Experimental Astroparticle Physics (a short introduction)

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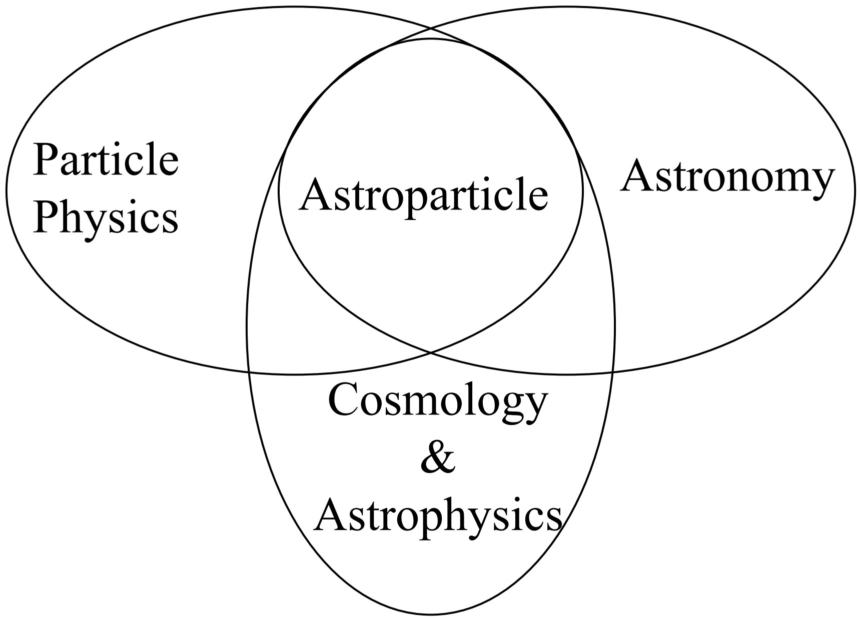
Lectures 1, 2 & 3

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

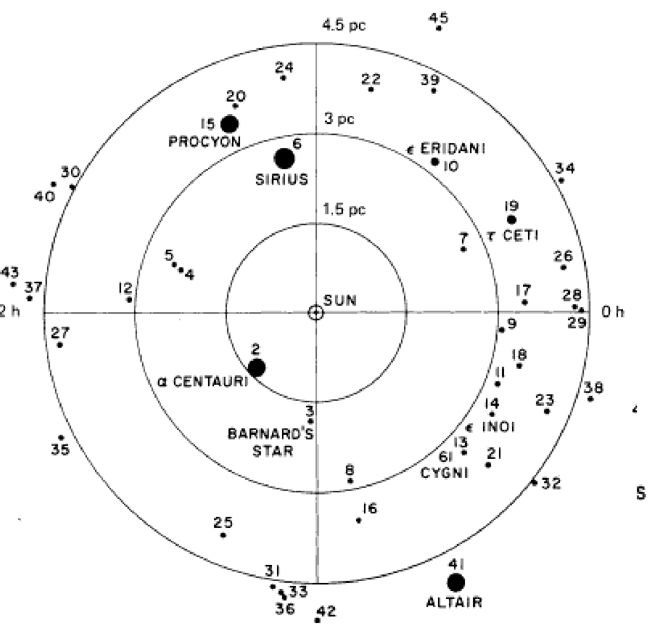
In this lecture I'll concentrate on the 2^{nd} topic

I

A quick look to our Universe

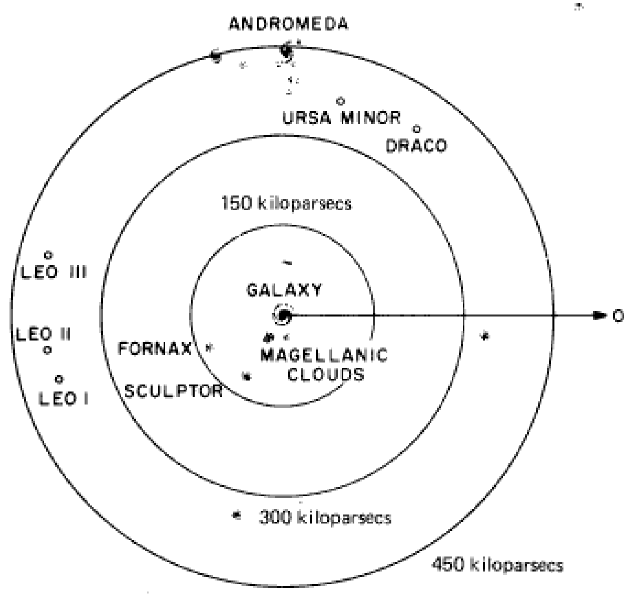
Astronomy Scales

Nearest Stars



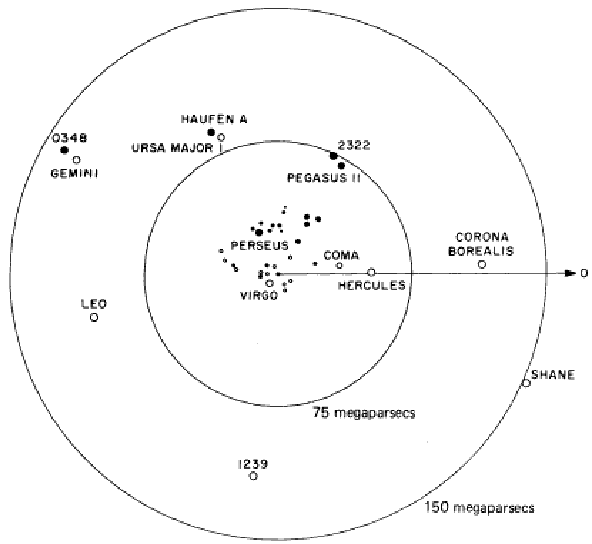
4.5 pc

Nearest Galaxies



450 kpc

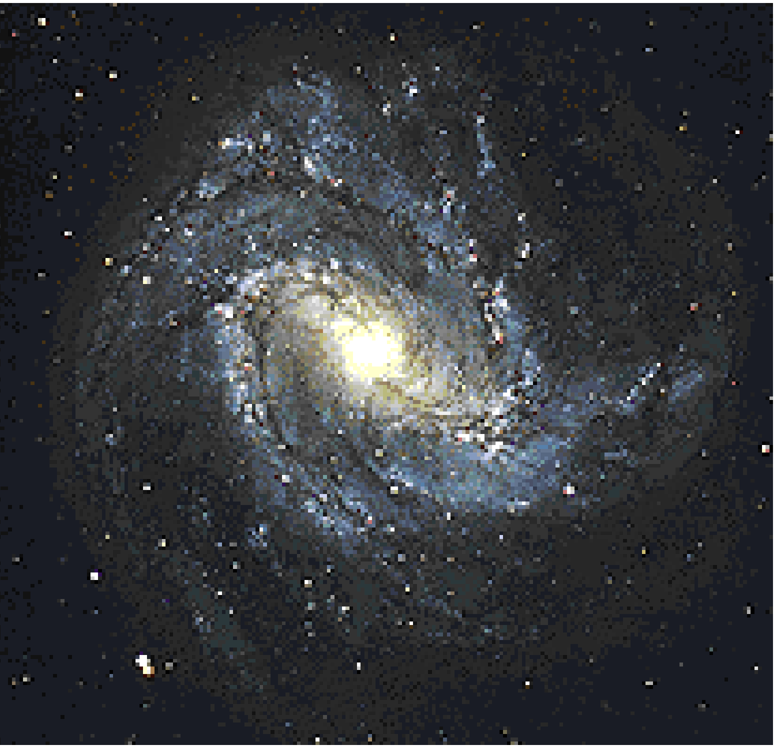
Nearest Galaxy Clusters

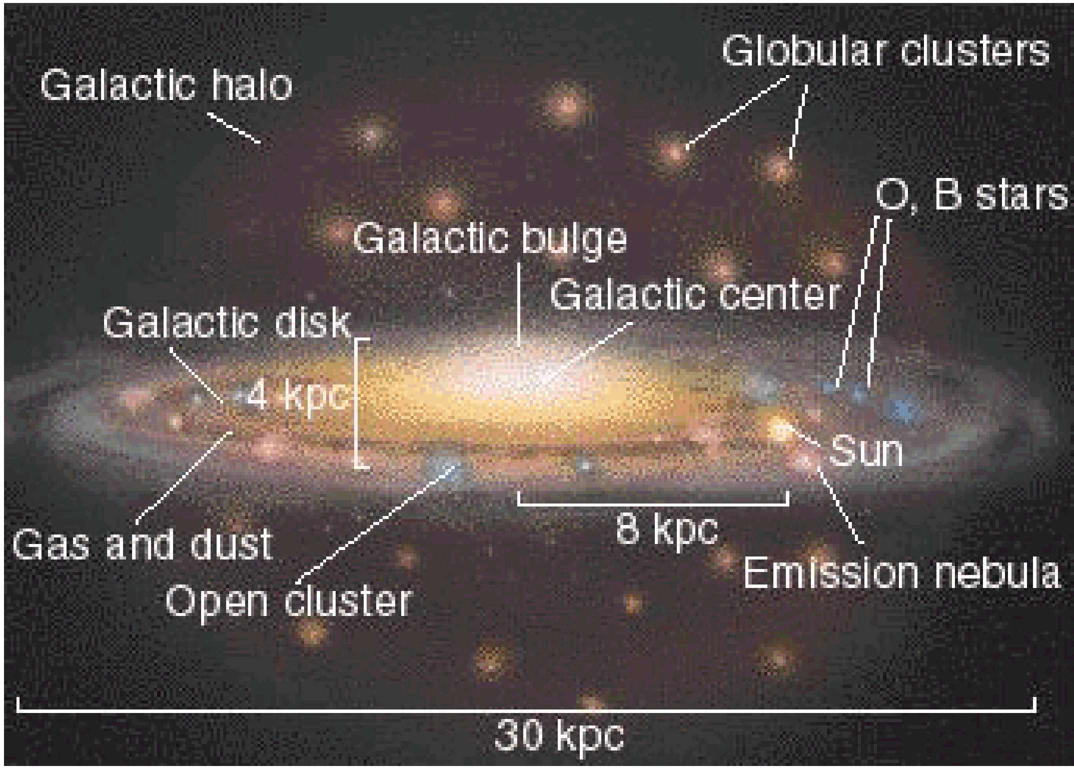


150 Mpc

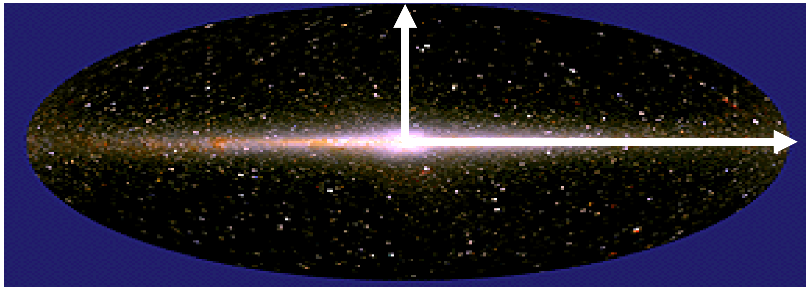
1 pc ~ 3.3 ly

Our Galaxy: The Milky Way



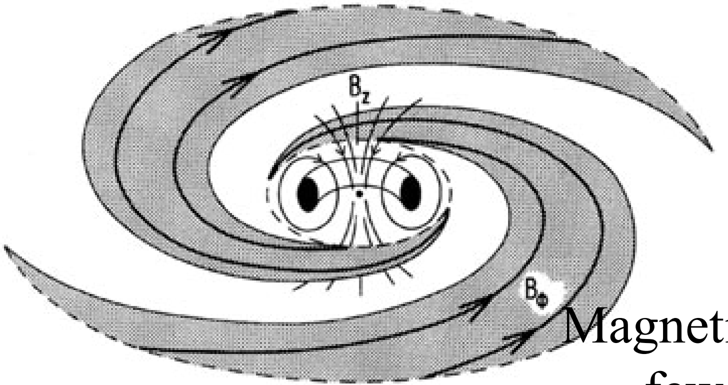


+90°



+180°

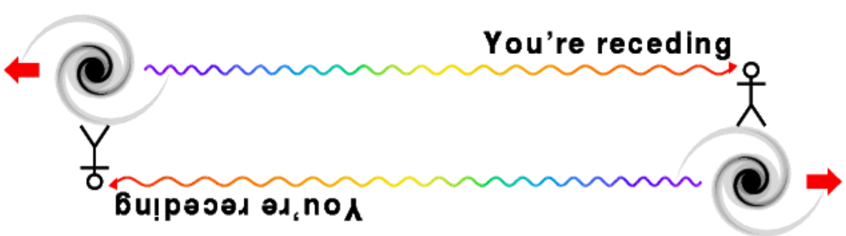
–90°

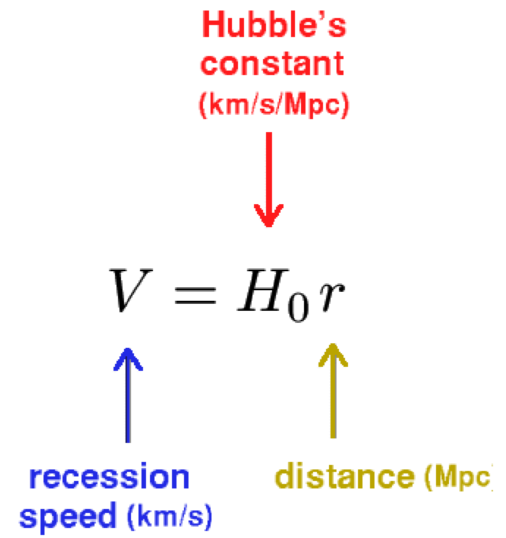


Magnetic field
~ few μG

What do we know about our Universe ?

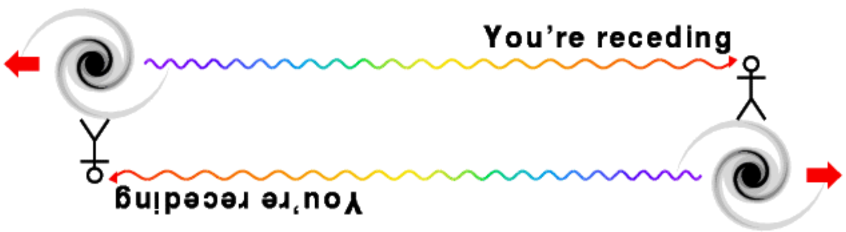
- Many things, including the facts that…
  - Particles are coming on Earth at energies 10^8 times larger than we are able to produce…
  - The Universe expands (Hubble ~1920): galaxies are getting far with a simple relationship between distance & recession speed



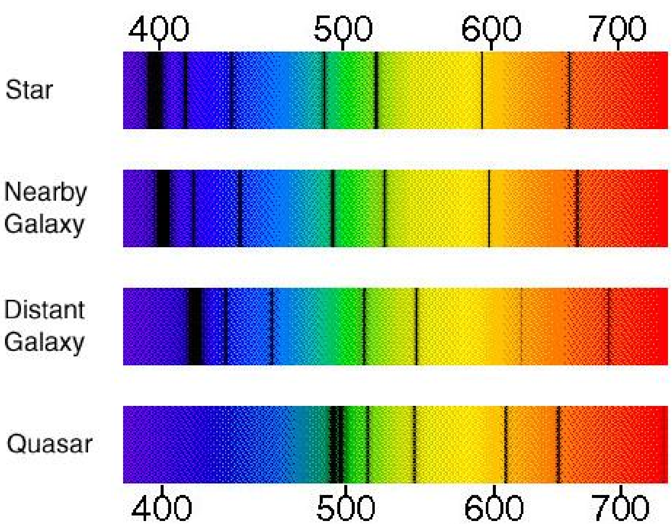


$$V = H_0 r$$

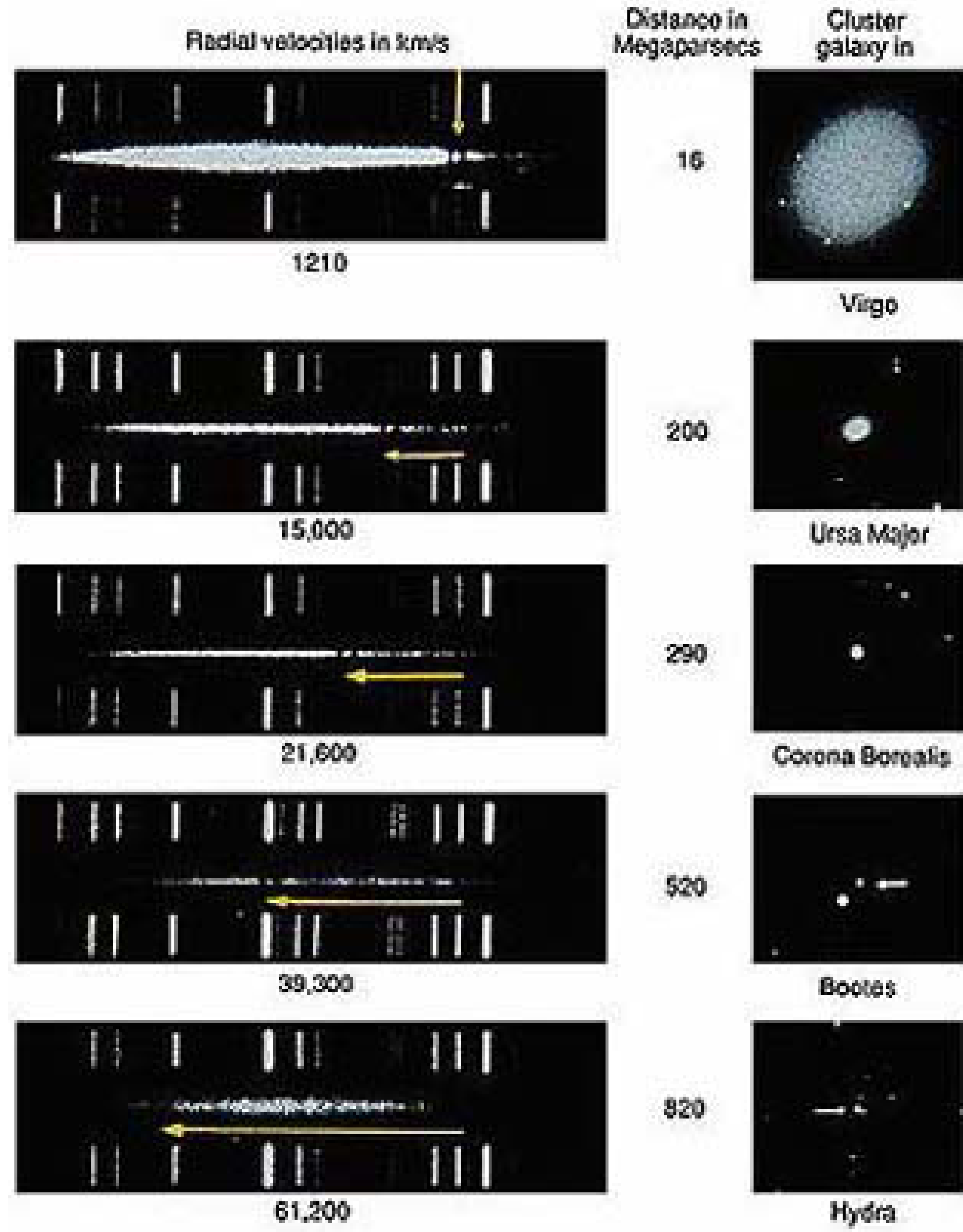
Redshift



You're receding
You're receding



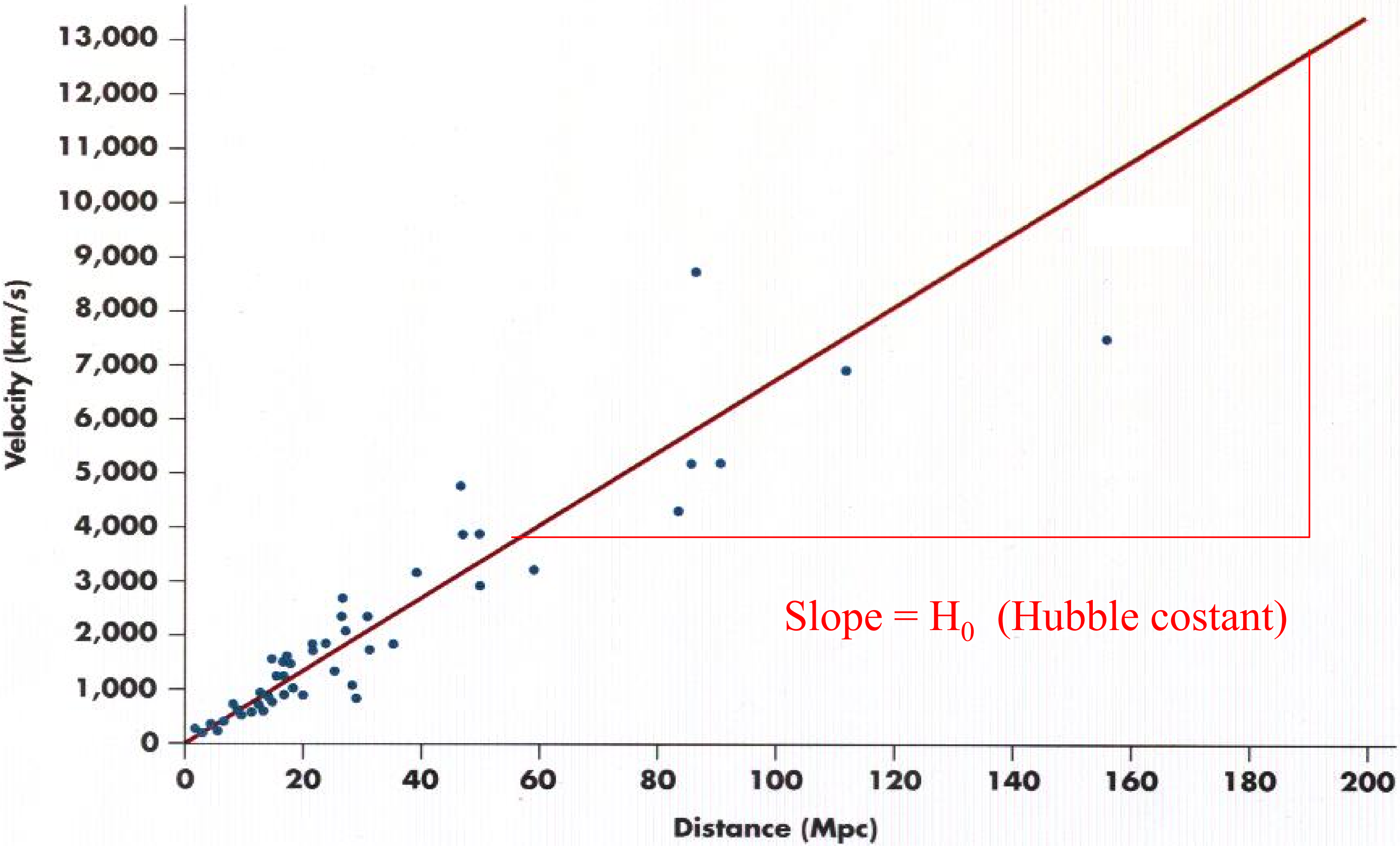
400
500
600
700
Star
Nearby Galaxy
Distant Galaxy
Quasar
400
500
600
700



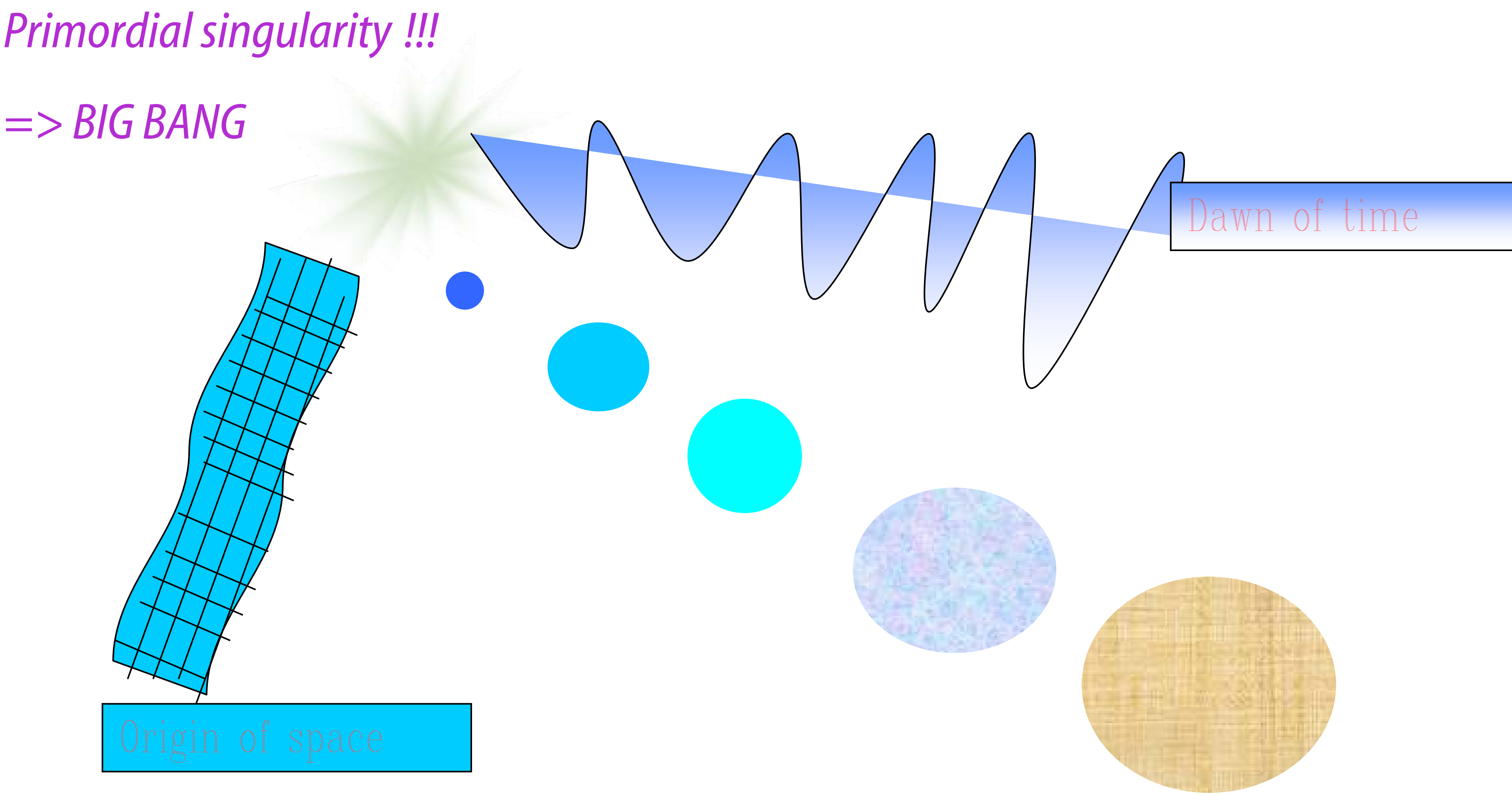
Radial velocities in km/s
Distance in Megaparsecs
Cluster galaxy in
1210
16
Virgo
15,000
200
Ursa Major
21,600
290
Corona Borealis
39,300
520
Bootes
61,200
820
Hydra

Hubble's law

Today: $H_0 = 71 \pm 4$ (km/s) / Mpc



Once upon a time...
our Universe was smaller



How far in time ?

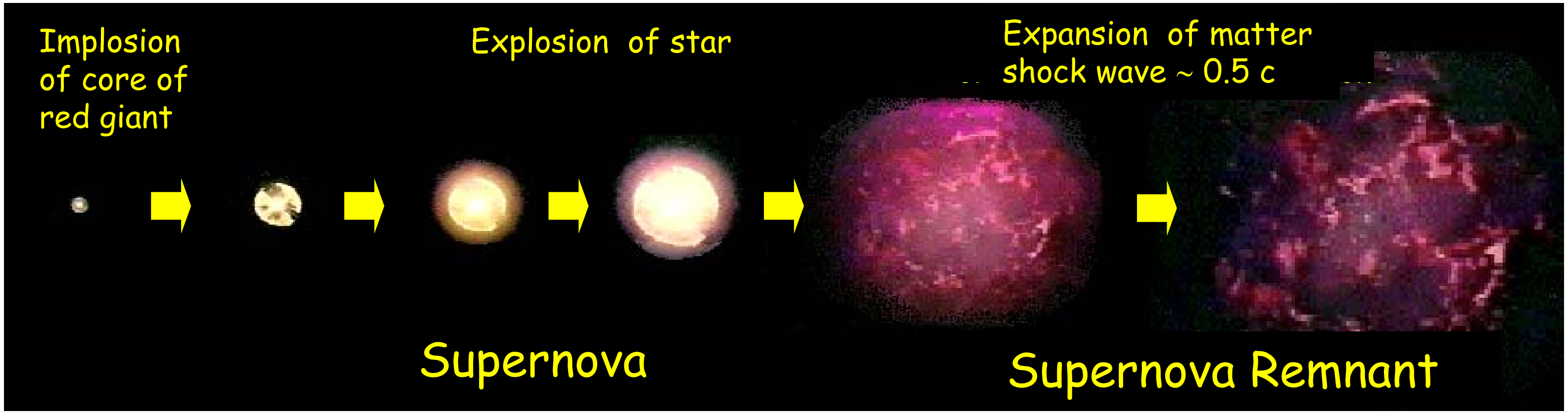
- Extrapolating backwards the present expansion speed towards the big bang

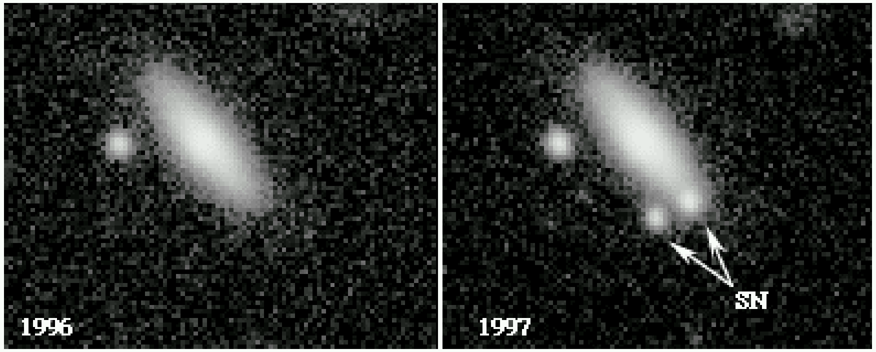
  T 🕔 $1/H_0 \sim 14$ billion years

  (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 2003: supernovae





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

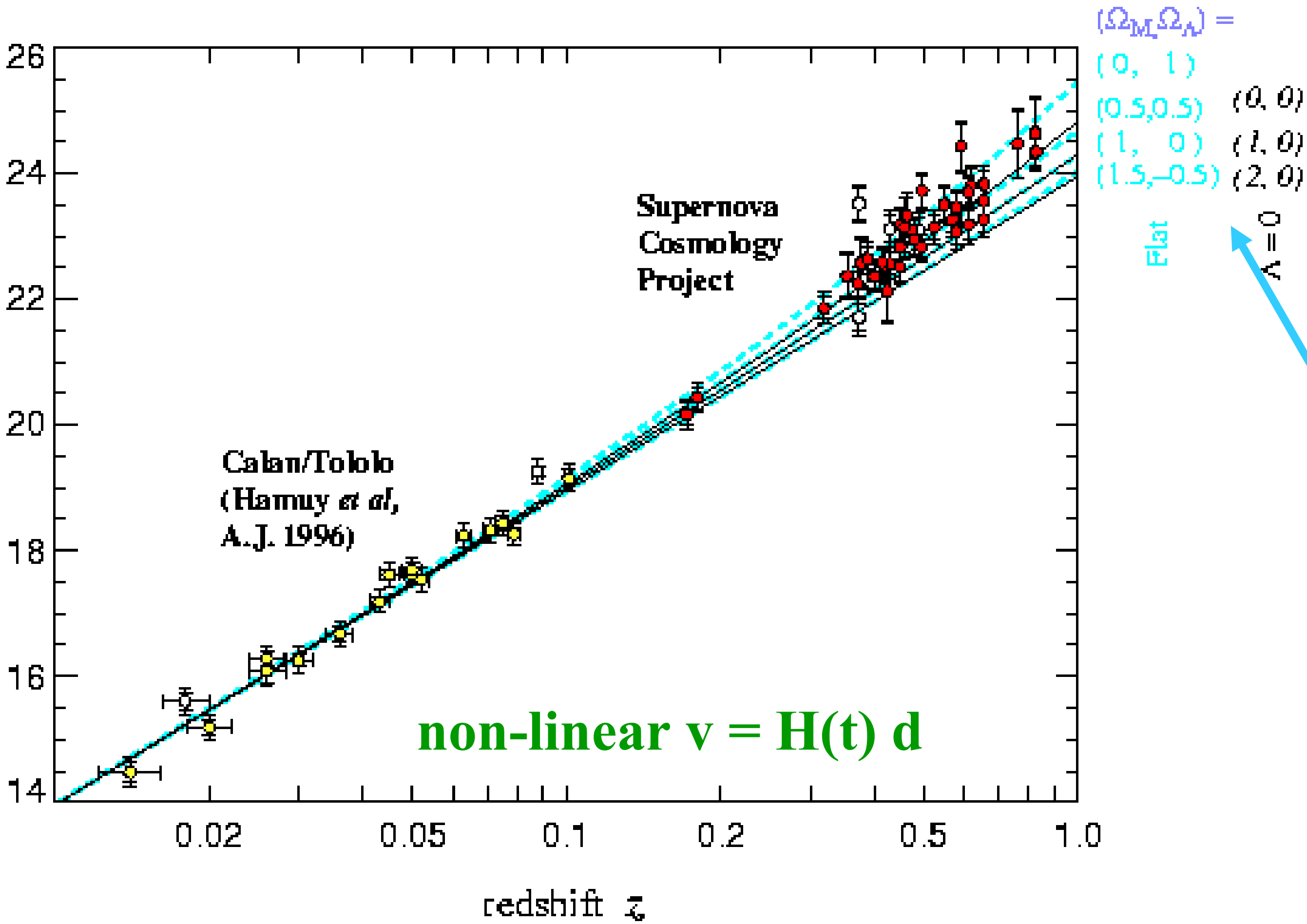
measure brightness → distance: $B = L / 4\pi d^2$

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



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

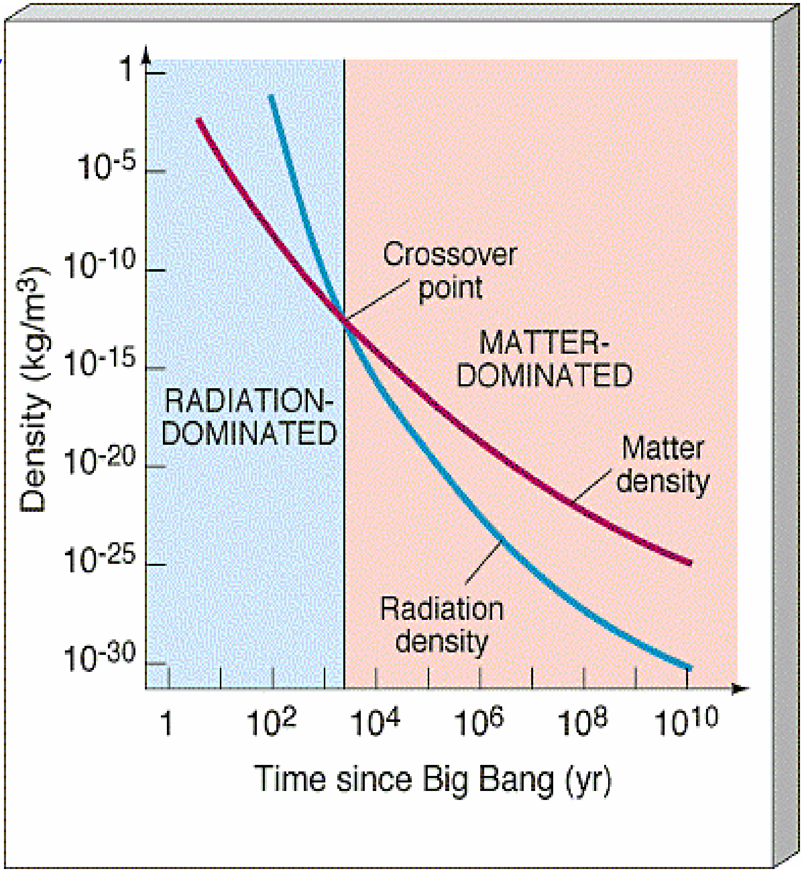
$\gamma \leftrightarrow$ proton-antiproton

$\gamma \leftrightarrow$ electron-positron

(…)

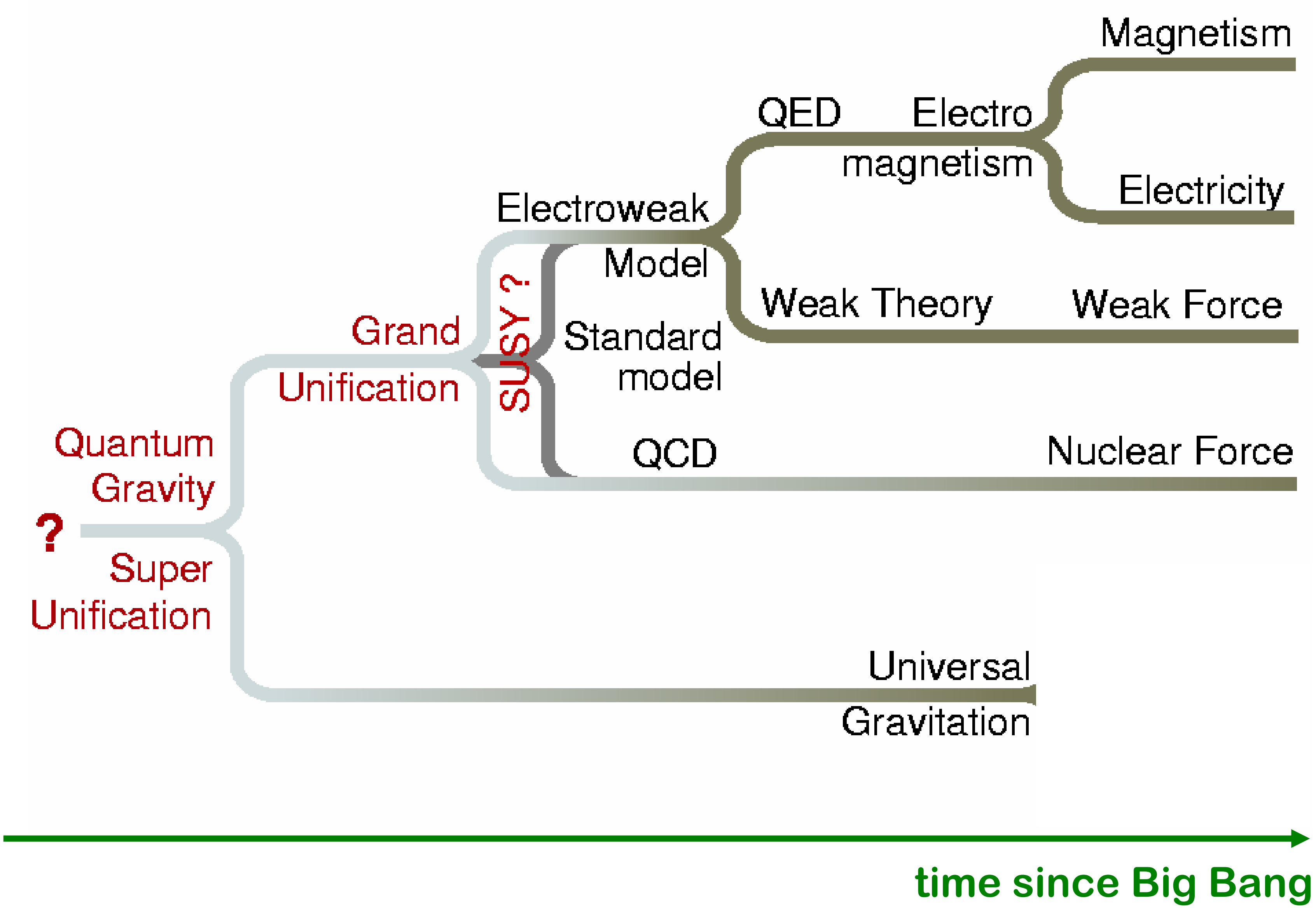
then matter became stable

Time



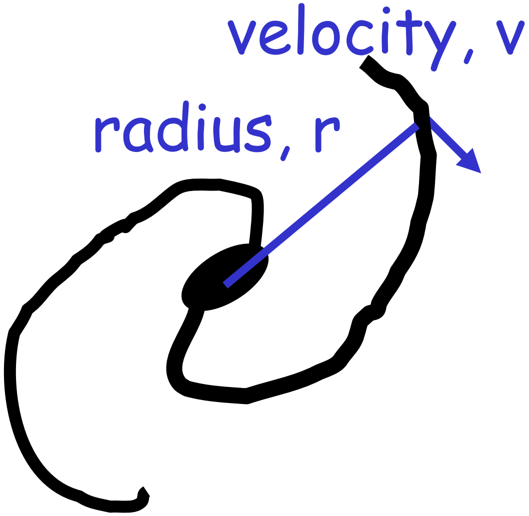
Two epochs

Particle Physics after Big Bang



THE QUEST FOR HIGHER ENERGIES IS ALSO A TIME TRAVEL

The Universe today: what we see is not everything

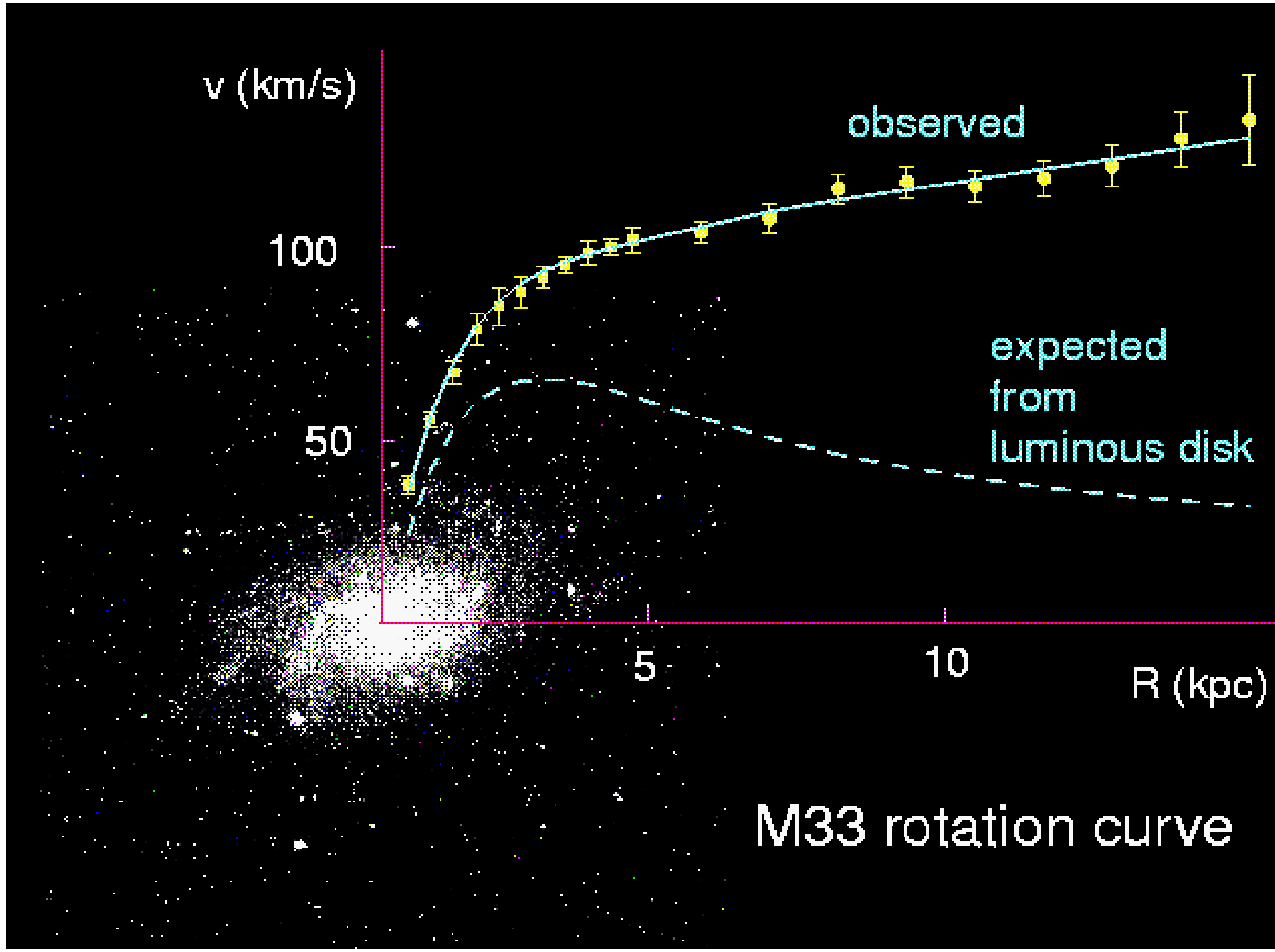


Gravity:

$G\,M(r) / r^2 = v^2 / r$

enclosed mass:

$M(r) = v^2\, r / G$



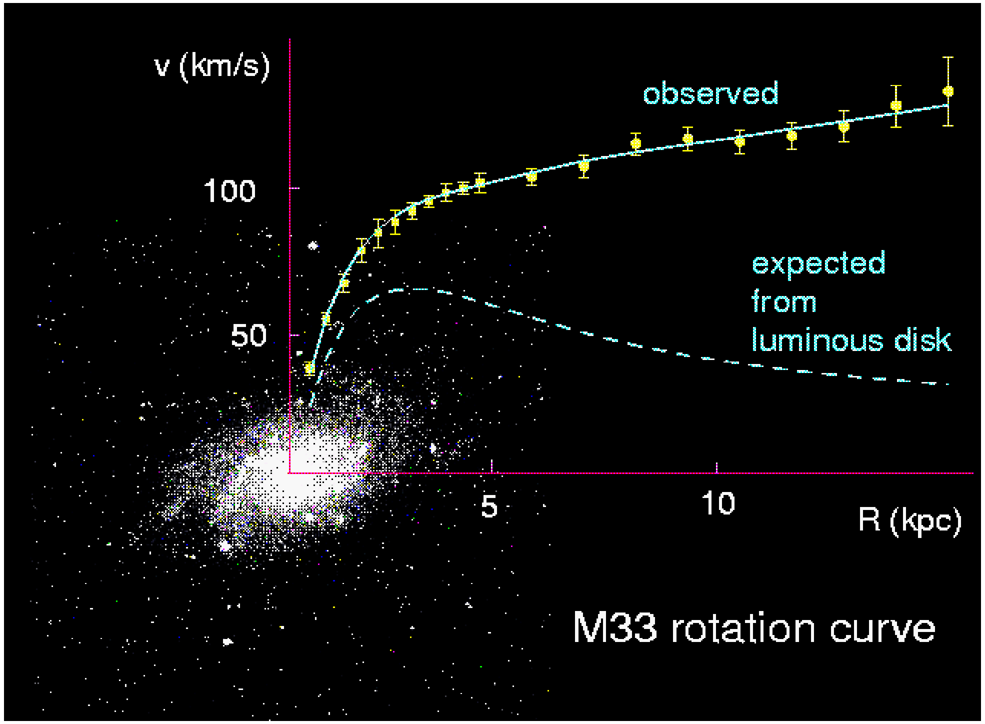
Luminous stars only small fraction of mass of galaxy

II

Dark matter searches

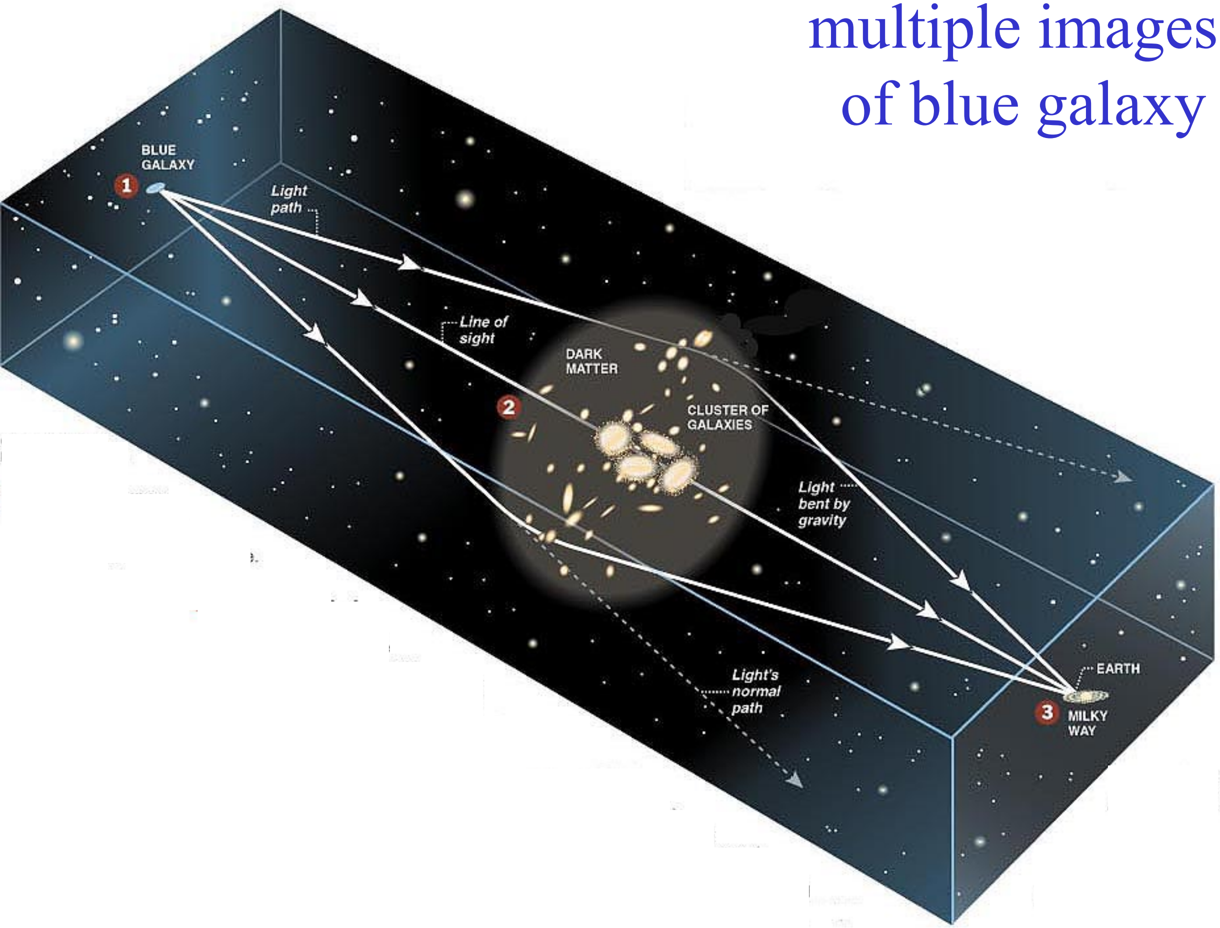
Dark matter searches

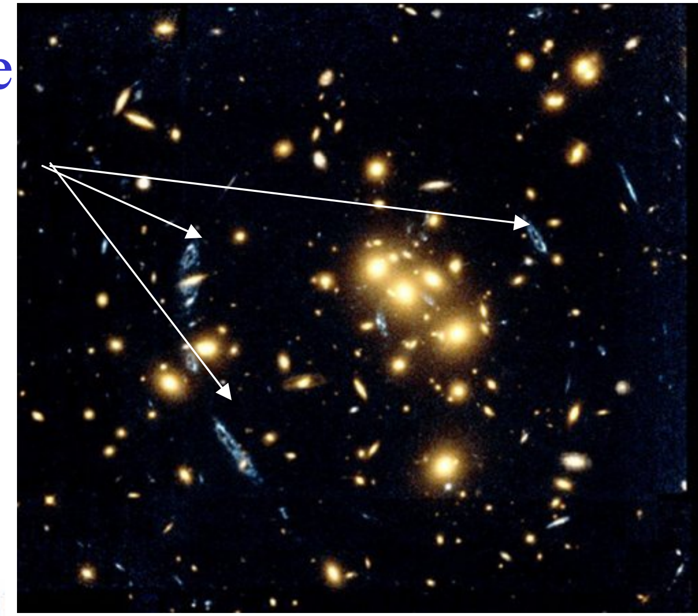
- Astronomy Dark Matter Candidates
  - Invisible macroscopic objects
    - Non-luminous objects
    - Black Holes
- Particle Dark Matter Candidates
  - Neutrinos
  - WIMPs



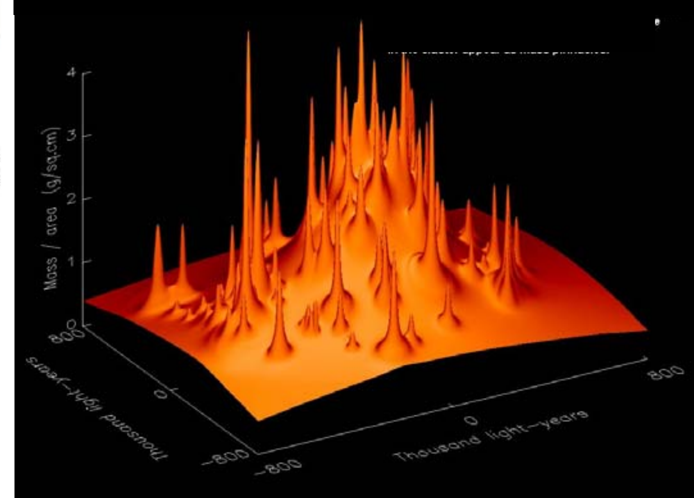
Gravitational Lensing by Dark Matter

Hubble Space Telescope
multiple images
of blue galaxy



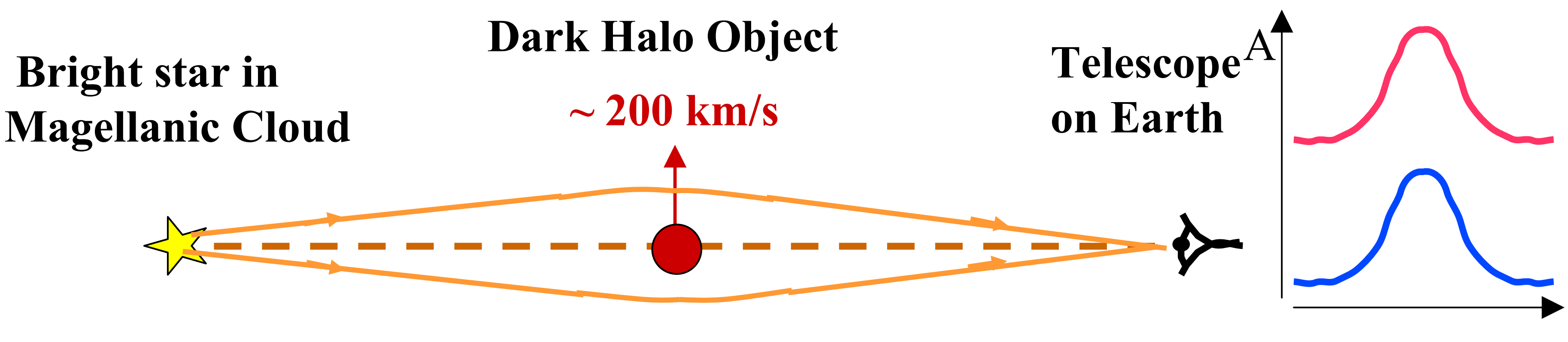


Reconstructed matter distribution



Black holes, etc.

Gravitational Lensing Searches for MACHOs

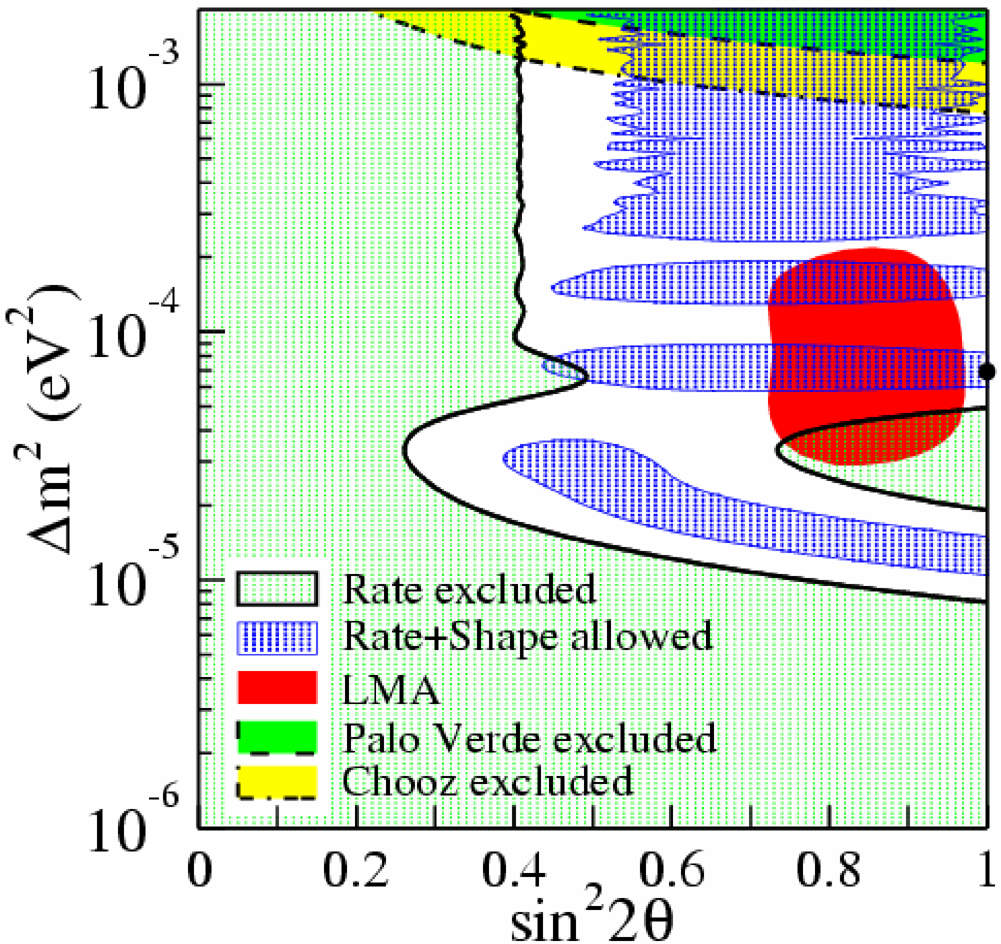


Neutrino Mass is not enough

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

Recent evidence of m>0 from

- SuperKamiokande
- SNO
- K2K
- KamLAND

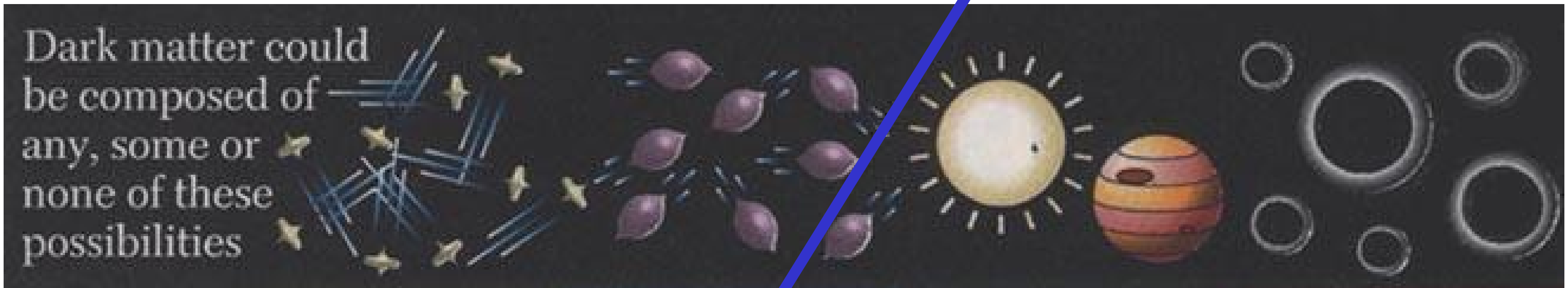


$\Delta M \sim 0.01$ eV

Mixing ~ maximal

Candidates: only WIMPS are left

M > ~ 40 GeV
if SUSY (LEP)

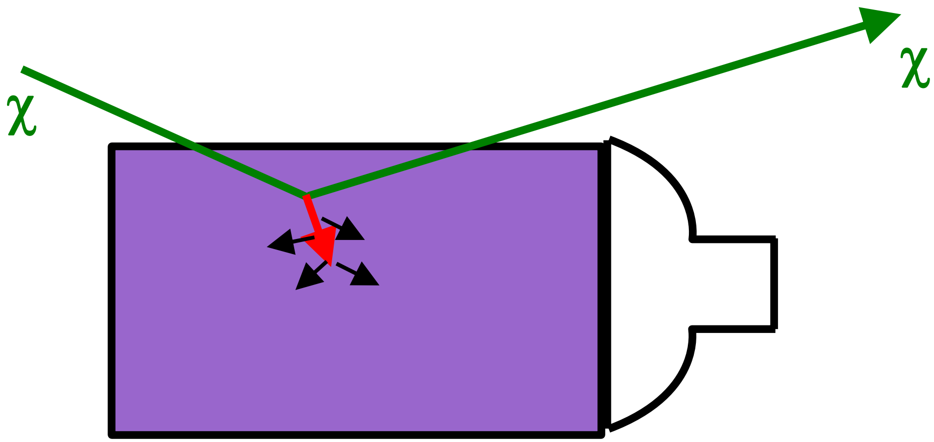


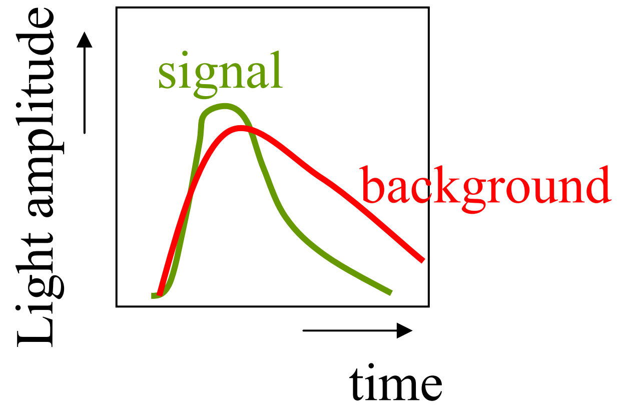
Name	Neutrinos	WIMPs	MACHOs	Black holes
What they are	Subatomic relatives of the electron that have no electrical charge and interact only weakly with ordinary matter	(Weakly interacting massive particles) Also known as cold dark matter	(Massive compact halo objects) Dim Jupiter-size planets or white 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

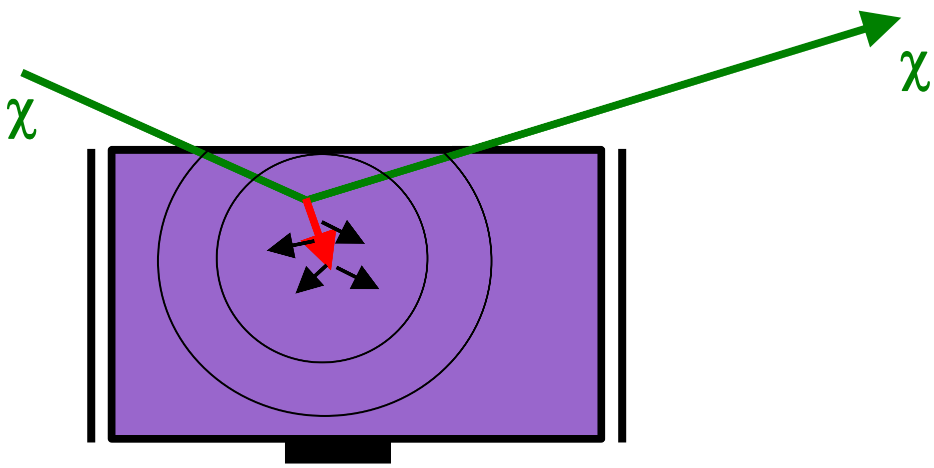
Rejection of background is the critical issue

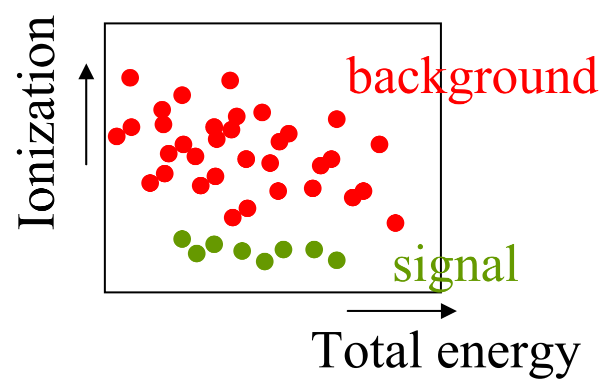
Na I





Ge

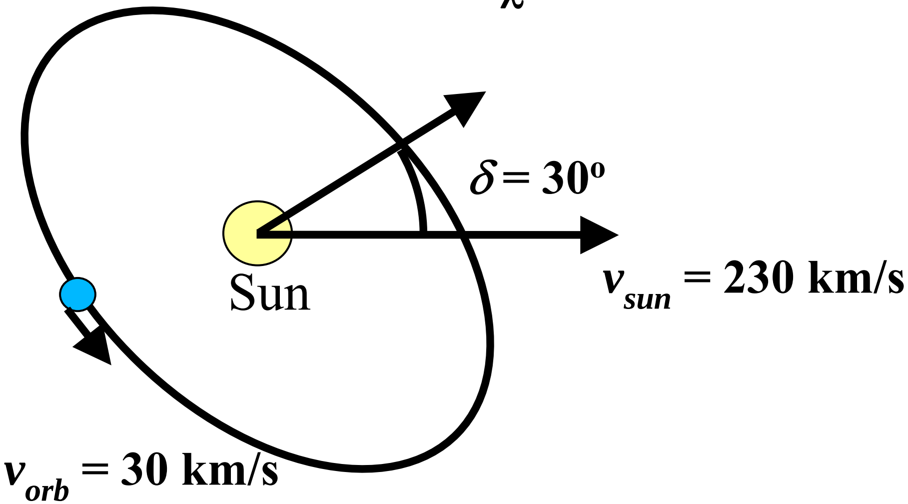


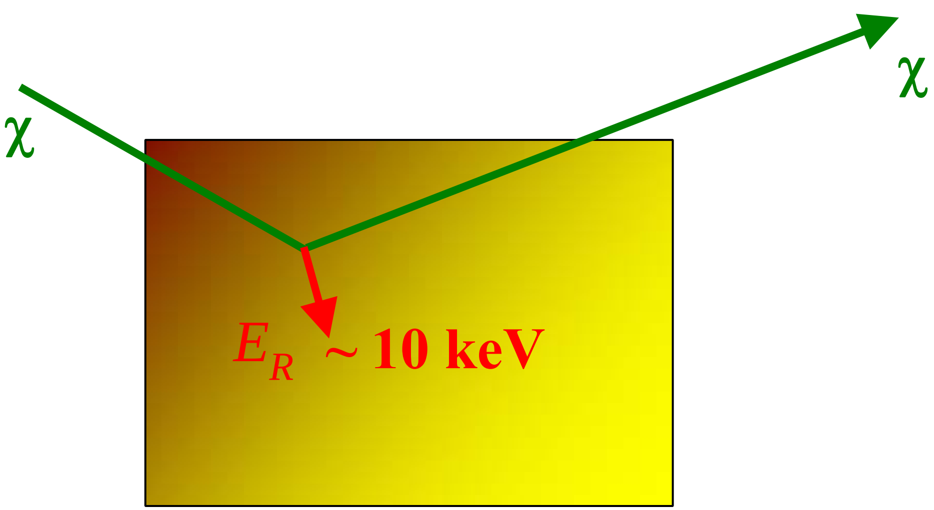


WIMP Direct Detection: modulation

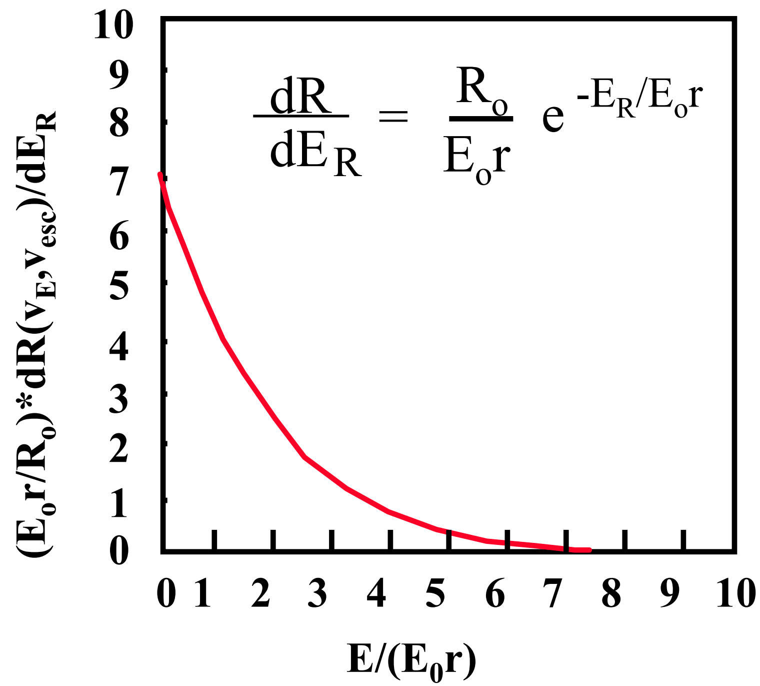
Elastic interaction on nucleus, typical χ velocity ~ 250 km/s ($\beta \sim 10^{-3}$)

Motion of Earth in the χ wind





Recoil Spectrum

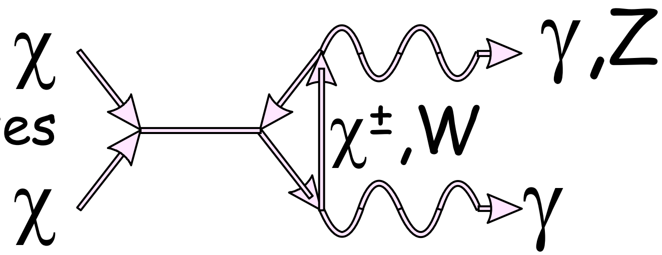


Featureless recoil energy spectrum
---> looks like electron background

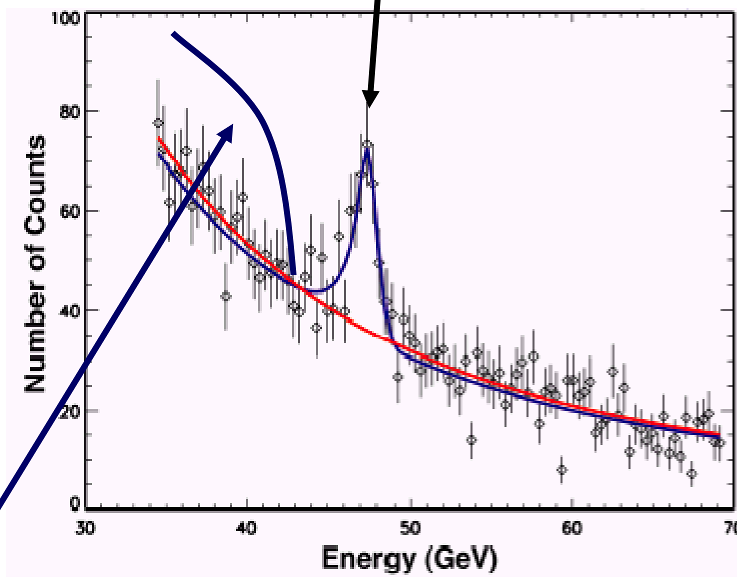
But… Annual modulation

WIMPS & gamma emission

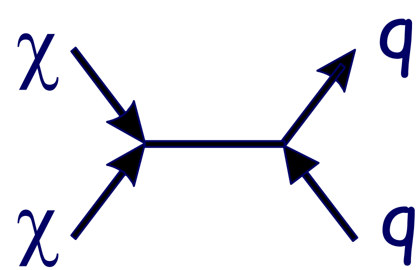
- Some DM candidates (e.g. SUSY particles) would lead to mono-energetic γ lines through annihilation into $\gamma\gamma$ or γZ:
  $E_\gamma = m_\chi$ / $m_\chi - m_Z^2/4 m_\chi$
  => clear signature at high energies
  but: loop suppressed



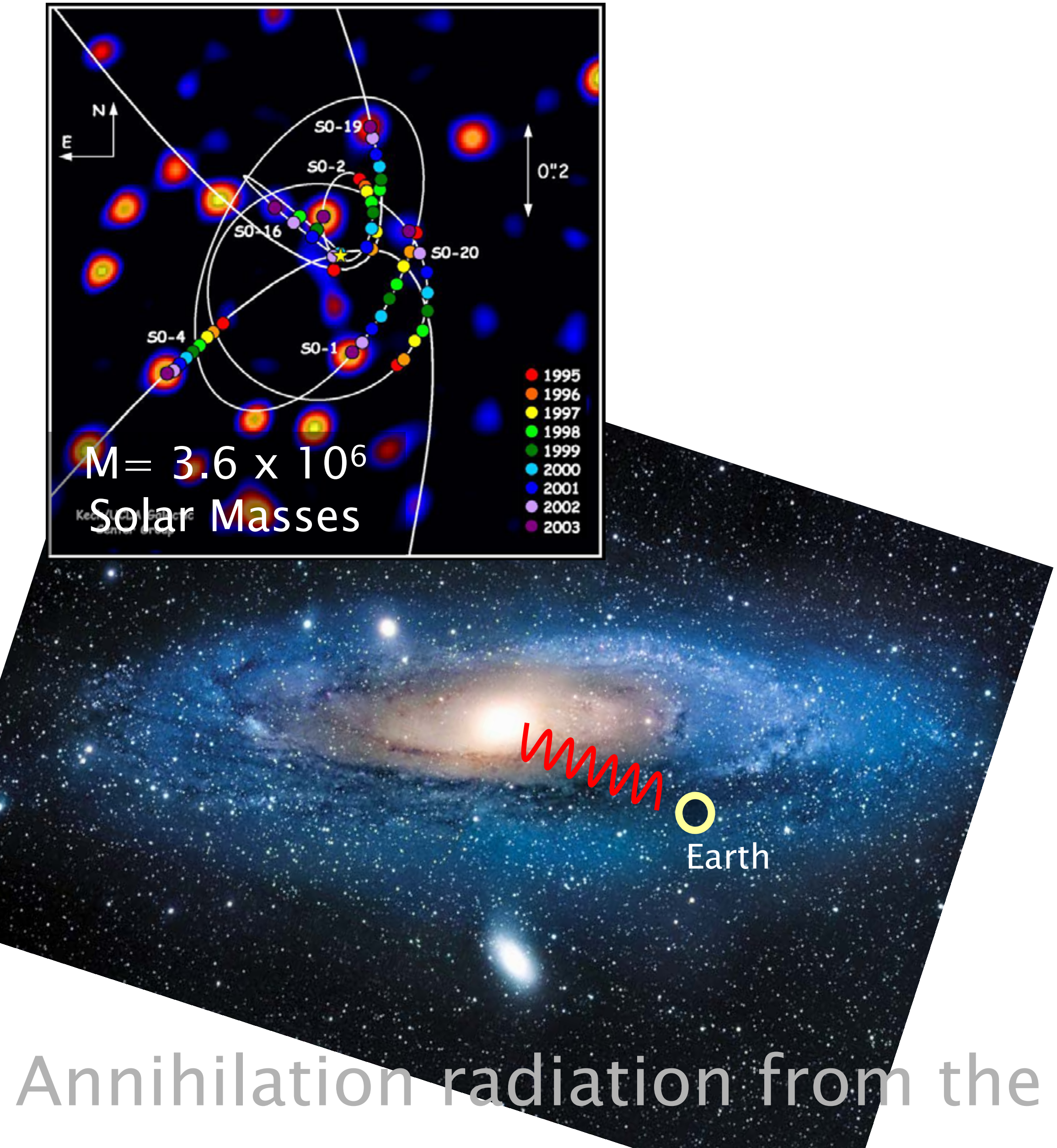
Good energy resolution in the few % range is needed

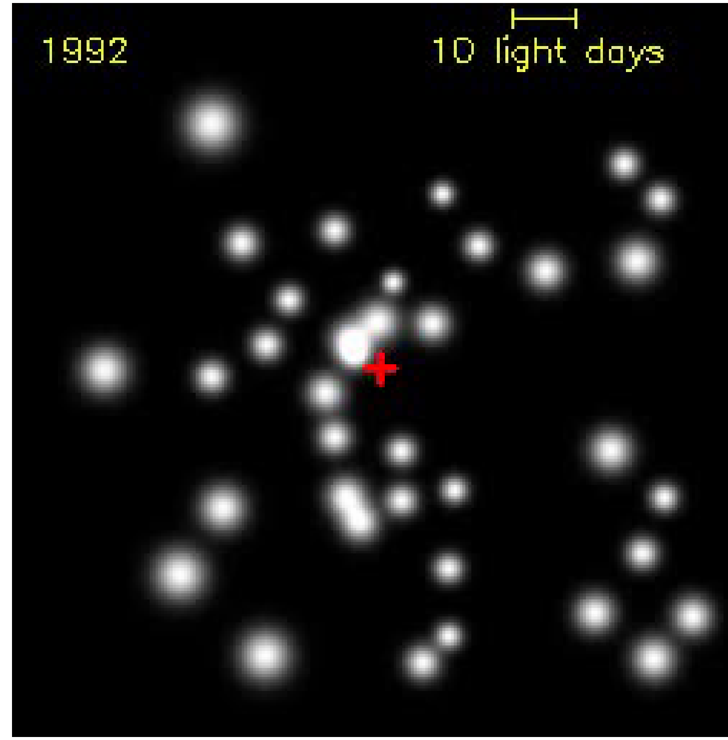


- annihilation into qq -> jets -> n γ's
  => continuum of low energy gammas
  difficult signature but large flux



Results: common sense suggests a look @the GC…





X emission (variable)

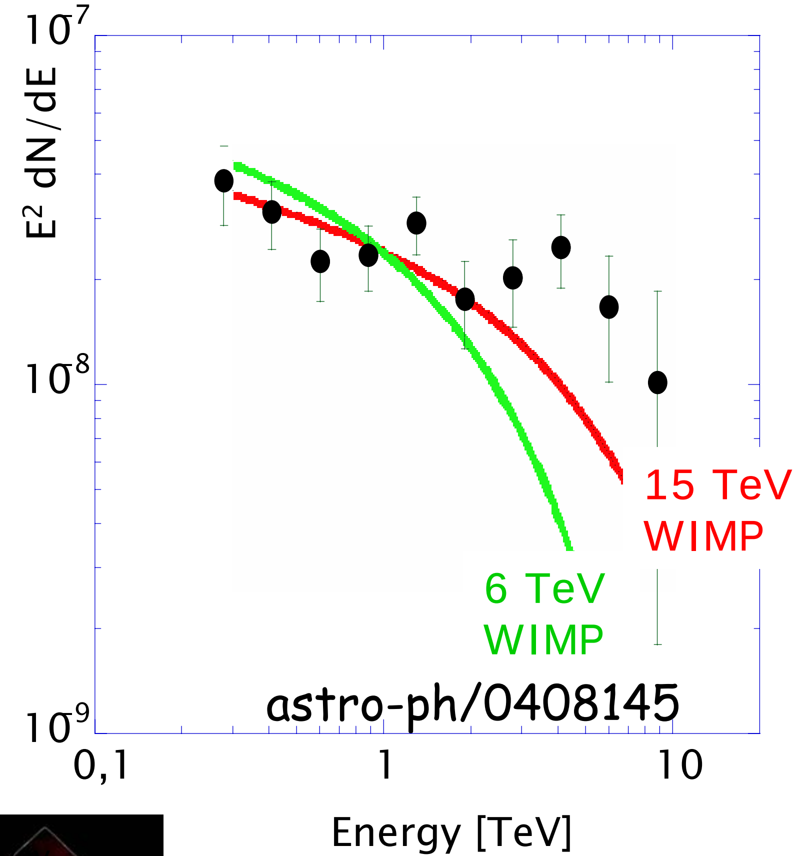
γ emission

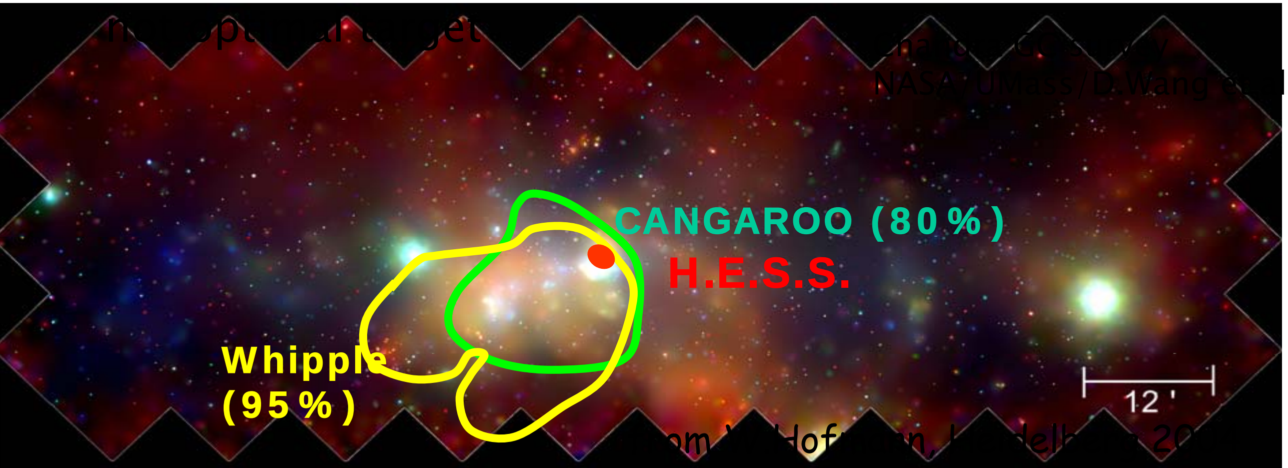
Annihilation radiation from the GC

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 =>



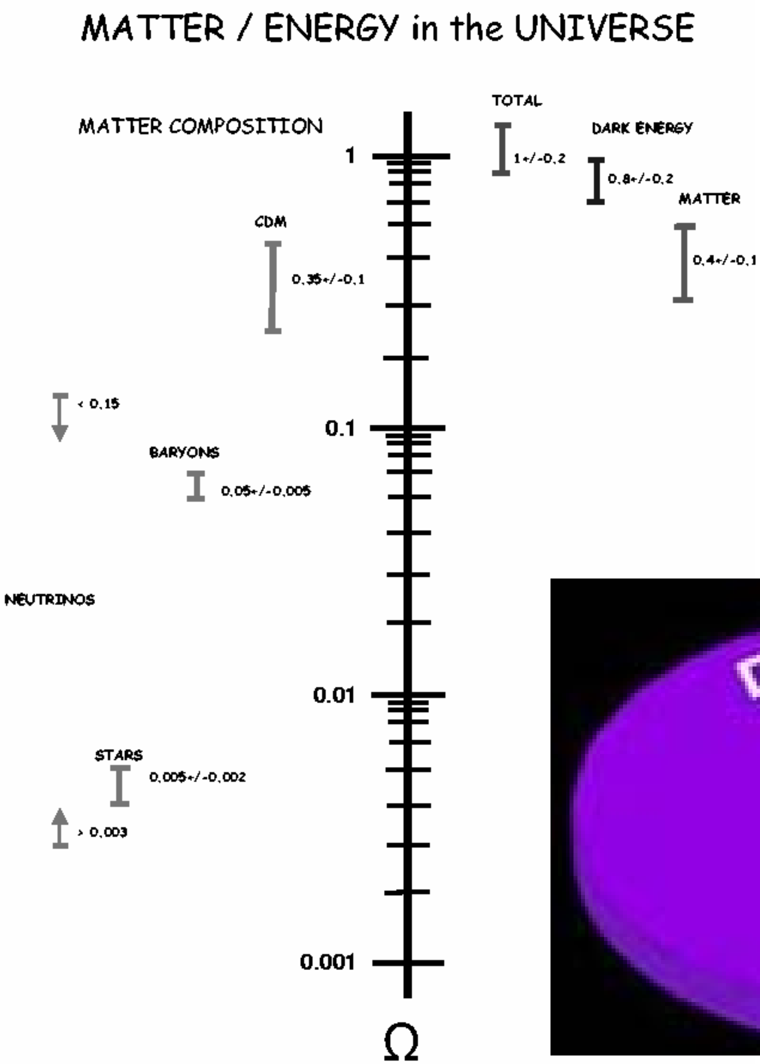


Milky Way satellites Sagittarius and Draco

- proximity (< 100 kpc)
- low baryonic content, no central BH (which may change the DM cusp)

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 :

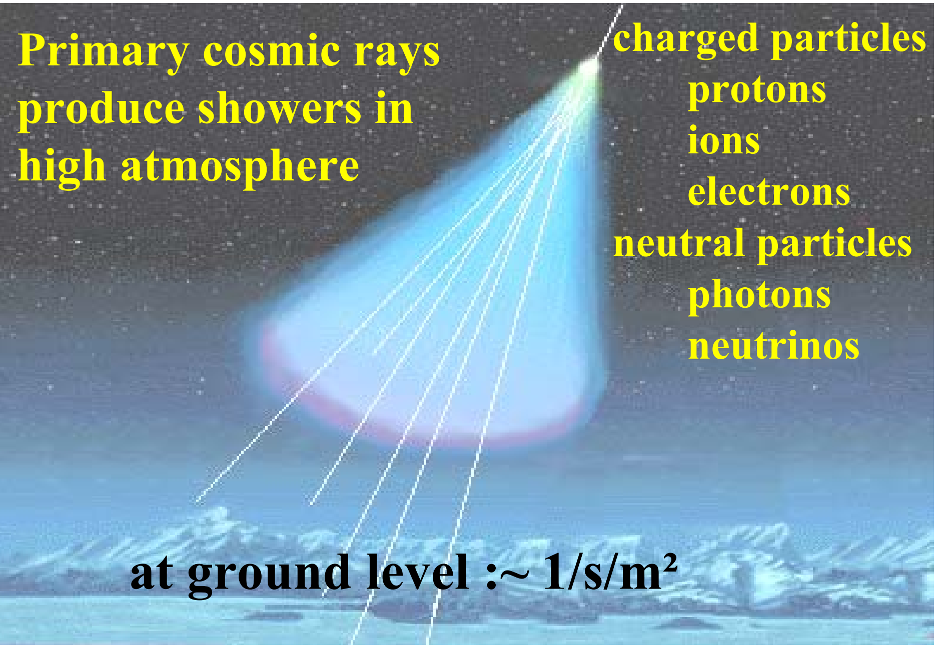
$\Omega_{CDM} \sim 0.23$

WIMPS/neutralinos, axions

III

High Energy Particles from space

Cosmic Rays

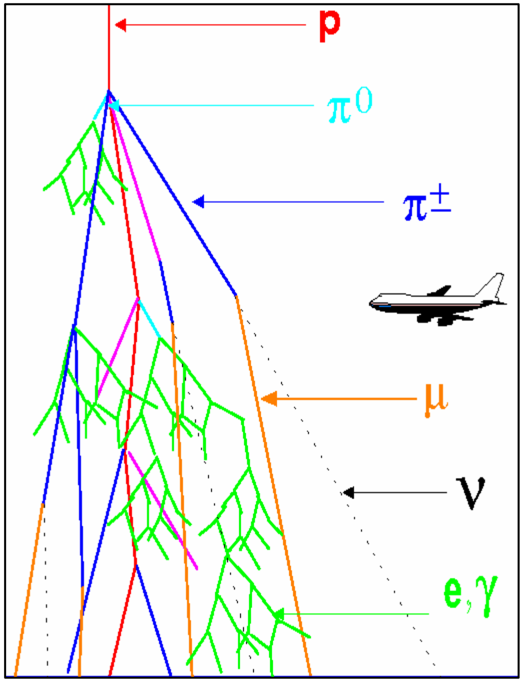


Primary:

p 80 %, α 9 %, n 8 %

e 2 %, heavy nuclei 1 %

γ 0.1 %, ν 0.1 % ?

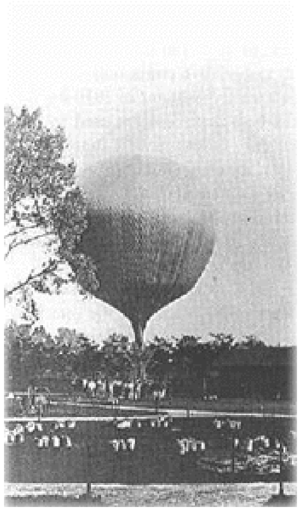


Secondary at ground level:

ν 68 %

μ 30 %

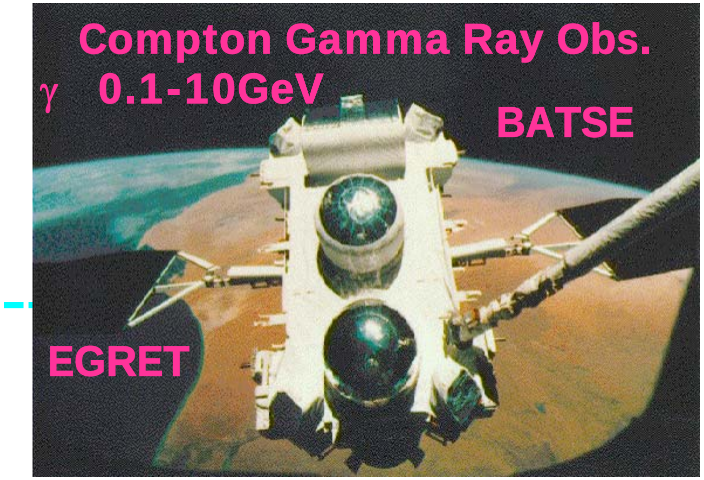
p, n, ... 2 %

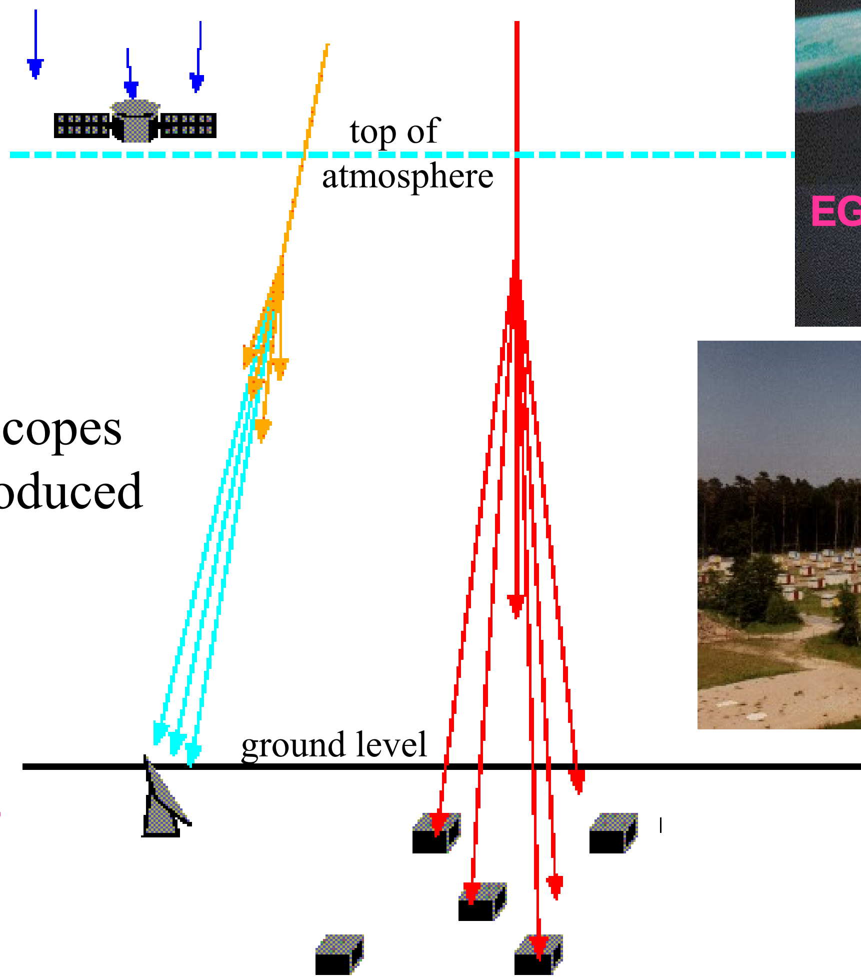


100 years after discovery by Hess origin still uncertain

Types of Cosmic Ray Detectors

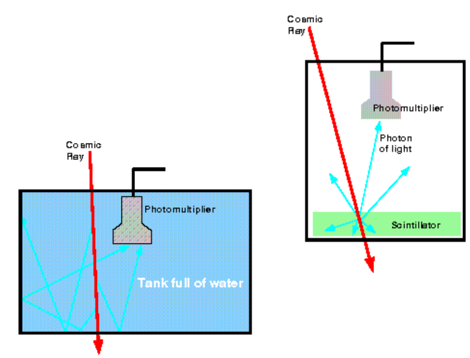
Satellites



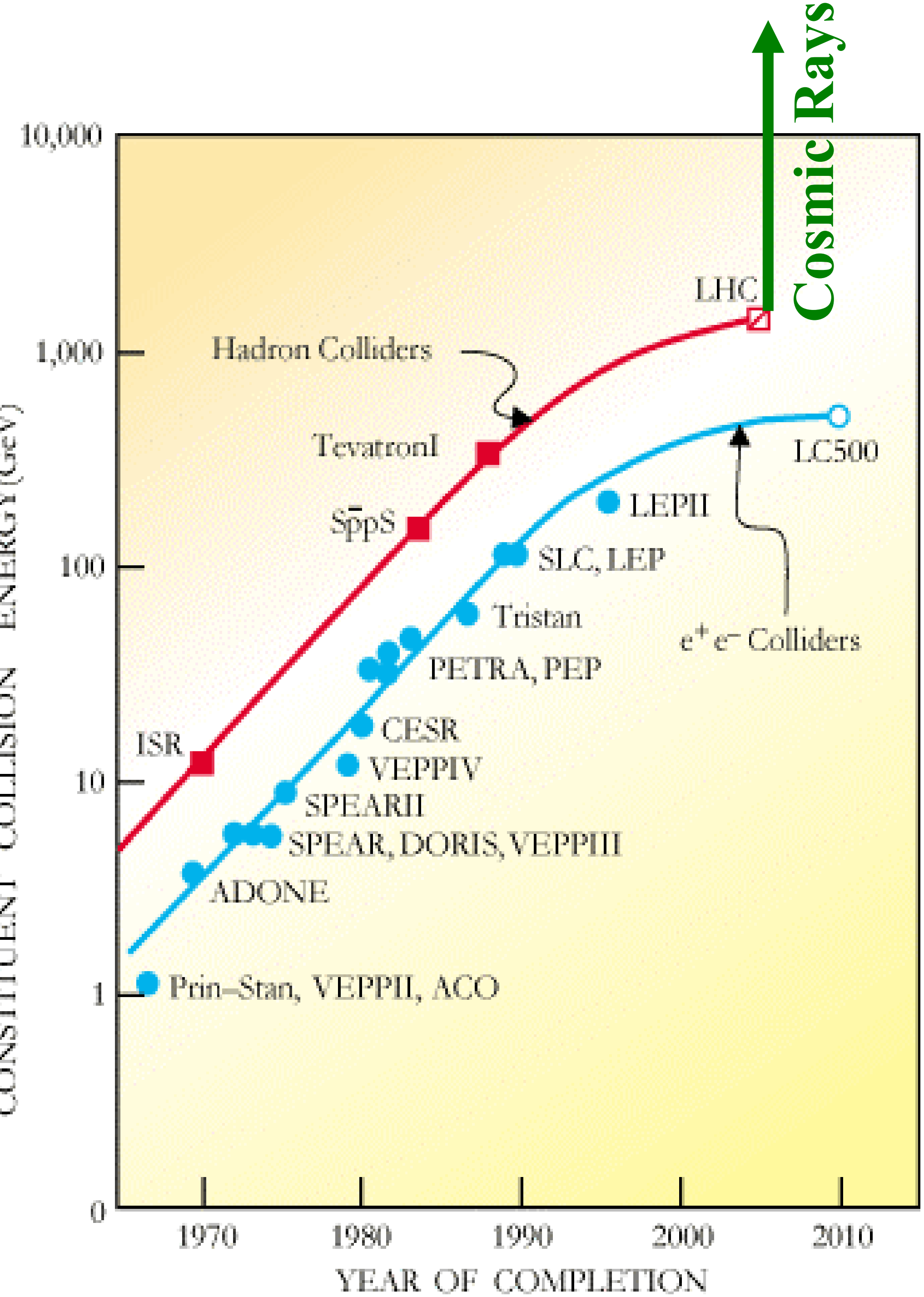


Ground based telescopes
looking at light produced
in atmosphere

Arrays of particle detectors



The future of HEP?



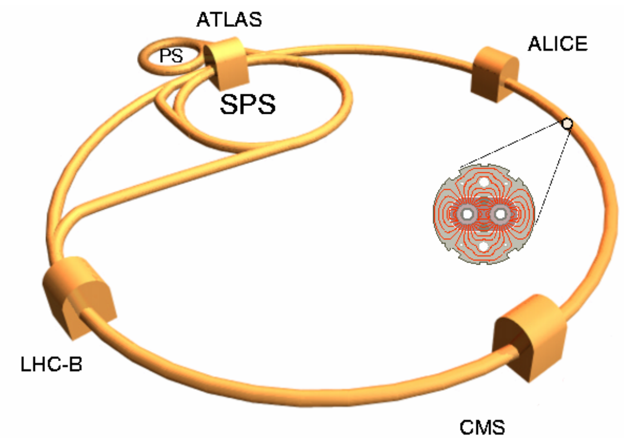
- Higher energies are not the full story…

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

Particle Acceleration

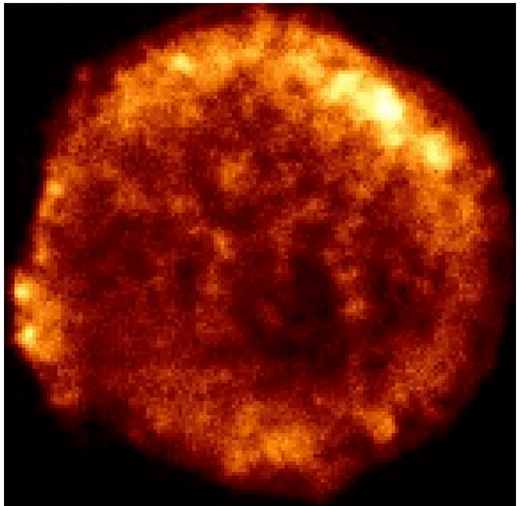
$E \propto BR$

Large Hadron Collider



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

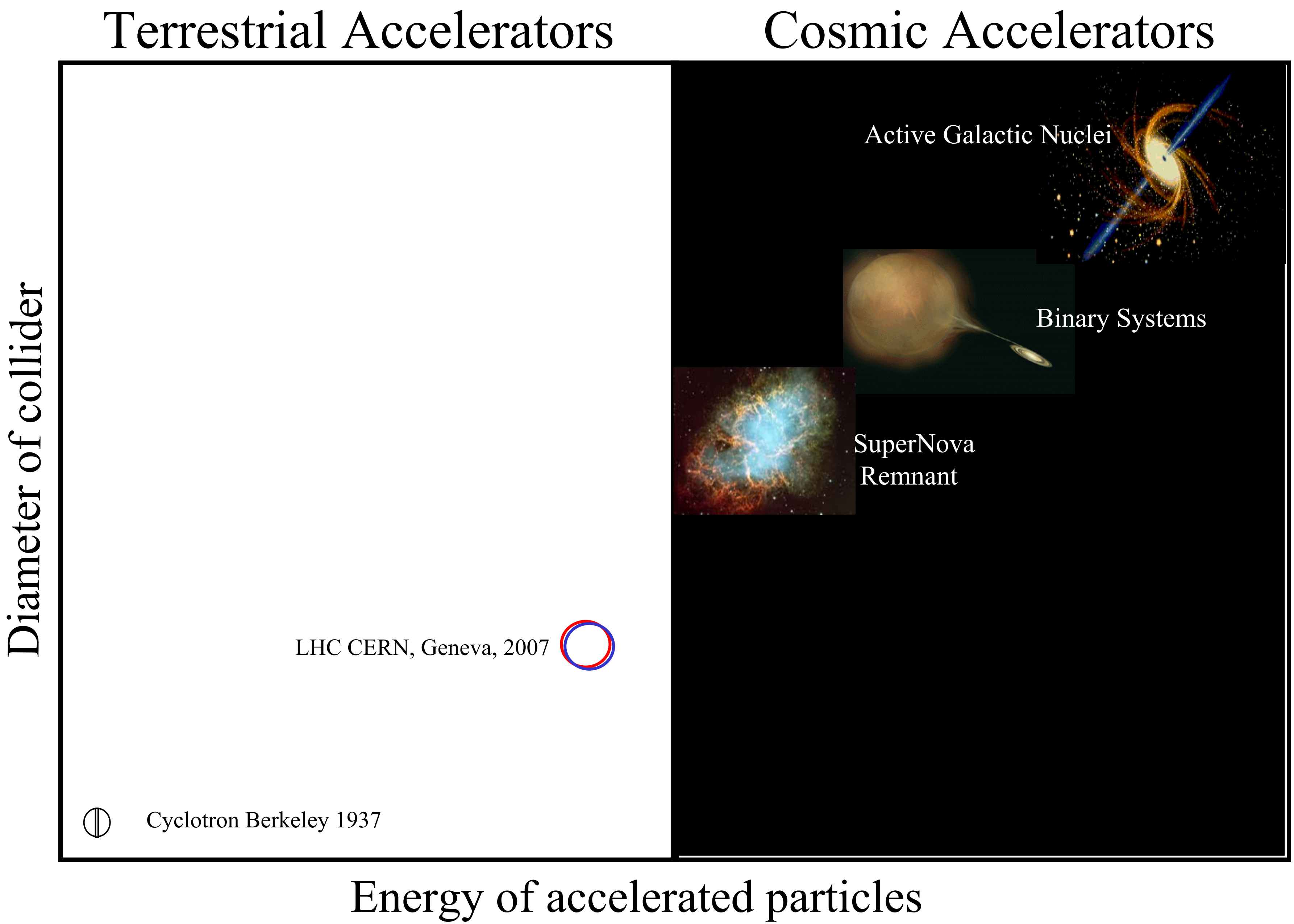
Tycho SuperNova Remnant



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

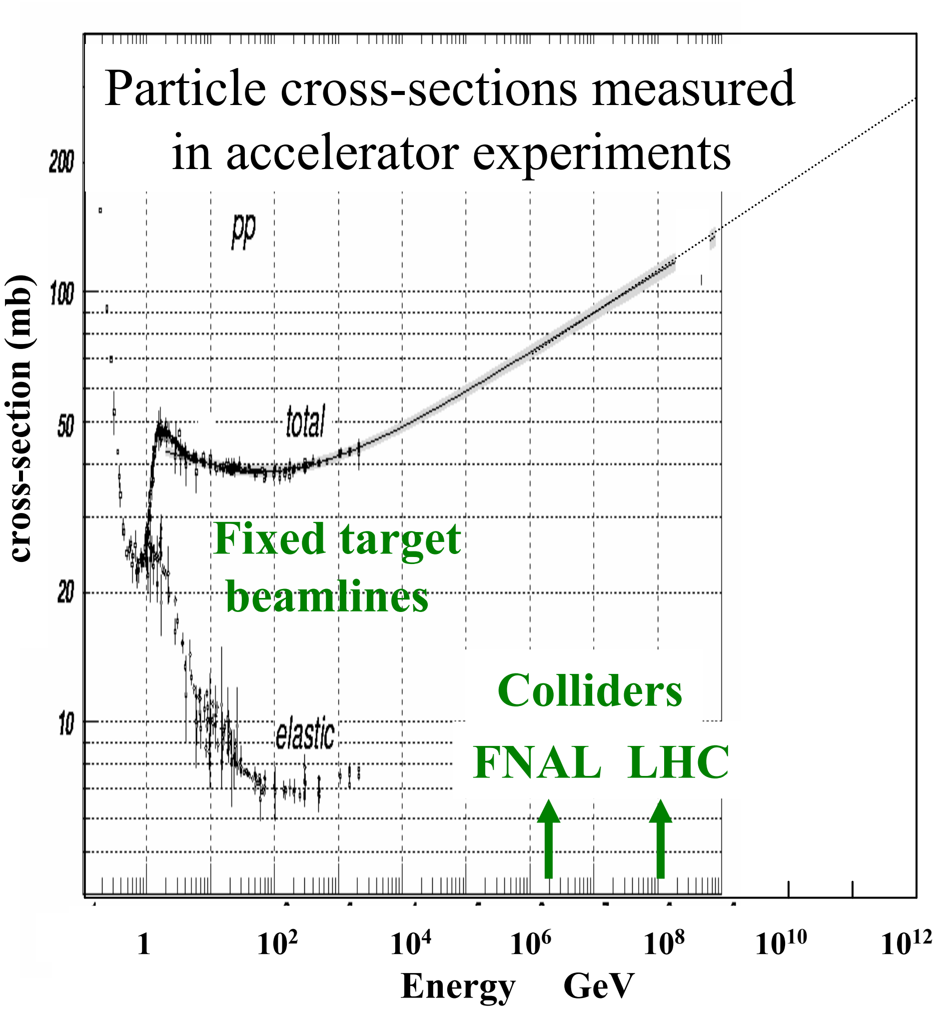
(NB. $E \propto Z \rightarrow$ Pb/Fe higher energy)

Particle Physics ⇒ Particle Astrophysics

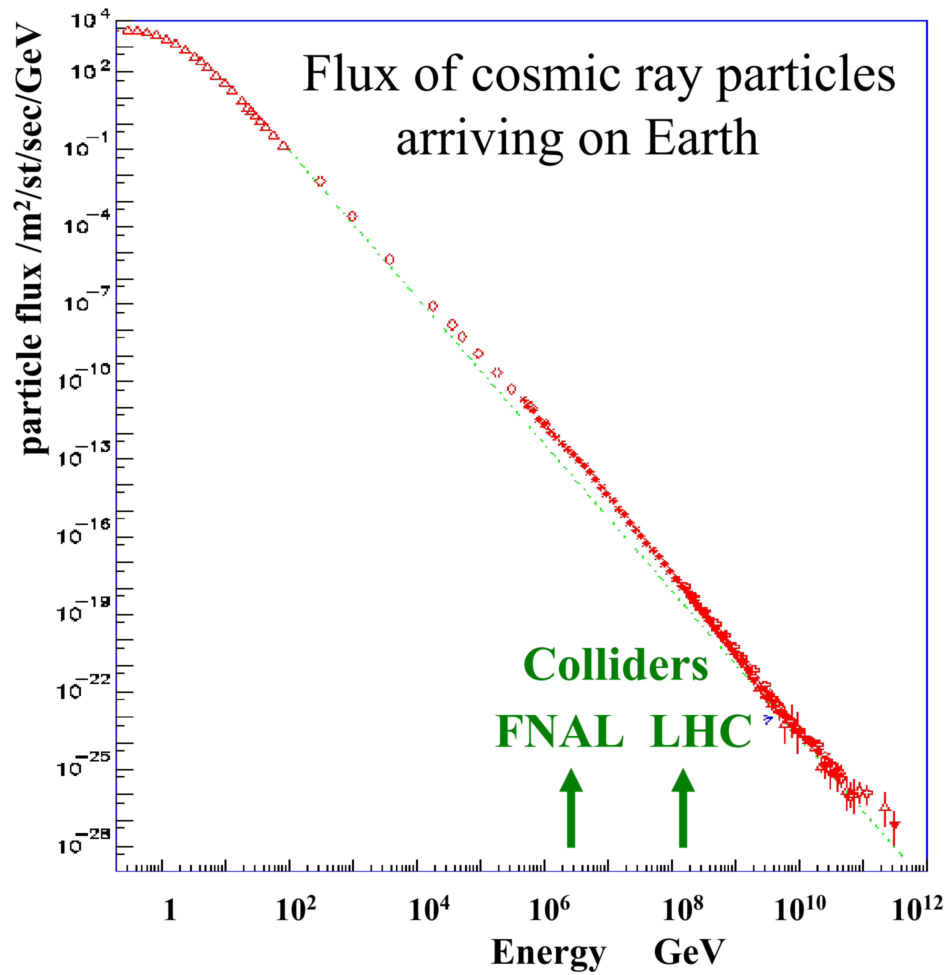


Ultra High Energy from Cosmic Rays

From laboratory accelerators

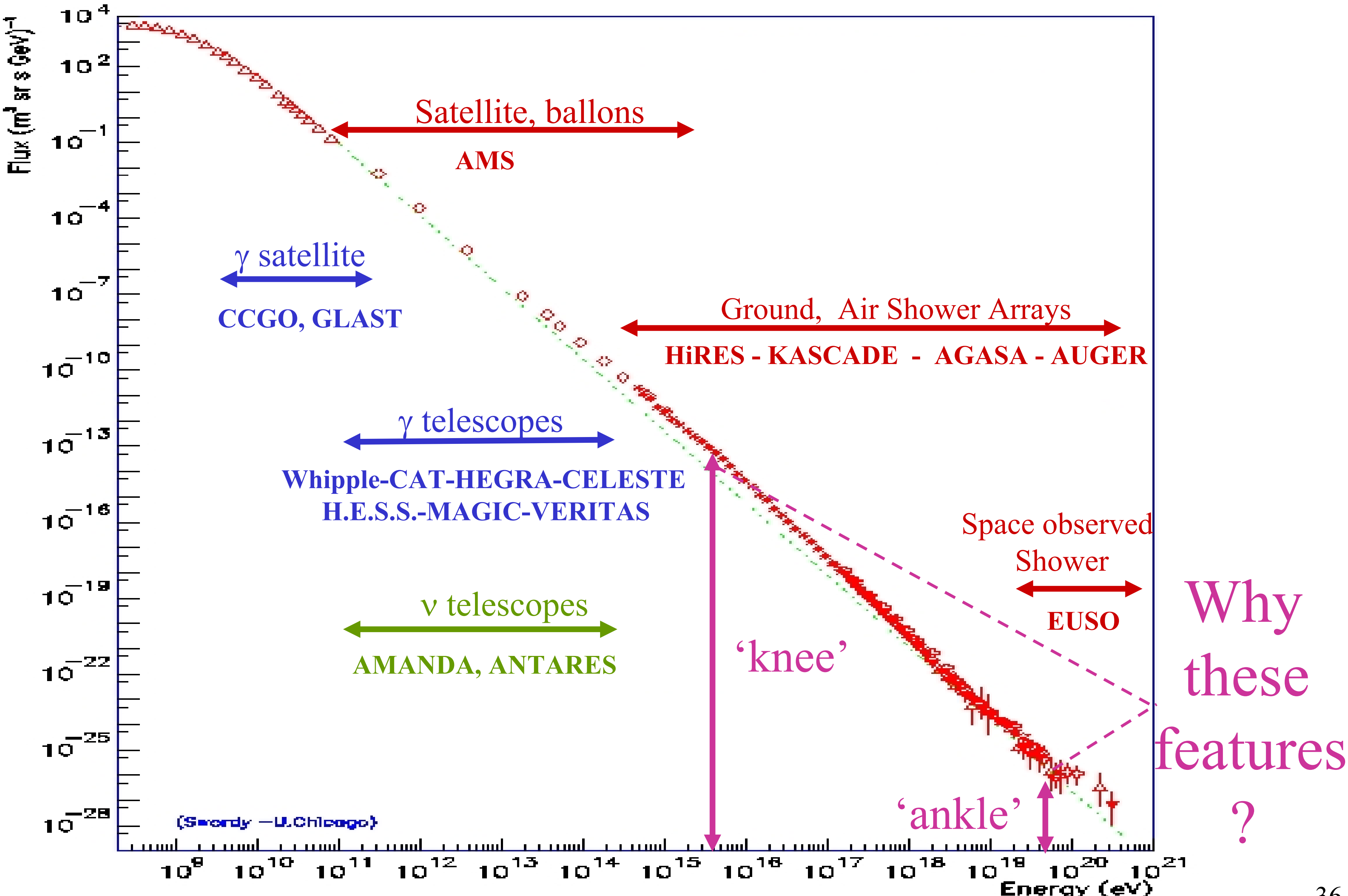


From cosmic accelerators

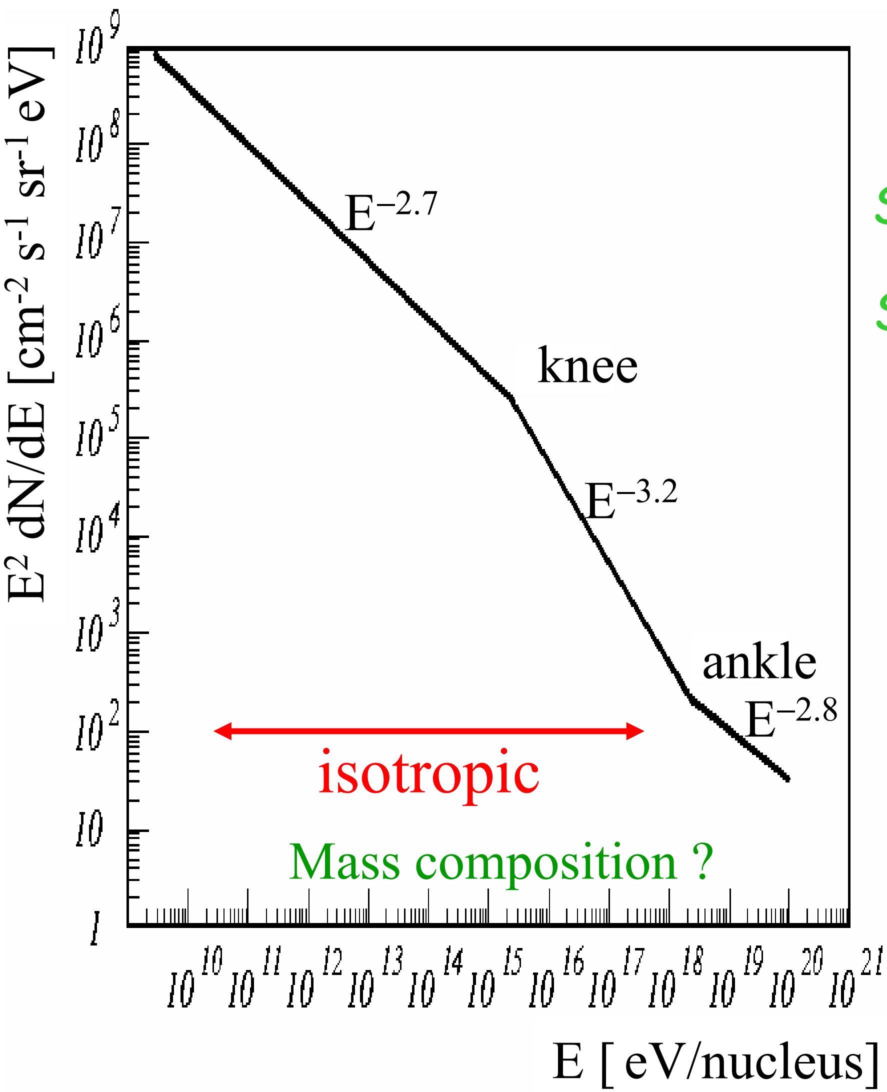


Ultra High Energy Particles arrive from space for free: make use of them

Charged Cosmic Ray Energy Spectrum



Features of Cosmic Ray Spectrum



Ingredients of models:

source propagation

$$dN/dE \sim E^{\alpha + \delta}$$

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

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

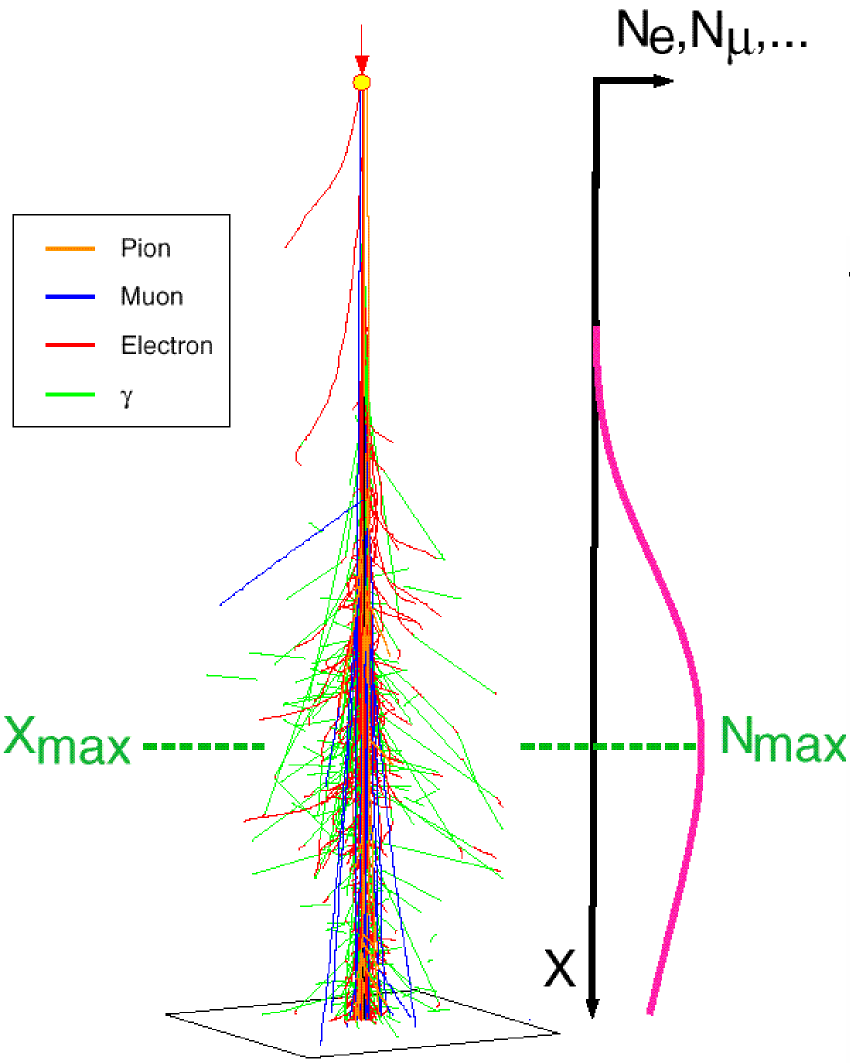
Diffusion models $\delta = -0.3$ to -0.6

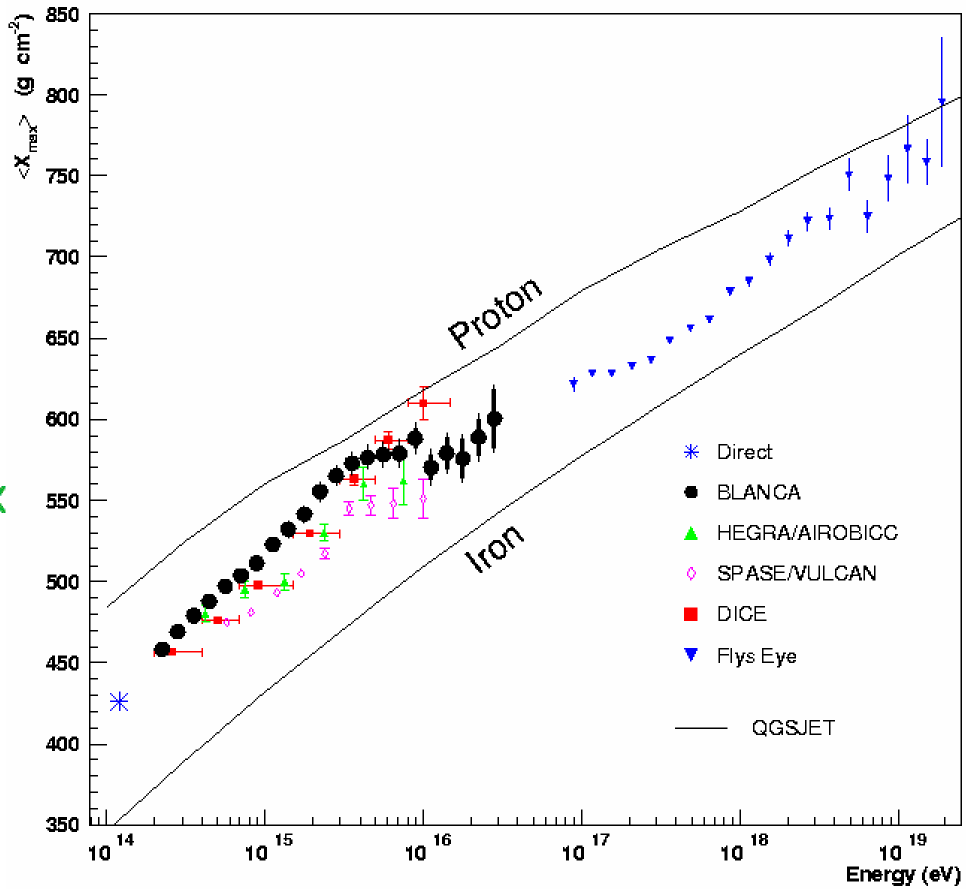
GZK cut-off on CMB γ $E \approx 7\ 10^{19}$ eV

'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

Mass composition from shower depth

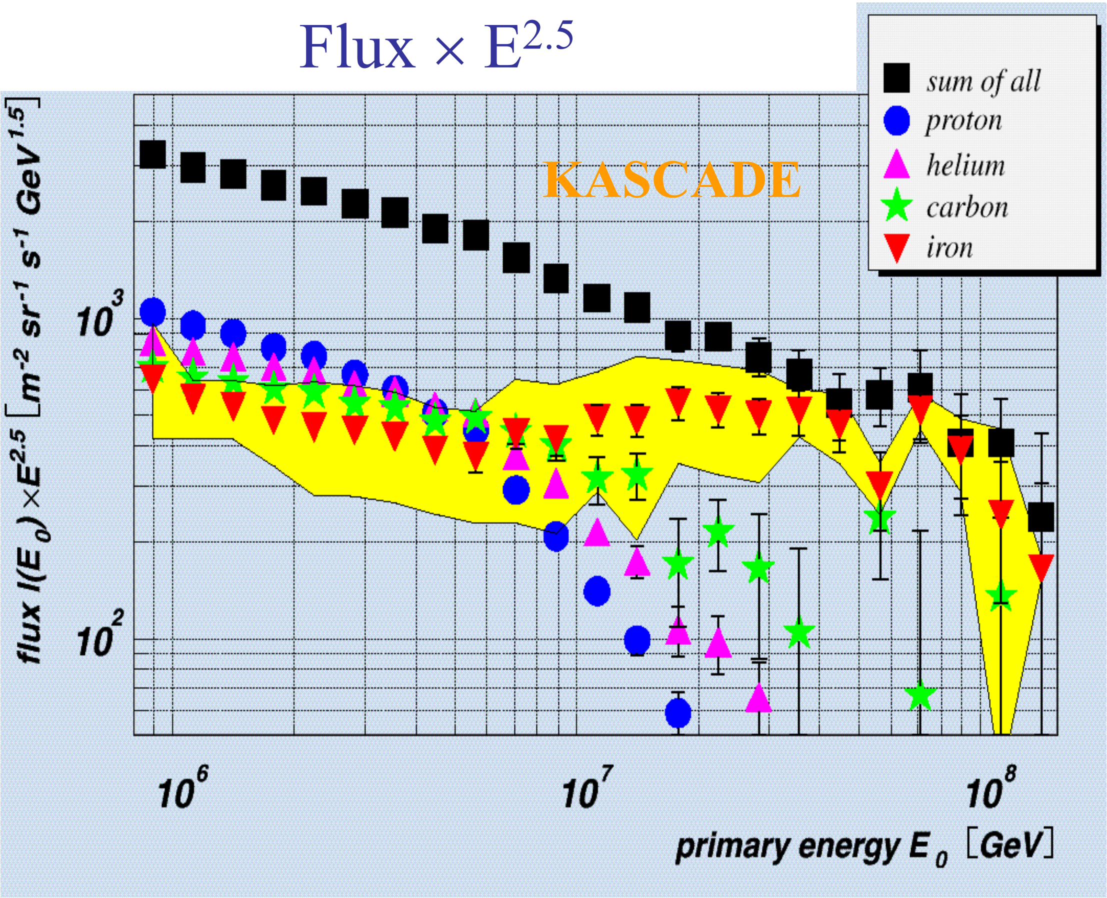




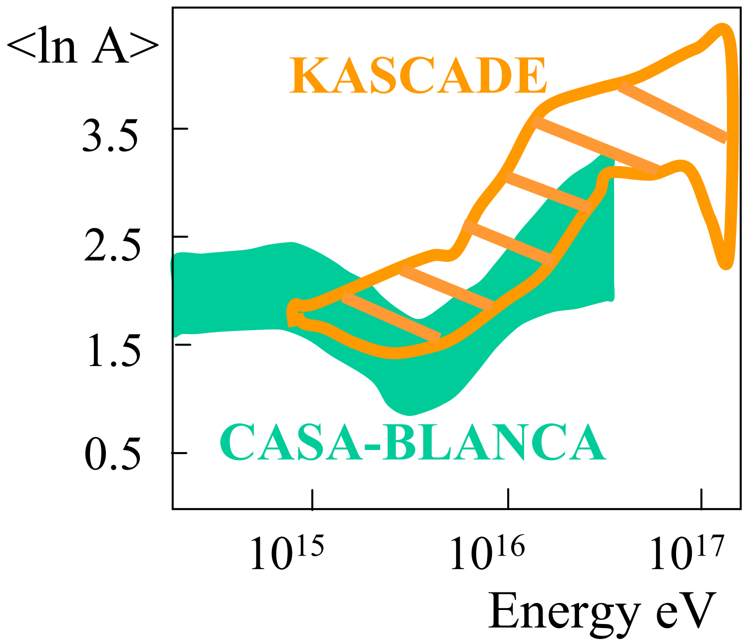
Mass composition at knee

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 × $E^{2.5}$

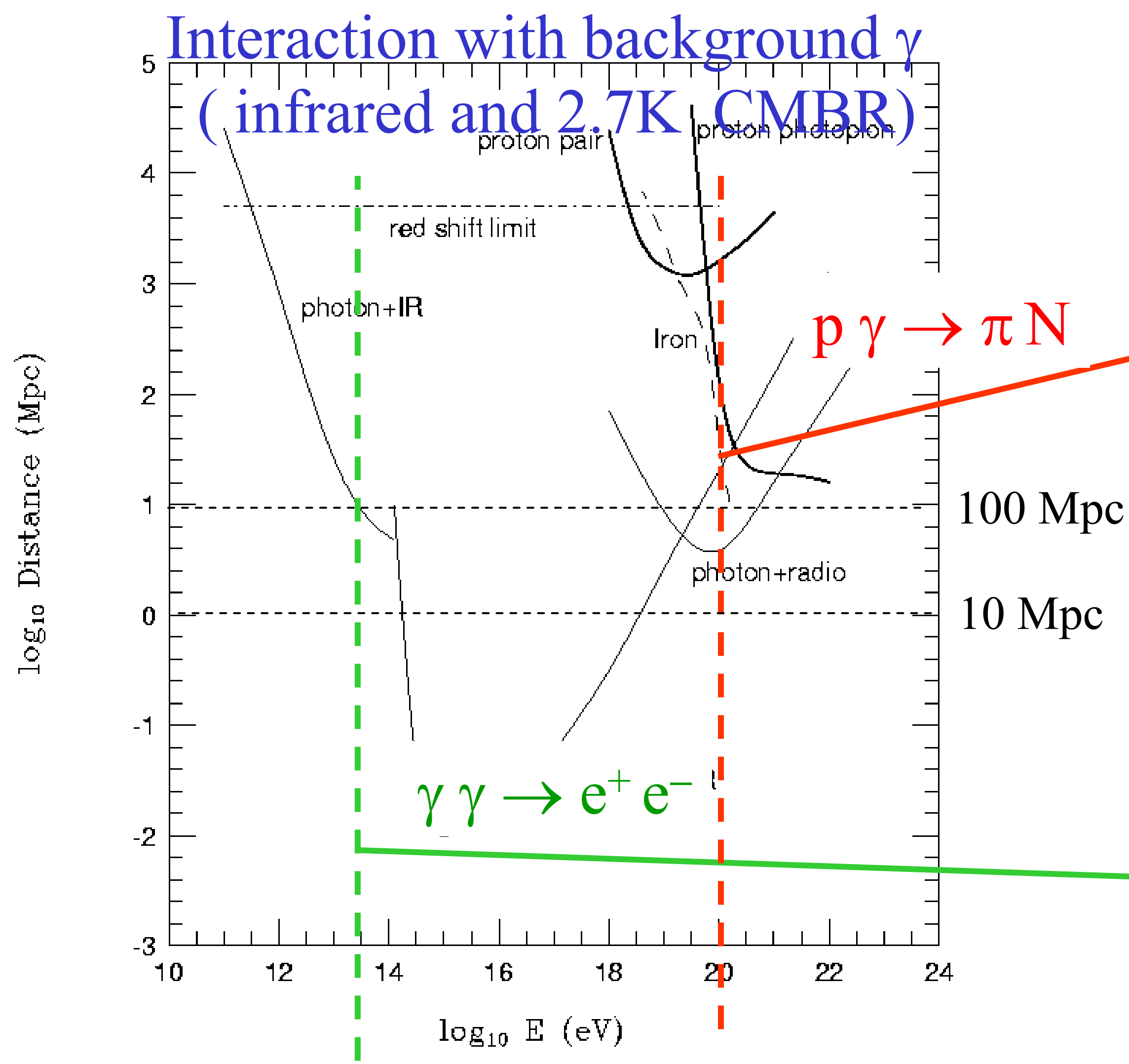


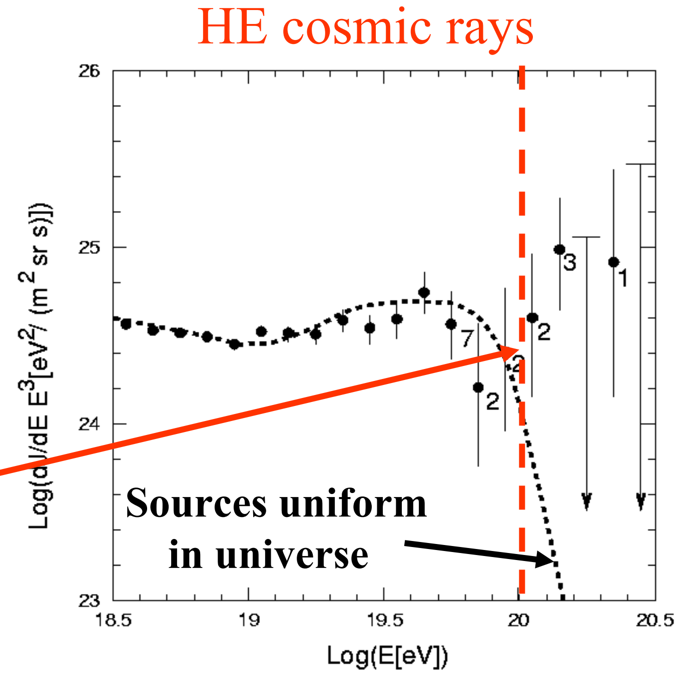
Mean ln(A)

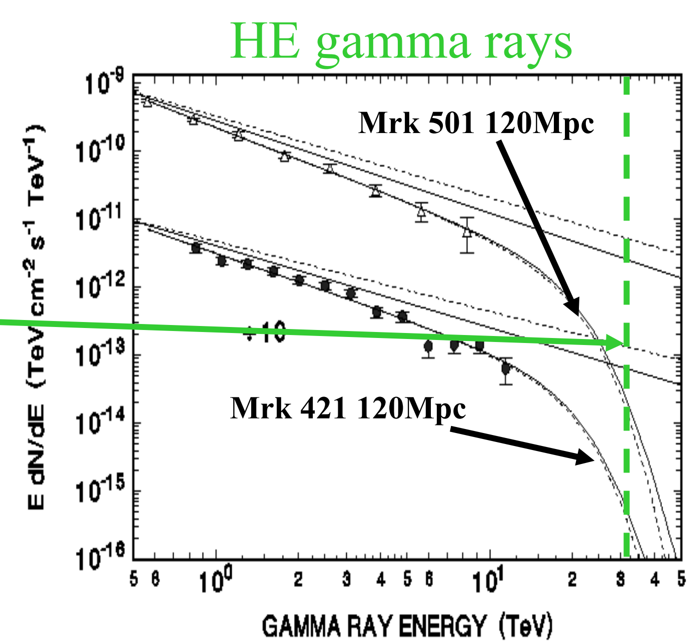


KASCADE ⇒ series of knees at different energies: p,He,..,C,..,Fe.
E(Knee) ∝ Z ⇒ knee due to source confinement cut-off ?

'GZK cutoff'







Are we observing new fundamental physics?

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

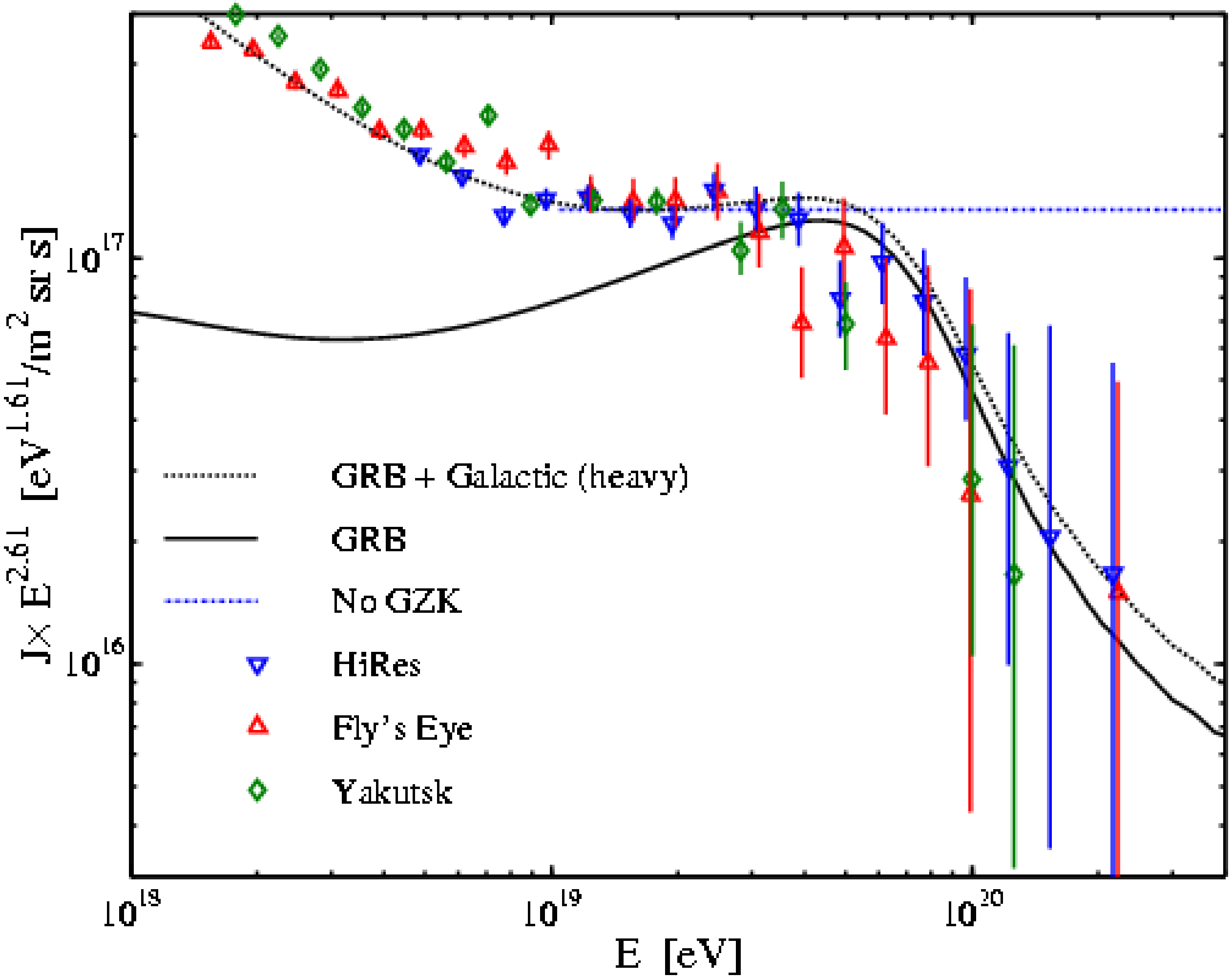
Astronomy type explanations

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

Particle Physics type explanations

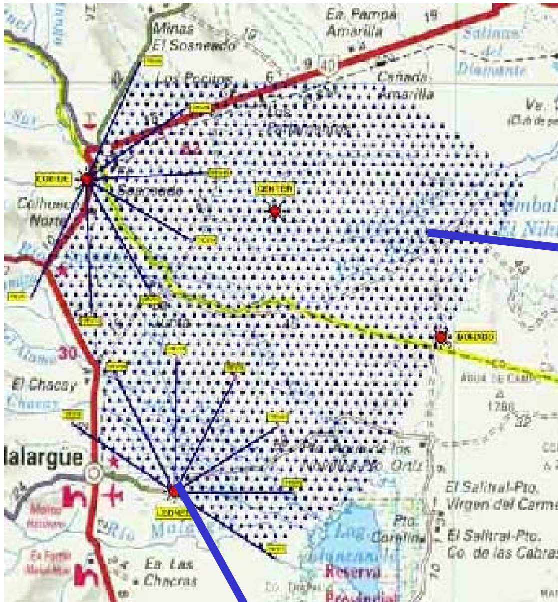
- 'Top-Down' : decay of massive particles
  - GUT X particles with mass > 10^{20} eV and long lifetimes
  - Topological defects
- New Physics (Lorentz violation)
- **Just wrong data from AGASA…**

HiRES (Fly's Eye)



AUGER

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



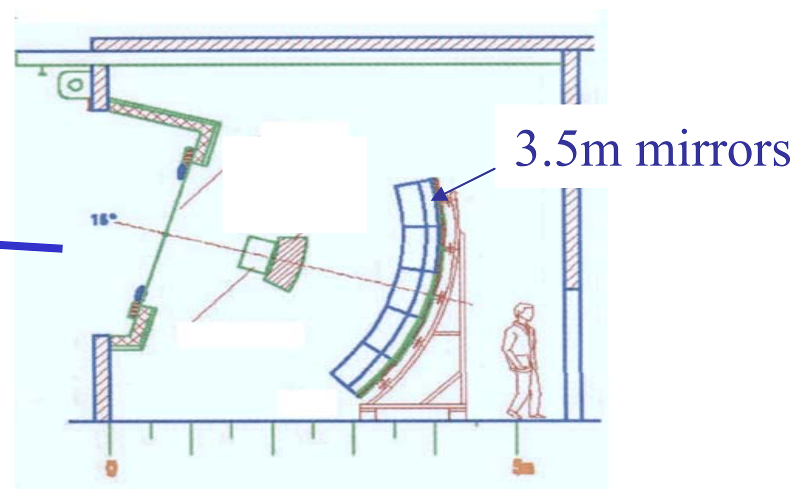
Southern site,
Mendoza Province,
Argentina

Water Cherenkov

Tanks

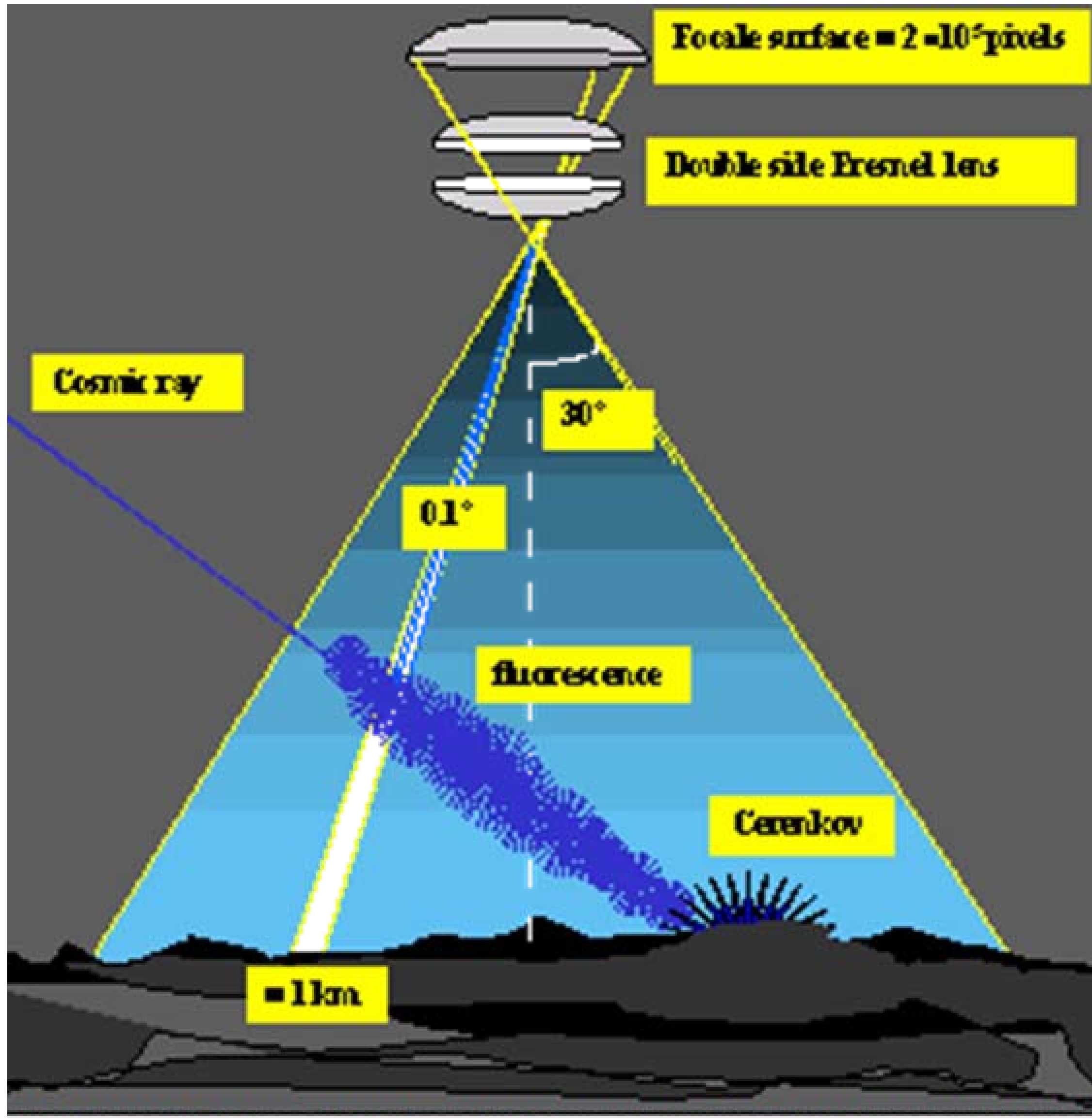
(1600 each 10m^2)

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



A new concept: EUSO (and OWL)

- The Earth atmosphere is the ideal detector for the Extreme Energy Cosmic Rays and the companion Cosmic Neutrinos. The new idea of EUSO (2010?-) is to watch the fluorescence produced by them from the top



Experimental Astroparticle Physics (a short introduction)

Alessandro De Angelis

INFN & Univ. Udine; IST Lisboa

March 2006

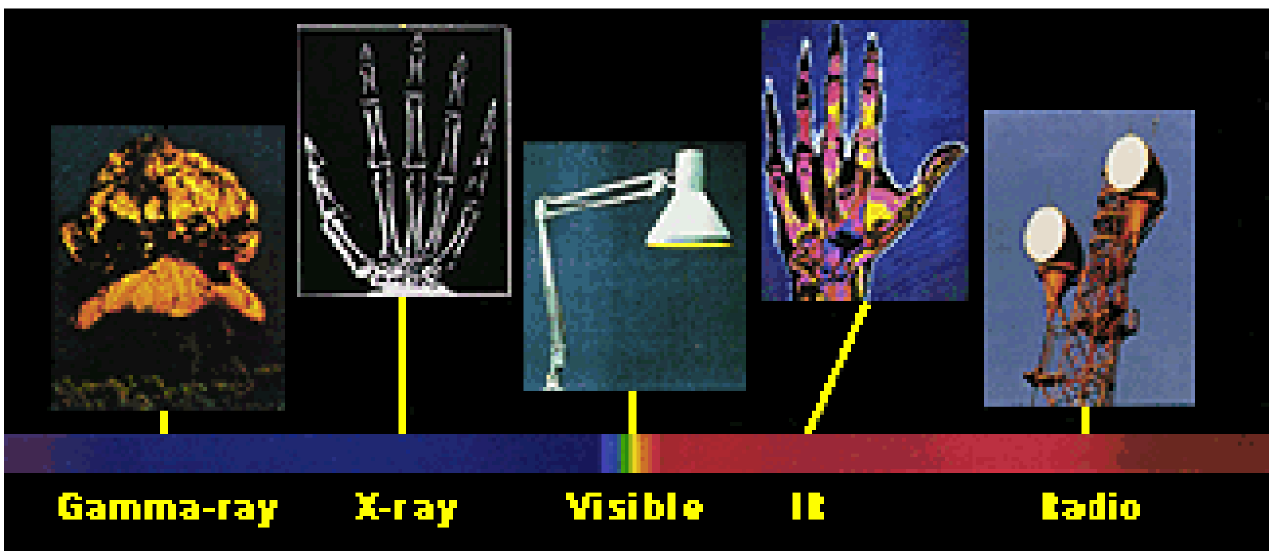
Lecture 4

IV

Detectors for multimessanger astrophysics

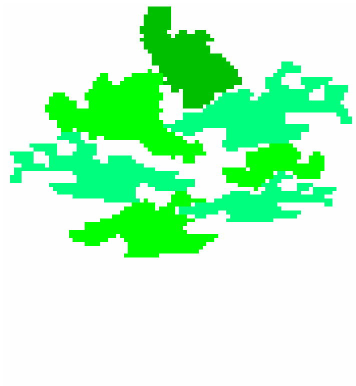
We see only partly what surrounds us

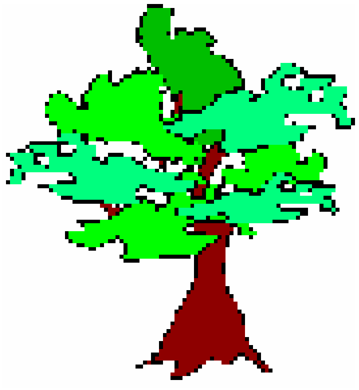
- We see only a narrow band of colors, from red to purple in the rainbow
- Also the colors we don't see have names familiar to us: we listen to the radio, we heat food in the microwave, we take pictures of our bones through X-rays…



What about the rest ?

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





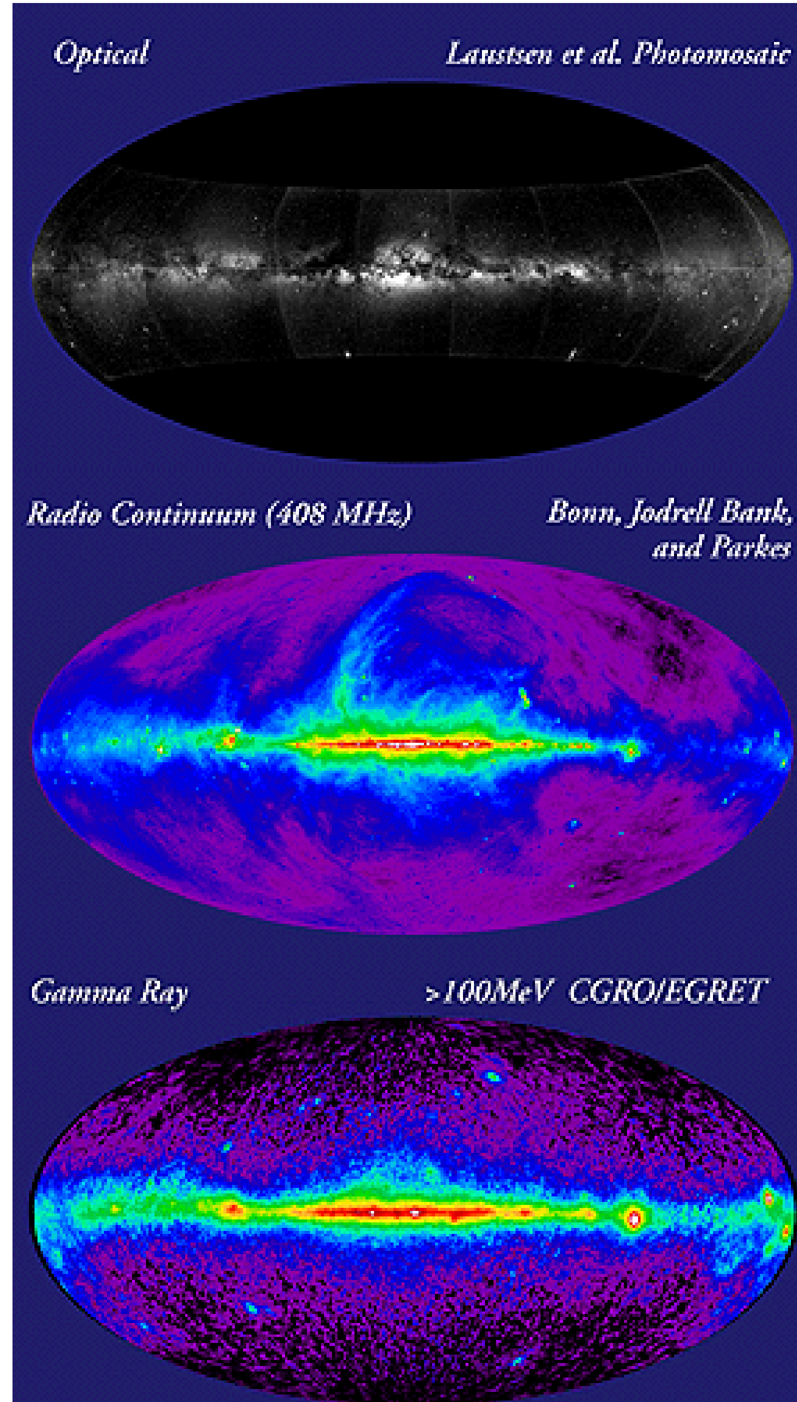
The universe we don’t see

- When we take a picture we capture light

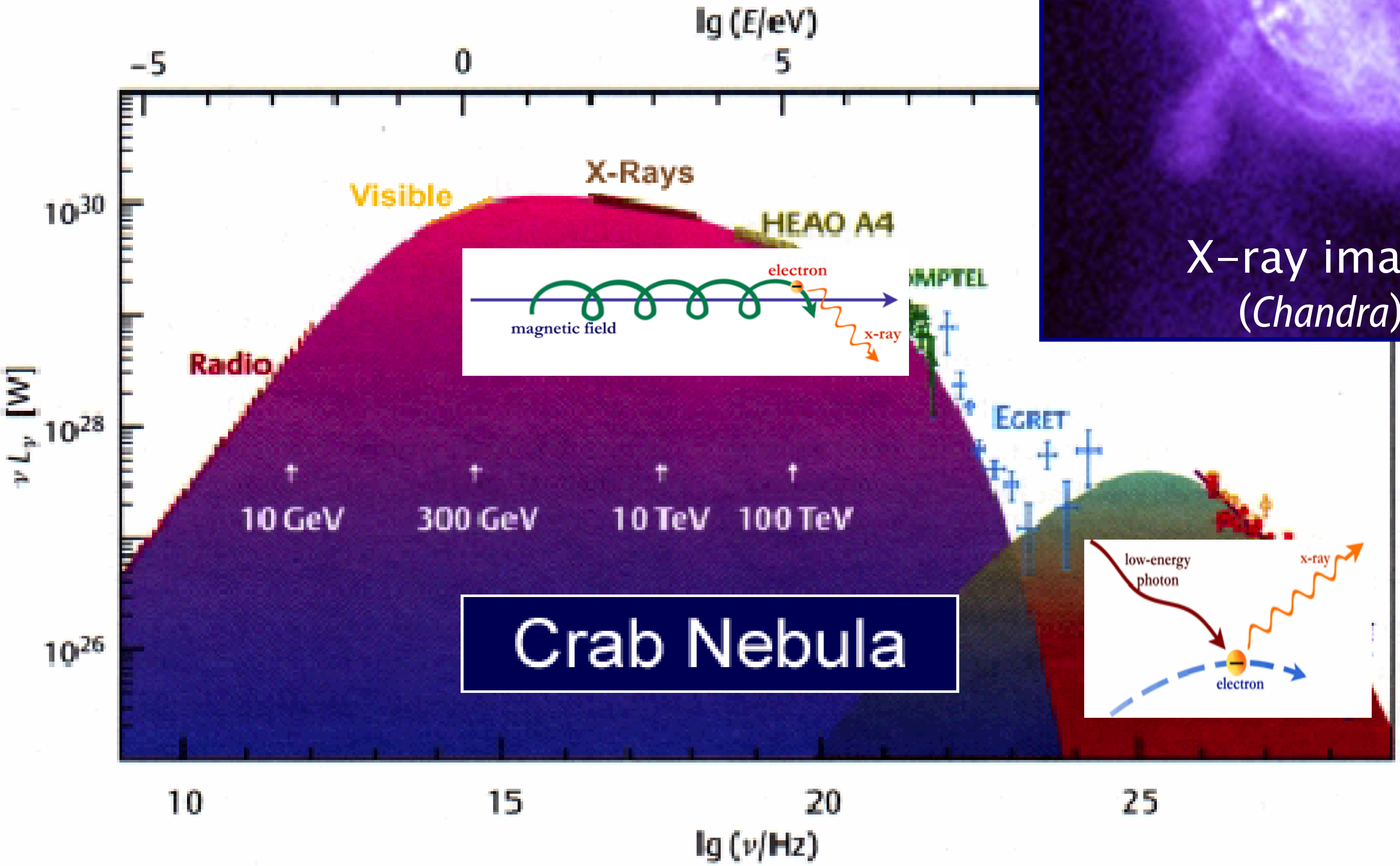
  (a telescope image comes as well from visible light)

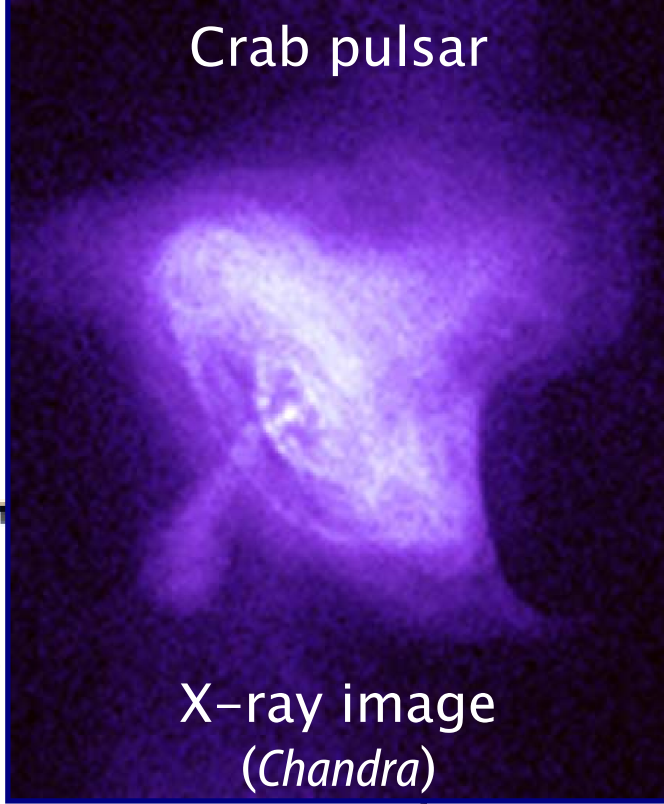
- In the same way we can map into false colors the image from a “X-ray telescope”

- Elaborating the information is crucial



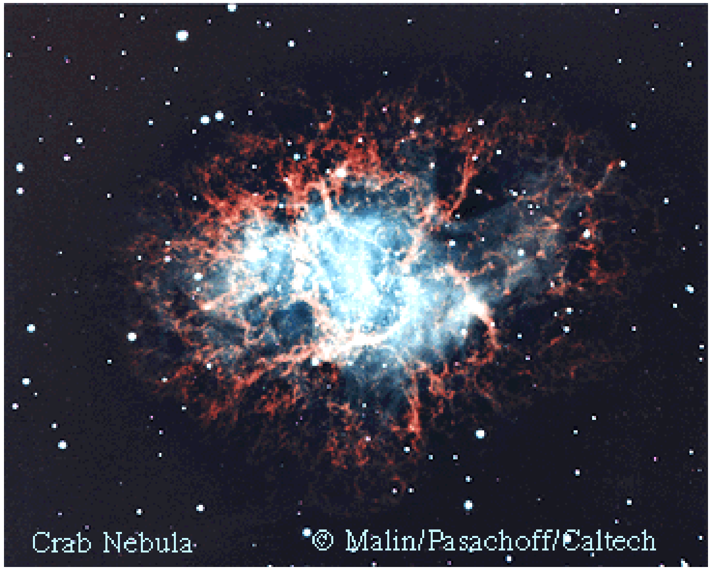
Many sources radiate over a wide range of wavelengths

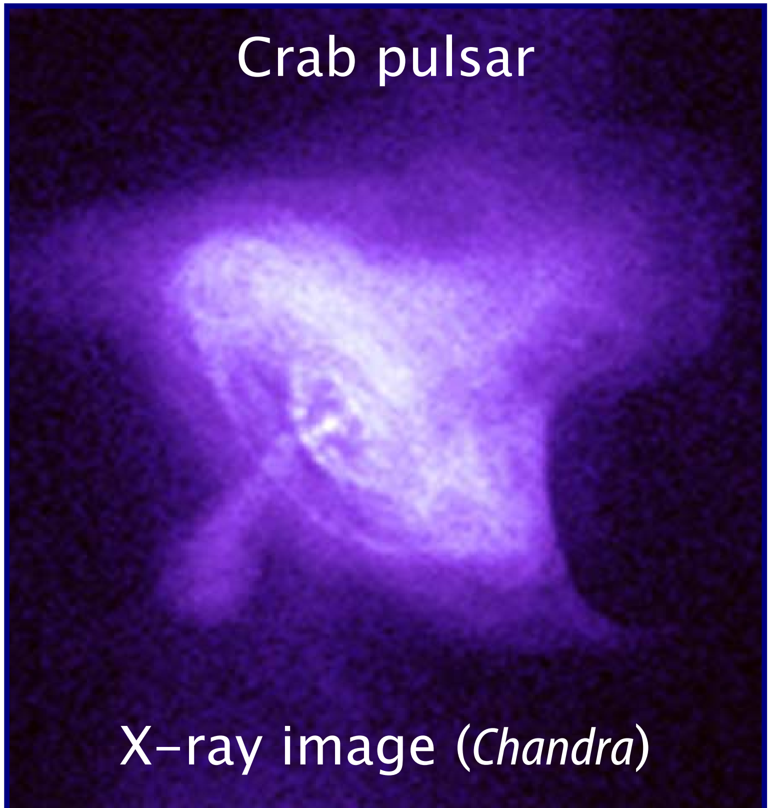




Pulsars

- Rapidly rotating neutron stars with
  - T between ~1ms and ~1s
  - Strong magnetic fields (~100 MT)
  - Mass ~ 3 solar masses
  - R ~ 10 Km (densest stable object known)
- For the pulsars emitting TeV gammas, such an emission is unpulsed

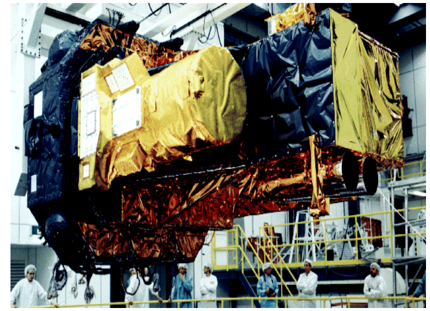




Multi Messenger Astronomy

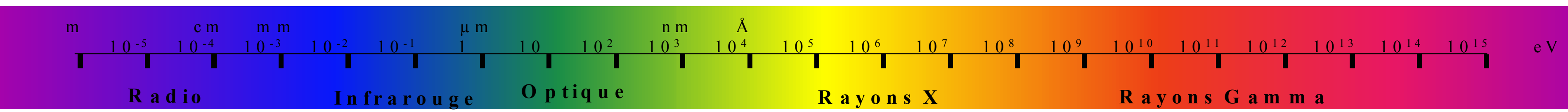
Radio Telescope
(Bonn)

Optical Telescope

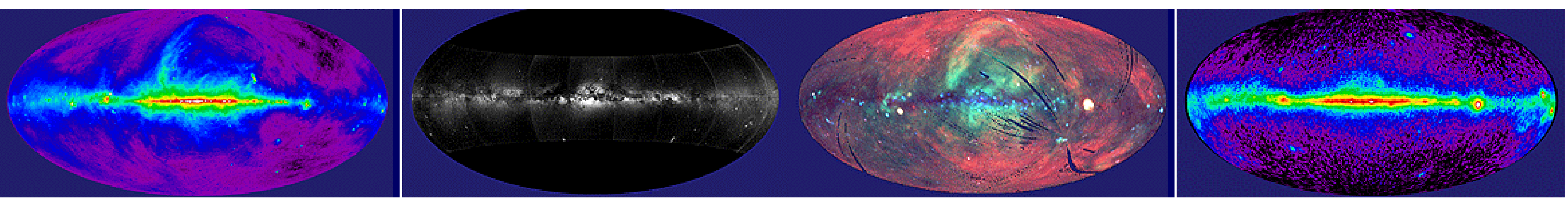


X - ray Satellite
(INTEGRAL/ESA)

γ - ray Telescope

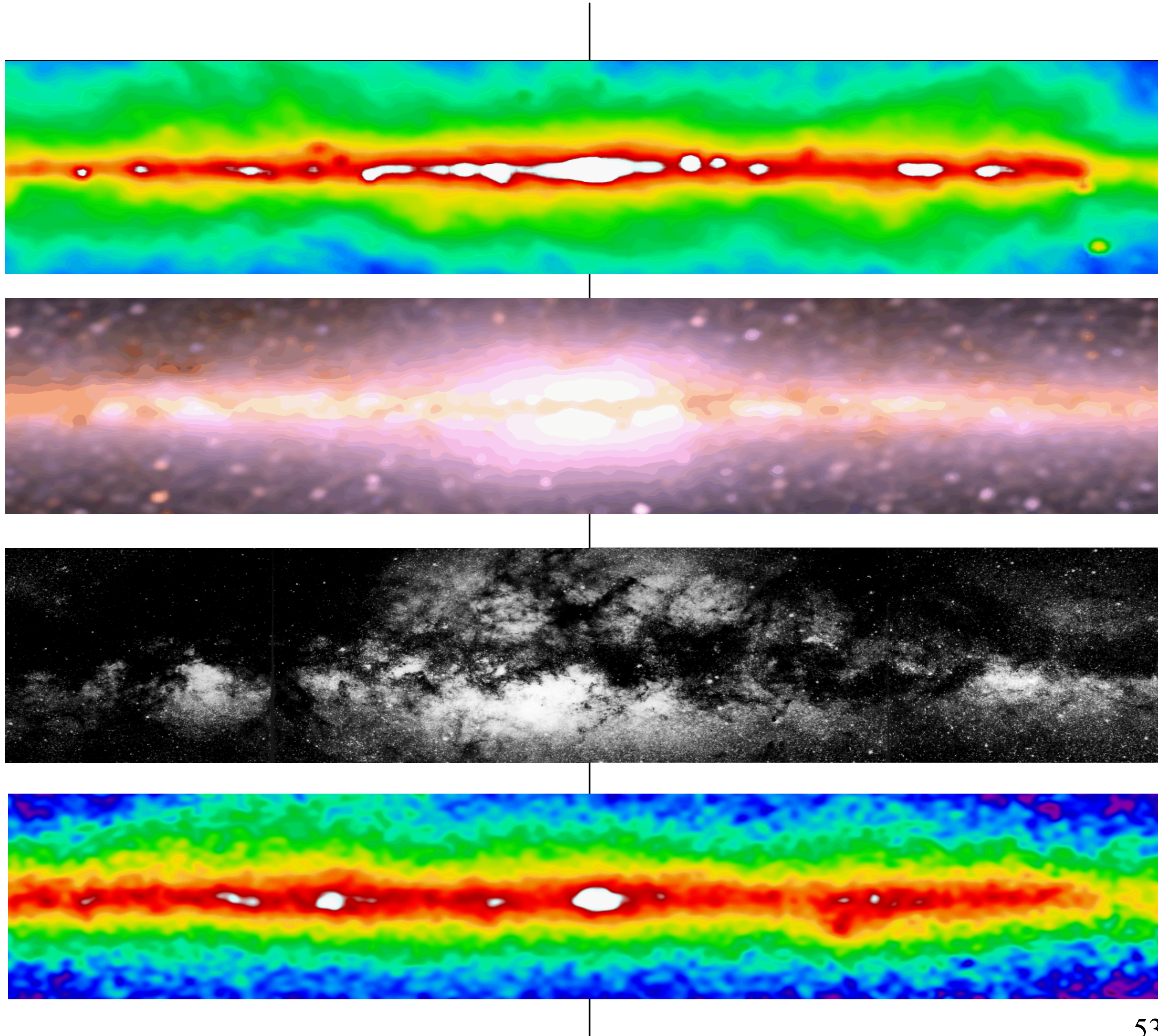


View of sky in Galactic Coordinates in four different photon wavelengths



Radio Visible light X - rays γ rays

Centre of Galaxy in Different Photon Wavelengths



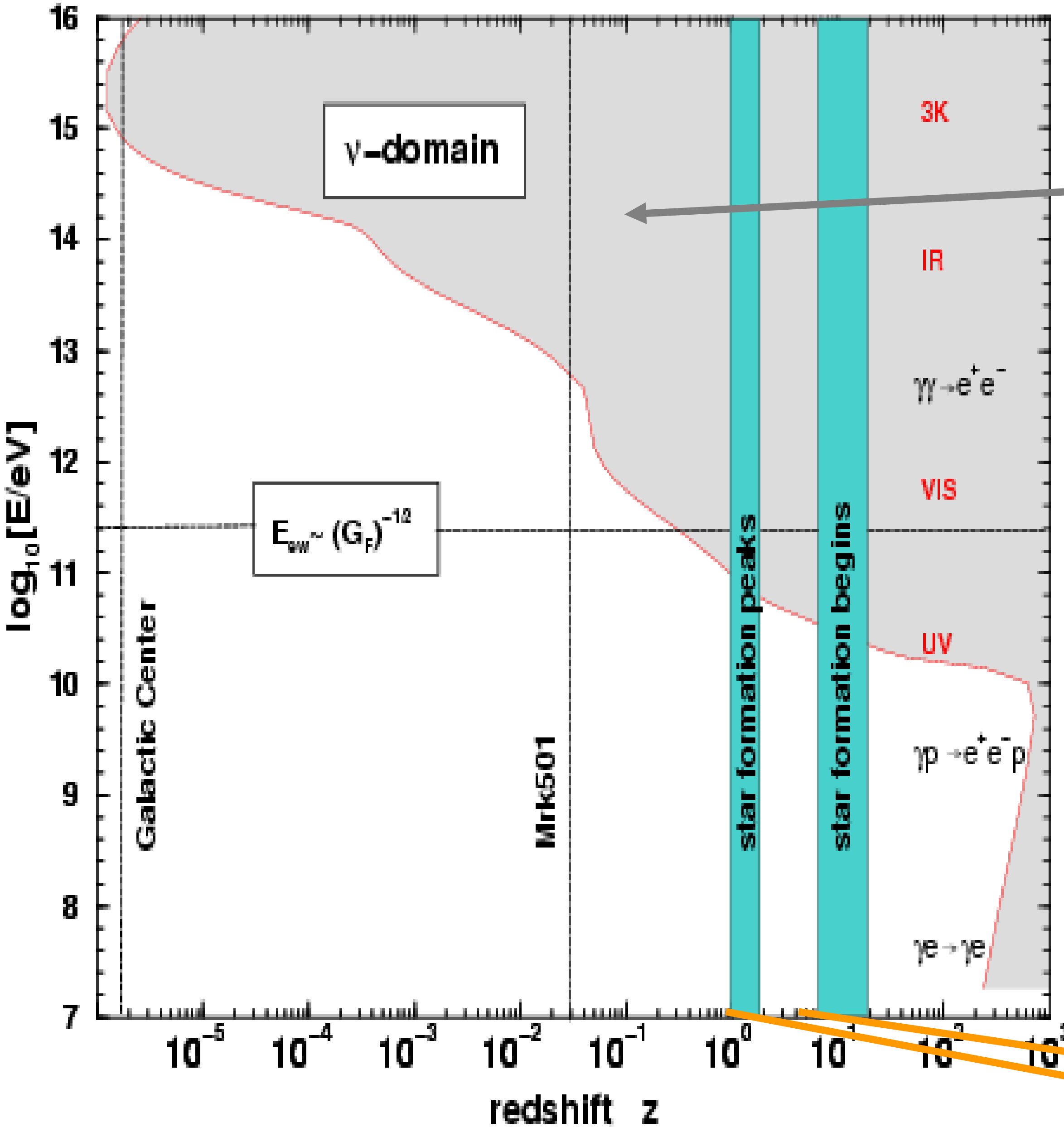
Radio 408 Mhz

Infrared 1-3 μm

Visible Light

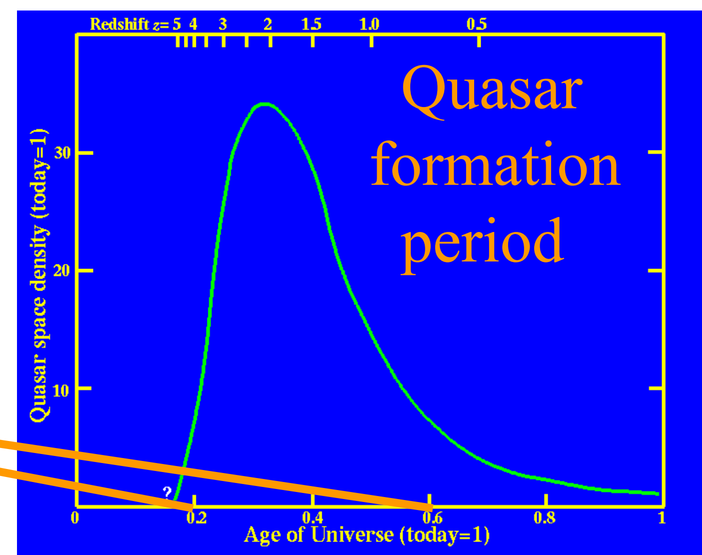
Gamma Rays

Multi-Messengers to see Whole Universe

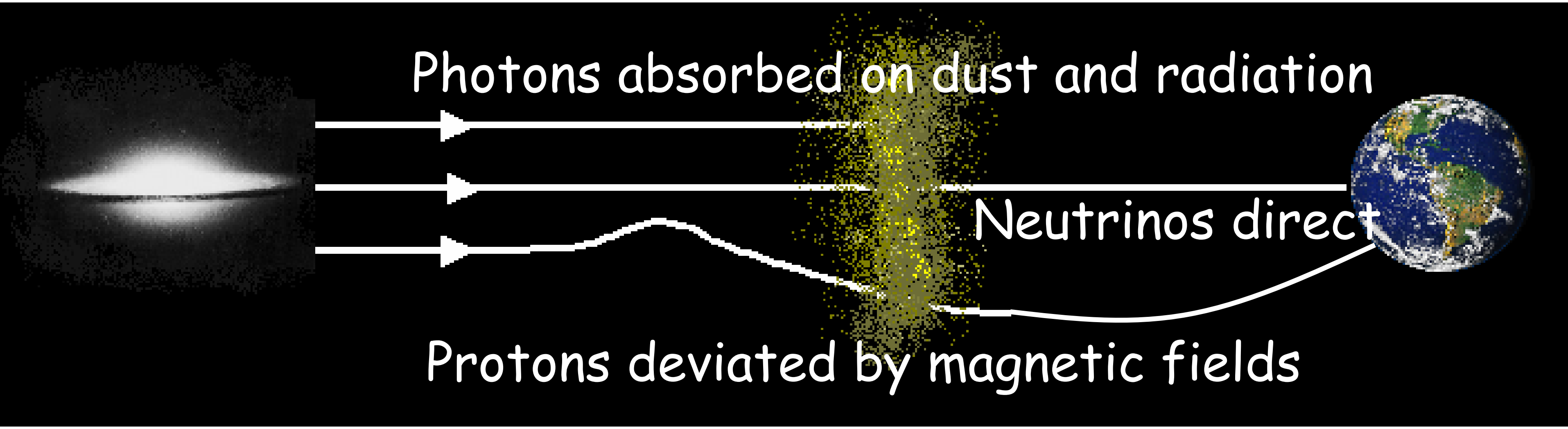


Distant universe invisible in high energy photons

need neutrinos



But also…



- Neutrino astrophysics
- *Graviton (?) astrophysics*

Surprises in history of astrophysics

New instruments often give unexpected results:

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreating binaires
Radio	Hewish,Bell	1967	Ionosphere	Pulsars
γ-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

With future new detector can again hope for completely new discoveries

The high-energy γ spectrum

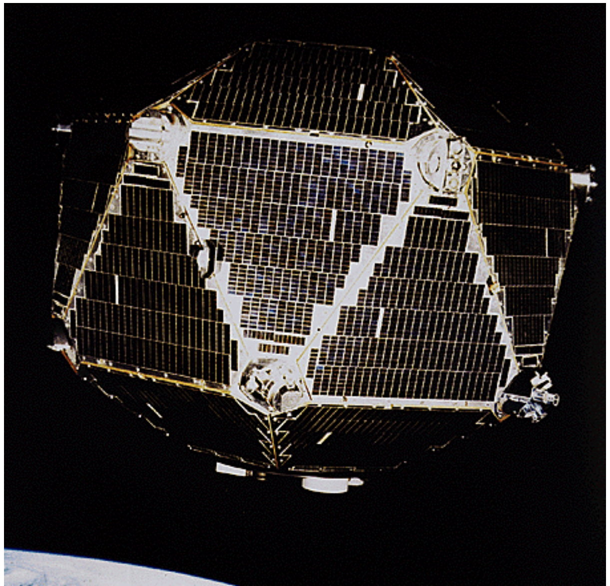
$E_\gamma > 30$ keV ($\lambda \sim 0.4$ A, $\nu \sim 7\ 10^9$ GHz)

Although arbitrary, this limit reflects astrophysical and experimental facts:

- Thermal emission -> nonthermal emission
- Problems to concentrate photons (-> telescopes radically different from larger wavelengths)
- Large background from cosmic particles

Study of exotic objects: γ-ray bursts (History, I)

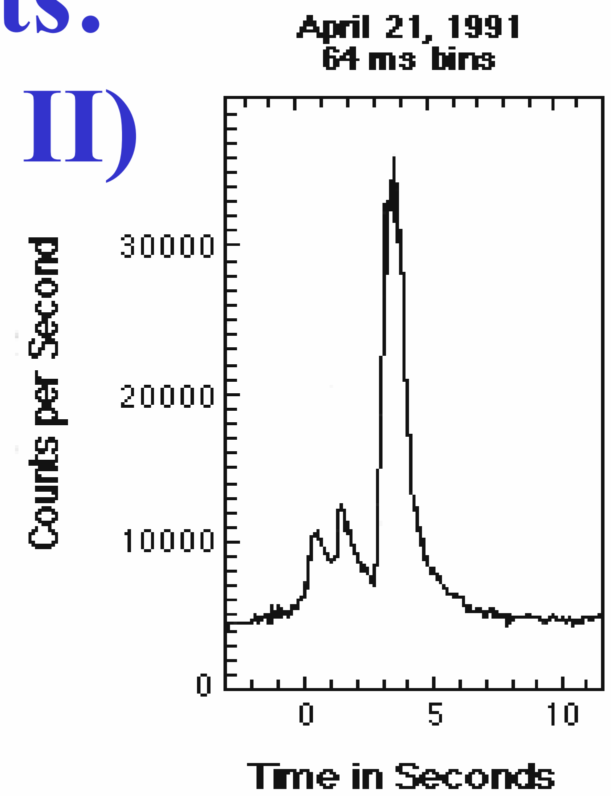
- An intriguing puzzle of today's astronomy… A brief history
  - Beginning of the '60s: Soviets are ahead in the space war
    - 1959: USSR sends a satellite to impact on the moon
    - 1961: USSR sends in space the 27-years old Yuri Gagarin
  - 1963: the US Air Force launches the 2 Vela satellites to spy if the Soviets are doing nuclear tests in space or on the moon
    - Equipped with NaI (Tl) scintillators

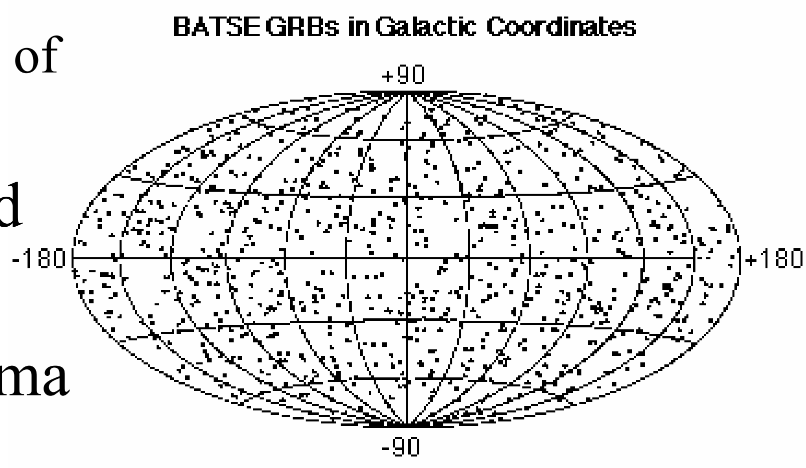


Study of exotic objects: γ-ray bursts (History, II)

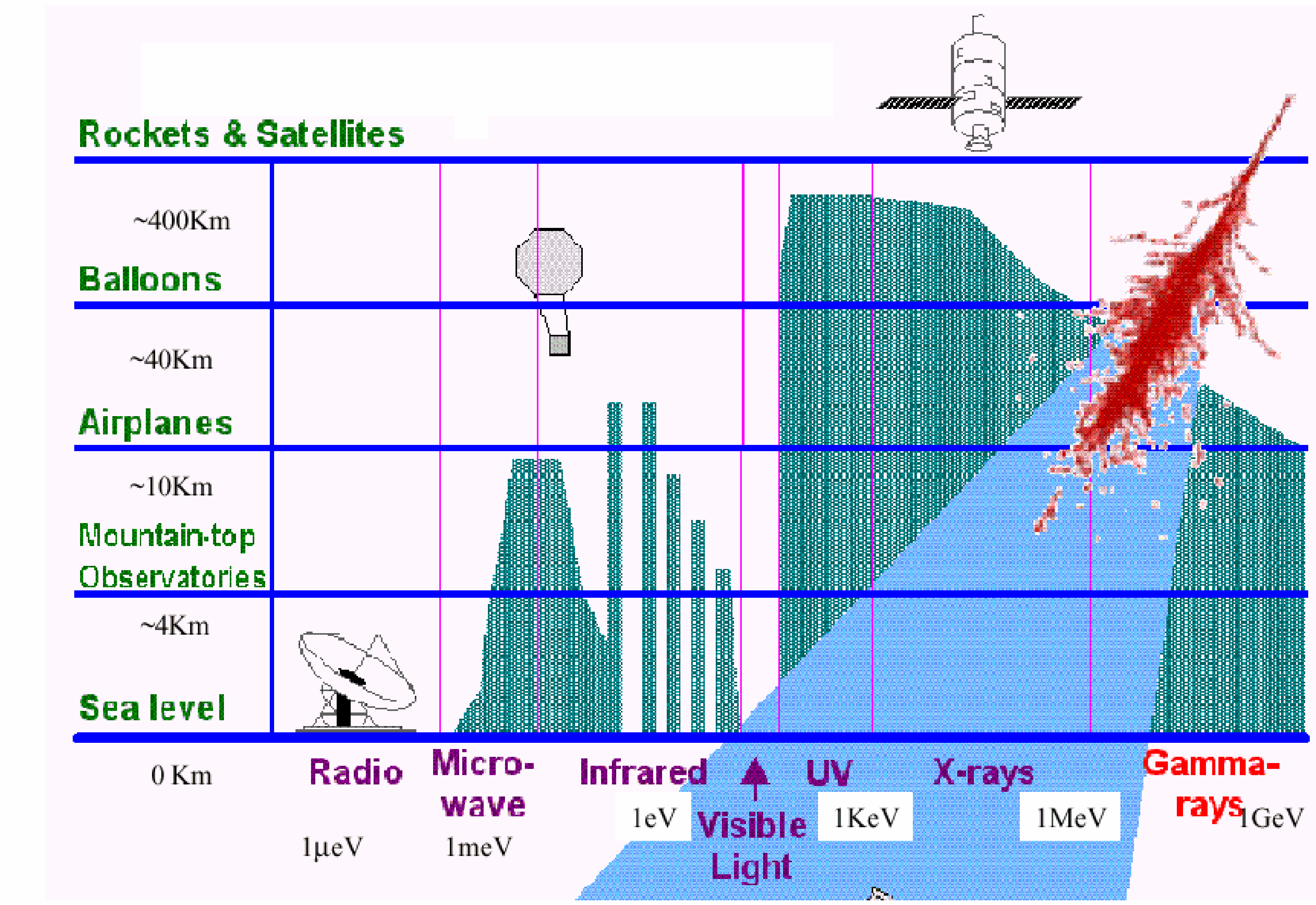
- 1967 : an anomalous emission of X and γ rays is observed. For a few seconds, it outshines all the γ sources in the Universe put together. Then it disappears completely. Another in 1969...

  After careful studies (!), origination from Soviet experiments is ruled out
  - The bursts don't come from the vicinity of the Earth
- 1973 (!) : The observation is reported to the world
- Now we have seen hundreds of gamma ray bursts...



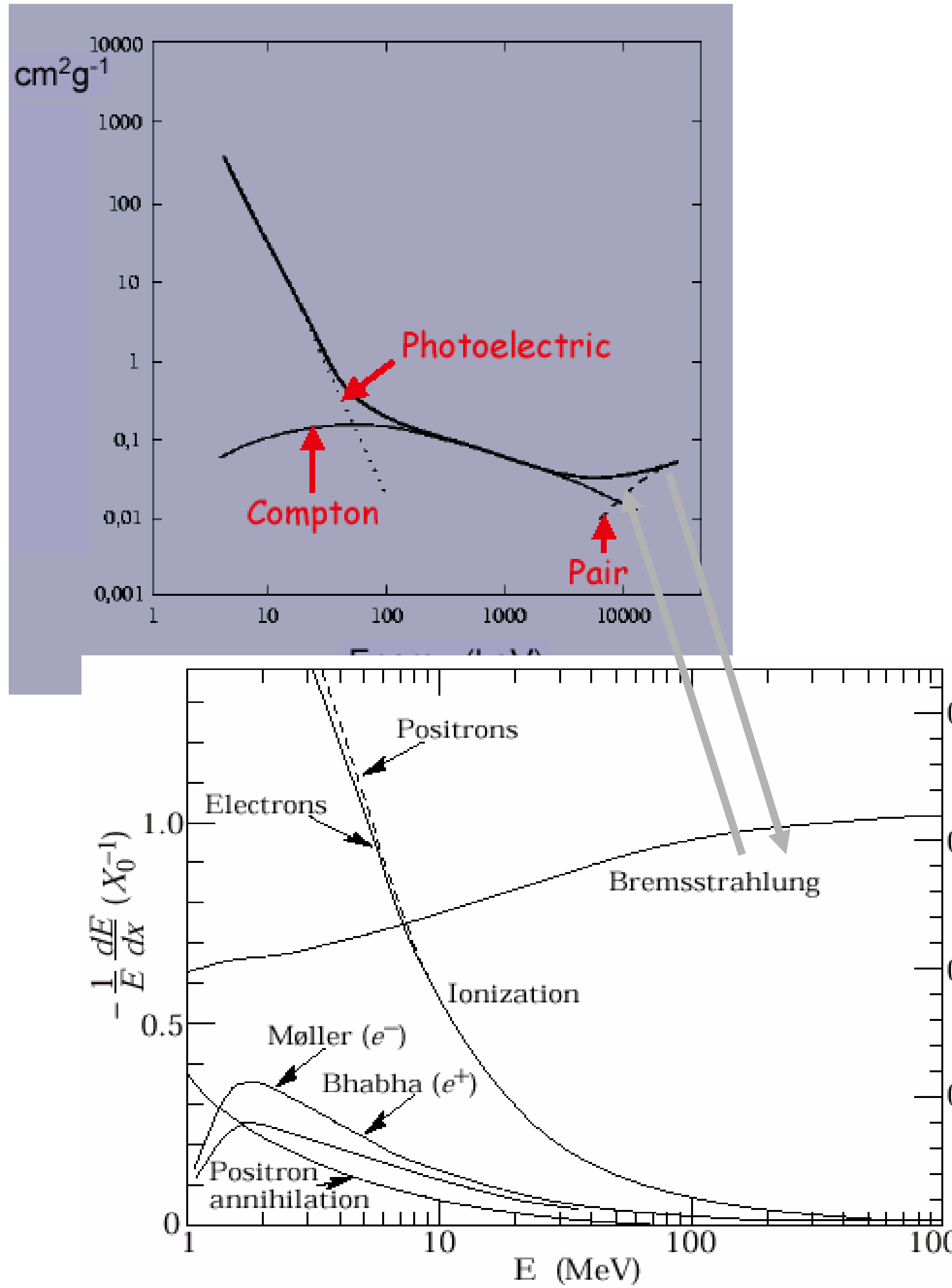


Transparency of the atmosphere

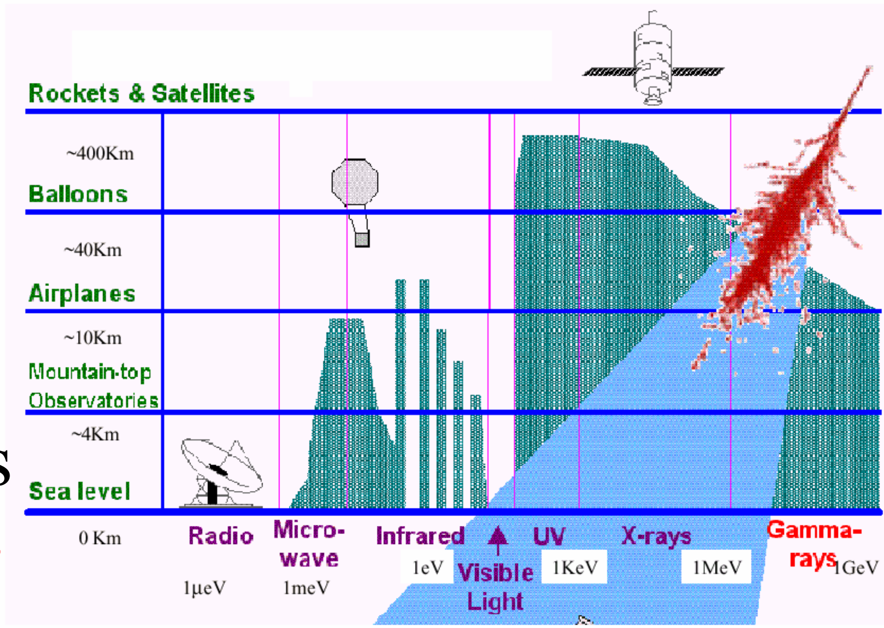


Detection of a high E photon

- Above the UV and below "50 GeV", shielding from the atmosphere
  - Below the e+e- threshold + some phase space ("10 MeV"), Compton/scintillation
  - Above "10 MeV", pair production
- Above "50 GeV", atmospheric showers
  - Pair <-> Brem



Consequences on the techniques



- The earth atmosphere (28 X_0 at sea level) is opaque to X/γ Thus **only a satellite-based detector can detect primary X/γ**

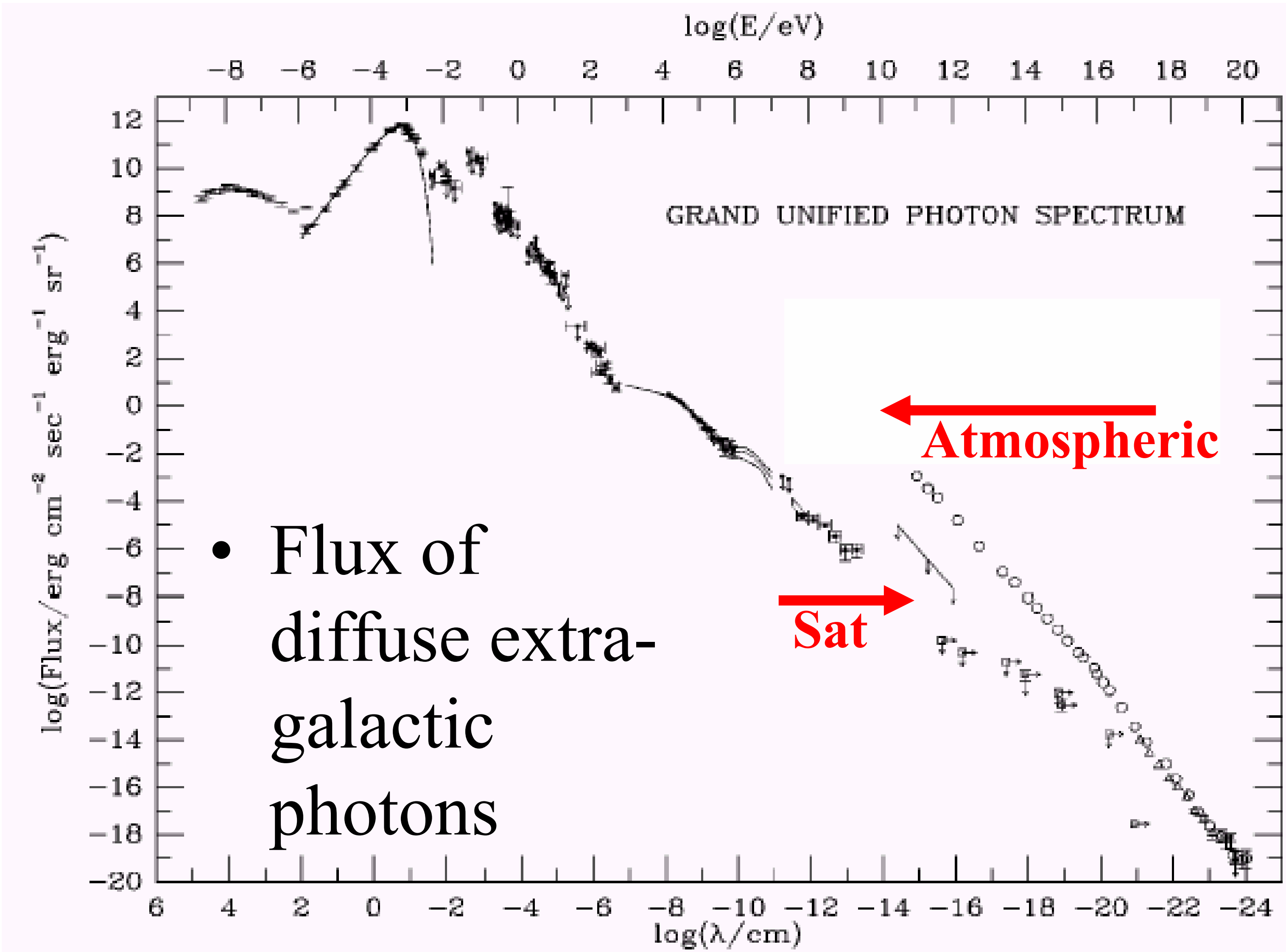
- The fluxes of h.e. γ are low and decrease rapidly with energy
  - Vela, the strongest γ source in the sky, has a flux above 100 MeV of 1.3 10^{-5} photons/(cm^2s), falling with $E^{-1.89}$ => a 1m^2 detector would detect only 1 photon/2h above 10 GeV

=> **with the present space technology, VHE and UHE gammas can be detected only from atmospheric showers**

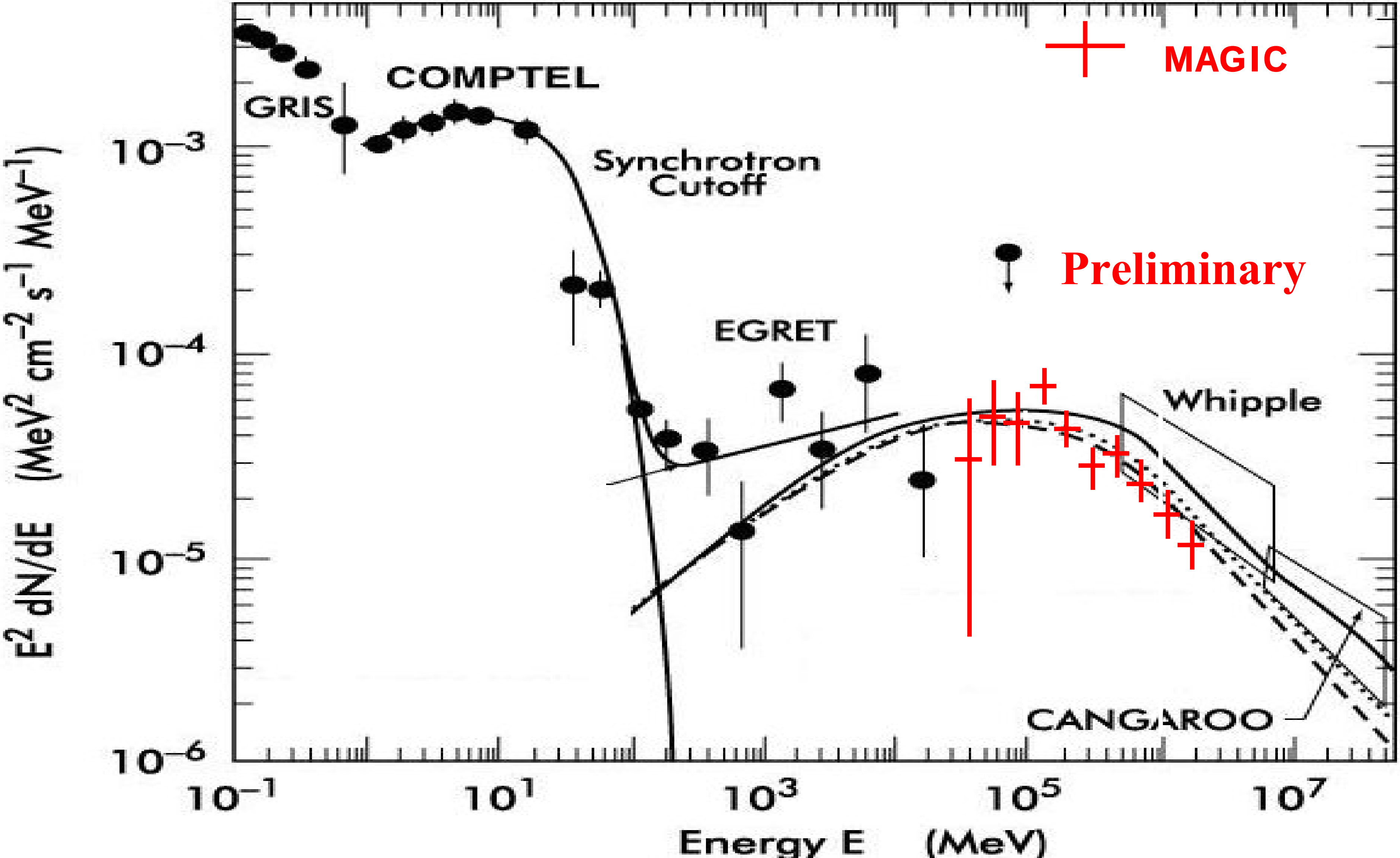
  - Earth-based detectors, atmospheric shower satellites

- The flux from high energy cosmic rays is much larger

Satellite-based and atmospheric: complementary, w/ moving boundaries



- Flux of diffuse extra-galactic photons



MAGIC
GRIS
COMPTEL
Synchrotron Cutoff
Preliminary
EGRET
Whipple
CANGAROO
10^{-3}
10^{-4}
10^{-5}
10^{-6}
E^2 dN/dE (MeV^2 cm^{-2} s^{-1} MeV^{-1})
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
Energy E (MeV)

Satellite-based detectors: figures of merit

- Effective area, or equivalent area for the detection of γ

$$A_{eff}(E) = A \times eff.$$

- Angular resolution is important for identifying the γ sources and for reducing the diffuse background

- Energy resolution

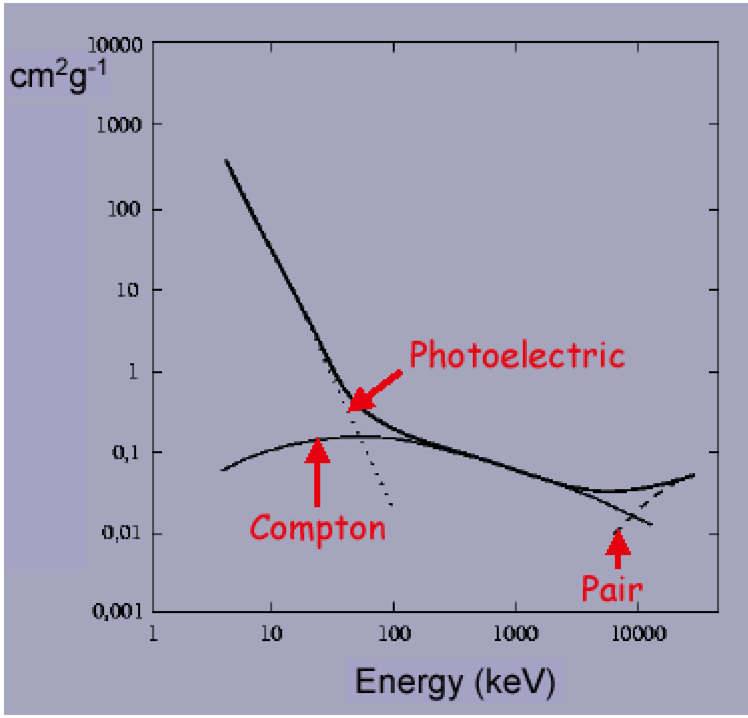
- Time resolution

X detectors

- The electrons ejected or created by the incident gamma rays lose energy mainly in ionizing the surrounding atoms; secondary electrons may in turn ionize the material, producing an amplification effect
- Most space X- ray telescopes consist of detection materials which take advantage of ionization process but the way to measure the total ionization loss differ with the nature of the material

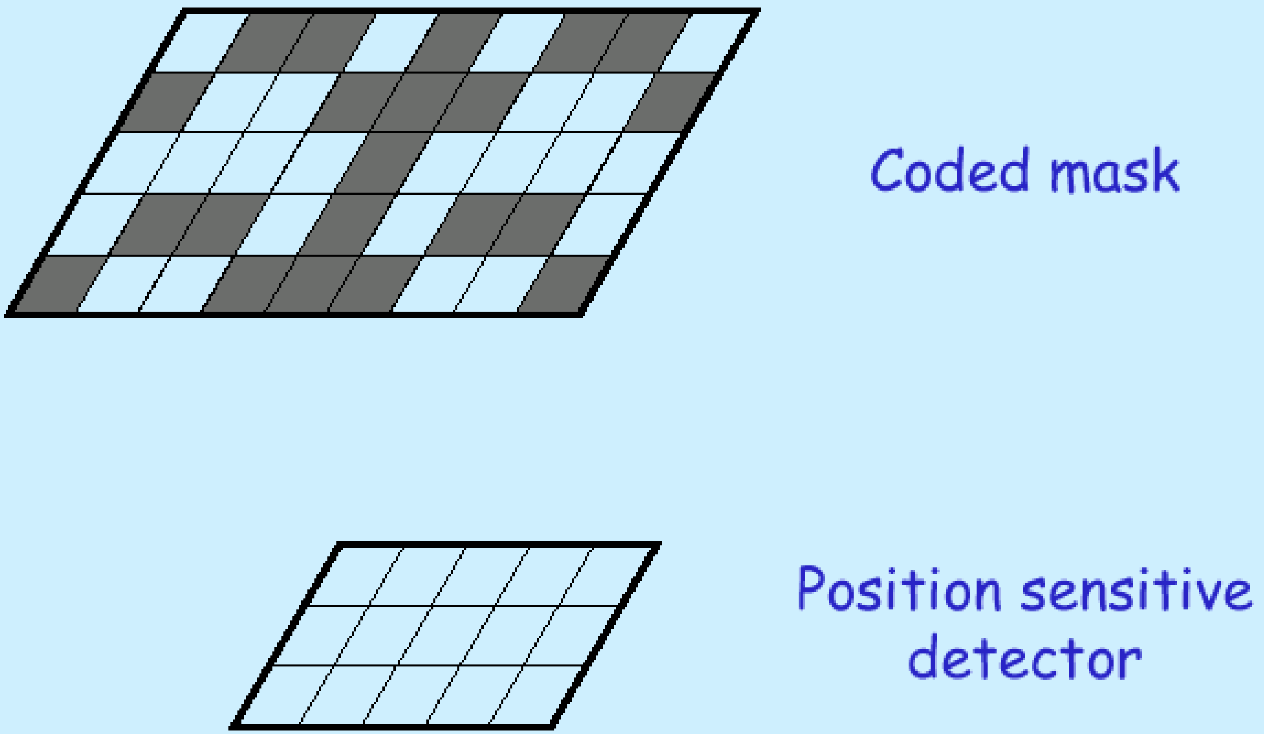
Commonly used detection devices are...

- gas detectors
- scintillation counters
- semiconductor detectors

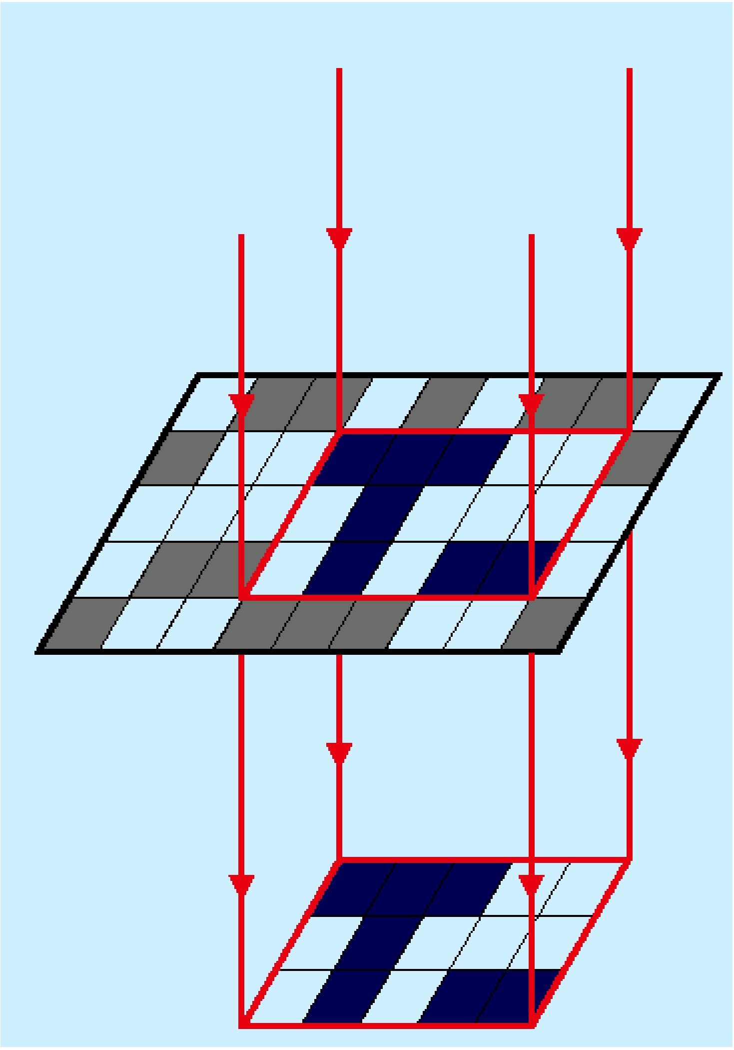


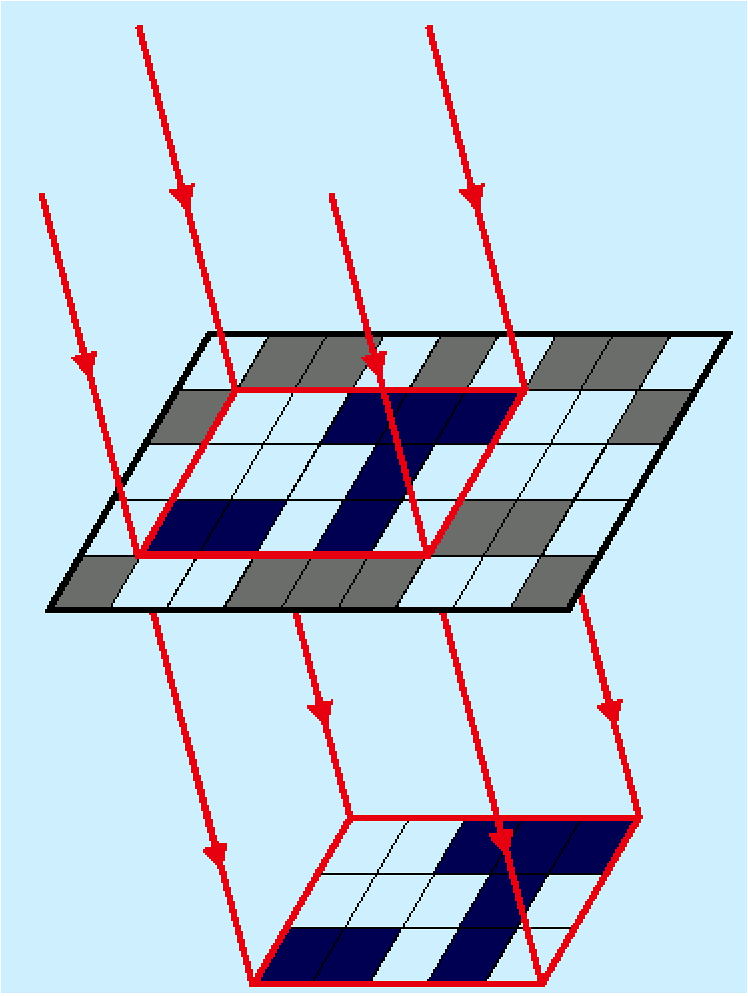
X detection (direction-sensitive)

A coded mask (array of opaque blocks) is disposed so that a point source at infinity projects on a position sensitive detector a pattern characteristic of the source direction



X detection (direction-sensitive)





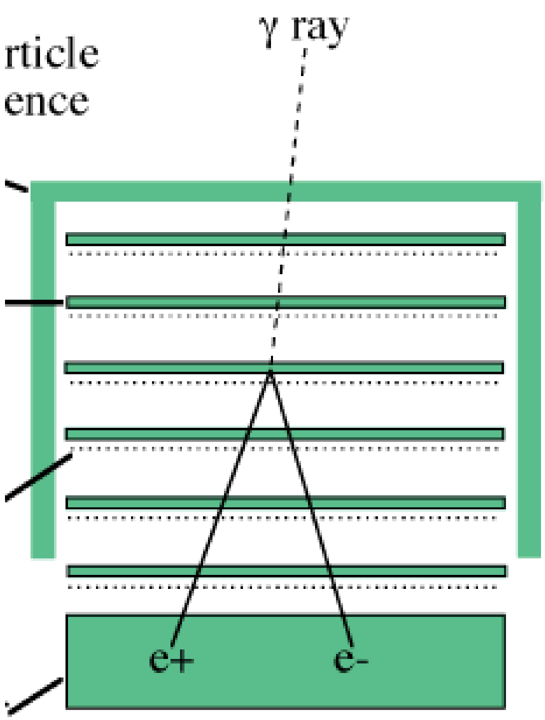
Unfolding is a nice mathematical problem !

INTEGRAL/CHANDRA

- INTEGRAL, the International Gamma-Ray Astrophysics Laboratory is an ESA medium-size (M2) science mission
- Energy range 15 keV to 10 MeV plus simultaneous X-ray (3-35 keV) and optical (550 nm) monitoring
- Fine spectroscopy ($\Delta E/E \sim 1\%$) and fine imaging (angular resolution of 5')
- Two main -ray instruments: SPI (spectroscopy) and IBIS (imager)

- Chandra, from NASA, has a similar performance

γ satellite-based detectors: engineering



- Techniques taken from particle physics

- γ direction is mostly determined by e+e- conversion
  - Veto against charged particles by an ACD
  - Angular resolution given by
    - Opening angle of the pair m/E ln(E/m)
    - Multiple scattering $(20/p\beta)\ (L/X_0)^{1/2}$ (dominant)

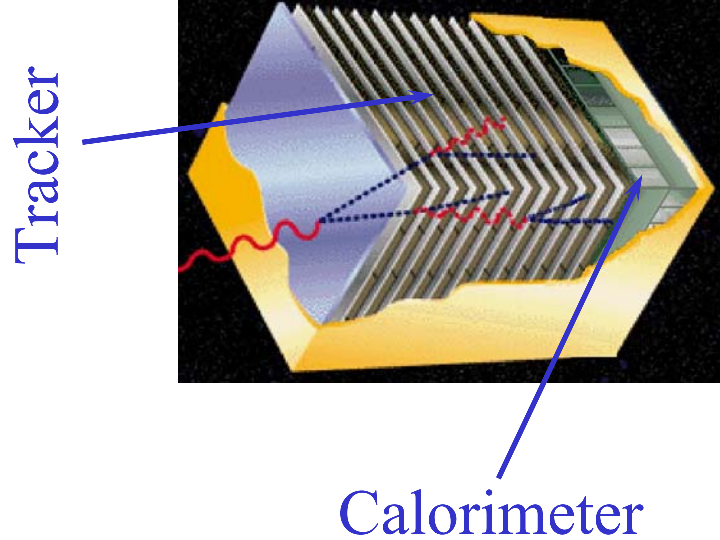
  => large number of thin converters, but the # of channel increases

  (power consumption << 1 kW)

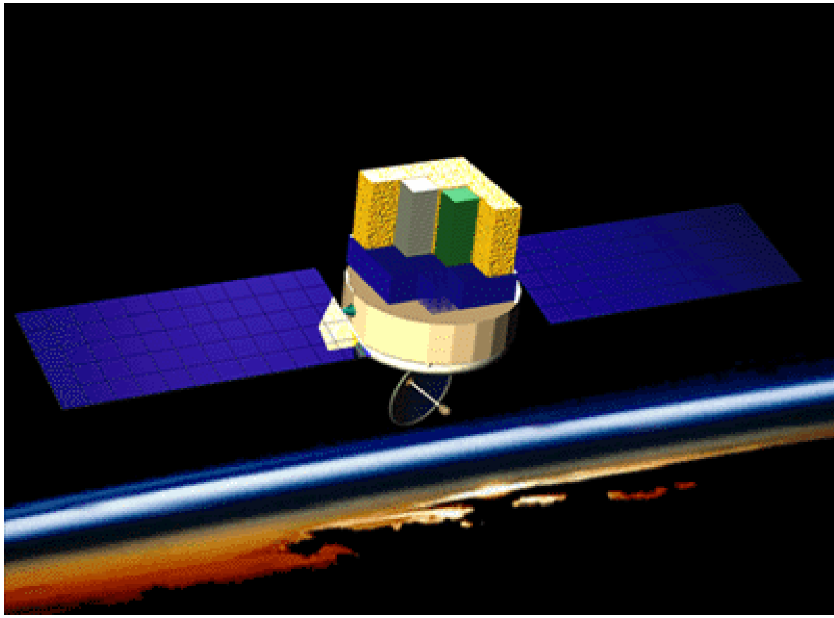
- If possible, a calorimeter in the bottom to get E resolution, but watch the weight (leakage => deteriorated resolution)

  Smart techniques to measure E w/o calorimeters (AGILE)

GLAST

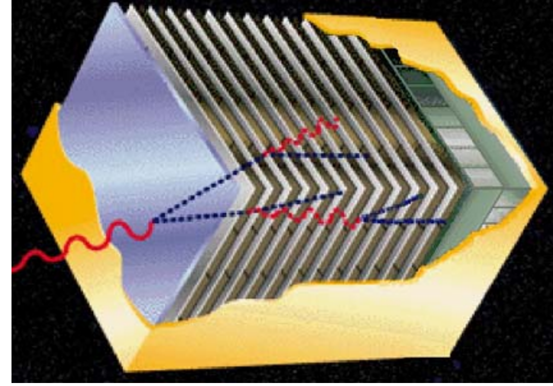


- γ telescope on satellite for the range 20 MeV-300 GeV
  - hybrid tracker + calorimeter
- International collaboration US-France-Italy-Japan-Sweden
  - Broad experience in high-energy astrophysics and particle physics (science + instrumentation)
- Timescale: 2007-2011 (->2016)
- Wide range of physics objectives:
  - Gamma astrophysics
  - Fundamental physics



A HEP / astrophysics partnership

GLAST: the instrument

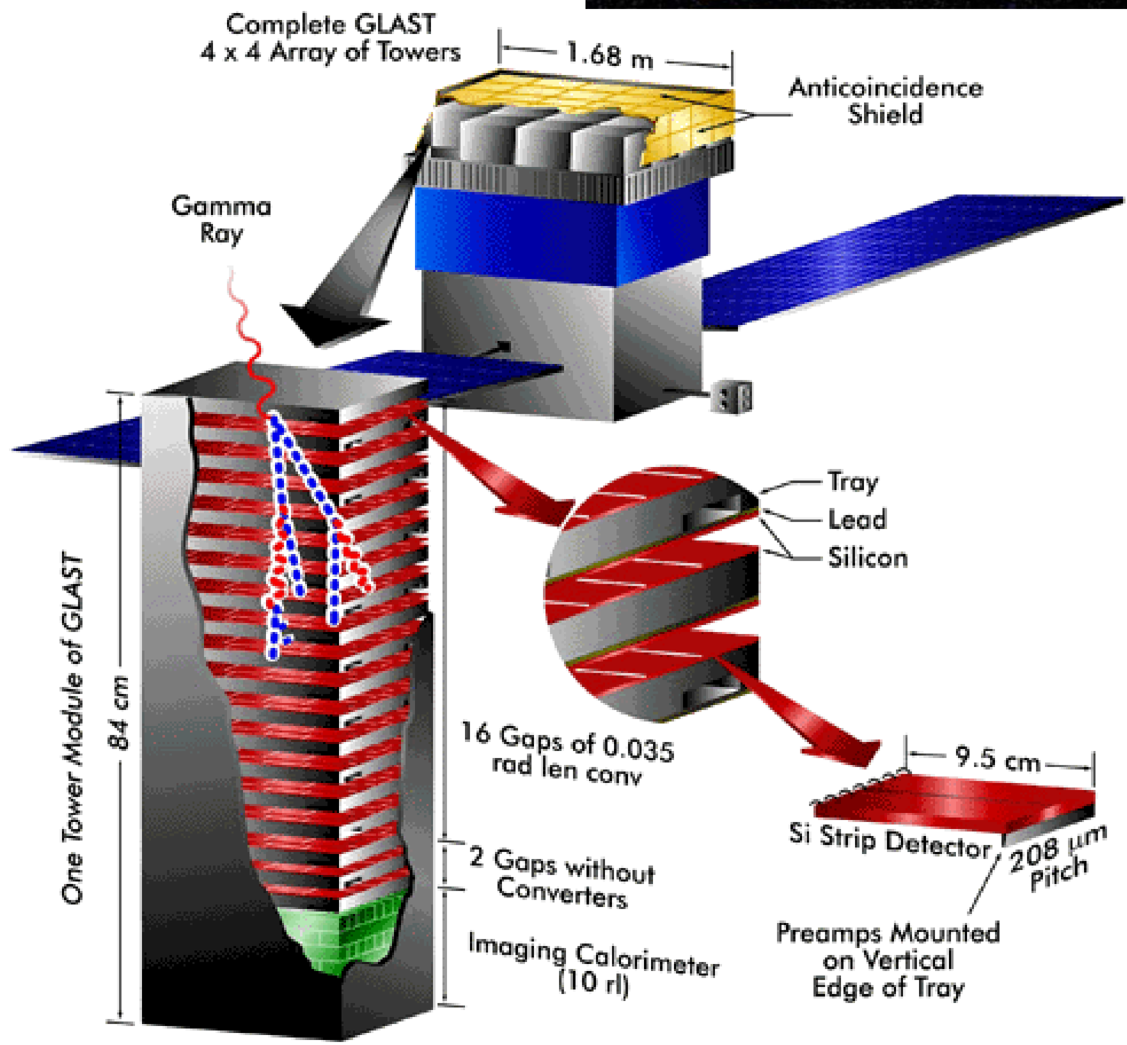


- Tracker
  Si strips + converter

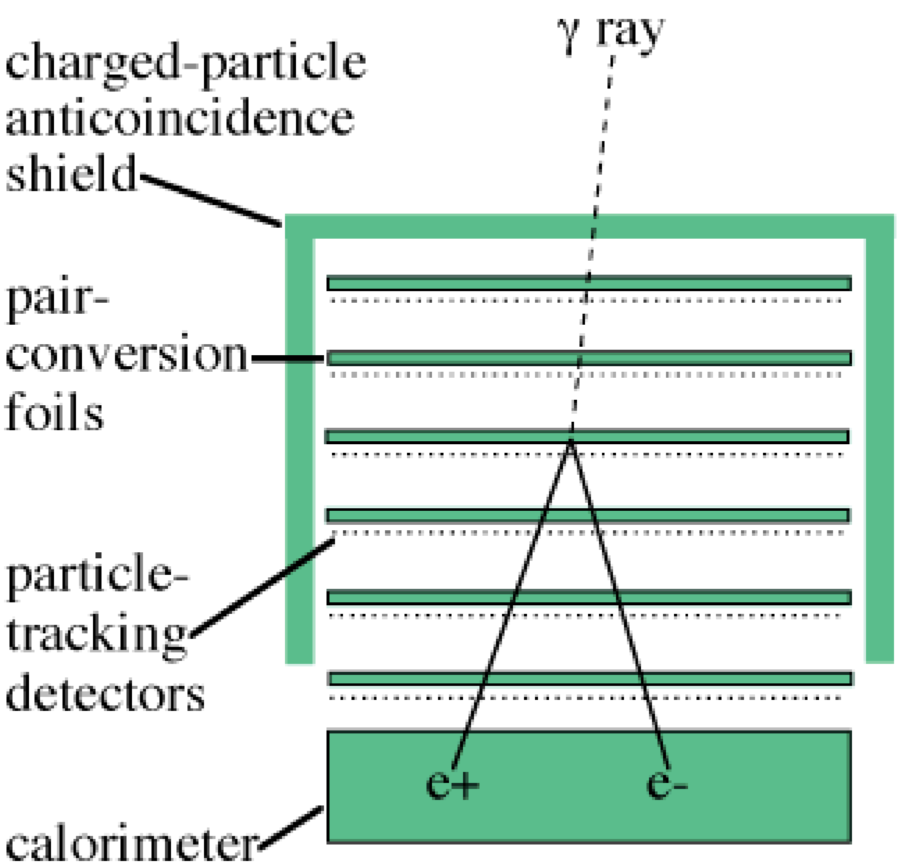
- Calorimeter
  CsI with diode readout

(a classic for HEP)

- 1.7 x 1.7 m^2 x 0.8 m
  height/width = 0.4 $\Rightarrow$
  large field of view
- 16 towers $\Rightarrow$ modularity



GLAST: the tracker



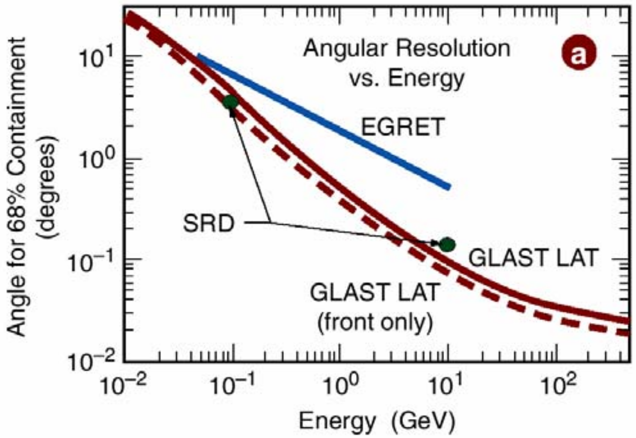
Si strips + converter

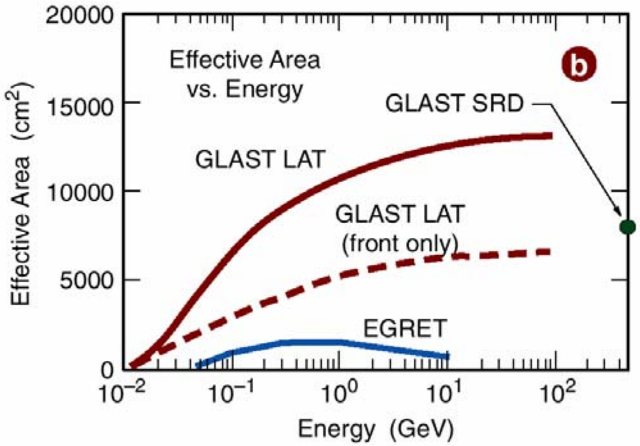
- High signal/noise
- Rad-hard
- Low power

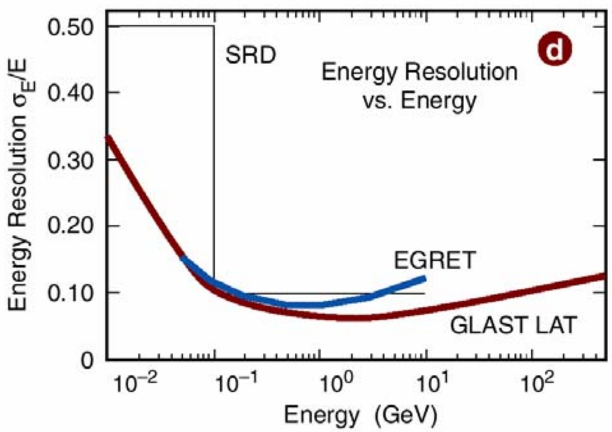
- 4x4 towers, of 37 cm × 37 cm of Si
- 18 *x*,*y* planes per tower
  - 19 "tray" structures
    - 12 with 2.5% Pb on bottom
    - 4 with 25% Pb on bottom
    - 2 with no converter
- Electronics on the sides of trays
  - Minimize gap between towers
- Carbon-fiber walls to provide stiffness

GLAST performance (compared to EGRET)

Quantity	GLAST	EGRET
Energy range	20 MeV- > 300 GeV	20 MeV- 30 GeV
Energy resolution	10 % (E>100 MeV)	10%
Peak Effective Area	> 8000 cm^2 (E>1 GeV)	1500 cm^2
Single photon angular resolution (68%, on-axis)	<3.5 deg (100 MeV) <0.15 deg (E>10 GeV)	5.8 deg (100 MeV)
*Field of view (FOV)	> 2 sr	0.5 sr
Time resolution	10 microseconds	0.1 milliseconds
Dead time	< 20 microsec/event	100 ms/event

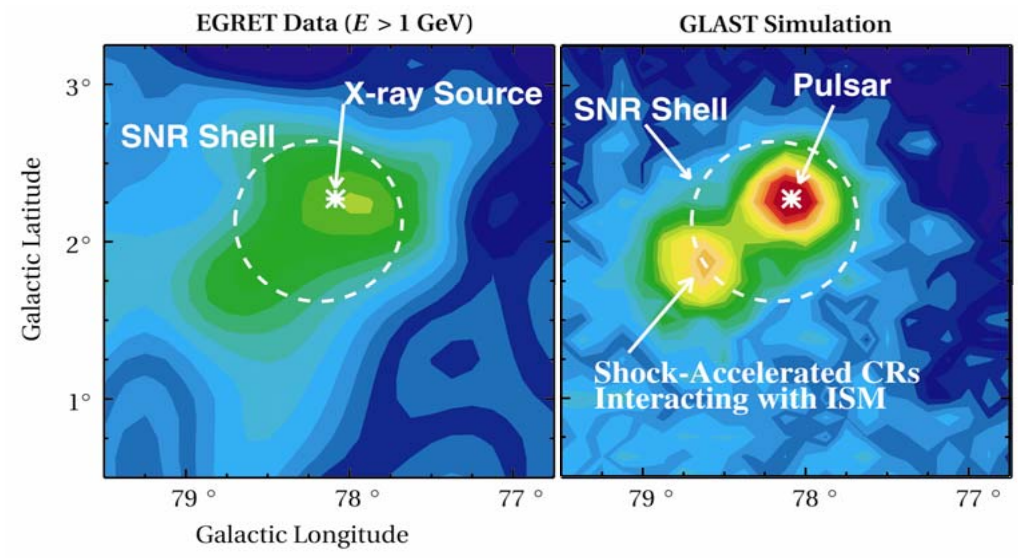




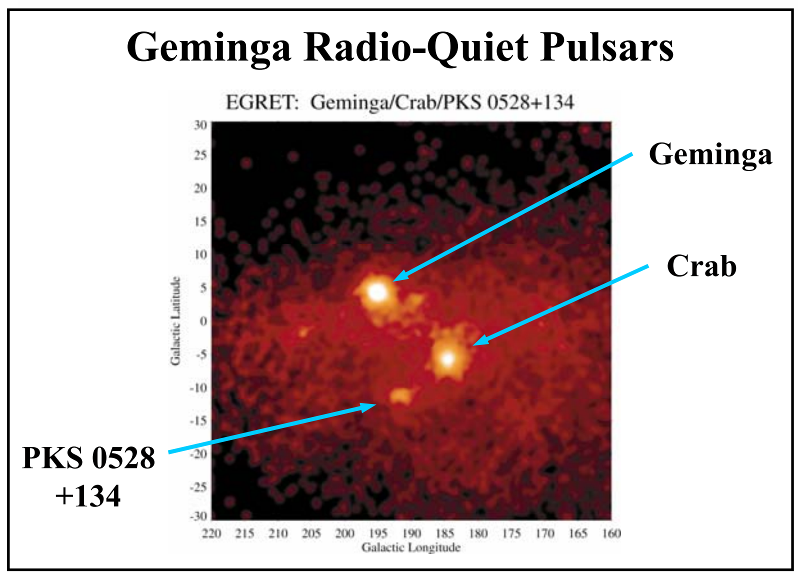


GLAST performance
two examples of application

- Cosmic ray production



- Facilitate searches for pulsations from millisecond pulsars

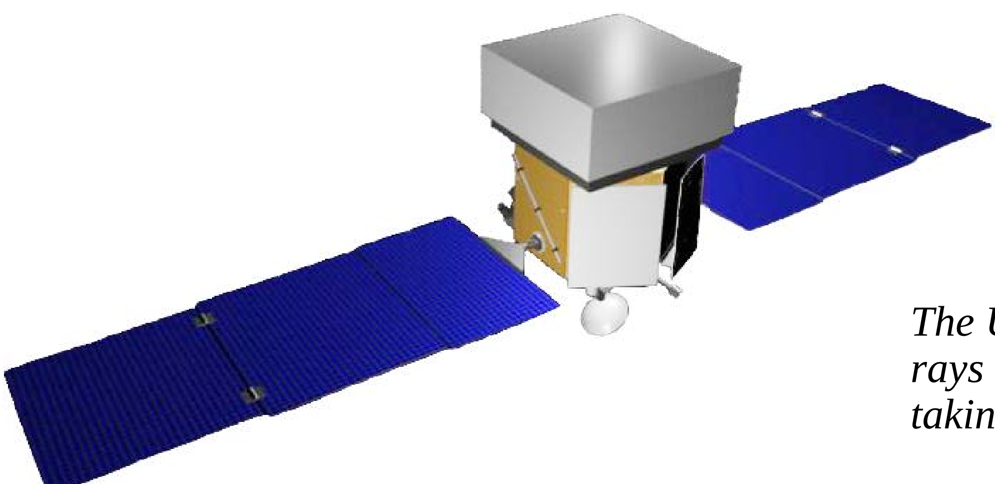


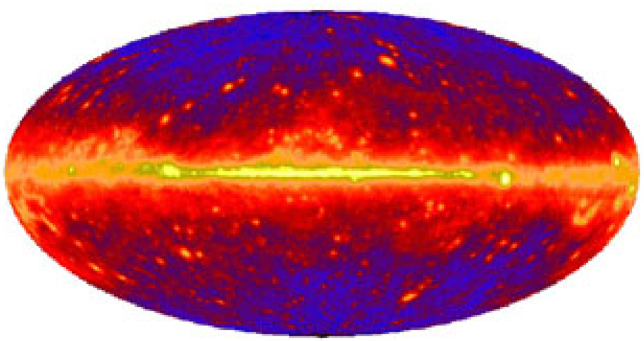
The Gamma-ray Large Area Space Telescope

GLAST will be sent in space in 2007

A collaboration USA-Japan-France-Italy-Sweden

Large part of the software is written in Udine... So come and help !

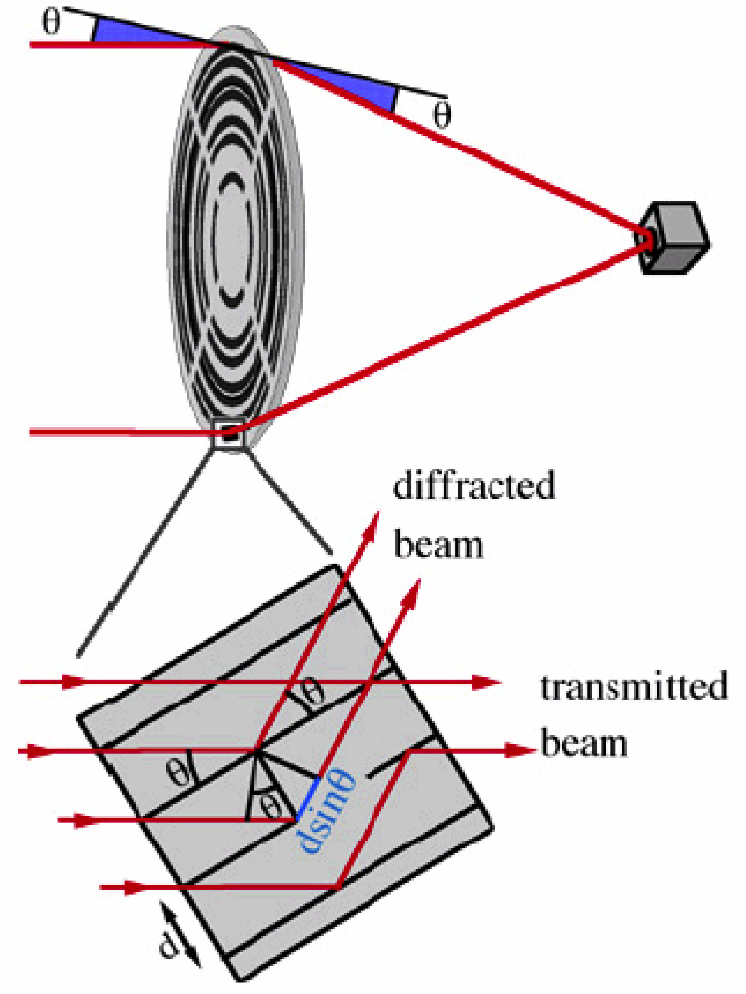




The Universe in the gamma rays after one year of data taking. Center: our galaxy

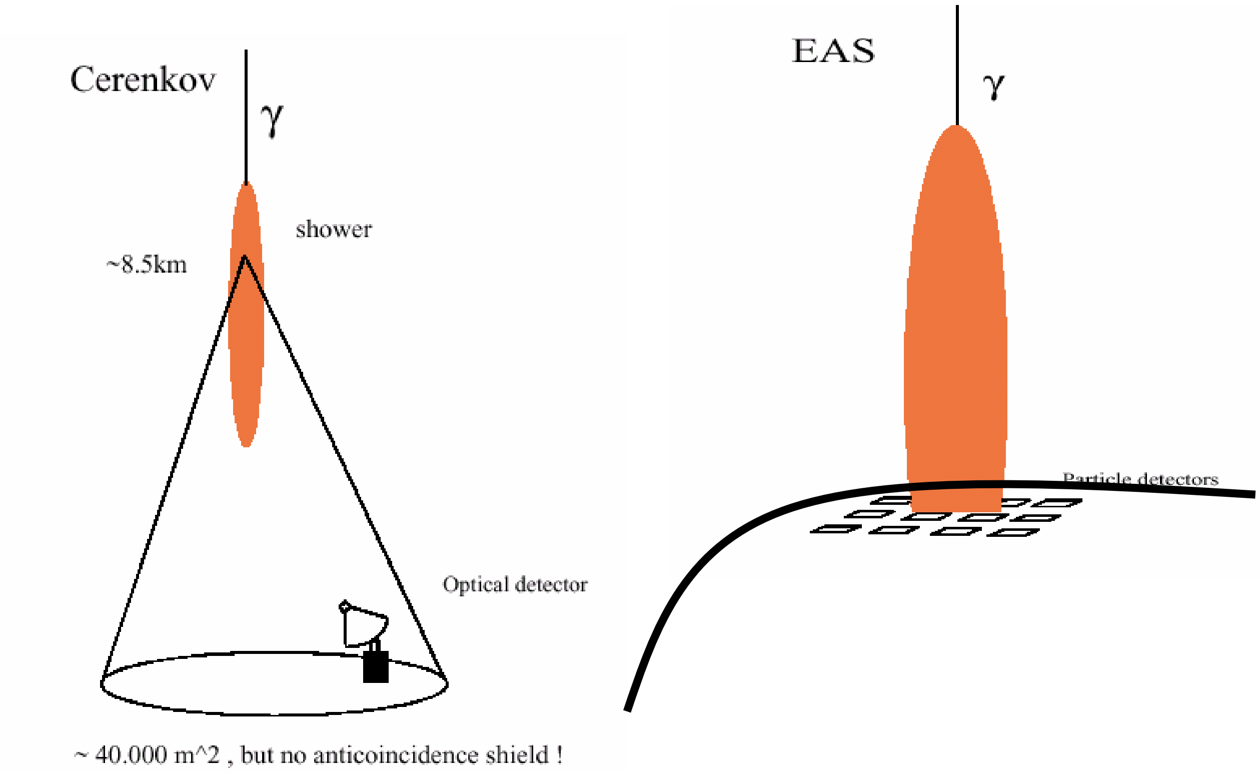
But despite the progress in satellites…

- The problem of the flux (~1 photon/day/km2 @ ~30 PeV) cannot be overcome
  - Photon concentrators work only at low energy
  - The key for VHE gamma astrophysics and above is in ground-based detectors
  - Also for dark matter detection…



Ground-based detectors

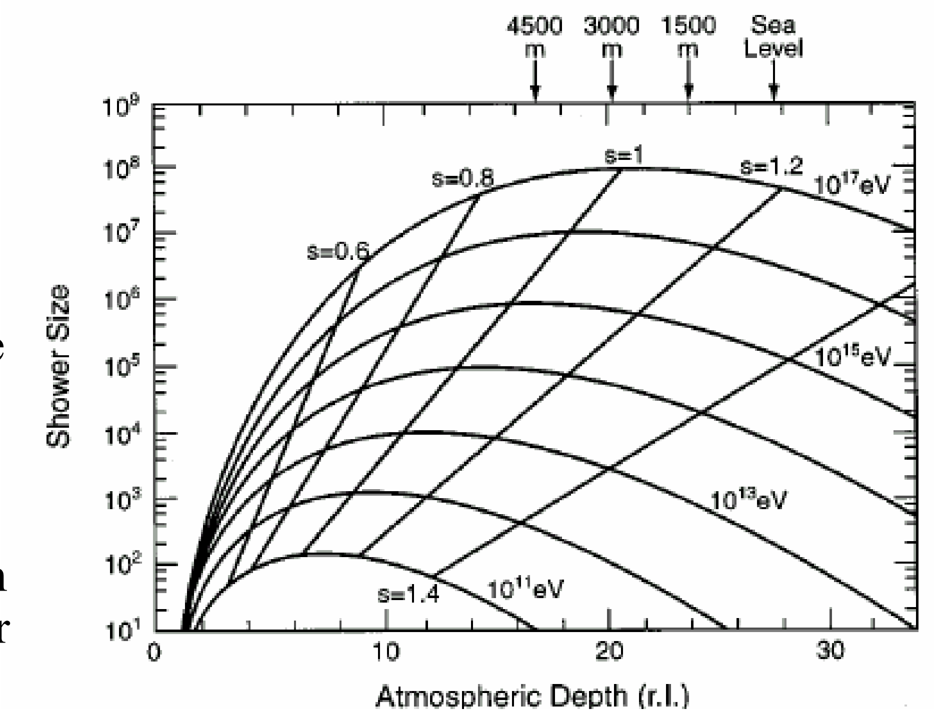
- An Extensive Air Shower can be detected
  - From the shower particles directly (EAS Particle Detector Arrays)
  - By the Cherenkov light emitted by the charged particles in the shower (Cherenkov detectors)



Earth-based detectors
Properties of Extensive Air Showers

- We **believe** we know well the γ physics up to EHE…

  Predominant interactions e.m.
  - e+e- pair production dominates
  - electrons loose energy via brem
  - Rossi approximation B is valid
    - Maximum at $z/X_0 \approx \ln(E/\varepsilon_0)$; ε_0 is the critical energy ~80 MeV in air; X_0 ~ 300 m at stp
    - Cascades ~ a few km thick
    - Lateral width dominated by Compton scattering ~ Moliere radius (~80m for air at STP)

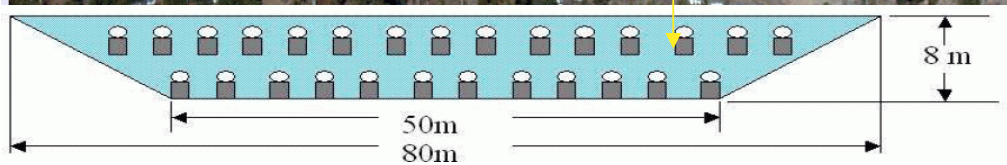


- Note: λ_{had} ~ 400 m for air

  hadronic showers have 20x more muons and are less regular than em

EAS

MILAGRO (New Mexico@2600m)
water Cherenkov,
60x80m^2 + outriggers,
γ/h: Muon-identification
in second layer)



Proposed: HAWC
10x bigger @ 4500m a.s.l.

Cherenkov (Č) detectors
Cherenkov light from γ showers

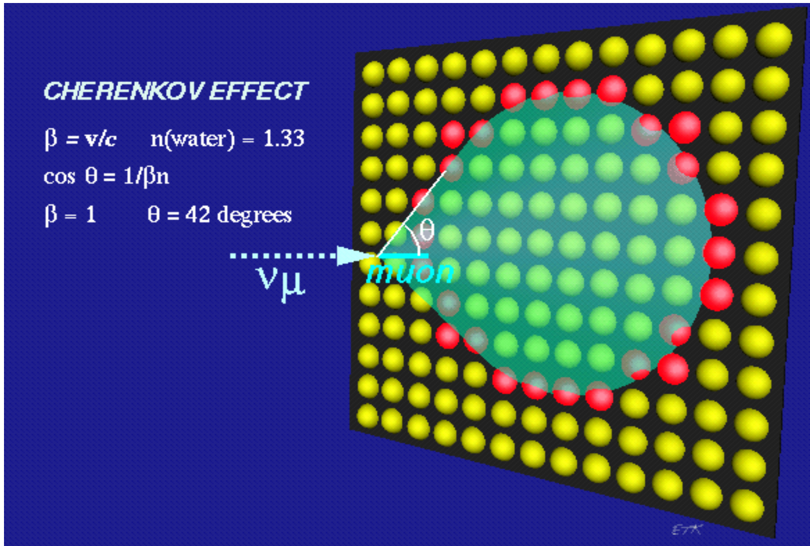
- Č light is produced by particles faster than light in air
- Limiting angle $\cos \theta_c \sim 1/n$
  - □ $\theta_c \sim 1^o$ at sea level, 1.3^o at 8 km asl
  - – Threshold @ sea level : 21 MeV for e, 44 GeV for μ

Maximum of a 1 TeV γ shower ~ 8 Km asl

200 photons/m^2 in the visible

Duration ~ 2 ns

Angular spread ~ 0.5^o



Cherenkov detectors
Principles of operation

- Cherenkov light is detected by means of mirrors which concentrate the photons into fast optical detectors
- In the beginning, heliostats operated during night
  - Problem: night sky background

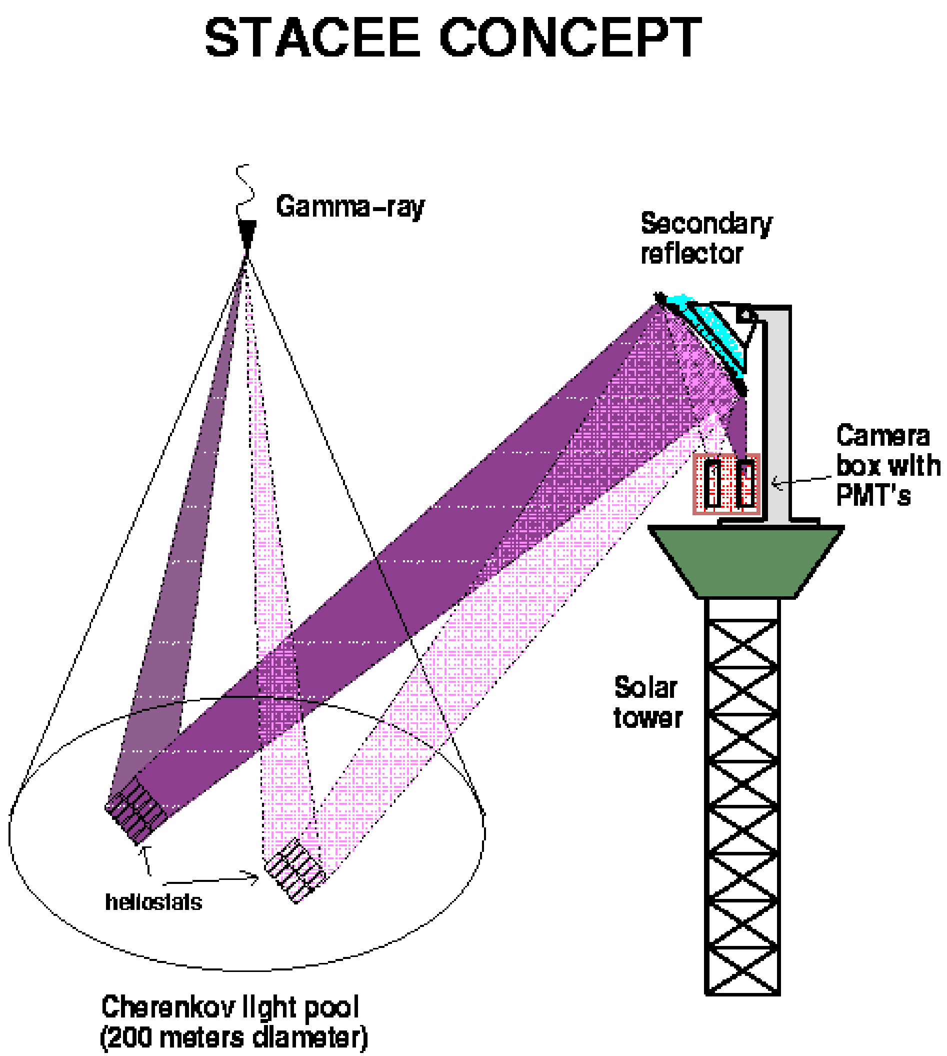
    On a moonless night

    ~ 0.1 photons/(m^2 ns deg)

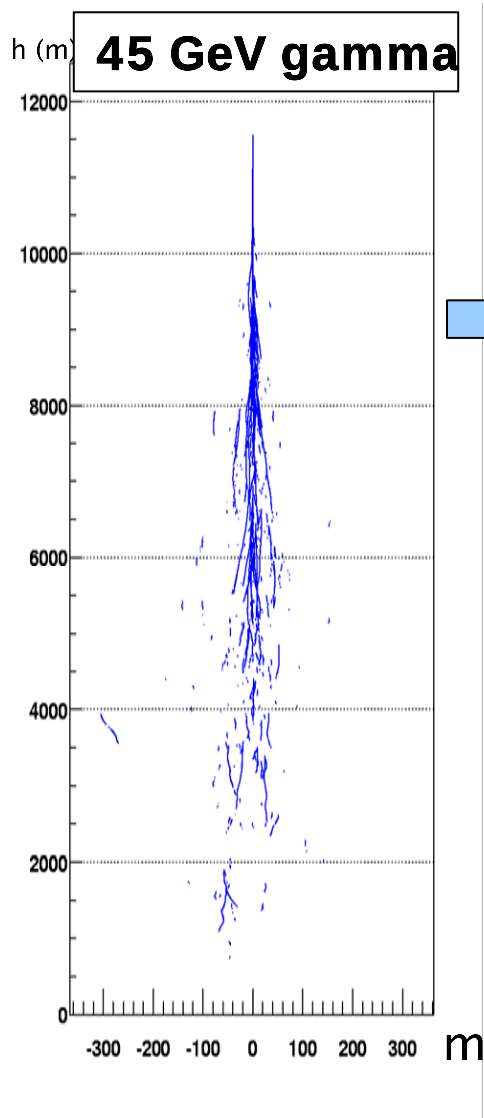
    Signal $\propto$ A

    fluctuations ~ $(A\tau\Omega)^{1/2}$

    => $S/B^{1/2} \propto (A/\tau\Omega)^{1/2}$

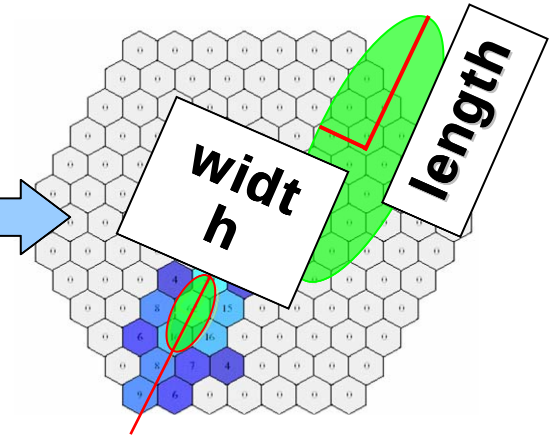


Gamma / hadron separation



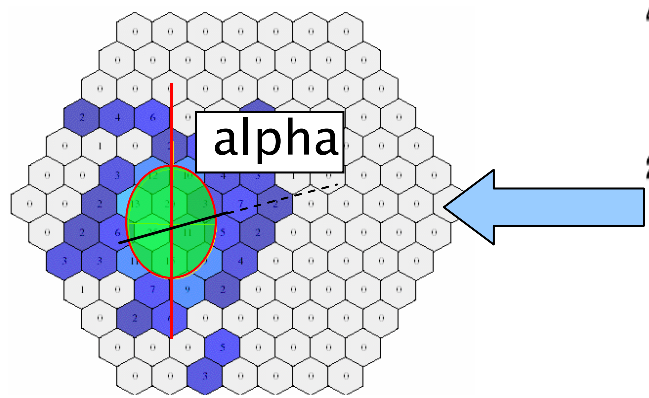
Gamma shower

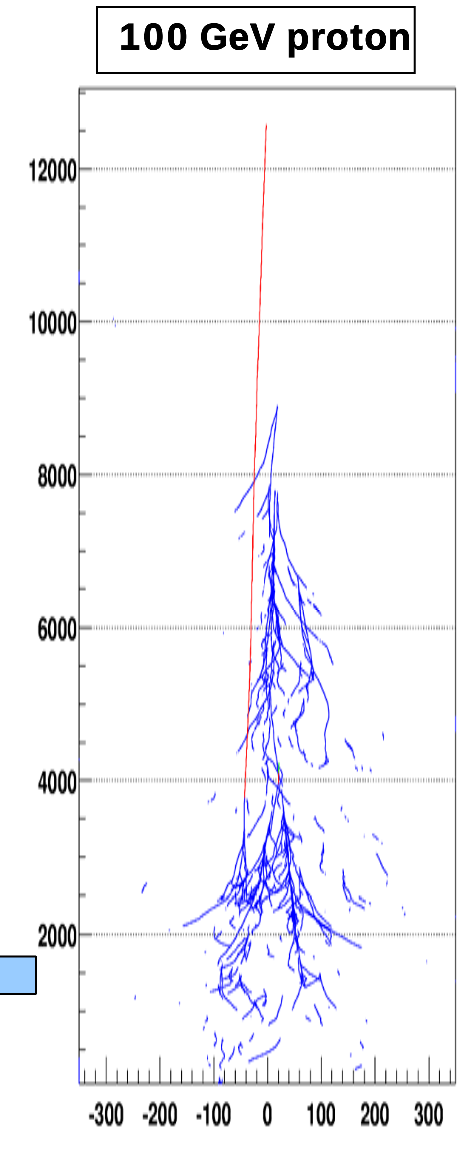
(narrow, points to source)



Proton shower

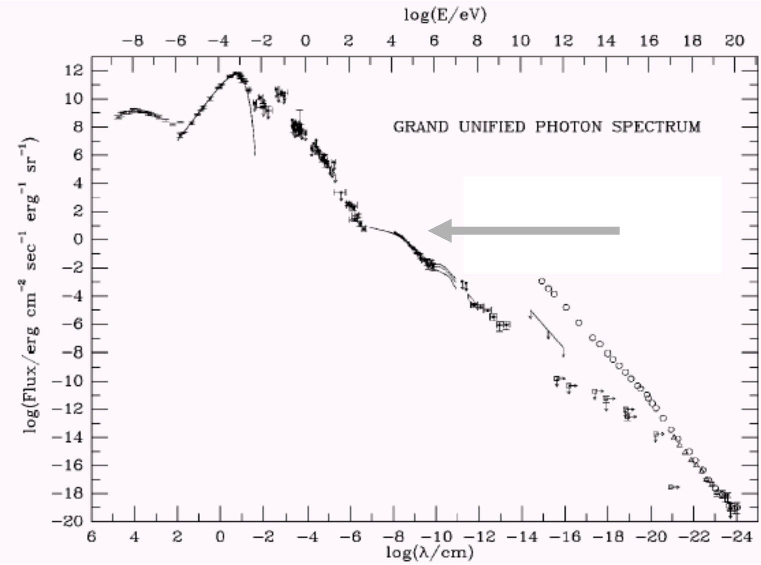
(wide, points anywhere)



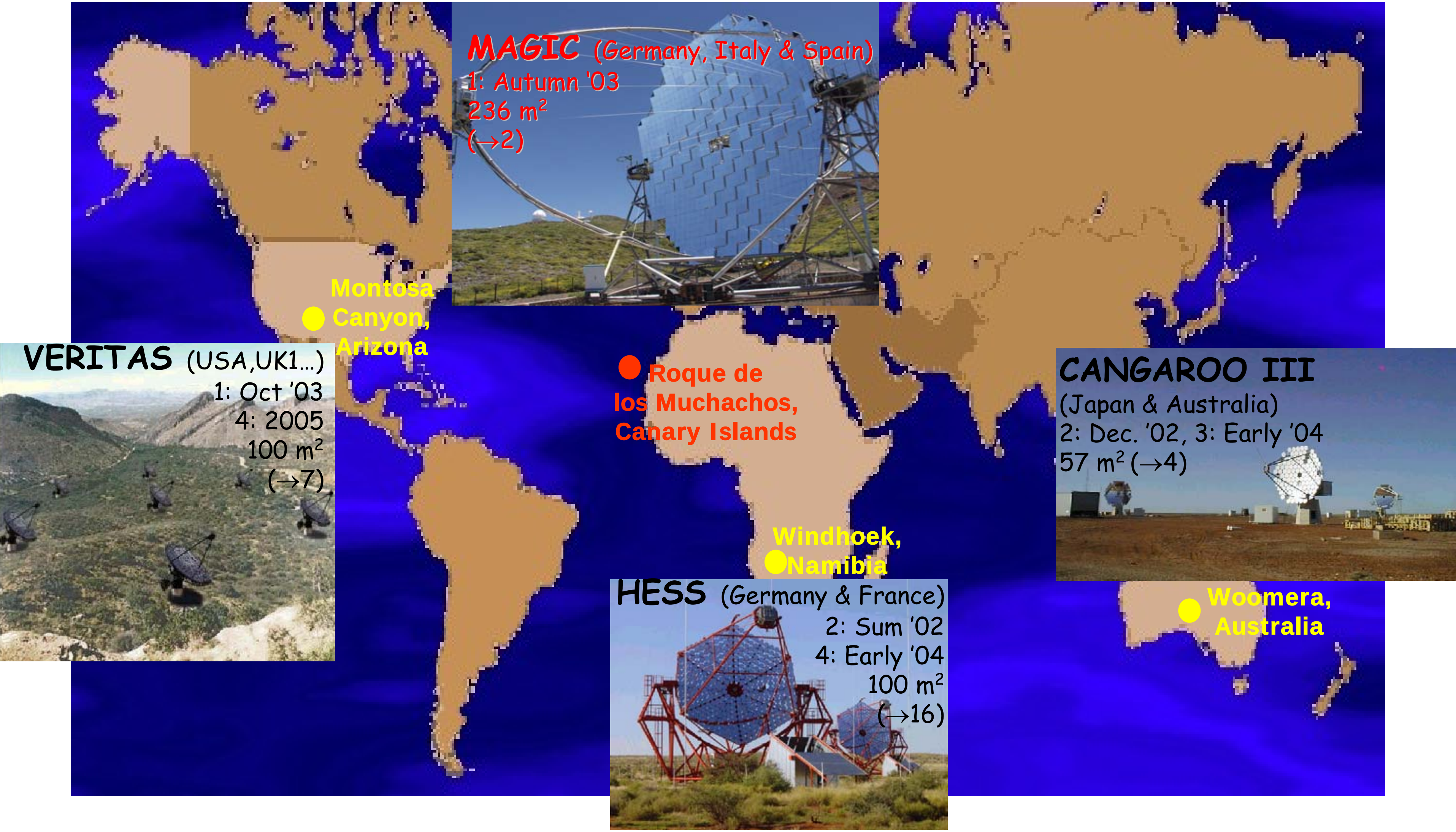


Ground-based detectors Improvements in atmospheric Č

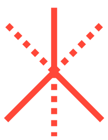
- Improving flux sensitivity
  - Detect weaker sources, study larger sky regions $S/B^{1/2} \propto (A/\tau\Omega)^{1/2}$
    - Smaller integration time
    - Improve photon collection, improve quantum efficiency of PMs
    - Use several telescopes
- Lowering the energy threshold
  - Close the gap ~ 100 GeV between satellite-based & ground-based instruments



The “Big Four”

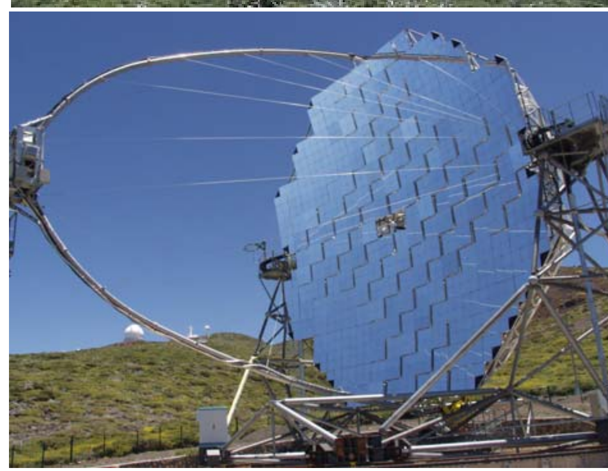

MAGIC (Germany, Italy & Spain)
1: Autumn '03
236 m²
(→2)
Montosa Canyon, Arizona
VERITAS (USA,UK1…)
1: Oct '03
4: 2005
100 m²
(→7)
Roque de los Muchachos, Canary Islands
CANGAROO III
(Japan & Australia)
2: Dec. '02, 3: Early '04
57 m² (→4)
Windhoek, Namibia
HESS (Germany & France)
2: Sum '02
4: Early '04
100 m²
(→16)
Woomera, Australia

Detector Parameters

In 2004:	#	~mirror area m^2	Camera pixels	FOV deg	Altit. m asl	arrangement
CANGAROO	4x	57	427	4	160	 ~100m
H.E.S.S.	4x	107	960	5	1800	 ~120m
MAGIC (2006)	1x 2x	240	577	3.5	2200	~80m
VERITAS (2006) (2007)	1x 4x 7x	110	499	3.5	1800	 ~80m

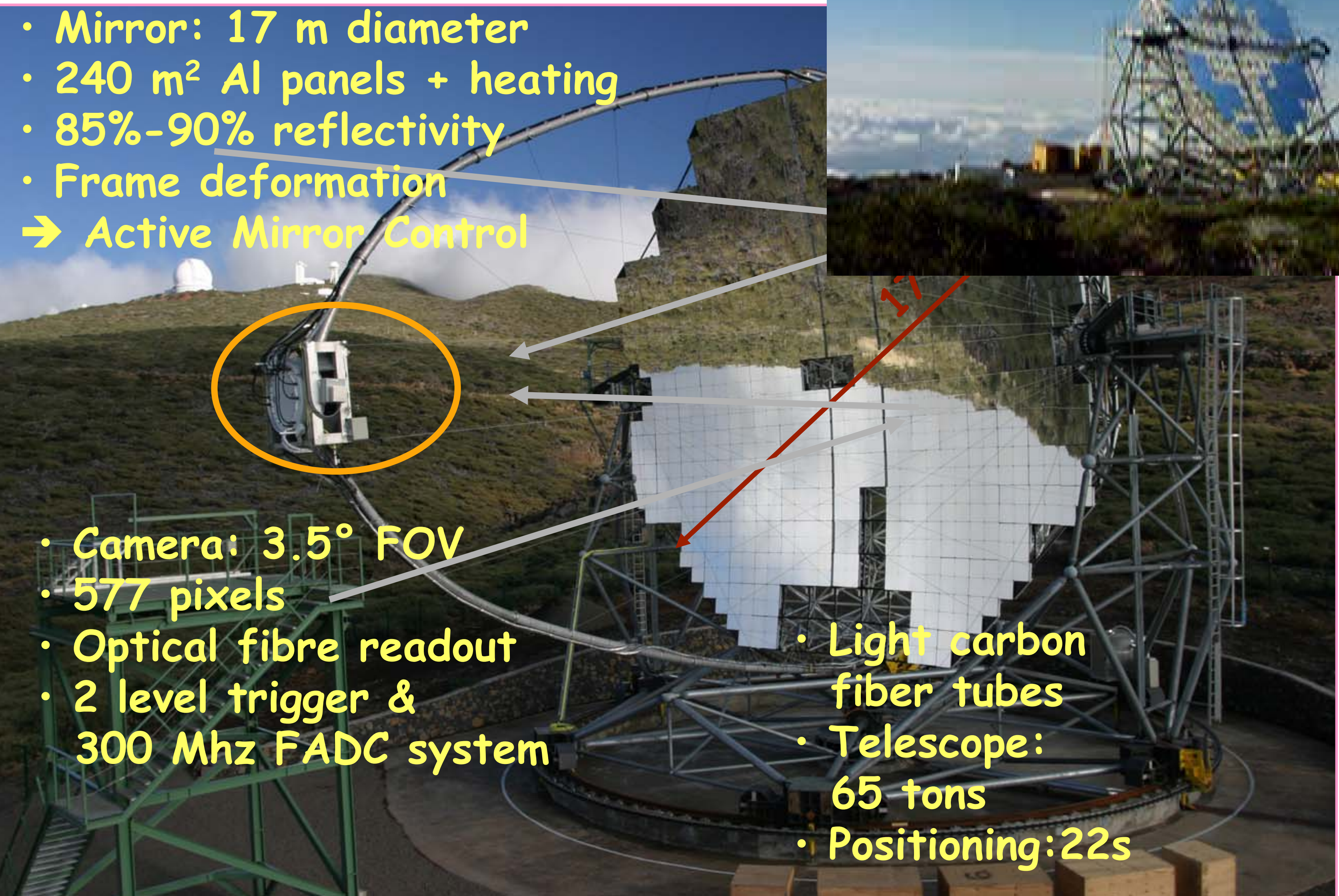
The MAGIC site

Telescopio Nazionale Galileo



MAGIC

MAGIC

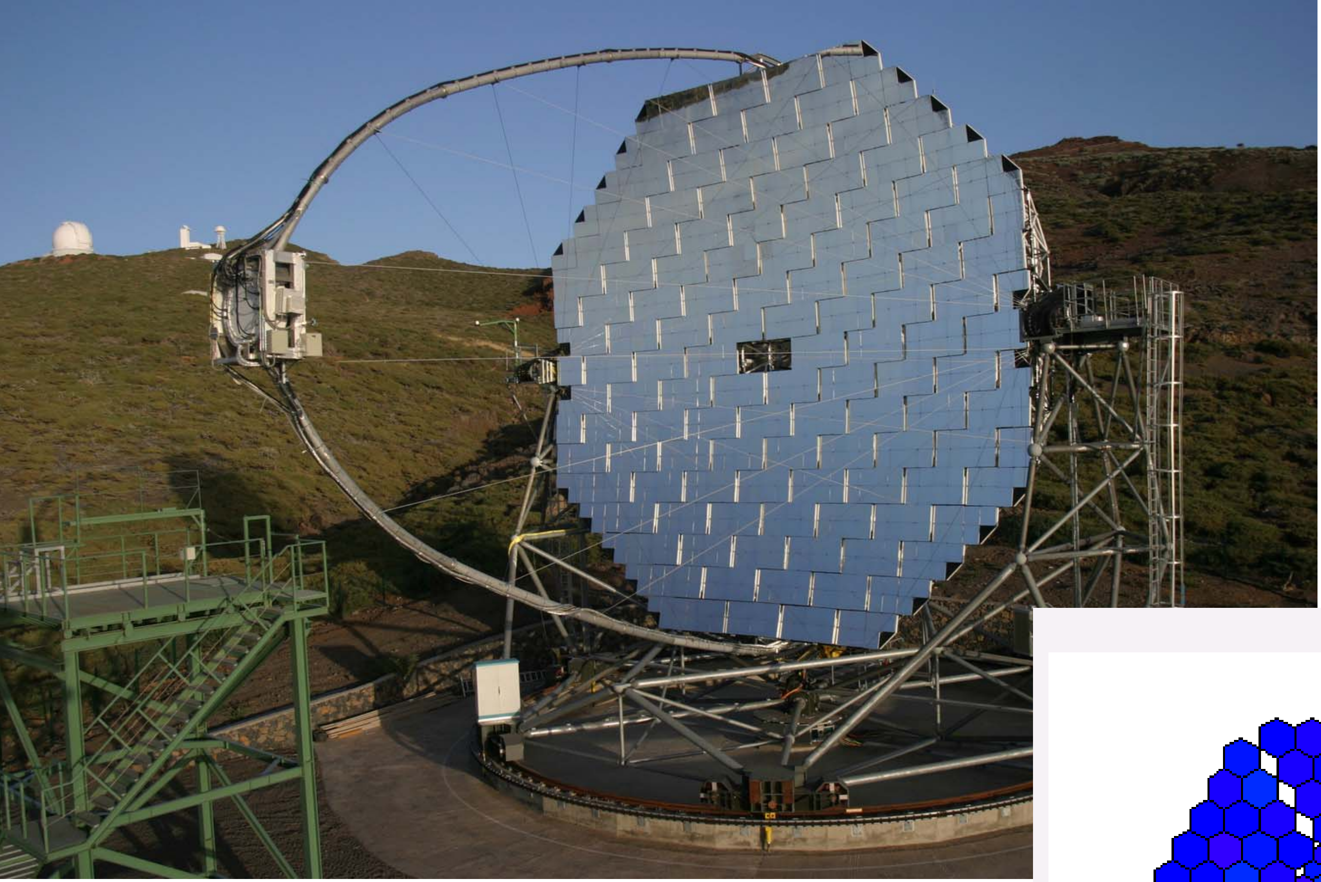


- Mirror: 17 m diameter
- 240 m² Al panels + heating
- 85%-90% reflectivity
- Frame deformation

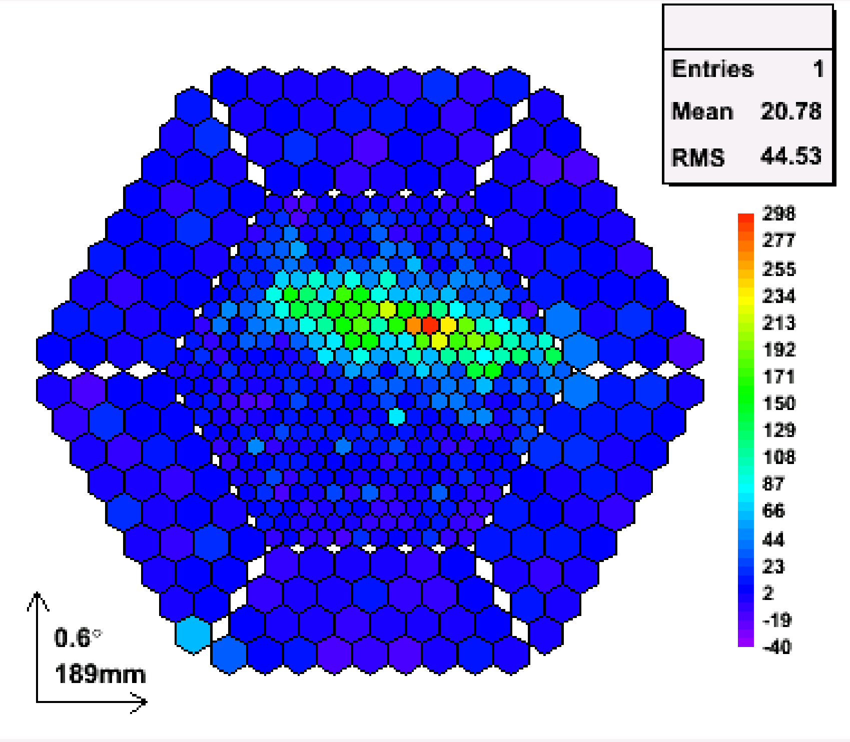
➔ Active Mirror Control

- Camera: 3.5° FOV
- 577 pixels
- Optical fibre readout
- 2 level trigger & 300 Mhz FADC system

- Light carbon fiber tubes
- Telescope: 65 tons
- Positioning:22s



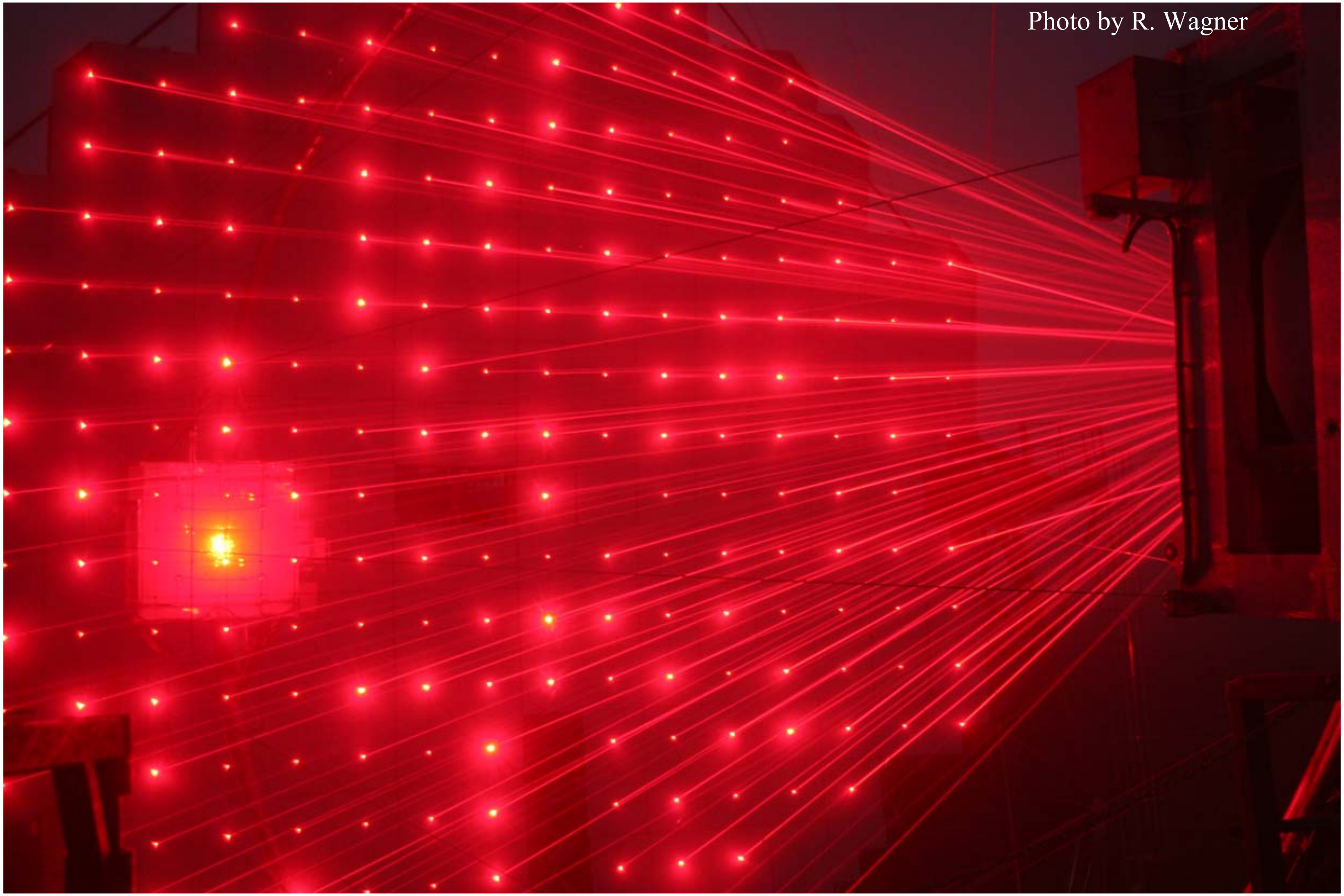
After upgrade of the optics in July 2004 the telescope is in its final shape



~300Hz shower rates

E_{th} ~40GeV

the Active Mirror Control laser beams



IACT Scientific Highlights (Aug 05)

Galactic observations:

I. Discovery of many new Galactic sources by HESS:

- ***HESS GP Survey* & targeted observations.**

II. Detailed studies of Galactic sources by HESS:

- ***Precision measurements (spectra, morphology, etc.).***
- ***Theoretical models and understanding.***

III. Discovery of new classes of VHE gamma-ray emitters by HESS:

- ***First variable galactic source***

IV. Study of the Galactic Center by CANGAROO,HESS and MAGIC:

- ***Evidence for a TeV signal; search for DM annihilation***

Scientific Highlights (Aug 05)

Extragalactic observations:

V. Discovery of 4 new AGN by HESS and MAGIC:

- ***Measurements of AGN properties and multi-λ studies.***
- ***Constraints on cosmological EBL density from absorption spectrum.***

VI. Observation of AGN with orphan flares by MAGIC:

- ***Connexion to neutrino and UHECR astronomy?***

VII. High time-resolution study of AGN flares by MAGIC:

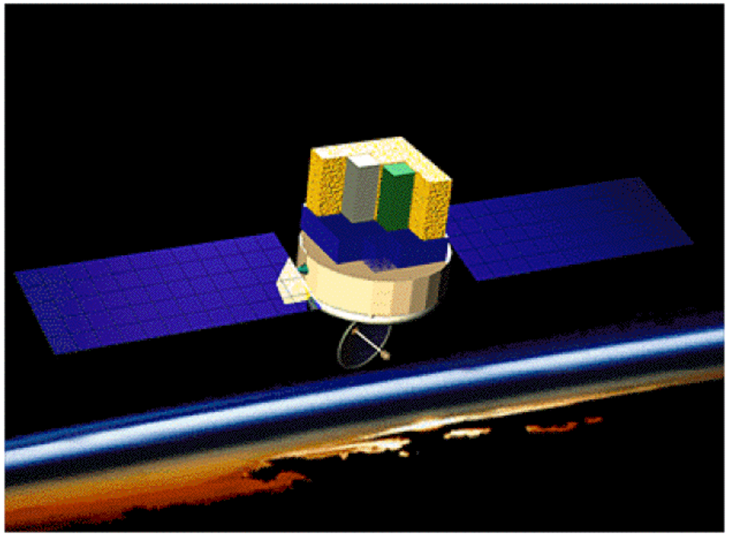
- ***New constraints on emission mechanisms and light speed dispersion relations.***

VIII. Prompt GRB follow-up by MAGIC:

- ***GRB follow-up in coincidence with observation in the X-ray domain.***

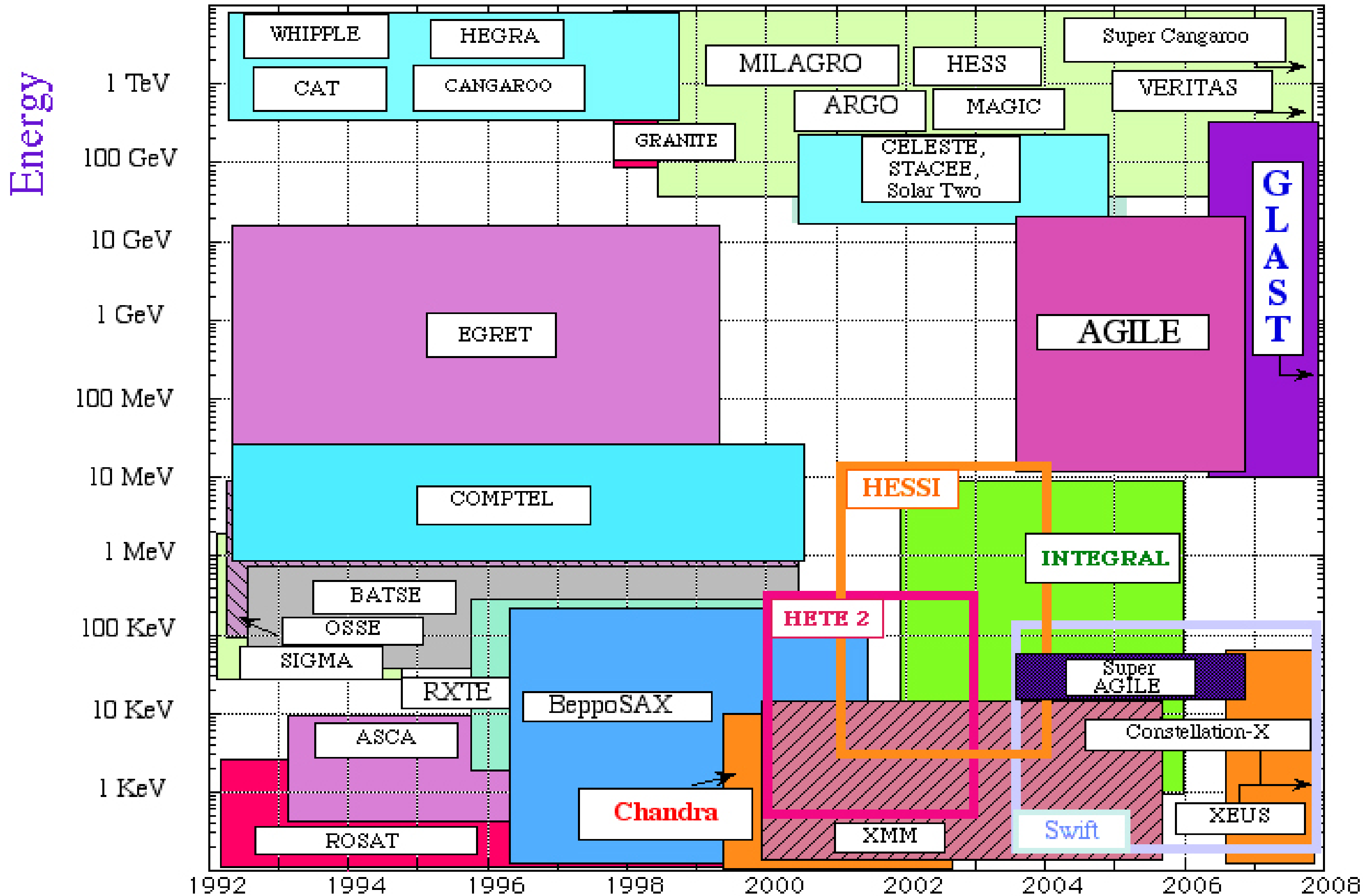
IACT vs Satellite

- Satellite :
  - primary detection
  - small effective area ~1m^2
    - lower sensitivity
  - large angular opening
    - search
  - large duty-cycle
  - large cost
  - lower energy
  - low bkg

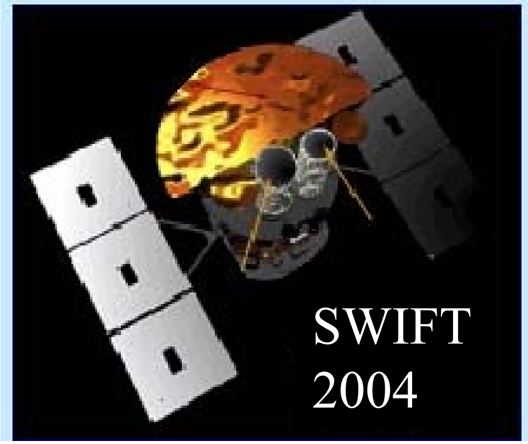


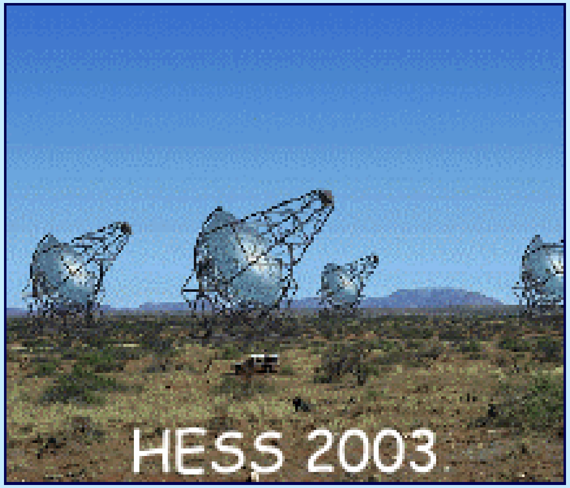
- IACT/ground based
  - secondary detection
  - huge effective area ~10^4 m^2
    - Higher sensitivity
  - small angular opening
    - Serendipity search
  - small duty-cycle
  - low cost
  - high energy
  - high bkg

An armada of detectors at different energy ranges

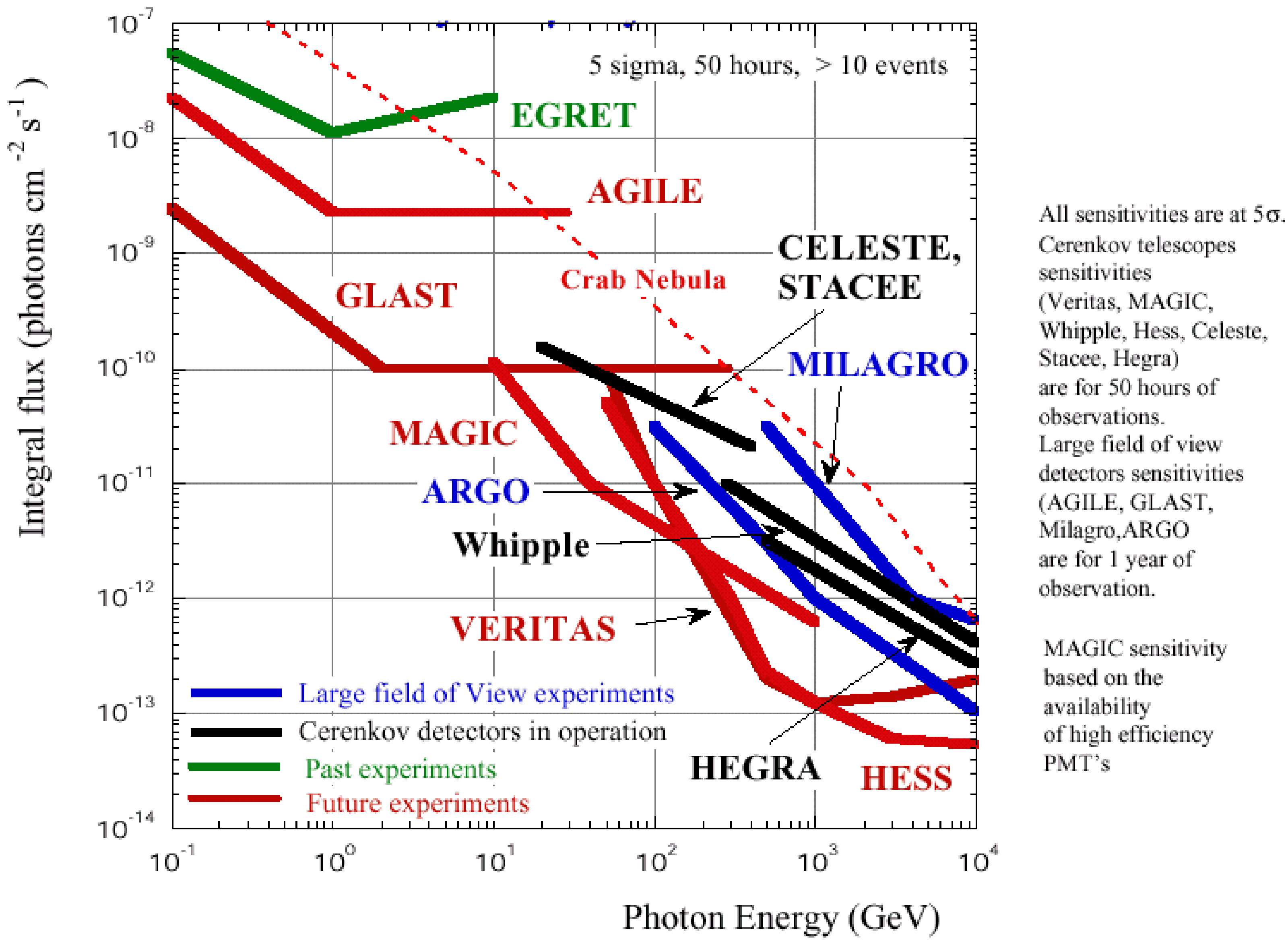


…some just starting now



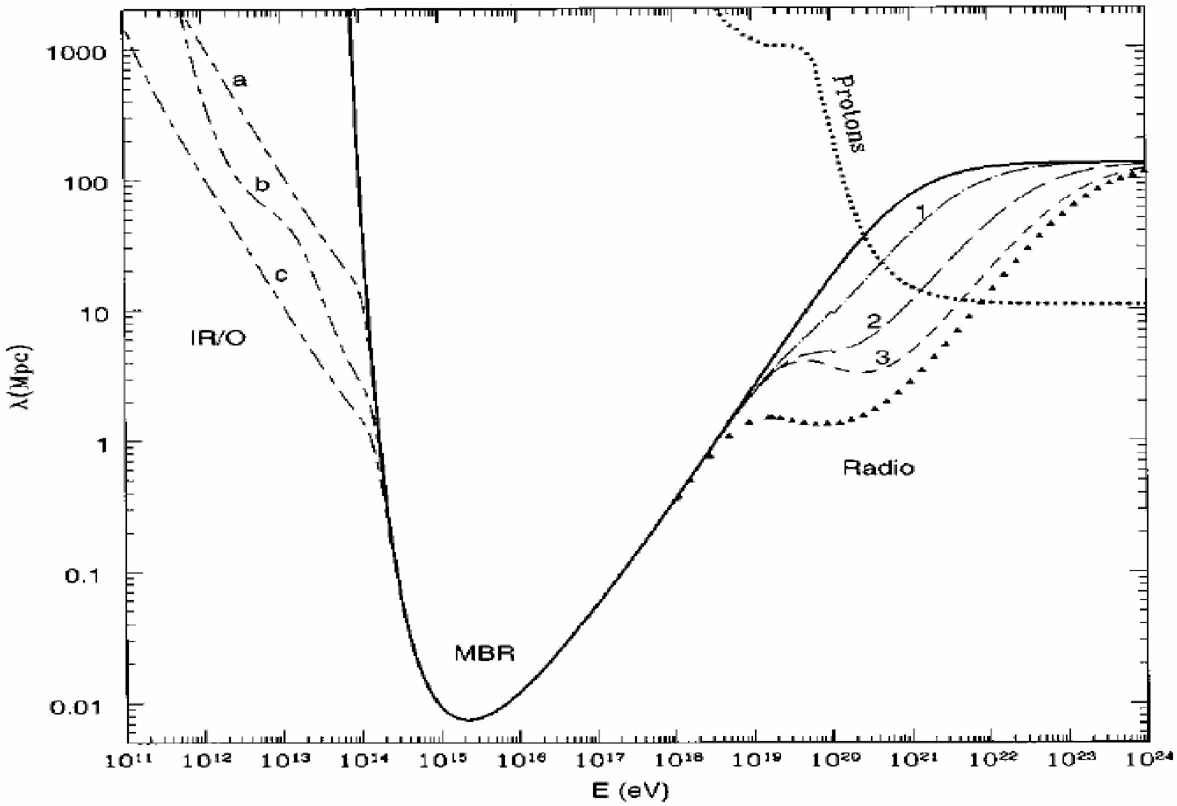


Sensitivity

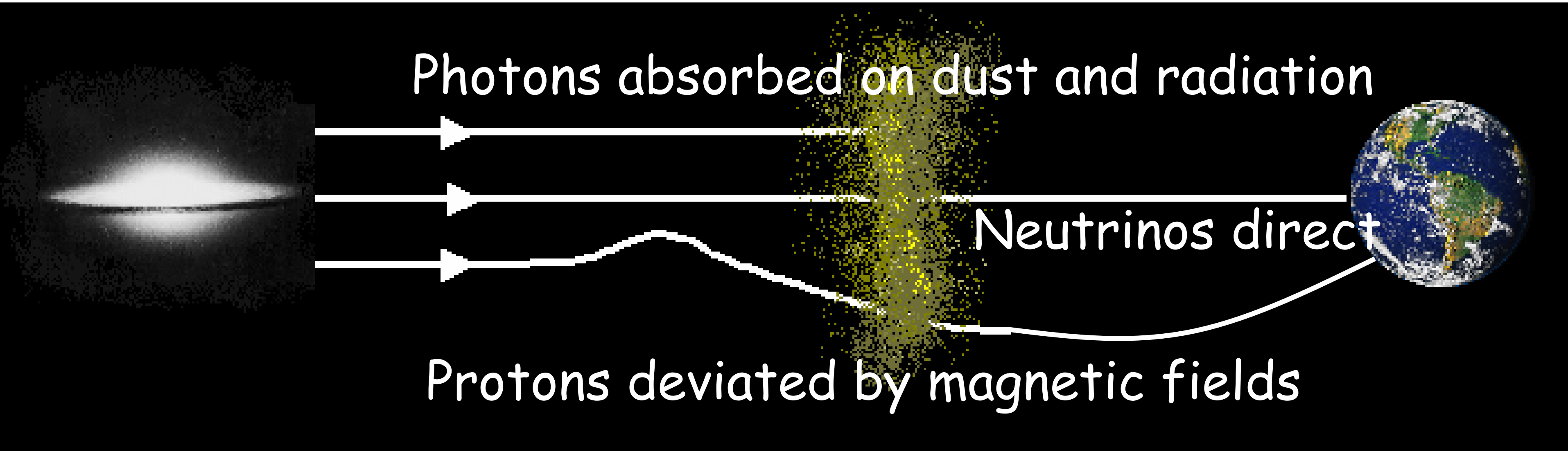


All sensitivities are at 5σ. Cerenkov telescopes sensitivities (Veritas, MAGIC, Whipple, Hess, Celeste, Stacee, Hegra) are for 50 hours of observations. Large field of view detectors sensitivities (AGILE, GLAST, Milagro,ARGO are for 1 year of observation.

MAGIC sensitivity based on the availability of high efficiency PMT's



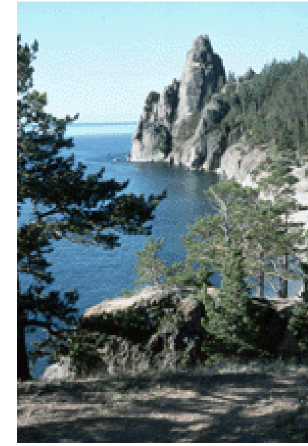
In the 100 TeV - 100 PeV region…

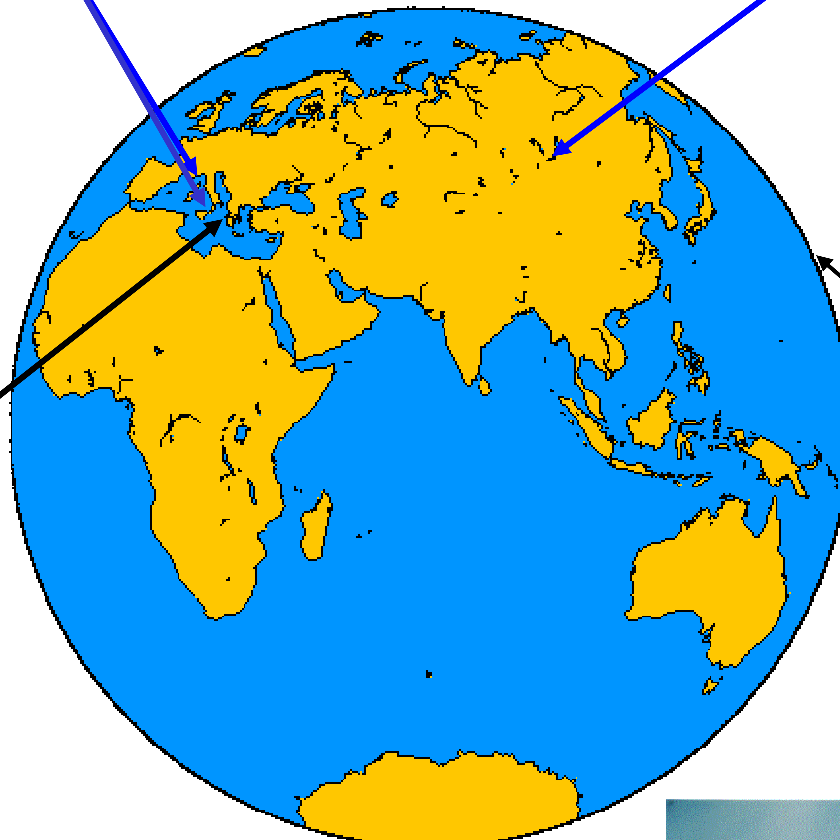


Neutrino Telescope Projects

ANTARES La-Seyne-sur-Mer, France
(NEMO Catania, Italy)

BAIKAL: Lake Baikal, Siberia





NESTOR : Pylos, Greece

DUMAND, Hawaii
(cancelled 1995)

AMANDA, South Pole, Antarctica

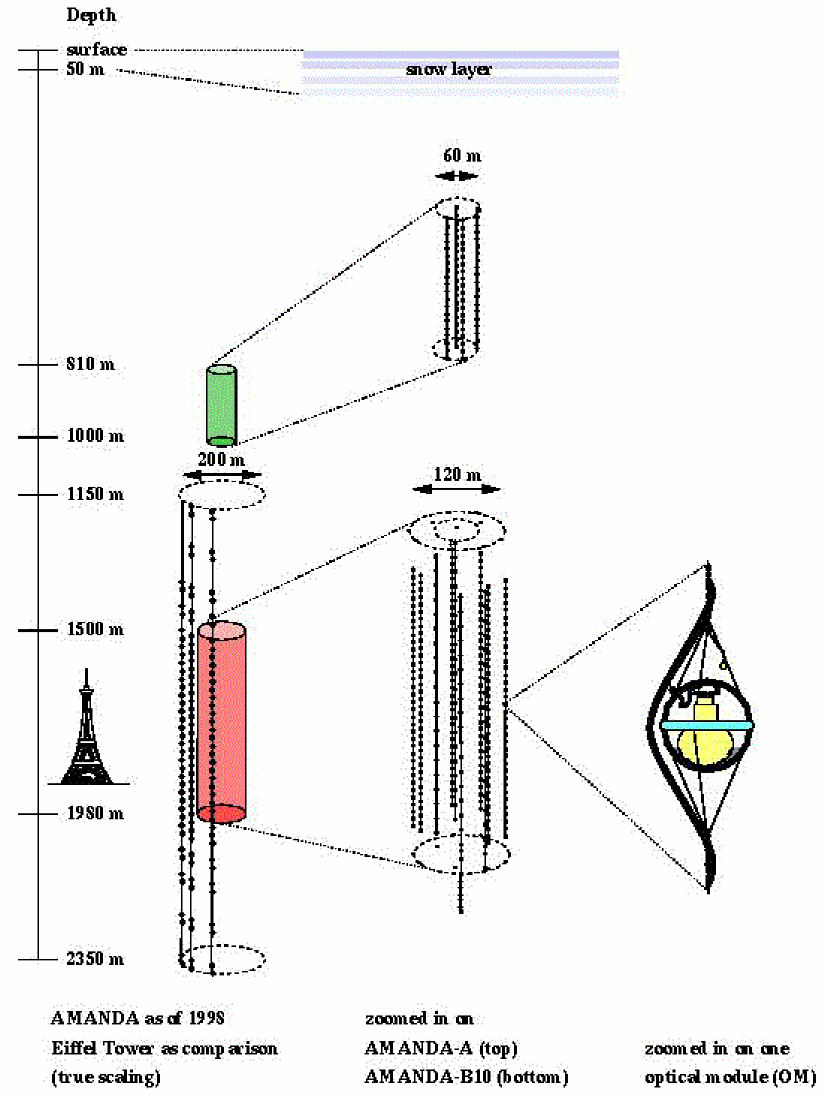
AMANDA-ICECUBE

South Pole: glacial ice

1993 First strings AMANDA A
1998 AMANDA B10 ~ 300 Optical Modules

2000 ~ 700 Optical Modules

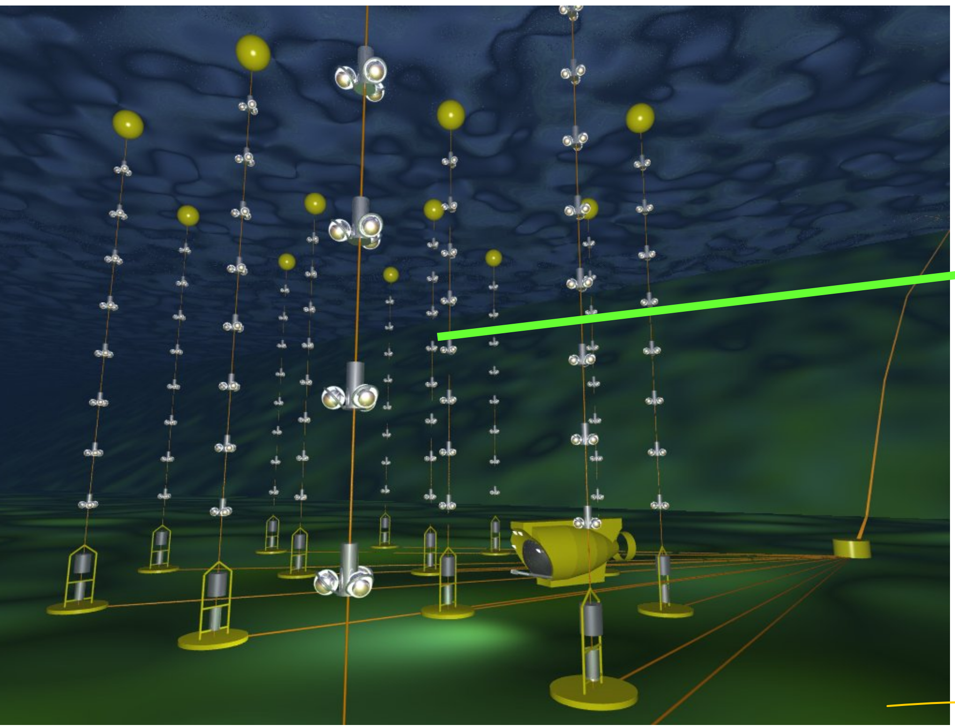
→ ICECUBE 8000 Optical Modules

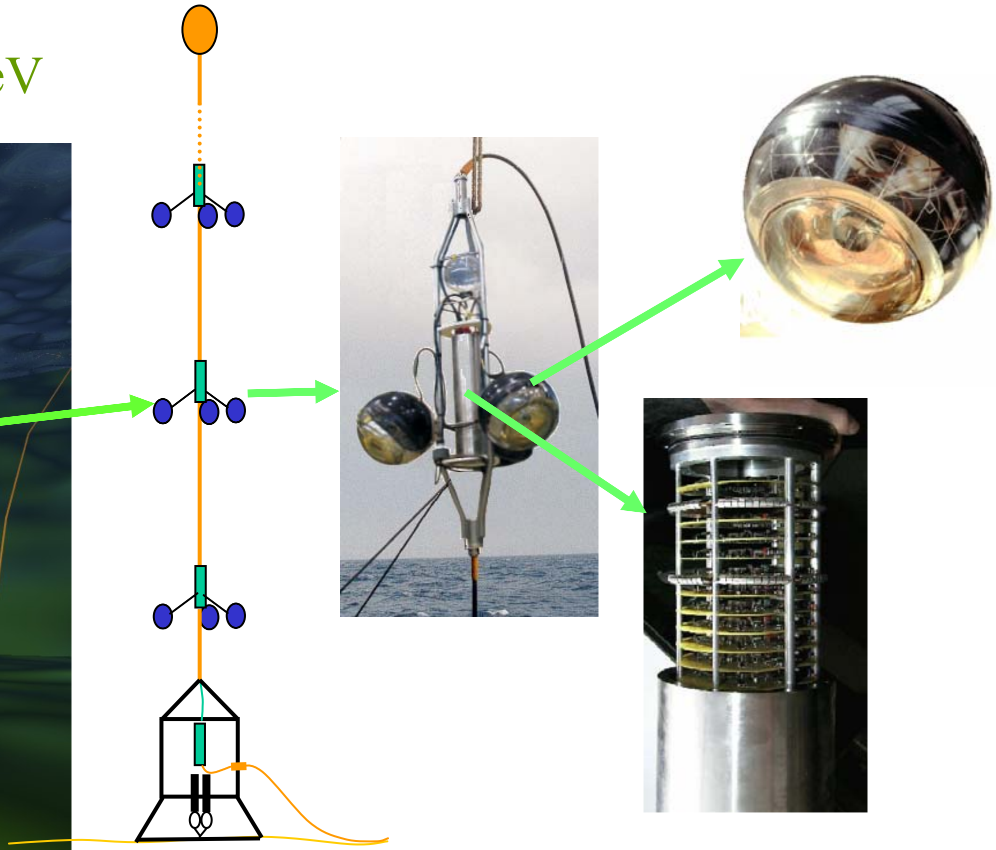


Future in ν telescopes: ANTARES

1996	Started
1996 - 2000	Site exploration and demonstrator line
2001 - 2004	Construction of 10 line detector, area ~0.1km^2 on Toulon site
future	1 km^3 in Mediterranean

Angular resolution <0.4° for E>10 TeV





To know more…

- Not to ingenerate confusion, just a book
  - It's swedish, and it connects well to Martin & Shaw:

    Bengström & Goobar, Cosmology and Particle Astrophysics, Wiley

- But careful: the field is in fast evolution…

  So if you are interested, talk to a teach' (to me if you pass by) and have a chat about a school