The High-Energy Universe: Cosmic Rays, Gamma Rays, Neutrinos

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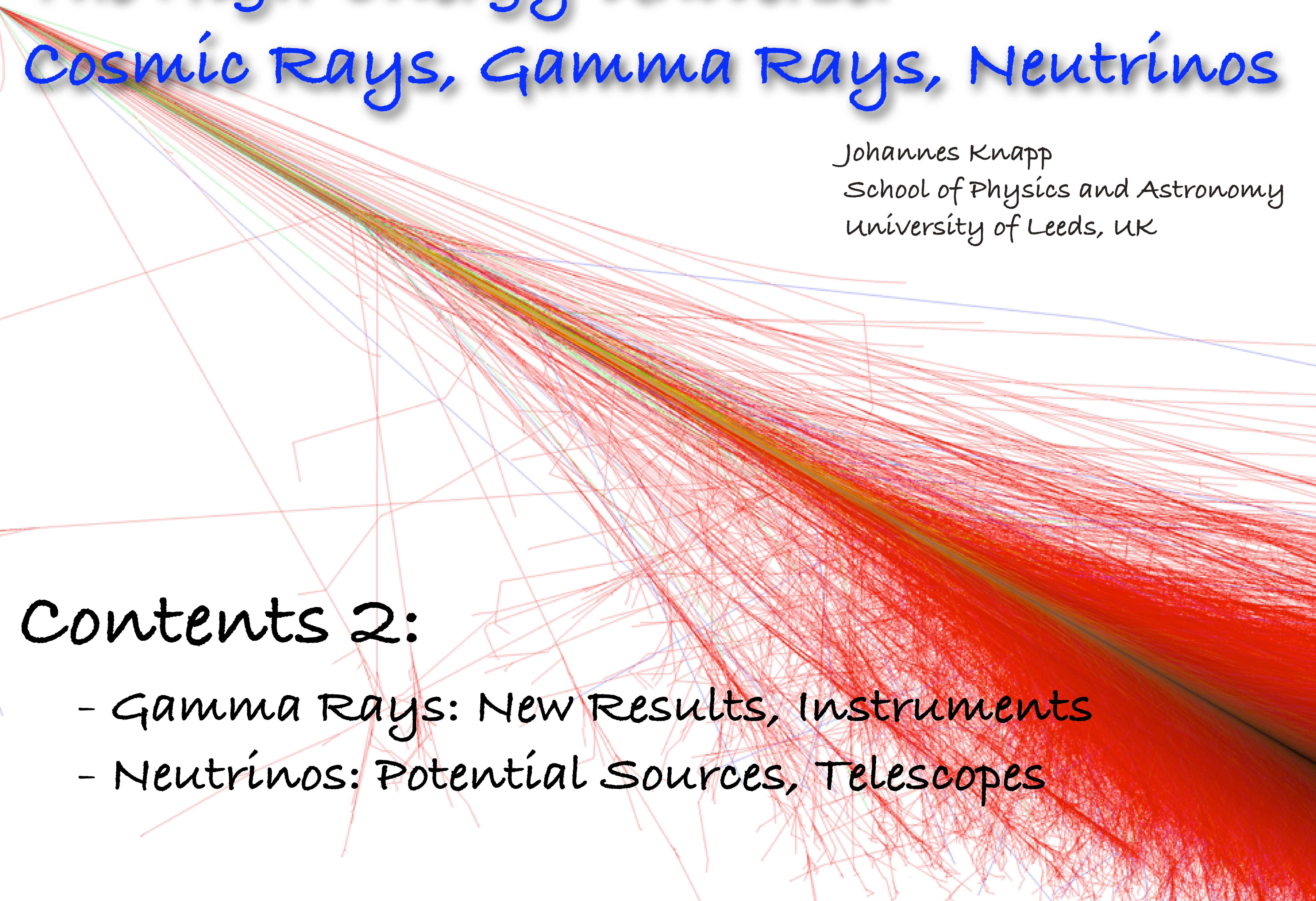


Contents 2:

- Gamma Rays: New Results, Instruments
- Neutrinos: Potential Sources, Telescopes

Cosmic Rays, Gamma Rays and Neutrinos are linked

$$\text{p, He, ... Fe} \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

$$\text{p, He, ... Fe} \rightarrow \pi^{0} \rightarrow \gamma\gamma$$

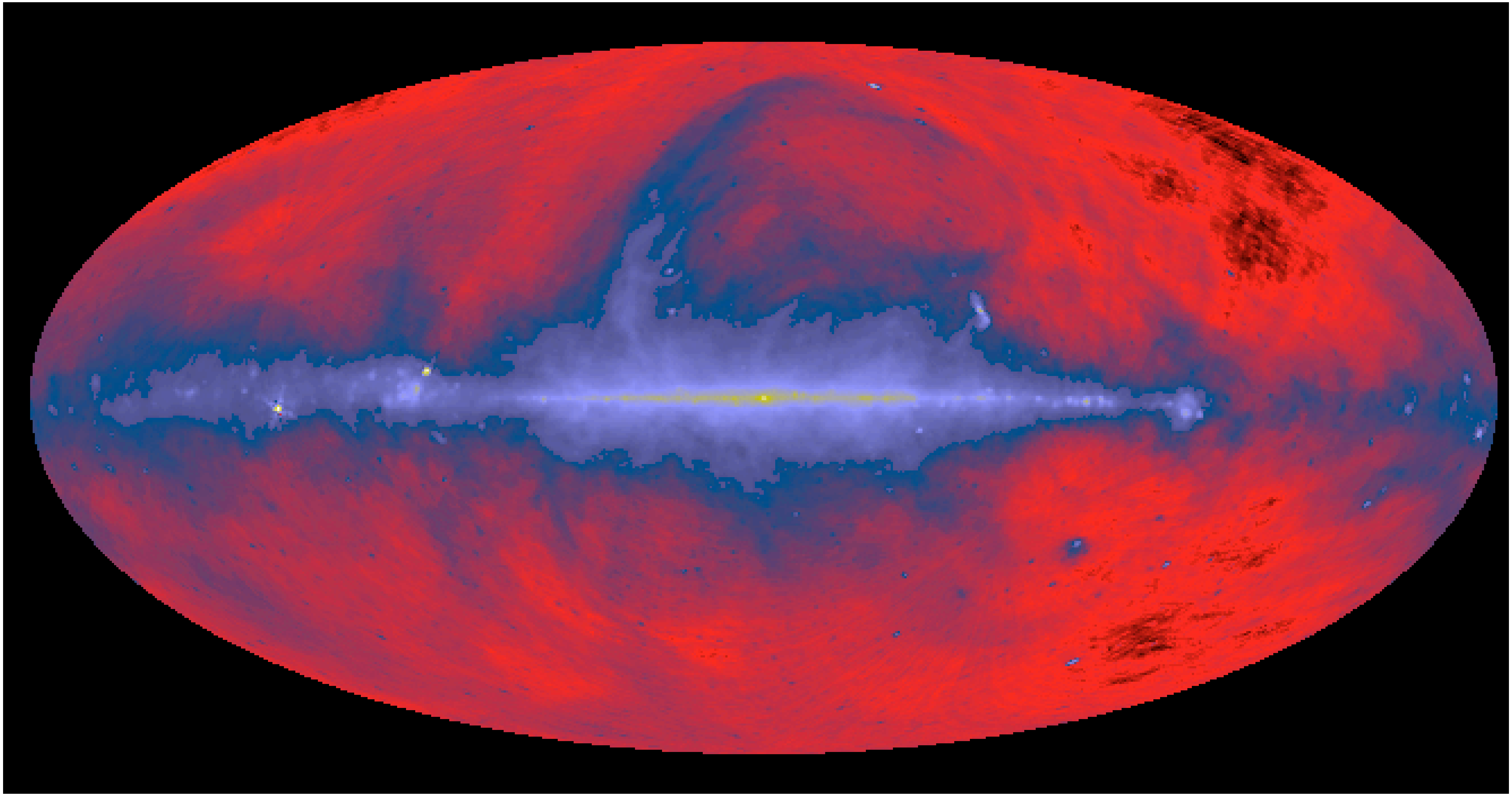
only charged particles can be accelerated by el.mag. fields

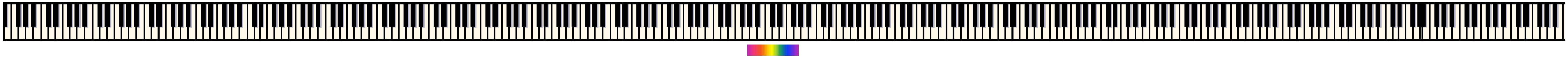
very difficult to detect

γ and ν travel in straight lines, i.e. point back at source.

... very successful in other branches of astronomy radio infrared visible X-ray gamma ray

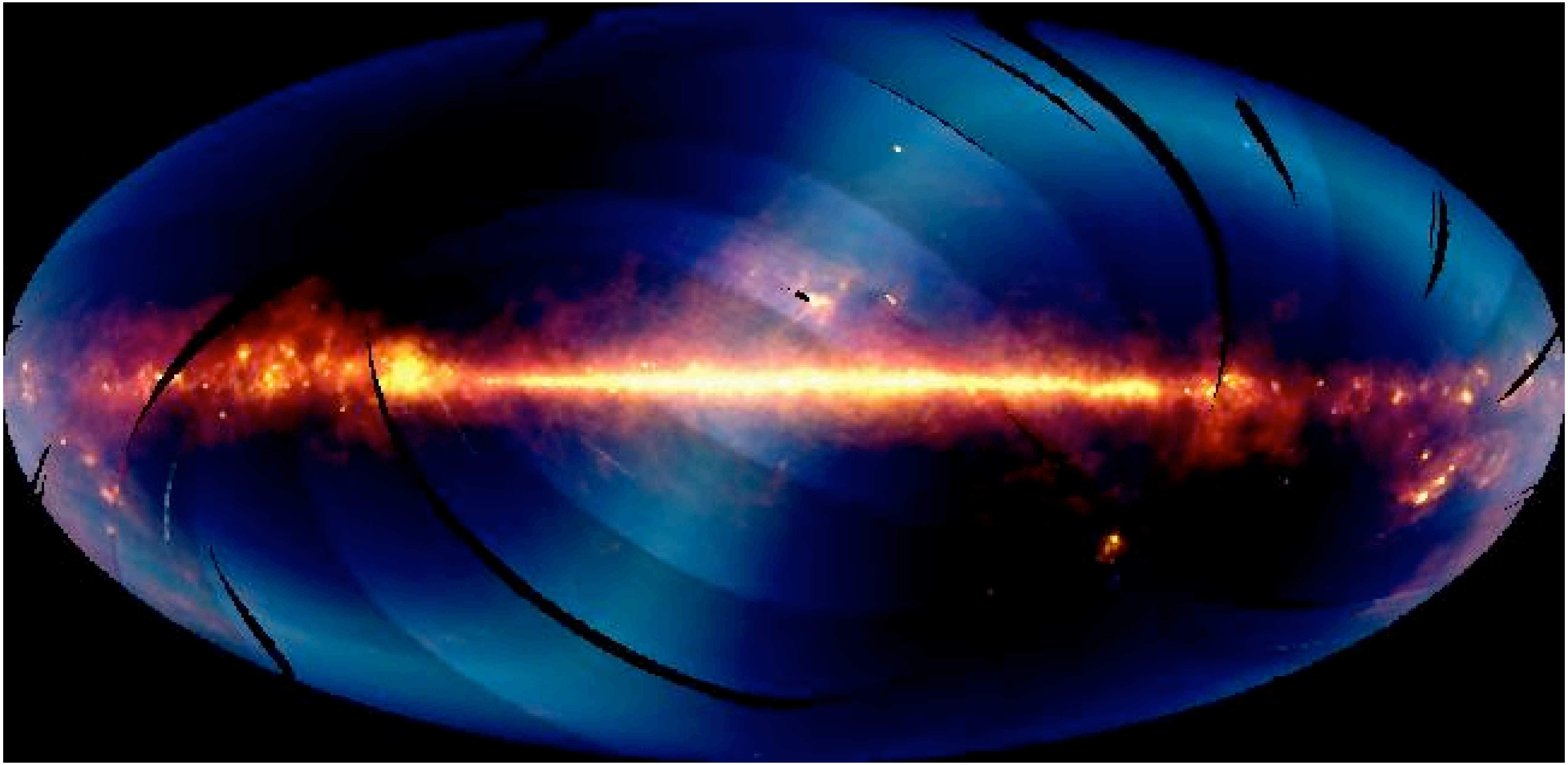
10^{-6} eV

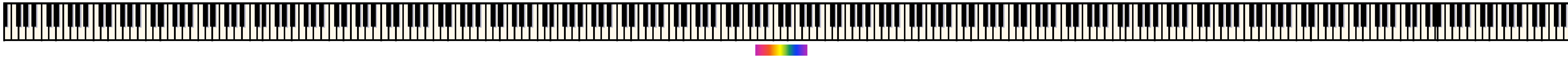


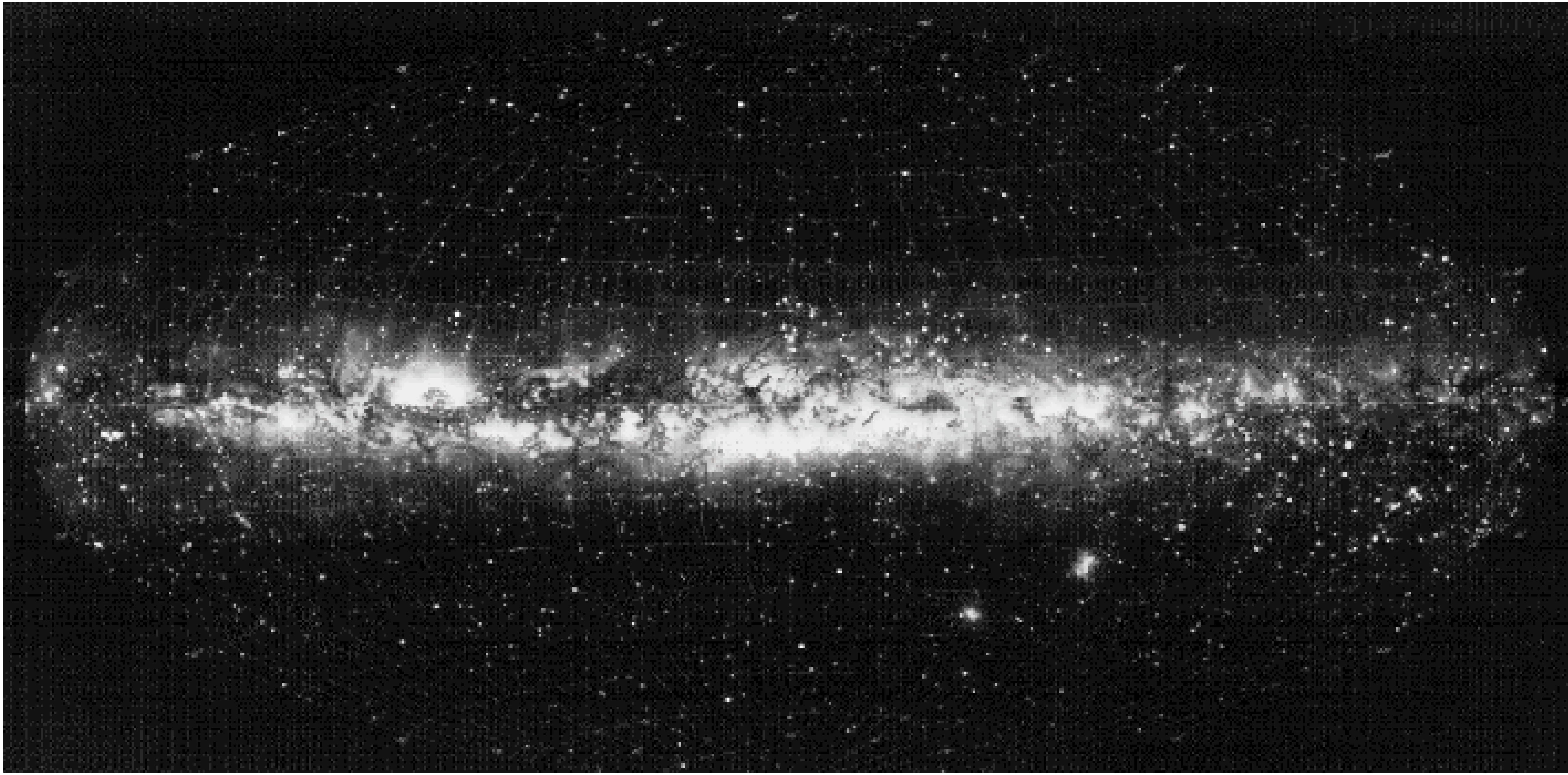


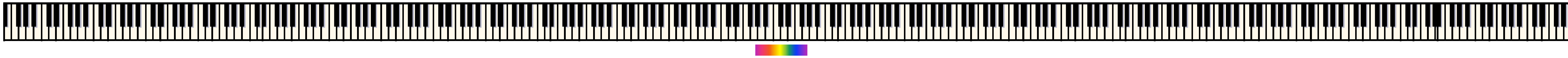
radio infrared visible X-ray gamma ray

10^-2 eV



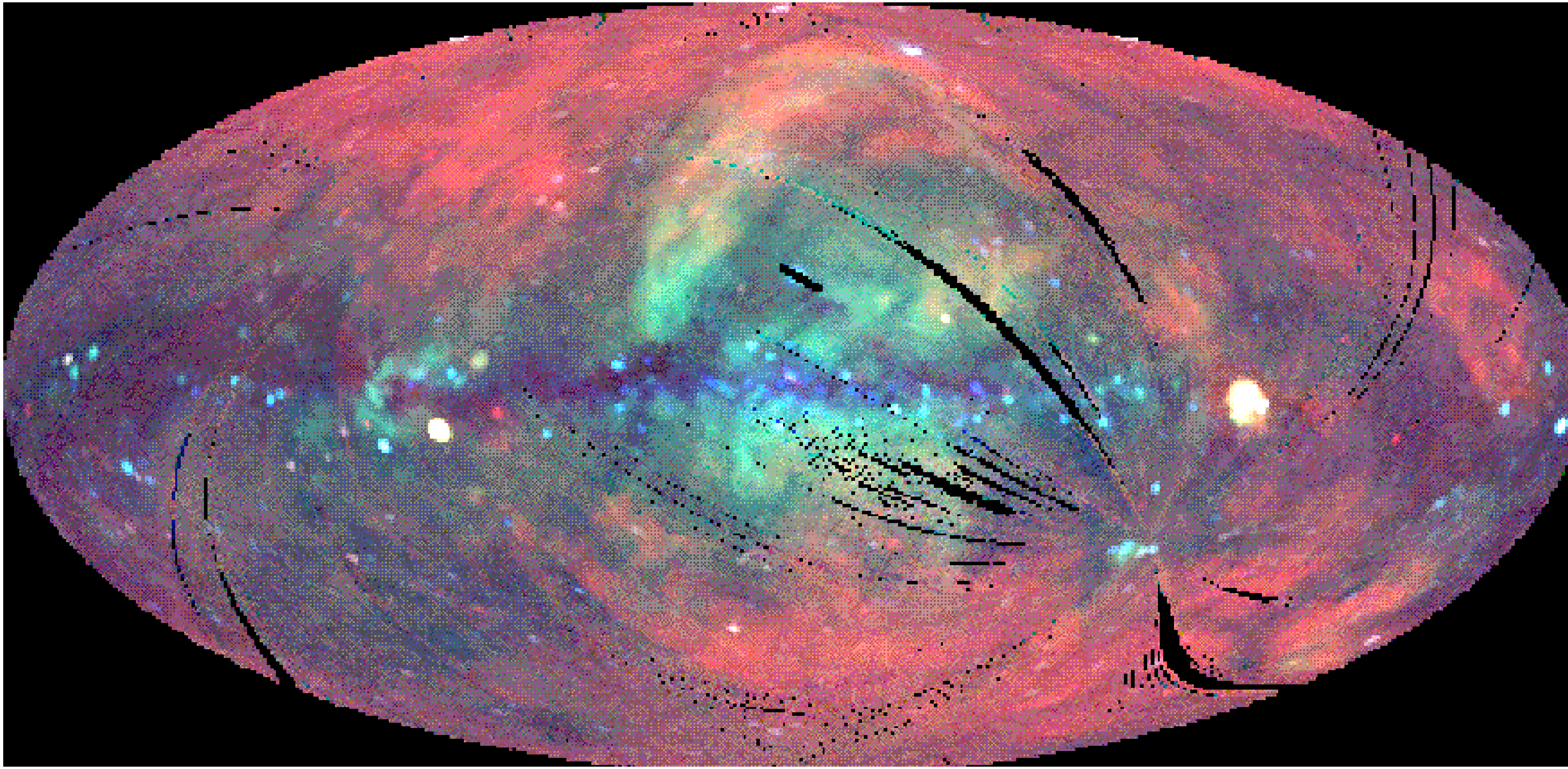

radio
infrared
visible
X-ray
gamma ray
1 eV

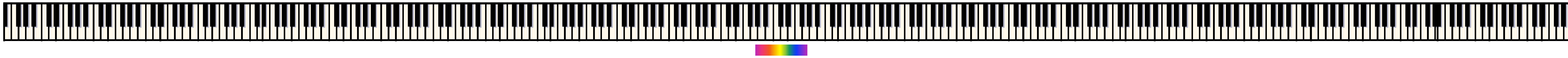




radio infrared visible X-ray gamma ray

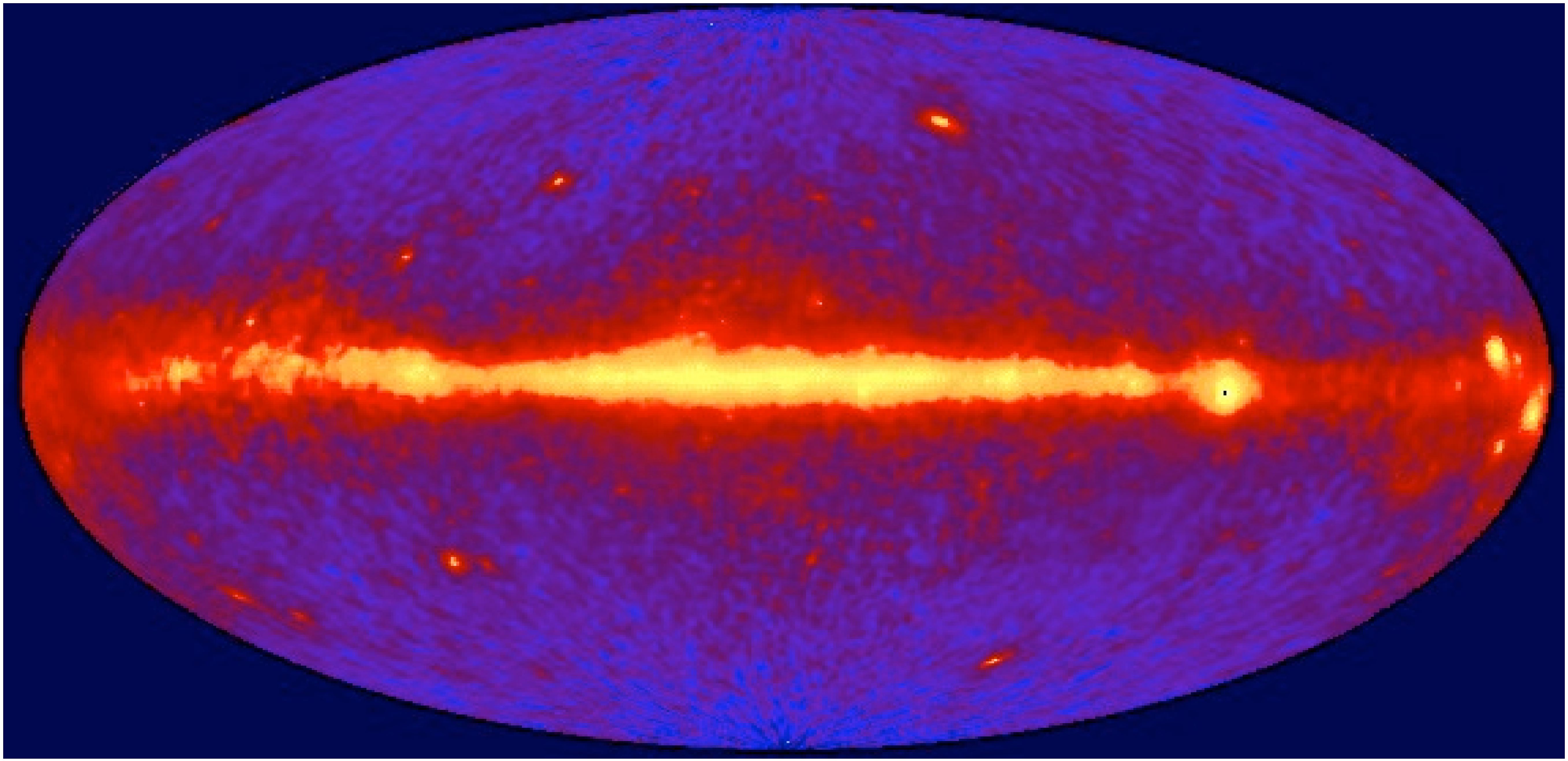
10^3 eV





radio infrared visible X-ray gamma ray

10^9 eV



>45 octaves

TeV Gamma Rays

... another probe for the extreme universe

thanks to Jim Hinton for slides

Extreme Energies ....
.... Extreme Environments:

Power sources ?

Accretion of matter onto compact objects

e.g. Neutron stars, black holes, supermassive black holes

Explosions: Supernova (SN), compact binary mergers

Rotation: rotating neutron star with strong magnetic field

generate relativistic electron-positron wind

How ? (all on charged particles)

Diffusive shock (Fermi) acceleration e.g. SN blast wave hits ISM

Magnetic reconnection ? Plasma waves ?

Creation of gamma rays ?

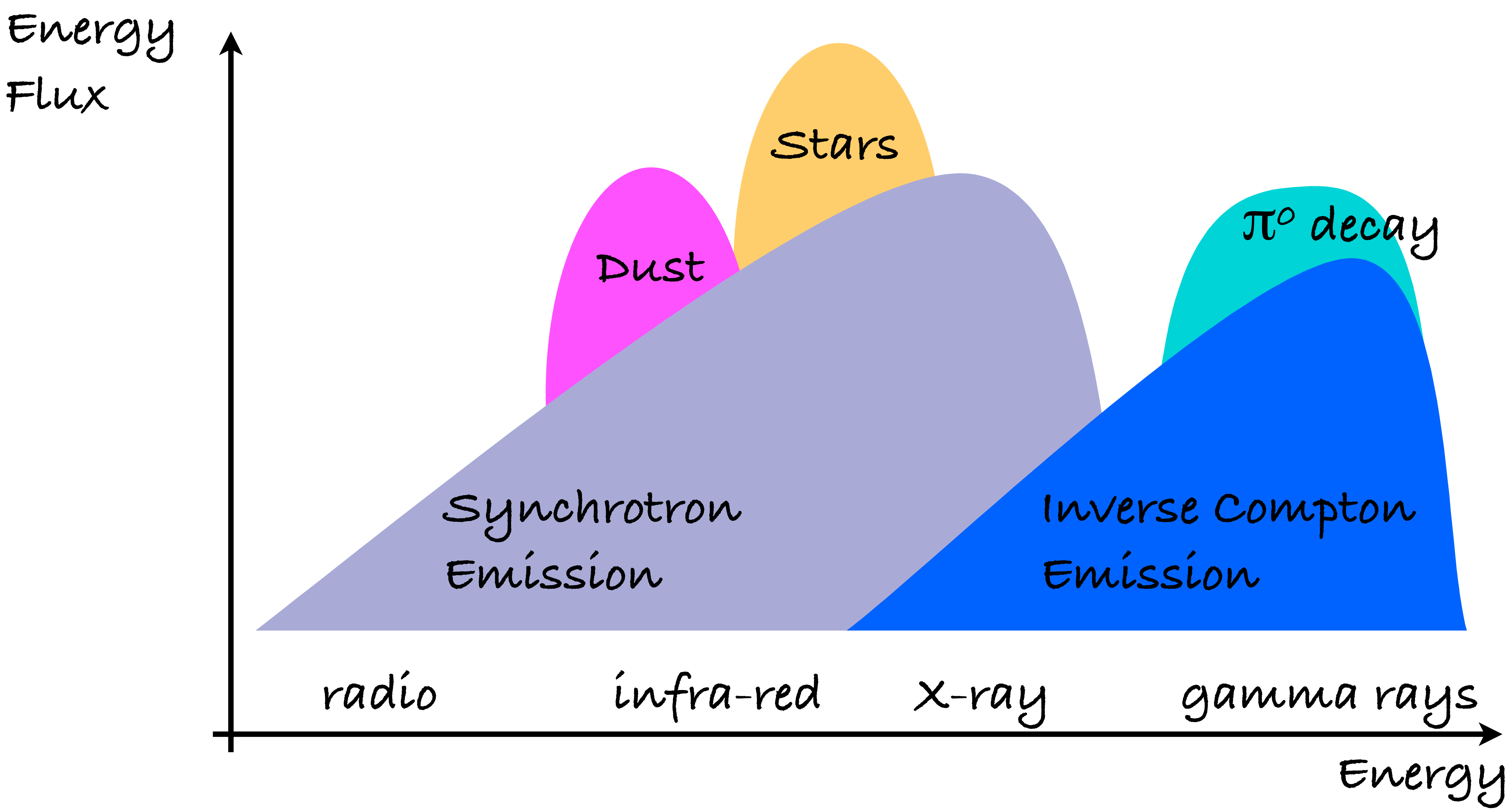
π^0 decay — hadronic primaries

synchrotron emission in magnetic fields

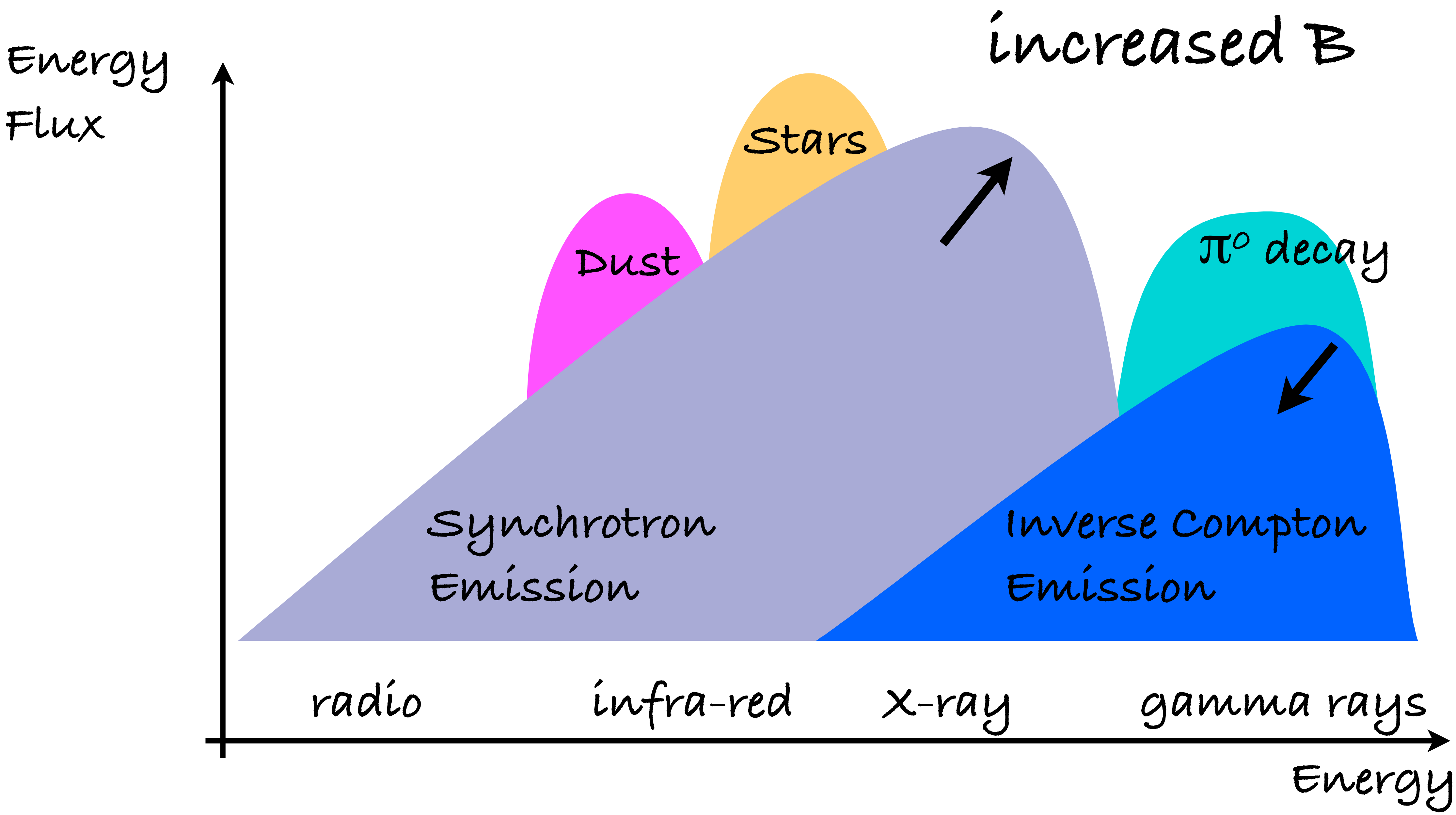
Inverse Compton effect

} relativistic e^+, e^-

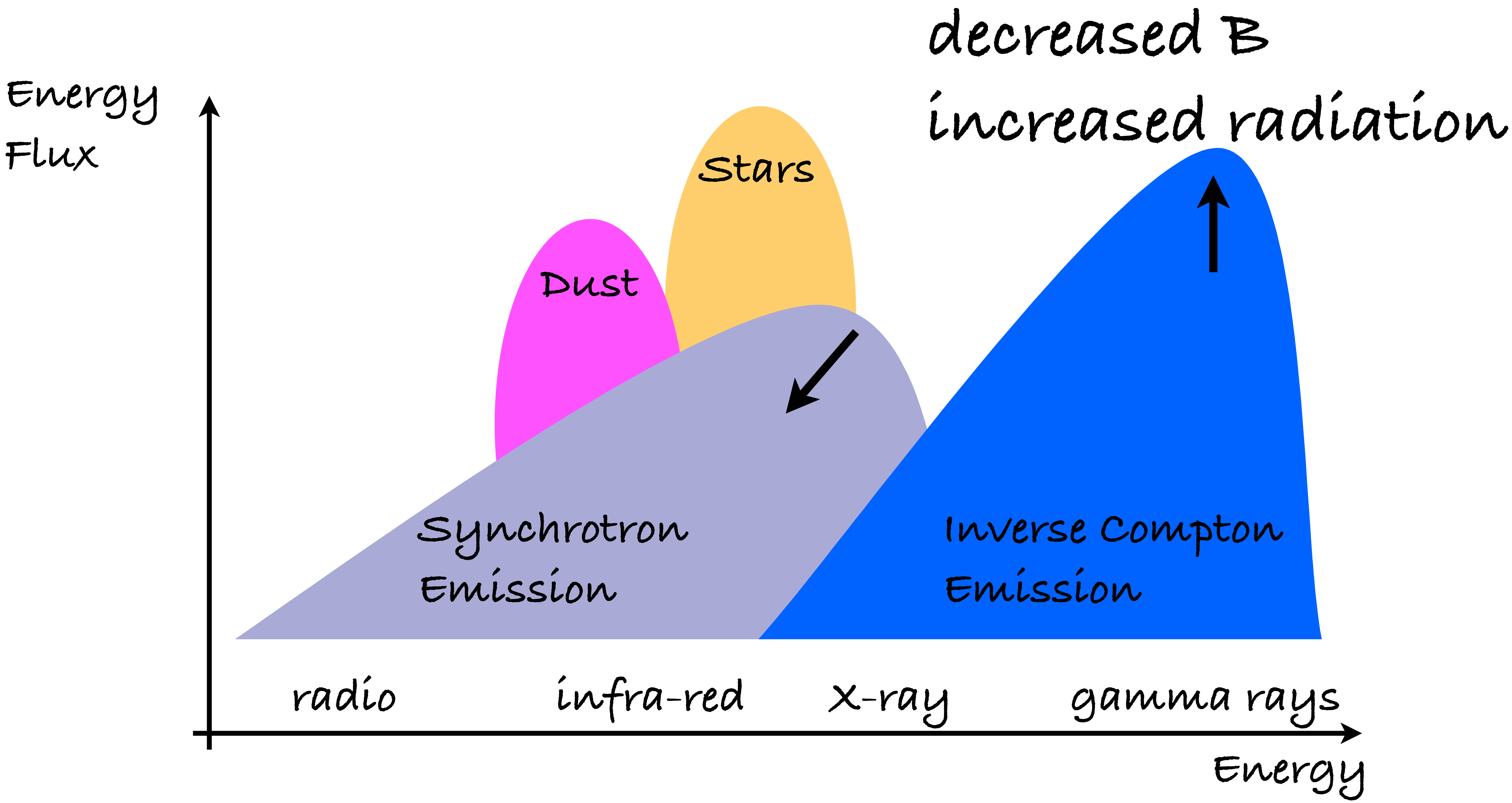
Non-Thermal Radiation



Non-Thermal Radiation



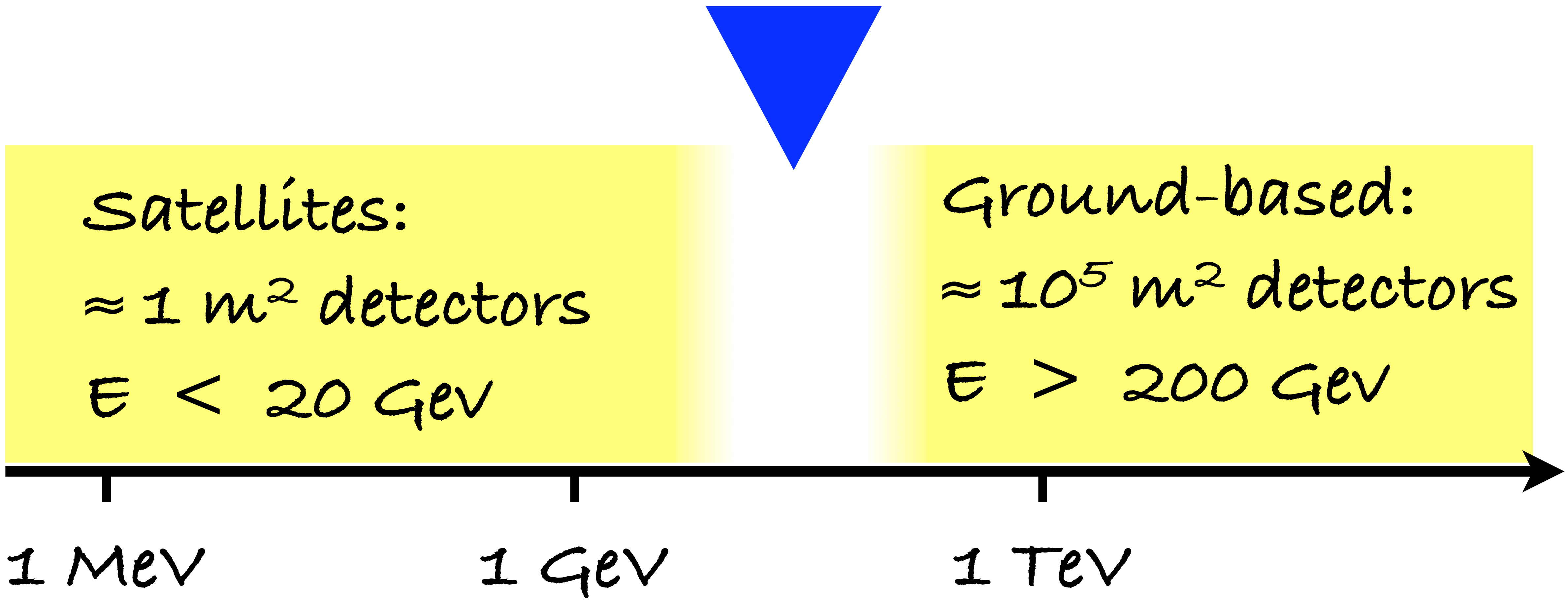
Non-Thermal Radiation



Gamma Astronomy Energies

un-opened window

$20 > E > 200$ GeV



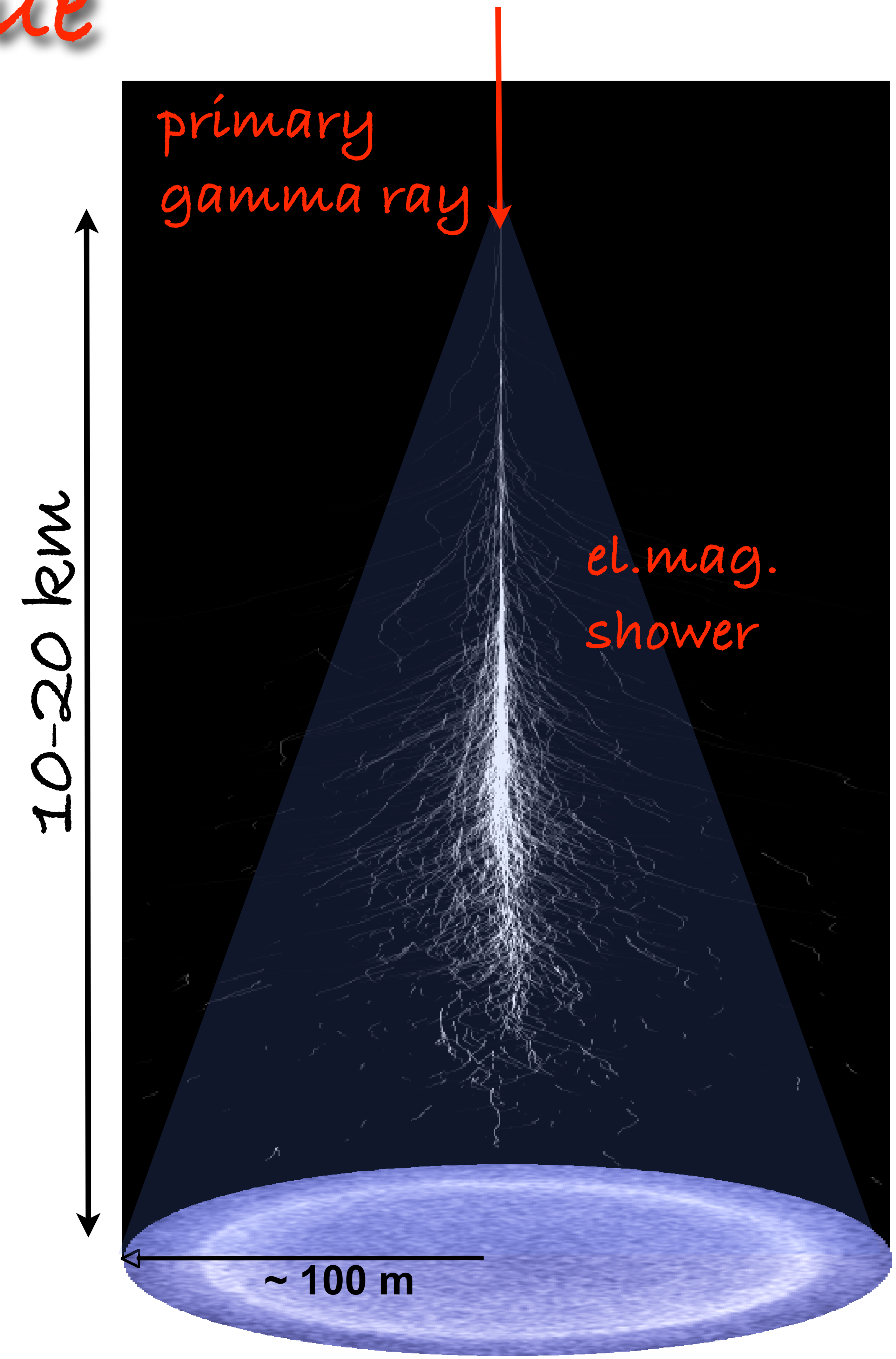
"air showers"

Cherenkov Technique

Cherenkov angle $\approx 1^\circ$
at 10 km altitude

Shower particles absorbed

Cherenkov photons arrive
at ground within 10 ns
in light pool of $r \approx 100$ m



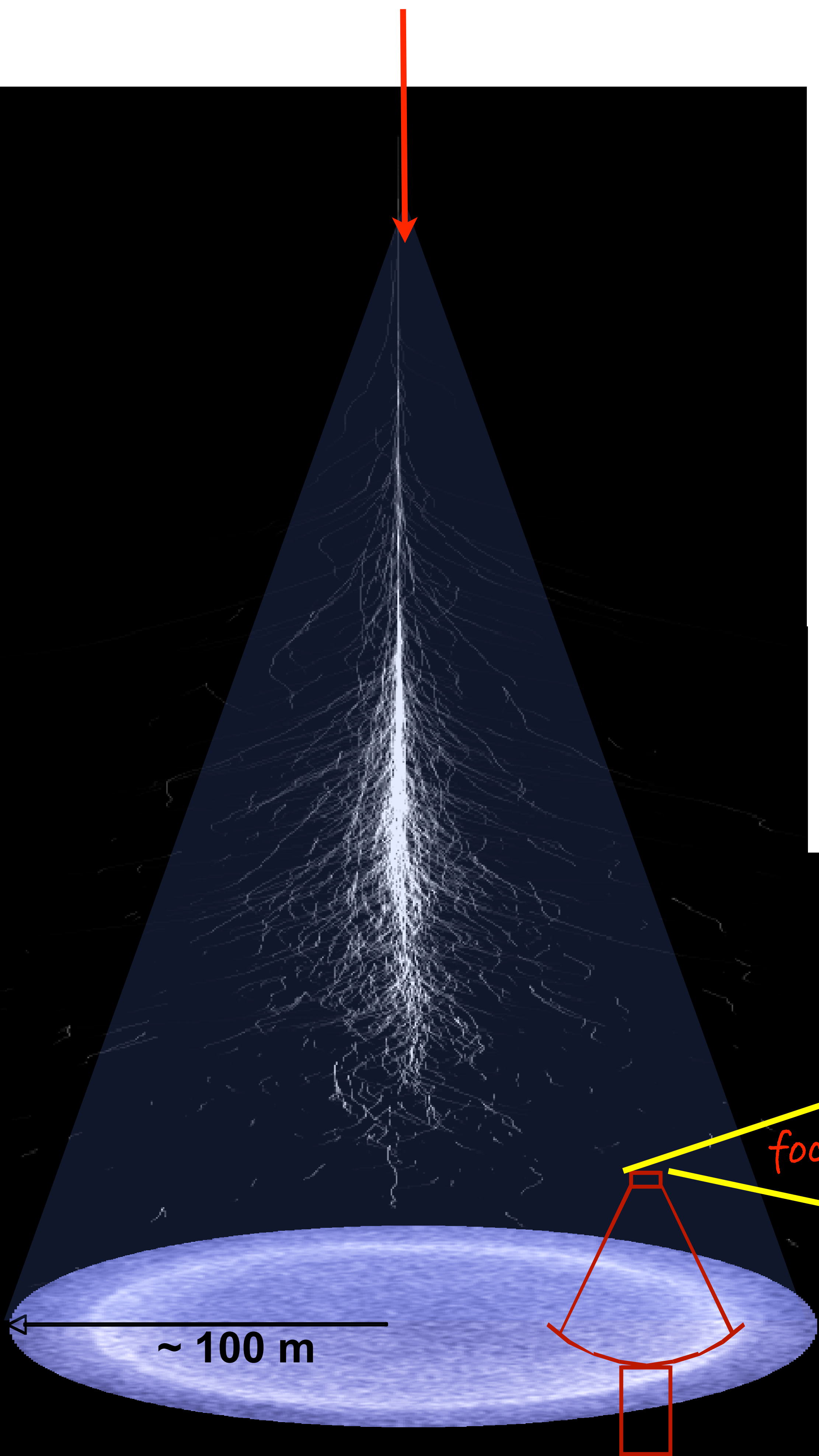
Put telescope in light pool
to get shower image

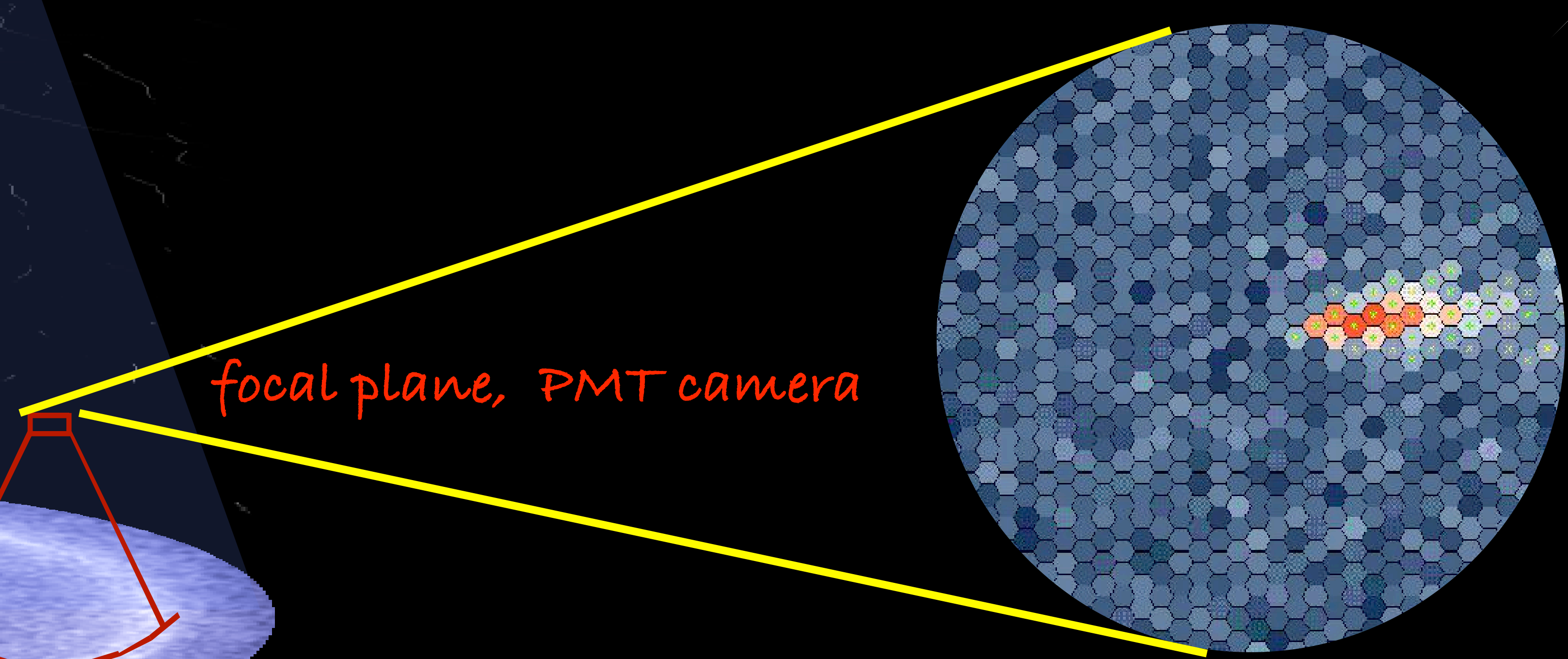
eff. area ≈ size of light pool ≈ 10^5 m^2

image analysis gives: energy, shower direction and background rejection

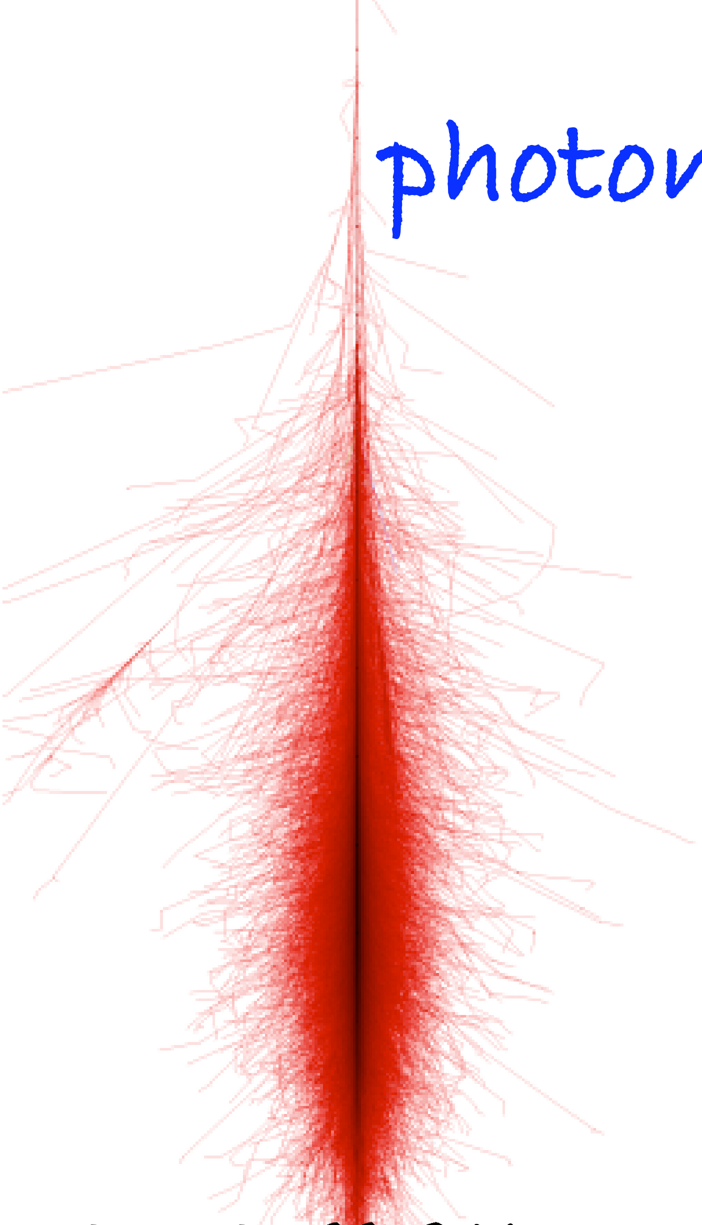
(10^2-10^3x more CRs than γ-rays)

but: Ch. telescopes have small field of view ($< 5^0$)





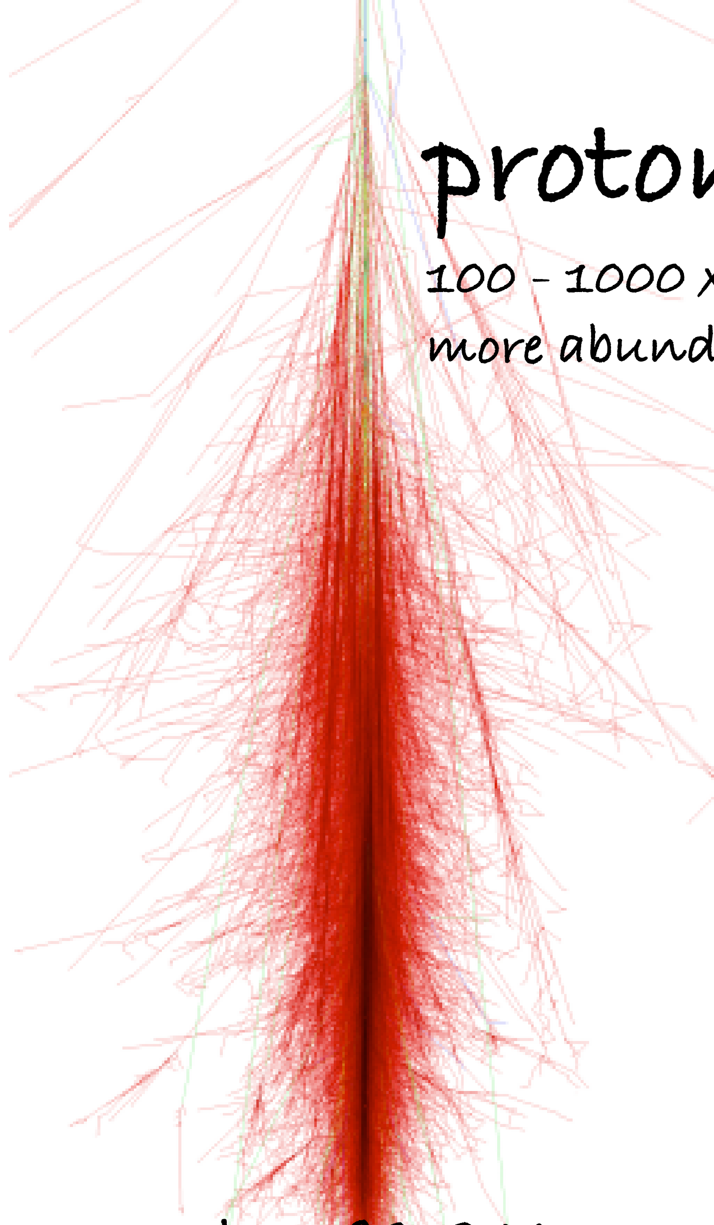
photon



proton

100 - 1000 x

more abundant

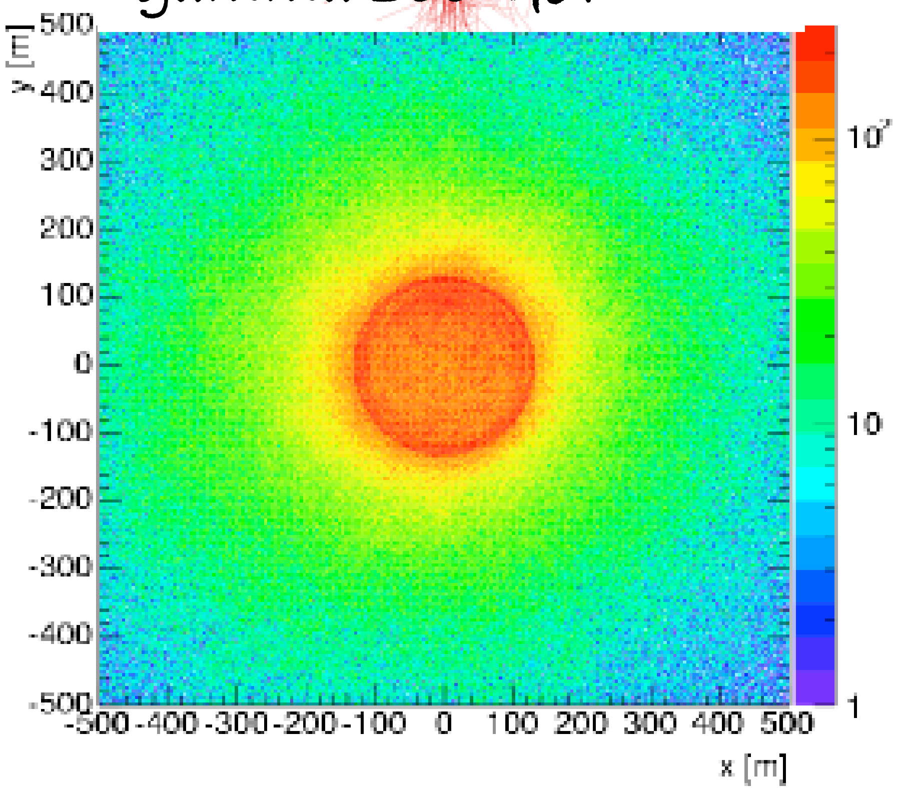


more structure,

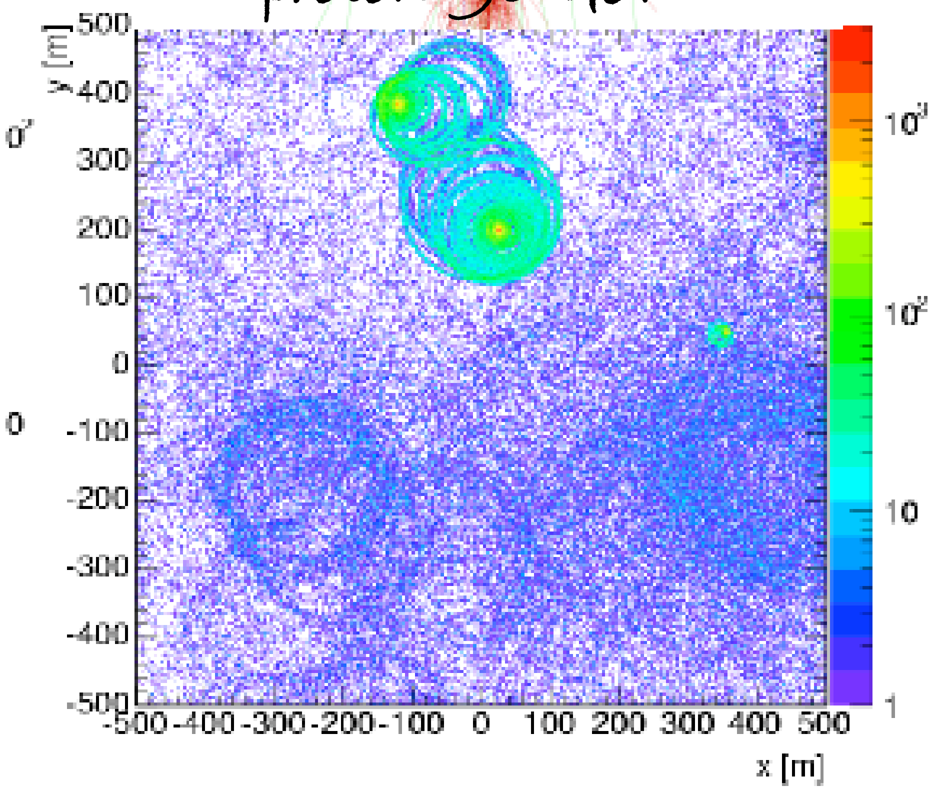
fluctuations

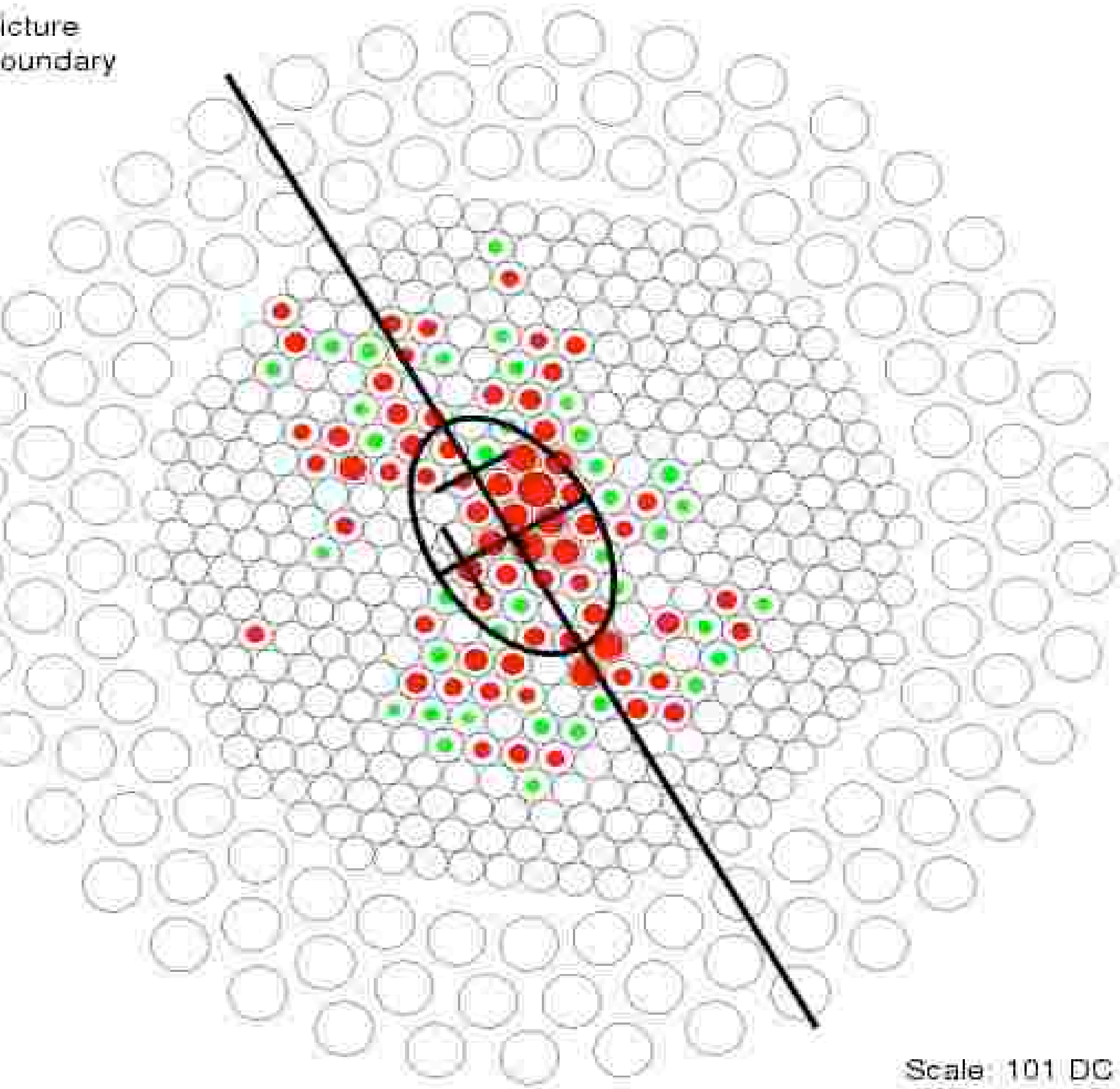
in CR showers

gamma 300 GeV

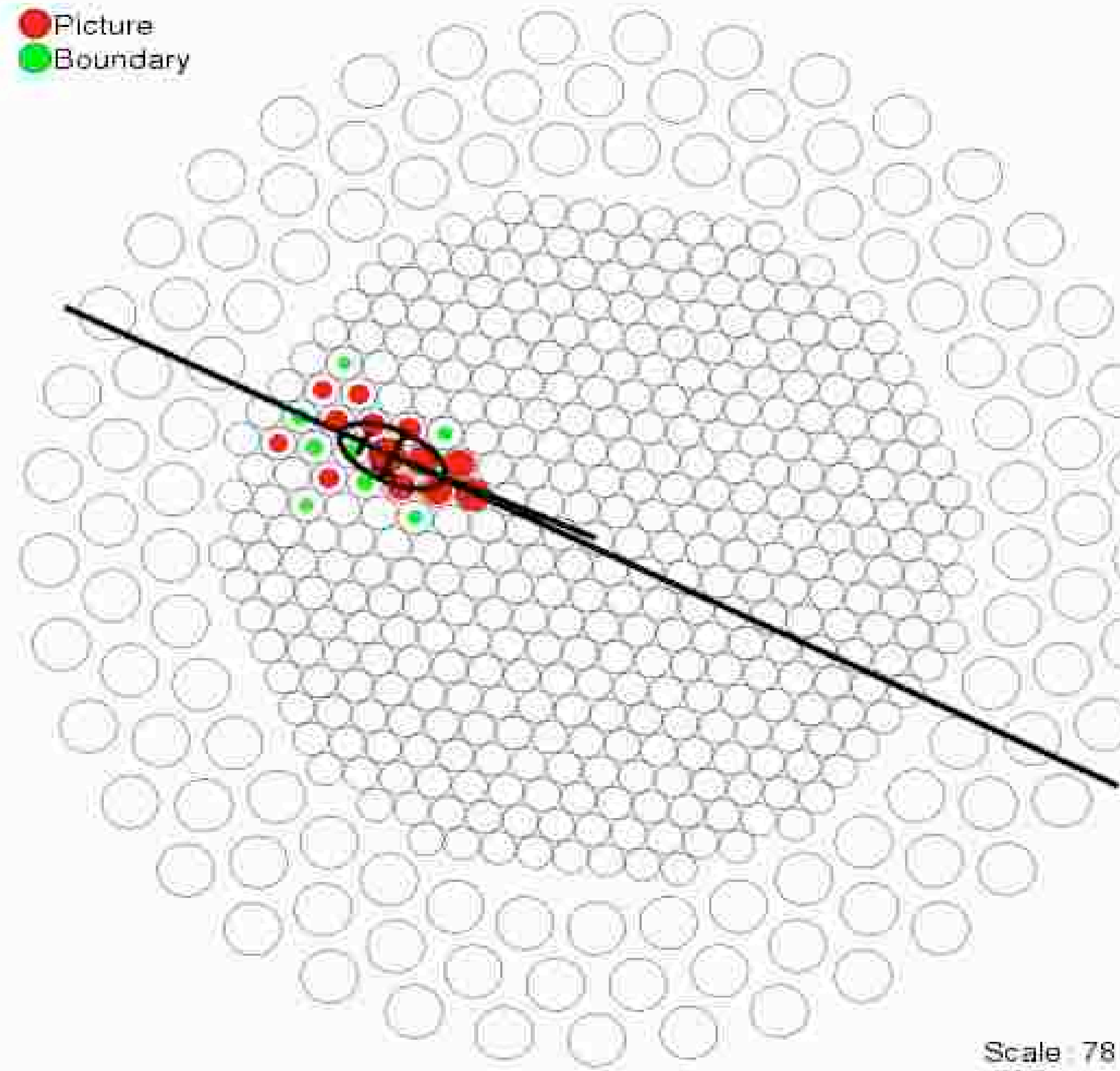


proton 90 GeV



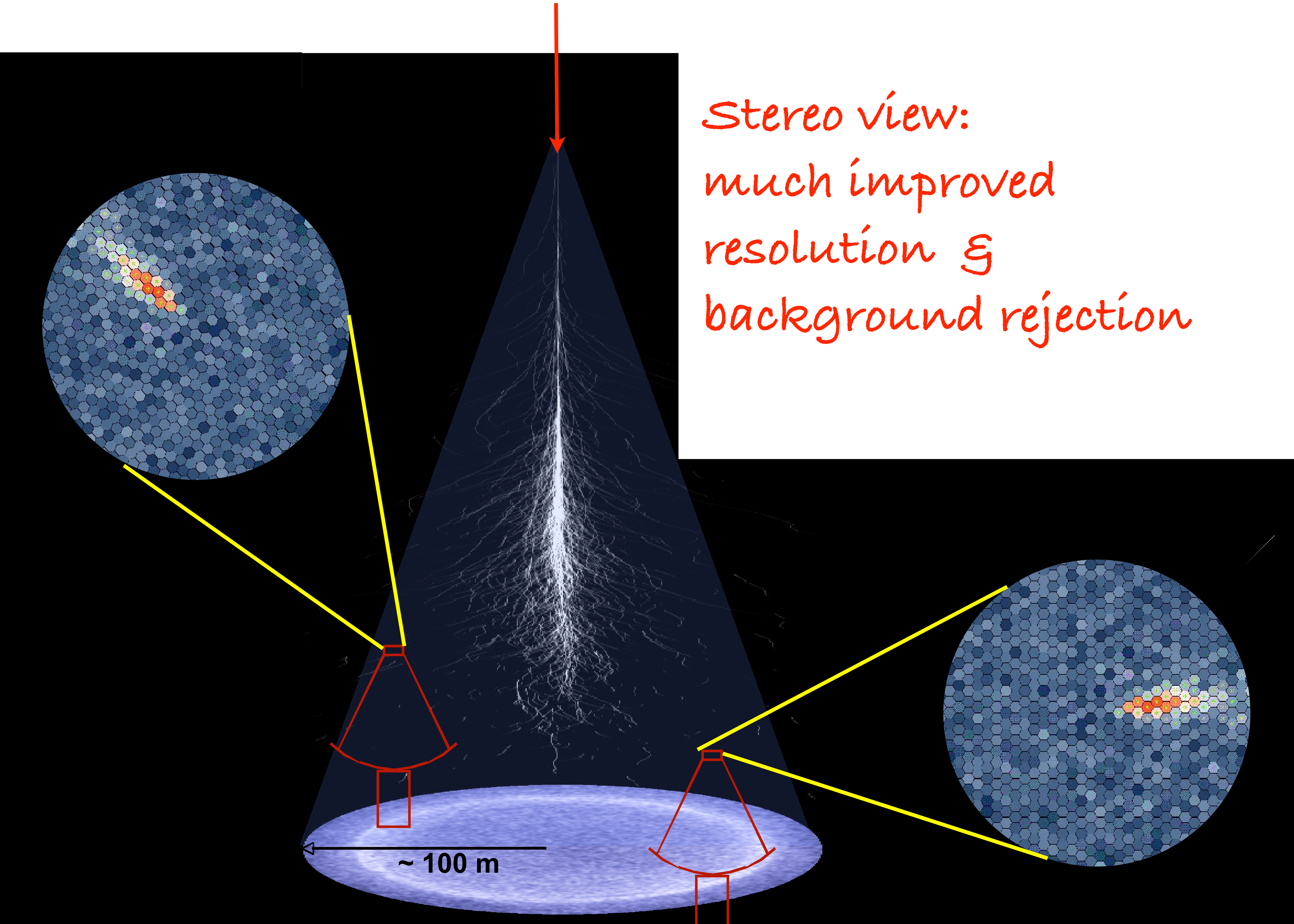


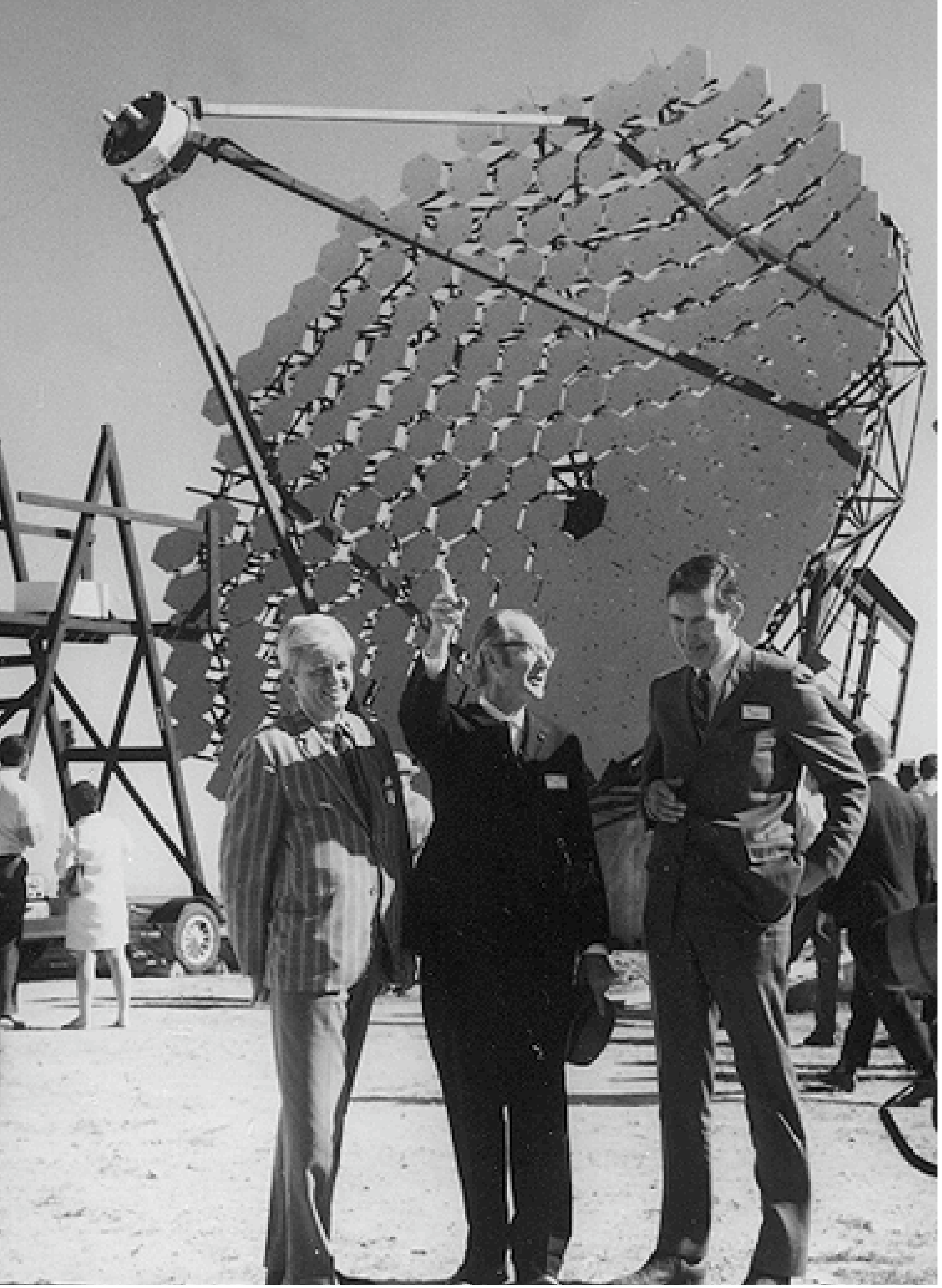
Proton



Photon

Stereo view:
much improved
resolution &
background rejection



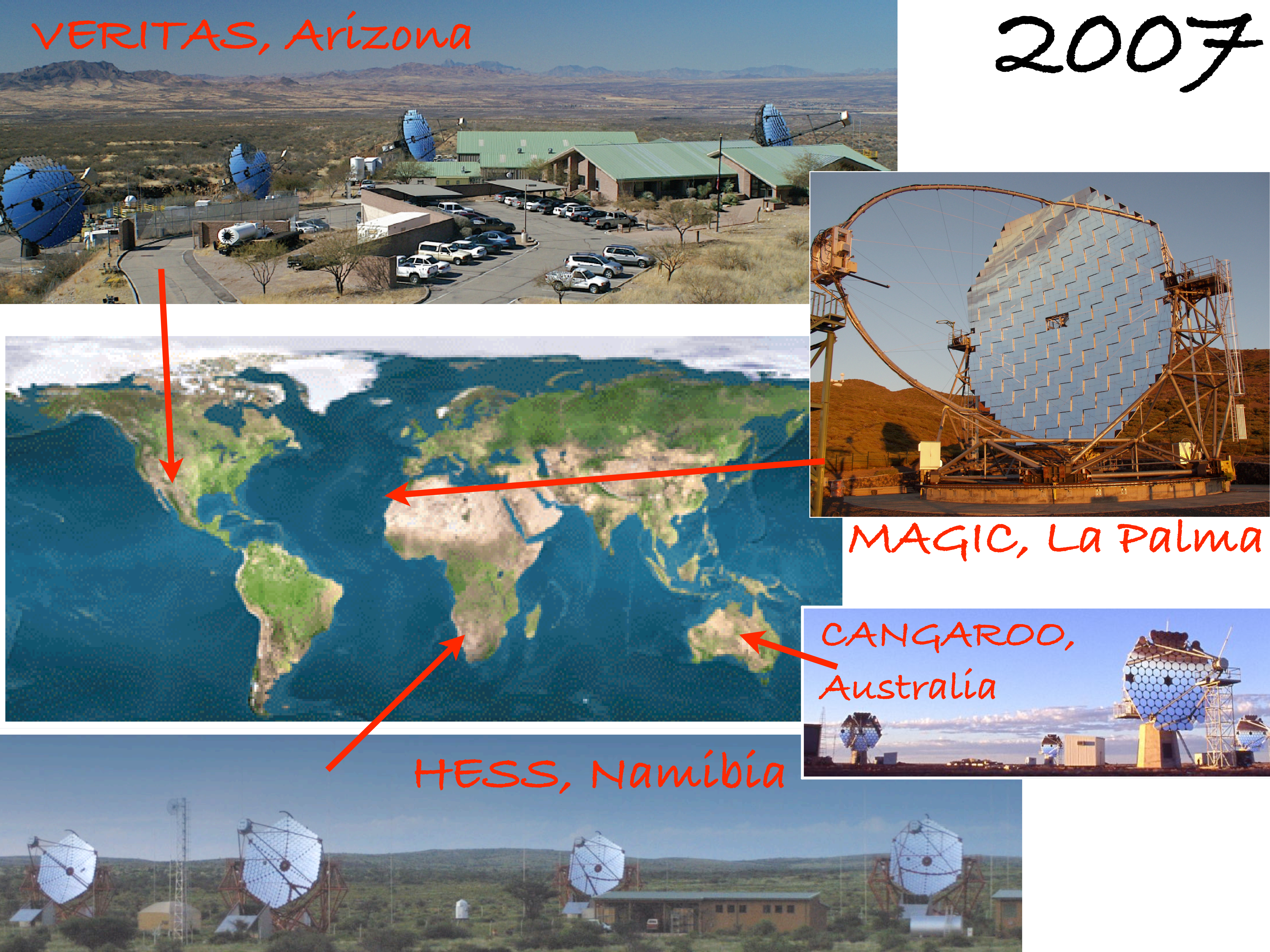


10 m Whipple Telescope
Mt Hopkins, Arizona

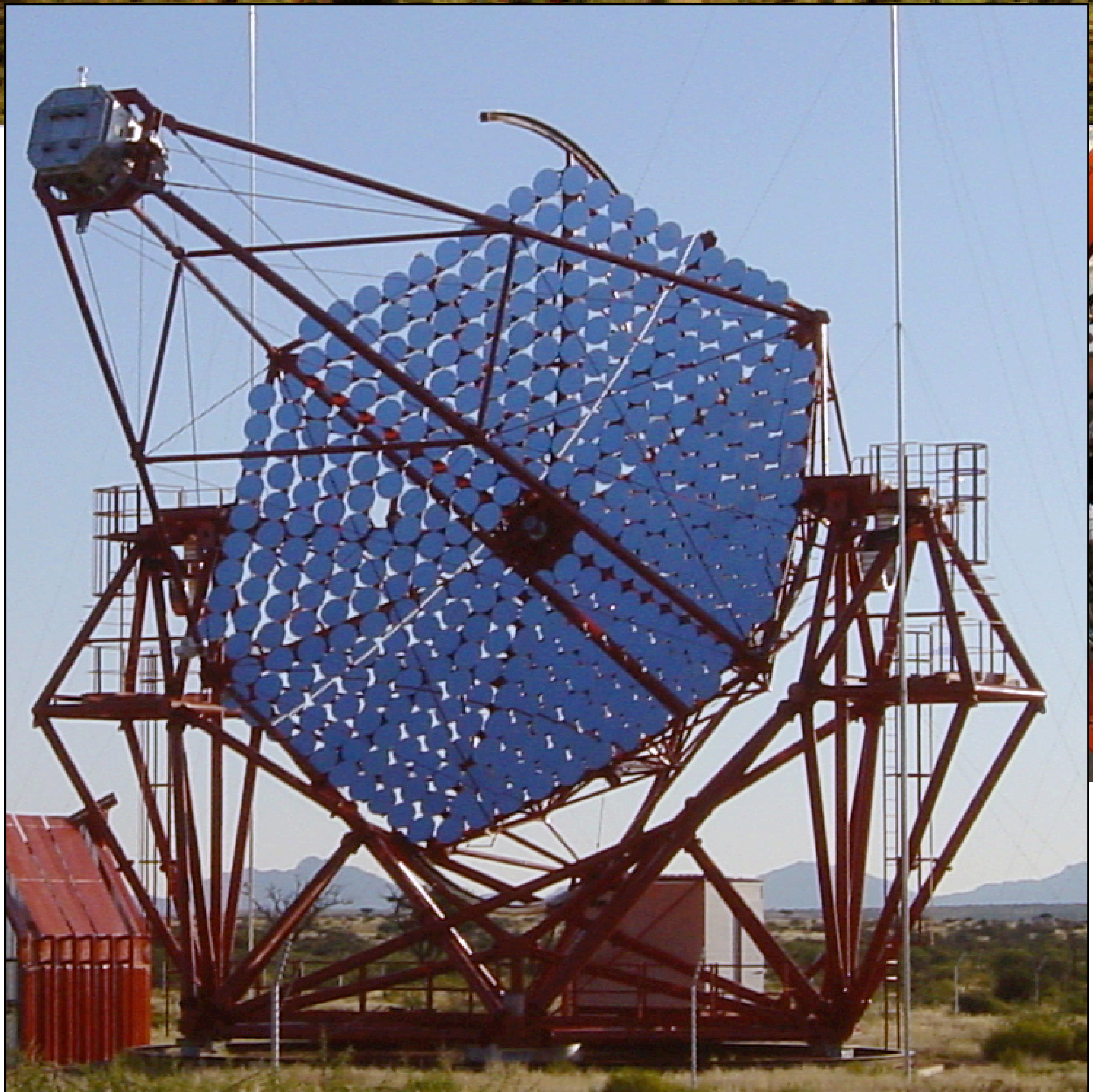
1968: Construction

- multi PMT camera
- image analysis

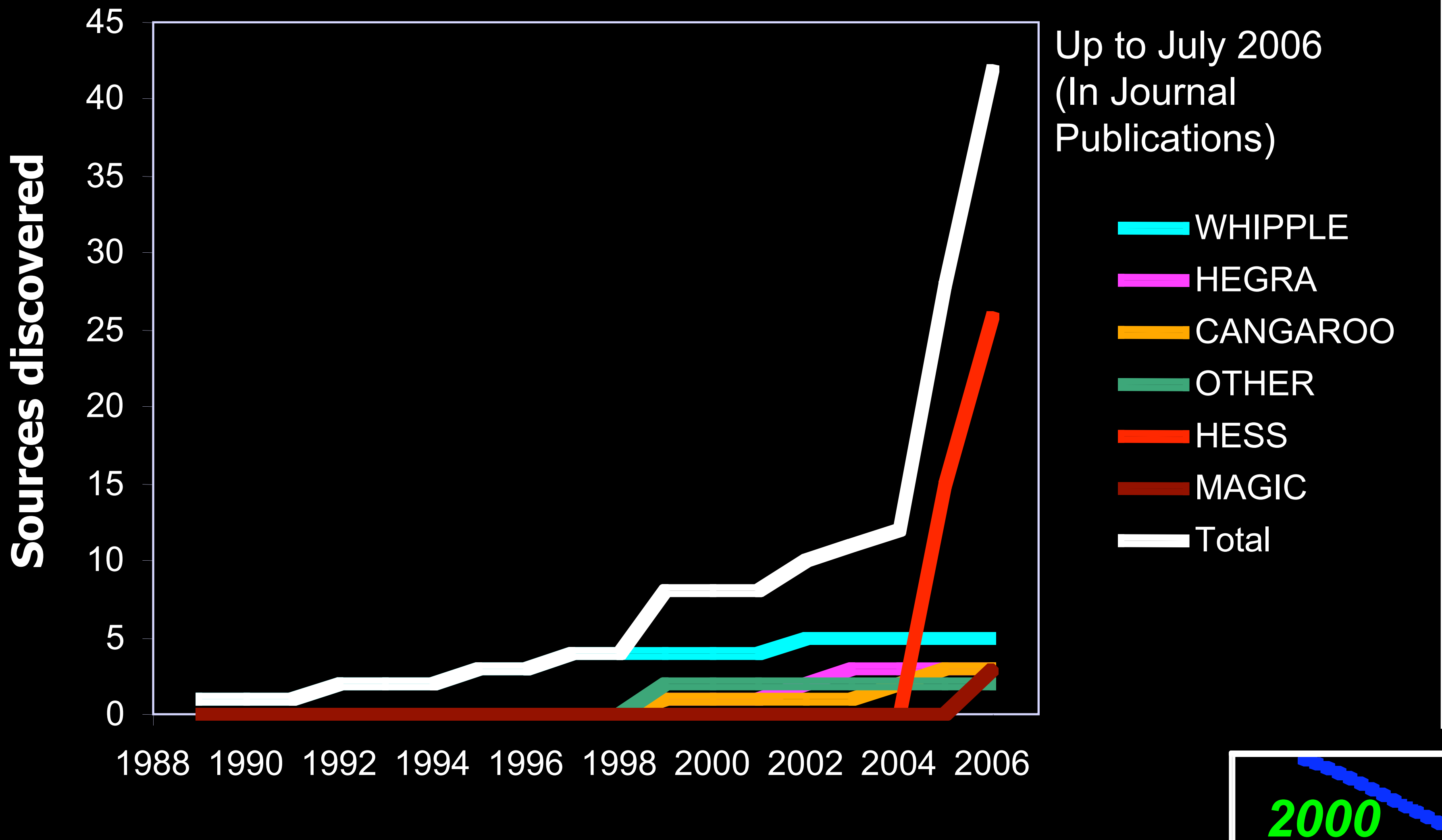
1989: Discovery of Crab Nebula at $E > 1$ TeV



2007
VERITAS, Arizona
MAGIC, La Palma
CANGAROO, Australia
HESS, Namibia

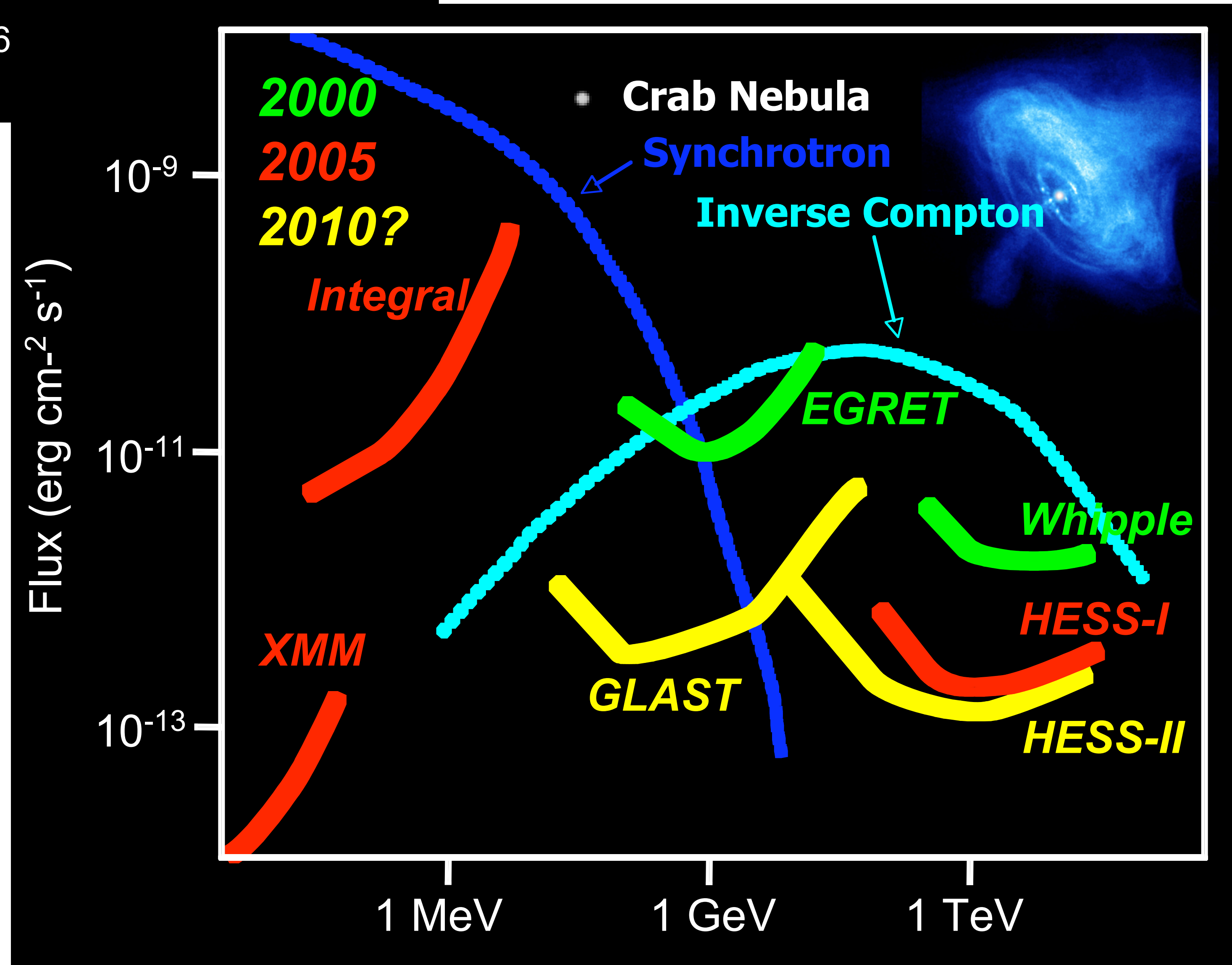


HESS: Khomas Highland, Namibia
four 13-m telescopes, 960-pixel cameras,
5° FOV

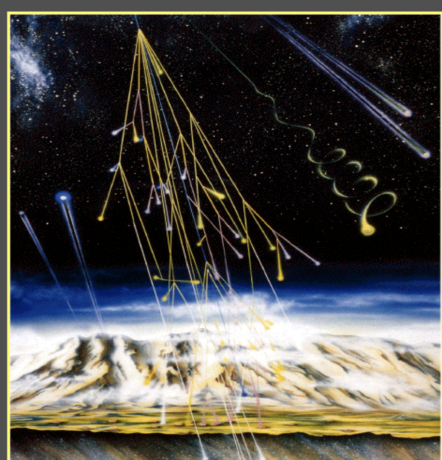


July 2007
ICRC Mexico :
71 soures

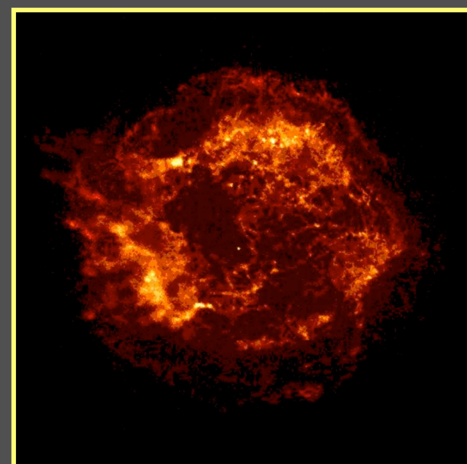
Rapid growth of number of sources,
due to improved sensitivity of
new instruments
(so far mainly due to HESS).



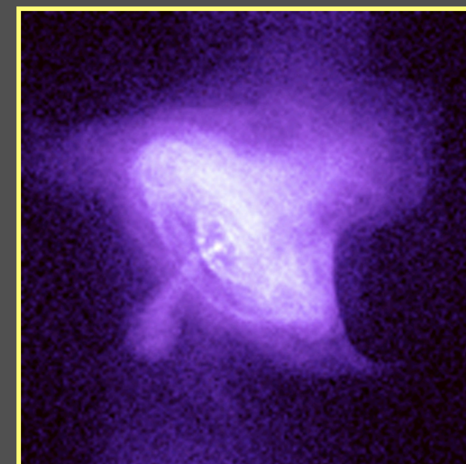
Science with VHE Gamma Rays



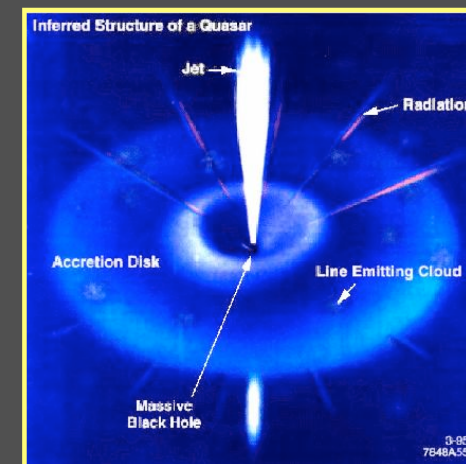
Origin of cosmic rays



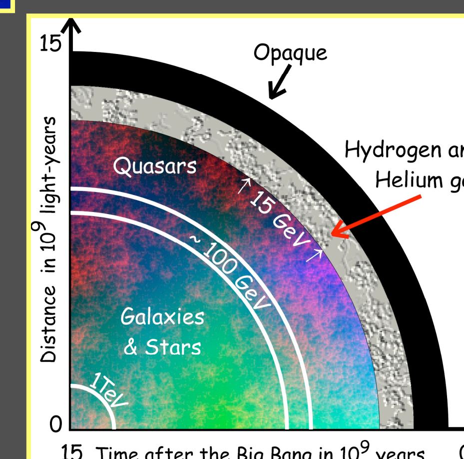
SNRs



Pulsars and PWN

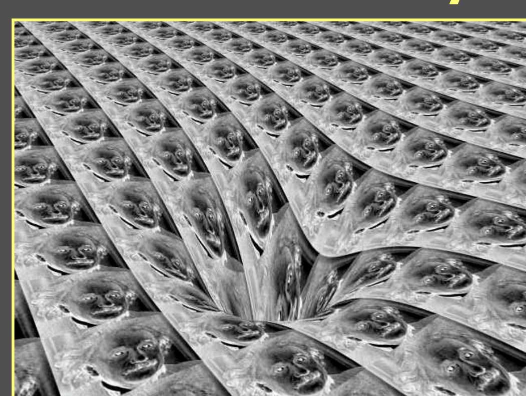


AGNs



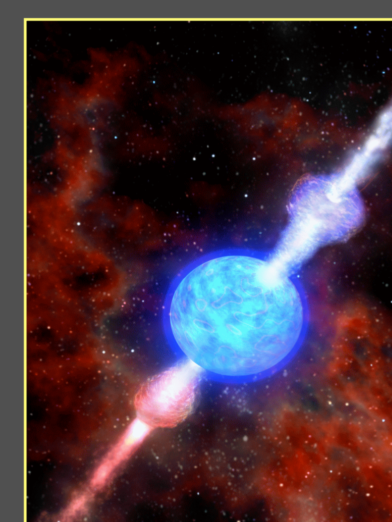
Cosmology

Space-time & relativity

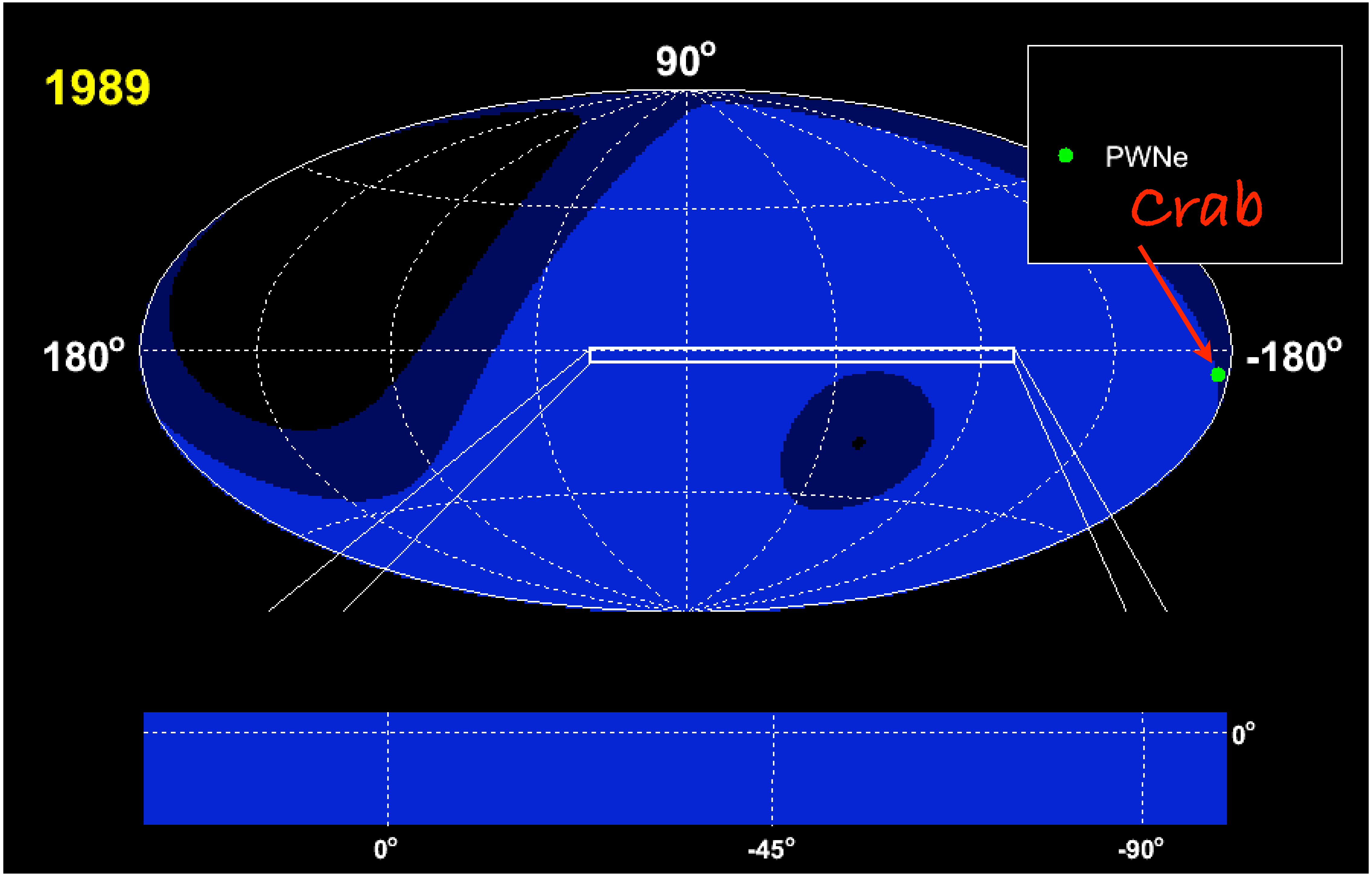


Dark matter

GRBs

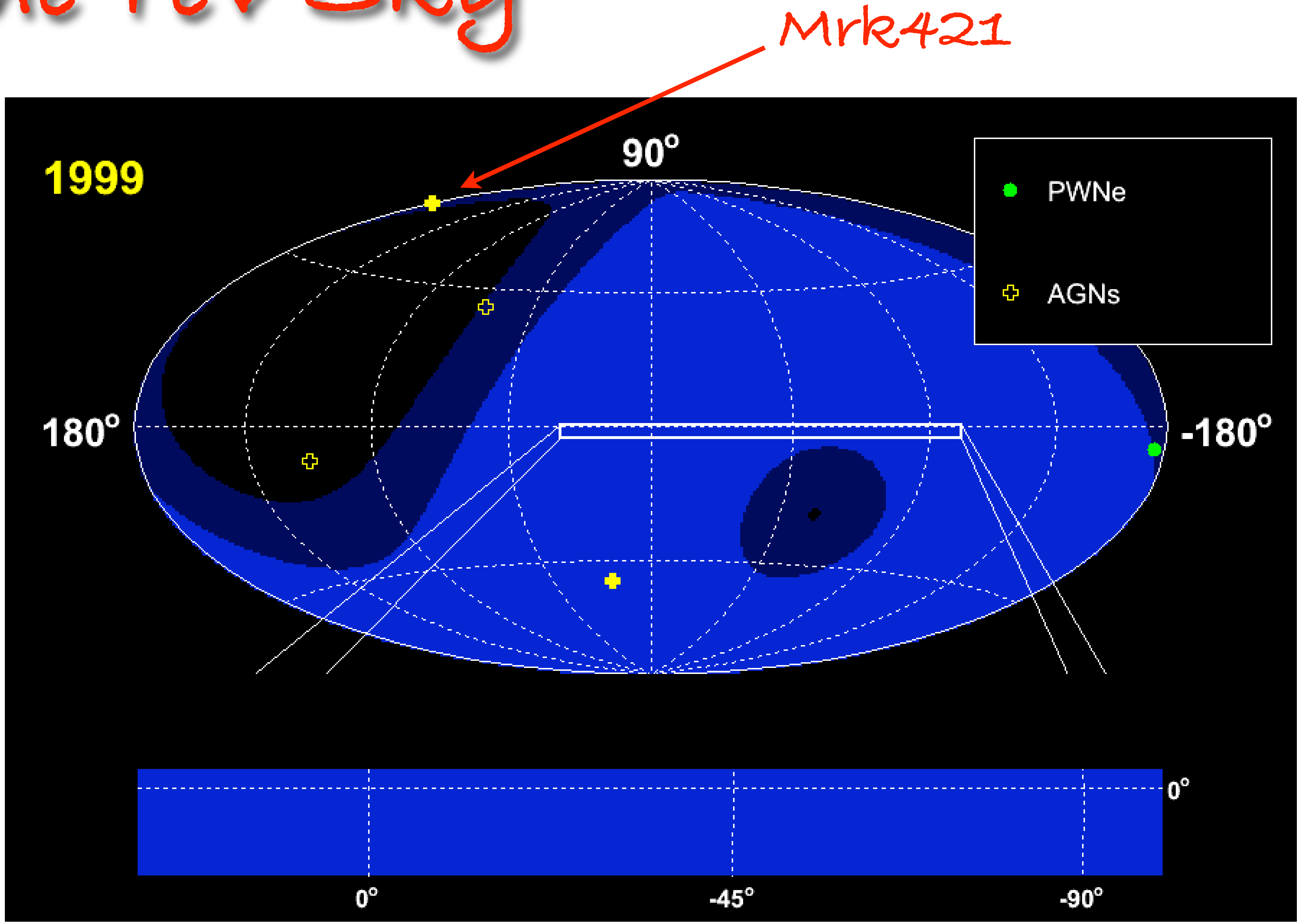


The TeV Sky



Whipple: Crab Nebula, first TeV source

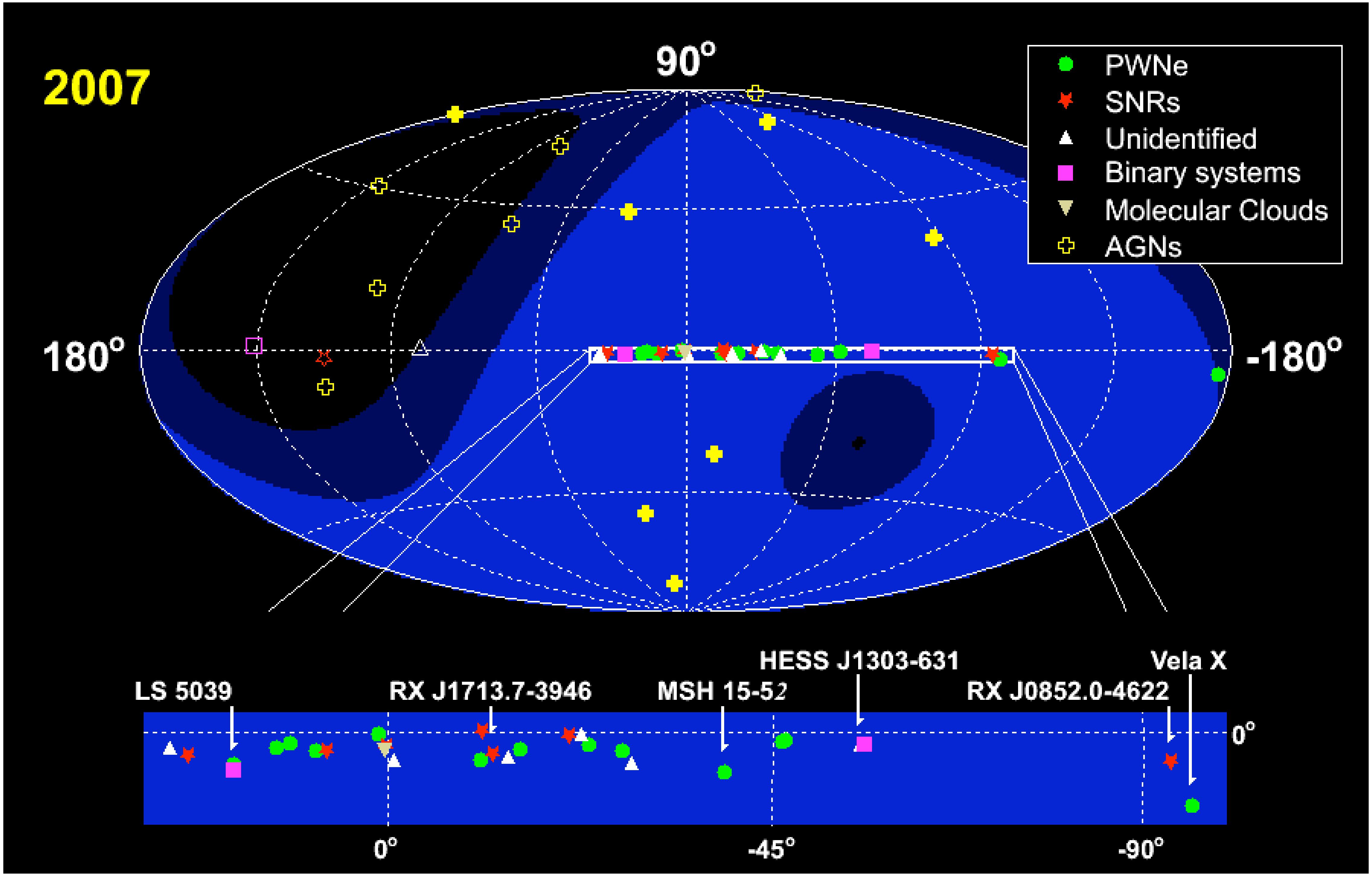
The TeV Sky

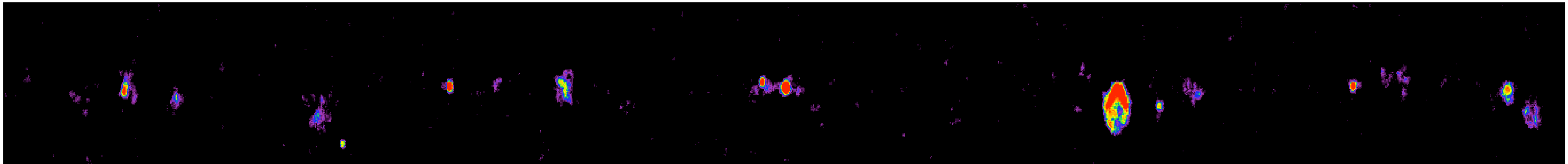


Whipple, Mark V : AGNs (Blazars)

The TeV Sky

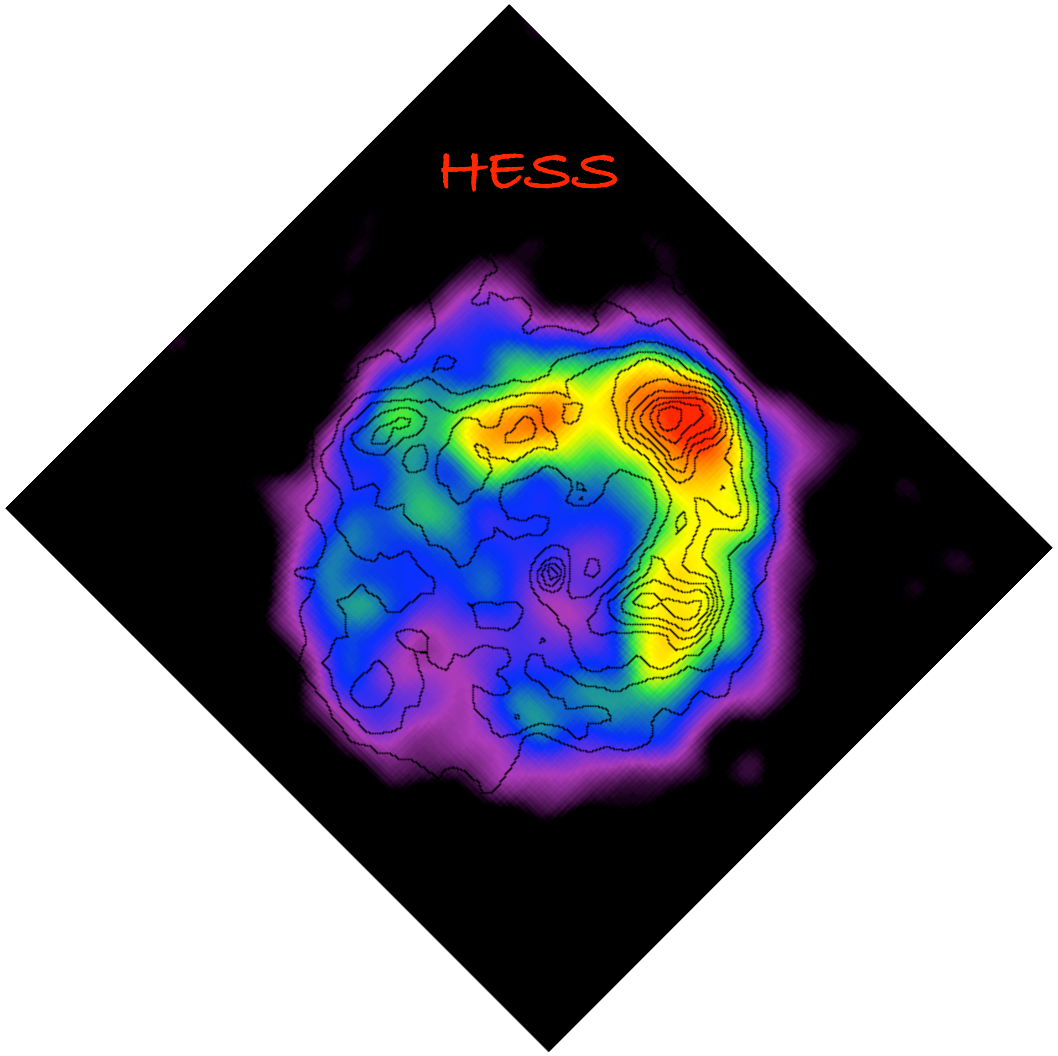
HESS: galactic plane survey
many new classes of objects



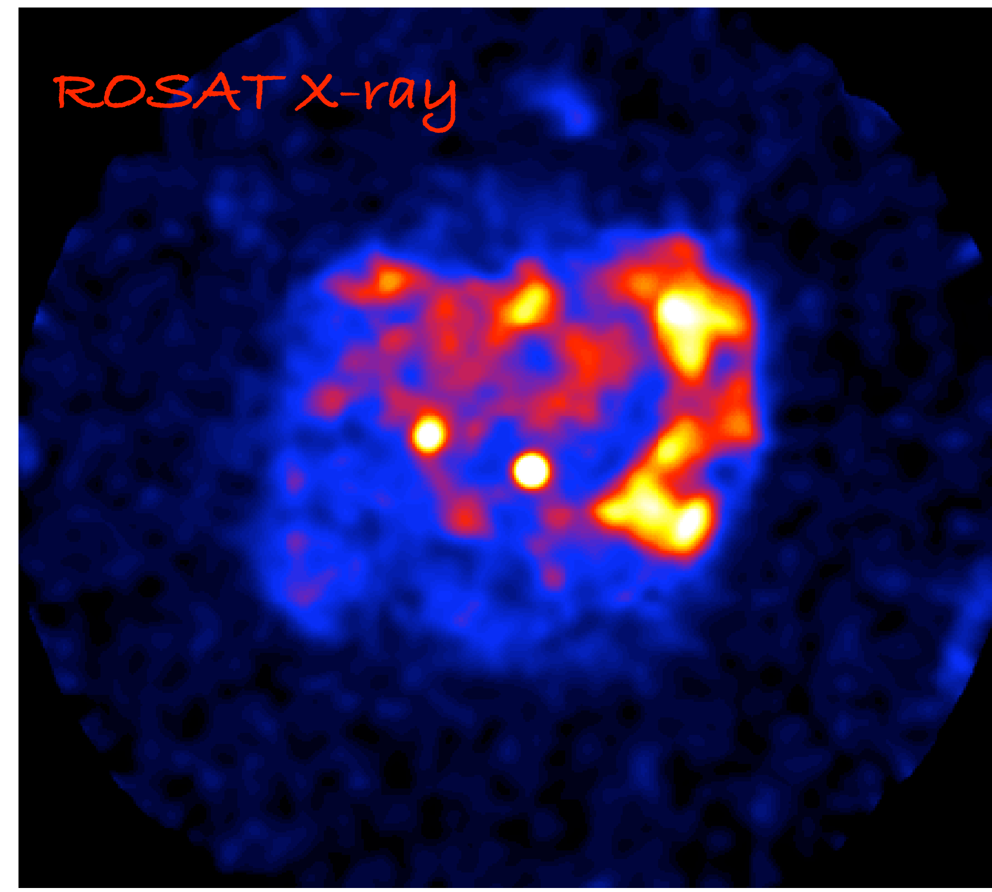


Supernova Remnants

e.g. RX J1713.7 -3946



Moon to scale



Purely non-thermal X-ray source

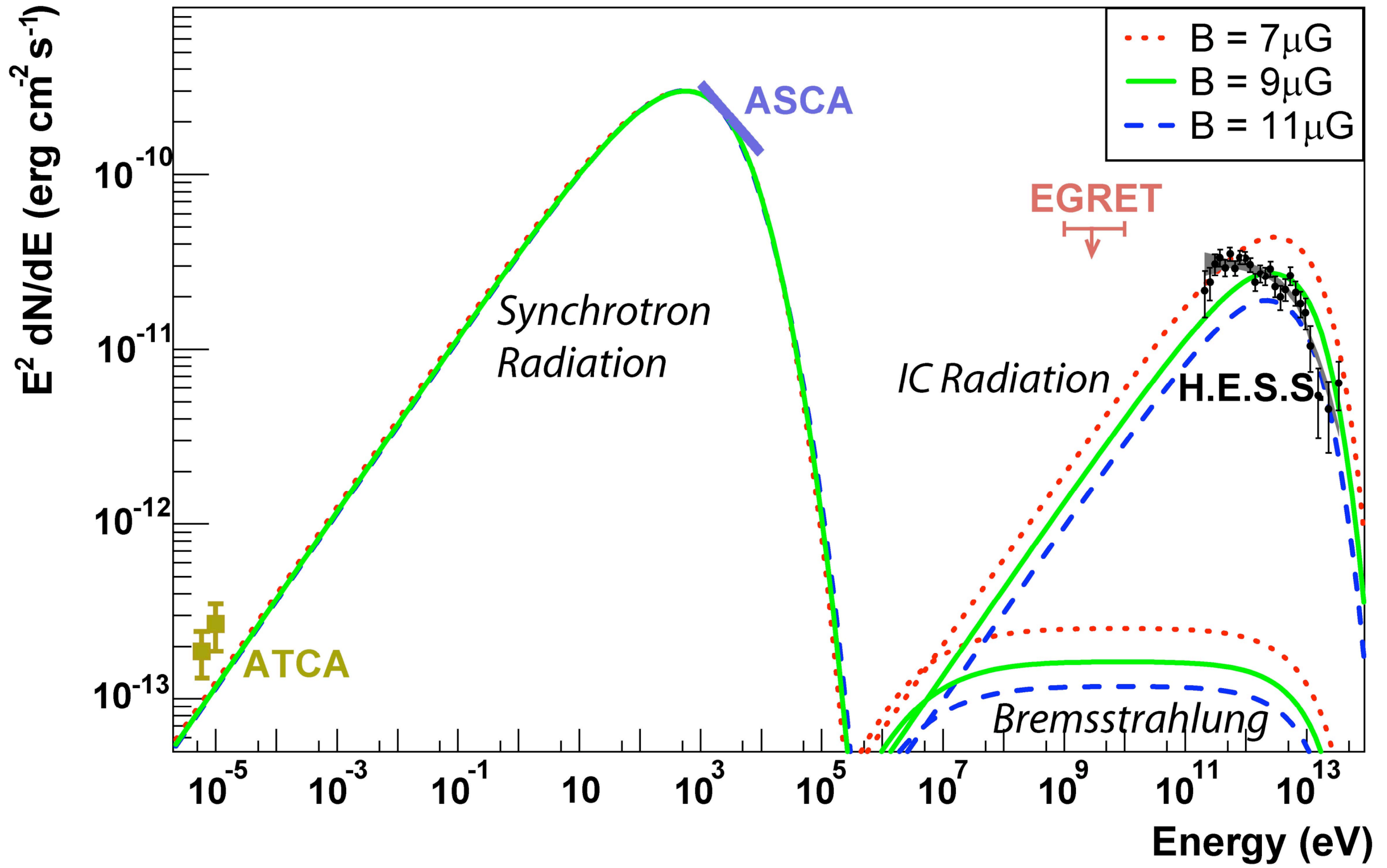
≈1000 years old, distance ≈ 1 kpc, dense environment?

First TeV gamma-ray SNR (and first resolved image)

Closely correlated keV/TeV morphology

Hadronic Origin ?

RX J1713.7 -3946



pro:

spectral shape

IC interpretation implies too low B field

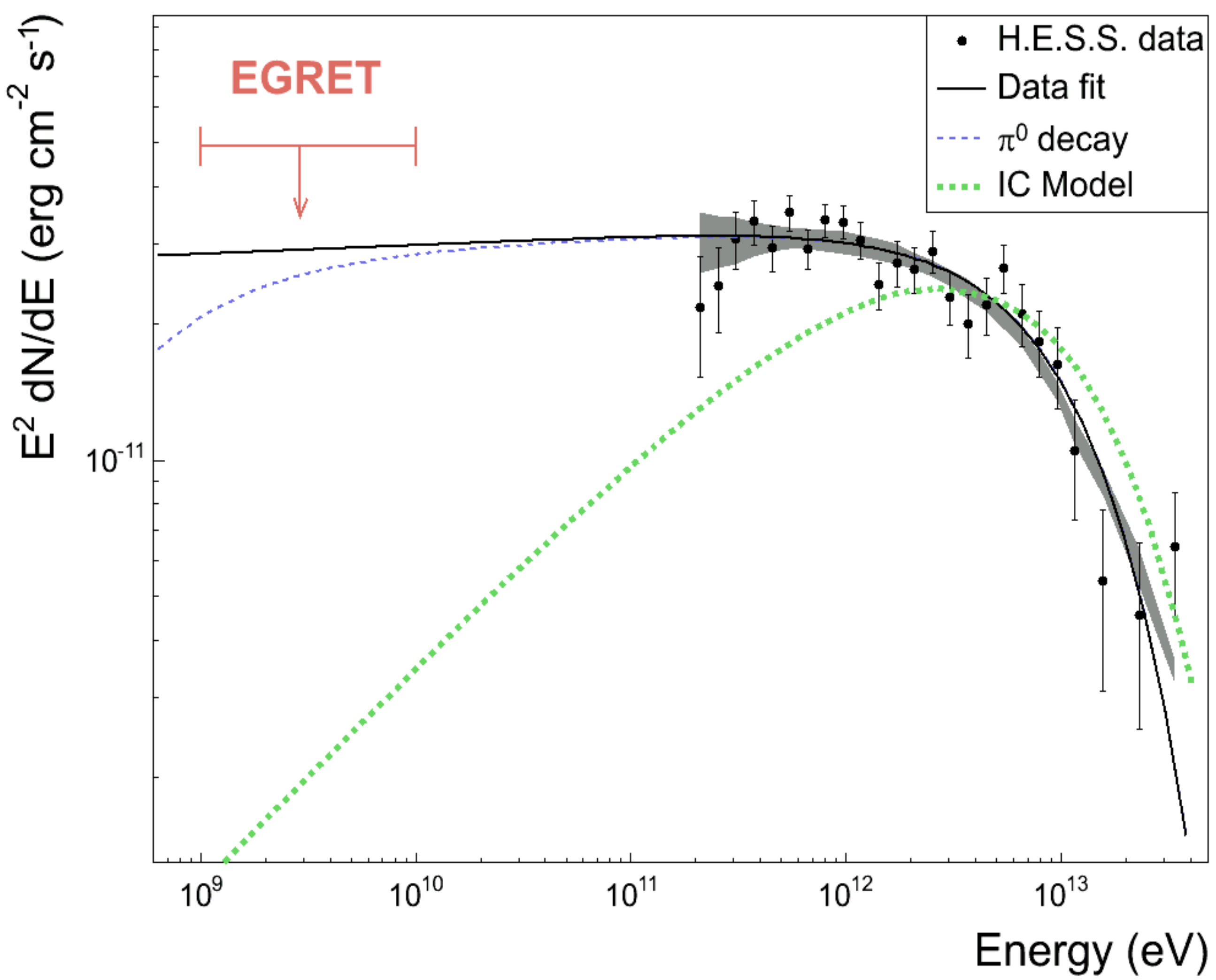
con:

close correlation with X-rays

no correlation with molecular material

Conclusion:

not clear yet; need data at lower energies



Micro Quasars

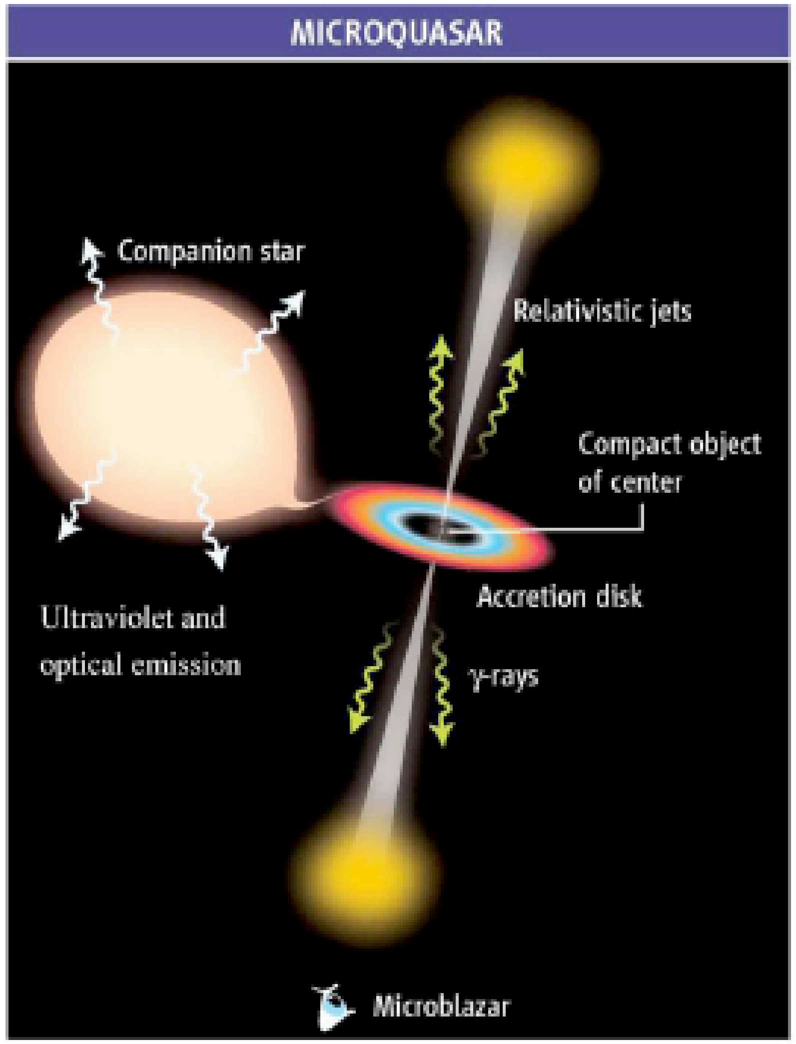
High-mass X-ray binary system (BH/NS with massive stellar companion) with radio jets.

Galactic analogue of a quasar

(Supermassive black hole with jets)

Two objects of this class emit TeV gamma-rays:

LS 5039 (HESS) and LSI +61 303 (MAGIC)



Micro Quasar LS 5039

Close binary system:

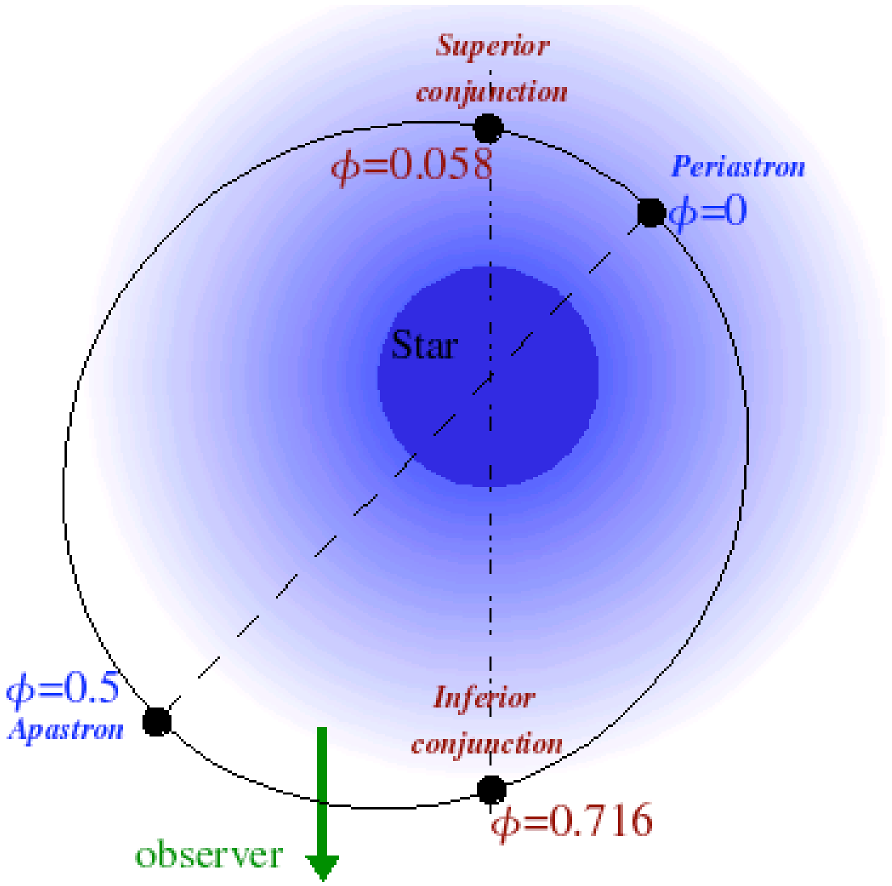
Period: 3.9 days, O-star: 25 M$_\odot$, Compact Object: 1.5-5 M$_\odot$,

Separation: 2-5 R$_*$

Exhibits radio jet

jet with v ~ 0.2 c aligned close to line of sight (microblazar?)

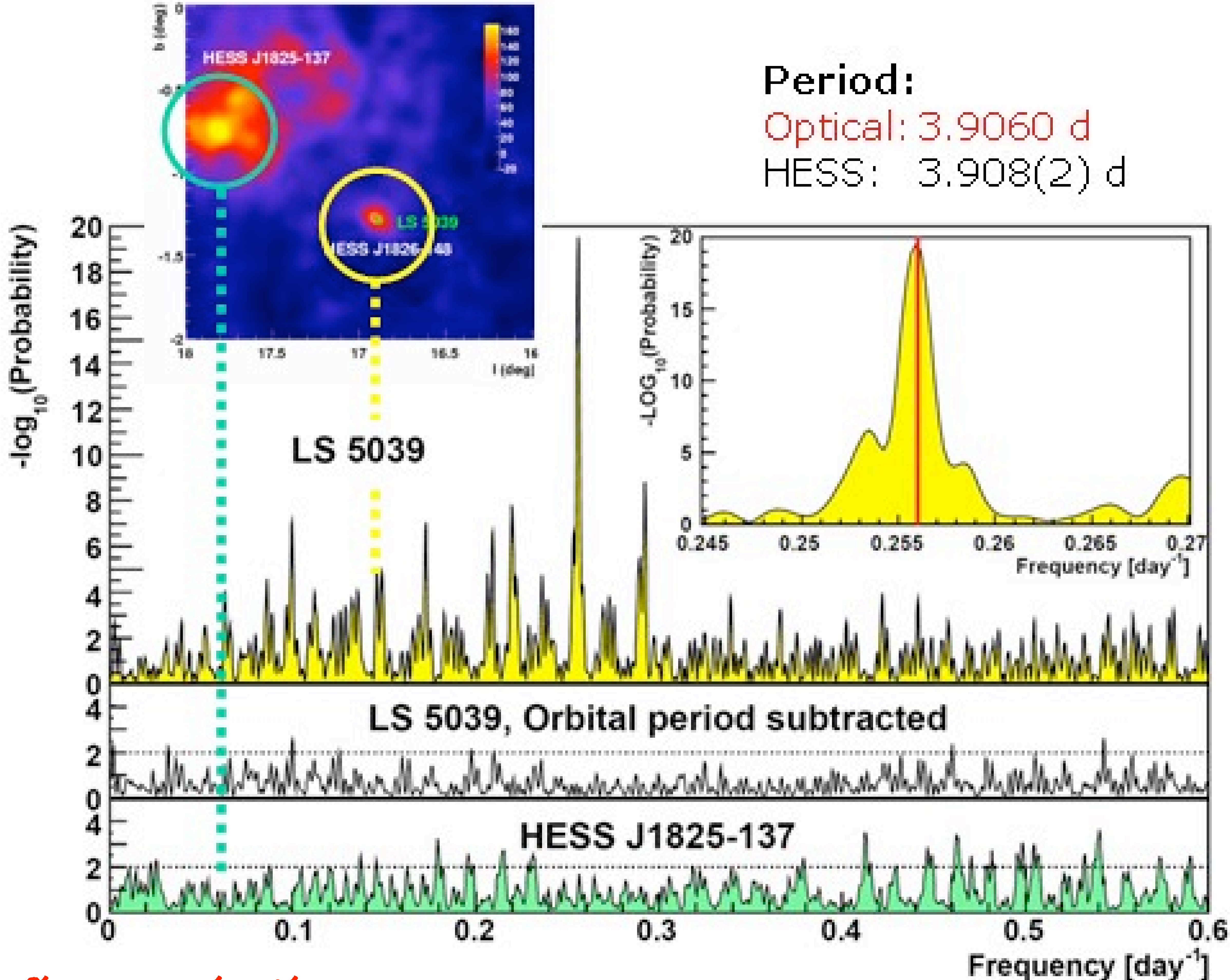
Associated with EGRET source?



Period:

Optical: 3.9060 d

HESS: 3.908(2) d



first periodic TeV source !

Spectral modulation

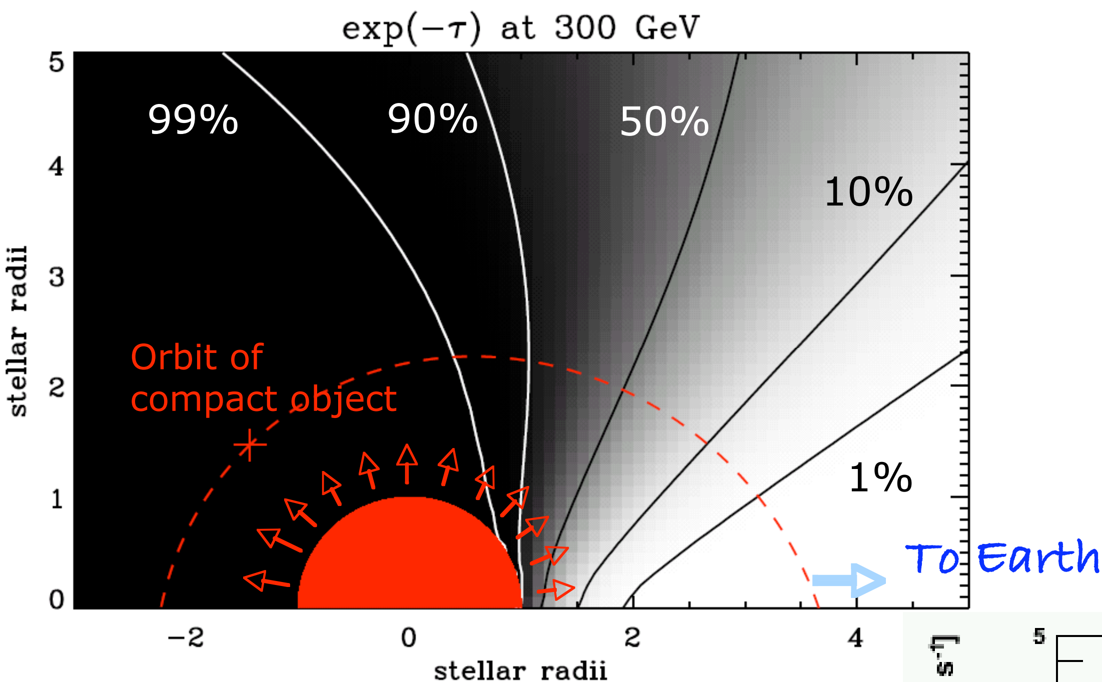
Minimum flux when

compact object is behind O-star

But energy dependant...

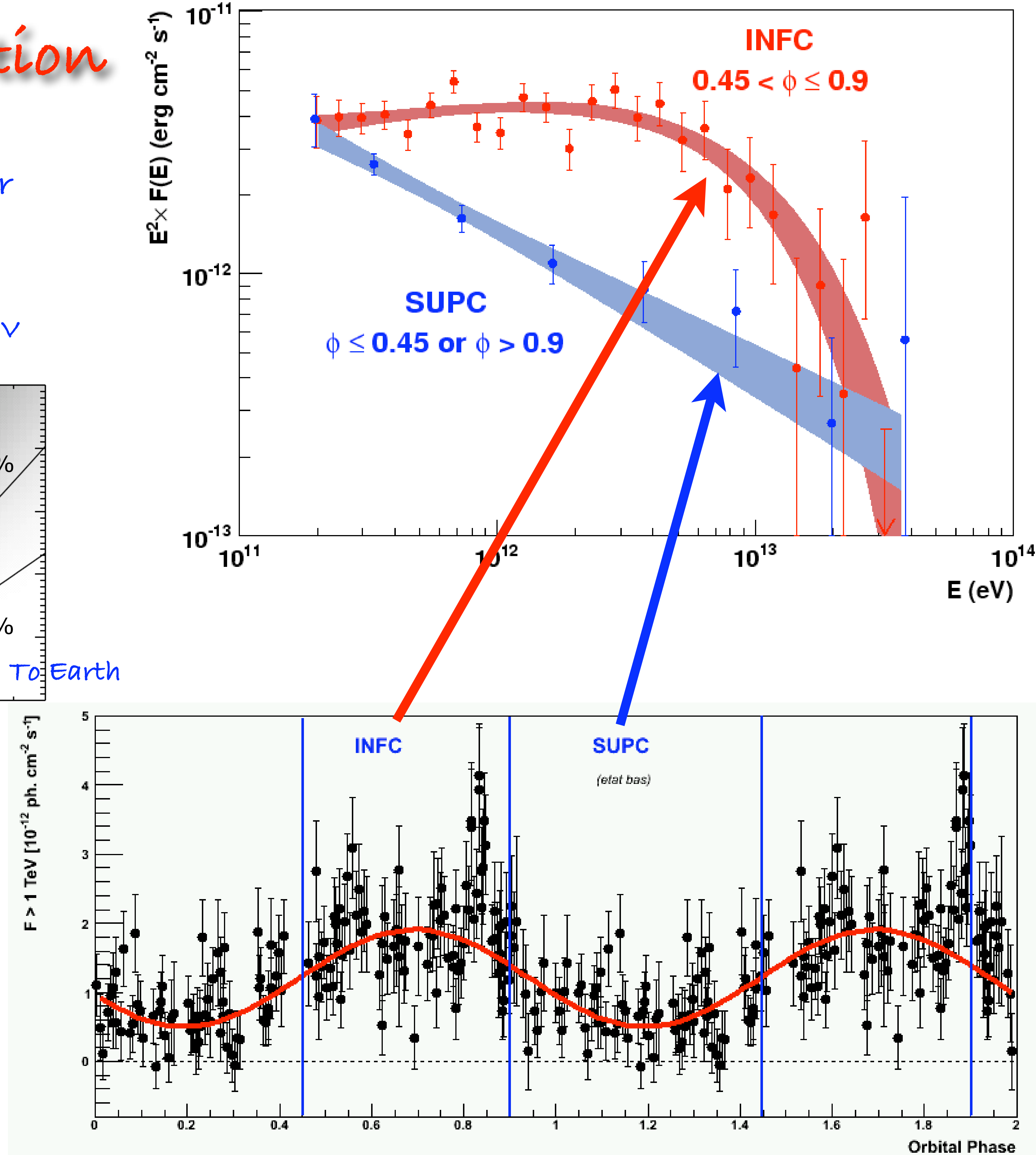
no modulation at 200 GeV,

maximum modulation at few TeV



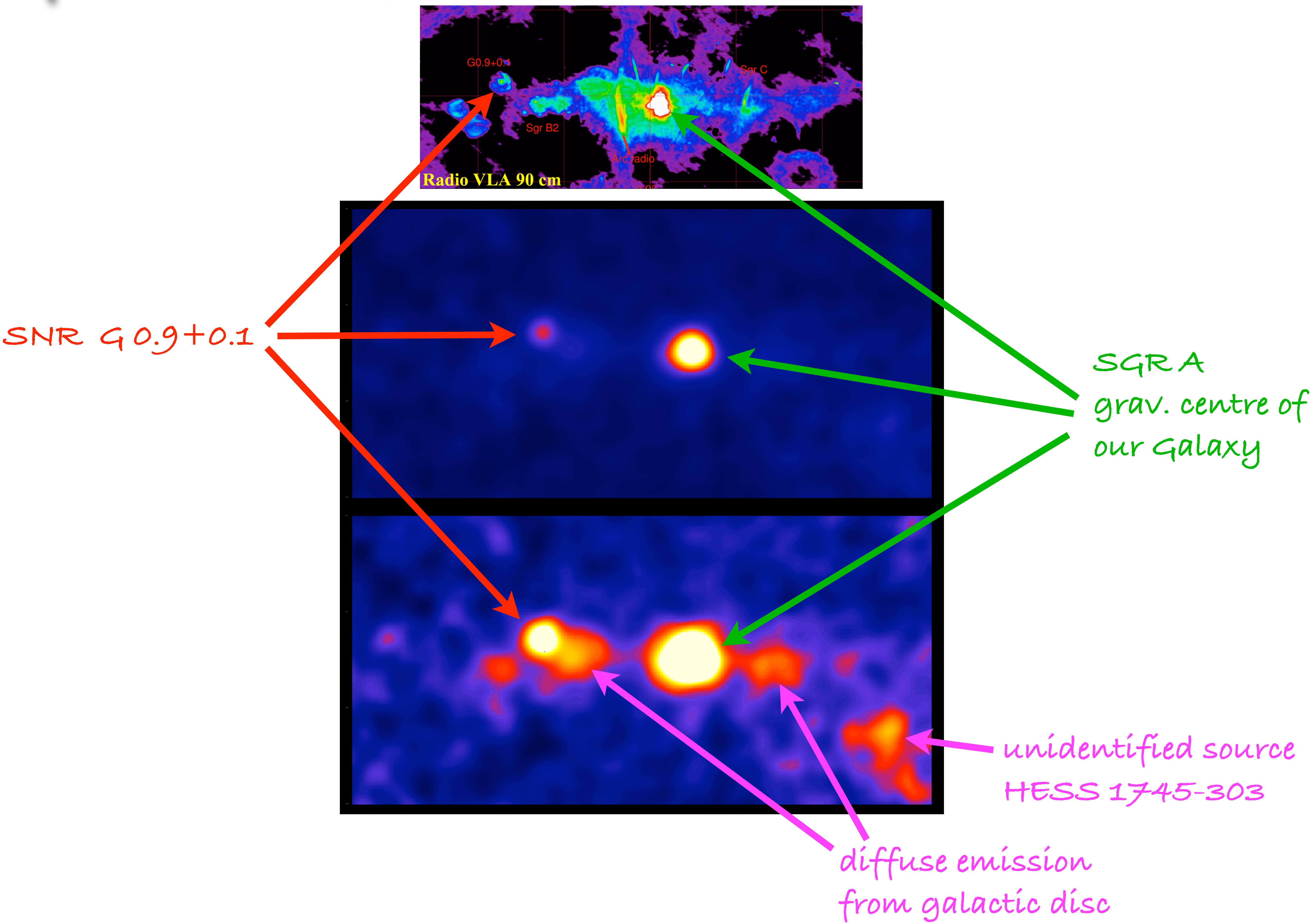
Modulation due to

accretion rate or absorption ?

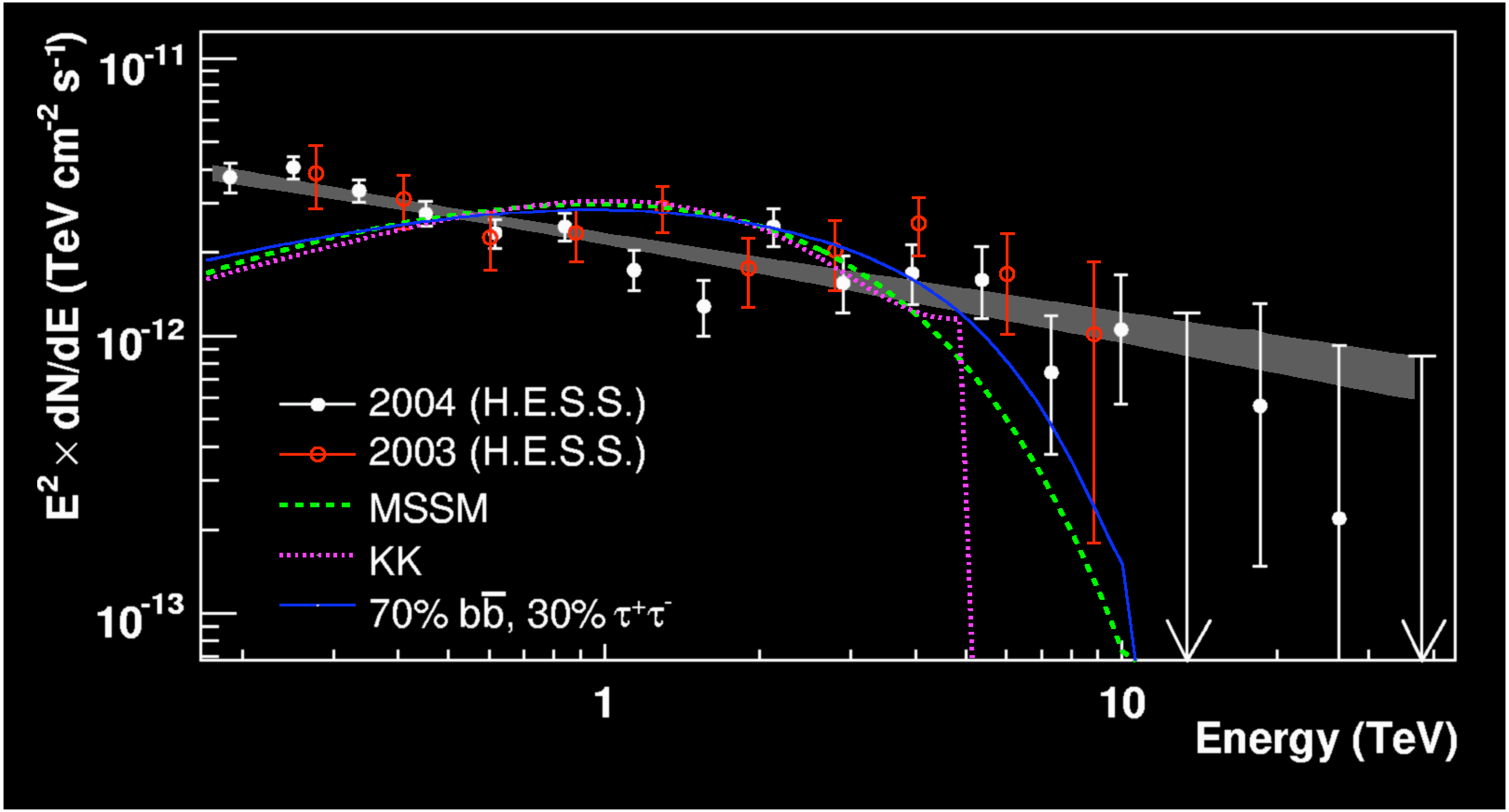


Galactic Centre

HESS, Nature 2006

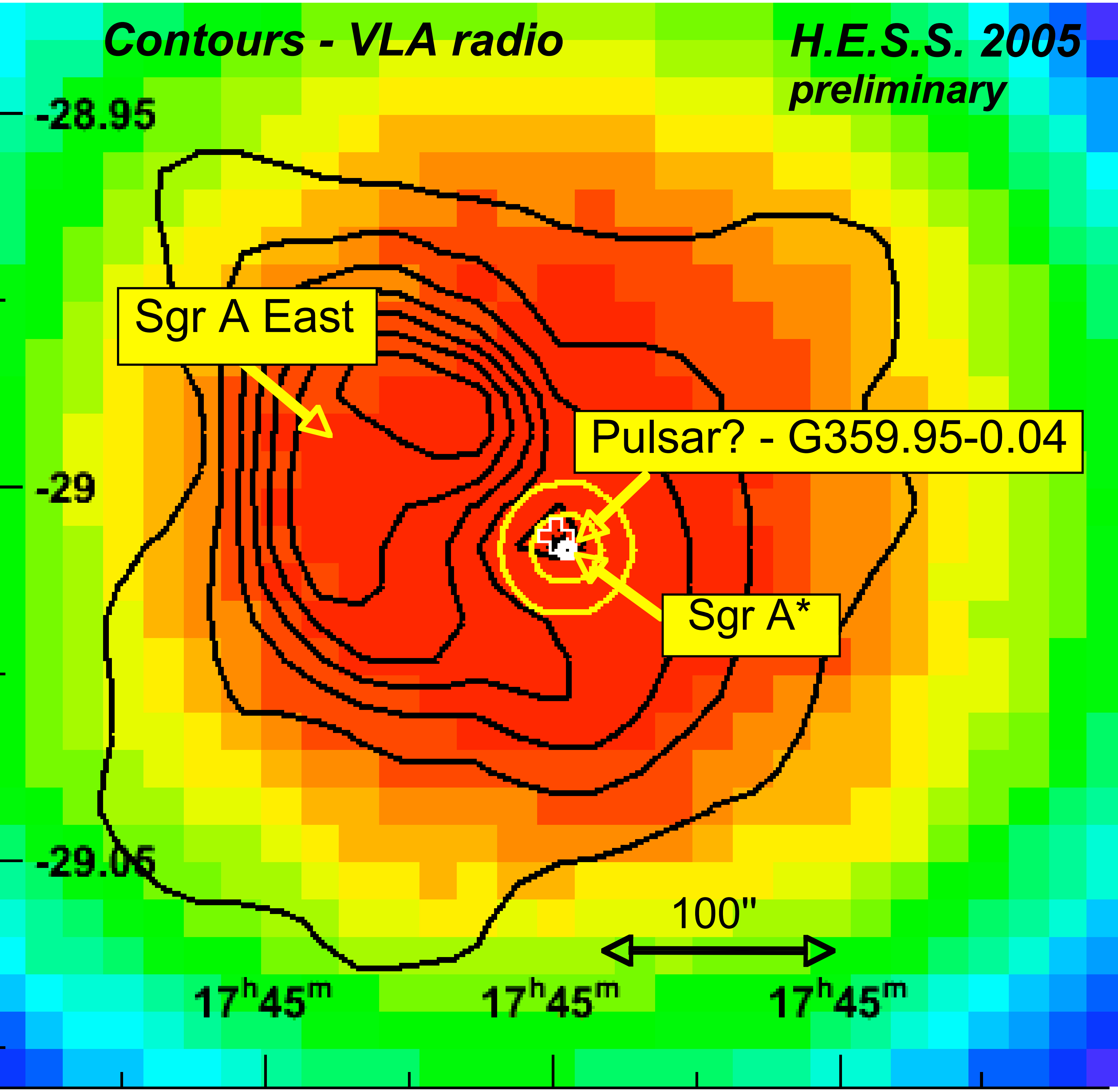


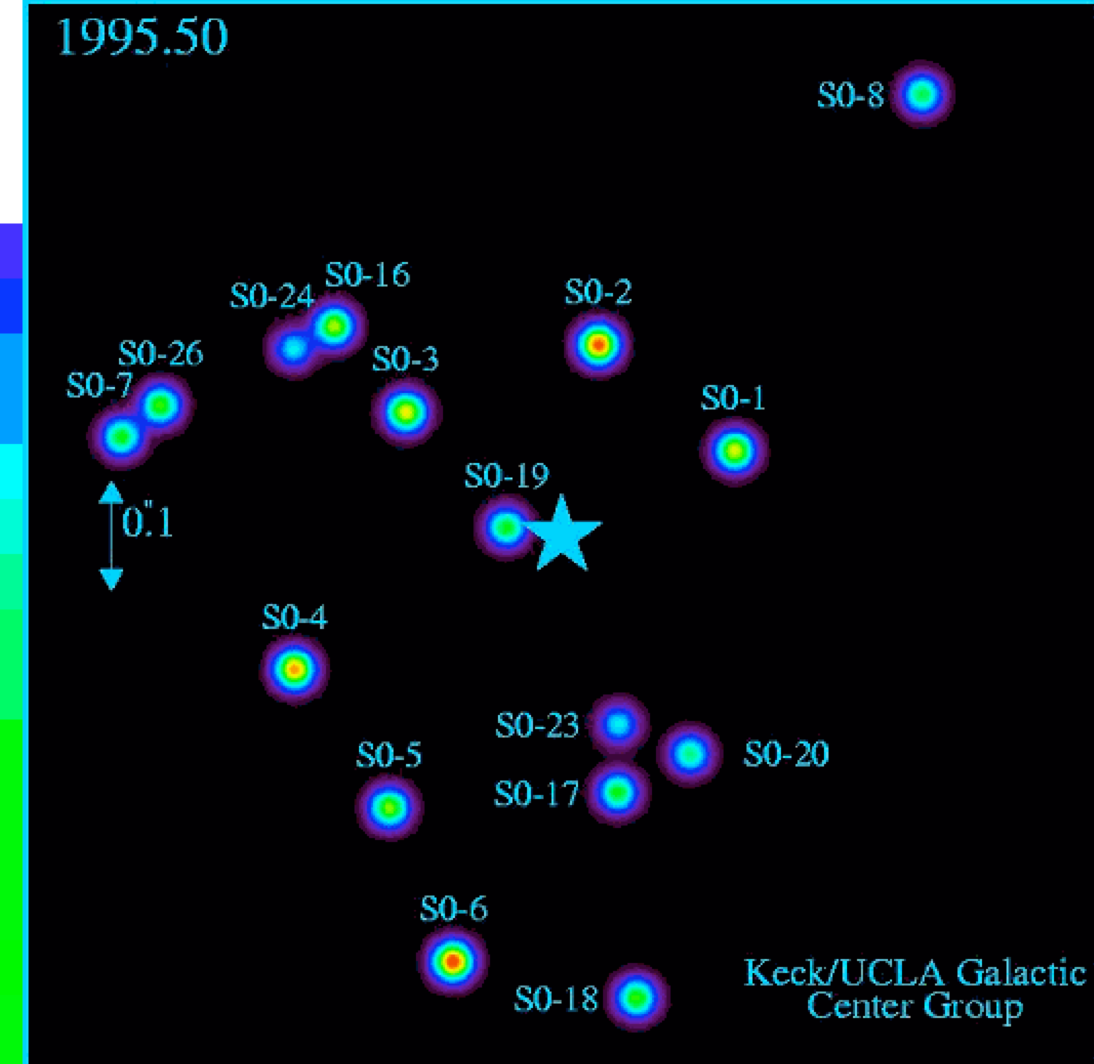
Spectrum of Sagittarius A

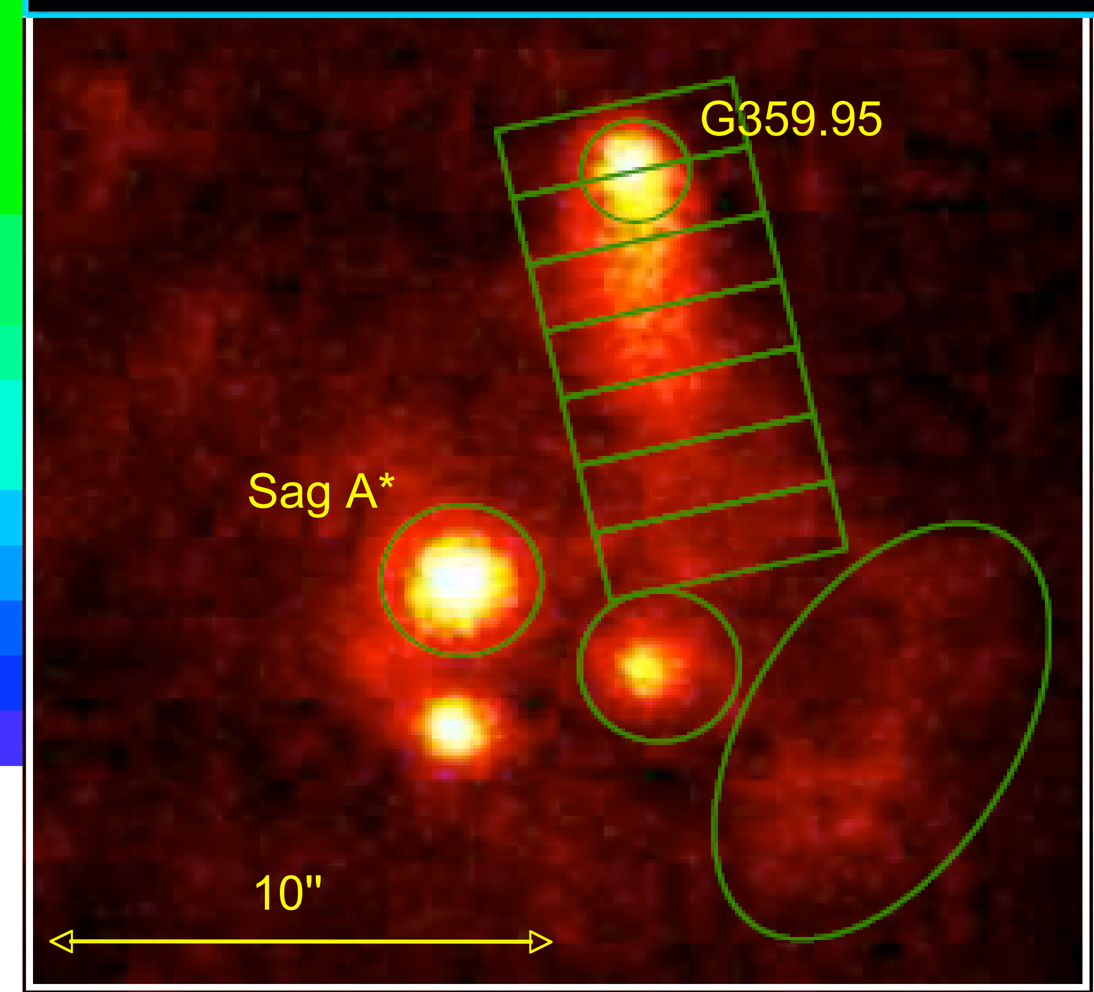


Power law spectrum: accelerated particles
not DM annihilation

Which is the accelerator ?

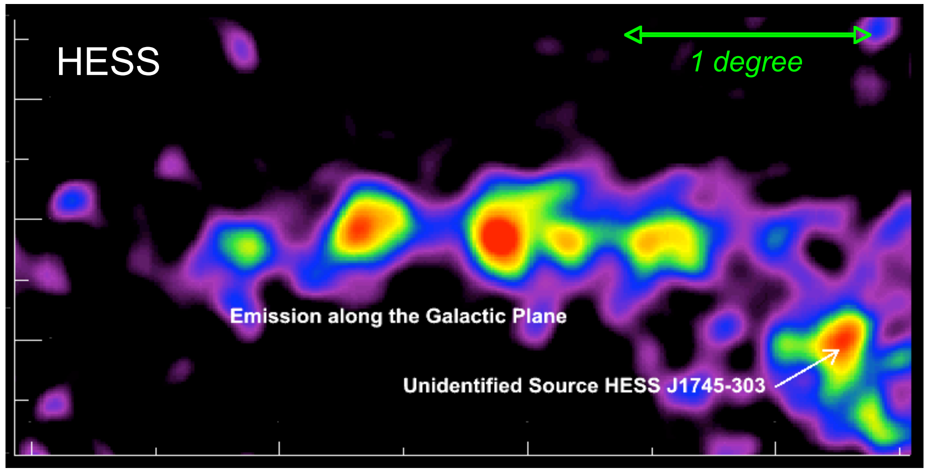

Contours - VLA radio
H.E.S.S. 2005
preliminary
-28.95
-29
-29.05
Sgr A East
Pulsar? - G359.95-0.04
Sgr A*
100"
17h45m
17h45m
17h45m

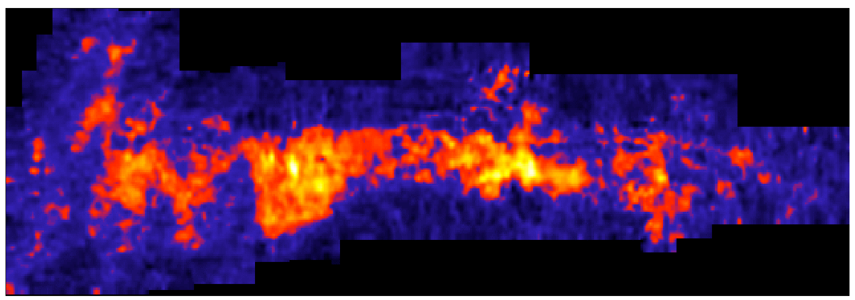

1995.50
S0-8
S0-24
S0-16
S0-2
S0-26
S0-3
S0-7
S0-1
S0-19
0."1
S0-4
S0-23
S0-20
S0-5
S0-17
S0-6
S0-18
Keck/UCLA Galactic
Center Group


G359.95
Sag A*
10"

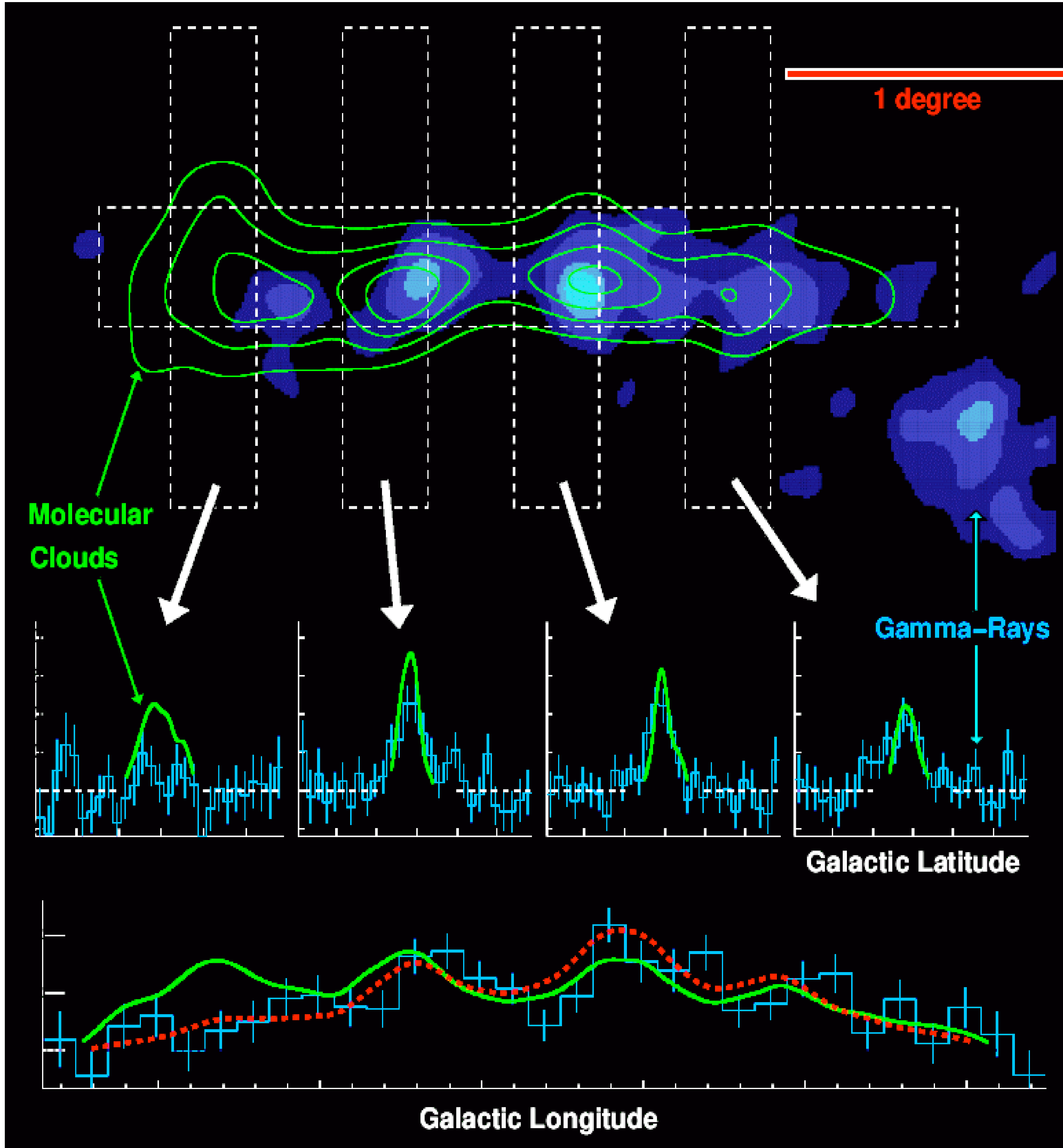
Diffuse Emission

after subtraction
of discreet sources



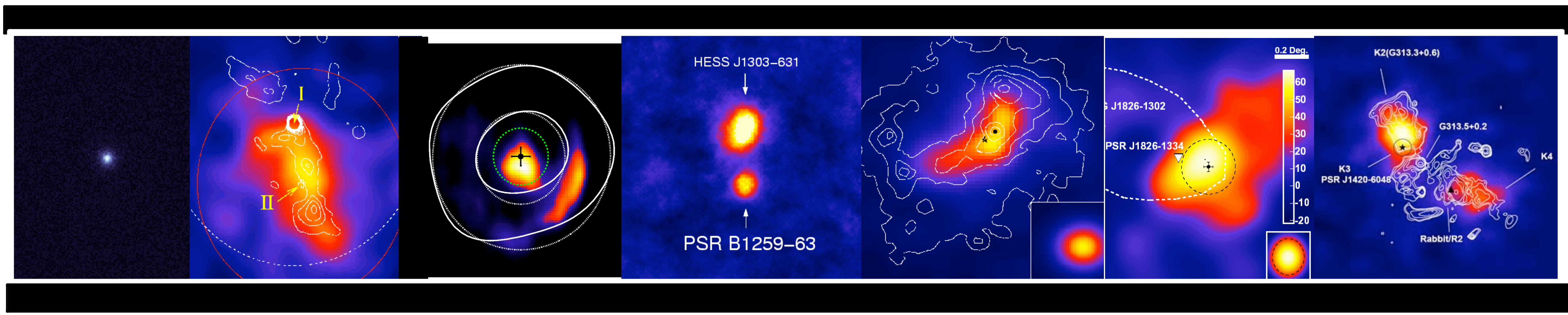


CS Line Emission
(dense clouds)
smoothed to match
HESS PSF

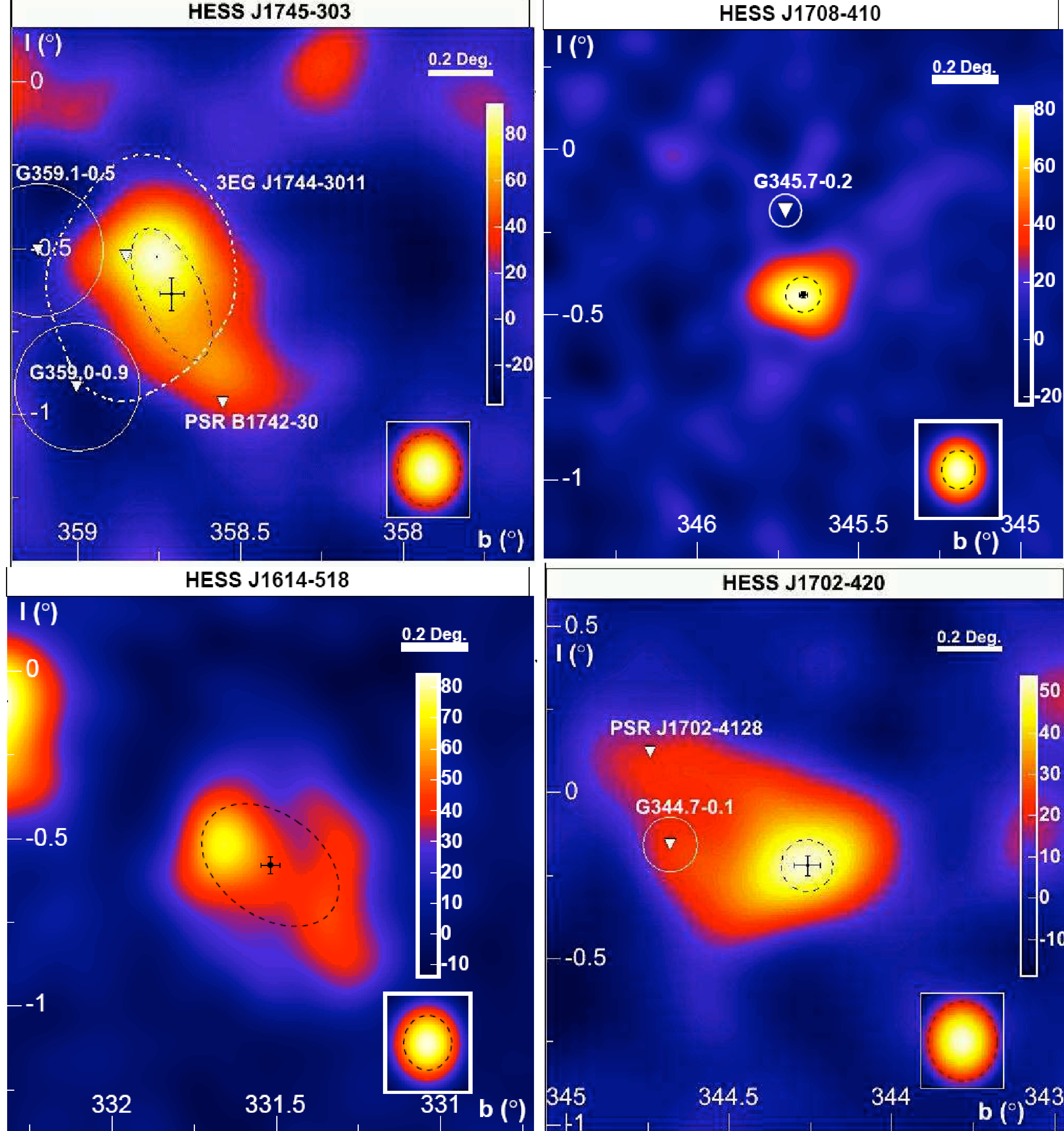


Molecular clouds
glow in TeV gamma-rays,
being bombarded by
cosmic ray protons and nuclei !

Pulsar Wind Nebulae

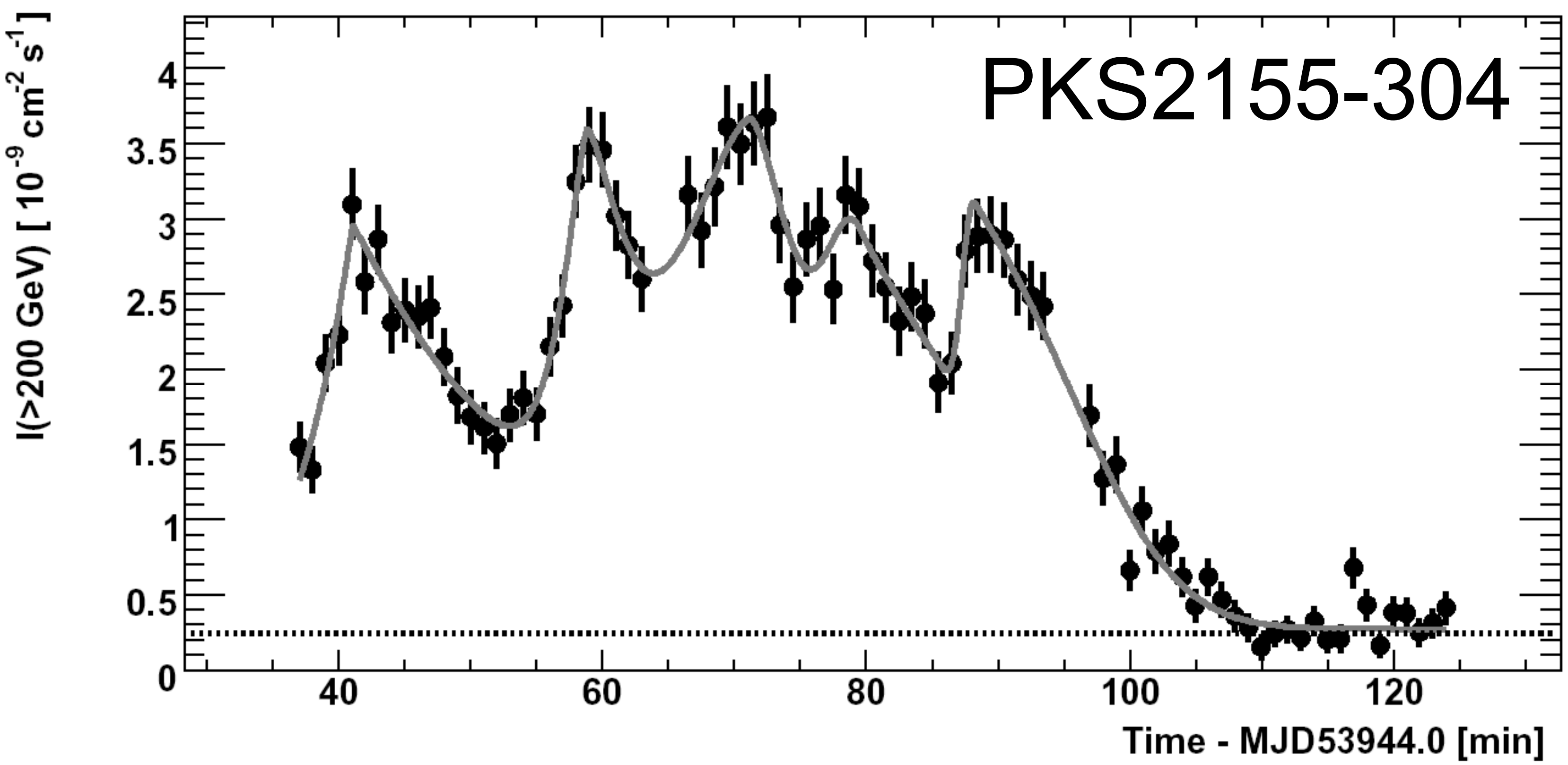


Sources without Counterpart



AGN: Blazars + M87

Outburst in 2006,
intensity doubling in < 5 min !!!

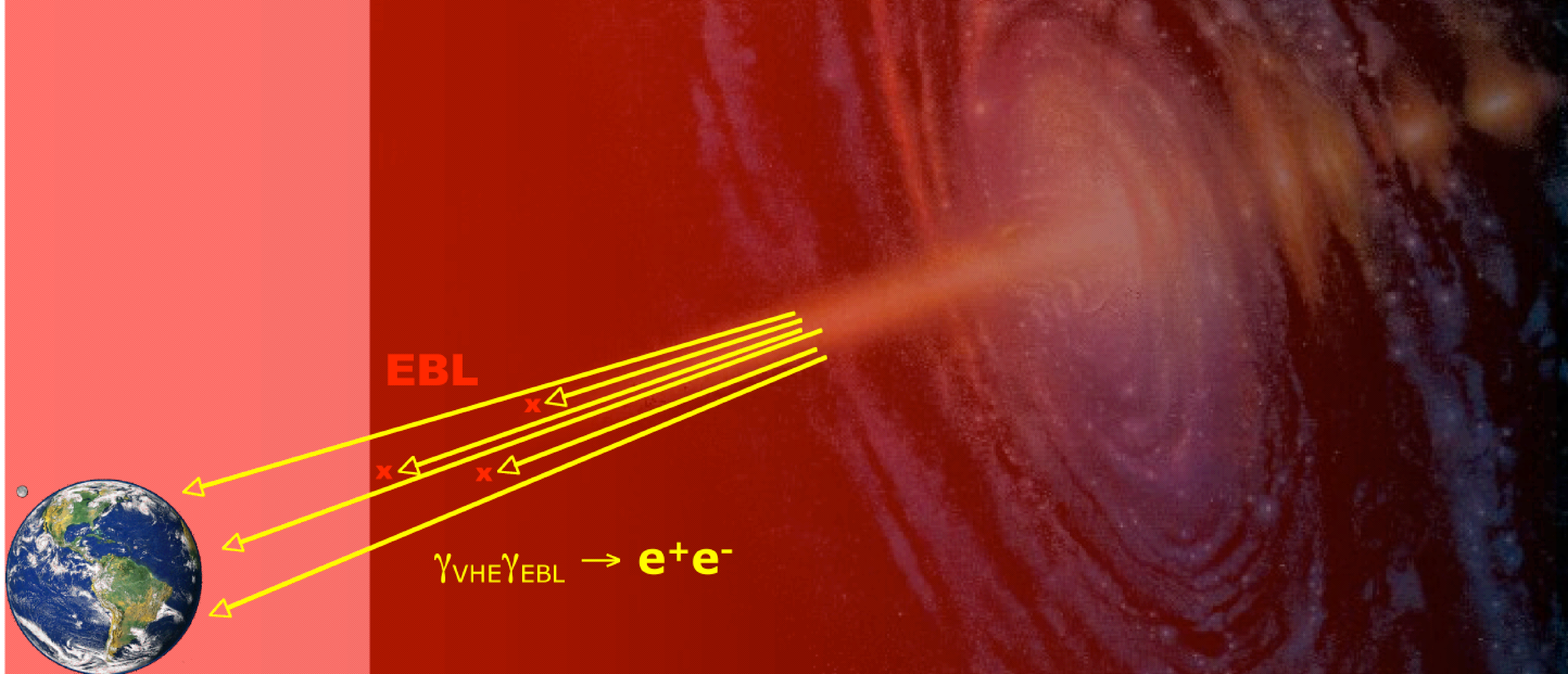


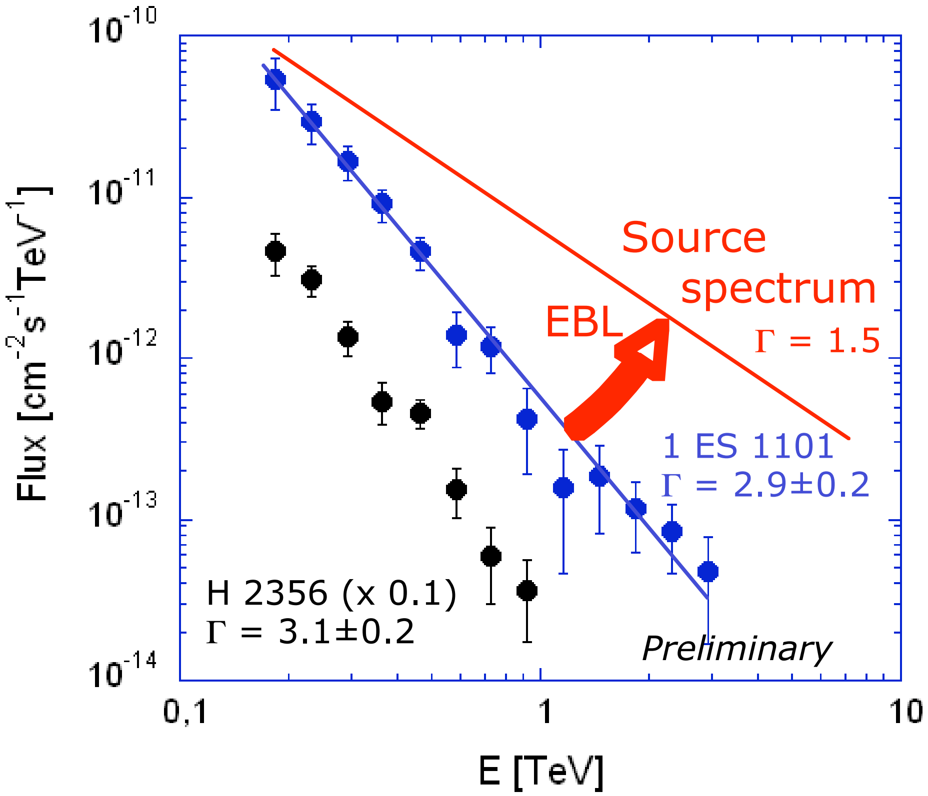
20 x brighter than the Crab Nebula.
The burst contained over 60000 gamma rays!

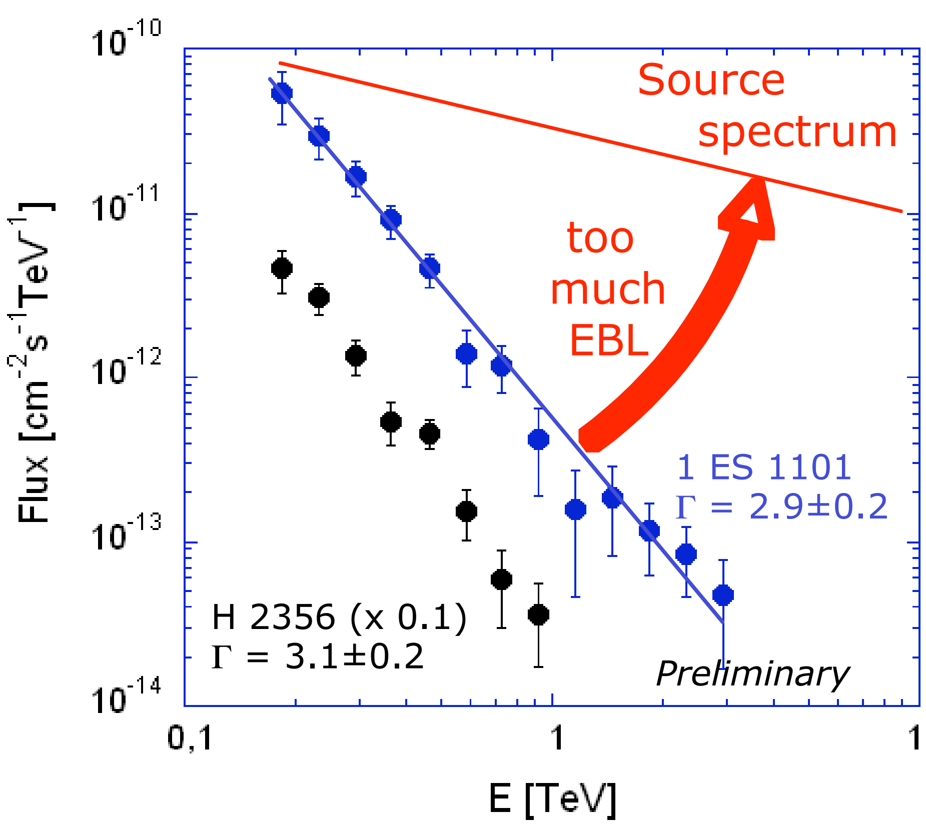
Allow limits on Quantum Gravity effects from time lag between high and low energy gammas

Extragalactic TeV astronomy

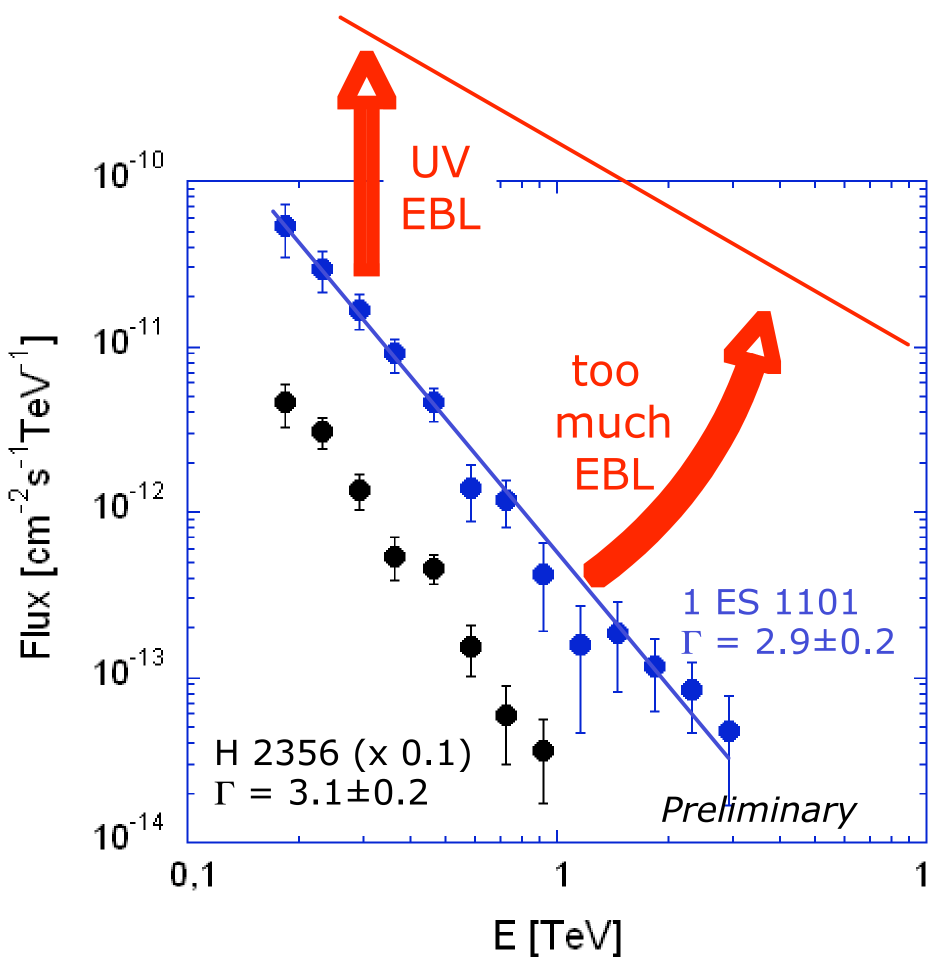
- Physics of AGN jets
- Density of cosmological extragalactic background light (EBL)







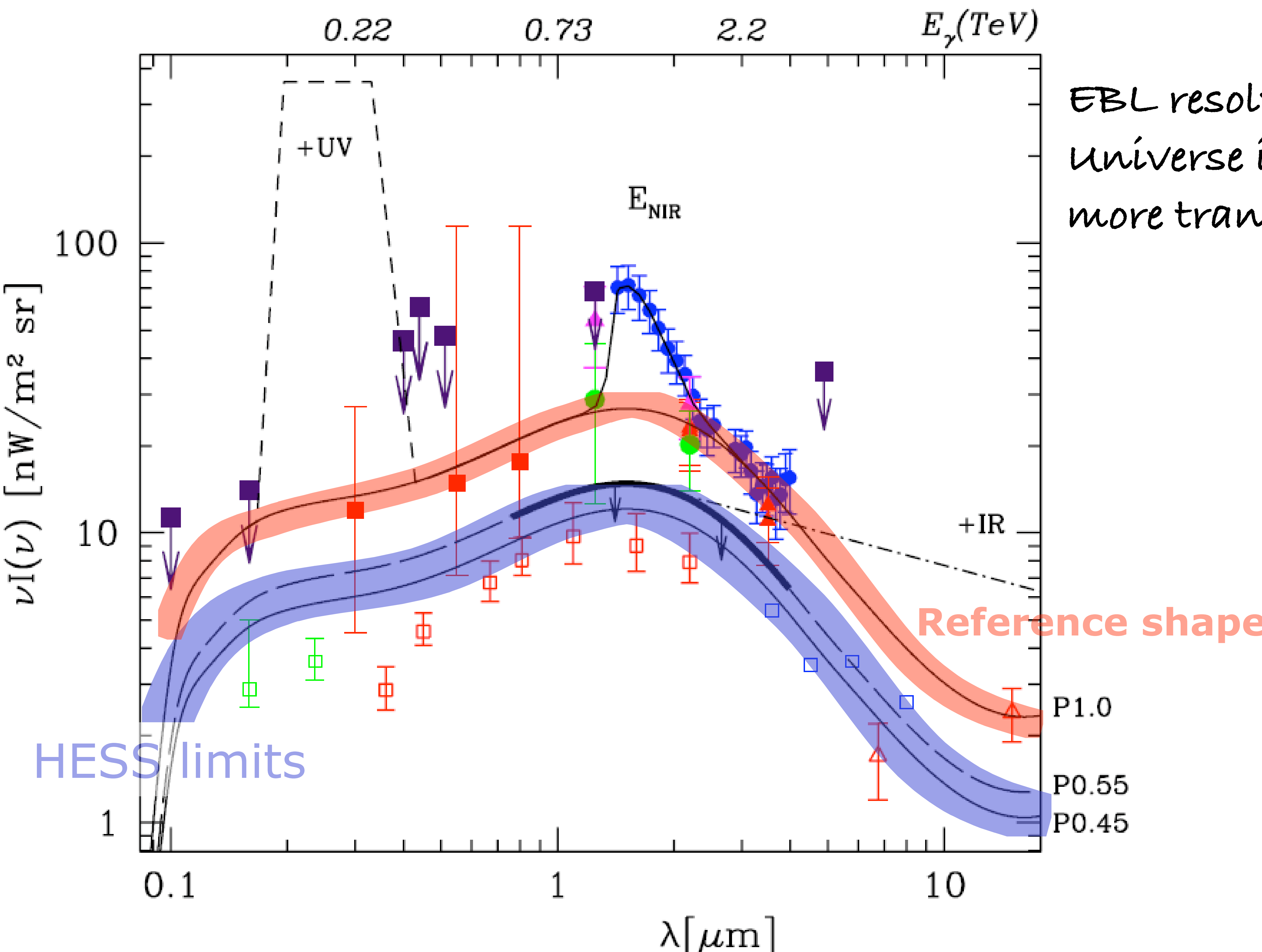
⏩ Upper limit on EBL



Not really a solution:

add huge amount of UV photons to EBL

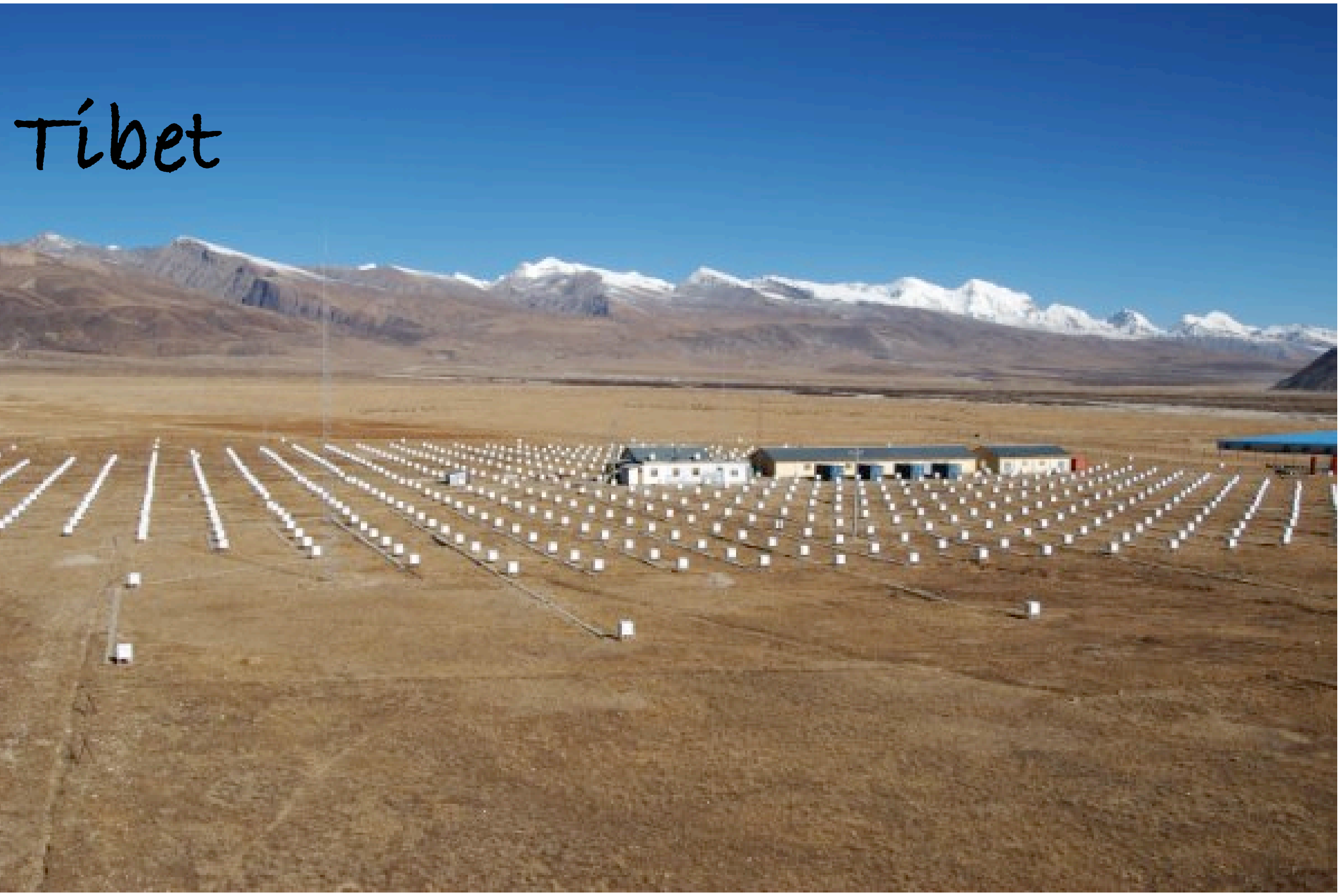
⏩ problems with source energetics, X-ray/gamma-ray SED ratio



EBL resolved,
Universe is
more transparent

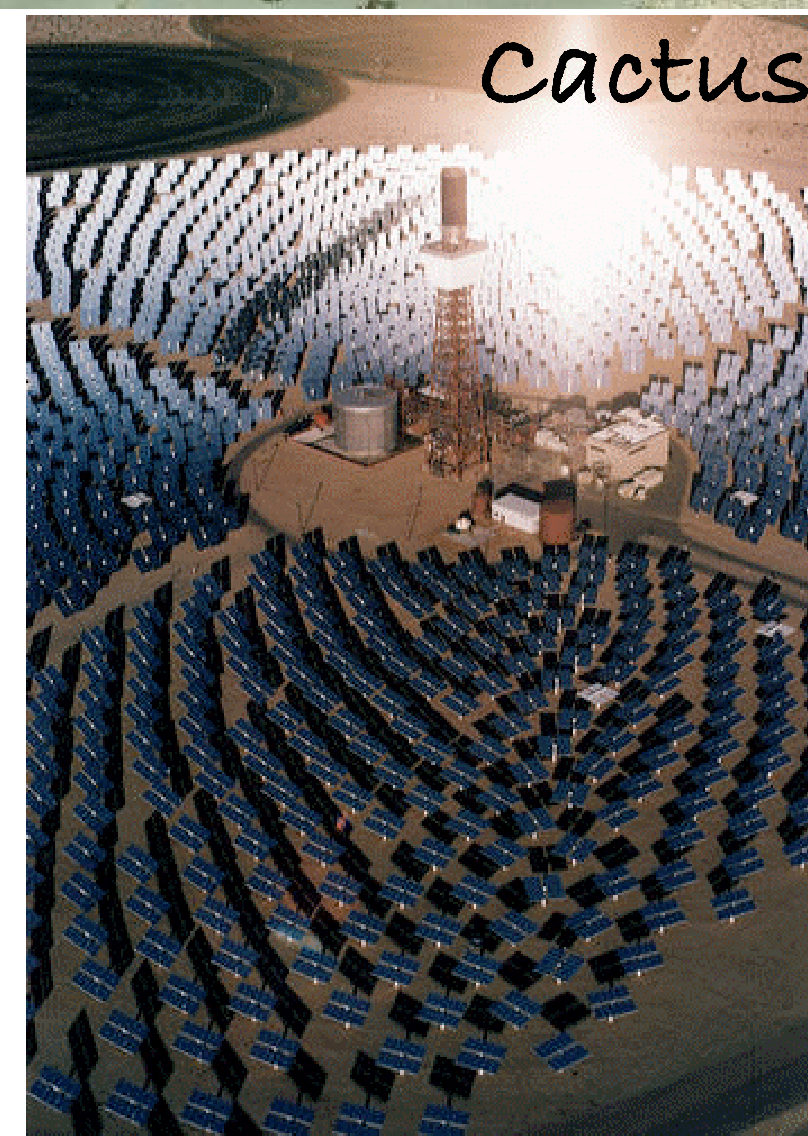
… and much more …

Truly, a new window
has been opened.



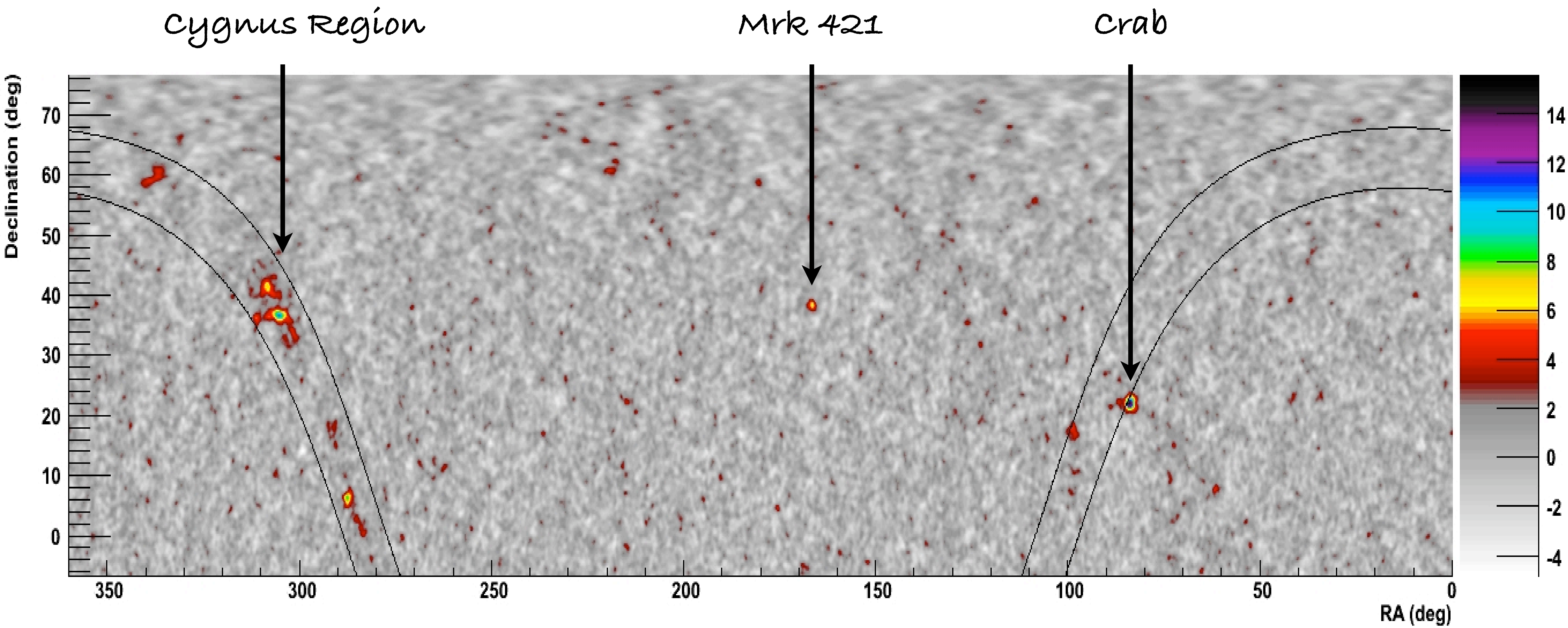
solar power plants:
low threshold, but
poor imaging &
limited resolution

arrays:
all-sky capability
but high threshold



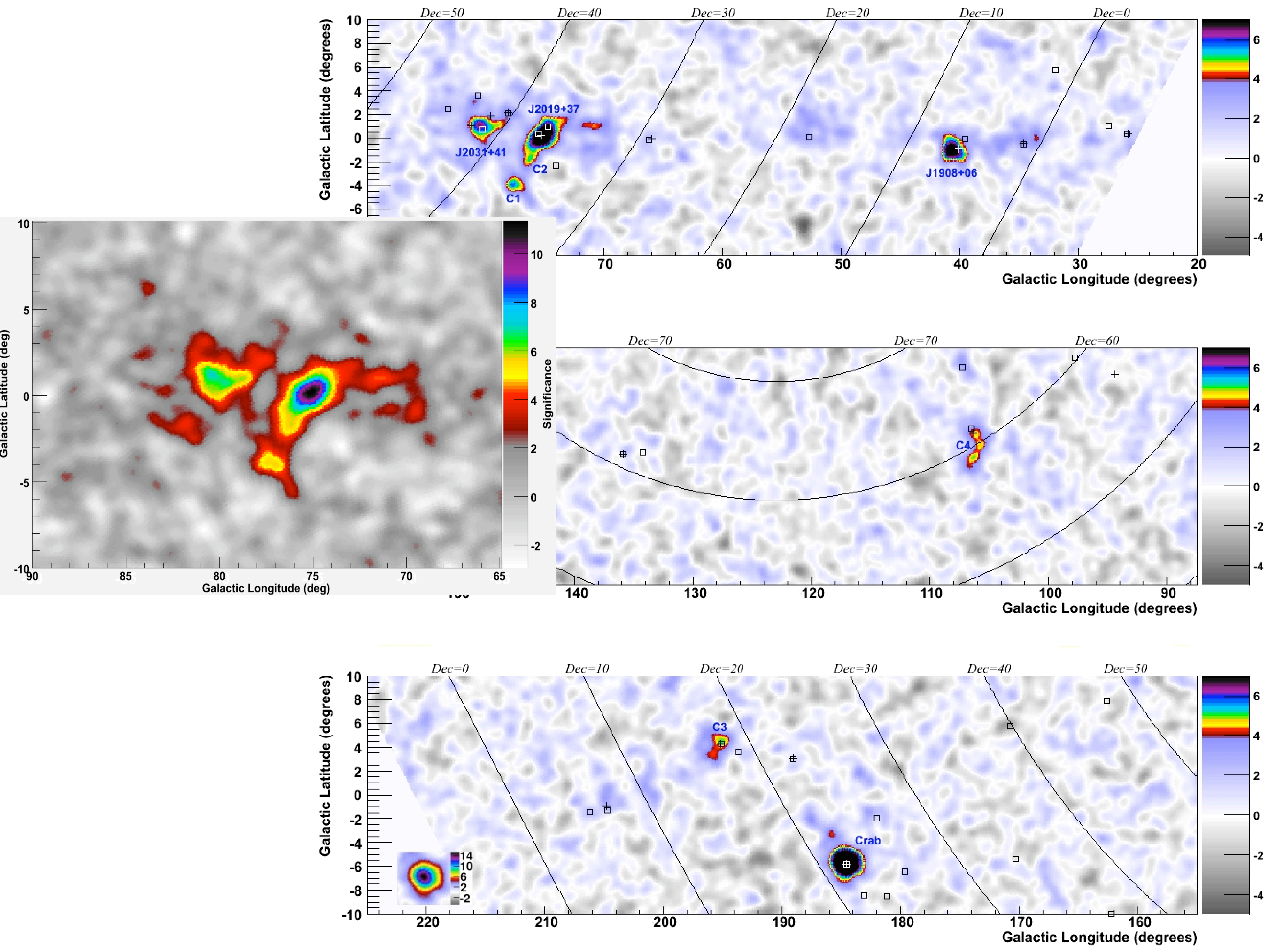
Milagro: Sky survey @ 20 TeV

ICRC 2007



Milagro: 6.5 years of data: Crab: 15 sigma

HESS: 10 h: 0.1 Crab: 15 sigma



Dec=50
Dec=40
Dec=30
Dec=20
Dec=10
Dec=0
J2019+37
J2031+41
C2
C1
J1908+06
Galactic Latitude (degrees)
Galactic Longitude (degrees)
Galactic Latitude (deg)
Galactic Longitude (deg)
Significance
Dec=70
Dec=60
C4
C3
Crab

Future of Gamma Ray Astronomy

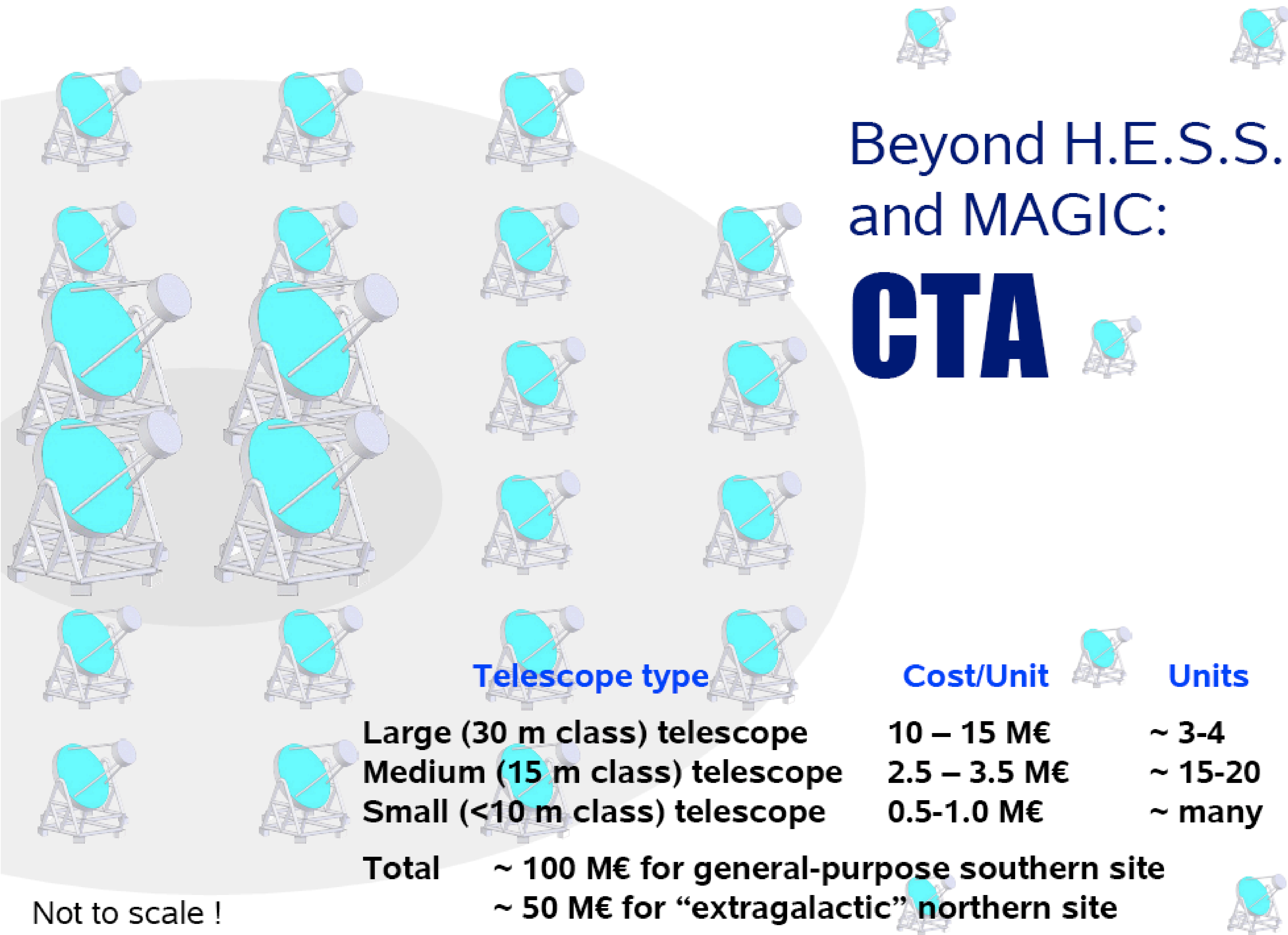
GLAST: launch in 2008
many sources at <100 GeV

MAGIC 2: second 17-m telescope
for stereo observations

HESS 2: 25 m diameter mirror
for improved sensitivity at lower energies

Cherenkov Telescope Array CTA (Euro 150M)
2 sites (N+S), arrays of different-sized telescopes
detect >1000 sources !

Beyond H.E.S.S. and MAGIC: CTA

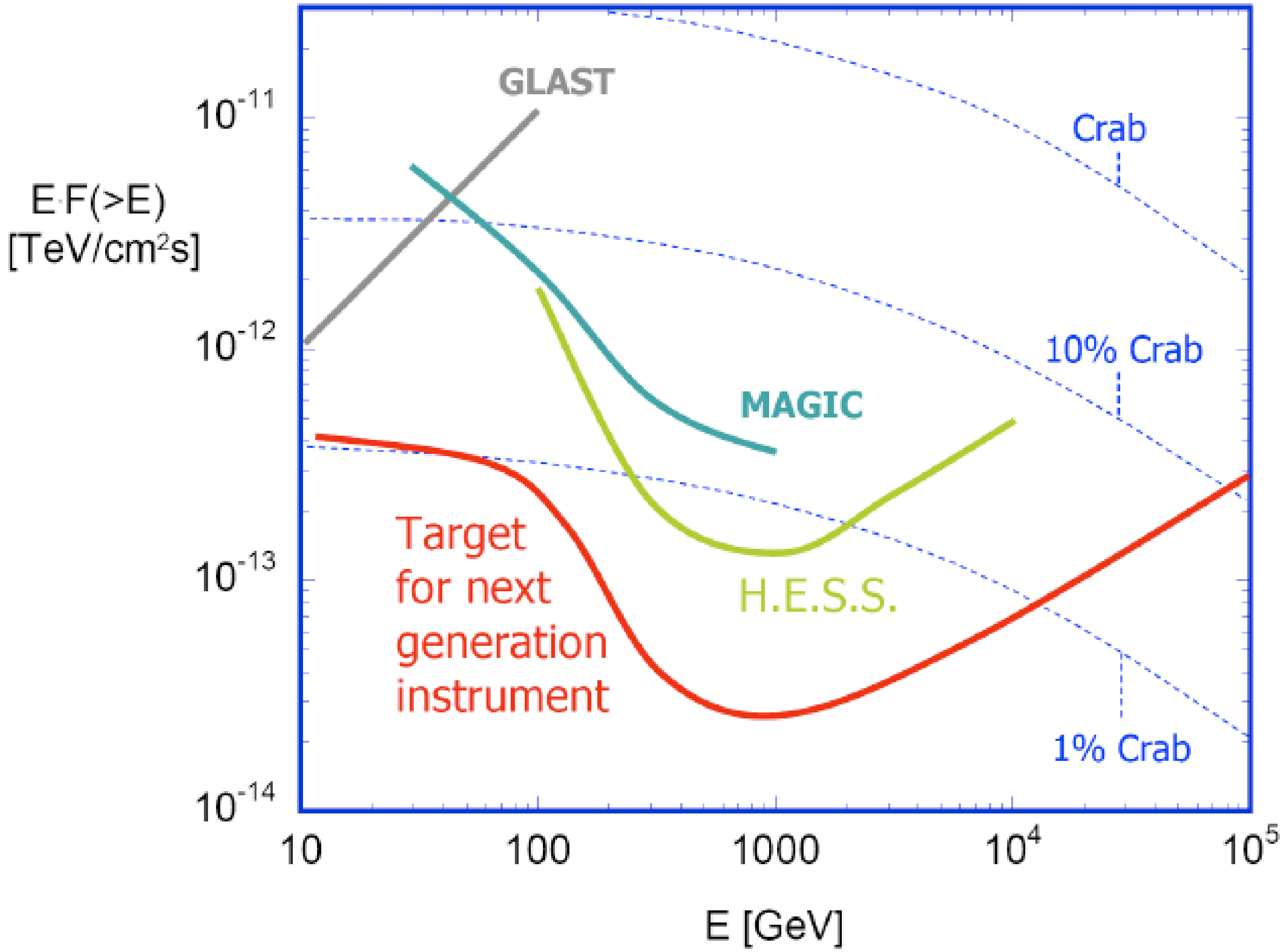


Telescope type	Cost/Unit	Units
Large (30 m class) telescope	10 – 15 M€	~ 3-4
Medium (15 m class) telescope	2.5 – 3.5 M€	~ 15-20
Small (<10 m class) telescope	0.5-1.0 M€	~ many

Total ~ 100 M€ for general-purpose southern site
~ 50 M€ for “extragalactic” northern site

Not to scale !

CTA Sensitivity: see 1000 sources



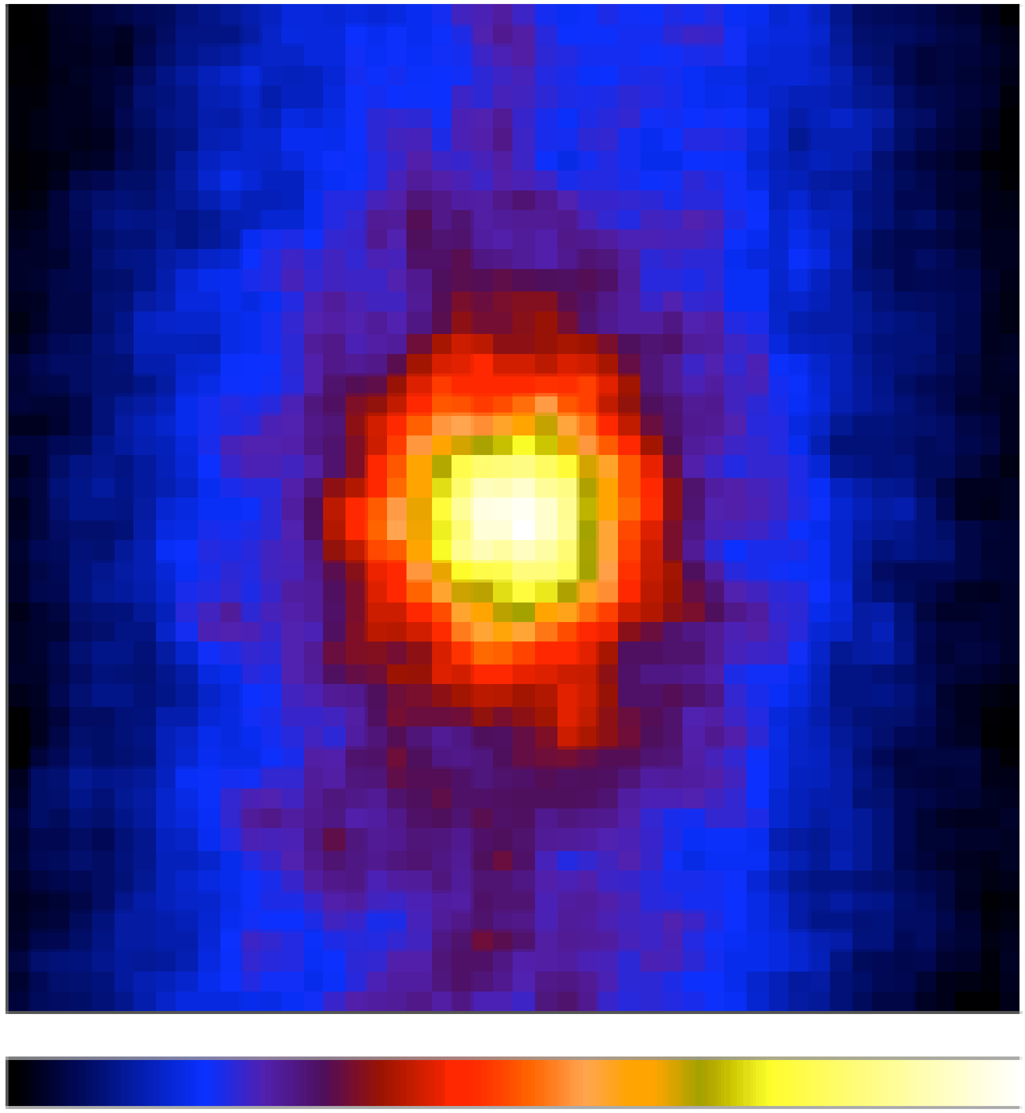
The TeV gamma ray window is wide open !

... with great views on the most energetic objects in the universe.

Neutrinos

The Neutrino Sky so far: (energies: MeV)

The Sun



Super- K (Japan) image
of the sun using neutrinos

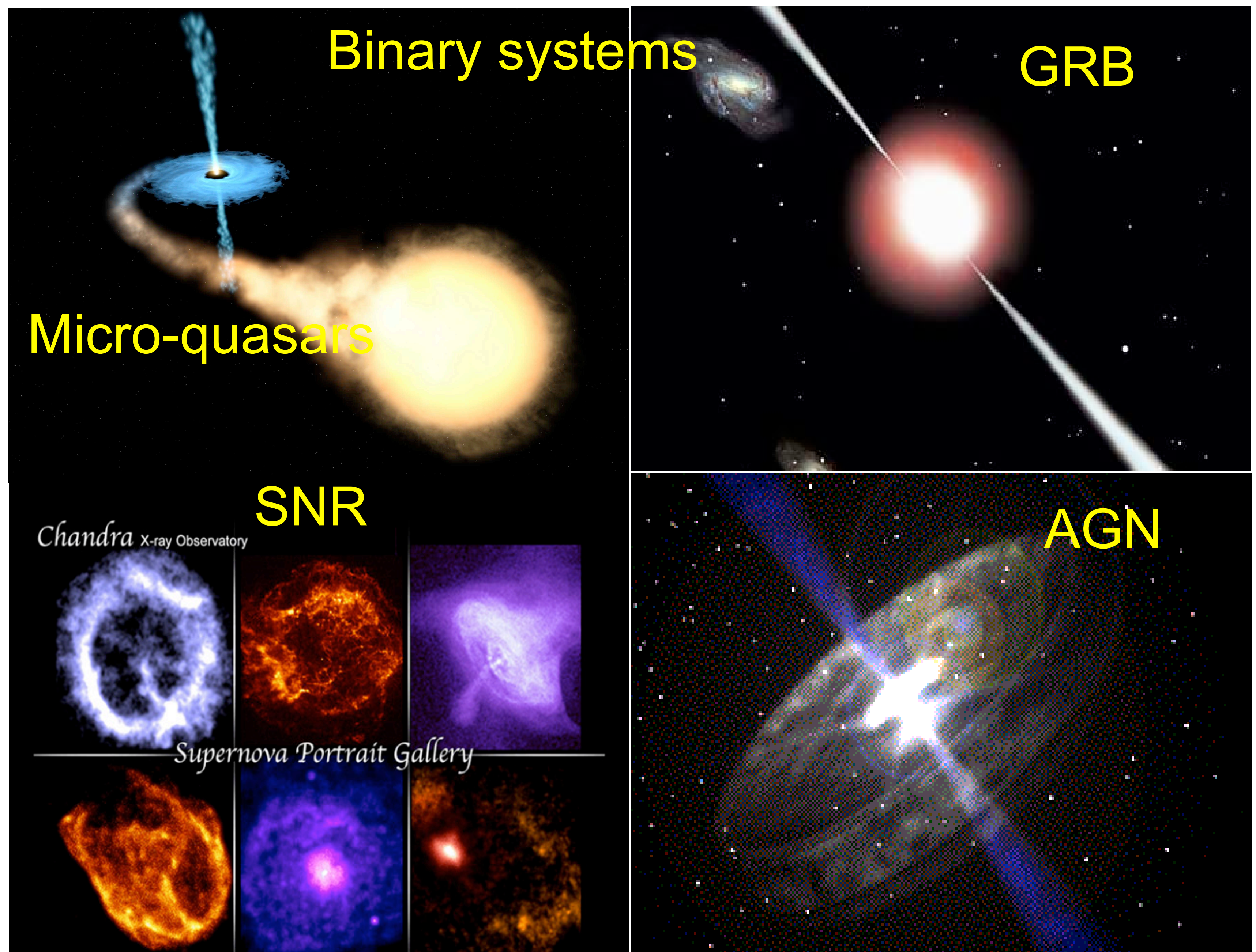
SN 1987 A

few (<20) neutrinos seen
by 3 experiments
during 10 seconds

Potential neutrino sources
(galactic and extra galactic)

... wherever energetic particles interact

e.g.:



Same sources as for gamma rays ...

but predicted neutrino fluxes are very uncertain.

Cosmic Rays, Gamma Rays and Neutrinos are linked

$$p, He, \ldots Fe \longrightarrow \pi^{\pm}, \pi^{0}$$

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}$$

$$\mu^{\pm} \longrightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

$$\pi^{0} \longrightarrow \gamma\gamma$$

only charged particles
can be accelerated by
el.mag. fields

very difficult
to detect

can't travel far
at high energies

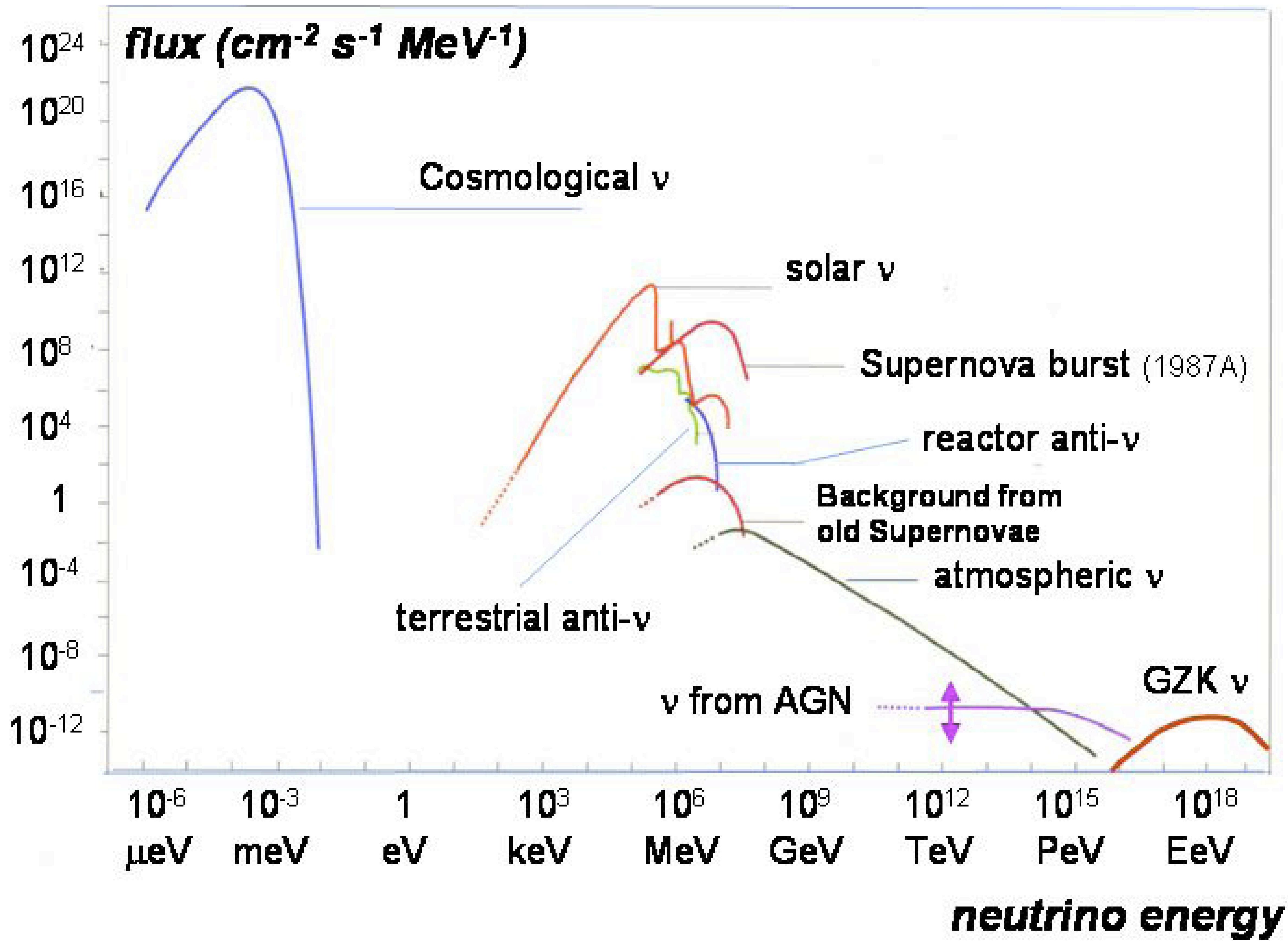
ν travel in straight lines and are not absorbed.

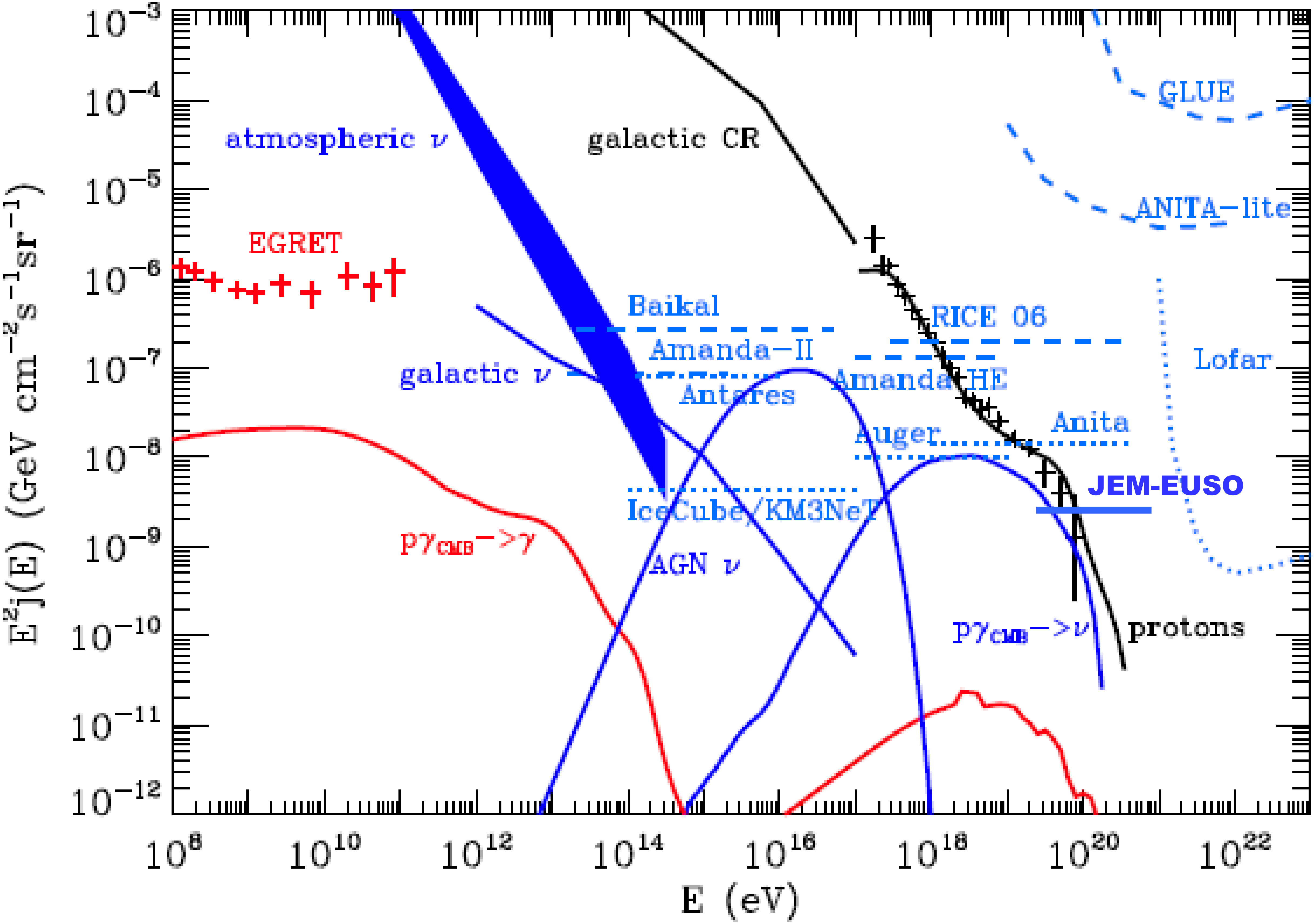
at source: νe : νmu : νtau $= 1 : 2 : 10^{-5}$

at Earth: νe : νmu : νtau $= 1 : 1 : 1$

but: probability of interacting in detector is small !!!

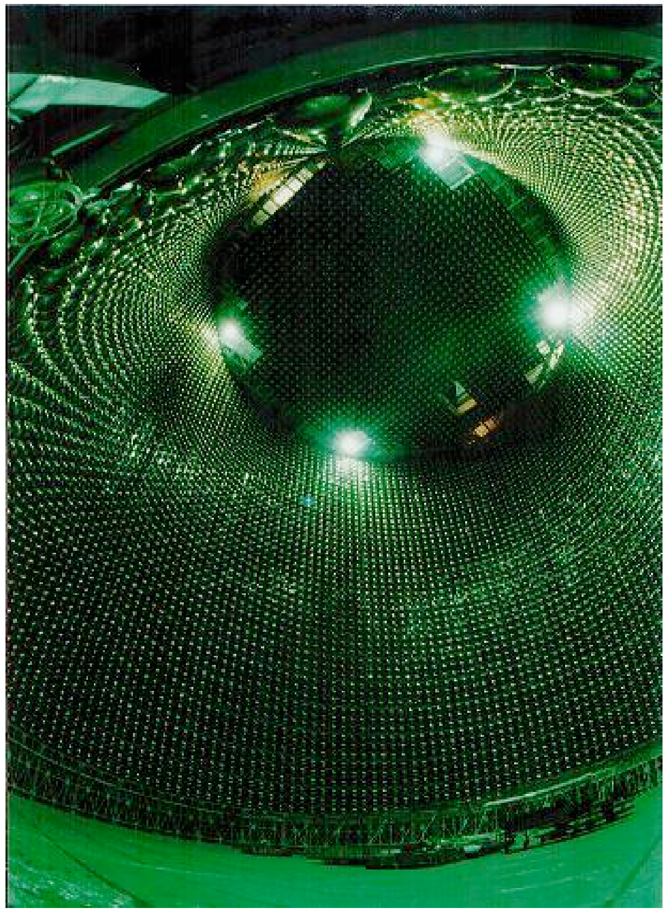
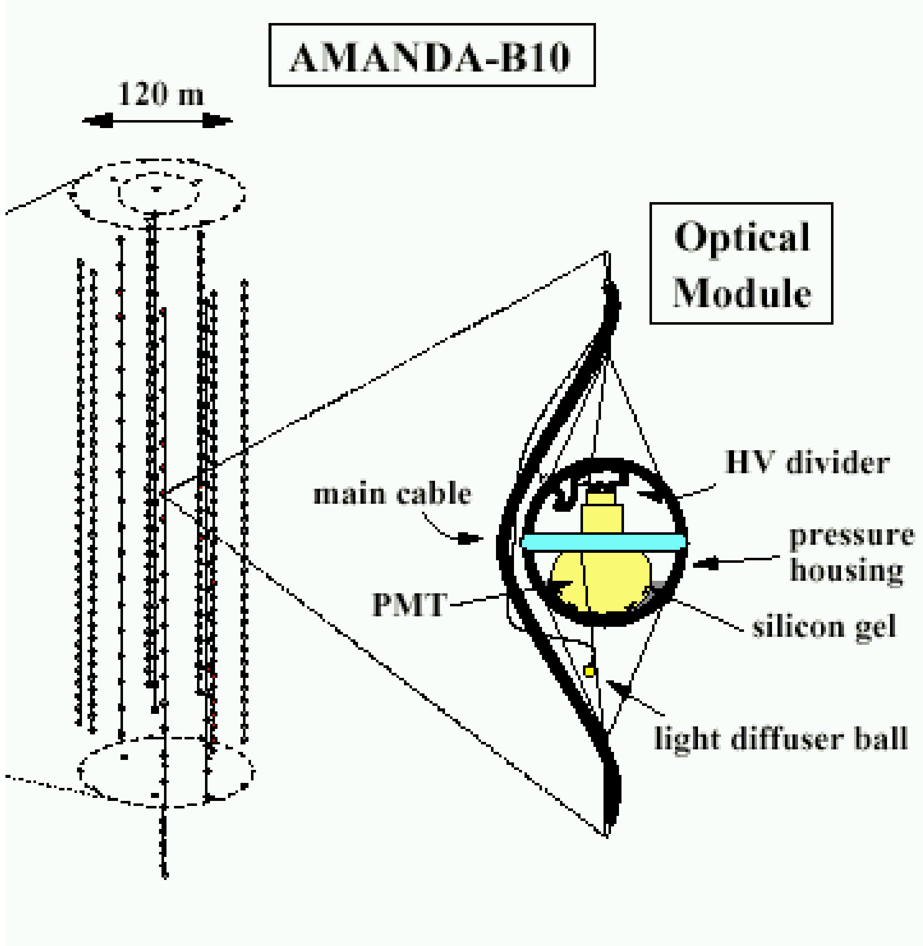
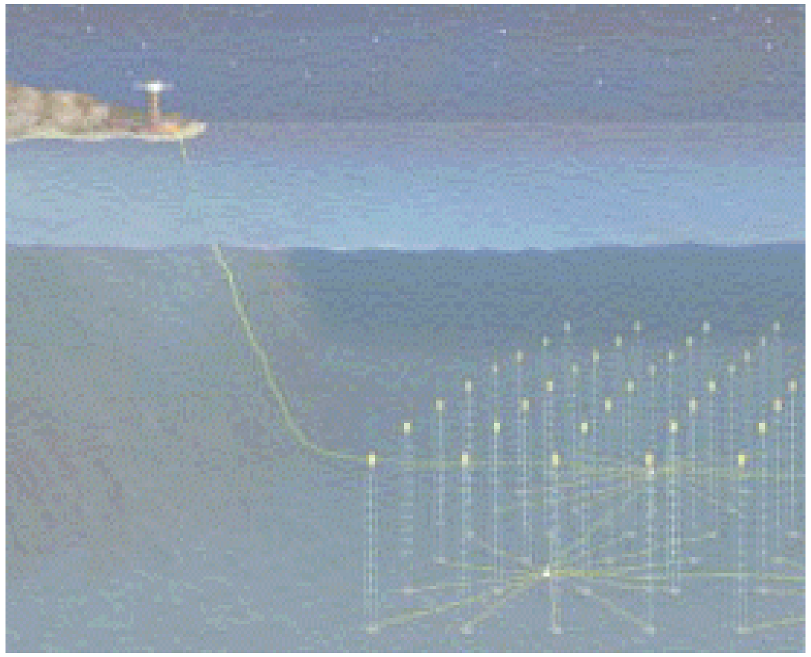
The Universal Neutrino Spectrum



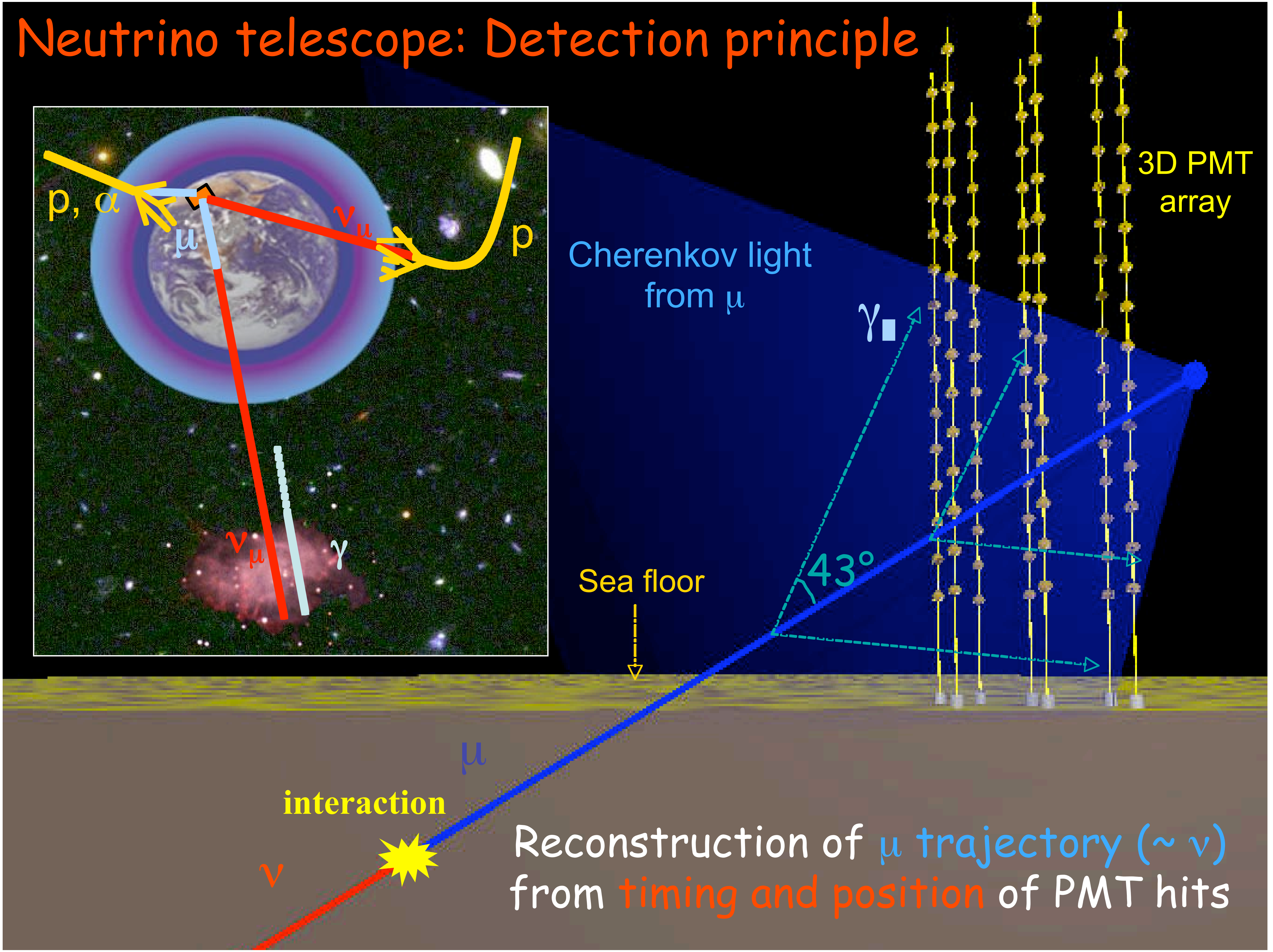


atmospheric ν
galactic CR
GLUE
ANITA−lite
EGRET
Baikal
RICE 06
Amanda−II
galactic ν
Antares
Amanda−HE
Lofar
Auger
Anita
JEM-EUSO
IceCube/KM3NeT
pγ_CMB−>γ
AGN ν
pγ_CMB−>ν
protons
E²j(E) (GeV cm⁻²s⁻¹sr⁻¹)
E (eV)

large detection volumes: e.g. water or ice;
Cherenkov effect to detect fast, charged particles;
deep underground to shield cosmic rays

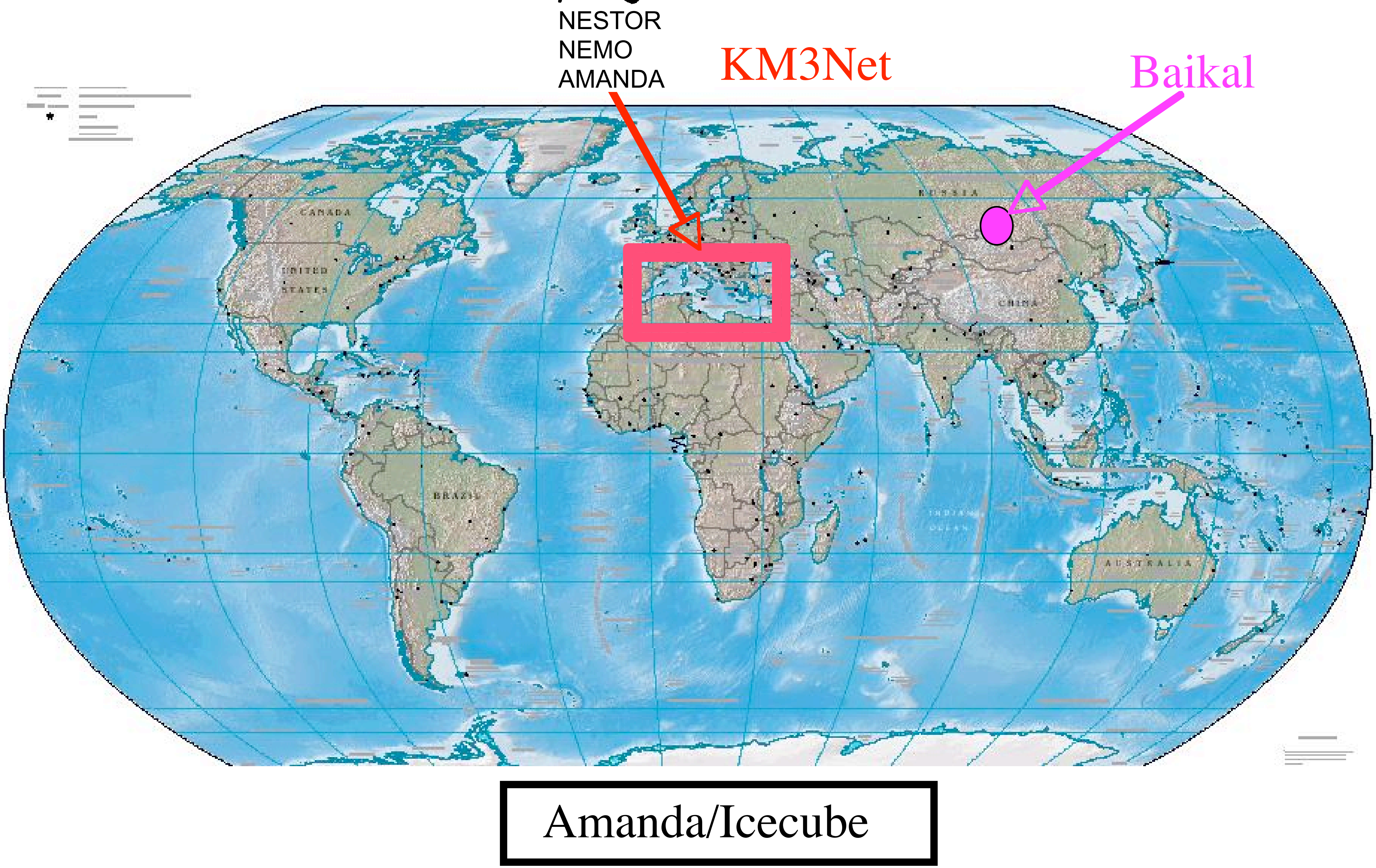
Super Kamiokande	AMANDA (south Pole)	KM3-Net (Mediterranean)
		
dist. of modules: 0.5 m	20 m	100 m
threshold: 5 MeV	50 GeV	200 GeV

Neutrino telescope: Detection principle



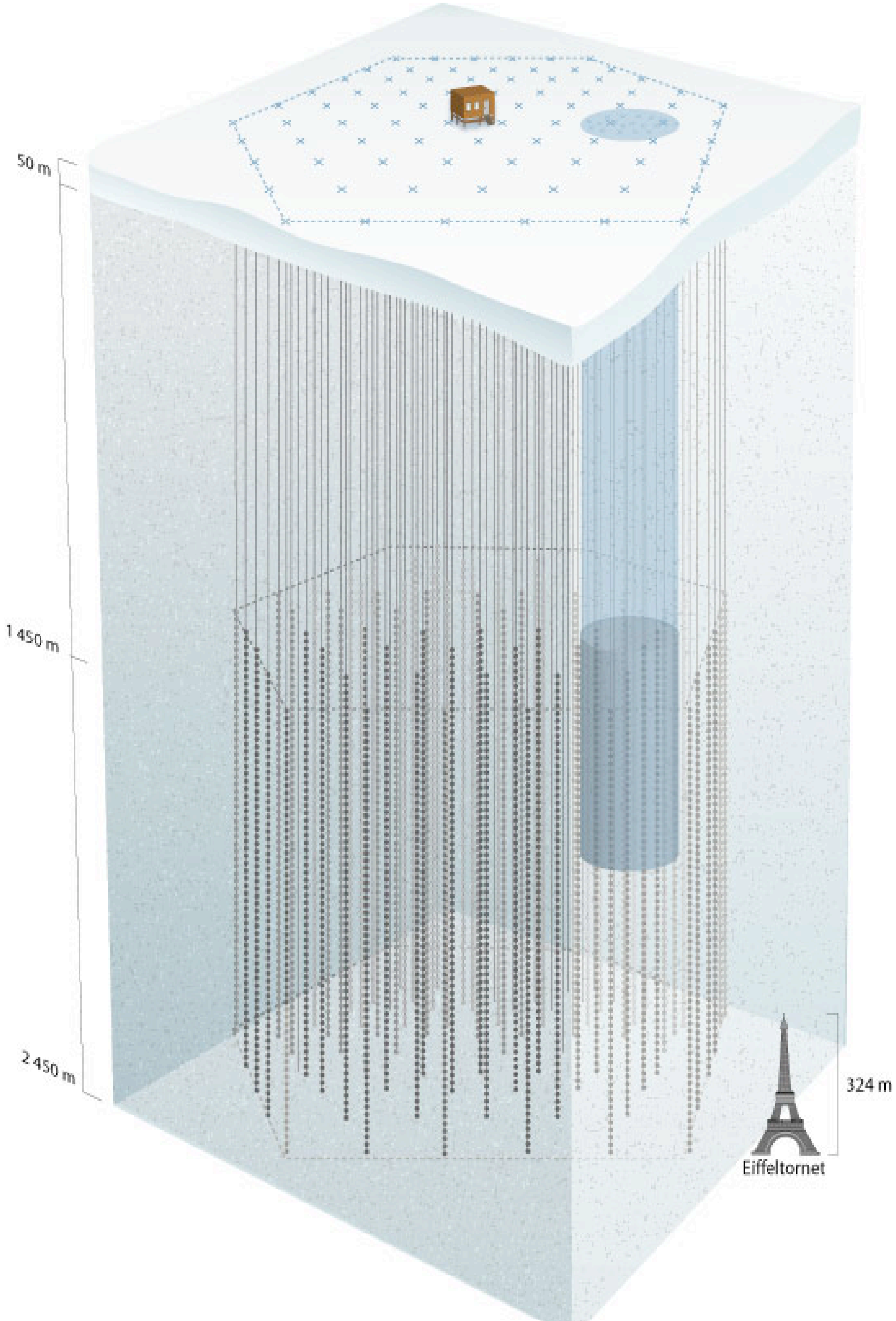
Reconstruction of μ trajectory (~ ν)
from timing and position of PMT hits

Existing and future projects



Earth used as shield: northern telescopes see southern sky (and vice versa)


IceCube / Amanda in Antarctic Ice Shield



IceCube

instrument 1 km^3 ice

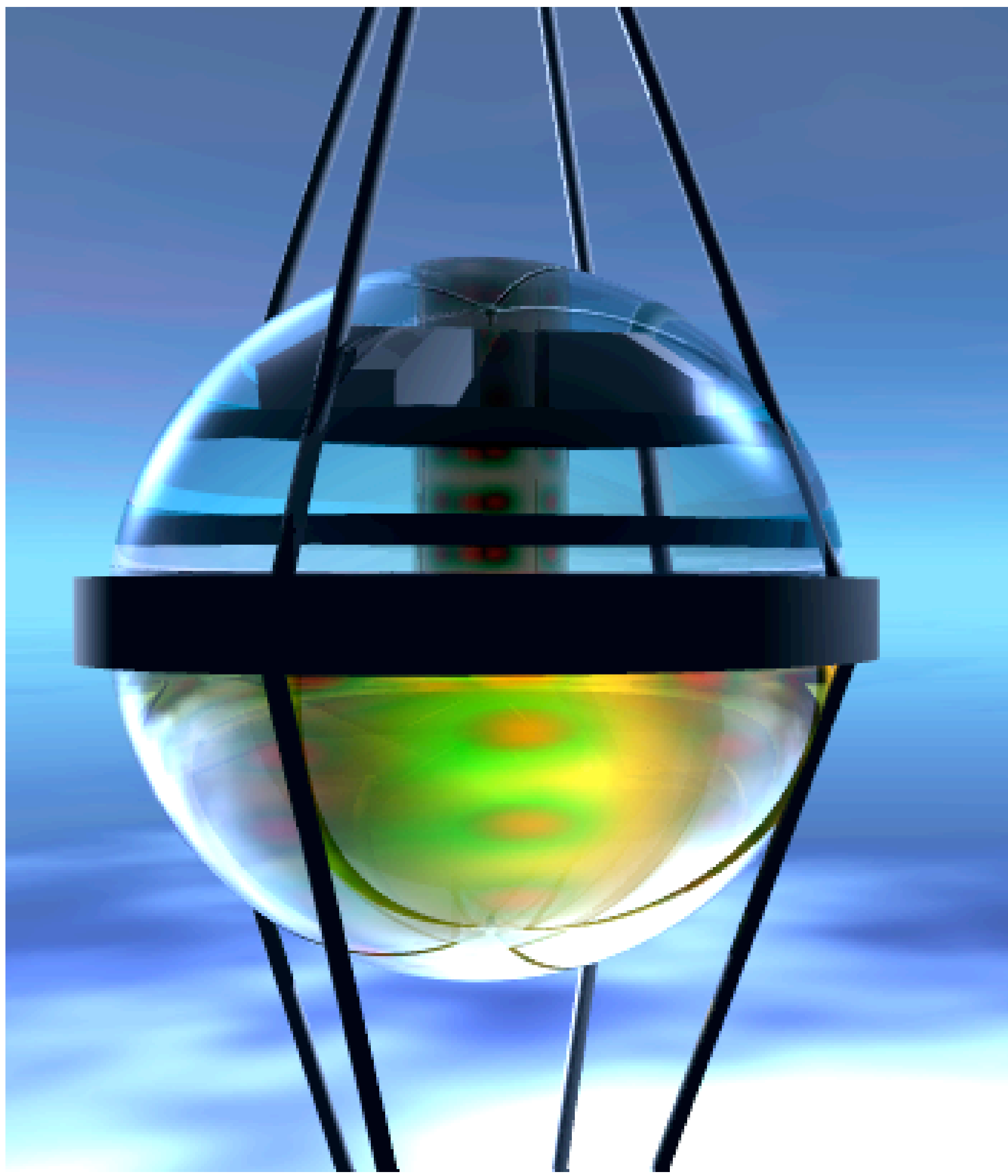
IceTop: 80 pairs of ice Cherenkov tanks

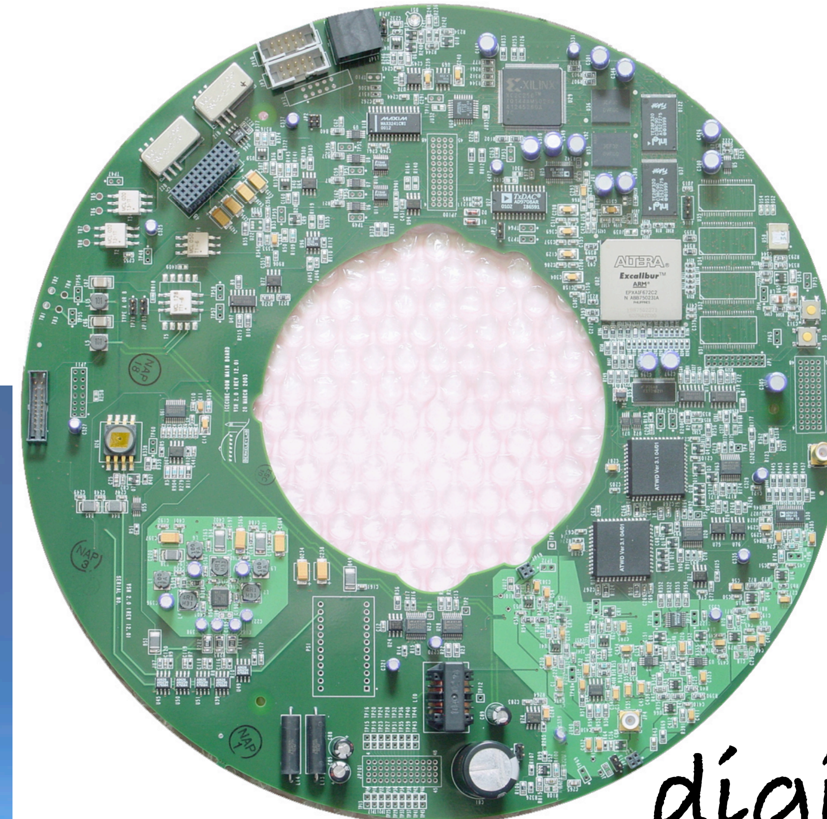
22/80 strings deployed
60 modules each

Amanda: 19 strings/ 677 modules

Completion: 2011

optical module

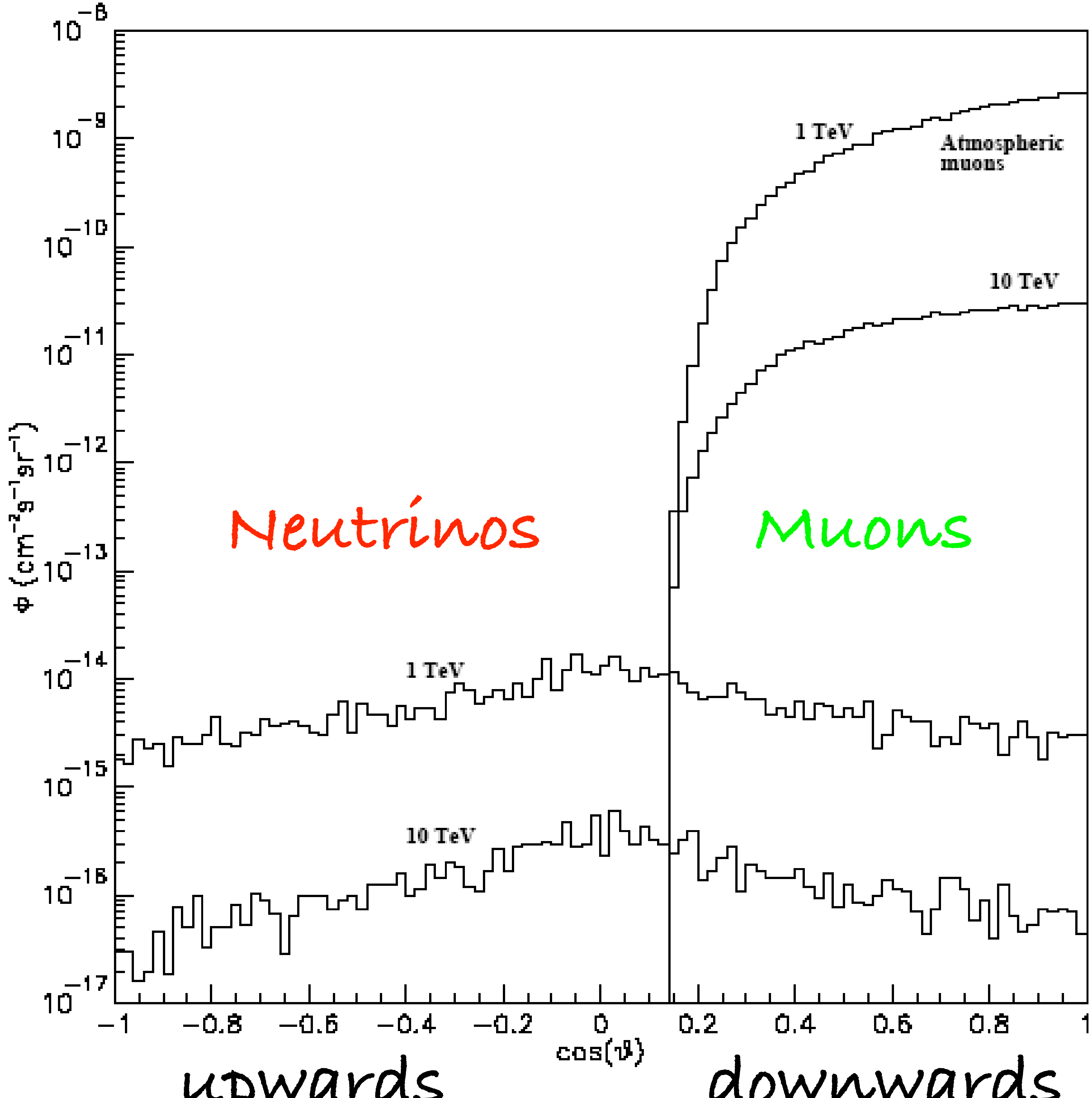




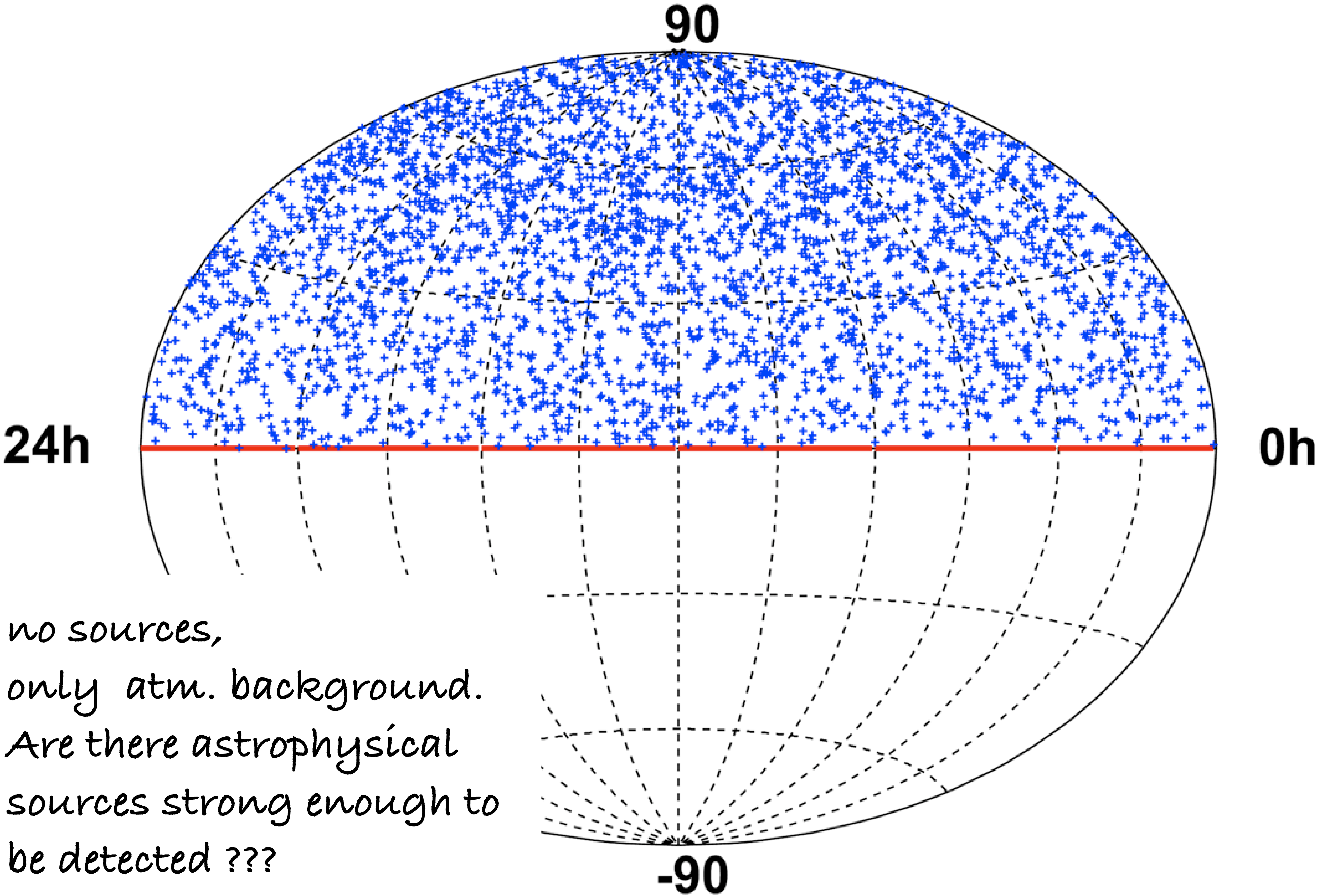
digital electronics

PMT

Rates of Muons / atmospheric Neutrinos



Amanda Skymap

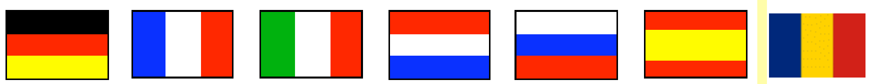


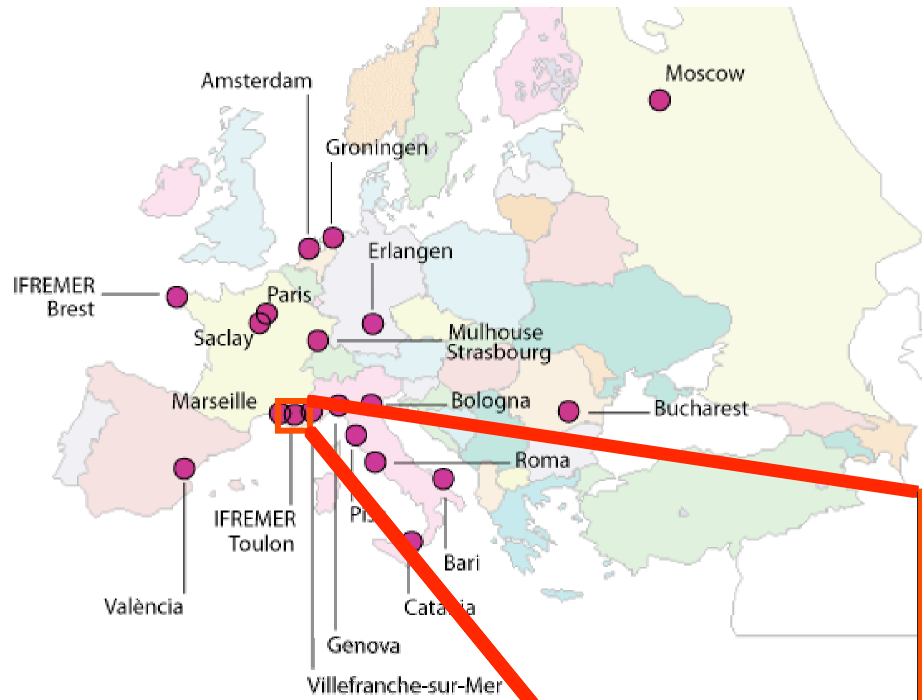
no sources,
only atm. background.
Are there astrophysical sources strong enough to be detected ???

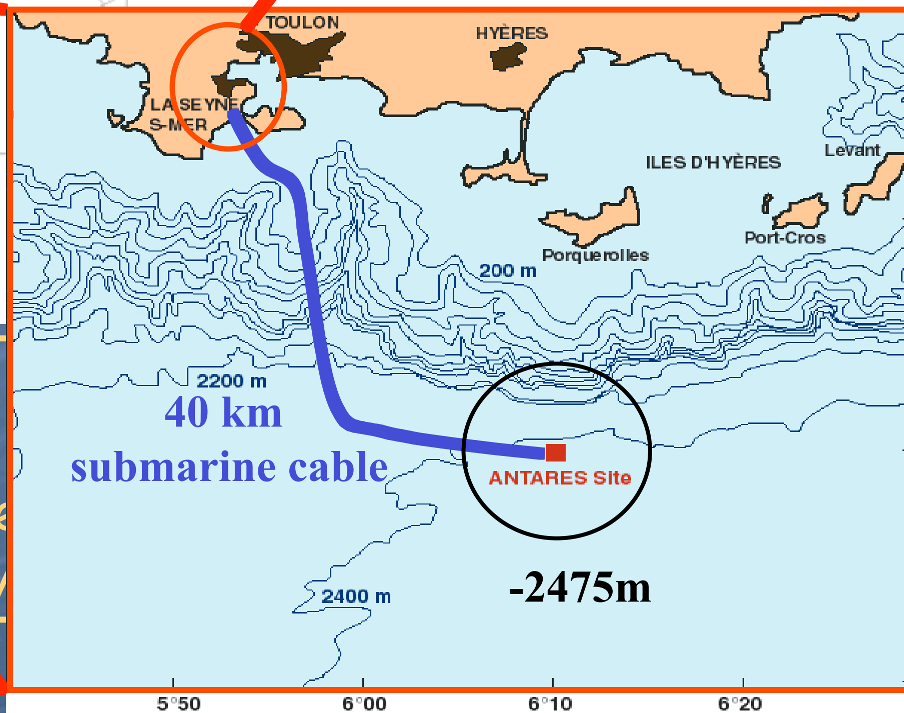
Antares

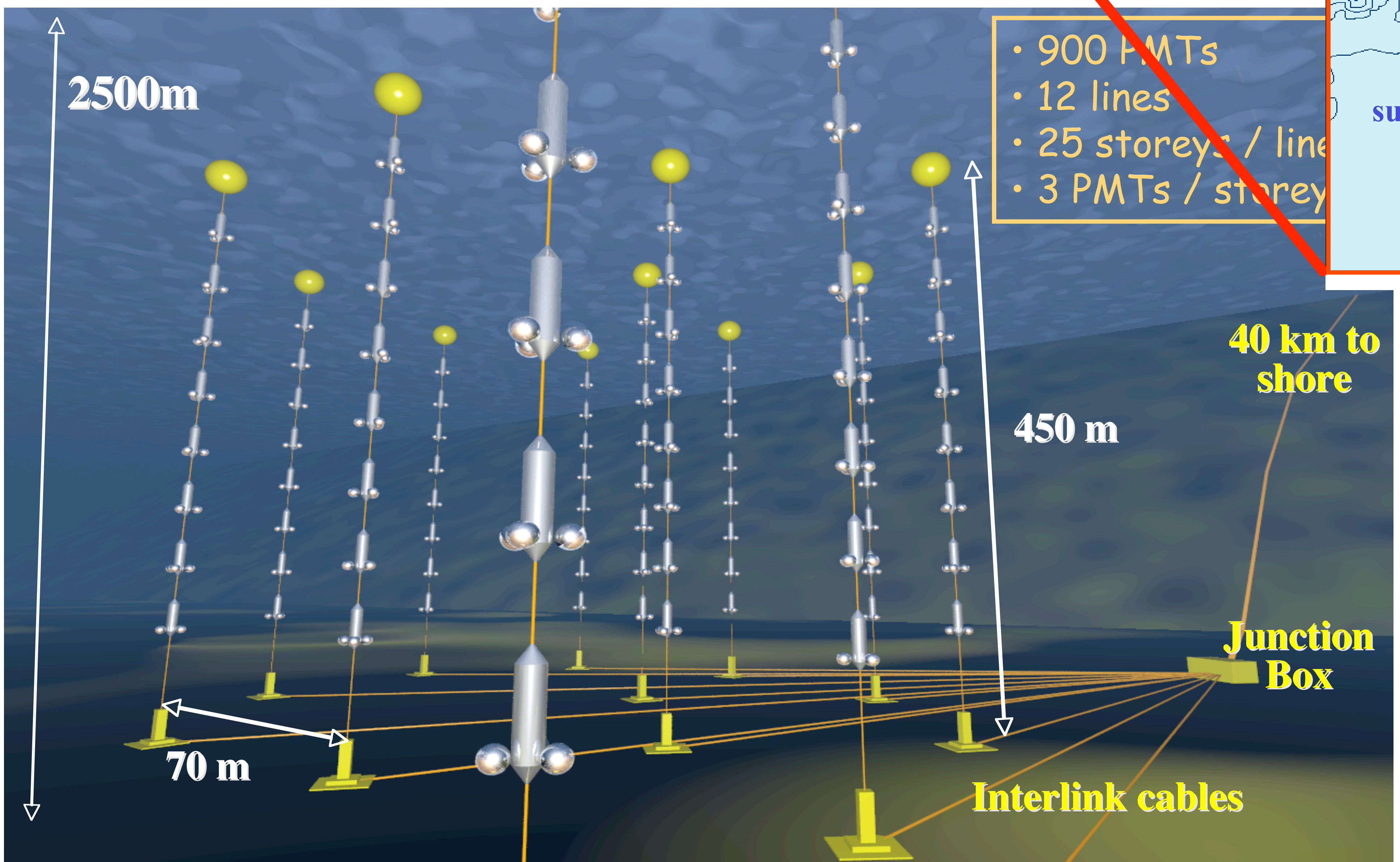
(near Marseille)

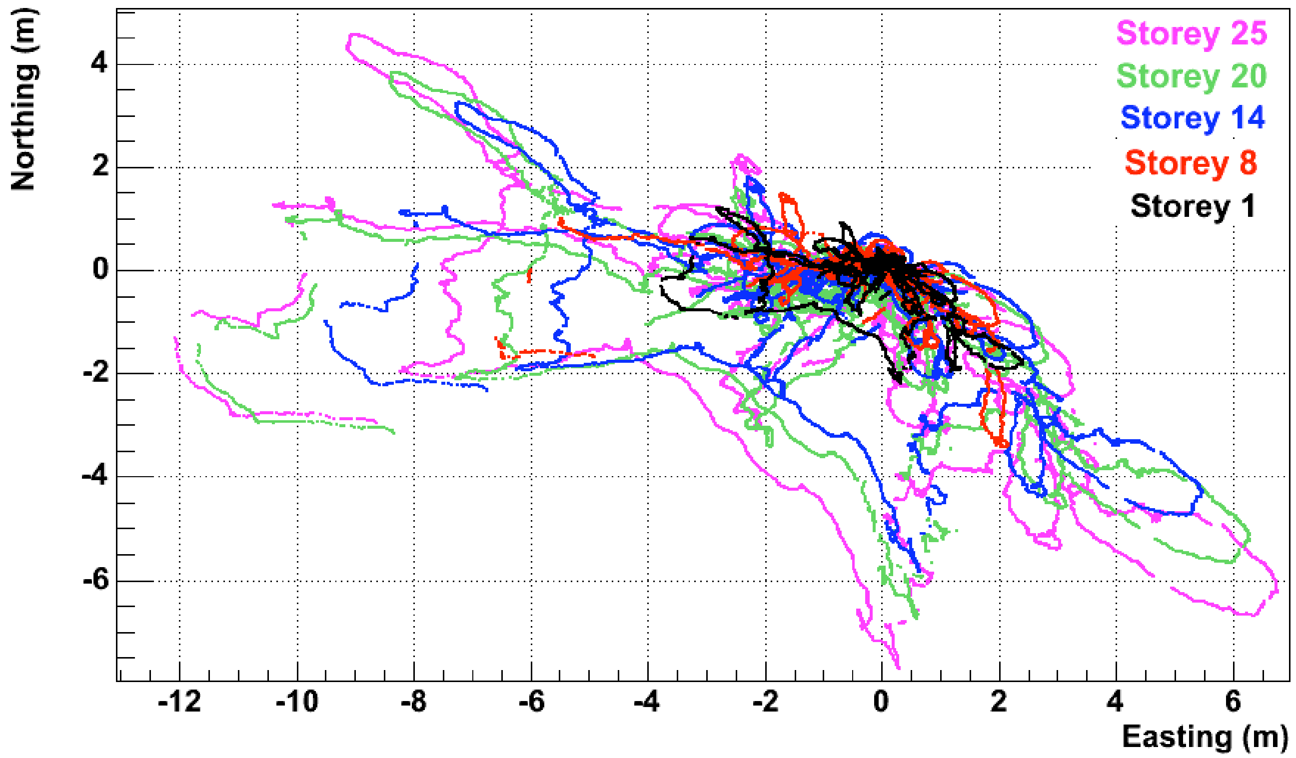
23 Institutes from
7 European countries

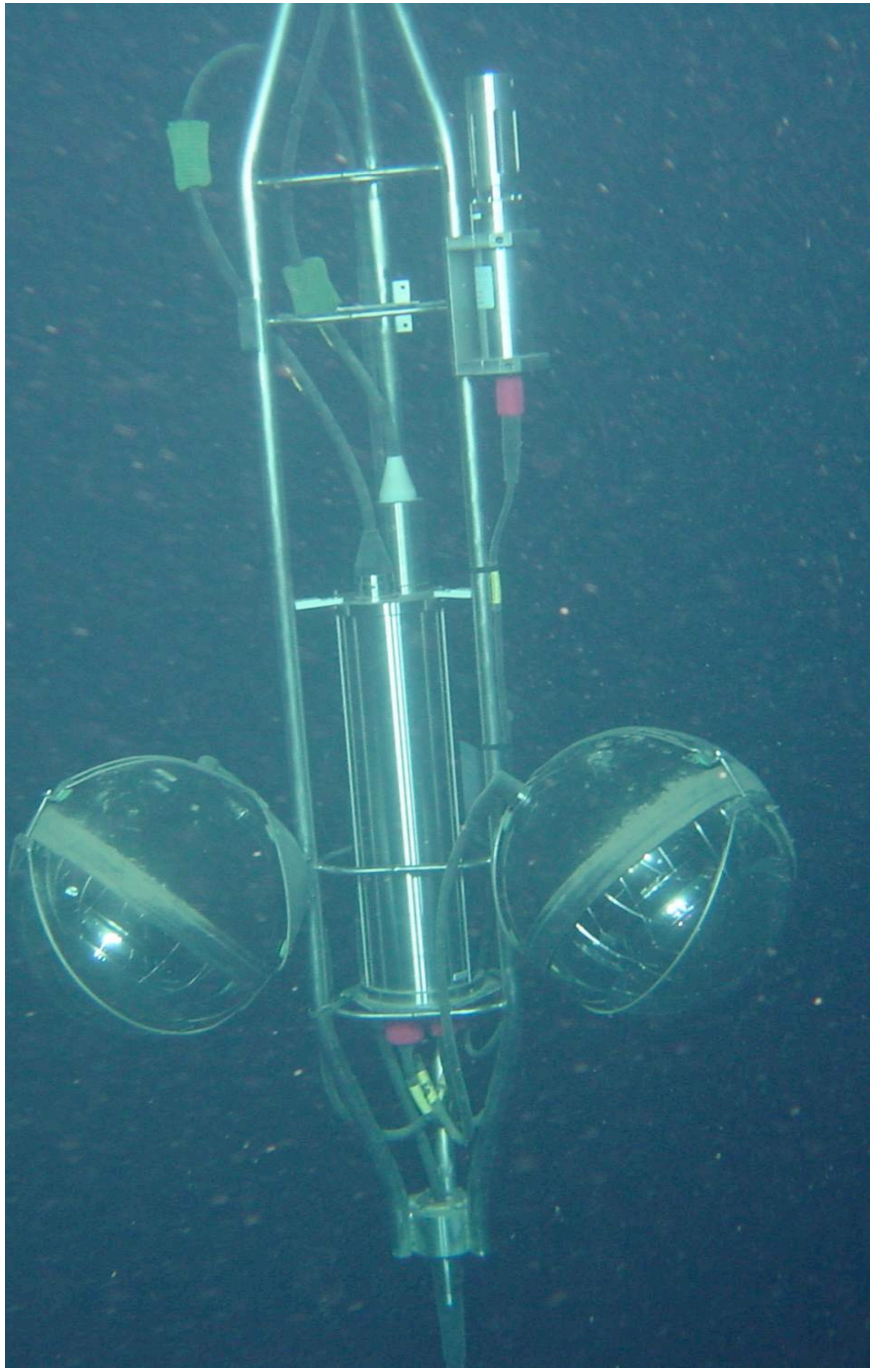


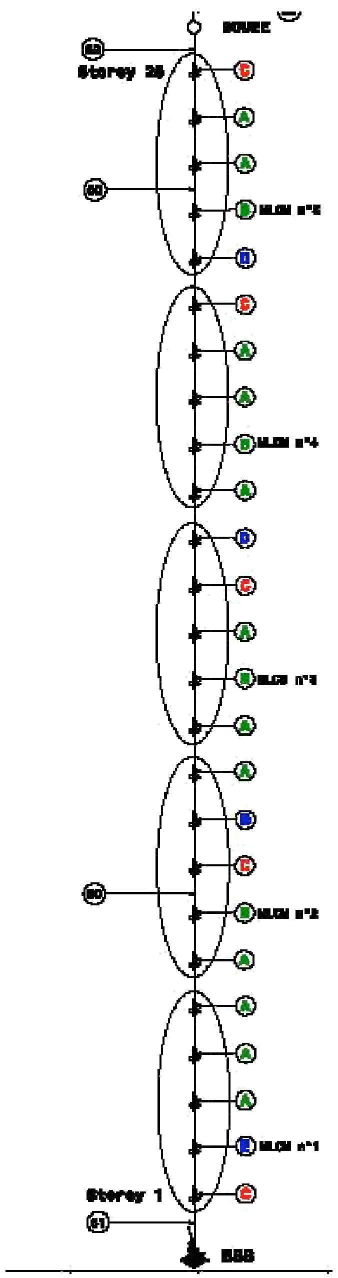


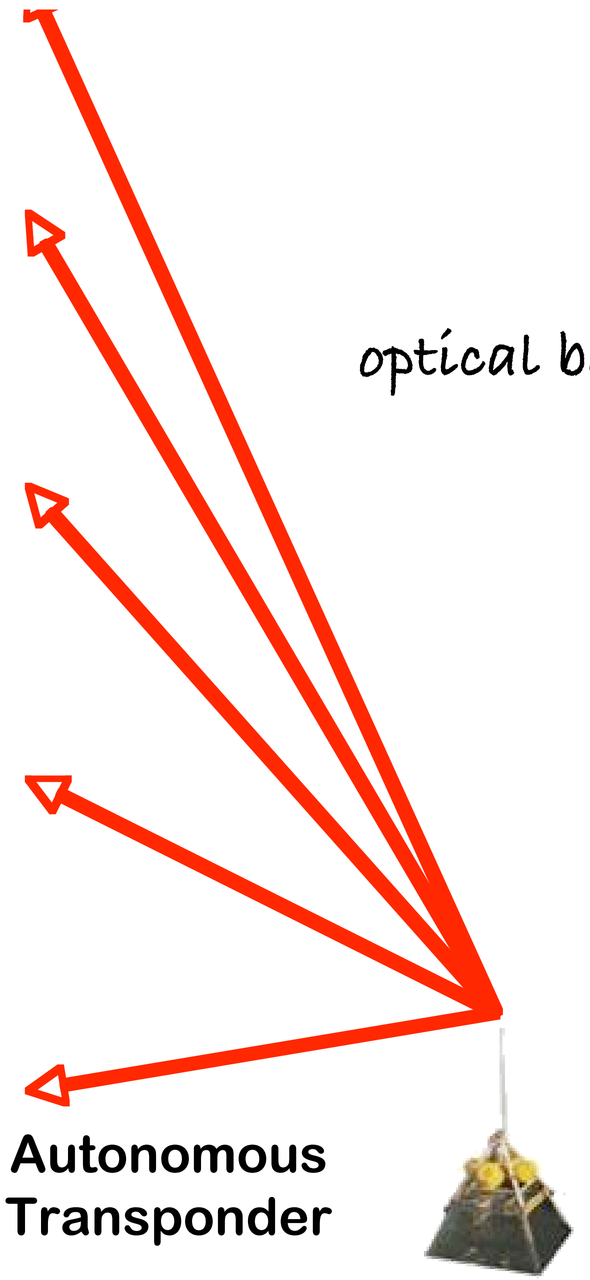






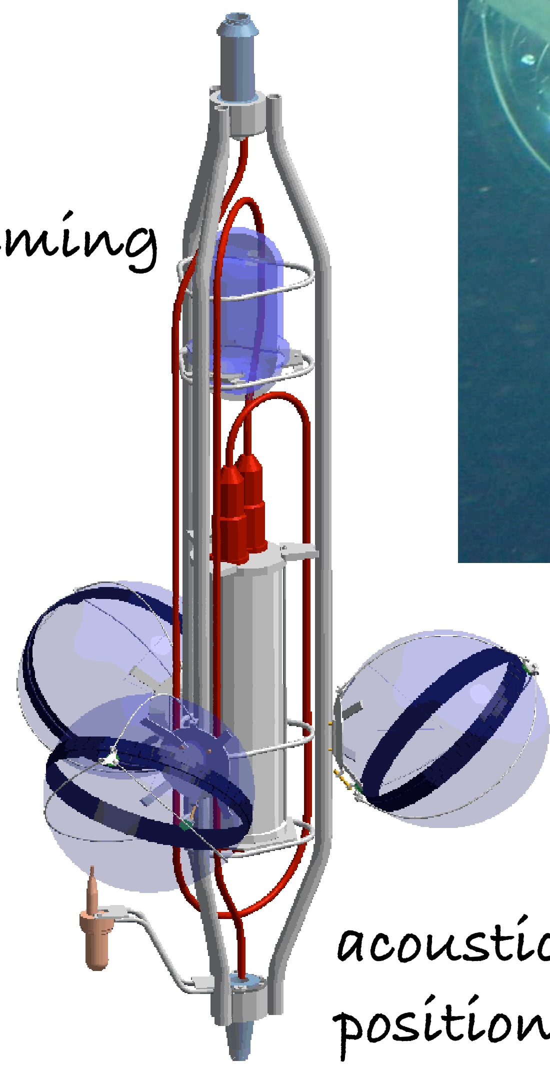






Autonomous
Transponder

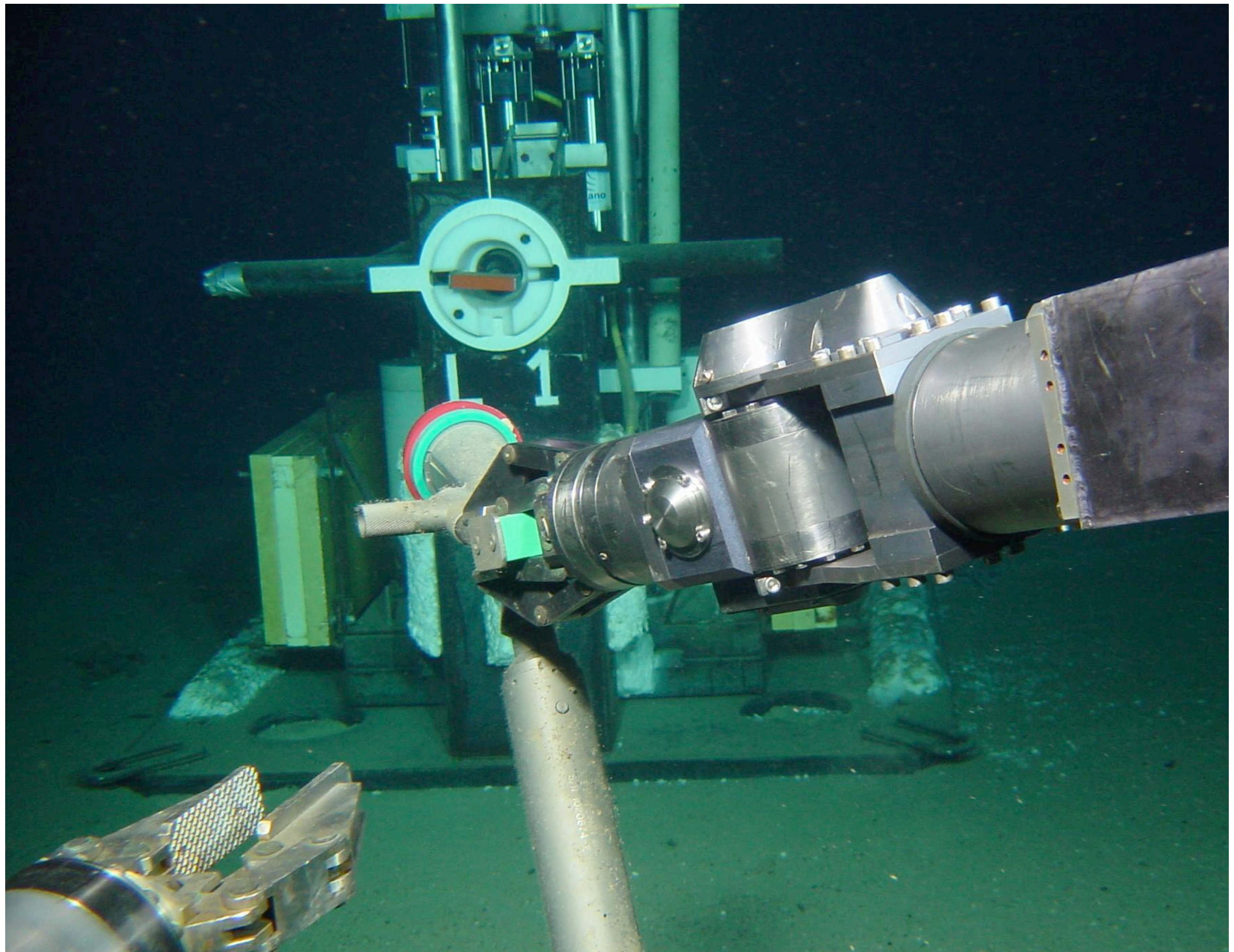
optical beacon, timing



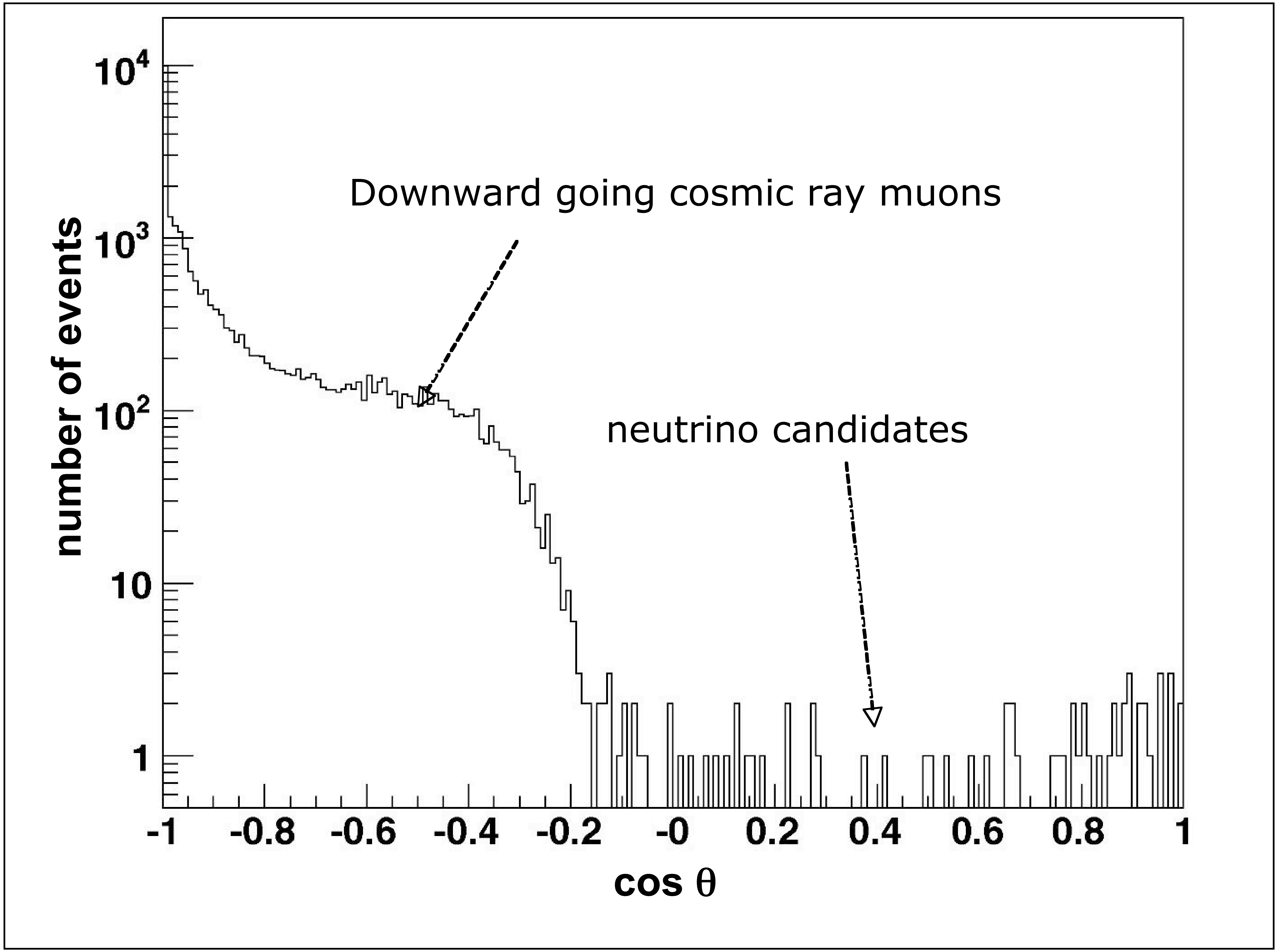
3 photo detectors

acoustic
positioning






Antares (prel.)



Are there sources strong enough ...

... to be unambigously detected?

... to do neutrino spectroscopy?

... to do astrophysics with the sources?

Current (optimistic?) estimates for AGN:

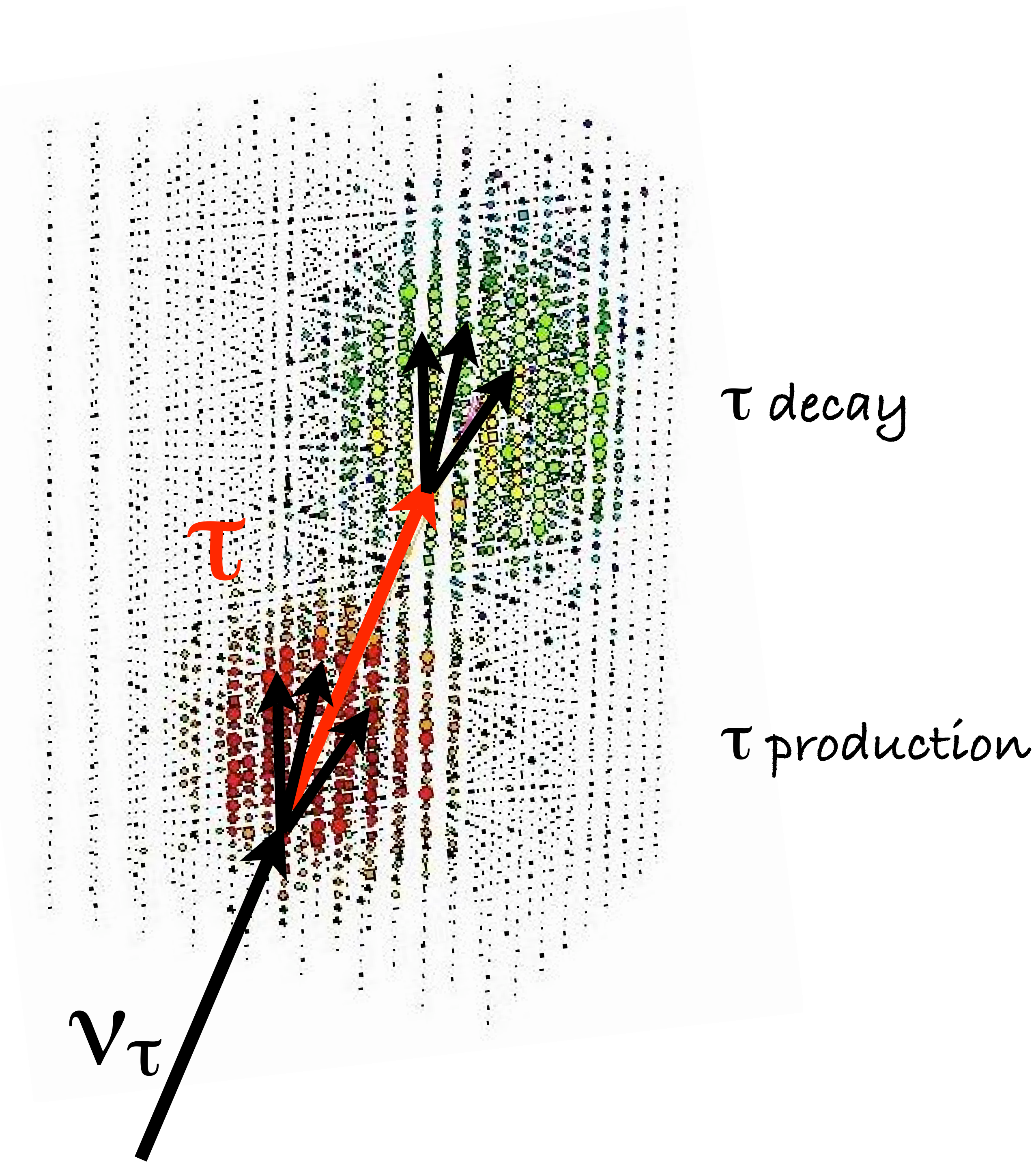
2-4 neutrinos per source in IceCube

Unexpected super-strong sources ?

Is 1 km^3 big enough ?

Is current technique usable for 100-1000 km^3 ?

Detection of τ neutrinos



Double bang events:
unique signature for
τ neutrinos

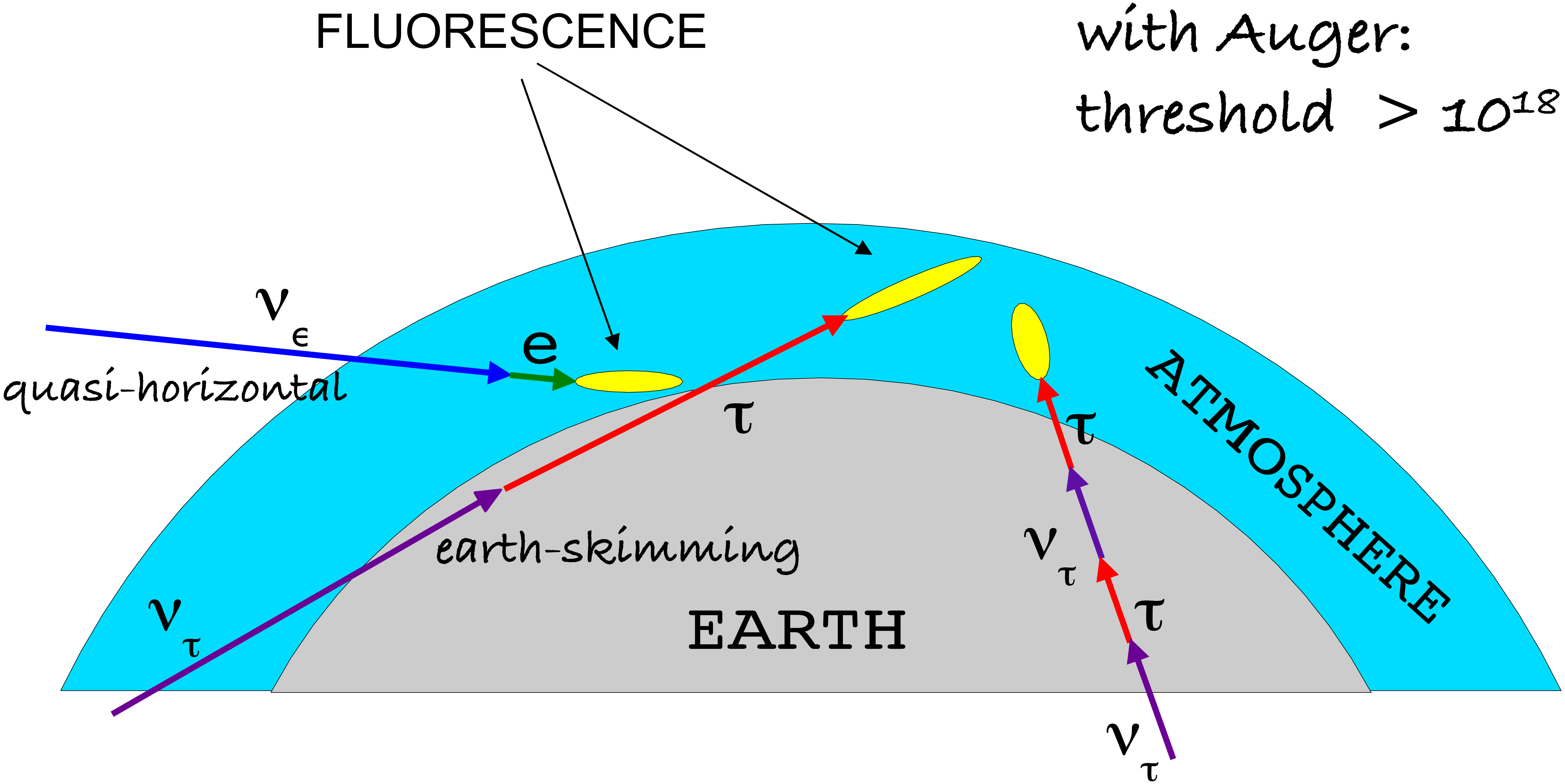
at 10^{18} eV

$\gamma c t \approx 6 \times 10^{9} \times 0.1$ mm

≈ 60 km

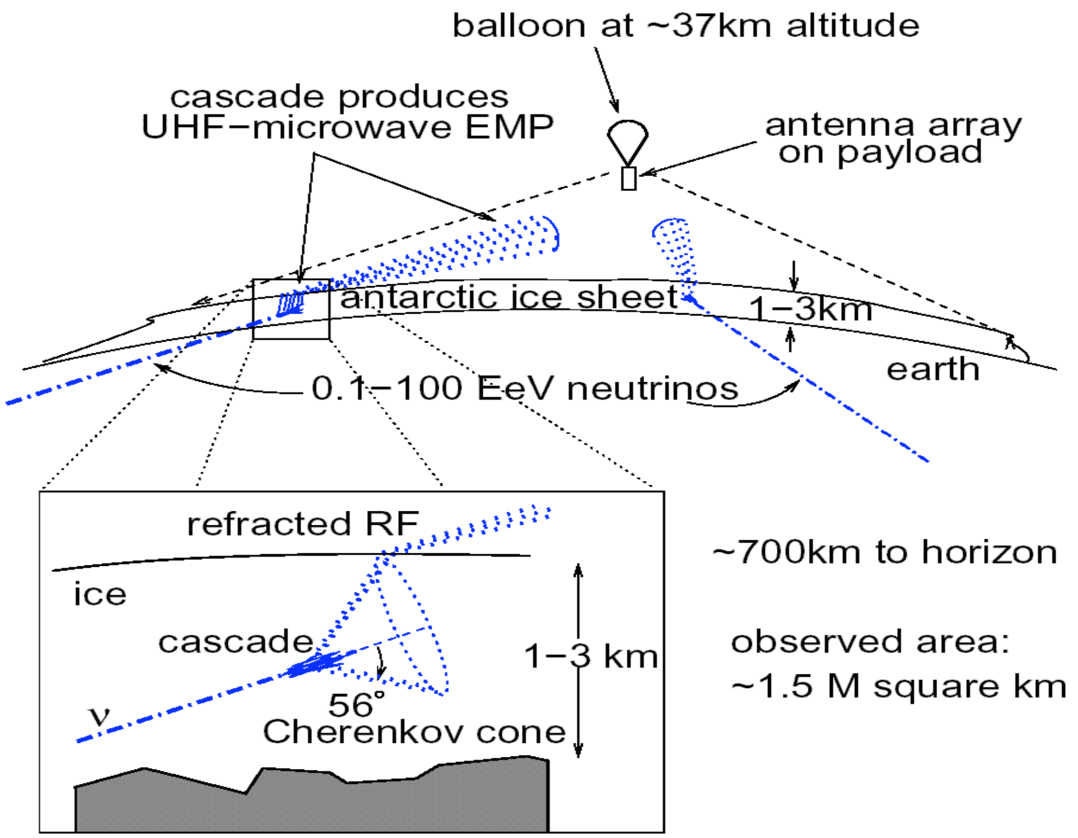
NEUTRINO EVENTS IN ATMOSPHERE

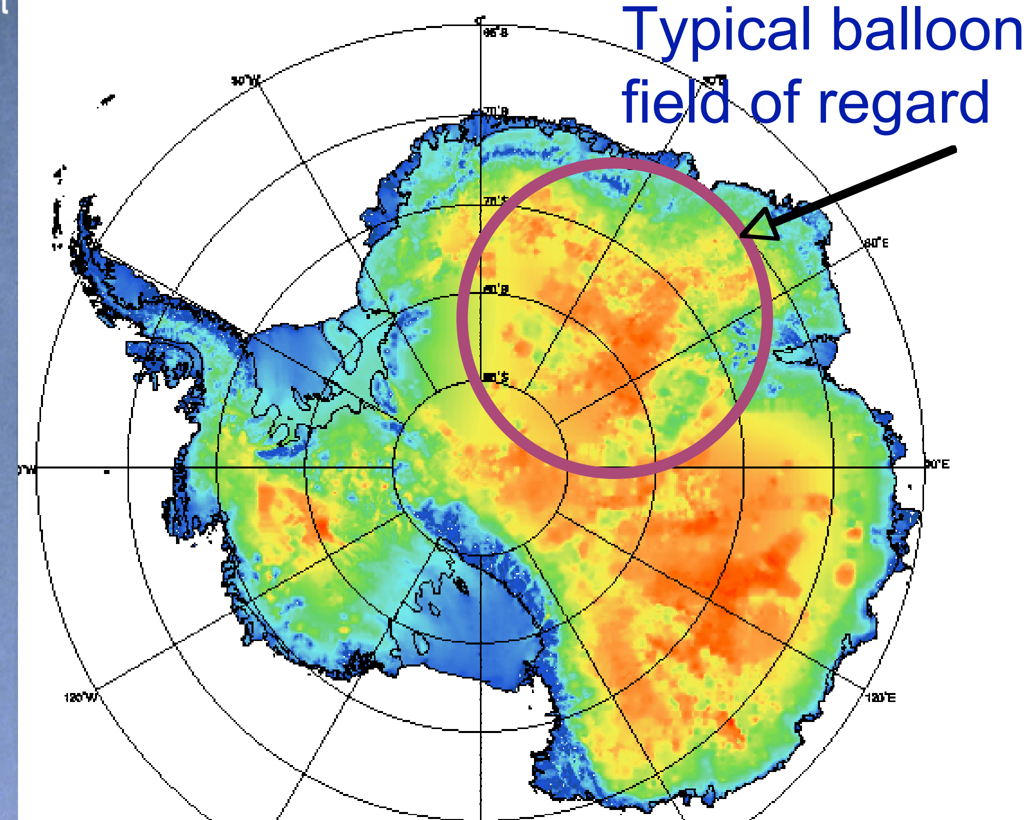
with Auger:
threshold $> 10^{18}$ eV



Ratio earth-skimming / quasi-horizontal neutrinos (i.e. ν_τ / ν_{all})
relates to ν-N cross-sections and allows test of standard model neutrino production.

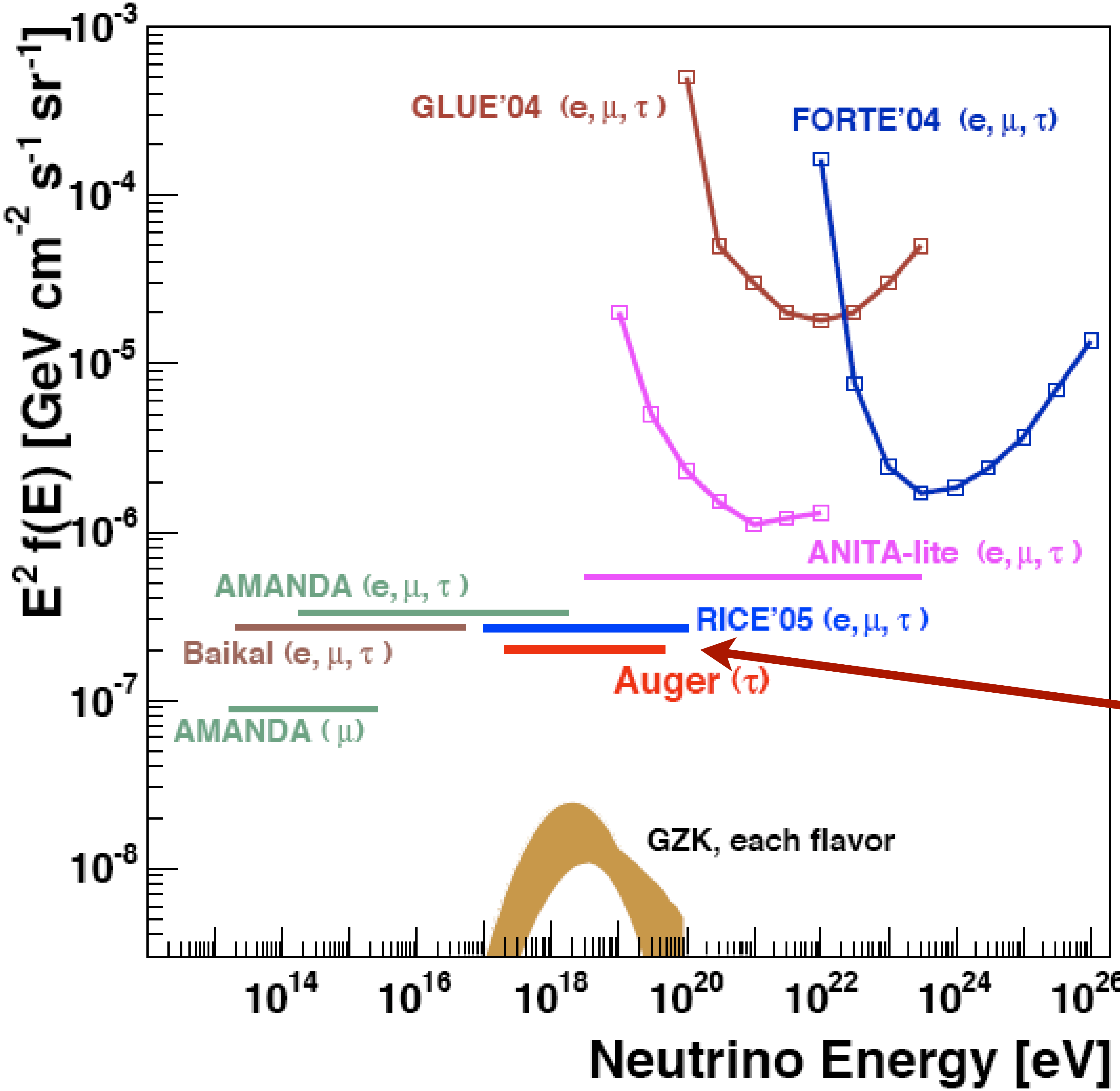
Radio emission of showers in Ice:
Antarctic Impulsive Transient Antenna ANITA

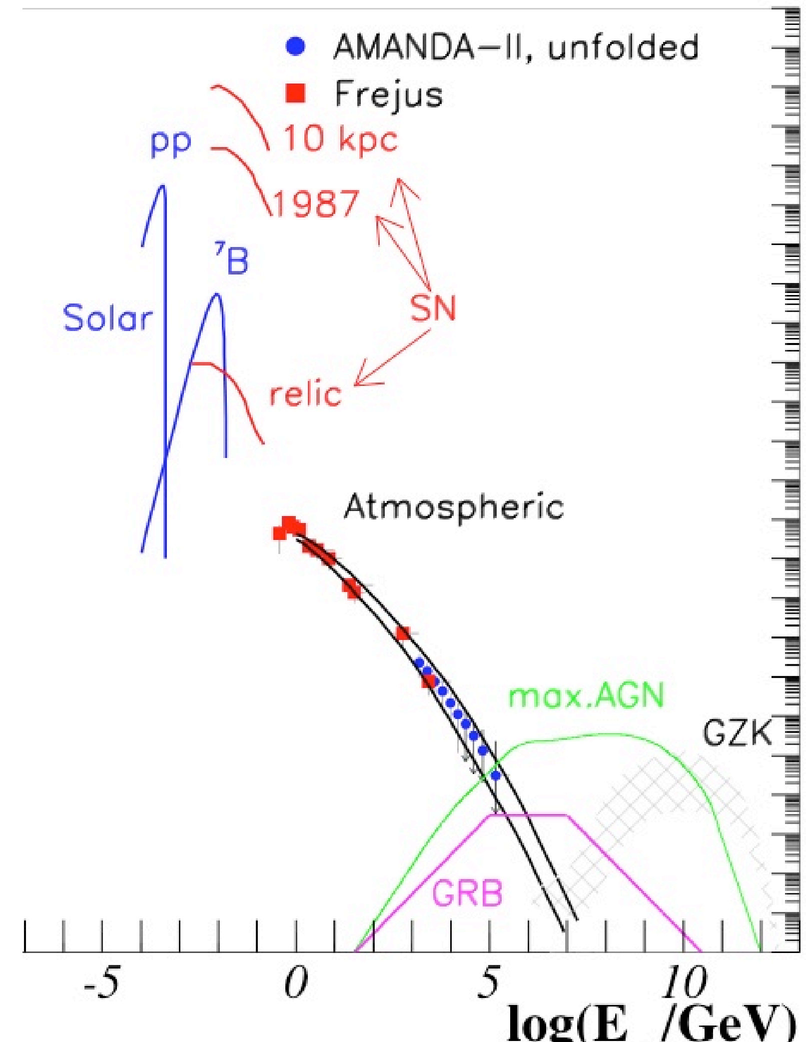




1st flight (2007)
successful,
2 more to come,
analysis ongoing

Auger: no neutrino candidate





neutrino limit

ICRC 2007, published soon

Summary:

- Astroparticle Physics is an exciting field.
- Highest energy particles are rare & difficult to detect ... but new experiments (with increased sensitivity) can detect these particle and identify their sources.
- The most-energetic CRs, gamma rays & neutrinos come likely from the same, most violent environments in the universe.

  (Multi-messenger approach for improved understanding)
- Three new windows in Astronomy:

  TeV gamma rays, UHECRs, Neutrinos
- Bright future with many challenges for bright young theorists and experimentalists.