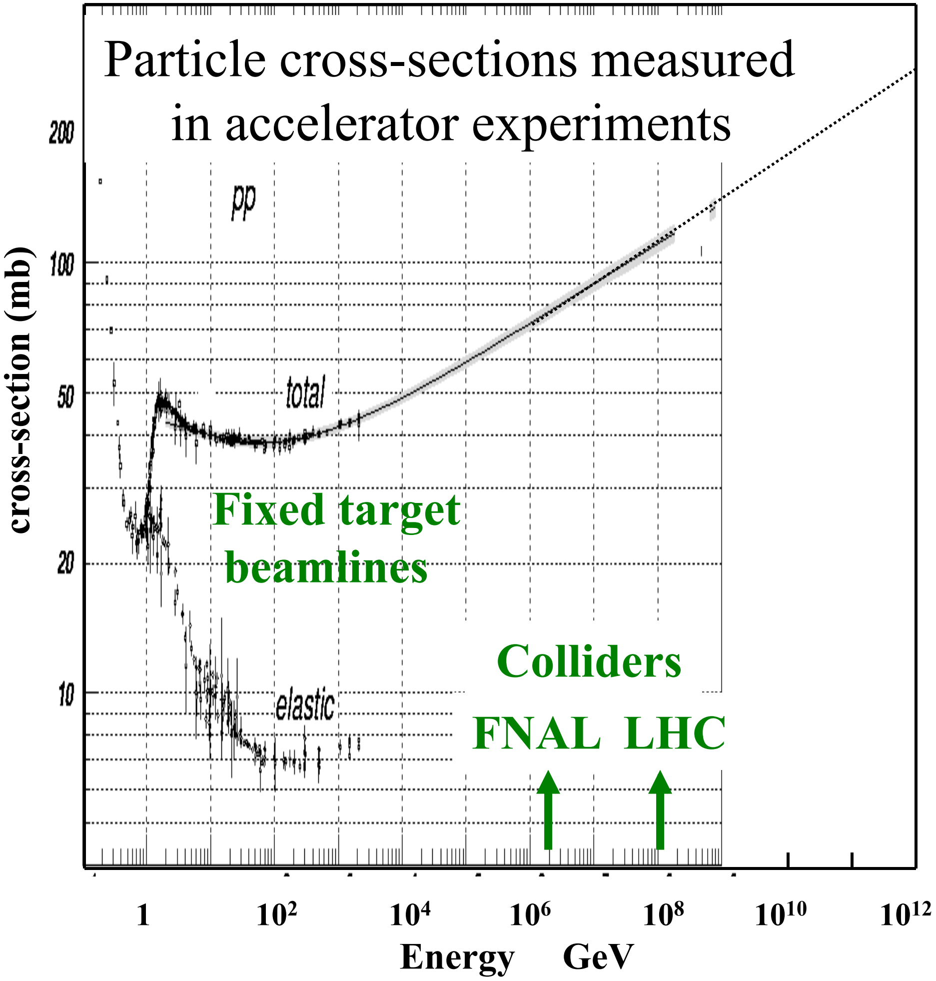
Cyclotron Berkeley 1937

Diameter of collider

Energy of accelerated particles

Ultra High Energy from Cosmic Rays

From laboratory accelerators

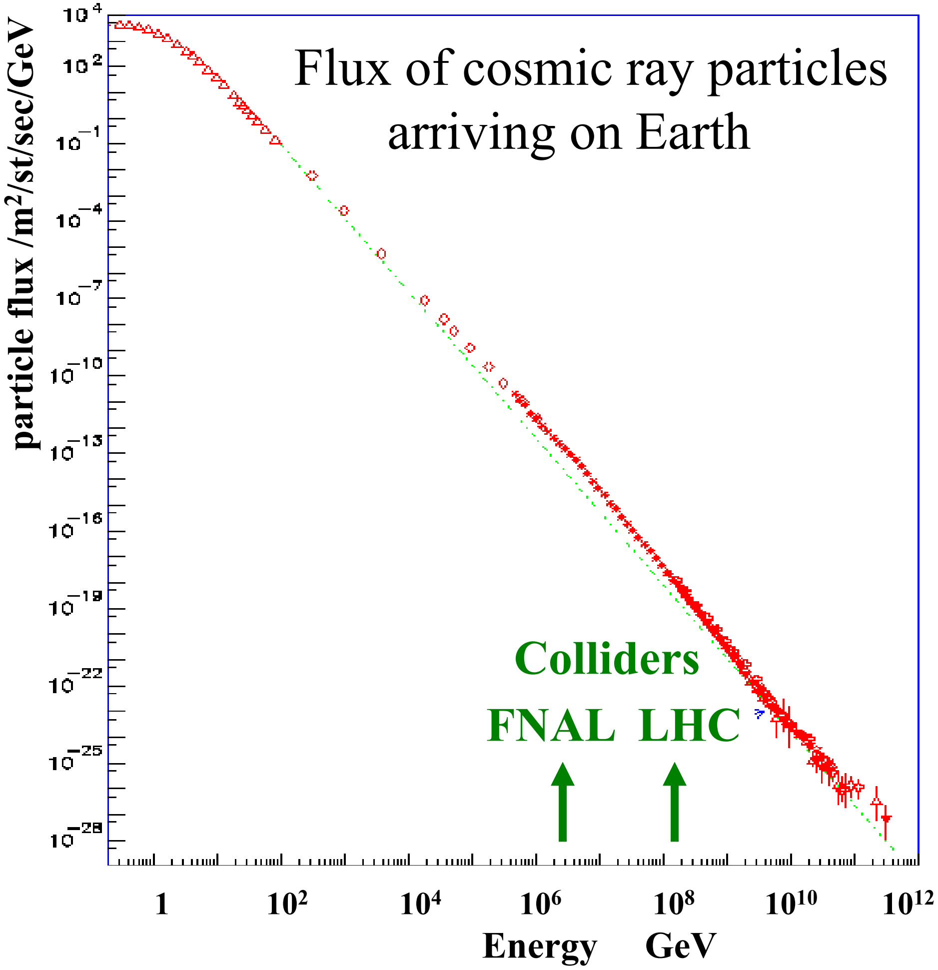

Particle cross-sections measured in accelerator experiments

Fixed target beamlines

Colliders

FNAL LHC

From cosmic accelerators


Flux of cosmic ray particles arriving on Earth

Colliders

FNAL LHC

Ultra High Energy Particles arrive from space for free: make use of them

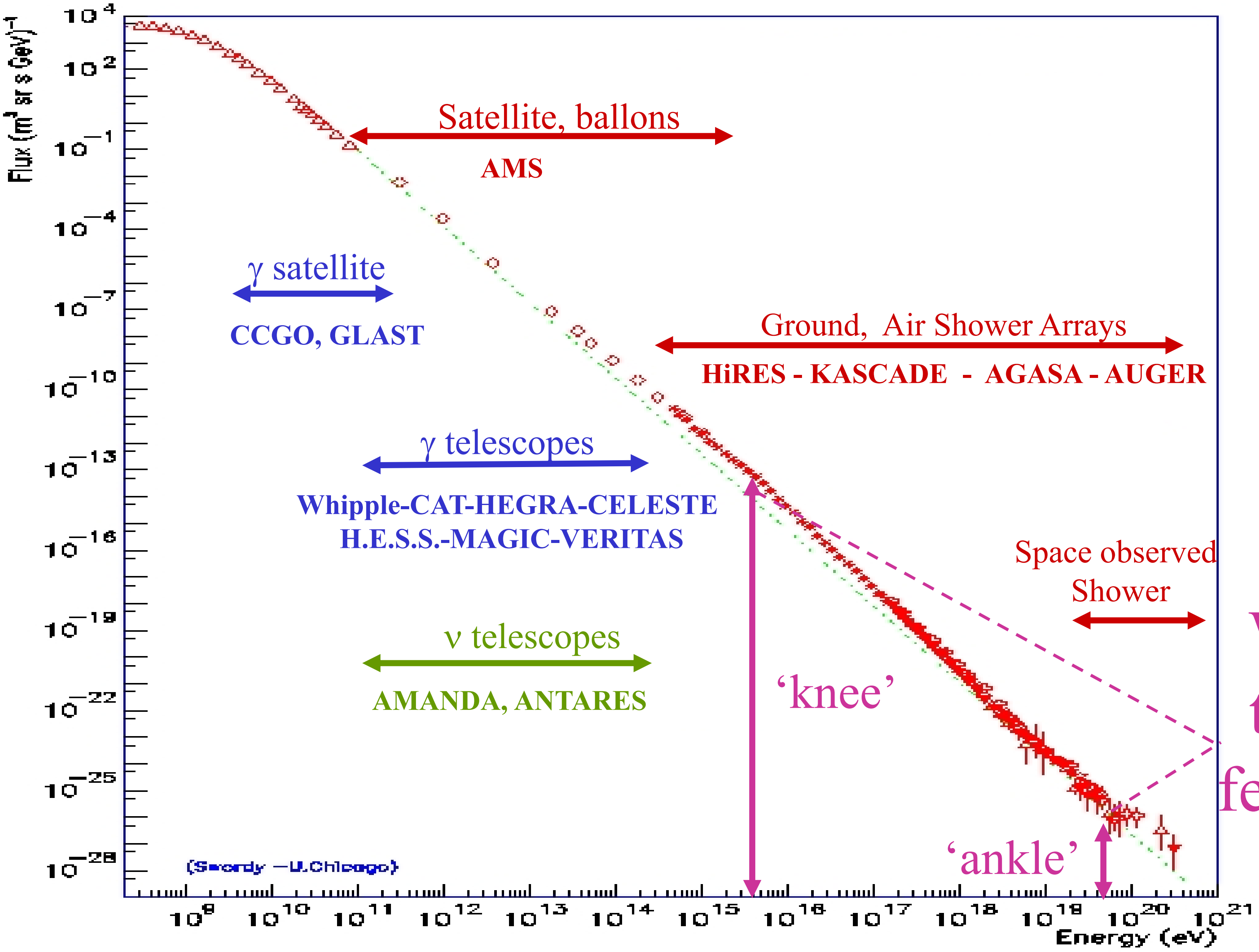
Experimental Astroparticle Physics (a short introduction)

Alessandro De Angelis
INFN & Univ. Udine; IST Lisboa

Lund 2009

Lectures 3-4

Charged Cosmic Ray Energy Spectrum



Satellite, ballons

AMS

γ satellite

CCGO, GLAST

Ground, Air Shower Arrays

HiRES - KASCADE - AGASA - AUGER

γ telescopes

Whipple-CAT-HEGRA-CELESTE
H.E.S.S.-MAGIC-VERITAS

Space observed Shower

ν telescopes

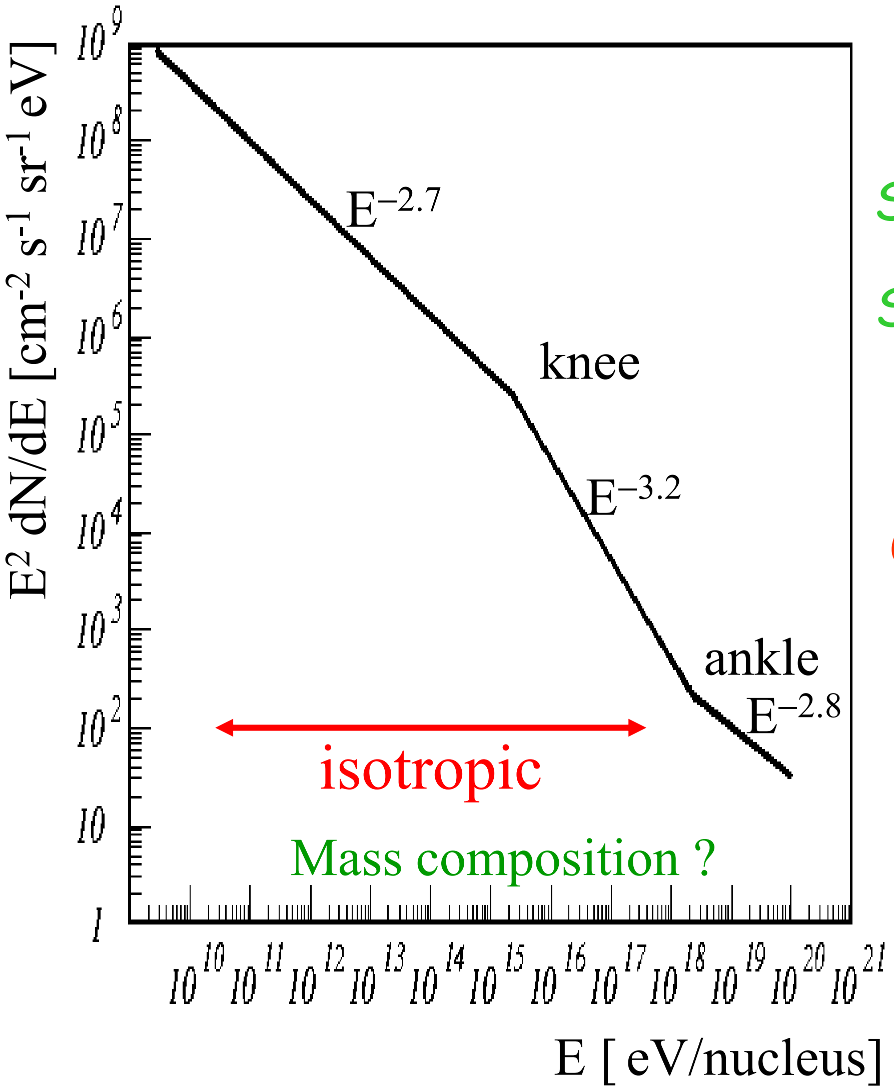
AMANDA, ANTARES

'knee'

'ankle'

Why these features ?

Features of Cosmic Ray Spectrum



Ingredients of models:

$$dN/dE \sim E^{\overset{\text{source}}{\alpha} + \overset{\text{propagation}}{\delta}}$$

Source acceleration: $\alpha = -2.0$ to -2.2,..

Source cut-off $E < 10^{18} Z \left[\frac{R}{\text{kpc}}\right]\left[\frac{B}{\mu G}\right] \text{eV}$

Diffusion models $\delta = -0.3$ to -0.6

GZK cut-off on CMB γ $E \approx 7\ 10^{19}$ eV

'Conventional Wisdom':

Galactic SNR $E < 3\ 10^{18}$ eV

Galactic losses $E > 4\ 10^{14}$ eV

Extragalactic $E > 3\ 10^{18}$ eV

exotic $E > 7\ 10^{19}$ eV

How are they produced? (Possible acceleration sites)

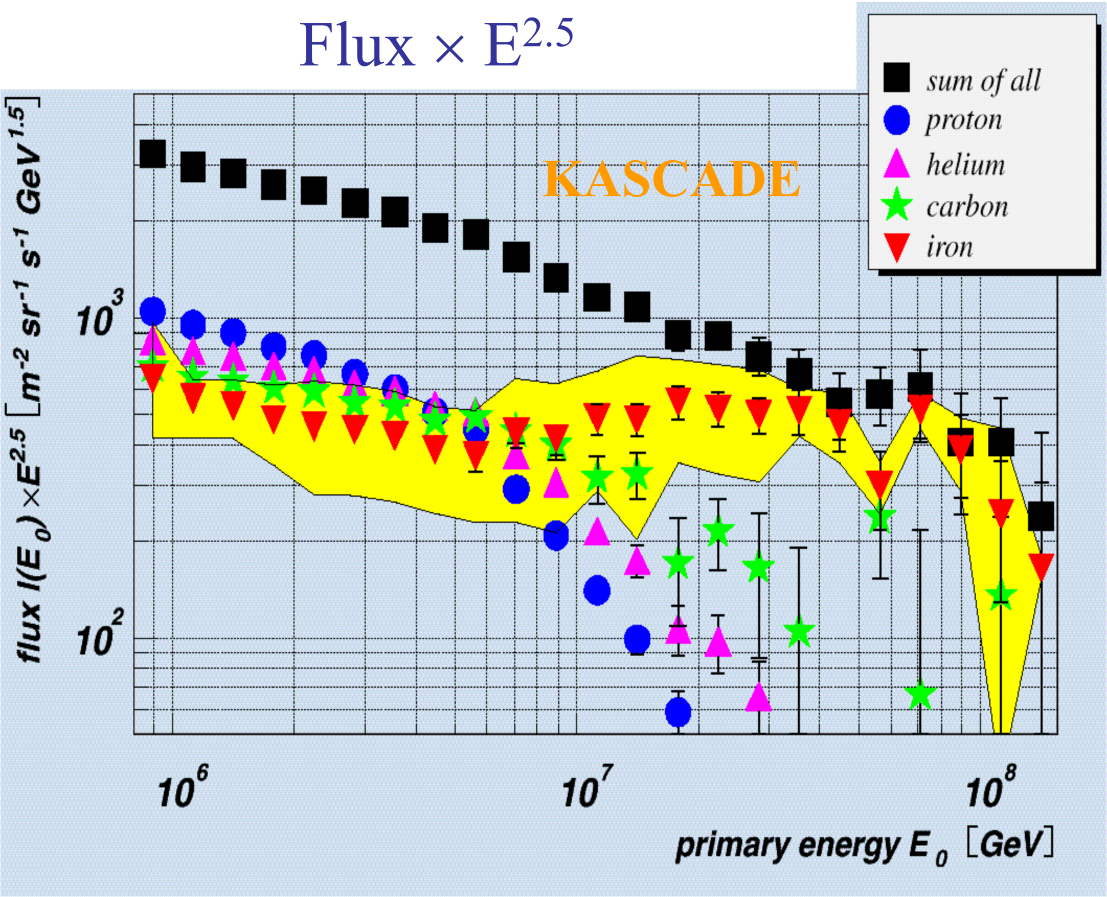
- Wherever you have gravitational collapses, you can convert gravitational potential energy into kinetic energy of particles
  - Galactic sources (supernova remnants, binaries…) certainly able to produce particles up to ~ 100 TeV
    - Below the knee?
    - Galactic magnetic field ~1-3 μG can trap protons 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)

Mass composition at knee

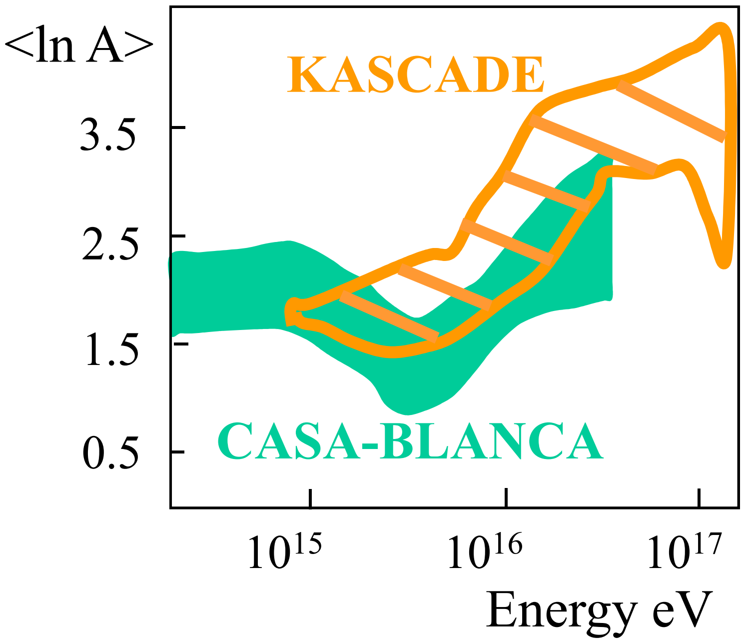
Average shower depth and ratio N_μ / N_e sensitive to primary mass

(NB. Mass composition extracted is very sensitive to Monte Carlo simulation)

Flux × $E^{2.5}$



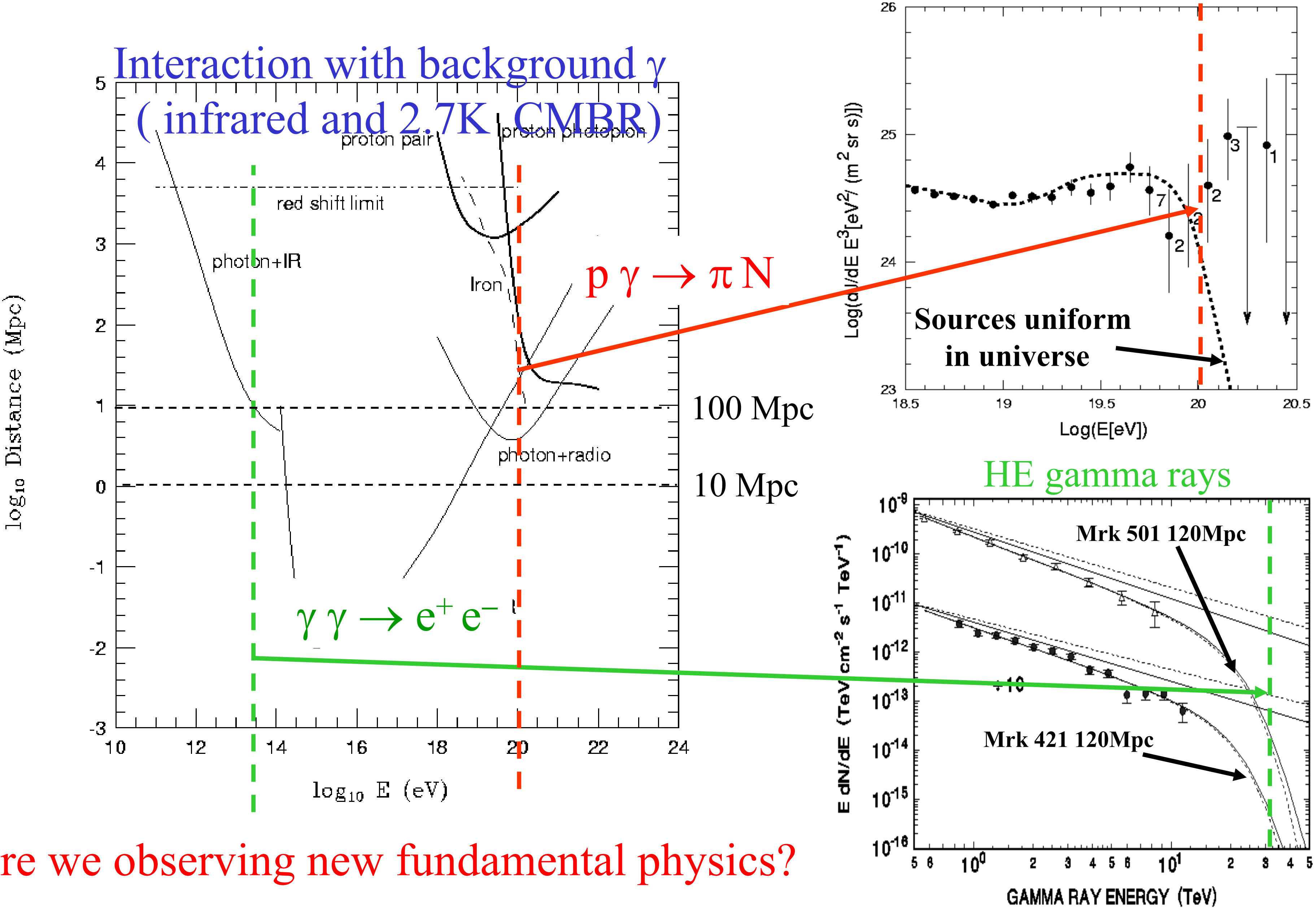
Mean ln(A)



KASCADE ⇒ series of knees at different energies: p,He,..,C,..,Fe.

$E(\text{Knee}) \propto Z$ ⇒ knee due to source confinement cut-off ?

‘GZK cutoff ’



Interaction with background γ (infrared and 2.7K CMBR)

p γ → π N

γ γ → $e^+ e^-$

100 Mpc

10 Mpc

HE cosmic rays

Sources uniform in universe

HE gamma rays

Mrk 501 120Mpc

Mrk 421 120Mpc

Are we observing new fundamental physics?

Explanations of Ankle/ E > 10^{20} eV events

Astronomy type explanations

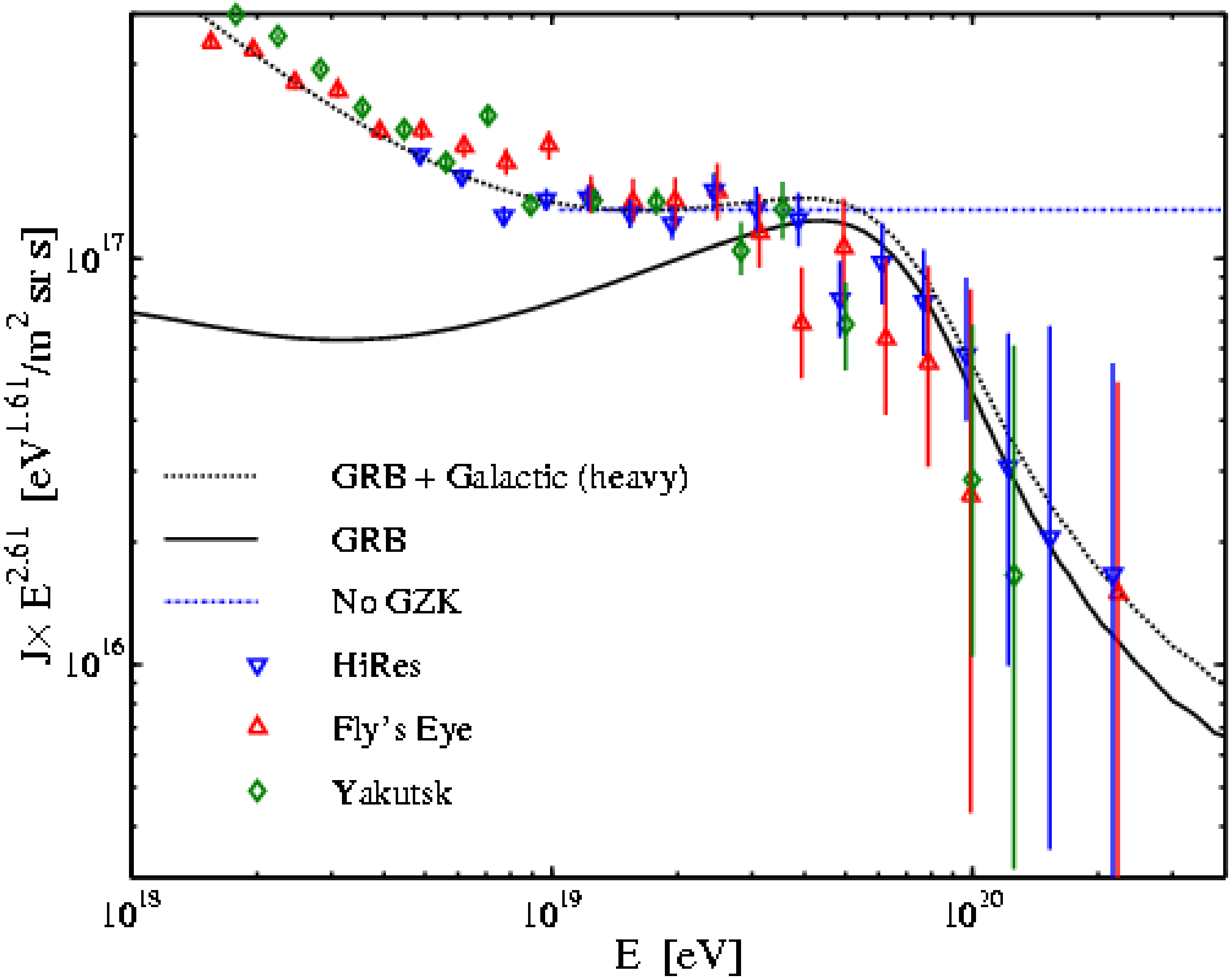
- ‘Bottom-Up’ : acceleration
  - pulsars in galaxy,
  - radio lobes of AGN (proximity a problem due to GZK, also should see source)

Particle Physics type explanations

- ‘Top-Down’ : decay of massive particles
  - GUT X particles with mass > 10^{20} eV and long lifetimes
  - Topological defects
- New Physics (Lorentz violation)
- **They don’t exist…**

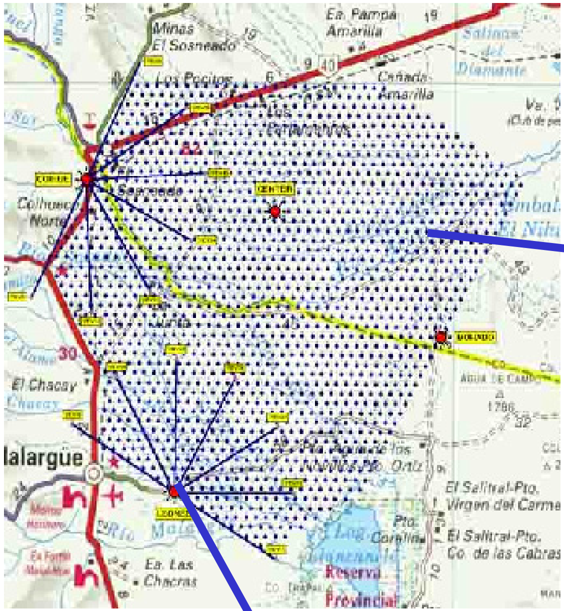
  (favorite explanation after Auger results)

HiRES (Fly's Eye)



AUGER

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



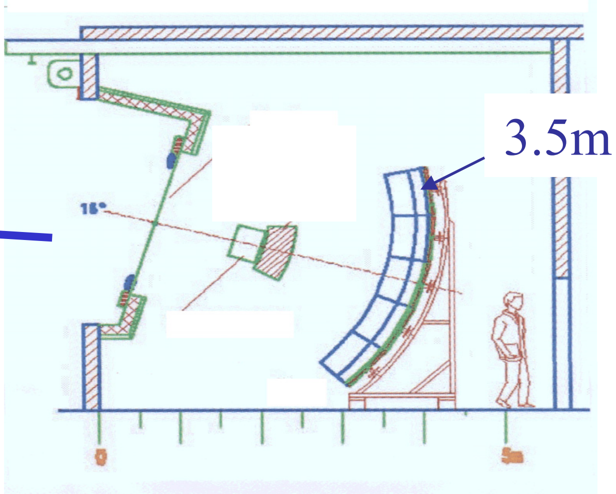
Southern site,
Mendoza Province,
Argentina

Water Cherenkov

Tanks

(1600 each 10m^2)

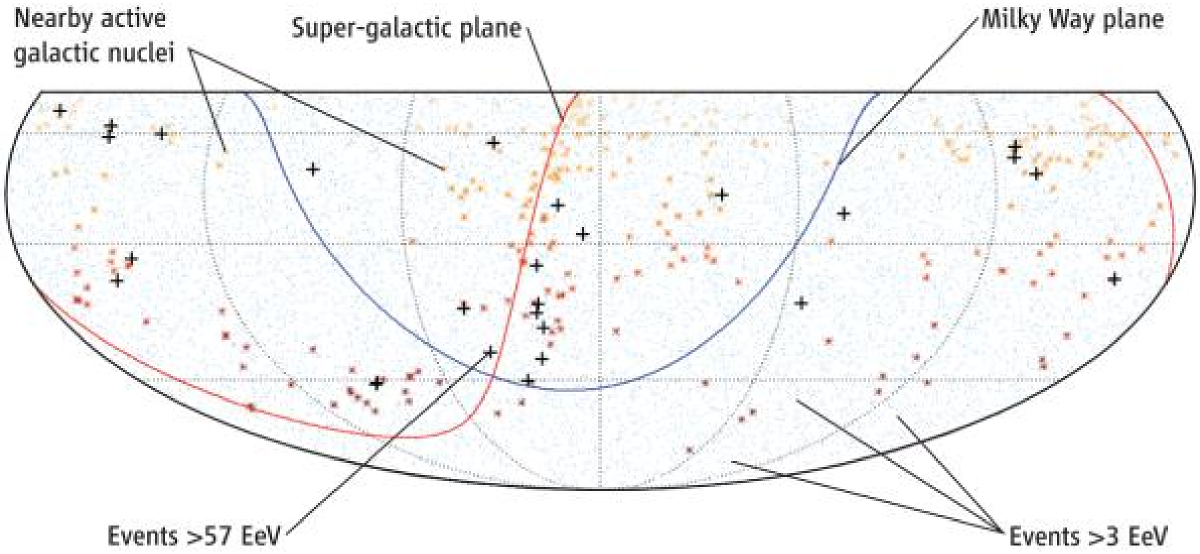
Fluorescence Telescopes (6 telescopes each 30° ×30° at 4 sites)



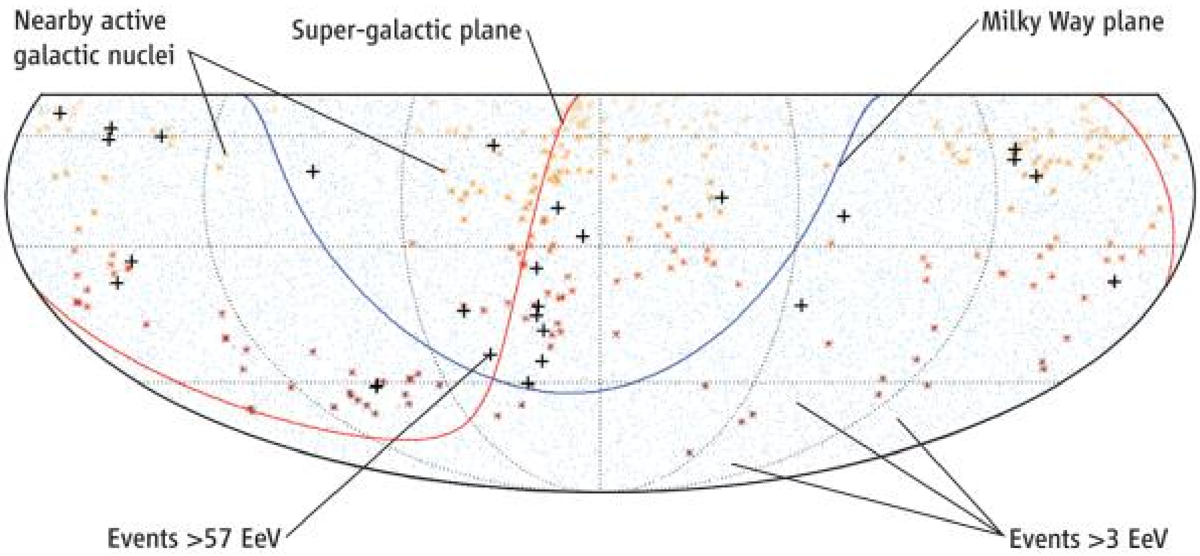
3.5m mirrors

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
  - Out of 15 events with energies > than about 60 EeV, 12 were located within 3.1° of AGN closer than 75 Mpc from Earth



Conclusion form the Auger result



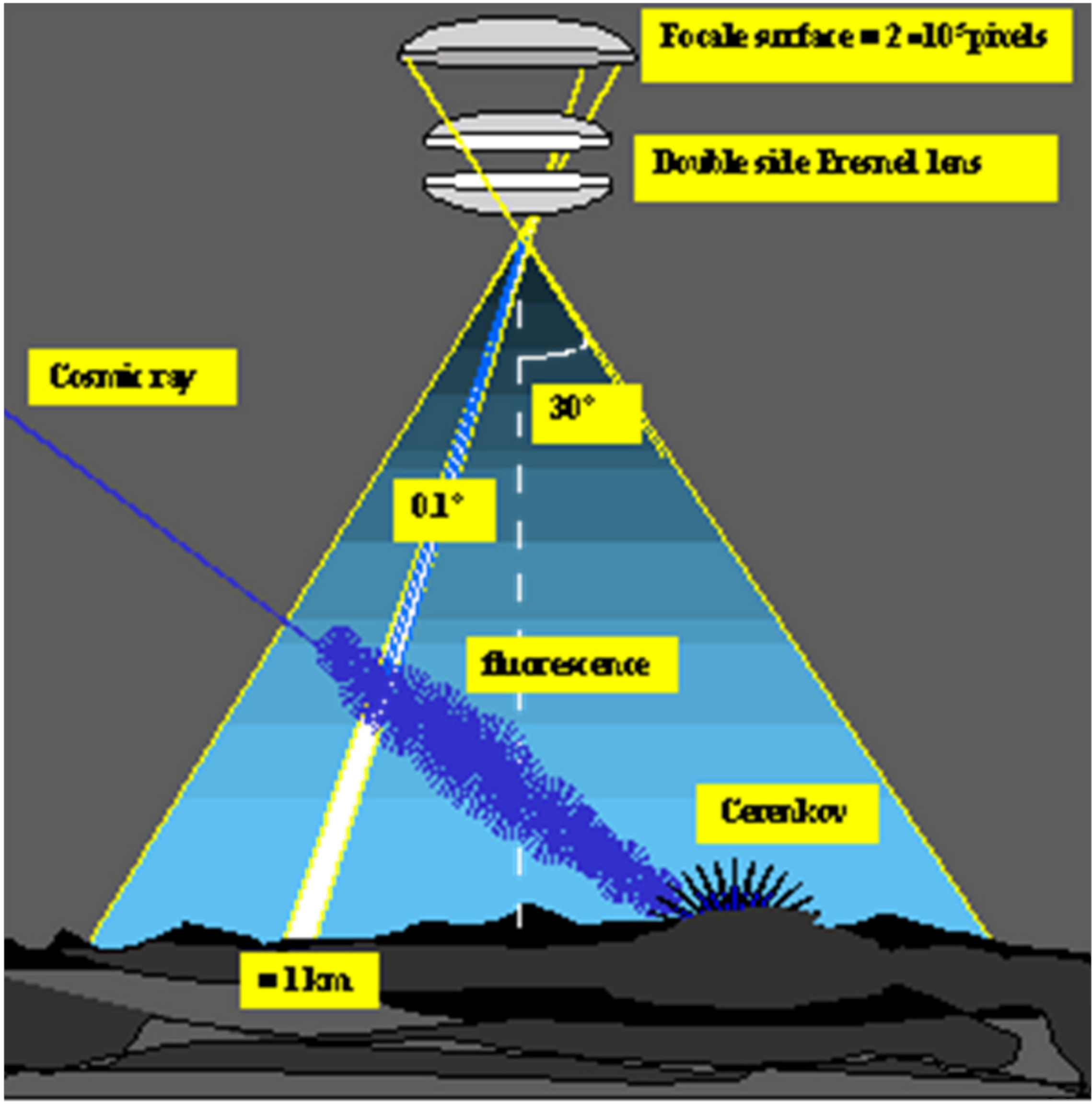
- Active Galactic Nuclei are the main source of VHE cosmic rays
- First measurement of the extragalactic magnetic field:

B ~ 0.1 – 1 nG

(dA, Roncadelli and Persic 2007, arXiv:0711.3346)

A new concept: EUSO (and …)

- The Earth atmosphere is the ideal detector for the Extreme Energy Cosmic Rays and the companion Cosmic Neutrinos. The new idea of EUSO (2012?-) is to watch the fluorescence produced by them from the top

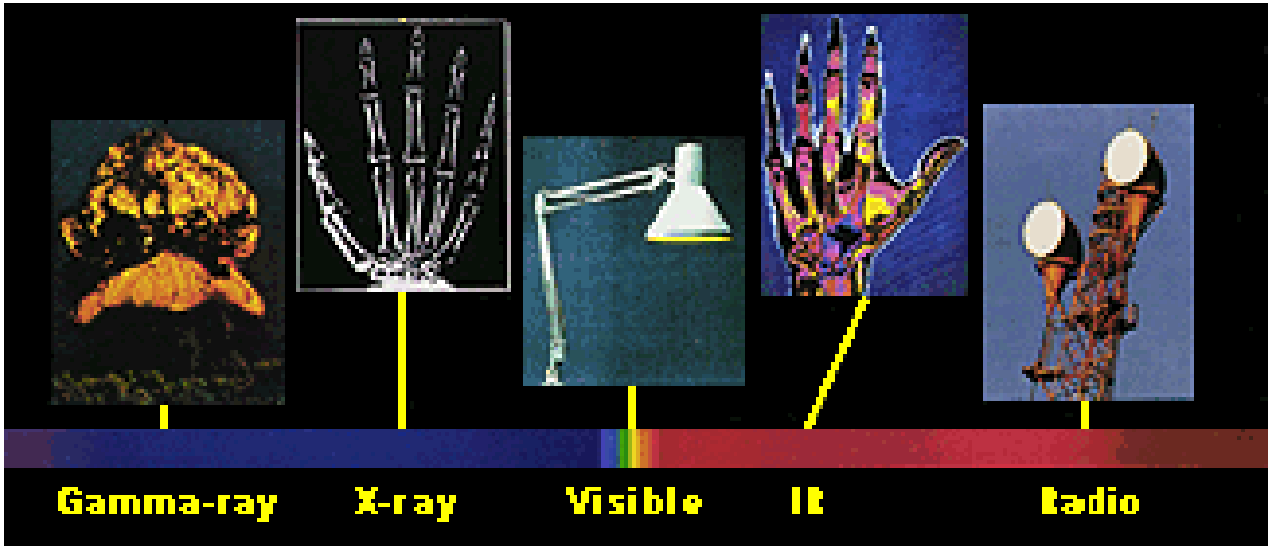


IV

Detectors for multimessanger astrophysics

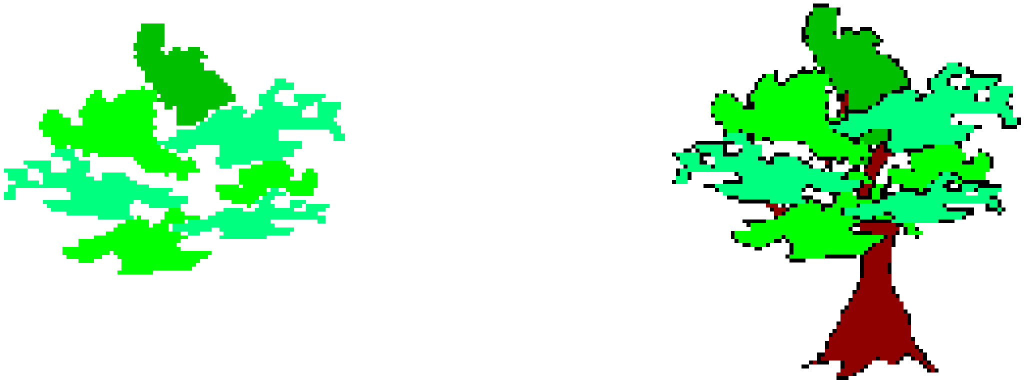
We see only partly what surrounds us

- We see only a narrow band of colors, from red to purple in the rainbow
- Also the colors we don’t see have names familiar to us: we listen to the radio, we heat food in the microwave, we take pictures of our bones through X-rays…



What about the rest ?

- What could happen if we would see only, say, green color?



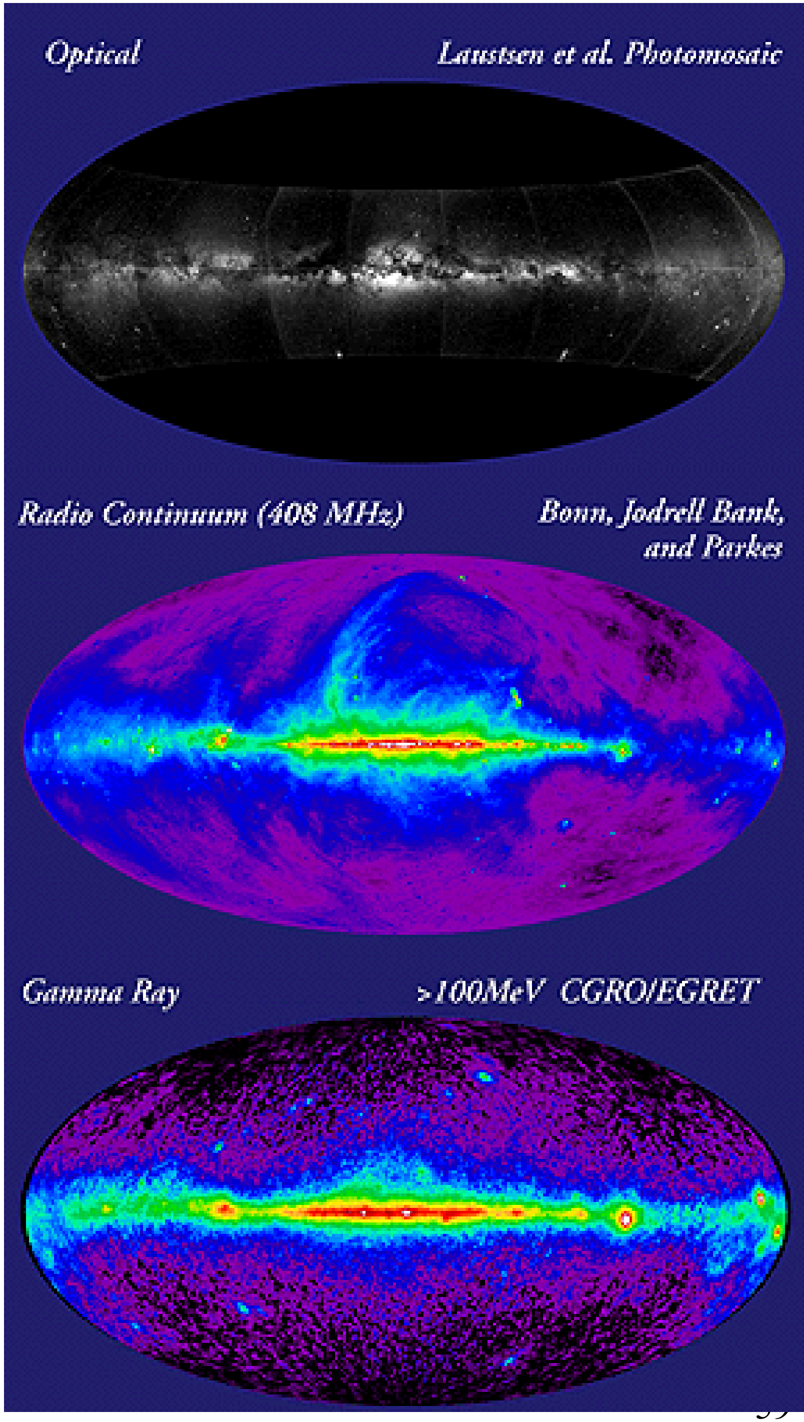
The universe we don't see

- When we take a picture we capture light

  (a telescope image comes as well from visible light)

- In the same way we can map into false colors the image from a "X-ray telescope"

- Elaborating the information is crucial



Many sources radiate over a wide range of wavelengths