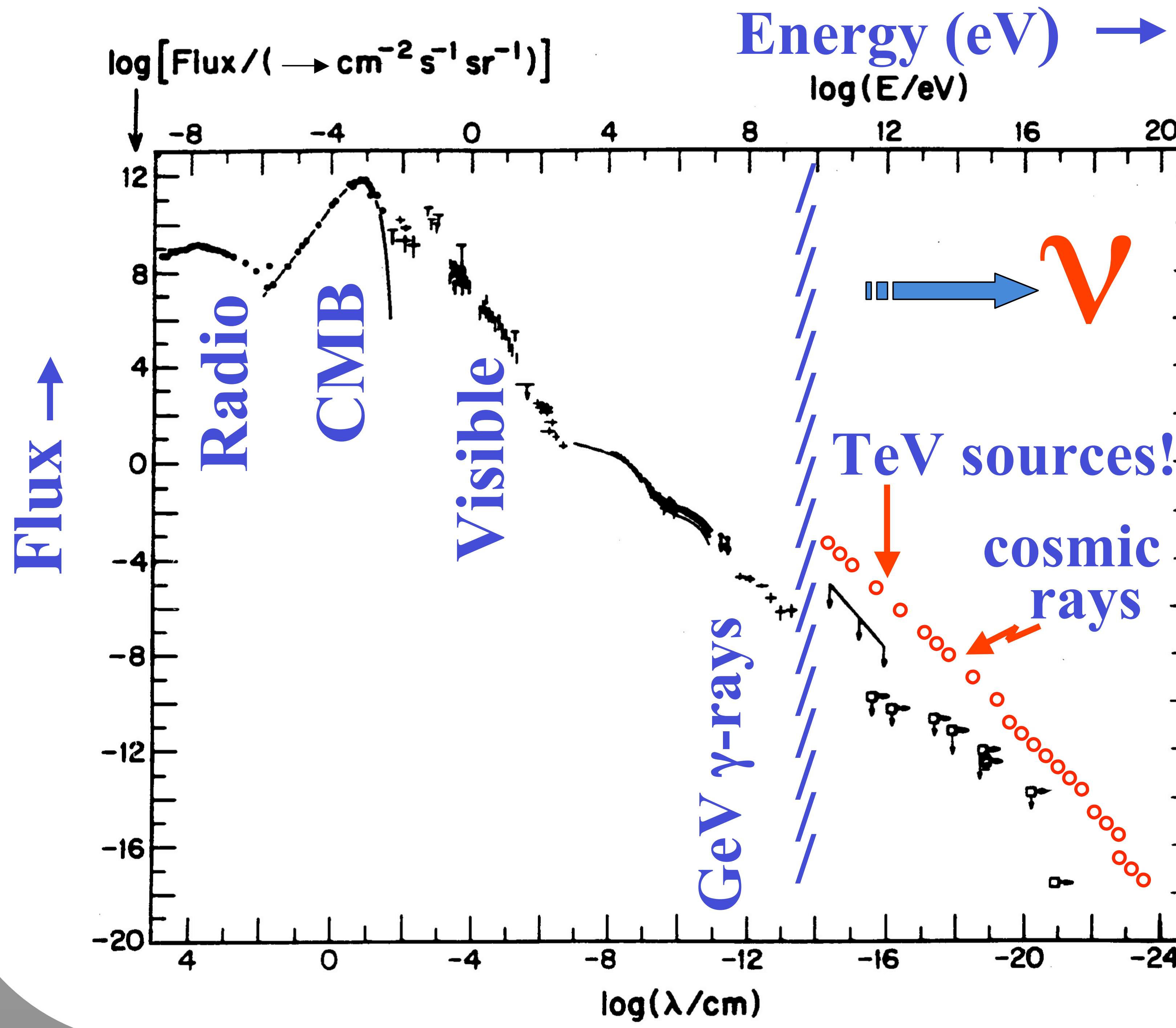
Francis Halzen
University of Wisconsin
http://icecube.wisc.edu

The real voyage is not to travel to new landscapes, but to see with new eyes. . .

Marcel Proust



Energy (eV) →
log(E/eV)
-8
-4
0
4
8
12
16
20
log[Flux/(→ cm^{-2} s^{-1} sr^{-1})]
12
8
4
0
-4
-8
-12
-16
-20
Flux →
Radio
CMB
Visible
GeV γ-rays
ν
TeV sources!
cosmic rays
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

Multi-Messenger Astronomy

protons, γ-rays, neutrinos, gravitational waves as probes of the high-energy Universe

1. protons: directions scrambled by magnetic fields

2. γ-rays : straight-line propagation but reprocessed in the sources, extragalactic backgrounds absorb $E\gamma$ > TeV

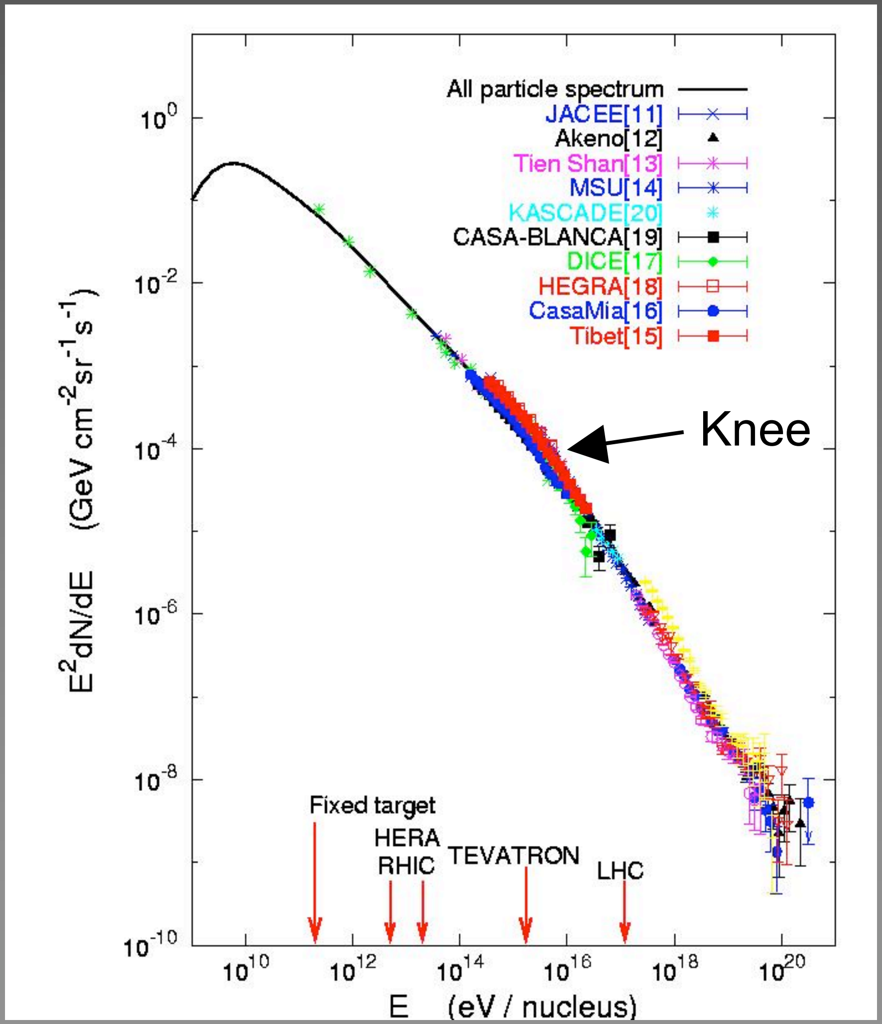
3. neutrinos: straight-line propagation, unabsorbed, but difficult to detect

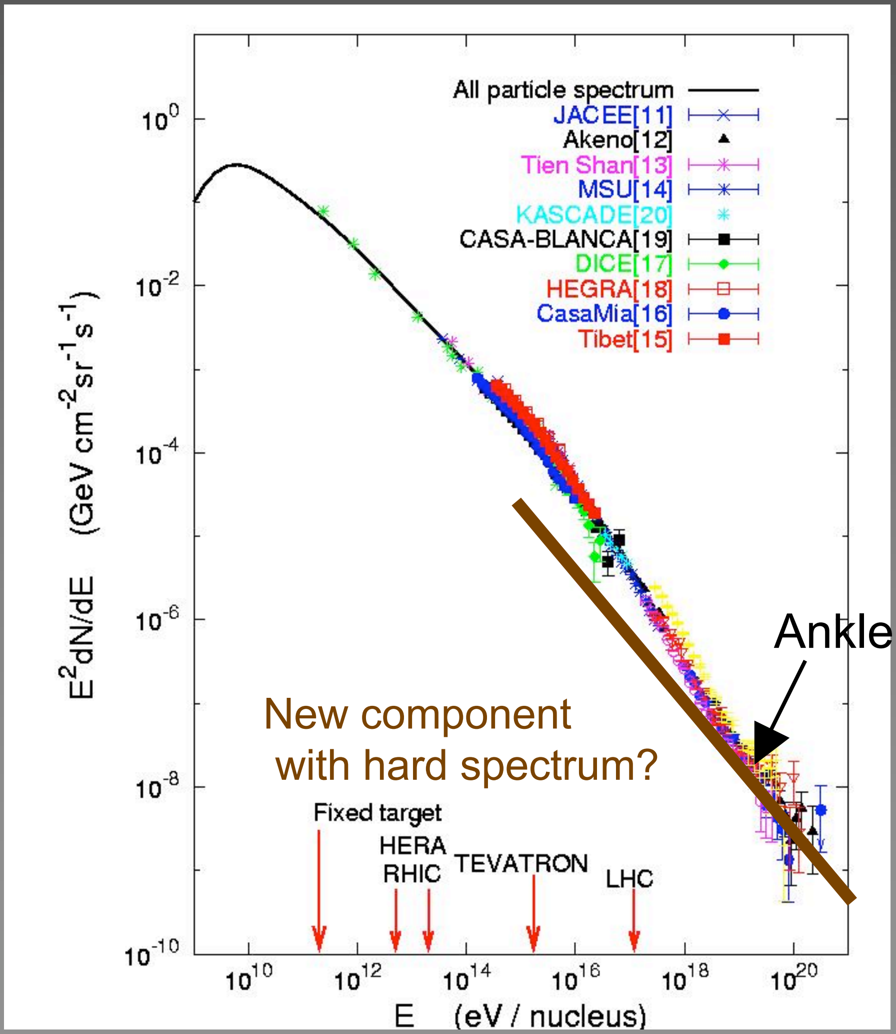
ν astronomy

- ν astronomy requires kilometer-scale detectors
- neutrinos and gamma rays
- may as well do particle physics

cosmic neutrinos associated with cosmic rays

Galactic and Extragalactic Cosmic Rays





>>> energy in extra-galactic cosmic rays:

~ 3×10^{-19} erg/cm^3 or
~ 10^{44} erg/yr per (Mpc)^3 for 10^{10} years

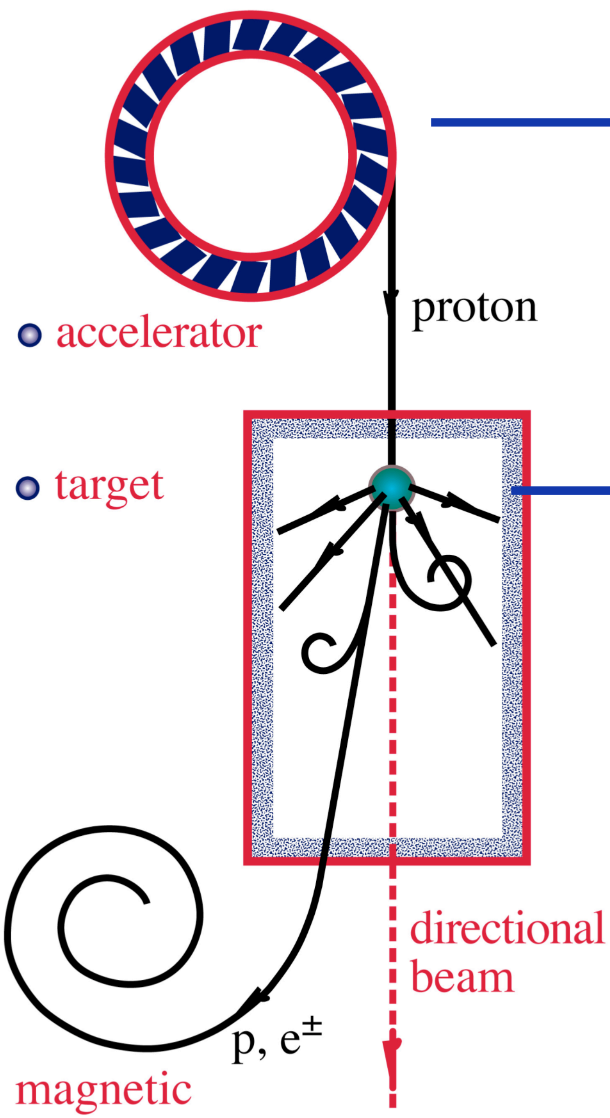
3×10^{39} erg/s per galaxy
3×10^{44} erg/s per active galaxy
2×10^{52} erg per gamma ray burst

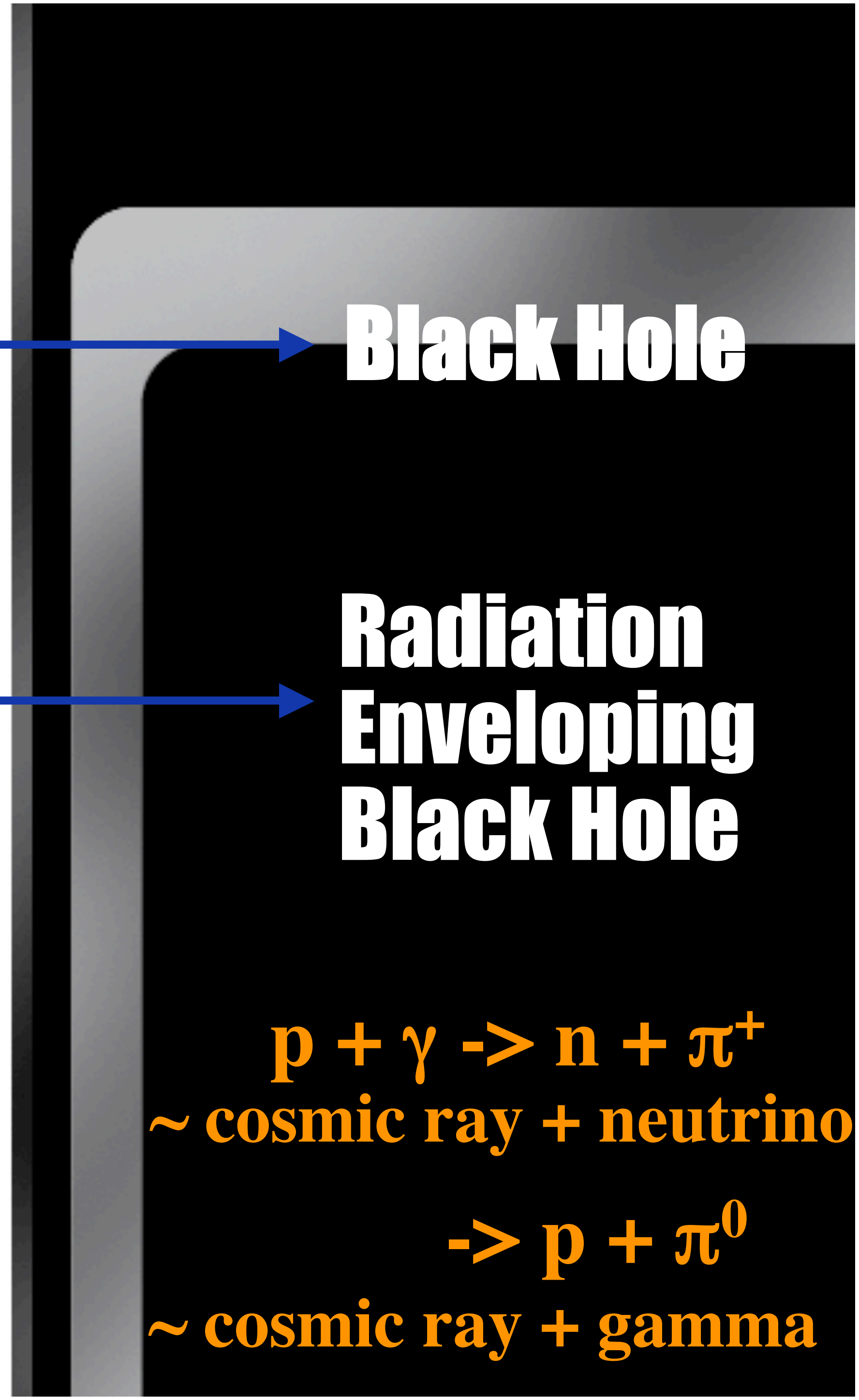
>>> energy in cosmic rays ~ equal to

the energy in light !

1 TeV = 1.6 erg

Neutrino Beams: Heaven & Earth





$p + \gamma \rightarrow n + \pi^{+}$

~ cosmic ray + neutrino

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

~ cosmic ray + gamma

we know that :

black holes accelerate electrons: seen as synchrotron photon

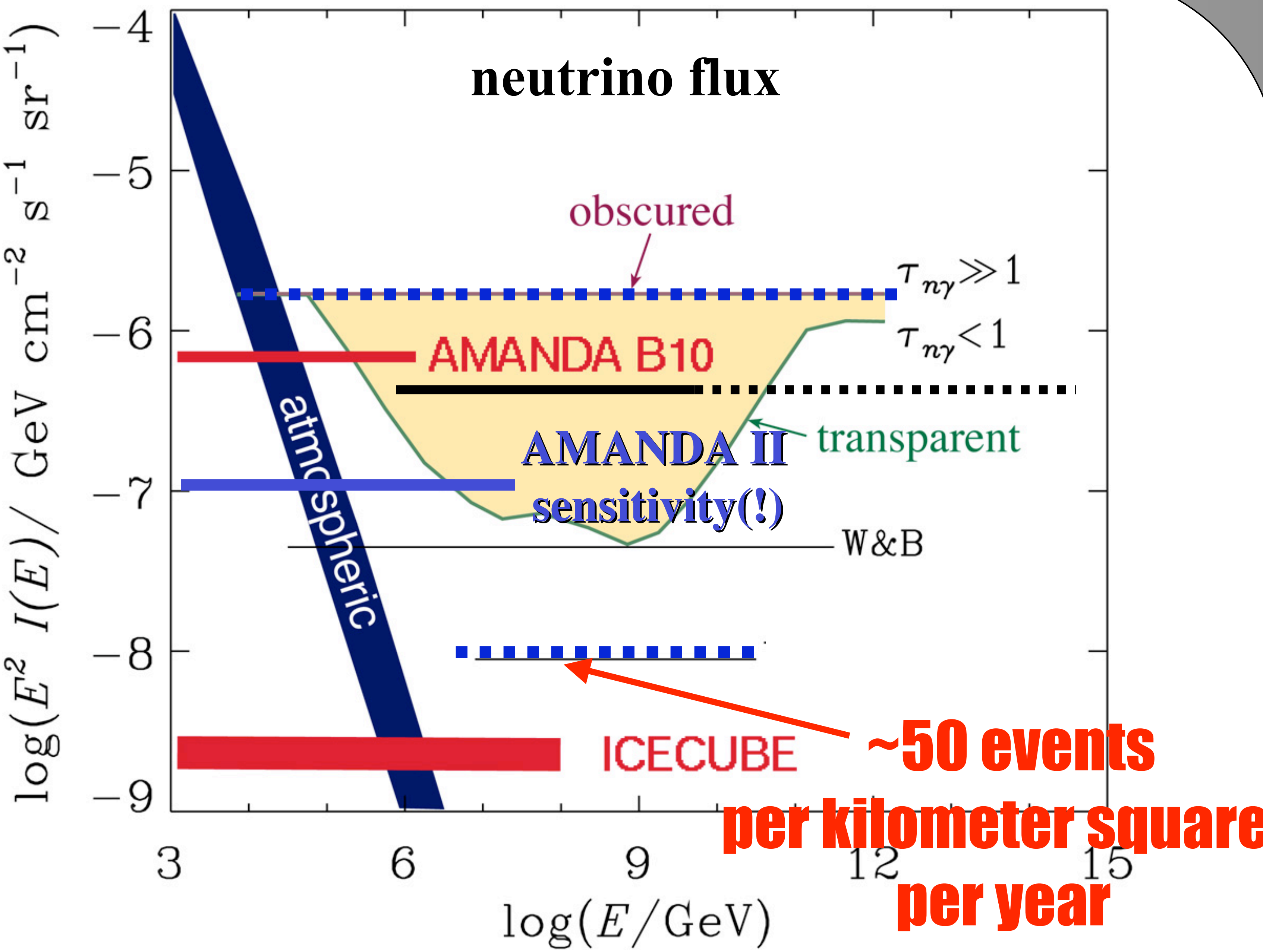
- black holes accelerate protons: seen as cosmic rays

- black holes are surrounded by radiation fields and gases

→ cosmic beam dumps exist

cosmic ray puzzle: which black hole ?

Neutrinos Associated With the Source of the Cosmic Rays?



why km^2 telescope area ?

- neutrinos associated with the observed sources of cosmic rays (and gamma rays)

- models of cosmic ray accelerators: 2 examples

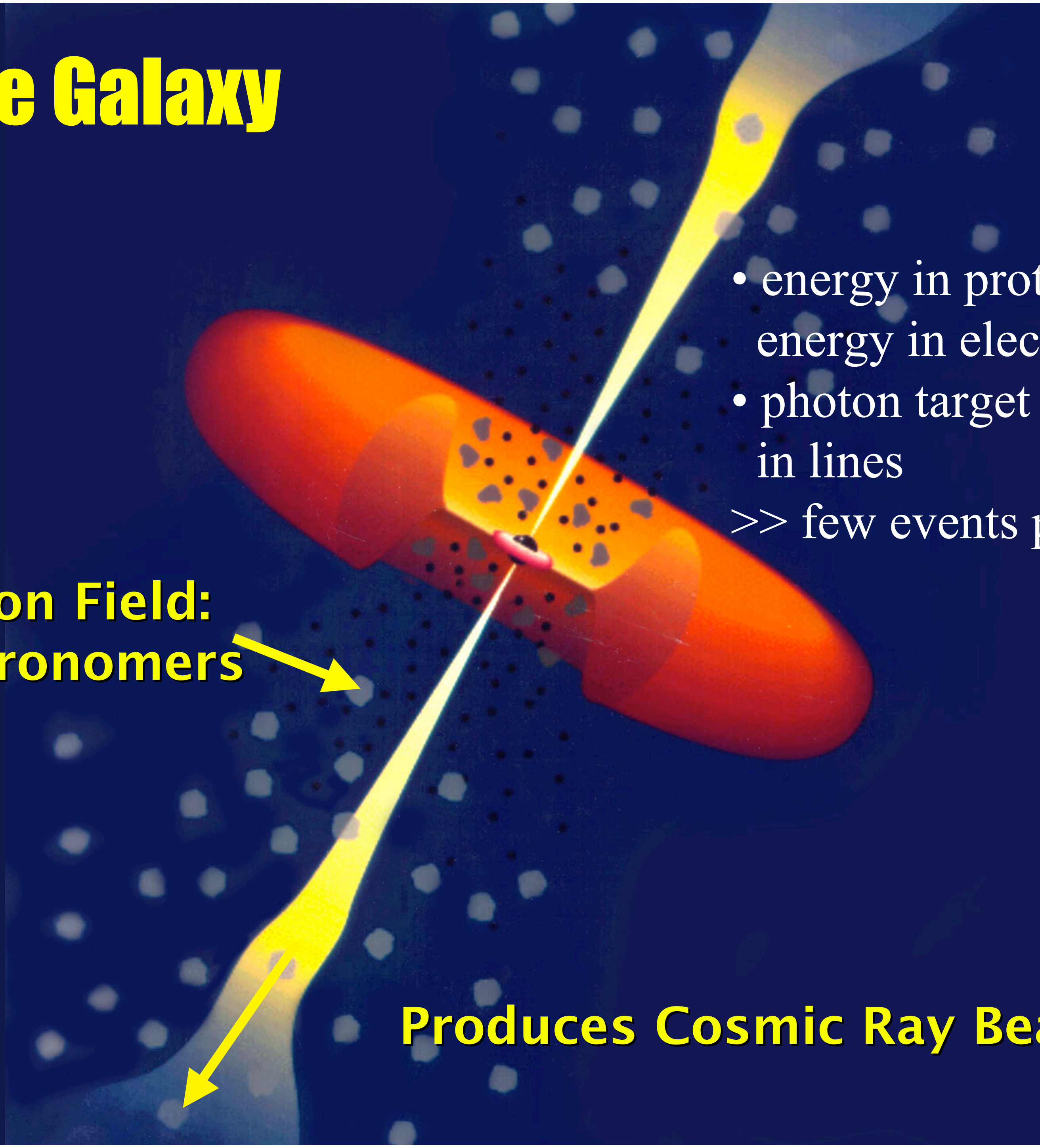
- “guaranteed" cosmic neutrino fluxes

  → cosmic ray interactions with CMBR
  → cosmic ray interactions in galactic plane, in galaxy clusters, in the sun
  → decaying EeV neutrons
  → gamma ray burst
  → RXJ 1713

Active Galaxy

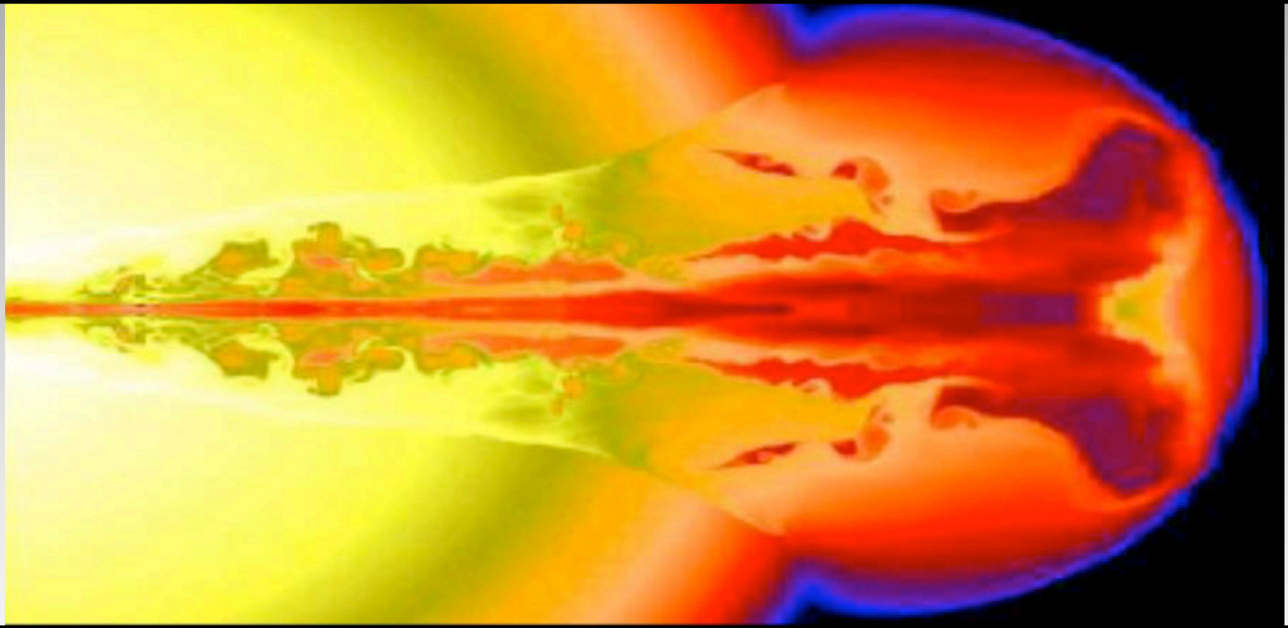
- energy in protons ~ energy in electrons
- photon target observed in lines

>> few events per year km^2



Gamma Ray Bursts

Fireball: Rapidly expanding collimated jet of photons, electro
and positrons becoming optically thin during expansi



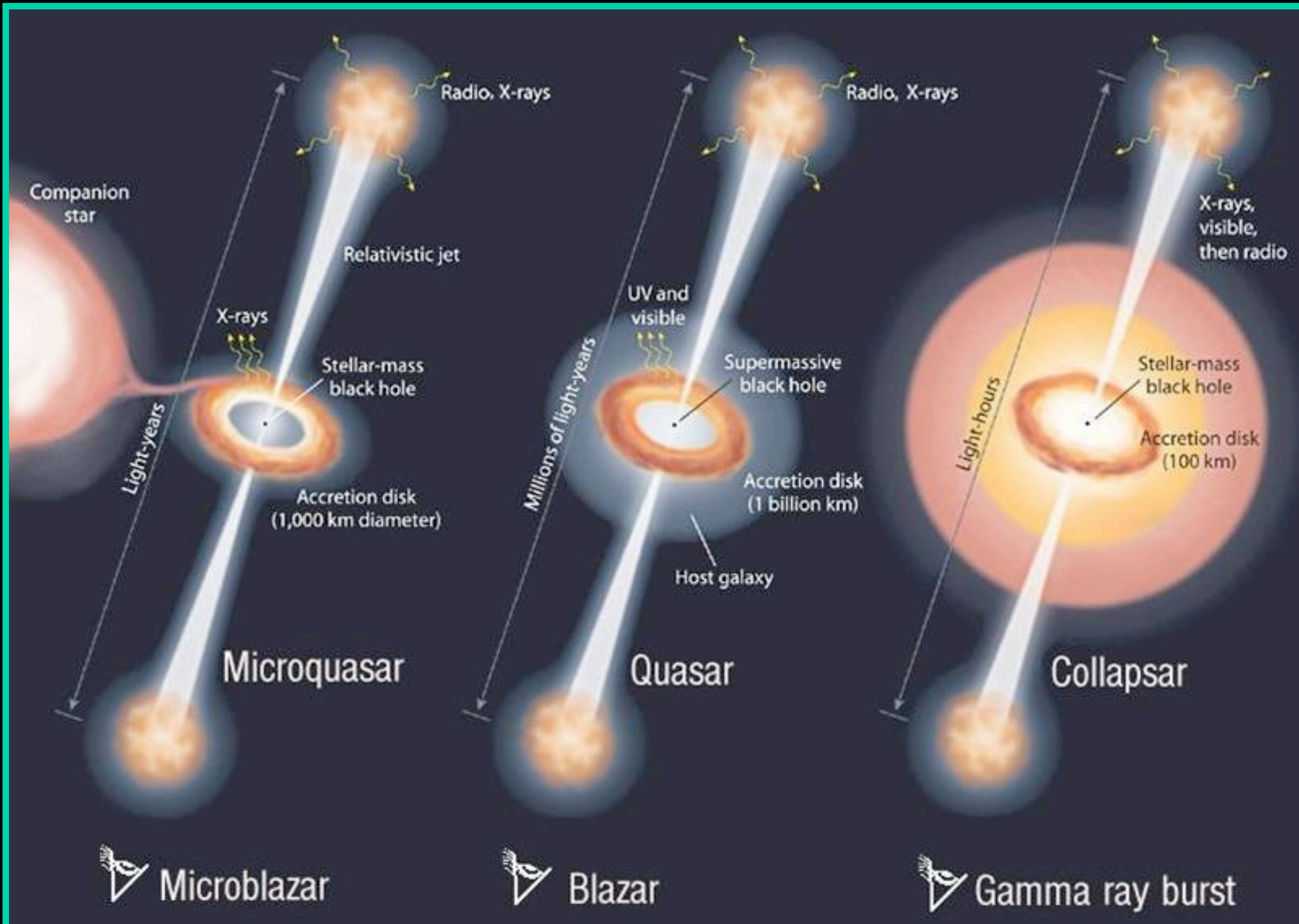
Neutrinos produced:

→ in external collisions with interstellar medium

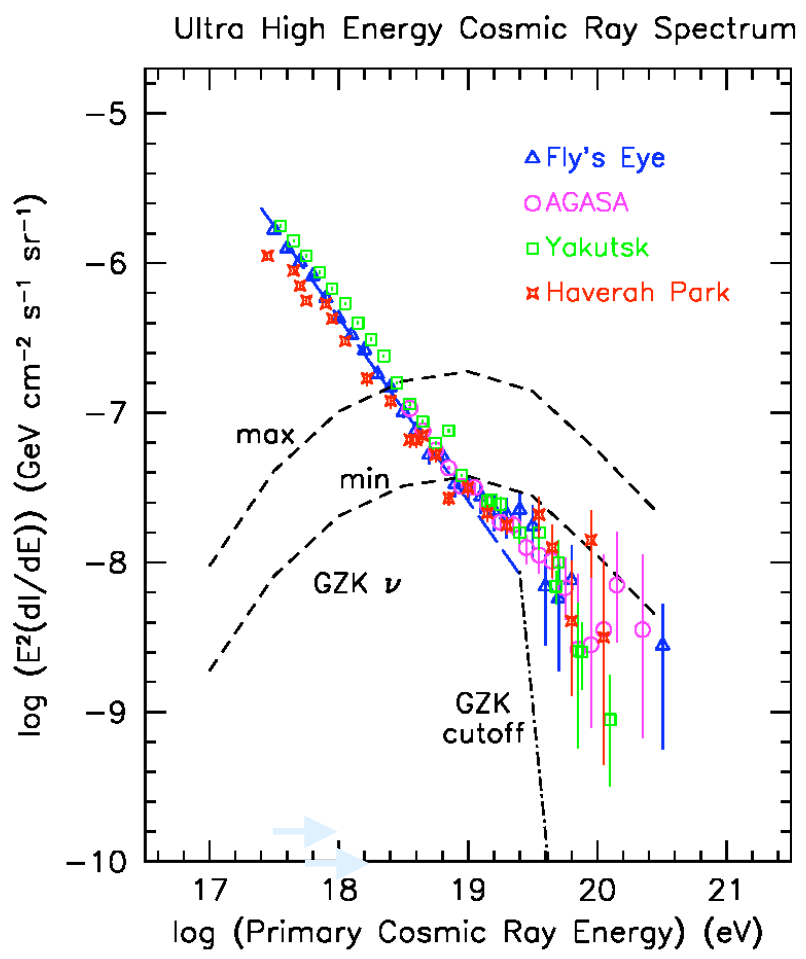
→ in interctions with the supernova remnant

→ in internal shocks during expansion

sources of the highest energy cosmic rays ?



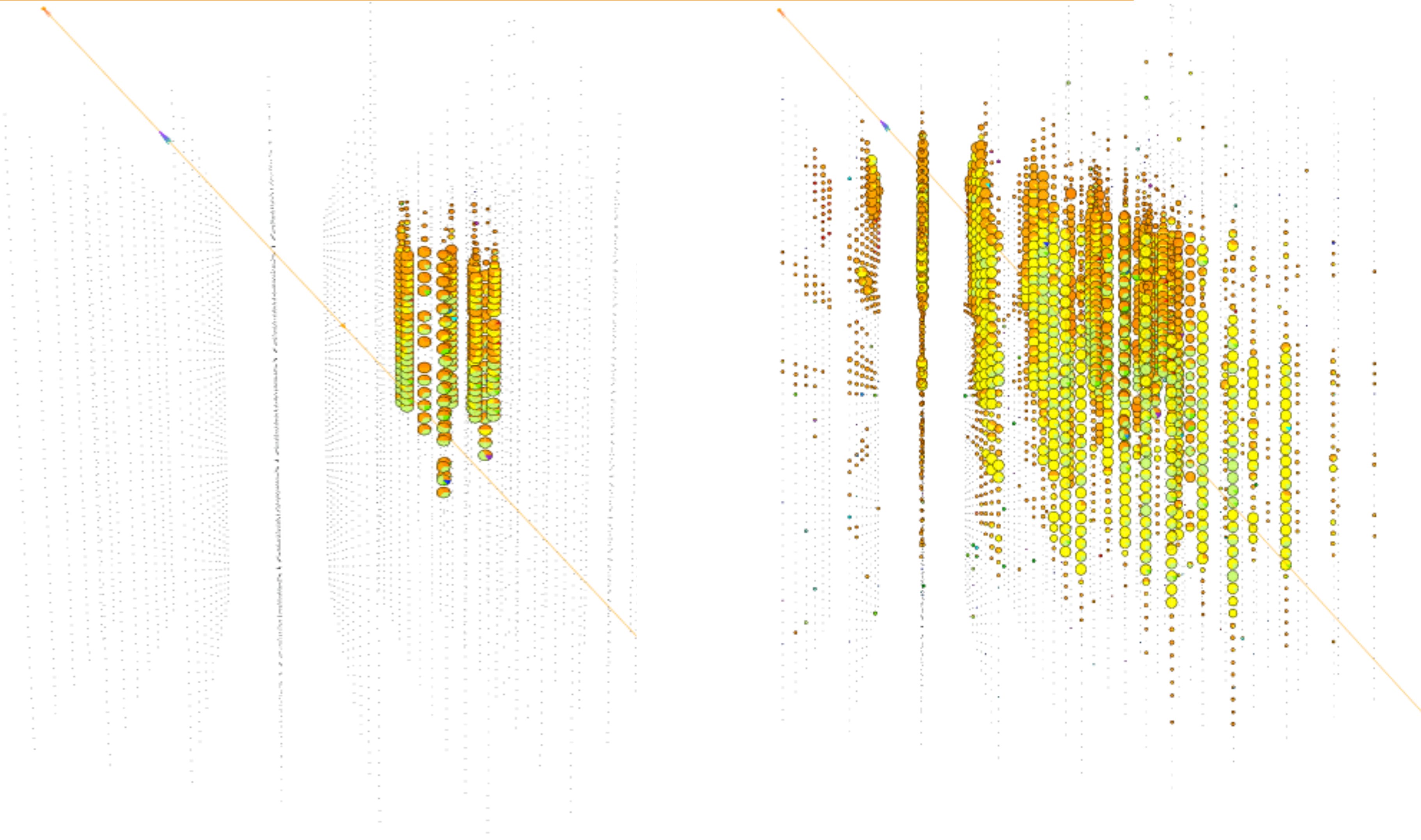
GZK Cosmic Rays & Neutrinos



- cosmogenic neutrinos are "guaranteed"
- 0.1– few events per year in IceCube

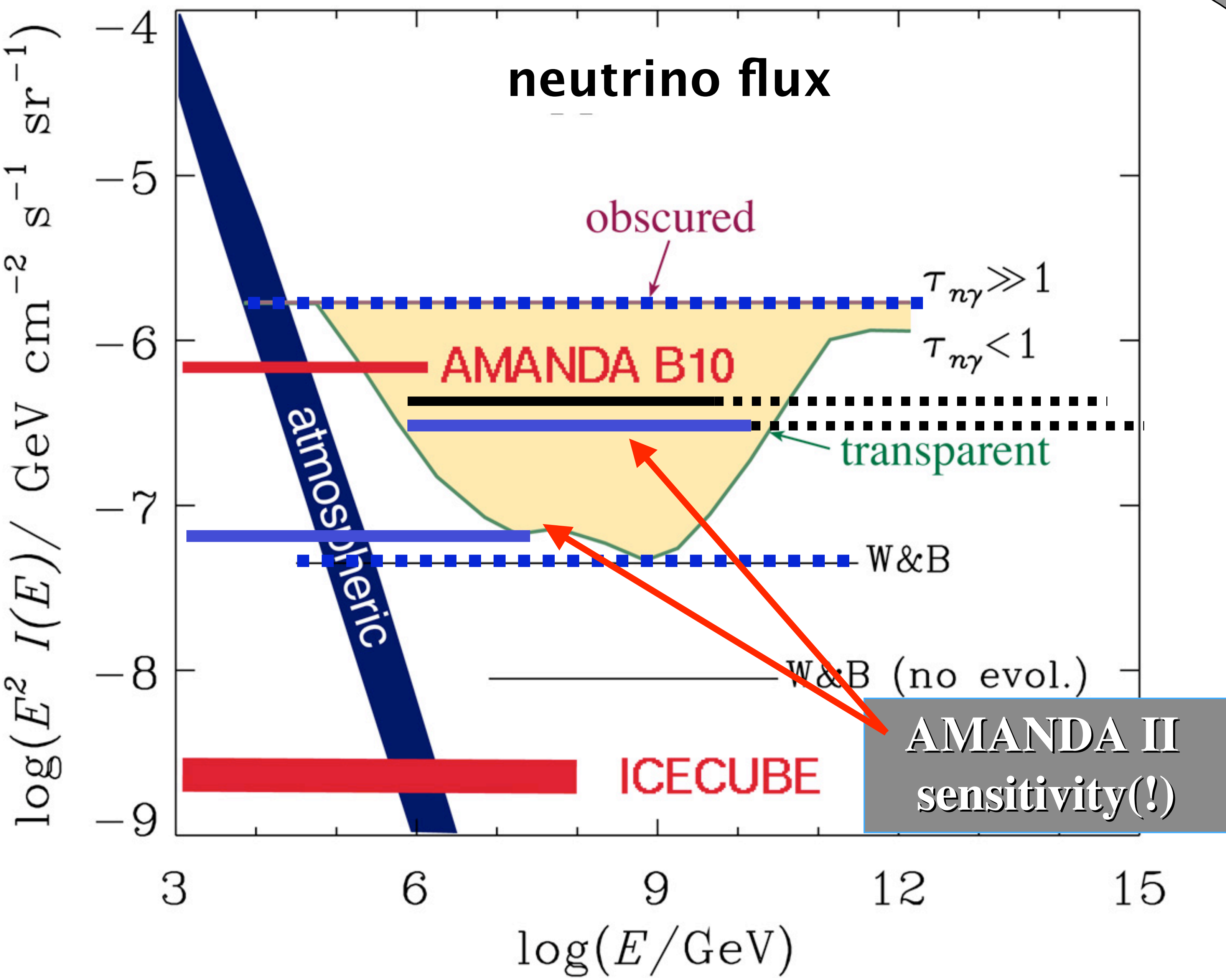
$$p + \gamma_{CMB} \rightarrow \pi + n$$

2 x 10^{19} eV event in AMANDA and IceCube:

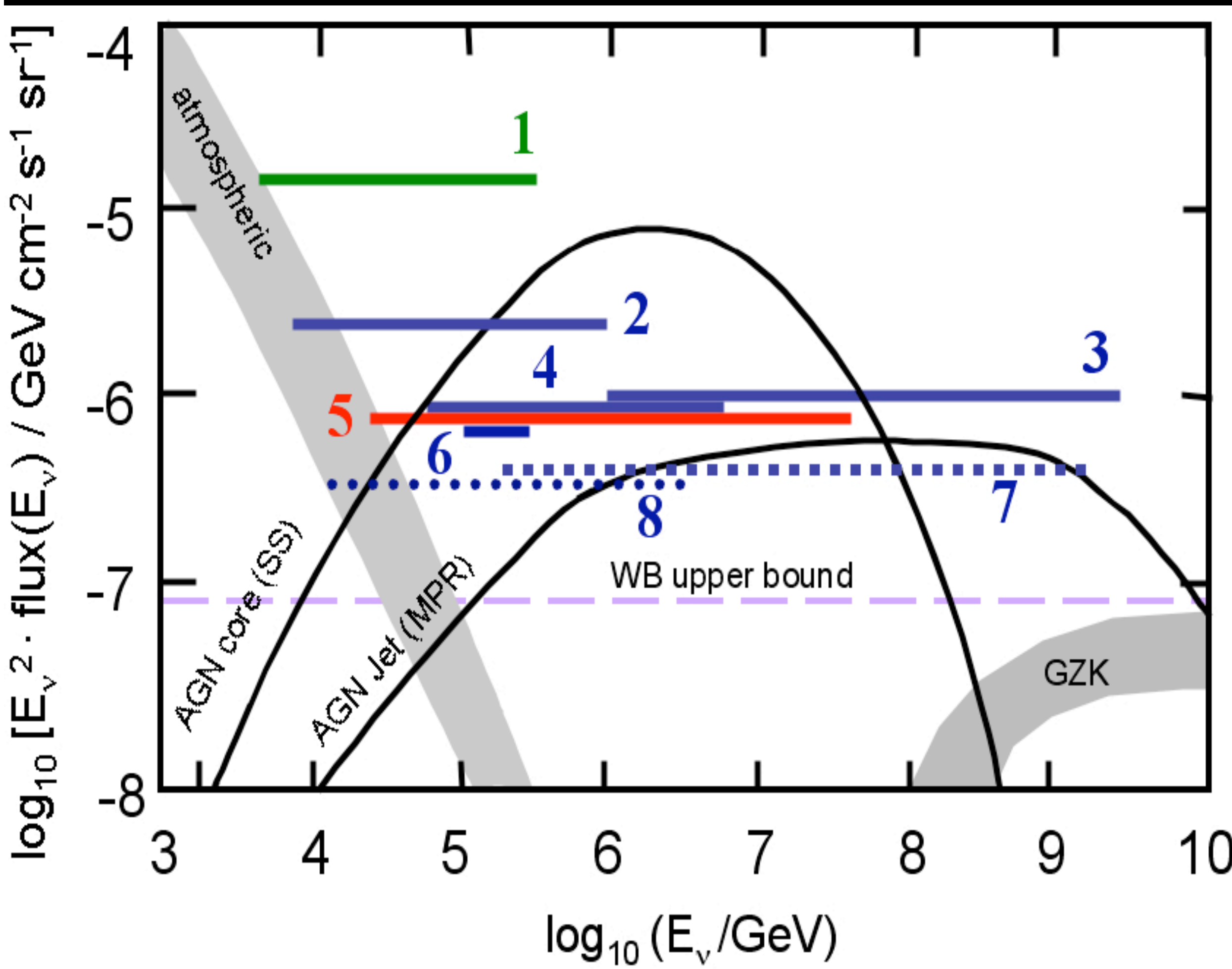


GZK neutrino: $p + \gamma_{CMB} \rightarrow \pi + n$

Neutrinos Associated With the Source of the Cosmic Rays?



diffuse neutrino flux limits 2005

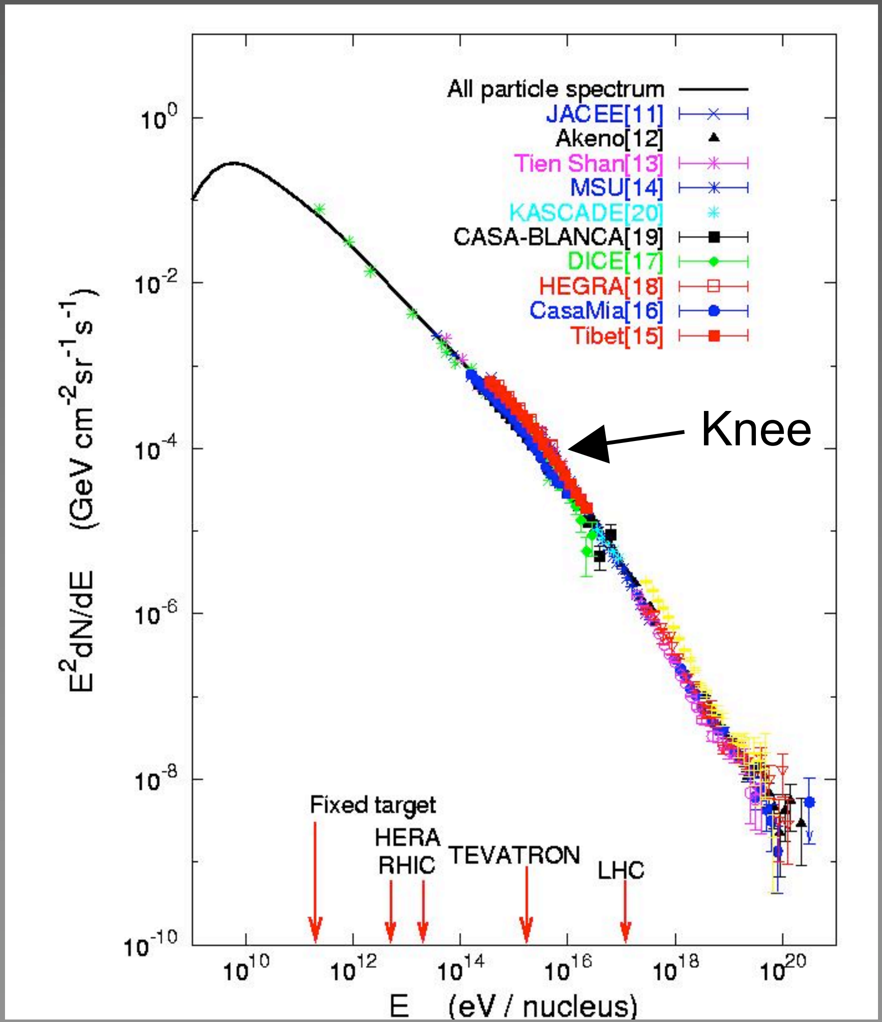


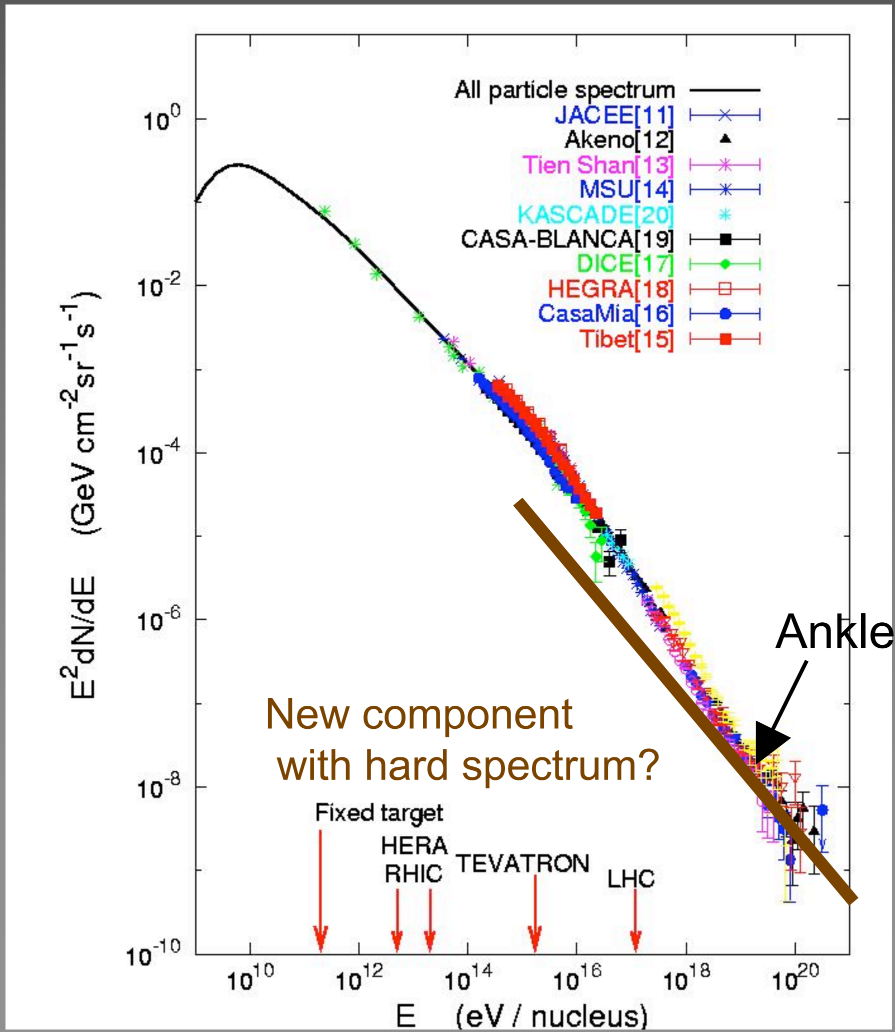
1. MACRO
2. AMANDA B10 ν_μ (1997)
3. AMANDA-B10 UHE (1997)
4. AMANDA-II cascades (2000)
5. Baikal cascades 1998-2003
6. AMANDA-II ν_μ-analysis (2000)
7. AMANDA-II UHE sensitivity !!
8. AMANDA ν_μ-analysis (2000-2003) sensitivity

preliminary!

limits multiplied by 3
for oscillations!

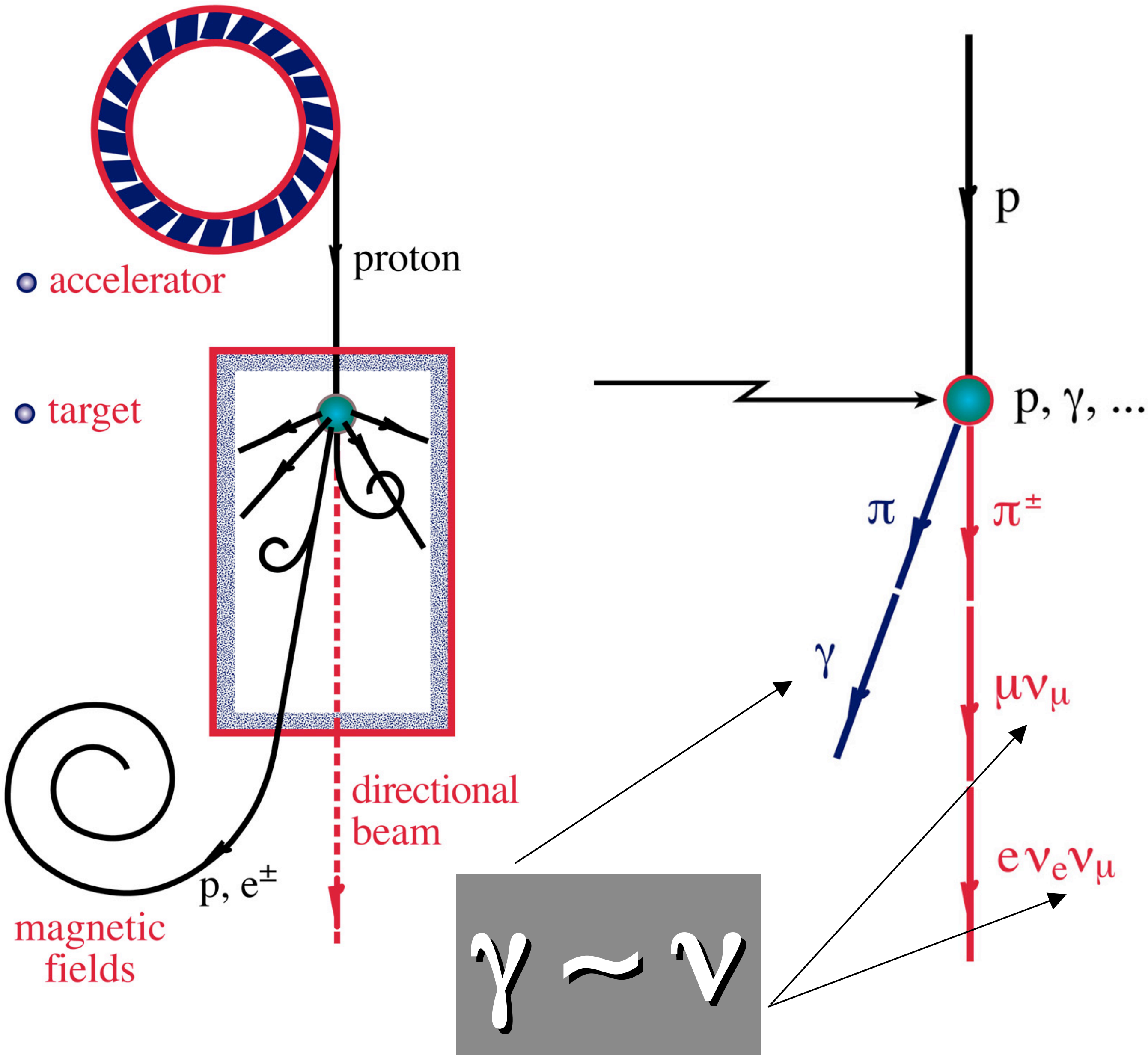
Galactic and Extragalactic Cosmic Rays

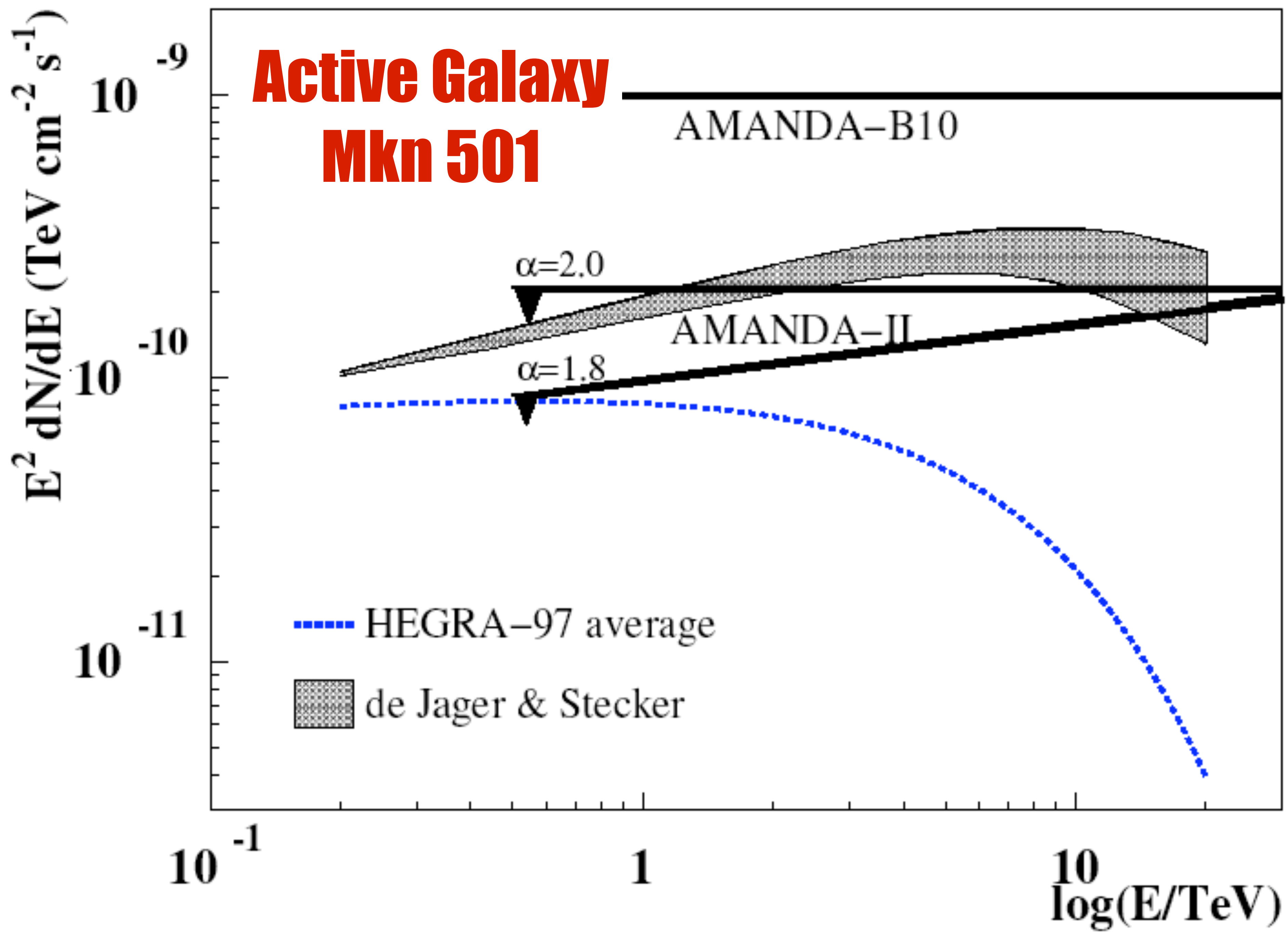




cosmic neutrinos associated with gamma rays

Neutrino Beams: Heaven & Earth



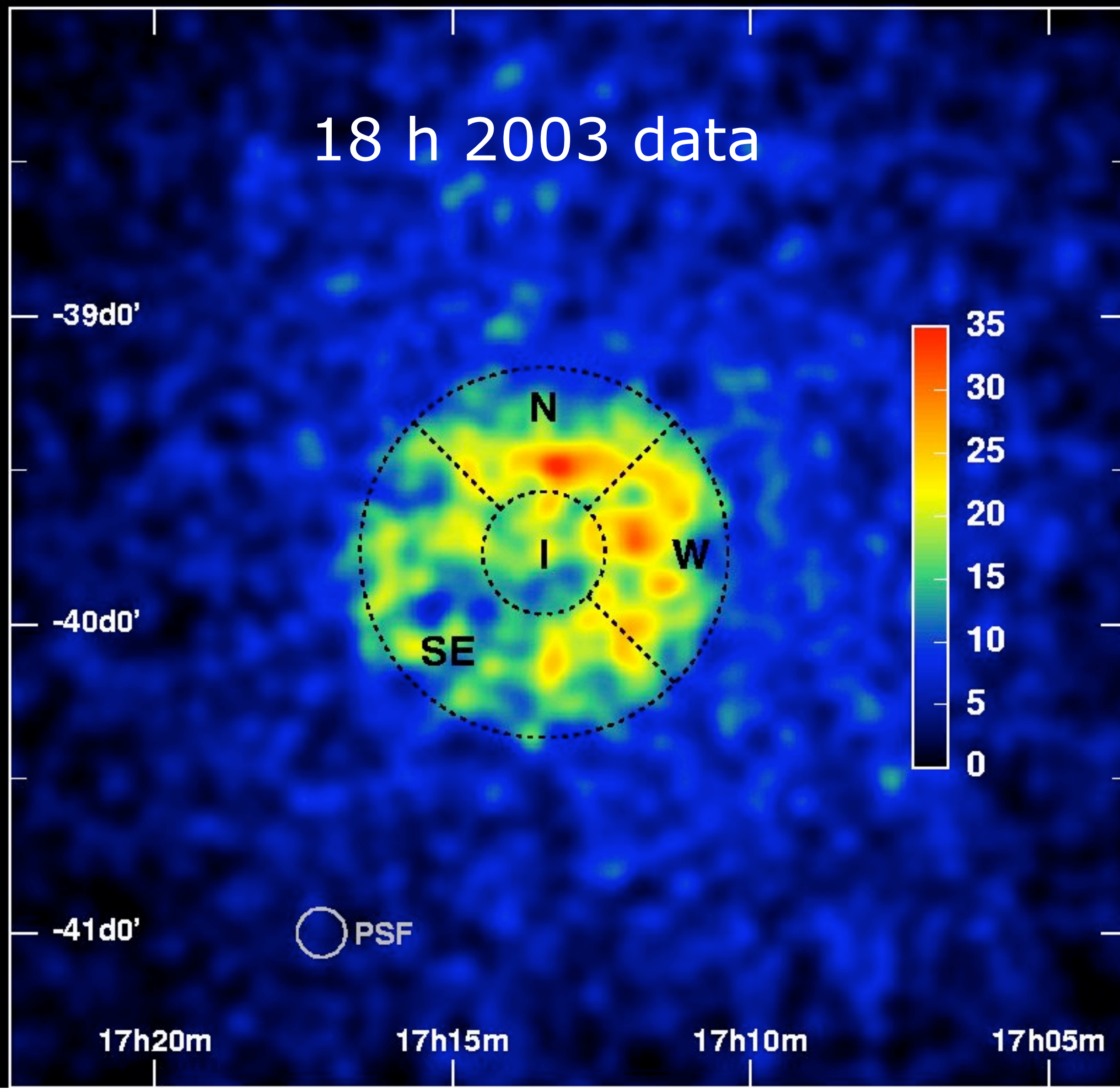


Active Galaxy
Mkn 501
E^2 dN/dE (TeV cm^{-2} s^{-1})
10^{-9}
10^{-10}
10^{-11}
AMANDA−B10
α=2.0
AMANDA−II
α=1.8
HEGRA−97 average
de Jager & Stecker
10^{-1}
1
10
log(E/TeV)

HESS: RX J1713 Spectrum

resolution
~10 arcmin

where are
the electrons?



γ-rays from π^0 decay discovered ?

$$\int E_\nu N_\nu (E_\nu) = \varepsilon \int E_\gamma N_\gamma (E_\gamma)$$

$$1 < \varepsilon < \infty$$

transparent source
$\pi^0 = \pi^+ = \pi^-$

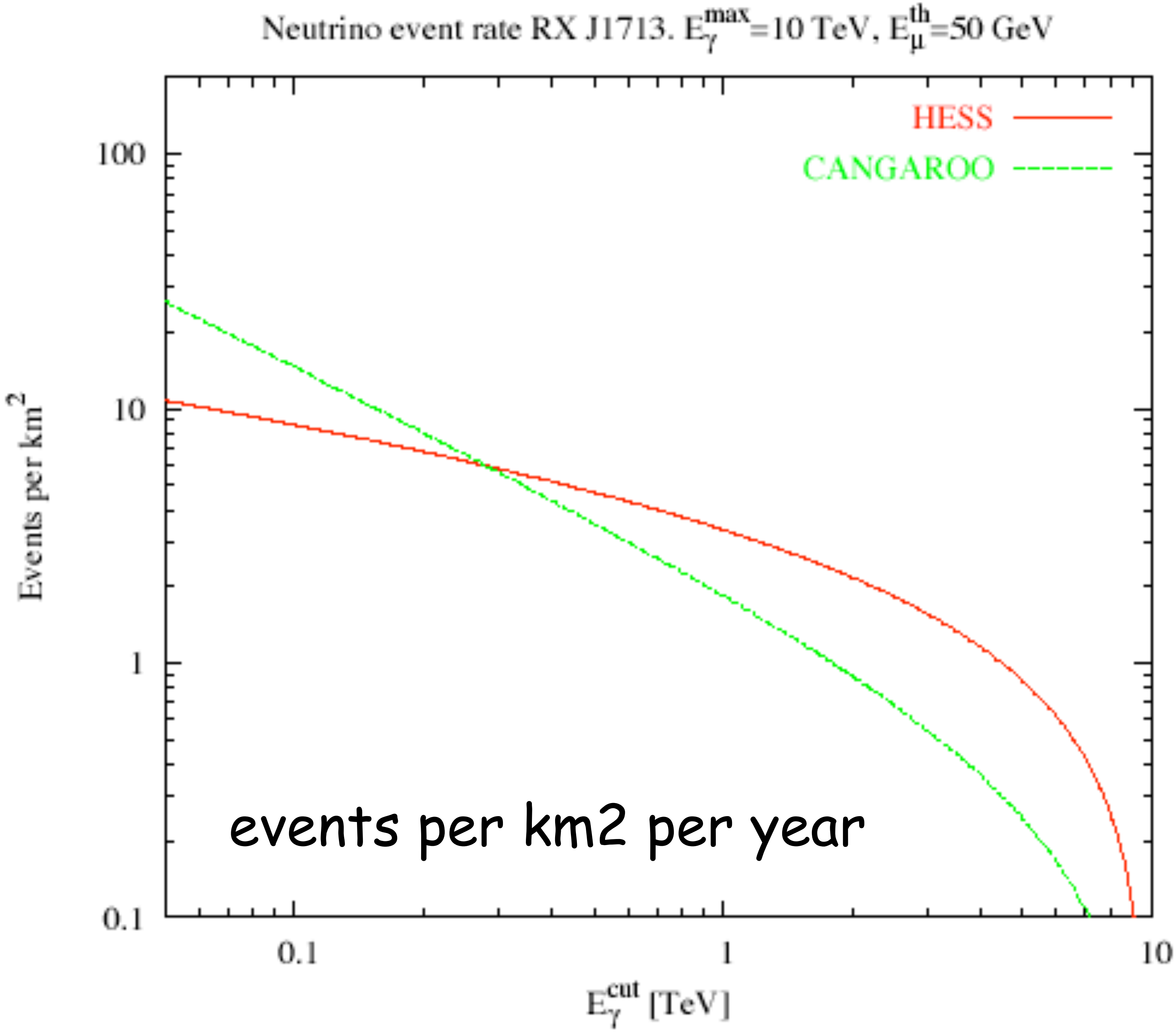
accelerator
beam dump
(hidden source)

ν flux predicted

observed γ-ray fl

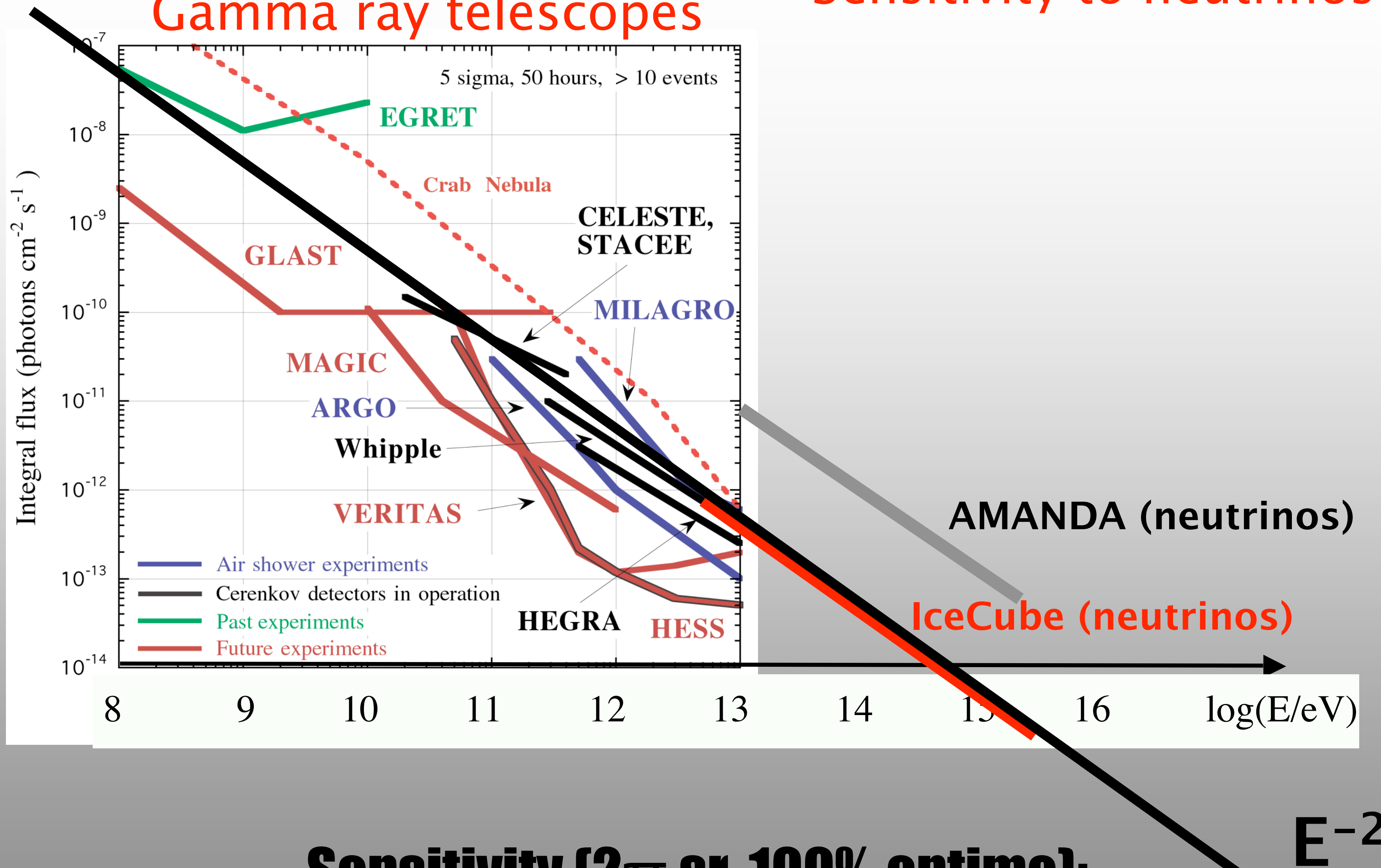
~ 20 per km2
per year

RX J1713-39
(galactic cent


Neutrino event rate RX J1713. E_γ^{max}=10 TeV, E_μ^{th}=50 GeV
HESS
CANGAROO
Events per km^2
100
10
1
0.1
0.1
1
10
E_γ^{cut} [TeV]
events per km2 per year

Sensitivity of Gamma ray telescopes

Sensitivity to neutrinos

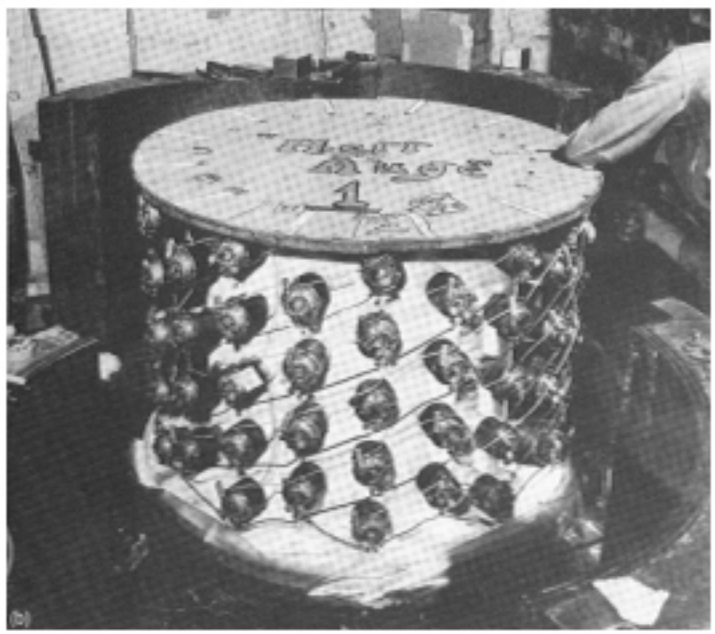


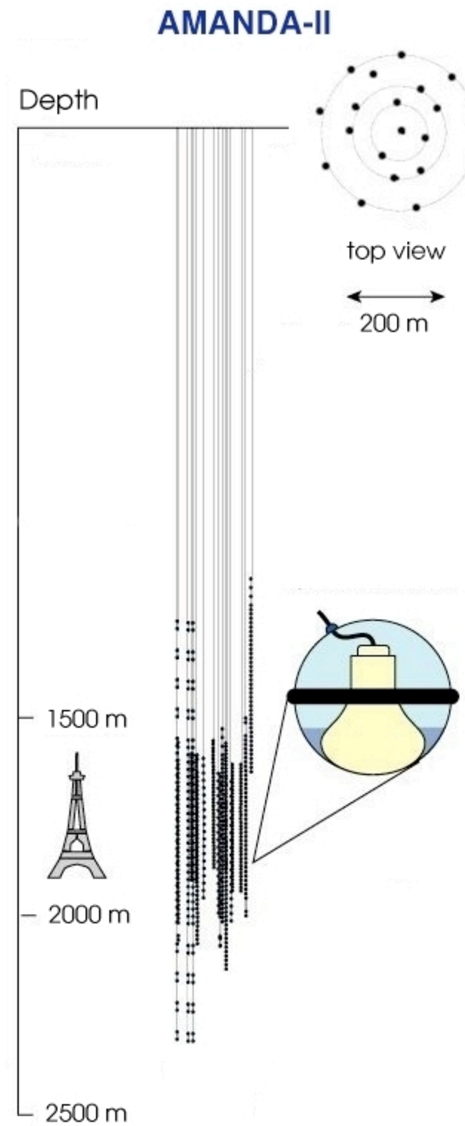
Sensitivity (2π sr, 100% ontime):

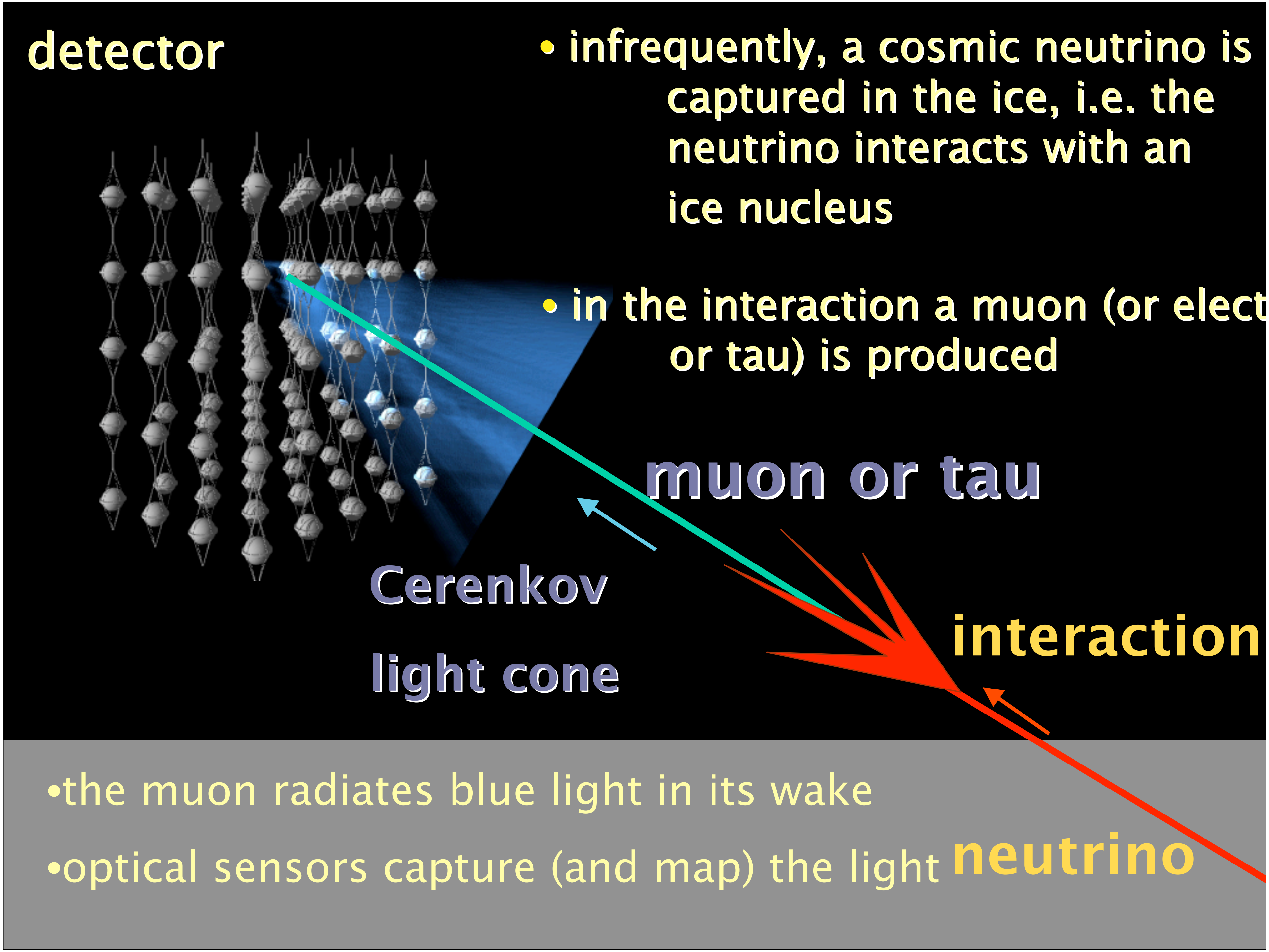
3 years exposure, 5 sigma

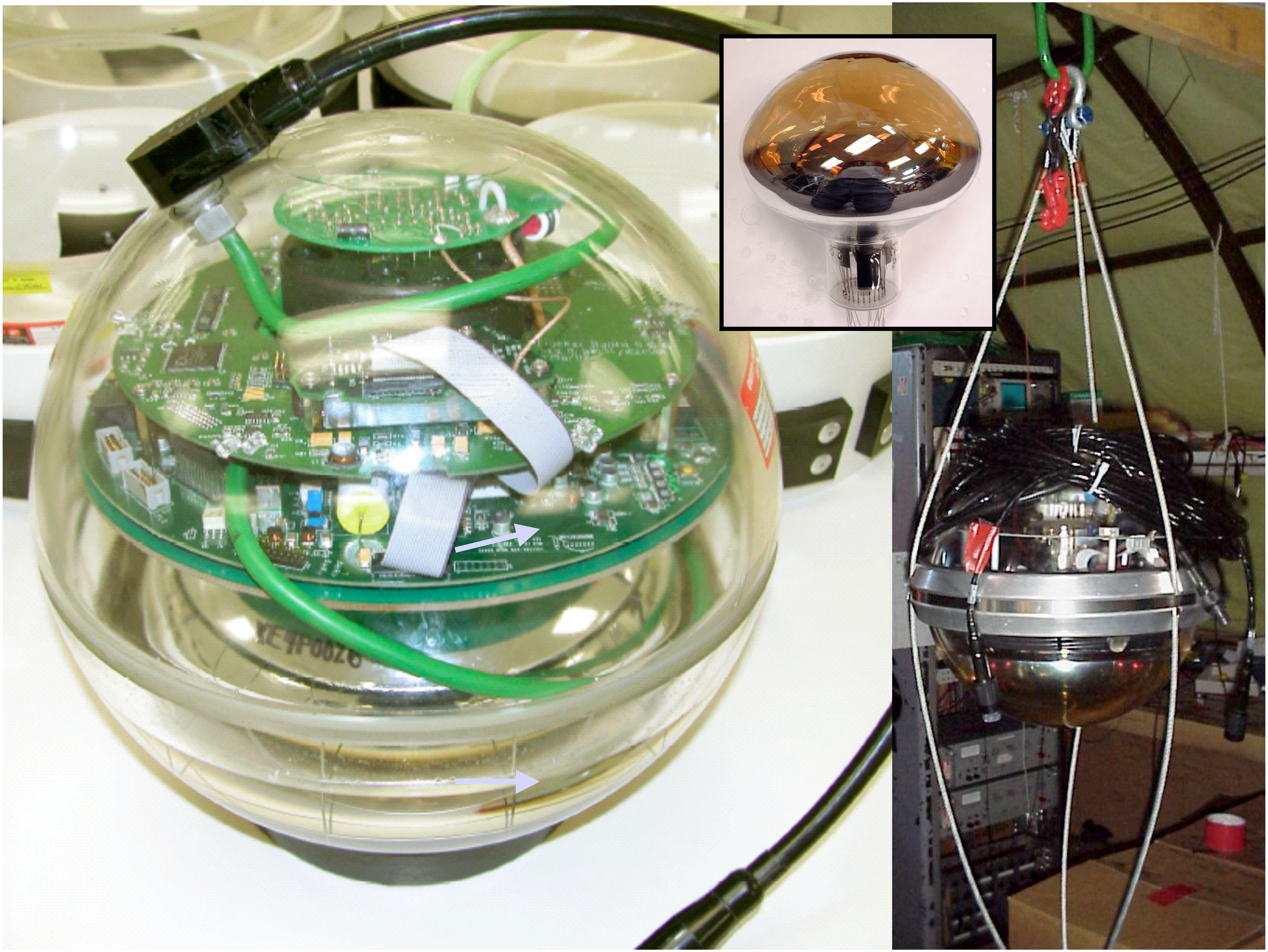
first-generation neutrino telescopes

Requires Kilometer-Scale Neutrino Detectors



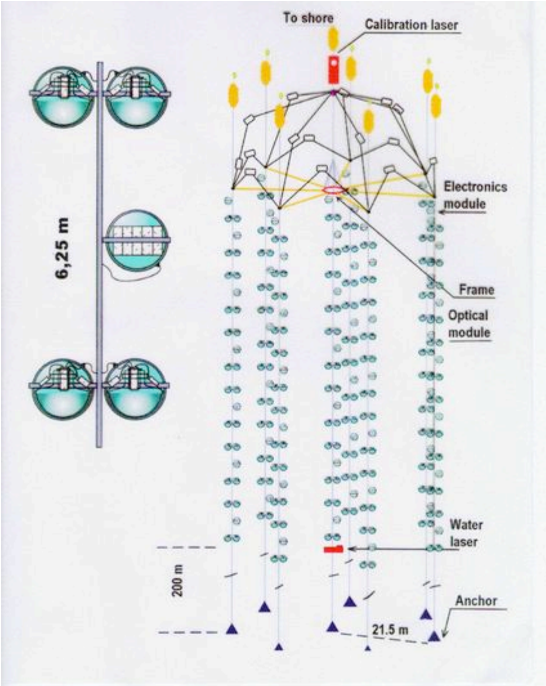



detector
• infrequently, a cosmic neutrino is captured in the ice, i.e. the neutrino interacts with an ice nucleus
• in the interaction a muon (or elect
or tau) is produced
muon or tau
Cerenkov
light cone
interaction
•the muon radiates blue light in its wake
•optical sensors capture (and map) the light
neutrino



Northern hemisphere detectors

Baikal NT200

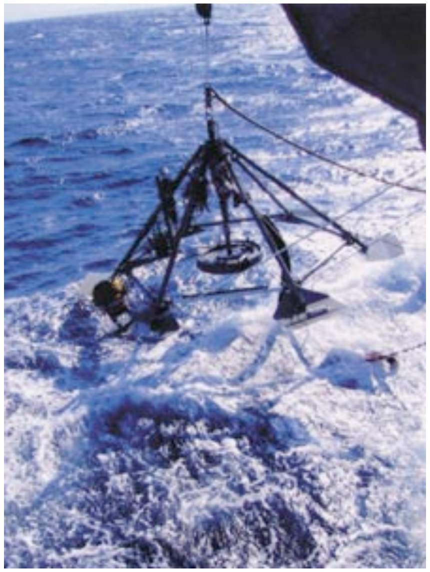


1100 m deep
data taking since 1998
new: 3 distant strings

Antares

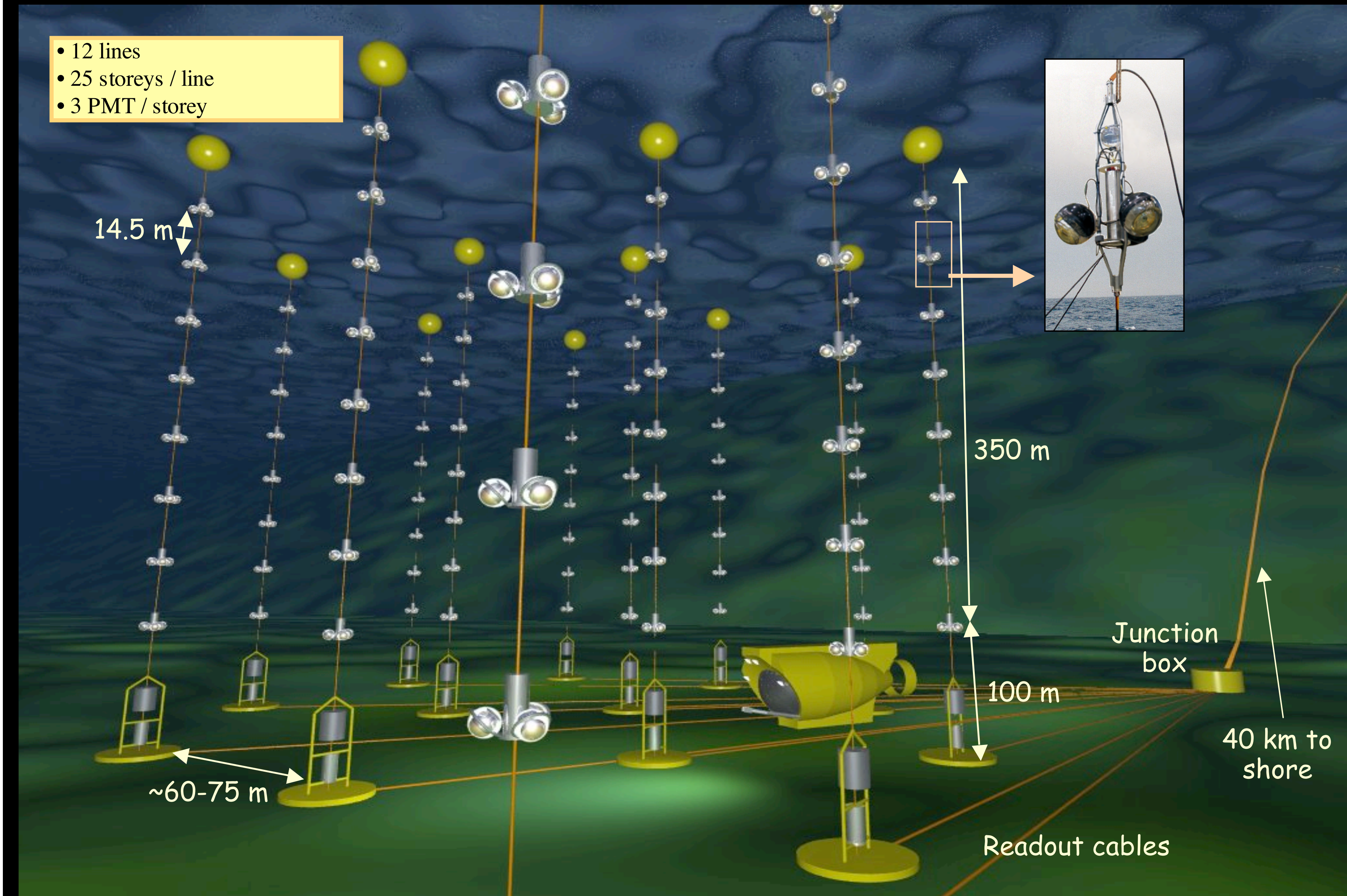
March 17, 2003
2 strings connected
2400 m deep
completion: start 2006

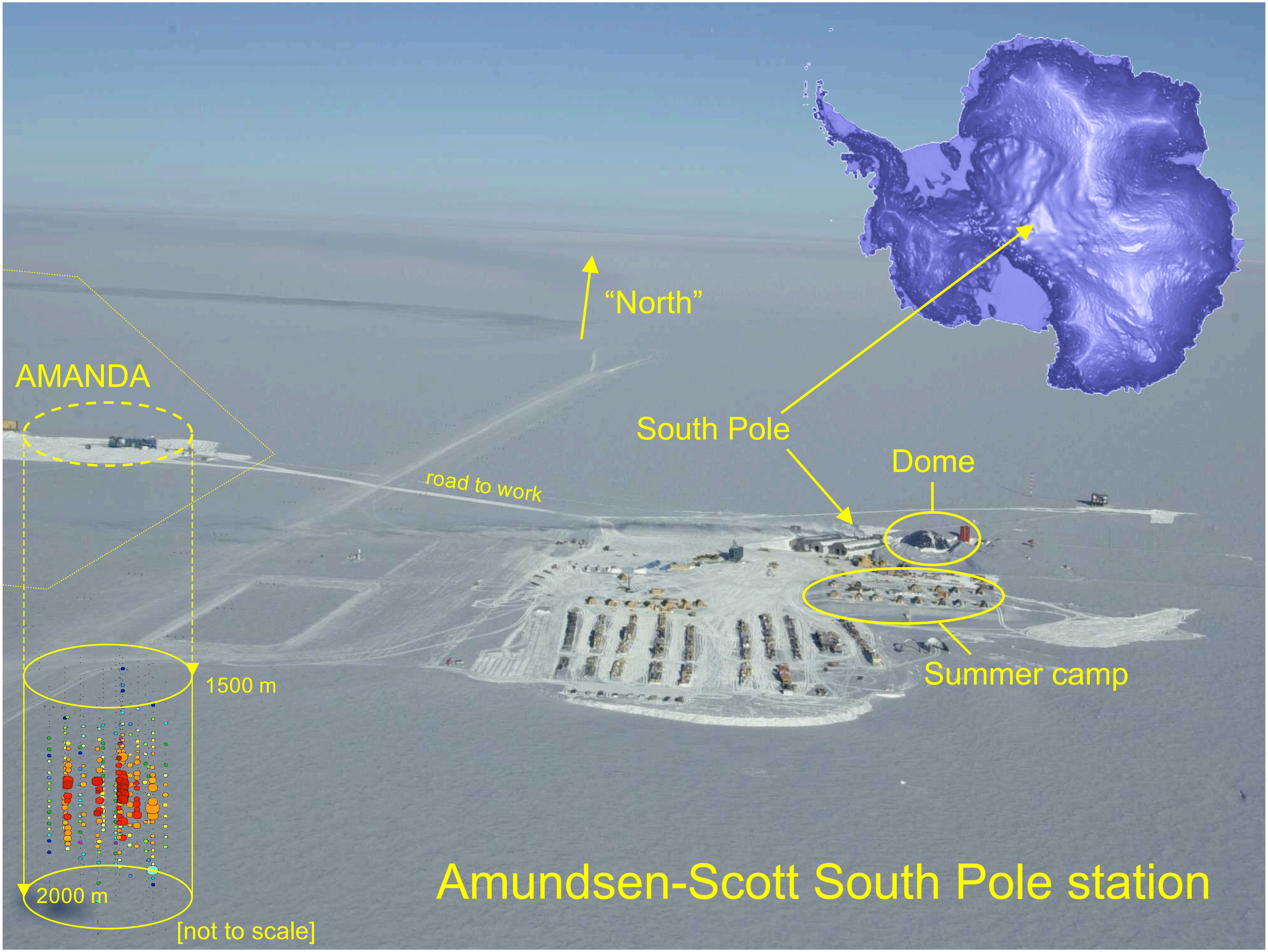
Nestor



March 29, 2003
1 of 12 floors deployed
4000 m deep
completion: 2006

ANTARES

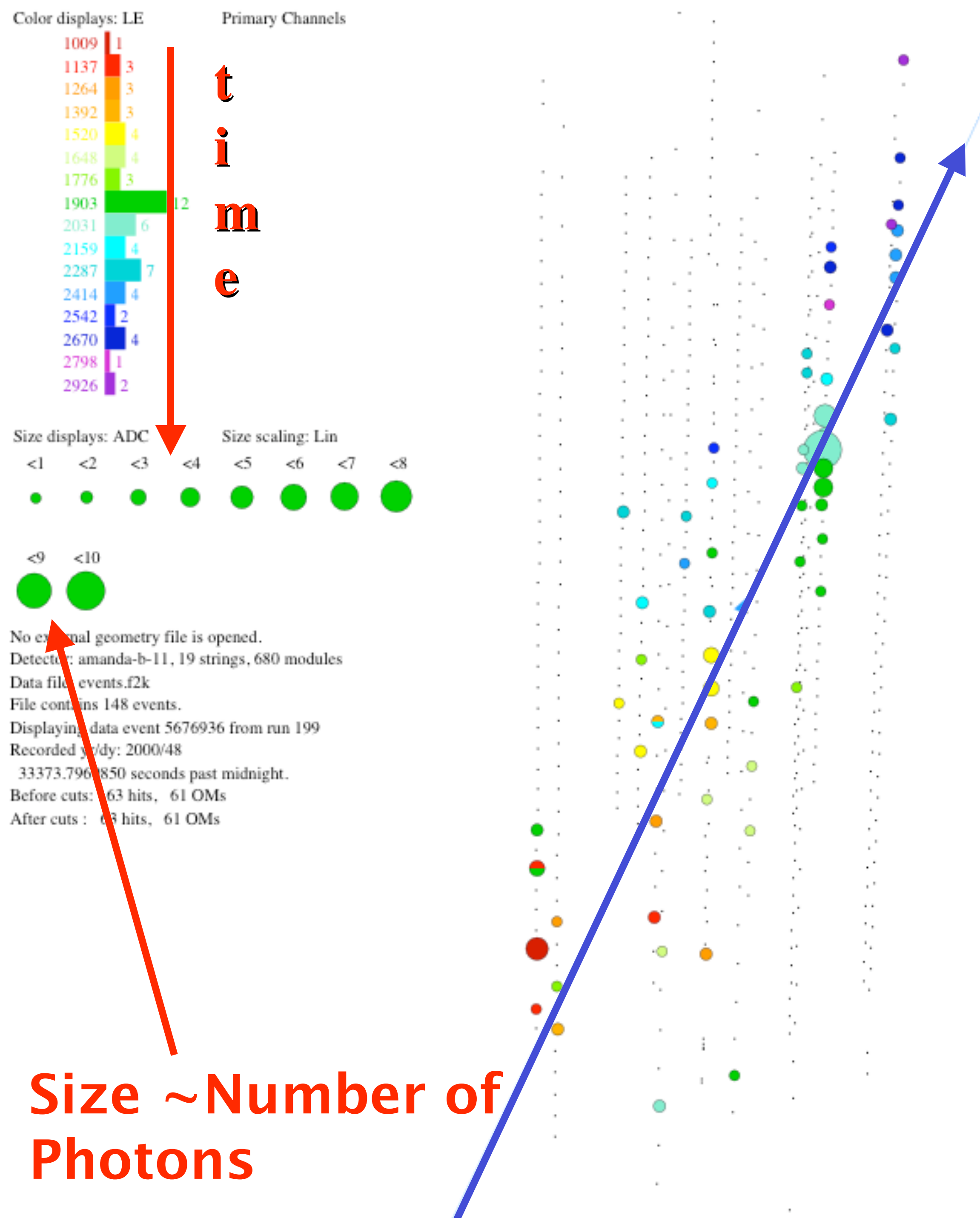

• 12 lines
• 25 storeys / line
• 3 PMT / storey
14.5 m
350 m
100 m
~60-75 m
Junction box
40 km to shore
Readout cables



"North"
AMANDA
South Pole
Dome
road to work
Summer camp
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station

AMANDA II

- up-going muon
- 61 modules hit

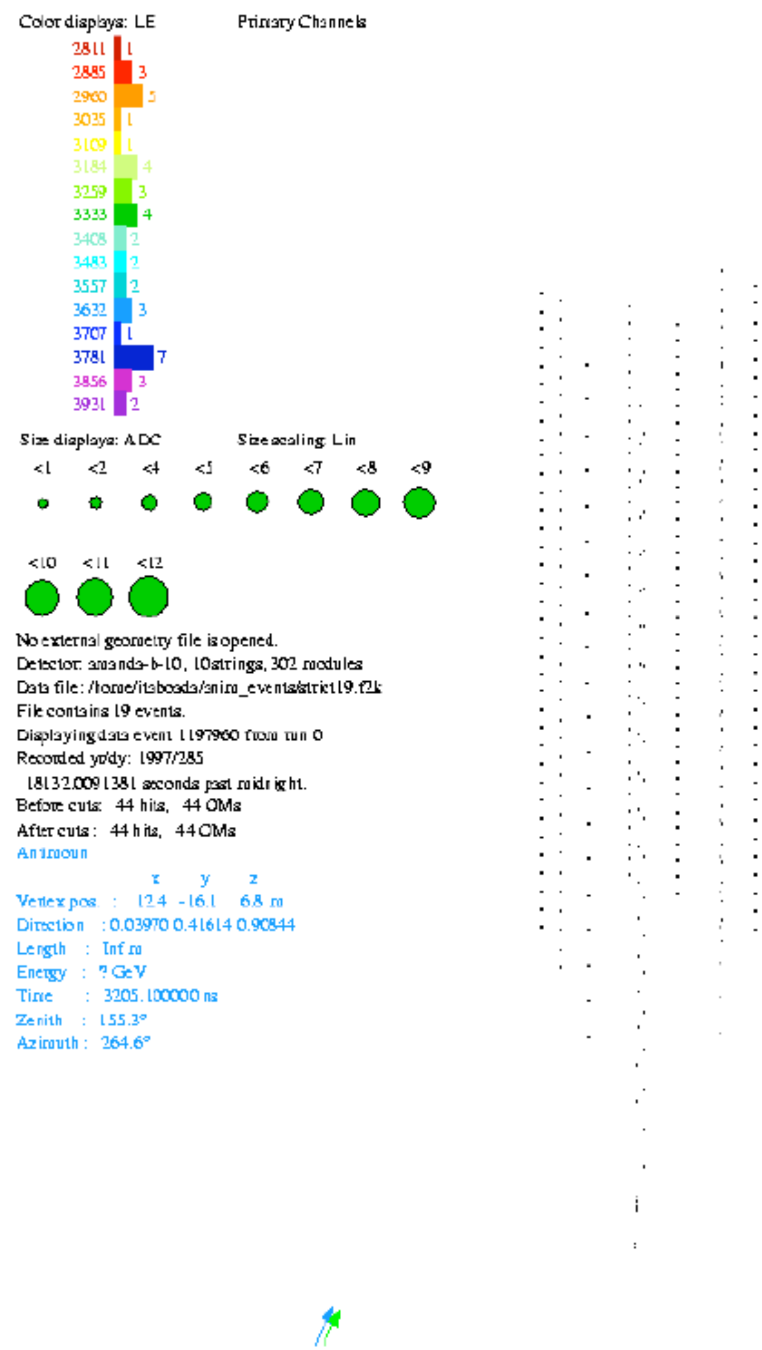


> 7 neutrinos/day on-line

AMANDA Event Signature: Muon

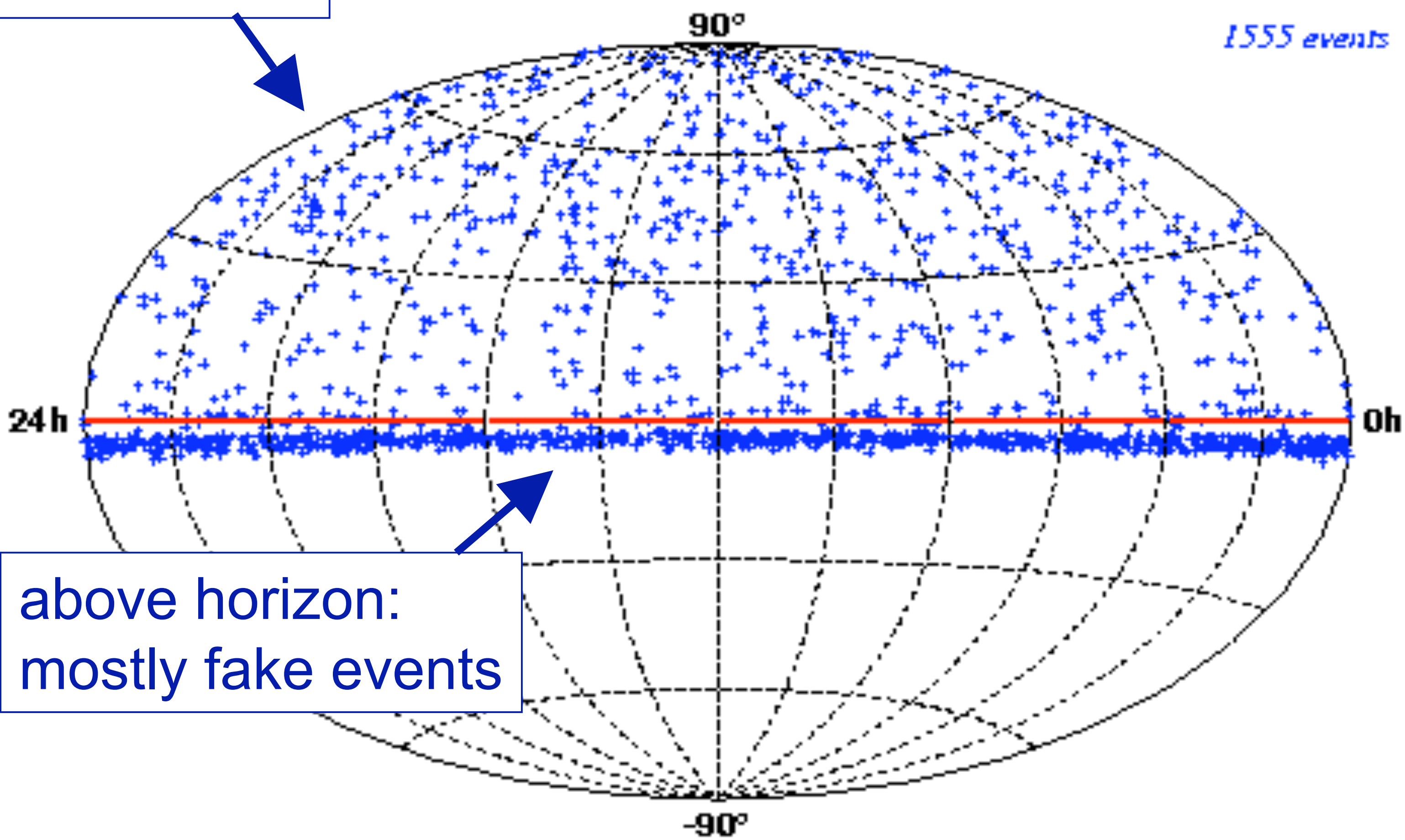
CC **muon neutrino interaction → track**

$$\nu_\mu + N \rightarrow \mu + X$$



Skyplot Amanda-II 2000

697 events below horizon

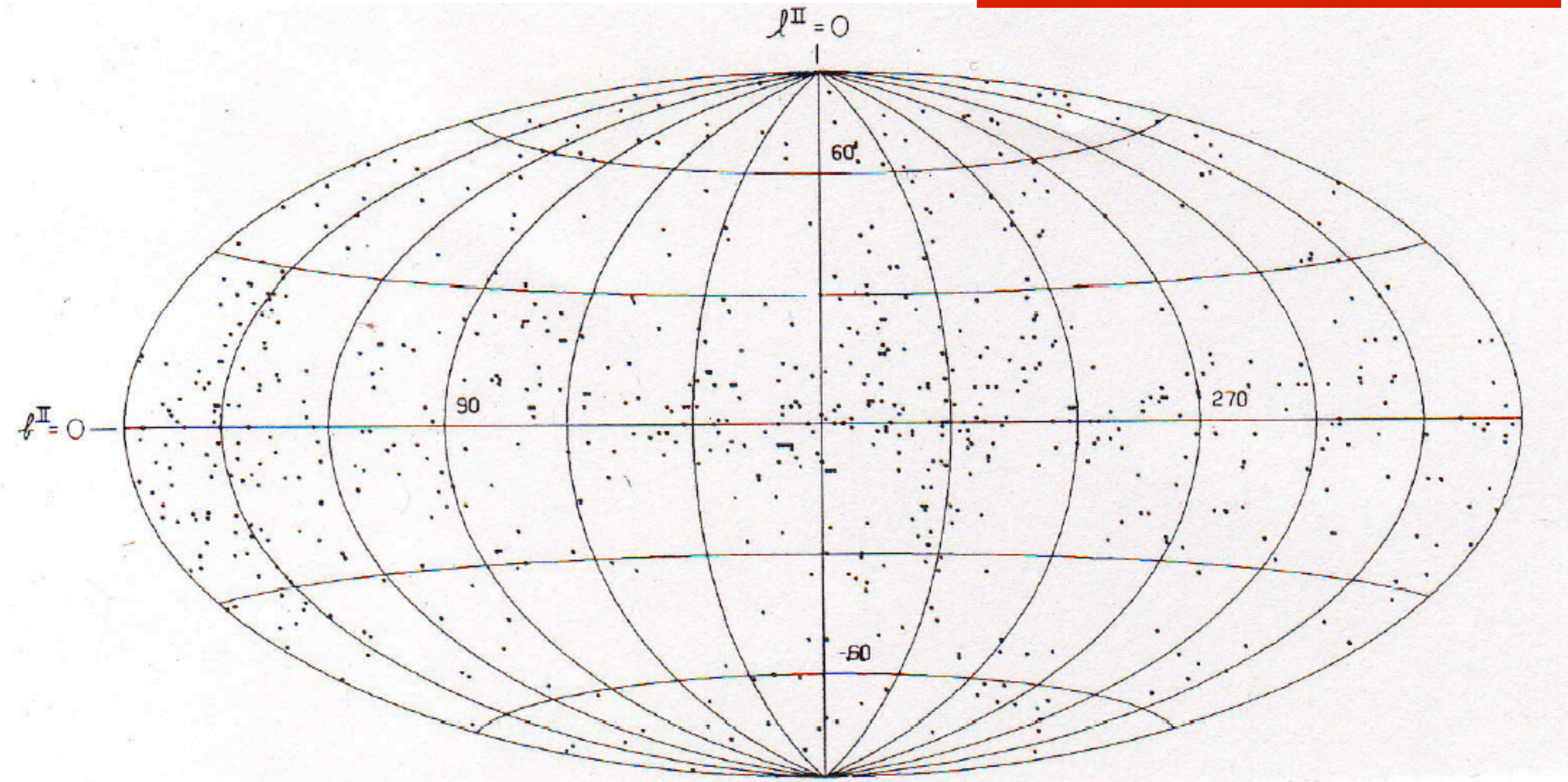


above horizon: mostly fake events

1968 OSO-3 (Kraushaar et al. 1972)

- effective area 4 cm^2
- 600 photons

sources seen in next mission! SAS-2 100 cm^2

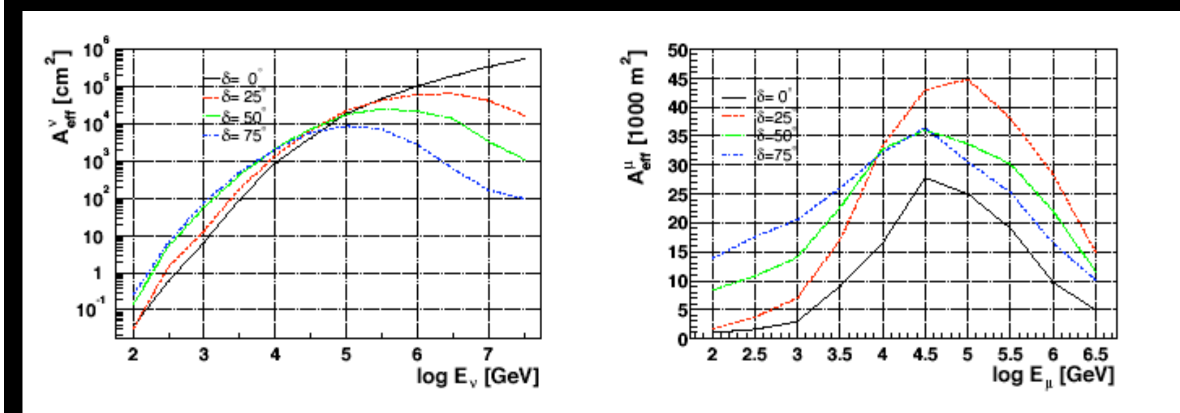


at TeV energy

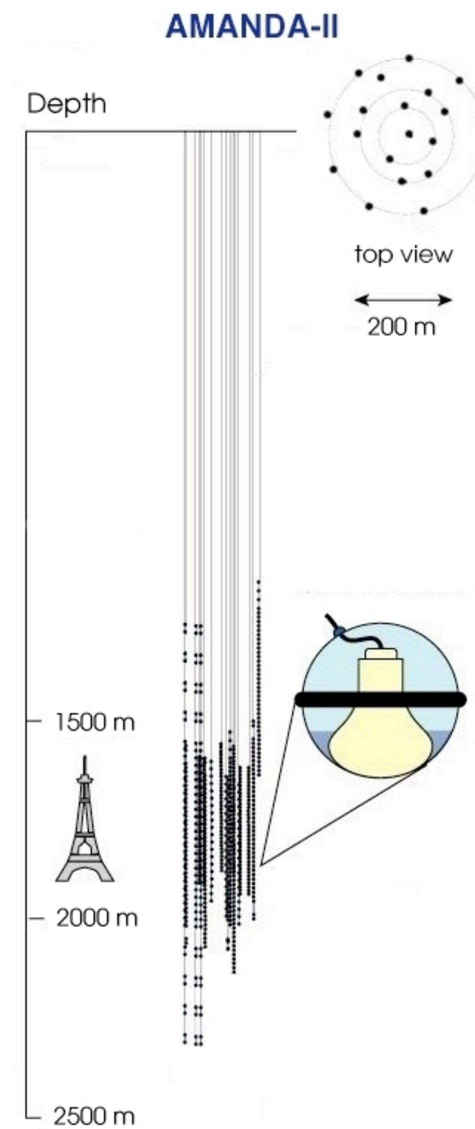
Neutrino area: 10~100 cm^2

Muon area: ~ 10,000 m^2

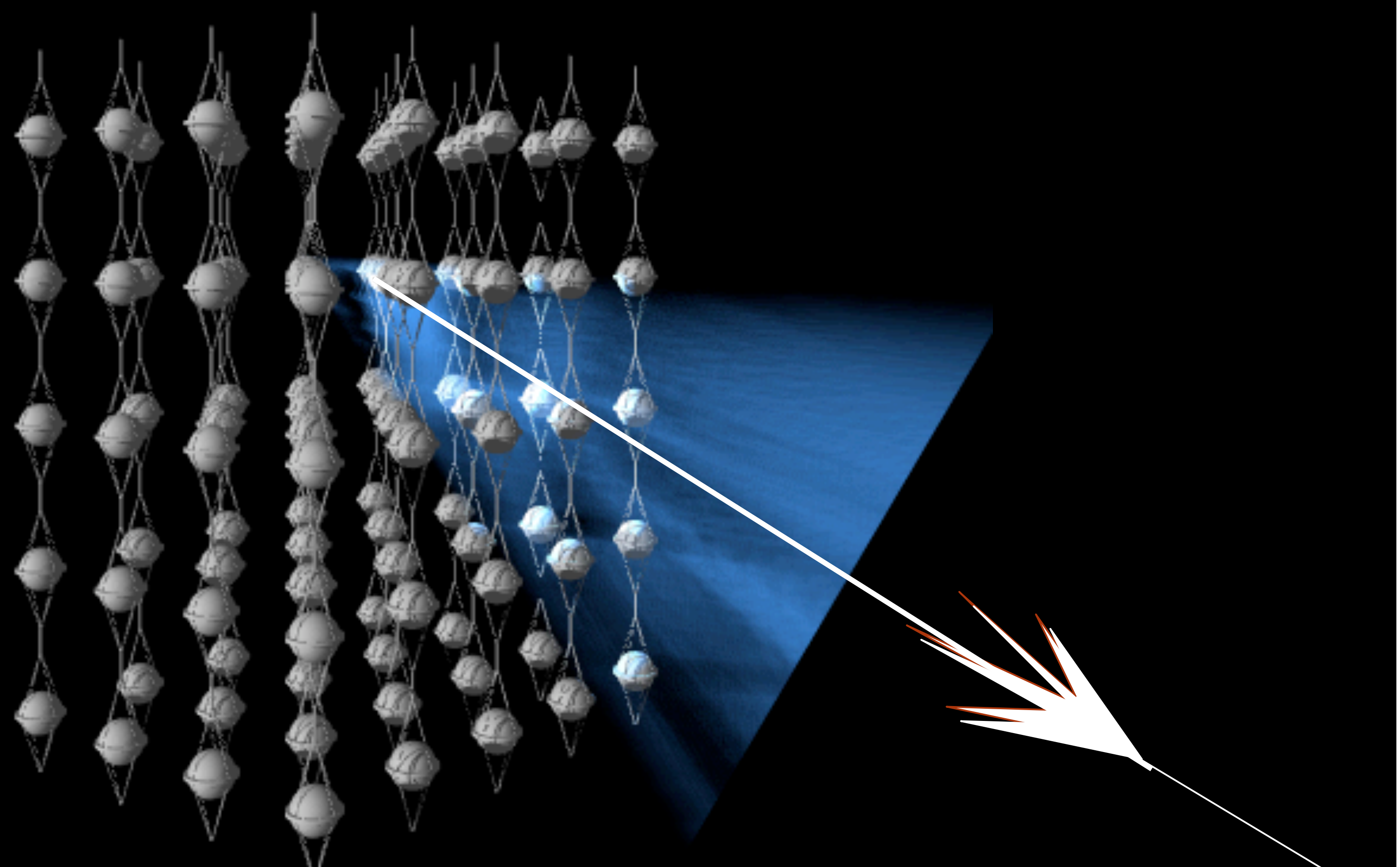
(geometric area 0.03—0.1 km^2)



The AMANDA Detector



detection method



lattice of light sensors

events from a flux $\phi_\nu(E_\nu)$

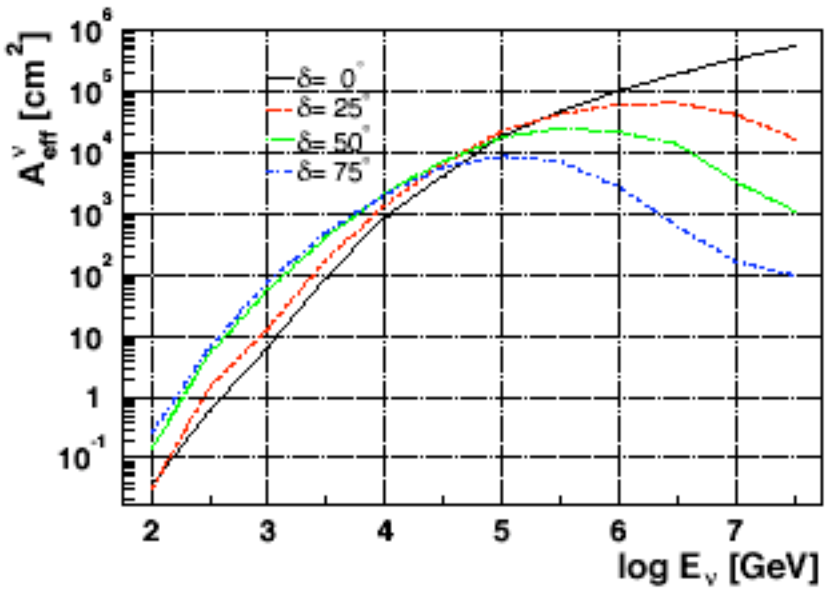
$$dN/dE = A_\nu \, \phi_\nu$$

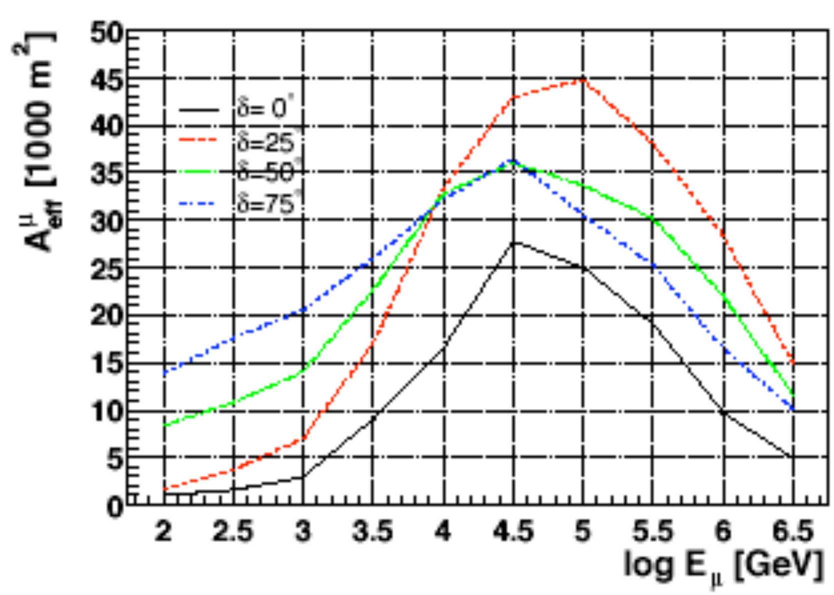
$$= \{P_{earth} \, P_\mu \, A_\mu\} \, \phi_\nu$$

with $P_\mu = n \, R_\mu \, \sigma_\nu \sim 10^{-6} \, E_{Tev}$

$$A_\nu = P_{earth} \, P_\mu \, A_\mu$$

amanda effective area

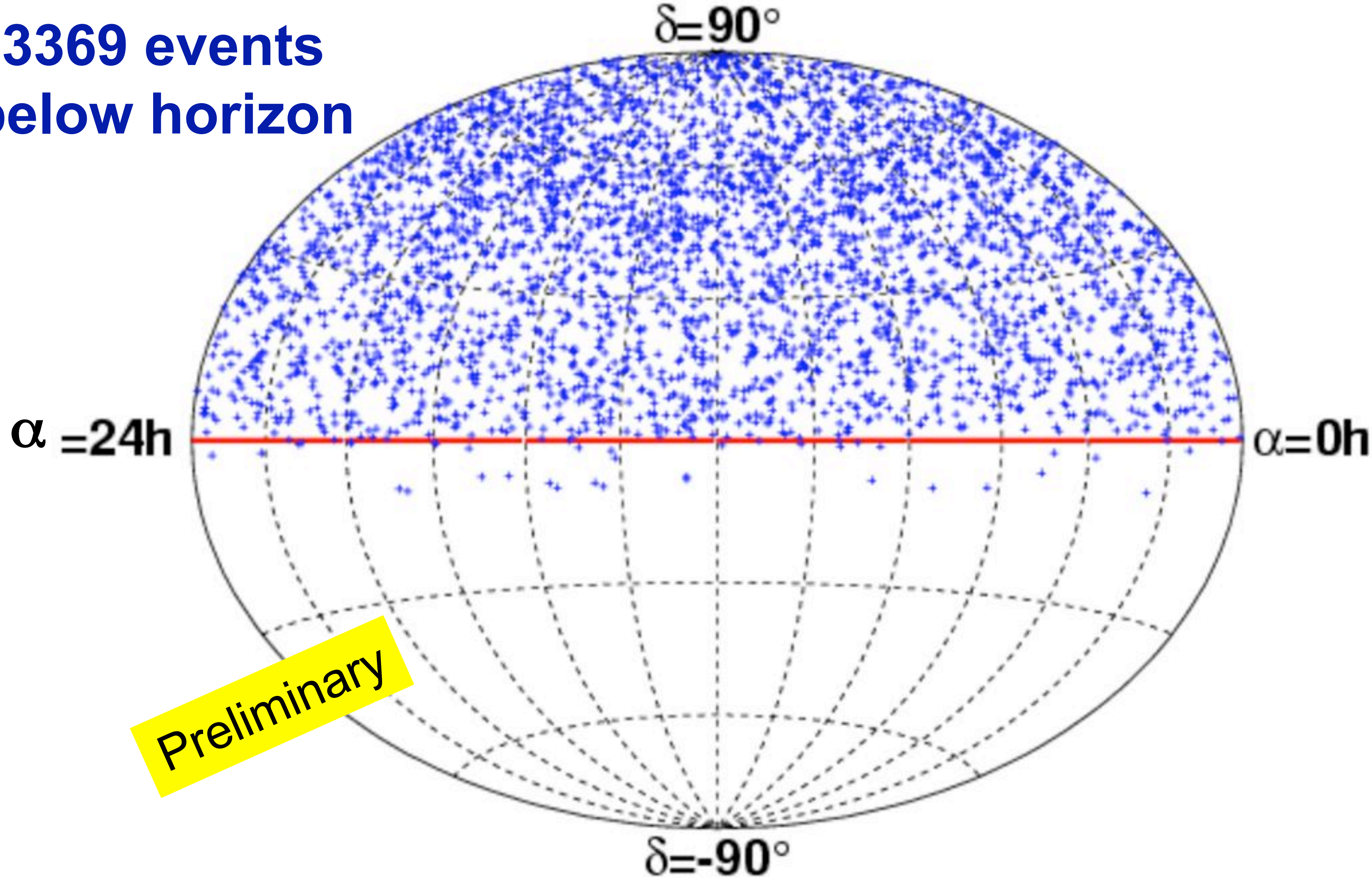




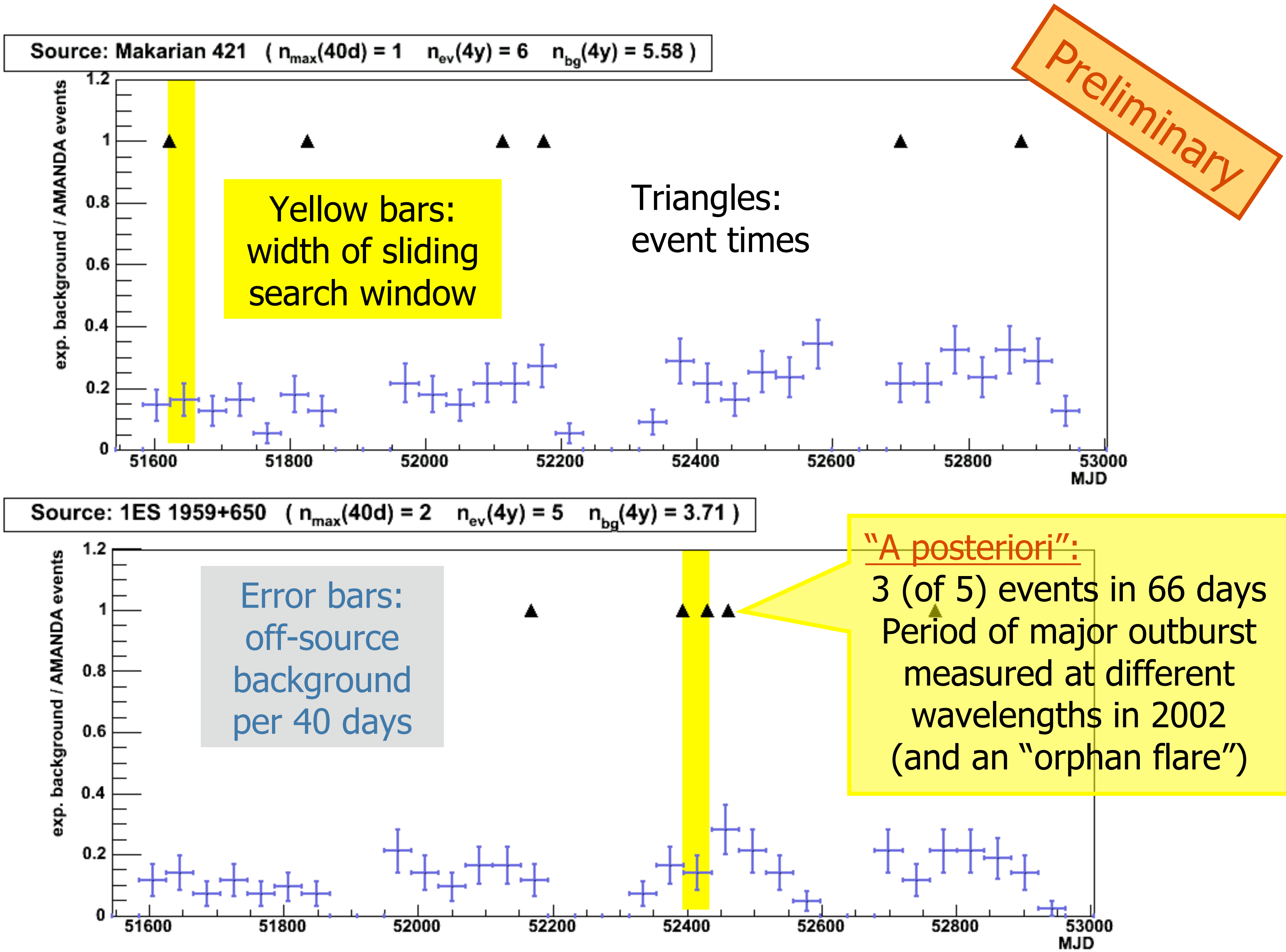
AMANDA skyplot 2000-2003

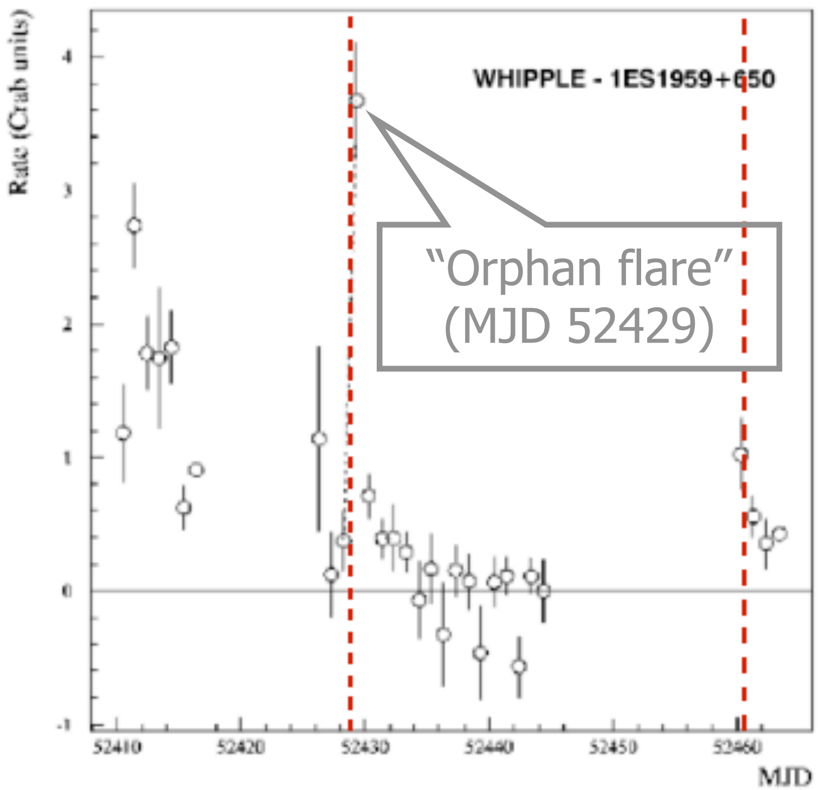
optimized for best sensitivity to E^{-3} – E^{-2} sources

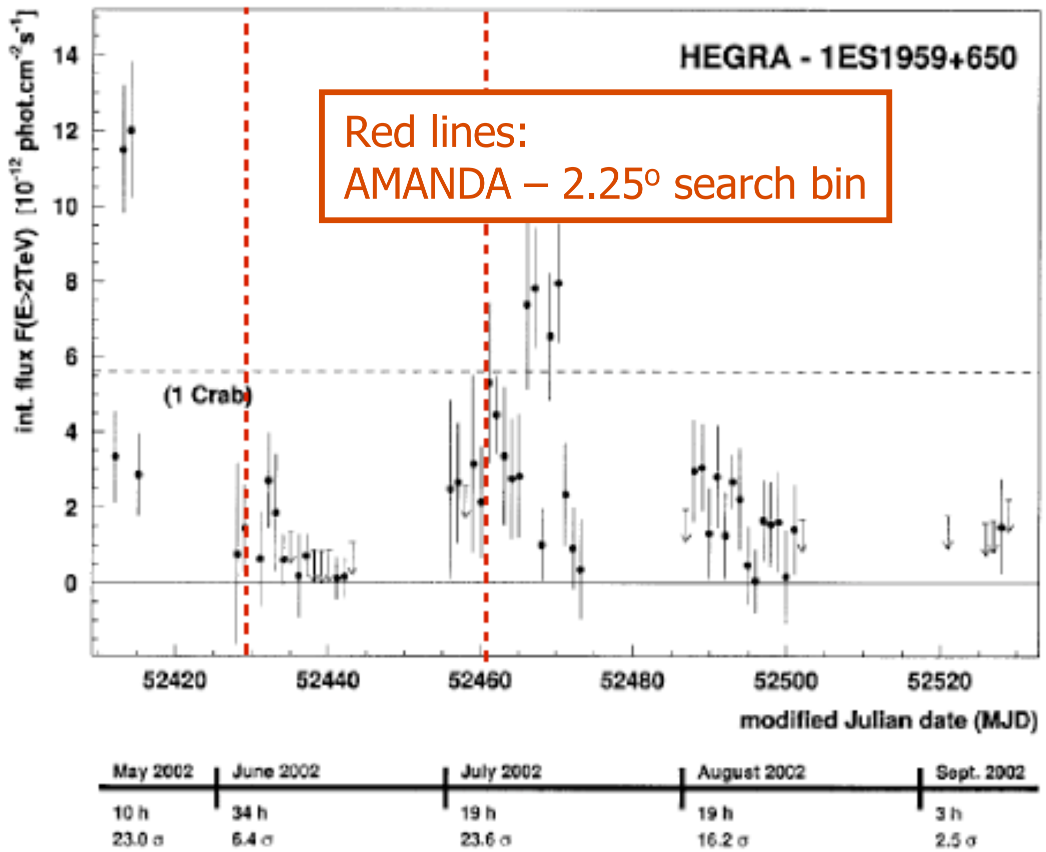
3369 events below horizon



multiwavelength

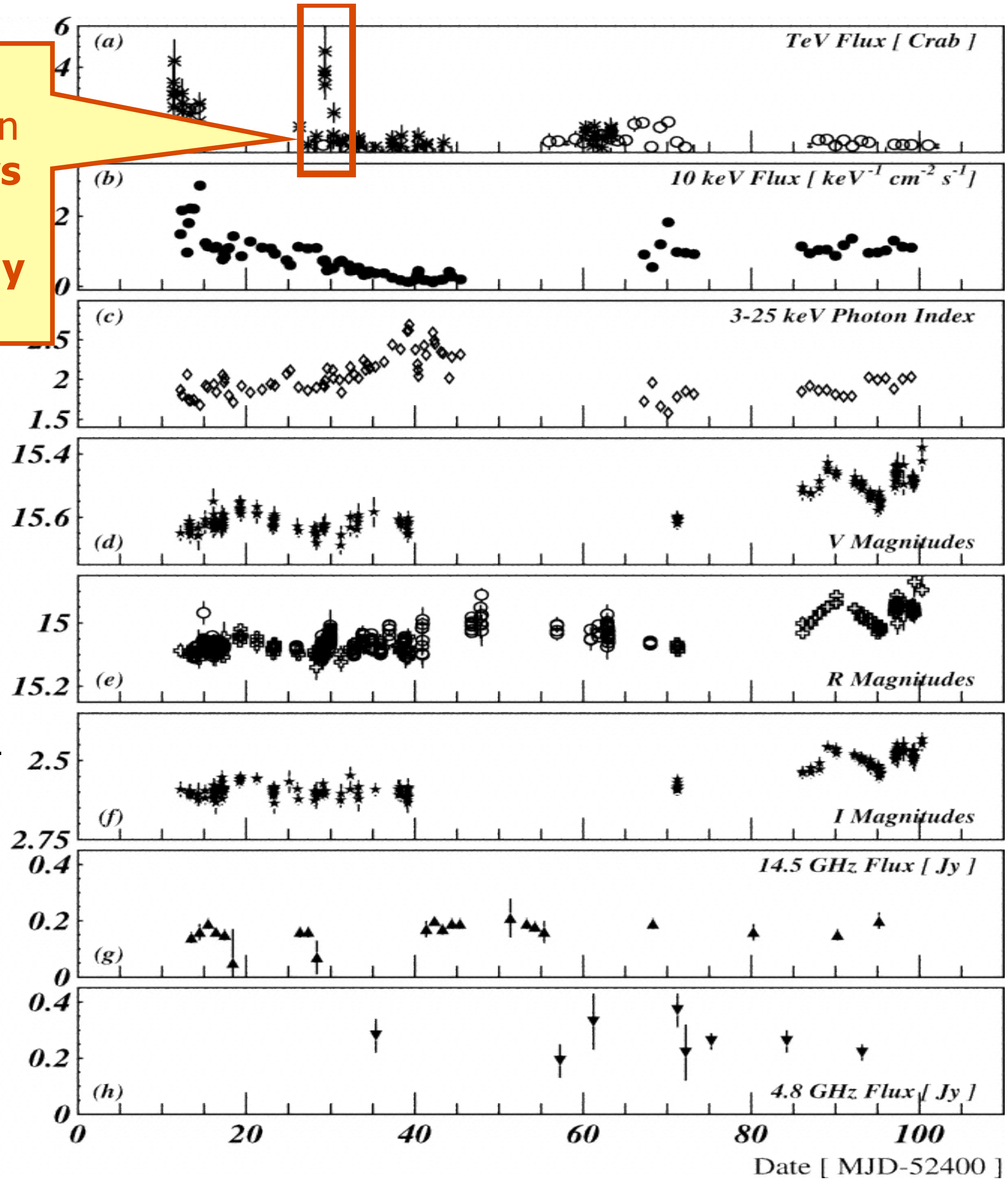

Preliminary
Source: Makarian 421 (n_max(40d) = 1 n_ev(4y) = 6 n_bg(4y) = 5.58)
exp. background / AMANDA events
0
0.2
0.4
0.6
0.8
1
1.2
51600
51800
52000
52200
52400
52600
52800
53000
MJD
Yellow bars:
width of sliding
search window
Triangles:
event times
Source: 1ES 1959+650 (n_max(40d) = 2 n_ev(4y) = 5 n_bg(4y) = 3.71)
exp. background / AMANDA events
0
0.2
0.4
0.6
0.8
1
1.2
51600
51800
52000
52200
52400
52600
52800
53000
MJD
Error bars:
off-source
background
per 40 days
"A posteriori":
3 (of 5) events in 66 days
Period of major outburst
measured at different
wavelengths in 2002
(and an "orphan flare")





<u>Probability of a random coincidence</u>
with the “orphan flare” or the enhanced γ-ray activity **<u>undefined</u>:** a-posteriori hypothesis relative to the test

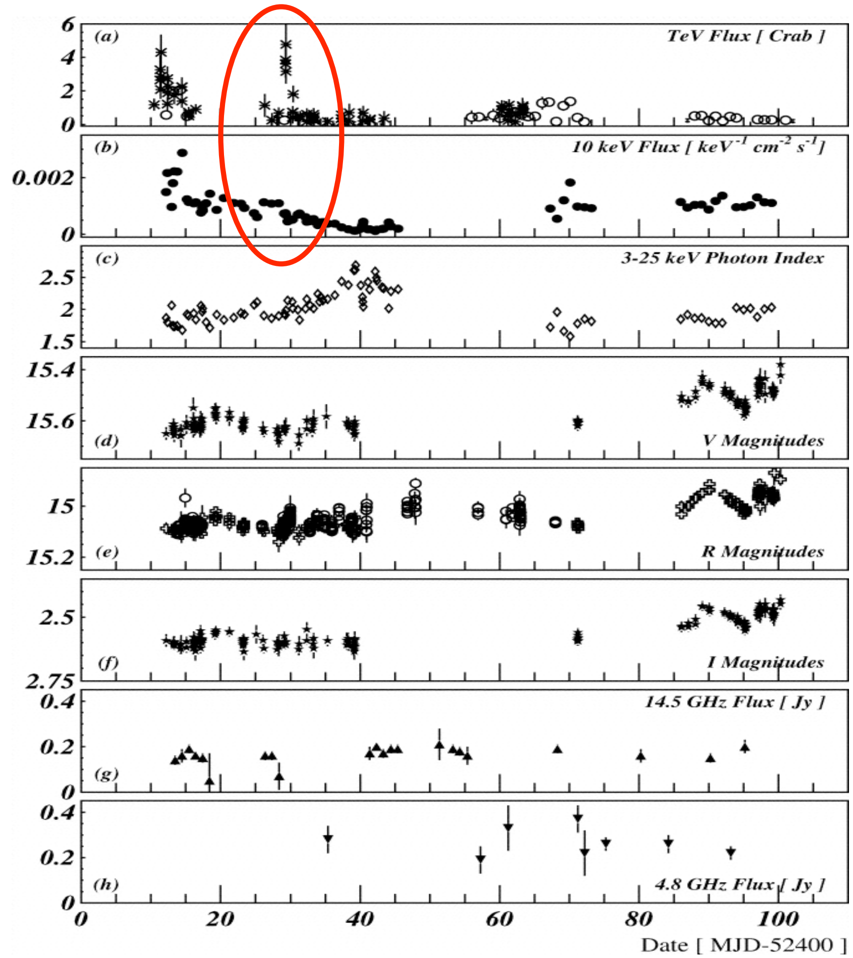
Unique observation of a high flux γ-rays flare without corresponding X-ray counterpart



Results from the multi-wavelength campaign
(a) Whipple and HEGRA
(b-c) X-ray
(d-f) optical
(g-h) radio
ApJ 601, 151 (2004)

Orphan flares

- Only one orphan flare known (1ES 1959+650, MJD 52429)
- very short duration
- NOT included in high state period defined by x-ray luminosity
- independent test was taken into consideration
- rejected for low detection probability (short flare duration)



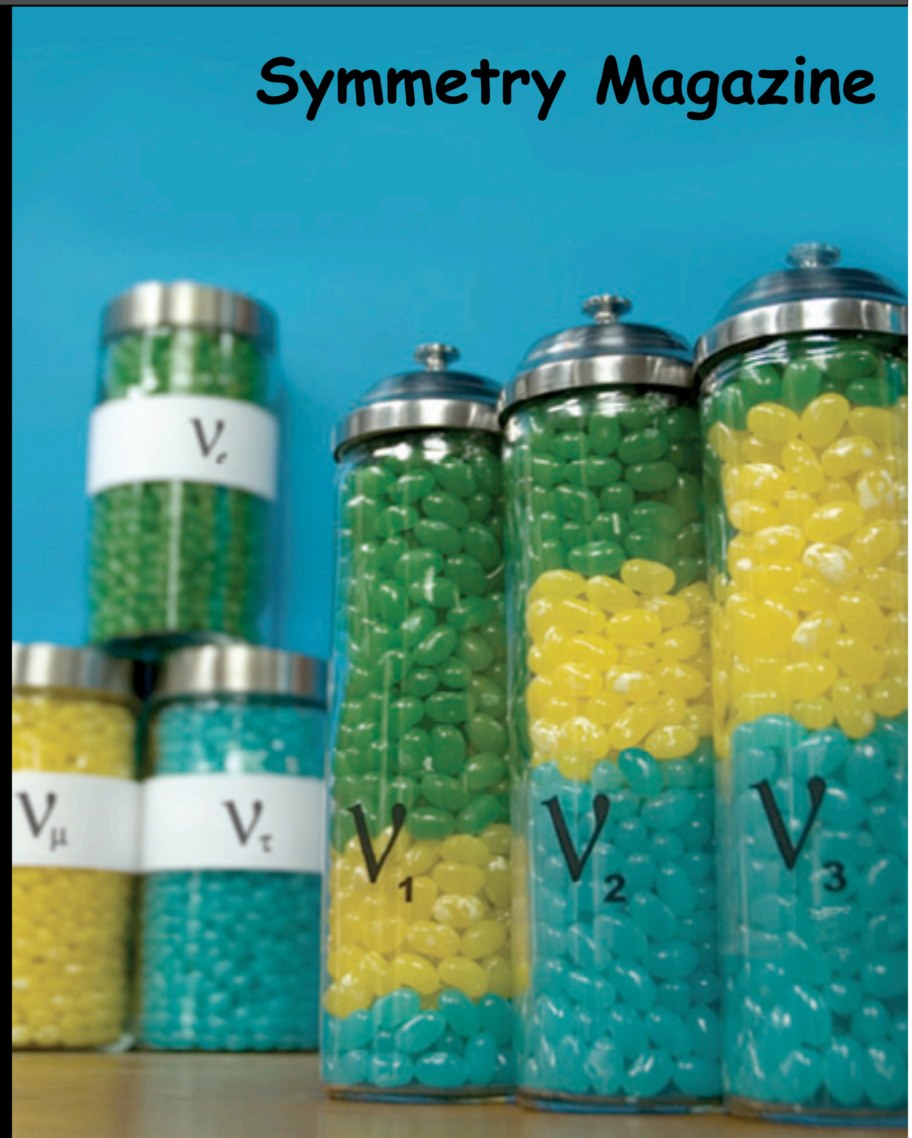
particle physics

neutrinos: the sun and the Earth

$$\nu_3 = \left(\frac{\nu_\mu + \nu_\tau}{\sqrt{2}}\right) + |s_{13}| e^{i\delta} \nu_e$$

$$\nu_2 = \sin\theta_\odot \nu_e + \cos\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right)$$

$$\nu_1 = -\cos\theta_\odot \nu_e + \sin\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right)$$



natural particle beams

- **Sun: resolution of solar neutrino puzzle**

  → ν's have mass
  → John Bahcall understands how the sun shines

- **Supernova 1987A: ~ 20 events only!**

  → confirmed basic scenario for the death of a star
  → set records on neutrino properties

- **Cosmic neutrinos? Discovery, but also**
  ~ 10^6 atmospheric and ~ 10^3 supernova neutrinos

  → origin of cosmic rays
  → beam for particle physics

AMANDA performance
(Antares, Nestor soon)

- ν's per day :

  3.5 → 10 per day

- total statistics

  10,000 in 00-05

- energy

  0.1 ~ 1,000 TeV

IceCube -KM3NET

- ν's per day :

> 100 per day

- total statistics

> 10^6 over 10yr

- energy

0.1 ~ 10,000 TeV

IceCube : particle physics with one million atmospheric neutrinos

- **Astronomy**: new window on the Universe

- **Physics**:
- measurement of the high-energy neutrino cross section
- TeV-scale gravity, quantum decoherence
- physics beyond 3-flavor oscillations
- test special and general relativity with new precision
- search for magnetic monopoles
- search for neutralino (or other) dark matter
- search for topological defects and cosmological remnants
- search for magnetic monopoles

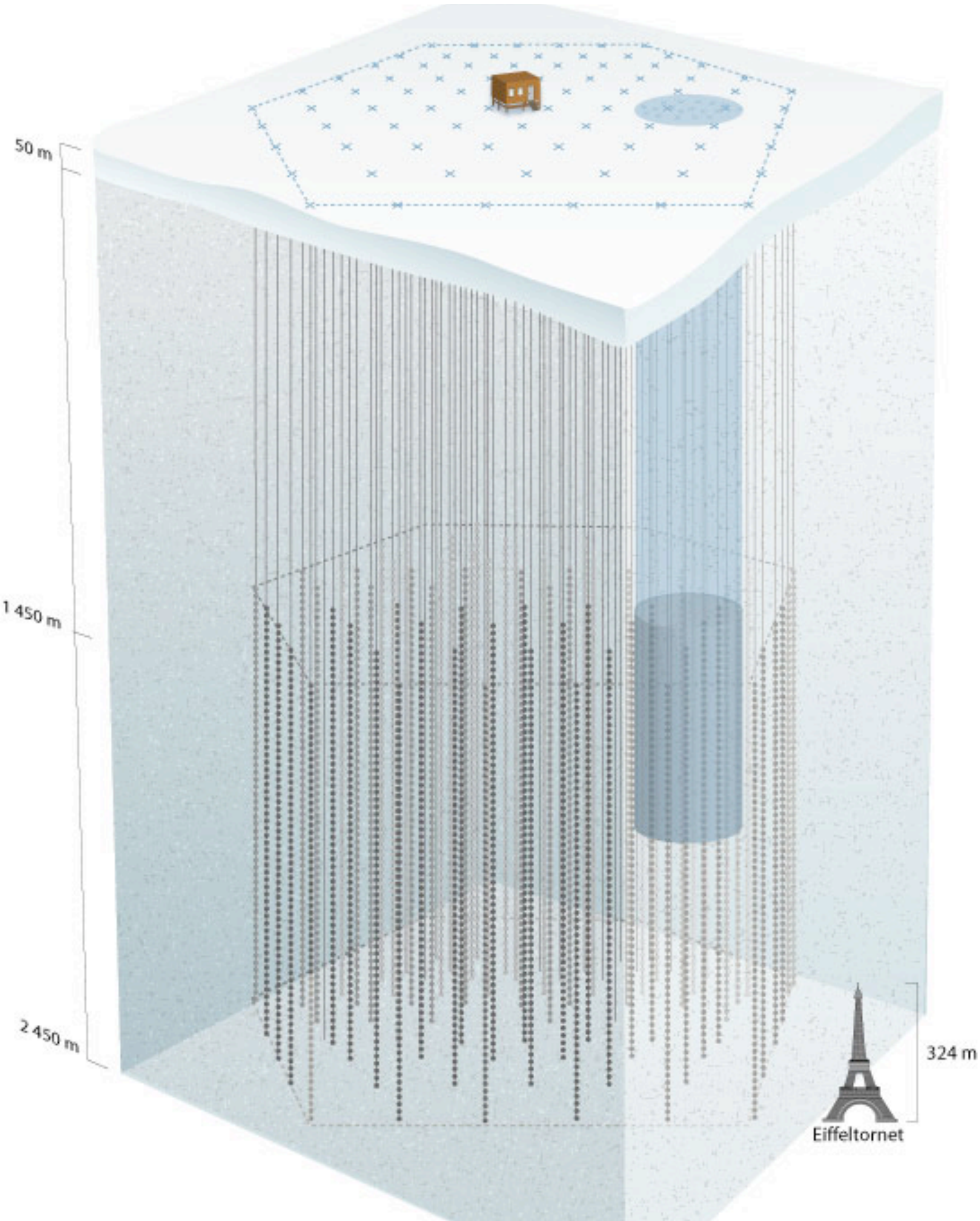
IceCube Neutrino Observatory

IceTop shower array

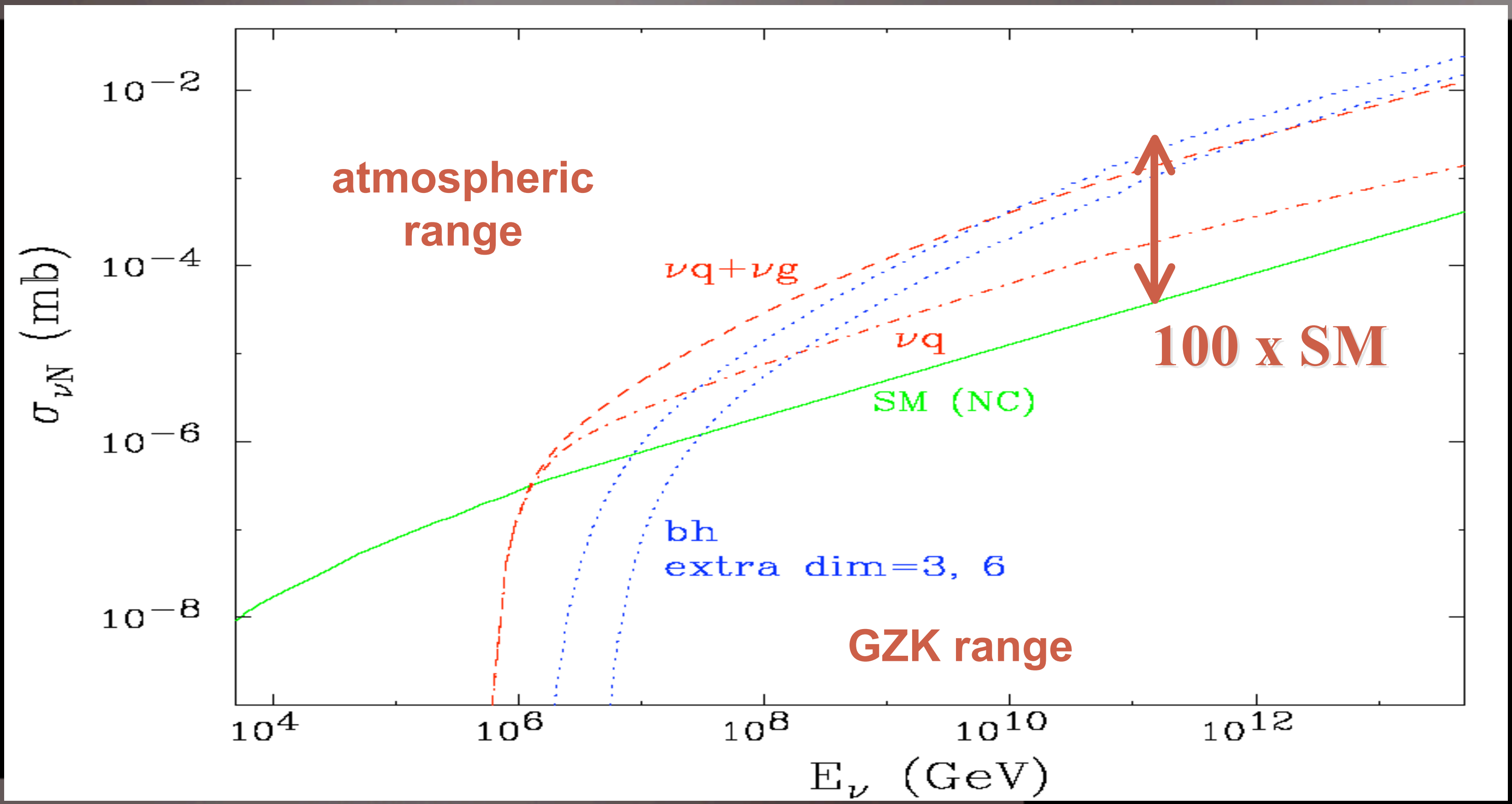
80 pairs of Cherenkov tanks

IceCube

4800 optical modules on 80 strings



Neutrino Astronomy Explores Higher Dimensions



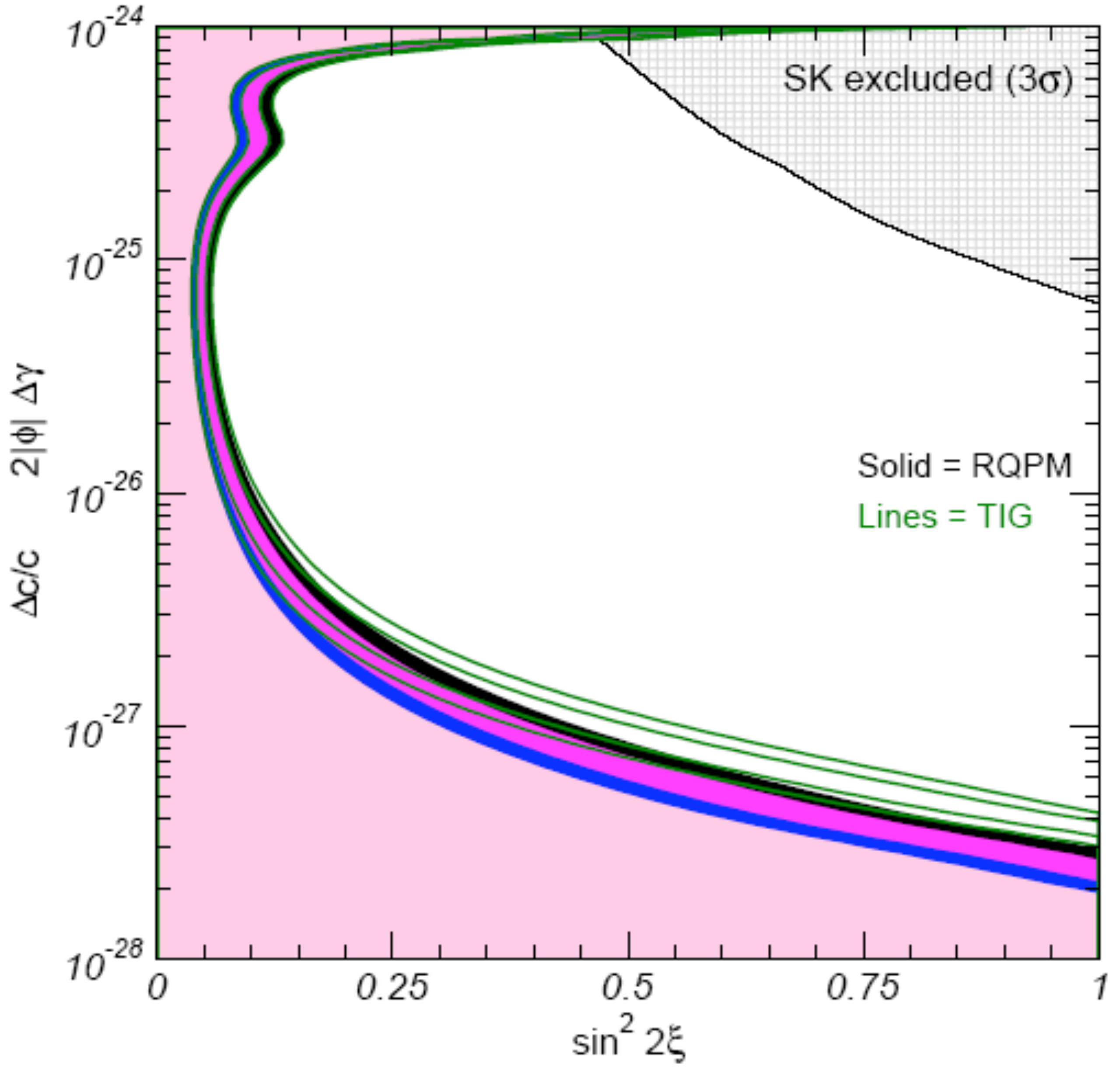
TeV-scale gravity increases PeV ν-cross section

IceCube

tests
- **equivalence principle**

and
- **Lorentz invariance**

…general relativity will not last 200 years… M. Turner



Cosmic neutrino beam from the decay of pions

$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : <10^{-5}$ @ the source

$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$ @ the detector

(maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing)

Or,

- zero mass eigenstates in vacuum
- neutrino decay
- neutrinos of varying mass

cosmic anti - ν_e beam from neutron decay

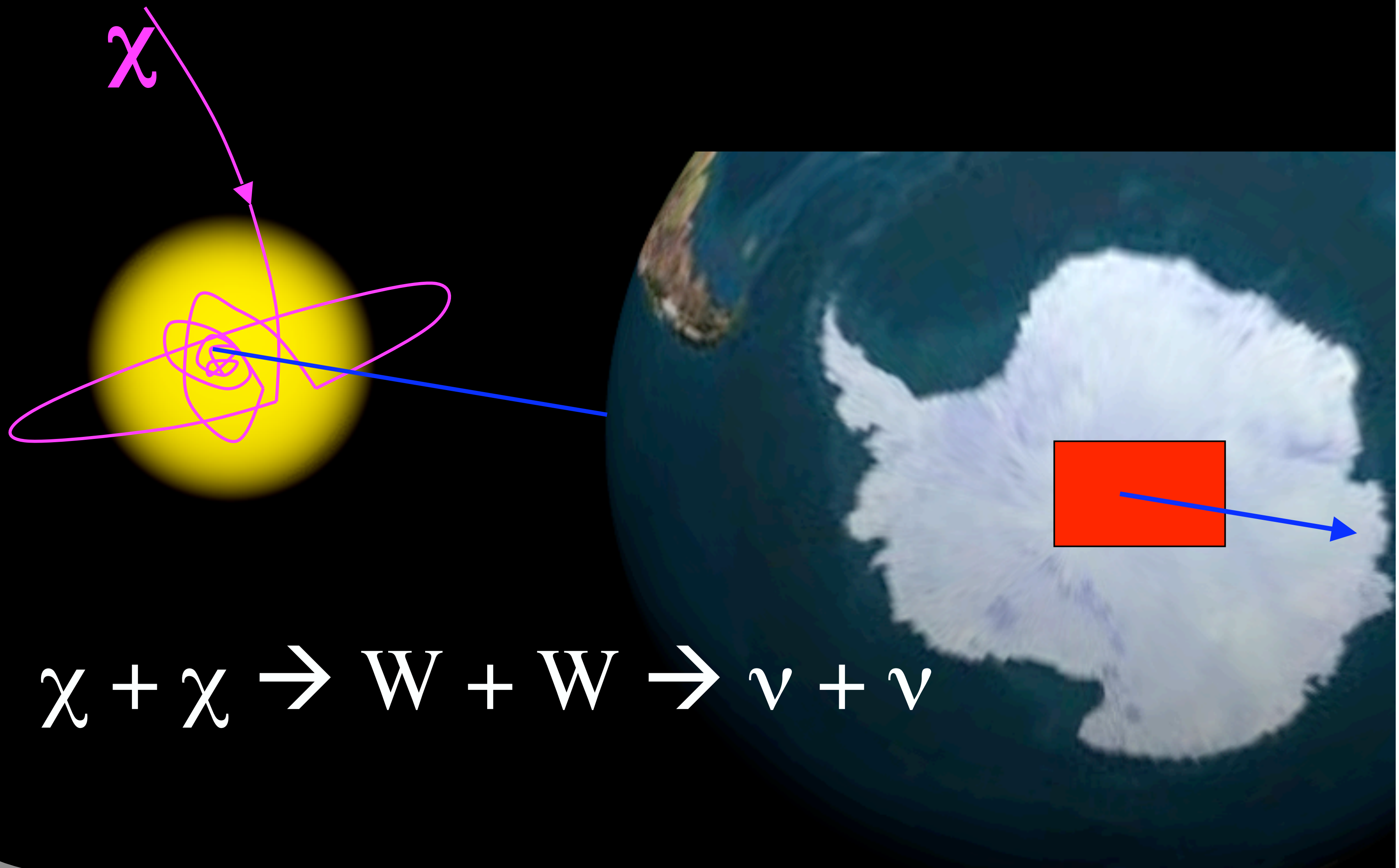
directional cosmic rays from the Cygnus region and from the center of the galaxy

ν_e	**@ the source**
?	**@ the detector**

- Measure $\sin^2\theta_{13}$ from flavor composition at the detector

- Decoherence?

WIMP Capture and Annihilation

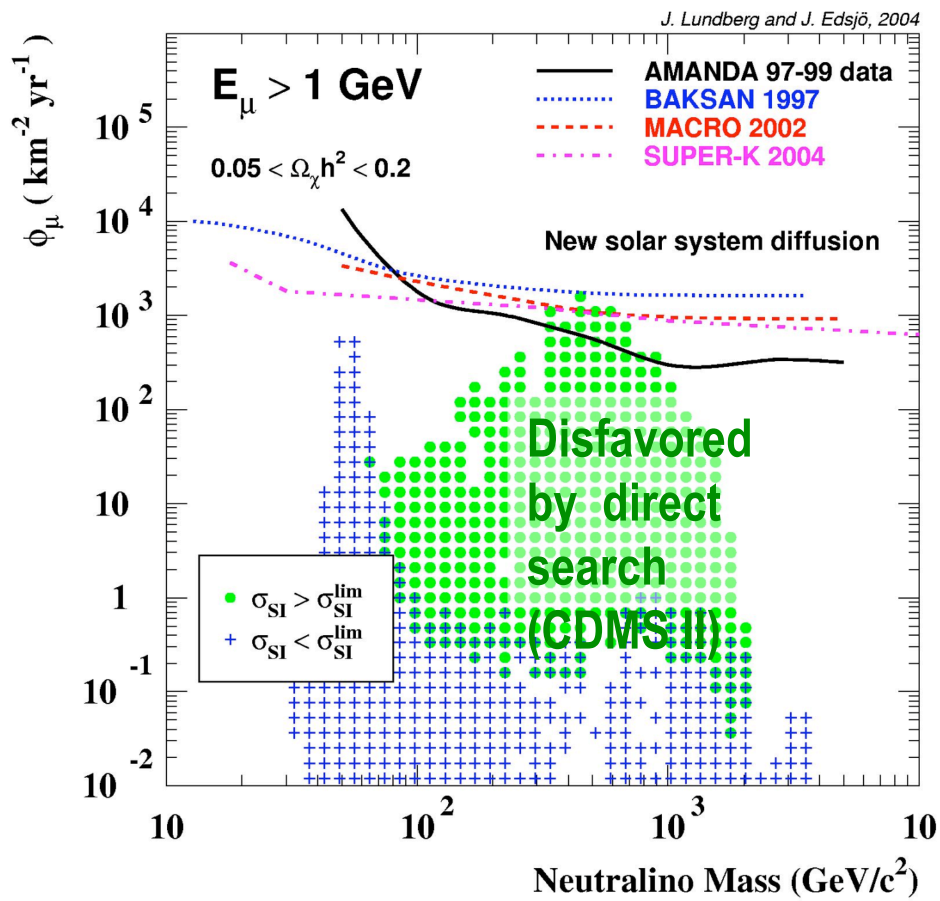


$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$

WIMP search

PRELIMINARY

Limits on muon flux from Earth



Limits on muon flux from Sun