KIT – University of the State of Baden-Württemberg and
National Research Center of the Helmholtz Association

Karlsruhe Institute of Technology

Experimental High-Energy Astroparticle Physics

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Content:

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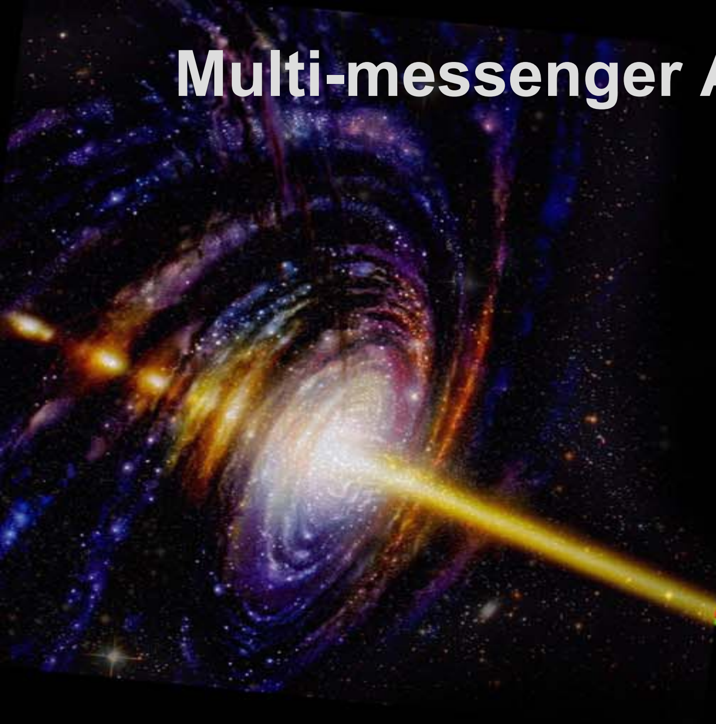
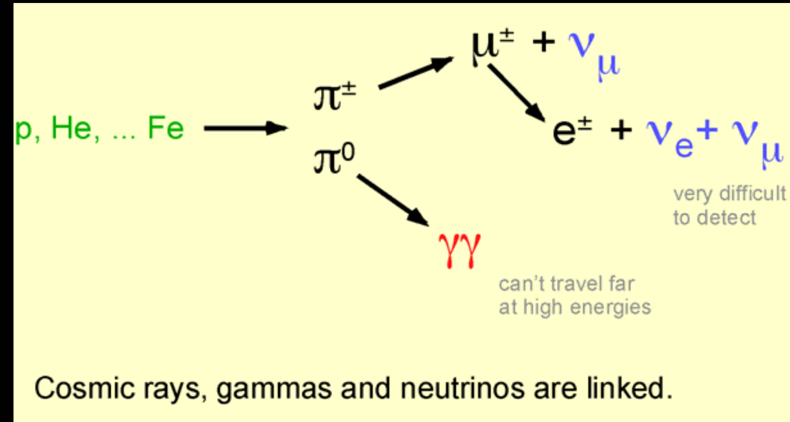
   - source-acceleration-transport
   - short history of cosmic ray research
   - extensive air showers
2. High-Energy Cosmic Rays
   - KASCADE, KASCADE-Grande and LOPES
3. Extreme Energy Cosmic Rays
   - Pierre Auger Observatory, JEM-EUSO
4. TeV-Gamma-rays & High-energy Neutrinos
   - TeV gamma rays

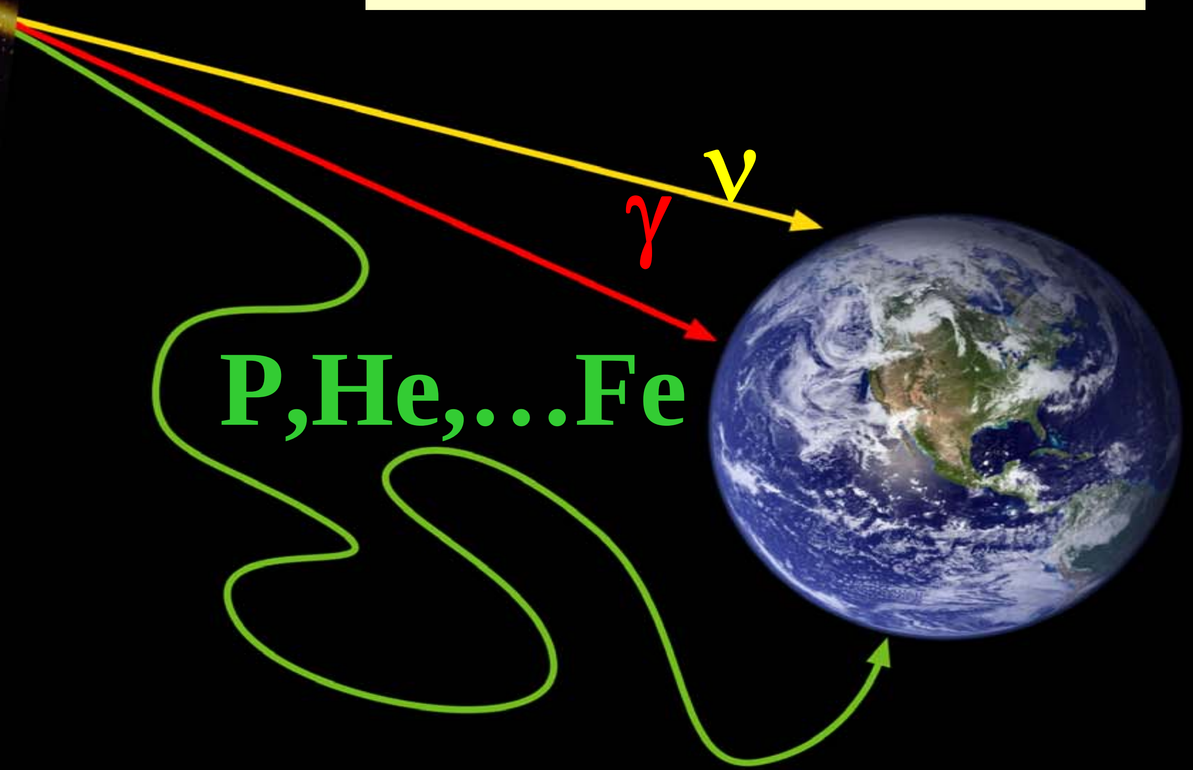
     H.E.S.S., MAGIC, CTA
   - high-energy neutrinos

     IceCube and KM3Net

Multi-messenger Approach in Astroparticle Physics



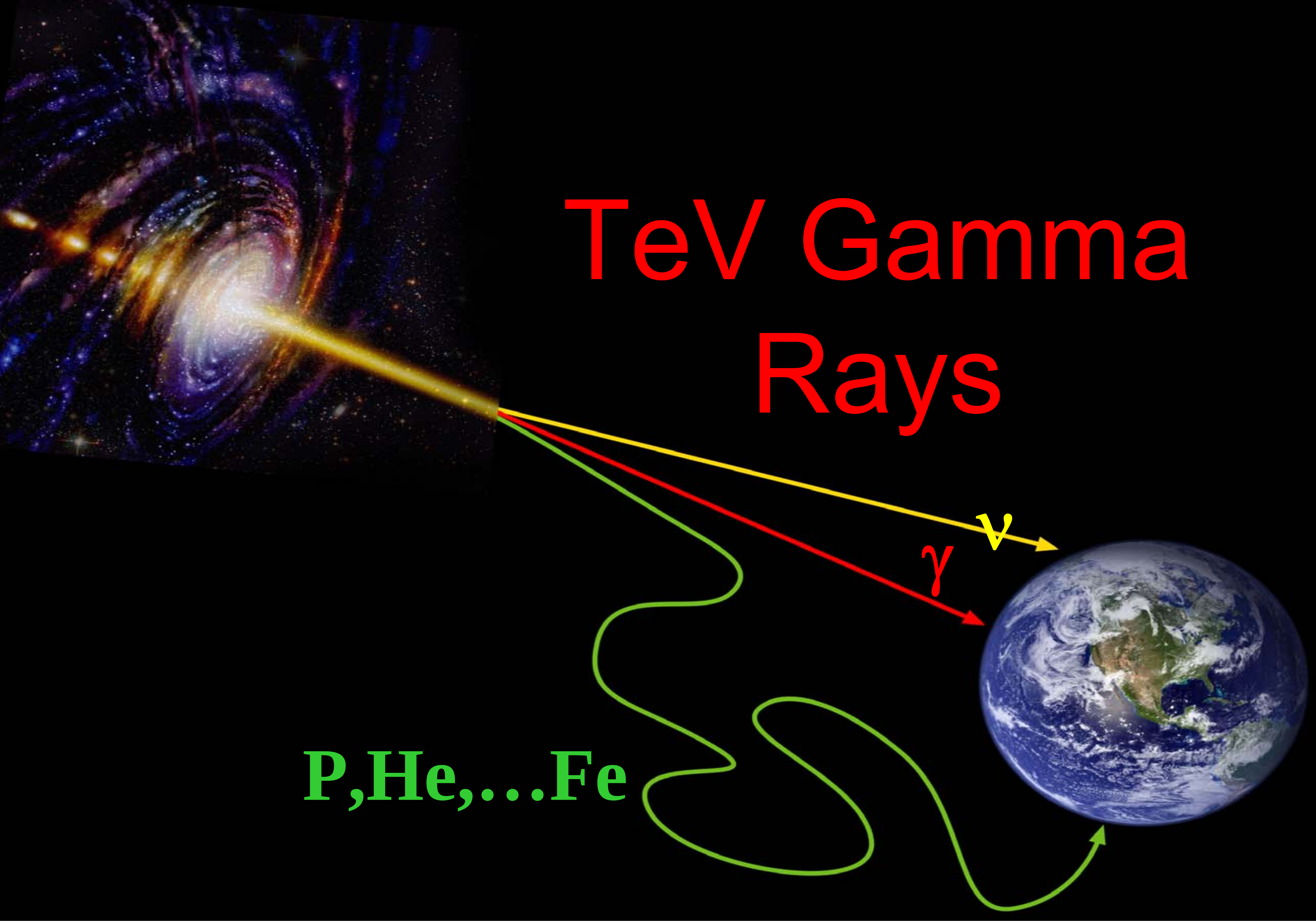




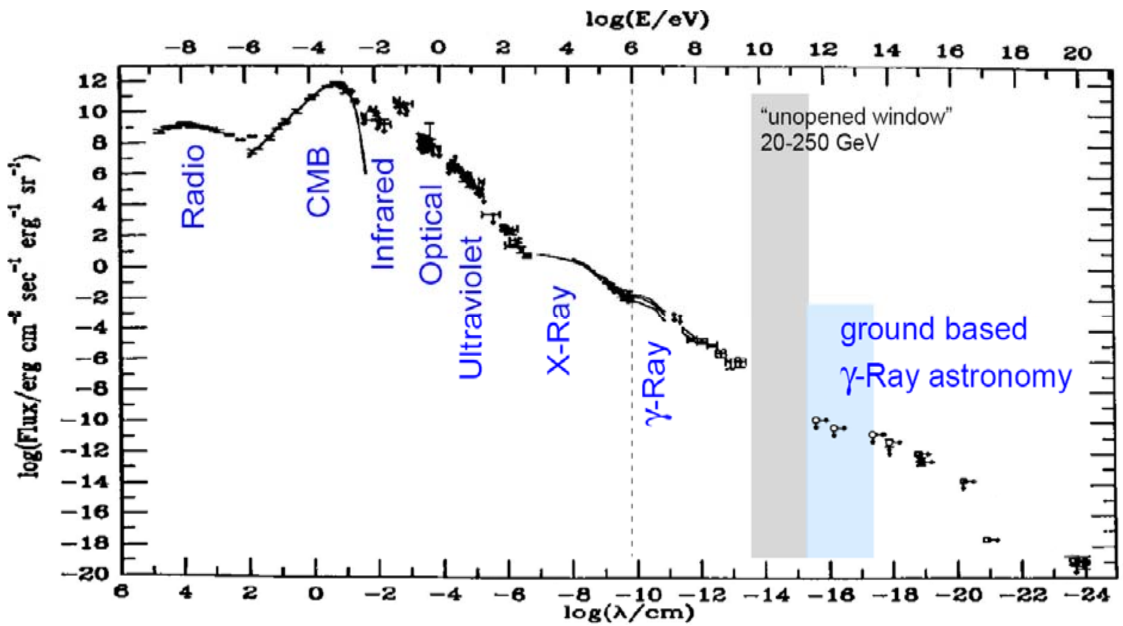
GZK:

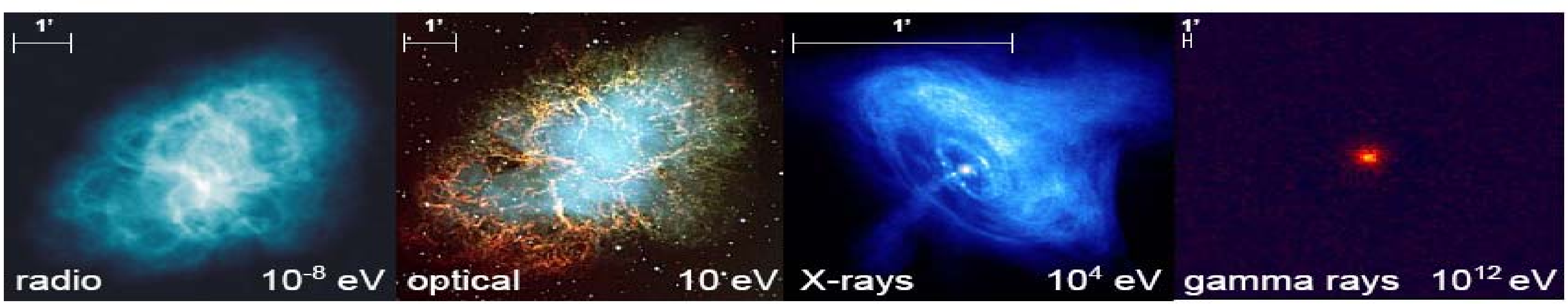
$$p + \gamma_{2.7K} \rightarrow \Delta^{+}(1232)$$
$$\rightarrow p + \pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n + \pi^{+} \rightarrow pe^{+}\nu$$

TeV Gamma Rays

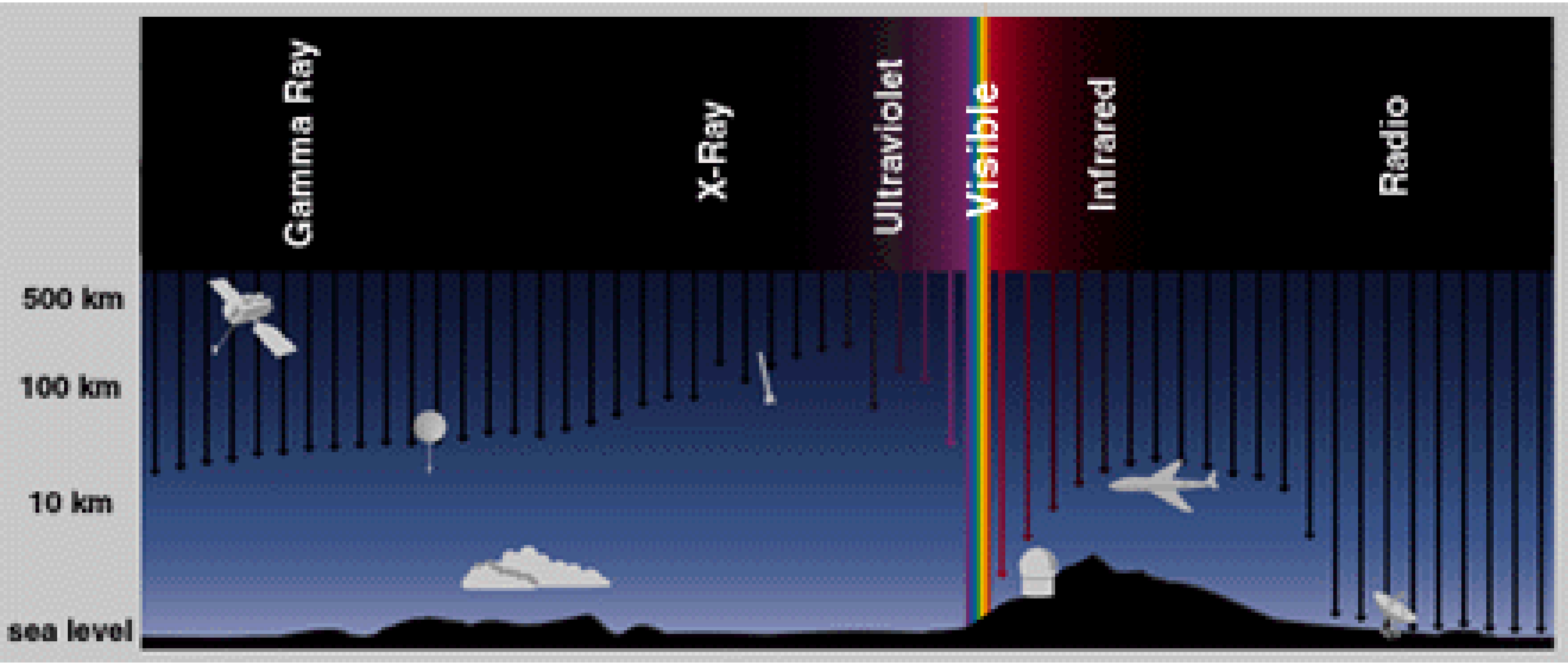


The broad-band electromagnetic spectrum





The electromagnetic spectrum
Absorption

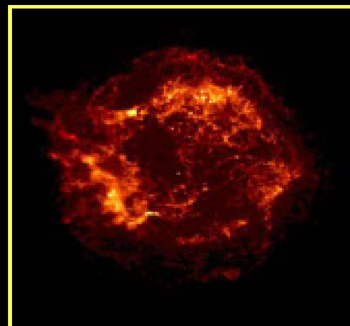


TeV – γ-ray astronomy science questions

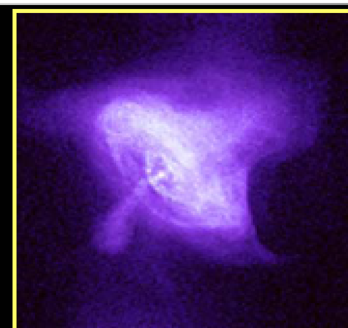
- **What is the origin of cosmic rays ?**
- **How works particle acceleration by accretion into a massive black hole**
- **Do pulsars produce VHE gamma rays ?**
- **Does Dark Matter annihilate producing gamma rays ?**
- **Is the origin of Extragalactic Background Light understood ?**
- **What is the impact of the measurements on EBL absorption in the understanding of the history of structure formation ?**
- **Can the absorption pattern in the spectrum of distant Blazars be used to measure Dark Energy ?**
- **Can VHE gammas emitted by flaring AGNs or GRBs unveil the quantum structure of gravity ?**
- **Do GRB produce VHE gamma rays ?**

TeV – γ-ray astronomy science topics

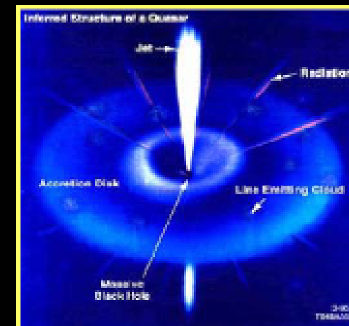
Origin of cosmic rays



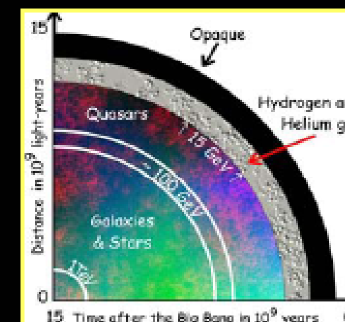
SNRs



Pulsars and PWN

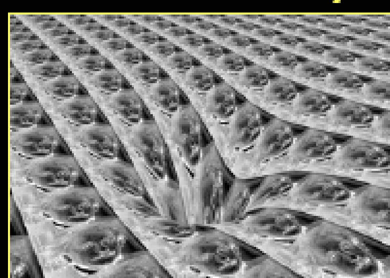


AGNs

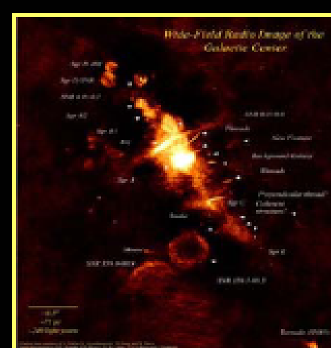


Cosmology

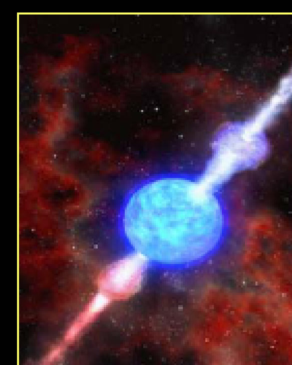
Space-time & relativity



Dark matter



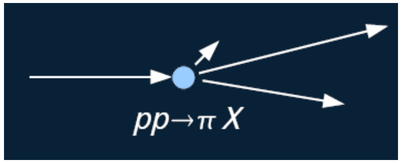
GRBs

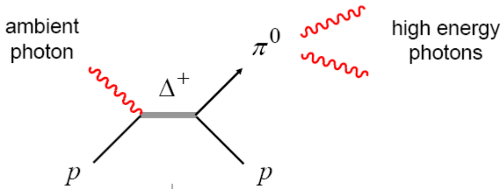


TeV – γ-ray production processes

By interaction with matter

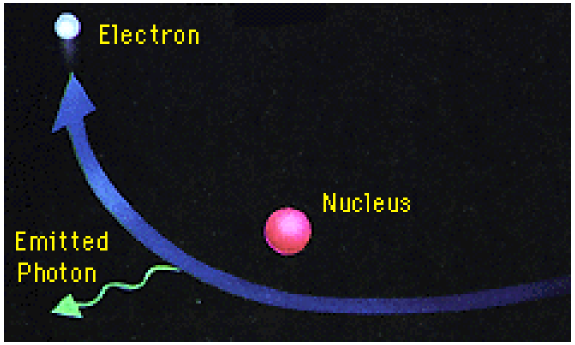
proton acceleration





<u>π° – decay:</u>

In hadronic interactions produced neutral pions decay immediately: $\pi^0 \rightarrow \gamma + \gamma$ (τ = **8.4 · 10^{-17} s**)



<u>Electron - Bremsstrahlung</u>:

Deflected electrons in the coulomb field of nuclei emit radiation with the probability

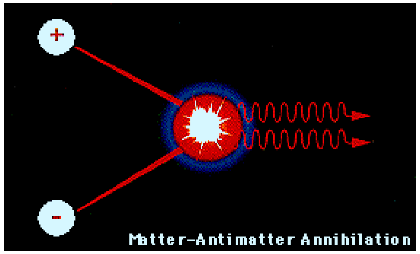
$\phi \propto z^2 Z^2 E_e / m^2$

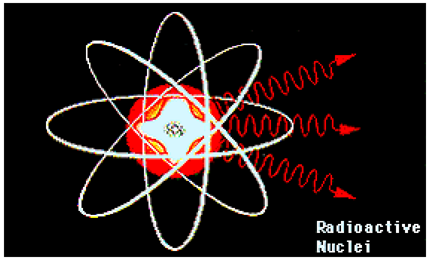
<u>Annihilation and radioactive decay</u>:

In dense matter annihilate electron-positron (proton-antiproton) pairs

$e^+ + e^- \rightarrow \gamma + \gamma \quad (\rightarrow E_\gamma = 511 \text{ keV})$

$p + \bar{p} \rightarrow \pi^+ + \pi^- + \pi^0$

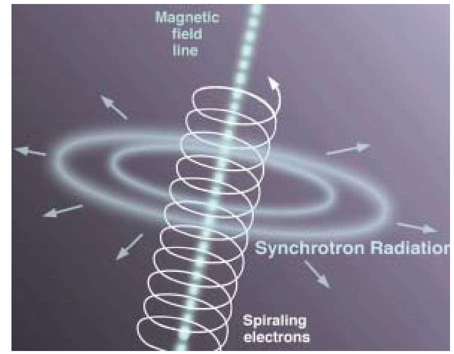




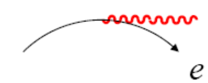
In elemental synthesis radioisotopes exist which have β – decay.

TeV – γ-ray production processes

By interaction with magnetic fields

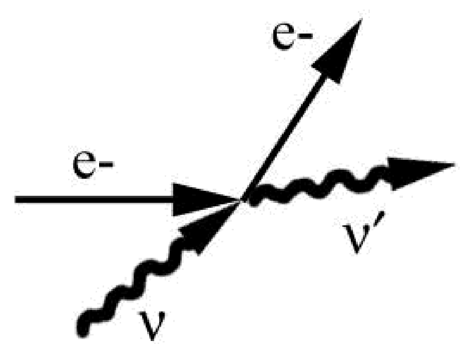


Synchrotron radiation

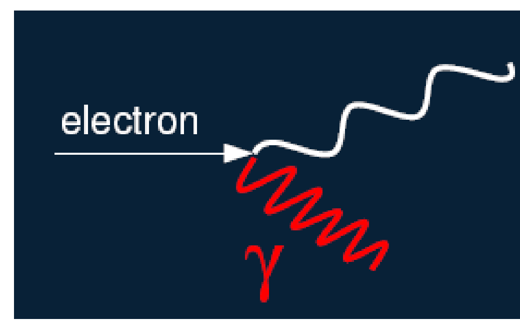


<u>Synchrotron radiation</u>:
Radiation of accelarated charged particles (electrons) in magnetic fields.
Power of the radiation: $P \propto E_e^{\,2} \cdot B^2$

Inverse Compton scattering



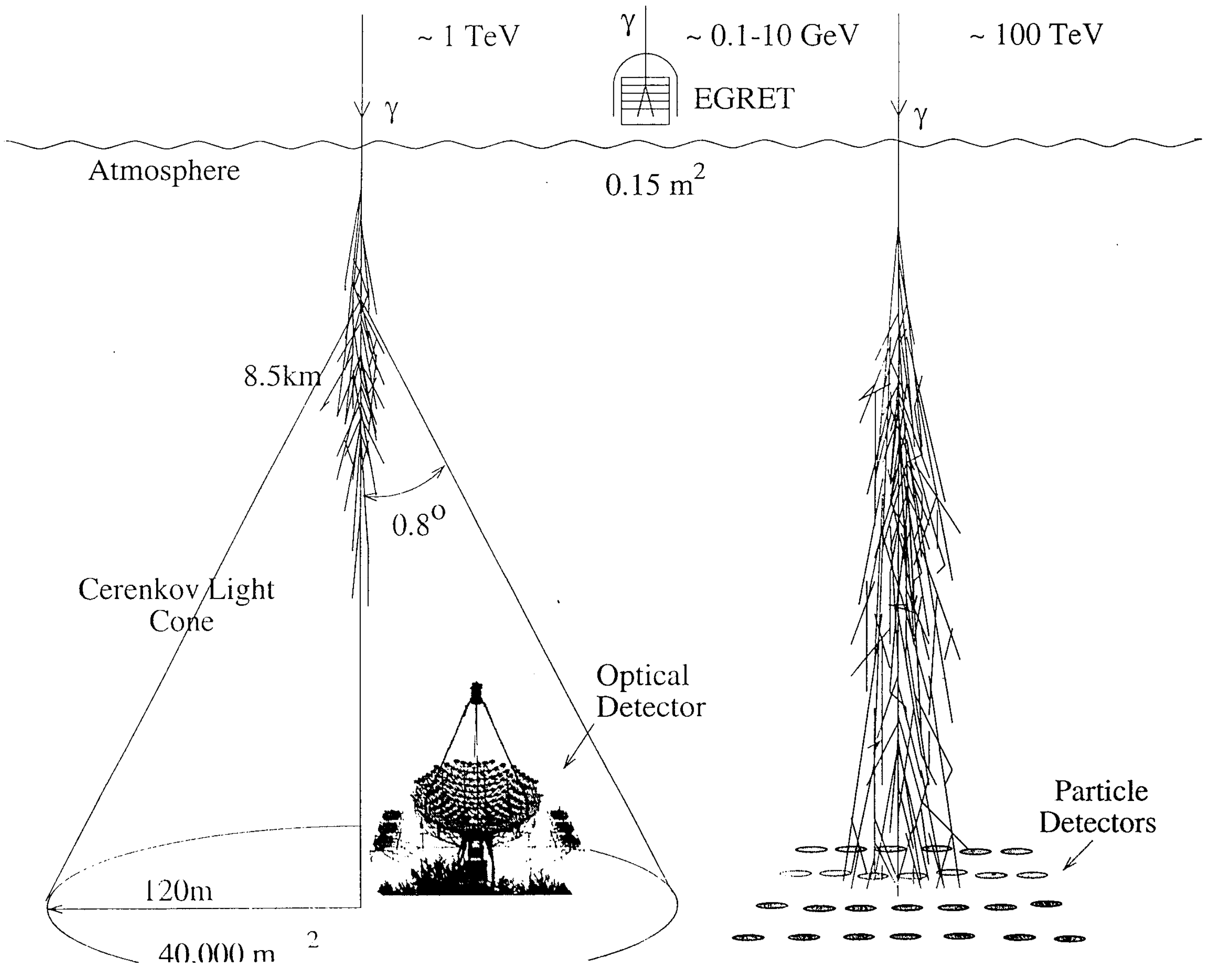
$\nu' > \nu$
High energy e- initially
e- loses energy



By interaction with photon fields

<u>Inverse compton scattering:</u>
fast electrons transfer energy on low energy photons
➔ Blue shifted photons

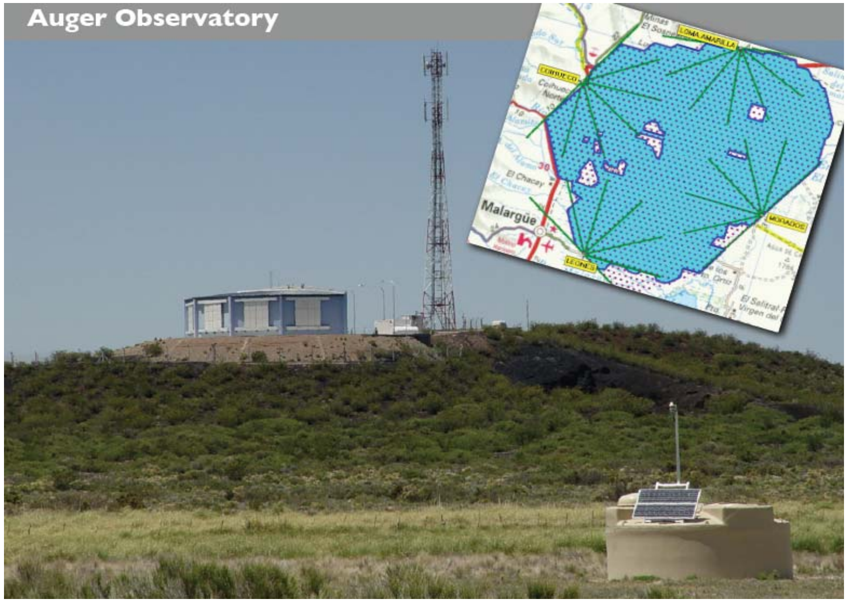
High Energy γ-rays detection principle

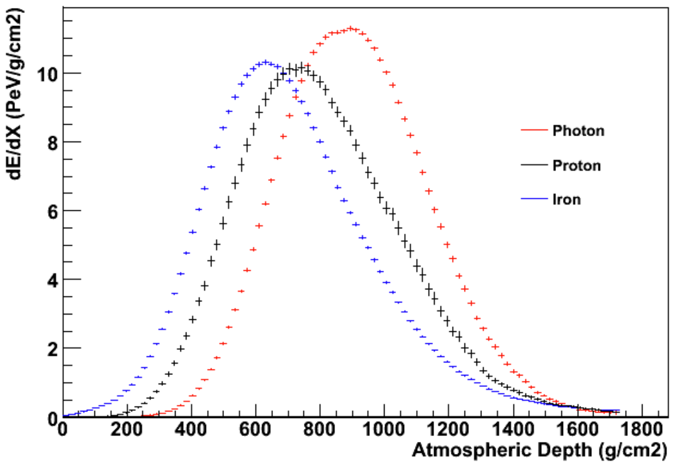


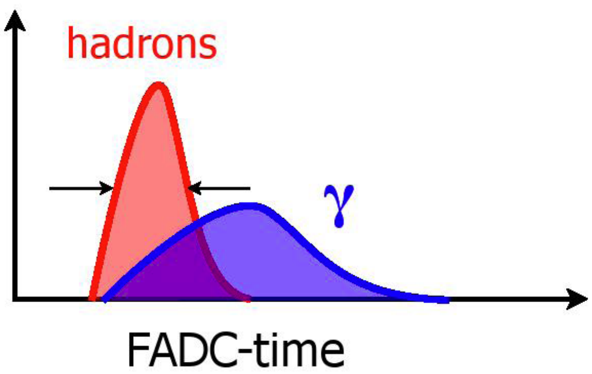
Photon search at the Pierre Auger Observatory
$E_\gamma = 10^{18}$-10^{20}eV

Photon inititated showers penetrate deeper in the atmosphere
➔higher X_{max} (FD)

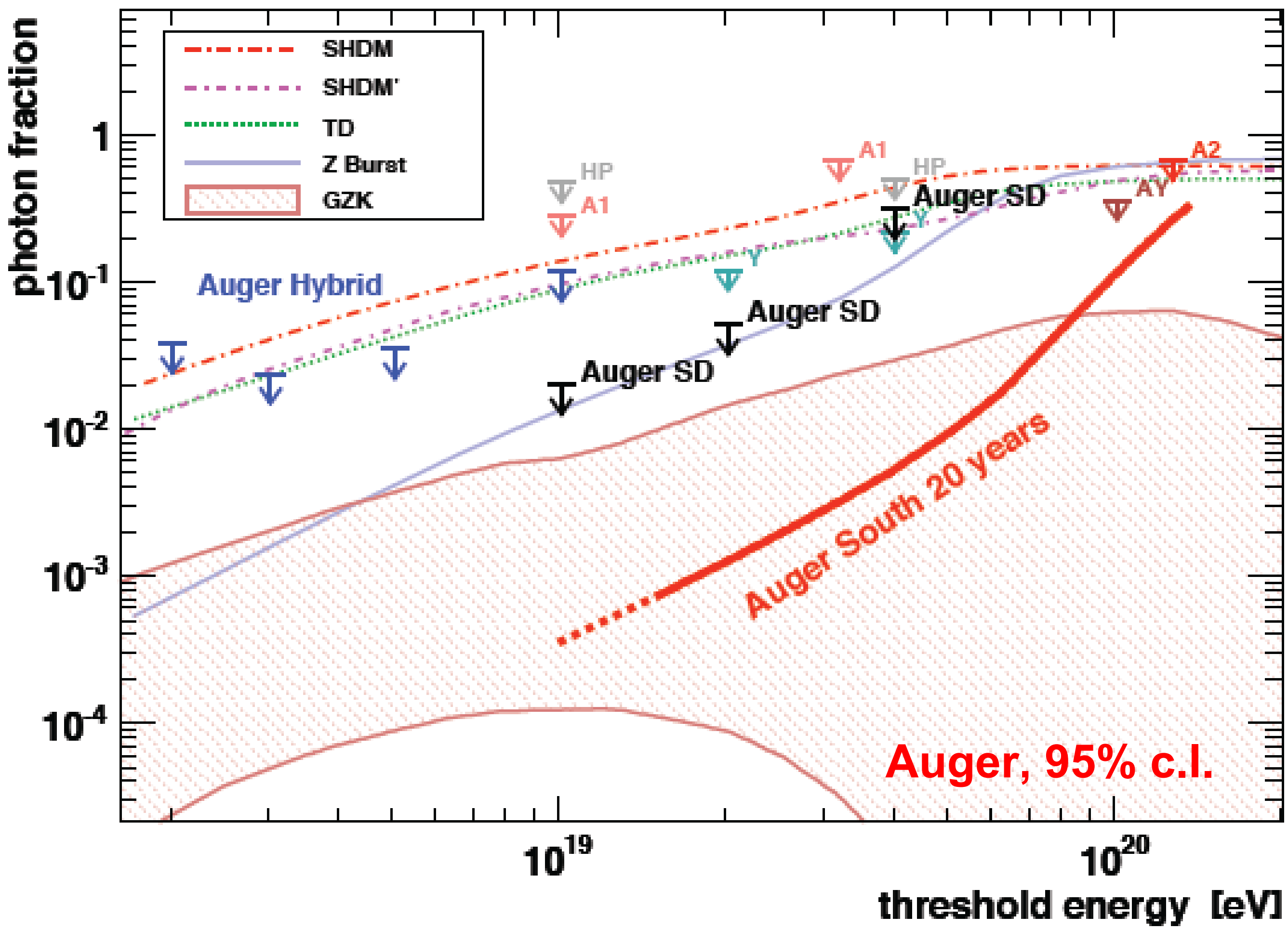
Photon inititated showers are pure electromagnetic EAS
➔less muons, different signal
➔shape in particle detector (SD)







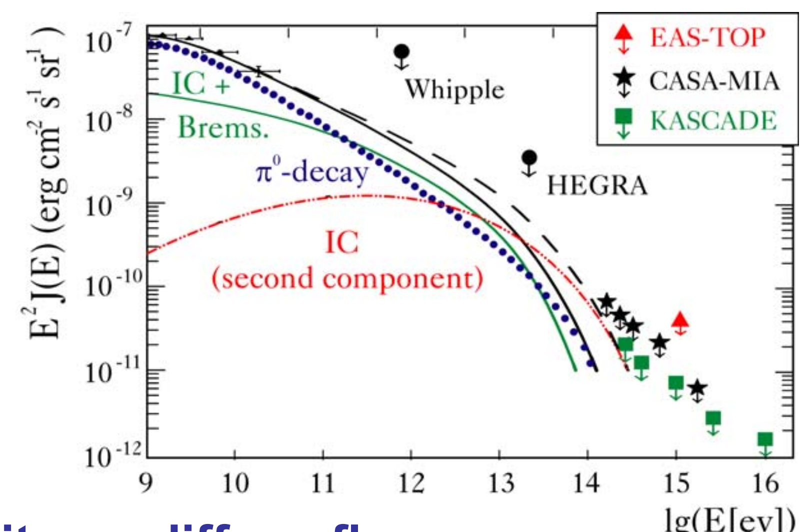
Limit on fraction of photons in UHECR flux



Astropart. Phys. 29 (2008) 243
Astropart. Phys. (2009) in press, arxiv 0903-1127

Many exotic source scenarios excluded

Photon-shower detection: Tibet AS\g – Argo – Grapes - …
$E_\gamma = 10^{13}$-10^{16}eV

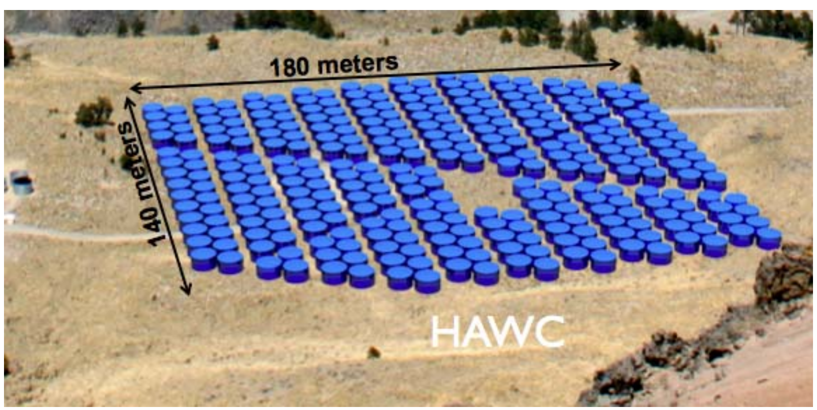


Limits on diffuse flux
Some point sources at low energies

shower detection: Milagro → HAWC
$E_\gamma = 10^{12}$-10^{14}eV

Milagro was a first generation wide-field gamma-ray telescope:

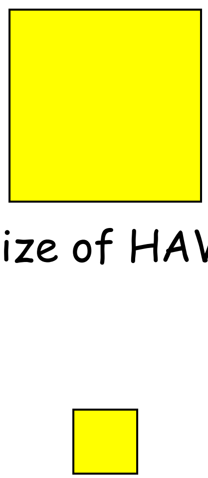
Discovered:
- more than a dozen TeV sources
- diffuse TeV emission from the Galactic plane
- a surprising directional excess of cosmic rays



HAWC will use what we have learned from Milagro

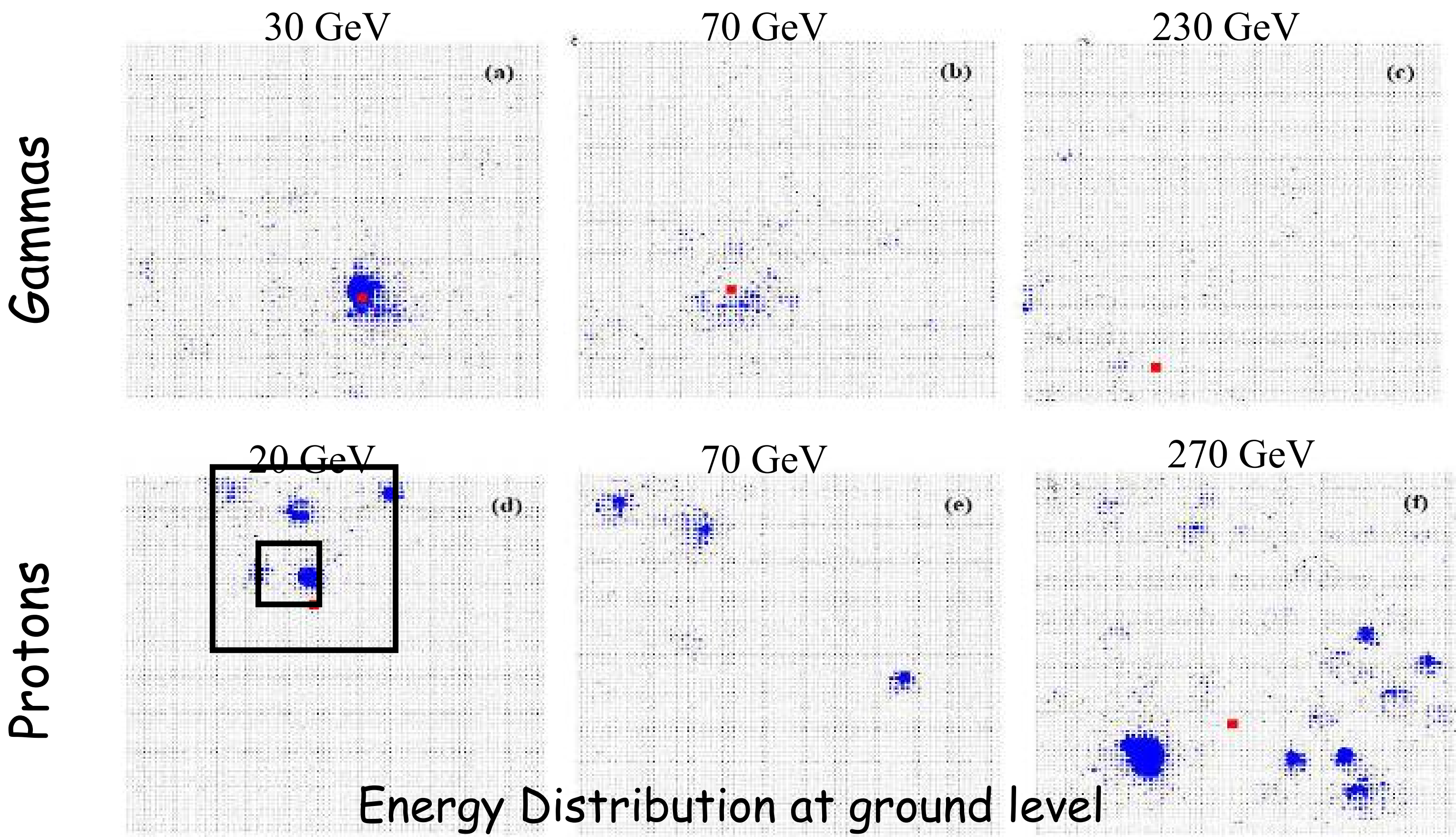
HAWC will:
- extend the reach of IACTs to ~100 TeV
- point to the sources of cosmic rays
- be the best instrument to study short GRBs and prompt emission at 100s of GeV

Gamma/Hadron Separation



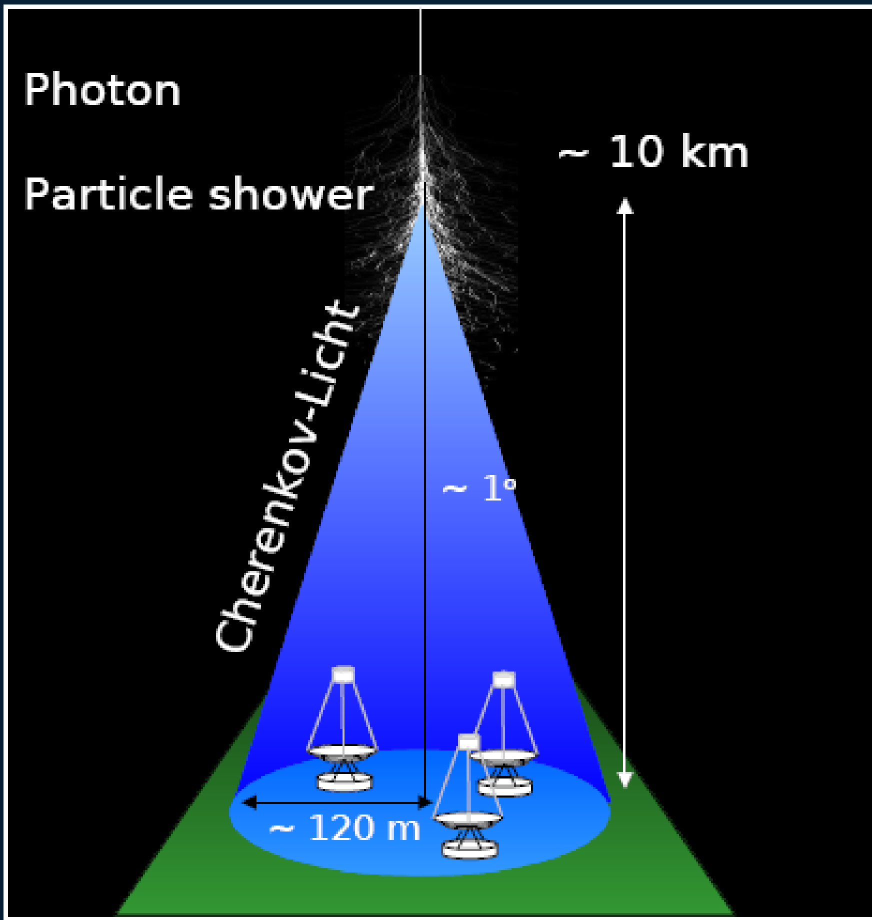
Size of HAWC

Size of Milagro deep layer

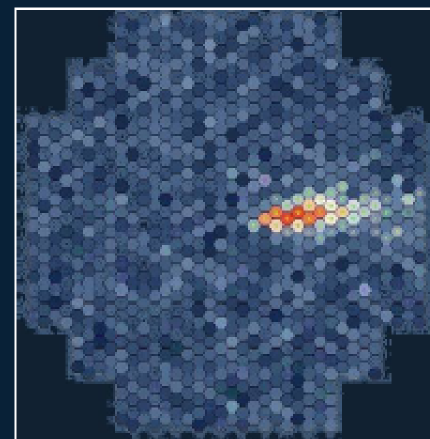


Energy Distribution at ground level

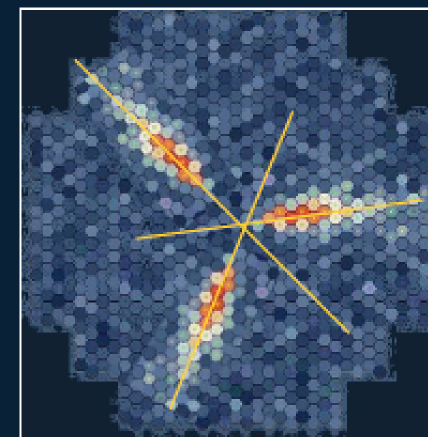
TeV – γ-rays: detection principle of Imaging Air-Cherenkov Telescopes



Single telescope event



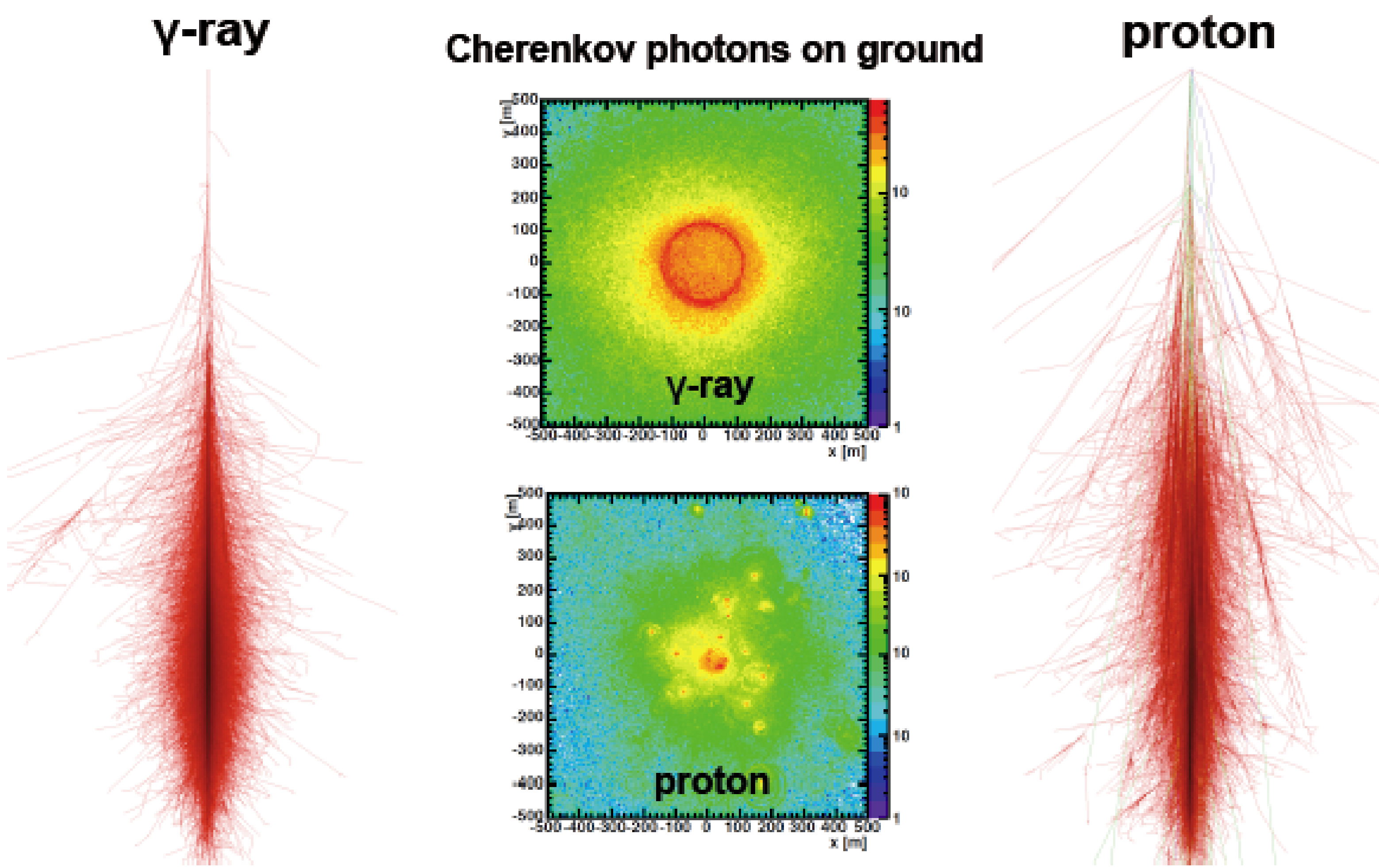
Three telescope event in common camera plane



- Image intensity → energy
- Image orientation → direction
- Image shape → primary particle

- Large collection areas ~50000 m^2

TeV – γ-rays: detection principle



G.Maier

TeV – γ-ray astronomy
the beginning

Detection of Crab Nebula 1989
by the Whipple telescope
50h for 5σ
HESS: 30 seconds

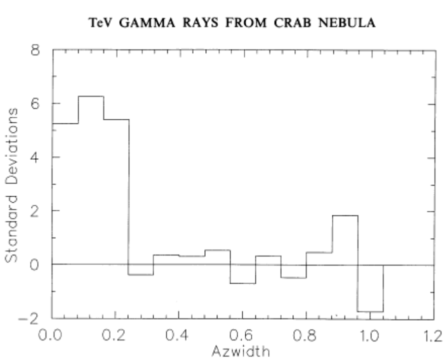
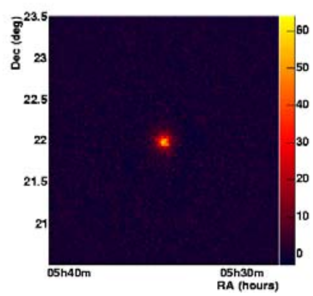


FIG. 7.—Distribution of *azwidth* (ON − OFF) in terms of standard deviations as a function of *azwidth*



TeV – γ-ray astronomy nowadays telescopes

MAGIC

Major Atmospheric Gamma Imaging Cherenkov

- **Single 17 meter (250 sqm) Cherenkov Telescope with several new technological elements**
- **Located at the La Palma Canary island (Northern Hemisphere)**
- **Fully operational since 2004**
- **Analysis E_th about 60 GeV and Crab-like detection in about 2 minutes**
- **Many of discoveries and high impact results**

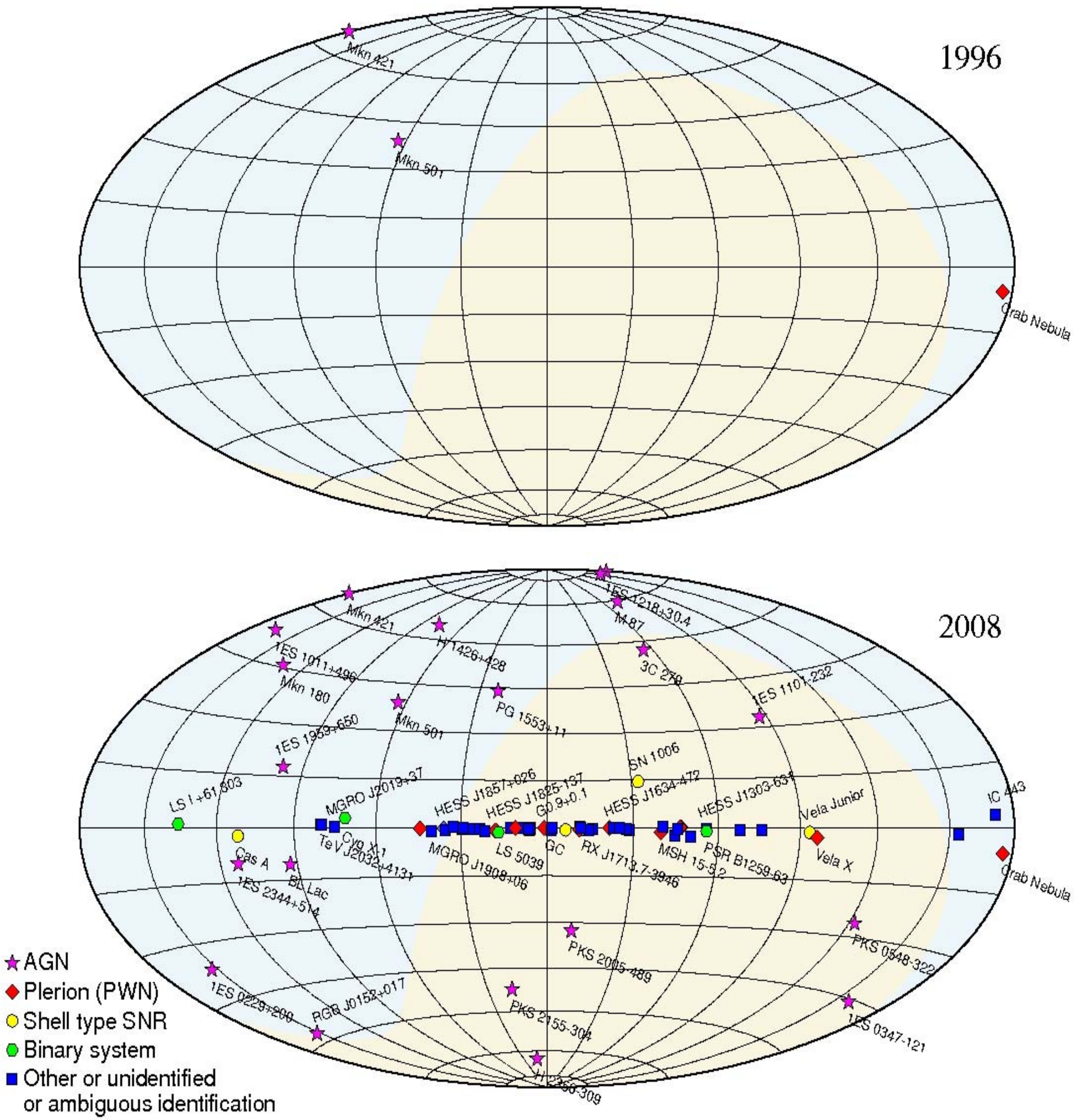
TeV – γ-rays: H.E.S.S.

H.E.S.S.

High Energy Stereoscopic System

- Array of 4 x 12 meter (100 sqm) Cherenkov Telescopes
- Located at the Khomas Highland Namibia (Southern Hemisphere)
- Fully operational since 2003
- Analysis E_th about 150 GeV and Crab-like detection in about 30 seconds
- Lots of discoveries and high impact results

The TeV γ-ray sky
Source Hunting



Background colours indicating northern / southern sky

Graphics by Konrad Bernlöhr 2008

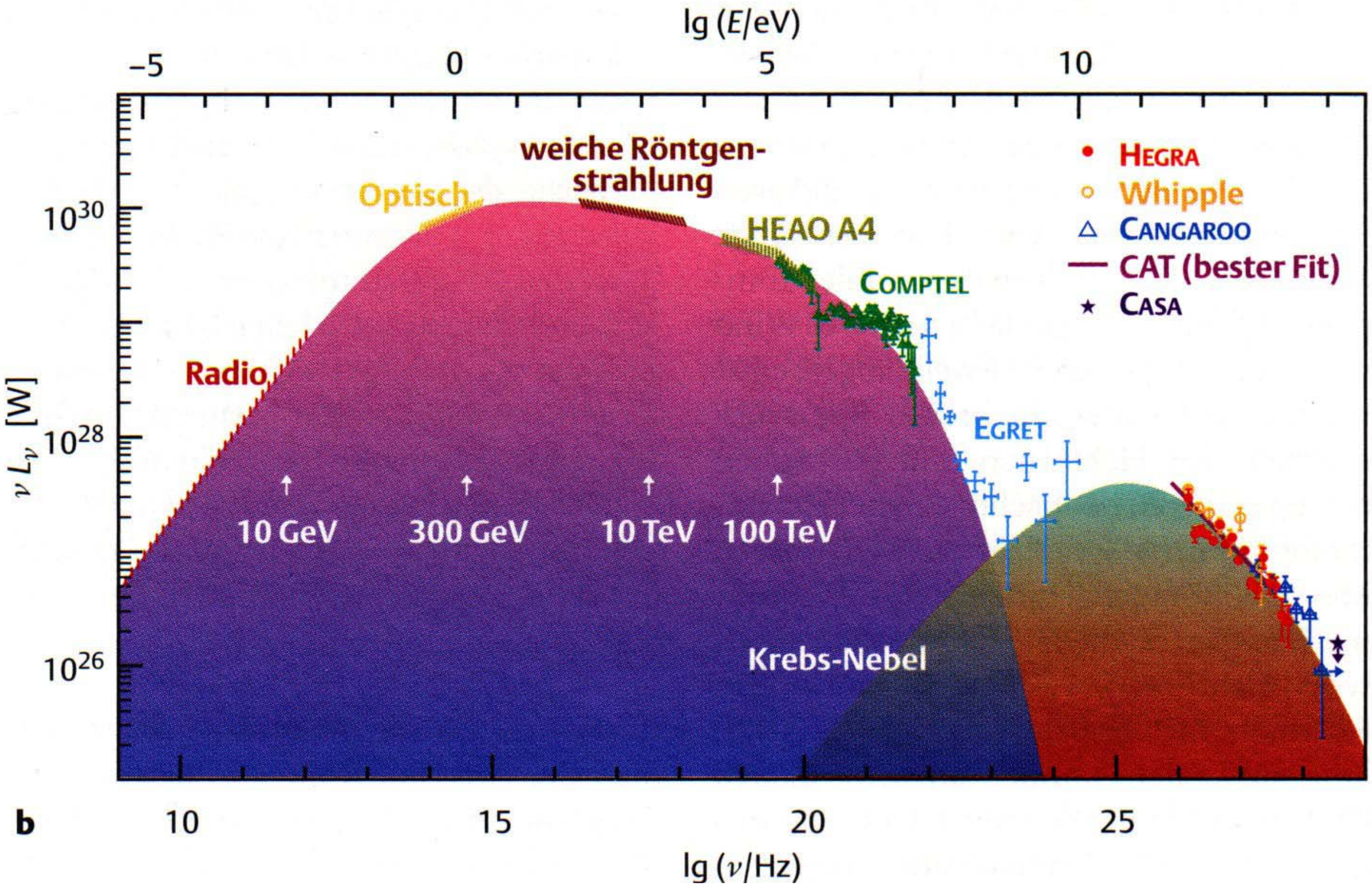
Class	2003	2005	2007
PWN	*1*	*6*	*18*
SNR	*2*	*3*	*7*
Binary	*0*	*2*	*4*
Diffuse	*0*	*2*	*2*
AGN	*7*	*11*	*19*
UnId	*2*	*6*	*21*
Total	12	33	71!

2011: 130 sources

TeV – γ-ray astronomy
from source hunting …… to astronomy

Emission model: synchrotron and inverse compton.

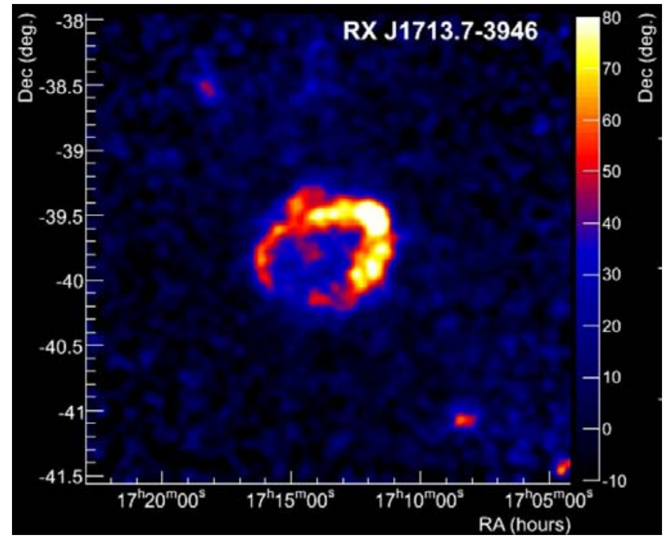
<u>Proof by multiwavelength observation</u>

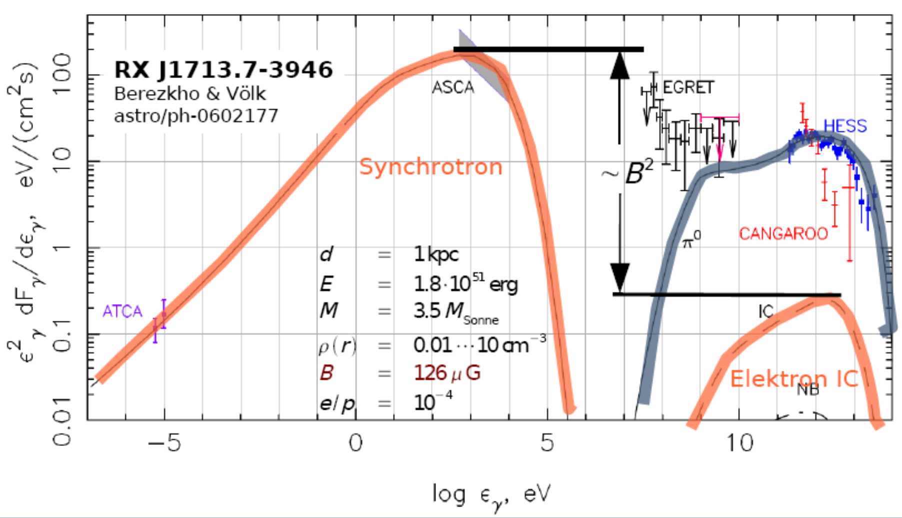


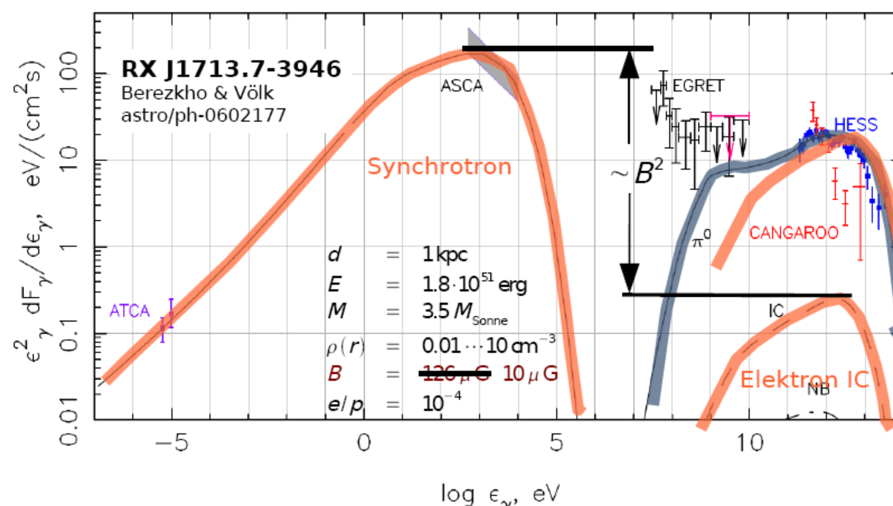
TeV – γ-ray astronomy
from source hunting …… to astronomy

Model works fine for most sources, but where are the hadronic cosmic rays produced?

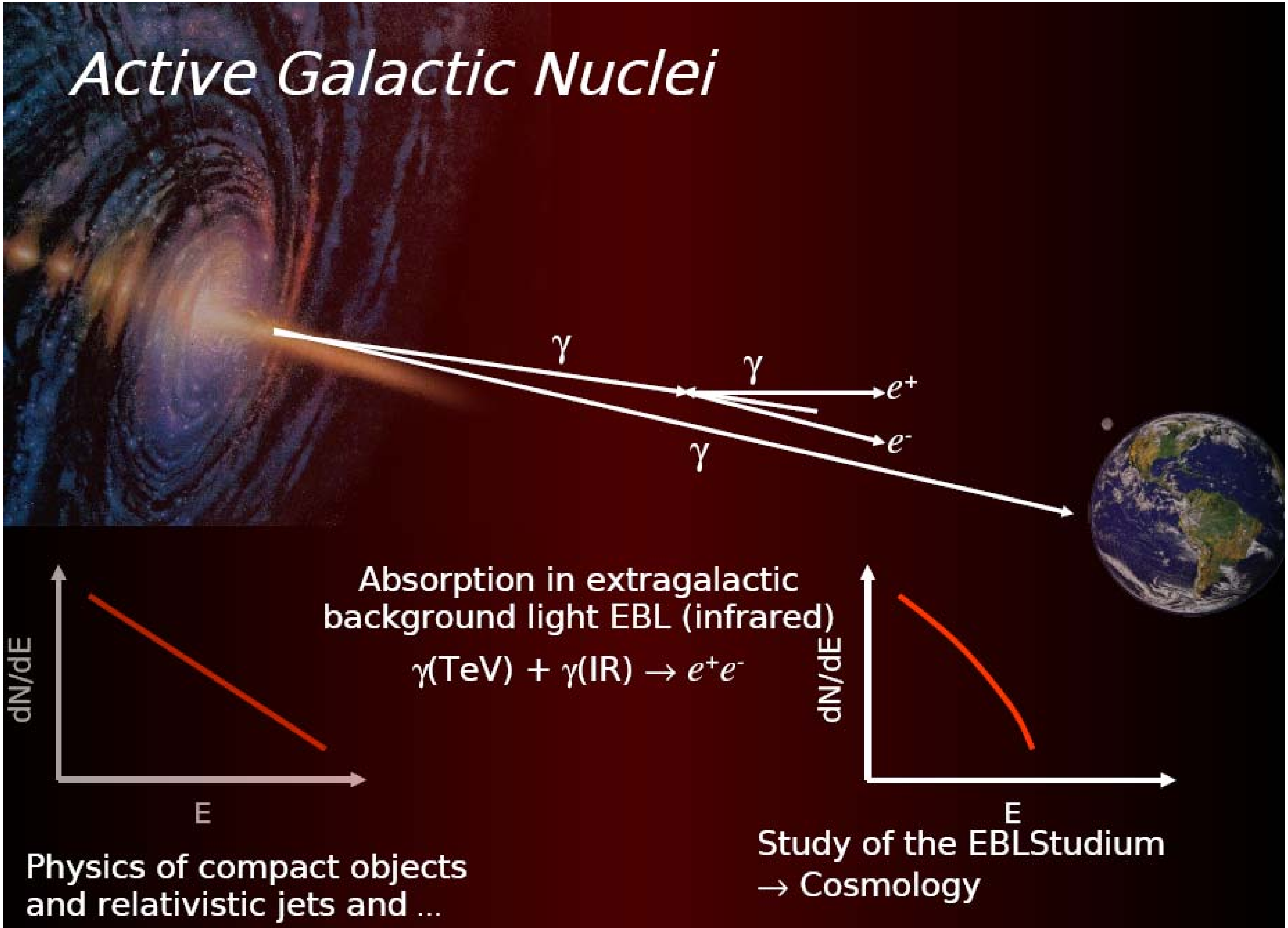
Supernova remnant shell type:
Shock wave acceleration up to
E > 100 TeV
- **Primary particle type (electrons, hadrons) still uncertain**



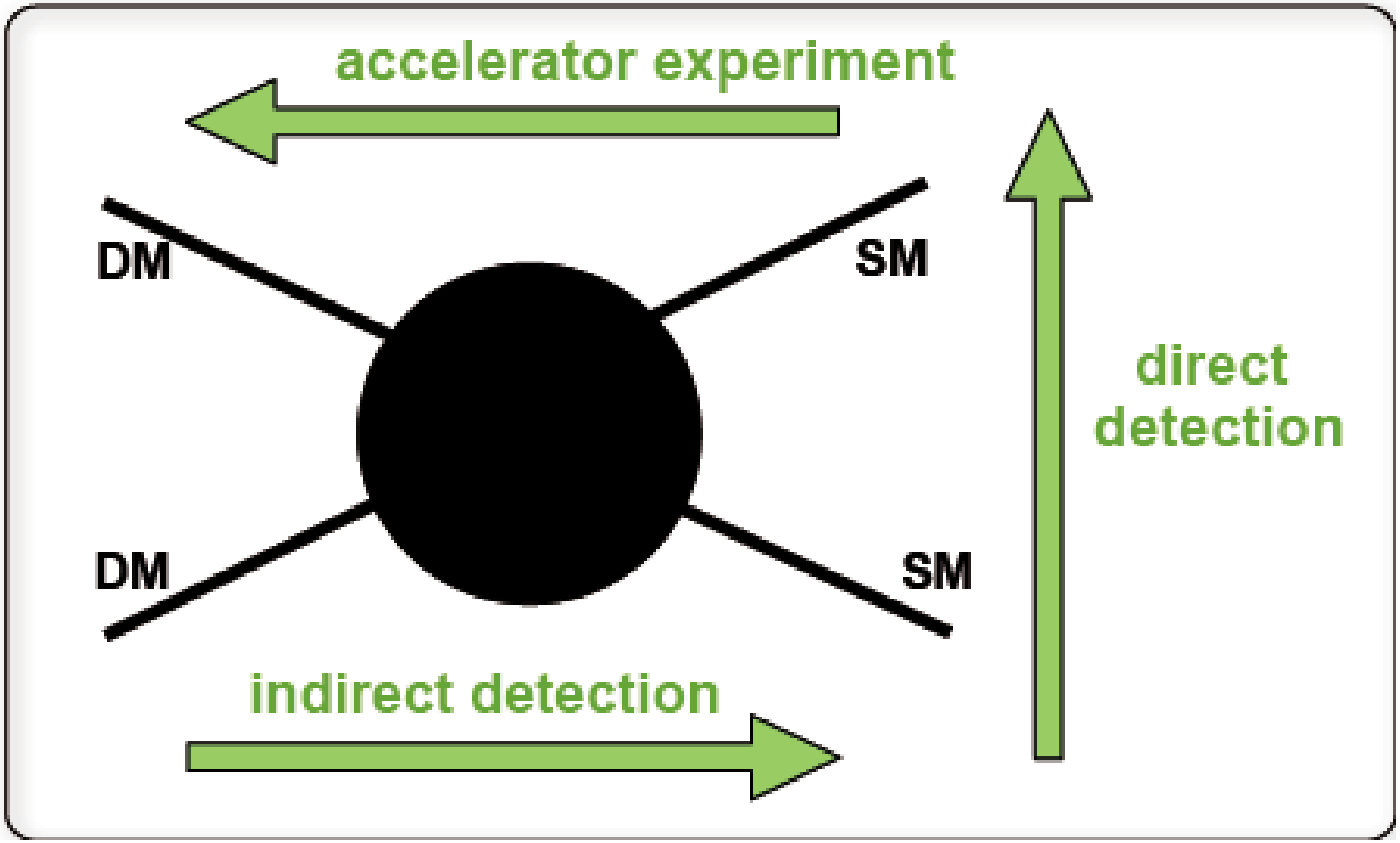




TeV – γ-rays: from source hunting …… to astronomy



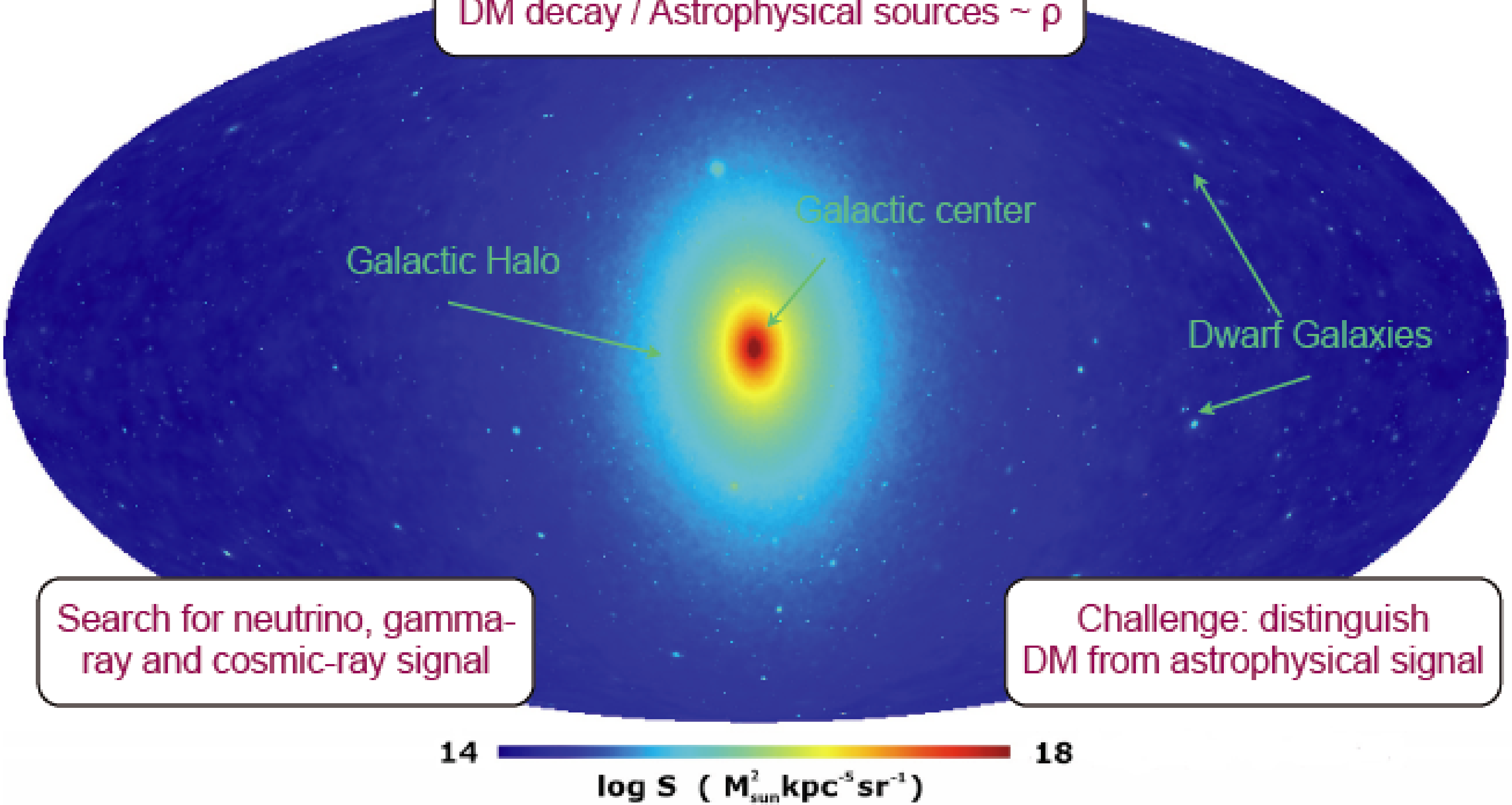
Dark Matter Search



TeV – γ-rays: from source hunting …… to cosmology

Dark Matter Search

DM annihilation ~ ρ^2
DM decay / Astrophysical sources ~ ρ

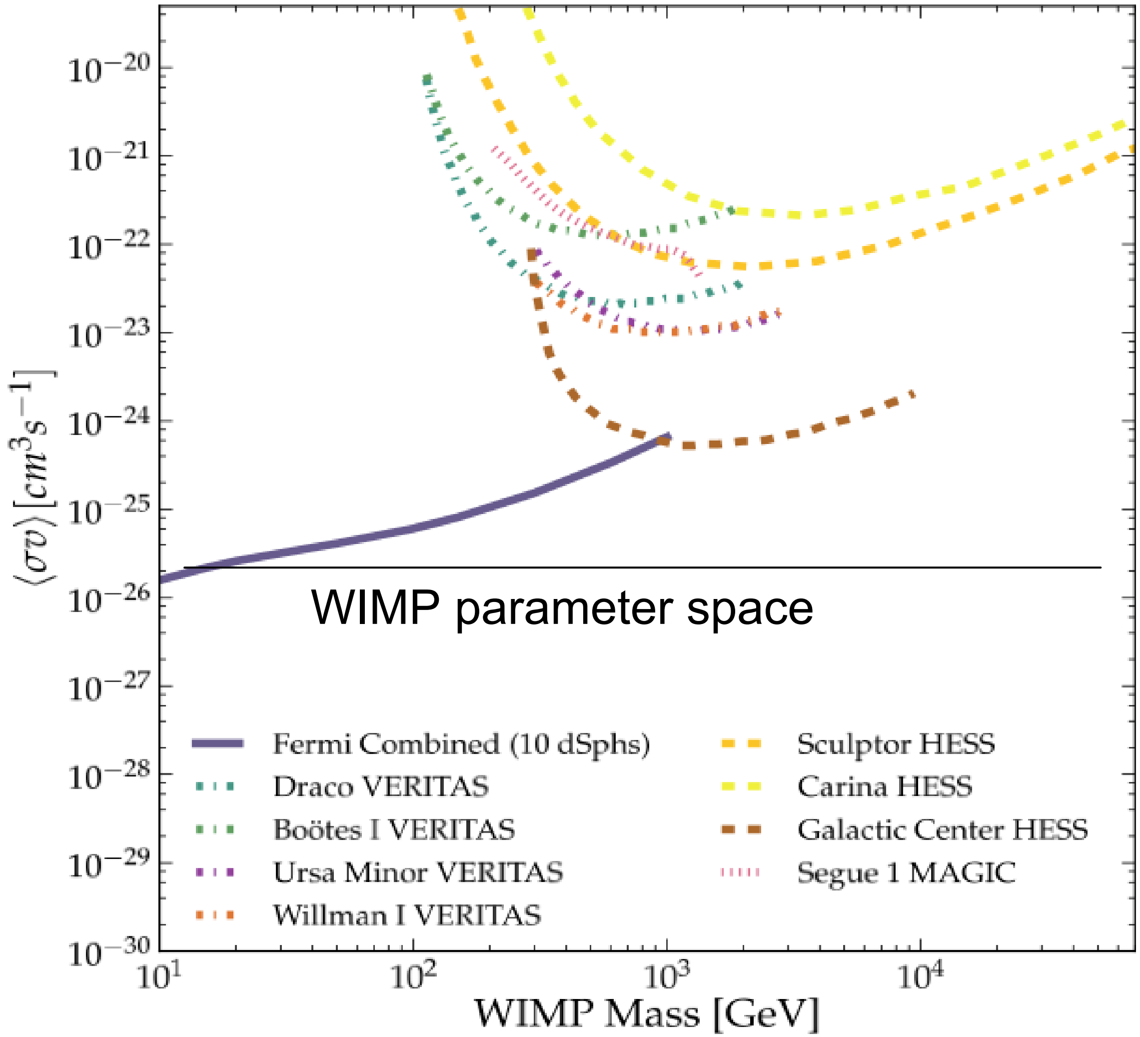


Search for neutrino, gamma-ray and cosmic-ray signal

Challenge: distinguish DM from astrophysical signal

TeV – γ-rays: from source hunting …… to cosmology

Dark Matter Search



TeV – γ-rays: The present future

MAGIC-II

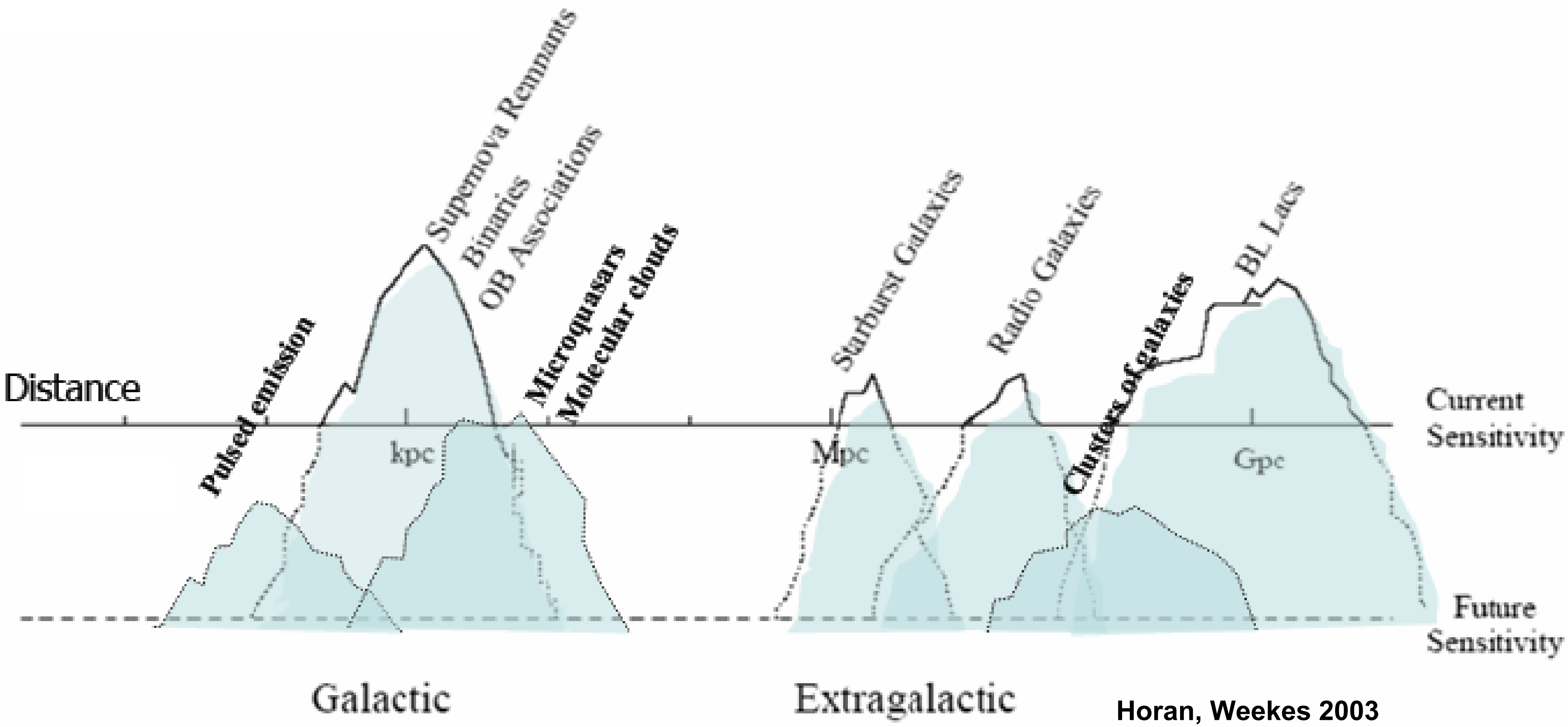
•Twin 17 meter Cherenkov telescopes with state-of-the-art technology
•Three times better sensitivity and physics E_{th} < 50 GeV

H.E.S.S.-II

• Giant 28m (600 sqm area) telescope at center of the HESS array (4x12m)
• Commissioning in 2011
• E_{th} reduction to ~30 GeV

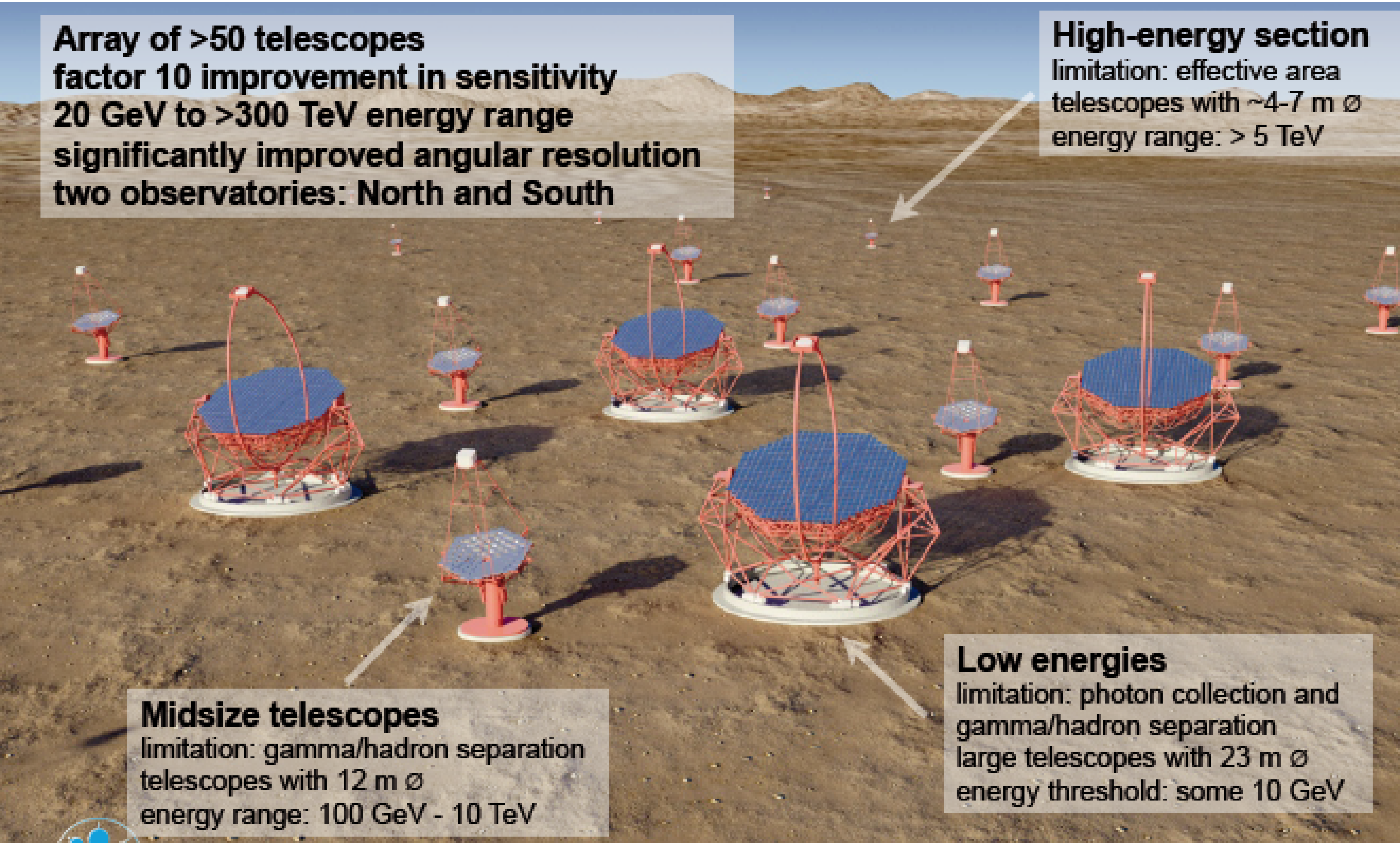
TeV – γ-rays: what comes next

We just see the tip of an iceberg!
Future provides guaranteed physics program and large discovery potential



Horan, Weekes 2003

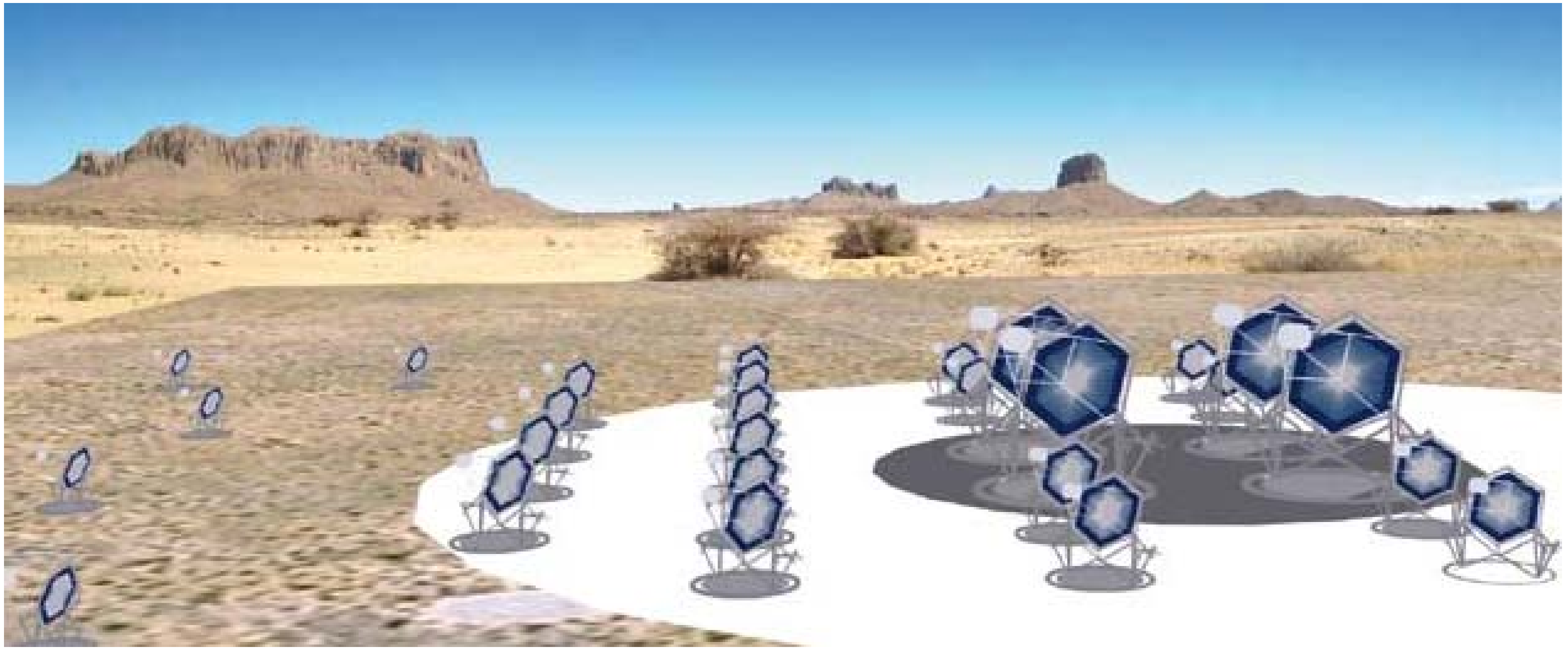
TeV – γ-ray astronomy: The future: CTA



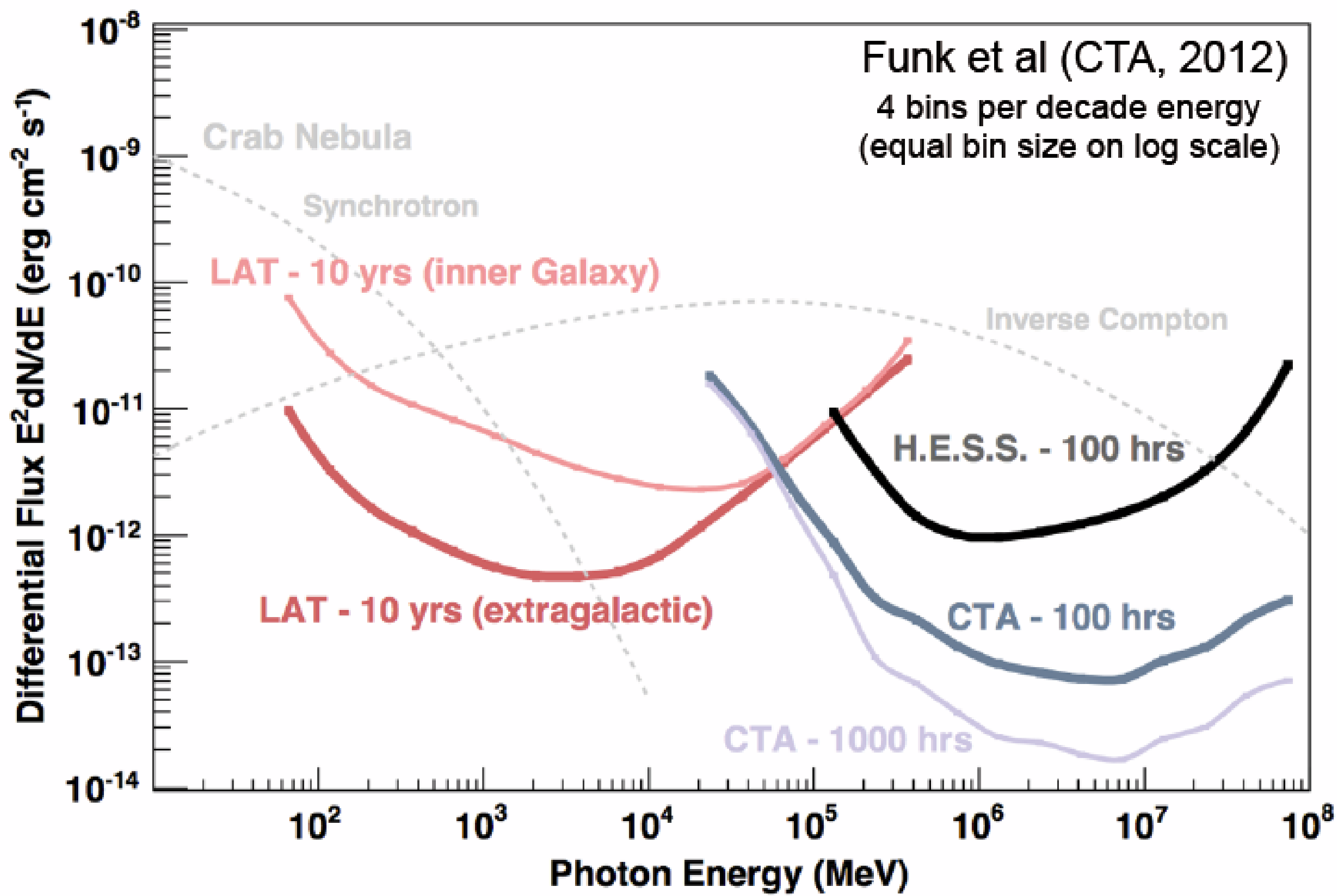
TeV – γ-ray astronomy: The future: CTA

-- Larger sensitivity (x10)
– Lower threshold (few 10 GeV)
– Larger energy range (>PeV)
– Larger field of view
– Improved angular resolution
– Larger detection rates

● more sources
● Pulsars, distant AGN, source mechanisms
● Cut-off of galactic sources
● extended sources, surveys
● structure of extended sources
● transient phenomena



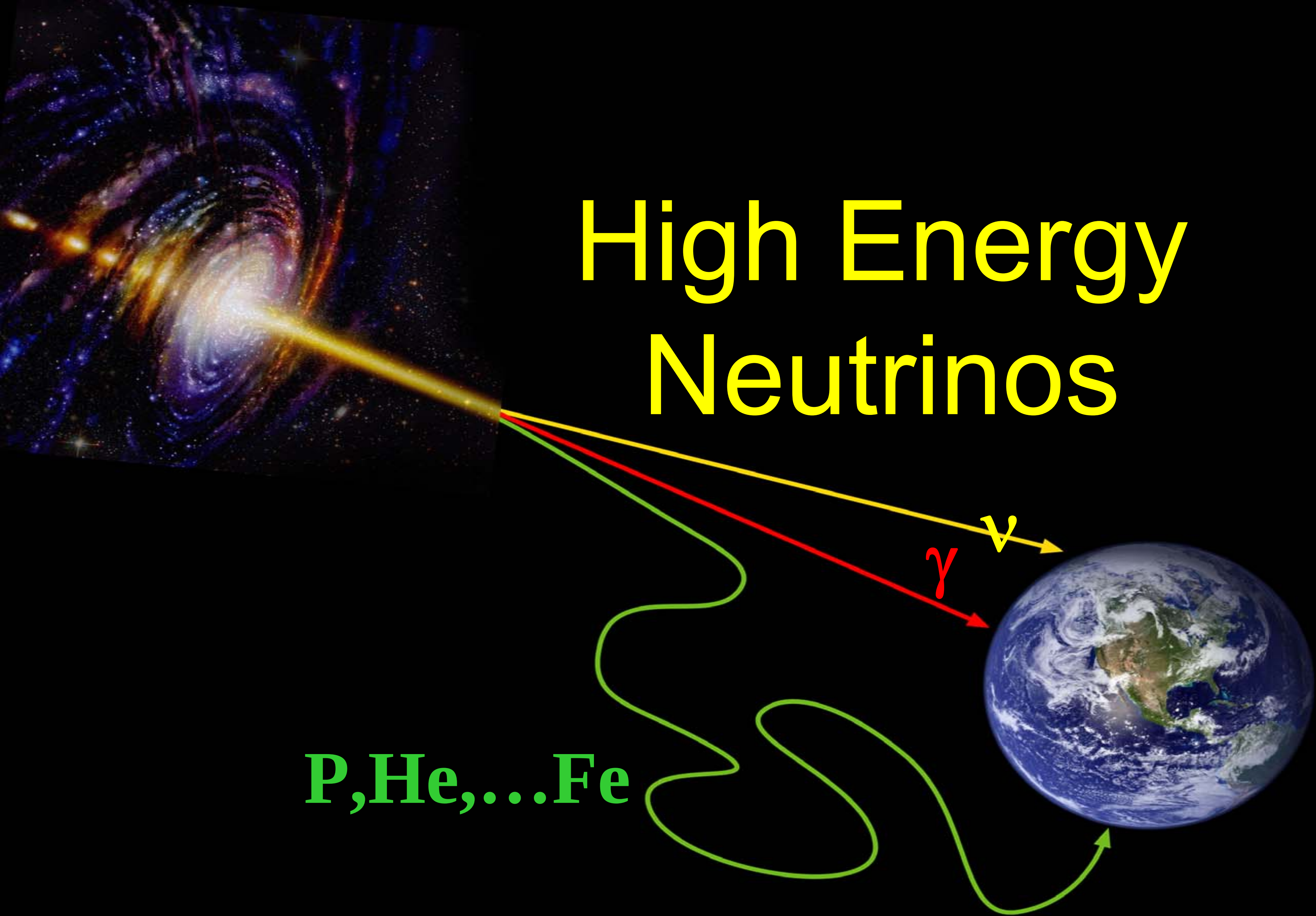
TeV – γ-ray astronomy: The future: CTA Sensitivity



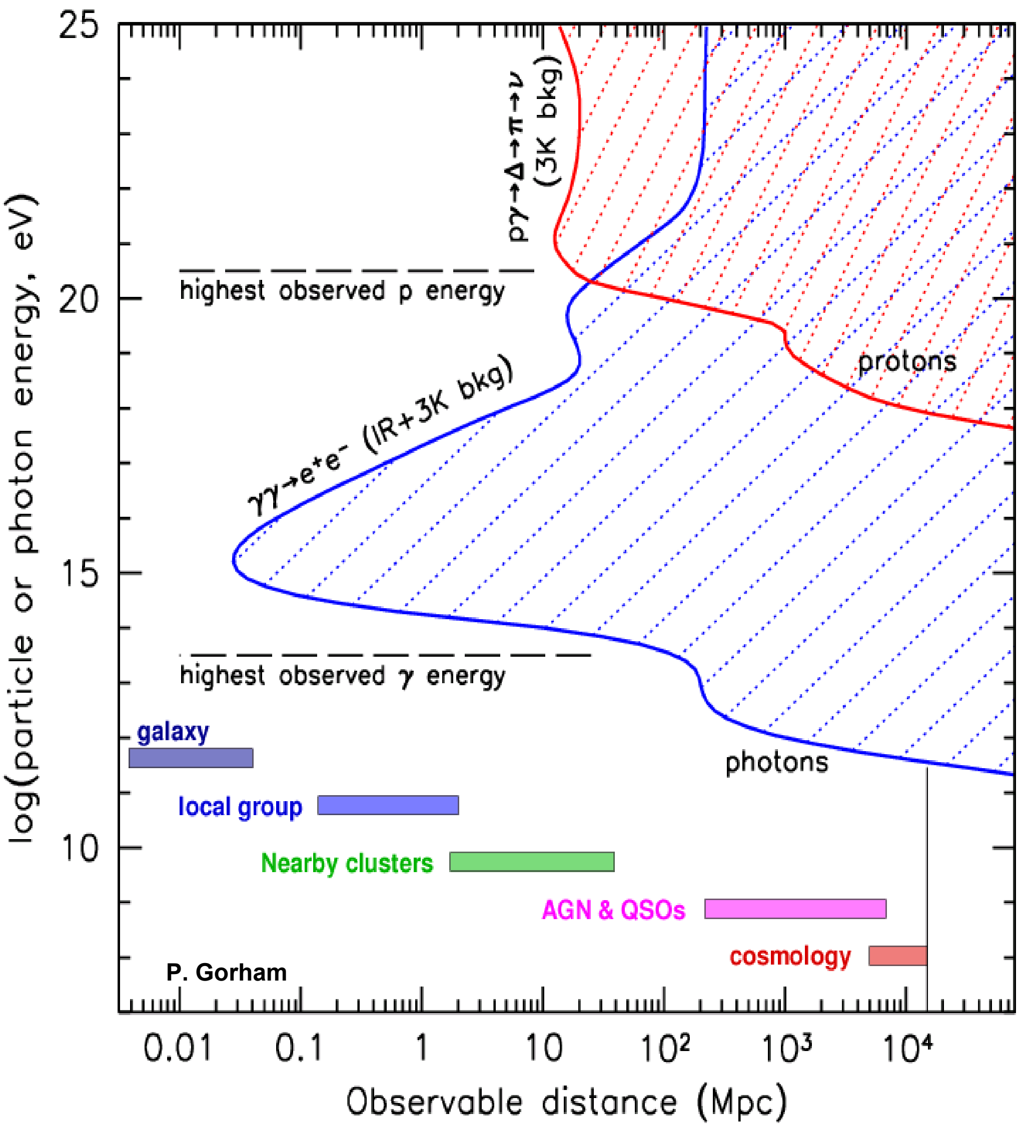
TeV – γ-ray astronomy: Summary

TeV gamma-ray astronomy is reality!

High Energy Neutrinos



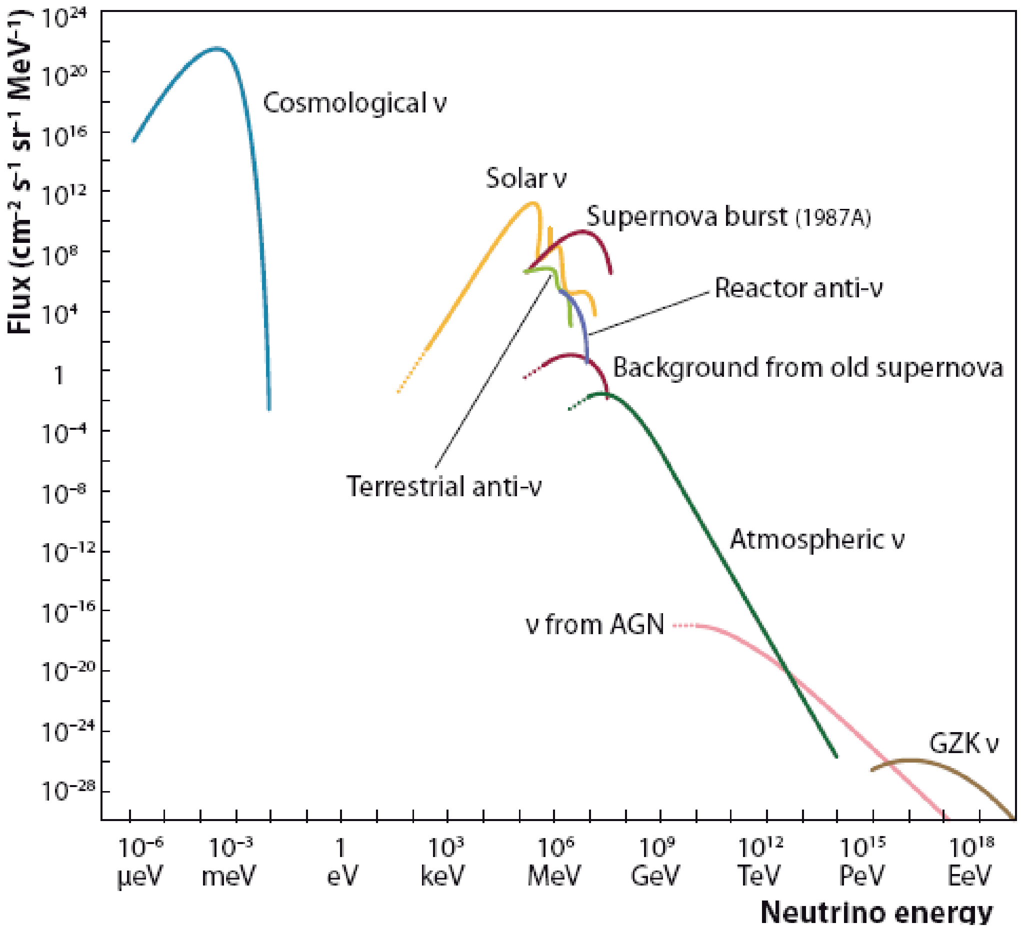
Motivation for the ν - approach



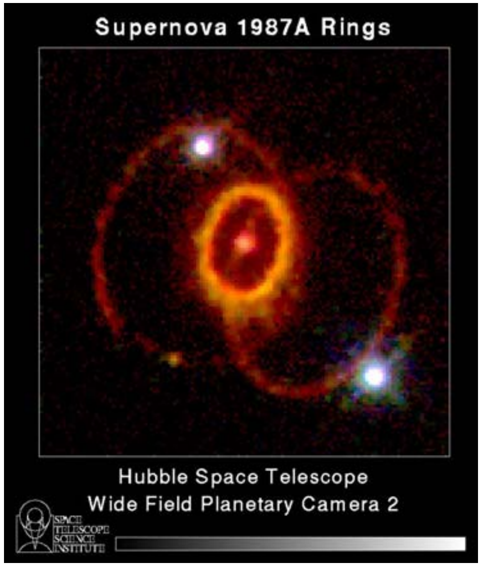
- **<u>Gammas:</u>**
  >30 TeV interaction with IR background
- **<u>Charged particles:</u>**
  - **Low energies: deflection in magnetic fields**
  - **High energies: GZK effect with CMB**
- **<u>Neutrinos:</u>**
  straight tracks from source
  But: needs huge detector volumes due to low cross-sections

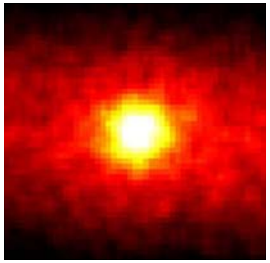
- **UHE neutrinos and HE photons are by-products of GZK and hadronic acceleration**

Cosmic Neutrinos



5 - 40MeV





> 1 GeV

Nothing seen so far…….

….except atmospheric ν from EAS

Neutrino Astronomy

- + Neutrinos penetrate the whole Universe
- + Neutrinos direction points back to the source
- + Neutrinos are produced at the sources of the cosmic rays
- + Neutrinos are not reprocessed at the sources
- + Neutrinos expected from dark matter particle annihilation

- - Low expected flux of extragalactic neutrinos
- - Small cross section
- - Needs gigantic detector volumes: water, ice, salt, rock, moon, ….

Observing Neutrinos

Fermi acceleration of protons gives particle spectrum

$$dN_p/dE \sim E^{-2}$$

Neutrino production at source:

p+γ or p+p collisions gives pions

$\pi \rightarrow \mu_\nu + \nu_\mu$

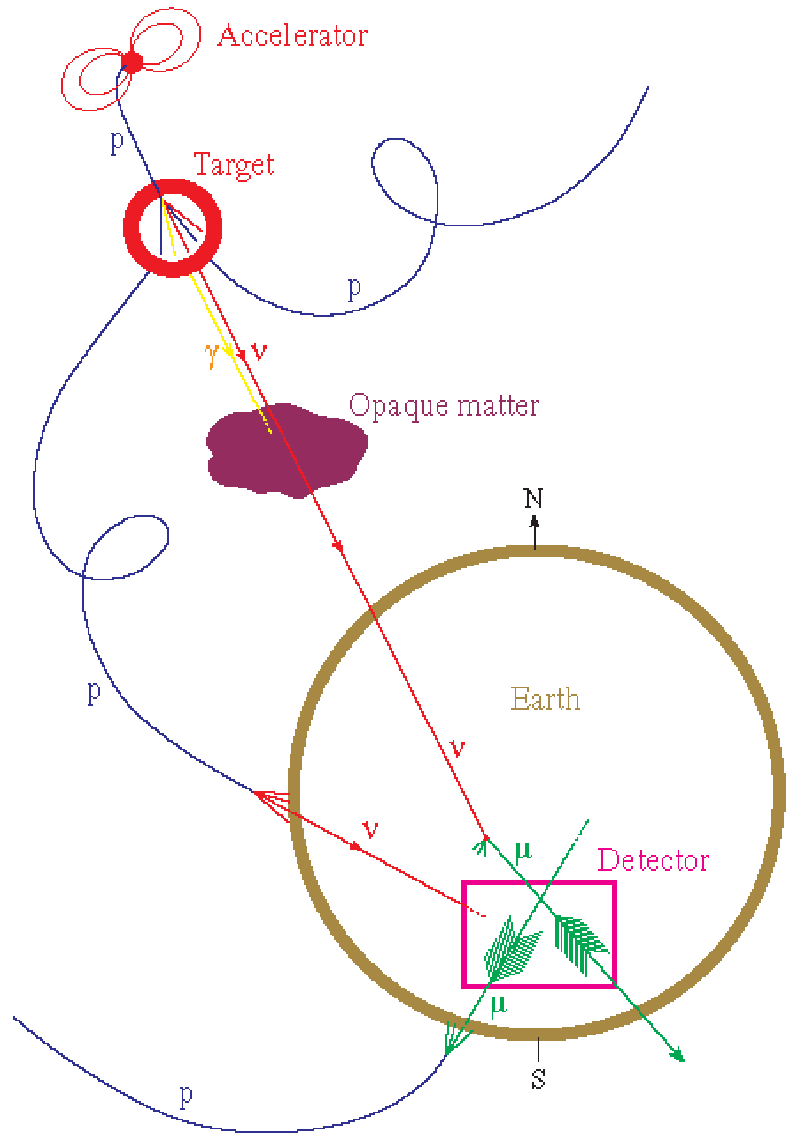
$\mu_\nu \rightarrow e^- + \nu_\mu + \nu_e$

Neutrino flavors:

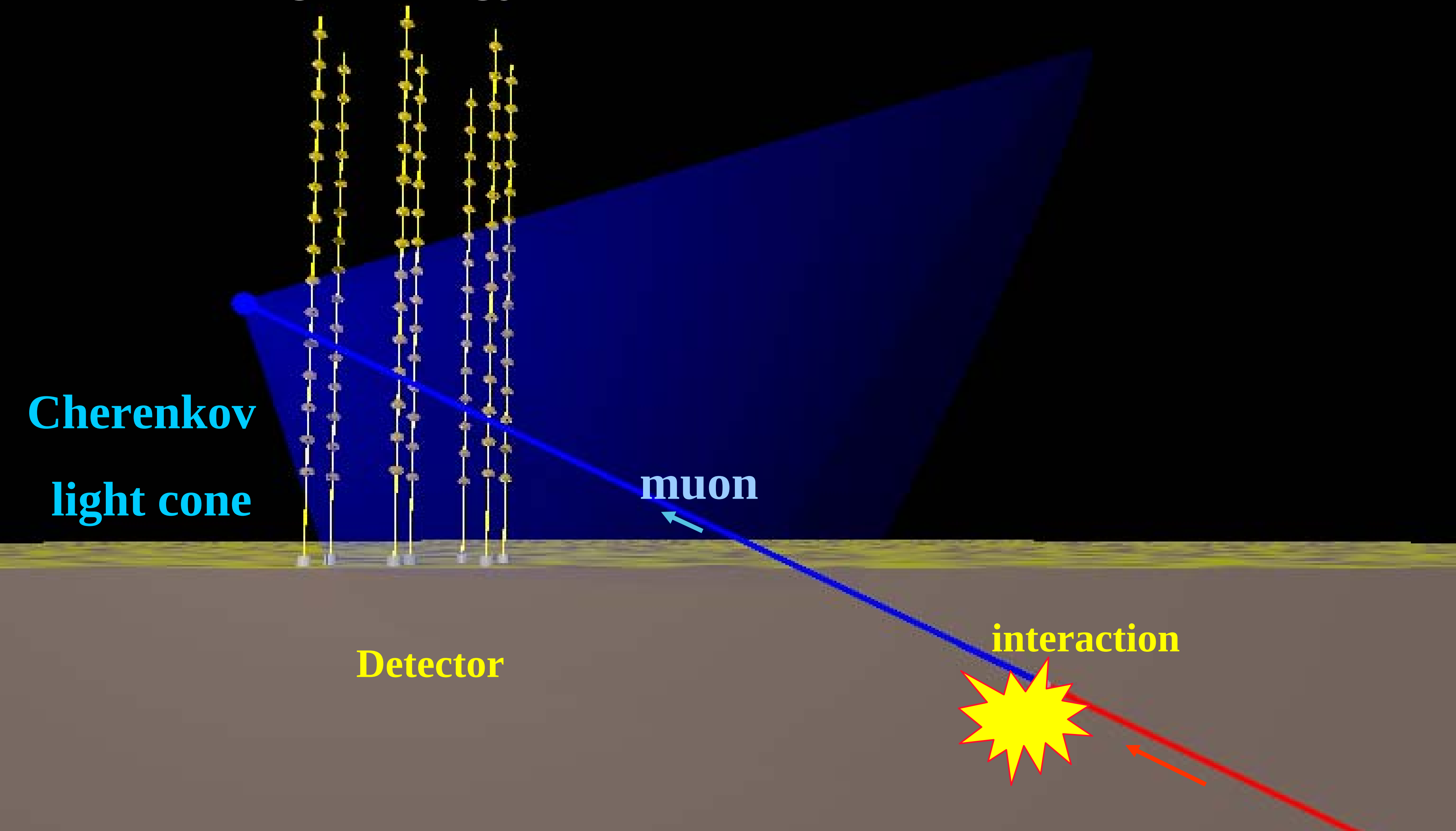
$\nu_e : \nu_\mu : \nu_\tau$

1:2:~0 at source

1:1:1 at detector (?)



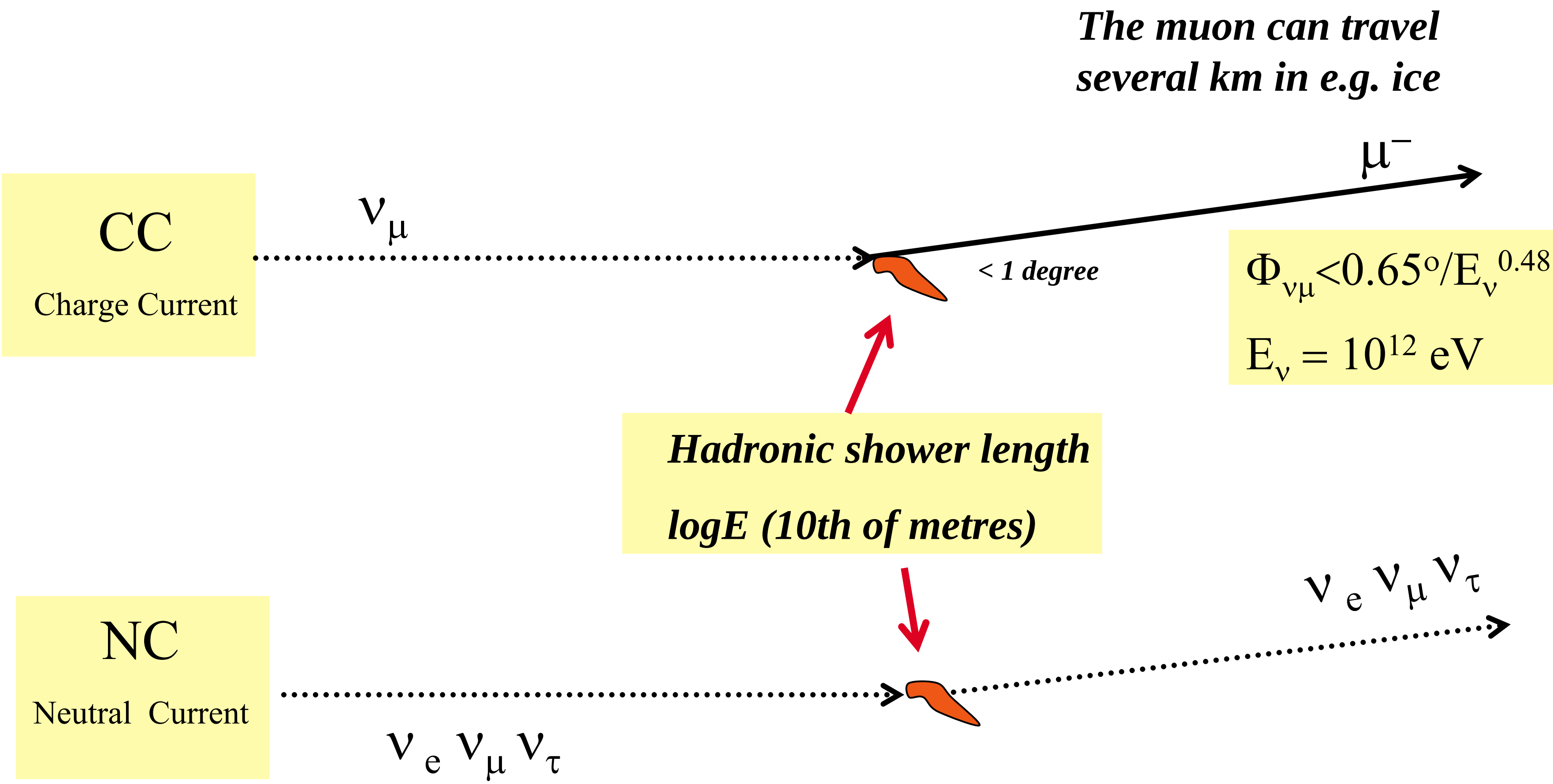
High-Energy Neutrinos: Detection principle



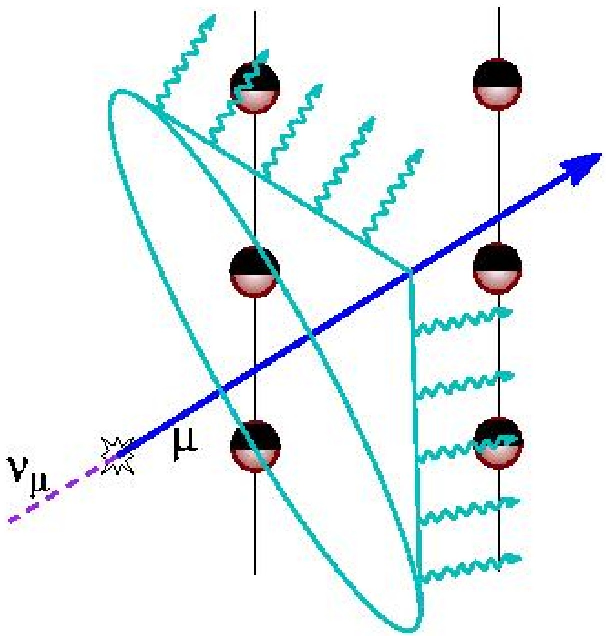
•The muon radiates blue light in its wake

•Optical sensors capture (and map) the light

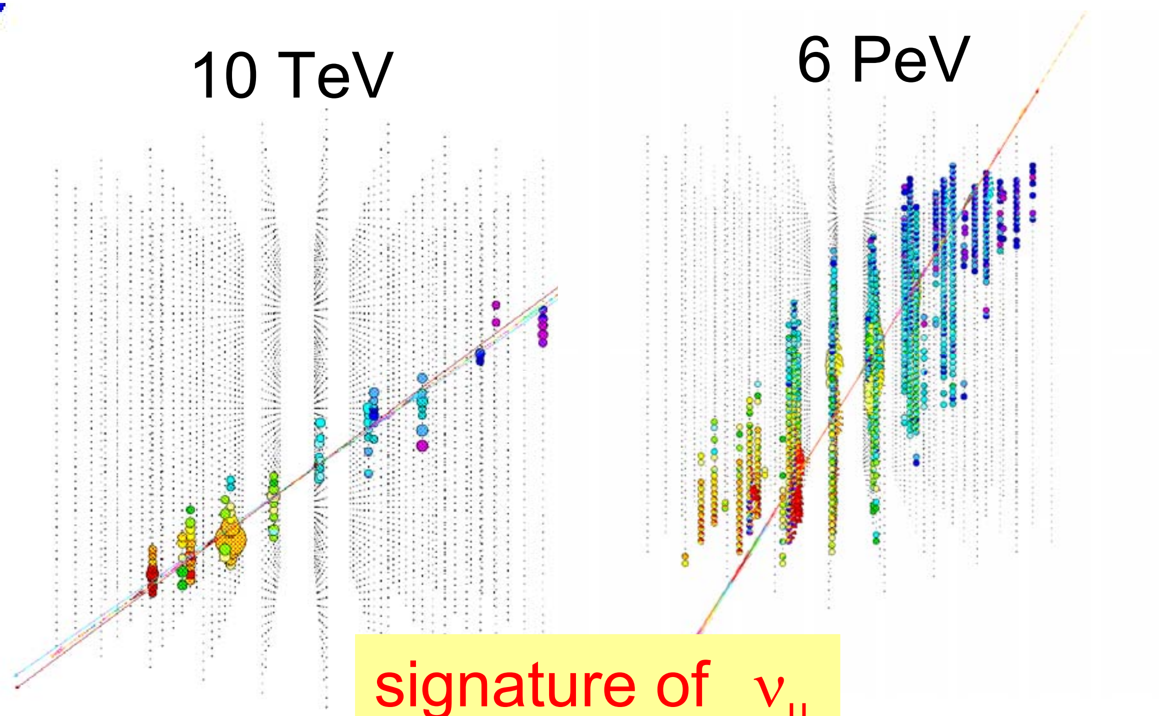
Neutrino interaction in ice and water



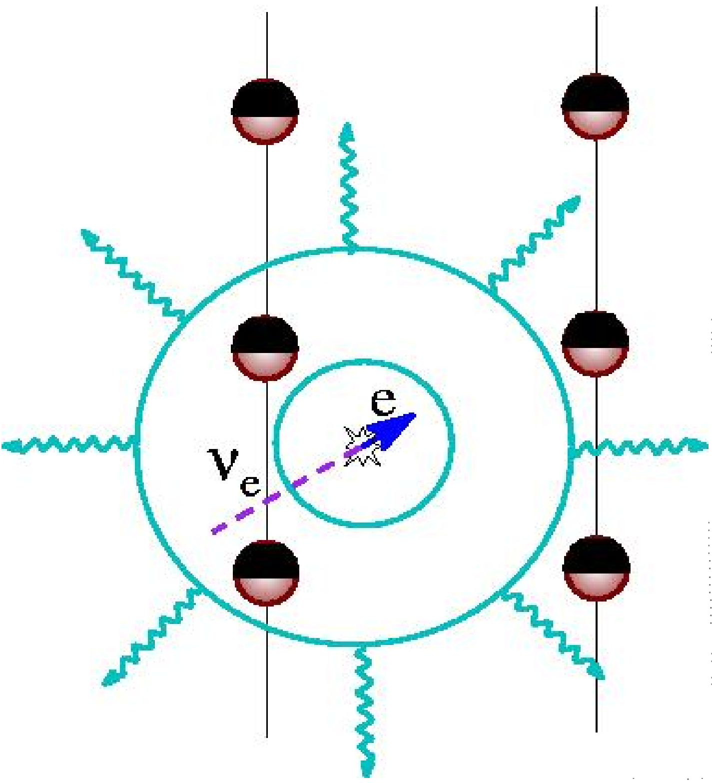
Neutrino signatures



Muon-tracks:
+ good pointing
+ large event rates due long muon range

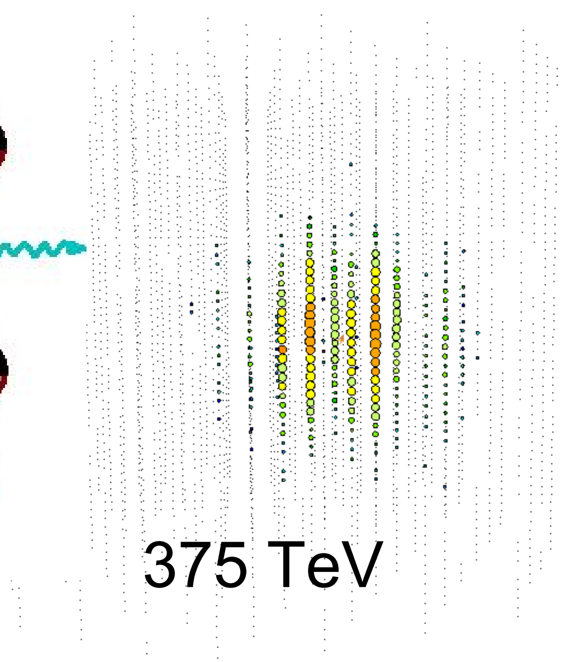


Neutrino signatures

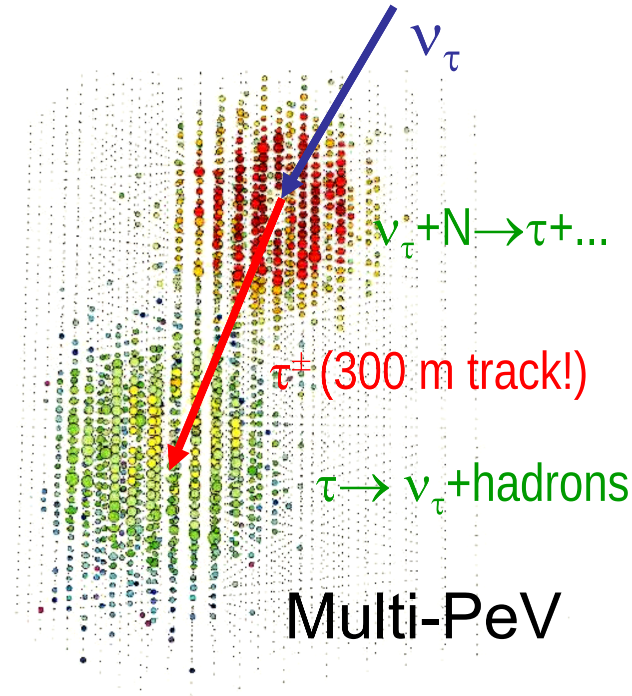


Particle shower (cascade)

- **+** ν_e , ν_t , (ν_m)
- **+ good energy resolution (~0.2 in logE)**
- **+ little background**



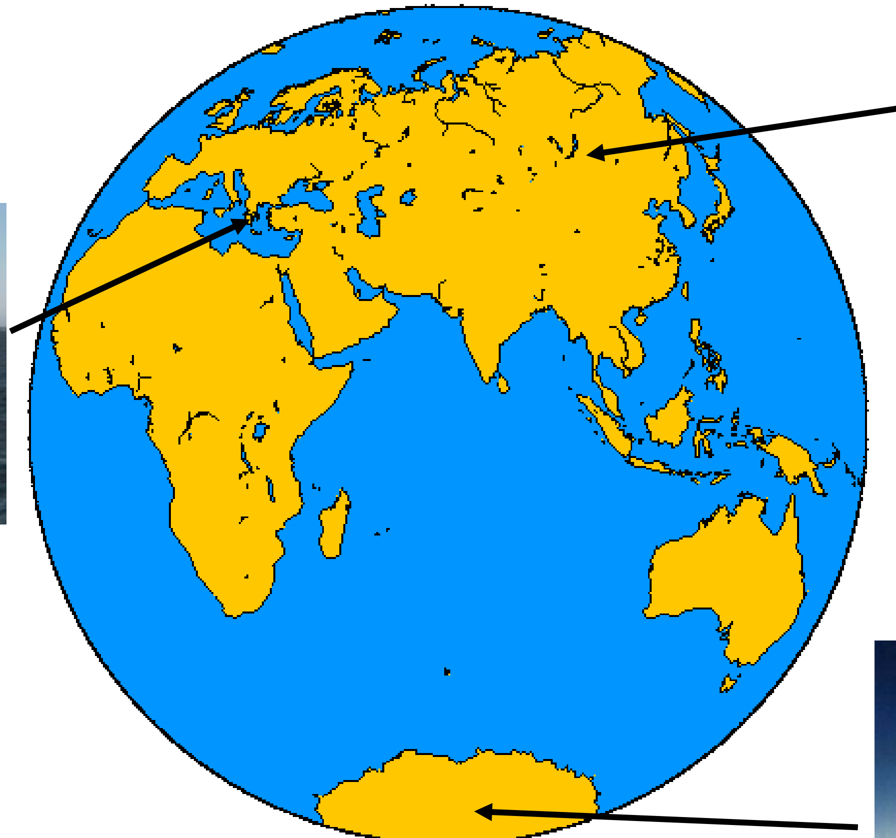
signature of ν_e



signature of ν_τ

High-Energy Neutrinos: Nowadays Experiments
$E_\nu = 10^{12}\text{-}10^{17}$eV

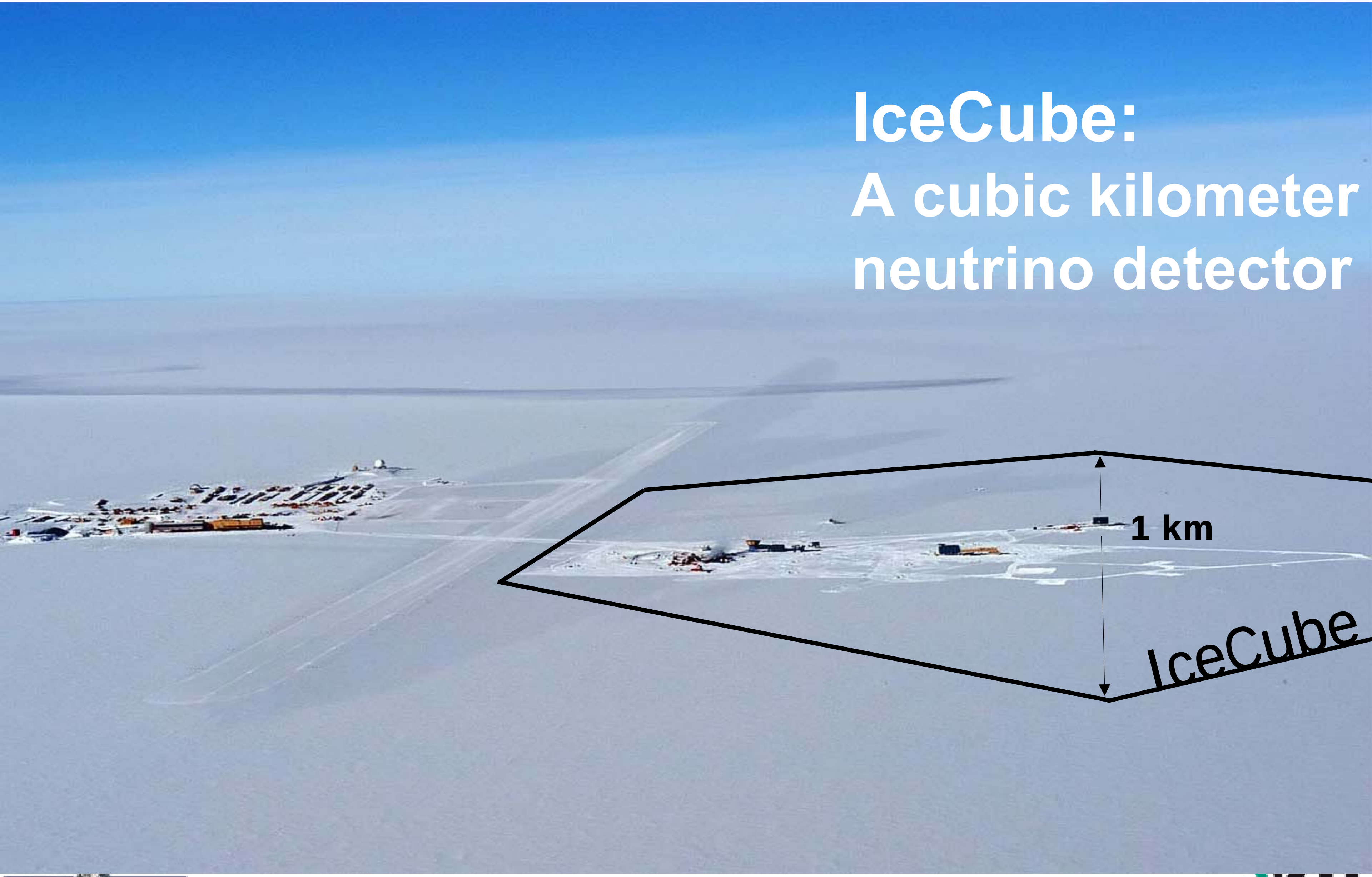
Mediterranean:
ANTARES, France
NESTOR, Greece
NEMO, Italy



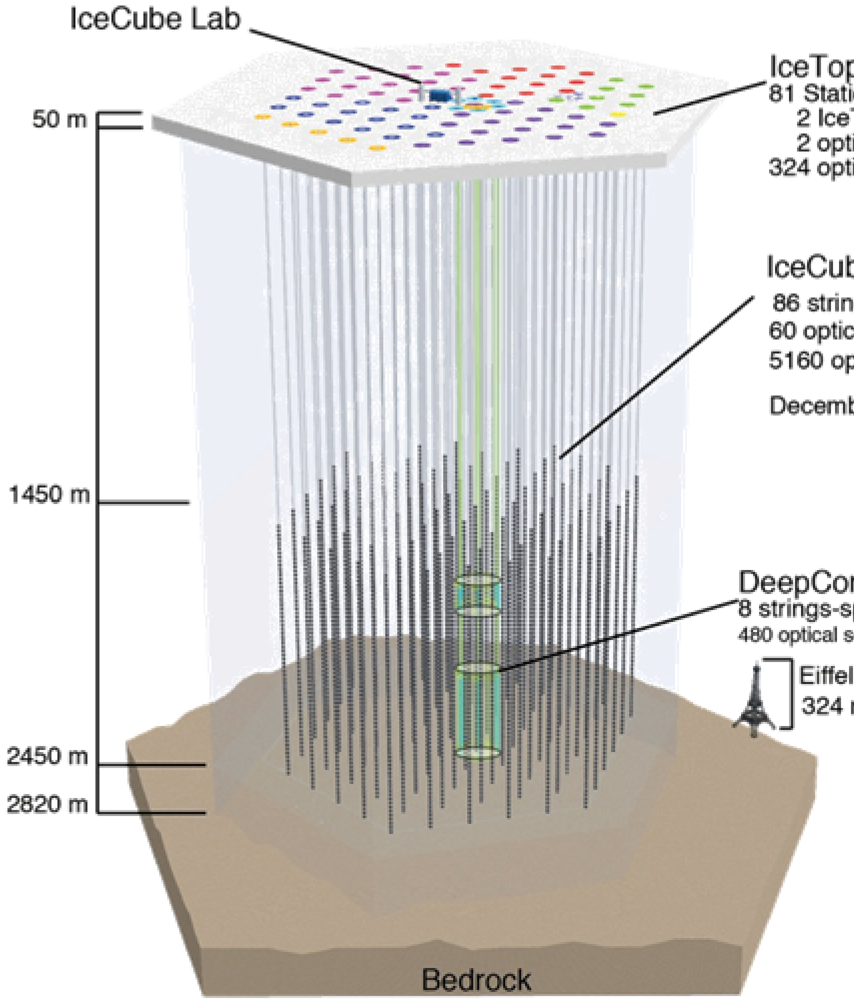
BAIKAL, Sibiria

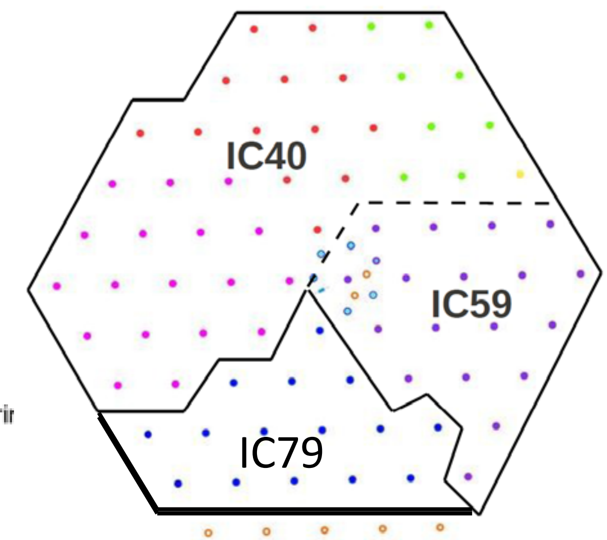
AMANDA & IceCube, South pole

IceCube:
A cubic kilometer neutrino detector



High Energy Neutrinos: the present future IceCube

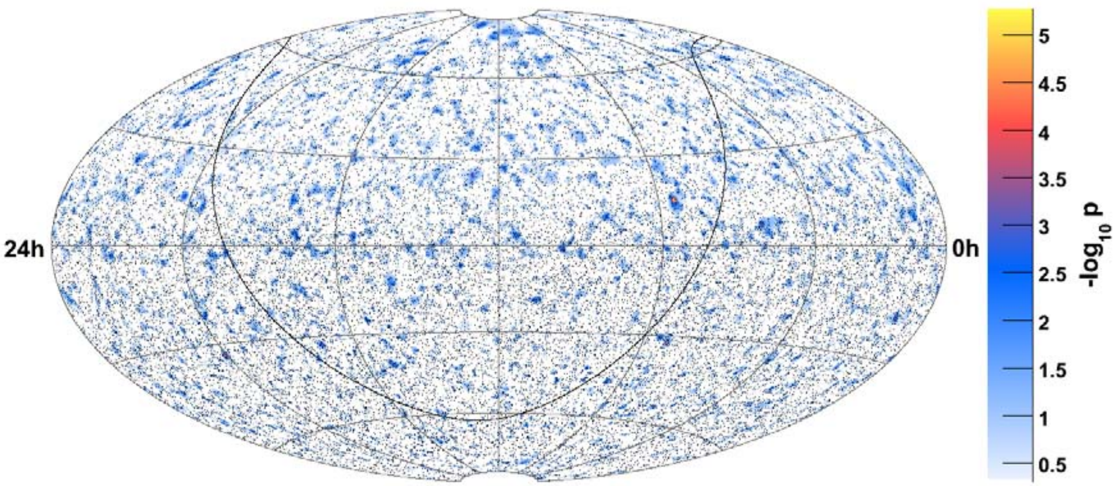


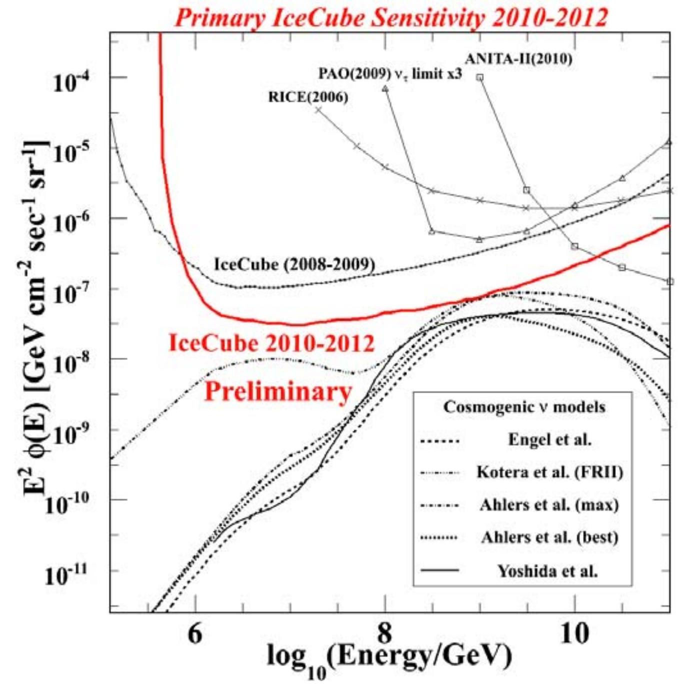


9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

70 times larger than AMANDA

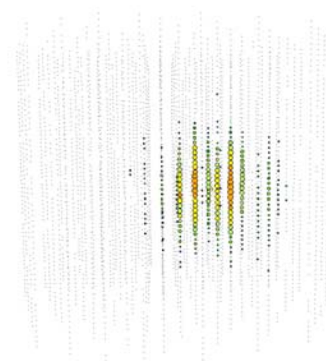
High Energy Neutrinos: actual result





IceCube-40 = 40 strings

(Live time 375 days, 14121 upgoing events, 22779 downgoing events)

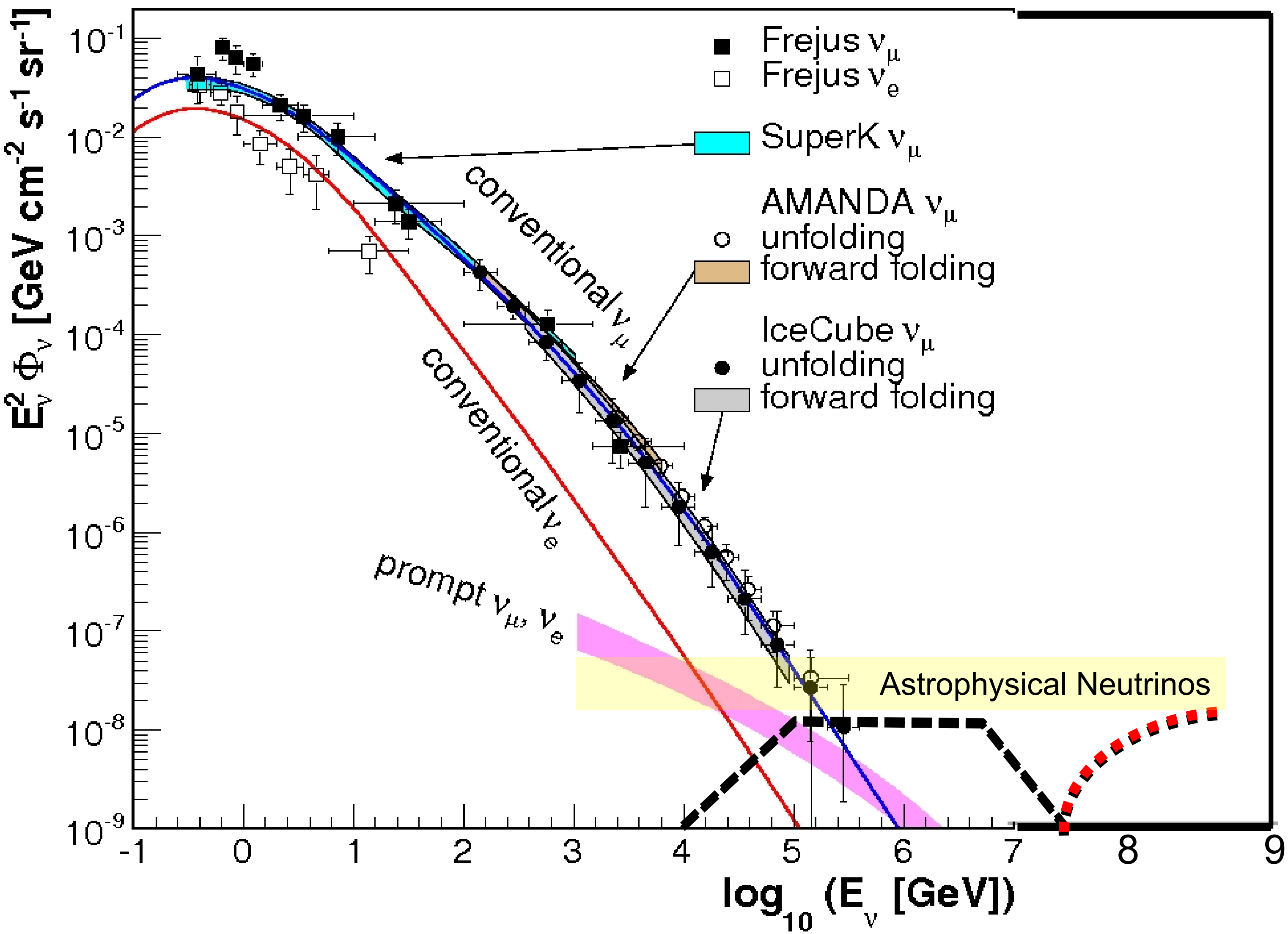


➔no statistically significant excess ➔ limits

(= Atmospheric neutrinos from air showers)

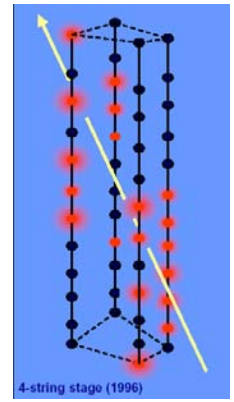
➔ 2 PeV cosmic neutrino candidates detected (cascades)

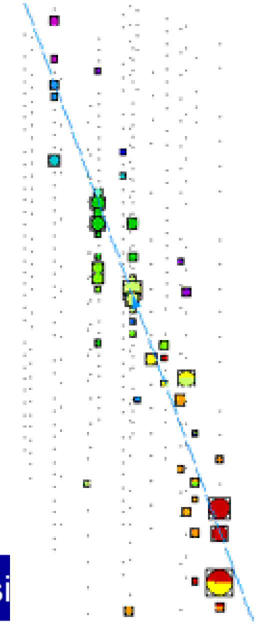
High Energy Neutrinos: actual result

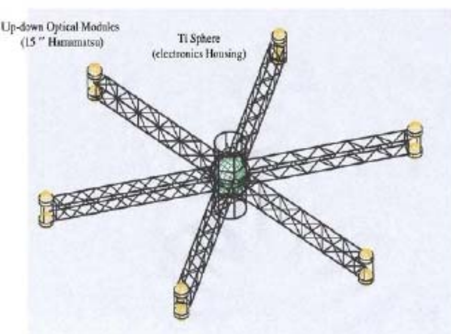


High Energy Neutrino Astronomy
present experiments

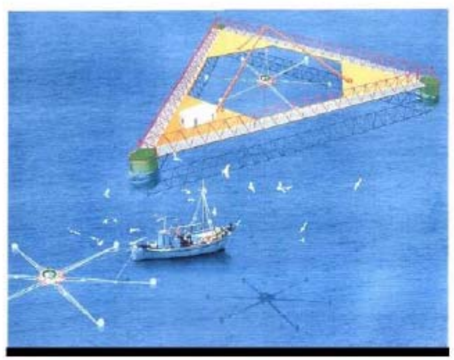
BAIKAL = Water-Cherenkov-Experiment
NESTOR = Water-Cherenkov-Experiment
ANTARES = Water-Cherenkov-Experiment



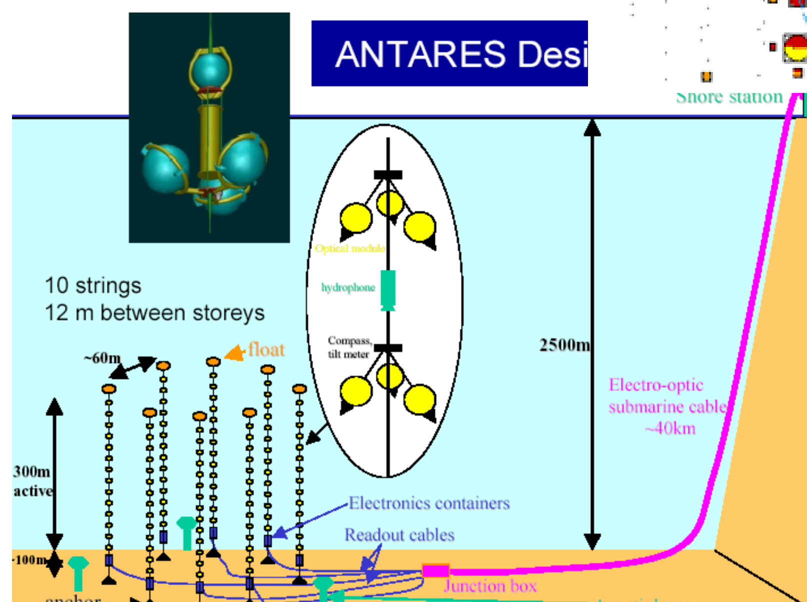




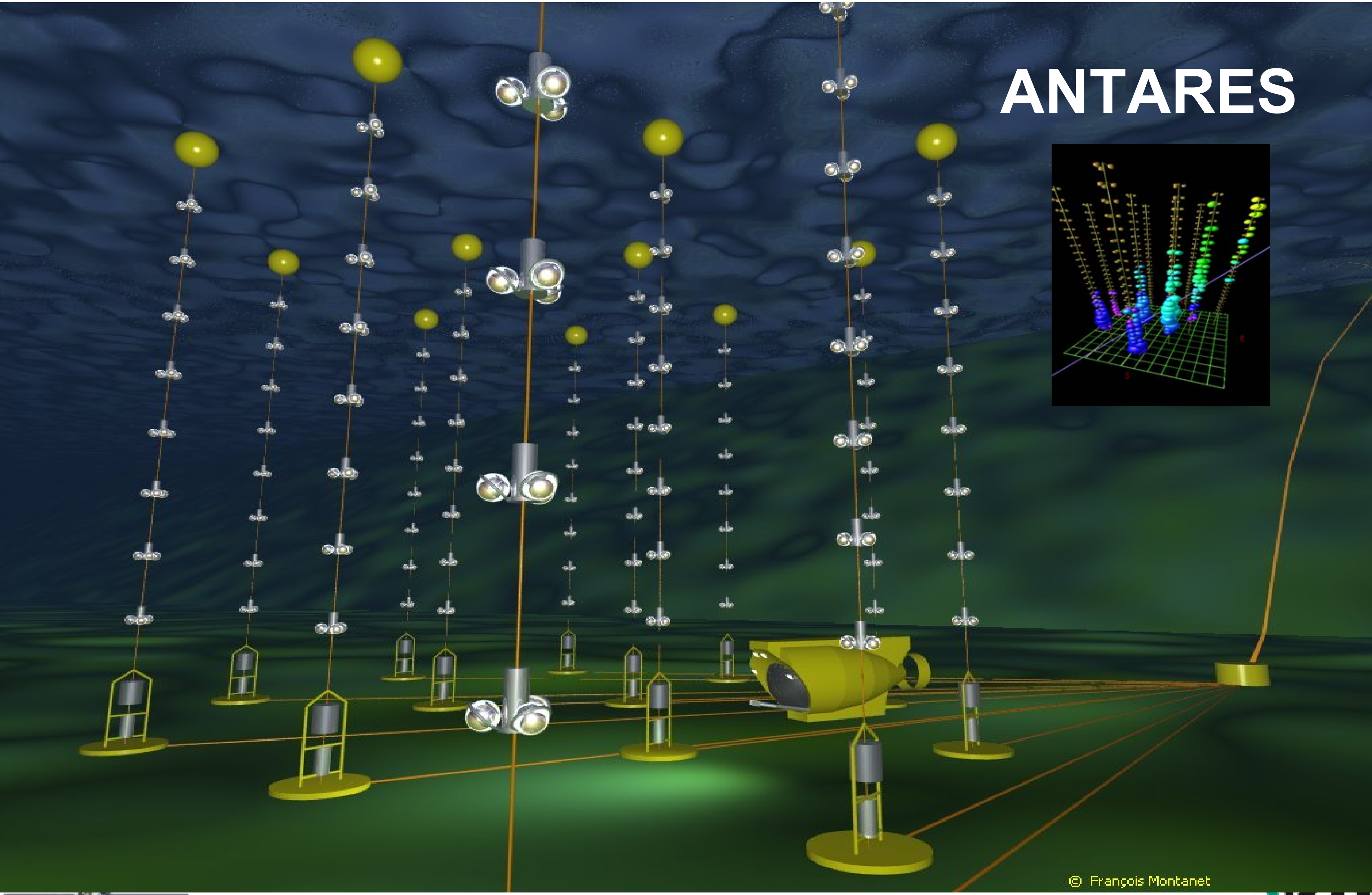
SHORT ARM (1/3 the usual diameter)
HEXAGONAL TITANIUM FLOOR



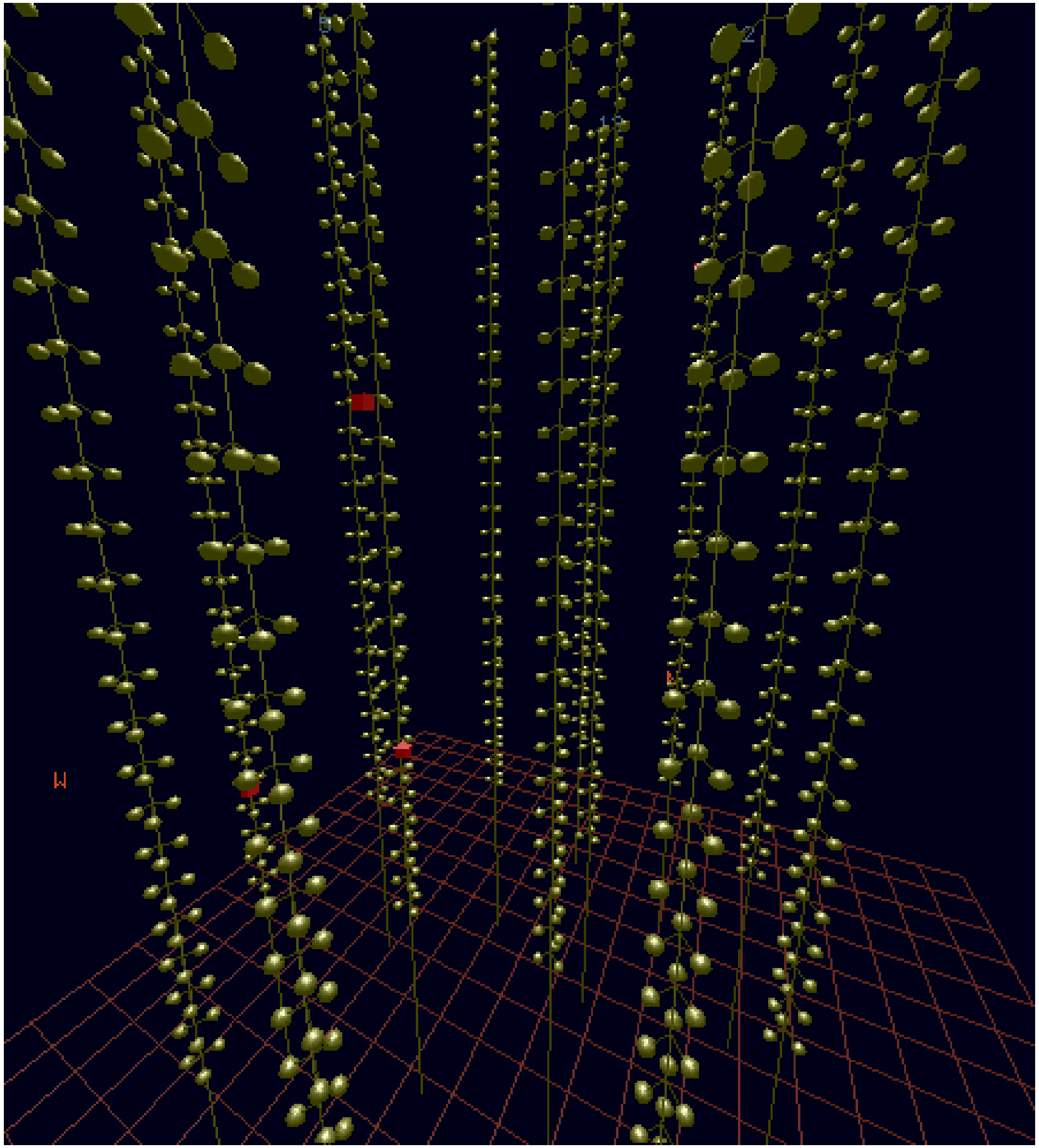
DELTA BERENIKE



High Energy Neutrinos: the present future

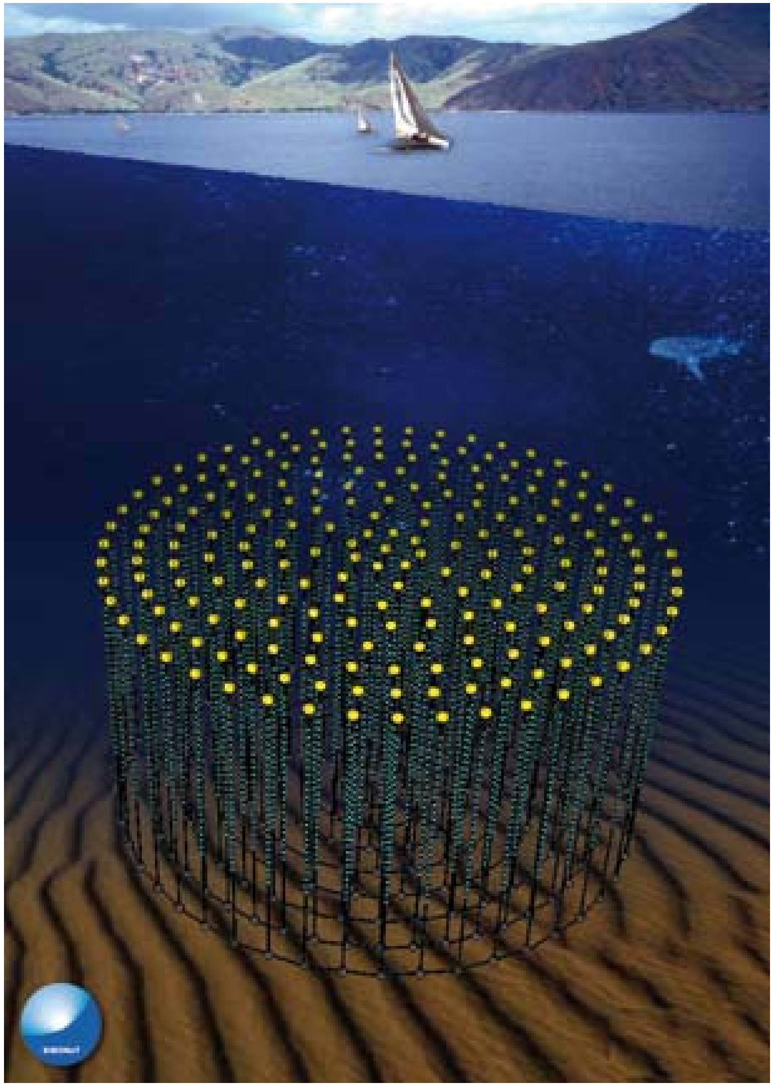


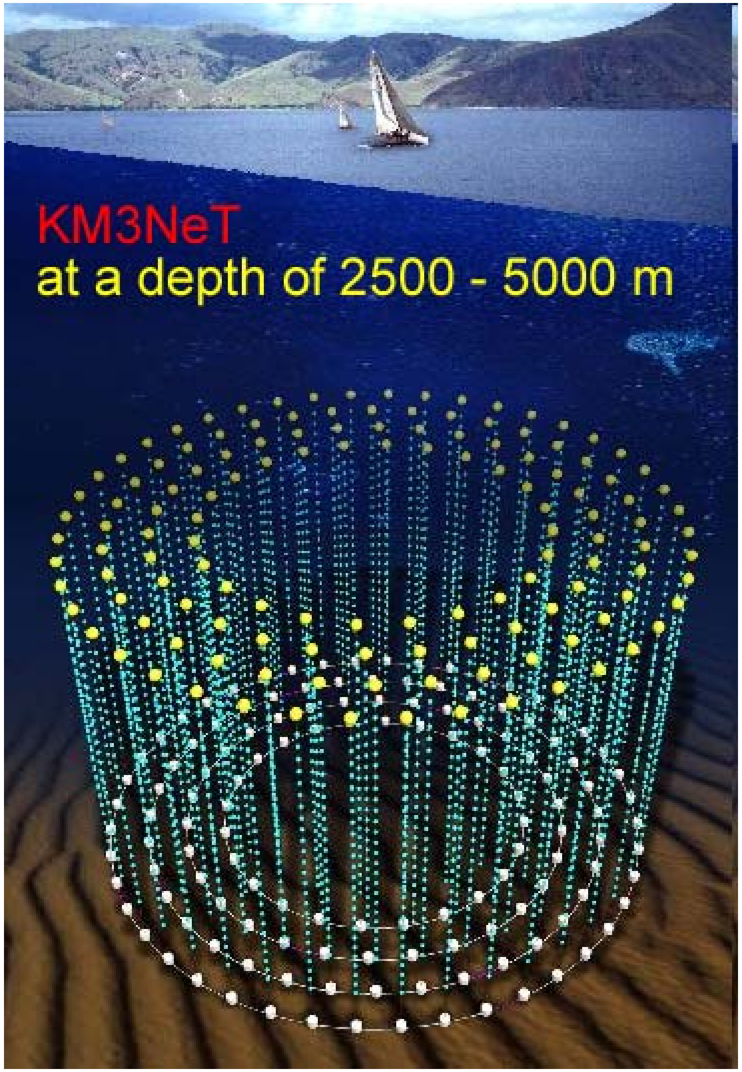
High Energy Neutrinos: the present future



ANTARES
hundreds of neutrinos

High Energy Neutrinos: the future: KM3Net
➔ high-energy neutrino astronomy

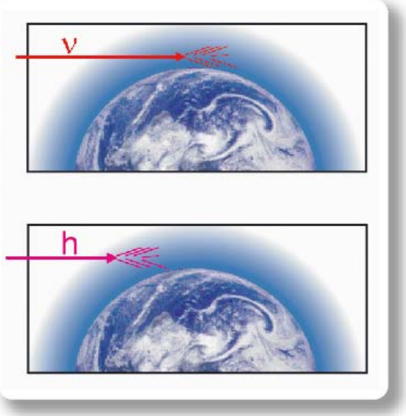




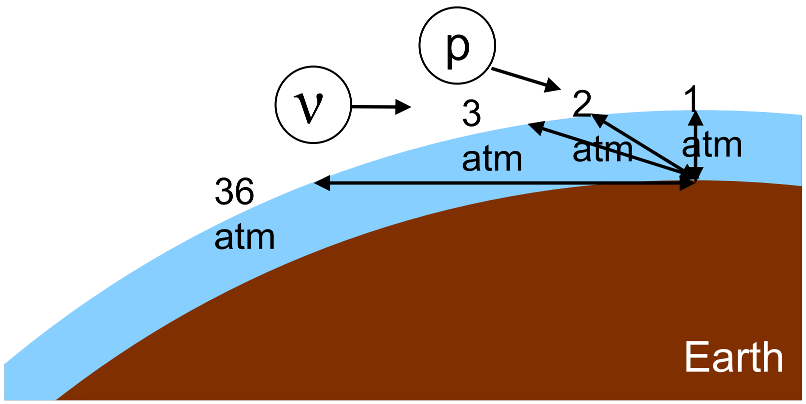
Karlsruhe Institute of Technology

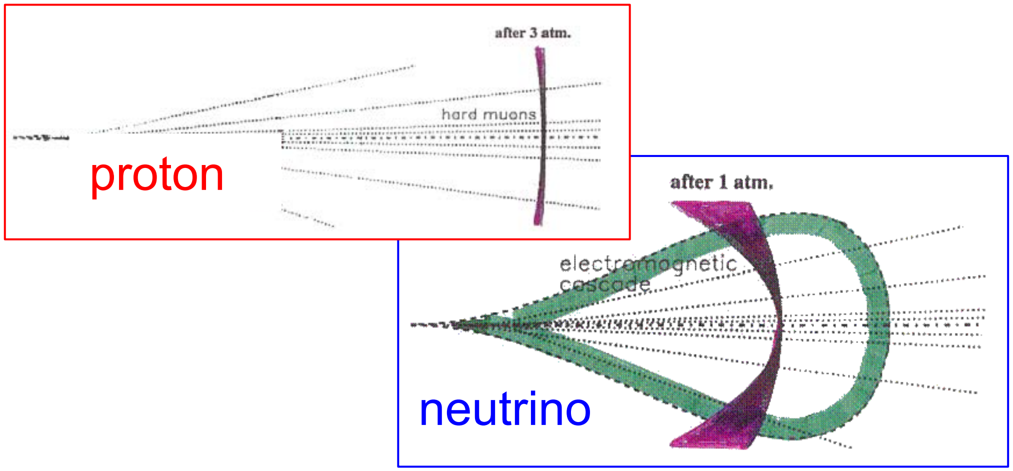
Neutrino search at Auger: horizontal air showers

$E_\nu = 10^{17}\text{-}10^{20}$eV

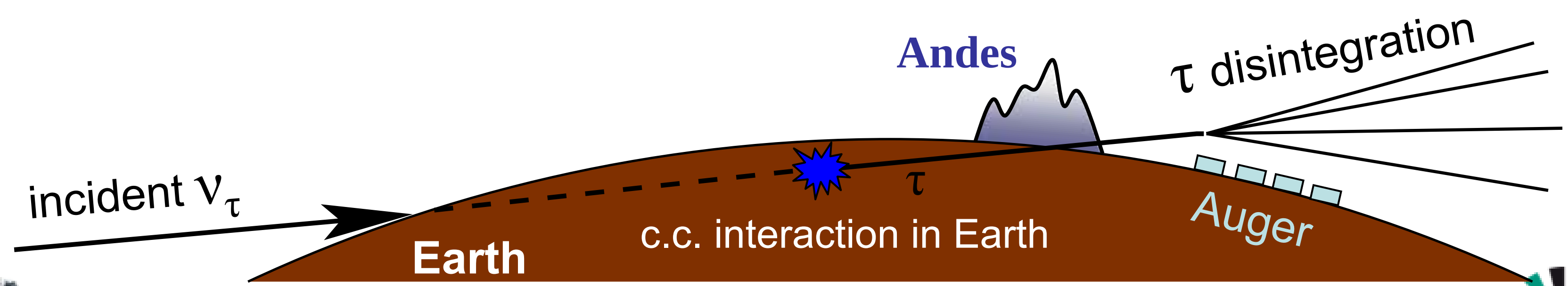


nearly horizontal air showers from extremely high energy ν_e or ν_μ neutrinos



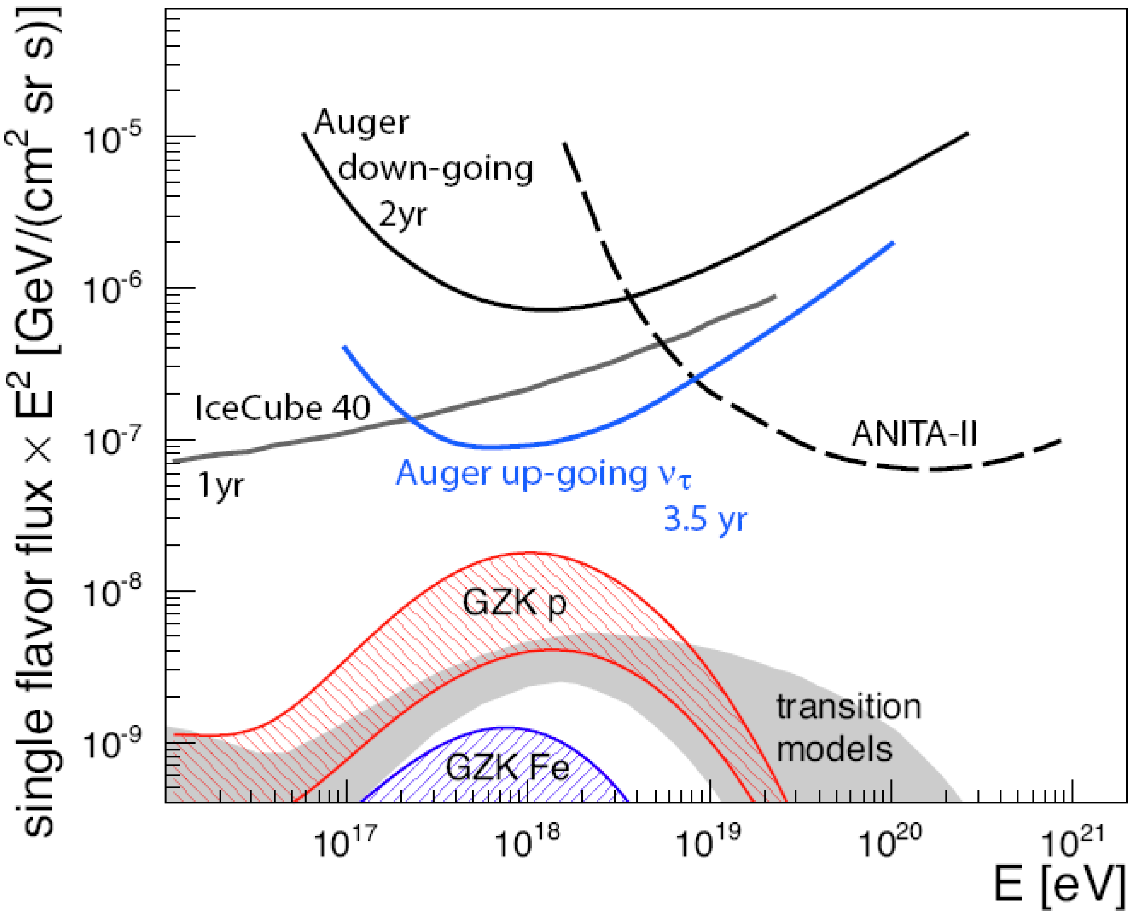


air showers from skimming ν_τ neutrinos



Limit on flux of neutrinos in UHECR flux

Horizontal or Earth skimming EAS with electromagnetic component



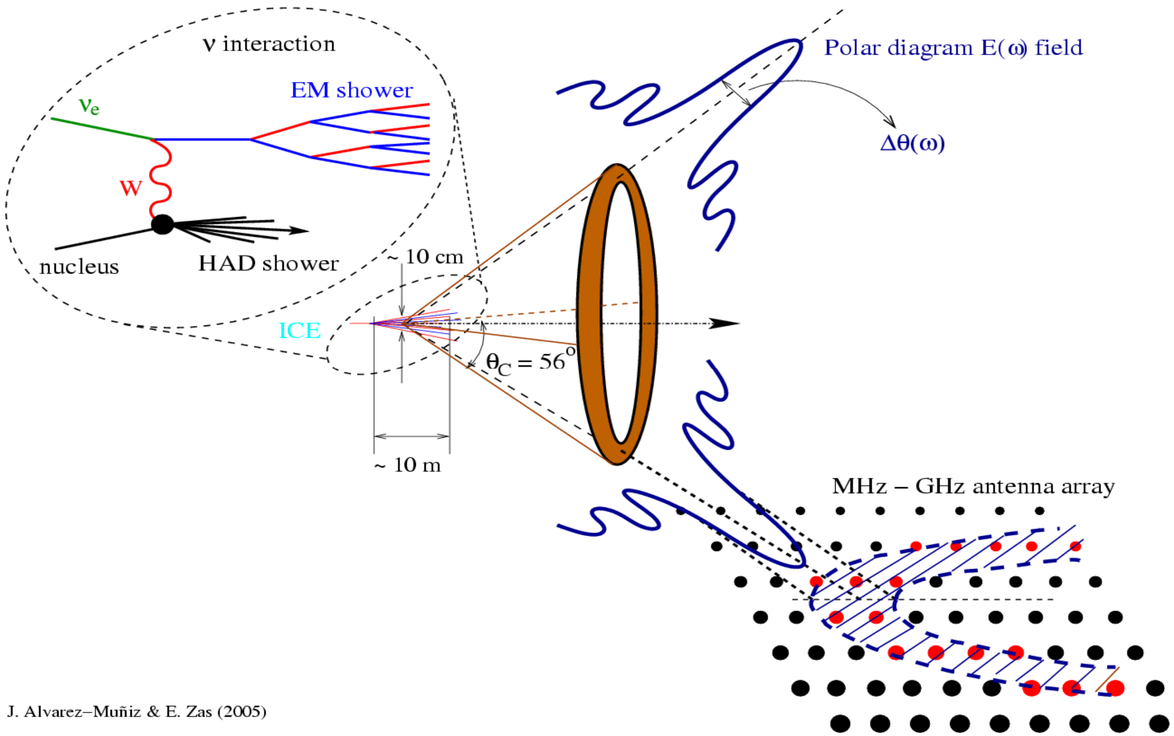
PRL 100 (2008) 211101
ApJ (2012) accepted

No Neutrinos detected

Radio detection of Neutrinos
Advantages

- Strong emission process given in nature by the so-called Askaryan-effect
- Large attenuation lengths (up to ~km) for radio emission in different dense media like Antarctic ice or salt in salt domes
- Large detector volumes can be equipped with relatively small detector sampling
- Different concepts for the detection of high-energetic neutrinos by their radio emission in dense media are available

Askaryan mechanism



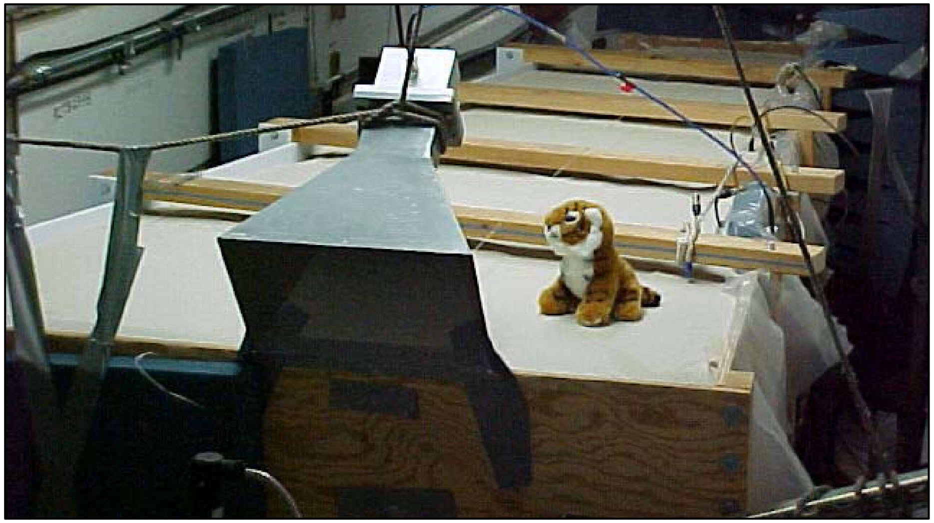
J. Alvarez–Muñiz & E. Zas (2005)

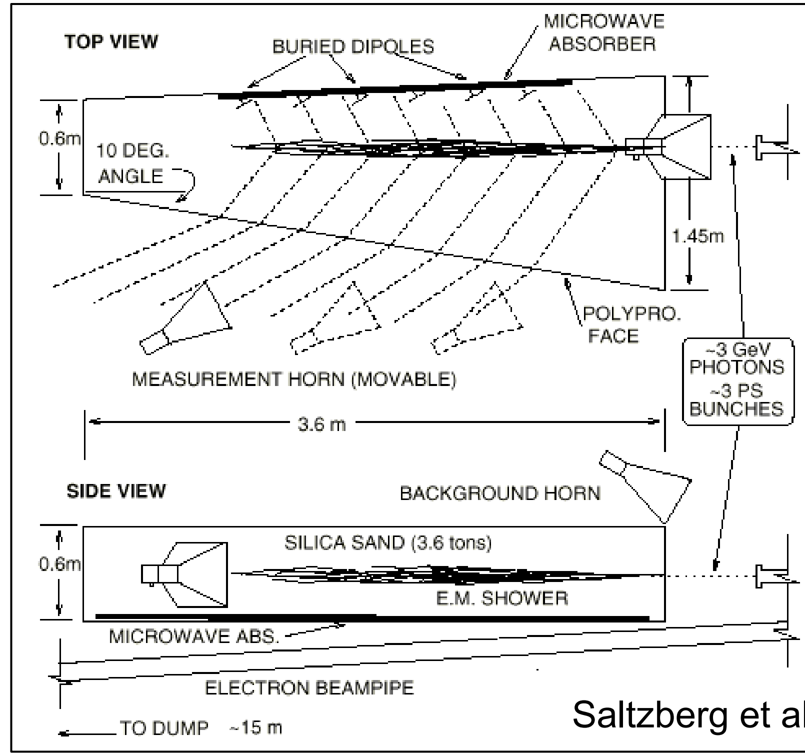
G.A. Askaryan

- **Neutrino interacts with detector material and generates an electromagnetic shower**
- **The electromagnetic shower has more electrons than positrons**
- **Charge enhancement propagates in the medium with $v > c_{med}$**
  → Radio-Cherenkov emission

➔ Dominant mechanism in dense media

Askaryan mechanism: proof at accelerators



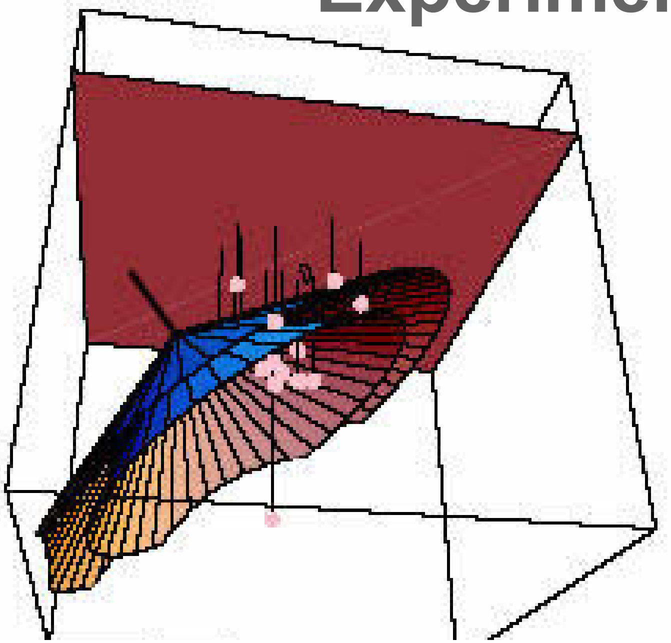


Saltzberg et al.

- **Large bundle of photons in a 3,6 t sand-target (also ice)**
- **measures 2 GHz radio emission**

➔experimental proof of the Askaryan-effect

Experiment: RICE @ AMANDA

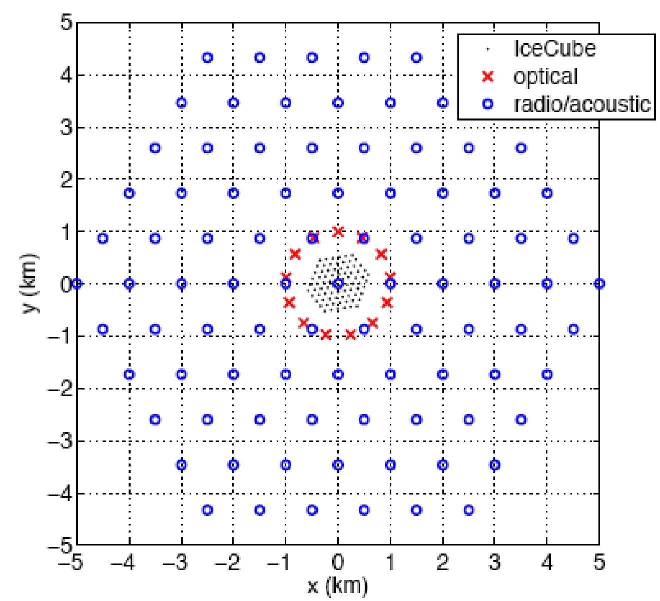


RICE:

- **17 receiver and 5 transmission antennas in 200 x 200 x 200 m³ above AMANDA**
- **Frequency-range 200-500 MHz**
- **DAQ since 1999**
- **Limits from 1,5 years data**

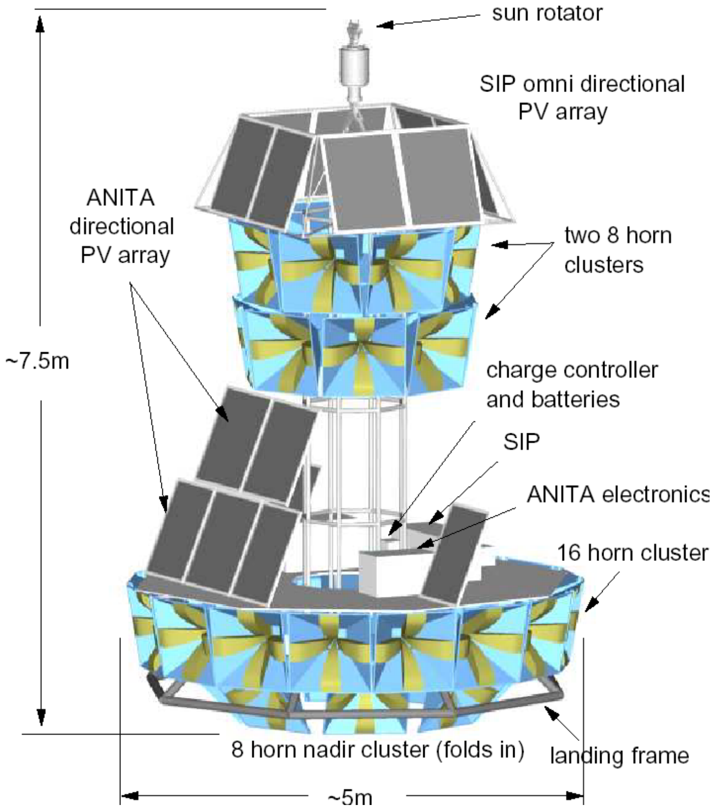
Planned: AURA

- **Radio measurements in ICECUBE**



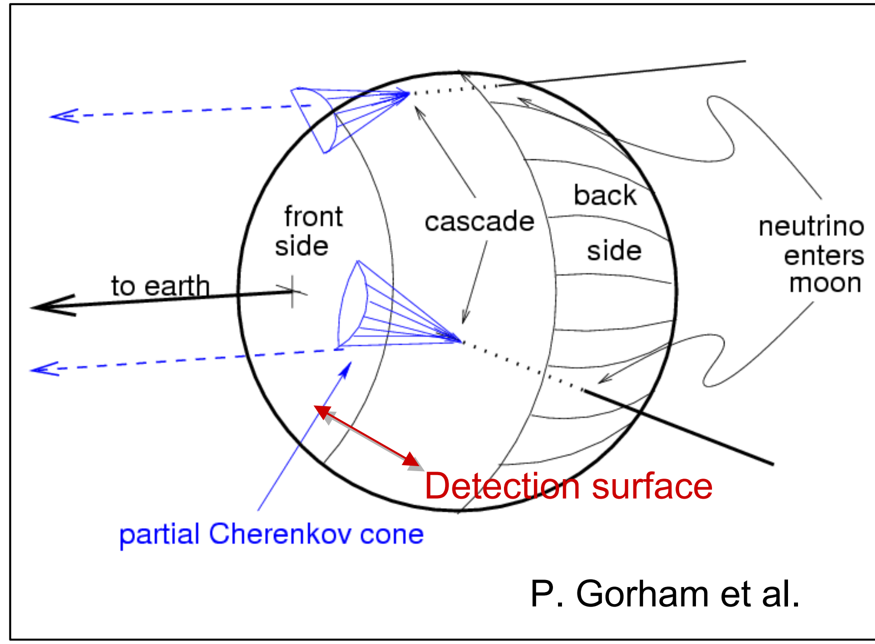
Kravchenko et al, Astrop Phys 20(2003)195

Experiment: ANITA



- **Balloon experiment watching a huge detector volume (200-1200 MHz)**
- **first test: ANITA Lite**
- **45 day flight planned for end of 2006**

Experiment: GLUE

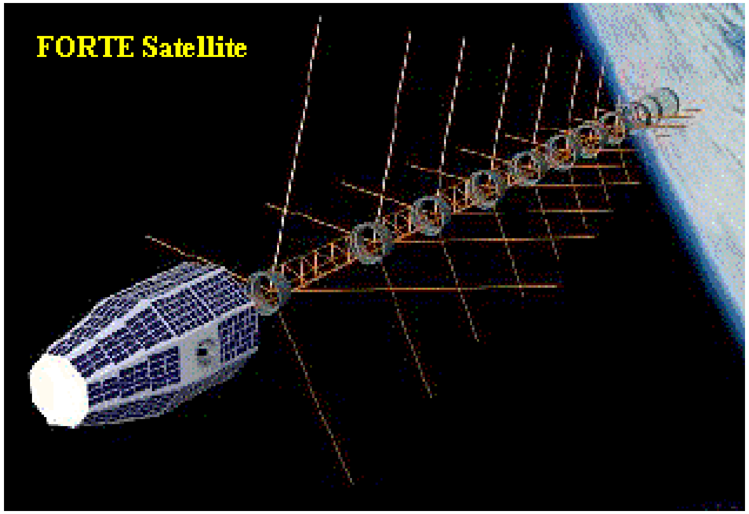


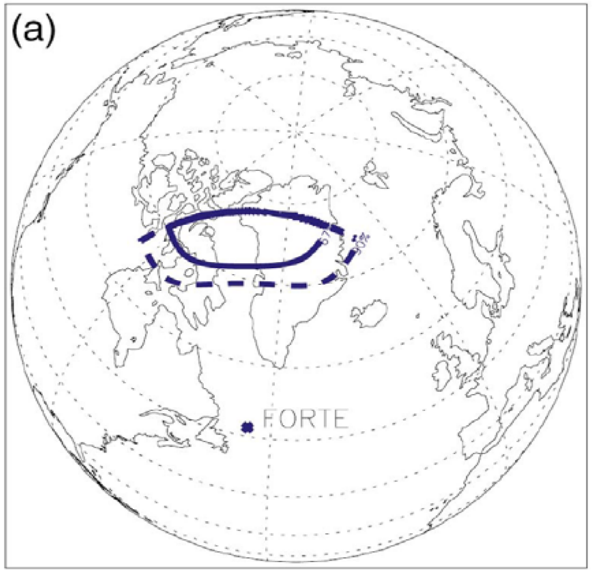
- **Use moon as detector volume for neutrino detection $>10^{20}$ eV**
- **Frequency 2.2 GHz**
- **Radio-attenuation length is only ~10 m at 2,2 GHz**
  - **➔ Only events which interacts close to the moon surface**
- **All together ~123 hours observation time**
- **No results, only limits**

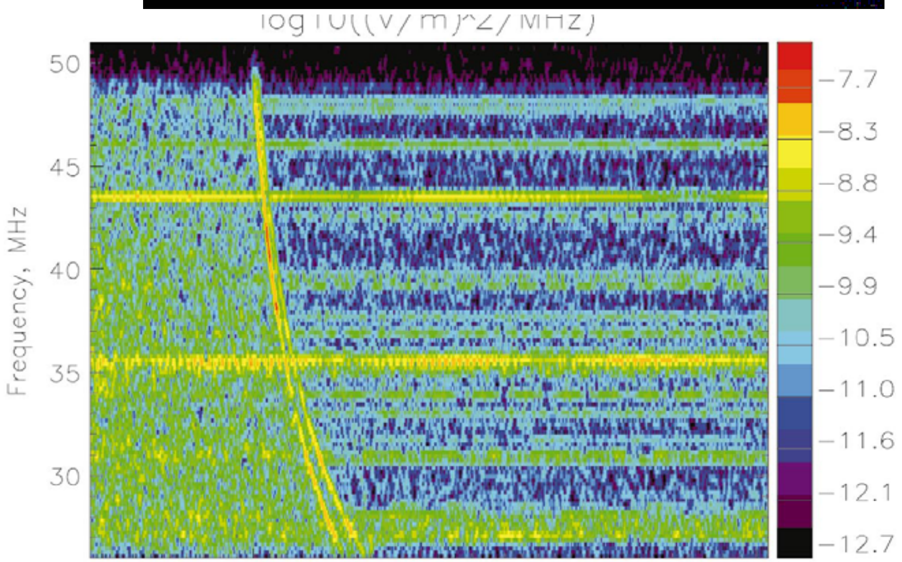
Gorham et al, Phys Rev Let 93(2004)041101

Experiment: FORTE

- **Records Cherenkov emission of particle cascades in ice**
- **Large detector volumes**
- **Frequency 30-300 MHz**
- **Event examples (not neutrinos, due to length of pulse 10µs)**
- **No results, only limits**



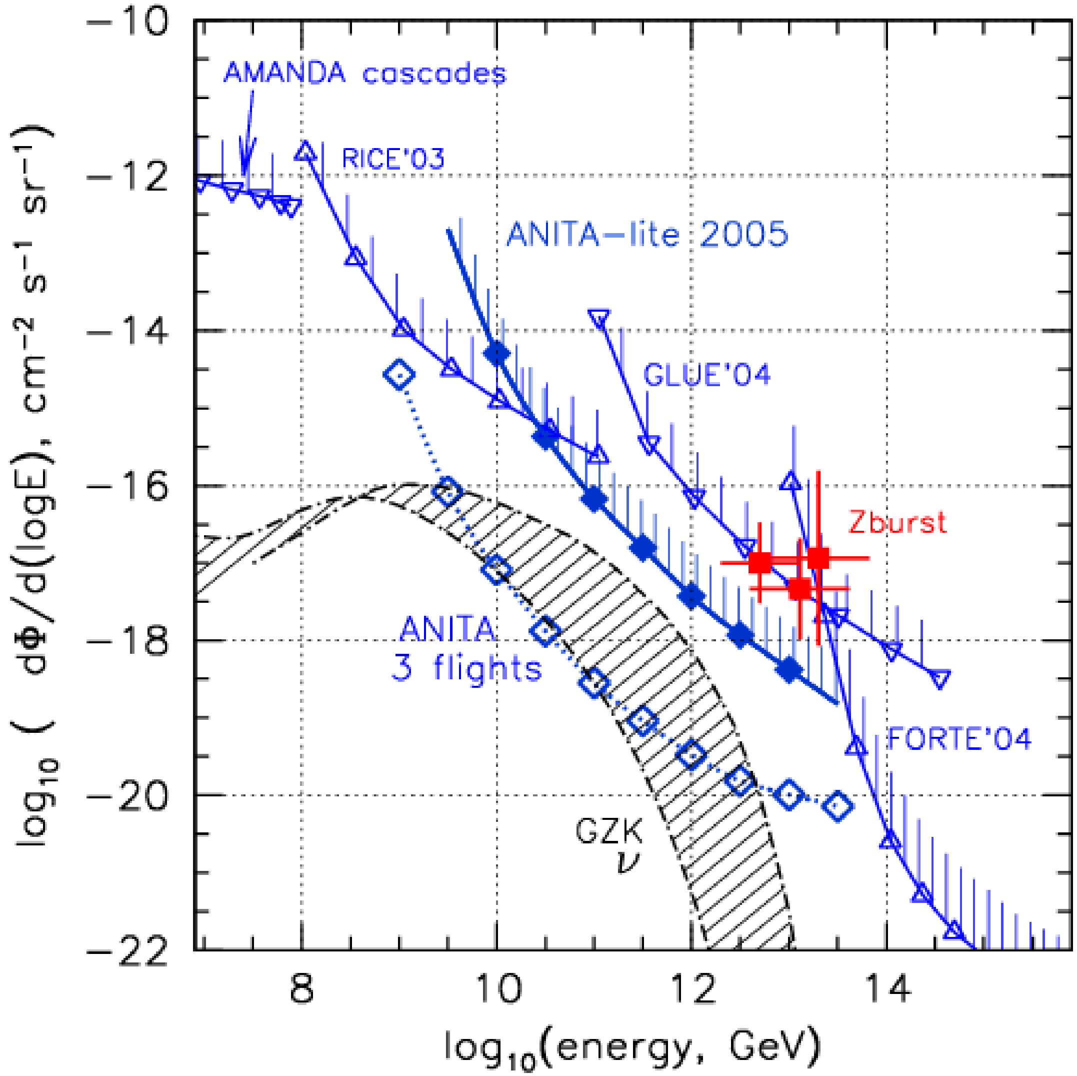




Lehtinen et al, Phys Rev D 69(2004)013008

Experimental Limits

- Limits for ANITA lite
- Limits for GLUE
- Limits for RICE
- Limits for Forte
- Expected limits for ANITA

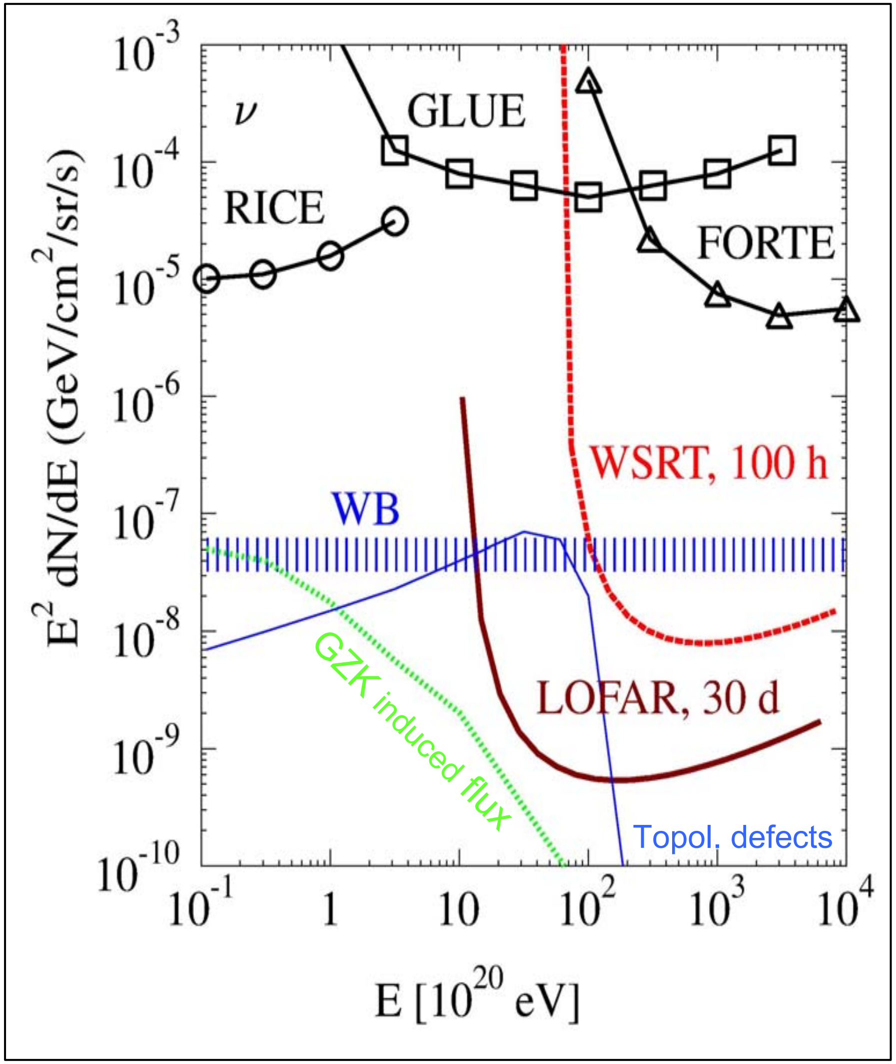


P. Gorham et al.

Gorham et al, Phys Rev Let 93(2004)041101

Performed Experiment: NuMoon

- Moon observation at 120 – 175 MHz with WSRT, later LOFAR
- At these frequencies attenuation length ~100 m and broader emission pattern ➔ larger detector volume than GLUE
- Detection of extreme high energetic neutrinos (and Cosmic Rays) >10^{21} eV



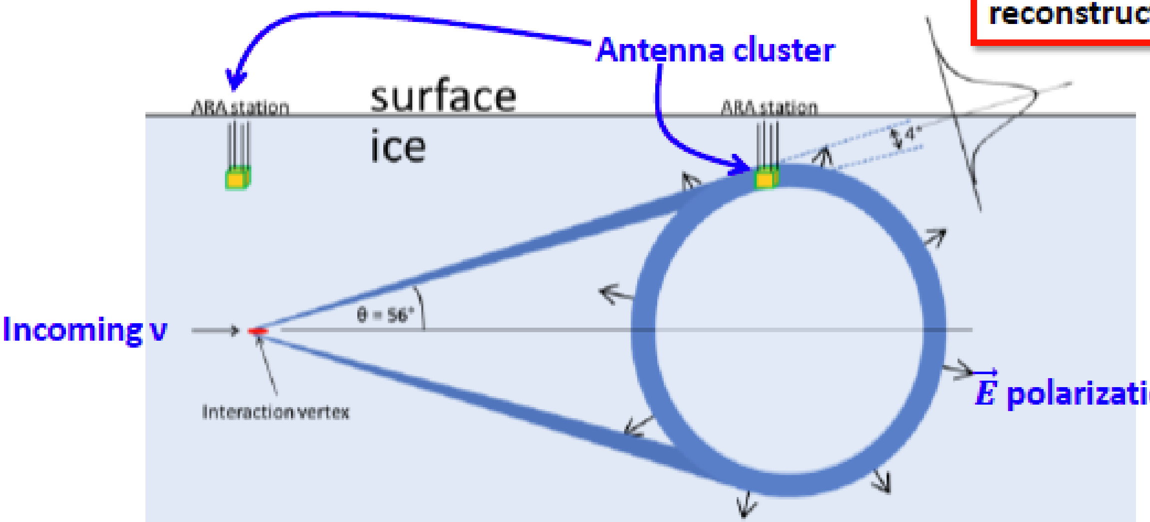
Scholten et al. (NuMoon Collab.) 2006, Astropart. Phys., in press

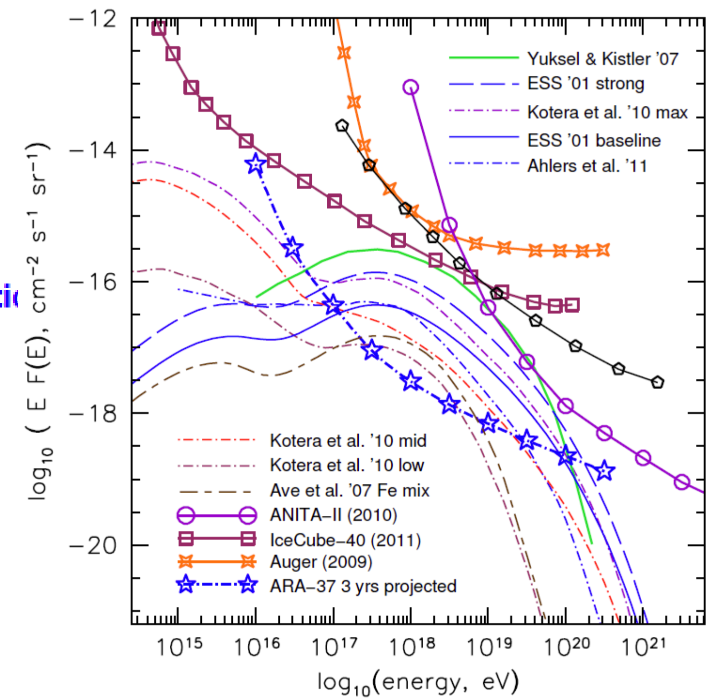
The present future: ARA @ Southpole
$E_\nu = 10^{17}$-10^{21}eV

1) Detection of Radio waves, emitted by neutrino induced cascades in ice

2) Achievement of O(100km³) detection volume using widely spaced antenna clusters, which detect "discrete" Cherenkov cones

3) Use timing + polarization information for neutrino reconstruction





Askaryan Radio Array

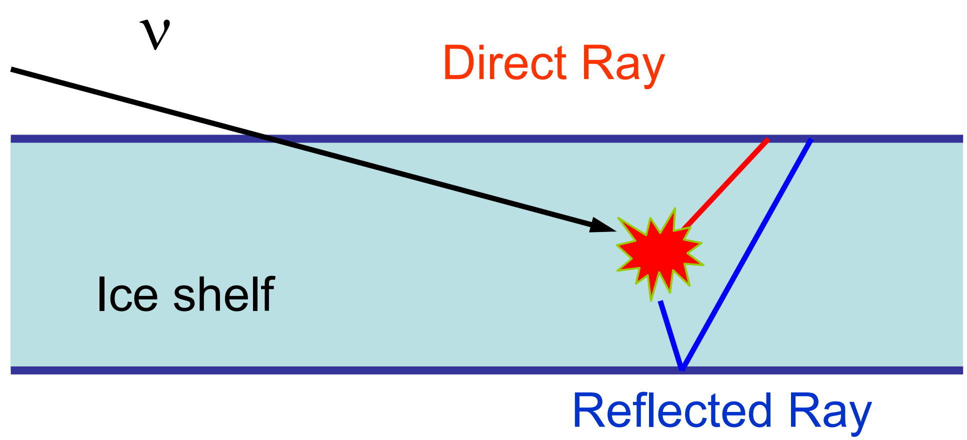
- **Prototype in operation**

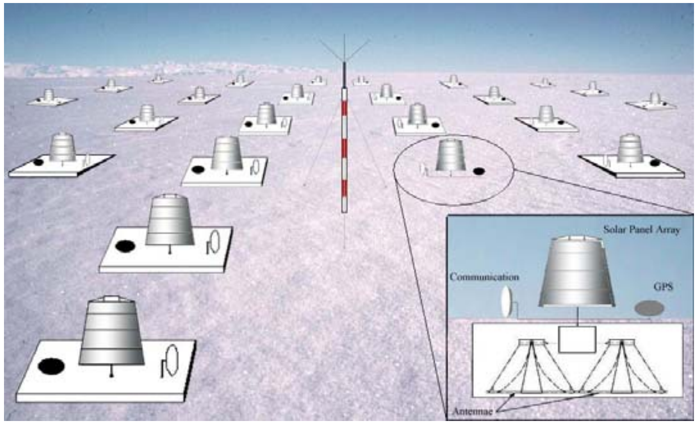
Kravchenko et al, Astrop Phys 20(2003)195

D. Besson et al.

Planned Experiment: ARIANNA

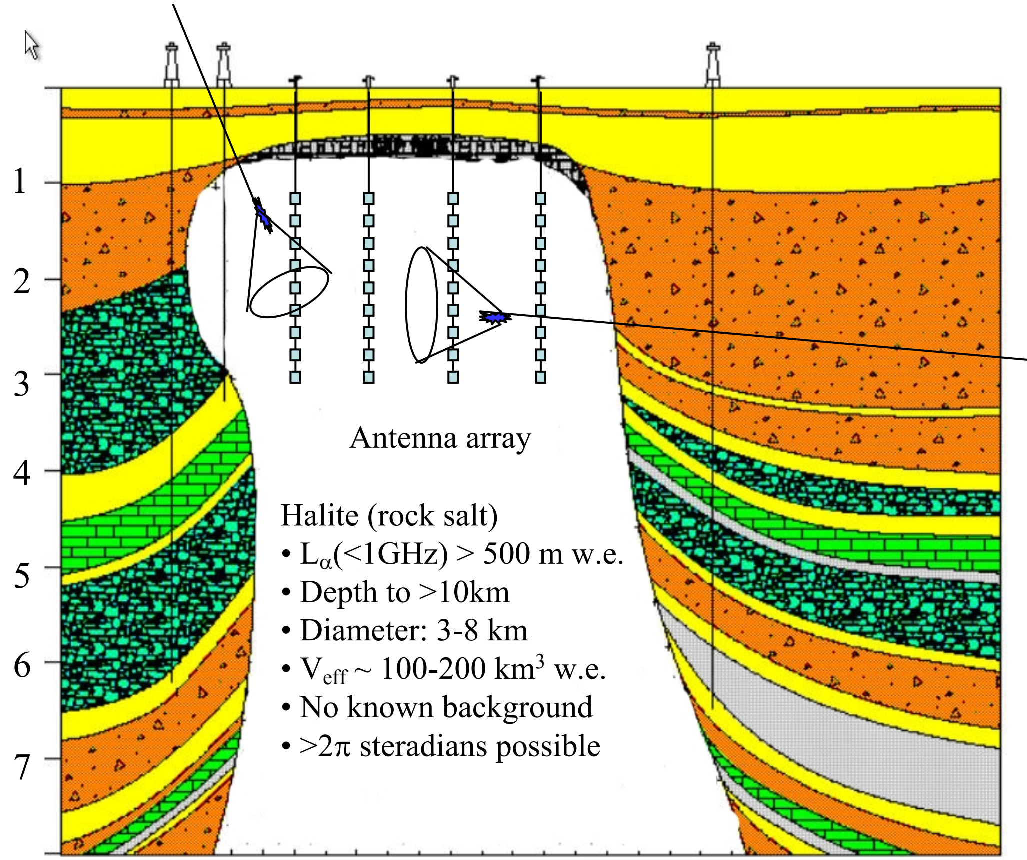
- Antarctic Ross Ice shelf ANtenna Neutrino Array
- Ice thickness ~500 meters
- Enough ice for interactions
- Thin enough for detecting reflections
- Salty sea water below ice → High Reflectivity
- Array of antennas atop the Ross Ice Shelf looking down
- No deep holes
- Very competitive predicted sensitivity
- Prototype in construction





Conolly et al, ARENA workshop 2006, Newcastle, UK

Planned Experiment (Concept): SALSA (Saltdome Shower Array)



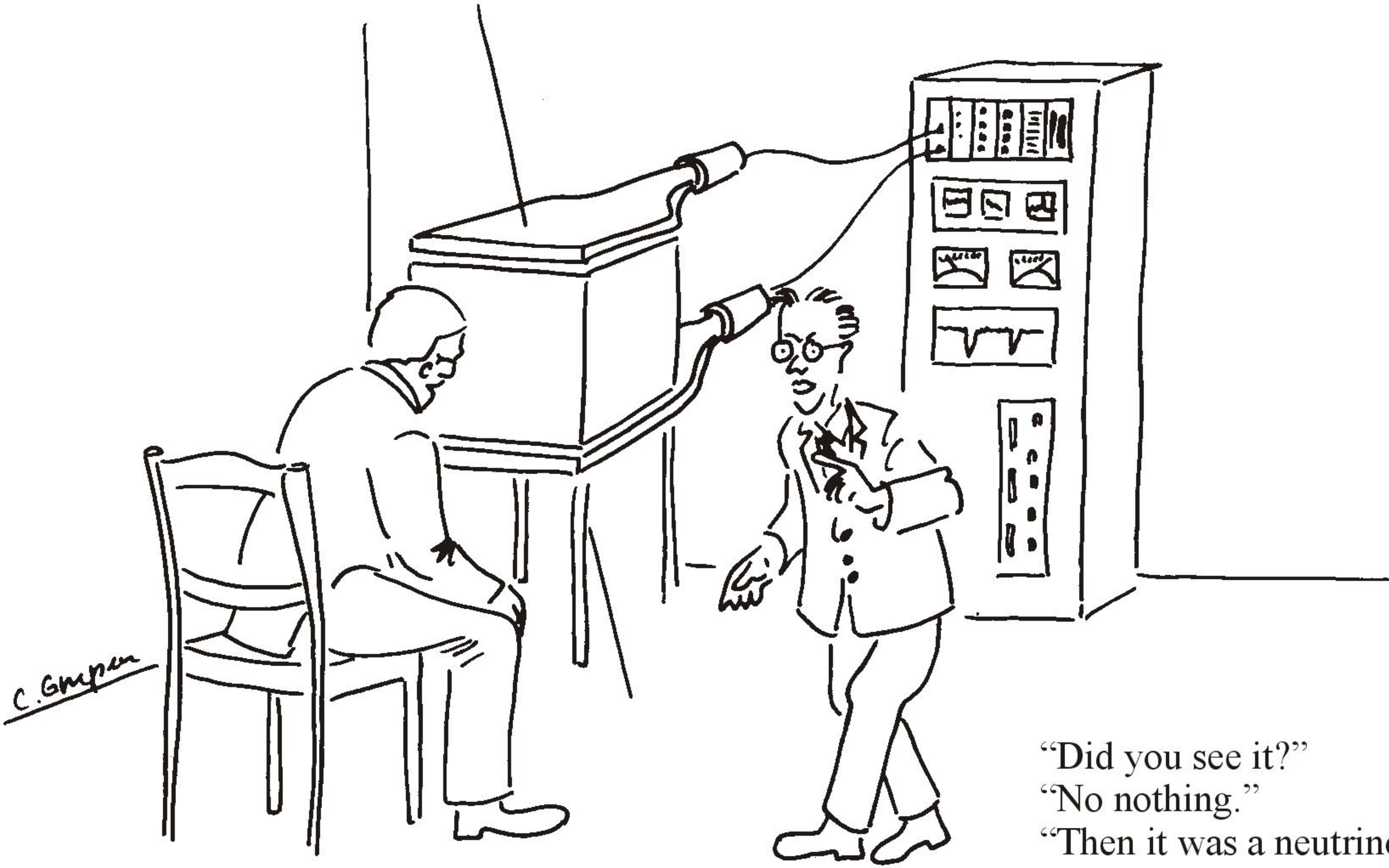
- Salt domes are extremely transparent for radio waves (as well as Antarctic ice)
- Factor ~2,4 more dense than ice
- Simpler environment conditions
  - Easier for installation and operation
  - But: unexpected high drilling costs

P. Gorham et al.

Summary Neutrino Detection By Radio

$E_\nu = 10^{20}\text{-}10^{23}$eV

- **Radio technique allows covering very large detector volumes for the detection of UHE neutrinos**
  - **Needed statistics in principal reachable in short time**
- **Different activities**
  - **Radio in ice**
  - **Radio in salt**
  - **Radio in the moon**
  - **Radio in air (horizontal EAS)**
- **Presently very active field, but yet no positive detection**



"Did you see it?"
"No nothing."
"Then it was a neutrino!"

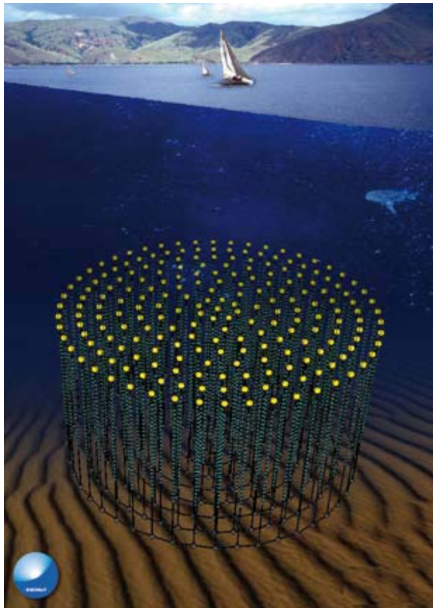
But we will hear it!!

The High Energy Universe

- **Gamma Rays**
  CTA
- **Neutrinos**
  KM3NeT
- **Charged Cosmic Rays**
  Next Ground Array + JEM-EUSO

The next phase in Astroparticle Physics: (European) Roadmap Priorities: High-Energy Universe

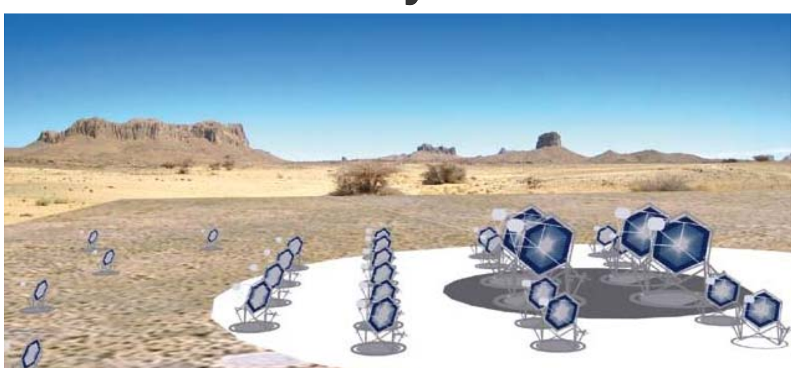
Neutrinos: KM3NeT



Charged Cosmic Rays:

Next... + JEM-EUSO

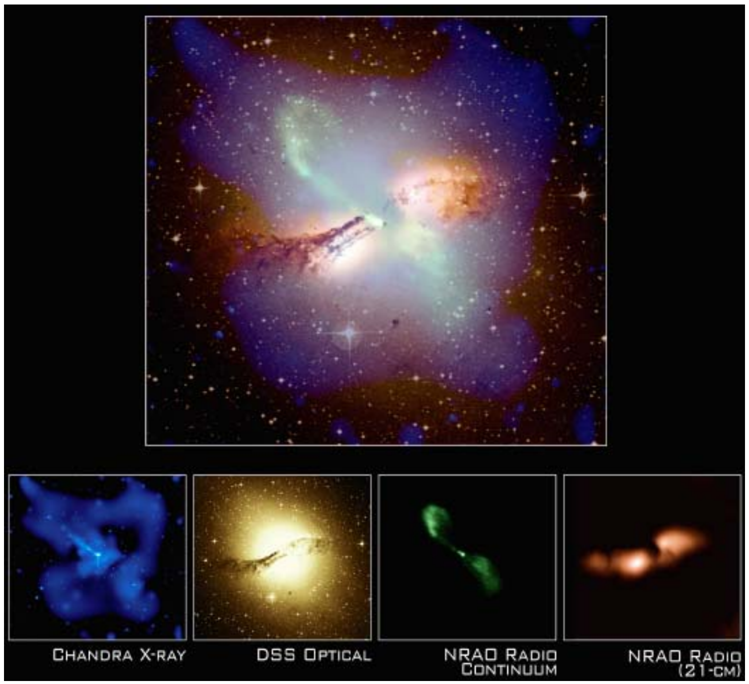
Gamma Rays: CTA

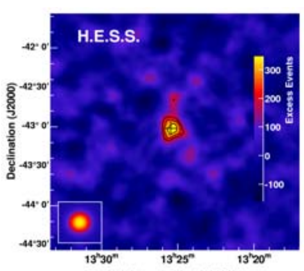


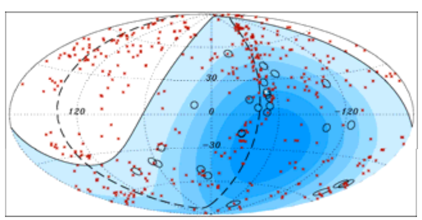
Roadmap from scientists for Funding Agencies!

Can we do Particle Astronomy?

i.e. multi-messenger observations of individual sources?
example: Centaurus A (NGC 5128, Cen A)







- closest radio-loud (d ~ 3.4Mpc) AGN
- one of the best studied active galaxies
- observed at many frequencies: from radio to X-ray

- gamma-rays

70's: Narrabri [Grindlay et al., 1975]
90's: EGRET [Sreekumar et al., 1999]
Feb. 2009: Fermi-LAT [Abdo et al., 2009]
March 2009: H.E.S.S. [Aharonian et al, 2009]

- UHECRs

2007: PAO [Abraham et al., 2007]
possible, but no agreement [Lemoine, 2008]

- neutrinos

no observation ... yet

➔ detailed calculations and predictions!

Can we do Particle Astronomy?

i.e. multi-messenger observations of individual sources?

Discussion / Question / Exercise

- **why TeV-Gamma-ray physics is already astronomy?**
  - **source morphology**
  - **source classes**
  - **used to model astrophysical processes**
- **what are the implications if IceCube events are real?**
  - **multi-messenger astroparticle physics is opened**
  - **one need more: support for larger experiment**
  - **why no muon-neutrinos seen?**
- **why radio measurements of neutrinos are so difficult?**
  - **too high treshold: maybe no neutrinos exist?**
  - **low cross-section: huge area required**
  - **homogeneous radio transparent medium is rare**