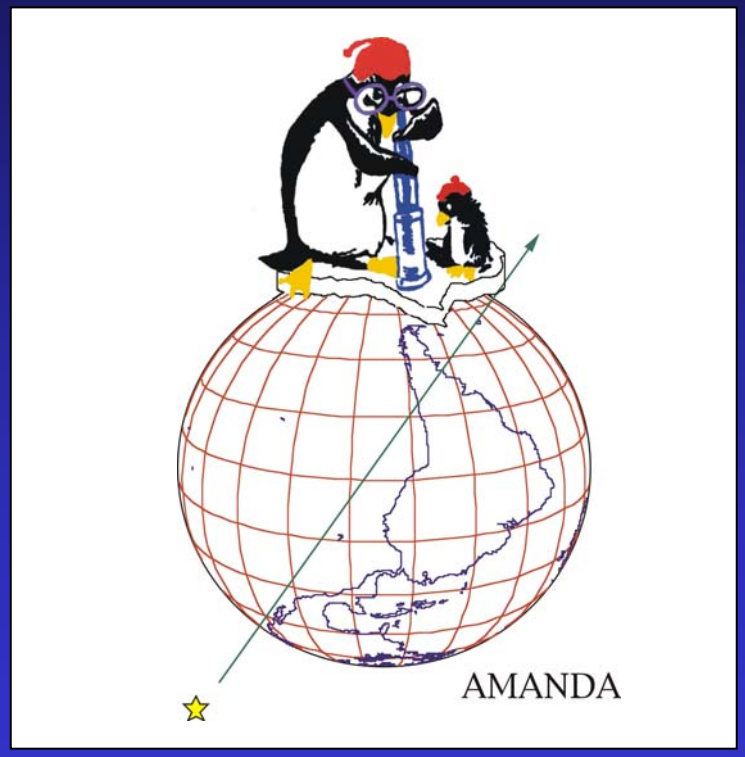
Neutrino Astrophysics



C. Spiering, CERN School Zeuthen, Sept.2003

Content

→ Neutrinos

→ Cosmic Neutrinos
- solar neutrinos (keV – MeV)
- neutrinos from a Supernova (MeV)
- atmospheric Neutrinos (GeV)
- extraterrestrial neutrinos (GeV-TeV-PeV)

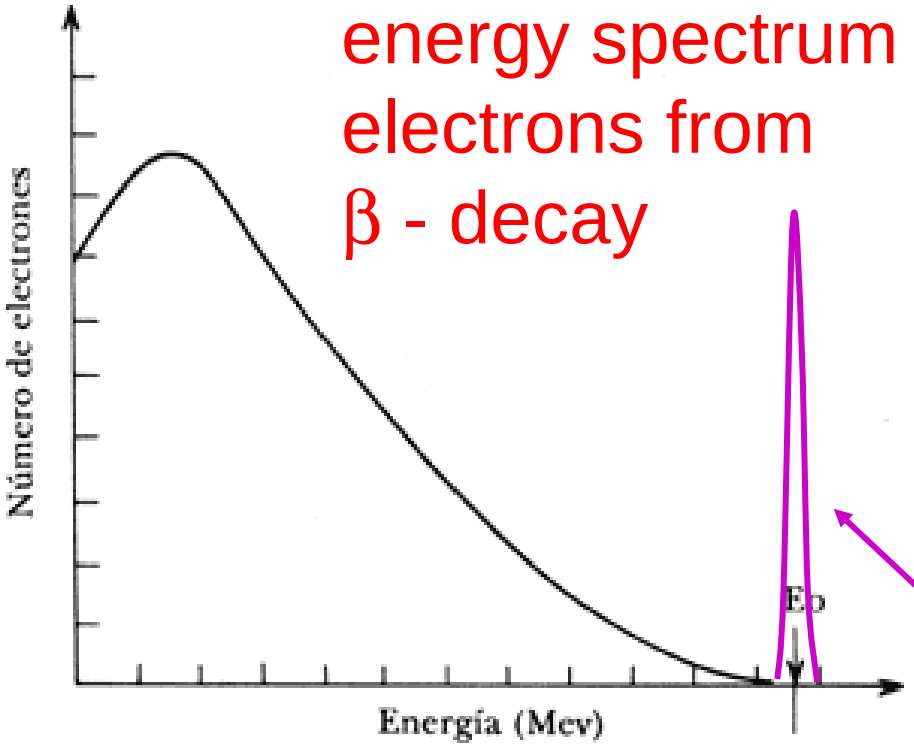
→ Low energy neutrinos: SN1987A and Sun

→ High energy neutrino astrophysics
- The mystery of high energy cosmics rays
- TeV gamma observations
- Neutrino telescopes
- Amanda
- Neutrino detection at ultra high energies

Neutrinos

Postulate of Neutrinos: Pauli 1930

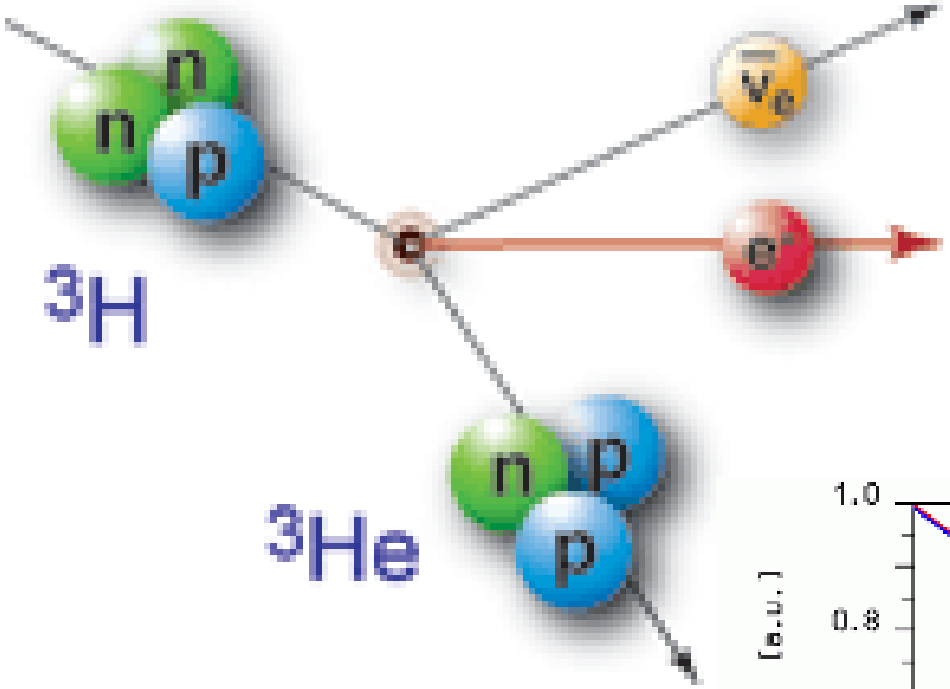
energy spectrum of electrons from β - decay



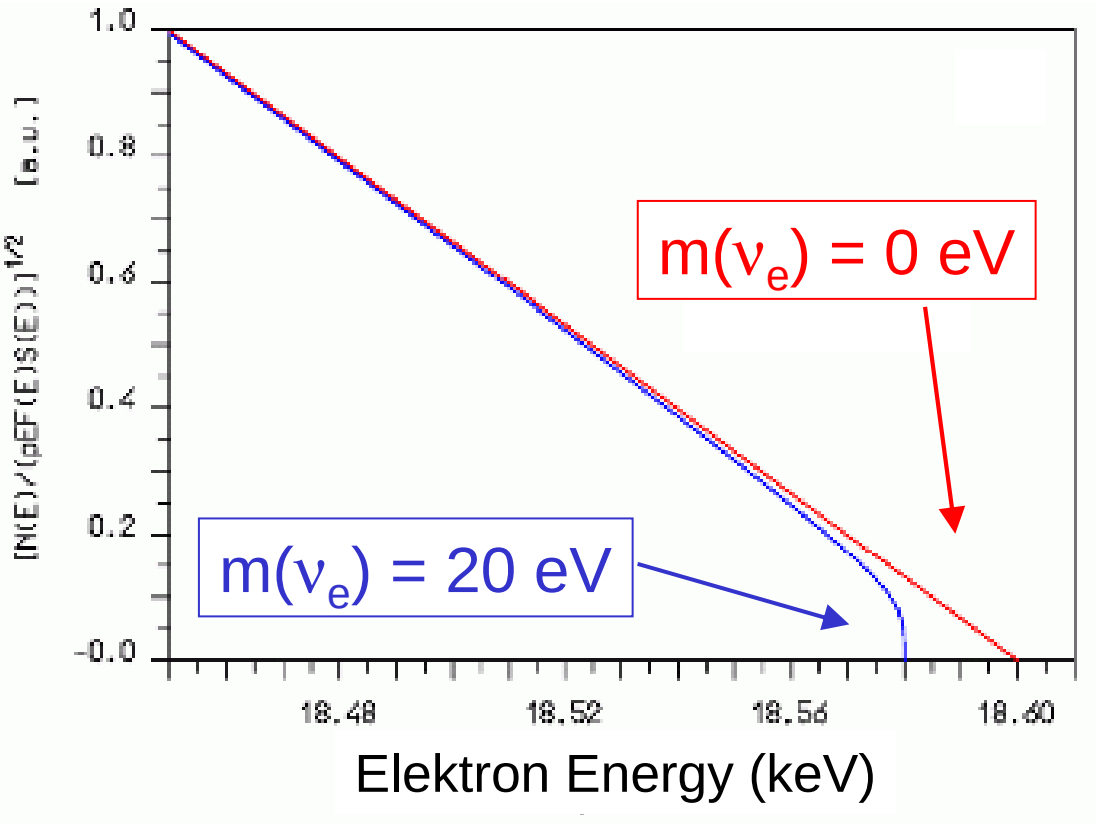
expected for 2-particle final state

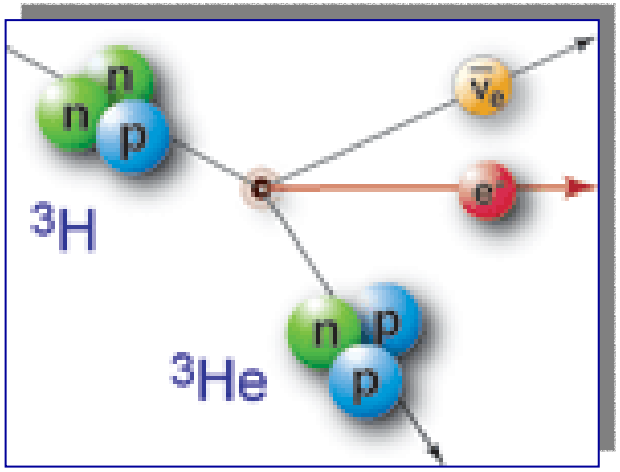
$$n \rightarrow p + e^- + \bar{\nu}_e$$

How large is the neutrino mass ?



Tritium Decay





Status 2003:

$m(\nu_e) < 2.2$ eV

Moscow, Mainz

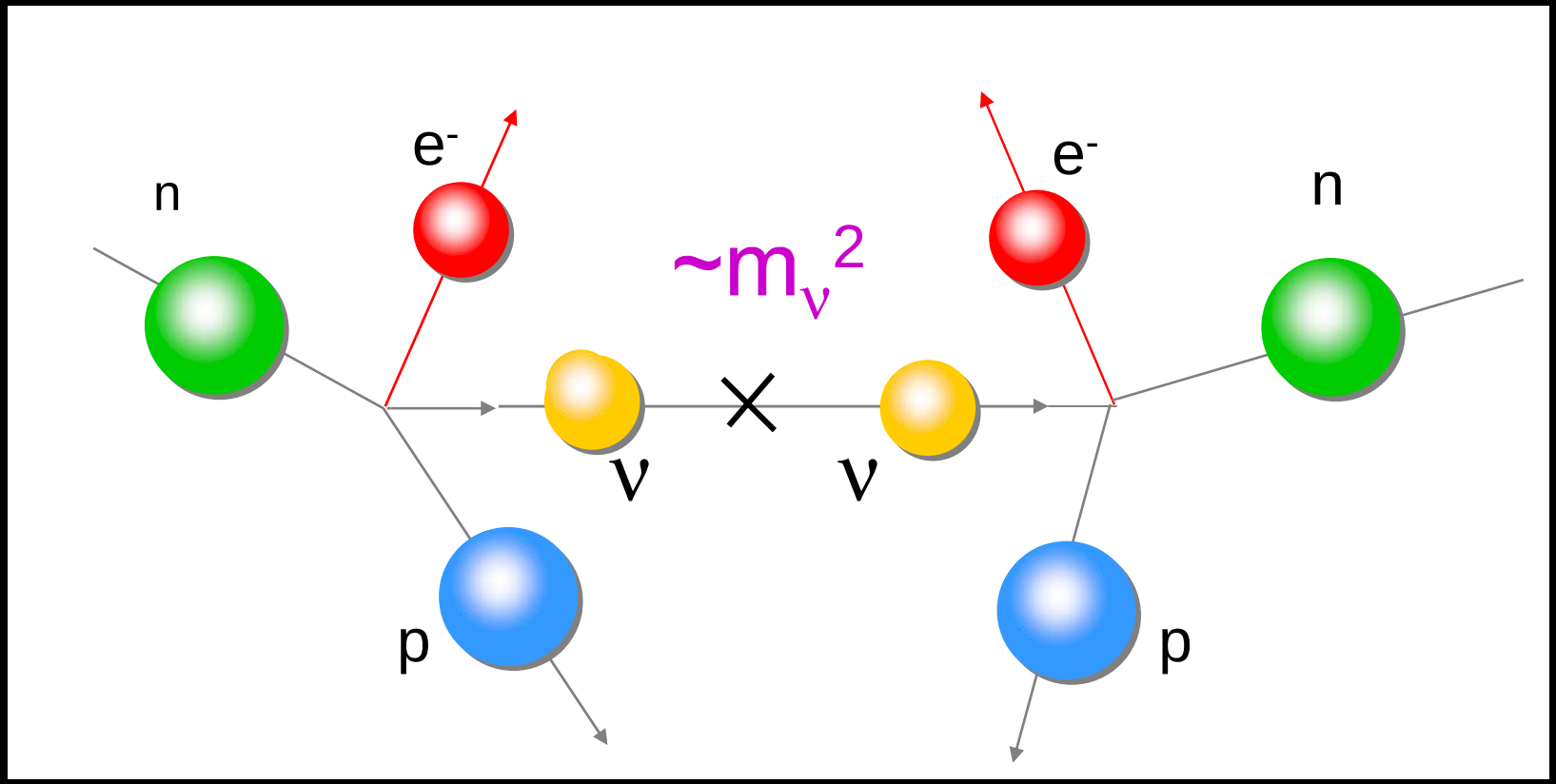
The Future: KATRIN Sensitivity

Karlsruhe

$m(\nu_e) \sim 0.2$ eV

Cosmology

... from WMAP follows: sum of all 3 neutrinos masses < 0.65 eV !!



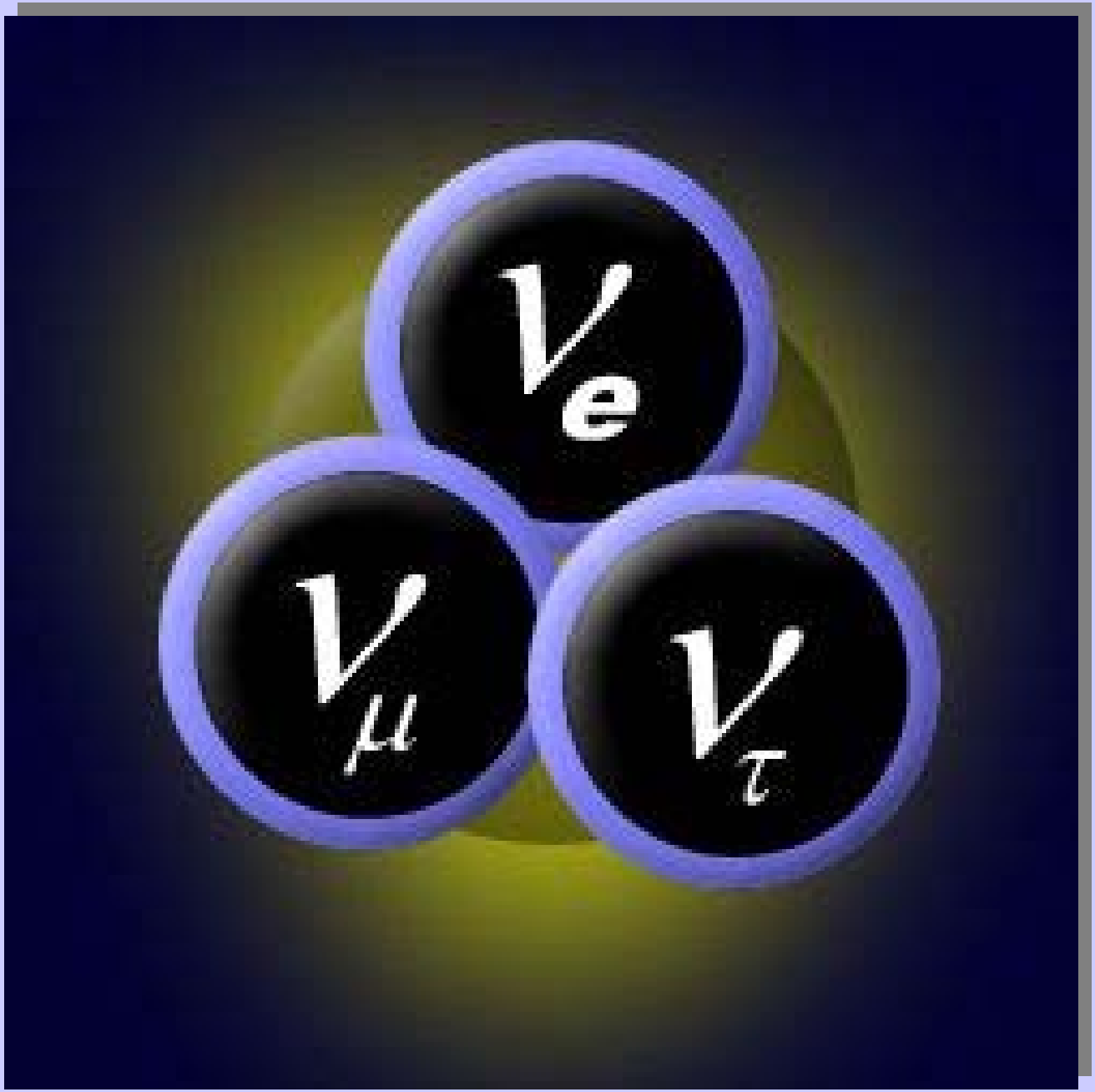
Double β-Decay

e.g.. ^{76}Ge

Present Limit ~ 0.3 eV

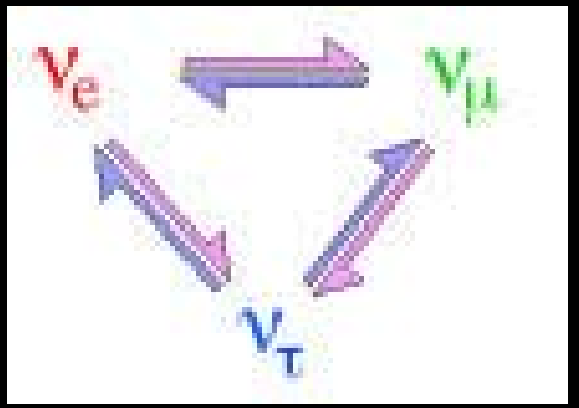
Future: $m_{\nu e}$ down to 0.01 eV

(works only for Majorana neutrinos)


ν_e
ν_μ
ν_τ

Neutrino Oscillations:

→ *All* 3 Neutrinos are lighter than 2.2 eV !



Observed for

- solar neutrinos and reactor neutrinos

  $\Delta m^2 \sim (10\ \text{meV})^2$

- atmospheric neutrinos and accelerator neutrinos

  $\Delta m^2 \sim (50\ \text{meV})^2$

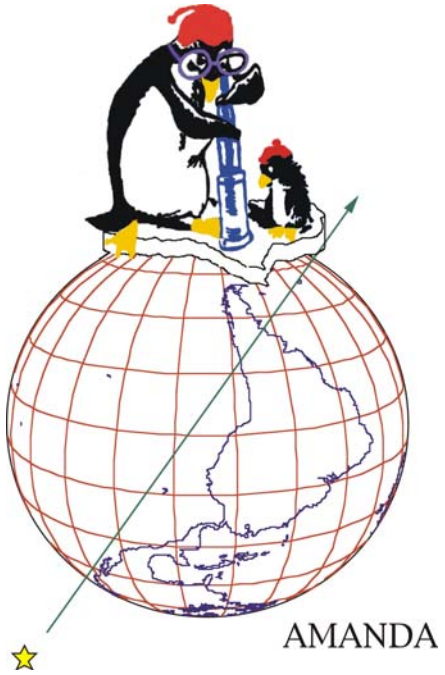
Cross section increases with energy

Solar Neutrinos:

One reaction per 100 billions of ν

1 TeV:

Every hundredth neutrino interacts.



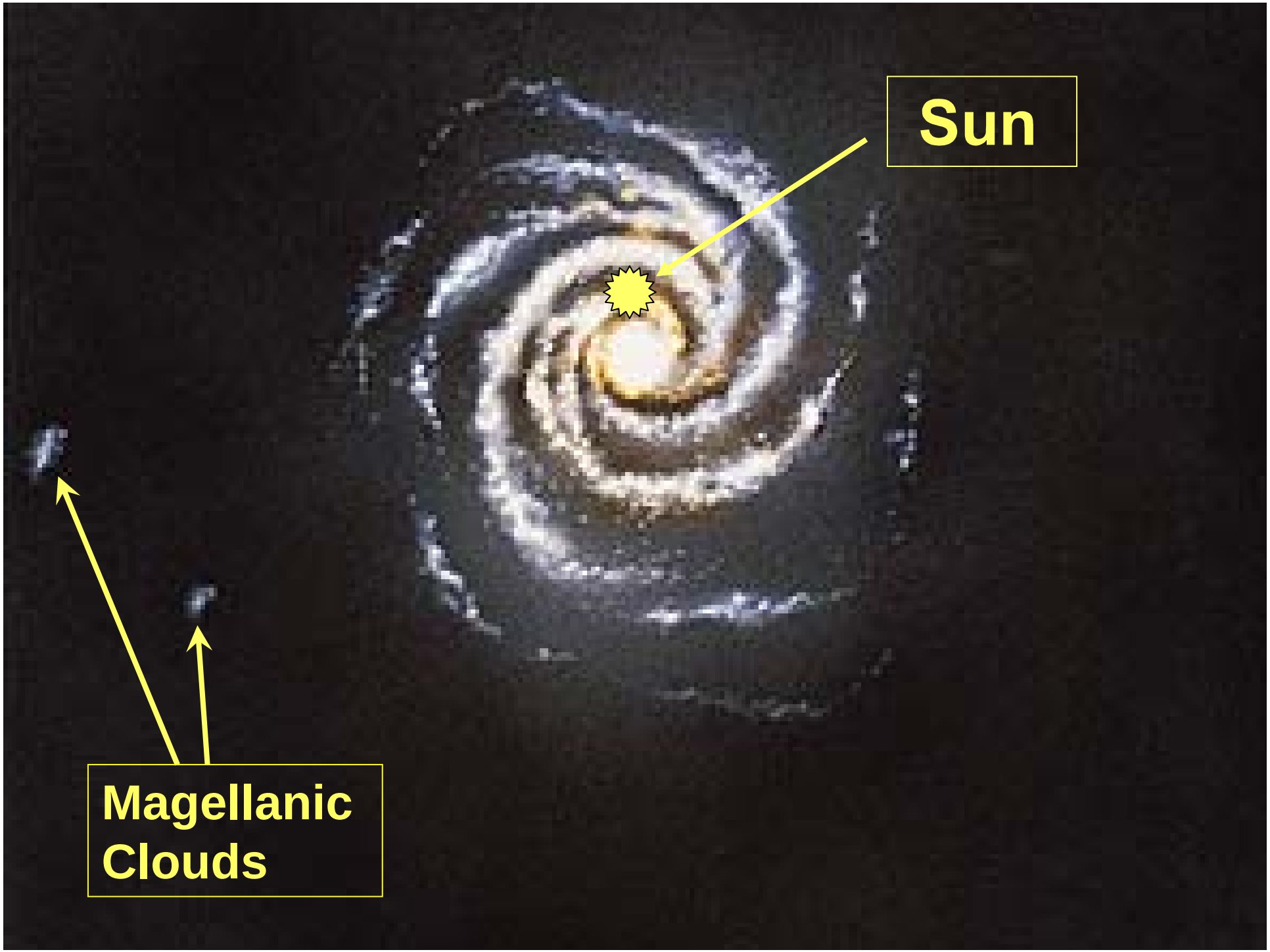
1000 TeV:

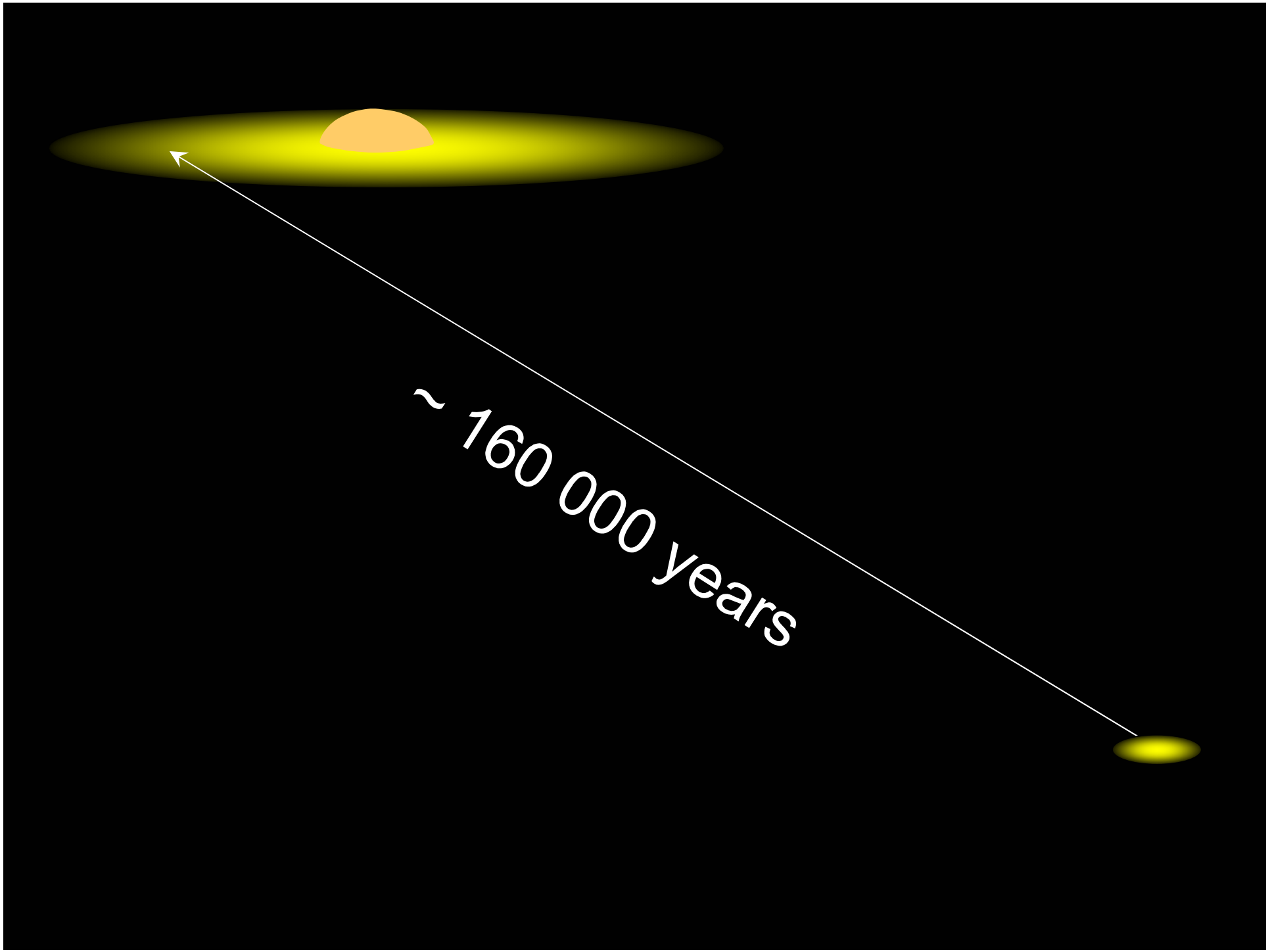
The Earth is opaque even for neutrinos.

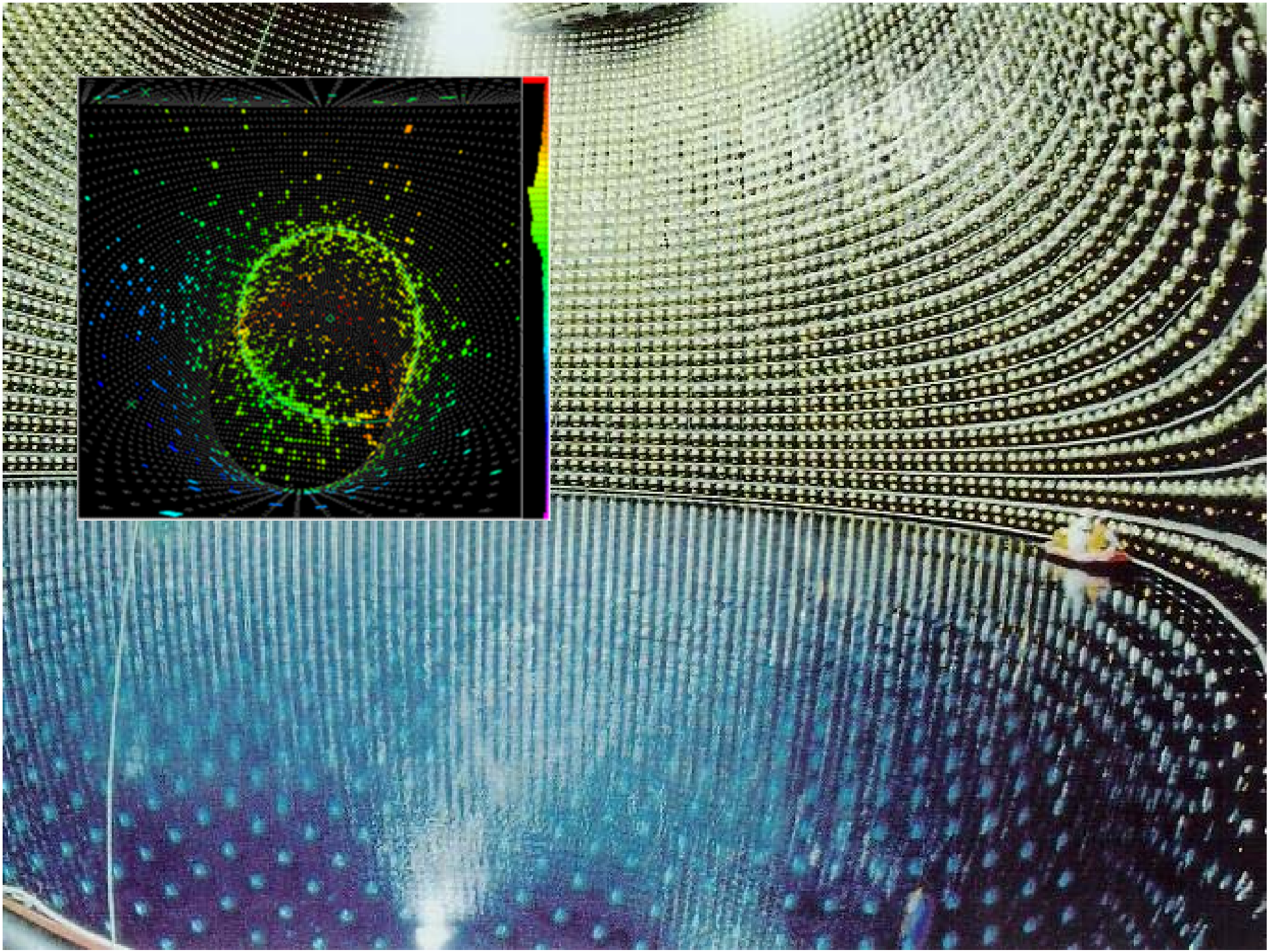
Neutrino Astrophysics at keV and MeV:

Supernova and Sun

Supernova 1987A
in the Large Magellanic Cloud

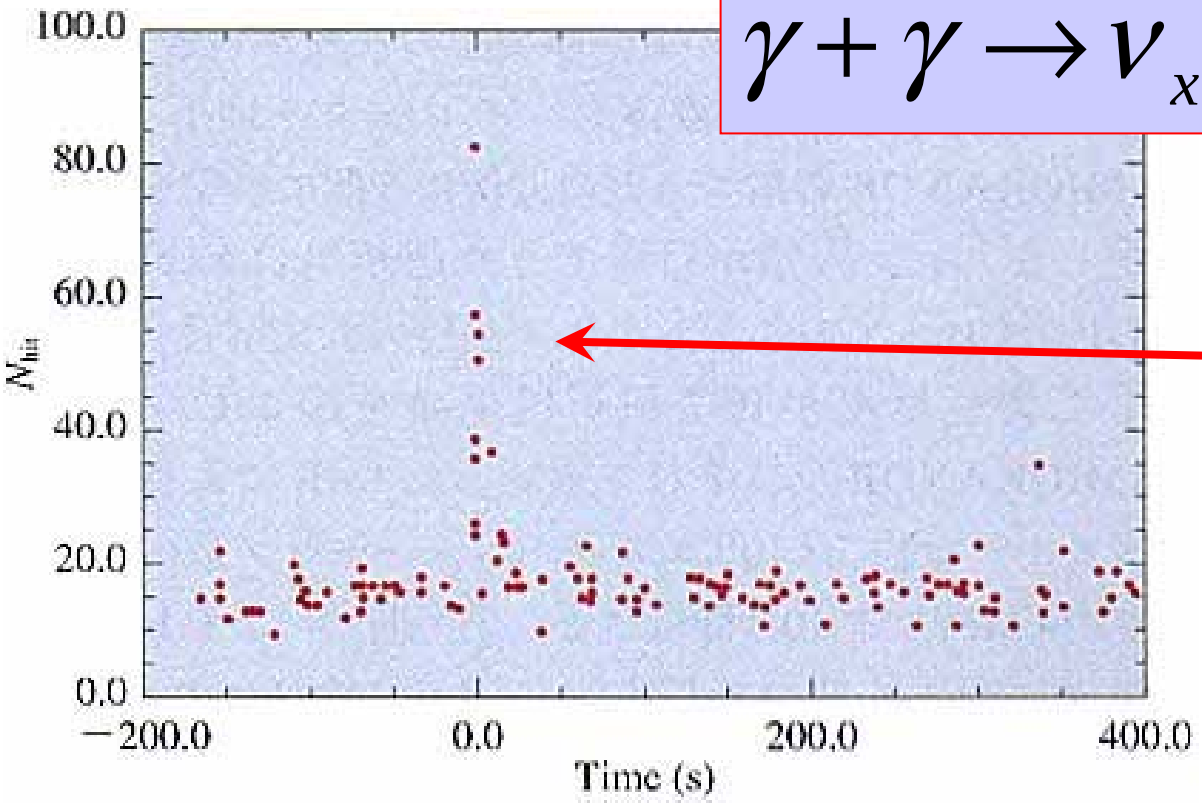

Sun
Magellanic
Clouds


~ 160 000 years



$$e^- + p \rightarrow n + \nu_e \quad (10ms)$$

$$\gamma + \gamma \rightarrow \nu_x + \bar{\nu}_x \quad (10s)$$



Kamiokande (Japan)
12 Events

IMB (USA)
8 Events

Baksan (Russia)
3 Events

→ Temperature in young neutron star ~ 40 Mia K

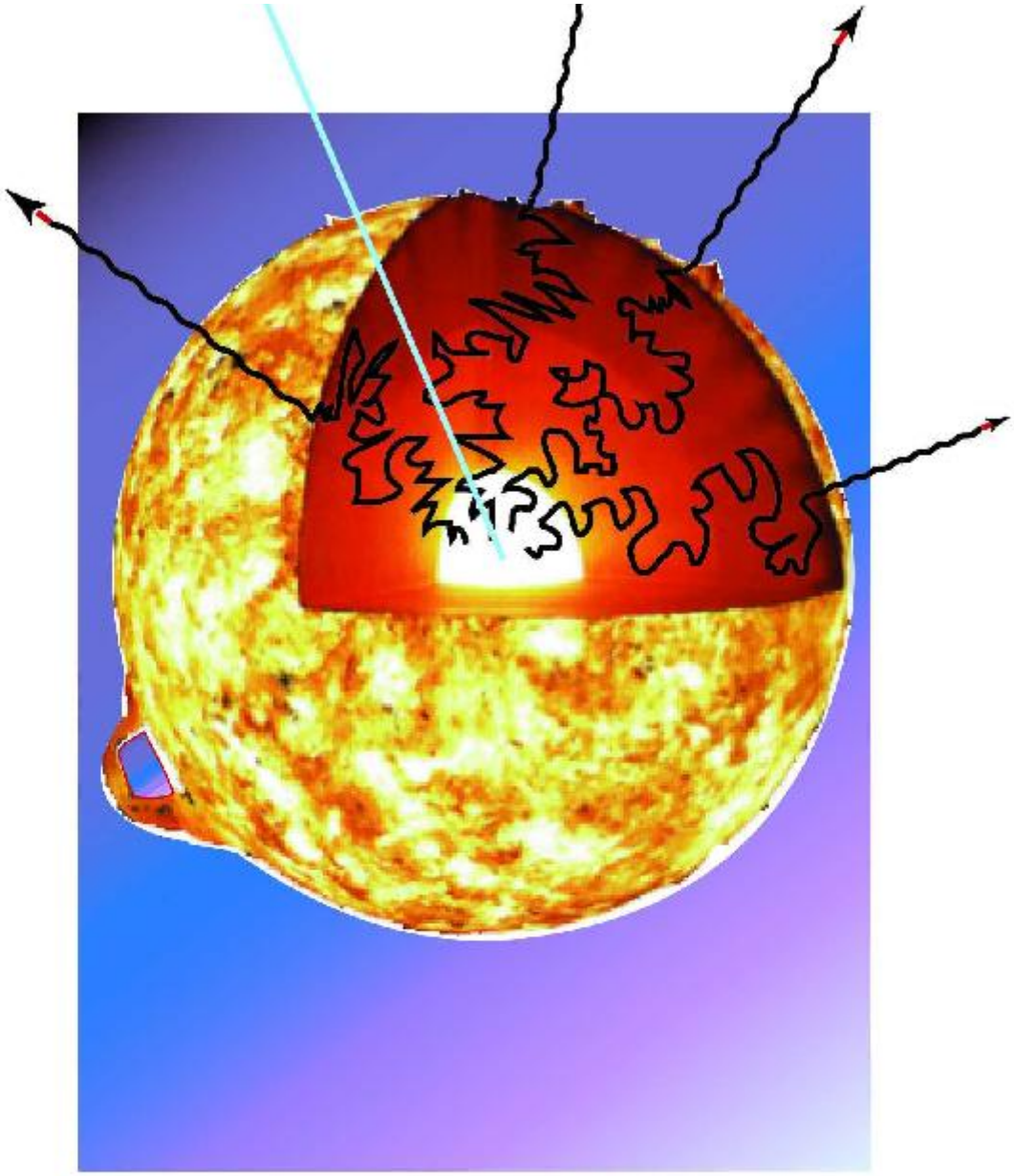
→ Neutrino mass < 23 eV

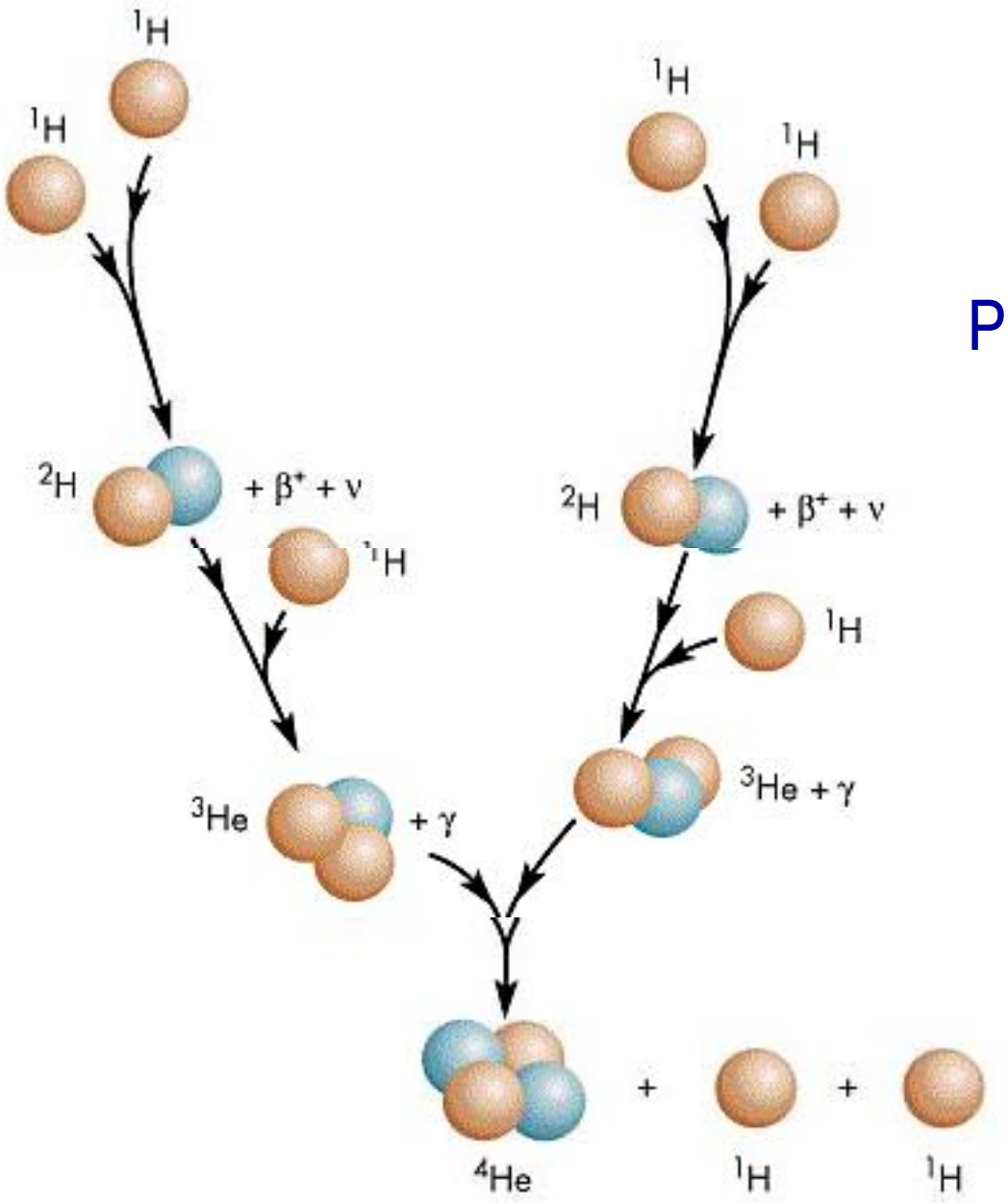
Solar Neutrinos

Temperature in core
~ 15 Mio K

Photon propagation through
0.6 Mio km radiation layer:
some million years

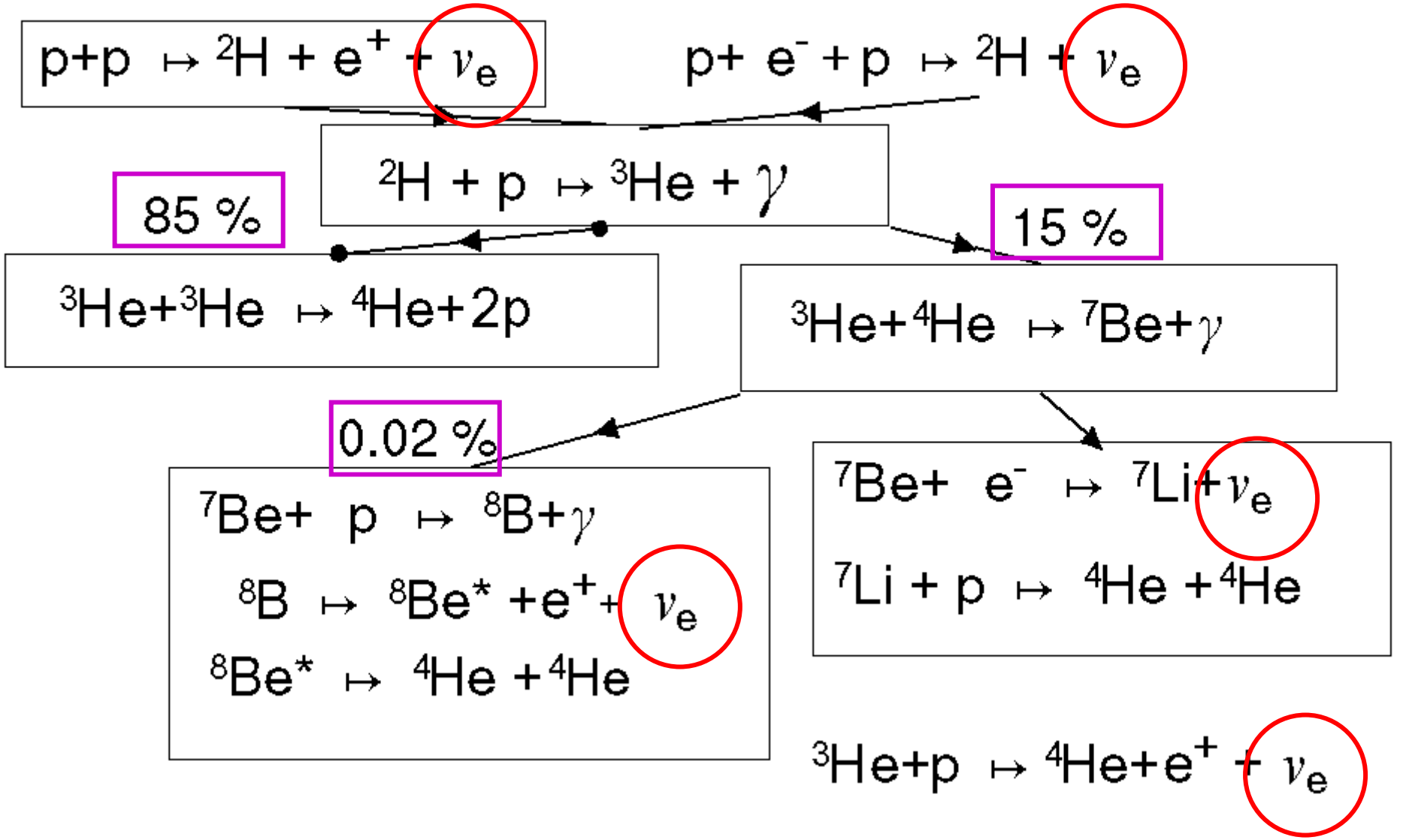
Neutrinos: 2 seconds

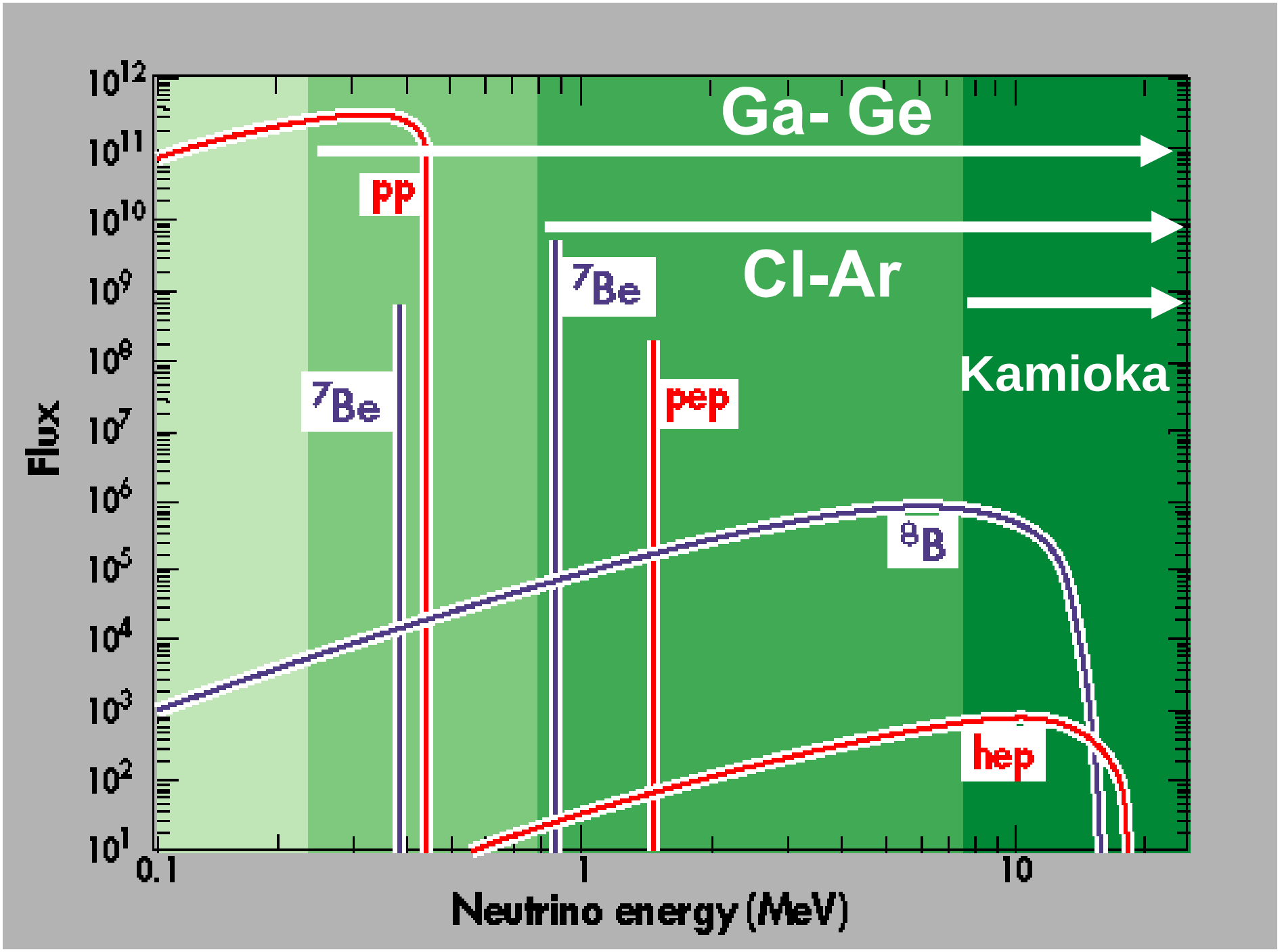




Proton-Proton-Cycle

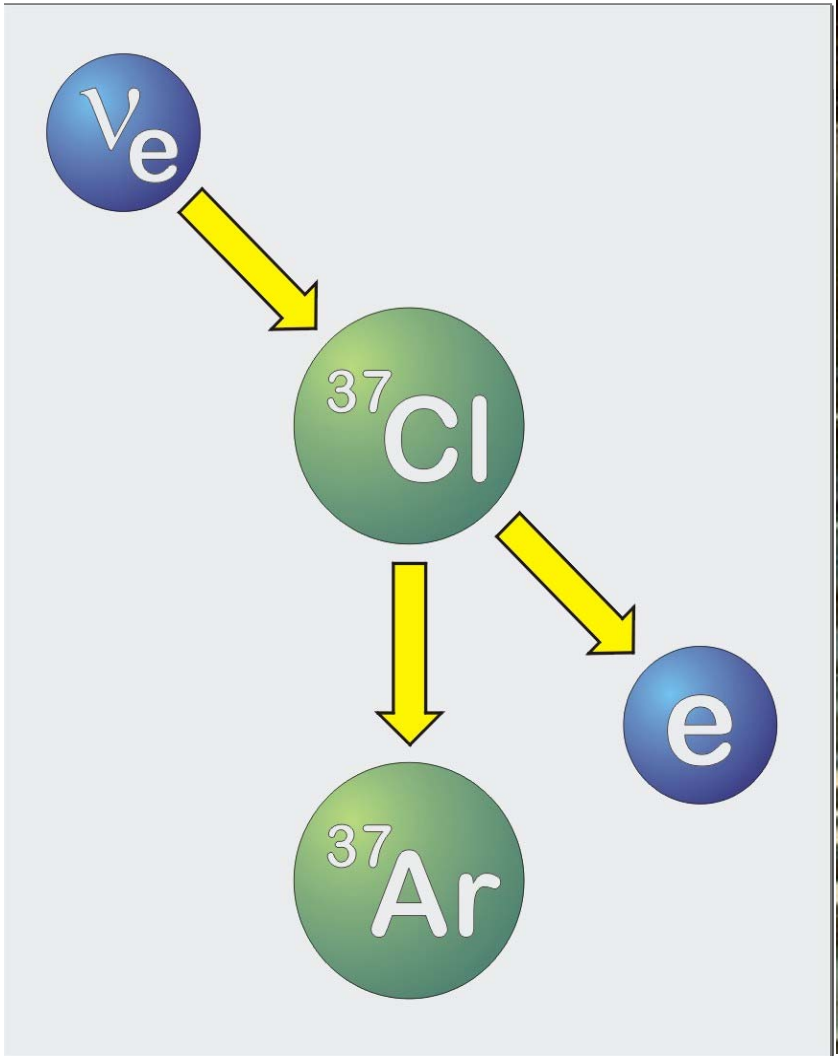
The nuclear reactions in the Sun generate a numerous amount of electron neutrinos. While the total number of neutrinos can be calculated very accurately, their energy spectrum contains more uncertainties. The following picture shows the principal energy producing reaction chains:

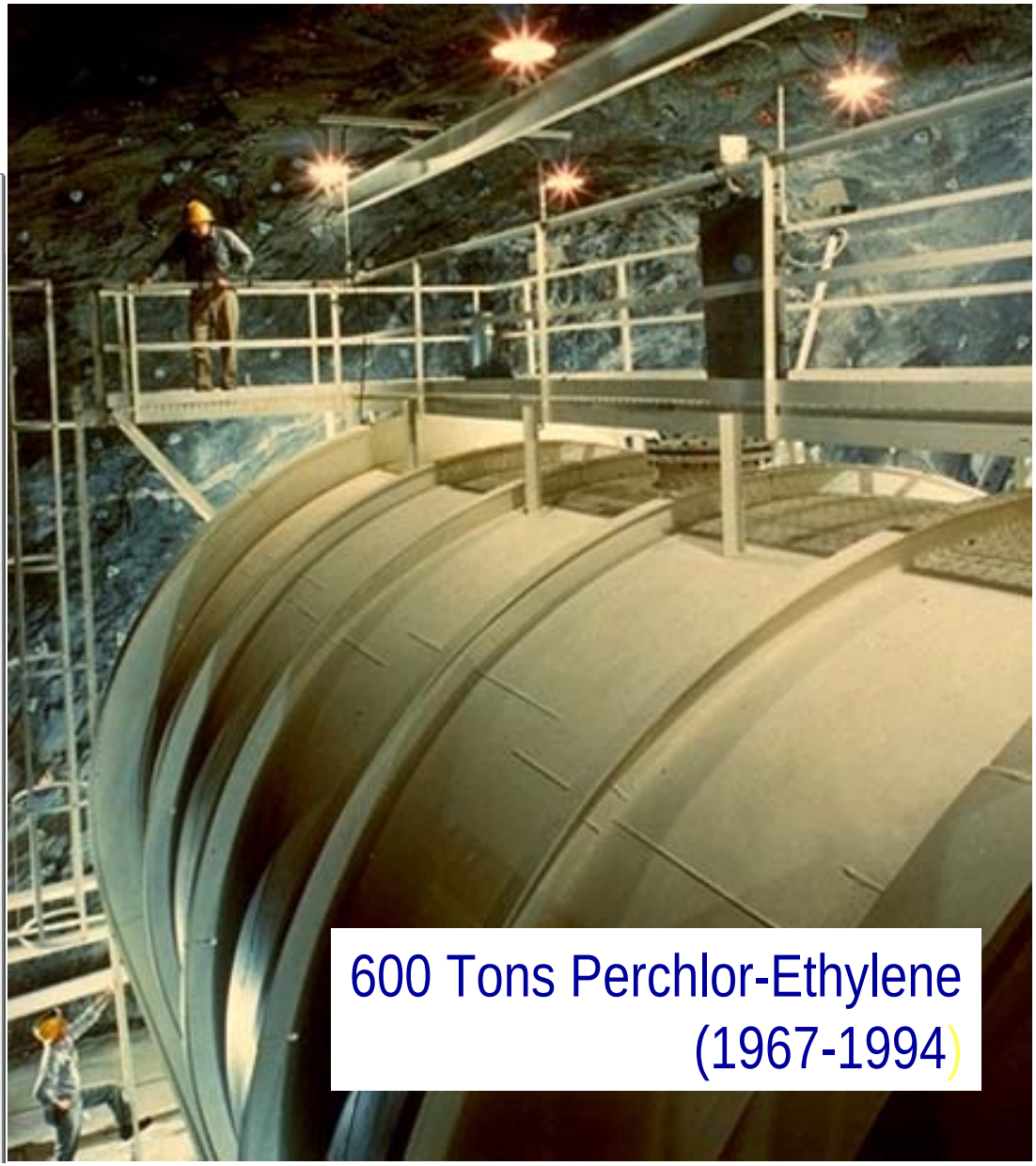



Ga- Ge
Cl-Ar
Kamioka
pp
^{7}Be
^{7}Be
pep
^{8}B
hep
Flux
Neutrino energy (MeV)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
0.1
1
10

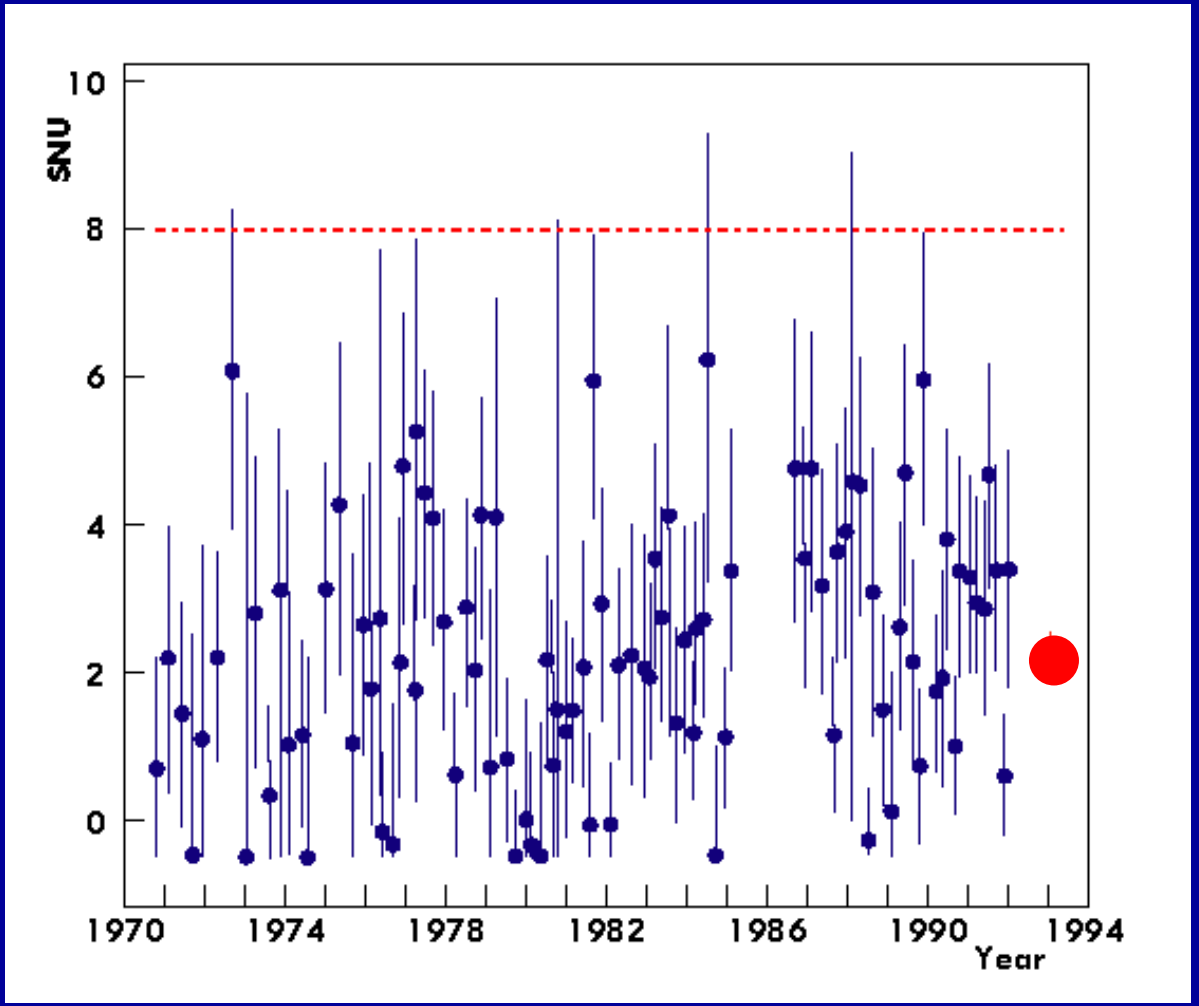
The Homestake Experiment

„Inverse“ Beta-Decay
(„Neutrino-Capture”)





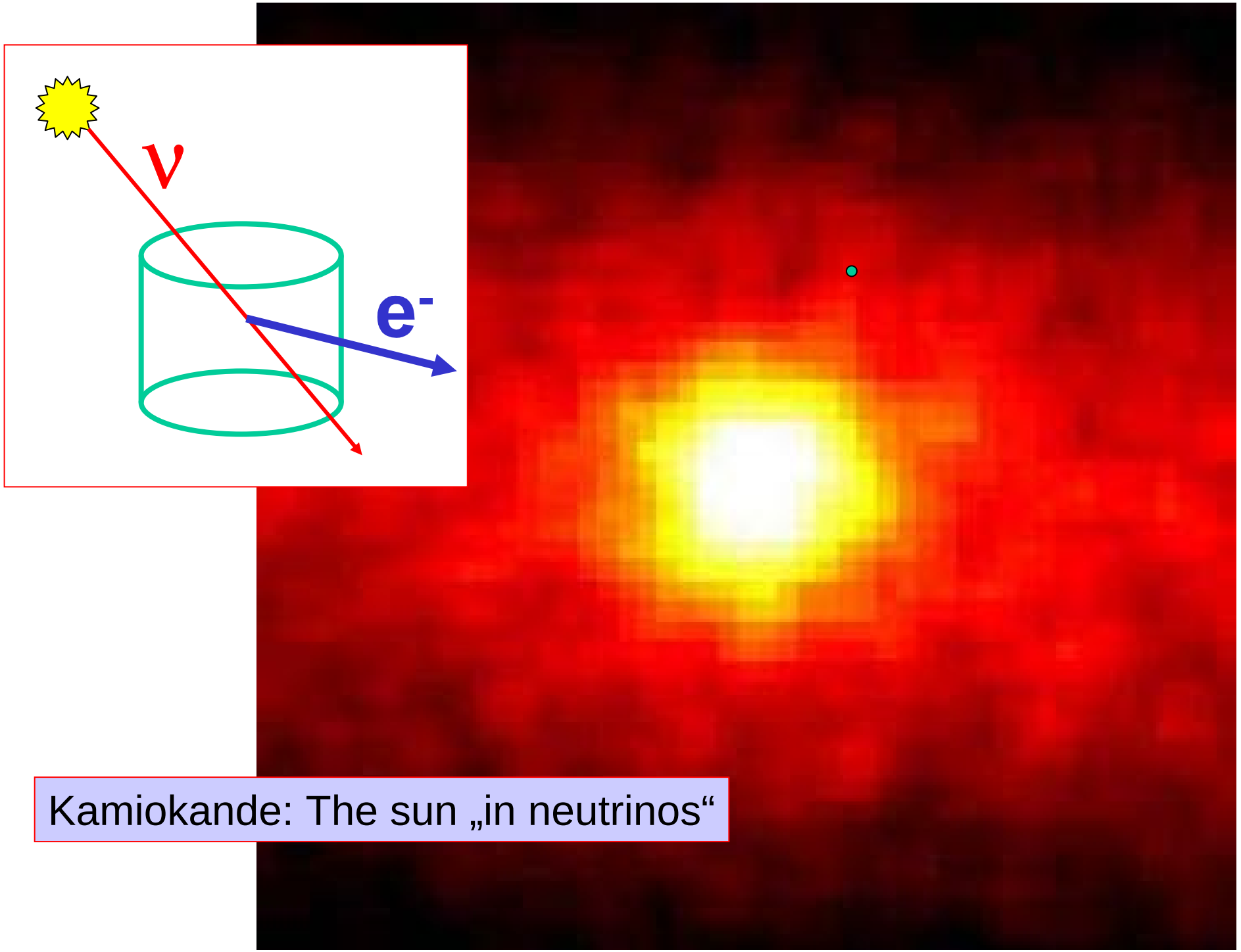
Result of Homestake



Expectation

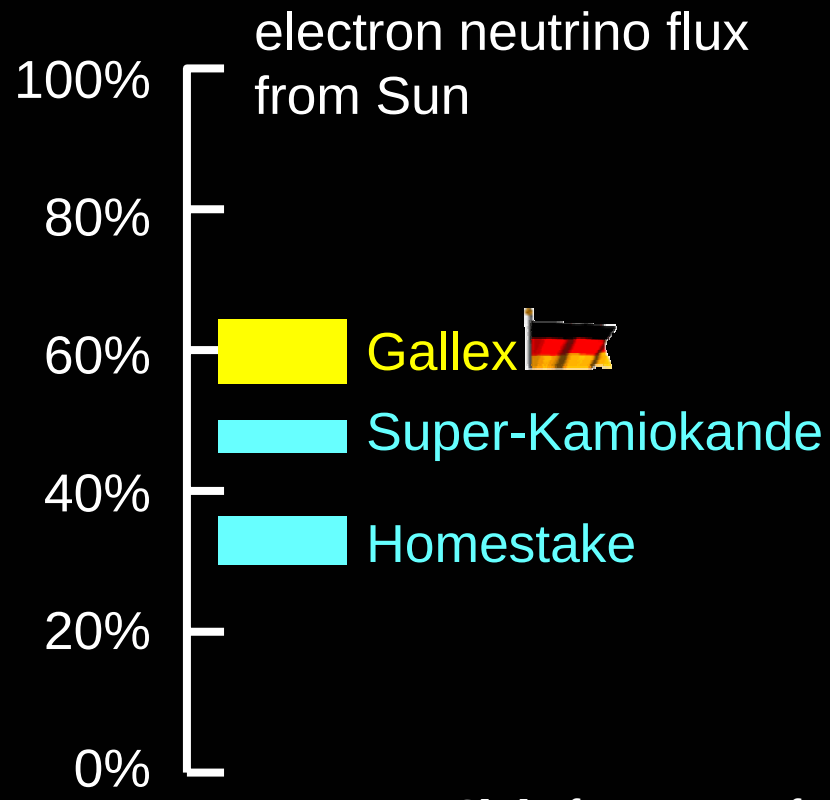
Measured

In 30 years 2000 neutrinos ....

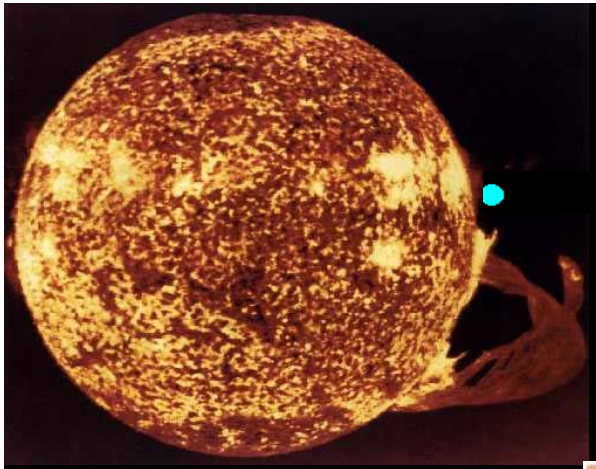


Kamiokande: The sun „in neutrinos“

Deficit confirmed by other experiments



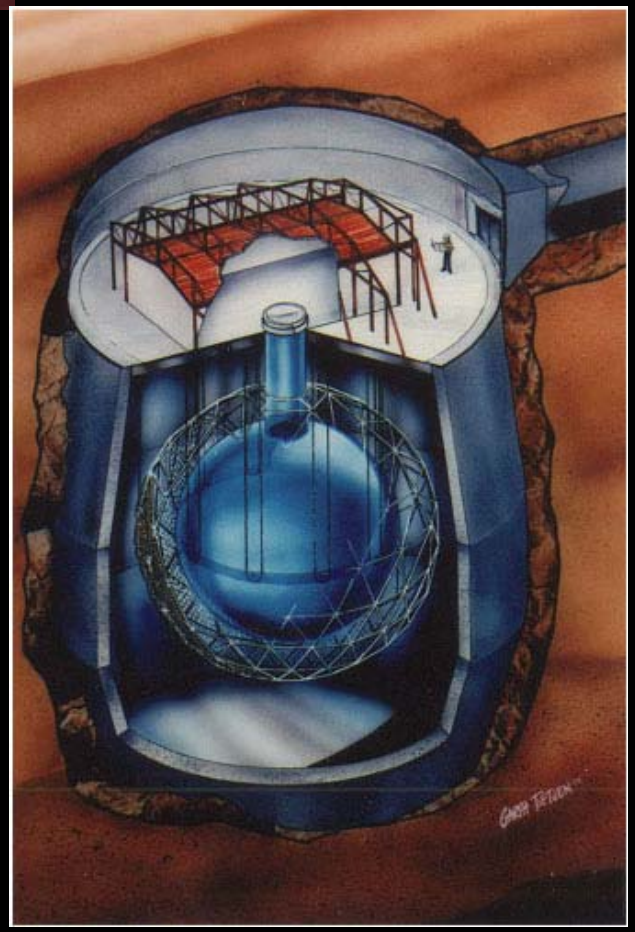
Slide from W.Hofmann

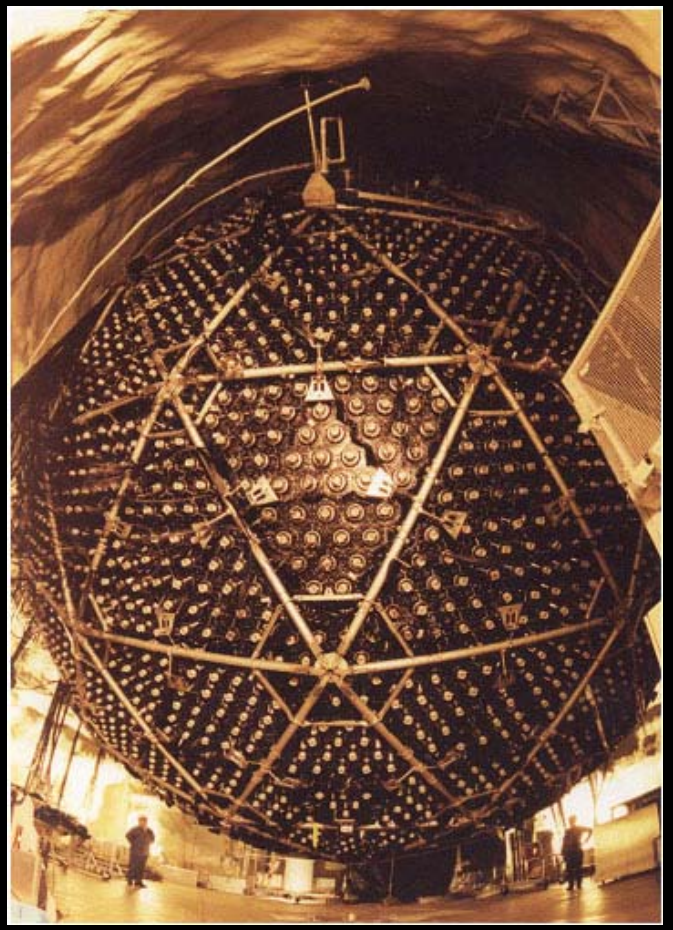


Neutrino Oscillations ?

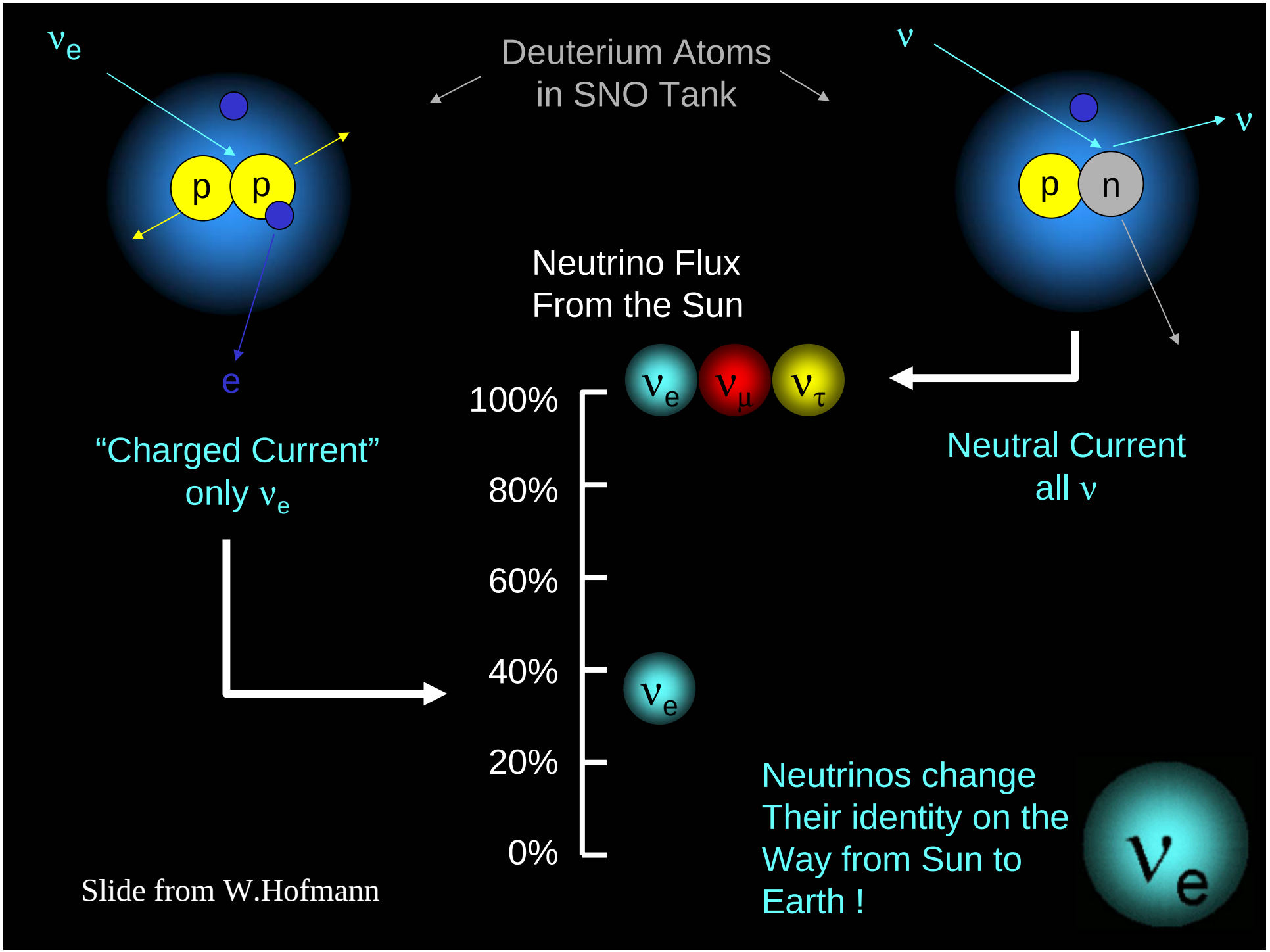
➔ Neutrinos have mass

SNO:
Sudbury
Neutrino
Observatory





Slide from W.Hofmann


ν_e
Deuterium Atoms
in SNO Tank
ν
p
p
e
p
n
ν
Neutrino Flux
From the Sun
100%
80%
60%
40%
20%
0%
ν_e ν_μ ν_τ
ν_e
"Charged Current"
only ν_e
Neutral Current
all ν
Neutrinos change
Their identity on the
Way from Sun to
Earth !
ν_e
Slide from W.Hofmann

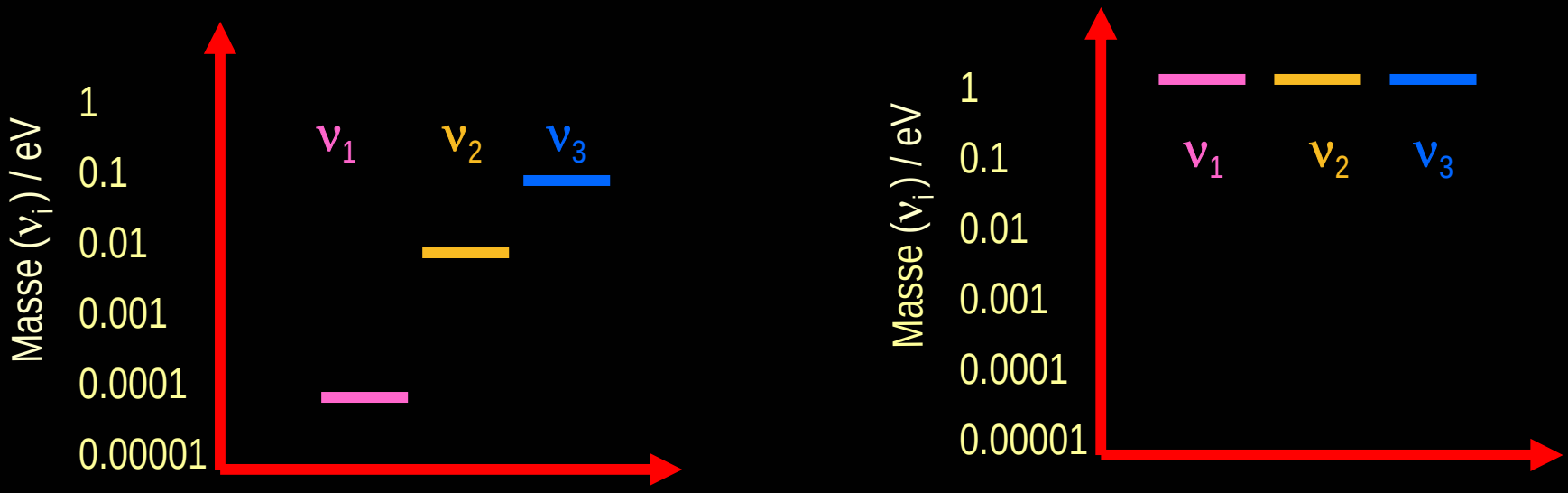
solar and reactor neutrinos

$\Delta m^2 \sim (10\ \text{meV})^2$

atmospheric neutrinos and accelerator neutrinos

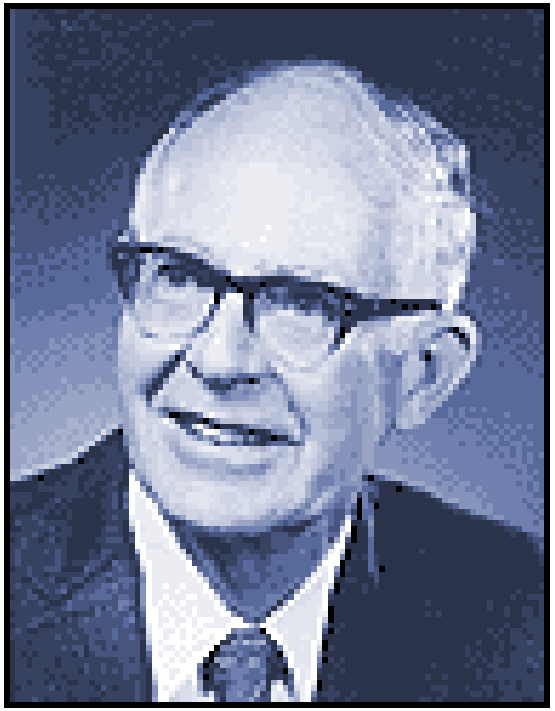
$\Delta m^2 \sim (50\ \text{meV})^2$

Hierarchy or Degeneration ?



Slide from W.Hofmann

Nobel prices 2002:
2x for Neutrino Astronomy

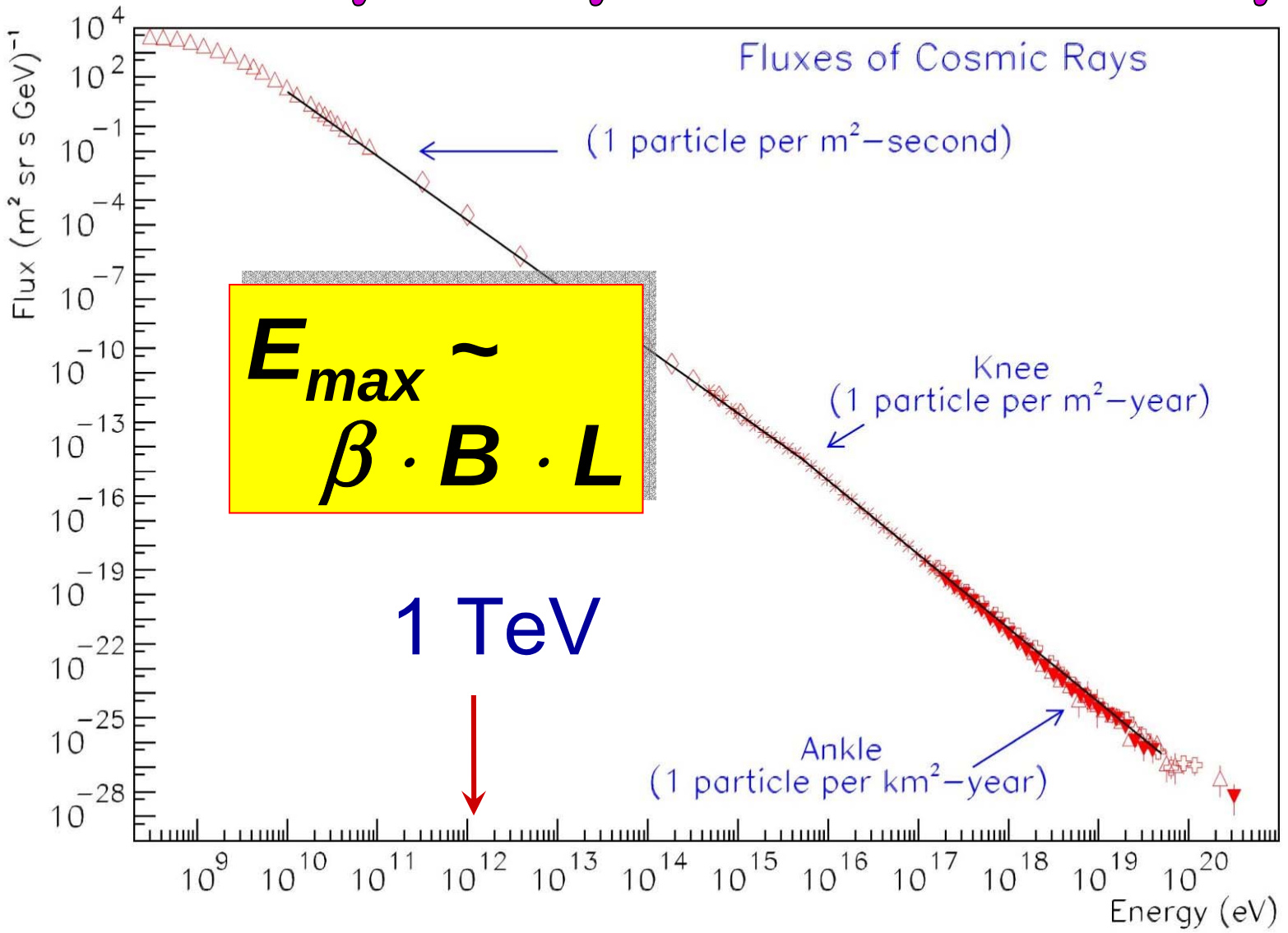


Raymond Davis jr.

Masatoshi Koshiba

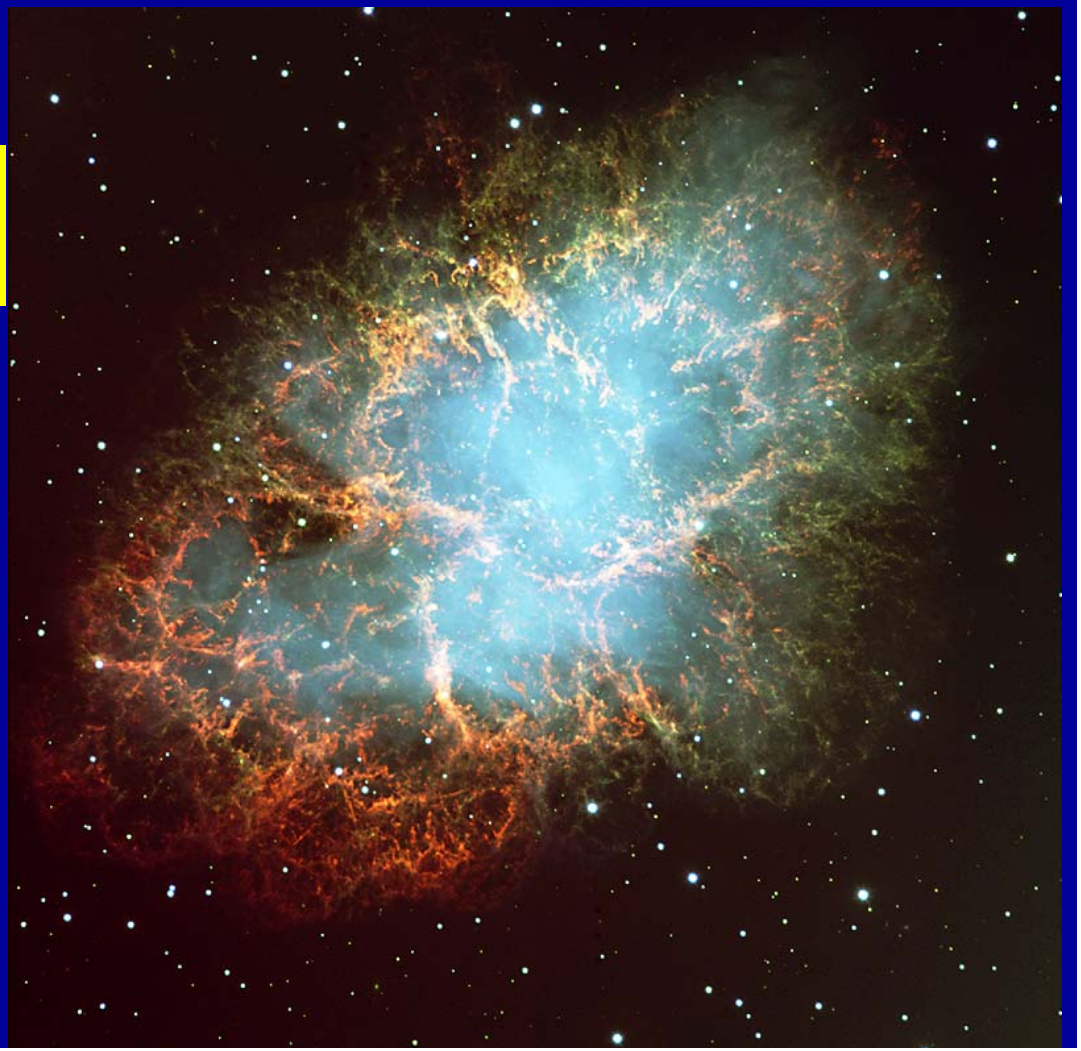
Neutrino Astrophysics at high Energies

The mystery of Cosmic Rays



Supernovae:
Shock Waves into interstellar medium

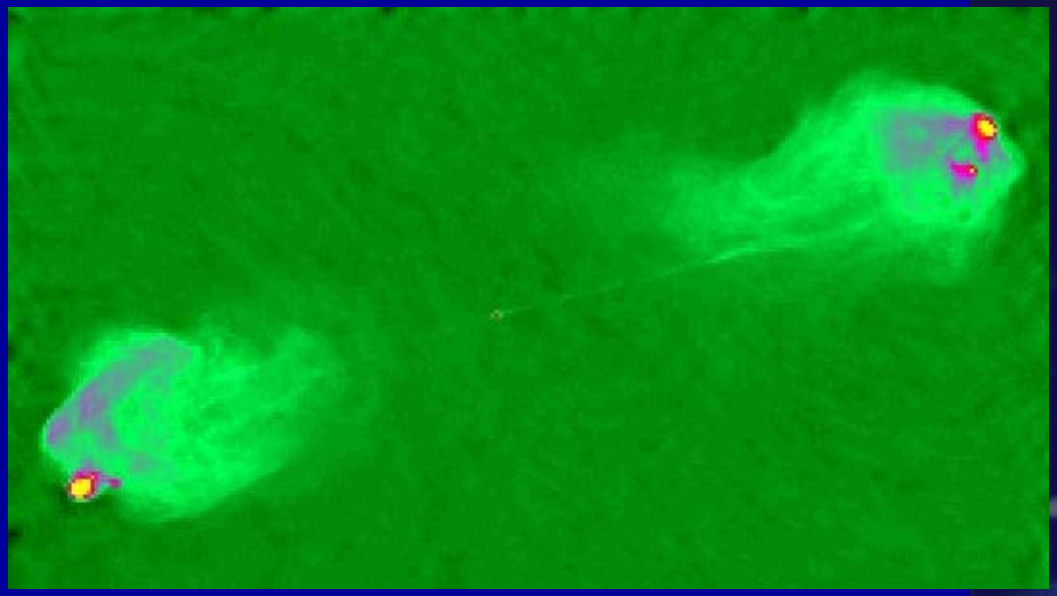
up to 10^{16} eV



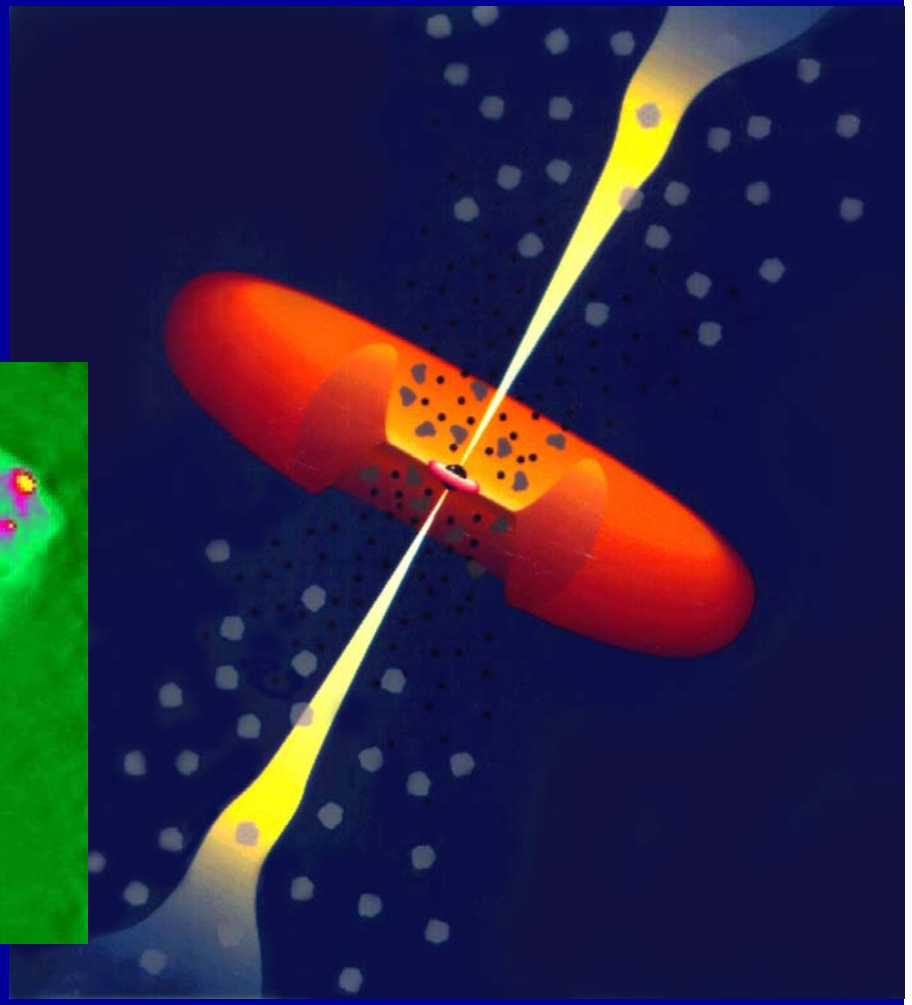
Crab Nebula

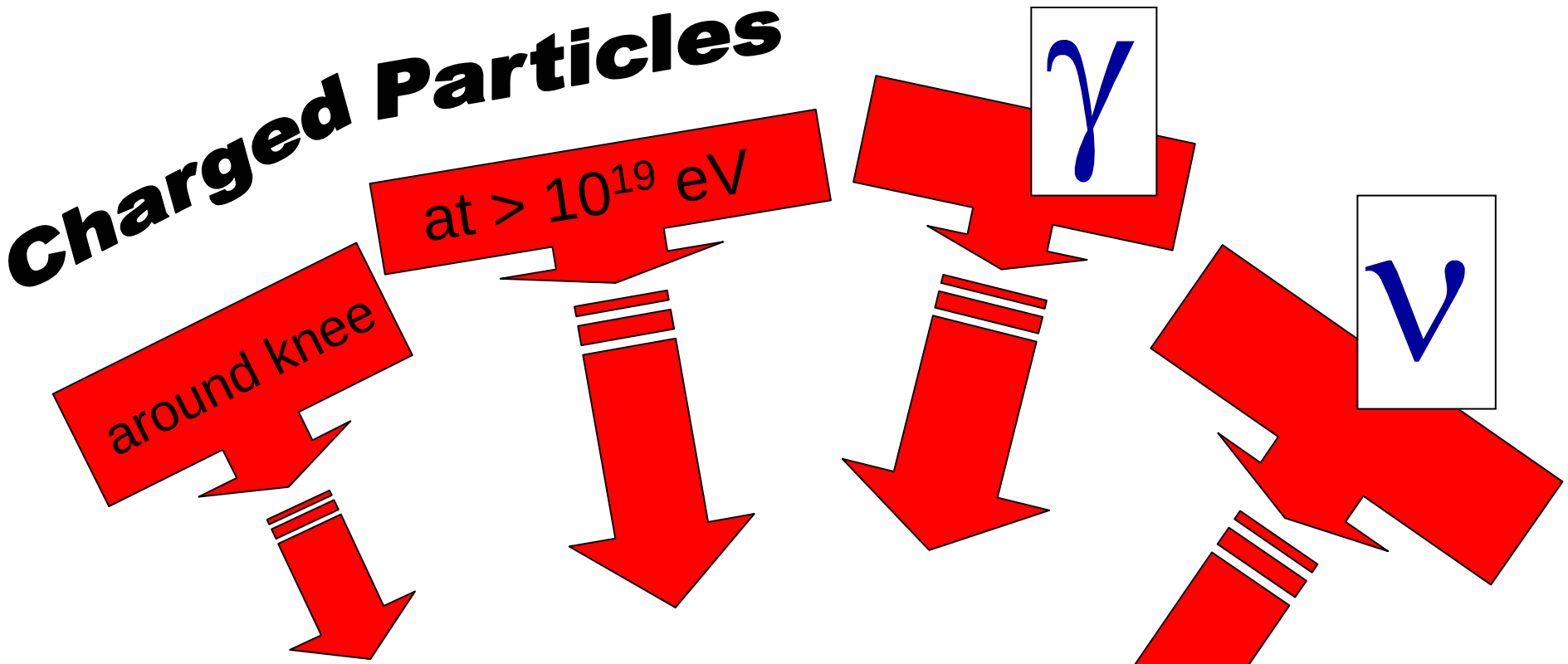
Active Galaxies: Accretion Disks and Jets

up to 10^{20} eV

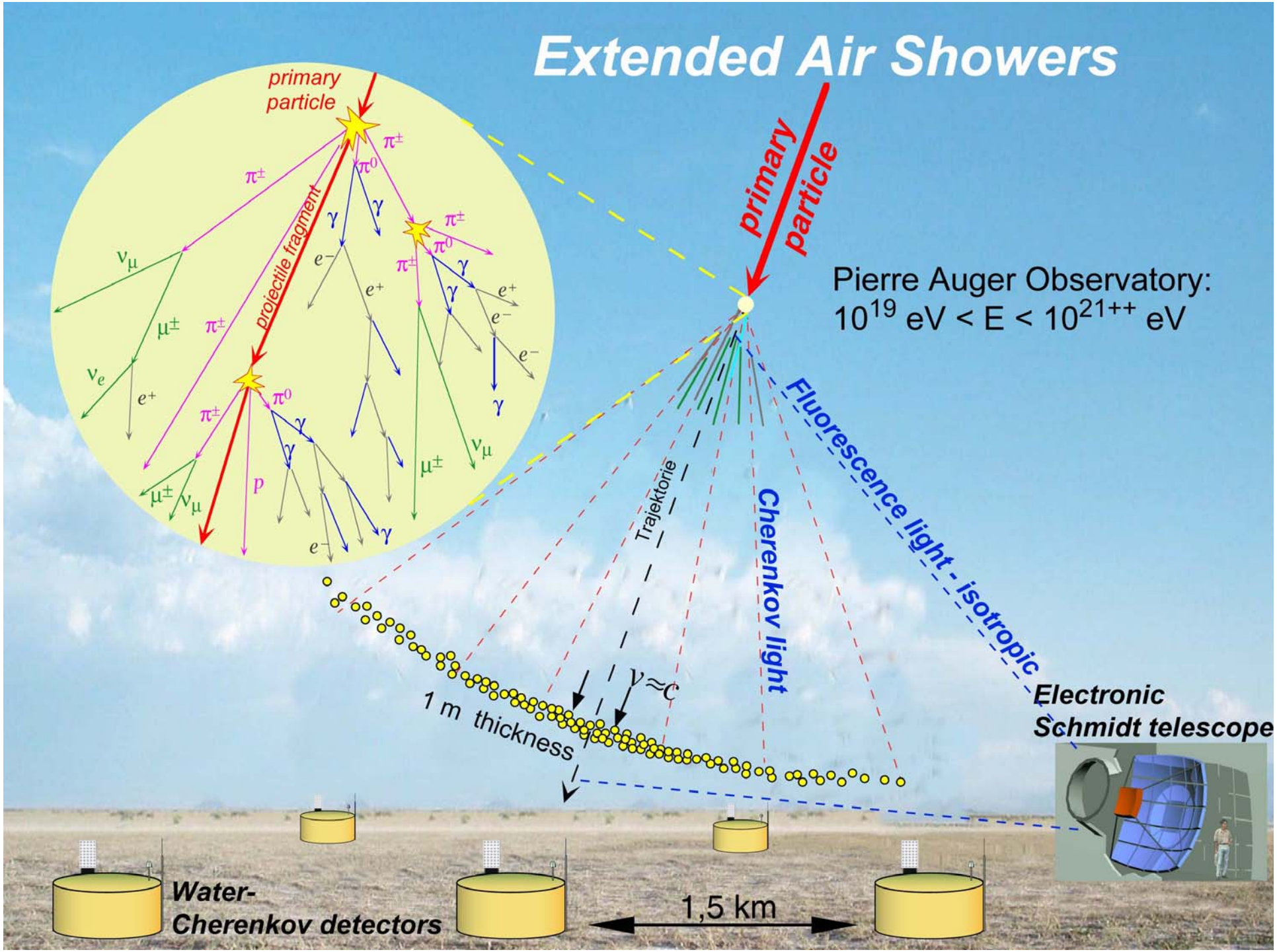


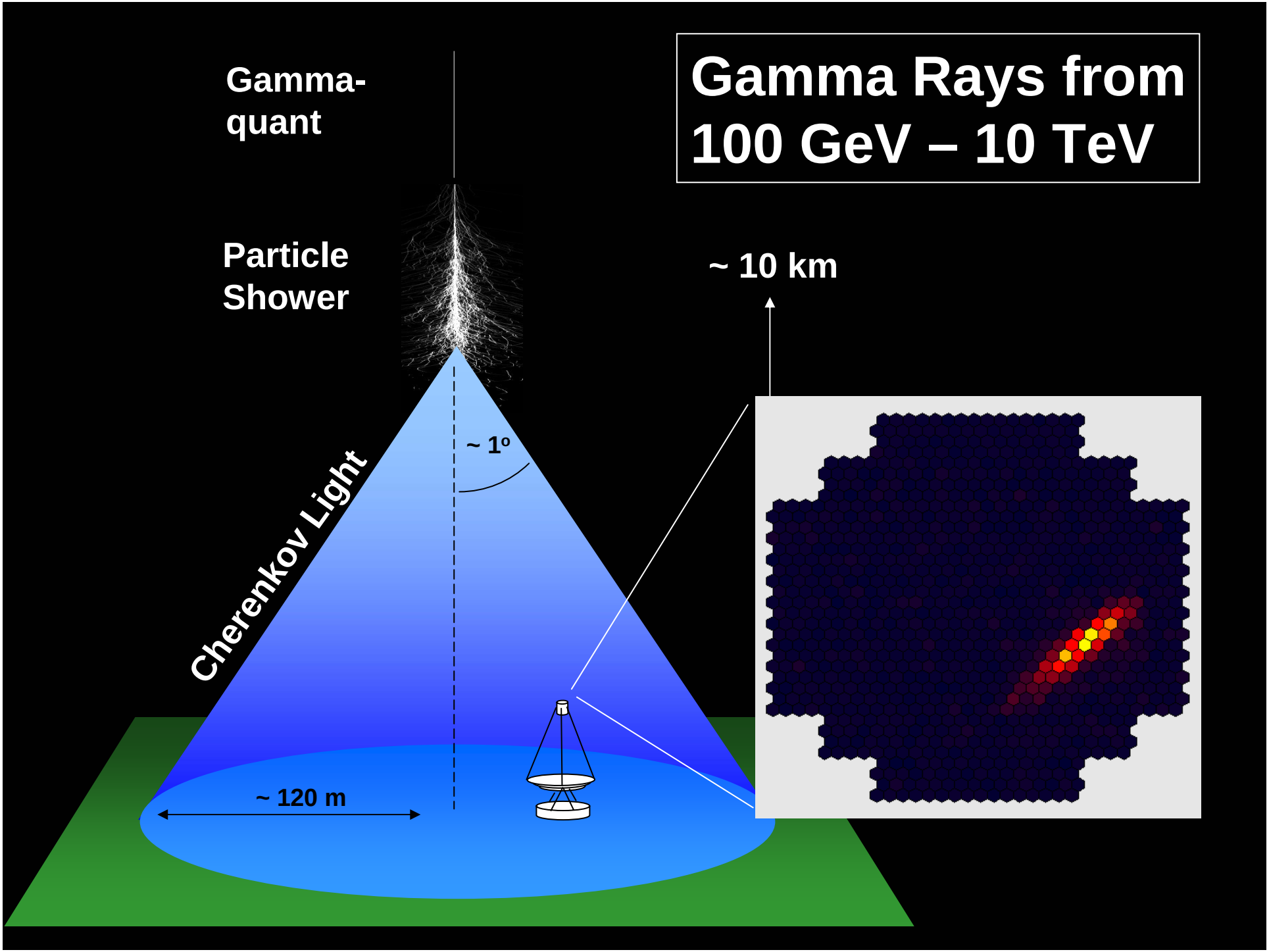
VLA image of Cygnus A





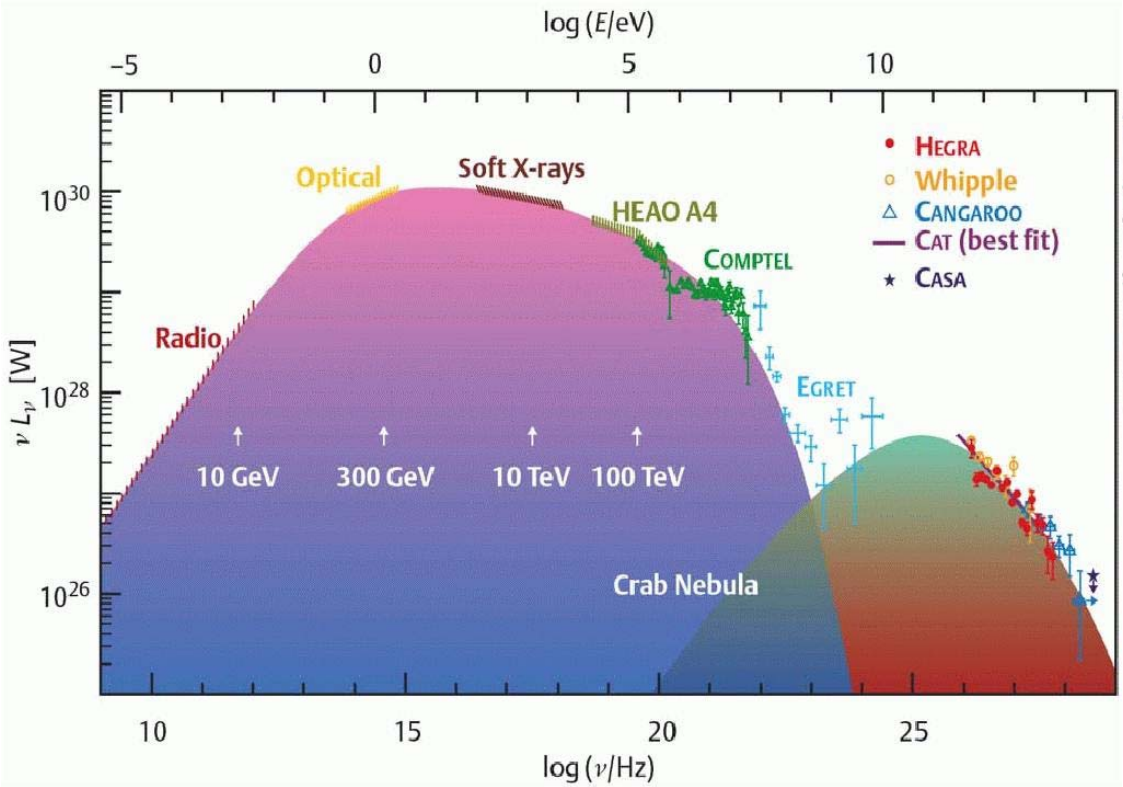
Origin of Cosmic Rays


Extended Air Showers
primary particle
primary particle
projectile fragment
Pierre Auger Observatory:
10^{19} eV < E < 10^{21++} eV
Fluorescence light - isotropic
Trajektorie
Cherenkov light
$v \approx c$
1 m thickness
Electronic Schmidt telescope
Water-Cherenkov detectors
1,5 km

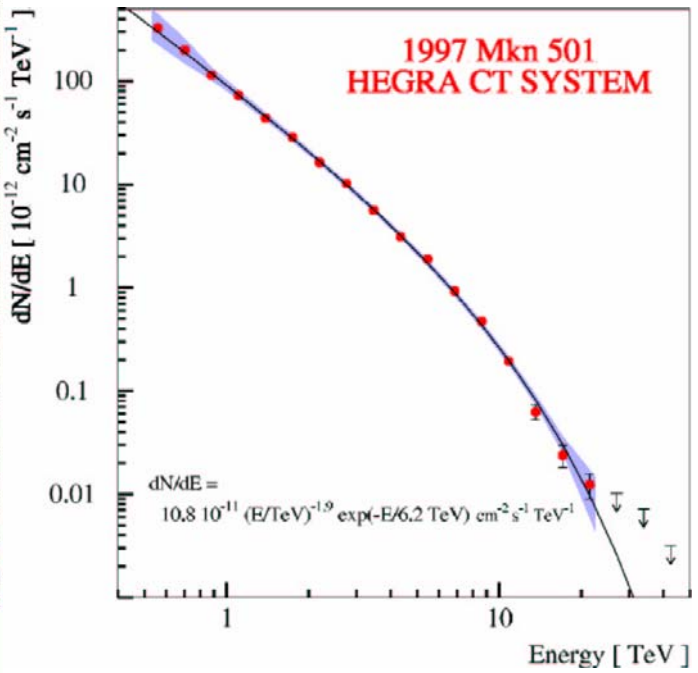


Gamma Rays from 100 GeV – 10 TeV

Supernova Remnant: Crab Nebula



AGN: Markarian 501

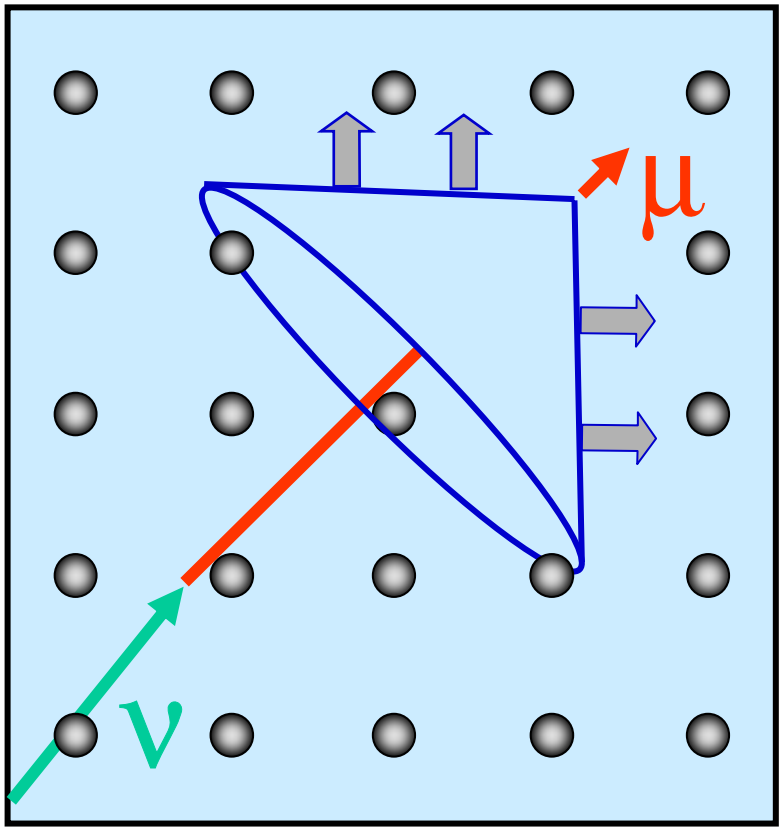


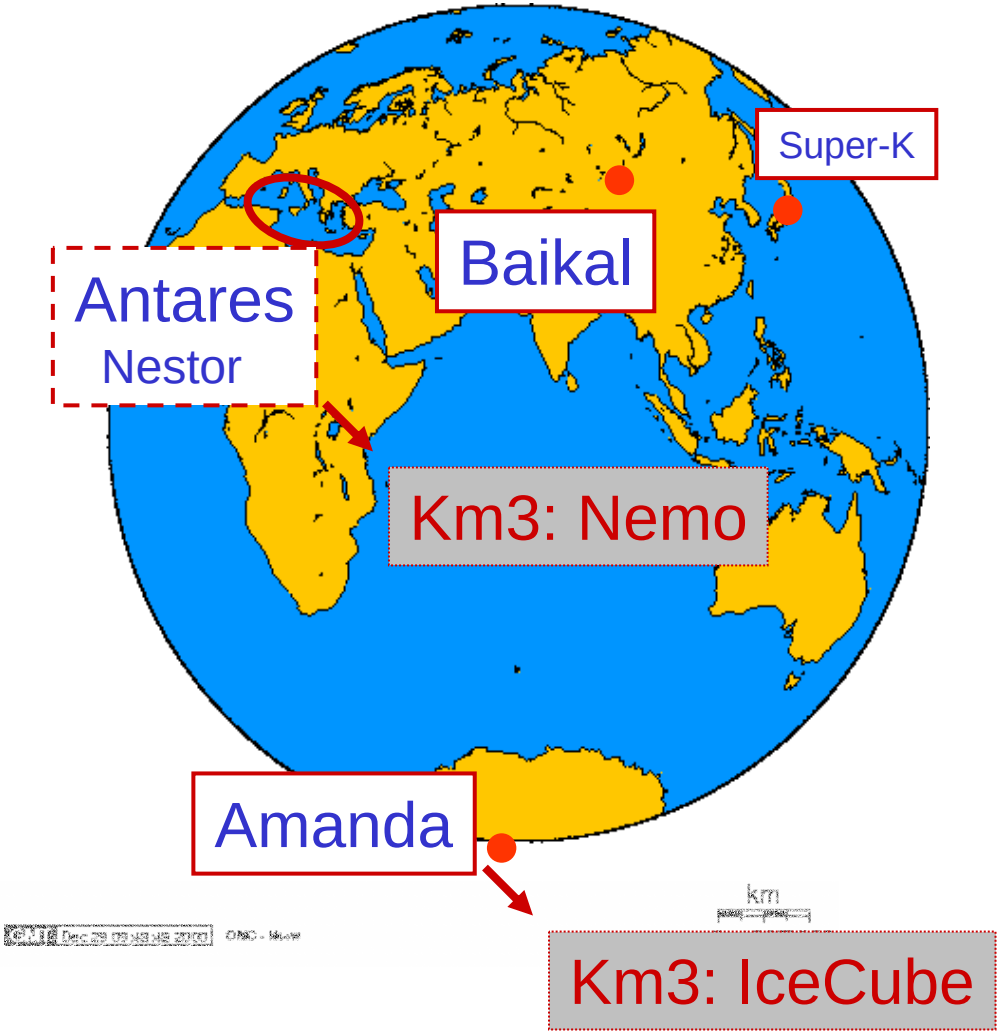
All observations consistent with

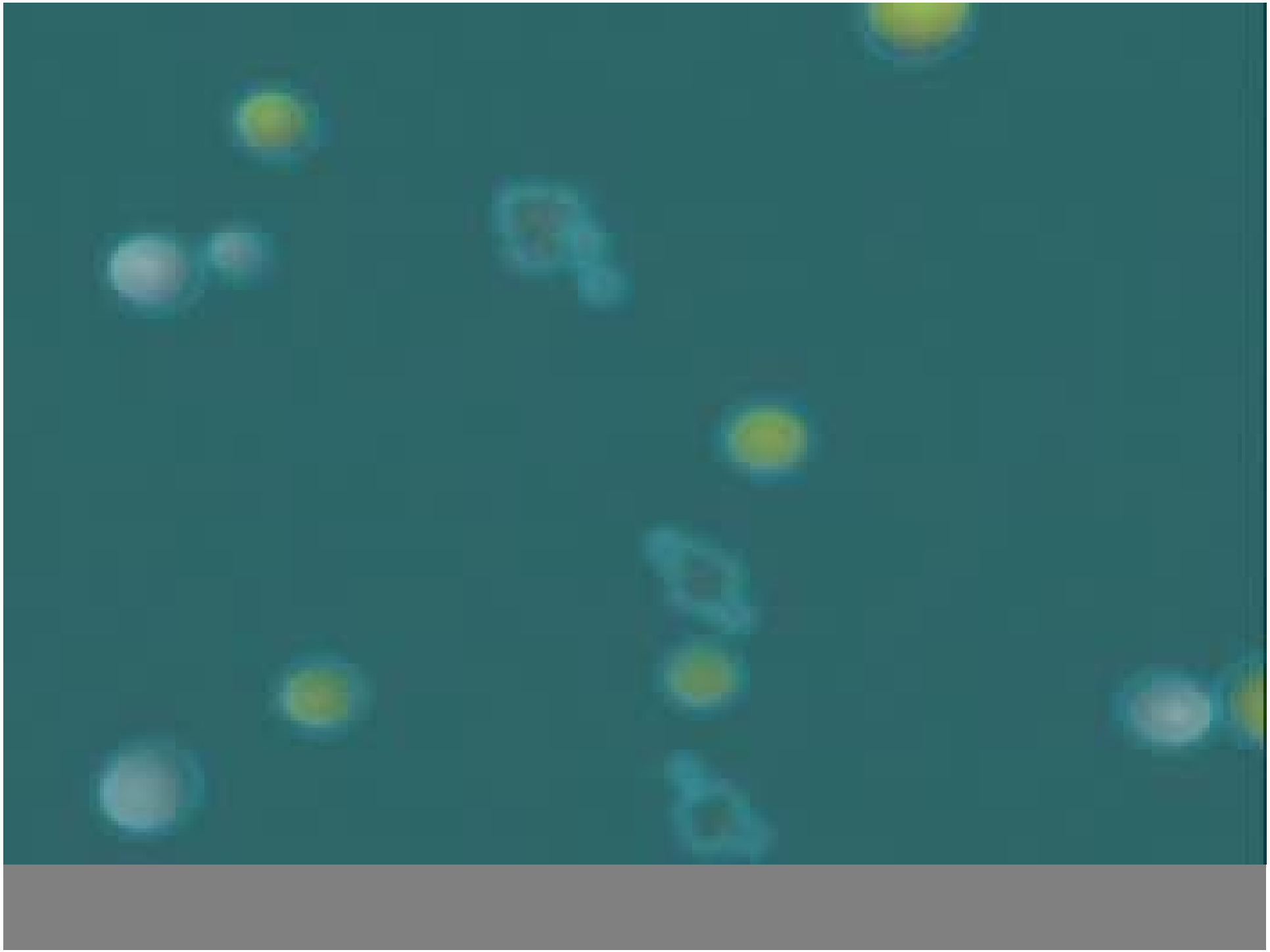
→ Synchrotron radiation at low energies

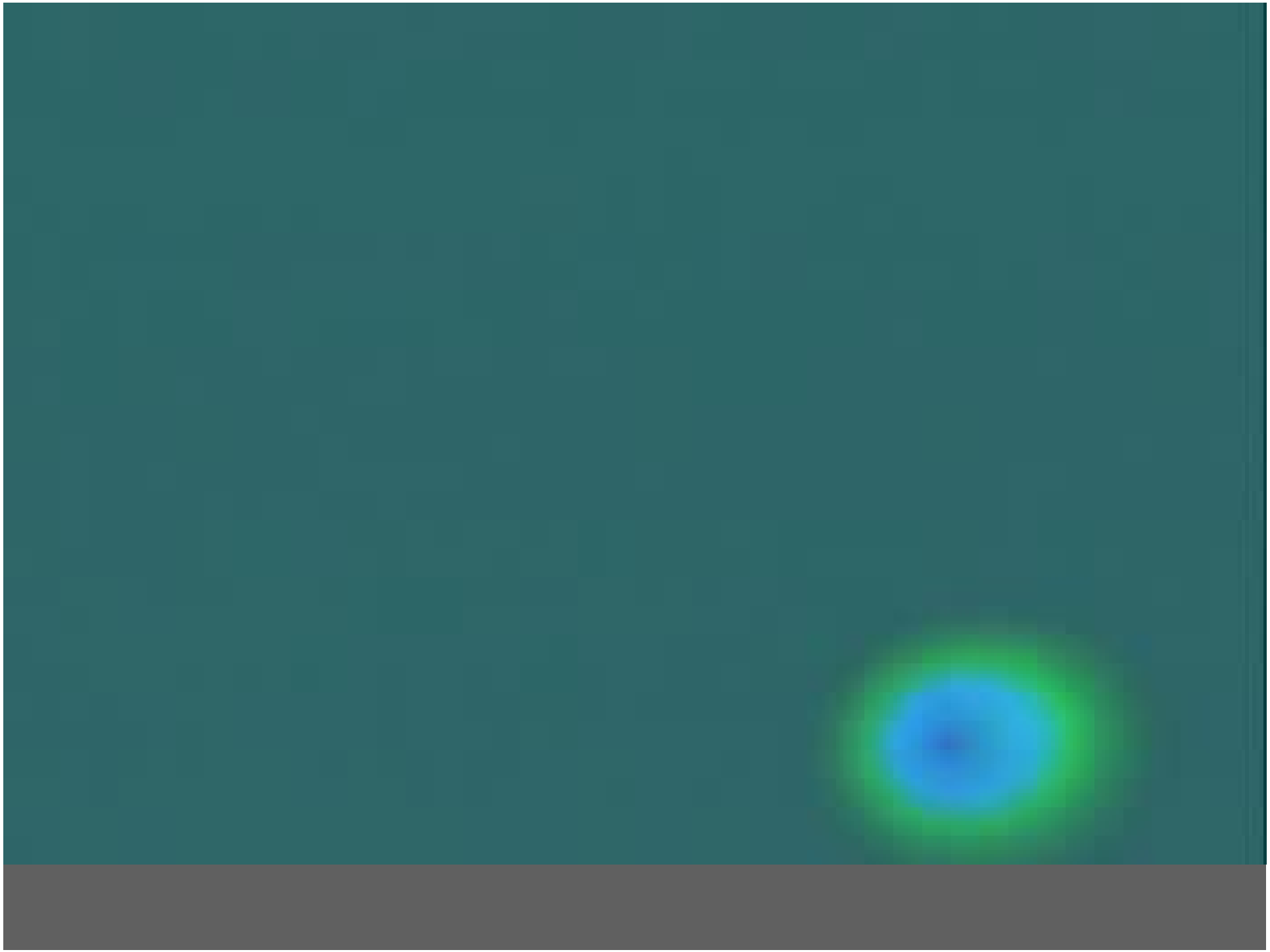
→ Inverse Compton scattering at high energies

Neutrino Telescopes in Water and Ice



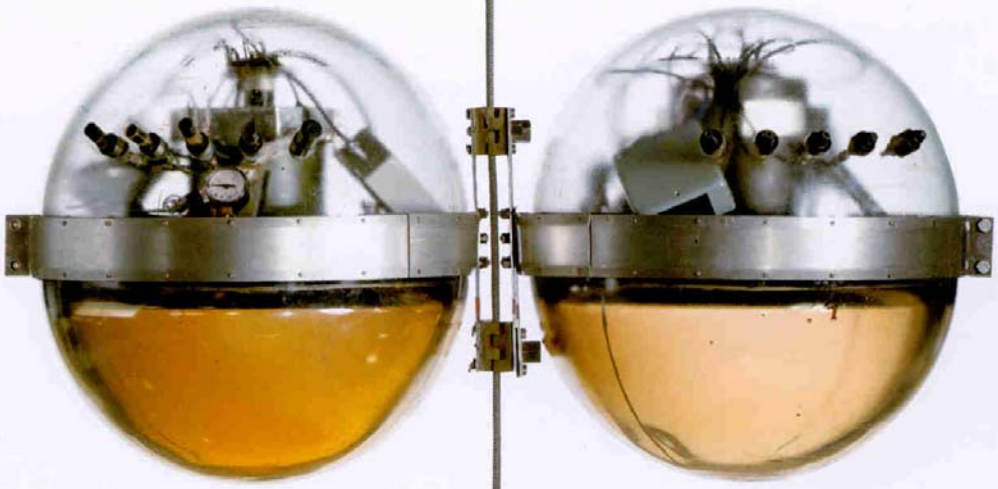


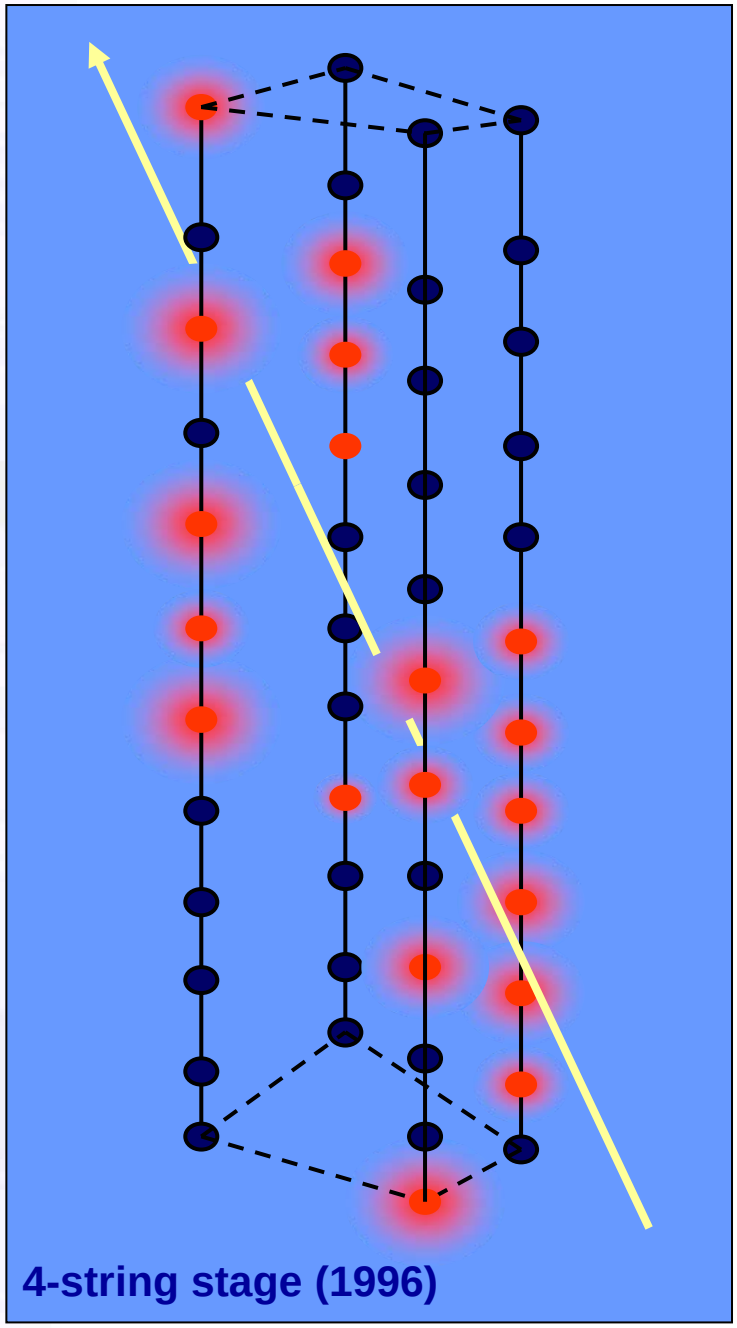




Lake Baikal

First Underwater Telescope
First Neutrinos underwater





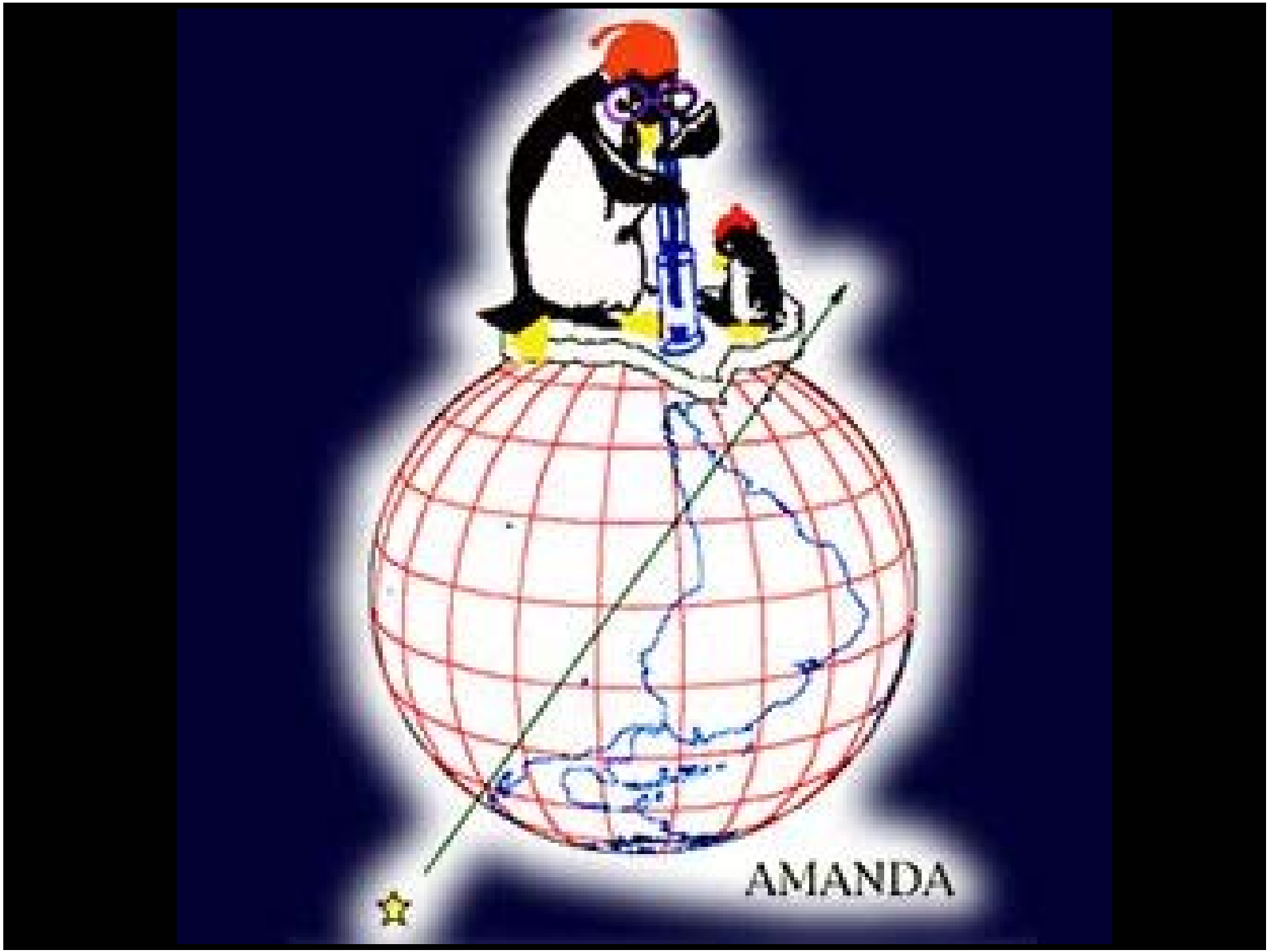
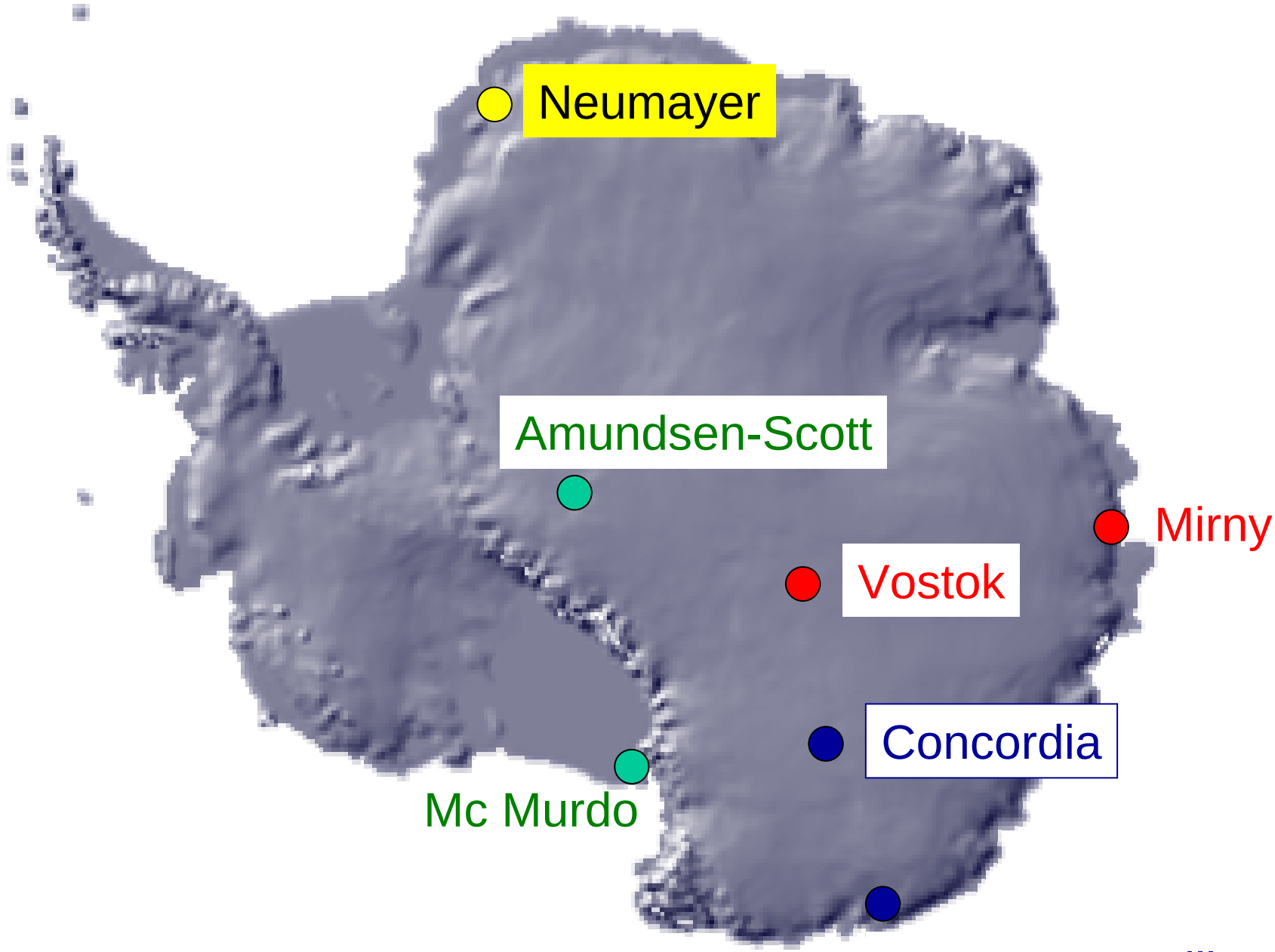
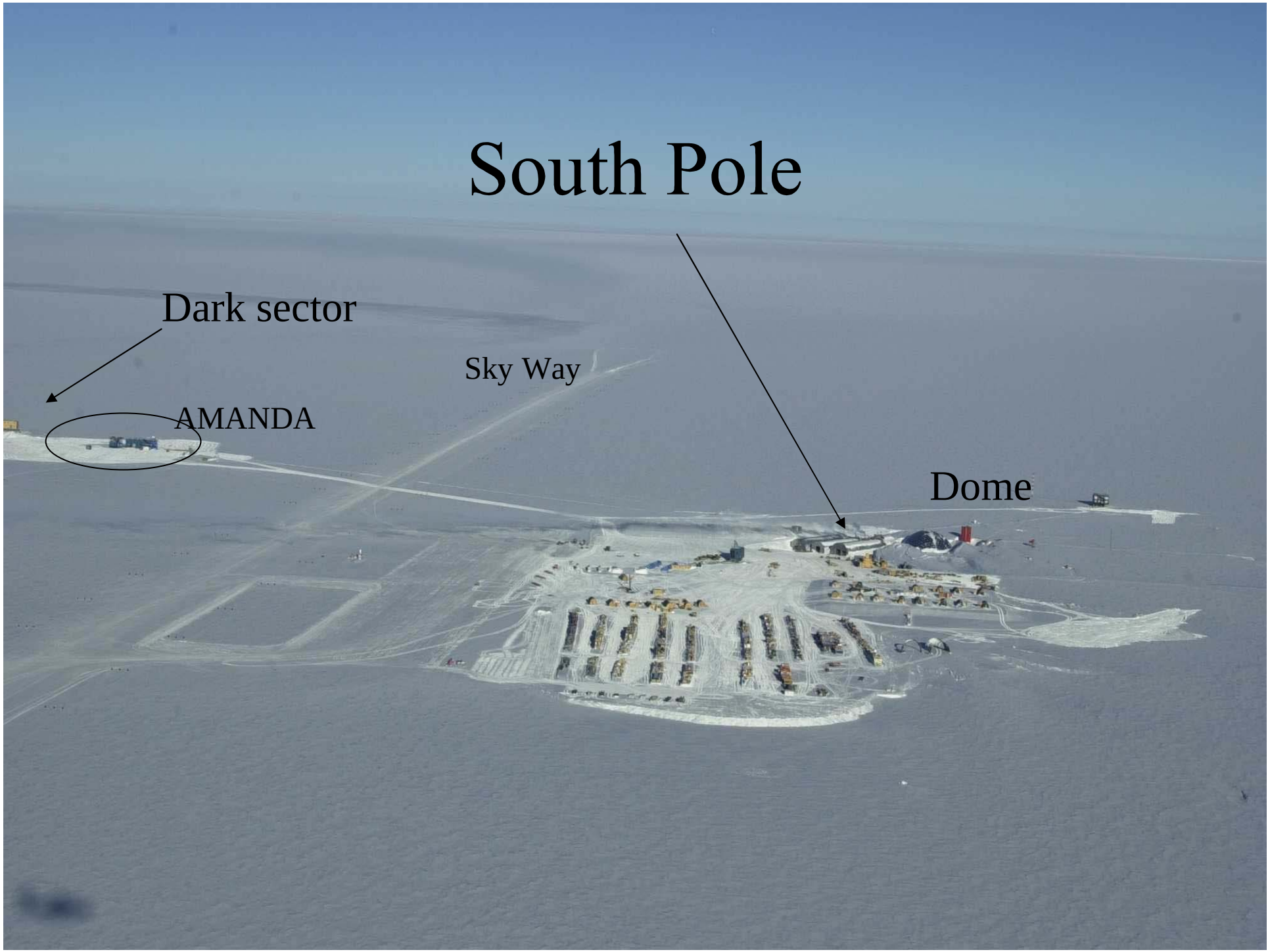
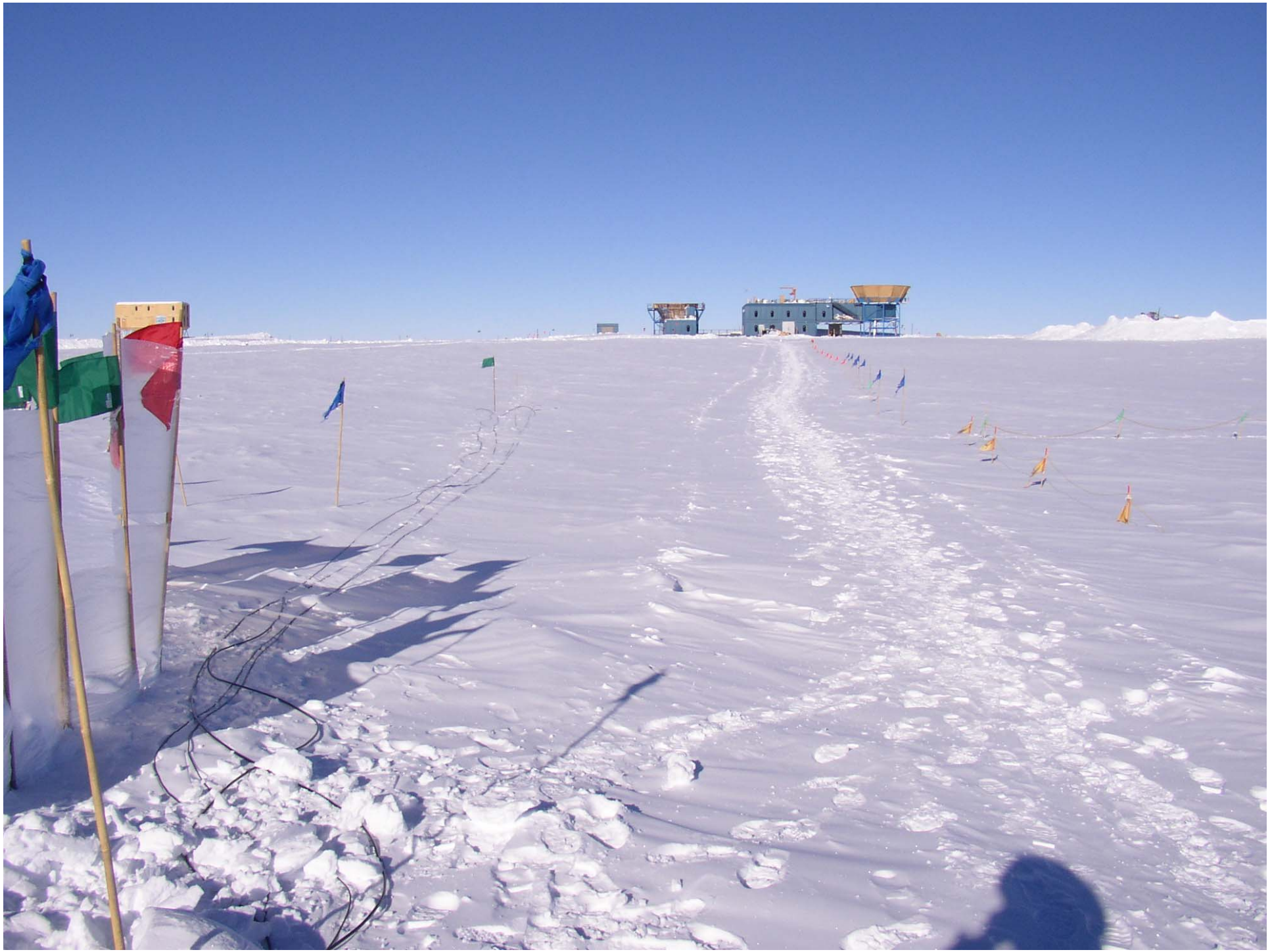

AMANDA

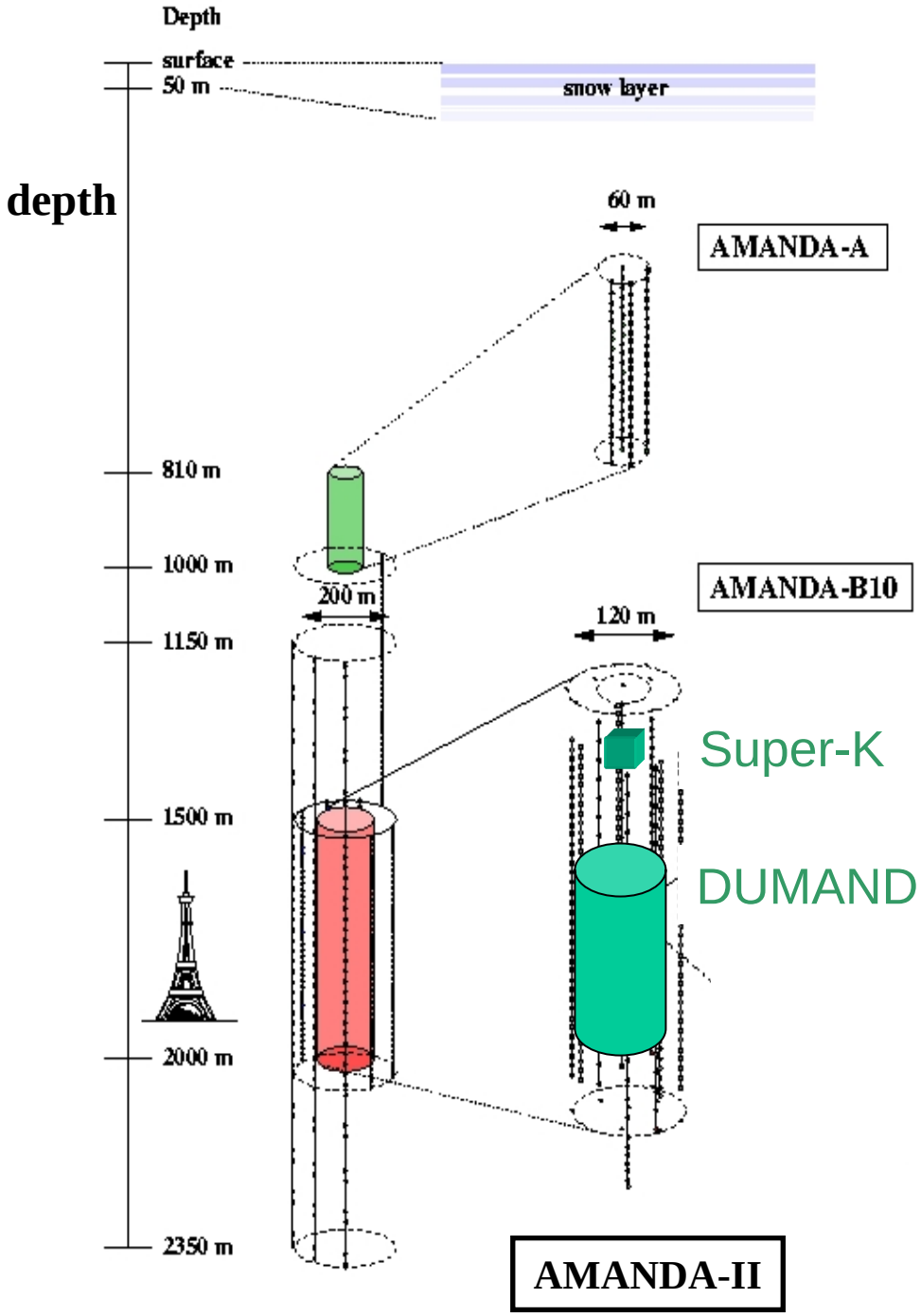

PHOTO BY CHARLIE KAMINSKI
SOUTH POLE DEC 2, 2006


Neumayer
Amundsen-Scott
Mirny
Vostok
Concordia
Mc Murdo
Dumont D‘Urville

Antarktis


South Pole
Dark sector
Sky Way
AMANDA
Dome

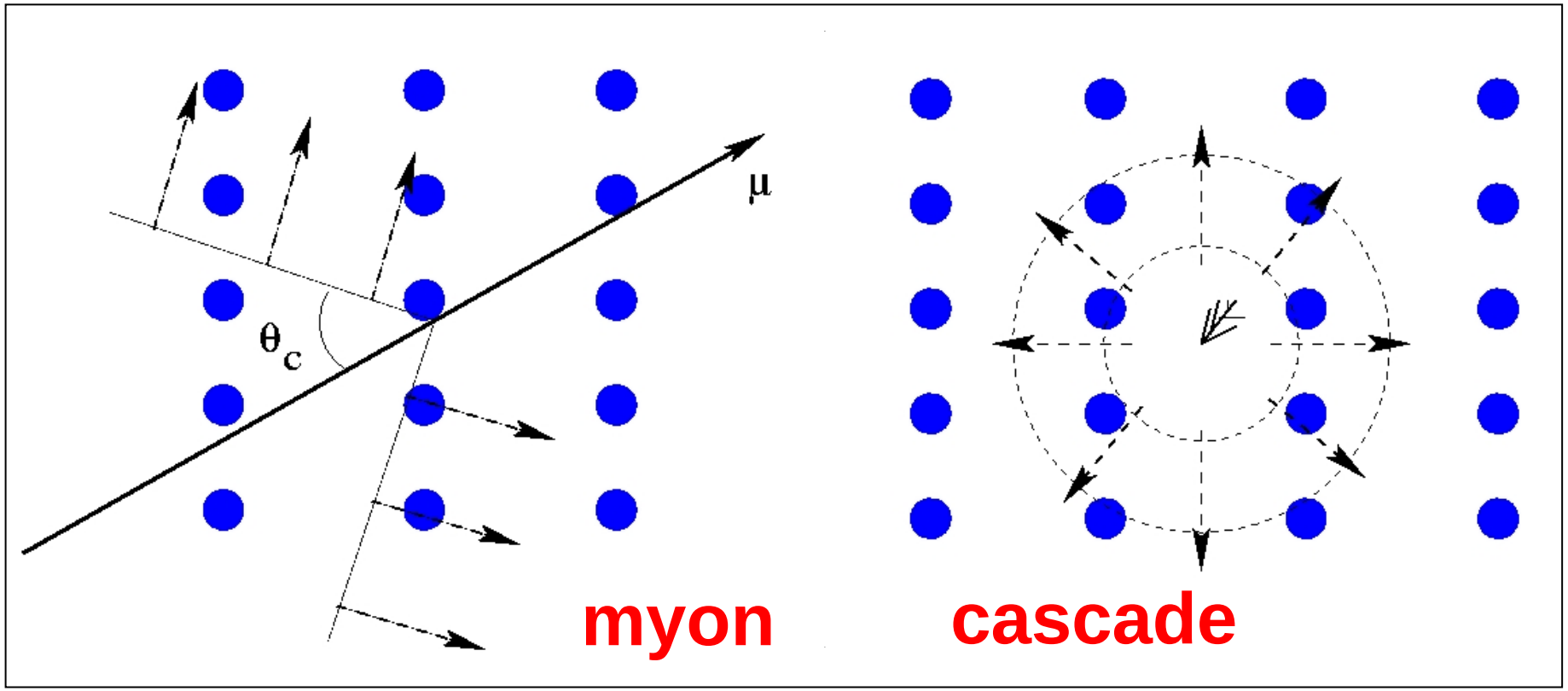




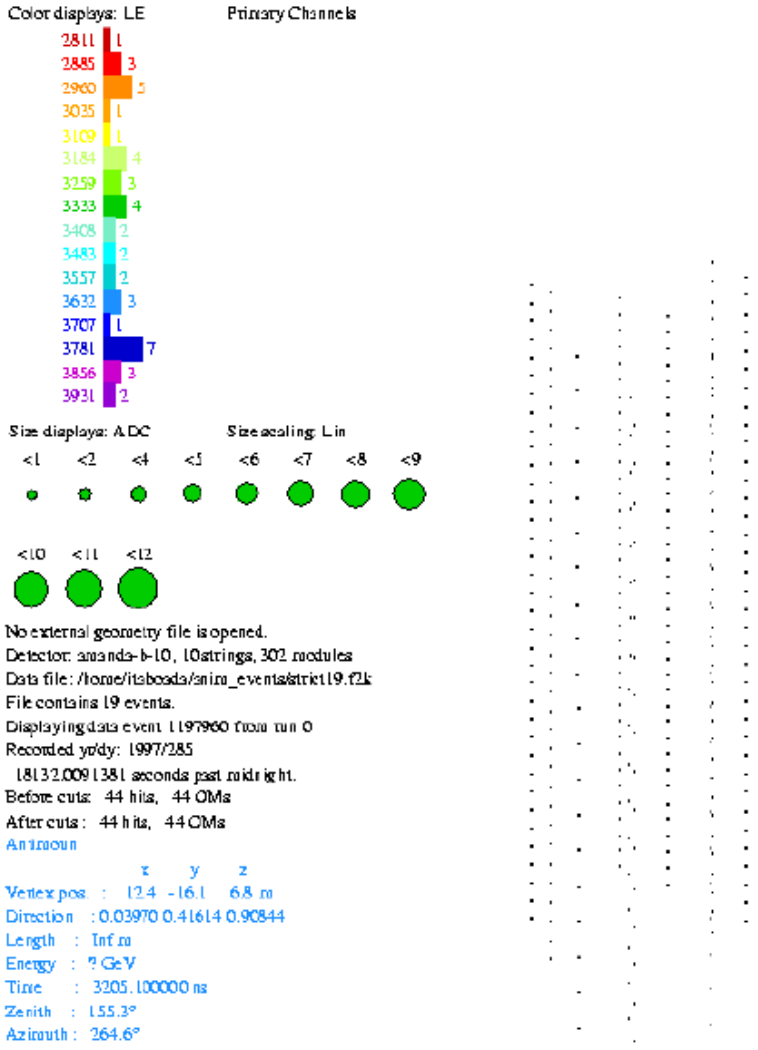
AMANDA

Amanda-II:
677 PMTs
at 19 strings

(1996-2000)


μ
θc
myon
cascade

AMANDA Event Signatures: Muons

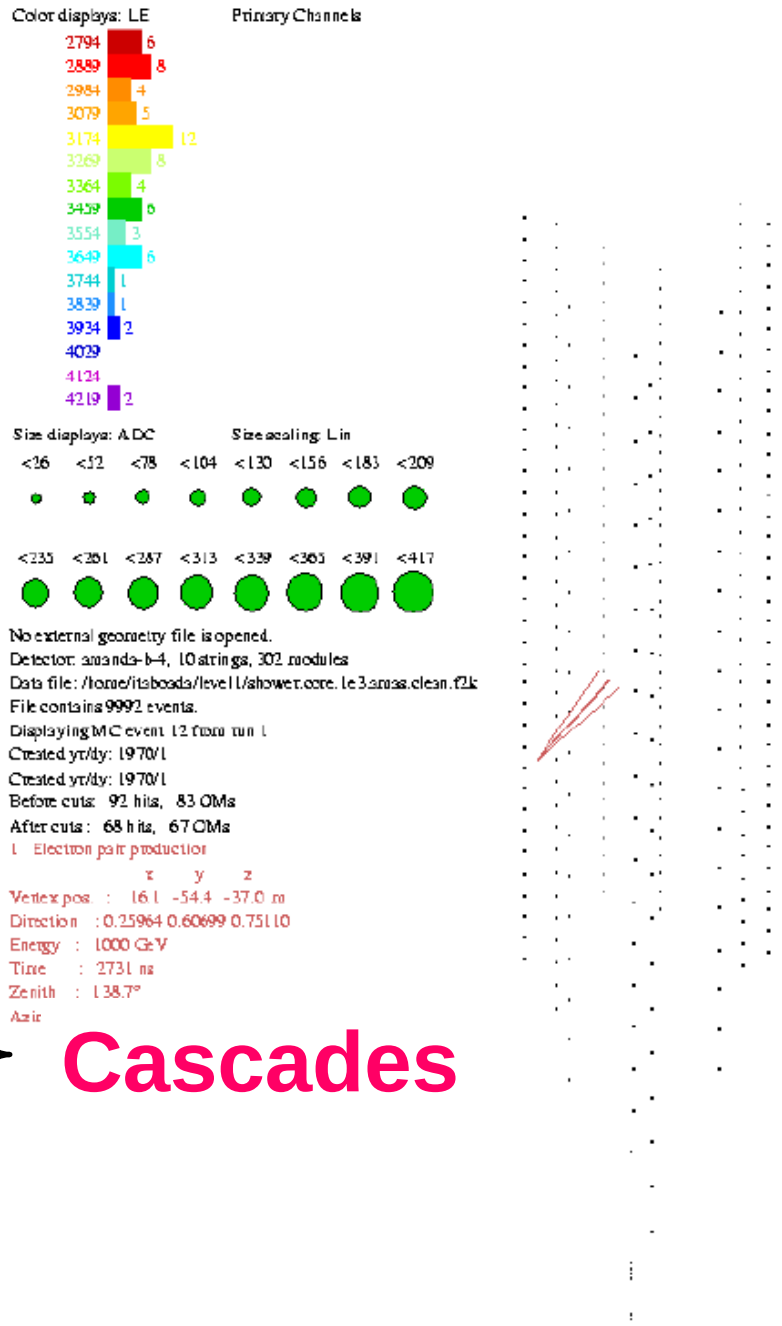


CC muon neutrino interaction

→ **track**

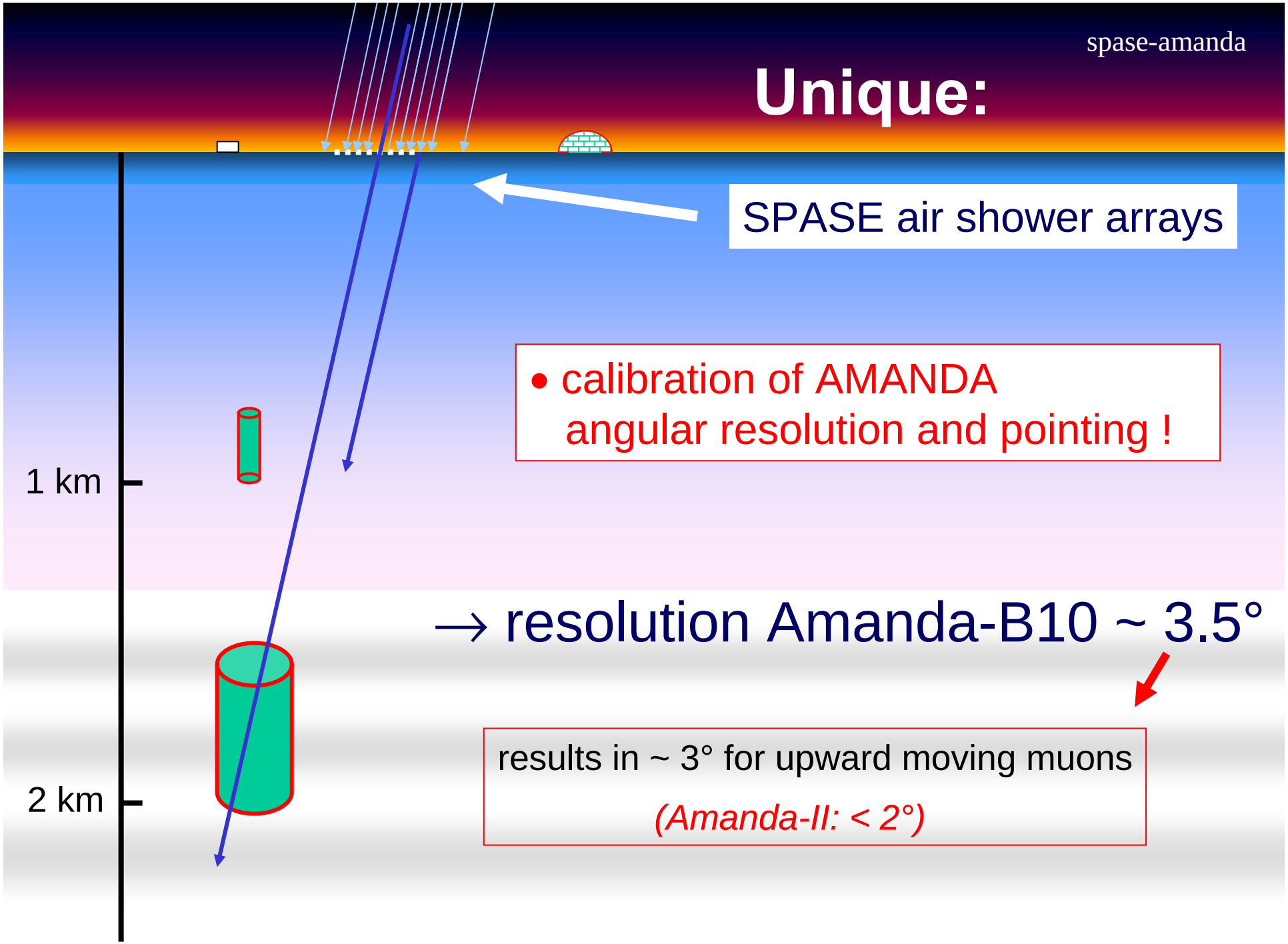
$$\nu_\mu + N \rightarrow \mu + X$$

AMANDA Event Signatures: Cascades

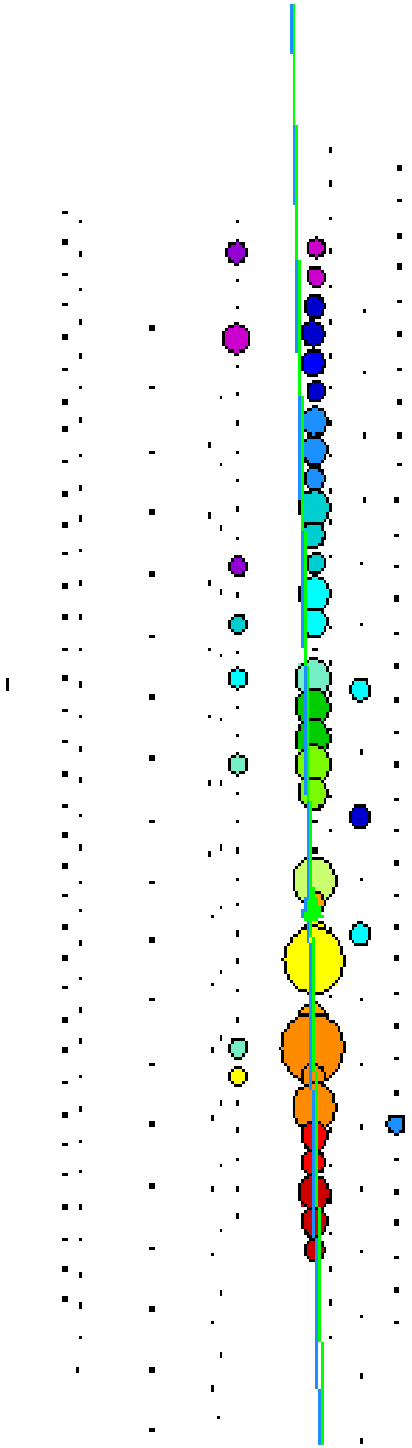


- CC electron and tau neutrino interaction:
- $\nu_{(e,\tau,)} + N \rightarrow (e, \tau) + X$
- NC neutrino interaction:

  $\nu_x + N \rightarrow \nu_x + X$


spase-amanda
Unique:
SPASE air shower arrays
• calibration of AMANDA
angular resolution and pointing !
1 km
2 km
→ resolution Amanda-B10 ~ 3.5°
results in ~ 3° for upward moving muons
(Amanda-II: < 2°)

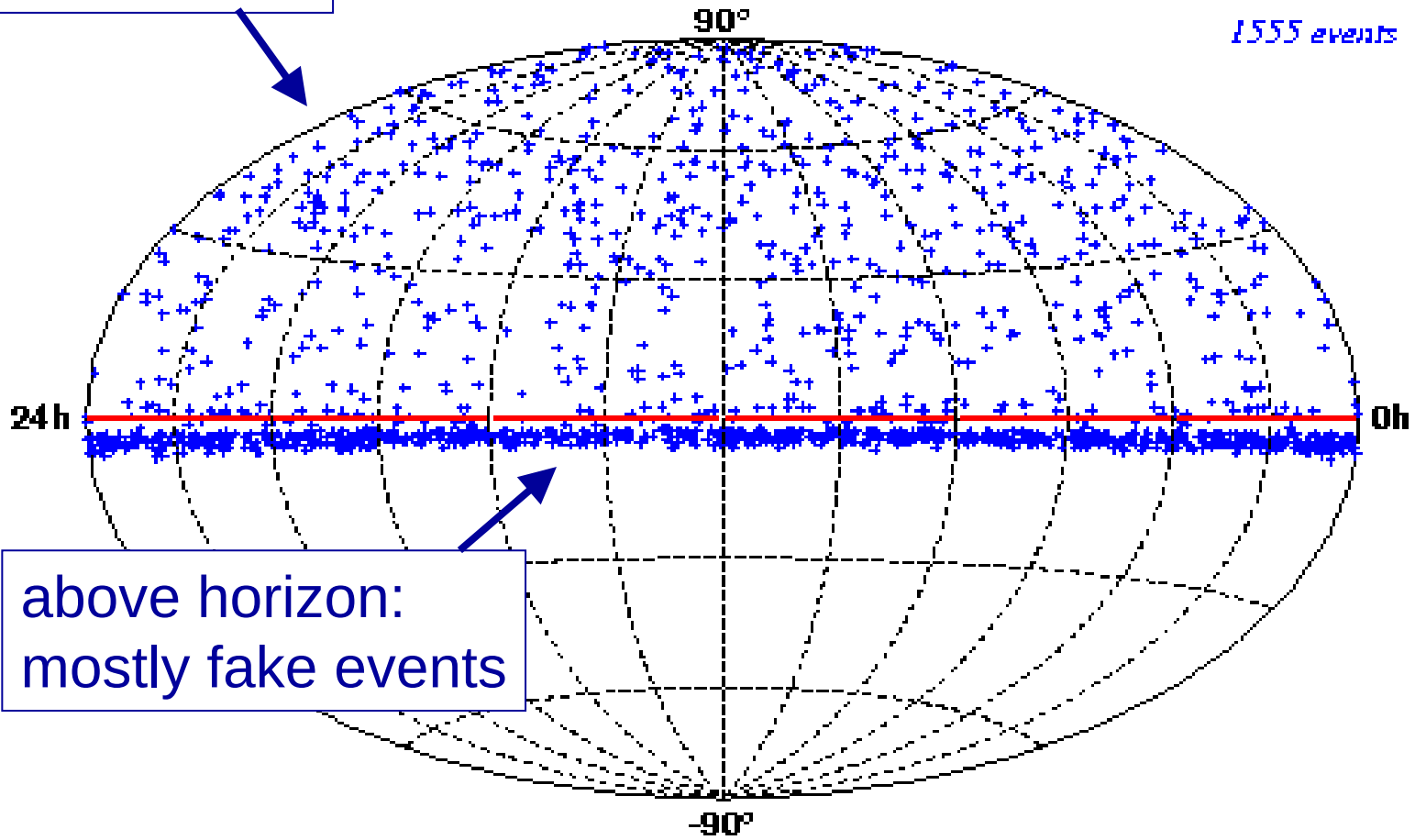

2000
das jahr der physik



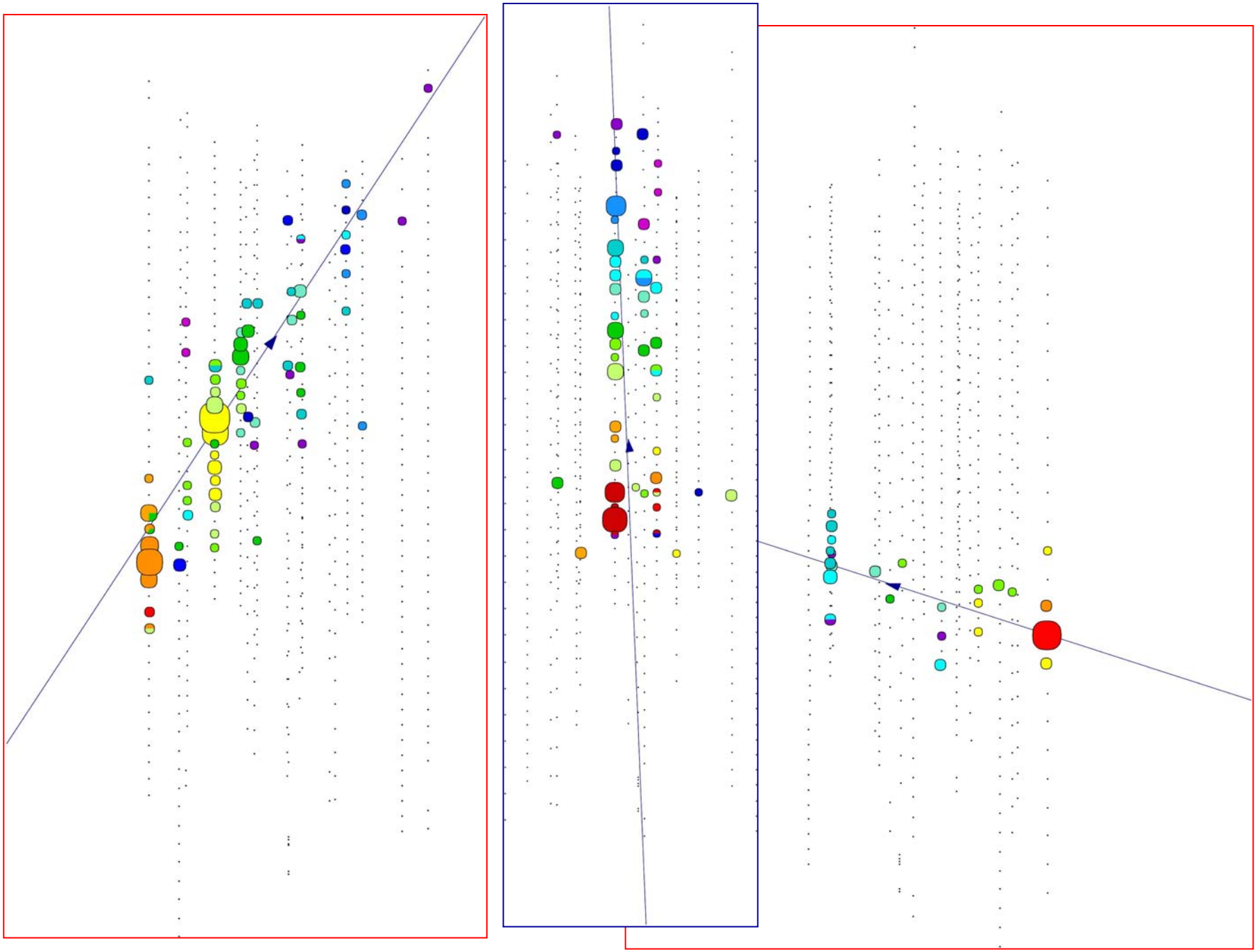
Search for Point Sources

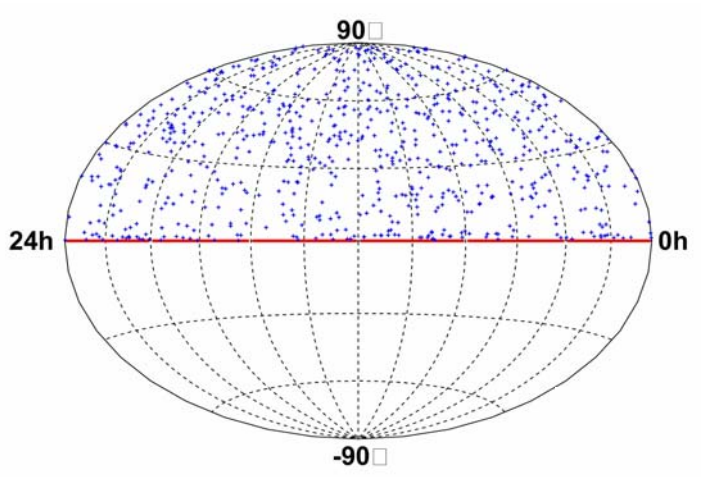
Skyplot Amanda-II, 2000

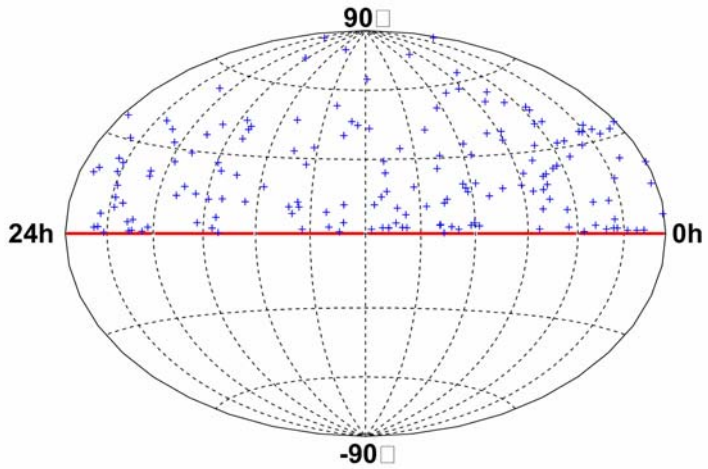
679 events
below horizon

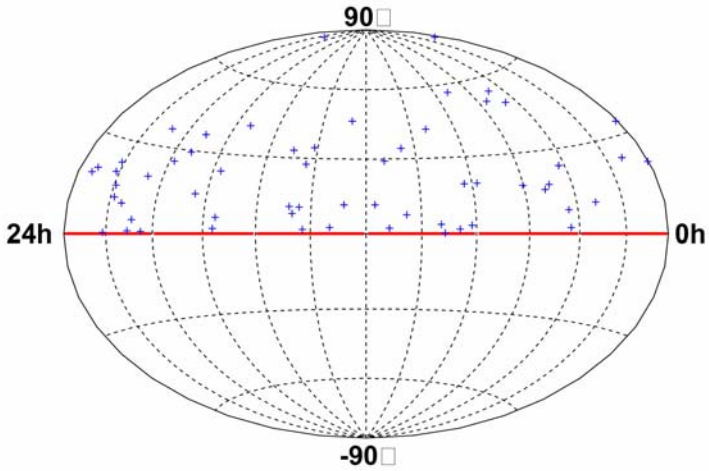


above horizon:
mostly fake events



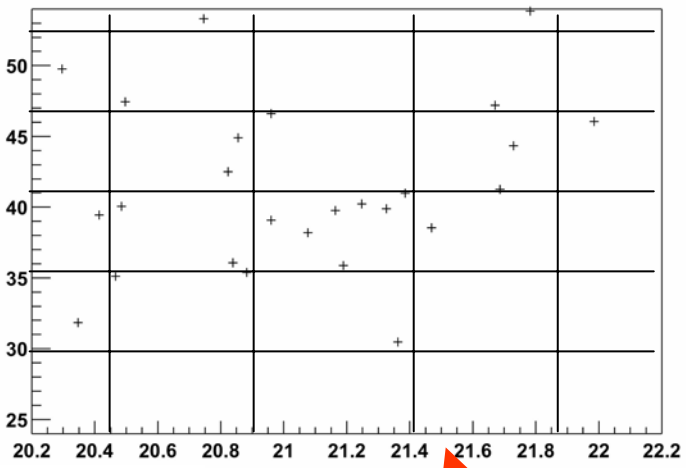




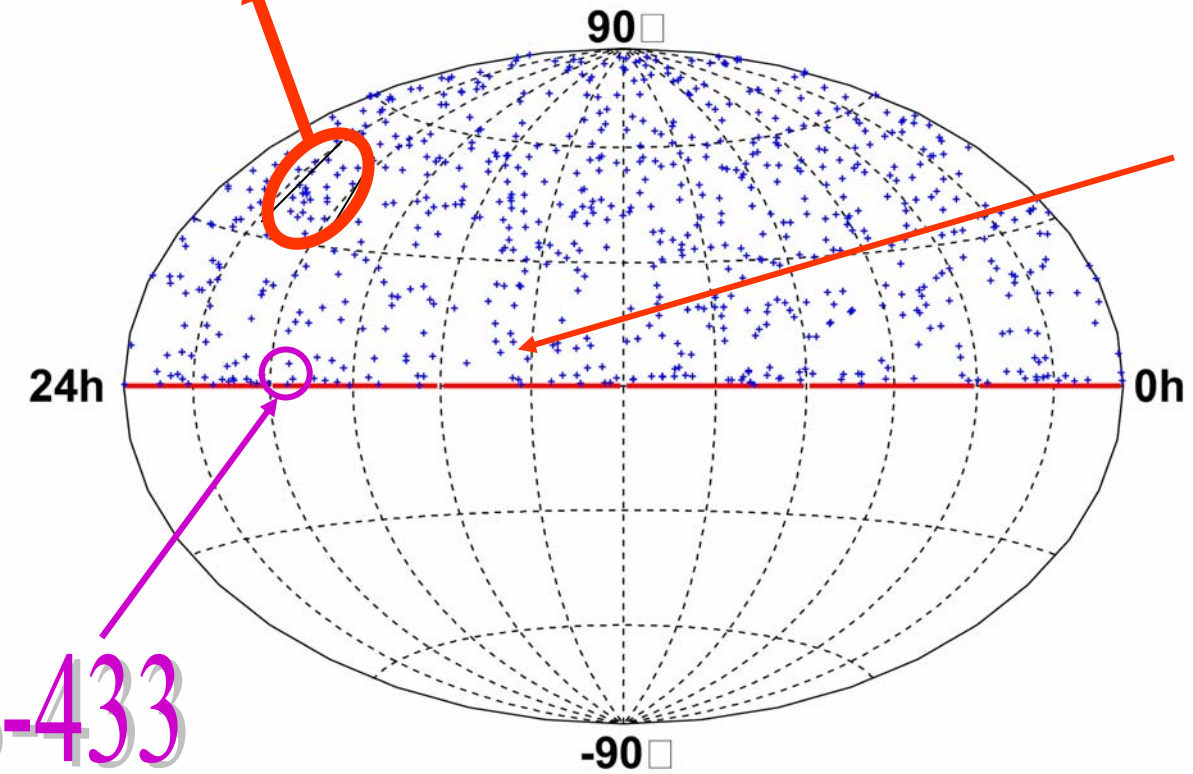


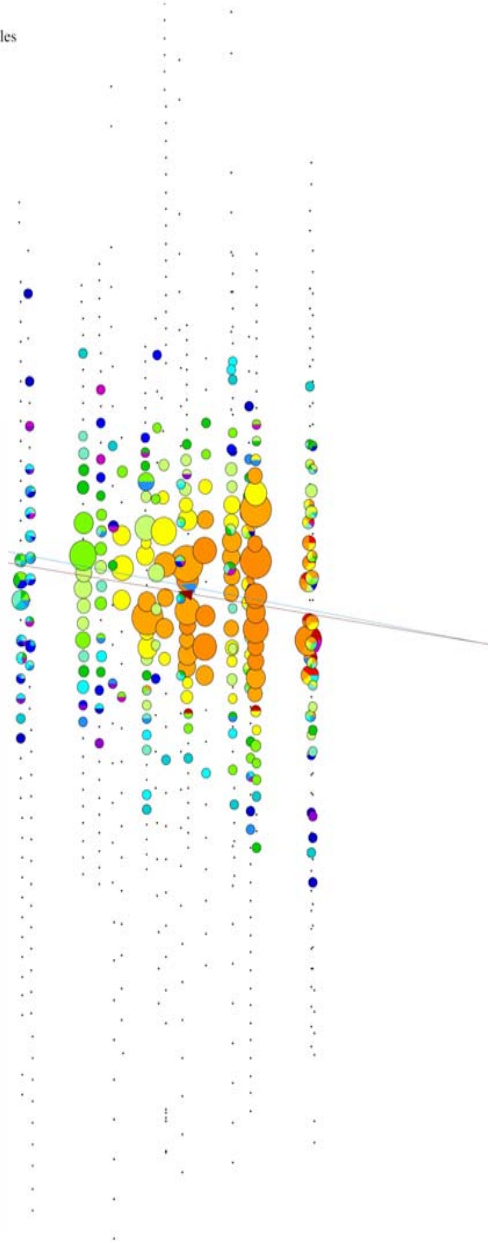
no indication of clustering at higher energies

increasing energy deposition

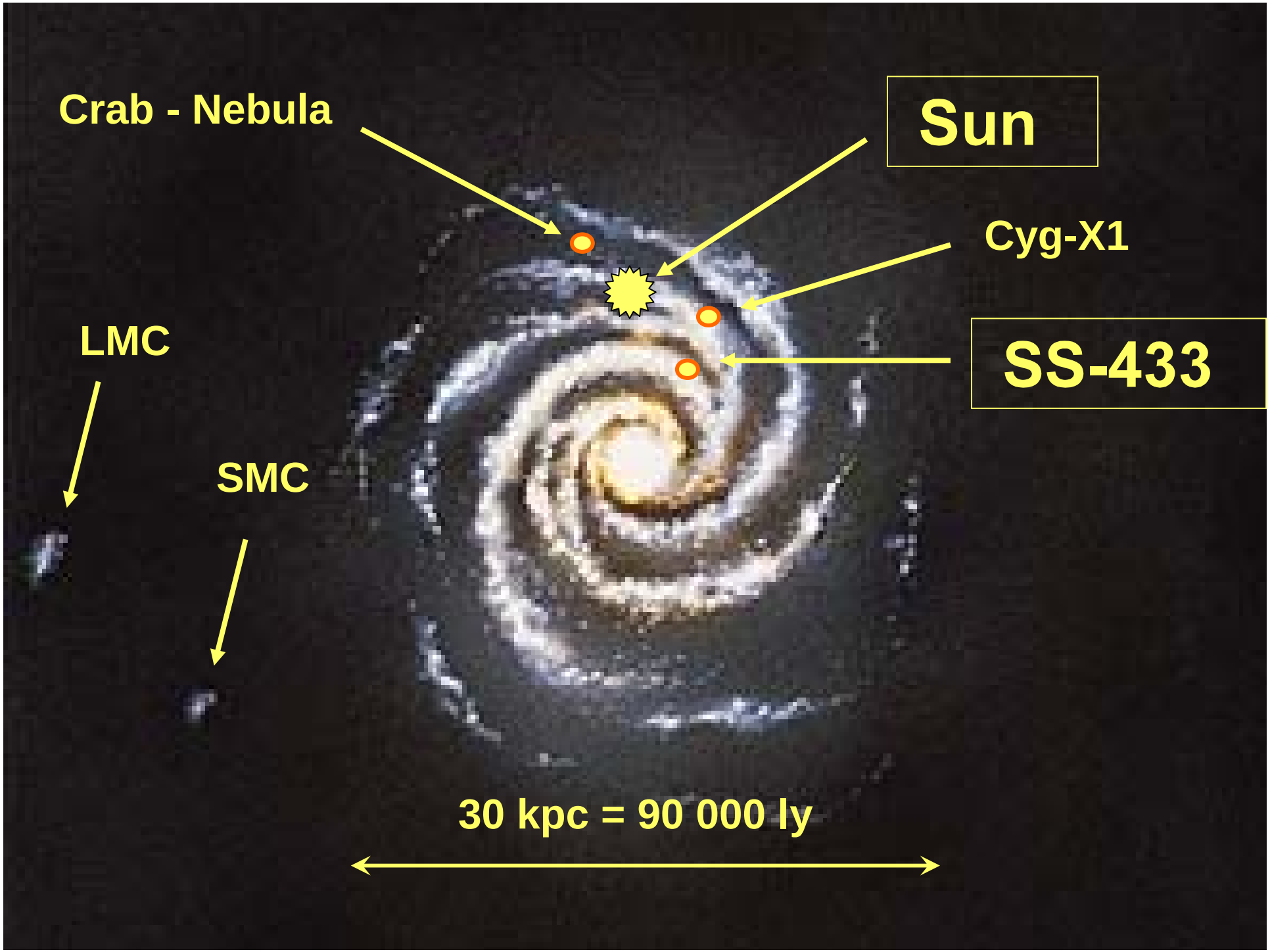


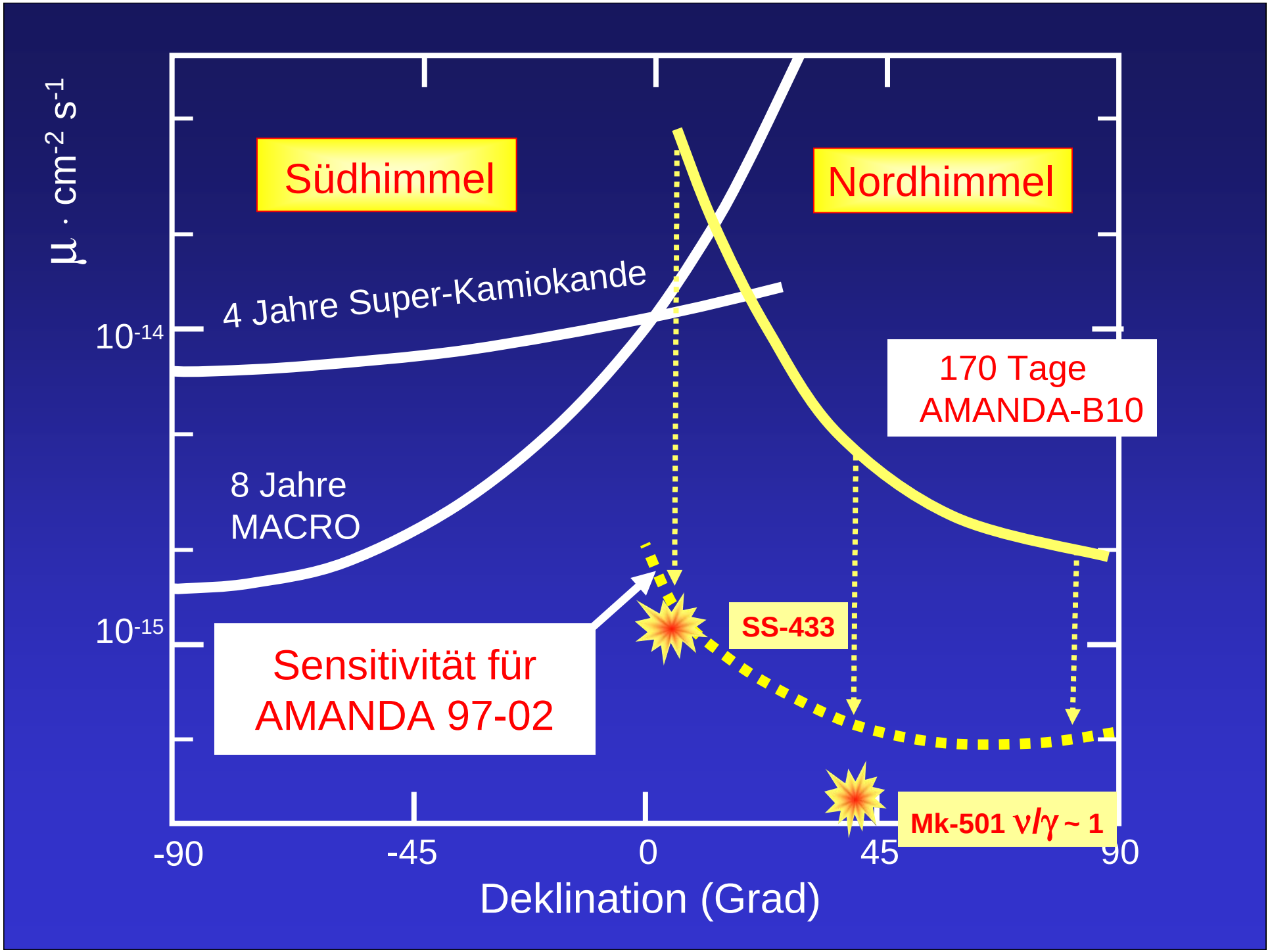
No external geometry file is opened.
Detector: amanda-b-10, 19 strings, 680 modules
Data file: final_deff_nch-gt-115.2.f2k
File contains 6 events.
Displaying data event 4028316 from run 349
Recorded yr/dy: 2000/184
8107.1548870 seconds past midnight.
Before cuts: 497 hits, 232 OMs
After cuts : 497 hits, 232 OMs





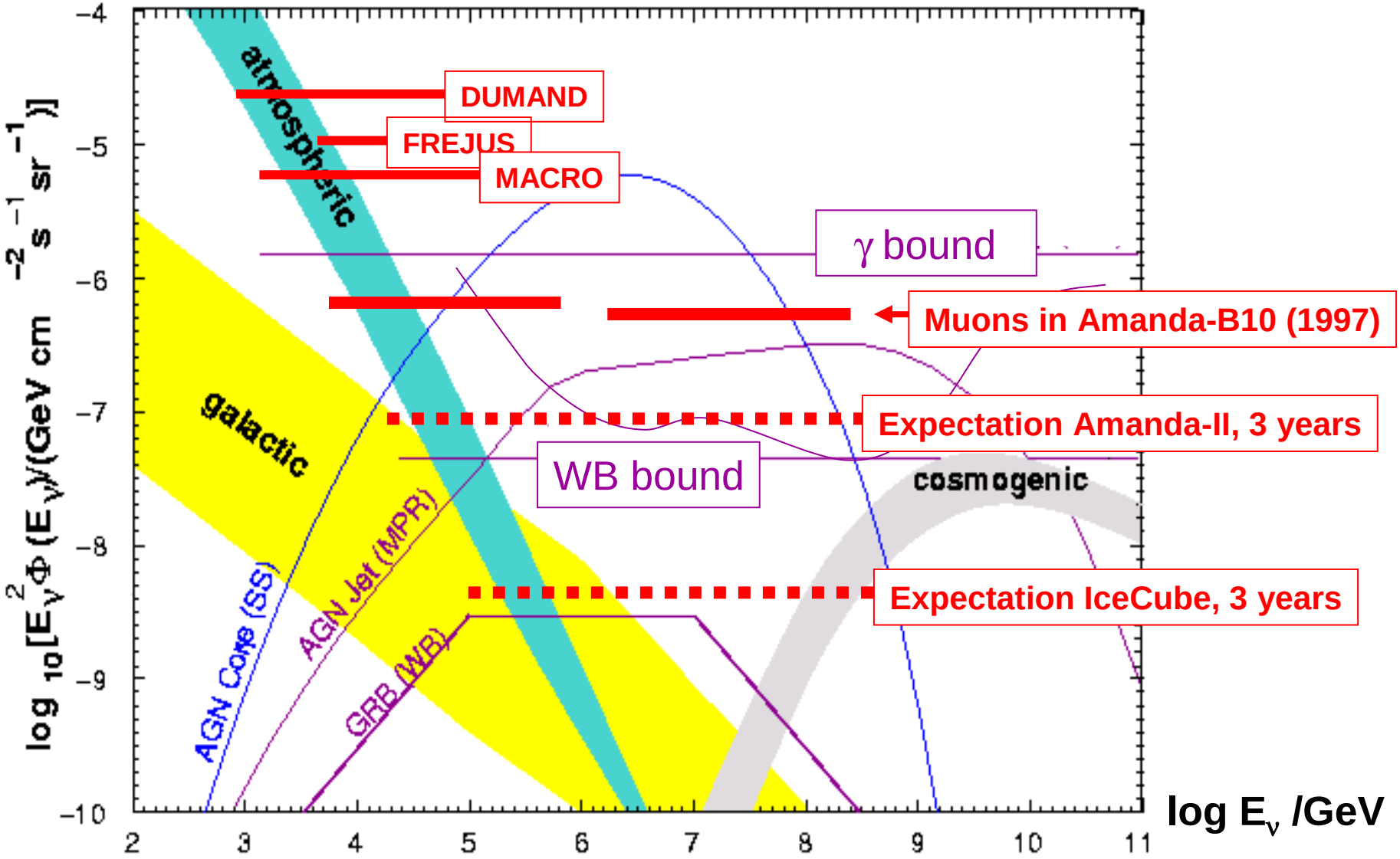
SS-433


Crab - Nebula
Sun
Cyg-X1
SS-433
LMC
SMC
30 kpc = 90 000 ly

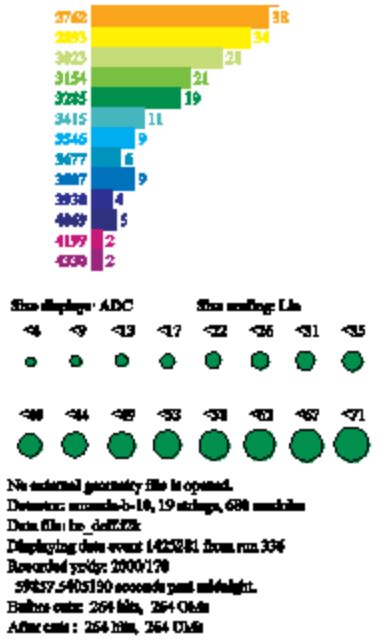

μ · cm-2 s-1
10-14
10-15
Südhimmel
Nordhimmel
4 Jahre Super-Kamiokande
8 Jahre
MACRO
170 Tage
AMANDA-B10
Sensitivität für
AMANDA 97-02
SS-433
Mk-501 ν/γ ~ 1
-90
-45
0
45
90
Deklination (Grad)

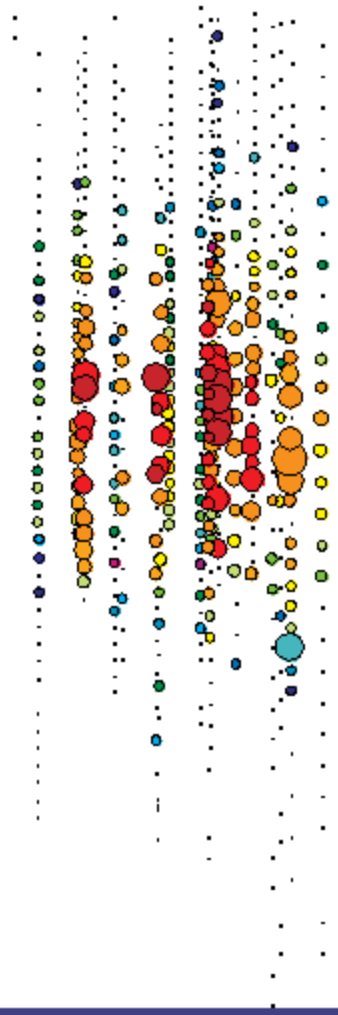
Search for a Diffuse Extraterrestrial Flux

Search for diffuse excess of extra-terrestrial high energy neutrinos

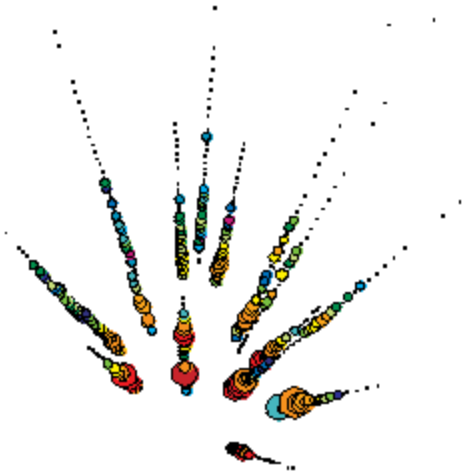


The highest energy event (200 TeV)





300 m



All-flavor limits

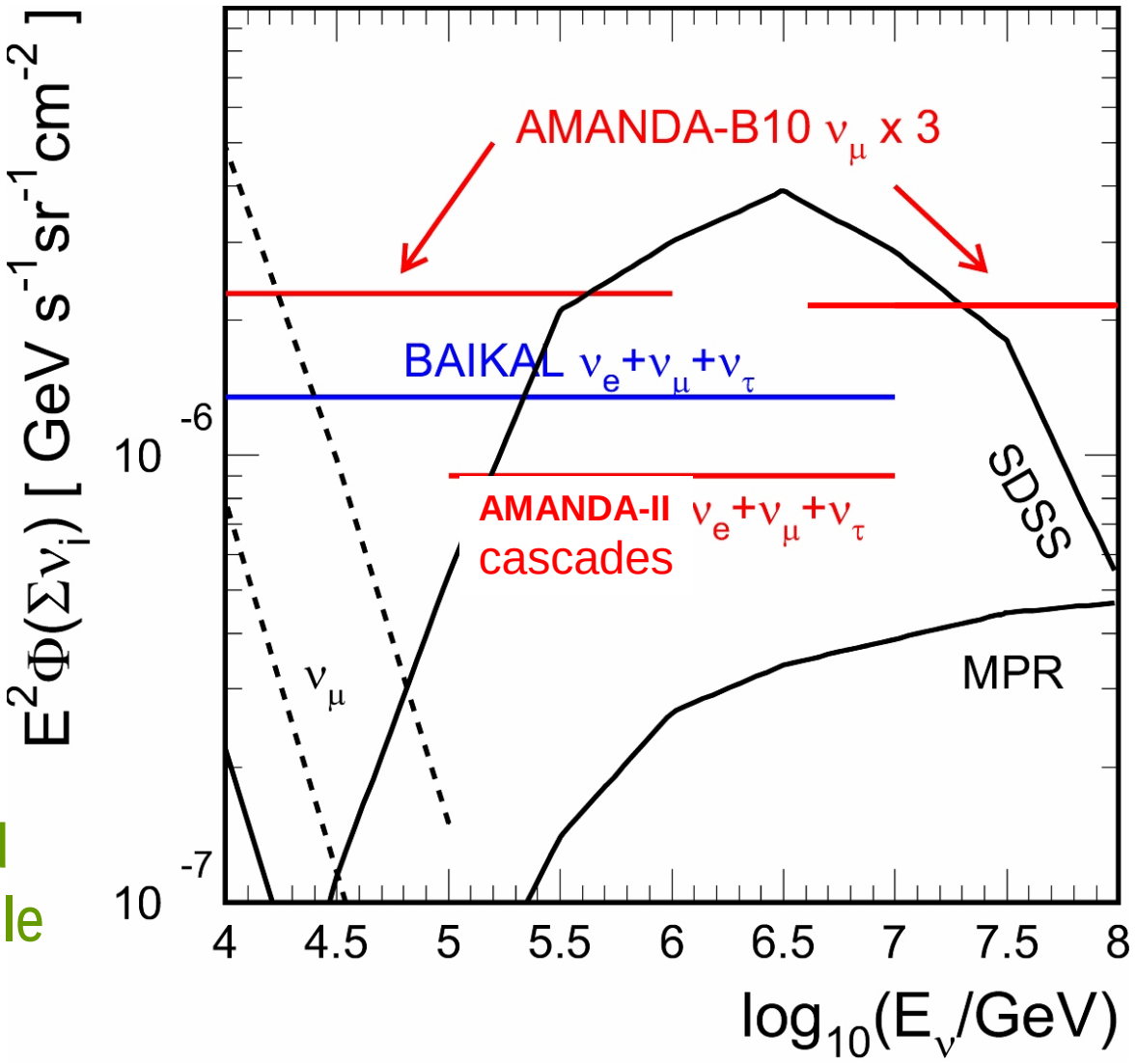
Assuming

$\nu_e:\nu_\mu:\nu_\tau$ *=1:2:0 at source*

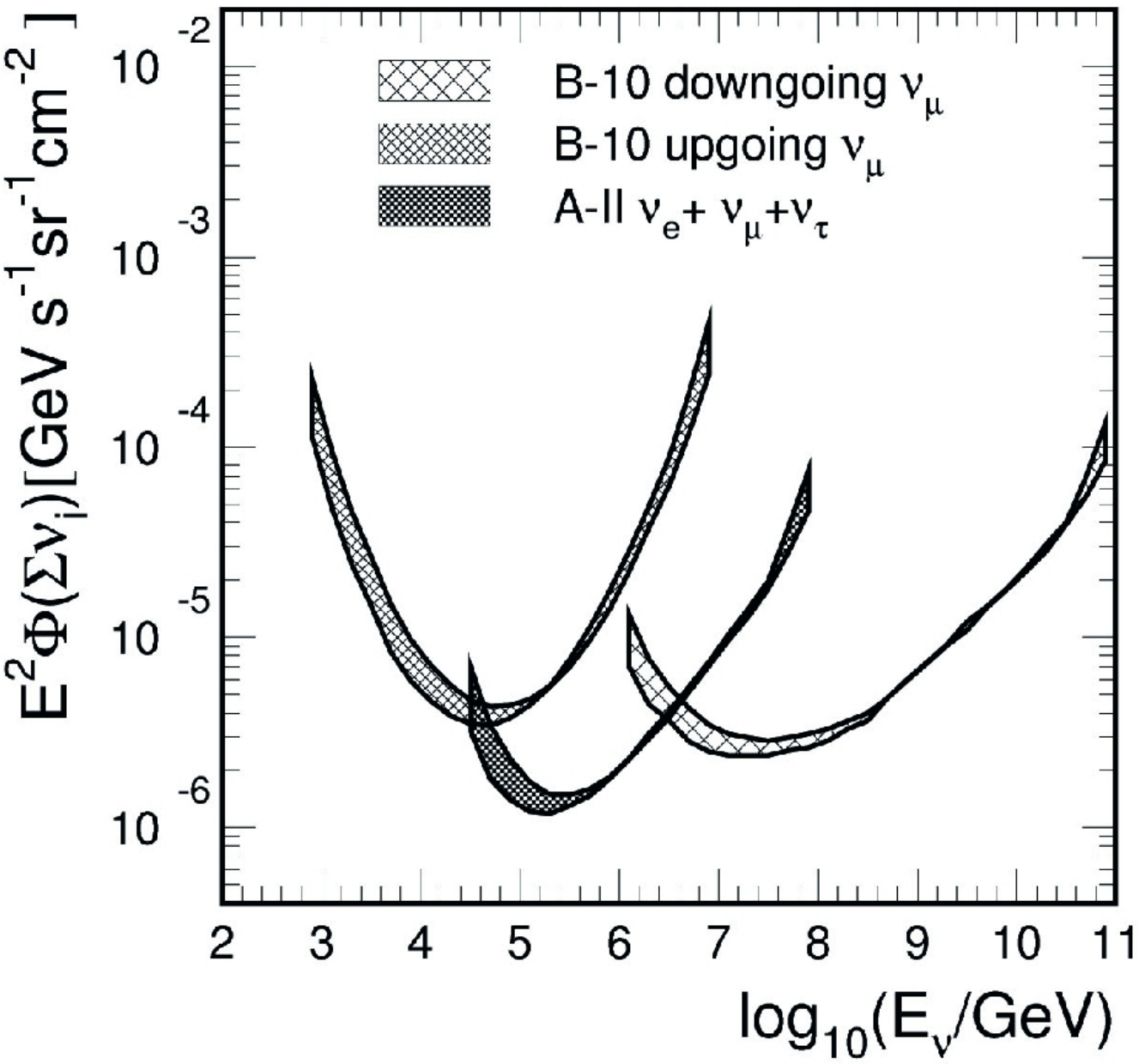
$\nu_e:\nu_\mu:\nu_\tau$ *=1:1:1 at Earth*

factor 3 applied to ν_μ channel

2000 ν_μ analysis will yield all-flavour limit comparable to cascade limit

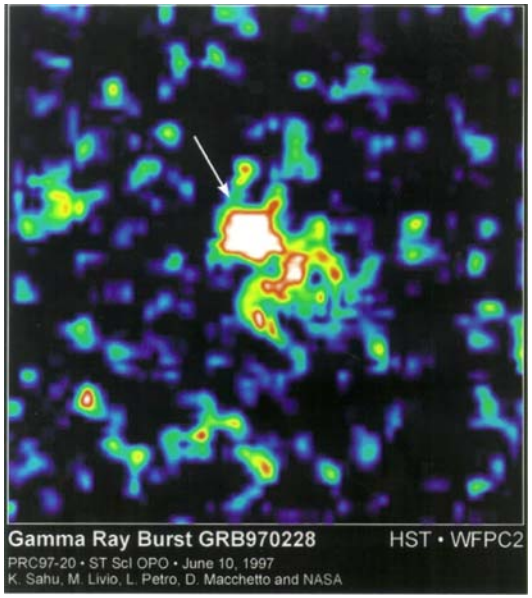


Differential all-flavor limits

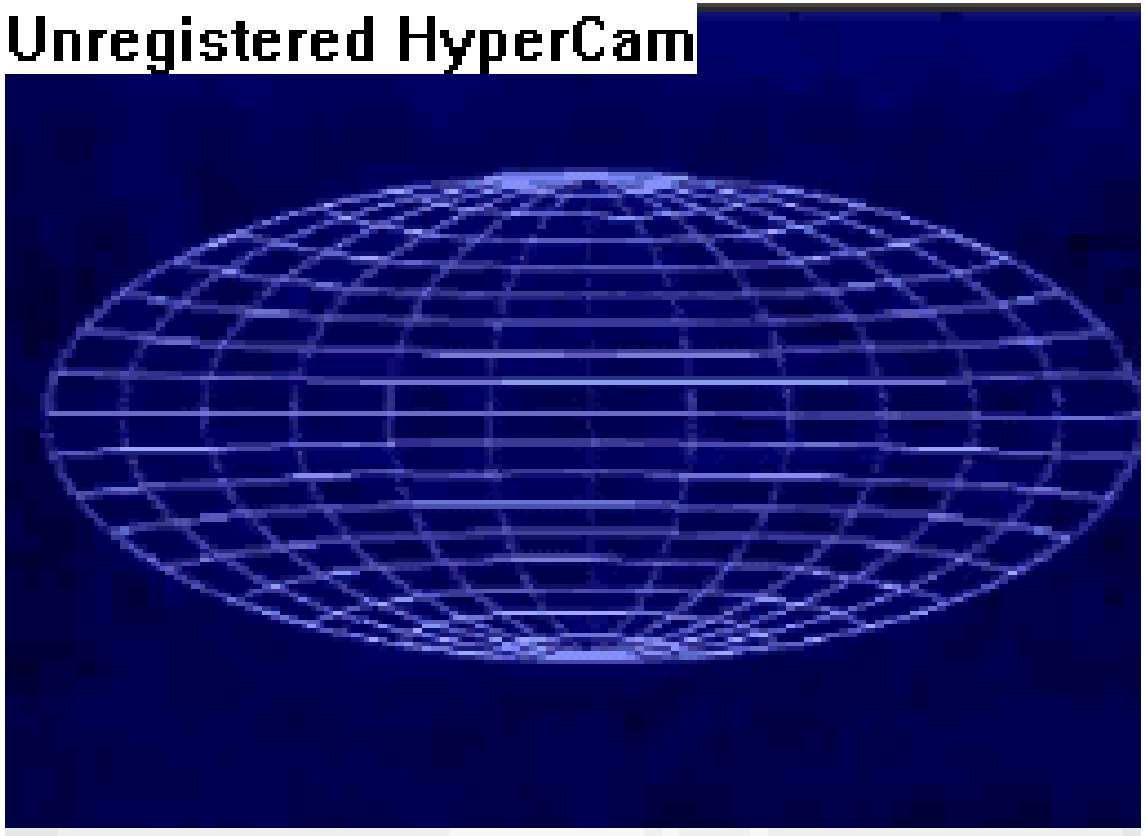


Neutrinos from Gamma Ray Bursts ?

1969

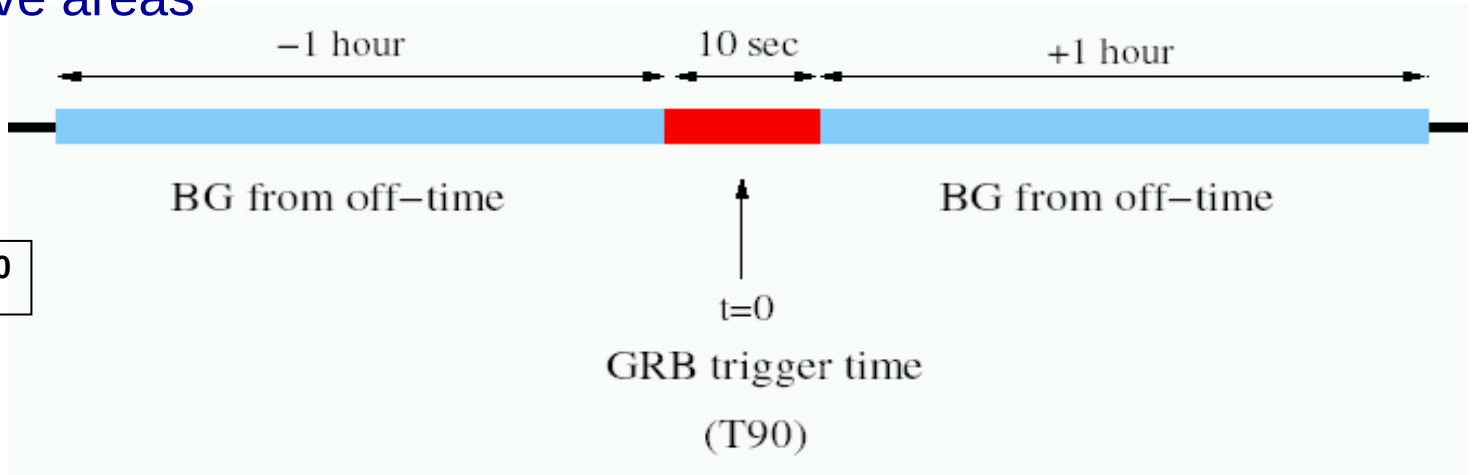


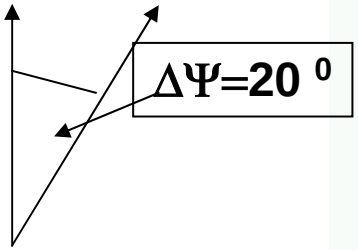
1997



BATSE: 1991-2003

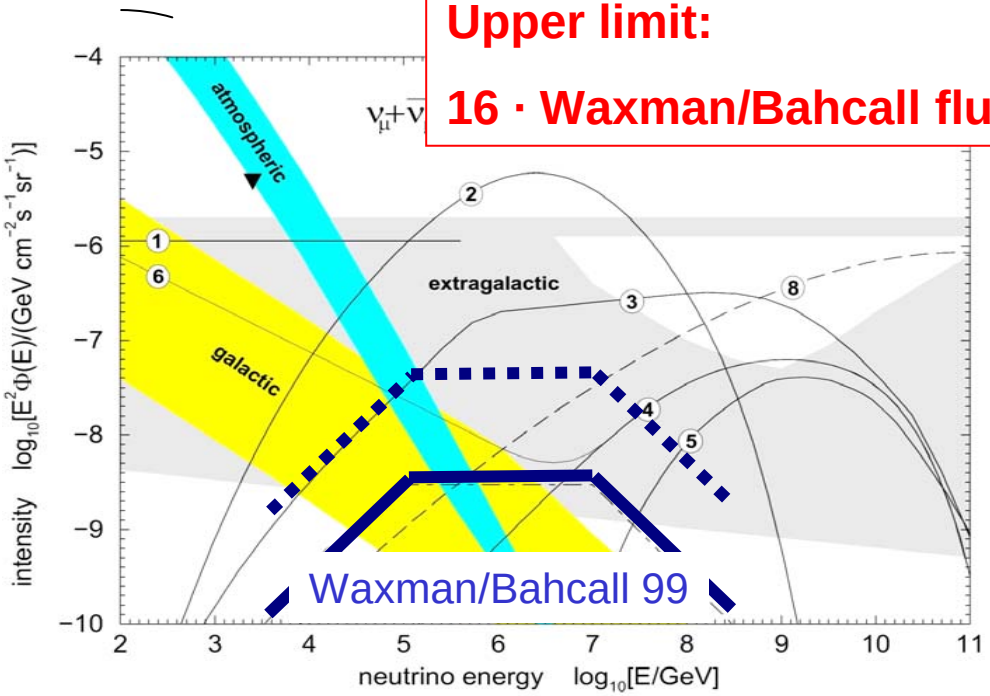
- Low background (due narrow time and space coincidence)
- Large effective areas





Upper limit:

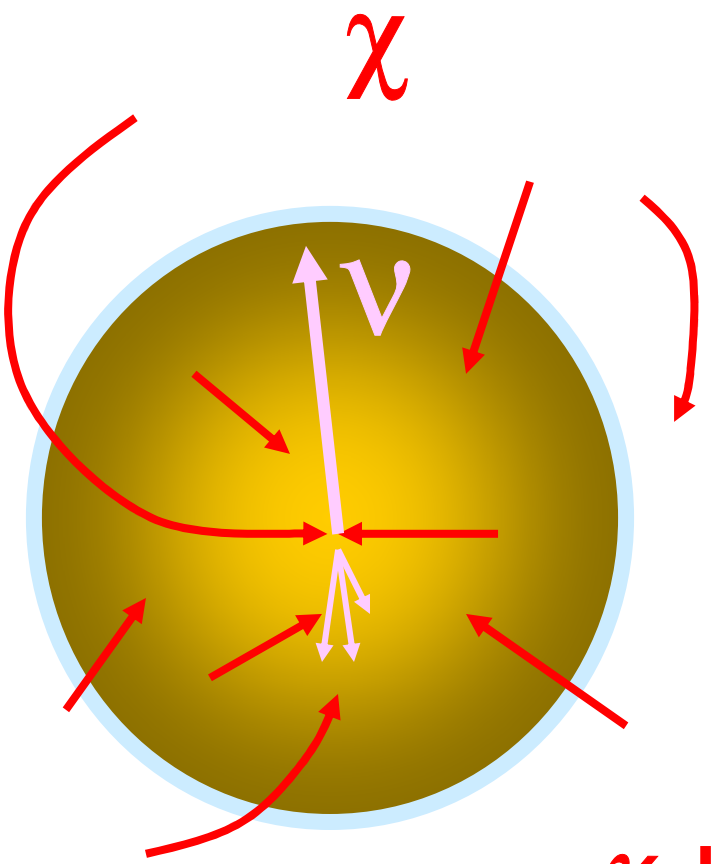
16 · Waxman/Bahcall flux



Year	# of GRB	Bkgd	seen events
1997	78	0.06	0
1998	99	0.20	0
1999	96	0.20	0
2000	44	0.40	0
Total	218	0.86	0

Indirect WIMP search

1. Neutrinos from the Center of Earth



Assumptions:

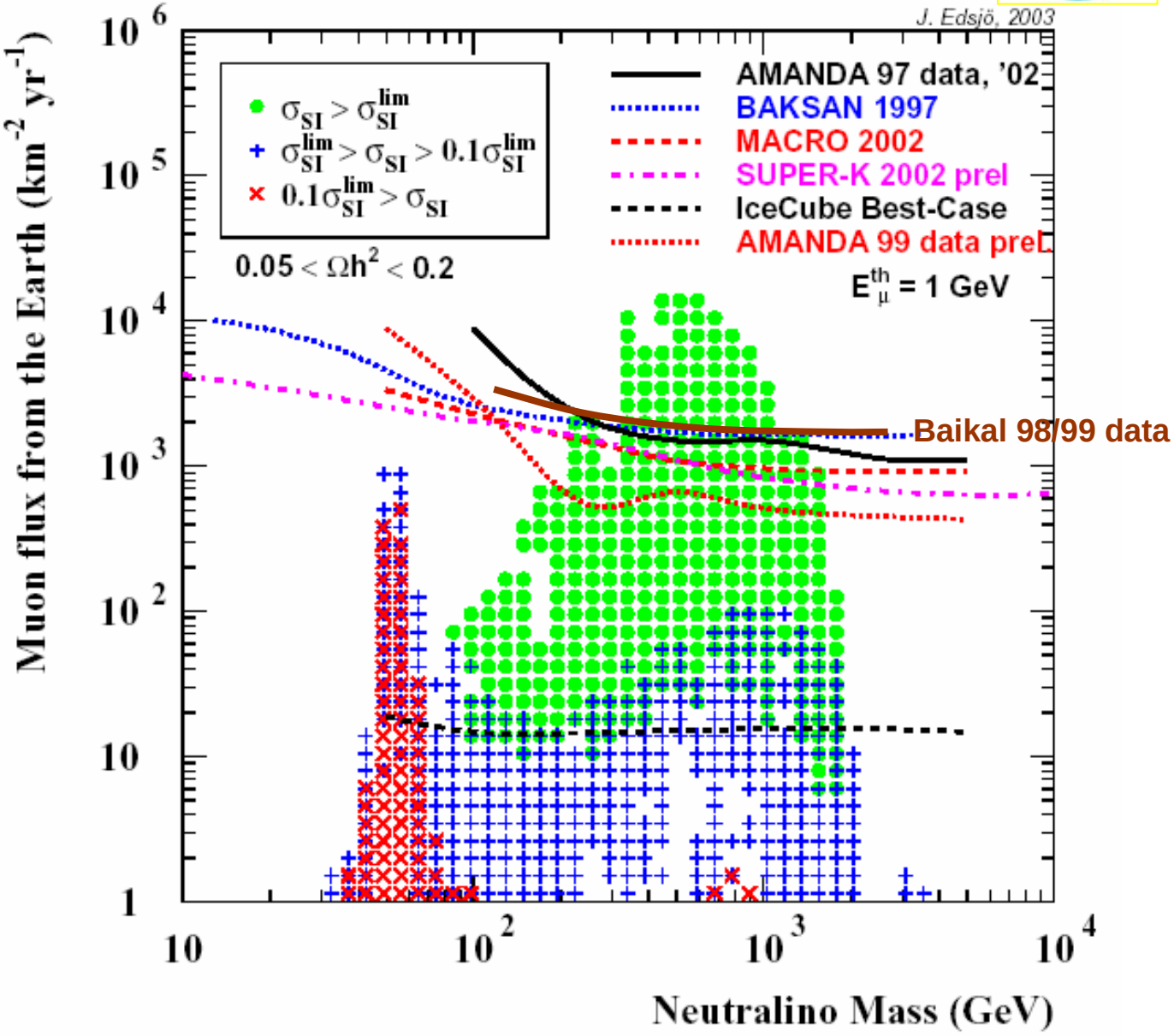
- Dark matter in Galaxy due to neutralinos
- Density ~ 0.3 GeV/cm^3

$$\chi + \bar{\chi} \rightarrow b + \bar{b}$$

$$\downarrow$$

$$c + \mu + \nu_\mu$$

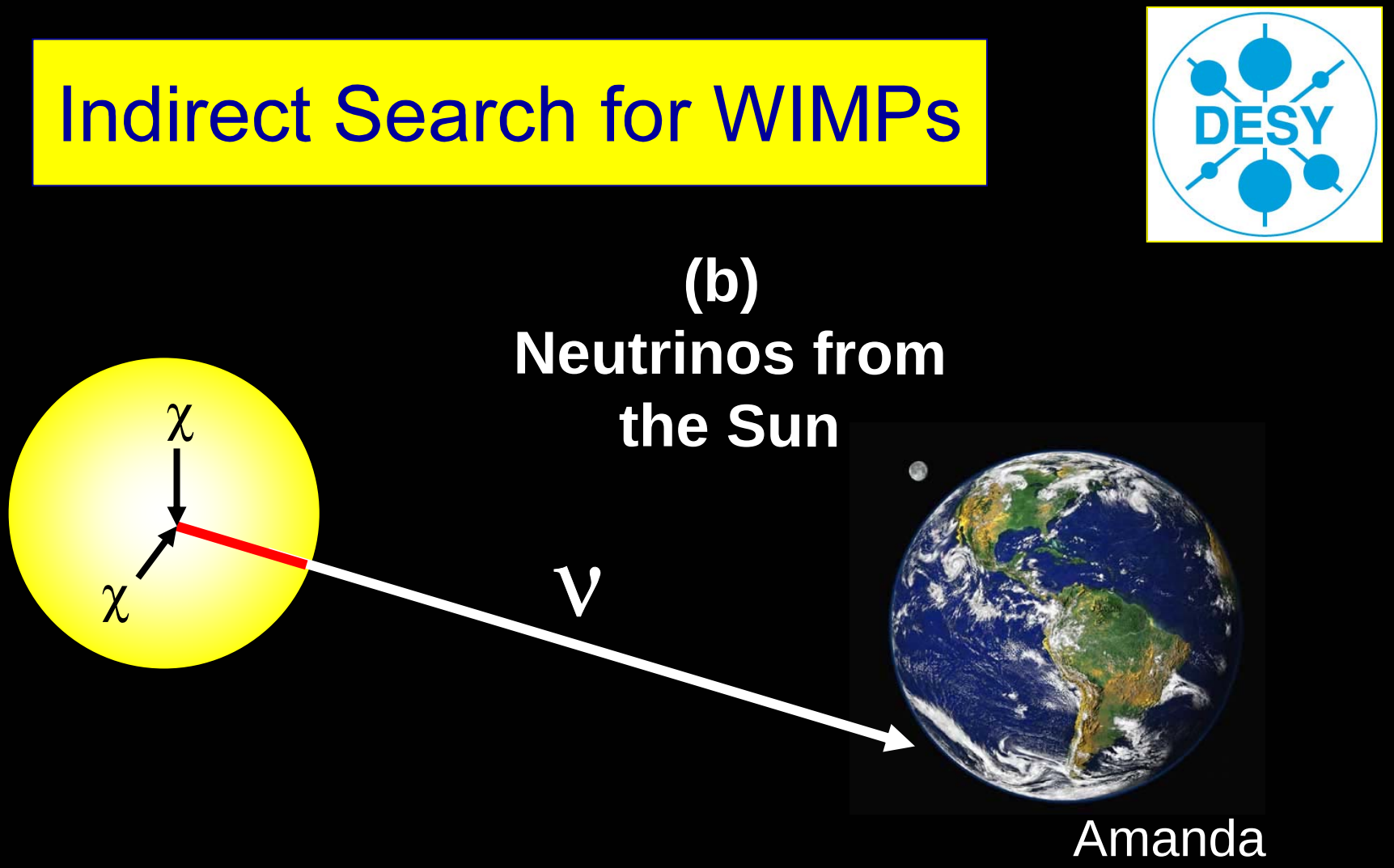
Upper limits on muon flux from neutralino annihilations in center of Earth



Green dots:
Excluded by present direct searches

Blue crosses:
can be excluded by 10 times more sensitive direct searches

Indirect Search for WIMPs



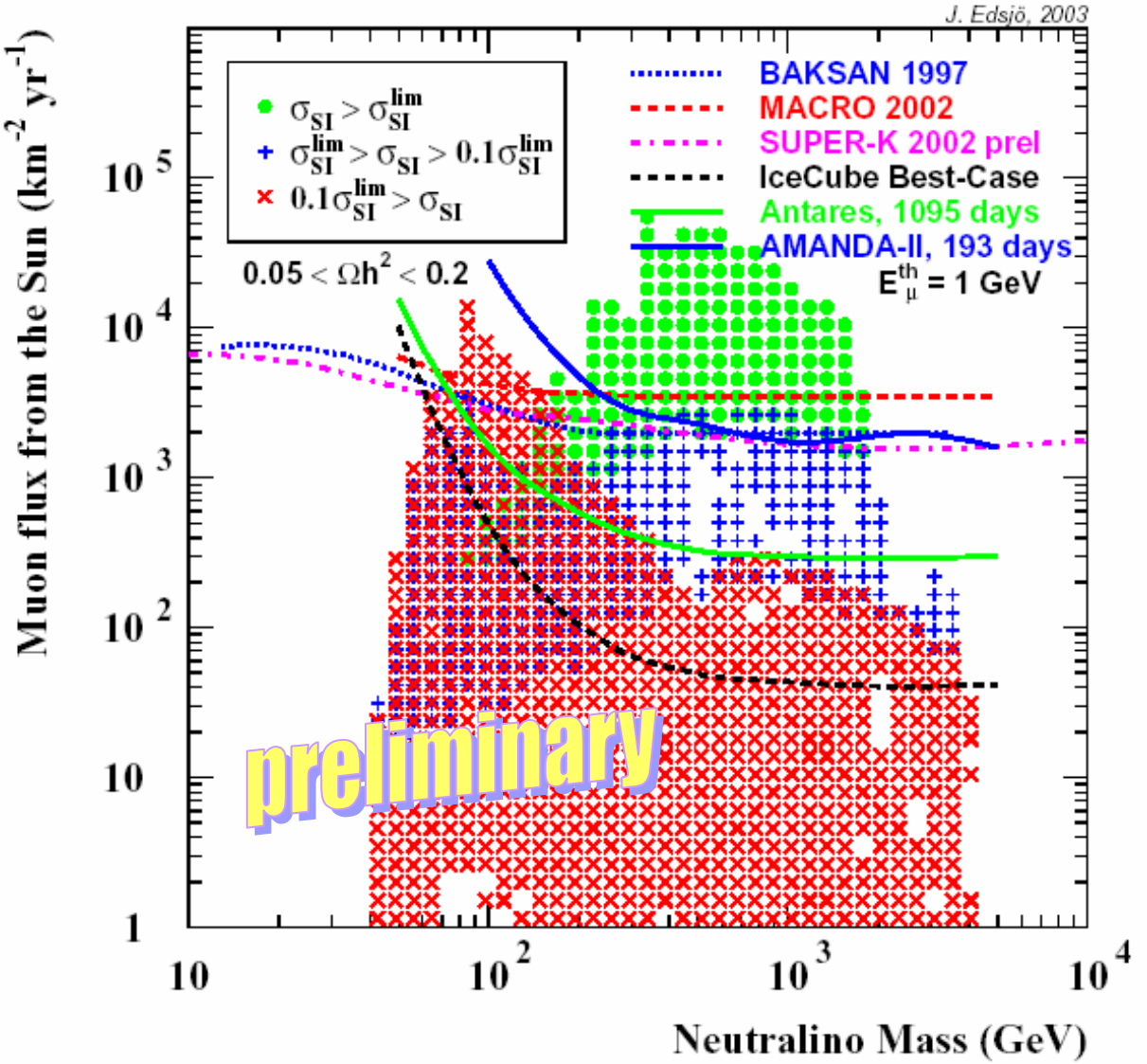
At South Pole the Sun sinks maximally 23° below horizon. Therefore only Amanda-II with its dramatically improved reconstruction capabilities for horizontial tracks (compared to Amanda-B10) can be used for solar WIMP search.

Upper limits on muon flux from neutralino annihilations in center of Sun

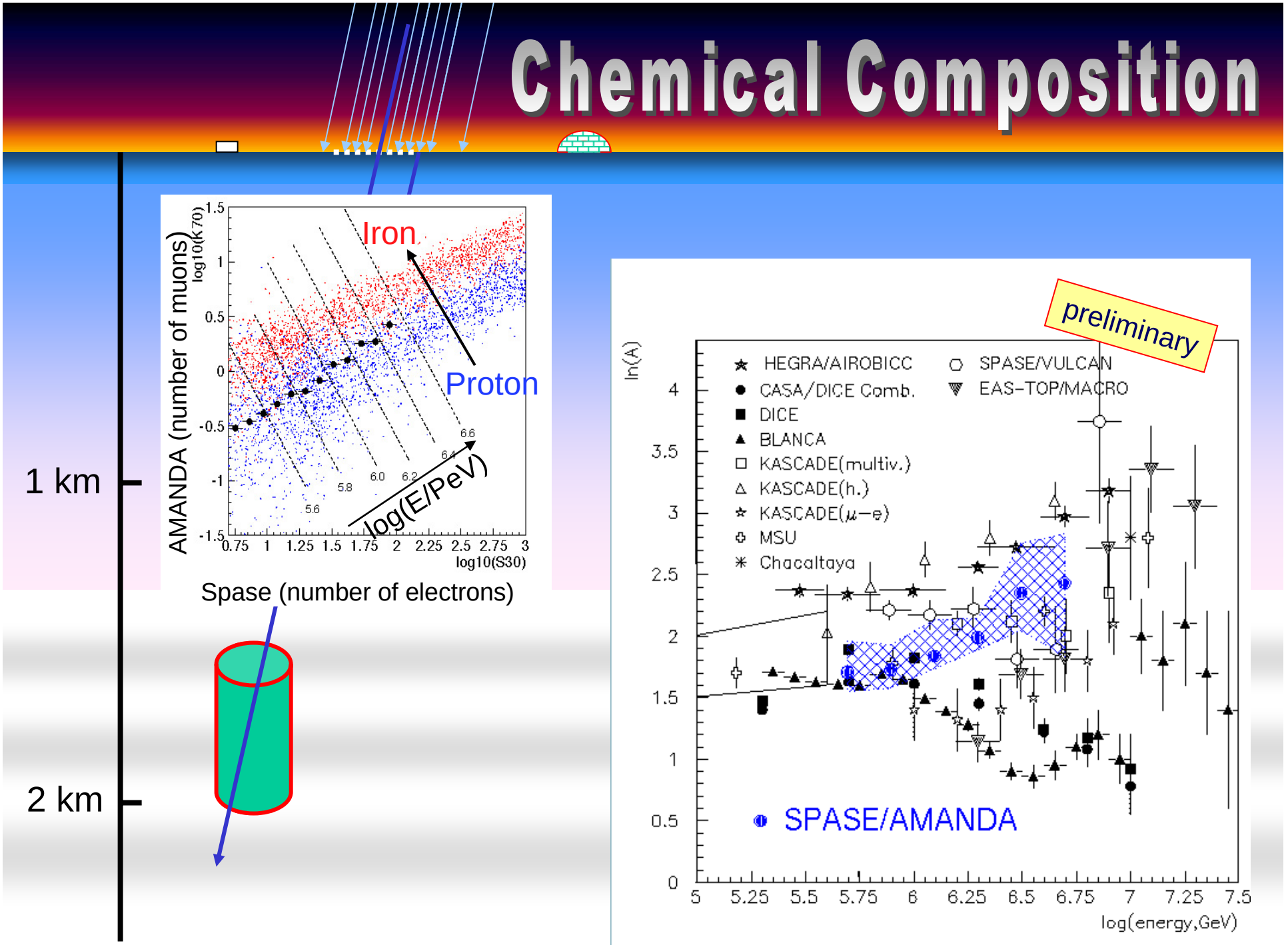
AMANDA-II results:

- based on 193 days of live time
- Exclusion sensitivity from analyzing the off-source bins
  →Will un-blind data soon and look to the Sun.

ANTARES and ICECUBE: MC-calculated sensitivities



Chemical Composition



Schedule and Cost

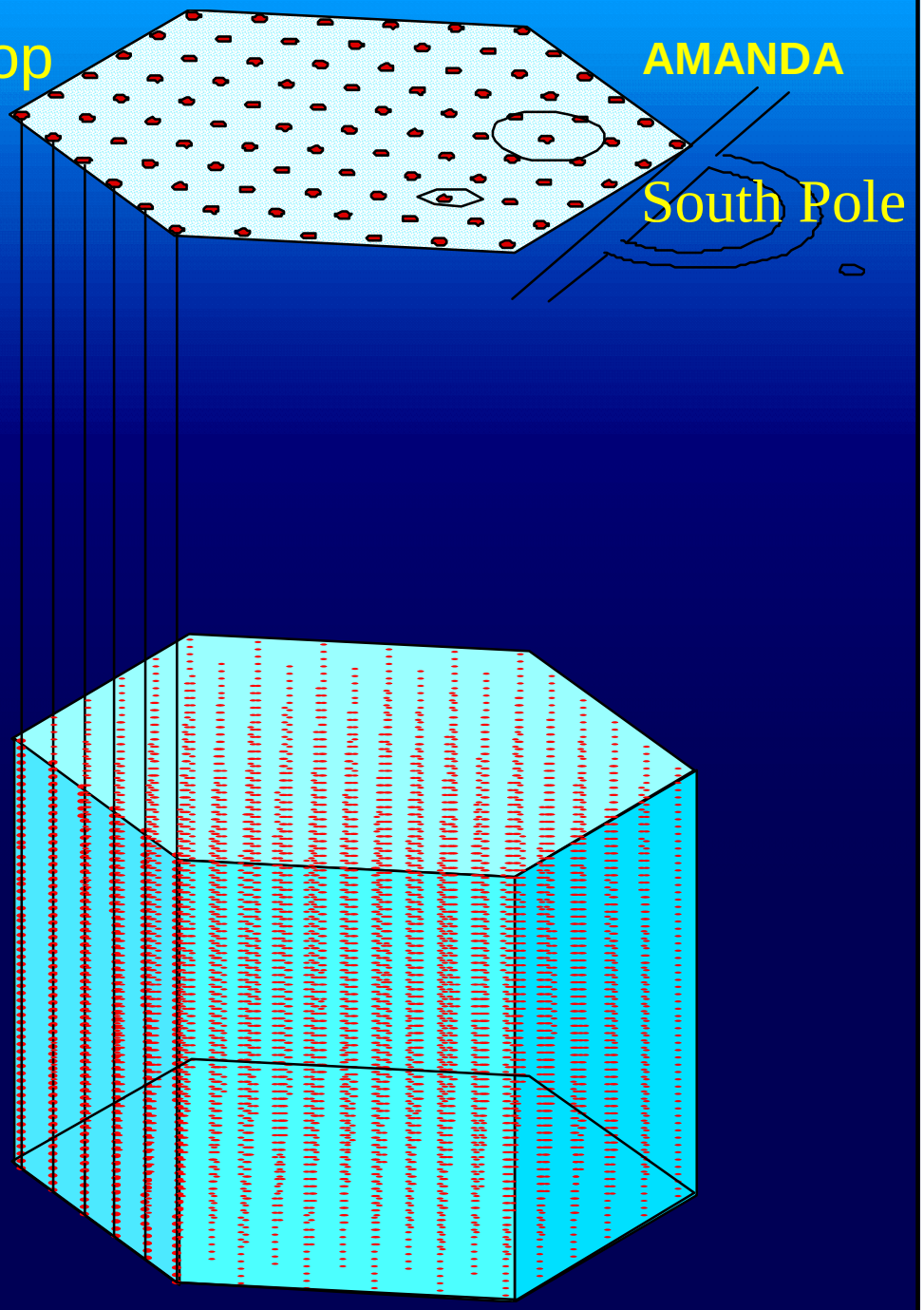
03-04	drill equipment to Pole
04-05	first strings (proof that 16/season are feasible, prepare 10 full strings)
05-06	16 strings
06-07	16 strings
07-08	16 strings
08-09	16 strings
09-10	remaining strings

Overall cost with personnel, contingency, overhead: ~ 250 M$

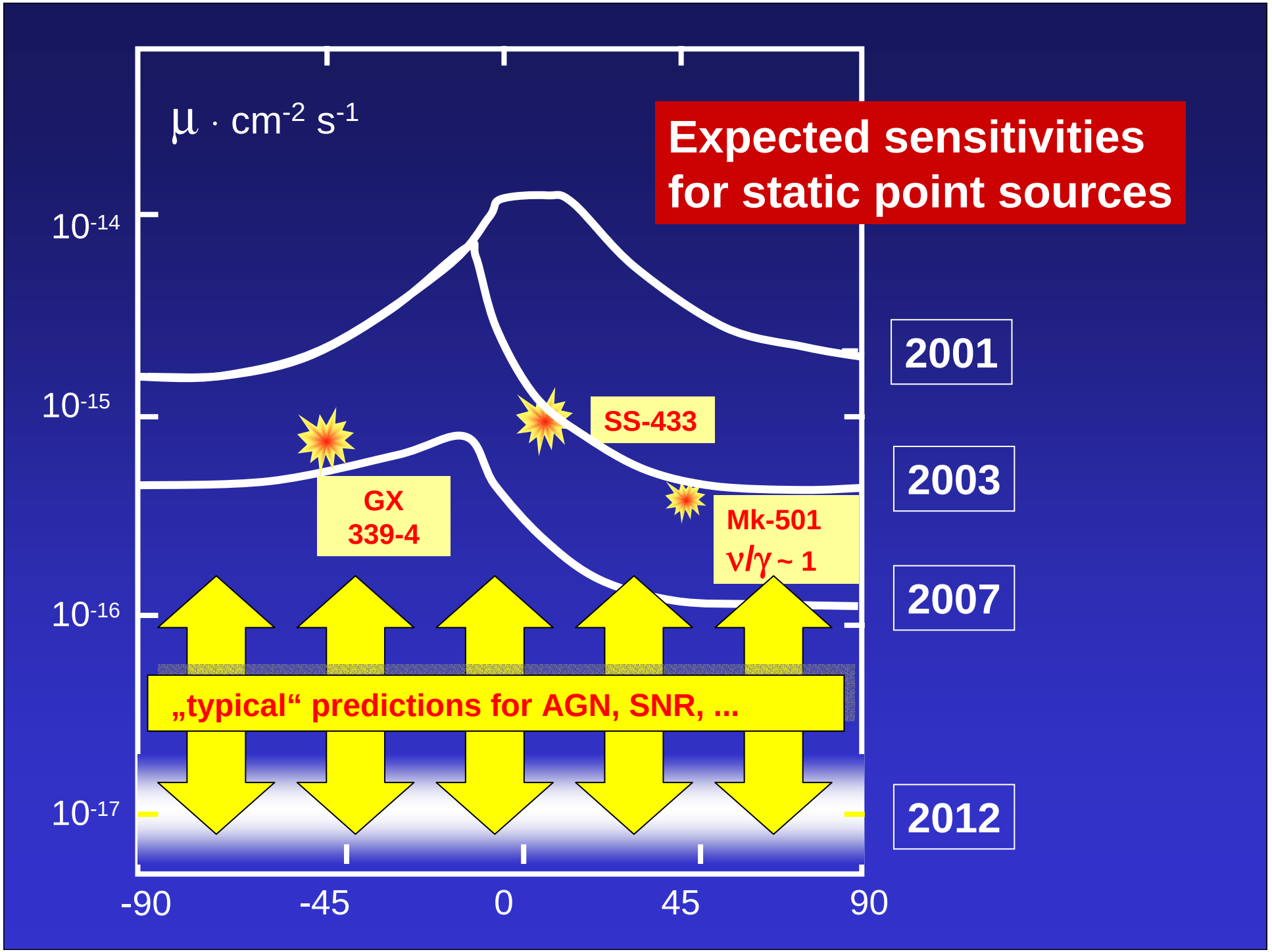
Detector: ~ 55 M$ Logistics, including drilling: ~ 40 M$

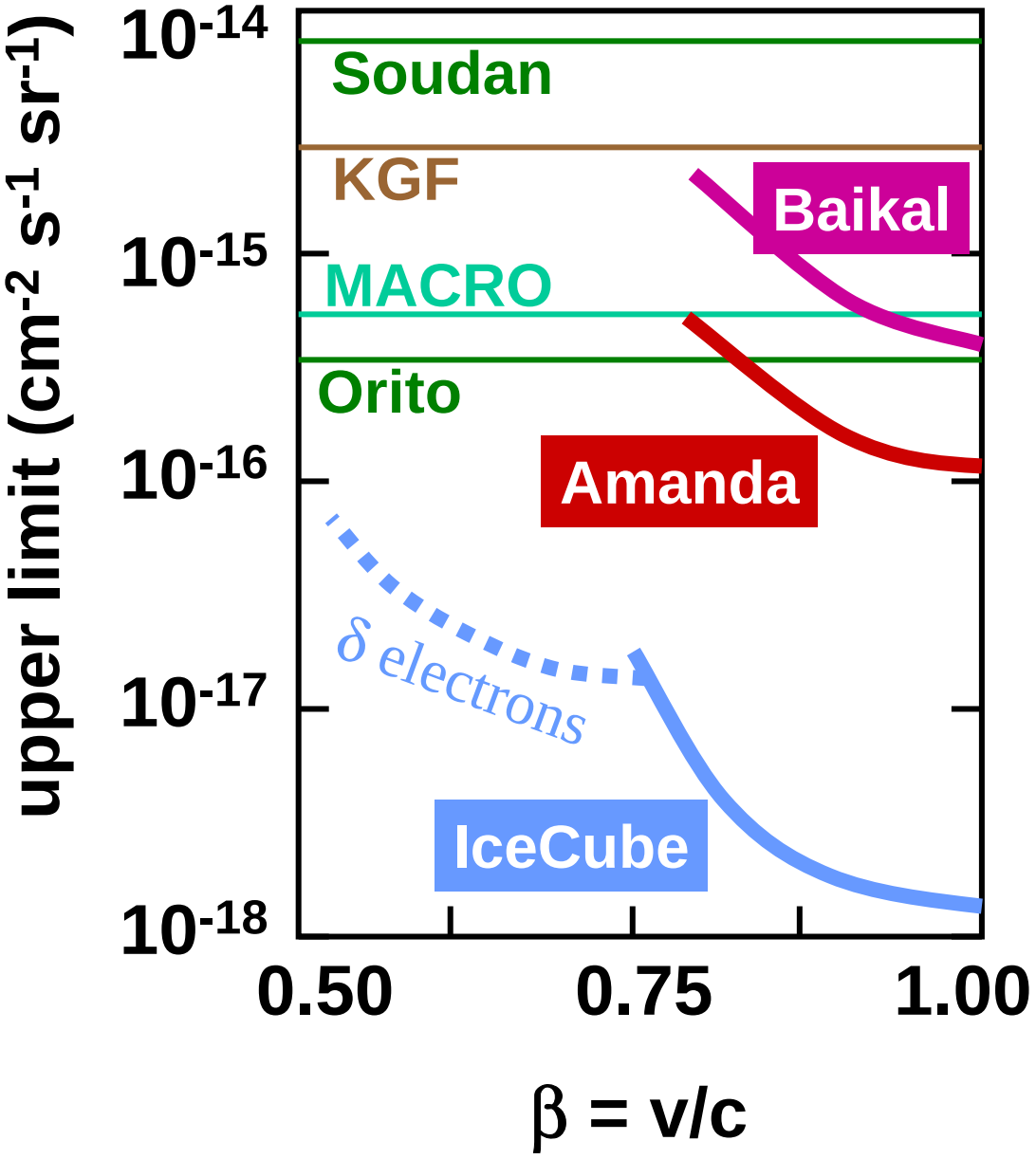
IceCube

- 80 Strings
- 4800 PMTs
- Instrumented Volume: 1 km^3
- Installation: 2004-2010



~ 80.000 atm.ν per Jahr


μ · cm-2 s-1
Expected sensitivities
for static point sources
10-14
10-15
10-16
10-17
2001
2003
2007
2012
SS-433
GX
339-4
Mk-501
ν/γ ~ 1
„typical“ predictions for AGN, SNR, ...
-90
-45
0
45
90



Relativistic Magnetic Monopoles

Cherenkov-Light $\propto$ $n^2 \cdot (g/e)^2$

$n = 1.33$

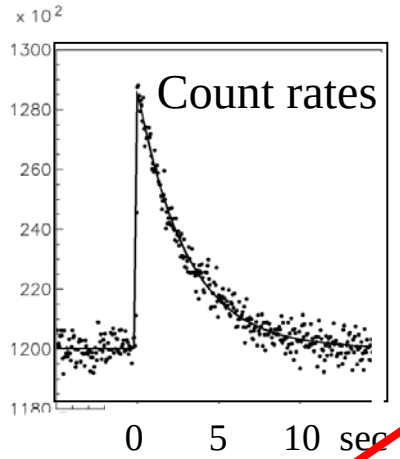
$(g/e) = {}^{137}/_{2}$

≈ 8300

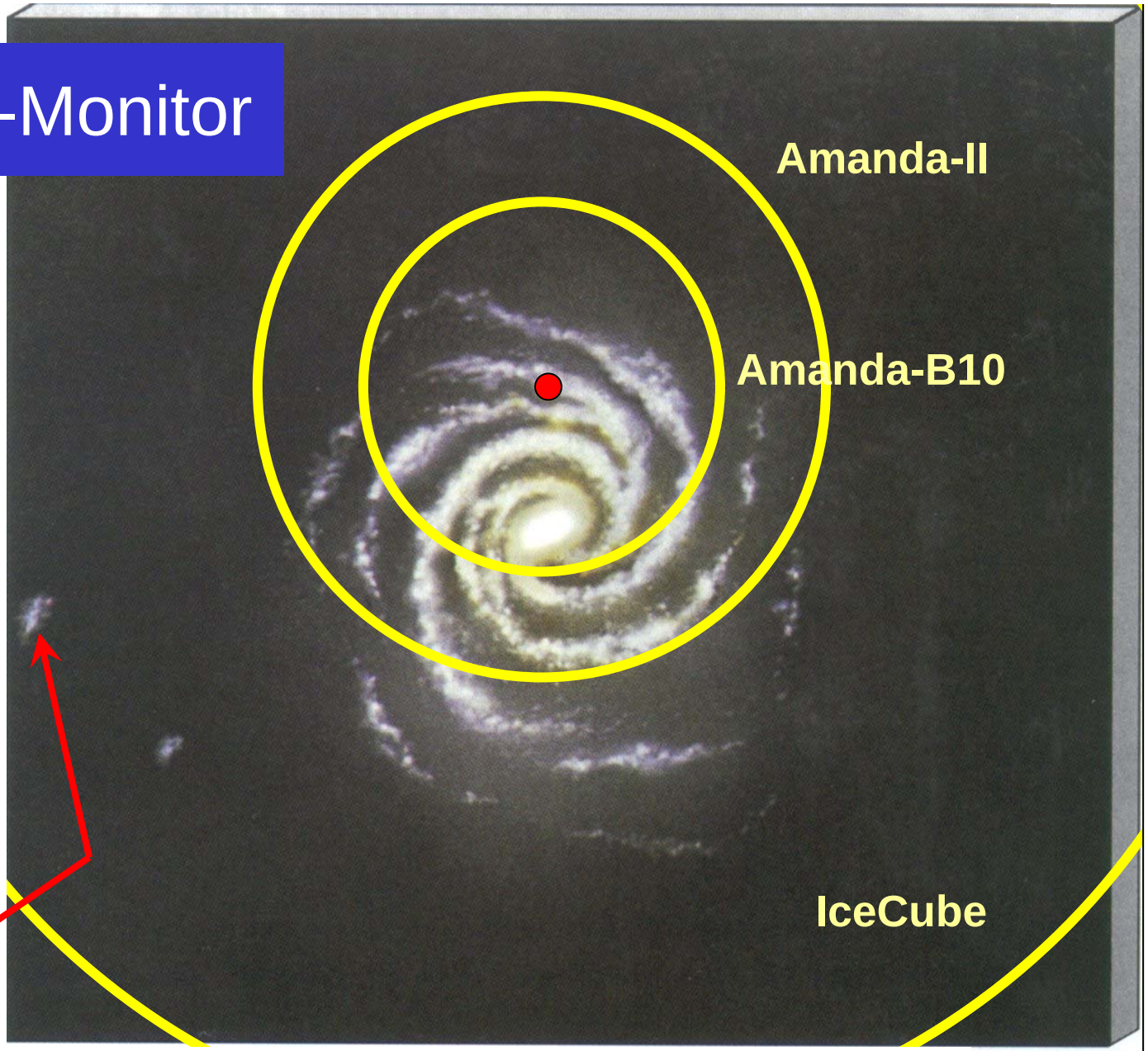
Supernova-Monitor

B10:
60% of Galaxy

A-II:
95% of Galaxy

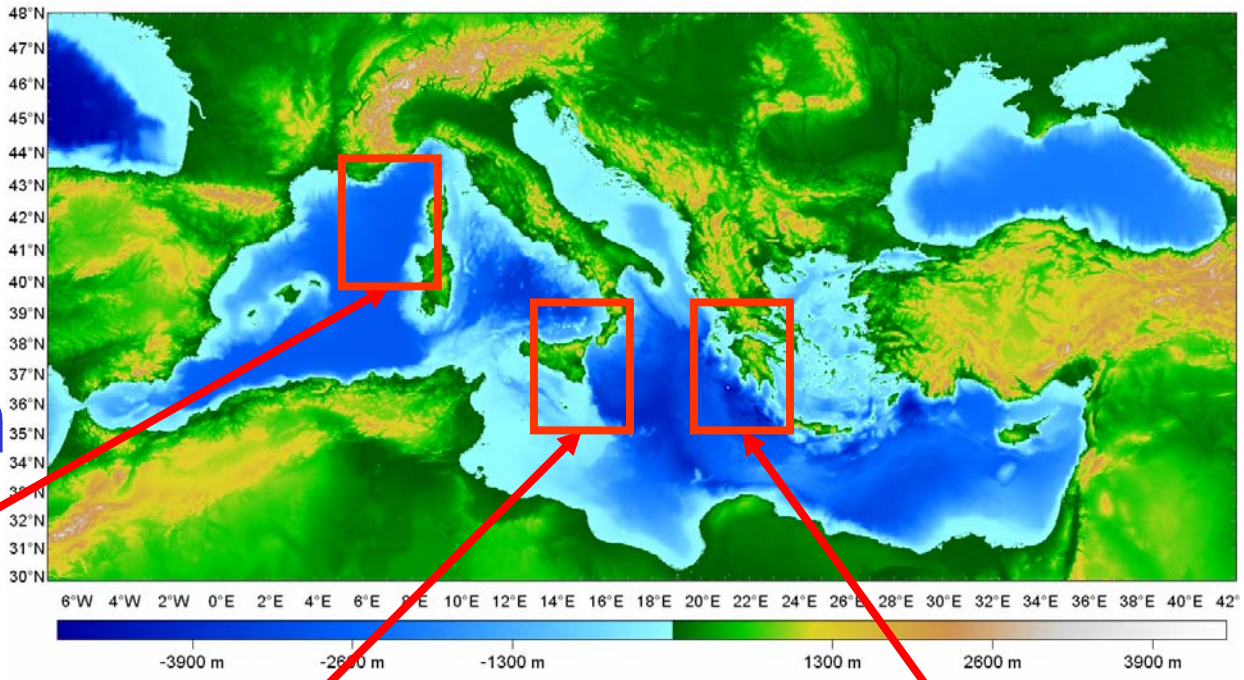


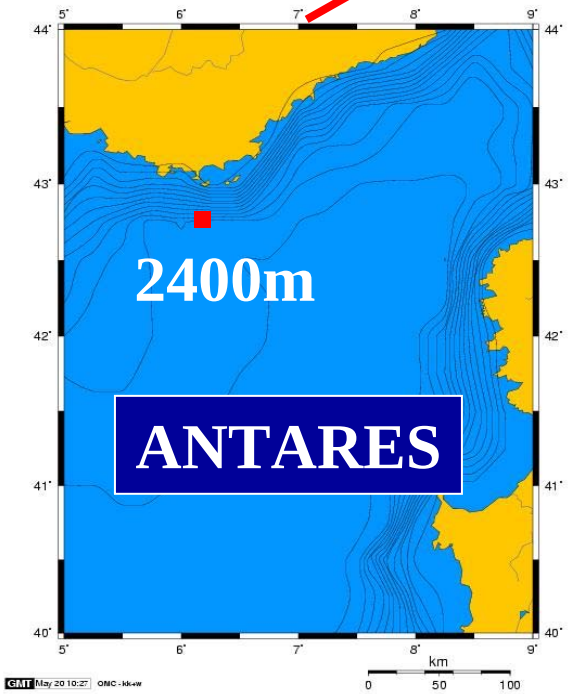
IceCube:
Up to LMC

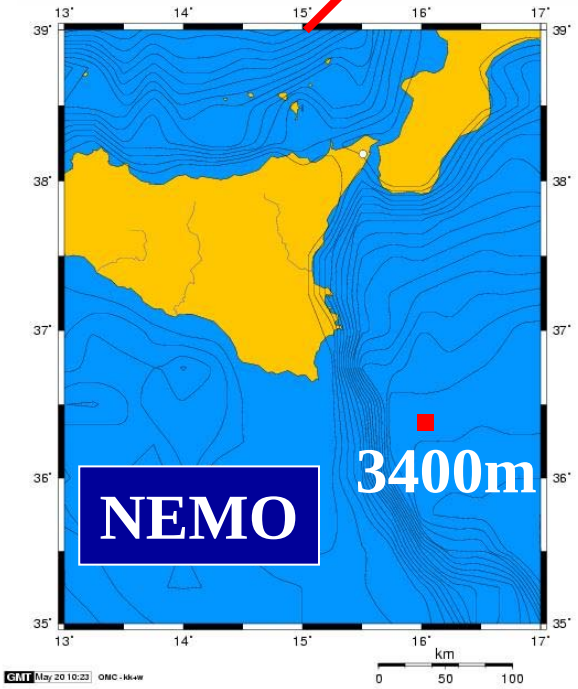


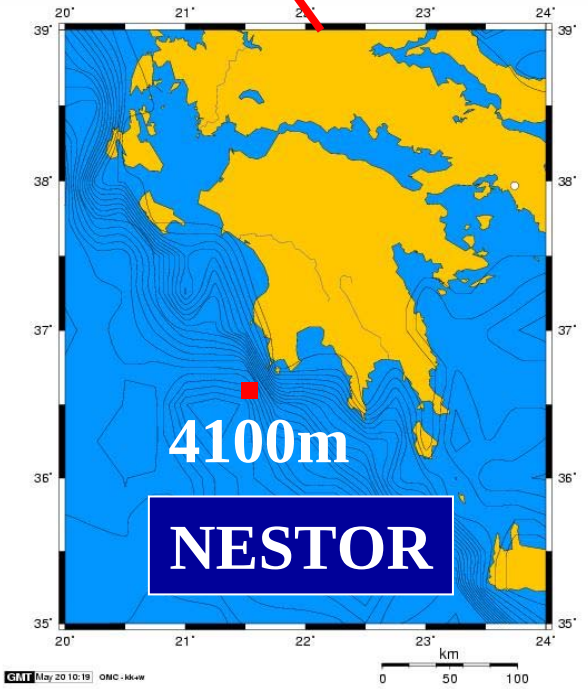
Under construction:

Telescopes in Mediterranean







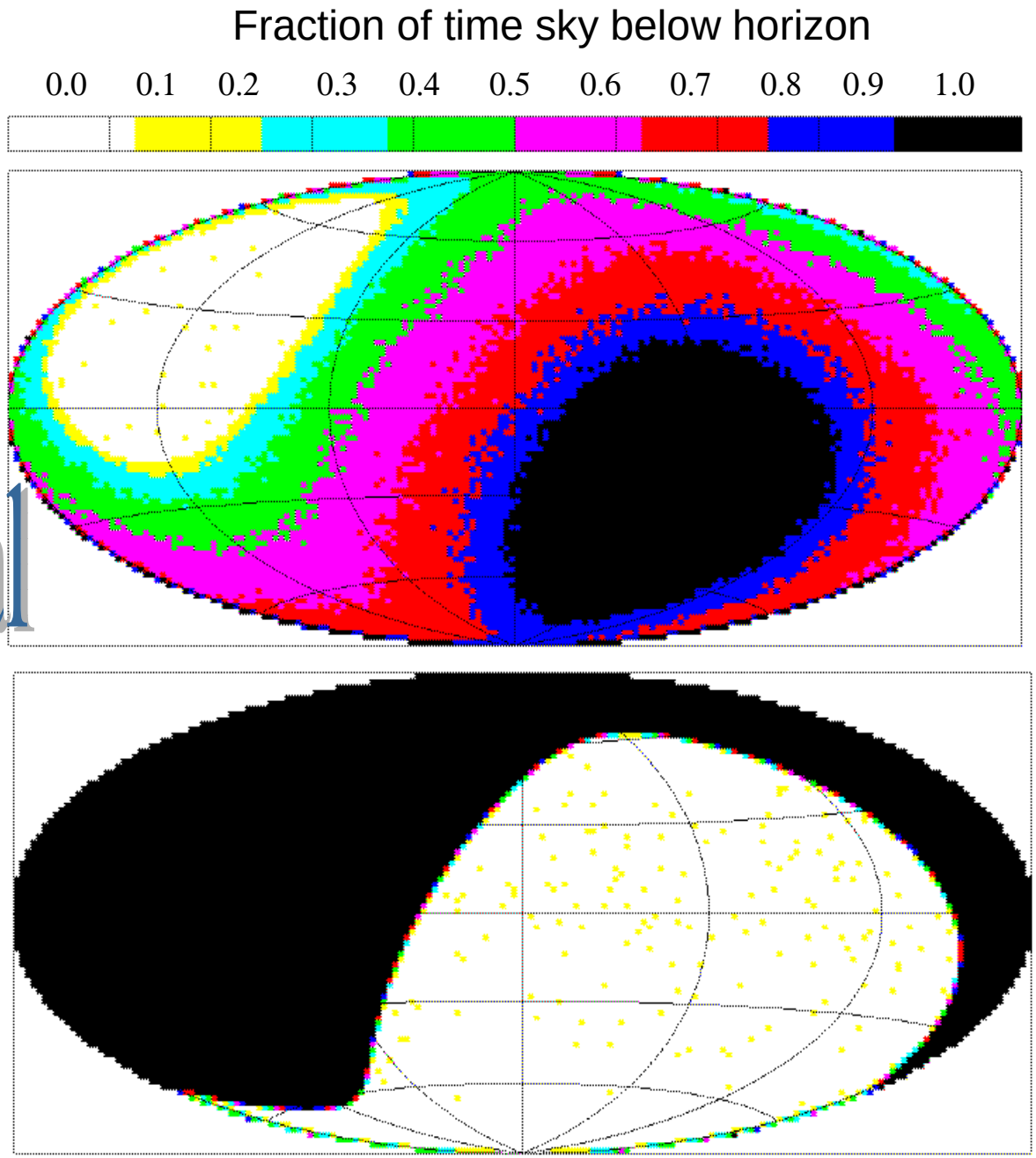


Point sources:

south detector +
north detector

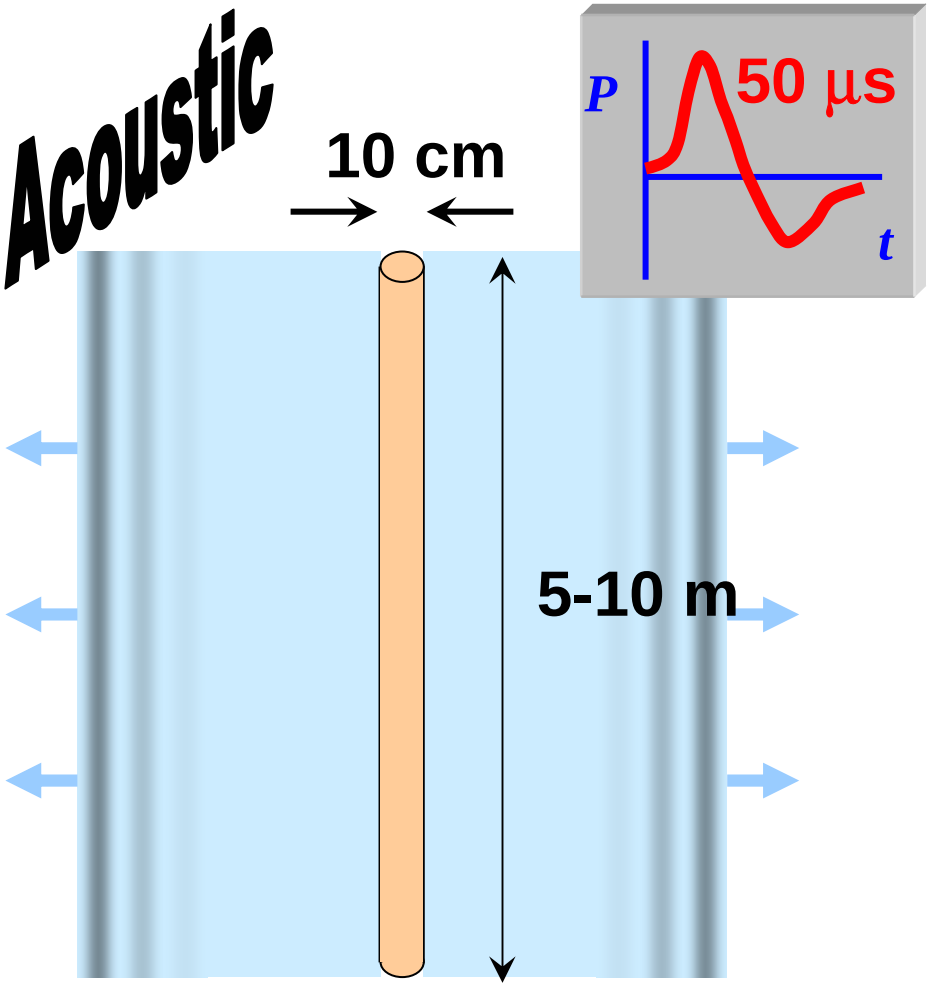
Mediterr./Baikal

South Pole

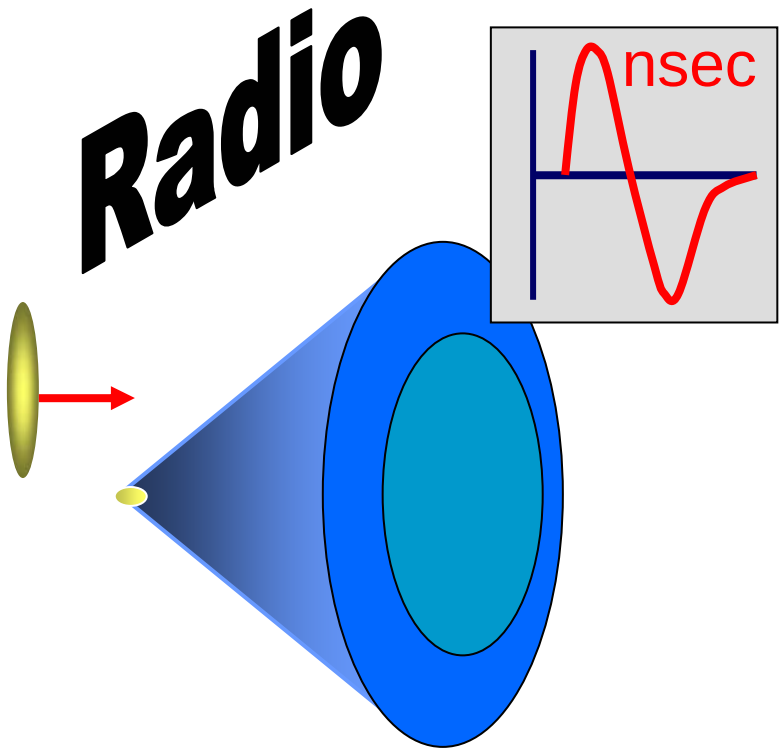


Above 10-100 PeV:

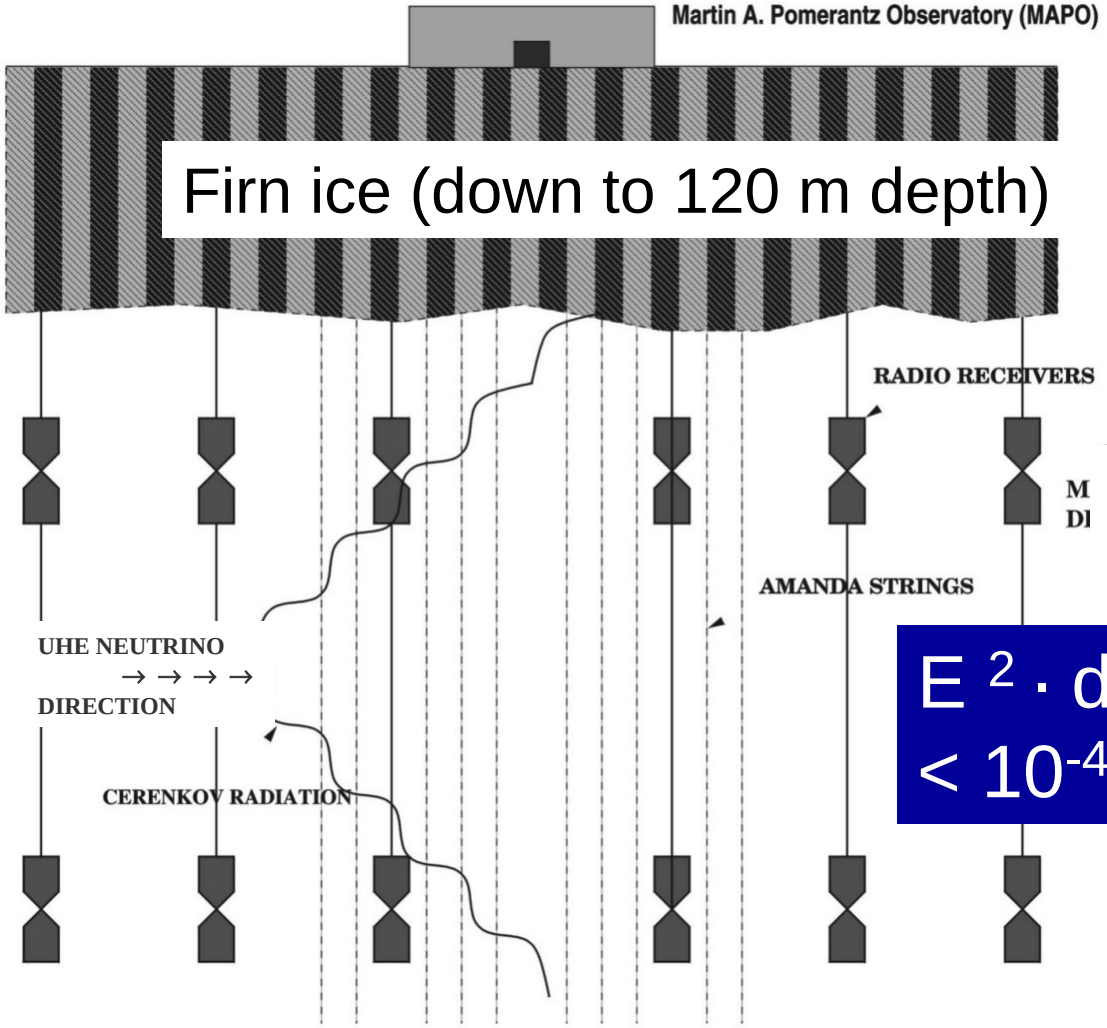
Detection by Acoustic and Radio Waves



attenuation length in ice 1-4 km !!



RICE **R**adio **I**ce **C**herenkov **E**xperiment



South Pole

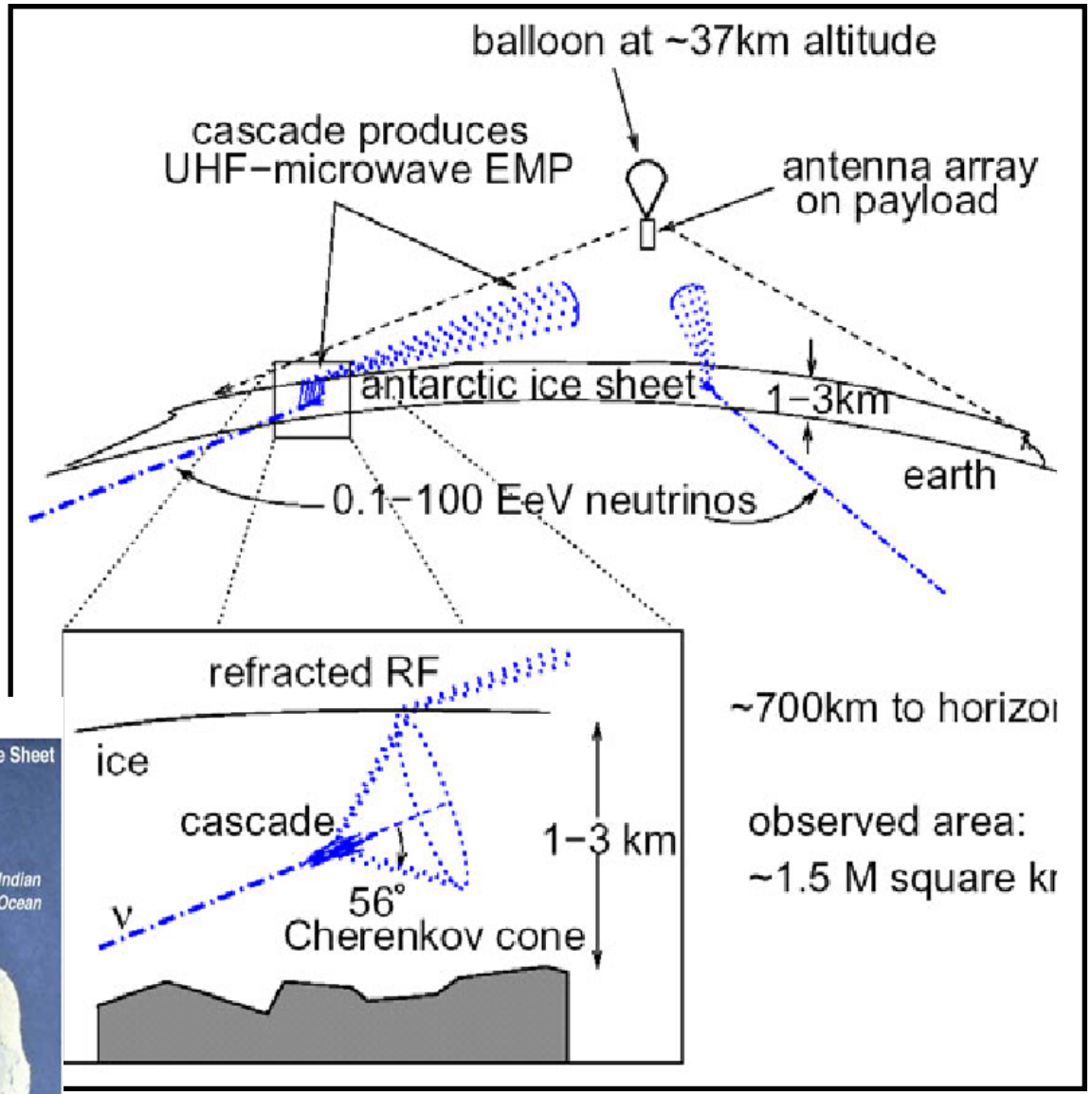
20 transmitter + receiver

$E^2 \cdot dN/dE$
$< 10^{-4}$ GeV $\cdot$ cm$^{-2} \cdot$ s$^{-1} \cdot$ sr^{-1}

at 100 PeV

ANITA

Antarctic
Impulsive
Transient
Array

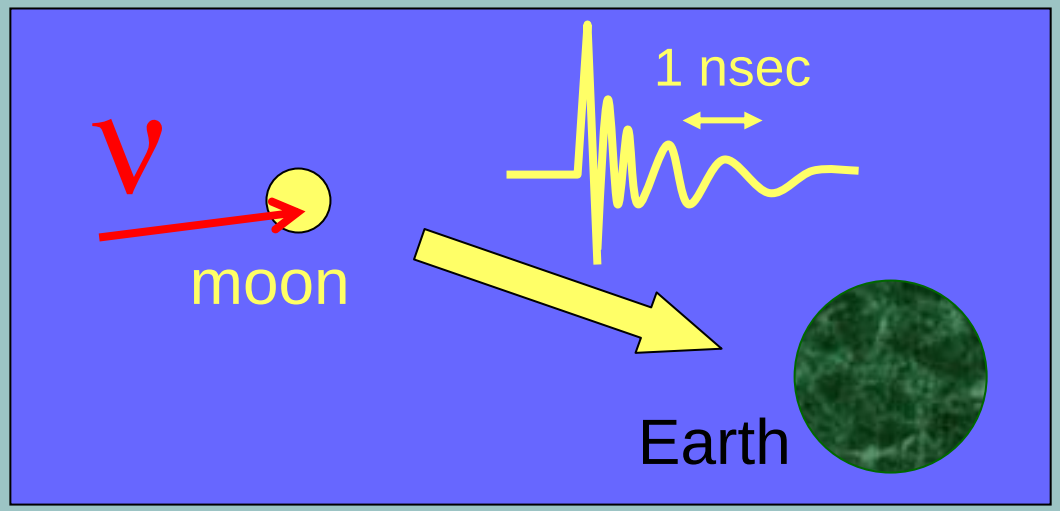


Flight in January 2006

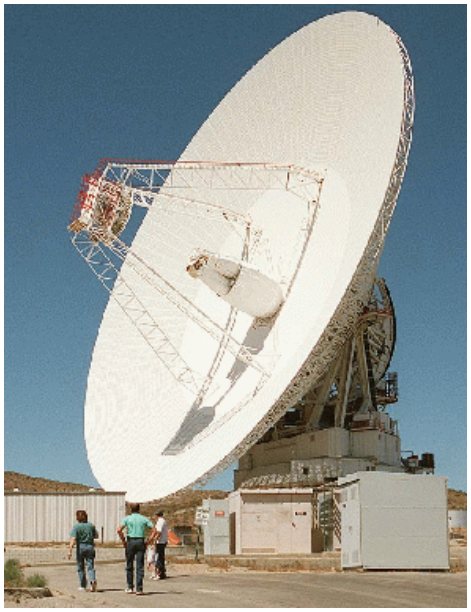
GLUE Goldstone Lunar Ultra-high Energy Neutrino Experiment

Lunar Radio Emission from Neutrino Reactions at > 10^{19} eV

Gorham et al. (1999), 30 hr NASA Goldstone 70 m antenna + DSS 34 m antenna



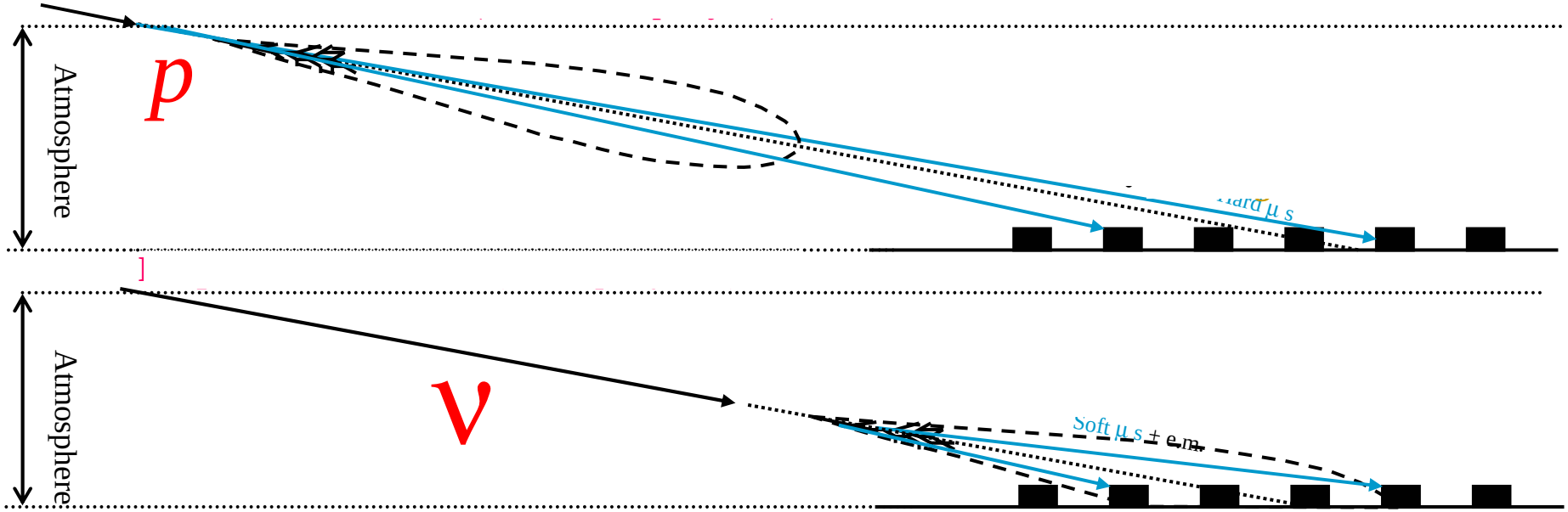
$\rightarrow E^2 \cdot dN/dE < 10^{-4}$ GeV·cm^{-2}·s^{-1}·sr^{-1} at 10^{20} eV



Effective target volume
~ antenna aperture (0.3°)
× 10 m stone layer

$\rightarrow 10^5$ km^3

Neutrinos in AUGER !?

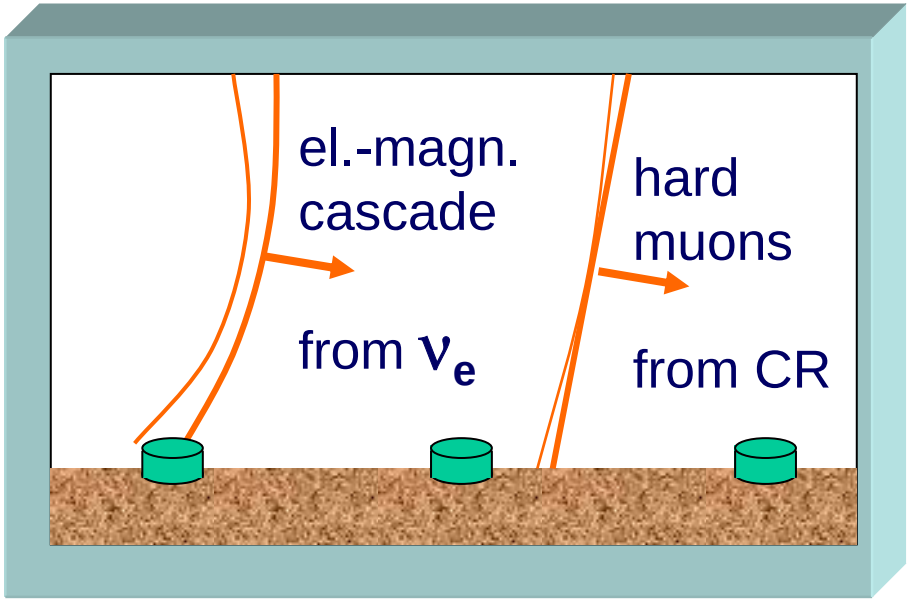


horizontal air showers

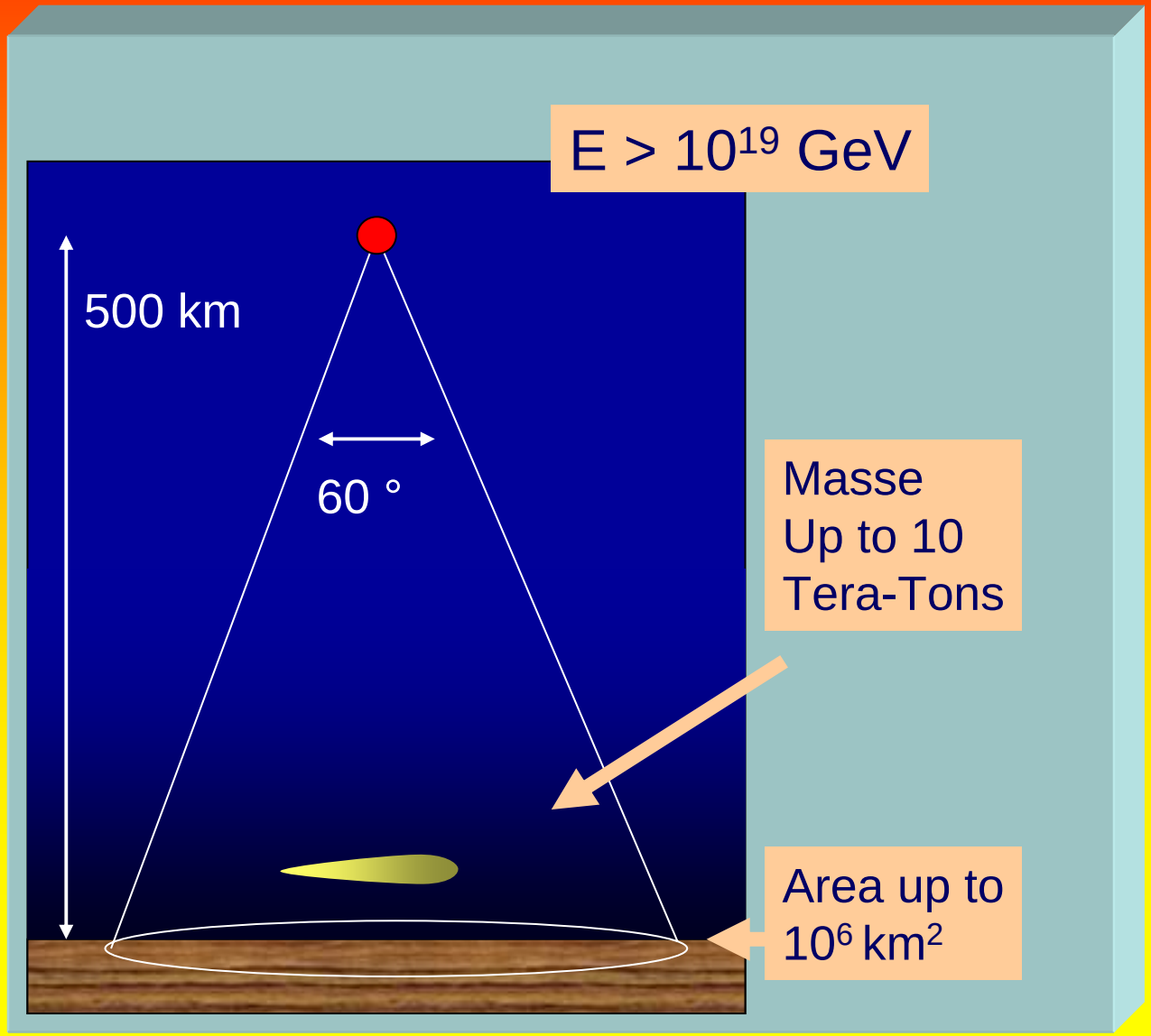
2001: AGASA (Japan)

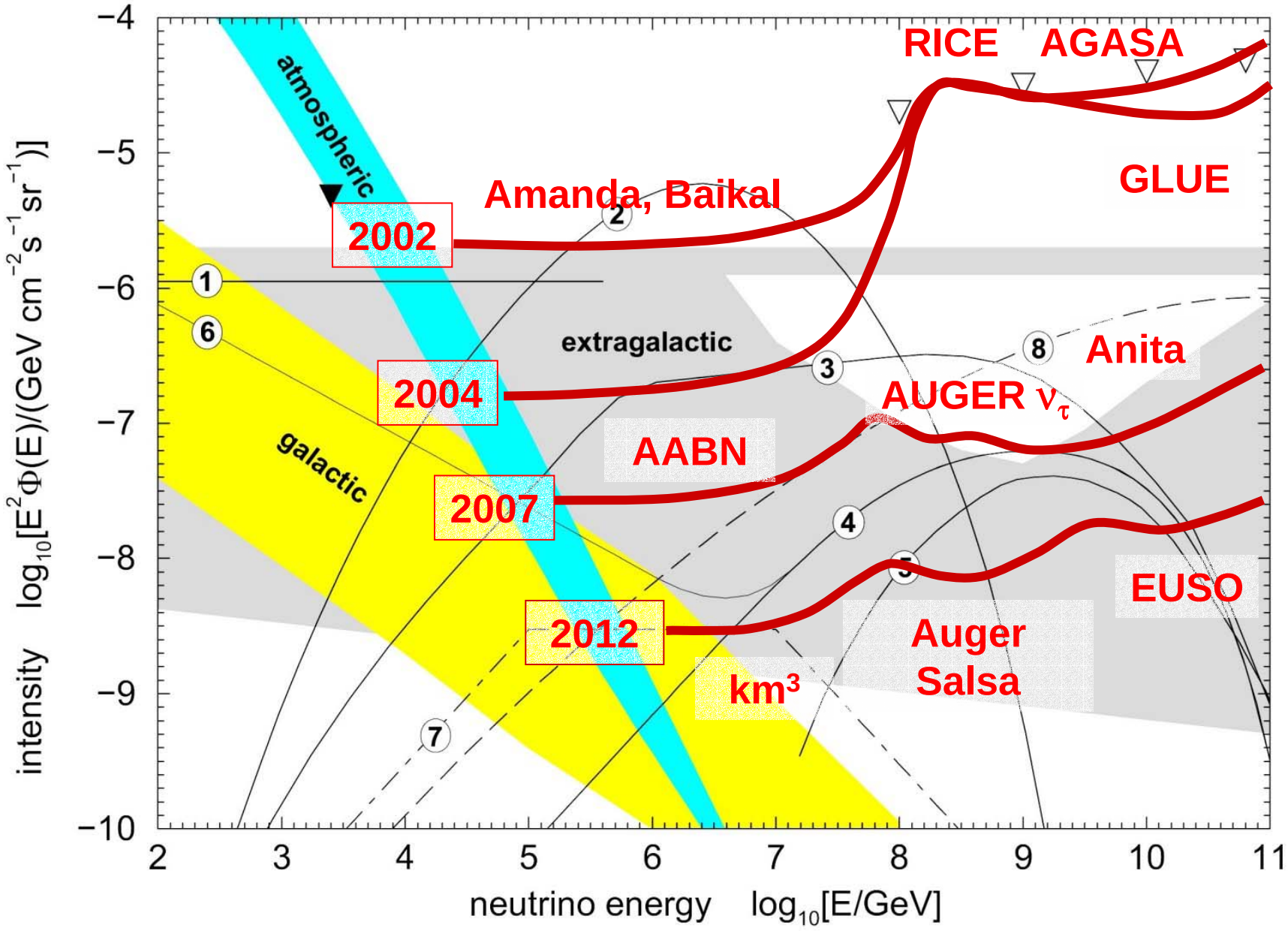
$< 10^{-5}$ GeV·cm^{-2}·s^{-1}·sr^{-1}

for E > 10 EeV



Measurement of horizontal air showers from Satellites




RICE
AGASA
GLUE
Amanda, Baikal
2002
2004
2007
2012
AUGER ν_τ
Anita
AABN
EUSO
Auger
Salsa
km³
atmospheric
galactic
extragalactic
1
2
3
4
5
6
7
8
intensity $\log_{10}[E^2\Phi(E)/(\mathrm{GeV\ cm^{-2}s^{-1}sr^{-1}})]$
neutrino energy $\log_{10}[E/\mathrm{GeV}]$
−4
−5
−6
−7
−8
−9
−10
2
3
4
5
6
7
8
9
10
11

Success not guarantied, but "history is on our side"