High Energy Neutrino Astronomy: Status and Prospects

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DFG

Outline

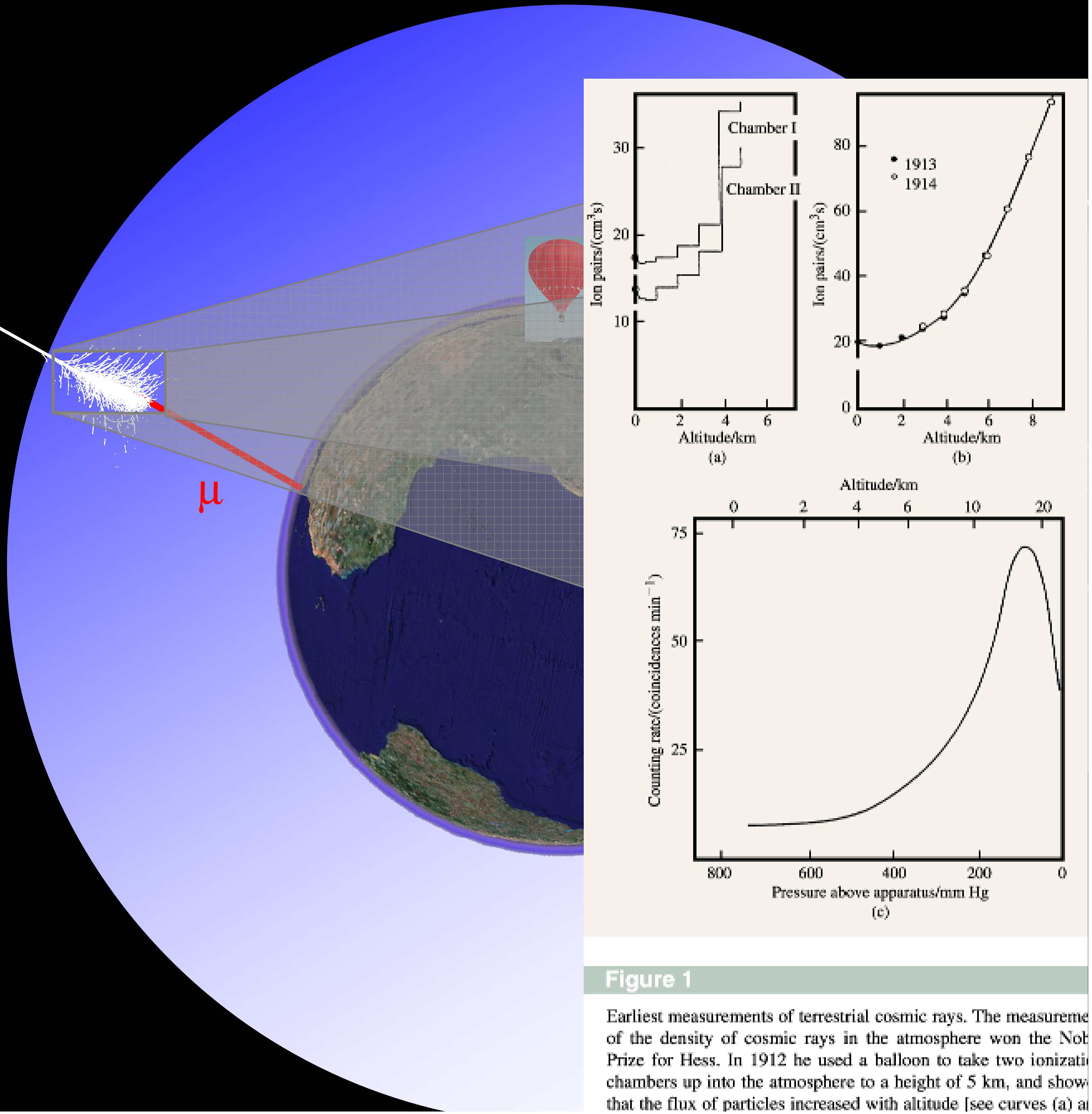
- Cosmic (Rays) Particles
- Neutrino Astronomy …
  - … in water
  - … in ice
- Latest Results
- Prospects: Towards Lower Energy

1912 Victo Hess et al

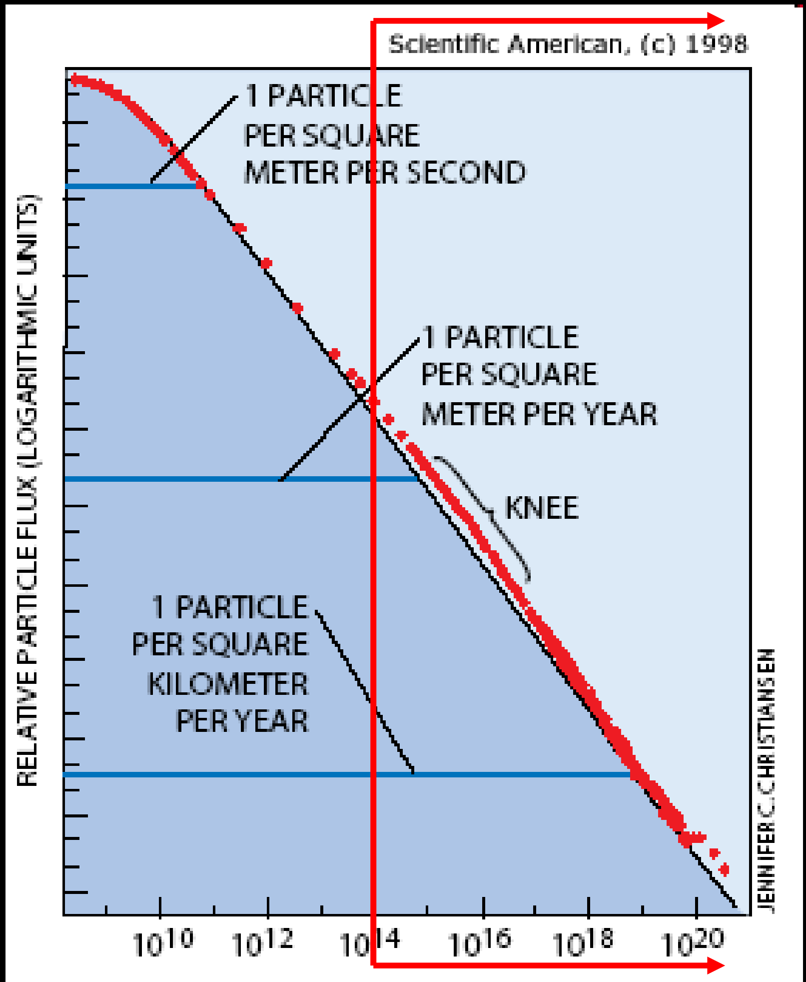
Energetic particles

(p, Fe, α, …)

on Earth's atmosphere



Cosmic (Rays) Particles

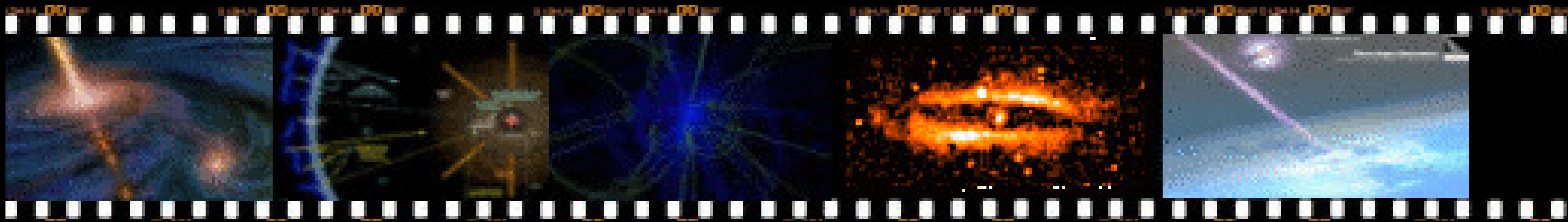


Power law spectrum [$10^9 – 10^{20}$ eV] $\propto E^{-2.7}$

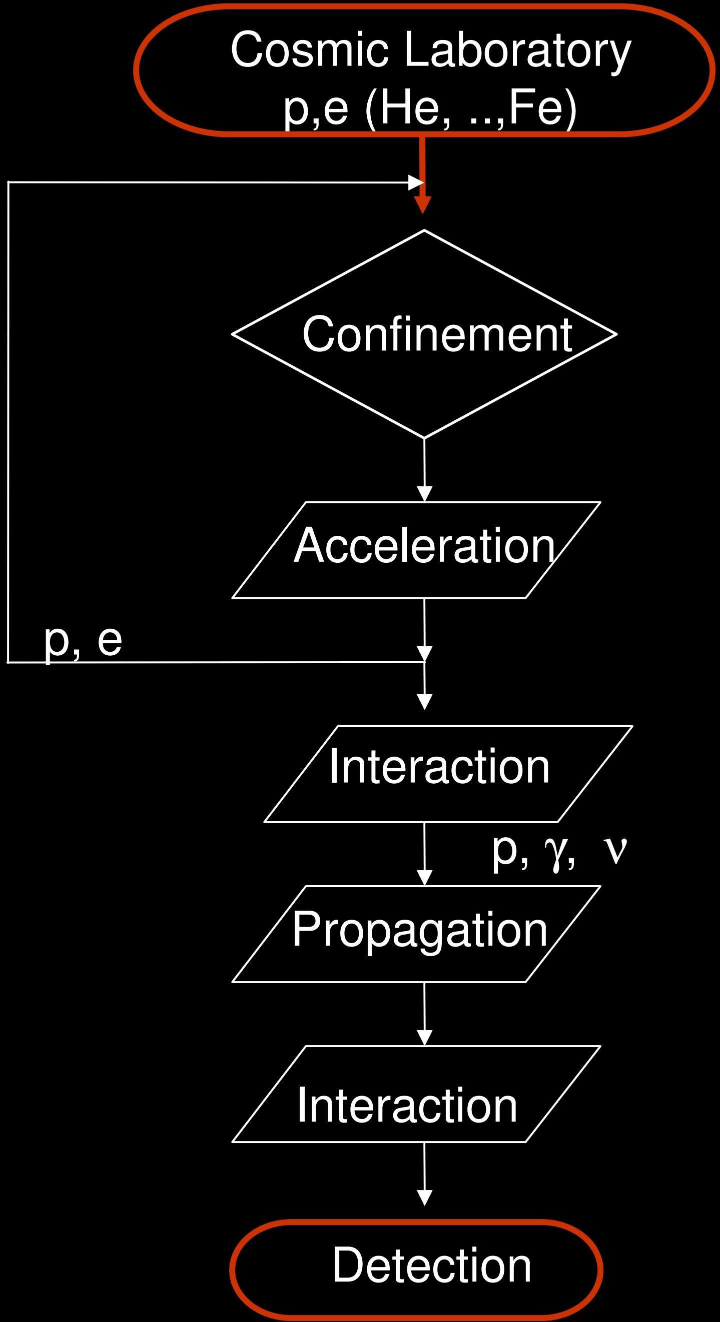
2 features: knee (~ 10^{15} eV), ankle (~ 10^{19} eV)

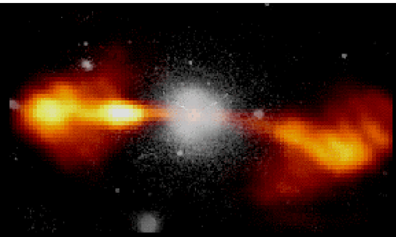
Cosmic (Rays) Particles

What we see is the superposition of: Many sources

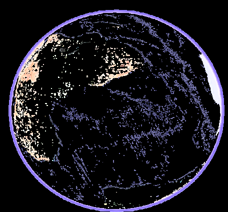


Magnetic field(s) randomization / Energy losses /Exotic particles, mechanisms

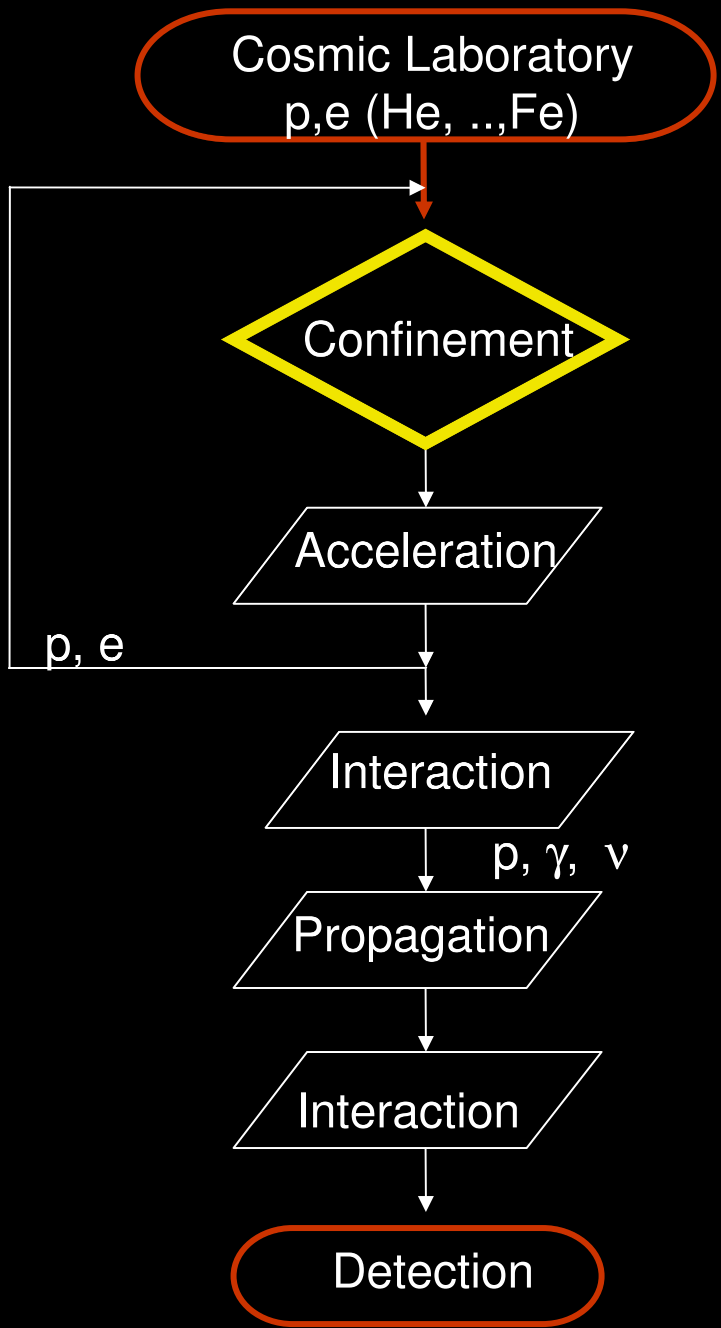


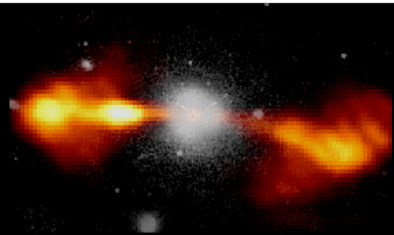


Cosmic particles flowchart

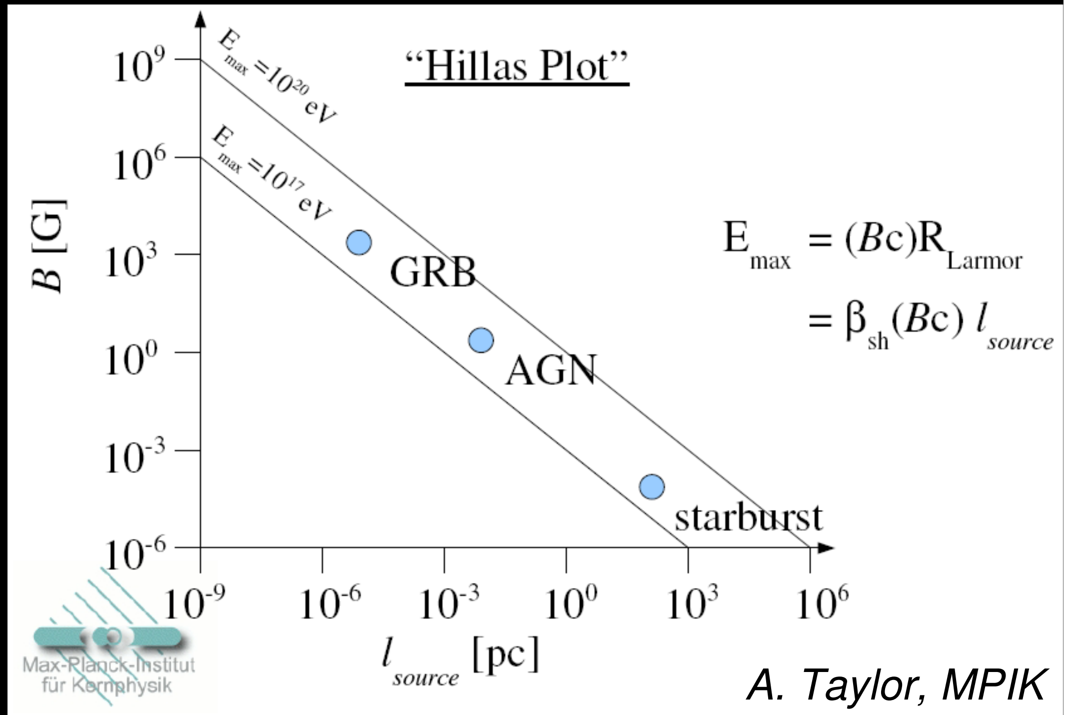


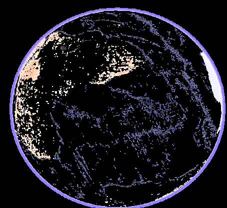
Cosmic particles flowchart



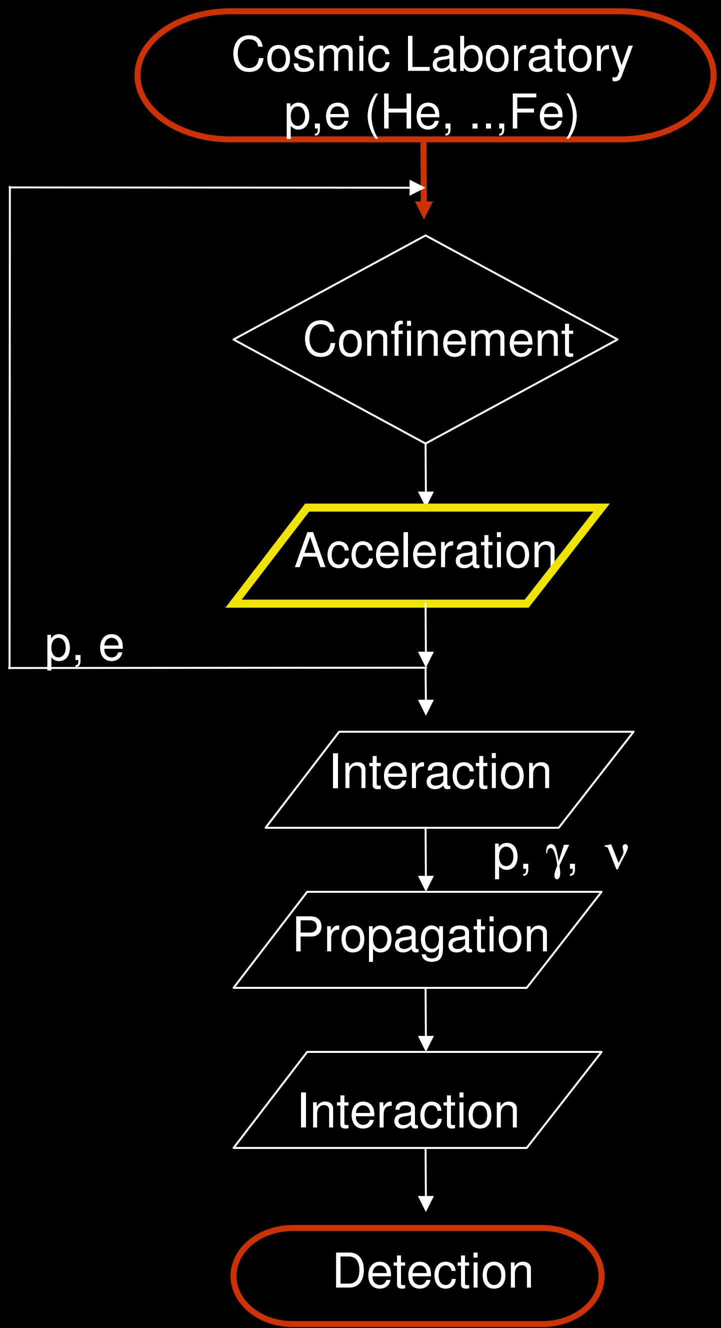


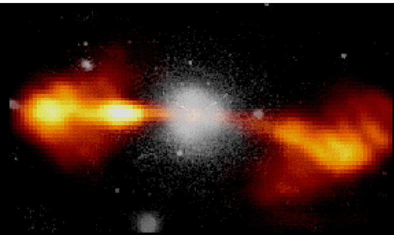
Source size, Magnetic Field



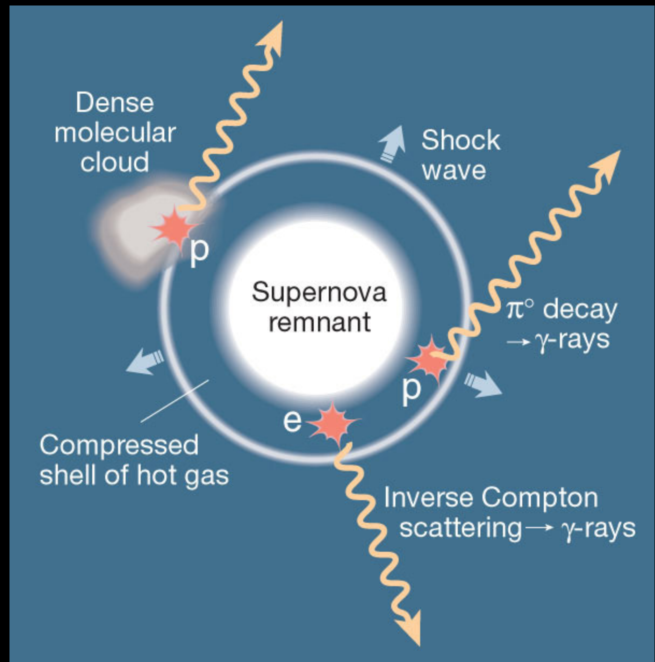


Cosmic particles flowchart

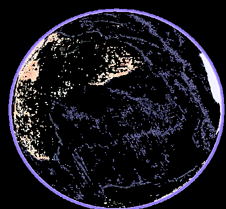


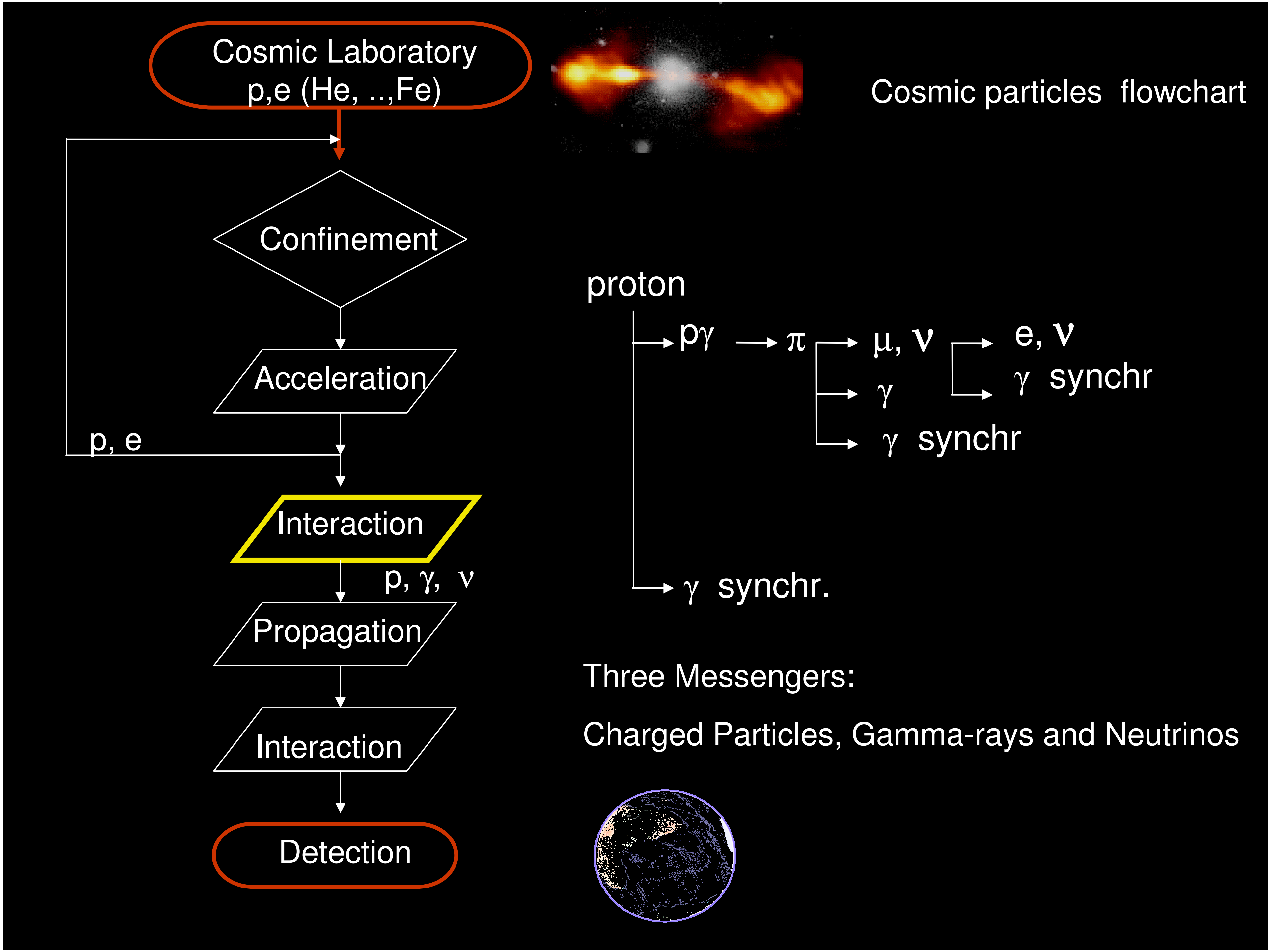


Diffusive shock acceleration

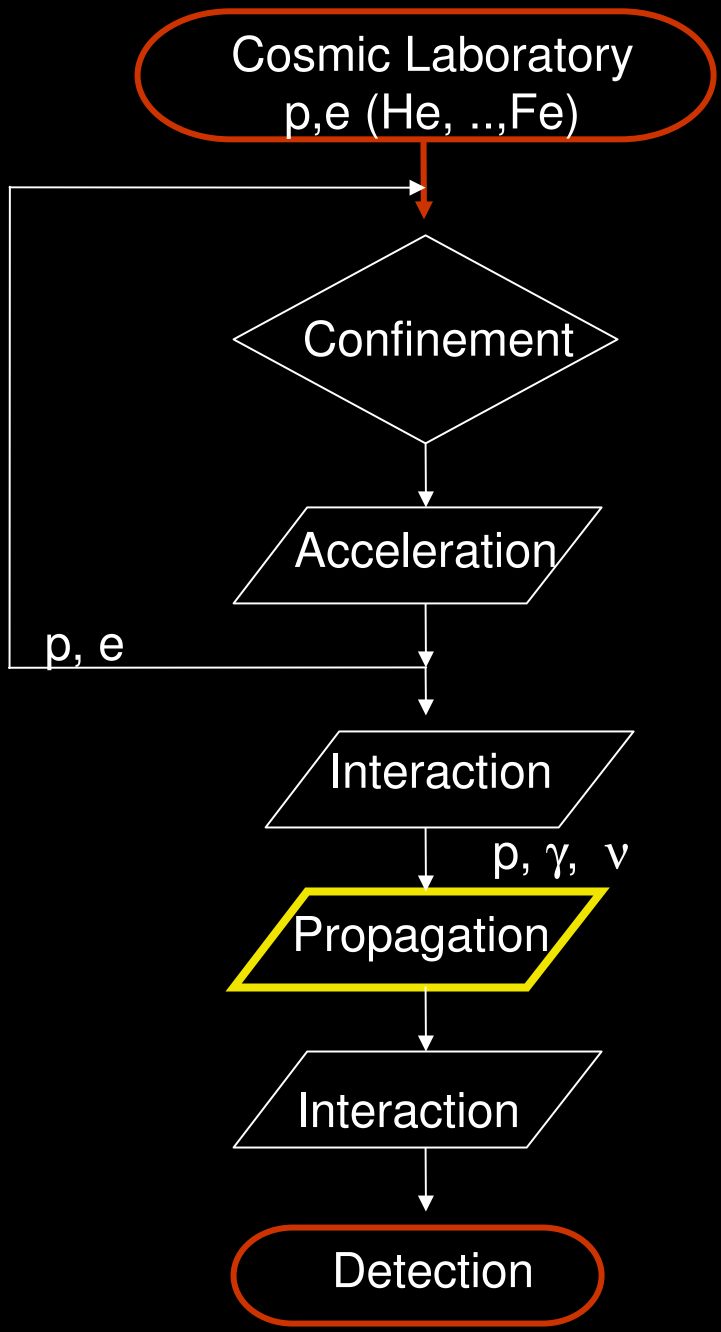


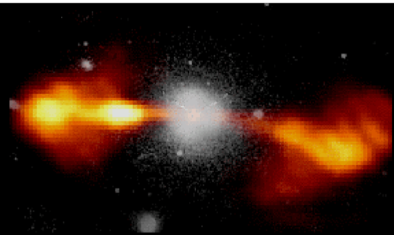
*Felix Aharonian, Nature **416**, 797-798,2002*



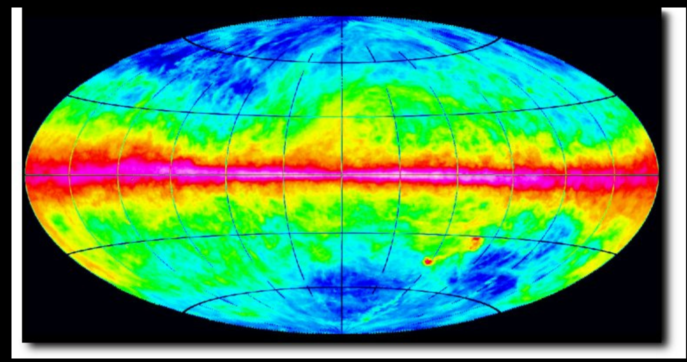

Cosmic particles flowchart
Cosmic Laboratory
p,e (He, ..,Fe)
Confinement
Acceleration
p, e
Interaction
p, γ, ν
Propagation
Interaction
Detection
proton
pγ
π
μ, ν
e, ν
γ synchr
γ
γ synchr
γ synchr.
Three Messengers:
Charged Particles, Gamma-rays and Neutrinos

Cosmic particles flowchart





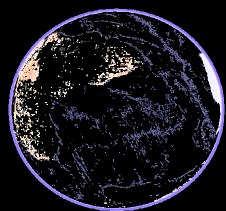
The Leiden/Argentine/Bonn (LAB)
Survey of Galactic HI

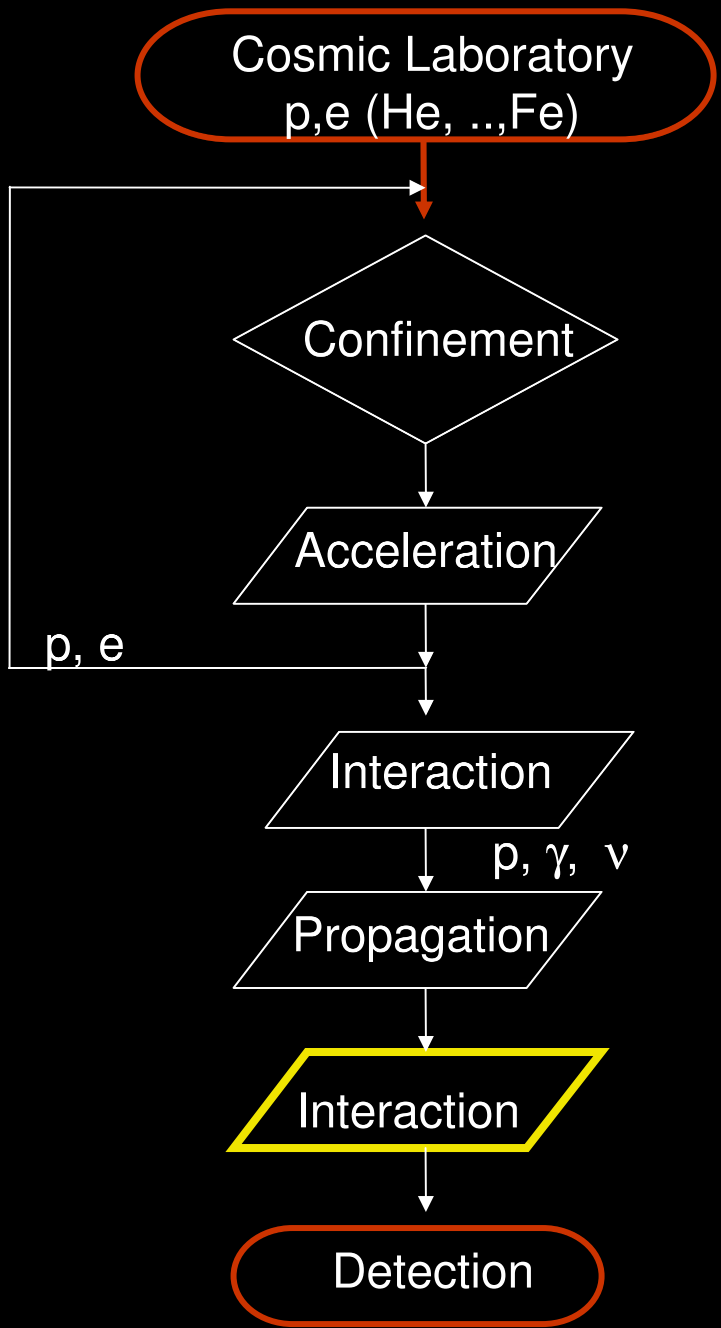


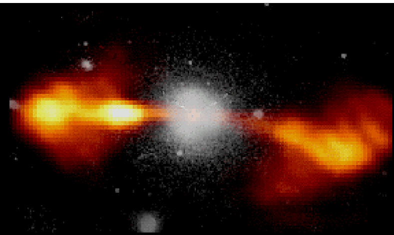
H2, NANTEN

Lorentz Invariance Violation?

p: magnetic field deviation
γ: absorption
ν: no interaction, point back to the source

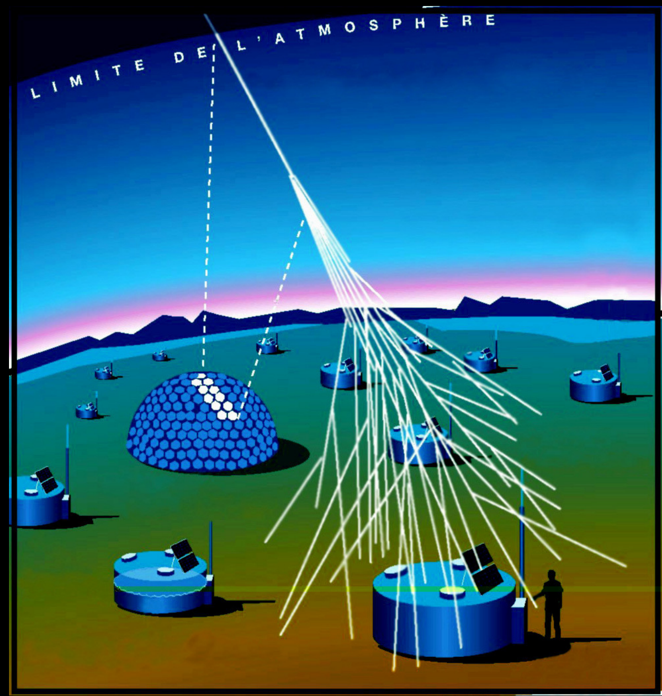


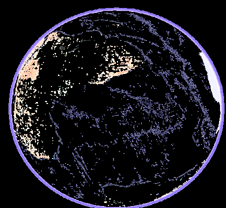




Cosmic particles flowchart

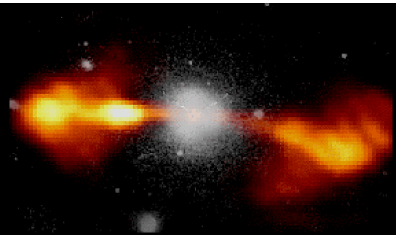
Proton interaction in Earth atmosphere
Air showers





Cosmic particles flowchart

Cosmic Laboratory
p,e (He, ..,Fe)



Confinement

Acceleration

p, e

Interaction

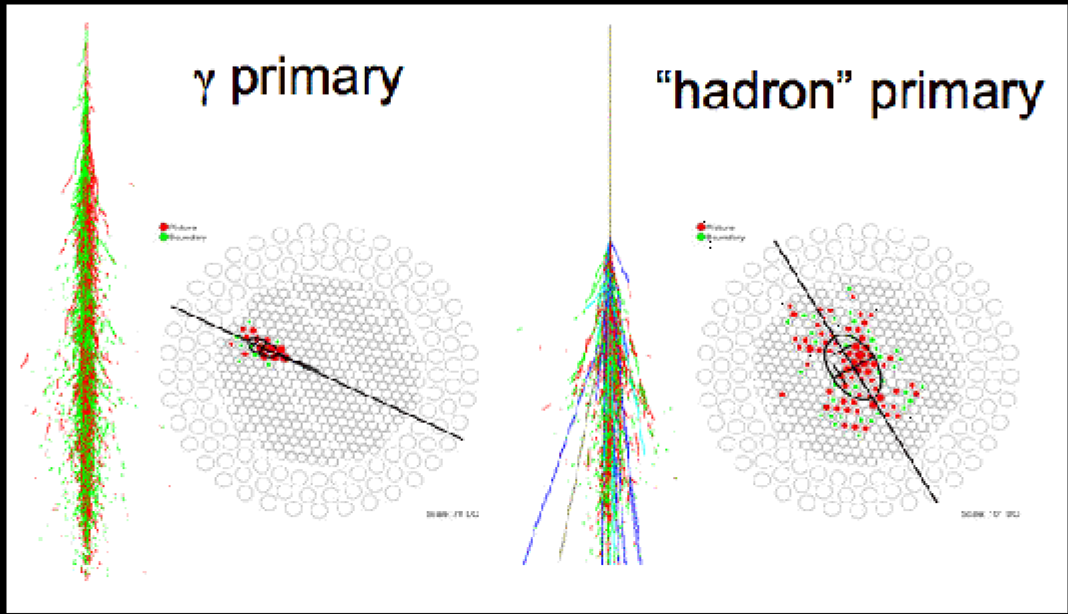
p, γ, ν

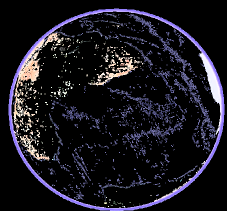
Propagation

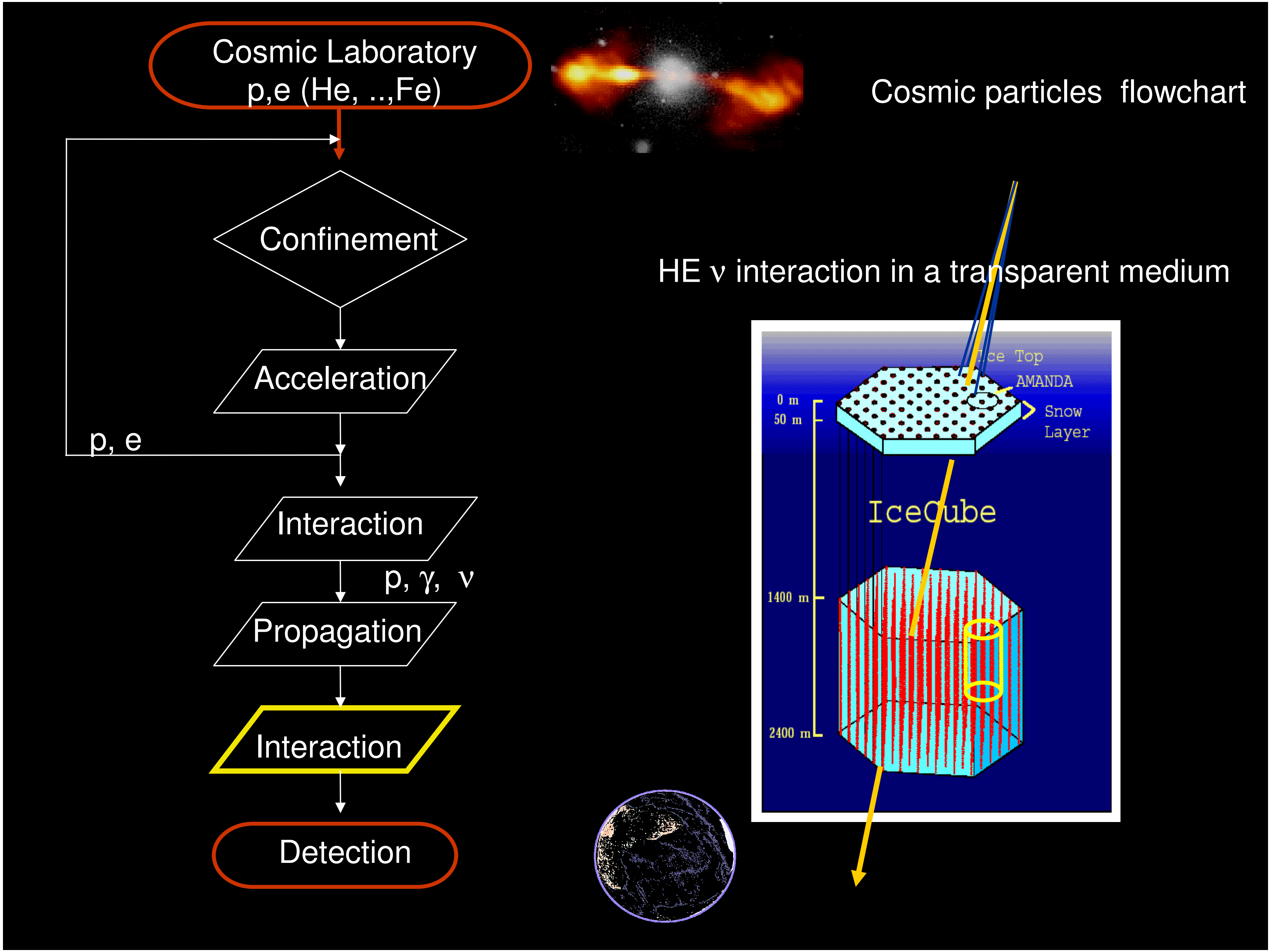
Interaction

Detection

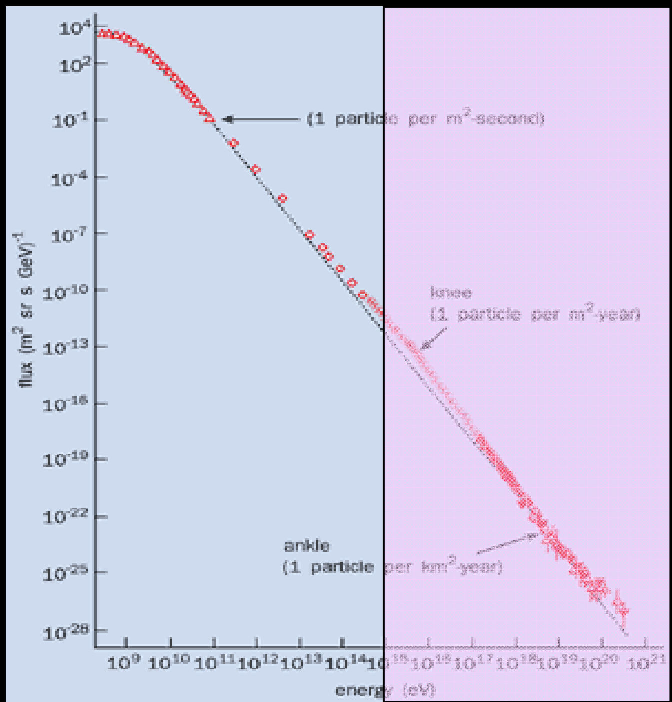
Proton and γ-rays interaction in Earth atmosphere
Air showers






Cosmic particles flowchart
Cosmic Laboratory
p,e (He, ..,Fe)
Confinement
Acceleration
p, e
Interaction
p, γ, ν
Propagation
Interaction
Detection
HE ν interaction in a transparent medium
Ice Top
AMANDA
0 m
50 m
Snow
Layer
IceCube
1400 m
2400 m

Neutrino Telescope



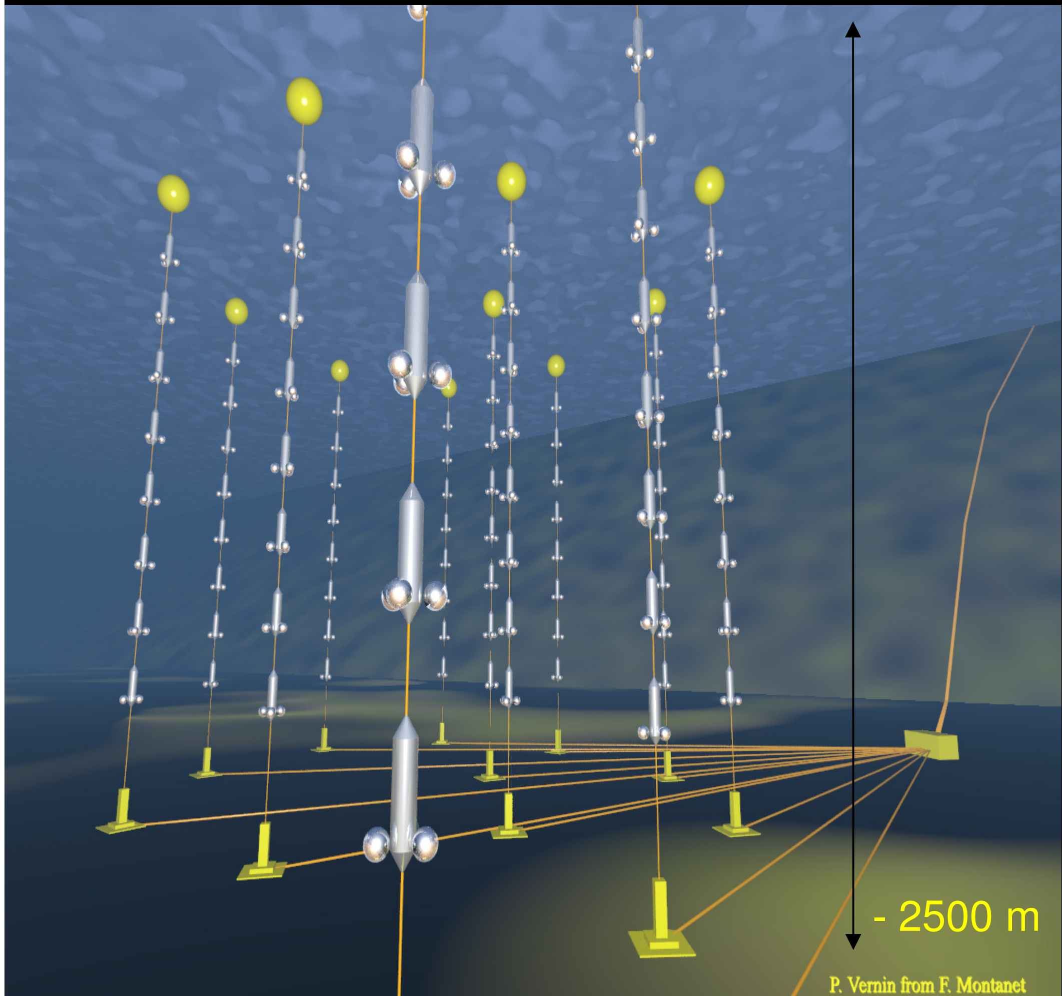
Energetic of Cosmic Rays

Neutrinos interact weakly
$\Rightarrow$ cross sections small

1 km^3

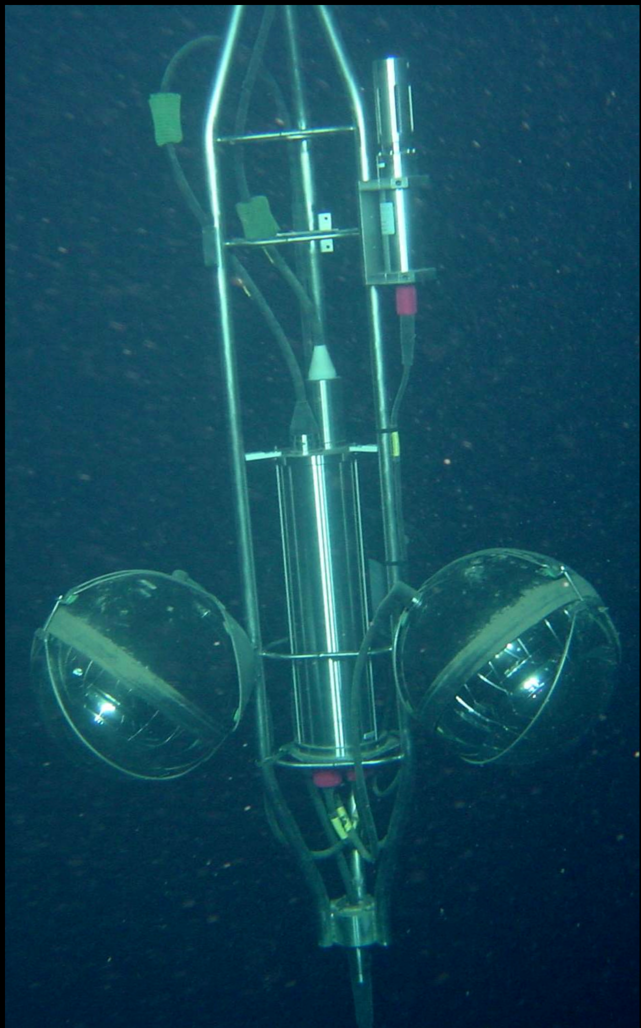
Neutrino Telescope: in water

(c) L.Fabre/CEA



- Antares (completed):
  - 13 lines in total:
    - 12 detection lines
    - 1 instrumentation line
  - Deployment completed June 08
  - Problem with connection cable fixed September 08
  - Good data are collected now!

Neutrino Telescope: in water



(c) L.Fabre/CEA

- Each line is composed by
  - 25 storey
  - Each storey by 3 Optical Modules (each at 45°)
  - Tiltmetro, compasses, acoustic triangulation: exact position and orientation of the line

Neutrino Telescope

South Pole IceCap:

- Ice cap holds over 90% of the world's fresh water in a frozen state

- The average thickness is over 2,500 metres (2,800 m, South Pole)

- The first South Pole base was Amundsen's tent (1912). Latest construction in 2004.

© 1987 Anne-Christine Jacobsen, Roland Huntford

NASA. Catalog #: PIA00729

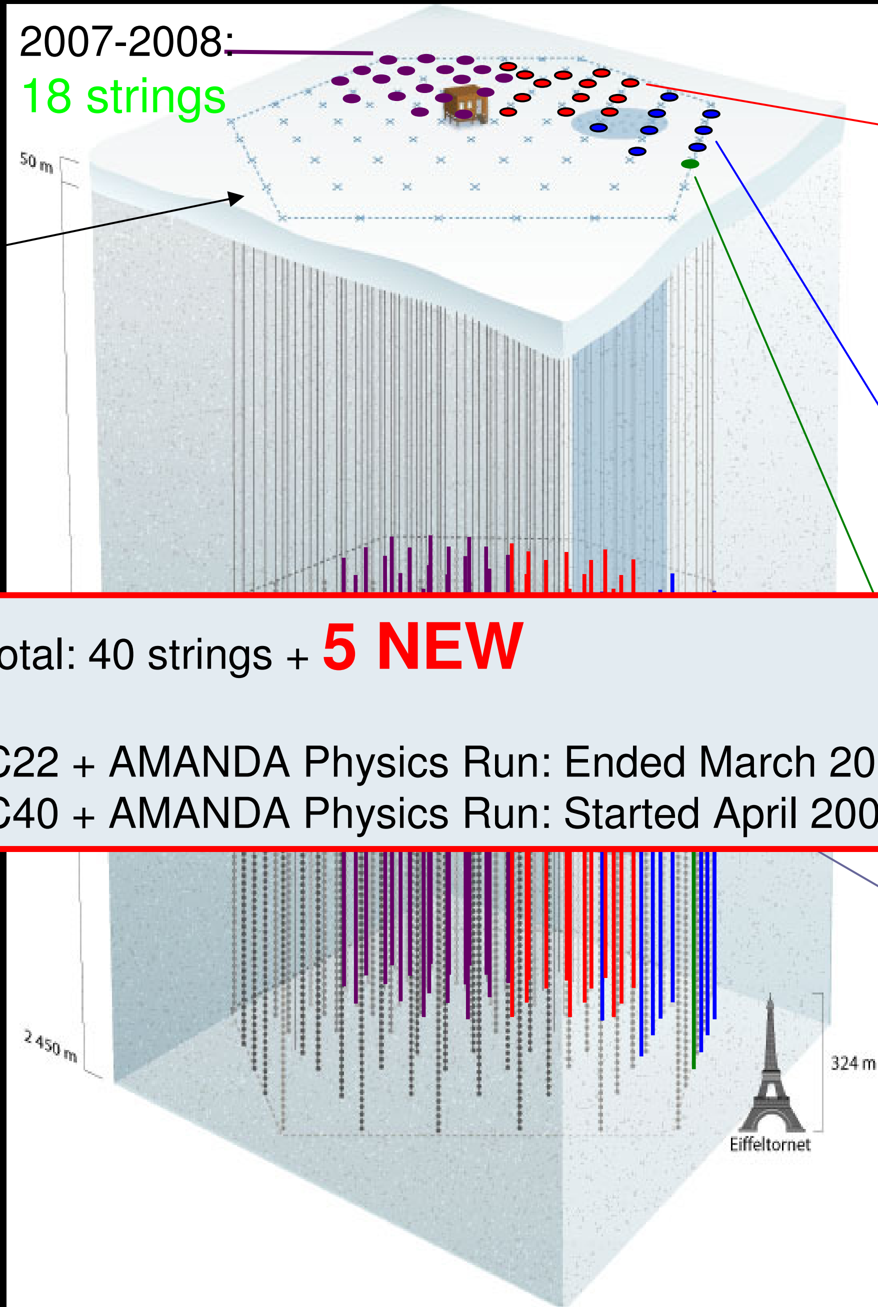
Amundsen-Scott South Pole Station

American research station at Earth's South Pole

IceTop

Air shower detetor

threshold ~ 300 TeV



2007-2008: 18 strings

2006-2007: 13 Strings

2005-2006: 8 Strings

2004-2005 : 1 String

Total: 40 strings + **5 NEW**

IC22 + AMANDA Physics Run: Ended March 2008
IC40 + AMANDA Physics Run: Started April 2008

InIce

70-80 Strings ,

60 Optical Modules

17 m between Modules

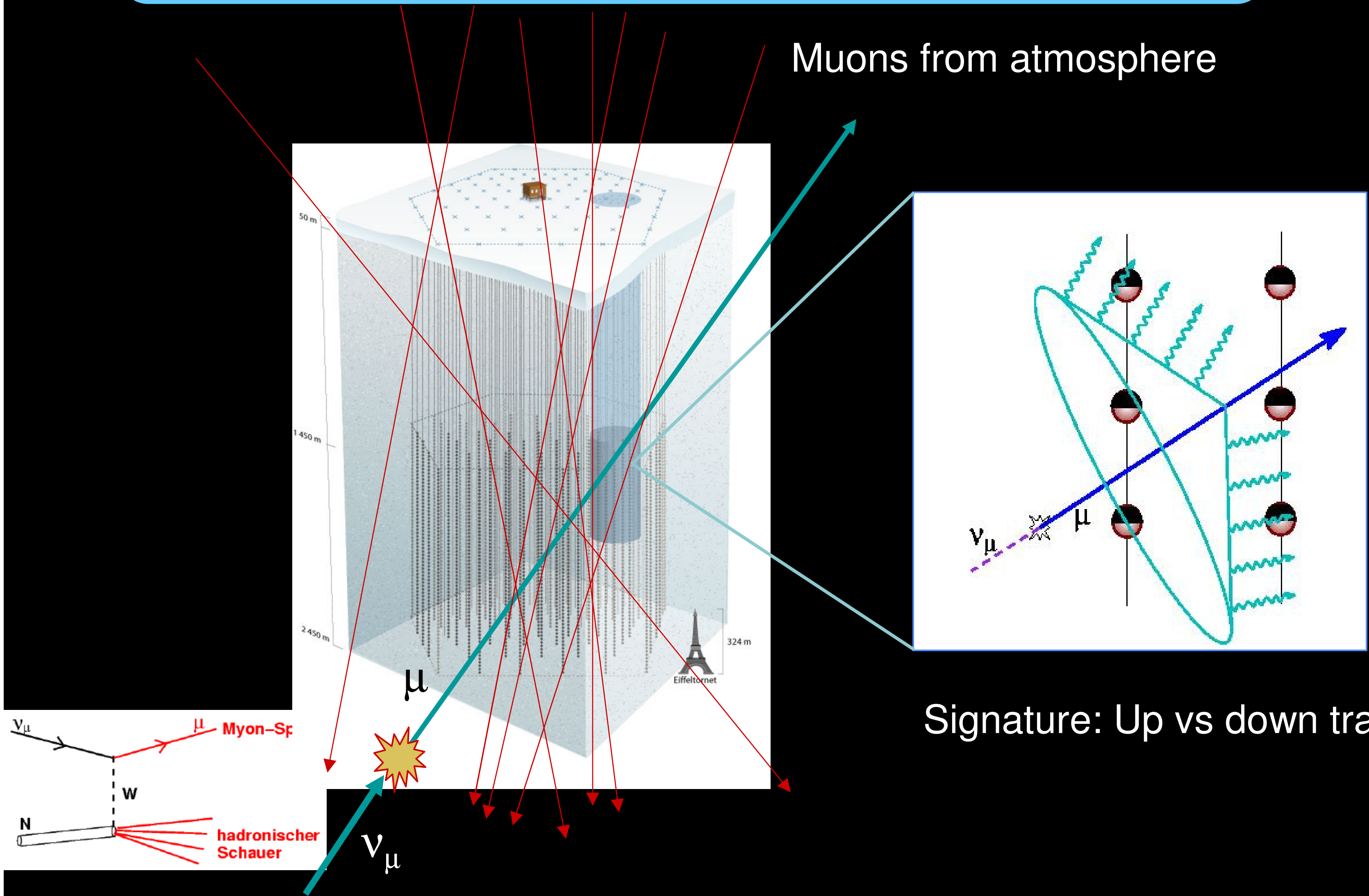
125 m between Strings

AMANDA

19 Strings

677 Modules

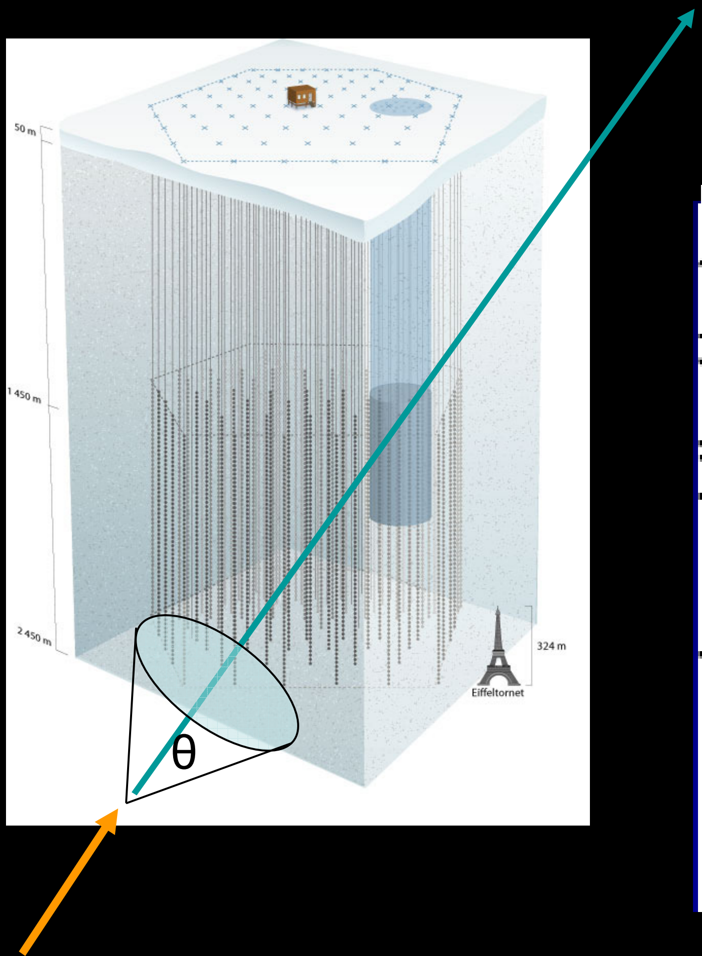
How neutrino telescopes work?
Neutrino Interaction

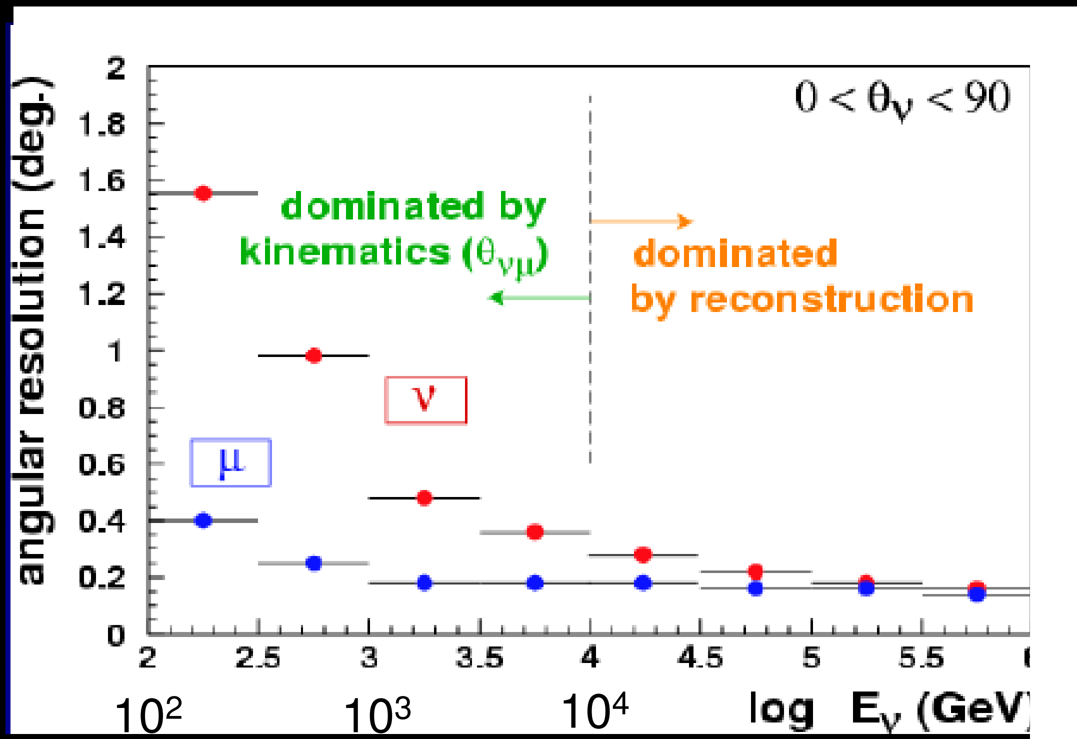


Signature: Up vs down tracks

How neutrino telescopes work?
Neutrino-Muon Angle

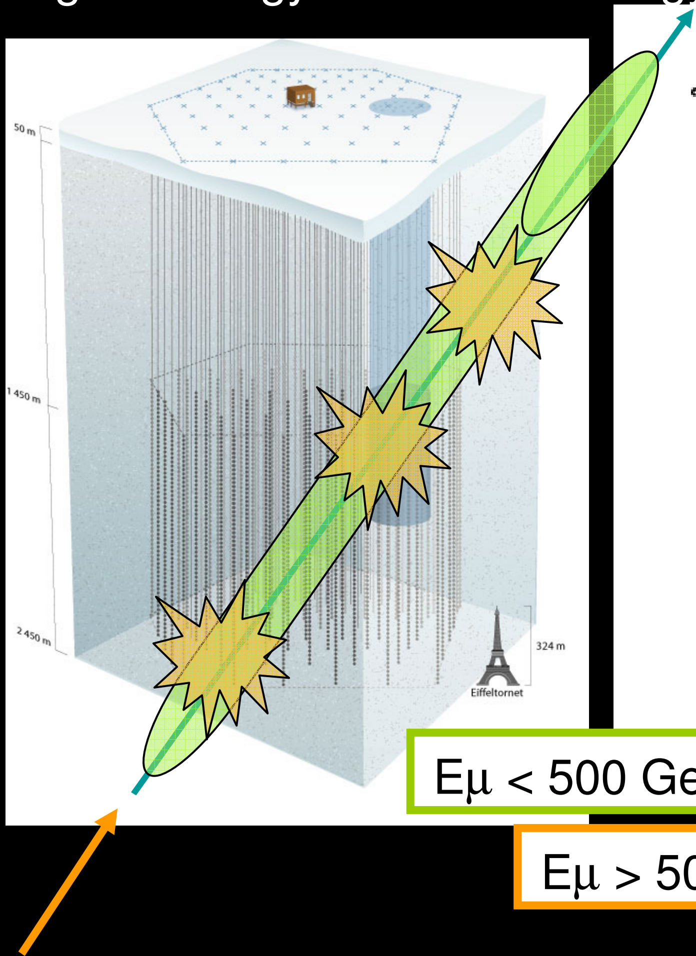
$$\langle\theta_{\nu\mu}\rangle \approx 0.7^{o} \cdot \left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)^{-0.7}$$



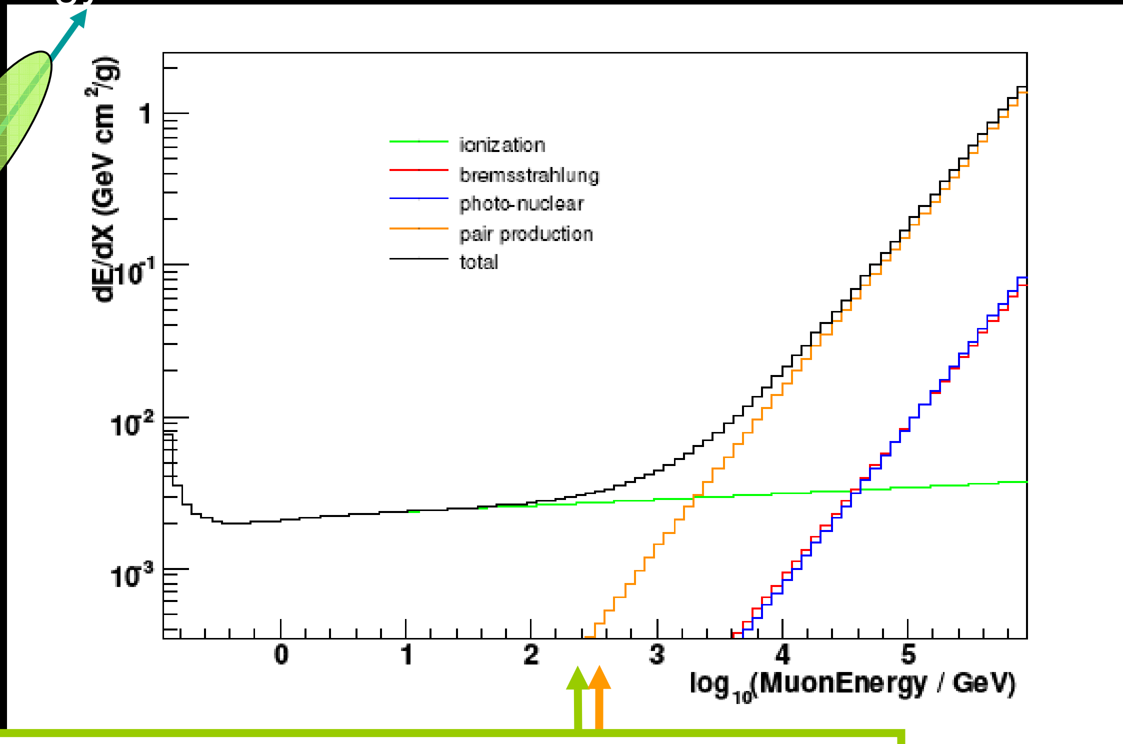


How neutrino telescopes work? Muon Energy Loss

Muon: 100 GeV ~ 500 m
Higher energy: stochastic energy loss



Muon Energy Loss in Ice

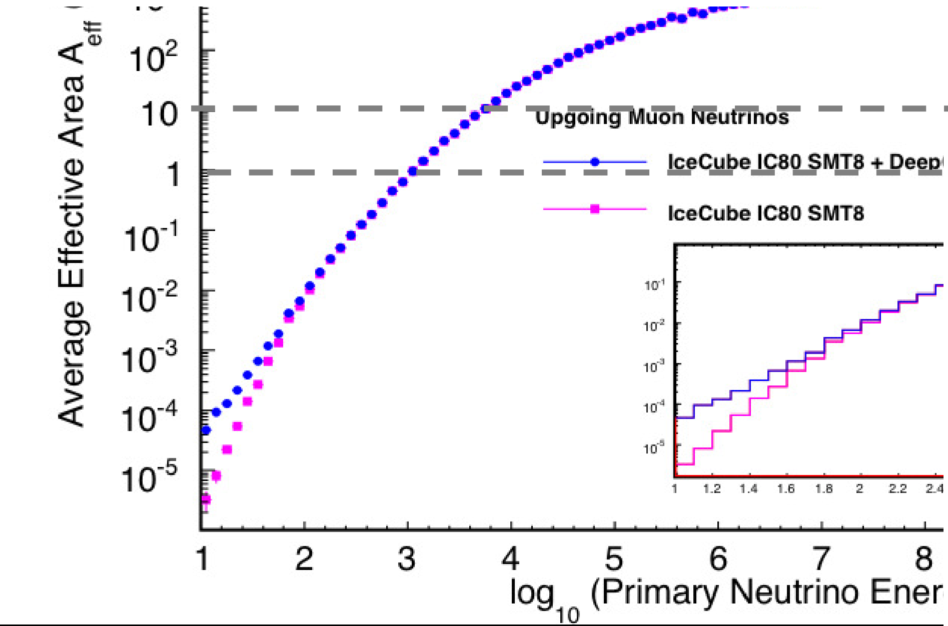


$E\mu$ < 500 GeV ionization dominant (~ 2 MeV / cm)

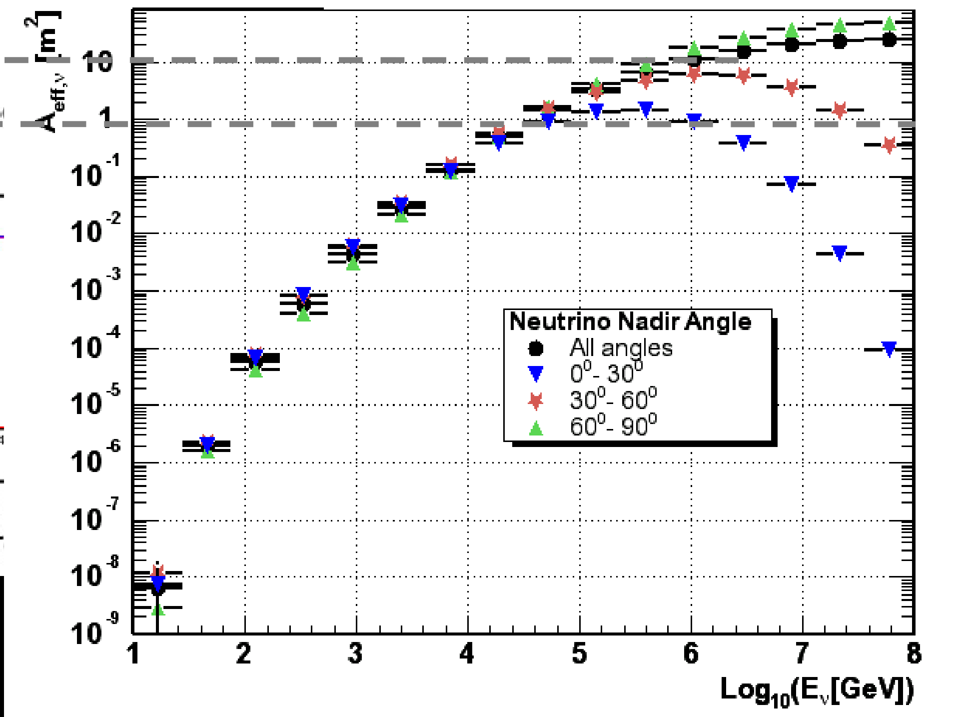
$E\mu$ > 500 GeV stochastic energy loss dominant

Neutrino Effective Area

IceCube 80 strings

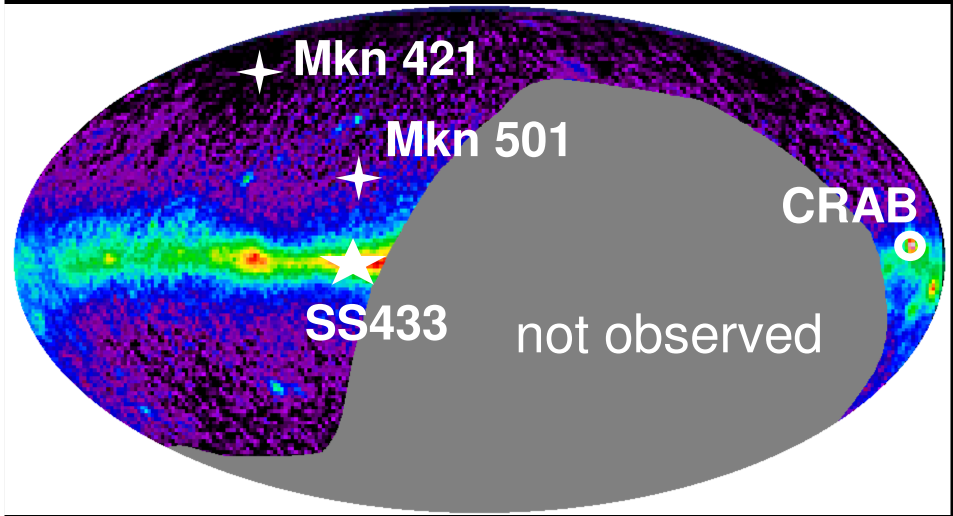


Antares: 12 lines

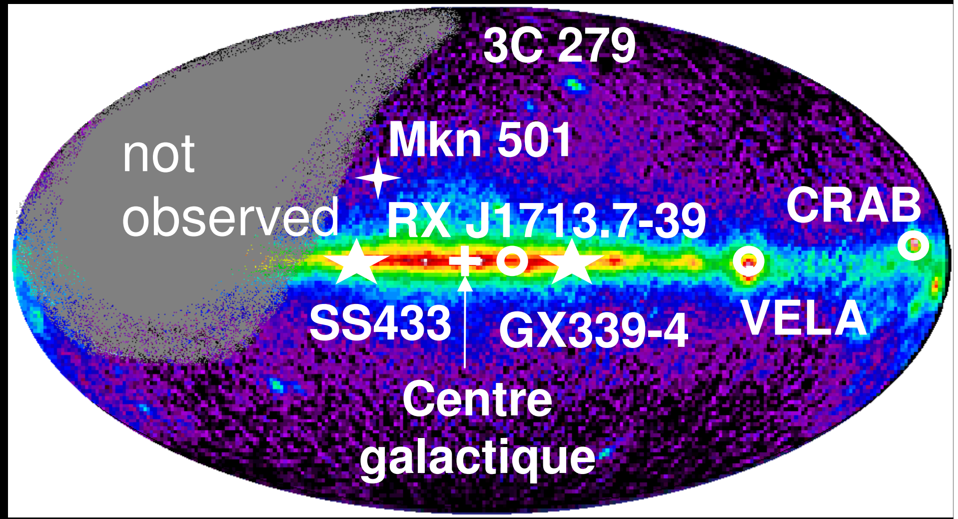


Neutrinos Telescopes Field of View

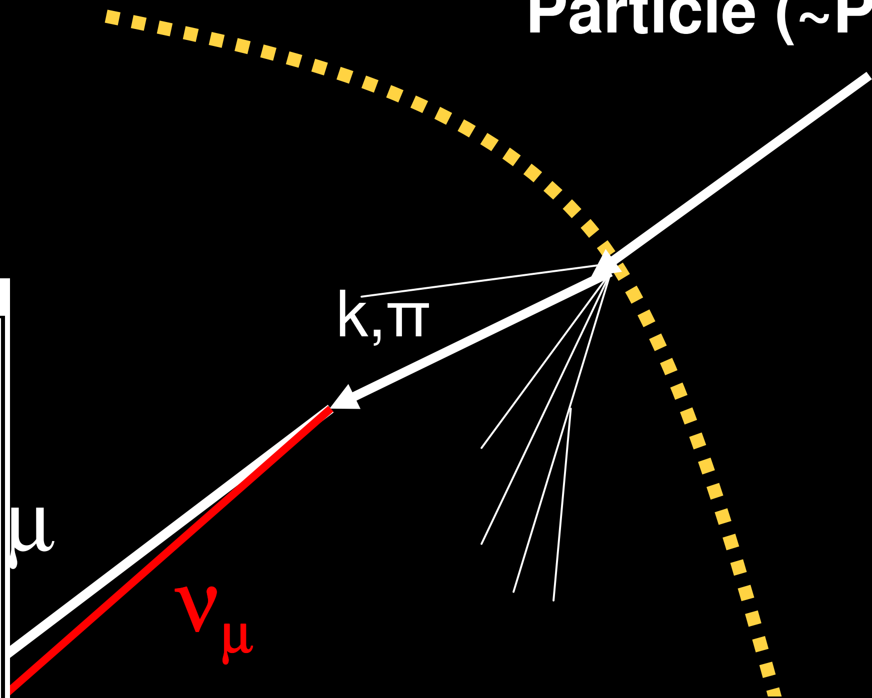
IceCube

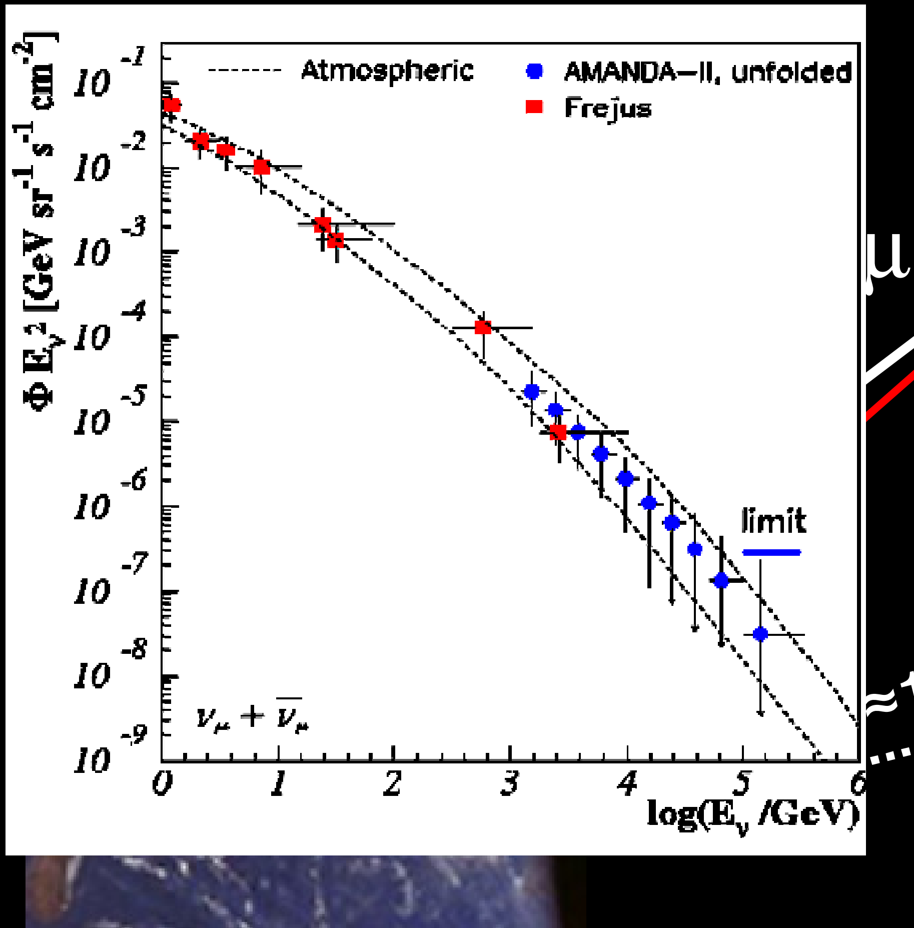


Antares / Km3Net



$\Phi_{atm}(E,\Omega)$





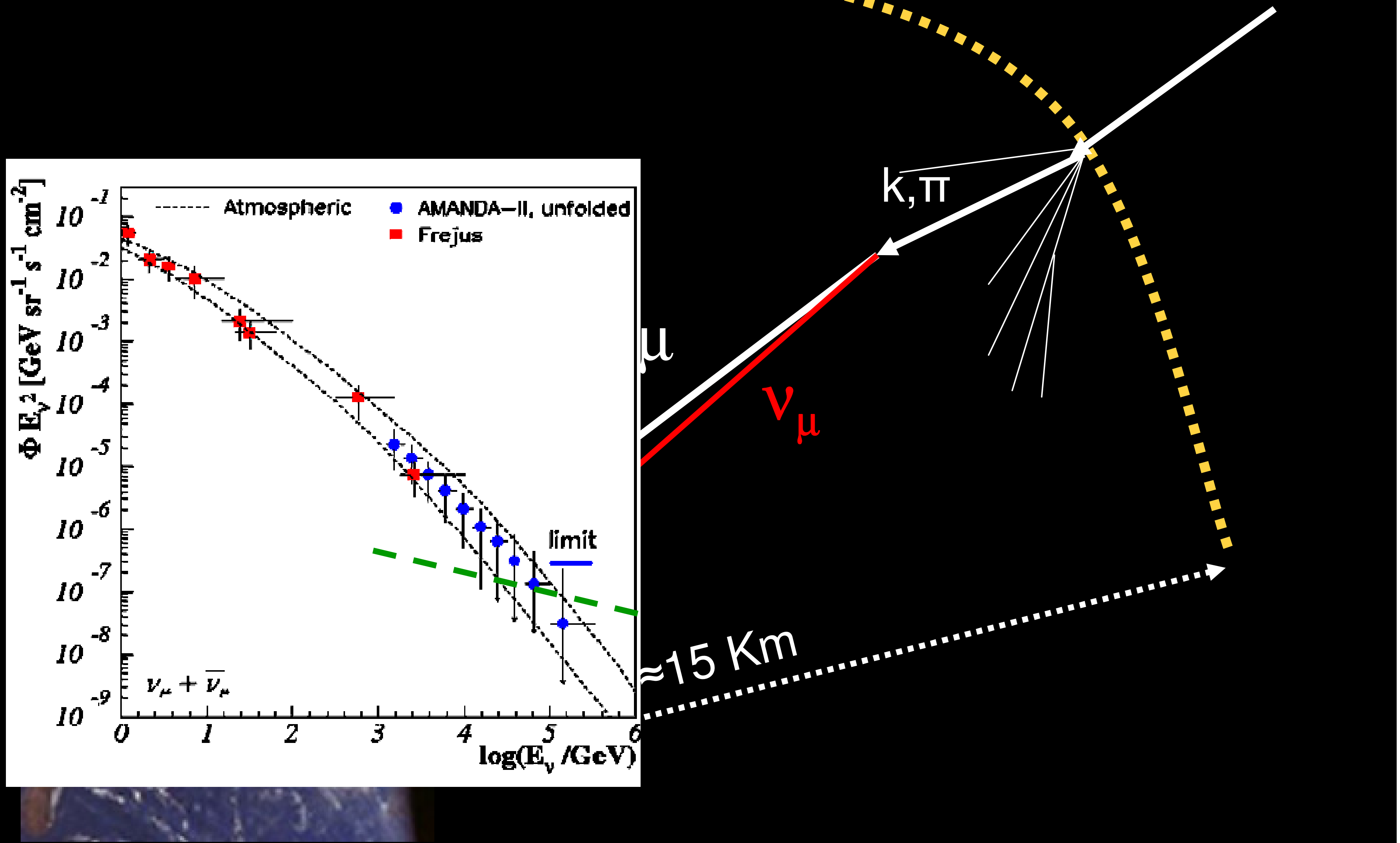
Declination dependence

$E^{-3.7}$

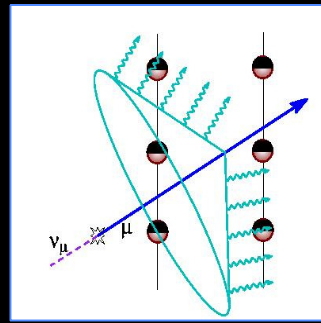
Uniform in time

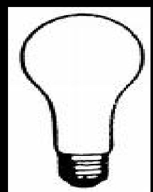
20 % uncertainty on the flux prediction

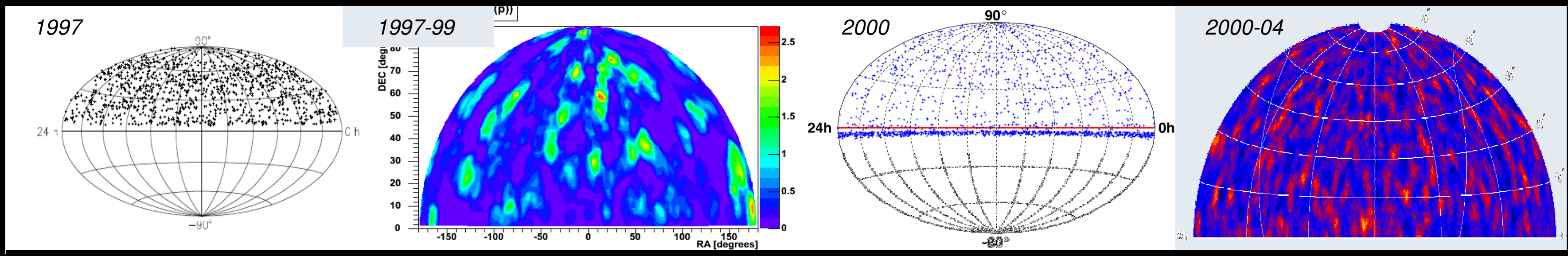
$\Phi_{atm}(E,\Omega)$ vs $\Phi_{galactic}(E,\Omega)$, $\Phi_{extra\text{-}galactic}(E,\Omega)$



Point Source Searches



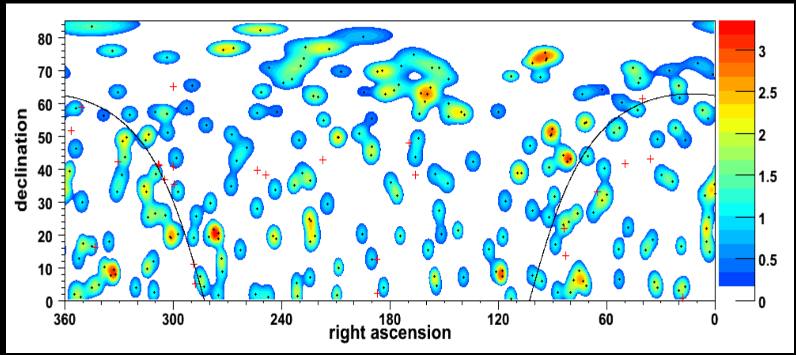
	Up-wards ν_μ	AMANDA	IceCube
Arrival time		~ 5-7 nsec	~ 3 nsec
Incoming direction		2° - 3° fov 2π	< 1° fov 2π
Estimated energy		± 0.5 order of magnitude	

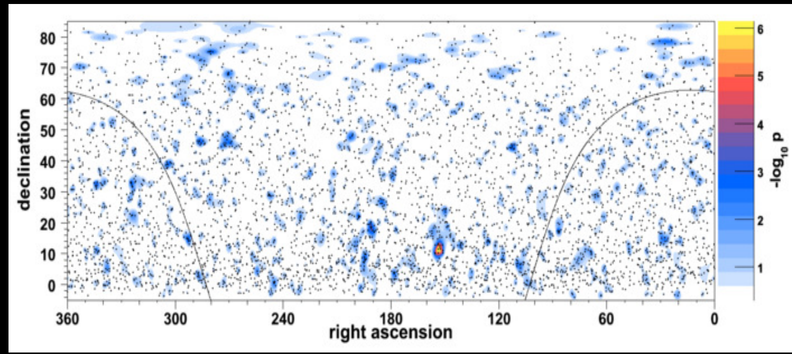


1997 2000 2004

AMANDA B10 AMANDA II

Detector	Energy Window (TeV)	Exposure Time (days)	Limit (TeV^{-1} cm^{-2} s^{-1})
AMANDA-B10 (1997-99)	~1 – 1000	623	$4.0 \cdot 10^{-10}$
AMANDA-II (2000-04)	1.6 - 2600 Phys.Rev.D75:102001,2007	1001	$5.5 \cdot 10^{-11}$
AMANDA-II (2005-06)			$7.0 \cdot 10^{-11}$





2006

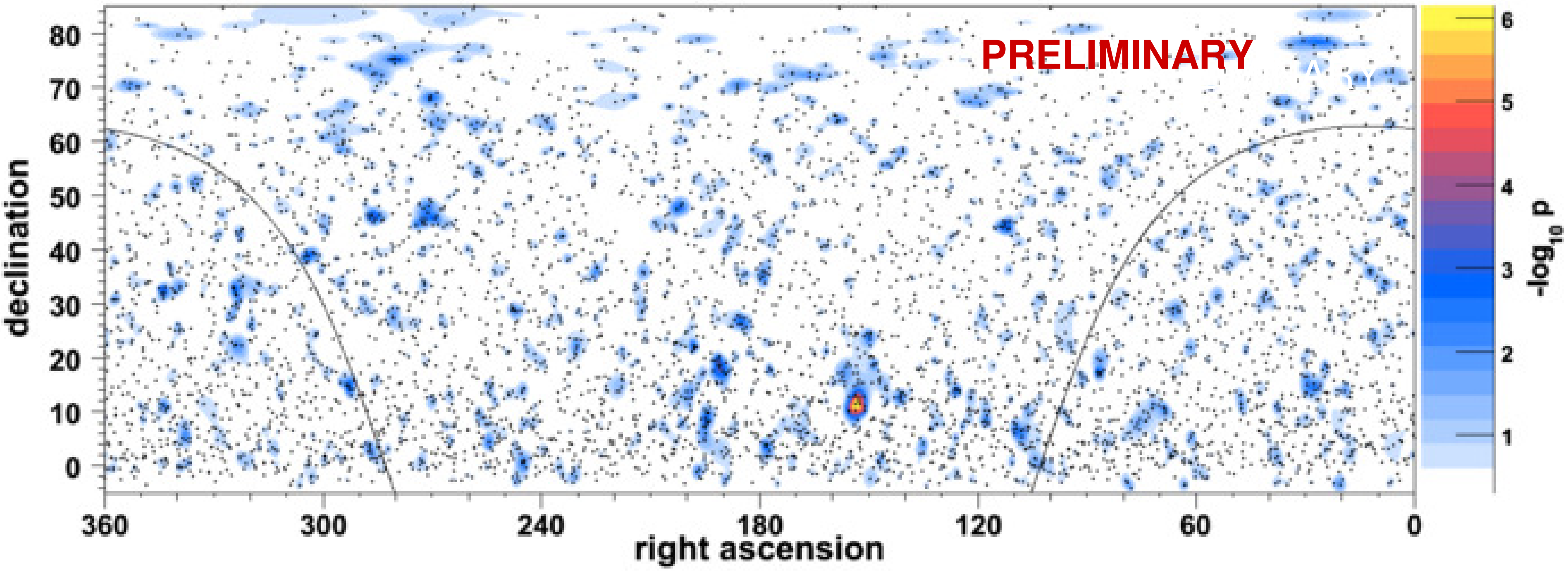
2007

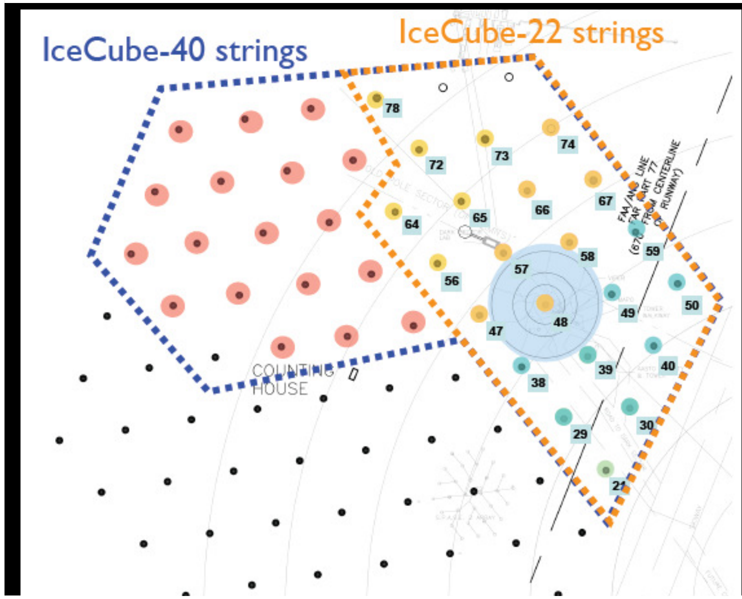
IceCube 9 strings

IceCube 22 strings

Detector	Energy Window (TeV)	Exposure Time (days)	Limit (L) Sensitivity (S) ($TeV^{-1}\ cm^{-2}\ s^{-1}$)
IC9 (2006)	~ 5 - 1000	137	$1.2 \cdot 10^{-10}$ (L)
IC22 (2007) IC22 + AMANDA	~ 5 – 5000 ~ 0.5 - 10	240	$\sim 10^{-11}$ (S) Only for specific
IC80	~ 5 - 5000	3 years	$2 \cdot 10^{-12}$ (S)

IceCube-22 sky-map, 275.70 days, 5114 events

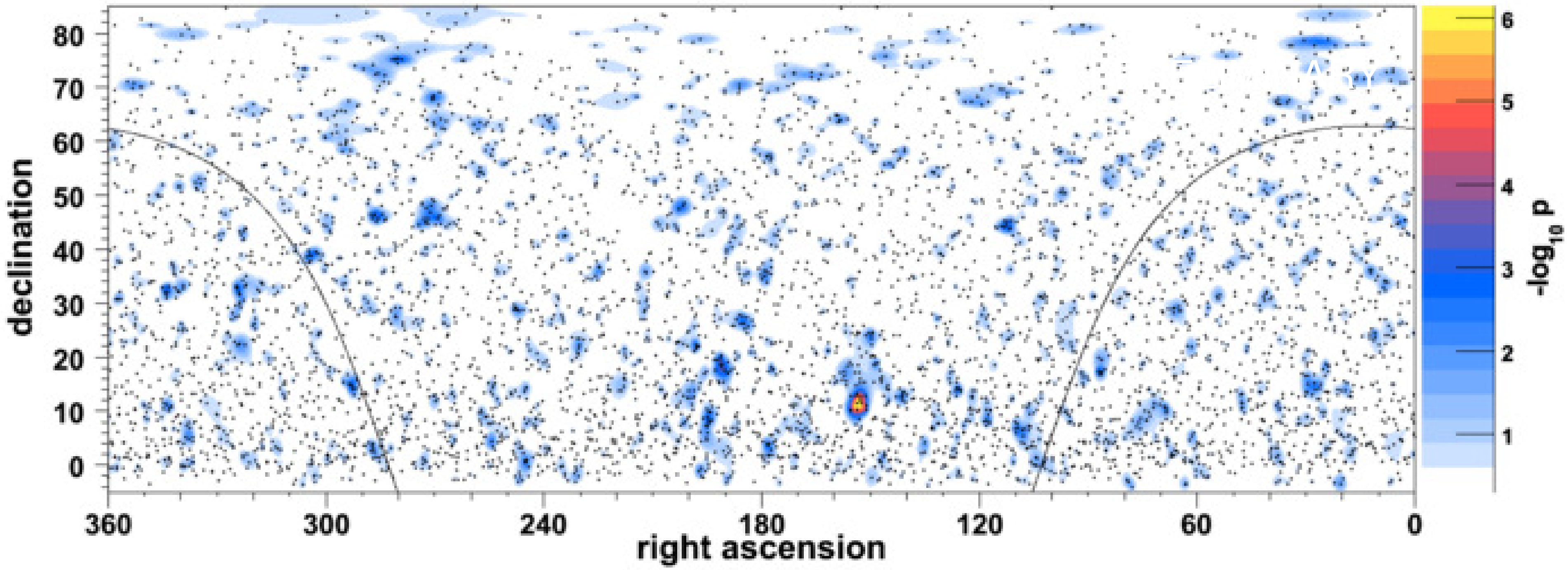




Location: <u>equatorial coordinates</u>
RA: 153.375° = HA: 10h13m30s (J2000.0)
Dec: +11.375° = 11d22m30s

Pre-trial: p-value = $7 \cdot 10^{-7}$
Post-trial: p-value = 0.0134

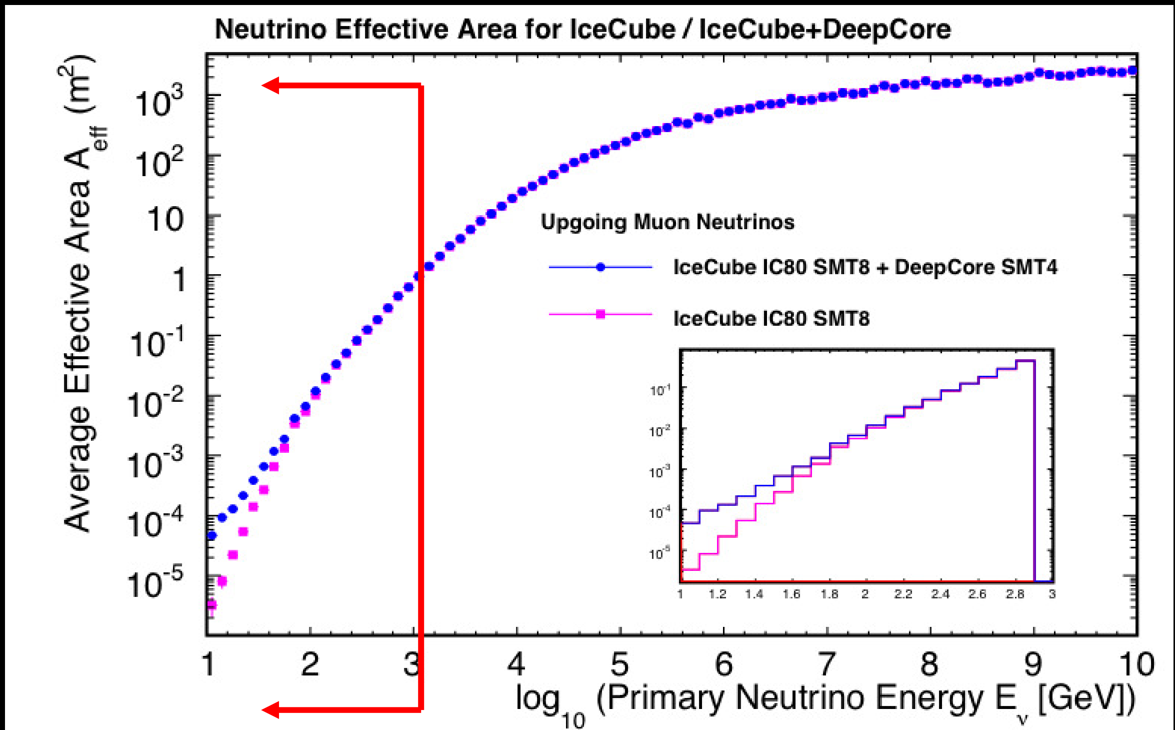
IceCube-22 sky-map, 275.70 days, 5114 events



- This can happen in 1.34% of random cases
- Compatible with a fluctuation of the background
- IceCube 40 new analysis ready before summer ‘09

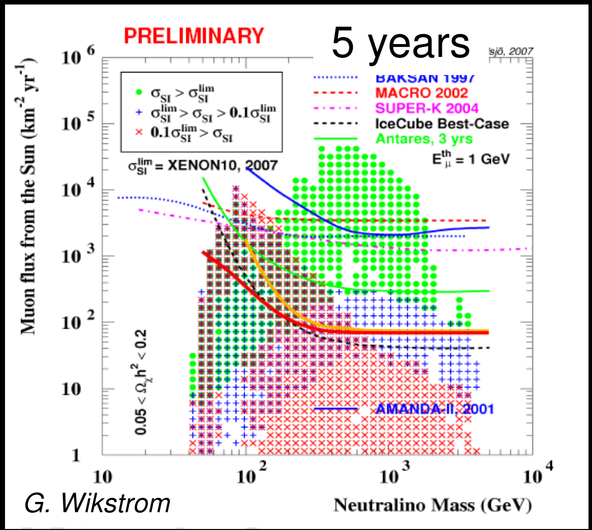
Towards Lower Energy (E < 1 TeV)

Trigger Level



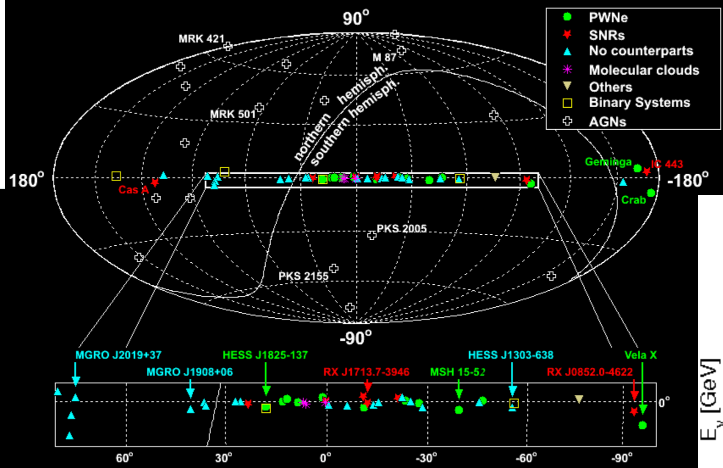
Towards Lower Energy (E < 1TeV)

1- Indirect Dark Matter Search

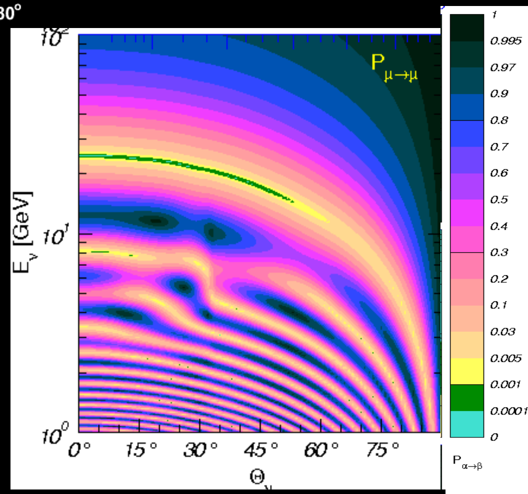


G. Wikstrom

2- Galactic Gamma-ray Sources



3- Atmospheric Neutrinos



E. Akhmedov, M. Maltoni,
A. Smirnov, hep-ph/0612285

IceCube DeepCore

Lower energies → denser string spacing

IceCube DeepCore (ICDC):

Proposed 2007

Design Study 07-08

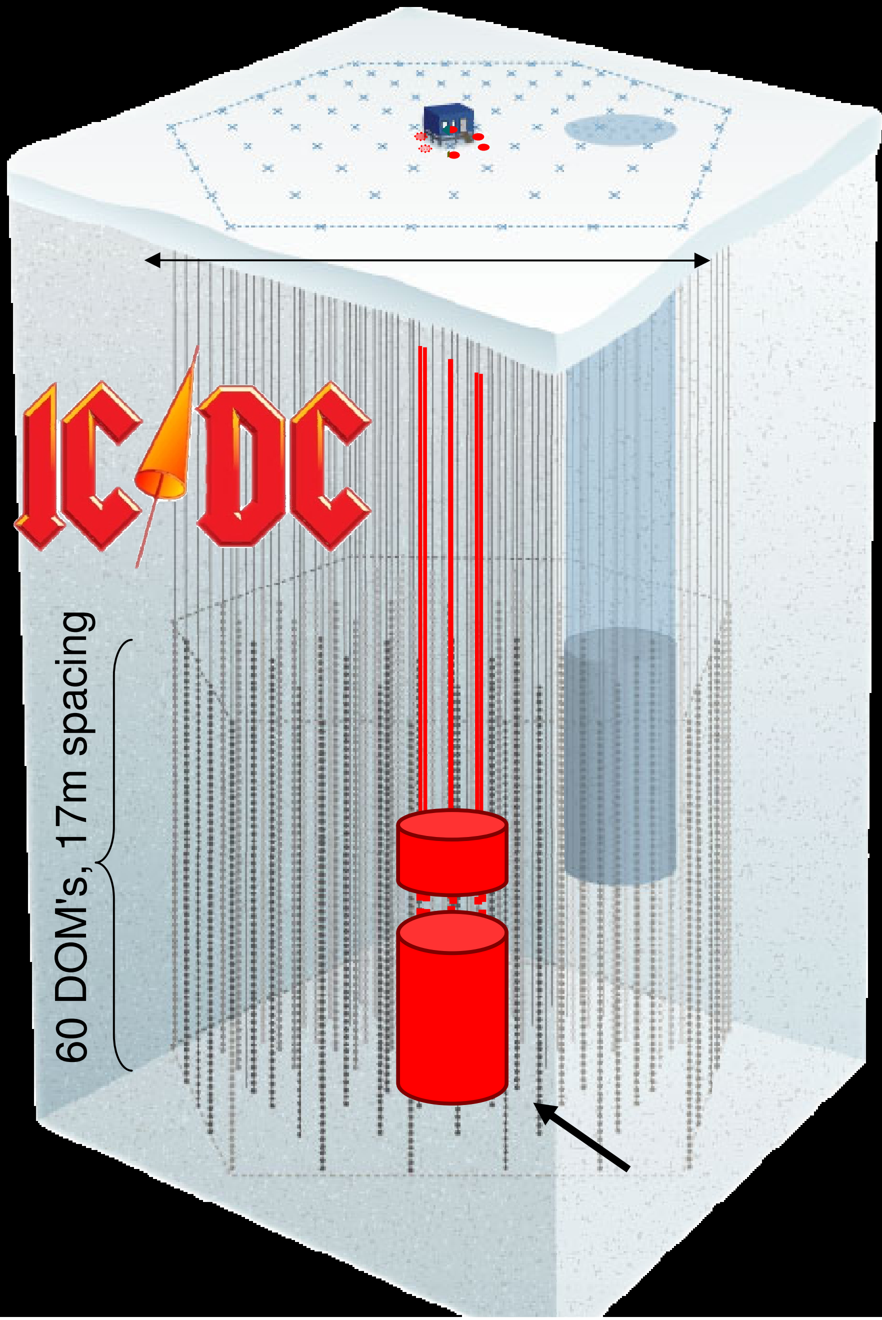
Approved (NSF) Spring 08

Financed by

Swedish Wallenberg Foundation,

BMBF

Belgium Ministry of Science



IceCube DeepCore

Lower energies → denser string spacing

IceCube DeepCore (ICDC):

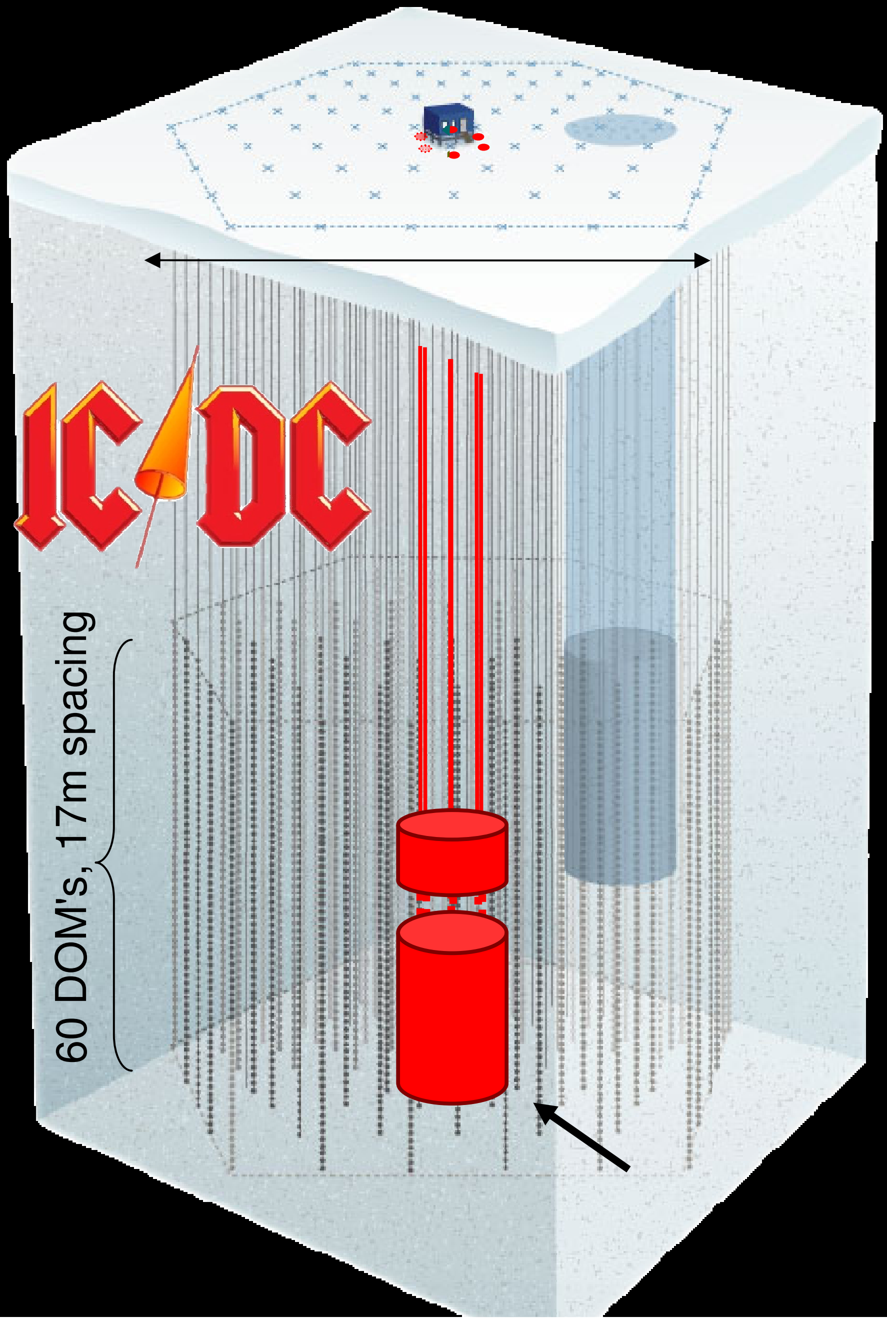
6 extra strings

60 DOM's each (7 m spacing)

Deep Ice is very clean

High QE PMT's

~ 15 Megaton detector



We can look UP ....

Challenge:

Reject down-wards muons

(~ 10^6 μ : 1ν)

Strategy:

Muon Veto: outer part of the detector

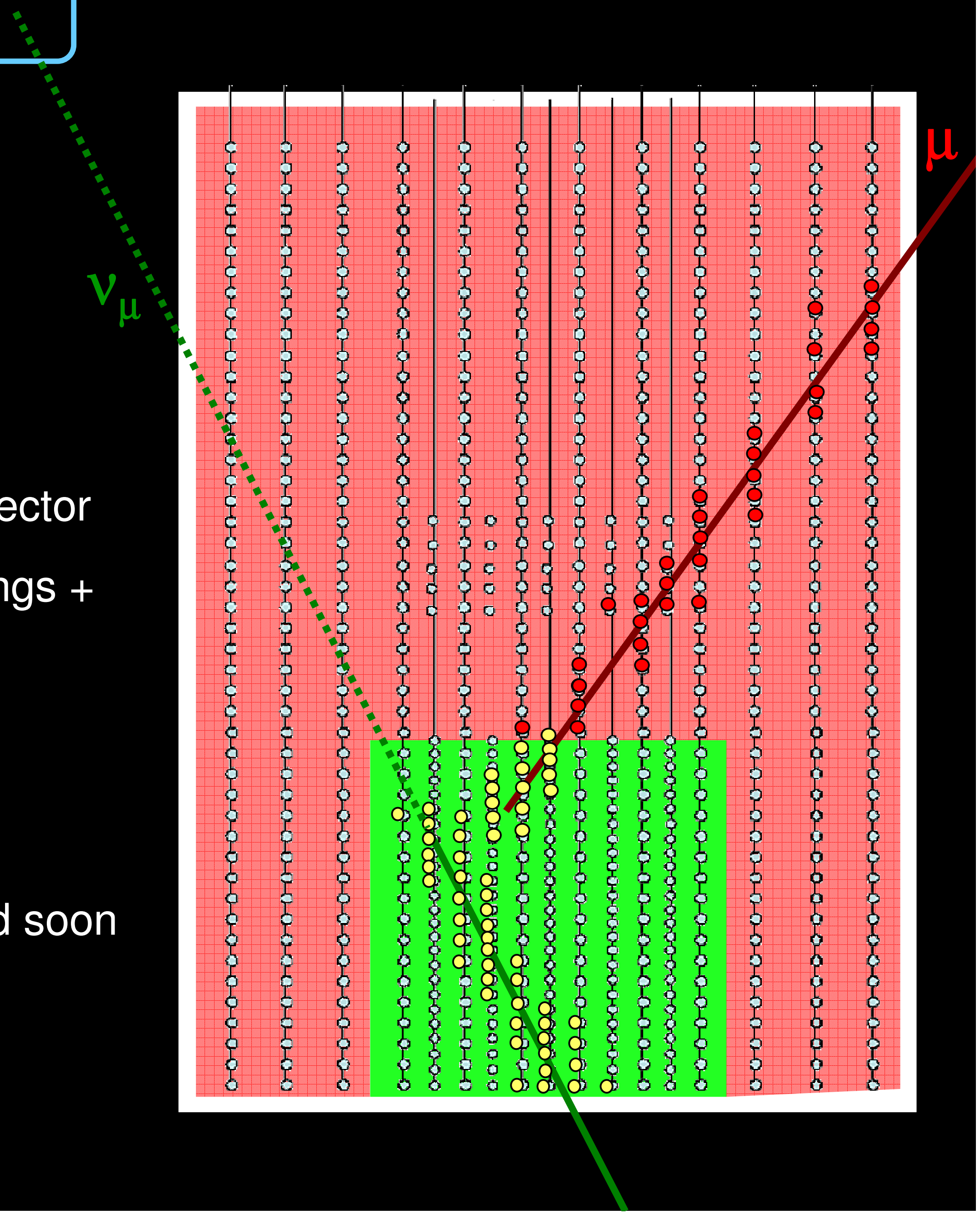
Fiducial volume: Deep Core strings +

IceCube central strings

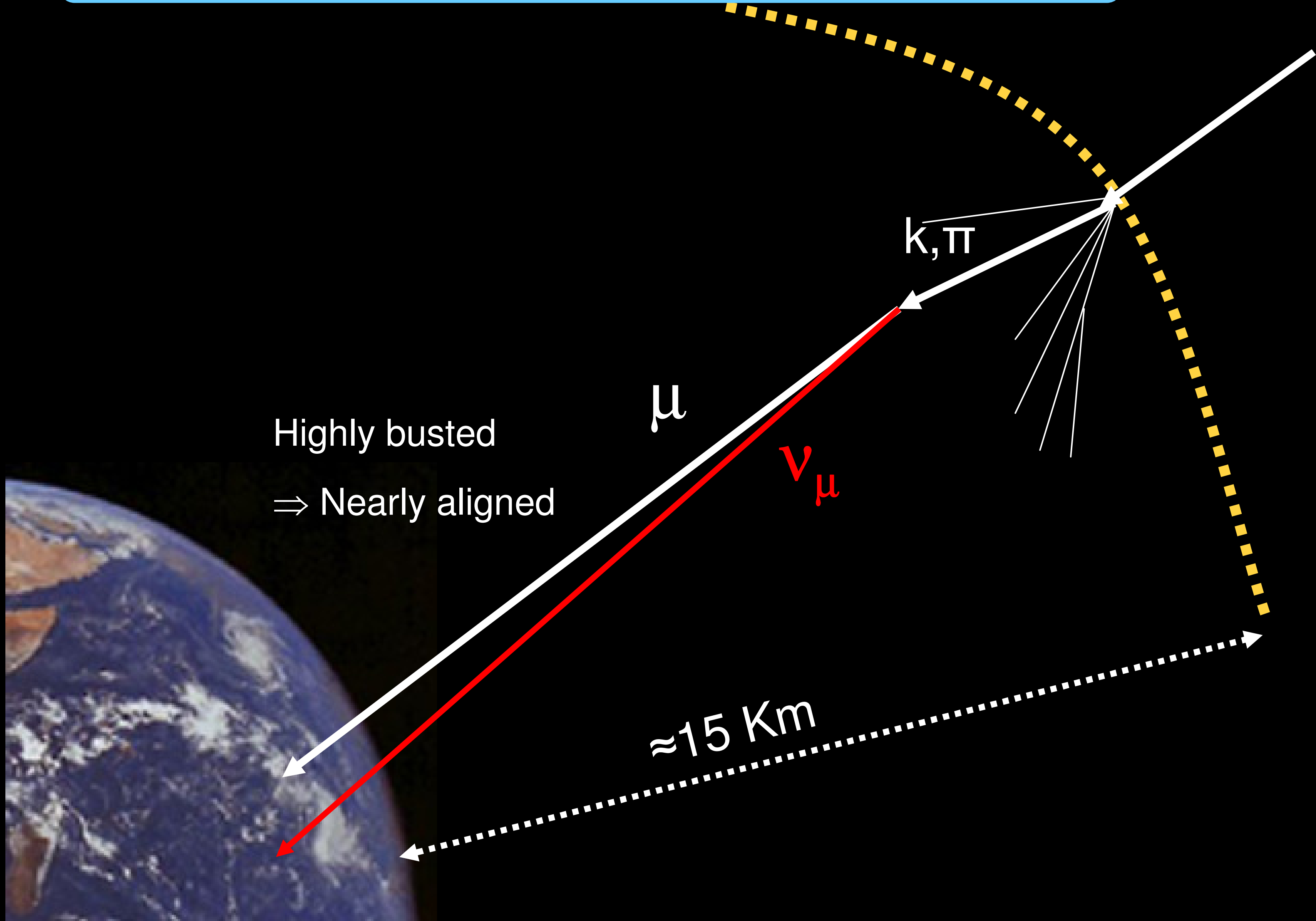
Status:

Muon Veto: feasible!

First ICDC string: to be deployed soon



…. AND veto Atmospheric Neutrinos



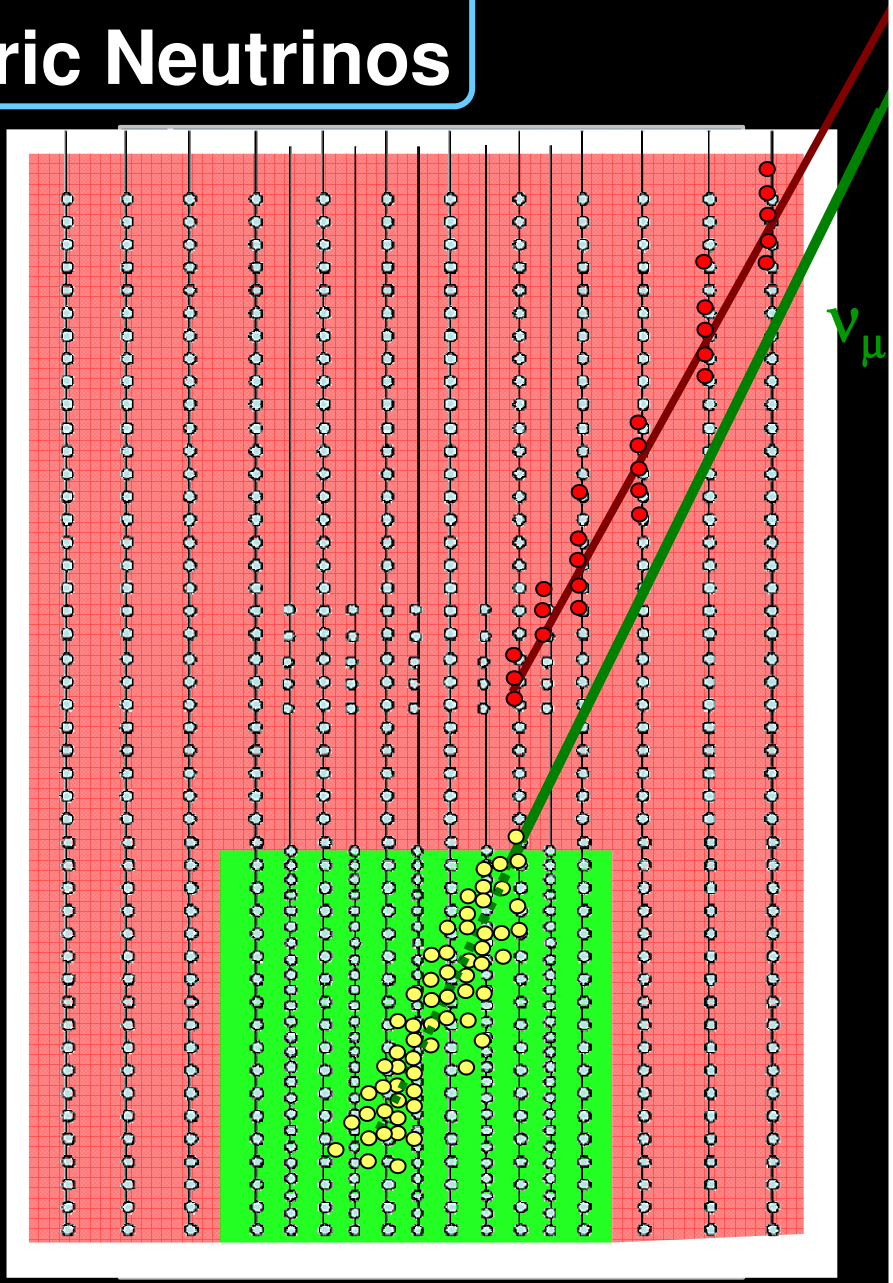
…. AND veto Atmospheric Neutrinos

Strategy:

Muon Veto: will veto atmospheric neutrinos

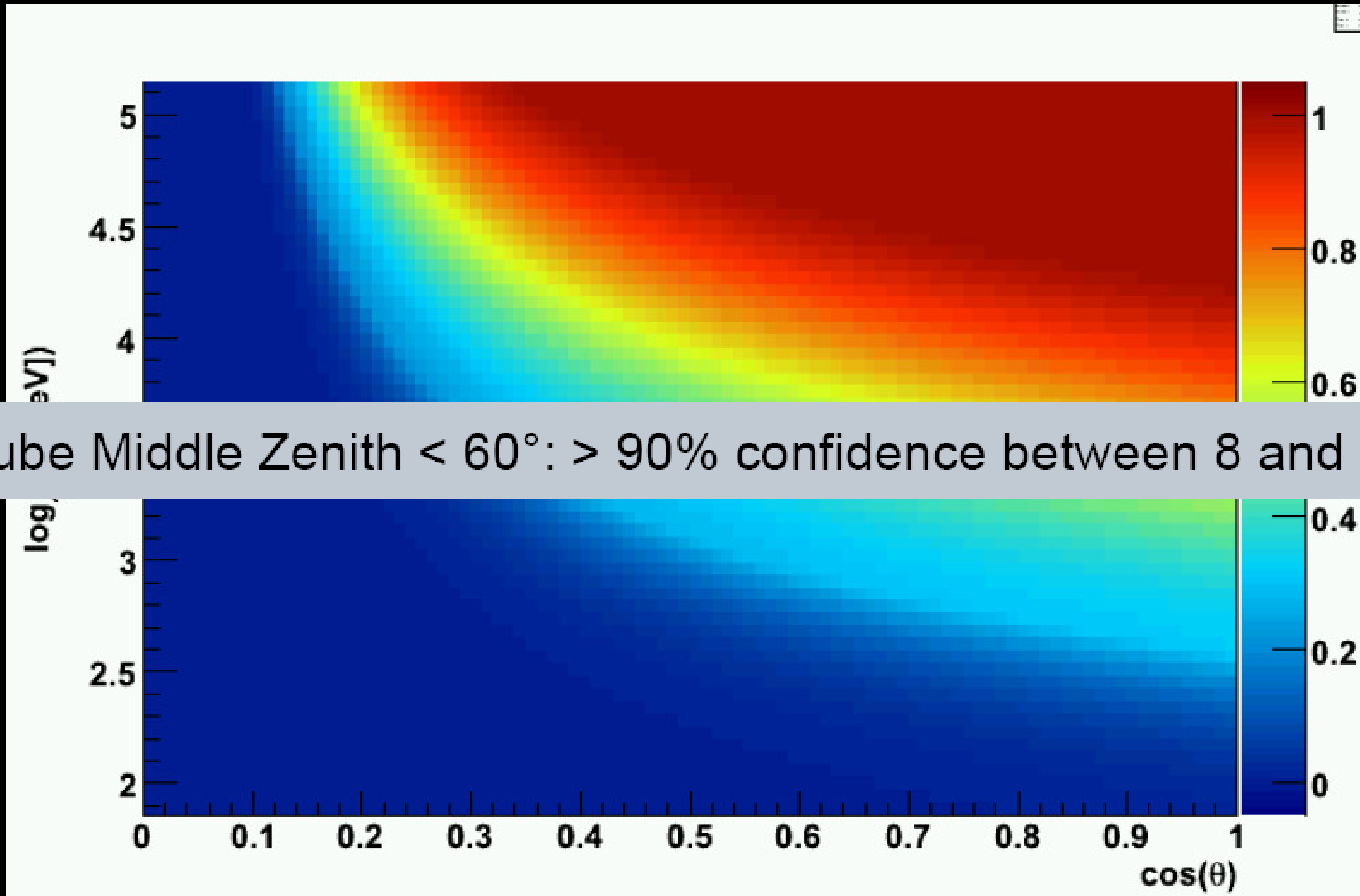
Status:

MonteCarlo study, analytical calculation



…. Atmospheric Neutrinos Veto Probability

Depth: 1800 mwe



IceCube Middle Zenith < 60°: > 90% confidence between 8 and 23 TeV

[S.Schönert, T. Gaisser, E.R., O. Schulz, draft submitted]

Conclusions

- Cosmic (Rays) Particles:
  - Result of a complex flow chart
  - Still many questions open
  - Auger results

- Neutrino Astronomy: status
  - In water: Antares completed (first generation neutrino telescope)
  - In ice: IceCube ½ deployed (km^3 scale generation)
  - Highly complementary

Conclusions

- IceCube provides exiting physics results
- Rich Physics Program: not cited in this talk
  - Indirect search of Dark Matter
  - Search for SuperNovae, GRBs explosion
  - Measurements of primary cosmic rays with IceTop
  - GZK neutrinos
- Prospects: contribute to one or more blocks of the cosmic flow chart
  - Unambiguous prove of acceleration of hadrons
  - Unambiguous connection cosmic accelerators, cosmic rays
- Paradigm Shift: IceCube Deep Core

~ Frohe ~
Weihnachten
~

BACKUP

Neutrino Astronomy

$$\Phi_\nu (E, \Omega) = \Phi_{\text{atm}} + \Phi_{\text{galactic}} + \Phi_{\text{extra- galactic}}$$

Cosmic ray showers in
the Earth's atmosphere:
- π, K decay

$\propto E^{-3.7}$
~ 20% uncertainty

"diffuse" flux:
CR interaction with
interstellar gas

"point-like":
galactic sources

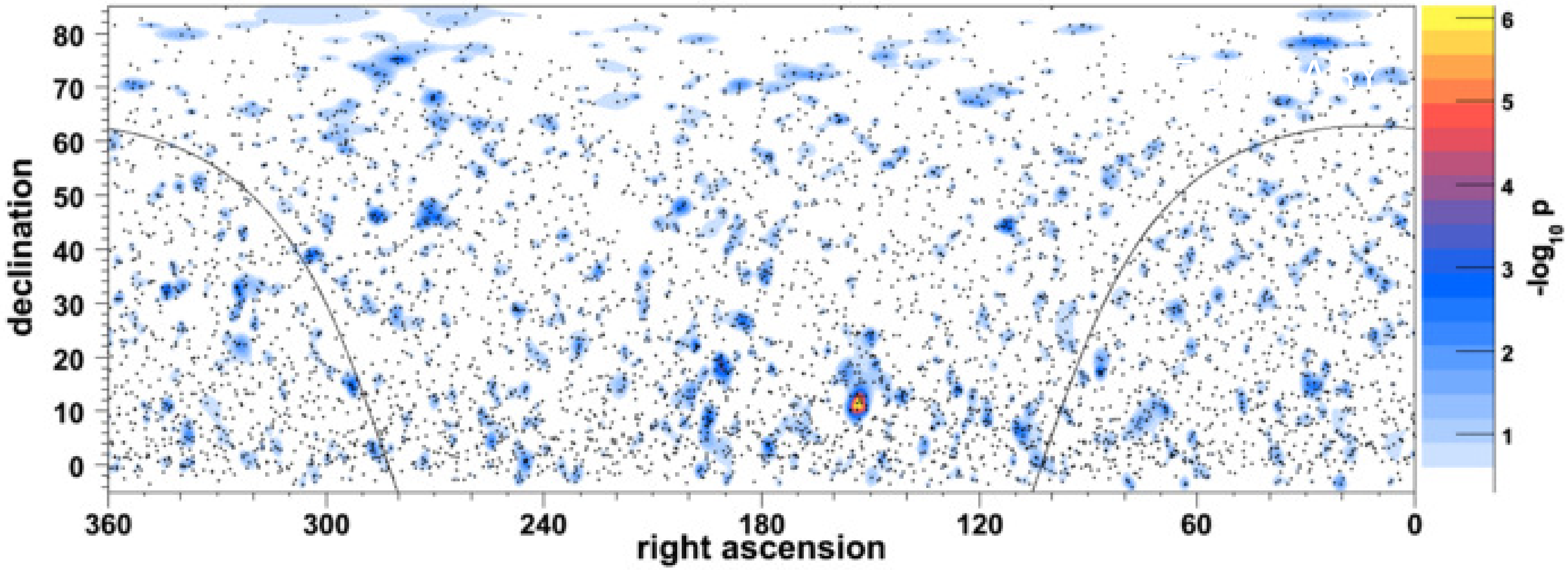
$\propto E^{-2 \pm ?}$

"diffuse" flux:
p decay from pγ interaction
with 2.7^{o}K cosmic radiation

"point-like":
extra-galactic sources

$\propto E^{-2 \pm ?}$

IceCube-22 sky-map, 275.70 days, 5114 events



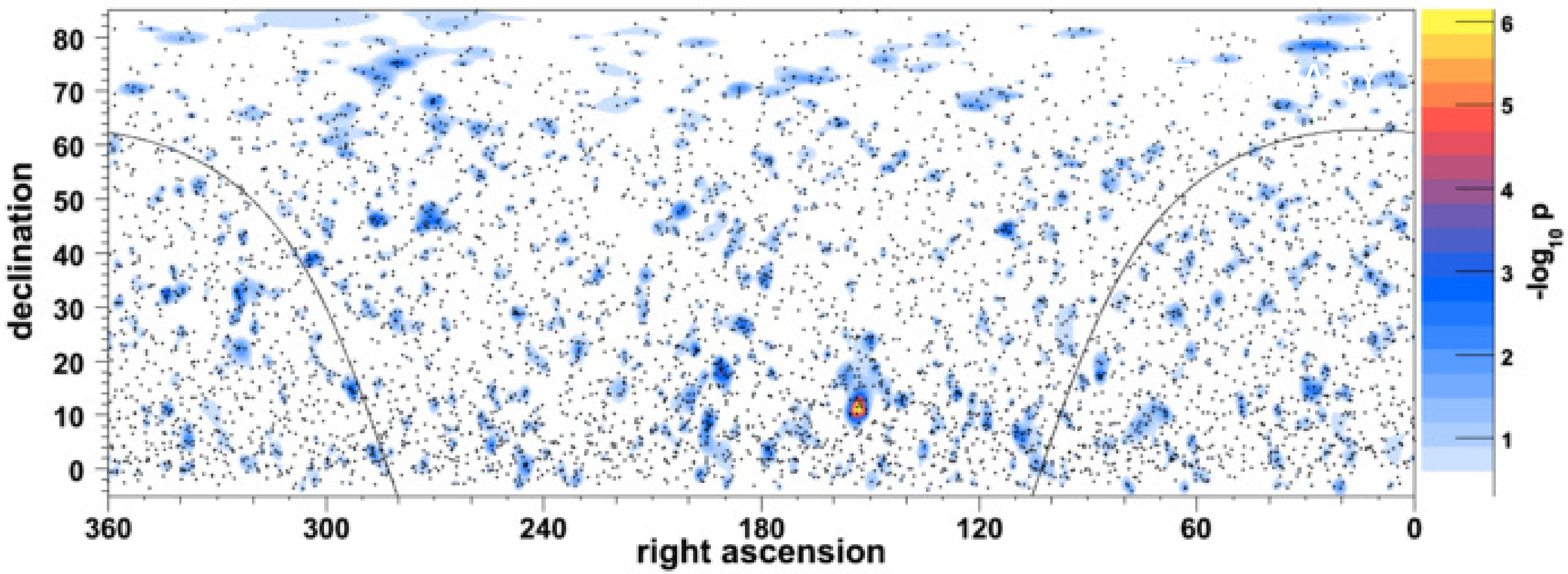
Signal pdf: $$S_i = \frac{1}{2\pi{\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

Spatial probability density function
Gaussian psf

Energy estimator:
nch = nr of hit channels

Source hp uses individual point spread functions for each event, based on angular uncertainty estimate of track reconstruction and energy estimators (MonteCarlo)

IceCube-22 sky-map, 275.70 days, 5114 events



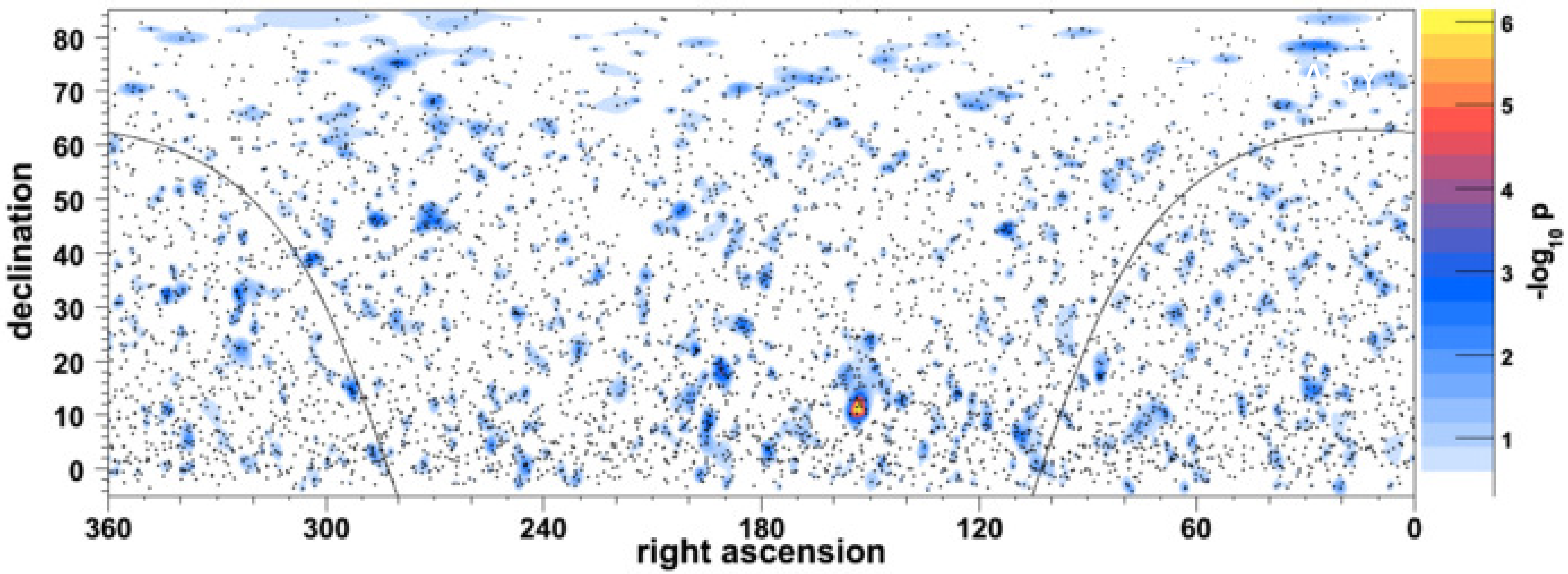
Background pdf: $\mathcal{B}_i = B_{\text{zen}} \cdot P_{\text{atm}}(E_i)$

Declination distribution of data events

Distribution of energy estimator for data

Background hp uses data, no MonteCarlo dependences
p-values solid

IceCube-22 sky-map, 275.70 days, 5114 events



Partial probability for each event

$$P_i(x, n_s) = \frac{n_s}{N} S_i(x) + \frac{N - n_s}{N} B_i(x)$$

Likelihood function

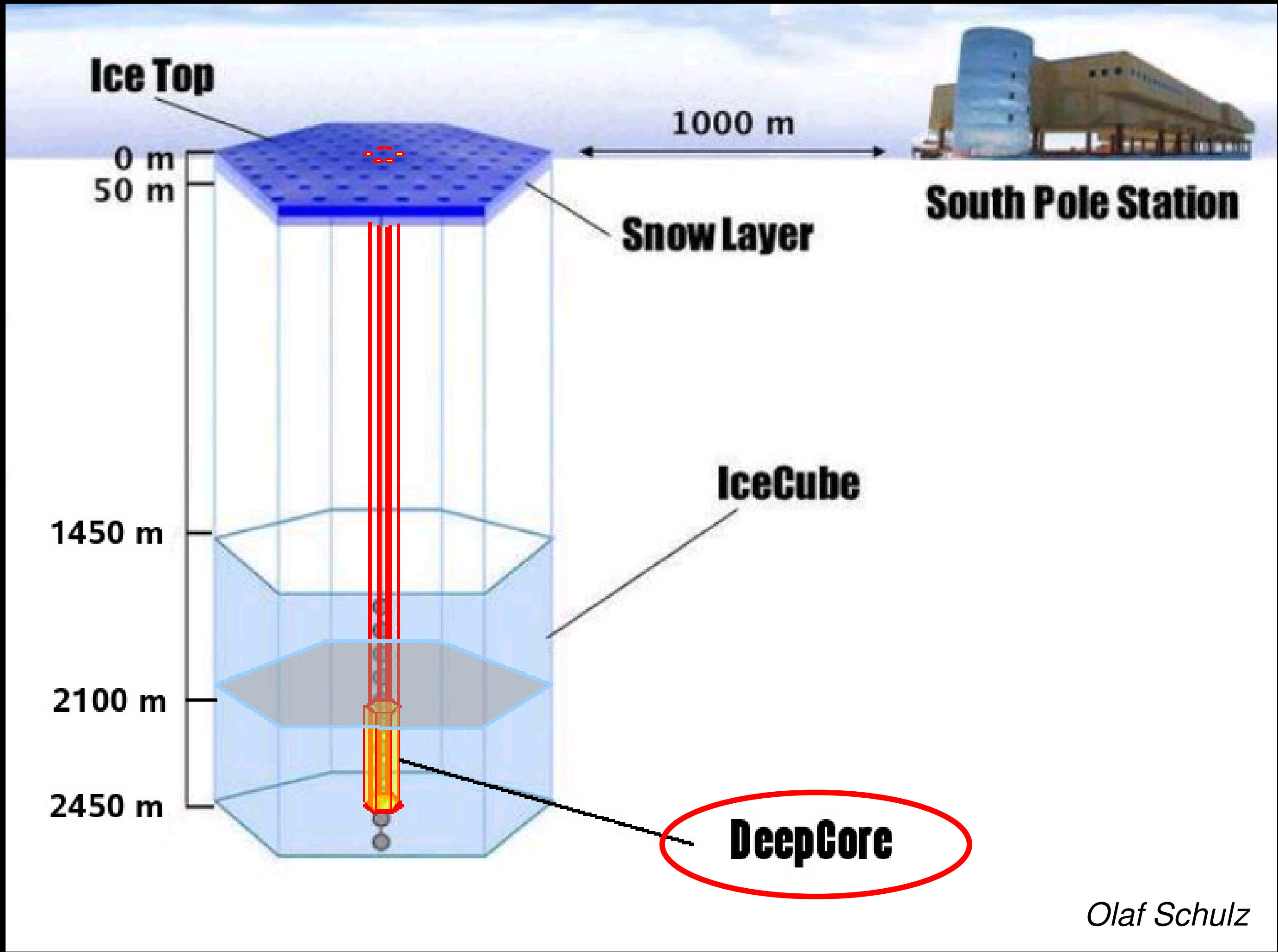
$$L(n_s) = \prod P_i(x_i, n_s)$$

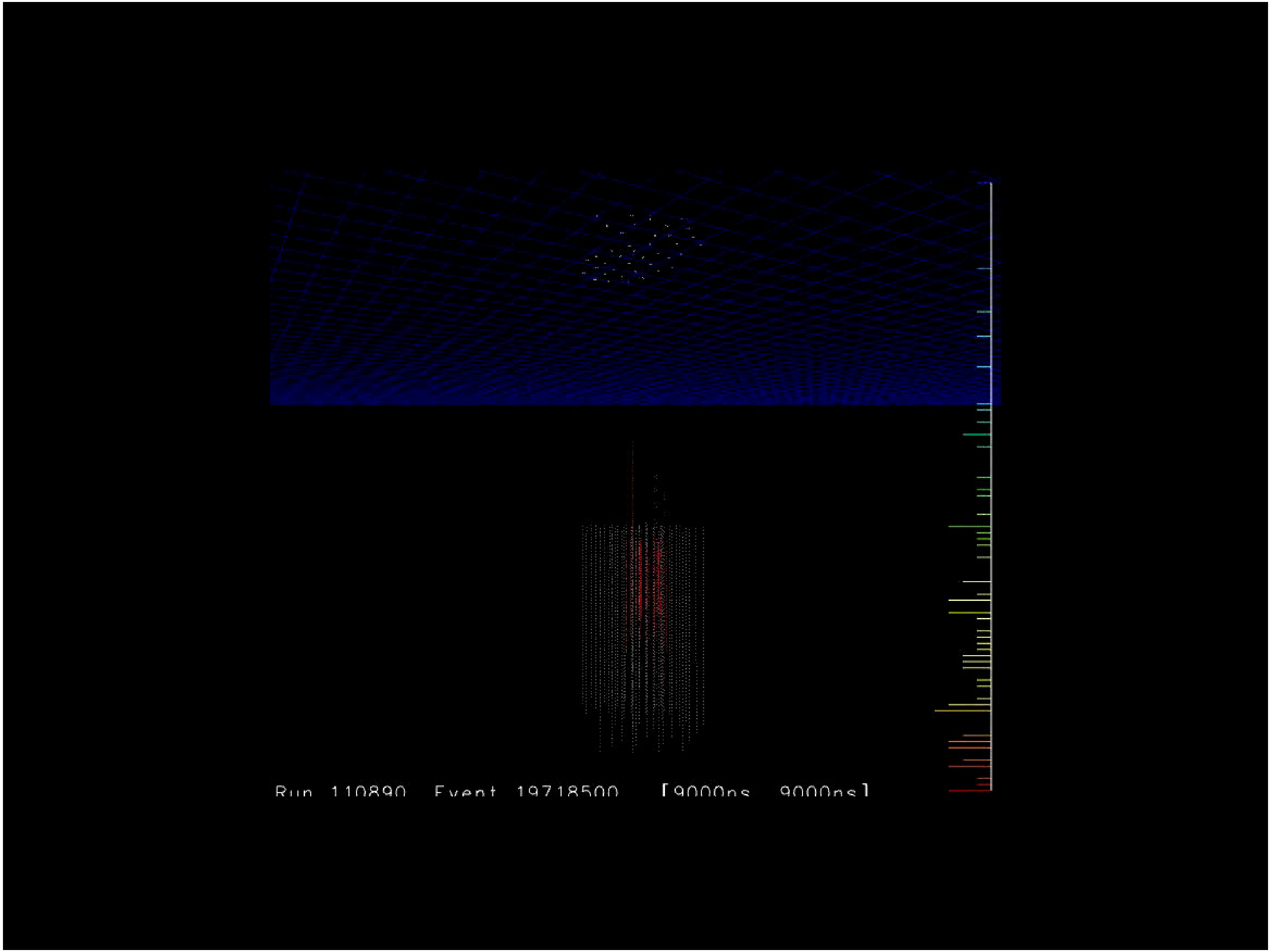
Log likelihood ratio

$$\log \lambda = \log \frac{L(\hat{n}_s)}{L(n_s = 0)}$$

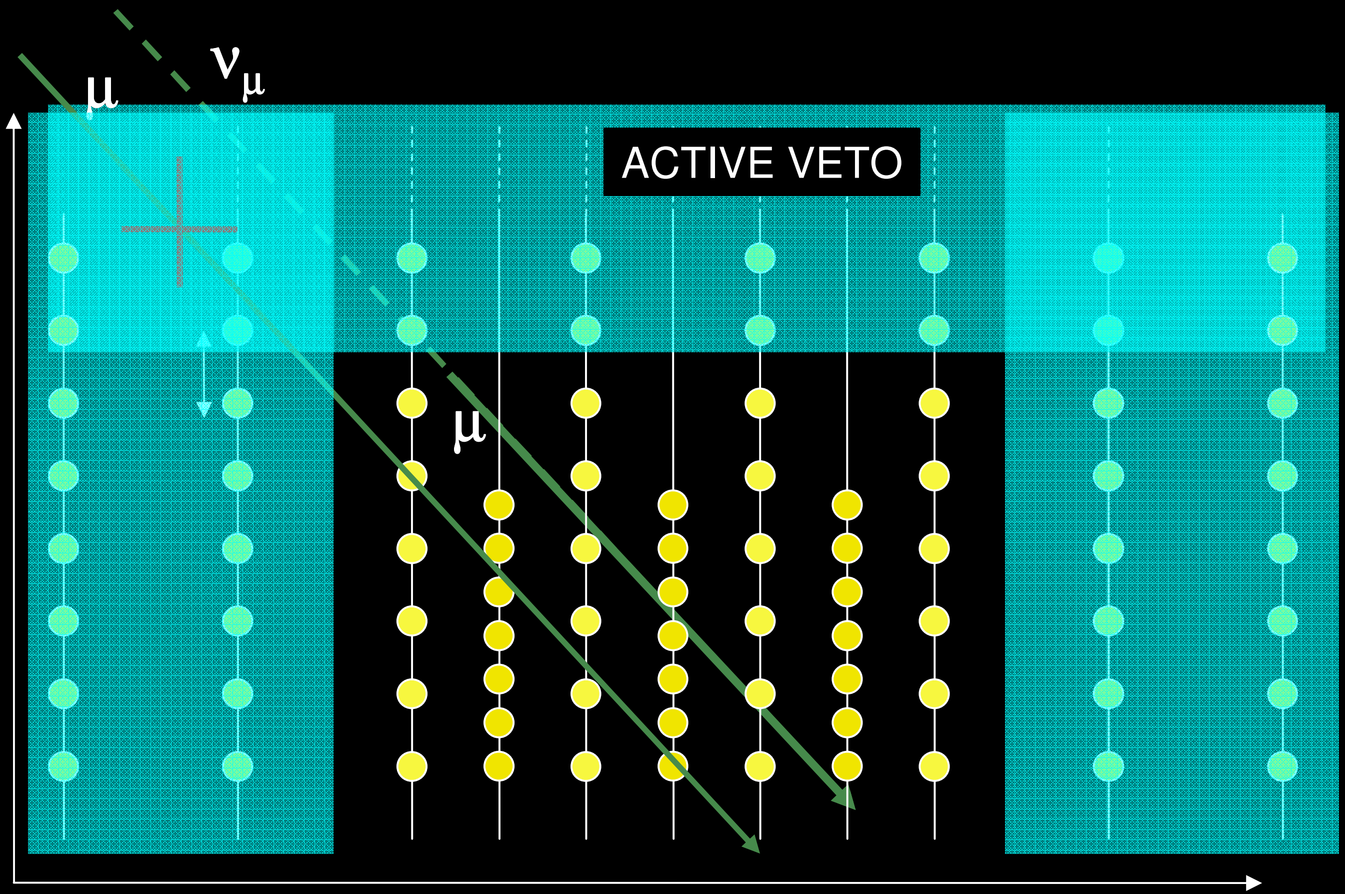
Method 1: IceCube Deep Core (IC-DC)

E.R., VLVnT 2008




Run 110890 Event 19718500 [9000ns 9000ns]

Method 1: IceCube Deep Core (IC-DC)

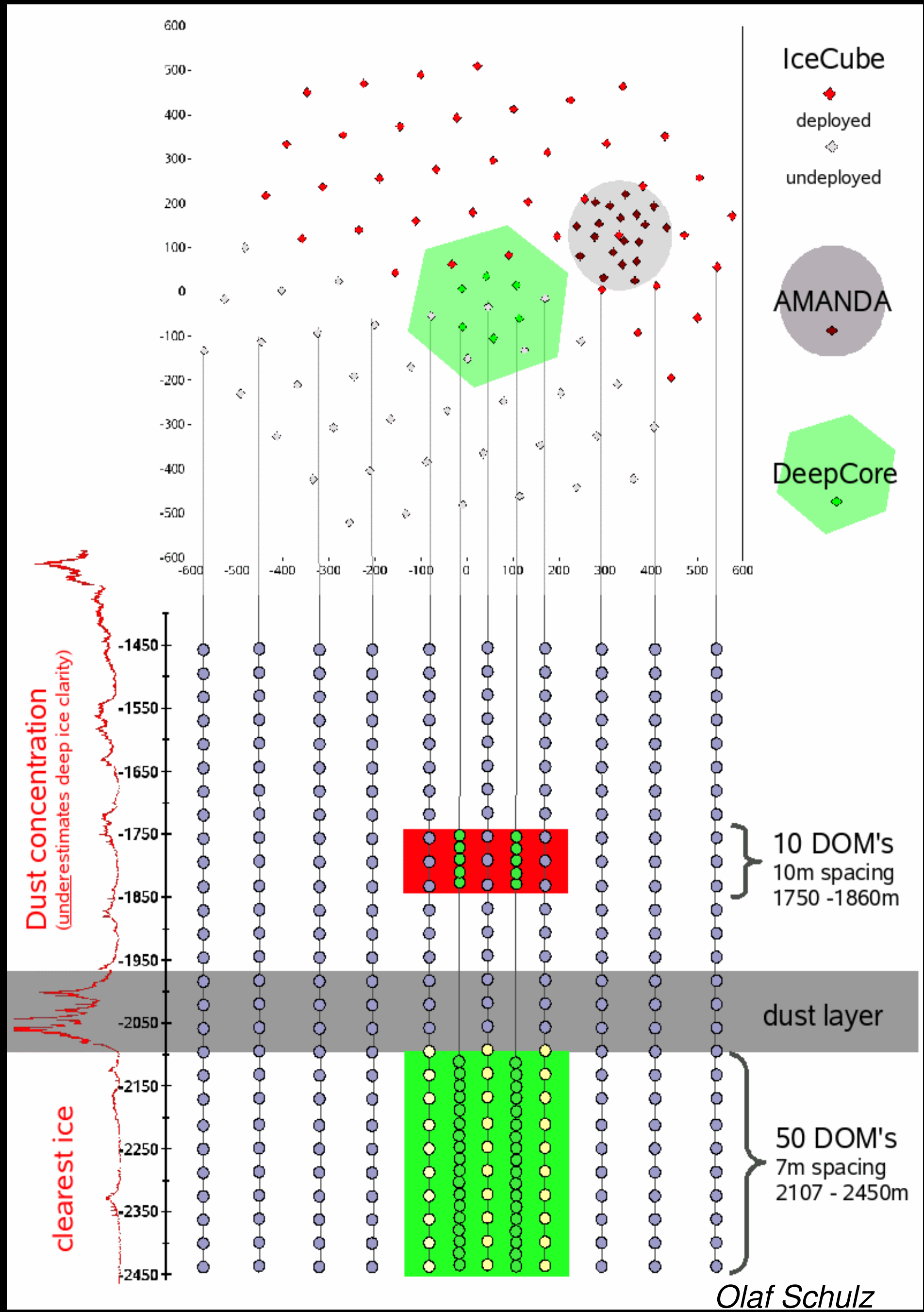


Access the Southern Hemisphere

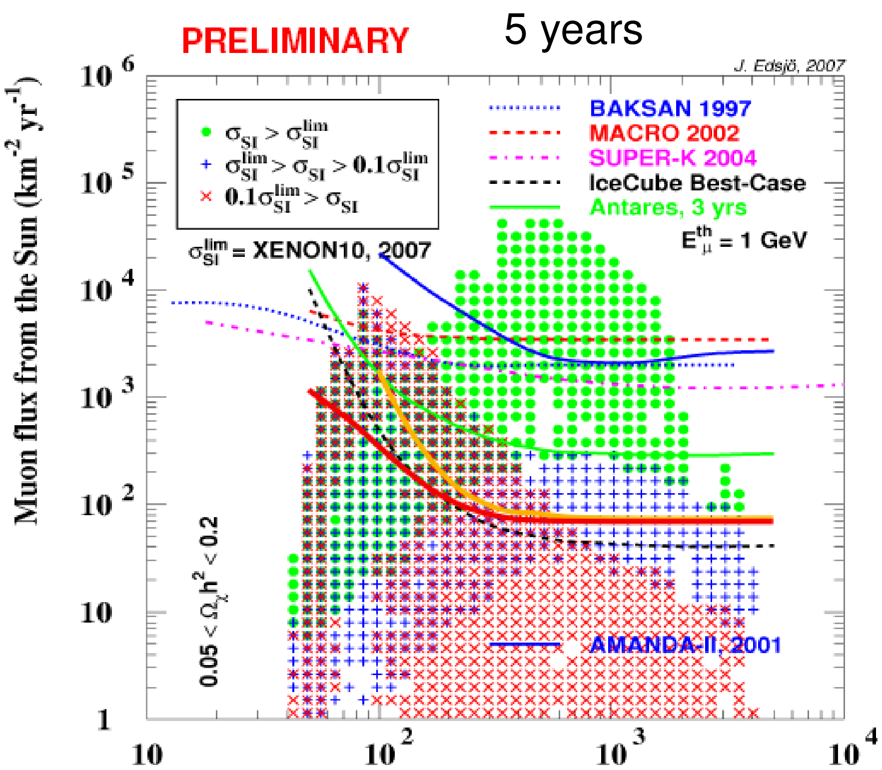
IceCube Deep Core (IC-DC)

6 strings founded and approved!
(Sweden, Germany, Belgium)

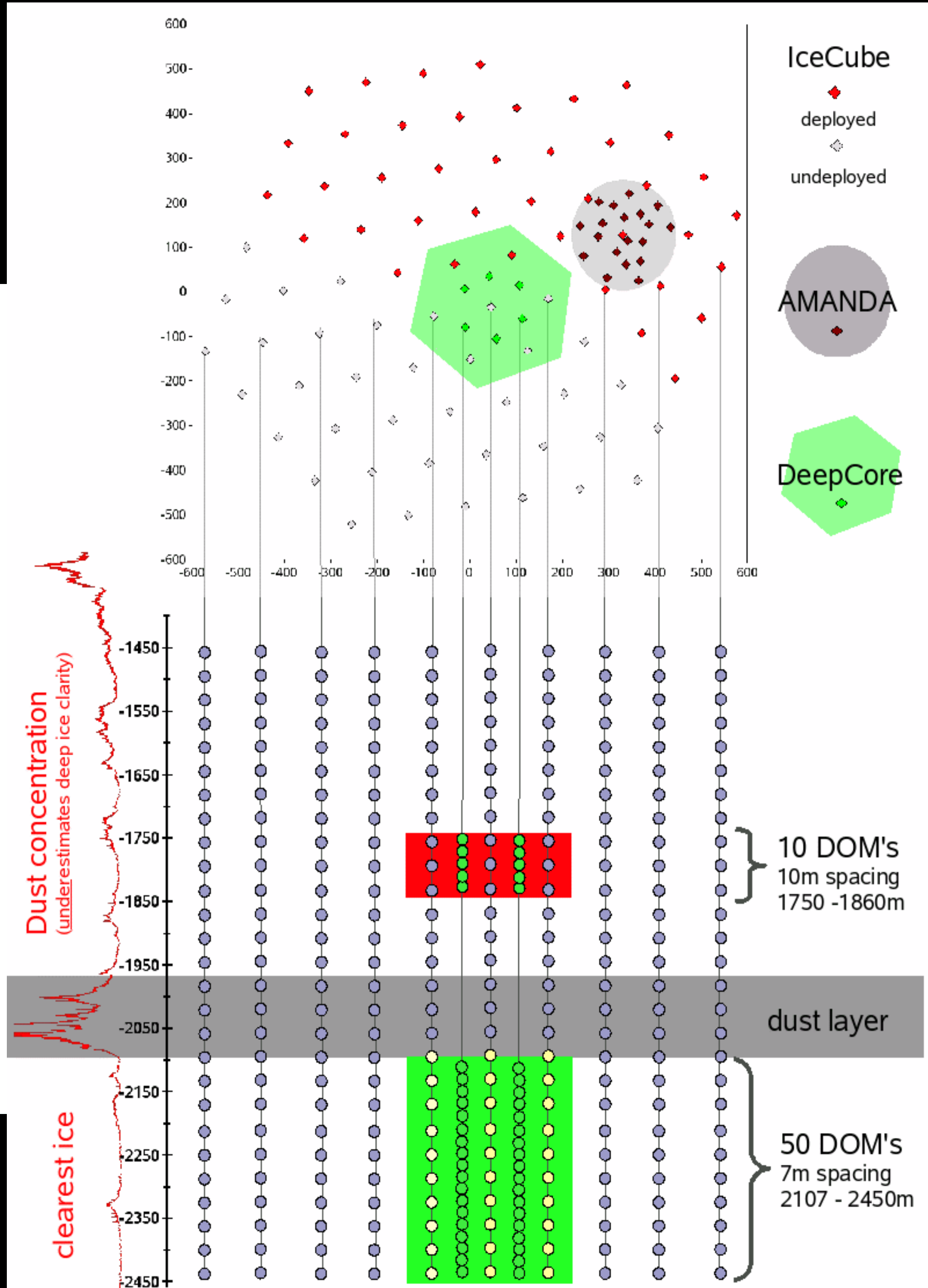
- 60 DOMs per string
- 50 DOMs below dust layer
- 7m spacing
- 1st IC-DC sting 08-09 season
- Veto efficiency 10^6
- Sensitivity for physics scenario under way



IceCube Deep Core (IC-DC)



G. Wikstrom



Olaf Schulz

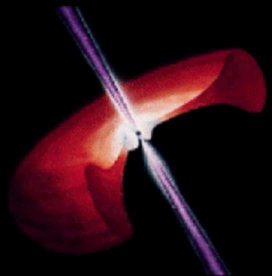
Muon Channel Point Source

Multi-messenger argument

Non-thermal activity ⟶ Single source candidate

32 sources pre-selected

Active Galactic Nuclei

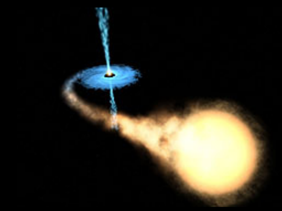


	Nr. Observed / Nr. expected	Flux Upper Limit 10^{-7} GeV cm^{-2} s^{-1}
Mkn 421	6 / 7.37	0.42
Mkn 501	8 / 6.39	0.85
1ES1959+650	5 / 4.77	0.78
3C273	8 / 4.72	1.00
M87	6 / 6.08	0.49

The IceCube coll., astro-ph/0611063

32 sources pre-selected

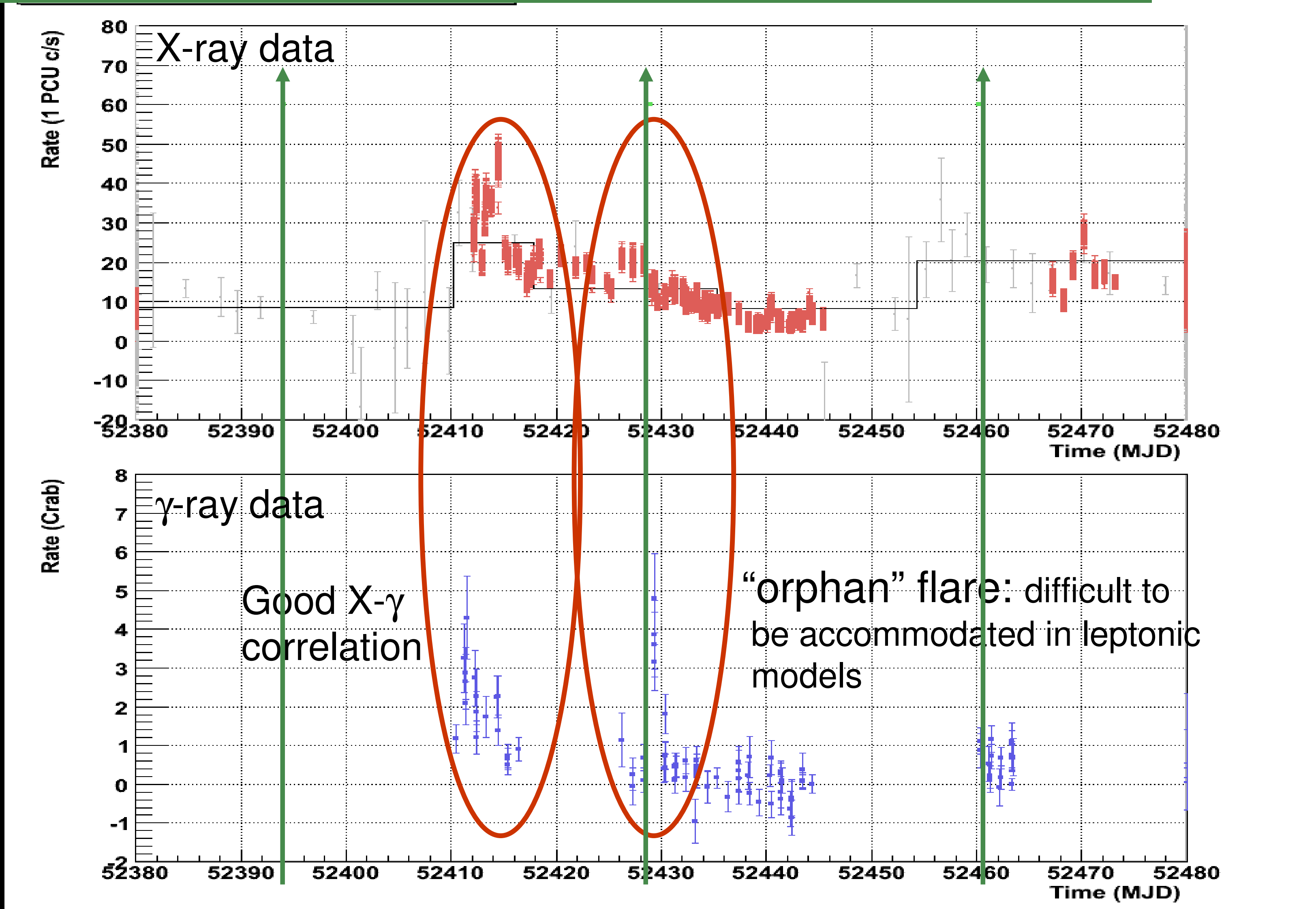
X-ray Binary Systems



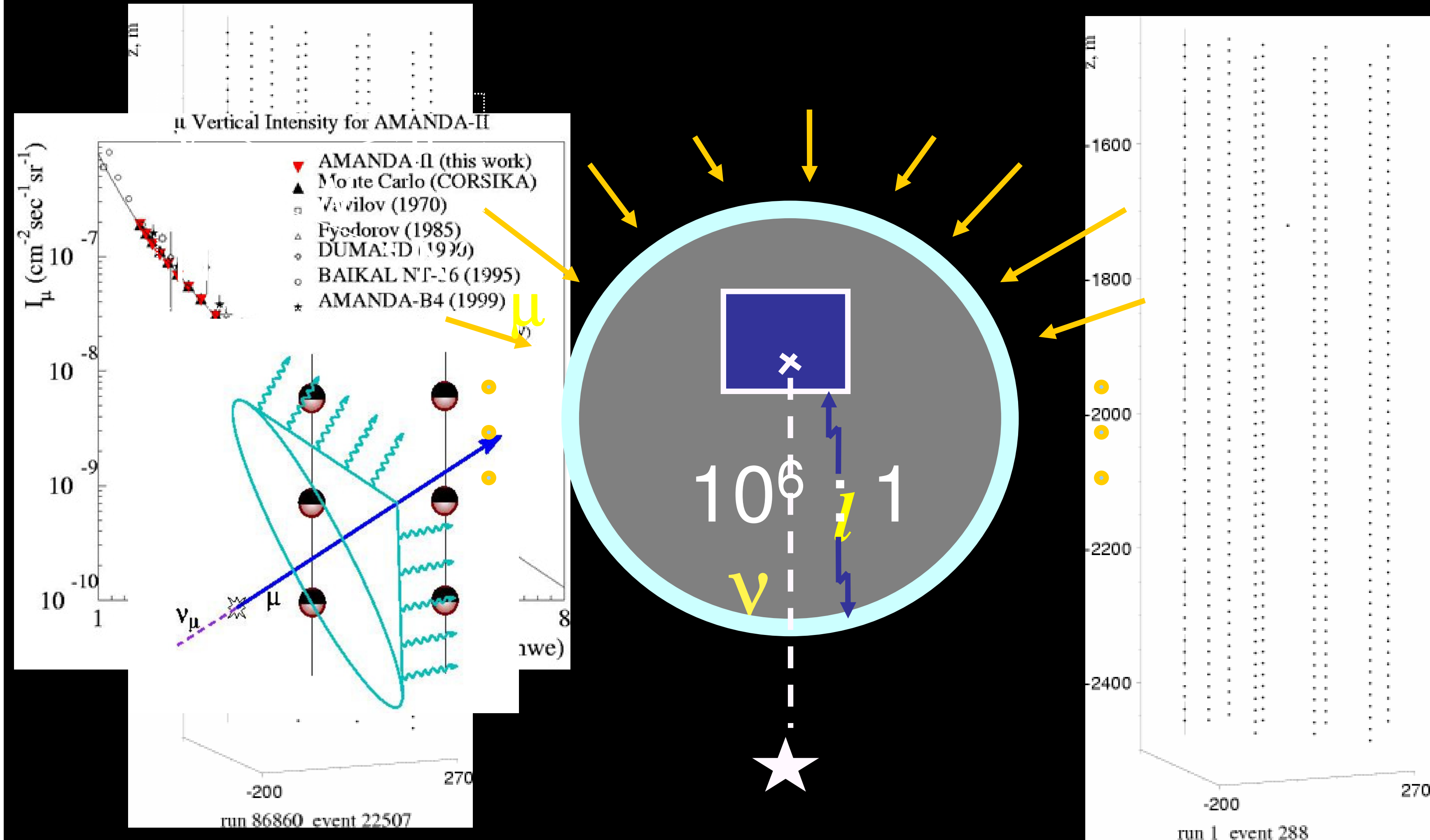
	Nr. Observed / Nr. expected	Flux Upper Limit 10^{-7} GeV cm^{-2} s^{-1}
SS433	4 / 6.14	0.27
LSI +61 303	5 / 4.81	0.74
Cyg X-1	8 / 7.01	0.77
Cyg X-3	7 / 6.48	0.68

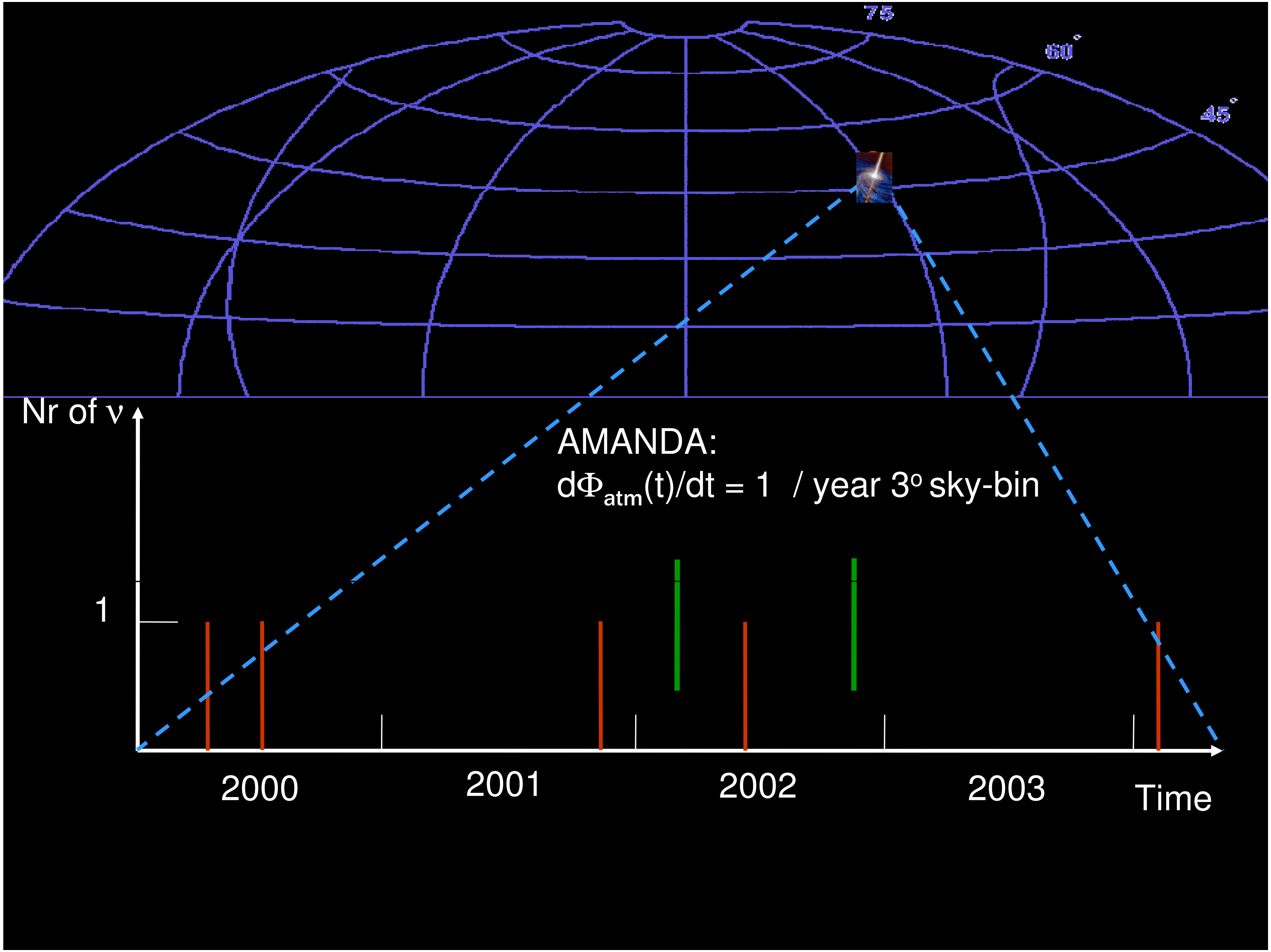
The IceCube coll., astro-ph/0611063

A first hint: 1ES1959+650

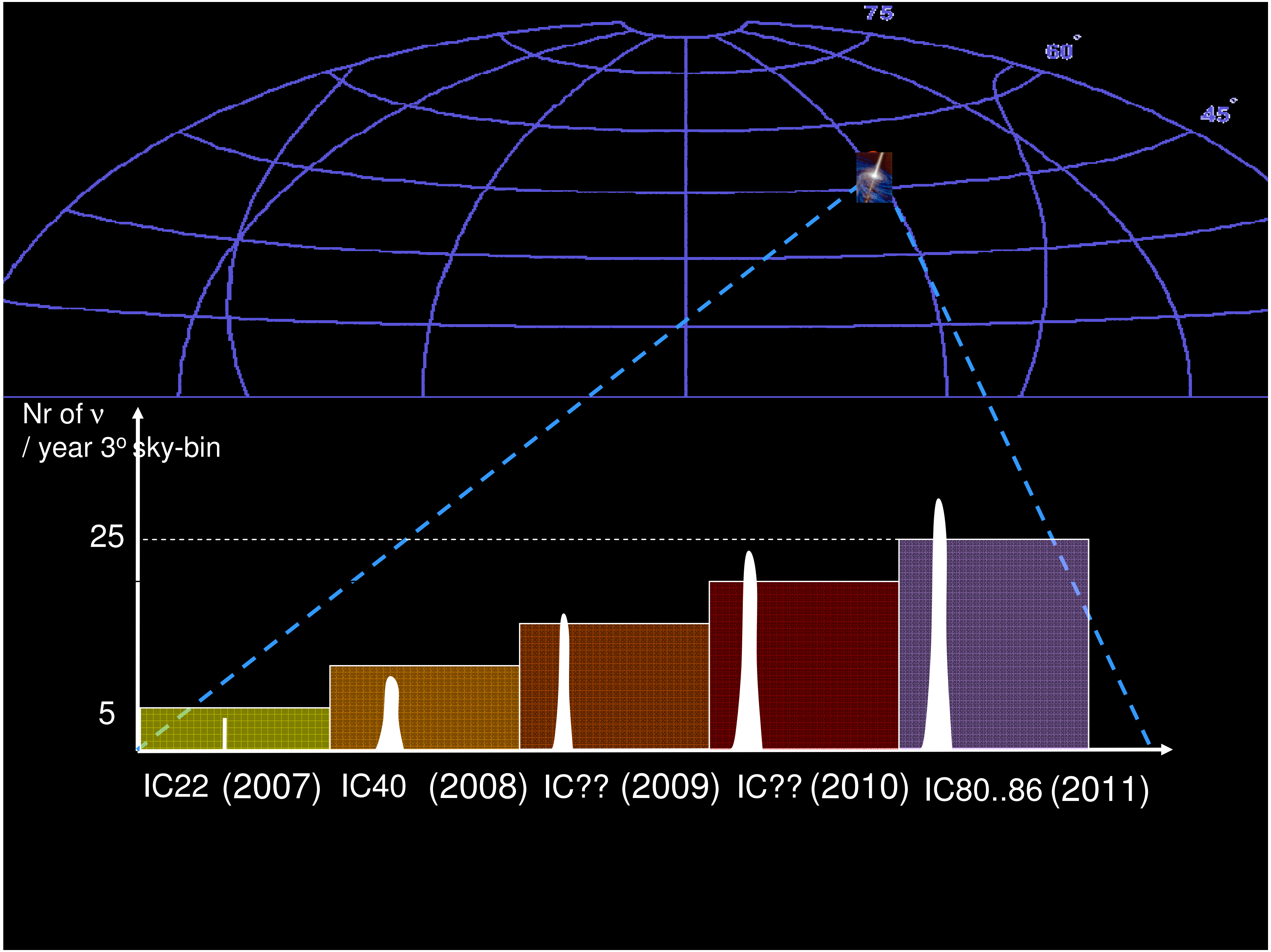


ν signal identification

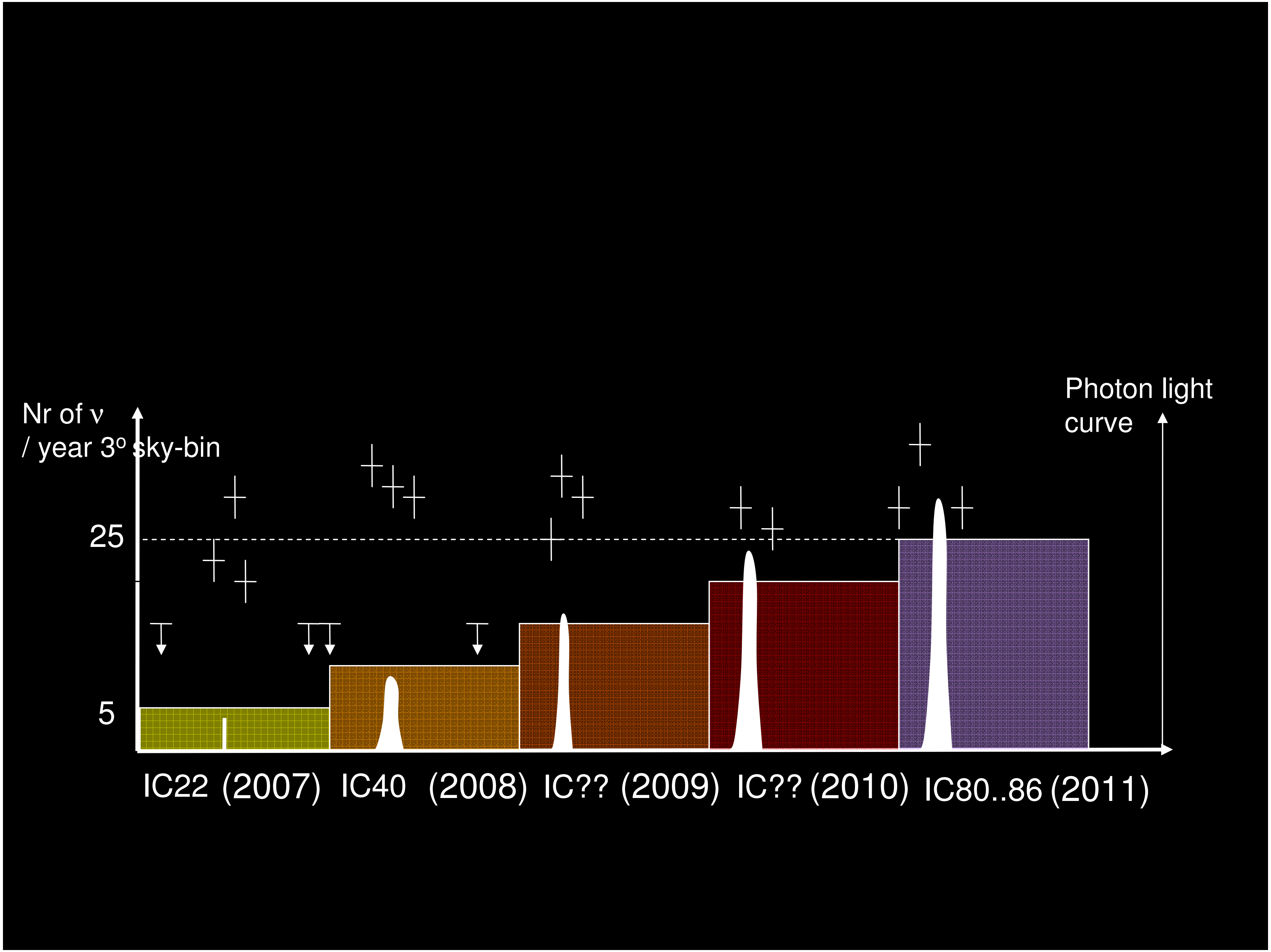




75
60°
45°
Nr of ν
1
AMANDA:
$d\Phi_{atm}(t)/dt = 1$ / year 3^{o} sky-bin
2000
2001
2002
2003
Time



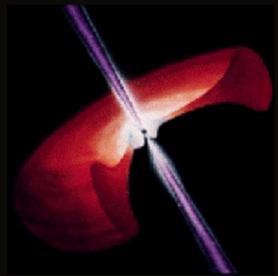
75
60°
45°
Nr of ν
/ year 3° sky-bin
25
5
IC22 (2007)
IC40 (2008)
IC?? (2009)
IC?? (2010)
IC80..86 (2011)



Nr of ν
/ year 3° sky-bin
25
5
Photon light
curve
IC22 (2007)
IC40 (2008)
IC?? (2009)
IC?? (2010)
IC80..86 (2011)

Method 2: multiwavelength approach

Active Galactic Nuclei



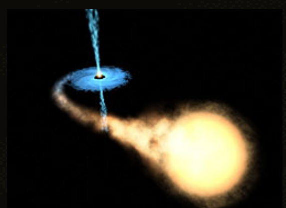
- Mkn 421
- Mkn 501
- 1ES1959+650

X- and γ-rays

- 3C273

Radio and X-rays

X-ray Binary Systems

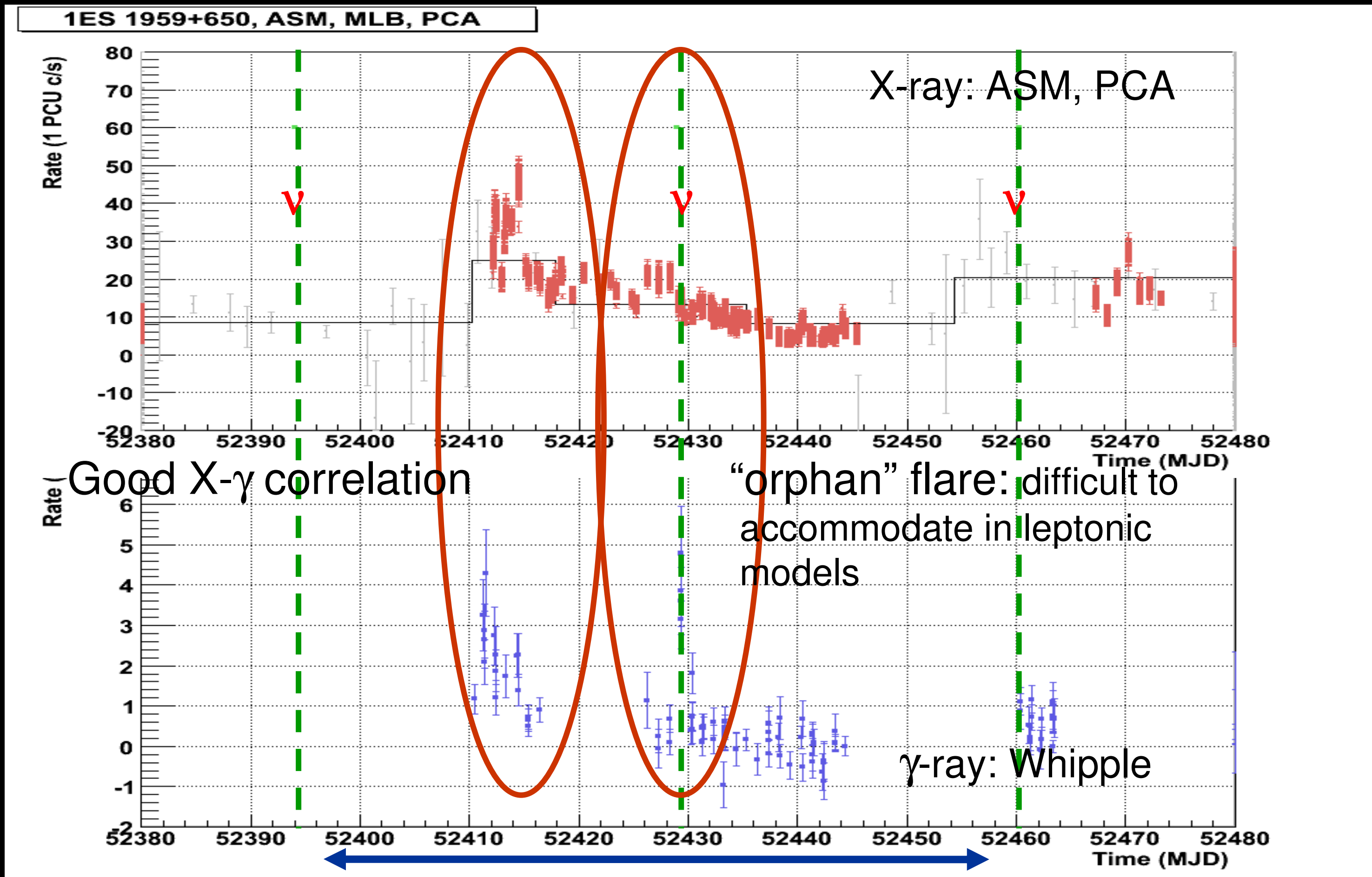


- SS433
- LSI +61 303
- Cyg X-1
- Cyg X-3
- .....

Radio

Periodicity (multiwavelength)

The hint: 1ES1959+650

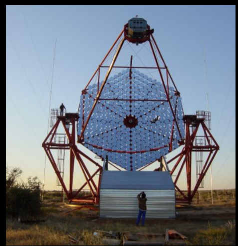


E.R., 2005 Aspen Winter Conference

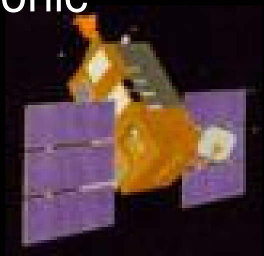
Future: Multi-Messenger

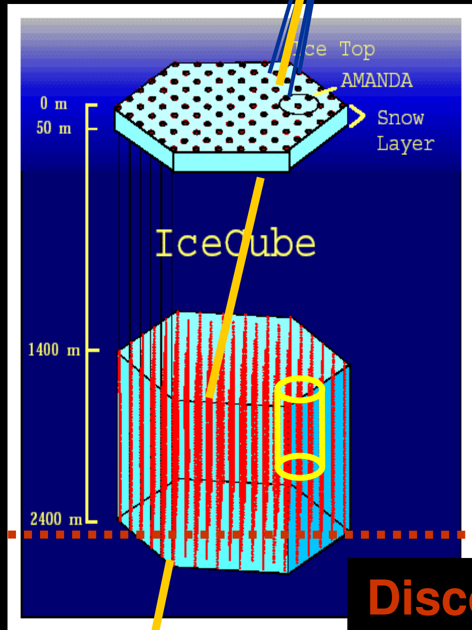
1. Multi-wavelength

Field of view compensation



Physics of hadronic sources





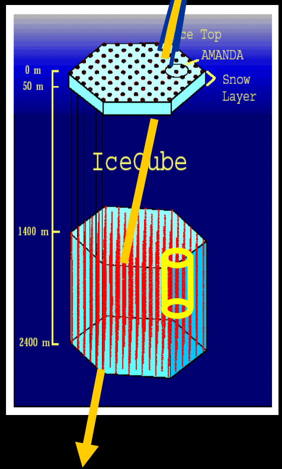
IceCube data analysis

Km3Net design

Discovery time

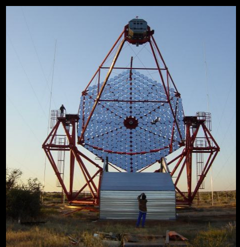
2. Multi-messenger

Future: we will be limited by …



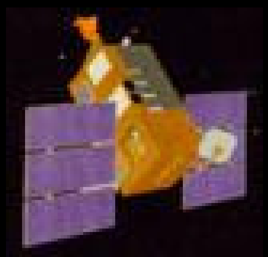
- Neutrino light curves with limited statistics:
  Detail study of temporal and spectral characteristic of highly variable sources limited

- At UHE effective area too small



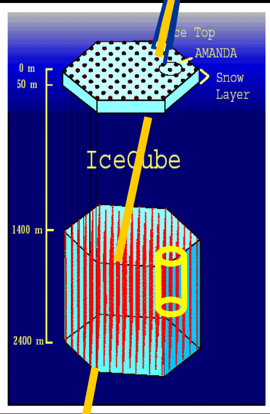
- Field-of-view limited

- Duty cycle limited



- GLAST: detection area limited
  Detail study of temporal and spectral characteristic of highly variable sources limited

Future: projects



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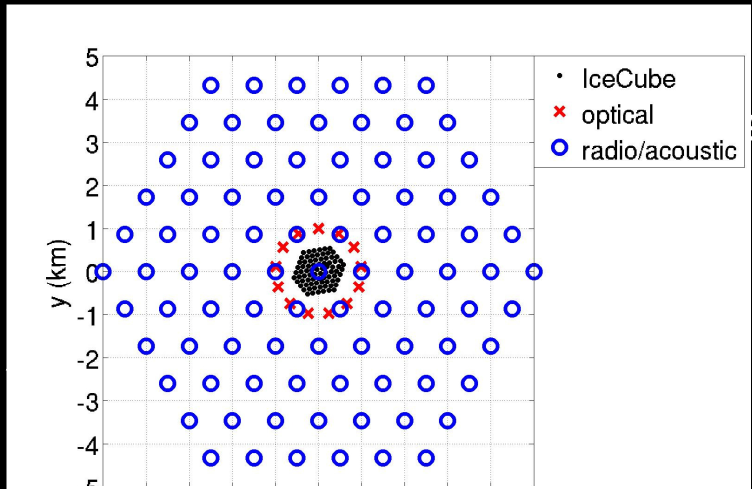
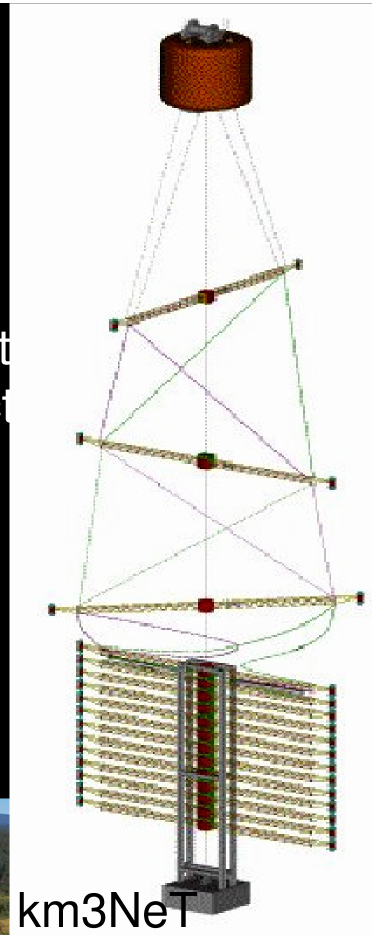
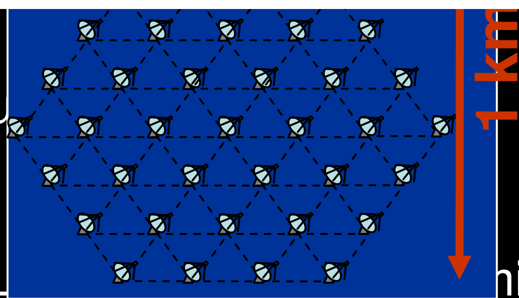
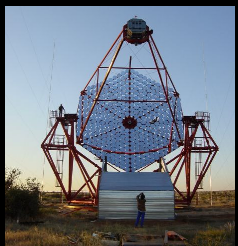


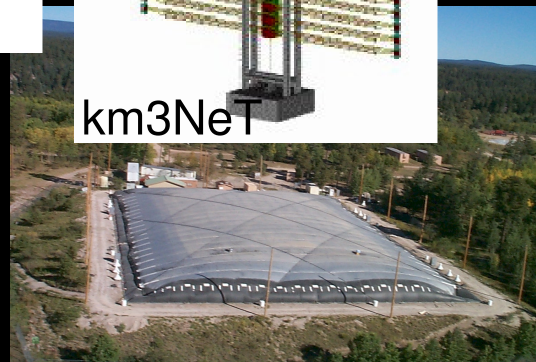
Hybrid Optical/Radio/Acoustic Detection of EeV Neutrinos

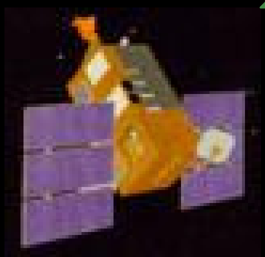


- F
- Du









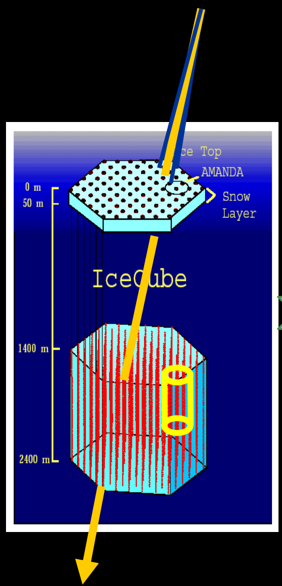
- GL nited

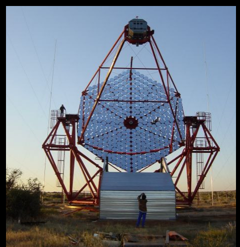
Detail study of temporal and spectral characteristic of highly variable sources limited

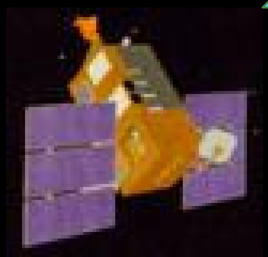
Large array of small IACTs

HAWC: wide angle, non-bias all sky survey

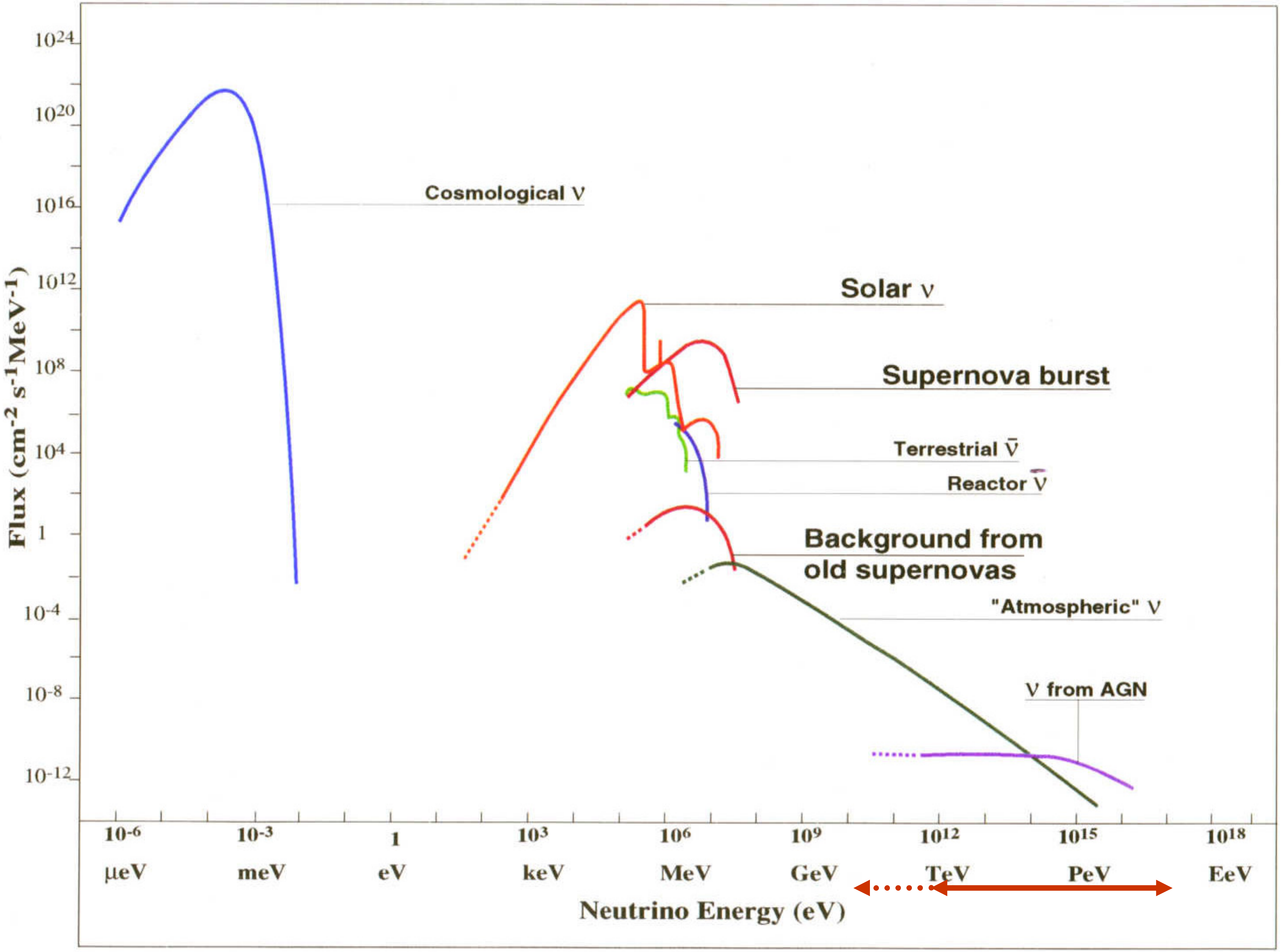
Conclusions







- Origin of the Cosmic Particles
  - galaxy properties (HI, H2 …)
  - extragalactic magnetic fields …
- Acceleration mechanisms
  - non-linear cases, relativistic cases …
- Non-thermal sources
  - most energetic sources in our Cosmos
- Indirect search for dark matter
- Exotics



Cosmological ν
Solar ν
Supernova burst
Terrestrial ν̄
Reactor ν̄
Background from
old supernovas
"Atmospheric" ν
ν from AGN
Flux (cm^{-2} s^{-1}MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-6}
10^{-3}
1
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
EeV
Neutrino Energy (eV)

Point Source Searches

 & 

- Sky-map:
  - bin and
  - un-binned method
- Source list
- Autocorrelation

- Time clusters
- Photons light curves