Title: High-energy neutrino astronomy: Towards kilometer-scale neutrino observatories

Date: Mar 01, 2006 02:00 PM

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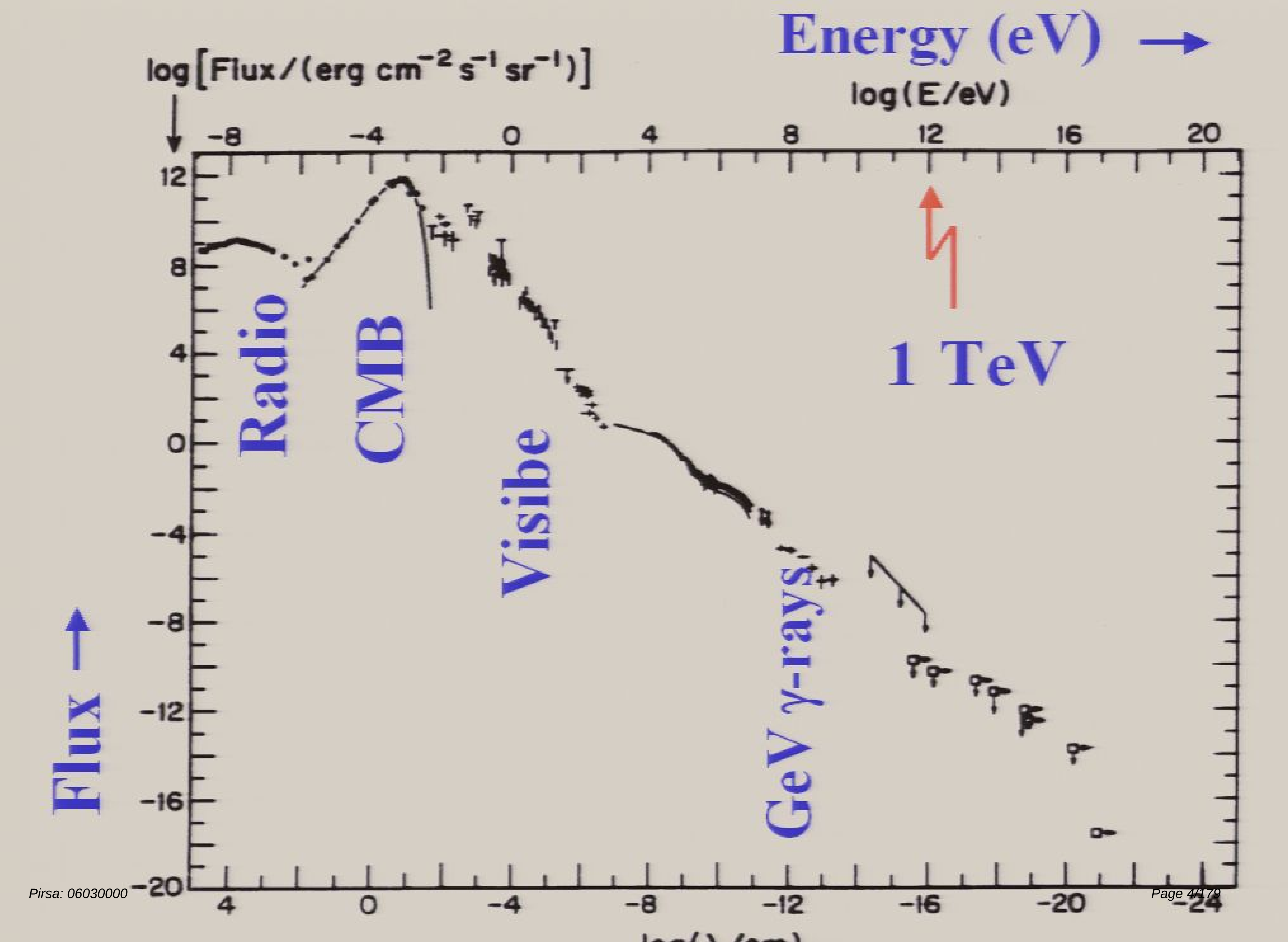
Abstract: Kilometer-scale neutrino detectors such as IceCube are discovery instruments covering nuclear and particle physics, cosmology and astronomy. Examples of their multidisciplinary missions include the search for the particle nature of dark matter and for additional small dimensions of space. In the end, their conceptual design is very much anchored to the observational fact that Nature produces protons and photons with energies in excess of 1020 and1013 electronvolts, respectively. The cosmic ray connection sets the scale of cosmic neutrino fluxes. The problem has been to develop a robust and affordable technology to build the kilometer-scale neutrino detectors required to do the science. The AMANDA telescope using clear deep Antarctic ice as a Cherenkov detector of muons and showers initiated by neutrinos of all 3 flavors, has met this challenge. We review the results obtained with more than 10,000 well-reconstructed neutrinos in the 50 GeV~500 TeV energy range collected during its first 5 years of operation. More importantly, we will show that AMANDA represents a proof of concept for the ultimate kilometer-scale neutrino observatory, IceCube, now under construction.


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 Prou

from AMANDA to Icecube

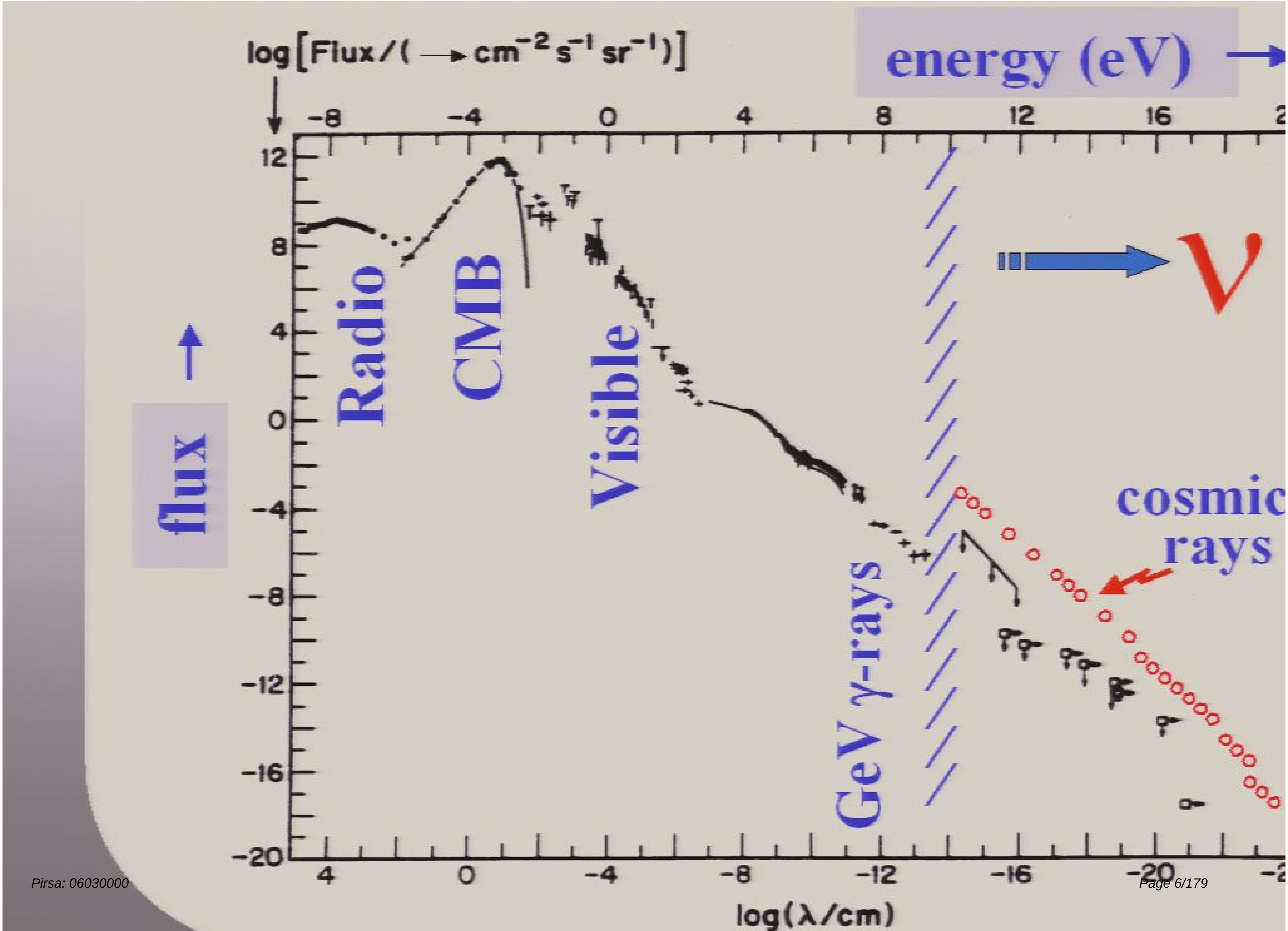
- ν astronomy requires kilometer-scale detectors
- AMANDA: proof of concept
- IceCube: a kilometer-scale ν observatory

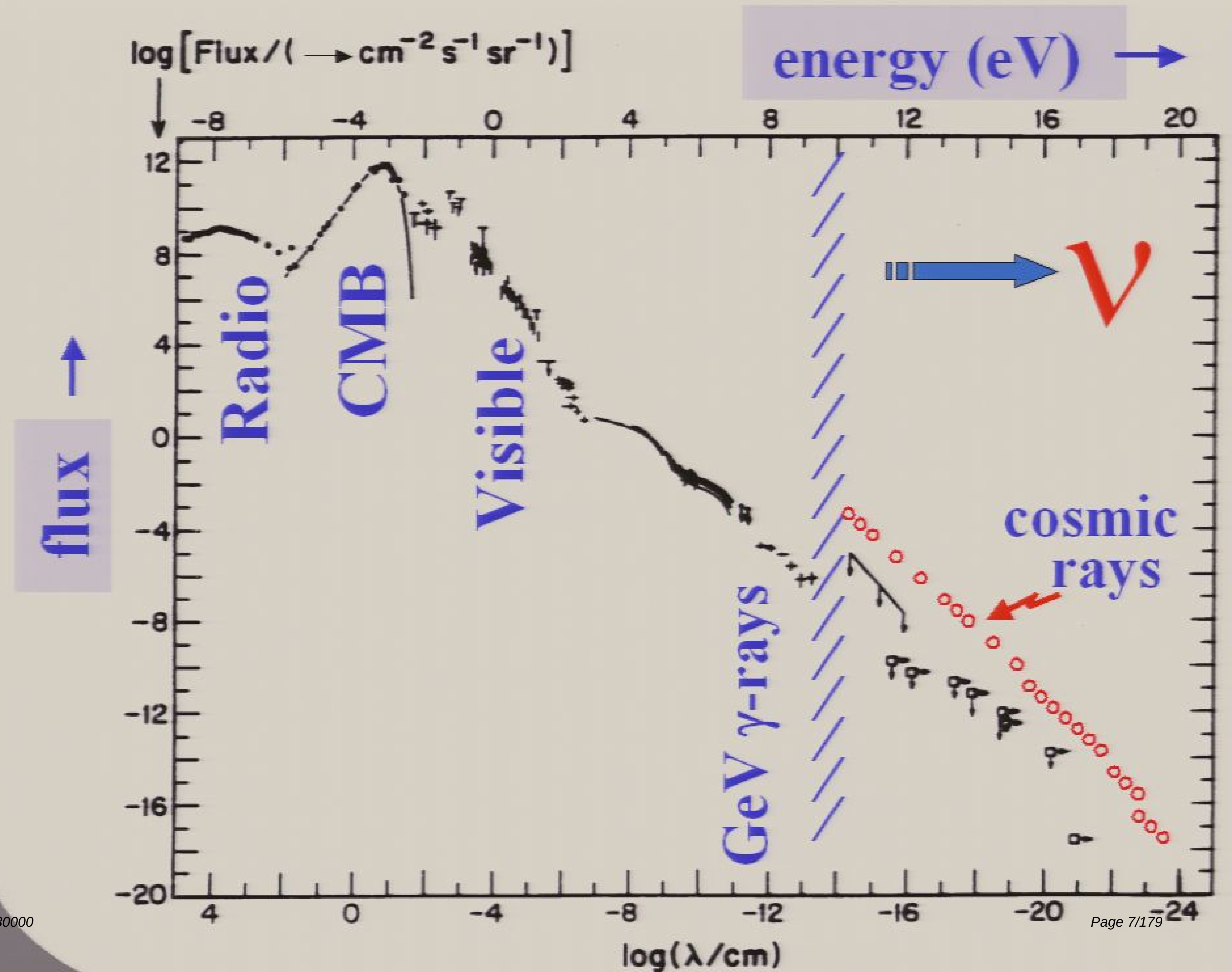
halzen@icecube.wisc.edu


Energy (eV)
log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
1 TeV
Radio
CMB
Visibe
GeV γ-rays
Flux

With 10^3 TeV energy, photons do not reach us from the edge of our galaxy because of their small mean free path in the microwave background.

$$\gamma + \gamma_{CMB} \longrightarrow e^+ + e^-$$


log[Flux/(→ cm^-2 s^-1 sr^-1)]
energy (eV)
-8
-4
0
4
8
12
16
12
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
ν
cosmic rays
4
0
-4
-8
-12
-16
-20
log(λ/cm)



log[Flux/(→ cm^-2 s^-1 sr^-1)]
energy (eV)
-8
-4
0
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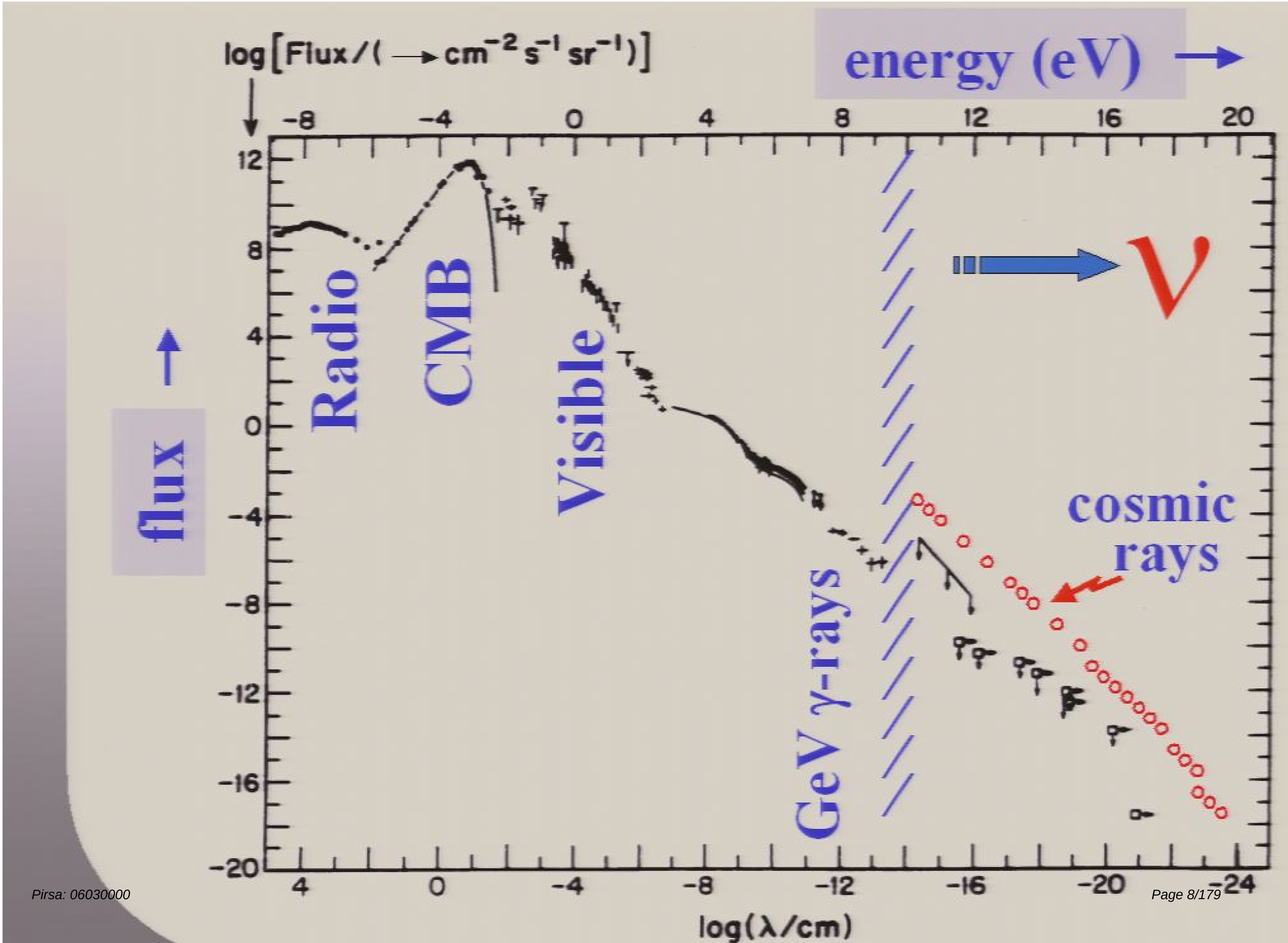
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
ν
cosmic rays
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)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log(λ/cm)

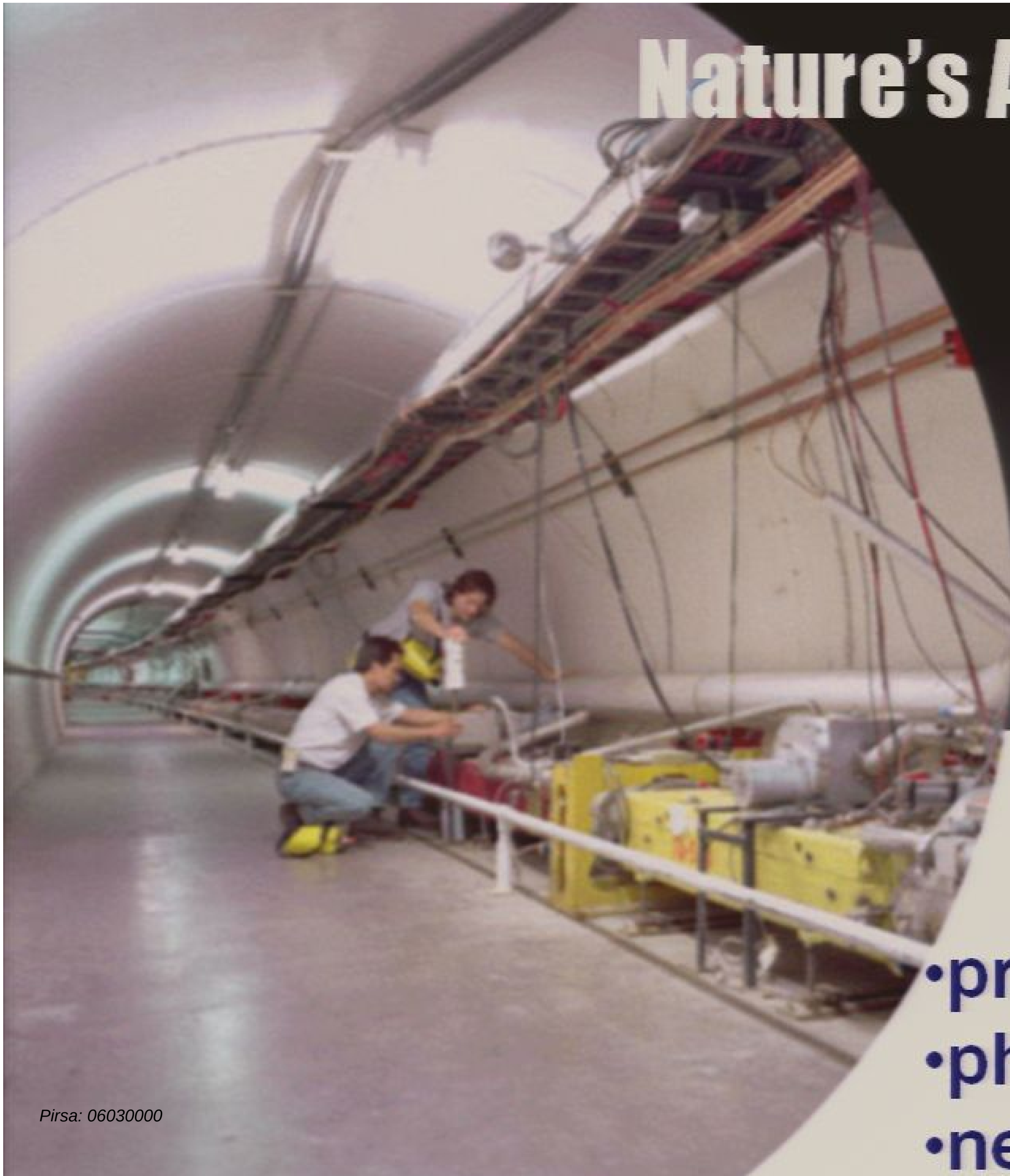
Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

New Window on Universe?

Expect Surprises

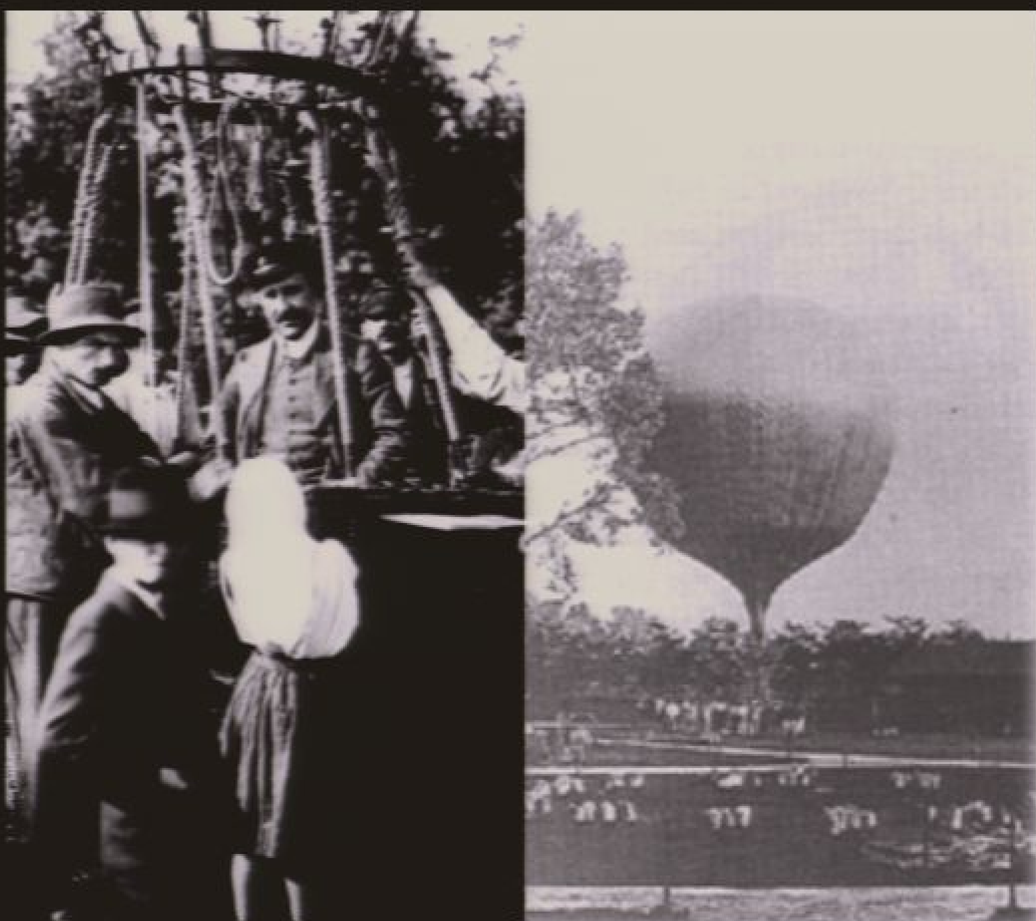
cosmic neutrinos associated with cosmic rays

Nature's Accelerator ?



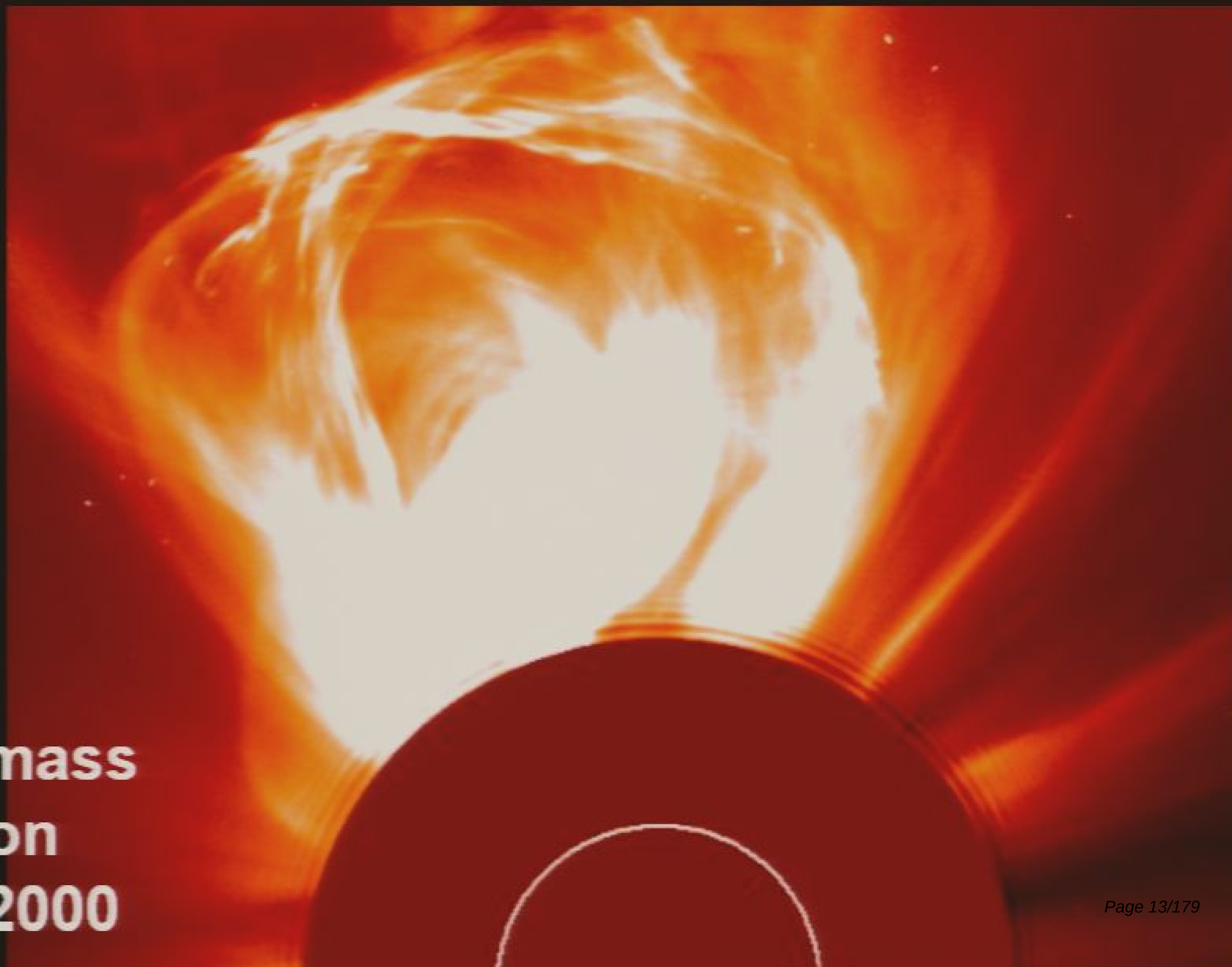
- protons > 10^8 TeV
- photons > 10 TeV
- neutrinos > 10^2 TeV

Cosmic Rays Observations



first discovered in 1912 by Austrian scientist ***Victor Hess***, measuring radiation levels aboard a balloon at up to 17,500 feet ***(without oxygen!)***

solar flare shock acceleration



Coronal mass ejection
09 Mar 2000

Acceleration to 10^{21} eV ?

$\sim 10^2$ Joules

$\sim 0.01\ M_{GUT}$

dense regions with exceptional gravitational force creating relativistic flows of charged particles, e.g.

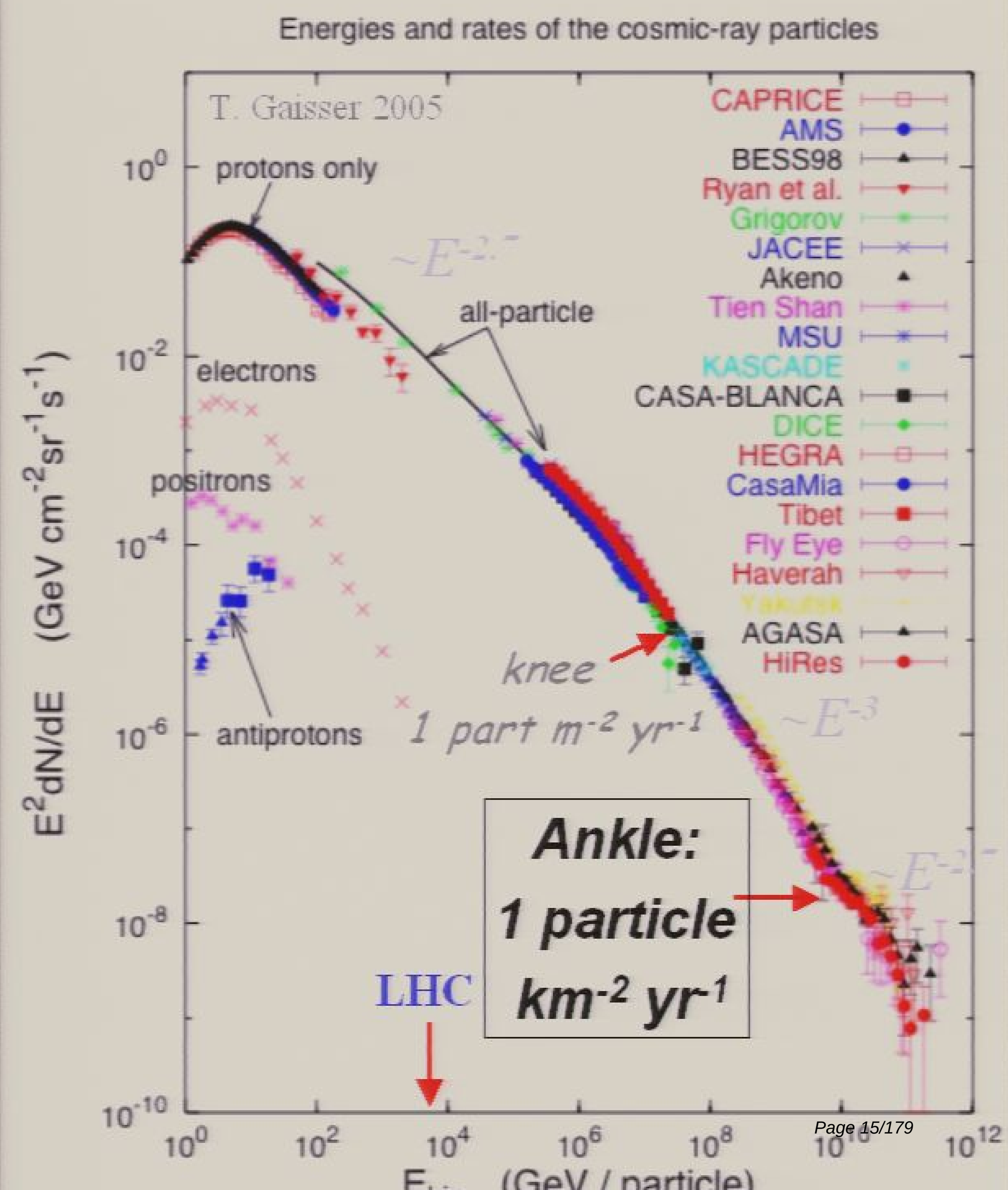
- dense cores of exploding stars
- supermassive black holes
- merging galaxies

cosmic rays

Nature accelerates particles 10^8 times the energy of the Tevatron

Where ?

How ?



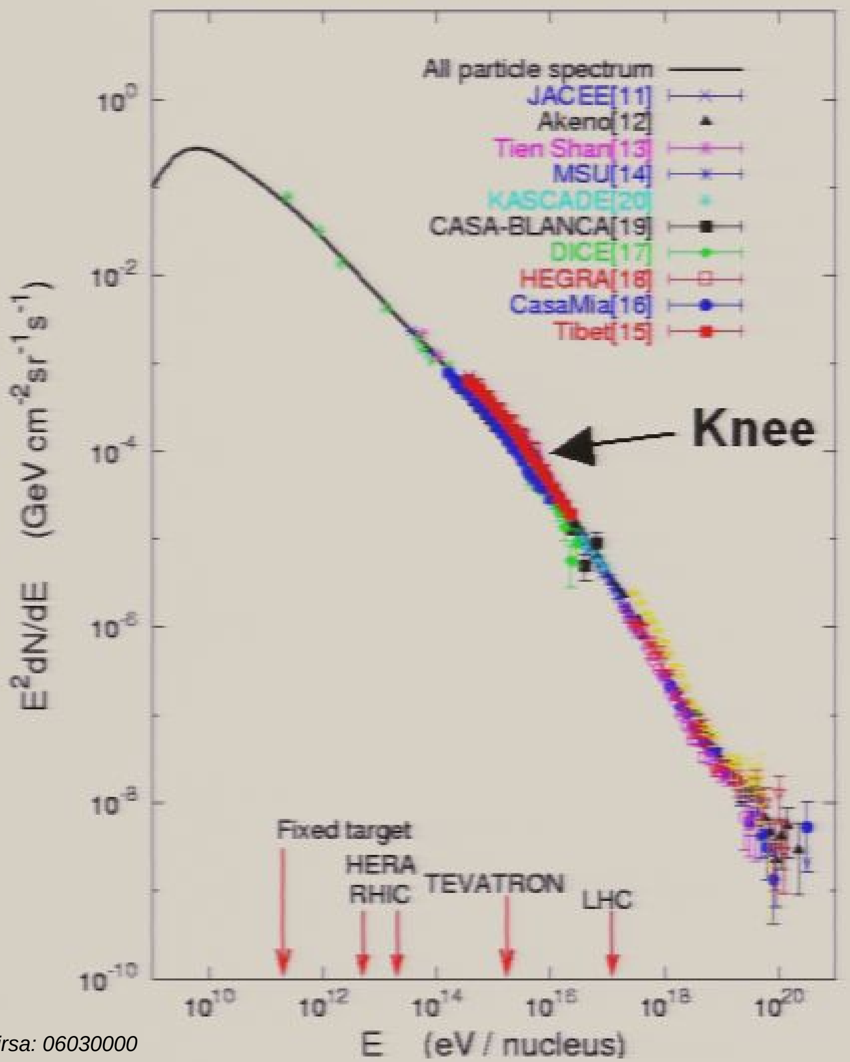
flux of extra-galactic cosmic rays

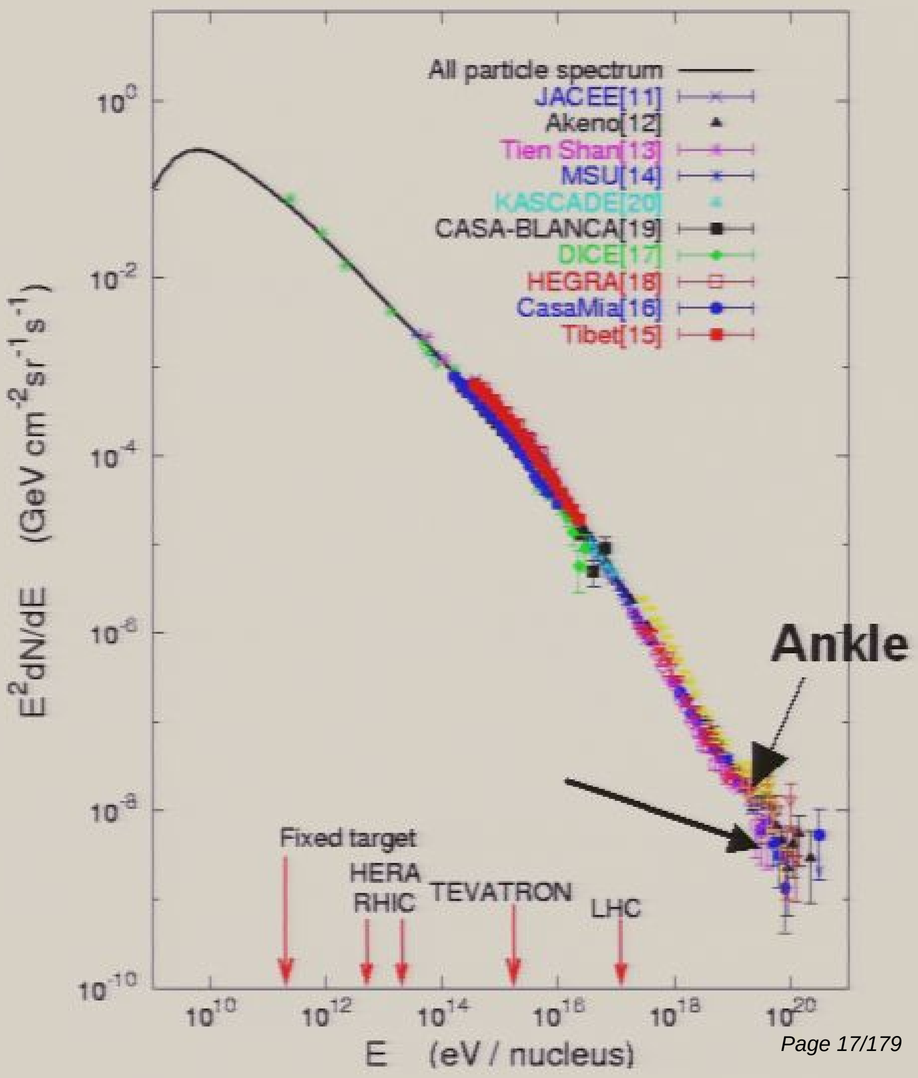
ankle → one 10^{19} eV particle per km squared per year per sr

$$E\{E\frac{dN}{dE}\} = \frac{10^{19}\,eV}{(10^{10}\,cm^2)(3\times 10^7\,sec)\,sr}$$

$$= 3\times 10^{-8}\,GeV\,cm^{-2}\,sec^{-1}\,sr^{-1}$$

galactic and extragalactic cosmic rays





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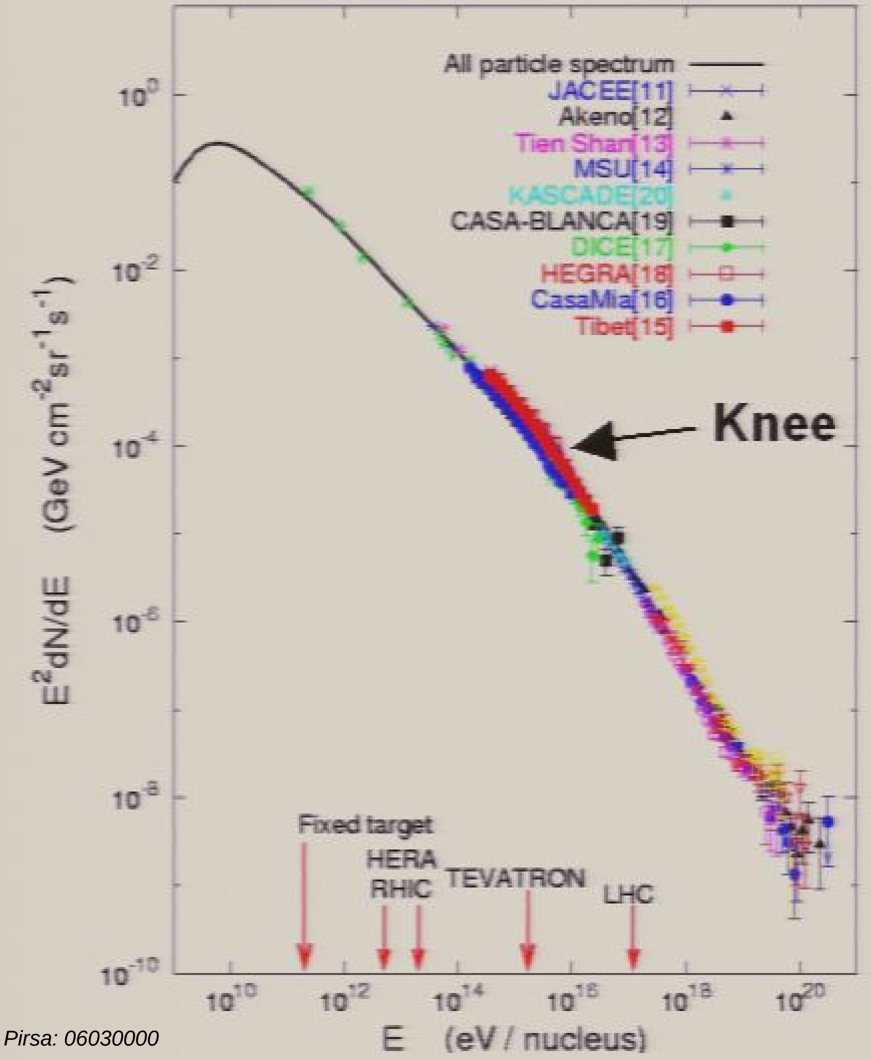
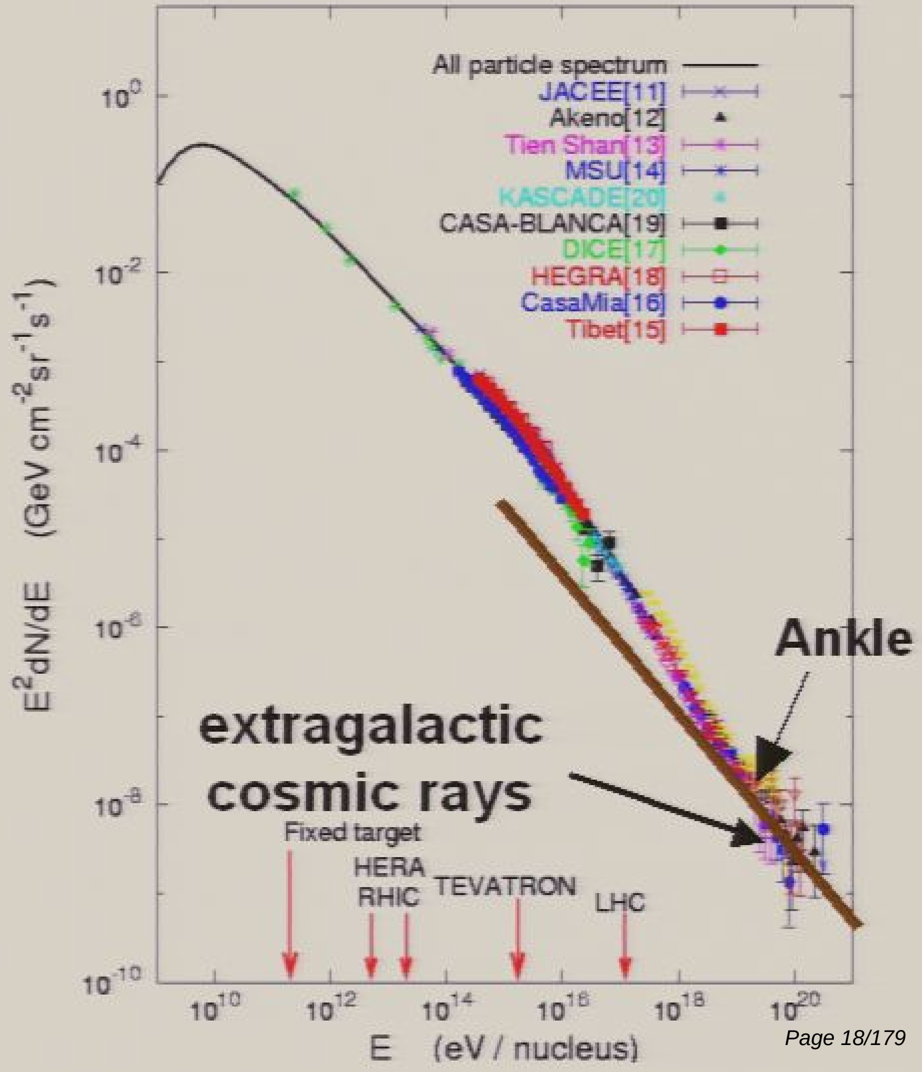




total flux = velocity x density :

$$\boxed{4\pi\int dE\,(E\,\frac{dN}{dE}) = c\,\rho_E}$$

$$\rho_E = \frac{4\pi}{c}\int\frac{3\times10^{-8}}{E}dE\,\frac{GeV}{cm^3}$$

$$= \cdots \log\frac{E_{max}}{E_{min}} \cong 10^{-19}\,\frac{TeV}{cm^3}$$

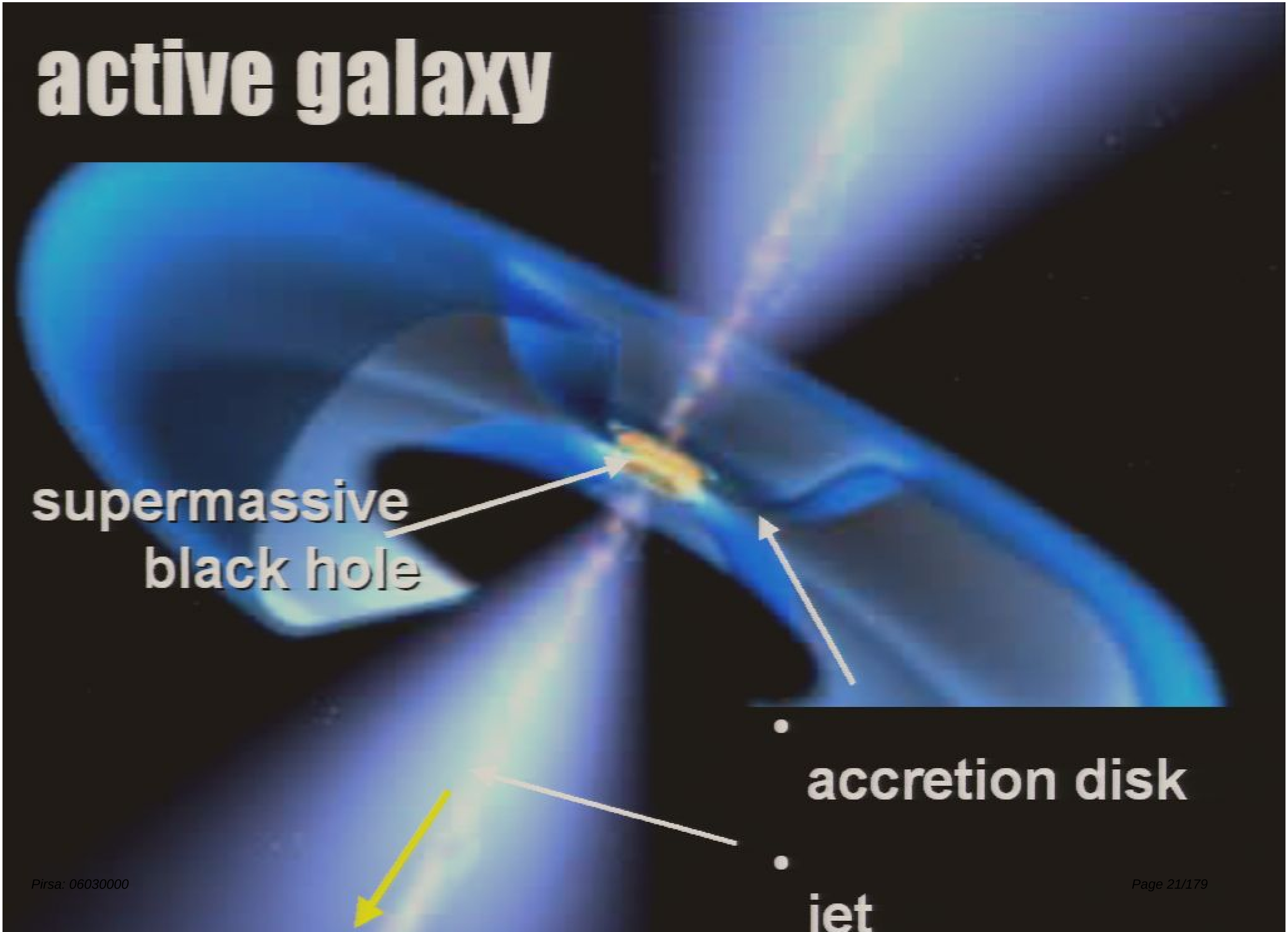
\>>> energy in extra-galactic cosmic rays:

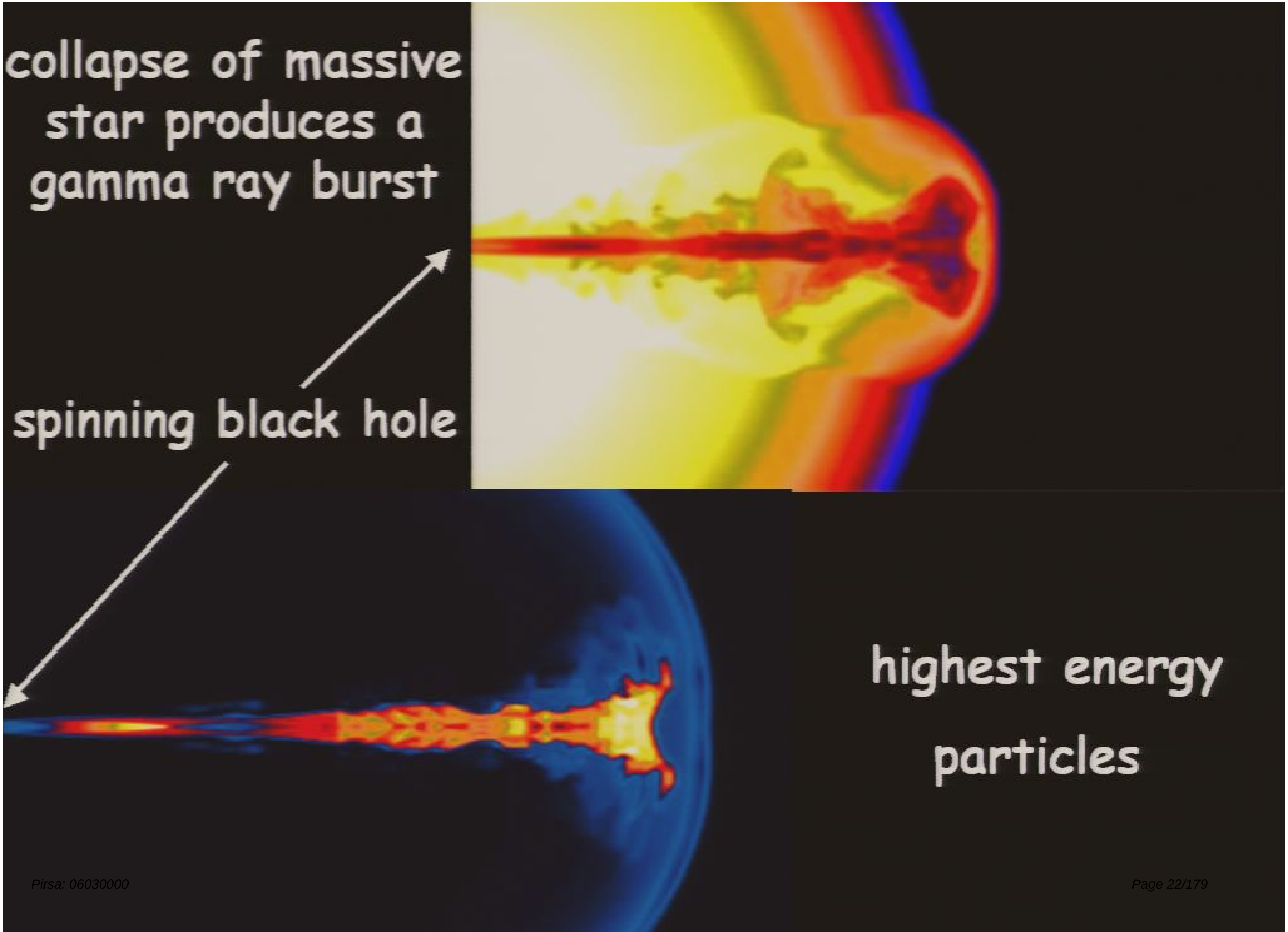
~ 3×10^{-19} erg/cm^3 or
~ 10^{44} erg/yr per (Mpc)^3 for 10^{10} years

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


active galaxy
supermassive black hole
accretion disk
jet


collapse of massive star produces a gamma ray burst
spinning black hole
highest energy particles

Hillas formula

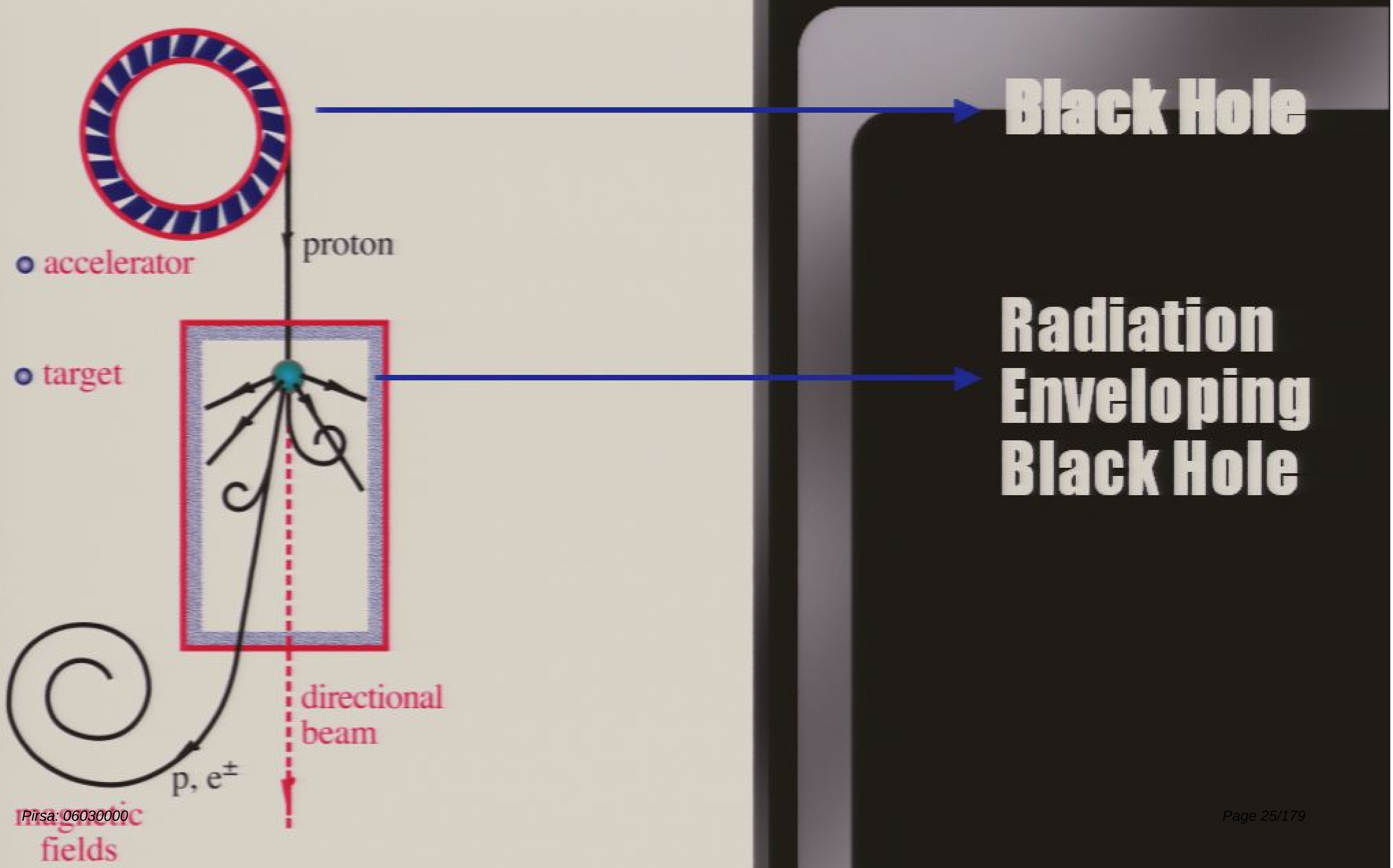
$$R_{gyro} \left(= \frac{E}{qB}\right) \le R$$

$$E \le qBR$$

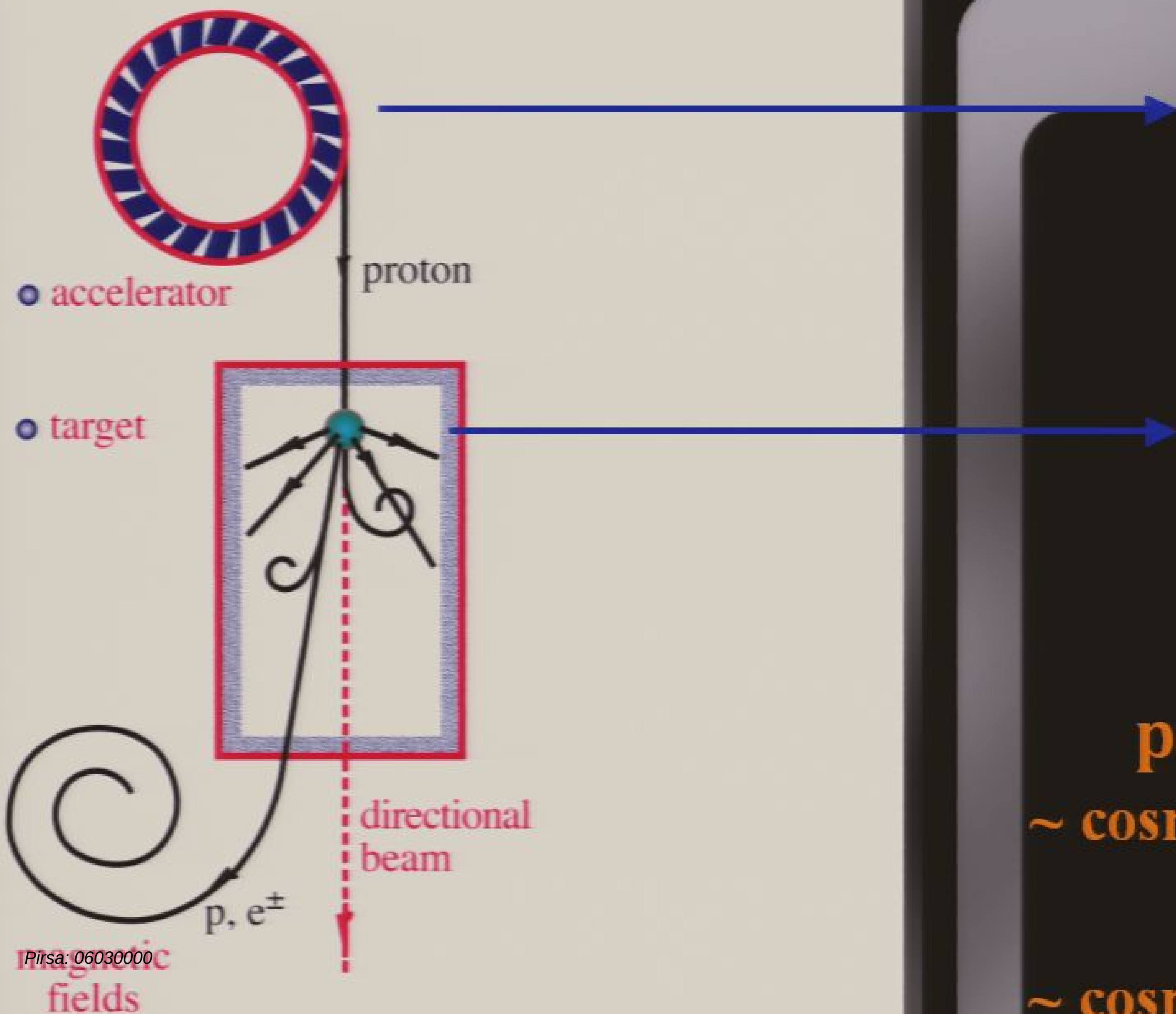
$$\boxed{E \le c\, qBR}$$

Georges Lemaitre believed that cosmic rays where primordial radiation from the Big Bang

Neutrino Beams: Heaven & Earth



Neutrino Beams: Heaven & Earth



Black Hole

Radiation Enveloping Black Hole

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

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~ 3×10^{-19} erg/cm^3 or
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→ energy in
cosmic rays ~ photons ~ neutrinos

flux of extra-galactic cosmic rays

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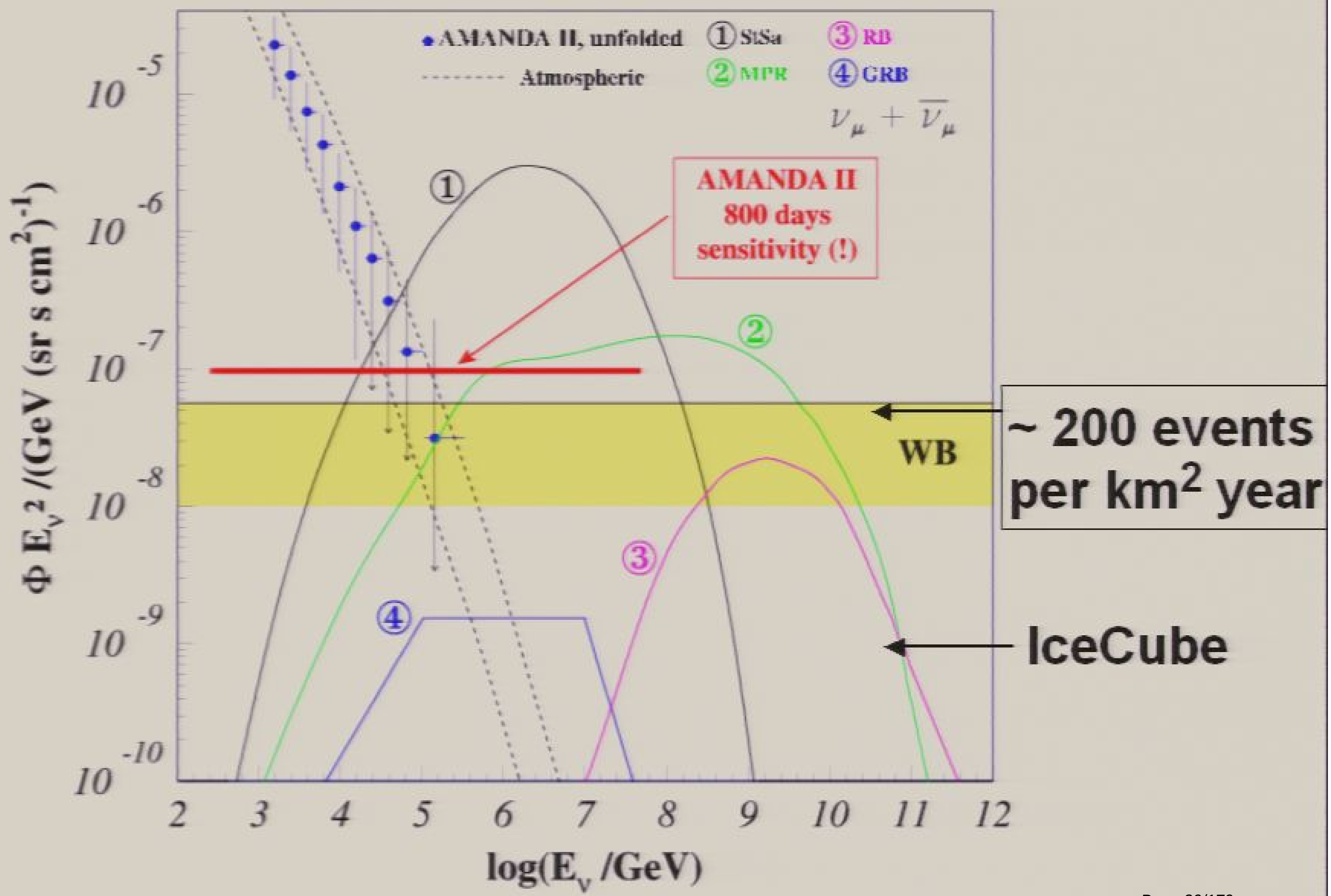
Waxman-Bahcall Flux

oscillations

$$\boxed{\Phi_\nu = \frac{1}{2} \times \frac{1}{2} \times \Phi_{CR} \times \frac{d_H}{d_{CMB}} \cong \Phi_{CR}}$$

$\dfrac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + e}$ in π^+ decay

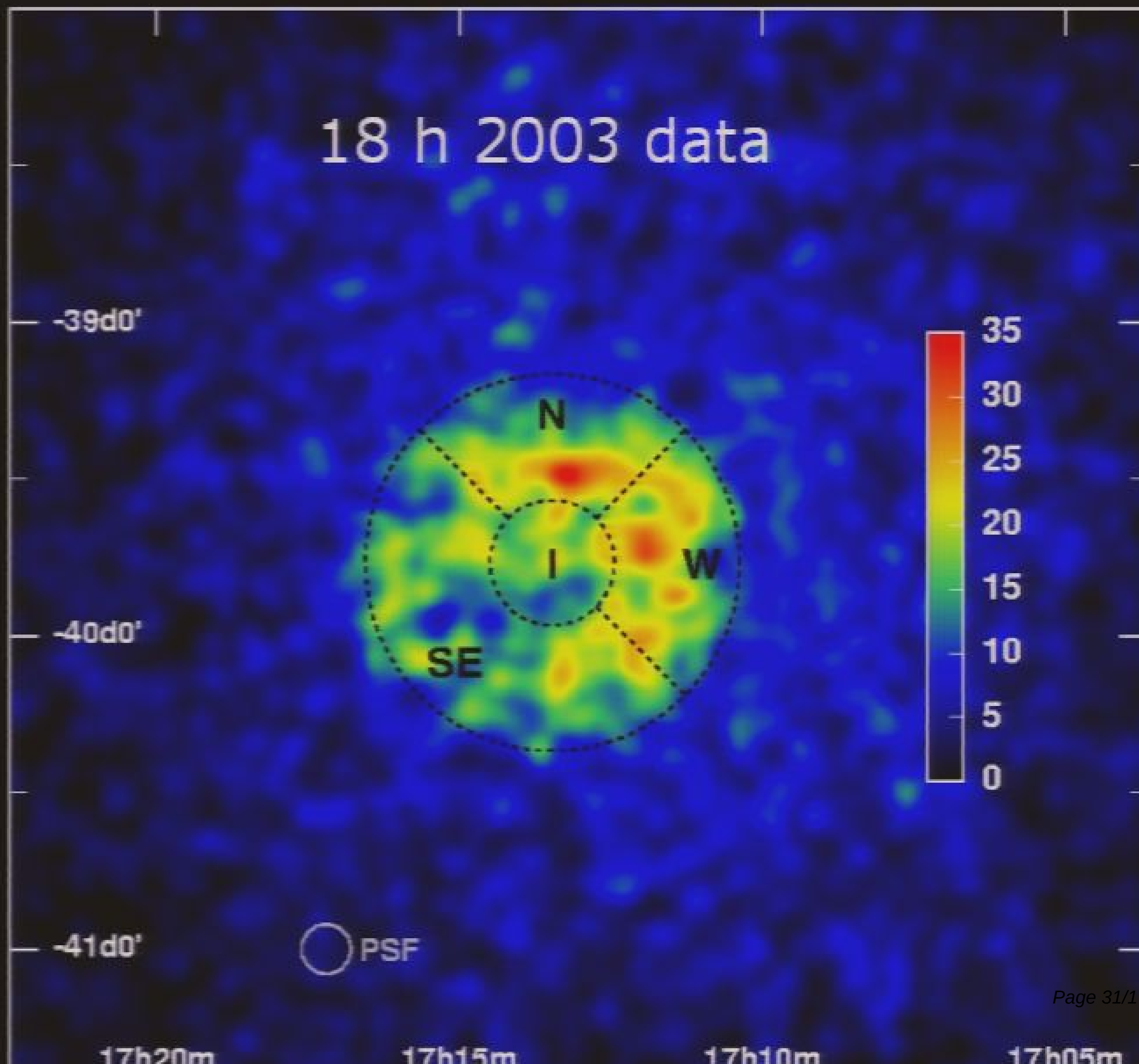


AMANDA II, unfolded
Atmospheric
① StSa
② MPR
③ RB
④ GRB
$\nu_\mu + \overline{\nu}_\mu$
AMANDA II
800 days
sensitivity (!)
WB
~ 200 events
per km^2 year
IceCube
ΦE_ν^2 /(GeV (sr s cm^2)$^{-1}$)
log(E_ν /GeV)

HESS: RX J1713 Spectrum

- ~ 10 neutrinos per km² year

- indirect evidence for the acceleration of protons at the level required to explain galactic cosmic rays



neutral pions

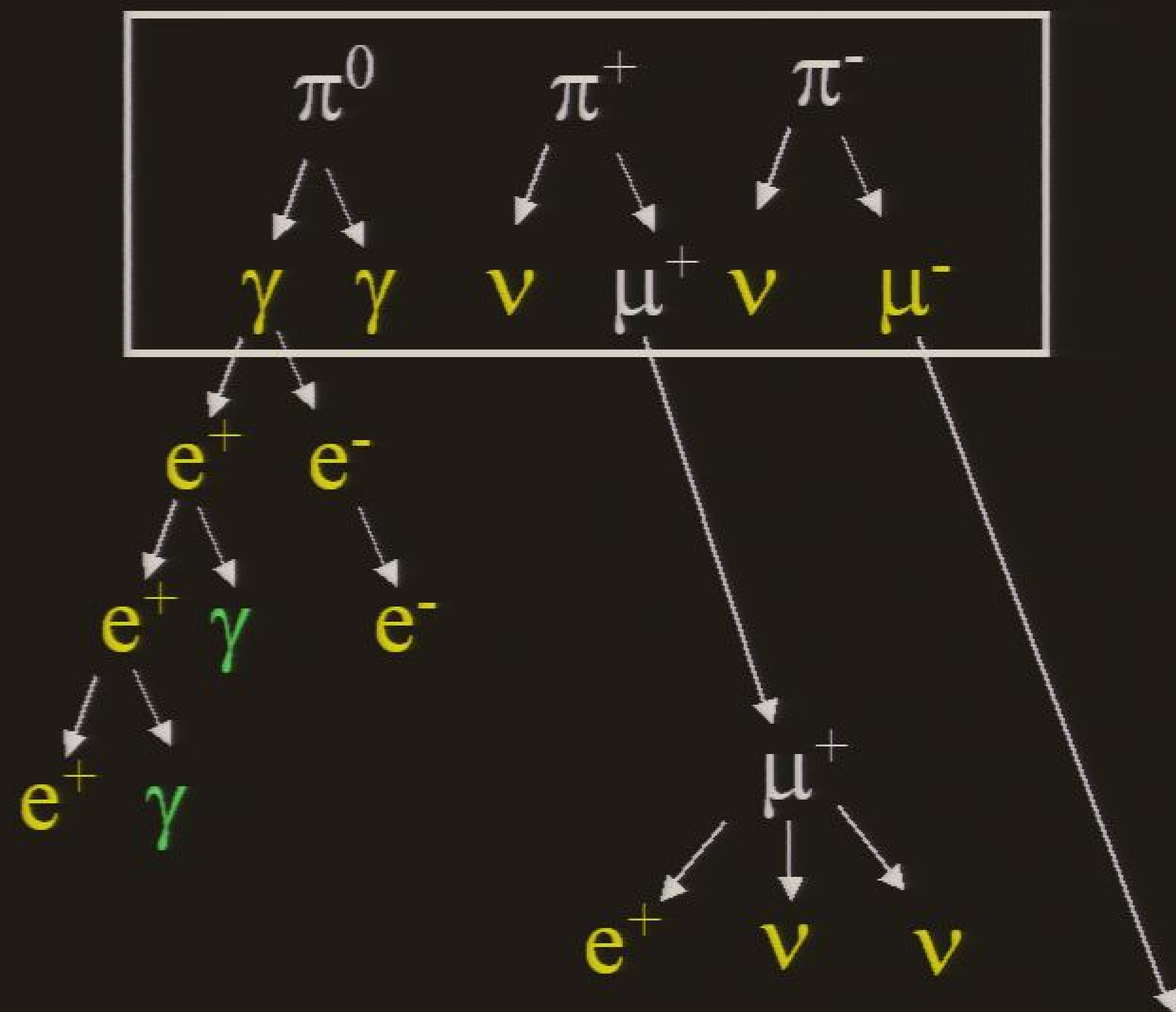
are observed as

gamma rays

charged pions

are observed as

neutrinos



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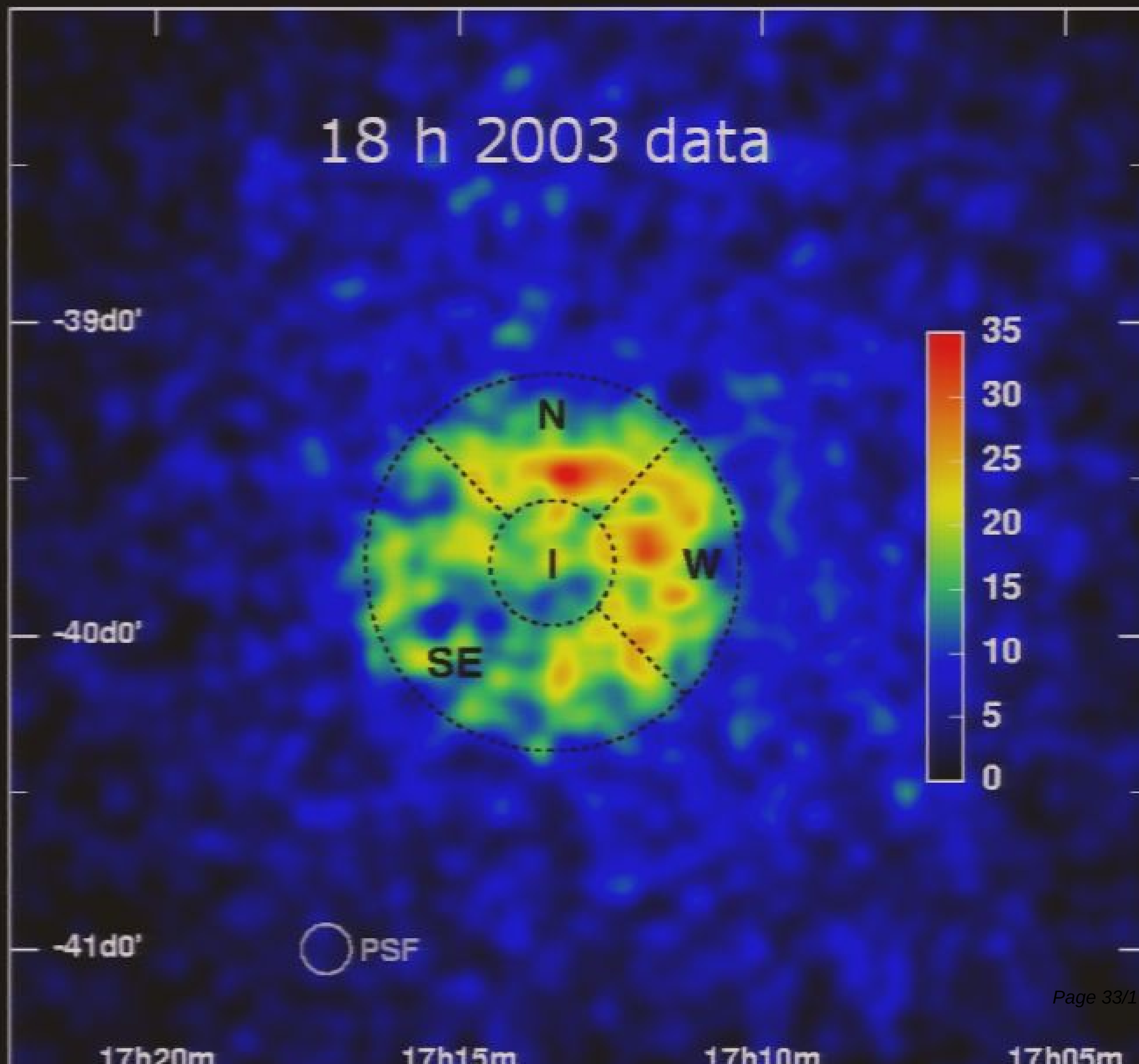
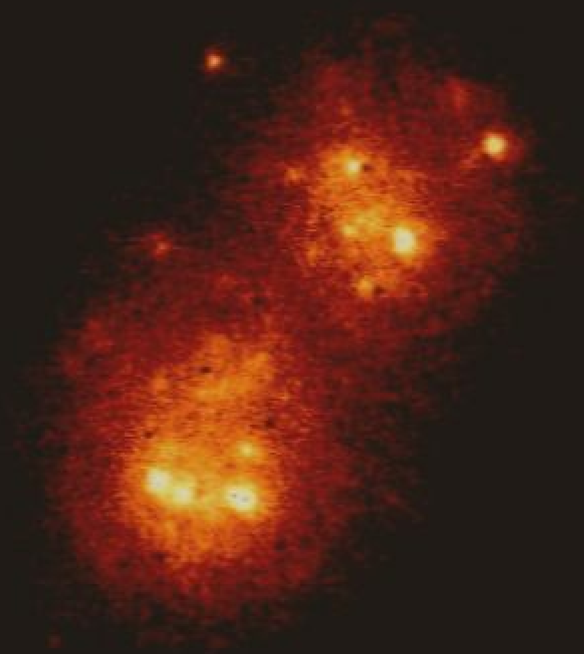




merging galaxies

starbursts

- $l \sim 100$ pc
- $v \sim 100$ km/s
- $t \sim 10^6$ years
- $\rho \sim 0.2$ g cm^{-2}
- $B \sim 0.1$ mGauss

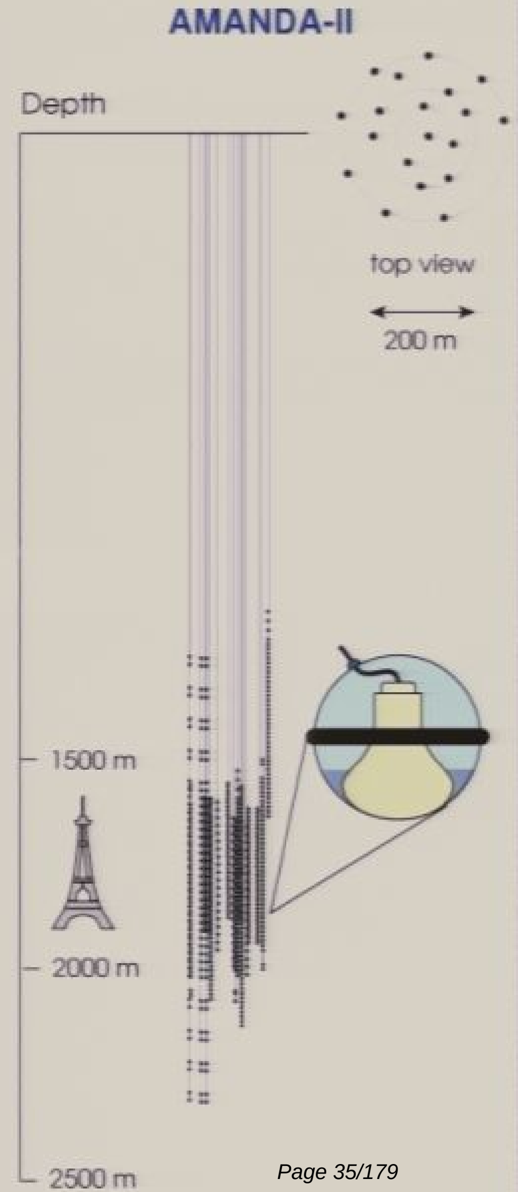
supernovae $\rightarrow$

cosmic rays

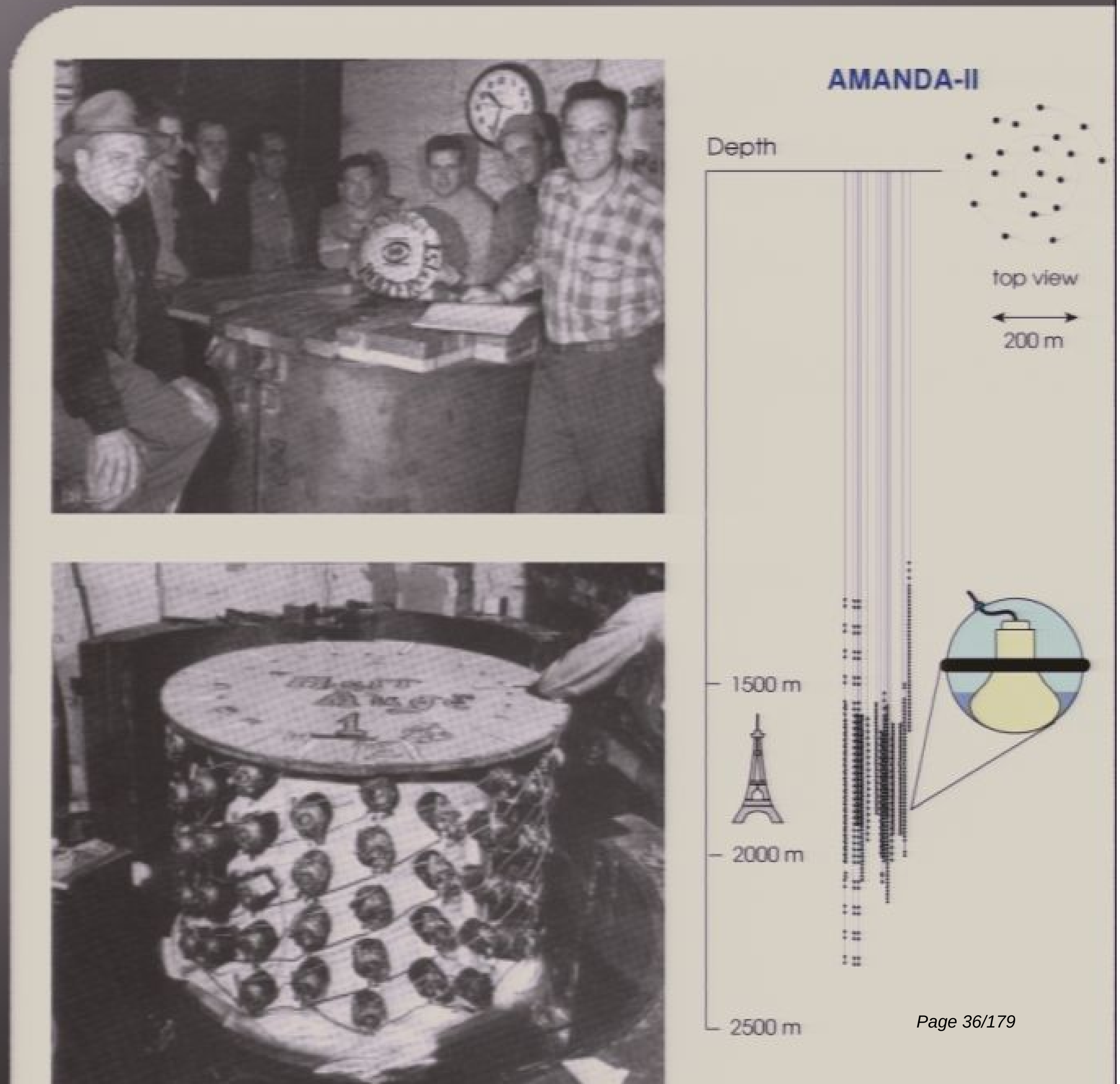
+ dense gas

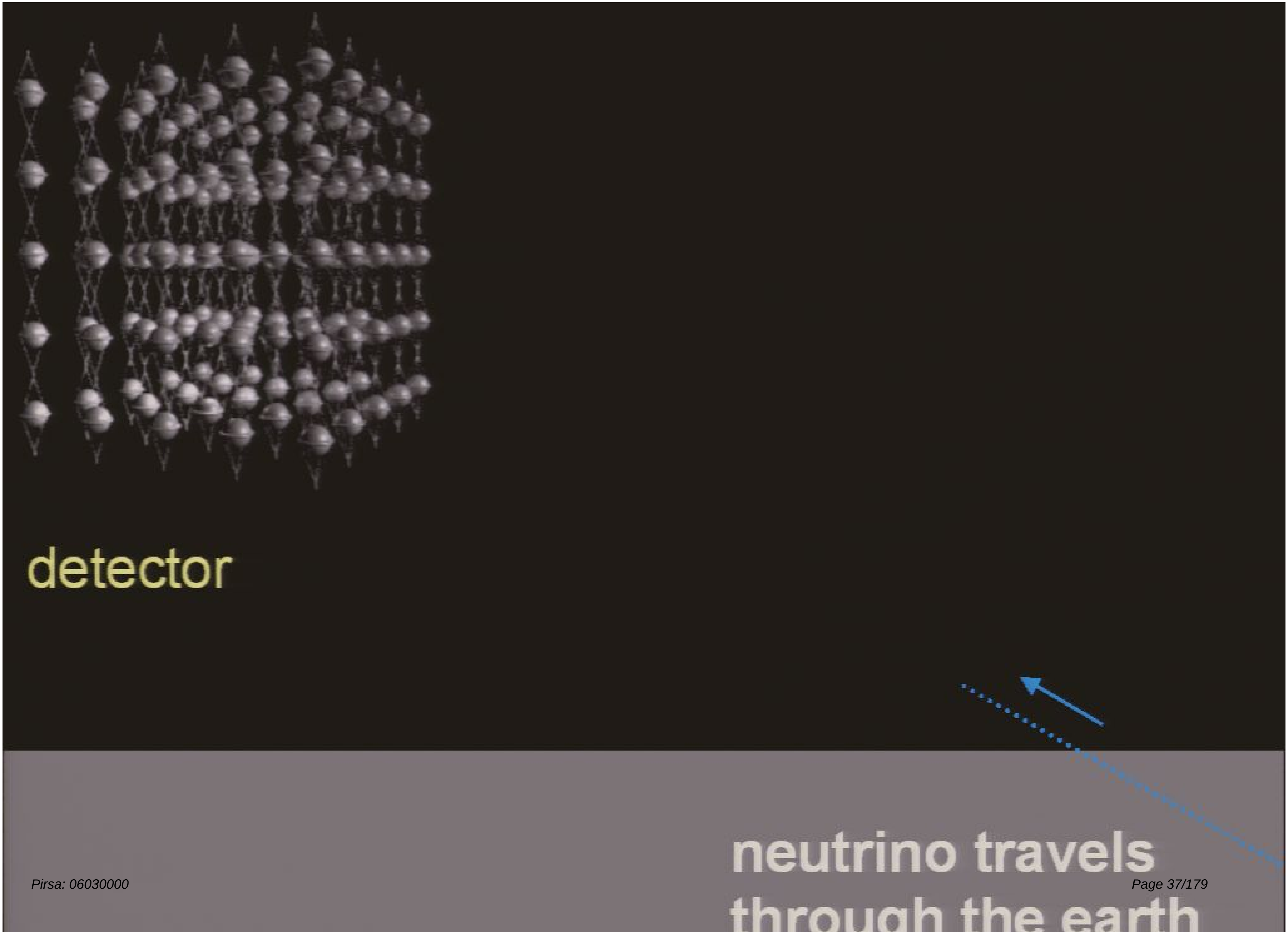
$\rightarrow$ pions

Requires Kilometer-Scale Neutrino Detectors

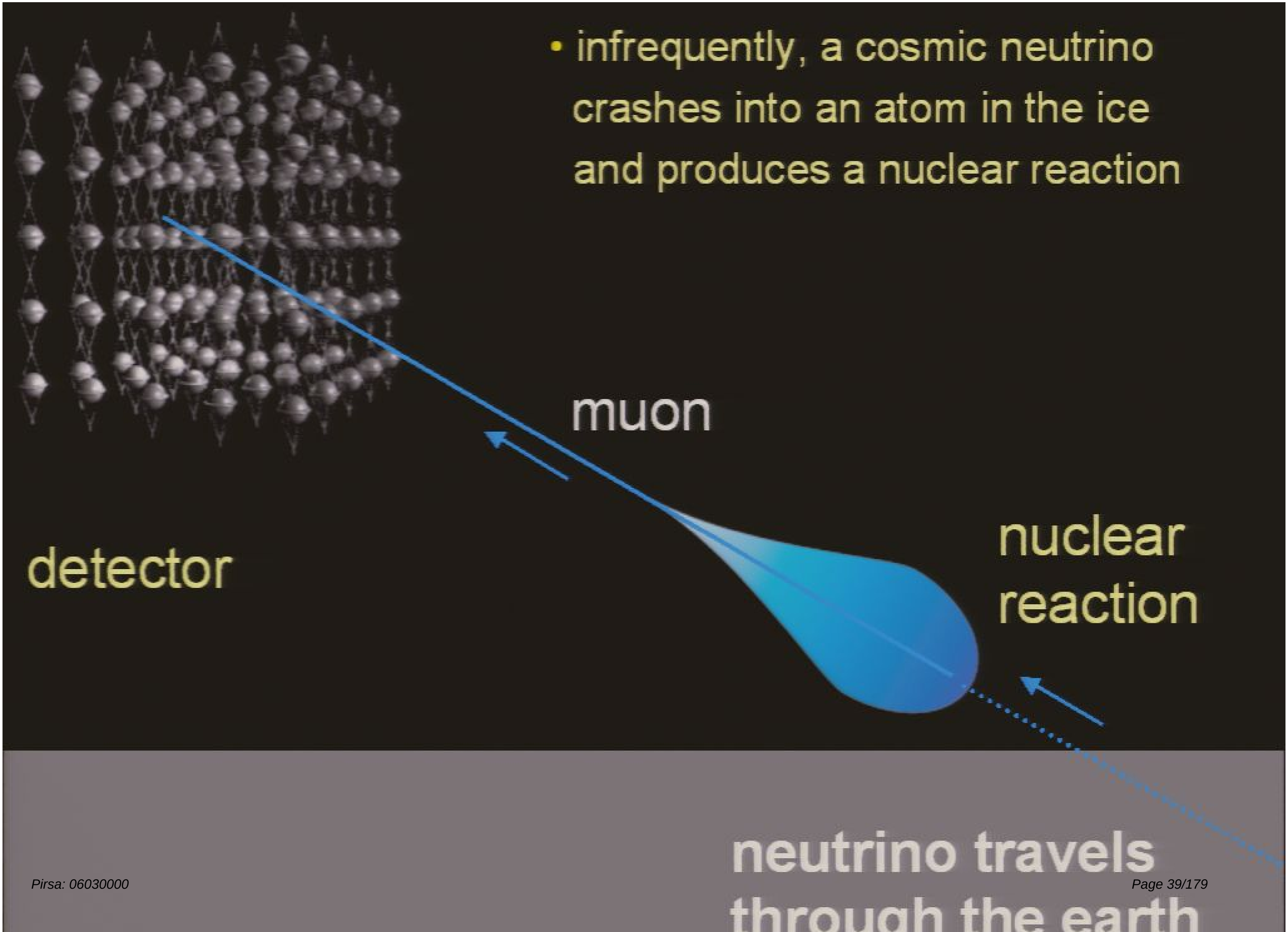


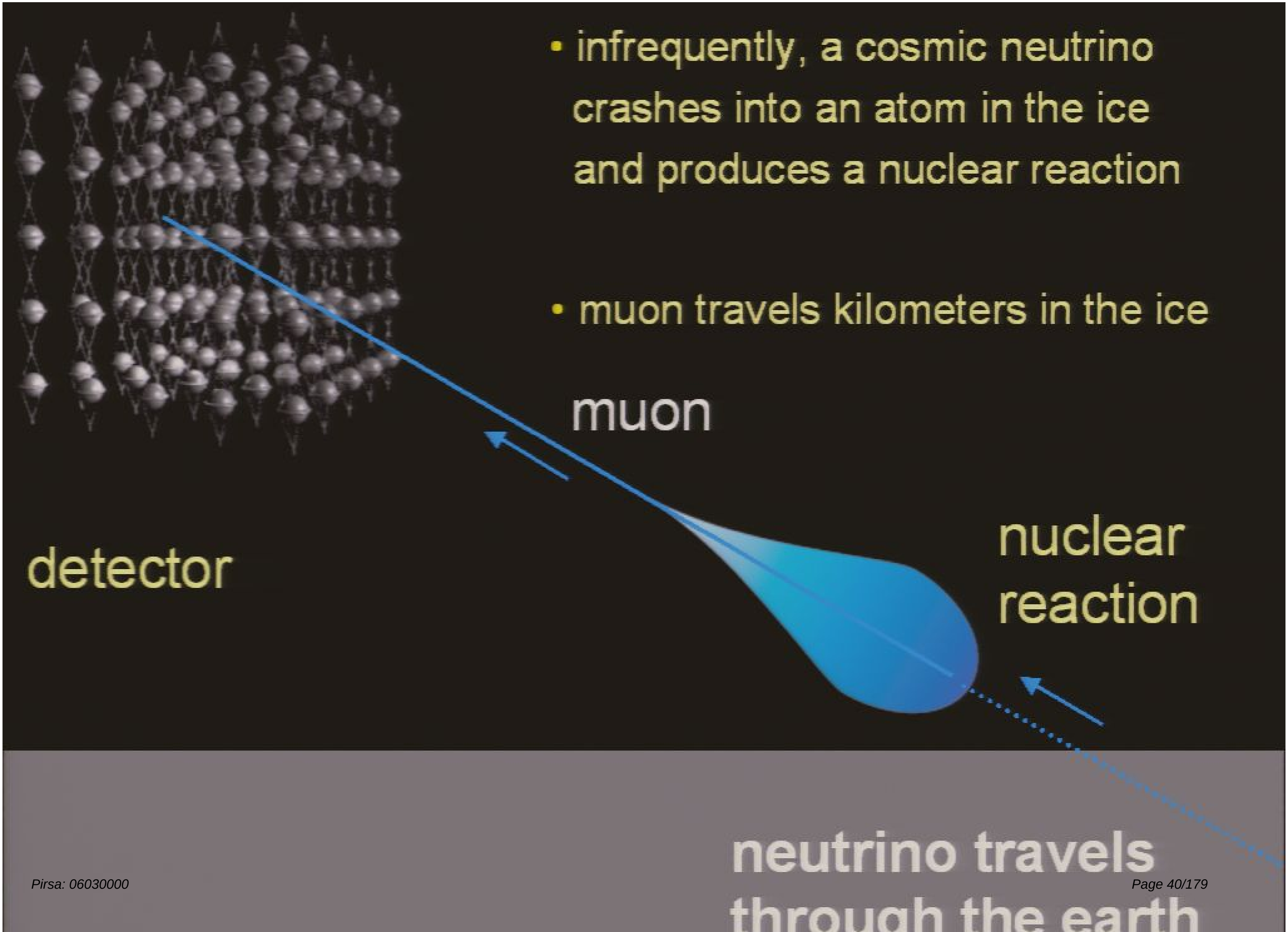
Requires Kilometer-Scale Neutrino Detectors

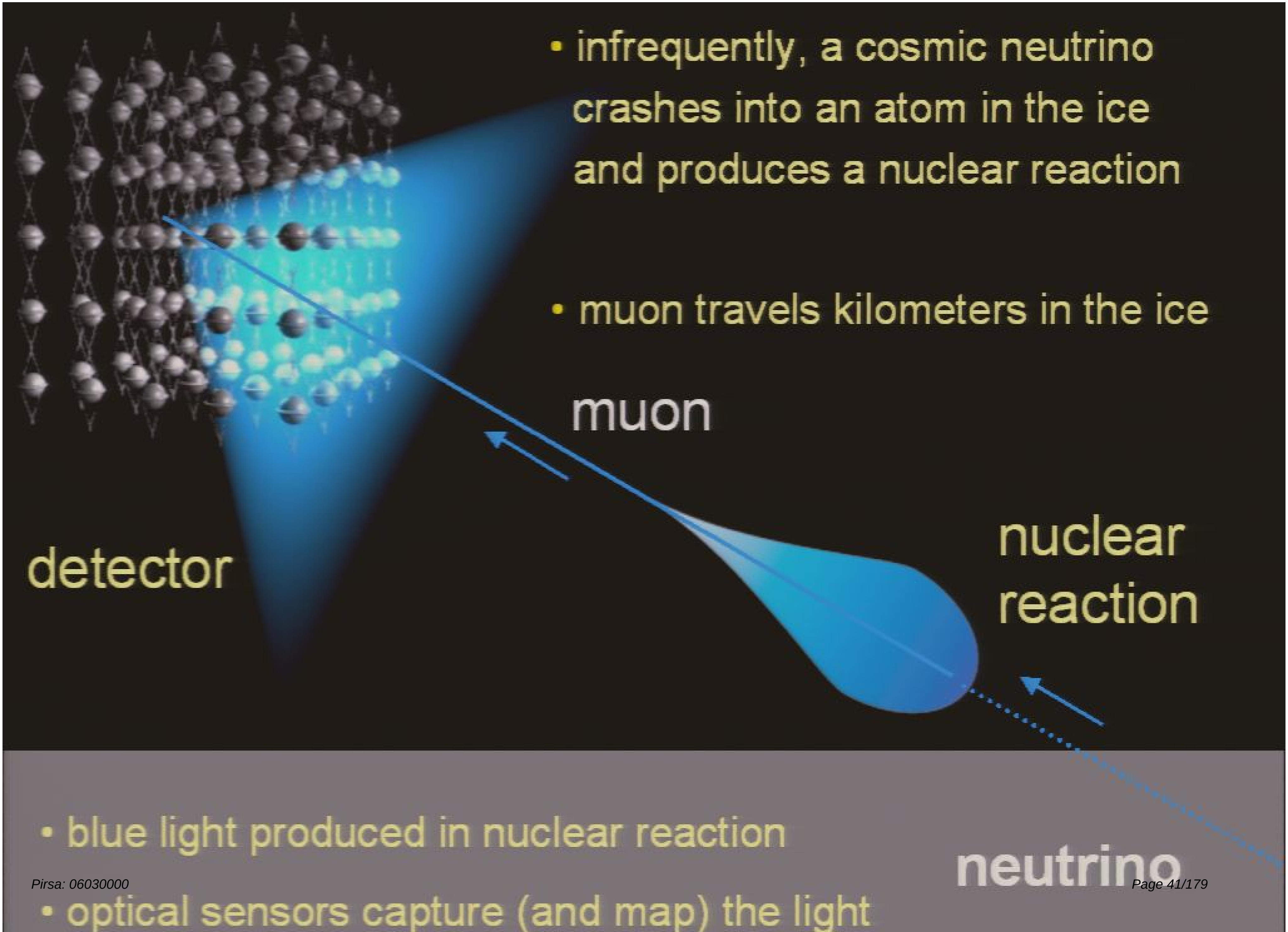



detector
neutrino travels
through the earth

Photomultiplier Tube

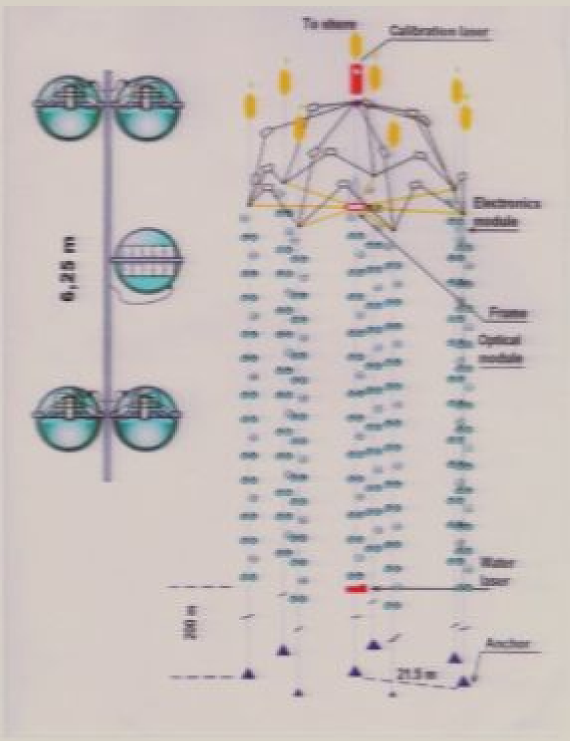

• infrequently, a cosmic neutrino crashes into an atom in the ice and produces a nuclear reaction
muon
detector
nuclear reaction
neutrino travels through the earth


• infrequently, a cosmic neutrino crashes into an atom in the ice and produces a nuclear reaction
• muon travels kilometers in the ice
muon
detector
nuclear reaction
neutrino travels through the earth


• infrequently, a cosmic neutrino crashes into an atom in the ice and produces a nuclear reaction
• muon travels kilometers in the ice
muon
detector
nuclear reaction
• blue light produced in nuclear reaction
neutrino
• optical sensors capture (and map) the light

Northern hemisphere detectors

Baikal NT200



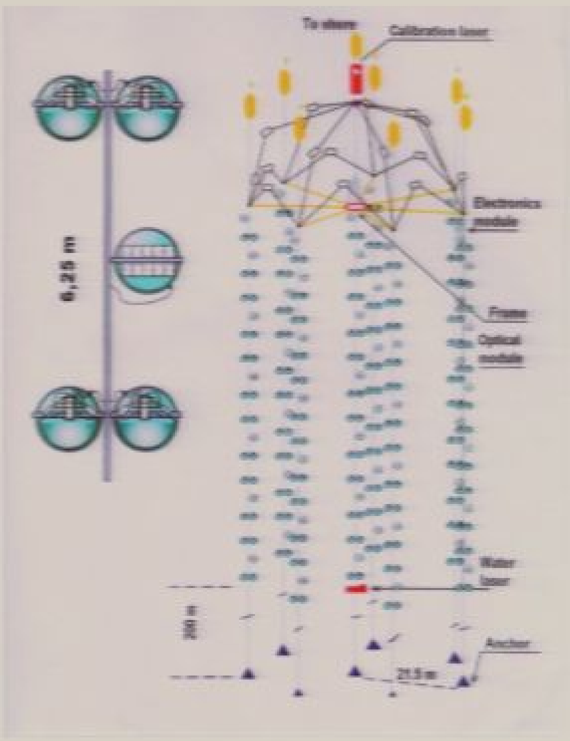
1100 m deep

data taking since 1998

new: 3 distant strings

Northern hemisphere detectors

Baikal NT200



1100 m deep
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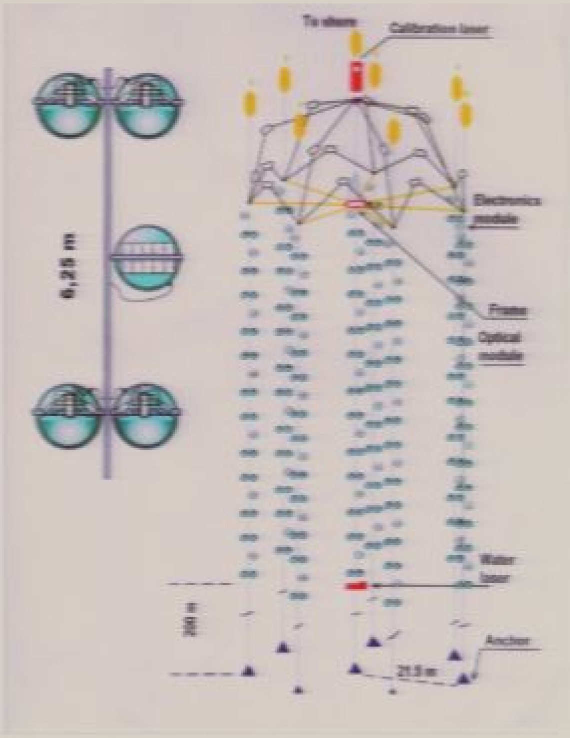
new: 3 distant strings

Antares

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

Northern hemisphere detectors

Baikal NT200

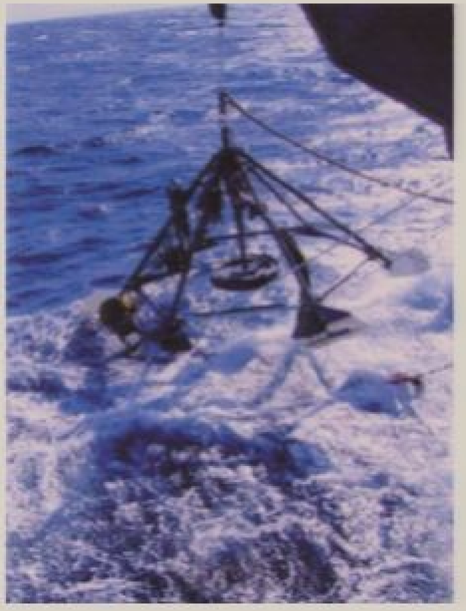


1100 m deep
data taking since 1998
new: 3 distant strings

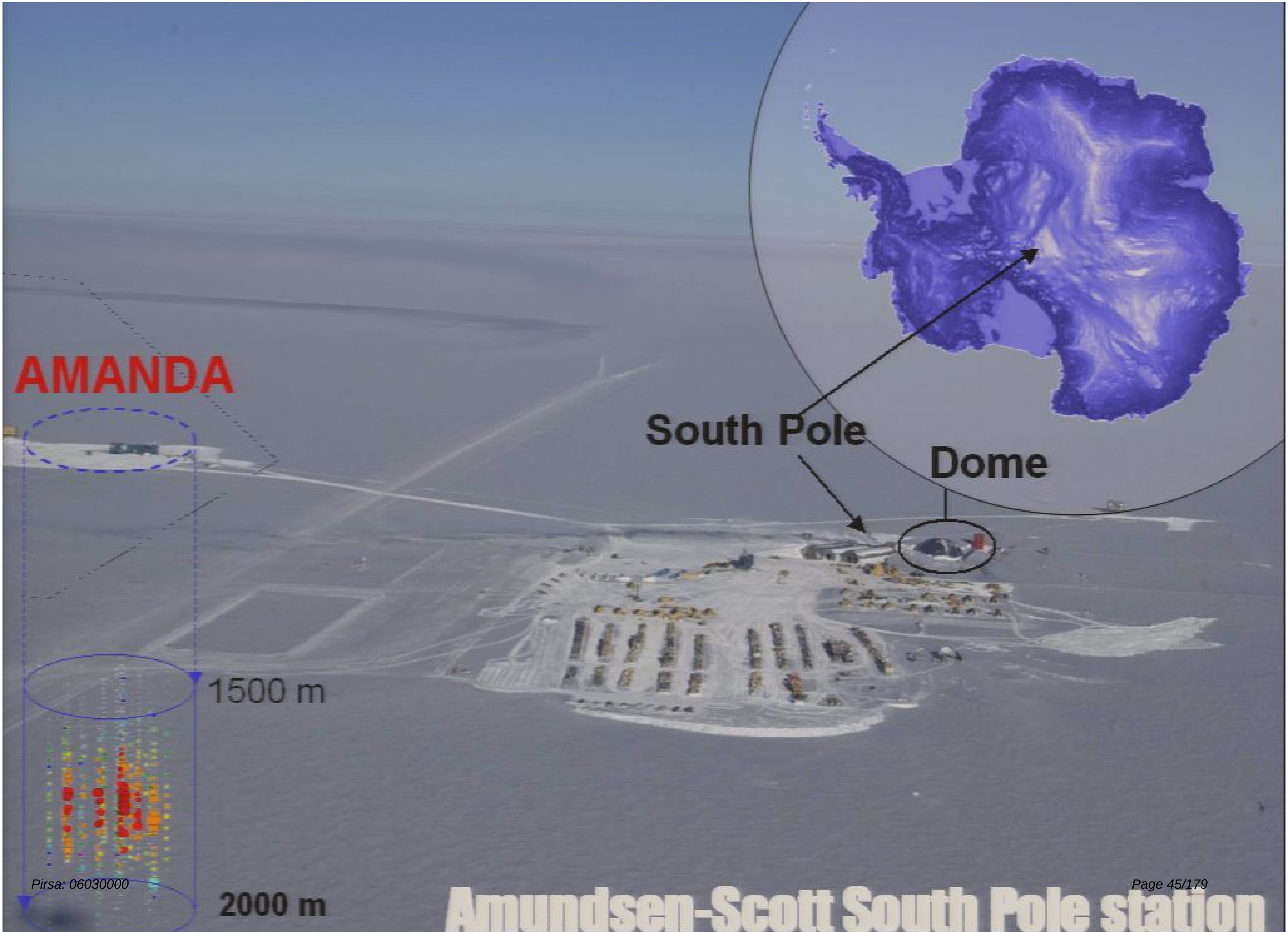
Antares

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



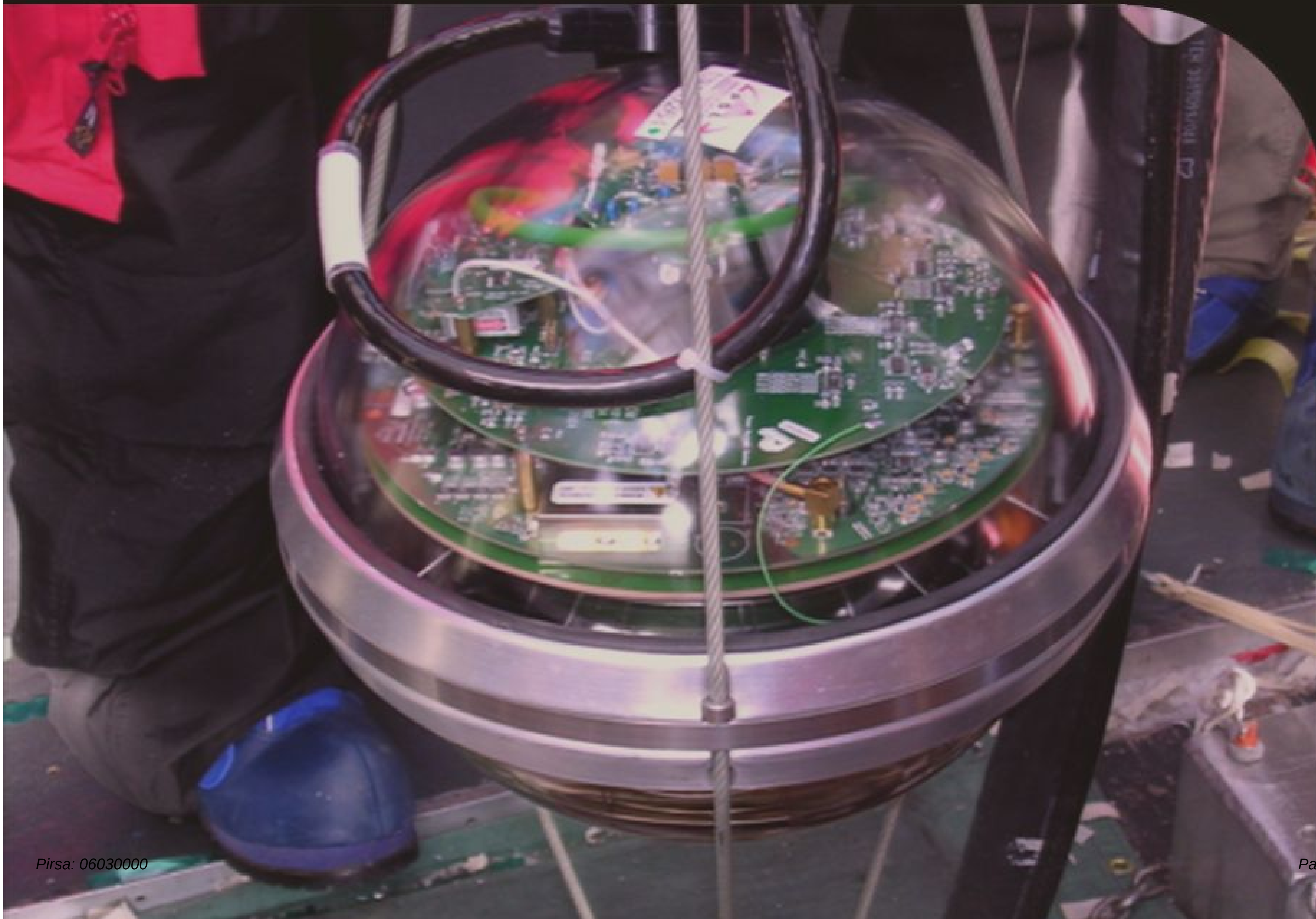
AMANDA
South Pole
Dome
1500 m
2000 m
Amundsen-Scott South Pole station

Building AMANDA

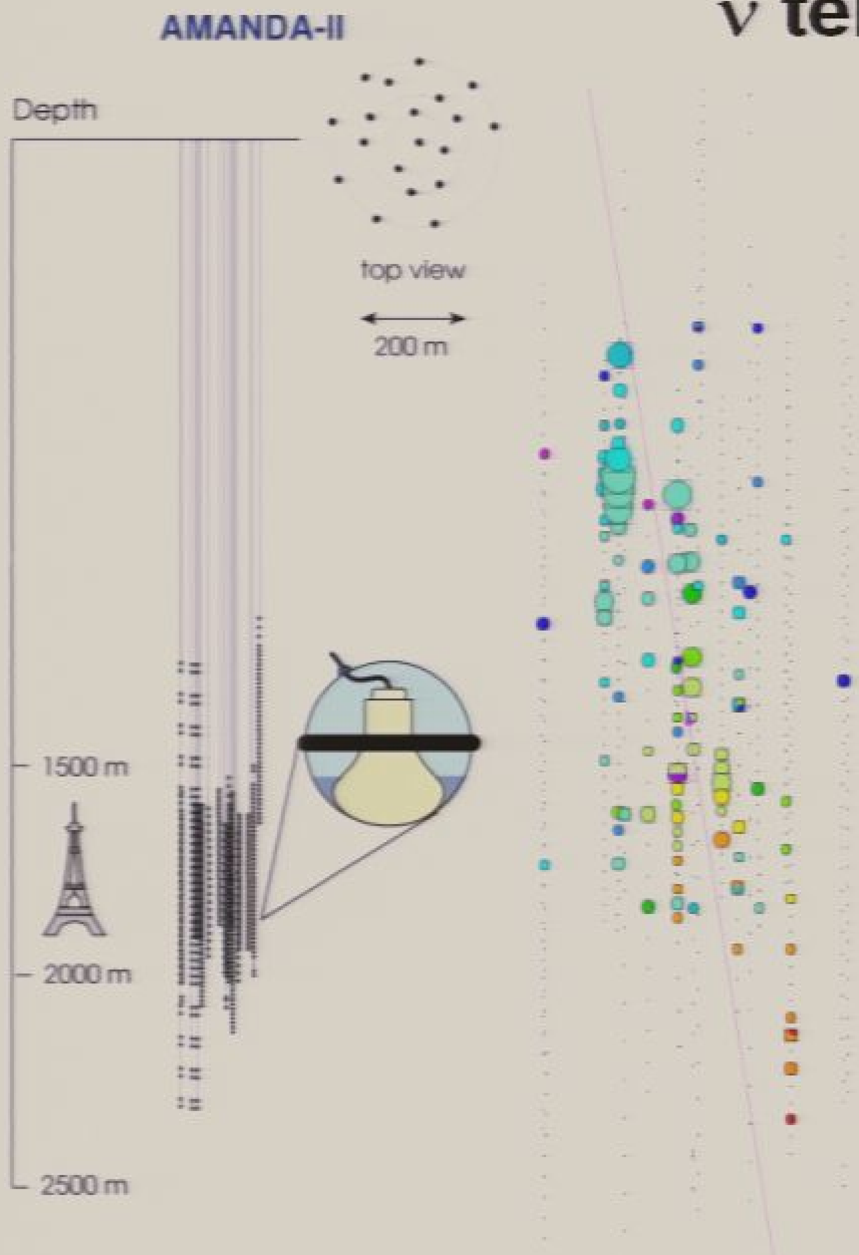
Drilling Holes with Hot Water

The Optical Module

optical sensor



ν telescope : AMANDA event



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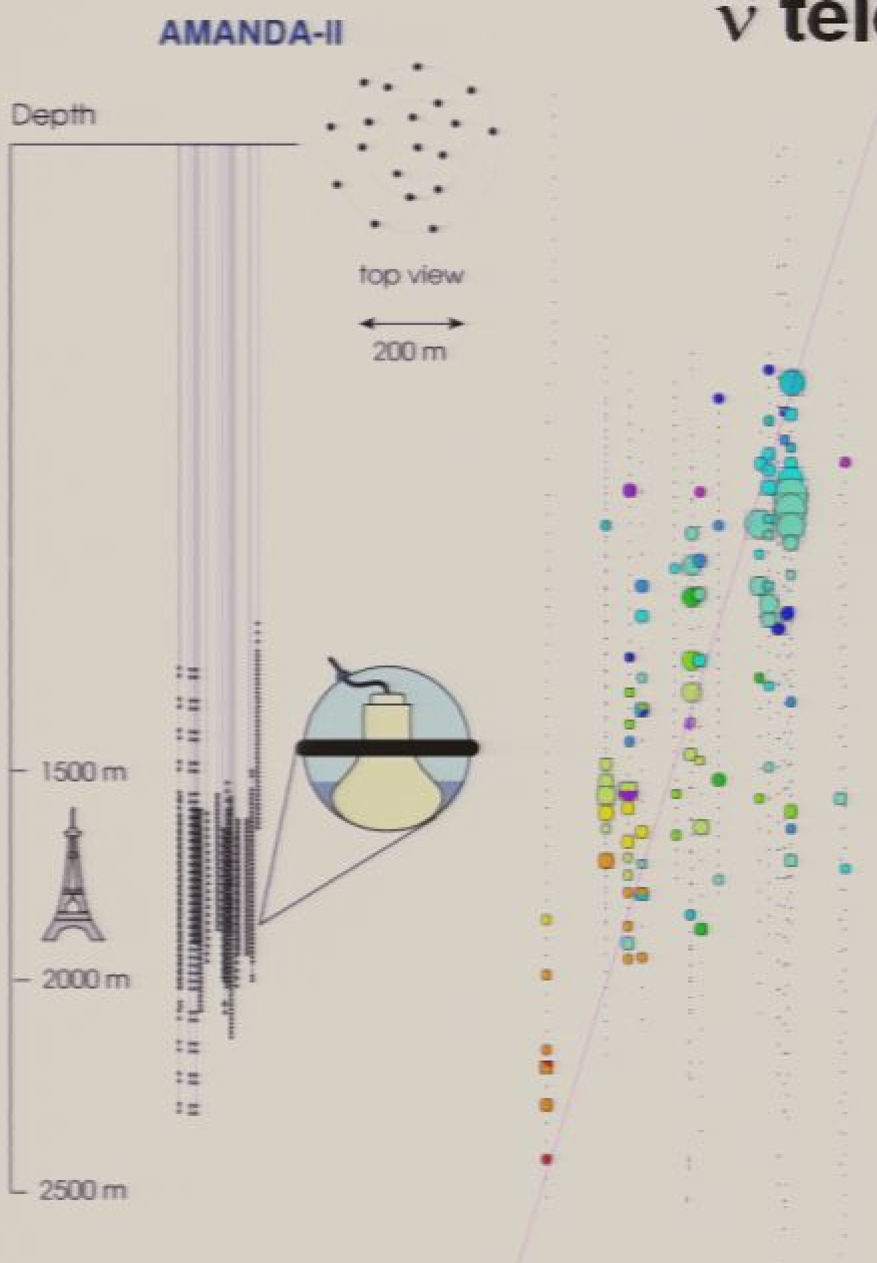
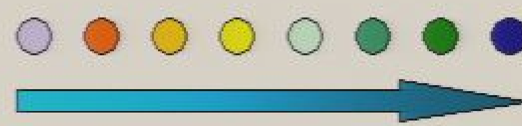


energy deposited in OM



time recorded on OM

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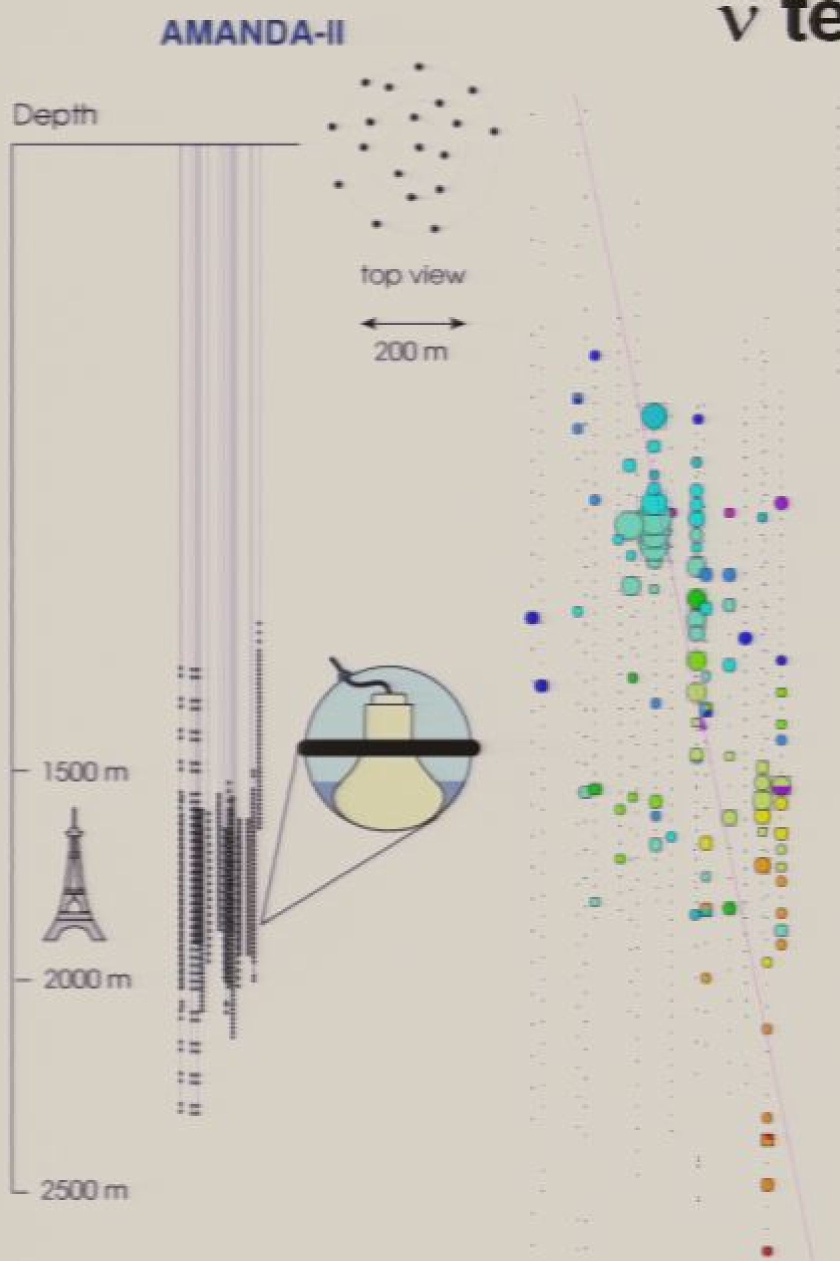

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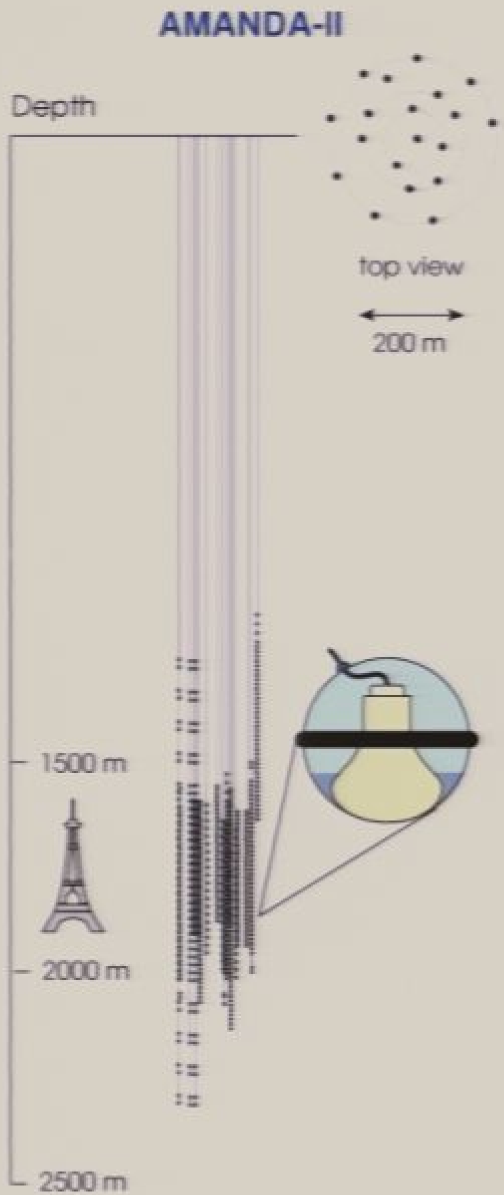

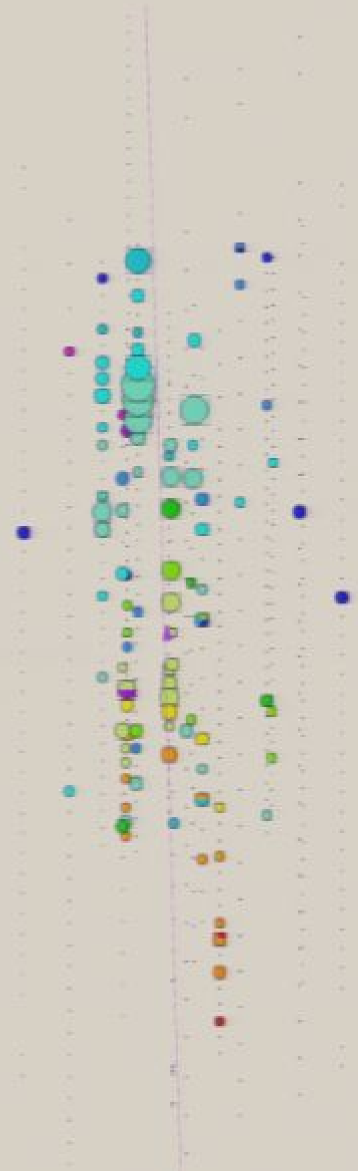

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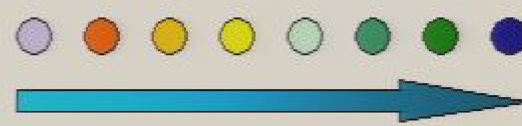

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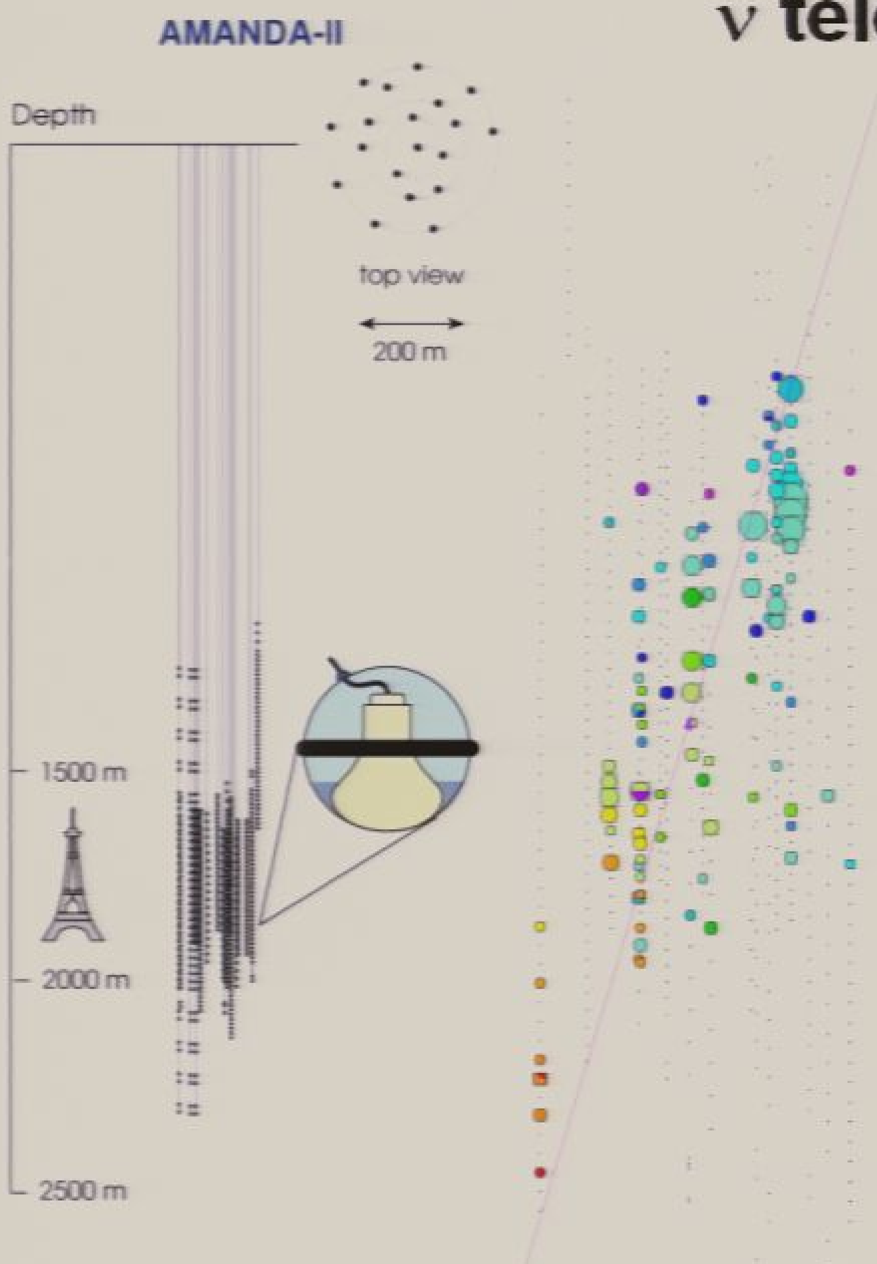
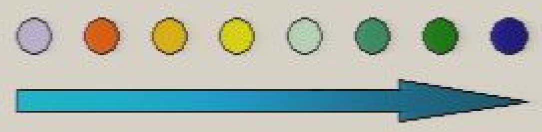


energy deposited in OM



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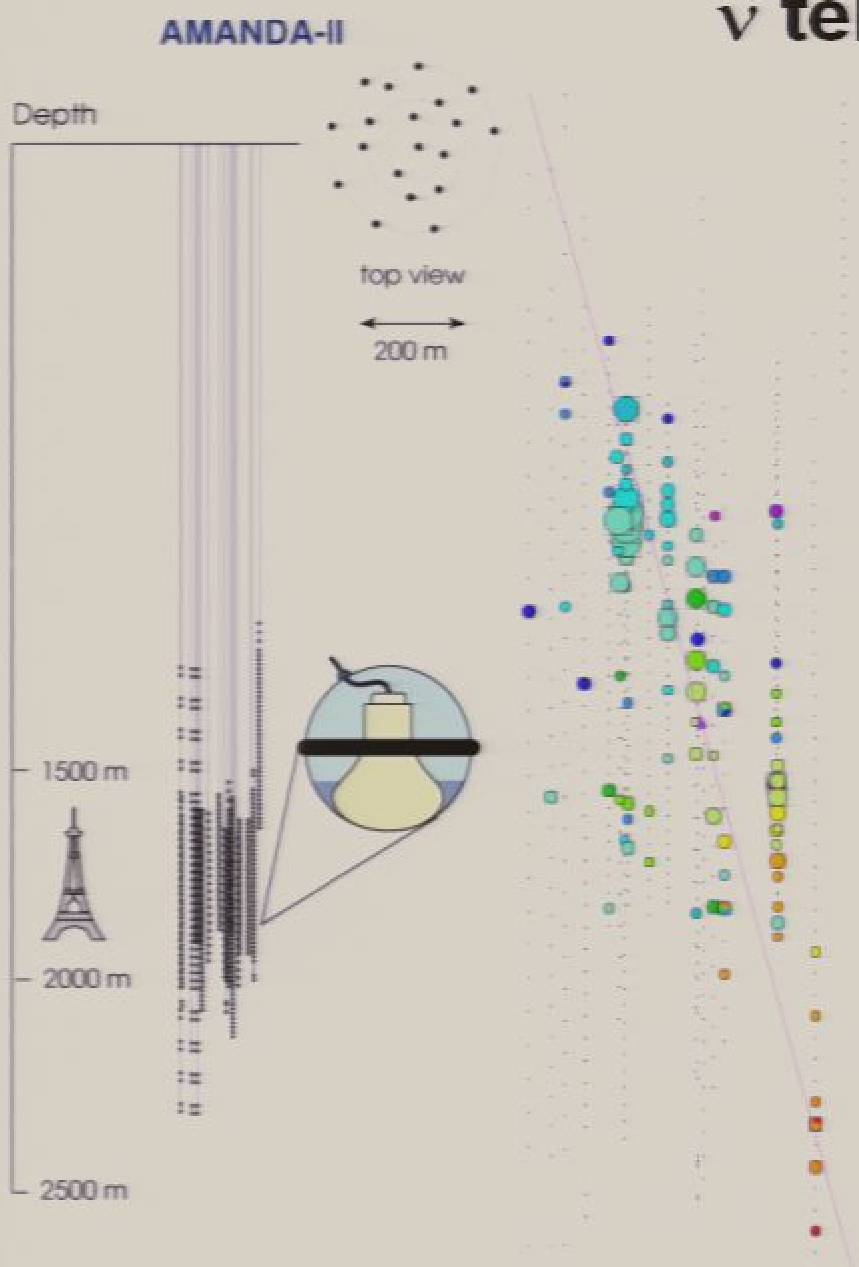

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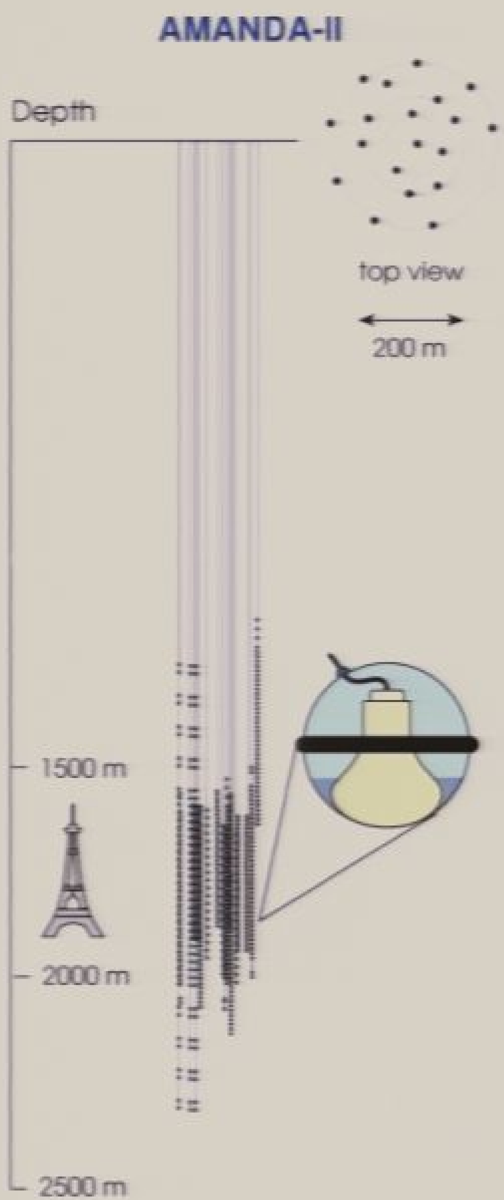

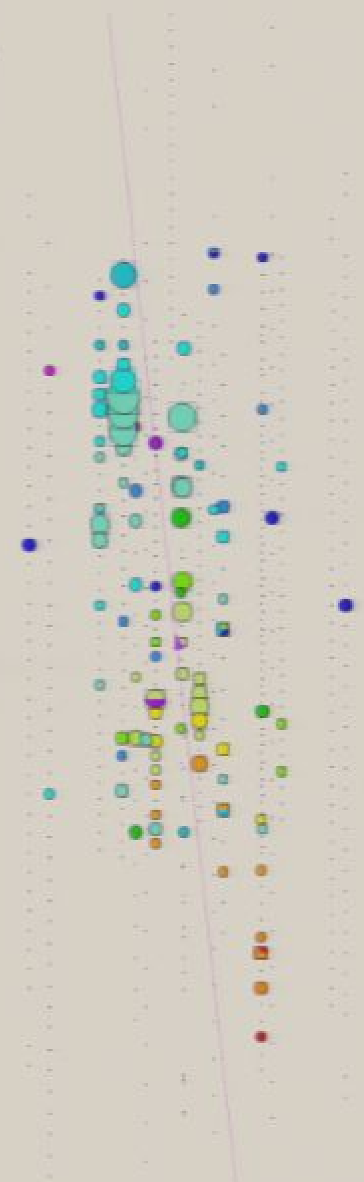

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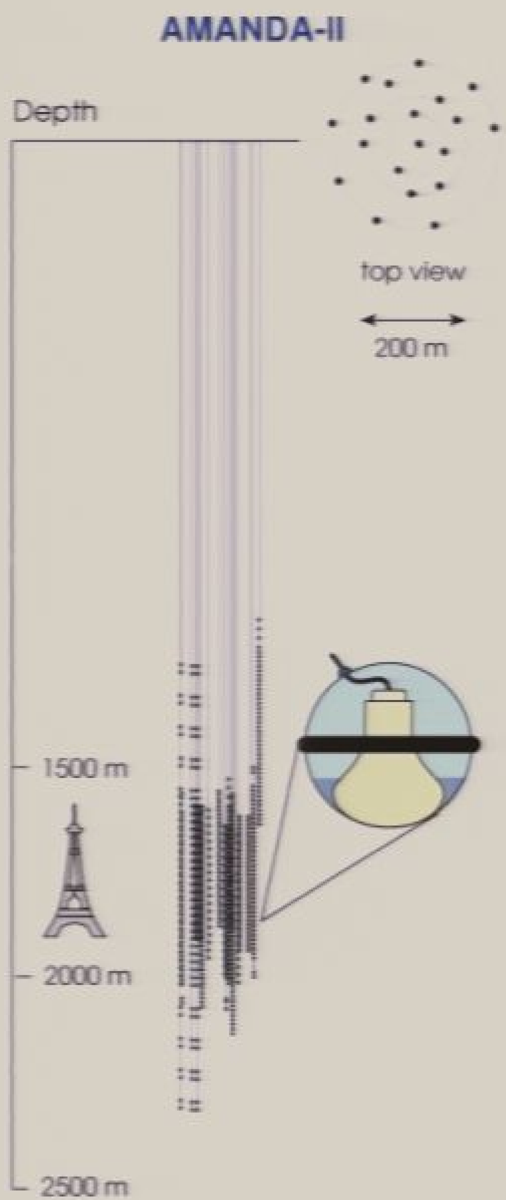

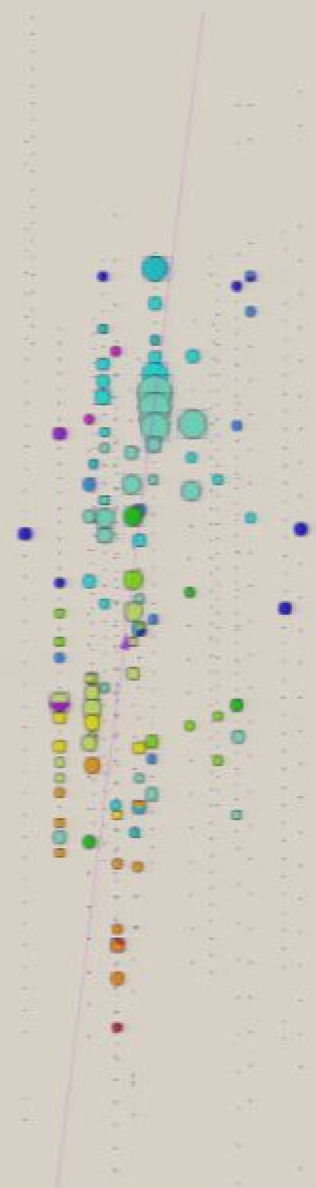

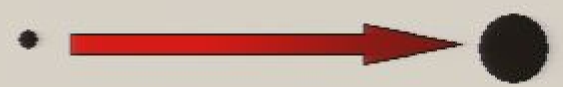

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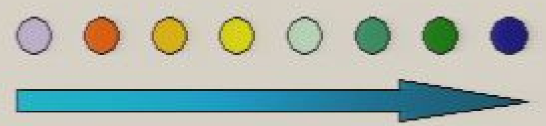
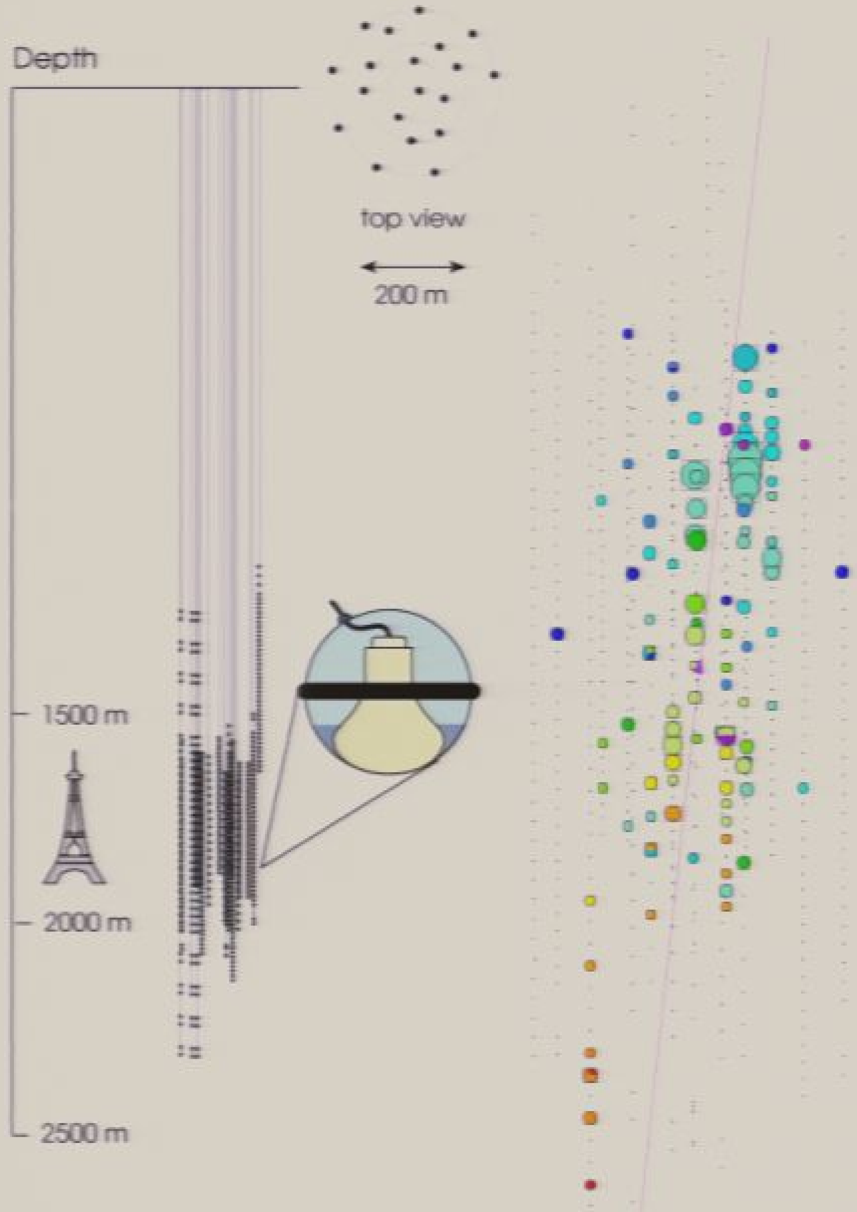
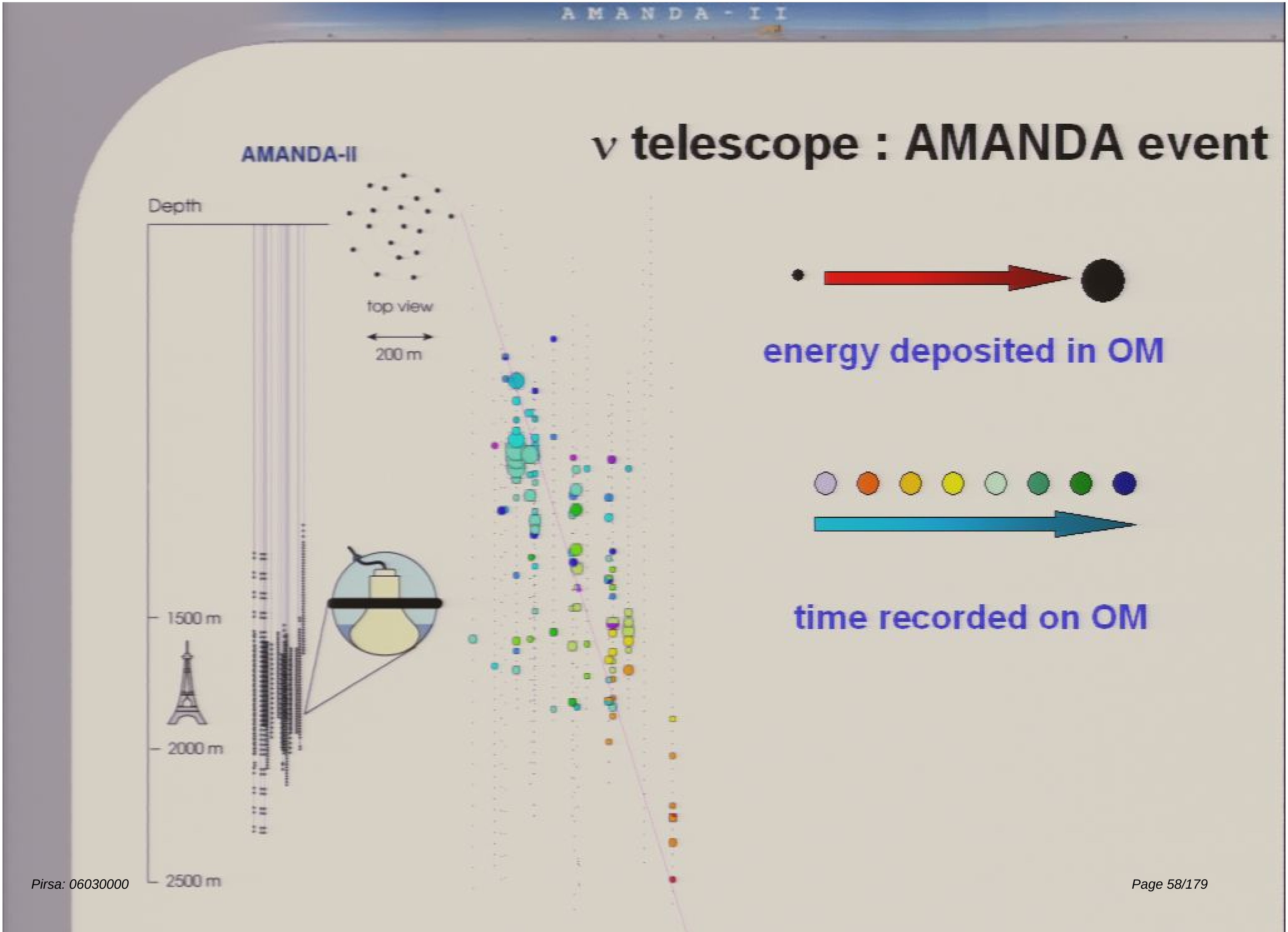


time recorded on OM

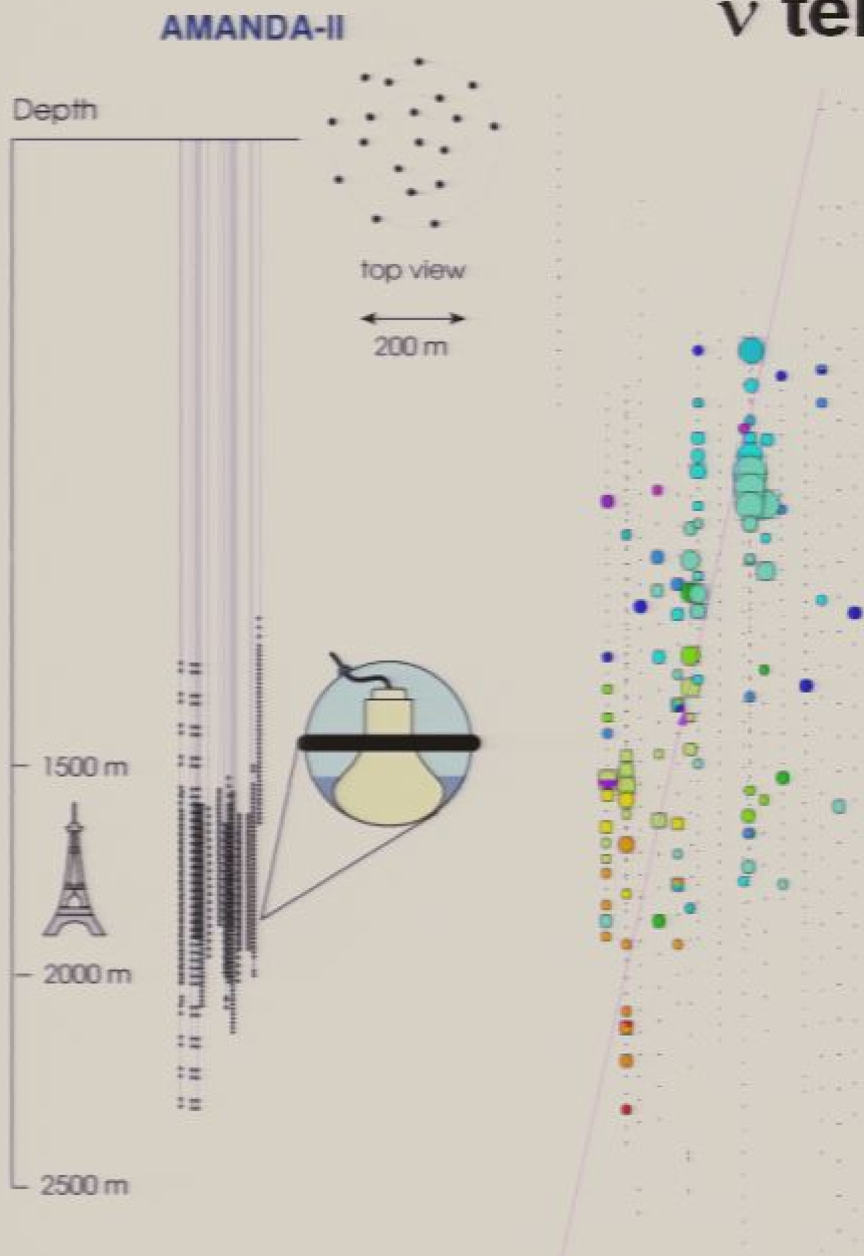
ν telescope : AMANDA event





A M A N D A - I I
ν telescope : AMANDA event
AMANDA-II
Depth
top view
200 m
1500 m
2000 m
2500 m
energy deposited in OM
time recorded on OM

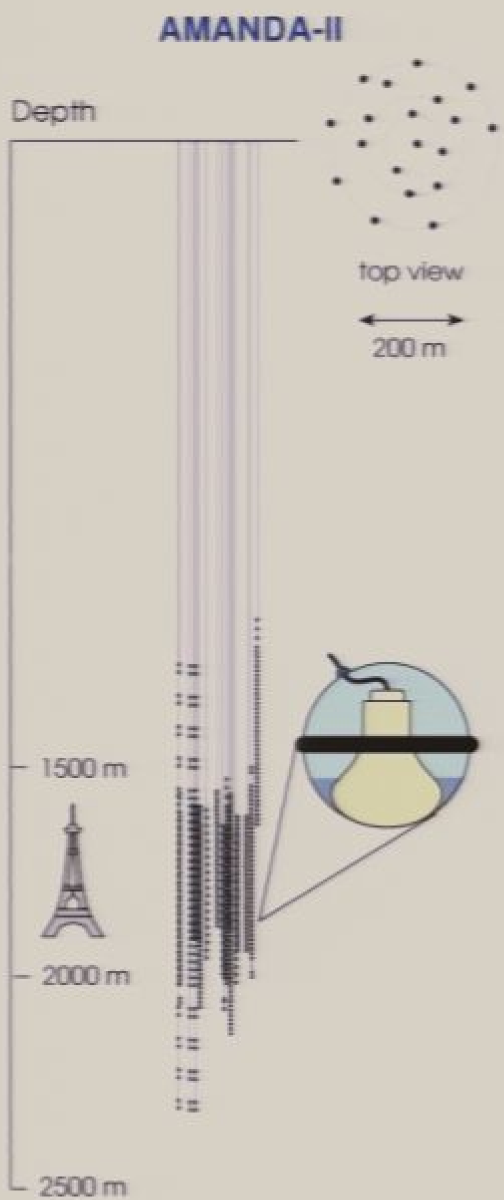
ν telescope : AMANDA event

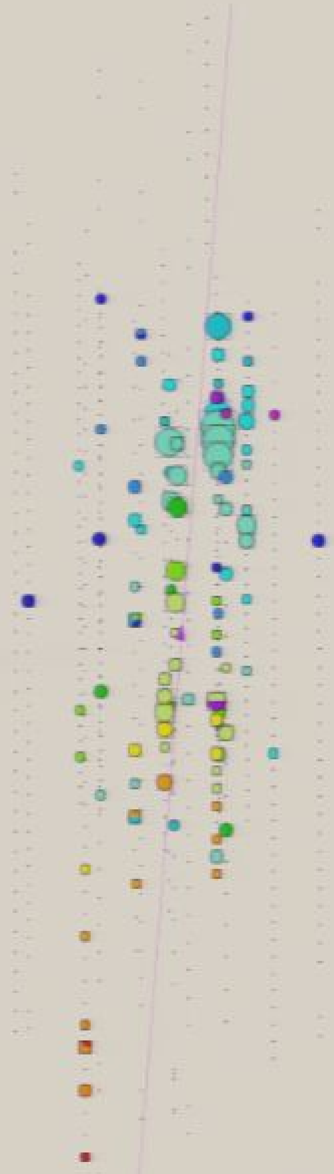


energy deposited in OM

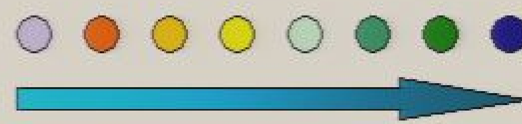
time recorded on OM

ν telescope : AMANDA event



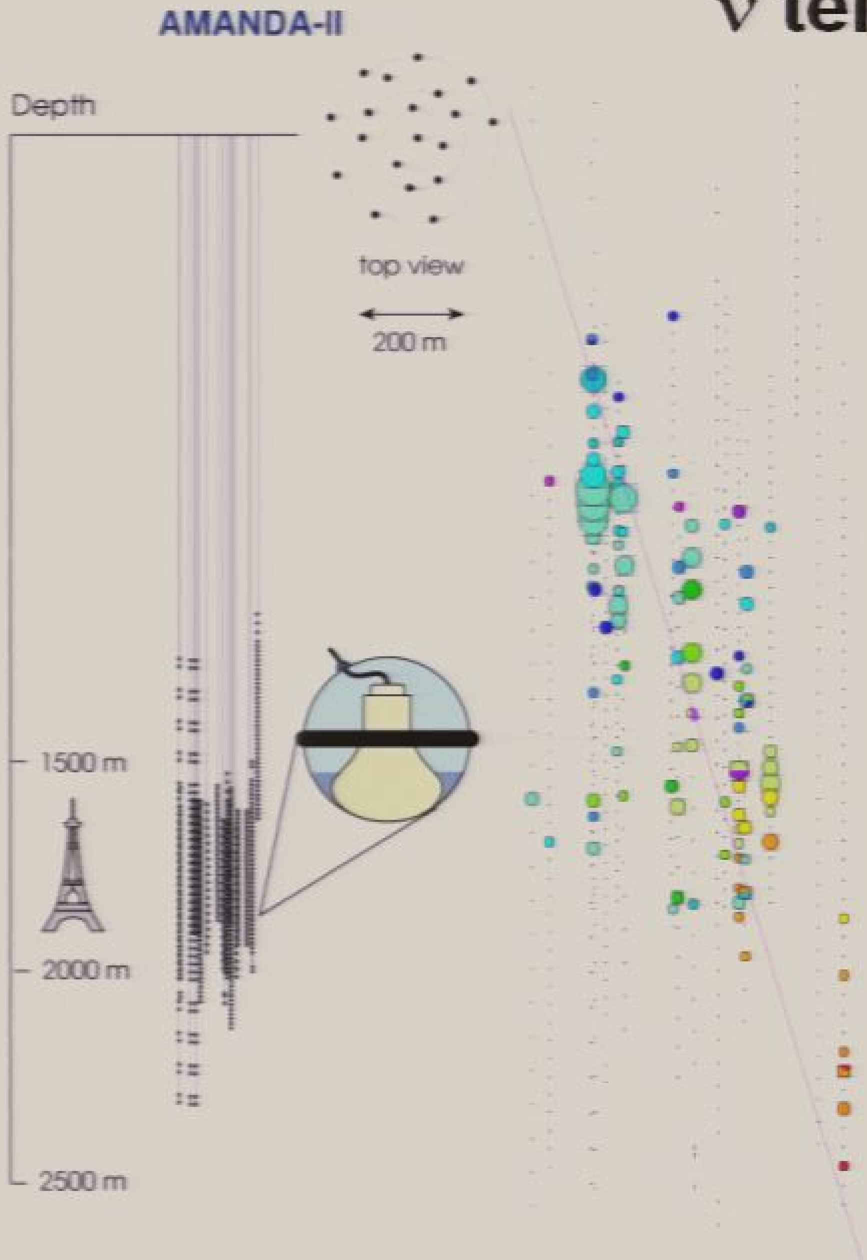


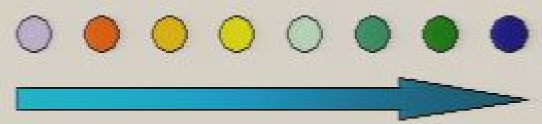
energy deposited in OM



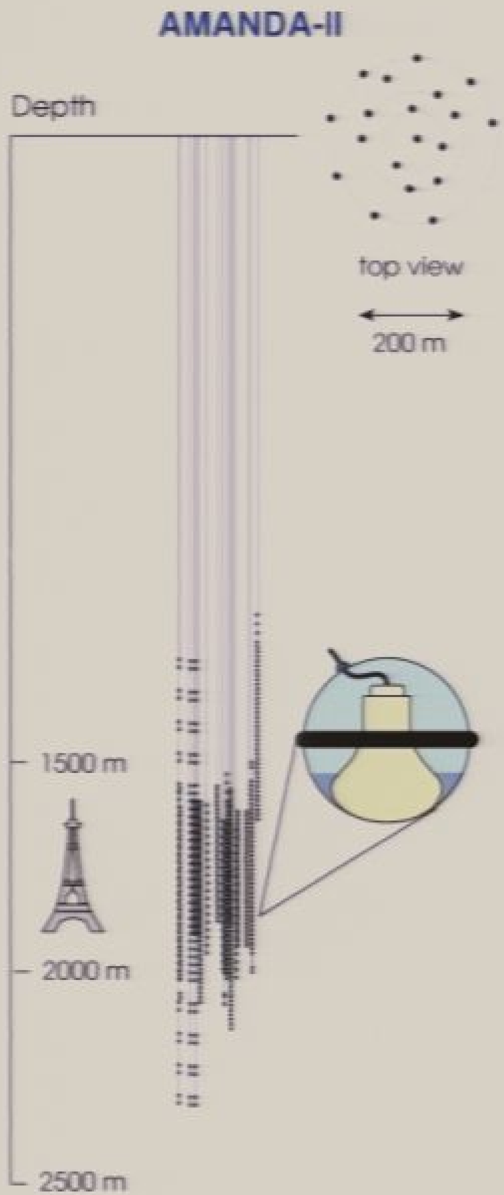
time recorded on OM

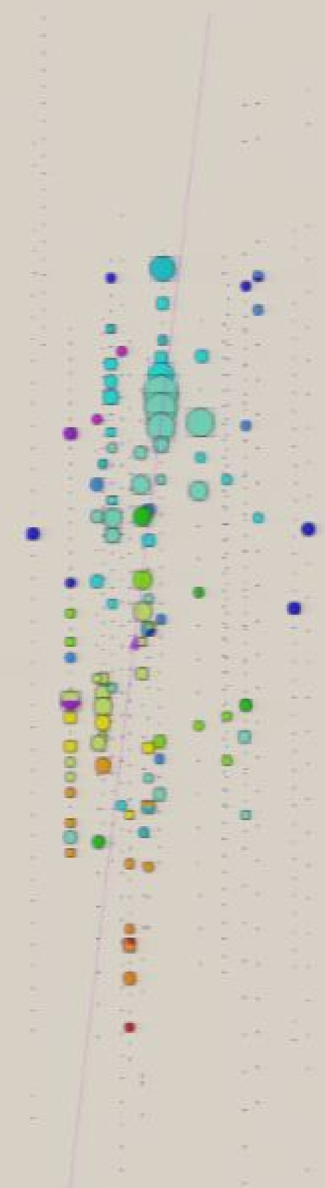
ν telescope : AMANDA event

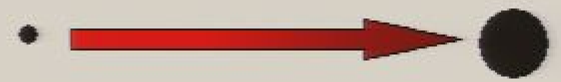




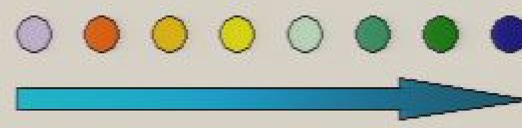
ν telescope : AMANDA event





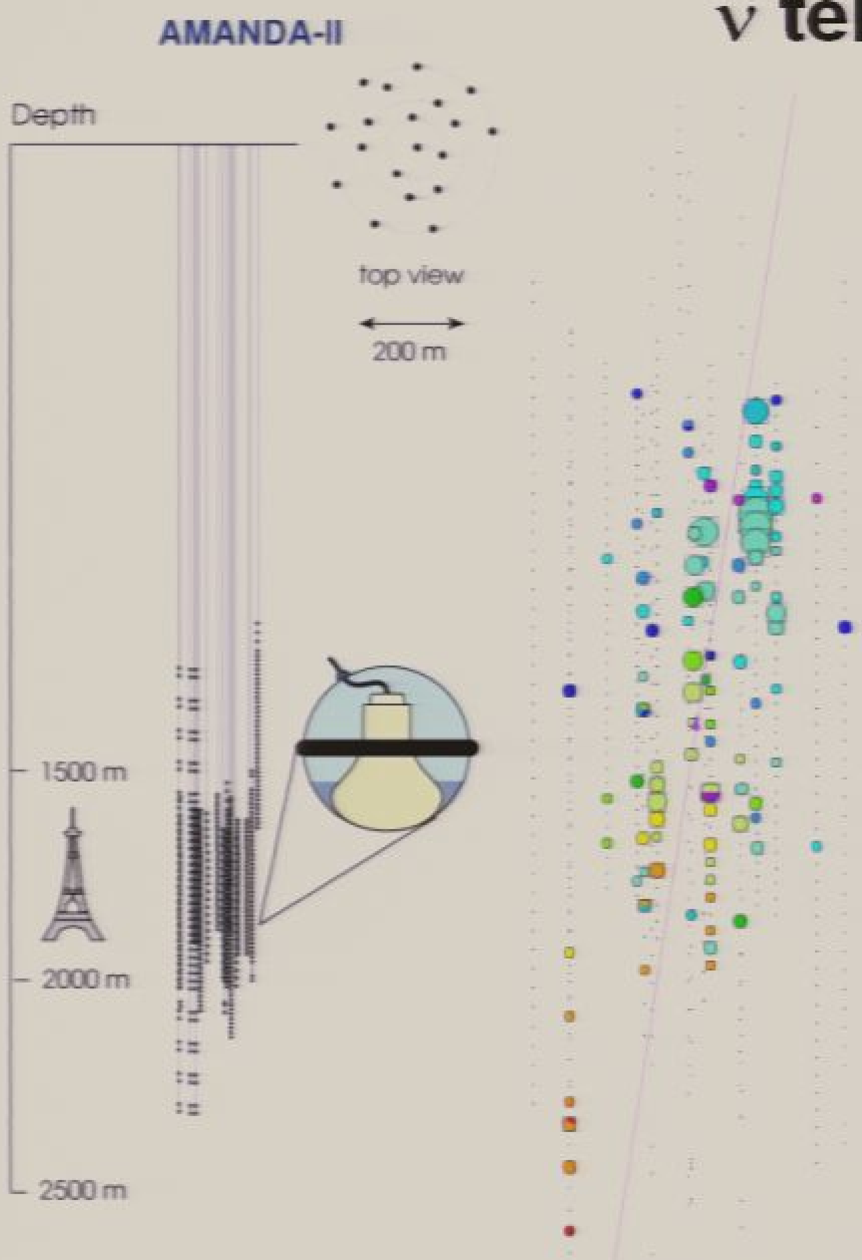


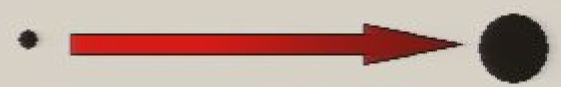
energy deposited in OM



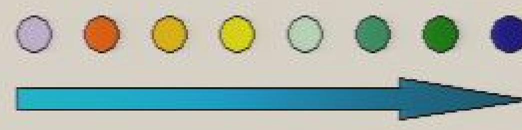
time recorded on OM

ν telescope : AMANDA event



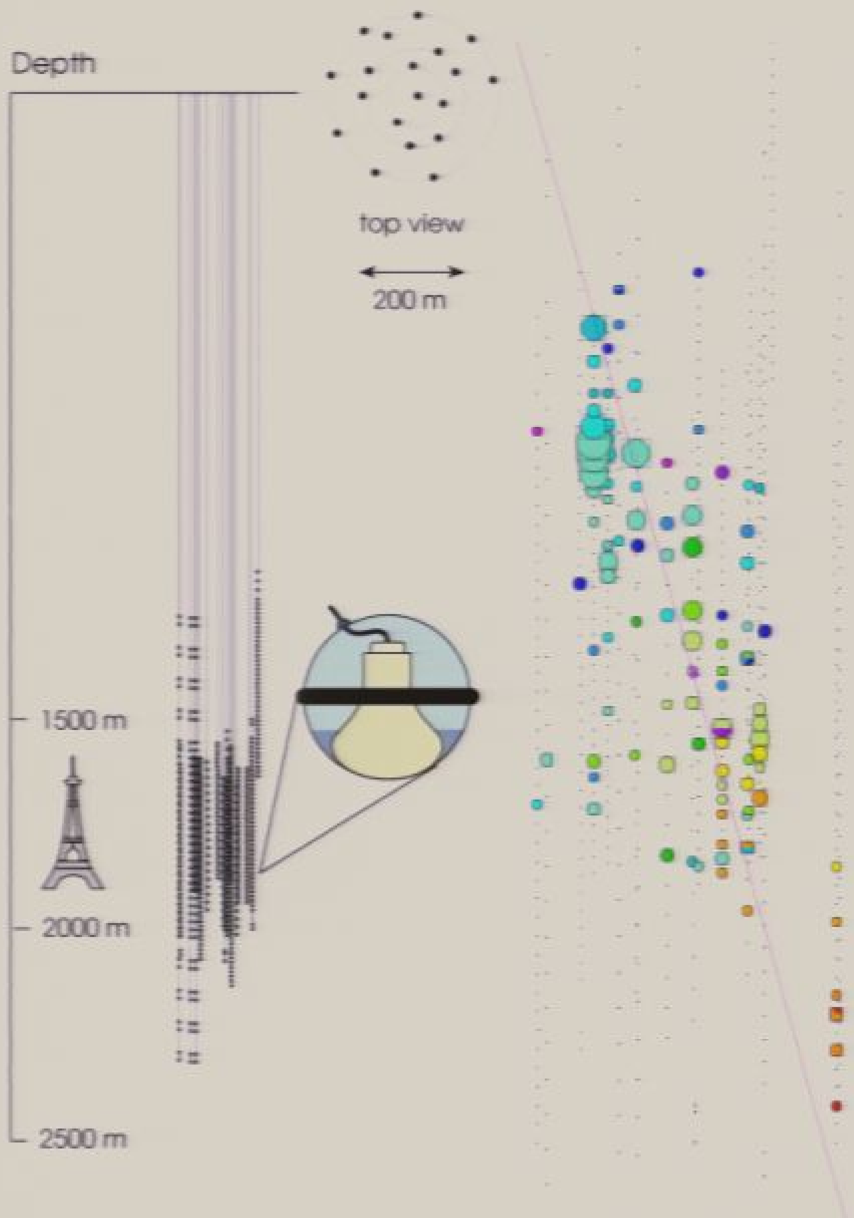


energy deposited in OM

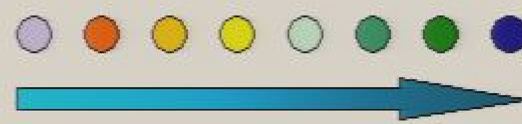


time recorded on OM

ν telescope : AMANDA event

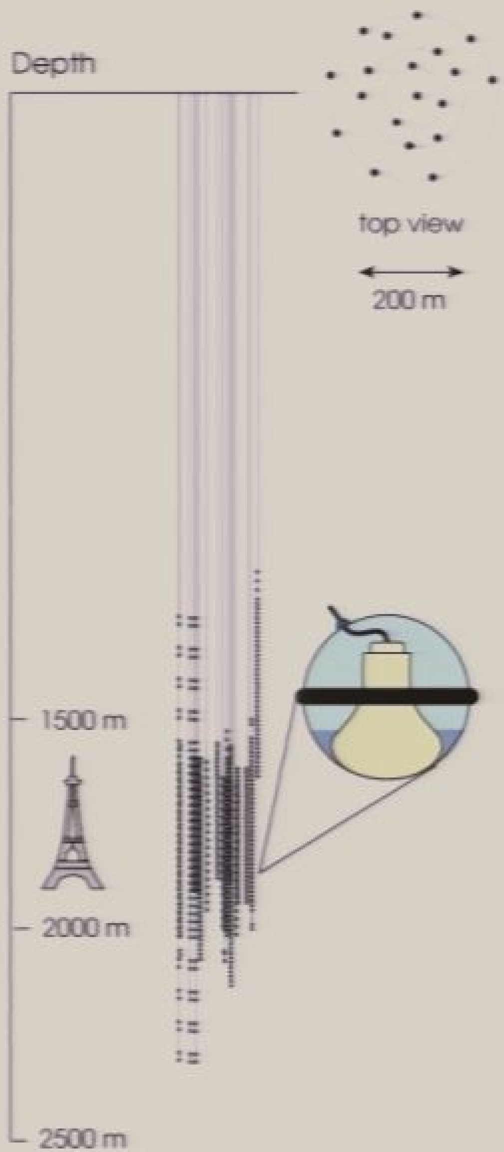


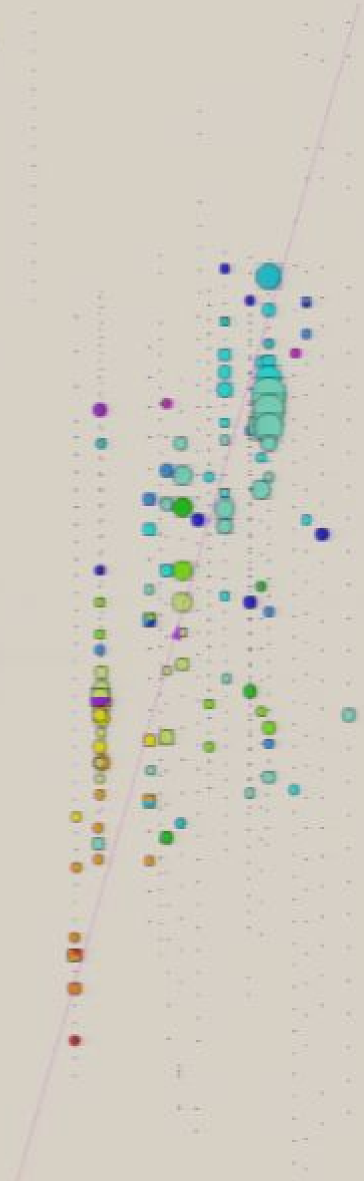
energy deposited in OM

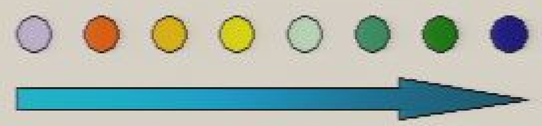


time recorded on OM

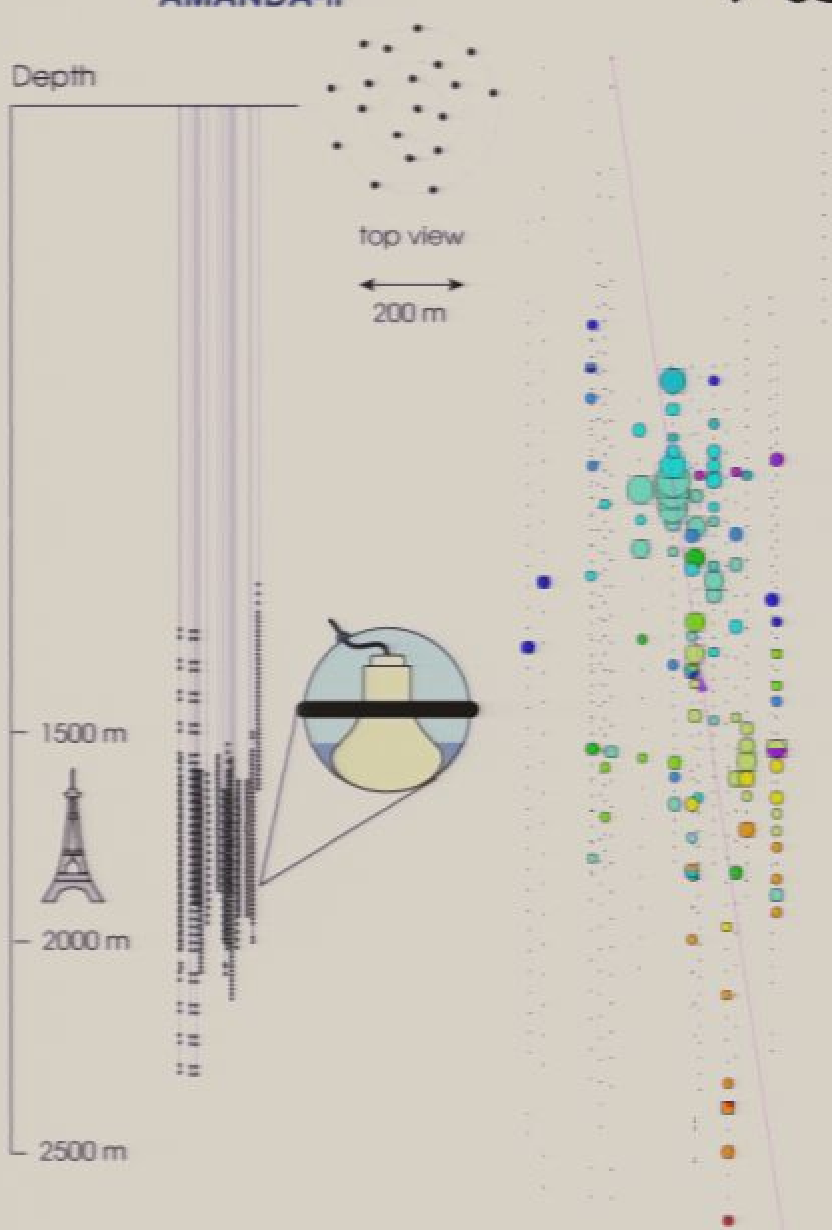
ν telescope : AMANDA event

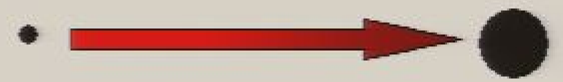




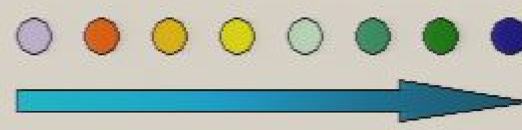


ν telescope : AMANDA event



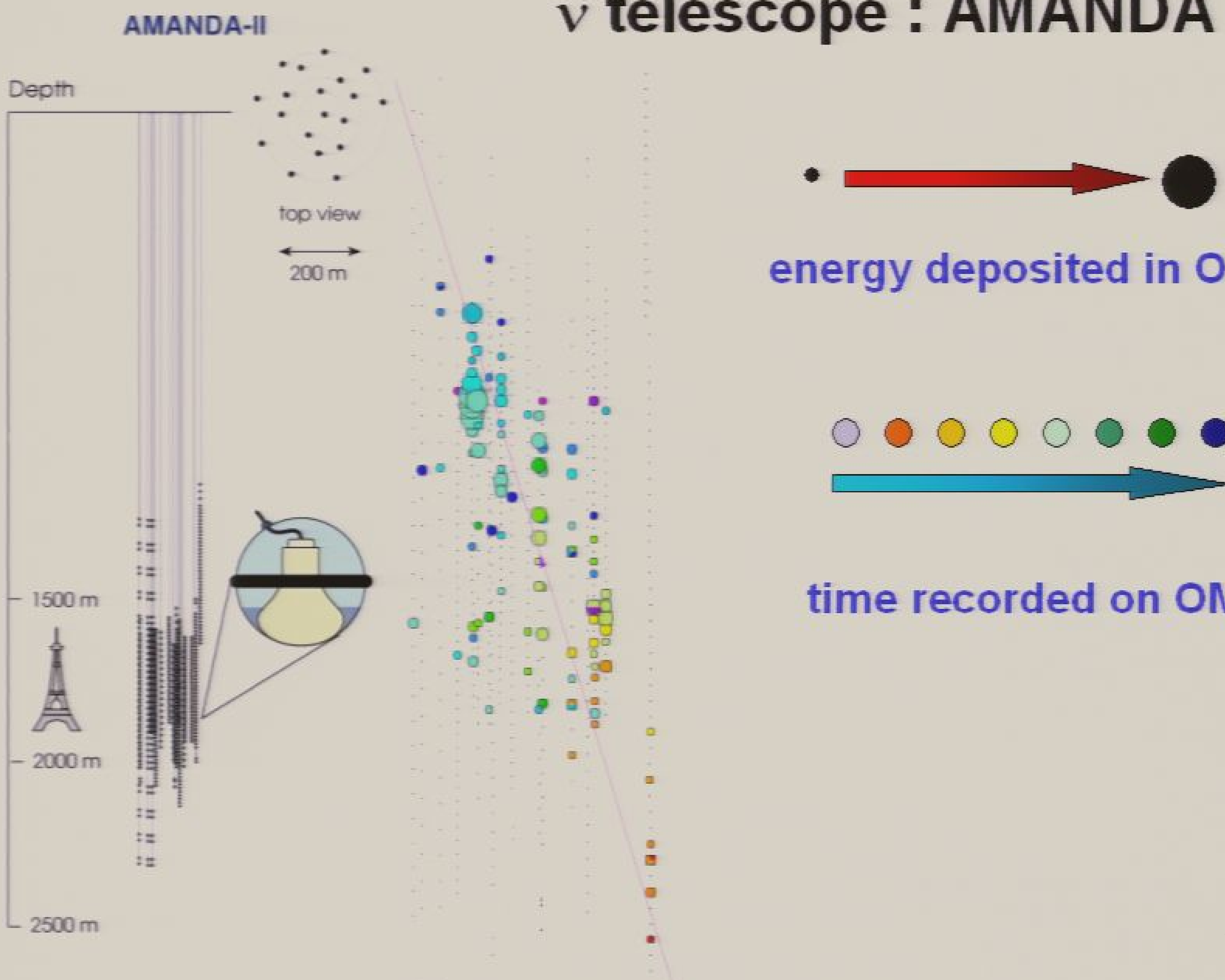


energy deposited in OM

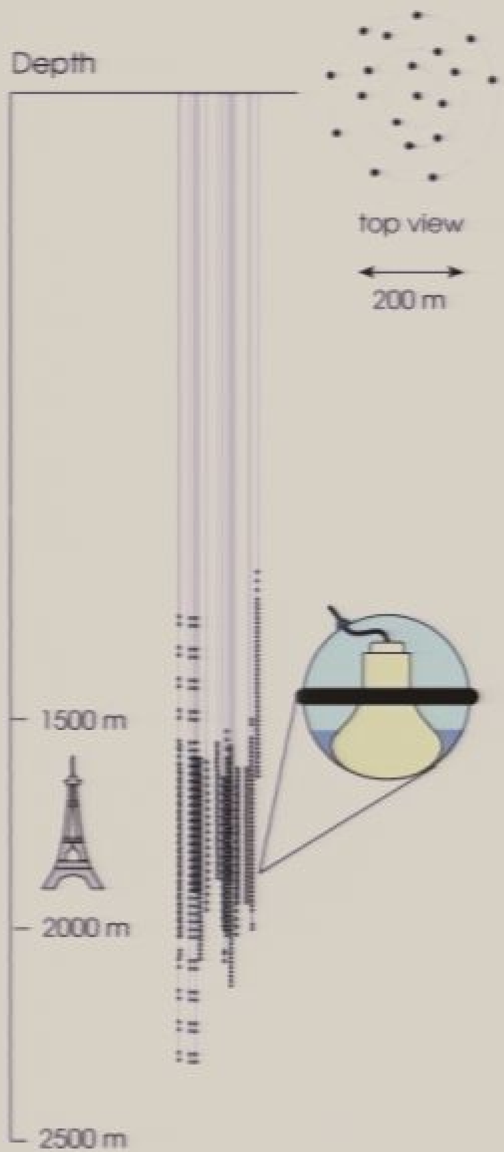


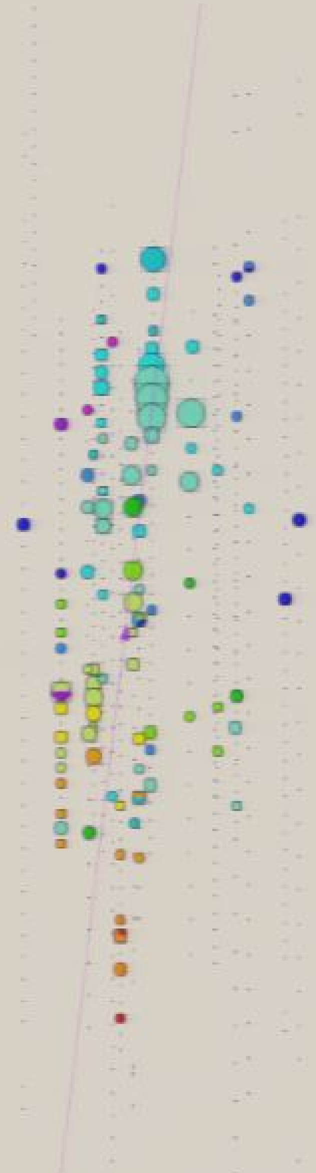
time recorded on OM

ν telescope : AMANDA event

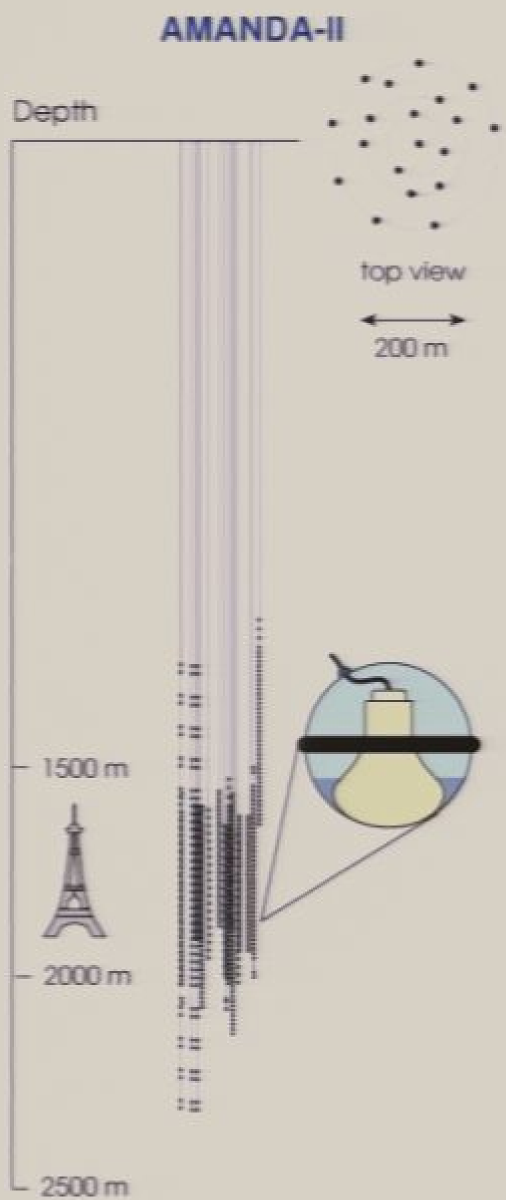


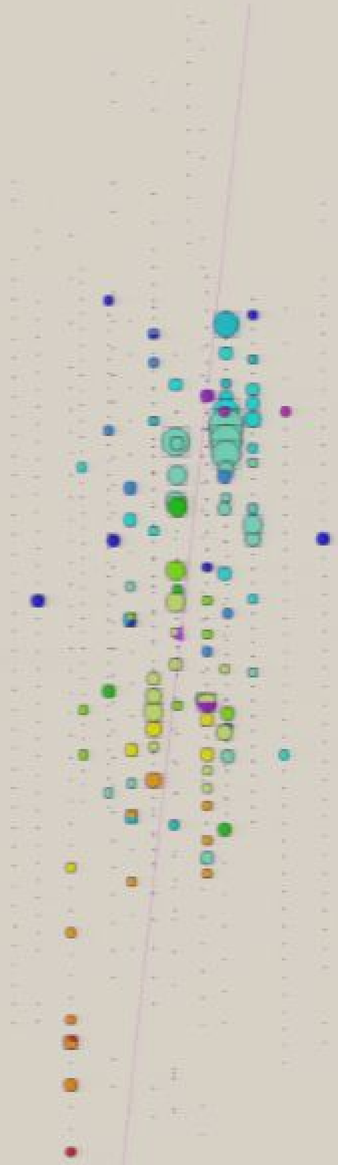
ν telescope : AMANDA event



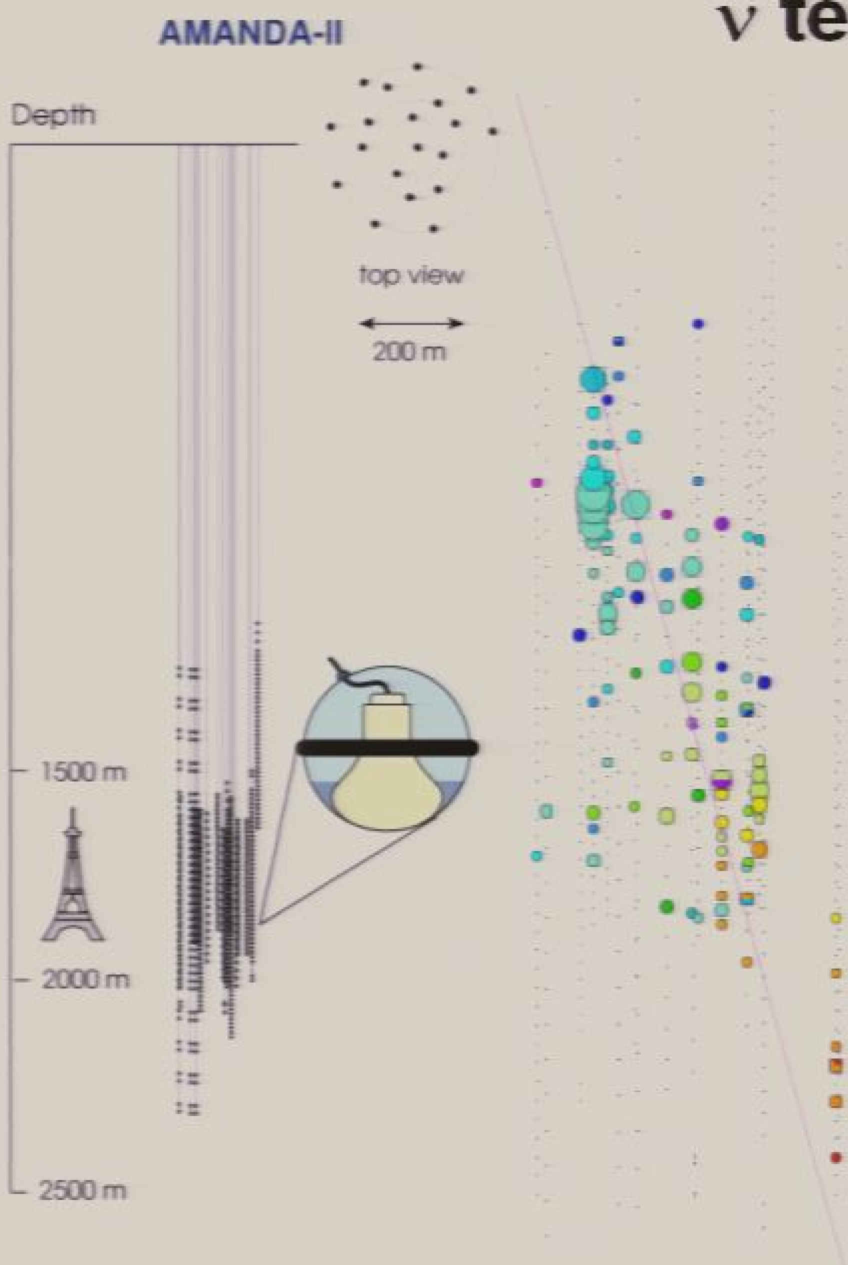


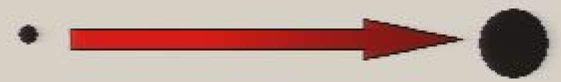
ν telescope : AMANDA event



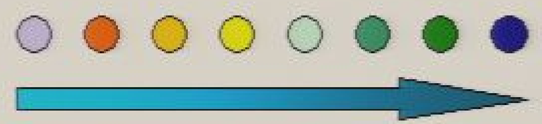


ν telescope : AMANDA event



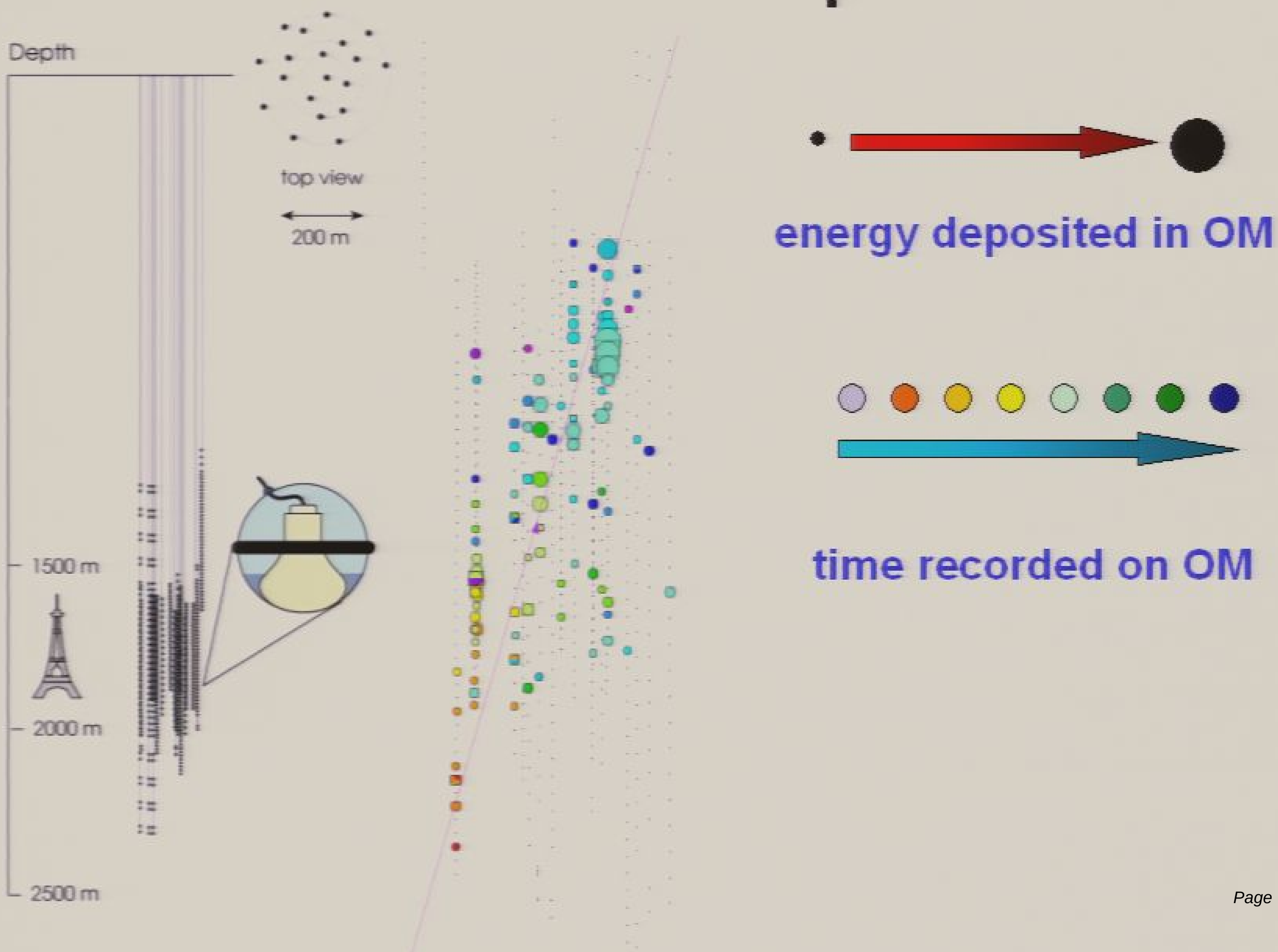


energy deposited in OM

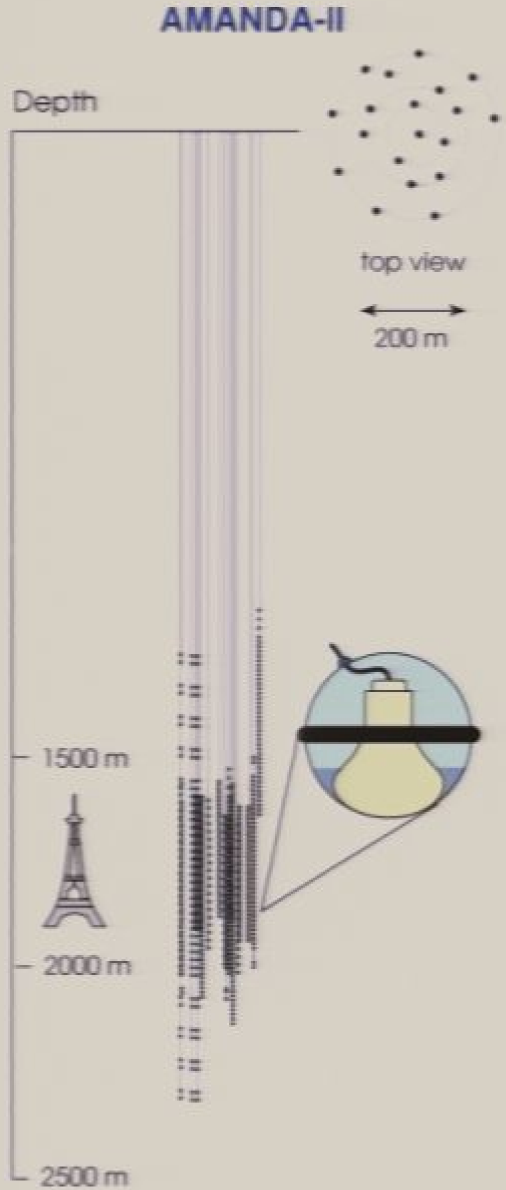


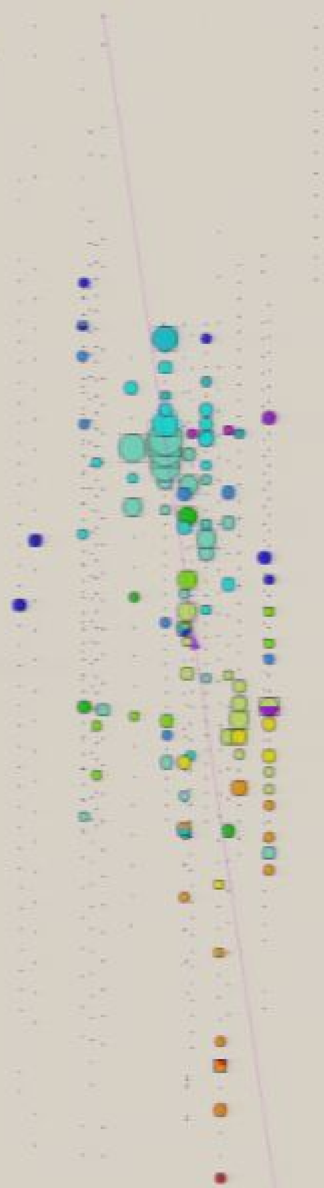
time recorded on OM

ν telescope : AMANDA event

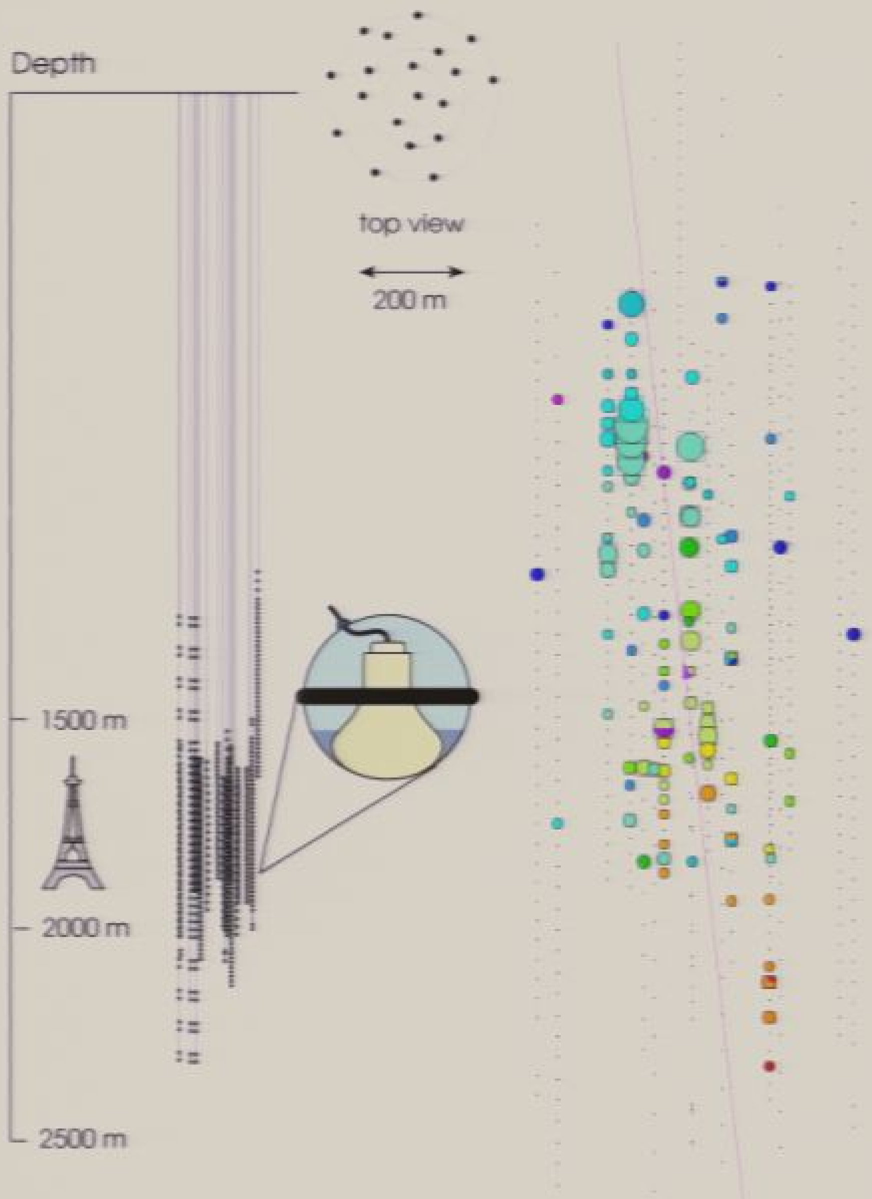


ν telescope : AMANDA event





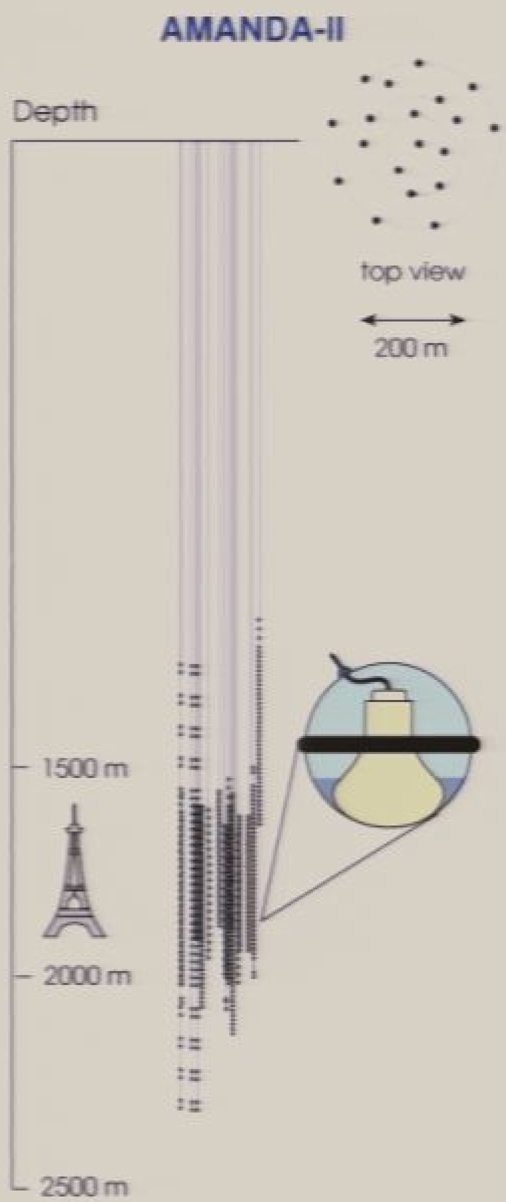
ν telescope : AMANDA event

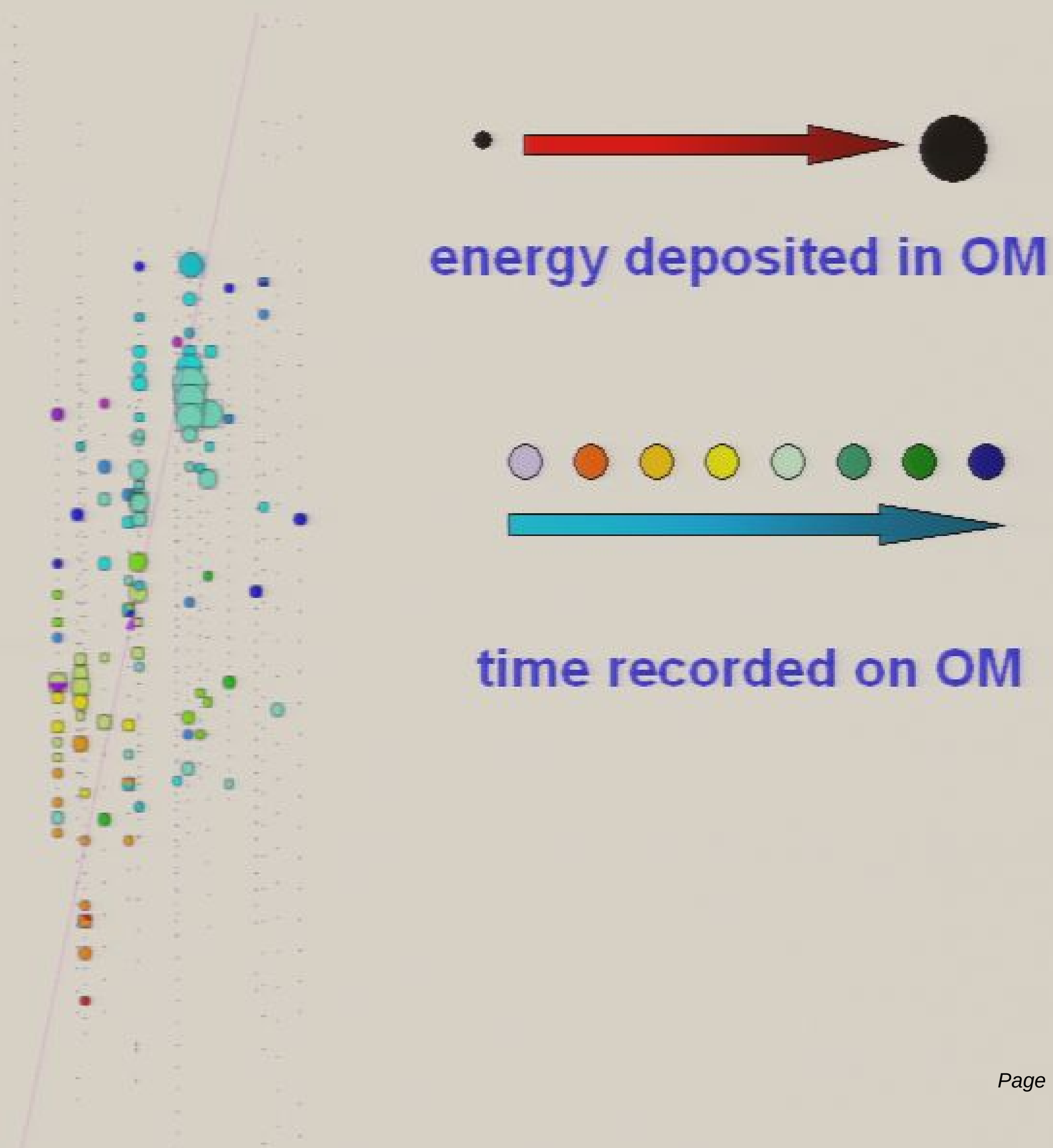


energy deposited in OM

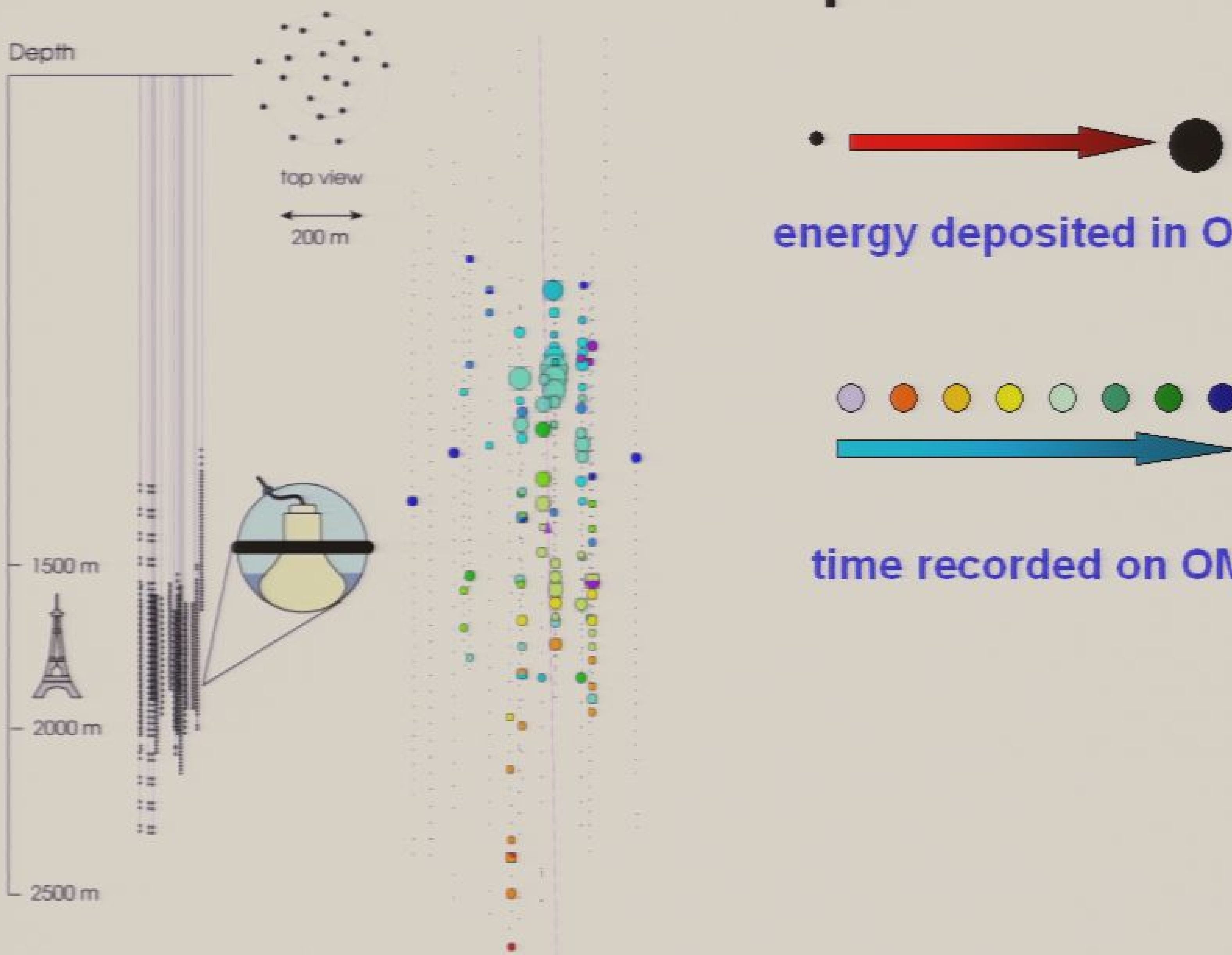
time recorded on OM

ν telescope : AMANDA event

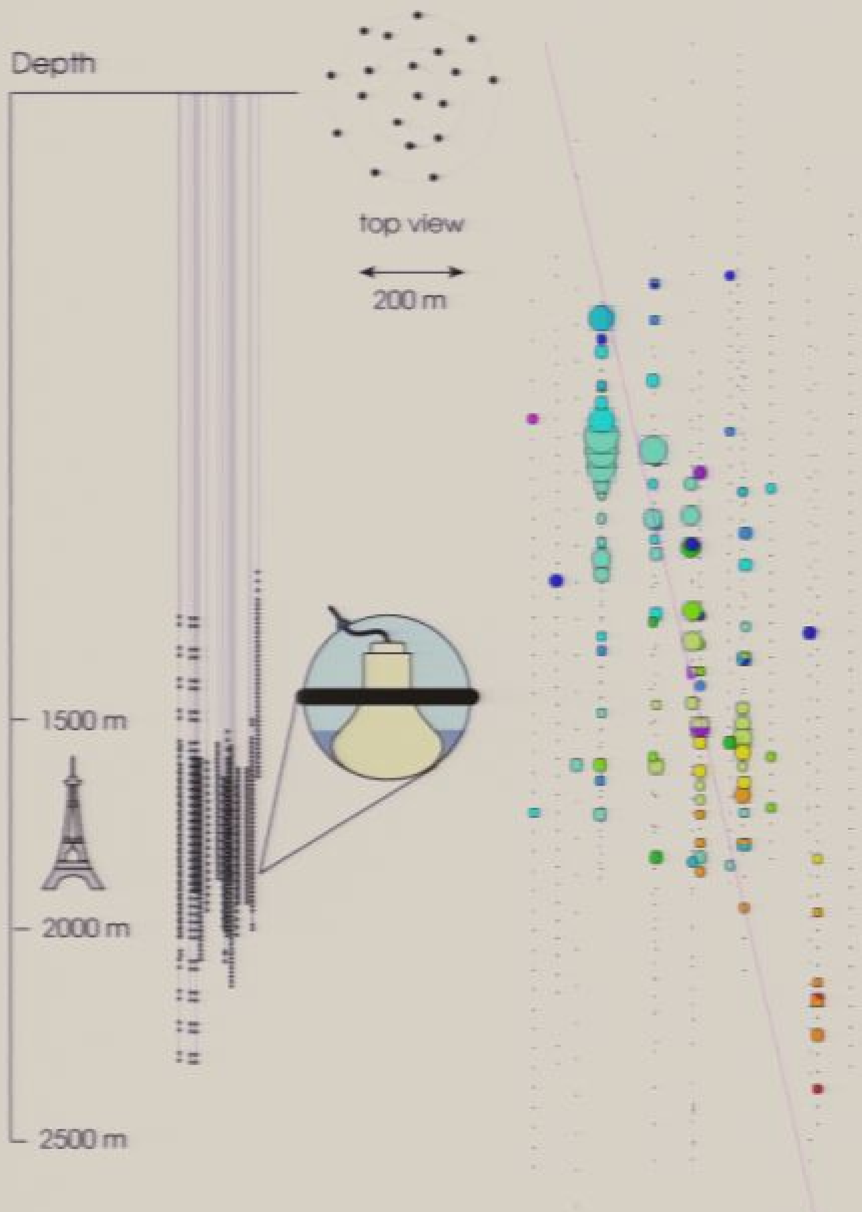




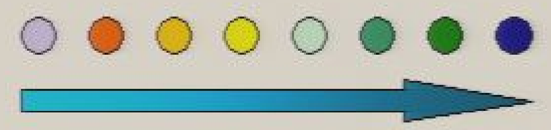
ν telescope : AMANDA event



ν telescope : AMANDA event

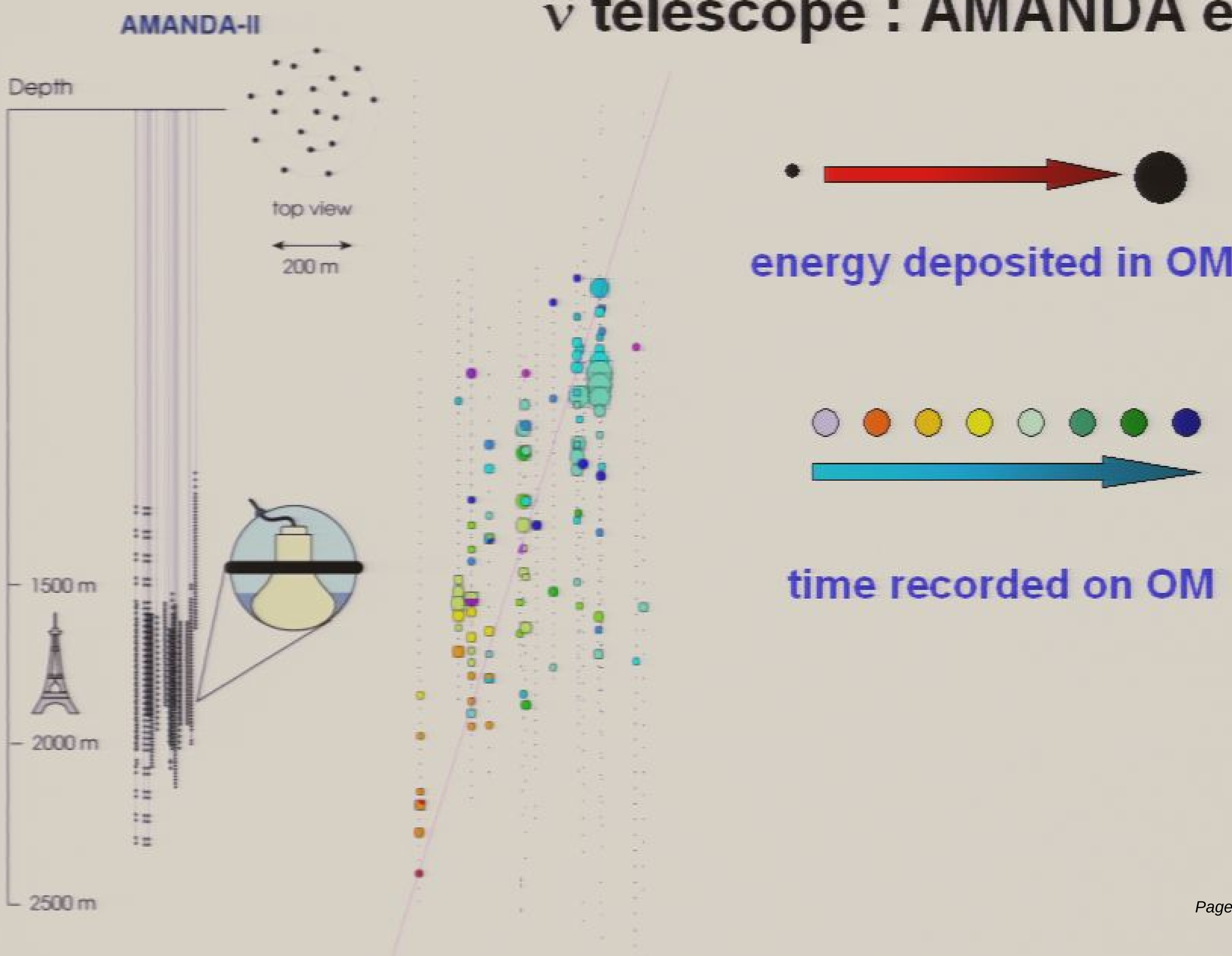


energy deposited in OM

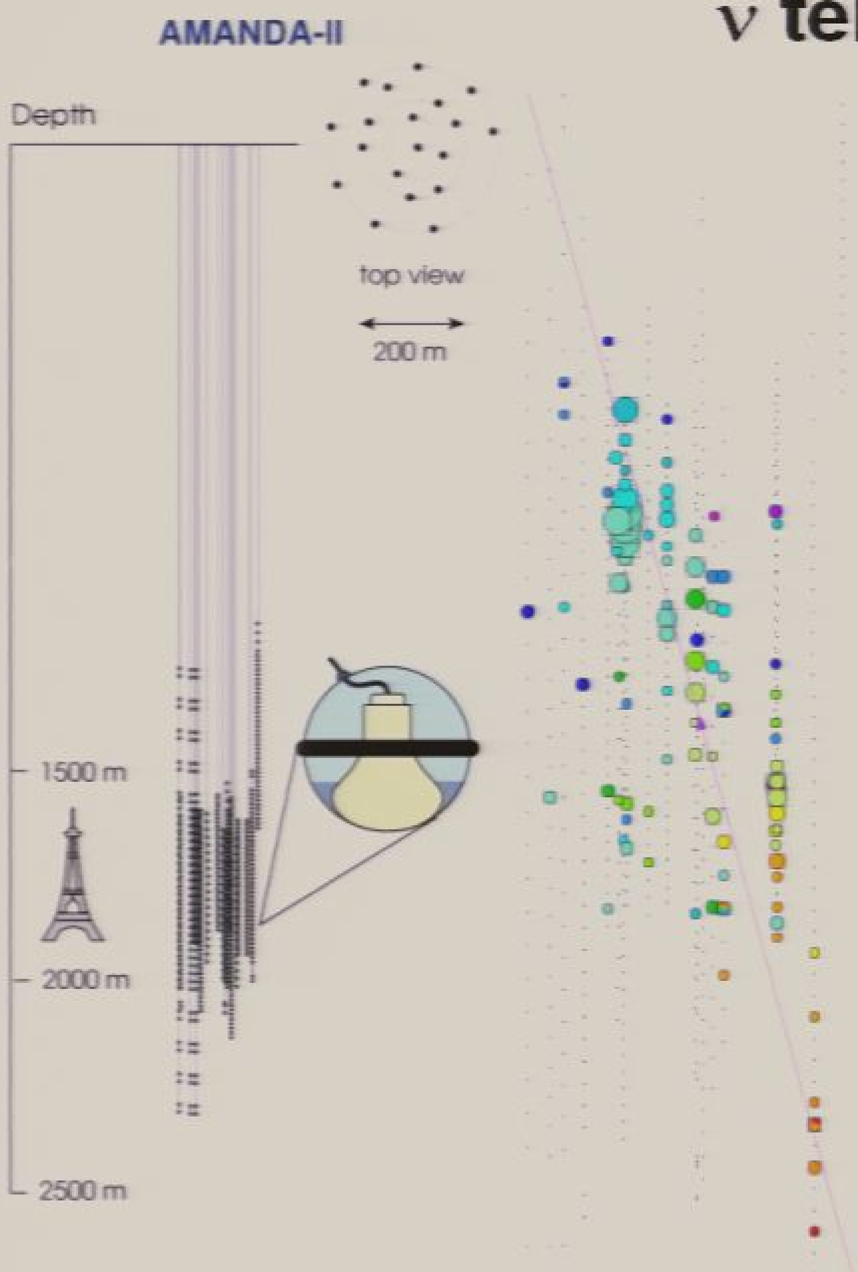


time recorded on OM

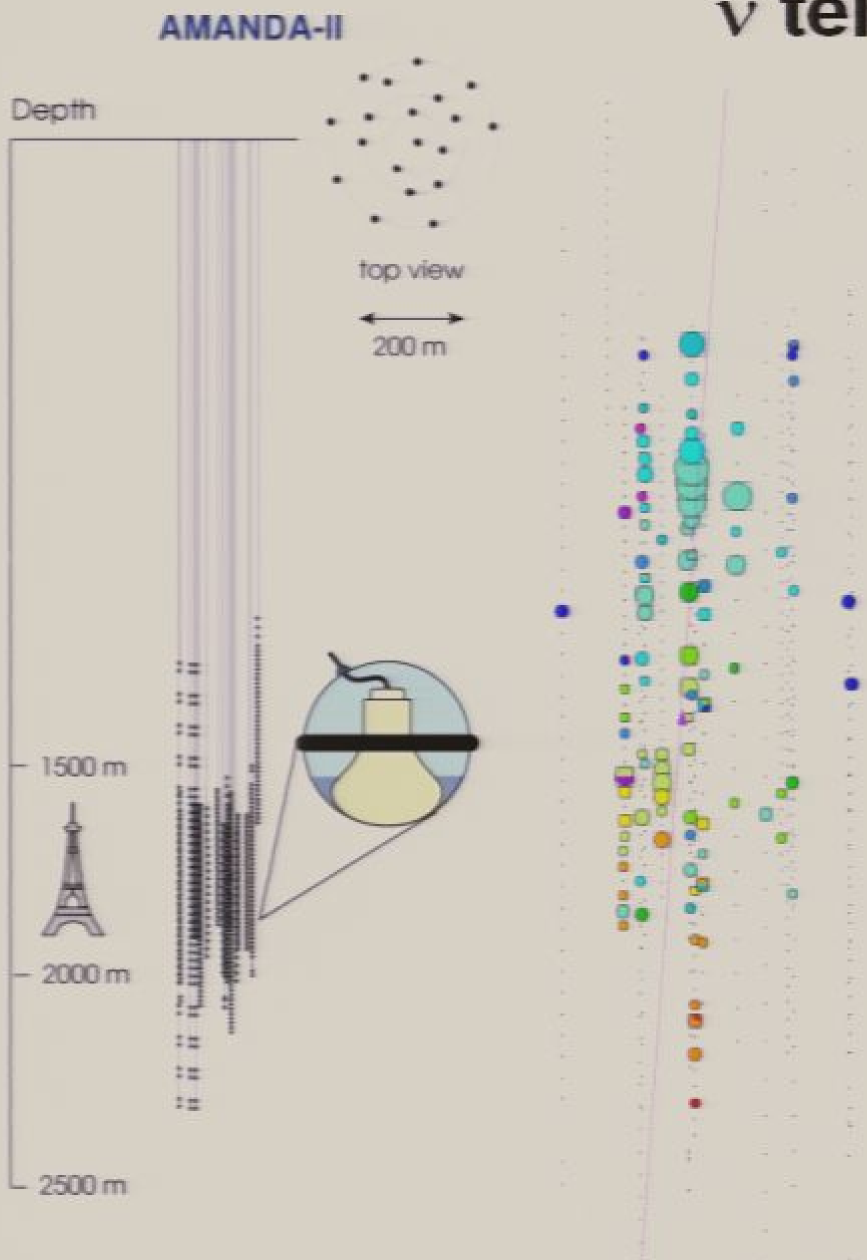
ν telescope : AMANDA event



ν telescope : AMANDA event



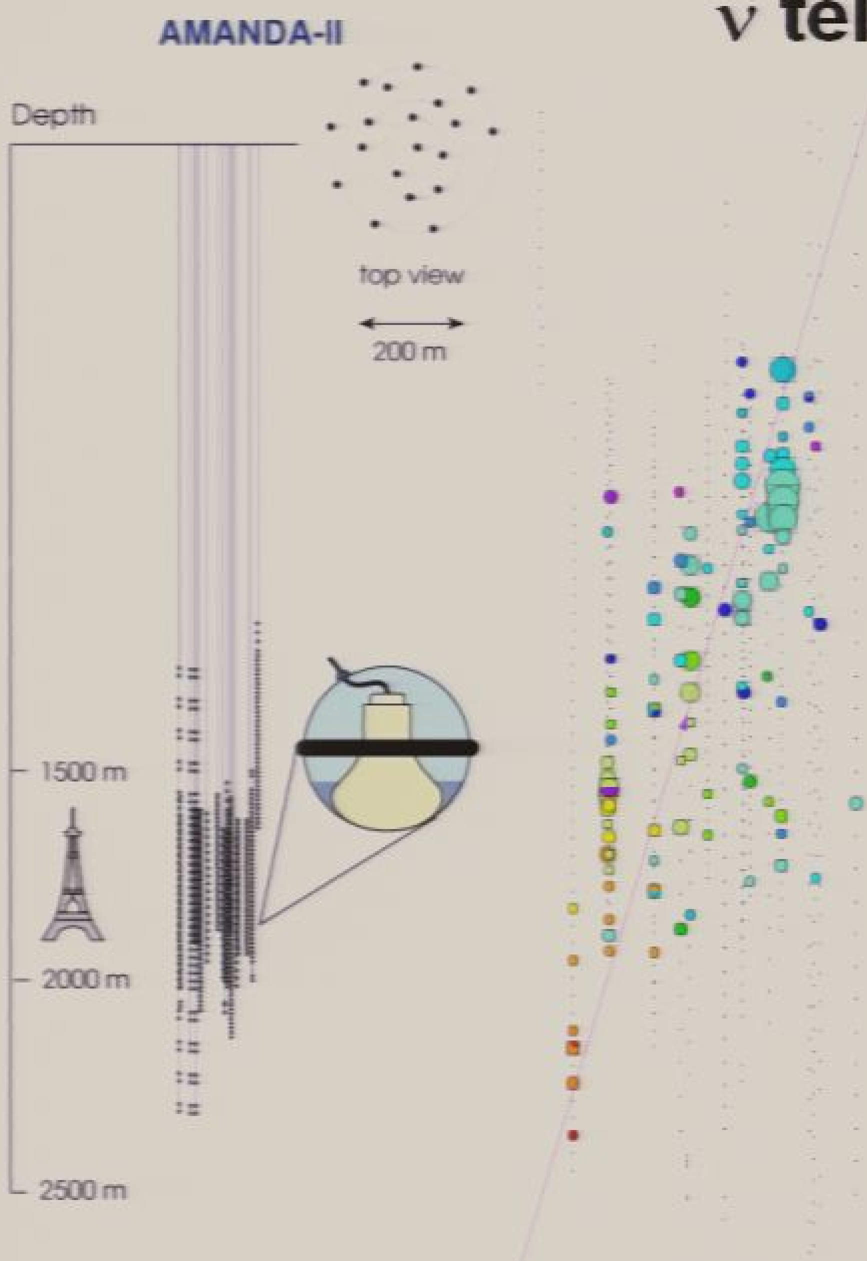
ν telescope : AMANDA event



energy deposited in OM

time recorded on OM

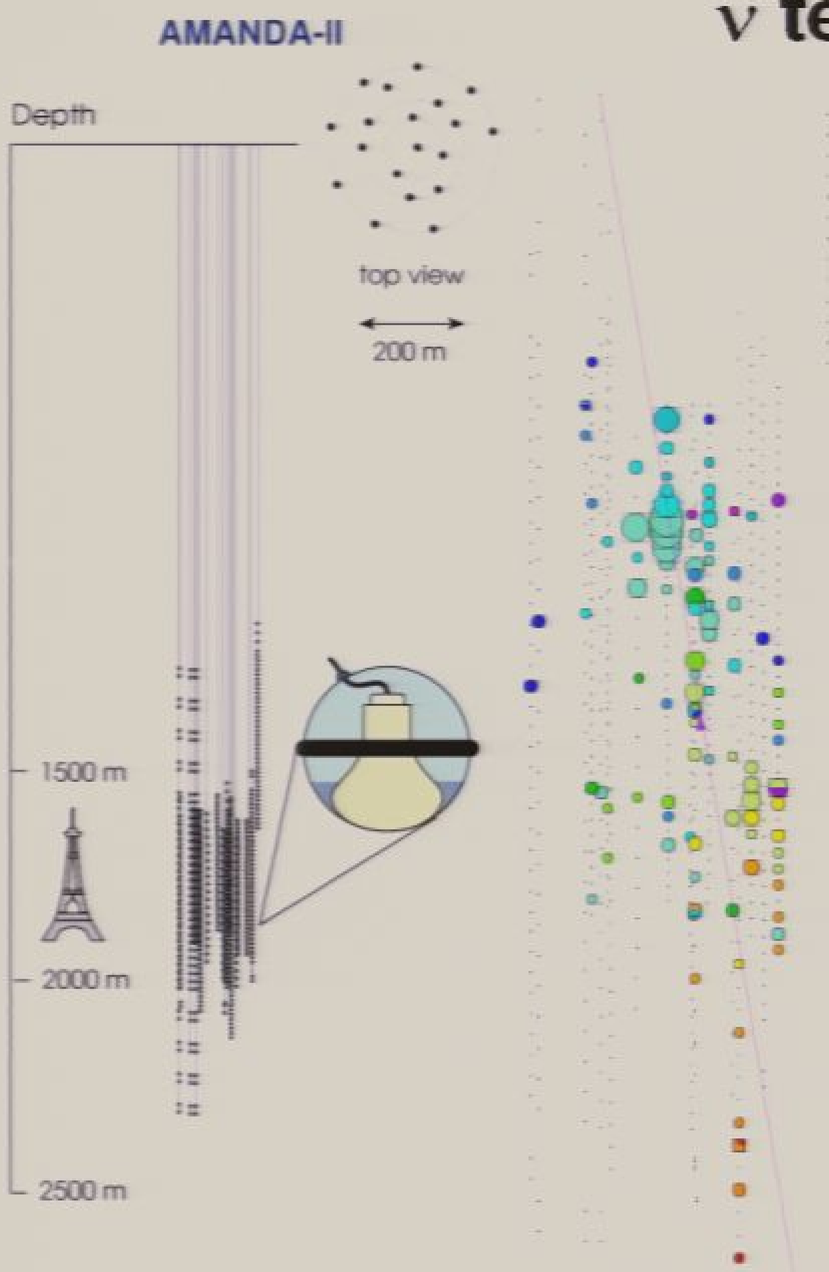
ν telescope : AMANDA event



energy deposited in OM

time recorded on OM

ν telescope : AMANDA event

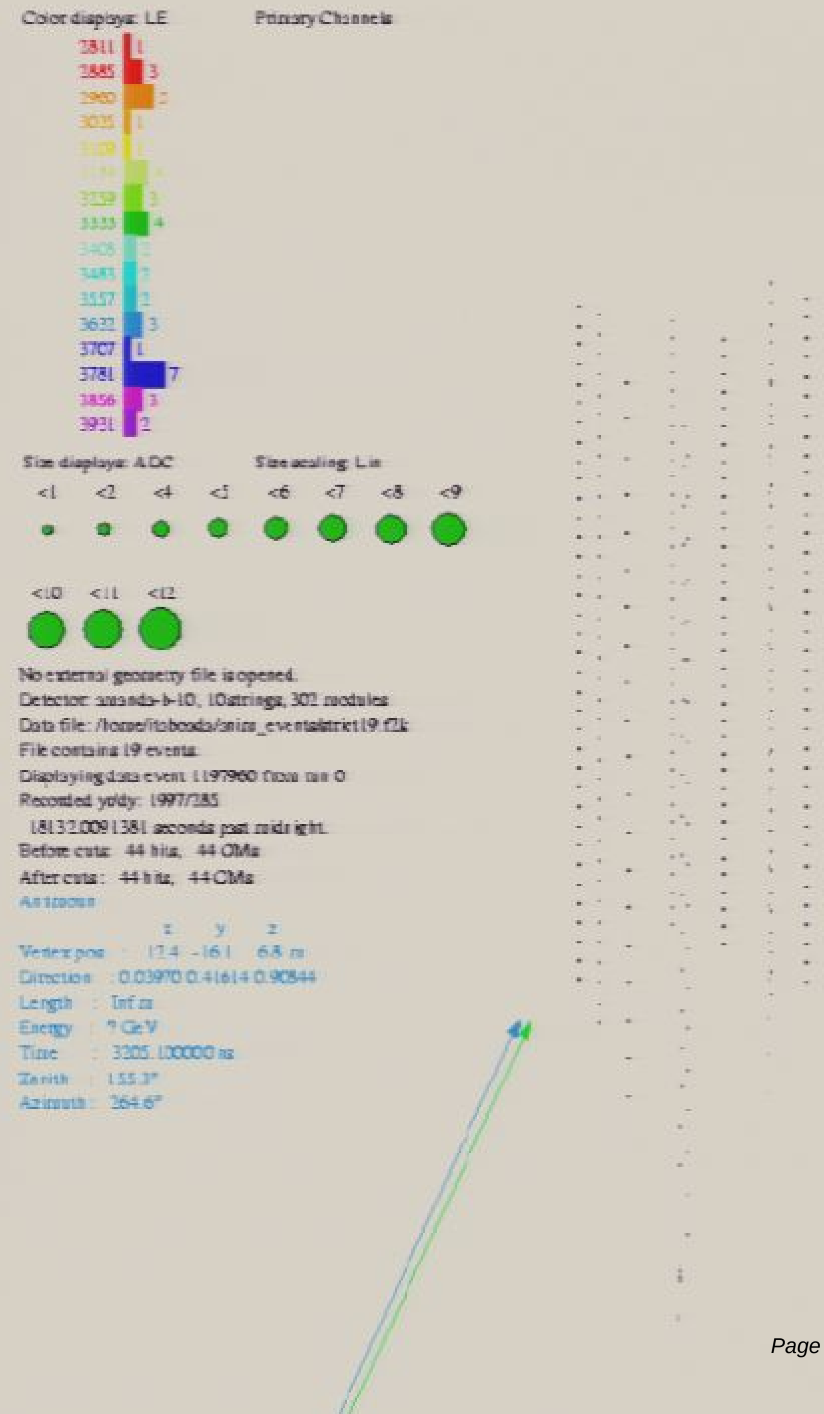


AMANDA Event Signatures: Muons

CC muon neutrino Interaction

$\rightarrow$ track

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



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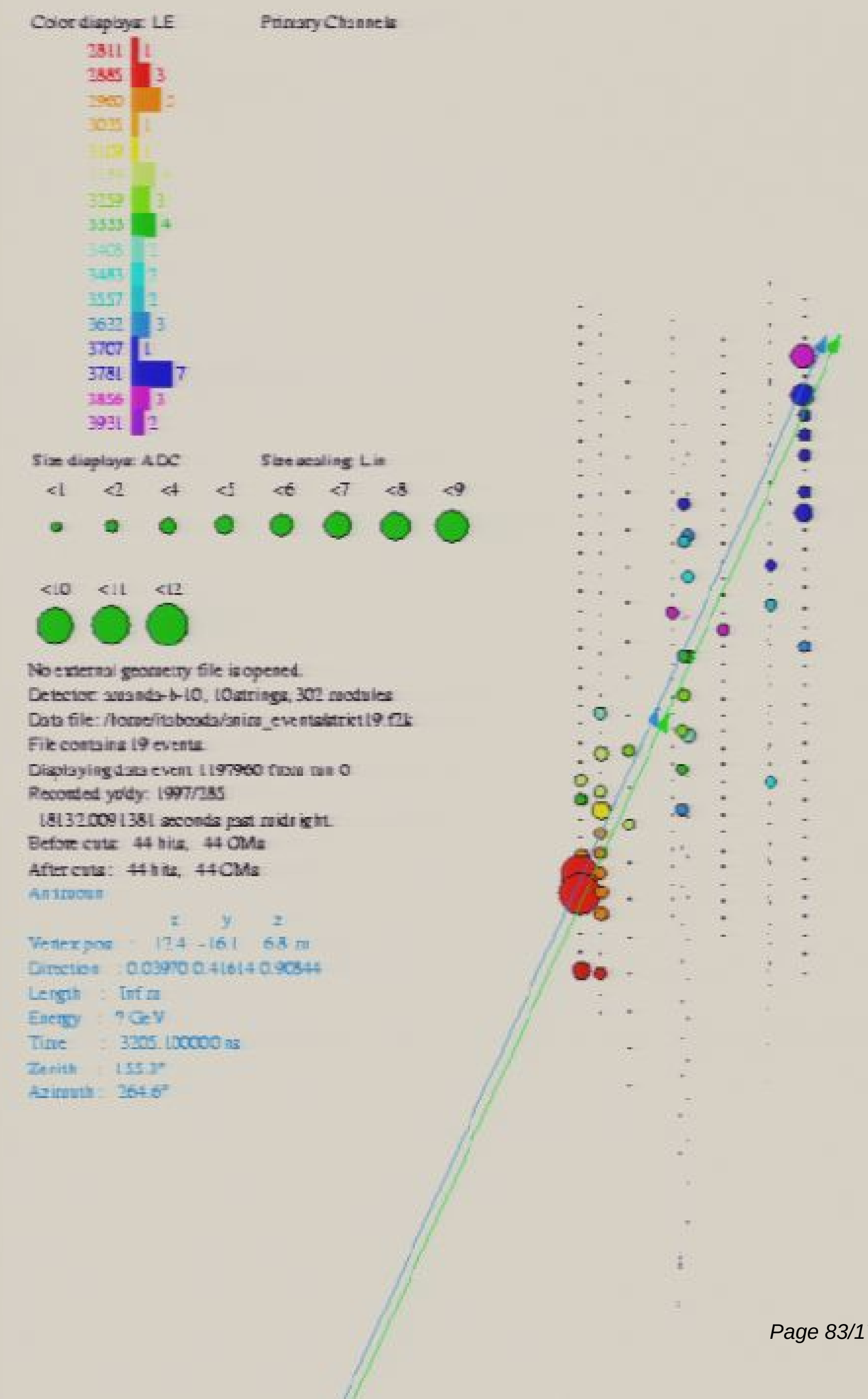

AMANDA Event Signatures: Muons

CC muon neutrino Interaction

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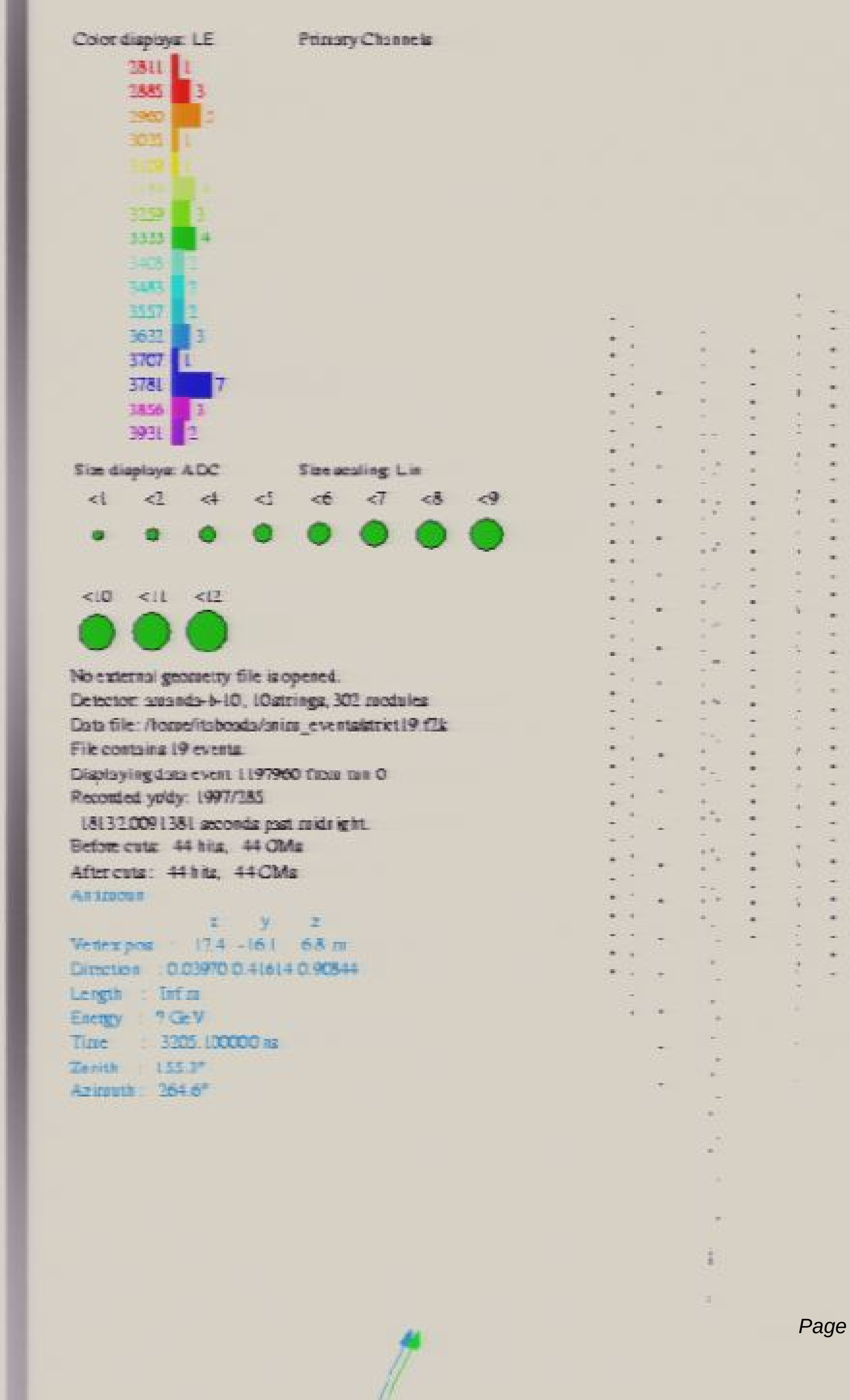
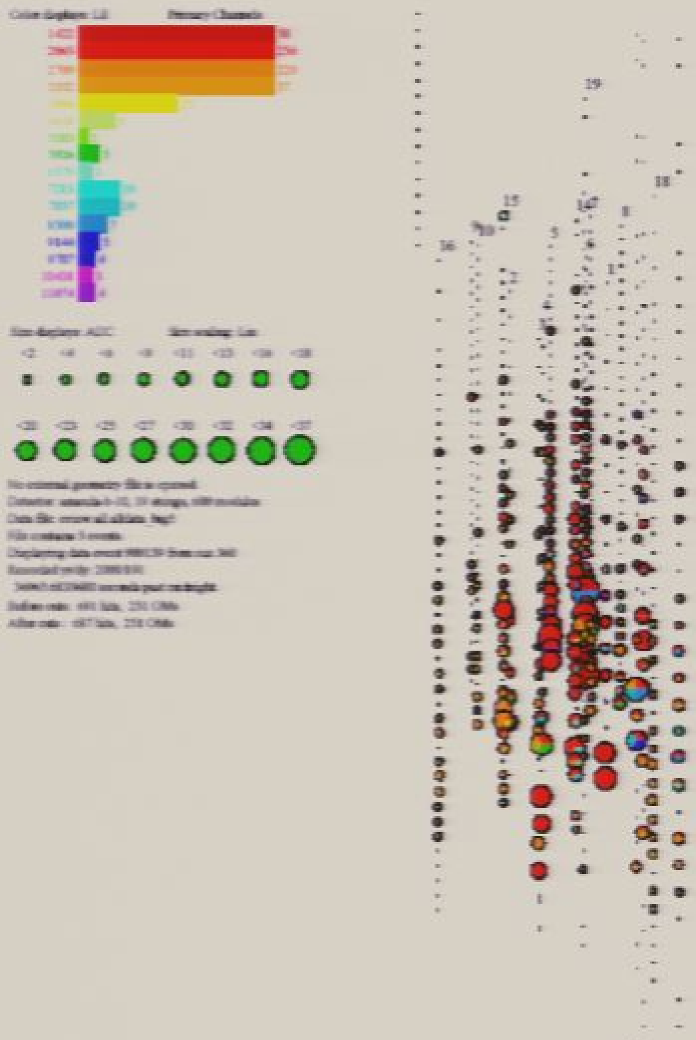
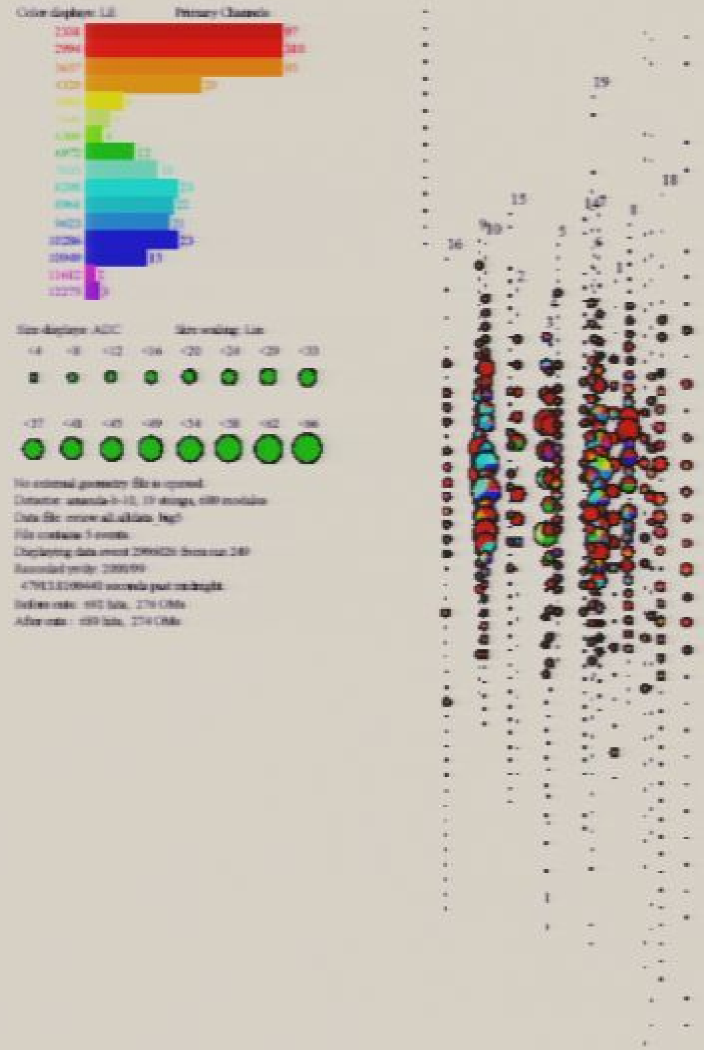
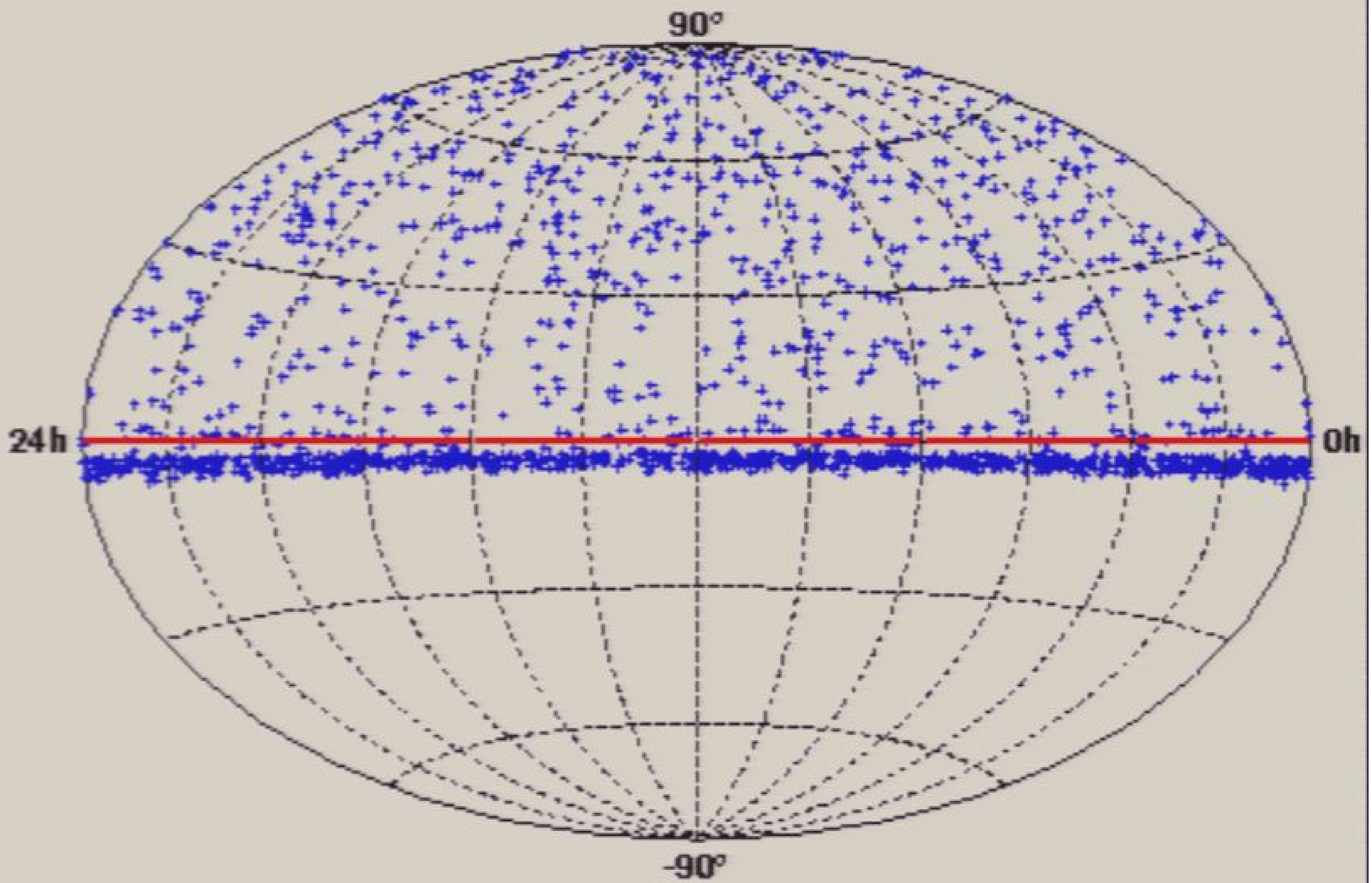






AMANDA II 2000

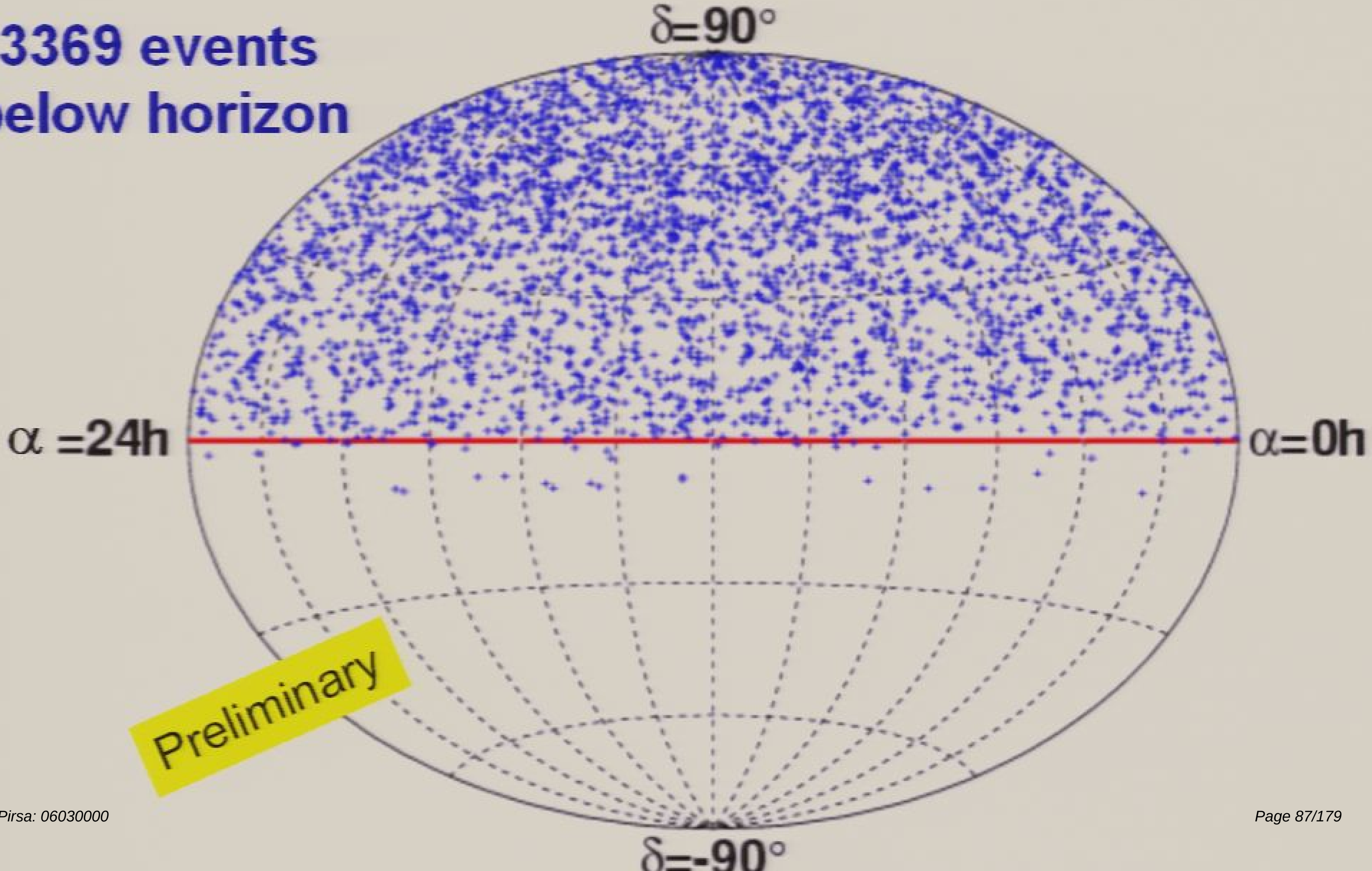
1555 Events

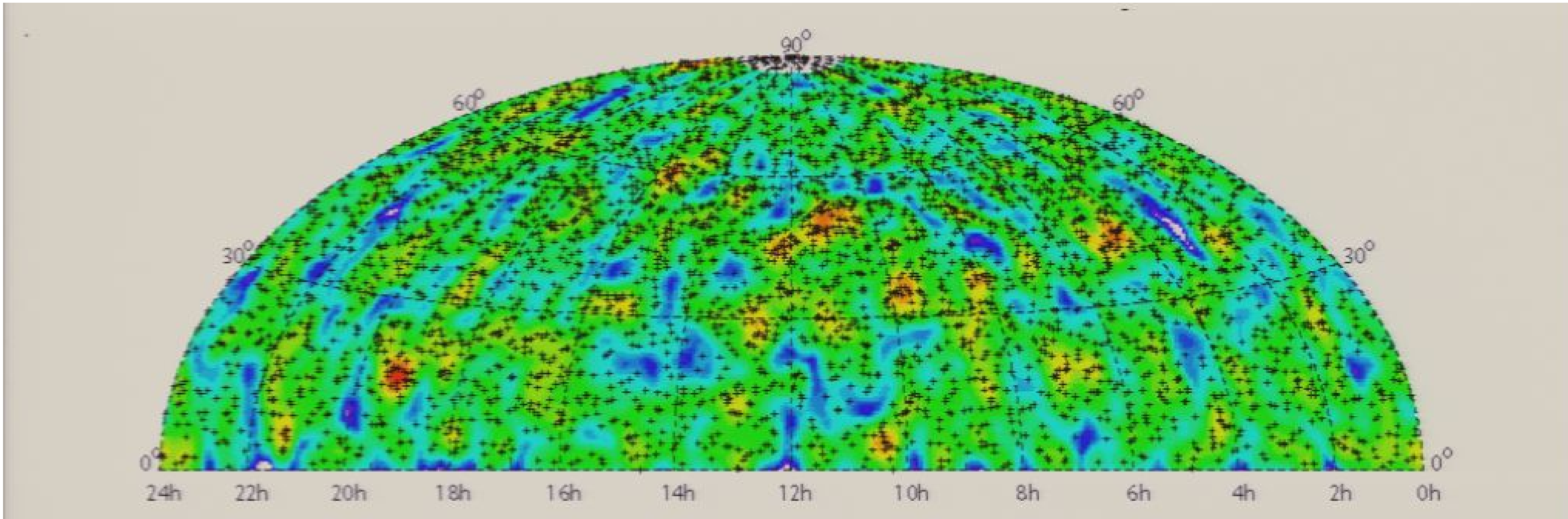


AMANDA skyplot 2000-2003

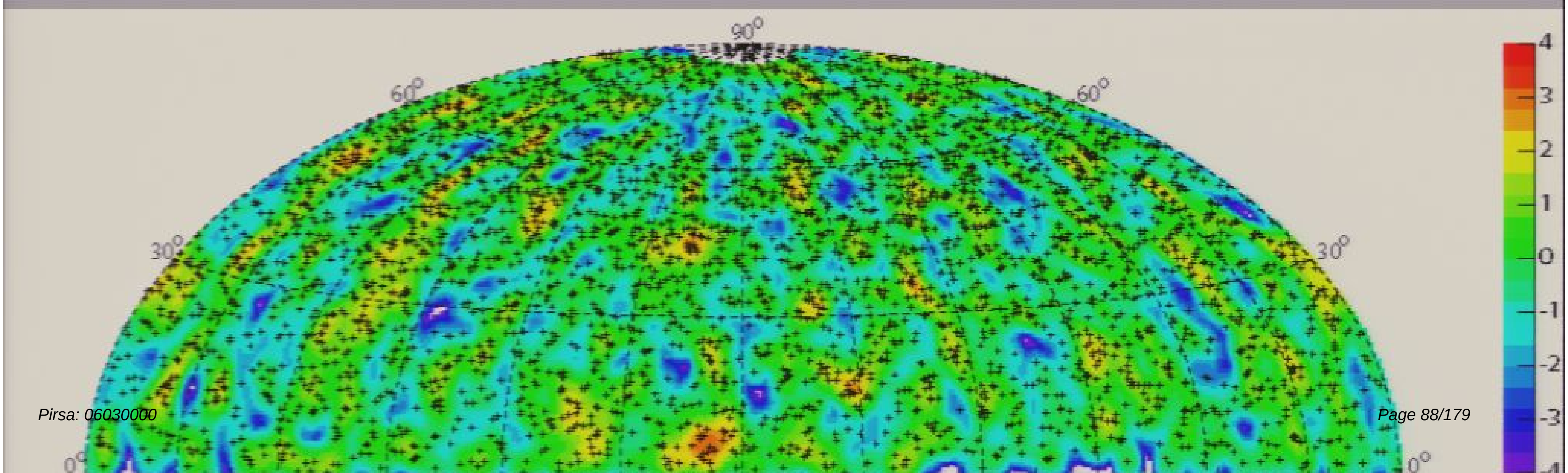
optimized for best sensitivity to E^{-3} – E^{-2} sources

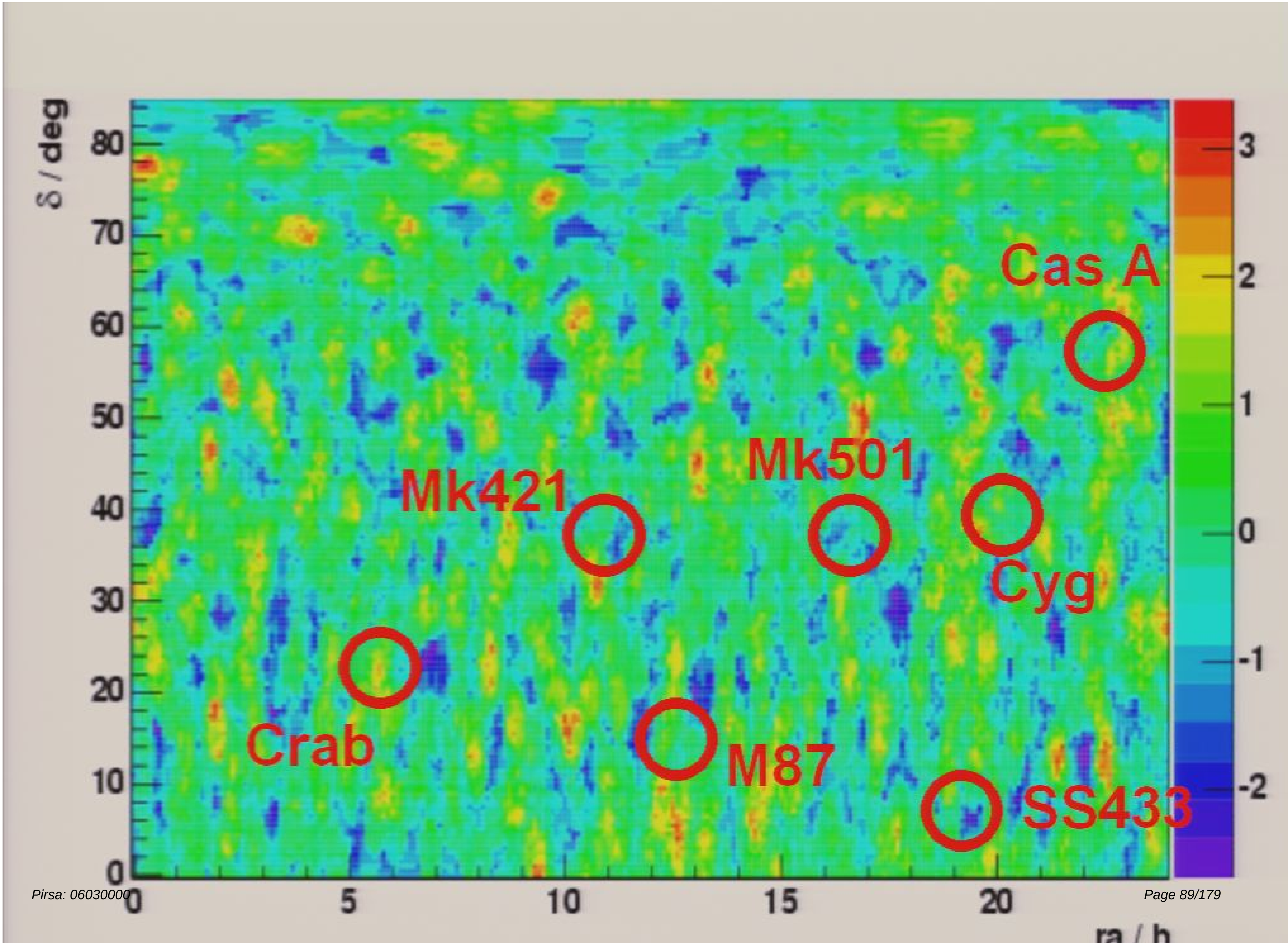
3369 events below horizon



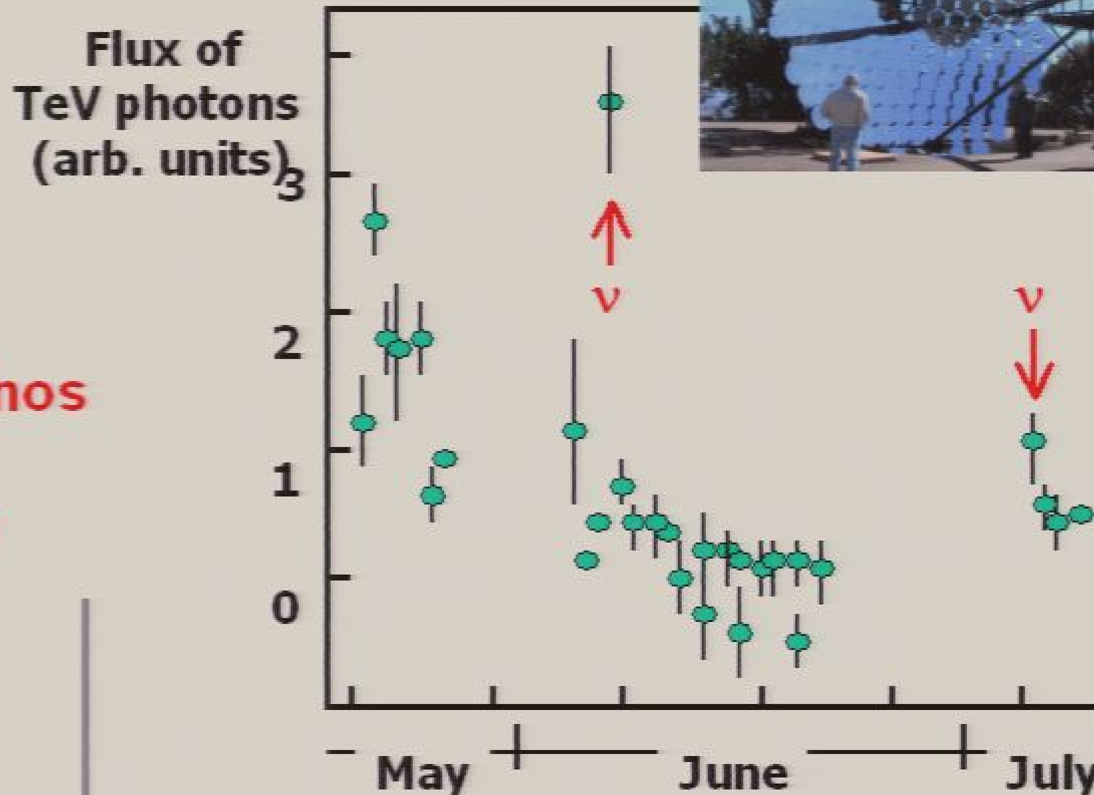


2000-03: scrambled (top) and unblinded (bottom)



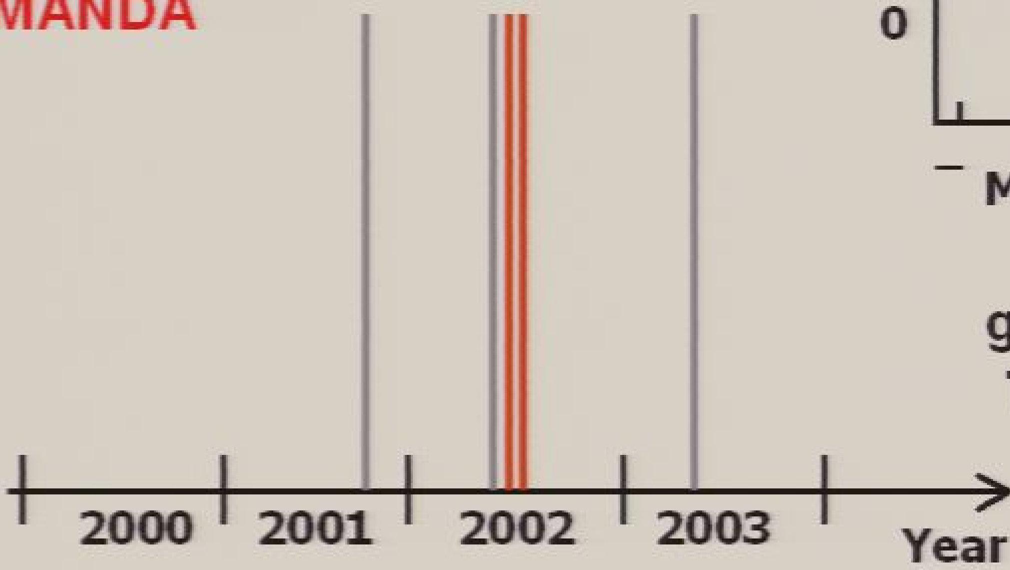

δ / deg
80
70
60
50
40
30
20
10
0
0
5
10
15
20
ra / h
Cas A
Mk421
Mk501
Cyg
Crab
M87
SS433
3
2
1
0
-1
-2

need a larger detector



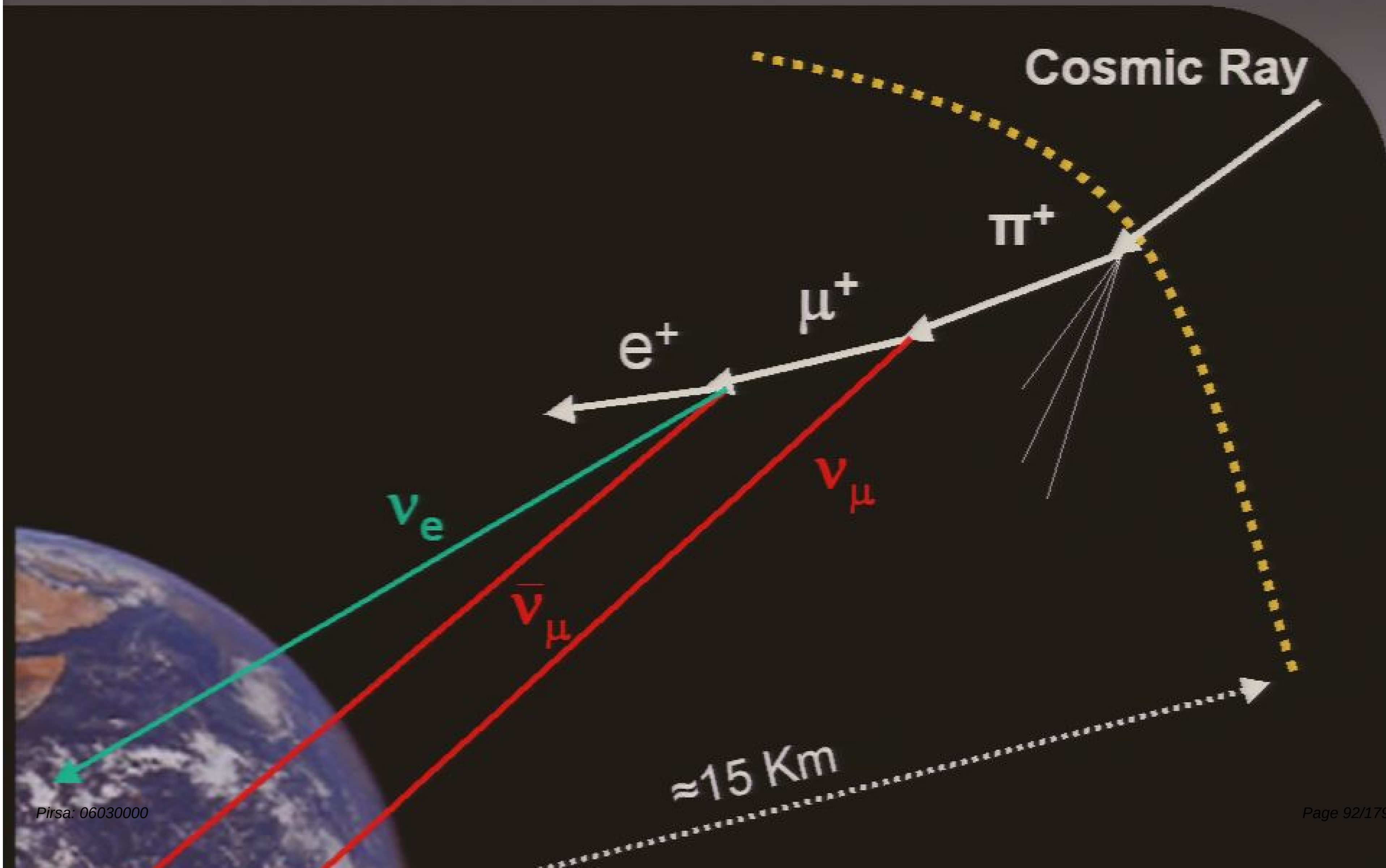
gamma-rays detected by TeV gamma telescopes

Arrival time of the neutrinos from the direction of ES1959+650 detected by AMANDA



AMANDA: proof of concept

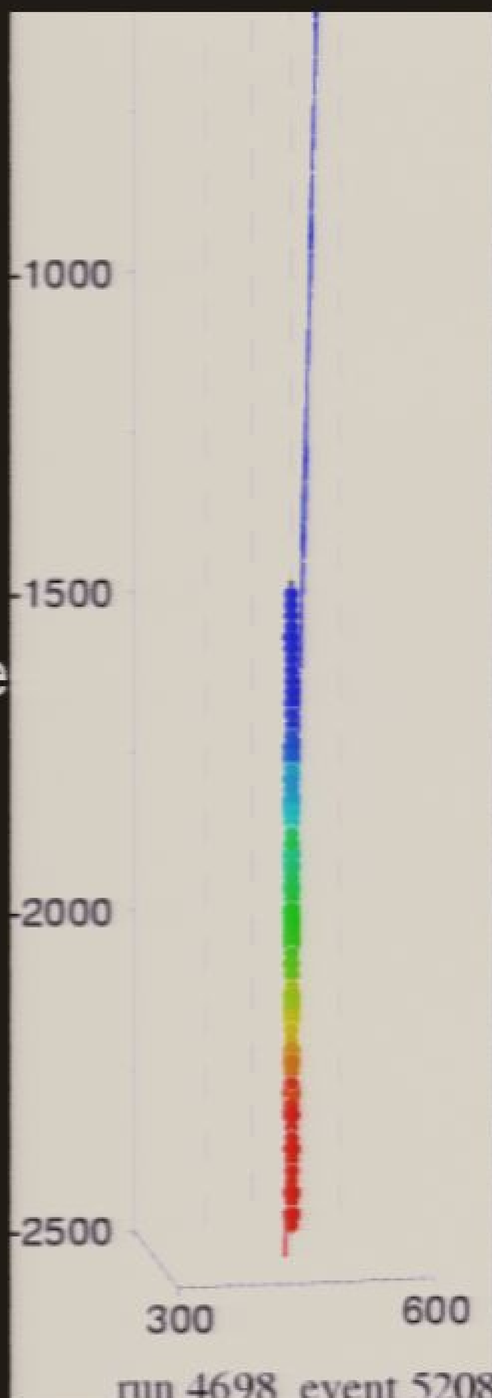
Atmospheric Neutrinos



down

background
cosmic ray
muon produced
in the atmosphere

100 per second



up

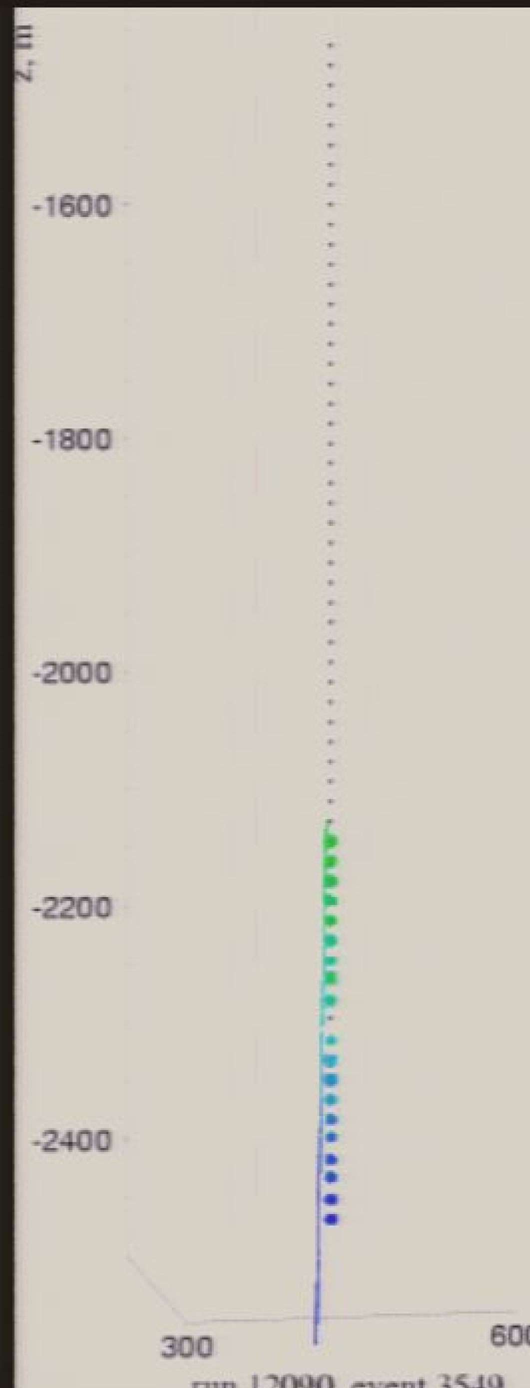
neutrino
traveled
through the
earth

10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second



up

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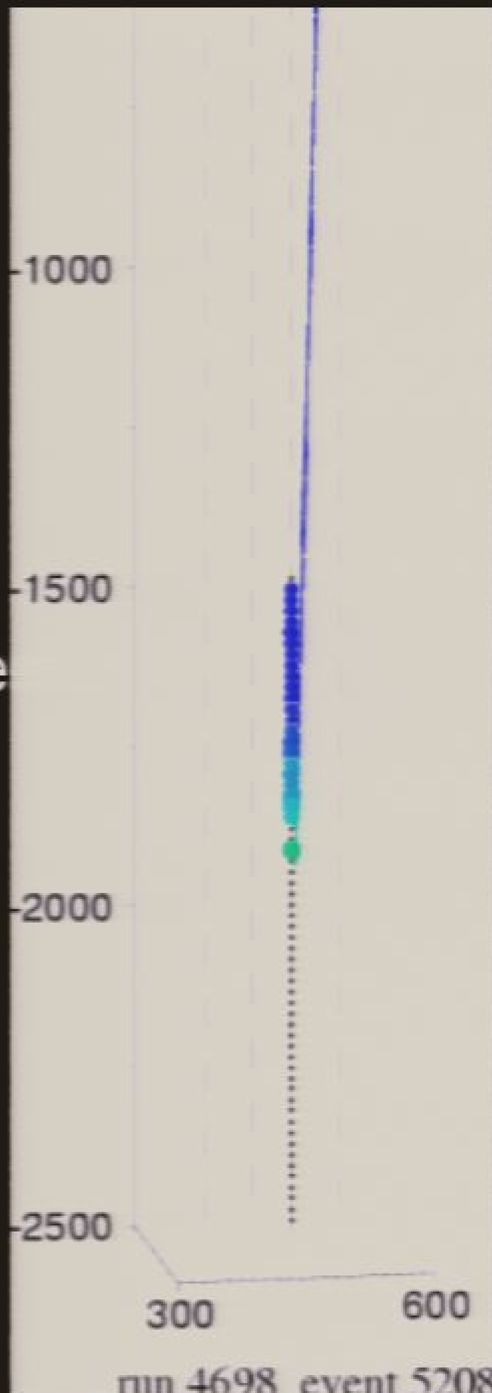
traveled
through the
earth

10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second



up

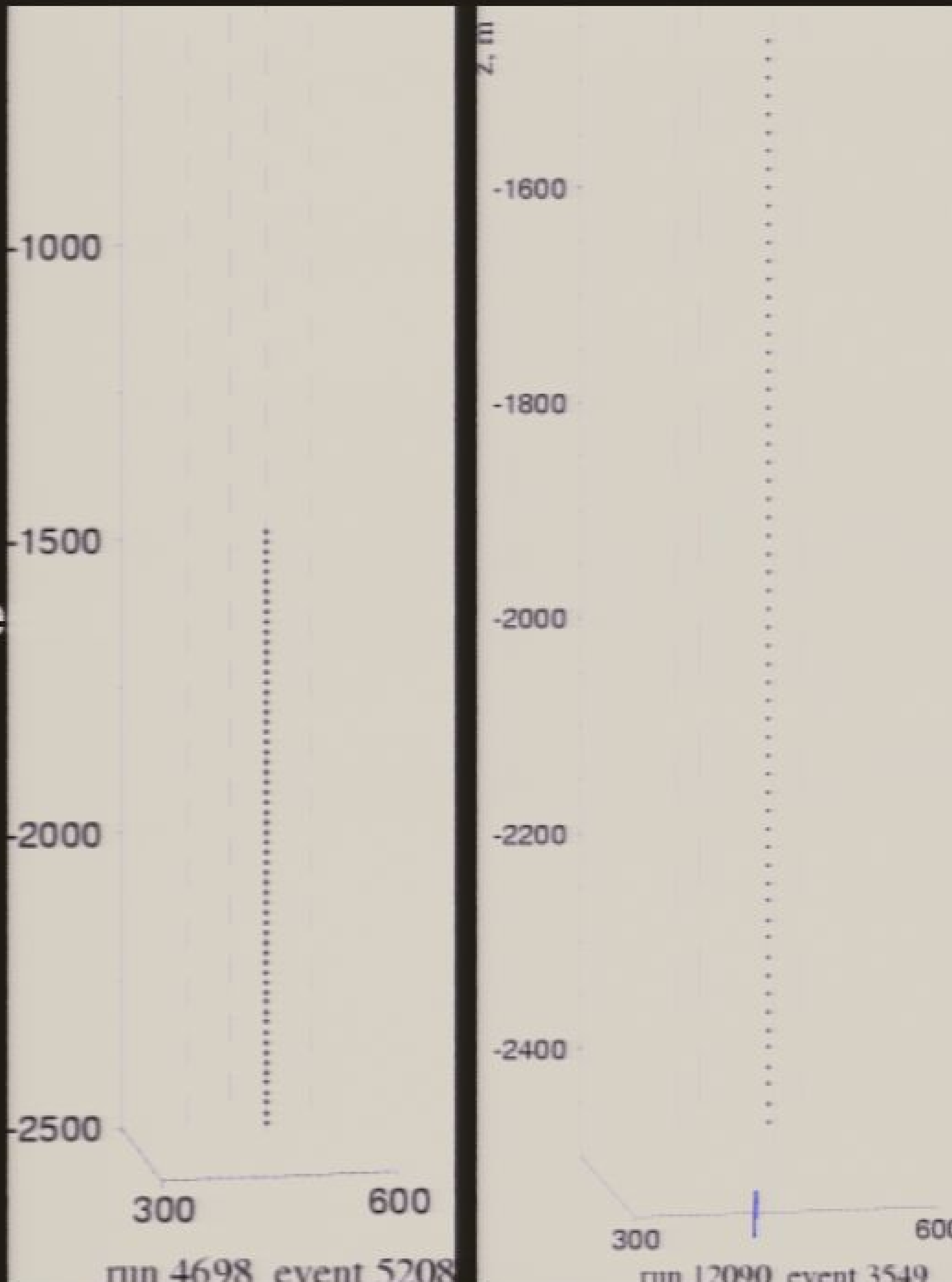
neutrino
traveled
through the
earth

10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second



up

neutrino
traveled
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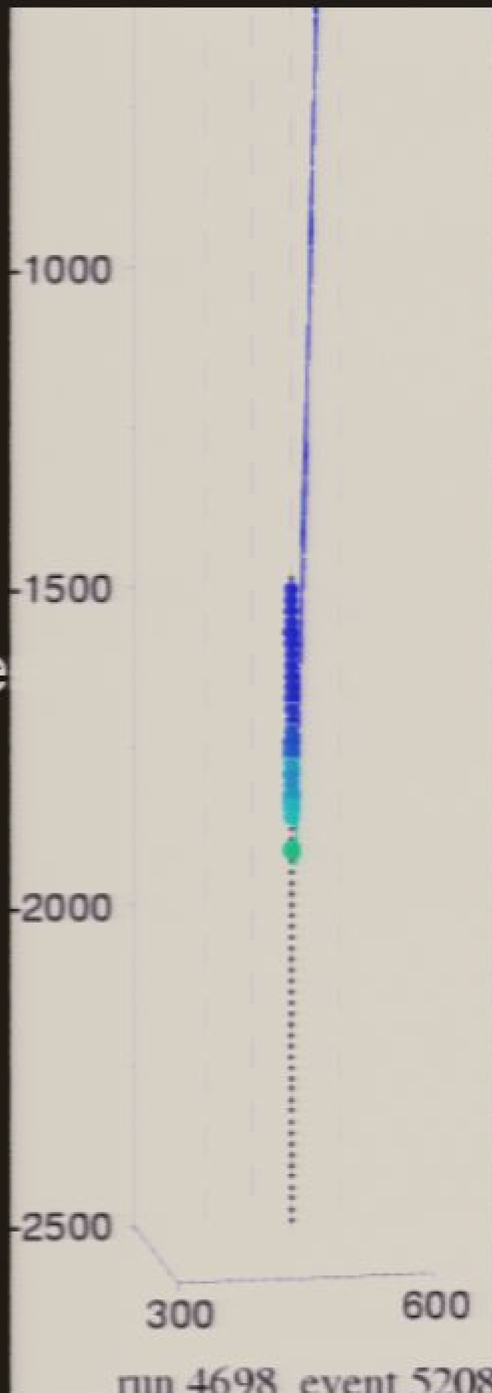
earth

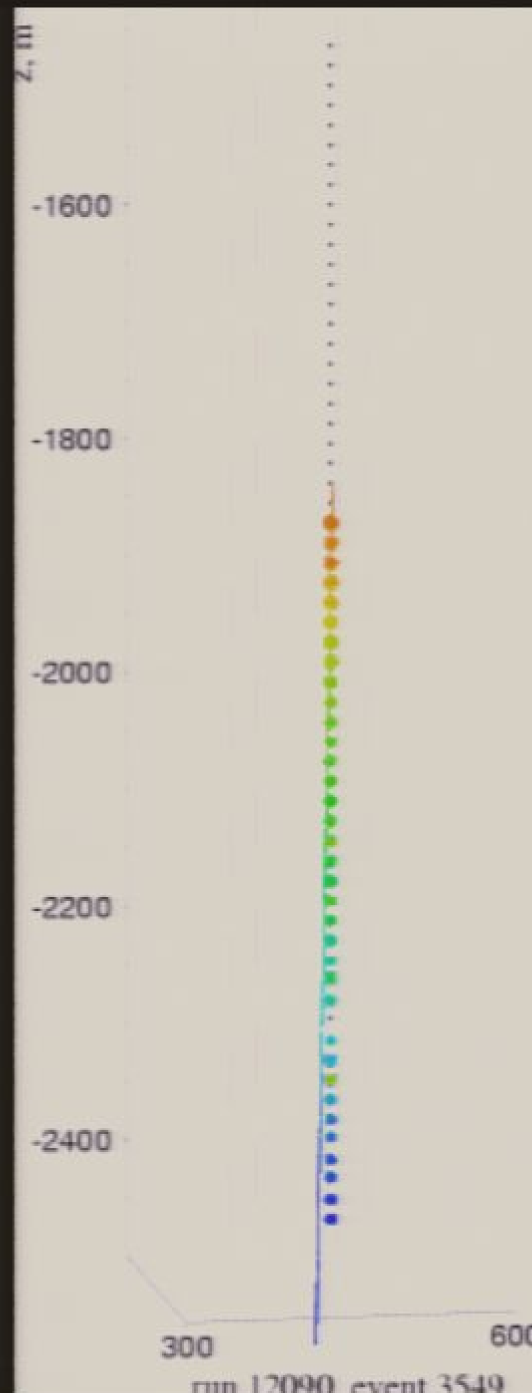
10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second





up

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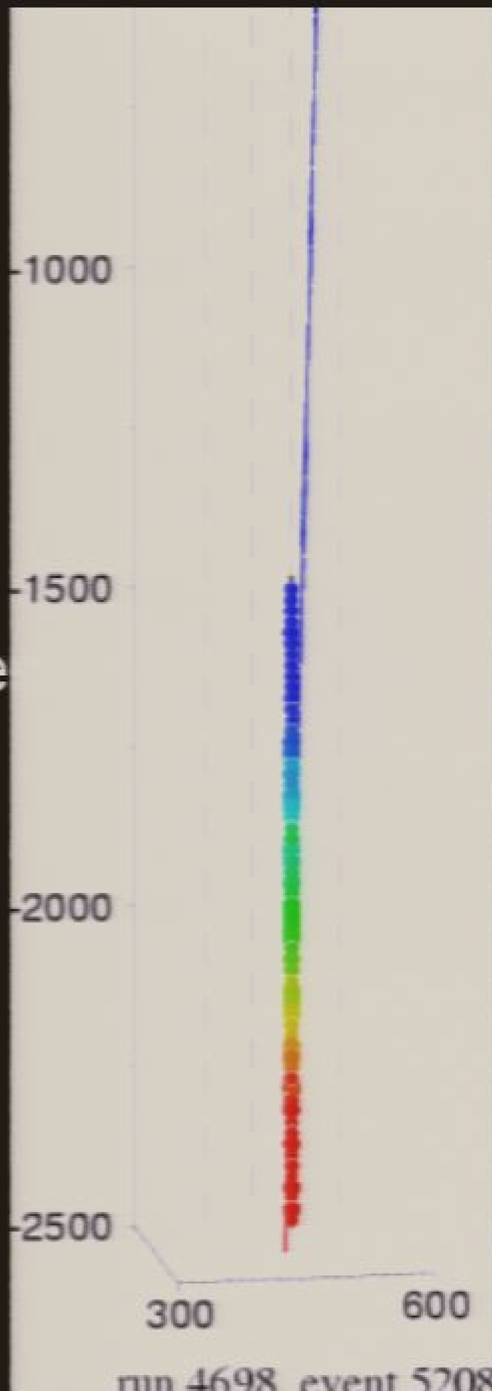
10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second



up

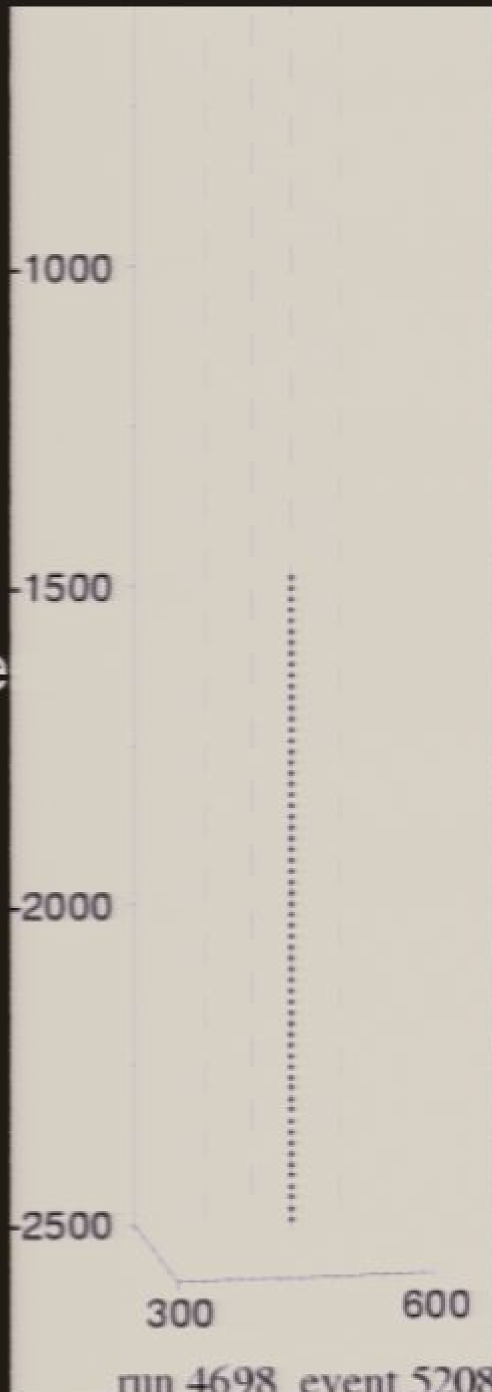
neutrino
traveled
through the
earth

10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second



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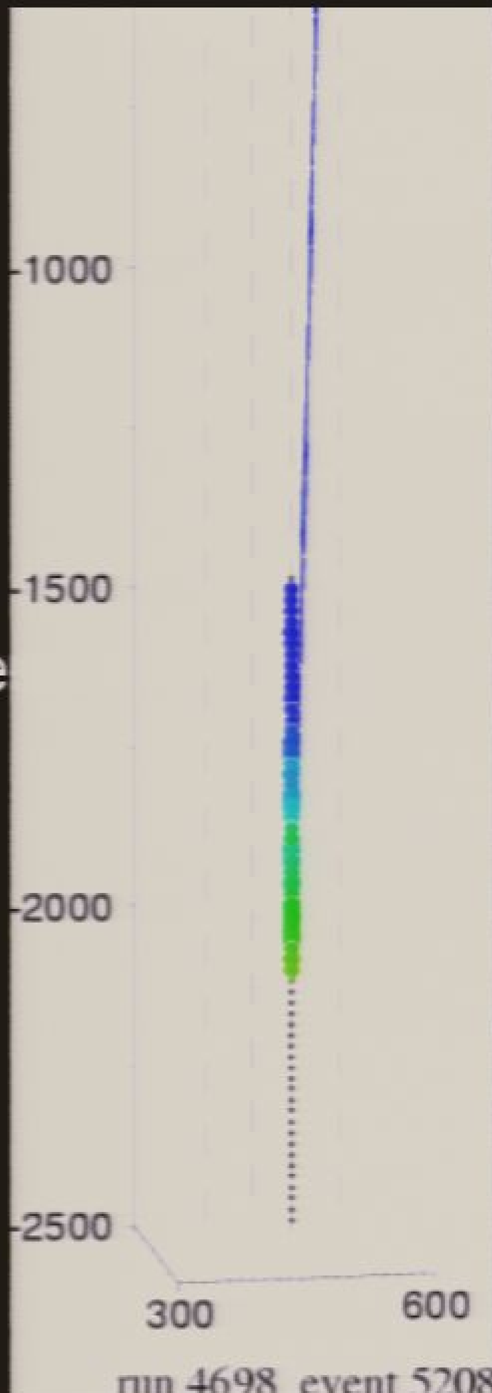
earth

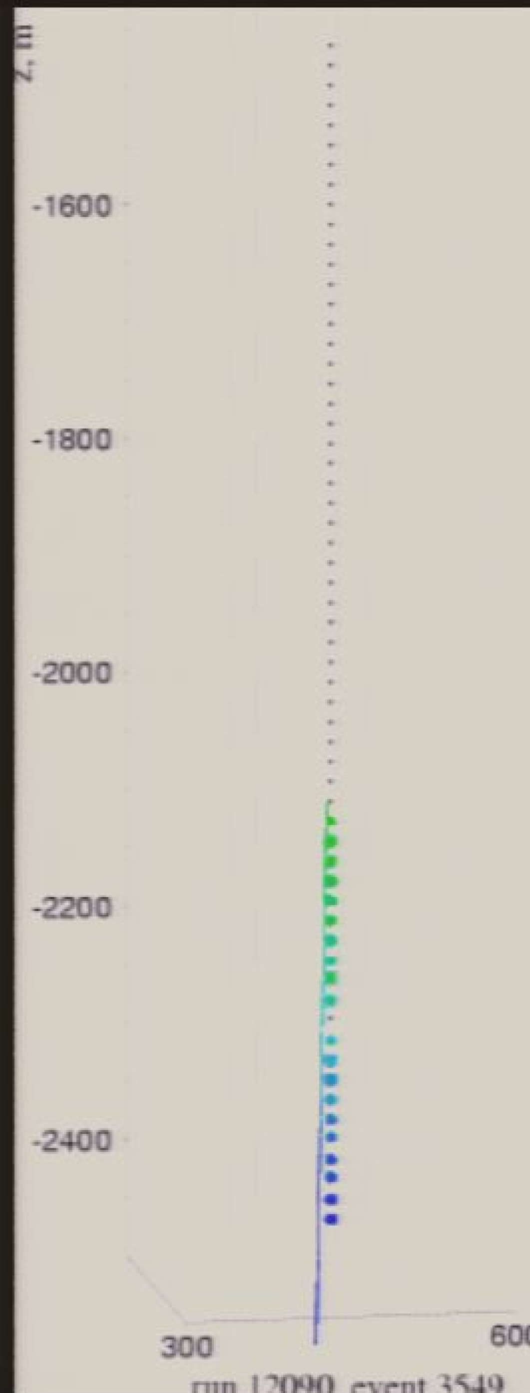
10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second





up

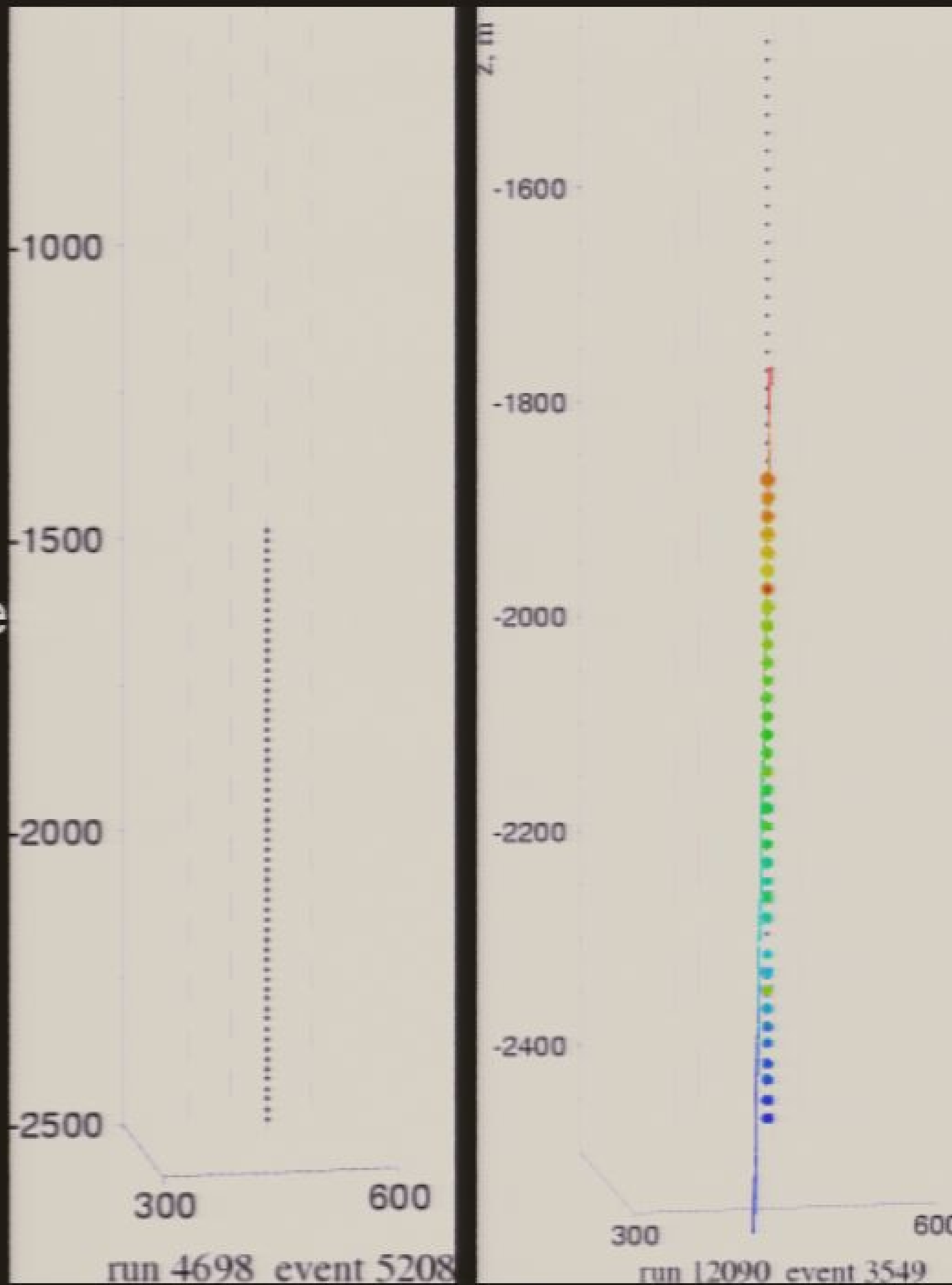
neutrino
traveled
through the
earth

10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second



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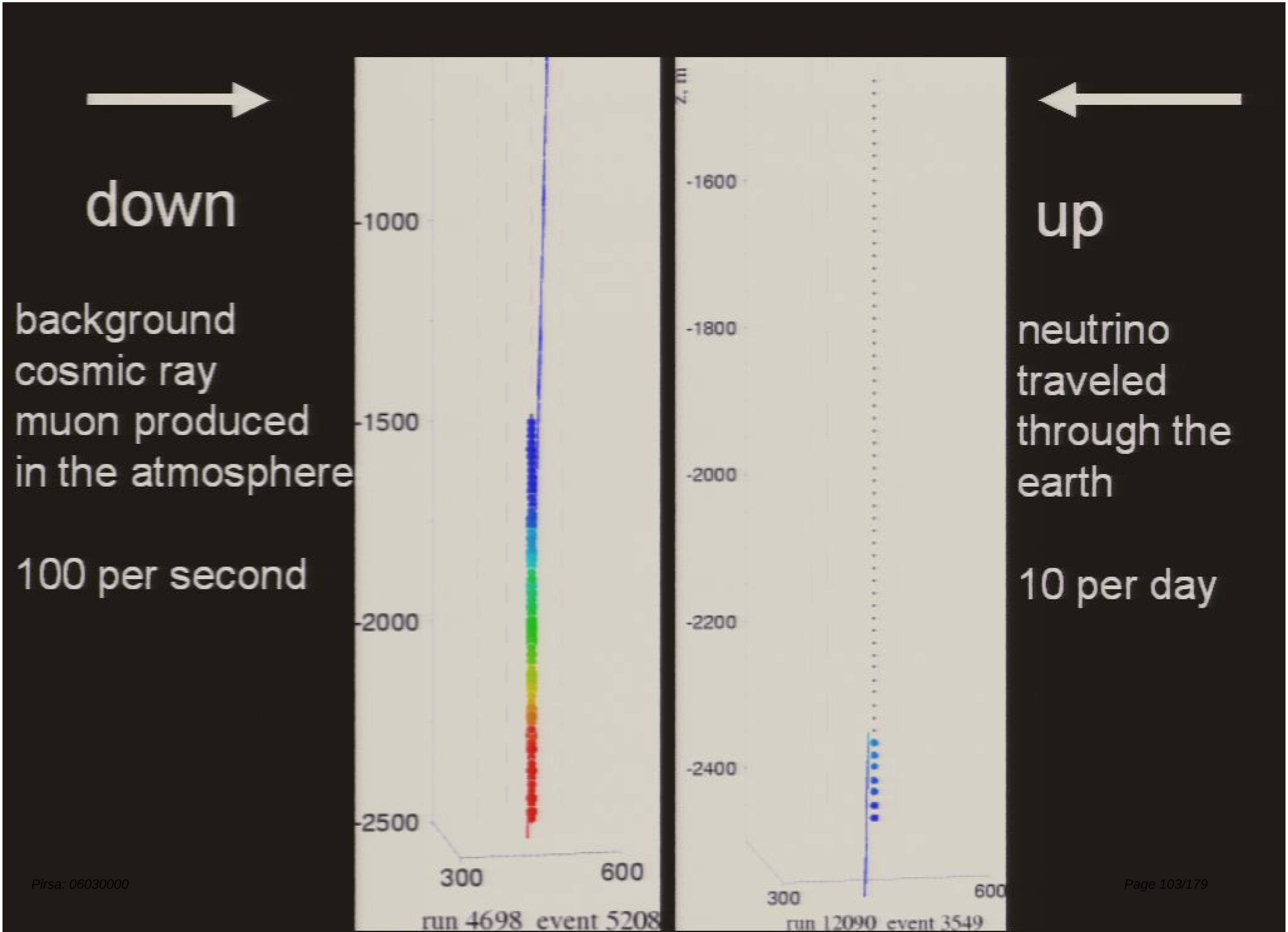
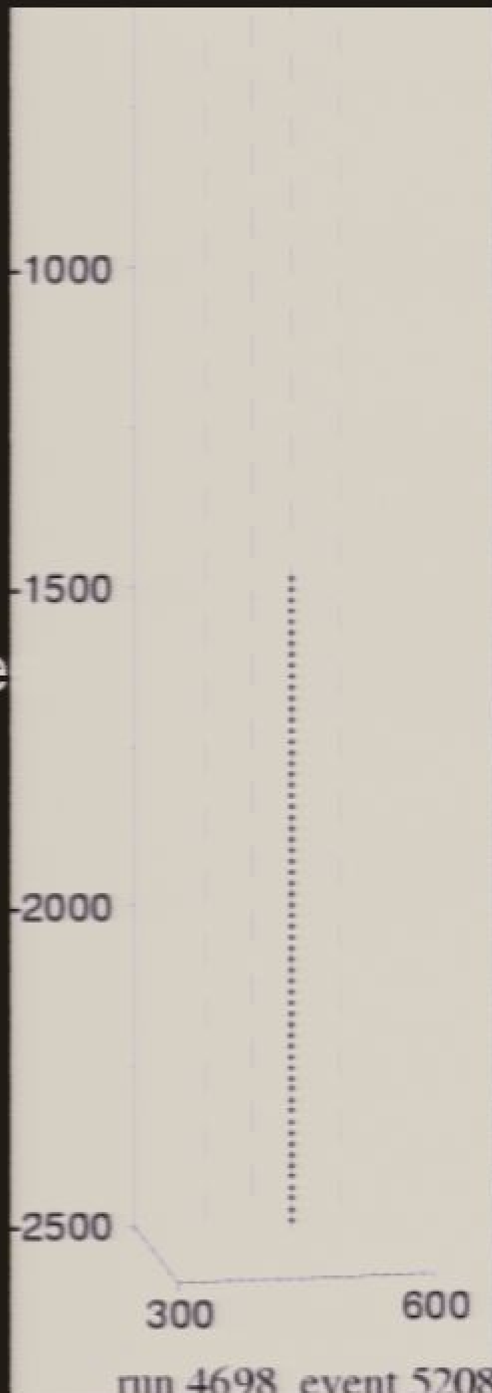
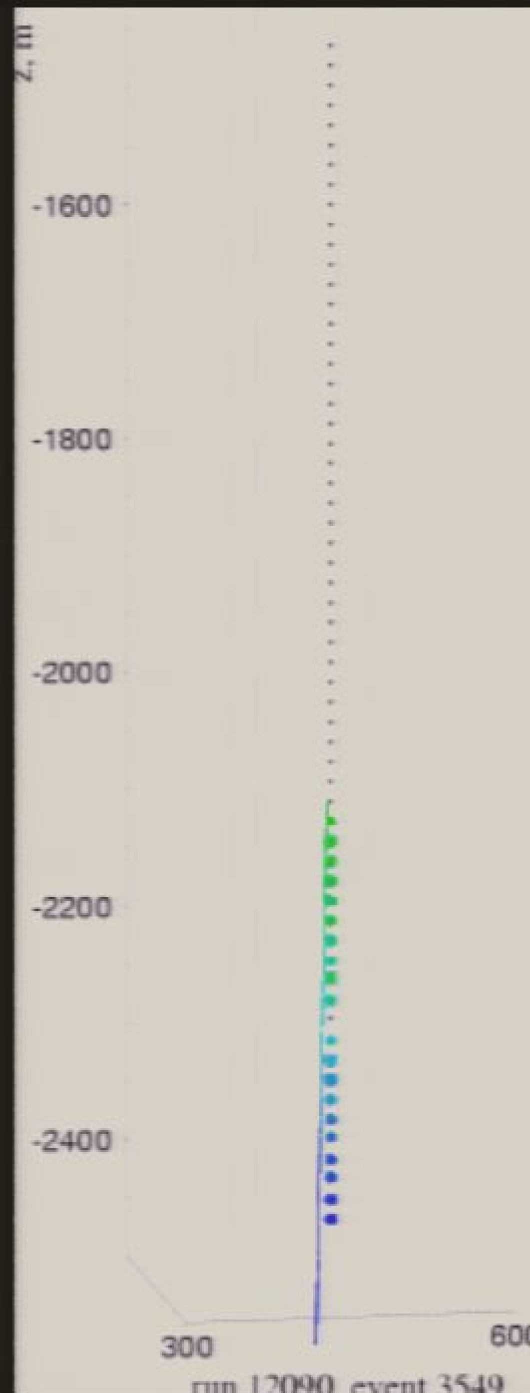

down
background
cosmic ray
muon produced
in the atmosphere
100 per second
-1000
-1500
-2000
-2500
300
600
run 4698 event 5208
-1600
-1800
-2000
-2200
-2400
300
600
run 12090 event 3549
up
neutrino
traveled
through the
earth
10 per day

down

background
cosmic ray
muon produced
in the atmosphere

100 per second





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background
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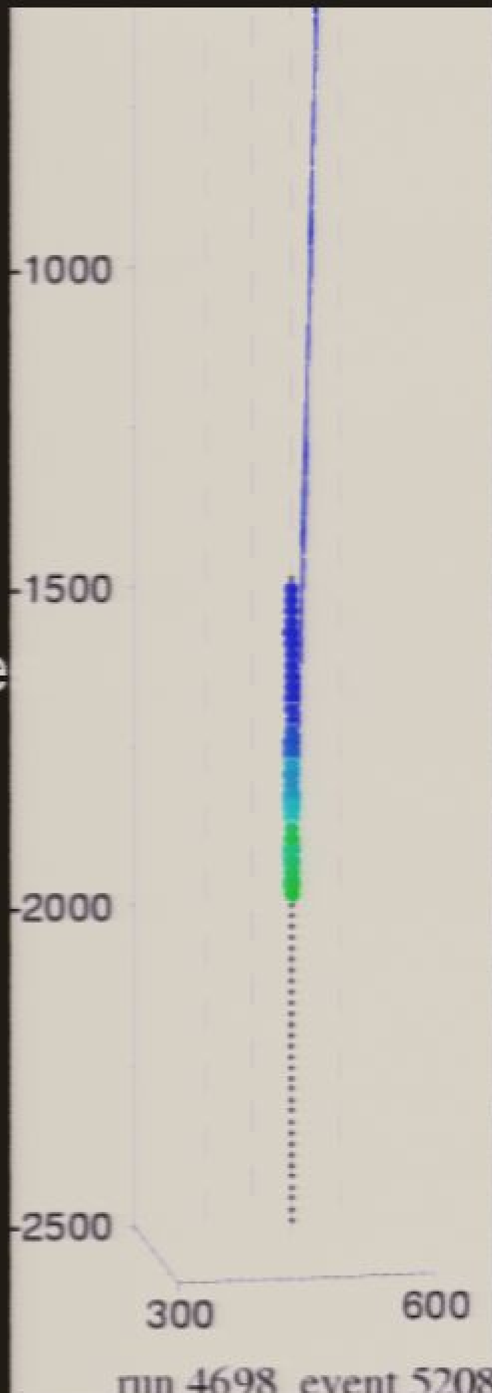
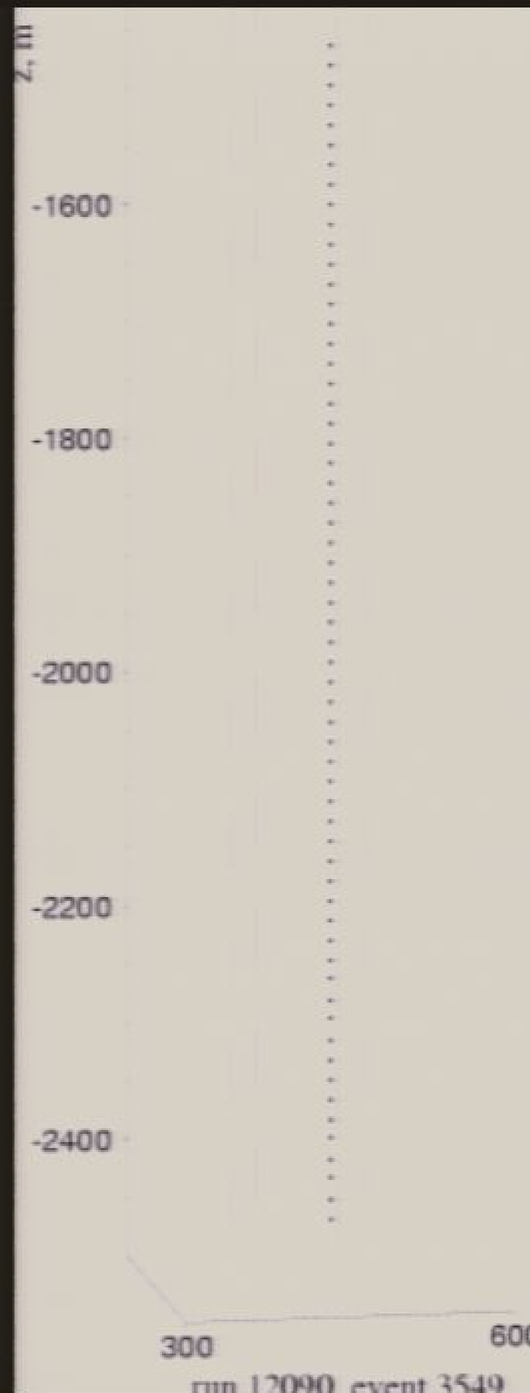
100 per second





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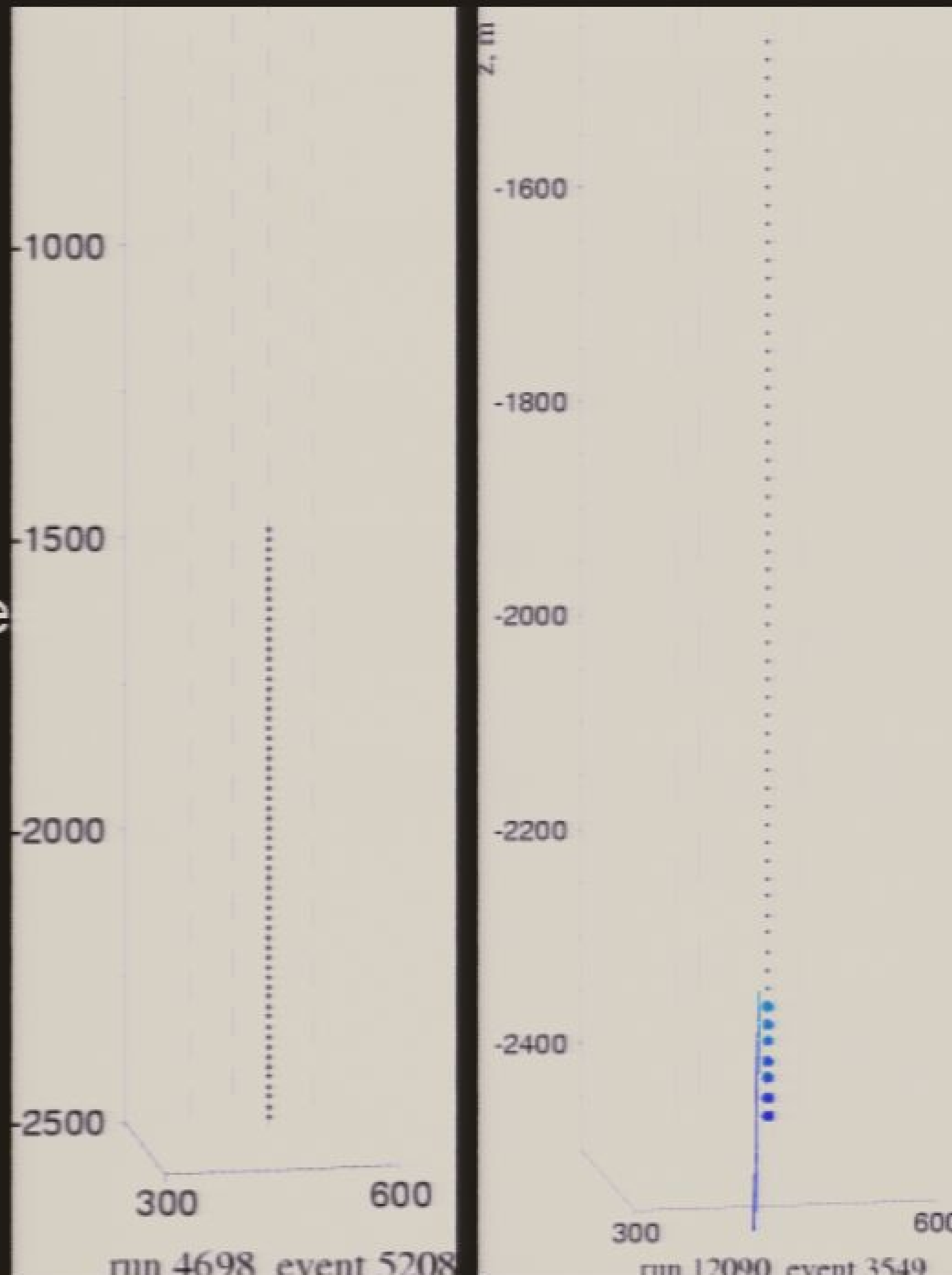

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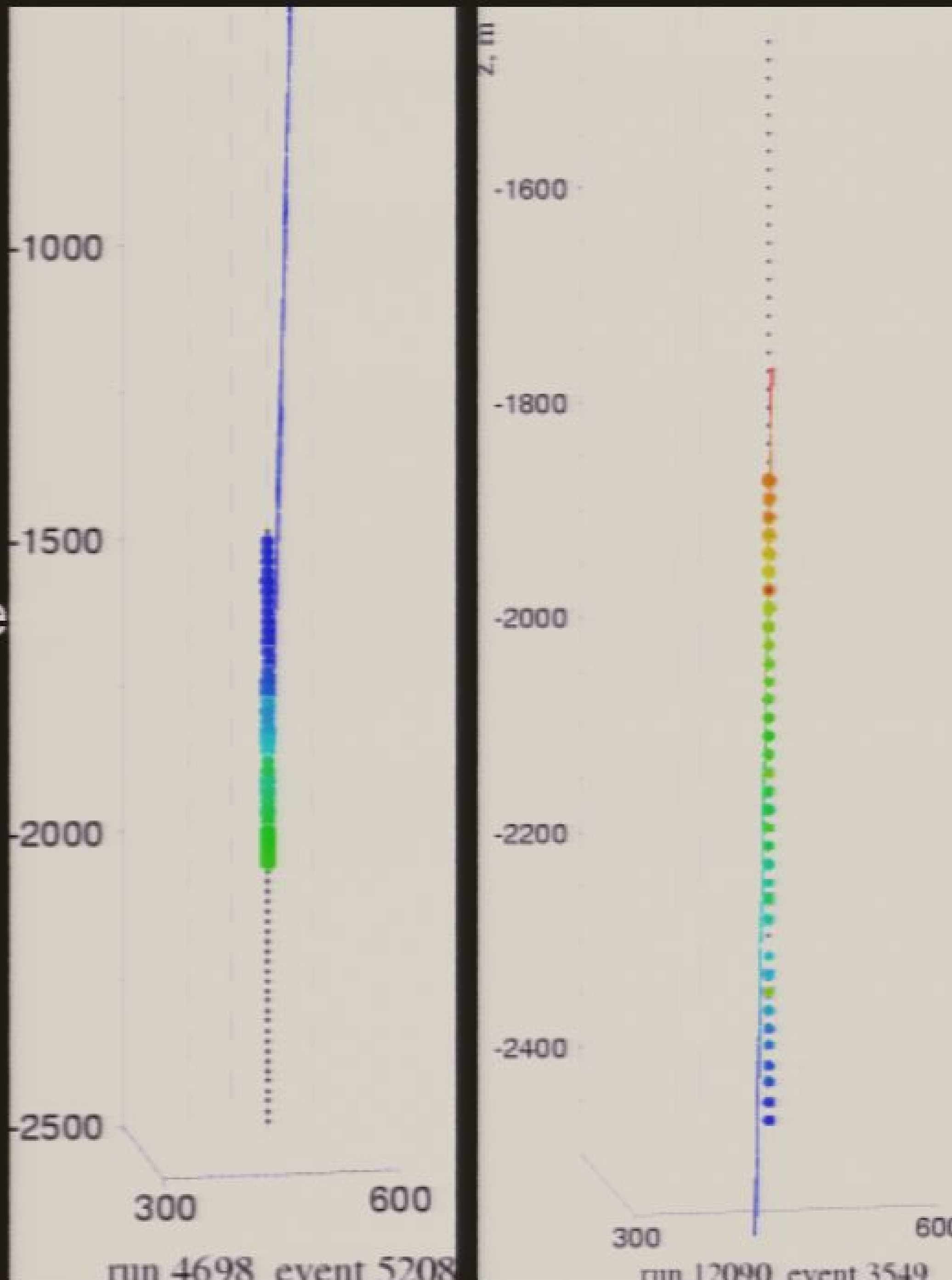

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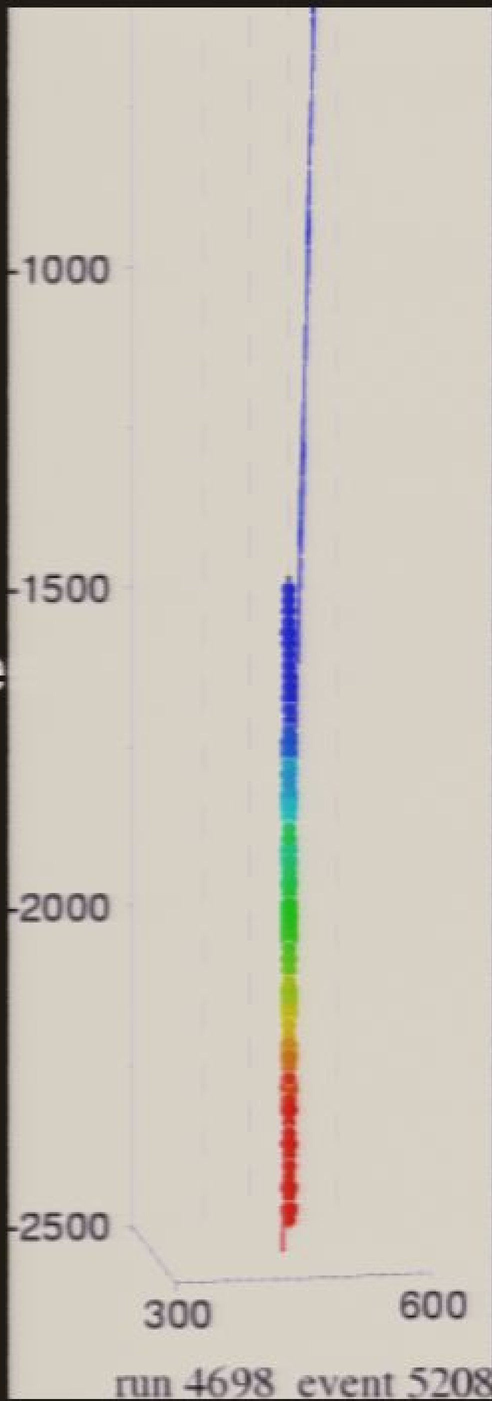

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background cosmic ray muon produced in the atmosphere

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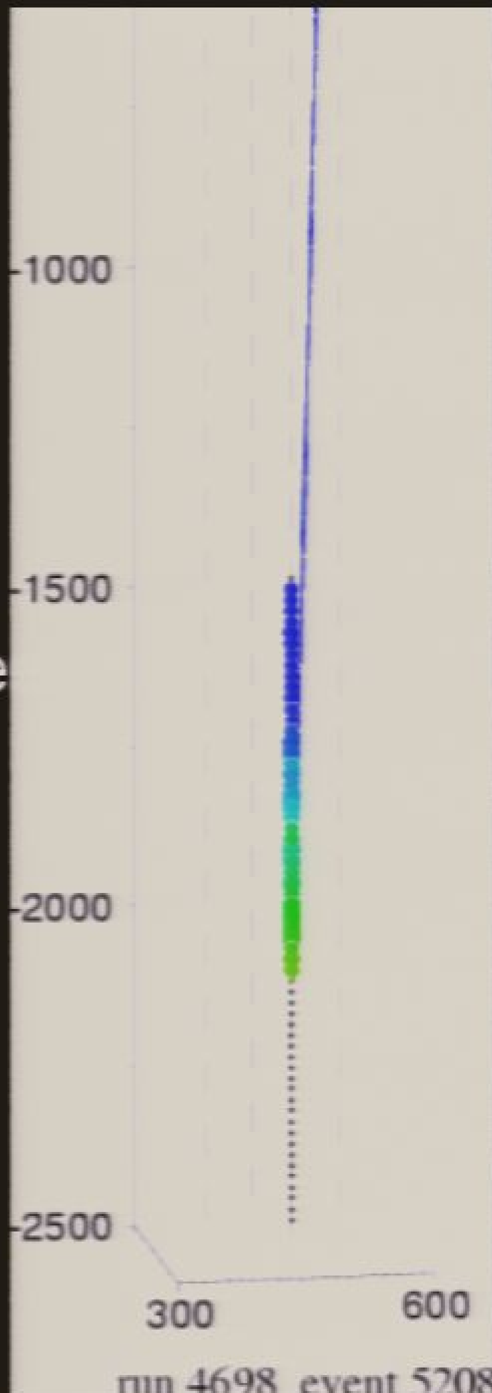

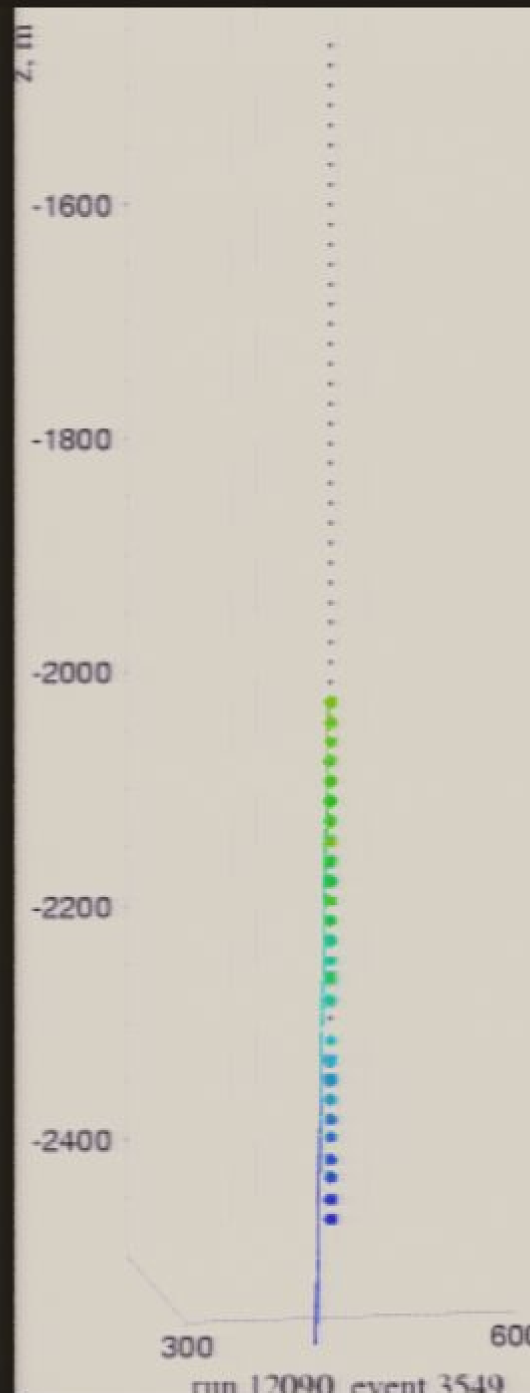

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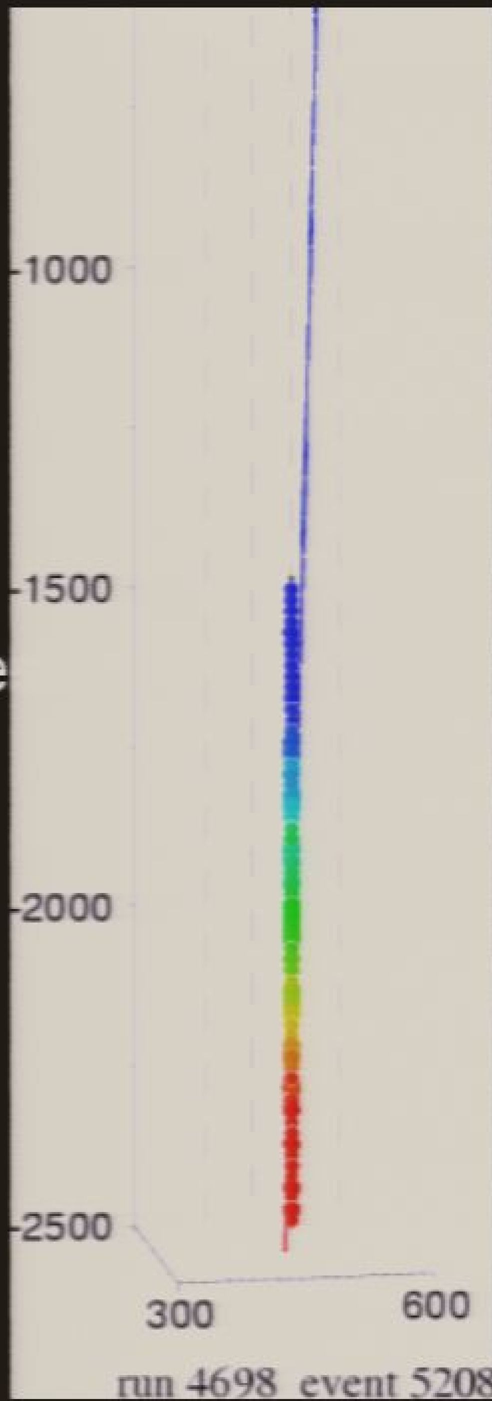

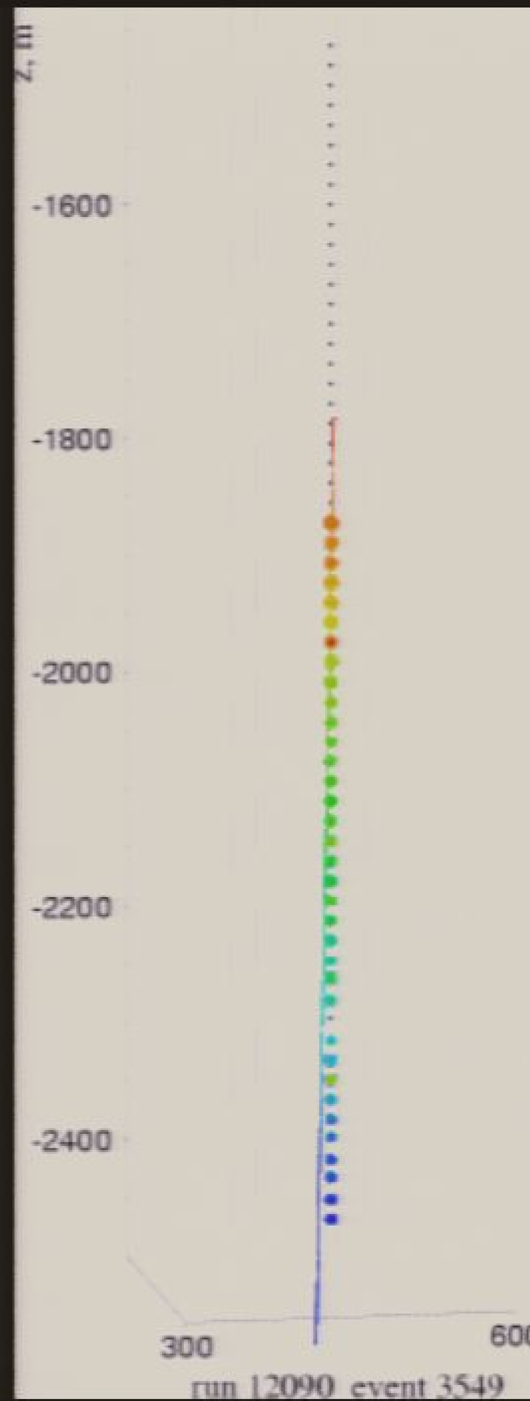

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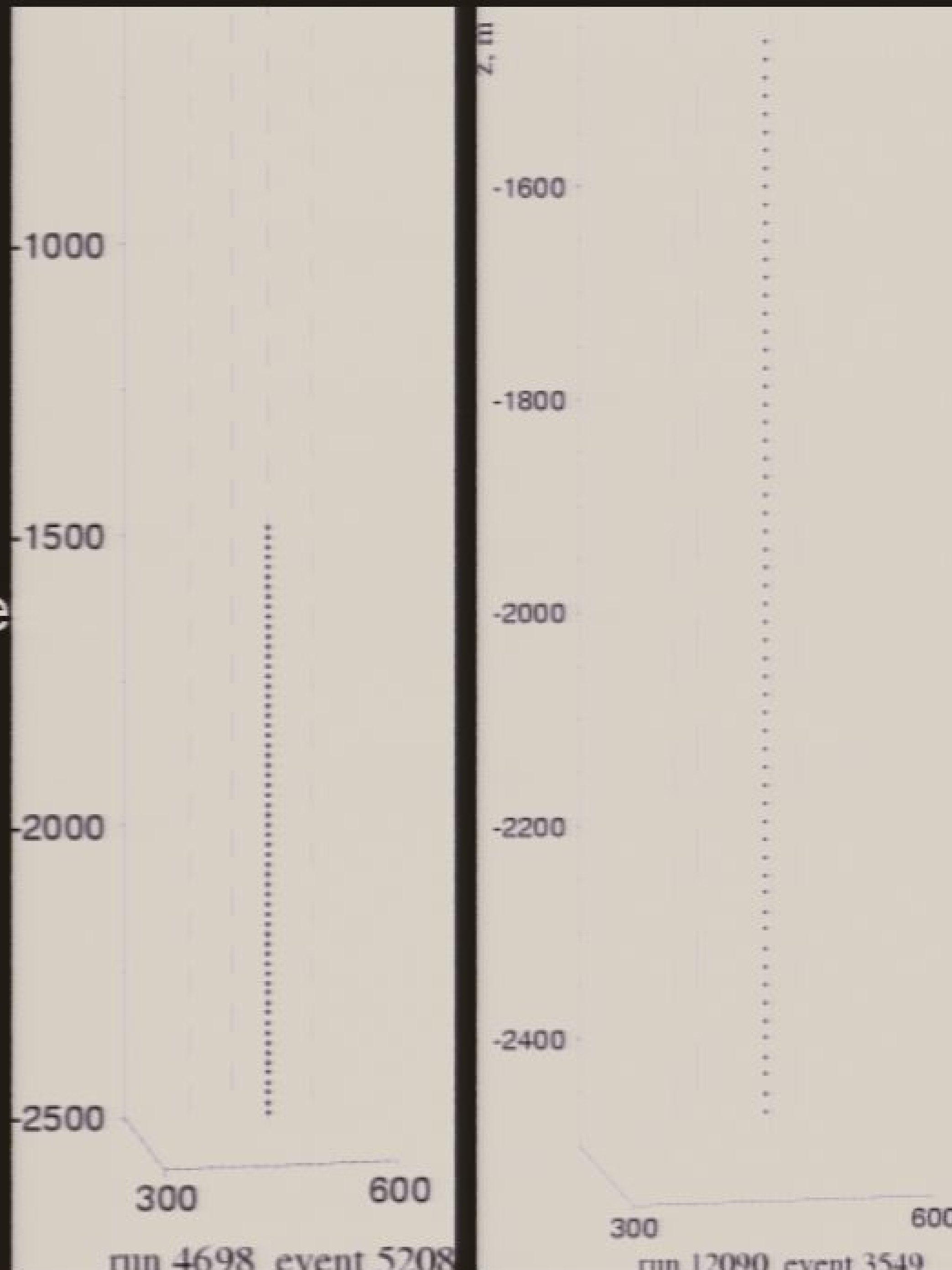

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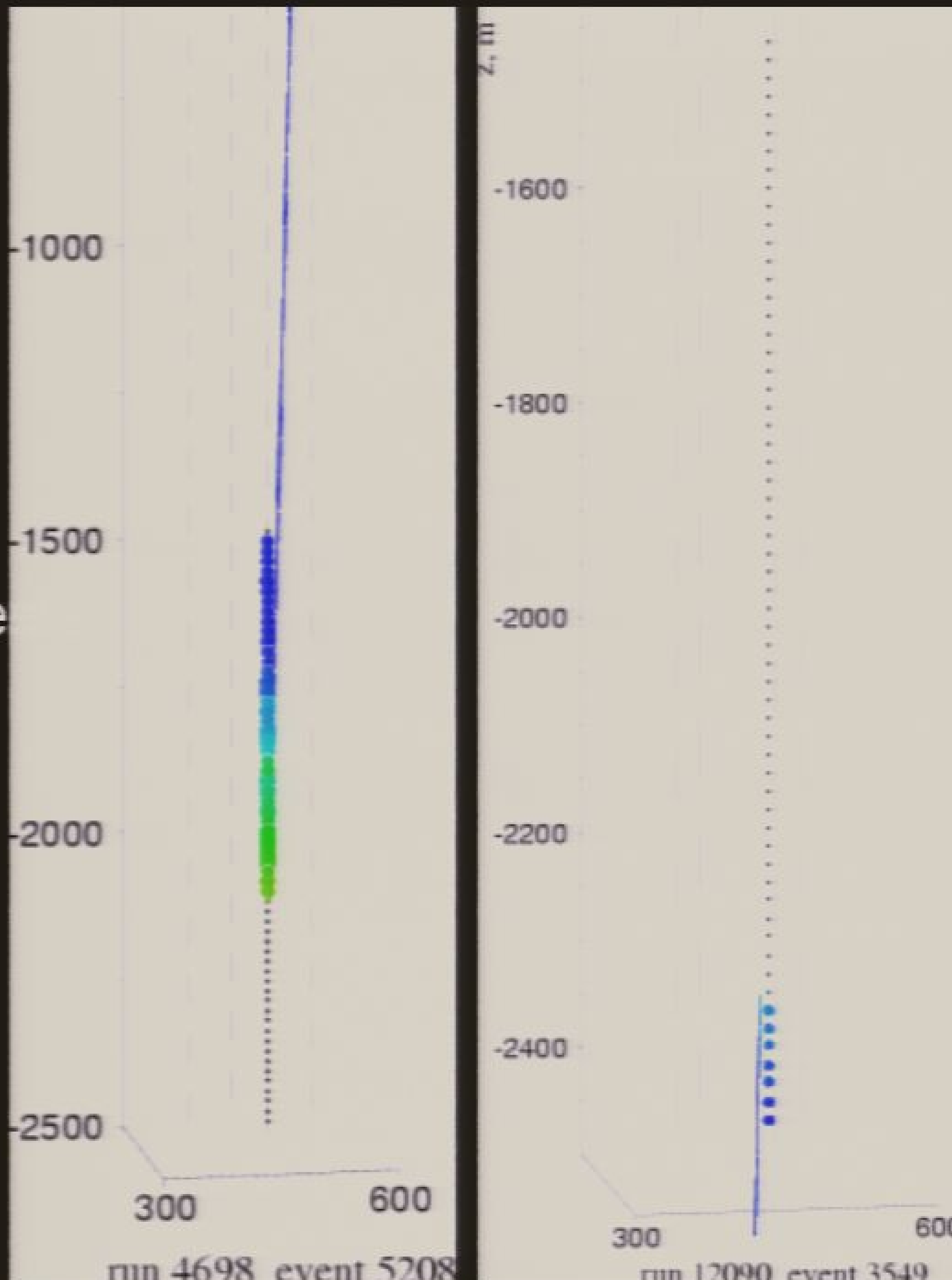

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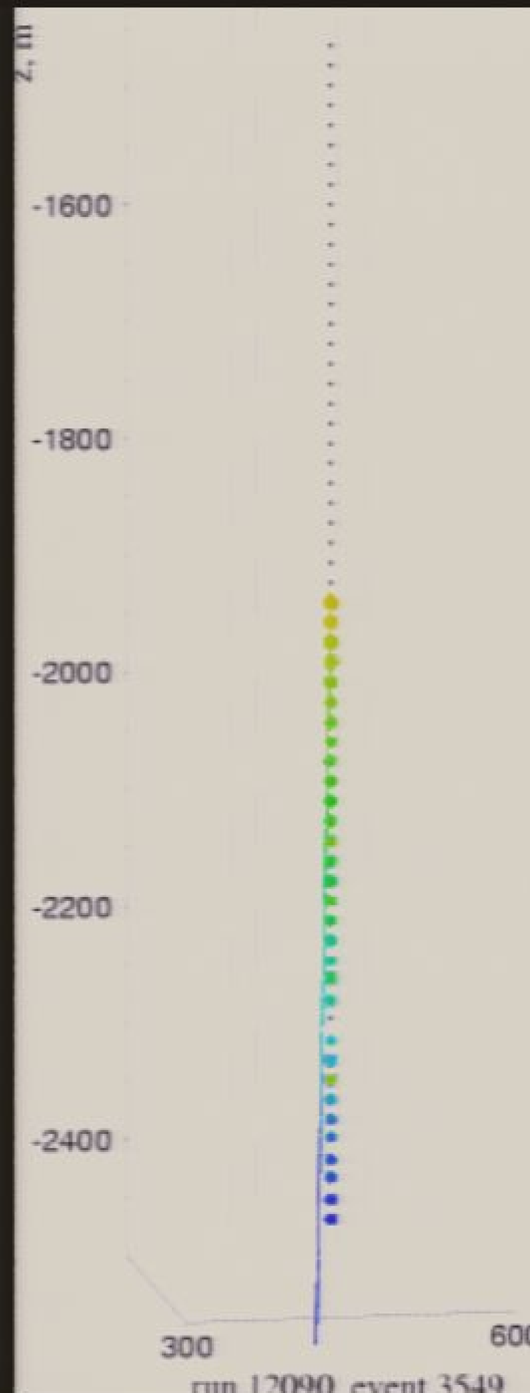

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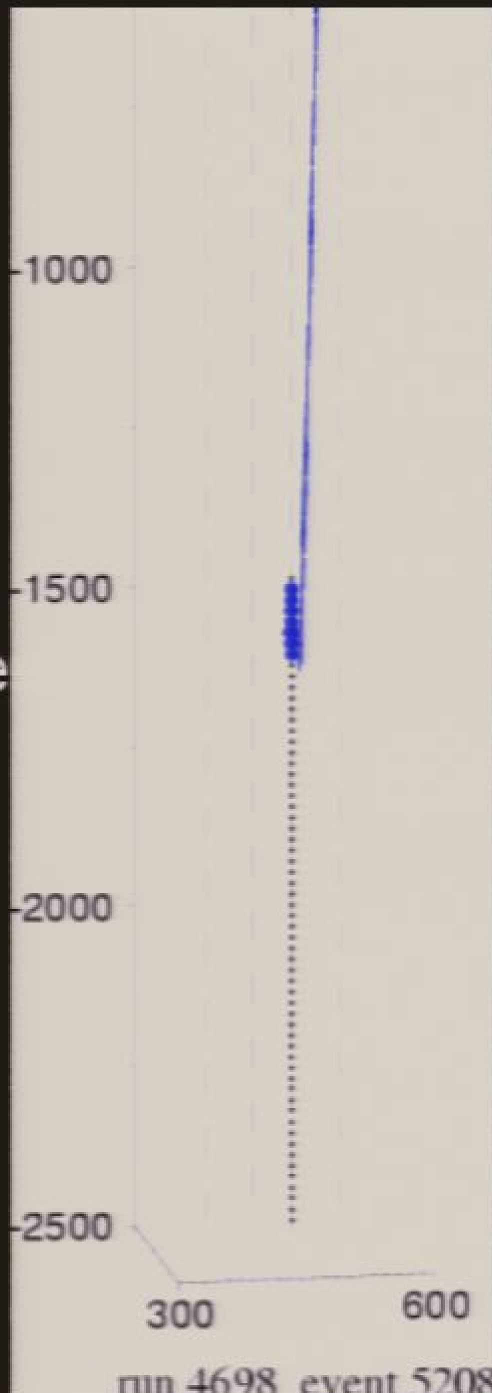


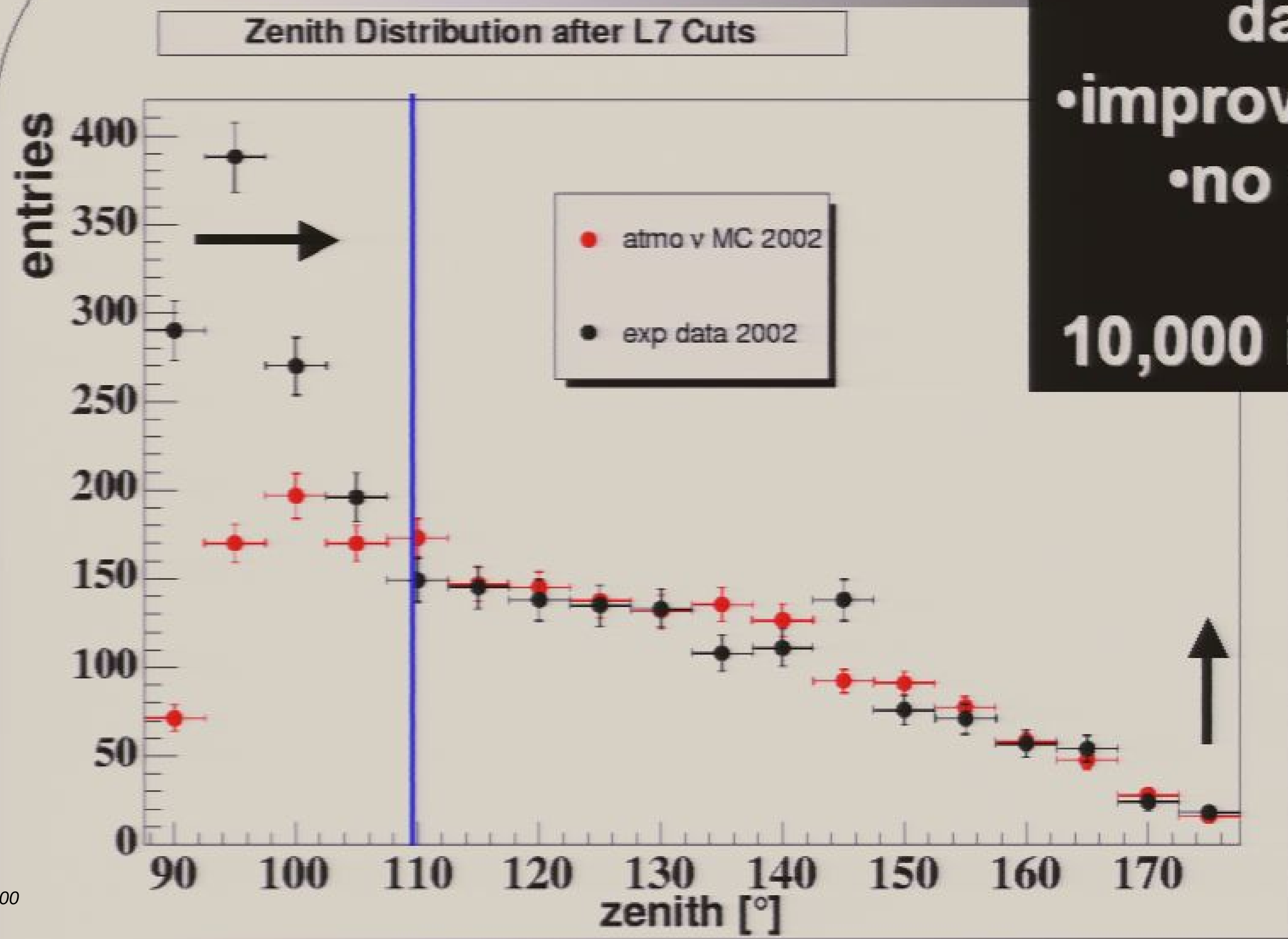
up

neutrino
traveled
through the
earth

10 per day

Optimized 2002 analysis

zenith distribution



→10 events per day:

- improved reco
- no cuts

10,000 in 00-05

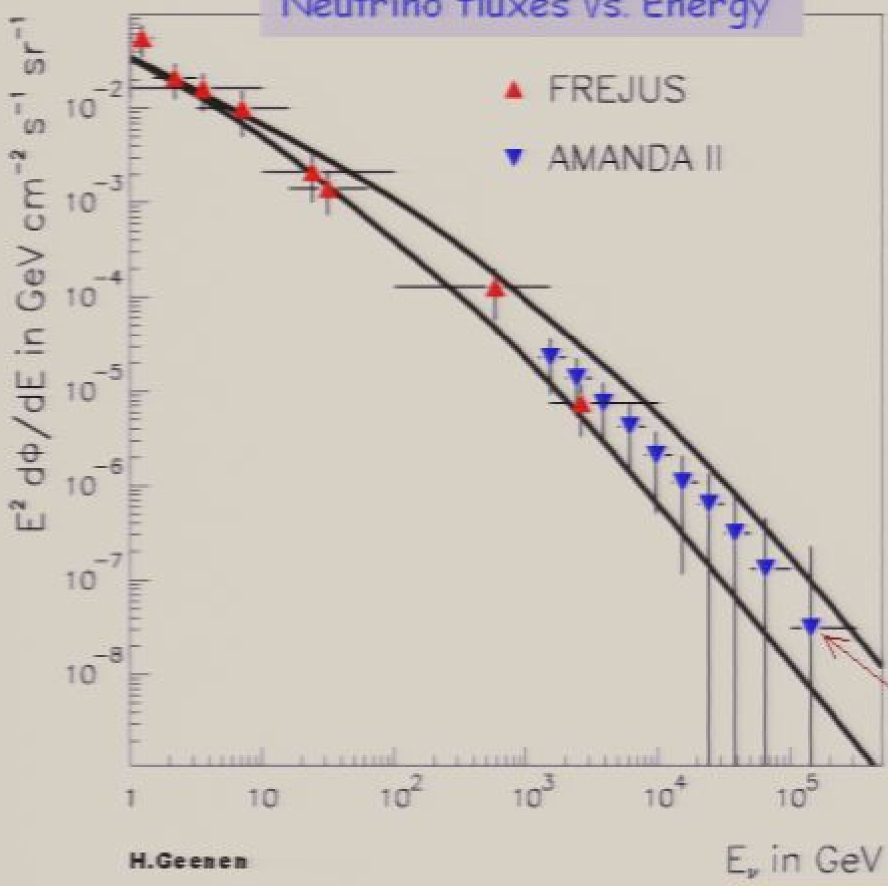
ATMOSPHERIC ν & DIFFUSE FLUX LIMITS [ν_μ]

Neural Network energy reconstruction
Regularized unfolding → energy spectrum

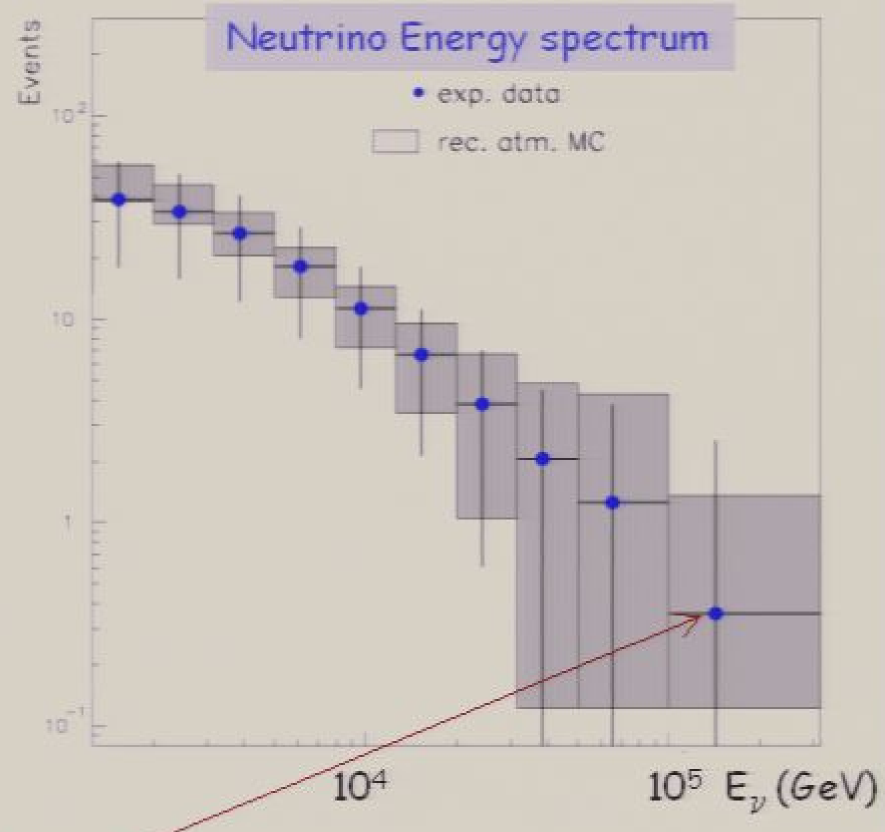
AMANDA test beams: atmospheric ν and μ

First spectrum > 1 TeV (up to 100TeV)

Neutrino fluxes vs. Energy



Neutrino Energy spectrum



Last bin info to calculate the limit to Extraterrestrial E^2 neutrino flux

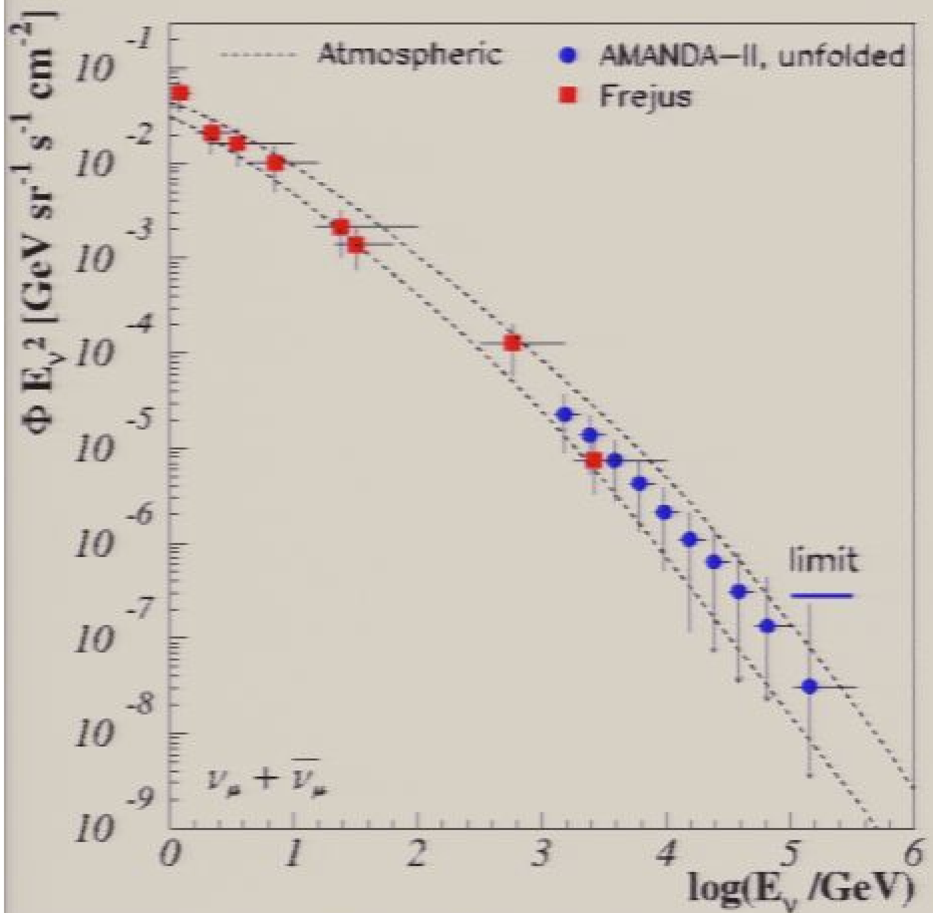
Previous analysis publication

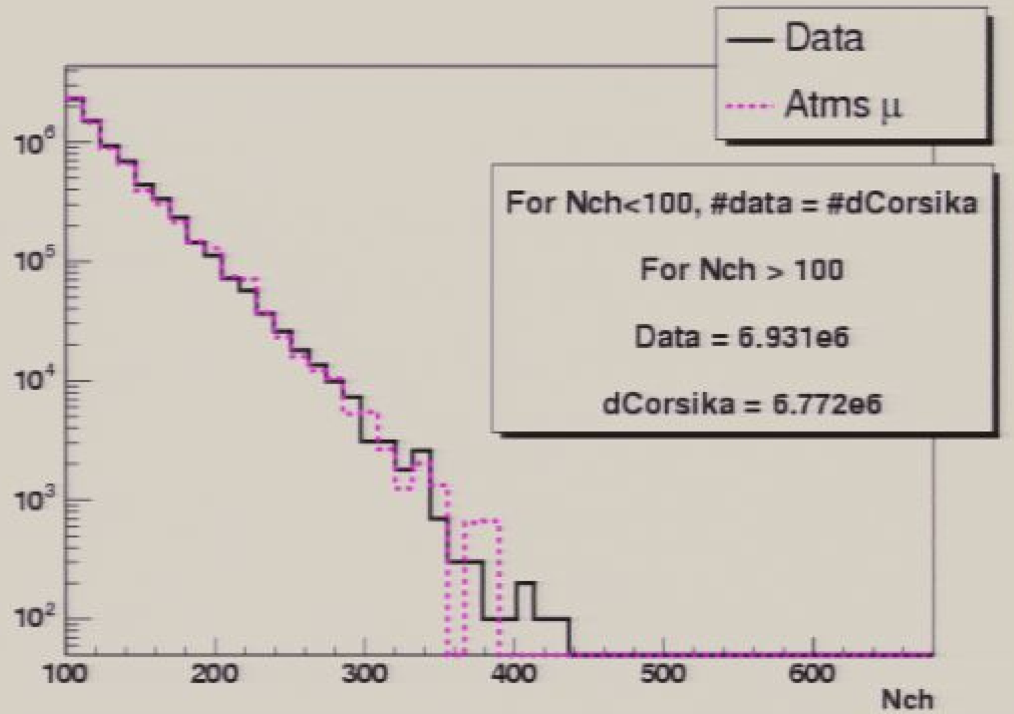
Phys. Rev. Lett. 90 251101 (2003)

Includes 33% systematic uncertainty

$$E^2\Phi_\nu(E) < 2.58\cdot10^{-7}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

calibration on down-going cosmic ray muon



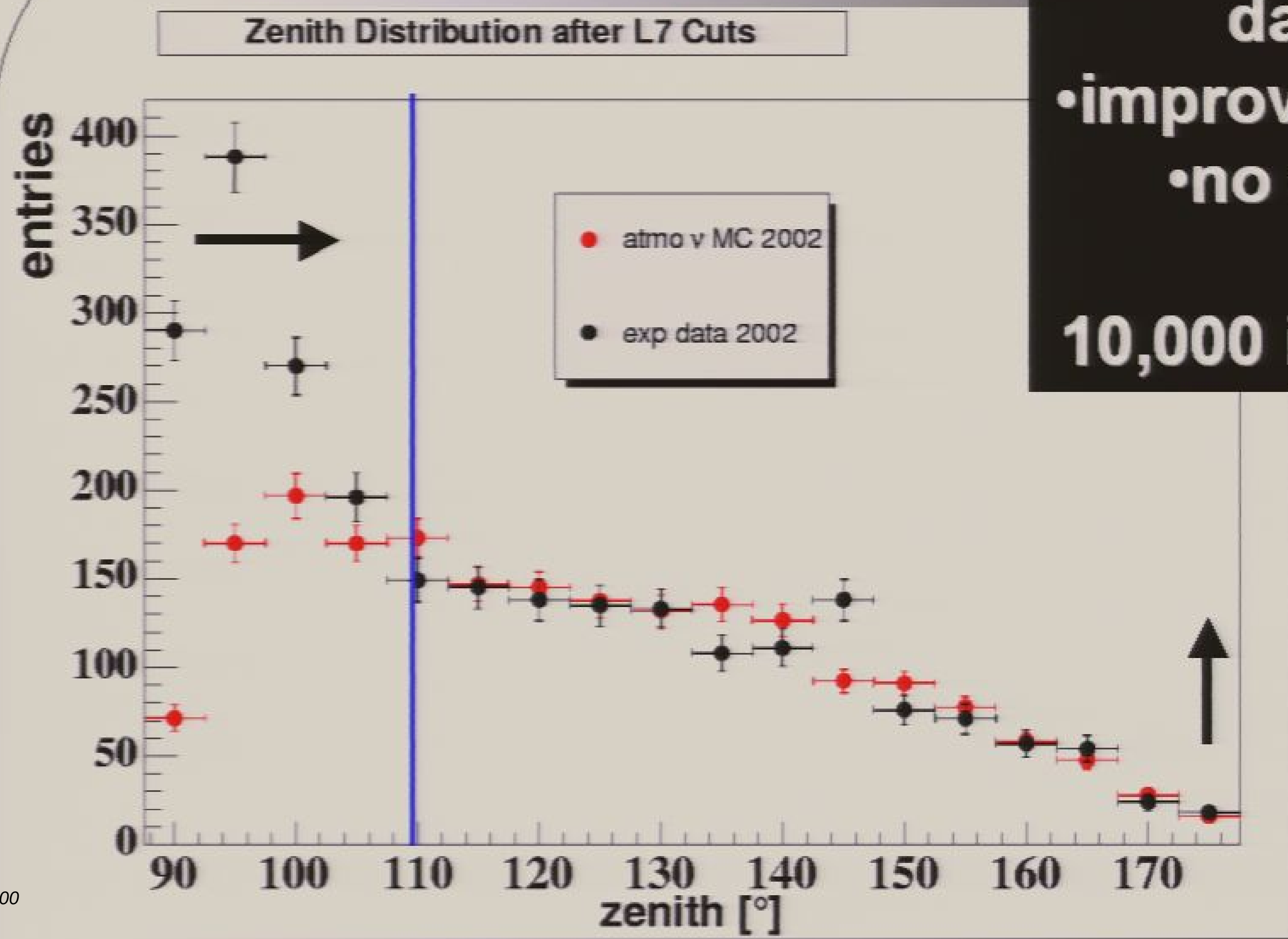


inverted analysis: use atm. muons to benchmark MC

• atmospheric ν_μ background (but uncertainties in theoretical calculations)

Optimized 2002 analysis

zenith distribution



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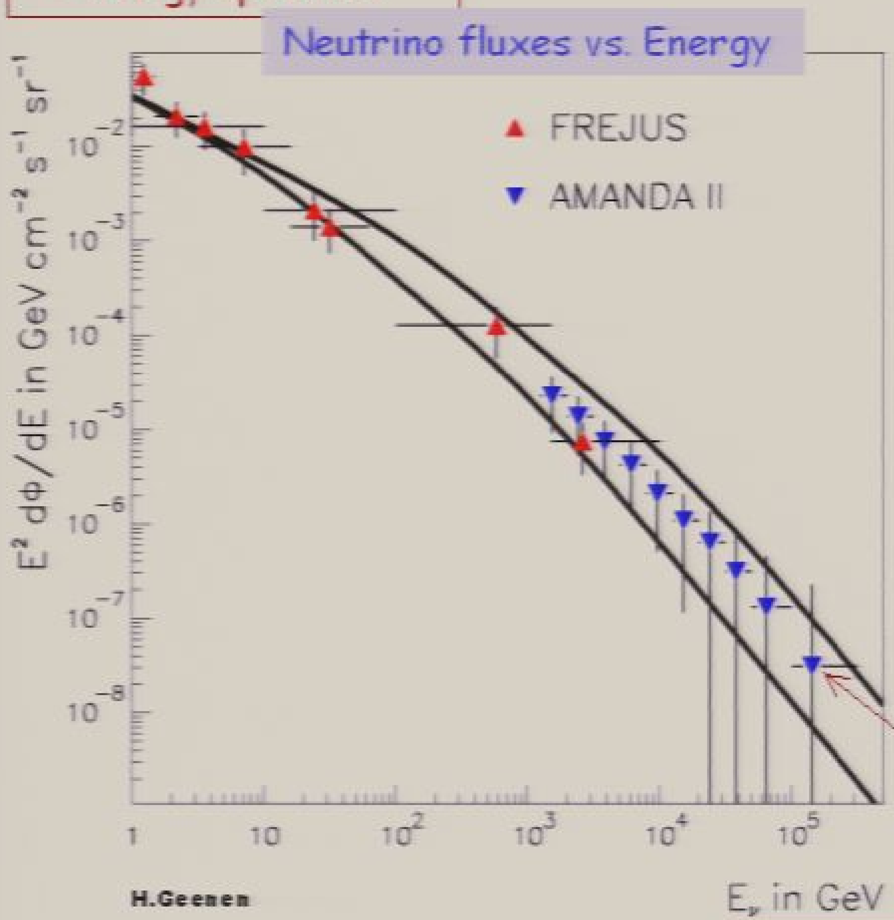

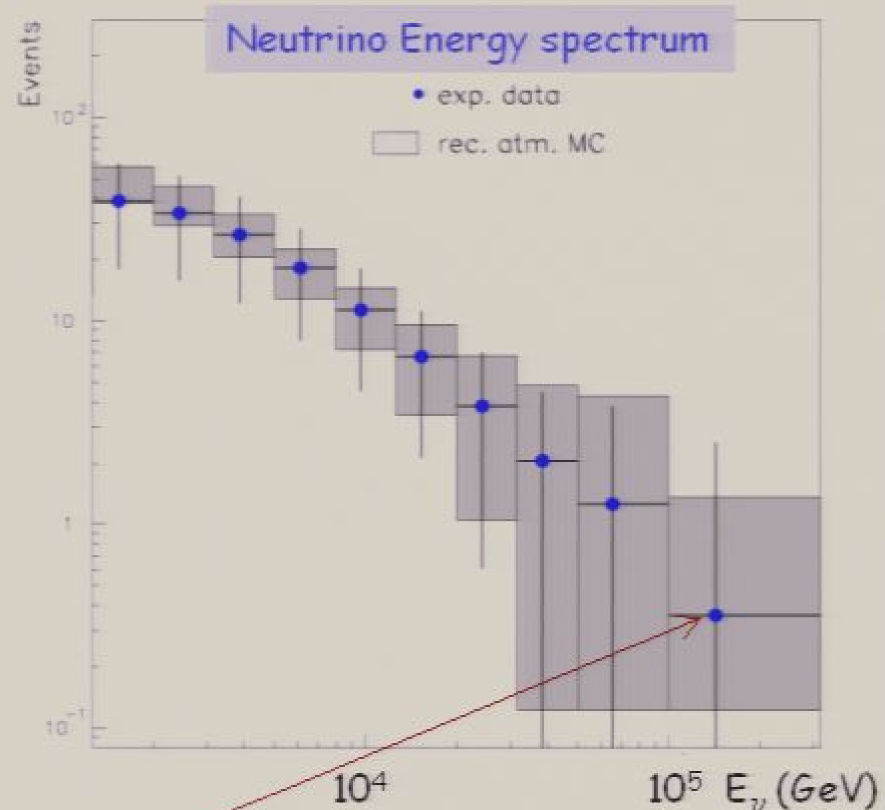

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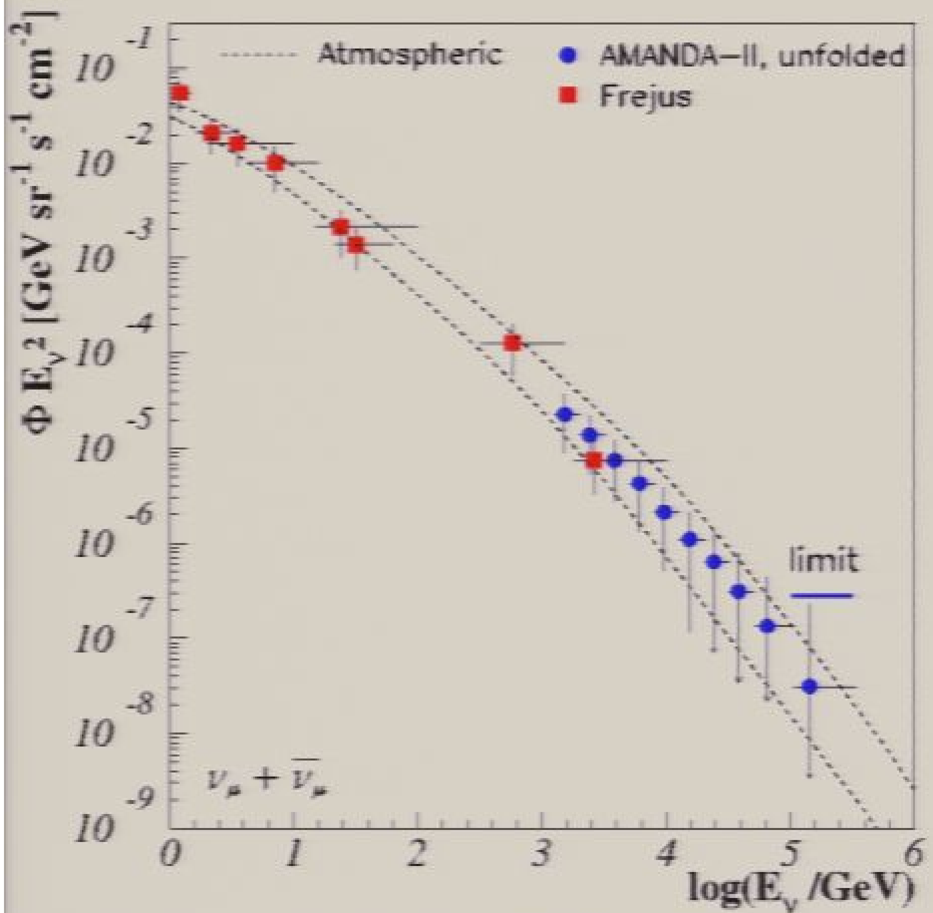
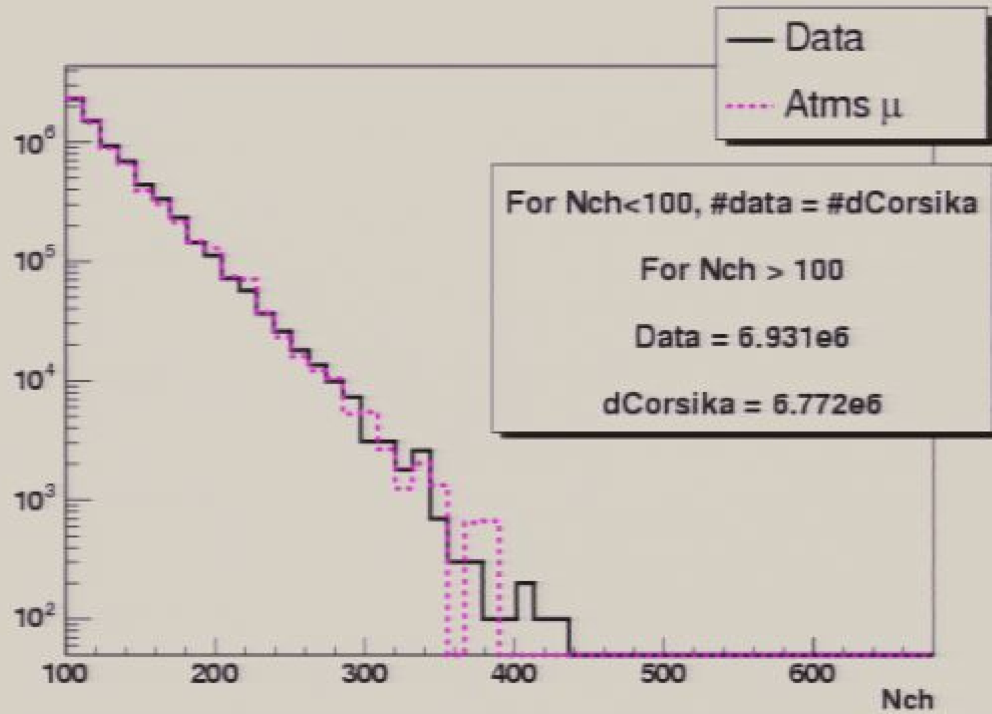




inverted analysis: use atm. muons to benchmark MC

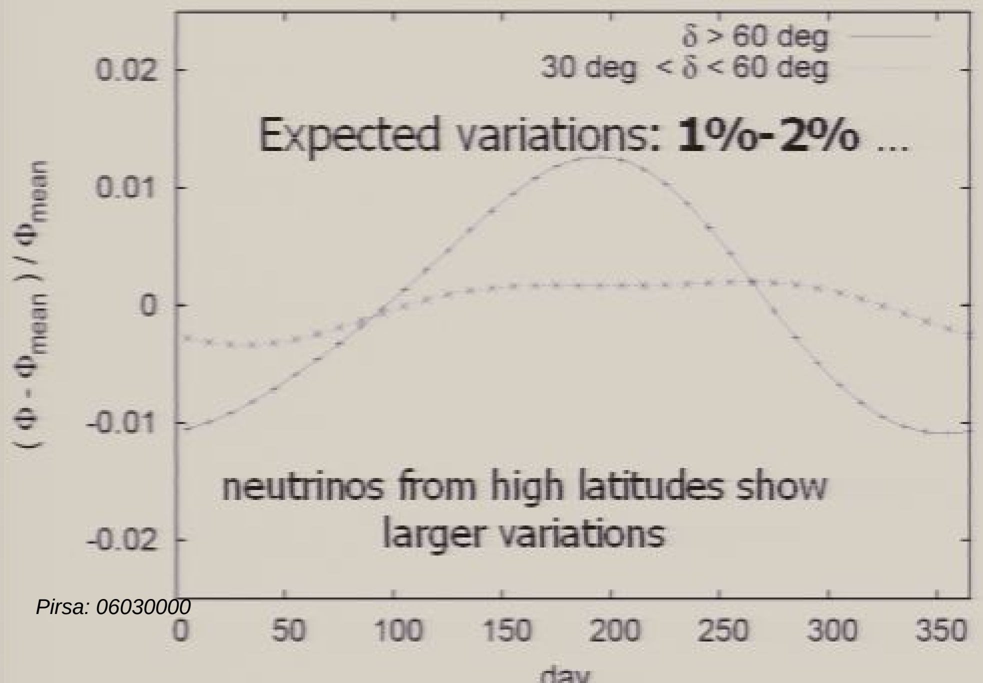
- atmospheric ν_μ background (but uncertainties in theoretical calculations)

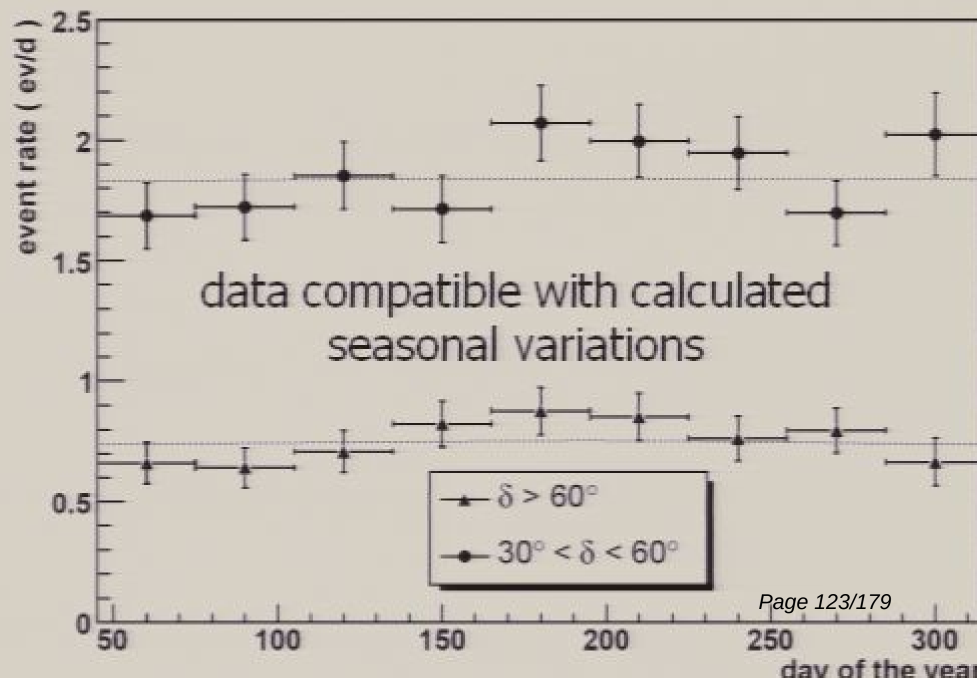
atmospheric neutrinos – a high precision measurement

Channel	E_{th} (@ AMANDA)	Source ($\varepsilon_{\pi,k}$)
Muons	≈ 400 GeV	≈ Pions (115 GeV)
Neutrinos	≈ 50 GeV	≈ Kaons (850 GeV)

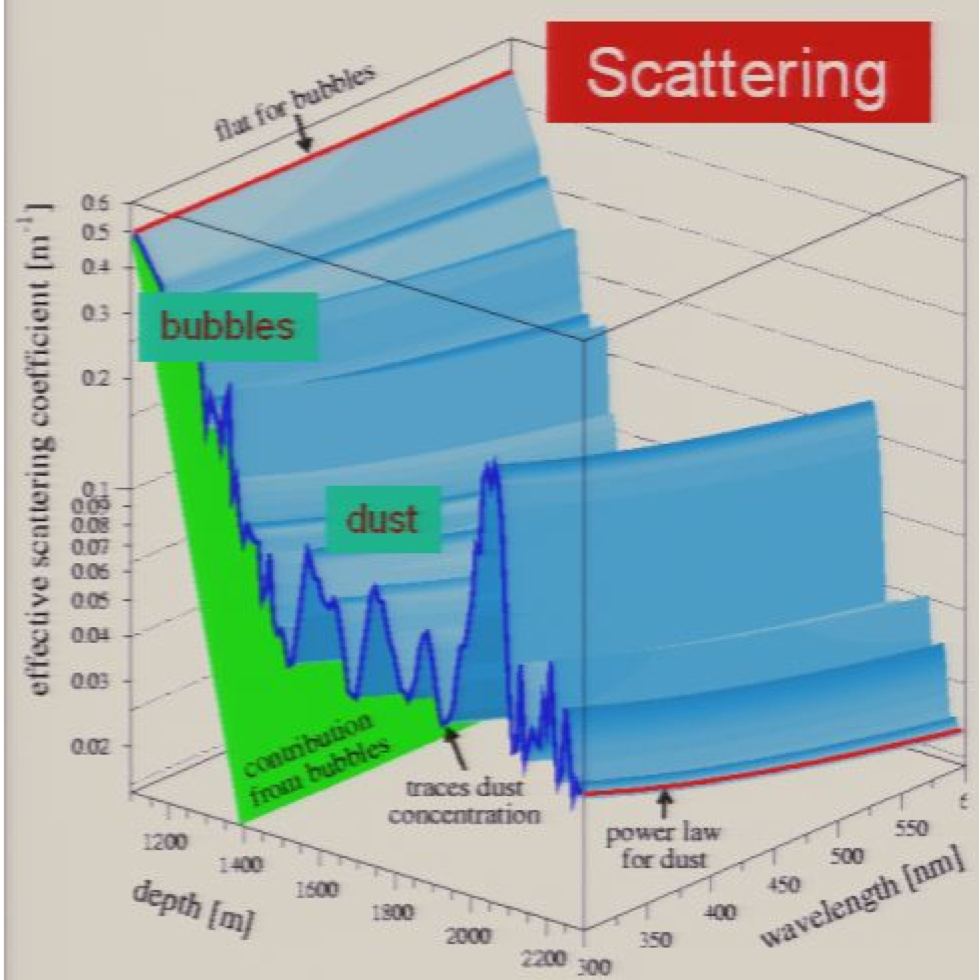
E » critical energy $\varepsilon_{\pi,k}$: interaction dominate over decay

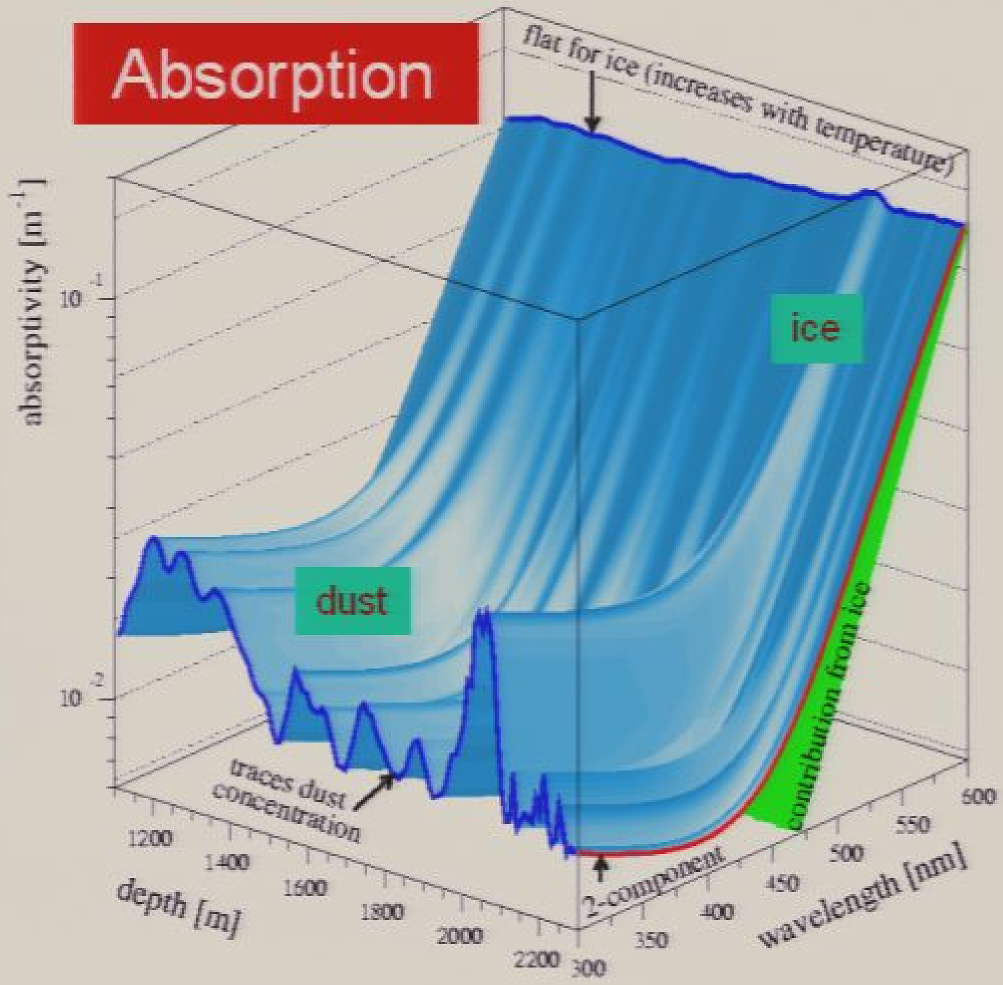
temperature increase ⇒ density decrease ⇒ more decays than interactions





Detector medium: ice to meet you

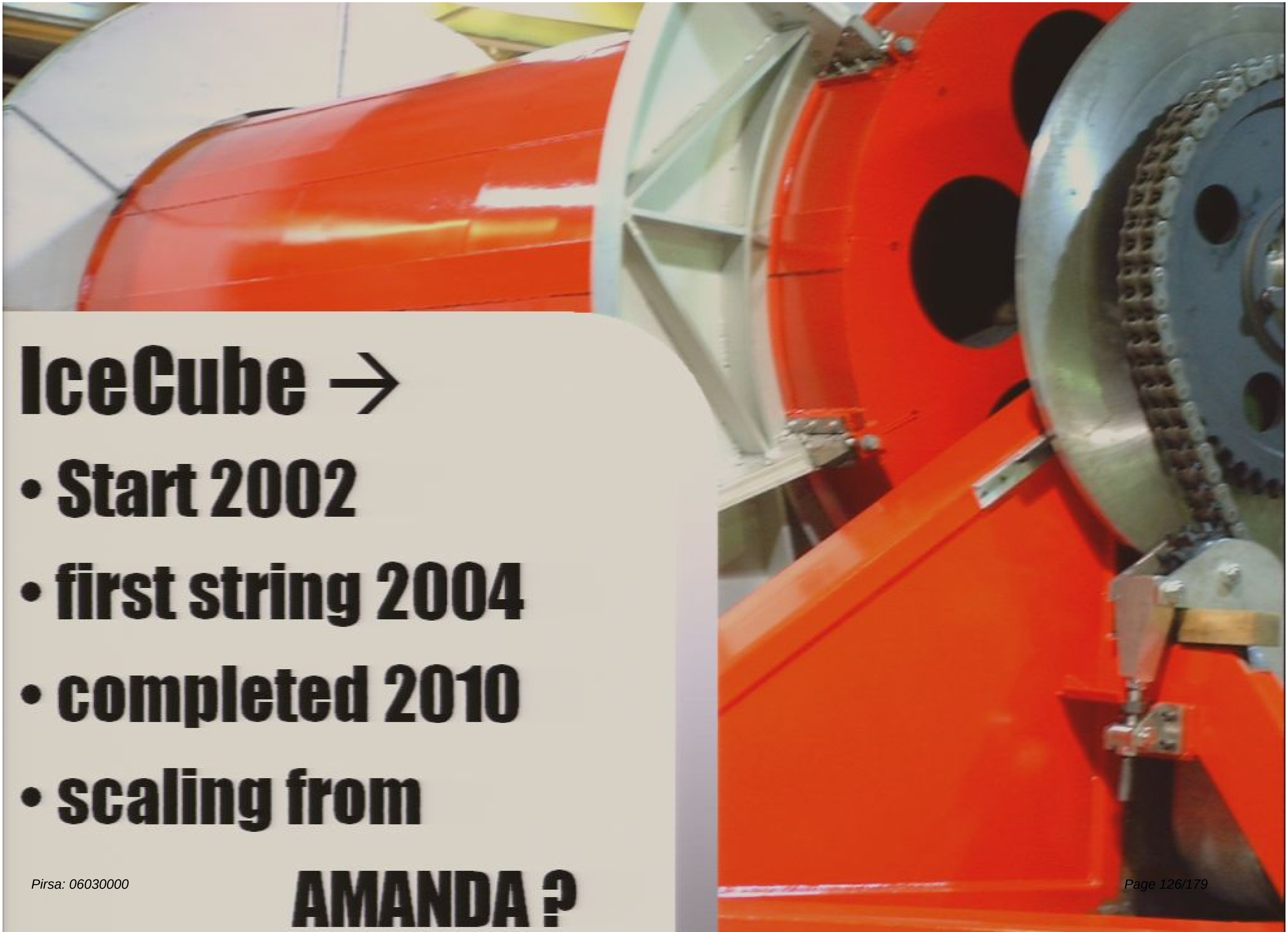




Measurements:
- ▶ in-situ light sources
- ▶ atmospheric muons

- **scattering length 6 ~ 52 m**
- **absorption length 9 ~ 240 m**
- **sterile medium**

icecube

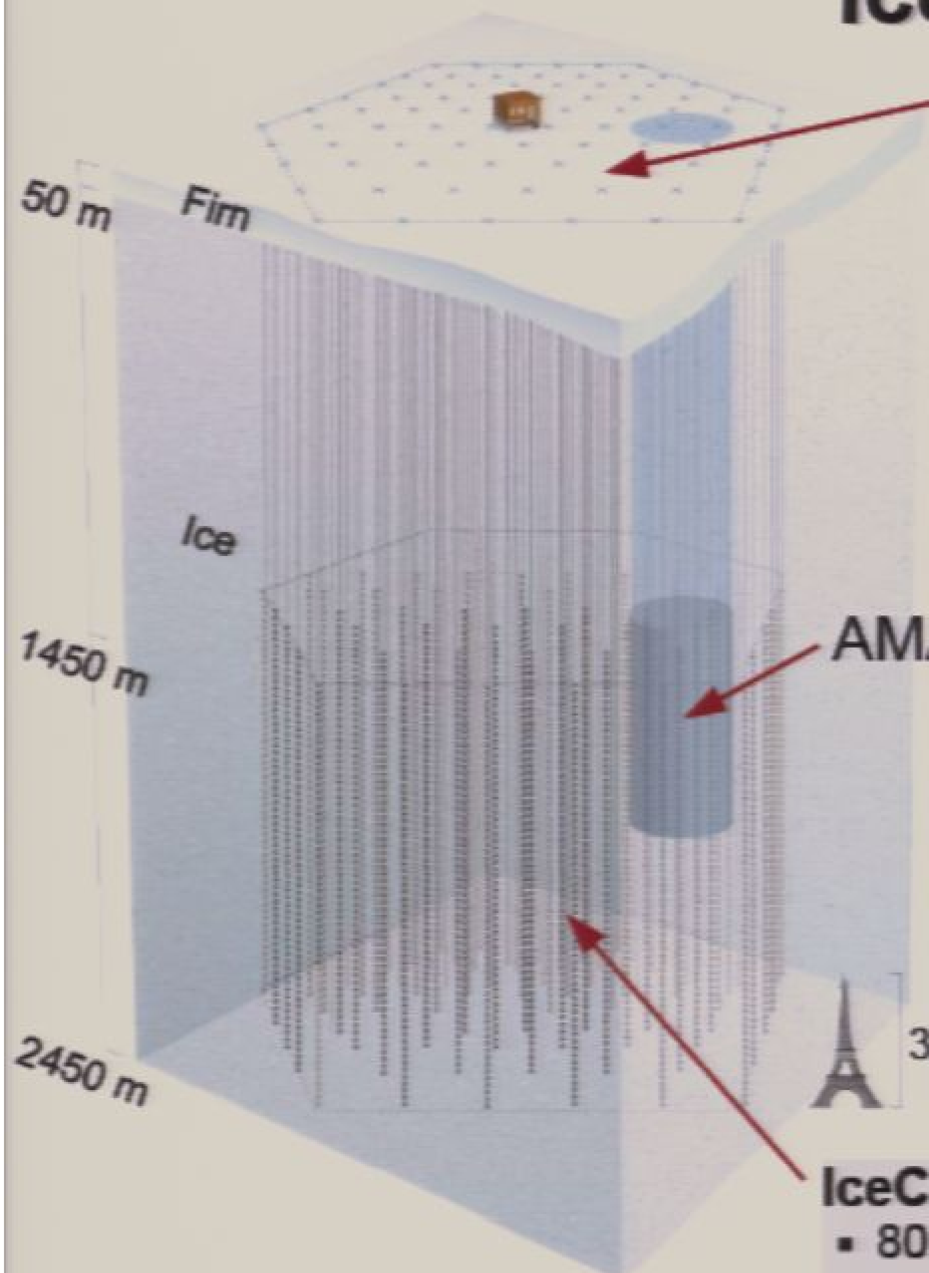


IceCube →

- Start 2002
- first string 2004
- completed 2010
- scaling from

AMANDA ?

IceCube



IceTop: air shower array

- 80 Stations / 2 Tanks each
- 2 DOMs each per tank
- 125 m grid, 1 km^2 at 690 g/cm^2
- E_{thres} ~ 300 TeV for ≥ 4 stations
- Useful rate up to ~EeV

Digital Optical Module

IceCube: deep ice array

- 80 Strings / 60 DOMs each
- 17 m DOM spacing
- 125 m between strings
- 1 km^3 instrumented

IceCube construction

05-06

- 1 million pounds of cargo
- C-130 planes: > 50 flights

IceCube construction

05-06

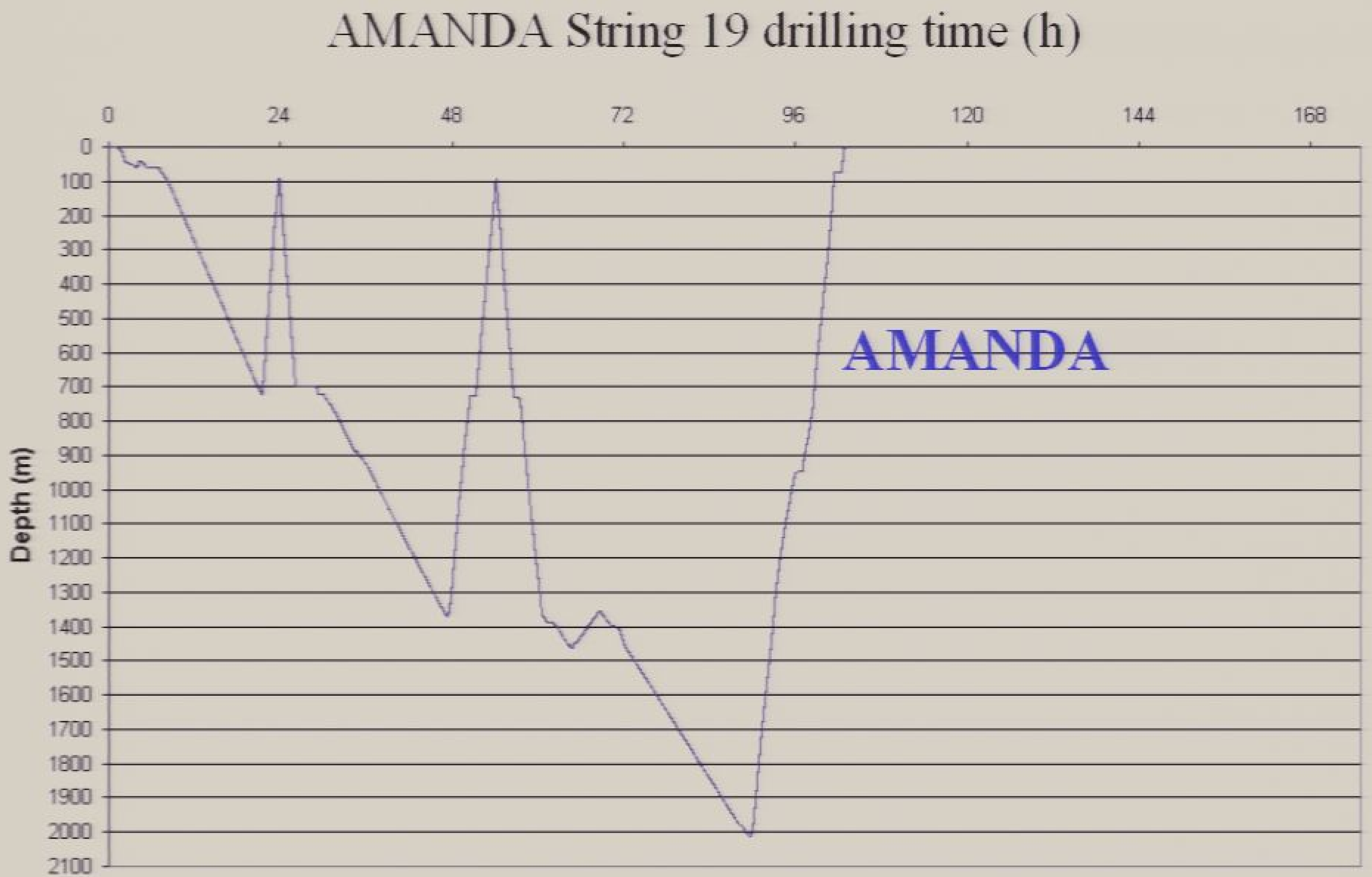
- 1 million pounds of cargo
- C-130 planes: > 50 flights

IceCube construction

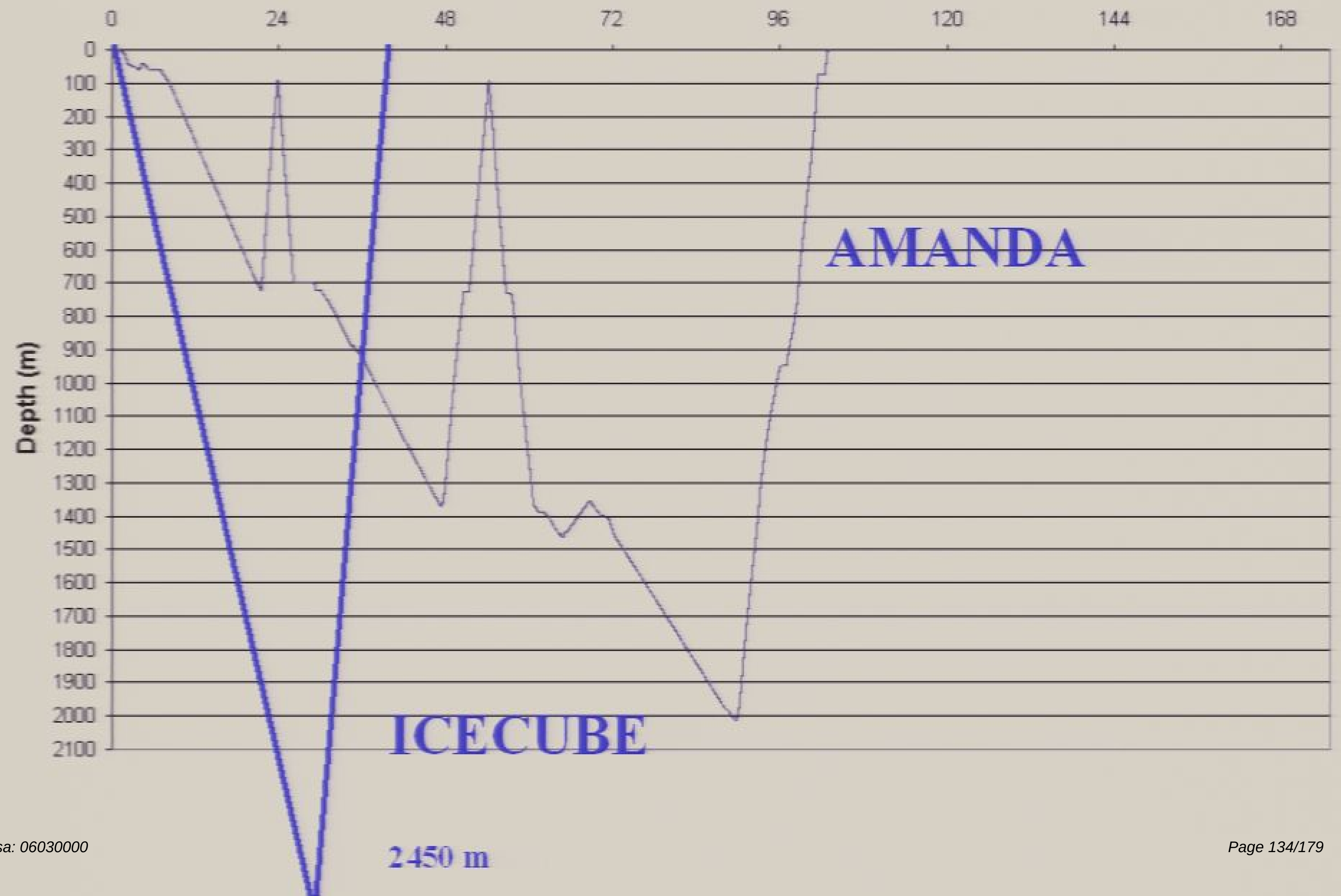
- 1 million pounds of cargo
- C-130 planes: > 50 flights

one of 21 drill modules arrive in antarctica

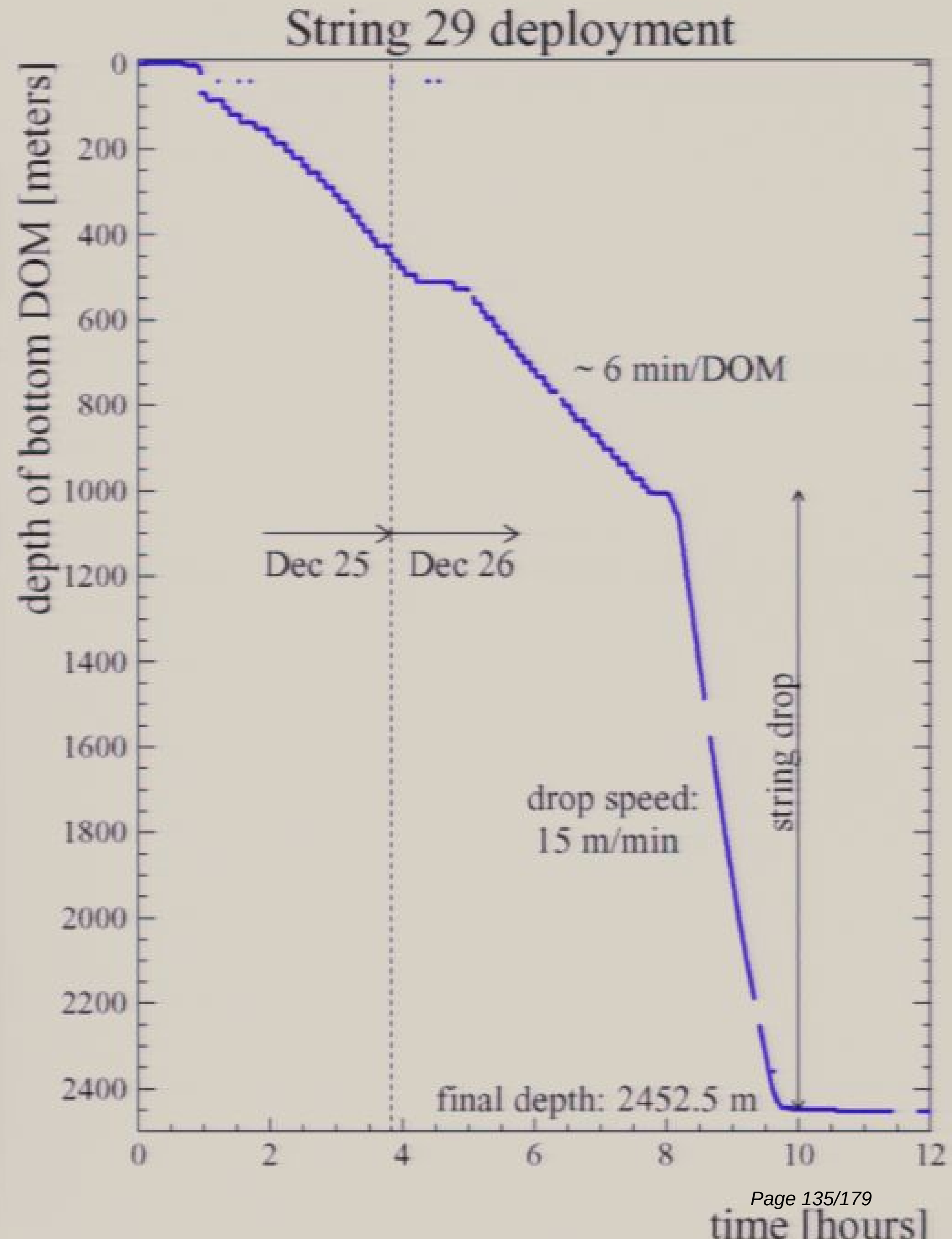
5 megawatt hot water drilling system

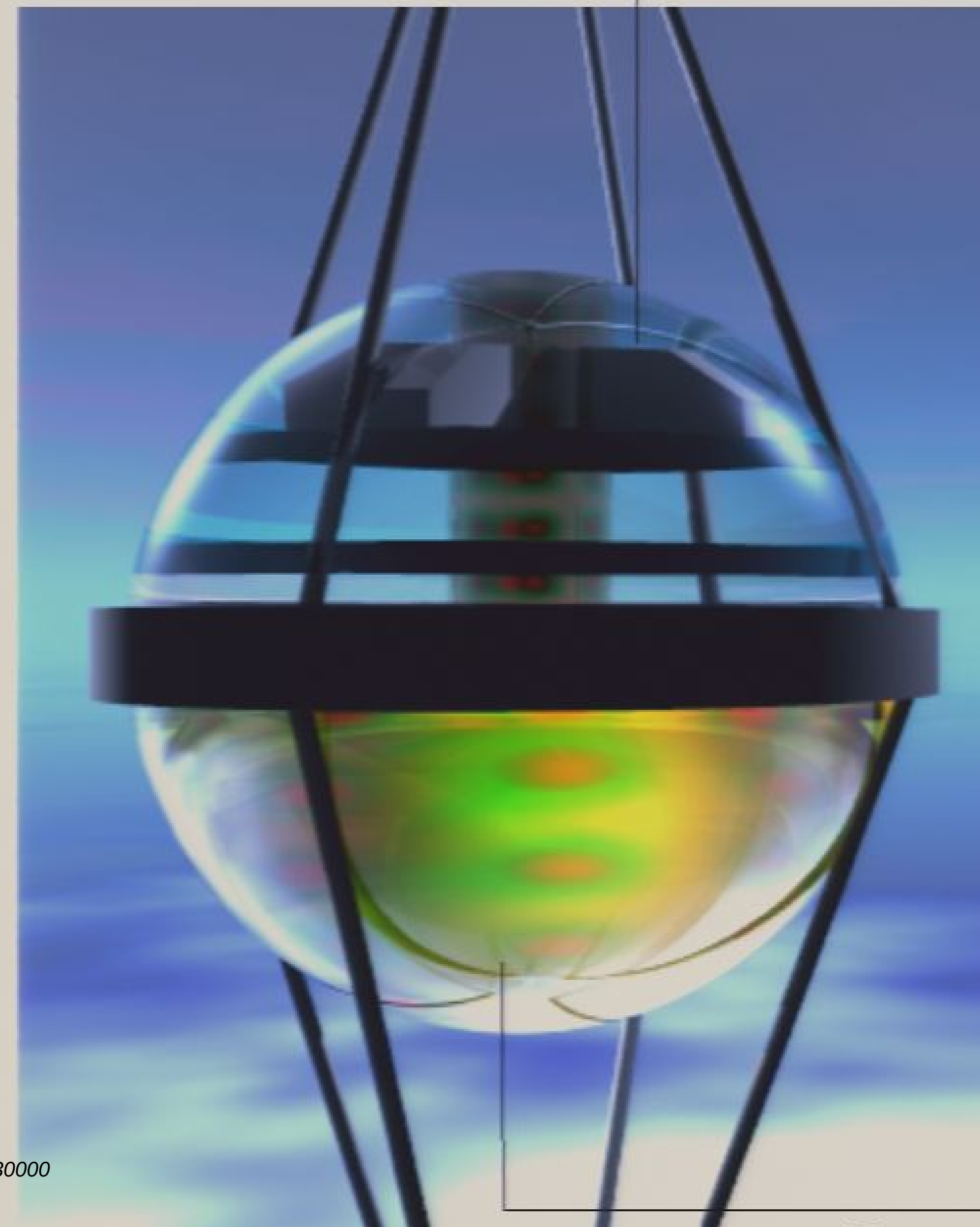

AMANDA String 19 drilling time (h)
0
24
48
72
96
120
144
168
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Depth (m)
AMANDA

AMANDA String 19 drilling time (h)

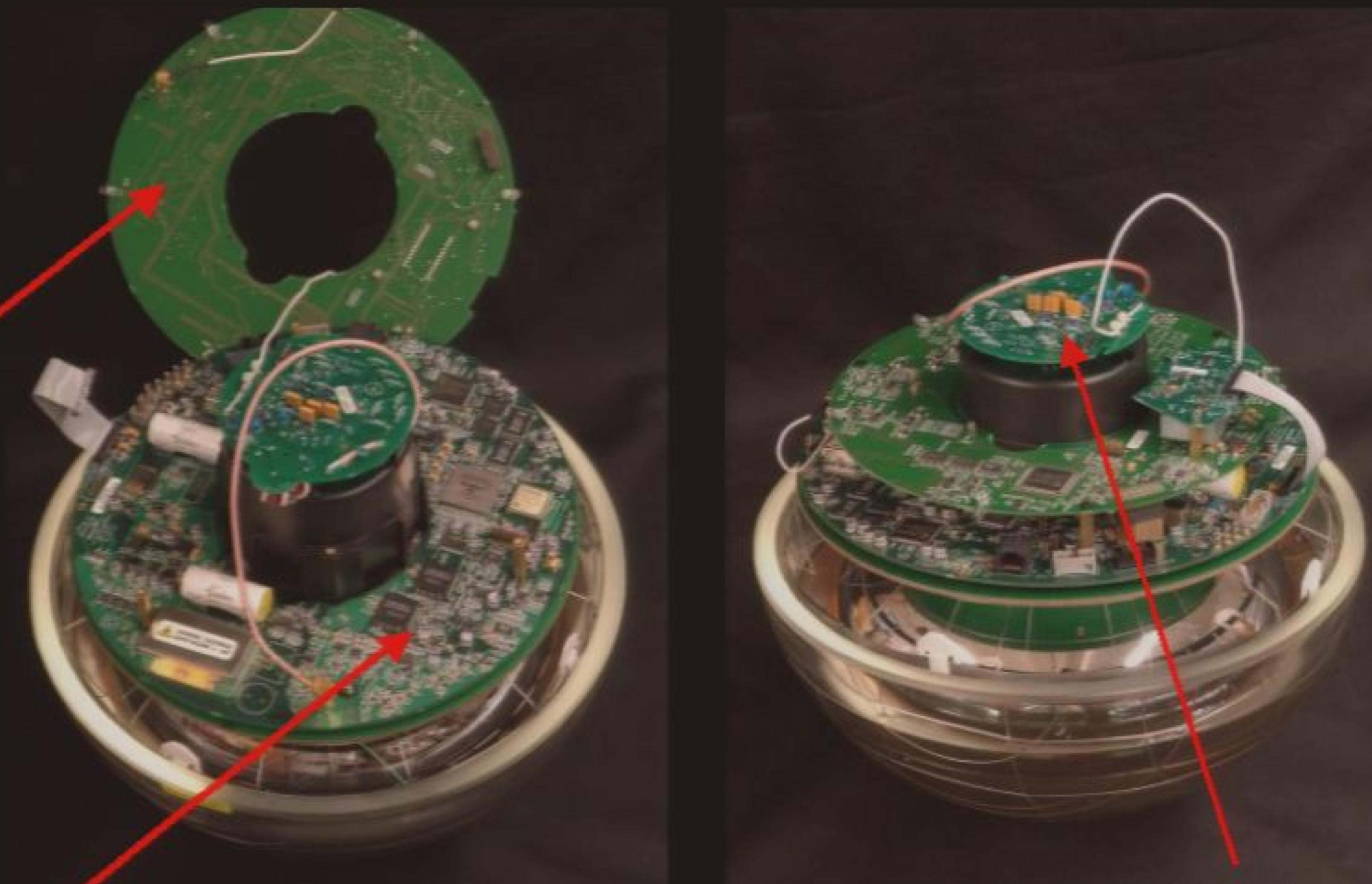



String cable 2500 m
Weight ~6 tons
11180 LBS


String 29 deployment
depth of bottom DOM [meters]
time [hours]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
0
2
4
6
8
10
12
~ 6 min/DOM
Dec 25
Dec 26
drop speed:
15 m/min
string drop
final depth: 2452.5 m

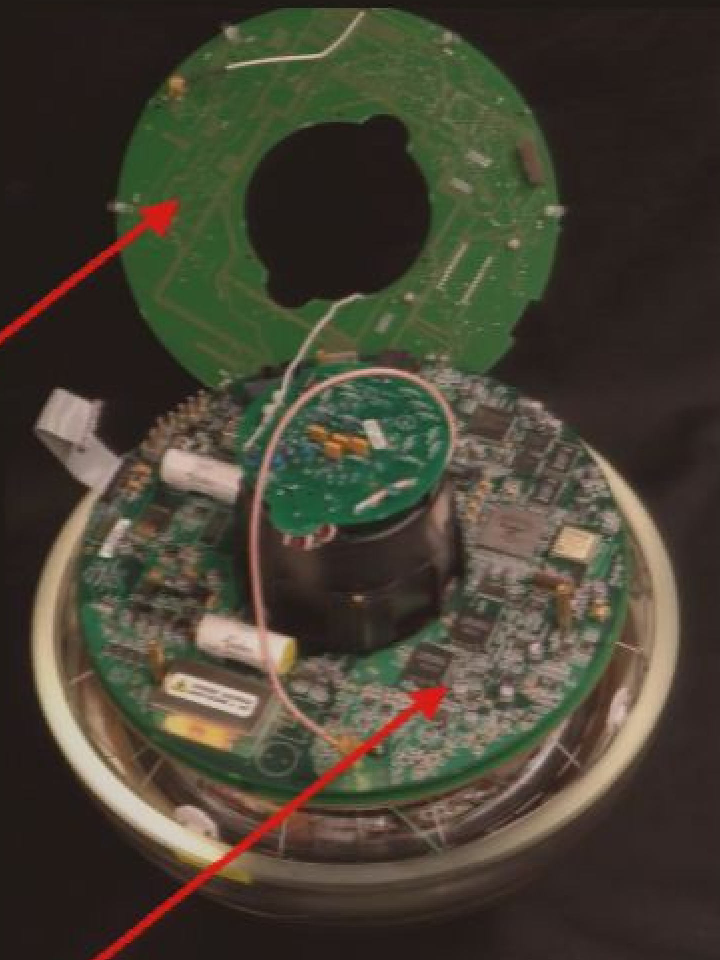

Digital Optical Module

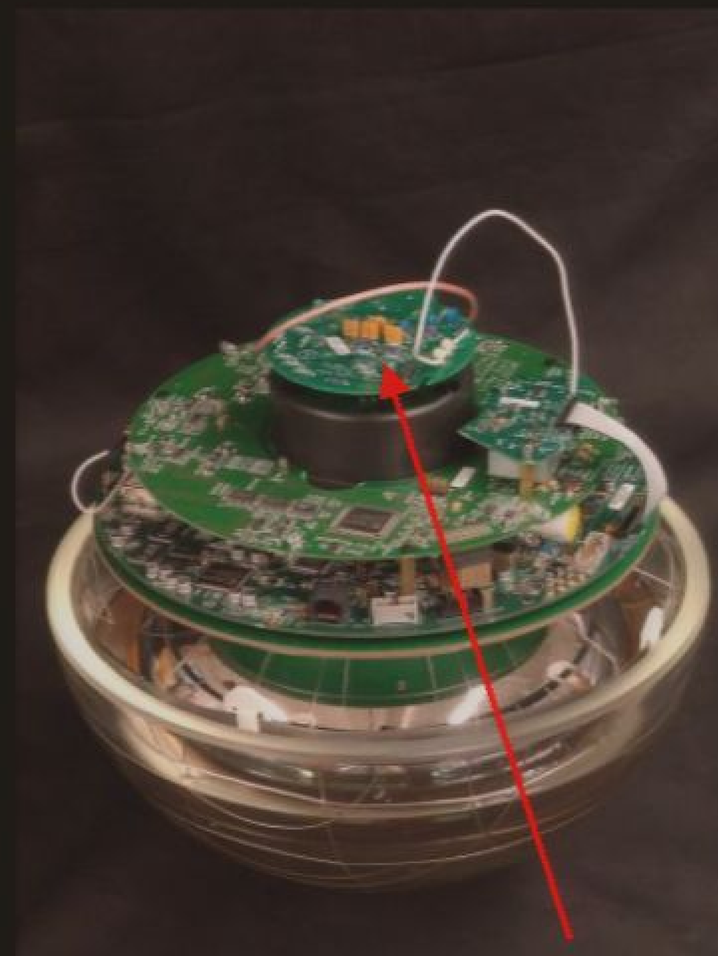
Digital Optical Module



Digital Optical Module

LED
flasher
board

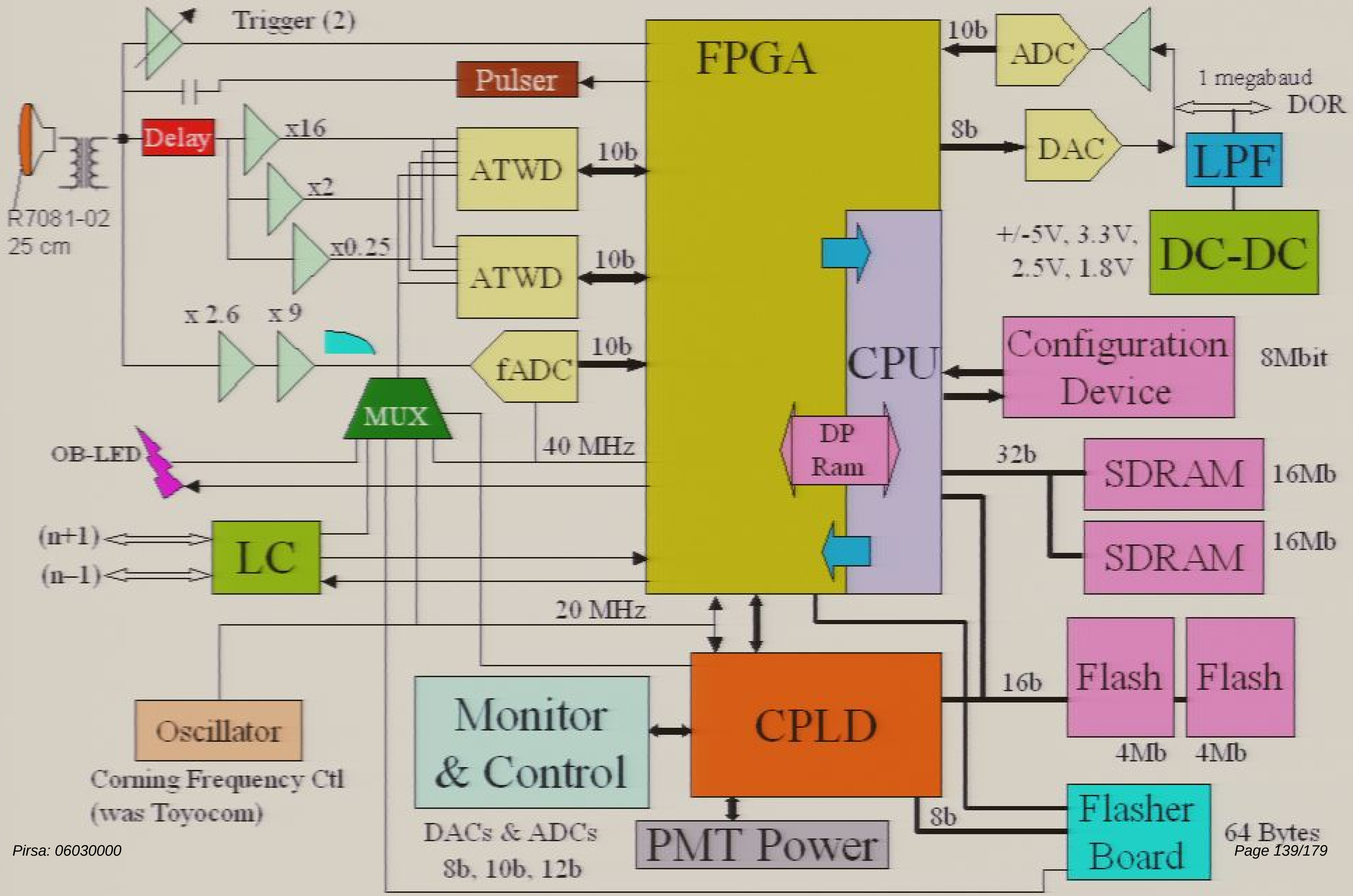




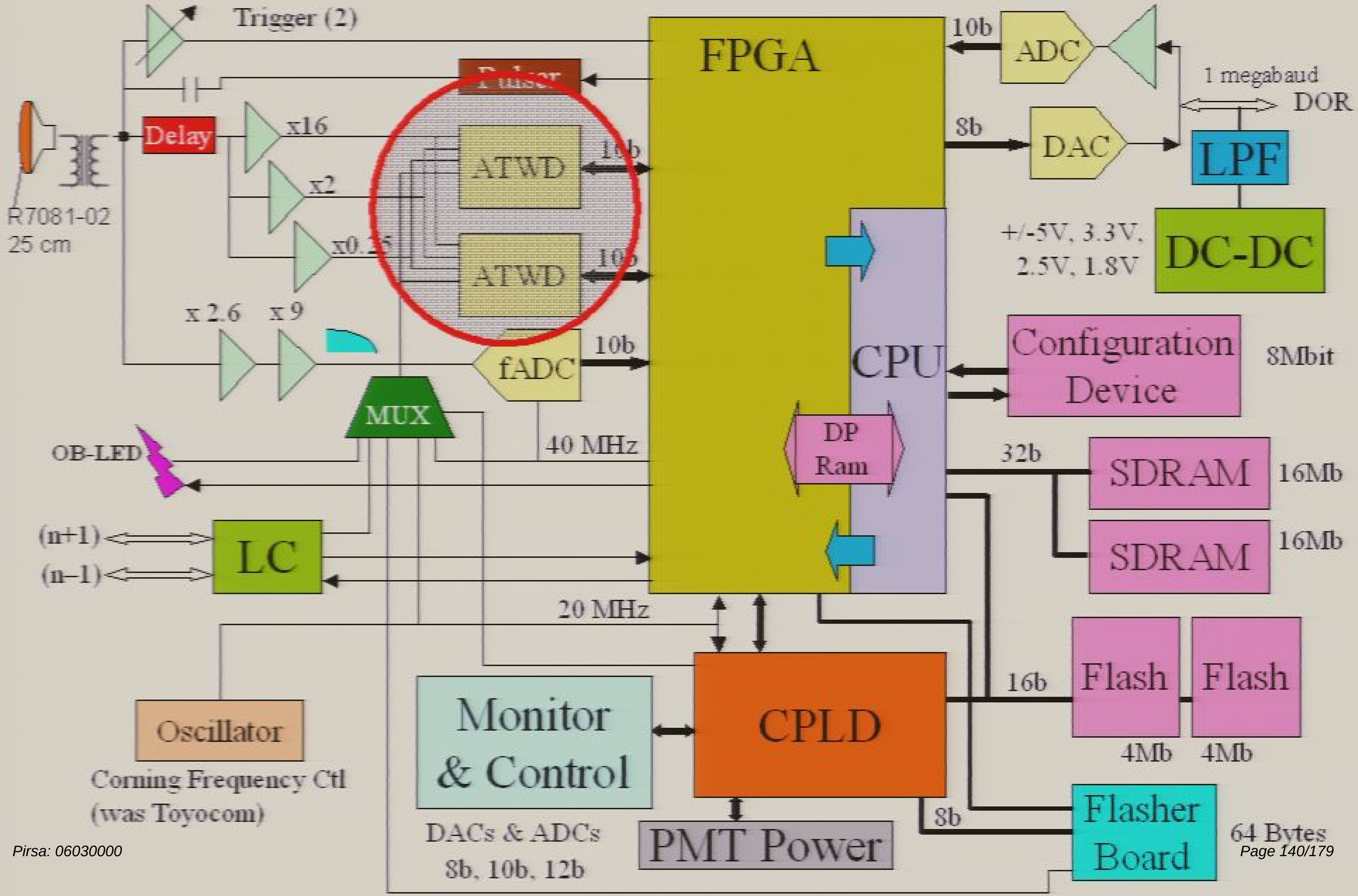
HV board

main
board

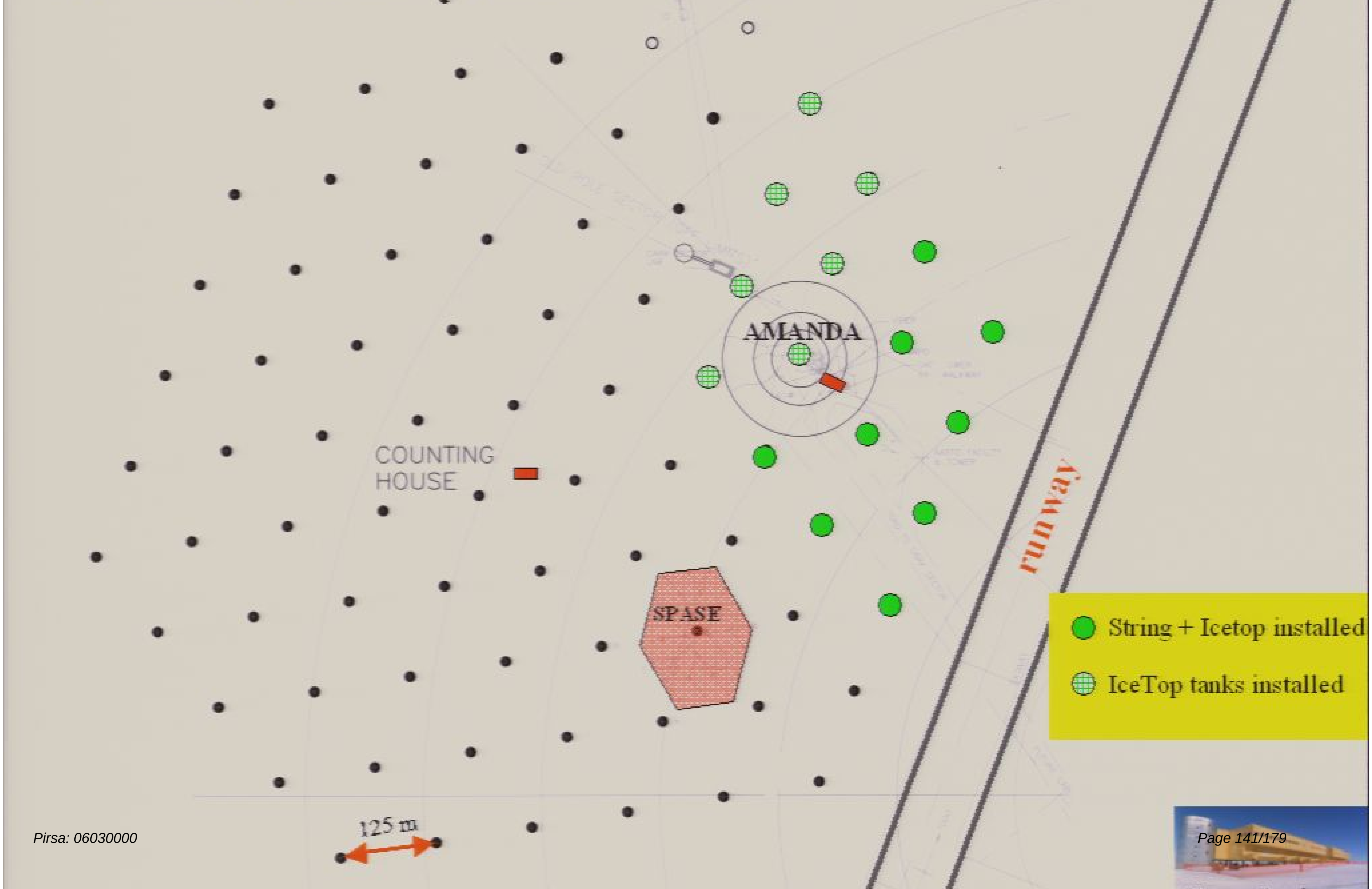
DOM MB Block diagram



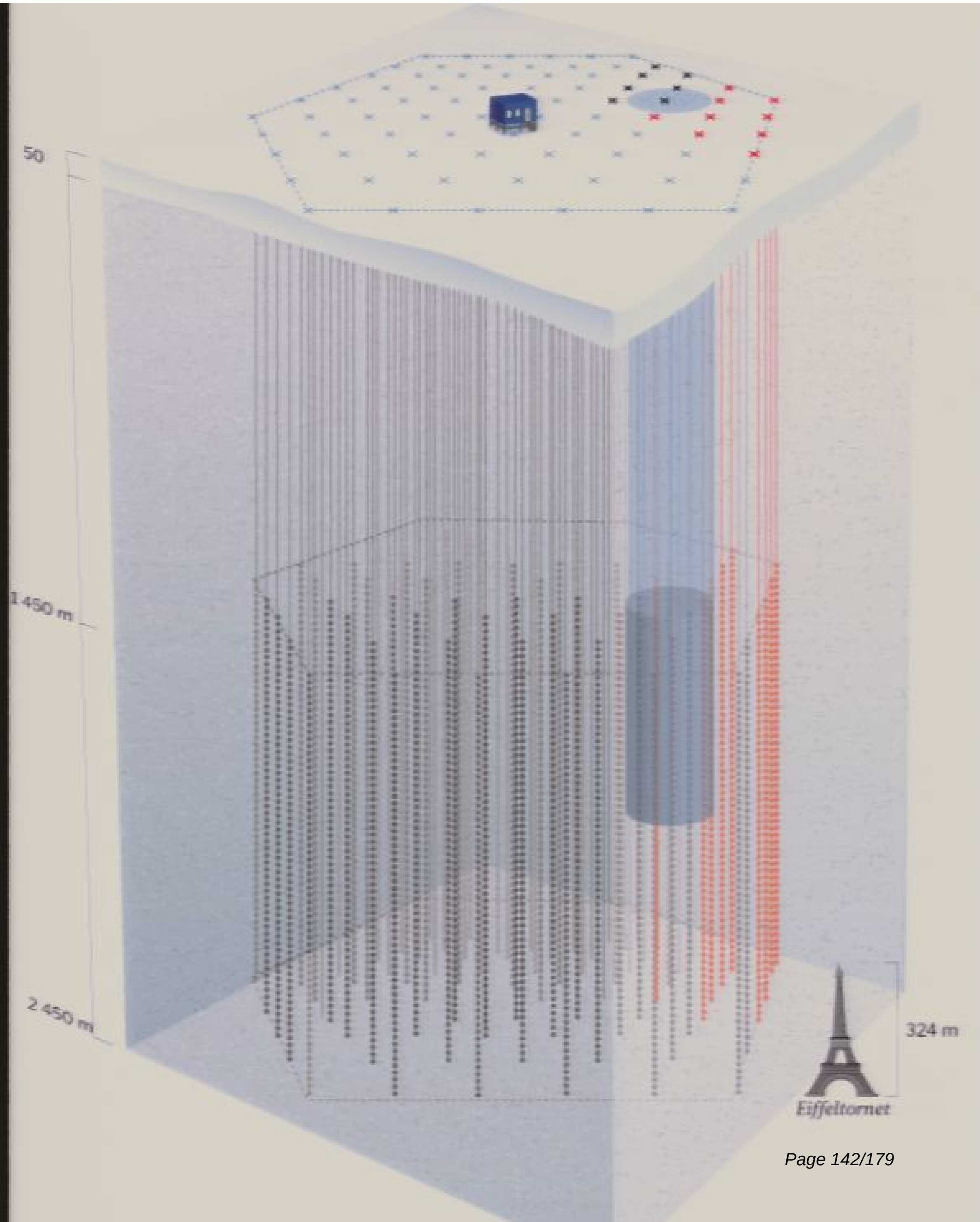
DOM MB Block diagram

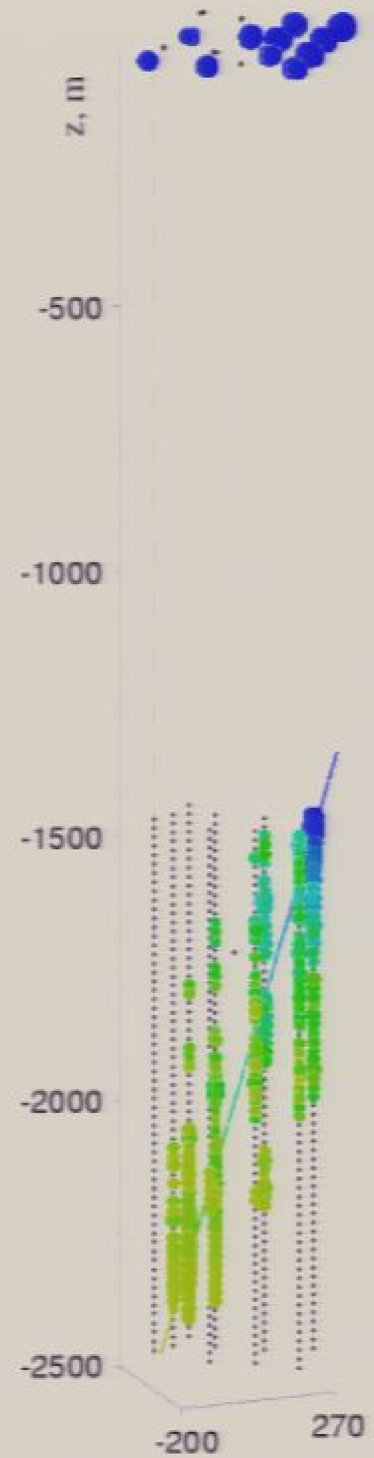


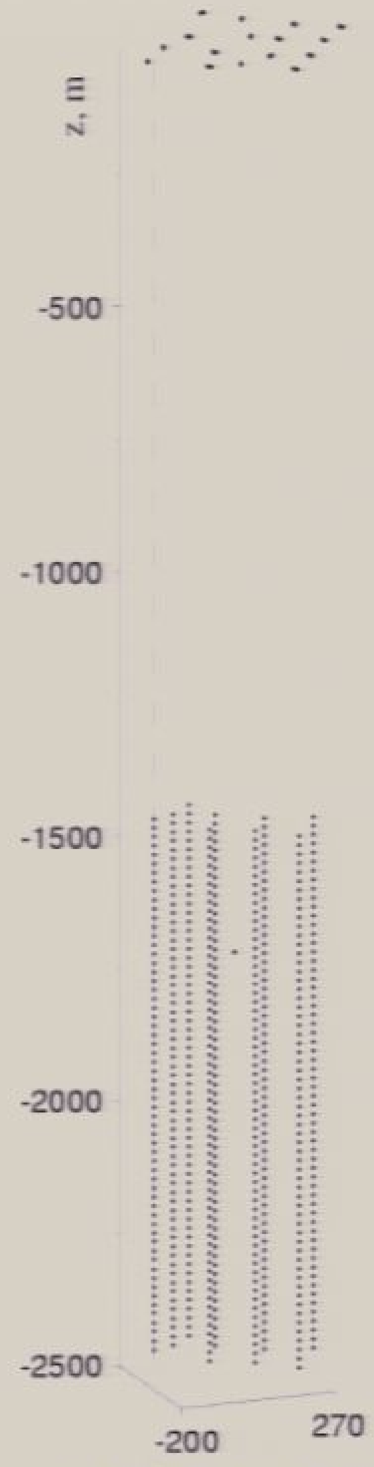
IceCube February 2006

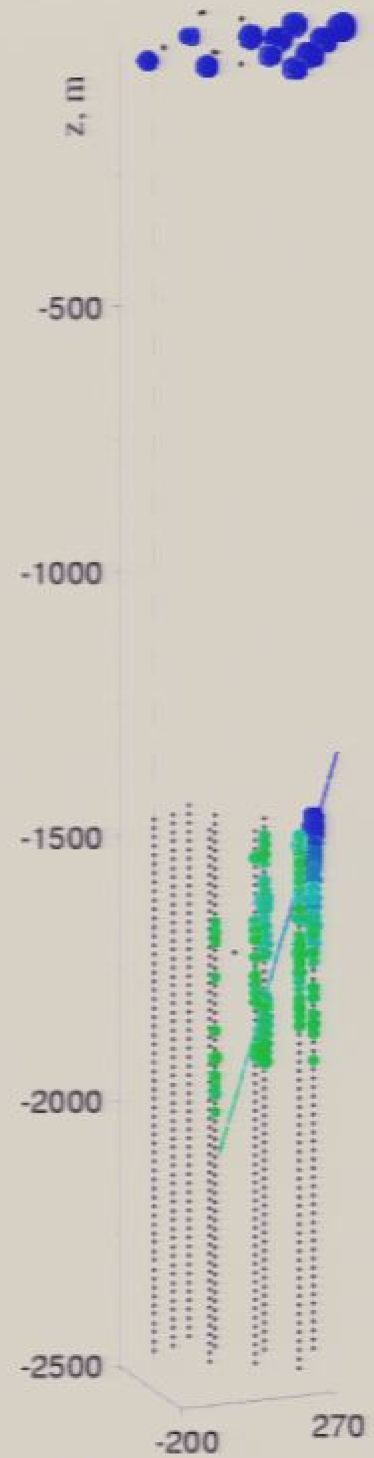


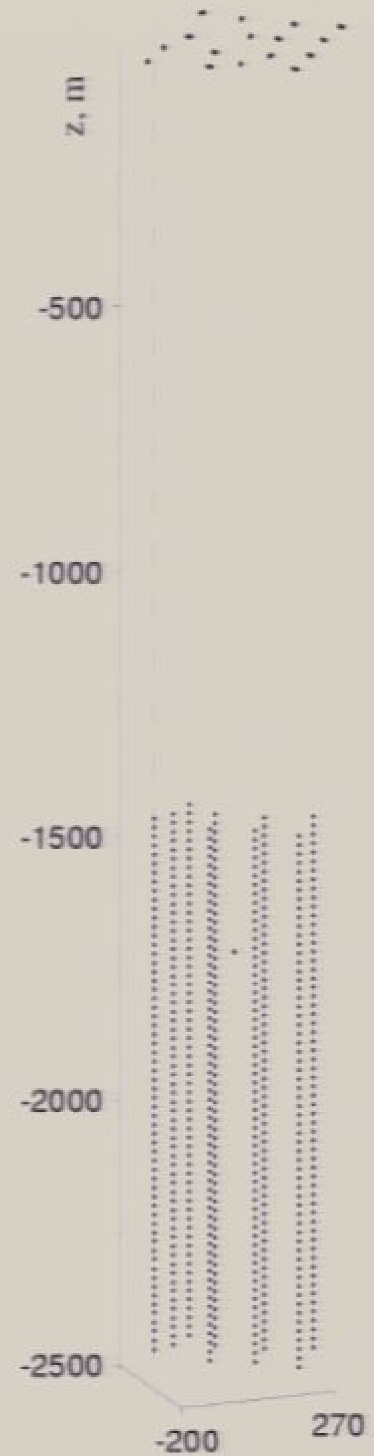
IceCube February 2006

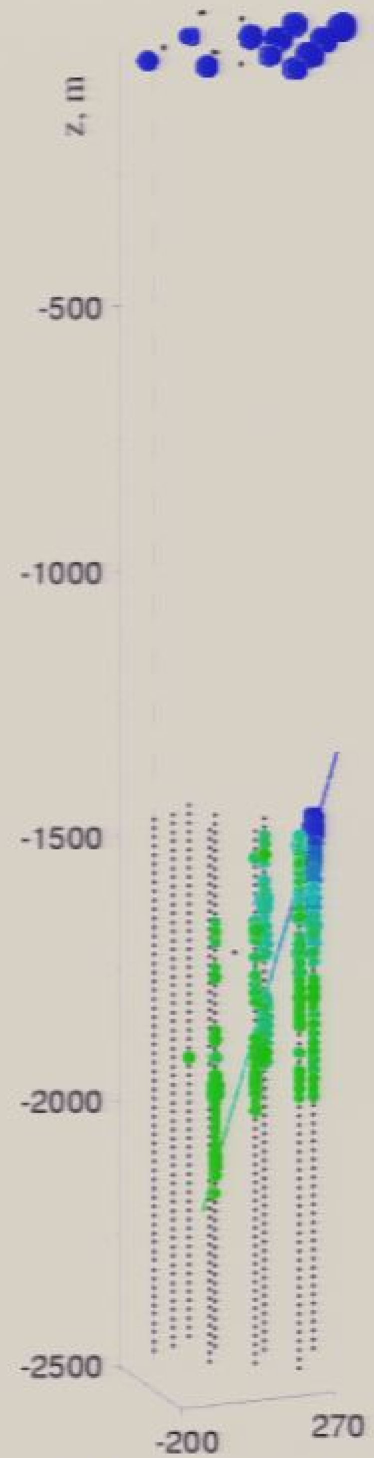


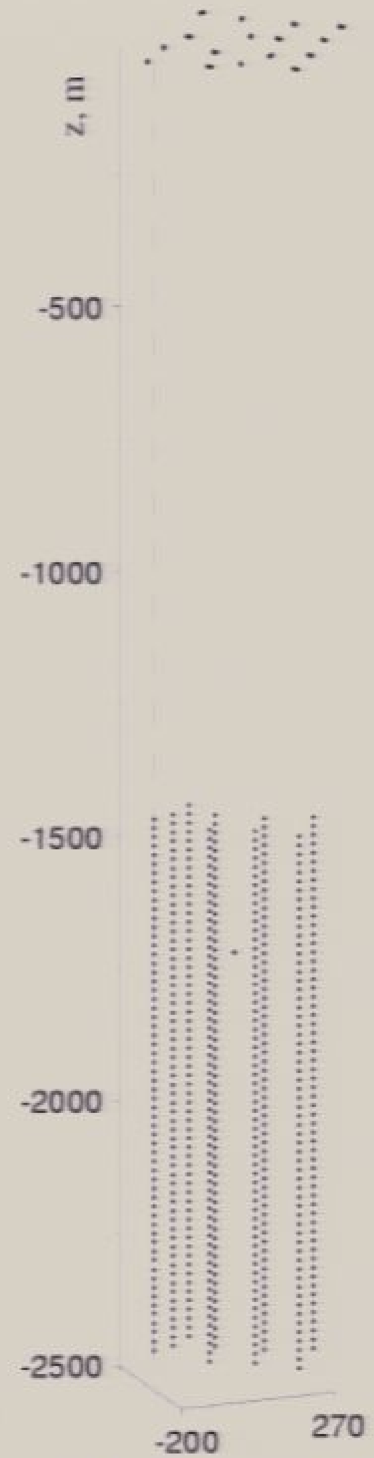

z, m
-500
-1000
-1500
-2000
-2500
-200
270


z, m
-500
-1000
-1500
-2000
-2500
-200
270

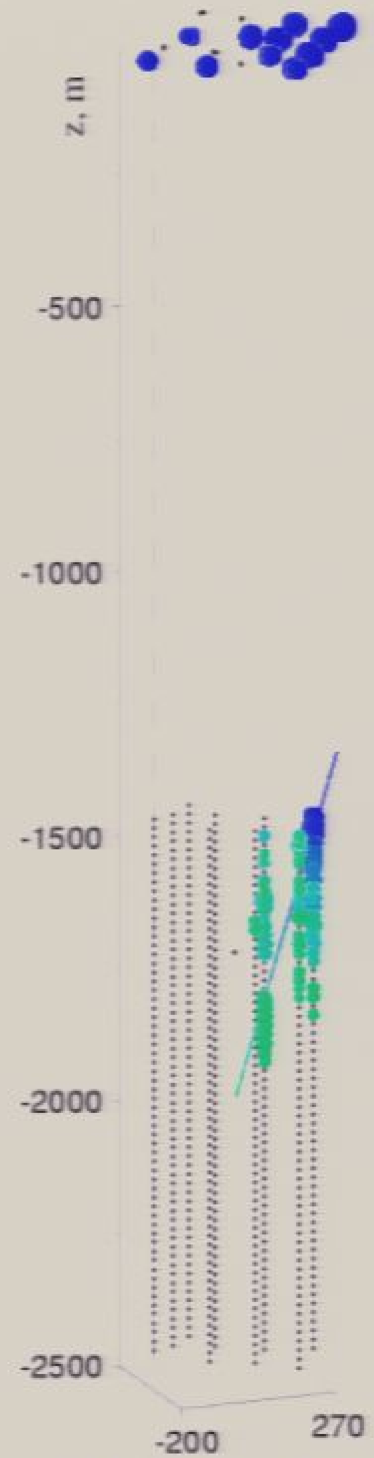

z, m
-500
-1000
-1500
-2000
-2500
-200
270


z, m
-500
-1000
-1500
-2000
-2500
-200
270

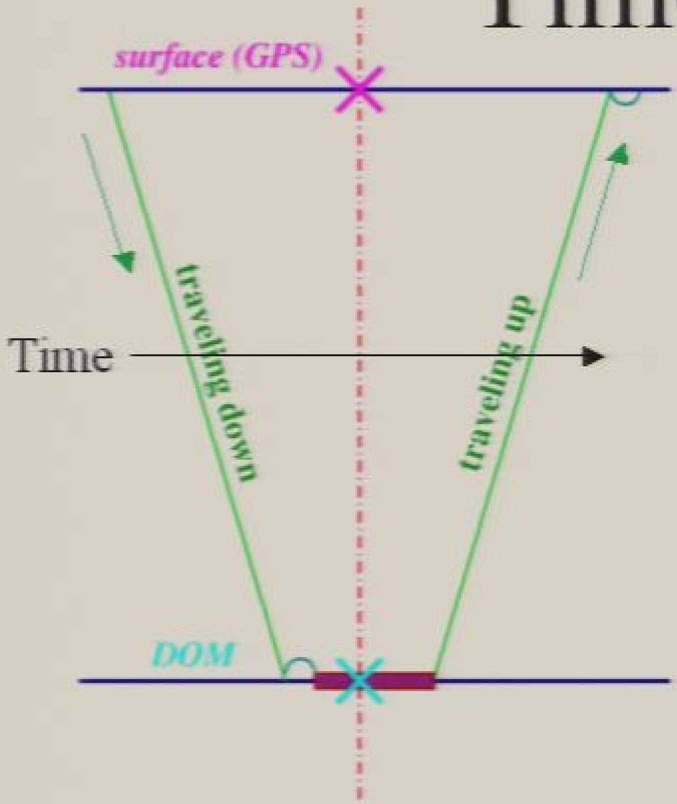

z, m
-500
-1000
-1500
-2000
-2500
-200
270



z, m
-500
-1000
-1500
-2000
-2500
-200
270

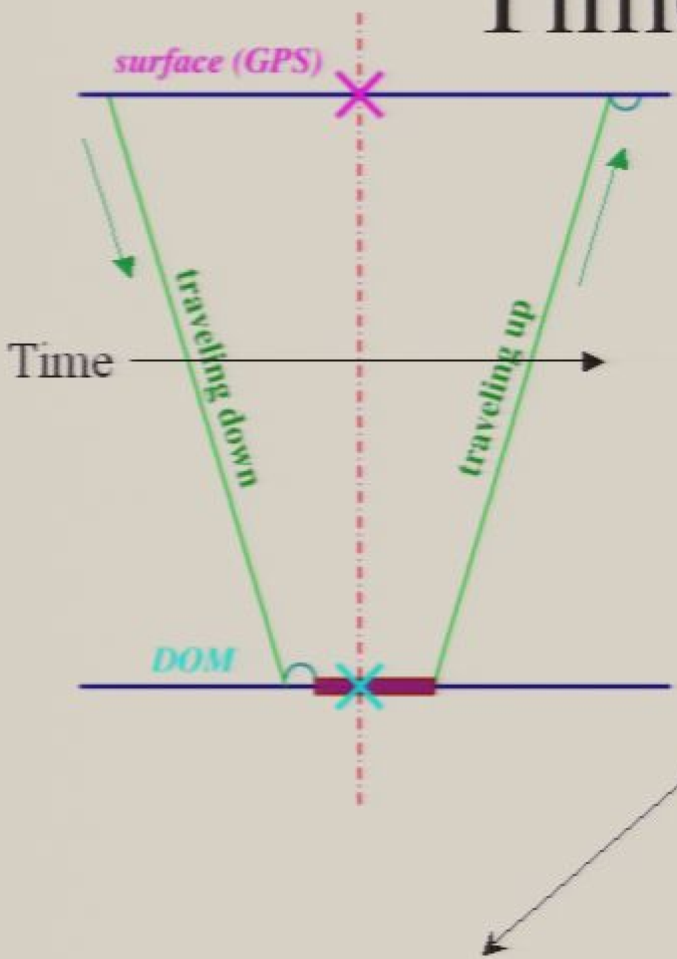

z, m
-500
-1000
-1500
-2000
-2500
-200
270

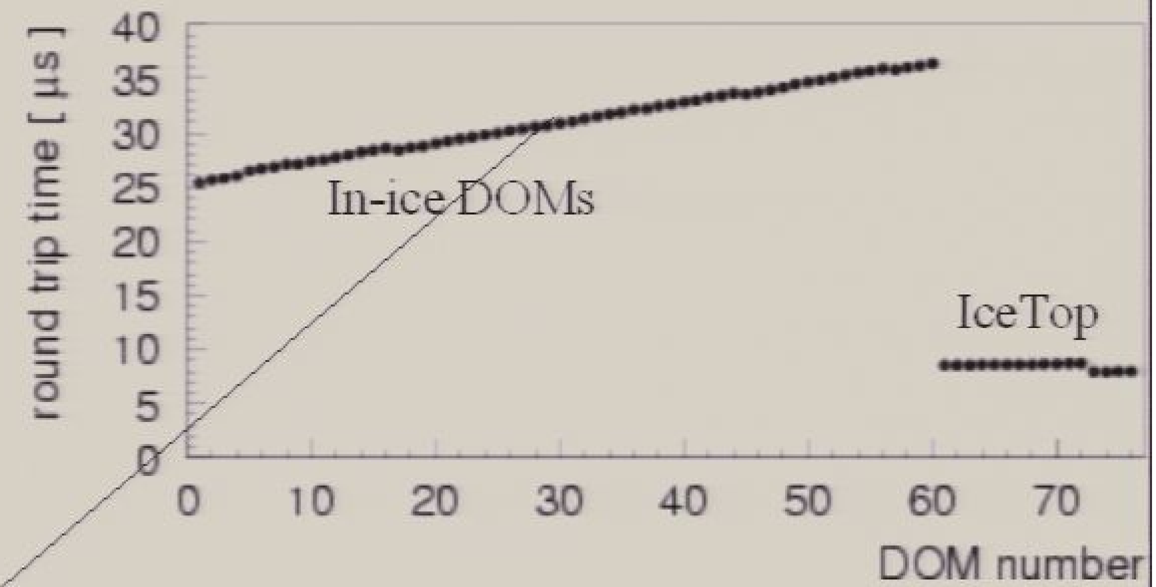
Time Calibration



Time Calibration

automatic, every few seconds





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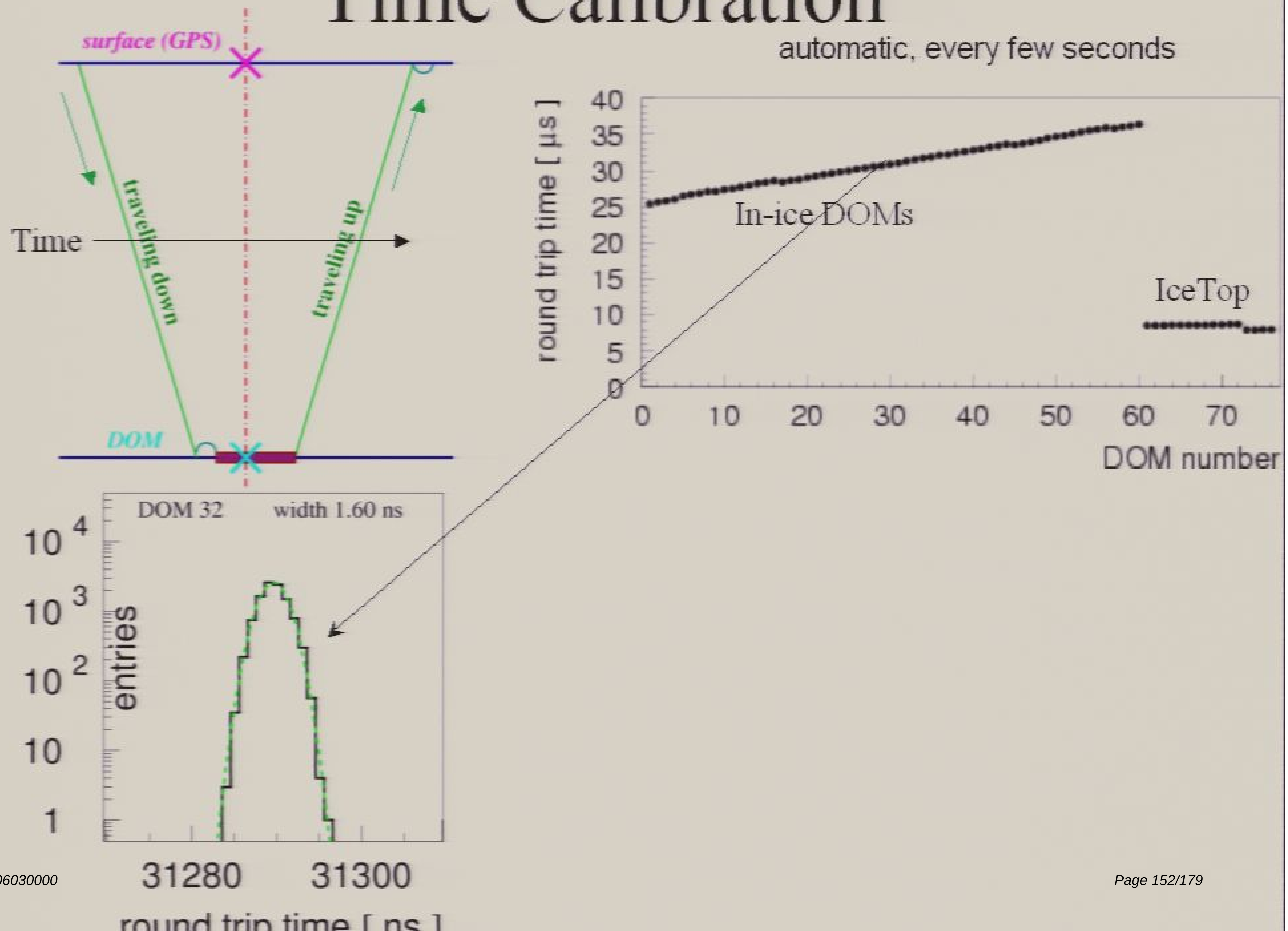
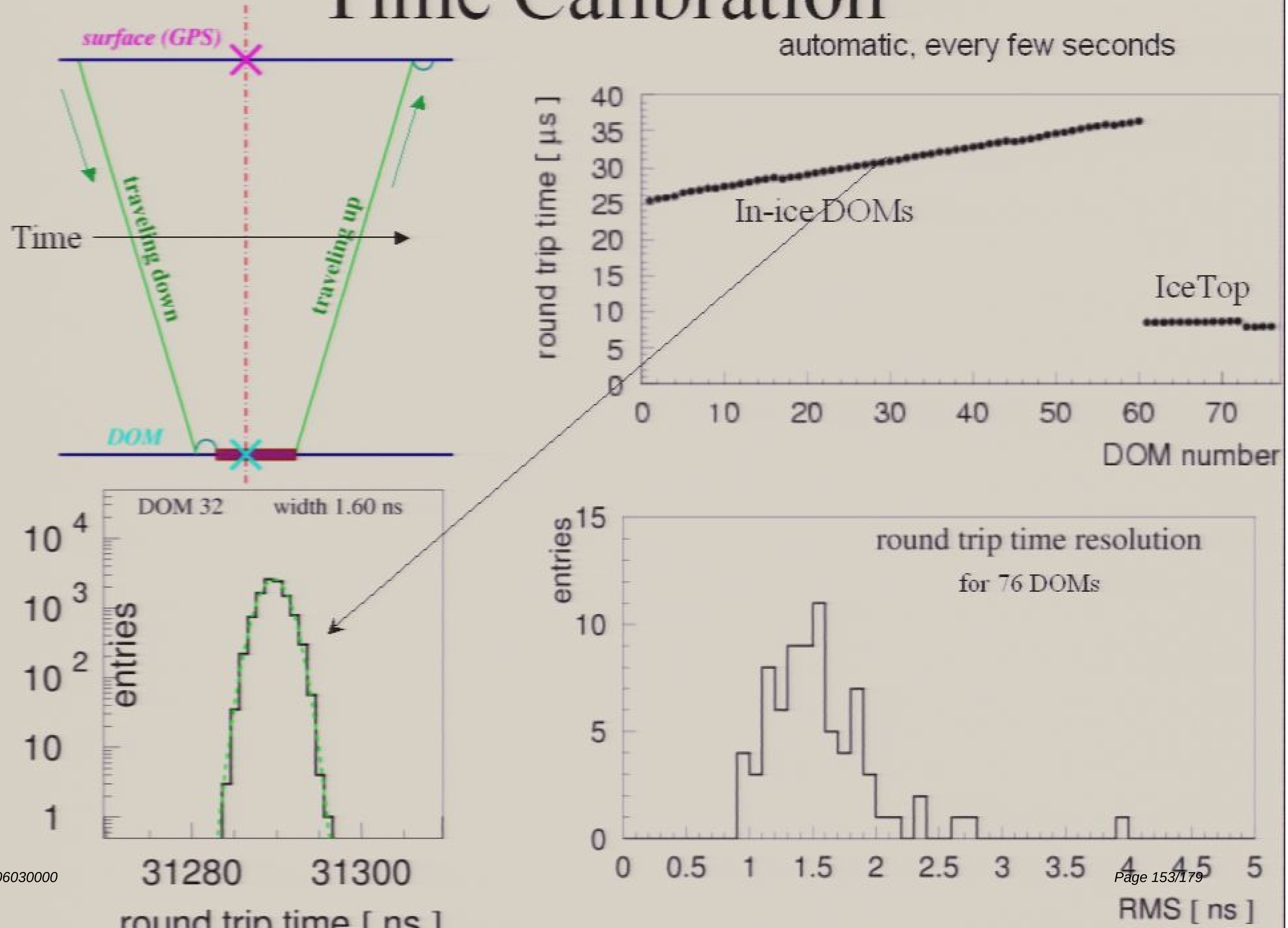


Time Calibration

automatic, every few seconds

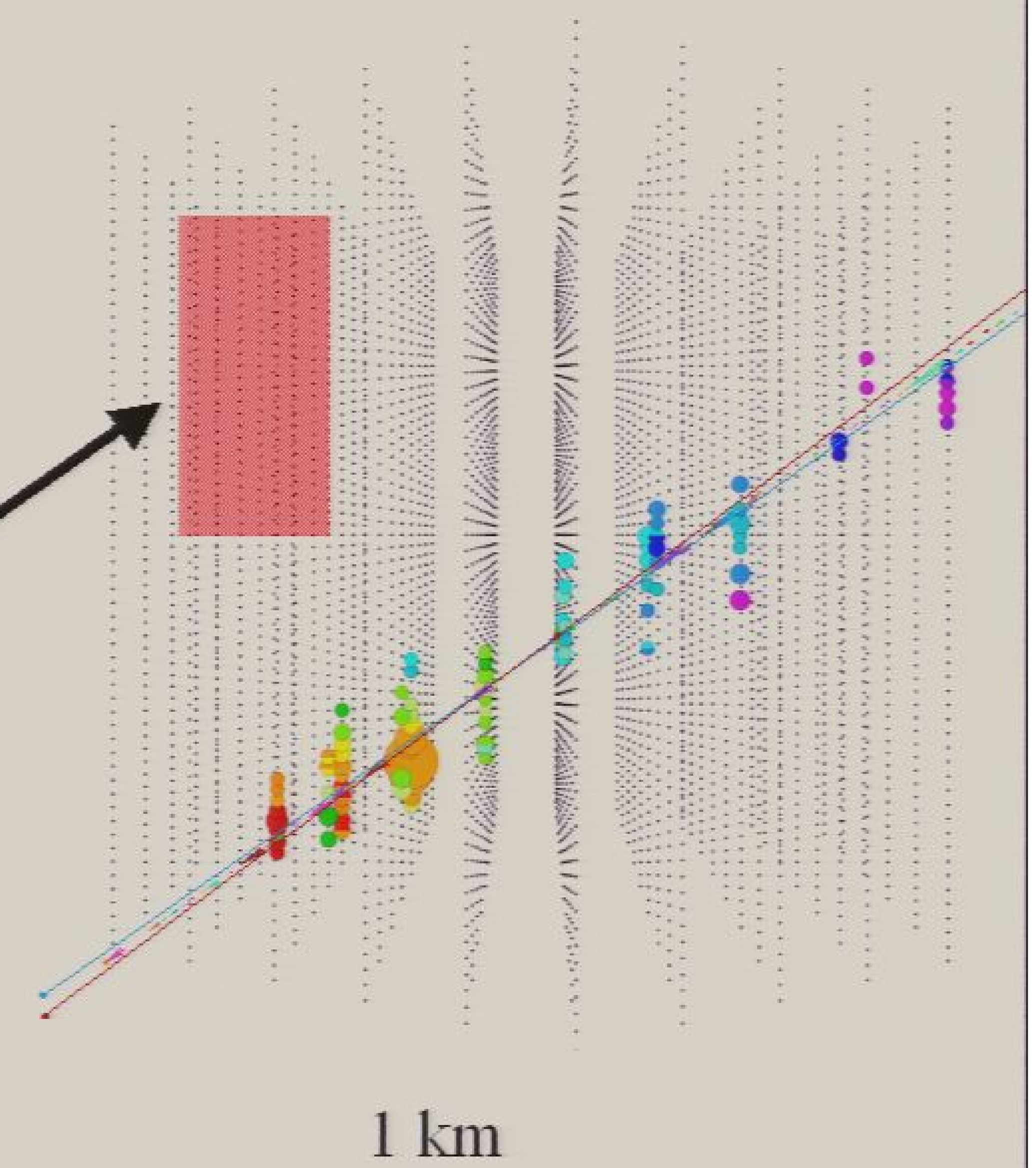


particle physics

μ-event in IceCube

300 atmospheric neutrinos per day

AMANDA II

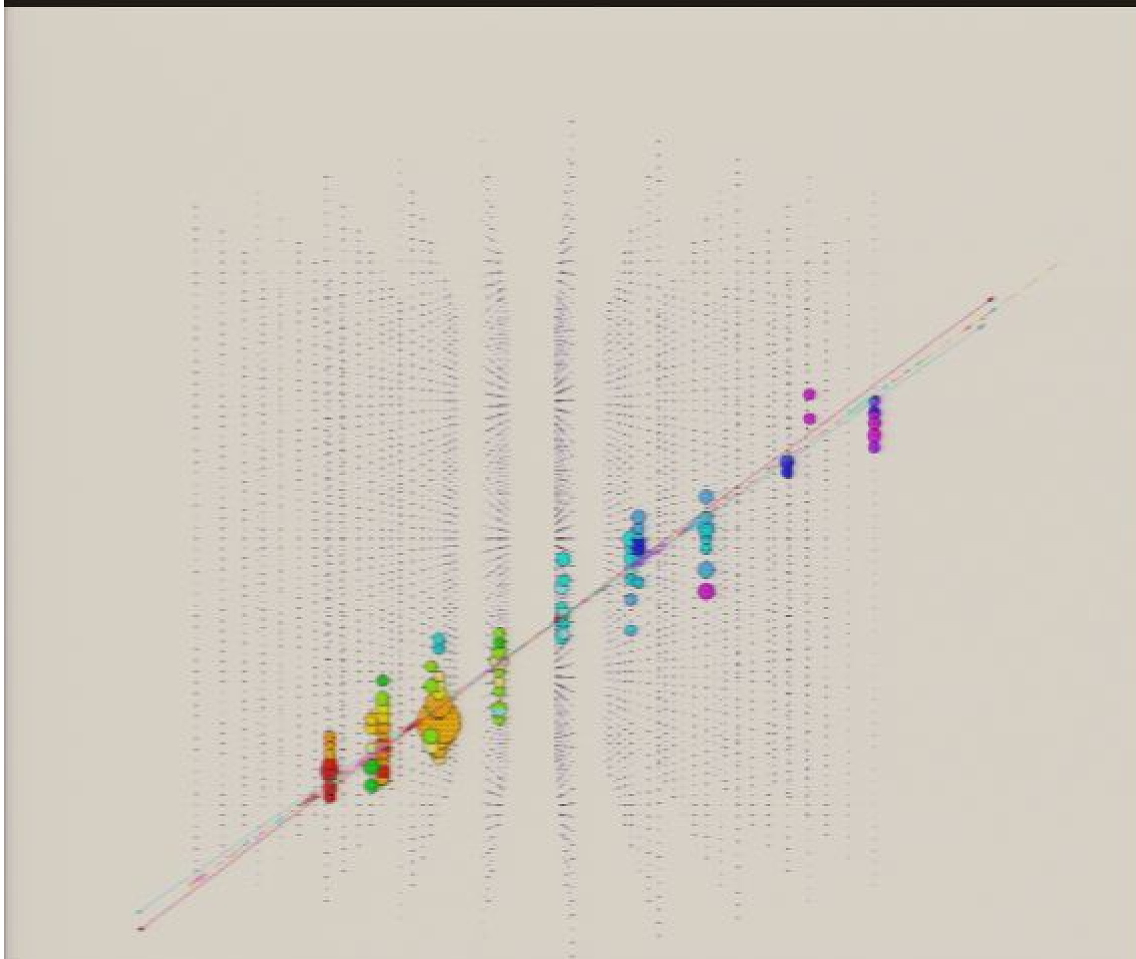


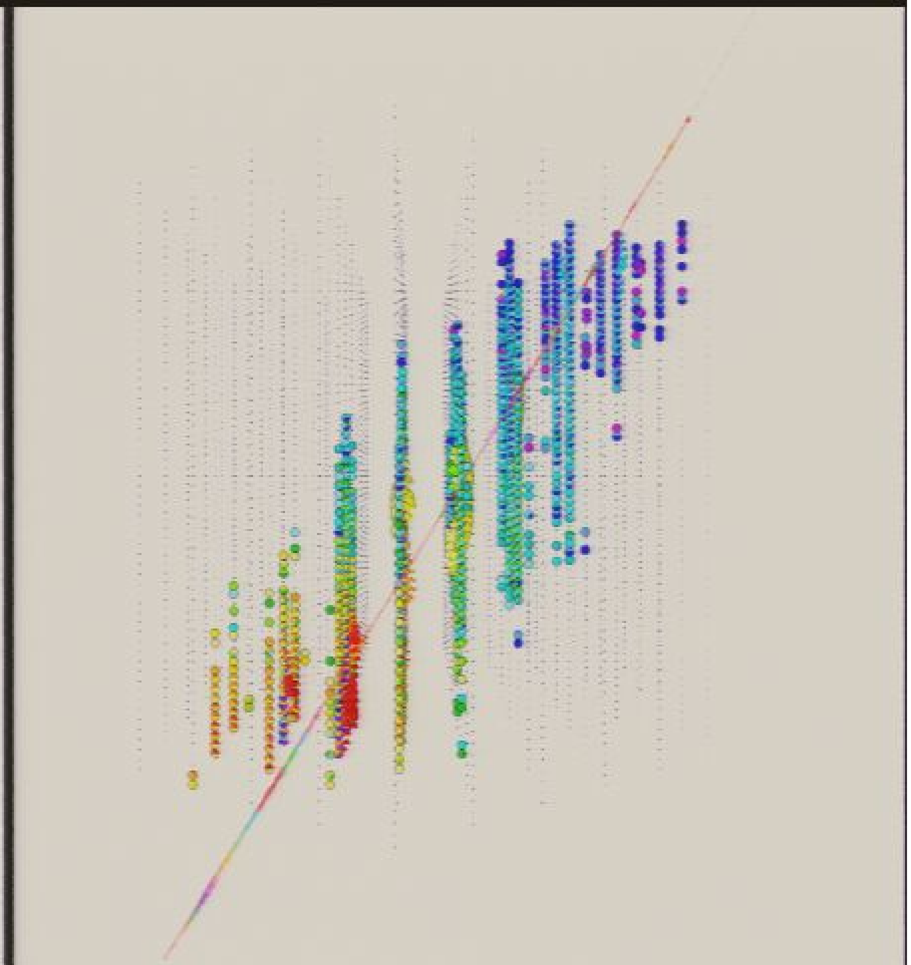
IceCube:

Larger Telescope

Superior Detector

ν_μ detection in IceCube





E = 6 TeV

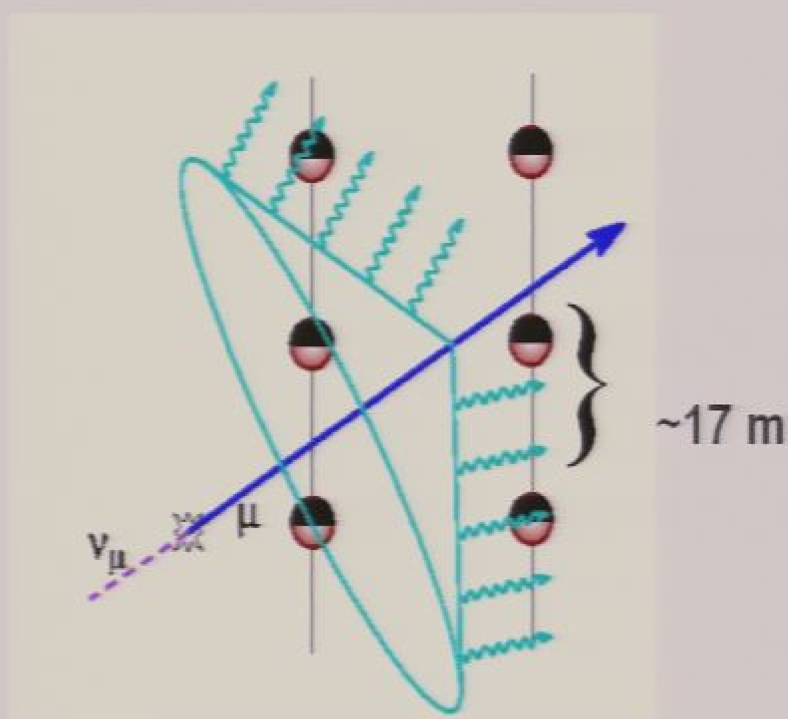
E = 6400 TeV

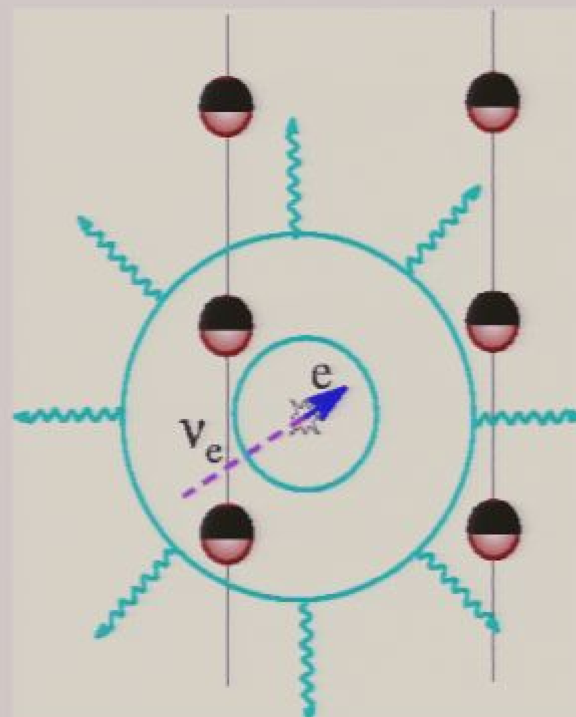
Neutrino Detection

event reconstruction by Cherenkov light timing

~ km-long muon tracks from ν_μ

~10m-long cascades, ν_e ν_τ neutral current

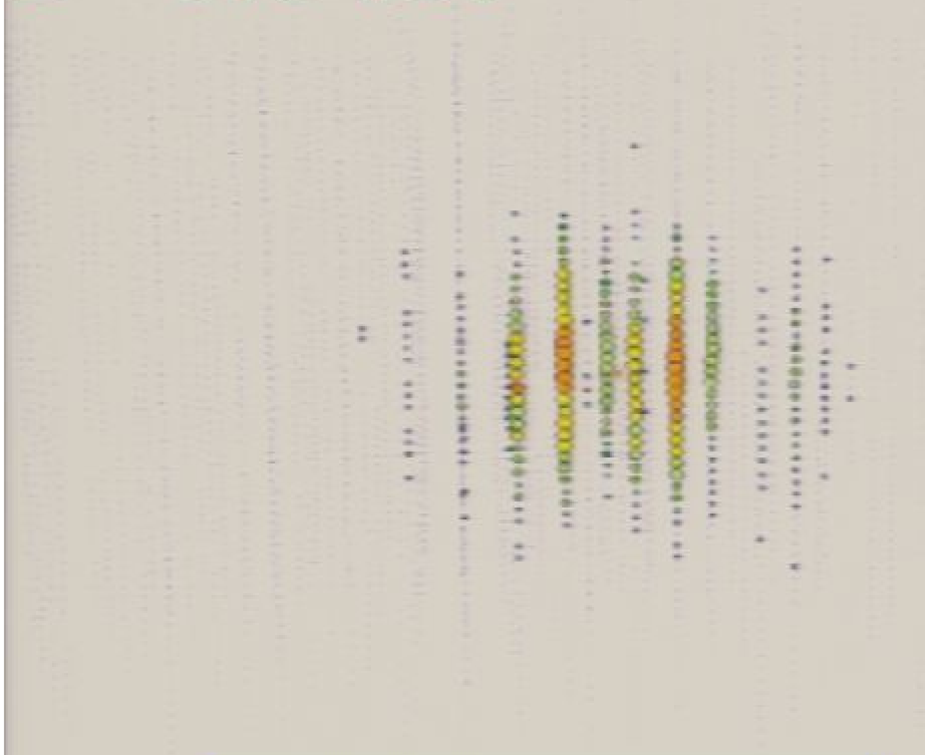




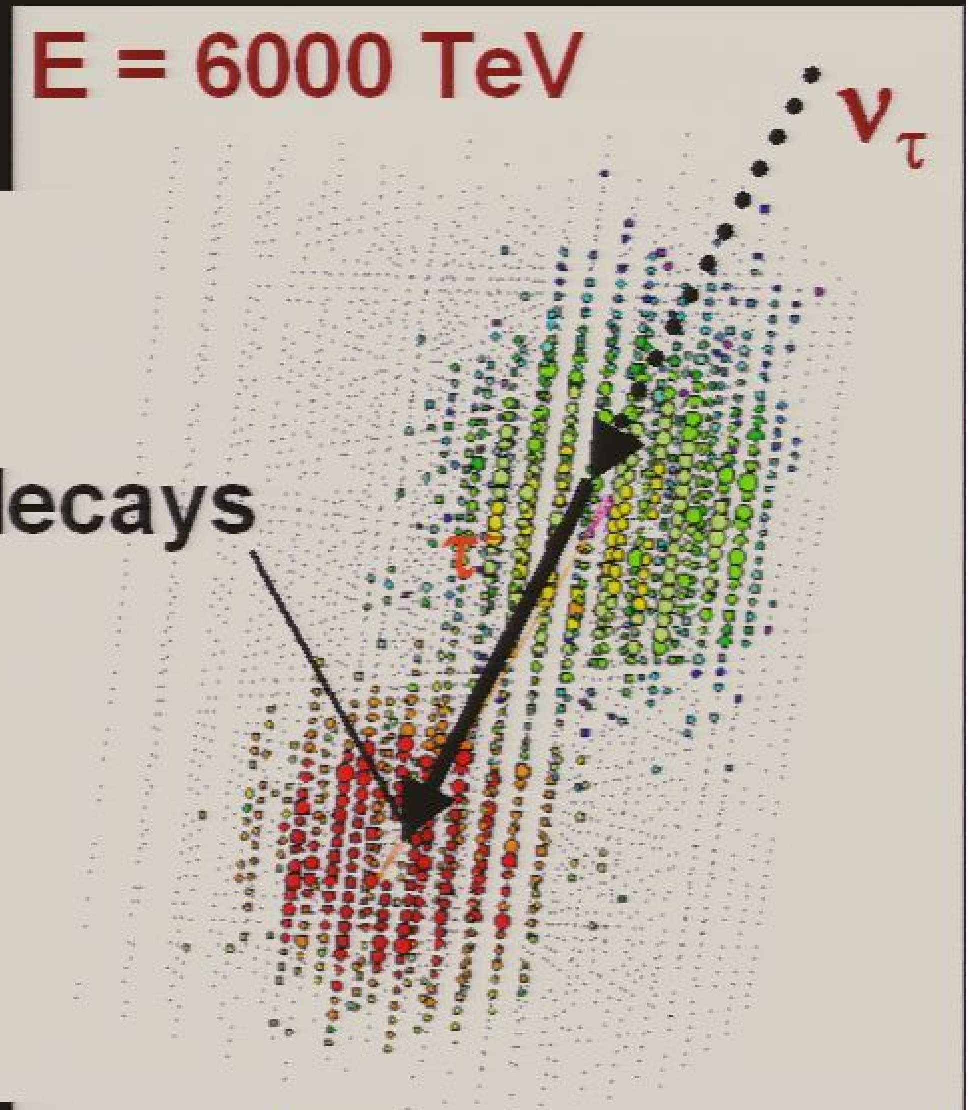
Longer absorption length => larger effective volume

ν_e and ν_τ detection in IceCube

E = 375 TeV



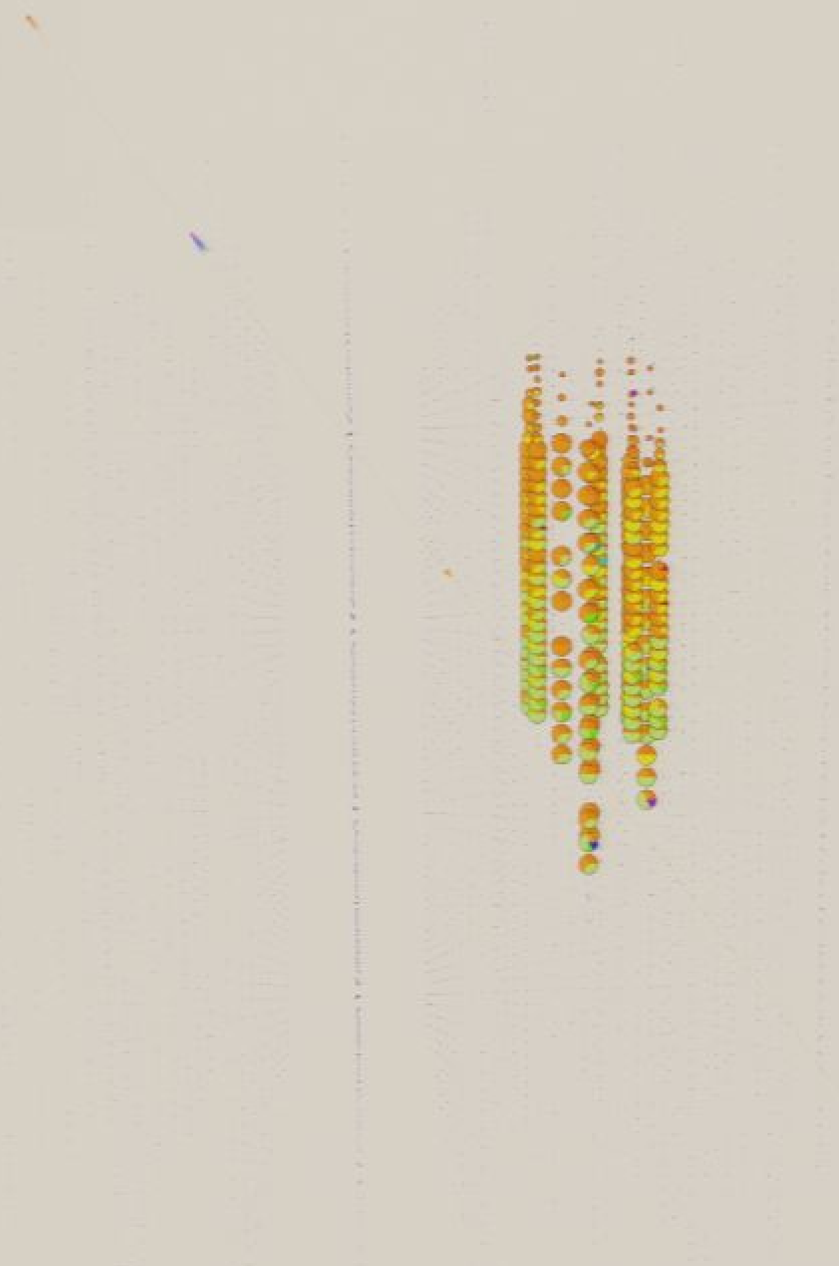
$$\nu_e + N \rightarrow e^- + X$$



$$\nu_\tau + N \rightarrow \tau^- + X$$

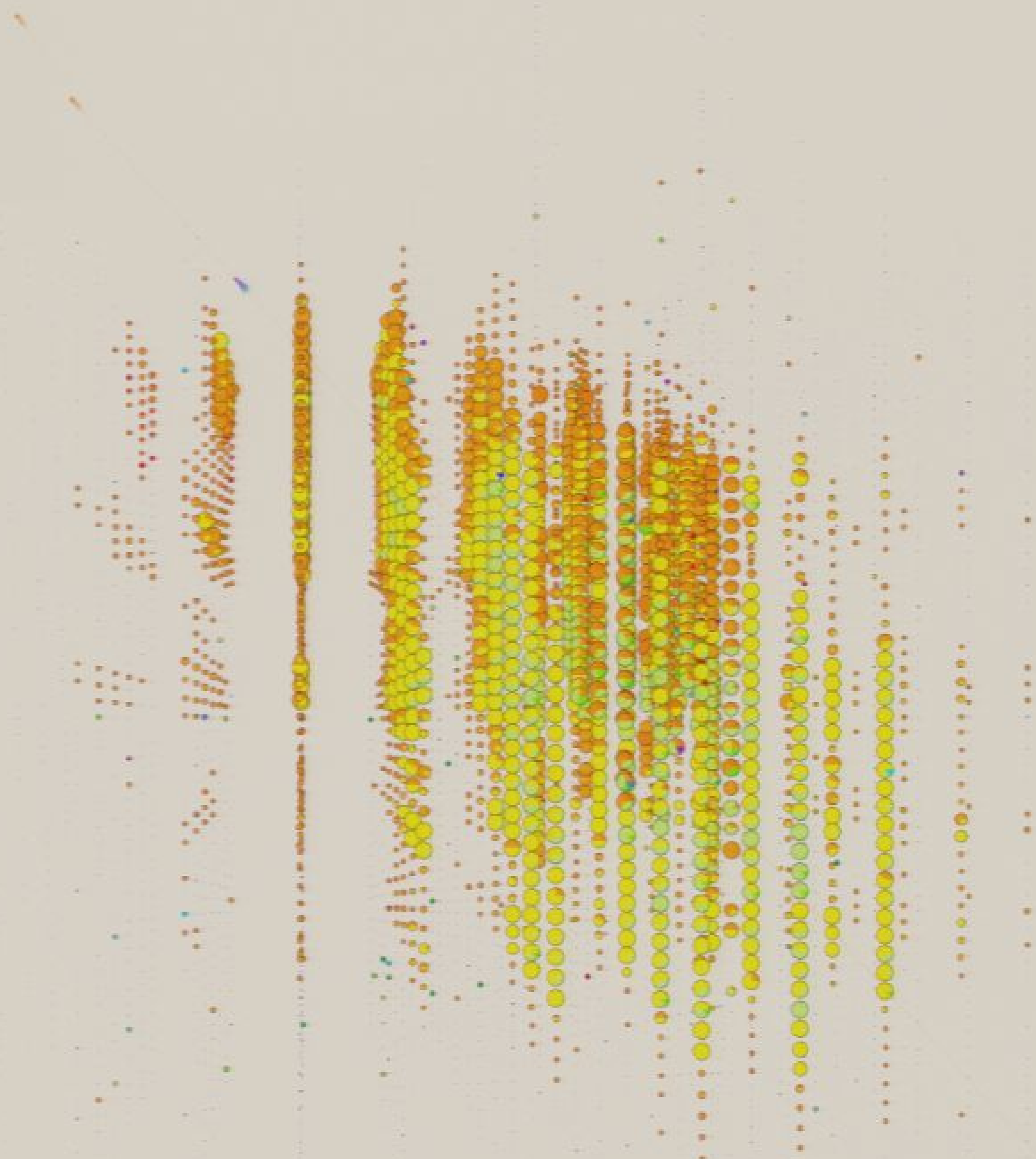
GZK event

10 EeV



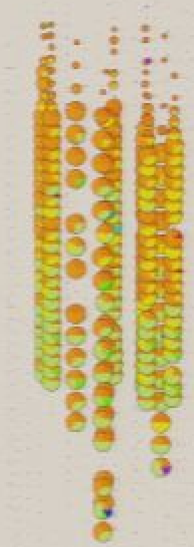
GZK event

10 EeV



GZK event

10 EeV



AMANDA performance

- ν's per day :

  3.5 → 10 per day

- total statistics

  10,000 in 00-05

- energy

  0.1 ~ 1,000 TeV

IceCube

- ν's per day :

  > 100 per day

- total statistics

  > 10^6 over 10yr

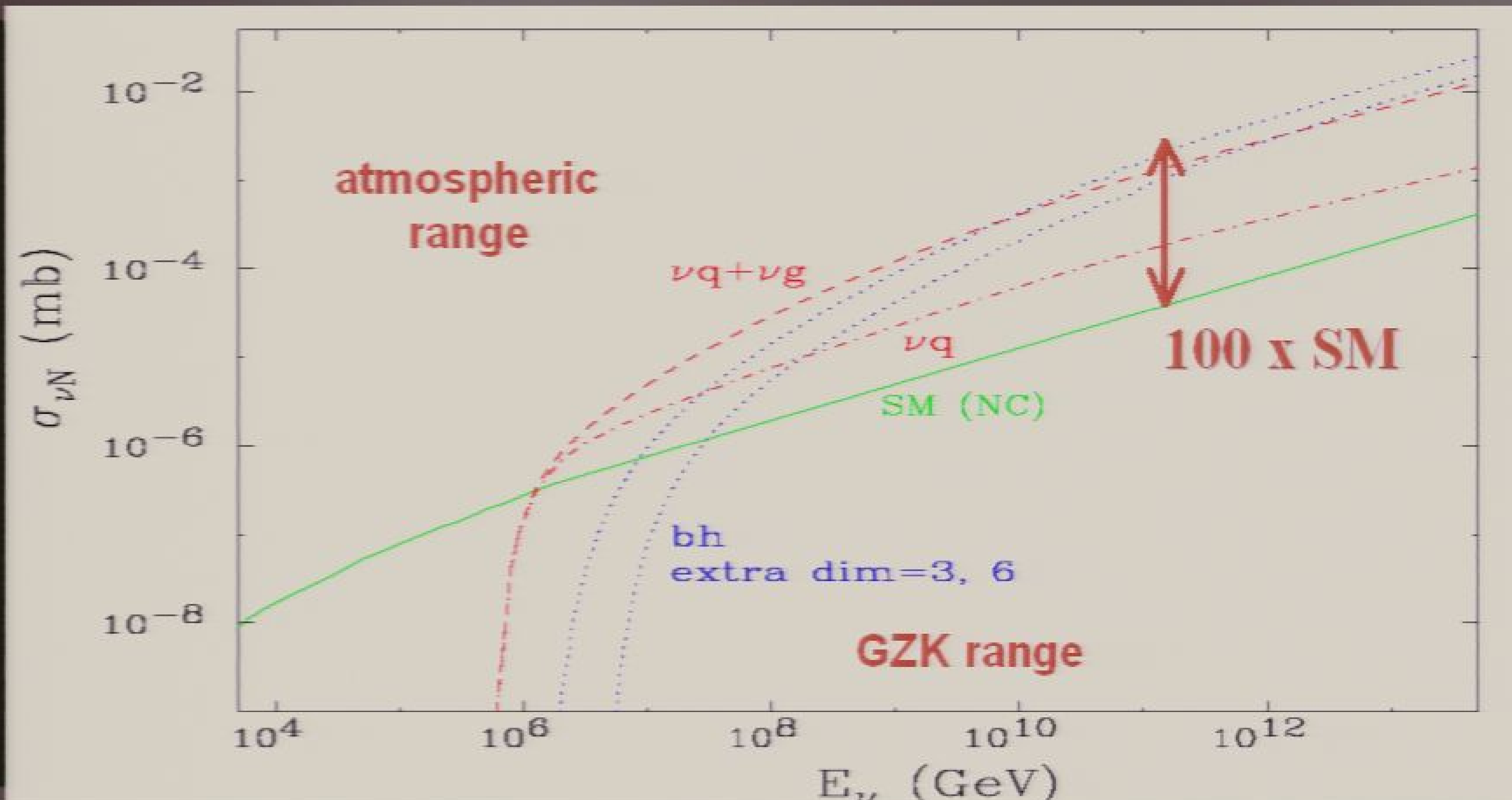
- energy

  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 non-standard model neutrino interactions
- ...

Neutrino Astronomy Explores Higher Dimensions



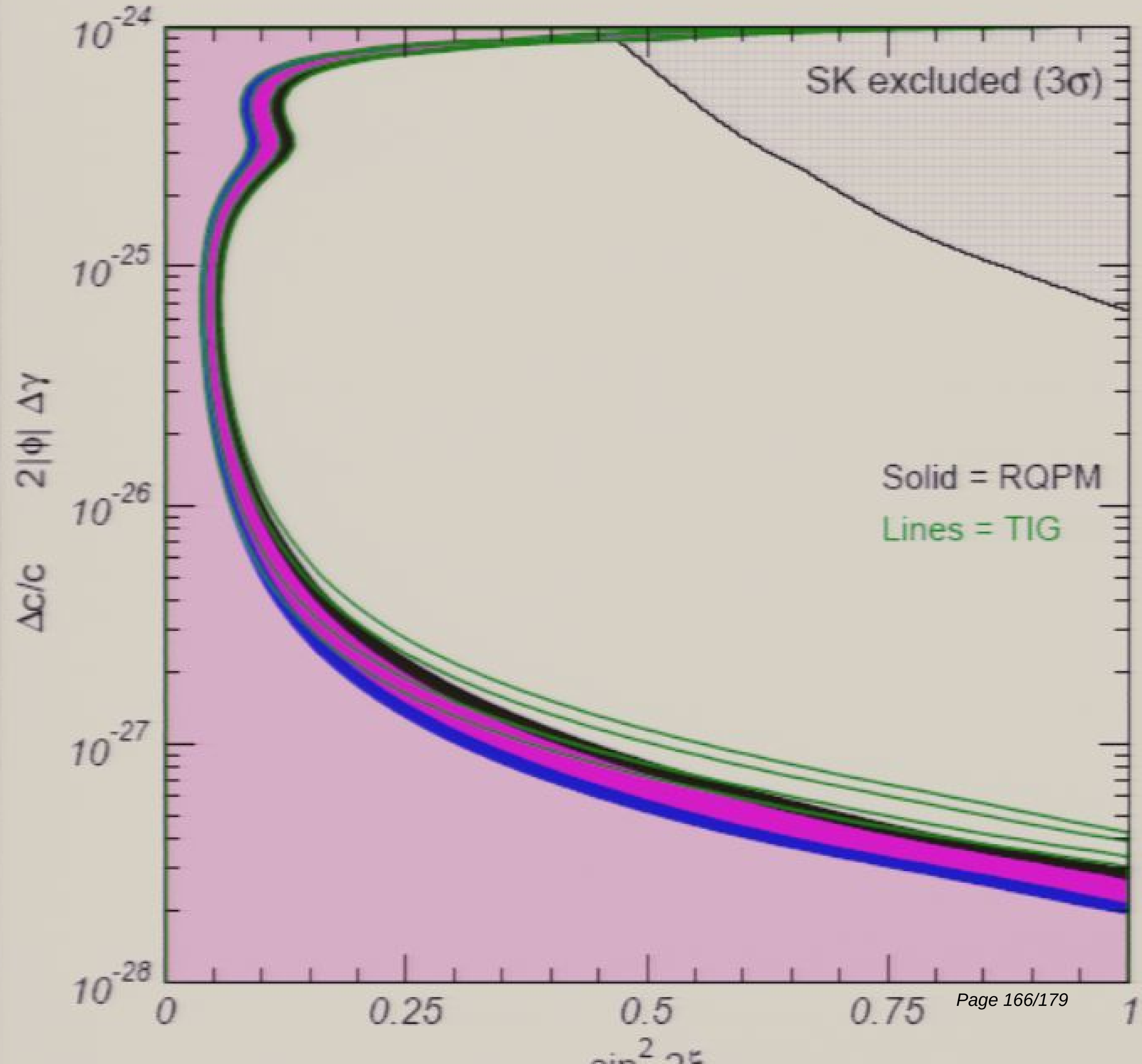
TeV-scale gravity increases PeV ν-cross section

IceCube

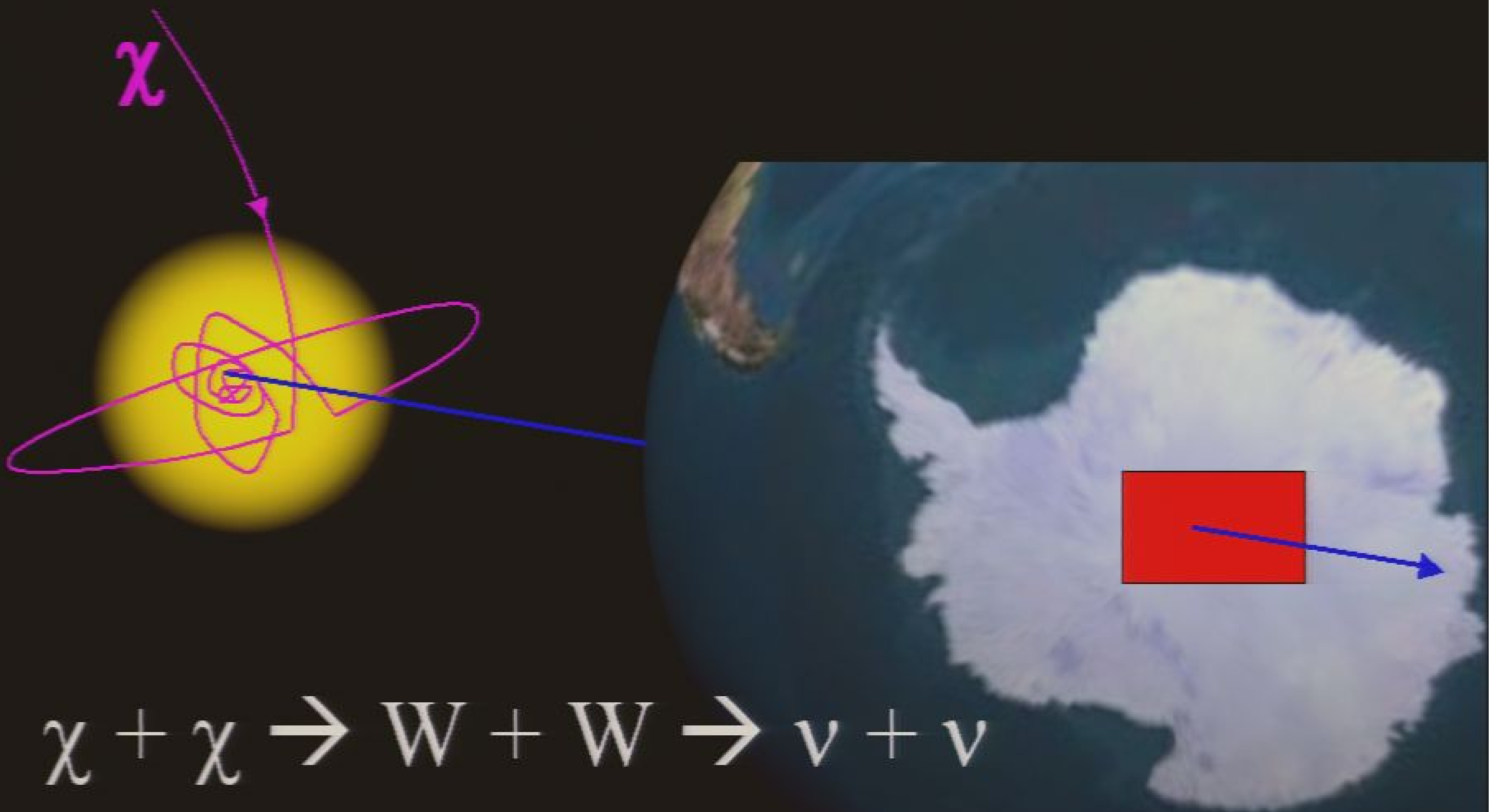
tests
• equivalence principle and
• Lorentz invariance

$\gamma > 10^{17}$

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



WIMP Capture and Annihilation



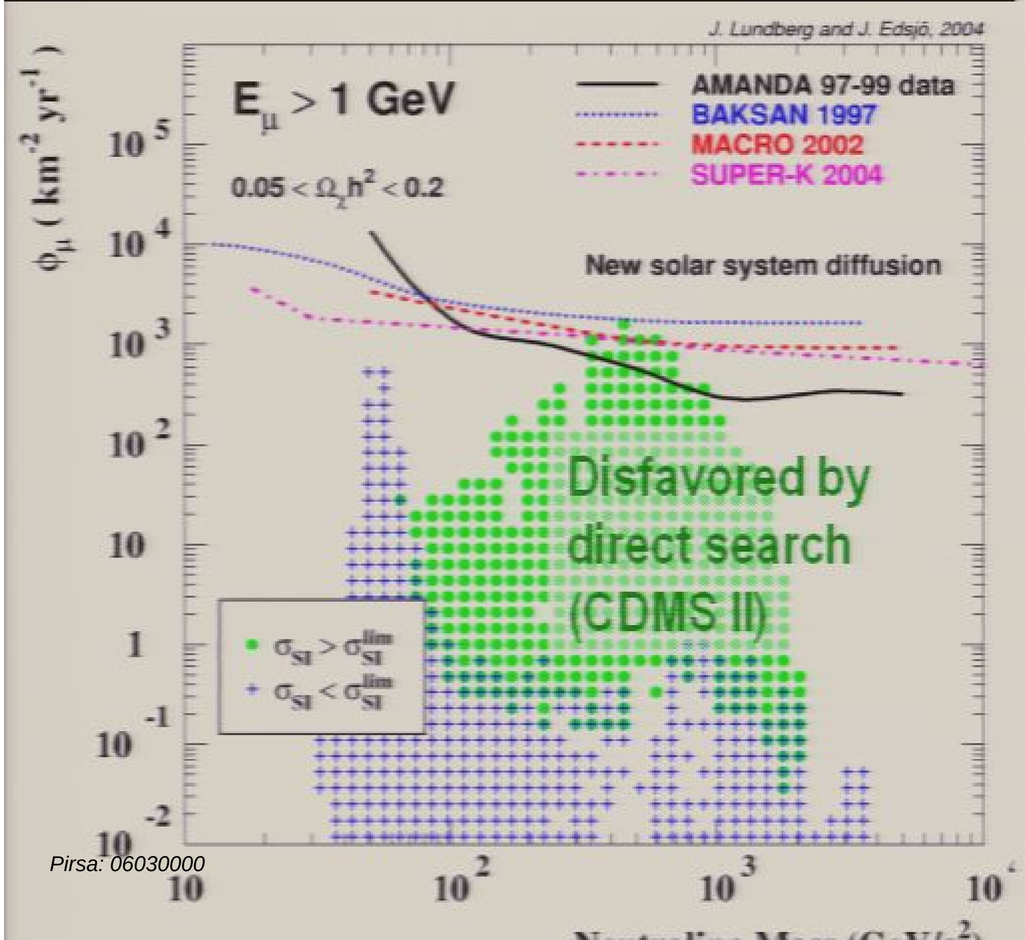
$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$

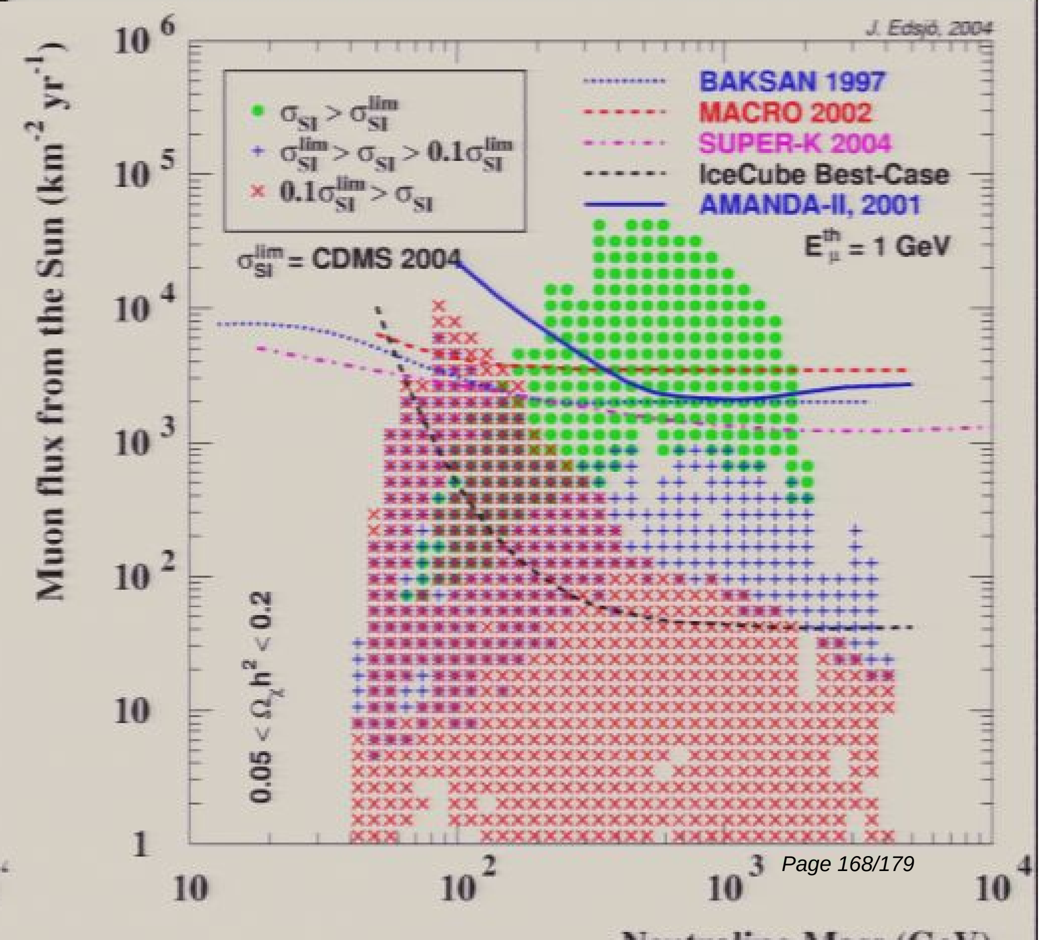
WIMP search

PRELIMINARY

Limits on muon flux from Earth

Limits on muon flux from Sun





WIMP search

PRELIMINARY

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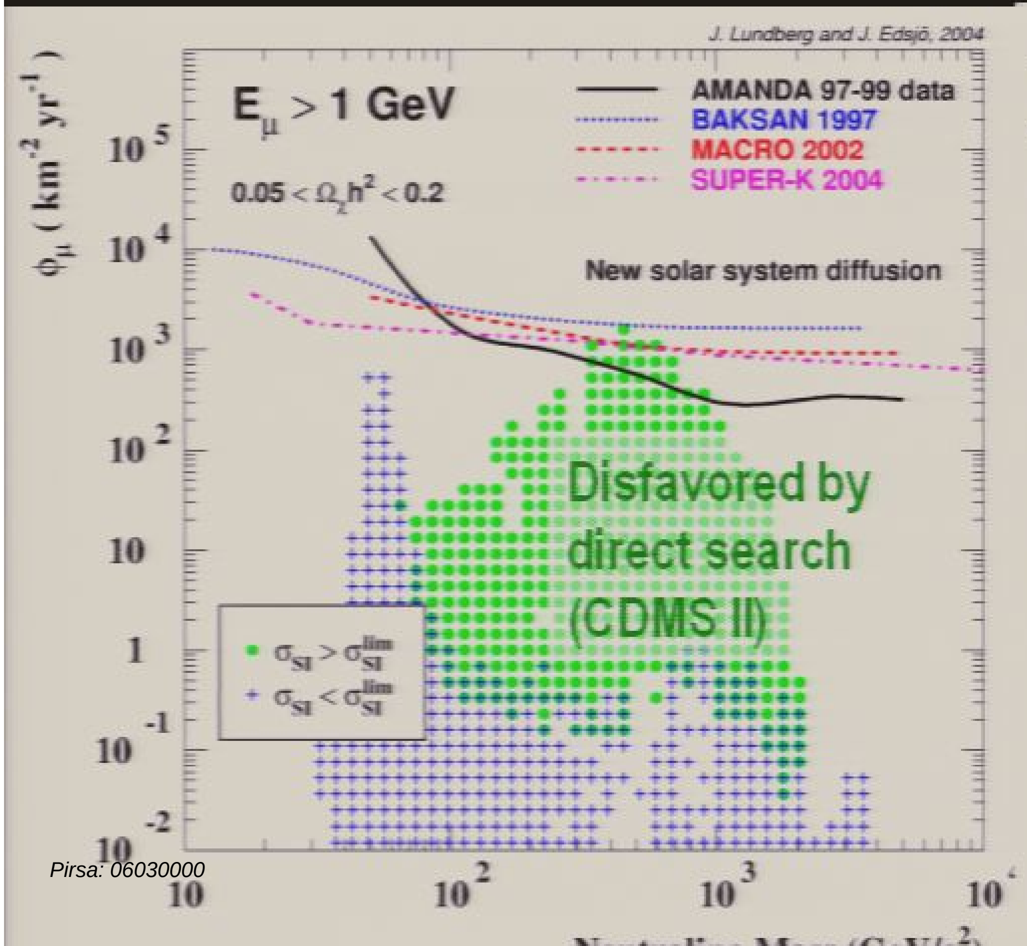
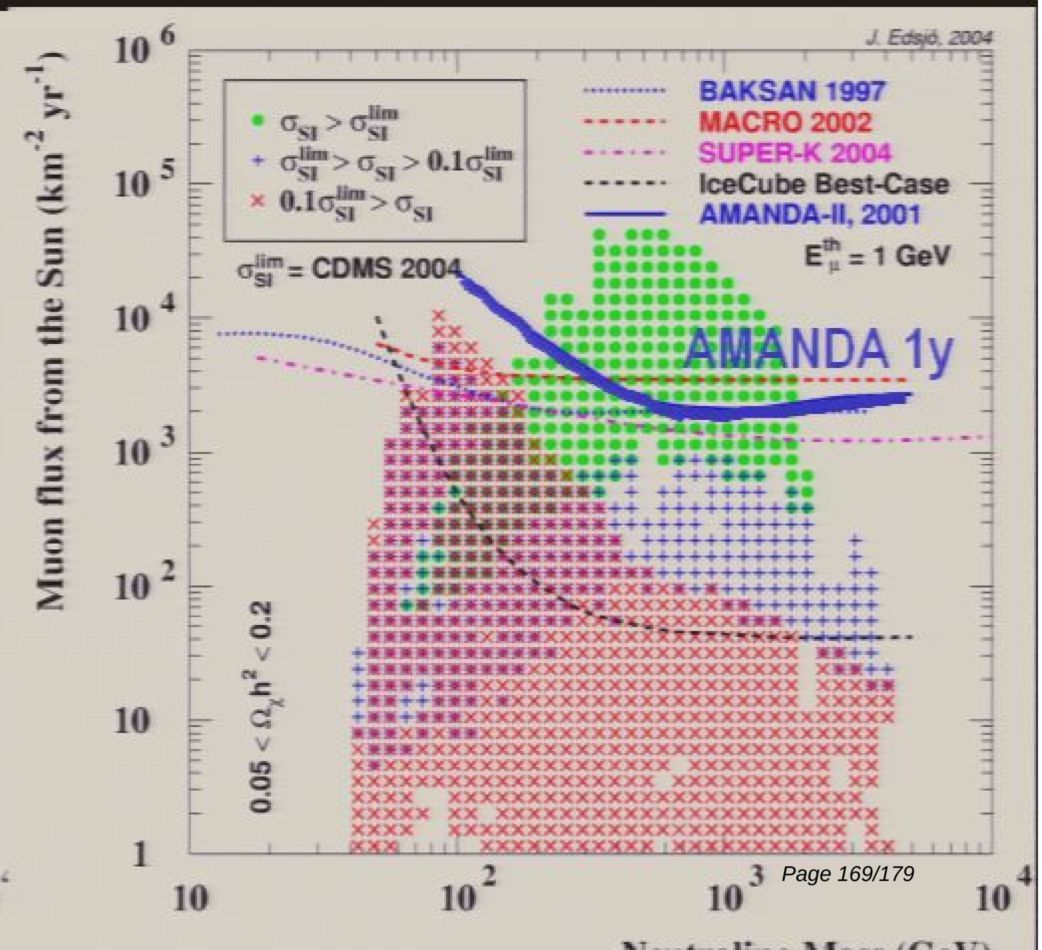


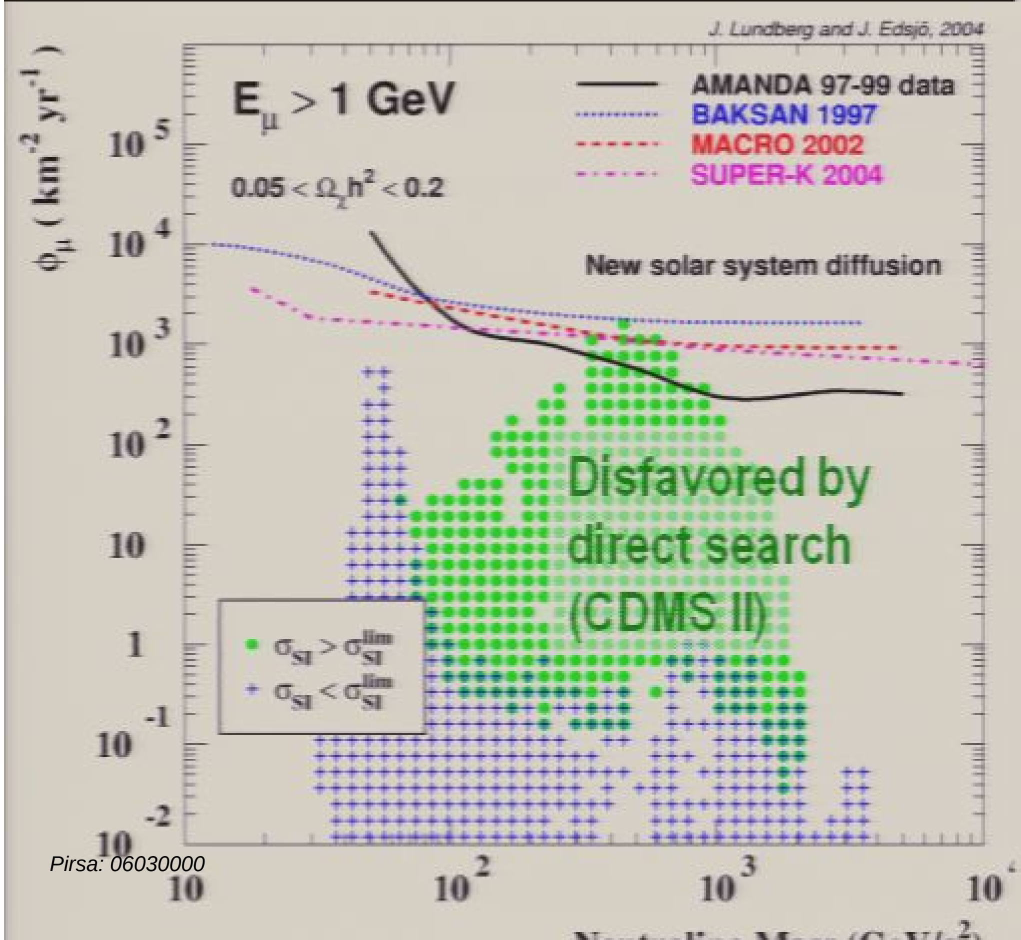
Limits on muon flux from Sun



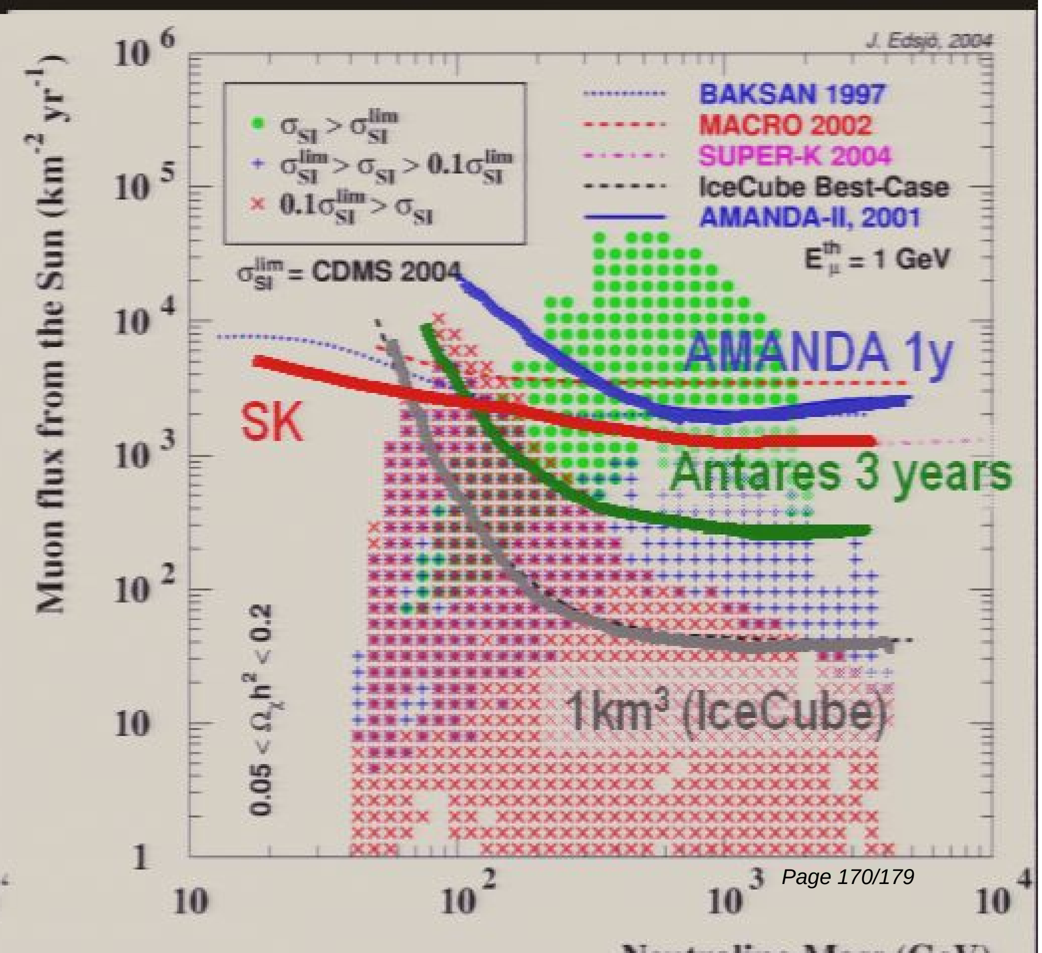
WIMP search

PRELIMINARY

Limits on muon flux from Earth



Limits on muon flux from Sun



summary

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- **AMANDA accumulating data for the 7th year**

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- AMANDA will continue to deliver results

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- *IceCube on track towards a 1 km^3 neutrino telescope!*

• Alabama University, USA
• Bartol Research Institute, Delaware, USA
• Pennsylvania State University, USA
• UC Berkeley, USA
• UC Irvine, USA
• Clark-Atlanta University, USA
• University of Alaska, Anchorage, USA
• Univ. of Maryland, USA
• IAS, Princeton, USA
• University of Wisconsin-Madison, USA (IceCube Project)
• University of Wisconsin-River Falls, USA
• LBNL, Berkeley, USA
• University of Kansas, USA
• Southern University and A&M College, Baton Rouge, USA
the IceCube collaboration
USA
Europe
Japan
• Chiba university, Japan
• University of Canterbury, Christchurch, NZ
New Zealand
ANTARCTICA
• Universite Libre de Bruxelles, Belgium
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