Astroparticle Physics

DESY Summer Student Lectures 2008

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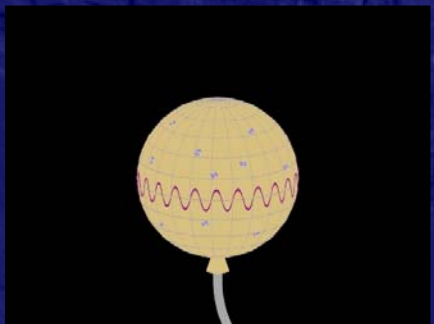
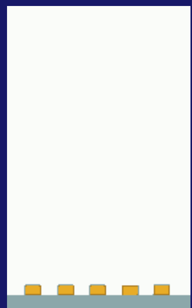




Astroparticle Physics

Topics for two lectures:

- A definition of (experimental) Astroparticle Physics

Introduction to selected areas:

- The violent Universe
  - High Energy Particles from the Cosmos
  - TeV-γ and υ Astronomy

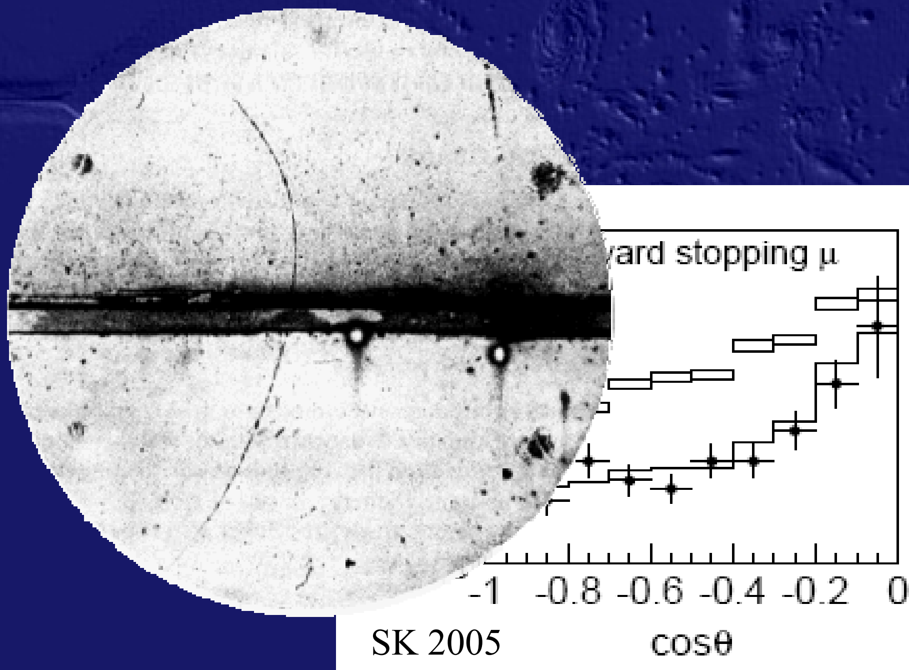
  } 1st session
- Precision Cosmology
  - Cosmic Microwave Background Radiation
  - Search for Dark Matter

  } 2nd session

Astroparticle Physics 1: History

High Energy Physics started with discoveries and analysis of particles generated by the Cosmic radiation.

- 1932: Positron
- 1937: Muons
- 1947: Pions, Λ, K
- 1952: Ξ^-, Σ^+
- 1971: Charm (?)
- 1998: Neutrino oscillation



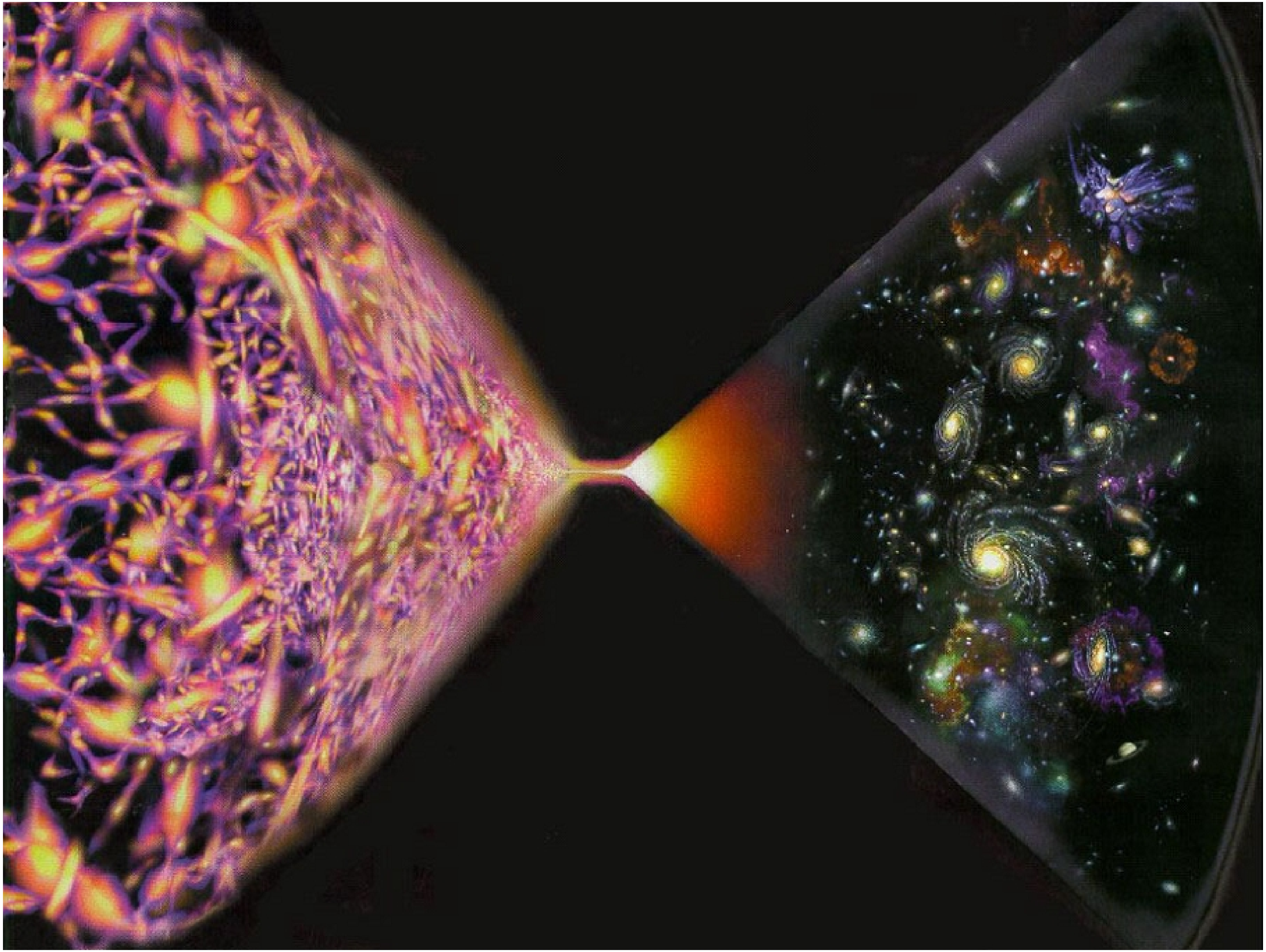
Astroparticle Physics 2: Cosmic Laboratory

Really high energies are only provided by the cosmos:

- particles beyond 10^{20}eV (10^{7}·LHC beam energy)
- Access to physics at the Planck scale via indirect observations of the very early universe

Really long baselines are only provided by the cosmos:

- Oscillation of υ from the sun: $150 \cdot 10^{9}$ m
- υ from SN 1987A (LMC): 150.000 light-years

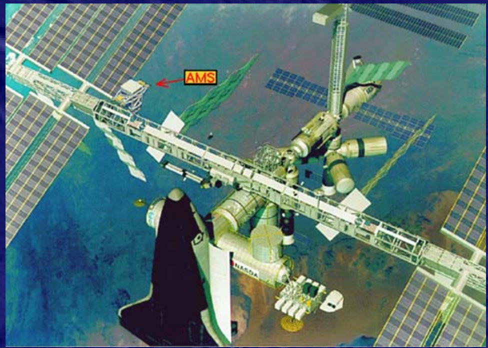


A Definition of Astroparticle Physics

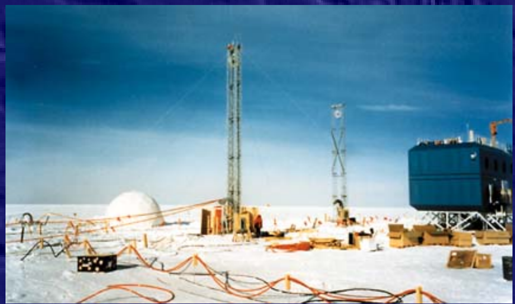
Three Aspects:

- Learning HEP from astrophysics:
  Neutrino properties, cross sections at ultra high energies, new forms of matter (dark matter and dark energy), time variation of fundamental constants, space-time structure
- Applying HEP techniques to astrophysics:
  calorimetry and tracking detectors onboard satellites and balloons, ground based scintillators and Cherenkov detectors, handling of large volume data sets, astronomy with neutrinos
- Cosmology with cognitions of HEP:
  Big Bang theory, nucleon synthesis, candidates for dark matter

Tools and Sites of Astroparticle Physics



(the real motivation?)



Unusual laboratories ...

... and a little adventure.

Collaborations in Astroparticle Physics

Size about an order of magnitude smaller than in HEP

MAGIC ("Cherenkov-Telescope")

ATLAS @ LHC

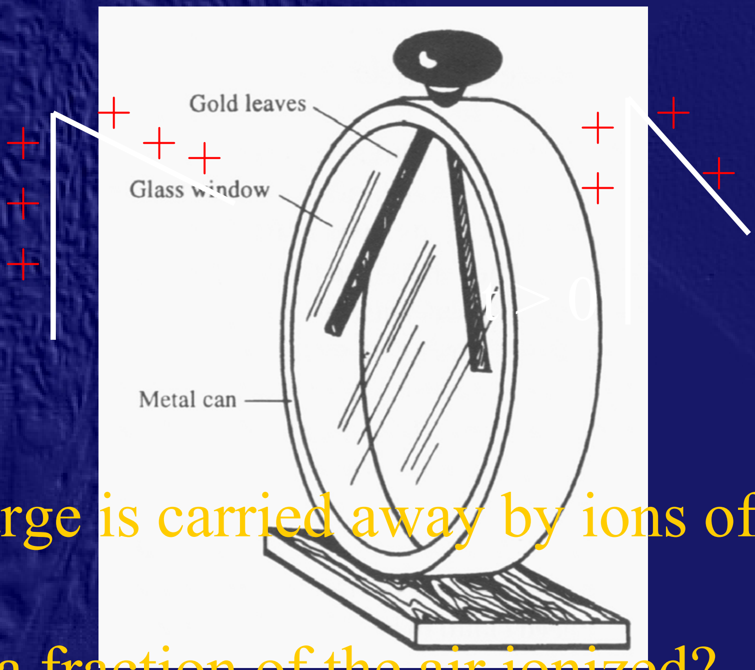
Astroparticle Physics

1. High Energy Particles from the Cosmos
2. The new Astronomy
3. The Cosmic Microwave Background Radiation
4. Search for Dark Matter (DM)

A simple Experiment

What happens to a charged electrometer?

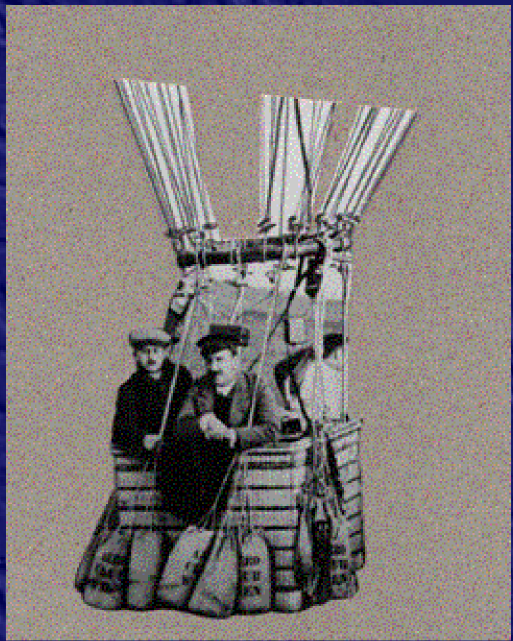
t = 0

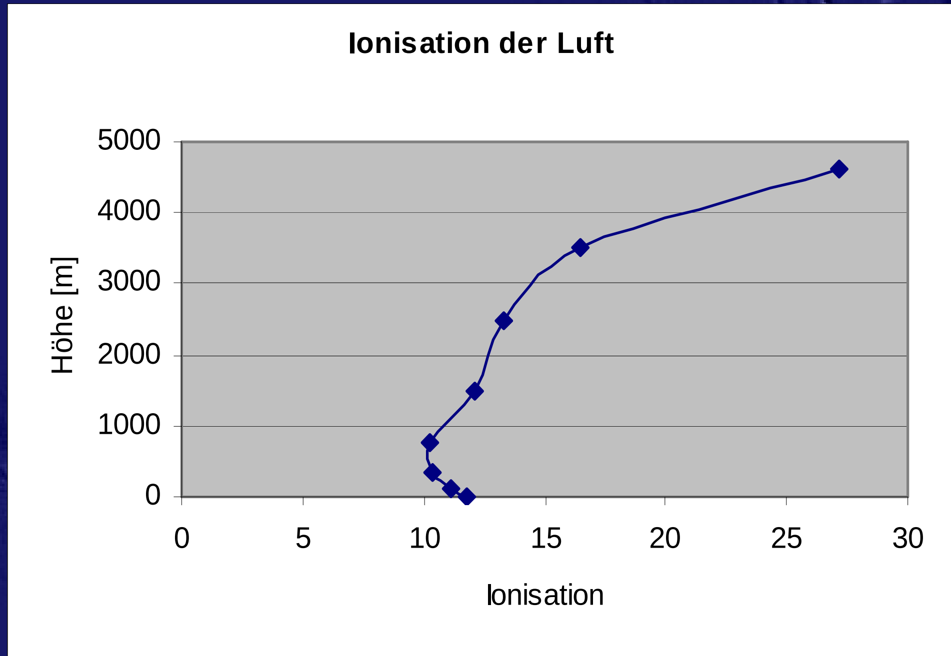


The charge is carried away by ions of the air.

Why is a fraction of the air ionized?

Discovery of Cosmic Rays





Viktor F. Hess 1912:
Ionisation of air increases with increasing altitude
↳ Radiation from the cosmos
hits the atmosphere
("Cosmic Rays")

http://helios.gsfc.nasa.gov/cosmic.html
http://ik1au1.fzk.de/KASCADE/KASCADE_general.html
http://www.auger.org/

Viktor F. Hess

Die Ergebnisse der vorliegenden Beobachtungen scheinen am ehesten durch die Annahme erklärt werden zu können, daß eine Strahlung von sehr hoher Durchdringungskraft von oben her in unsere Atmosphäre eindringt, und auch noch in deren untersten Schichten einen Teil der in geschlossenen Gefäßen beobachteten Ionisation hervorruft. Die Intensität dieser Strahlung scheint zeitlichen Schwankungen unterworfen zu sein, welche bei einstündigen Ablesungsintervallen noch erkennbar sind. Da ich im Ballon weder bei Nacht noch bei einer Sonnenfinsternis eine Verringerung der Strahlung fand, so kann man wohl kaum die Sonne als Ursache dieser hypothetischen Strahlung ansehen, wenigstens solange man nur an eine direkte γ-Strahlung mit geradliniger Fortpflanzung denkt.

Physik. Zeitschr. 13, 1084 (1912)

CR induce Extended Air Showers (EAS)

Pierre Auger 1938:

Observation of CR induced coincidences in widely separated detectors at the Jungfrau Joch.

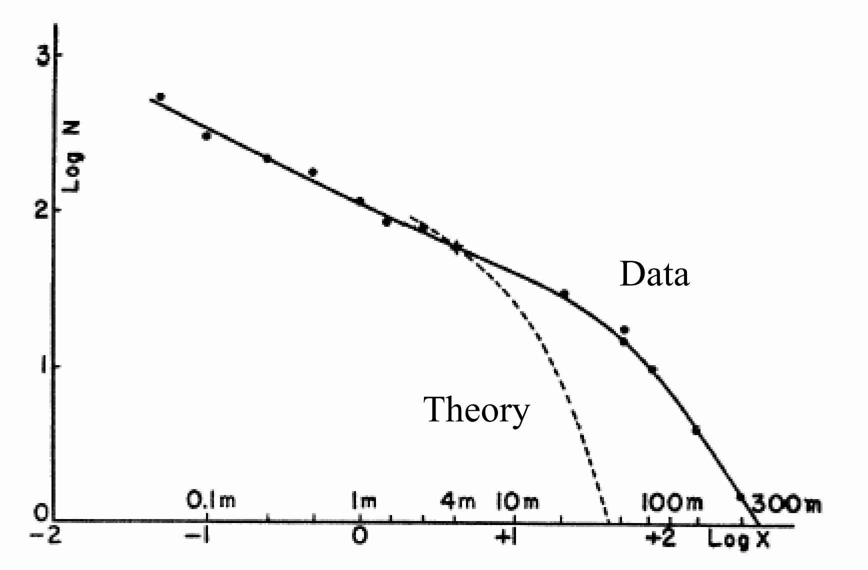


FIG. 1. Results with two parallel and horizontal counters.

One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.

CR induce Extended Air Showers (EAS)

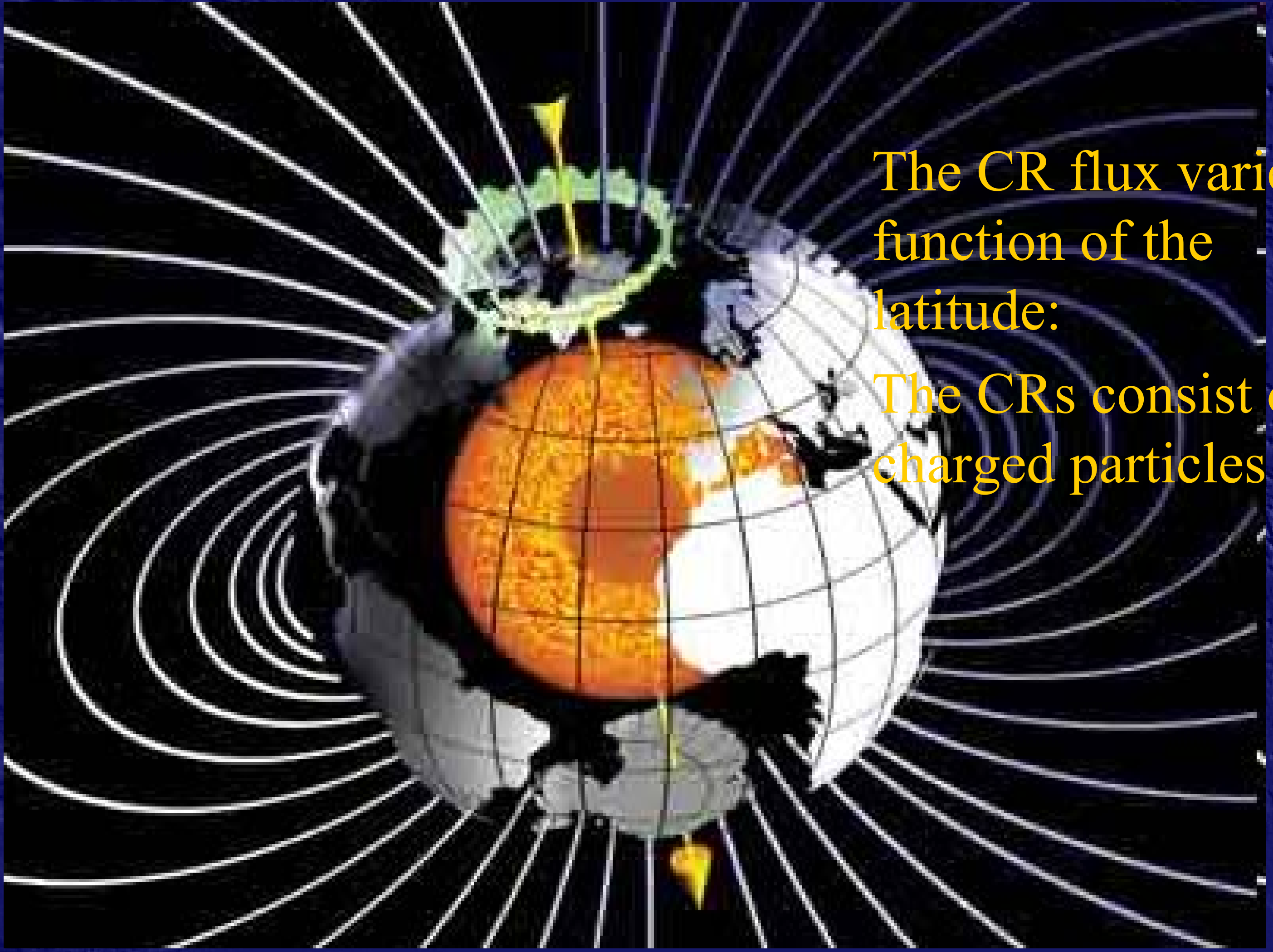
Pierre Auger 1938:

Observation of CR induced coincidences in widely separated detectors at the Jungfrau Joch.

Explanation:

Primary cosmic particle interacts with atoms in atmosphere, secondary particles undergo further interactions
↳ avalanche of particles (EAS)

A. H. Compton, 1932: What are the constituents of CRs?



The CR flux varies as function of the latitude:

The CRs consist of charged particles!

A. H. Compton, 1932: What are the constituents of CRs?

TABLE I. *Cosmic ray intensity at different localities*
(Ions per cc per sec. through 5 cm Pb, 2.5 cm Cu and 0.5 cm Fe)

Location	Lat.	Long.	Elev.	Barom.	I_C	I_L	Date
1 Mt. Evans	40°N	106°W	14,200ft	17.61in	6.88 ions	0.57	9/31
2 Summit Lake	40 N	106 W	12,700	18.70	5.84	0.34	9/31
3 Denver	40 N	105 W	5300	24.8	2.93	—	9/31
4 Jungfraujoch	47 N	6 E	11,400	19.70	5.08	0.51	10/31
5 Haleakala	21 N	156 W	9300	21.47	3.35±0.05	0.60	4/32
6 Idlewild	21 N	156 W	4200	25.99	2.40±0.05	0.37	4/32
7 Honolulu	21 N	158 W	70	30.09	1.89±0.02	0.11	4/32
8 S. S. Aorangi	4 S	173 W	60	29.65	1.83±0.05	0.32	4/32
9 Southern Alps	44 S	170 E	6700	23.69	3.39±0.05	0.22	4/32
10 Southern Alps	44 S	170 E	3900	26.10	2.70±0.04	0.21	4/32
11 Dunedin	46 S	170 E	80	30.08	2.16±0.03	0.11	4/32
12 Wellington	41 S	175 E	400	29.85	2.16±0.03	0.12	5/32

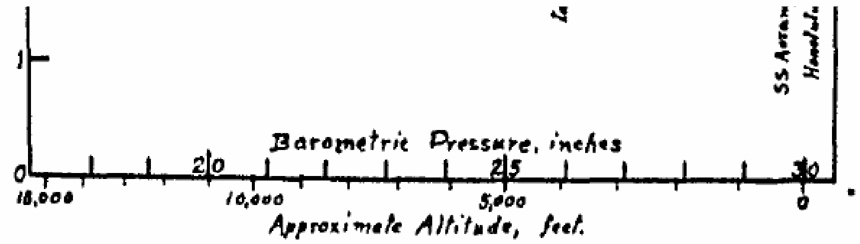
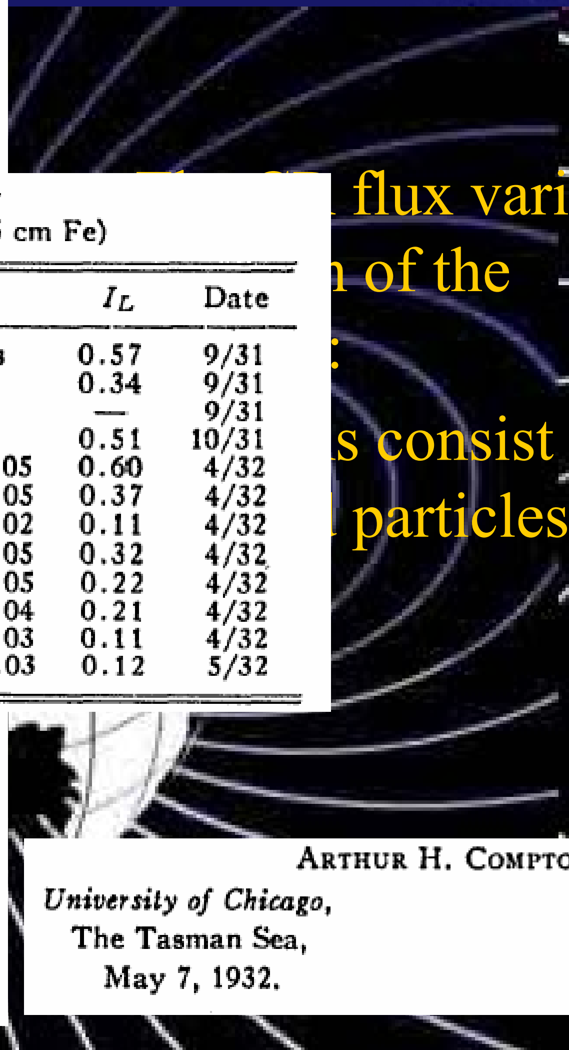


Fig. 1.



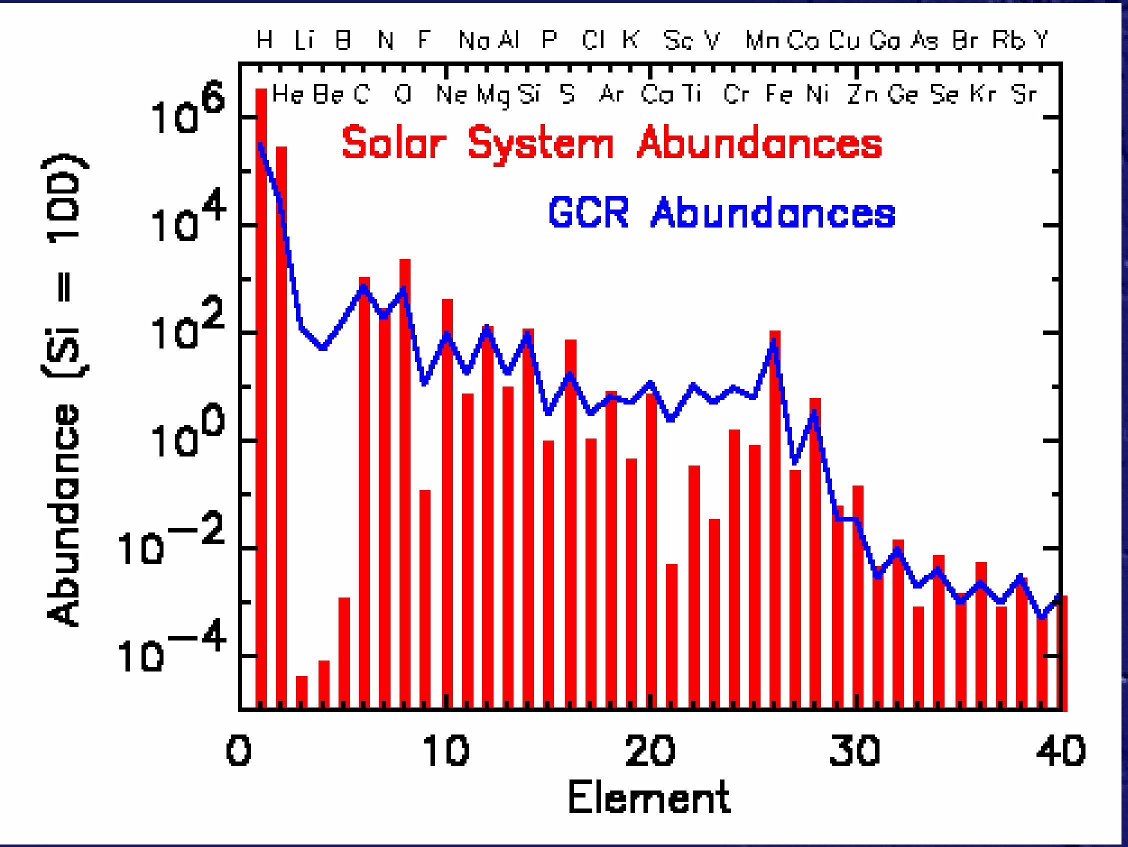
... flux varies as
... of the
... :
... s consist of
... particles!

ARTHUR H. COMPTON
University of Chicago,
The Tasman Sea,
May 7, 1932.

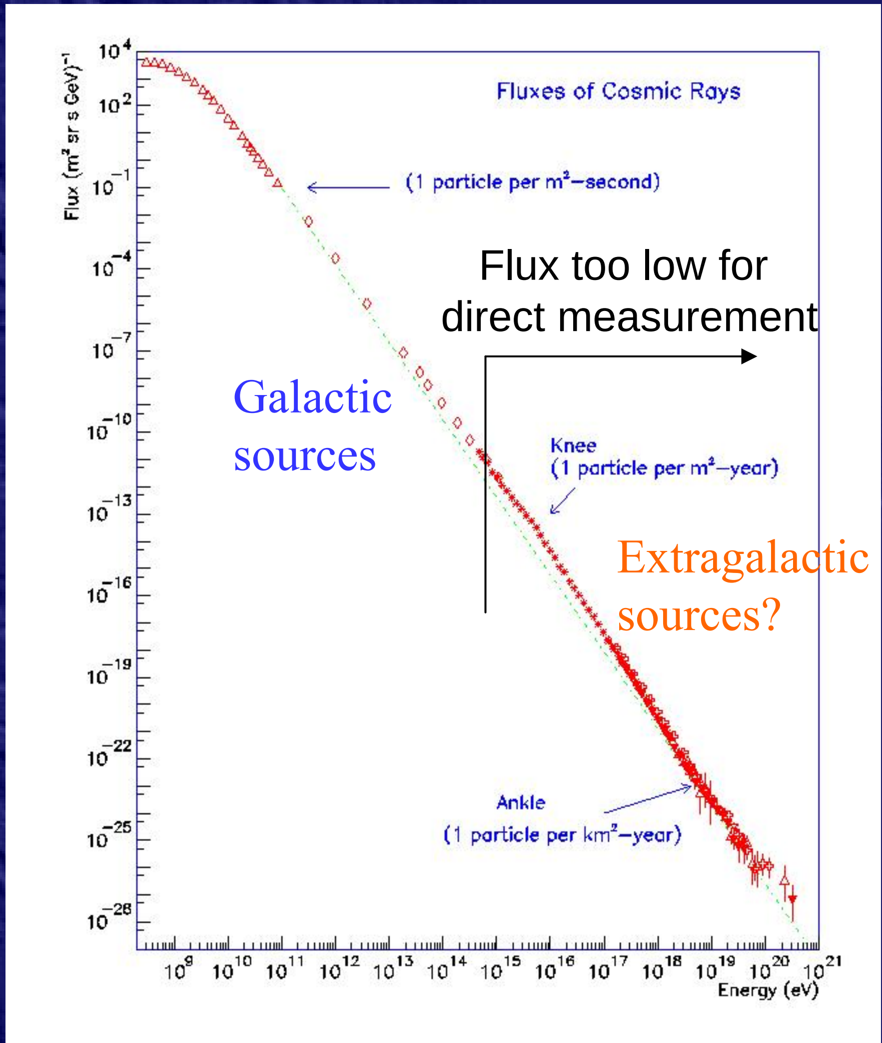
Composition of Cosmic Rays (low energies)

CR consist mainly of fully ionized nuclei with abundances comparable to the solar system.

CR are charged!



Energy Spectrum of CR

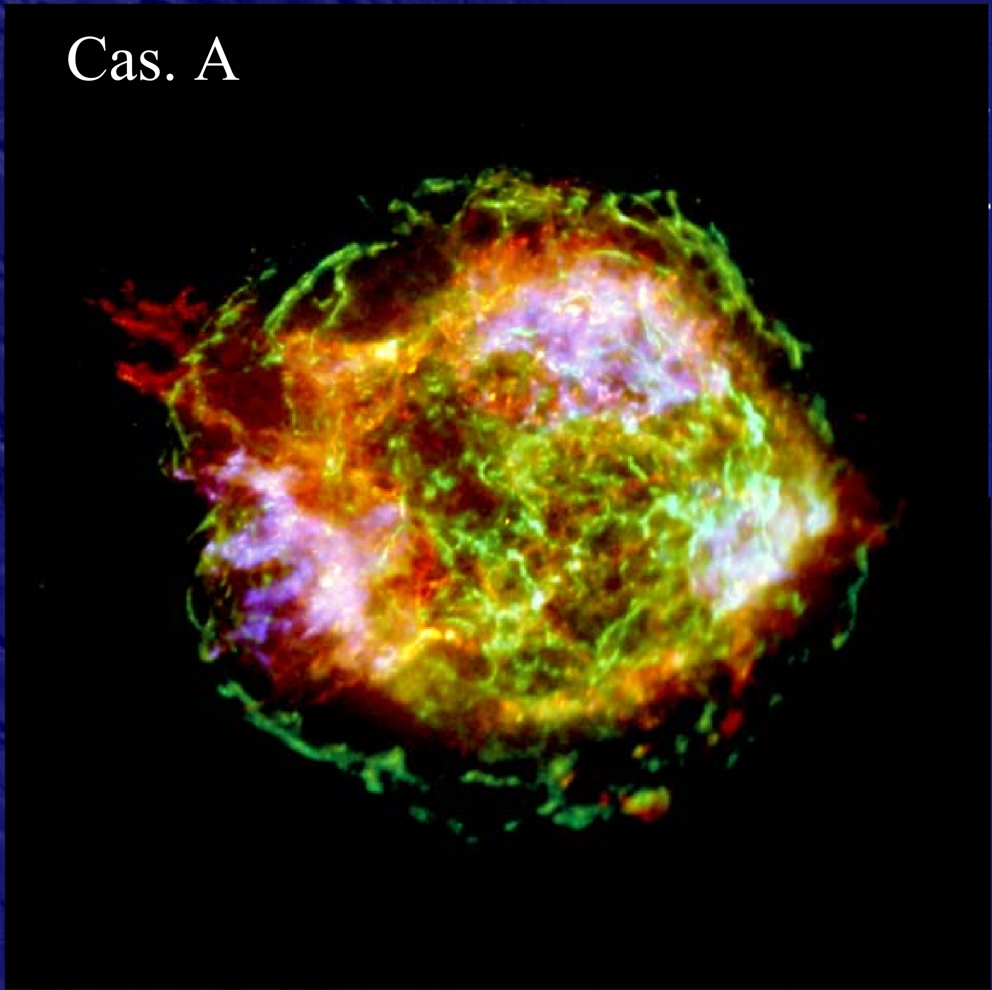


At high energies very large detector installations necessary:
10^4 m^2 (knee) to 10^9 m^2

Effect of $3 \cdot 10^{21}$eV:

Full Name
Height: 6-
Bats: Righ
Born: Sep reek, CA,
College: U
2004 Sala

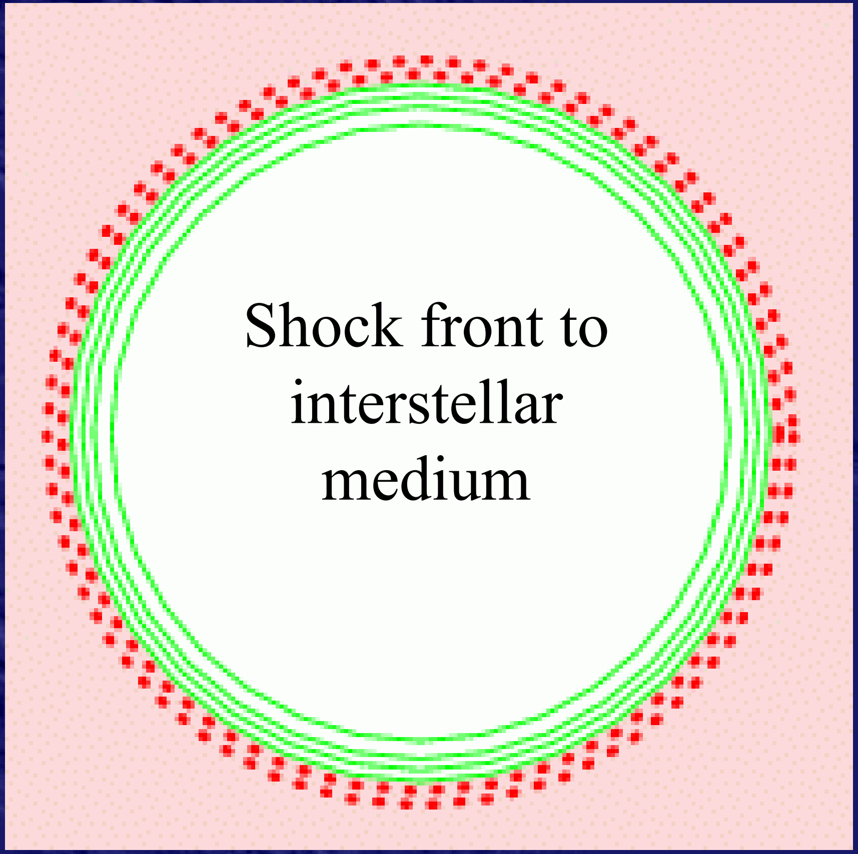
Possible galactic accelerators



- Supernova remnants develop shock fronts in the interstellar medium.
- Turbulent processes in the shock fronts are visible in radio and X-rays.

Are these the cosmic accelerators?

Acceleration by interstellar shock fronts



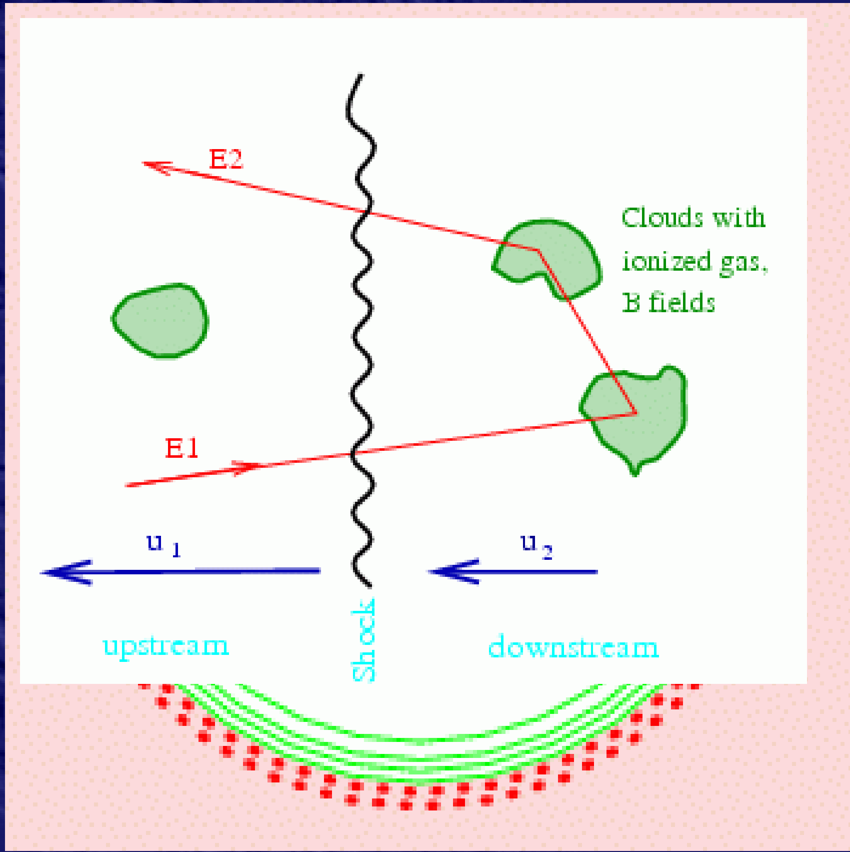
Proposed by E. Fermi 1949:

- Energy gain per crossing:
  $\Delta E = E \cdot (1+d)$
- Probability to escape from shock region:
  P_{esc}

☞ Many crossings:
$N(E) \sim E^{-\alpha}$
with $\alpha = \ln(1/(1-P_{esc}))/\ln(1+d) + 1$

☞ power law with $\alpha \approx 2$ (Cas. A)

Acceleration by interstellar shock fronts



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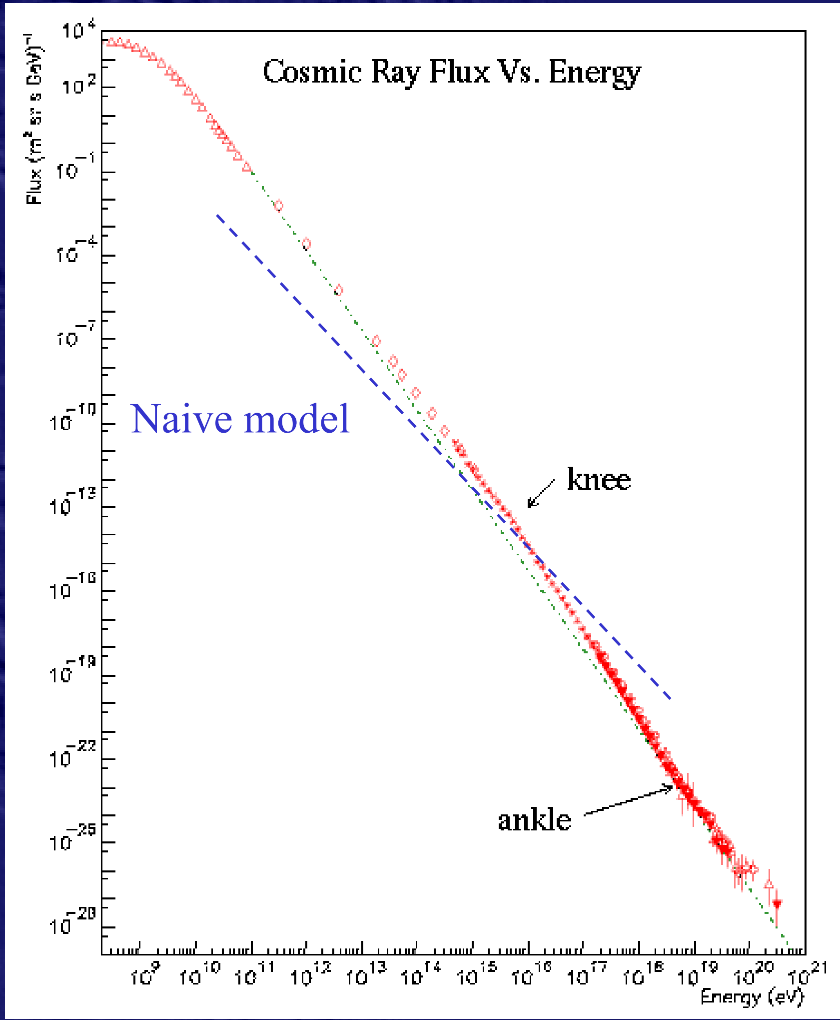

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Acceleration by interstellar shock fronts

particles „surf“ interstellar shock fronts

Proposed by E. Fermi 1949:

- Energy gain per crossing:
  $\Delta E = E \cdot (1+d)$
- Probability to escape from shock region:
  P_{esc}

☞ Many crossings:
$N(E) \sim E^{-\alpha}$
with $\alpha = \ln(1/(1-P_{esc}))/\ln(1+d) + 1$

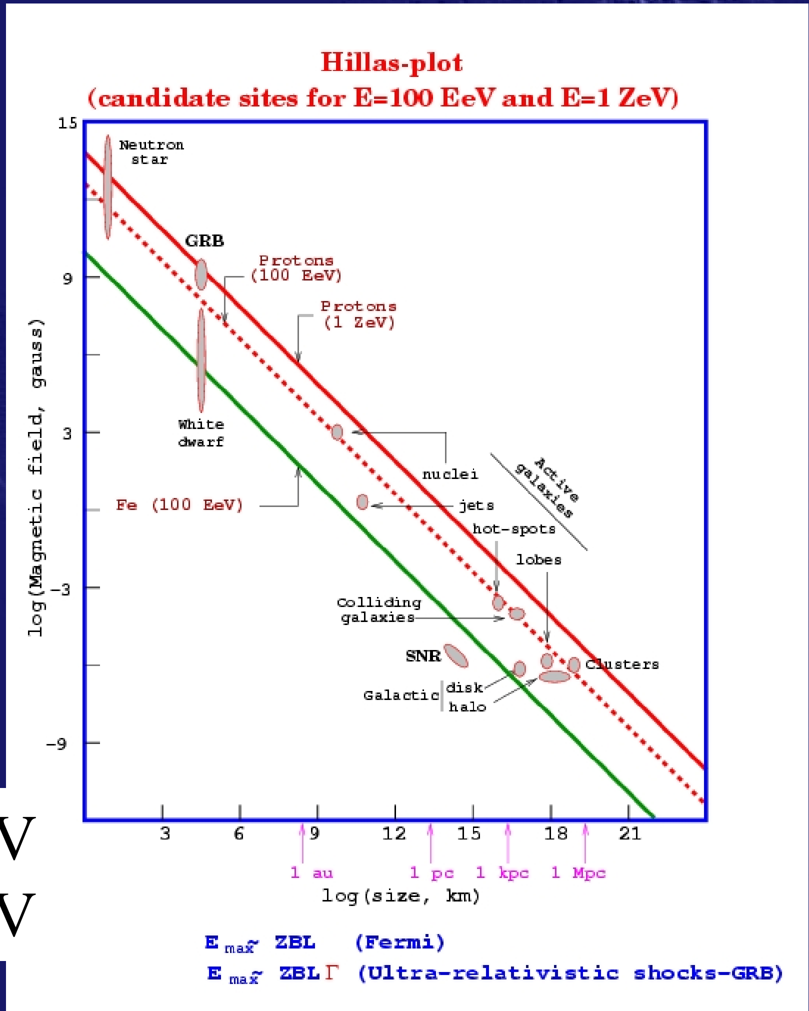
☞ power law with $\alpha \approx 2$ (Cas. A)

More possible cosmic Particle Accelerators

Maximal energy given by extension (L) and magnetic field strength (B) of accelerator and charge of particle:

$$E_{max} \approx Z \cdot B \cdot L$$

In most cases: particle acceleration not measured convincingly yet!



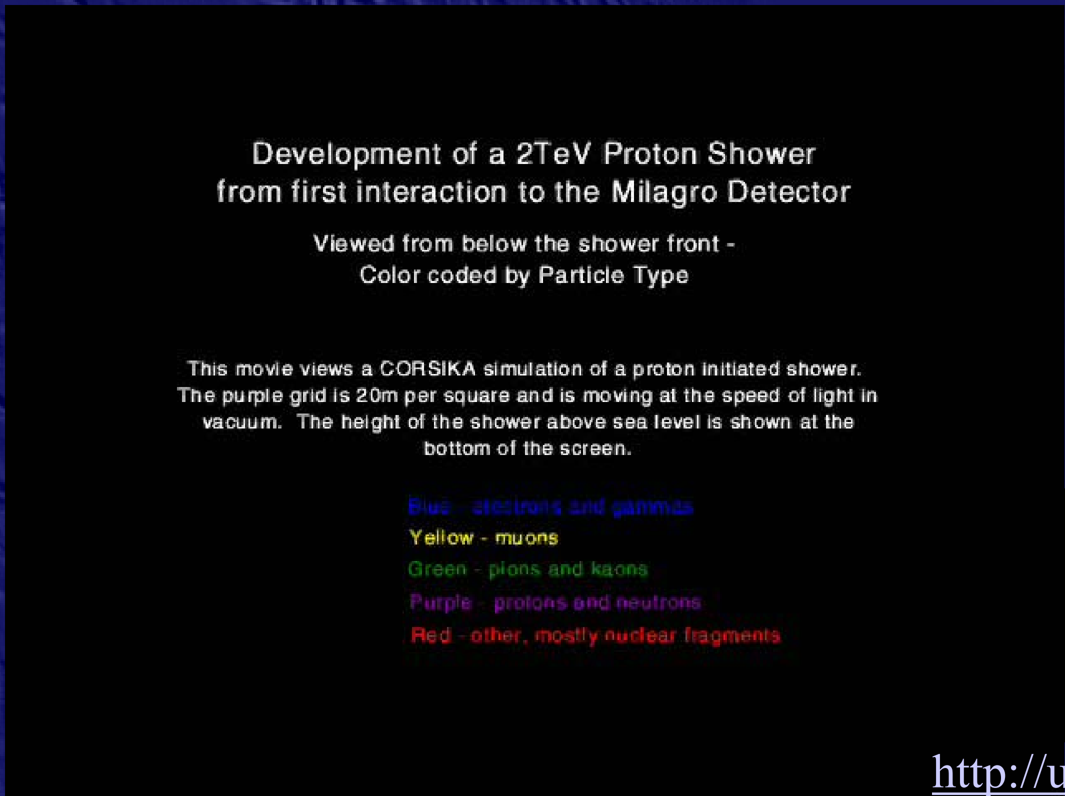
$100 \text{ EeV} = 10^{20}\text{eV}$

$1 \text{ ZeV} = 10^{21}\text{eV}$

The experimental challenge

From observation of extended air showers:

- direction, energy and mass range
  of the primary particle on a statistical basis



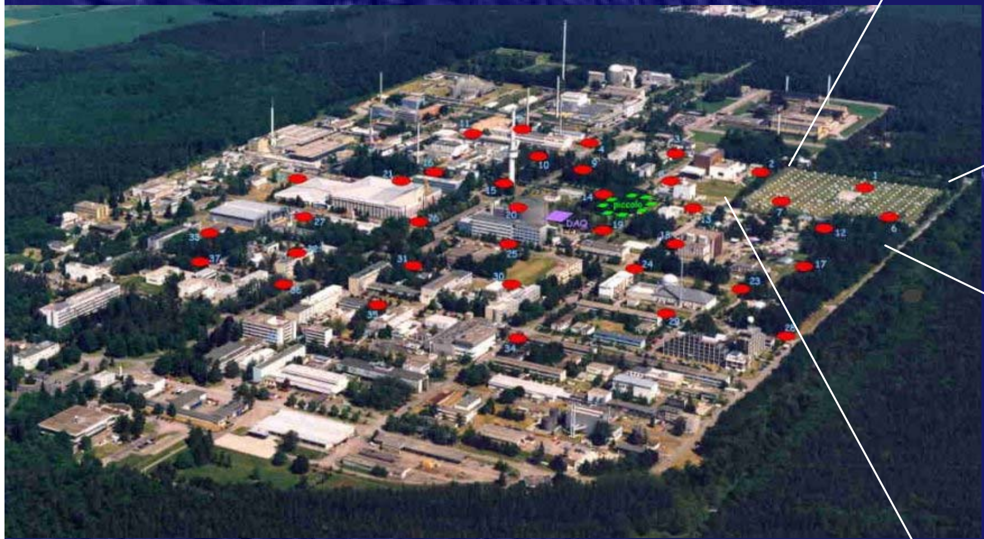
simulation of a EAS, observation from bottom, grid moves with the velocity of light

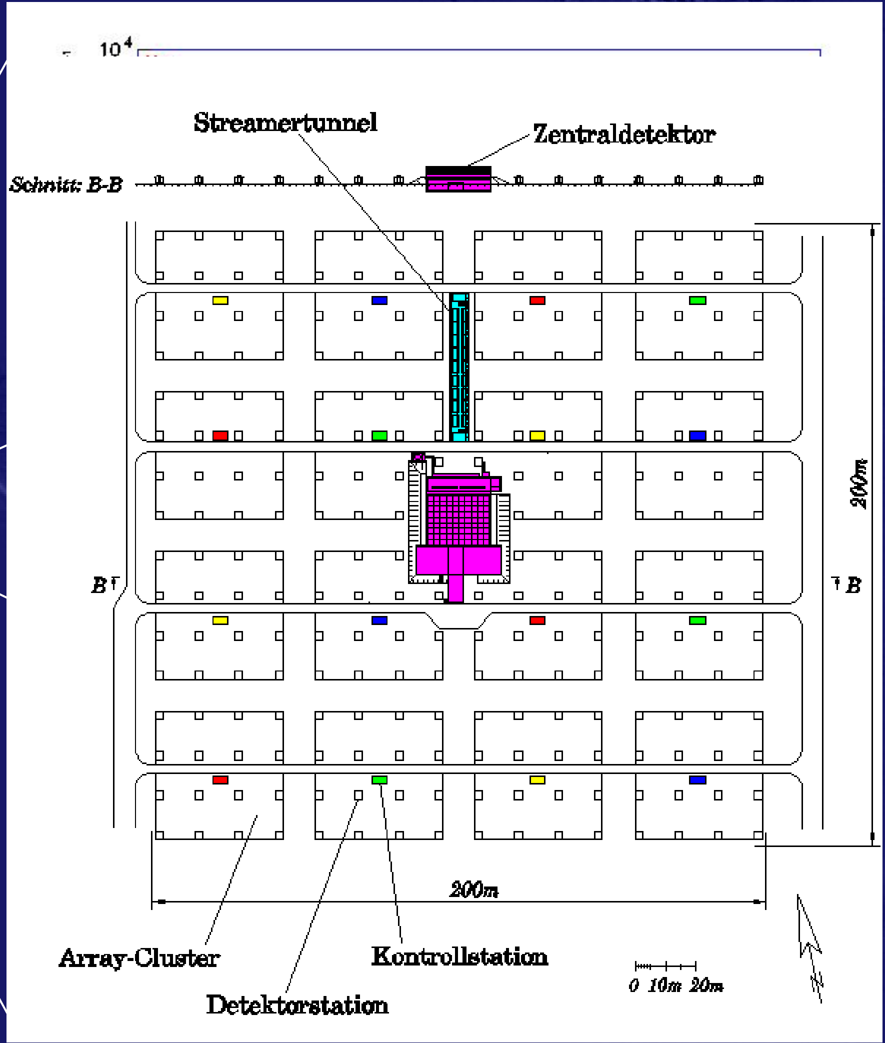
$e^{\pm}$, γ, $\mu^{\pm}$, π, K, p, n, N

http://umdgrb.umd.edu/cosmic/milagro.html

KASCADE-Grande: an experiment at the CR-Knee

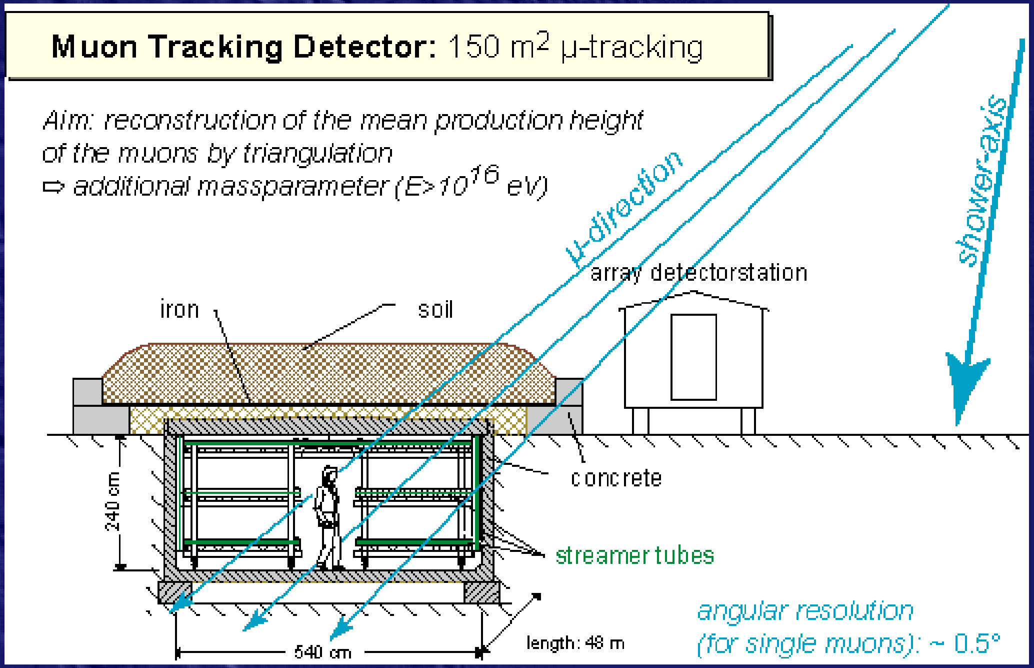
KArlsruhe Shower Core and Array DEtector





KASCADE (1)

Measure different EAS components:



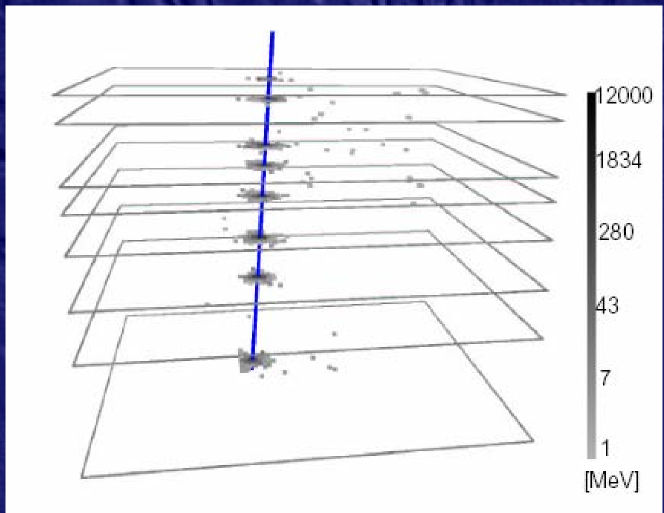
Muons

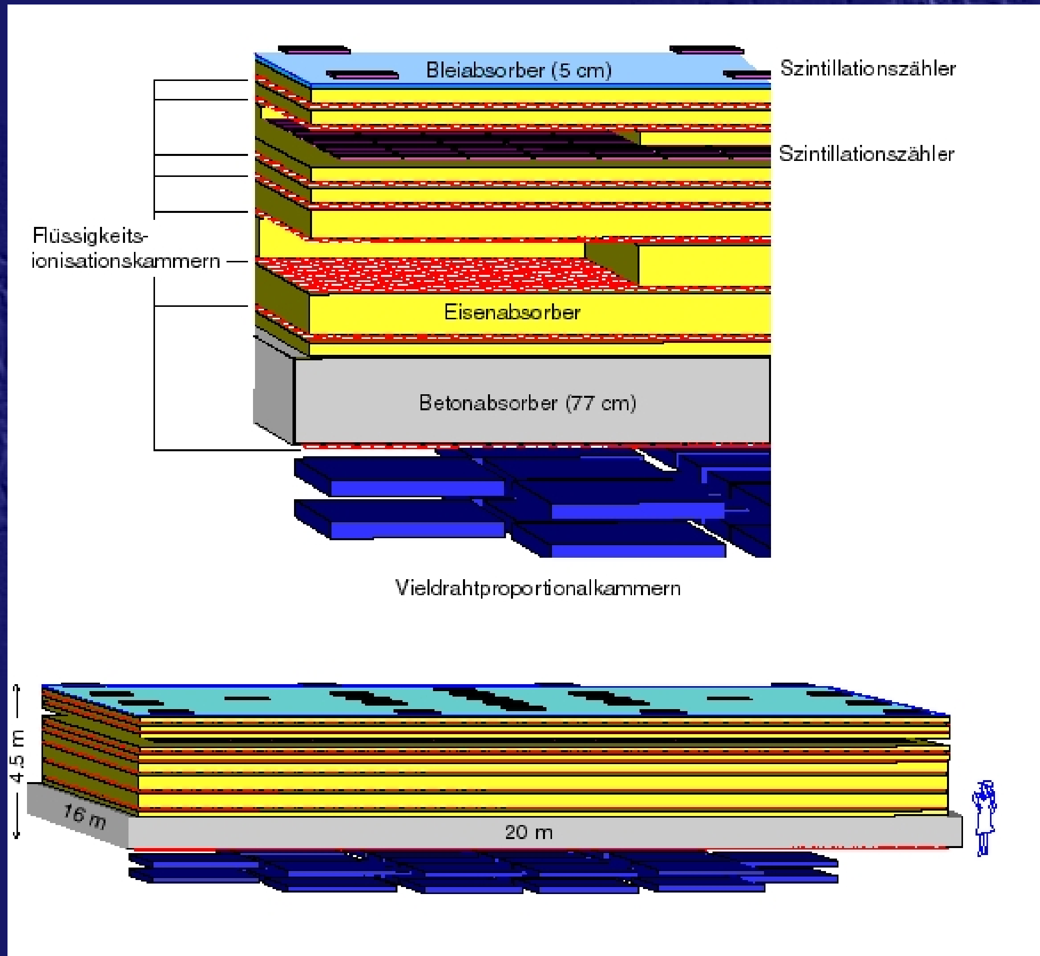
Electrons and photons

KASCADE (2)

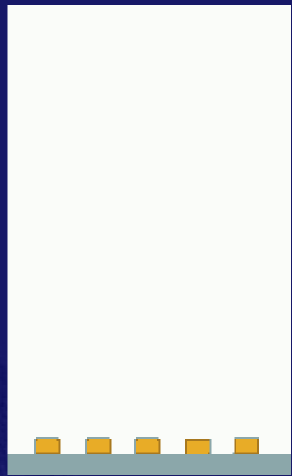
$320\ m^2$ central calorimeter

Single 12 TeV hadron:



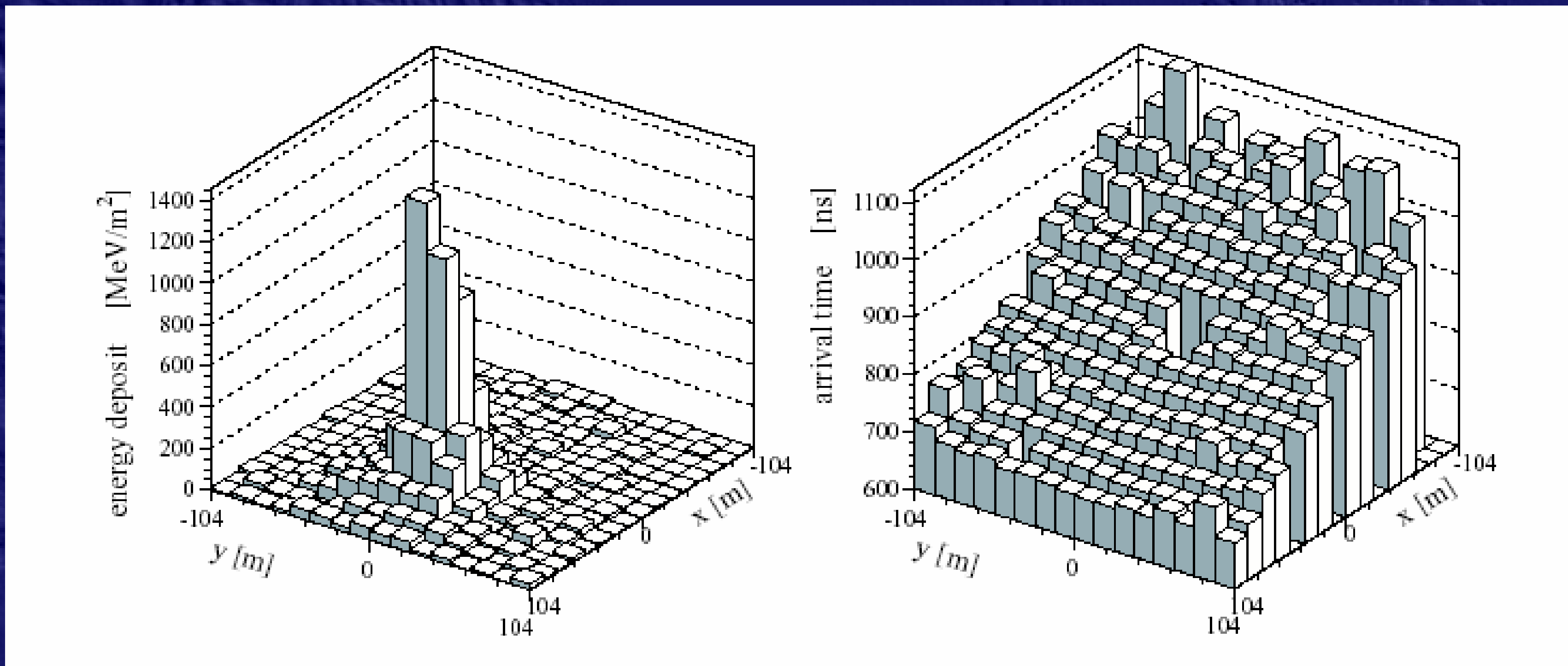


EAS Event

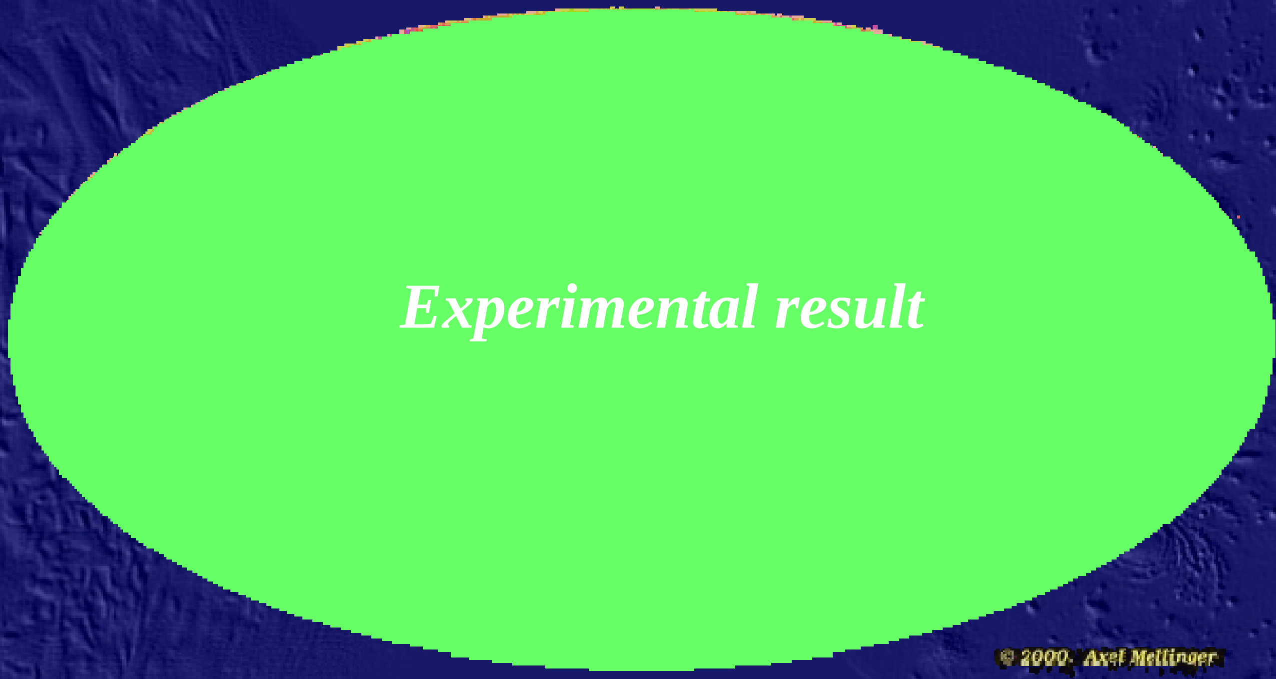


Particle distribution
↳ energy

Arrival time of shower front
↳ direction



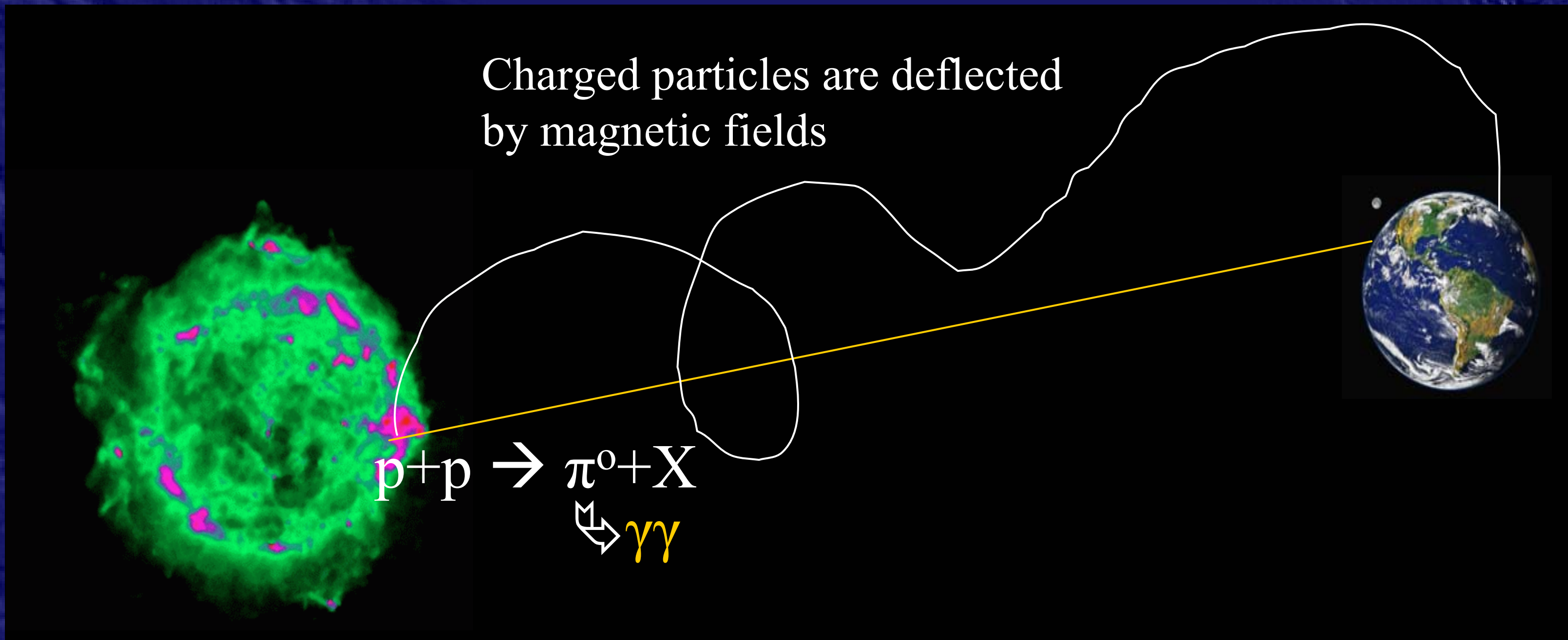
"Sky map" with cosmic rays



From direction of (charged) CR:

No cosmic accelerators visible!

Why are CR isotropic?



- Charged CR do not point back to accelerators
- Number of neutral CR too small to identify accelerators with KASCADE type experiments.

What to do??

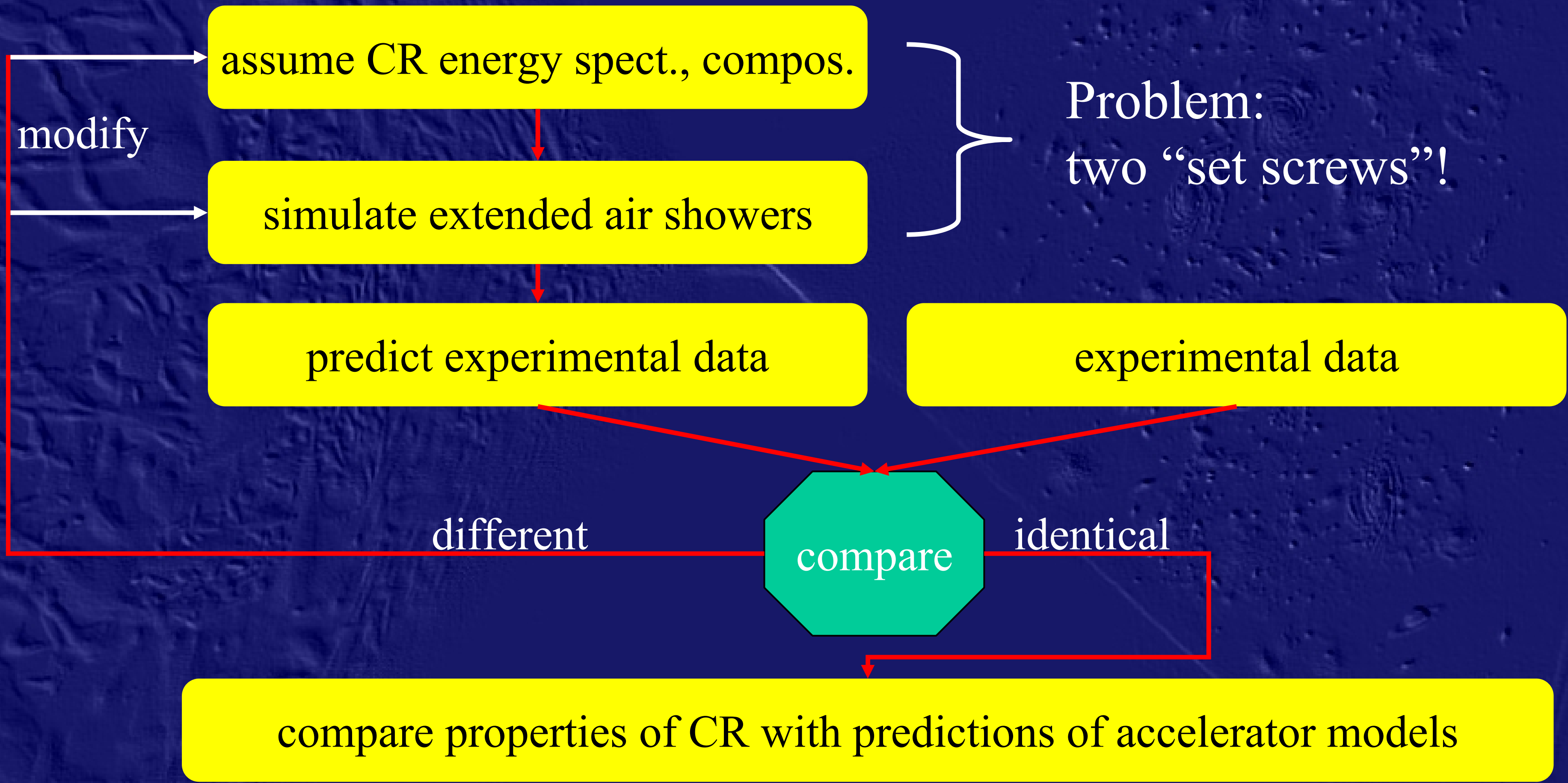
Strategies to identify the cosmic accelerators

1. select photons (not charged) out of the CR ☞ later

2. compare detailed measurements of the energy spectrum and mass composition of CR with accelerator models

Analyses of energy spectrum and composition

Compare measurements with models

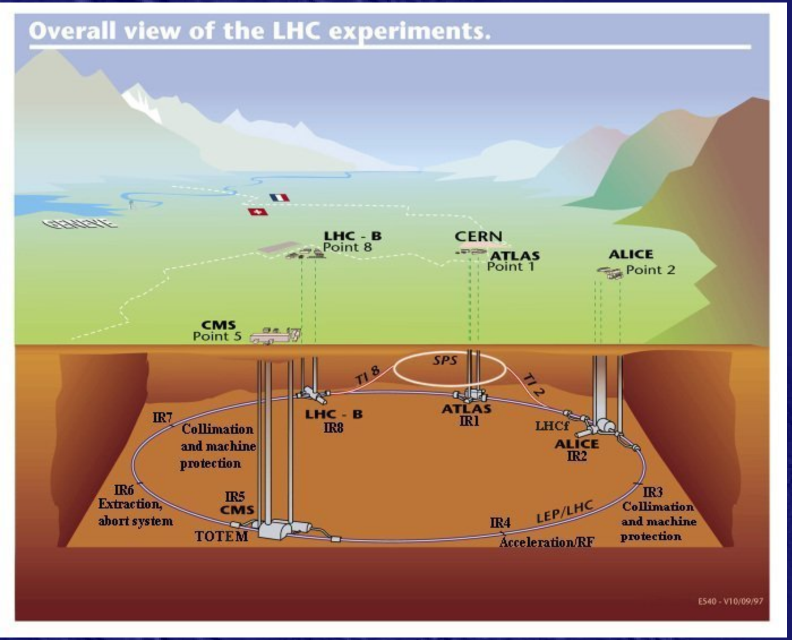


However …

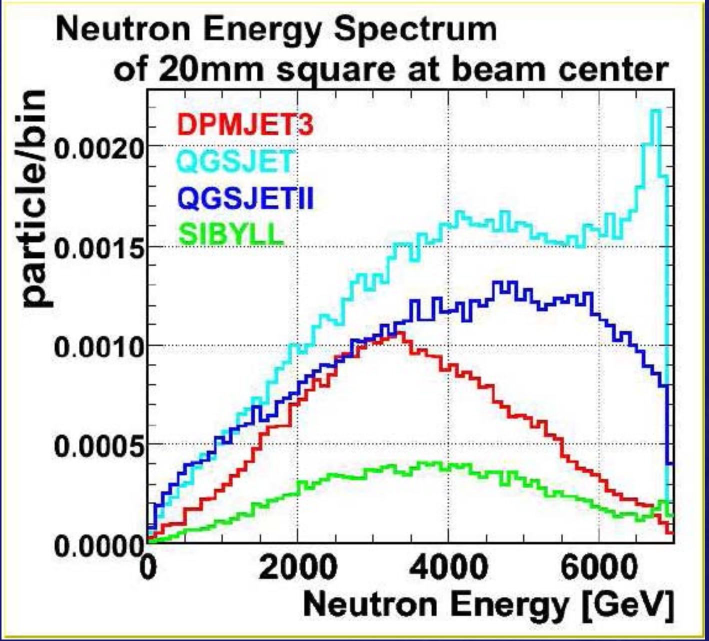
KASCADE collaboration (astro-ph/0505413):

- “None of the interaction models used to simulate extended air showers is capable of describing the measured data consistently over the whole measurement range.”
- “At present, the limiting factors of the analysis are the properties of the high energy interaction models used ...”

Answers from the LHCf- Experiment at LHC?



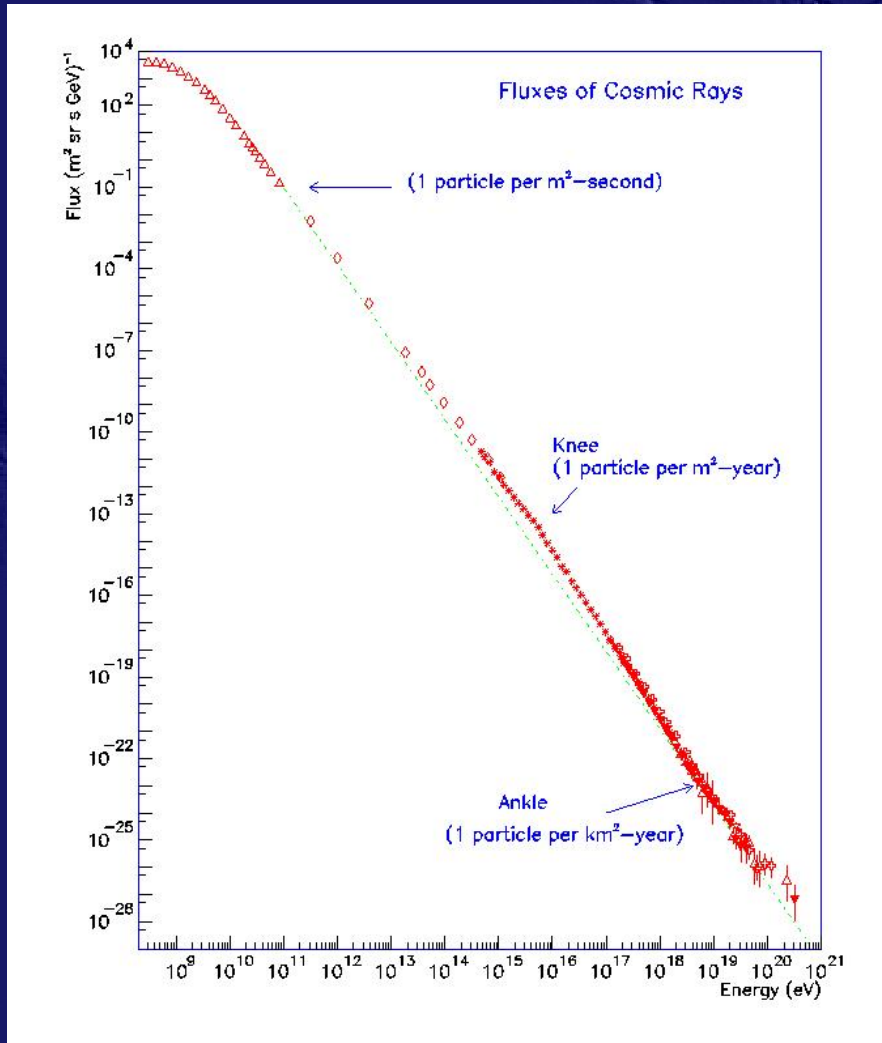
Technical Design Report LHCf



Measure energy flux in the very forward region to constrain air shower simulations:

– 7TeV + 7TeV correspond to 10^{17}eV CR, beyond the “knee”!

From the “knee” to the highest CR energies

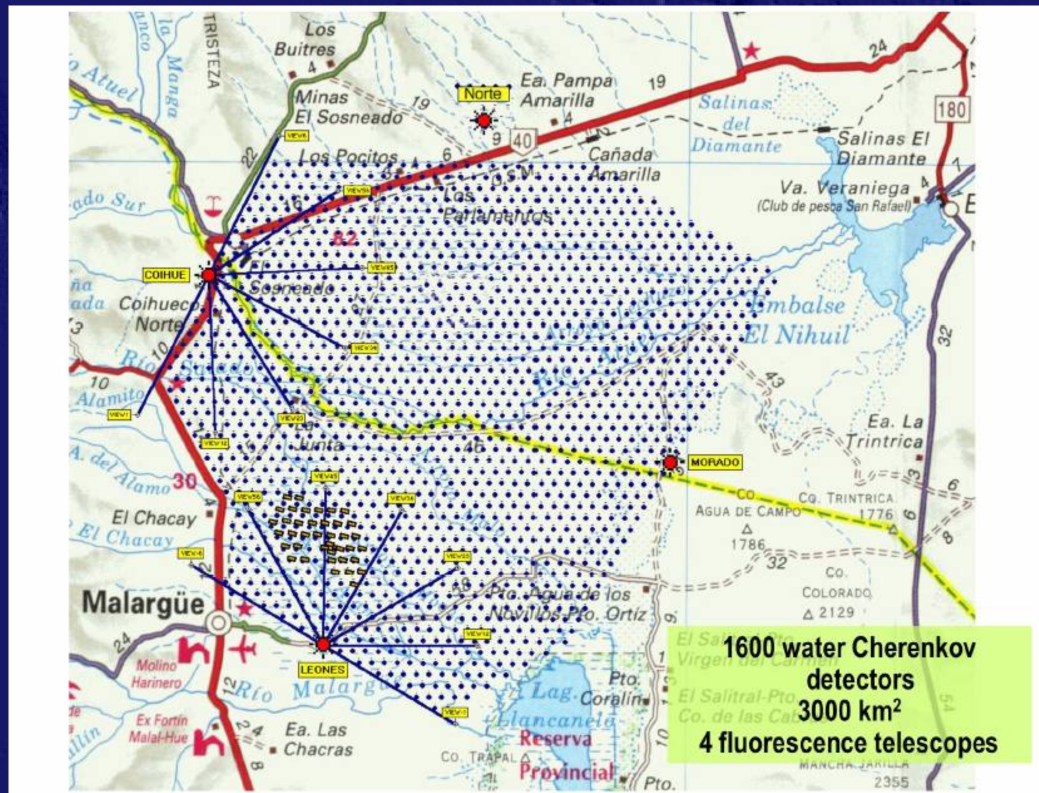


New challenges …

10^4 m^2 Detector Area ⇨⇨⇨⇨ 10^9 m^2 Detector Area

KASCADE

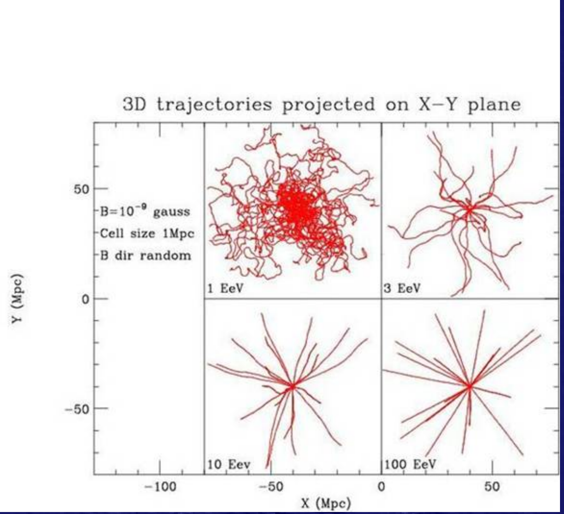
AUGER



(nearly) fully operational
since end of 2007

… and chances

- CR at highest energies are hardly deflected by magnetic fields. Possibility of "astronomy"?



- New measurements possible: scintillation light, initiated by the air shower in the atmosphere.
  ☞ measure the whole shower development!

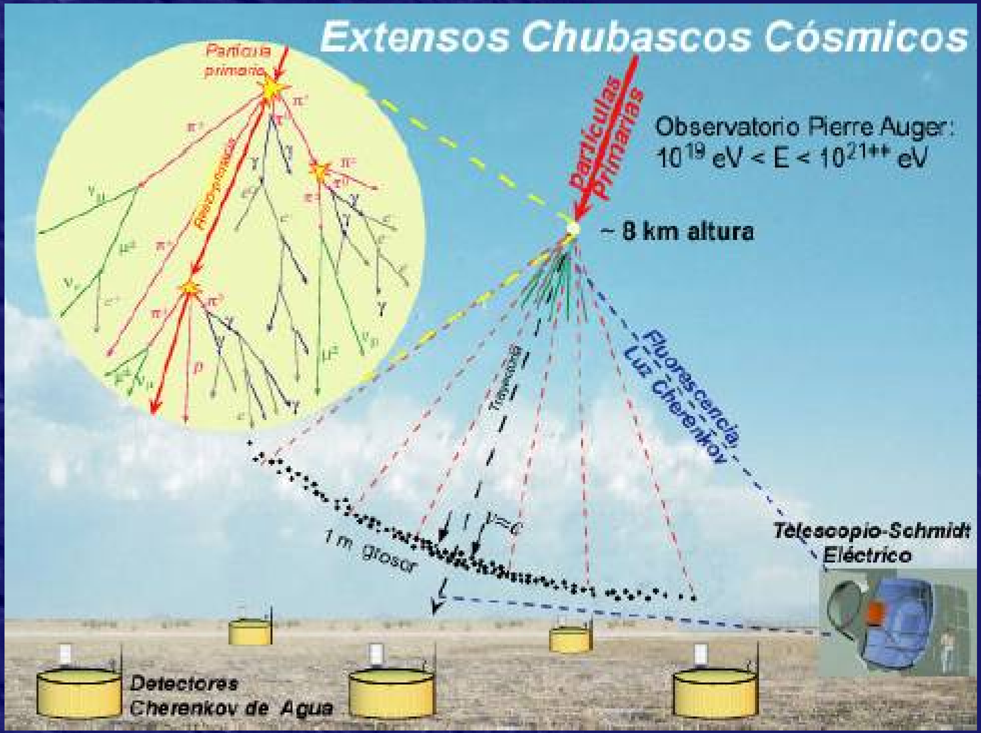
From Karlsruhe to the Pampa Amarilla

- Large flat area
- Clear nights
- Only few villages
  ↳ dark nights

Use the atmosphere as a "fully active" calorimeter!

KASCADE:
only one active layer at ground level

Auger: an integral view of EAS



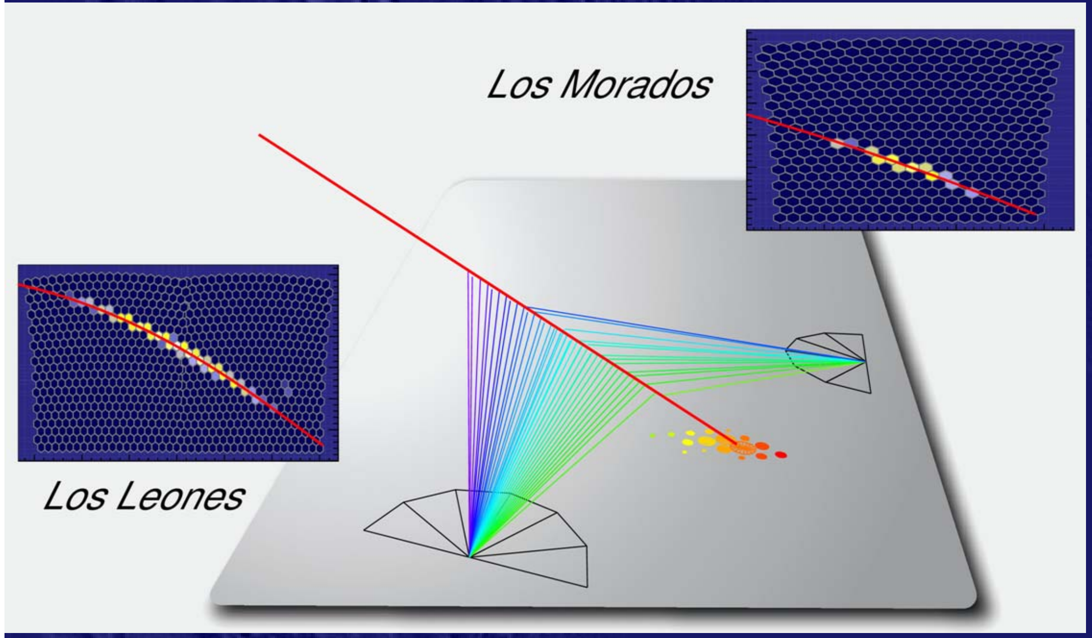
1600 surface detectors on $3000\ km^2$ to register charged particles reaching ground.

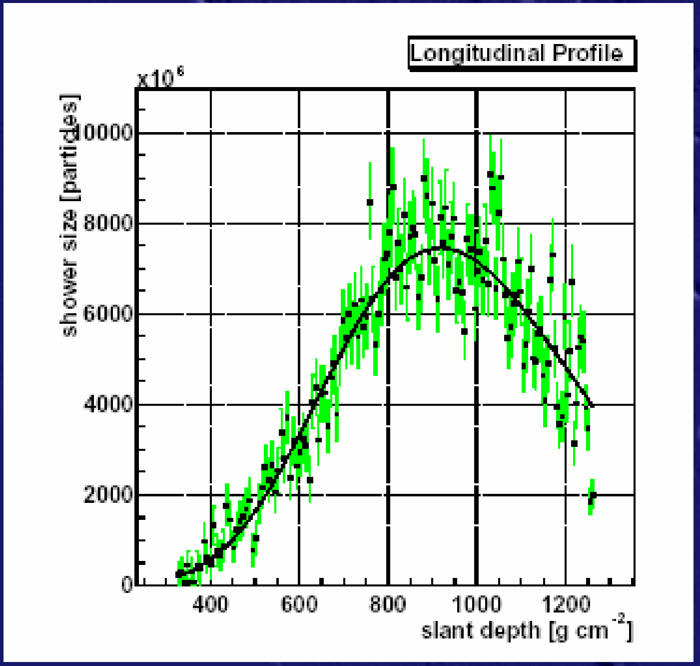
Four sites to measure Nitrogen fluorescent light.

↳ Measure longitudinal EAS development

The Pierre AUGER Observatory

air shower development





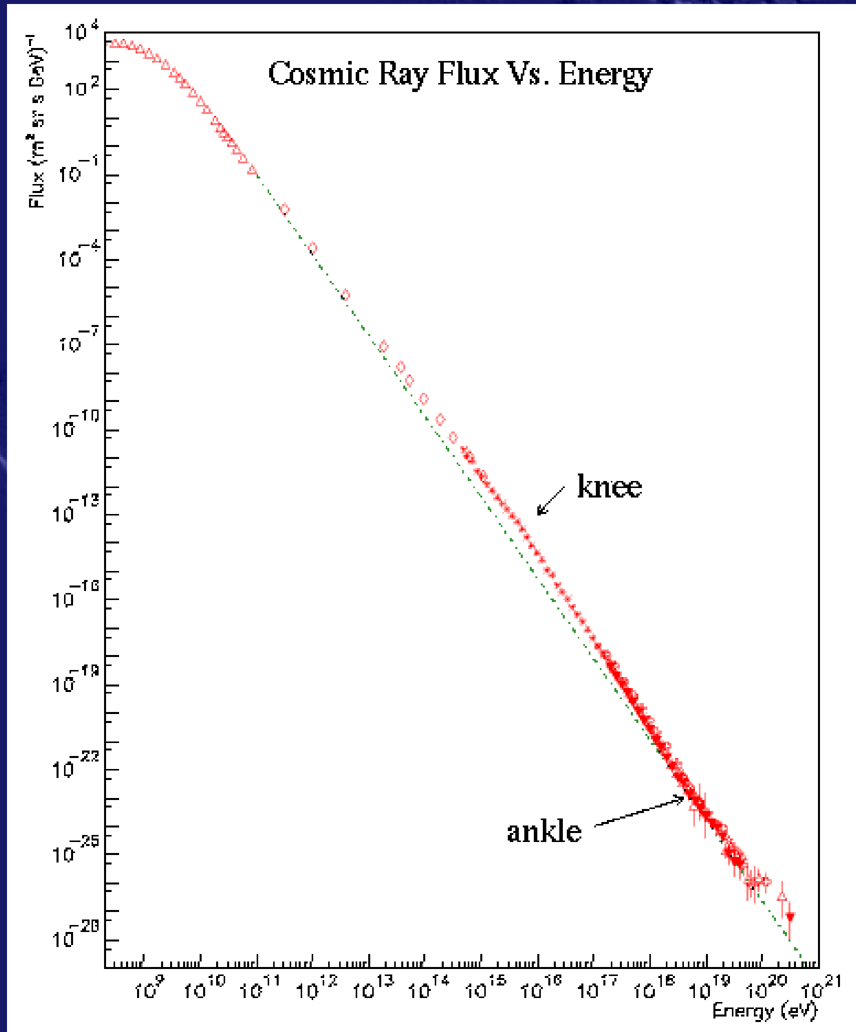
Physics with much better systematics!

Physics with the Auger Observatory

- Energy spectrum of highest energy CR
- Composition of highest energy CR
- Sources of highest energy CR
- Neutrino physics
- Air shower physics
- Tests of simulations
- …

Energy Spectrum: the GZK-Cutoff I

If the accelerators of highest energy CR are located at cosmological distances: particles with $E > 5 \cdot 10^{19}$eV should not reach earth due to interactions with the CMBR (cosmic microwave background radiation).



The GZK-Cutoff II

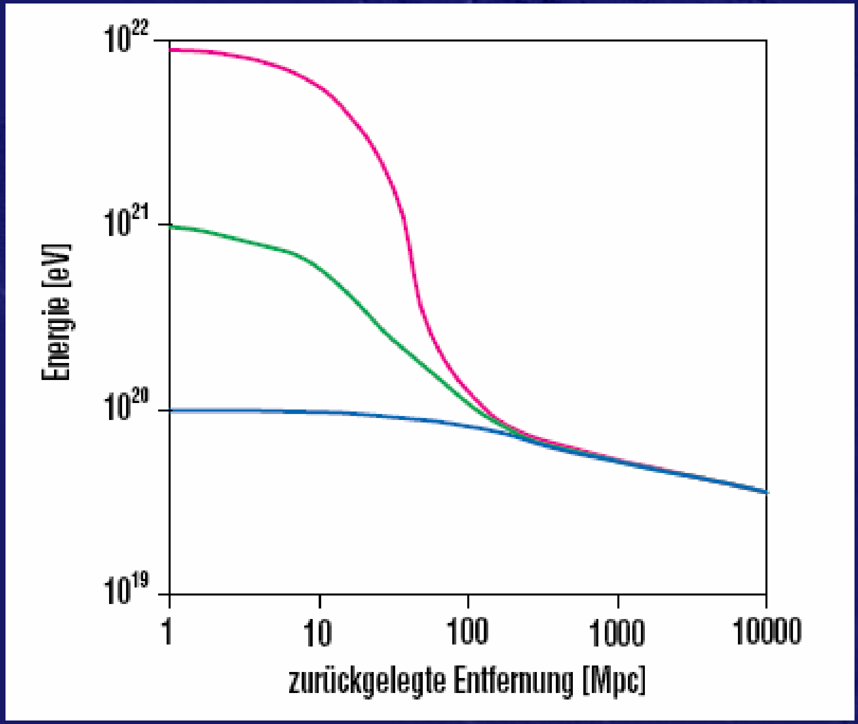
Greisen-Zatsepin-Kuz'min:

The universe appears opaque to CRs of highest energies due to photoproduction of pions

$N + \gamma \rightarrow N' + n \cdot \pi$

with CMBR-photons ($E_\gamma = 10^{-3}$ eV):

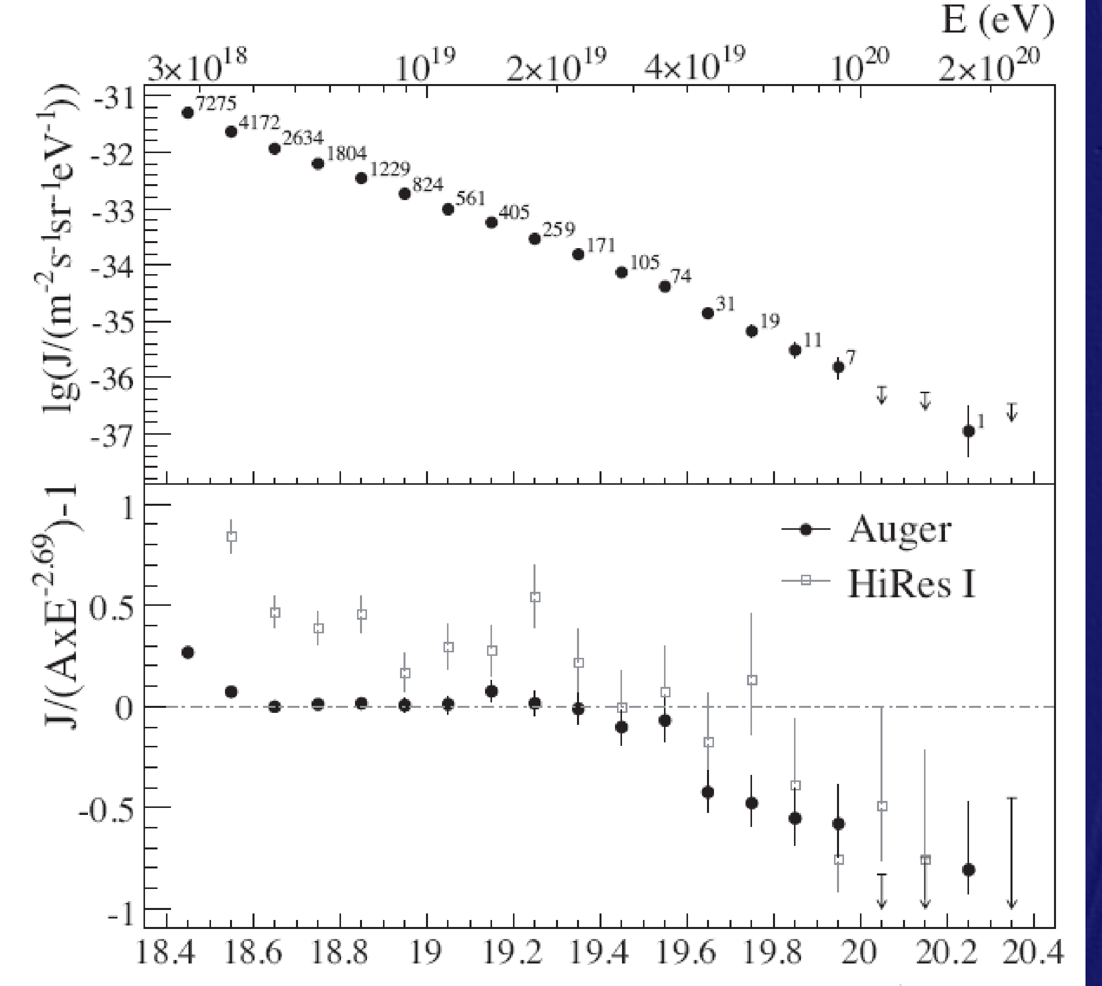
photoproduction for
$E(N) > 5 \cdot 10^{19}$ eV
mean free path length:
"only" 30 million light years



AUGER: Energy Spectrum

- Indication of the GZK-cutoff?
- Determination of the CR composition needed for confirmation.

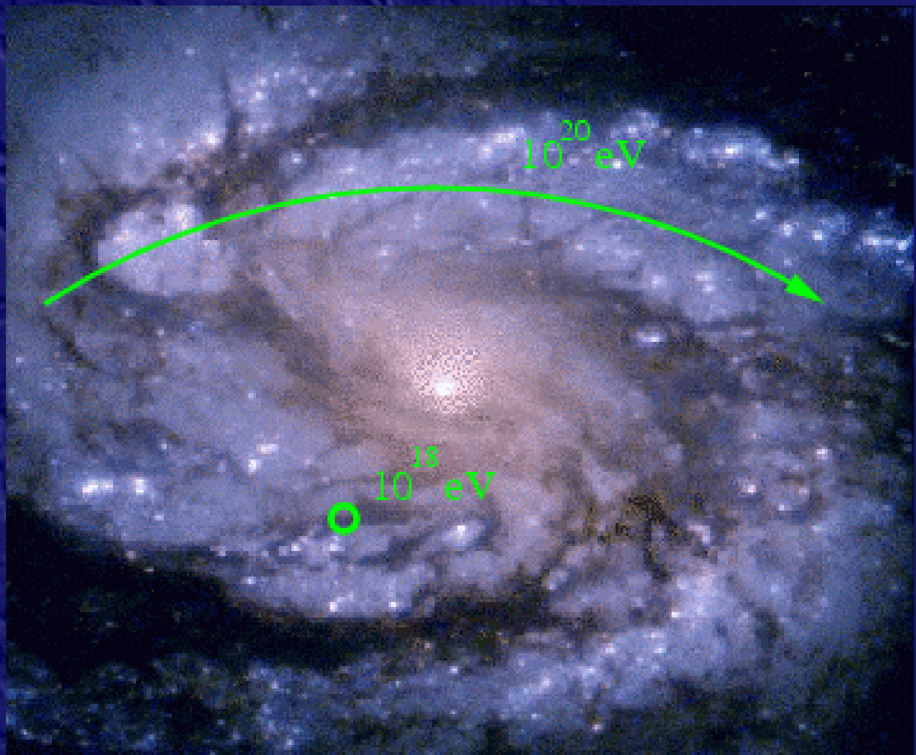
Expectation:
If GZK-cutoff, sources are at cosmological distances!

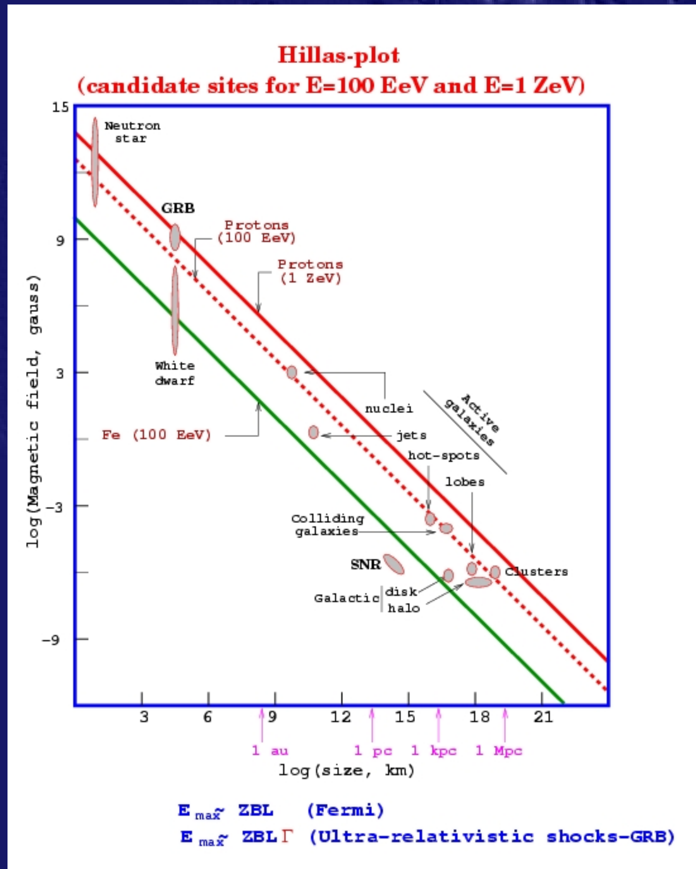


arXiv:0806.4302

Possible origins of highest energy CR

Above $5 \cdot 10^{19}$eV CR not bound to galaxy (gyroradius > galaxy)





Possible origins of highest energy CR

Above $5{\cdot}10^{19}$eV CR not bound to galaxy (gyroradius > galaxy)

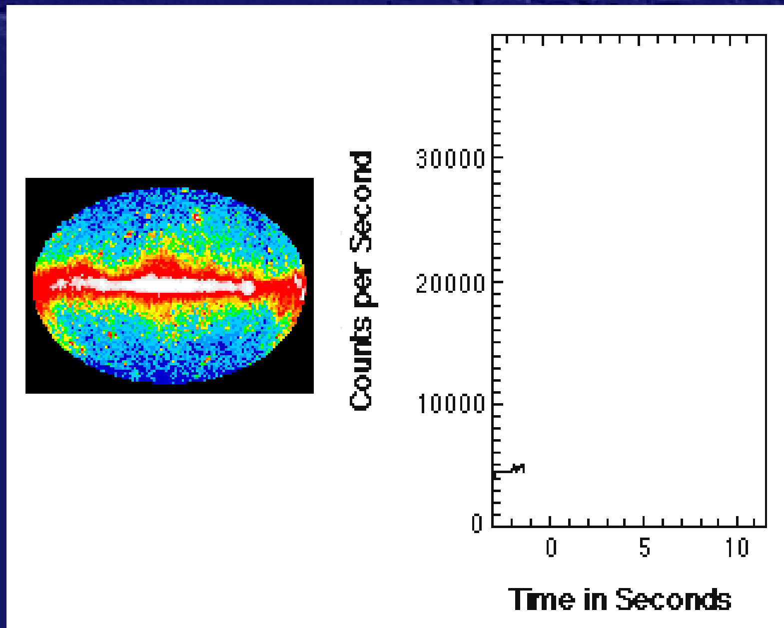
↳ Extragalactic sources at cosmological distances likely

Active Galactic Nuclei

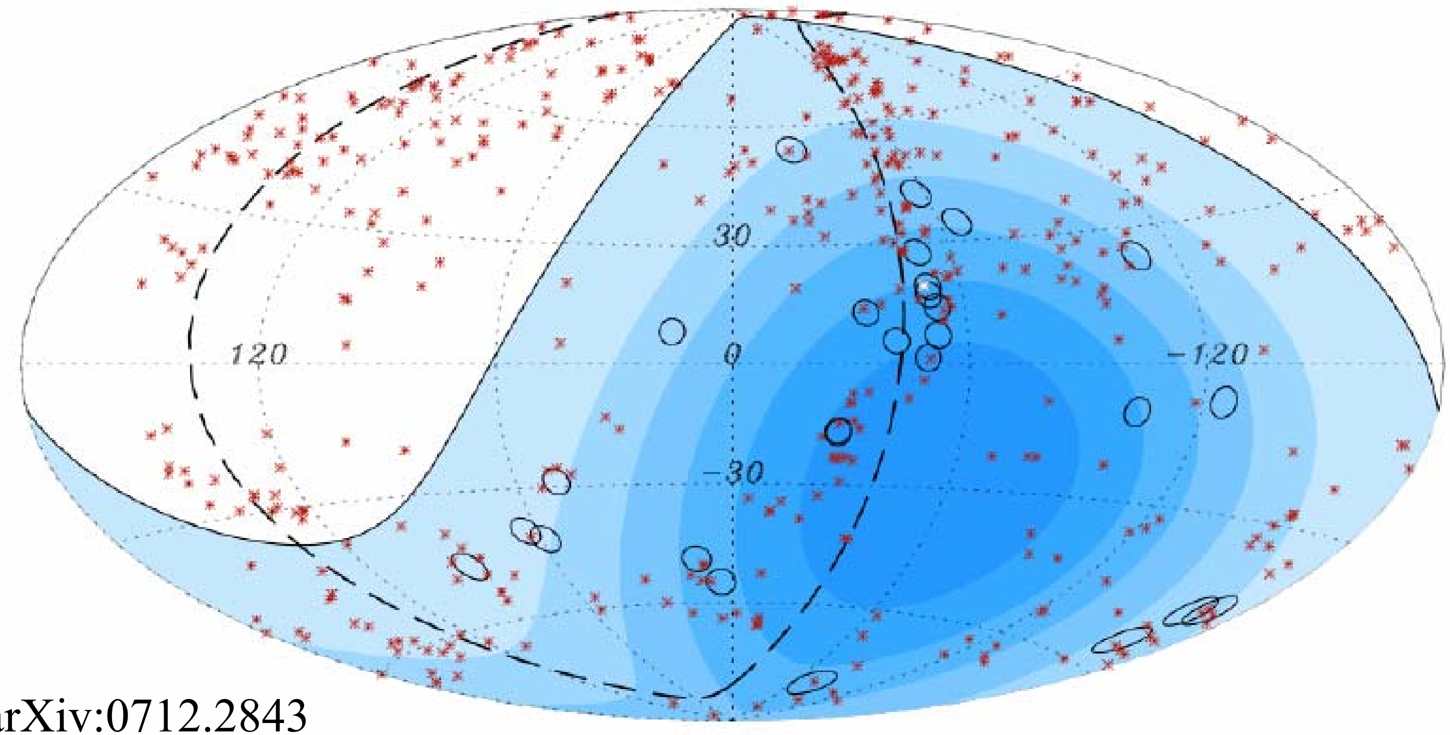
active black holes with more 10^{10} solar masses

Gamma Ray Bursts

extremely violent supernovae (?) at cosmological distances



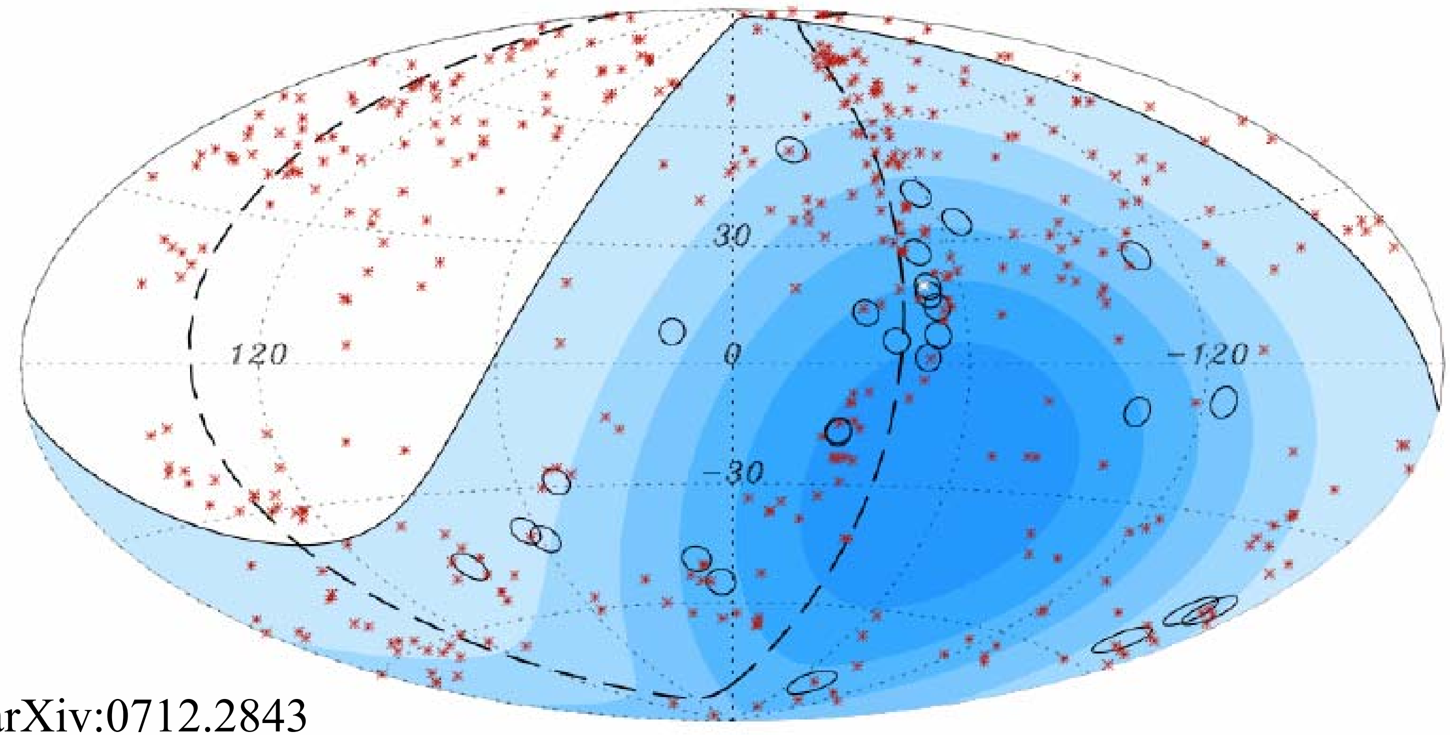
AUGER: Accelerators of Cosmic Rays



arXiv:0712.2843

Circles:	CR with E > 57 EeV *(= 8,000,000 · LHC-beam)*
asterisks:	AGNs with z < 0.017 (< 71 Mpc, within GZK horizon)
blue areas:	exposure time

AUGER: Accelerators of Cosmic Rays



arXiv:0712.2843

Statistical analyses show a 99% confidence level for a correlation of the arrival direction with AGNs (5σ = 99.994%).

More data needed to prove “high energy CR astronomy”!

Cosmic Rays: topics for discussion

- How do we know that CR are charged?
- How do we know the composition of CR at lower energies?
- Why is the simulation of extended air showers doubtful and hence problematic?
- How to improve interaction models for high energy air showers?
- Would a detector for CR above the knee located at the moon be meaningful?
- How to do neutrino-physics with a CR detector?

Astroparticle Physics

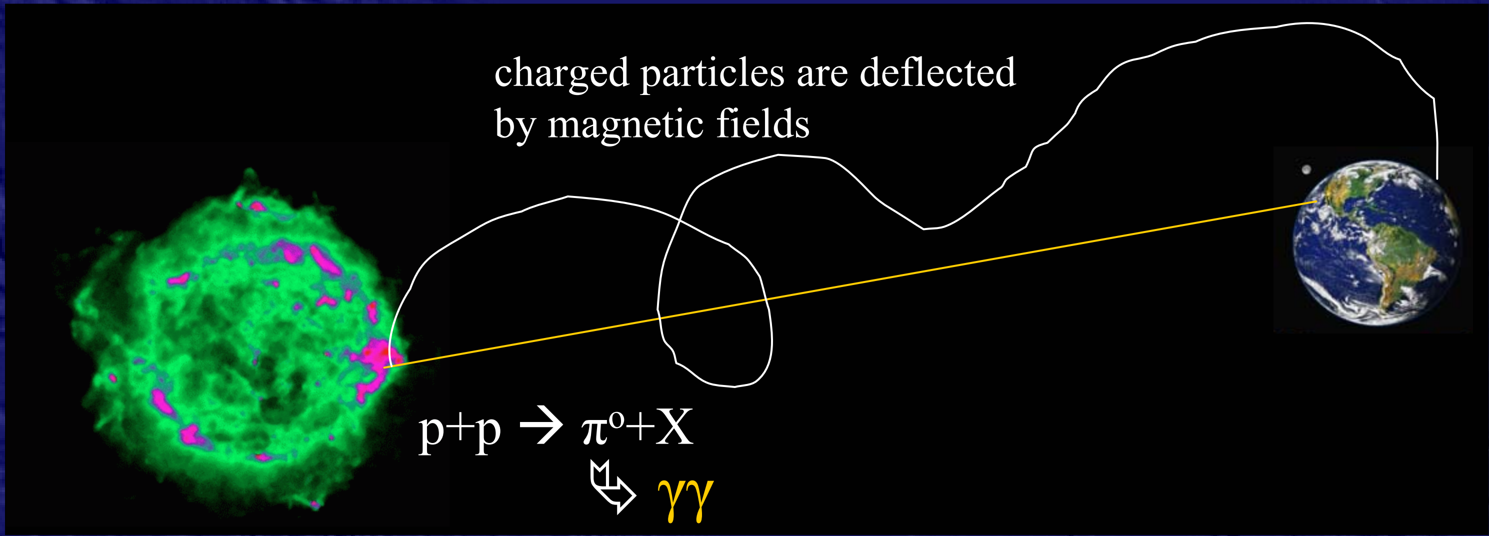
1. High Energy Particles from the Cosmos

2. **The new Astronomy**

3. The Cosmic Microwave Background Radiation

4. Search for Dark Matter (DM)

Motivation for Astronomy with E > 100 GeV



- Indirect identification of CR accelerators
  via analyses of the charged CR problematic
- Look for high energy photons which are produced at the accelerator

New experimental methods required!

Instruments for GeV-TeV photons

The challenge:

Flux of photons of the crab nebula
(brightest galactic source in the GeV-TeV range)

$F(E_\gamma > 500\text{GeV}) = 10\ /\text{m}^2/\text{year}$

↳ Not detectable with satellites!

The solution:
register air showers initiated by photons!

- select photon induced air showers
- aim for lowest possible energy threshold to maximize number of detected photons.

Proton and photon induced air showers

http://umdgrb.umd.edu/cosmic/milagro.html

simulation of a EAS,
observation from bottom,
grid moves with the velocity
of light

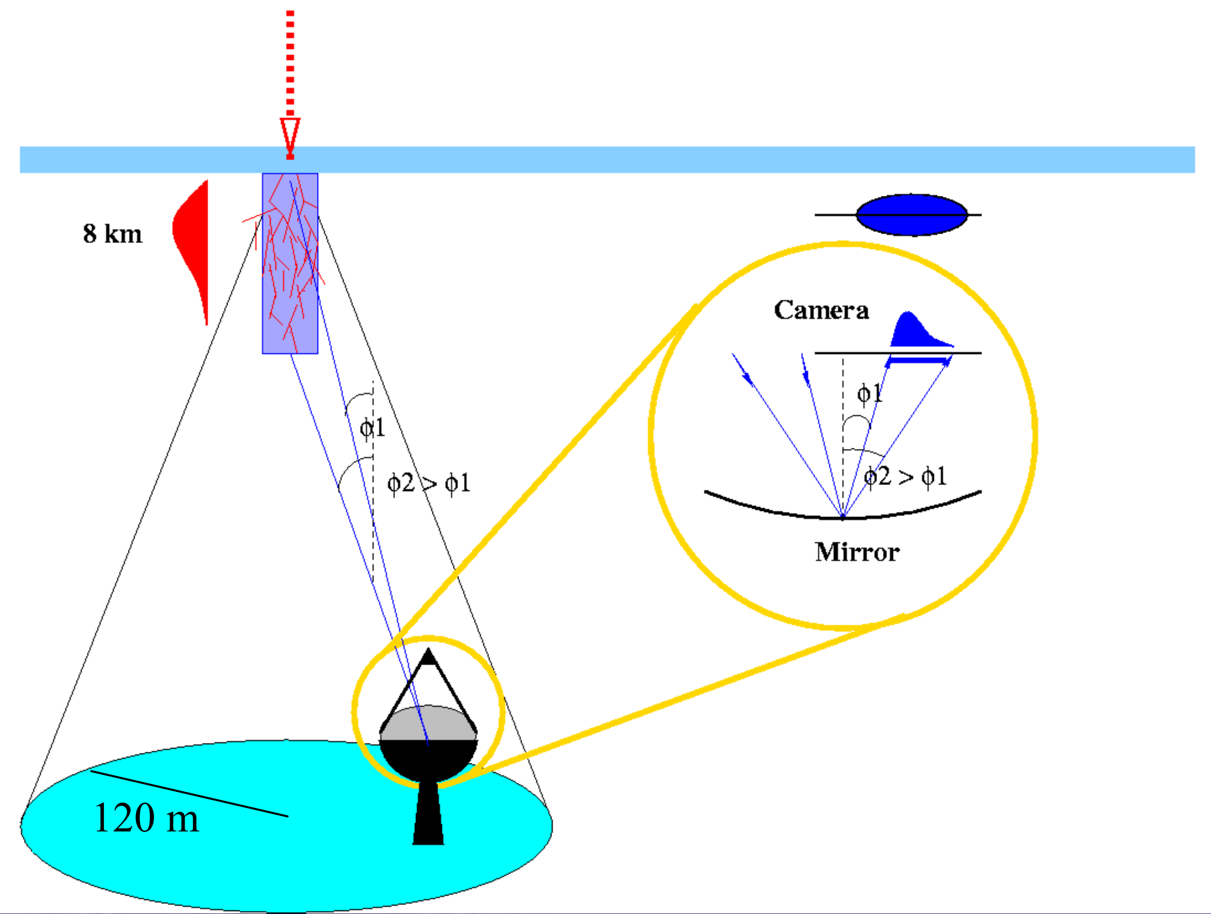
$e^{\pm}$, γ, $\mu^{\pm}$, π, K, p, n, N

Proton and photon induced air showers

Compared to proton induced showers photon induced showers

- contain only electrons, positrons and photons,
- are more compact,
- are more uniform,
- decay faster.

Imaging Air Cherenkov Telescopes (IACTs)



Register Cherenkov light emitted by the air shower:

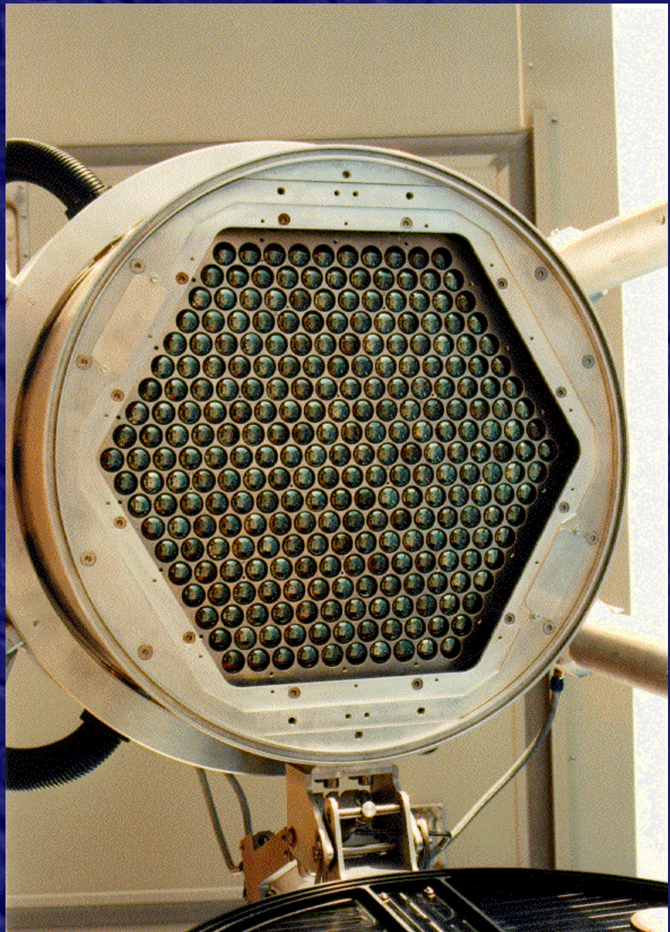
by nature sensitive area of 10^4 m^2

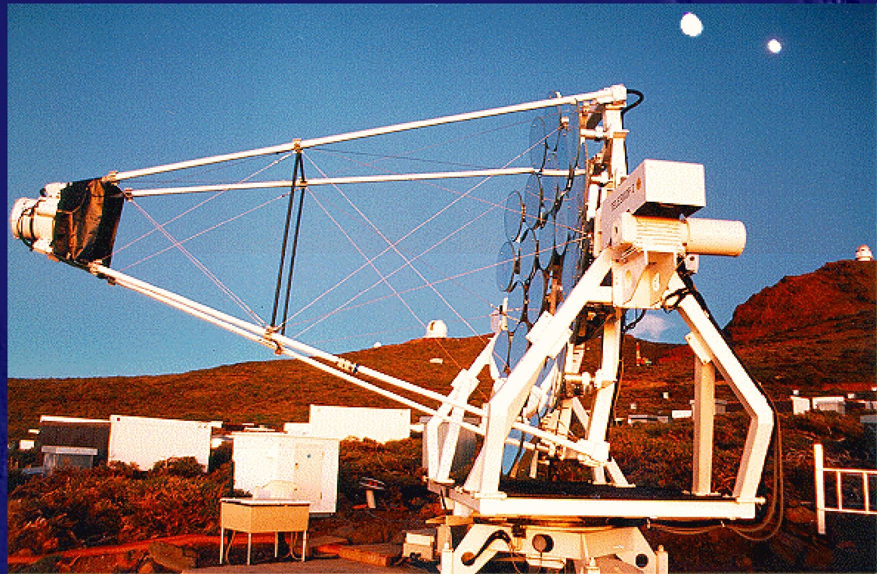
secondary shower particles do not have to reach ground level
☞ low energy threshold

But operation only in clear moonless nights!

http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html
http://veritas.sao.arizona.edu/
http://magic.mppmu.mpg.de/index.en.html

A Pioneer: The HEGRA Experiment





- Segmented mirror
  (optical demands much less than for optical astronomy)
- Camera made of several hundred photomultipliers
  (register ns signals, high amplification)

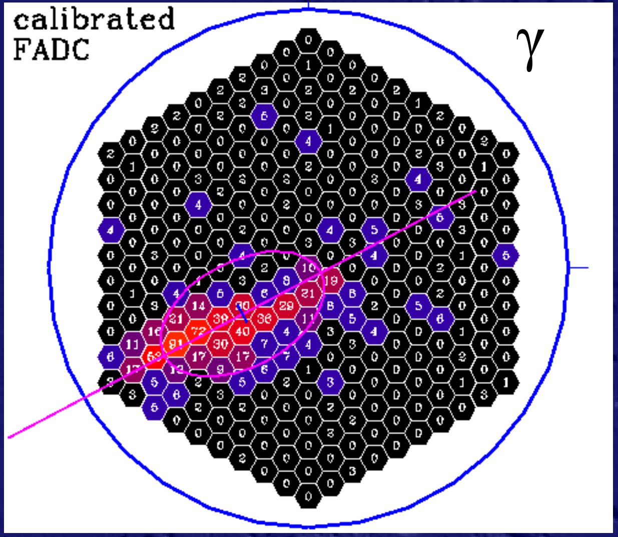
Selection of Photon induced EAS

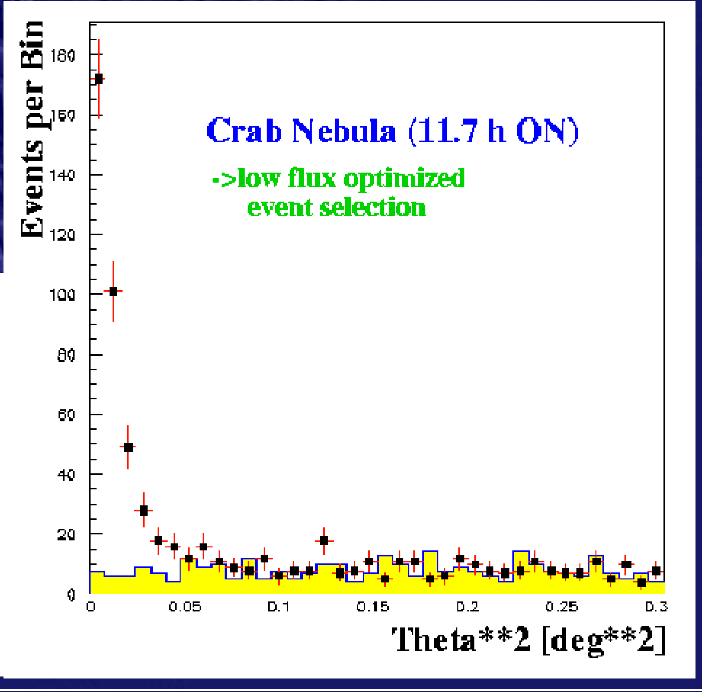
Images of EAS

Photon showers: only em. interaction

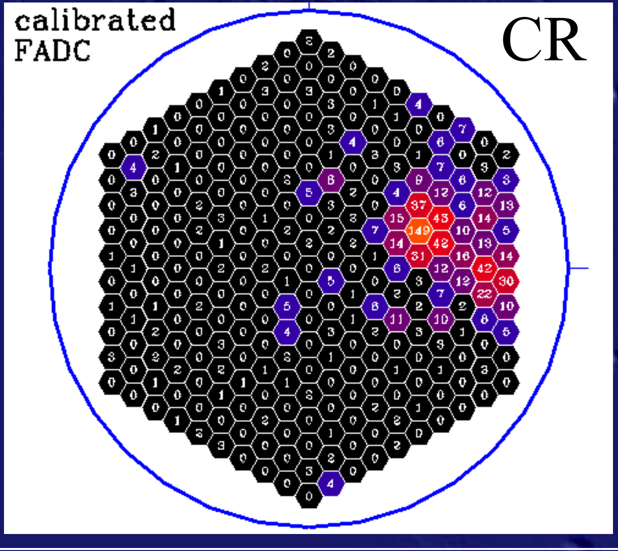
↳ Photon induced EAS more compact and homogeneous than showers of CRs

↳ Image analysis!

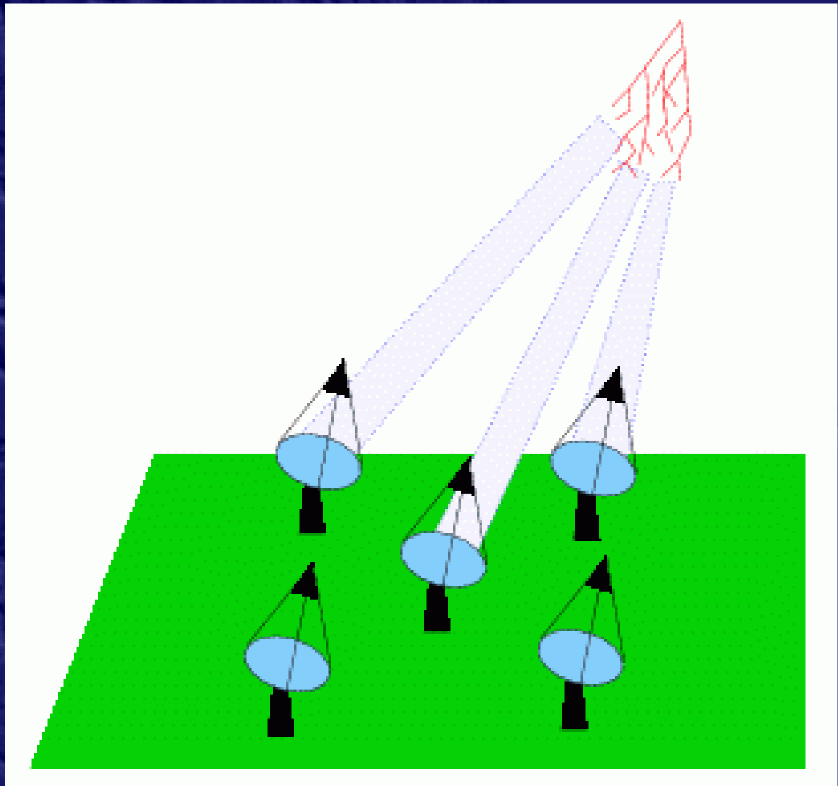


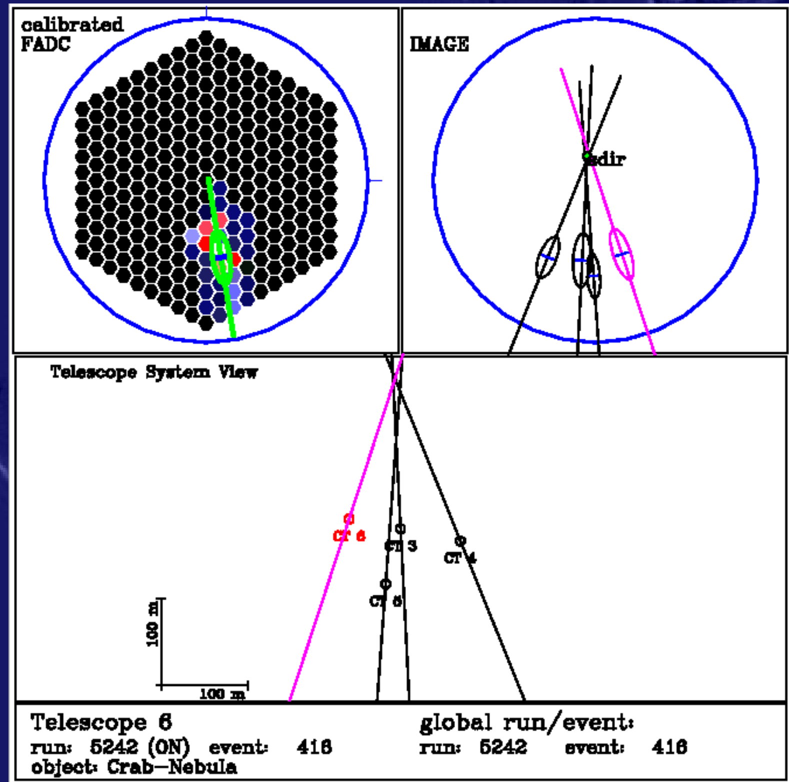


- Strong CR suppression
- Very good angular resolution



Even better : Stereo Imaging



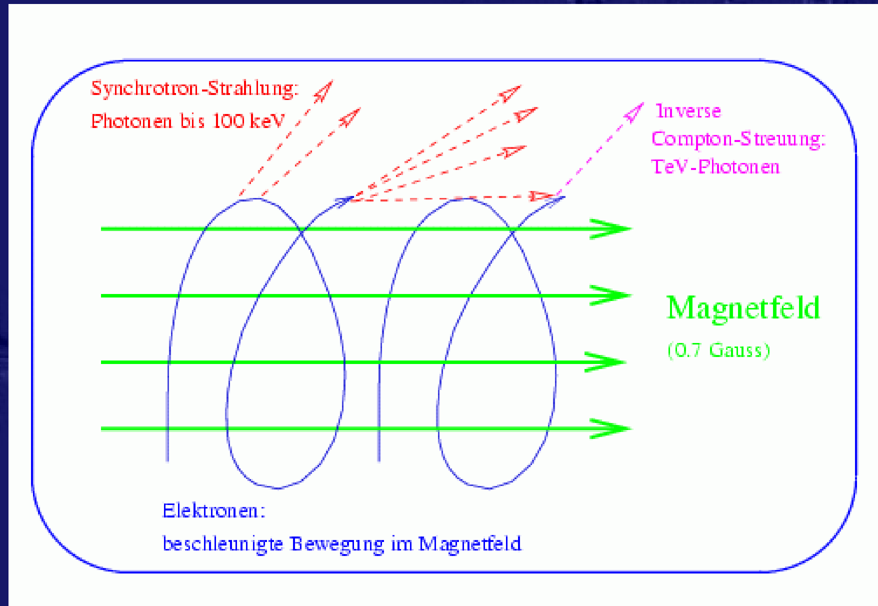


Enhancement of precision (energy and direction of primary photon) and sensitivity by combined analysis of different views of the same shower.

Single photons: σ_E=10%, σ_Θ<0.1°

Crab nebula (M1): the TeV standard candle

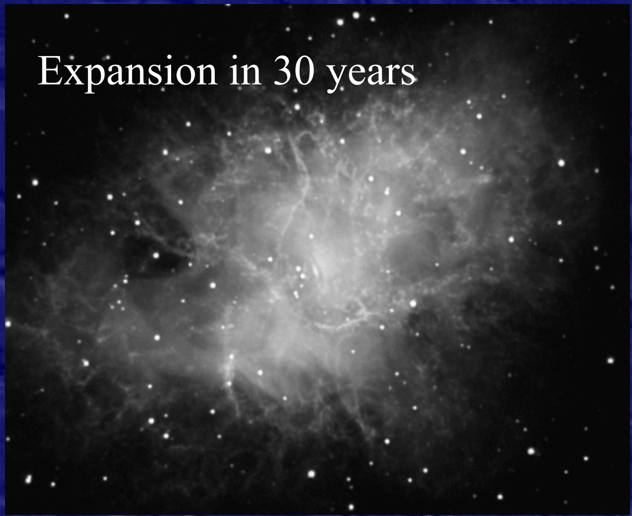
Remnant of a supernova in the year 1054 with a central pulsar

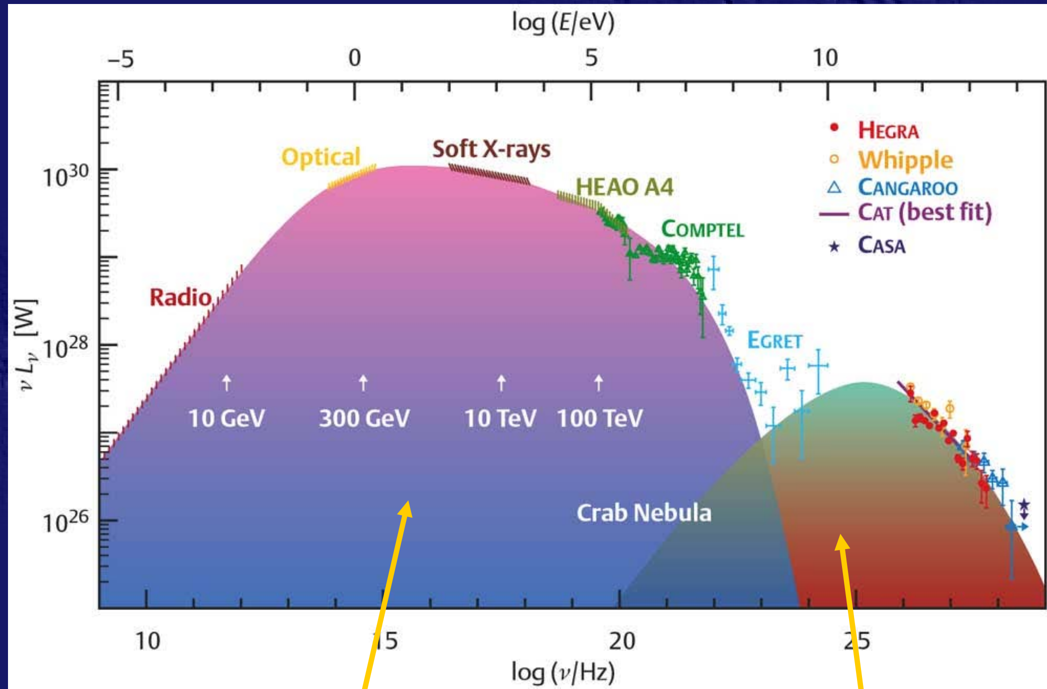


- synchrotron emission of X-rays
- inverse Compton-scattering of X-rays to TeV energies
- Parameters:
  - strength of magnetic field
  - energy of electrons

Crab nebula (M1): the TeV standard candle

Remnant of a supernova in the year 1054 with a central pulsar





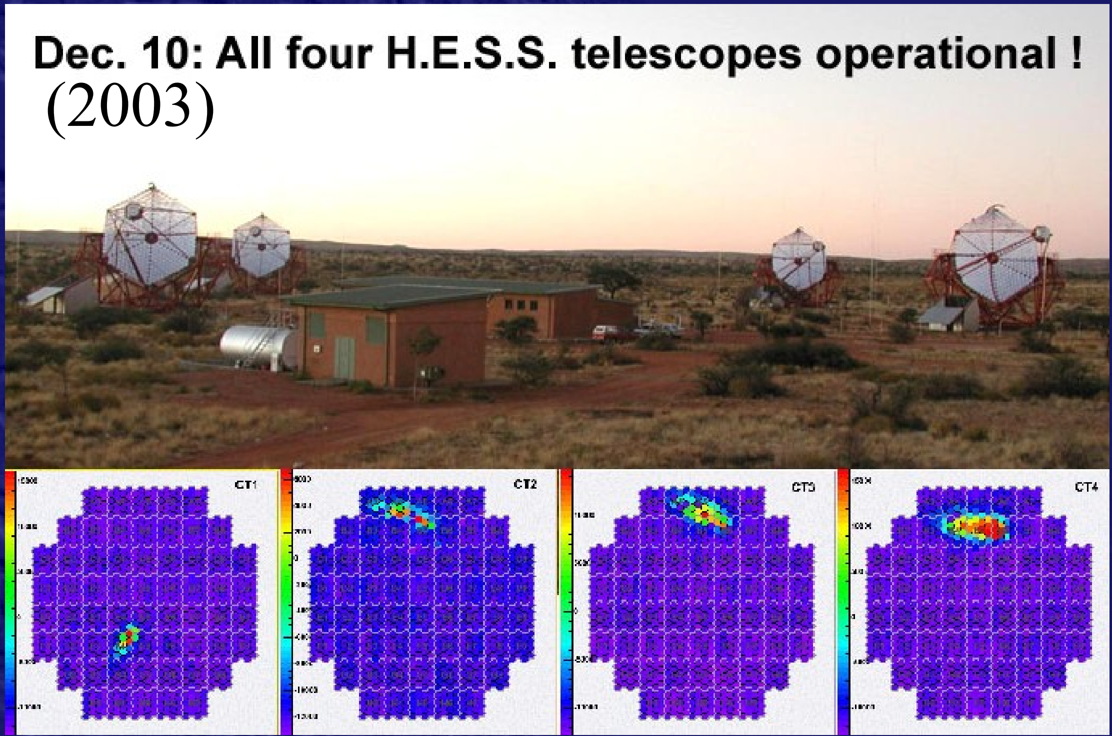
Synchrotron radiation from electrons

Compton-scattered photons

no CR accelerator!

State of the Art Experiments

HESS: 4 10m-IACTs, Namibia

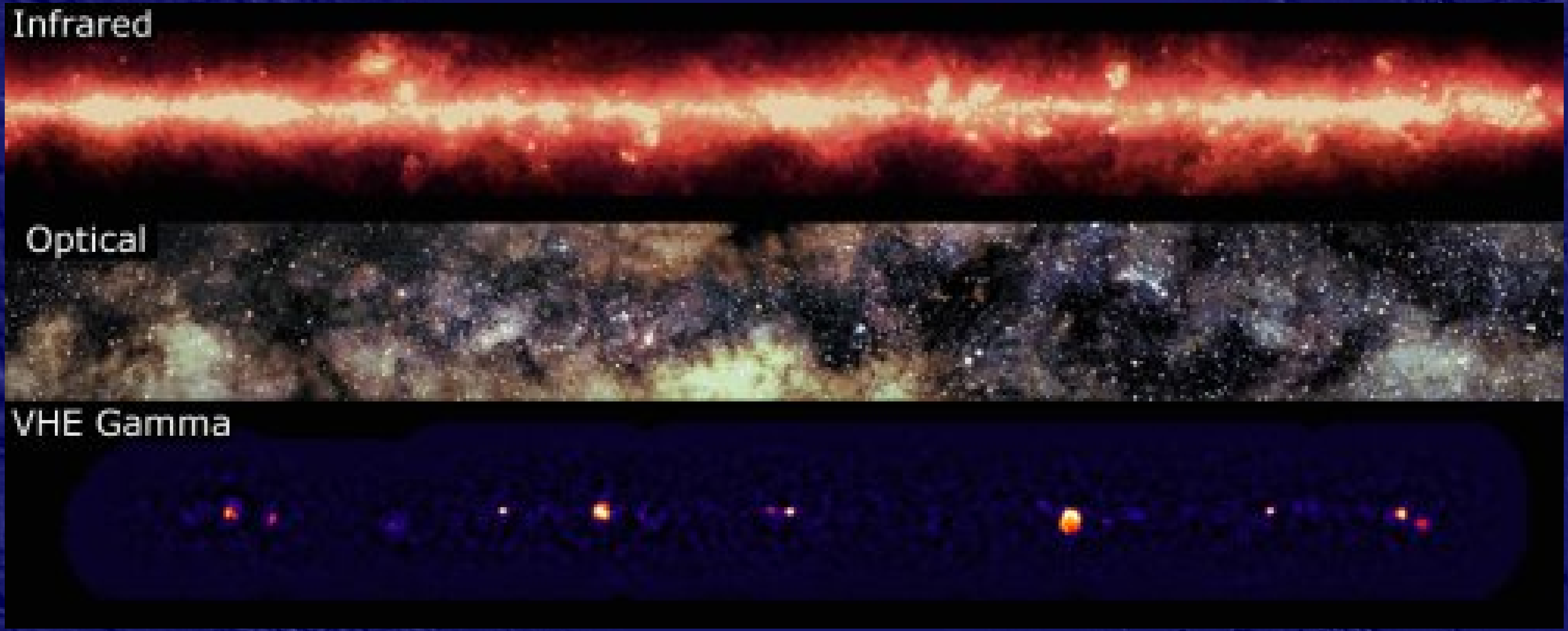


MAGIC: 17m IACT, La Palma

1989: First observation of the Crab nebula at TeV energies: 50h observation time needed (WHIPPLE, Arizona)

2003/2004: HESS and MAGIC measure the Crab in 30s!

Great success of H.E.S.S.

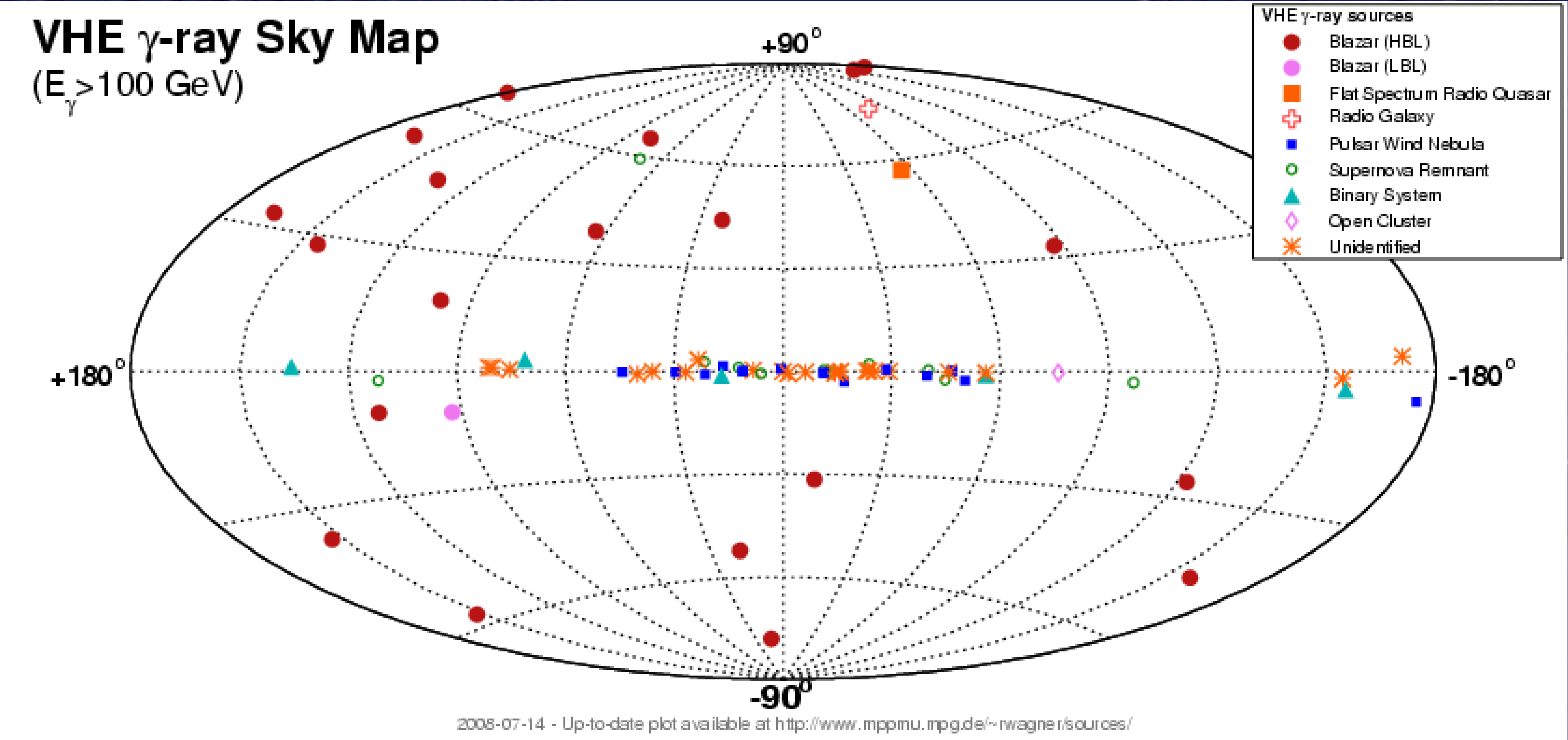


First sensitive survey of milky way reveals eight previously unknown sources.

Science 307, p. 1938 (2005)

Opening a new window for astronomy

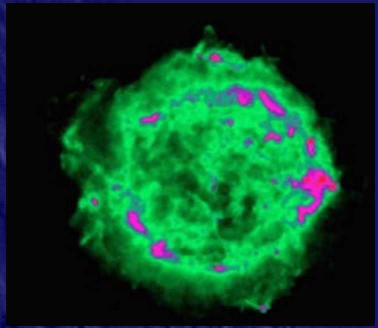
First TeV photon source in 1989,
now (July 2008) already 54 galactic and 23 extragalactic sources!



http://www.mppmu.mpg.de/~rwagner/sources, http://tevcat.uchicago.edu

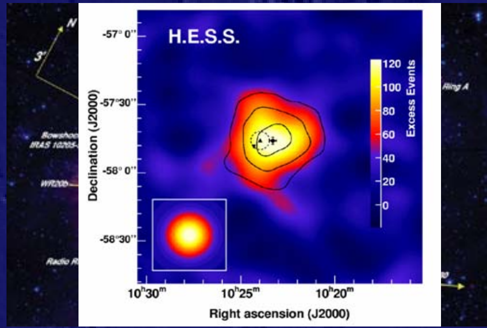
Types of galactic TeV photon sources

Crab Nebula

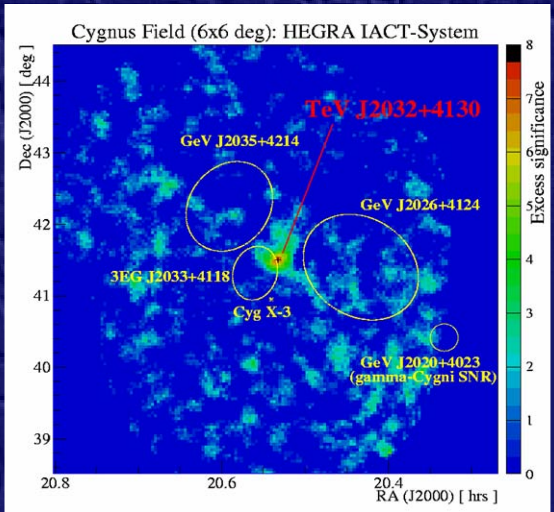


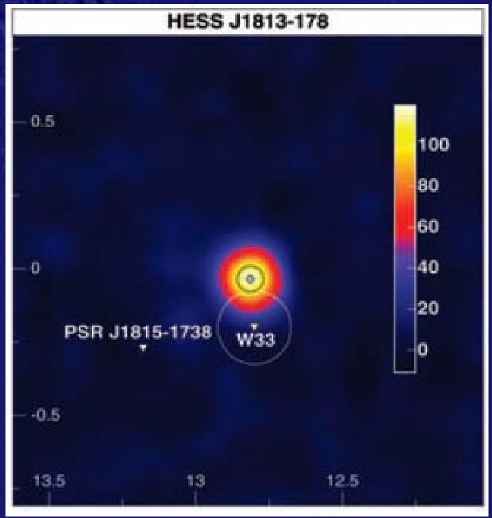
Cassiopeia A

microquasar



young open cluster

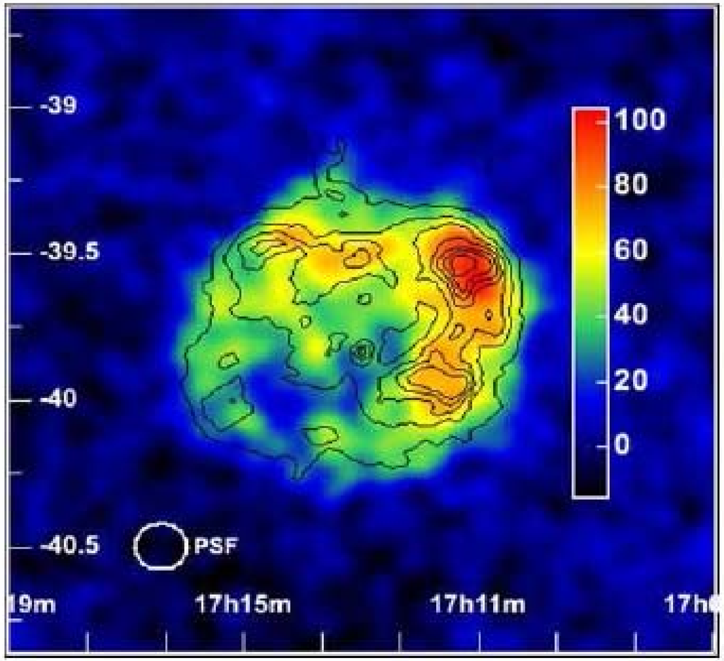


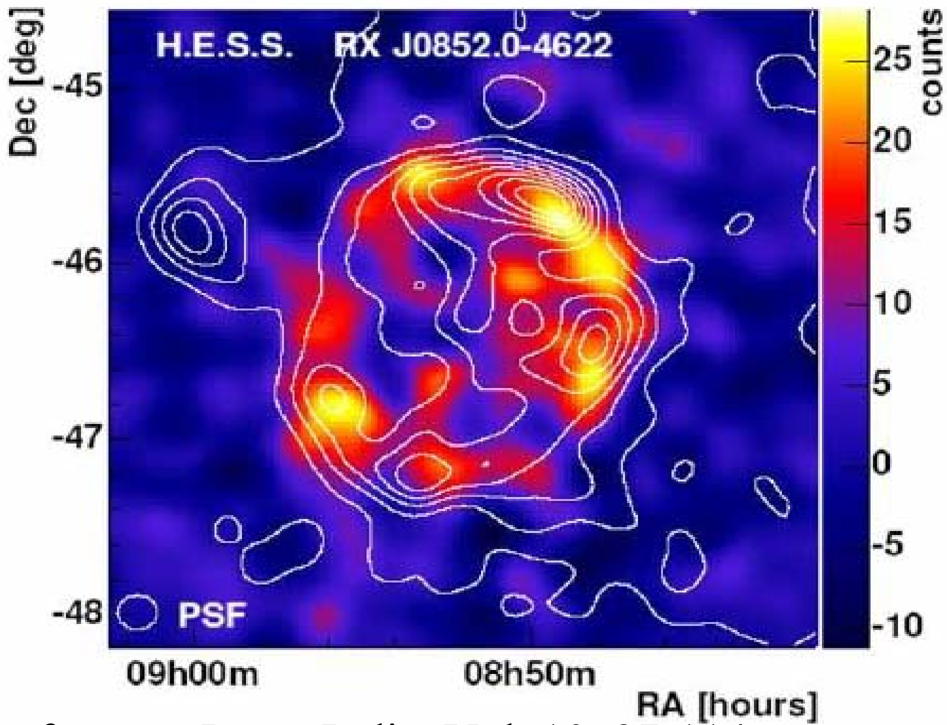


HEGRA and HESS found "dark accelerators": new class of TeV emitters? Sources of CR?

Where are the accelerators of galactic CR ?

With H.E.S.S. very detailed analyses of supernova remnants:





W. Hofmann, Proc. 29 Int. Cosmic Ray Conference, Pune, India, Vol. 10, 97-114

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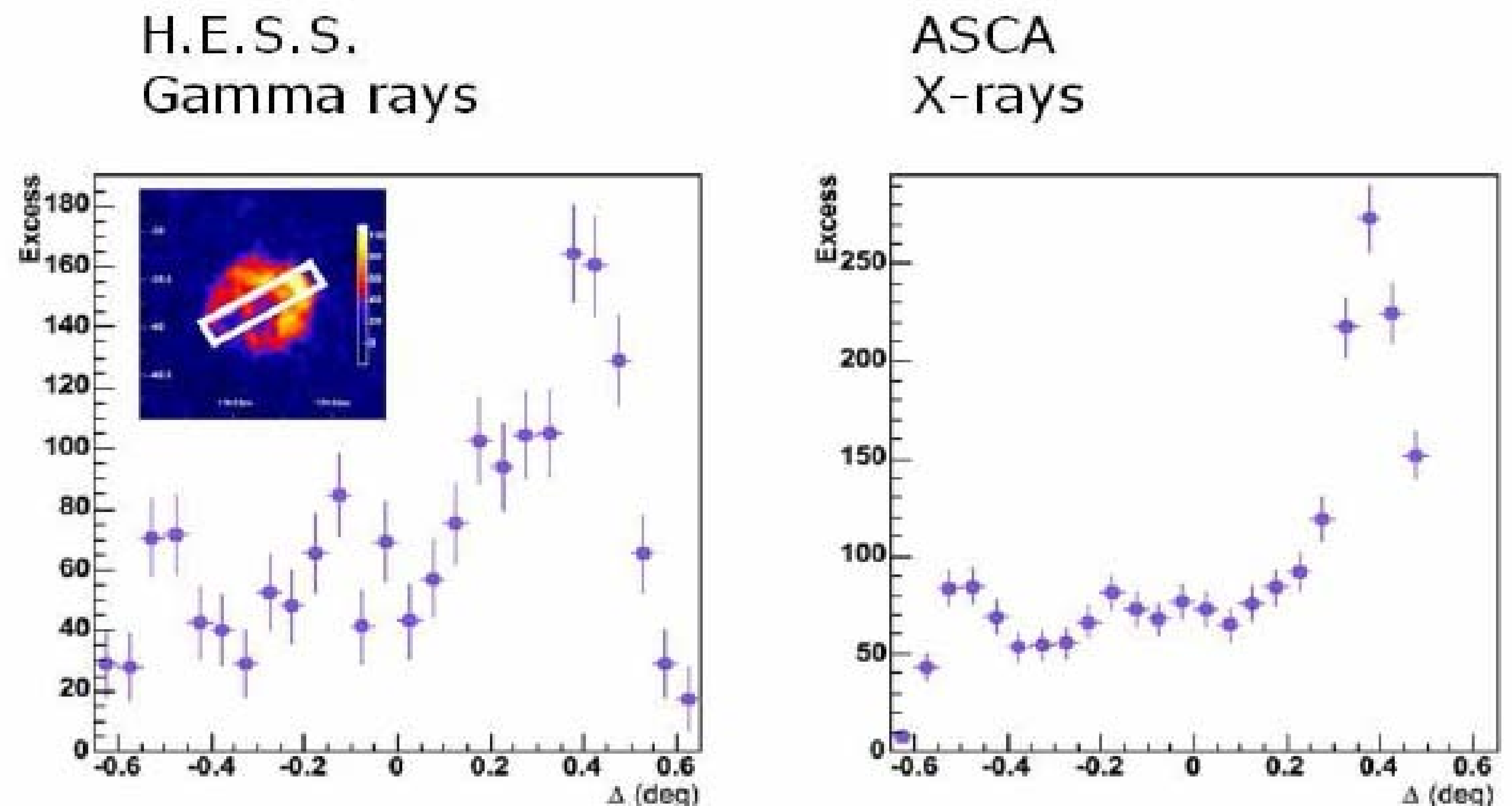
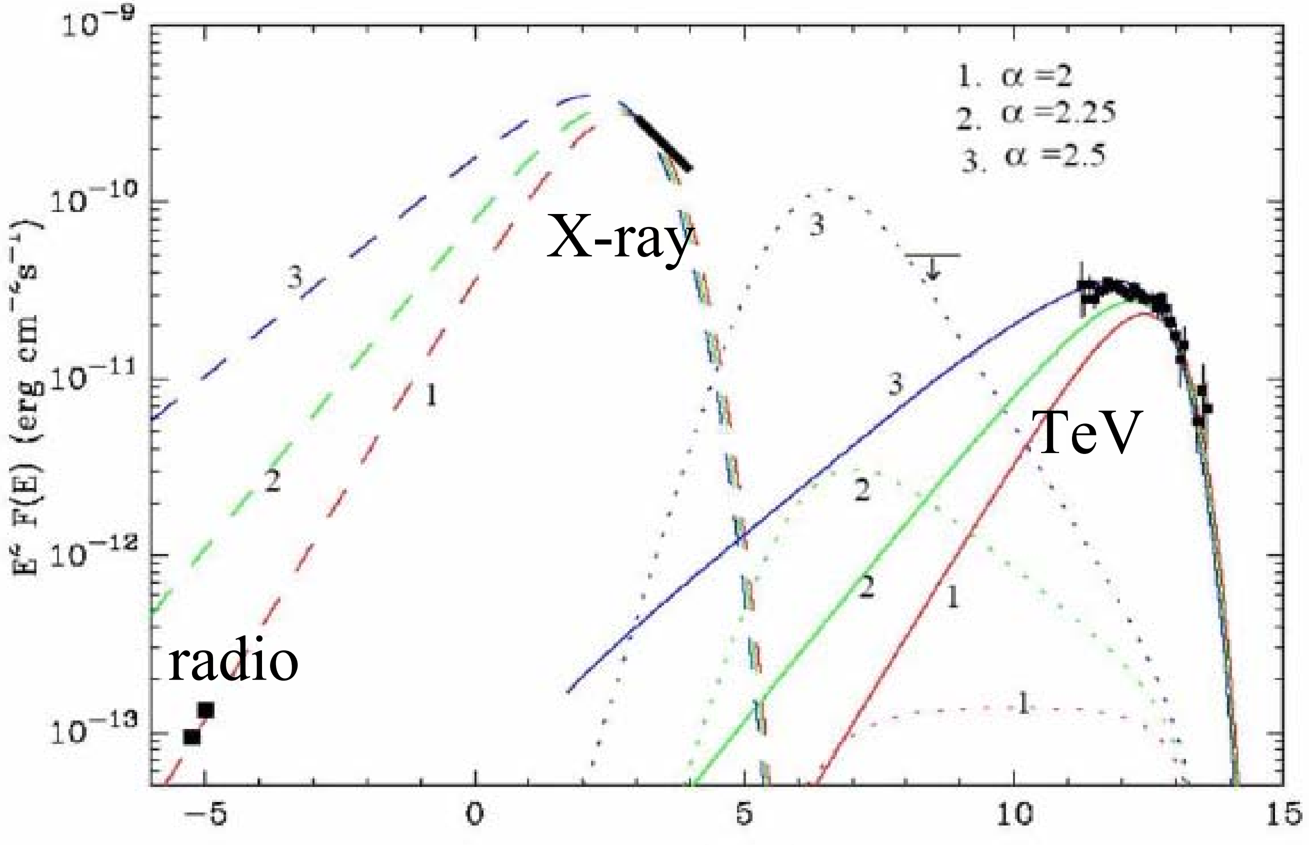


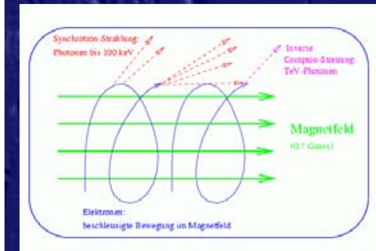
W. Hofmann, Proc. 29 Int. Cosmic Ray Conference, Pune, India, Vol. 10, 97-114

Where are the accelerators of galactic CR ?

Multiwavelengths observation:

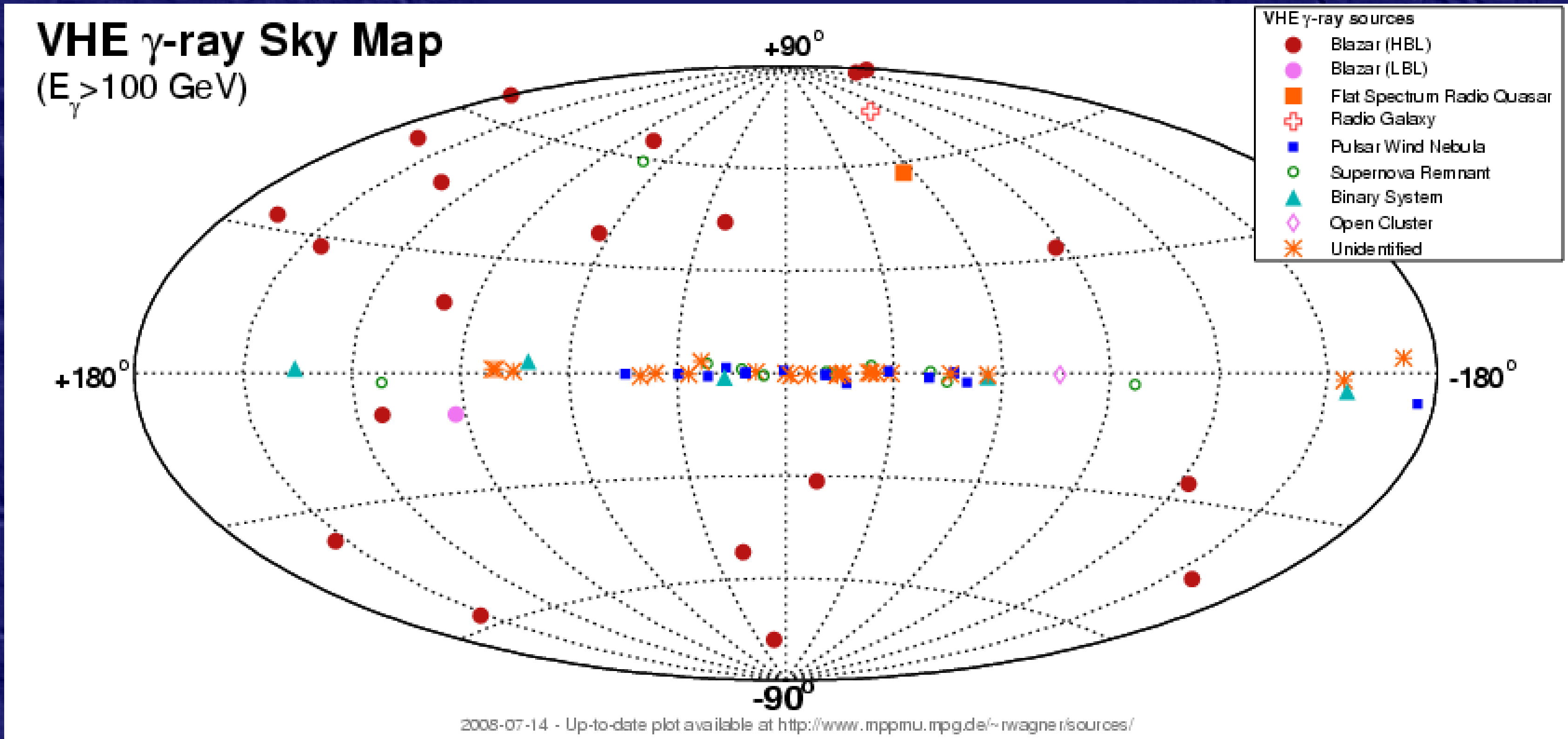


W. Hofmann, Proc. 29 Int. Cosmic Ray Conference, Pune, India



SSC models fail to describe the data:
hint to acceleration of CR (nuclei)?

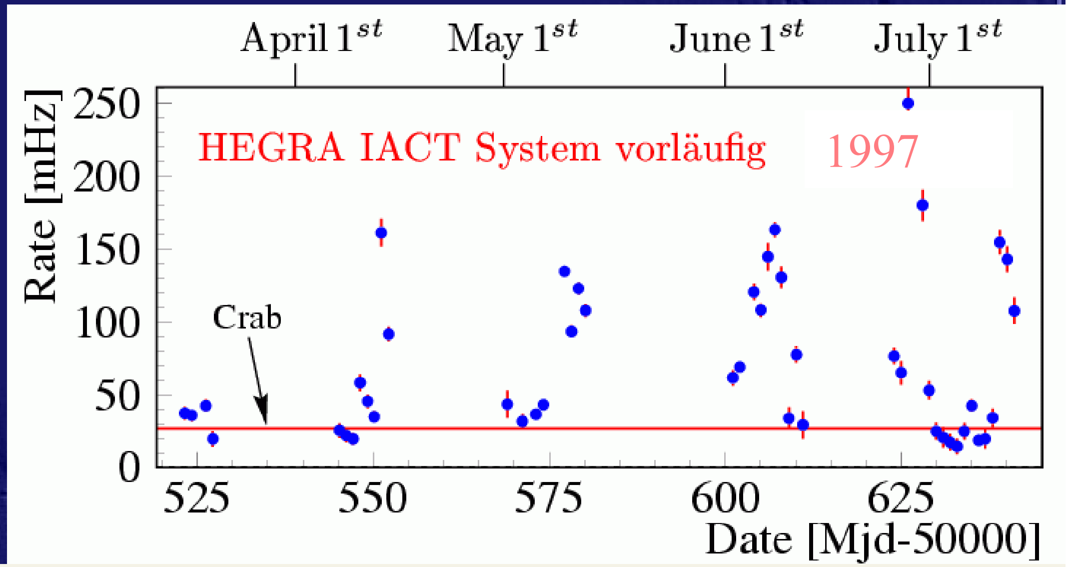
Surprise: TeV Photons from distant Galaxies

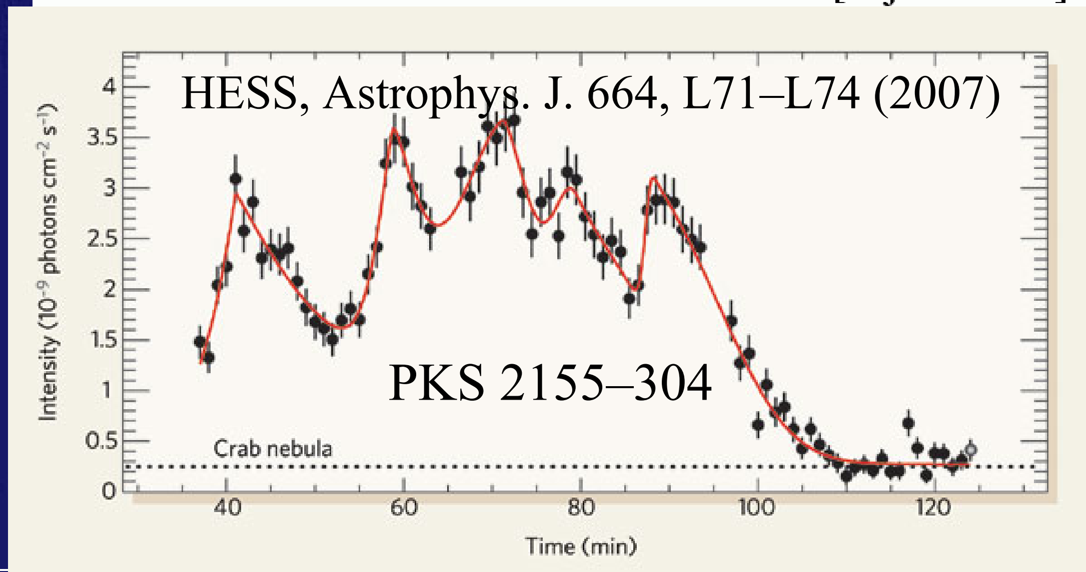


Surprise: TeV Photons from distant Galaxies

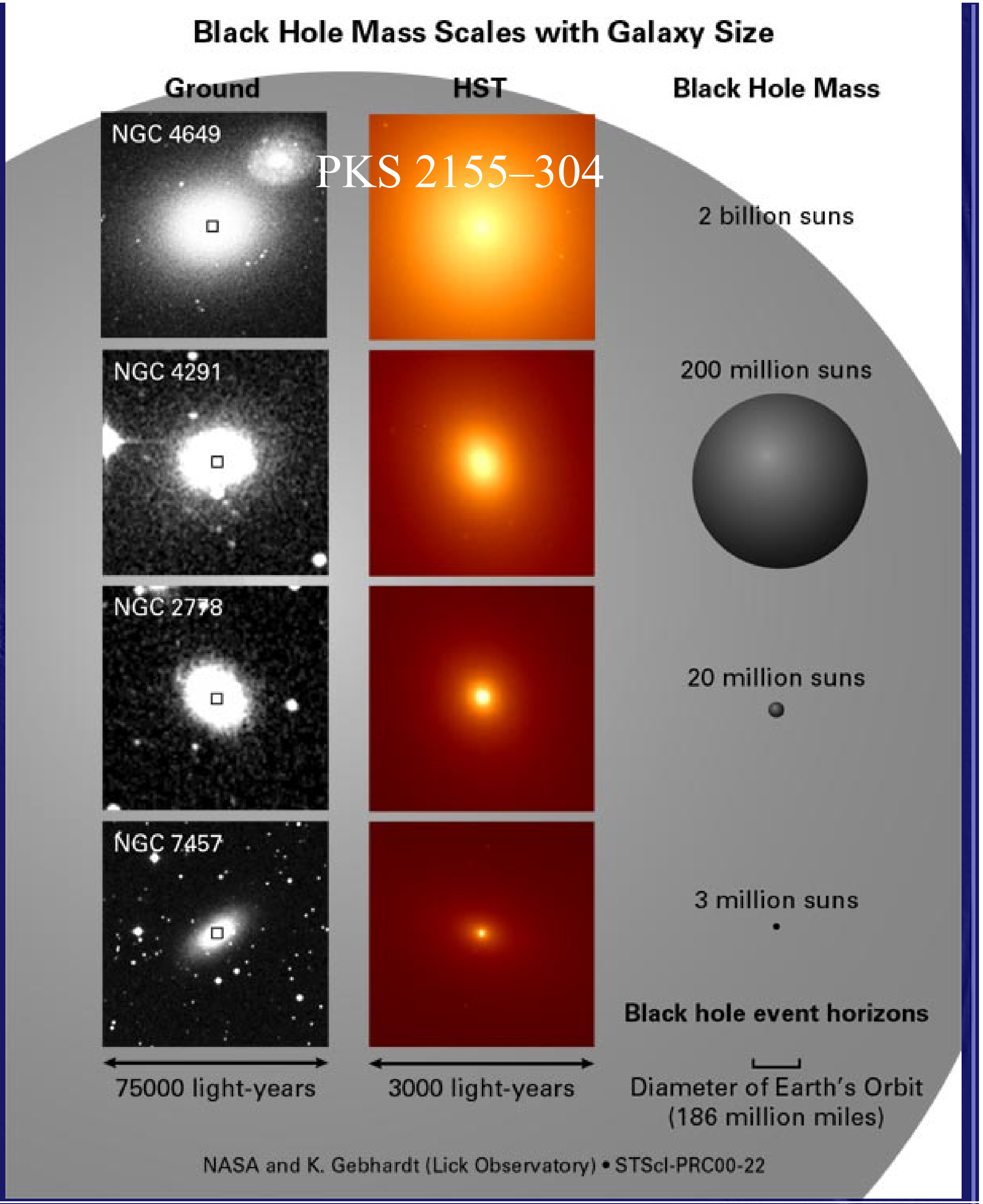
Extragalactic sources:

- Very large intensity fluctuations, sometimes brightest sources in the TeV-sky
- TeV intensity variations correlated with X-ray measurements
- All sources are galaxies containing an active galactic nucleus (AGN)
- Reminder: AGNs are the likely sources of highest energy CR!

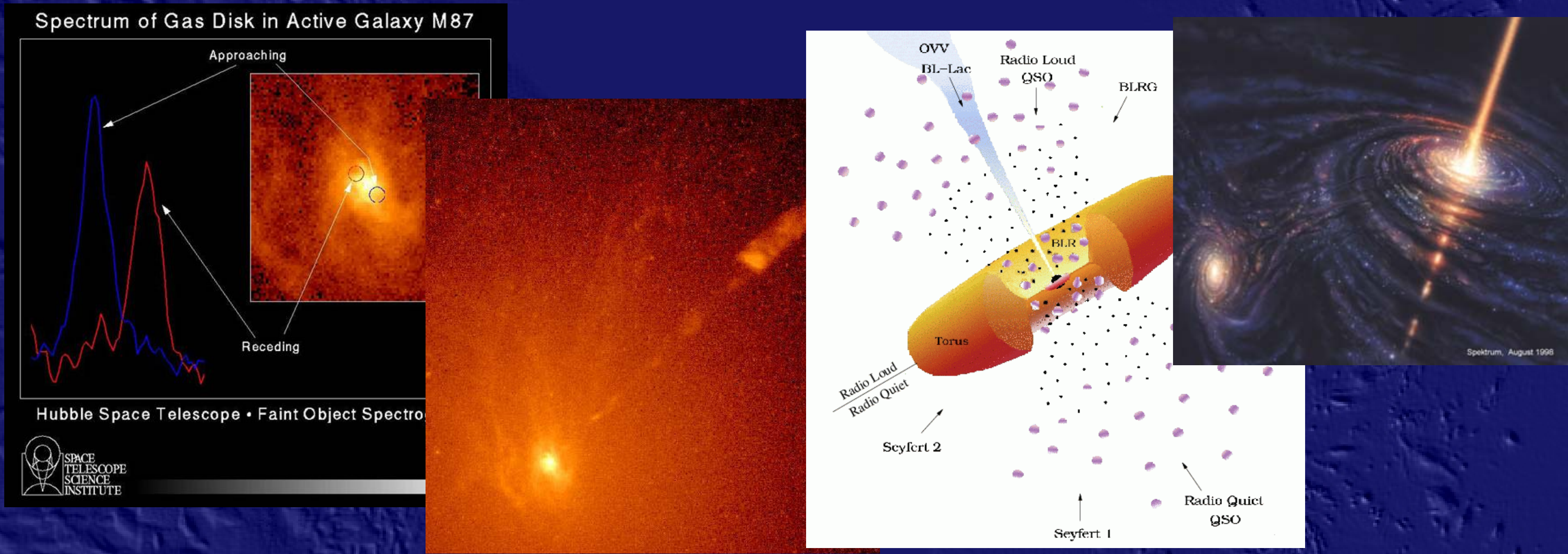




Active Galactic Nuclei (AGN)

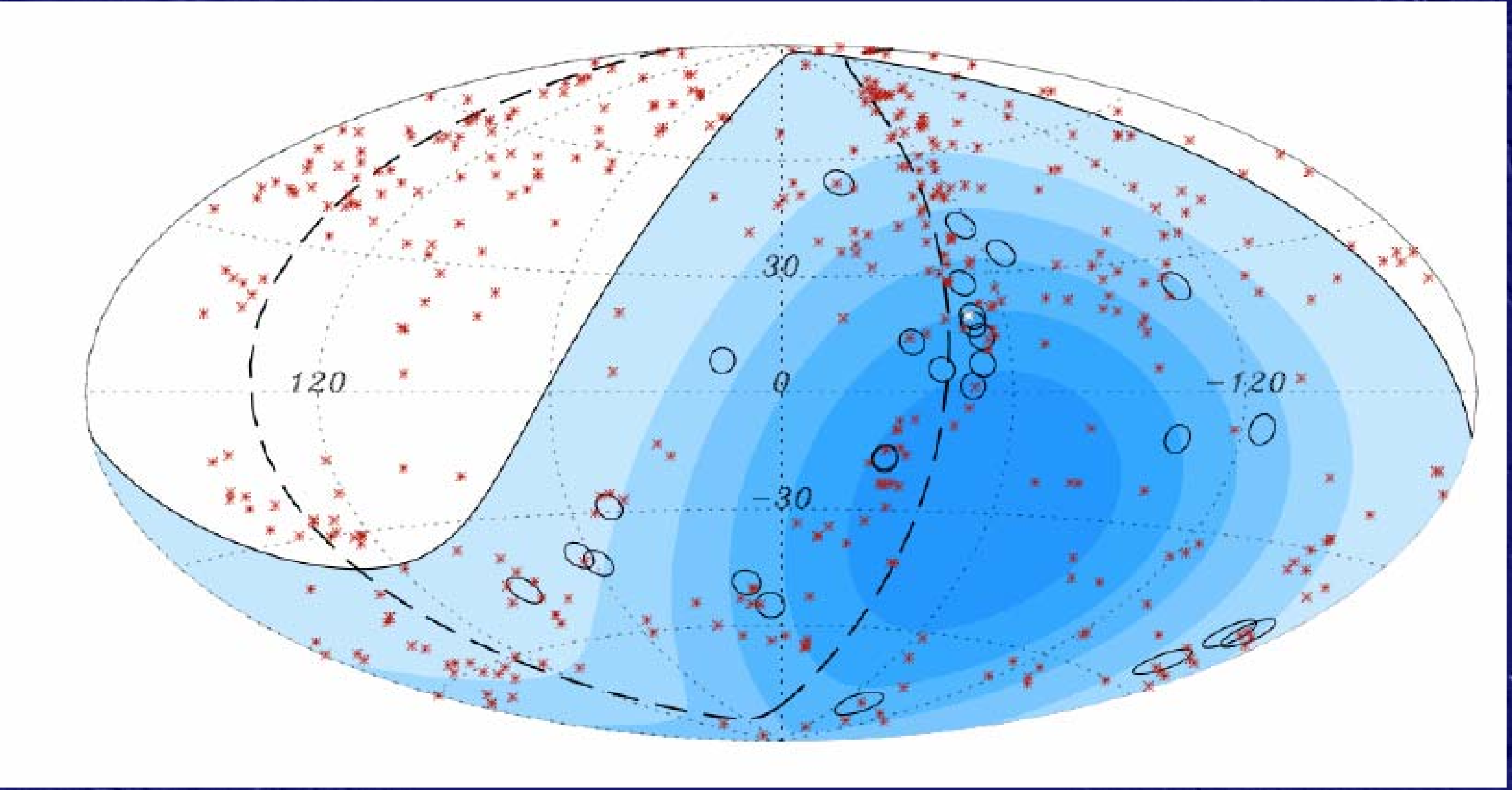


Active Galactic Nuclei (AGN)



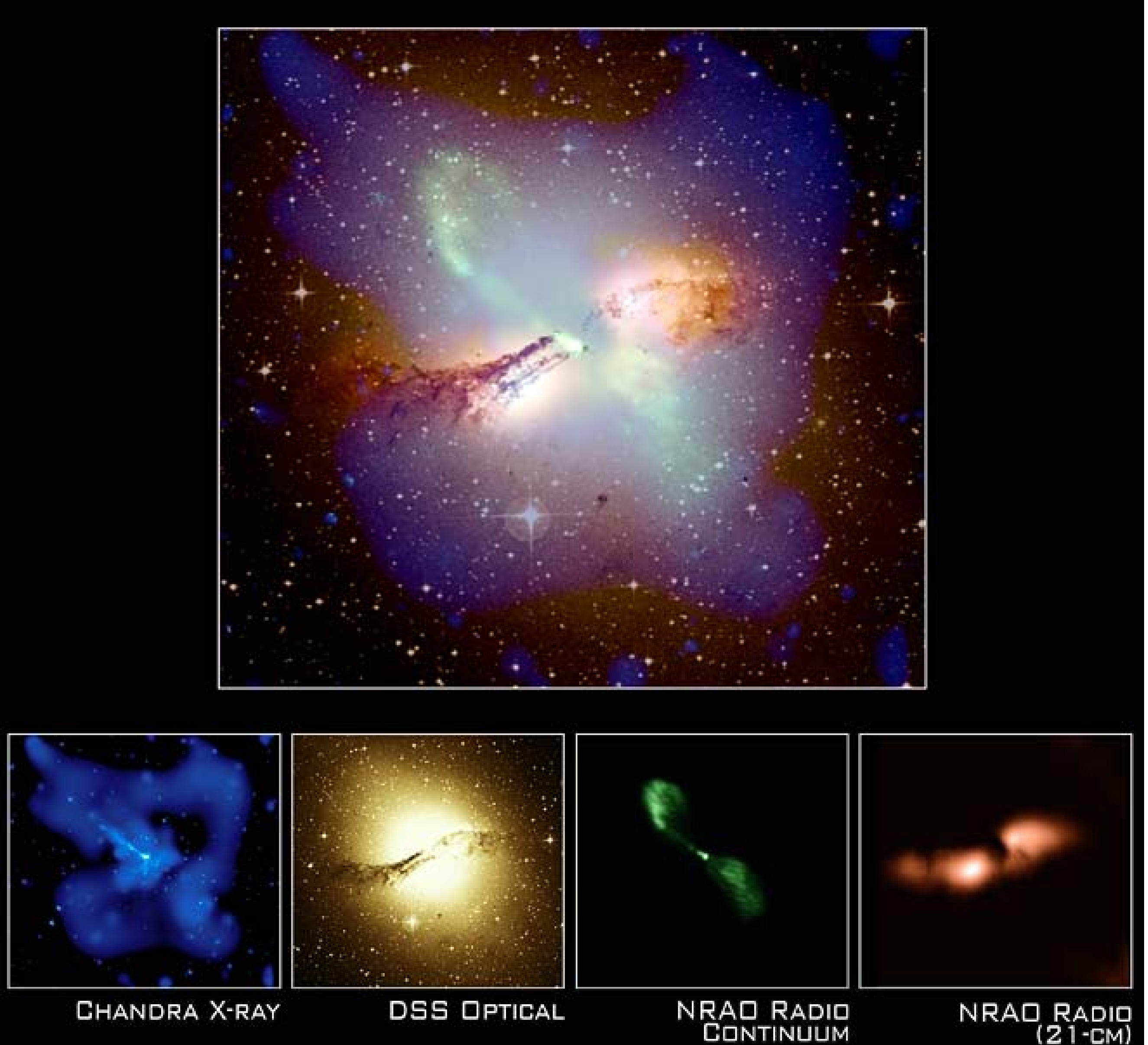
- Centre of AGNs: black hole with up to 10^{10} solar masses
- Gravitational energy: accretion of matter
  ↳ relativistic jets on rotation axis
- If jet points toward observer
  ↳ TeV photons

Centaurus A (closest AGN)

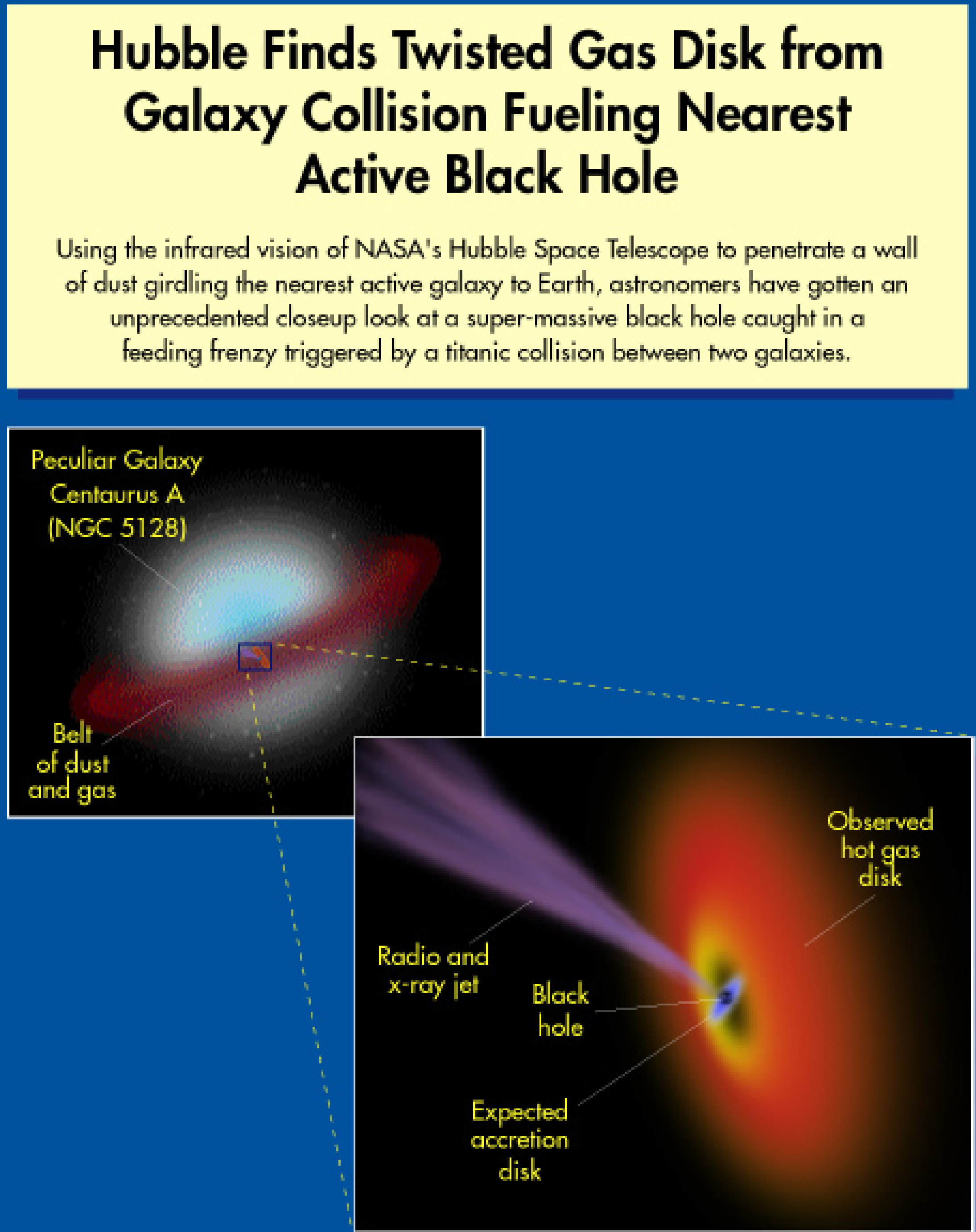


Centaurus A (closest AGN)

http://chandra.harvard.edu/press/02_releases/press_080702.html/

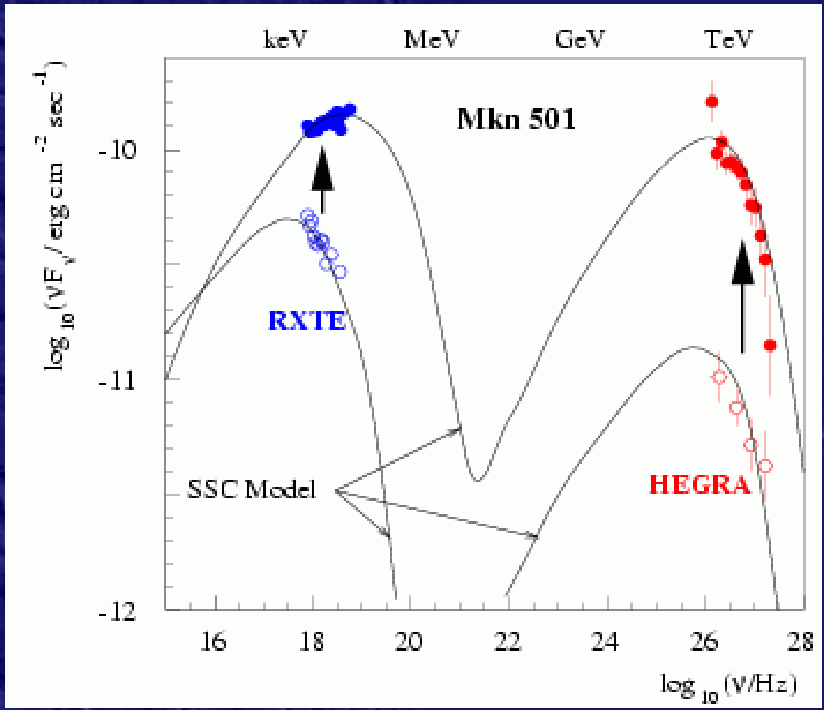


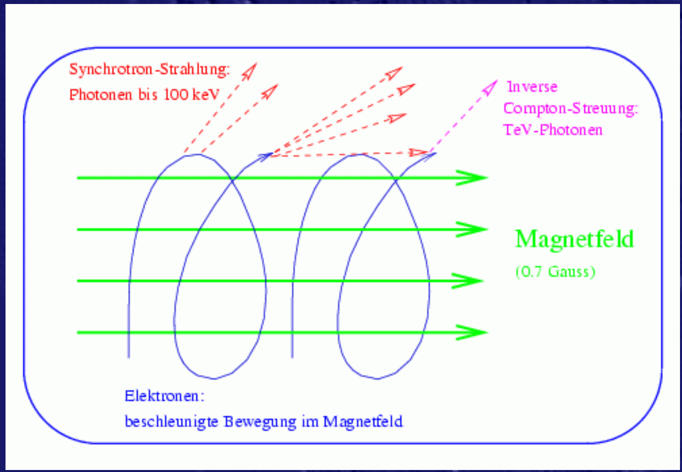
http://www.spacetelescope.org/images/html/opo9814p.html



Which particles are accelerated in AGNs?

Observation: tight correlation between X-ray and TeV emission of AGNs

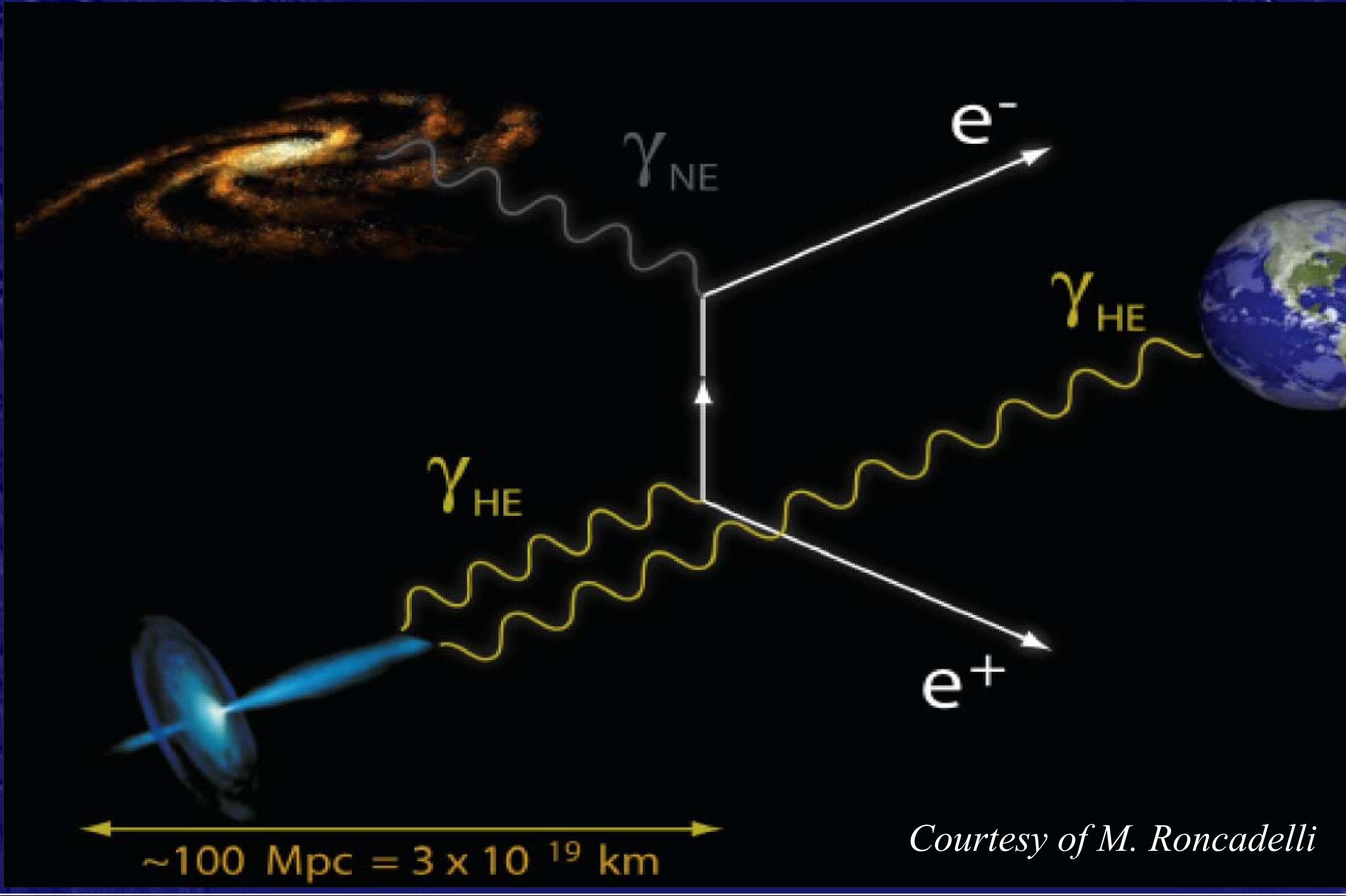




AGNs may accelerate electrons!

Do they also accelerate nuclei (protons)?

Absorption of TeV Photons in the Universe

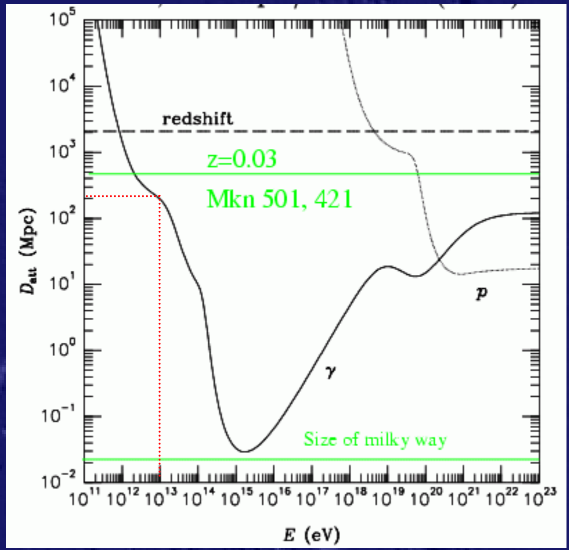


Courtesy of M. Roncadelli

Probing intergalactic Radiation Fields

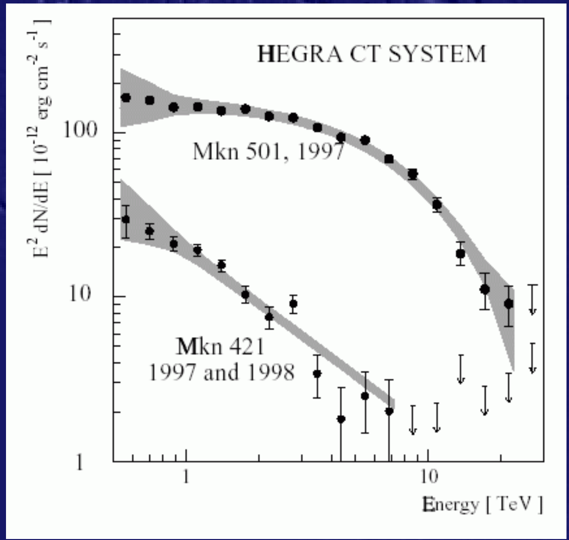
The universe is not transparent to high energy photons:

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



Analysis of photons around 10 TeV:

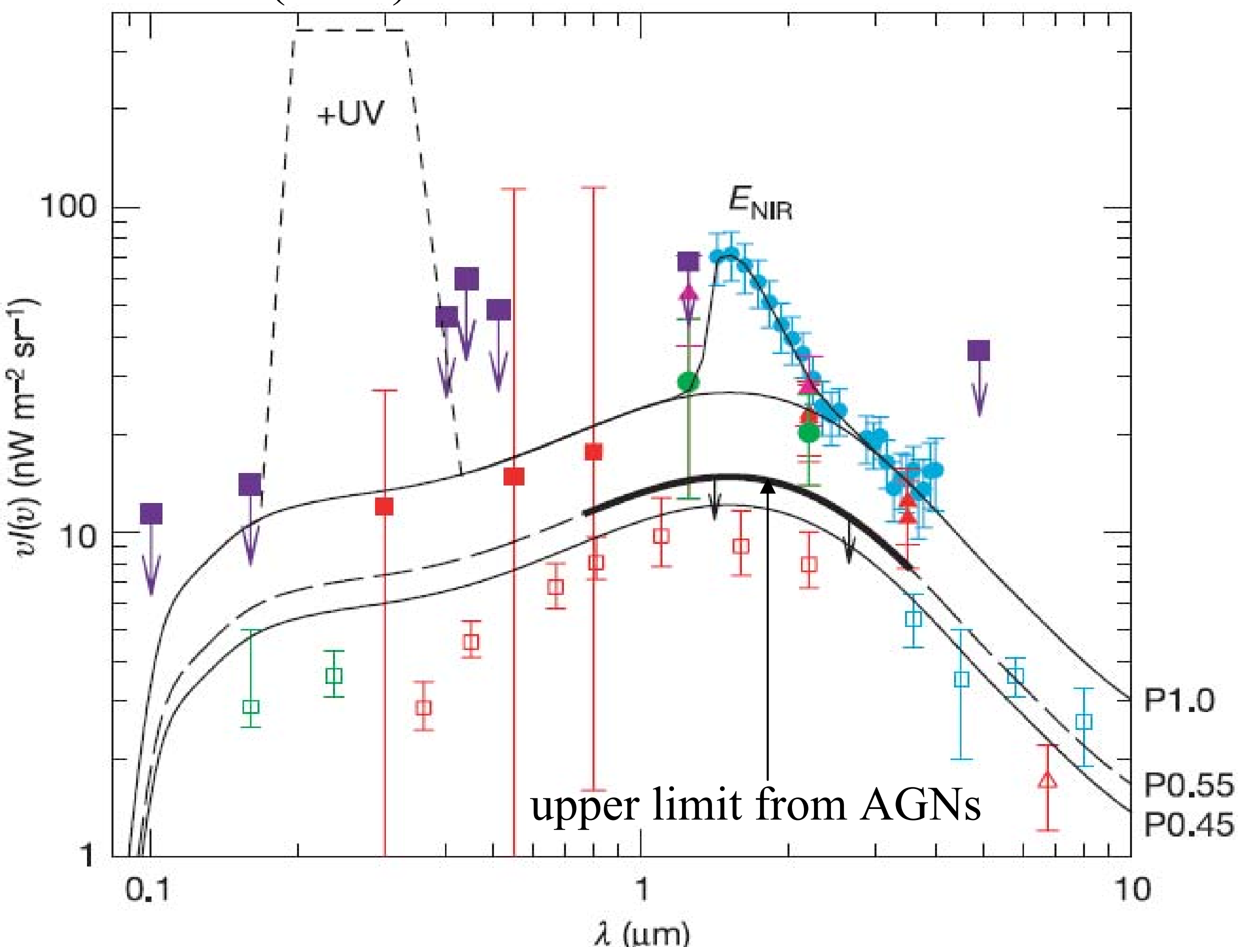
- Information on intergalactic radiation
  ⇨ history of star formation
- Does Lorentz invariance hold?



Need data from many AGNs at different distances (redshifts)!

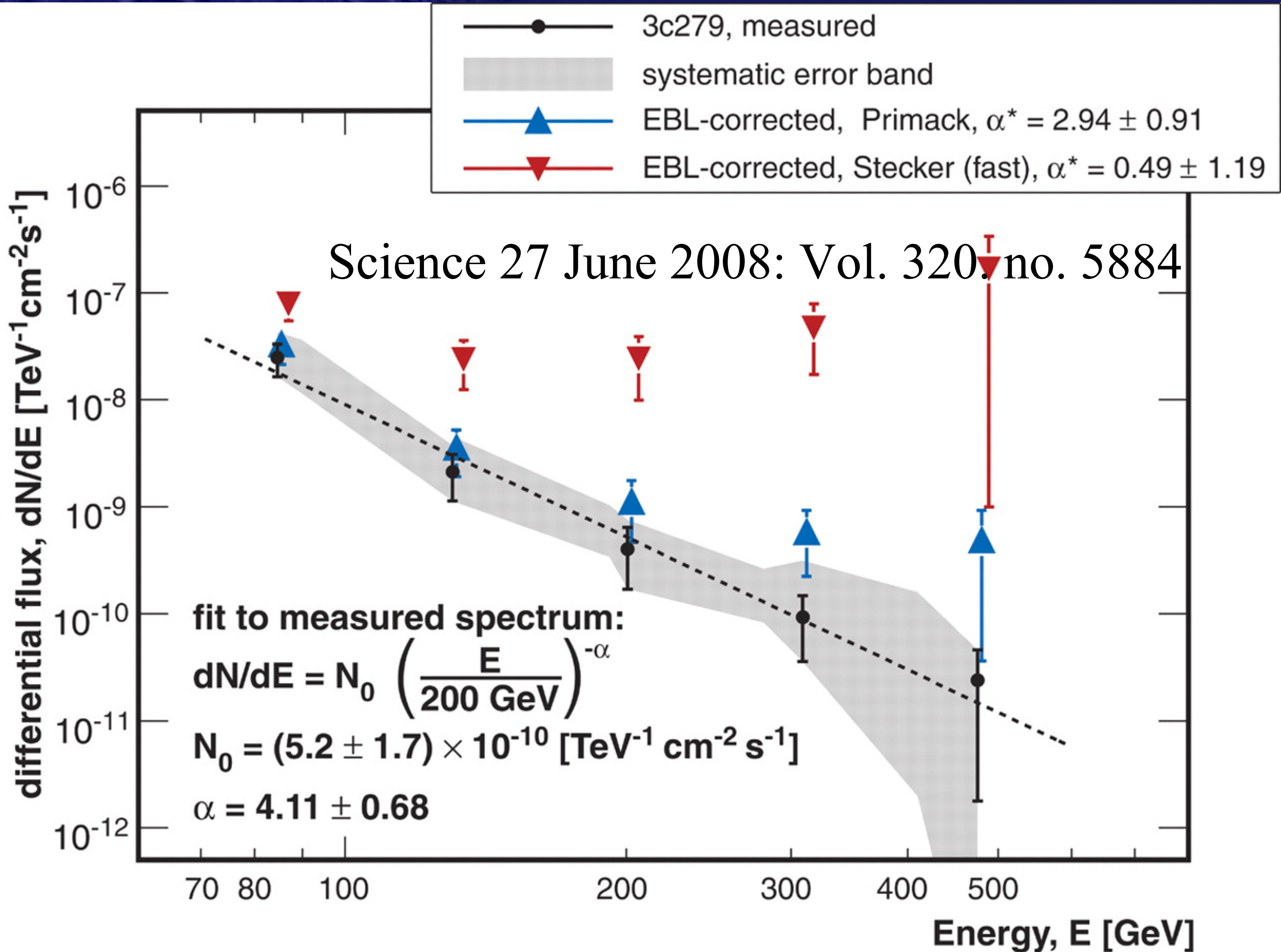
H.E.S.S.: 1ES 101-232 (z=0.186)

Nature 440 (2006)



- Exclude many very massive early stars
- However: are the intrinsic features of AGNs sufficiently well known ?

MAGIC: 3C 279 (z=0.536)

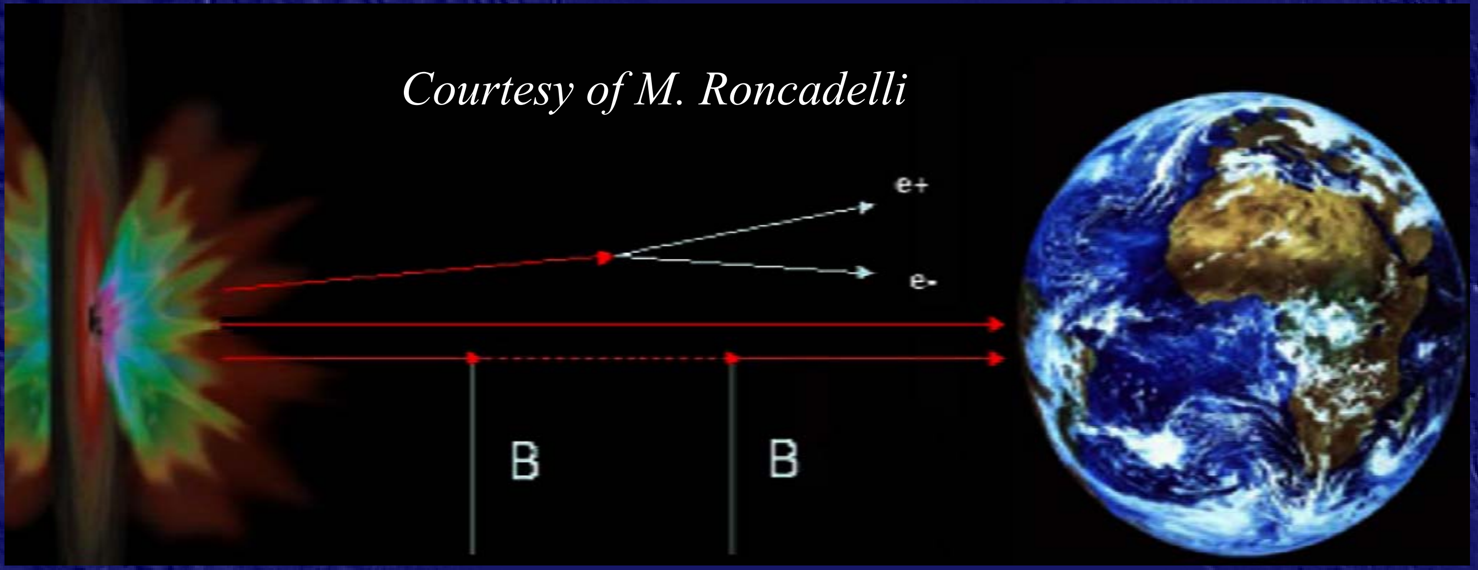


Science 27 June 2008: Vol. 320. no. 5884

- Exclude many very massive early stars
- However: are the intrinsic features of AGNs sufficiently well known ?

A Hint to new Kinds of Particles?

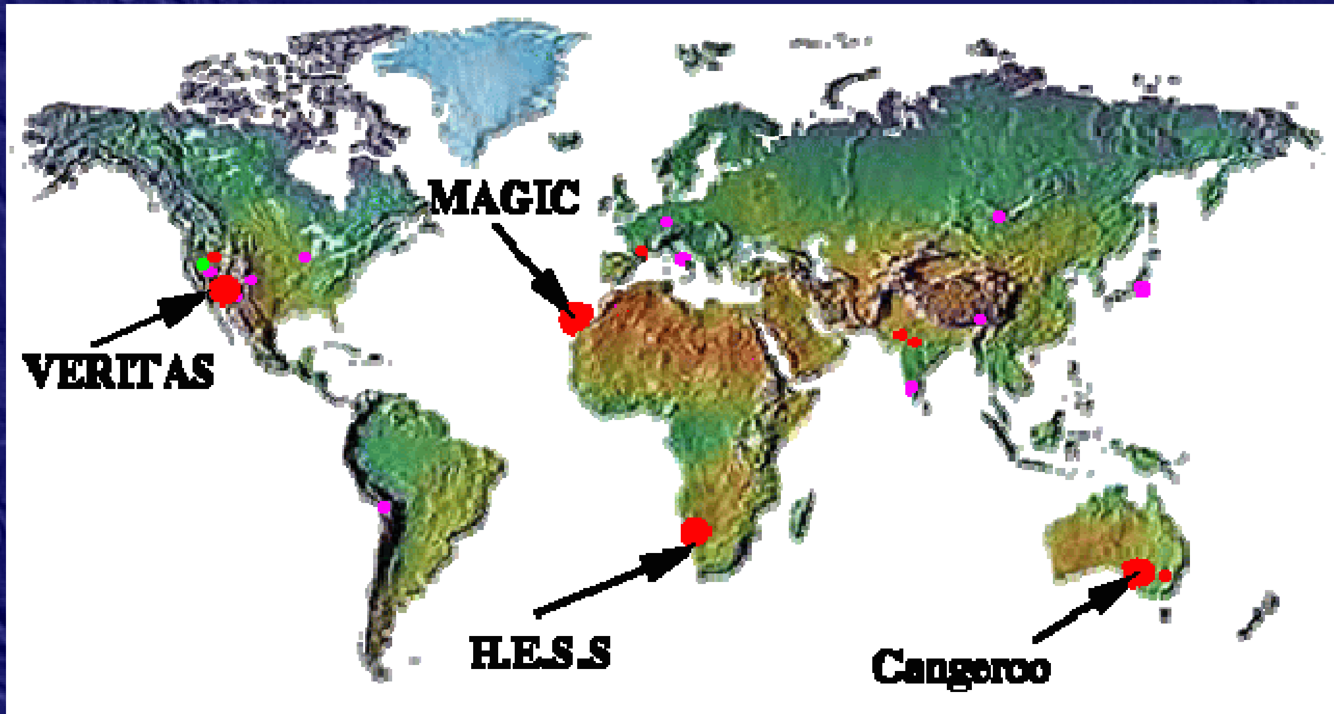
Photons may escape absorption by converting into hypothetical axion-like particles which later convert back into photons.



Simet et al., PhysRevD.77.063001 (2008)

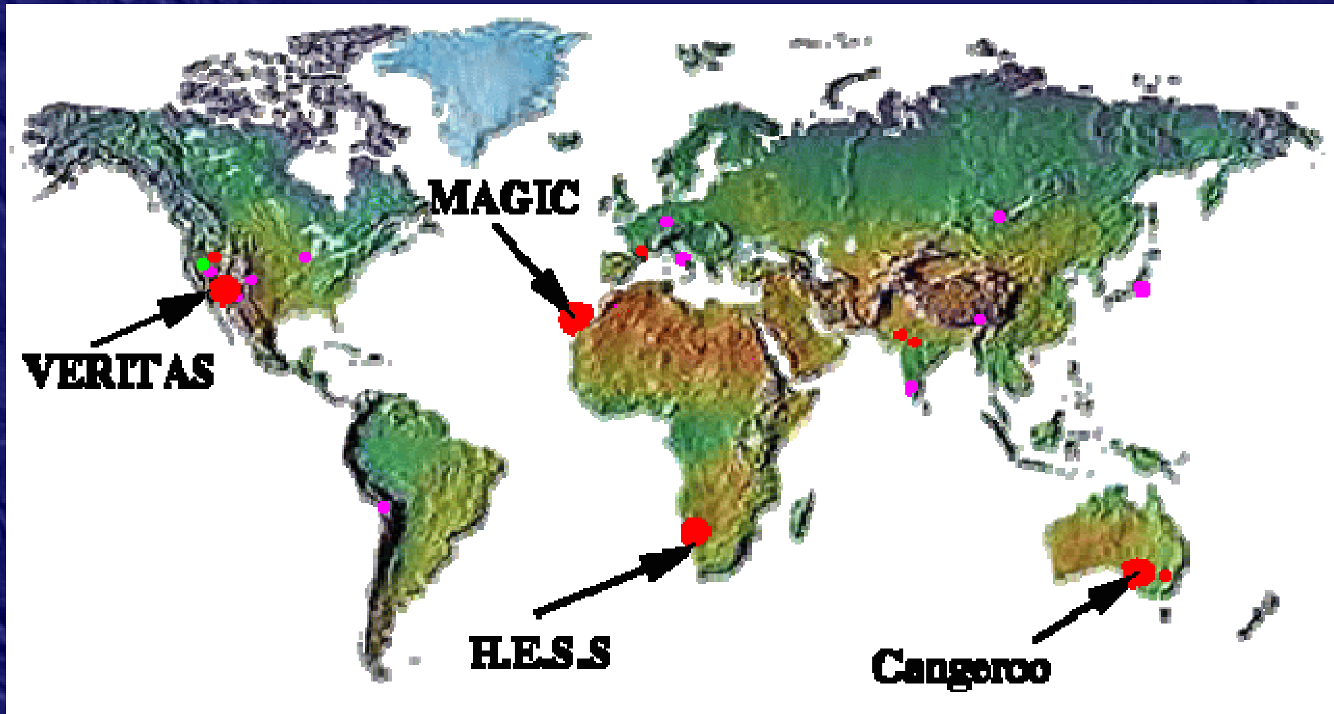
De Angelis et al., arXiv:0807.4246 (astro-ph, 2008)

A new Branch of Astronomy



- Discover galactic sources of CR
- Understand AGNs and intergalactic fields
- Search for photons from annihilation of Dark Matter
- More surprises?

A new Branch of Astronomy



HESS: http://www.mpi-hd.mpg.de/hfm/HESS/
MAGIC: http://wwwmagic.mppmu.mpg.de/
VERITAS: http://veritas.sao.arizona.edu/
CANGAROO: http://icrhp9.icrr.u-tokyo.ac.jp/index.html

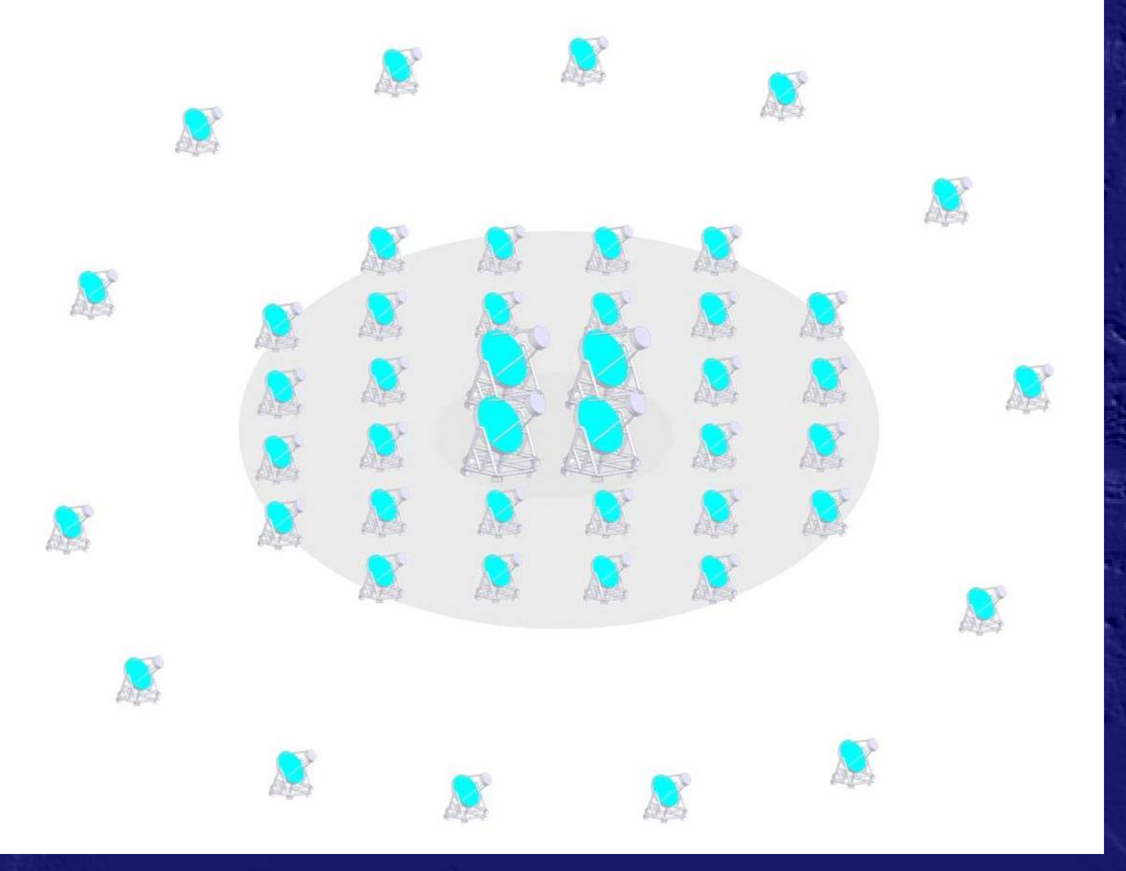
The future 2nd Phase of H.E.S:S.

Add IACT with 600 m^2 mirror (40 m high!)
to existing IACTs with 108 m^2 mirror.

http://www.mpi-hd.mpg.de/hfm/HESS/

The future Cherenkov Telescope Array

Presently under study: telescope array including 30m dishes



http://www.mpi-hd.mpg.de/hfm/CTA/CTA_home.html

A future new Branch: Neutrino Astronomy?

Advantage:

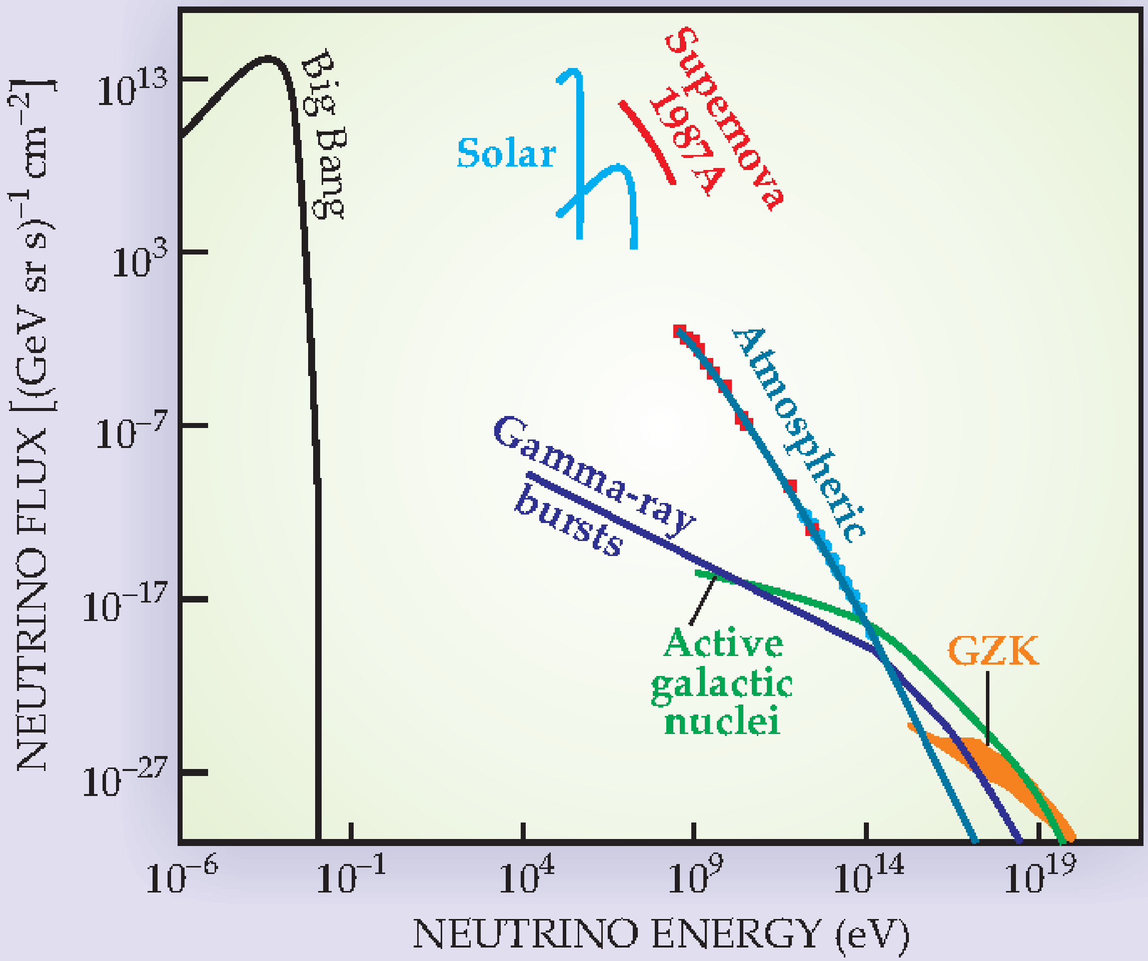
- Neutrinos travel on straight lines like photons
- Neutrinos are produced in hadronic environments
- Neutrinos are hardly absorbed
  ↳ direct look into the cosmic engines!

Disadvantage:

- Neutrinos are hardly absorbed
  ↳ very large detectors necessary

http://amanda.uci.edu/
http://icecube.wisc.edu/
http://antares.in2p3.fr/

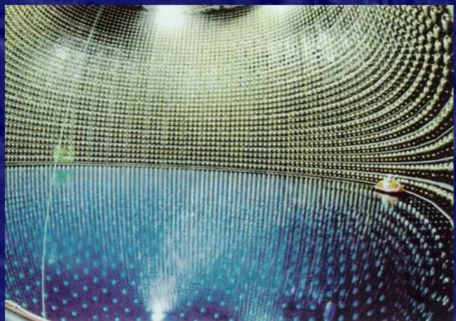
The expected Neutrino Spectrum



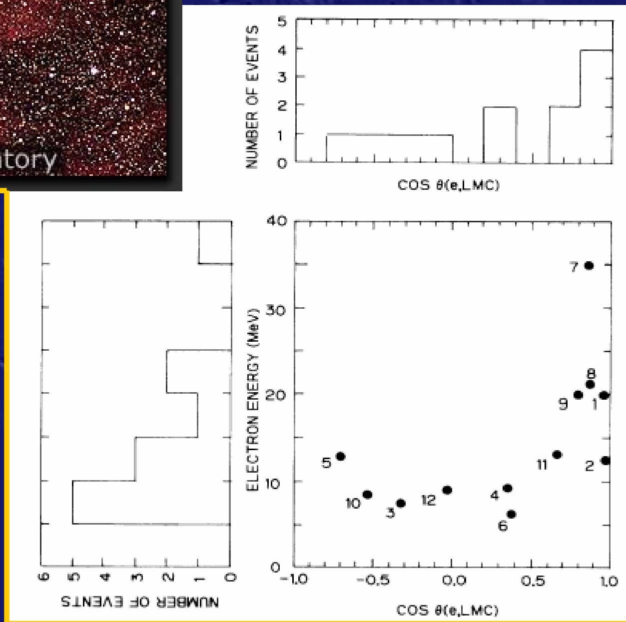
http://www.lbl.gov/today/2008/Jun/06-Fri/PTNuAstronomy.pdf

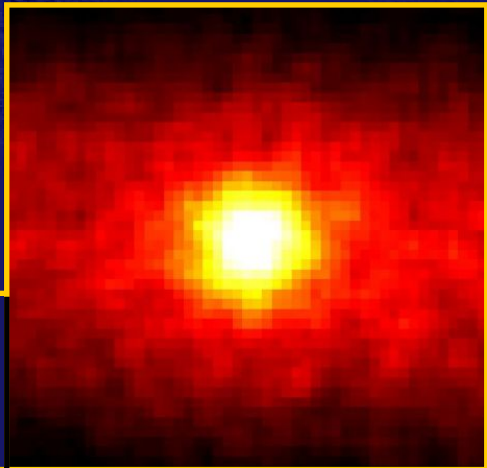
Two sources in the neutrino sky

Super Kamiokande Experiment: 50,000 t of water watched by photomultipliers



Neutrinos from SN1987A
(with Kamiokande, 2000 t of water)

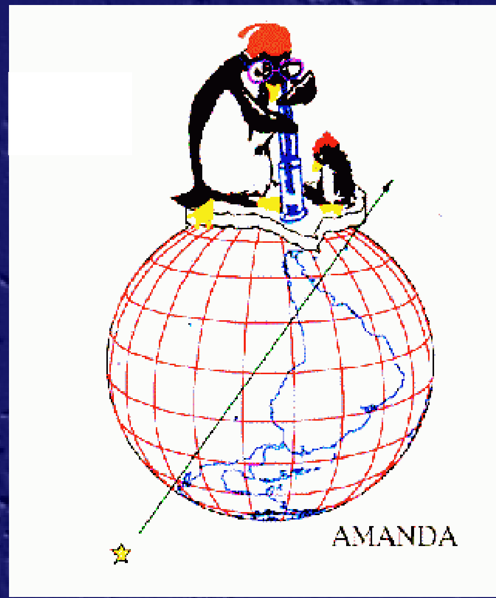


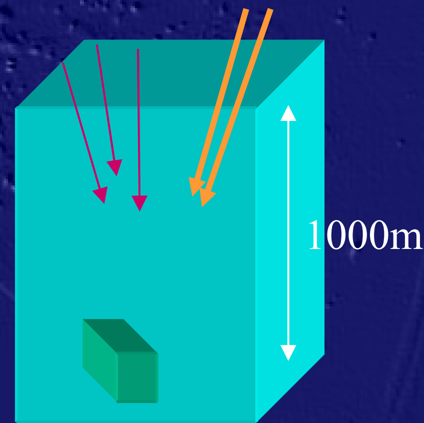


Neutrinos from the sun

Detector Basics to find more Sources

- Use the whole earth as a shielding (background mainly from interactions of CRs in the atmosphere, also υ!)
- Search for "upward" going muons from υ-interactions close to the detector
  Detect muons by their Cherenkv light emission
- Install detectors at depths of about 1000m to shield from "downward" going CRs
- Build detectors of several 10 M tons
  ➯ Install detector elements in natural water, ice at the south pole





Performance and Physics

- Neutrino Energy > 50 GeV
- Angular resolution < 10°

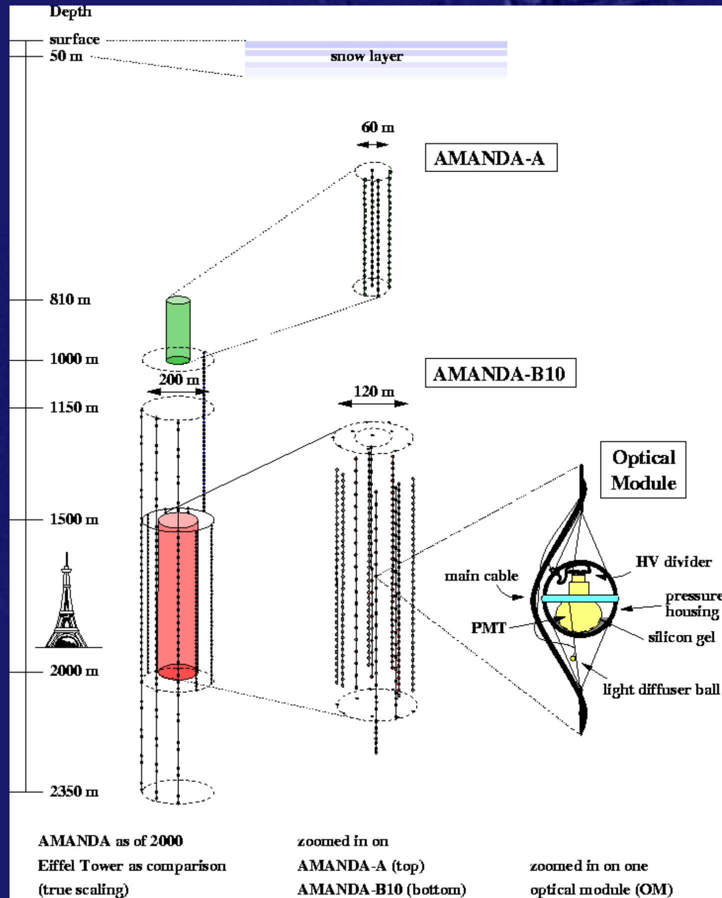
Physics Questions:

- Galactic Supernovae
- Gamma Ray Bursts
- Active Galactic Nuclei
- Dark Matter Annihilation
- Topological defects
- Surprises?

The AMANDA Experiment

Uses Antarctic ice shield as the detector

- Drill holes with hot water and deploy optical modules (to detect Cherenkov light)
- Since 2000: 700 modules
- **Extension to ICECUBE with 8000 optical modules (ready 2012)**



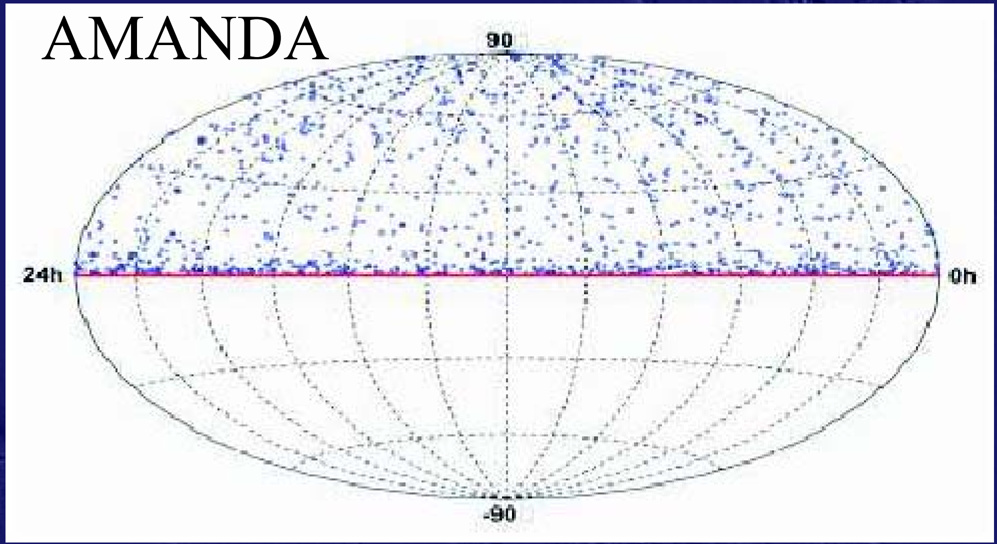
With participation of DESY

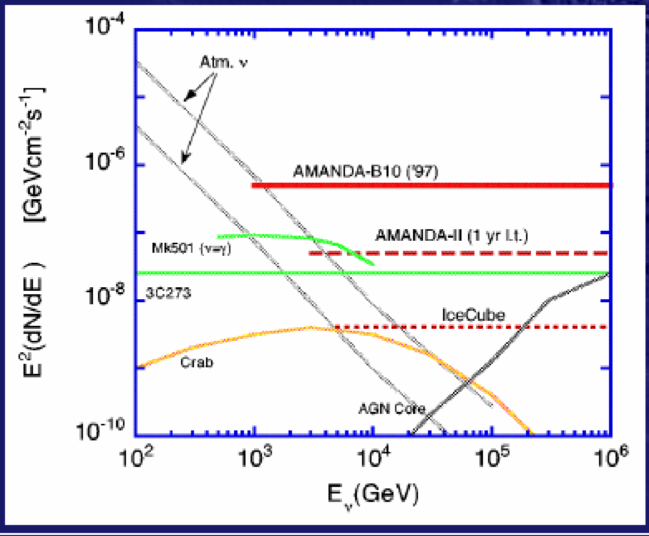
AMANDA Neutrino Skymap

- No hints for sources
- Consistent with expected υ from CR interactions in the atmosphere
- Limit on υ from Dark Matter annihilation in the core of the earth

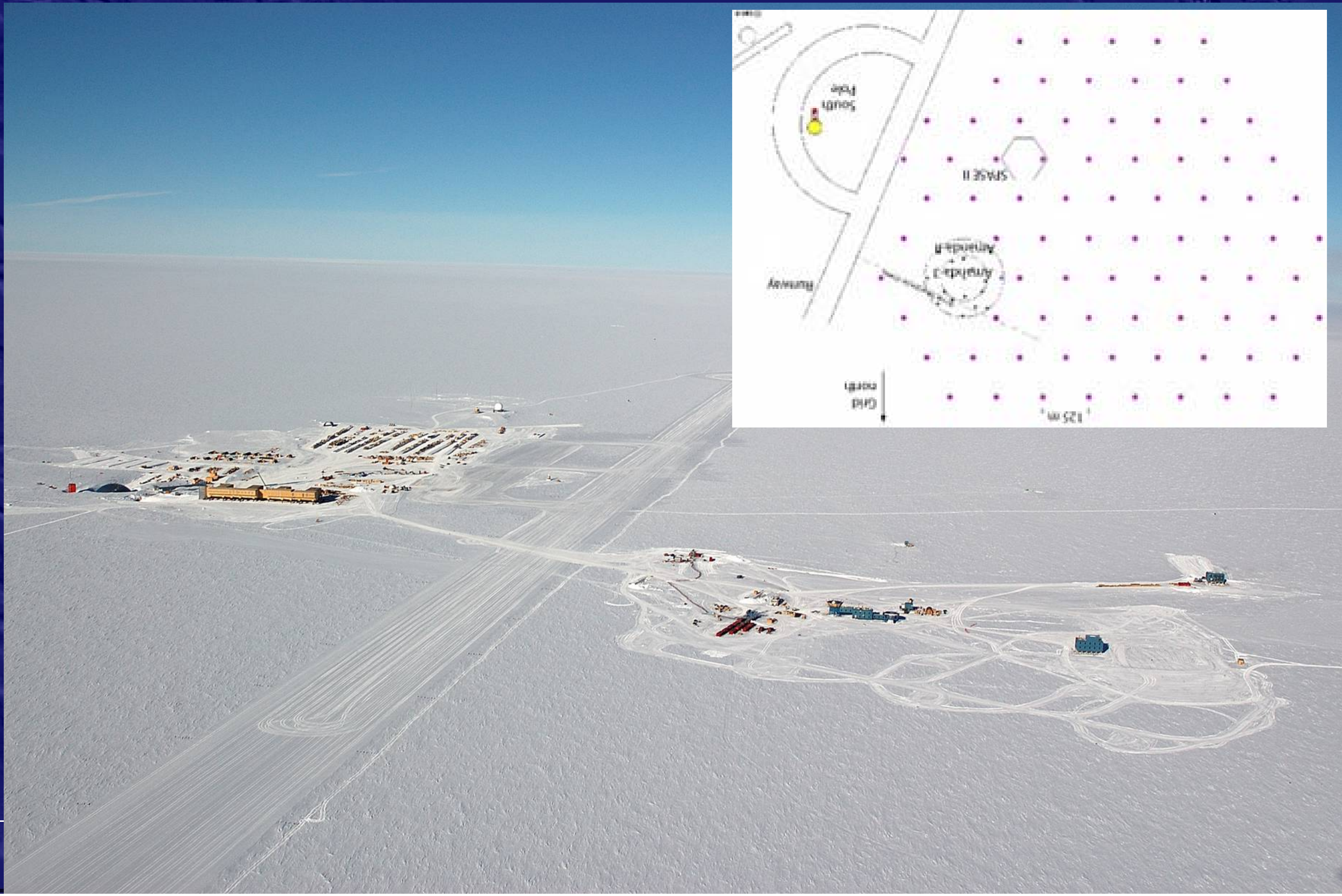
Successful proof of concept!

ICECUBE could see AGNs

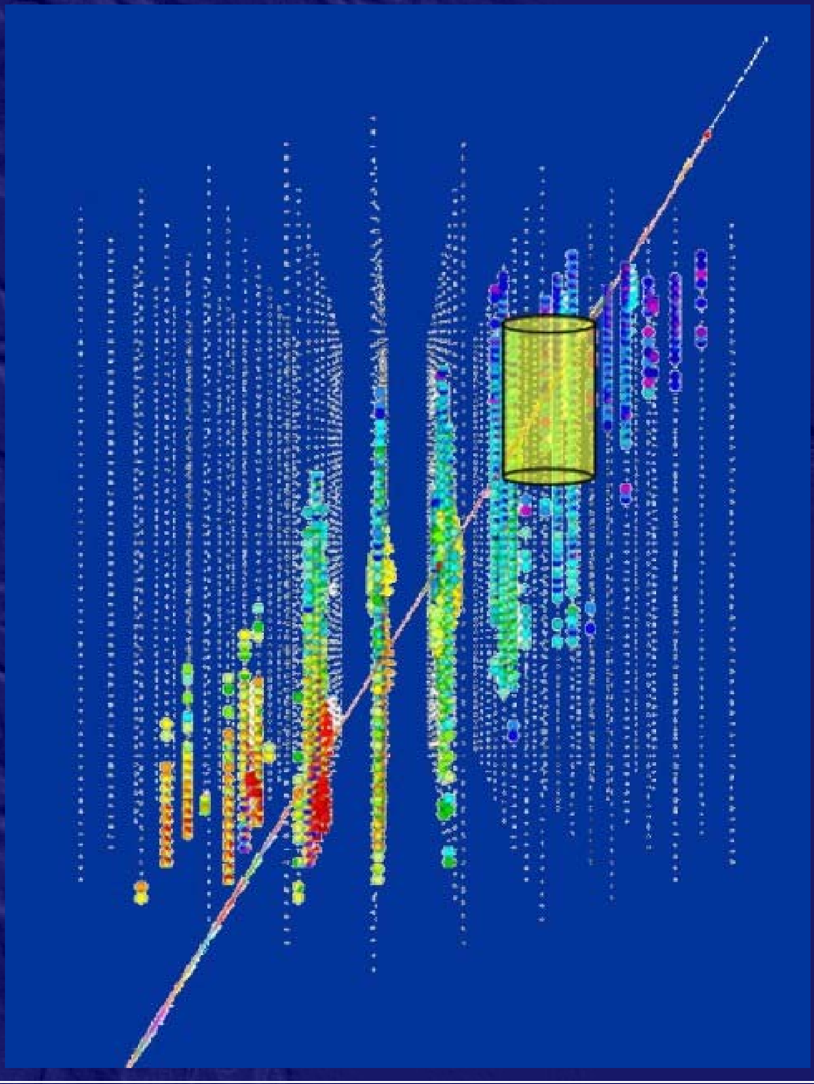




AMANDA and ICECUBE



AMANDA and ICECUBE



DESY in AMANDA/IceCube:

- optical modules
- data analysis
- data "hub" to universities
- R&D for future extensions

New astronomy: topics for discussion

- Why may the discovery of neutrino sources in the sky be crucial to solve the riddle of cosmic ray accelerators?
- Which effect limits the low energy threshold of the IACT technique?
- Why did hardly anyone expected 15 years ago to find TeV photon sources beyond our galaxy?
- How to understand the extremely small doubling times of TeV emission from AGNs?
- Can you imagine techniques to extend neutrino detectors far beyond the km^3 scale?

Summary on Cosmic Rays

from

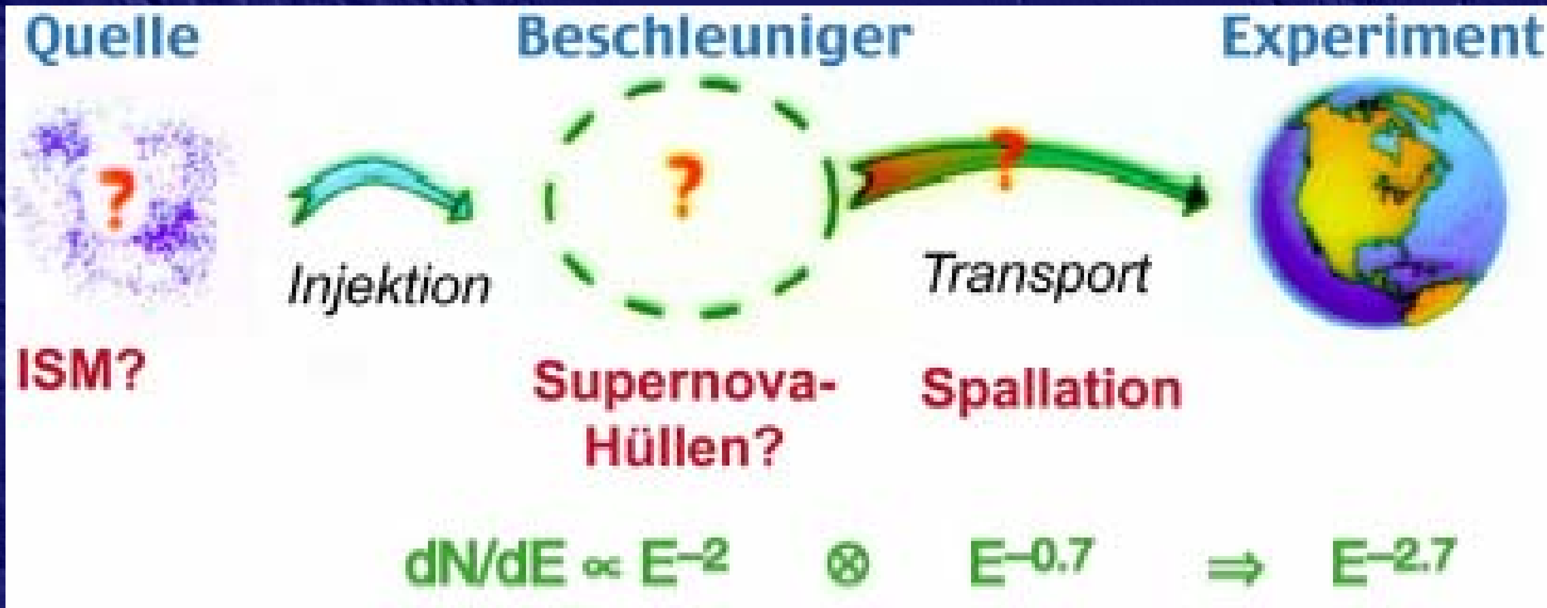
Measurements of Cosmic Rays (Nuclei)
and
TeV Astronomy

The origin of cosmic rays

Our model:

atomic nuclei are accelerated to highest energies at shock fronts.

Candidates for such accelerators (shock fronts):

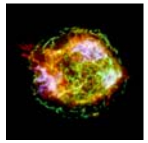
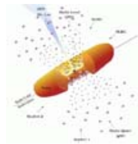
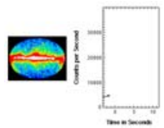


The origin of cosmic rays

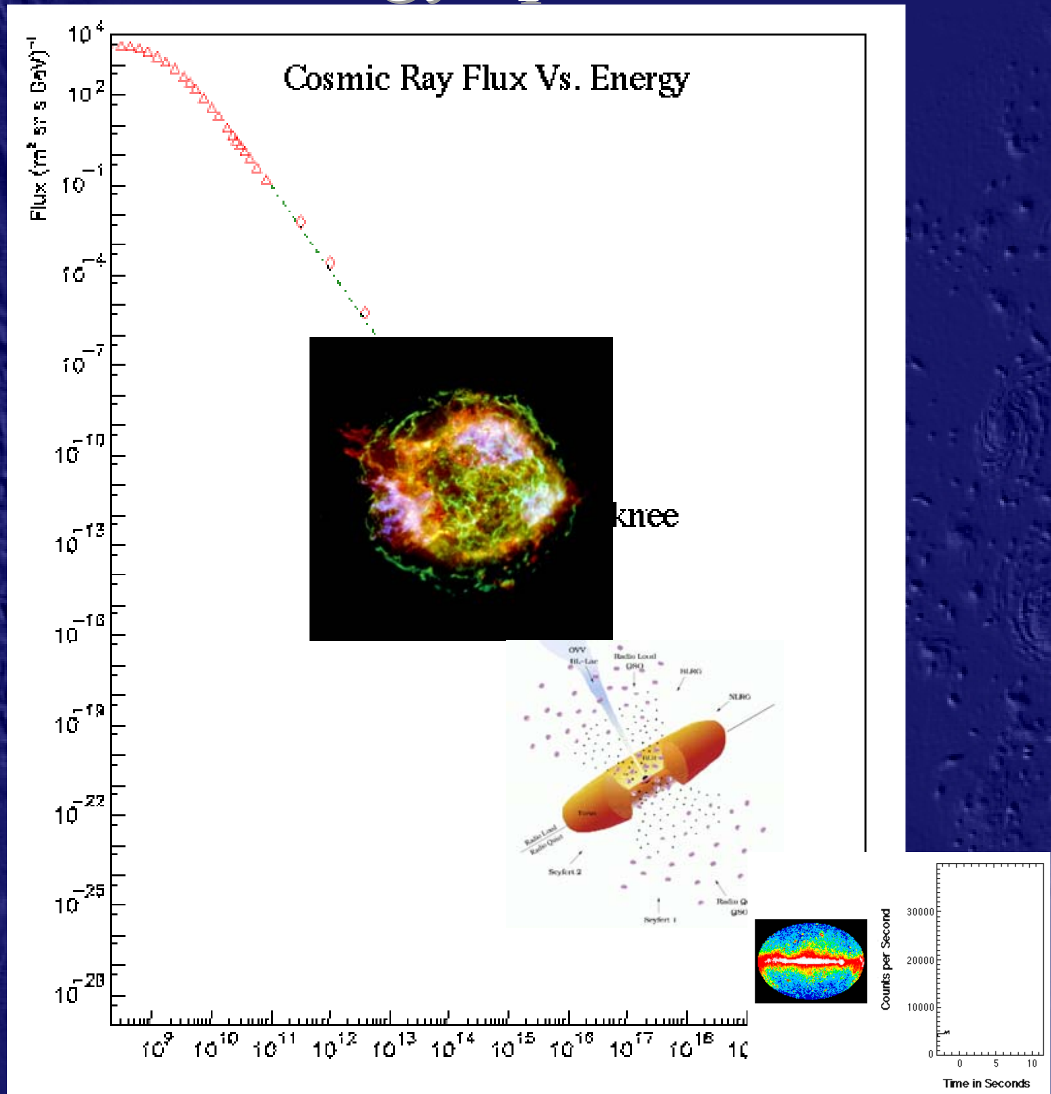
Our model:

atomic nuclei are accelerated to highest energies at shock fronts.

Candidates for such accelerators (shock fronts):

Accelerator		Extension	B-Field	Max. Energy	
Supernova-remnant	✓	100 pc	10^{-3} G	10^{17} eV	
AGN Jets	?	0,01 pc	10 G	10^{18} eV	
Gamma Ray Bursts (GRB)	??	100 km	10^{10} G	10^{20} eV	

The energy spectrum of cosmic rays



However …

See first, think later, then test. But always see first. Otherwise you will only see what you were expecting. Most scientists forget that.

Douglas Adams

English humorist & science fiction novelist (1952 - 2001)

http://www.quotationspage.com/quotes/Douglas_Adams