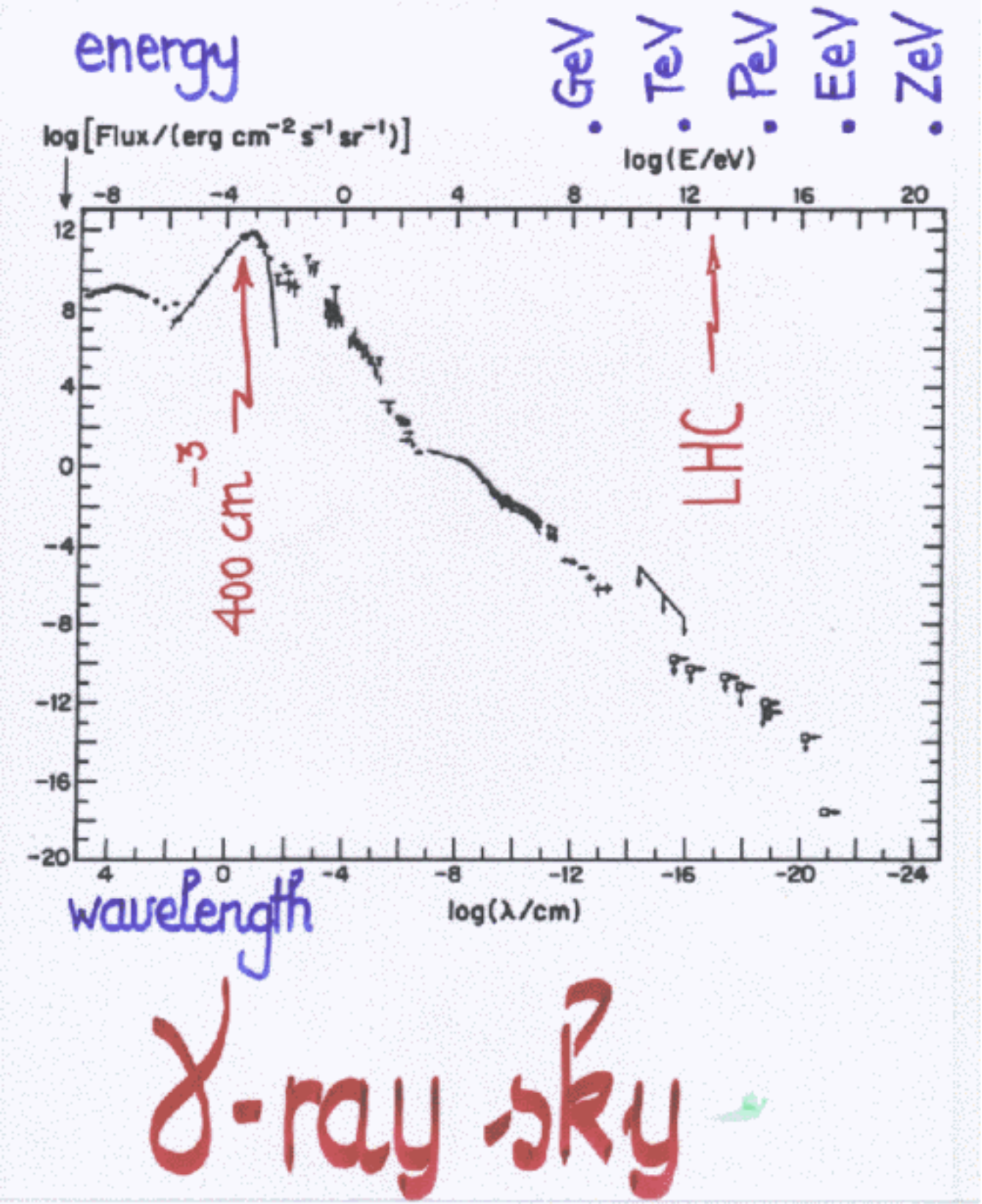
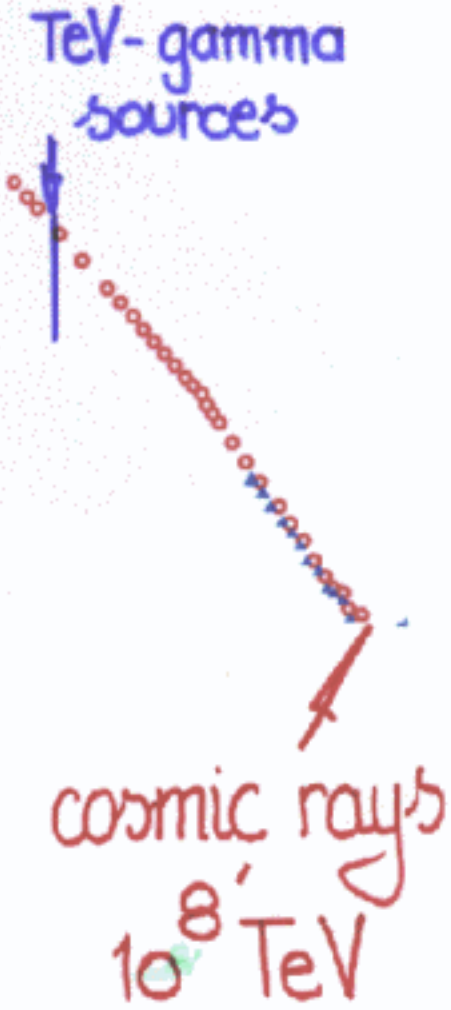
Kilometer-Scale ν detectors

f. halzen

- scale set by the observed flux of high energy cosmic rays and gamma rays
- proof of concept
- better detectors, not just bigger

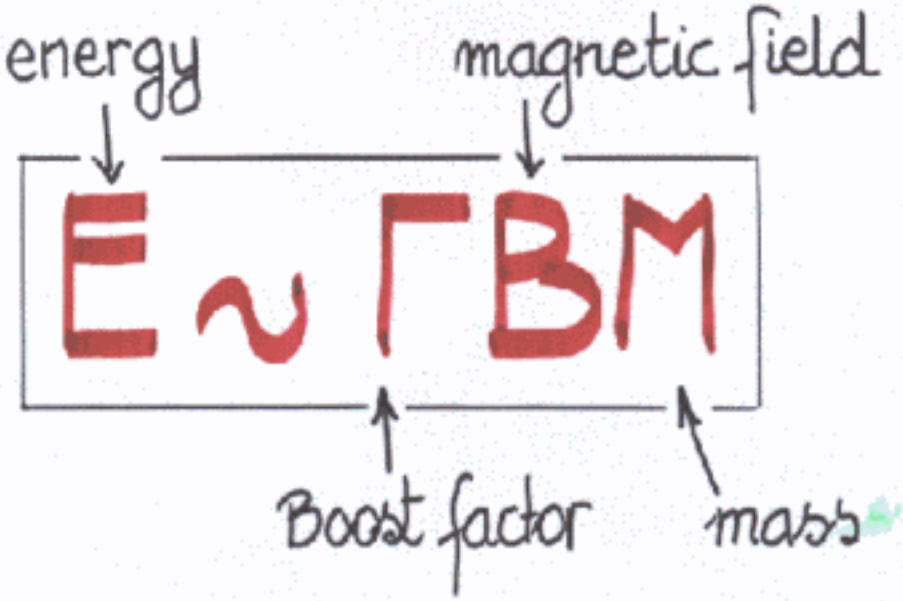

energy
GeV
TeV
PeV
EeV
ZeV
log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
-3
400 cm
LHC
4
0
-4
-8
-12
-16
-20
-24
wavelength
log(λ/cm)

γ-ray sky


TeV-gamma
sources
cosmic rays
10^8 TeV

Cosmic Accelerators

- $E \sim \Gamma c B R$
- $R \sim \frac{GM}{c^2}$



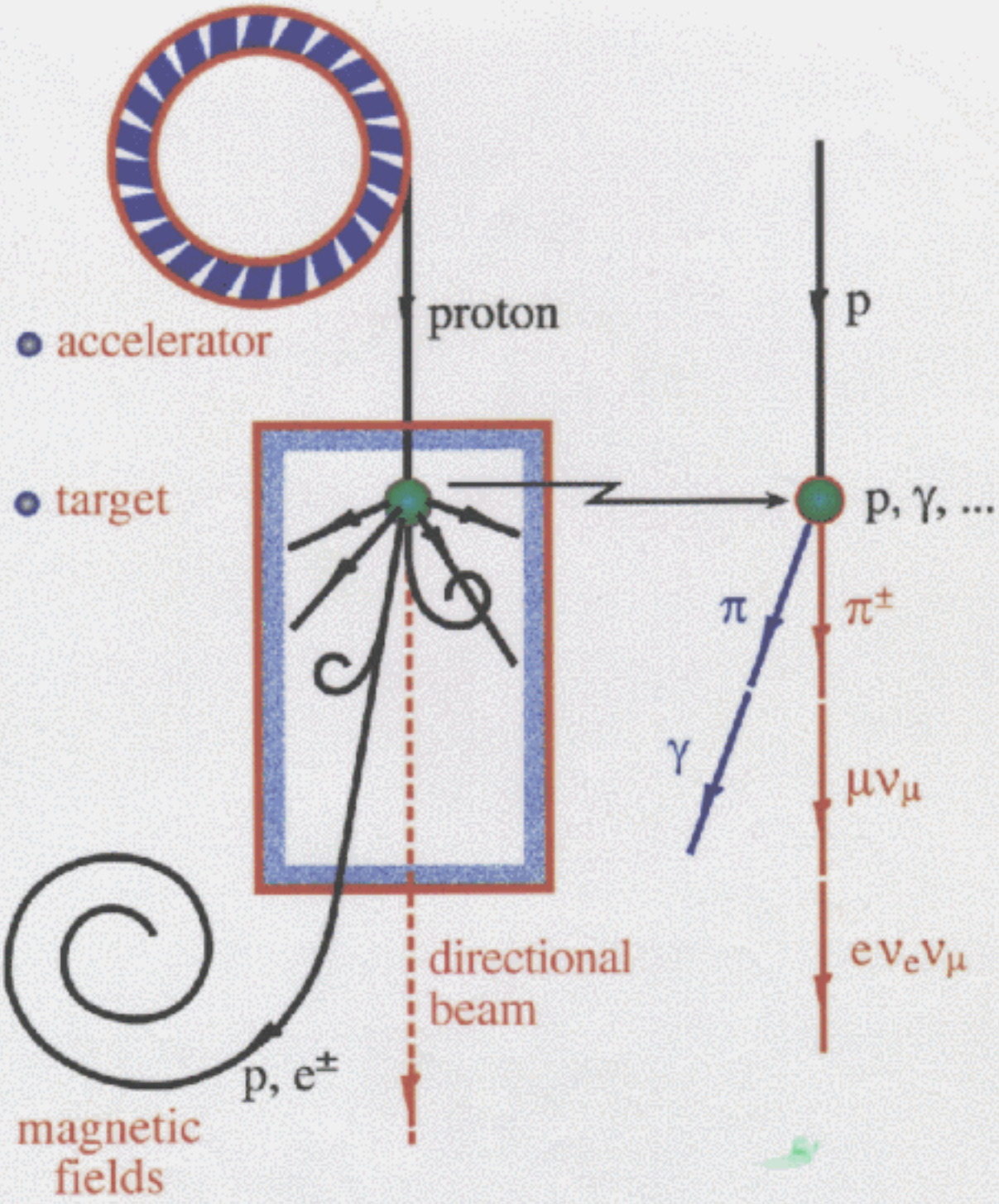
$E \propto \Gamma BM$

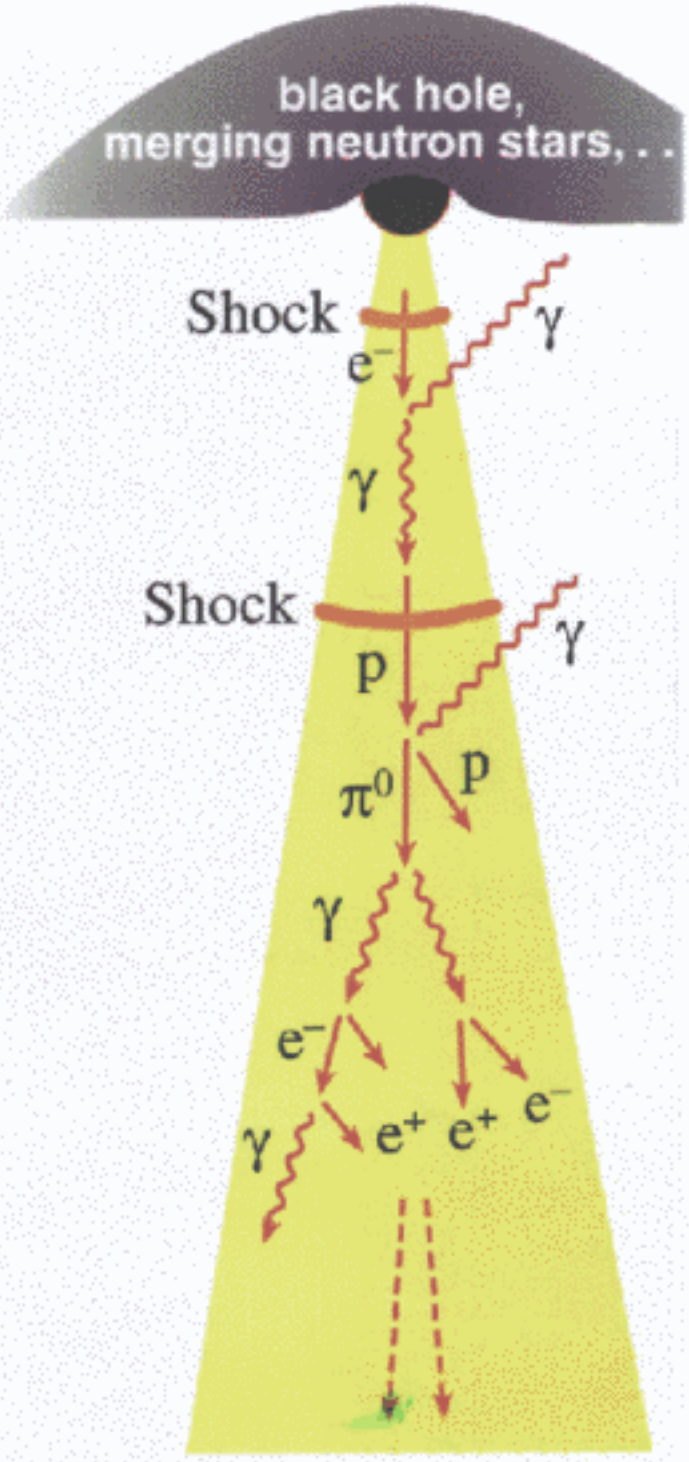
$E > 10^{19}$ eV ?

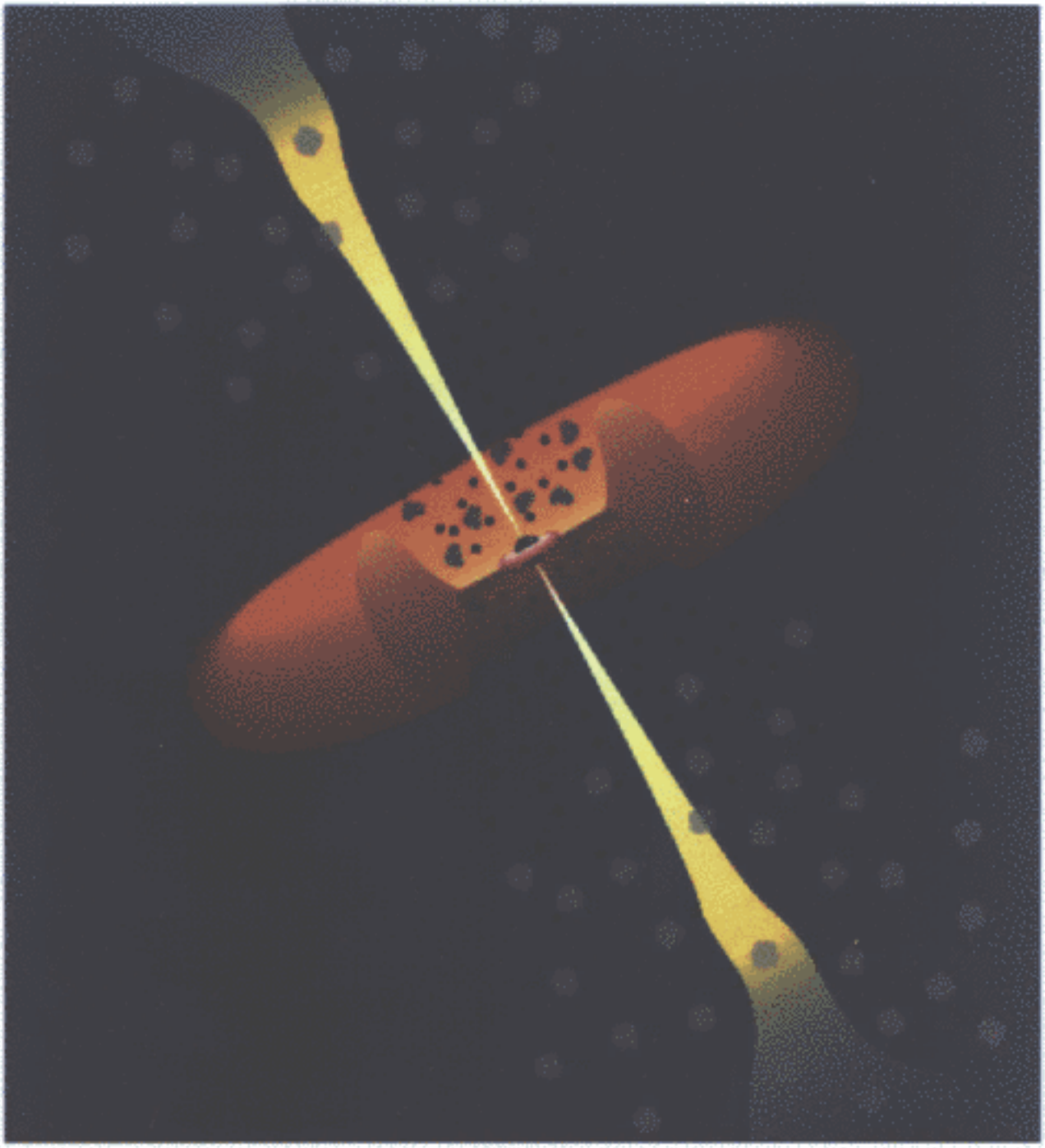
• quasars	$\Gamma \simeq 1$	$B \simeq 10^3$ G	$M \simeq 10^9 M_\odot$
• blazars	$\gtrsim 10$		
• neutron stars	$\Gamma \simeq 1$	$B \simeq 10^{12}$ G	$M \simeq M_\odot$
black holes			
⋮			
• grb	$\gtrsim 10^2$		

↑ emit highest energy γ's!

NEUTRINO BEAMS: HEAVEN & EARTH




black hole,
merging neutron stars, . .
Shock
e⁻
γ
γ
Shock
p
γ
π⁰
p
γ
e⁻
γ
e⁺
e⁺
e⁻



ν flux from cosmic rays

what is the neutrino flux associated with the source(s) of the highest energy cosmic rays?

Source	accelerated beam	Target	ν-flux
agn	observed cosmic ray beam	UV γ's	a few $km^{-2} yr^{-1}$
grb	observed cosmic ray beam	MeV γ's	$10\text{-}10^2$ $km^{-2} yr^{-1}$
?			

↕ from astronomical observations

10^{20} eV cosmic rays exist !

γ-rays from π^0 decay?

$$E_\nu N_\nu(E_\nu) = \epsilon E_\gamma N_\gamma(E_\gamma)$$

$$1 < \epsilon < \infty$$

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

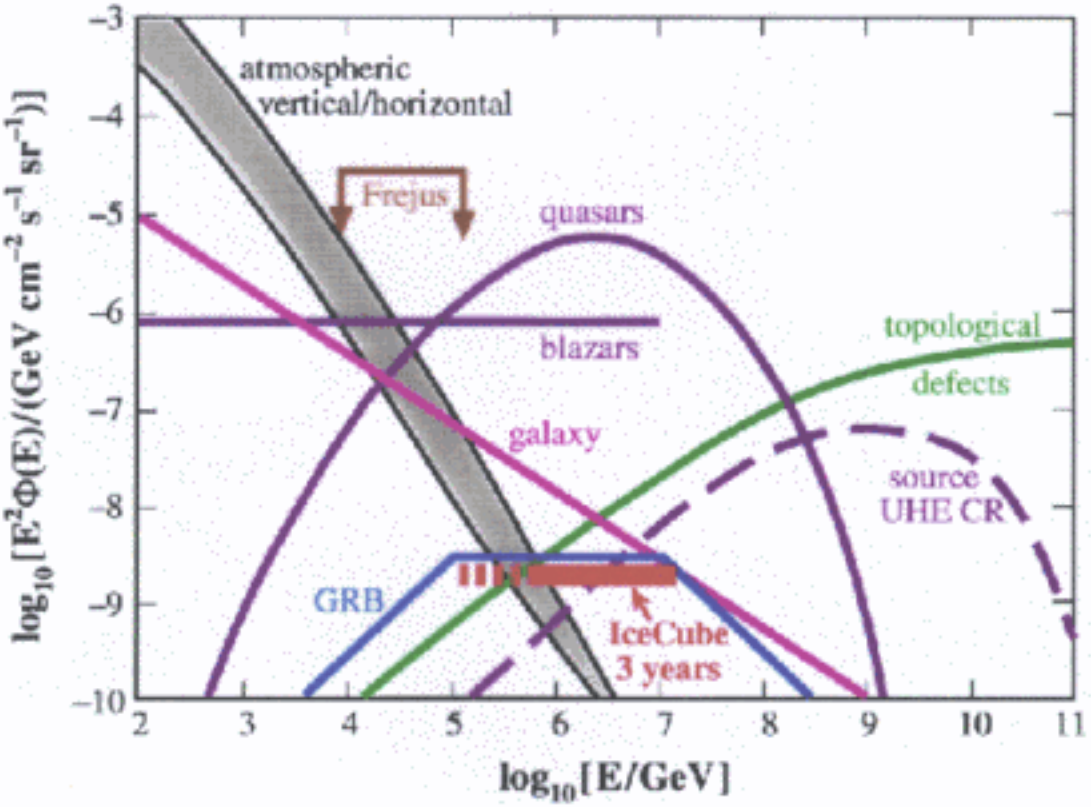
accelerator beam dump (hidden source)

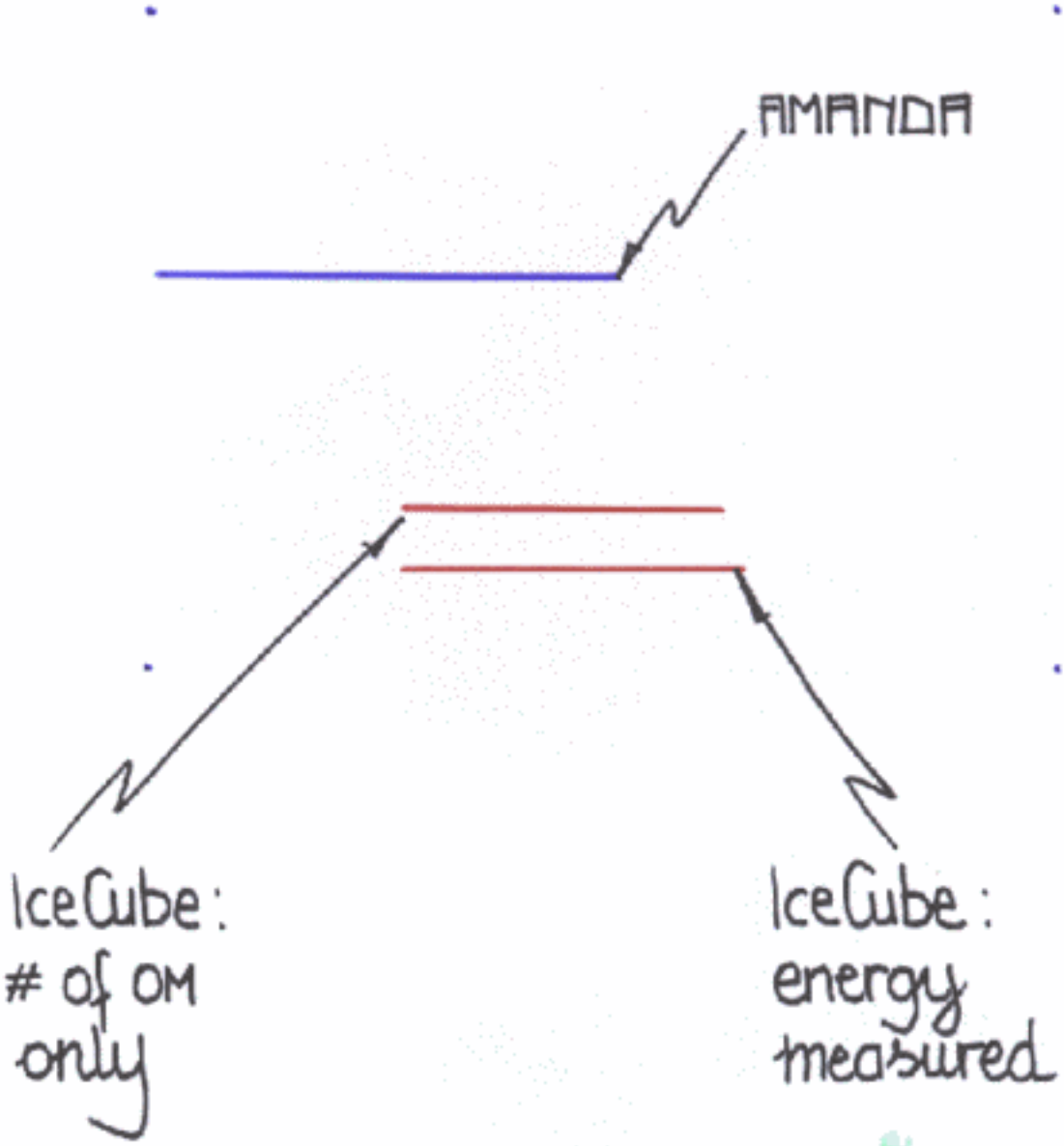
ν flux predicted

Observed γ-ray flux

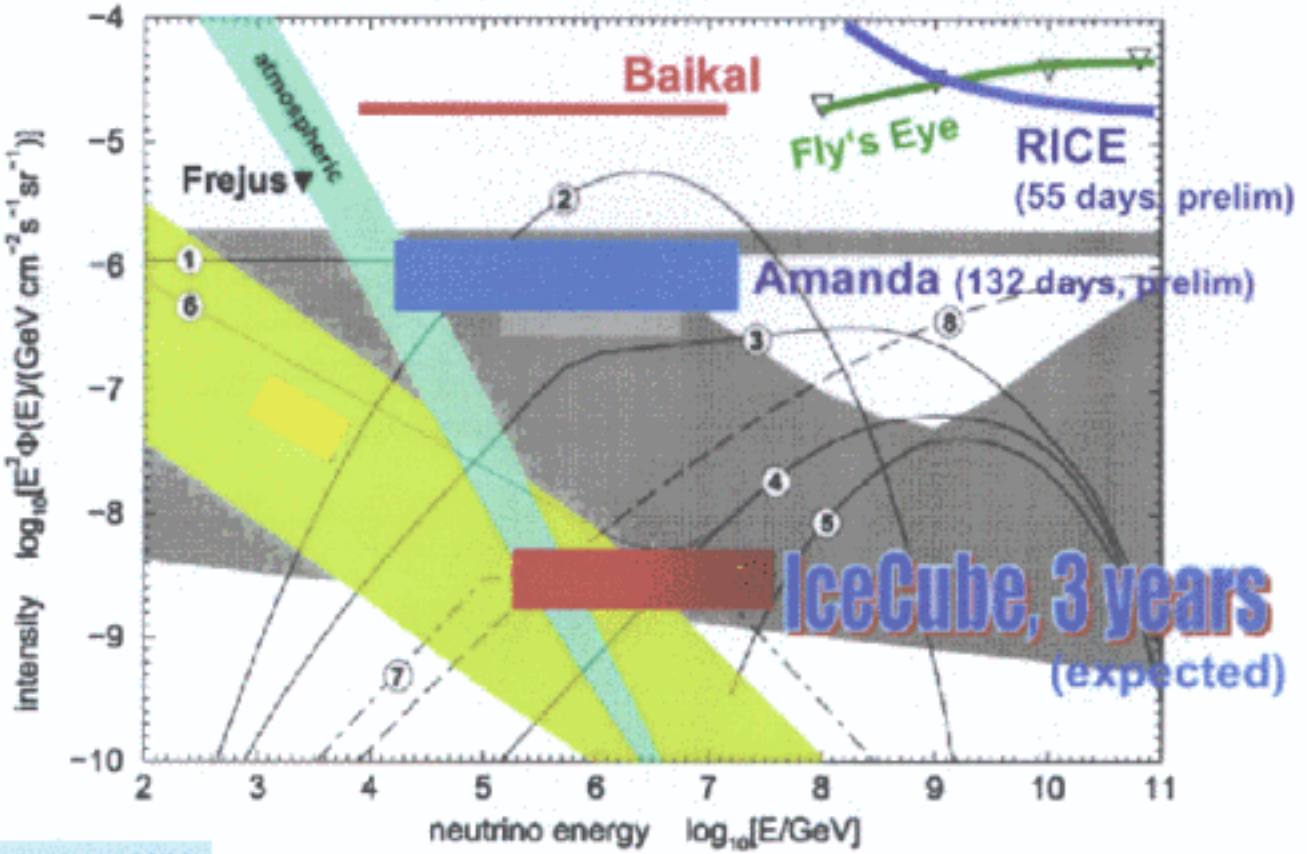
$20\ km^{-2}\ yr^{-1}$ ← crab sn remnant

$35\ km^{-2}$ in 97 ← markarian 501
(9 for pγ)


atmospheric
vertical/horizontal
Frejus
quasars
blazars
galaxy
topological
defects
source
UHE CR
GRB
IceCube
3 years
log10[E2Φ(E)/(GeV cm−2 s−1 sr−1)]
log10[E/GeV]
−3
−4
−5
−6
−7
−8
−9
−10
2
3
4
5
6
7
8
9
10
11


AMANDA
IceCube :
# of OM
only
IceCube :
energy
measured

Diffuse Fluxes: New Limits



C.Spiering, v2000

beam : ultra high energy cosmic rays

target : CMBR photons

flux : $3.2\ km^{-2}\ yr^{-1}$ $(z = 2.2)$

DUMAND 1975

Science:

- oscillating atmosperic ν's (long-baseline)
- prompt atmospheric ν's (charm†,...)
- gamma ray bursts
- active galaxies
- Greisen ν's $^{\dagger?}$
- WIMPS (neutralinos)
- SS433 type sources
- galactic binaries
- past supernovae$^{\circ}$
- super/hyper novae (network!)$^{\circ}$
- galaxy formation (supermassive bh)$^{\circ}$
- primordial black holes$^{\circ}$
- plane of the galaxy†
- sun/moon†
- ν_{τ}
- ν magnetic moment
- topological defects (mag. monopoles)

- extra-dimensions

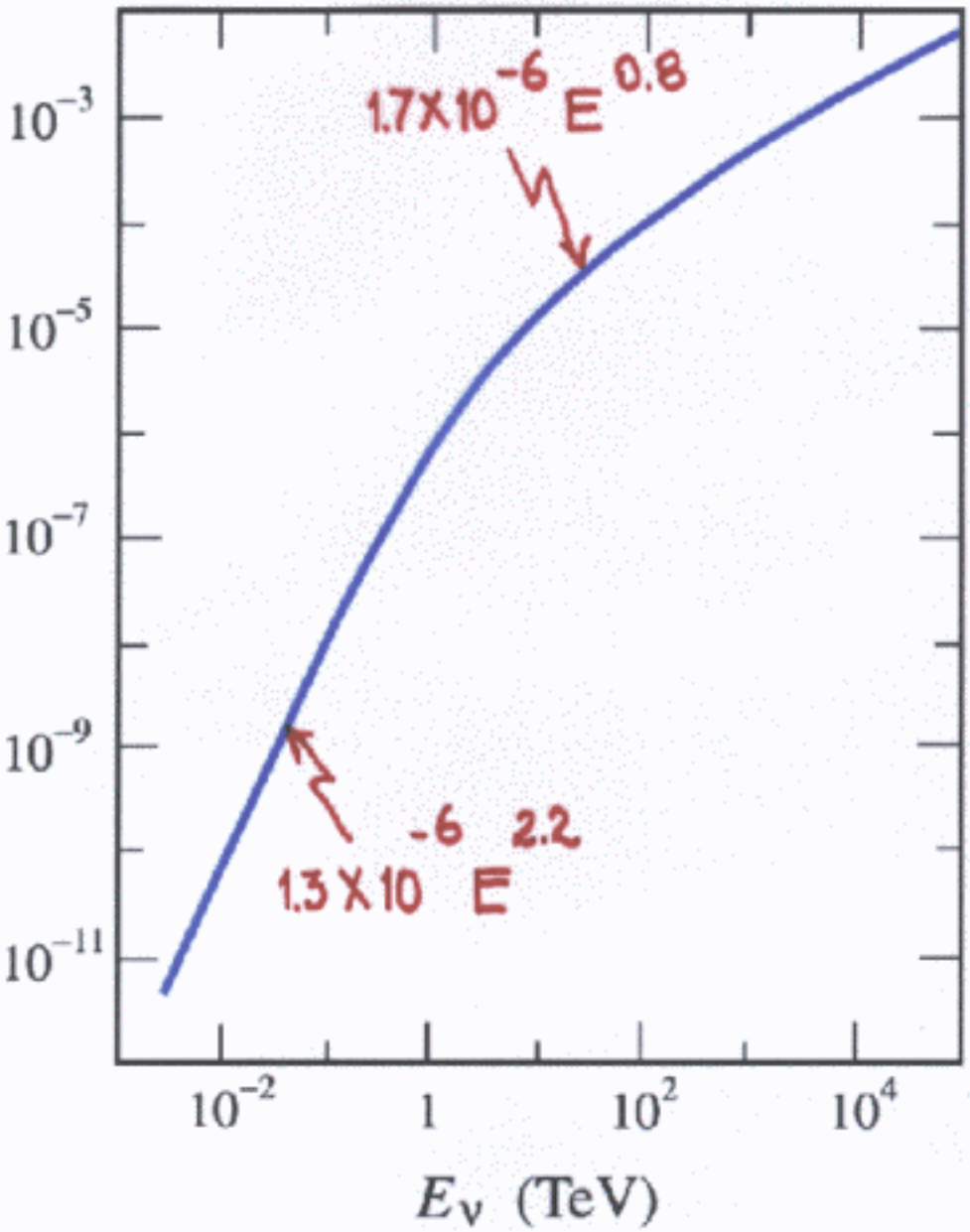
MeV-TeV double burst

→ TeV γ's!

$^{\circ}$ MeV burst trigger

† guaranteed

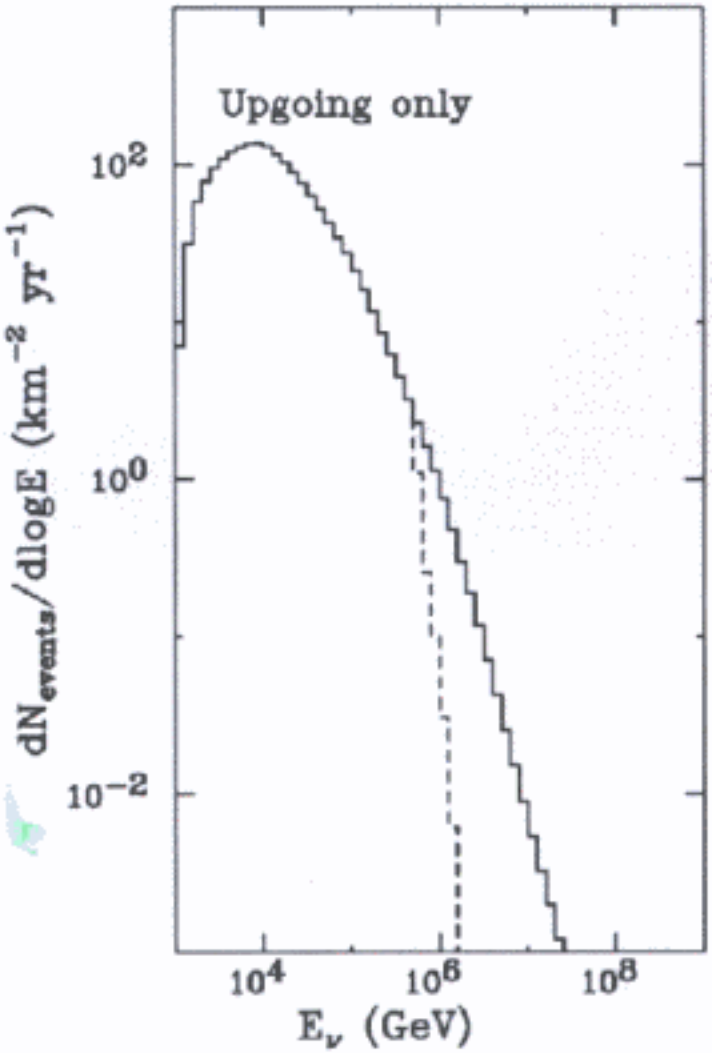
- $P_{\nu\to\mu}$ = density $\cdot\ \sigma_\nu(E) \cdot R_\mu(E)$

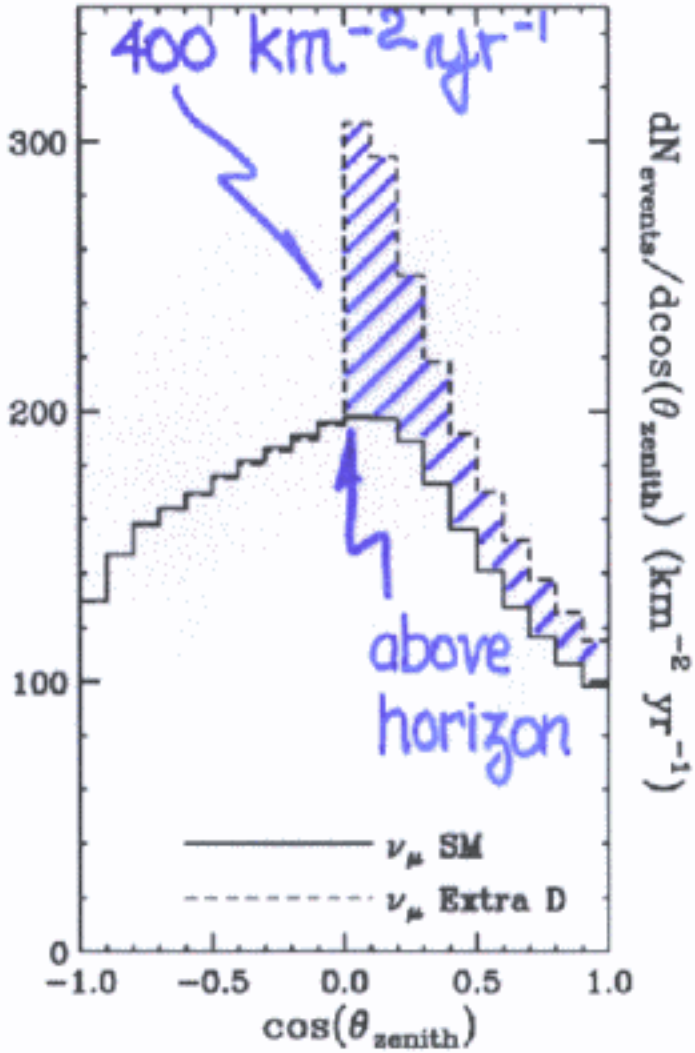


- $N_{events} = AREA \int \frac{dN_\mu}{dE} P_{\nu\to\mu}\, dE$

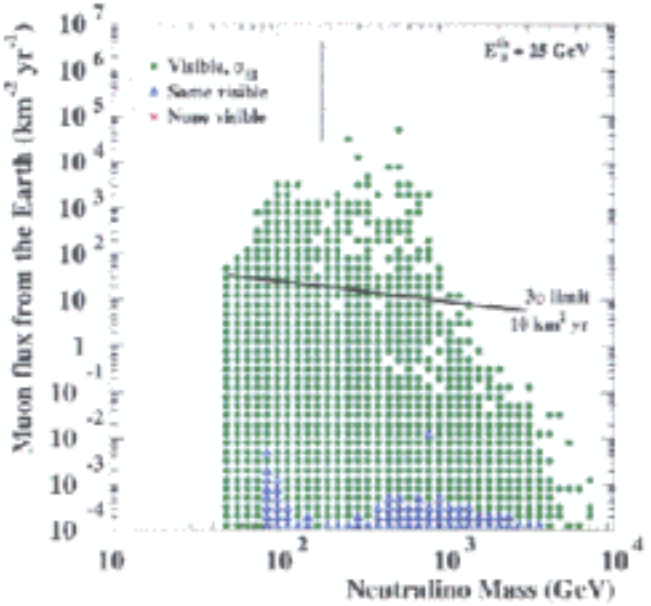
Extra dimensions : $\sigma_{\nu p} \rightarrow \sigma_{pp}$ @ 1PeV

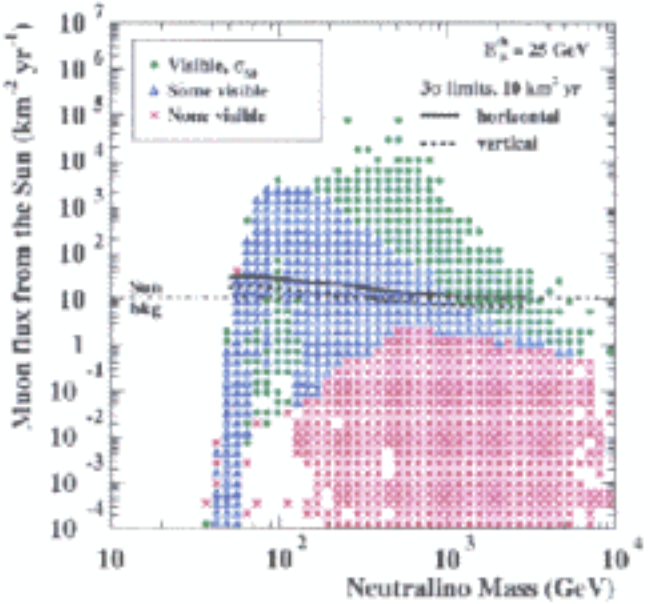
Events in ICECUBE: Prompt atmospheric ν_μ (QGS model)





$\Phi_\mu^{\text{Earth/Sun}}$ and future GENIUS / CRESST limits



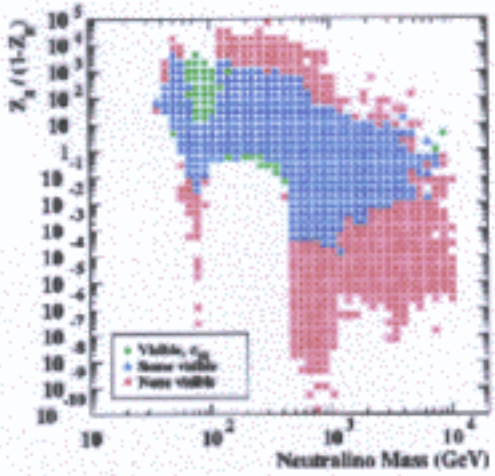


$0.025 < \Omega_\chi h^2 < 1$

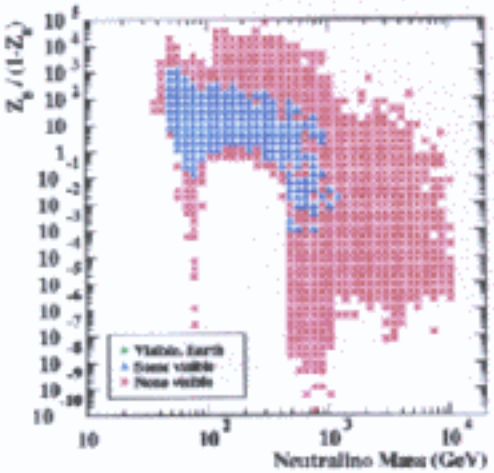
E.A. Baltz, J. Edsjö and P. Gondolo

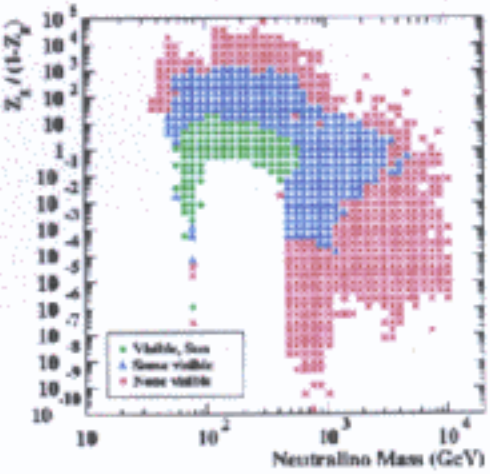
MSSM parameter space – future probed regions I

GENIUS/CRESST



Φ_μ^{Earth} Φ_μ^{Sun}





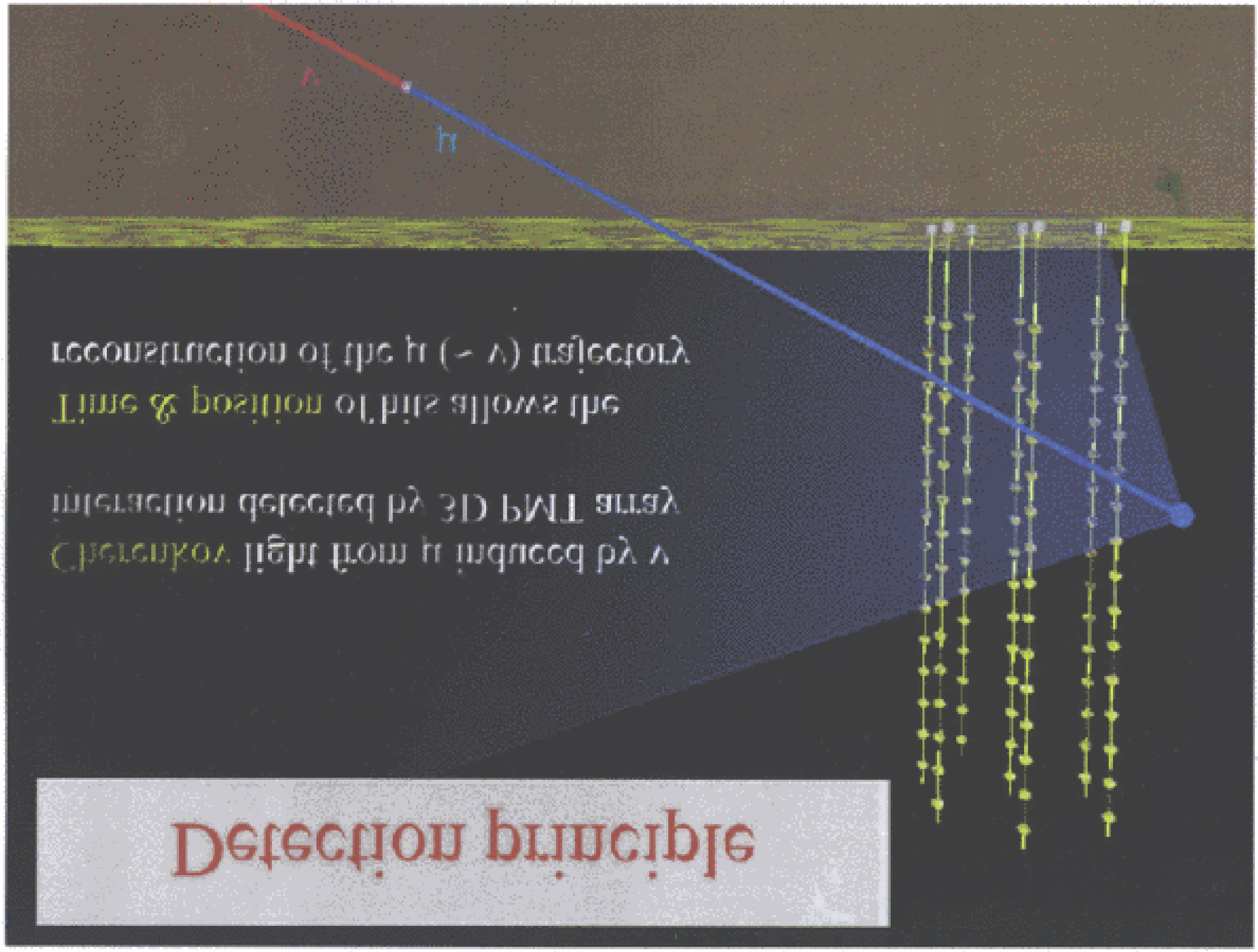
$0.025 < \Omega_\chi h^2 < 1$

E.A. Baltz, J. Edsjö and P. Gondolo

ν-telescopes

overwhelmingly motivated by discovery potential

- astronomy (multi-wavelength)
- particle physics
- multi-disciplinary science


Detection principle
Cherenkov light from μ induced by ν
interaction detected by 3D PMT array
Time & position of hits allows the
reconstruction of the μ (~ ν) trajectory
ν
μ

need 2 miracles

- **large absorption length**
  - → photomultiplier spacings
  - → cost (<1% conventional)
- **large scattering length**
  - → angular resolution
  - → bkg of misreconstructed μ's ($< 10^{-8}$)

Pioneers: DUMAND, Baksan, IMB, Kamiokande, Fréjus

Italy, USA — Effective Area: $A \leq 10^3$ m^2

MACRO since 1989	LNGS Gran Sasso	Liquid scint. + streamer tubes	$E_{\uparrow\mu} > 1$ GeV 1100 $\uparrow\mu$
Baikal NT36→NT200 1993 1998	Lake Baikal 1.1 km	Water Cherenkov 192 O.M.s on 8 strings	$E_{\uparrow\mu} > 10$ GeV

Russia, Germany

Effective Area: $A \sim 10^4$ m^2

USA, Belgium, Germany, Sweden

AMANDA B4 → B10 1996 – 1998	South Pole Ice 1.5 – 2 km	Cherenkov 302 O.M.s on 10 strings	$E_{\uparrow\mu} > 20$ GeV
NESTOR	Mediterranean (Greece) 3.8 km	Cherenkov 168 O.M.s on 1 tower	Under development

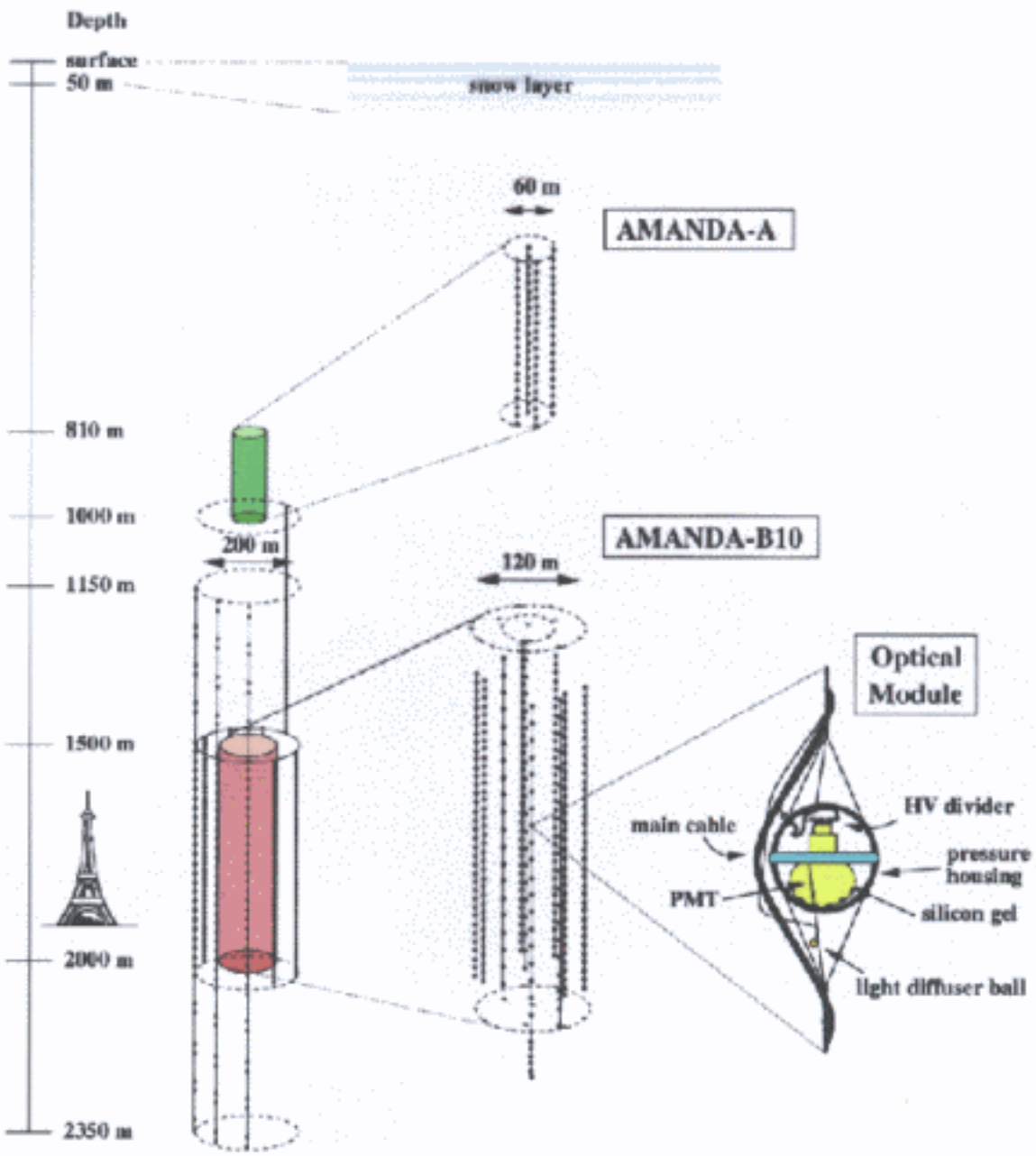
Effective Area: $A \sim 10^5$ m^2 Towards km^2 →

USA, Germany, Sweden

AMANDA II 2000 → . . .	South Pole Ice 1.5 – 2 km	Cherenkov 681 O.M.s on 19 strings	Taking data	→ IceCube 2002–08
ANTARES start 2003	Mediterranean (France) 2.4 km	Cherenkov 1000 O.M.s on 13 strings	Building phase 2002 – 2003	→ Antares II

NEMO

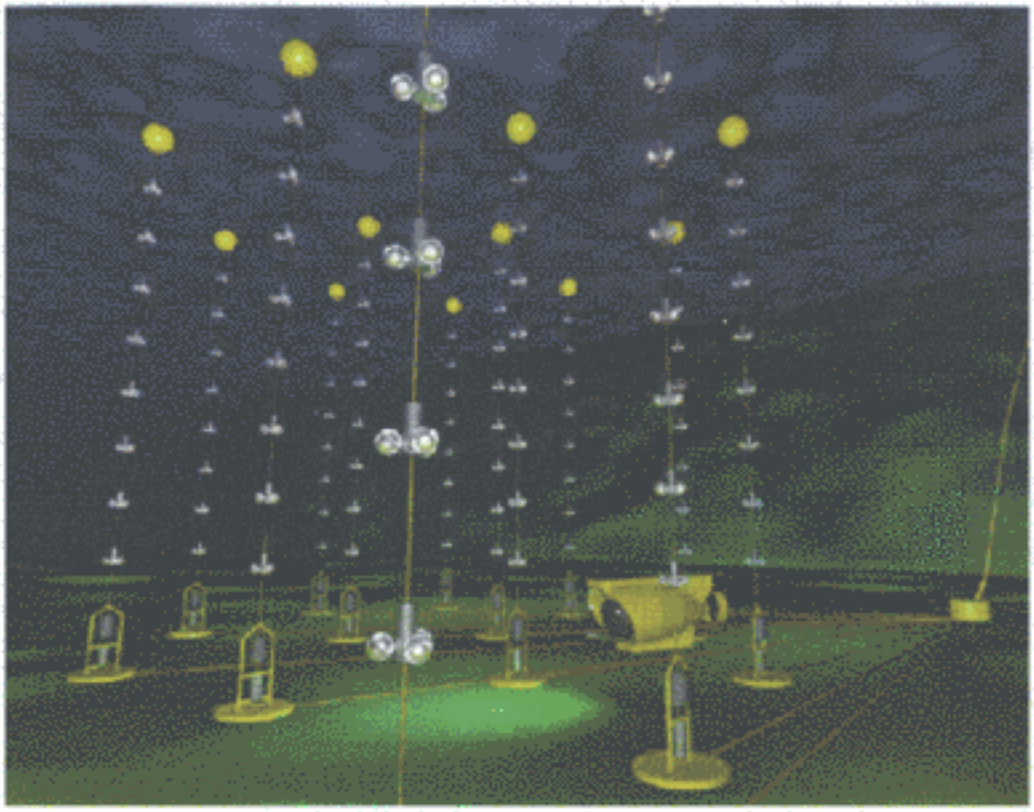
France, UK, Spain, Italy, Netherlands, Russia

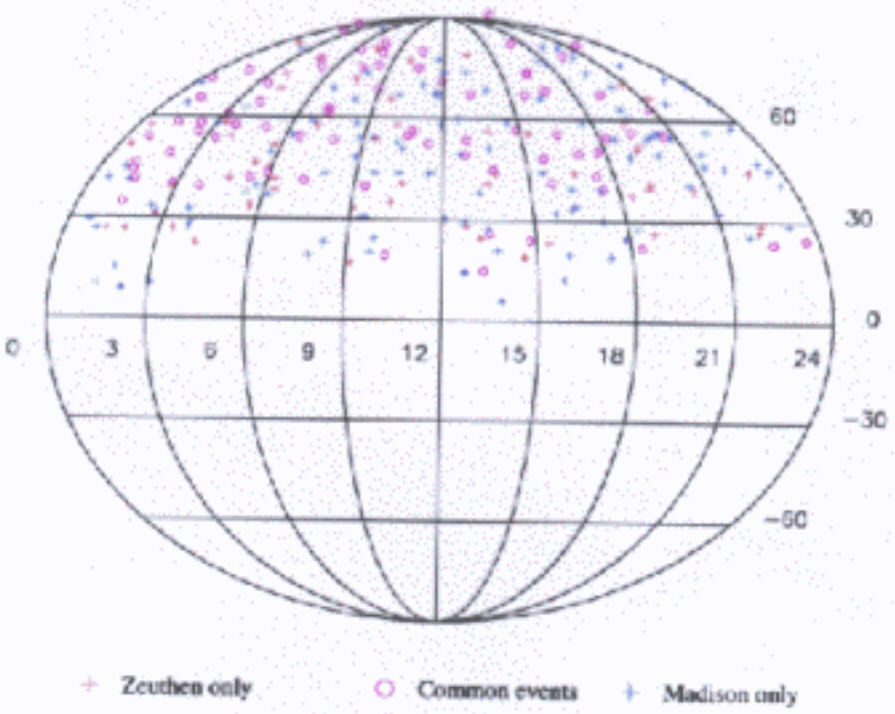


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)



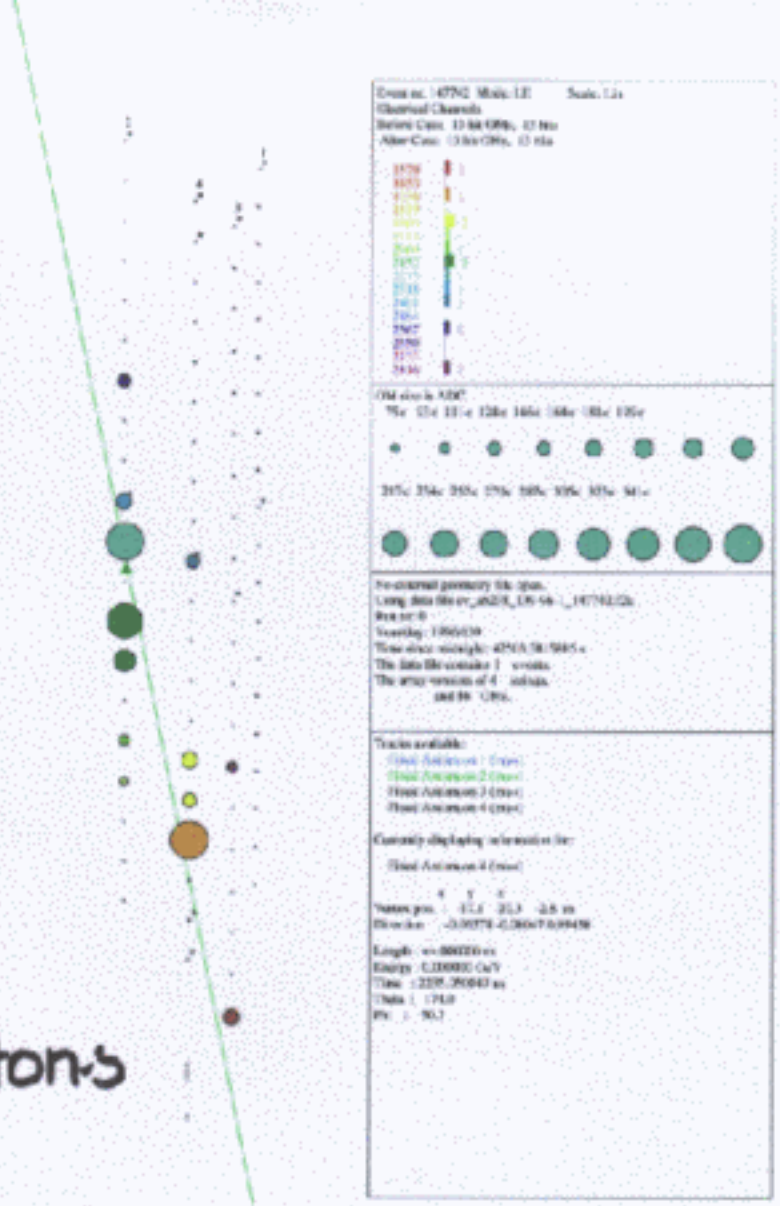

60
30
0
−30
−60
0
3
6
9
12
15
18
21
24
Zeuthen only
Common events
Madison only

- **AMANDA 97-99**
  - proof of concept ✓
- **AMANDA II 00- .....**
  - calibrated ✓
  - > 6 months of data ✓
  - $\lesssim 0.1\ km^2$ (discovery?)
- **ICECUBE**

302 pmt

677 pmt

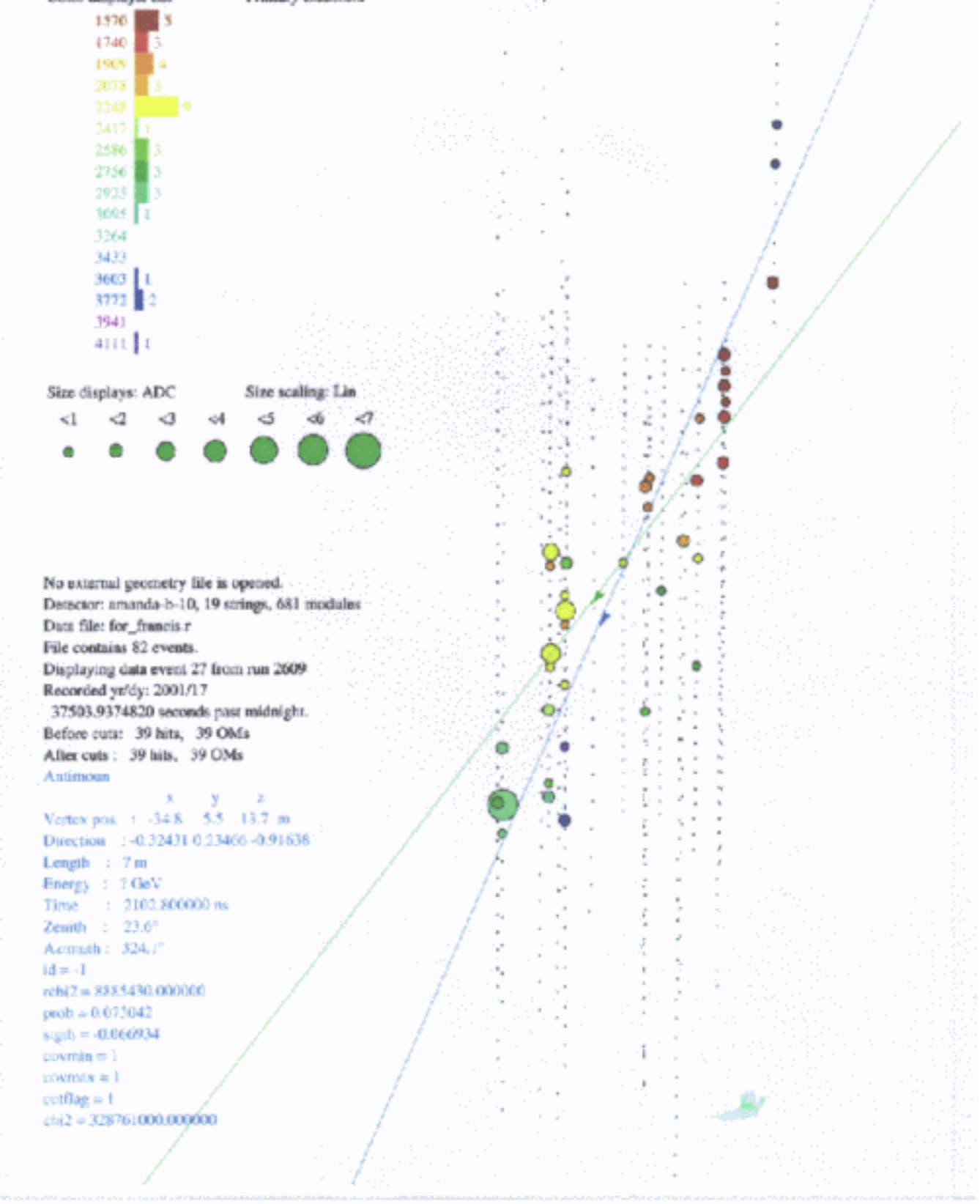
4800 pmt
(8→10 in)



circle size
= # photons

circle color
= time
red early, blue late

Astroparticle Physics,
13 (2000) 1

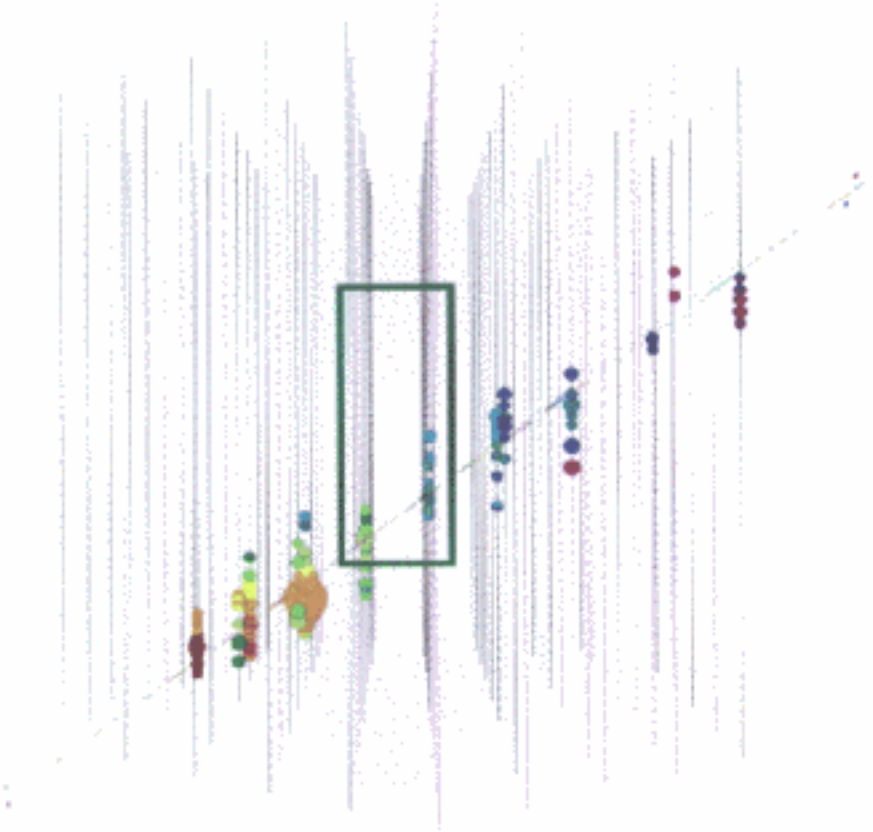


No external geometry file is opened.
Detector: amanda-b-10, 19 strings, 681 modules
Data file: for_francis.r
File contains 82 events.
Displaying data event 27 from run 2609
Recorded yr/dy: 2001/17
37503.9374820 seconds past midnight.
Before cuts: 39 hits, 39 OMs
After cuts : 39 hits, 39 OMs
Antimuon

	x	y	z	
Vertex pos.	: -34.8	5.5	13.7	m

Direction : -0.32431 0.23466 -0.91638
Length : 7 m
Energy : 7 GeV
Time : 2102.800000 ns
Zenith : 23.6°
Azimuth : 324.1°
id = -1
rchi2 = 8885430.000000
prob = 0.073042
sigb = -0.066934
ccwmin = 1
ccwmax = 1
cutflag = 1
chi2 = 328761000.000000

Amanda ⇒ Ice Cube



Amanda-B10

302 OMs

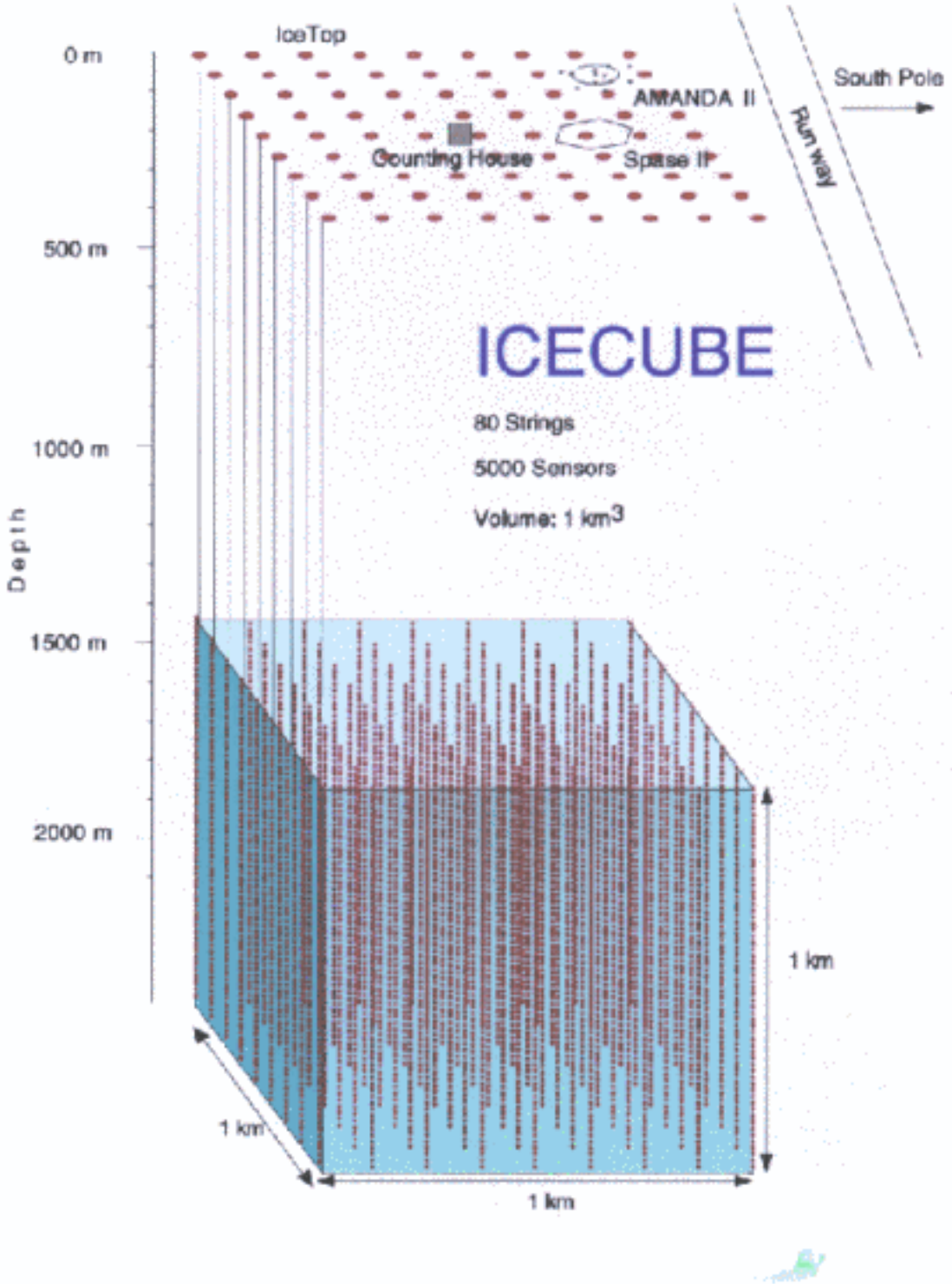
200 ν_{atm} in

130 days

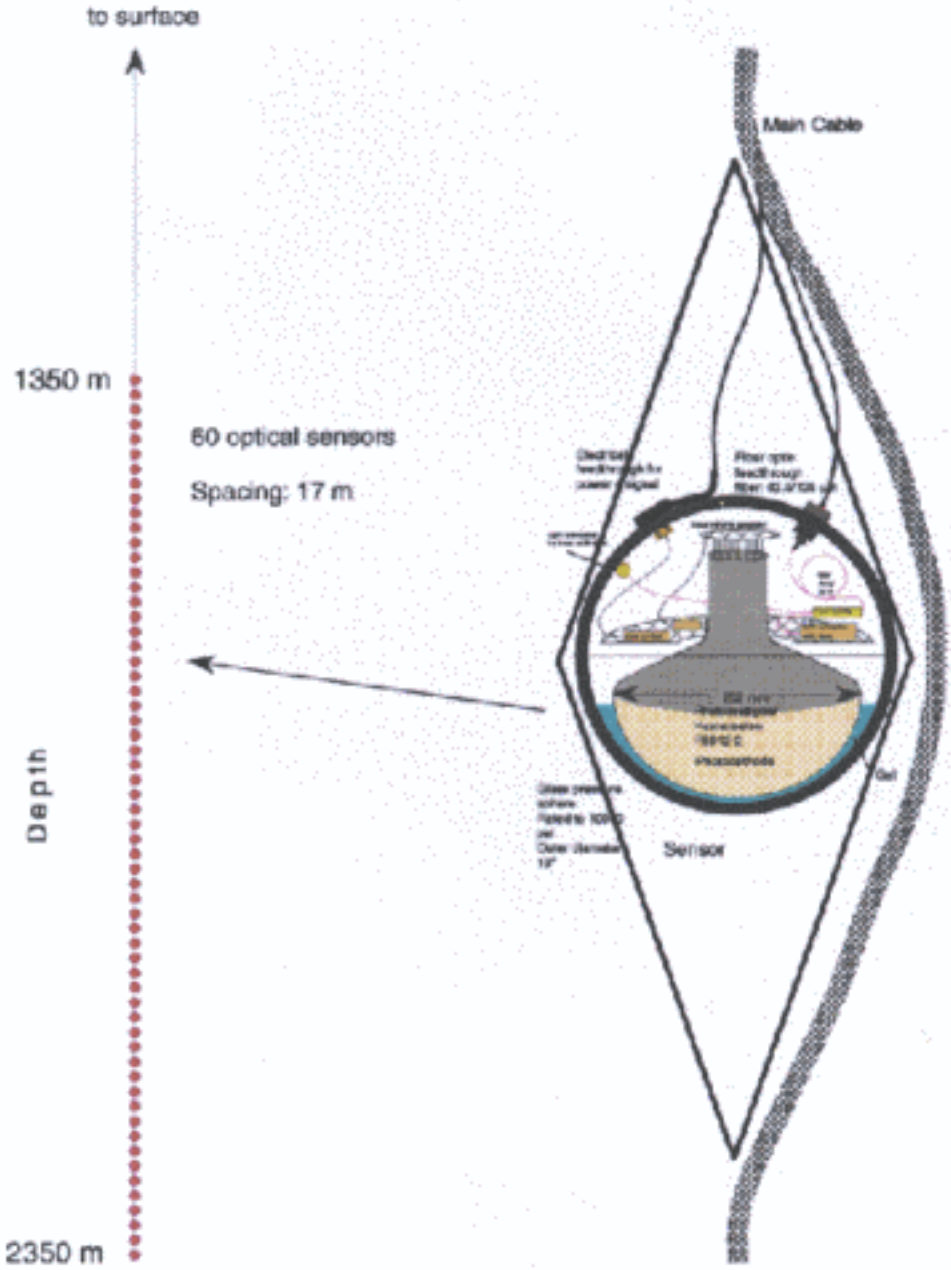
Ice Cube

5000 OMs

250 ν_{atm} per day


IceTop
0 m
AMANDA II
South Pole
Run way
Counting House
Spase II
500 m
ICECUBE
80 Strings
5000 Sensors
Volume: 1 km3
1000 m
Depth
1500 m
2000 m
1 km
1 km
1 km

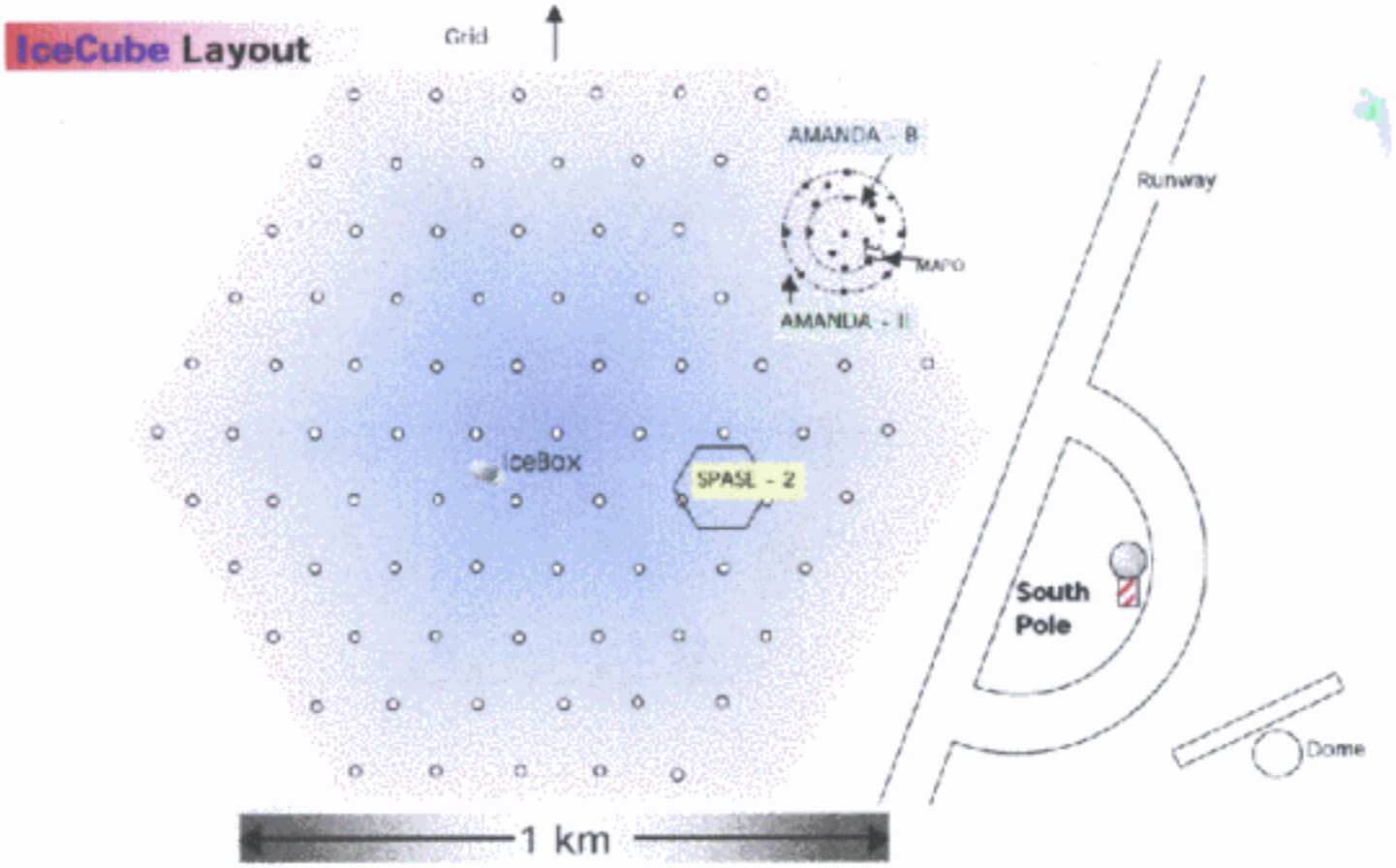
ICECUBE - String



Tracks and Cascades

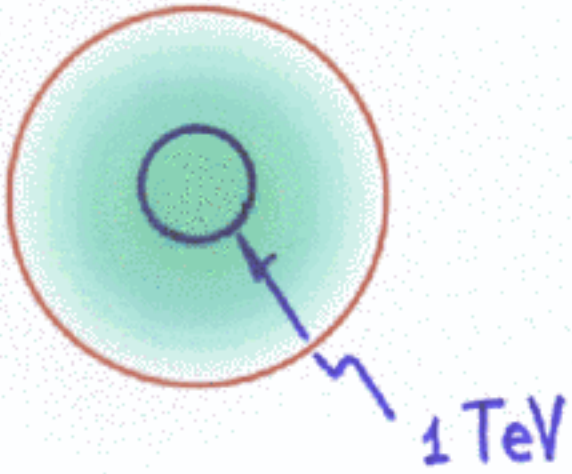
$$L_{shower} \propto \ln E_e$$

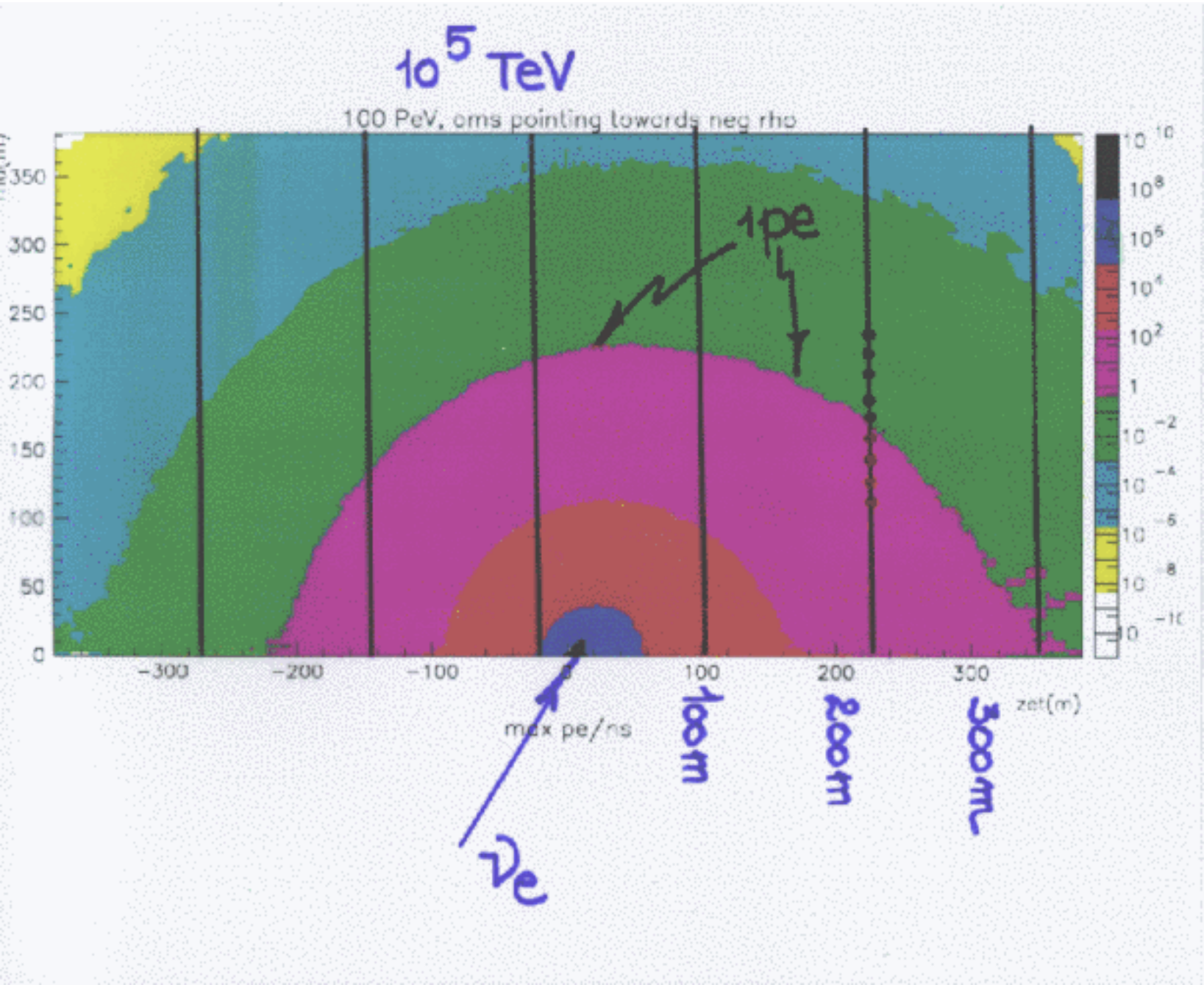
$$dE/dx \propto a + b \cdot E_\mu$$


IceCube Layout
Grid
AMANDA - B
MAPO
AMANDA - II
IceBox
SPASE - 2
Runway
South Pole
Dome
1 km

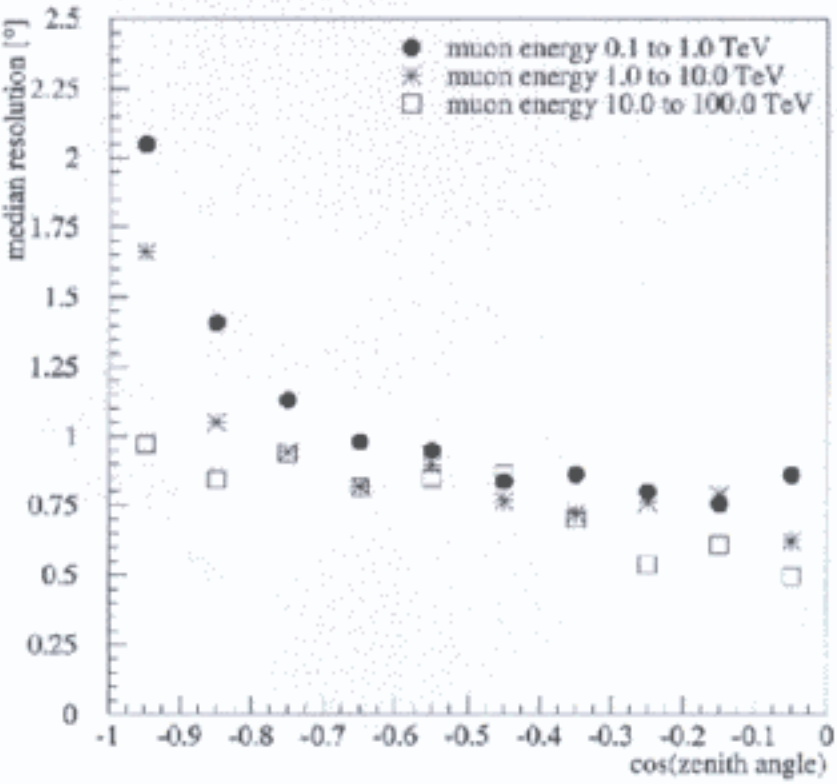
1 TeV muon track

1 PeV Cascade




10^5 TeV
100 PeV, cms pointing towards neg rho
1pe
max pe/ns
100m
200m
300m
ν_e
zet(m)
350
300
250
200
150
100
50
0
−300
−200
−100
100
200
300

Angular Resolution Versus Zenith Angle



IceCube performance (ctd)

- energy resolution:

  muons $\sigma\left(\log \frac{E_{reco}}{E_{true}}\right)(E > 1\,TeV) \simeq 0.3$

  cascades $\sigma\left(\frac{E_{reco} - E_{true}}{E_{true}}\right)(E > 10\,TeV)$

  $\simeq 0.1\text{-}0.2$

  (Σ TOT only)

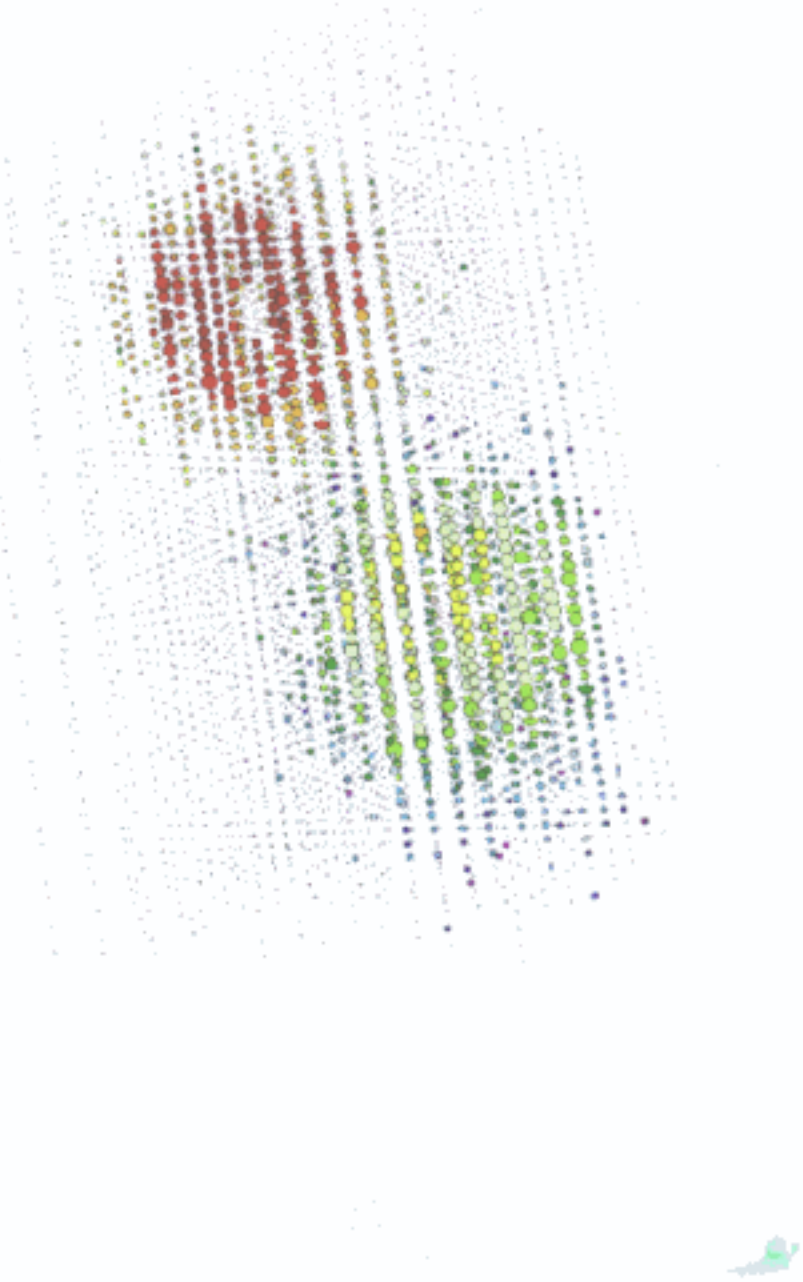
- signal-to-background

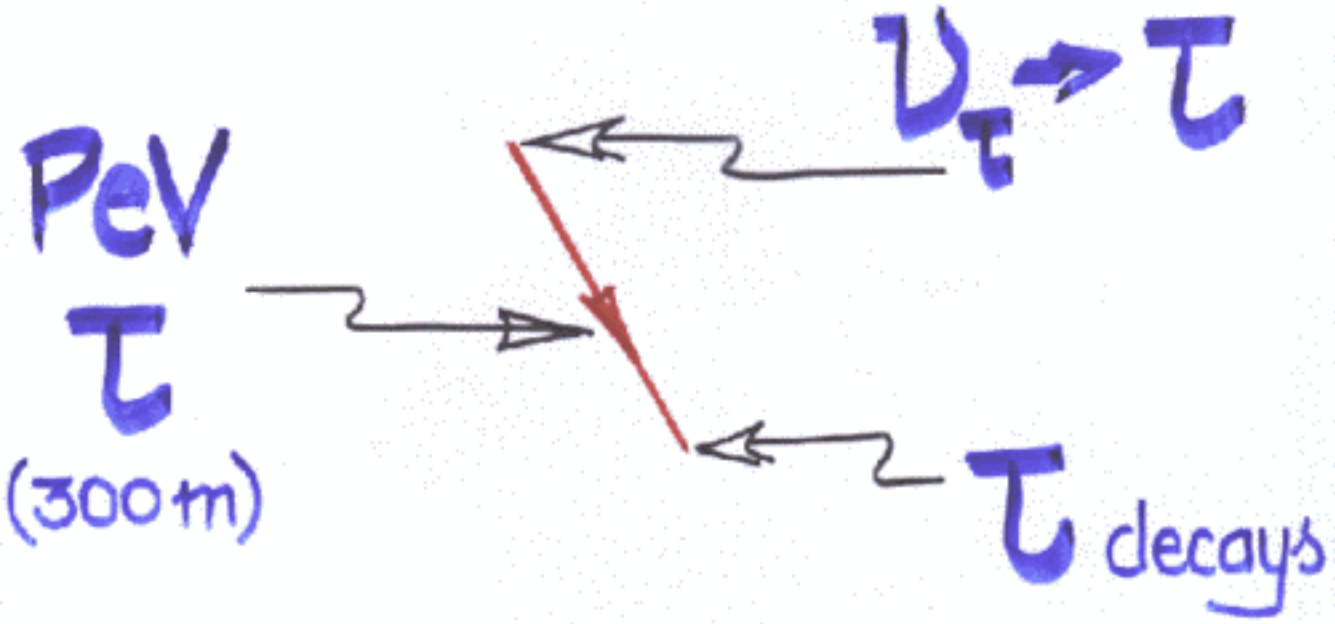
  diffuse $S/N\,(E > 10\,TeV) > 5$

  point source $S/N\,(E > 10\,TeV) > 500$

- ν_τ detection efficiency (double bang)

  3% for $E_{\nu_\tau} = 1 \sim 10\,PeV$




PeV
τ
(300 m)
$\nu_\tau \rightarrow \tau$
τ decays

Why is Searching for ν's from GRBs of Interest?

- Test origin of highest energy cosmic rays
- Verify understanding of fireball models
- Search for vacuum oscillations ($\nu_\mu \rightarrow \nu_\tau$):

$$\Delta m^2 \gtrsim 10^{-17}\ \mathrm{eV}^2$$

- Test weak equivalence principle: 10^{-6}
- Test $\frac{c_{\mathrm{photon}} - c_\nu}{c_\nu}$: 10^{-16}

IceCube

- Measures energy
  - fully active calorimeter
  - linear resolution
  - eliminates all background
- Separates ν_e, ν_μ, ν_τ
  - ν_e cascade events ($\Delta\theta \simeq 10^\circ$)
  - ν_μ tracked over 1 km
  - ν_τ double bang (Glashow resonance) (~~discover ν_τ?~~)
- Sensitivity reaches to guaranteed sources
- Different instrument (mostly) because of size