- What are cosmic rays?
- Particle acceleration
- Sources of cosmic rays
- Air shower experiments
- Čerenkov Detectors
- Neutrino Detectors

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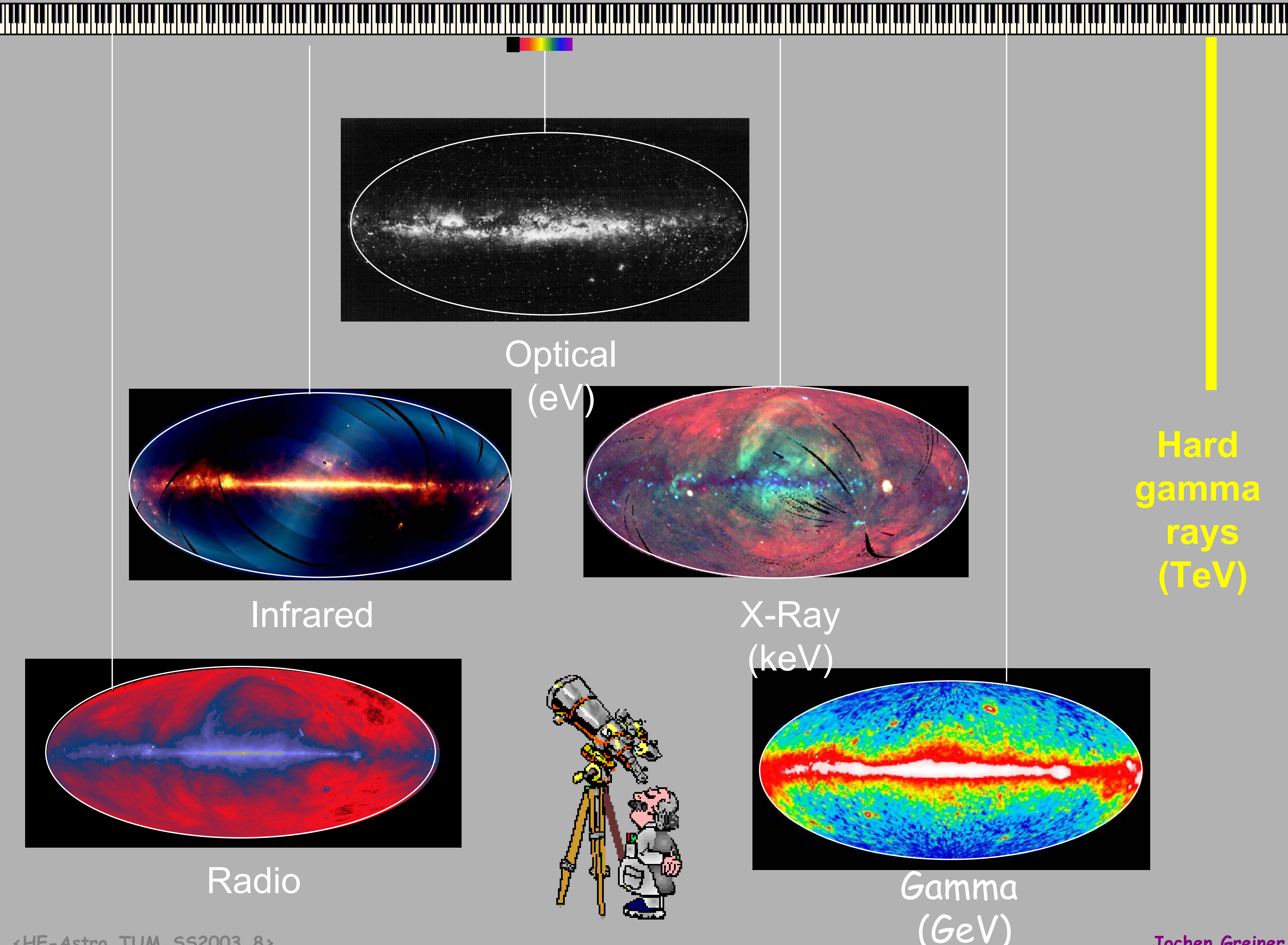
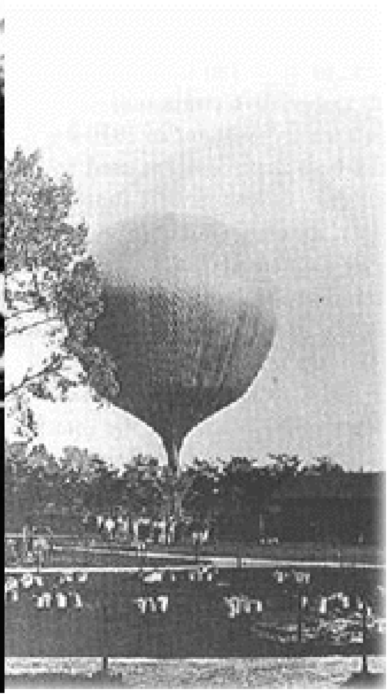

Optical
(eV)
Infrared
X-Ray
(keV)
Hard
gamma
rays
(TeV)
Radio
Gamma
(GeV)

Cosmic Rays

1912 - VICTOR HESS (Nobel Prize 1936)

- **Balloon flights, Measurement of the "Höhenstrahlung" with an ionisation chamber**



- **Results:**
  - ➢ up to 2000 m small decrease of ionisation (soil radioactivity)
  - ➢ but then dramatic increase (Hess reached a maximum height of 5300 m)

➢ Confirmation of the extraterrestrial origin of the cosmic radiation

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What are cosmic rays?

... 98 % ionized nuclei

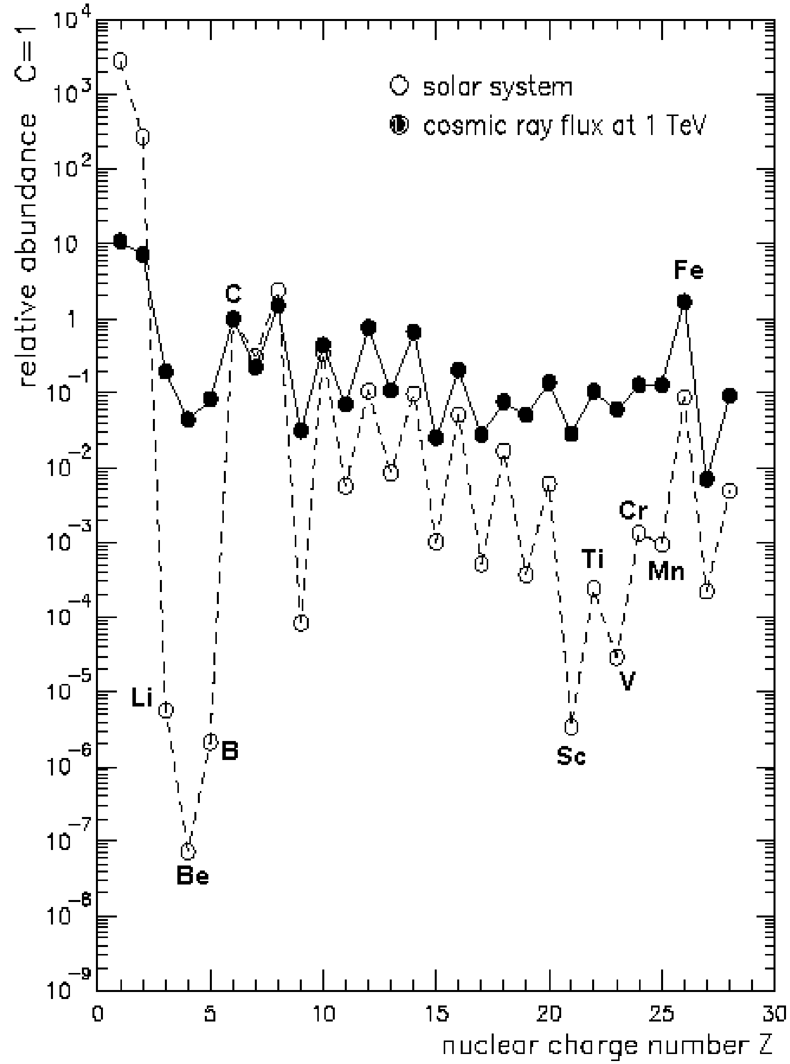
among them 87 % protons

12 % α-particles

1 % heavy elements

... 2 % electrons

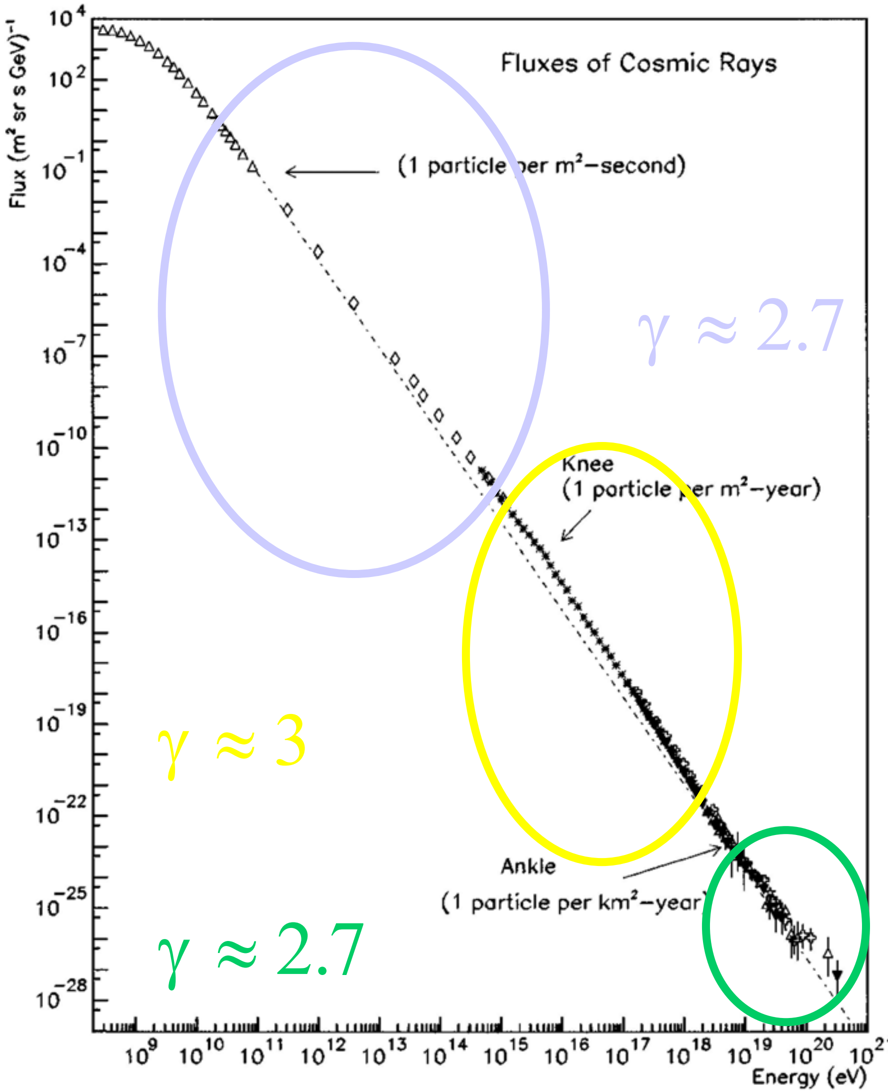
➢ cosmic rays is particle radiation !!



Chemical composition – comparison with Solar System

- ➢ many similarities
- ➢ BUT: deviations with Li, Be, B (Z = 3 – 5) as well as Sc, Ti, V, Cr, Mn (Z = 21 – 25)
- ➢ discrepancies: elements are not end products of nuclear synthesis!
- ➢ spallation of Carbon (Z=6), Nitrogen (Z=7), Oxygen (Z=8) or Iron (Z=26)
- ➢ deduce cosmic ray life time in Galaxy (10^6 years) from ratio of primary (e.g. C) to secondary (e.g. Li, Be, B) particles

Energy spectrum of cosmic rays



- very wide energy range from 10^{8}eV up to 10^{20} eV
- Flux falls rapidly with increasing energy:

$$\frac{dN}{dE} \propto E^{-\gamma}$$

- Knee:
  1. Galactic magnetic field can keep only particles which Lamorradius is smaller or similar to dimension of Milky Way
     - $> 10^{15}$ eV particles leave Milky Way
  2. Maximum acceleration in supernovae
- Ankle: contribution of extragalactic component

TeV/PeV Gamma rays are secondary products

their emission traces primary particle populations

- Hadrons
  - π^0 decay
- Electrons
  - Synchrotron radiation
  - Inverse Compton scattering
  - Bremsstrahlung
- Heavy instable particles (strings, monopoles, ...)

Problem:
to relate the gamma ray flux and the primary spectra, one needs to

- Know the properties of the production "target"
- Deconvolve energy spectra

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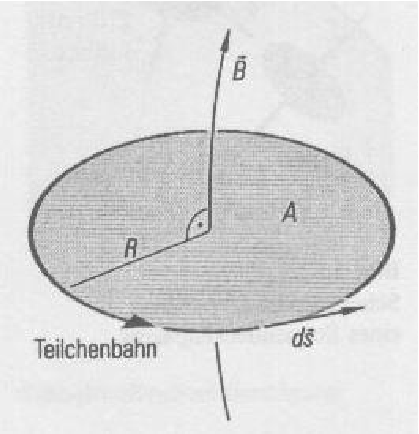
Particle Acceleration

• 1. Cyclotron mechanism – Acceleration in Solar Spots

- Field strength in solar spots reaches 1000 Gauß
- Magnetic fields originate through turbulent plasma motion (= currents)
- changing magnetic fields produce electric fields which accelerate protons and electrons

➢ $$E = e\pi R^2 \frac{dB}{dt}$$



typische Werte: $B = 2000$ G, $R = 10^9$ cm, $\frac{dB}{dt} = 2000 \frac{G}{Tag}$

➢ Energies up to 10^{11} eV

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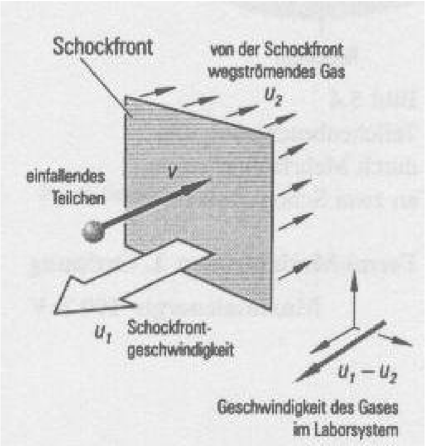
• 2. Acceleration in shock fronts (Fermi-Mechanism 1. Order)

- expelled supernova-shell exhibits a shock front against the interstellar medium
- Consider shock front moving with u_1 and particle moving with velocity v against this shock front



➢ relative energy gain: $$\frac{\Delta E}{E} \approx \frac{2(u_1 - u_2)}{v}$$

➢ relativistic treatment of shock acceleration and taking into account variable scatter angles gives (mit v = c): $$\frac{\Delta E}{E} = \frac{4}{3}\frac{u_1 - u_2}{c}$$

➢ Energies up to 10^{14} eV

Particles bounce between magnetic field sheets

acceleration takes 10000 years

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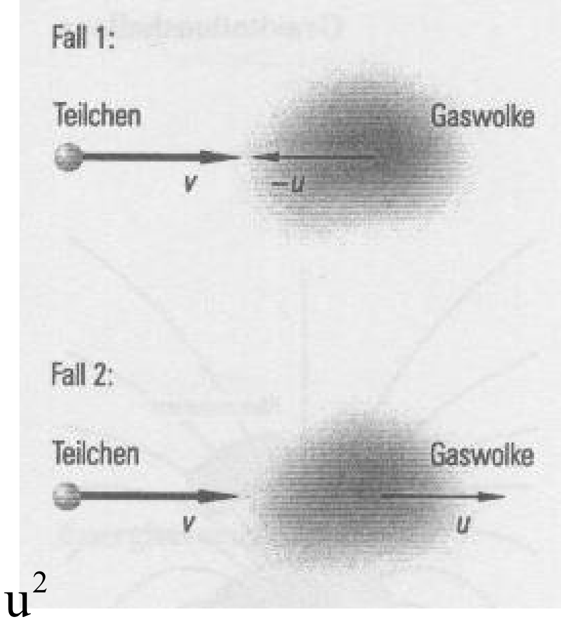
• 3. Acceleration in magnetic clouds (Fermi-Mechanism 2. Order)



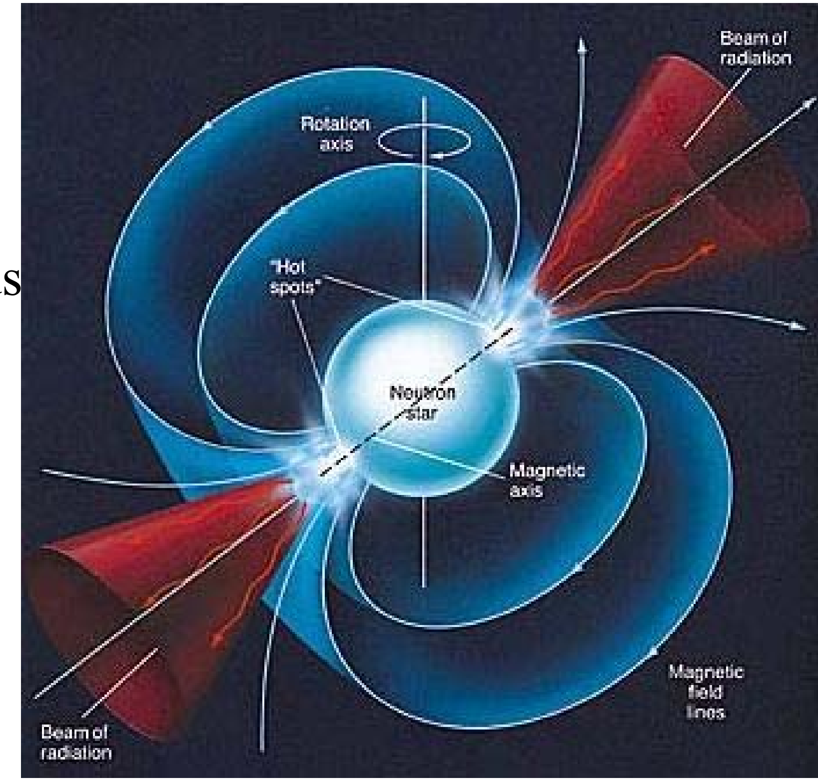
- interaction of cosmic particles with magnetic clouds
- Energy gain, if u and v are antiparallel
  Energy loss, if u and v parallel
- but in average energy gain

➢ Relative energy gain: $$\frac{\Delta E}{E} = 2\frac{u^2}{v^2}$$

➢ for statistically distributed scatter angles: $$\frac{\Delta E}{E} = \frac{4}{3}\frac{u^2}{v^2}$$

• 4. Acceleration in Pulsars

- acceleration of primary particles in young, fast rotating pulsar in „outer gaps“ (plasma free zone between open and closed field lines)



- With typical values for pulsars (Magnetic field strength upto $2.5 \cdot 10^8$ T, rotation in ms-range) we get electric fields of up to 10^{15} V/m
- Converions of rotation energy in kinetic (acceleration) energy

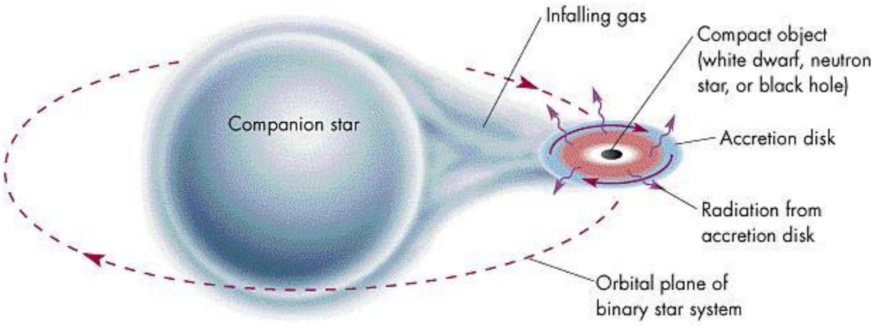
- Energies up to several 10^{19} eV

• 5. Acceleration in Microquasars and Quasars

- Doppelsternsystem aus Pulsar/Neutronenstern und Hauptreihenstern
- In Akkretionsscheibe aus ionisierter Materie werden vorhandene Magnetfelder verstärkt und auf Keplerbahnen mitbewegt

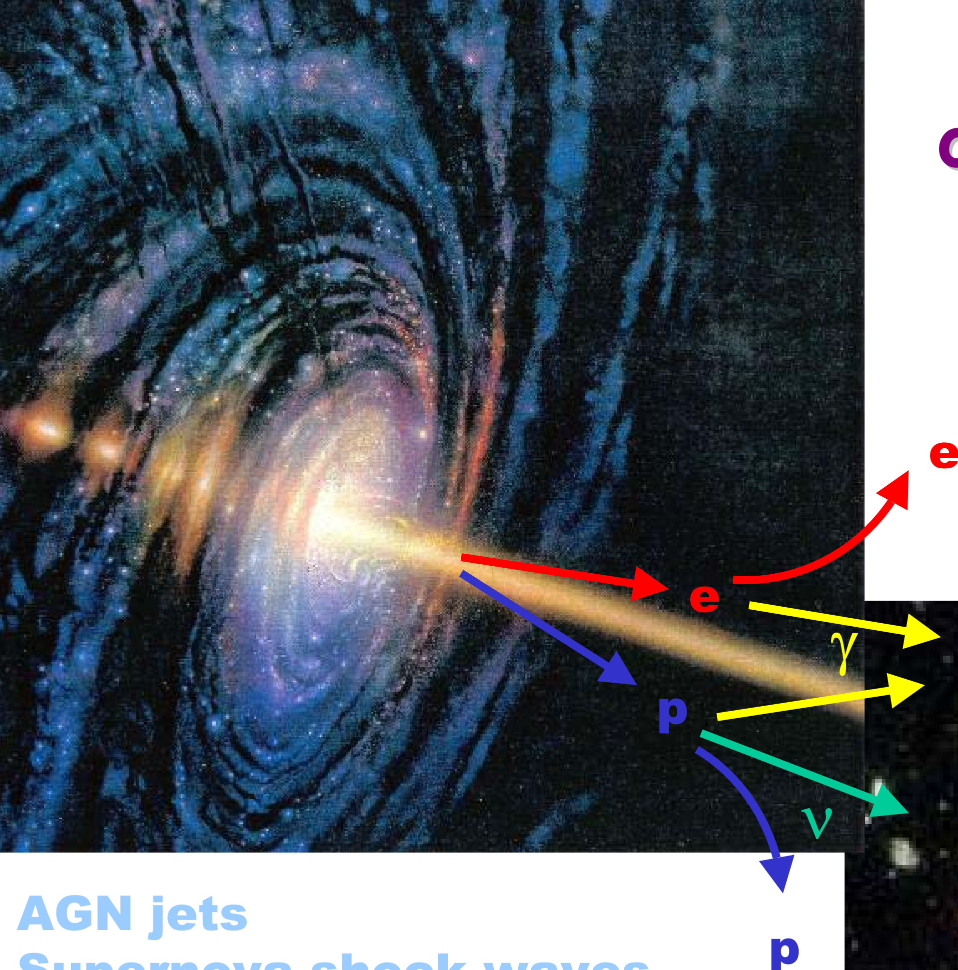
➢ strong electric field in disk (dynamo-like generated)

➢ charged particles are accelerated along rotation axis

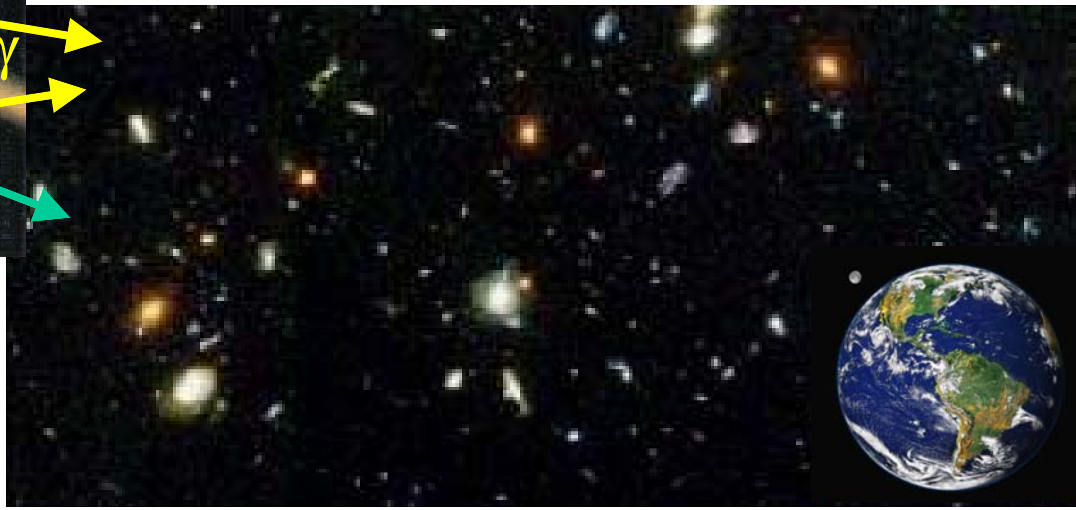


➢ Energies up to $3 \cdot 10^{19}$ eV

Cosmic sources of high-energy particles



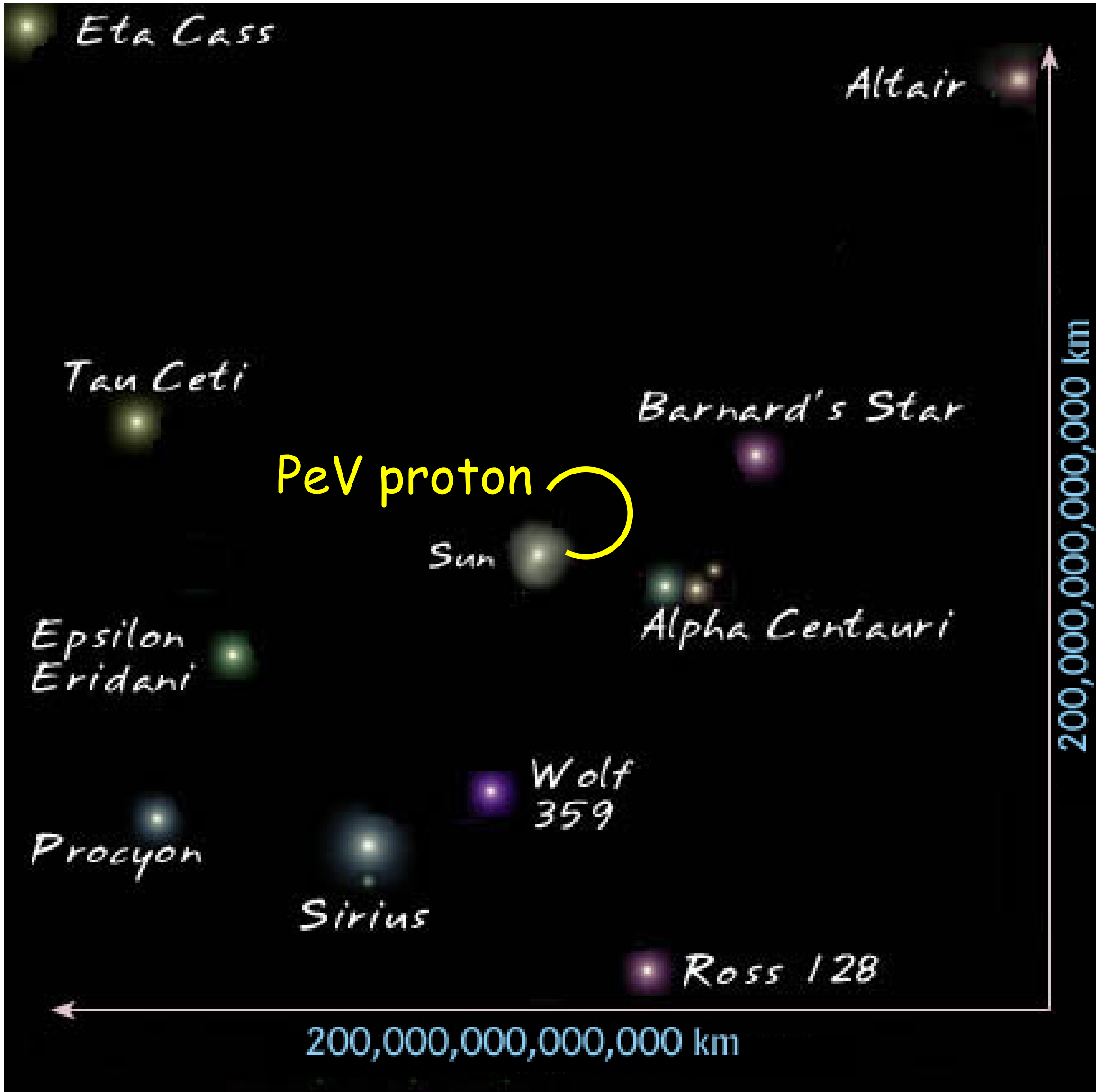
Propagation
- **Optically thick sources**
- **Interactions with “starlight”**
- **Interactions with CMB**
- **Diffusion in magn. fields**
- **Effects of quantum gravity …**



AGN jets
Supernova shock waves
Decaying strings
Annihilating SUSY particles
…

Identify mechanisms using
- **Particle composition**
- **Wide-band energy spectra**
- **Spatial and temporal characteristics**

however, cosmic rays cannot be used to image the Universe...



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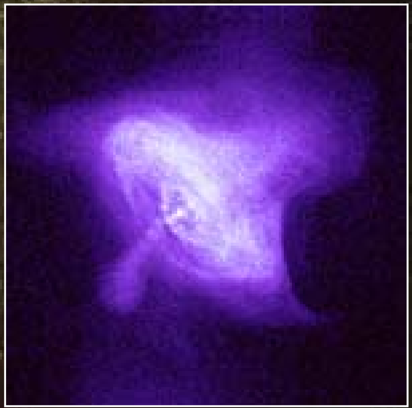
Emission mechanisms: the Crab tutorial

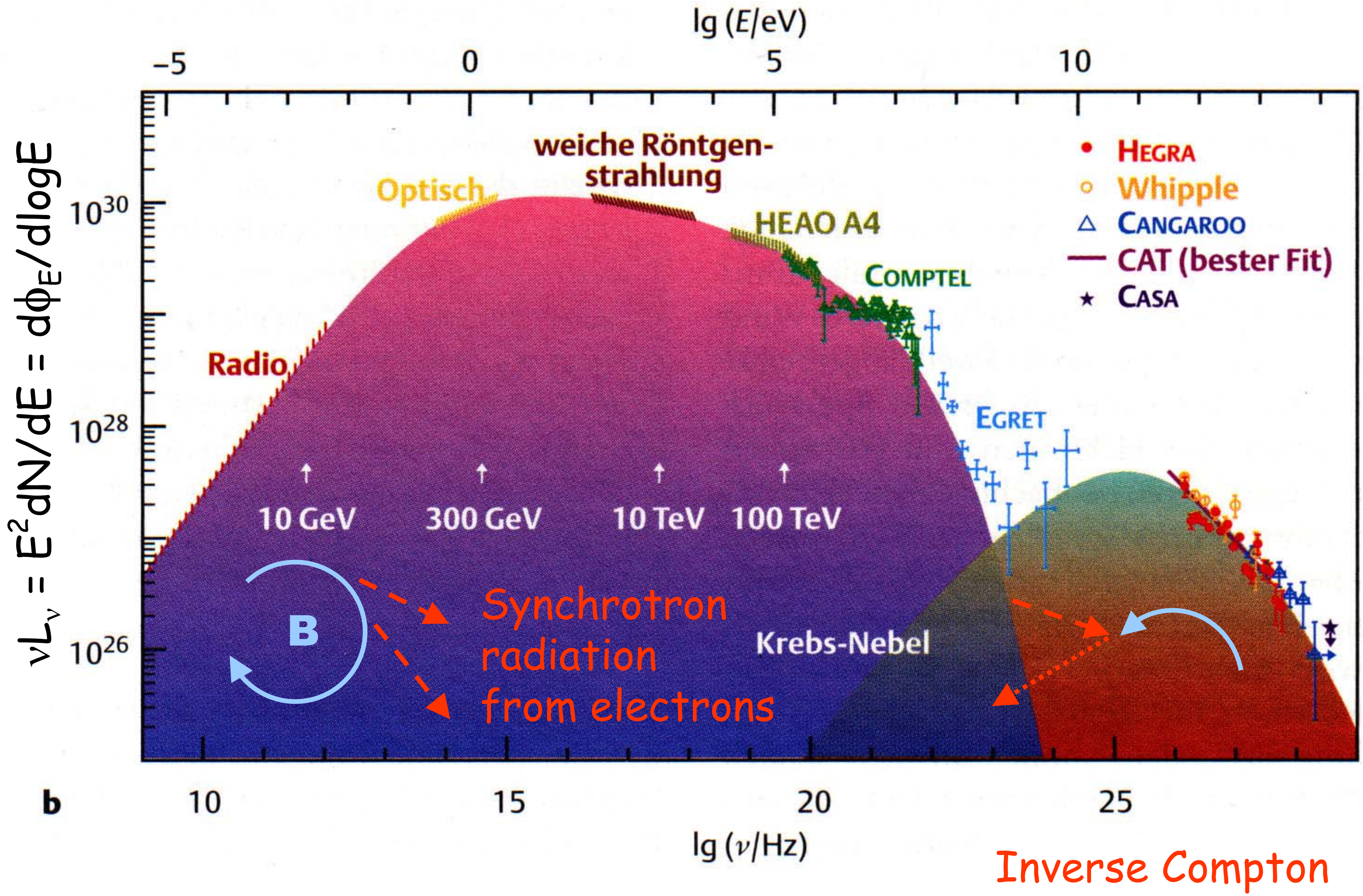

Radio


Infrared


Optical


X-ray

The Crab: gammas from electrons



Primarily electron accelerator, not protons!

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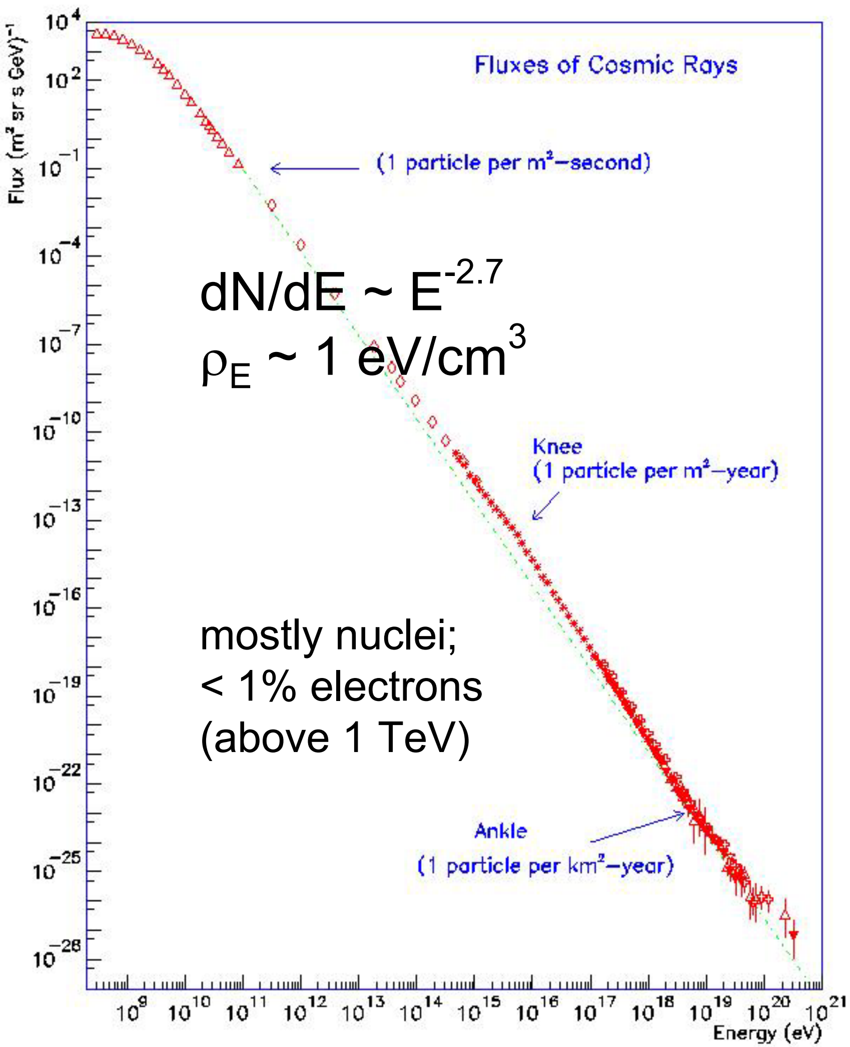
The quest for the sources of cosmic rays



$dN/dE \sim E^{-2.7}$

$\rho_E \sim 1$ eV/cm^3

mostly nuclei;
< 1% electrons
(above 1 TeV)

Best (only?) candidate:
Supernova explosions

Argument 1:
Energy balance

$E_{CR} \sim \rho_E V / \tau_{esc} \sim 10^{41}$ erg/s

$E_{SN} \sim 10^{51}$ erg/30 y $\sim 10^{42}$ erg/s

... need O(10%) efficiency

Argument 2:
Shock acceleration as mechanism

$dN/dE_{\text{Shock acc}} \sim E^{-2.1}$

$dN/dE_{\text{Obs}} \sim dN/dE_{\text{Acc}}\ \tau_{esc}(E)$

where $\tau_{esc}(E) \sim E^{-0.6}$

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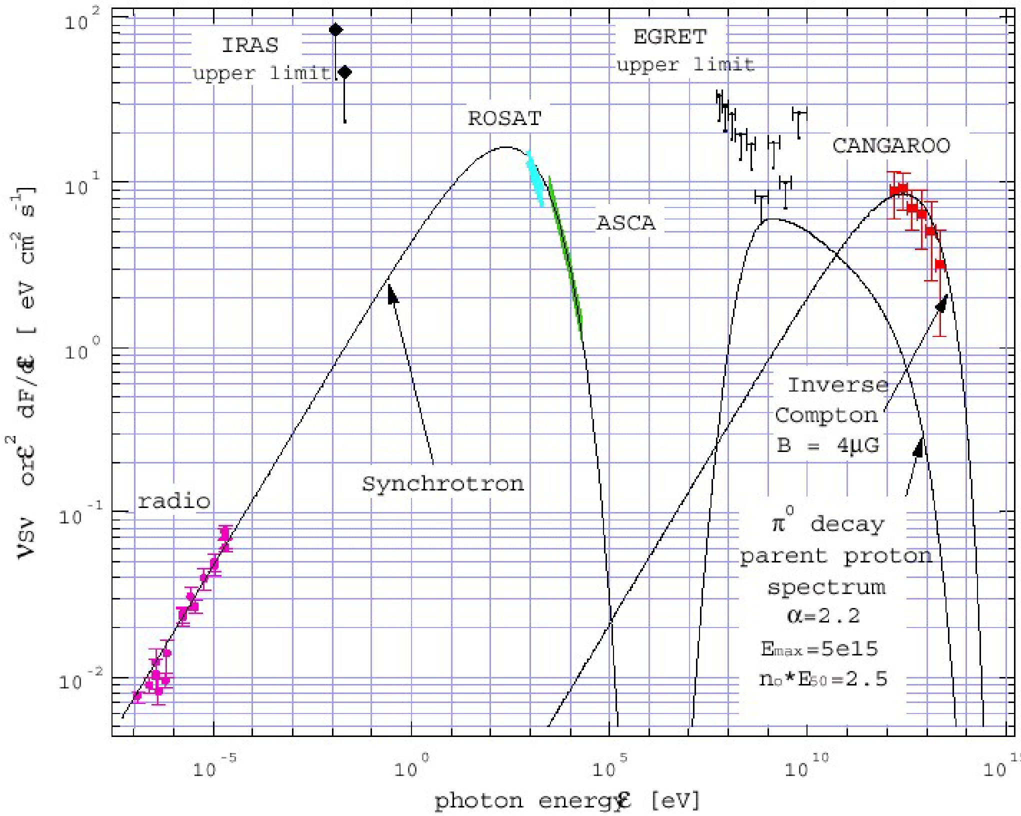
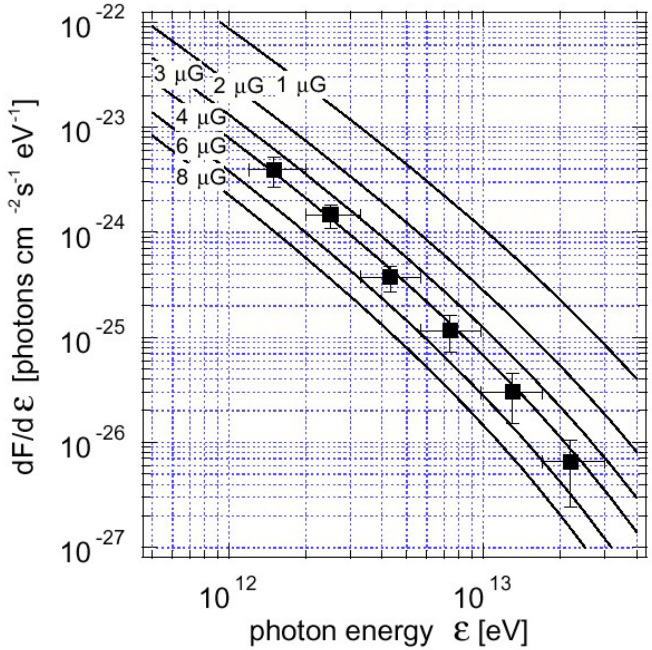
Supernova Remnant 1006



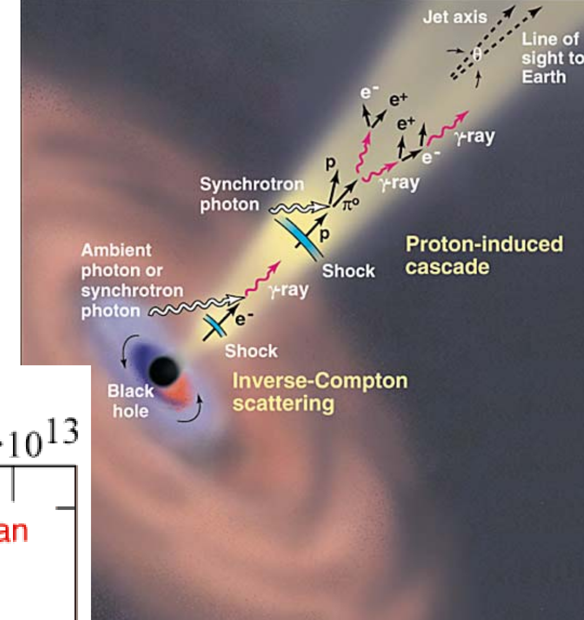
CANGAROO
Tanimori et al. 1998
Tanimori et al. 2001

Mastichiadis, Stecker 1996
Aharonian, Atoyan 1999
...

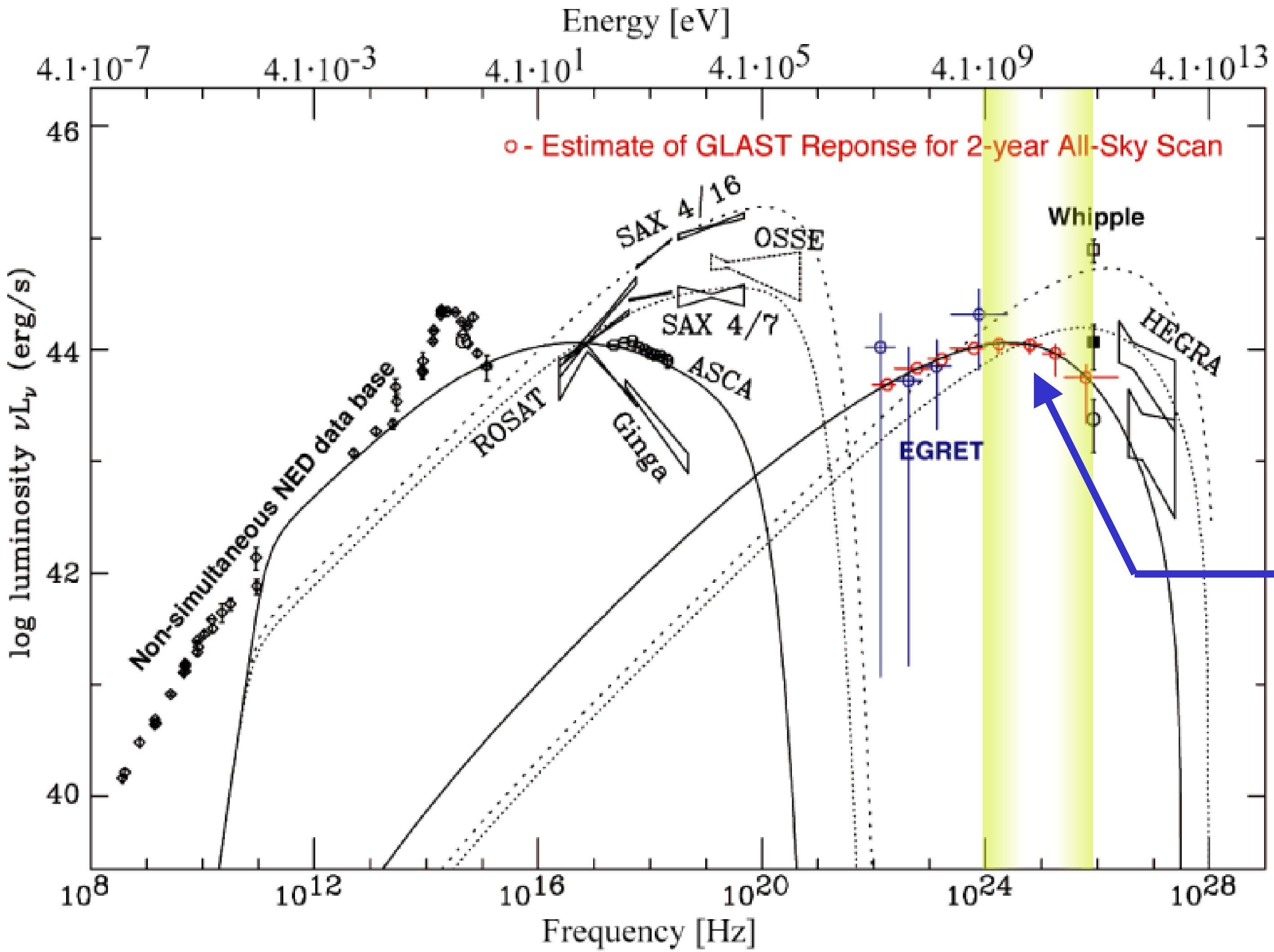


- SN 1006 accelerates electrons up to energies of ~100 TeV
- No evidence for (or against) proton acceleration

AGN as proton accelerators?



Radio-loud, flat spectrum ⟶ Blazars



Peak of Spectrum

?

Mrk 501

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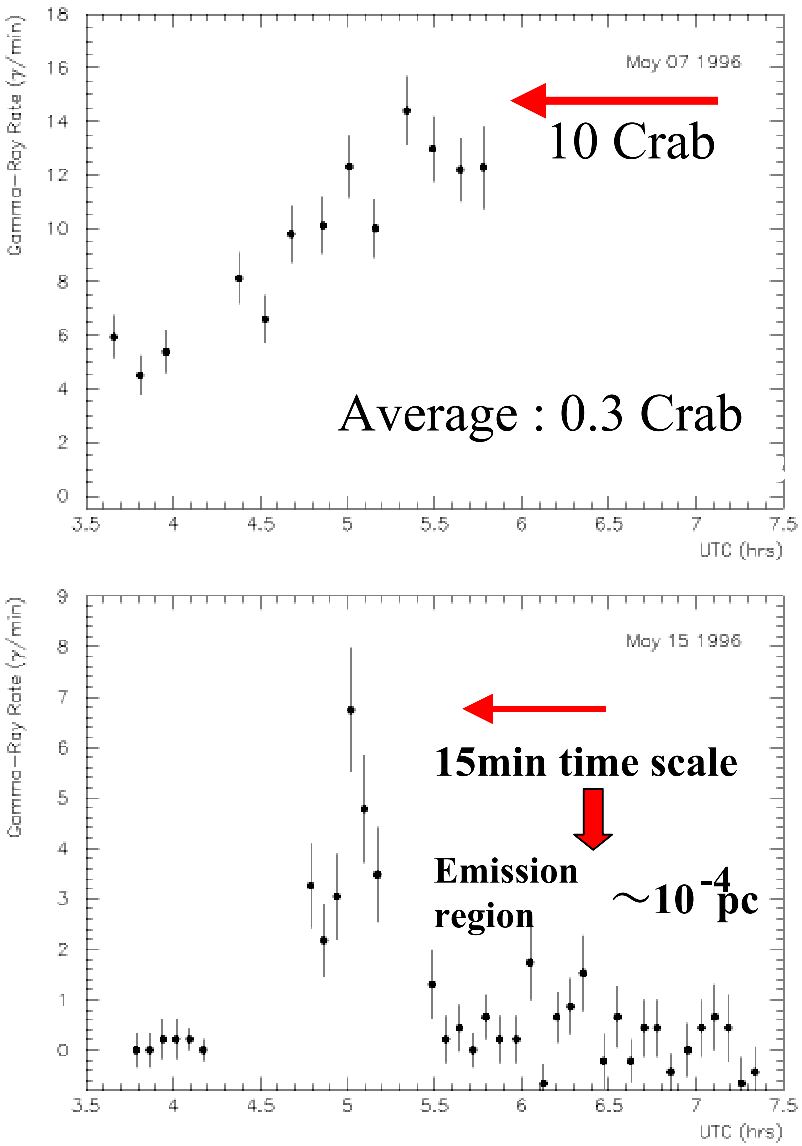
Highly variable emission

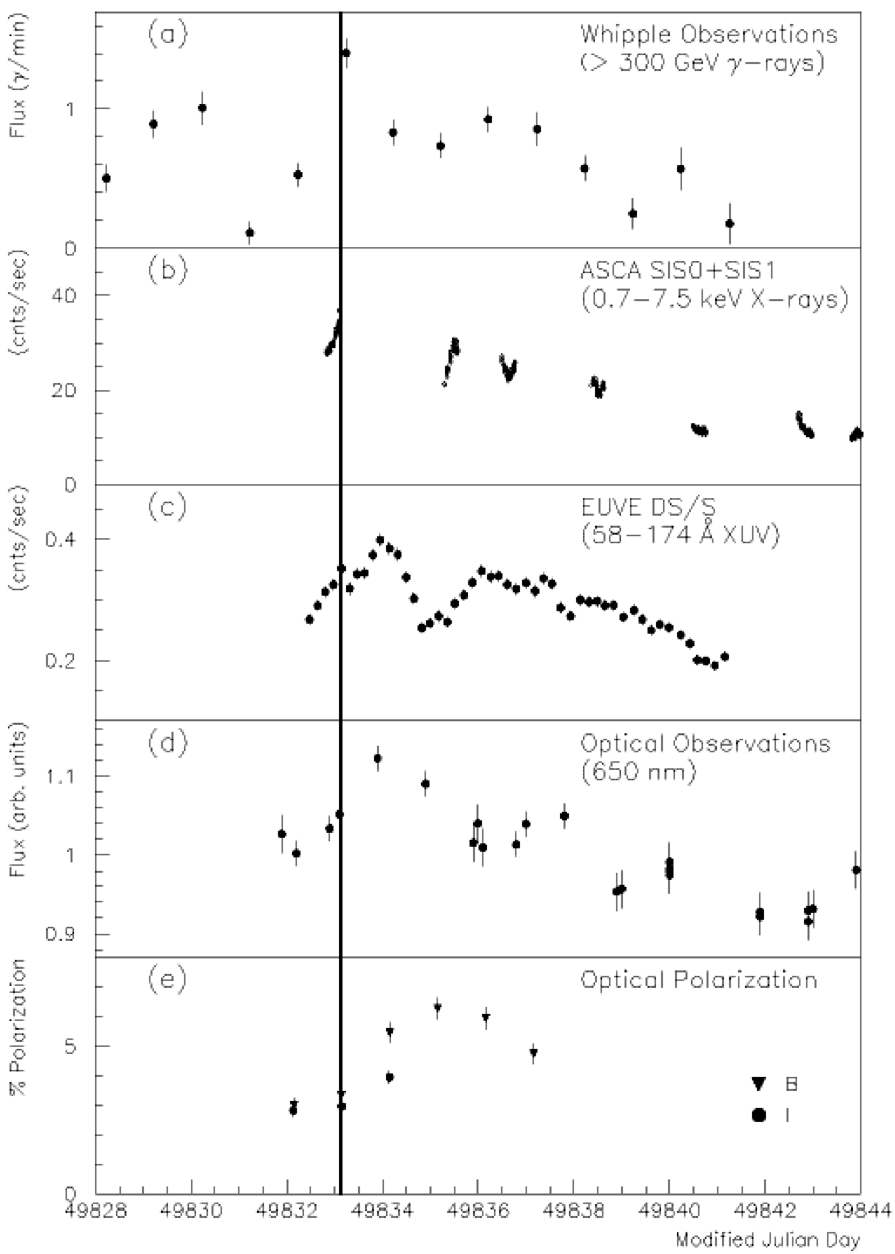
Mkn 421



- Time variability in requires compact source and significant boost (~10)
- SSC models describe data reasonable well, but other (e.g. hadronic) models are not completely excluded
- AGN spectra deviate from power laws, with cutoffs around a few TeV for Mkn 421 and 501 (with z ~ 0.03)
- More precise data (multiwavelength spectra, time variability) are needed to fix model details
- More sources are needed, at different z, luminosity, etc

Many new results expected for the next years ...
with O(100) sources

Multi wavelength campaigns



- Correlations between X-rays and VHE γ

  Both wavelengths are produced by same electrons

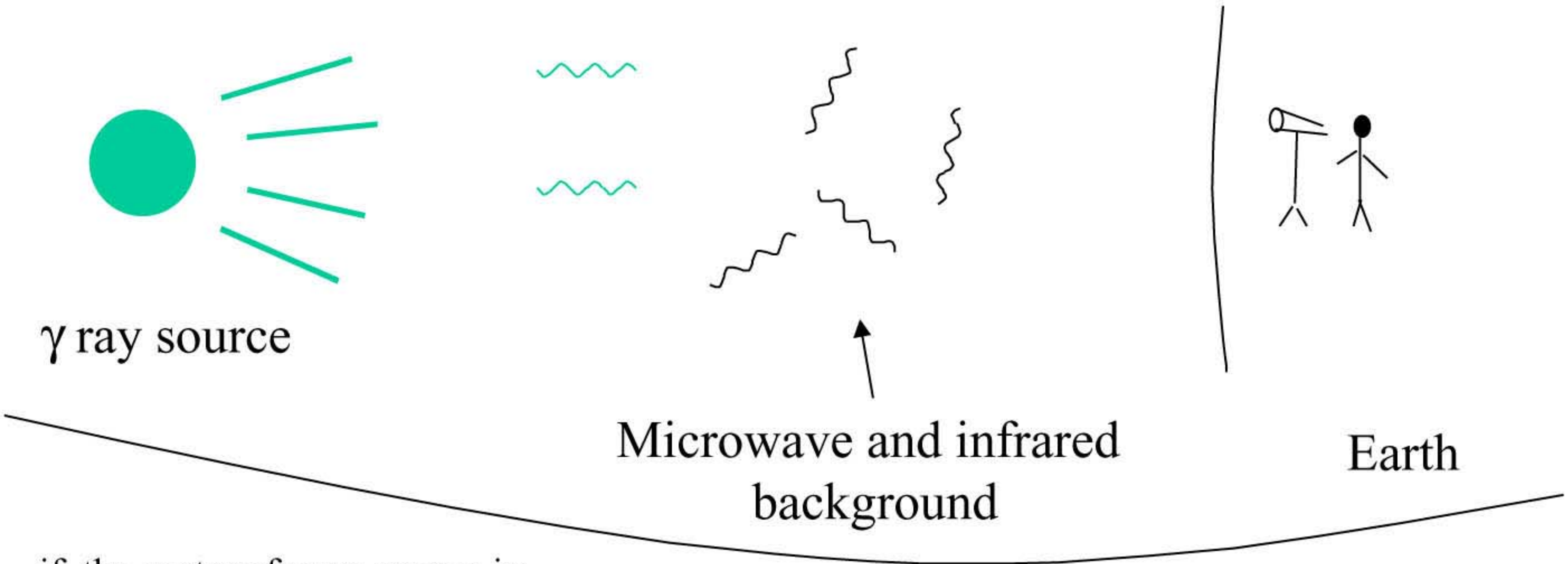
- UV and Optical flare was delayed

★Multi-wavelength campaigns (1995, Mrk 421)

✓Whipple(VHE γ)
✓EGRET(γ)
✓ASCA(X-ray)
✓EUVE(XUV)
✓Optical Telescope
✓Optical Polarimeter
✓UMRAO(radio)

Infrared background I

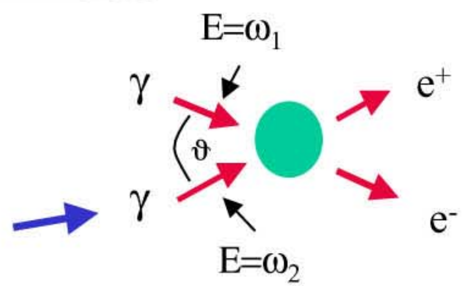
Flux absorption due to the interaction with the infrared and microwave background



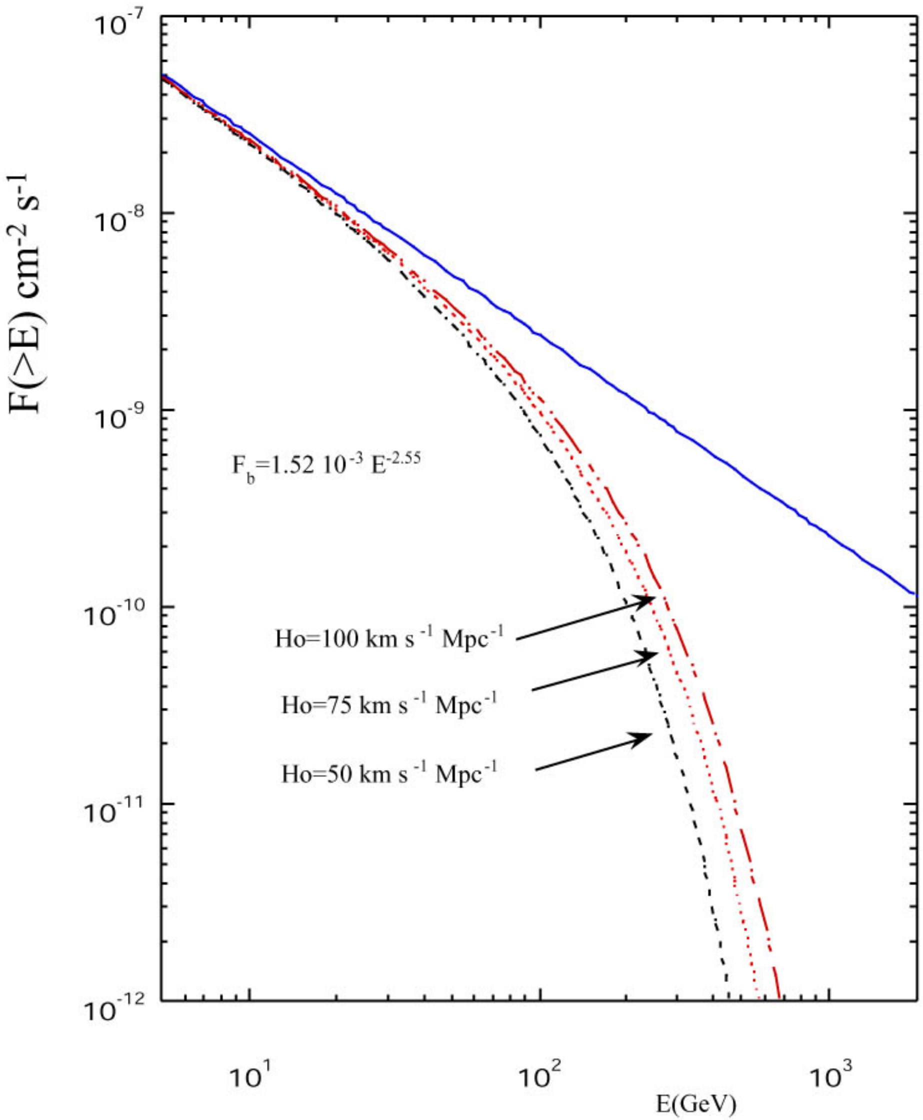
if the center of mass energy is:

$$\sqrt{2\omega_1\omega_2(1-\cos\vartheta)} \geq 2m_e$$

photons interactions produce electron positron pairs



Infrared background II



Measurement spectrum and density of IR

↓

Information about evolution of formation process

VHE γ spectrum for e.g. Blazars
Indirect investigation of IR field
and measurement of Hubble constant

Catalog of TeV sources

Adapted from Weekes, astro-ph/0010431

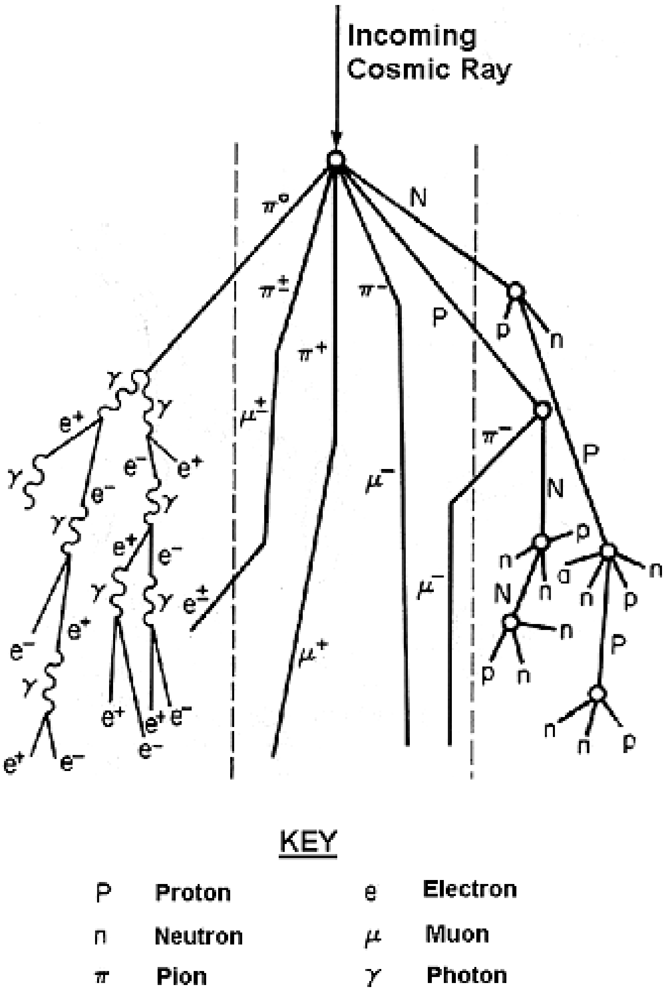
Source	Type	Distance	Discovery	Flux (CU)	Grade	Group
Galactic						
Crab Nebula	**Plerion**	**~ 2 kpc**	**1989**	**1**	A	**Whipple, ...**
PSR 1706-44	**Plerion ?**	**~ 2 kpc**	**1995**	**~ 0.5**	A	**CANGAROO, ...**
Vela	**Plerion ?**	**0.2 – 0.5 kpc**	**1997**	**~ 0.7**	**B**	**CANGAROO**
SN 1006	**Shell SNR**	**~ 2 kpc**	**1997**	**~ 0.5**	**B**	**CANGAROO**
RXJ 1713.7-3946	**Shell SNR**	**1 – 6 kpc**	**1999**	**~ 0.7**	**B**	**CANGAROO**
Cassiopeia A	**Shell SNR**	**~ 3.5 kpc**	**1999**	**~ 0.03**	**C**	**HEGRA**
Monoceros	**Shell SNR**	**~ 1.6 kpc**	**2001**	**-**	**C**	**HEGRA**
Centaurus X-3	**Binary**	**~ 8 kpc**	**1999**	**~ 0.4**	**C**	**Durham**
Extragalactic						
Markarian 421	**XBL**	**z=0.031**	**1992**	**up to ~ 10**	A	**Whipple, ...**
Markarian 501	**XBL**	**z=0.034**	**1995**	**up to ~ 10**	A	**Whipple, ...**
1ES 2344+514	**XBL**	**z=0.044**	**1997**	**up to ~ 0.6**	**C**	**Whipple**
PKS 2155-304	**XBL**	**z=0.116**	**1999**	**up to ~ 2**	**B**	**Durham**
1ES 1959+650	**XBL**	**z=0.048**	**1999**	**up to ~ 2**	**B**	**Tel. Array**
H 1426+428	**XBL**	**z=0.129**	**2001**	**~ 0.1**	**B**	**Whipple, ...**
BL Lac	**XBL**	**z= 0.069**	**2001**	**up to ~ 2**	**B**	**Crimean**
3C66A	**RBL**	**z=0.44**	**1998**	**~ 1.5**	**C**	**Crimean**
GRB 970417a	**GRB**		**1999**		**C**	**Milagrito**

A: $> 5\ \sigma$, confirmed B: $> 5\ \sigma$, unconfirmed C $\leq 5\ \sigma$

Conclusions

- A number of astrophysical objects produce gamma rays with energies well beyond TeV scales (Crab: > 50 TeV, SNRs > 10 TeV, AGNs > 20 TeV)
- Many of these objects emit as much or more energy at TeV energies than in other wavelength ranges
- In current objects, data are consistent with a primary electron population (with energies up to and beyond 100 TeV)
- Shock wave acceleration is strongly supported, but...
- High energy electrons are much more efficient in producing gammas – O(10...100) at TeV energies – hence not obvious if electron sources will also accelerate sufficient cosmic rays
- No proof for nucleon acceleration... just around the corner?

Air Shower Experiments



Air showers consist of 3 components:

- hadronic component
  primary proton scatters off atmospheric nuclei, thereby producing protons, neutrons, pions, kaons, ...

- myonic component
  the decay of charged pions and kaons generates myons

- electromagnetic component
  the decay of neutral pions generates γ`s, which initiate electromagnetic cascade through pair creation and bremsstrahlung

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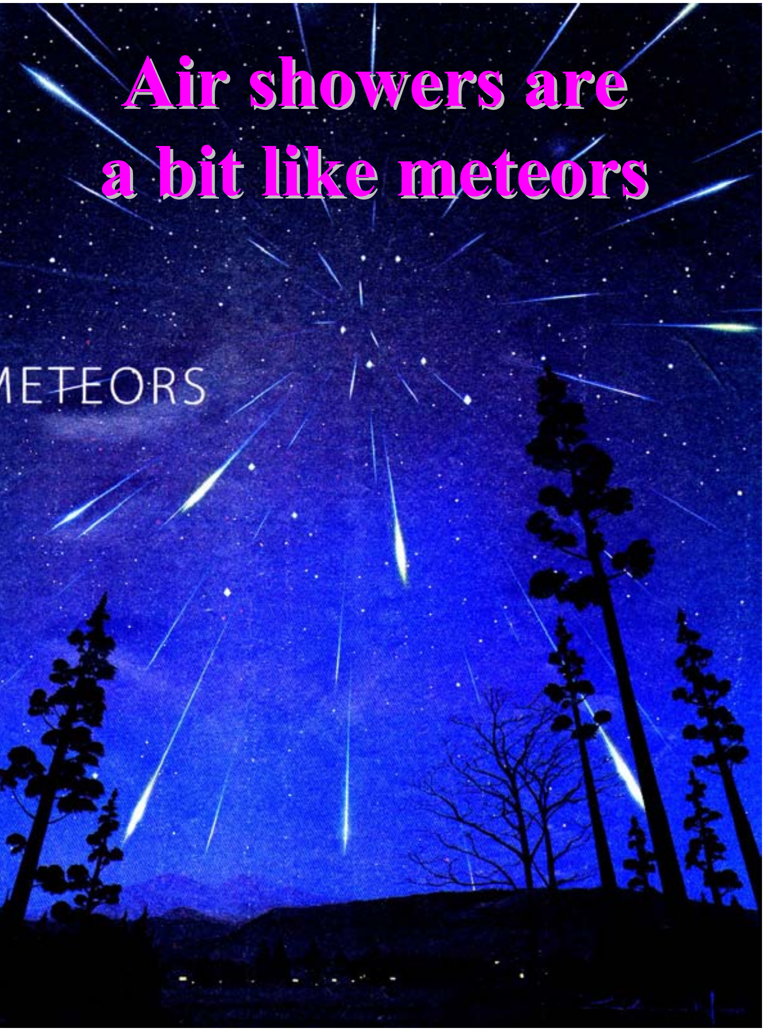
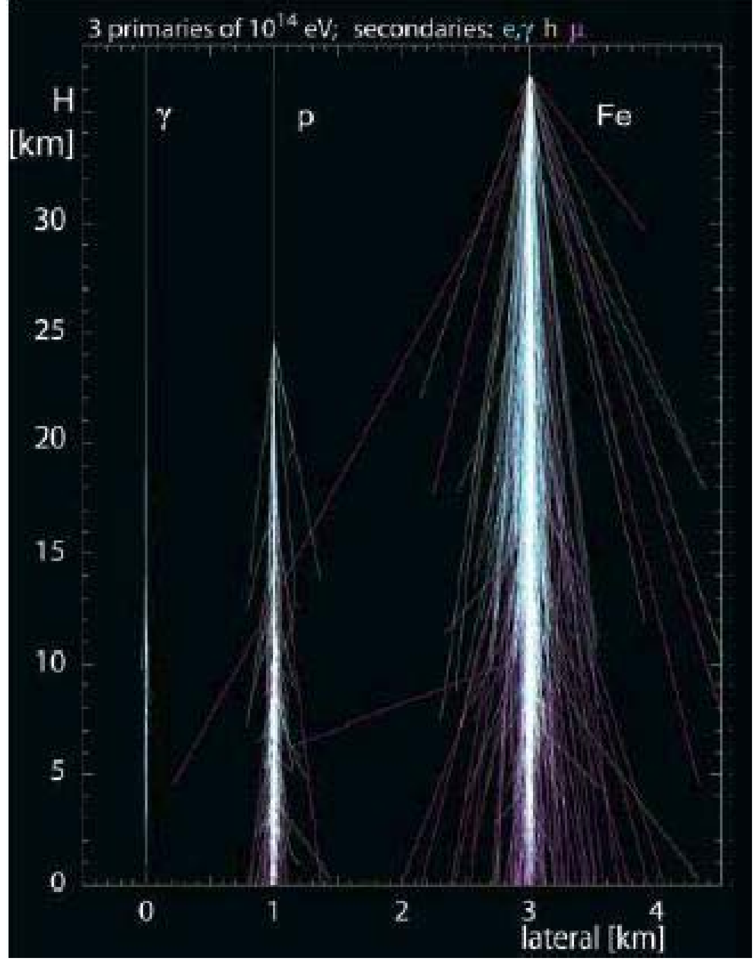
What to measure?





- appearance of shower
  - ➢ primary particle (photon or hadron)
- penetration depth
  - ➢ heavy or light particle
- particles detected on ground
  - ➢ e.g. mass estimate from ratio of myon to electon number

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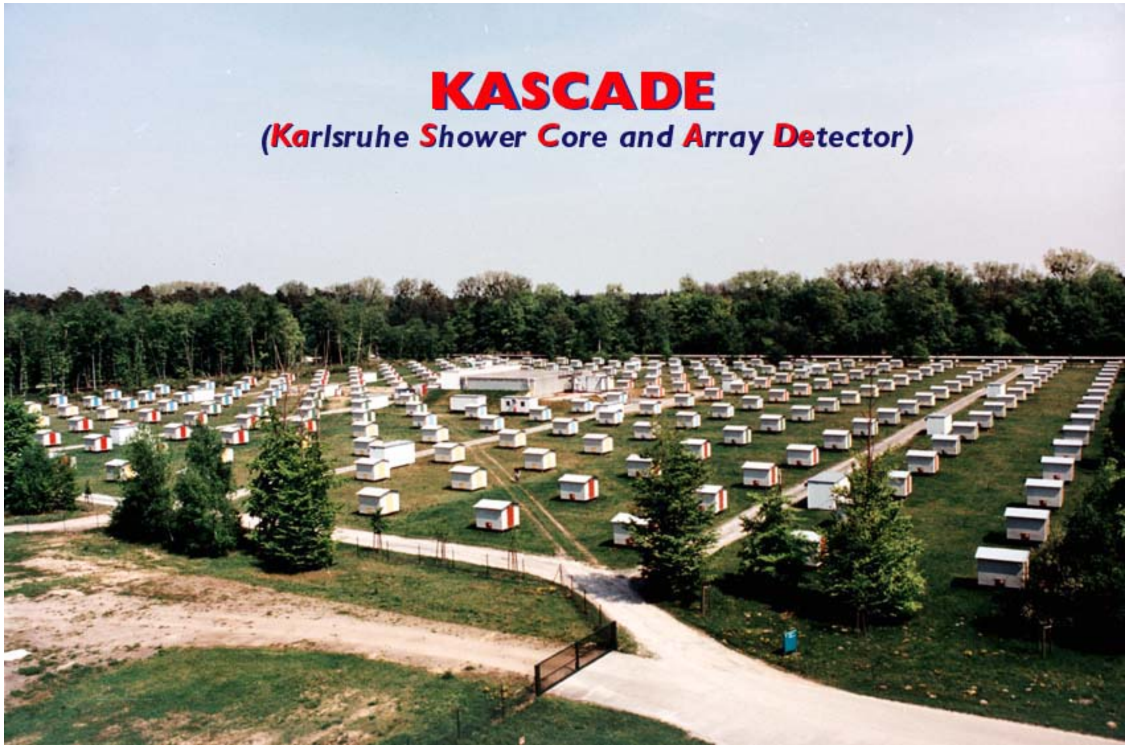
KASCADE (KARLSRUHER SHOWER CORE AND ARRAY DETECTOR)

Measurement and study of extended air showers (all 3 components)

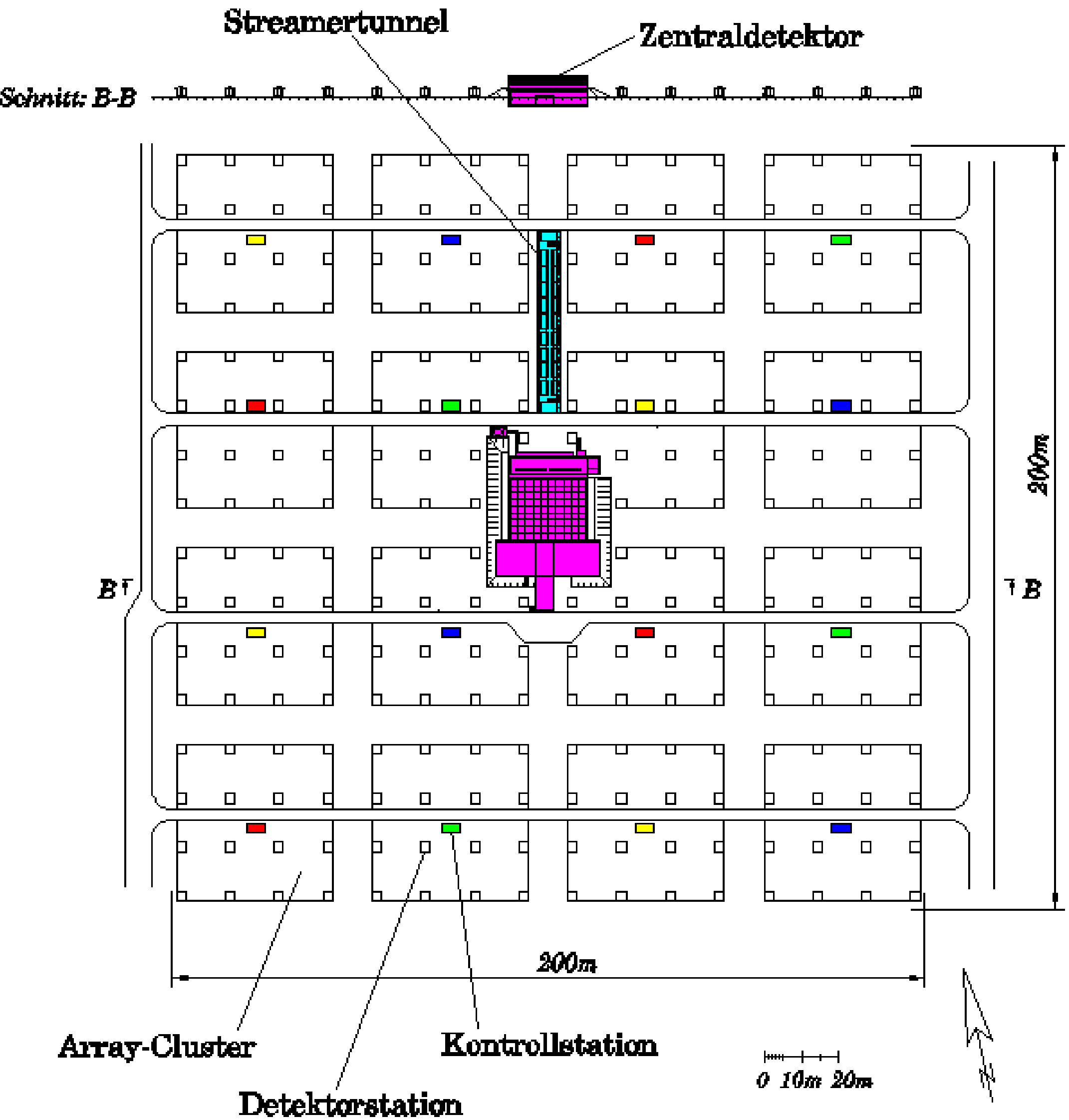
- Measurement of energy spectrum
- Determination of chemical composition



Energy range: $10^{14} - 10^{17}$ eV

- detailed study of the „knee“ in the spectrum

KASCADE – Schematics



Central detector

- Measurement of the hadronic component and high-energy myons in shower center

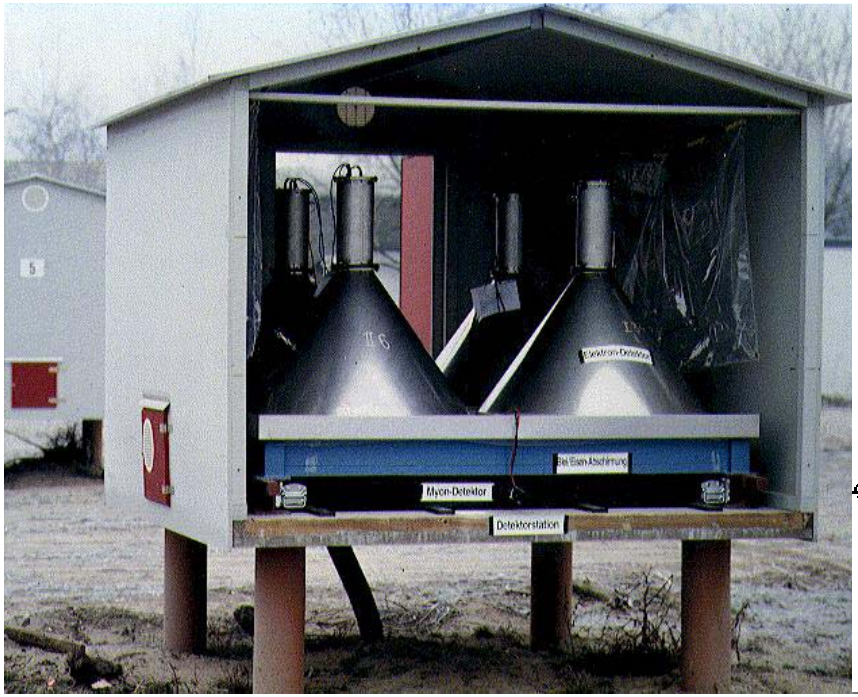
200 x 200 m Detector array

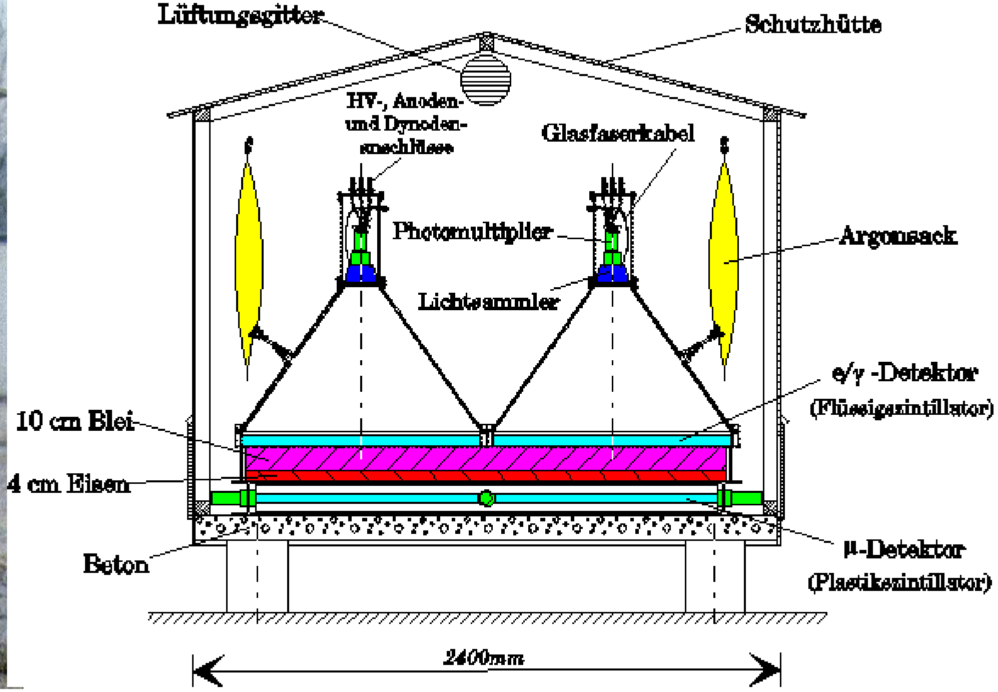
- trace the extended electromagnetic and myon components

Streamer tunnel

- Tunnel with detector system for rekonstruction of myons

KASCADE – Detector Station





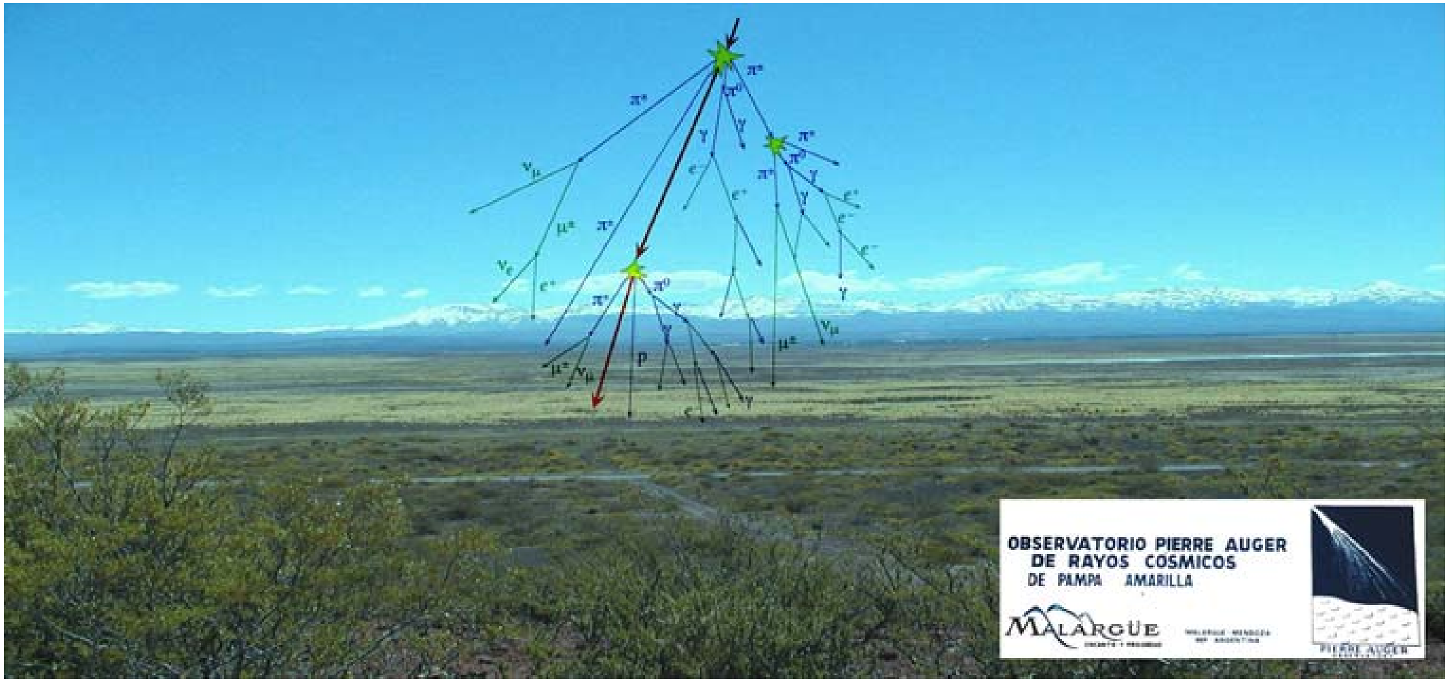
Matrix of 16 x 16 detector stations at distance of 13 m

➢ total of 252 stations

PIERRE AUGER PROJECT

(First) Combination of particle detectors and fluorescence light detectors
- reproduce complete evolution of shower
- determine direction, energy and type of the cosmic particles

Energy range: above 10^{18} eV
- study of the highest energy particles



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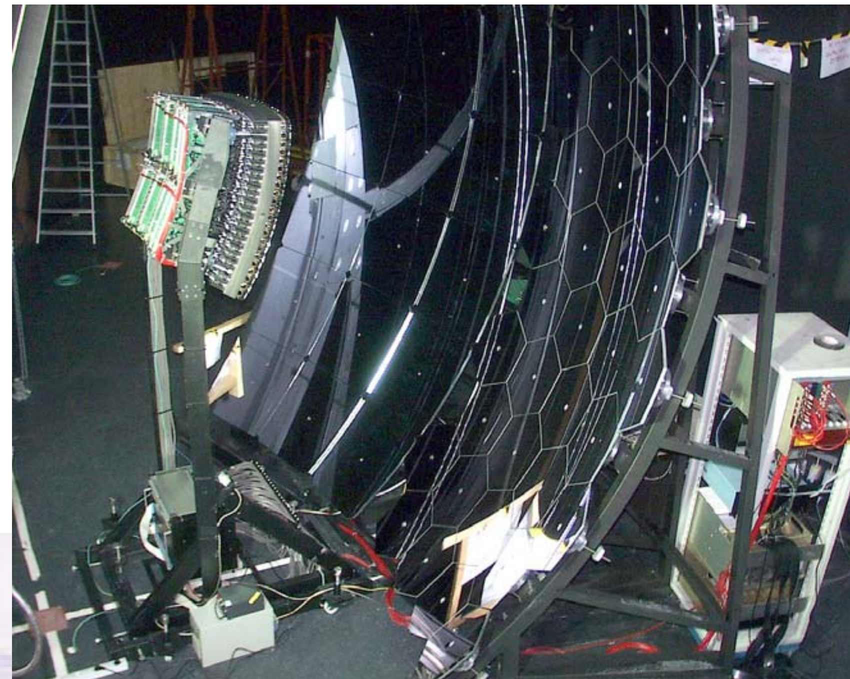
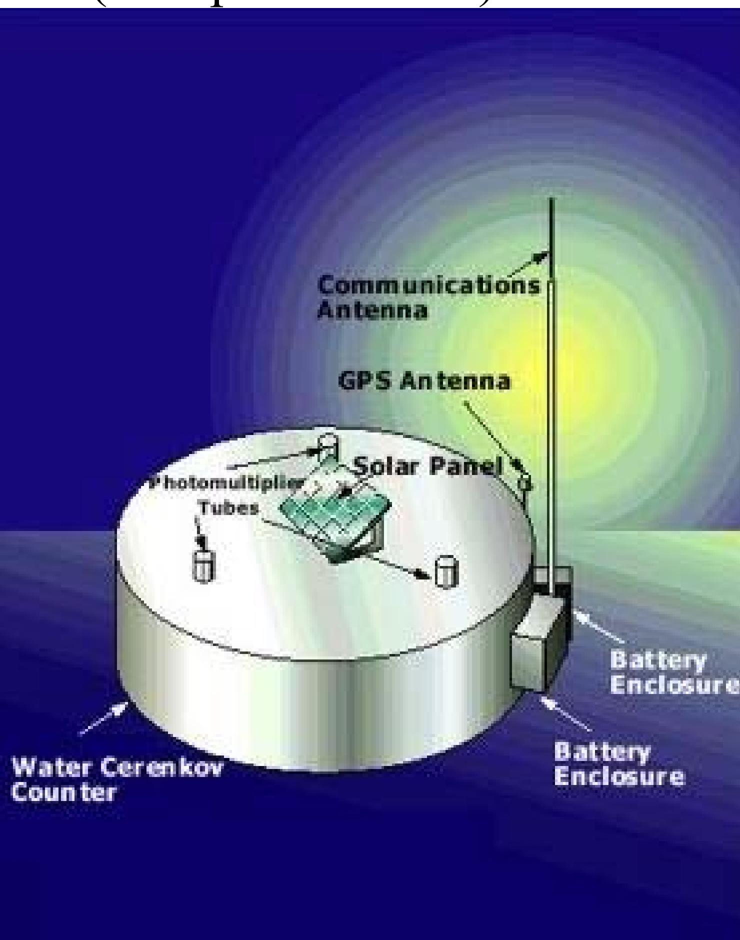
Pierre Auger Project – Mendoza (Argentinia)

1600 Water-Čerenkov-detectors, distributed over area of 3000 km^2
(Completion 2004)

One of 4 fluorescence light detectors
(in total 30 telescopes)





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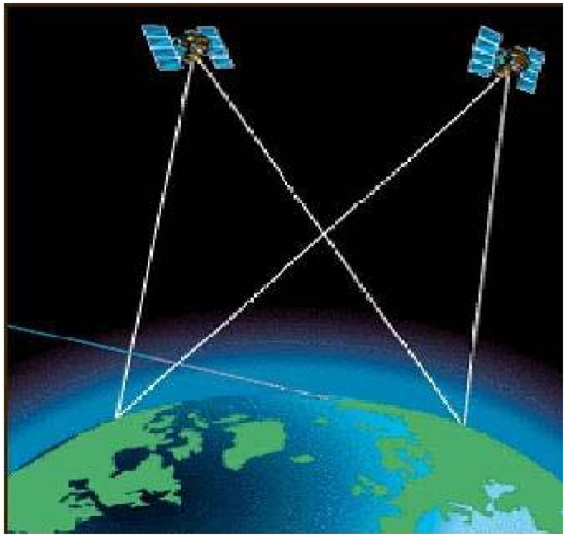
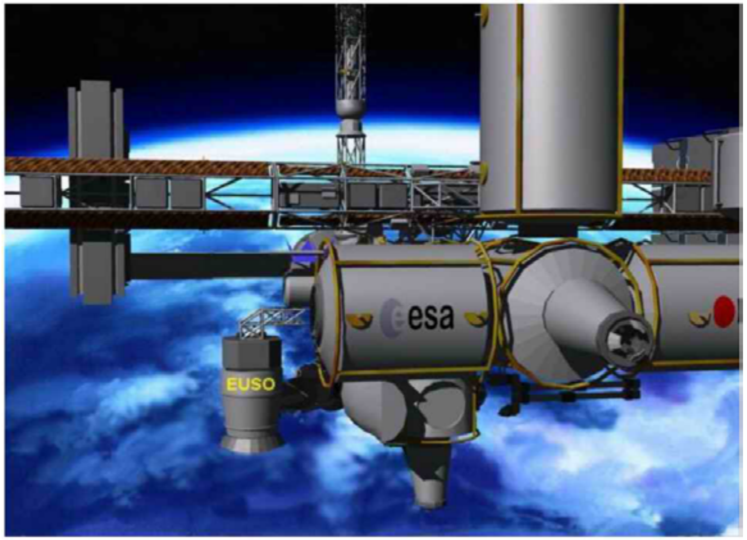
Future Experiments

- OWL (<u>O</u>rbiting <u>W</u>ide-angle <u>L</u>ight-collectors)

  - Use of the (full) Earth atmosphere as detector
  - Observation of the fluorescence light from two satellites

  „in study phase“





- EUSO (<u>E</u>xtreme <u>U</u>niverse <u>S</u>pace <u>O</u>bservatory)

  - also use of Earth atmosphere as detector
  - Detector instrument(s) on the international space station ISS

  „Phase A study“ – Goal: Launch 2009

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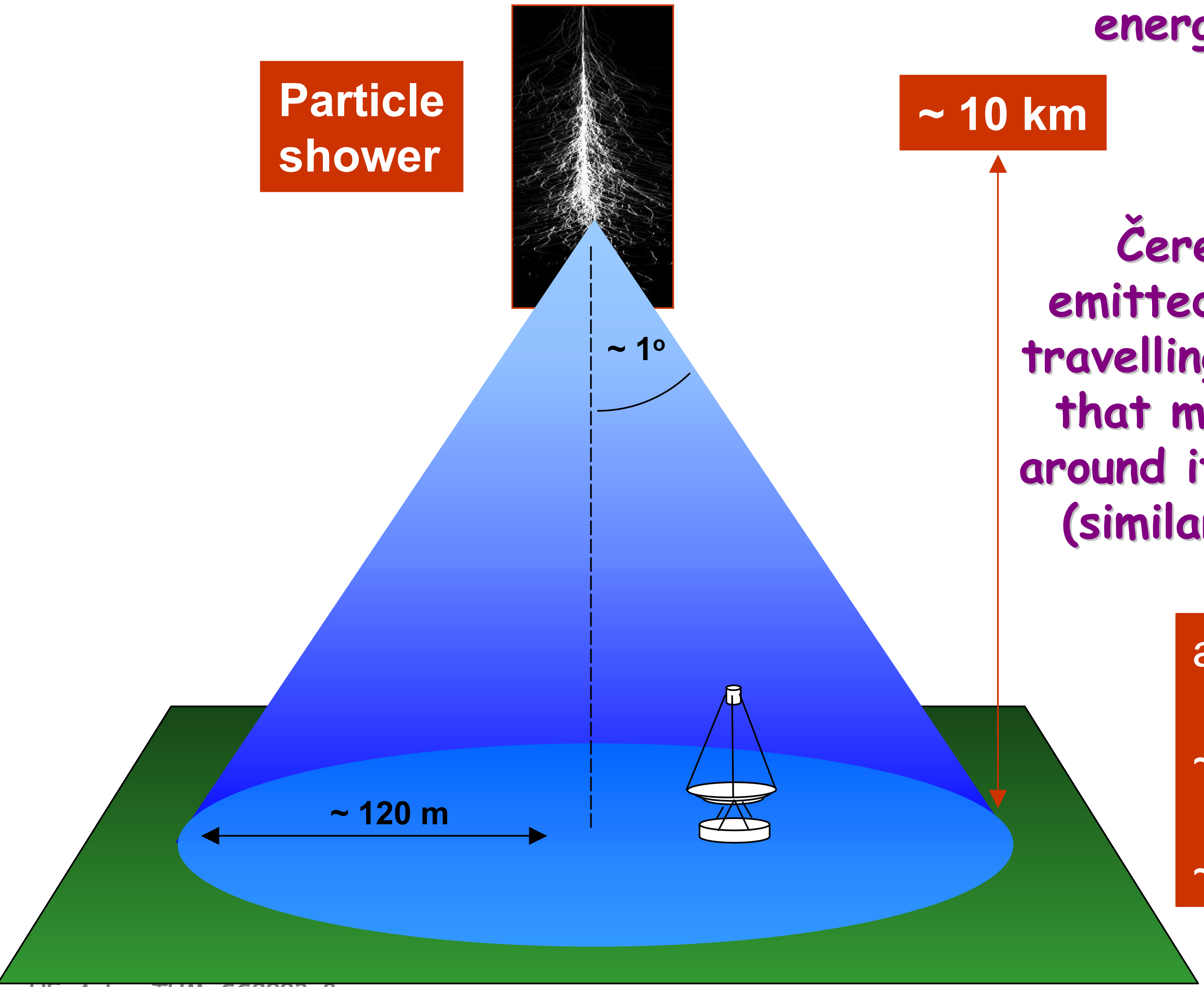
Čerenkov Detectors

Gamma-ray

detection of highest energy gamma-rays

Particle shower



Čerenkov radiation: emitted from a particle travelling faster than c in that medium, in a cone around its travel direction (similar to sonic boom)

at 1 TeV

~ 100 photons/m^2
(300 – 600 nm)
~ 10 – 20 photoel./ m^2

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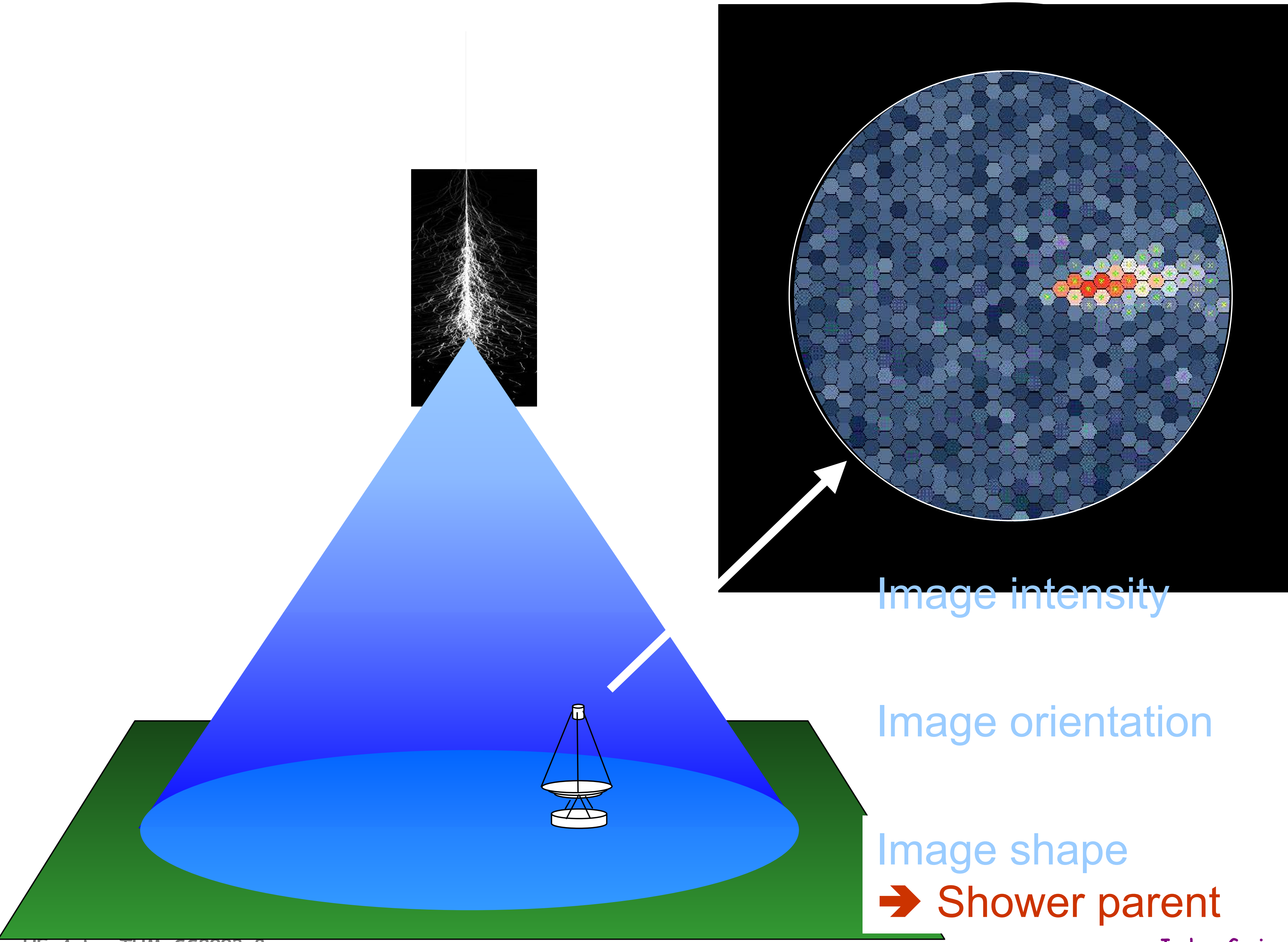

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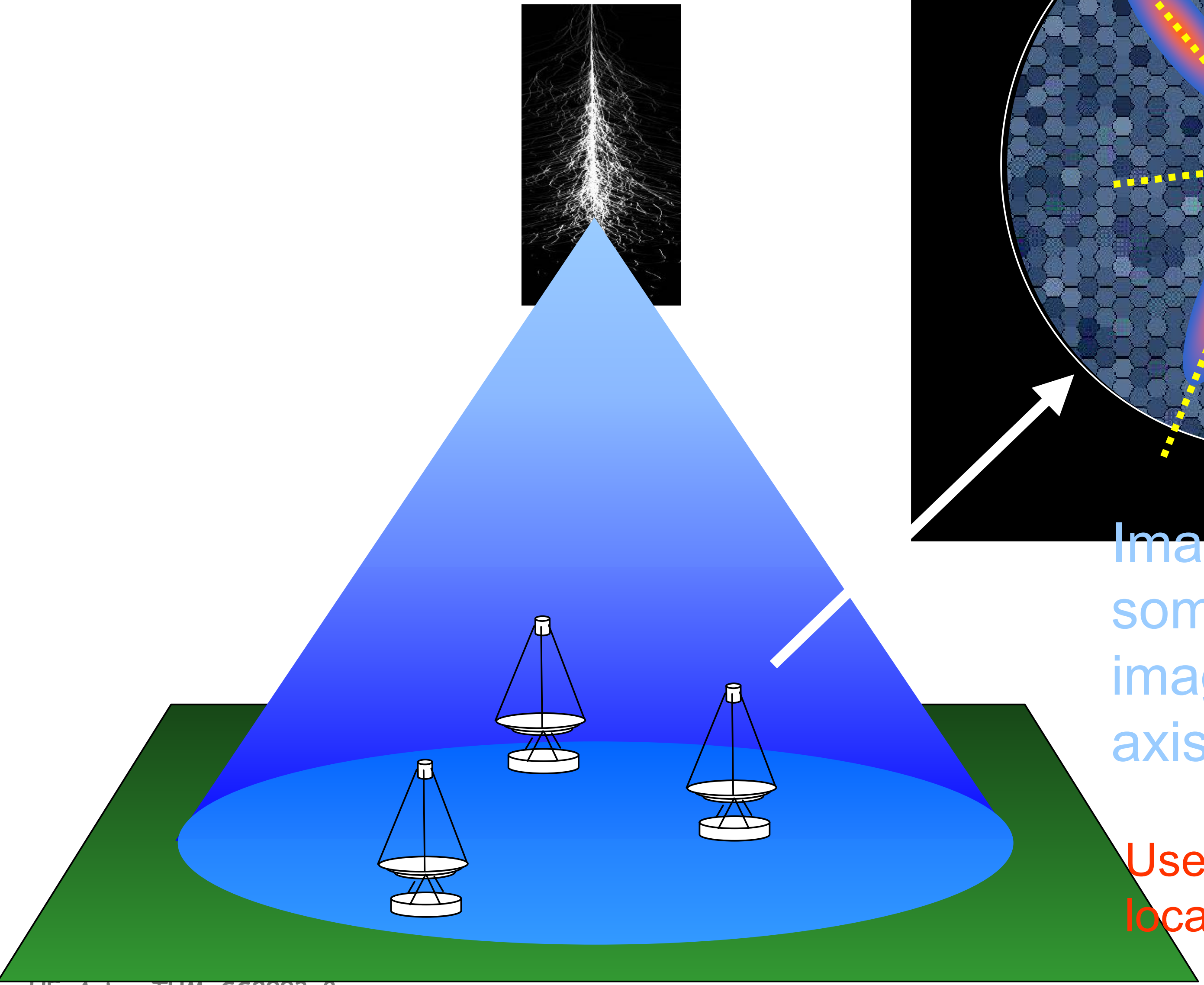
Systems of Čerenkov telescopes and stereoscopy



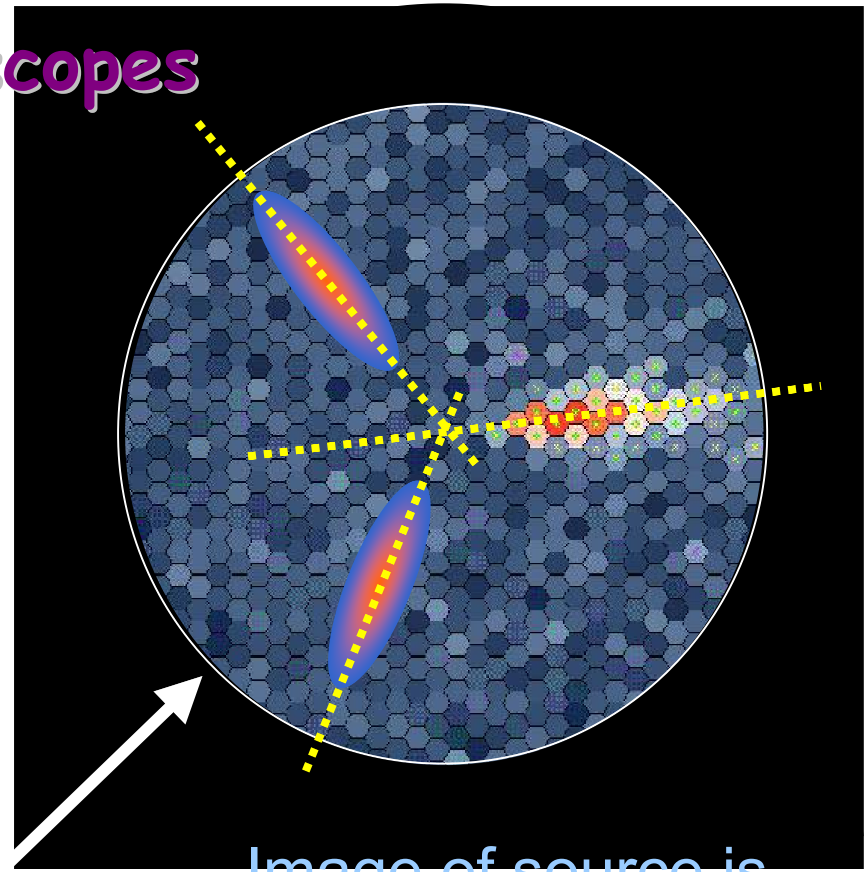


Image of source is somewere along image of shower axis ...

Use more views to locate source!

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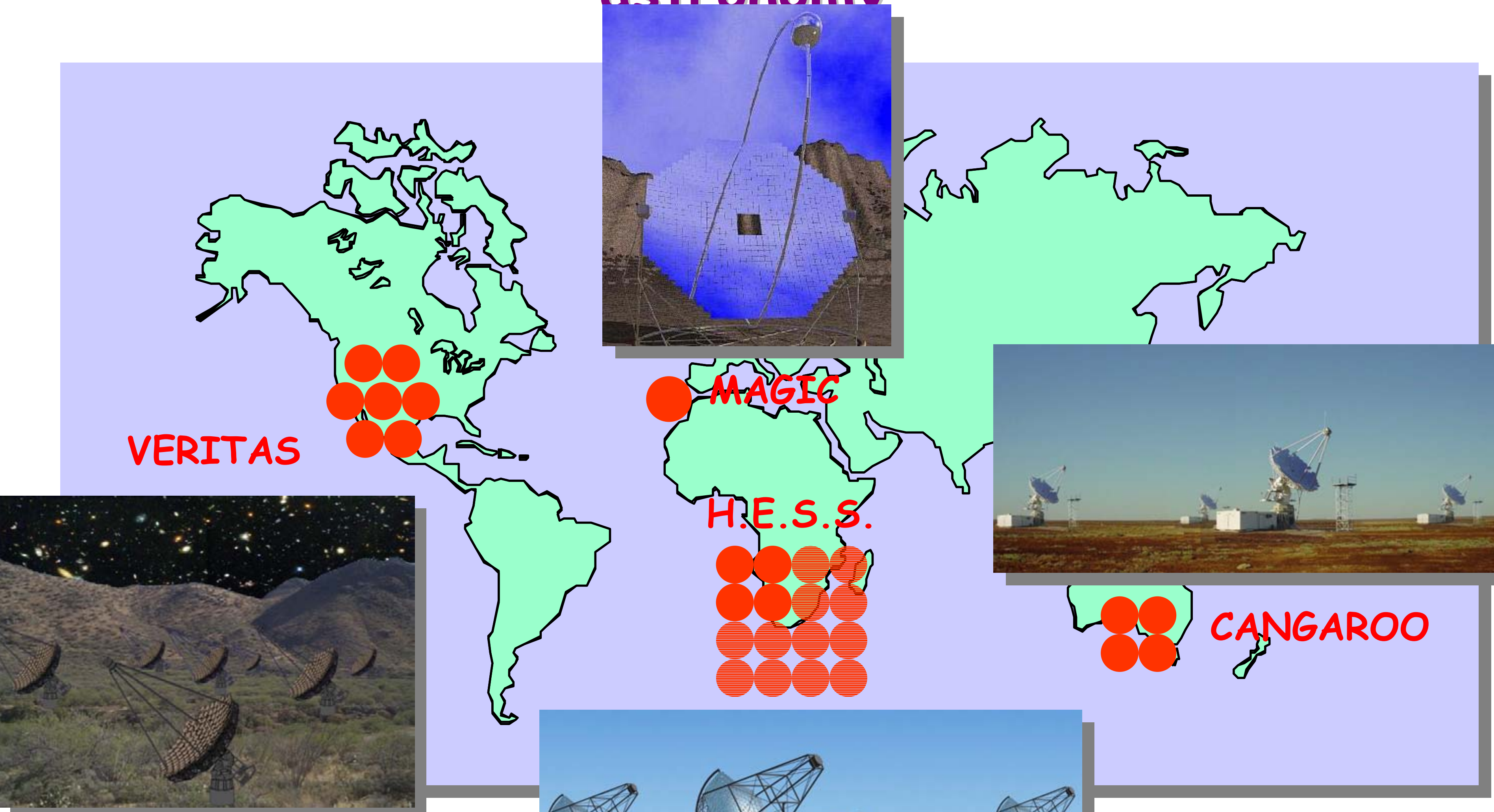
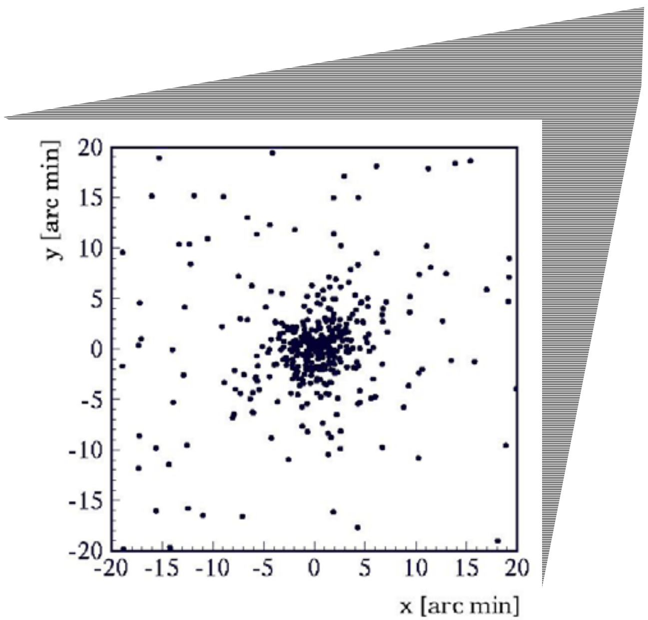
Large projects in high-energy gamma-ray astronomy

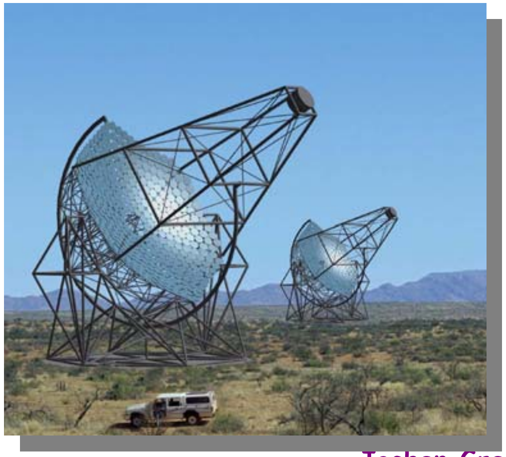


Telescope parameters

Telescope	Mirror area (m^2)	Focal length (m)	f/d	Mirror type	PMTs per camera
Whipple	**72**	**7.3**	**0.7**	**Glass**	**37 → 490**
CANGAROO I	**11**	**3.8**	**1.0**	**Alum.-Polished**	**256**
Durham MK VI	**3 x 42**	**7**	**1.0**	**Alum. HC**	**109 / 19**
CAT	**18**	**6**	**1.2**	**Ground-Glass**	**600**
HEGRA System	**4 x 8.5**	**5**	**1.4**	**Ground-Glass**	**271**
MAGIC	234	17	1.0	Alum.-Milled	577
CANGAROO III	4 x 57	8	0.8	Composite	427
H.E.S.S.	4 x 108	15	1.2	Ground-Glass	960
VERITAS	7 x 75	12	1.2	Glass	499

Progress





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Parameters of optical s

	Reflector	f/d	# of mirror tiles	Material	Shape	Align-ment
MAGIC	Parabolic	1.0	936	Milled aluminum comp. anodized	square	Motors
H.E.S.S.	Davies-Cotton	1.2	382	Ground glass, alumin., quartz coated	round	Motors
VERITAS	Davies-Cotton	1.2	~ 300	Glass, aluminized, anodized	hex	Manual
CANGAROO III	Parabolic	0.8	114	Composite, aluminum, fluoride coated	round	Motors

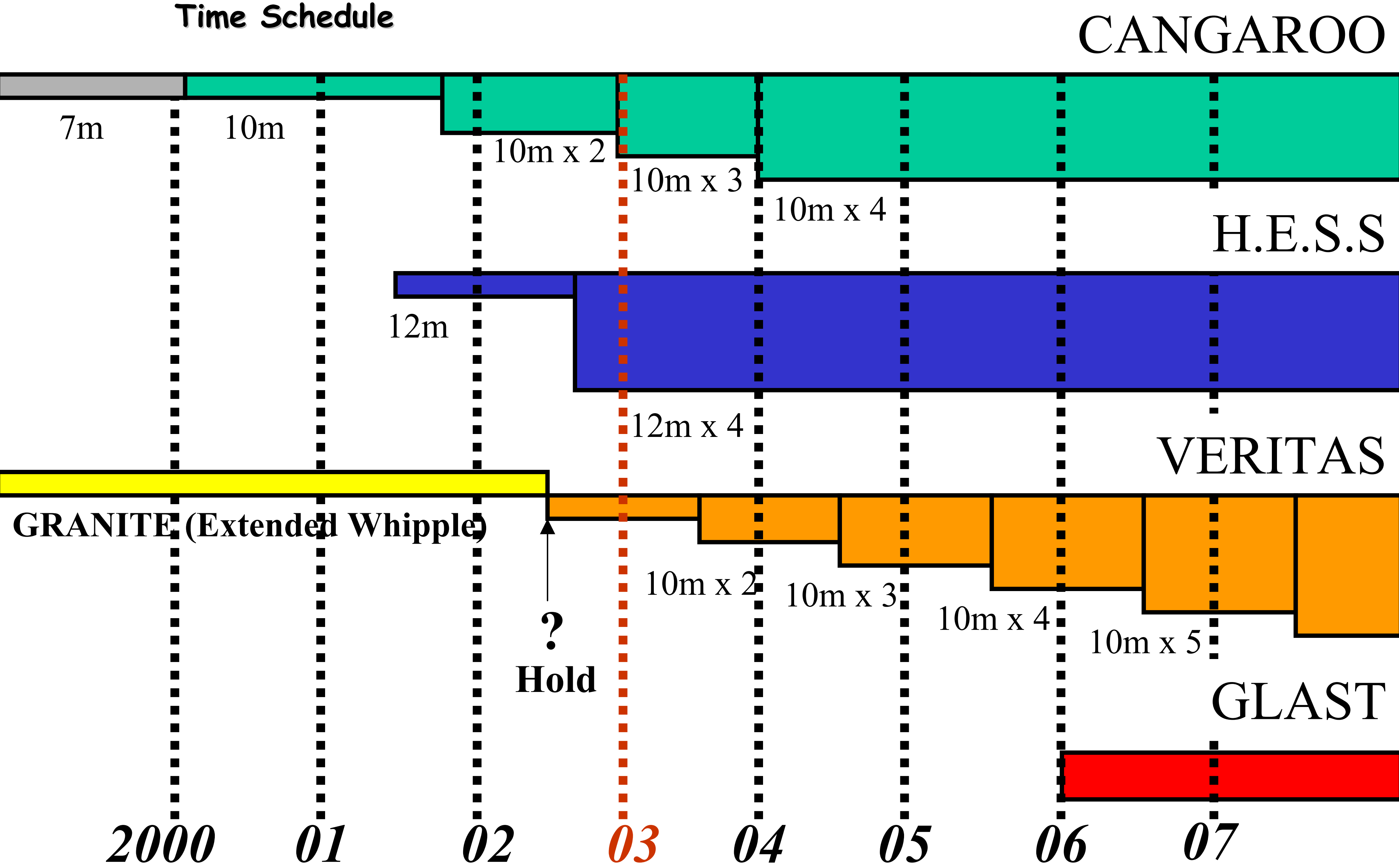
Davies-Cotton
- better off-axis imaging
- Same focal length for all mirror elements

Parabolic
- Minimizes time dispersion of photons

Composite / aluminum mirrors are lightweight

Square or hex mirrors
Allow full area coverage

Time Schedule



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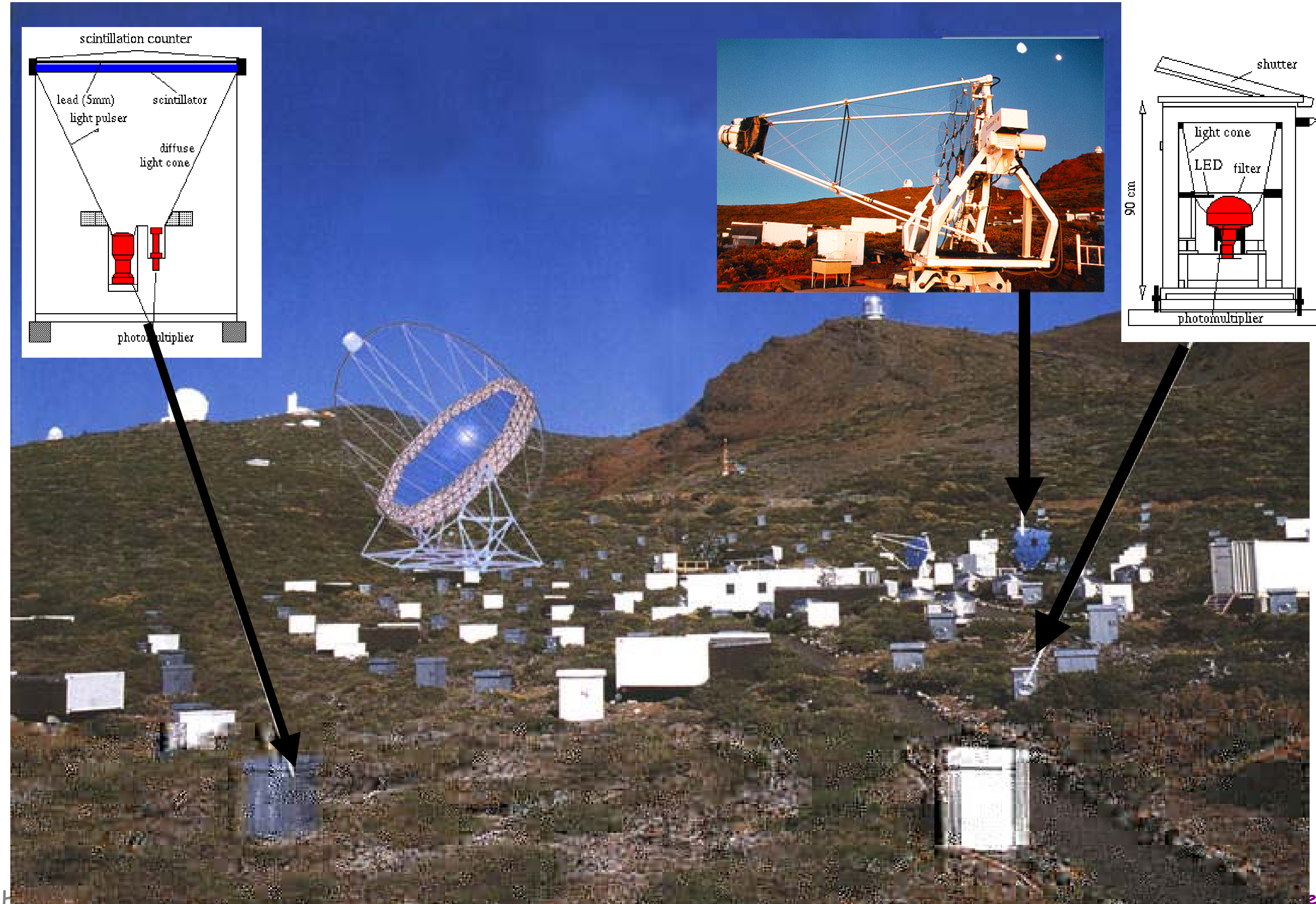
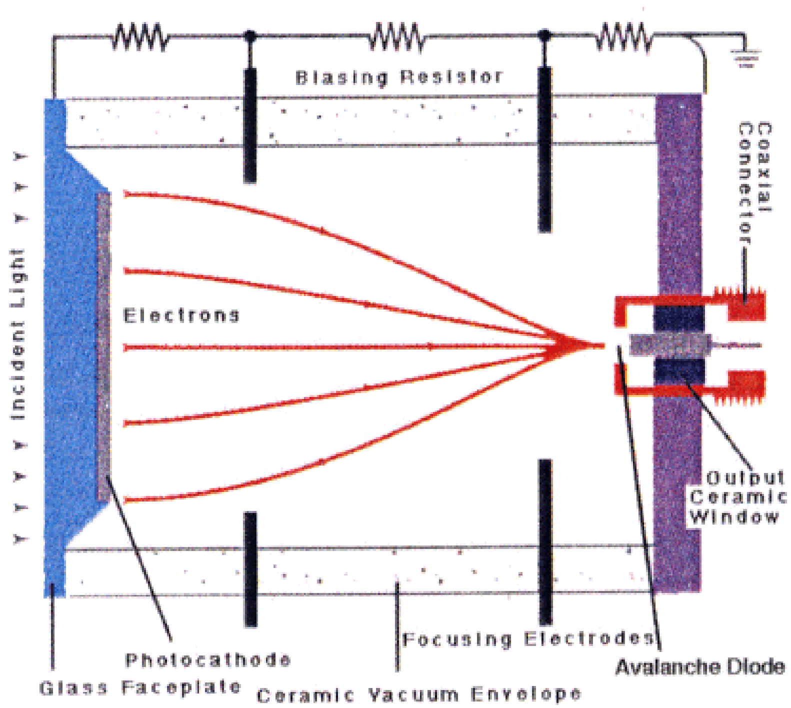
MAGIC

AIROBICC counter



MAGIC Photo sensor (2nd phase)

- **GaAsP-intensified photocell (Intevac)**



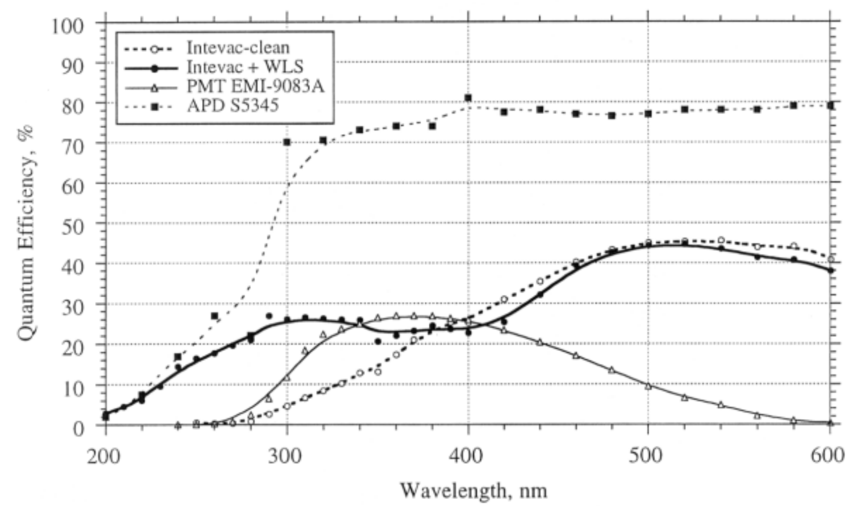
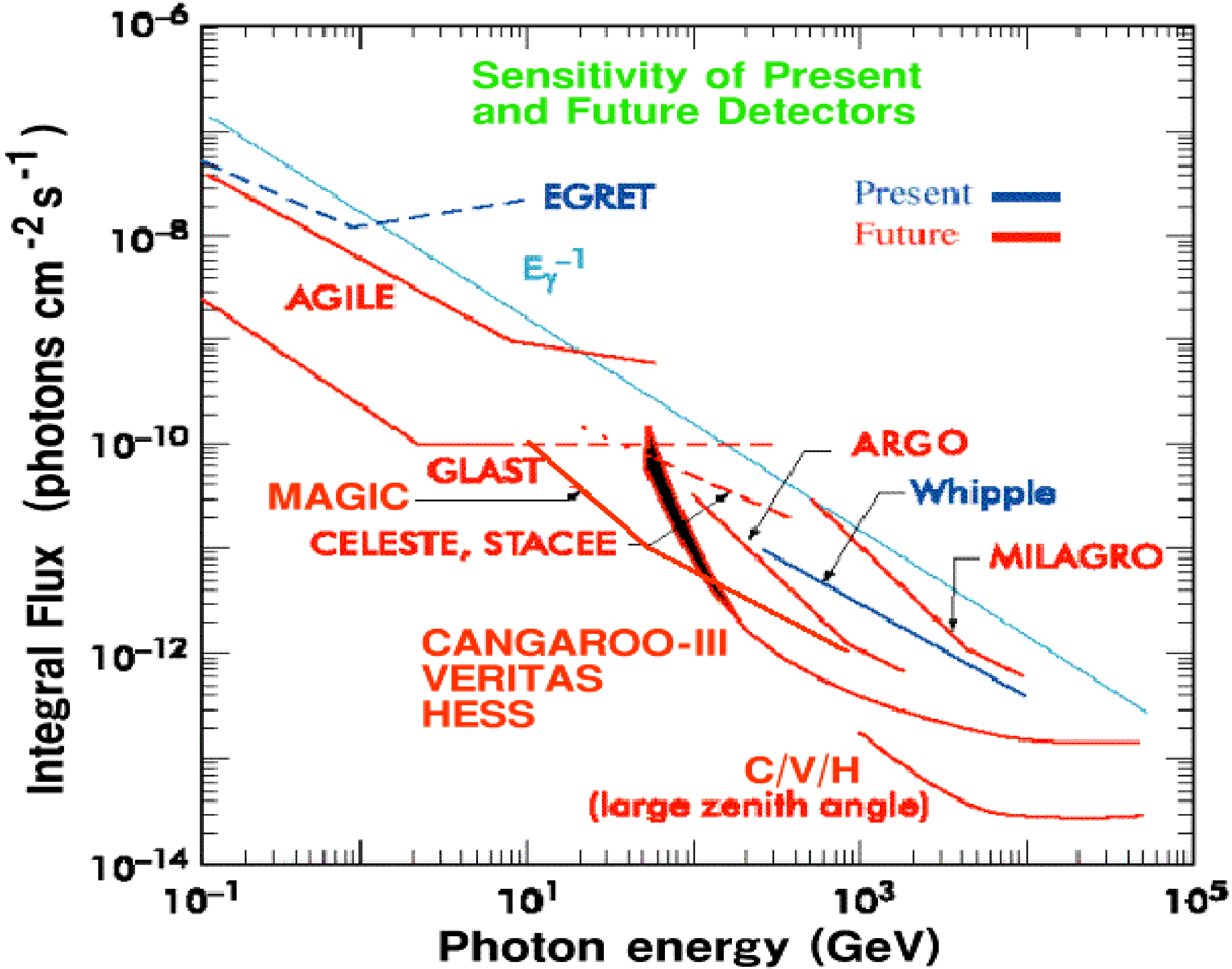
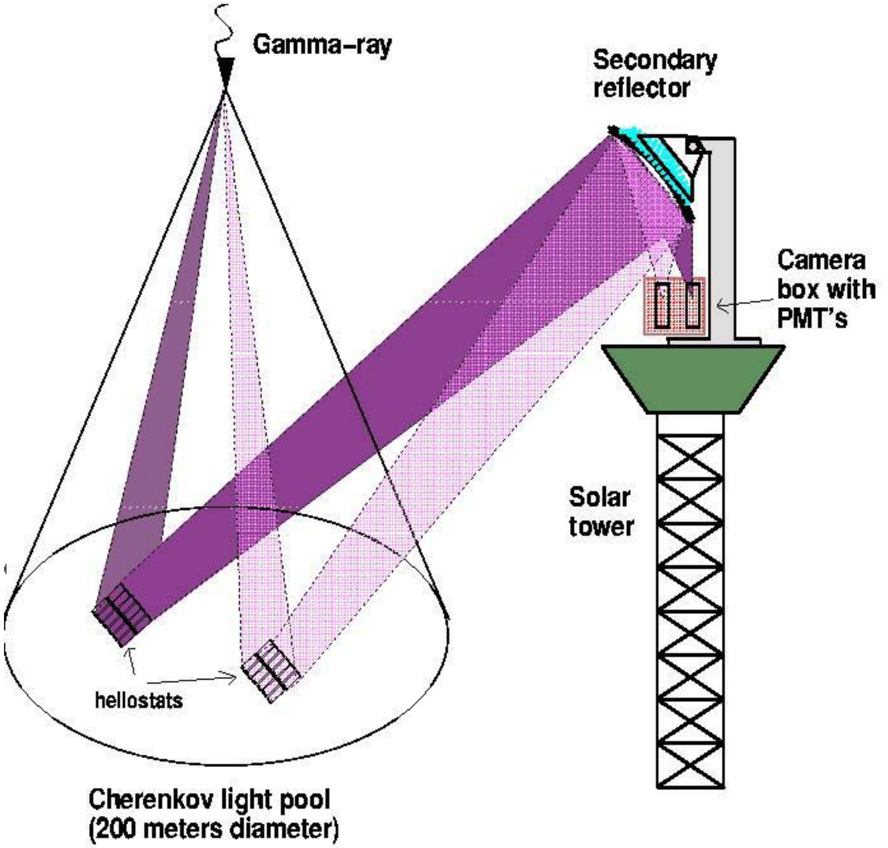


Figure 4.23: Cross section of a hybrid photomultiplier with avalanche diode readout.



Sensitivity of Present and Future Detectors
Present
Future
EGRET
E_γ^{-1}
AGILE
GLAST
MAGIC
CELESTE, STACEE
ARGO
Whipple
MILAGRO
CANGAROO-III
VERITAS
HESS
C/V/H
(large zenith angle)
Integral Flux (photons cm^{-2}s^{-1})
Photon energy (GeV)

Non-imaging Čerenkov instruments

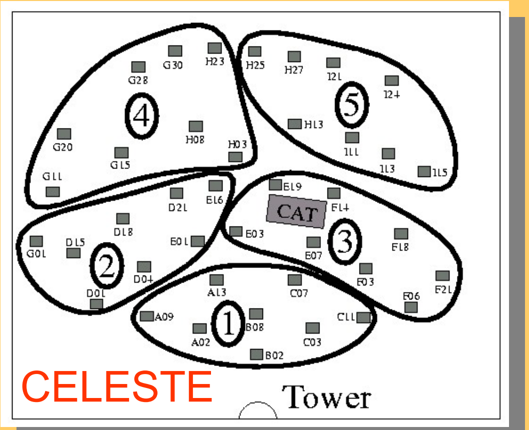


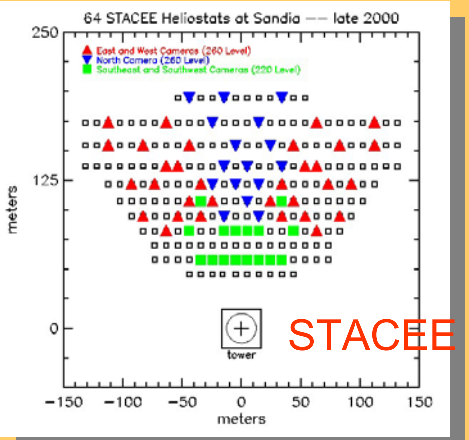
Sample light distribution on the ground, rather than angular distribution

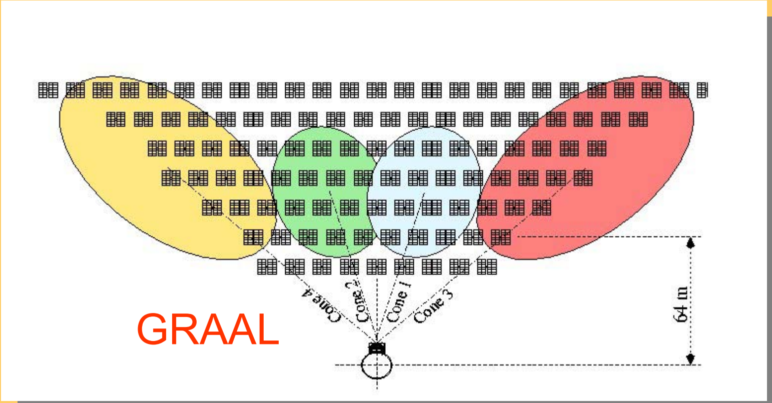
STACEE

CELESTE secondary reflector and PMTs

“CELESTE was designed to reach a very low energy threshold without a large expenditure in time and resources by exploiting the mirrors of an existing structure...”

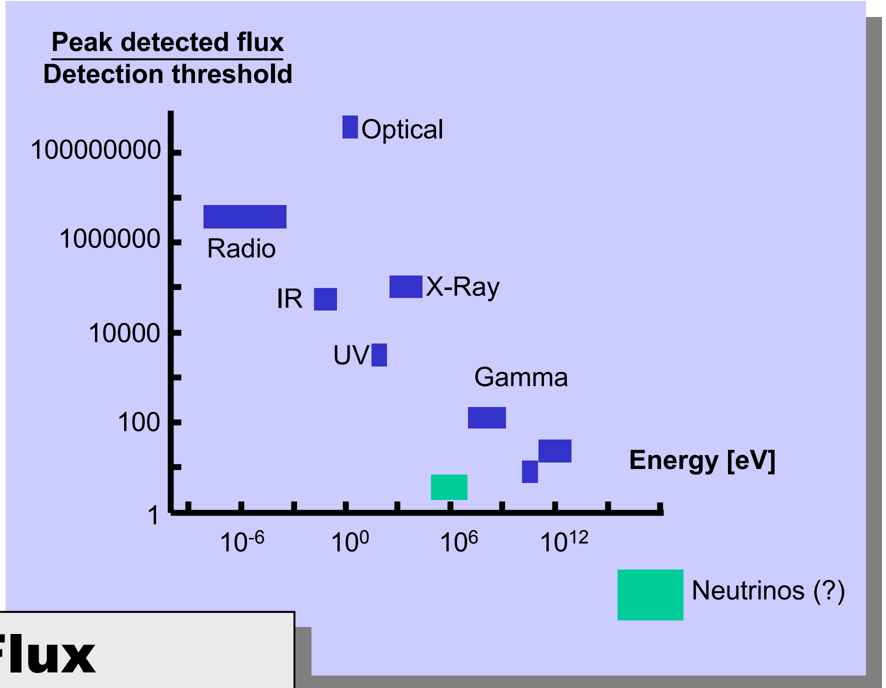




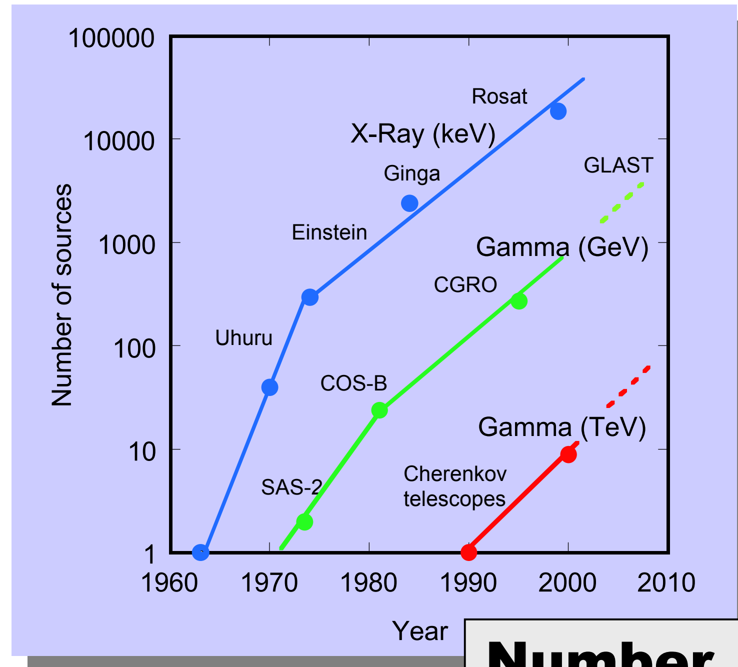


Instrument	Location	No. of heliostats	Mirror area (sqm)	No. of PMTs	F.o.V. mrad	Threshold (GeV)
CELESTE	Pyrenees, France	40 (→ 53)	2000 (→ 2700)	40	~10	60
STACEE	Albuquerque, US	32 (→ 64)	1200 (→ 2400)	32	~12	190
GRAAL	Almeria, Spain	63	2500	4	7 - 12	250
SOLAR 2	Barstow, US	32 - 64	1300 - 2600	32 - 64	~ 10	?

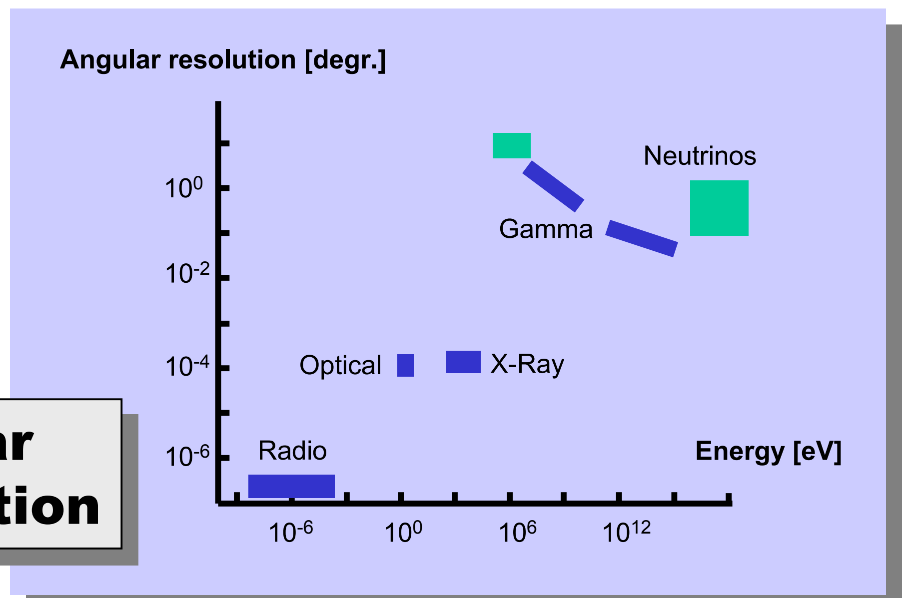
State of the field



Flux sensitivity



Number of sources



Angular resolution

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Neutrino Detectors

Detector Classification

(by energy and physics)

- MeV energy range
  - ☆ Reactor neutrinos - Δm_{12}^2 and Δm_{23}^2 range
  - ☆ Solar neutrinos - Δm_{12}^2 range
  - ☆ Terrestial neutrinos
- GeV energy range
  - ☆ Accelerator experiments - Δm_{23}^2 range
  - ☆ Atmospheric ν experiments - Δm_{23}^2 range
- TeV to PeV energy range
  - ☆ Neutrino astrophysics

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Tracing cosmic rays

$$\Phi_p \sim E^{-s}$$

$$p\gamma \rightarrow \Delta^+$$

$$\Delta^+ \rightarrow \pi^0 p, \quad \pi^0 \rightarrow \gamma\gamma$$

$$\Delta^+ \rightarrow \pi^+ n, \quad n \rightarrow p e^- \overline{\nu_e}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu, \quad \mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$$

$$pp \rightarrow \ldots$$

Maximum neutrino flux associated with cosmic rays

$$E_\nu = \frac{4}{3} E_\gamma$$

$$\frac{\Phi_\gamma}{\Phi_{\nu_\mu}} = \frac{2}{1}$$

$$\frac{\Phi_{\nu_\mu}}{\Phi_{\overline{\nu_\mu}}} = \frac{1}{1}$$

$$\frac{\Phi_{\nu_\mu}}{\Phi_{\nu_e}} = \frac{1}{1}$$

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- Superbeams - **electron** identification
- Neutrino Factory - **muon** identification (with **charge**)
- Beta beams - **muon** identification

Superbeam detectors

- ☆ Water Cherenkov
- ☆ Low Z Calorimeter
- ☆ Liquid Argon

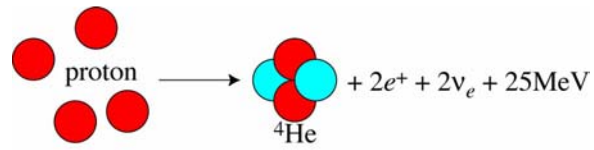
Neutrino factory

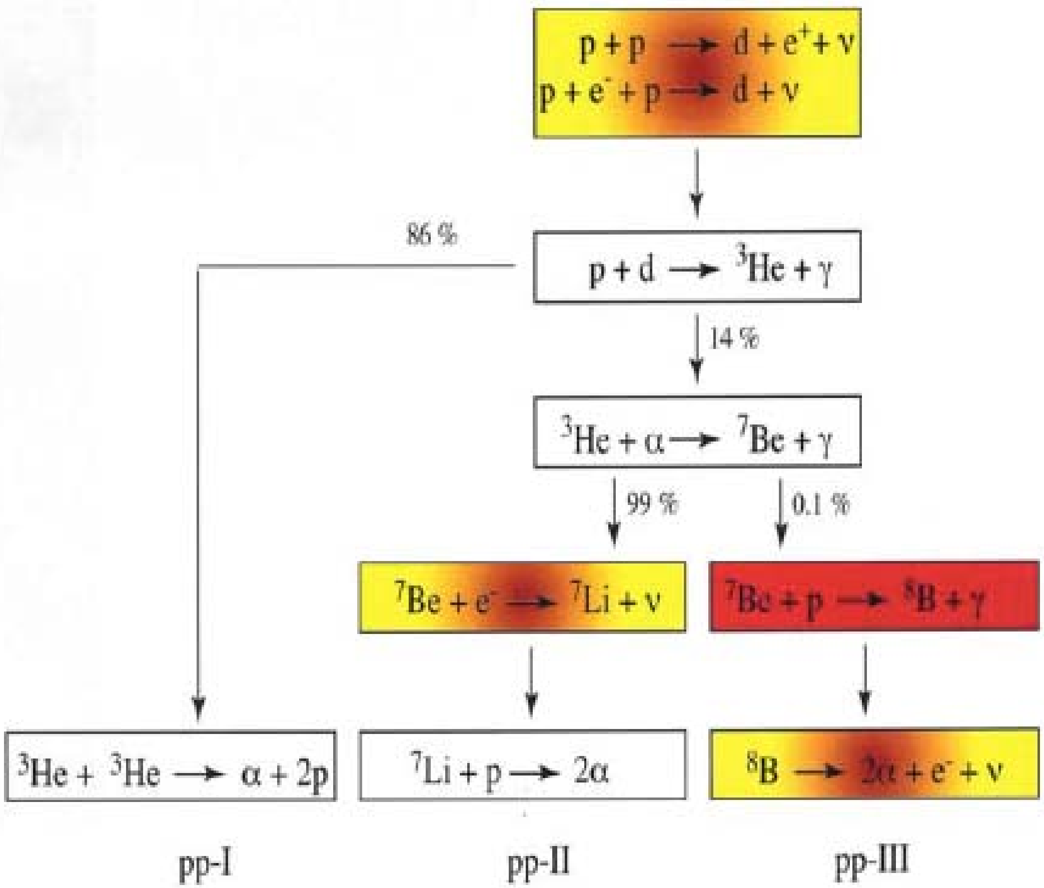
- ☆ neutrino beam consists of well understood mixture of ν_μ's and ν_e's
- ☆ The "golden" signature is the appearance of a wrong sign muon
- ☆ Magnetic sampling calorimeter appears to be detector of choice

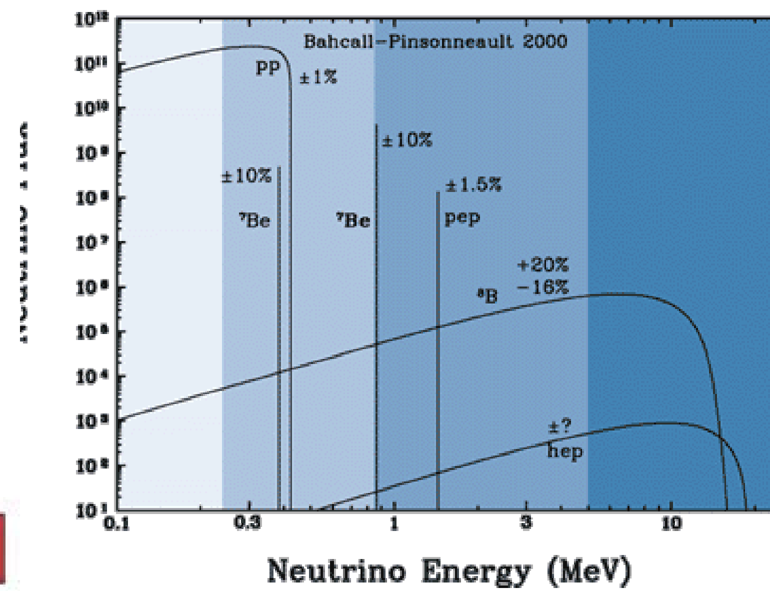
Beta beams

- ☆ accelerate He^6 (β^- emitter) and Ne^{19} (β^+ emitter) to few hundred GeV/nucleon
- ☆ resulting neutrino beam is then either pure ν_e or ν_e with few 100 MeV
- ☆ detector would need to identify μ's without needing to measure the charge

The Sun is Fueled by Nuclear Reactions!







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Summary of potential Sources (≡ cosmic ray sources)

I. Guaranteed sources (Galactic disk, Sun, GZK)

II. Likely steady sources at 100 TeV (Knee-CR sources, AGN)

$F_n \sim 10^{-10}$ GeV/(cm2 s)

III. Omnidirectional intensity from 100 TeV to GZK energies

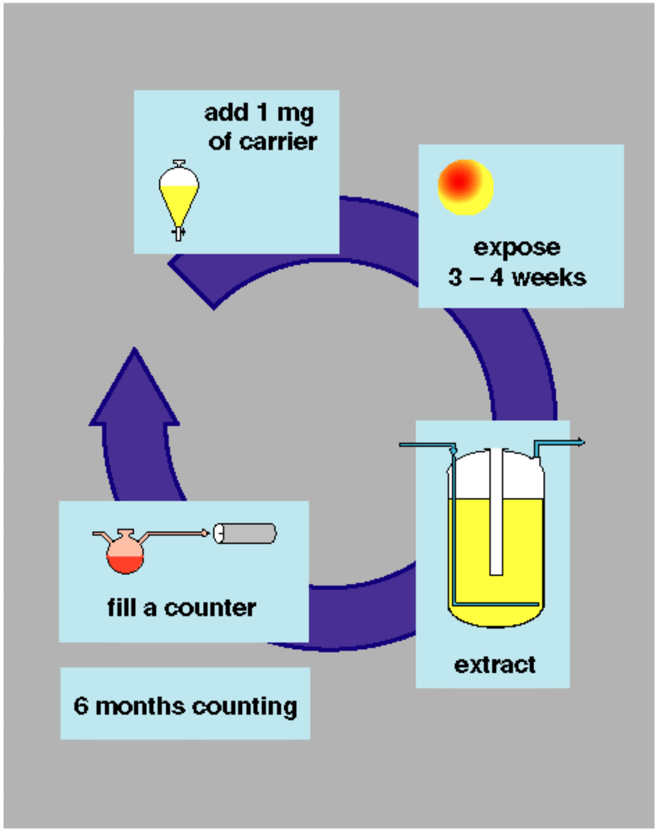
$I_n \sim 5\ 10^{-8}$ GeV/(cm2 s sr)

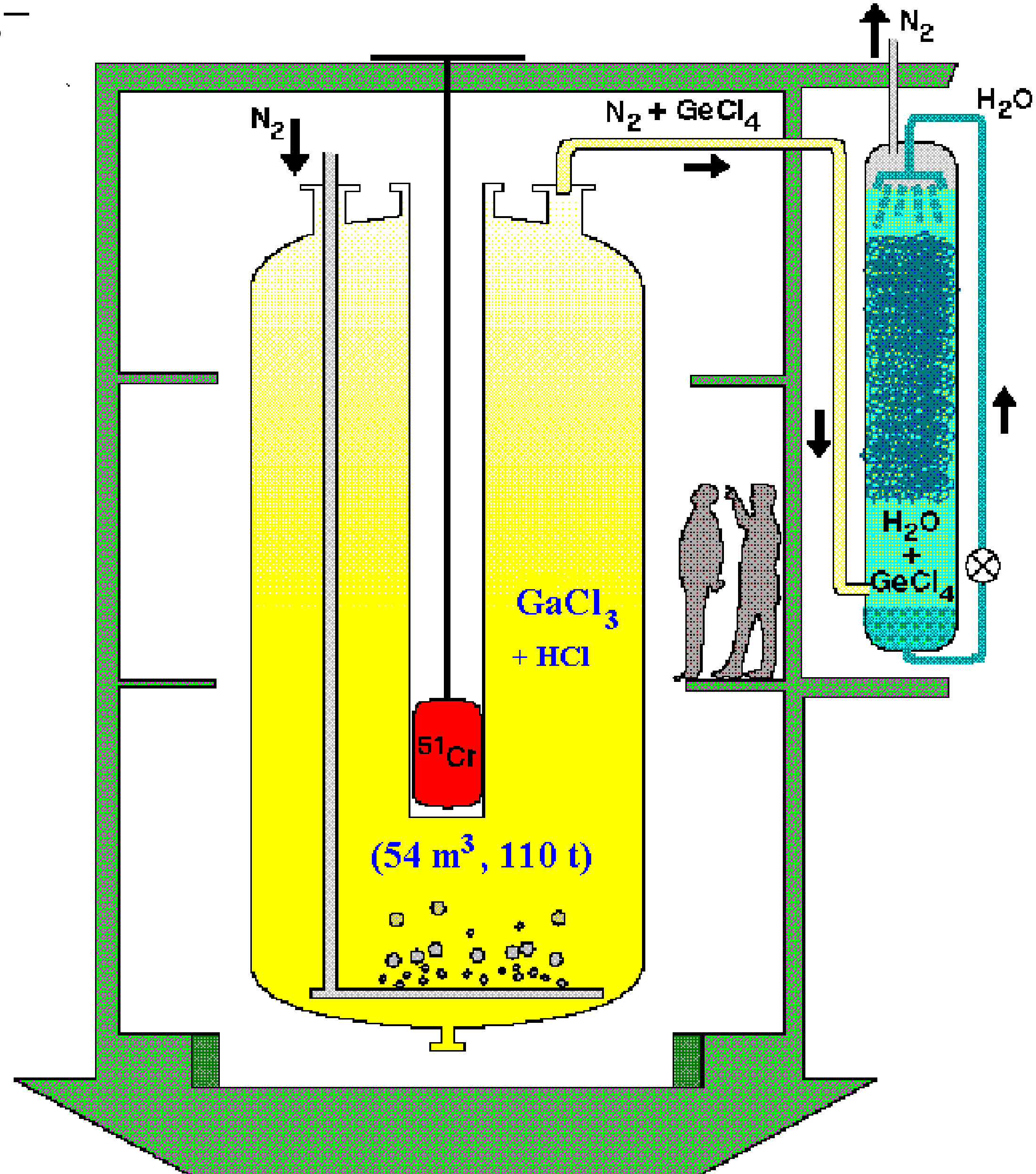
(due to sources of extragalactic cosmic rays and g-ray background)

IV. GRB contribution to I_n small (unless splendid TeV emitters), nevertheless likely neutrino sources

V. Hidden sources unlikely (need space to accelerate)

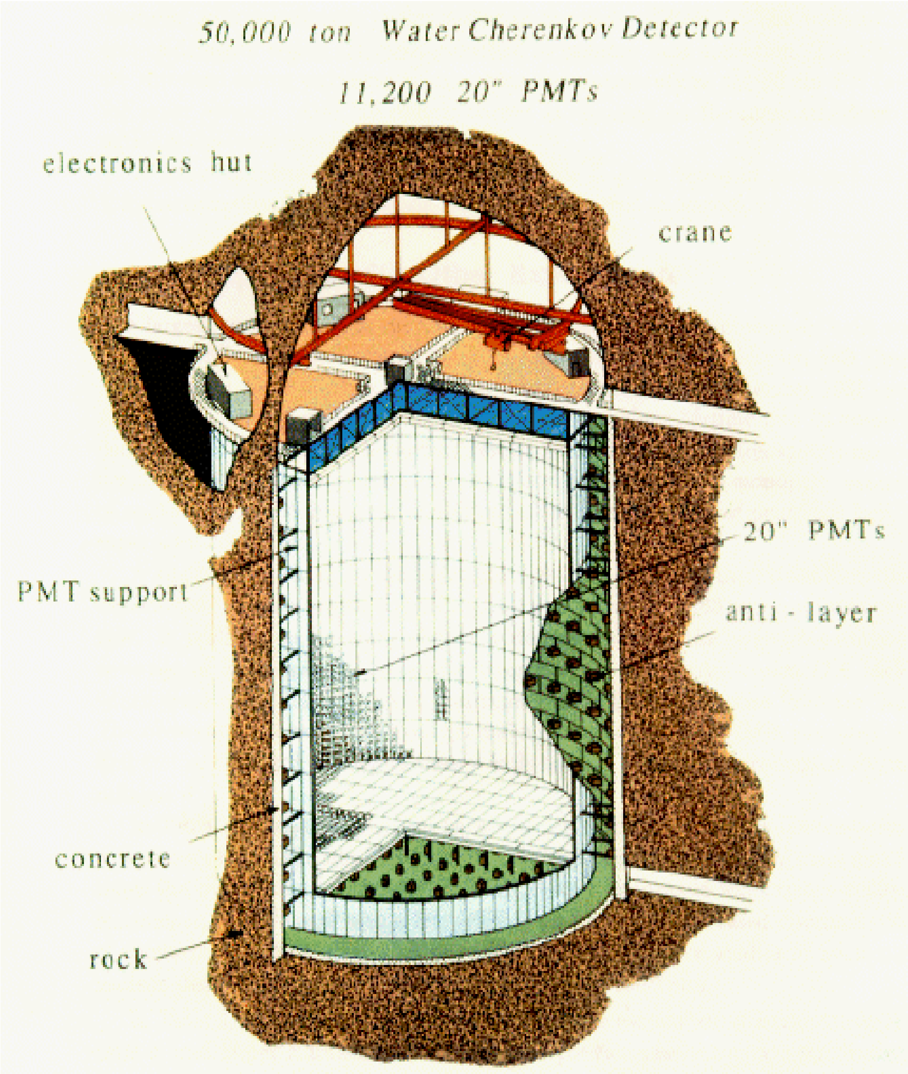
$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

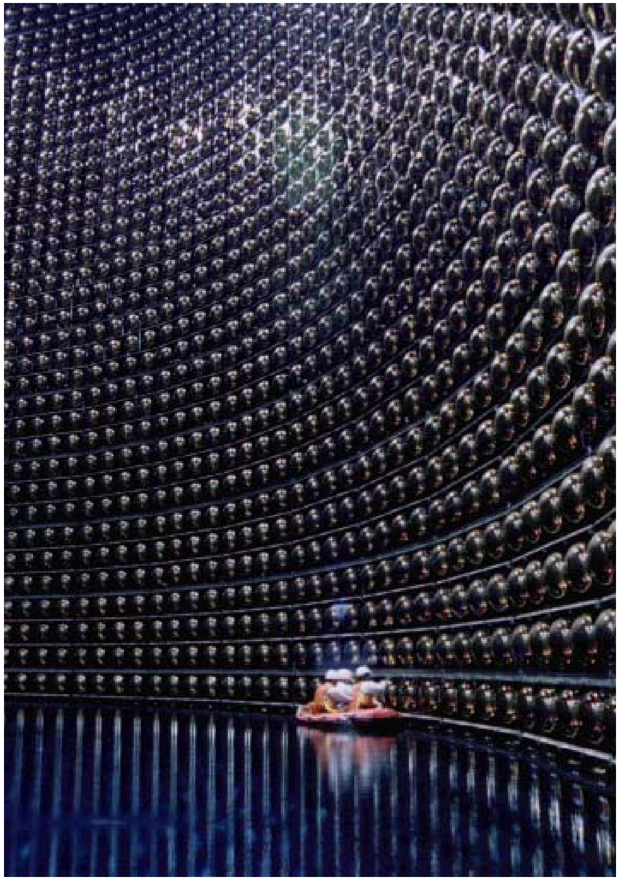




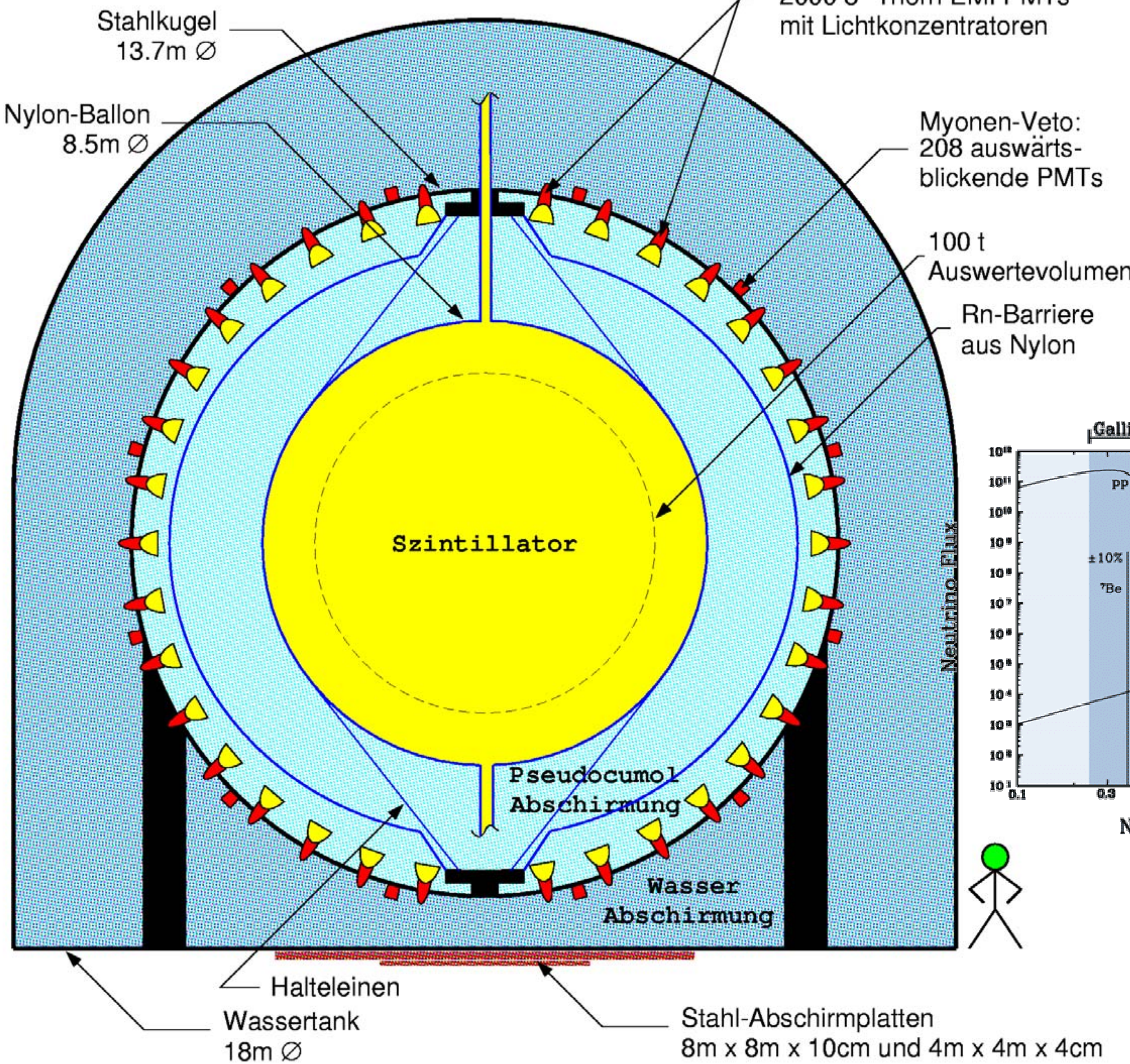
Gallium Experiment-Gallium Neutrino Observatory

SuperKamiokande





Borexino Design



Sensitive to ^{7}Be ν_e