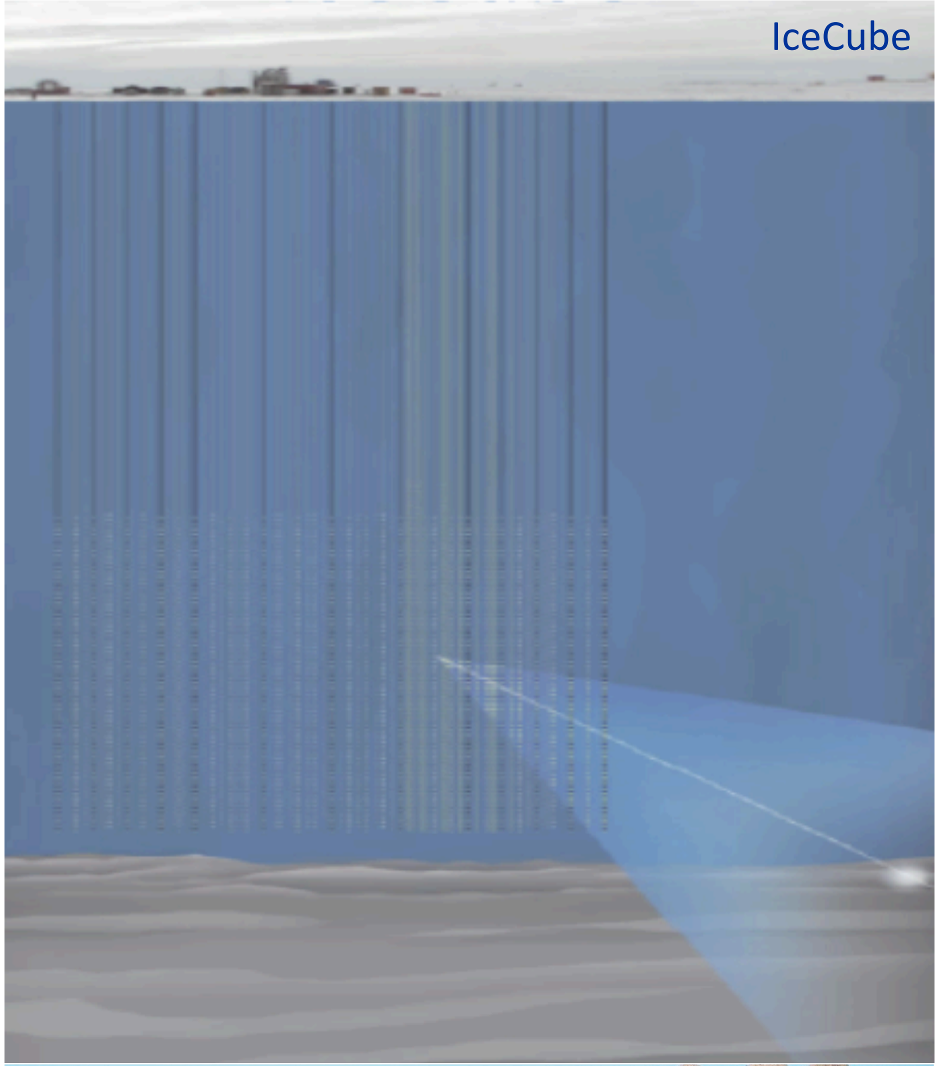
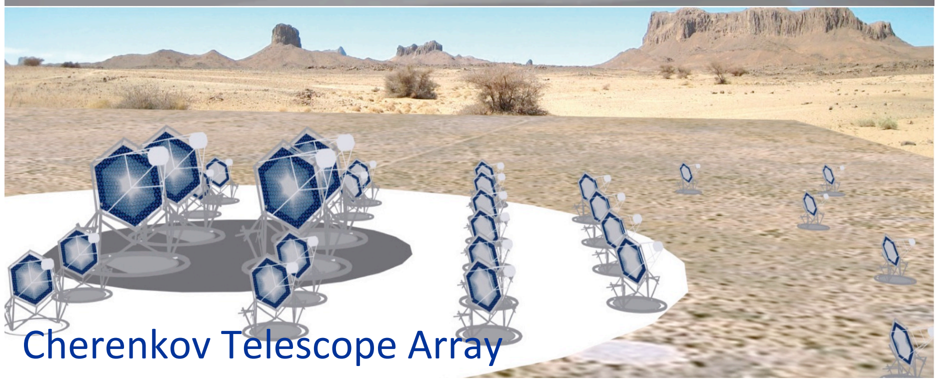



# Astroparticle Physics: Seeing the high energy universe

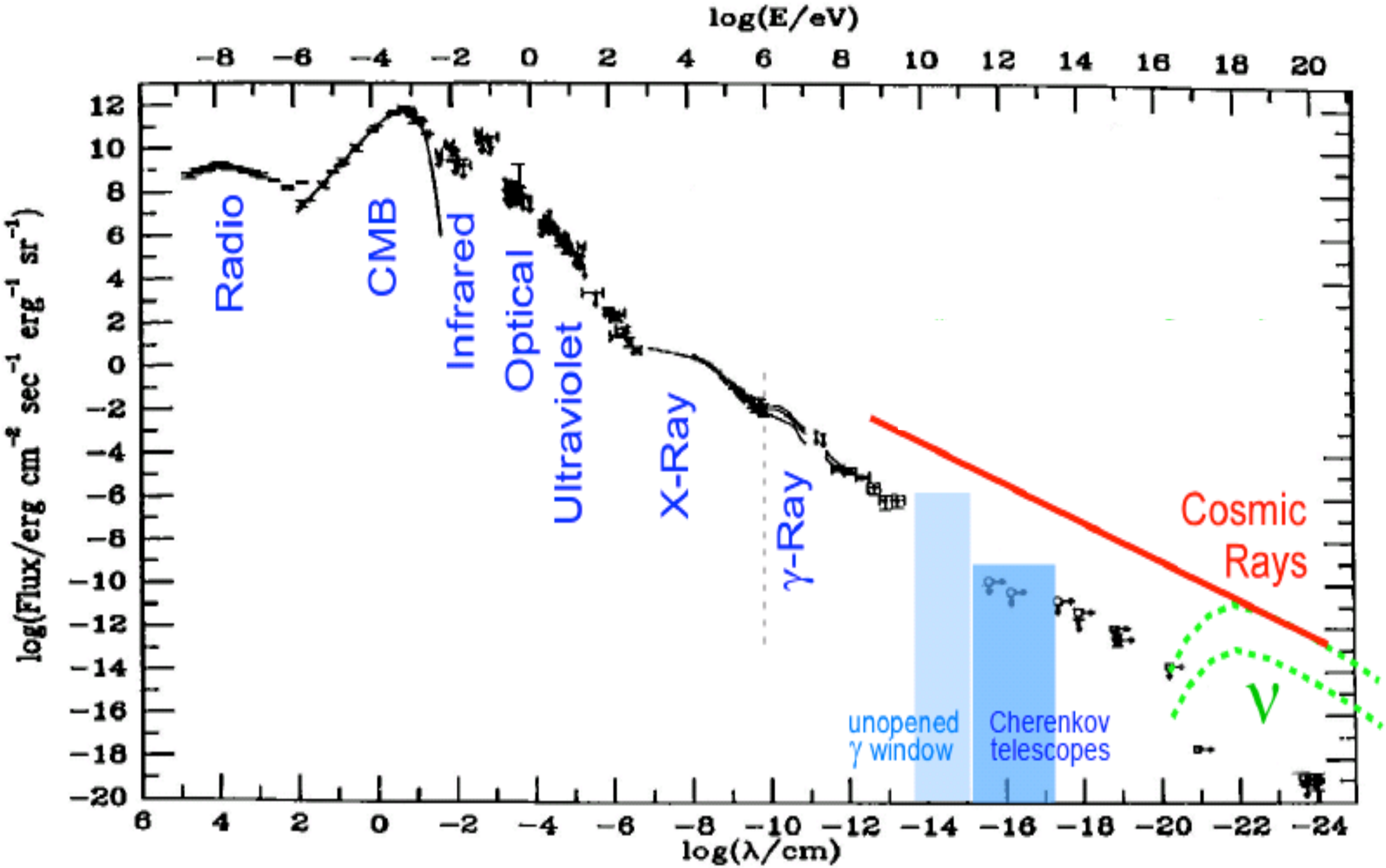
centre for particle physics
Discovery

**Subir Sarkar**
University of Oxford

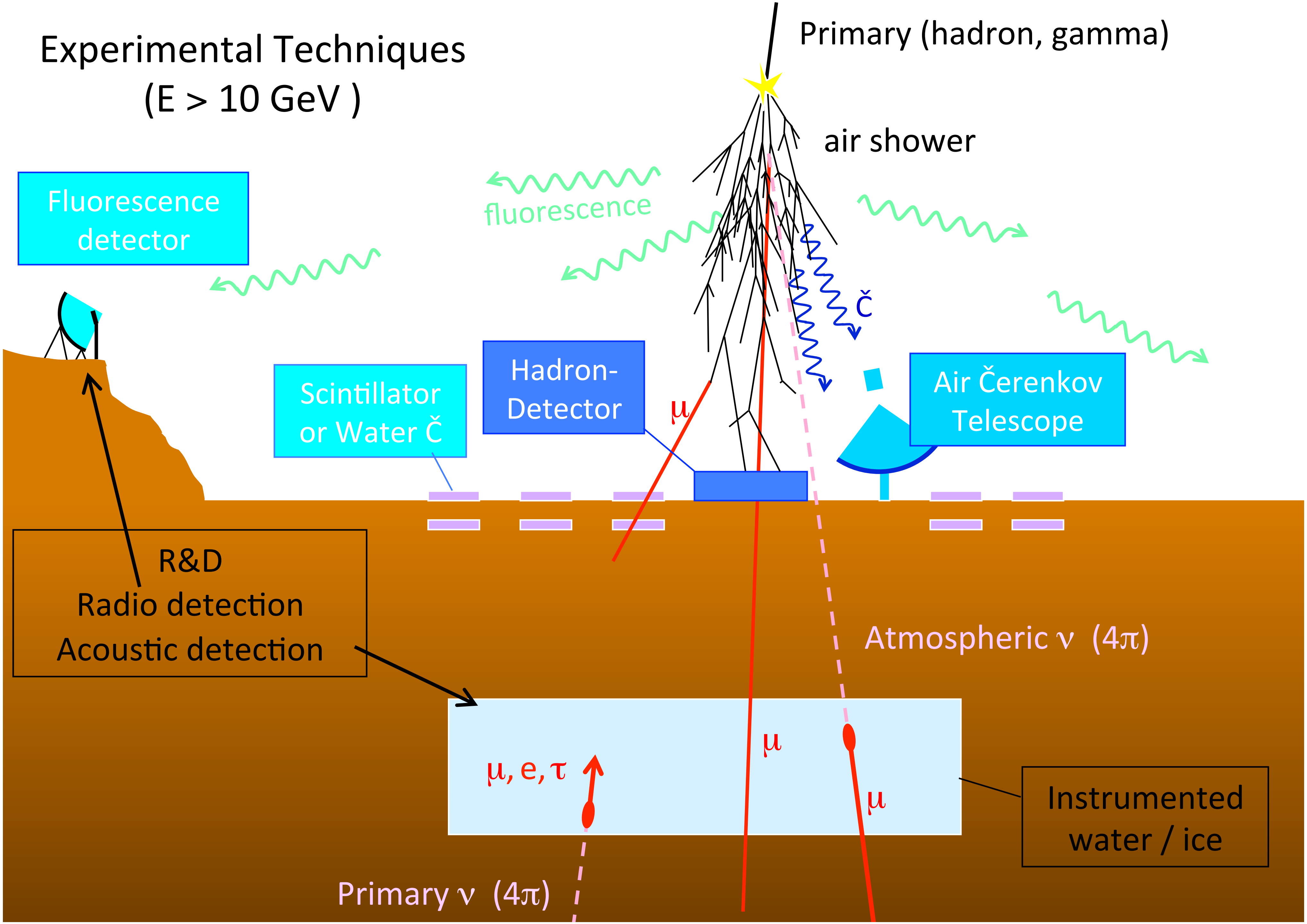
Discovery Associate & Sabbatical Visitor, 2011-12
(Niels Bohr Professor @ NBIA, 2013-18)

*Discovery Strategy Meeting, 13th November 2012*

We can see the deep universe at energies of up to a few TeV, before photons get attenuated through $\gamma\gamma \rightarrow e^+e^-$ on cosmic radiation backgrounds

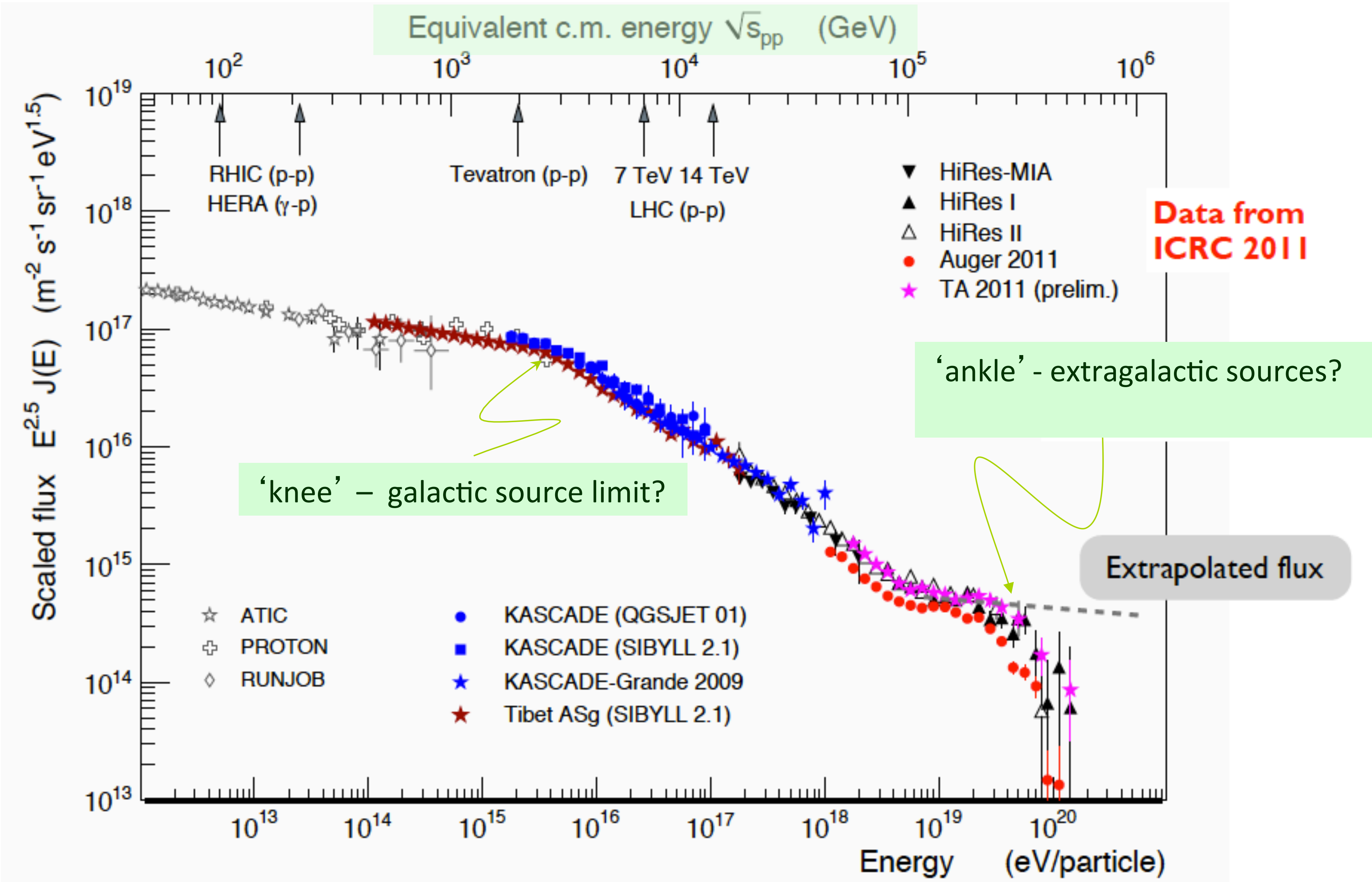



… and the universe is ~transparent to neutrinos at effectively *all* energies



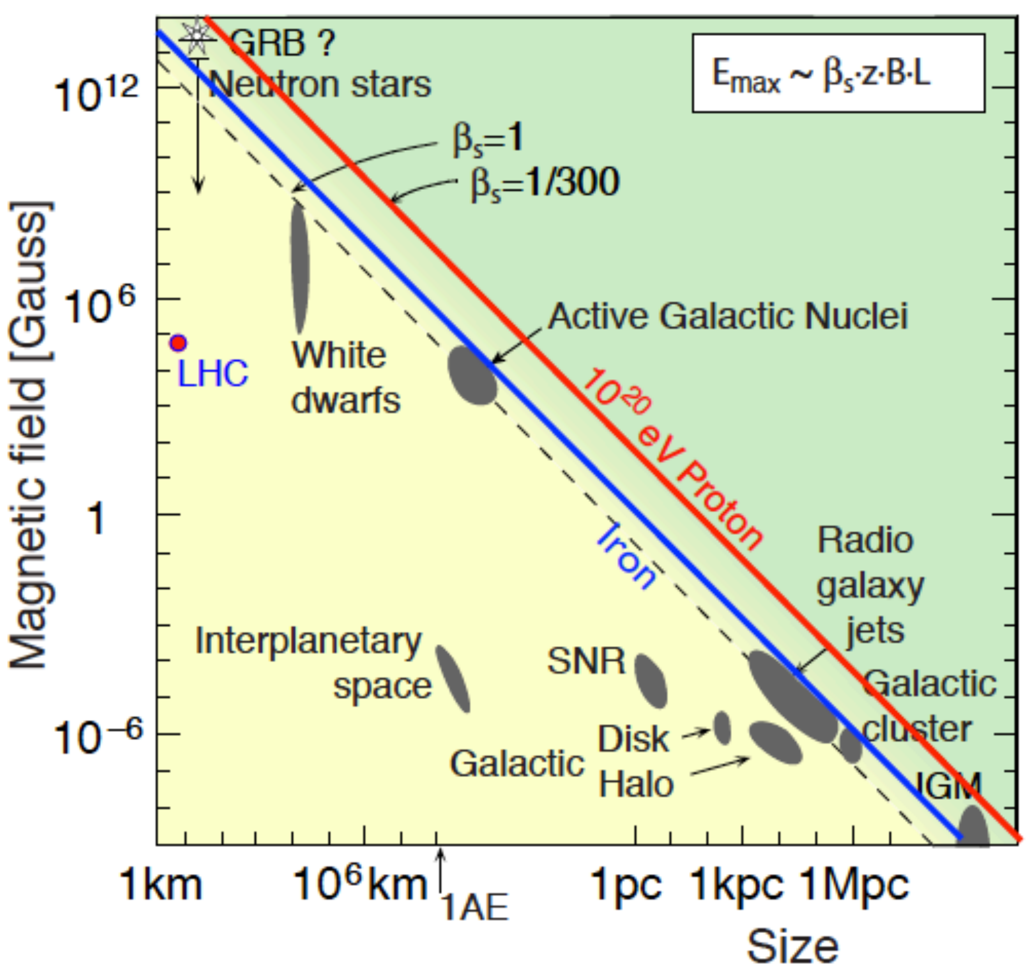
Experimental Techniques
(E > 10 GeV )
Primary (hadron, gamma)
air shower
Fluorescence detector
fluorescence
Č
Scintillator or Water Č
Hadron-Detector
μ
Air Čerenkov Telescope
R&D
Radio detection
Acoustic detection
Atmospheric ν (4π)
μ, e, τ
μ
μ
Instrumented water / ice
Primary ν (4π)

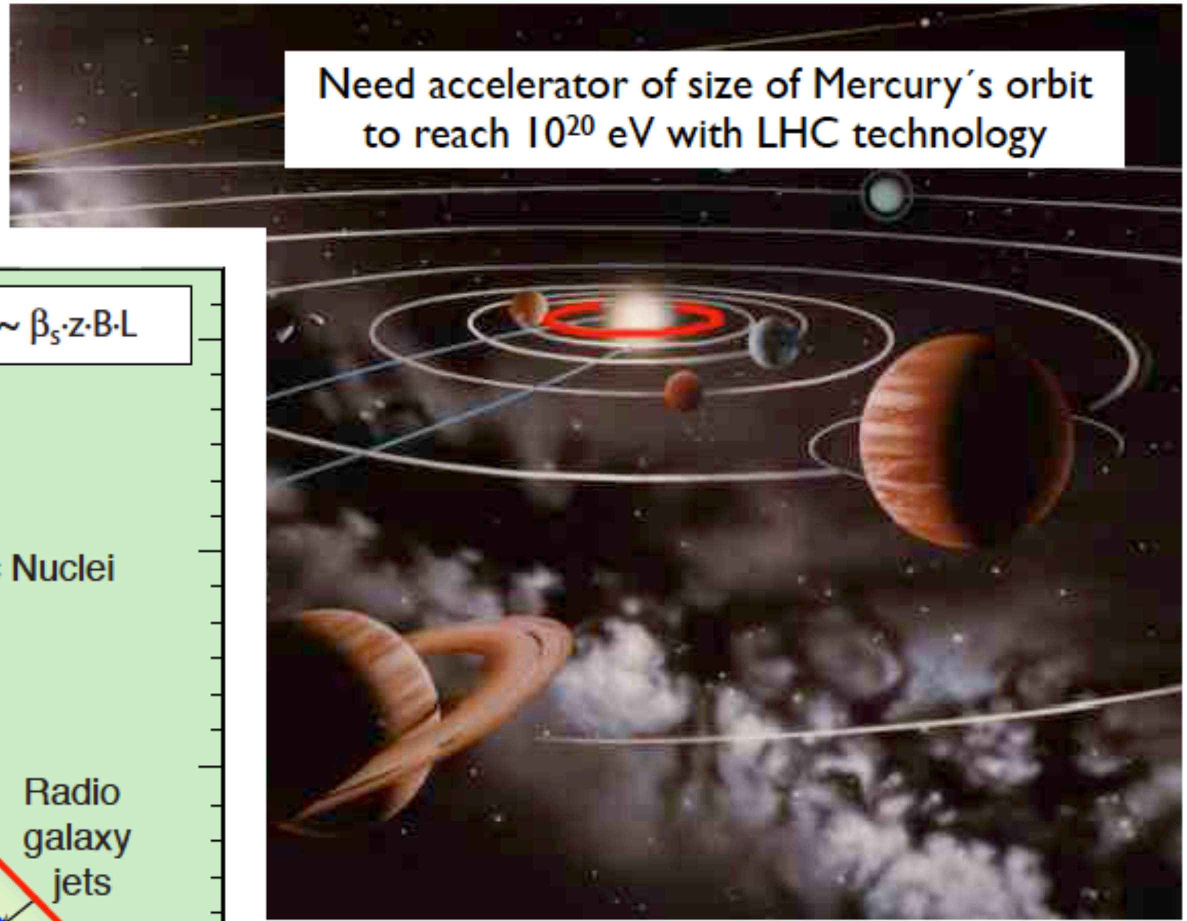
# By studying cosmic ray ($p$, $\gamma$, $\mu$, $\nu$) interactions we also 'see' into the microscopic universe … well beyond the reach of terrestrial accelerators



# How does Nature manage to accelerate particles to ~ZeV energies?

**Hillas plot (1984)**

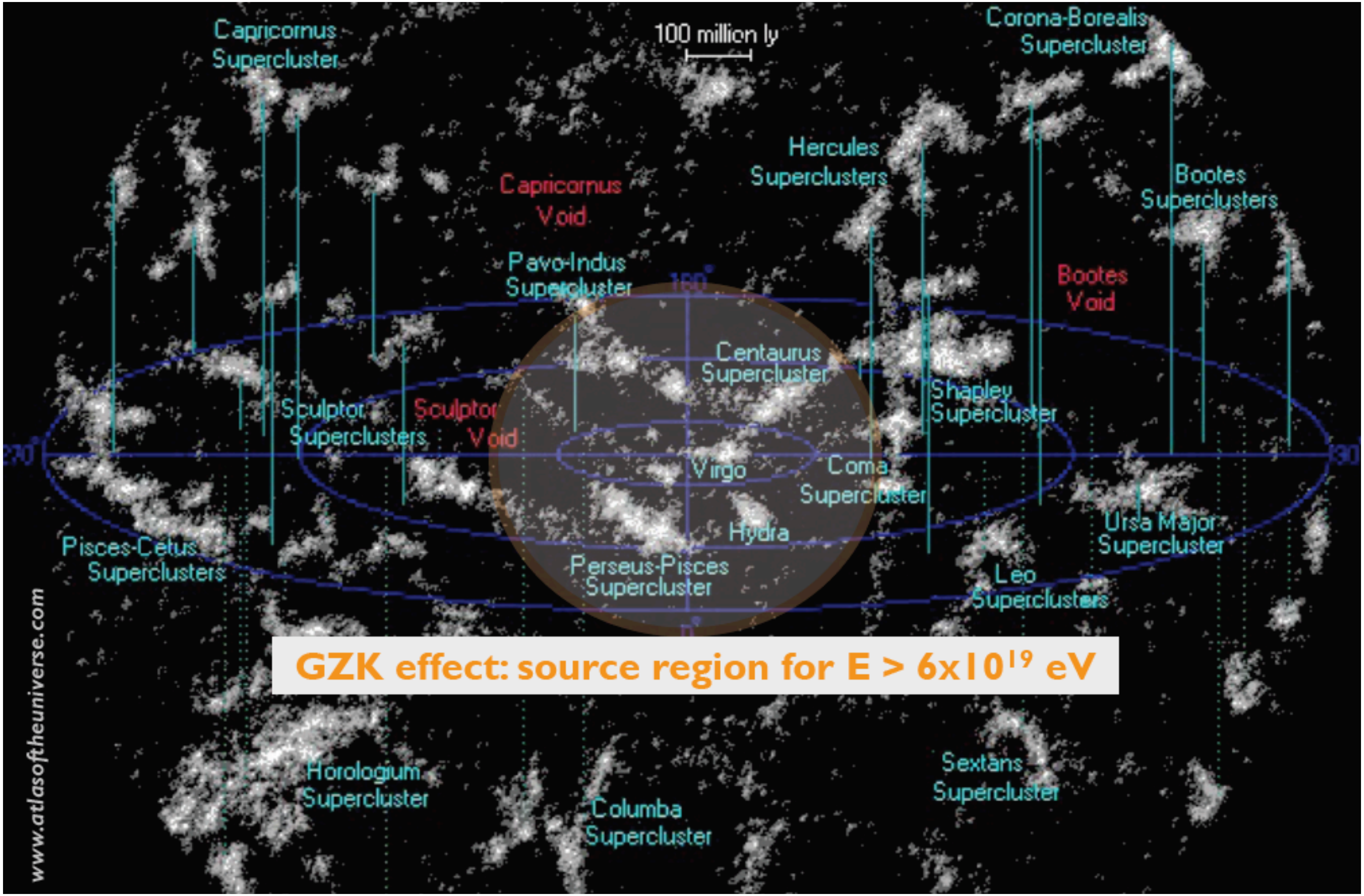


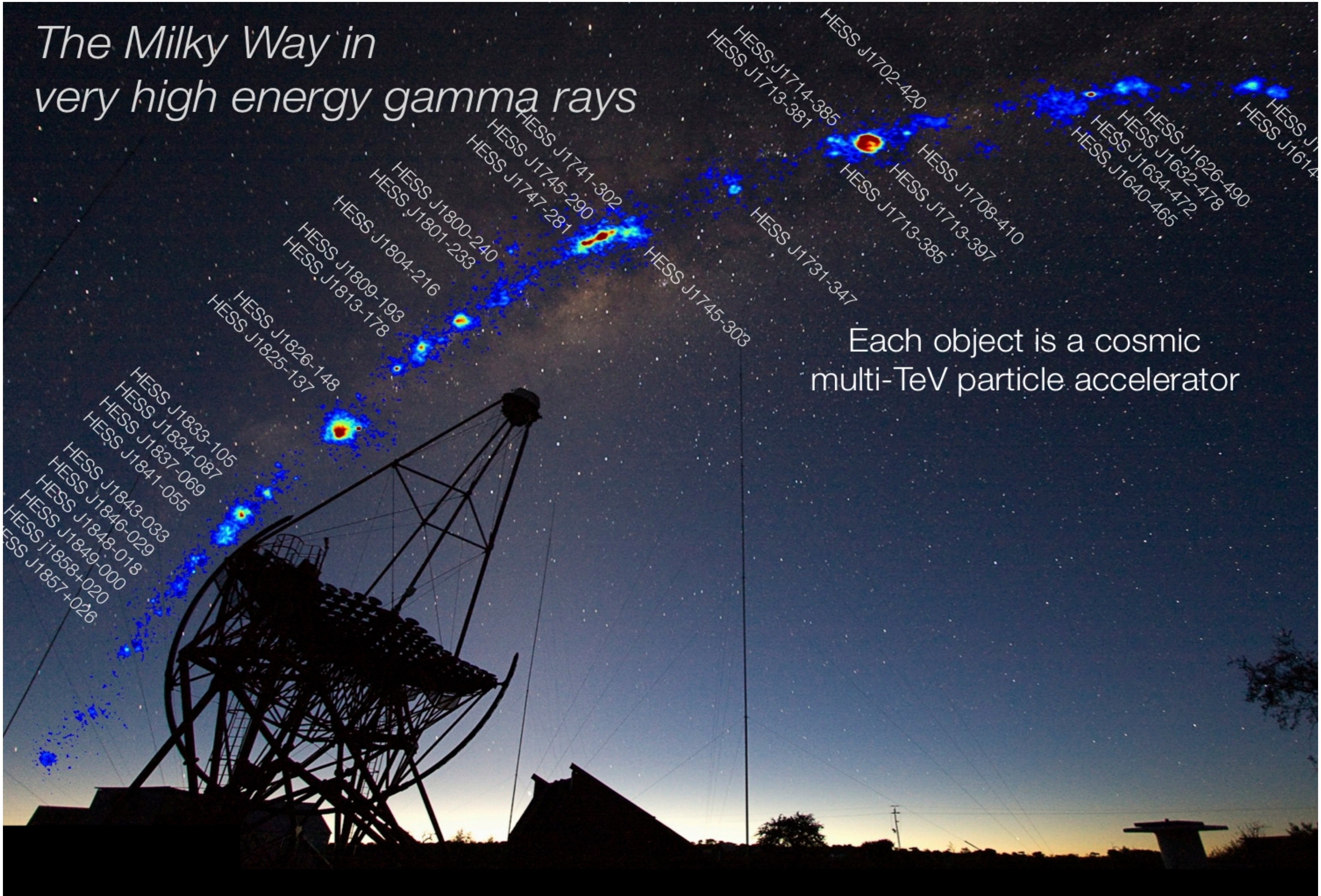




**Realistic constraints more severe**

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

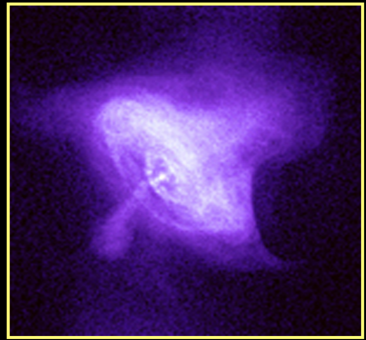
# Because of the GZK cutoff, the UHECR sources must be within ~100 Mpc



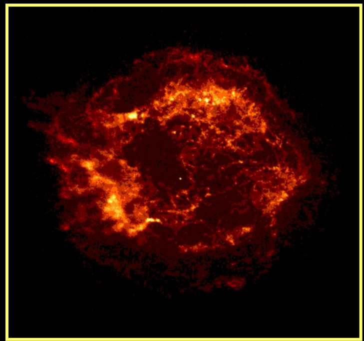



Even closer – within our own Galaxy – are the cosmic ‘pevatrons’

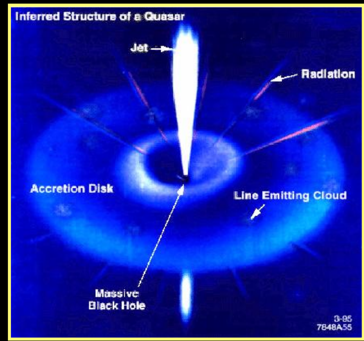
# Science with VHE gamma-ray astronomy



Pulsars and PWN

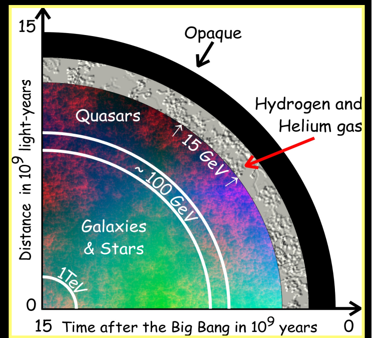


SNRs



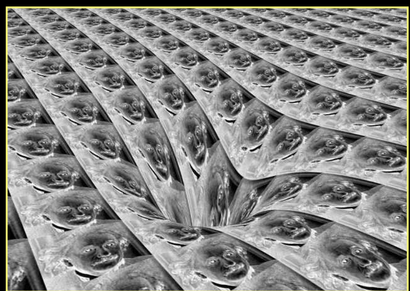

AGNs

Origin of cosmic rays

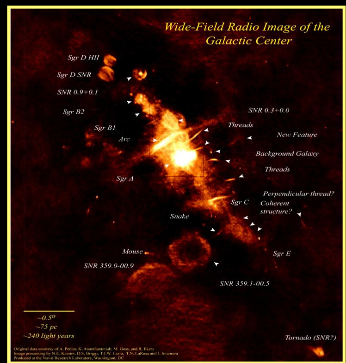



Cosmology

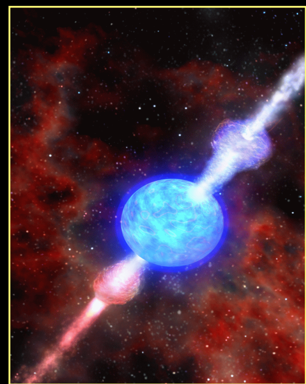
Space-time & relativity



Dark matter

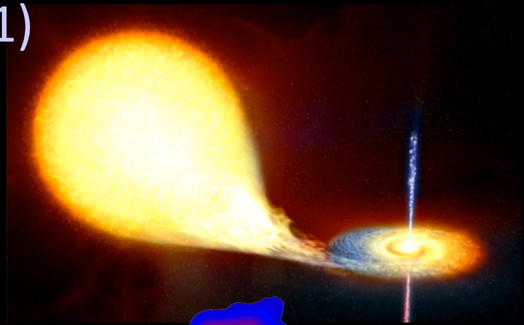


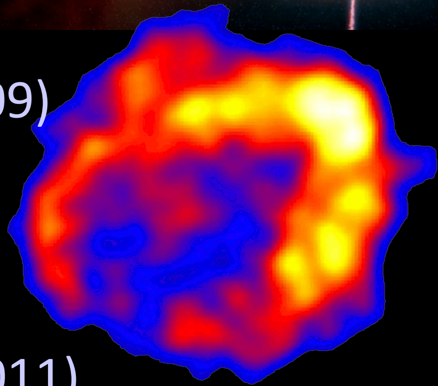

GRBs



# VHE astronomy: some highlights

- *Microquasars:* Science 309, 746 (2005), Science 312, 1771 (2006)
- *Pulsars*: Science 322, 1221 (2008), Science 334, 69, (2011)
- *Supernova remnants*: Nature 432, 75 (2004)
- *The Galactic centre*: Nature 439, 695 (2006)
- *Galactic survey*: Science 307, 1839 (2005)
- *Starbursts*: Nature 462, 770 (2009), Science 326,1080 (2009)
- *AGN:* Science 314,1424 (2006), Science 325, 444 (2009)
- *EBL:* Nature 440, 1018 (2006), Science 320, 752 (2008)
- *Dark matter:* PRL 96, 221102 (2006) , PRL 106, 161301 (2011)
- *Lorentz invariance*: PRL 101, 170402 (2008)
- *Cosmic ray electrons:* PRL 101, 261104 (2008)





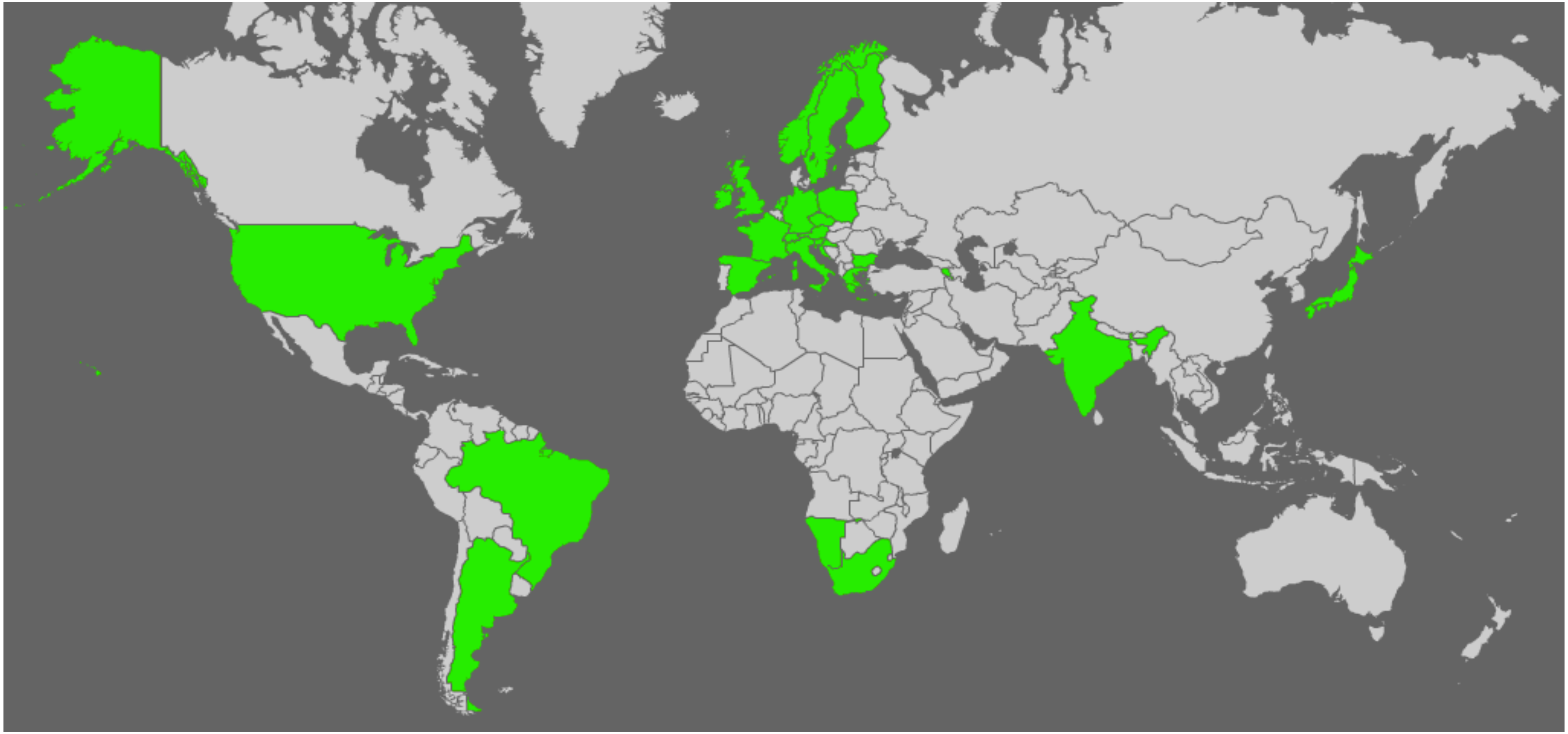
Results from **HESS, MAGIC** and **VERITAS**

# The next big step

- Mix of guaranteed science and discovery potential
- Safe extrapolation of proven technologies, predictable performance
- Supported by a large and diverse community
- Highly ranked by major science roadmaps
- Currently in FP7-supported Preparatory Phase
- Aim for deployment over 5 years: 2014-2018

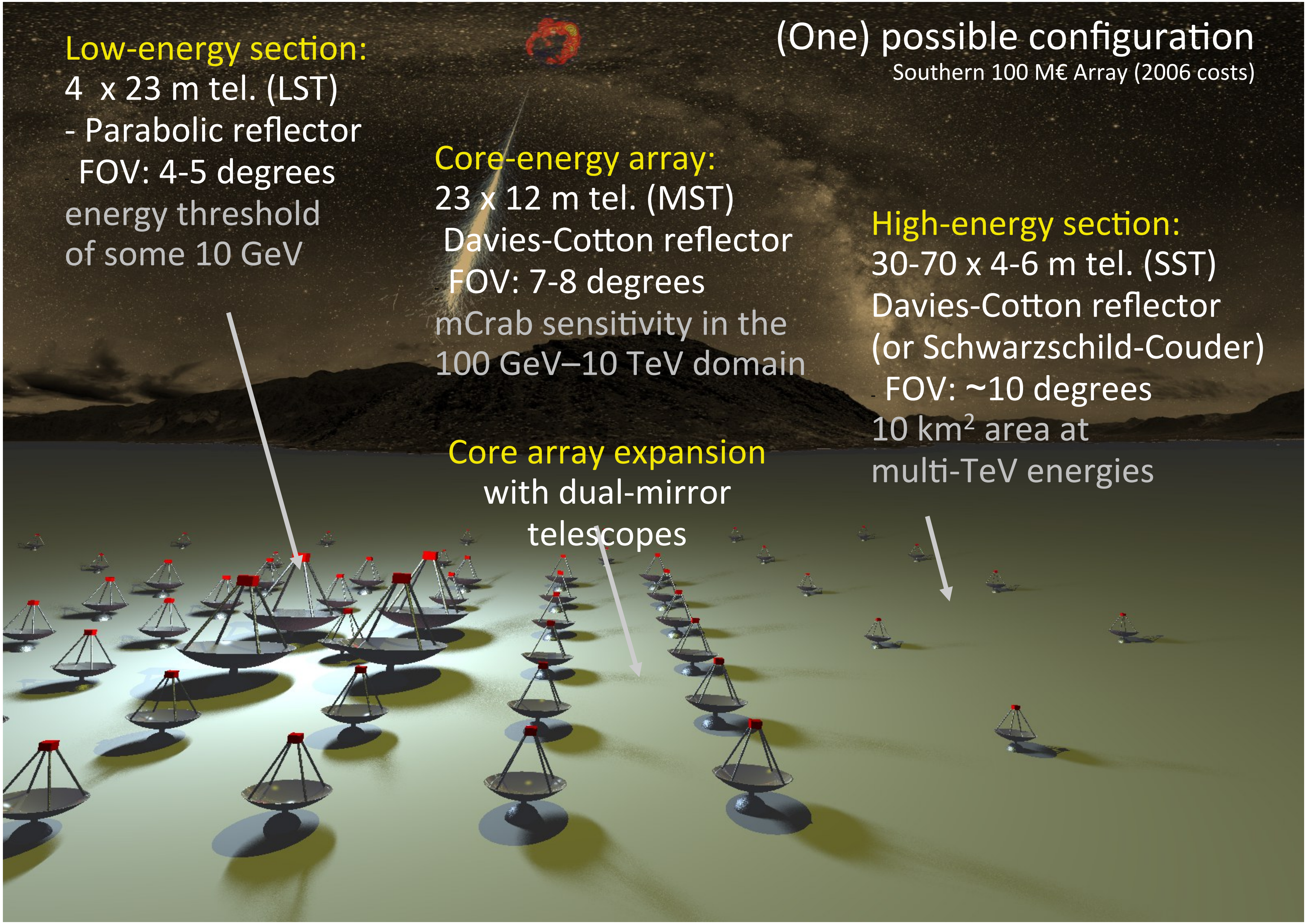
# CTA Members: 26 Countries

~1000 scientists and engineers from >150 institutions

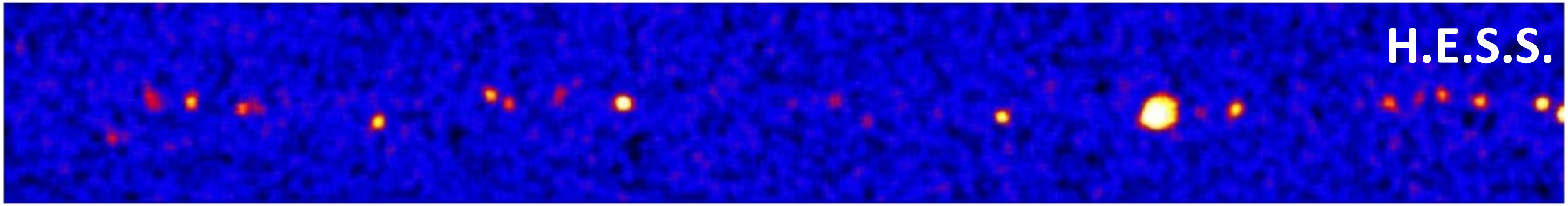


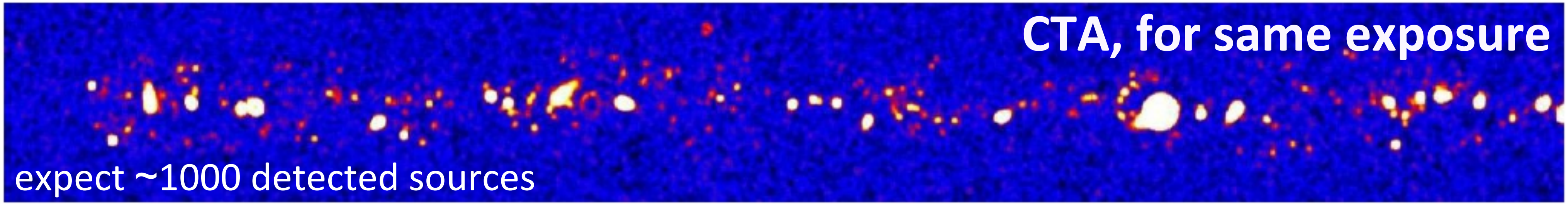
Argentina, Armenia, Austria, Brazil, Bulgaria, Czech Republic, Croatia, Finland, France, Germany, Greece, India, Italy, Ireland, Japan, Namibia, Netherlands, Norway, Poland, Slovenia, Spain, South Africa, Sweden, Switzerland, UK, USA

Declaration of Intent being signed – initially - by 13 countries (representing ~85% of CTA participants)

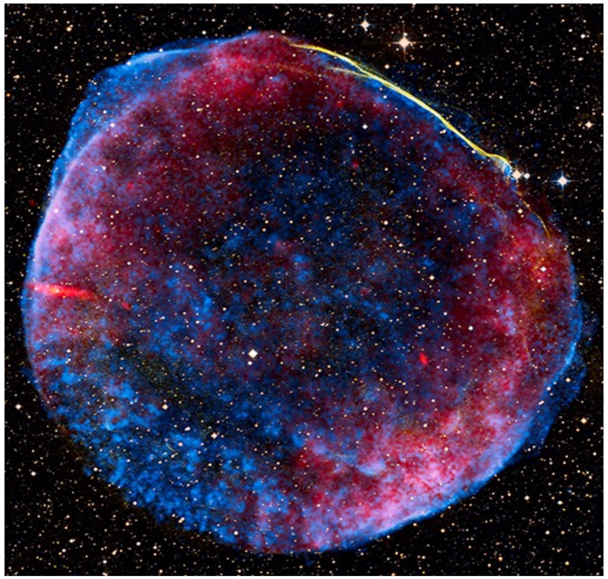

(One) possible configuration
Southern 100 M€ Array (2006 costs)
Low-energy section:
4 x 23 m tel. (LST)
- Parabolic reflector
FOV: 4-5 degrees
energy threshold
of some 10 GeV
Core-energy array:
23 x 12 m tel. (MST)
Davies-Cotton reflector
FOV: 7-8 degrees
mCrab sensitivity in the
100 GeV–10 TeV domain
High-energy section:
30-70 x 4-6 m tel. (SST)
Davies-Cotton reflector
(or Schwarzschild-Couder)
FOV: ~10 degrees
10 km² area at
multi-TeV energies
Core array expansion
with dual-mirror
telescopes

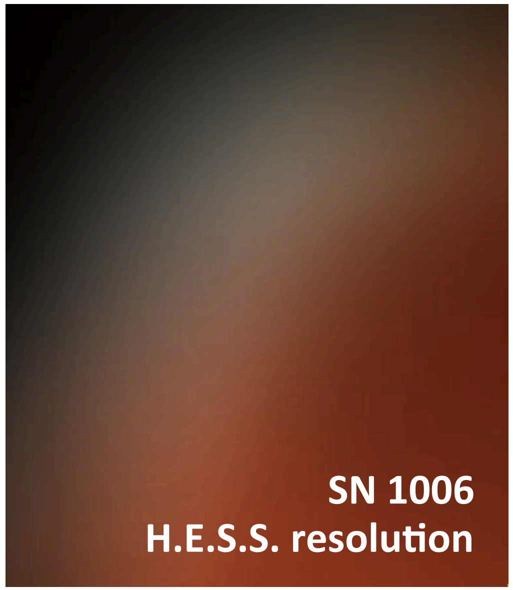
# Example: Galactic Plane Survey



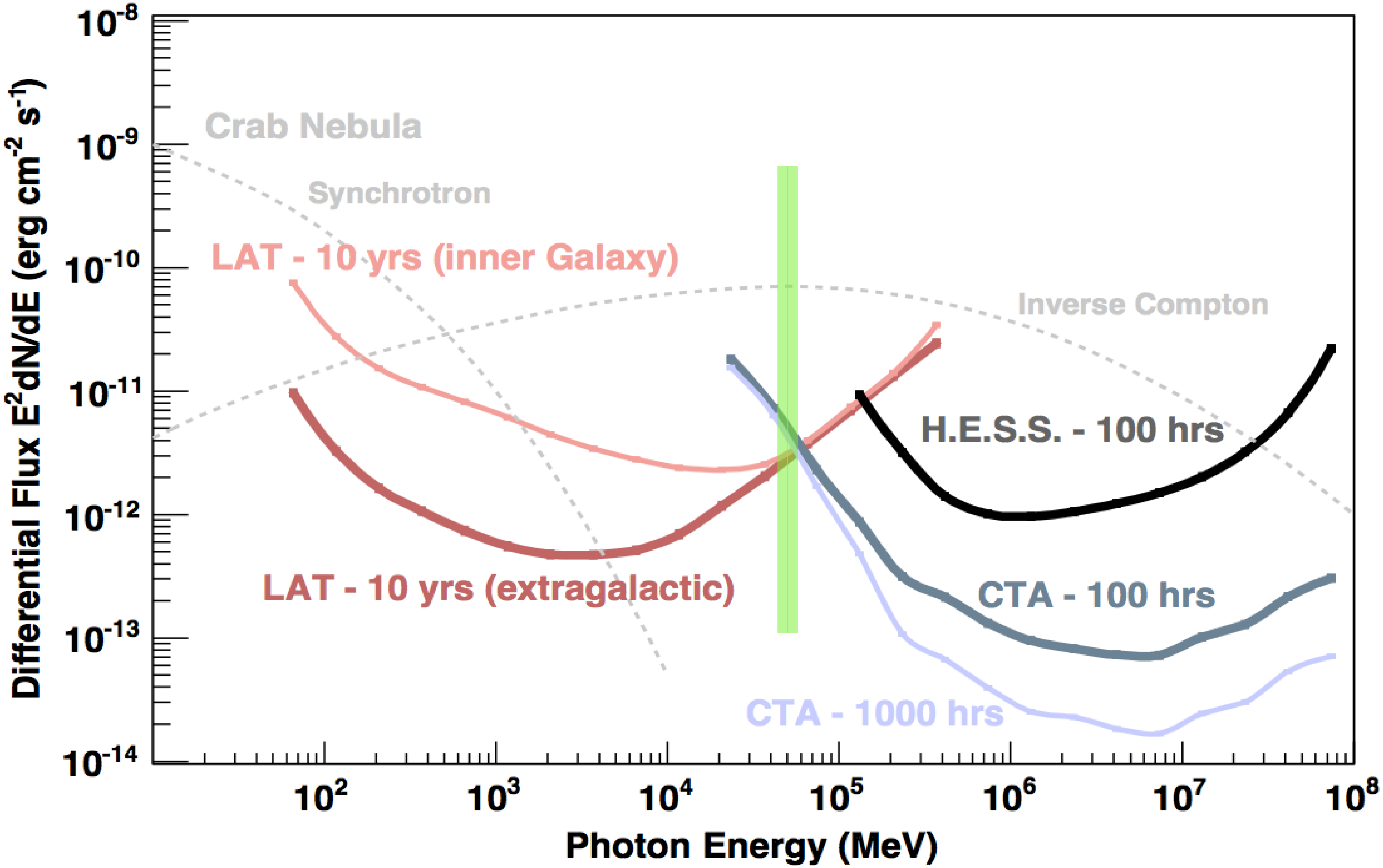




# Resolving complex sources

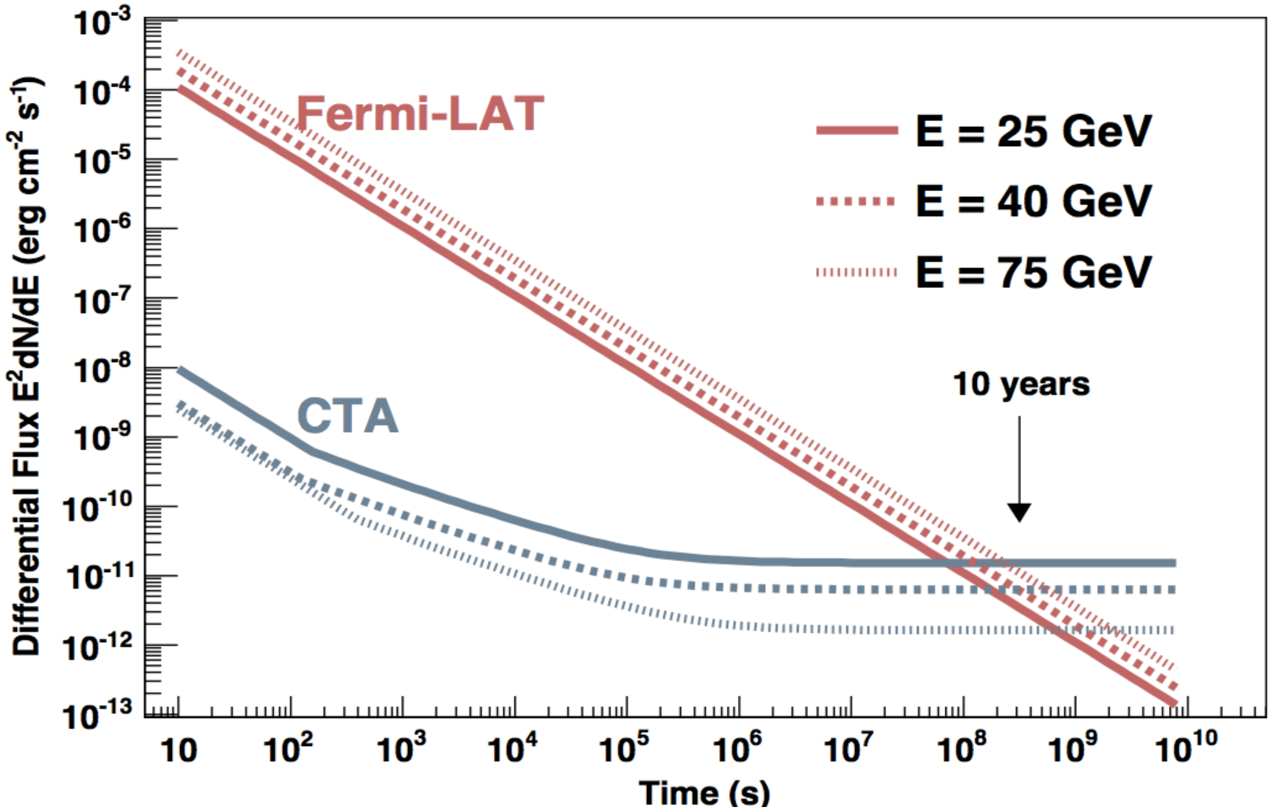


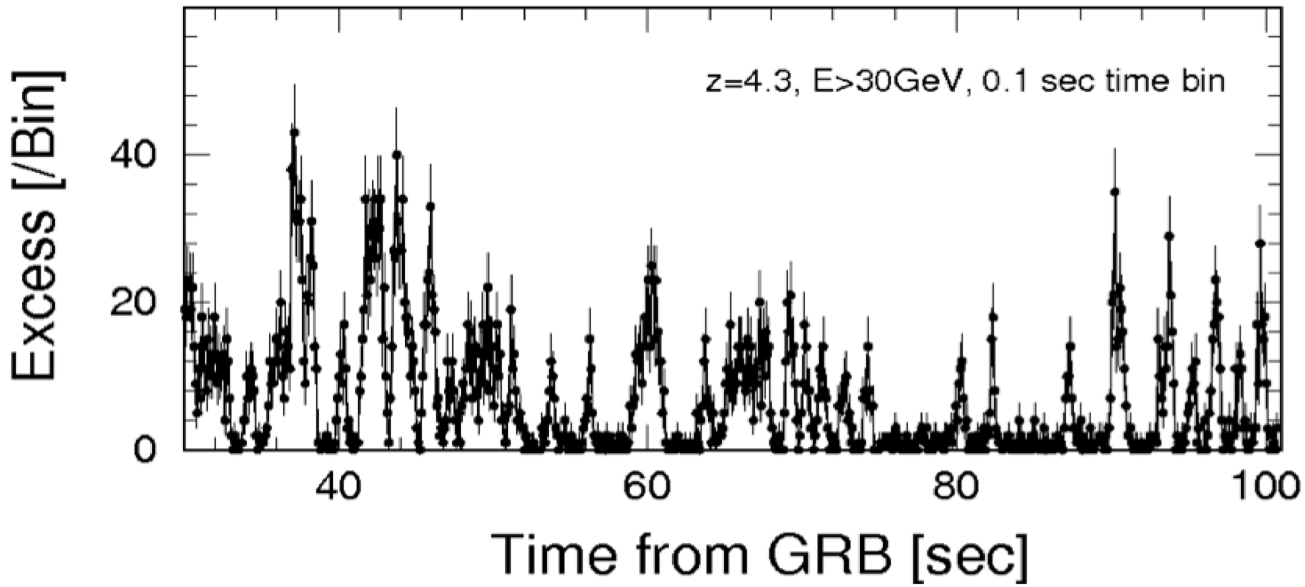
# CTA versus Fermi – steady sources



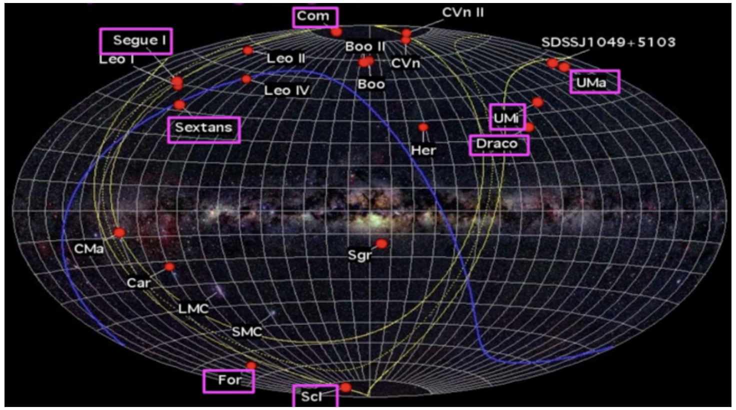
# CTA vs. Fermi
## – transient sources

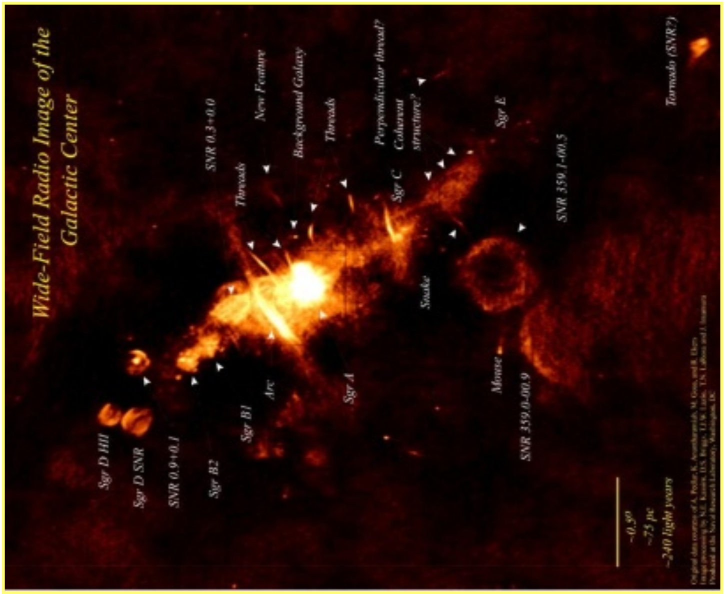


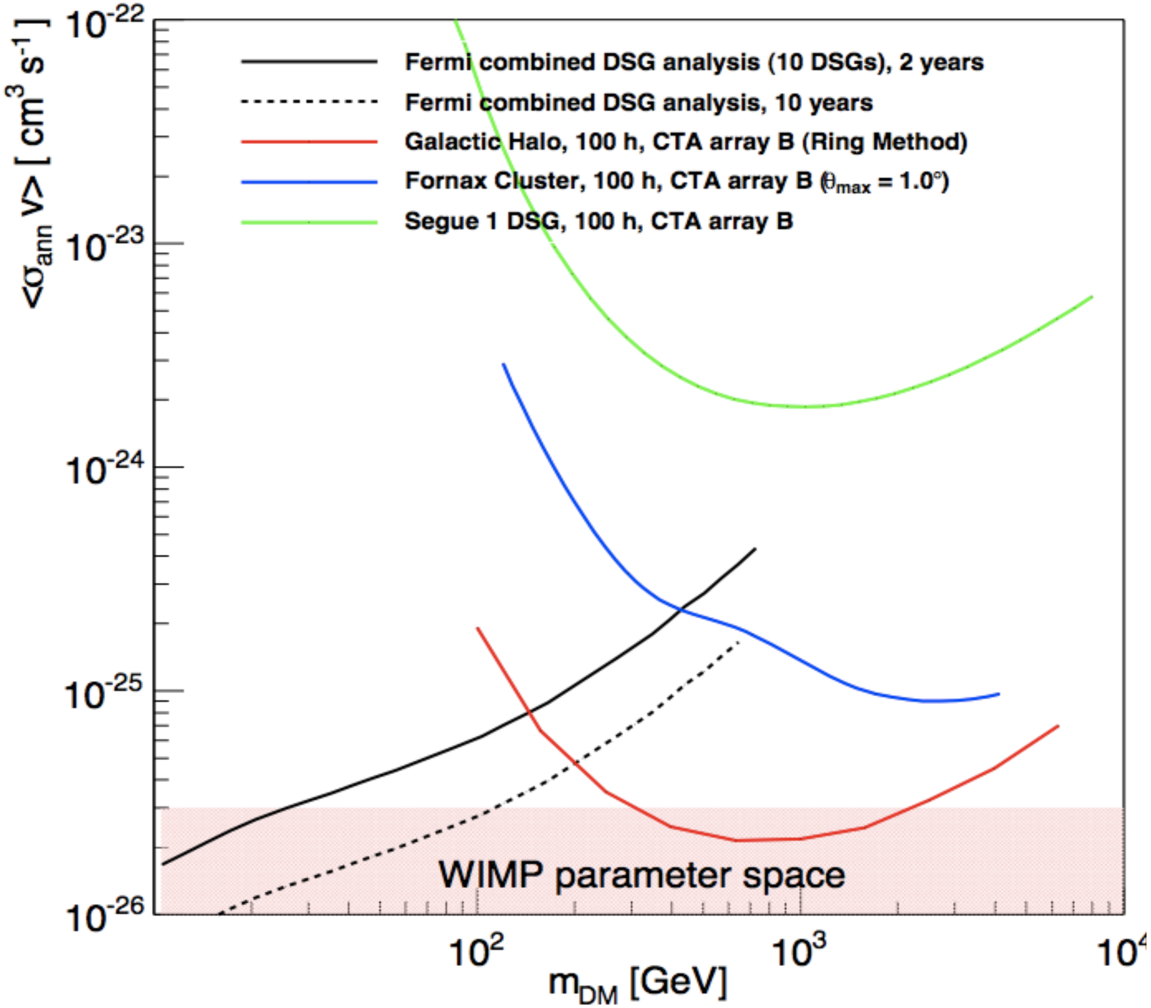

A simulated GRB
(E > 30 GeV)



Prospects for detection of the **dark matter annihilation signal** are best for the Galactic halo, followed by galaxy clusters and dwarf spheroidal galaxies




These limits are *complementary* to those set by direct detection expts

# What is my role in CTA?

- Member of PHYSICS Working group

(e.g. invited talk at *International Astronomical Union General Assembly*, Beijing, Aug 2012)

- Co-editor of *Astroparticle Physics* Special Issue on CTA science

- Member of *Science Requirements Review* Panel

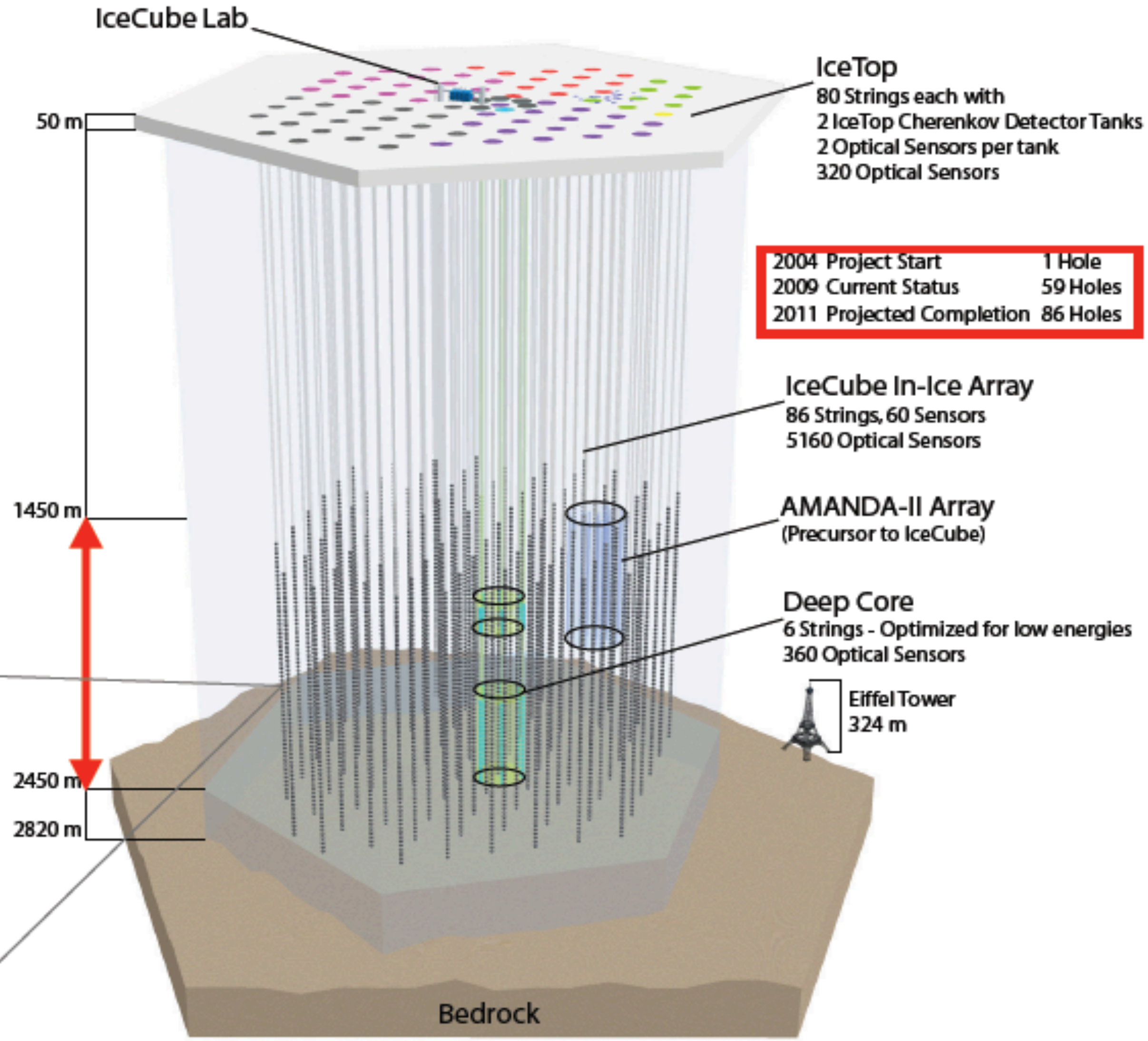
Proposal: Appoint 3+2 yr Associate Professor: 2013-18
(funded by my Niels Bohr Professorship grant)

Find suitable candidate who is already involved in CTA design phase … s/he can interact closely with the ATLAS and ALICE experimentalists in the Discovery Centre @ NBI

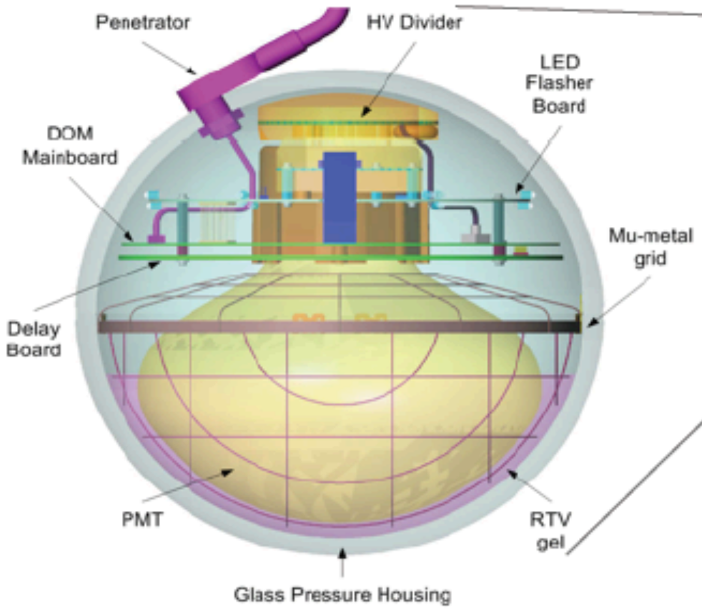
This candidate may also be involved in IceCube
(I have been Member of Collaboration Board since 2004)

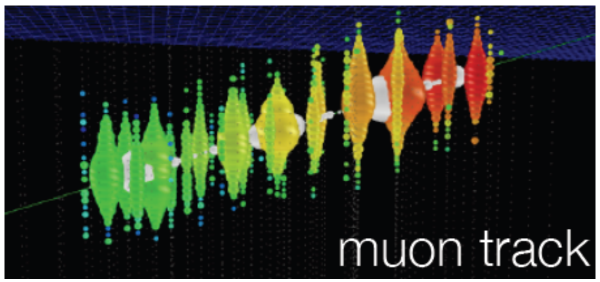
# IceCube Observatory

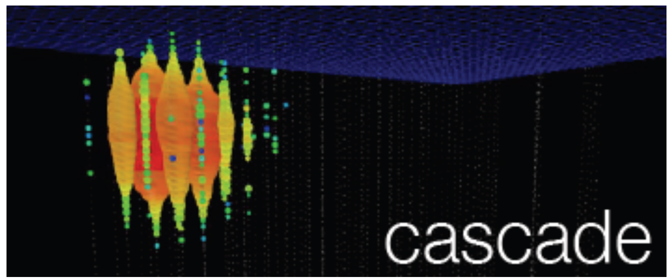
- 86 strings
- 5160 DOMs
- 17 m vertical spacing
- 125 m between strings




## Digital Optical Module - DOM



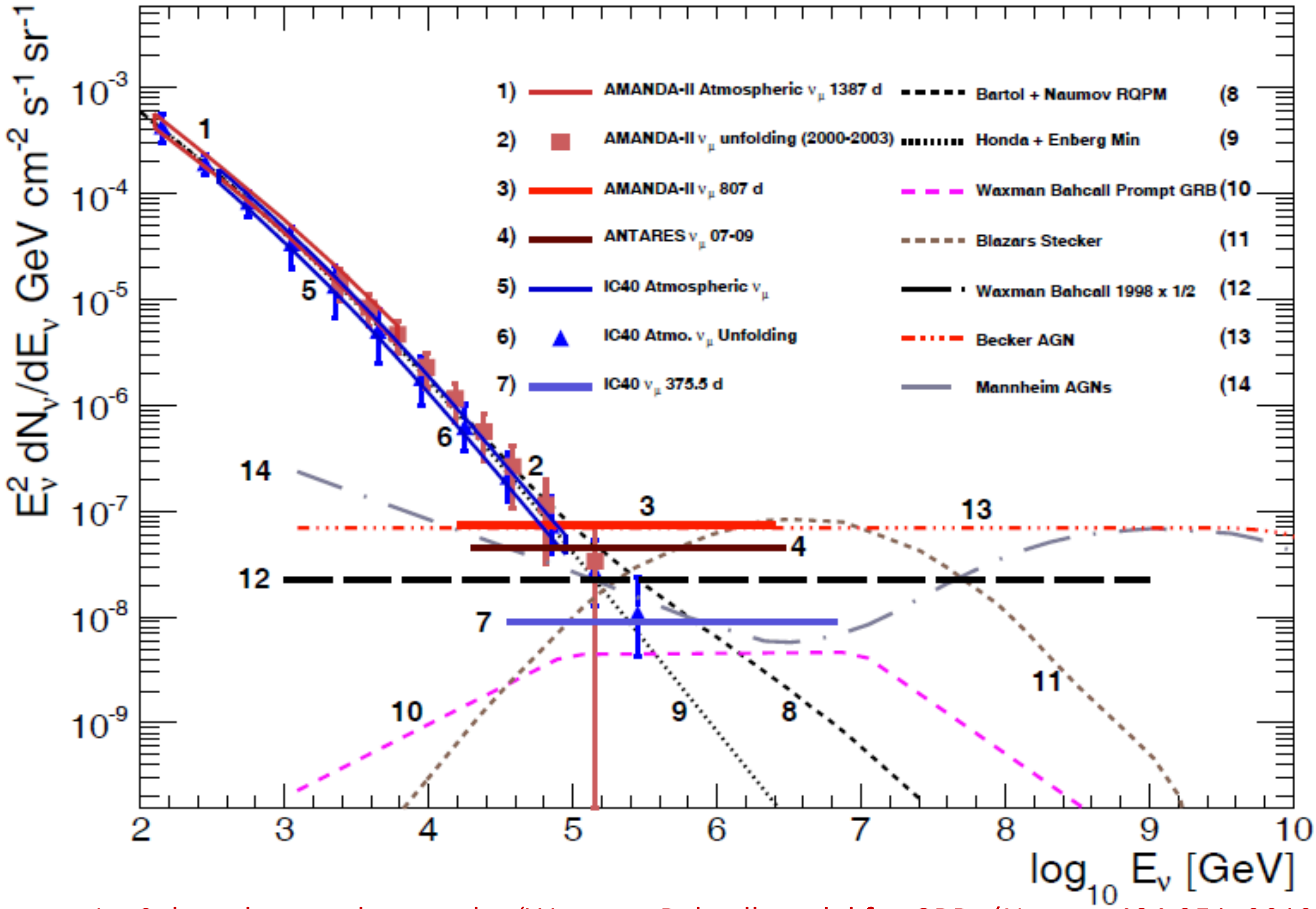
# The IceCube Collaboration


39 Institutions ~ 250 Members

**Internationl Funding Agencies**

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

# *Measured* atmospheric $\nu_\mu$ spectrum constrains likely cosmic sources




… e.g. IceCube rules out the popular 'Waxman-Bahcall model for GRBs (Nature, 484:351, 2012)

**STOP PRESS: Now we do have possible cosmic neutrino events**

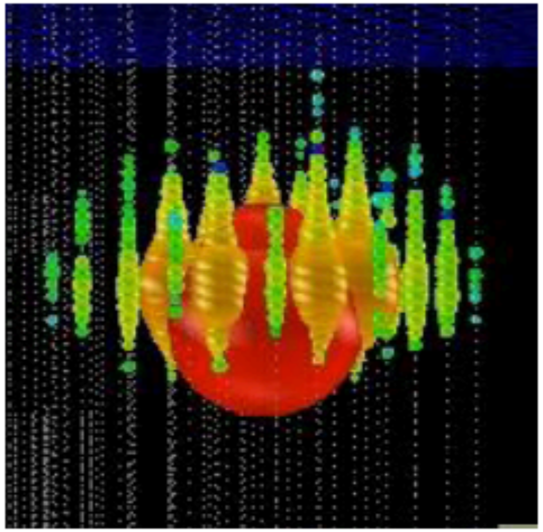
# 2 $\nu_e$-like PeV events in IceCube 86

Found in search for cosmogenic neutrinos with IC79 & IC86 (May 2010 – May 2012)

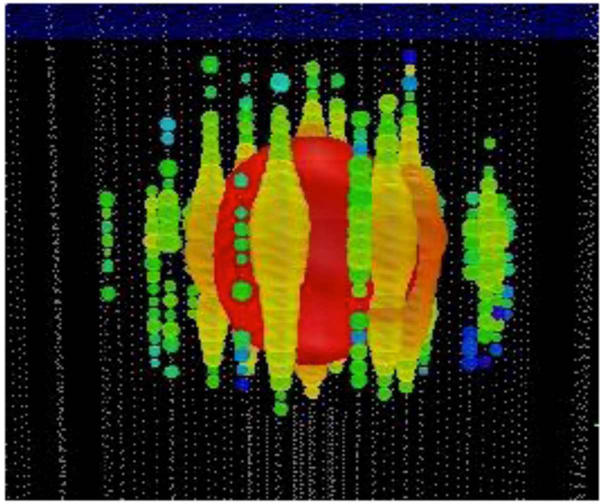
2 events / 672.7 days - background (atm. $\mu$ + conventional atm. $\nu$) expectation 0.14 events

preliminary p-value: 0.0094 (2.36$\sigma$)

Run119316-Event36556705
Jan 3rd 2012
NPE $9.628 \times 10^4$
Number of Optical Sensors 312



Run118545-Event63733662
August 9th 2011
NPE $6.9928 \times 10^4$
Number of Optical Sensors 354



These are unlikely to be due to charm (in the atmospheric neutrino flux) and the energies are below the 'Glashow resonance' … so what are they?

# cosmic ray anisotropy

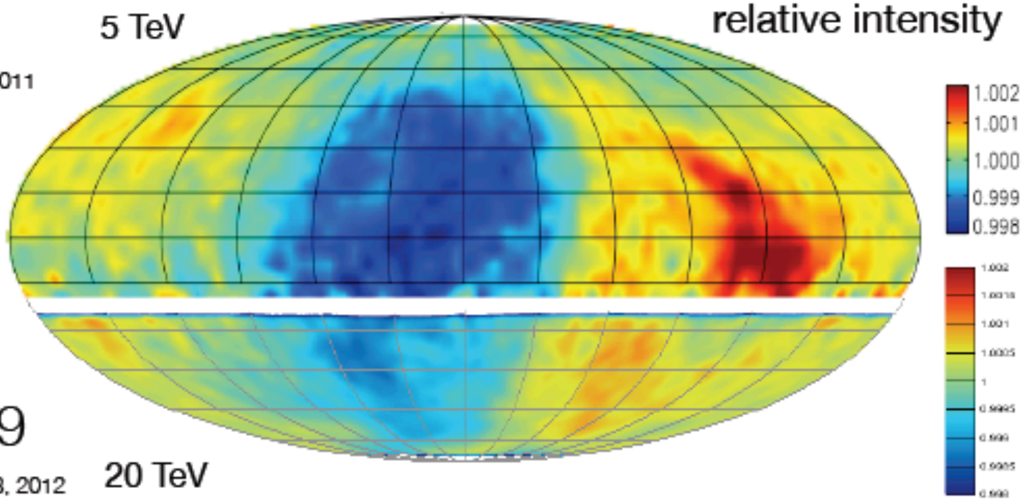
**indications of a nearby source?**

Tibet-III

Amenomori et al., ICRC 2011

5 TeV

relative intensity




IceCube-59

Abbasi et al., ApJ, **746**, 33, 2012

20 TeV

large scale anisotropy

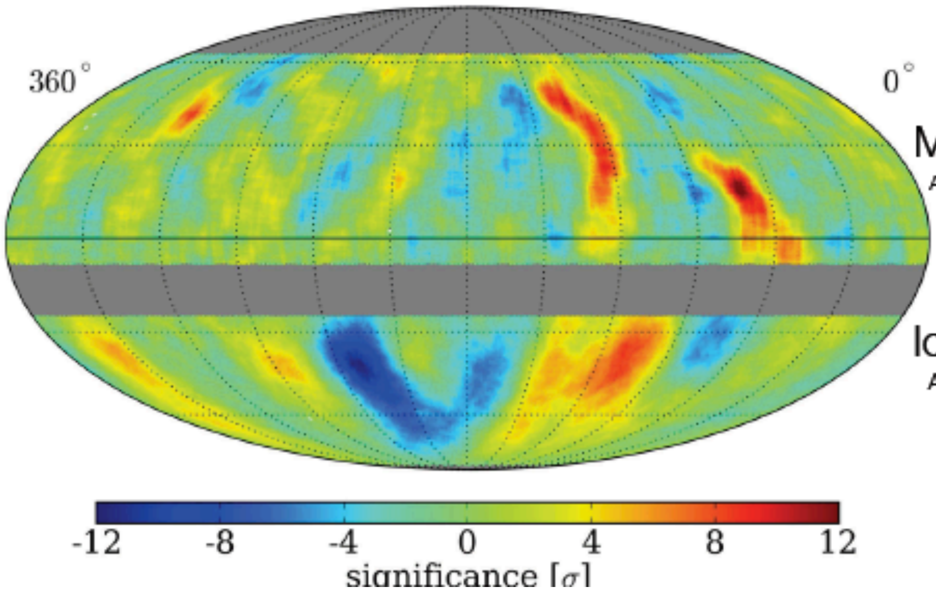
statistical significance

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)

2 hr = 30°

4 hr = 60°

small scale anisotropy




Milagro 1 TeV

Abdo et al., PRL, **101**, 221101, 2008

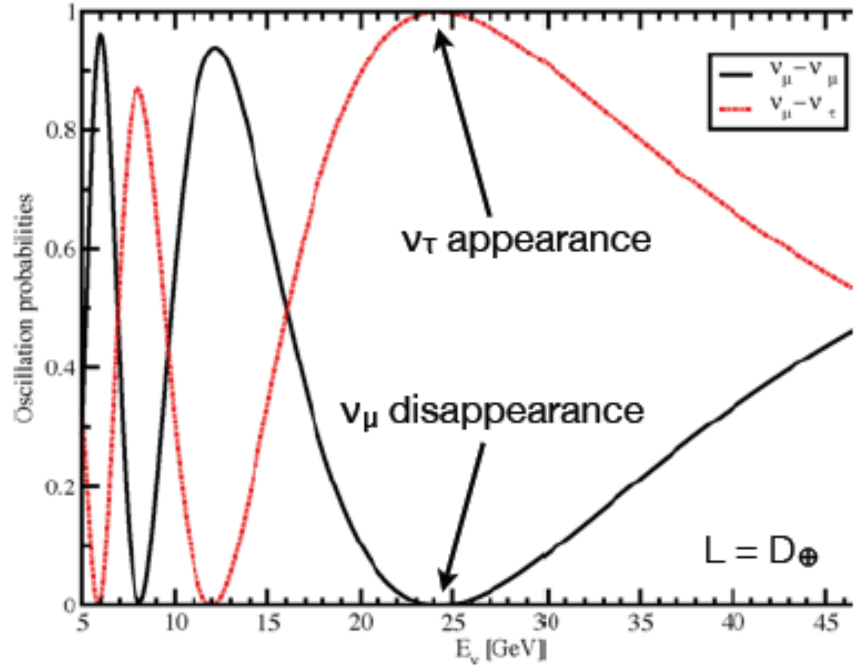
IceCube 20 TeV

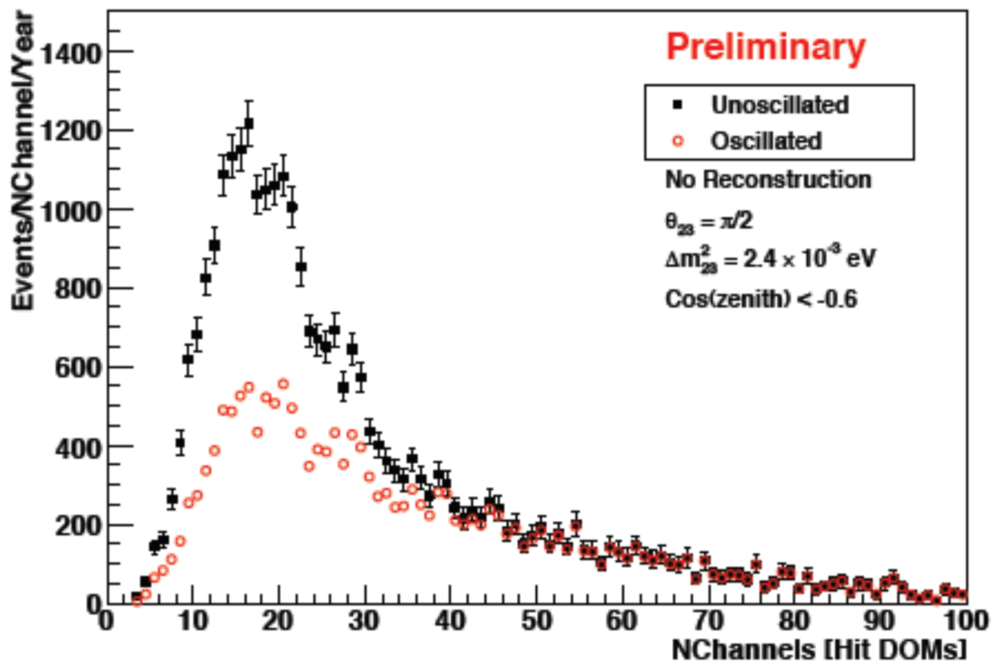
Abbasi et al., ApJ, **740**, 16, 2011

**consistent with lower energy observations**

# Neutrino Oscillations

- Atmospheric neutrinos from Northern Hemisphere oscillating over one earth diameter have $\nu_\mu$ oscillation minimum at ~25 GeV
  - Higher energy region than accelerator-based experiments
- Plot of $\nu_\mu$ disappearance shows only simulated signal
  - Analysis efficiencies not included yet – work ongoing
  - Uses number of hit DOMs as a simple energy estimator



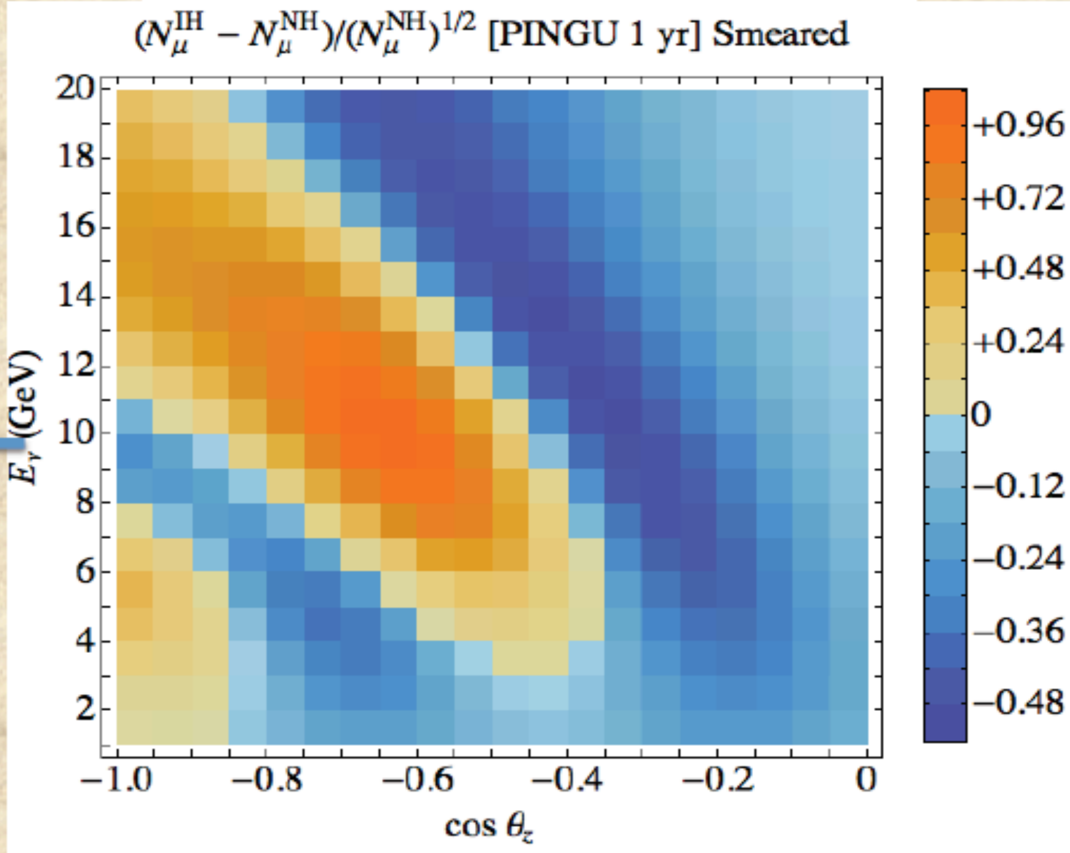



# Neutrino Oscillations in PINGU?

PINGU is a concept for even higher density infill to DeepCore that lowers the energy range of IceCube to several GeV range with MT's effective volume

Ref: E. Kh. Akhmedov, S. Razzaque, A. Y. Smirnov   arXiv:1205.7071 [hep-ph]

$\sigma_E$ = 2 GeV, $\sigma_\theta$ = 11.25°




Statistical significance of Normal versus Inverted Mass Hierarchy.

Sets PINGU requirements on:

1) Energy Resolution
2) Angular Resolution
3) Systematic Errors

*We are currently studying the feasibility of reaching the needed requirements.*

$3\sigma - 11\sigma$ in 5 Years of running

Includes systematic error ≤ 10%

# Summary

The non-thermal universe revealed by high energy cosmic radiation provides new probes of fundamental physics and cosmology

Radio, X-ray, and $\gamma$-ray astronomy have yielded dramatic discoveries of many new phenomena … and neutrino astronomy is about to open up

This is an opportune time to become involved in the next generation $\gamma$-ray observatory (➥ **Cherenkov Telescope Array)** and the world's biggest neutrino observatory (➥ **IceCube)**

*"The real voyage of discovery consists not in seeking new landscapes but in having new eyes"*

Marcel Proust