Experimental Astroparticle Physics (a short introduction)

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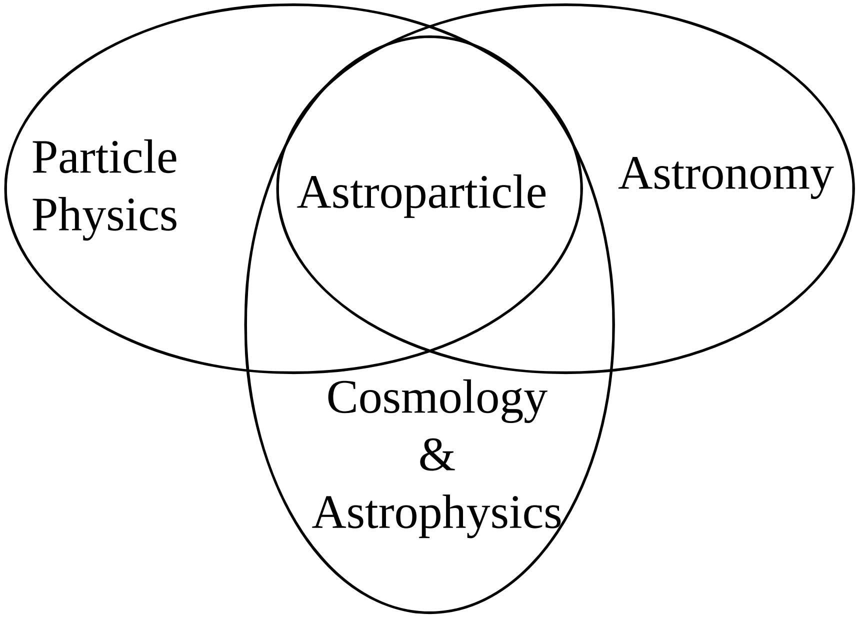
Lectures 1, 2 & 3

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

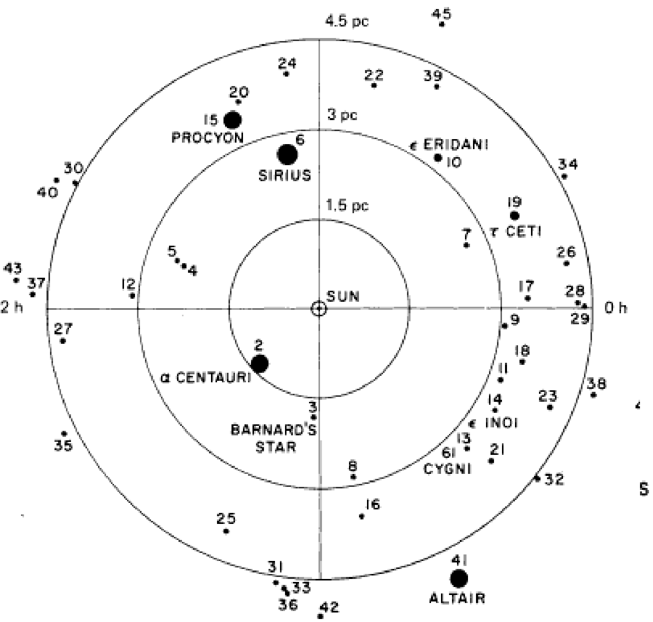
In this lecture I'll concentrate on the 2^{nd} topic

I

A quick look to our Universe

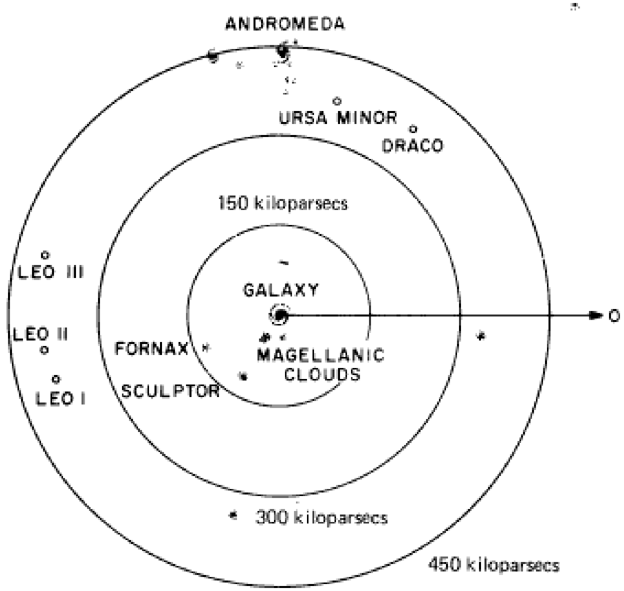
Astronomy Scales

Nearest Stars



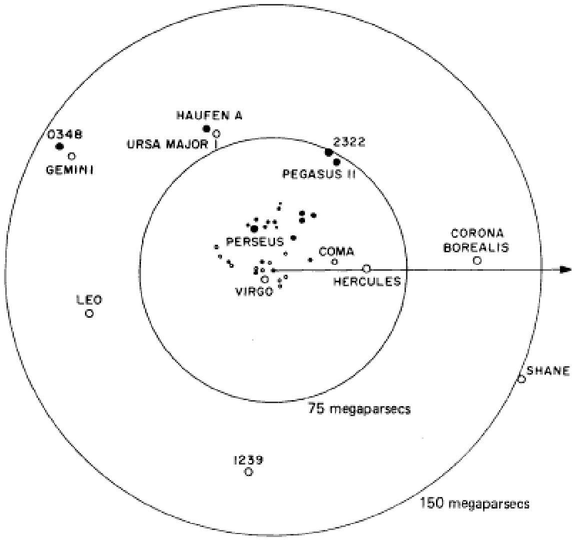
4.5 pc

Nearest Galaxies



450 kpc

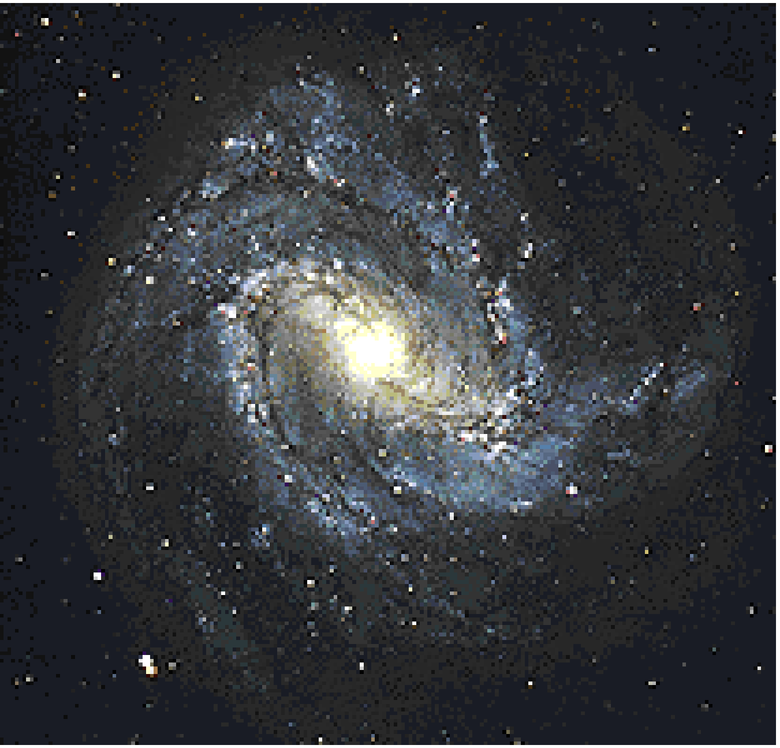
Nearest Galaxy Clusters

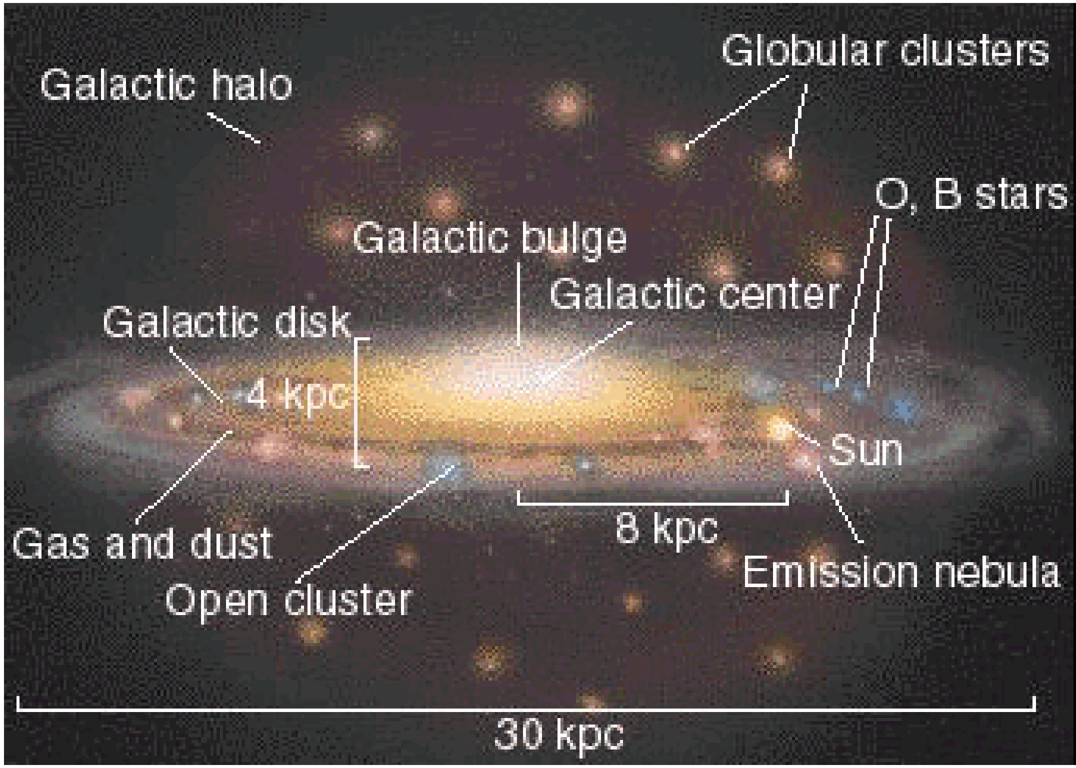


150 Mpc

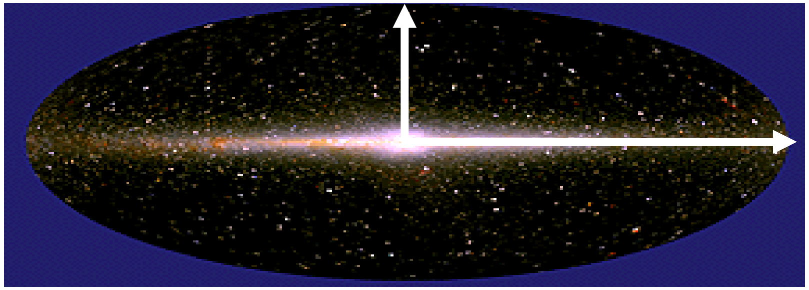
1 pc ~ 3.3 ly

Our Galaxy: The Milky Way



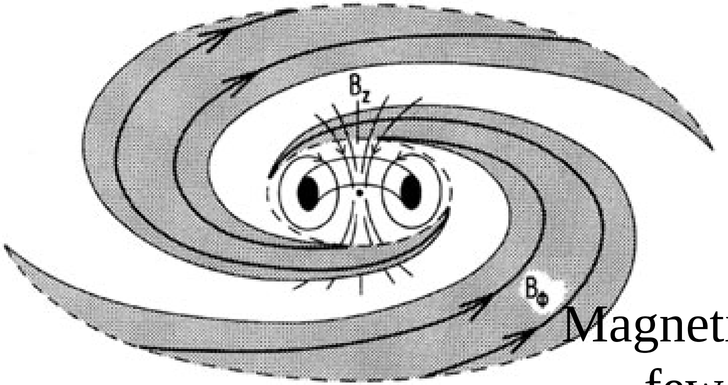


+90°



+180°

–90°



Magnetic field
~ few μG

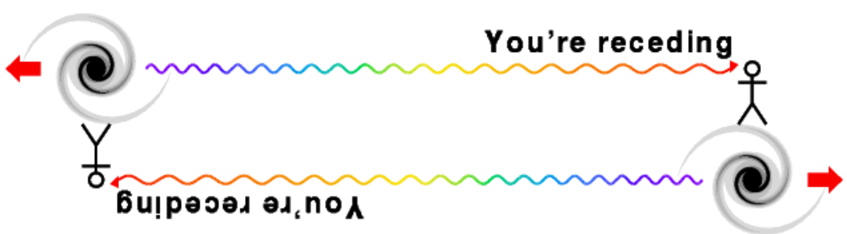
What do we know about our Universe ?

- 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

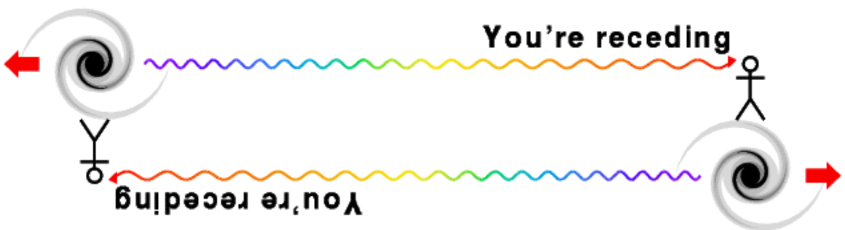
Hubble's constant (km/s/Mpc)

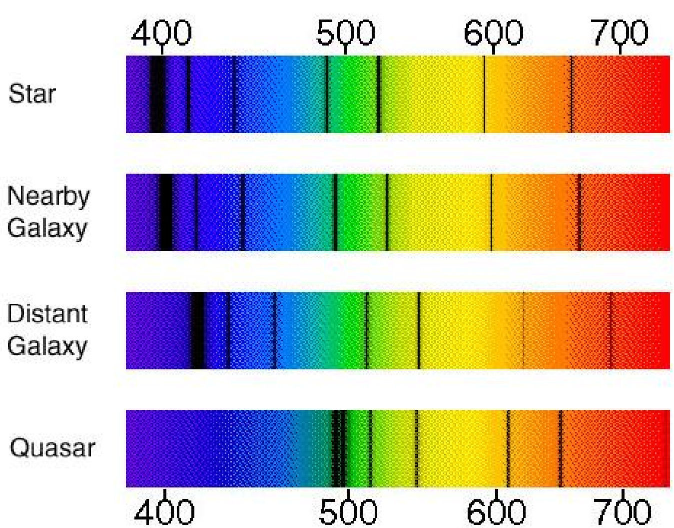
$$V = H_0 r$$

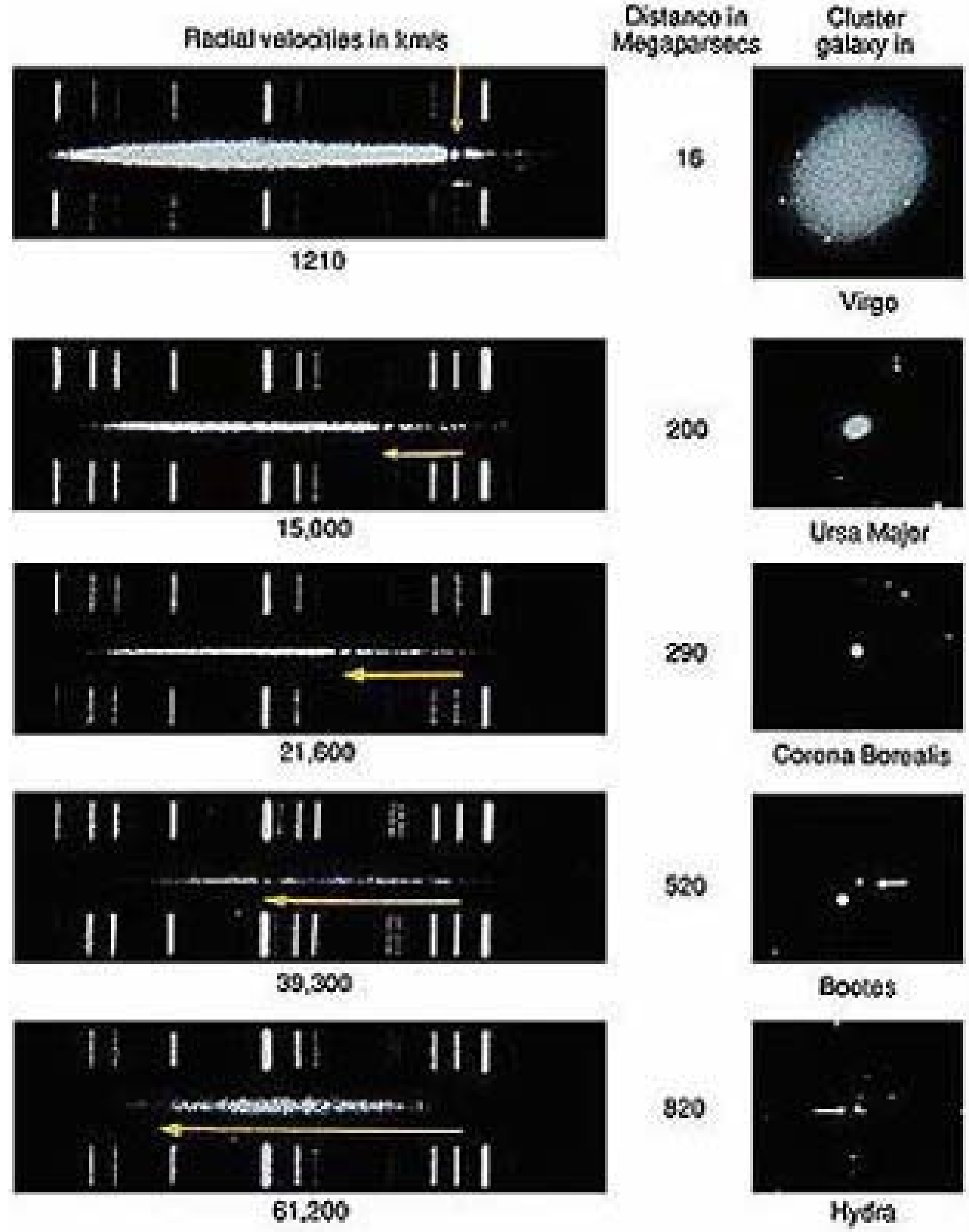
recession speed (km/s) — distance (Mpc)



Redshift

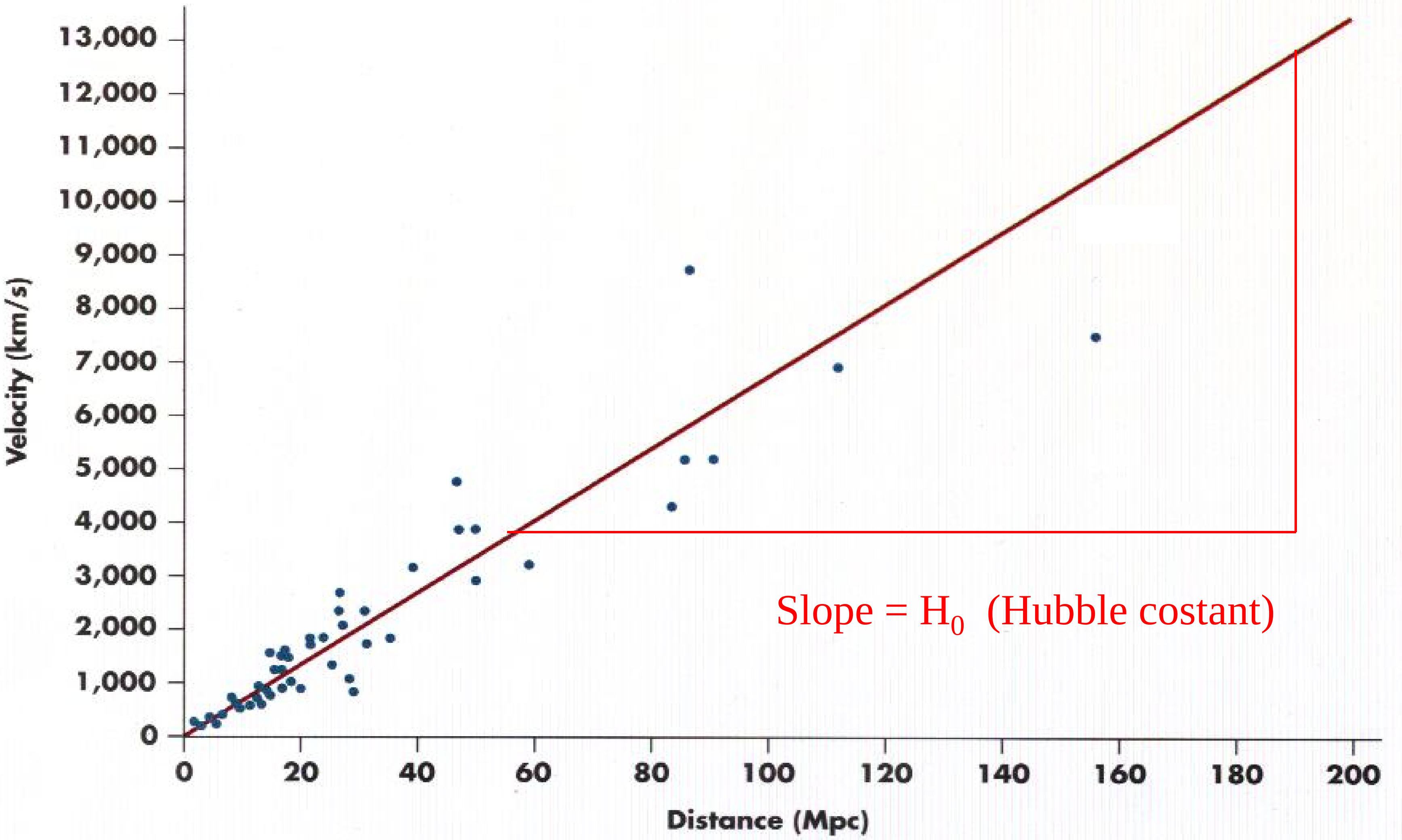

You're receding
You're receding


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
Virgo
1210
200
Ursa Major
15,000
290
Corona Borealis
21,600
520
Bootes
39,300
820
Hydra
61,200

Hubble's law

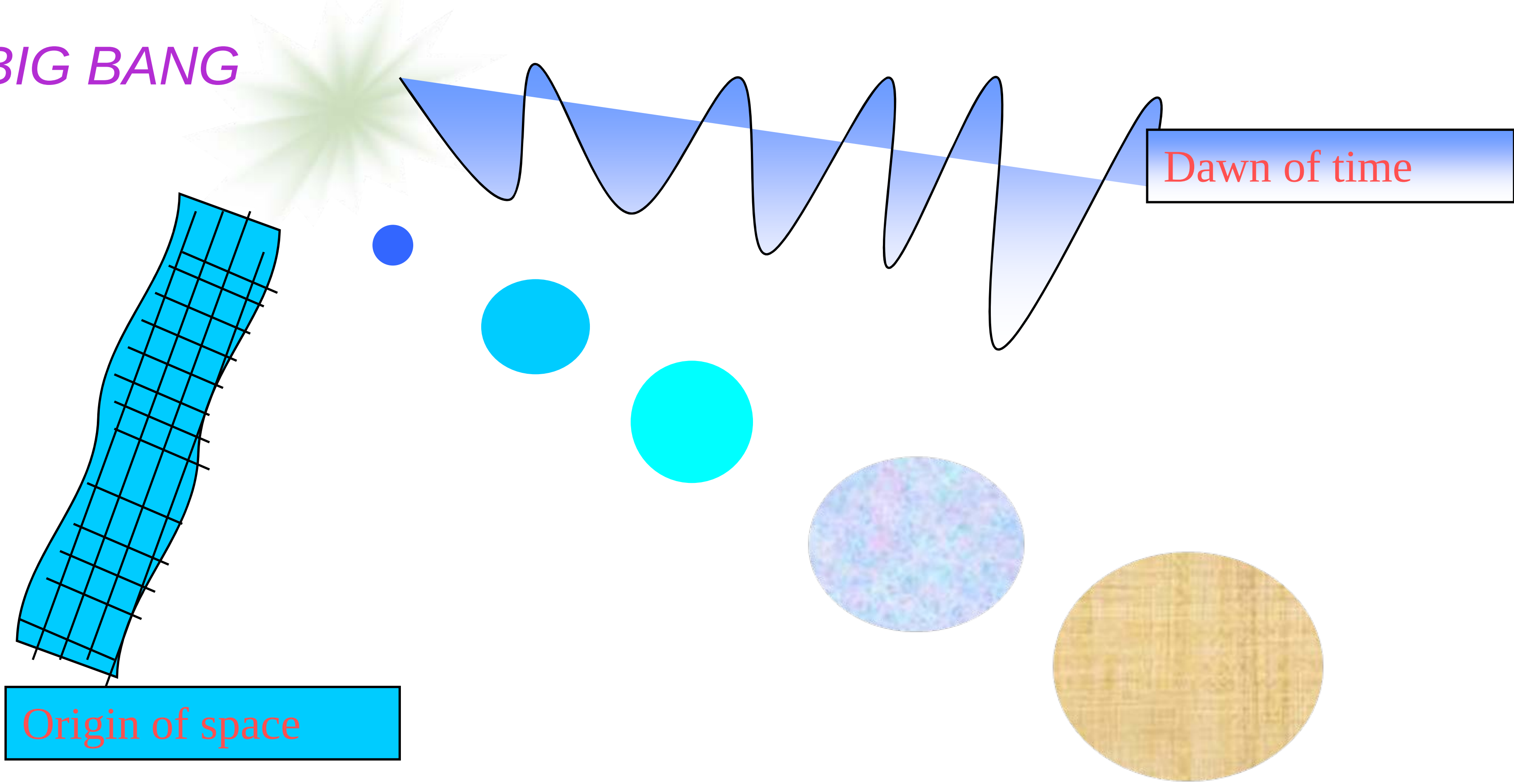
Today: H_0 = 72 ± 3 (km/s) / Mpc



Once upon a time...
our Universe was smaller

Primordial singularity !!!

=> BIG BANG



How far in time ?

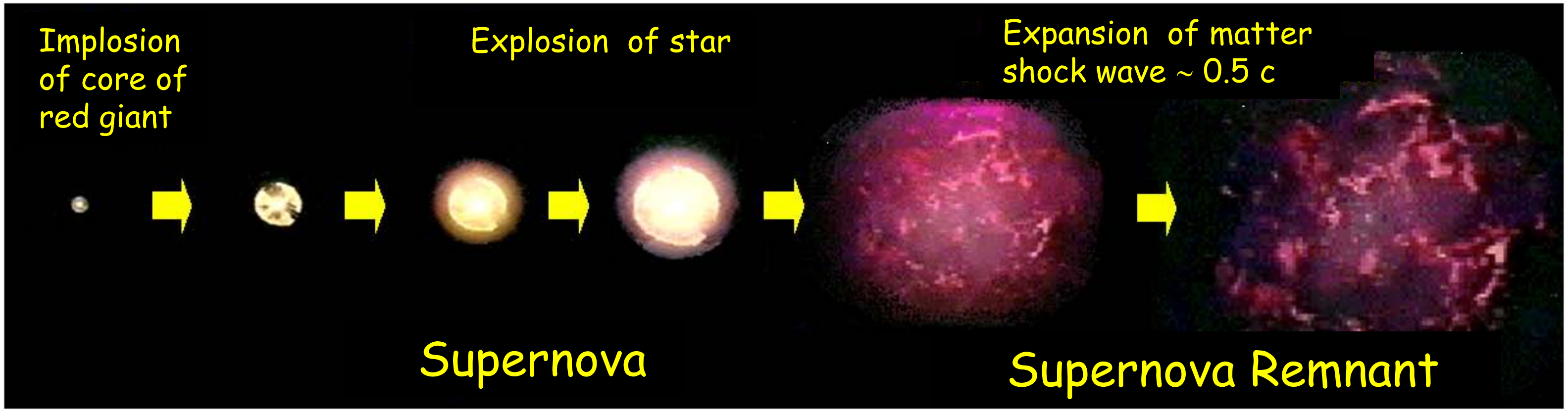
- Extrapolating backwards the present expansion speed towards the big bang

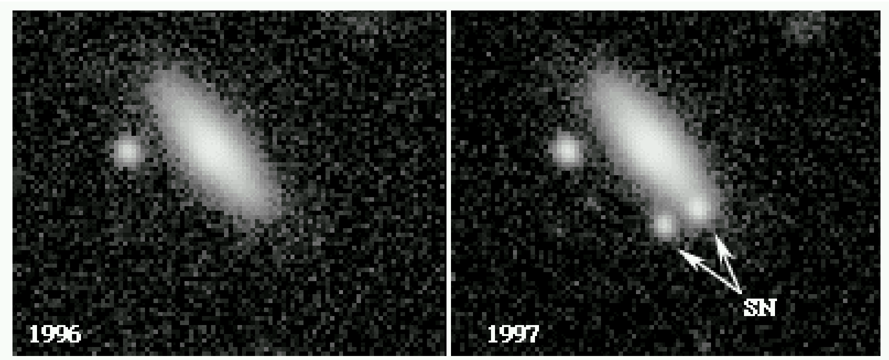
$$T \sim 1/H_0 \sim 14 \text{ billion years}$$

(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 2007: supernovae





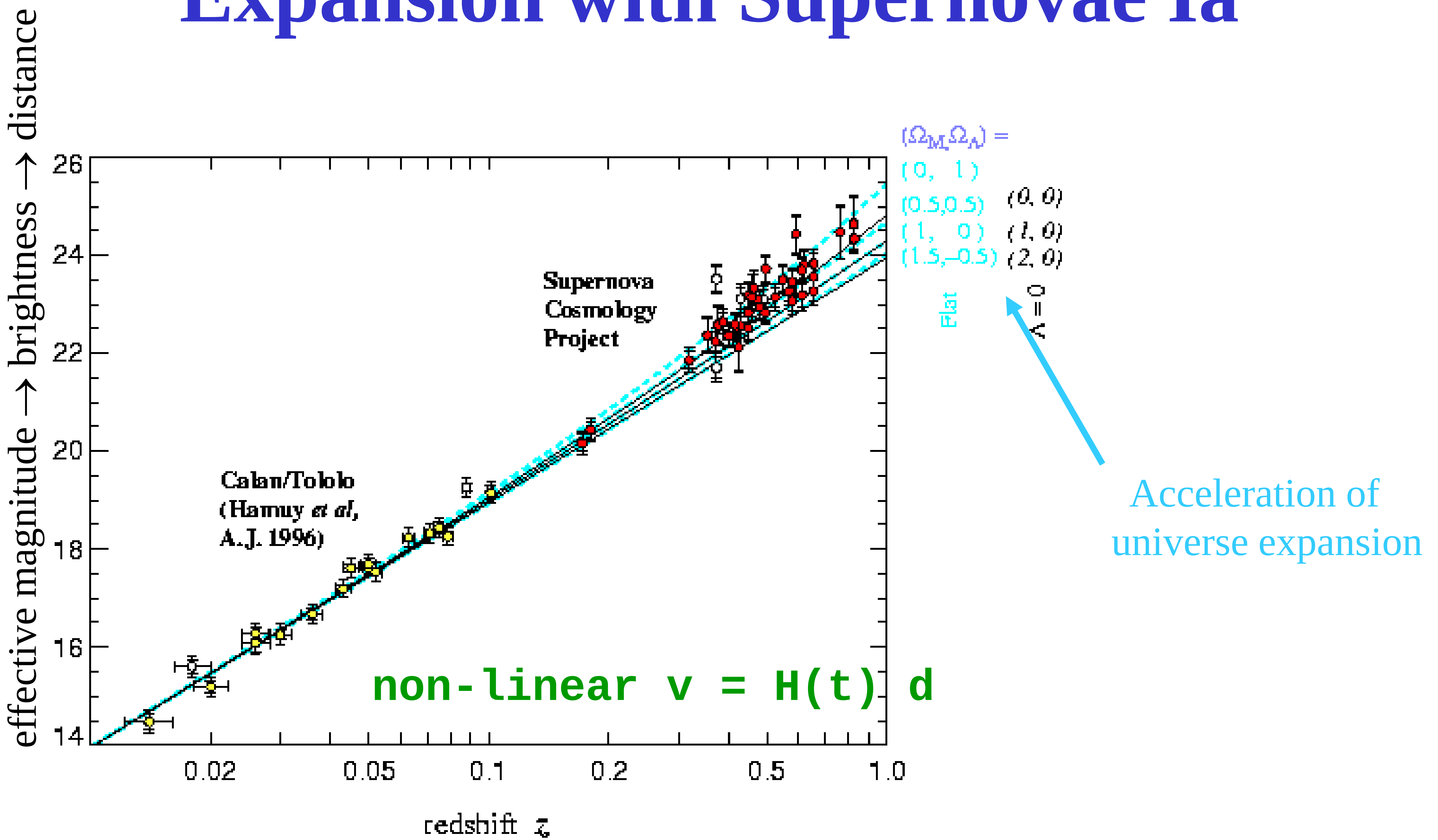
SNIa occurs at Chandra mass, 1.4 M_{sun} ⇒ 'Standard

measure brightness →

measure host galaxy redshift → get

test Hubble's Law: v = H d

Expansion with Supernovae Ia



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

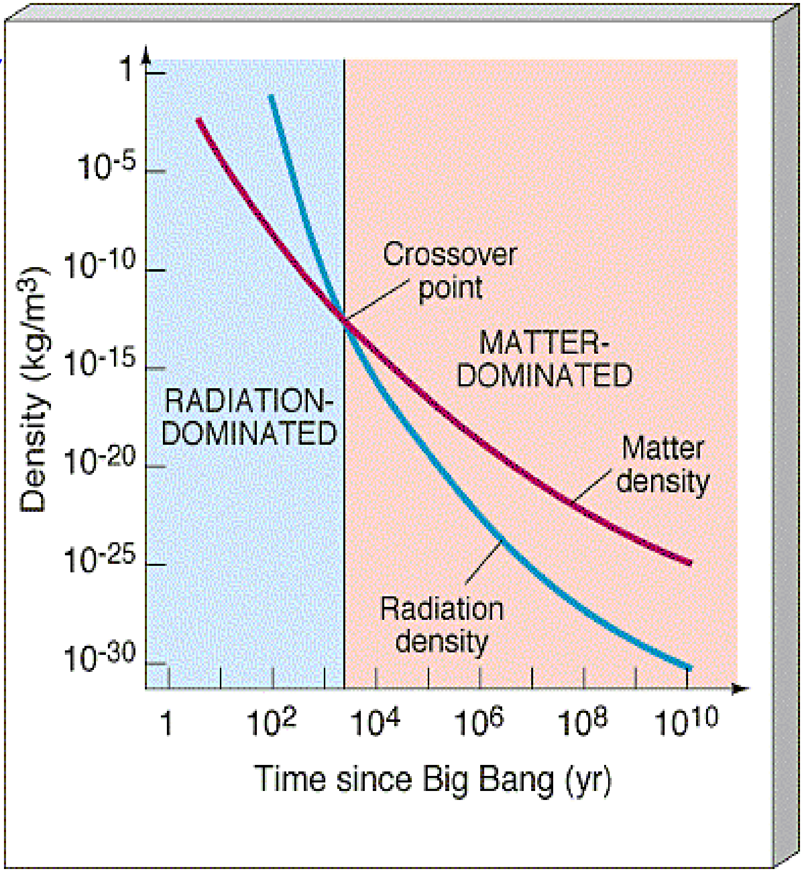
$\gamma \leftrightarrow$ electron-positron

(…)

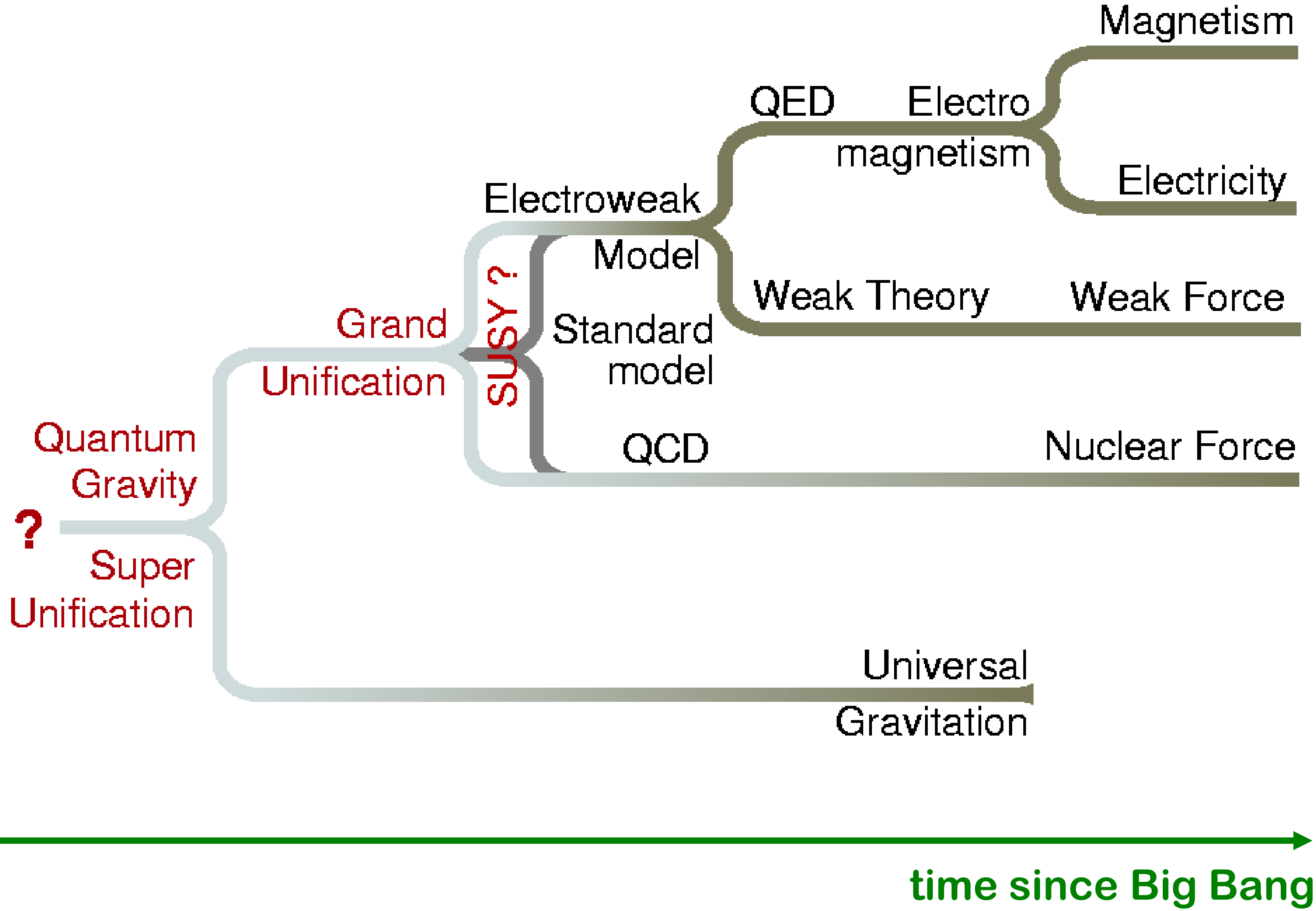
then matter became stable

Time

Two epochs

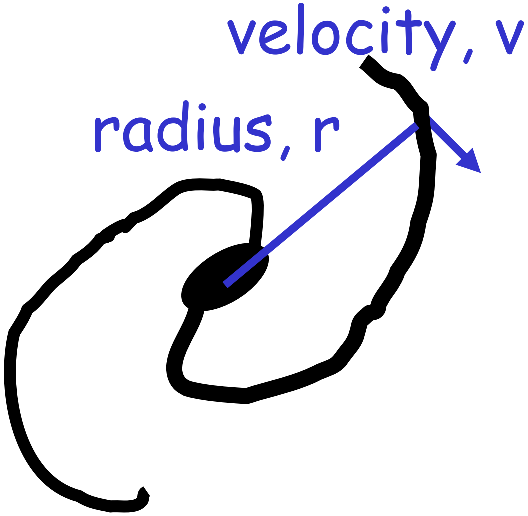


Particle Physics after Big Bang



THE QUEST FOR HIGHER ENERGIES IS ALSO A TIME TRAVEL

The Universe today: what we see is not everything

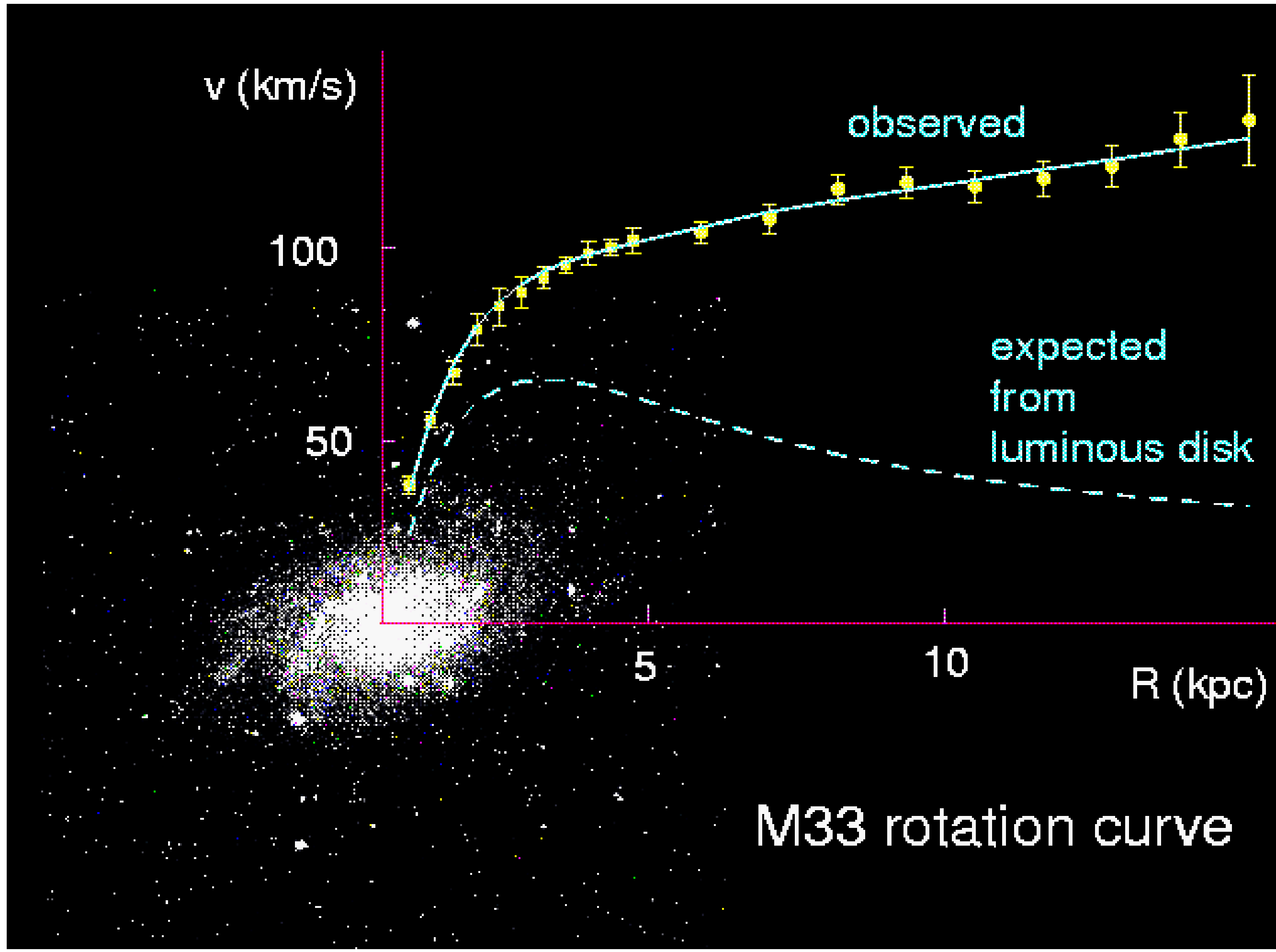


Gravity:

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

enclosed mass:

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

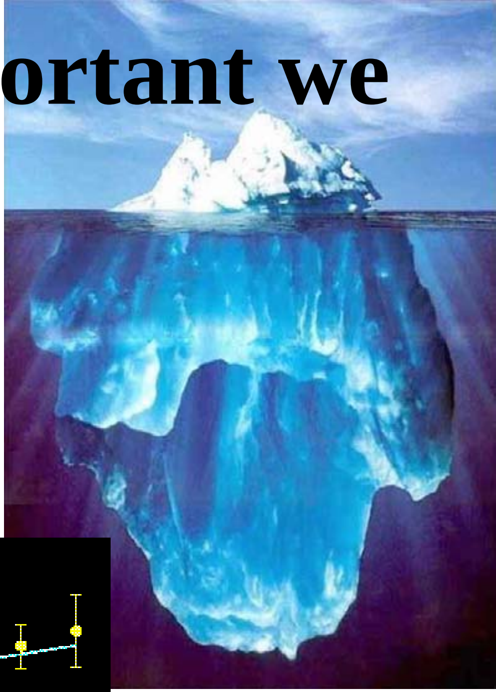


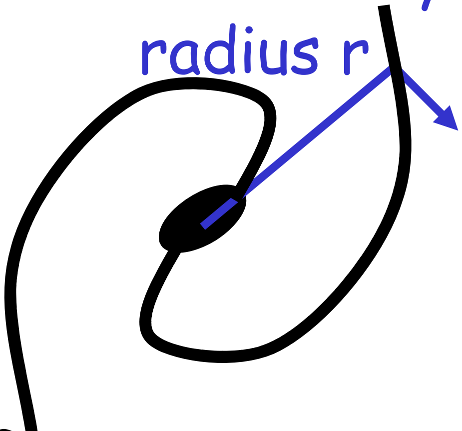
Luminous stars only small fraction of mass of galaxy

II

Dark matter searches

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





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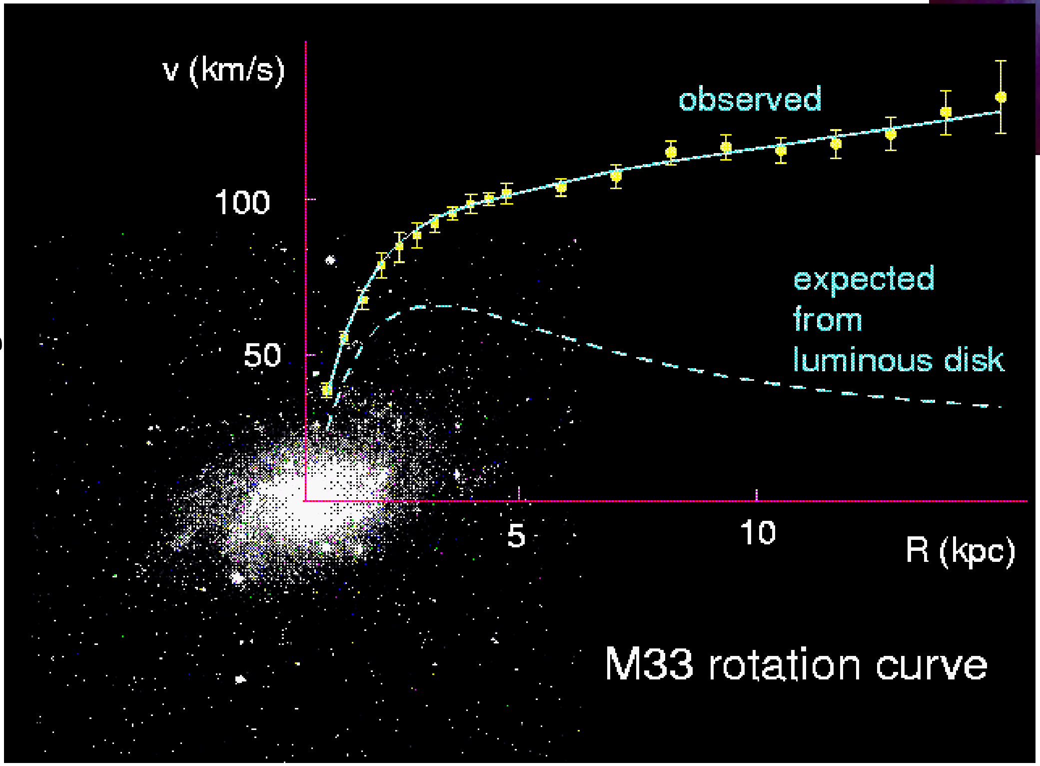
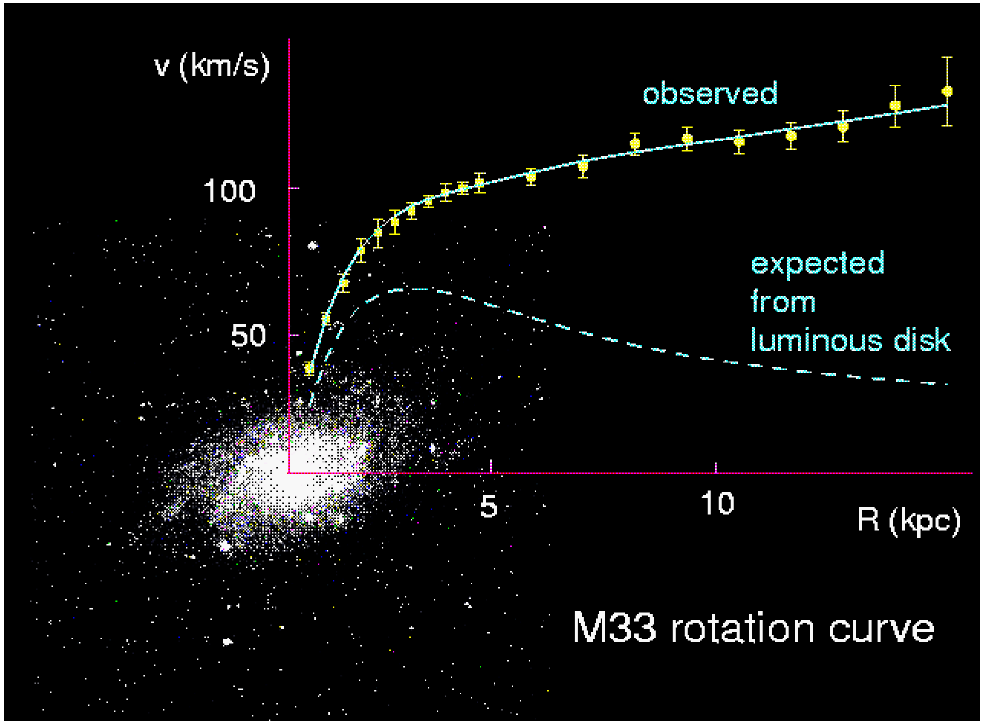


Luminous stars only small fraction of mass of galaxy

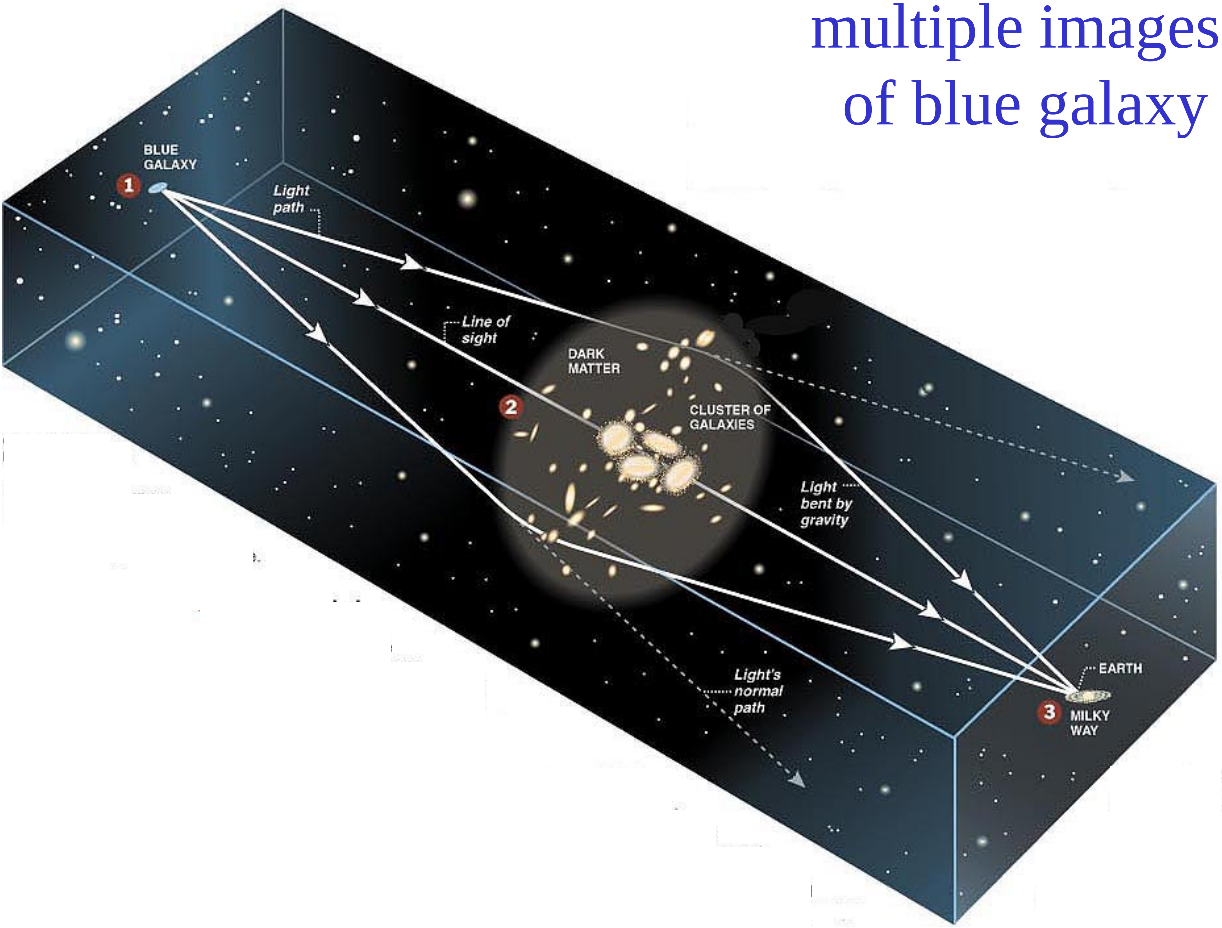
Dark matter searches

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

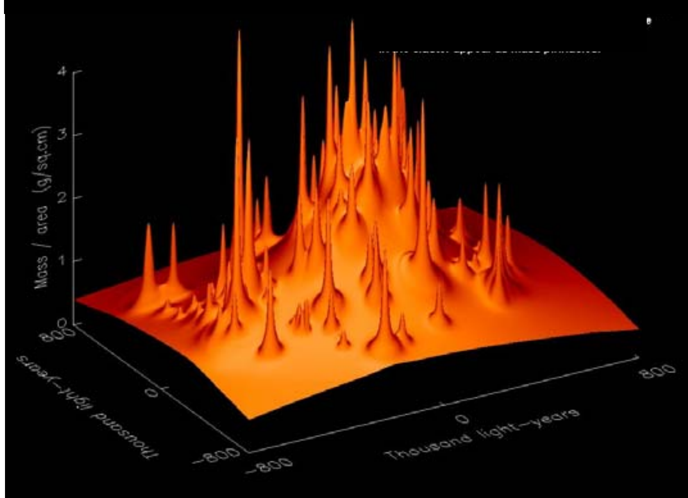


Gravitational Lensing by Dark Matter

Hubble Space Telescope
multiple images
of blue galaxy

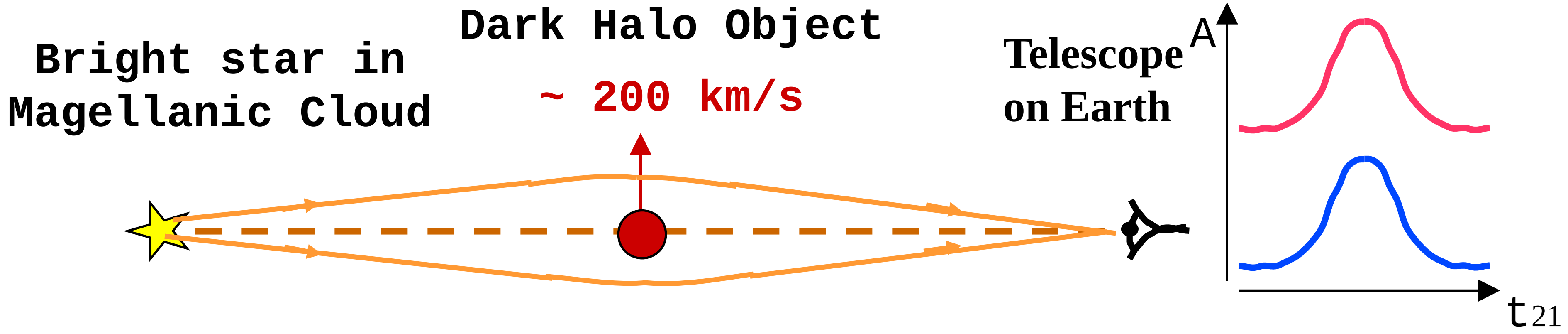


Reconstructed matter distribution



Black holes, etc.

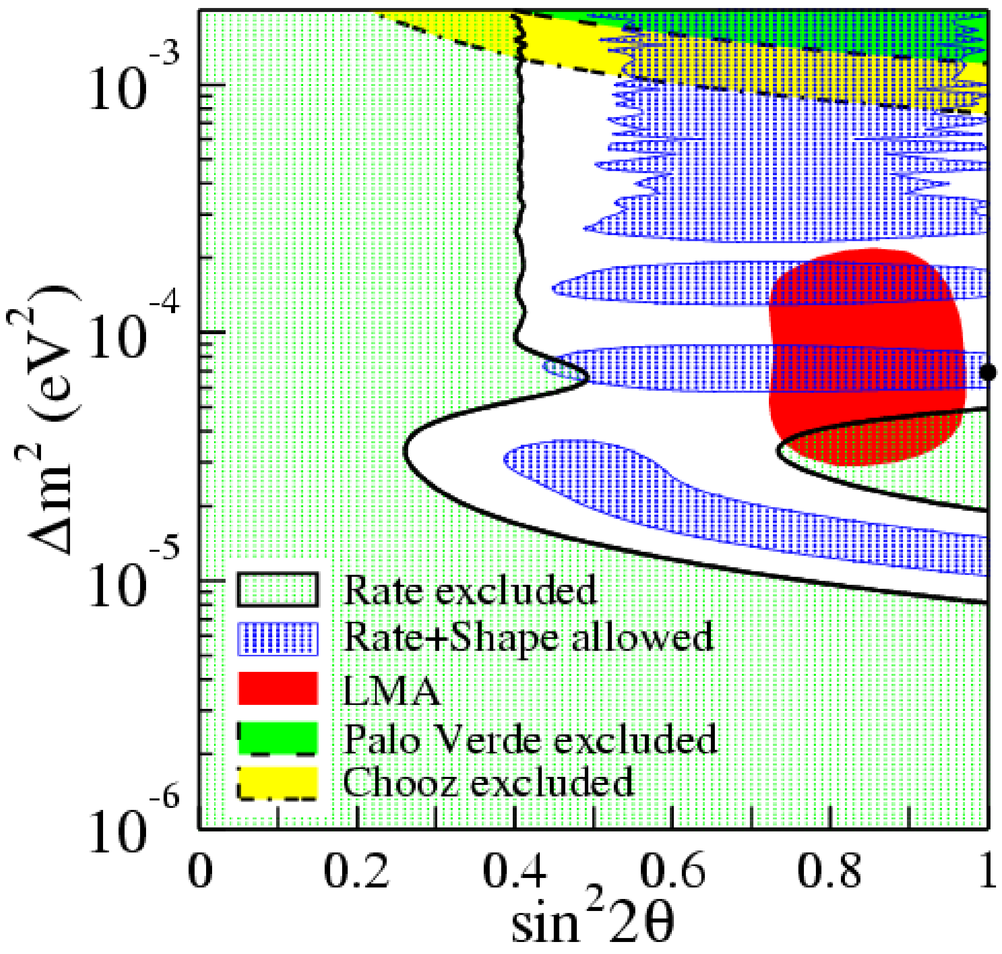
Gravitational Lensing Searches for MACHOs



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

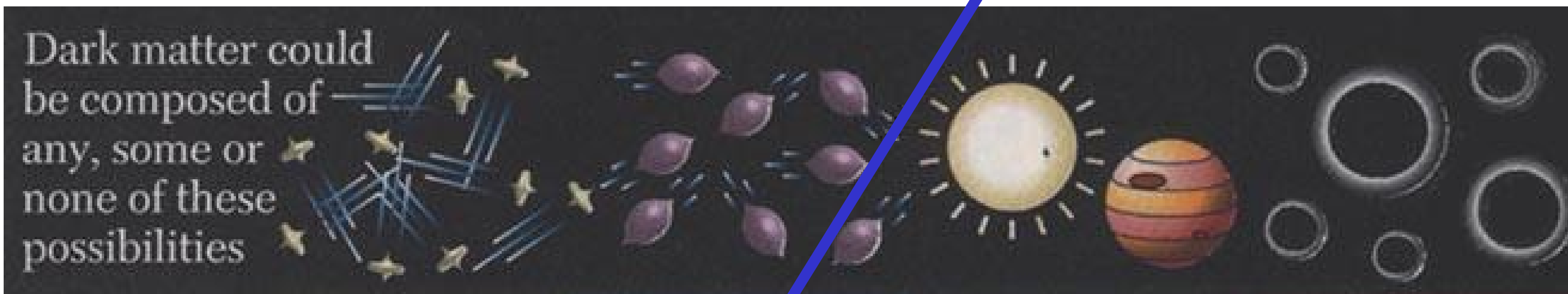


$\Delta M \sim 0.01$ eV

Mixing ~ maximal

Candidates: only WIMPS are left

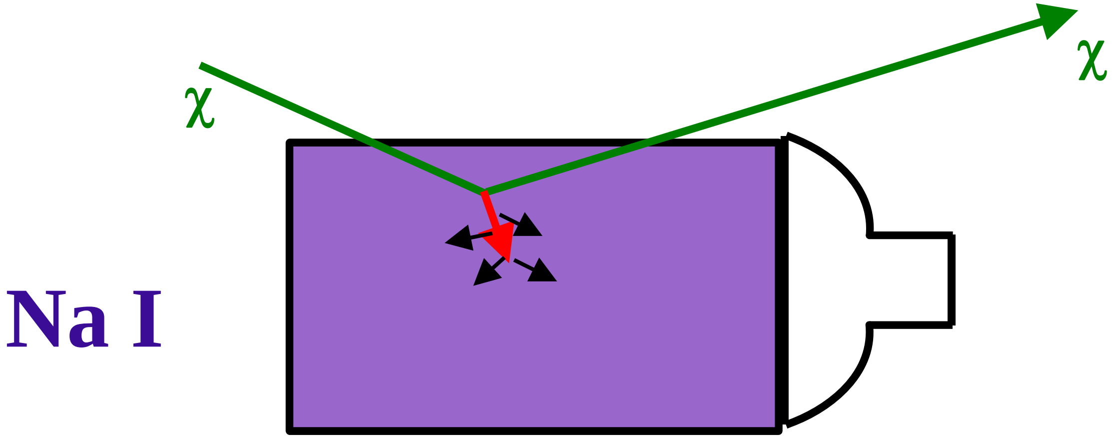
M > ~ 40 GeV
if SUSY (LEP)

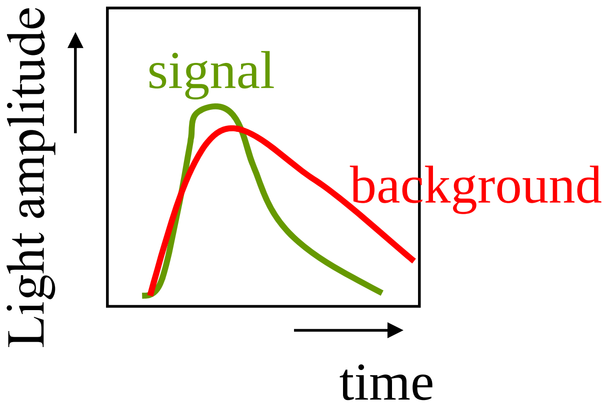


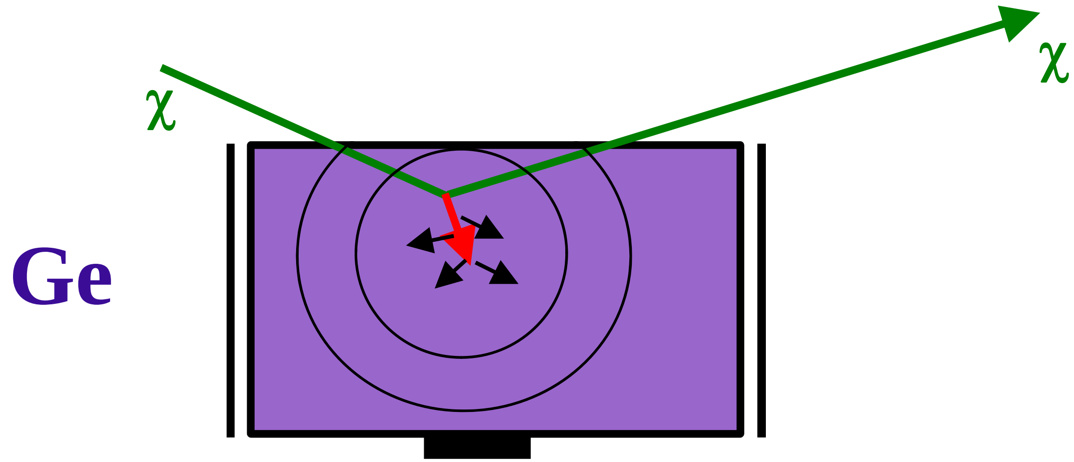
Name	Neutrinos	WIMPs	MACHOs	Black holes
What they are	Subatomic relatives of the electron that have no electrical charge and interact only weakly with ordinary matter	(Weakly interacting massive particles) Also known as cold dark matter	(Massive compact halo objects) Dim Jupiter-size planets or white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

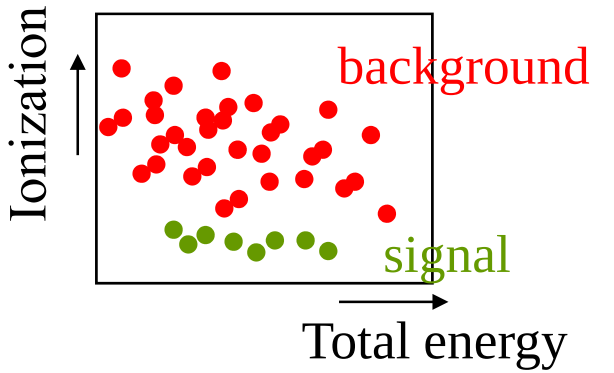
Direct WIMP Detection

Rejection of background is the critical issue





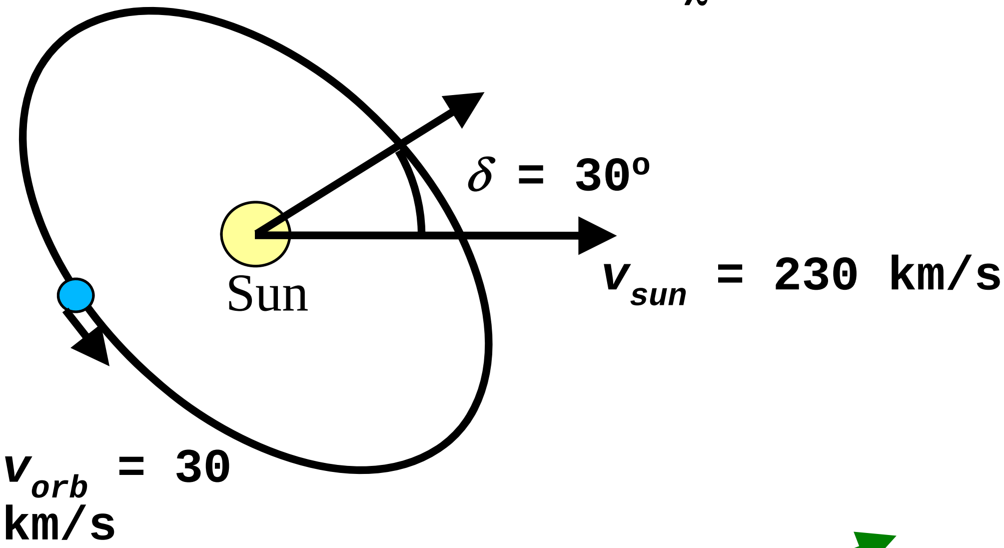


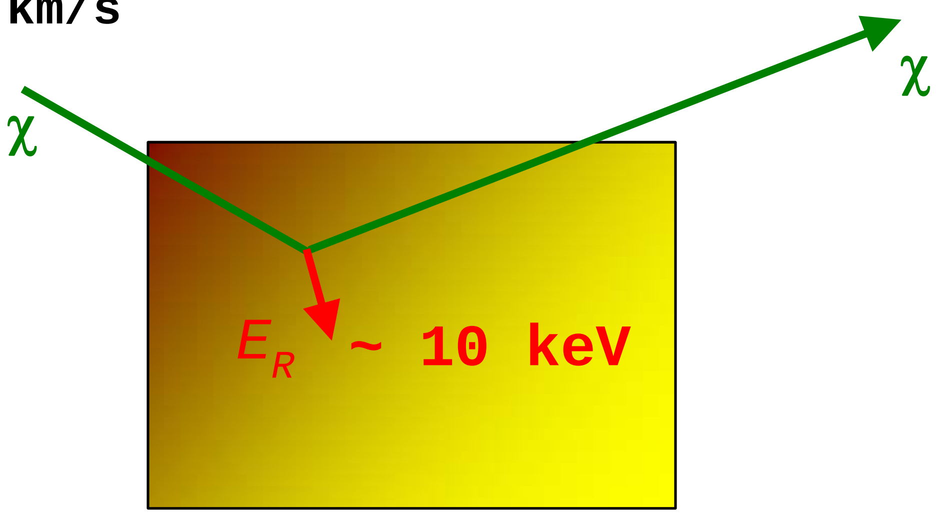


WIMP Direct Detection: modulation

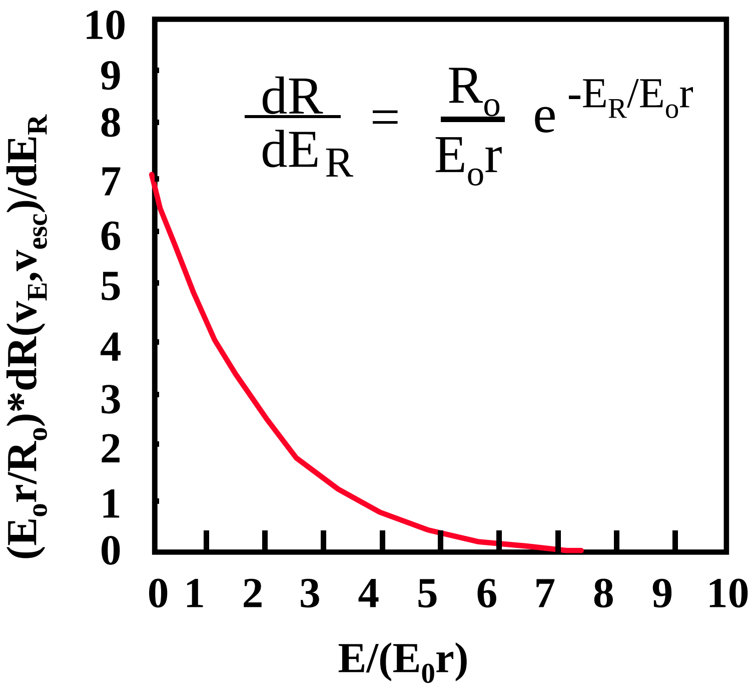
Elastic interaction on nucleus, typical χ velocity ~ 25

Motion of Earth in the χ wind





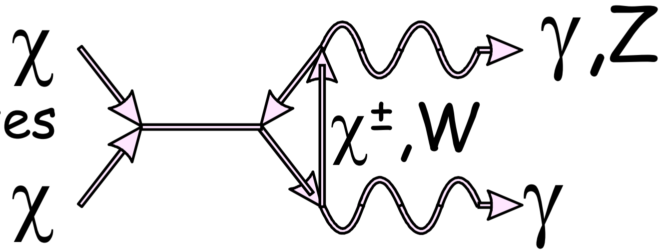
Recoil Spectrum



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

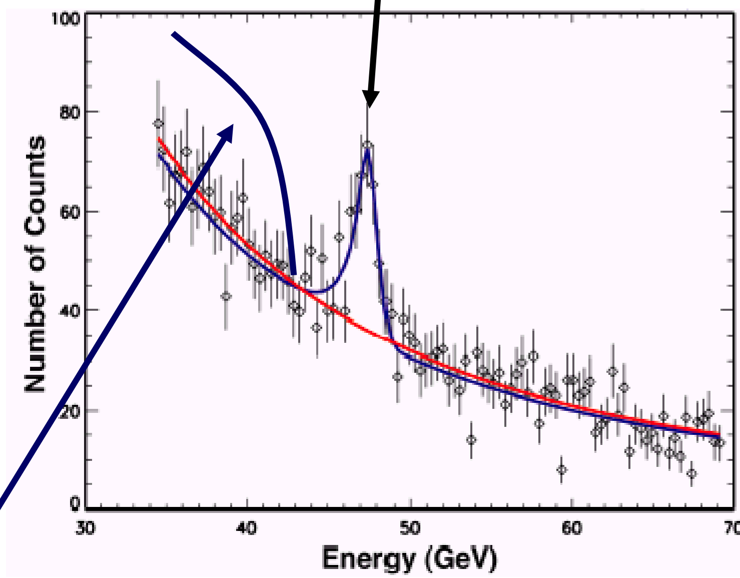
But… Annual modulation

WIMPS & gamma emission

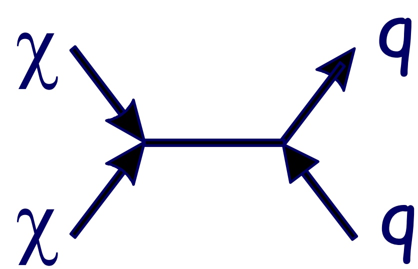


- Some DM candidates (e.g. SUSY particles) would lead to mono-energetic γ lines through annihilation into $\gamma\gamma$ or γZ:
  $E_\gamma = m_\chi$ / $m_\chi - m_Z^2/4\, m_\chi$
  => clear signature at high energies
  but: loop suppressed

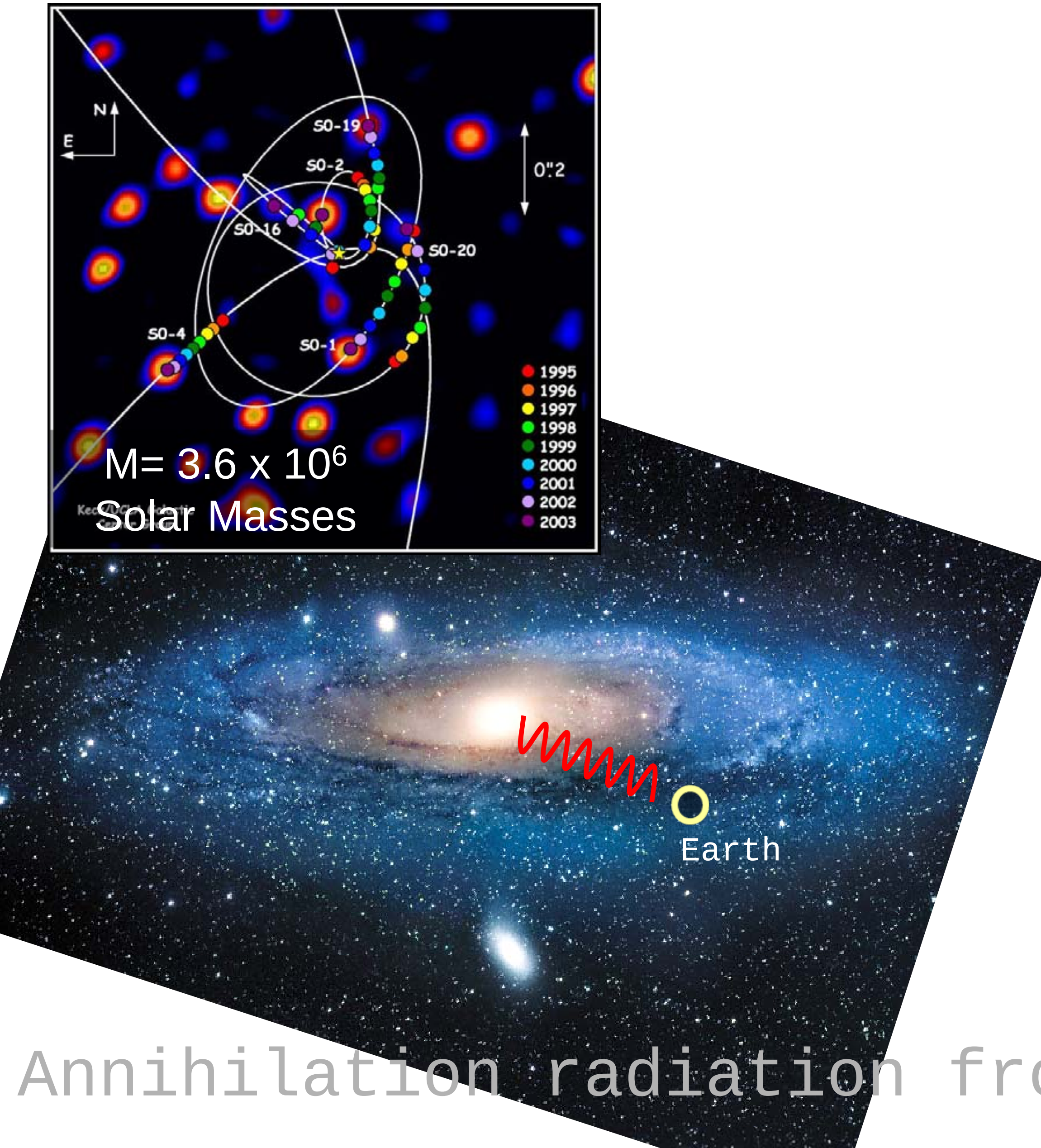
Good energy resolution in the few % range is needed

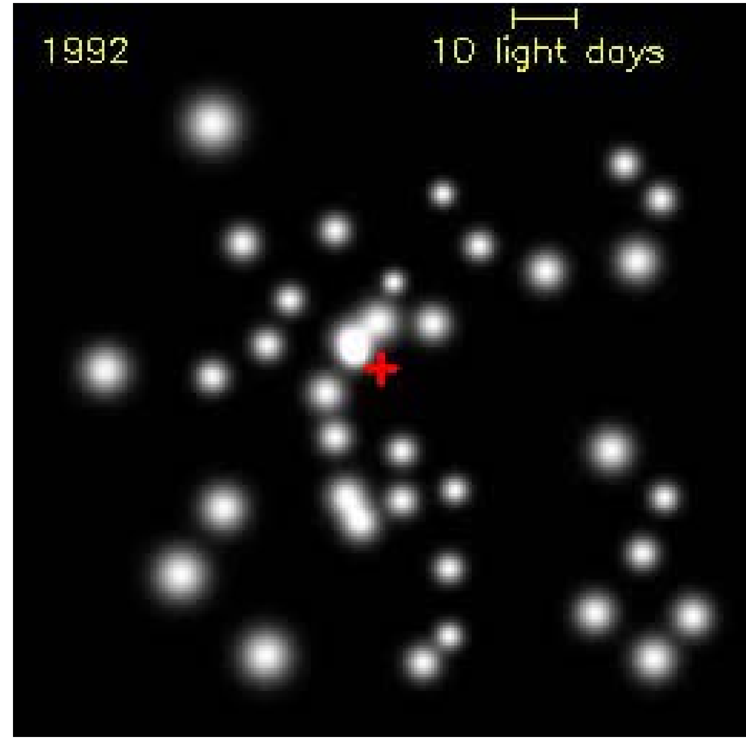


- annihilation into qq -> jets -> n γ's
  => continuum of low energy gammas
  difficult signature but large flux



Results: common sense suggests a look @the GC…





X emission (variable)

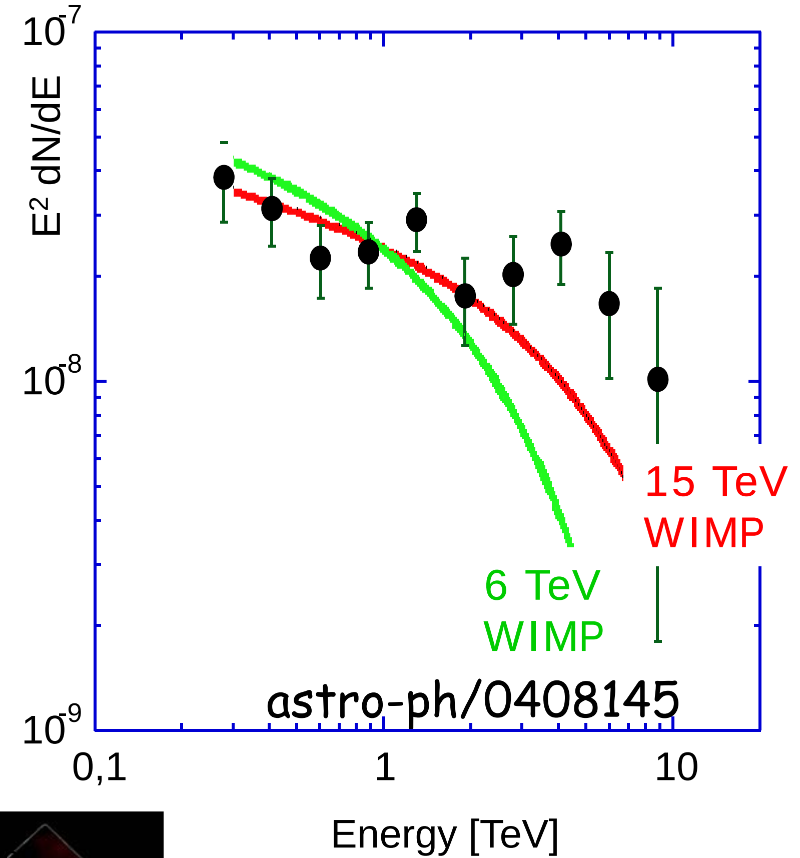
γ emission

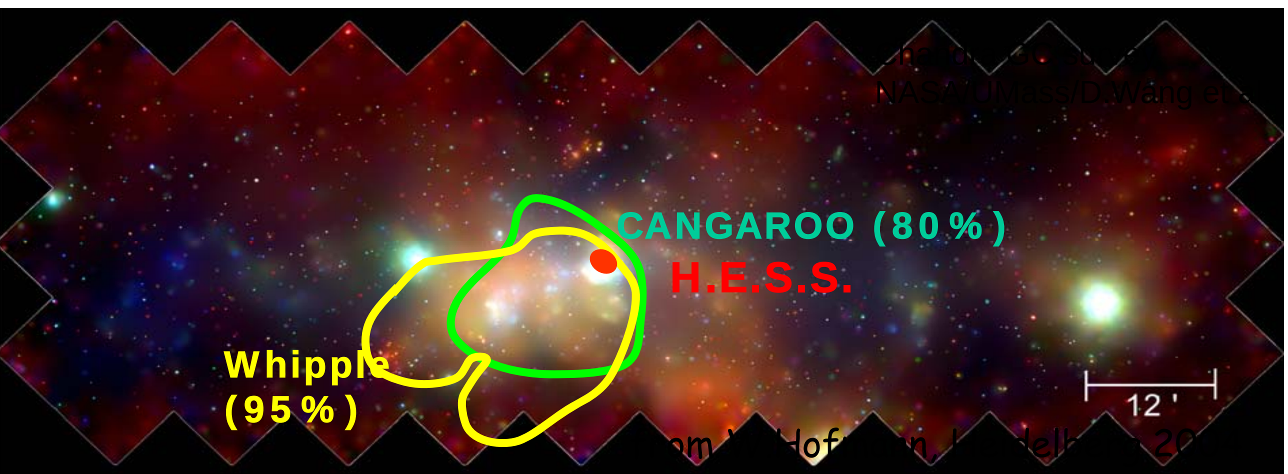
Annihilation radiation from the GC

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 => not optimal target



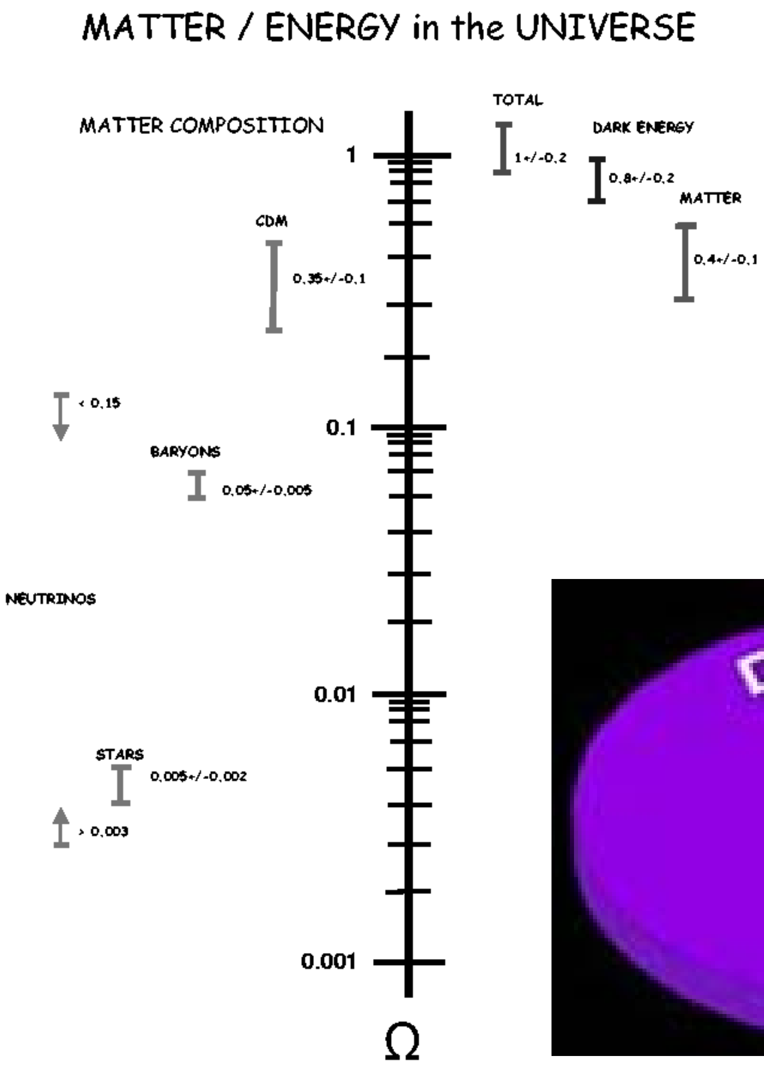


Milky Way satellites Sagittarius and Draco

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

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 :

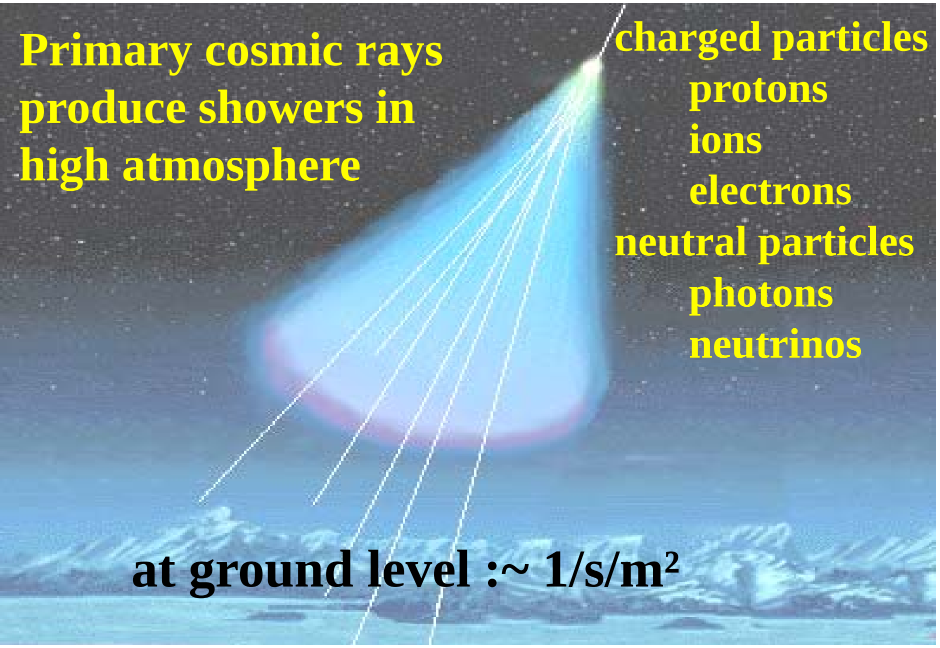
$$\Omega_{CDM} \sim 0.23$$

WIMPS/neutralinos, a

III

High Energy Particles from space

Cosmic Rays

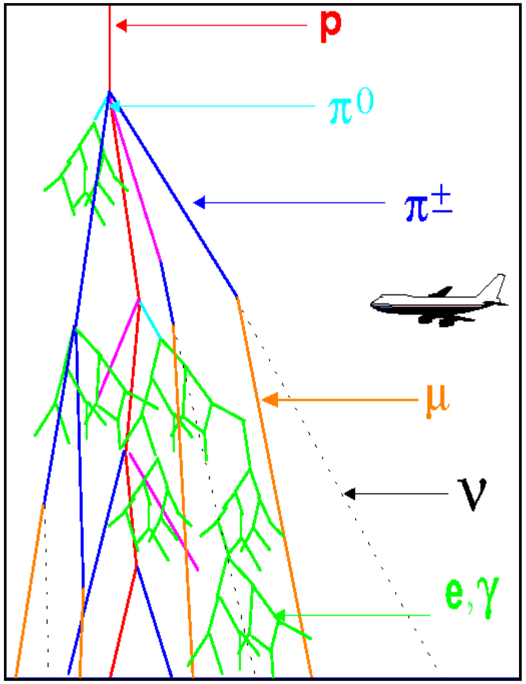


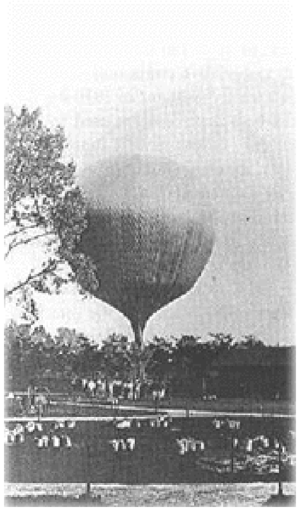
Primary:

p 80 %, α 9 %, n 8 %

e 2 %, heavy nuclei 1 %

γ 0.1 %, ν 0.1 % ?





100 years after discovery by Hess origin still uncertain

Secondary at ground level:

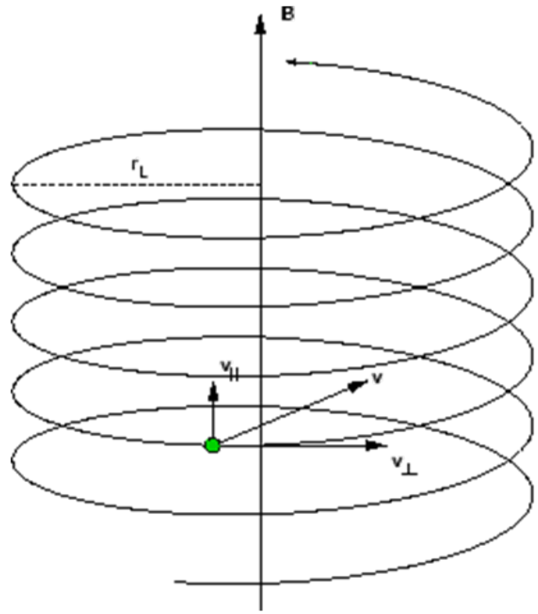
ν 68 %

μ 30 %

p, n, ... 2 %

Raggio di curvatura di una particella in moto in un campo magnetico

- Determiniamo il raggio di curvatura (denominato ***raggio di Larmor***) di una particella con carica q ed energia E in moto in un campo magnetico **B**.



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

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

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

Confinamento:

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

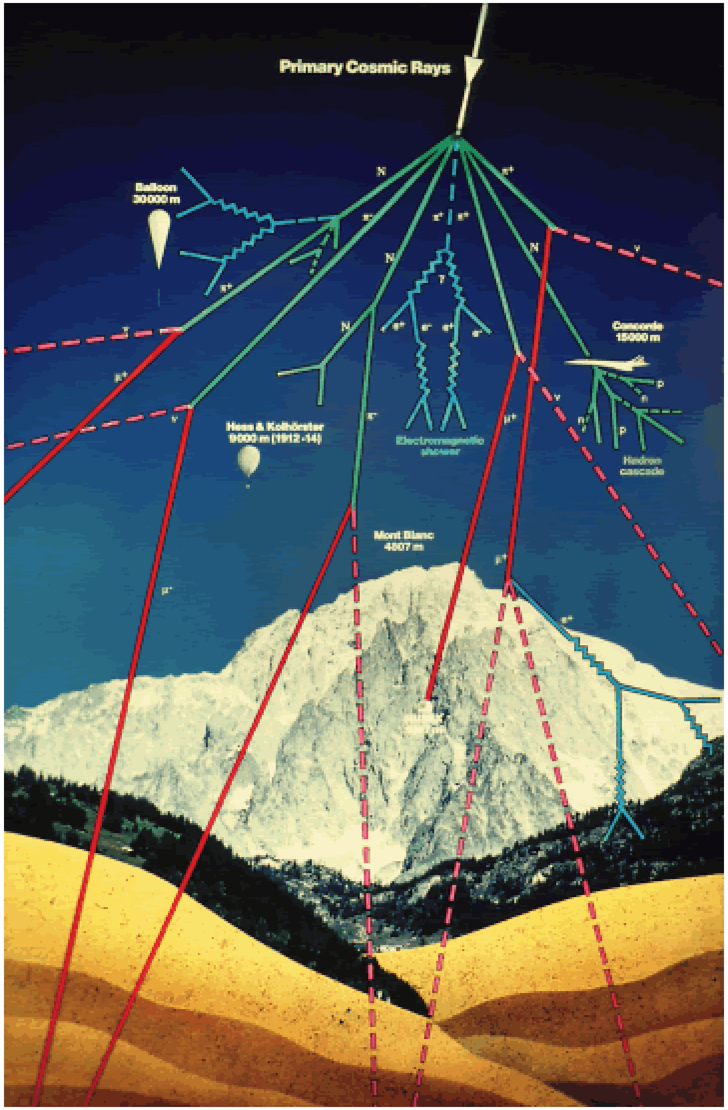
- Utilizziamo i valori tipici del campo B (3×10^{-6} G) galattico per protoni:

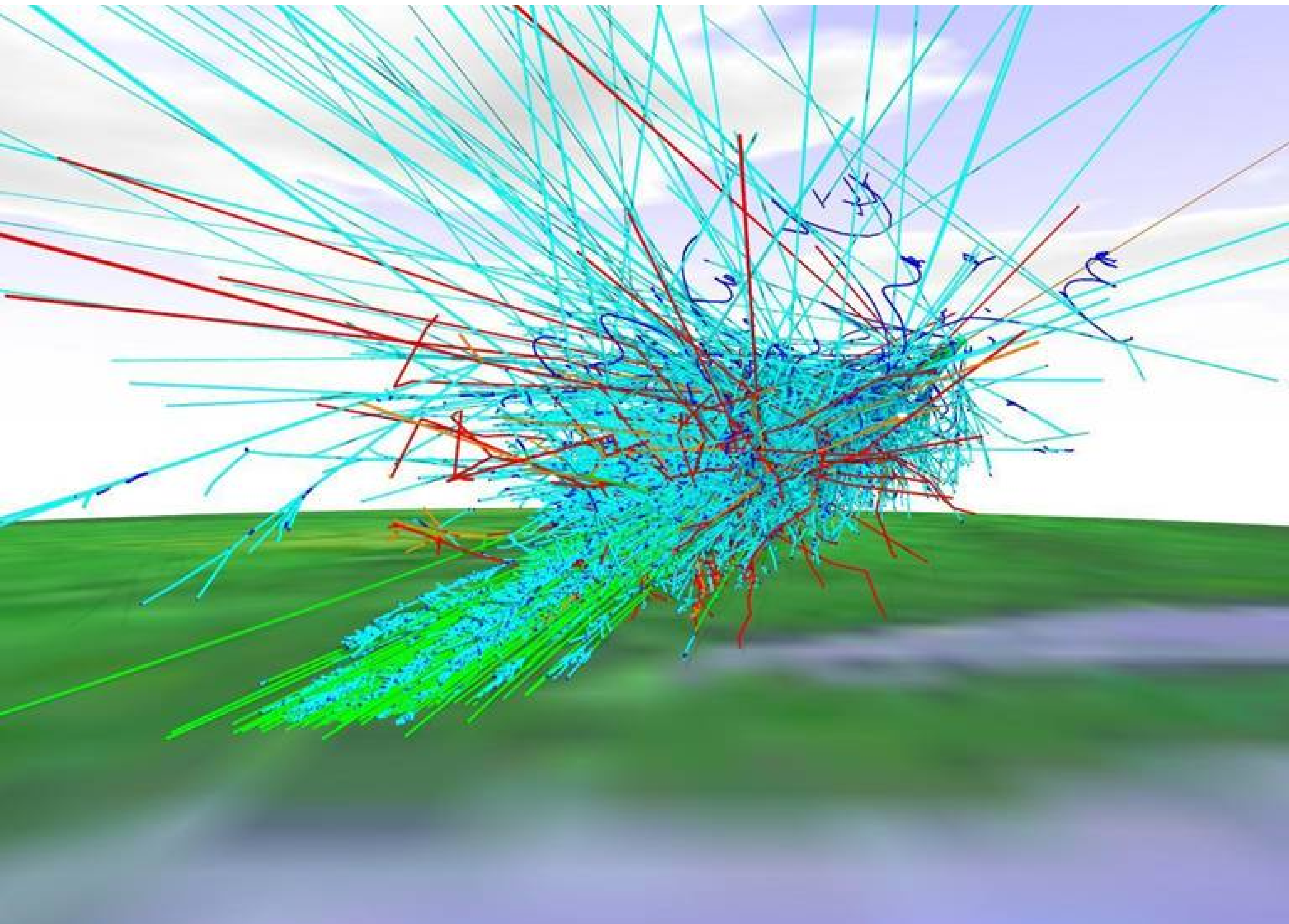
$$r_L = \begin{cases} (E = 10^{12} eV) & = 10^{15} cm = 3 \cdot 10^{-4}\ pc \\ (E = 10^{15} eV) & = 10^{18} cm = 0.3\ pc \\ (E = 10^{18} eV) & = 10^{21} cm = 300\ pc \end{cases}$$

- I p hanno un raggio di Larmor sempre minore dello spessore del disco galattico (300 pc) se $E<10^{18}$ eV. Per questo motivo tutti i RC (meno quelli di energia estrema) sono ***confinati*** nel piano Galattico dal campo magnetico.

I RC secondari

- Interazione dei RC coi nuclei dell'atmosfera → sciami di particelle secondarie → **RC secondari** .
- L'atmosfera funge da *convertitore*
- La radiazione primaria può essere direttamente studiata solo fuori dall'atmosfera terrestre (sonde)
- La radiazione al suolo può essere studiata con rivelatore di sciami
- Esperimenti *underground* per la componente penetrante (muoni e neutrini)





Hajo Drescher, Frankfurt U.

I Raggi Cosmici sulla Terra

- I RC bombardano continuamente la Terra: circa 100000 particelle originate dai Raggi Cosmici ci attraversano ogni ora.
- Questo contribuisce alla dose di radioattività ambientale a cui siamo continuamente soggetti.

RC secondari

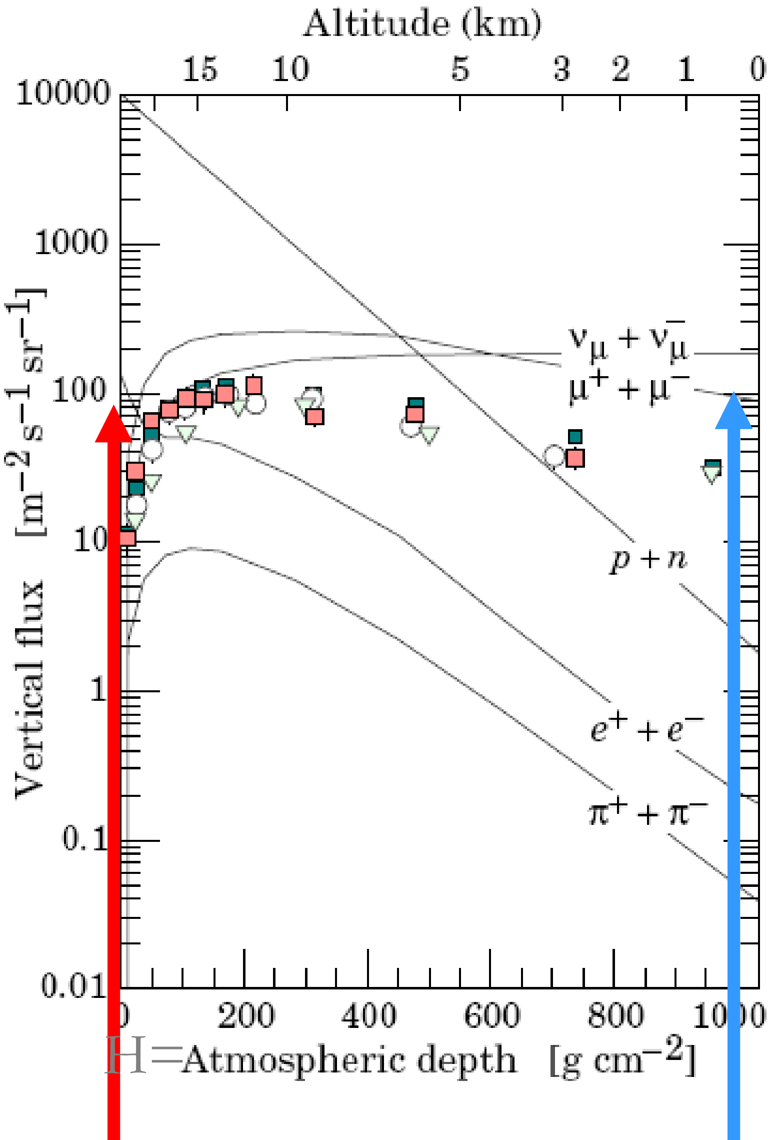
- Lo spessore di atmosfera equivale a 10 m di acqua

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

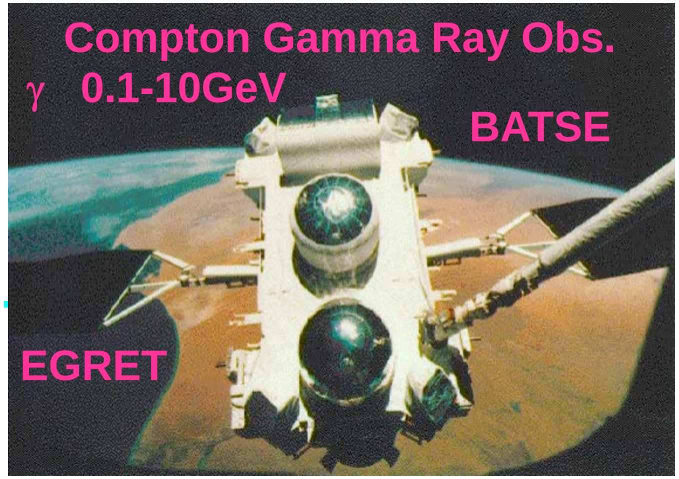
$$= 1000 \quad (gcm^{-2})$$

1. Flusso sulla sommità (H=0 gcm^{-2}):
   - 10000 m^{-2} s^{-1}sr^{-1}
   - p (90%), He (9%), A (1%)

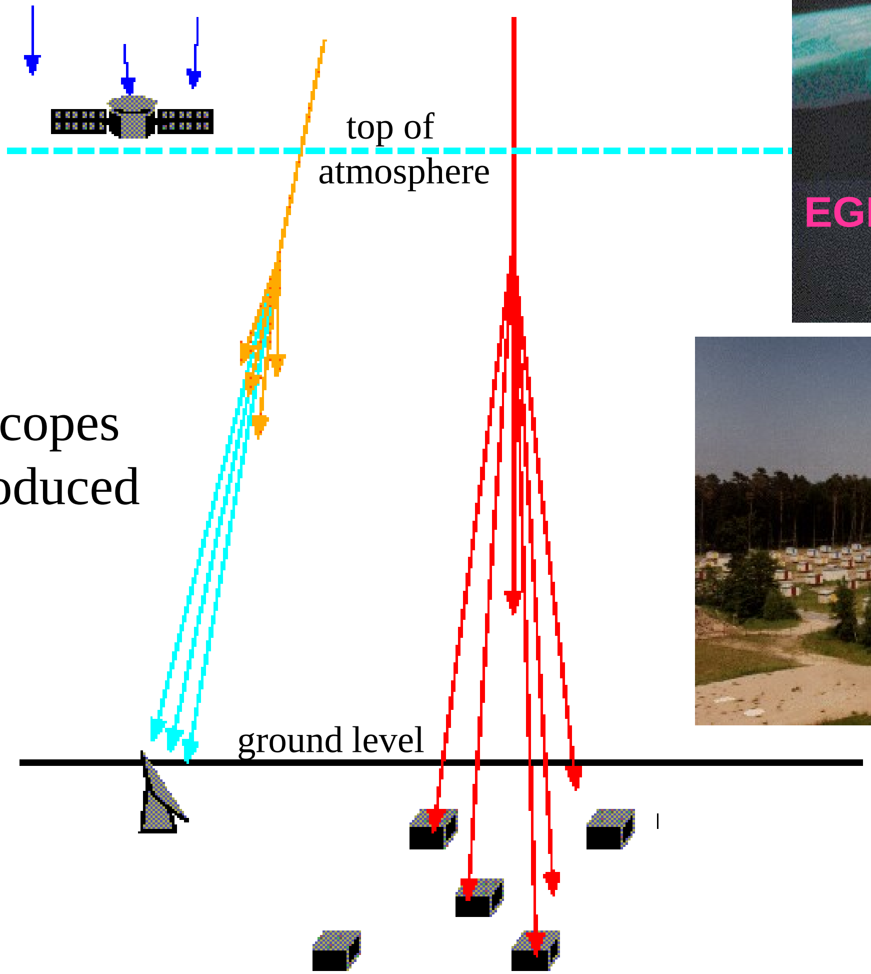
2. Flusso a livello del mare (H=1000 gcm^{-2}):
   - 200 m^{-2} s^{-1}sr^{-1}
   - Muoni, neutrini, e+e-, γ



Types of Cosmic Ray Detectors

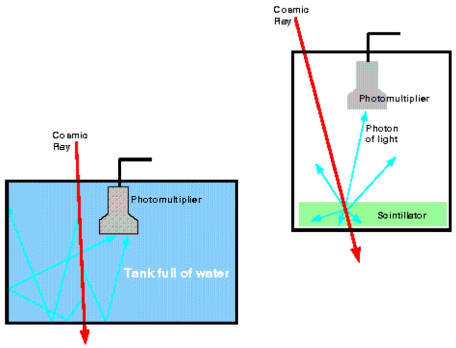


Satellites

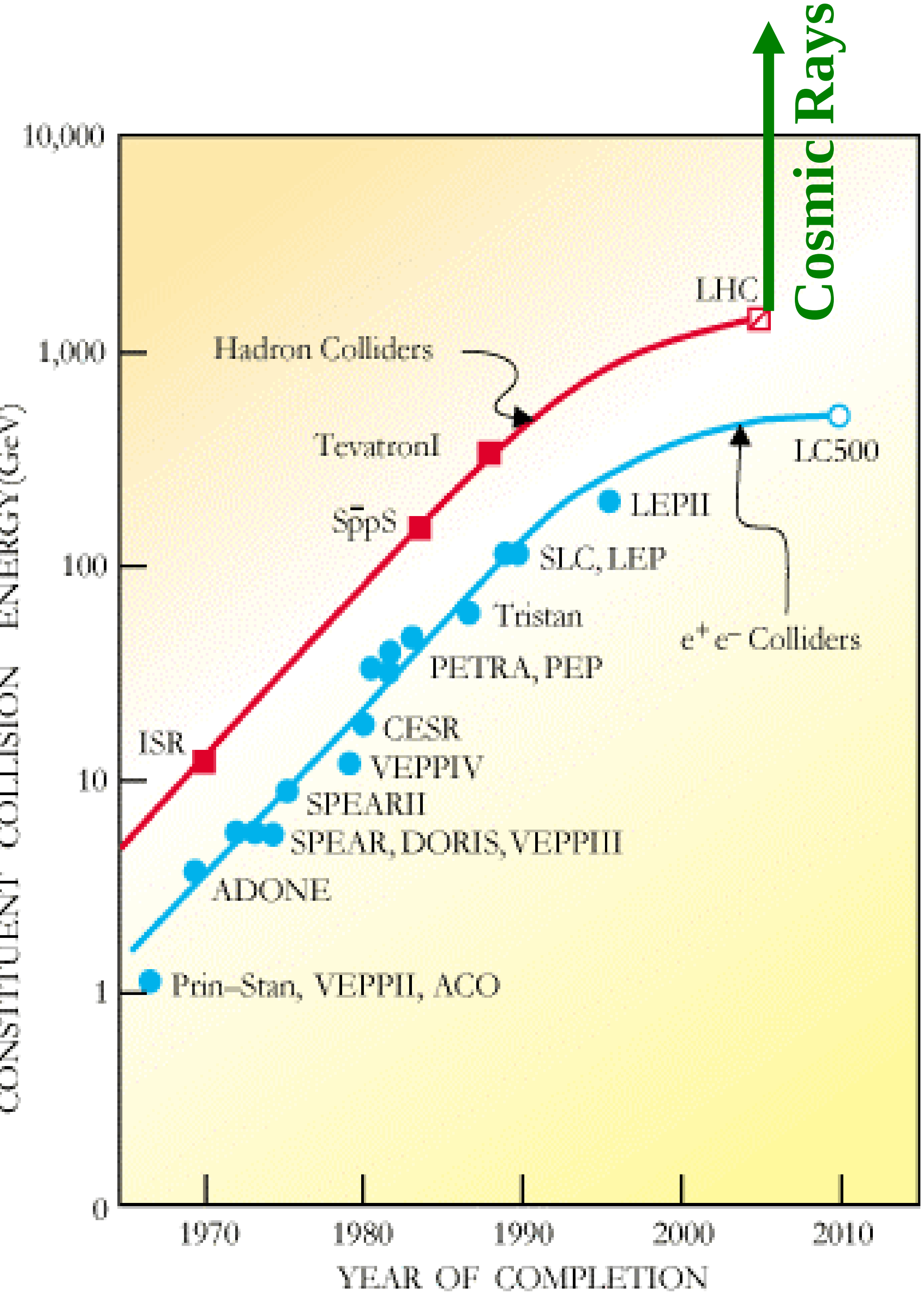


Ground based telescopes
looking at light produced
in atmosphere

Arrays of particle detectors



The future of HEP?



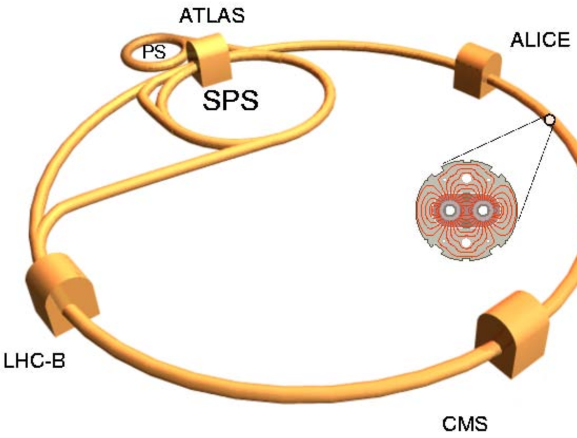
- Higher energies are not the full story…

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

Particle Acceleration

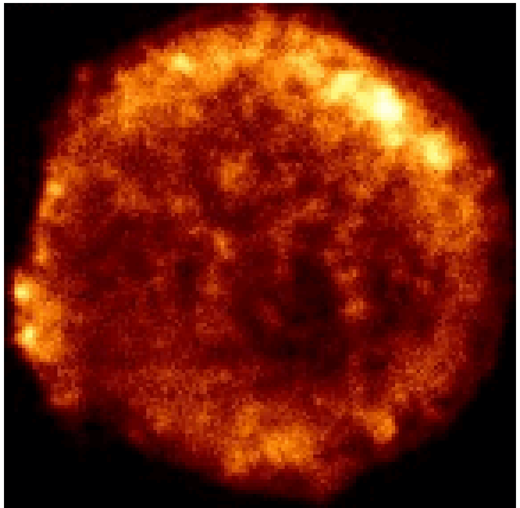
$E \propto BR$

Large Hadron Collider



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

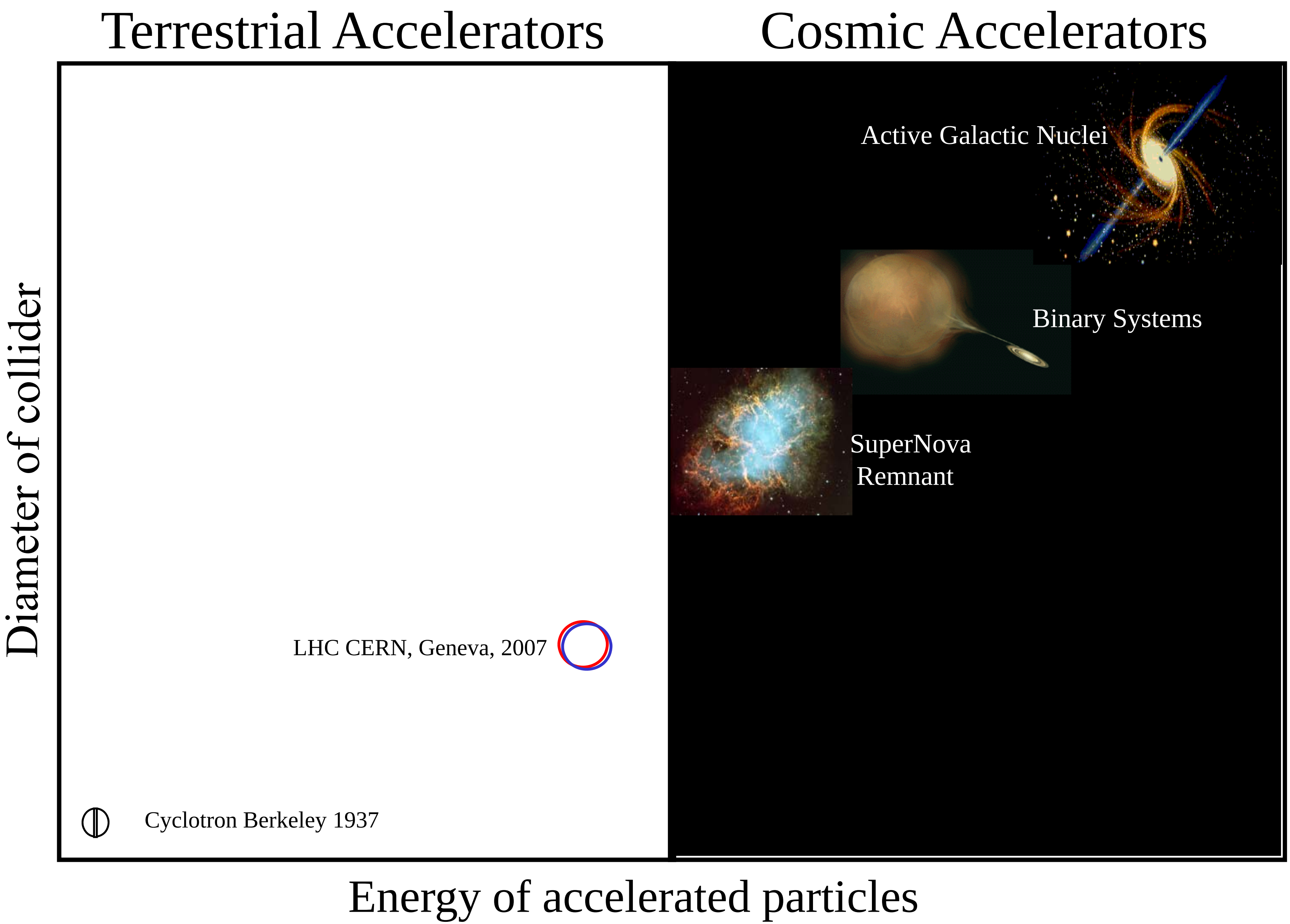
Tycho SuperNova Remnant



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

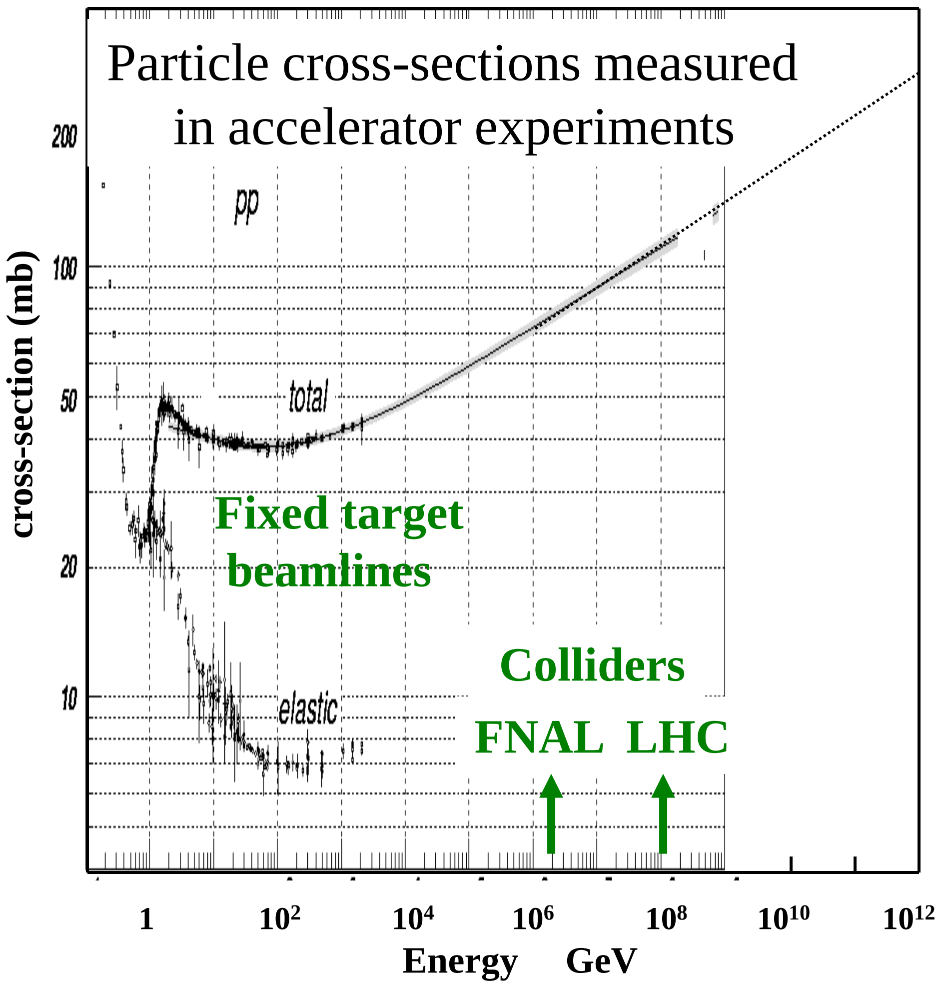
(NB. $E \propto Z \rightarrow$ Pb/Fe higher energy)

Particle Physics ⇒ Particle Astrophysics

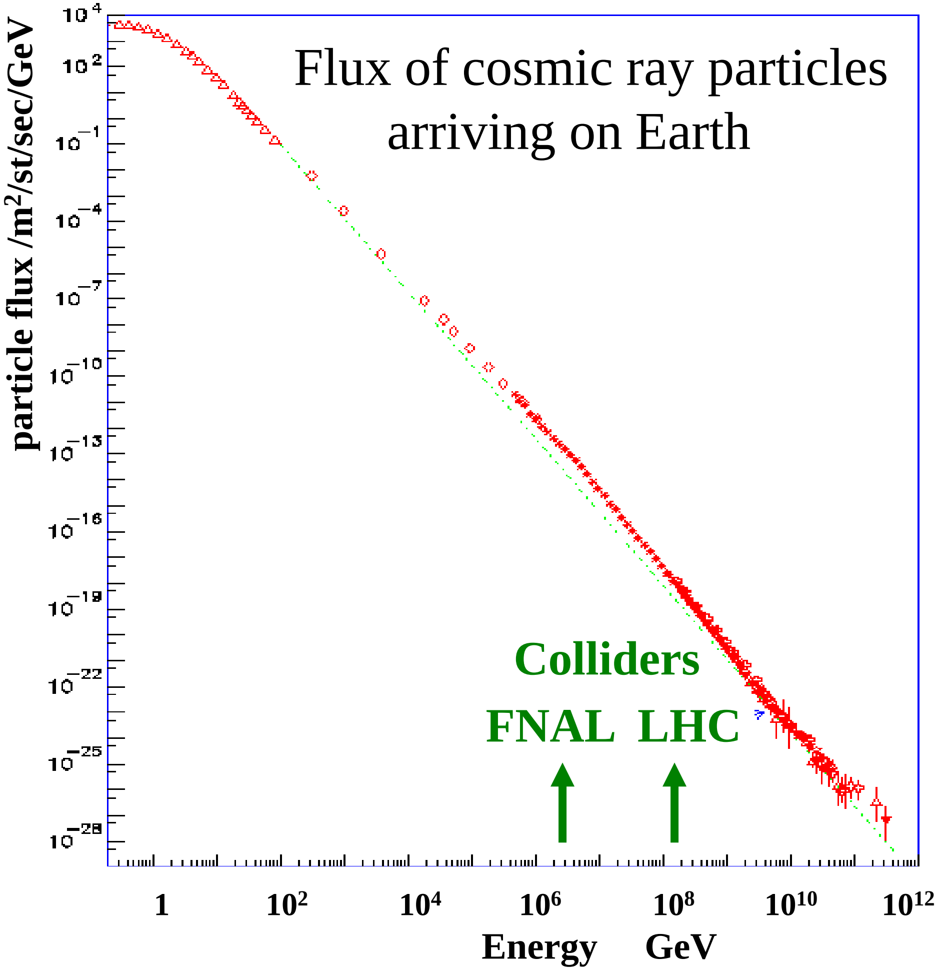


Ultra High Energy from Cosmic Rays

From laboratory accelerators



From cosmic accelerators



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

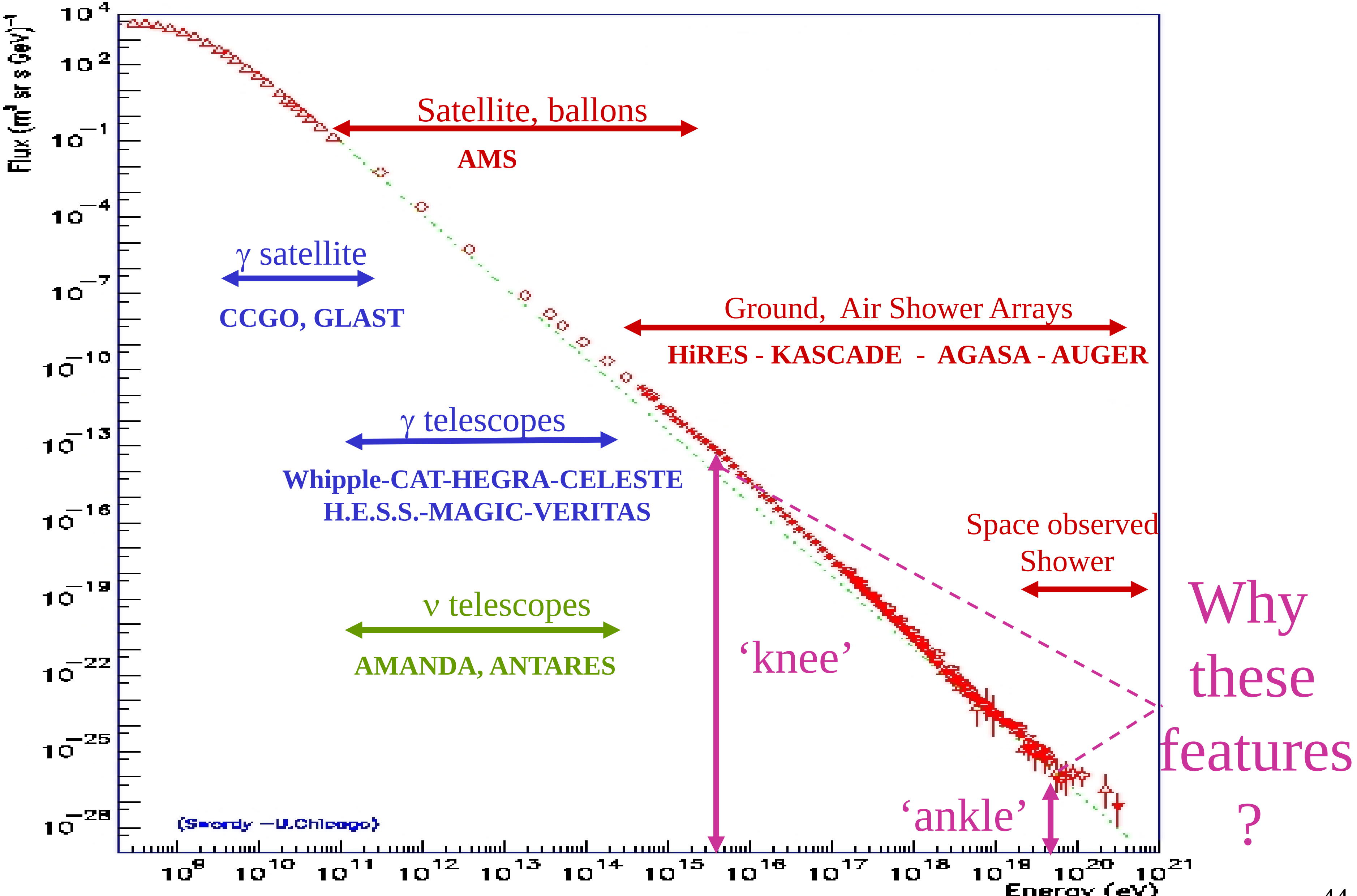
Experimental Astroparticle Physics
(a short introduction)

Alessandro De Angelis
INFN & Univ. Udine; IST Lisboa

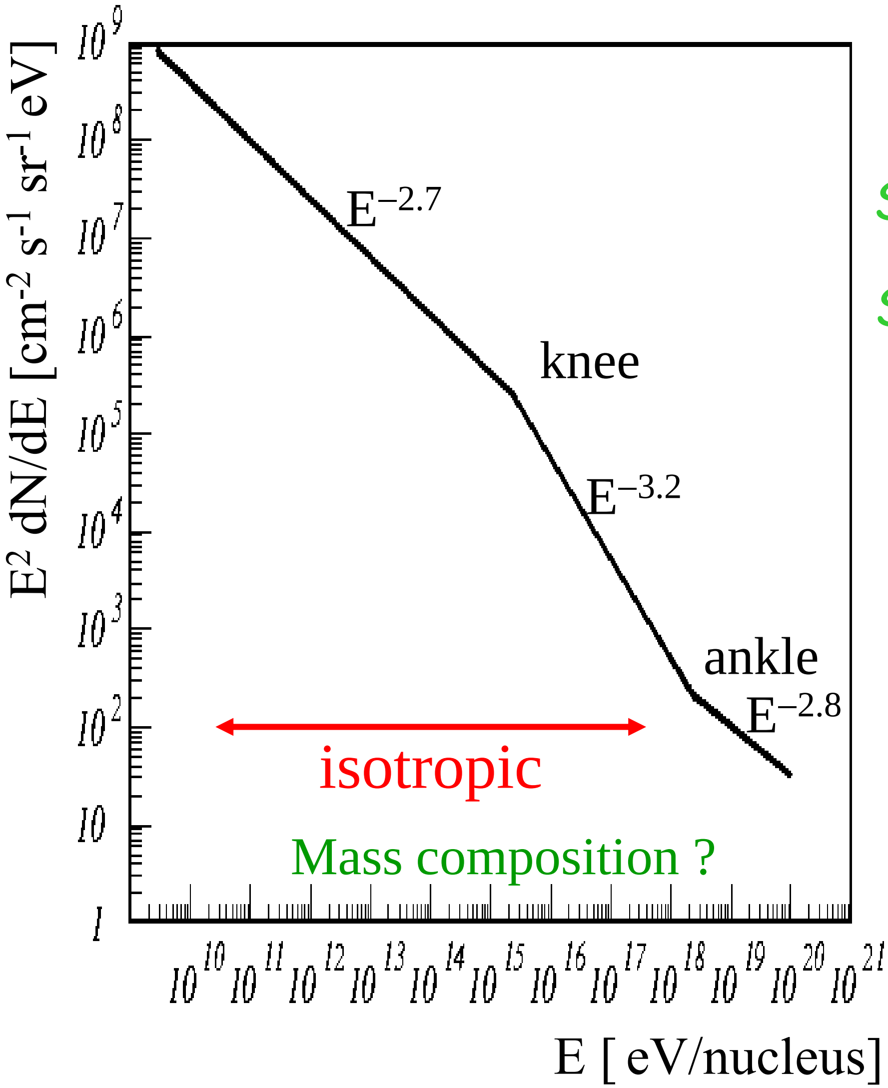
Lund 2008

Lectures 3-4

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

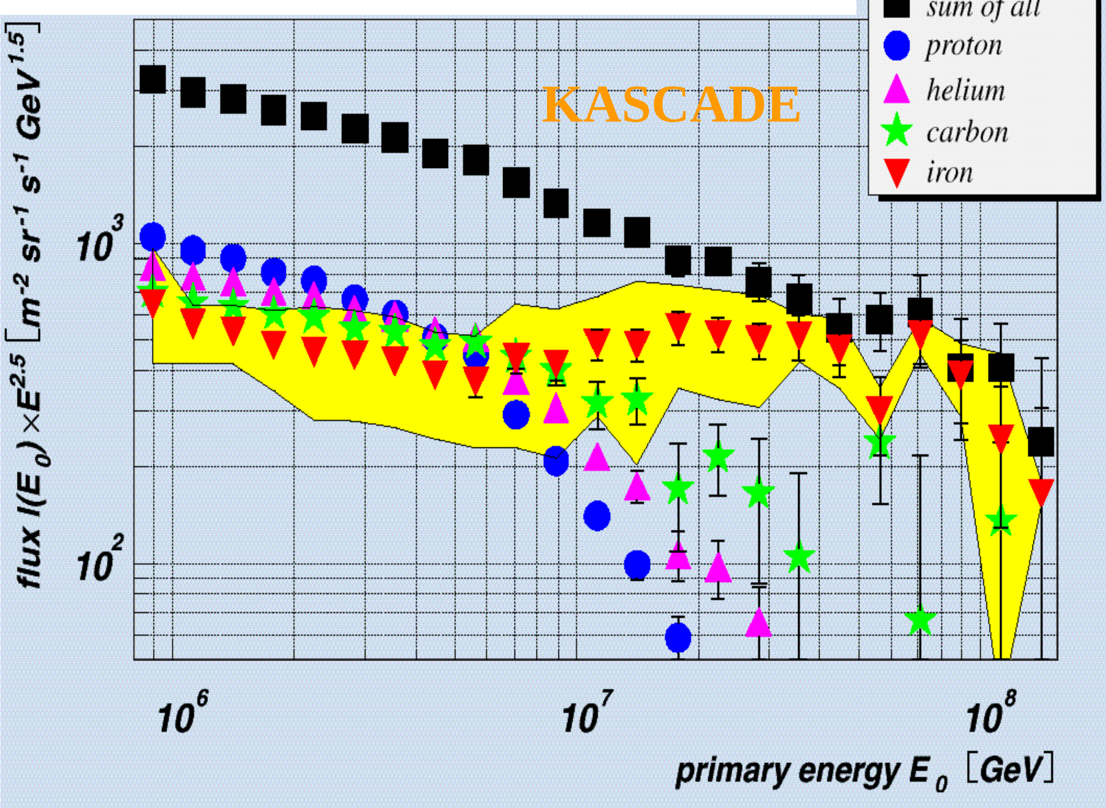
How are they produced?
(Possible acceleration sites)

- 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)

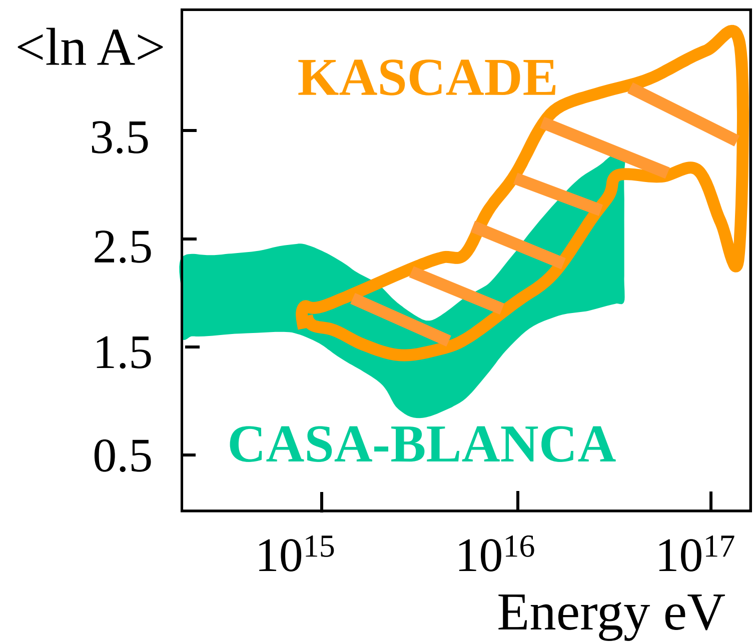
Mass composition at knee

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 × $E^{2.5}$



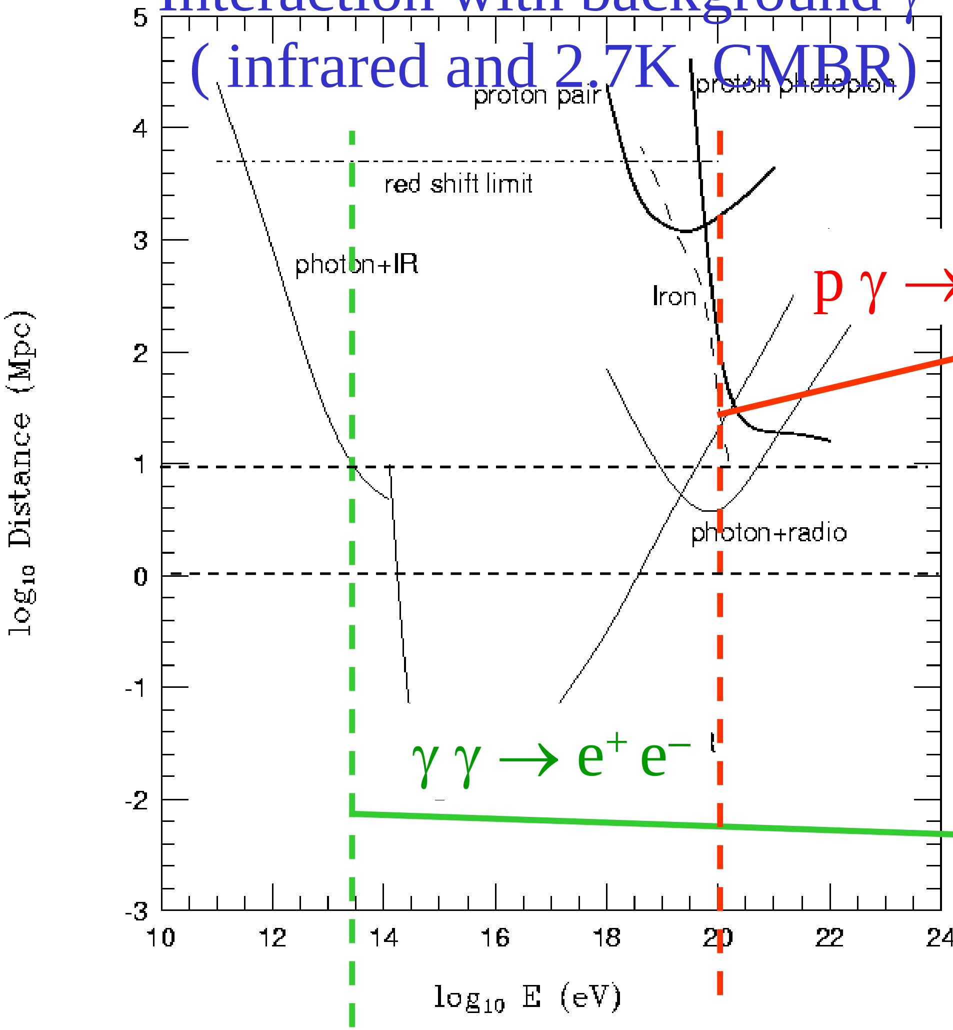
Mean ln(A)



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

'GZK cutoff'

Interaction with background γ (infrared and 2.7K CMBR)



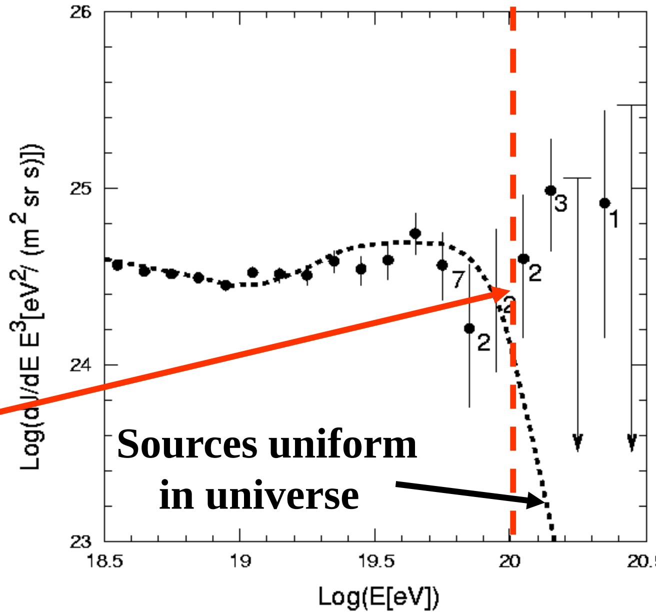
$p\,\gamma \rightarrow \pi\,N$

100 Mpc

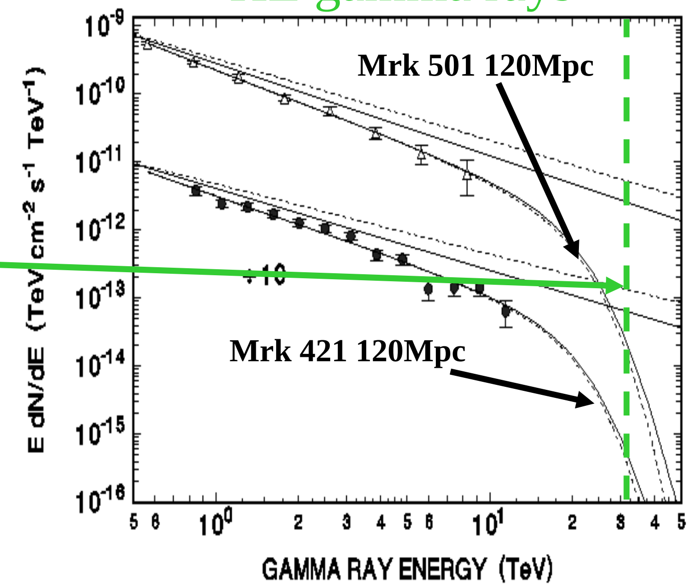
10 Mpc

$\gamma\,\gamma \rightarrow e^{+}\,e^{-}$

HE cosmic rays



HE gamma rays



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)

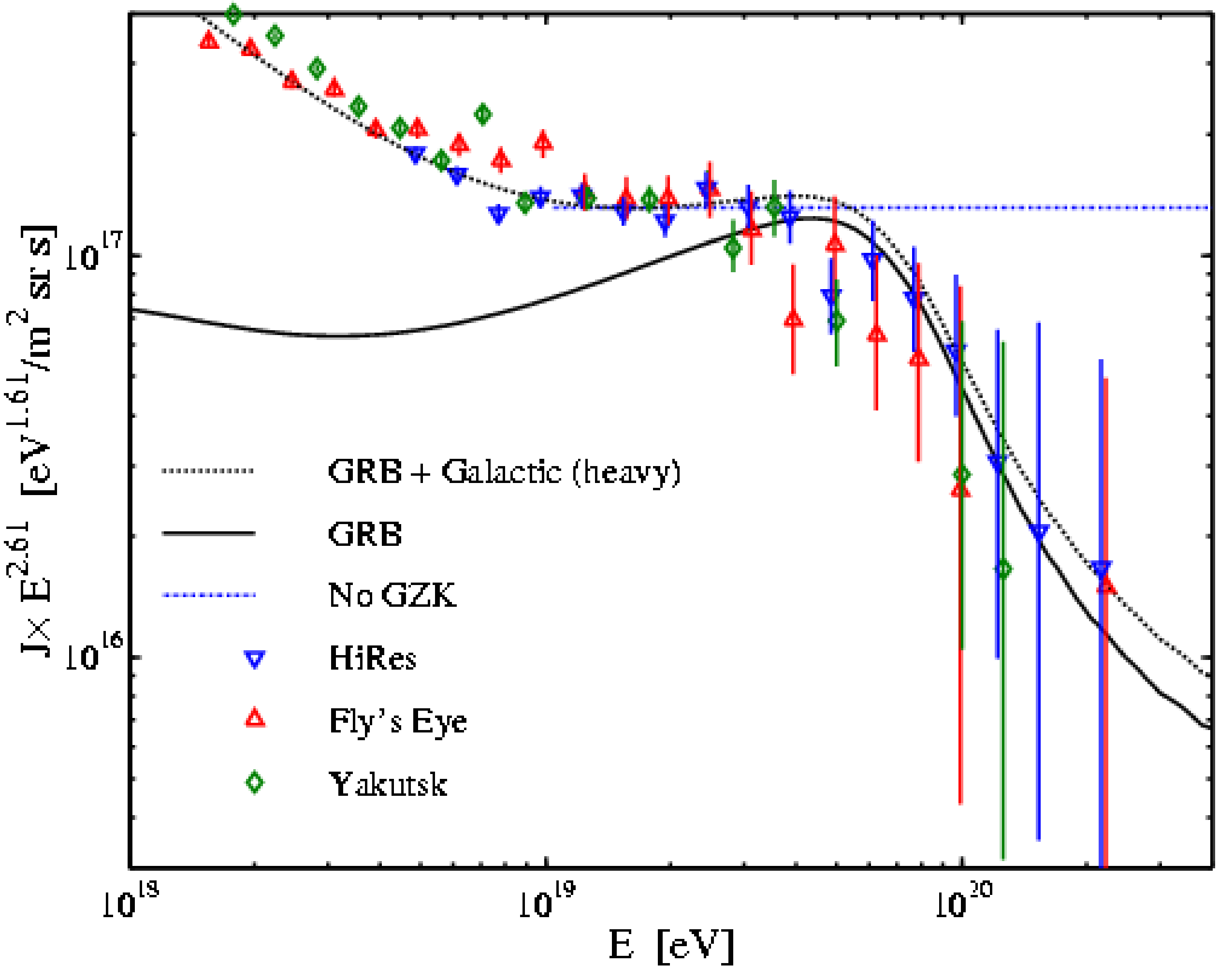
Particle Physics type explanations

- '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…**

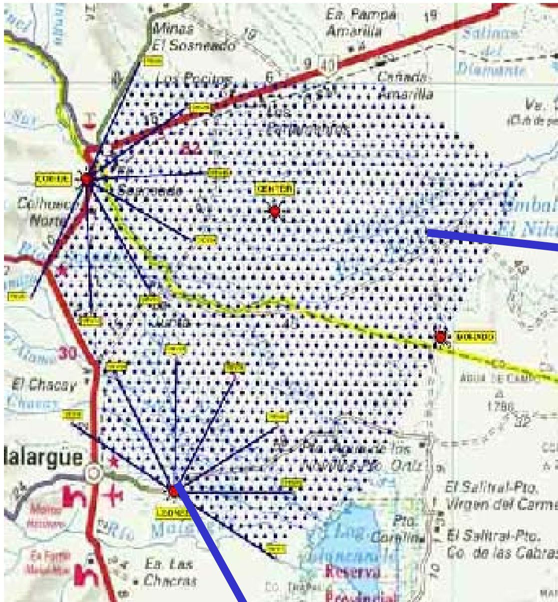
  (favorite explanation after Auger results)

HiRES (Fly's Eye)



AUGER

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



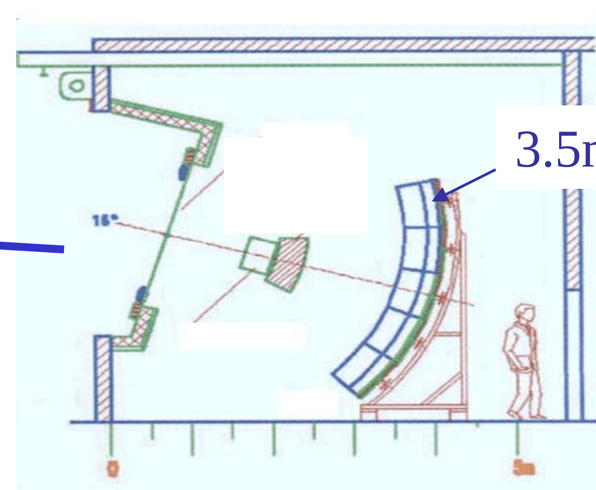
Southern site,
Mendoza Province,
Argentina

Water Cherenkov

Tanks

(1600 each 10m^2)

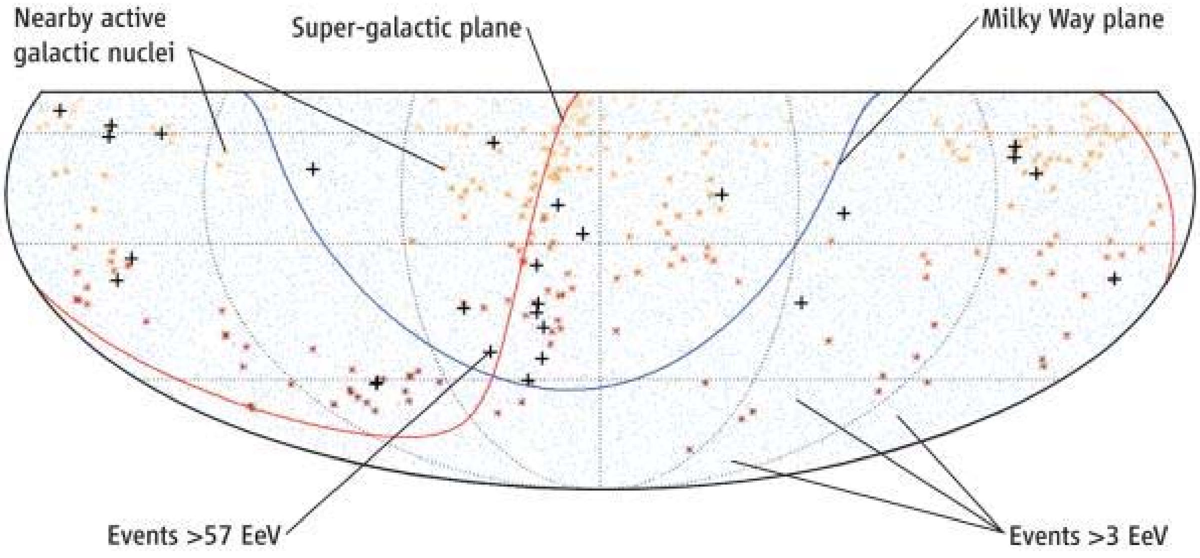
Fluorescence Telescopes (6 telescopes each 30° ×30° at 4 sites)



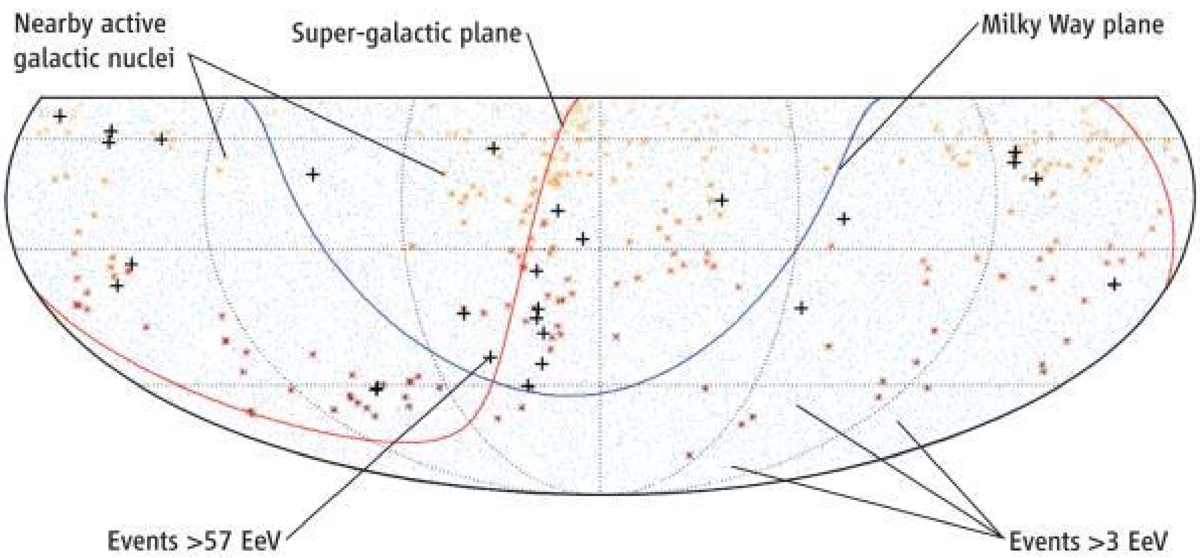
3.5m mirrors

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



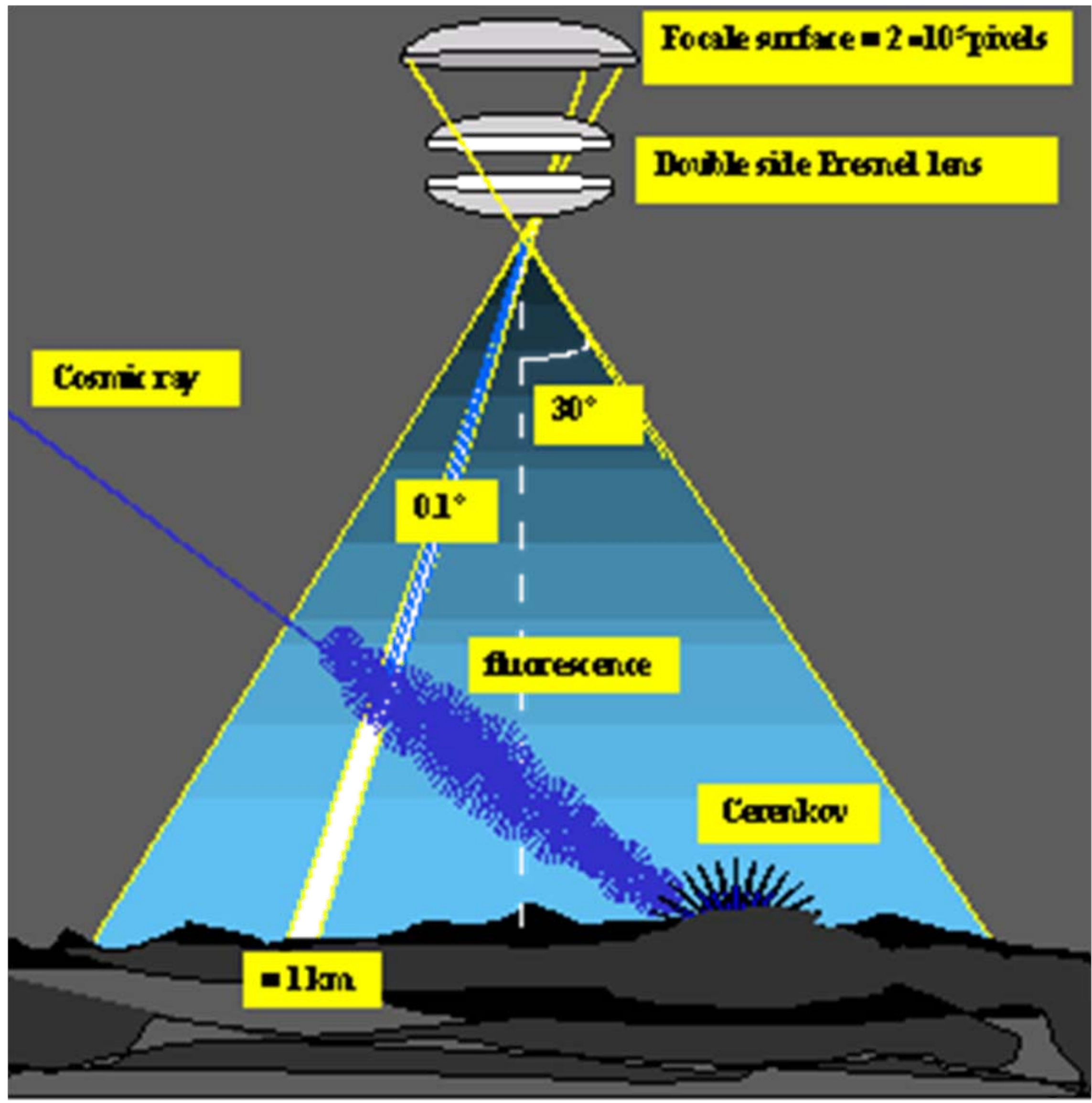
– Active Galactic Nuclei are the main source of VHE cosmic rays
– First measurement of the extragalactic magnetic field:

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

(AdA, 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 (2010?-) is to watch the fluorescence produced by them from the top

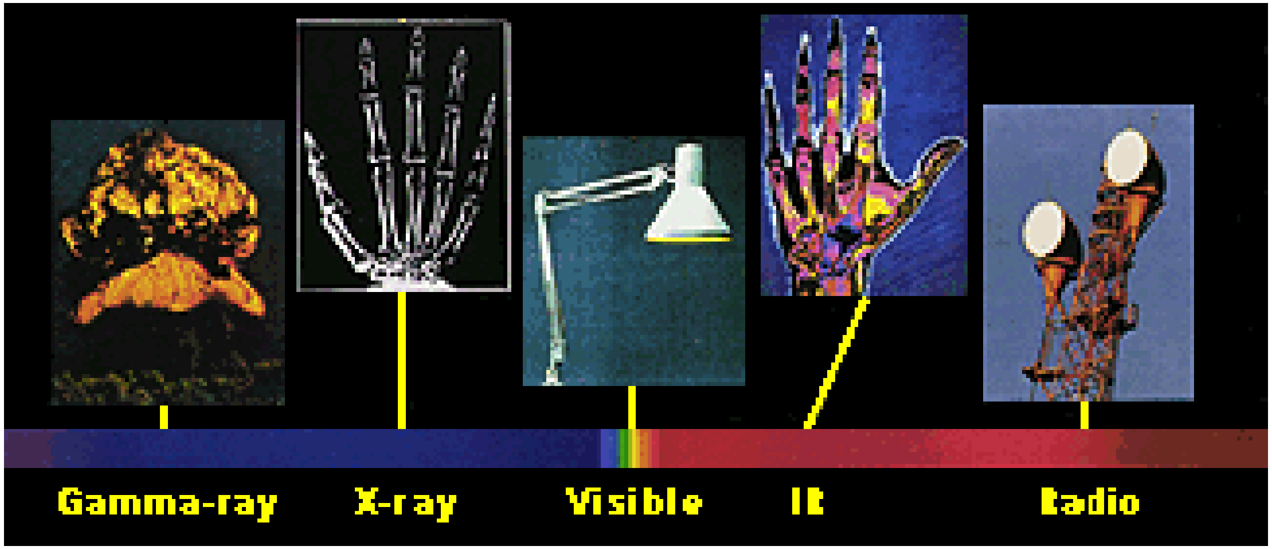


IV

Detectors for multimessanger astrophysics

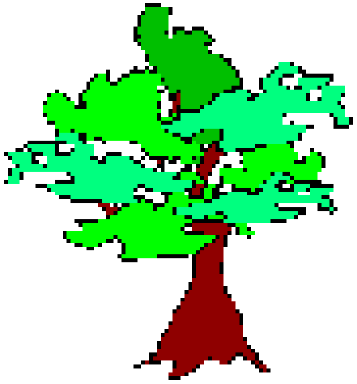
We see only partly what surrounds us

- 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?



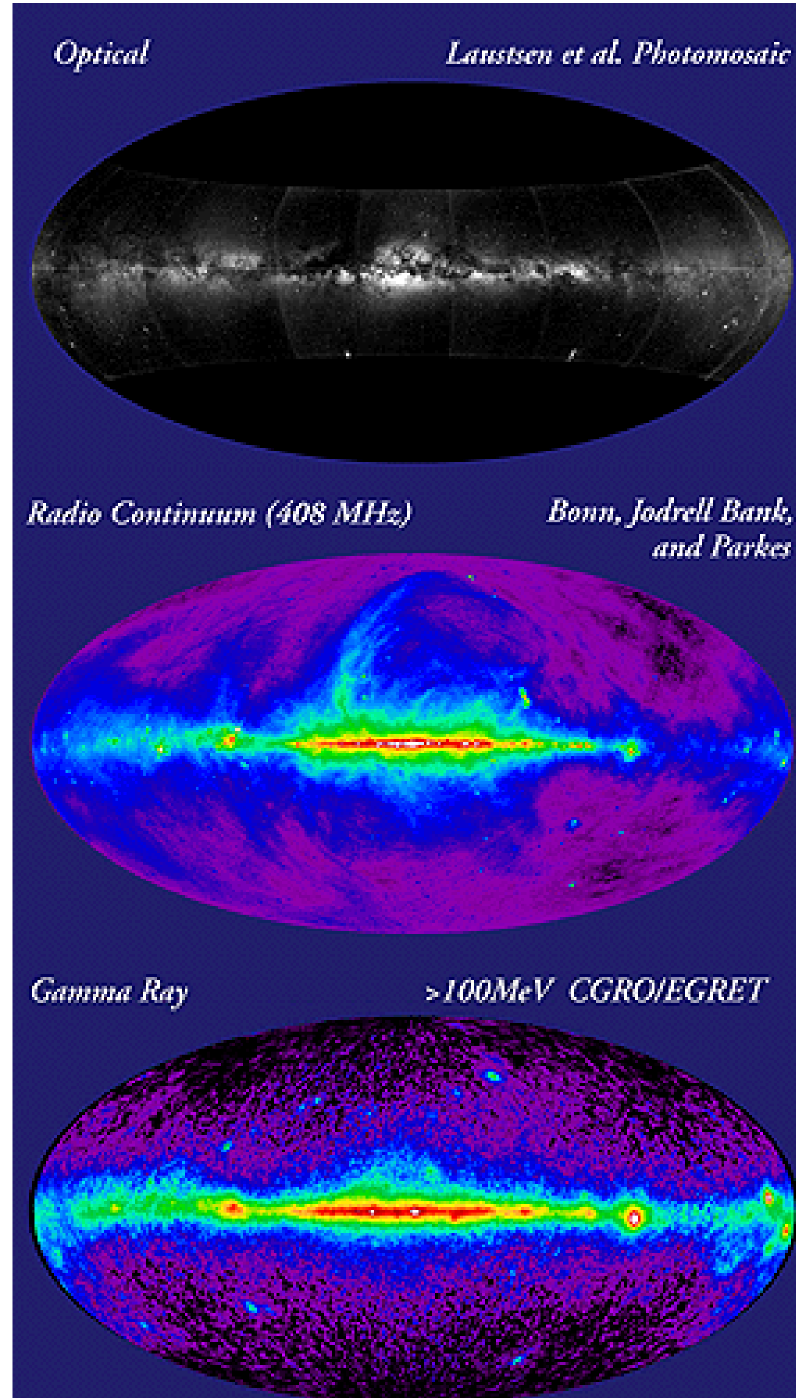
The universe we don’t see

- When we take a picture we capture light

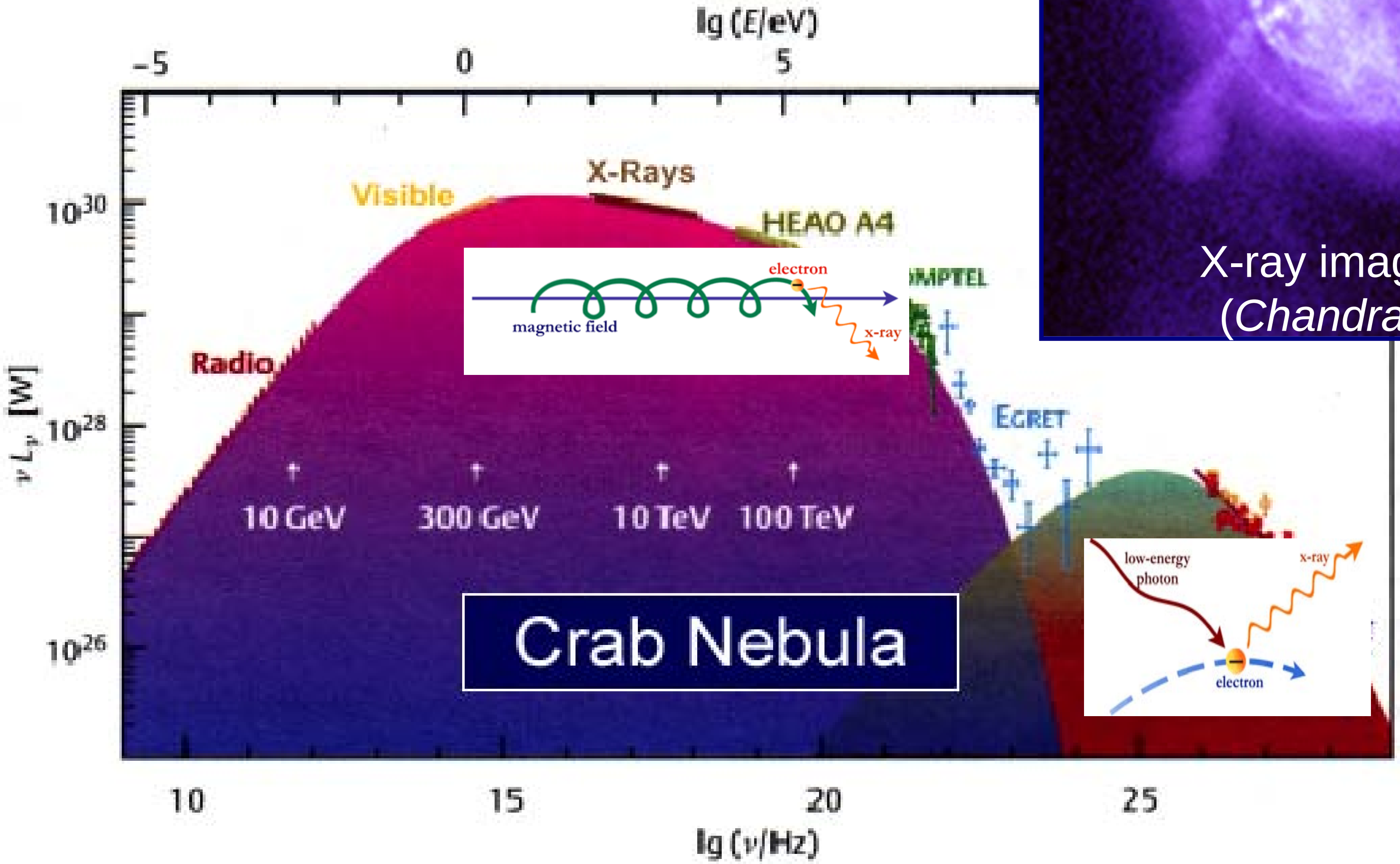
  (a telescope image comes as well from visible light)

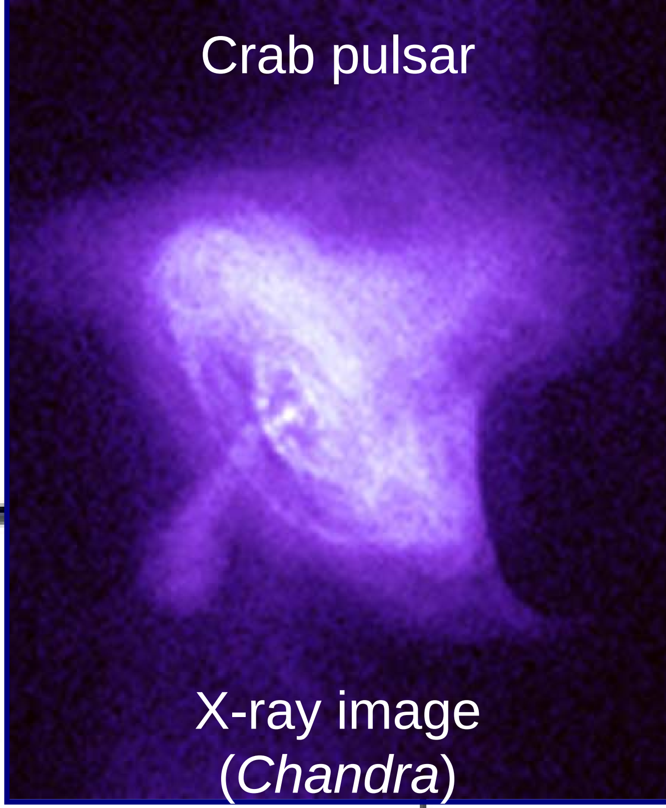
- In the same way we can map into false colors the image from a “X-ray telescope”

- Elaborating the information is crucial



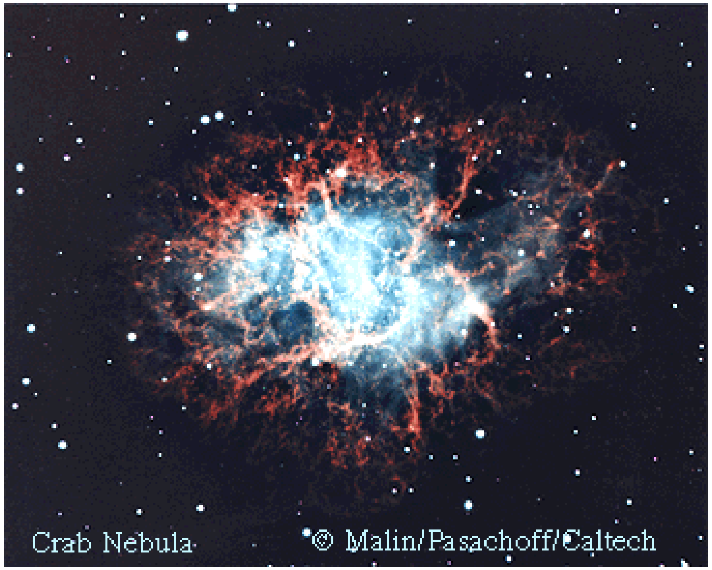
Many sources radiate over a wide range of wavelengths

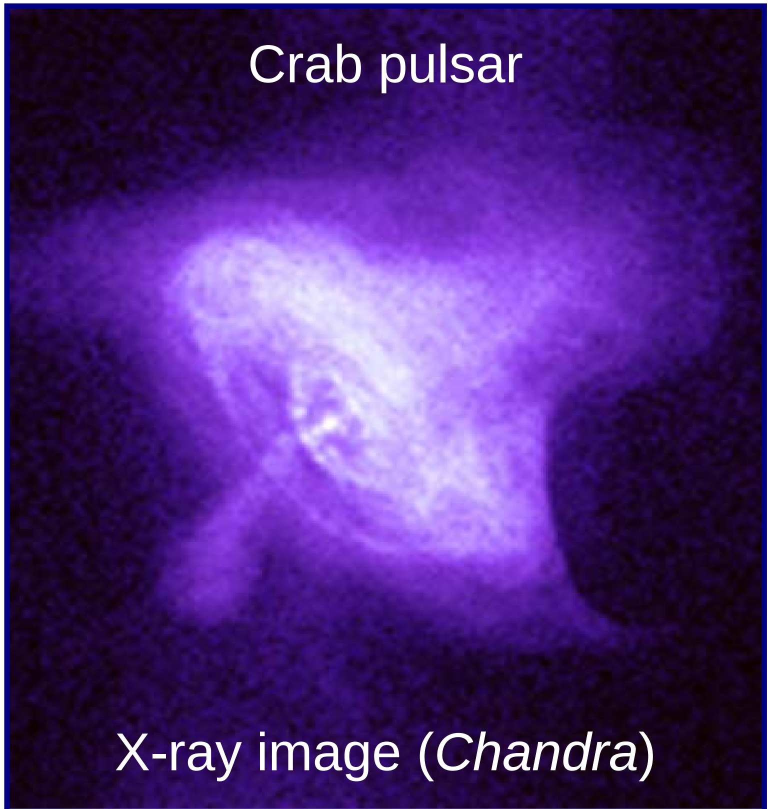




Pulsars

- 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





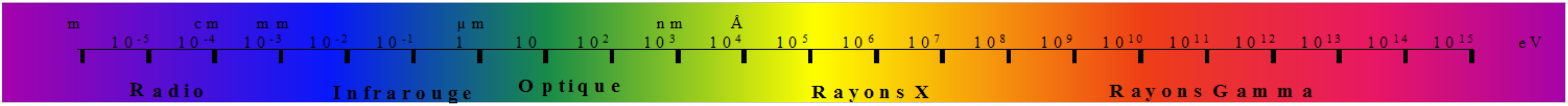
Multi Messenger Astronomy

Radio Telescope
(Bonn)

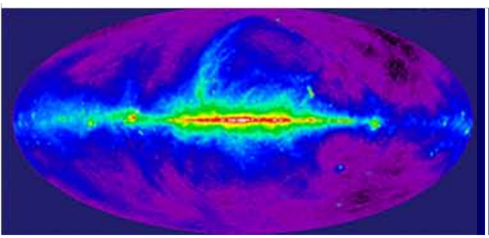
Optical Telescope

X - ray Satellite
(INTEGRAL/ESA)

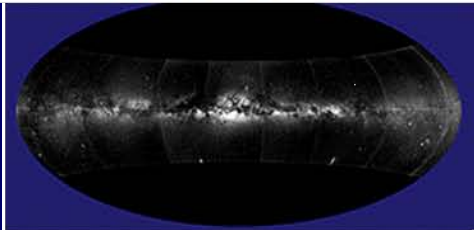
γ - ray Telescope



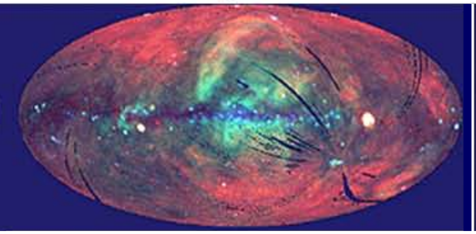
View of sky in Galactic Coordinates in four different photon wavelengths



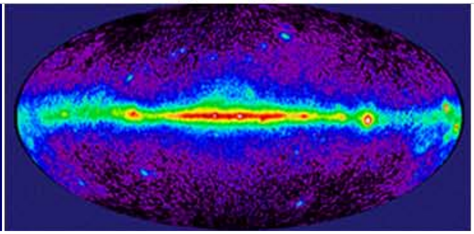
Radio



Visible light

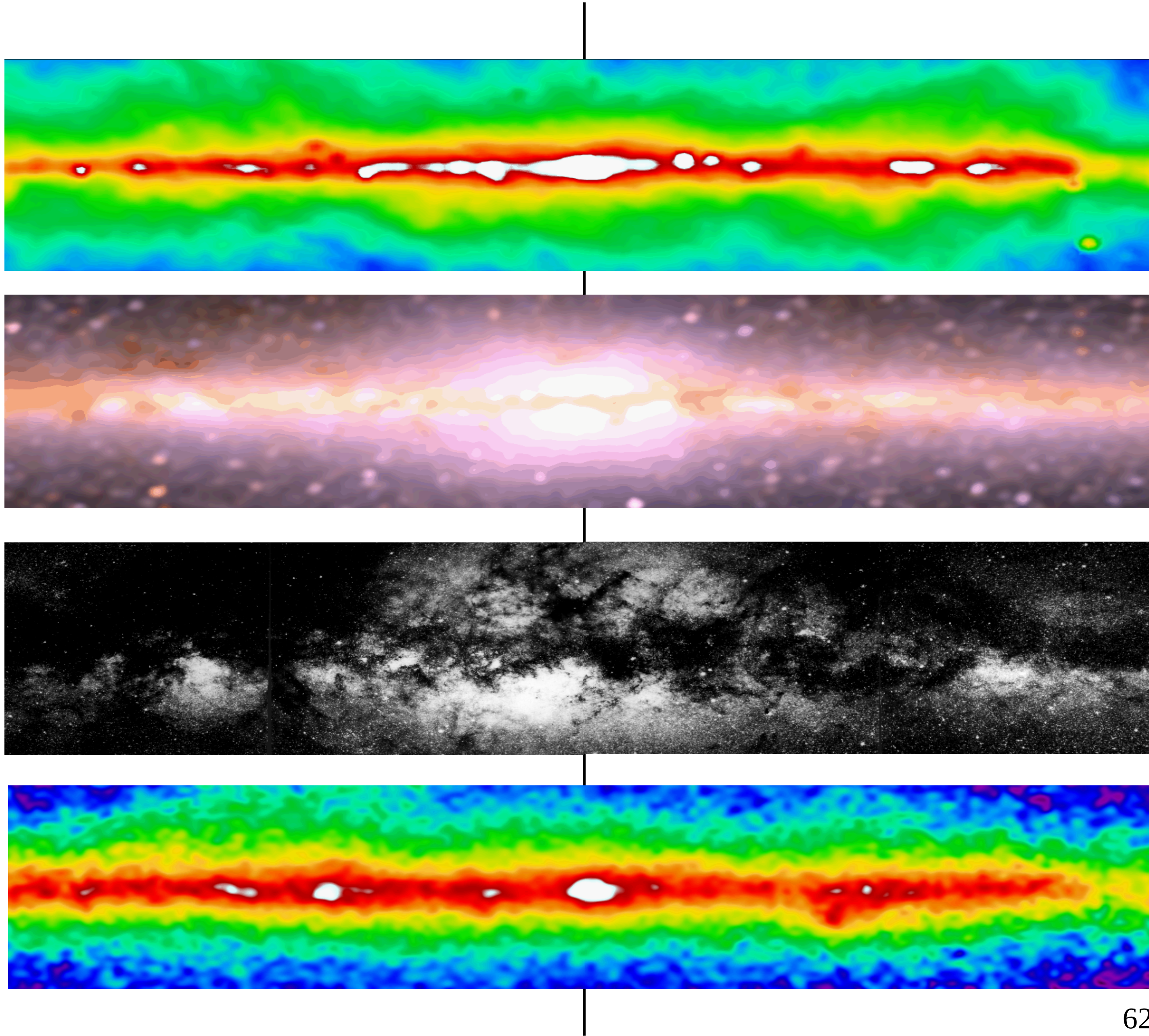


X - rays



γ rays

Centre of Galaxy in Different Photon Wavelengths



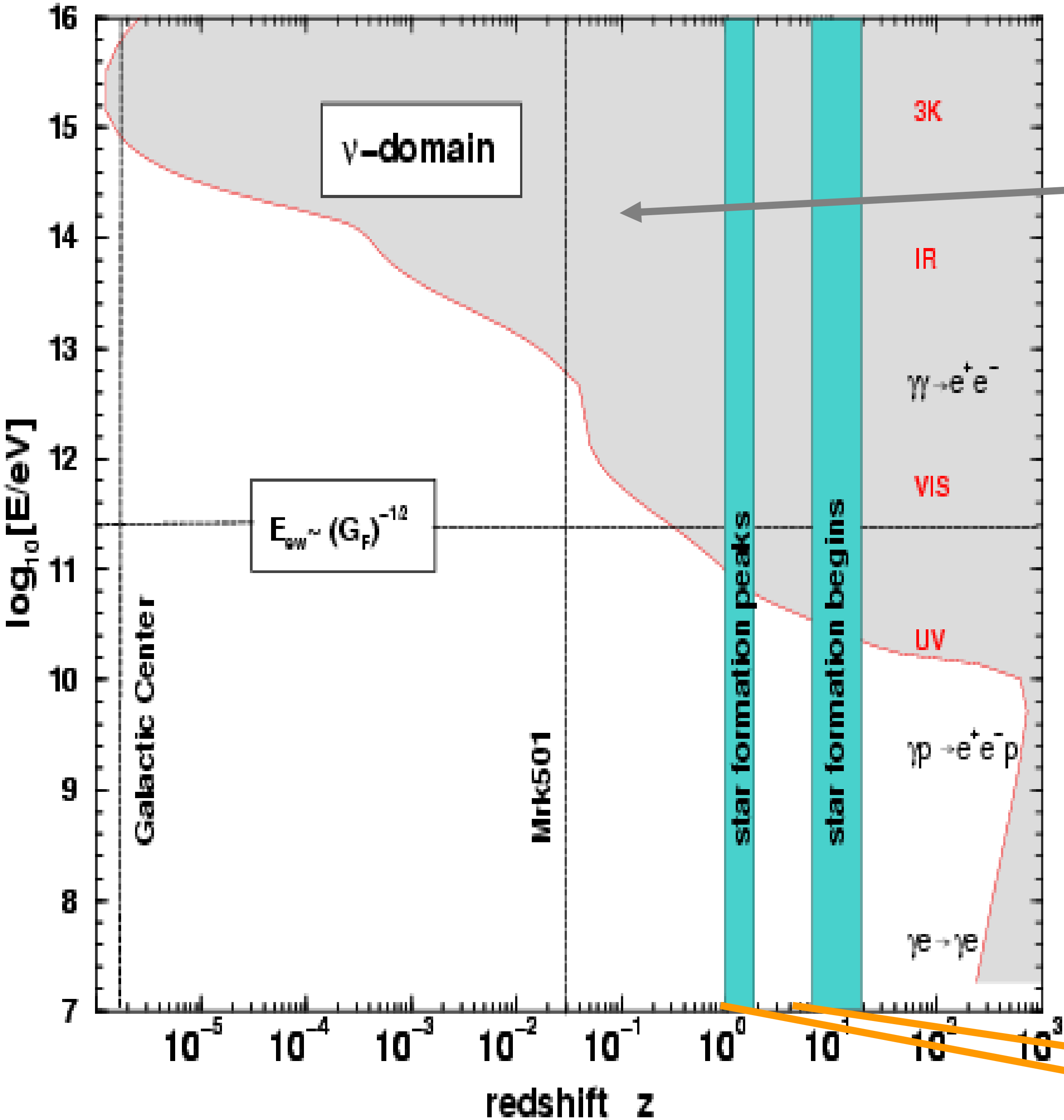
Radio 408 Mhz

Infrared 1-3 μm

Visible Light

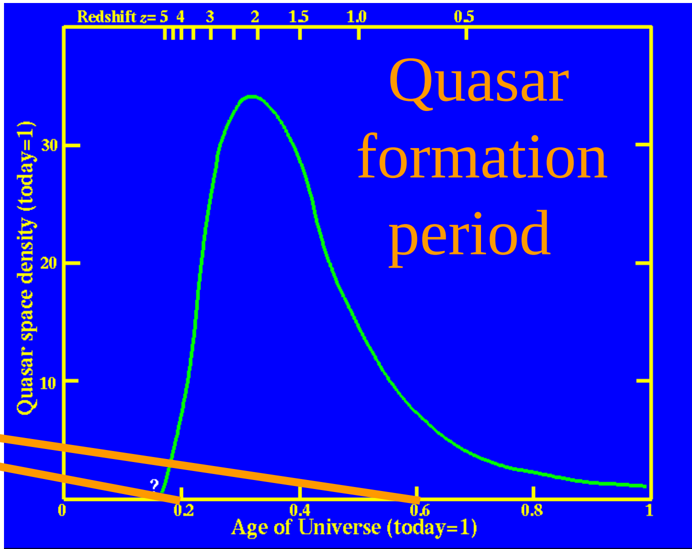
Gamma Rays

Multi-Messengers to see Whole Universe

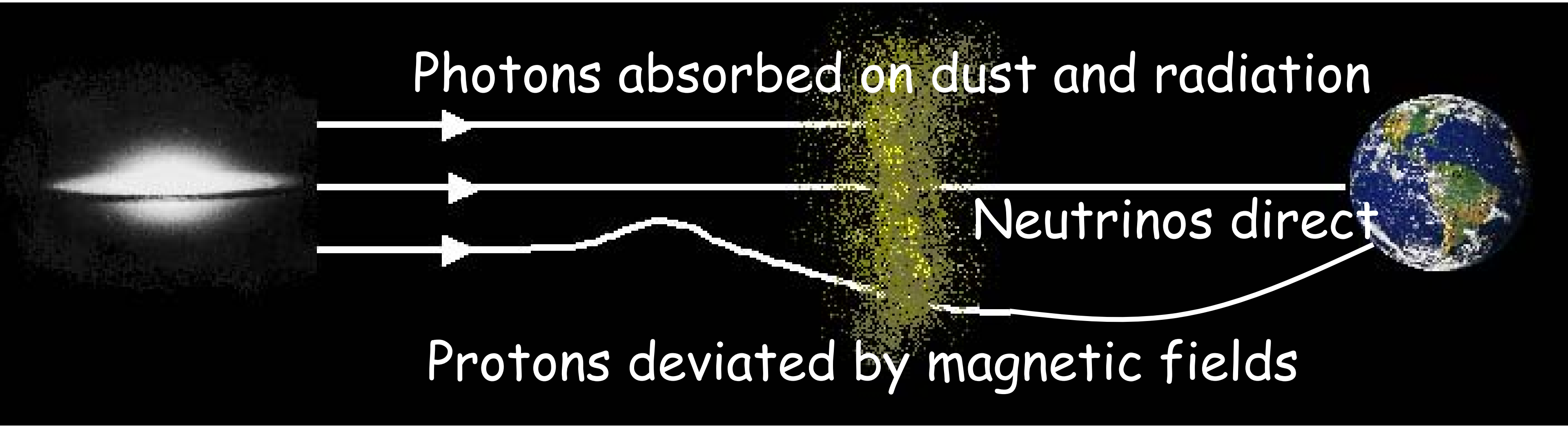


Distant universe
invisible in
high energy photons

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

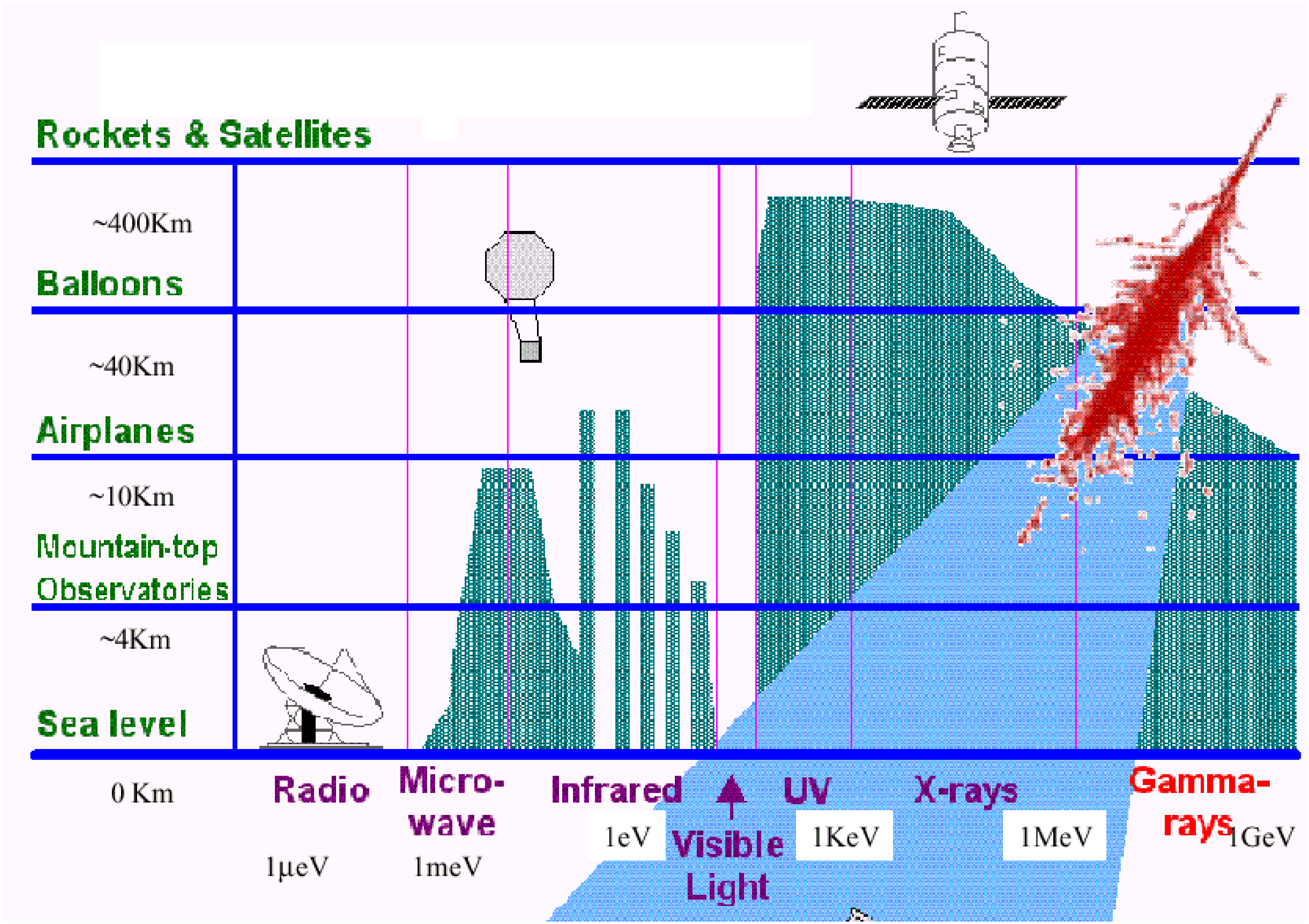
The high-energy γ spectrum

E_γ > 30 keV (λ ~ 0.4 A, ν ~ 7 10^9 GHz)

Although arbitrary, this limit reflects astrophysical and experimental facts:

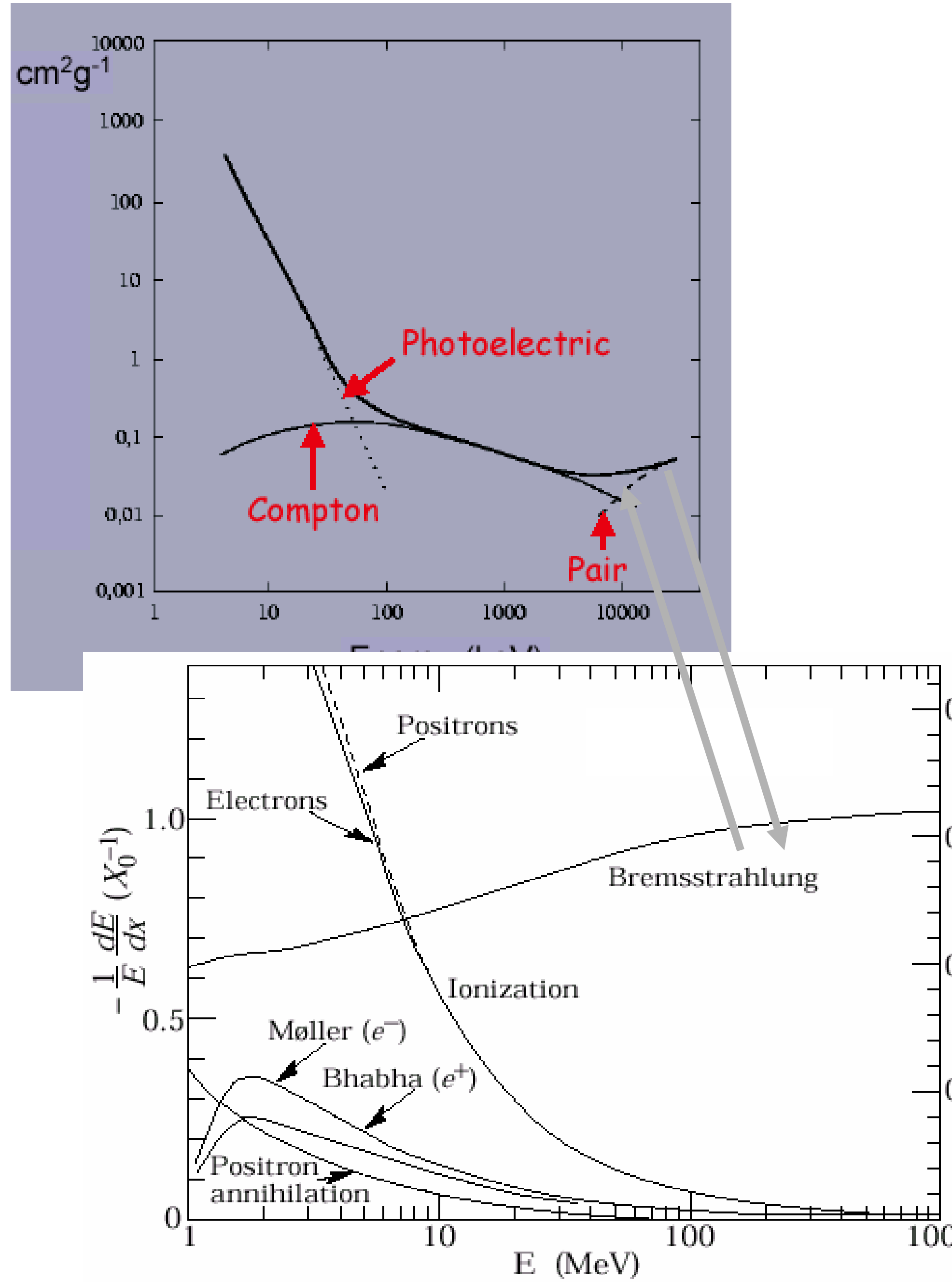
- Thermal emission -> nonthermal emission
- Problems to concentrate photons (-> telescopes radically different from larger wavelengths)
- Large background from cosmic particles

Transparency of the atmosphere

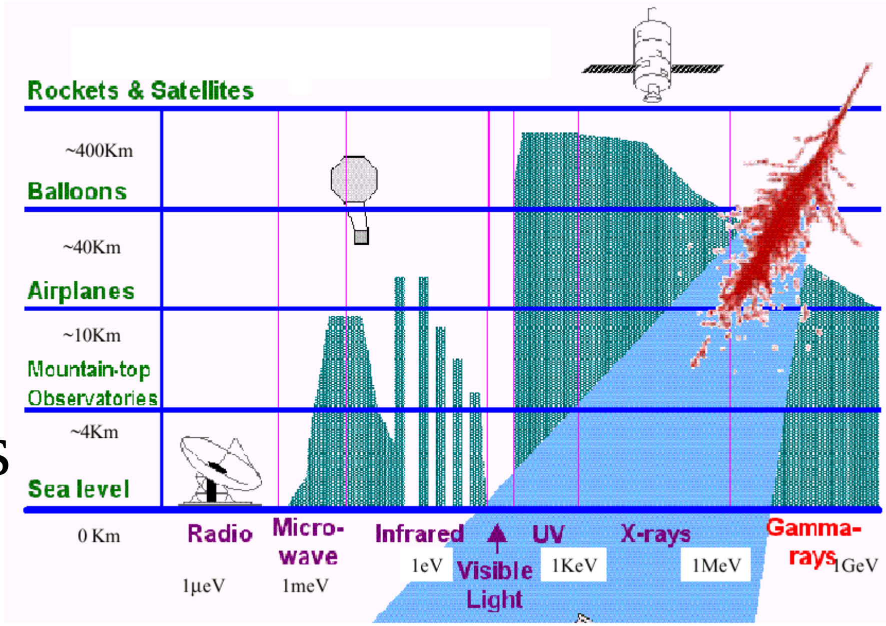


Detection of a high E photon

- 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



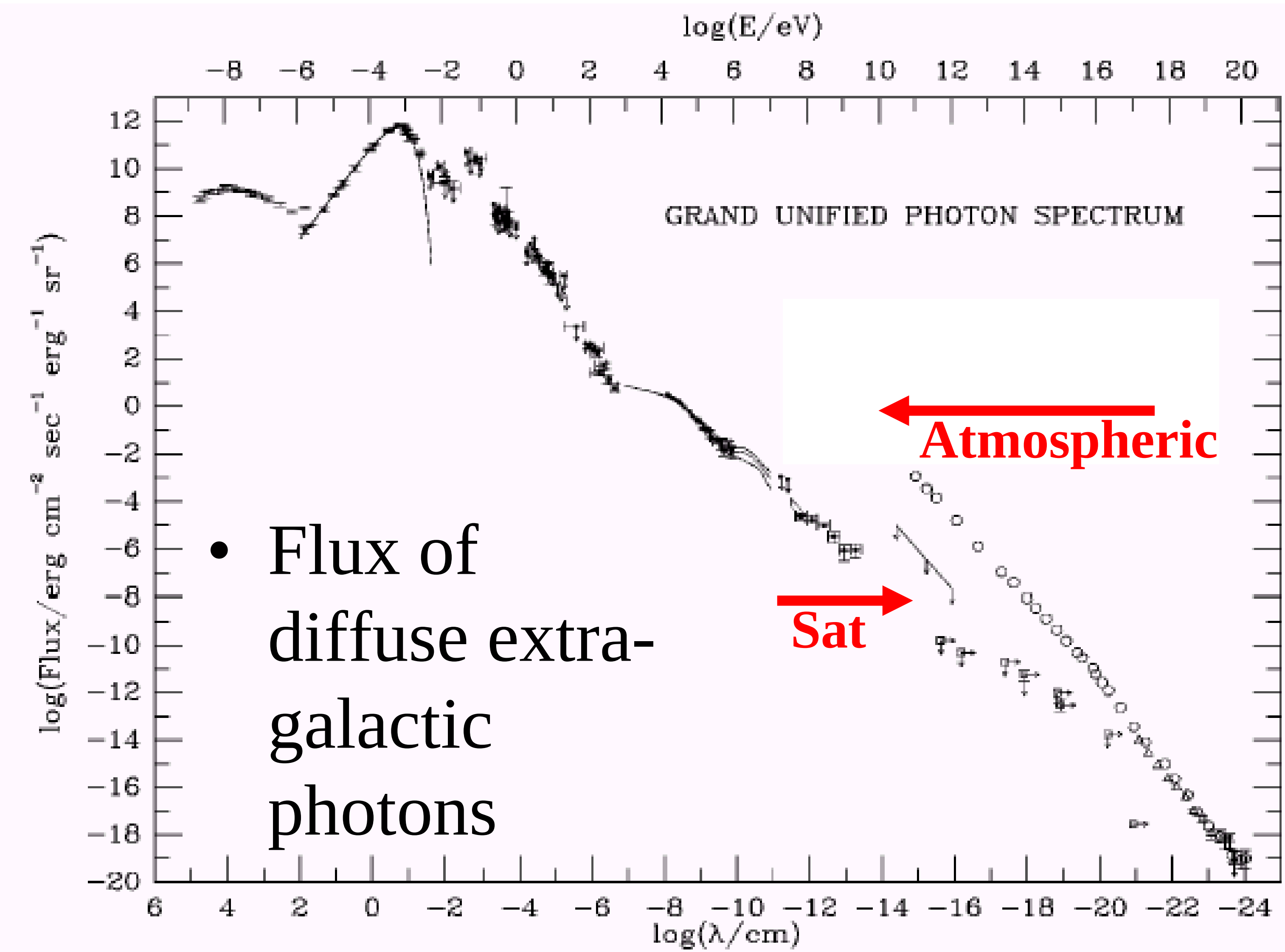
- The earth atmosphere (28 X_0 at sea level) is opaque to X/γ Thus **only a satellite-based detector can detect primary X/γ**

- 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

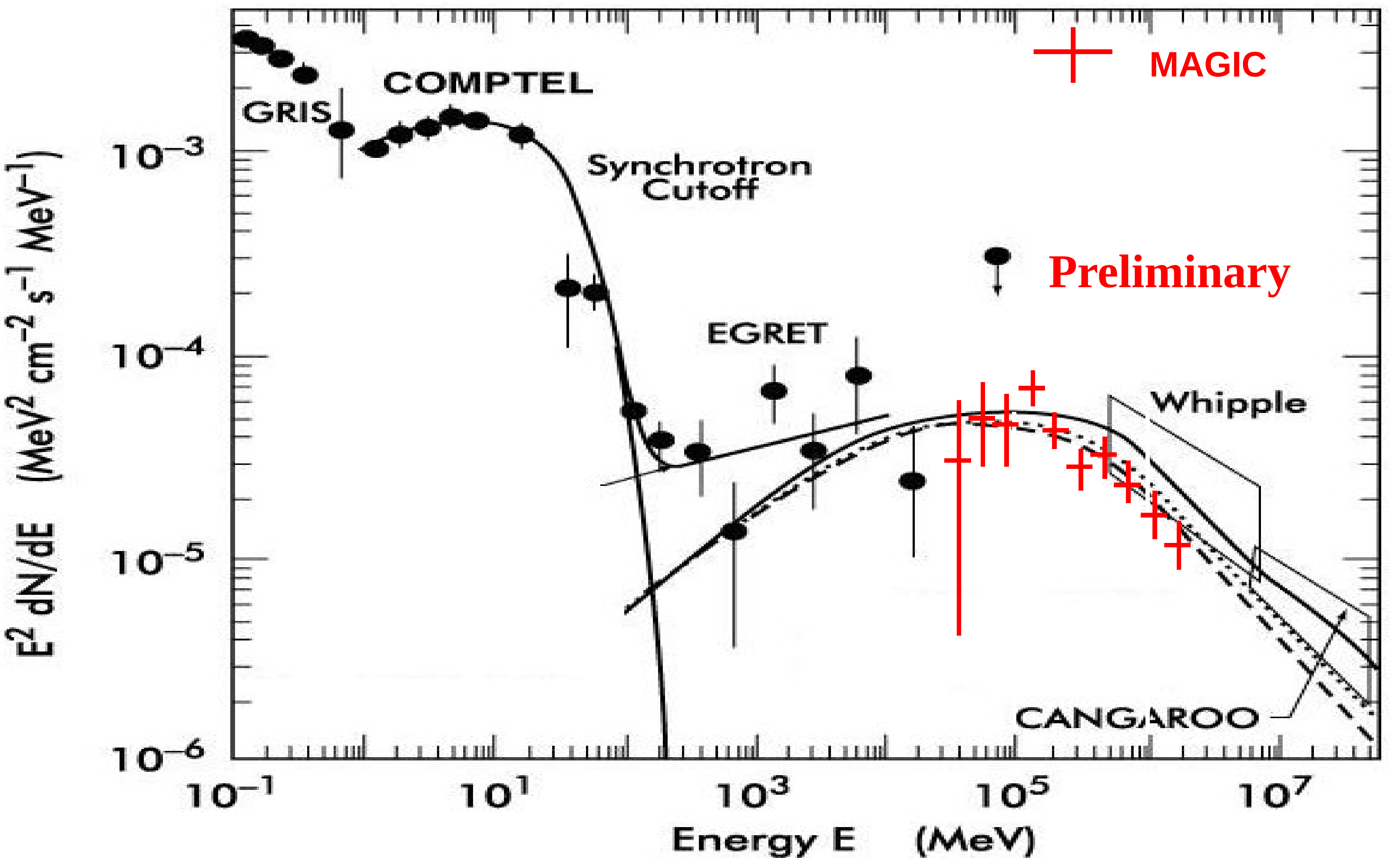
  => **with the present space technology, VHE and UHE gammas can be detected only from atmospheric showers**
  - Earth-based detectors, atmospheric shower satellites

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

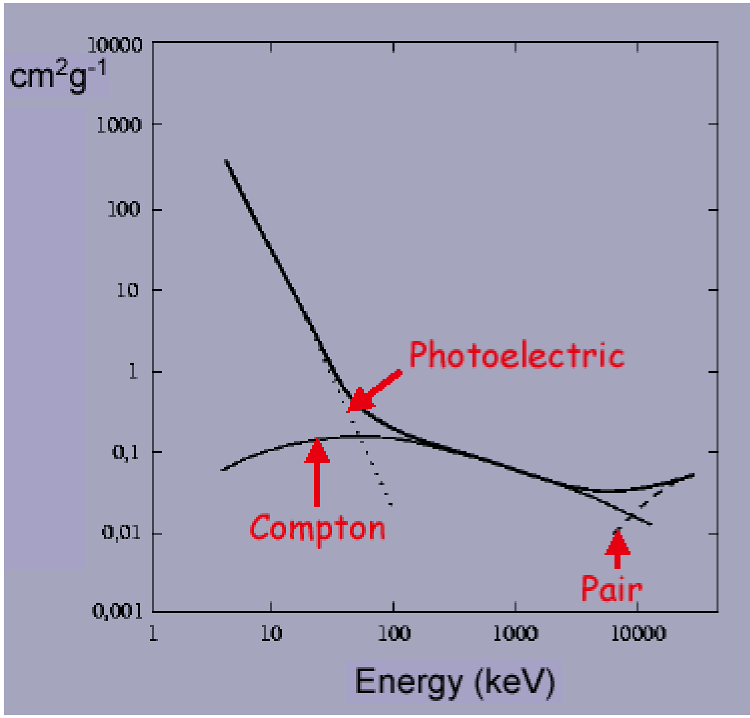
- Time resolution

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

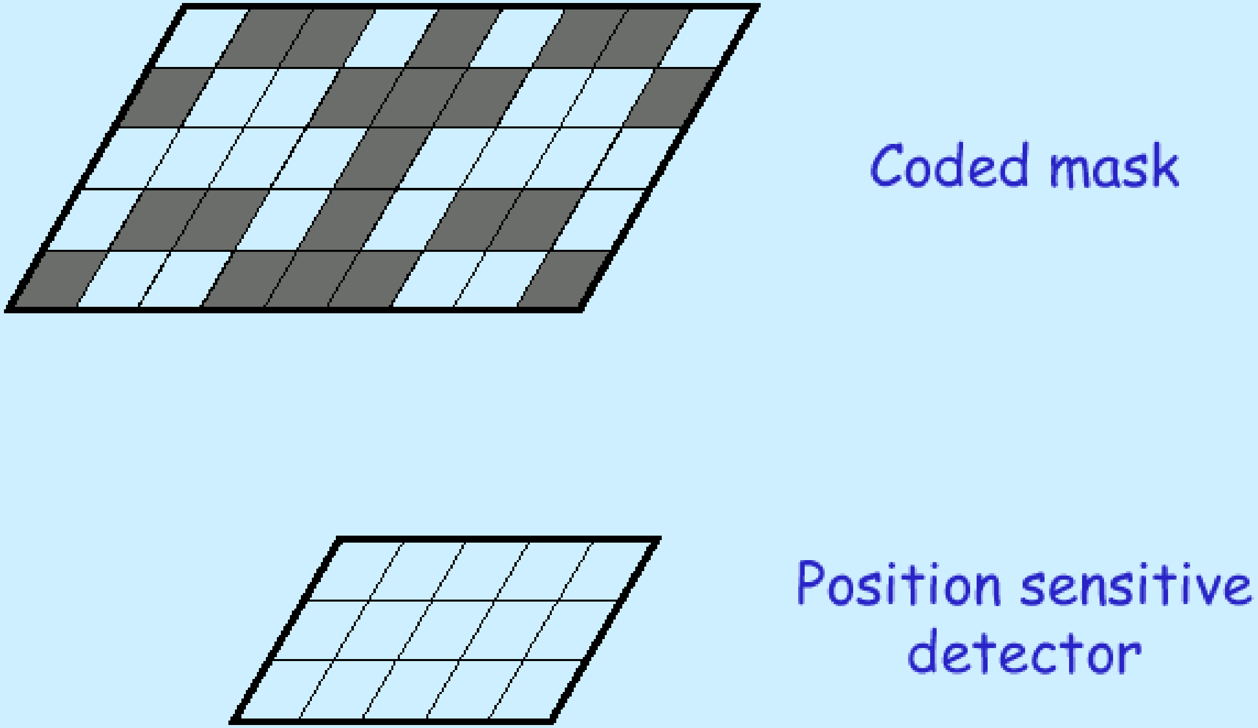
Commonly used detection devices are...

  - gas detectors
  - scintillation counters
  - semiconductor detectors

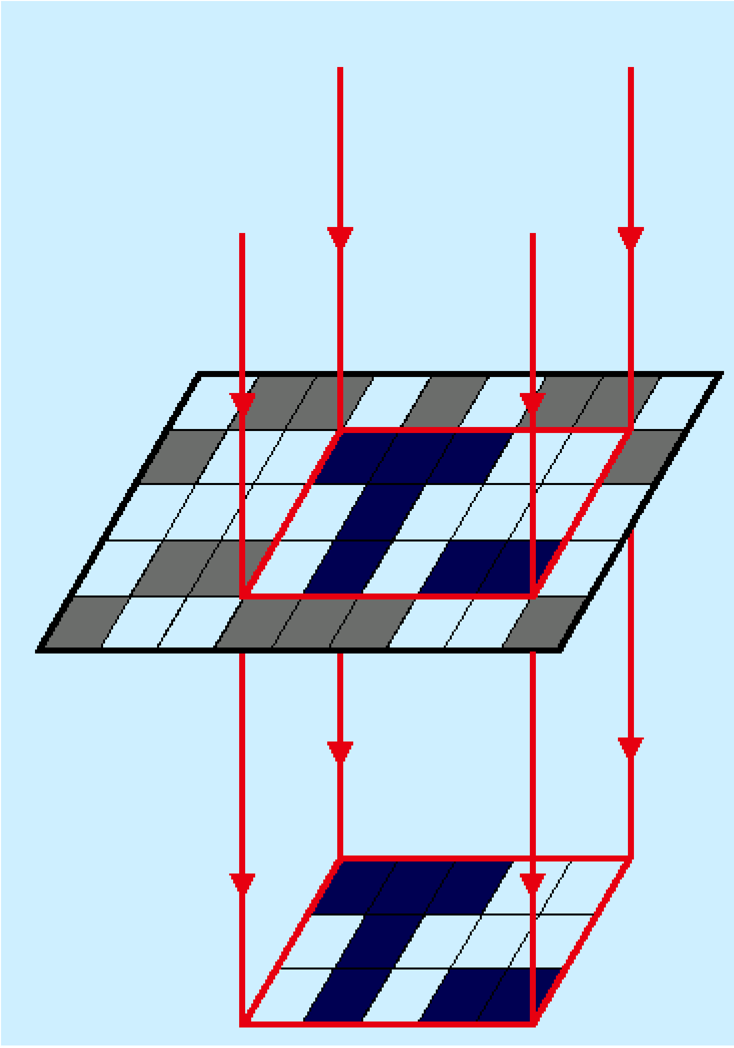


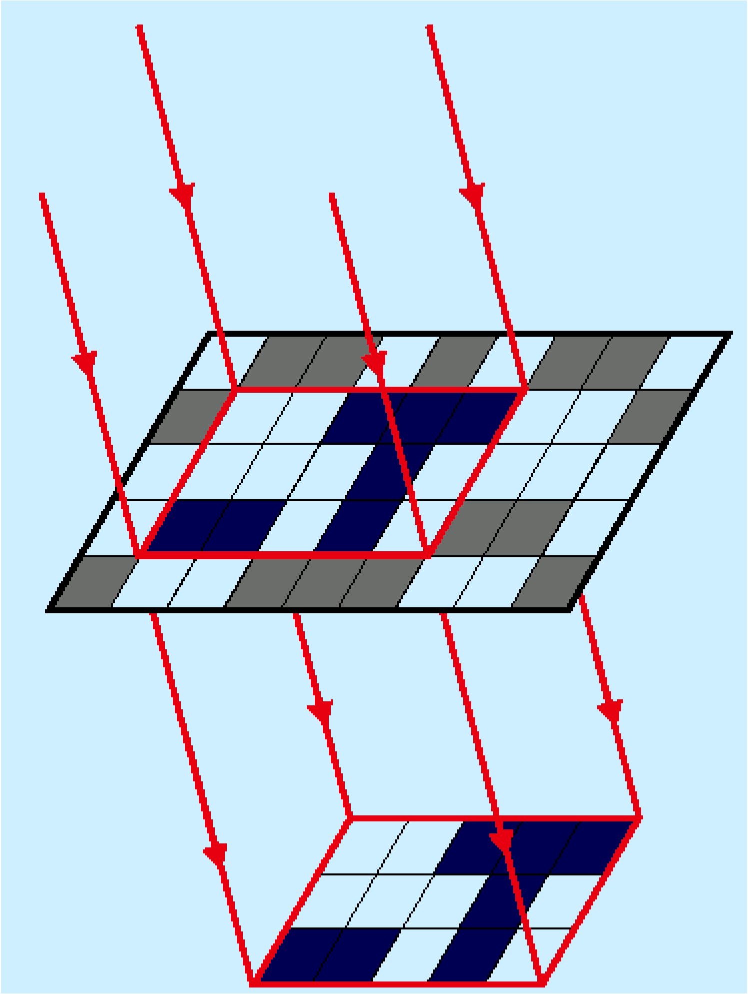
X detection (direction-sensitive)

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)





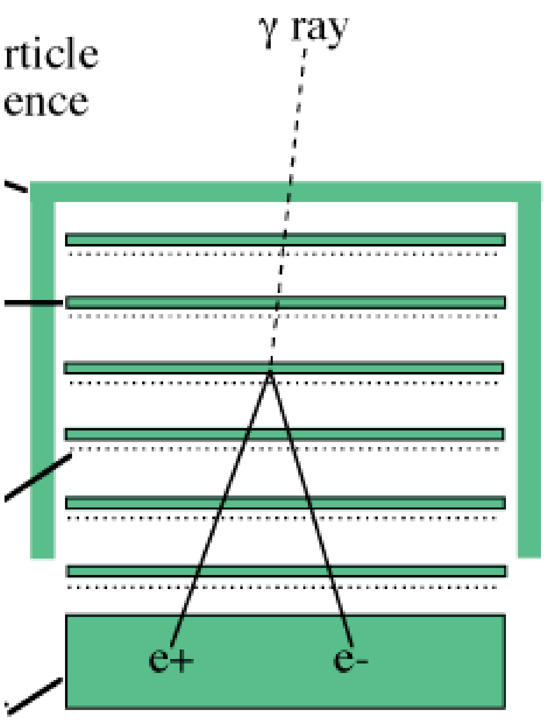
Unfolding is a nice mathematical problem !

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/pβ) $(L/X_0)^{1/2}$ (dominant)

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

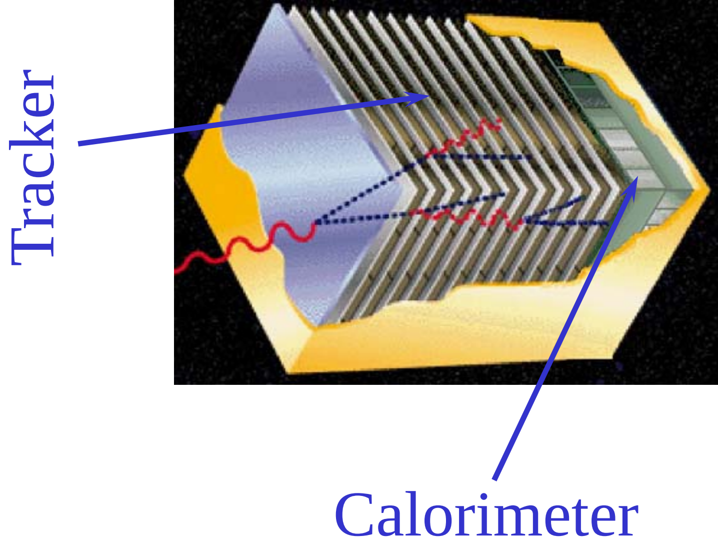
  (power consumption << 1 kW)

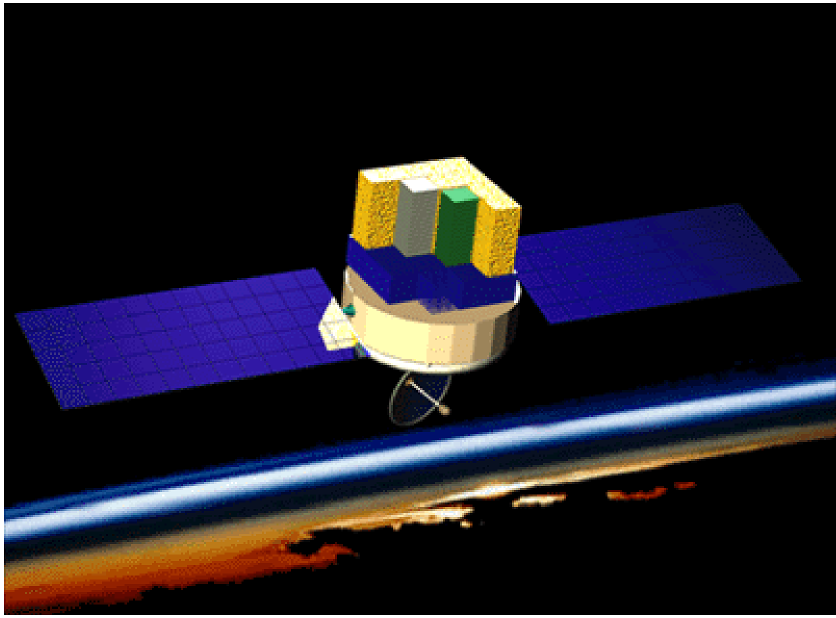
- If possible, a calorimeter in the bottom to get E resolution, but watch the weight (leakage => deteriorated resolution)

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

GLAST

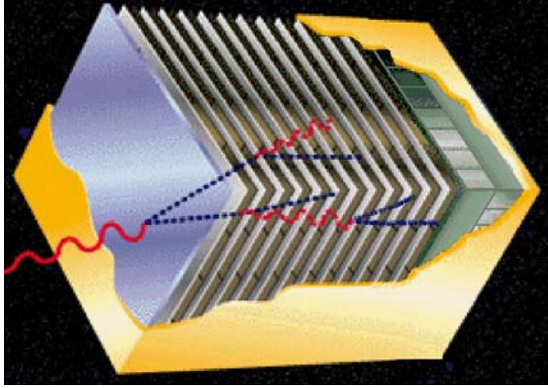
- γ telescope on satellite for the range 20 MeV-300 GeV
  - hybrid tracker + calorimeter
- International collaboration US-France-Italy-Japan-Sweden
  - Broad experience in high-energy astrophysics and particle physics (science + instrumentation)
- Timescale: 2008-2012 (->2017)
- Wide range of physics objectives:
  - Gamma astrophysics
  - Fundamental physics





A HEP / astrophysics partnership

GLAST: the instrument

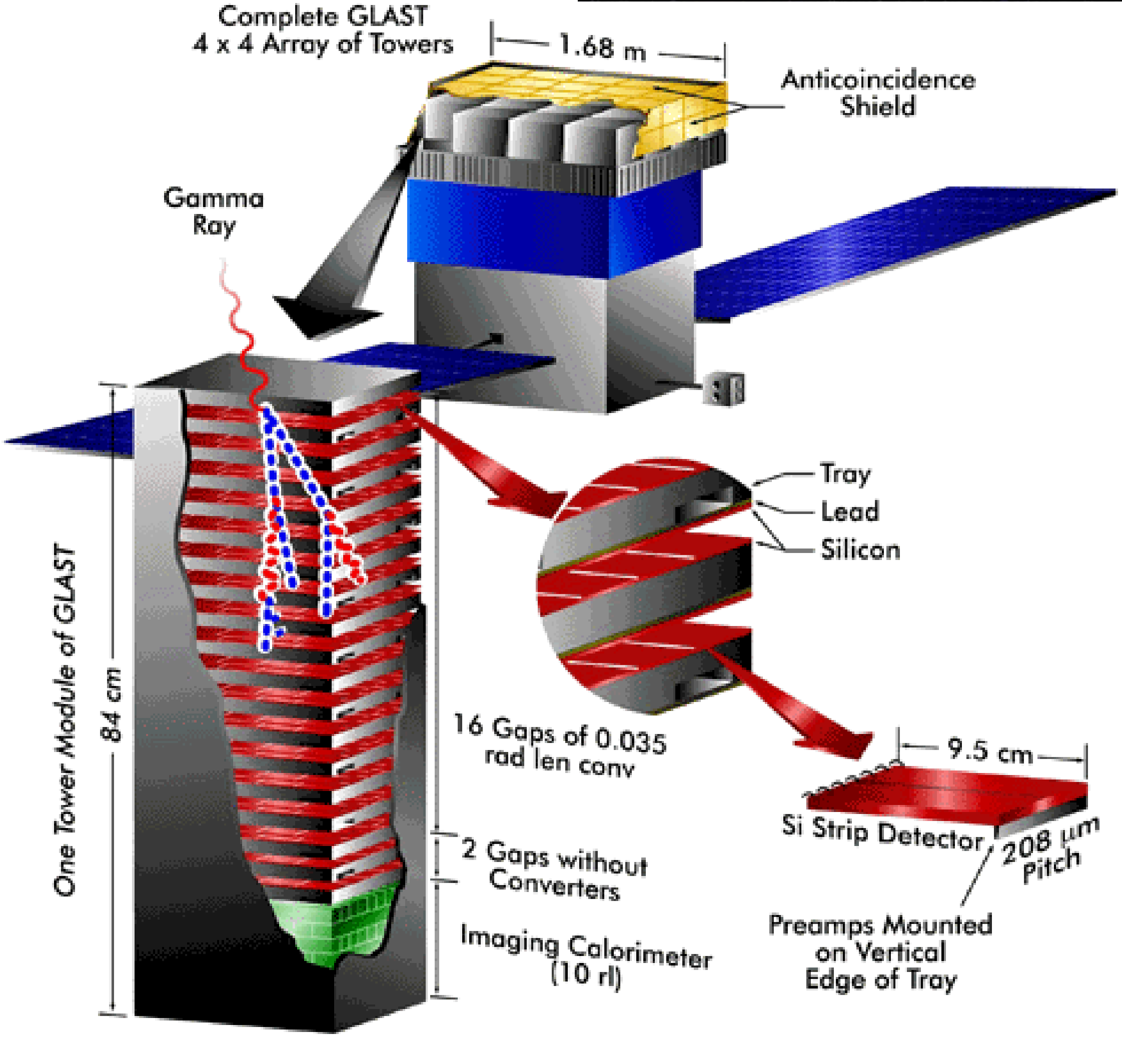


- Tracker
  Si strips + converter

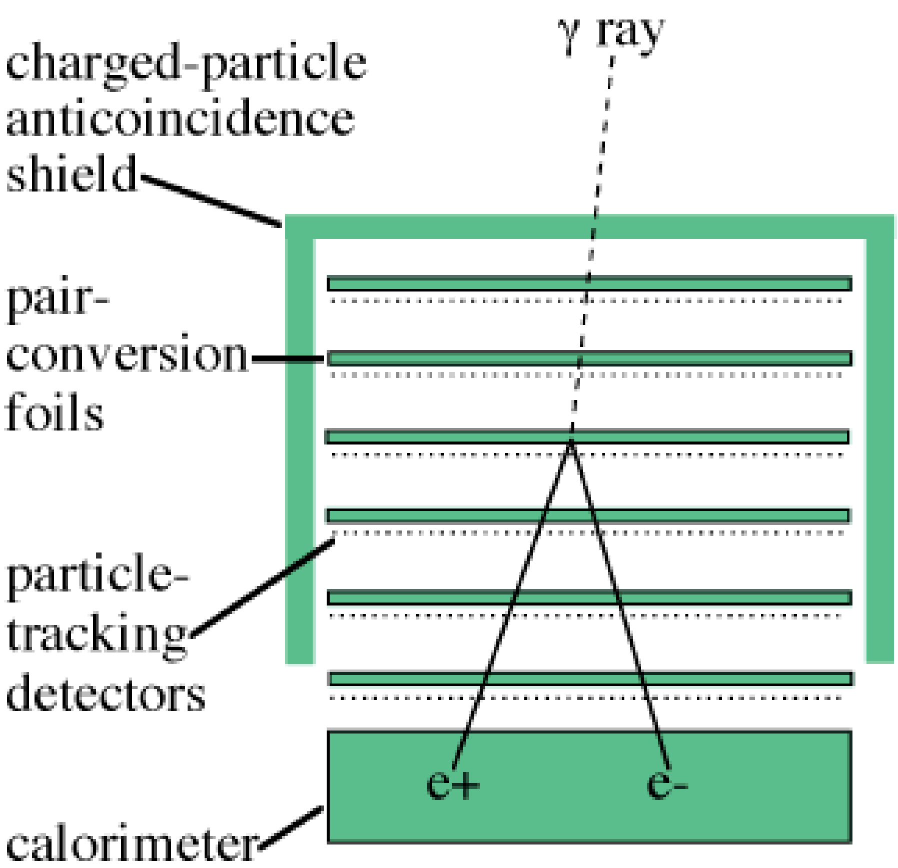
- Calorimeter
  CsI with diode readout

(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

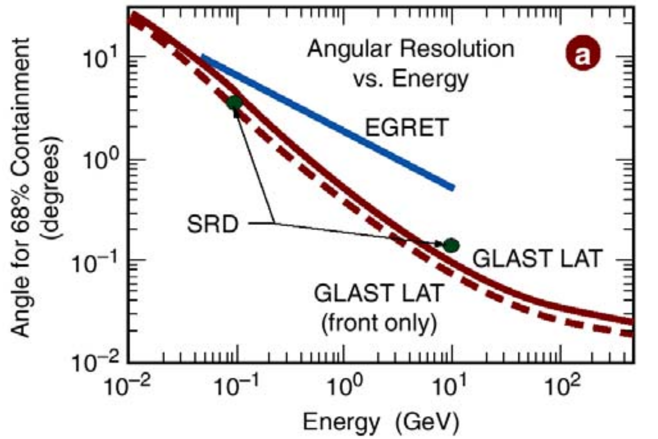


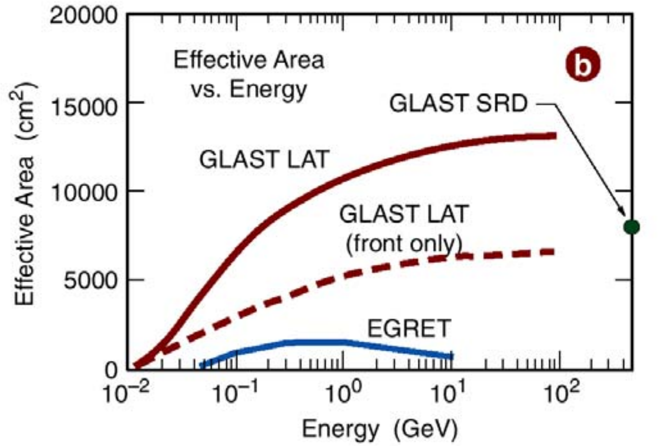
Si strips + converter
- – High signal/noise
- – Rad-hard
- – Low power

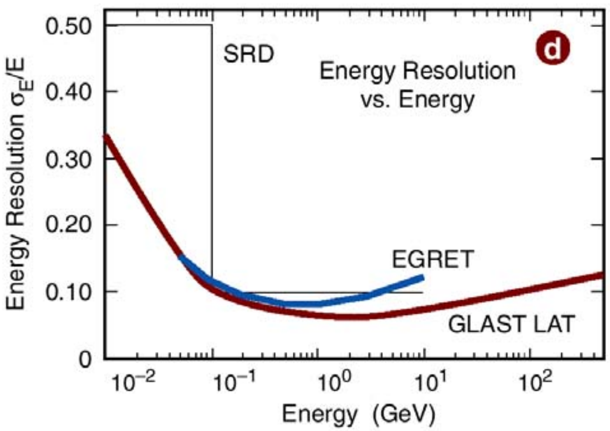
- 4x4 towers, of 37 cm × 37 cm of Si
- 18 *x*,*y* planes per tower
  - – 19 "tray" structures
    - 12 with 2.5% Pb on bottom
    - 4 with 25% Pb on bottom
    - 2 with no converter
- Electronics on the sides of trays
  - – Minimize gap between towers
- Carbon-fiber walls to provide stiffness

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

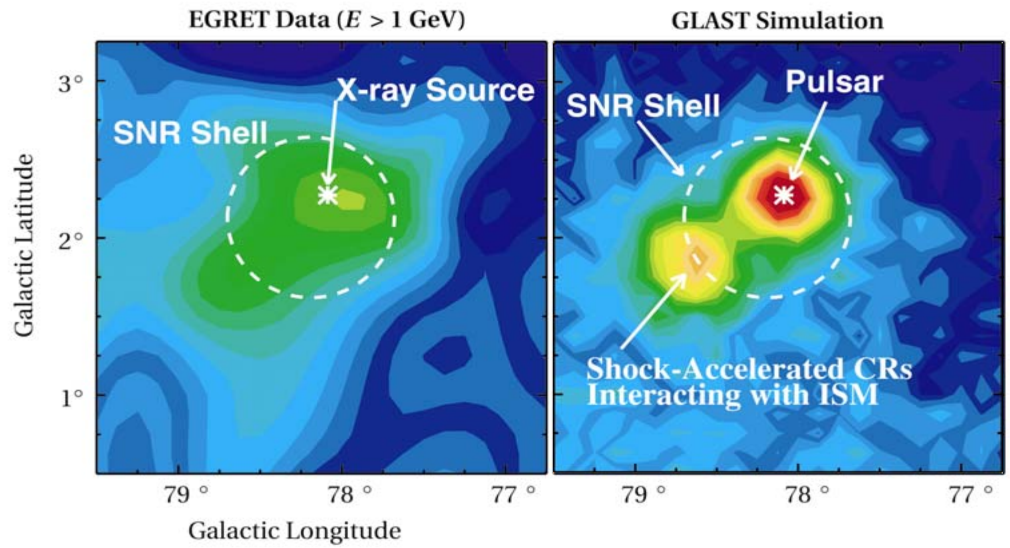




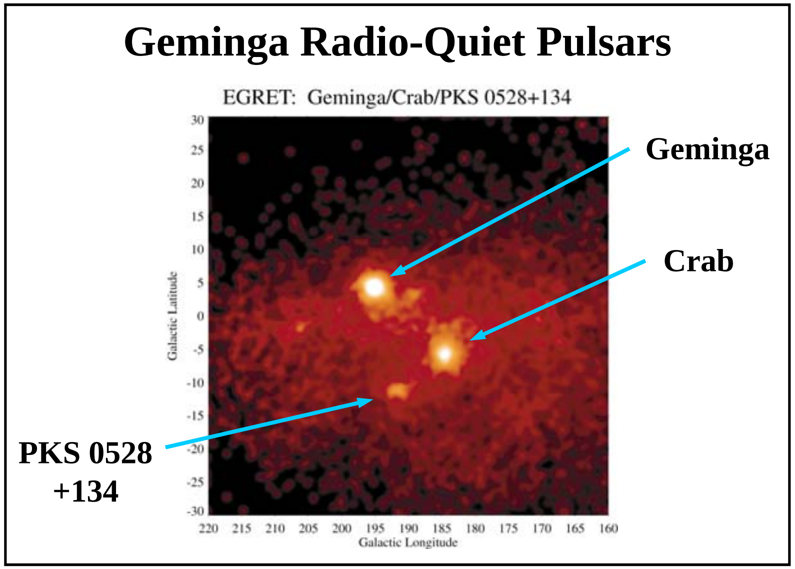


GLAST performance two examples of application

- Cosmic ray production



- Facilitate searches for pulsations from millisecond pulsars

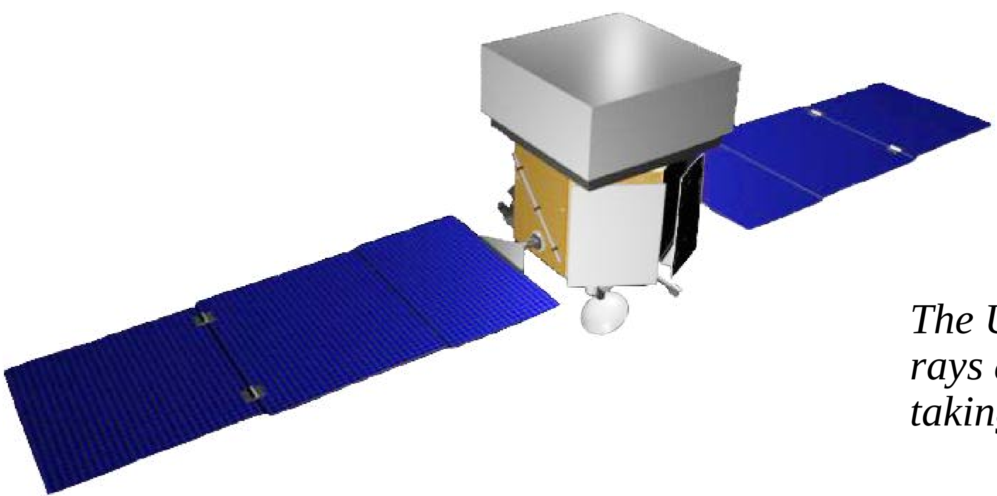


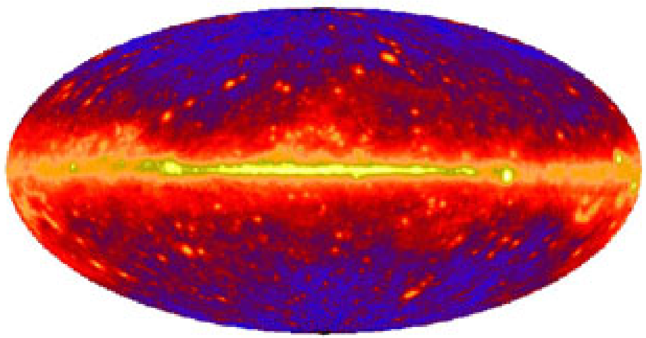
The Gamma-ray Large Area Space Telescope

GLAST will be sent in space in May 2008

A collaboration USA-Japan-France-Italy-Sweden

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

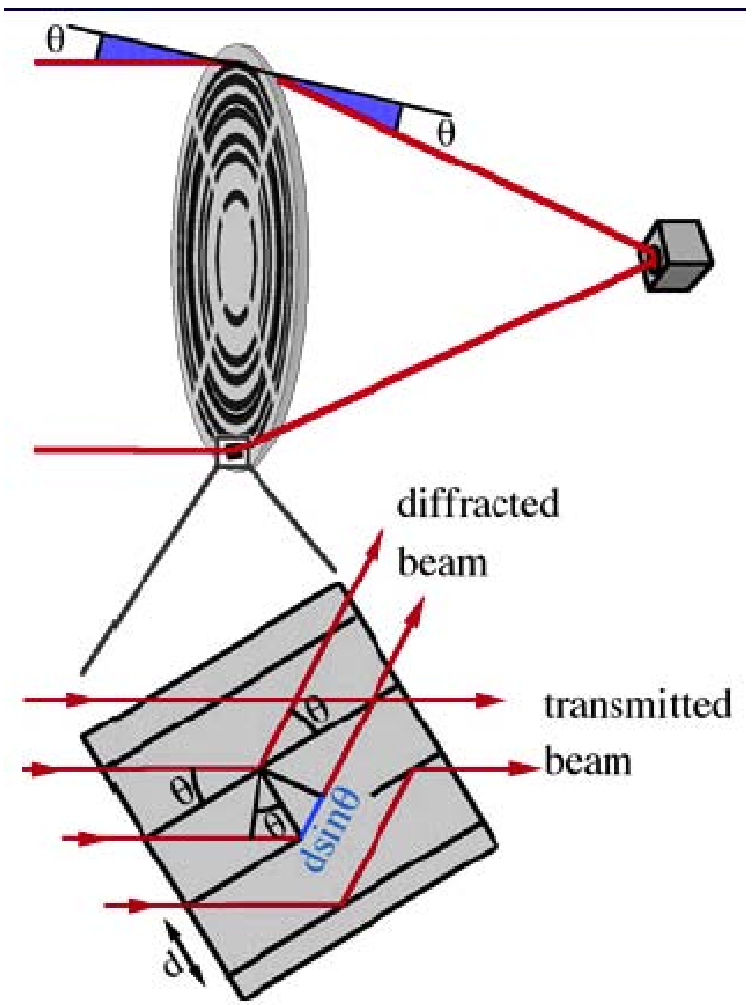




The Universe in the gamma rays after one year of data taking. Center: our galaxy

But despite the progress in satellites…

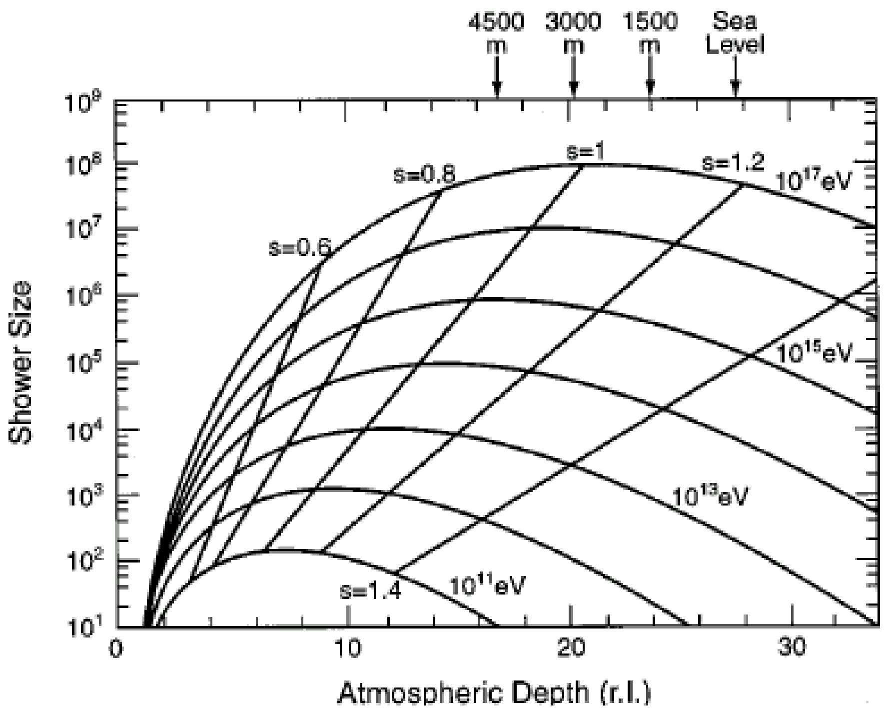
- The problem of the flux (~1 photon/day/km2 @ ~30 PeV) cannot be overcome
  - Photon concentrators work only at low energy
  - The key for VHE gamma astrophysics and above is in ground-based detectors
  - Also for dark matter detection…



Earth-based detectors
Properties of Extensive Air Showers

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

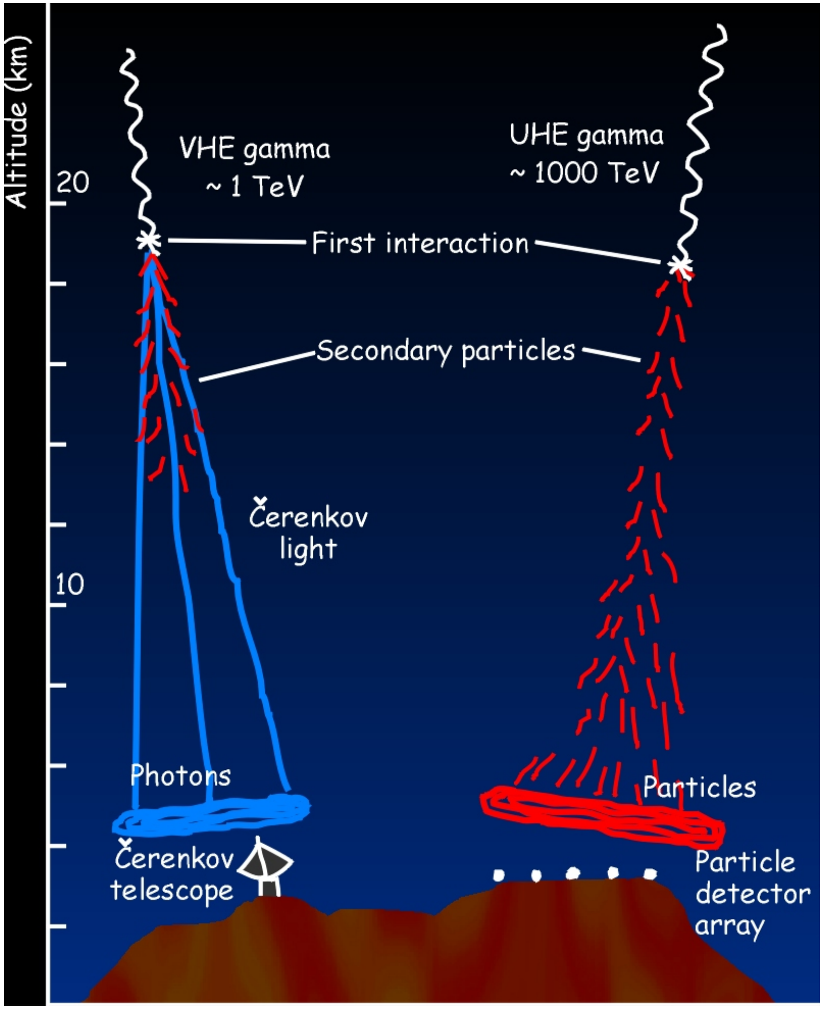
  Predominant interactions e.m.
  - e+e- pair production dominates
  - electrons loose energy via brem
  - Rossi approximation B is valid
    - Maximum at $z/X_0 \approx \ln(E/\varepsilon_0)$; ε_0 is the critical energy ~80 MeV in air; X_0 ~ 300 m at stp
    - Cascades ~ a few km thick
    - Lateral width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

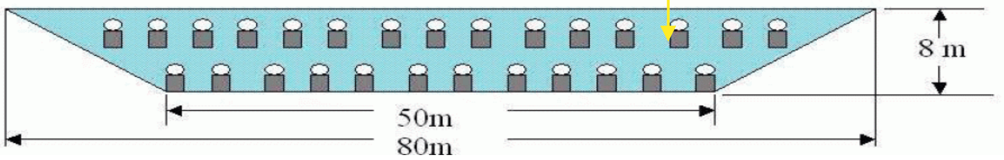
Ground detectors: EAS vs. IACT



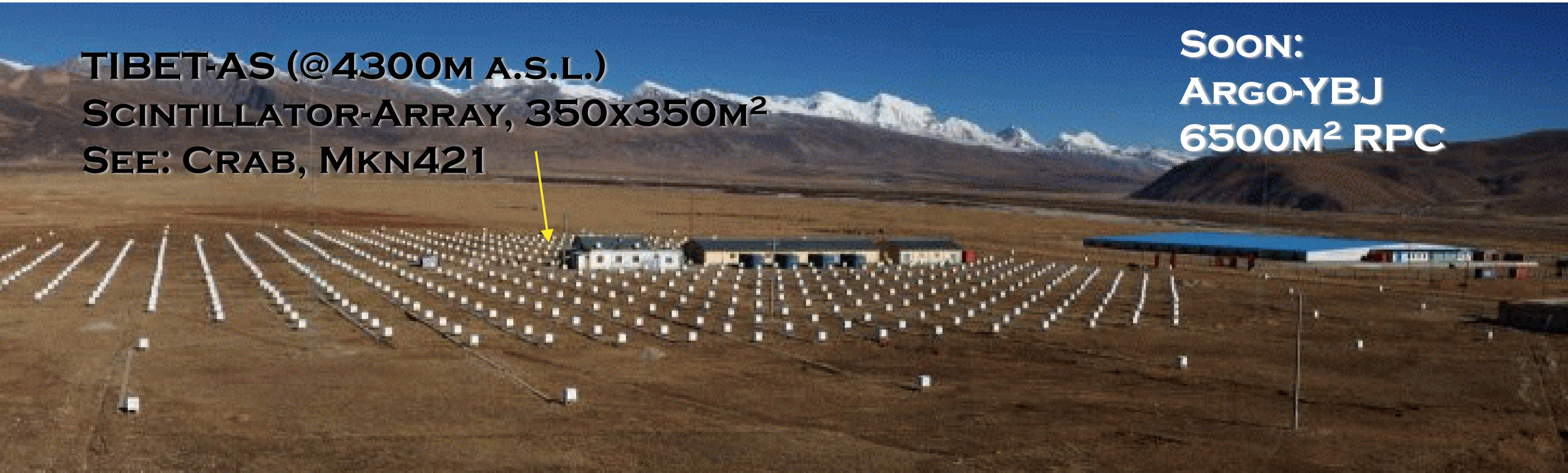
- EAS (Extensive Air Shower): detection of the charged particles in the shower
- Cherenkov detectors: (IACT): detection of the Cherenkov light from charged particles in the atmospheric showers

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

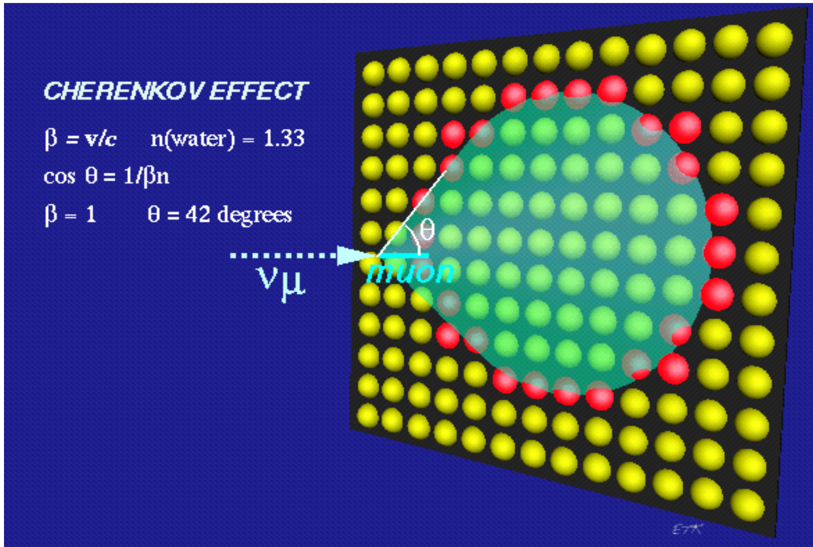
- Č light is produced by particles faster than light in air
- Limiting angle $\cos \theta_c \sim 1/n$
  - $\theta_c \sim 1^o$ at sea level, 1.3^o at 8 km asl
  - Threshold @ sea level : 21 MeV for e, 44 GeV for μ

Maximum of a 1 TeV γ shower ~ 8 Km asl

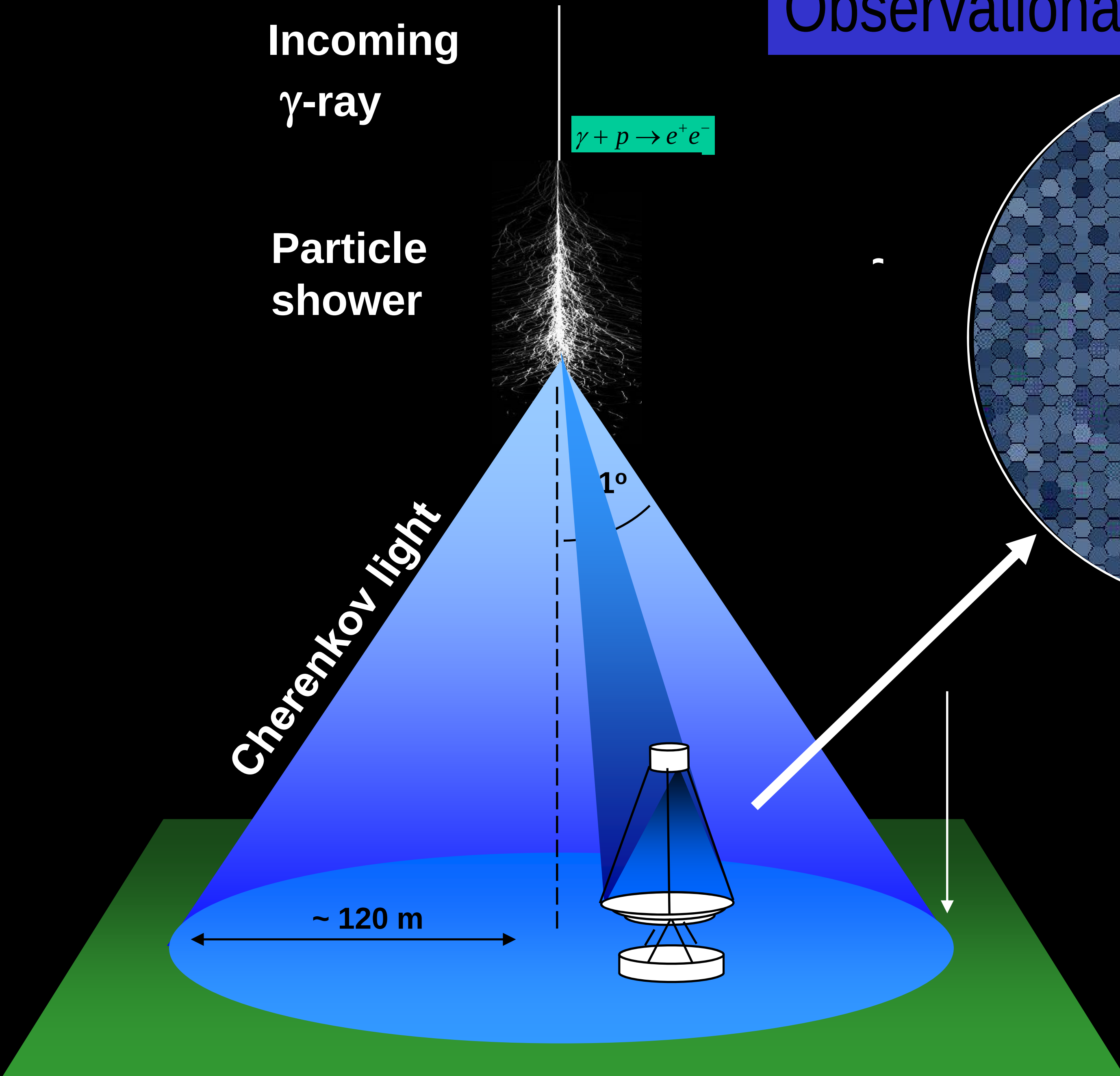
200 photons/m^2 in the visible

Duration ~ 2 ns

Angular spread ~ 0.5^o



Observational Technique



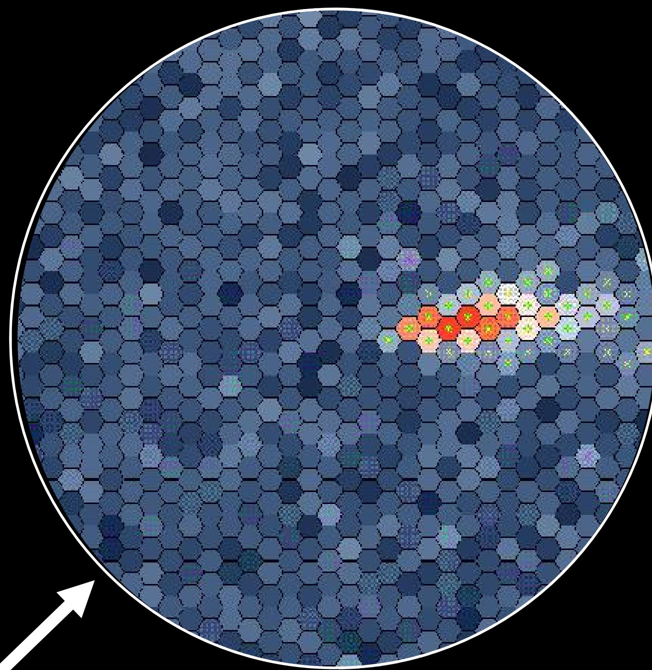
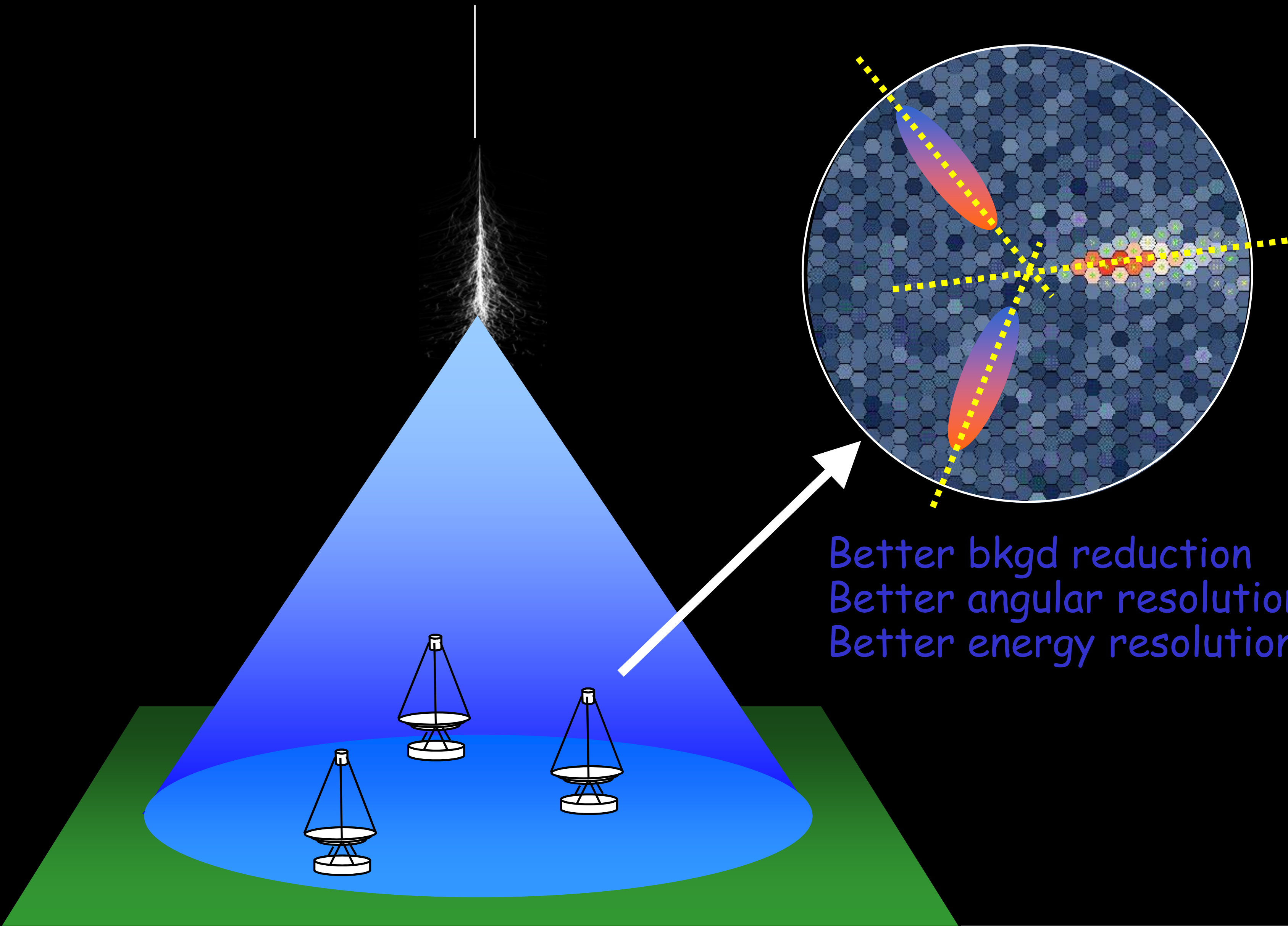


Image intensity
➔ Shower energy

Image orientation
➔ Shower direction

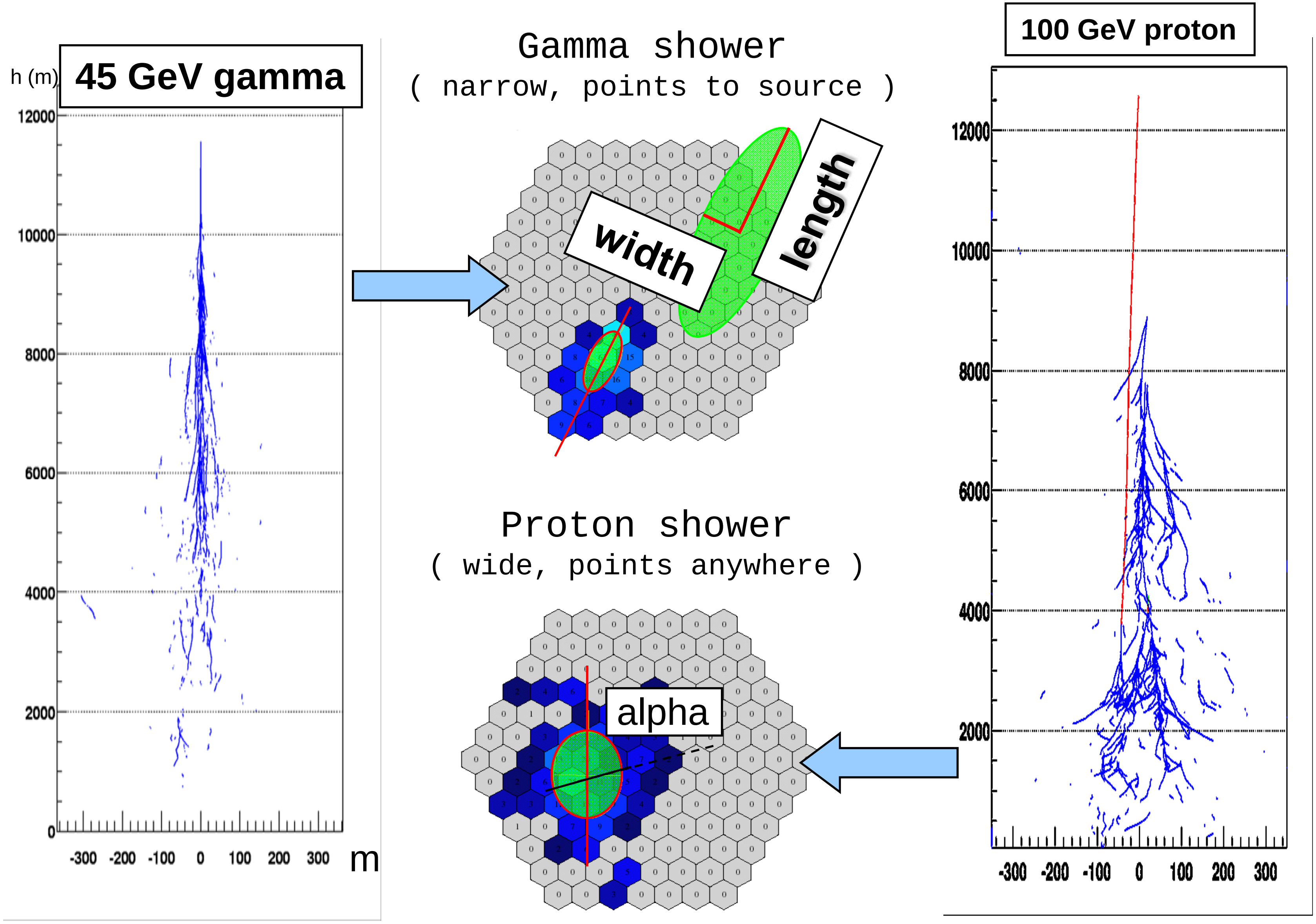
Image shape
➔ Primary particle

Systems of Cherenkov telescopes



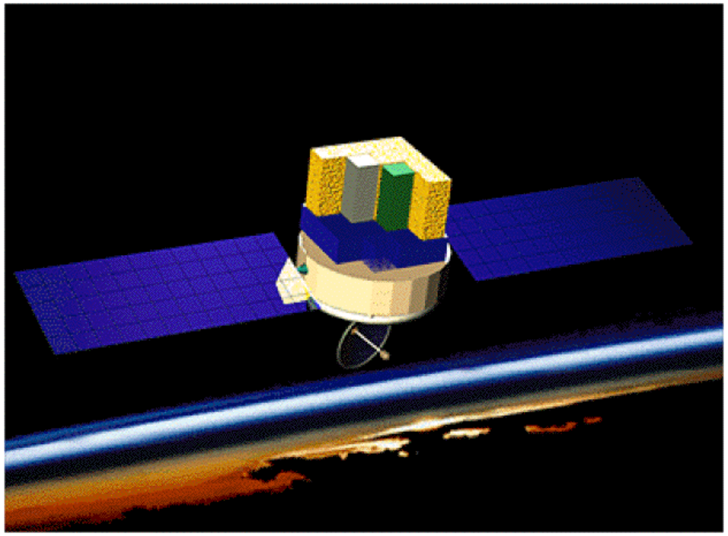
Better bkgd reduction
Better angular resolution
Better energy resolution

Gamma / hadron separation



IACT vs Satellite

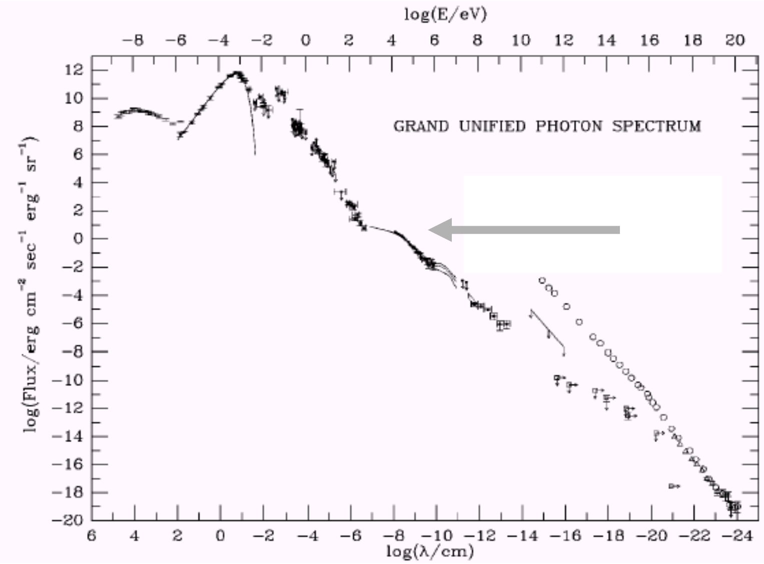
- Satellite :
  - primary detection
  - small effective area ~$1 m^2$
    - lower sensitivity
  - large angular opening
    - search
  - large duty-cycle
  - large cost
  - lower energy
  - low bkg



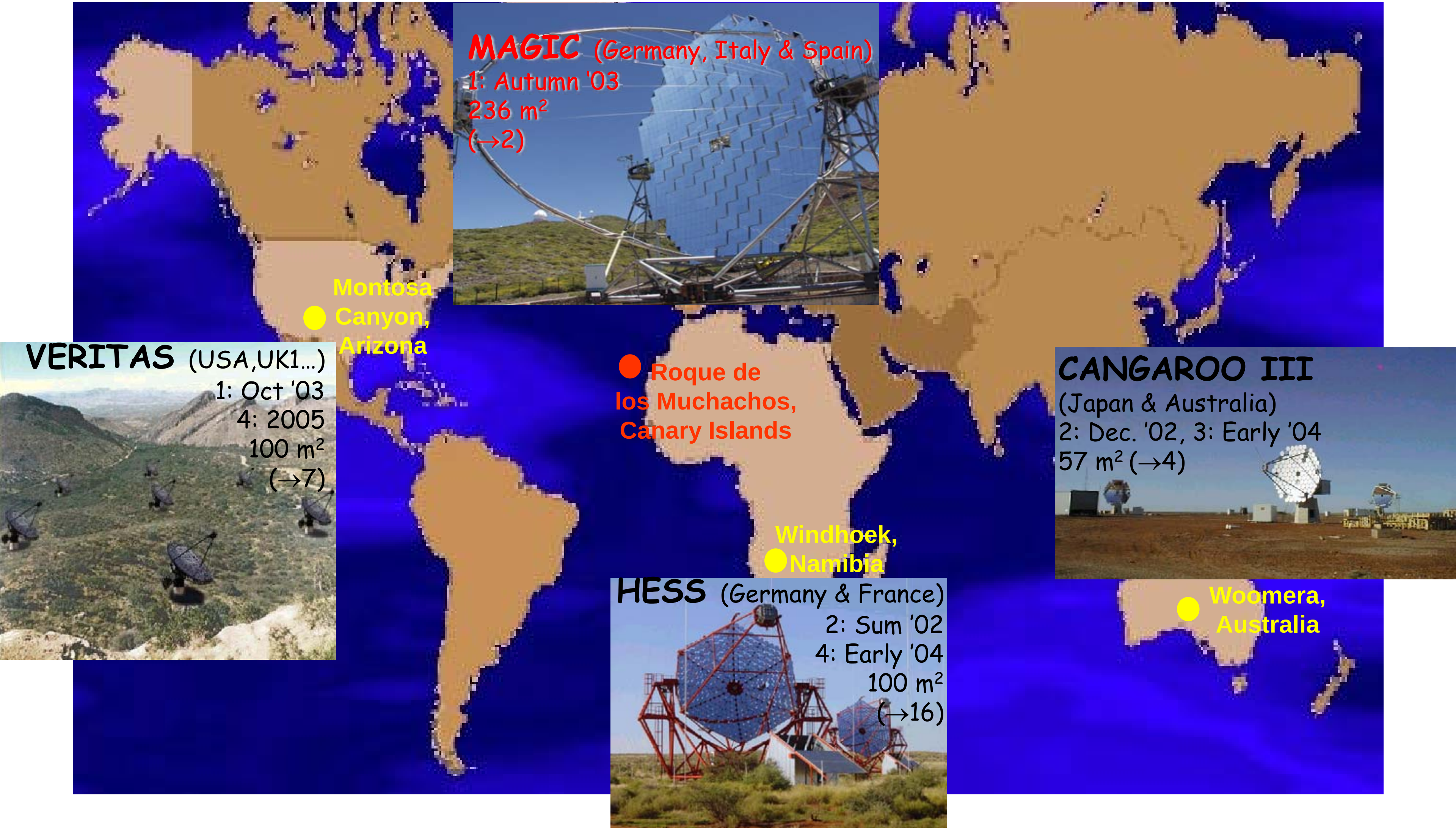
- IACT/ground based
  - secondary detection
  - huge effective area ~10^4 m^2
    - Higher sensitivity
  - small angular opening
    - Serendipity search
  - small duty-cycle
  - low cost
  - high energy
  - high bkg

Ground-based detectors
Improvements in atmospheric Č

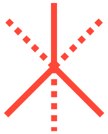
- Improving flux sensitivity
  - Detect weaker sources, study larger sky regions $S/B^{1/2} \propto (A/\tau\Omega)^{1/2}$
    - Smaller integration time
    - Improve photon collection, improve quantum efficiency of PMs
    - Use several telescopes
- Lowering the energy threshold
  - Close the gap ~ 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 2007:	#	~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	2x	240	577	3.5	2200	~80m
VERITAS	4x	110	499	3.5	700	 ~40m

The MAGIC site

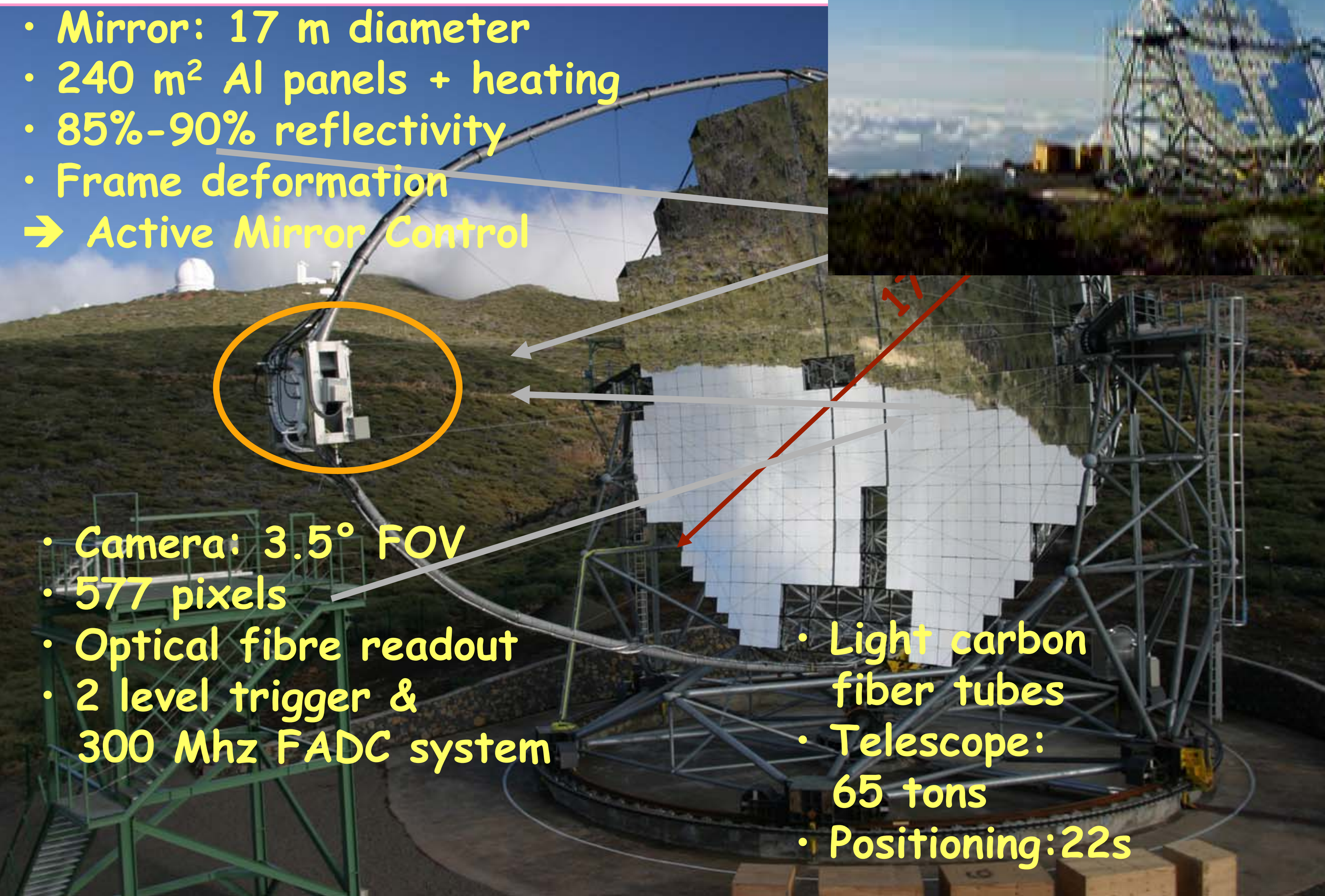
Telescopio Nazionale Galileo

MAGIC

MAGIC

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

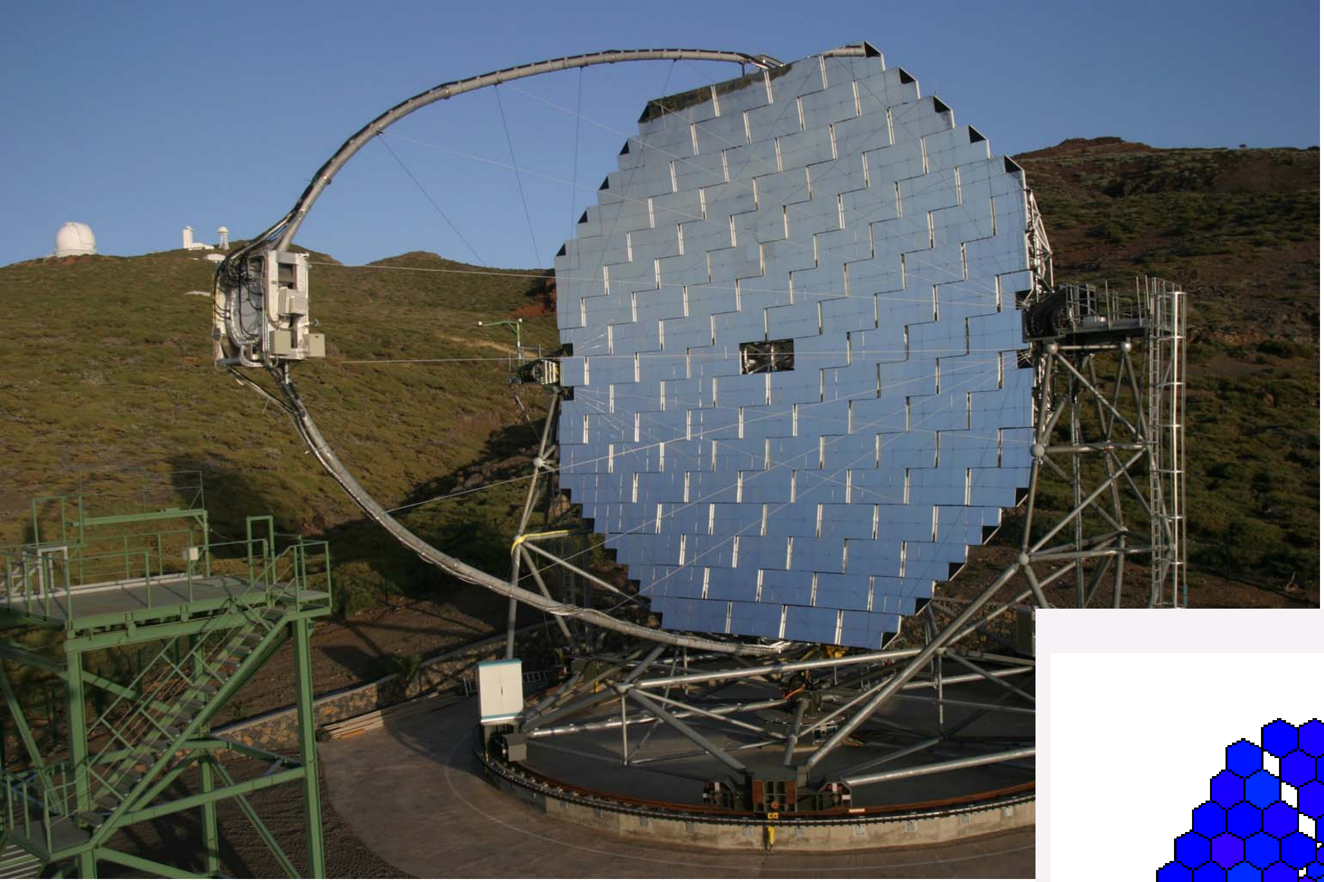
→ Active Mirror Control

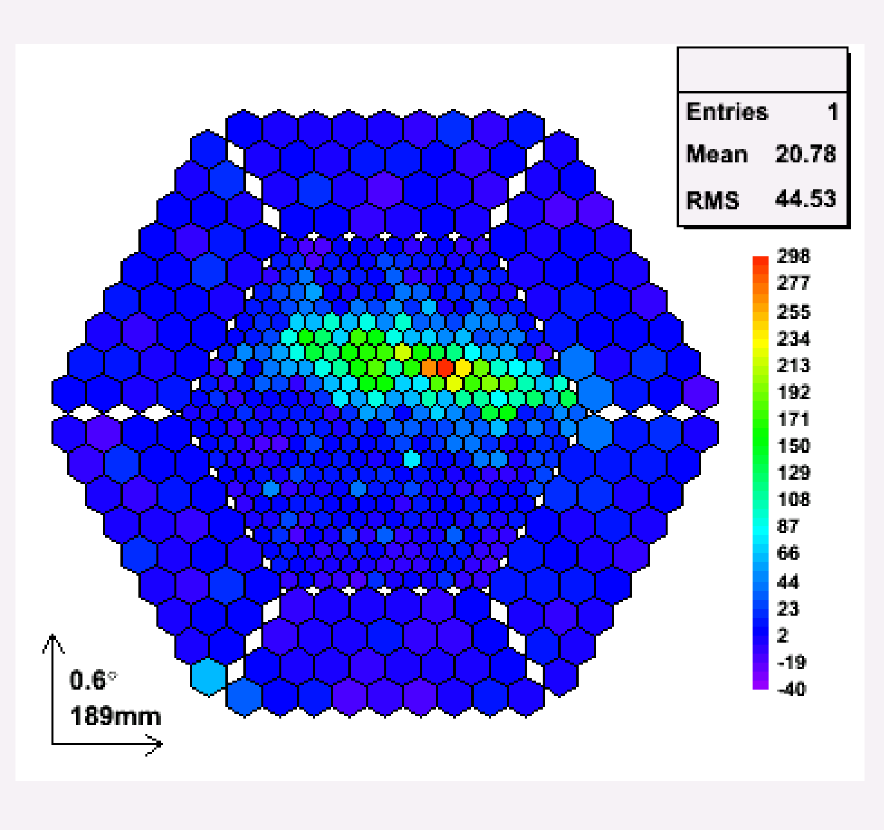


- Camera: 3.5° FOV
- 577 pixels
- Optical fibre readout
- 2 level trigger & 300 Mhz FADC system

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

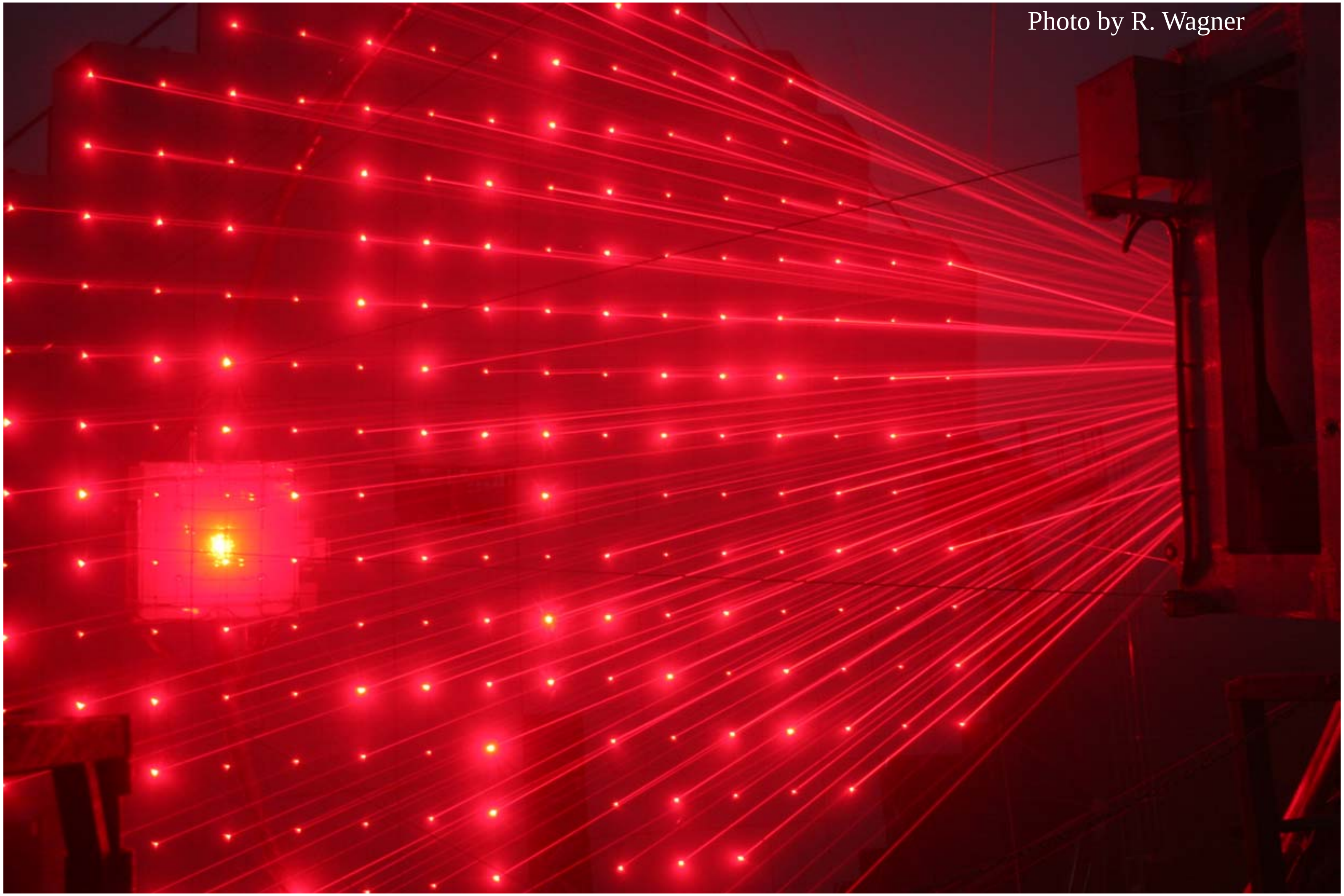
After upgrade of the optics in July 2004 the telescope is in its final shape





~300Hz shower rates
E_{th} ~40GeV

the Active Mirror Control laser beams



IACT Scientific Highlights

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***

V. New class of periodical galactic sources by MAGIC and HESS

Scientific Highlights

Extragalactic observations:

VII. Discovery of ~20 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?***

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

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

IX. Prompt follow-up of 11 GRB (implosion of hypernovae) by MAGIC:

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

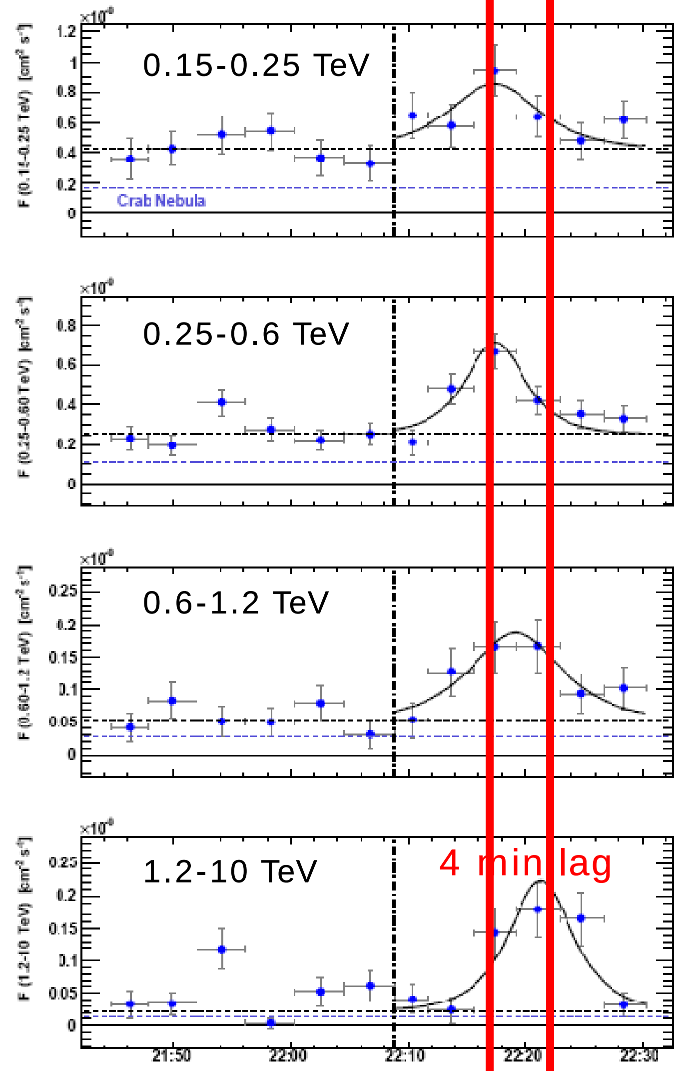
Violation of the Lorentz-Invariance?

Light dispersion due to quantum gravity effects expected in some QG models

$$V = c\,[1 \pm \xi\,(E/E_{QG}) - \xi_2\,(E/E_{QG})^2 \pm \ldots]$$

1st order $\Delta t \sim \xi \frac{E}{E_{QG}} \frac{z}{H_0} = \xi \frac{E}{E_{QG}} \frac{L}{c}$

Mrk 501,
MAGIC, astro-ph/0702008



MAGIC Mkn 501, arXiv:0708.2889

- $E_{QG} \sim 0.03\ M_P$
- $E_{QG} > 0.02\ M_P$

HESS PKS 2155, ICRC 2007 prel.

- $E_{QG} > 0.04\ M_P$

Whipple 1999, PRL 83(1999)2108

- $E_{QG} > 0.005\ M_P$

GRB X-ray limits:

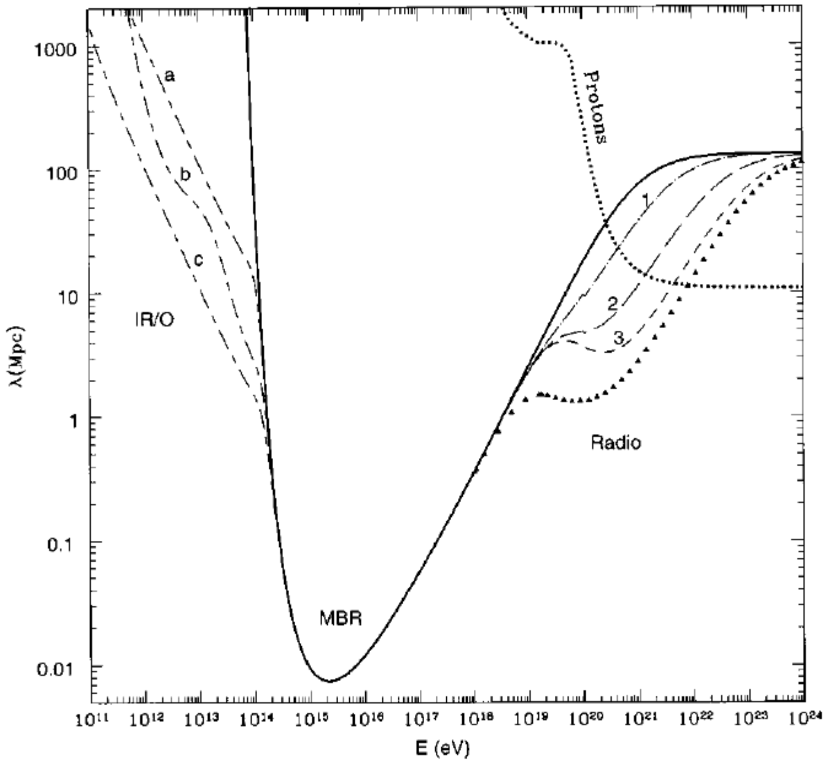
- $E_{QG} > 0.001 \ldots 0.01\ M_P$

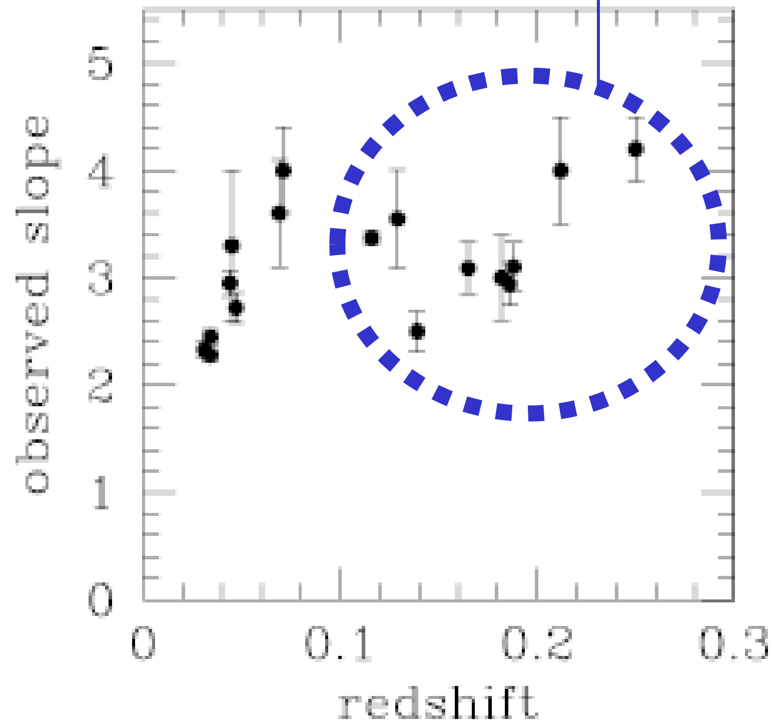
... but in most scenarios
$\Delta t \sim (E/E_{QG})^{\alpha}$, $\alpha > 1$

- ▶ VHE gamma rays even better
- ▶ Mrk 501: $E_{QG} > 3 \cdot 10^{-9}\ M_P$, $\alpha = 2$

Propagation physics

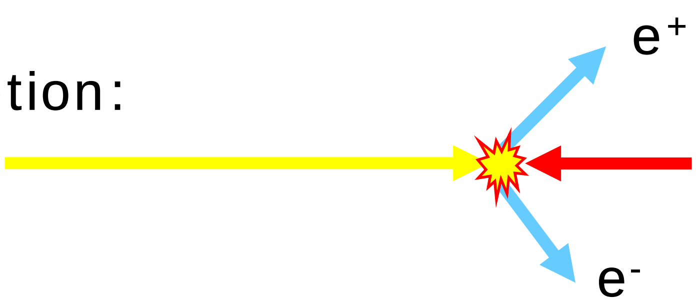
Selection bias?
New physics ?





(Persic & AdA, arXiv:0711.2317)

Absorption:



visible/infrared light
accumulated by all
stars in history of Universe

Too large transparency of the Universe to gamma rays

- More than 20 AGN at VHE discovered by γ telescopes
  - Including 3C279 at z=0.54
- Unexpectedly large, due to attenuation expected for γ
  - Dominant process for the absorption of γ is

$$\gamma + \gamma_{background} \rightarrow e^+ e^-$$

$$\sigma(E,\epsilon) = 1.25 \cdot 10^{-25} (1-\beta^2) \left[2\beta(\beta^2 - 2) + (3 - \beta^4) \ln \left(\frac{1+\beta}{1-\beta} \right) \right] \mathrm{cm}^2$$

maximal for

$$\epsilon \simeq \frac{2 m_e^2 c^4}{E} \simeq \left(\frac{500\ \mathrm{GeV}}{E} \right) \mathrm{eV}$$

  - Only QED, relativity and cosmology in the formula above
    - For γ rays, relevant background component is optical/infrared (EBL)
    - EBL density given by cosmology/star formation

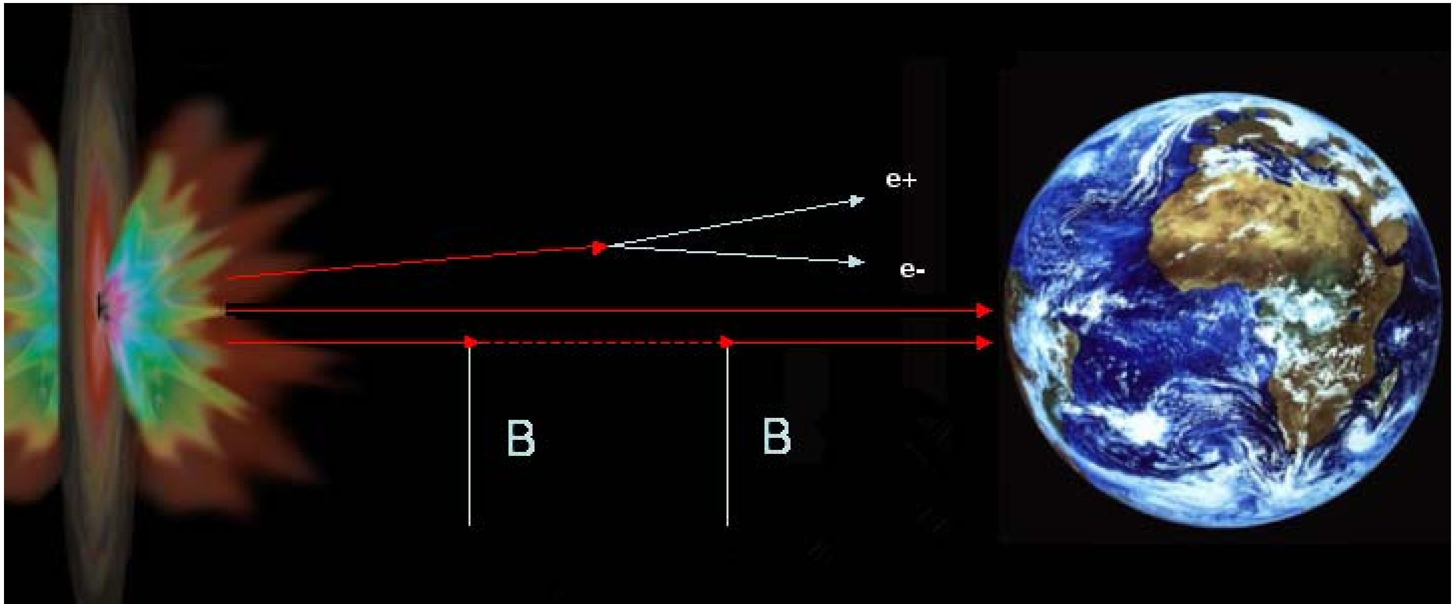
- How to explain observations?

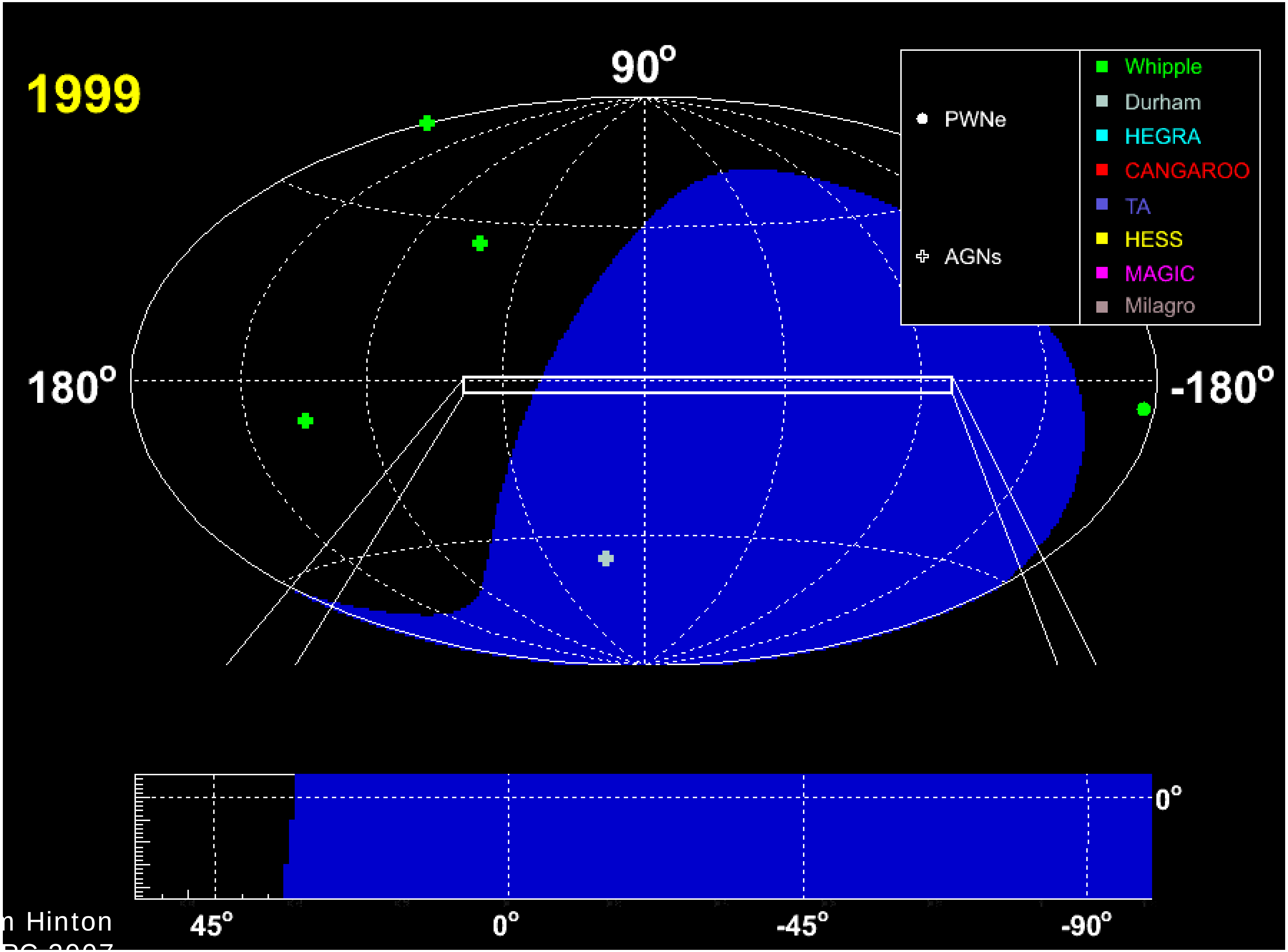
Interaction with a new light neutral boson? (AdA, Roncadelli & Mansutti [DARMA], arXiv:0707.4312)

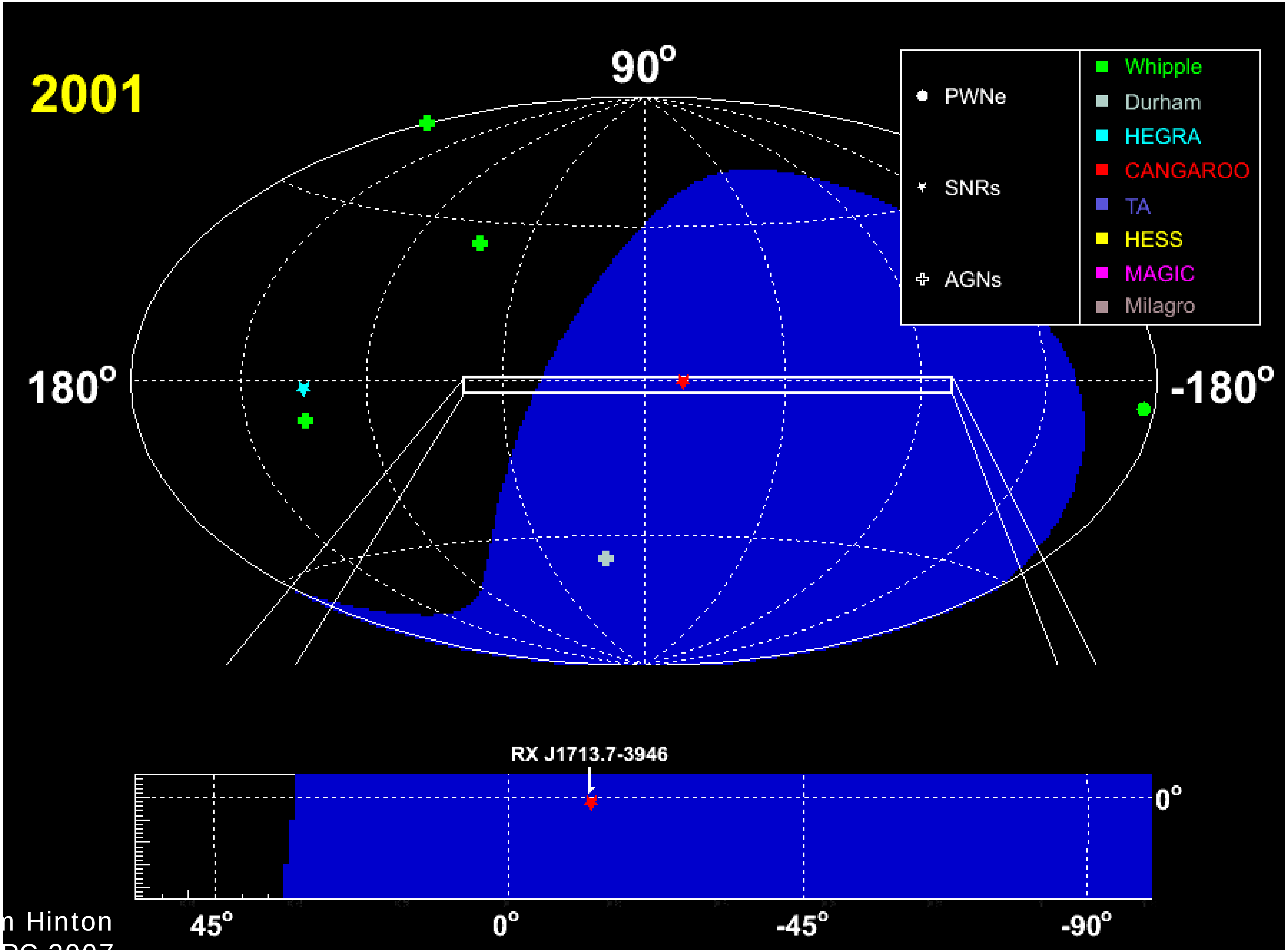
- Photons might oscillate into a neutral (pseudo)scalar particle ϕ of mass m, which travels unimpeded
- ϕ interacting with γ through the Lagrangian

$$L = -\frac{1}{4M}\varepsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}\phi = \frac{1}{M}\left(\vec{E}\cdot\vec{B}\right)\phi$$

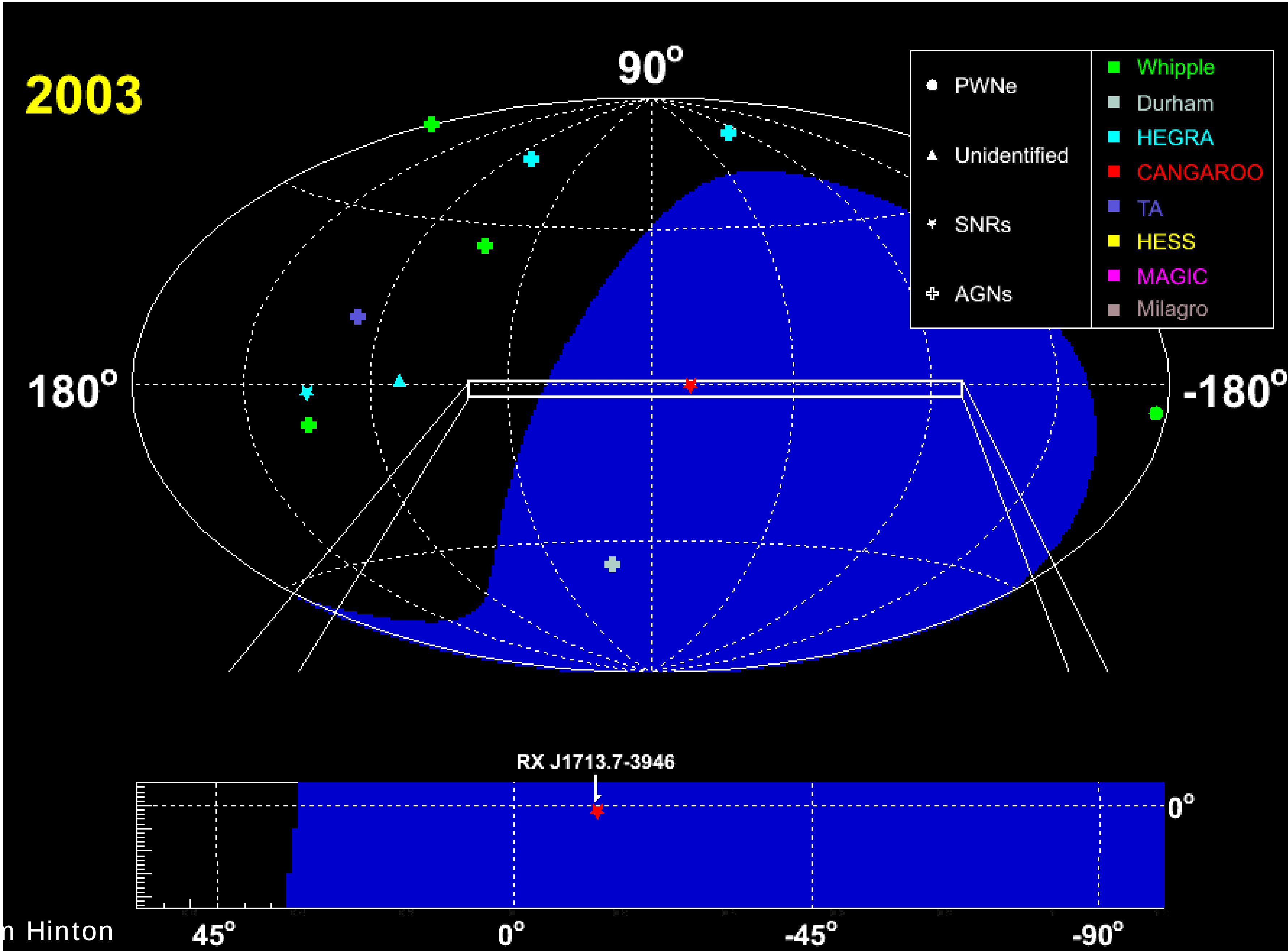
- **If m(ϕ) << 10^{-10} eV** (1 μK) **and M > 3 10^{11} GeV the experimental observations are explained!**



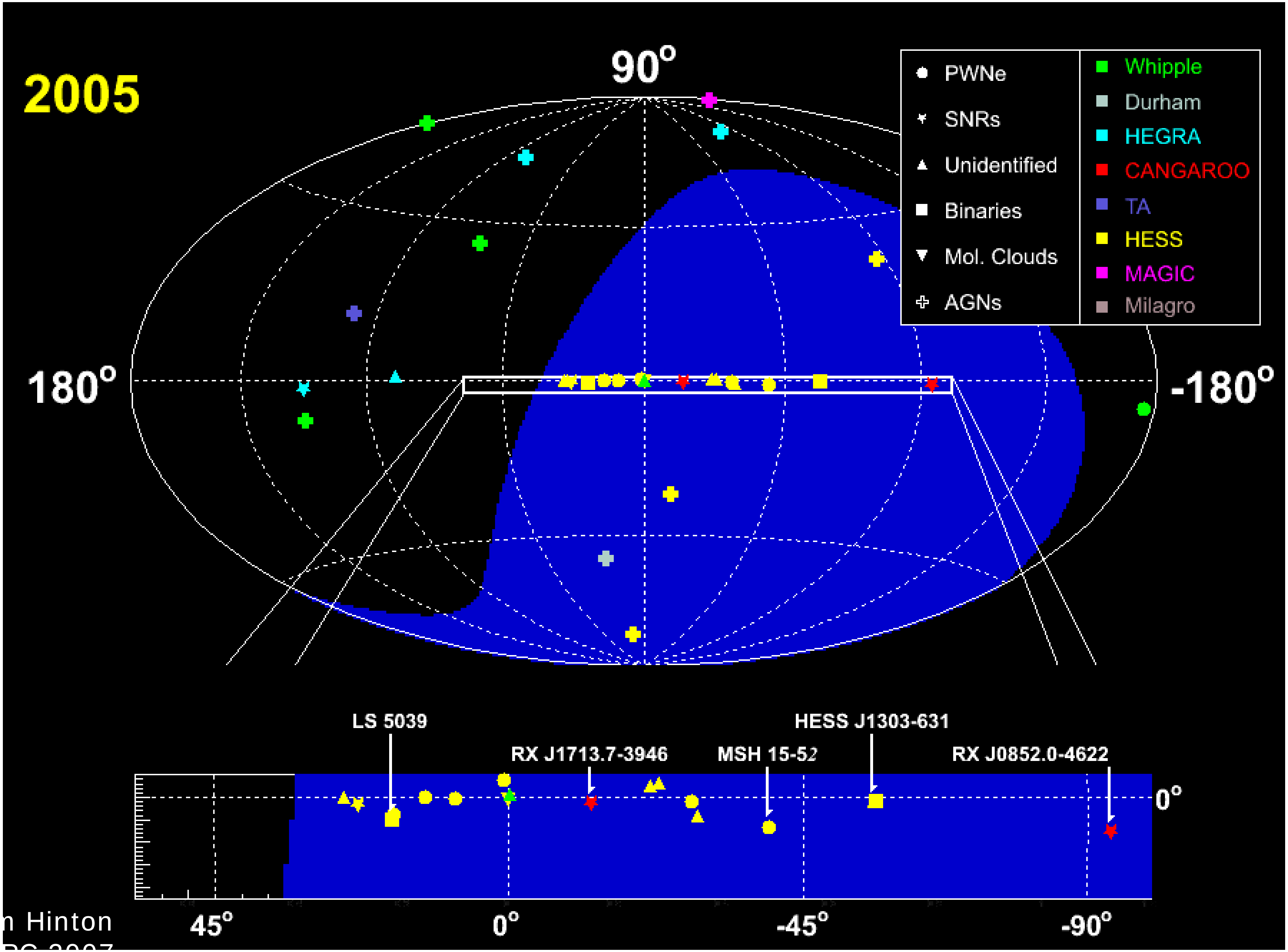

1999
90°
180°
-180°
PWNe
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
0°
45°
0°
-45°
-90°
n Hinton


2001
90°
180°
-180°
PWNe
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°

n Hinton



2003
90°
180°
-180°
PWNe
Unidentified
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°
n Hinton


2005
90°
180°
-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
HESS J1303-631
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
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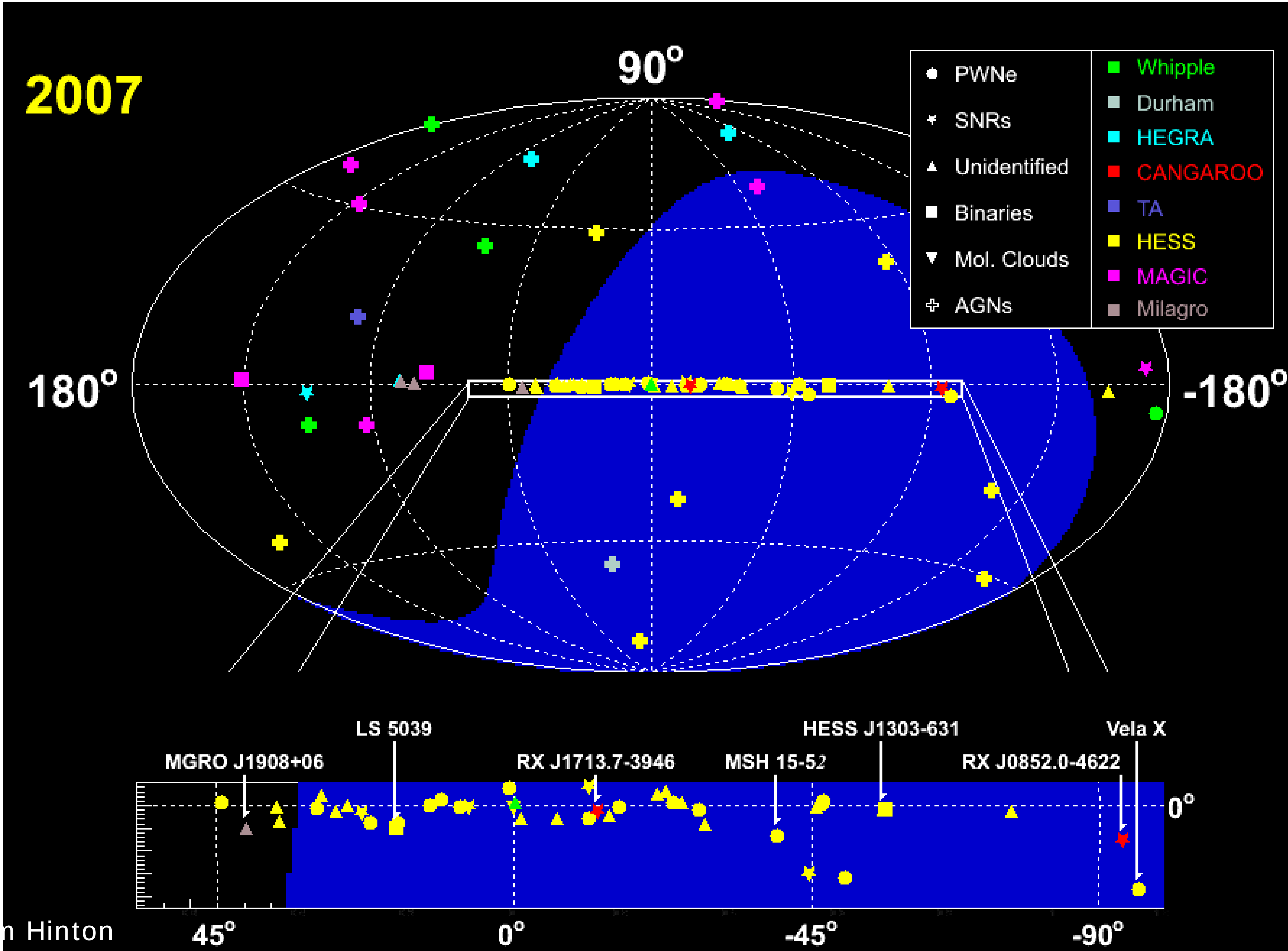
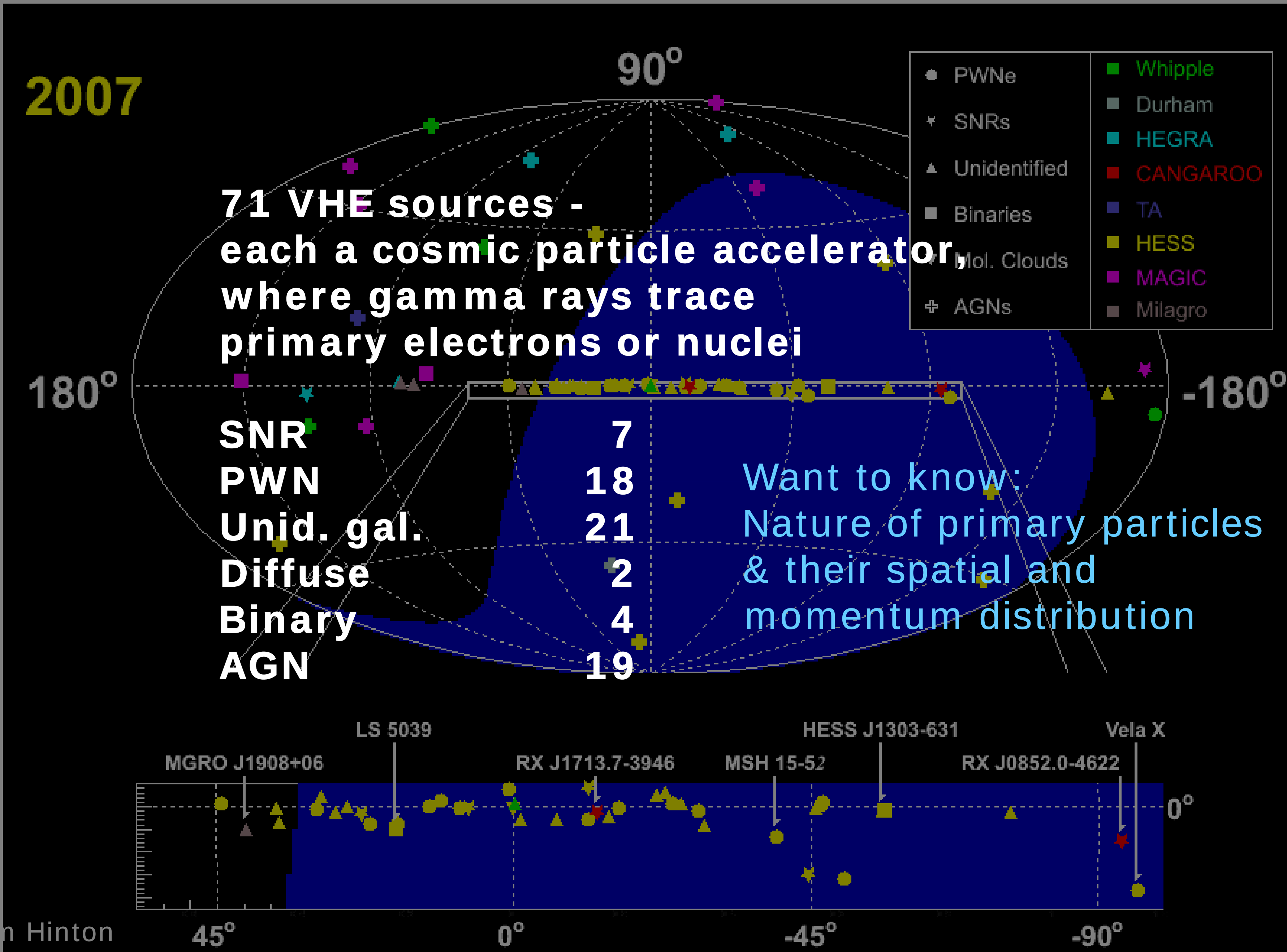
45°
0°
-45°
-90°
n Hinton

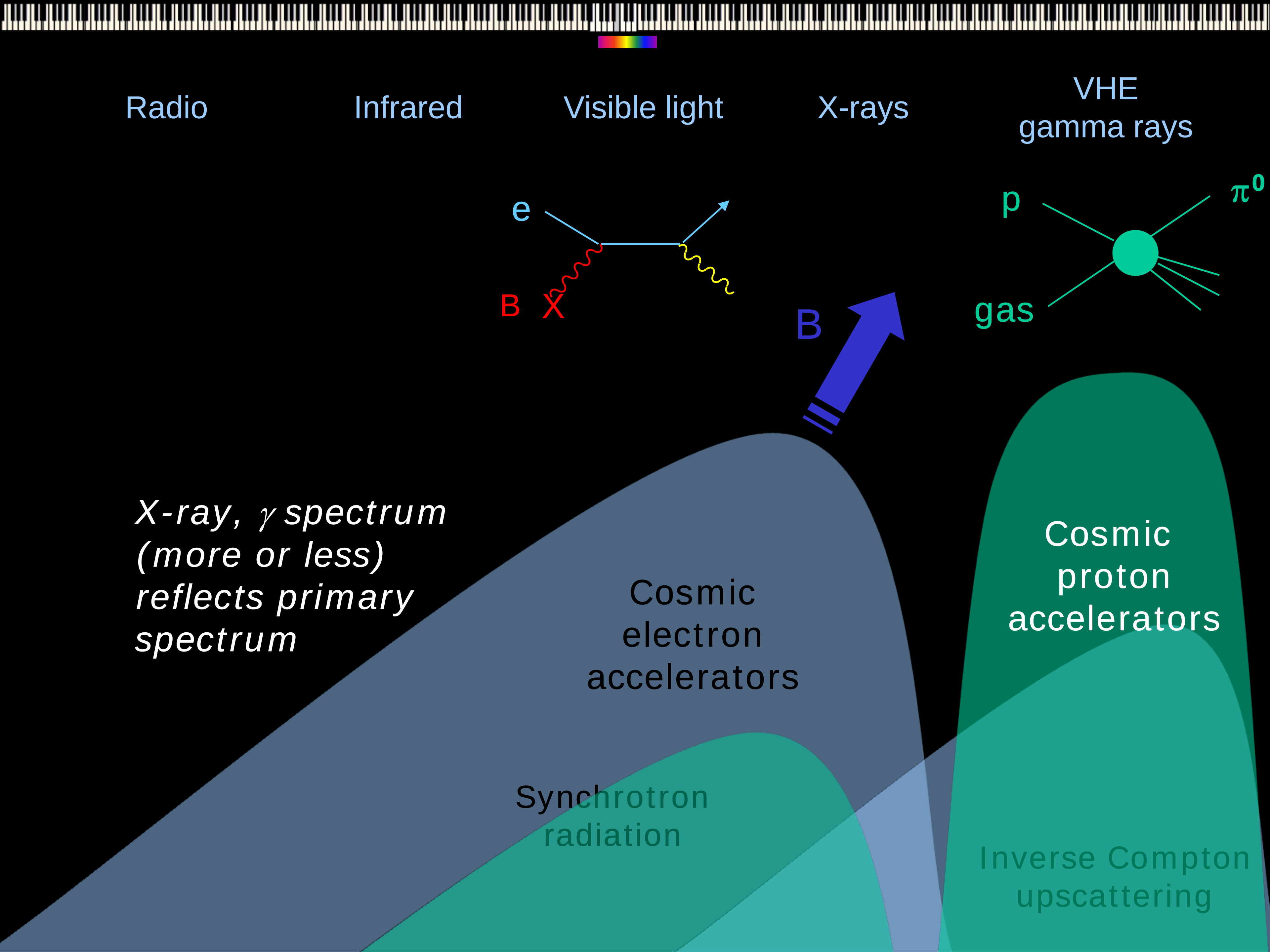

2007
90°
180°
-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
HESS J1303-631
Vela X
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
0°
45°
0°
-45°
-90°
n Hinton



71 VHE sources -
each a cosmic particle accelerator,
where gamma rays trace
primary electrons or nuclei

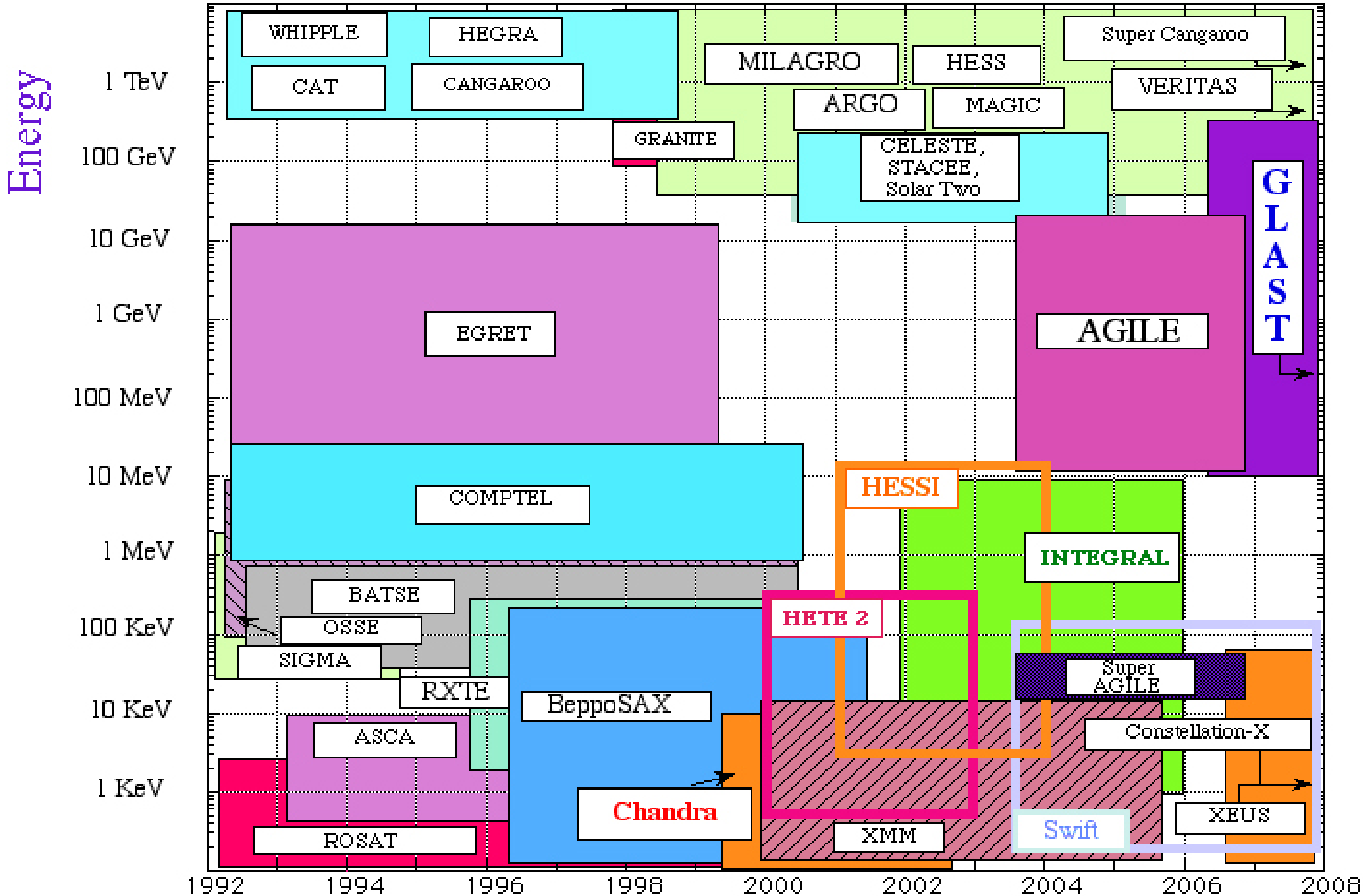
SNR	**7**
PWN	**18**
Unid. gal.	**21**
Diffuse	**2**
Binary	**4**
AGN	**19**

Want to know:
Nature of primary particles
& their spatial and
momentum distribution

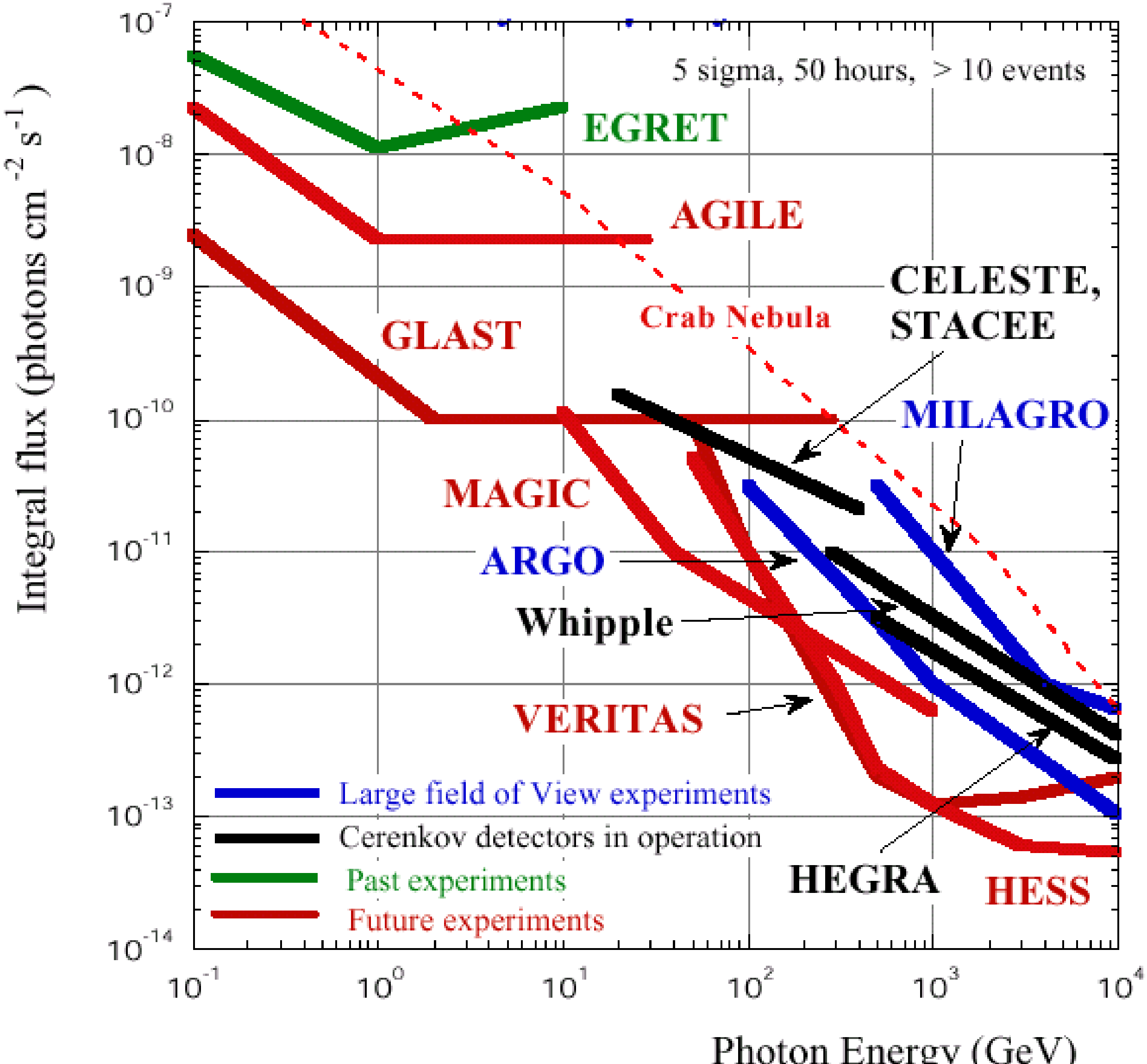


Radio
Infrared
Visible light
X-rays
VHE gamma rays
e
B X
B
p
π^0
gas
X-ray, γ spectrum (more or less) reflects primary spectrum
Cosmic electron accelerators
Cosmic proton accelerators
Synchrotron radiation
Inverse Compton upscattering

An armada of detectors at different energy ranges



Sensitivity



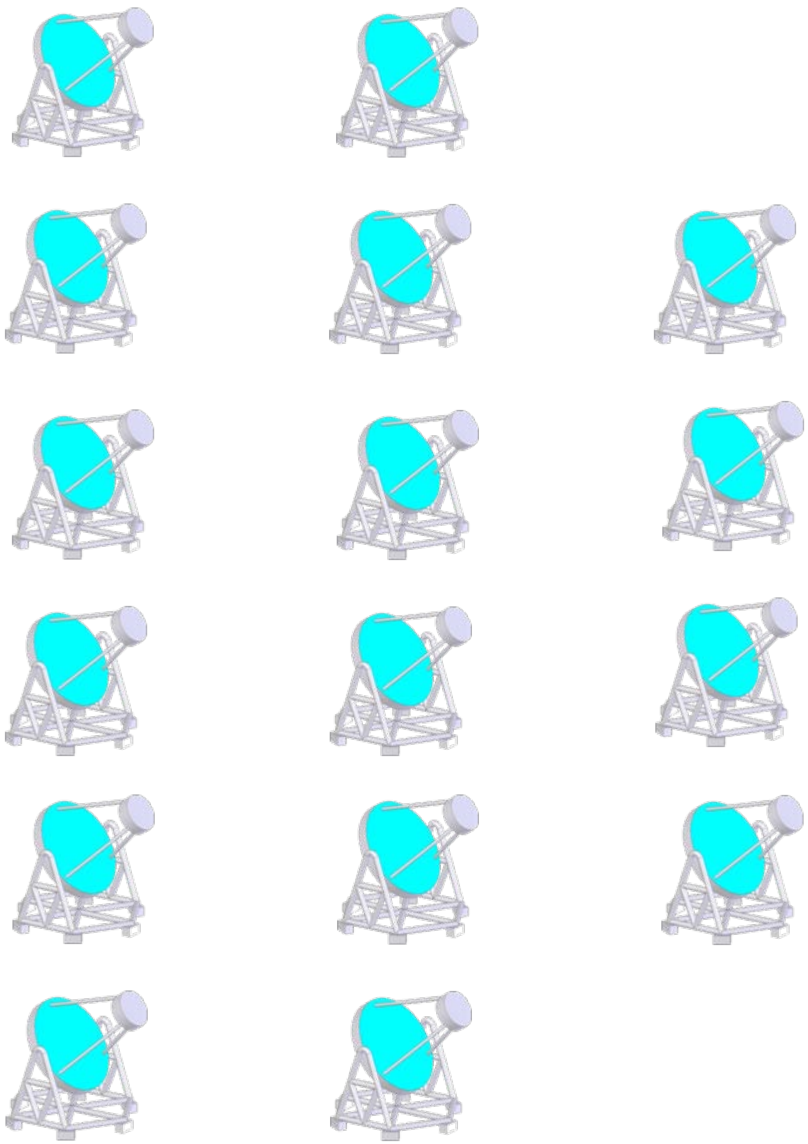
All sensitivities are at 5σ.
Cerenkov telescopes sensitivities (Veritas, MAGIC, Whipple, Hess, Celeste, Stacee, Hegra) are for 50 hours of observations.
Large field of view detectors sensitivities (AGILE, GLAST, Milagro, ARGO) are for 1 year of observation.

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

The second MAGIC telescope

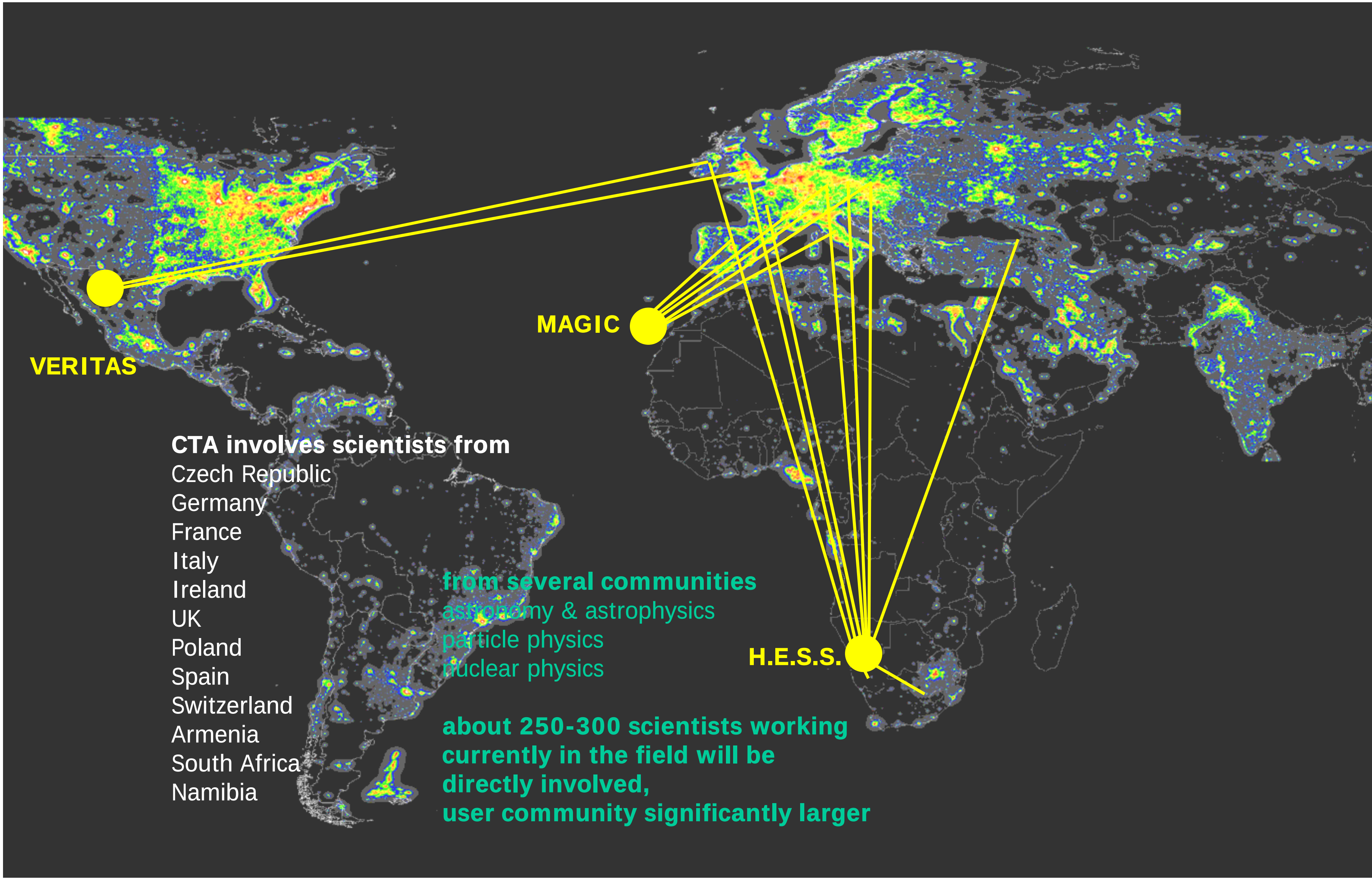
News: Electronics, mirrors

The Cherenkov Telescope Array facility



- aims to explore the sky in the 10 GeV to 100 TeV energy range
- builds on demonstrated technologies (?)
- combines guaranteed science with significant discovery potential
- is a cornerstone towards a multi-messenger exploration of the nonthermal universe

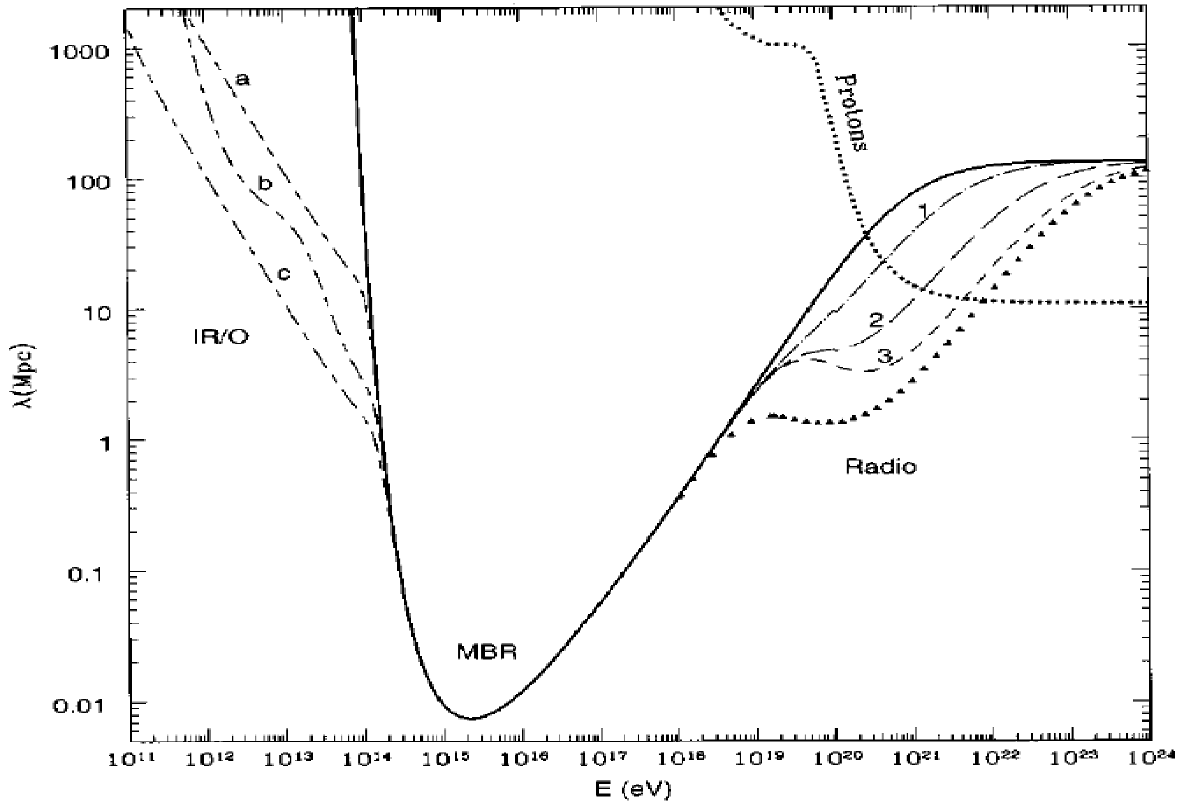
European lead…



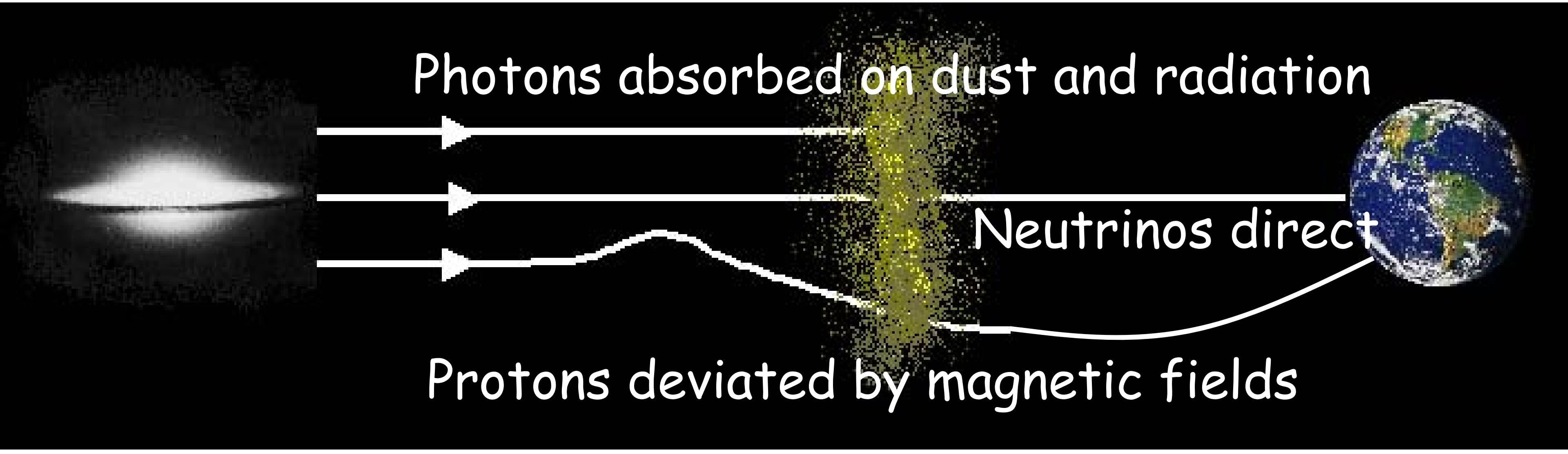
CTA involves scientists from
Czech Republic
Germany
France
Italy
Ireland
UK
Poland
Spain
Switzerland
Armenia
South Africa
Namibia

from several communities
astronomy & astrophysics
particle physics
nuclear physics

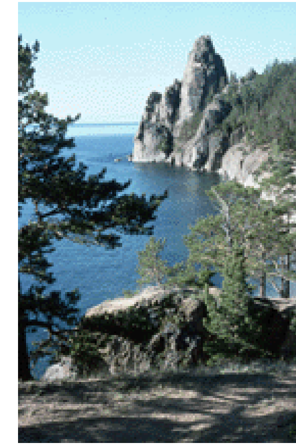
about 250-300 scientists working currently in the field will be directly involved, user community significantly larger

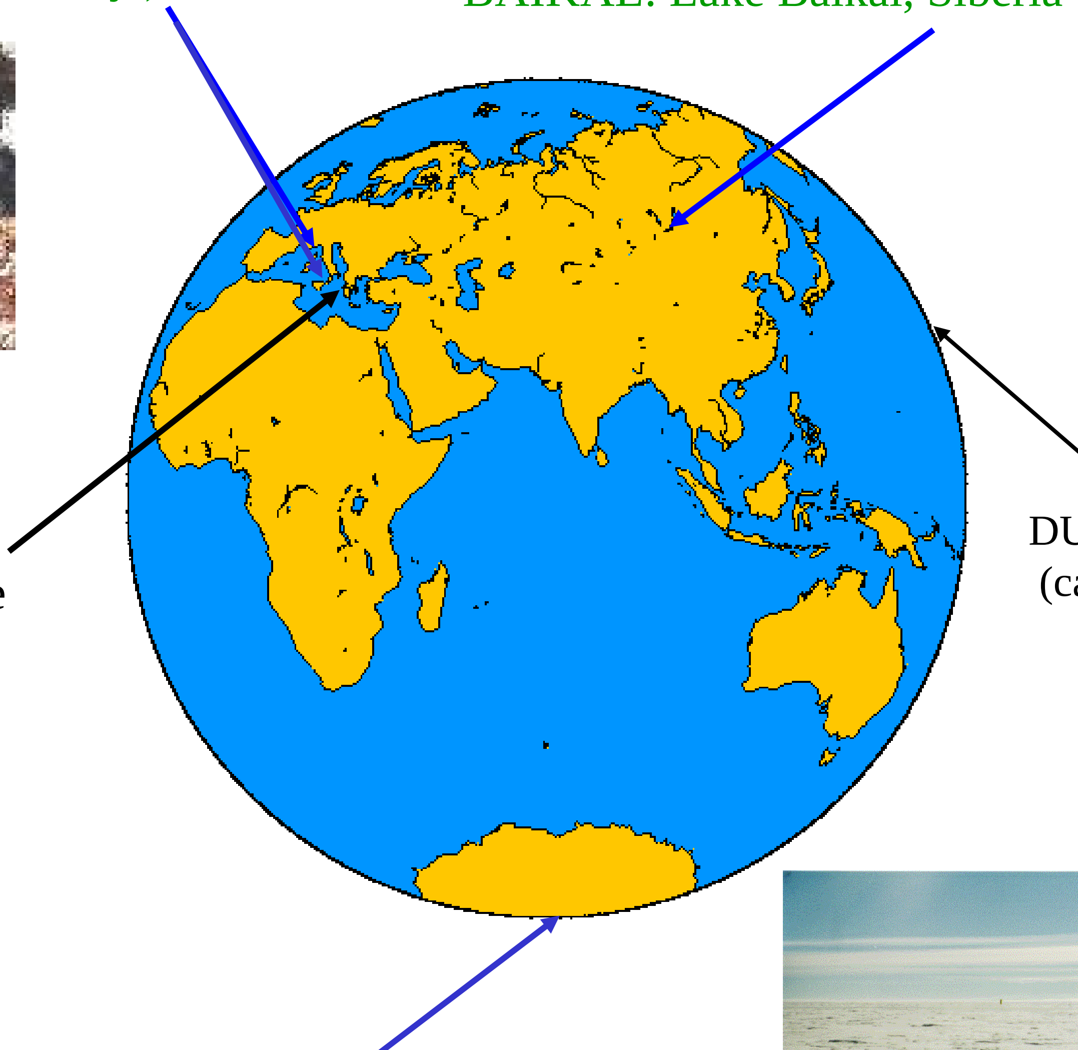


In the 100 TeV - 100 PeV region…



Neutrino Telescope Projects





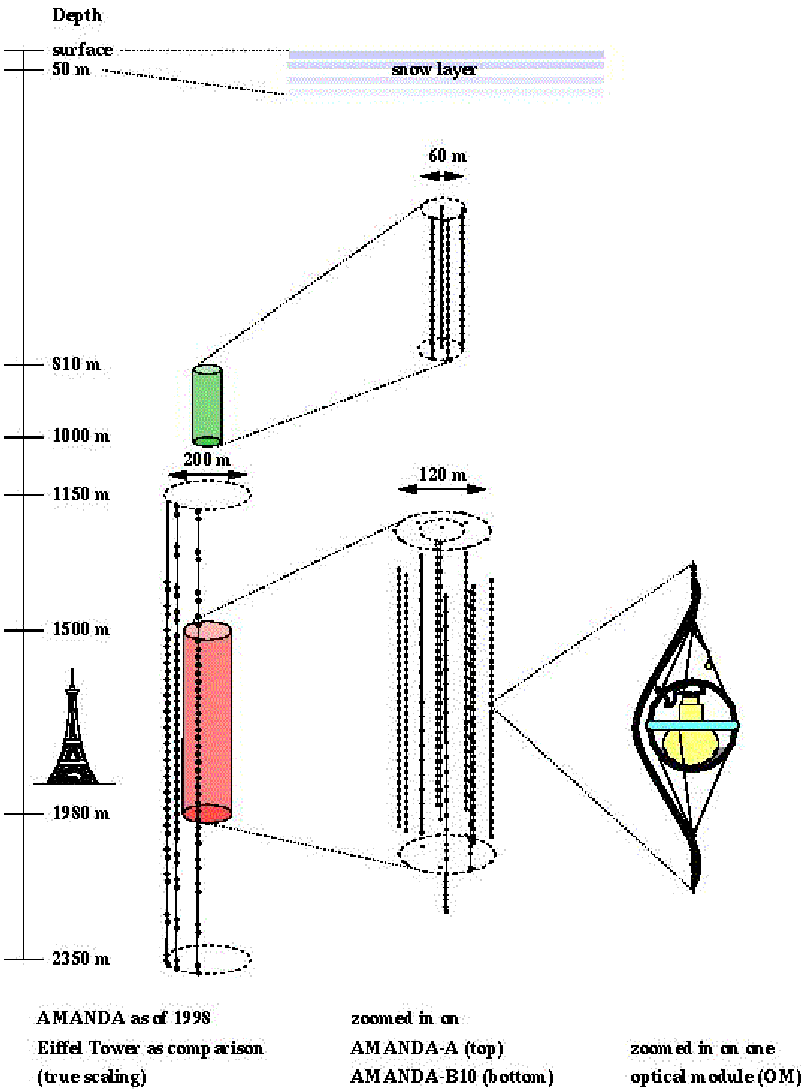
AMANDA-ICECUBE

South Pole: glacial ice

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

2000 ~ 700 Optical Modules

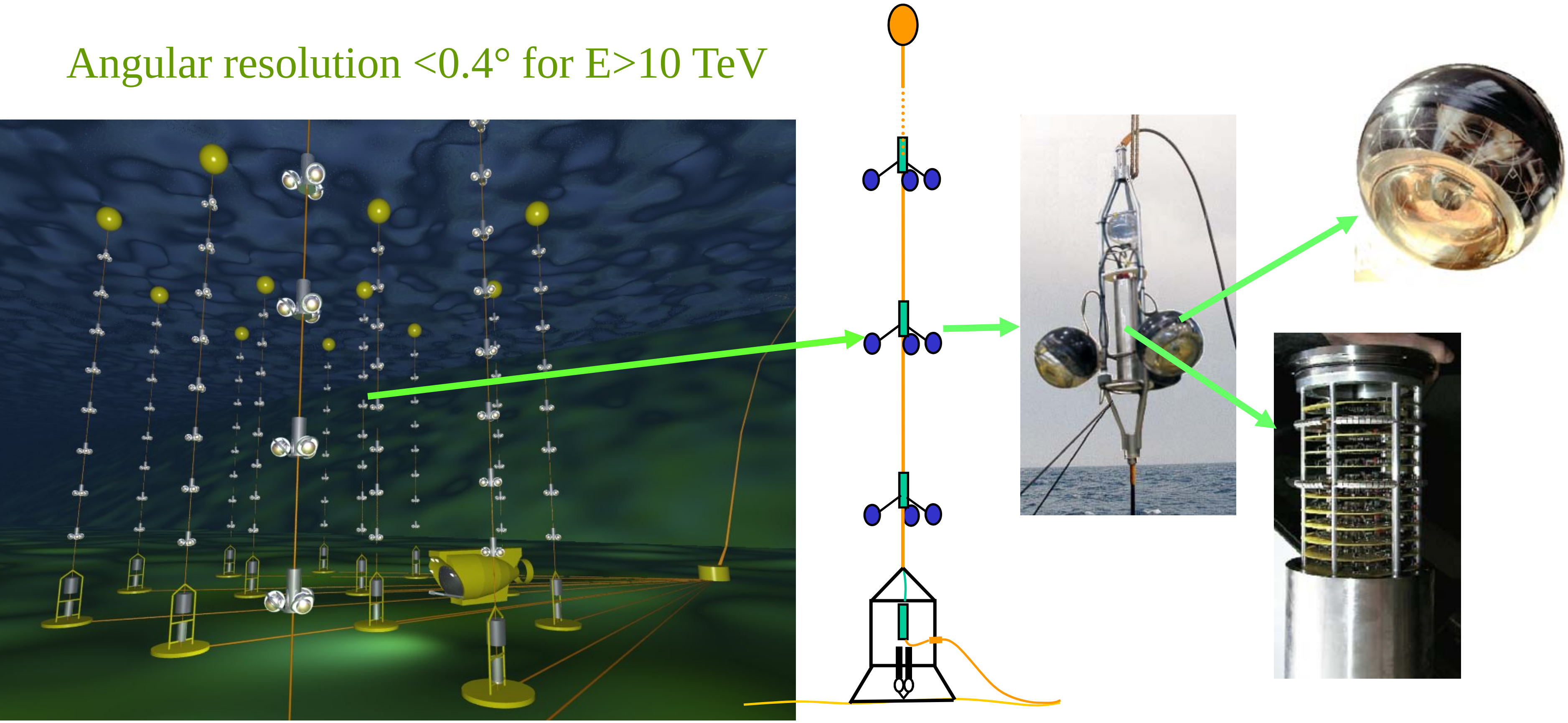
→ ICECUBE 8000 Optical Modules



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