The High-Energy Astro-Particle Physics Program at DESY: News on IceCube Plans for CTA

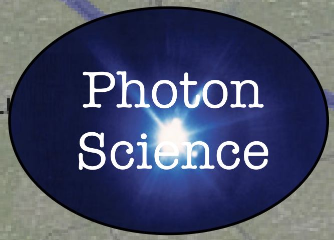
Stefan Schlenstedt, DESY

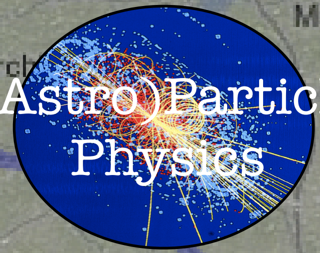
ANL, April 23, 2008

DESY Deutsches Elektronen-Synchrotron

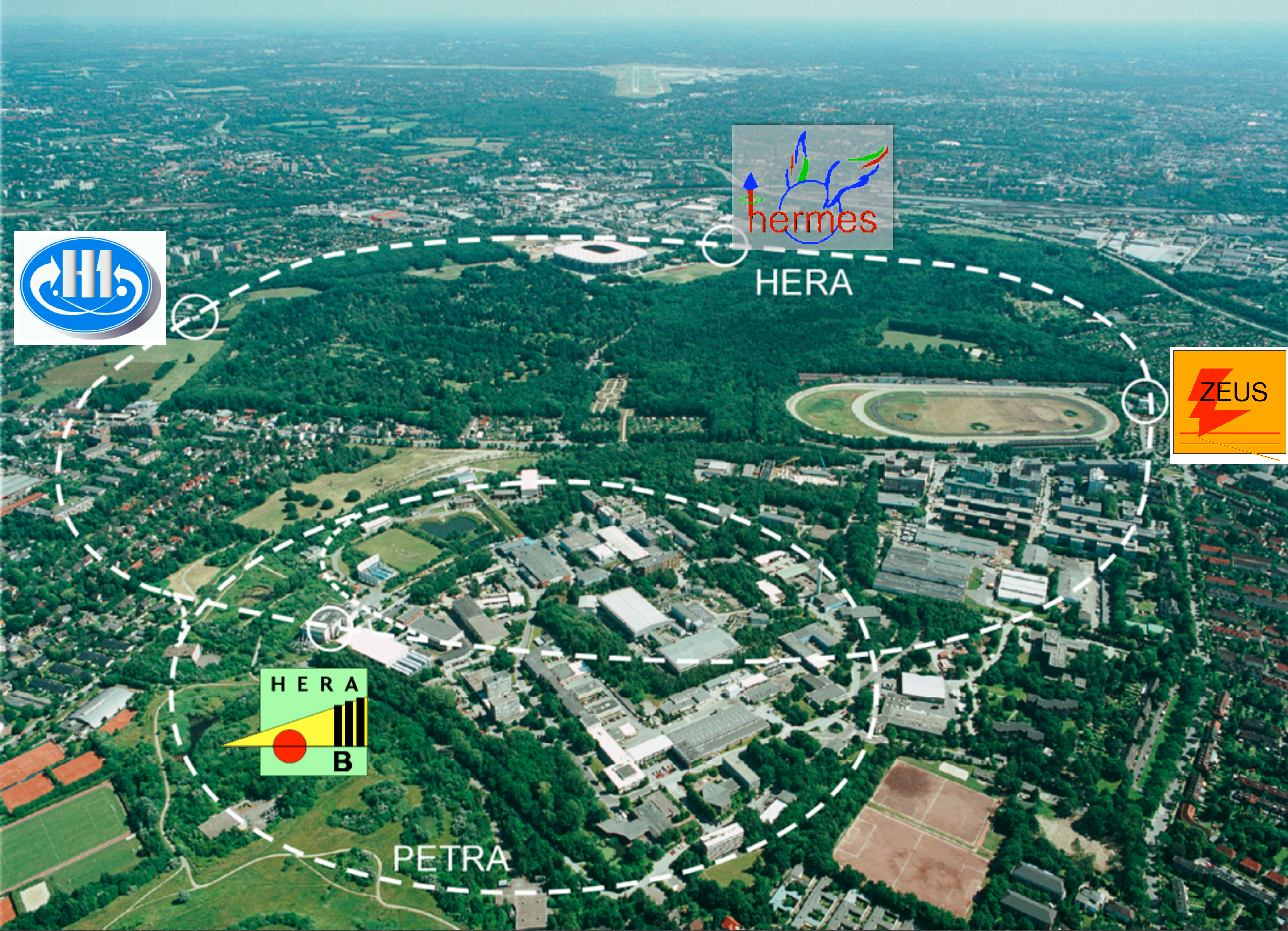
HELMHOLTZ ASSOCIATION

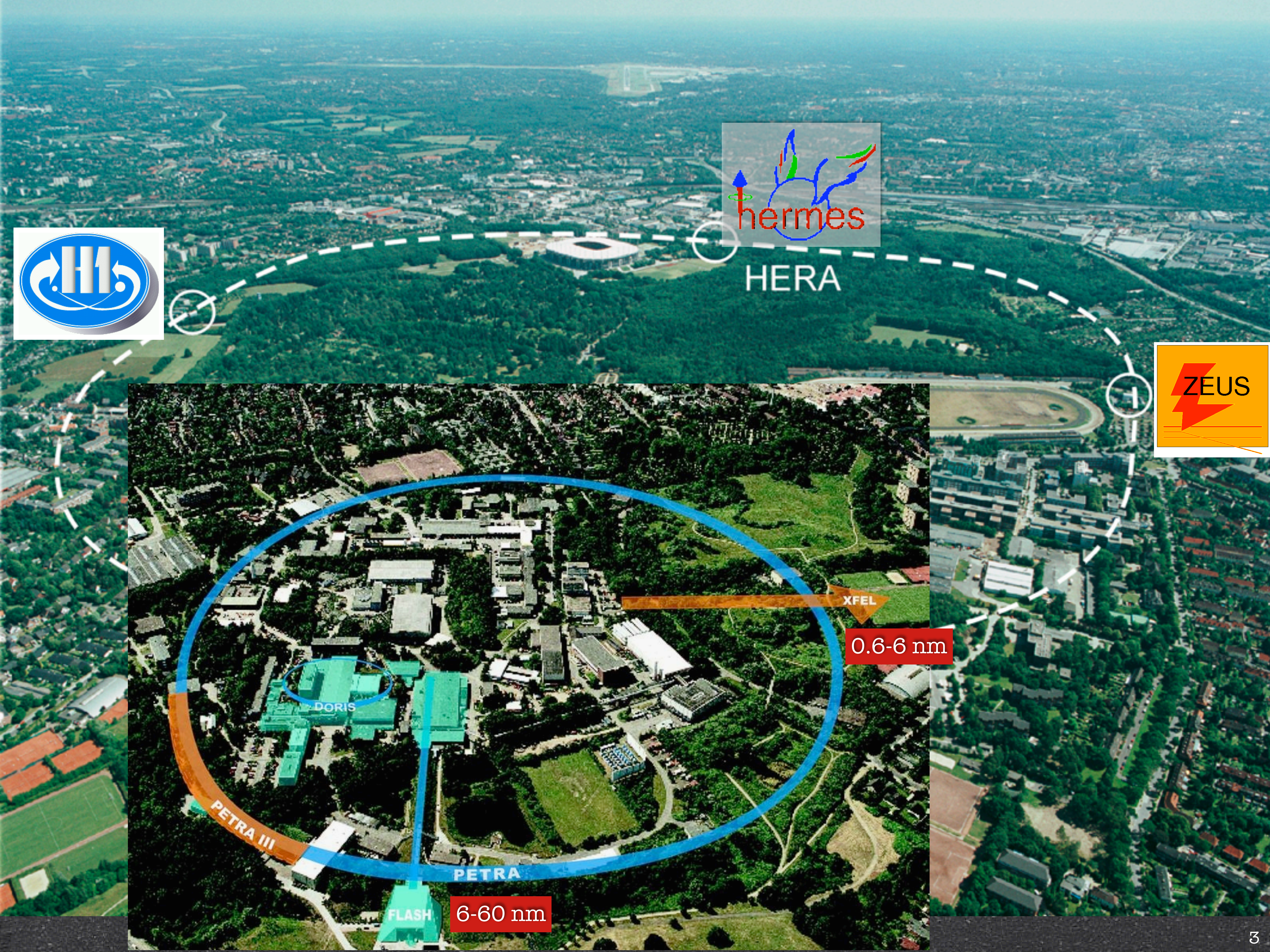
- mission:

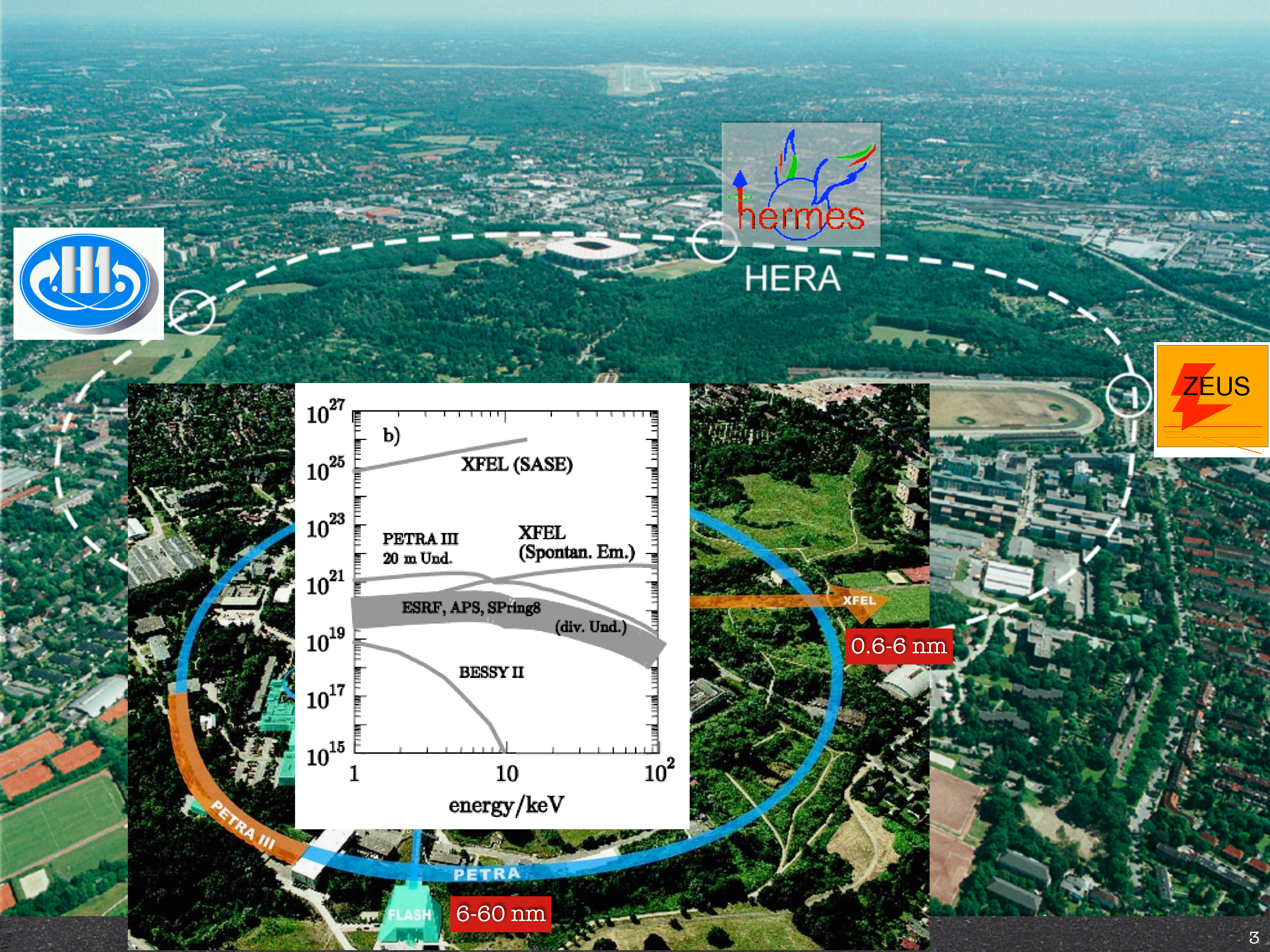




- 1900 employees – 600 scientists
- 3000 guest scientists
- 700 diploma and PhD students and postdocs
- Sites in Hamburg and Zeuthen


hermes
HERA
ZEUS
HERA
B
PETRA


hermes
HERA
ZEUS
XFEL
0.6-6 nm
DORIS
PETRA III
PETRA
FLASH
6-60 nm


hermes
HERA
ZEUS
b)
XFEL (SASE)
PETRA III
20 m Und.
XFEL
(Spontan. Em.)
ESRF, APS, SPring8
(div. Und.)
BESSY II
10^{27}
10^{25}
10^{23}
10^{21}
10^{19}
10^{17}
10^{15}
1
10
10^2
energy/keV
XFEL
0.6-6 nm
PETRA III
PETRA
FLASH
6-60 nm

Cosmic Rays

Victor F. Hess, Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten, Phys Z, 1912

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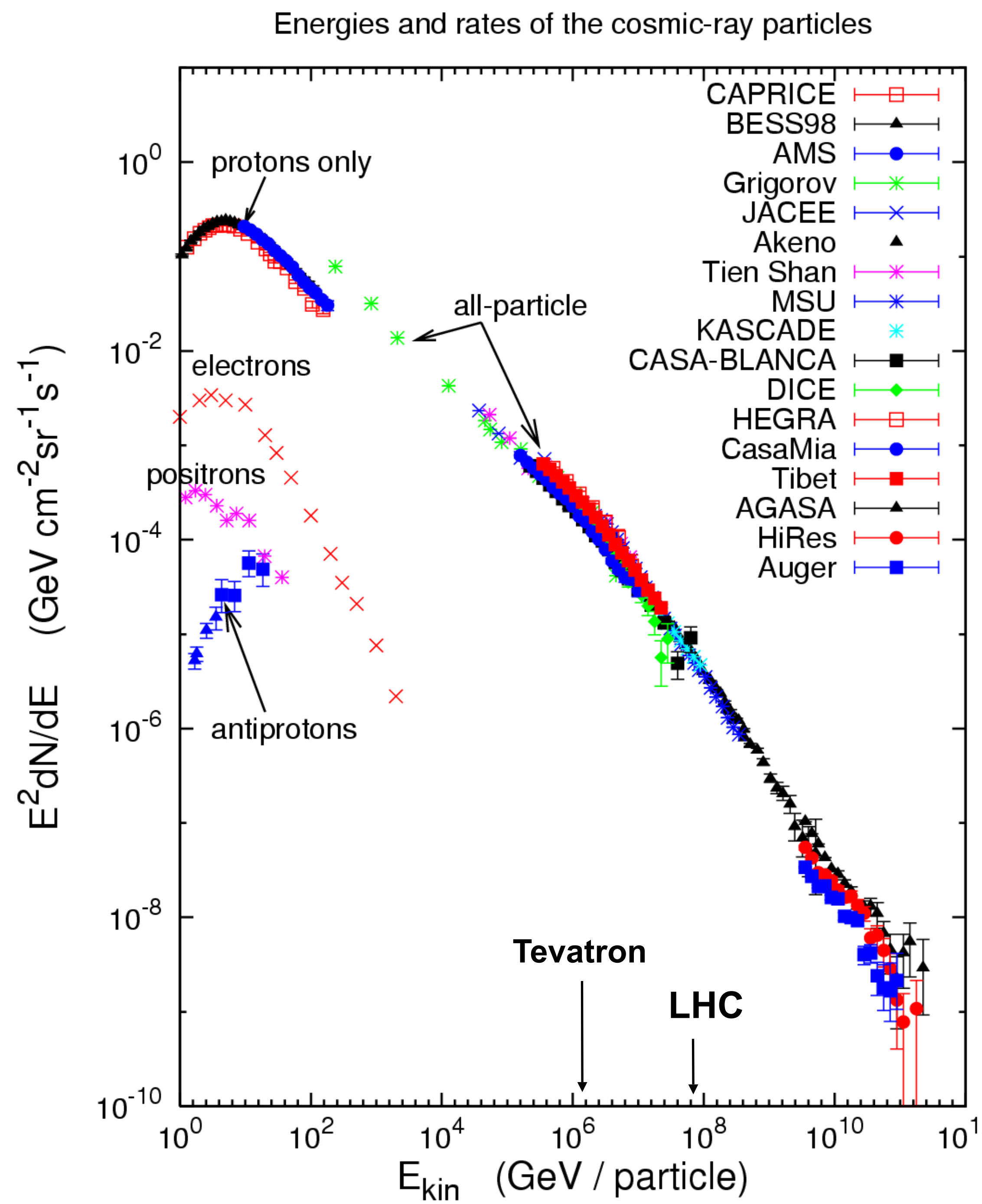
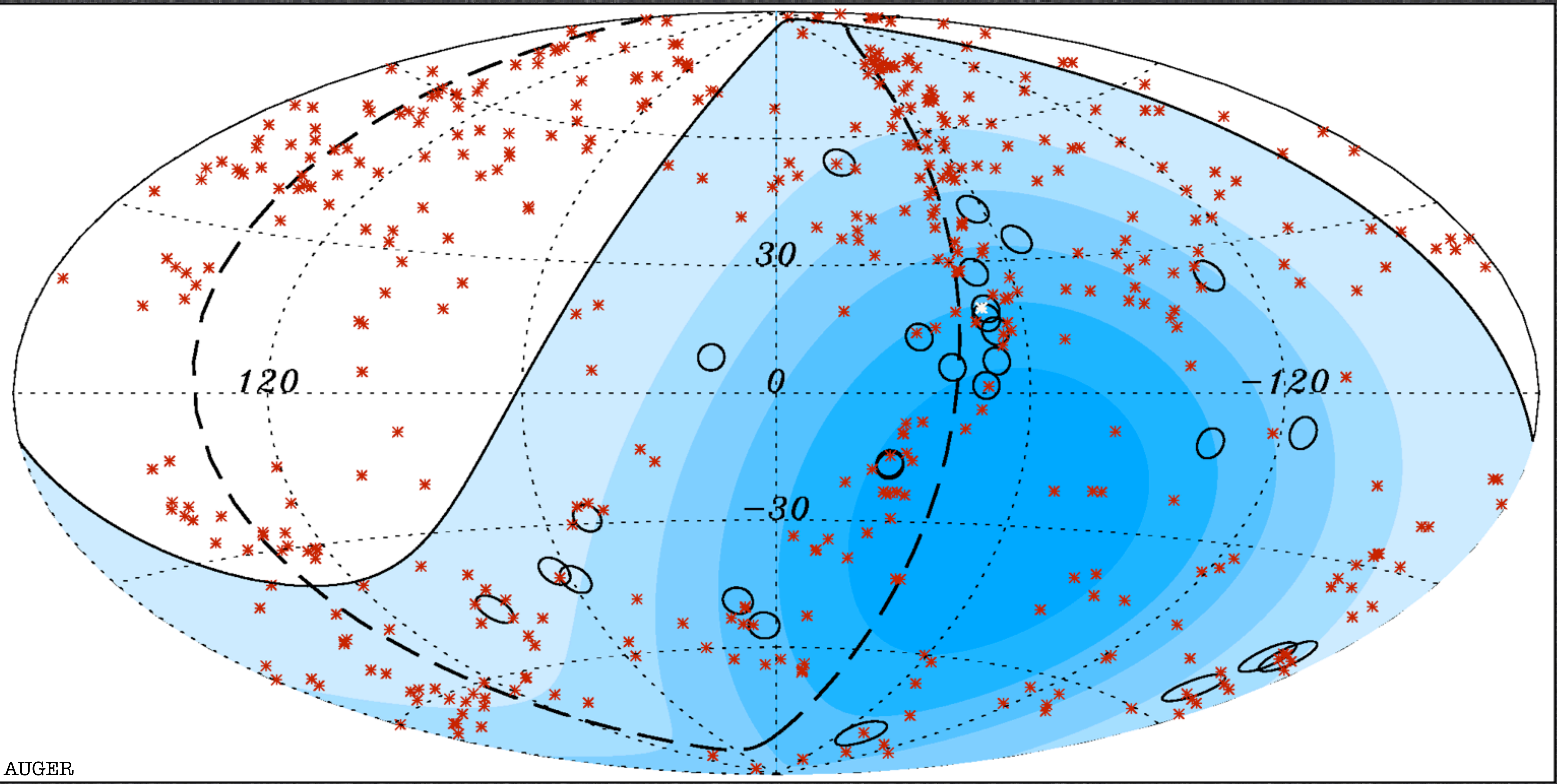
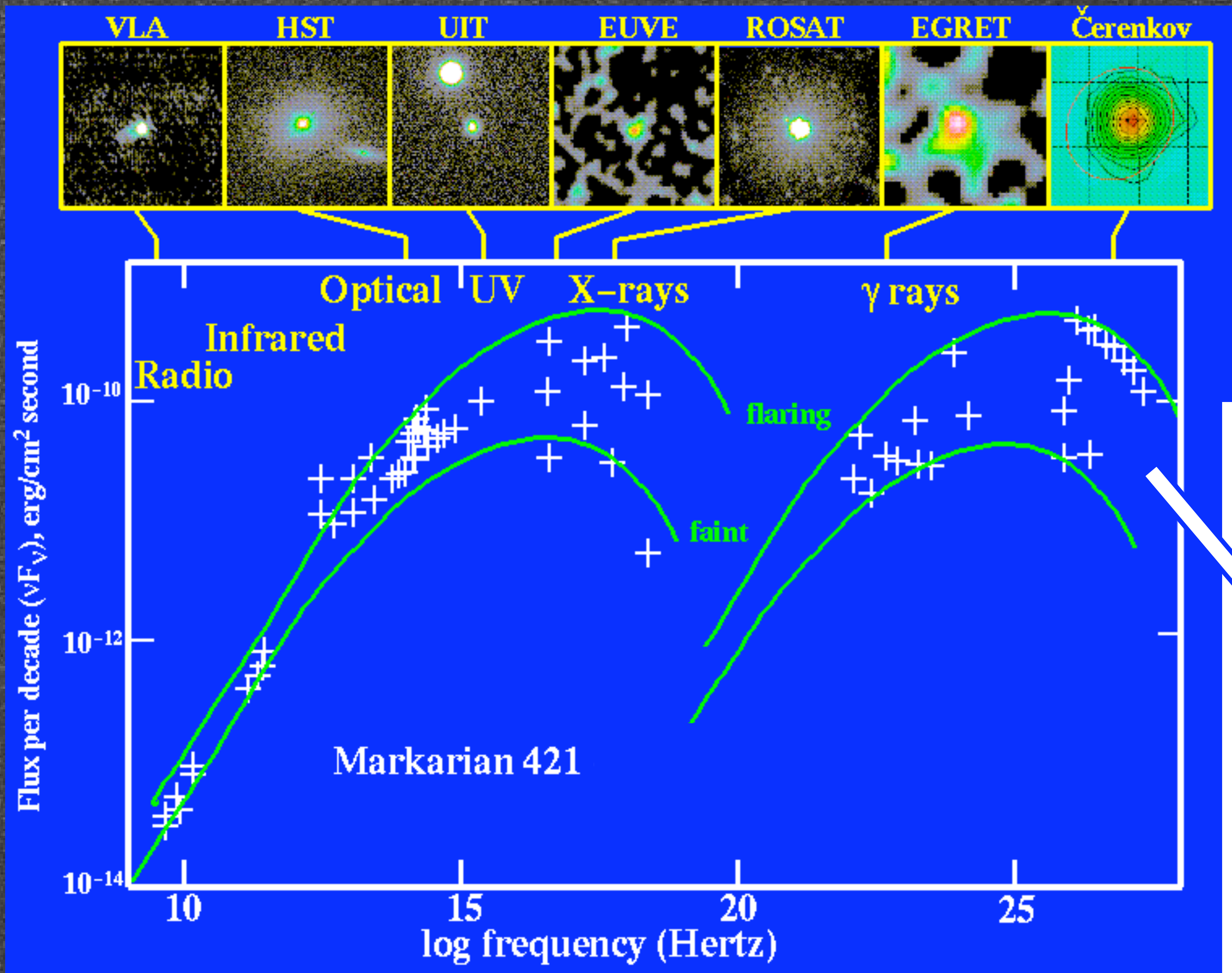


Highest Energy Cosmic Rays



- from Active Galactic Nuclei?

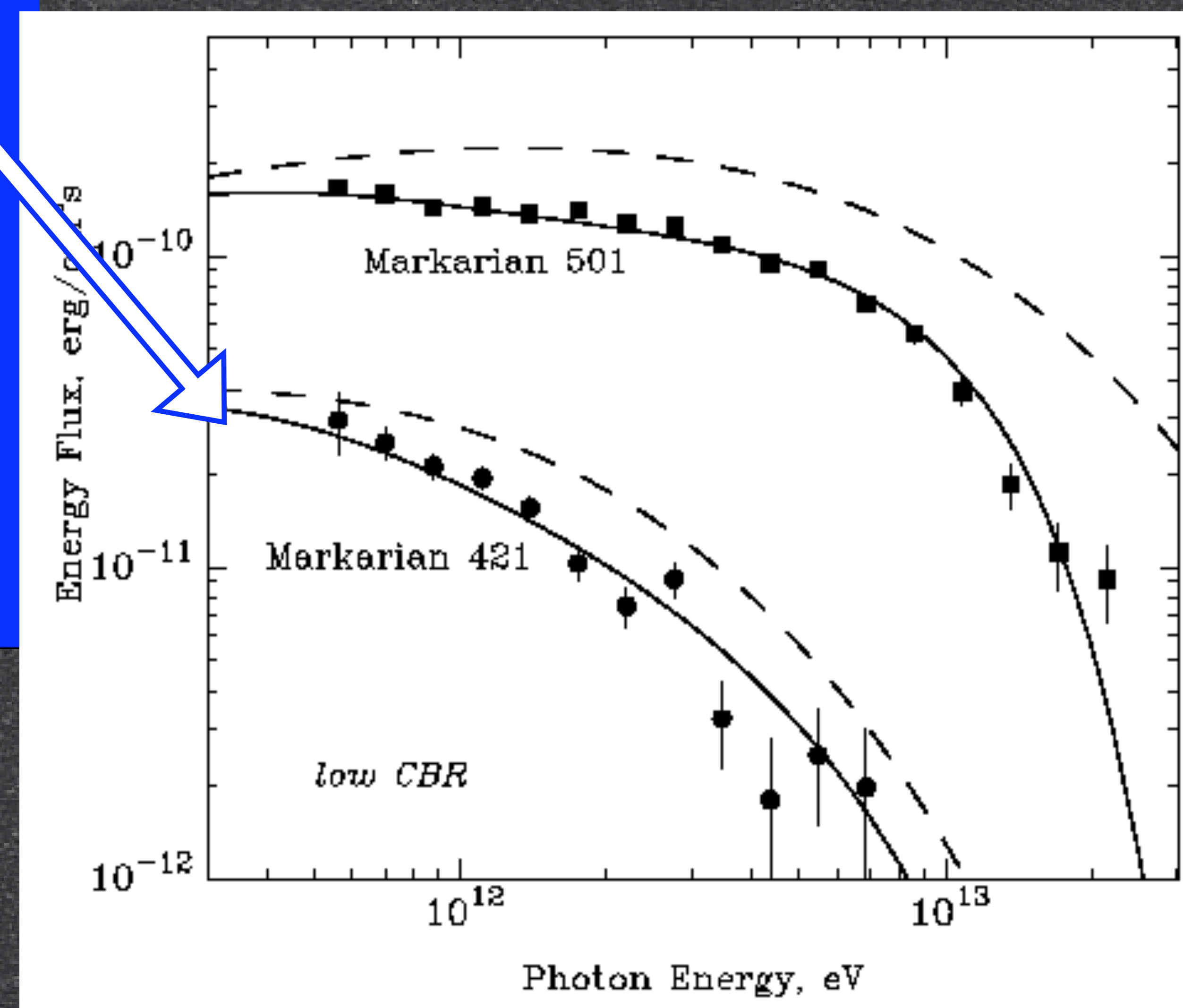
Cosmic Gamma-Rays



synchrotron

inverse Compton

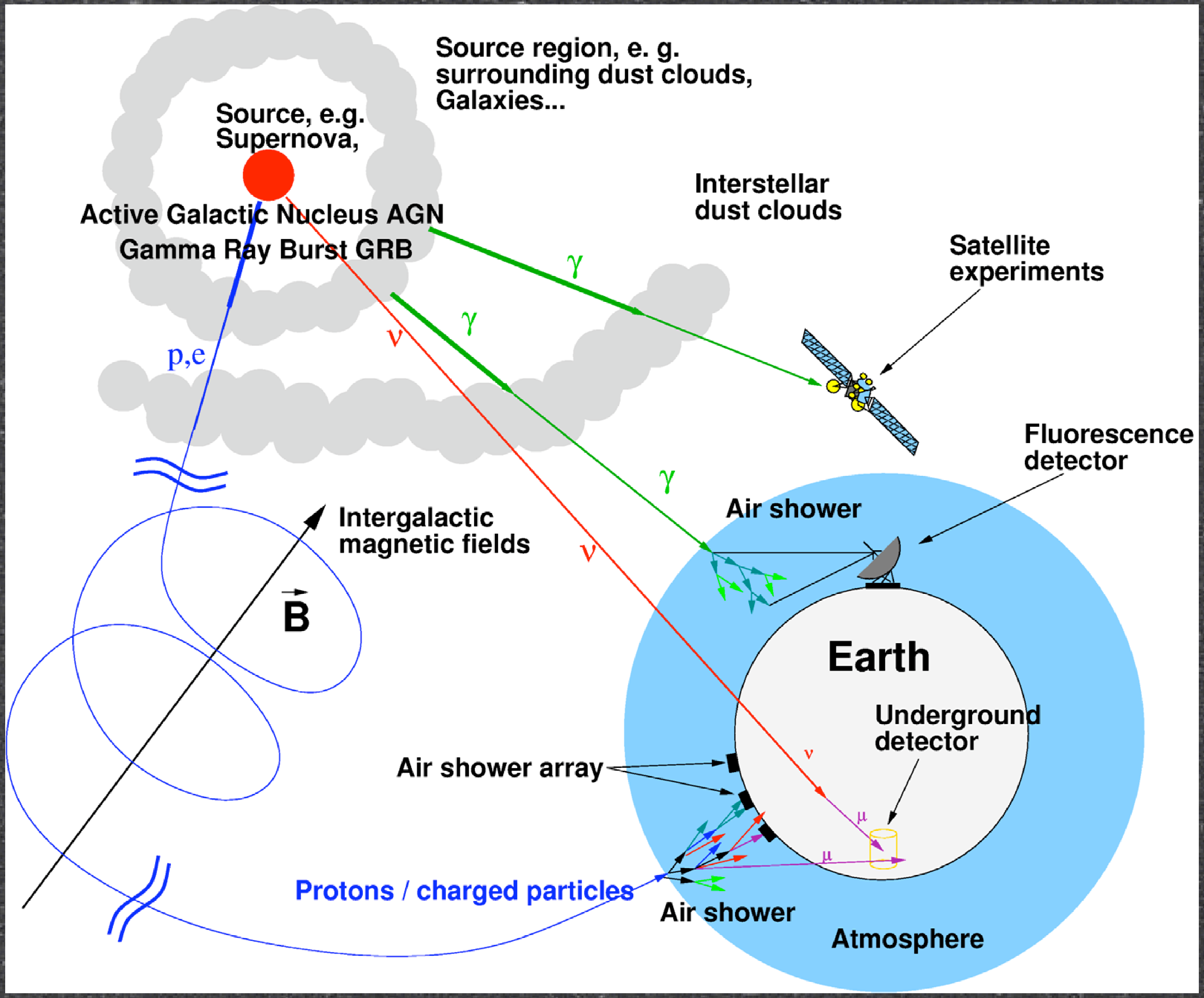
HEGRA



Many Questions on High-Energy Extraterrestrial Particles

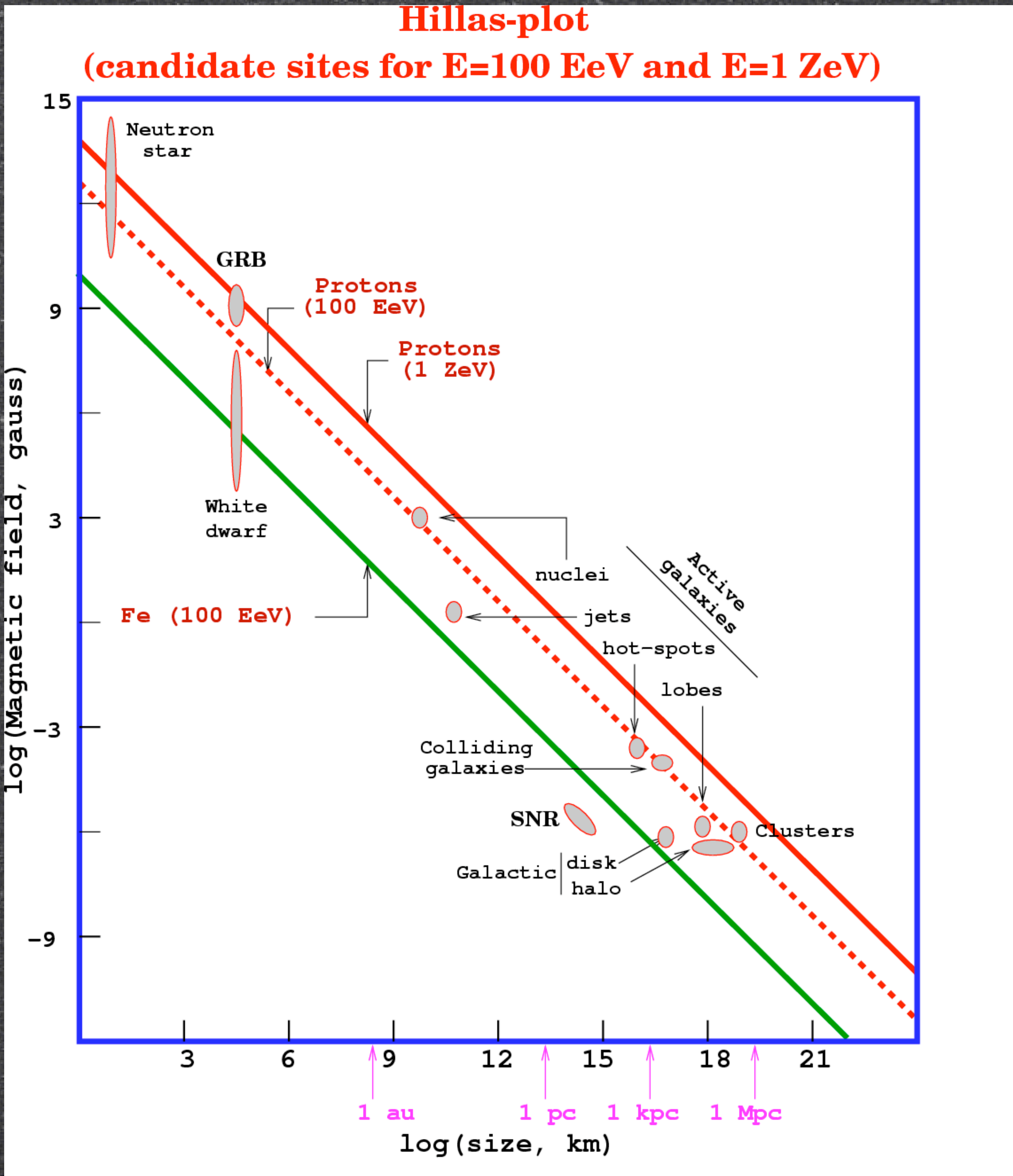
- Where do they come from?
- What is the acceleration mechanism?
- What are they?
- CRs and γs ☞ where are the neutrinos?

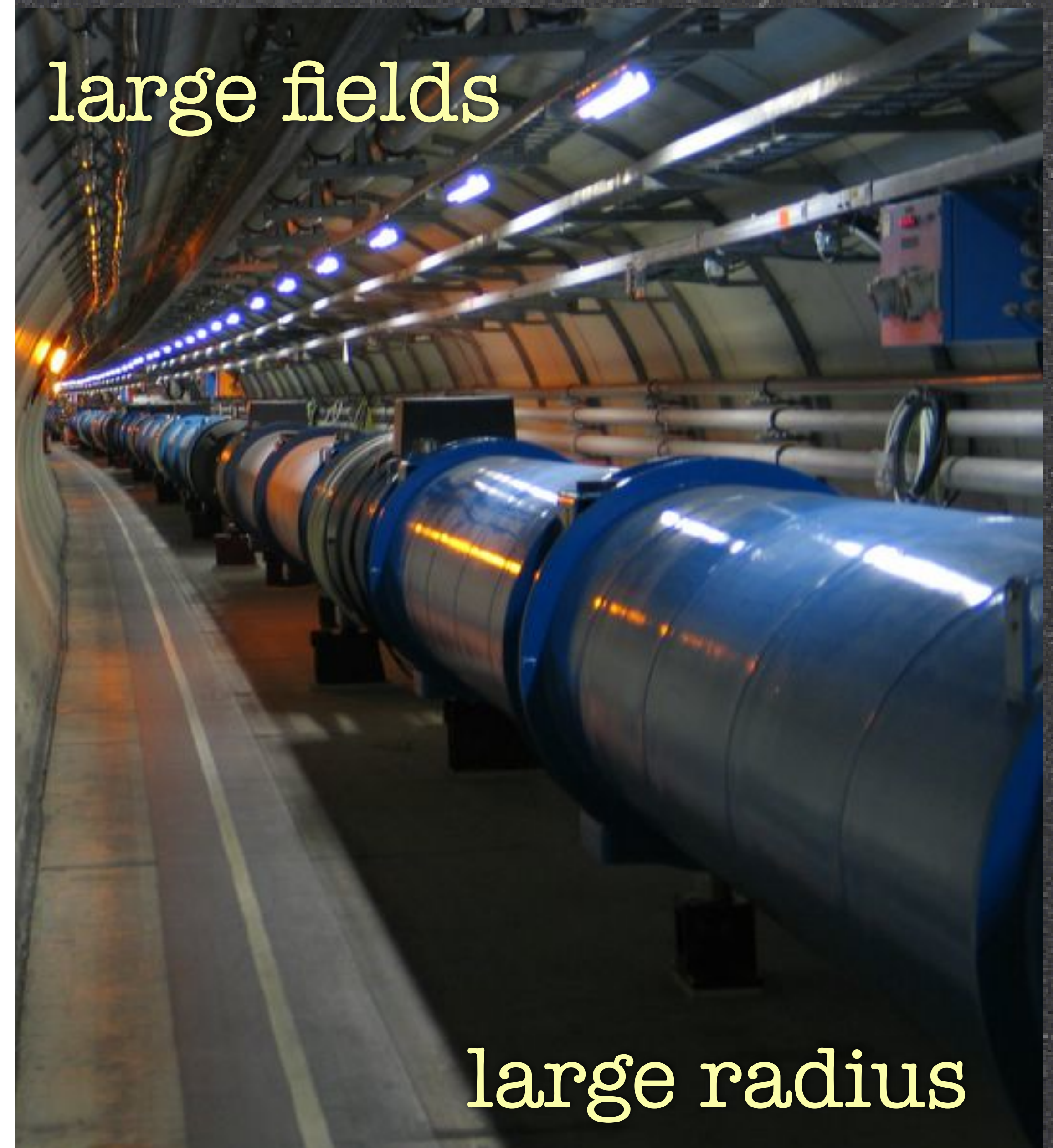
Particle Propagation



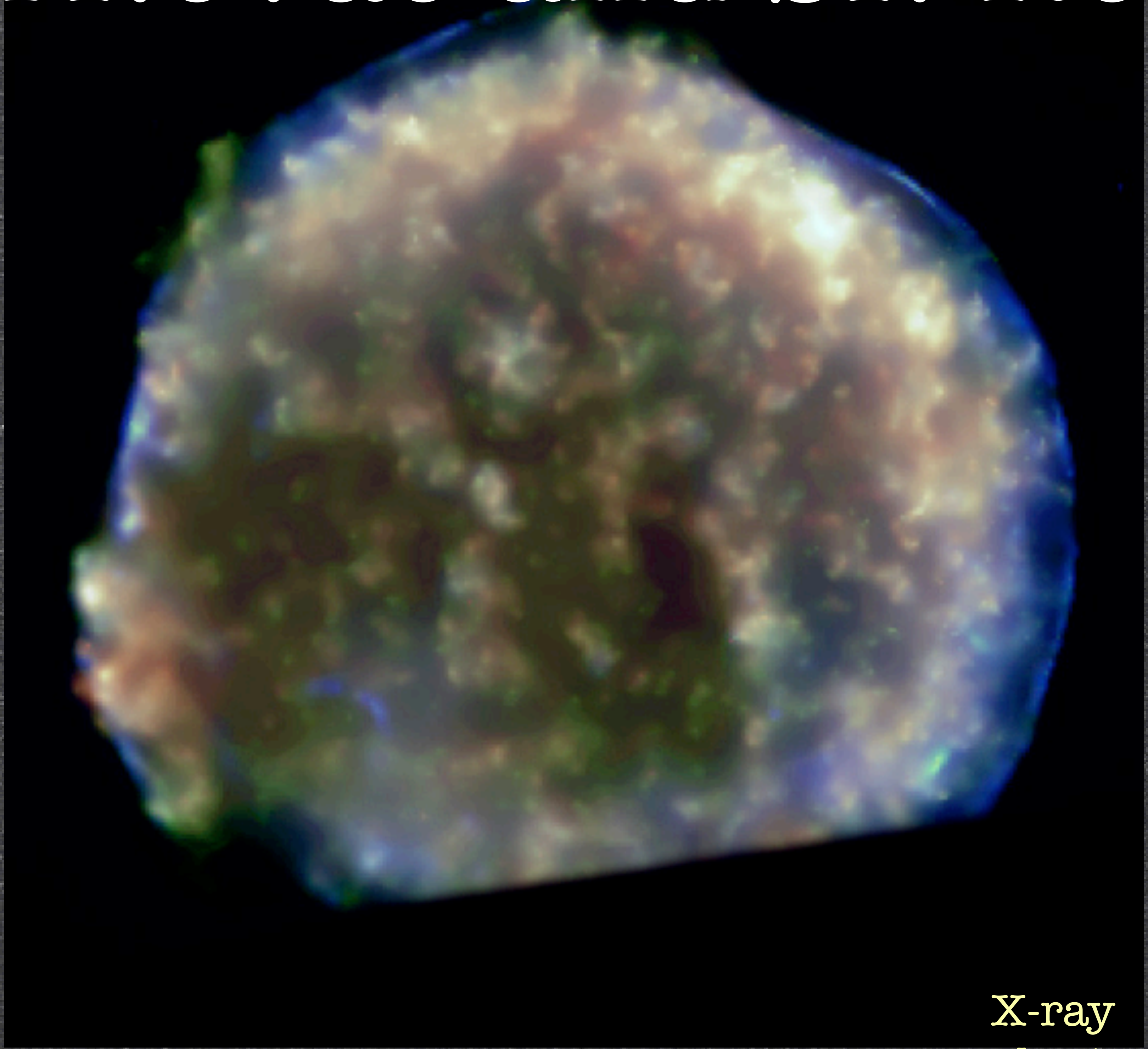
Protons/nuclei	deflected by magnetic fields
Photons	absorbed by dust and radiation
Neutrinos	...

Cosmic Accelerators





Possible source of CR: SuperNovae and SN Remnant



X-ray
also in radio and optical

Tycho Brahe, 1572

Possible extra-galactic source of CR: Gamma-Ray Bursts

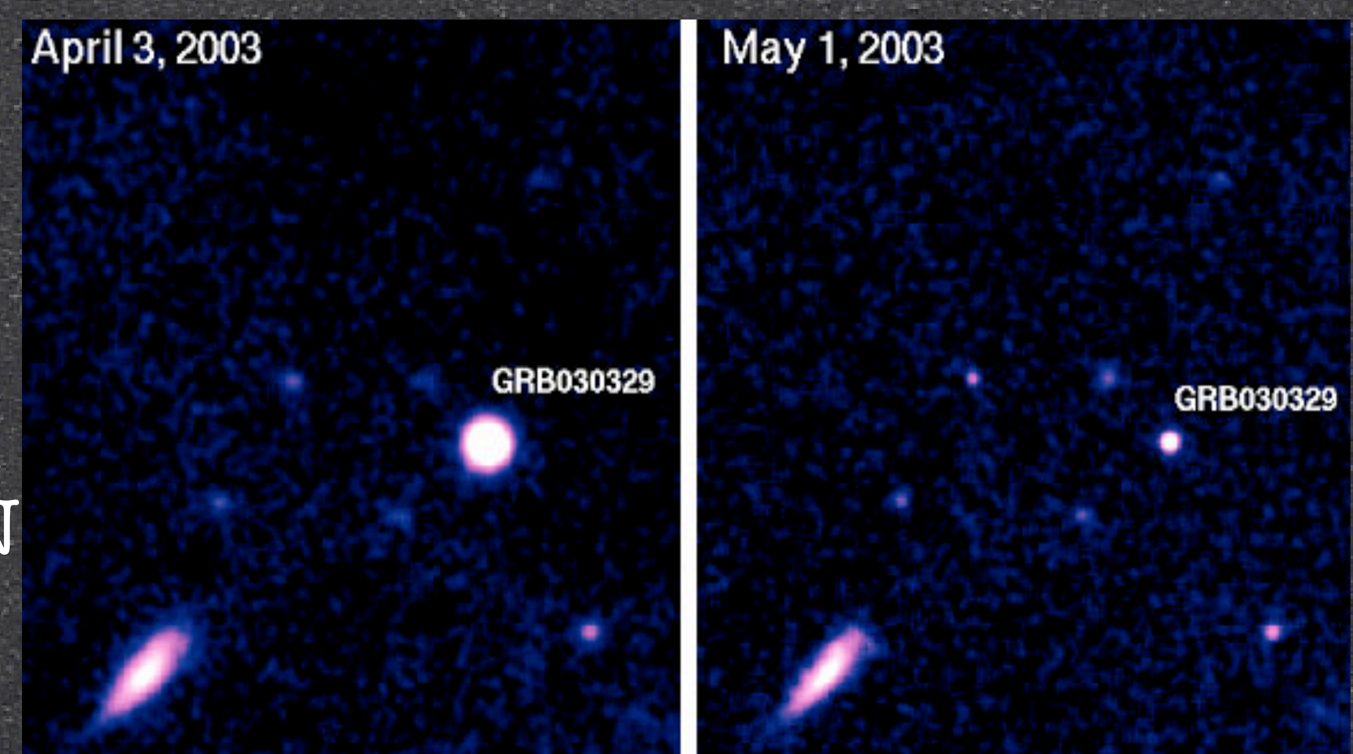
Most powerful emissions of γ rays

$L_\gamma = 10^{51\ldots53}$ erg/s (sun 10^{41} erg/y)

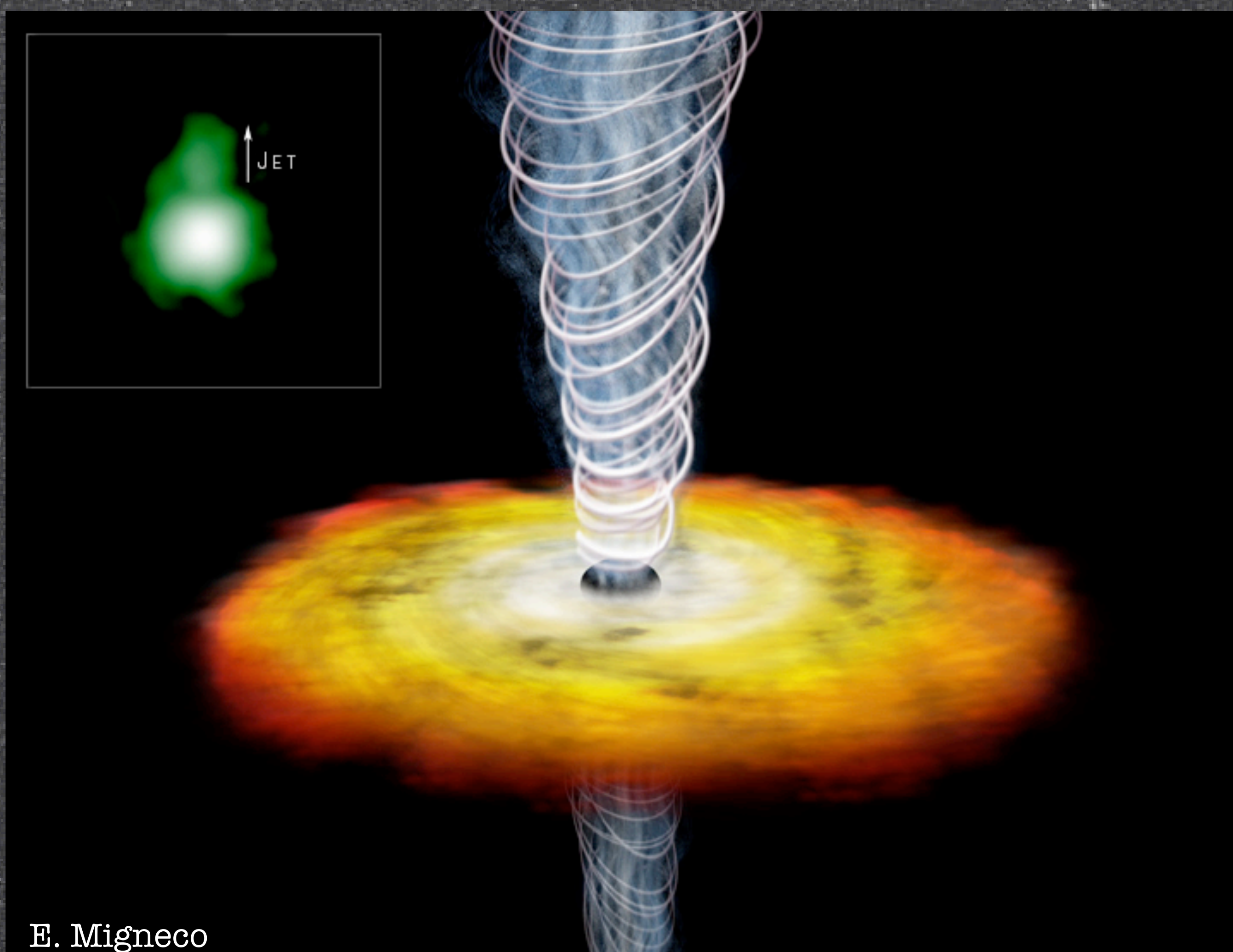
– few/day

GRB shown to be associated with SN

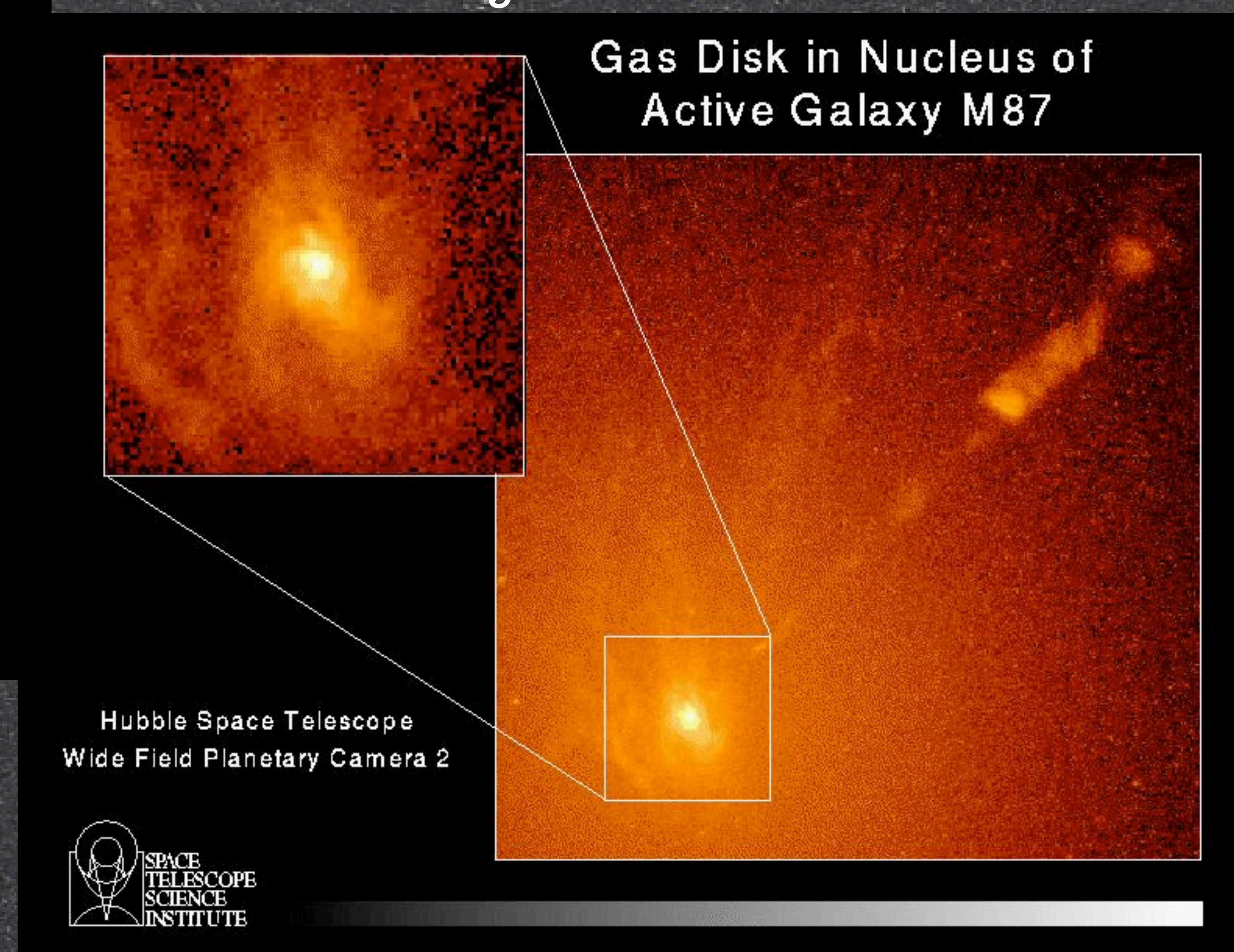
(e.g. GRB030329 – SN 2003dh at z=0.17)



Possible extra-galactic sources of CR: Active Galactic Nuclei



- Massive Black Hole $10^{6...9}\ M_\odot$
- Accretion disk
- Collimated jets $\Gamma : 10$



The brightest observed steady sources: $L_\gamma = 10^{42} \div 10^{47}$ erg/s

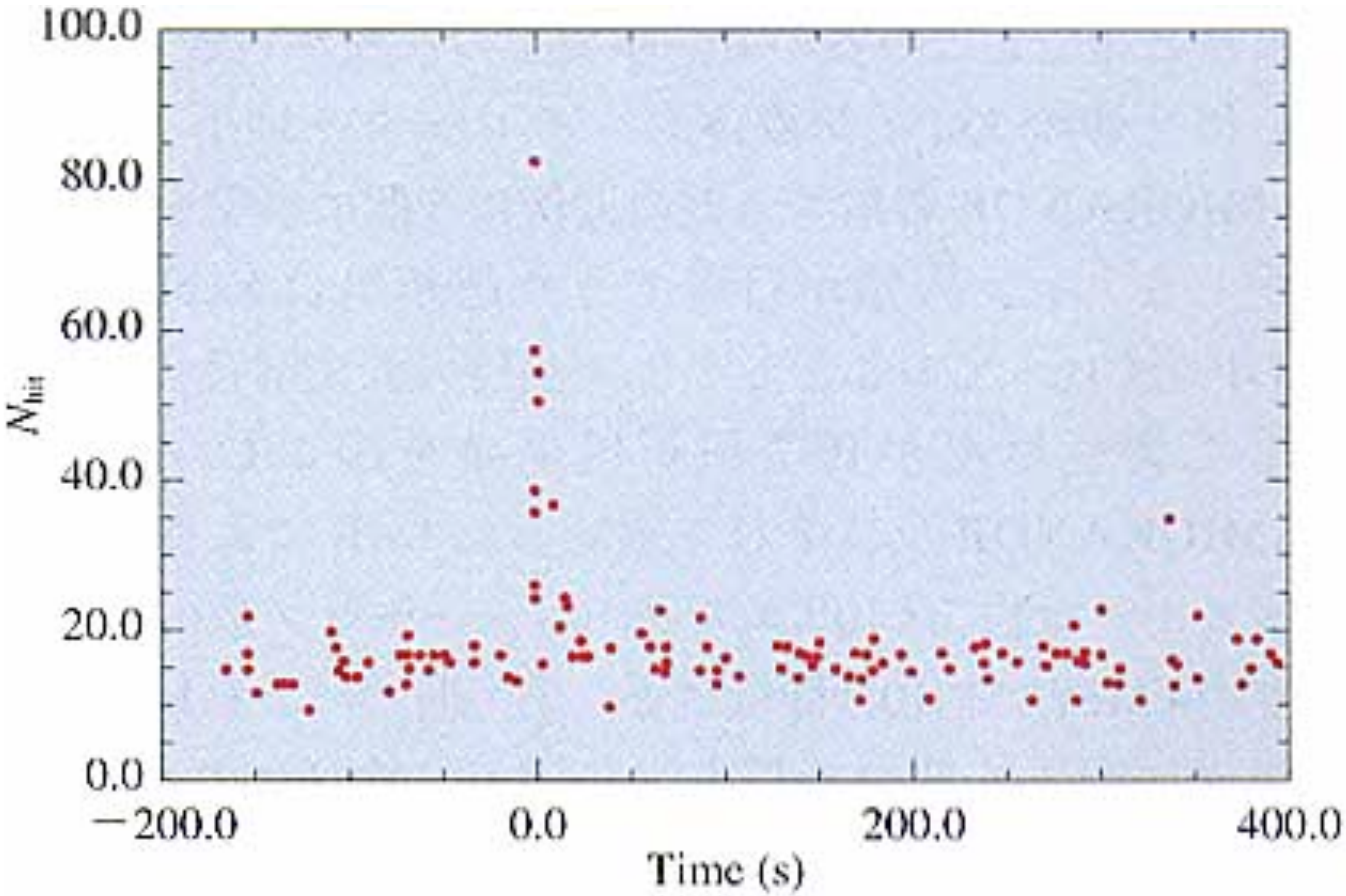
Neutrinos from SN 1987a

Large Cloud of Magellan

small irregular galaxies – satellites of the Milky Way

Neutrinos from SN 1987a

Large Cloud of Magellan



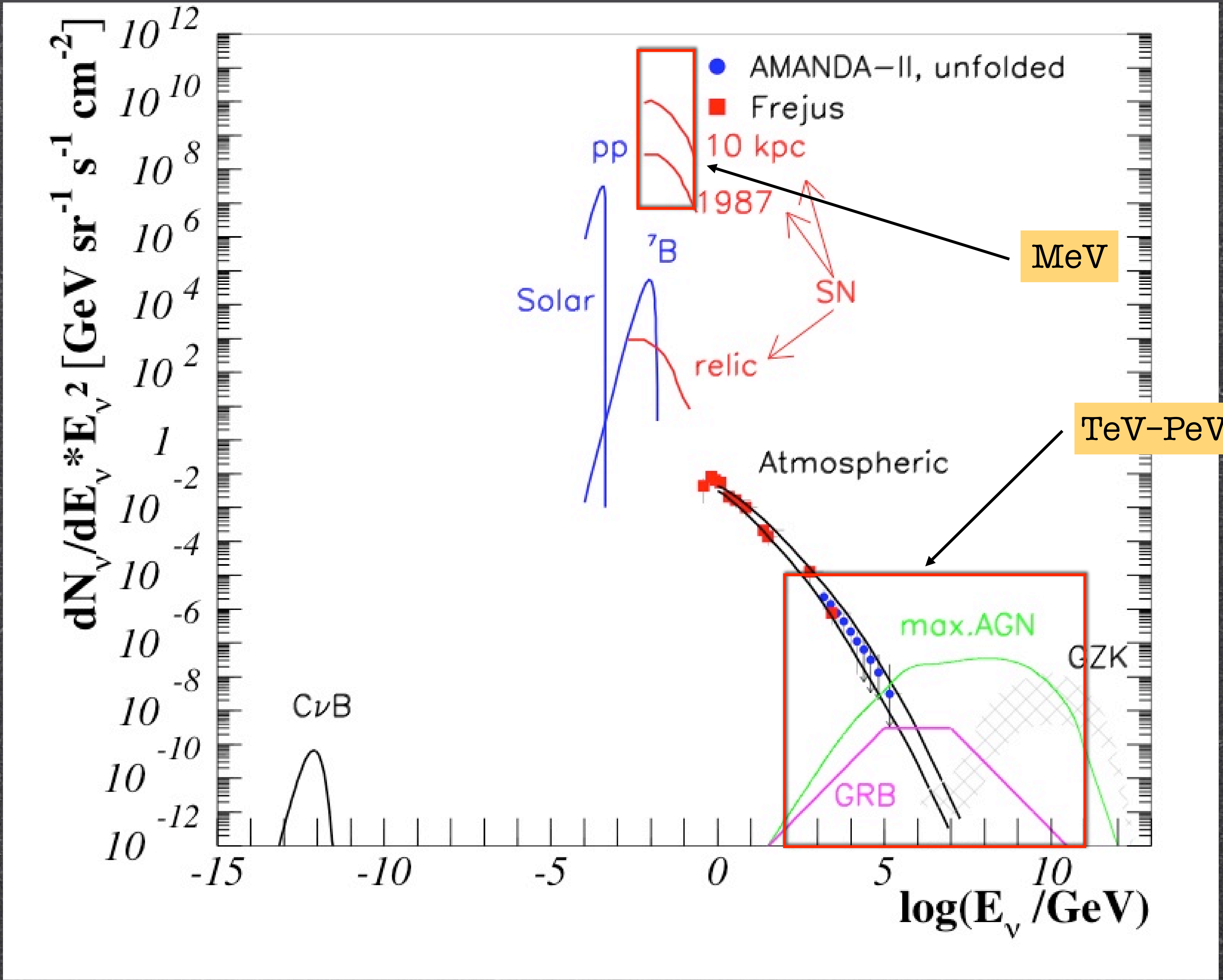
Kamiokande (Japan)
12 events

IMB (USA)
8 events

Baksan (Russia)
3 events

→ temperature in the new neutron star ~40 Billion K
→ neutrino mass < 23 eV

Neutrino Astro-Physics



ν Astro-Particle Physics

connects astro-physics and particle physics

- light
- neutral
- interact only by weak force

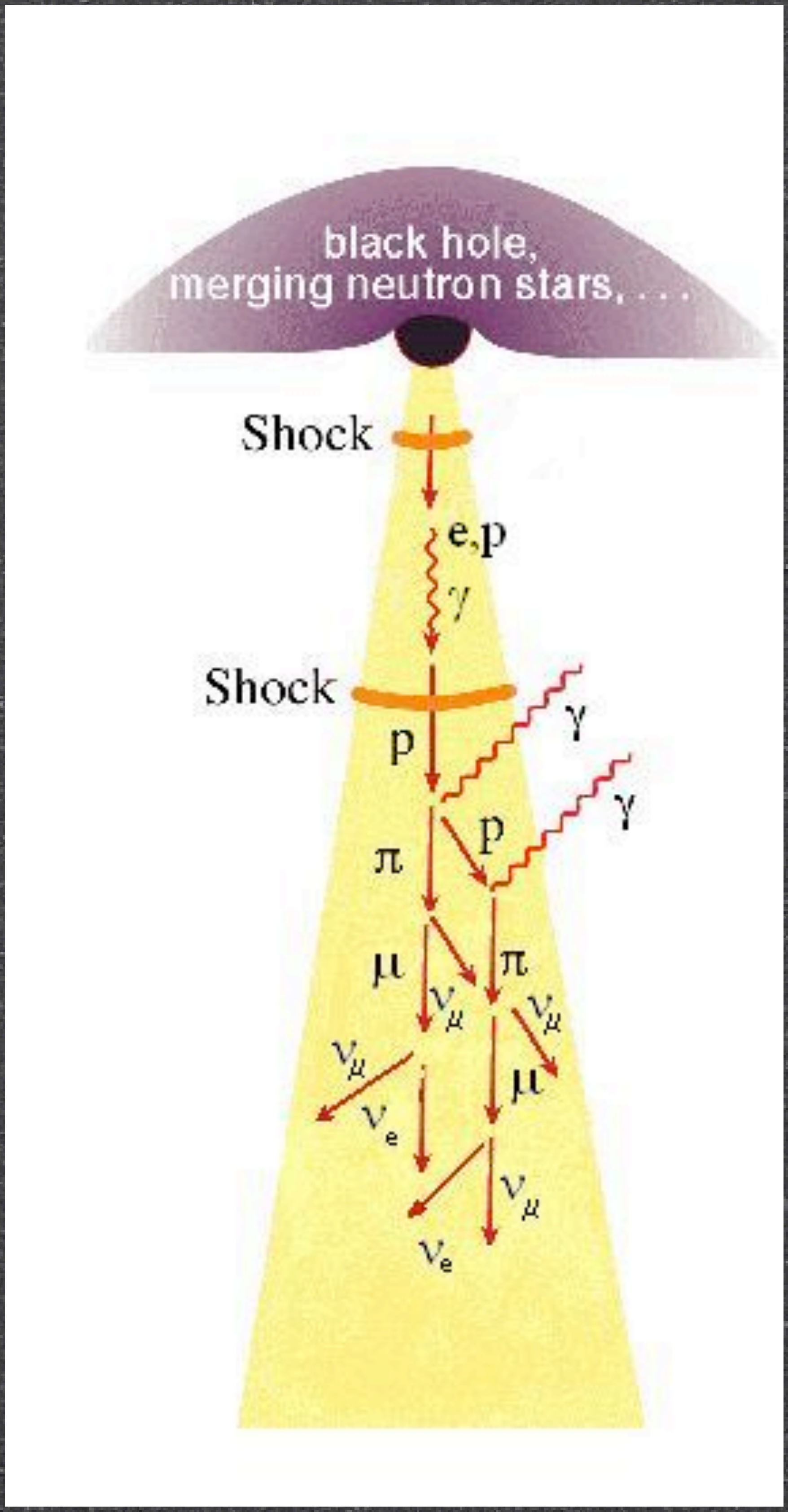
⇛ good astrophysical probes:

- travel straight
- ‘not’ absorbed over cosmological distances and dense environment

understand

- the origin of cosmic rays
- cosmic cataclysms
- basic properties (σ, m_ν, ν_τ)
- dark matter
- new kinds of objects
- ○ tests of relativitiy, search for big bang relics, effects of ED...

ν's from Cosmic Accelerators

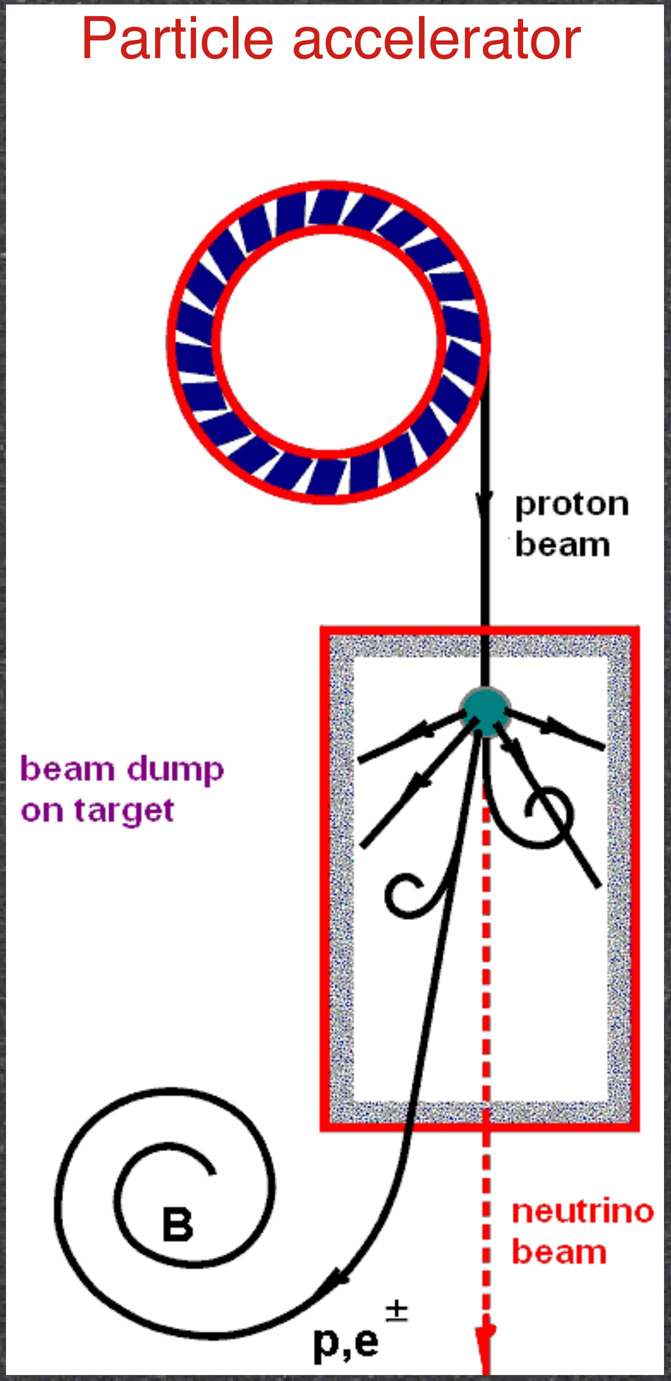


proton (Fermi) acceleration in shock waves $\rightarrow dN/dE \sim E^{-2}$

neutrino production
- Proton interactions
  - p → p (SNR, X-Ray Binaries)
  - p → γ (AGN, GRB, microQS)
- decay of pions and muons

simultaneous γ production
- π^0 decay

Cosmic ray acceleration yields neutrinos and gammas with similar abundance and energy spectra



Long-term Astro-Particle Physics Program

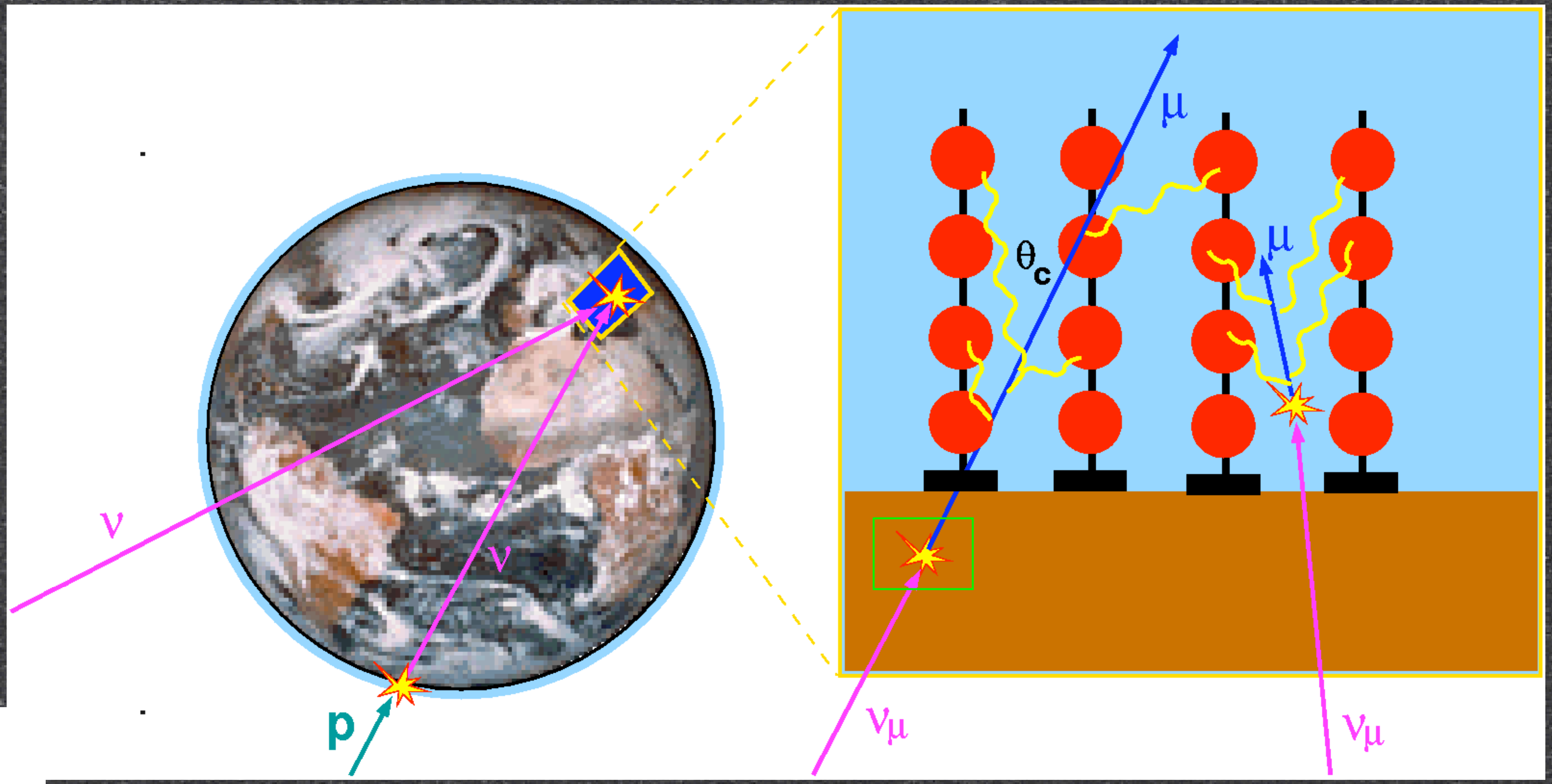
- Non-thermal universe
- 20 years: Baikal ⇒AMANDA⇒IceCube
- Multi-messenger with MAGIC
- Cherenkov Telescope Array CTA

Principles of ν–Telescopes

Earth screens against all particles except neutrinos

Atmosphere target for production of 'background' neutrinos

detector exploits Cherenkov light: spectral range 350-500 nm



energy thresholds

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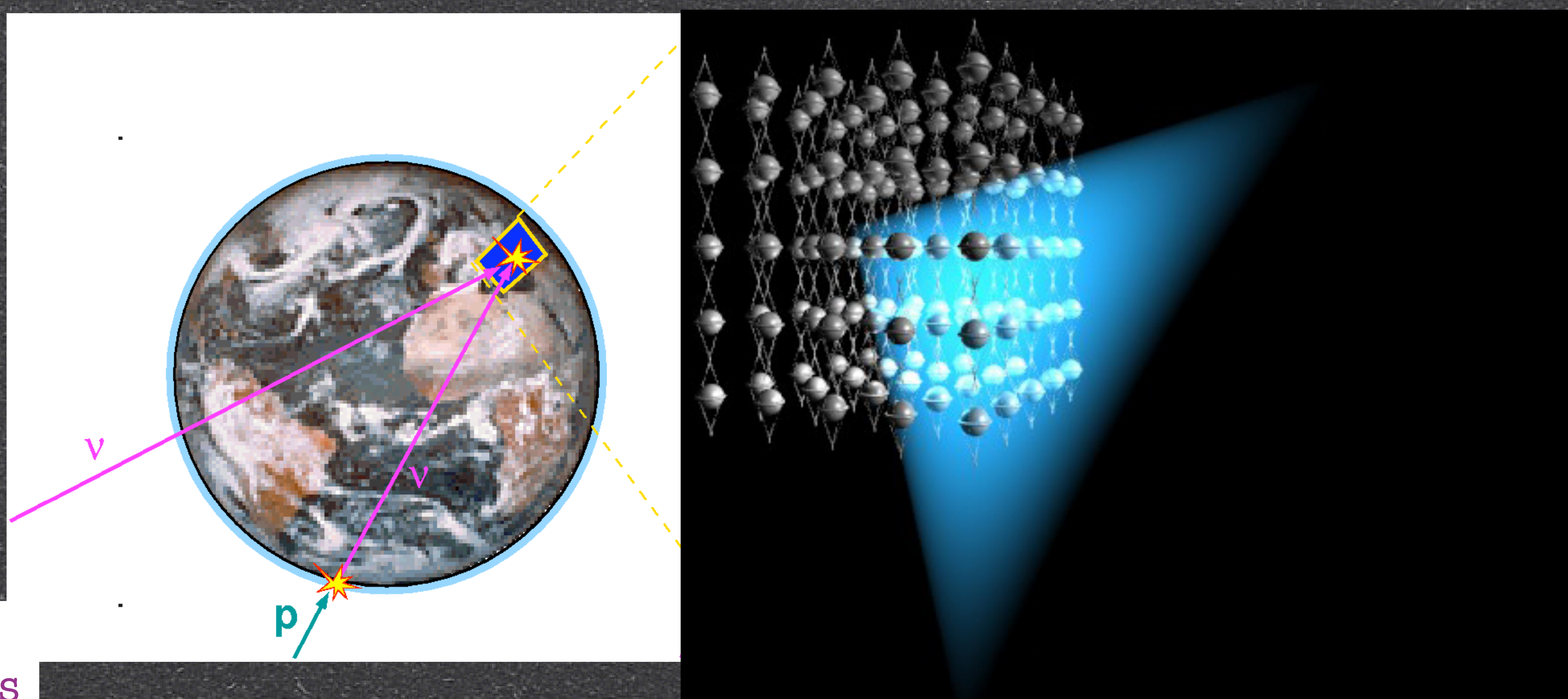
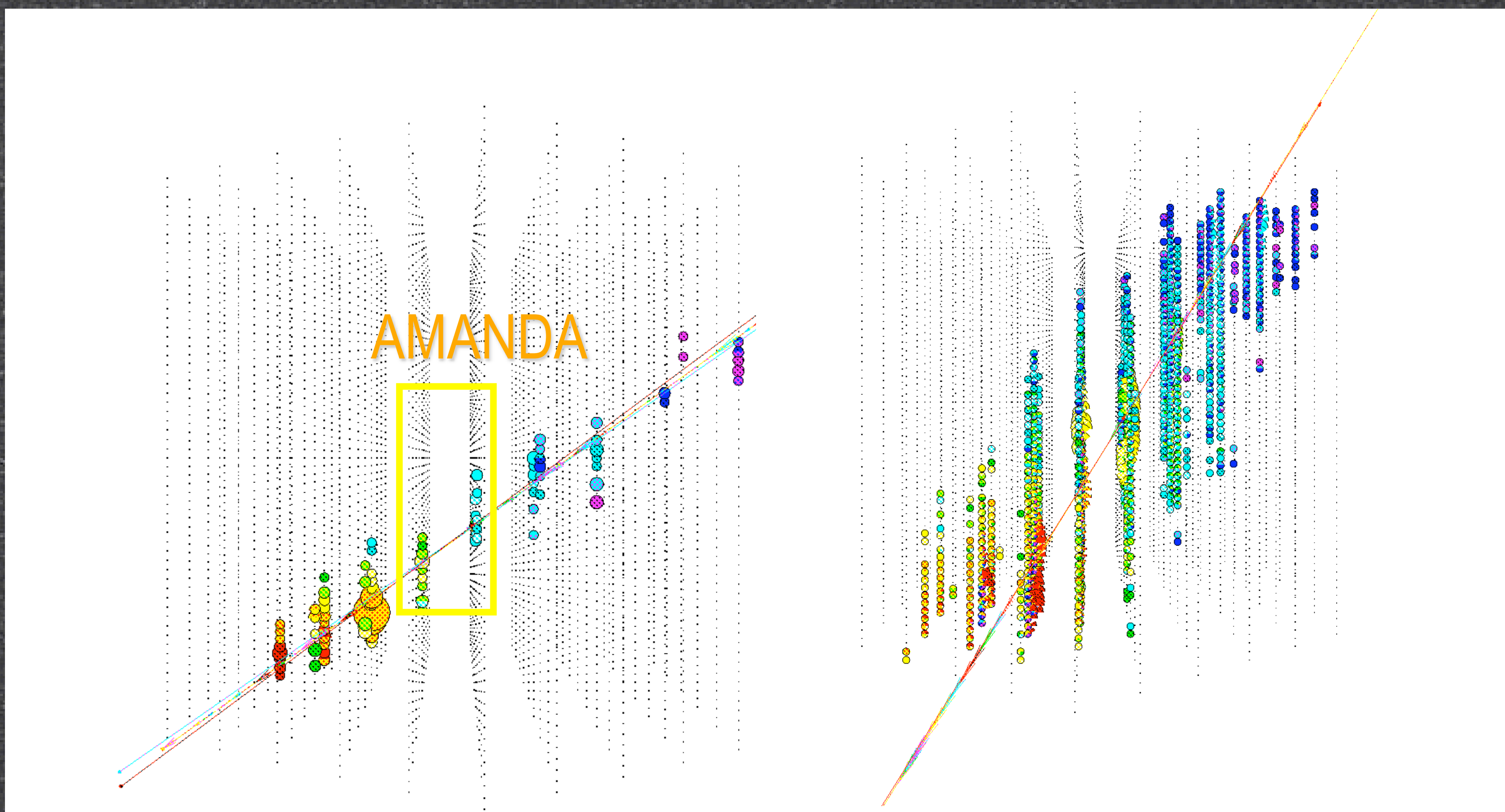


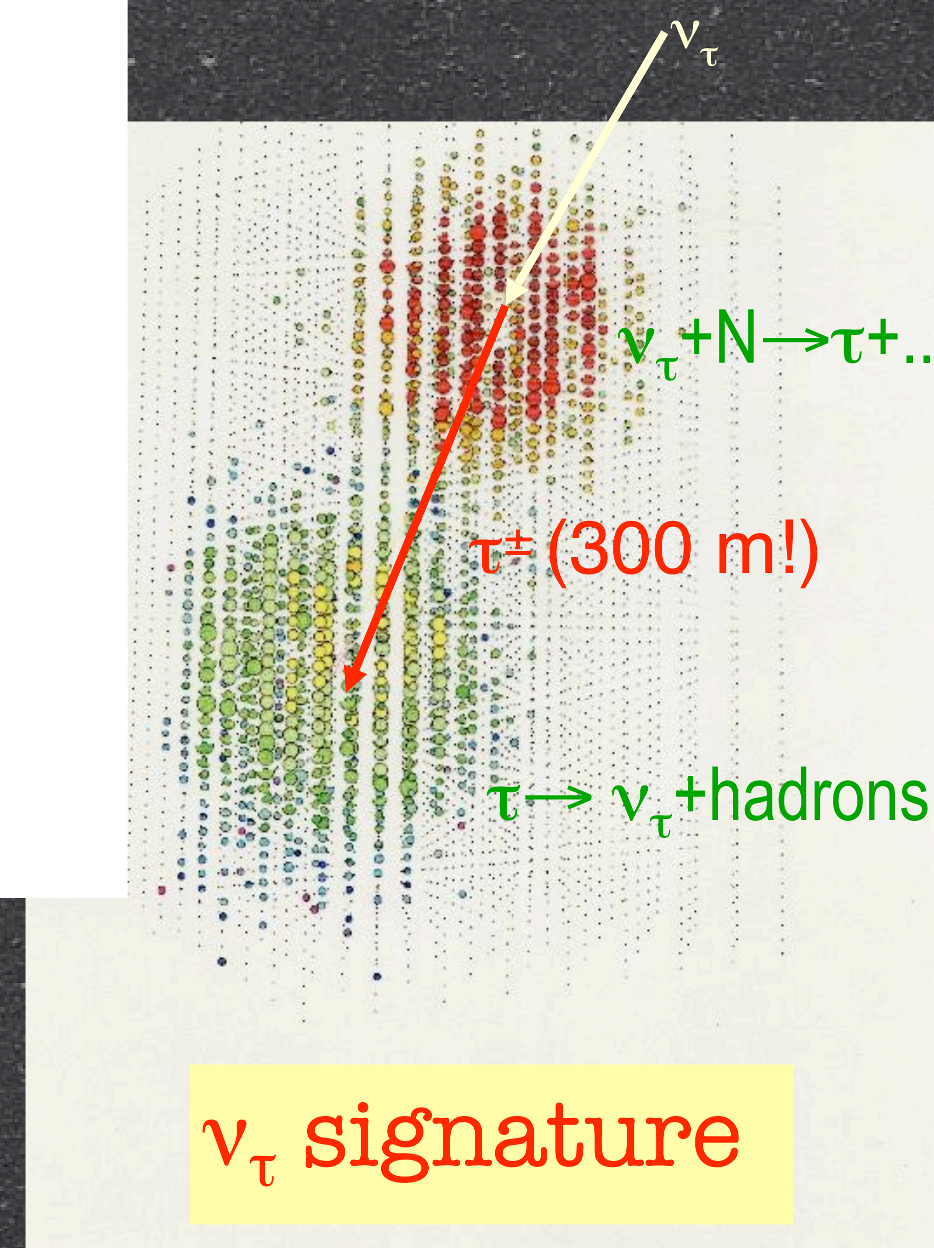
energy
thresholds

Neutrino Particle ID

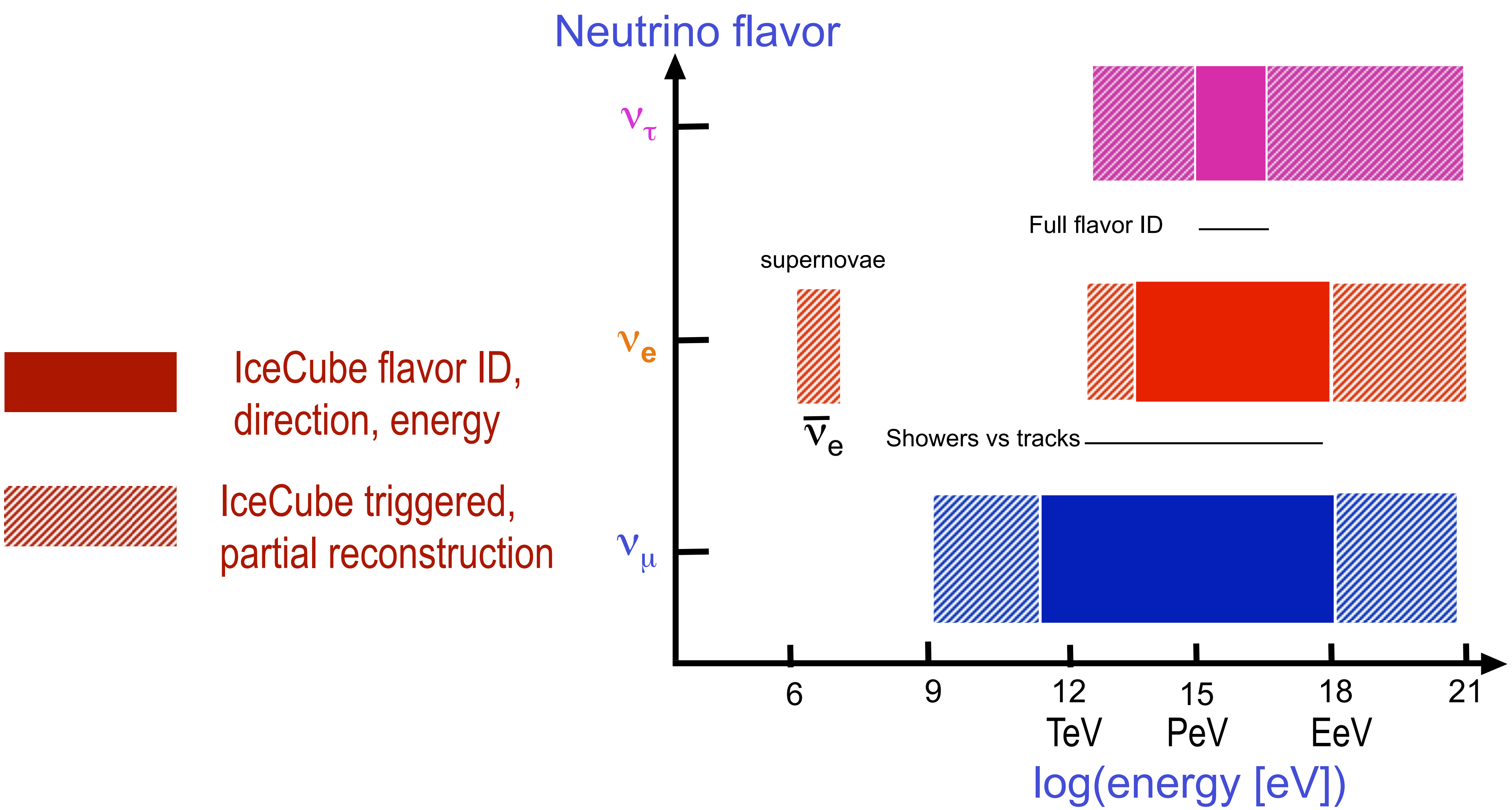
10 TeV　　6 PeV　　multi-PeV



ν_μ signature

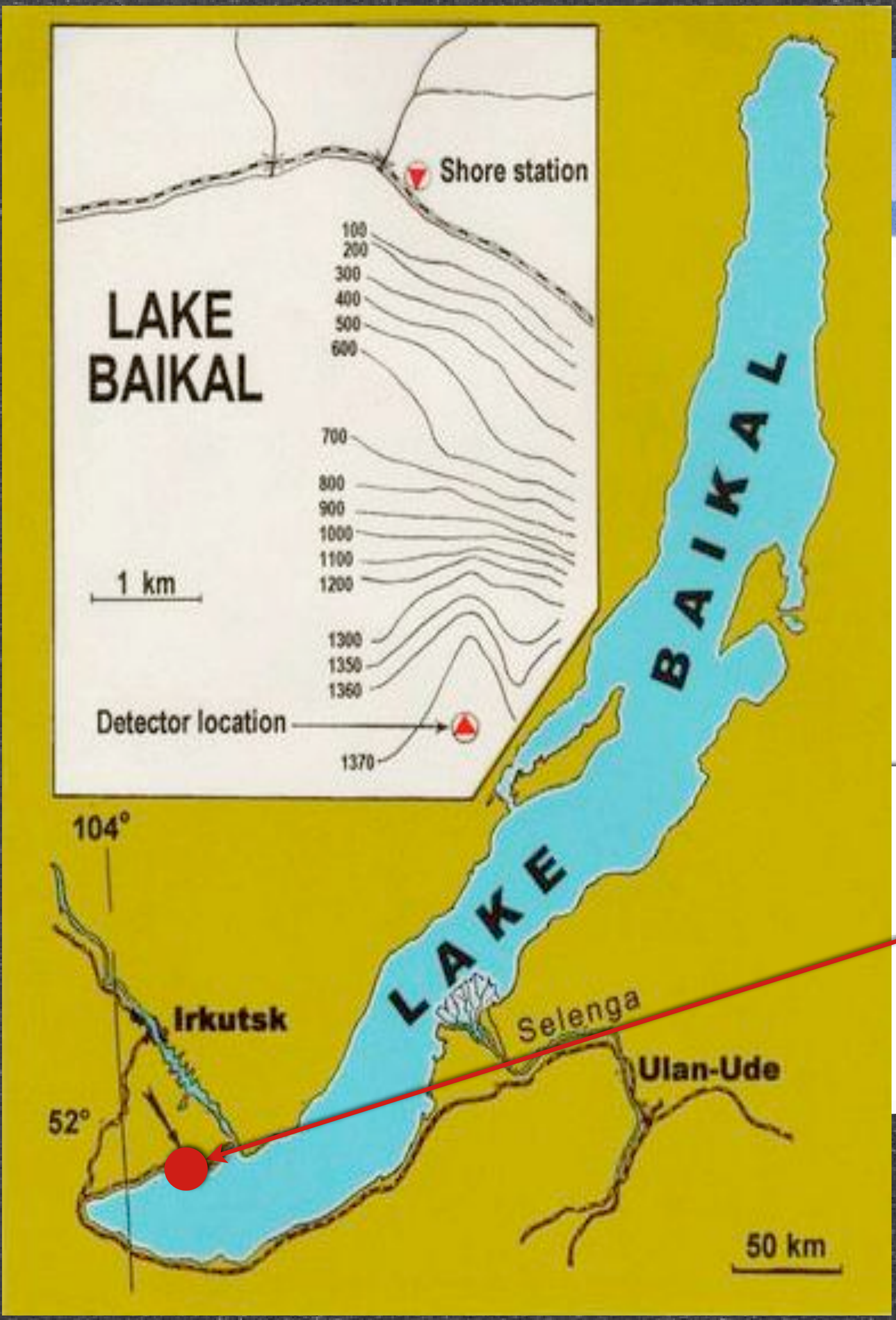


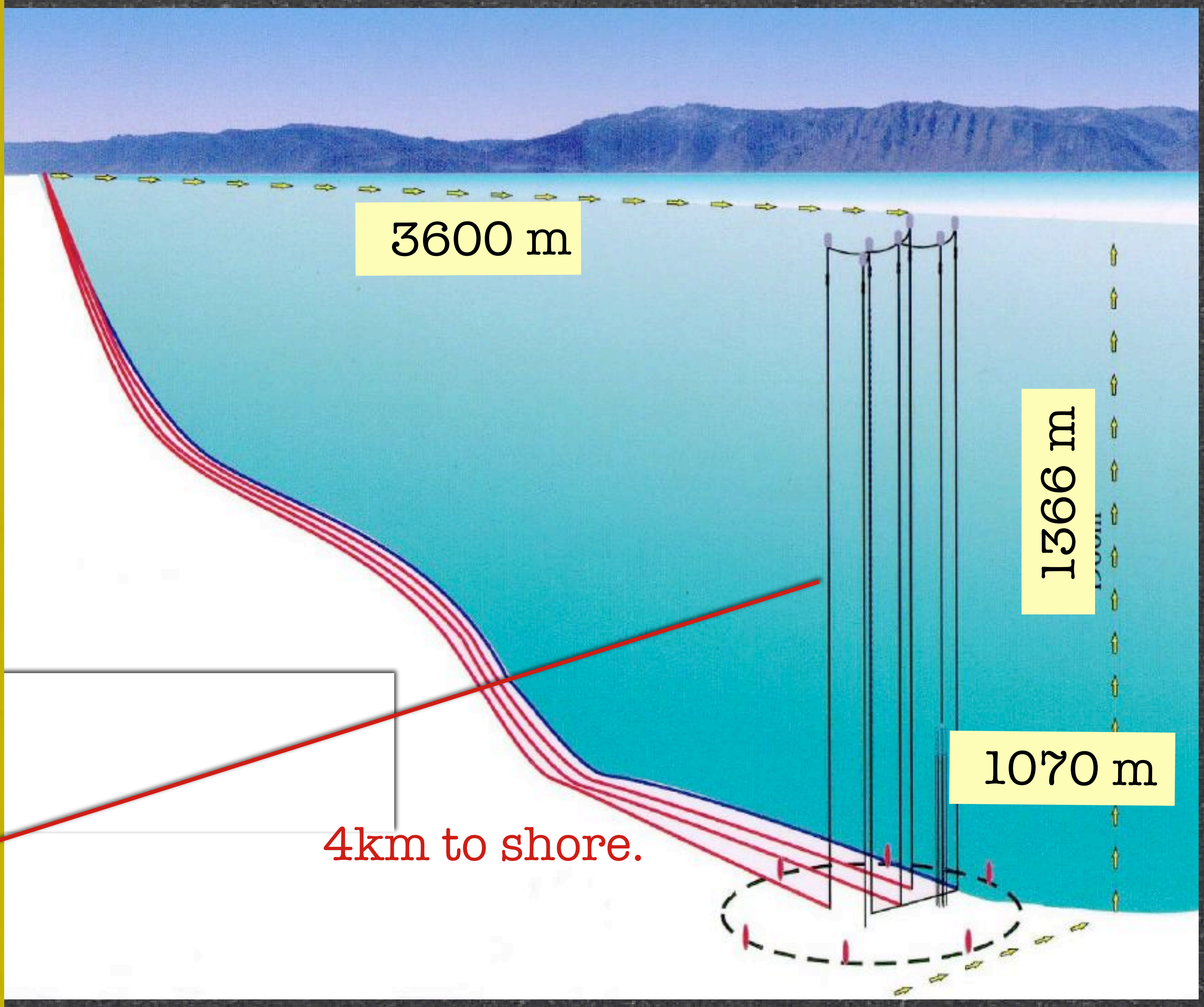
Neutrino Particle ID



Lake Baikal

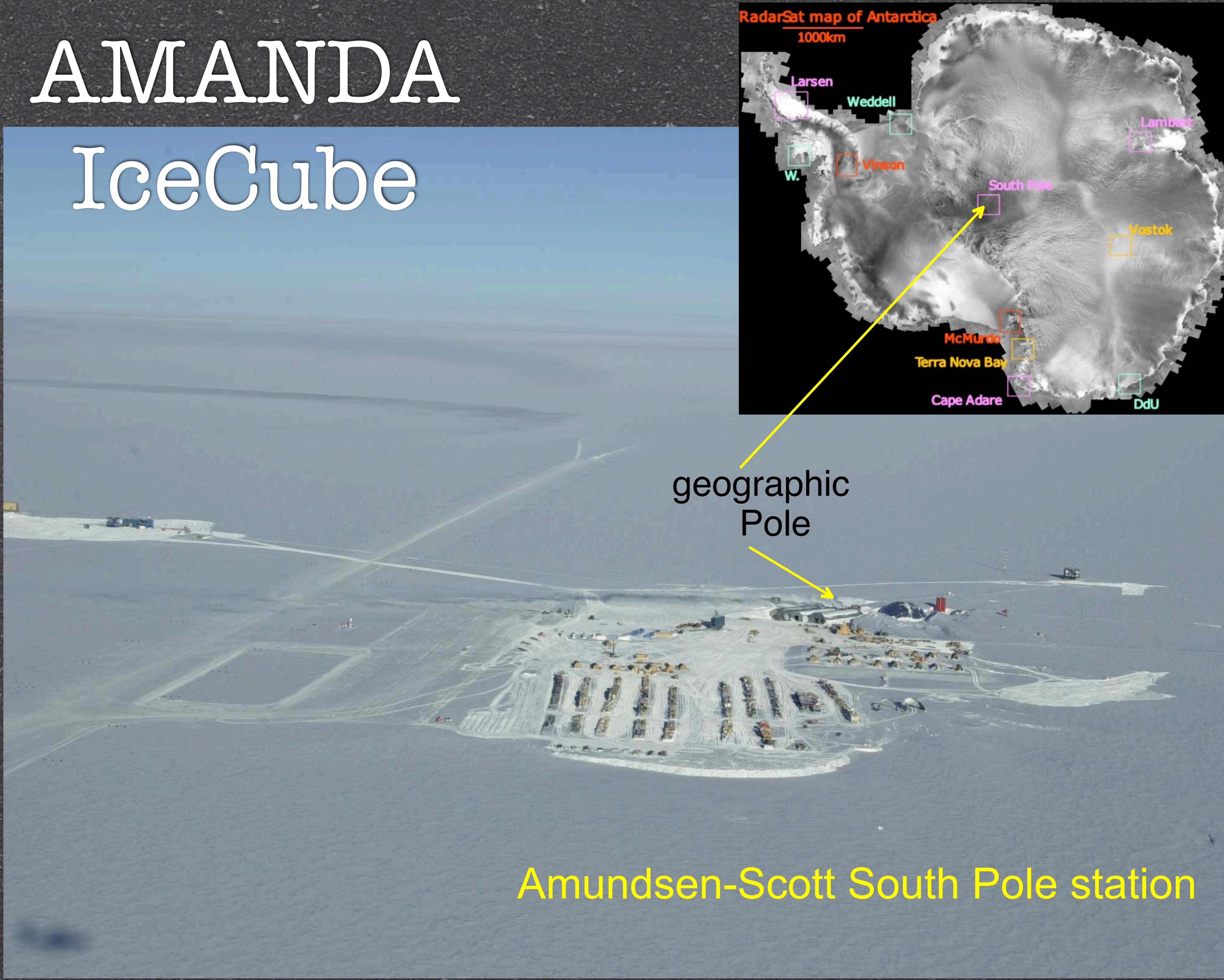
The Baikal Detector NT-200



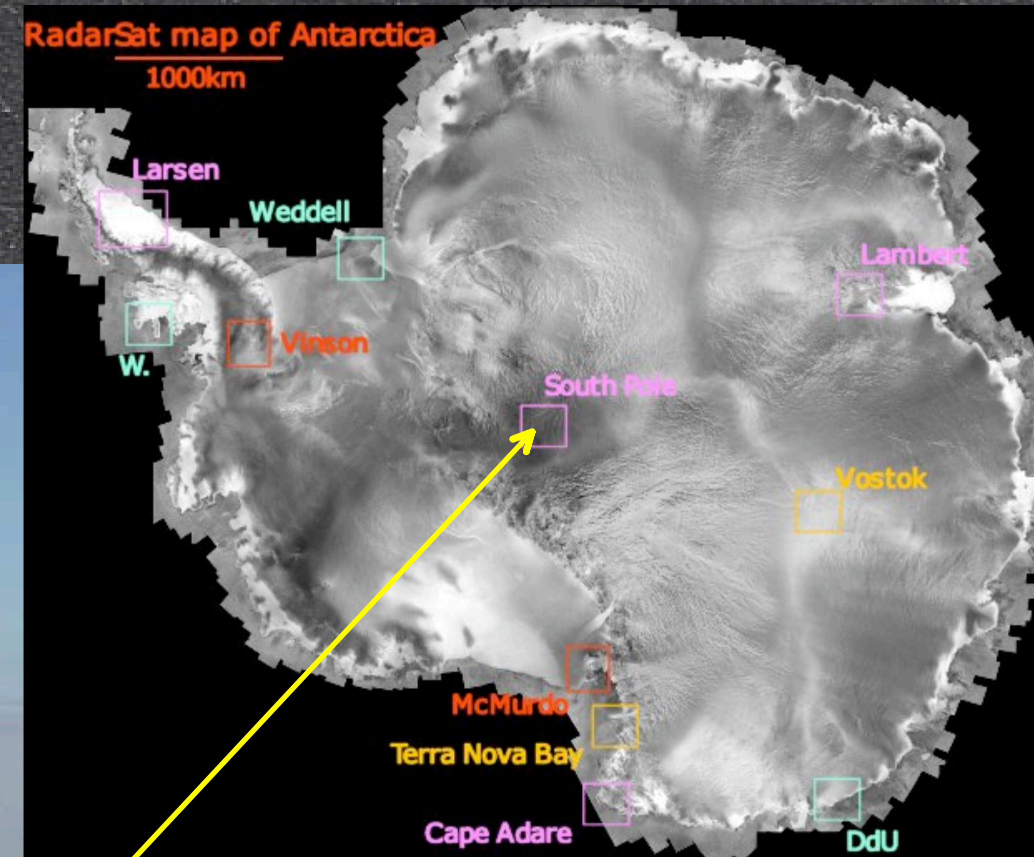


use ice as
deployment
platform

AMANDA
IceCube



AMANDA
IceCube



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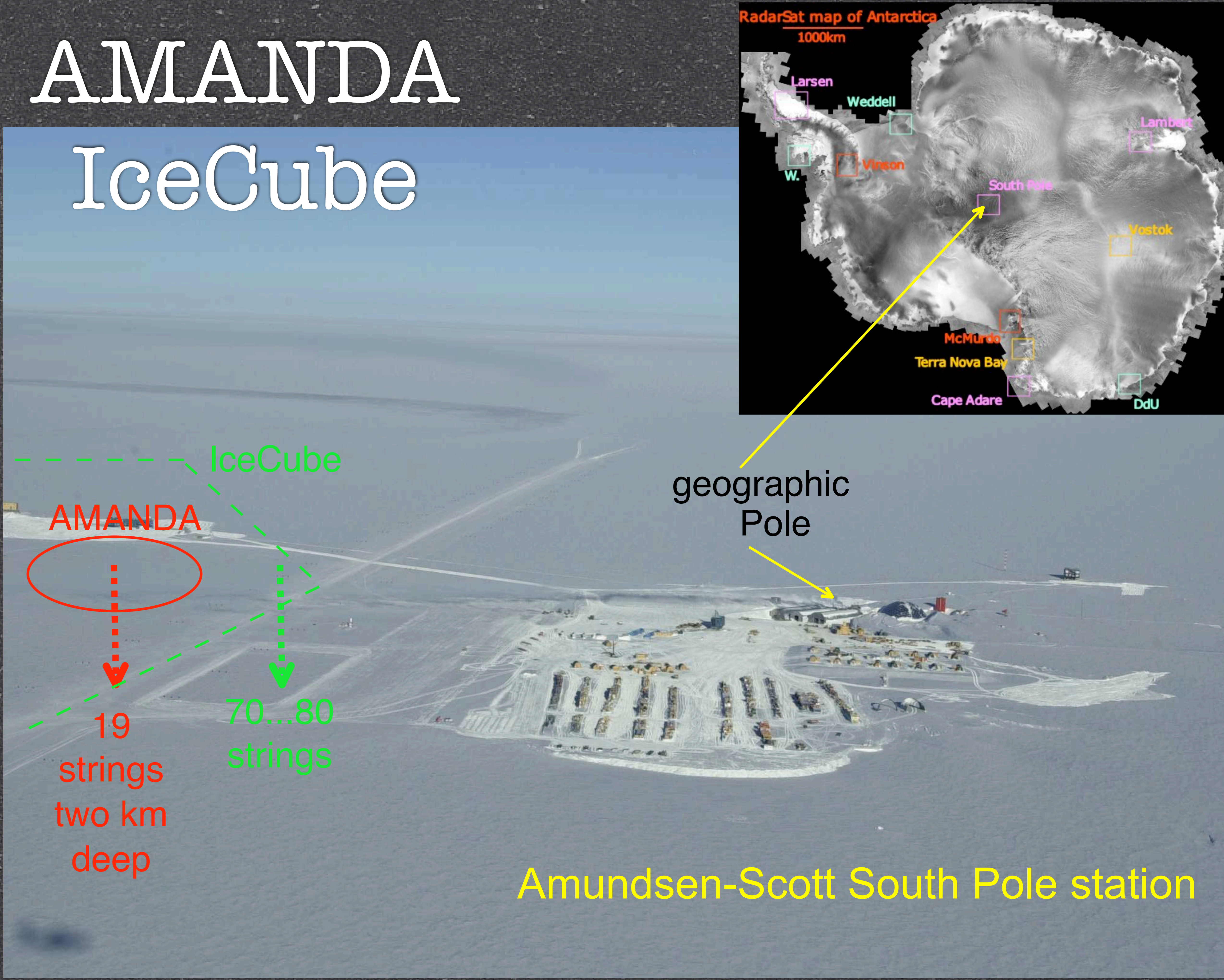
IceCube



IceCube

The Collaboration

University of Alaska, Anchorage
University of California, Berkeley
University of California, Irvine
Clark-Atlanta University
University of Delaware / Bartol Research Institute
University of Kansas
Lawrence Berkeley Natl. Laboratory
University of Maryland
Pennsylvania State University
Southern University and A&M College
University of Wisconsin, Madison
University of Wisconsin, River Falls

RWTH Aachen
DESY, Zeuthen
Universität Dortmund
MPIfK Heidelberg
Humboldt Universität, Berlin
Universität Mainz
BUGH Wuppertal

Stockholms Universitet
Uppsala Universitet

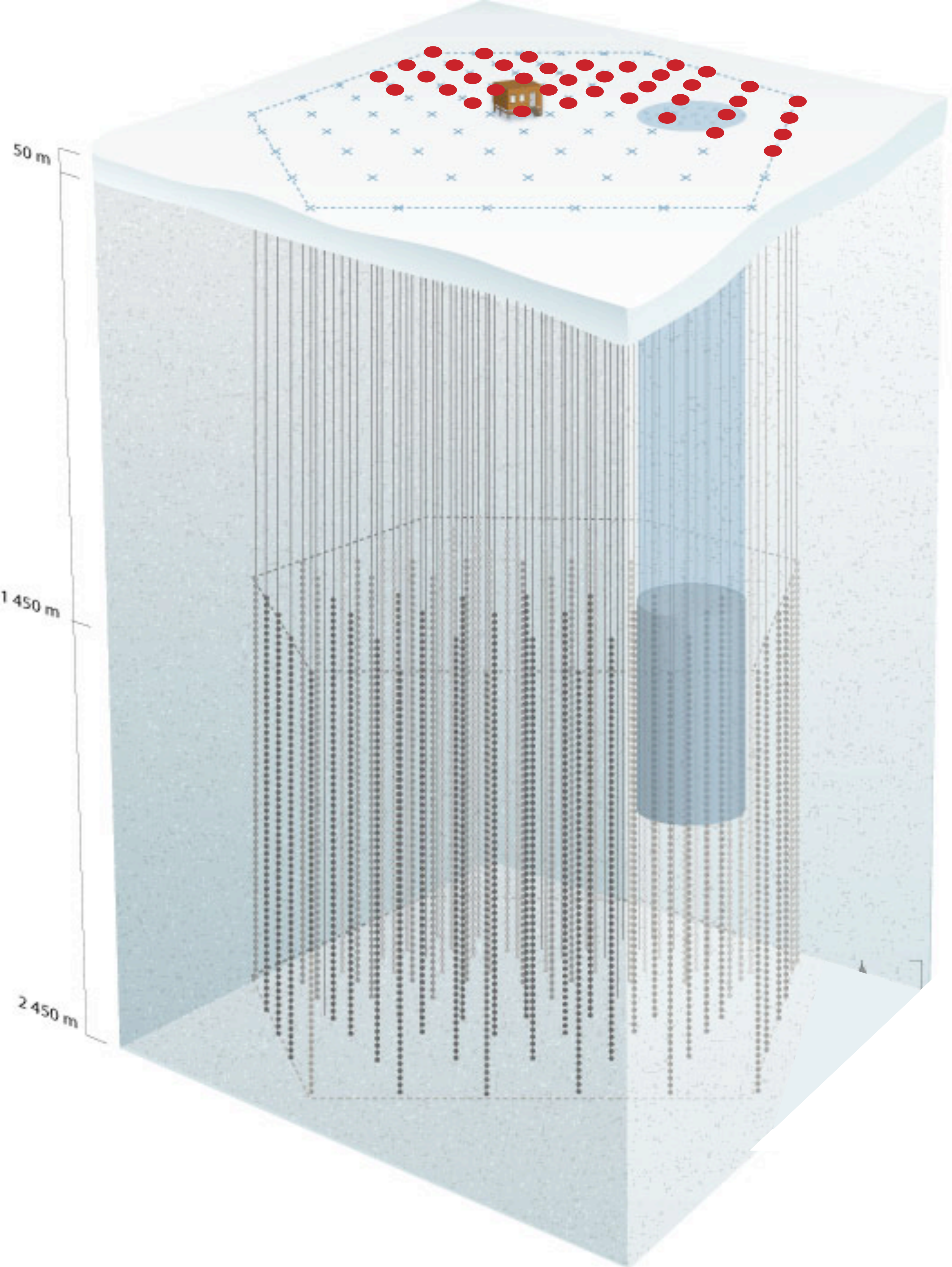
Vrije Universiteit Brussel
Université Libre de Bruxelles
Universiteit Gent
Université de Mons-Hainaut

Chiba University

University of Canterbury, Christchurch

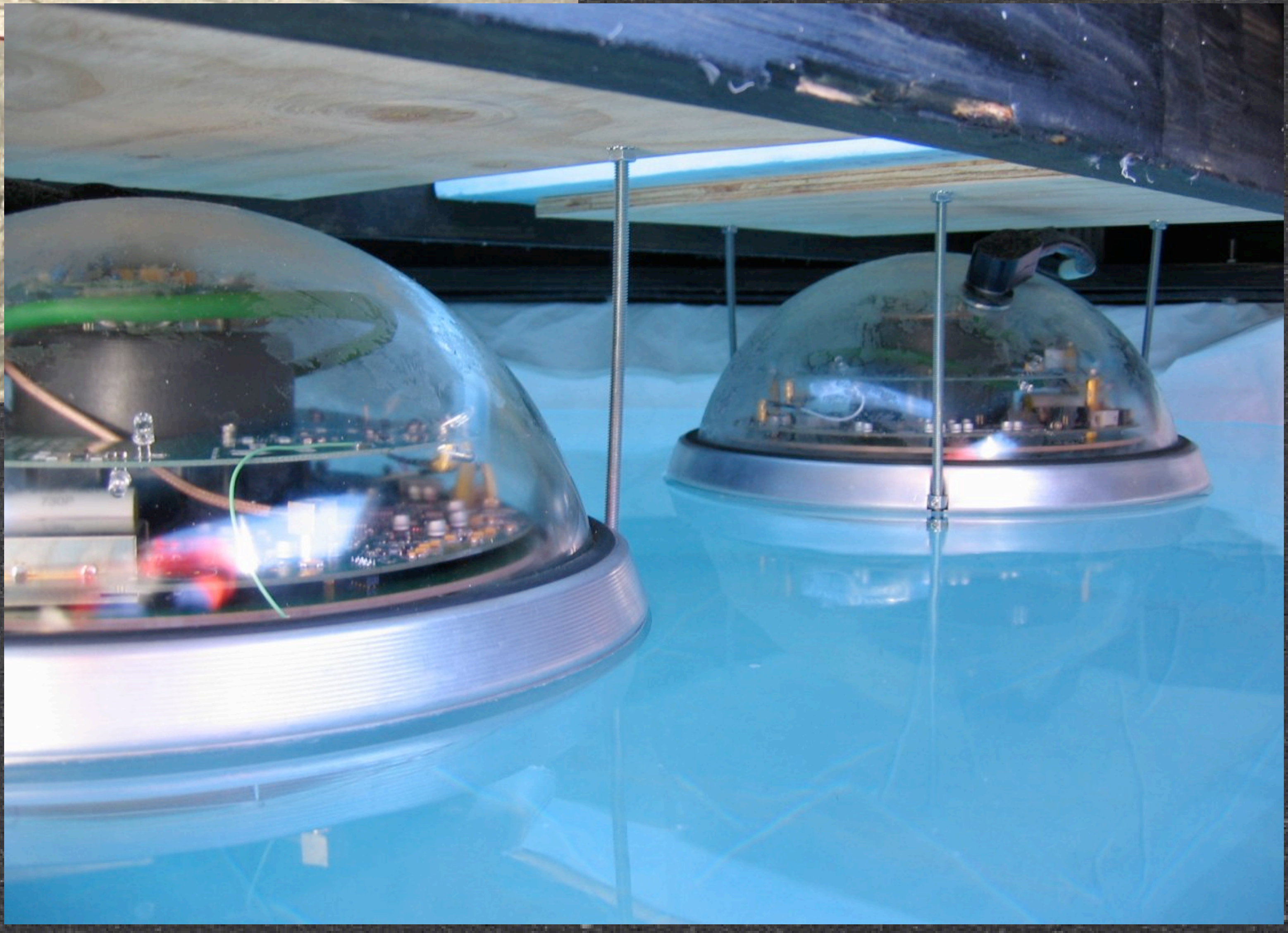
Universiteit Utrecht

Oxford University



½ km^3

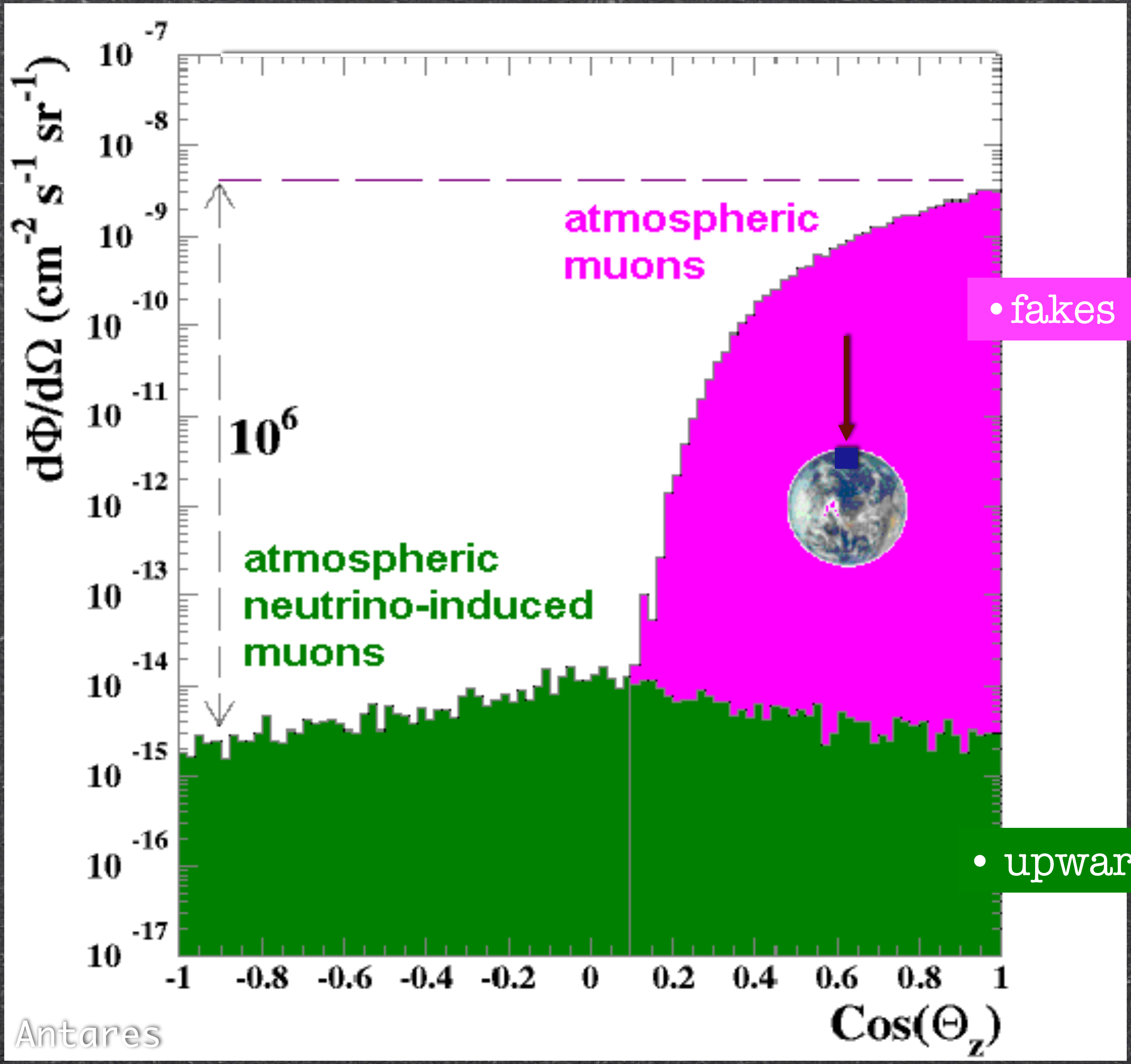
IceTop



IceCube Physics Program

- Atmospheric neutrinos
- Point source search: muon-neutrino
- Search for diffuse flux: electron/tau neutrino
- Gamma-ray bursts
- Search for WIMPs
- Supernova search
- Exotics: monopoles etc
- Cosmic rays: energy spectrum and composition

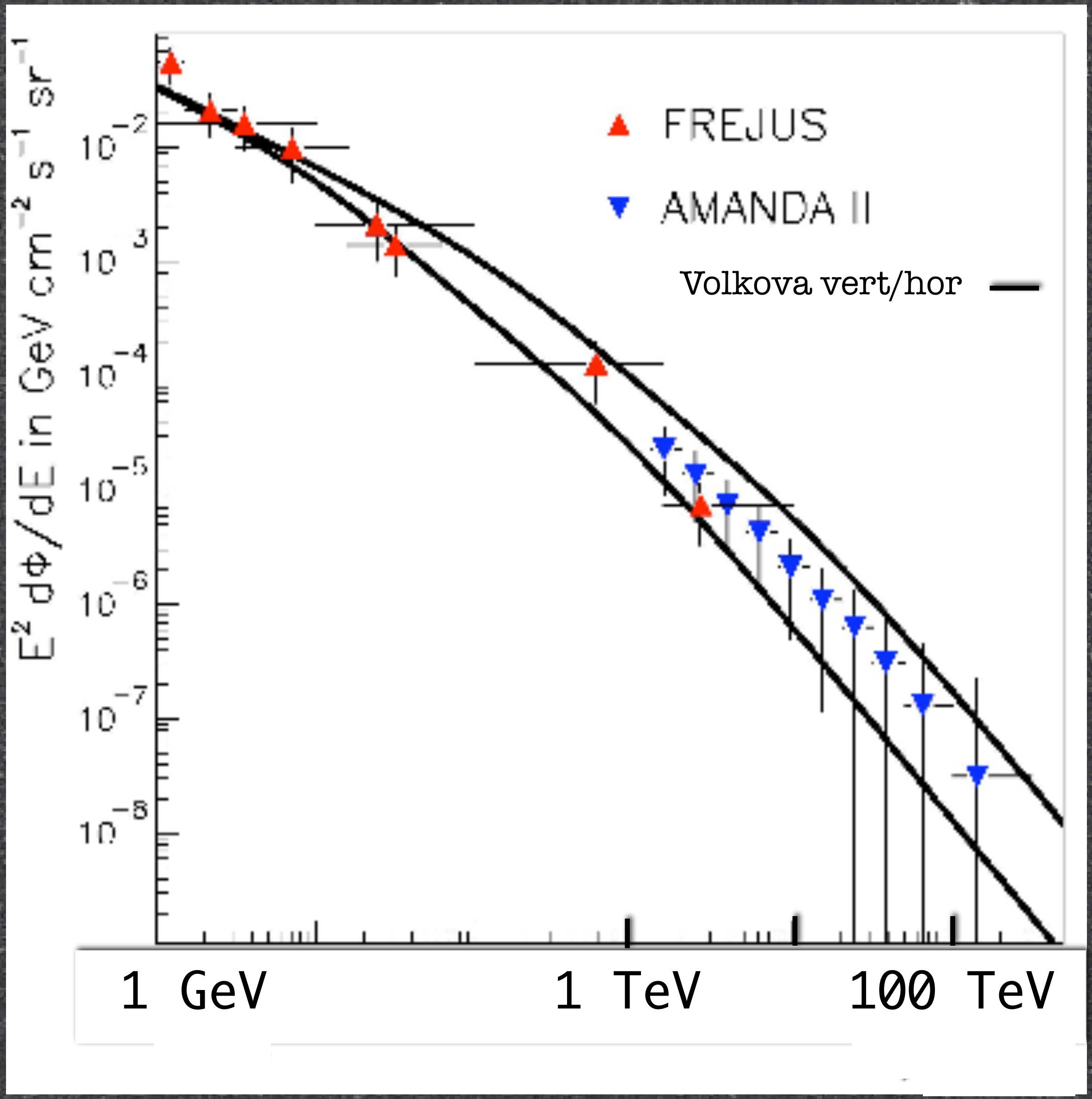
Atmospheric Muons and Neutrinos



- fakes

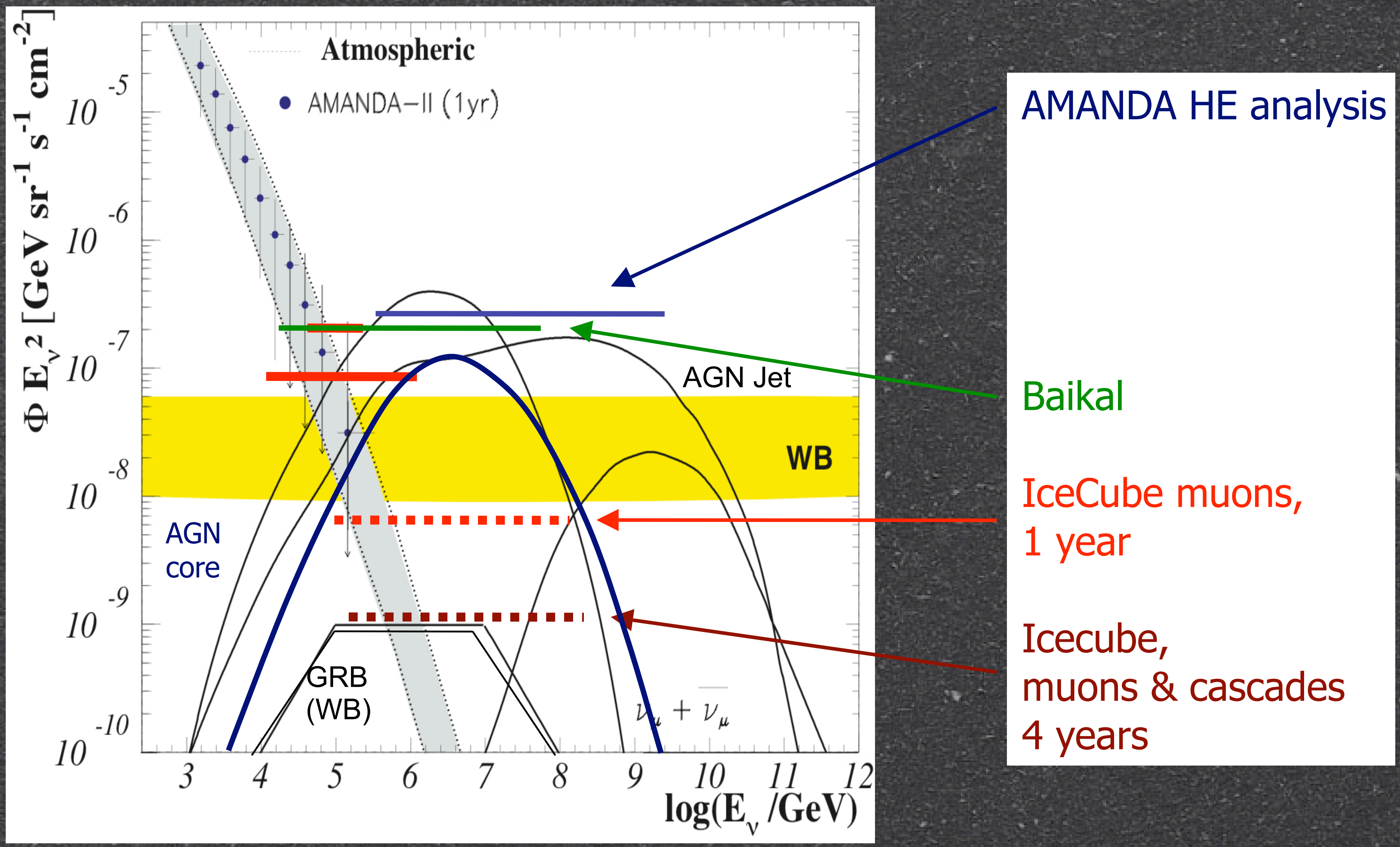
- upward tracks are ν candidates

Atmospheric Neutrinos



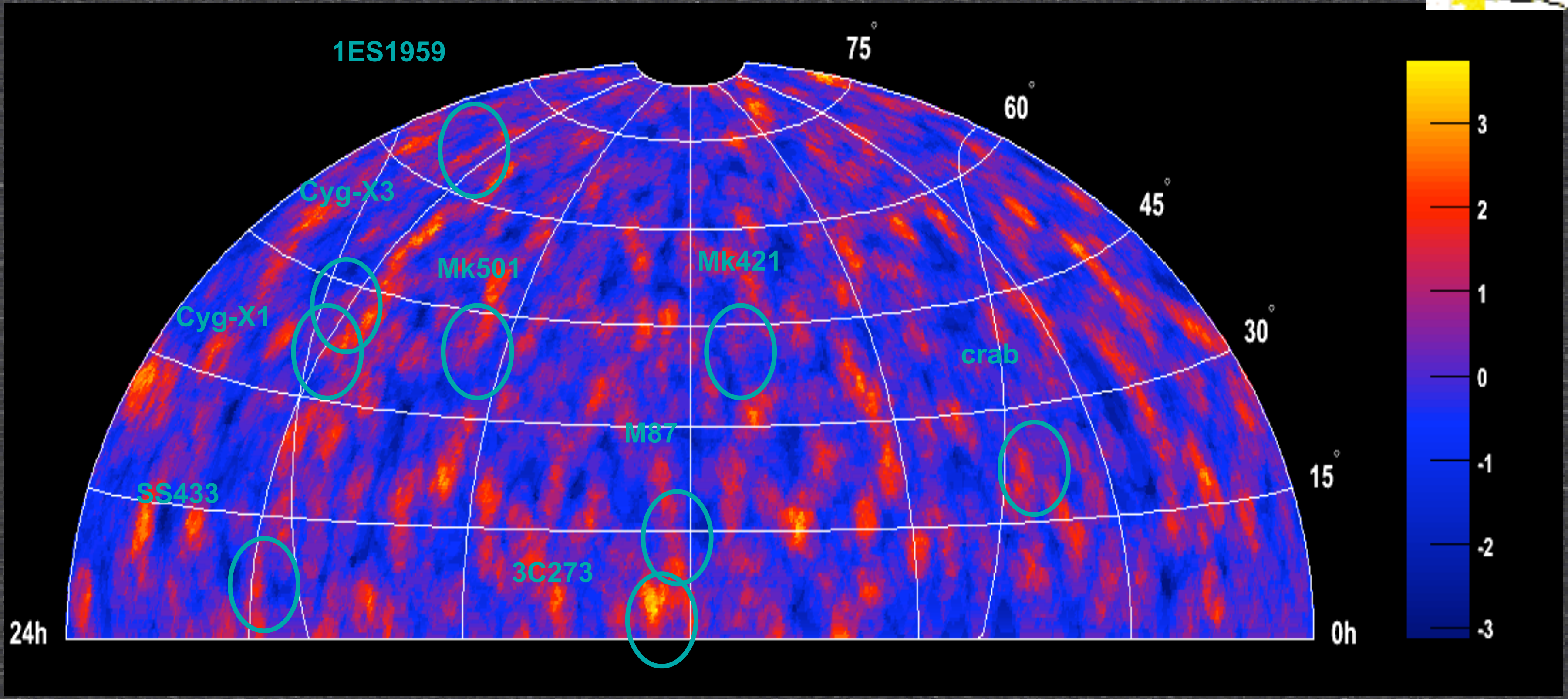
Test beam of neutrinos is also the background to the extraterrestrial signal

Measurements of an Diffuse Extraterrestrial ν Flux



Several models of AGN neutrino emission are ruled out by current measurements
→ precise flux measurement needs km^3-size detector

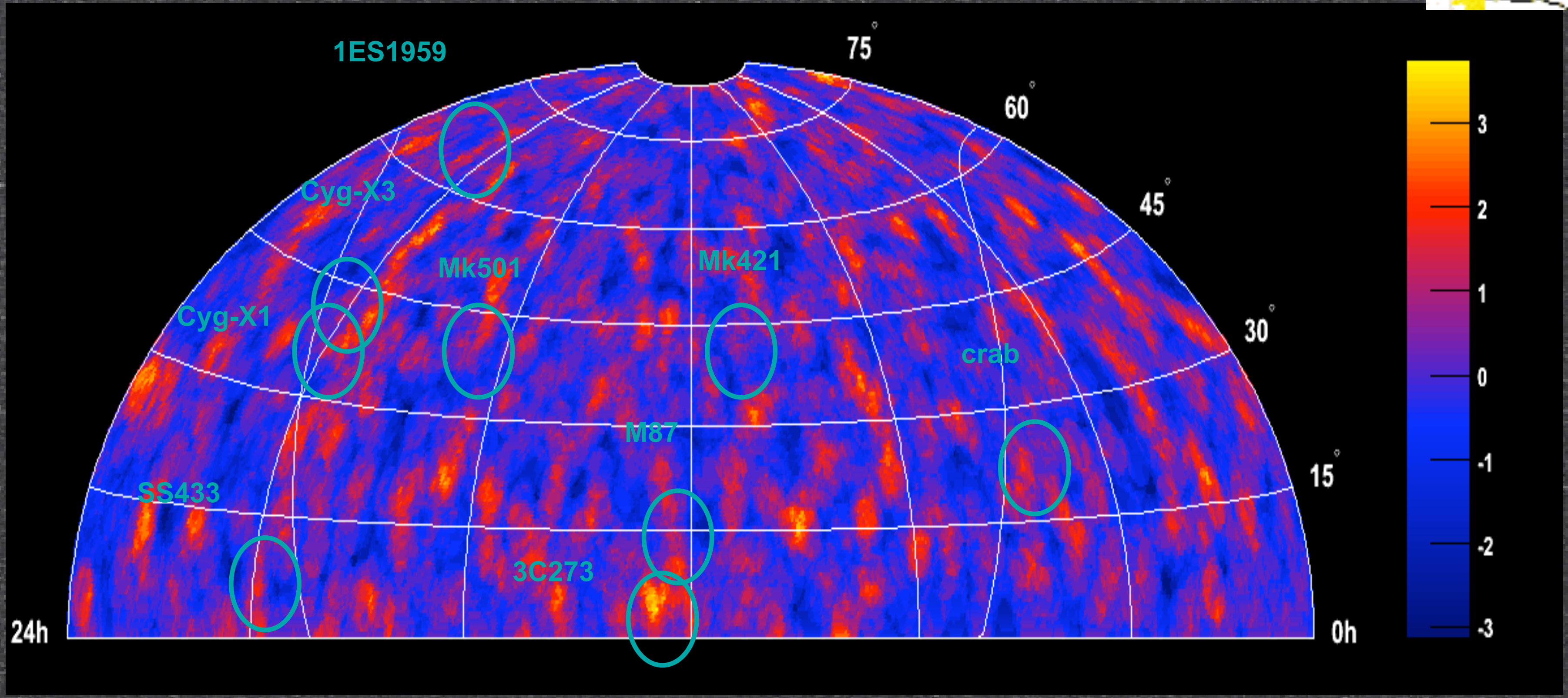
Neutrinos from specific Sources



examples (out of 32 sources) of a five year data analysis

source	nr. of ν events	expected background	E^{-2} flux upper limit (90% c.l.) $[10^{-11}\ TeV^{-1}\ cm^{-2}\ s^{-1}]$
Markarian 421	6	7.4	7.4
M87	6	6.1	8.7
1ES 1959+650	5	4.8	13.5
SS433	4	6.1	4.8
Cygnus X-3	7	6.5	11.8 ⇒
Cygnus X-1	8	7.0	13.2
Crab Nebula	10	6.7	17.8
3C 273	8	4.72	18.0

Neutrinos from specific Sources



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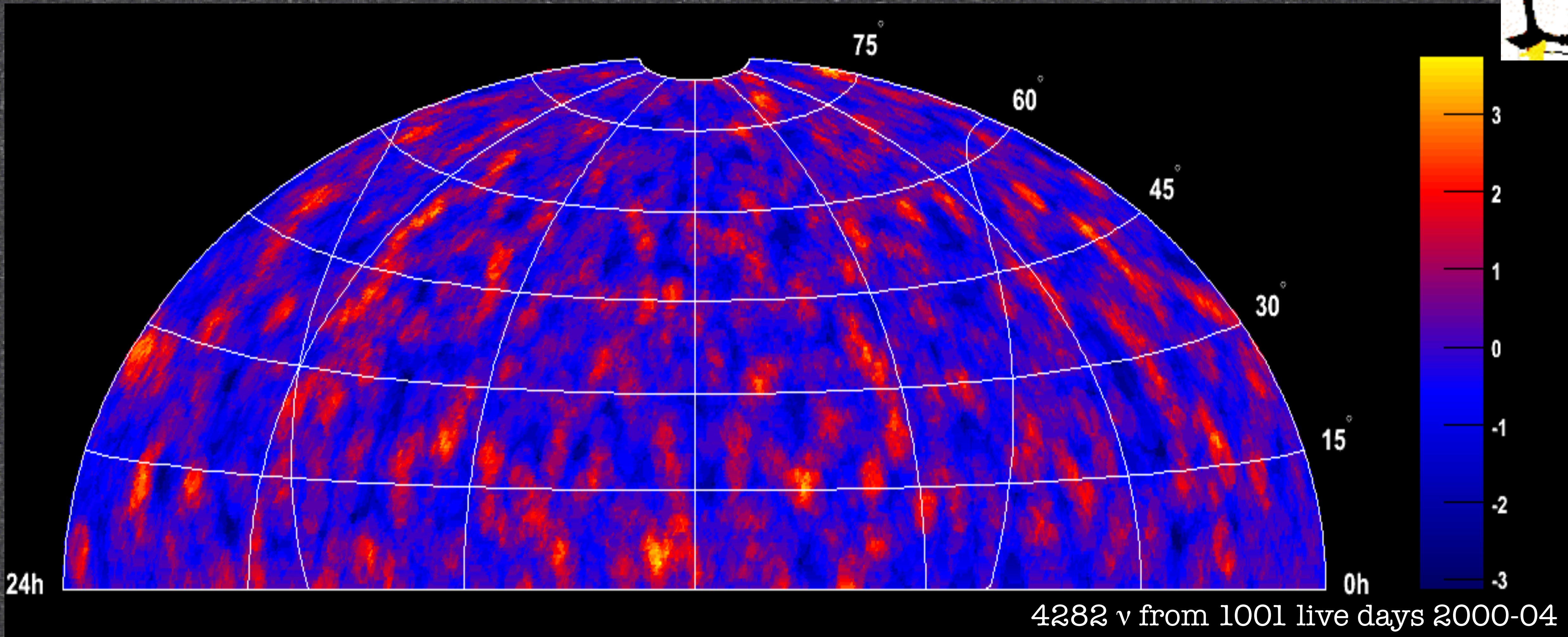
⇒ No significant excess observed

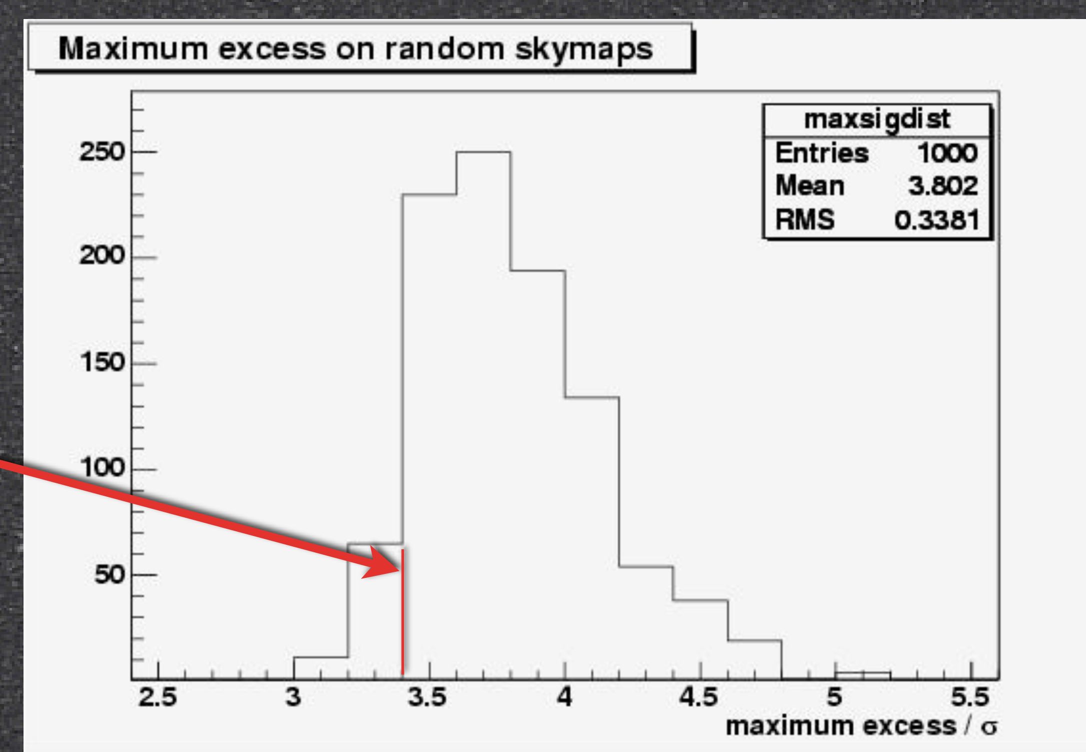
Point Source Search

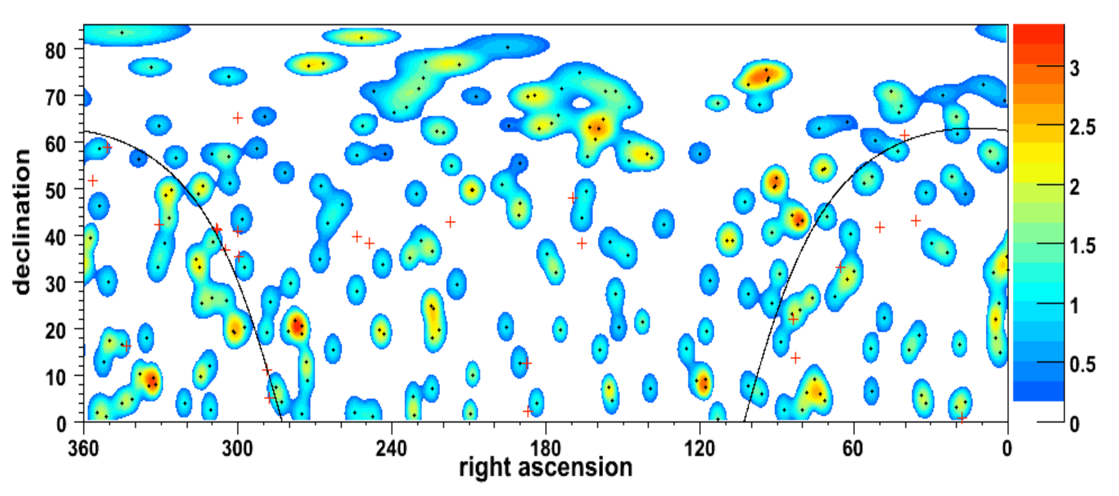


→ no significant excess found

calculate significance of local fluctuations from expectation of atmospheric neutrinos

- un-binned statistical analysis
- maximum of 3.4 σ - compatible with background fluctuation





2006

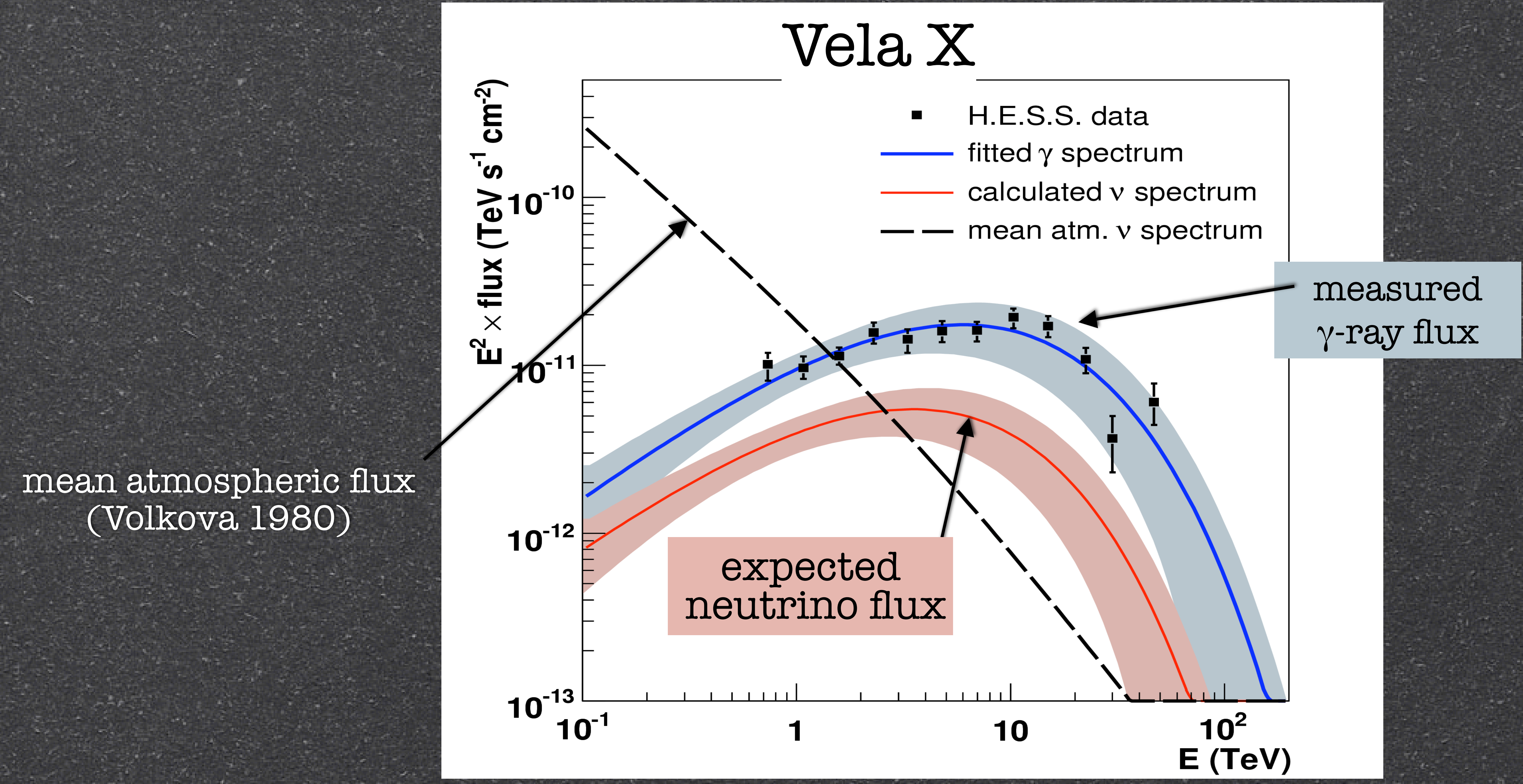
2007

IceCube 9 strings

IceCube 22 strings (+ AMANDA)

IceCube Detector	Energy Window (TeV)	Exposure Time	Limit (L) Sensitivity (S) (TeV^{-1} cm^{-2} s^{-1})
9 string (2006)	5 - 1000	137 d	$1.2 \cdot 10^{-10}$ (L)
22 string (2007) + AMANDA	5 – 5000 0.5 - 10	240 d	~ 10^{-11} (S) for specific scenarios
80 string	5 - 5000	3 y	$2 \cdot 10^{-12}$ (S)

ν-Flux Predictions from γ-Ray Measurements



A. Kappes et al., astro-ph 0607286

Low Signal Statistics in km^3 Neutrino-Telescopes

5 years

	Type	Ø [°]	$E_\nu > 1$ TeV Src	Bkg
Vela X	PWN	0.8	9 - 23	23
RX J1713.7-3946	SNR	1.3	7 - 14	41
HESS J1825-137	PWN	0.3	5 - 10	9.3
Crab Nebula	PWN	<0.1	4.0 - 7.6	5.2
HESS J1303-631	NCP	0.3	0.8 - 2.3	11
LS 5039* (INFC)	Binary	<0.1	0.3 - 0.7	2.5

(NCP: No counterpart at other wavelengths
*no γ-ray absorption)

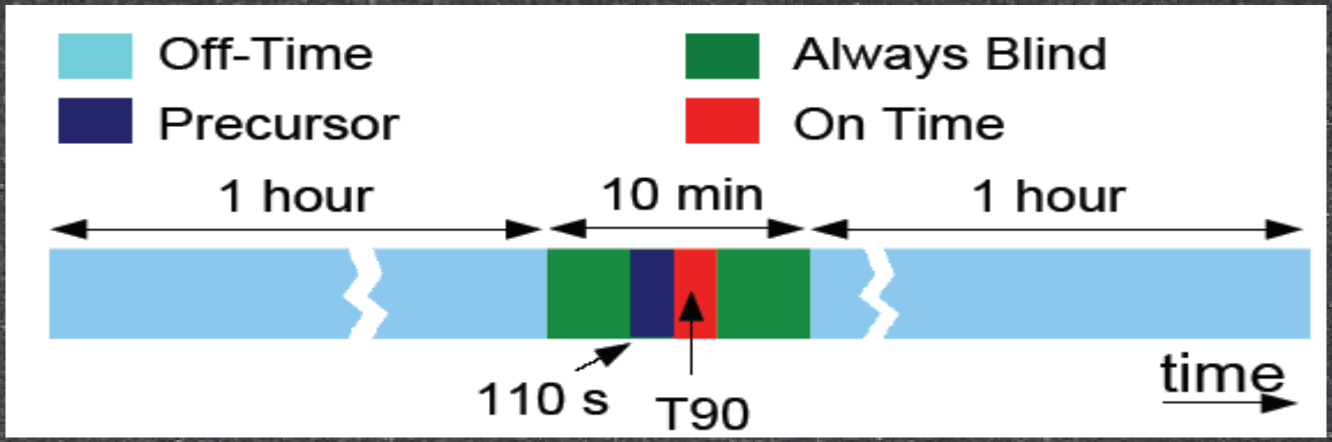
23 more sources investigated

A. Kappes et al., astro-ph 0607286
C Stegmann ICRC07

- Enhance sensitivity for
  - transient sources
  - opaque sources
  - sources at higher (PeV) energies

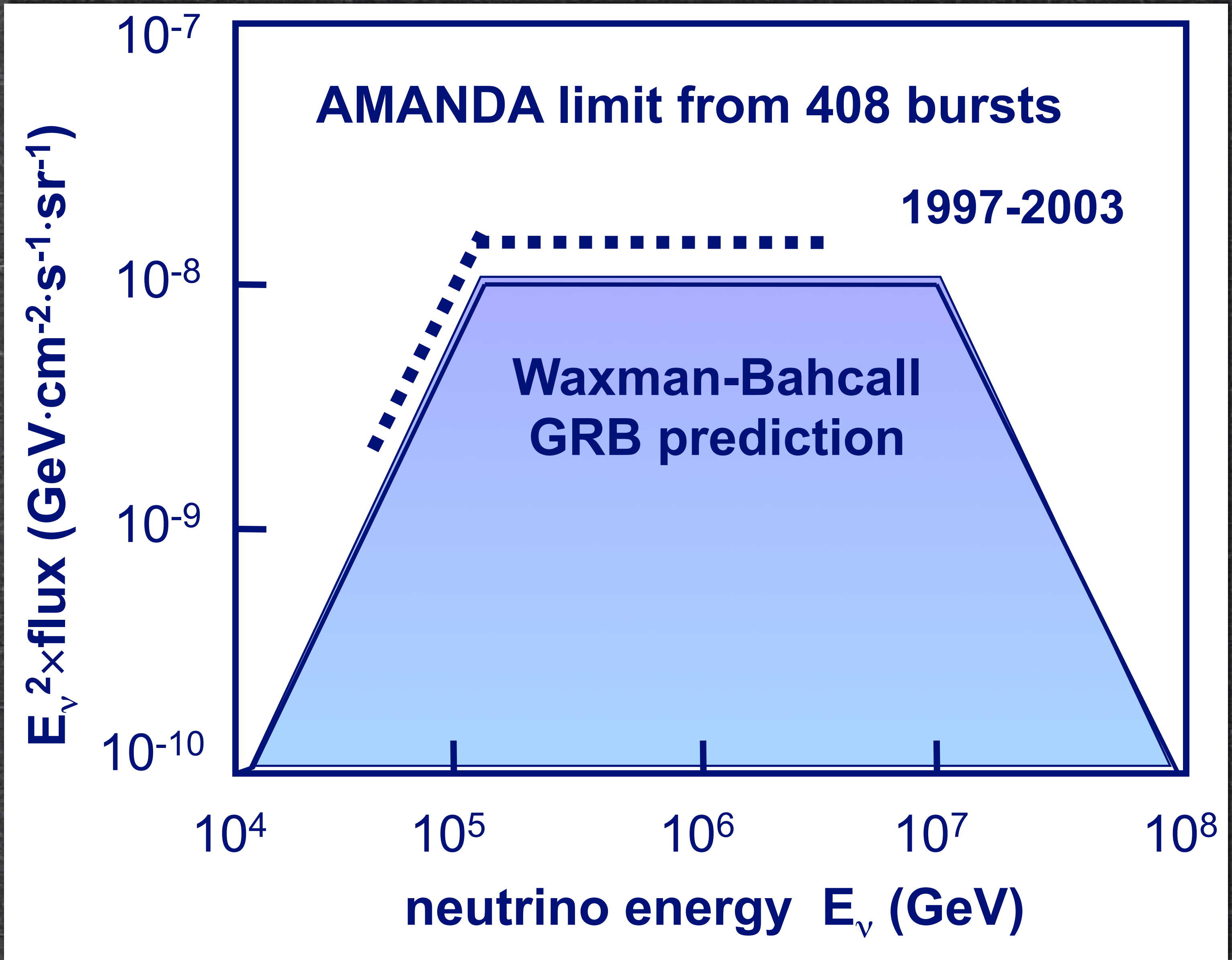
Many calculations and predictions on neutrinos from diffuse and point-sources from Dermer, DiStefano, Mannheim, Protheroe, Stecker, Waxman...

Find ν from GRBursts

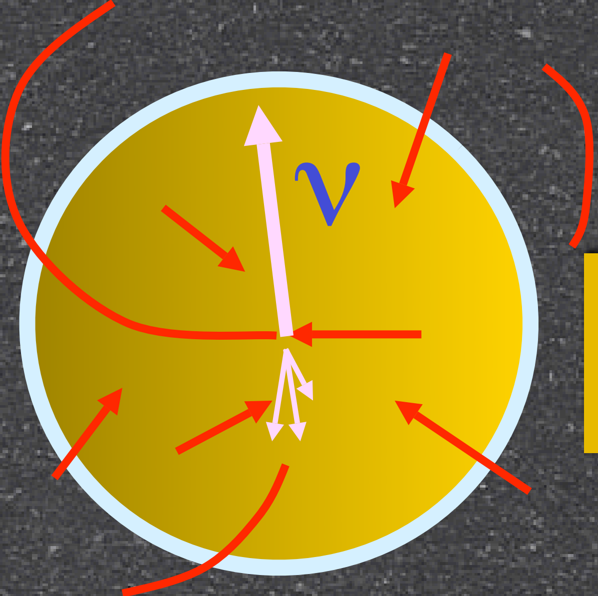


Check for coincidences with BATSE, IPN, SWIFT

- Factor ~2 above predictions with AMANDA
- With full IceCube test within a few month

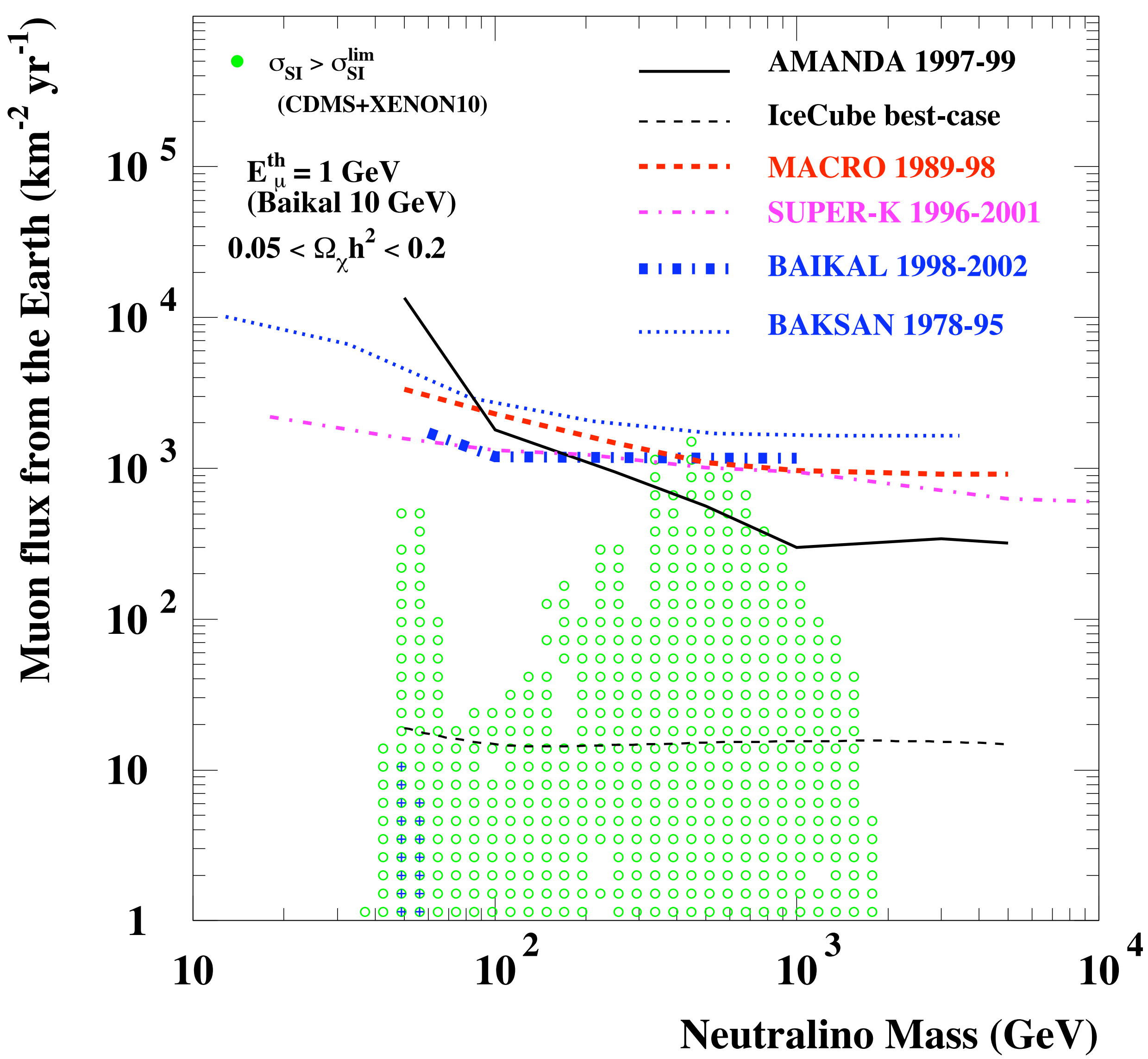


Neutralino Search

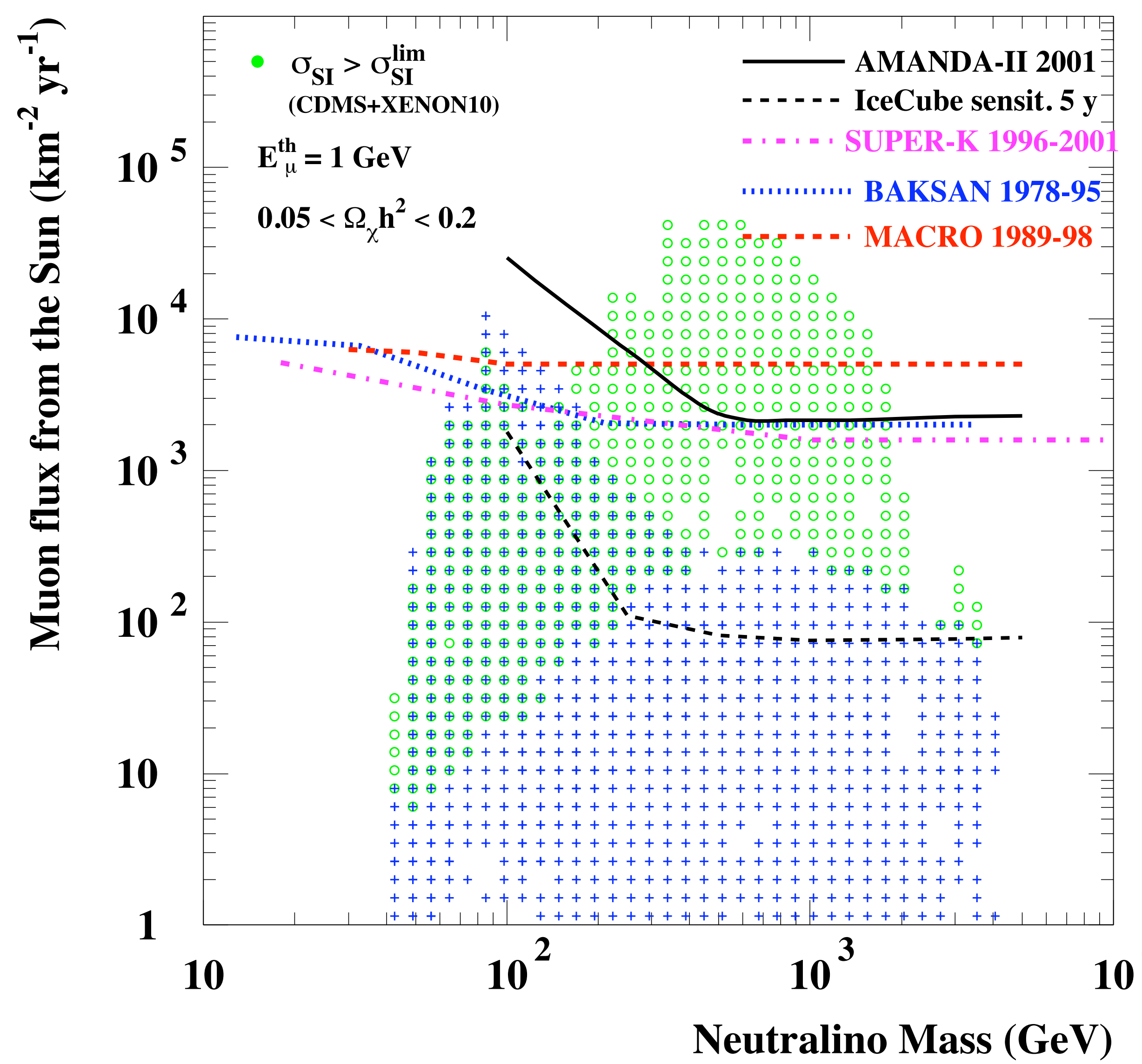


e.g.soft channel $\chi + \bar{\chi} \rightarrow b + \bar{b}, b \rightarrow c\ \mu\ \nu$
hard channel through W

Limits on muon flux from Earth center



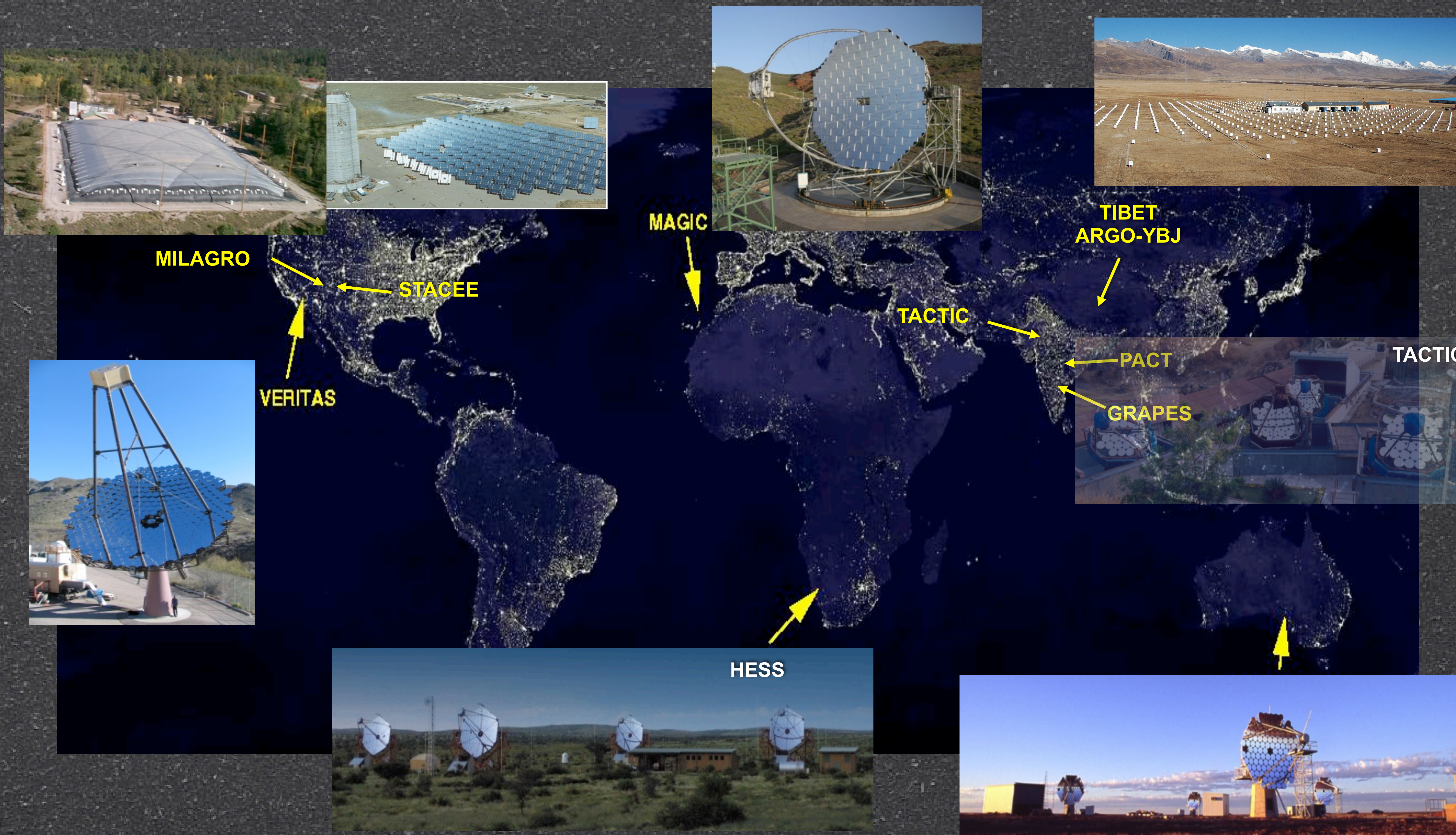
Limits on muon flux from Sun



Compared to the Earth, much better complementarity due to spin-dependent capture in the Sun

Measure Very High-Energy Gammas

Measure Very High-Energy Gammas



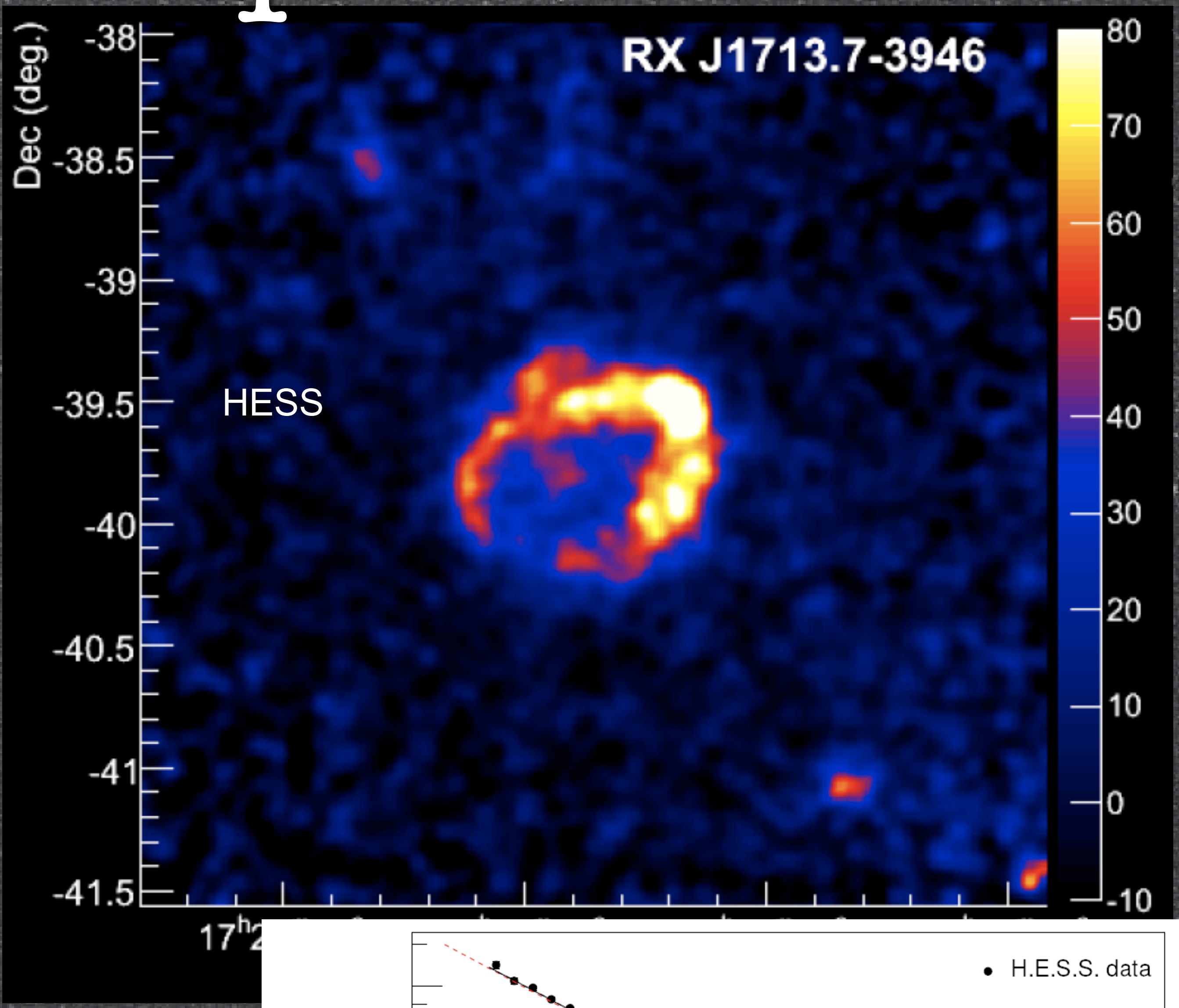
VHE γ-Ray Sources

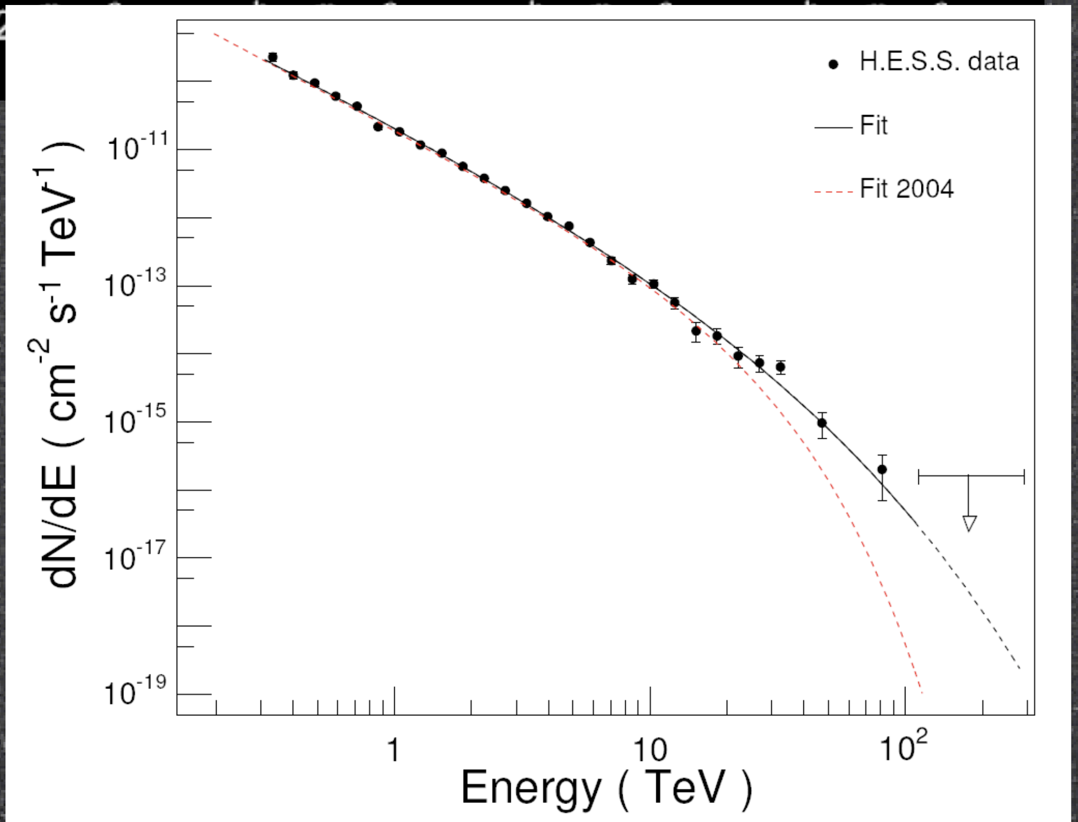
- Supernova Remnants (SNR)
- Pulsar Wind Nebulae (PWN)
- Unidentified Galactic Sources
- Diffuse Sources
- Binary systems
- Active Galactic Nuclei (AGN)

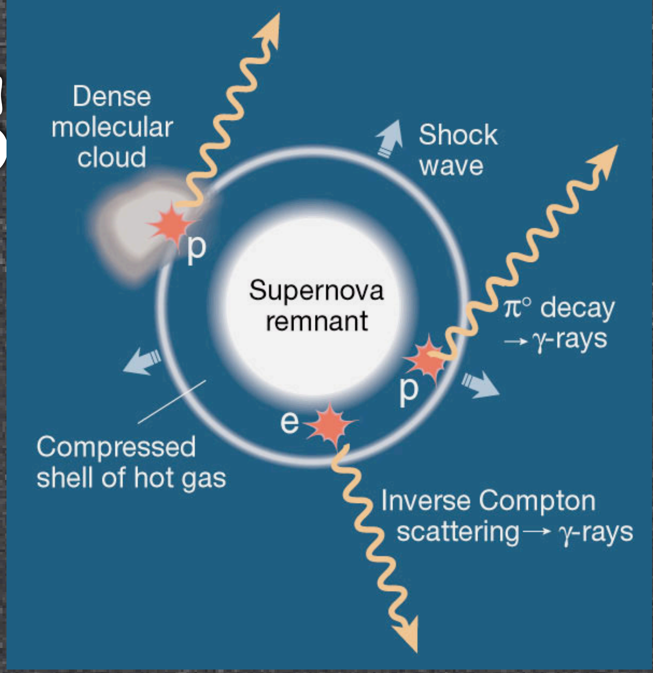
Want to know:

- Nature of primary particles
- Their spatial and momentum distribution
- Acceleration mechanism
- Propagation characteristics

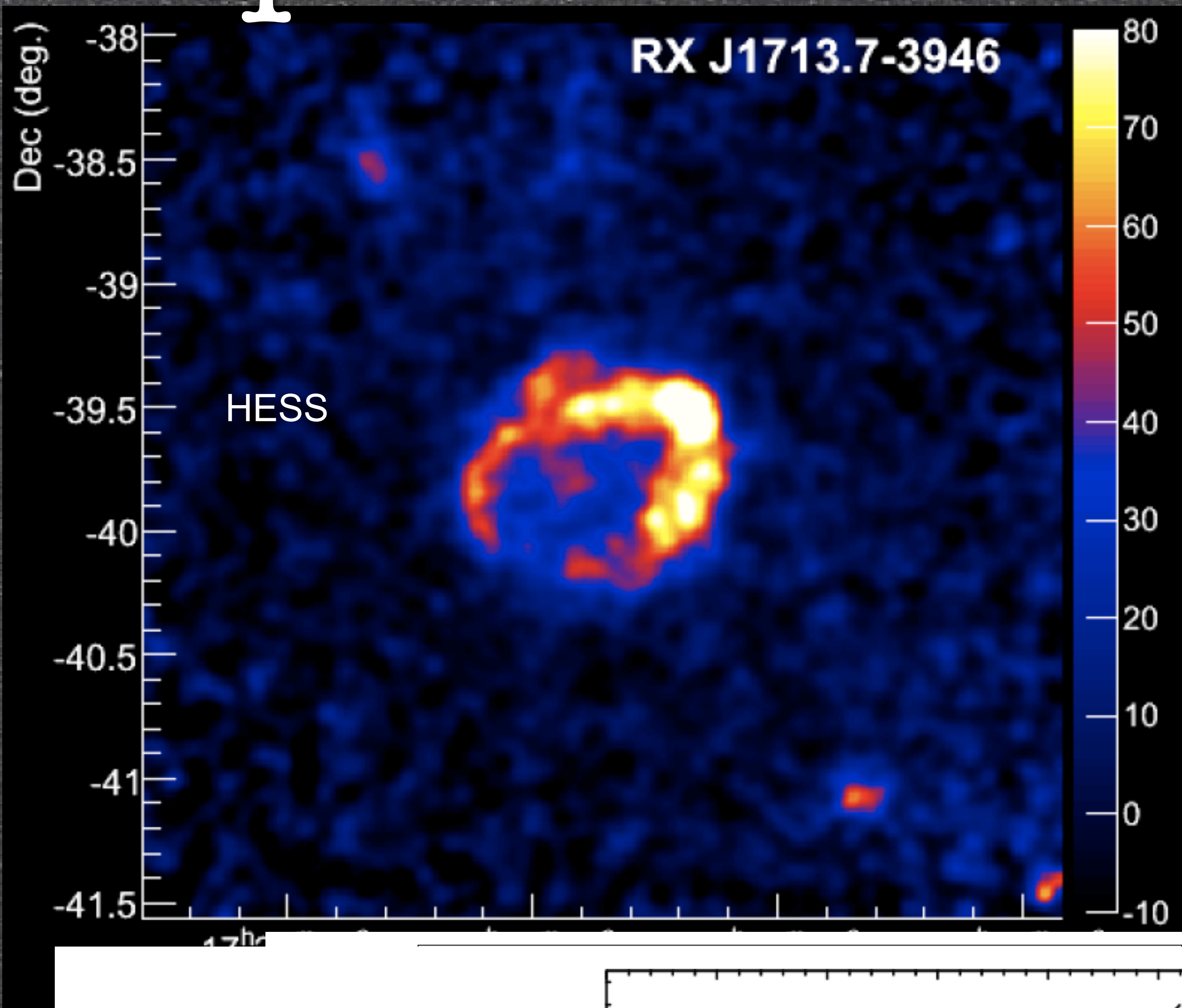
Super Nova Remnants

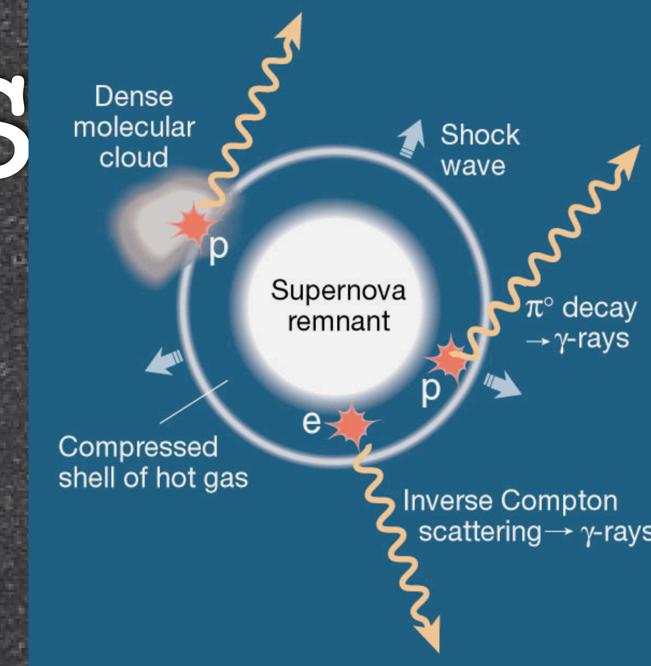




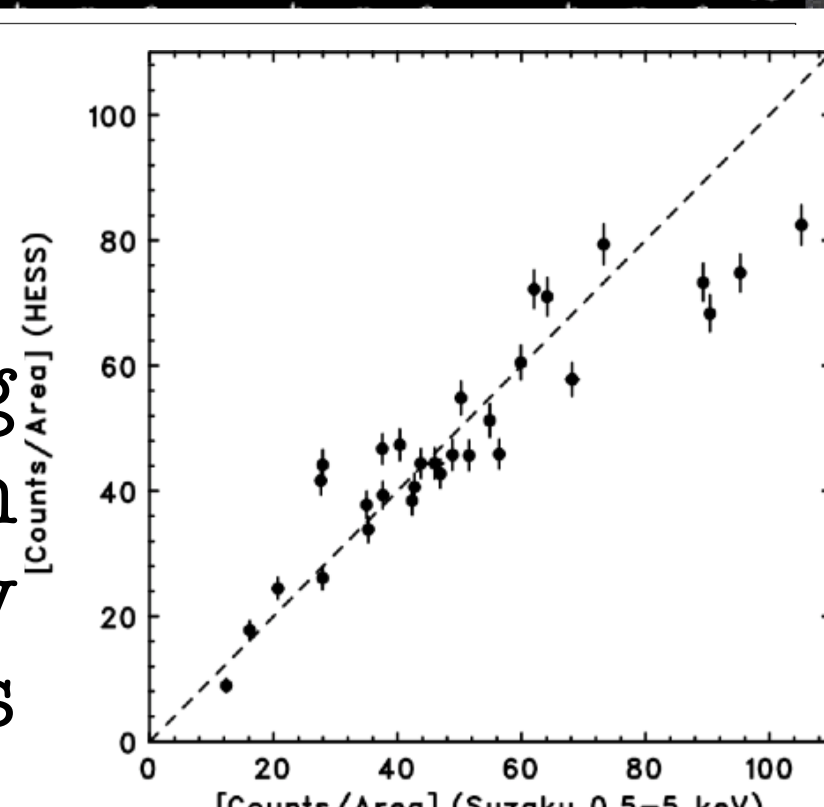


Super Nova Remnants

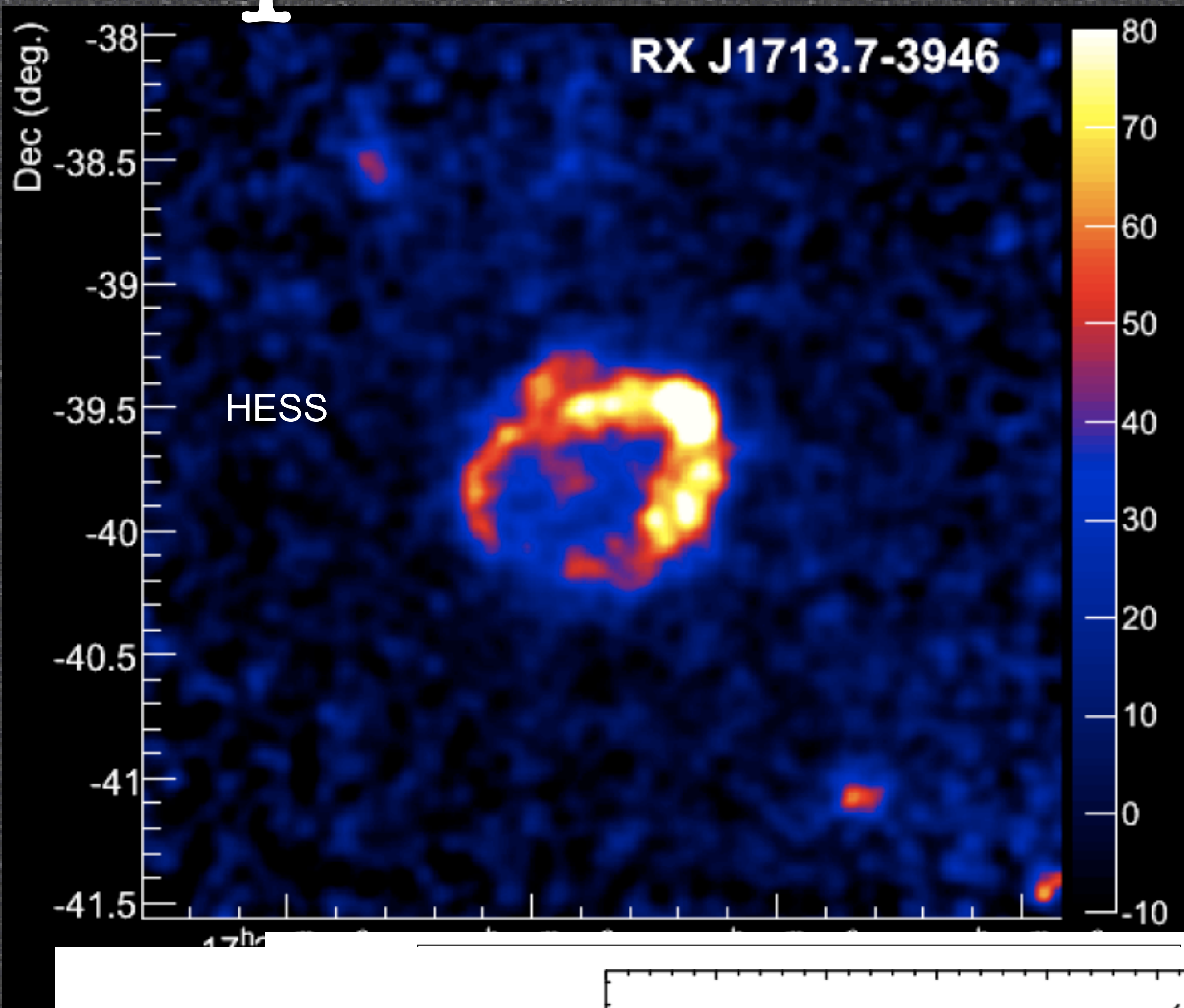


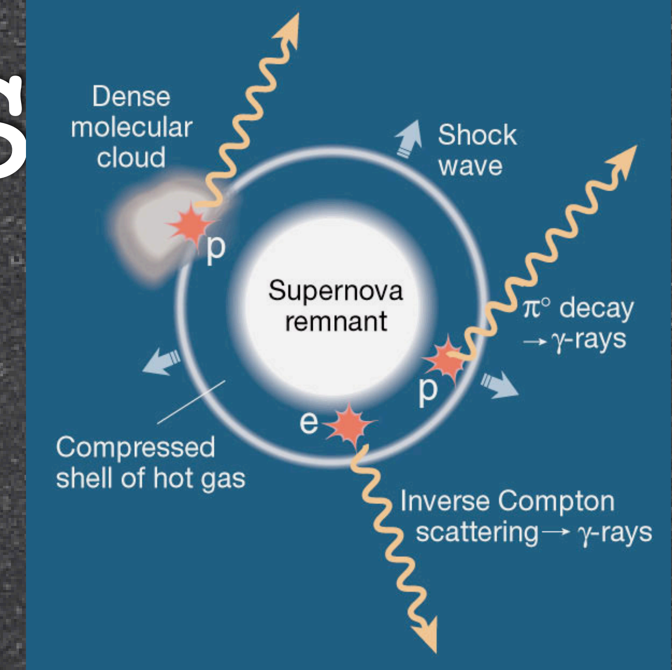


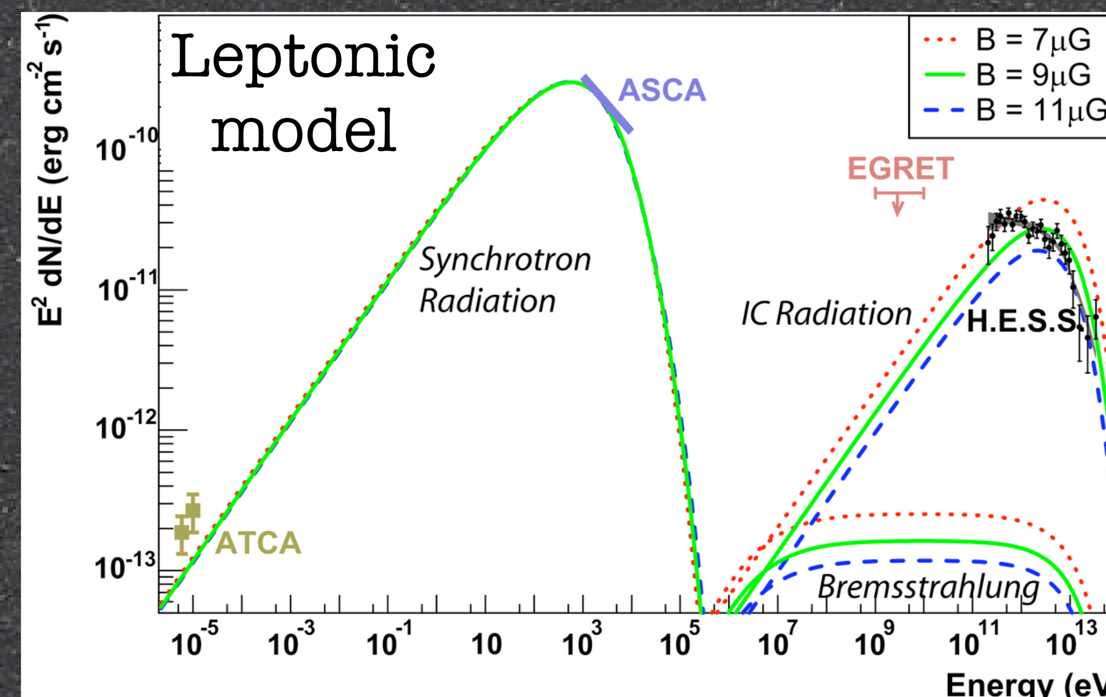
Strong correlation with X-ray intensities

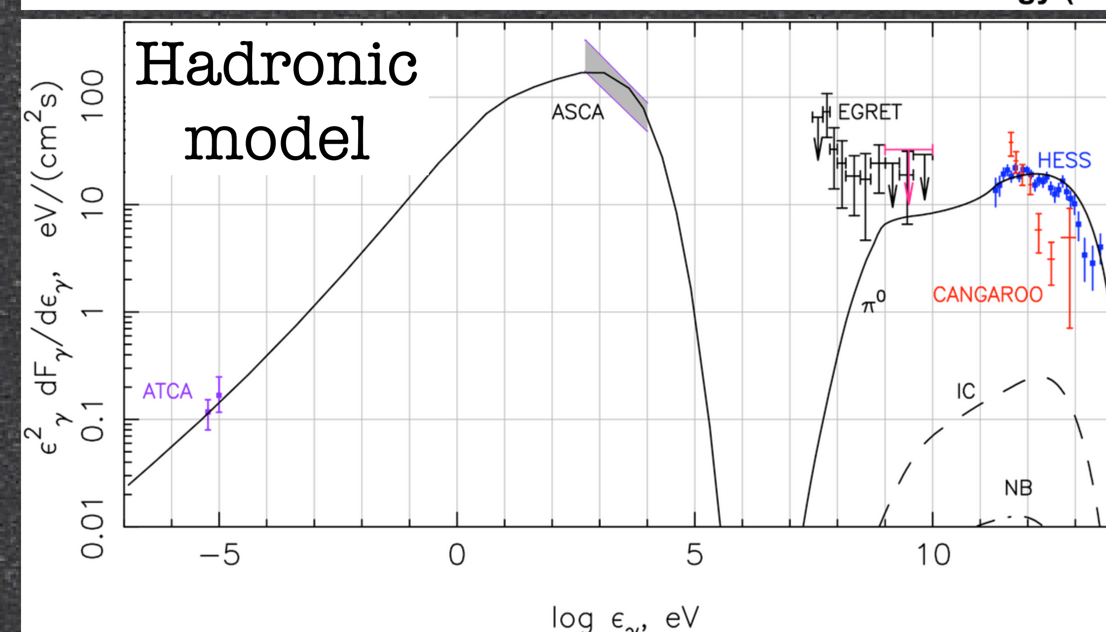


Super Nova Remnants

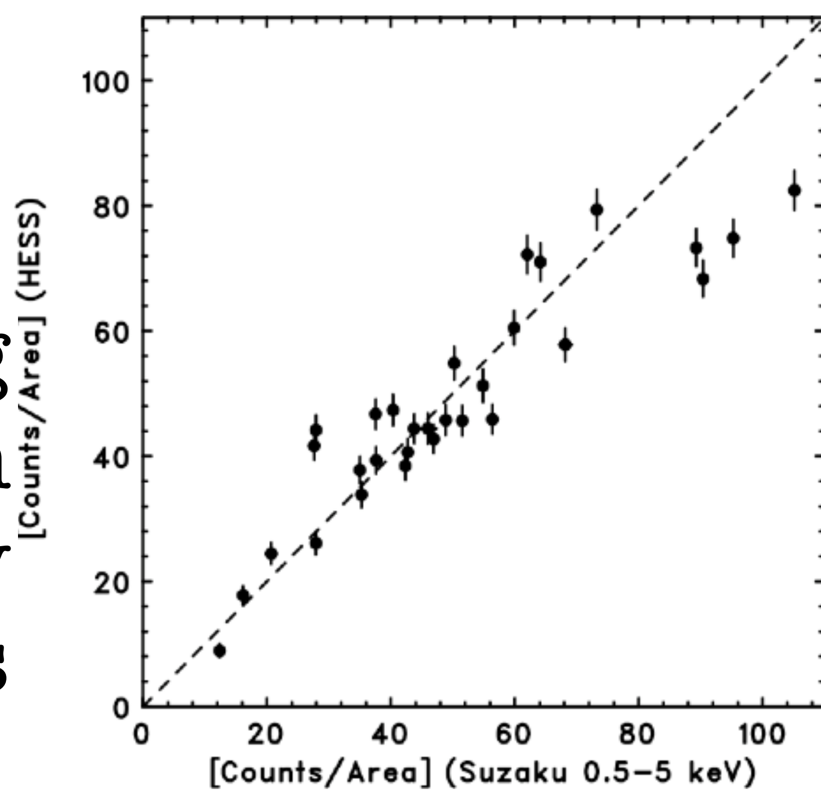




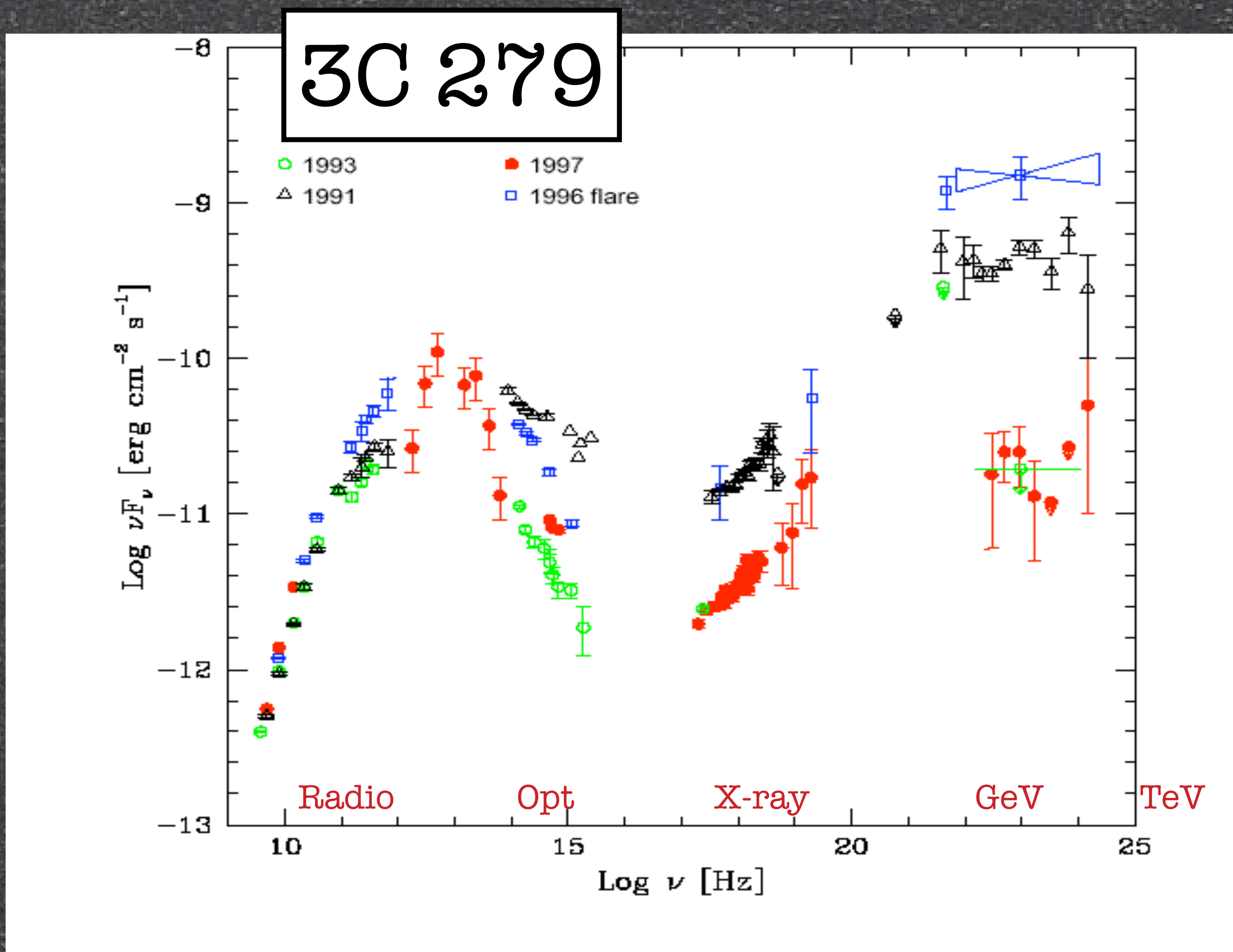




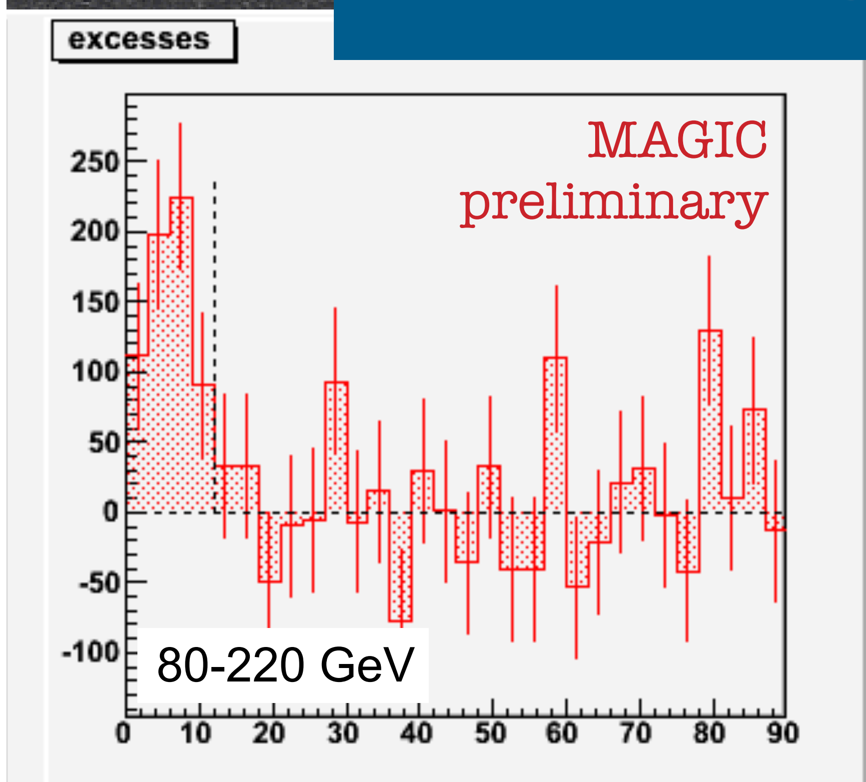
Strong correlation with X-ray intensities

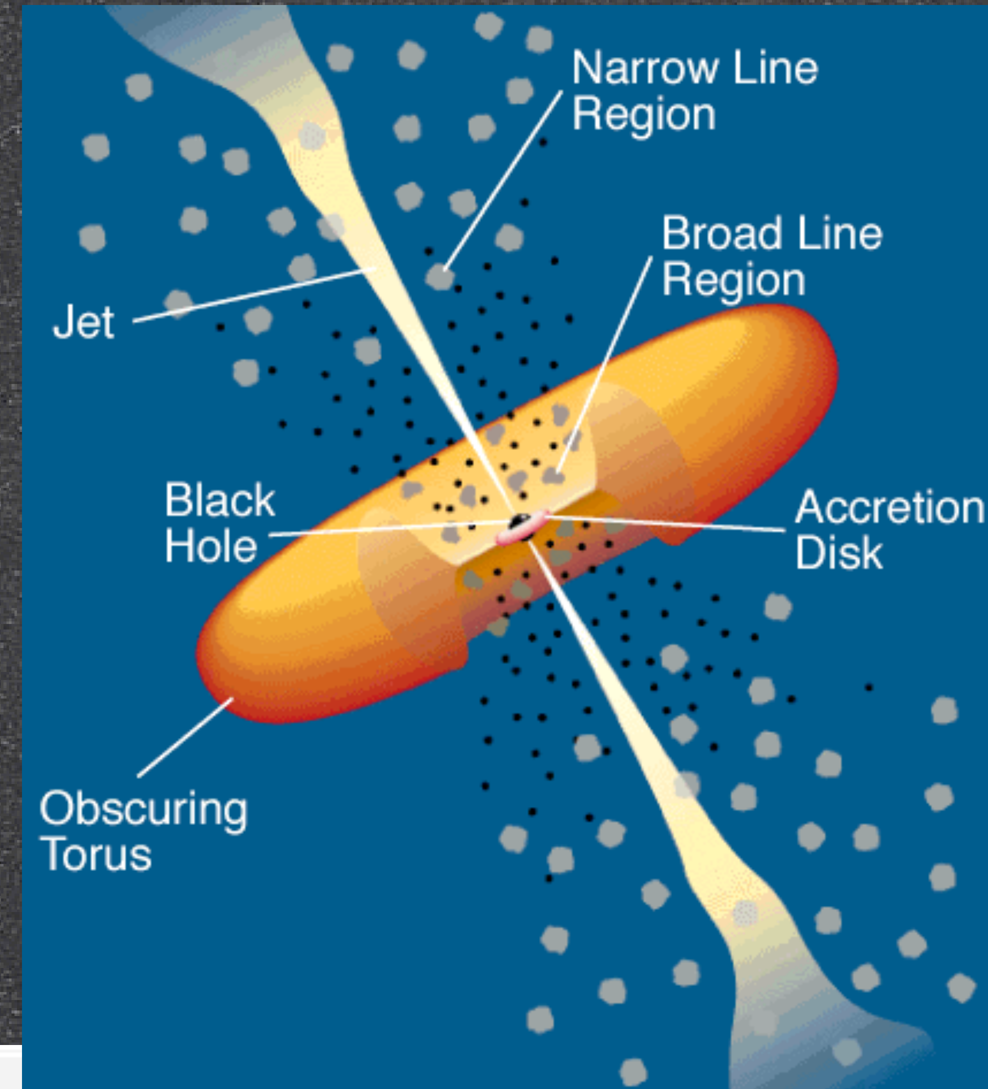


Blazars



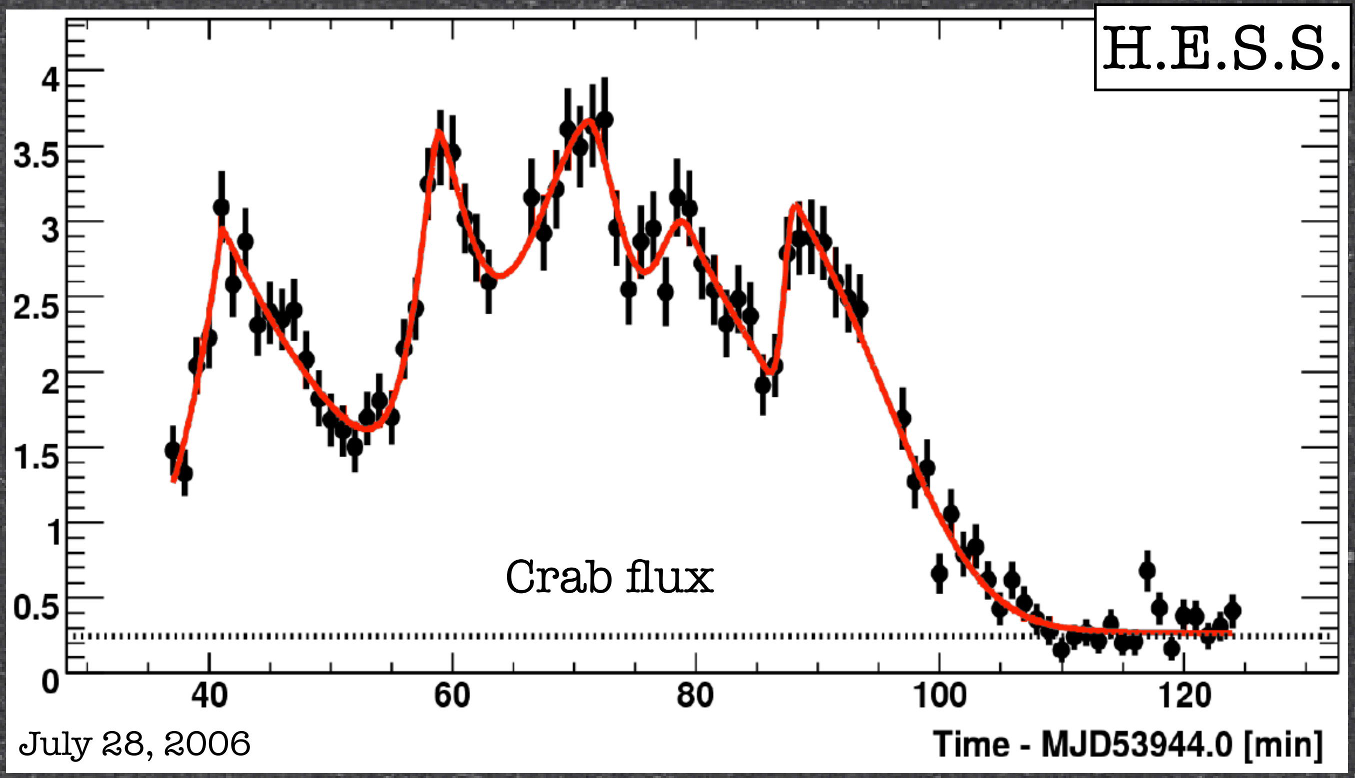
high variability



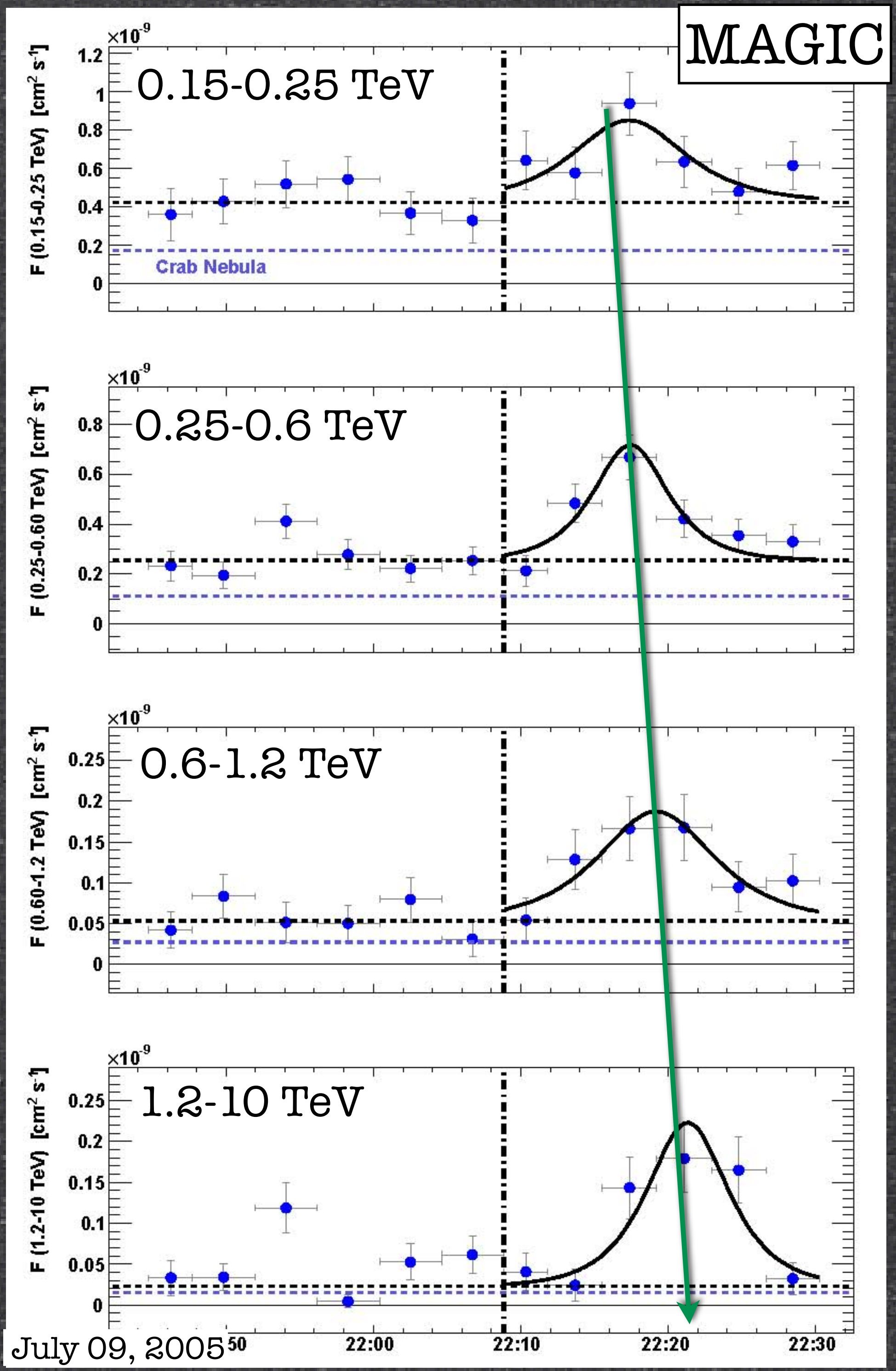


Blazars: exceptional Flares

PKS 2155



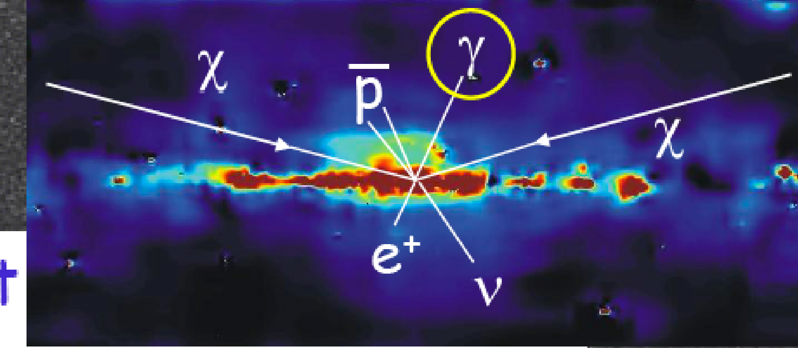
Mkn 501



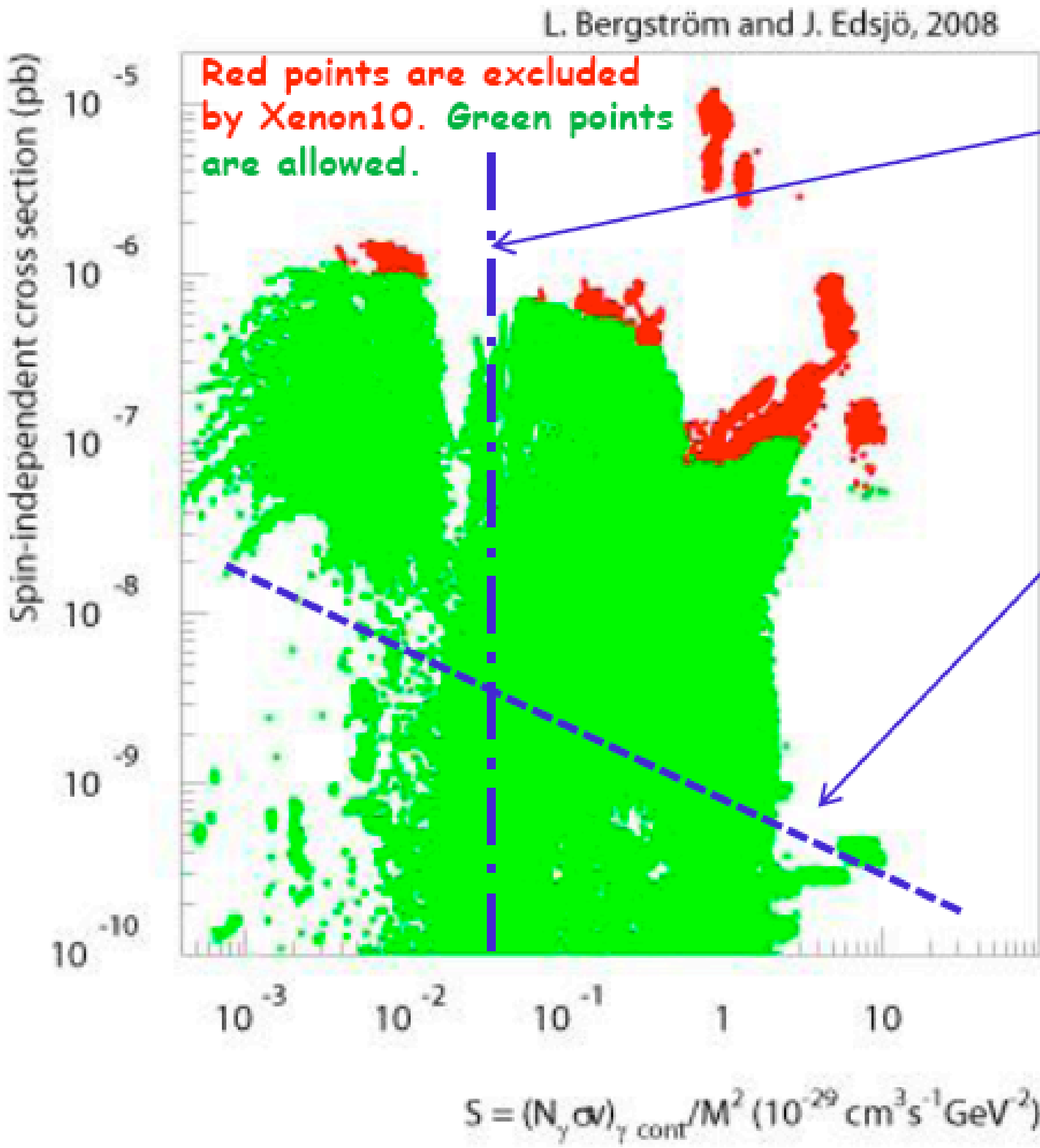
- peak flux ≈ 50 times average
- doubling times < 3 min

- Dynamics of acceleration?
- Vacuum dispersion from quantum gravity? $M_{QG1} > 2.6 \times 10^{17}$ GeV

Dark Matter Search

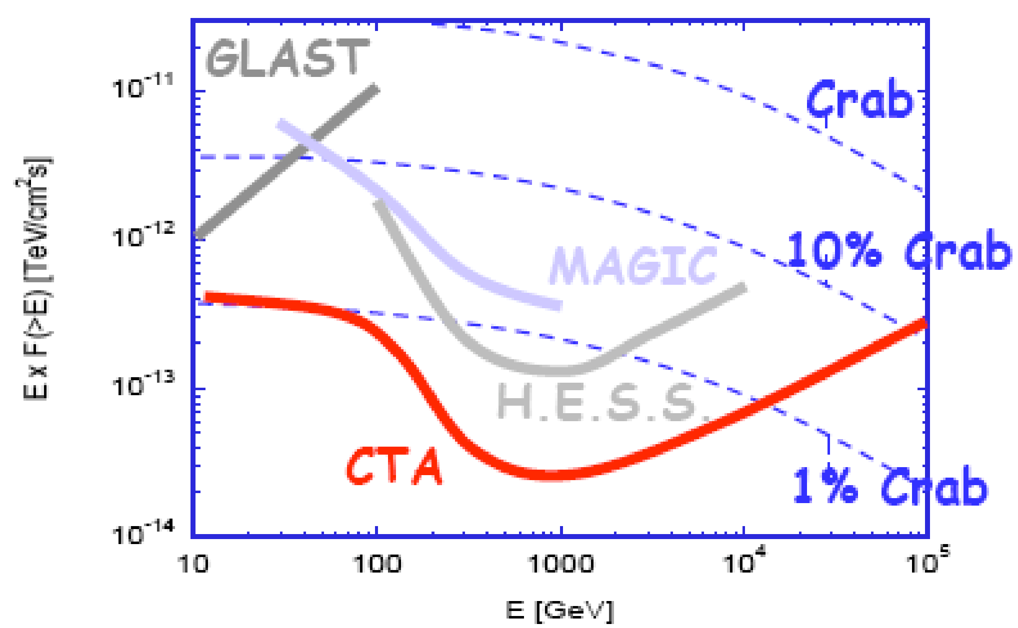


Complementarity between direct detection and indirect detection through gamma-rays



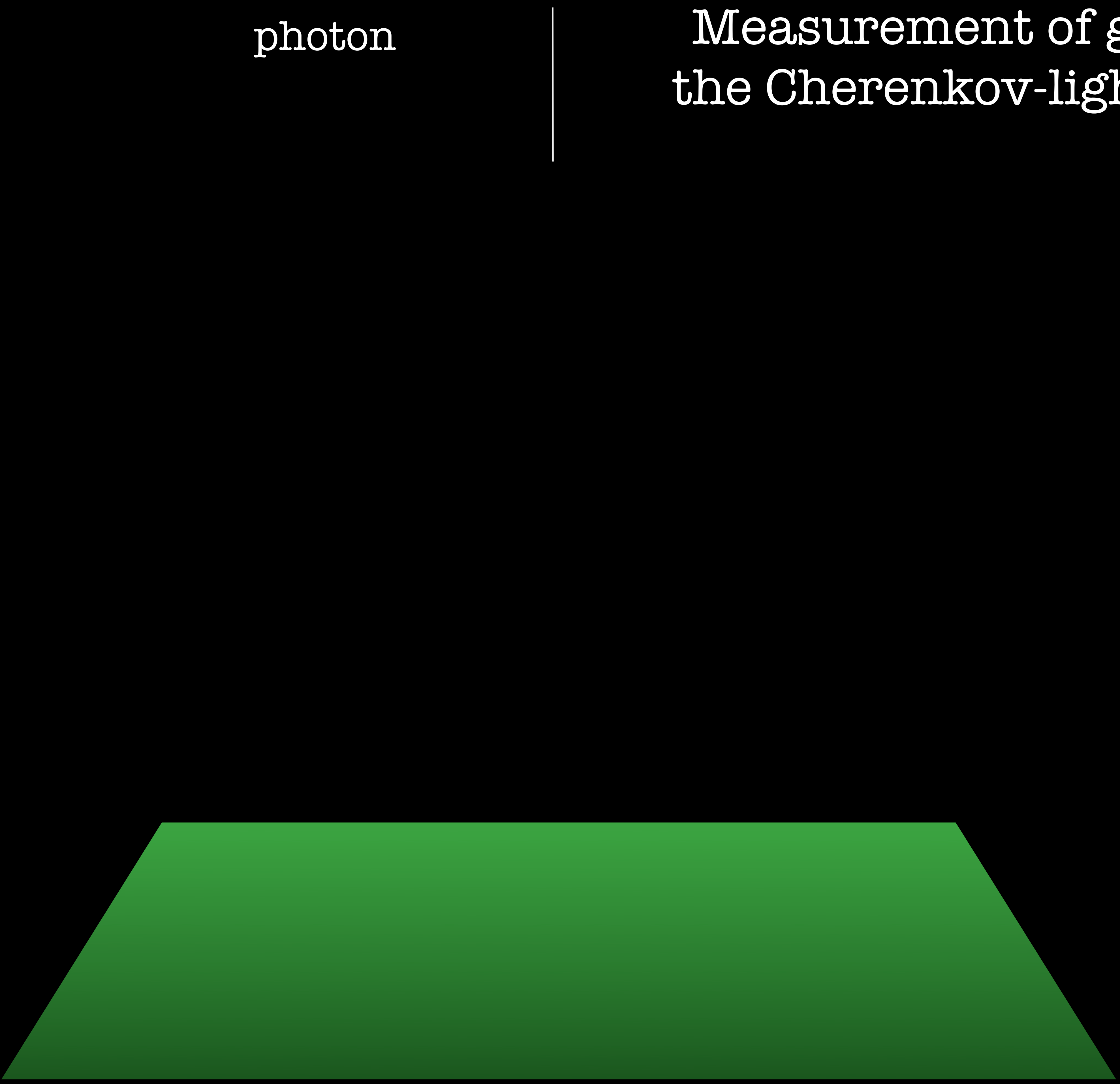
Approximate reach of CTA

Approximate reach of future direct searches.

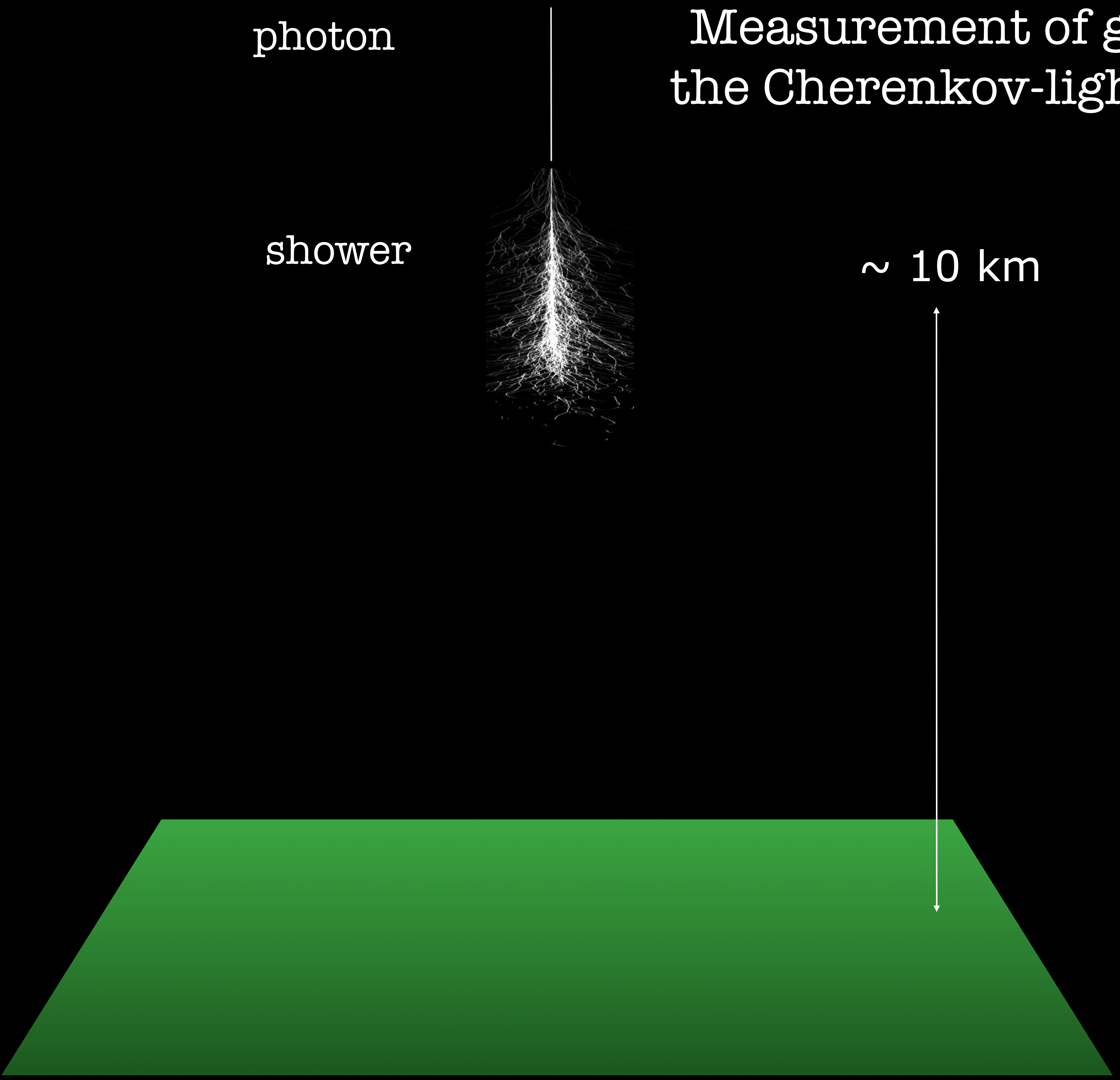


L Bergström, 2008

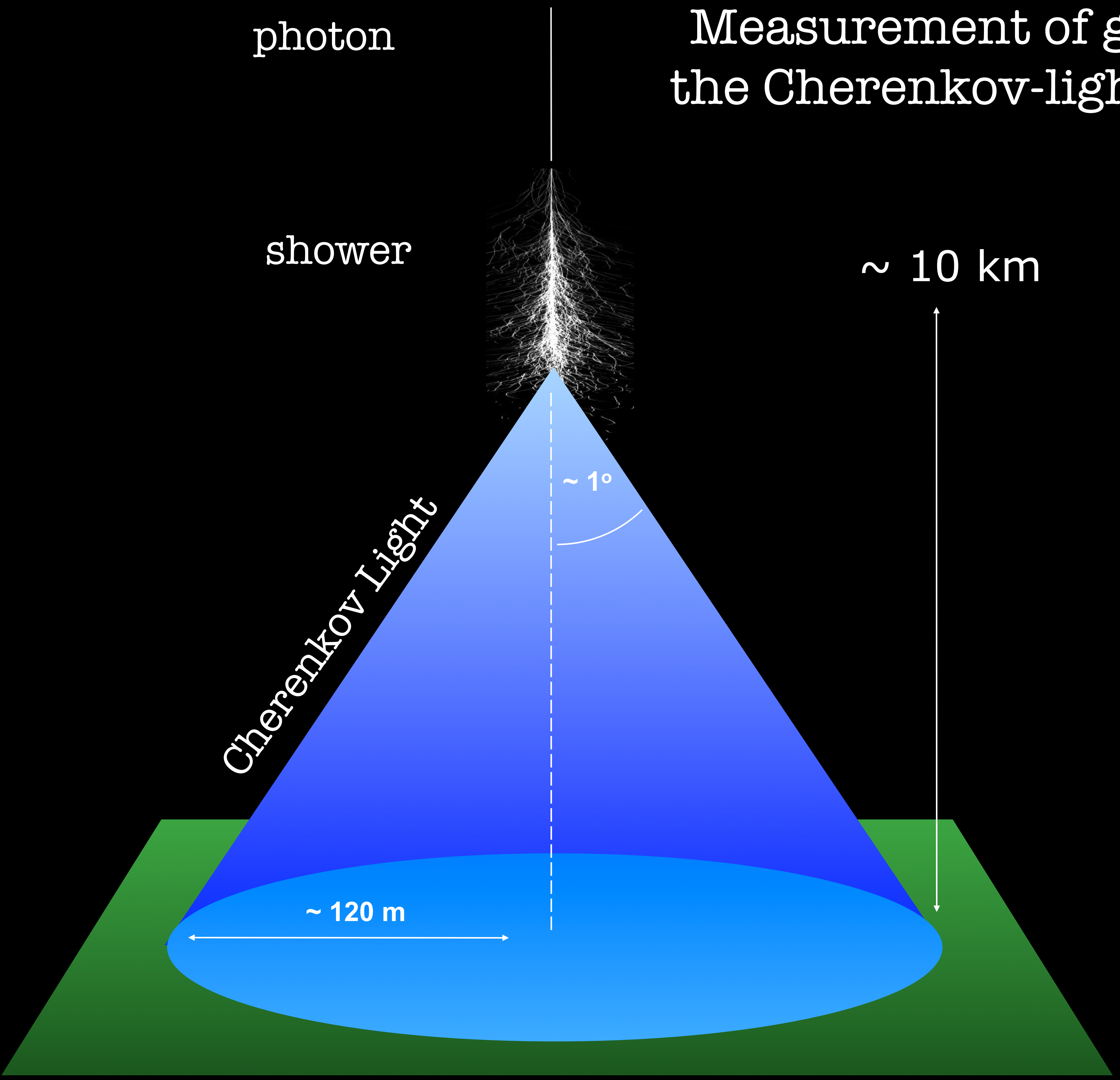
Measurement of gamma-rays via the Cherenkov-light of air showers

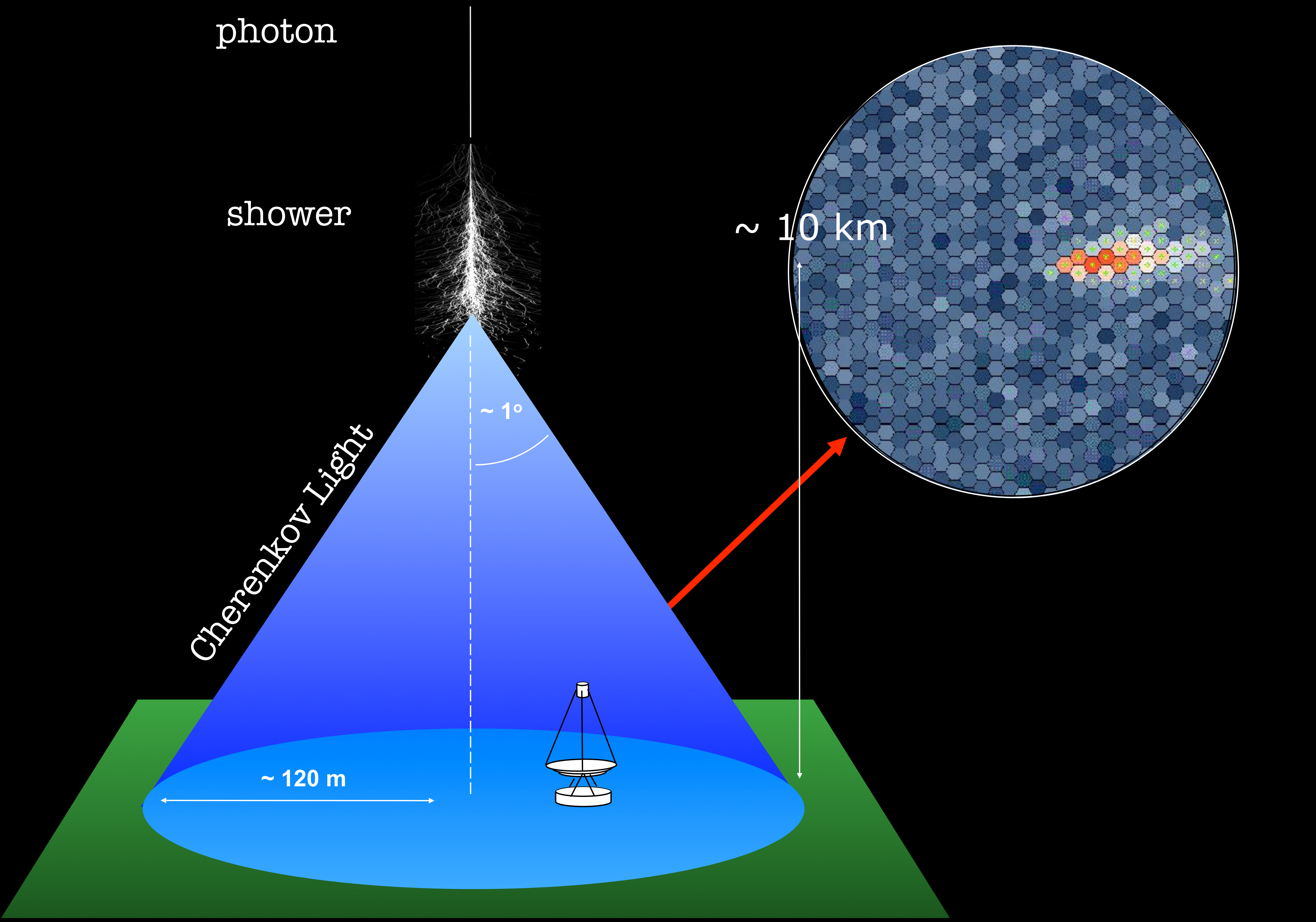


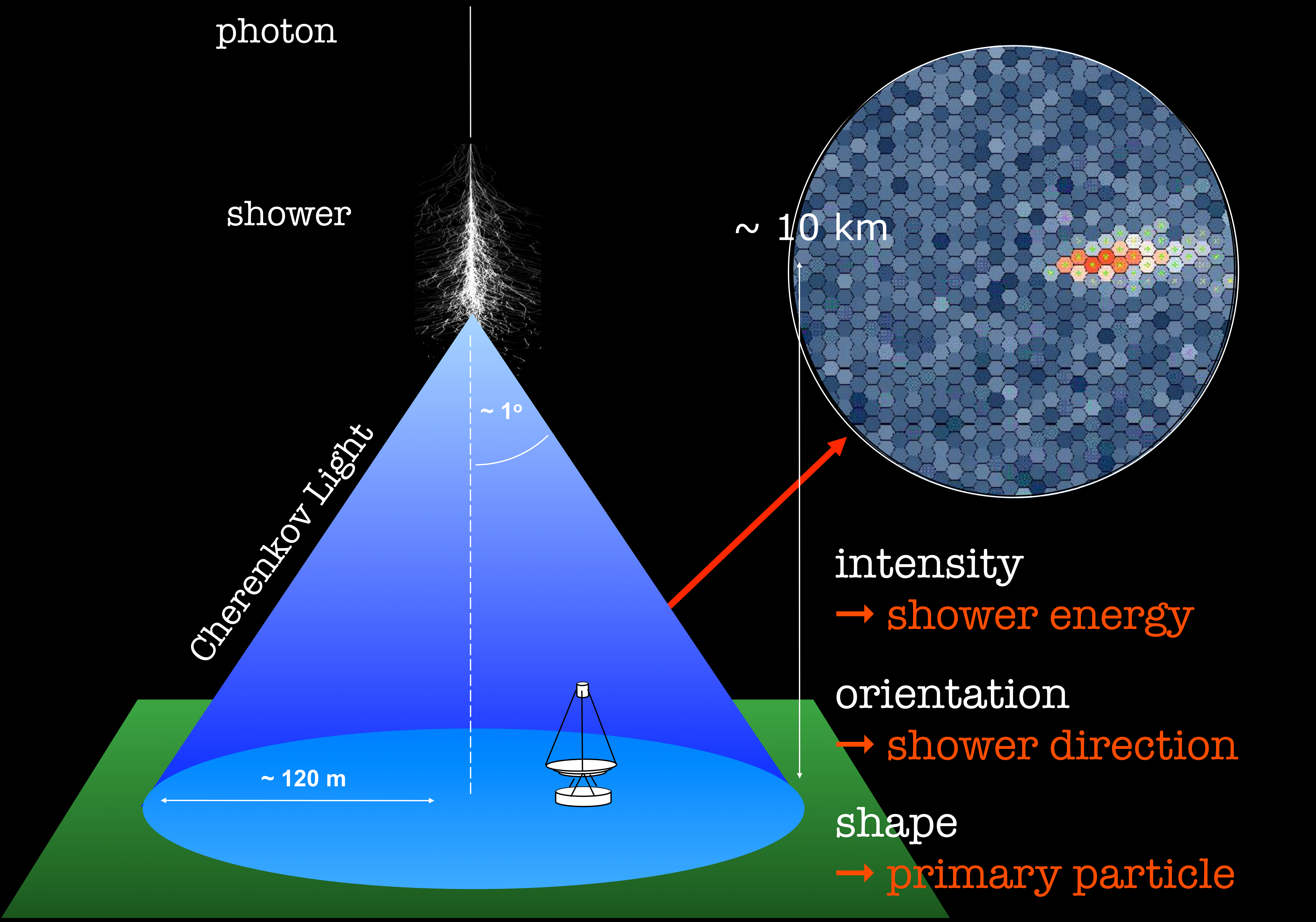
Measurement of gamma-rays via the Cherenkov-light of air showers



Measurement of gamma-rays via the Cherenkov-light of air showers

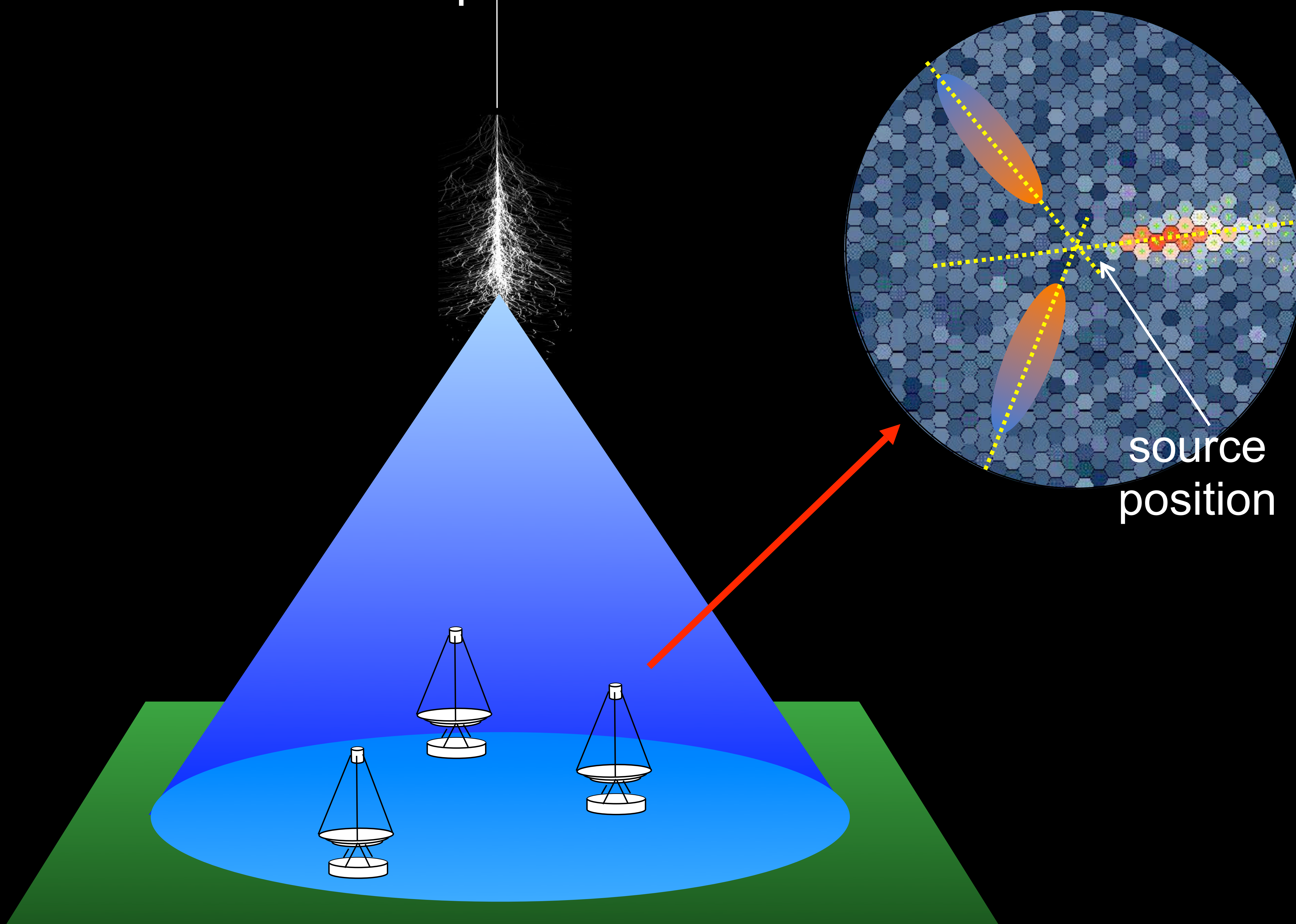


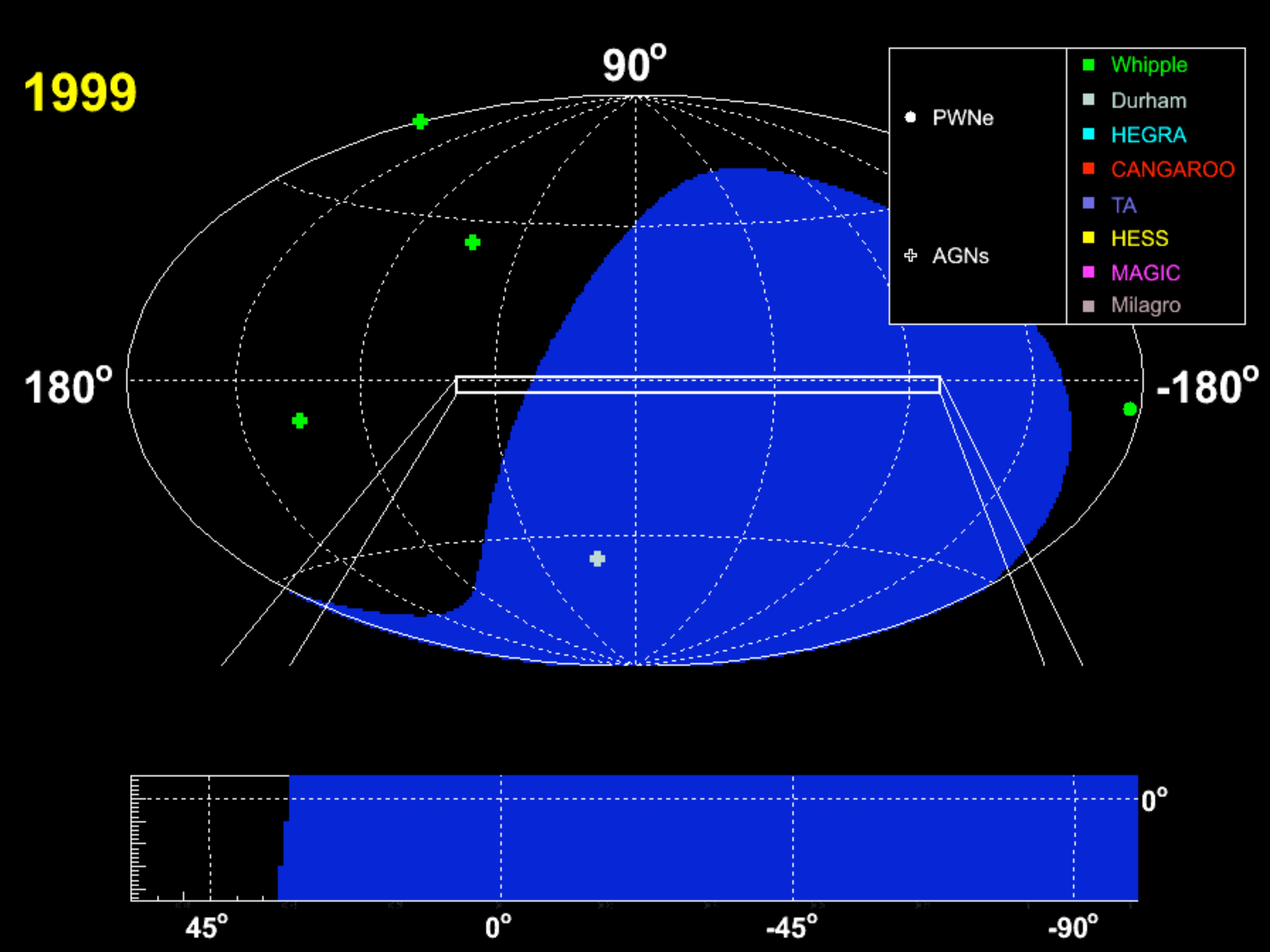

photon
shower
Cherenkov Light
~ 1°
~ 120 m
~ 10 km



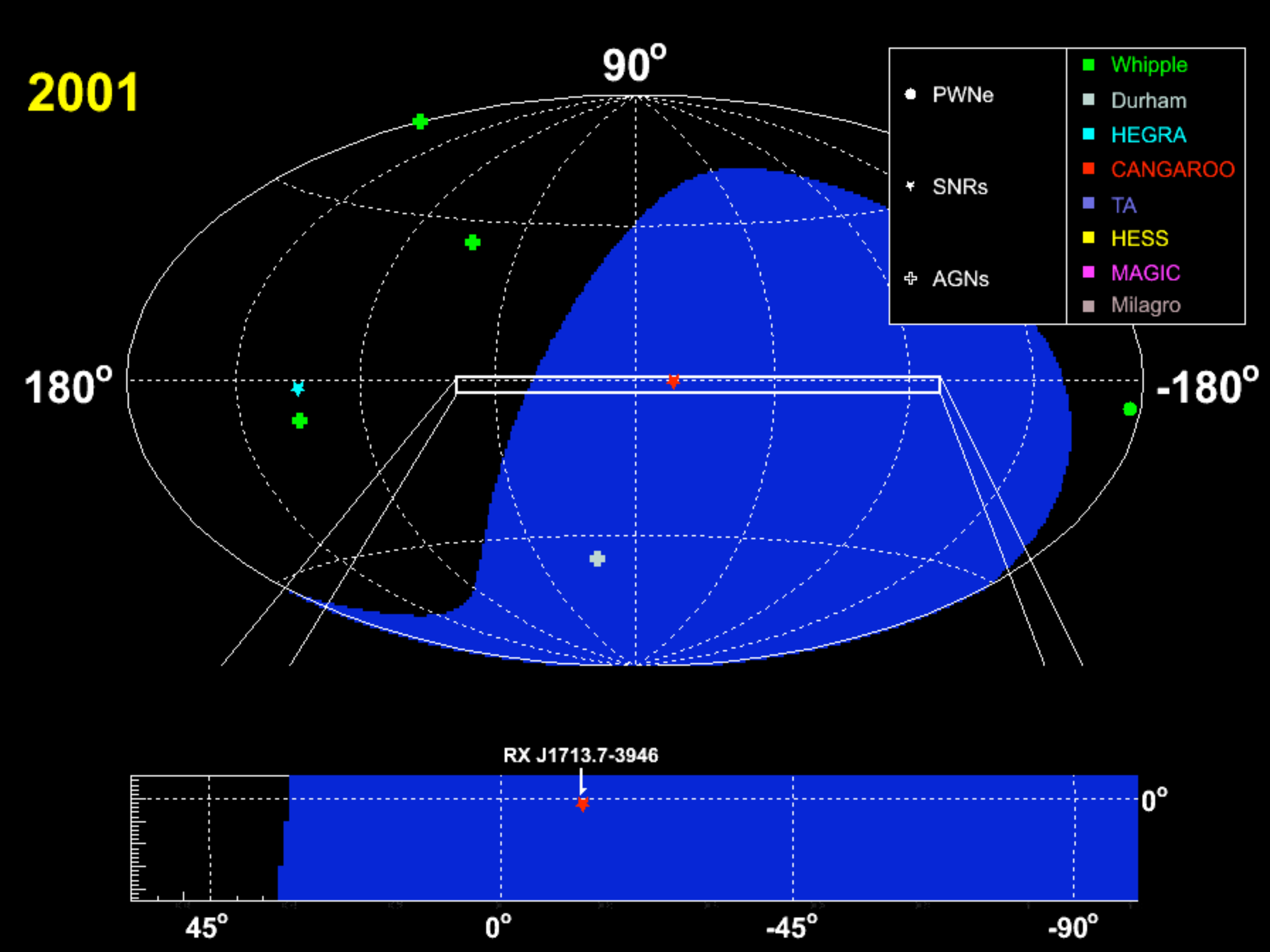
photon
shower
~ 10 km
~ 1°
Cherenkov Light
~ 120 m
intensity
→ shower energy
orientation
→ shower direction
shape
→ primary particle

Stereoscopic observation

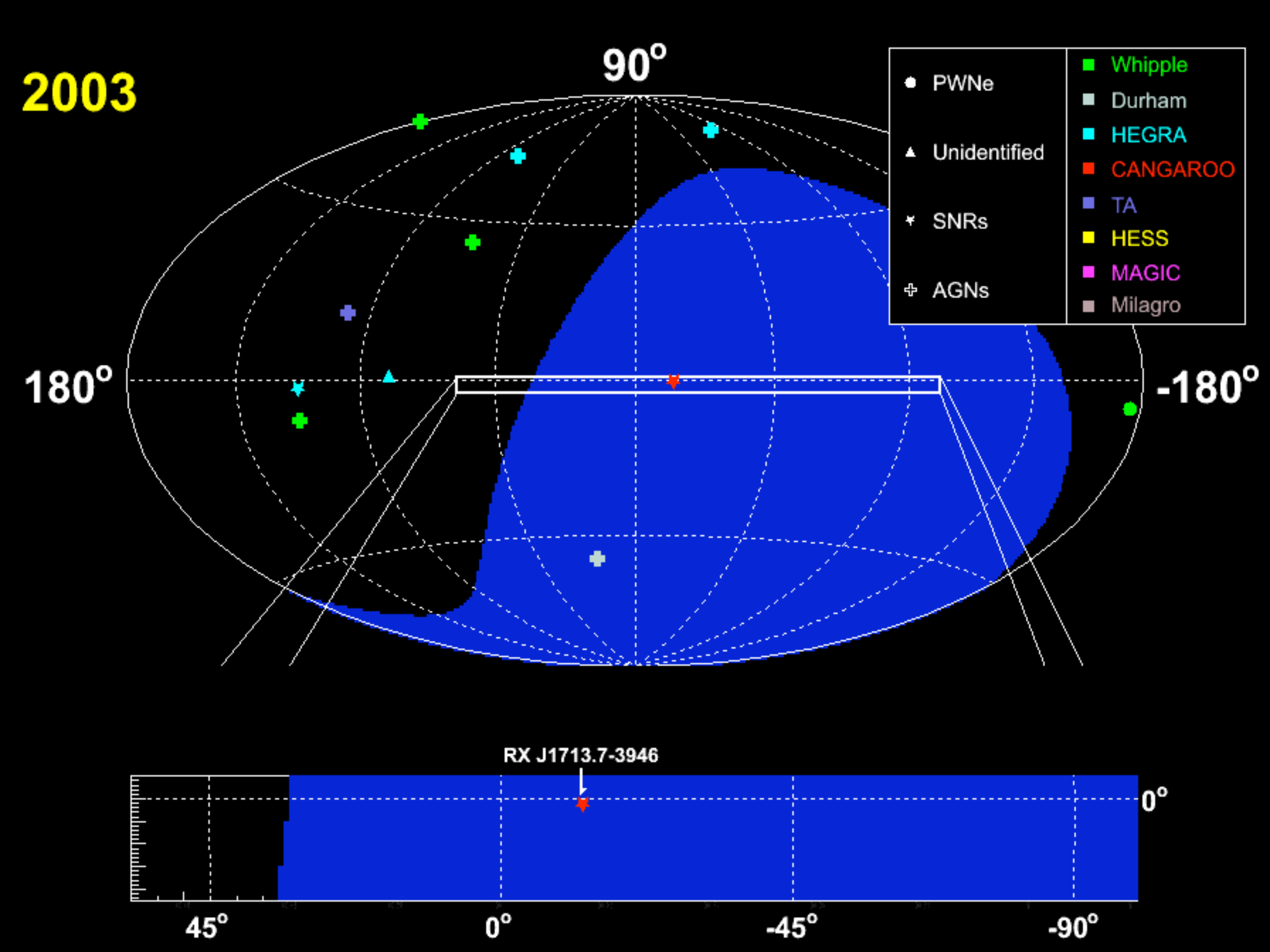




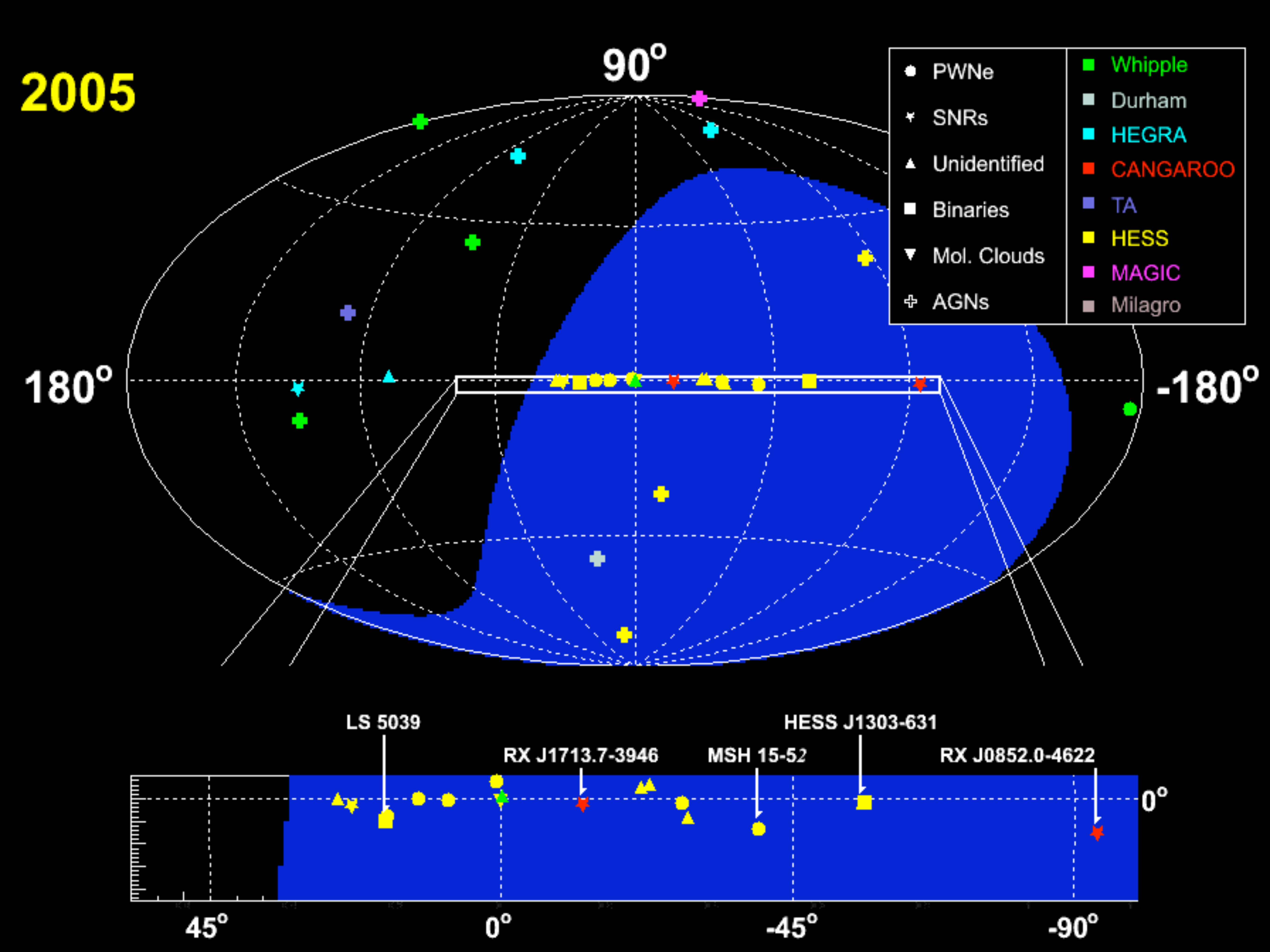
1999
90°
180°
-180°
PWNe
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
0°
45°
0°
-45°
-90°



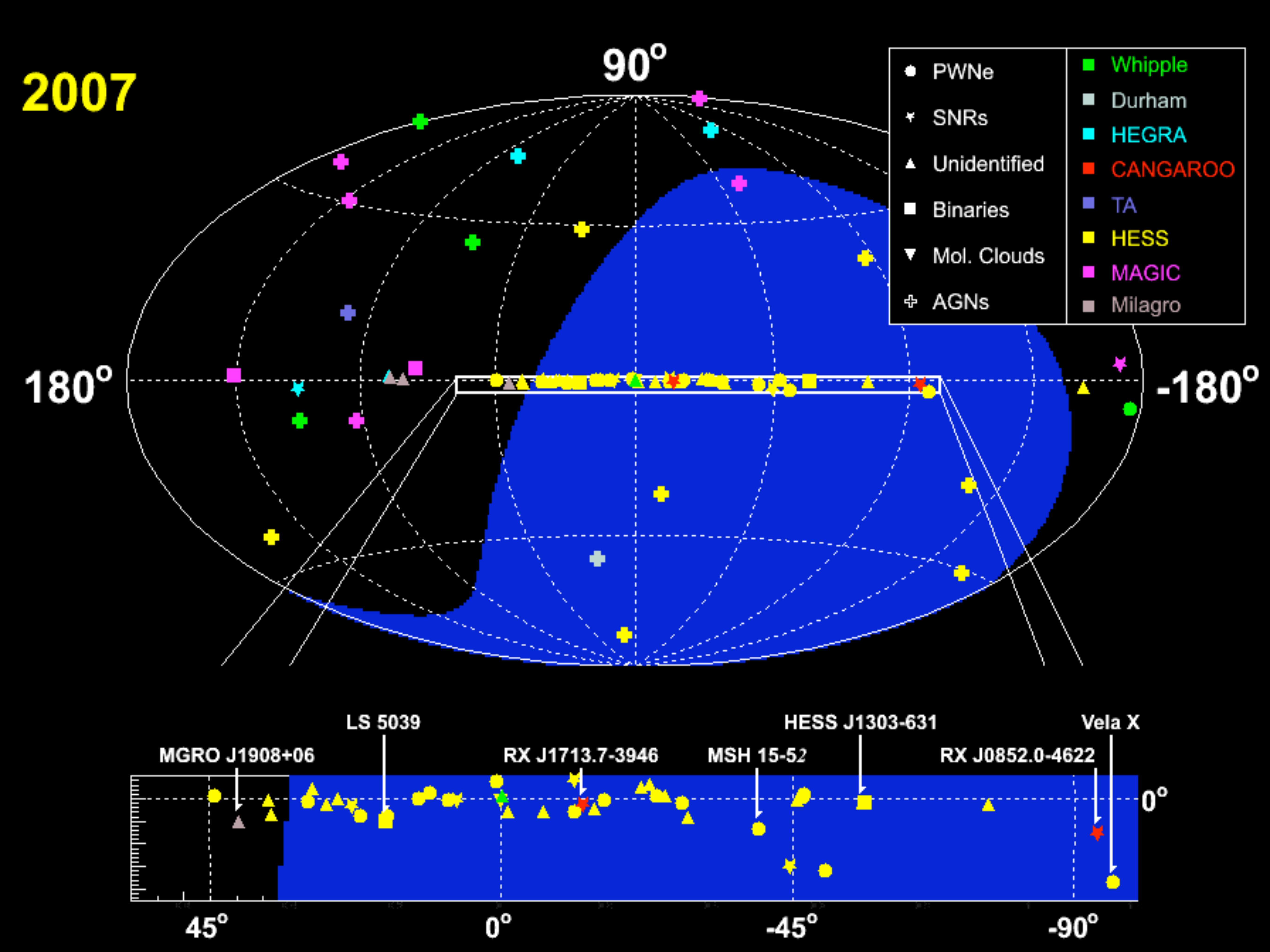
2001
90°
180°
-180°
PWNe
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°



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

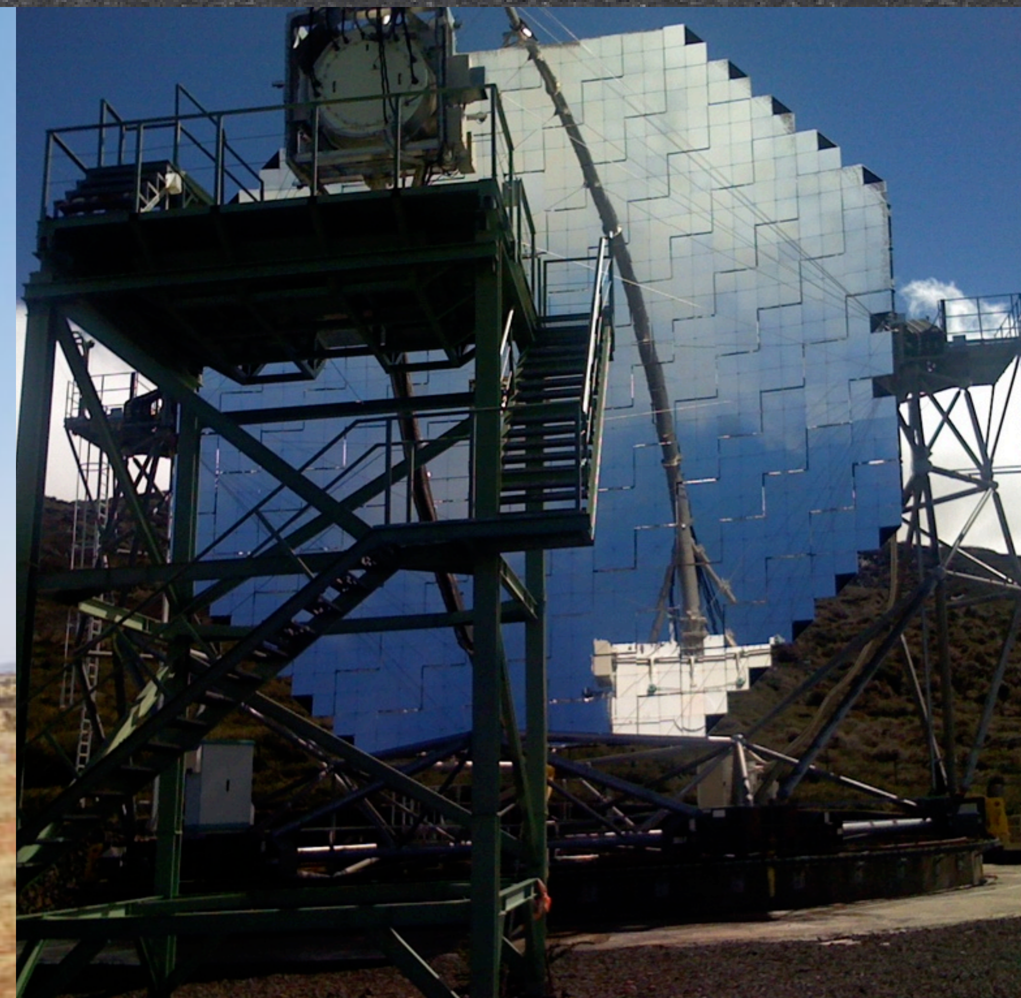


2005
90°
180°
-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
0°
45°
0°
-45°
-90°



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

The Next Generation

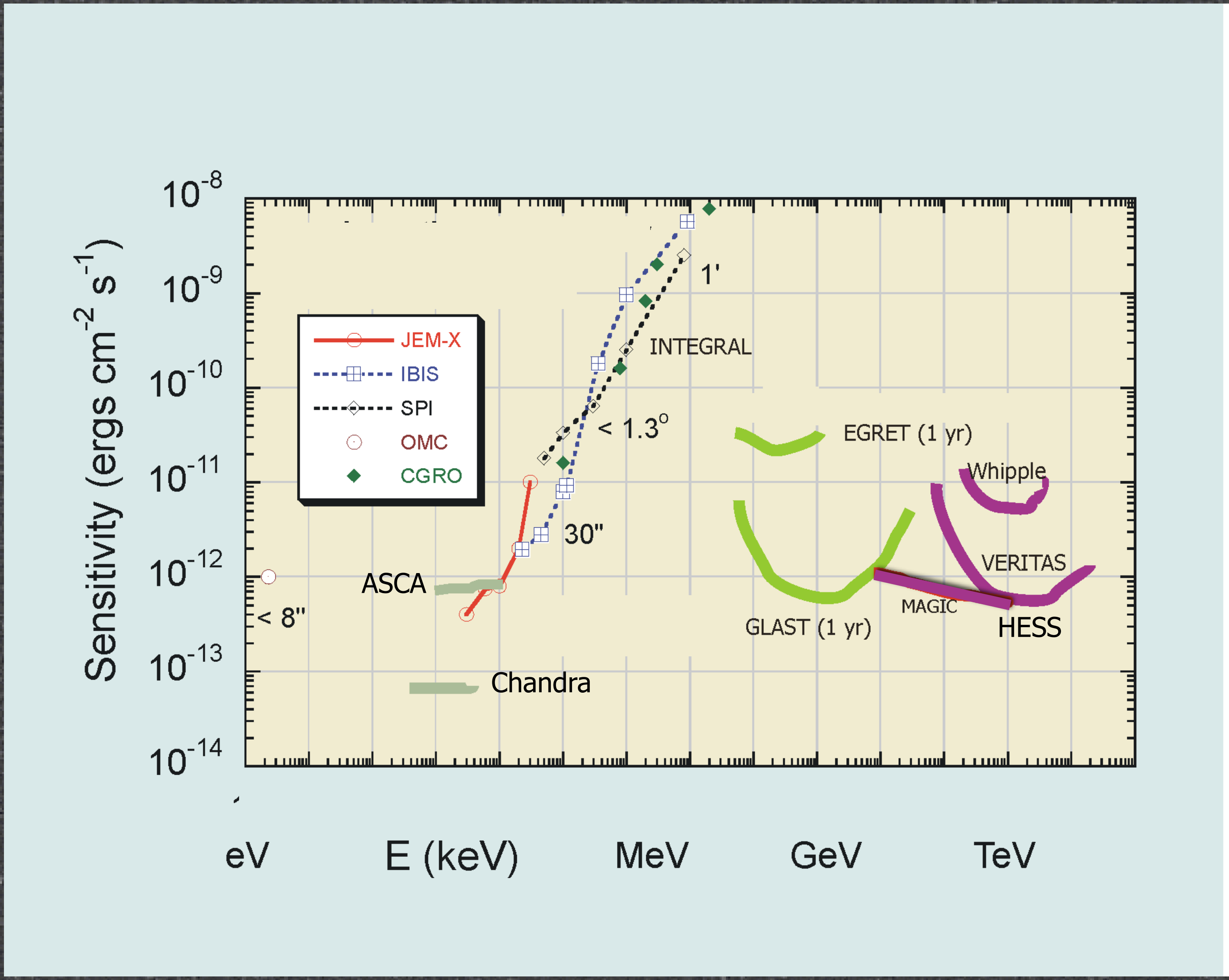




- ten times higher sensitivity
- extended energy range
- observatory

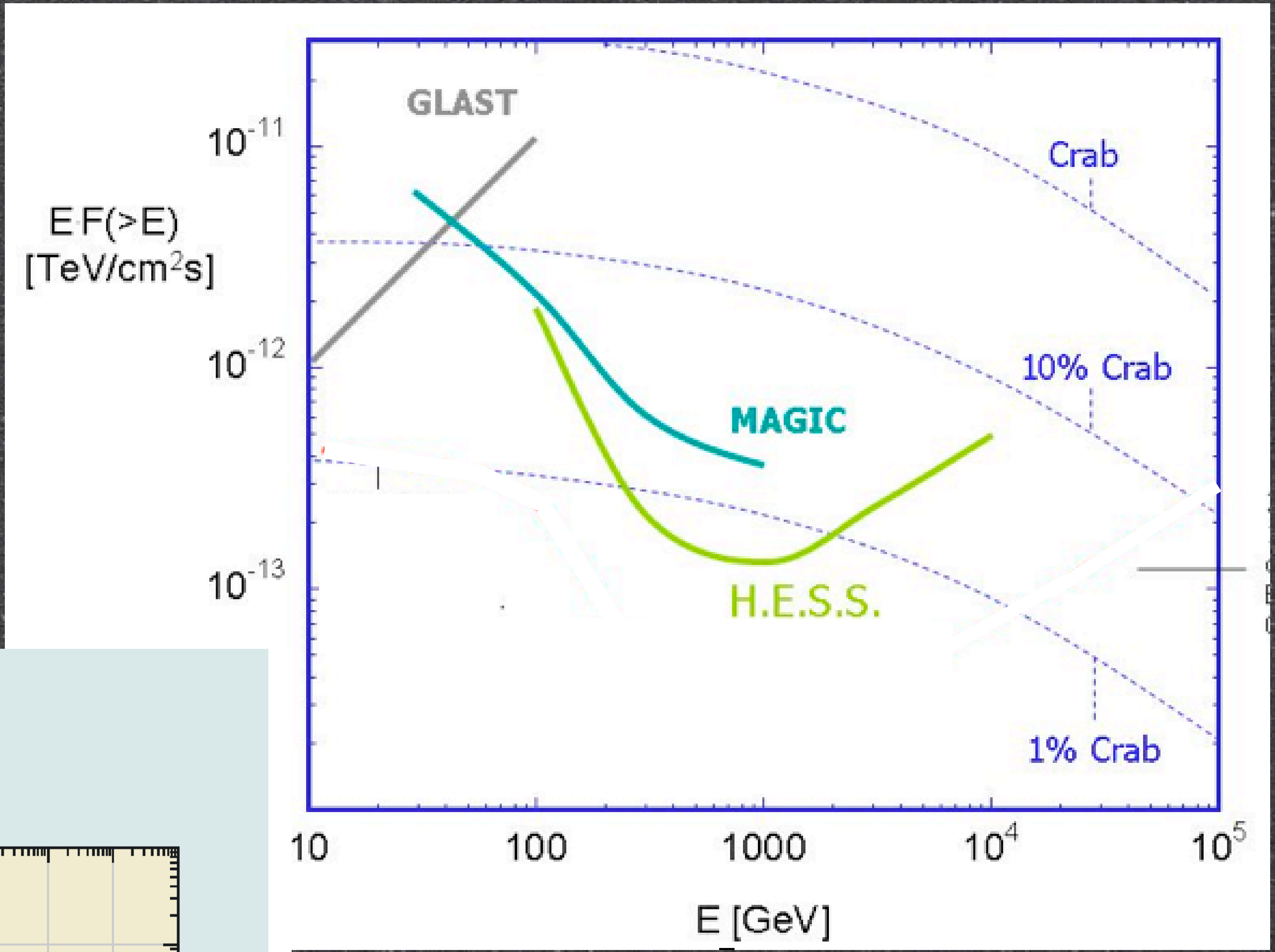
Cherenkov Telescope Array

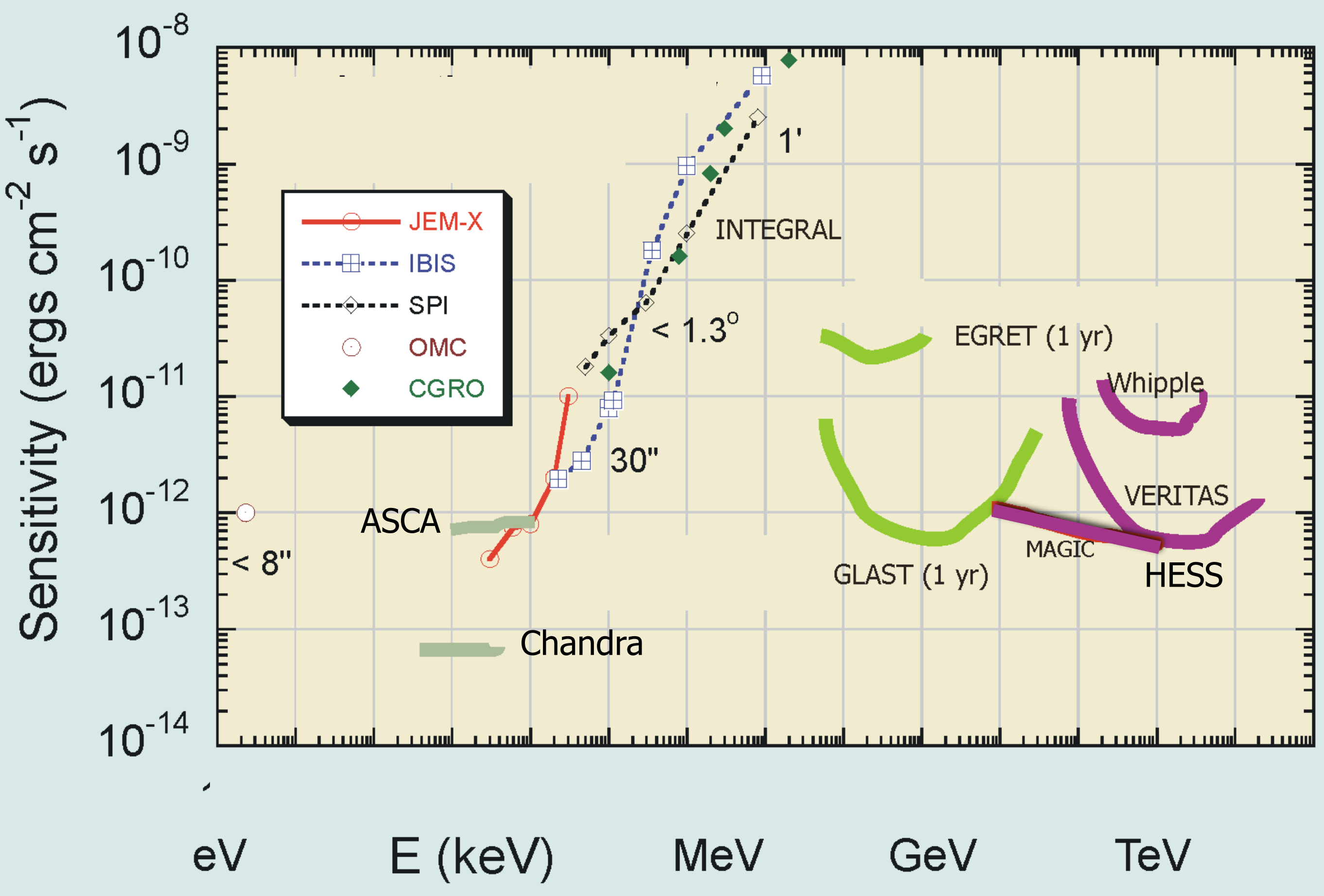
An advanced facility for ground-based γ-ray astronomy

Sensitivity

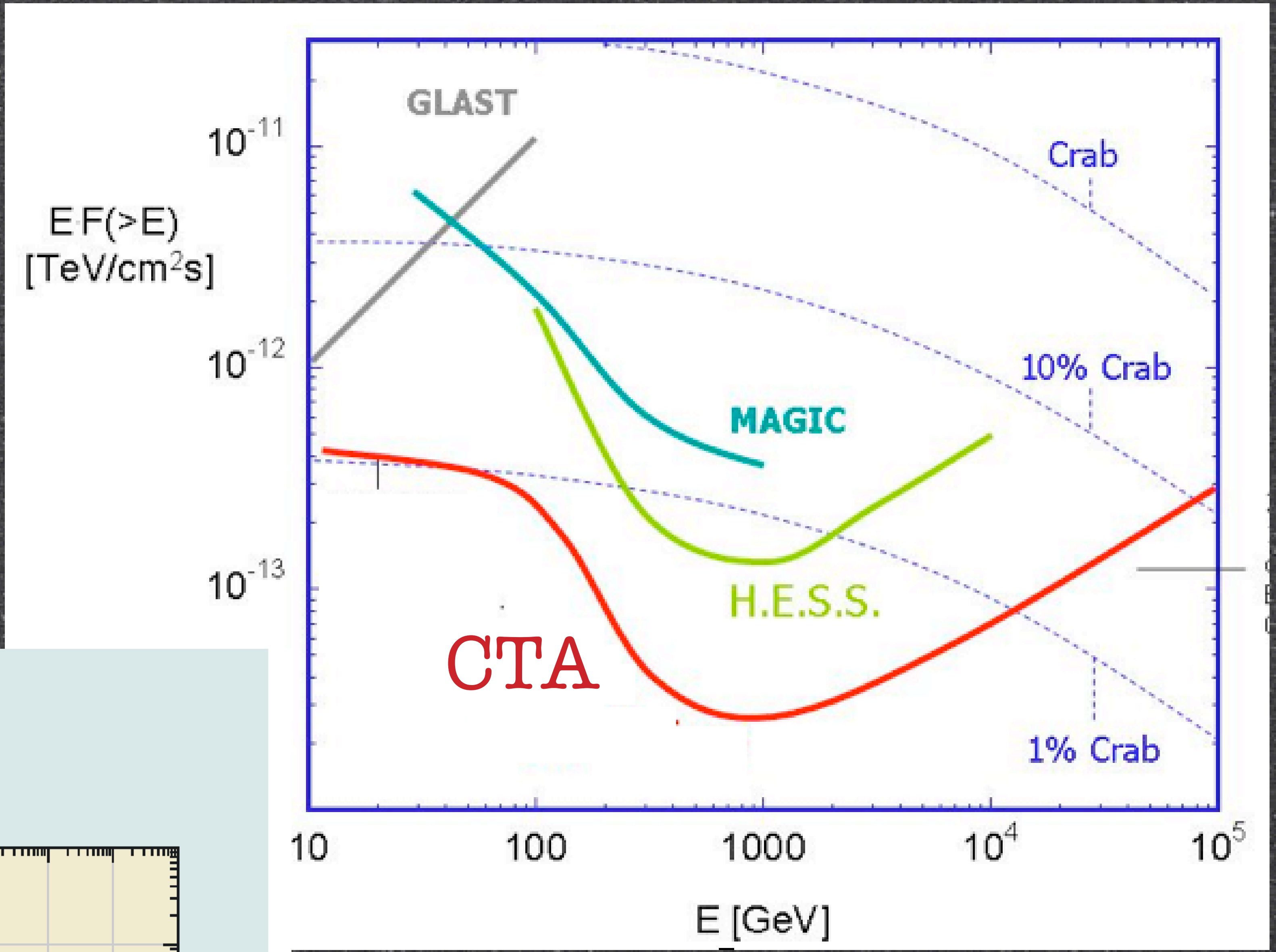


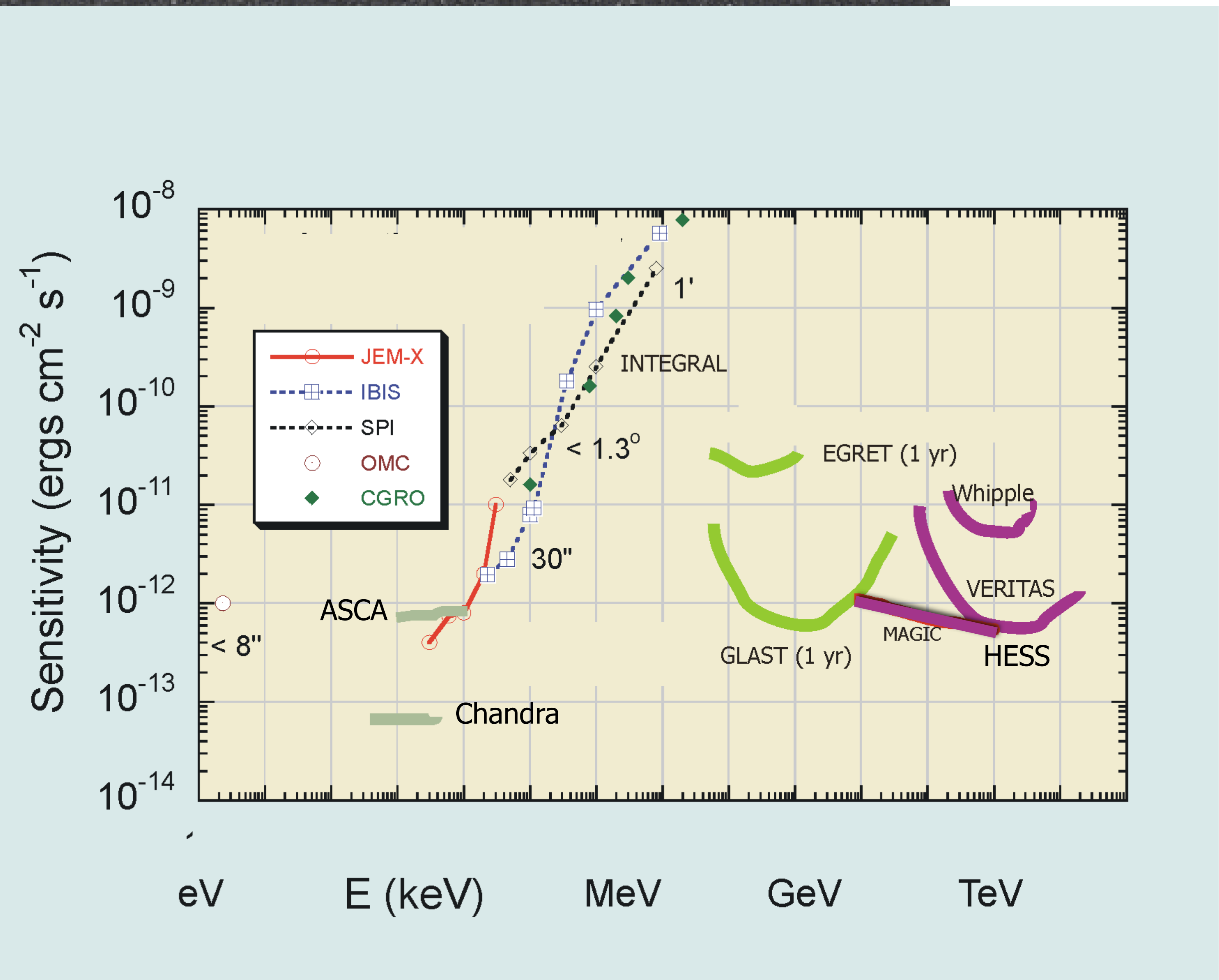
Sensitivity



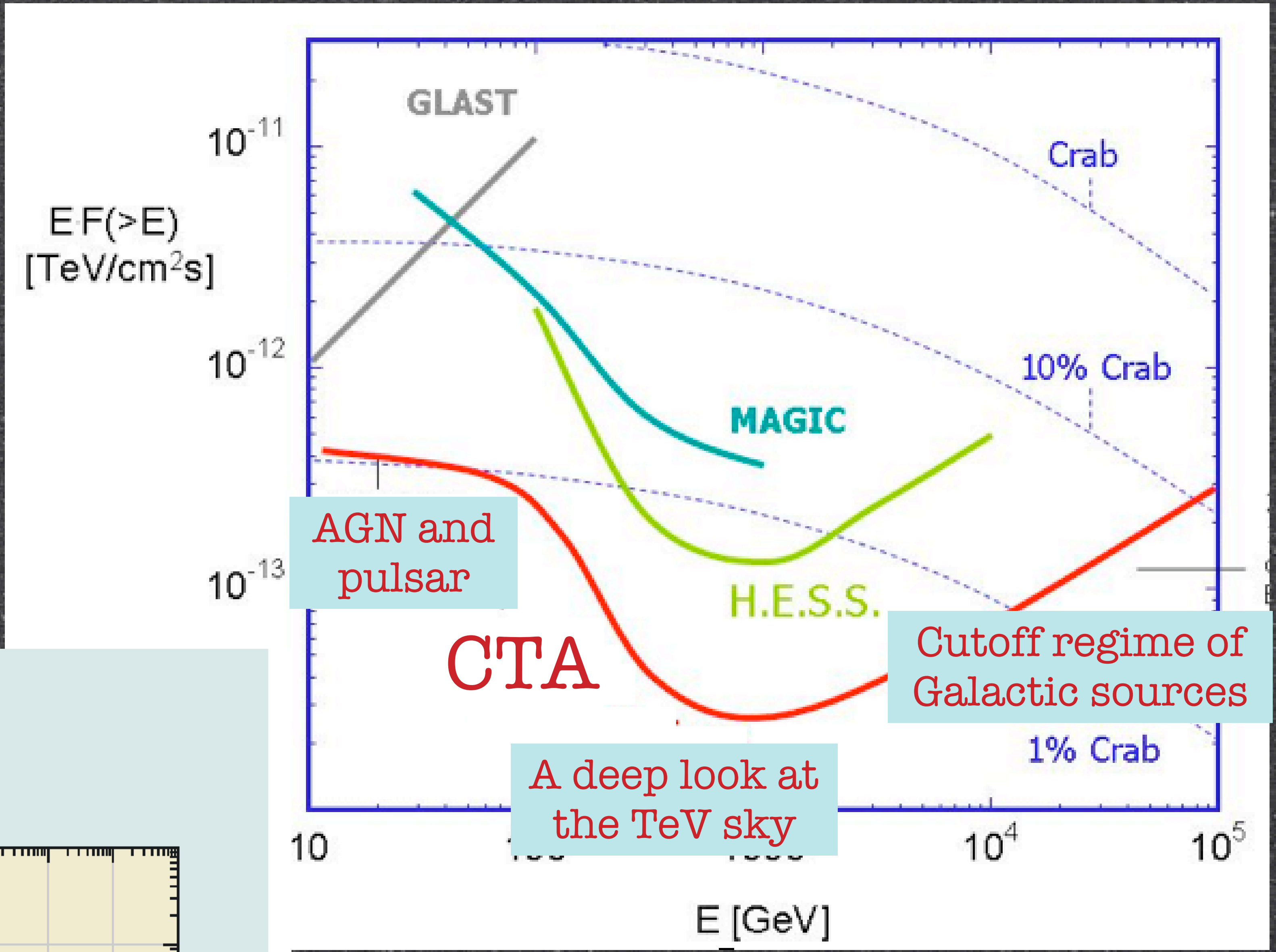


Sensitivity





Sensitivity

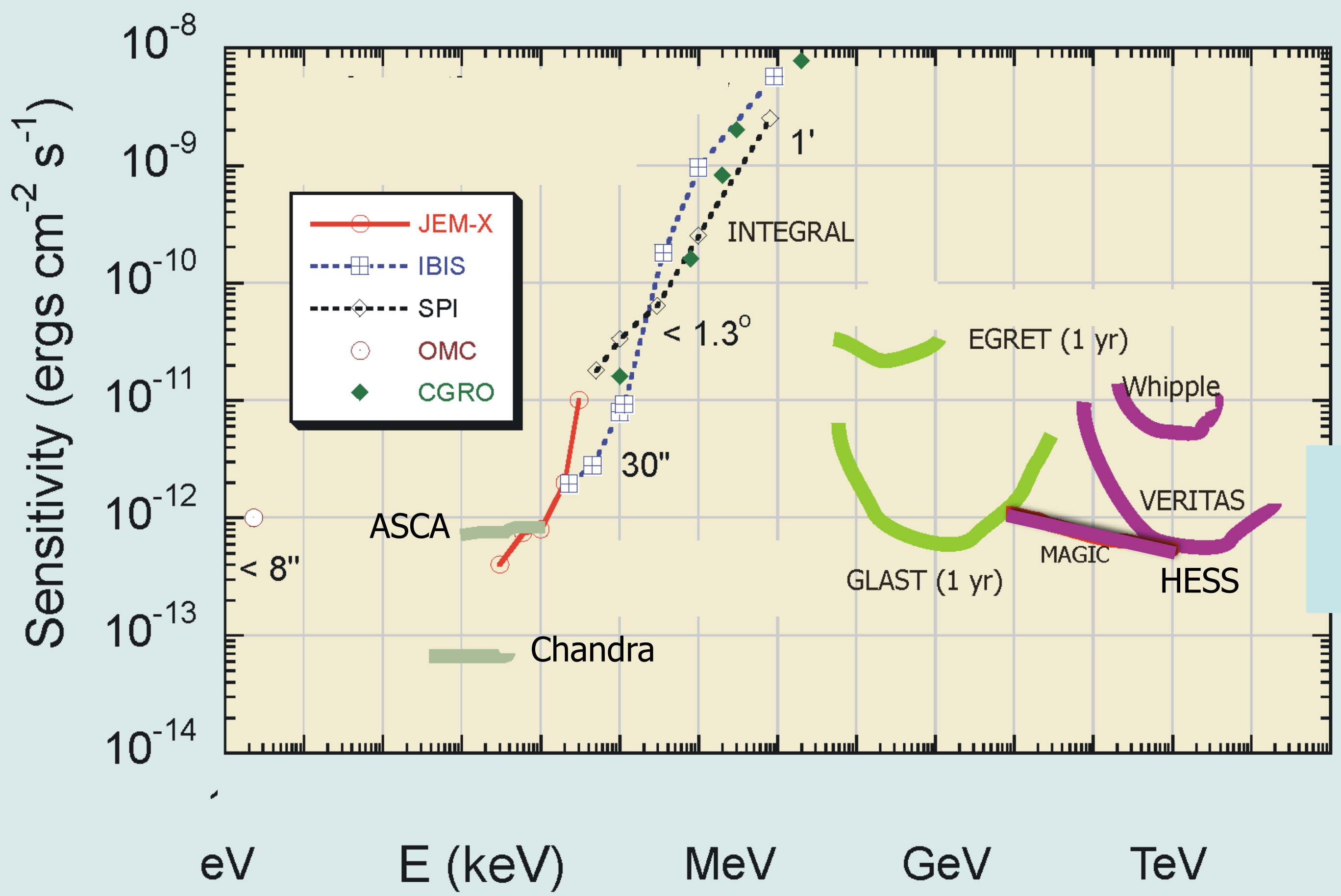


AGN and pulsar

CTA

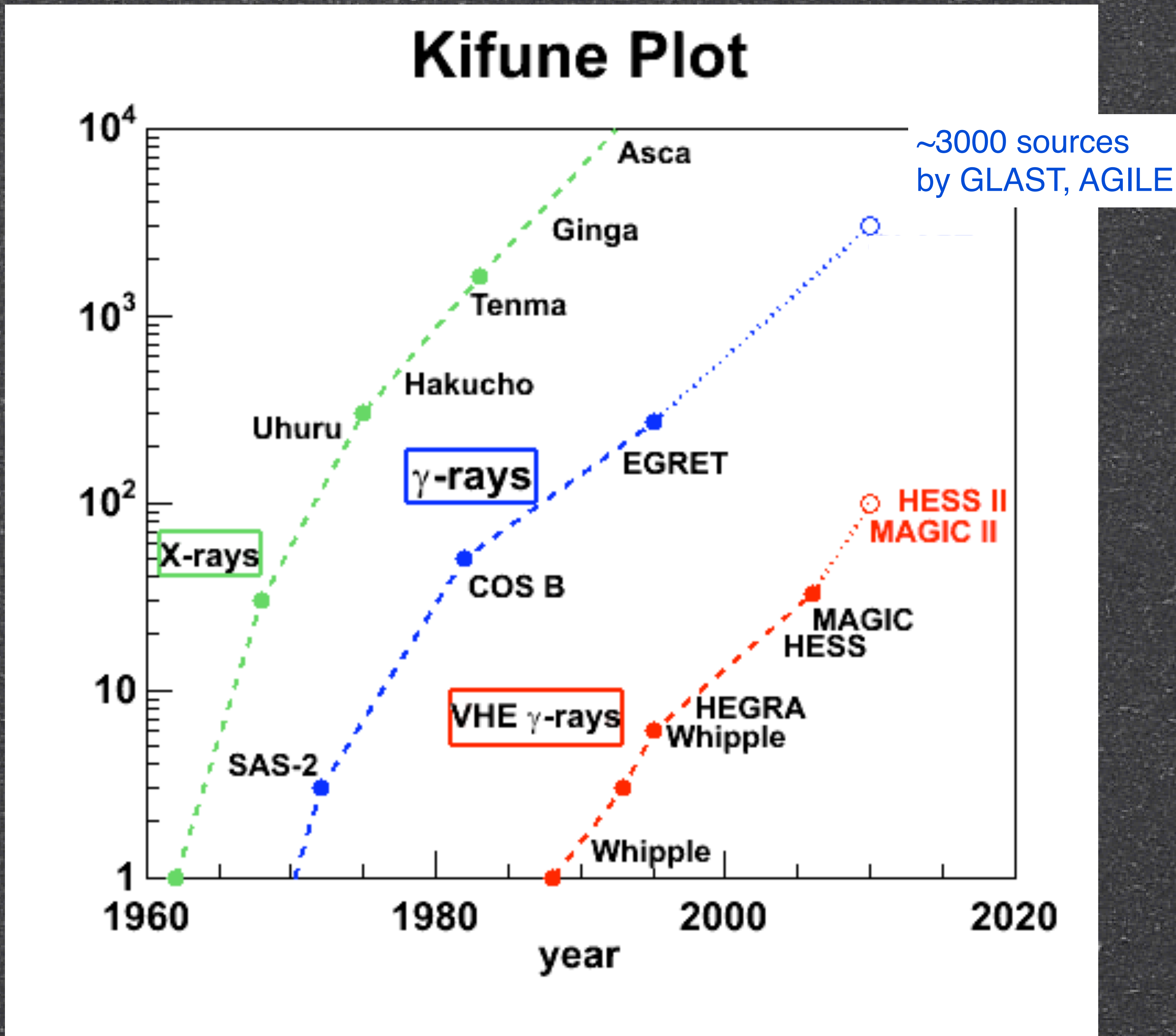
Cutoff regime of Galactic sources

A deep look at the TeV sky

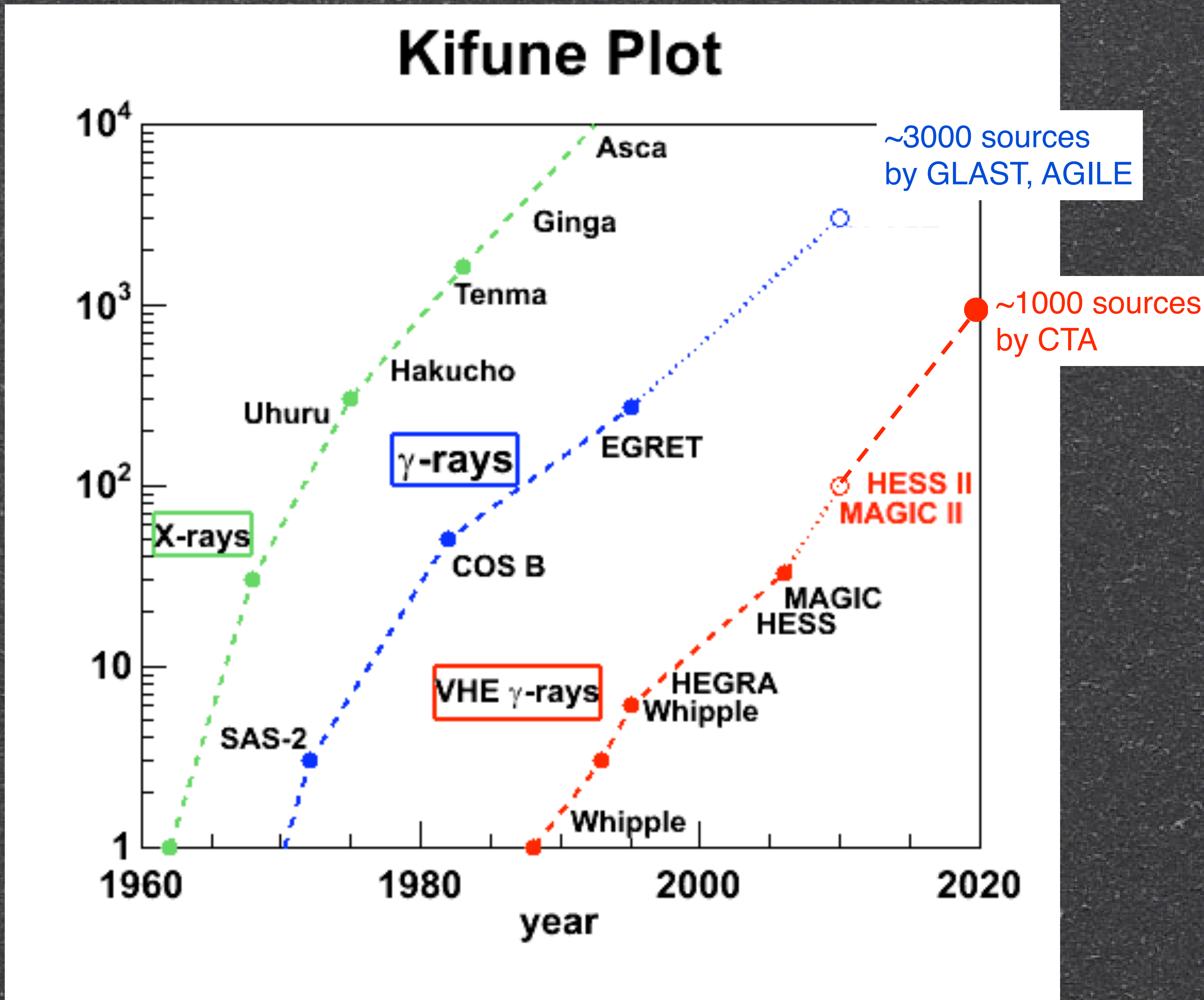


measure variable sources within short time scales

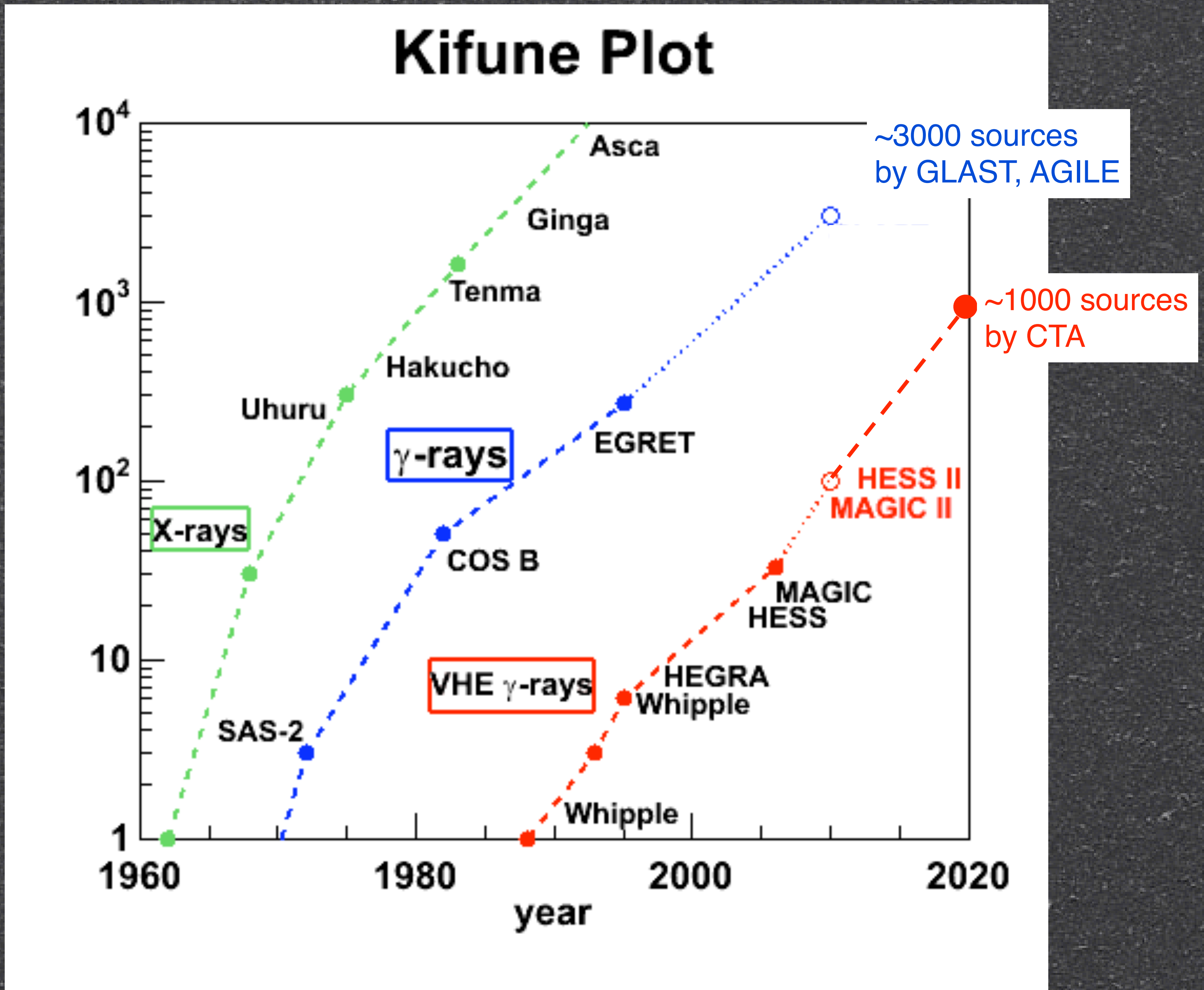
Number of Sources

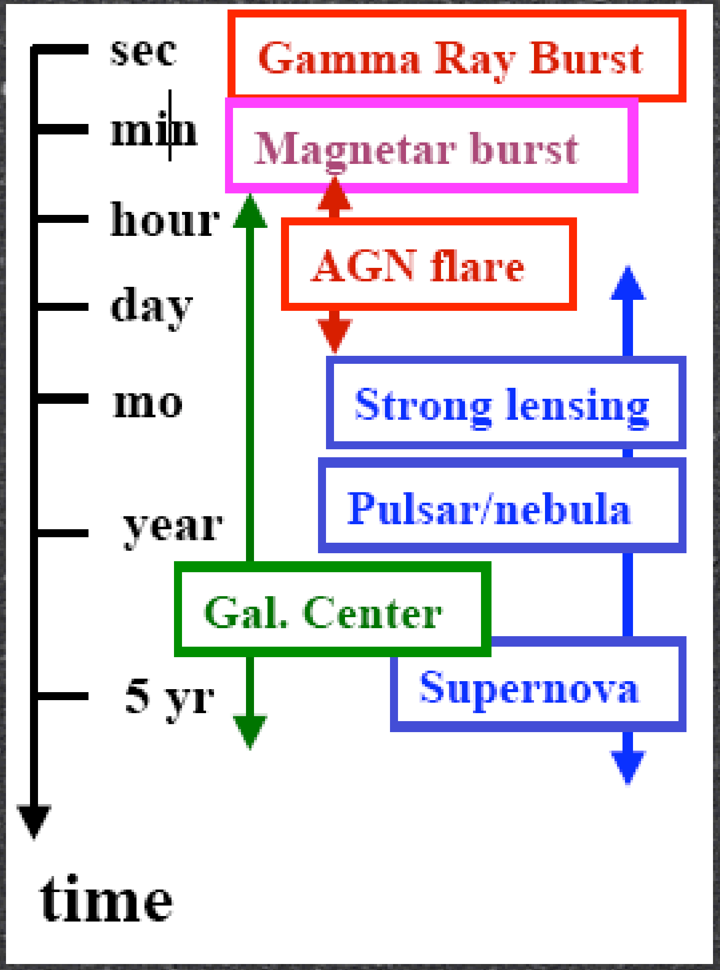


Number of Sources

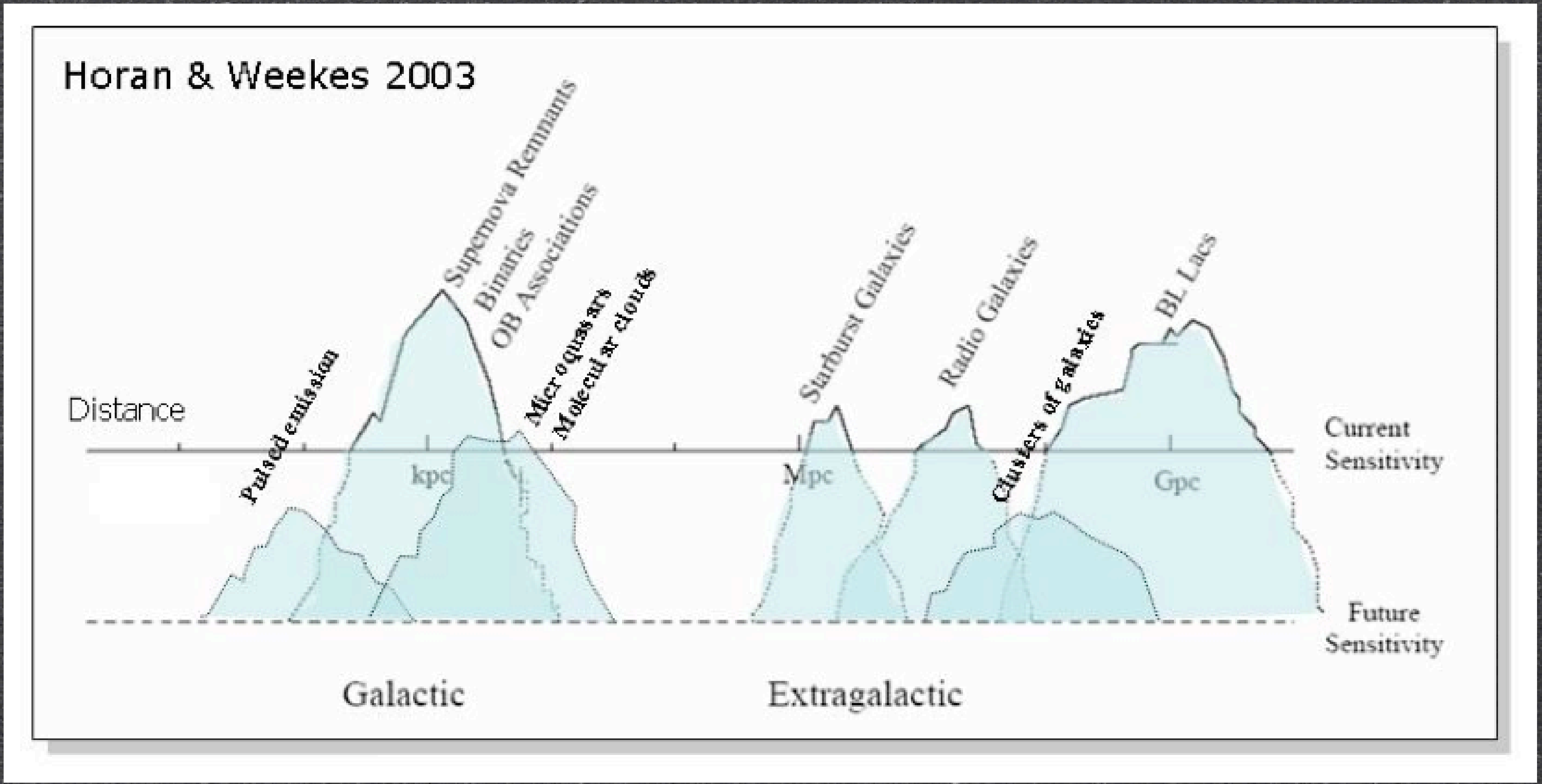


Number of Sources and shorter time-scales





Science Potential in Classes of Objects



European Initiative

- H.E.S.S. + MAGIC community ++
- Germany (MPI, universities and DESY), France, Spain, Italy, Switzerland, Poland...
- APpEC and ASPERA, ASTRONET
- Letter of Intent for a CTA consortium
- Memoranda of Understanding
- Japan plans to join CTA
- USA initiative AGIS

Project Schedule

- 2008-2011: R&D and prototyping
  - Layout studies, design
  - Prototypes of components
  - Prototypes of "standard" telescope
- 2012-2017: Construction
  - 2014: start of partial science operation

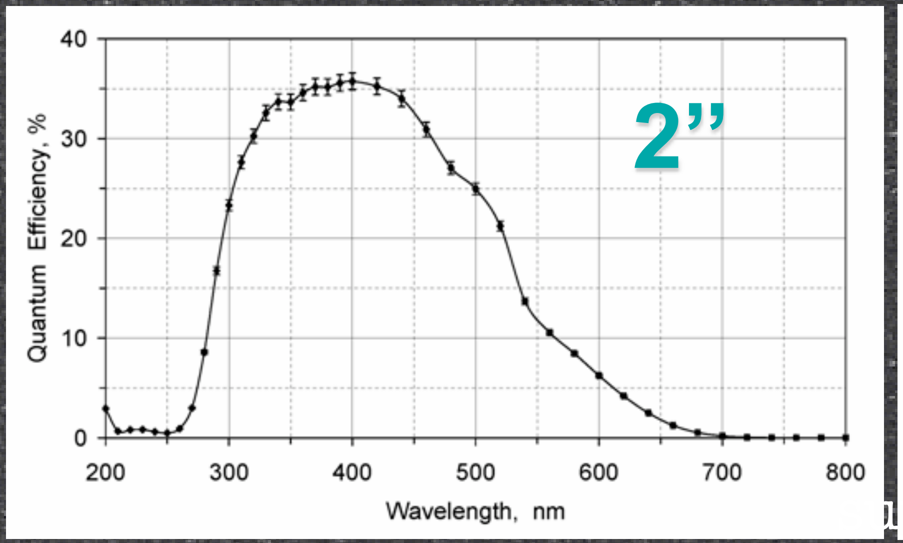
Base-line Design Criteria

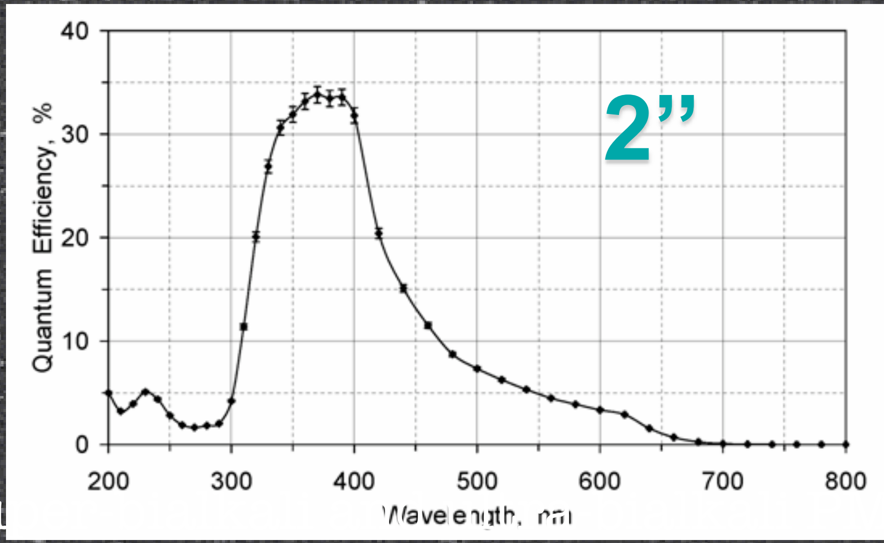
- Stereoscopic telescope system with $\gg$ 4 telescopes
- Alt-Az mount on rails
- Davies-Cotton for small dishes, parabola for large dishes
- Segmented mirror facets of $\sim$1-2.5 m^2 size
- F/D > 1
- Lifetime > 10 years
- Robust, simple, reliable system , robotic operation
- Safety: Human safety, protection of the instrument (Survival winds > 160 km/h), redundancy in power, drives, protection during ice, snow, low temperatures

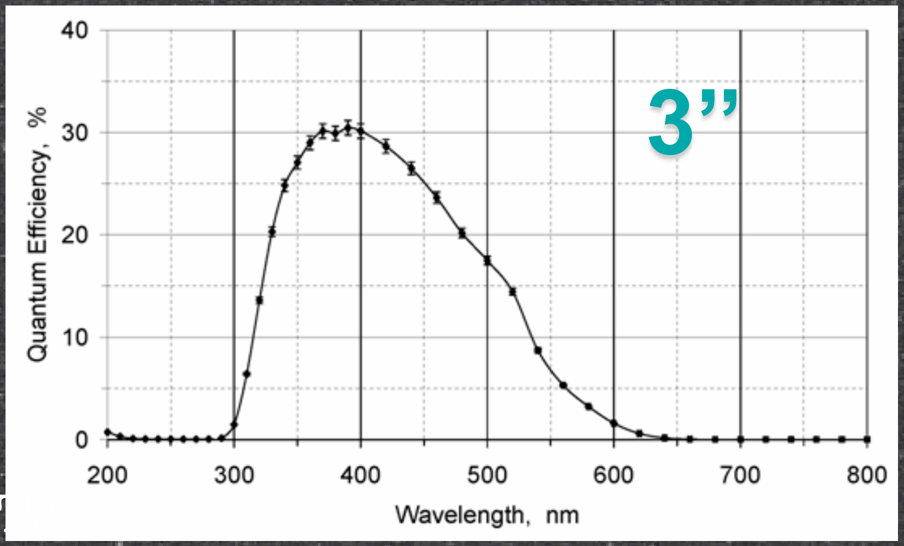
Baseline Camera: PMTs

- Improvements of classical PMTs

Tested by MPIK Munich







HAMAMATSU PHOTONIS electron tubes

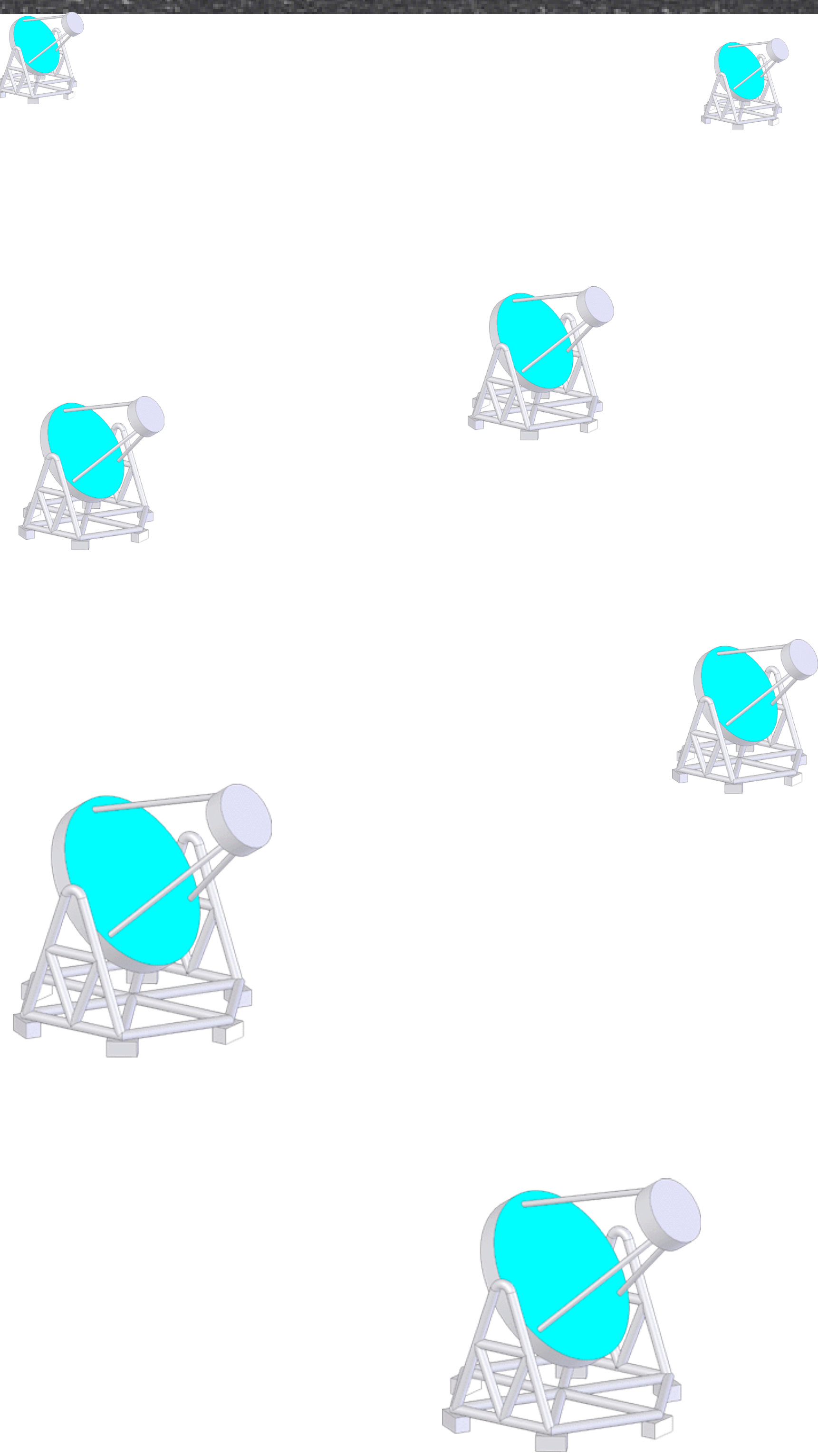
super-bialkali and ultra-bialkali PMTs

- Alternative light sensors
  - APDs, SiPMs, HPDs
  - performance, costs, open issues...

Prototype Phase

- Sensitivity and trigger studies
- Array Operation Center
- Drive and Control system

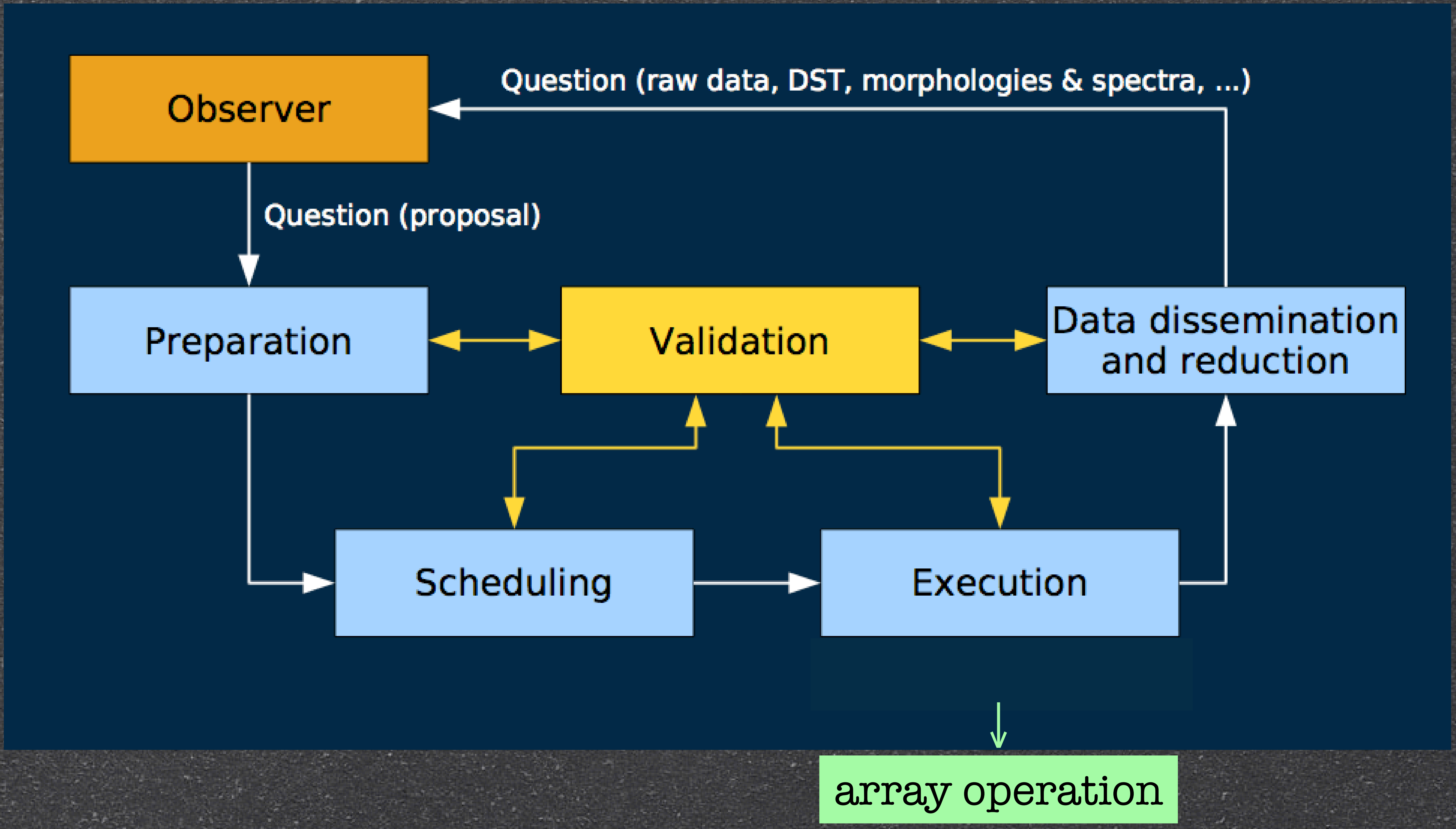
Array Layout Studies



- 2008: decide on # different telescopes, telescope size, field of view and pixel size range for each energy band, timing information
- 2008: provide ≥ one array layout/design that meets the project budget
- 2009: optimize the layout in detail with fixed parameters

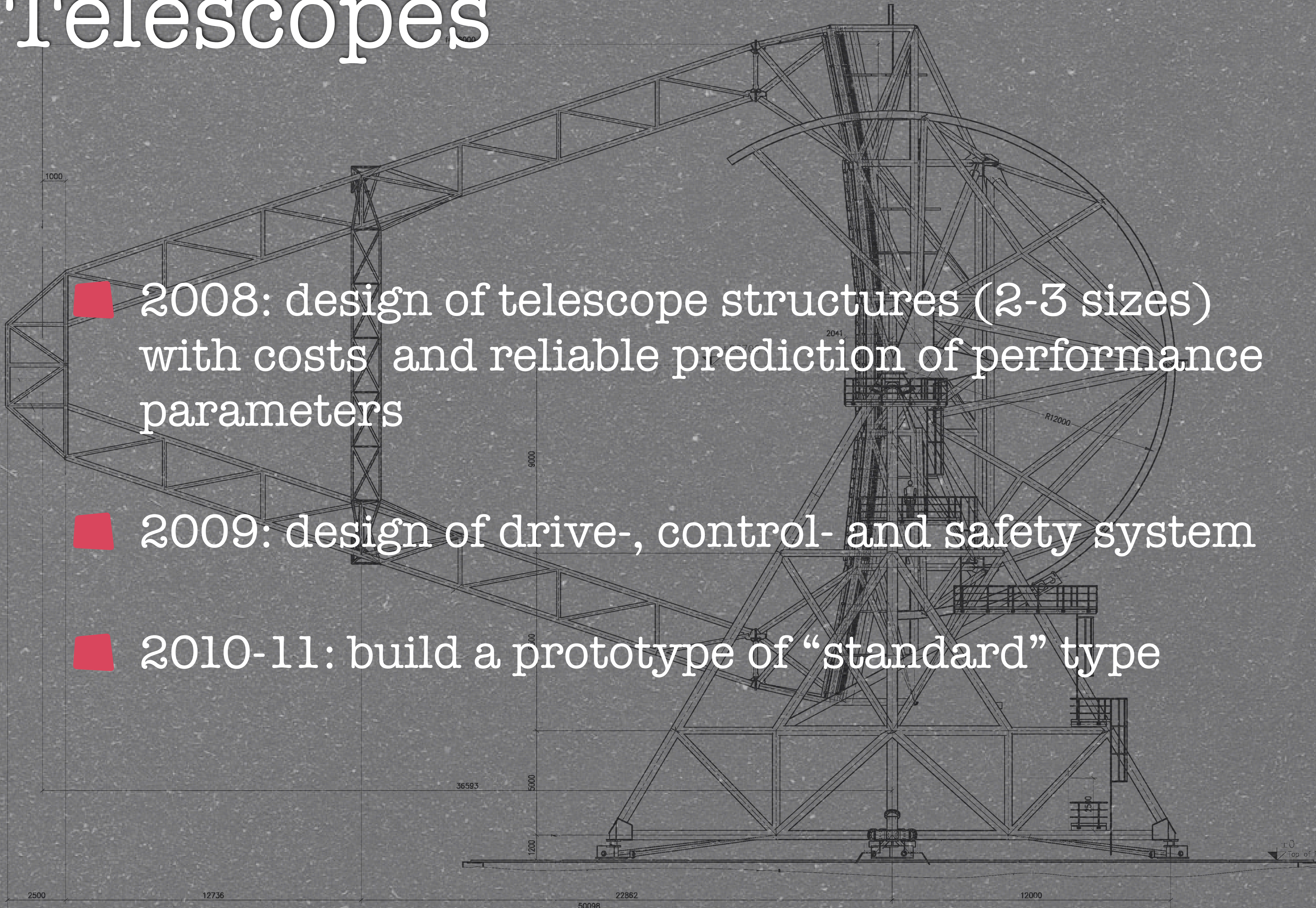
Array Operation Center

Array Operation Center



prototype for telescope prototype operation

Telescopes

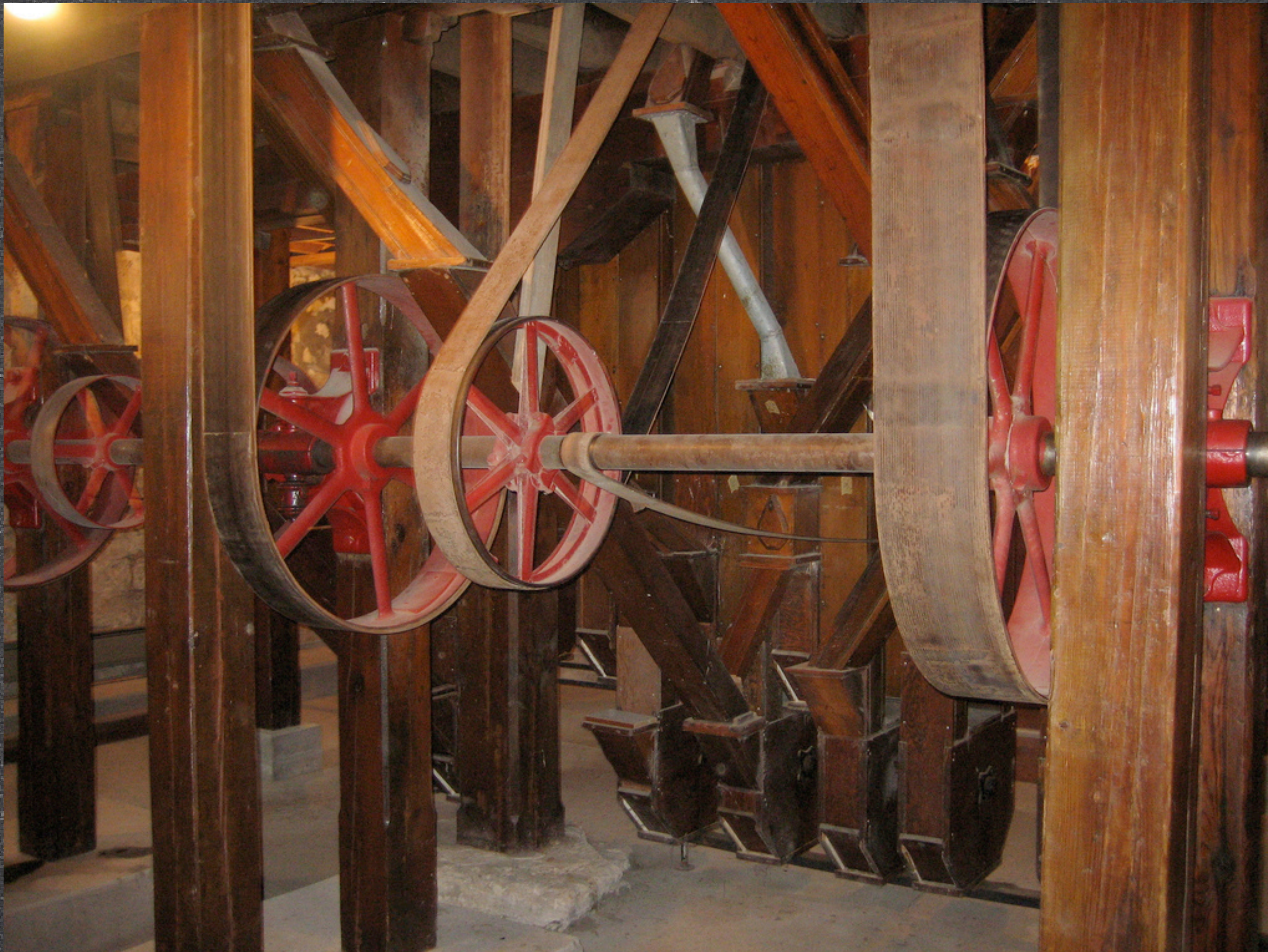


- 2008: design of telescope structures (2-3 sizes) with costs and reliable prediction of performance parameters

- 2009: design of drive-, control- and safety system

- 2010-11: build a prototype of “standard” type

Drive System



Safety System

Drive and Safety System

- Motors
- Feedbacks
- Gears
- End switches
- Emergency system

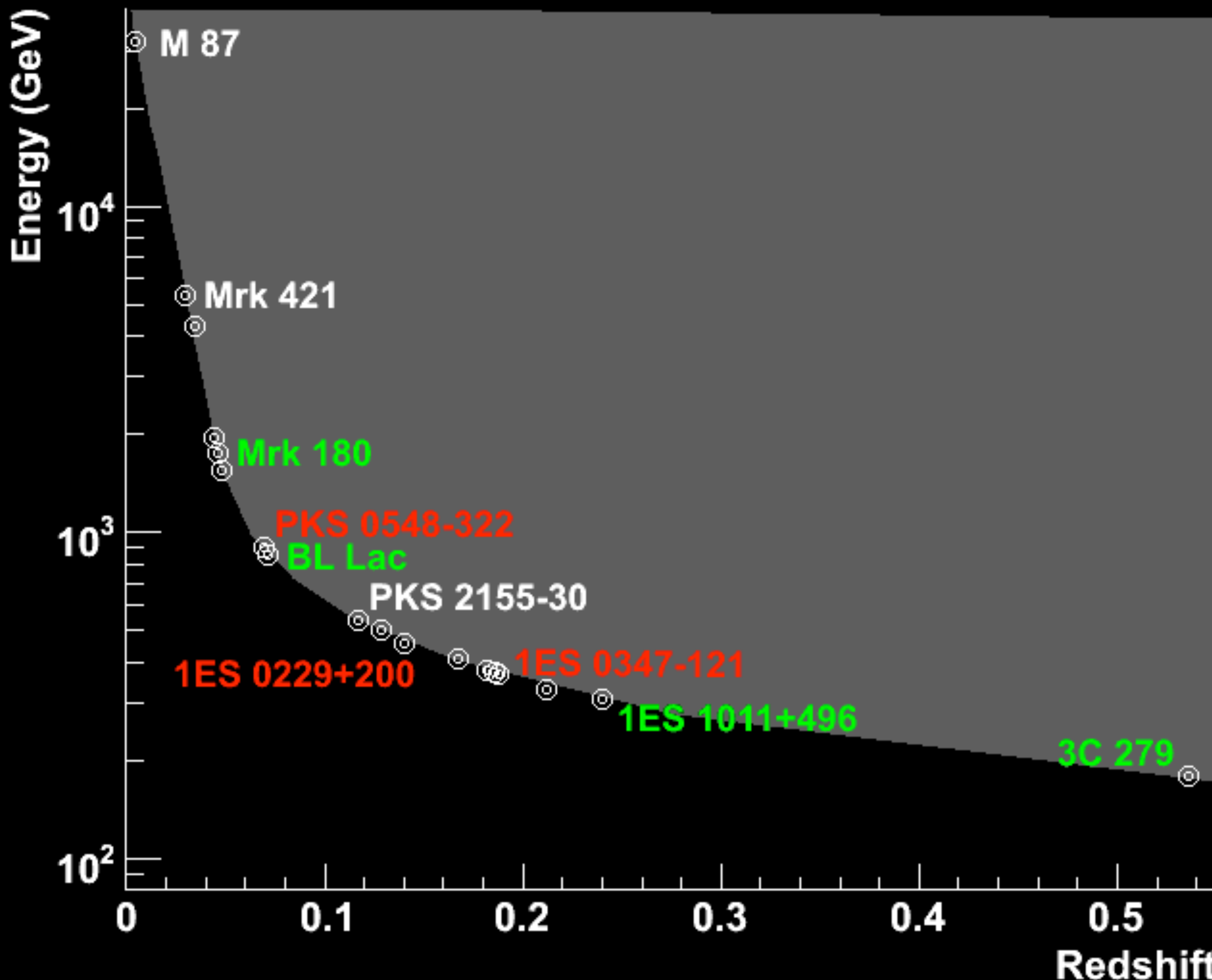
robotic operation

- R&D and prototyping: ~10 M€
- Construction of an array
  - South ~100 M€
  - North ~50 M€

Astro-Physics Program

- ν-physics with IceCube
  - Construction
  - Search for point sources and non-resolved flux, GRBs, Supernovae
  - Search for WIMPs, monopoles, ...
- γ-ray physics with CTA
  - Physics Program
  - Observatory

The Gamma Ray Horizon



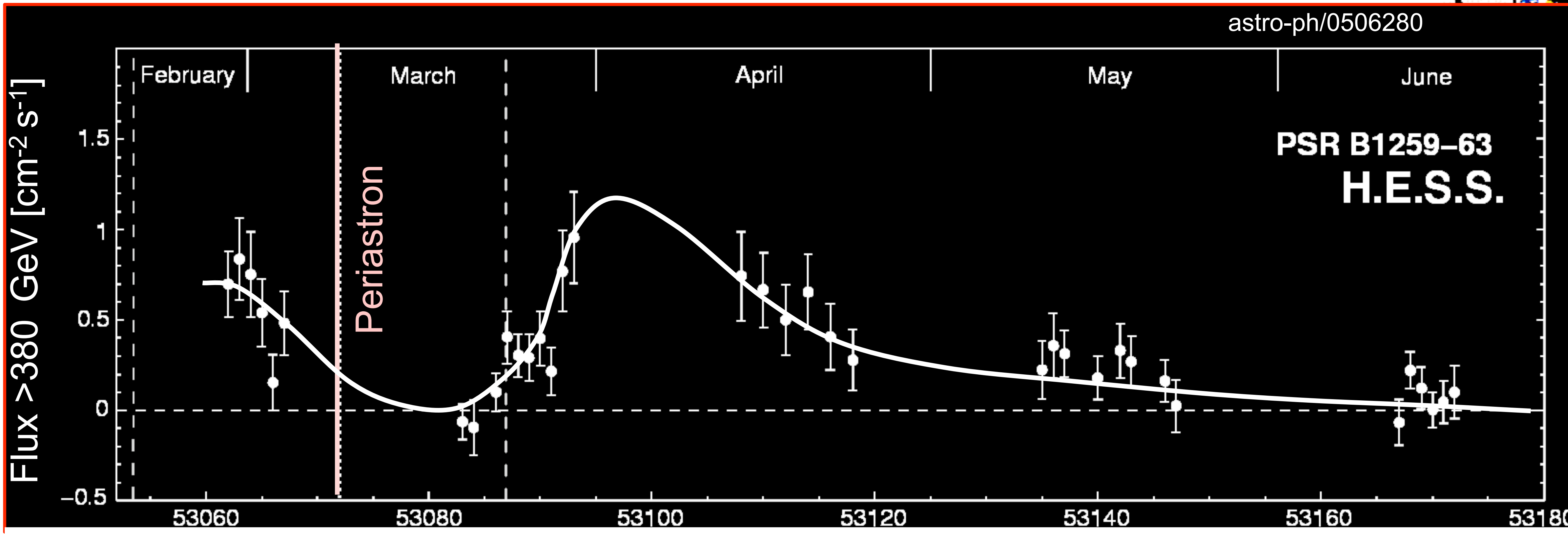
Hinton, ICRC 2007

Energy threshold of 100 GeV allows to detect high luminosity sources up to $z \approx 1$

Project Challenges

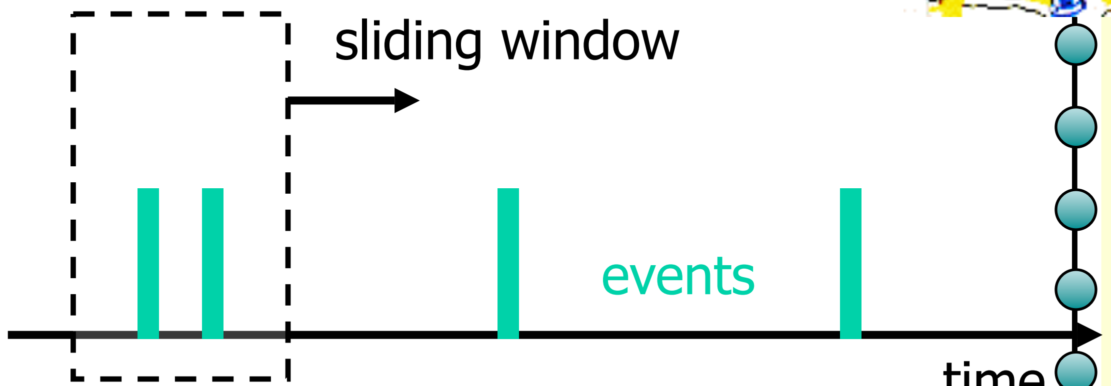
- Agreement on array layout
- Cost and funding
- Reliability
- Coordination
- Production
- Organization as observatory

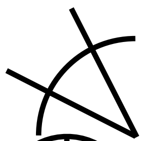
Search for Neutrino Flares

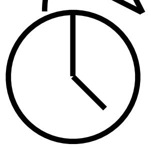


Search for Neutrino Flares

Excess in time-sliding windows?



 = 2.25°-3.75°

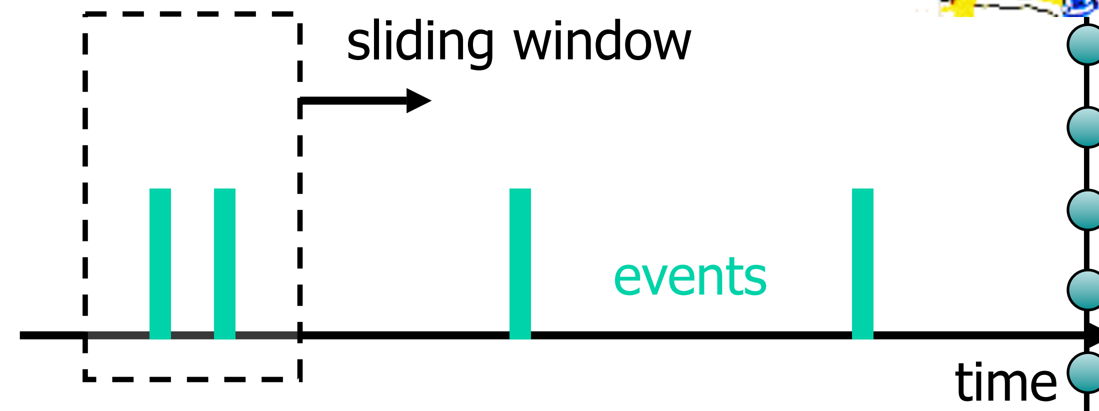
 = 40/20 days for extra-galactic/ galactic objects

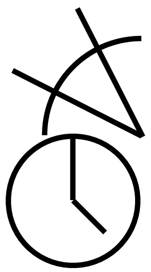
Preliminary

… out of **12** Sources: No statistical significant effect observed

Search for Neutrino Flares

Excess in time-sliding windows?





= 2.25°-3.75°

= 40/20 days for extra-galactic/ galactic objects

Preliminary

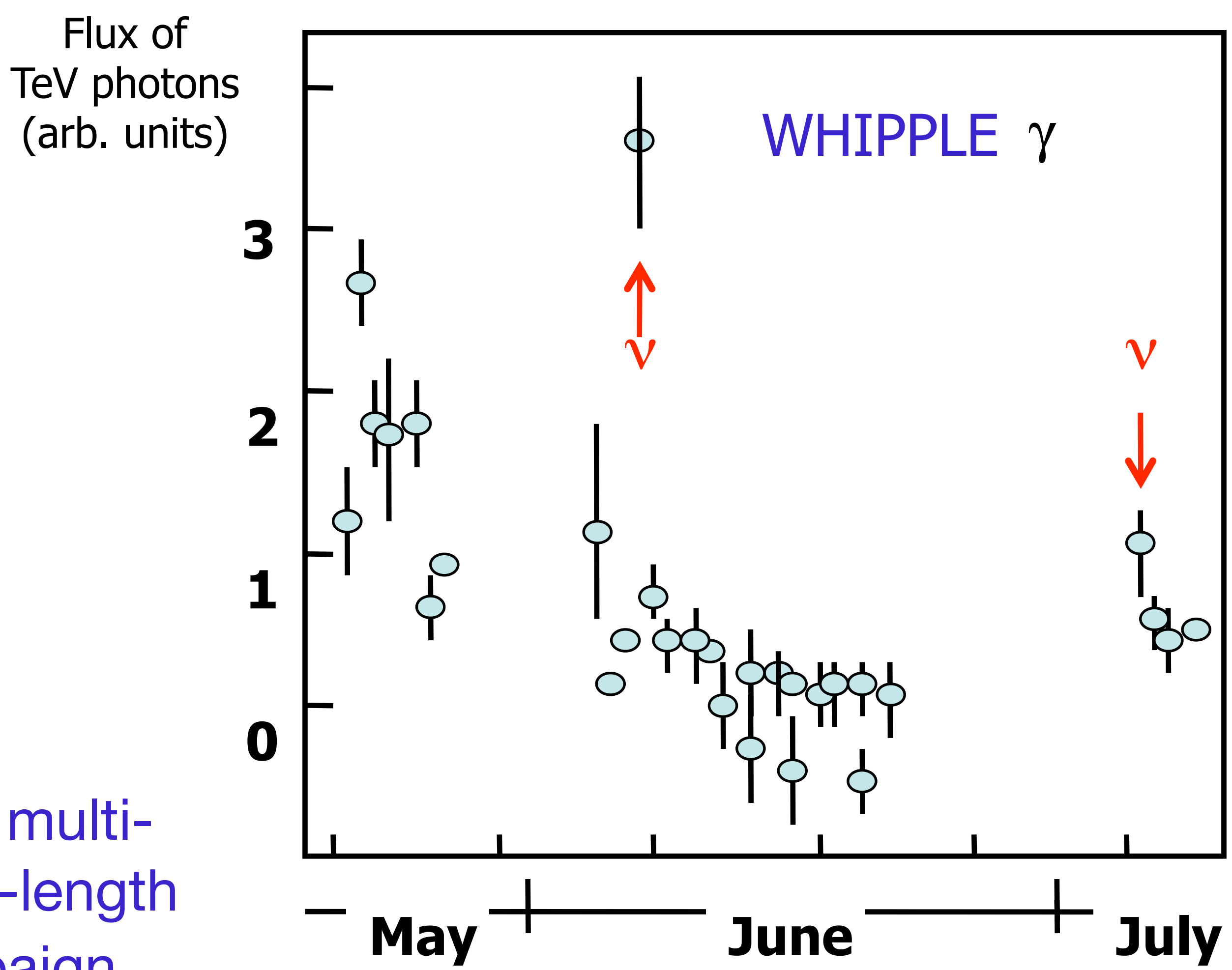
Source	Nr. of ν events (4 years)	Expected backgr. (4 years)	Period duration	Nr. of doublets	Probability for highest multiplicity
Markarian 421	6	5.58	40 days	0	Close to 1
1ES1959+650	5	3.71	40 days	1	0.34
3EG J1227+4302	6	4.37	40 days	1	0.43
QSO 0235+164	6	5.04	40 days	1	0.52
Cygnus X-3	6	5.04	20 days	0	Close to 1
GRS 1915+105	6	4.76	20 days	1	0.32
GRO J0422+32	5	5.12	20 days	0	Close to 1

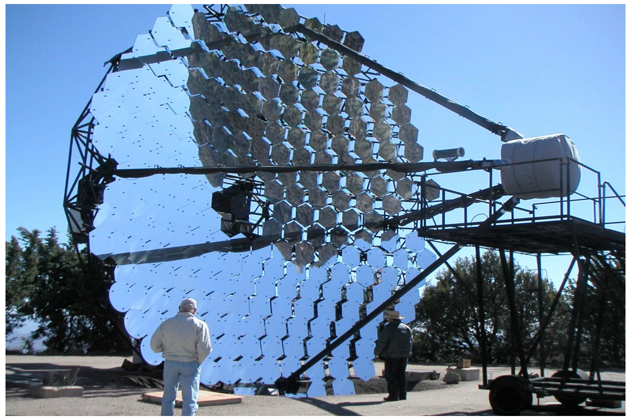
… out of **12** Sources: No statistical significant effect observed

Neutrinos and 1ES1959

A posteriori search: three events in 66 days in a period of major outburst – “the orphan flare” (TeV– but no X-ray signal)

2002 multi-wave-length campaign





– one event is within a few hours of the orphan flare

– a blazar with γ-ray flare without X-ray counterpart: some interpret this as hadronic acivity in the blazar jet

not statistically significant – but interesting observation

⇛ lead to a modified search strategy and a close collaboration with the γ-ray community

Beyond km³ Volumes

- At best a few ten astrophysical neutrino per year and km³ – IceCube or Auger can detect ~one GZK neutrino per year
- ~EeV neutrinos, particularly GZK neutrinos, will be a valuable source for astro- and particle physics
- 10-100 GZK events would give a quantitative measurement will allow tests of cosmic ray production models and new physics
- Many projects (e.g. Rice, ANITA, SalSA, Glue, Lofar, acoustics…) are actively seeking this goal
- IceCube: if acoustic and radio ice properties are measured to be as good as predicted

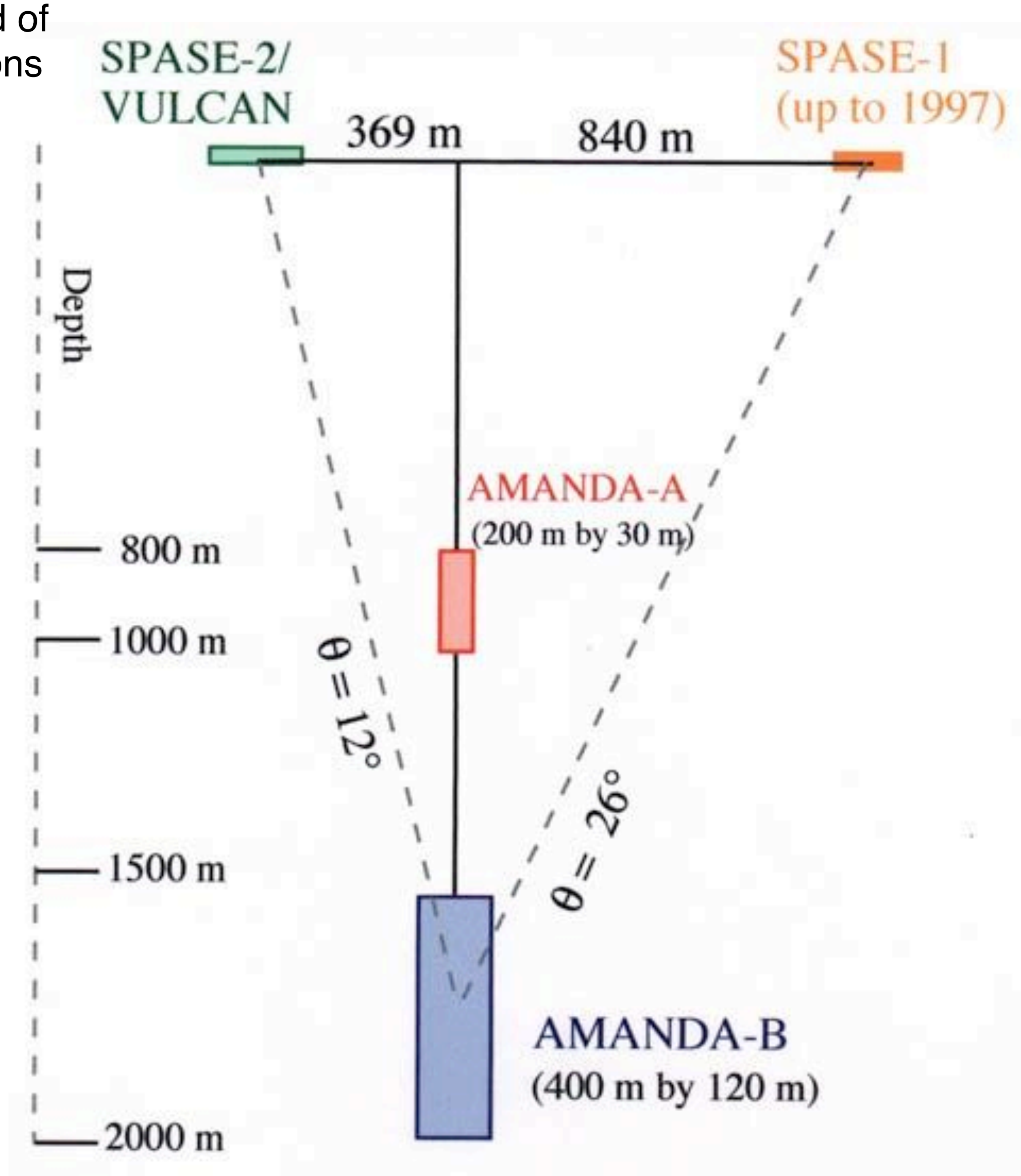
properties of ice	optical	radio	acoustic
absorption [km]	0.1	1	~10 ?
energy threshold [eV]	$\sim 10^{9}$	$\sim 10^{15}$	$\sim 10^{18}$

- proceed from a South Pole acoustic and radio test set-up to a hybrid detector (IceCube + Acoustic + Radio) EeV Neutrino Array

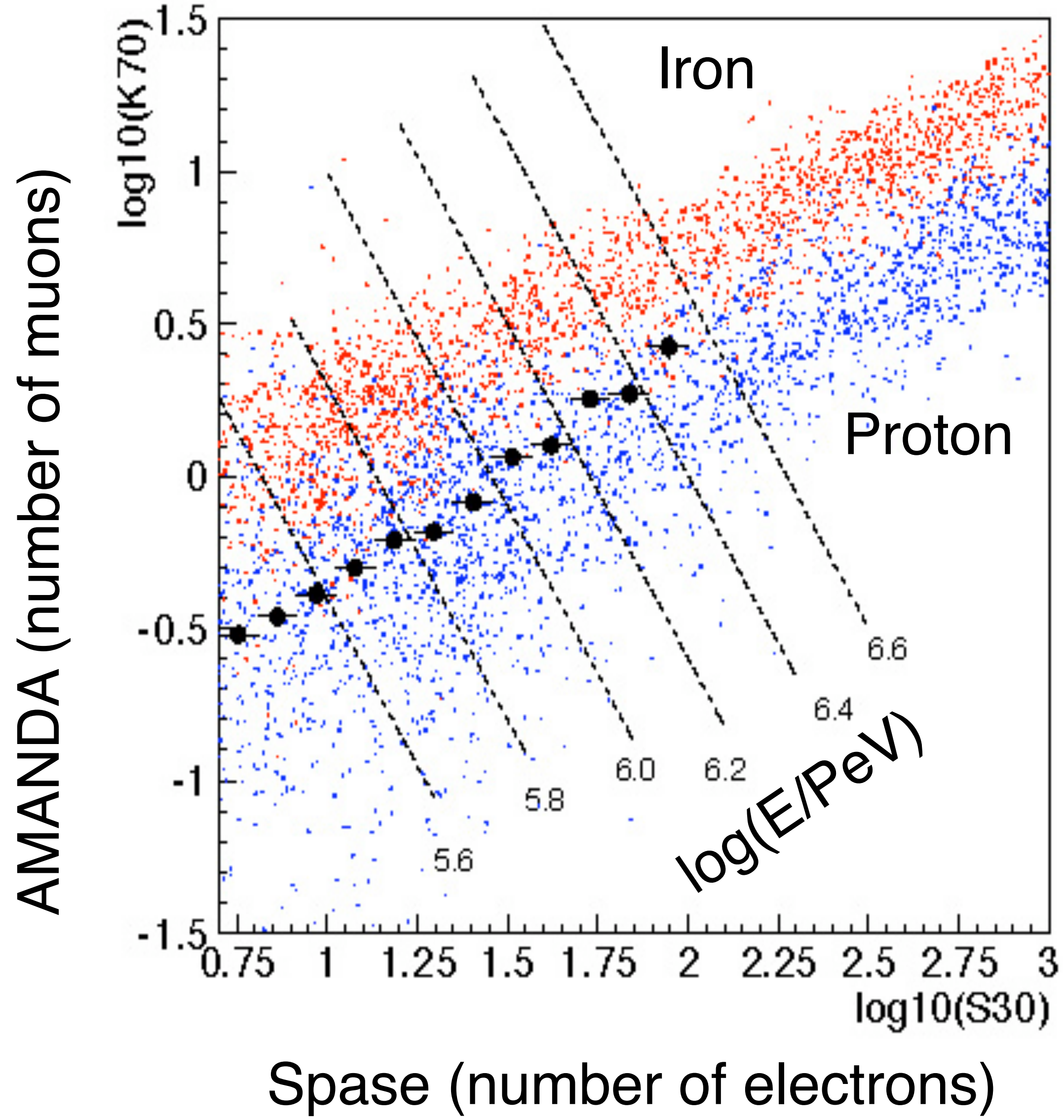
Cosmic Ray Composition

What is the matter that comes from the cosmos made of?

30m grid of 30 stations

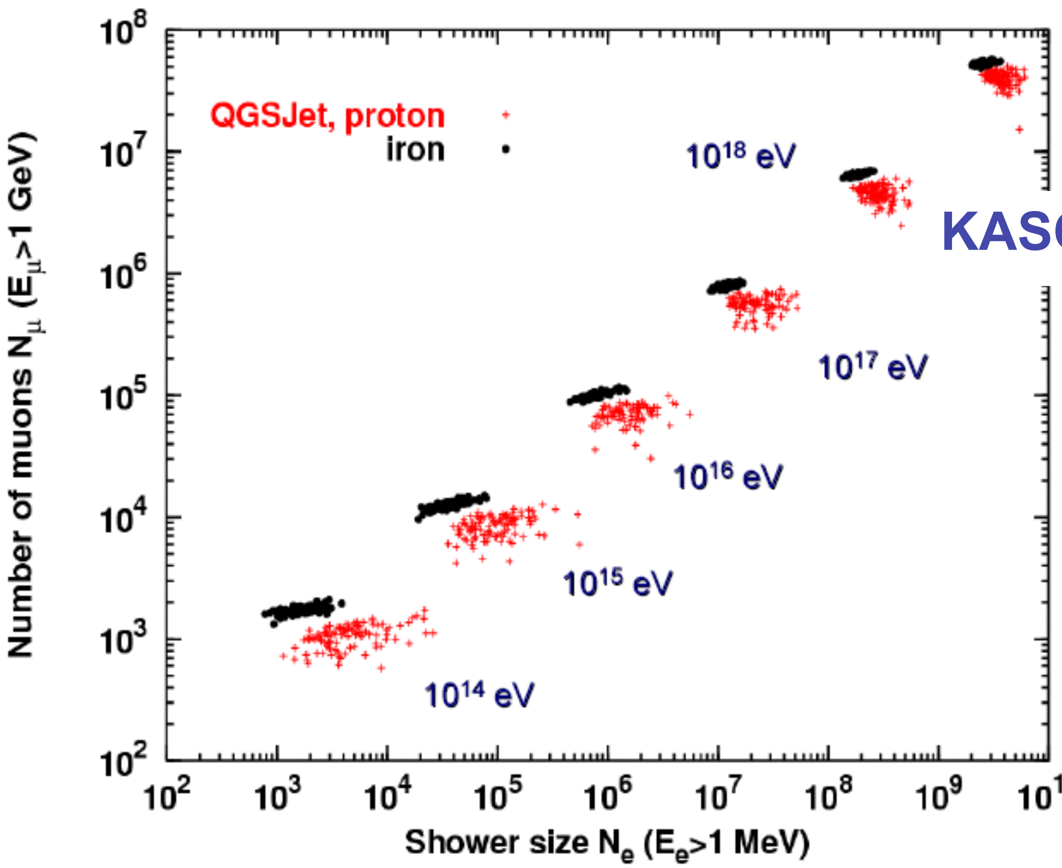


Unique combination with SPASE-2



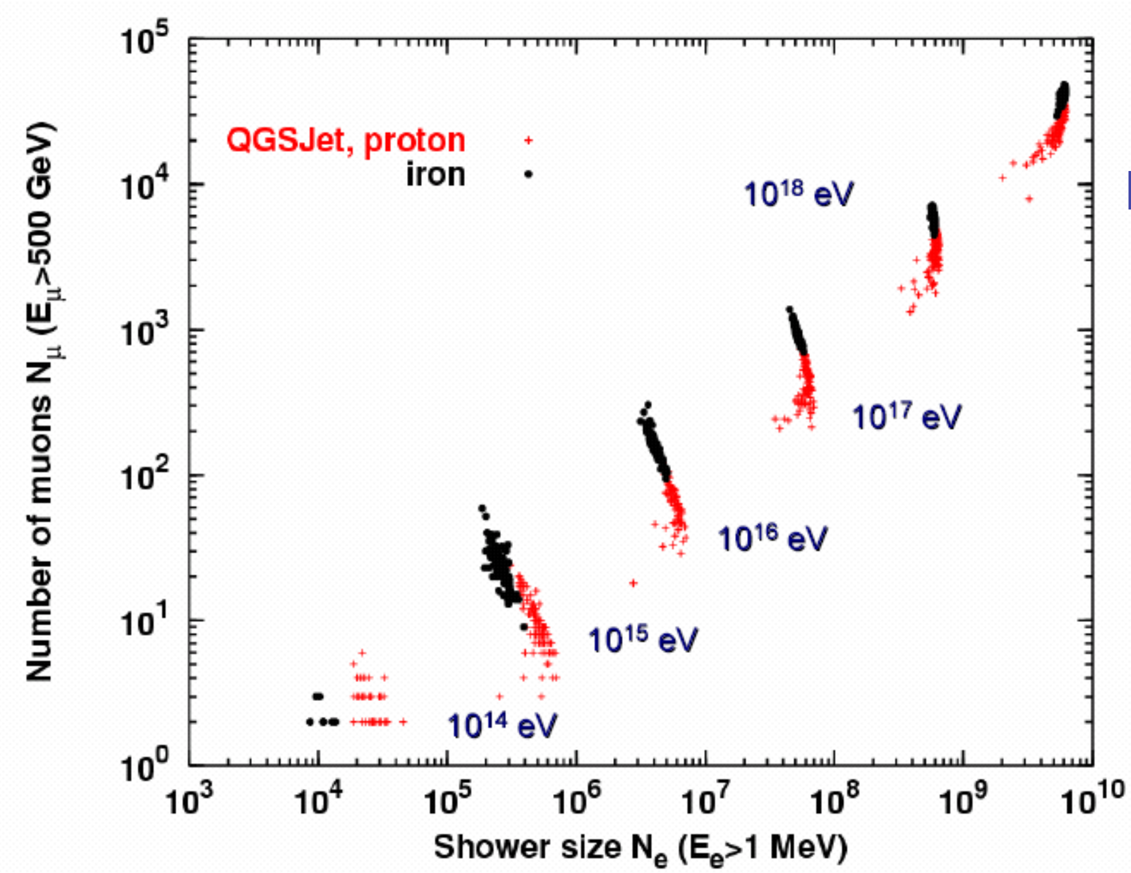
μ/e Ratio reflects CR Composition

Calculations of Ralph Engel,
presented at Aspen, April 2005



KASCADE-Grande

- Sea level
- Low-energy muons



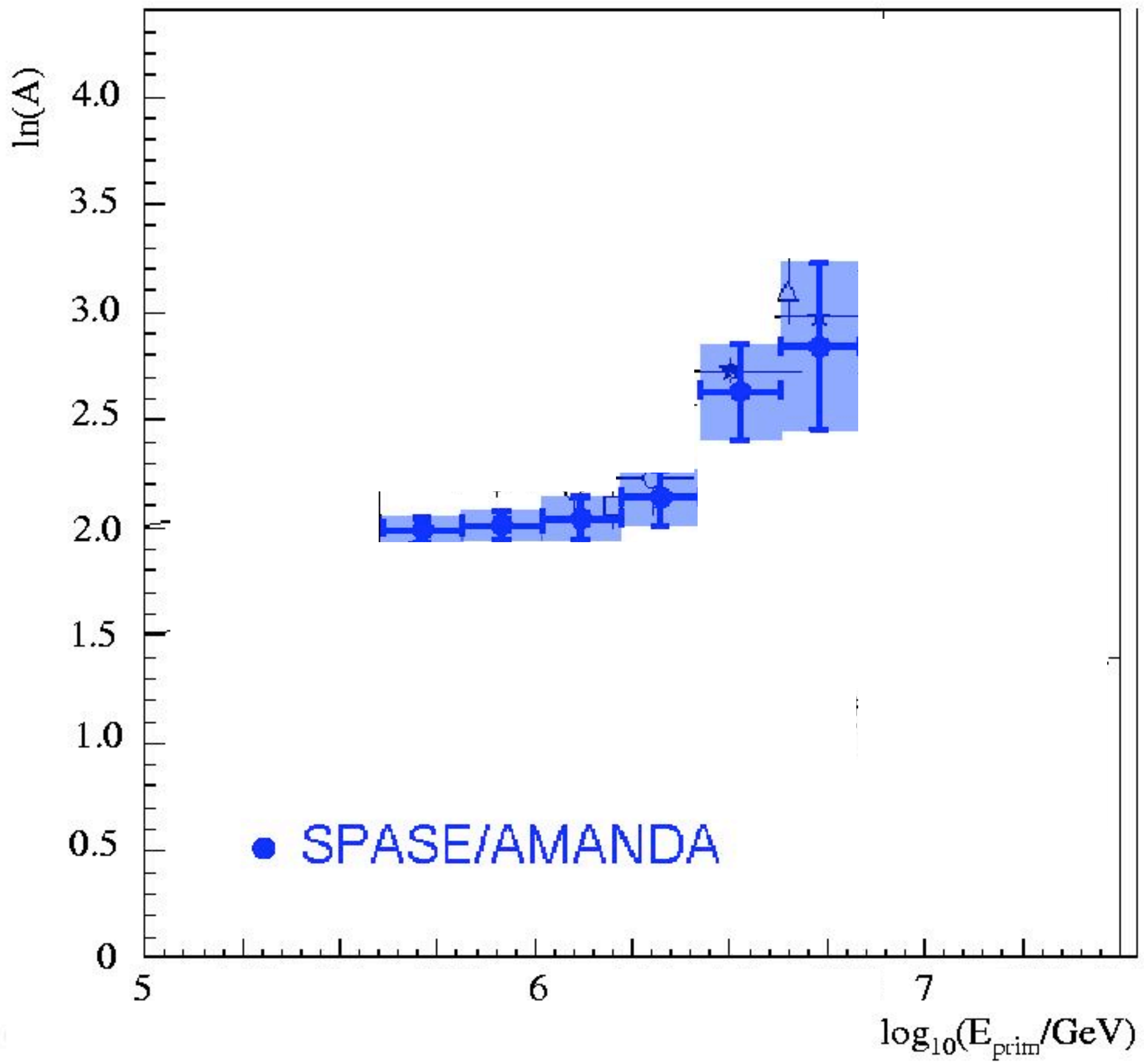
IceCube

- Mountain altitude
- High-energy muons
- Single model

Cosmic Ray Composition

– resolution ~7% in $E_{primary}$
– mean ln(A) normalized to direct measurements (normalization bin not shown)

Cosmic ray spectrum becomes heavier around the knee



1998 data set

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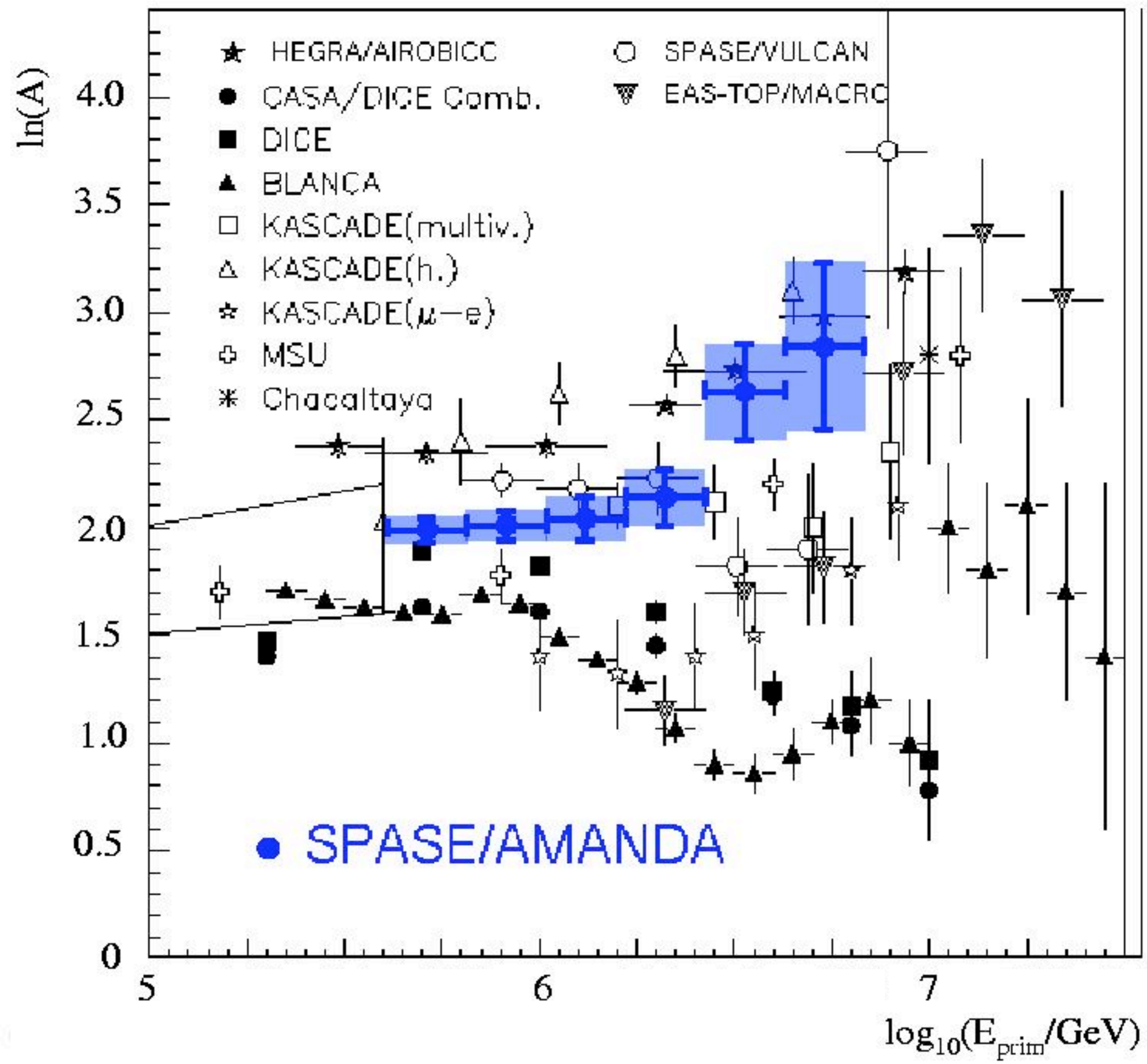
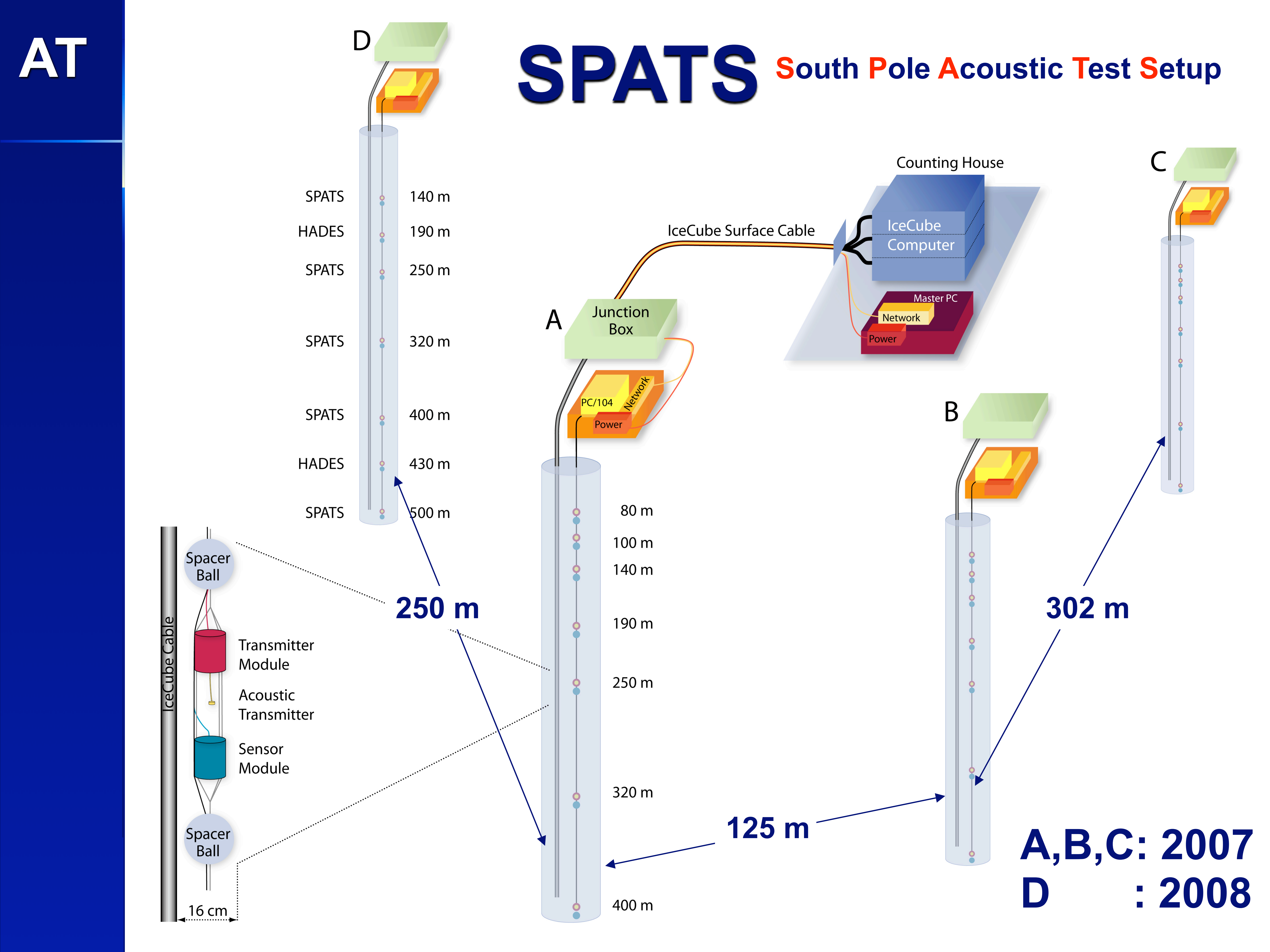


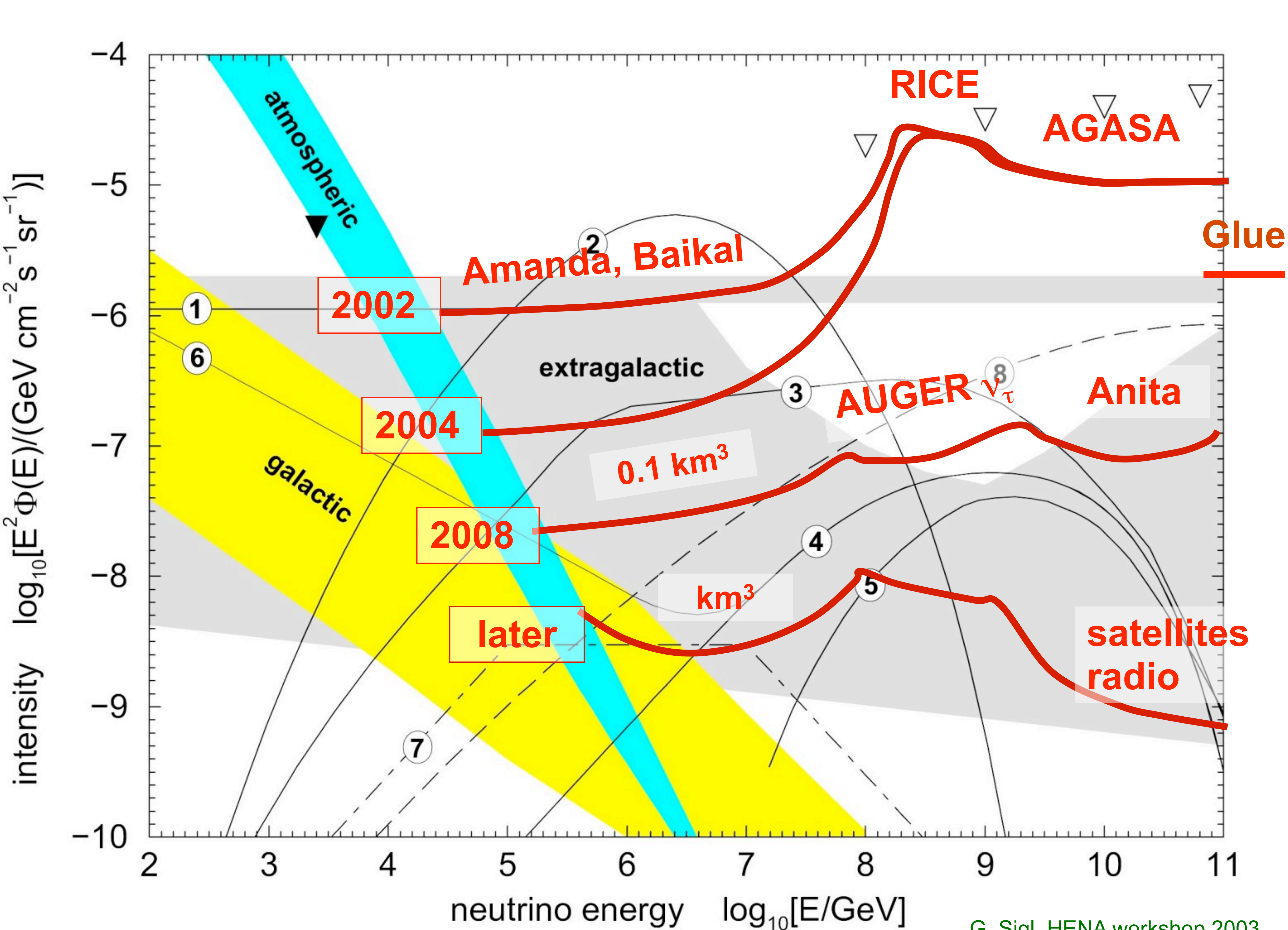
1998 data set

SPATS South Pole Acoustic Test Setup



A,B,C: 2007
D : 2008

Diffuse Searches now and in the Future



G. Sigl, HENA workshop 2003

Supernova system