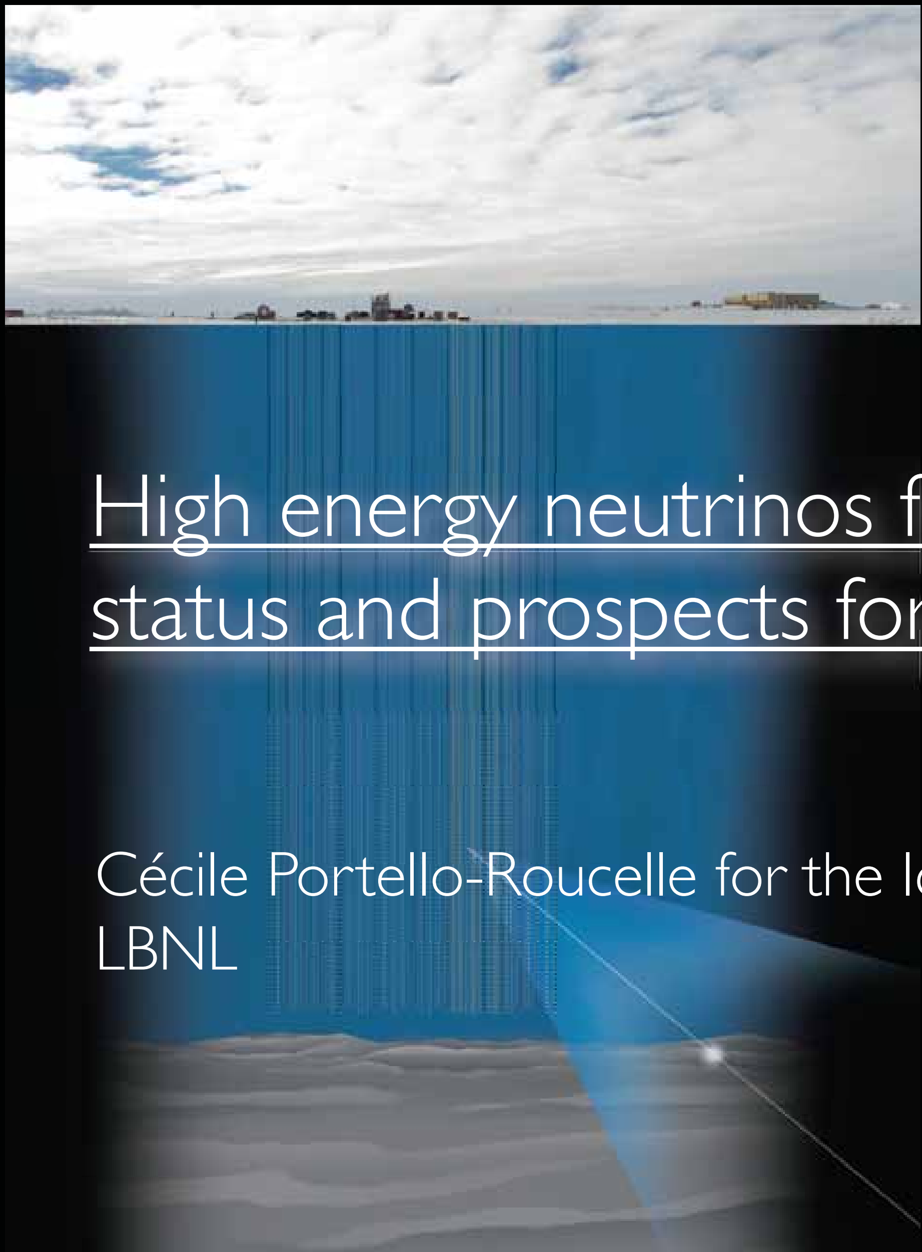
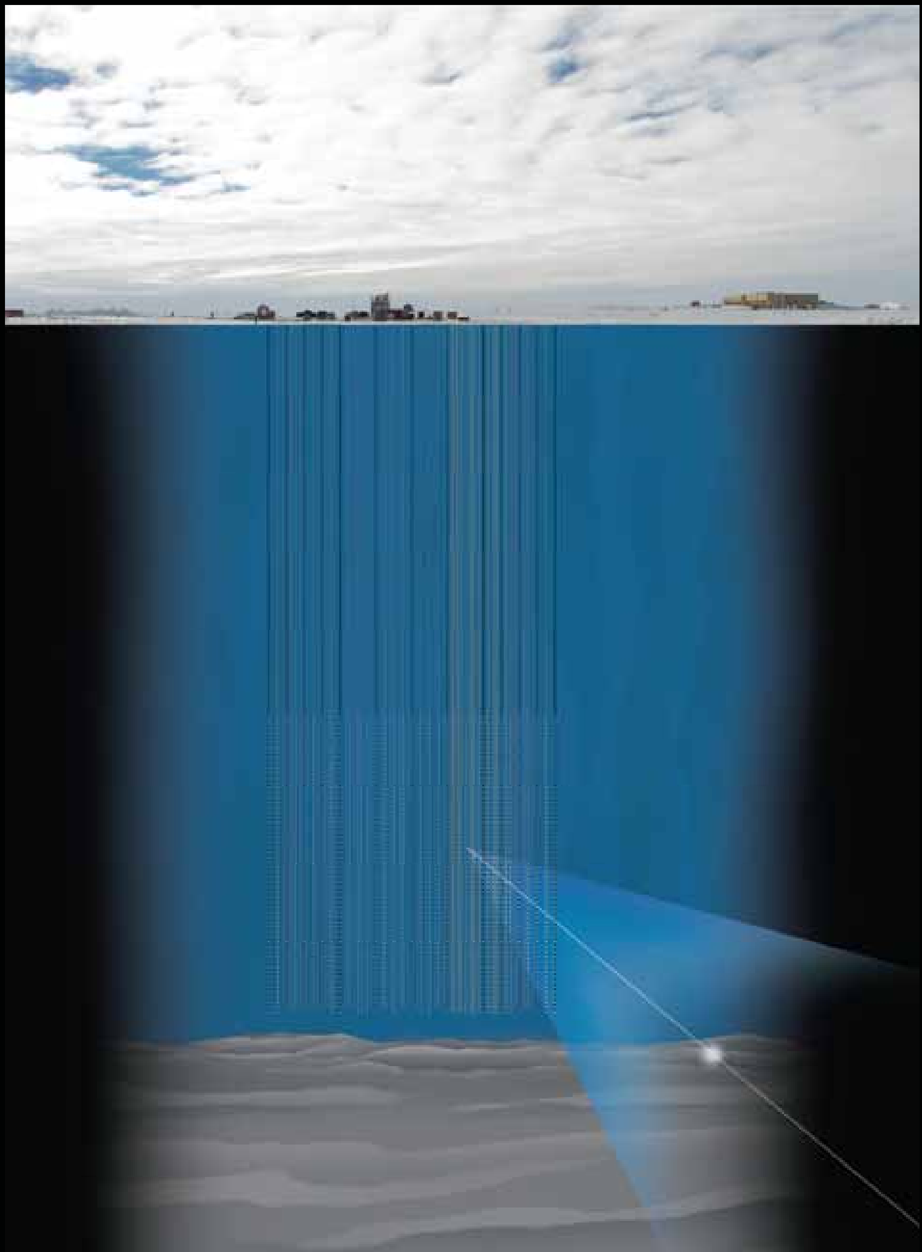


High energy neutrinos from the cold : status and prospects for the IceCube experiment

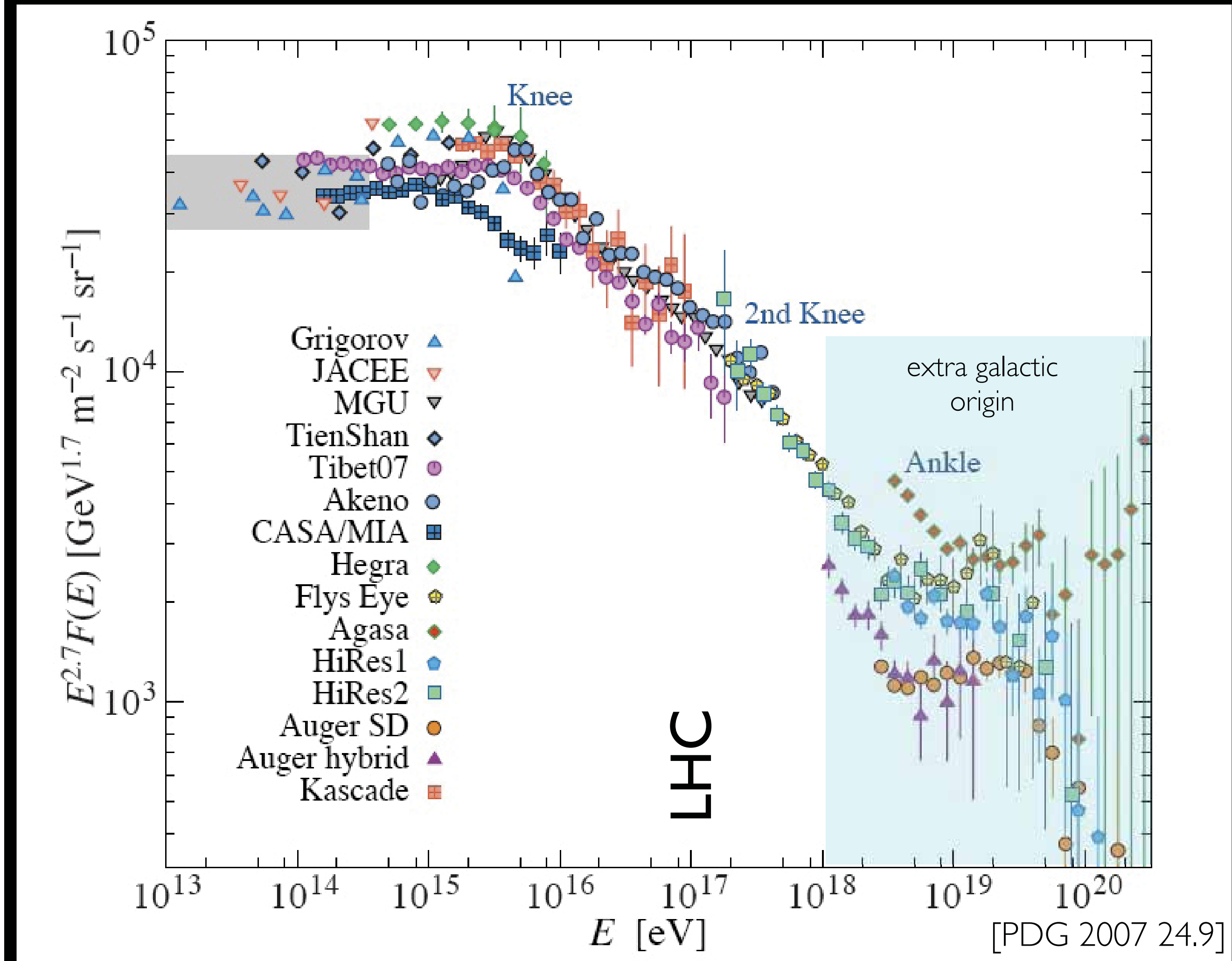
Cécile Portello-Roucelle for the IceCube collaboration
LBNL

Neutrinos on the rocks



- *A pinch of neutrino astronomy...*
  - Why ?
  - What are we looking for ?
- *...with IceCube*
  - Status of the experiment
  - First analyses with IC-9 (2006 configuration)

The cosmic ray puzzle : understanding astro-accelerators



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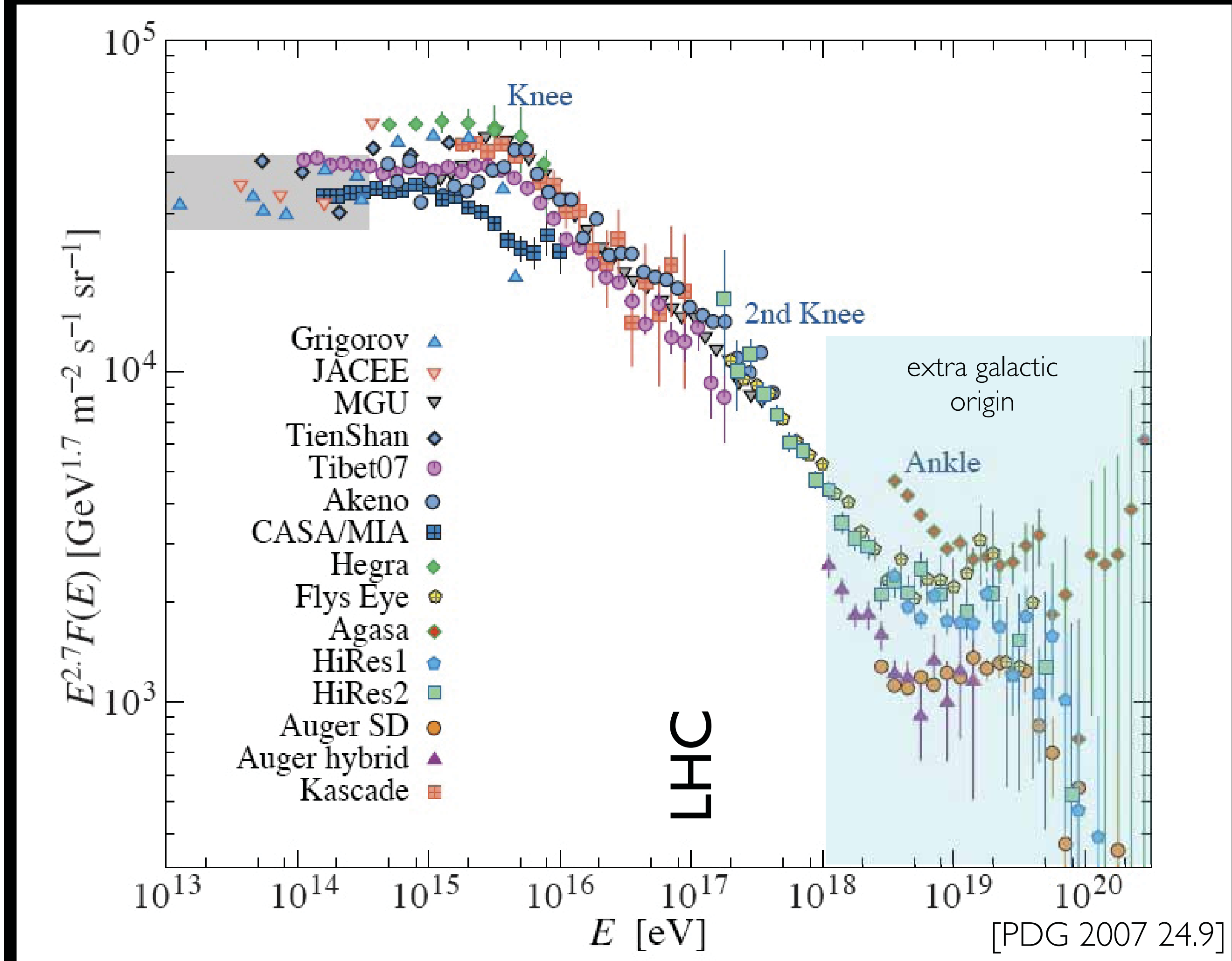
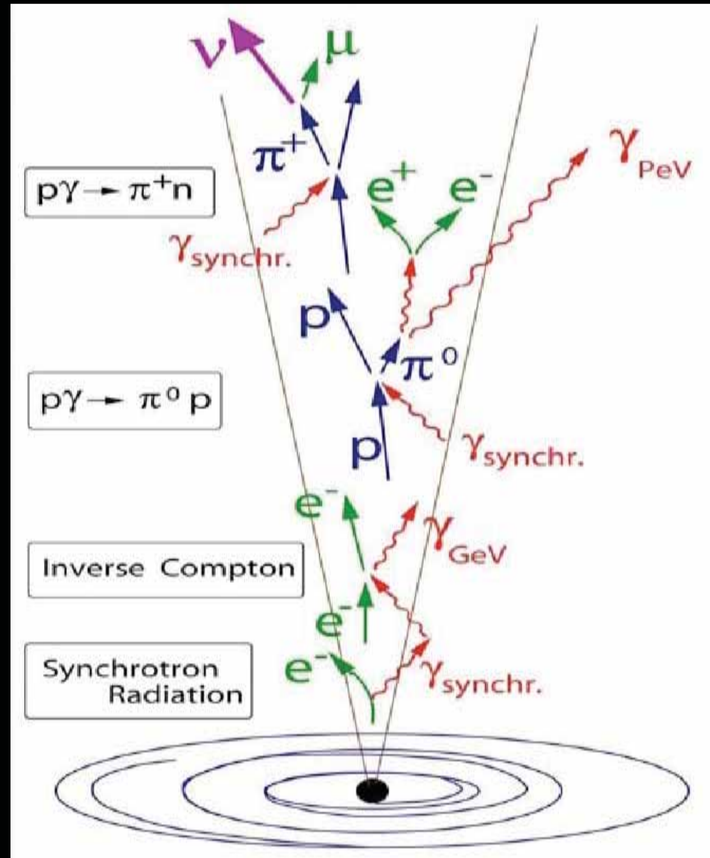




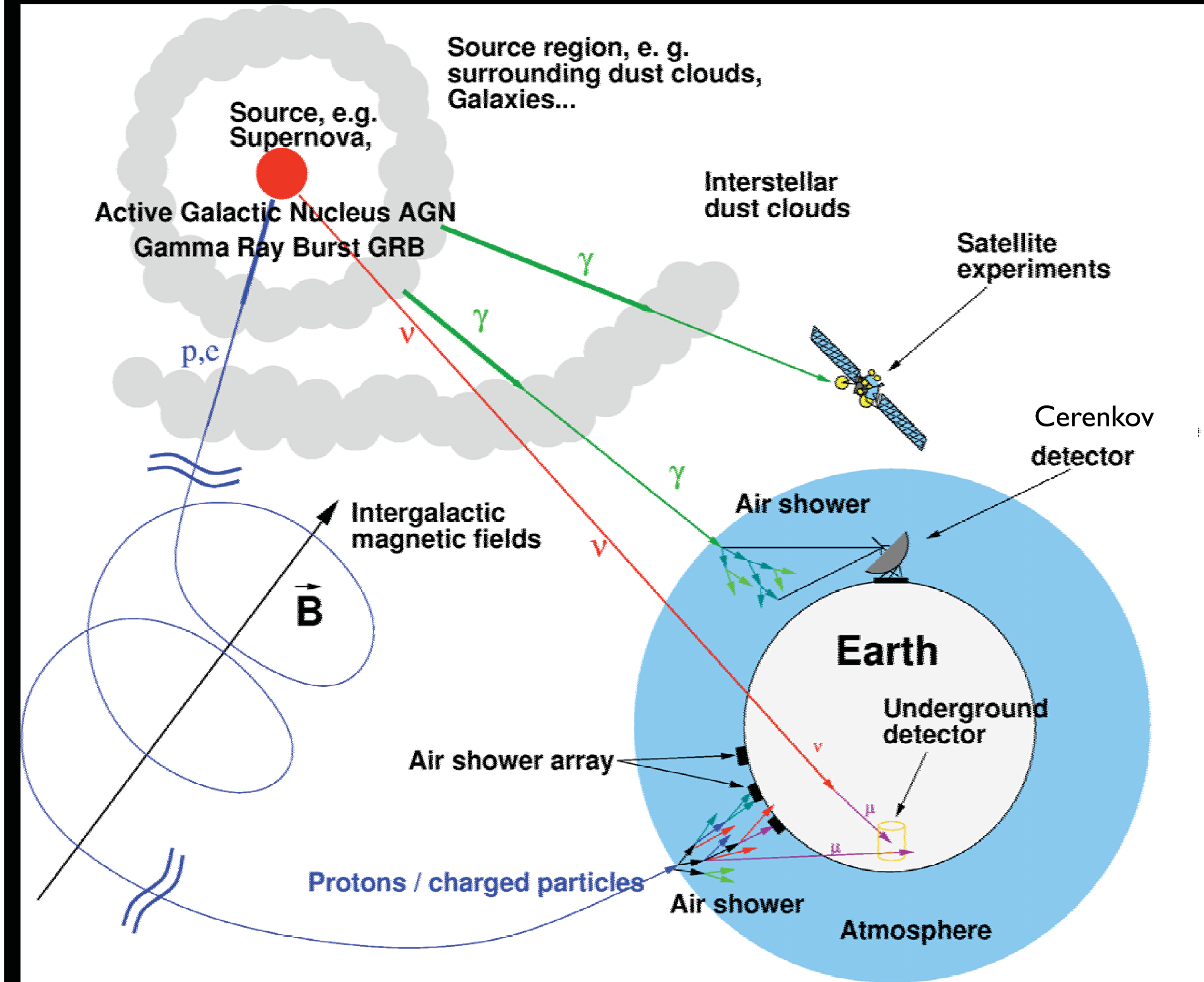
Production of HE ν at the source :
for *hadronic acceleration processes*
pγ interactions
[pp interactions]
➡ $\pi^{\pm}$ decay produces ν

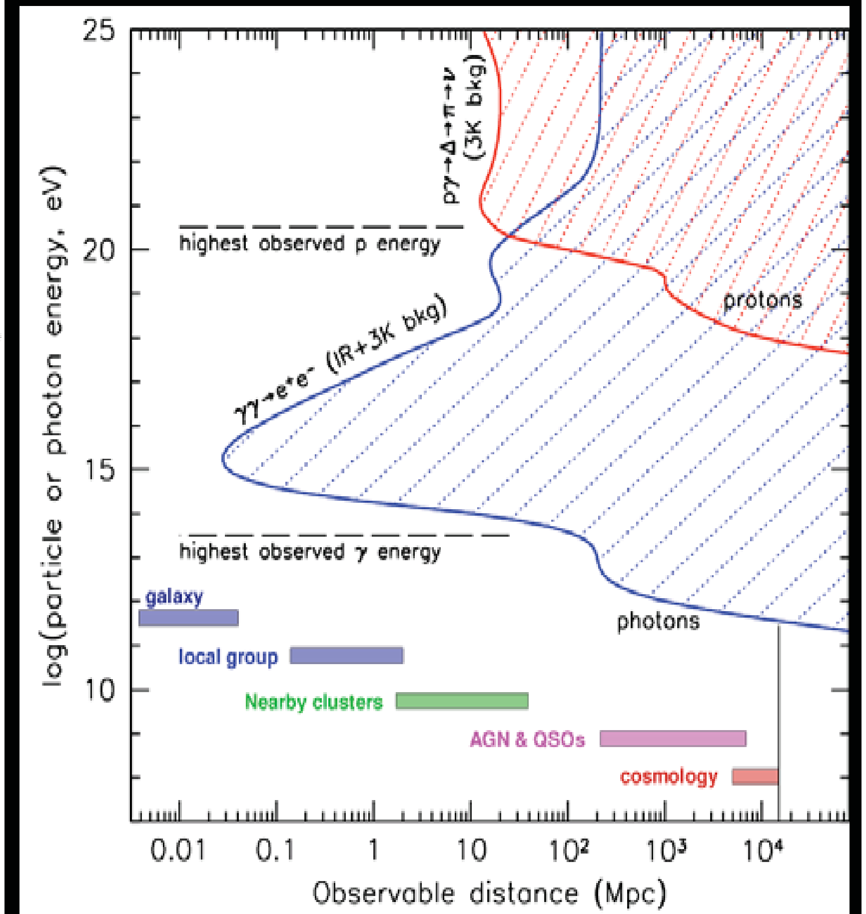
An unique messenger

ν point back toward their sources
+ can go through dust

charged CR deviated at low E

γ absorbed at the source + interaction EM fields





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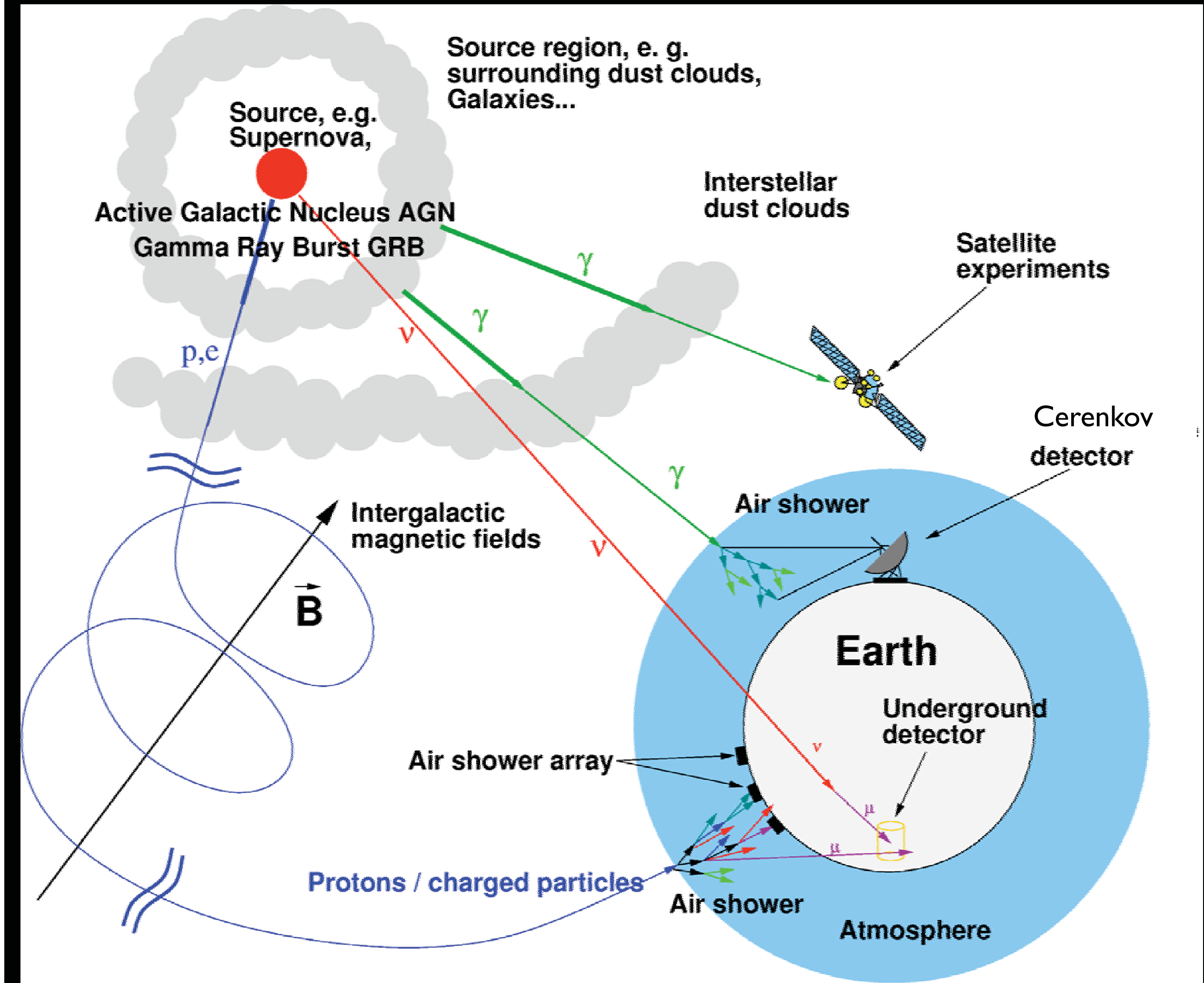
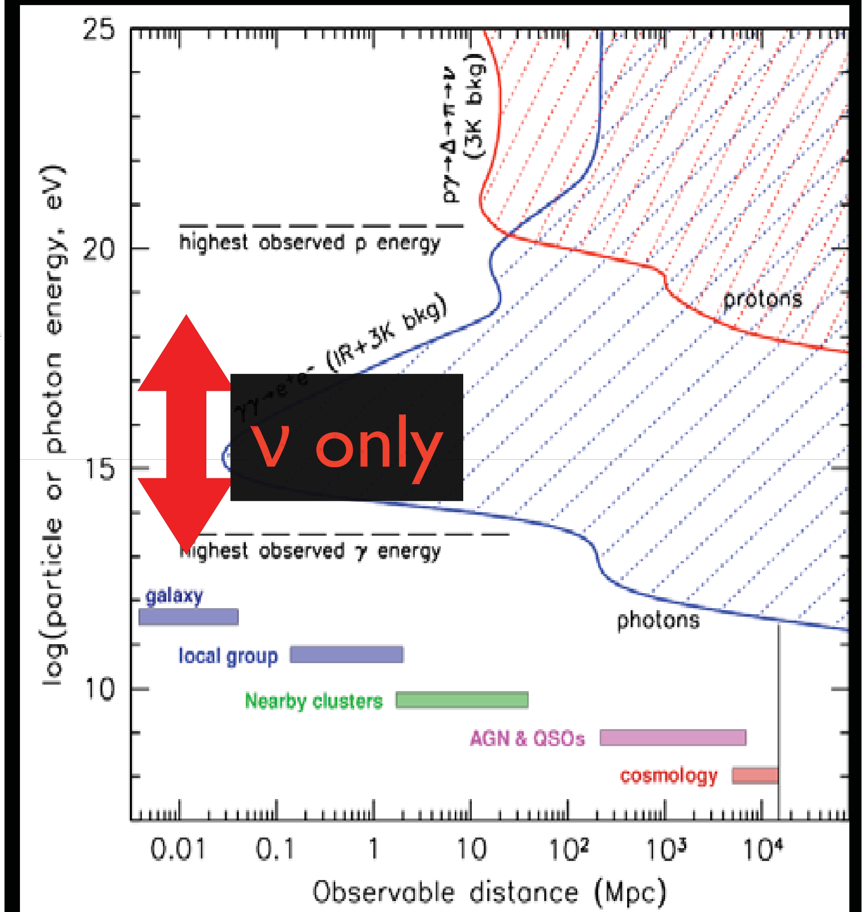
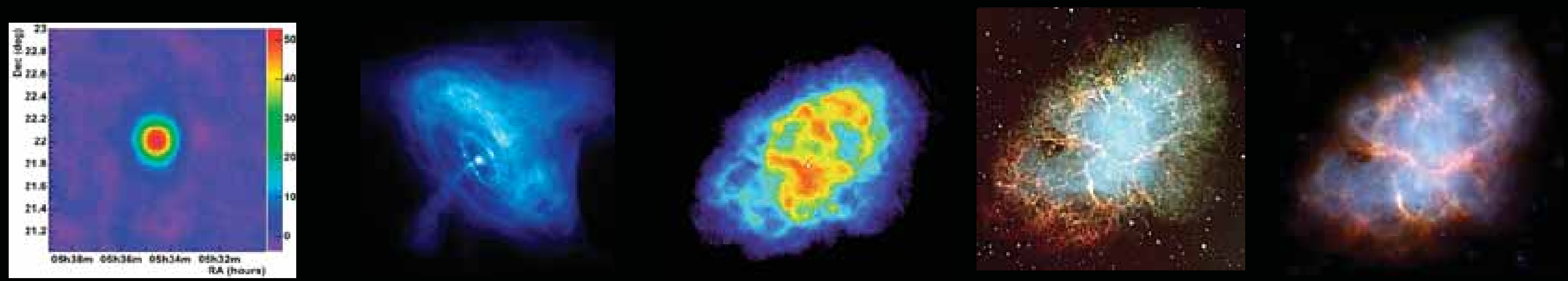




Multimessenger astronomy ?

- Astrophysical objects have been studied in different wavelengths

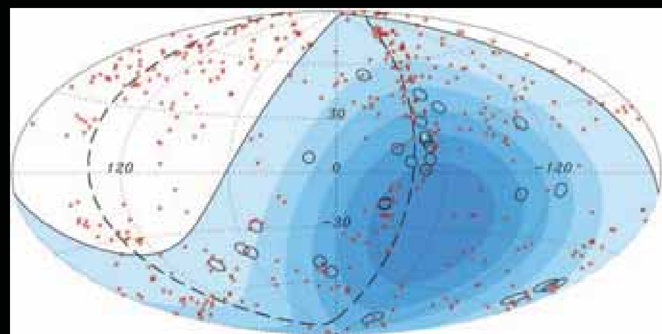
?



...Observations with neutrino telescopes ?

- *Understanding the mechanisms in astrophysical accelerators*
- Many sources observed in gamma rays

- Possible correlation of UHECR arrival directions with AGN



[Pierre Auger coll. arXiv:0712.2843]

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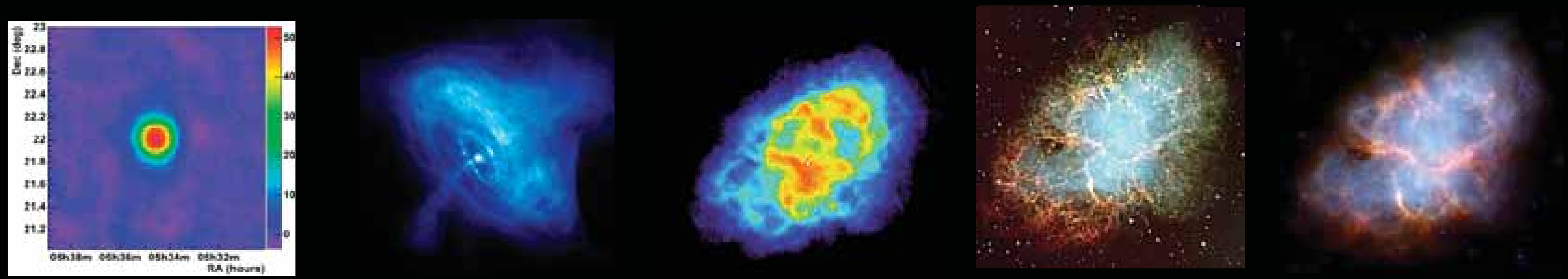

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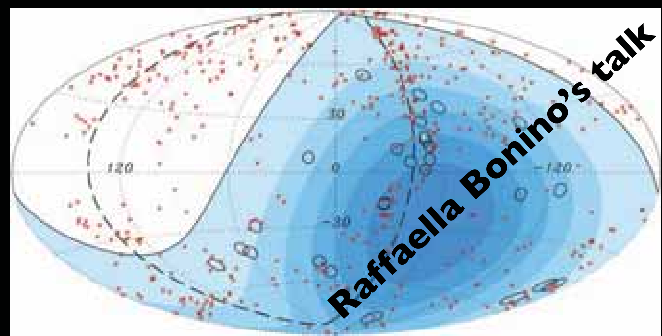

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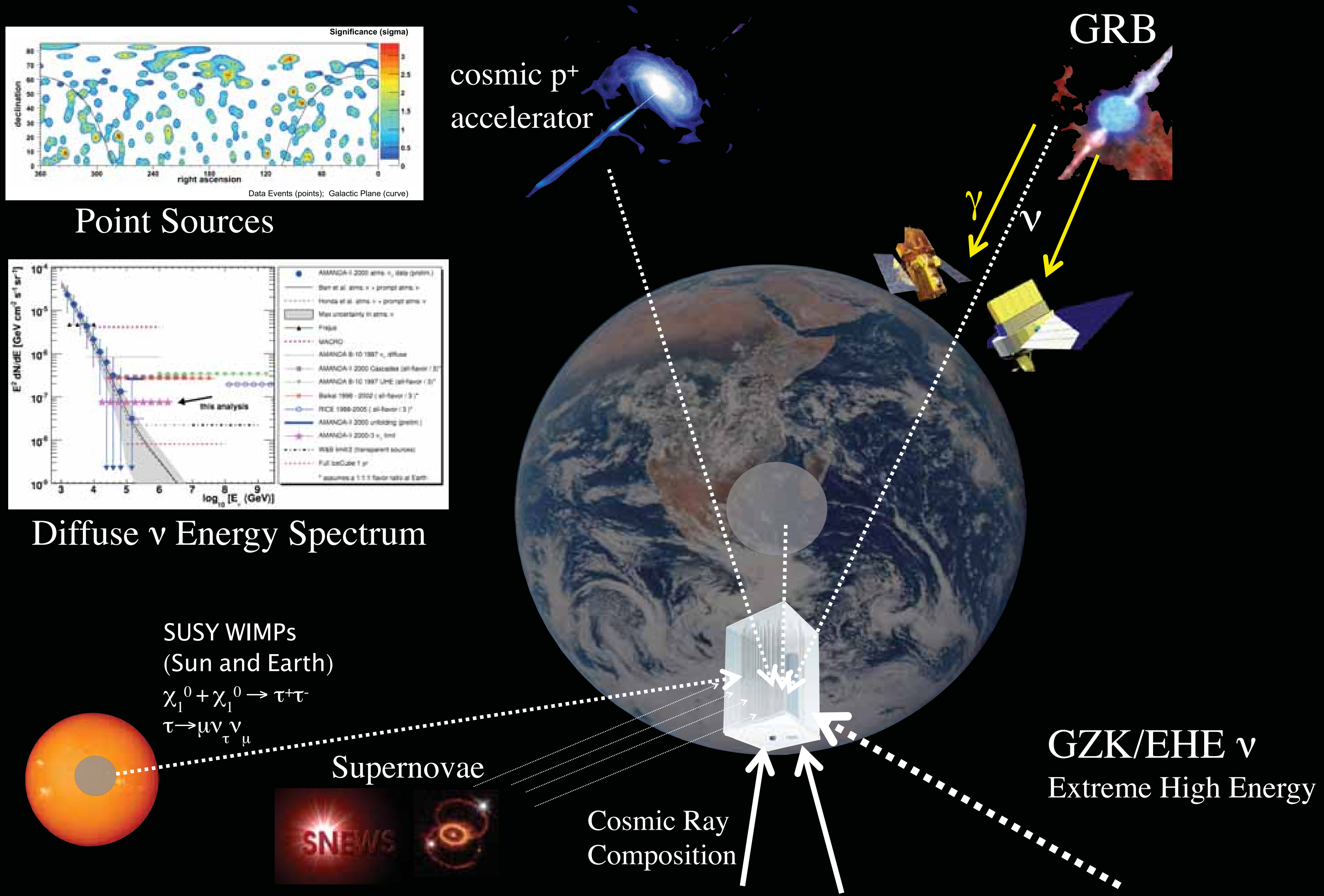
An even broader potential



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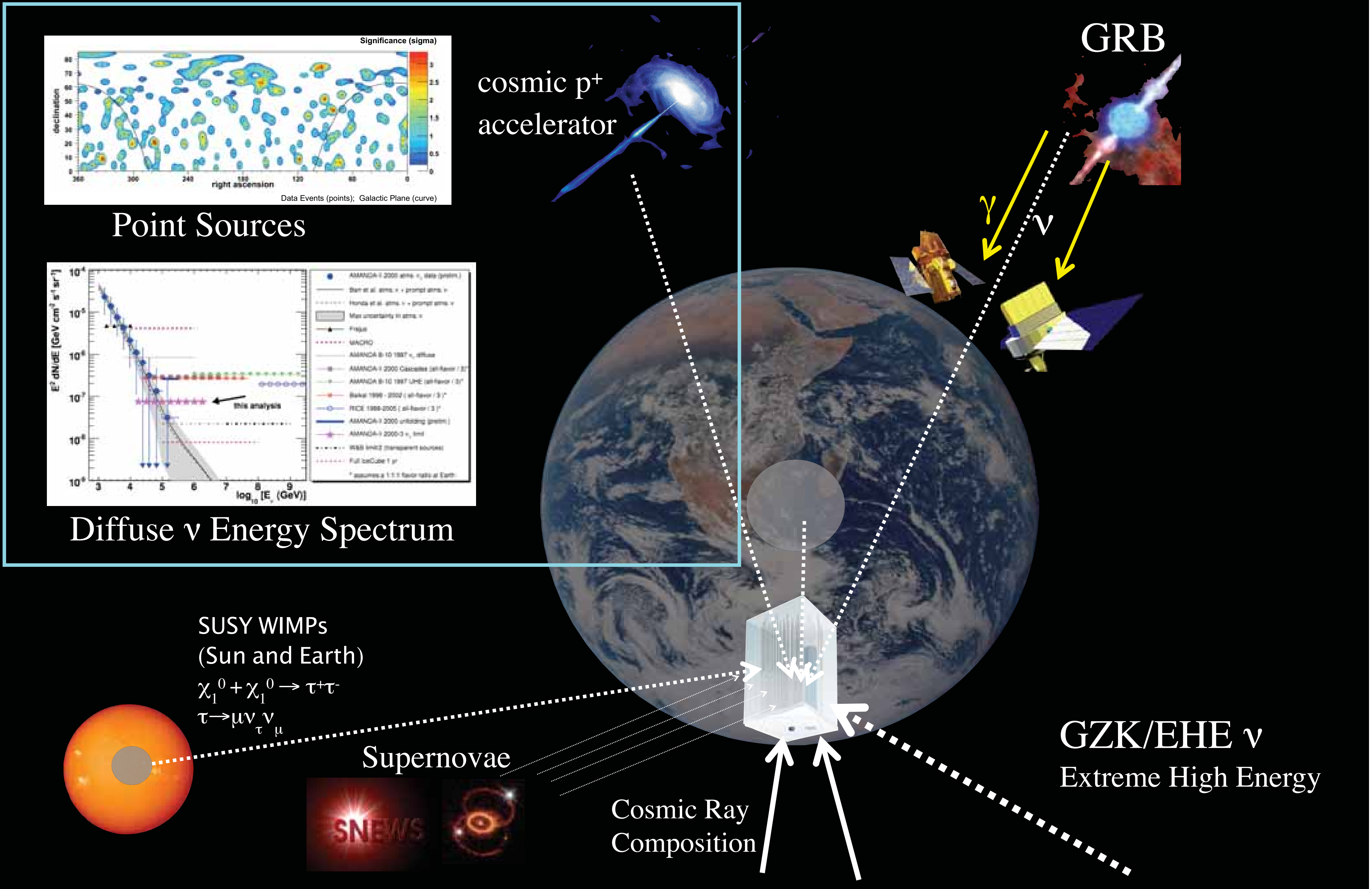
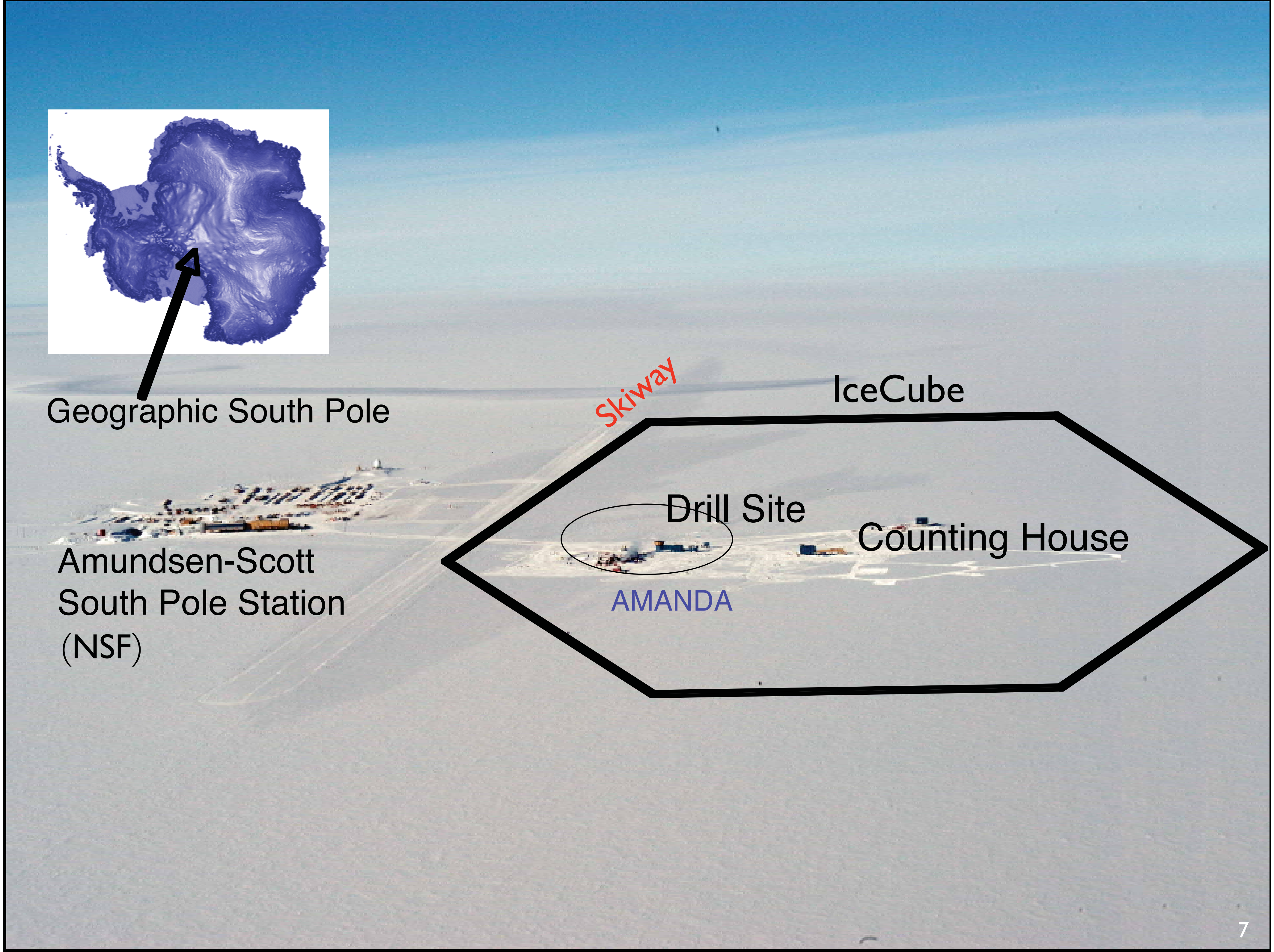
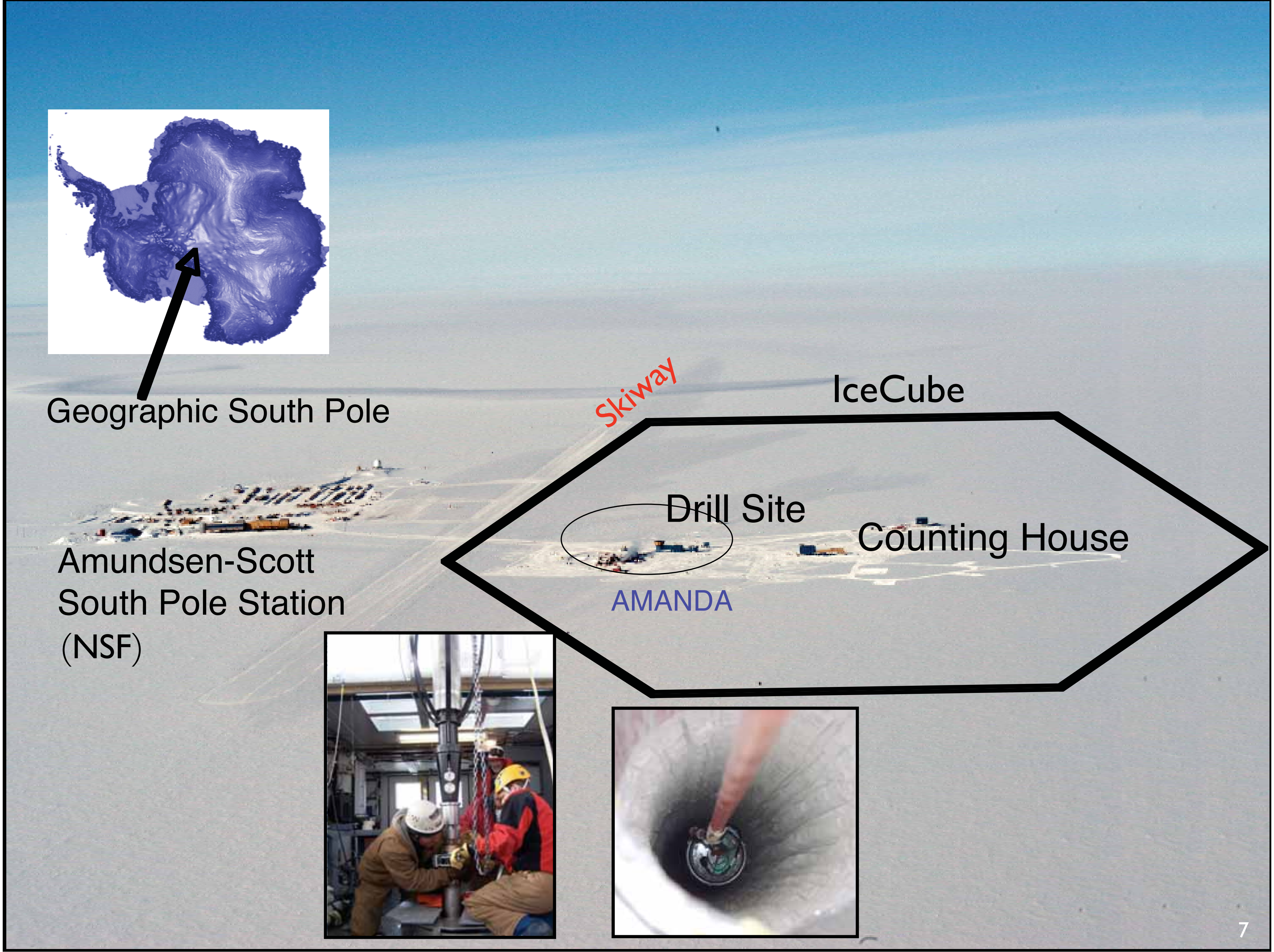



Geographic South Pole
Skiway
IceCube
Drill Site
Counting House
Amundsen-Scott
South Pole Station
(NSF)
AMANDA


Geographic South Pole
Skiway
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The IceCube detector

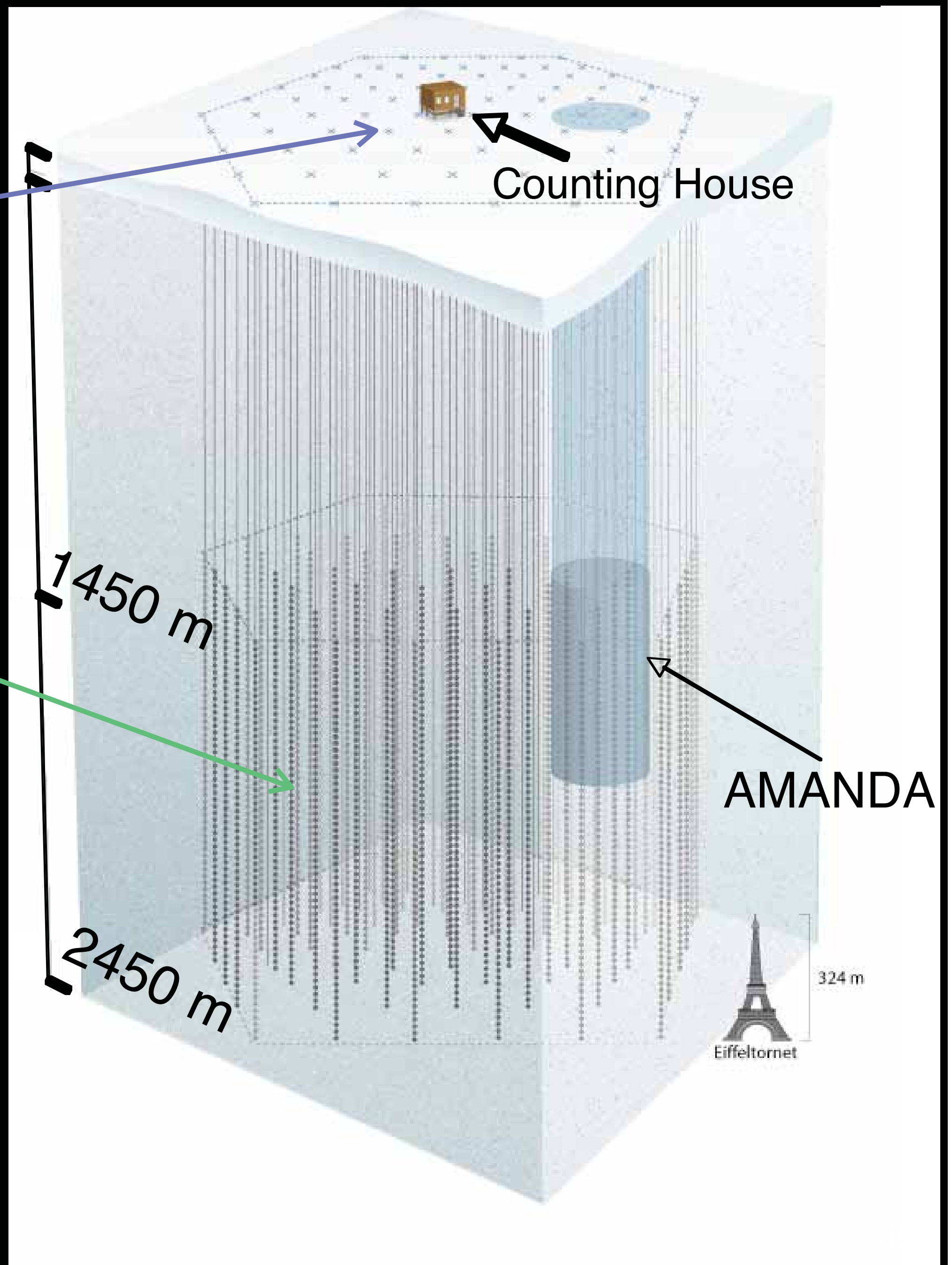
instrumenting 1 km^3 of ice

IceTop :
Surface air shower array
Frozen tanks - 2DOMs

InIce :
80 strings each with 60 digital optical modules (DOM)

125m spacing between strings
17m between DOMs

Detect ν of all flavors
E range : 10^{11} to 10^{20} eV



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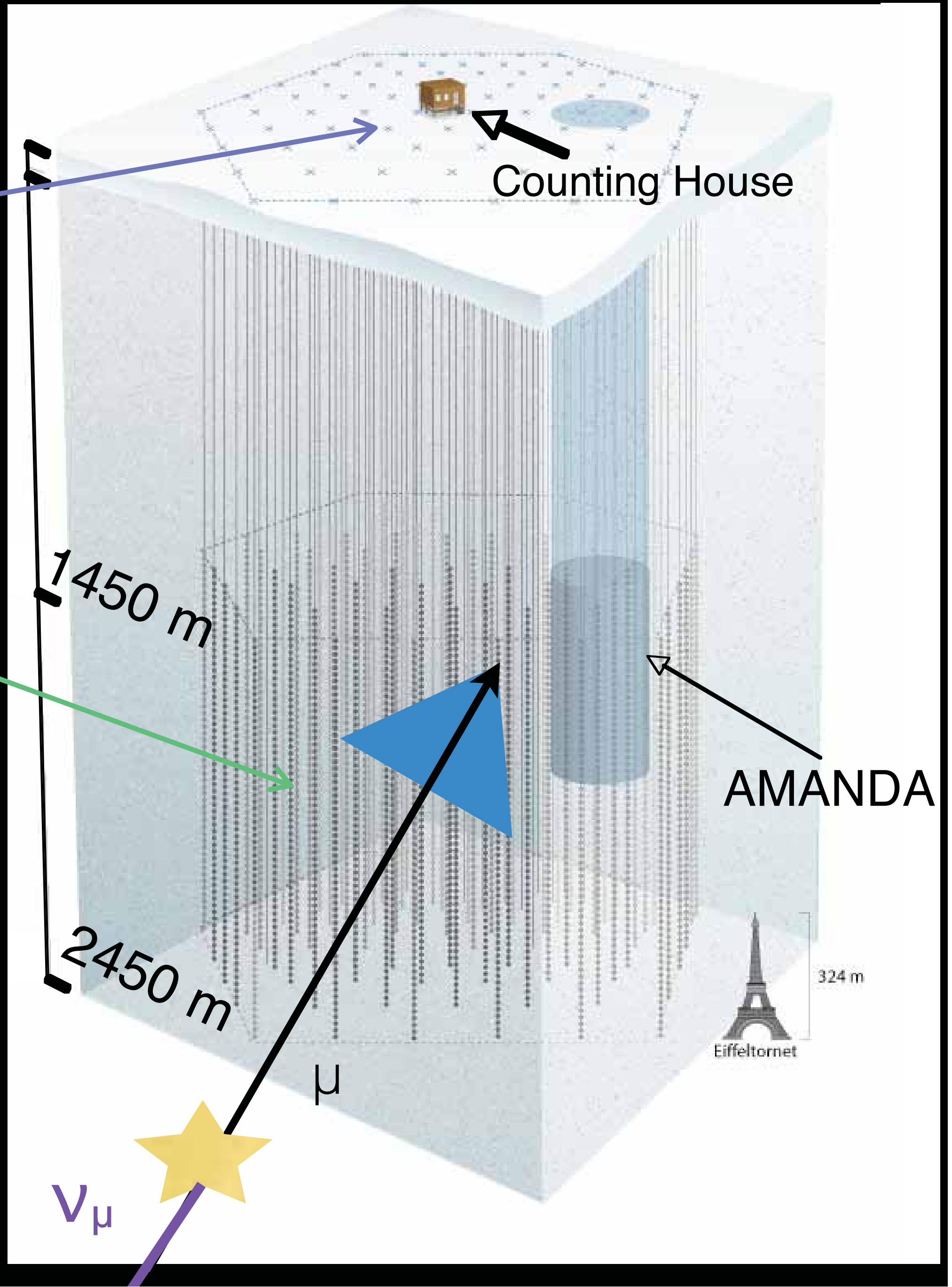
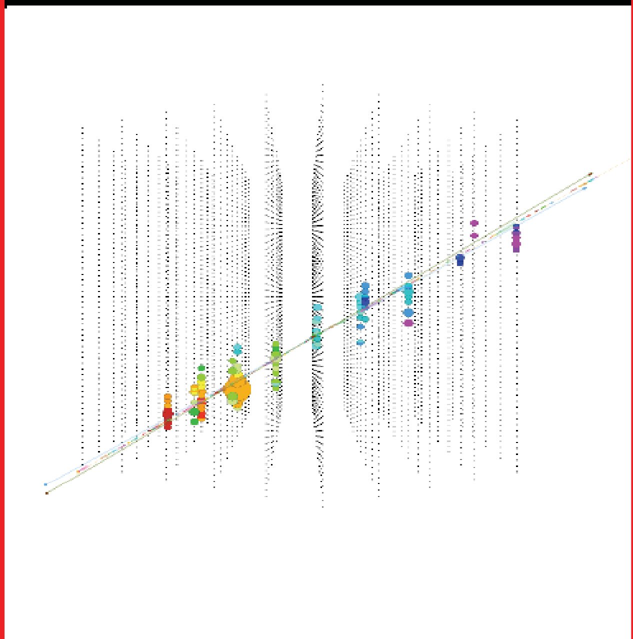
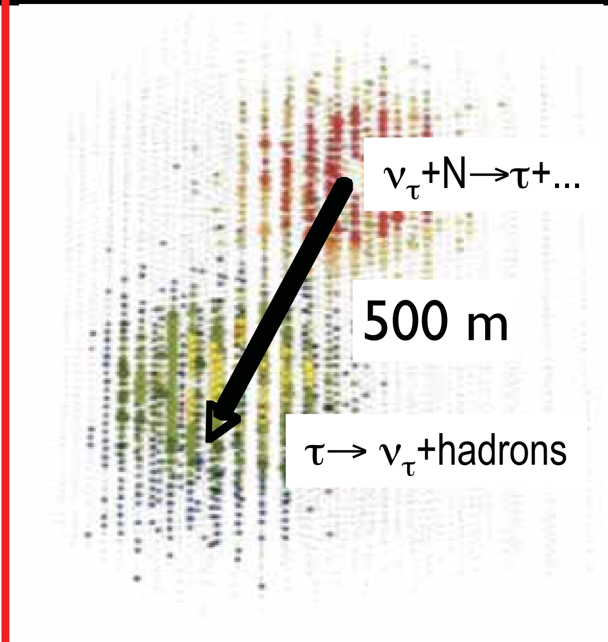


Particle tracking in IceCube : signatures

ν_μ	ν_e	ν_τ
E_μ = 10TeV ~90 DOMs hit	E = 375 TeV "spherical" shell	E = 10 PeV 2 bangs separated by ~ 50*(E_τ/PeV)
		
E~dE/dx , e>1TeV E res. : Δlog(E)~0.3 ang res : 0.8-2 deg	poor angular resolution E res : Δlog(E)~0.1-0.2	very low background pointing capability good E measurement

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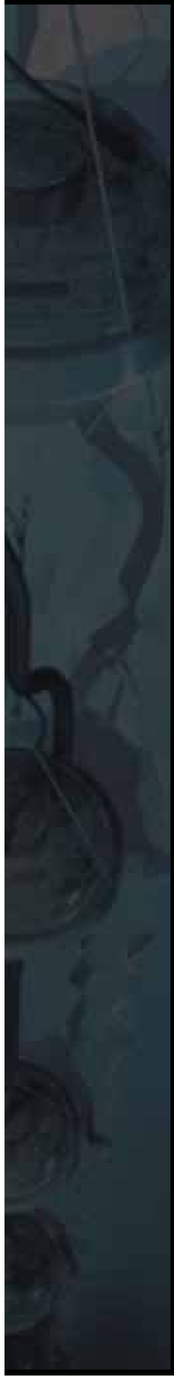
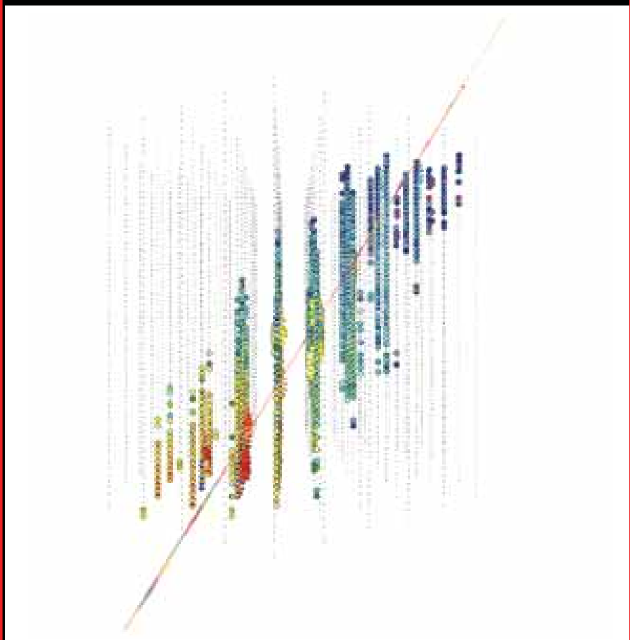
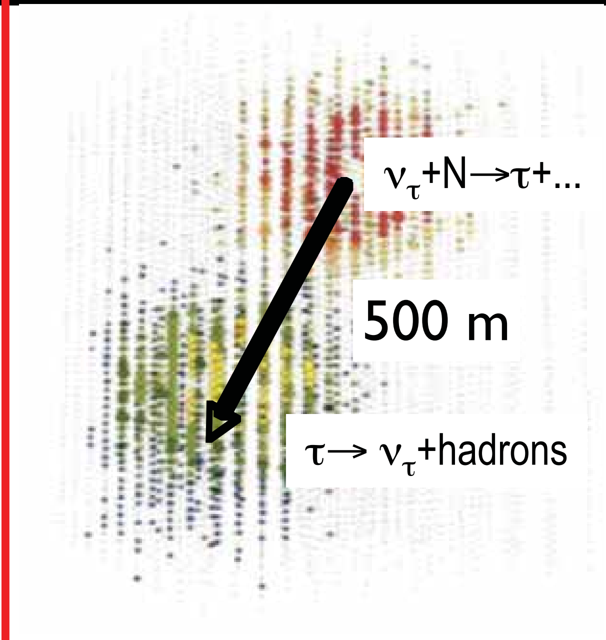


ν_μ	ν_e	ν_τ
6×10^{15} eV (6 PeV) ~1000 DOMs hit ~ 20 km	E = 375 TeV "spherical" shell	E = 10 PeV 2 bangs separated by ~ 50*(E_τ/PeV)
		
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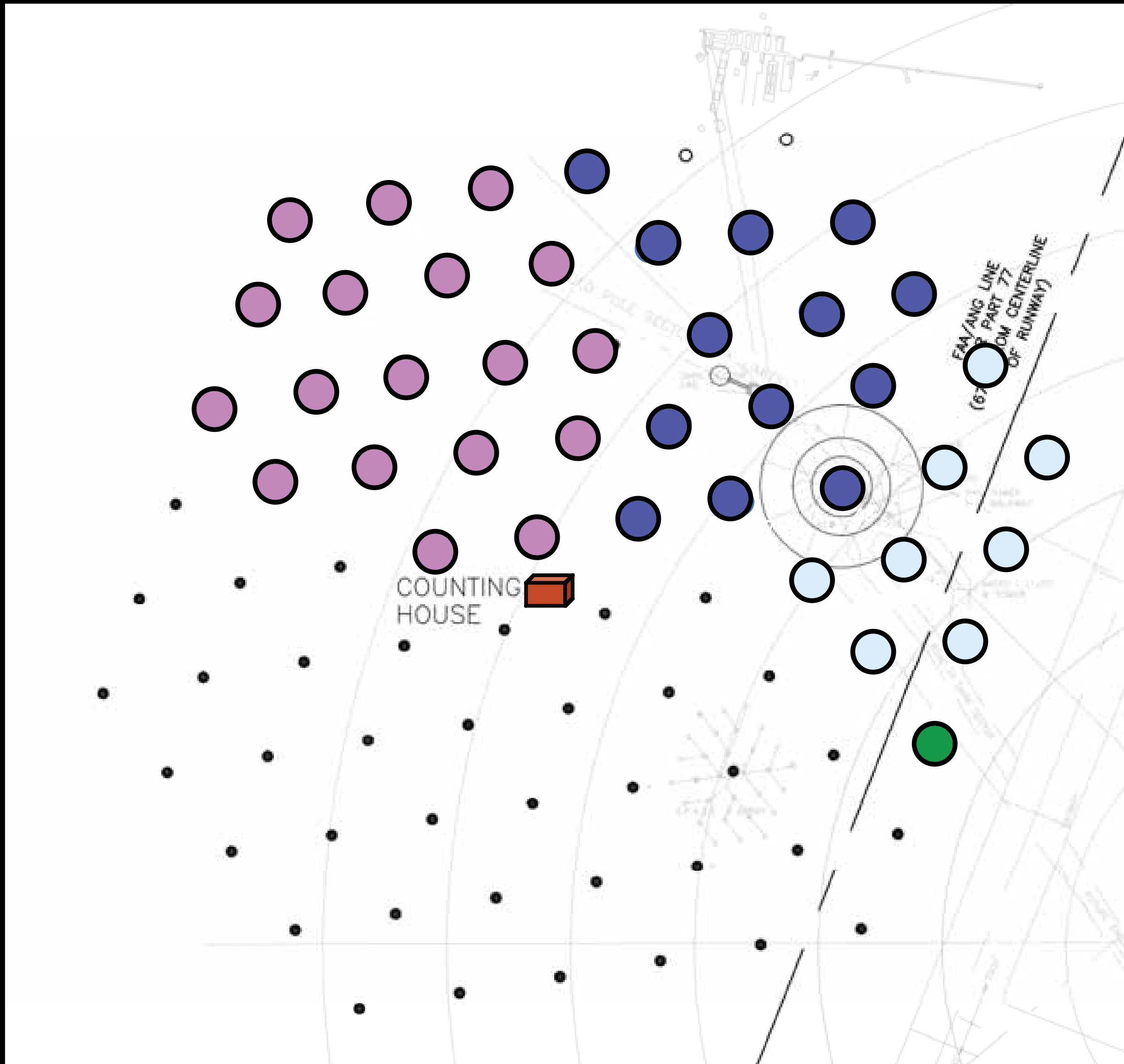
Building IceCube



AMANDA

2004-2005
1 string deployed
First data
astro-ph/0604450

2005-2006 *IC-9* IT-16
8 string deployed

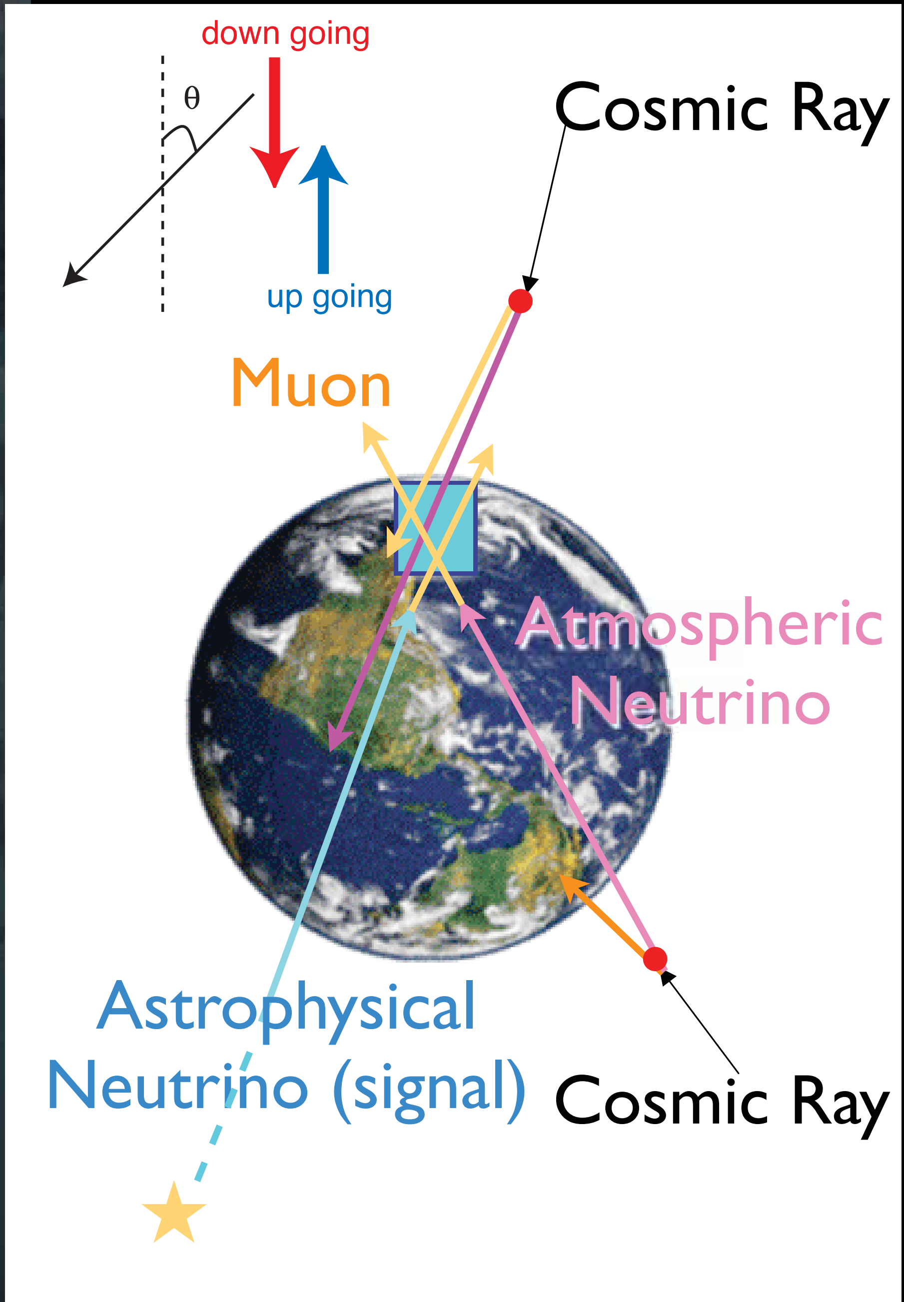
2006-2007 *IC-22* IT-26
13 strings deployed

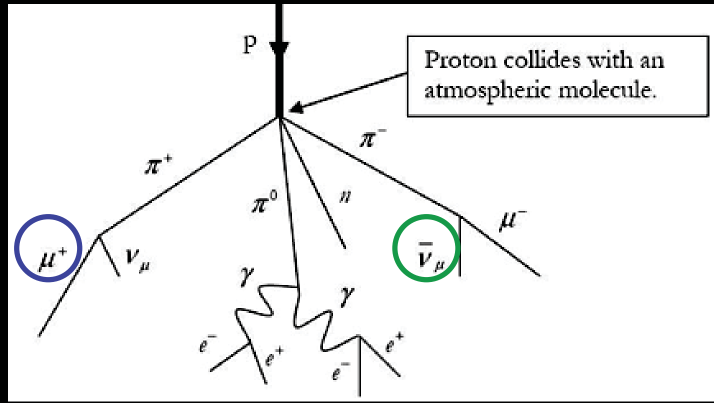
2007-2008 *IC-40* IT-40
18 strings deployed!
Commissioning ongoing.

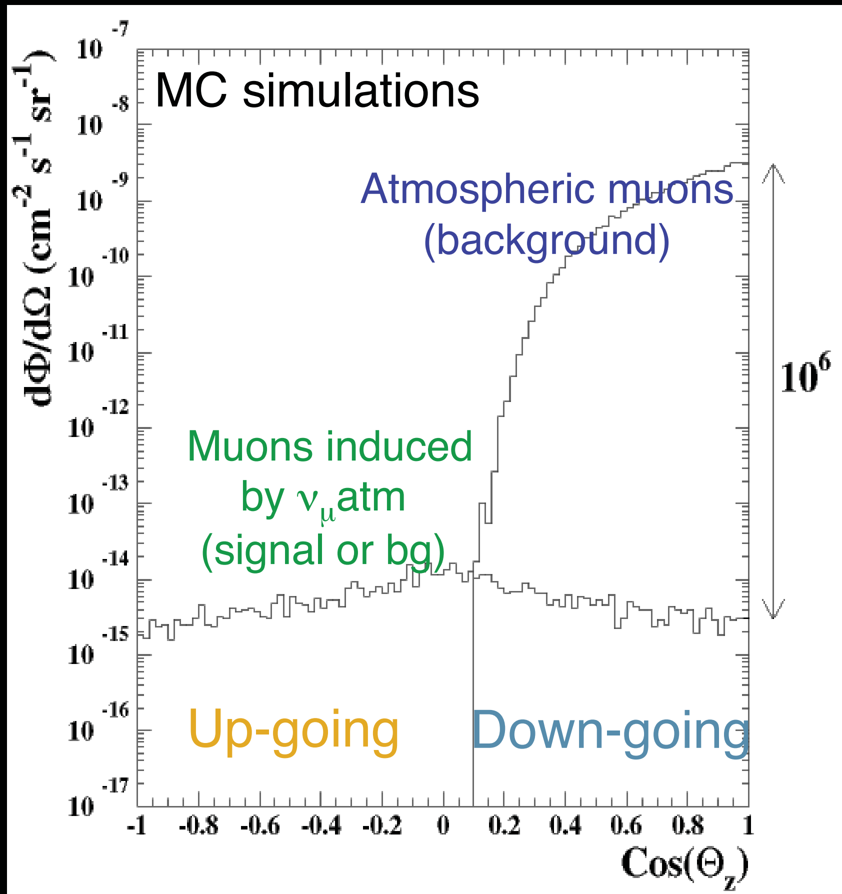
Half the detector is built !

Very steady deployment pace completion in 2011

Looking for ν_μ ...







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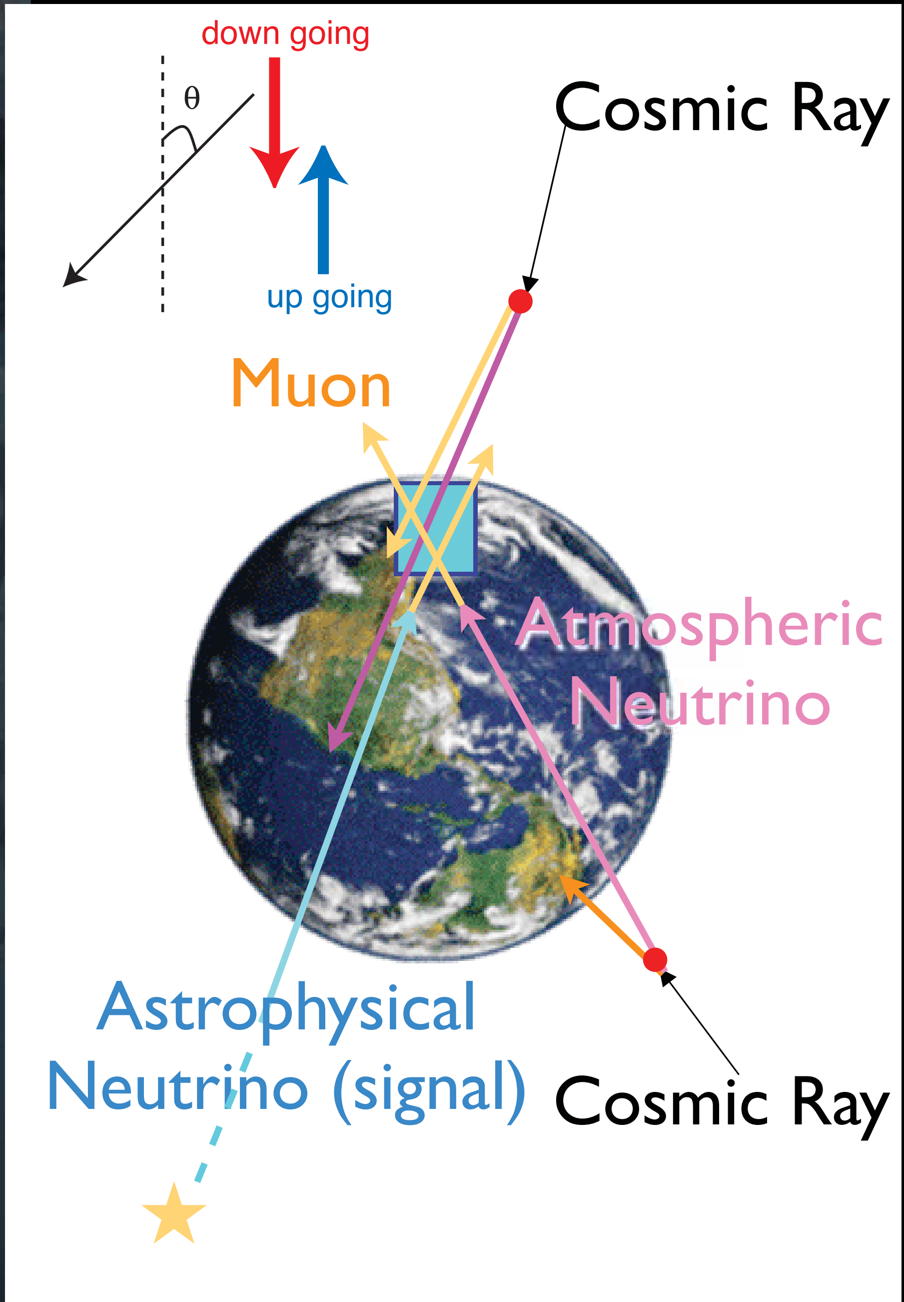
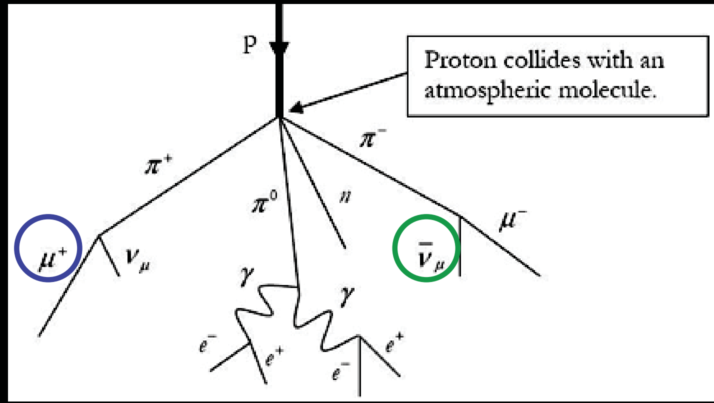
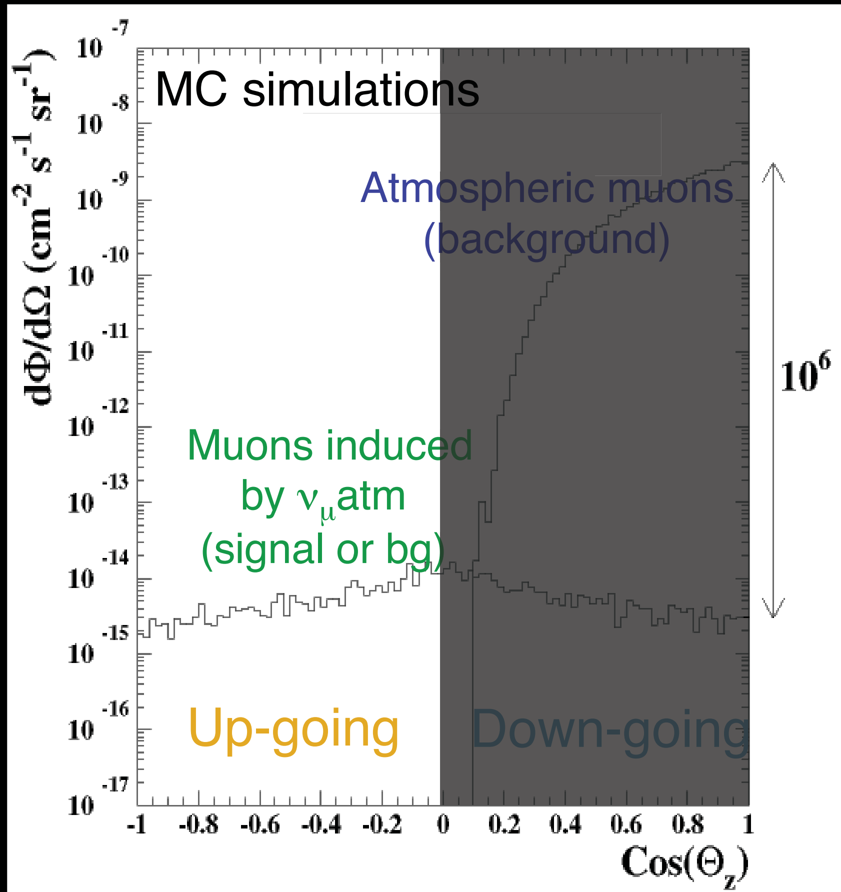


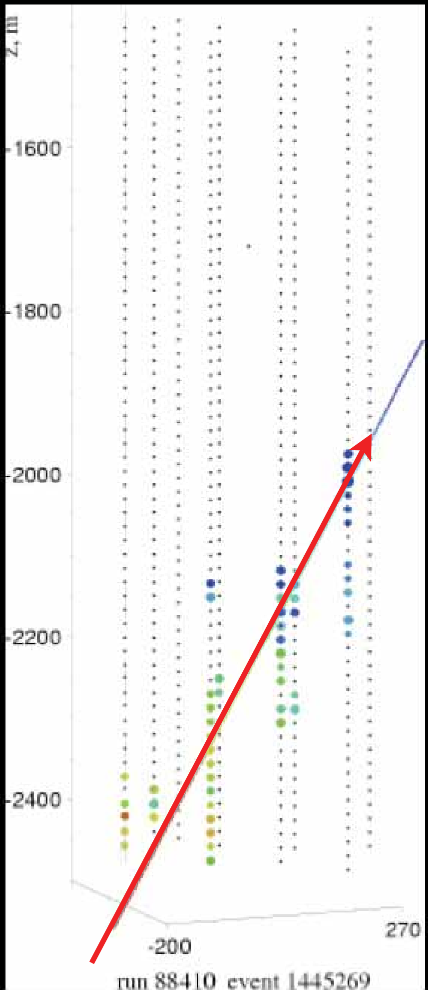




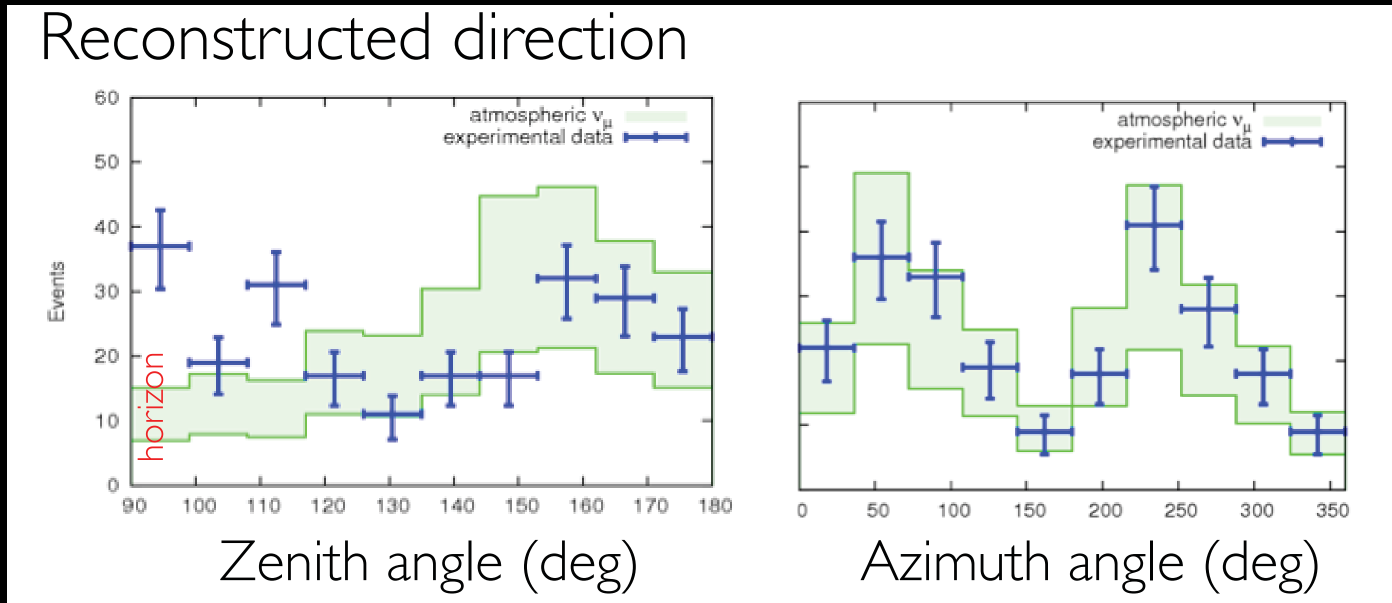
2006 data : IC-9 configuration

137.4 days of total livetime

234 events measured   *expected : 211 ±76(syst) ±14(stat)*



A real IC-9 ν_μ candidate
7 strings hit



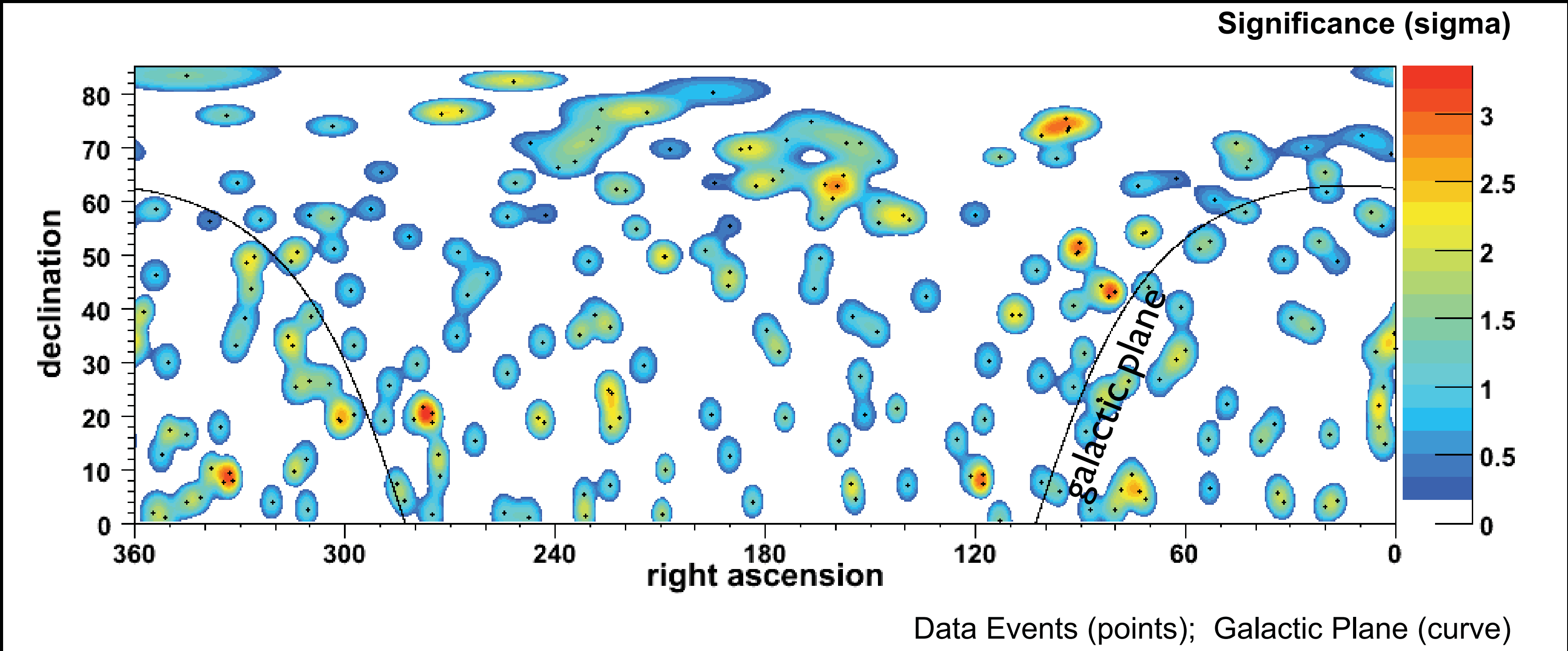
< 10% mis-reconstructed downgoing muons predominantly near horizon

We can detect neutrinos !

2006 results with IC9 [Phys. Rev.D76 (2007) 027101]

IC-9 point source search : first IceCube sky map

IC-9 angular resolution 2° - sensitivity comparable to AMANDA II
will get better as detector grows



C.Finley et.al., arXiv:0711.0353 [astro-ph] , p.107-110.

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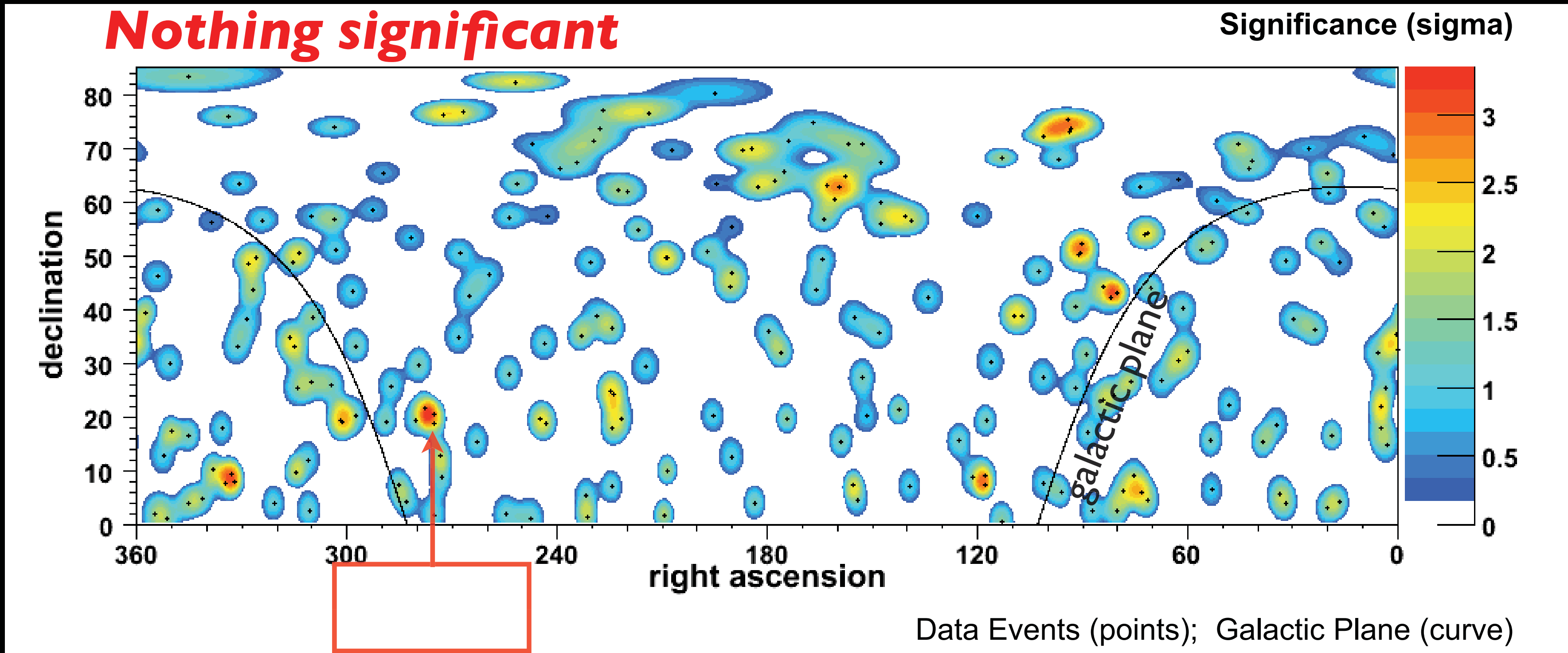

C.Finley et.al., arXiv:0711.0353 [astro-ph] , p.107-110.

Random clustering of background: 60% of simulated background trials (data scrambled in right ascension), have a maximum deviation (anywhere) of 3.35 sigma or greater.

Chance probability of the hottest spot = 60% ... not significant.

Search for a diffuse flux of ν with IC-9

Diffuse flux = effective sum from all (unresolved) extraterrestrial sources evidence for hadronic acceleration processes.
Possibility of a signal even if sources are too faint to be resolved

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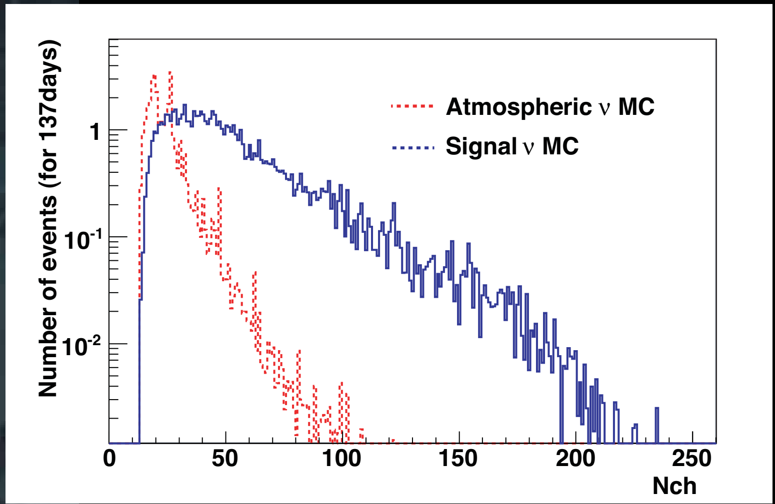

Investigate energy related variables (nb of channels) to look for astrophysical neutrinos !

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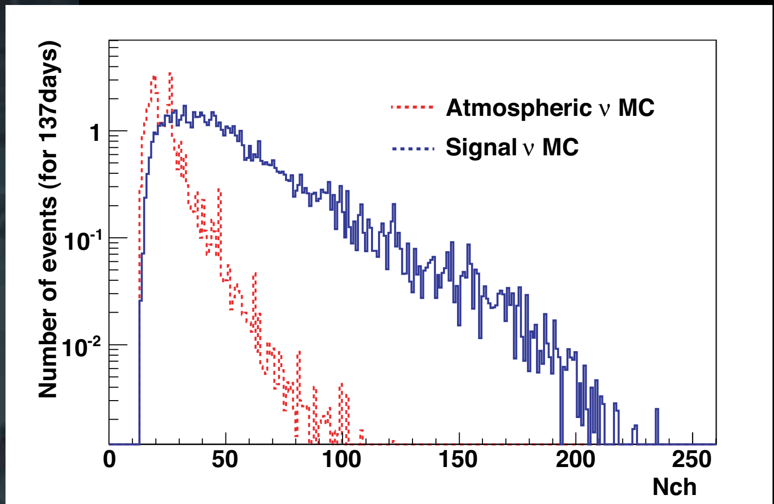
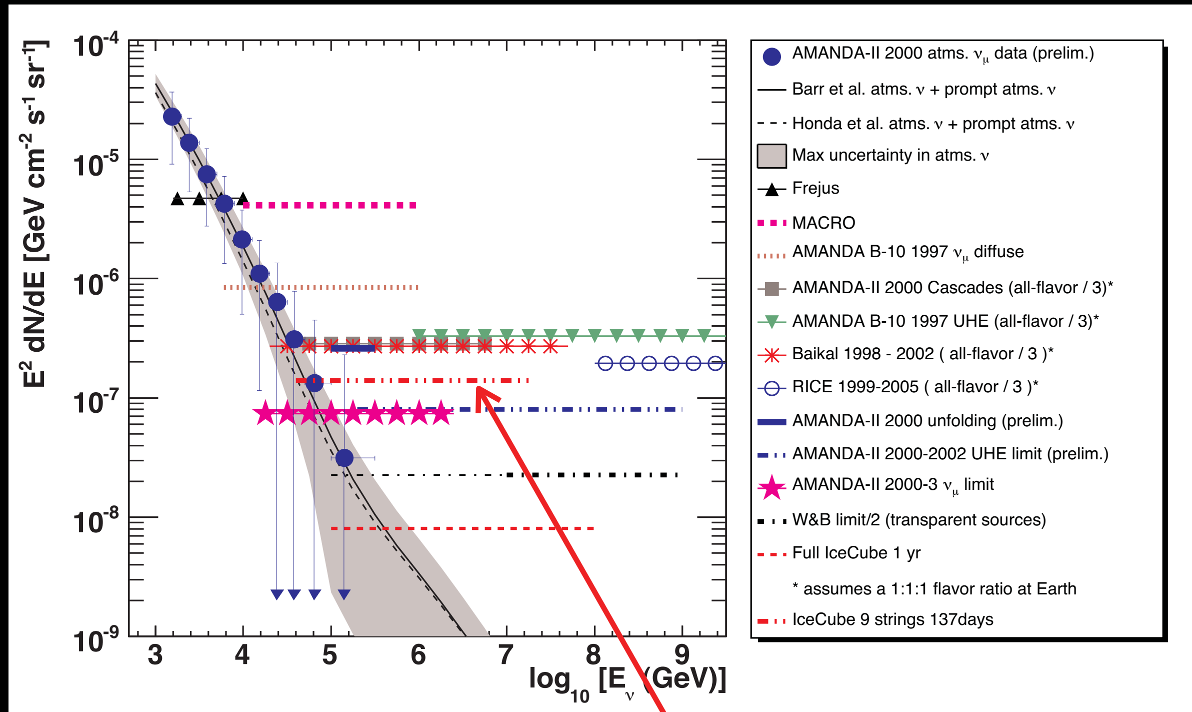


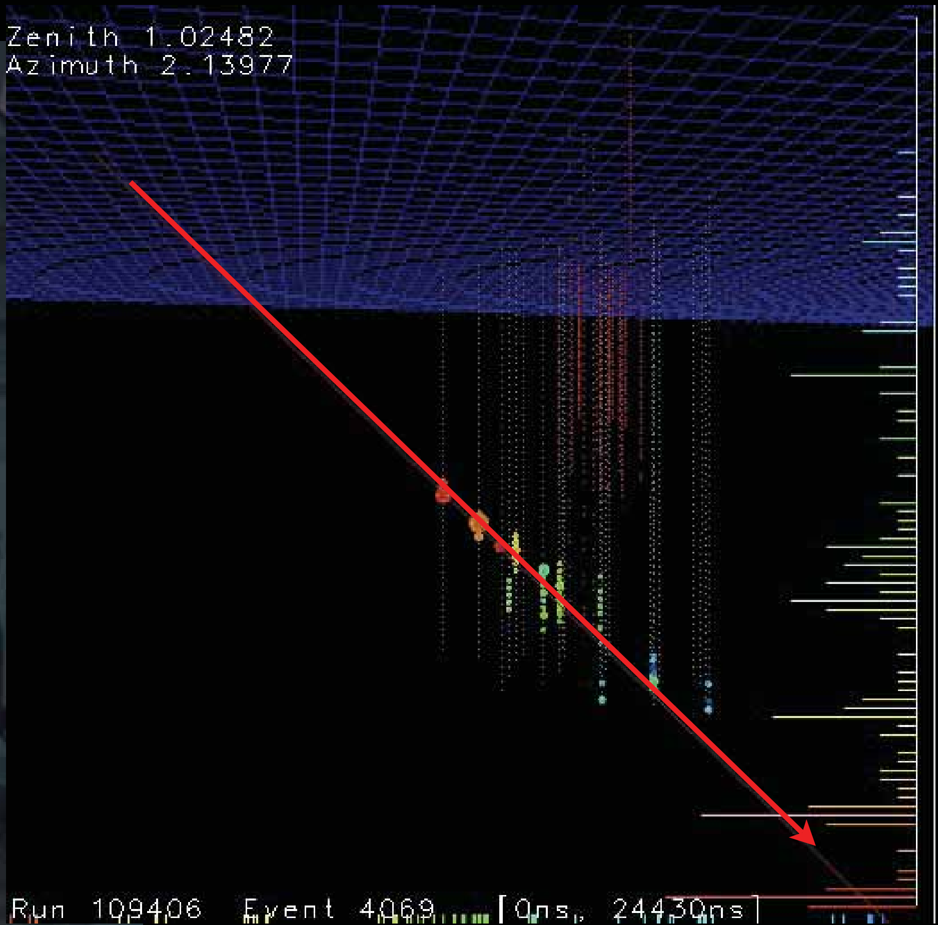


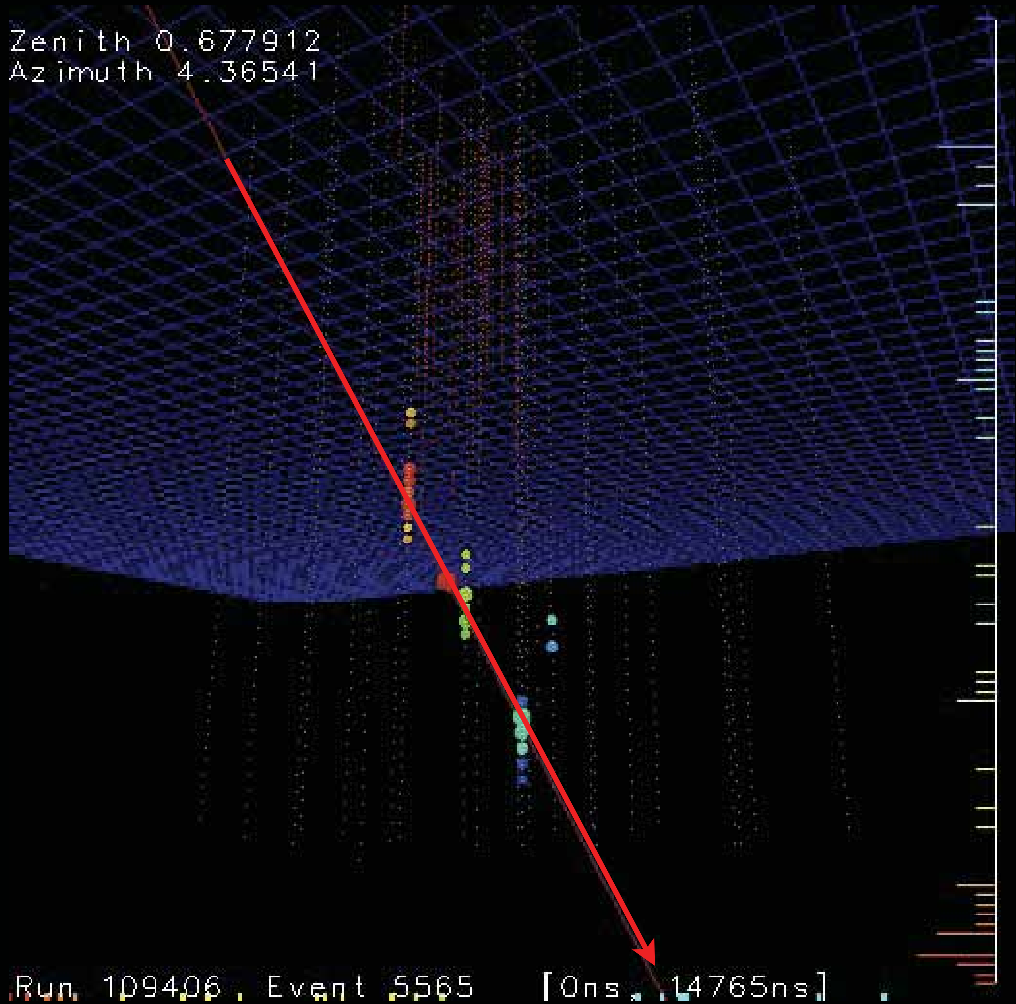
Investigate energy related variables (nb of channels) to look for astrophysical neutrinos !

E^2 dN/dE < 1.4 x 10^{-7} GeV/cm^2/s/sr

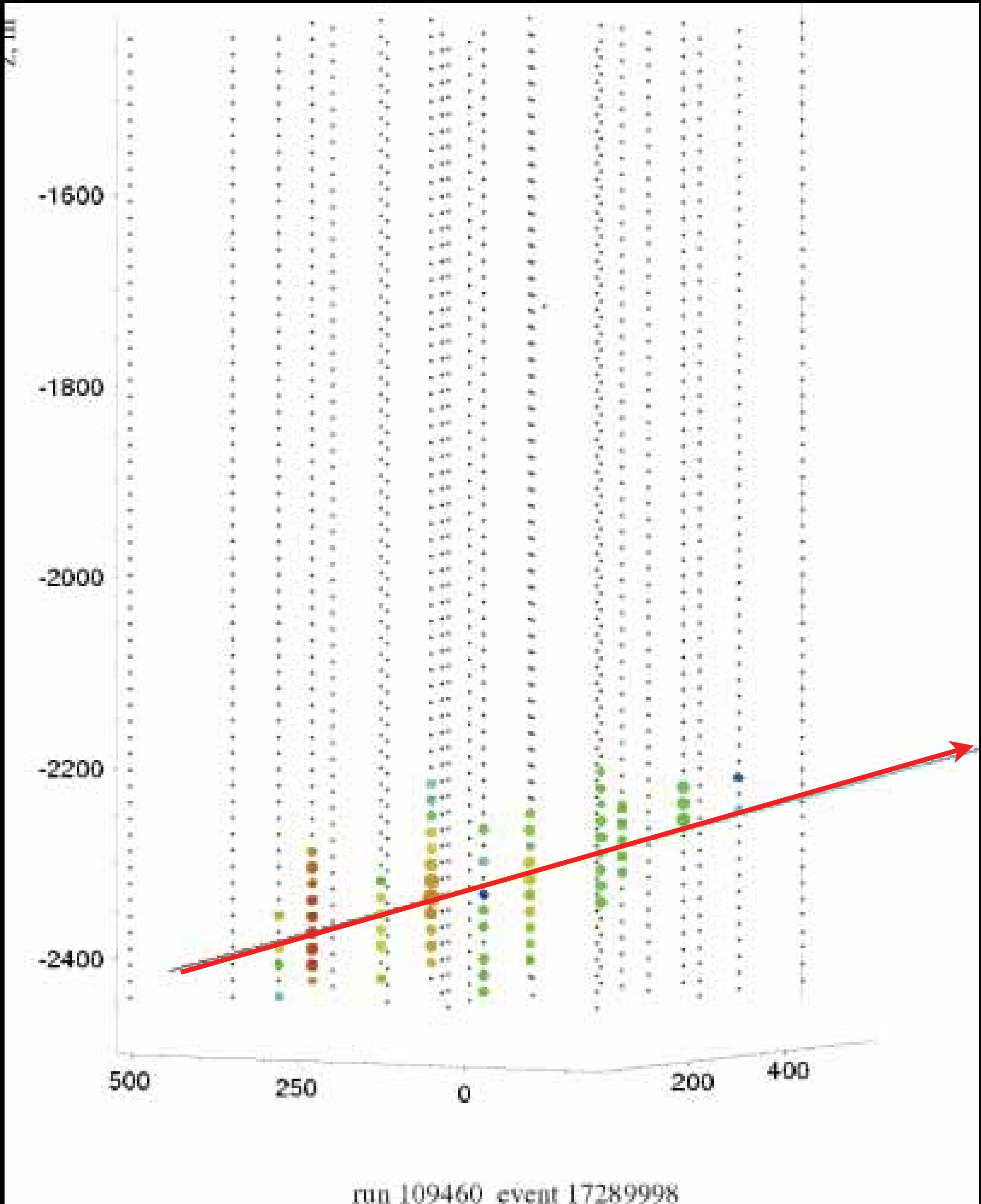
IceCube has already better instantaneous sensitivity than AMANDA II

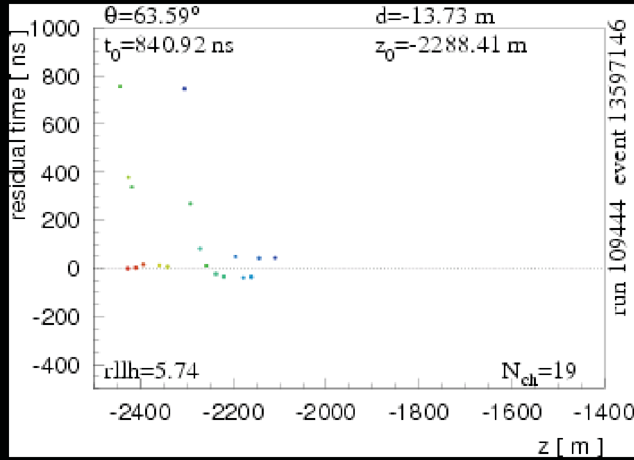
Going further IC-22 - 2007 data (downgoing μ)...

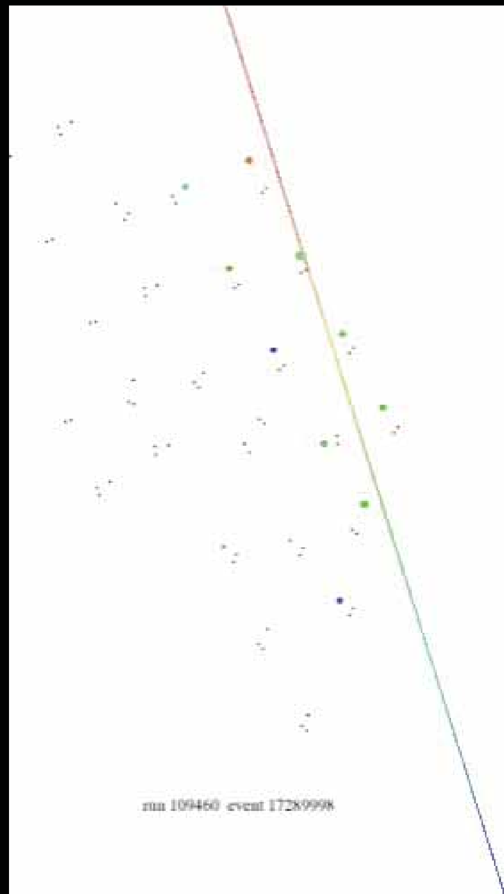




Real ν_μ candidate with IC22...To be continued...







Summary

- The largest neutrino telescope running
- 50% already deployed.
- IceCube will be complete in 2011
- We benefit from AMANDA experience

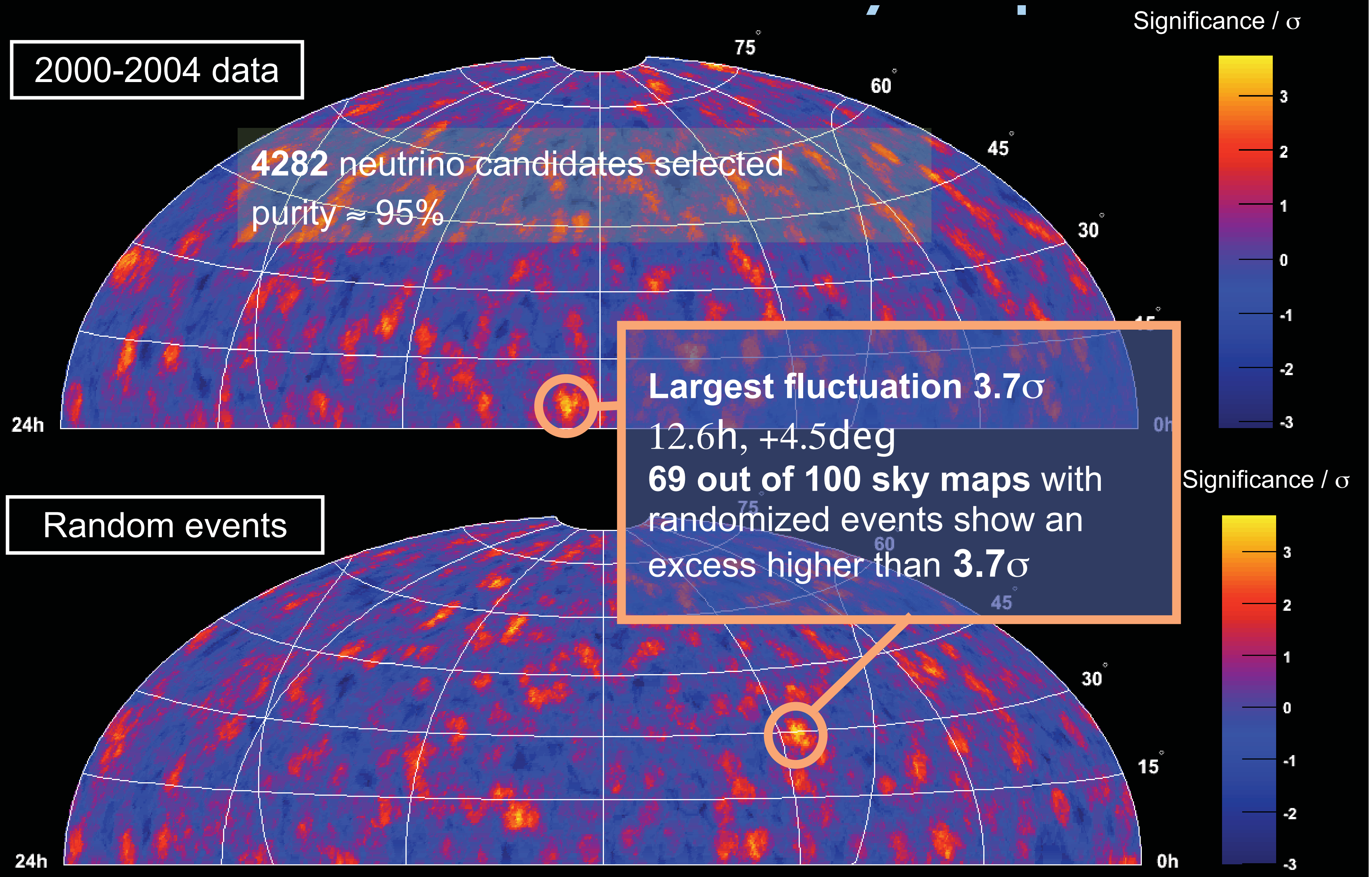
- Potential in neutrino astronomy and fundamental physics
- *IceCube analysis are ongoing and refining :*
- IC-9 released, IC-22 under progress
- 1km^3.yr of integrated exposure in 2009

➡ More to come ! Be patient...

Backup

"I have done a terrible thing -
I have invented a particle that cannot be detected"
-- Wolfgang Pauli, 1930

AMANDA II sky map

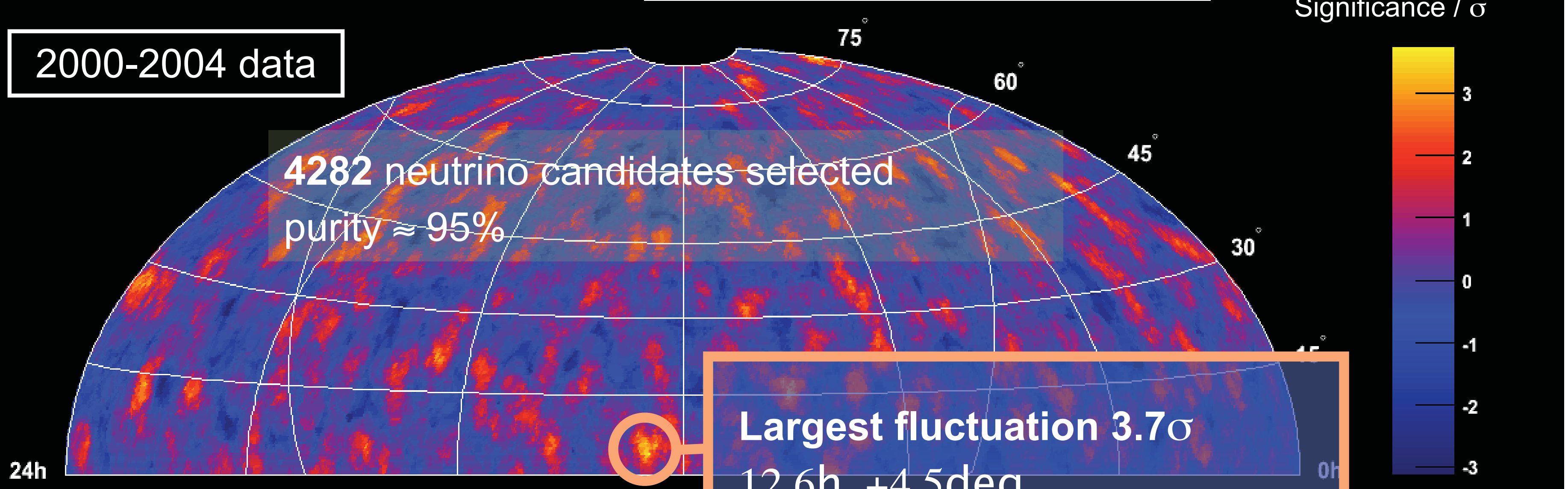


Achterberg et al. 2007, PRD75 (2007) 102001

AMANDA II sky map

Nothing Significant

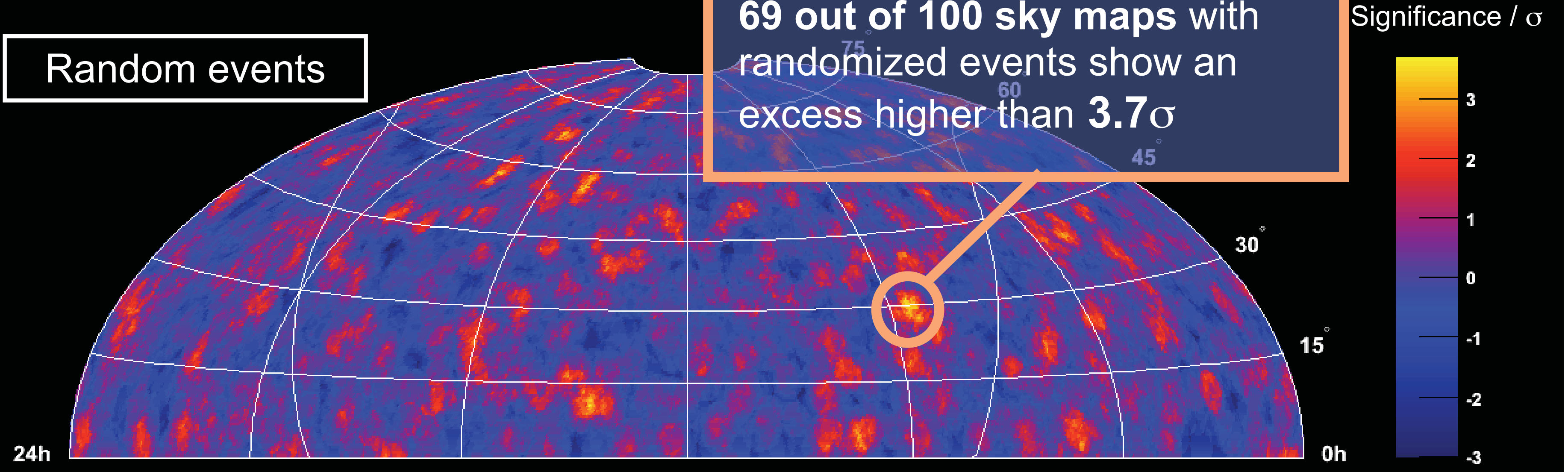
2000-2004 data



4282 neutrino candidates selected
purity ≈ 95%

Largest fluctuation 3.7σ
12.6h, +4.5deg
69 out of 100 sky maps with randomized events show an excess higher than **3.7σ**

Random events



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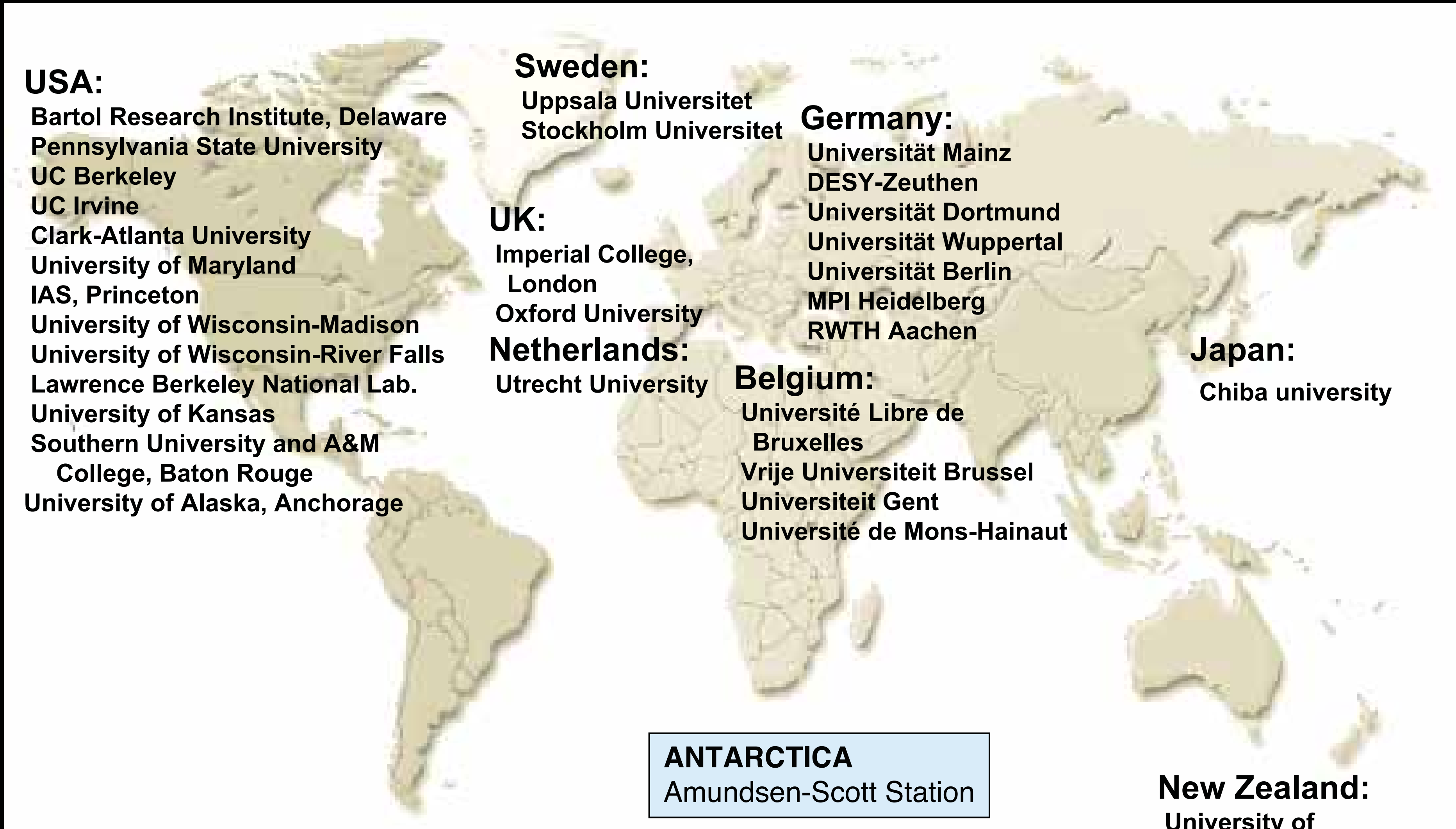
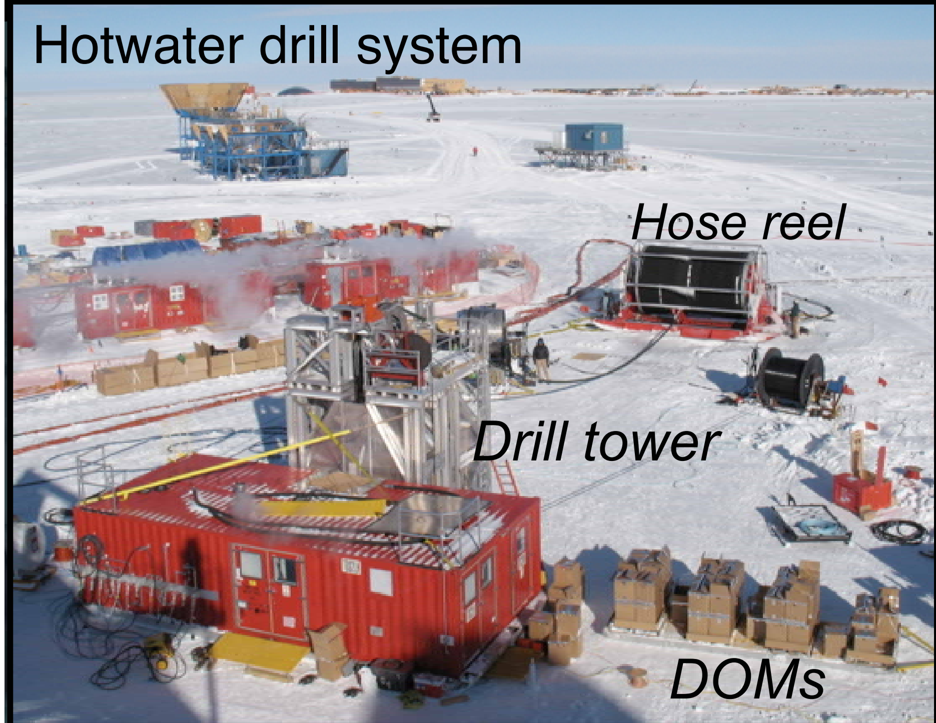
THE ICECUBE COLLABORATION



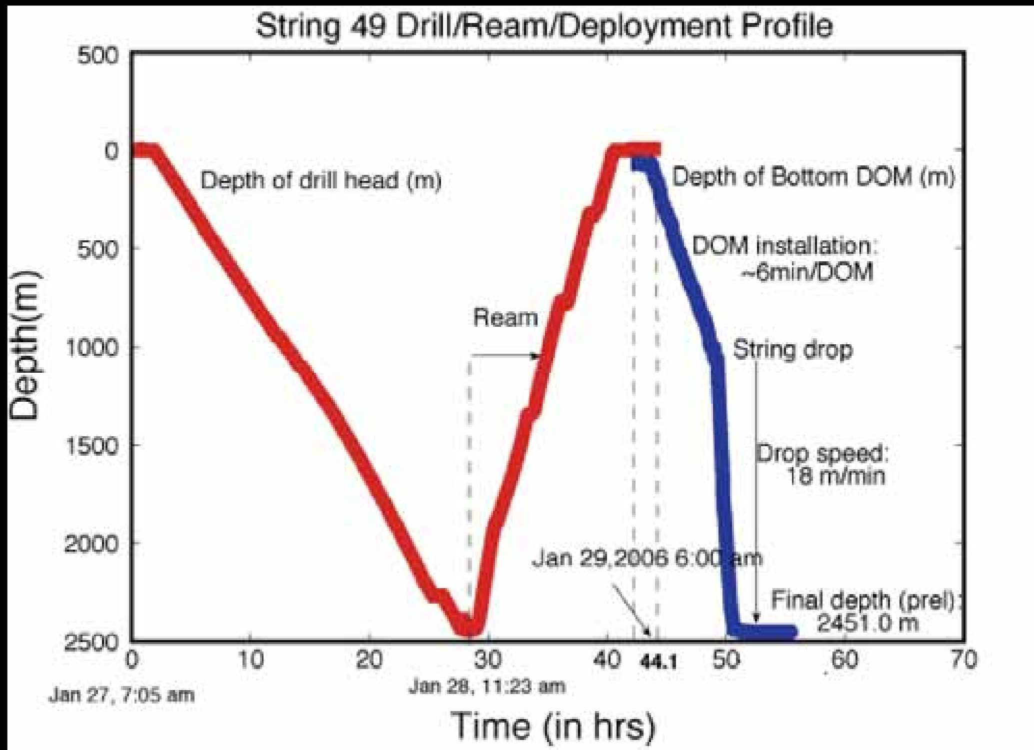
33 institutions, ~250 members

http://icecube.wisc.edu

Drilling...

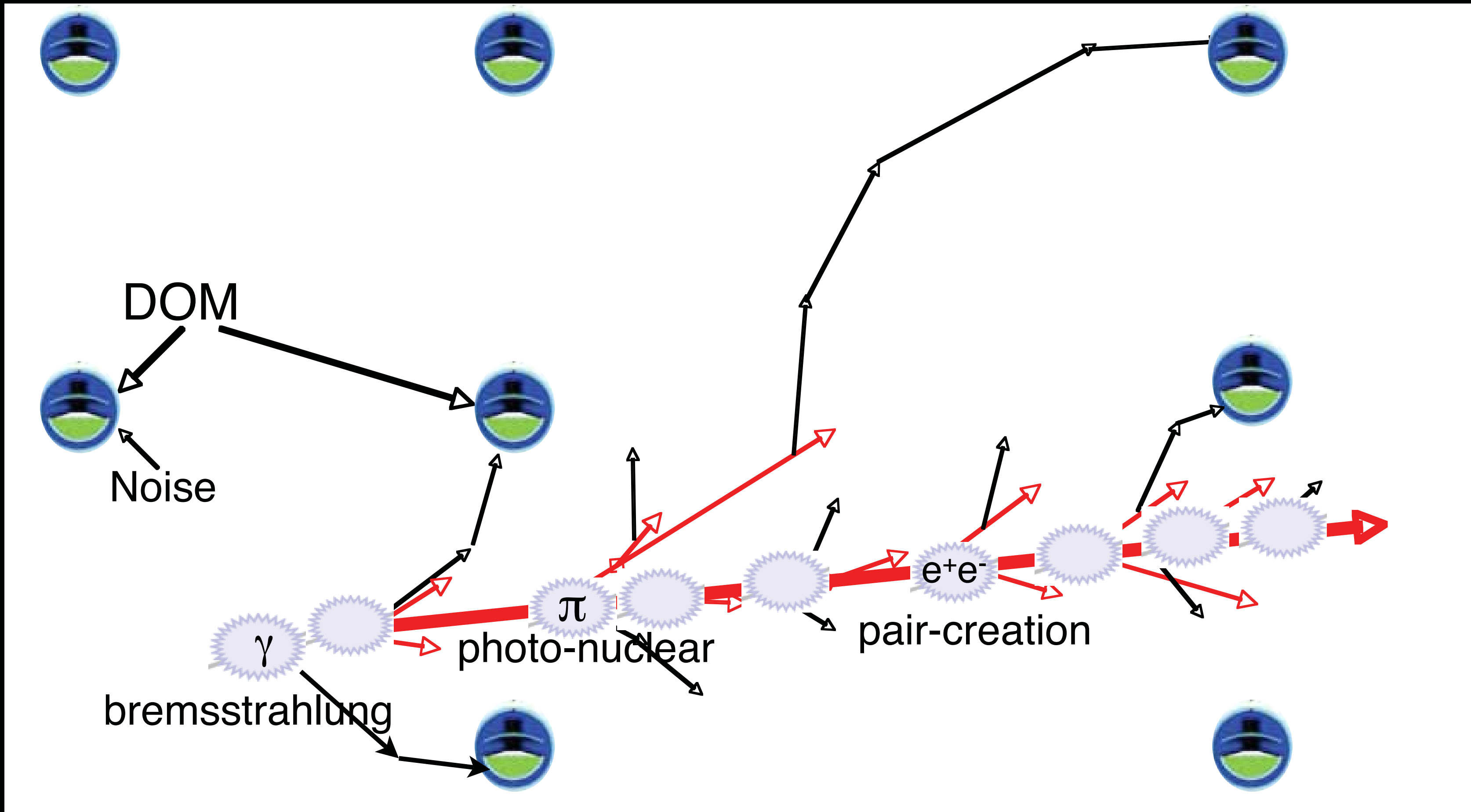


98% of DOMs survive to their deployment



Particle tracking (μ) in the detector

tracks lose energy by emitting , e^+e^- pairs and hadronic interactions



Charged particles emit Cherenkov radiation angle $= \cos^{-1}(1/n) = 41^0$

The photons scatter (L ~ 25 m)

Some ($<10^{-6}$) photons are observed in photodetectors

We measure points 0-30 meters from the track

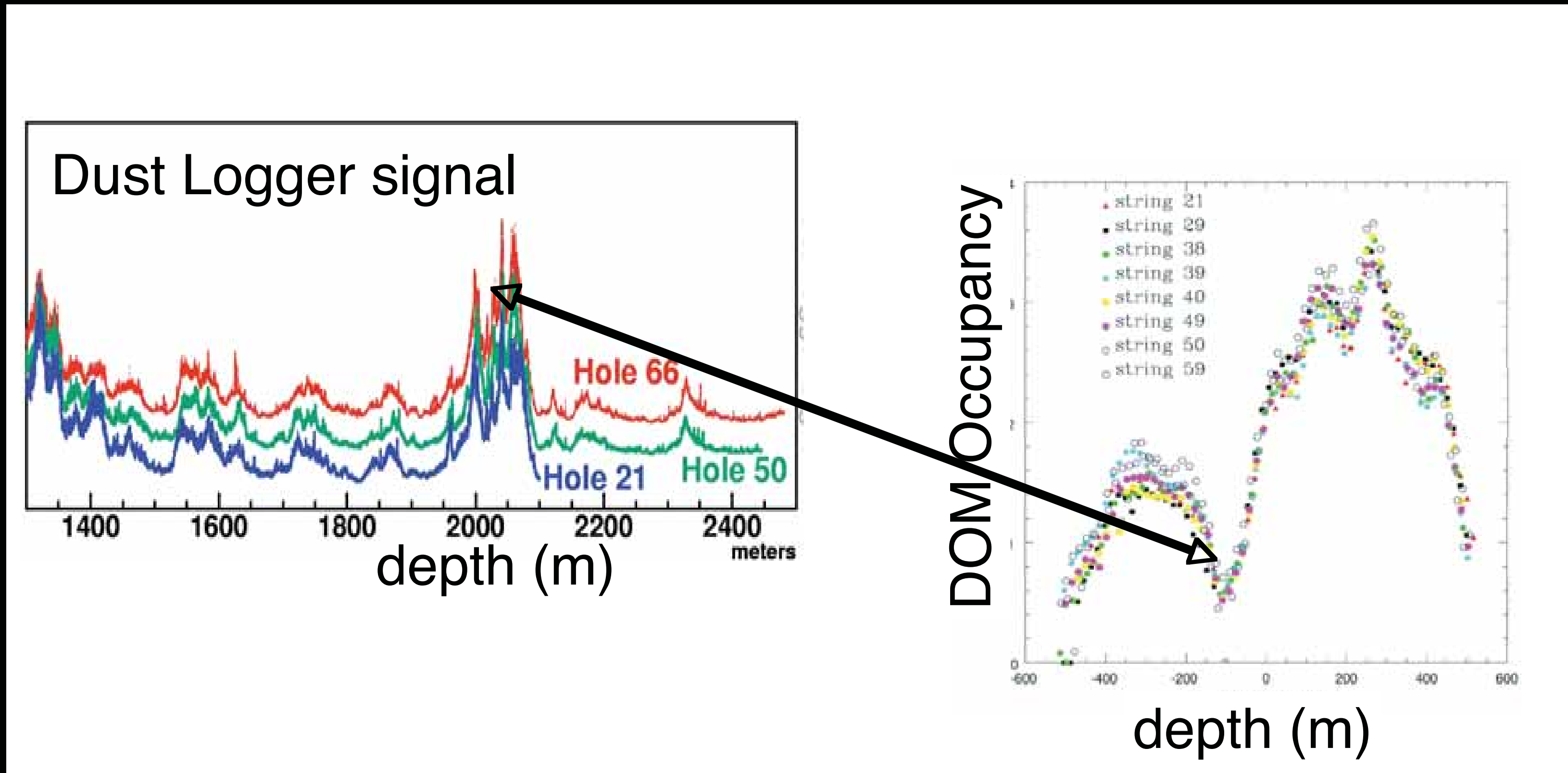
Angular resolution $< 1^0$ for long tracks

Ice optical properties

λ_{abs}~110m@ 400nm
λ_{sca}~ 20m@ 400nm

Scattering length varies from 6 to 30m depending on depth

Measurements: in-situ light sources, atmospheric muons and dust loggers (cm resolution)



Key point for IceCube !

	AMANDA II 5 year	IceCube 9
Livetime	1001 days	137 days (13.7%)
Events	4282	242 (5.6%)
Central 90% Energy Region:		
Atmospheric spectrum [$\log_{10}$ E/GeV]	2.0 - 3.9	2.3 - 4.2
E^{-2} spectrum [$\log_{10}$ E/GeV]	3.2 - 6.2	3.6 - 6.3
ν_μ Sensitivity [$(E/GeV)^{-2}$ $(GeV\ cm^2\ s)^{-1}$]	0.5×10^{-7}	1.2×10^{-7}

For comparable livetime, IC-9 would run 7.3 times longer, improving sensitivity by a factor of ~ $\sqrt{7.3} = 2.7$, reducing upper limit to ~ 0.45×10^{-7}

Combination of many factors (poor angular resolution except along detector axis; reduced effective area at lower energy, increased at higher energy) results in detector with point source sensitivity comparable to AMANDA II.

IceCube : a neutrino telescope

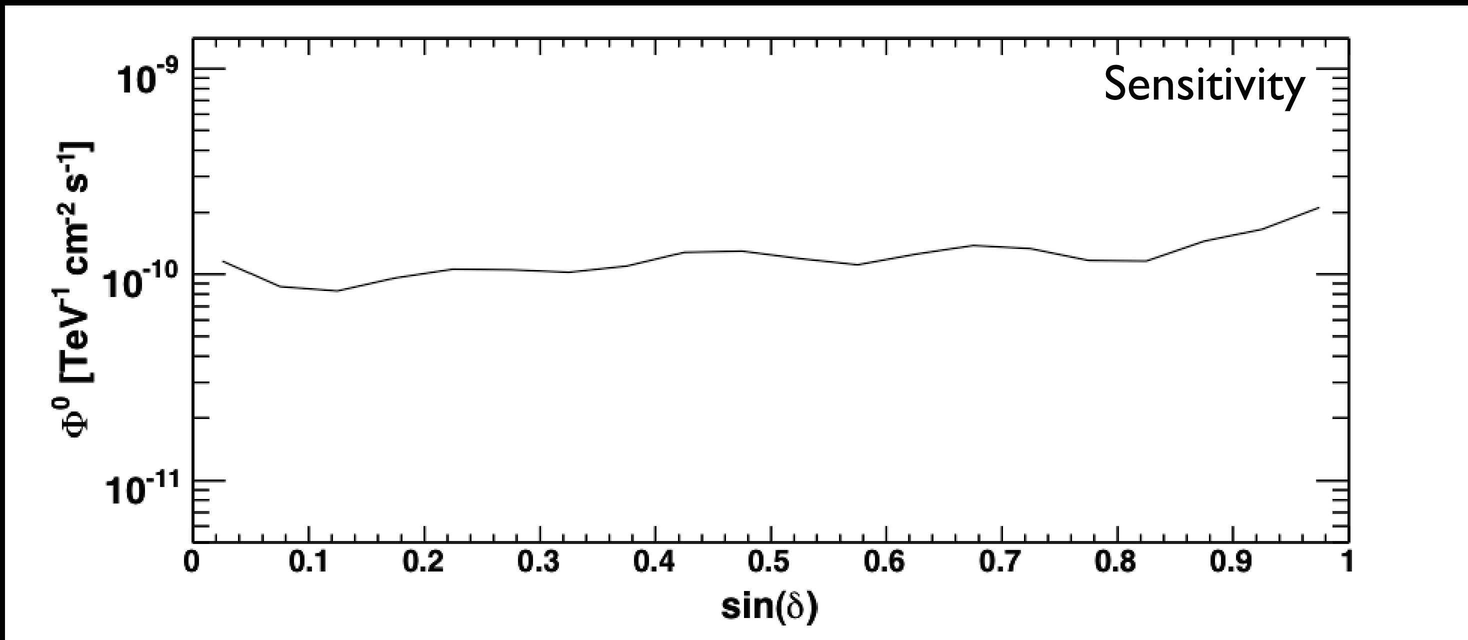
- Angular resolution from 0.8° to 2°

  (angle μ / ν_μ ~0.8° above TeV)
- IC-9 ~2°

- Sky averaged sensitivity to a source with E^{-2} spectrum :

  $12.\ 10^{-11}\ TeV^{-1}.cm^{-2}.s^{-1}$

  Comparable to AMANDA-II 2005 sensitivity



IC9 point source analysis (bis)

source strength weight

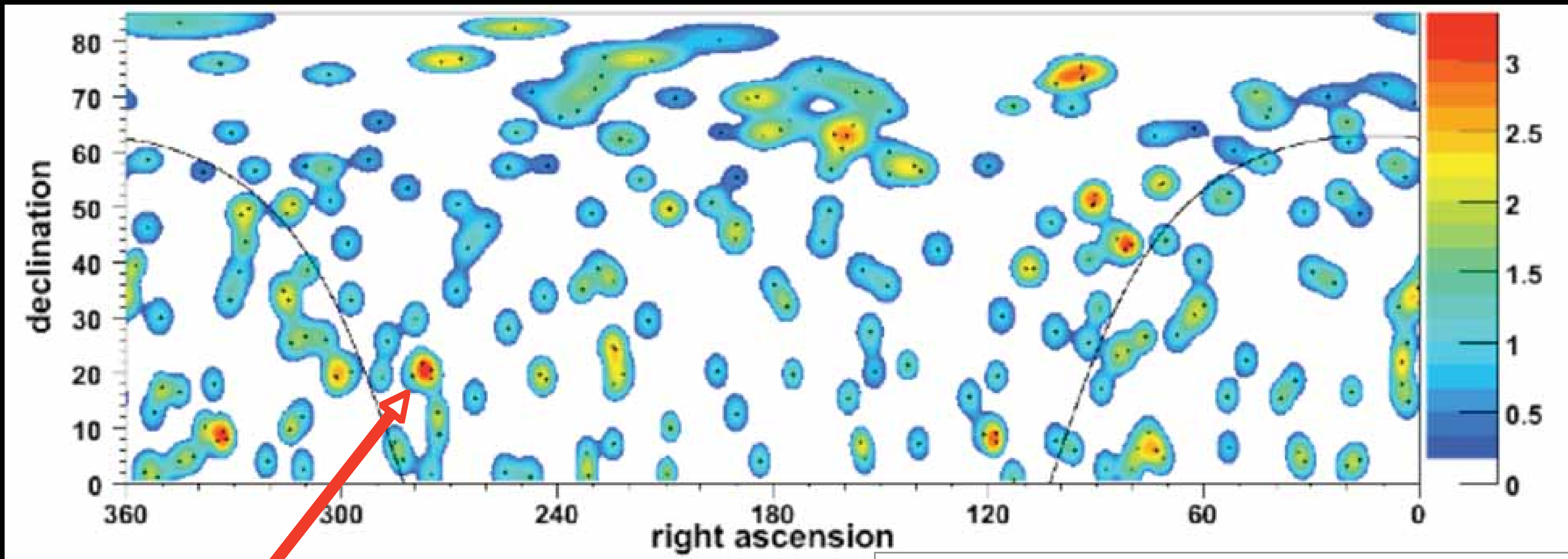
maximum likelihood analysis

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

probability distribution of signal events (point spread ~2 deg.)

probability distribution of background events

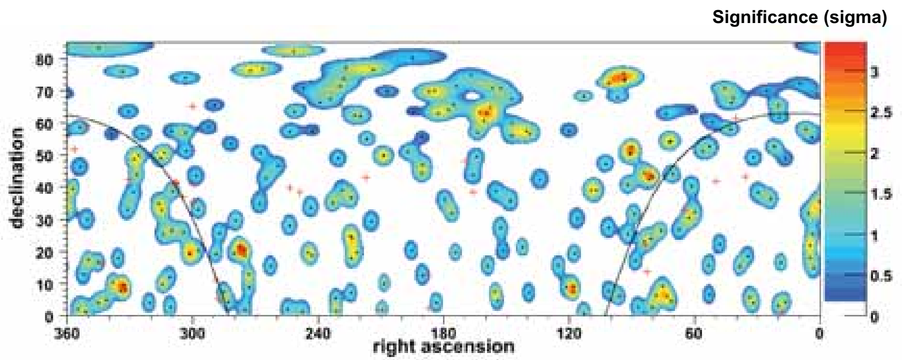
10-20% improved sensitivity over binned analysis



hottest spot: 3.35 σ

60% of background trials gave a chance clustering of events at 3.35 σ somewhere in the sky

IC-9 searches with a priori source locations



Data Events (points); Galactic Plane (curve)

26 *a priori* Source Locations

Largest deviation from bkg : 1.77σ in direction of the Crab

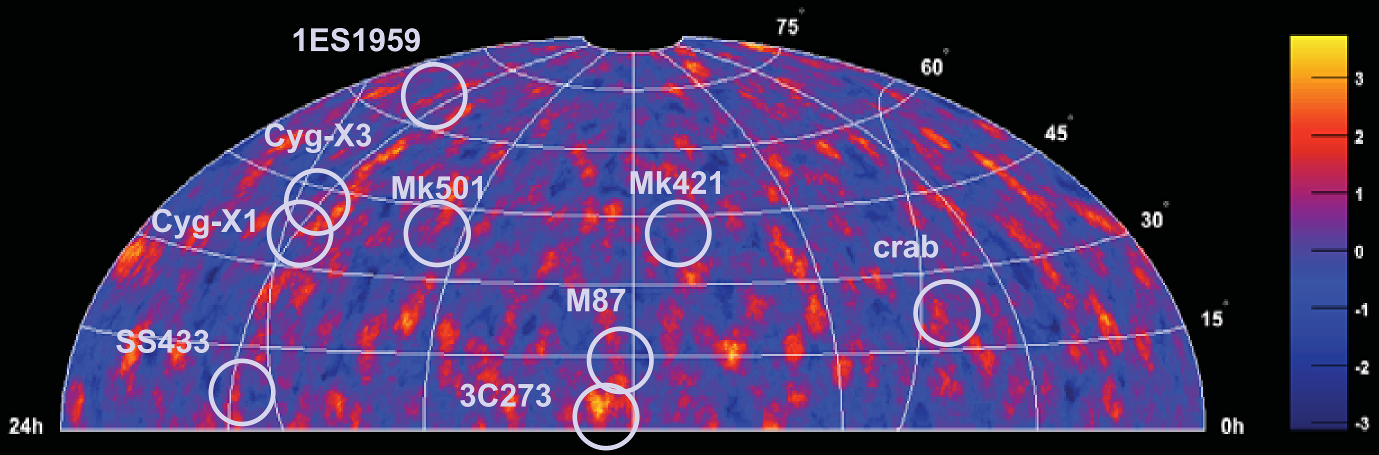
One sided p-value 0.04
Chance to obtain this with 26 trials : 65%

None of the a priori source locations shows a significant excess

Object	(r.a. , dec)	:	sigma	n_s est.	90% C.L. upper limits n_s	Φ
MGRO J2019+37	(304.8, 36.8)	:	0.00	0.0	2.8	12.7
Cyg OB2/TeV J2033+4130	(308.3, 41.3)	:	0.23	0.2	2.9	14.0
Mrk 421	(166.1, 38.2)	:	0.00	0.0	2.9	13.1
Mrk 501	(253.5, 39.8)	:	0.00	0.0	2.7	11.5
1ES 1959+650	(300.0, 65.2)	:	0.00	0.0	3.3	14.6
1ES 2344+514	(356.8, 51.7)	:	0.00	0.0	2.8	11.4
H 1426+428	(217.1, 42.7)	:	0.00	0.0	3.0	14.5
BL Lac (QSO B2200+420)	(330.7, 42.3)	:	0.28	0.4	3.2	15.7
3C66A	(35.7, 43.0)	:	0.00	0.0	3.0	13.3
3C 454.3	(343.5, 16.1)	:	1.08	0.7	3.6	14.4
4C 38.41	(248.8, 38.1)	:	0.00	0.0	2.8	12.6
PKS 0528+134	(82.7, 13.5)	:	0.00	0.0	2.8	10.3
3C 273	(187.3, 2.0)	:	0.00	0.0	2.5	11.0
M87	(187.7, 12.4)	:	0.67	0.5	3.2	11.4
NGC 1275 (Perseus A)	(50.0, 41.5)	:	0.00	0.0	2.8	13.4
Cyg A	(299.9, 40.7)	:	0.41	0.4	3.0	14.5
SS 433	(288.0, 5.0)	:	0.12	0.1	2.4	8.2
Cyg X-3	(308.1, 41.0)	:	0.51	0.4	3.0	14.5
Cyg X-1	(299.6, 35.2)	:	0.52	0.4	3.0	12.2
LS I +61 303	(40.1, 61.2)	:	0.00	0.0	3.2	14.2
GRS 1915+105	(288.8, 10.9)	:	0.00	0.0	2.8	9.8
XTE J1118+480	(169.6, 48.0)	:	0.00	0.0	2.8	12.4
GRO J0422+32	(65.4, 32.9)	:	0.65	0.8	3.1	13.5
Geminga 98.48	(17.8, 0.6)	:	0.65	0.8	3.0	16.4
Crab Nebula	(83.6, 22.0)	:	1.77	1.6	5.2	21.8
Cas A	(350.9, 58.8)	:	0.67	0.5	4.4	19.9

Φ Flux Units: $10^{-11}\,(E\,/\,\mathrm{TeV})^{-2}\ \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Search for sources from known objects with AMANDA II



event selection optimized for both $dN/dE \sim E^{-2}$ and E^{-3} spectra

Out of 32 sources in candidate list

No significant excess,
no indication for a neutrino source

Systematic error on signal prediction included in limits

	source	nr. of ν events (5 years)	expected background (5 years)	E^{-2} flux upper limit (90% c.l.) [10^{-11} TeV^{-1} cm^{-2} s^{-1}]
AGN	**Markarian 421**	**6**	**7.4**	**7.4**
	M87	**6**	**6.1**	**8.7**
	1ES 1959+650	**5**	**4.8**	**13.5**
	3C 273	**8**	**4.72**	**18.0**
Microquasar	**SS433**	**4**	**6.1**	**4.8**
	Cygnus X-3	**7**	**6.5**	**11.8**
	Cygnus X-1	**8**	**7.0**	**13.2**
SNR	**Crab Nebula**	**10**	**6.7**	**17.8**

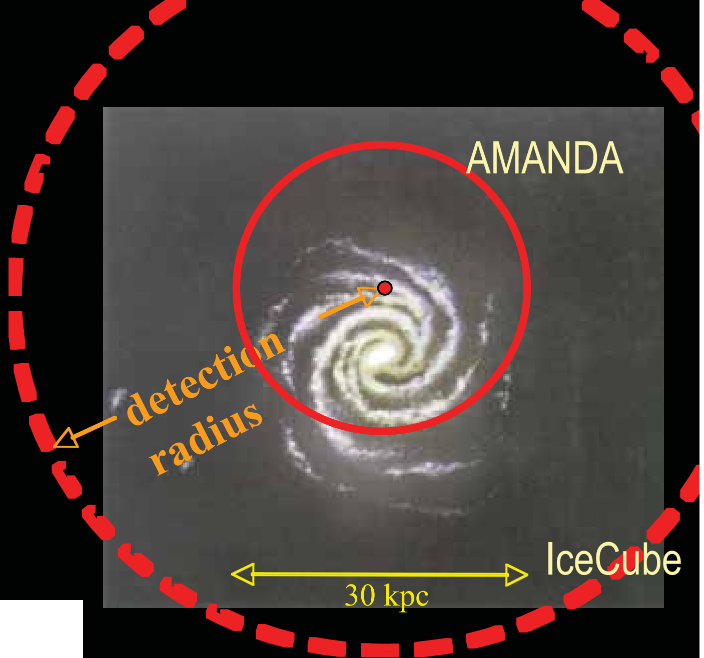
Detection of supernovae

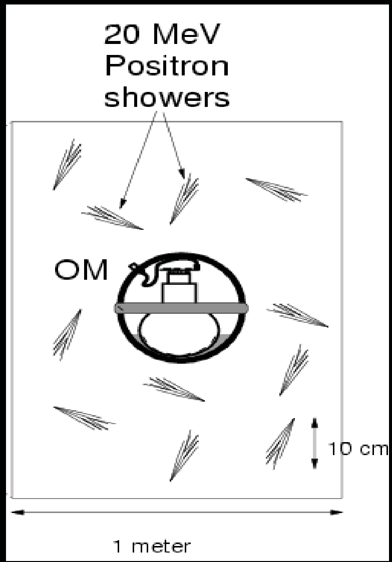
We expect a burst of low energy (MeV) neutrinos from core collapse of supernovae

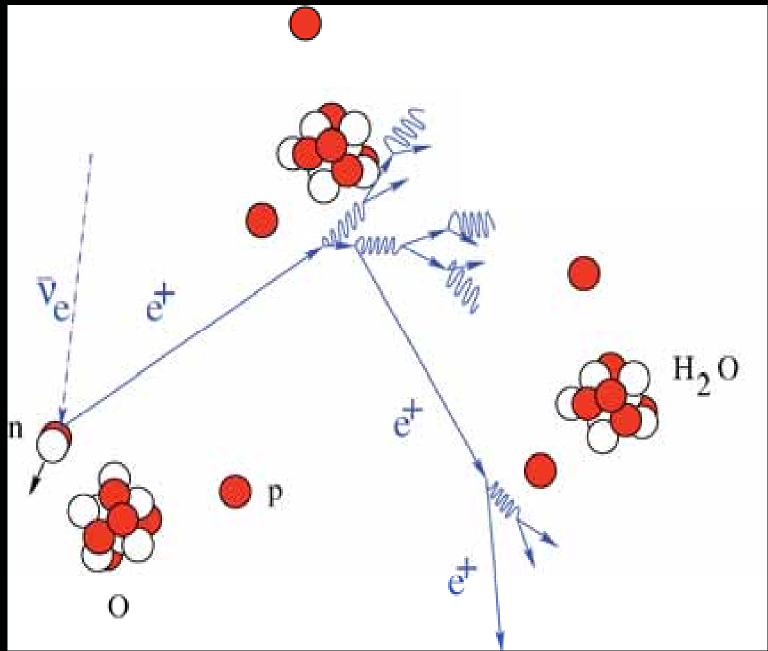
A burst of ν has been observed by 3 observatories 3h before the observation in visible

Detection of supernovae

We expect a burst of low energy (MeV) neutrinos from core collapse of supernovae





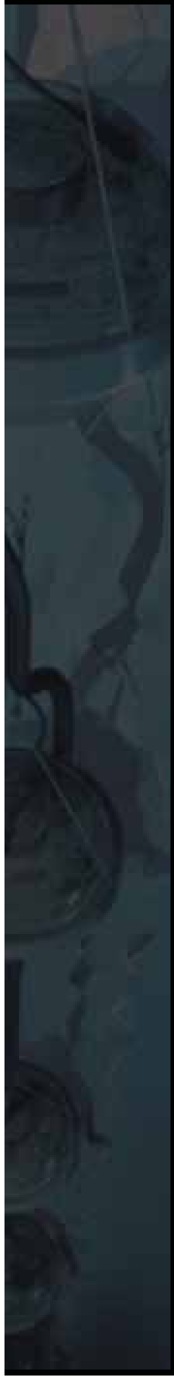


$$\nu_e + p \rightarrow n + e^+$$

Detection via increase in "dark noise" rate

low noise PMTs (300Hz) enhance IceCube's sensitivity.

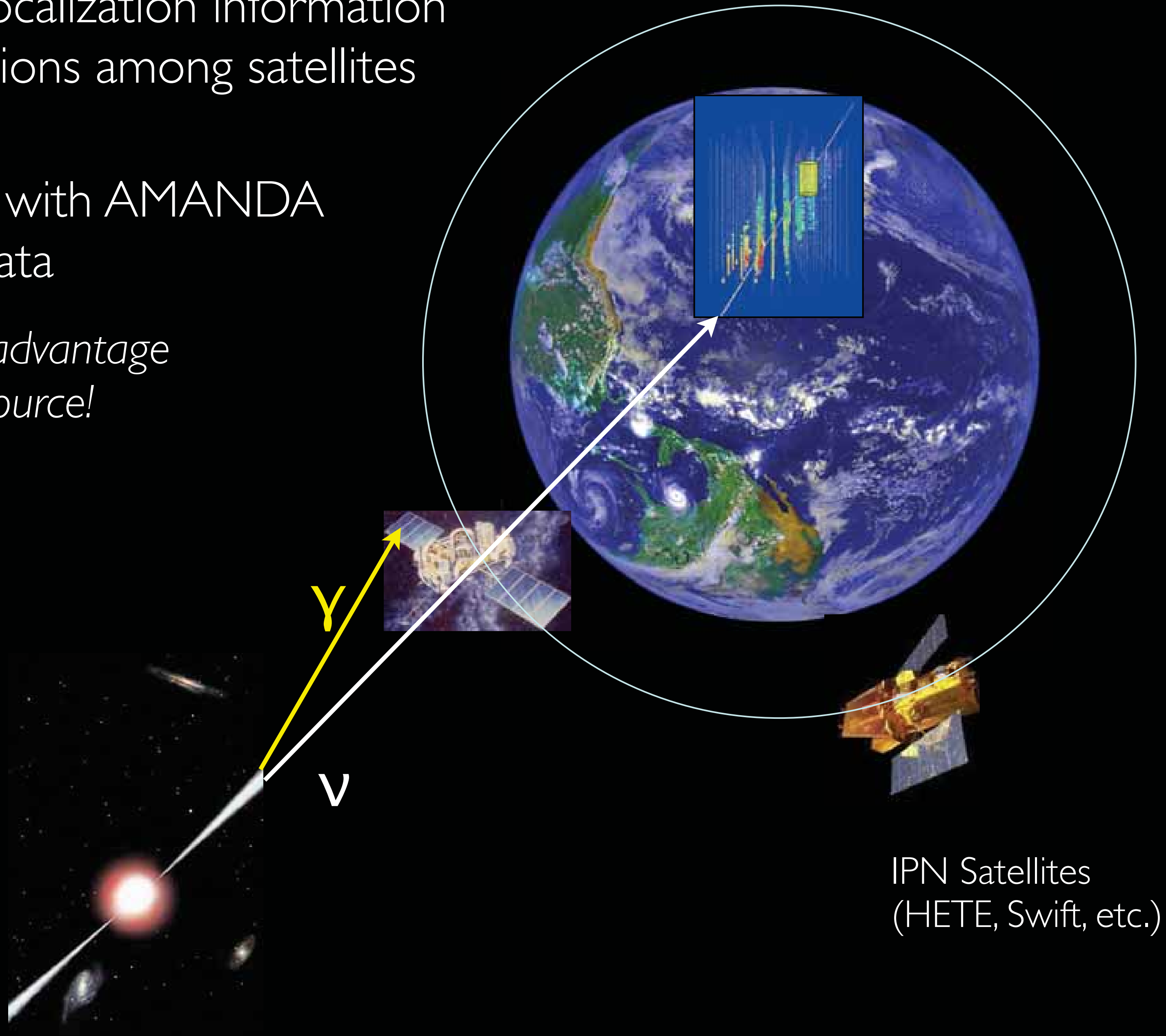
ν from GRBs



GRB timing/localization information from correlations among satellites

Correlations with AMANDA & IceCube data

big statistical advantage to look for a source!



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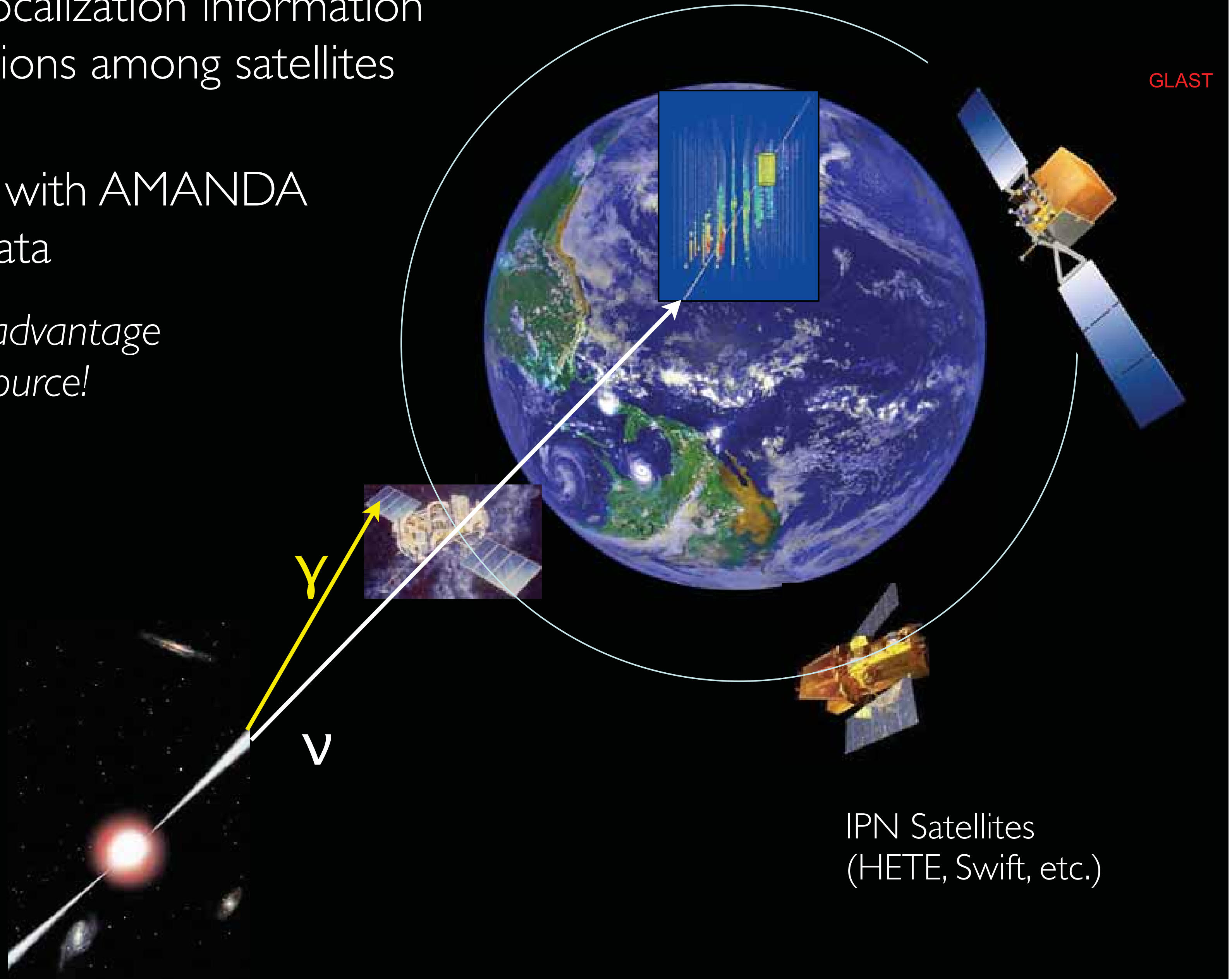


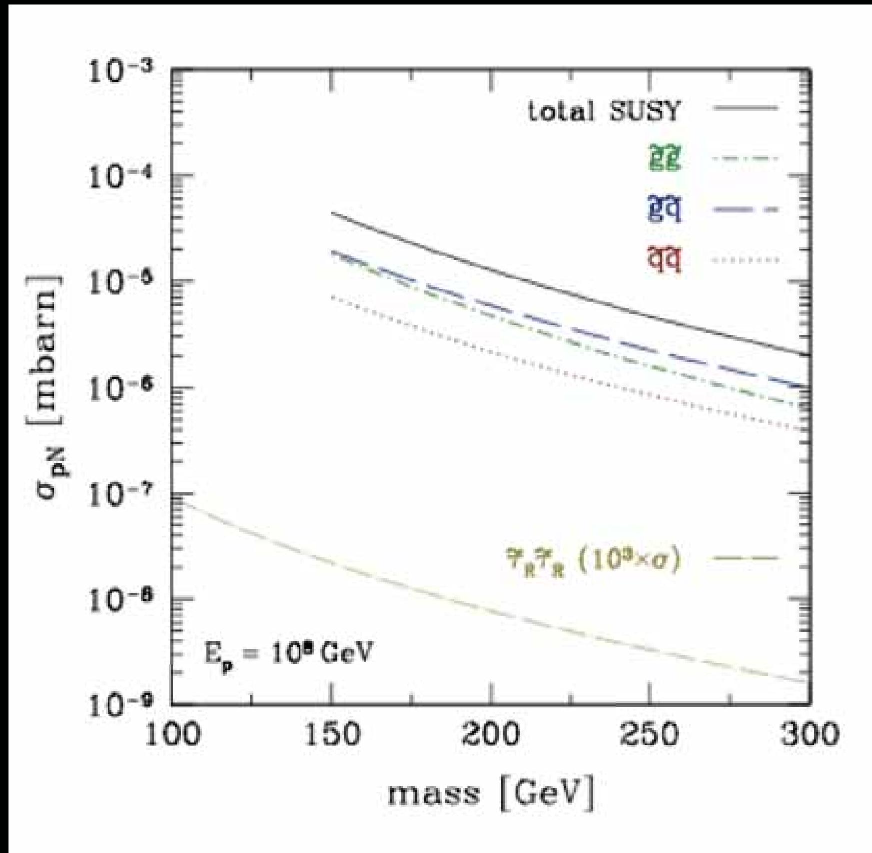
SUSY in Cosmic Rays

MSSM w/ conserved R parity
Weakly interacting LSP
Charged meta-stable NLSP

Names	Spin	$P_{\mathcal{R}}$	Mass Eigenstates
Higgs bosons	0	+1	h^0 H^0 A^0 $H^{\pm}$
squarks	0	−1	$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$ $\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$ $\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$ $\tilde{\mu}_L$ $\tilde{\mu}_R$ $\tilde{\nu}_\mu$ $\tilde{\tau}_1$ $\tilde{\tau}_2$ $\tilde{\nu}_\tau$
neutralinos	1/2	−1	χ_1^0 χ_2^0 χ_3^0 χ_4^0
charginos	1/2	−1	χ_1 χ_2
gluino	1/2	−1	$\tilde{g}$
gravitino	3/2	−1	$\tilde{G}$

NLSP

LSP



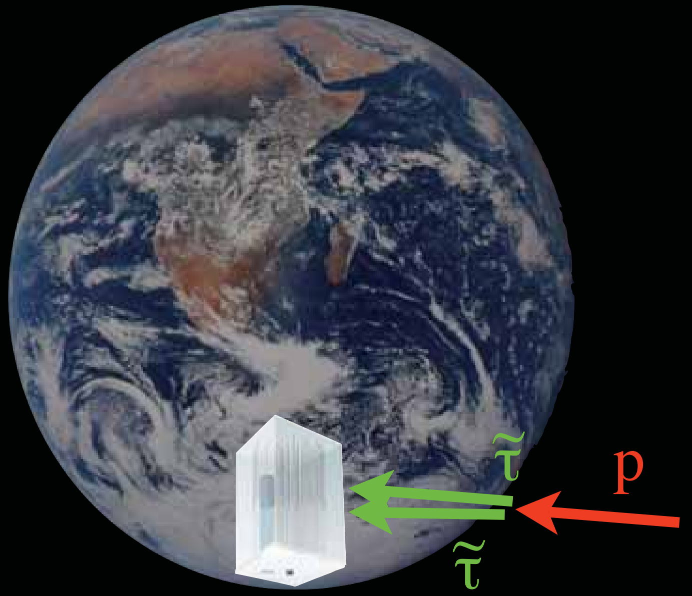
M.Ahlers, J.I. Illana, M. Masip, D. Meloni
arXiv:0705.3782v1 [hep-ph]

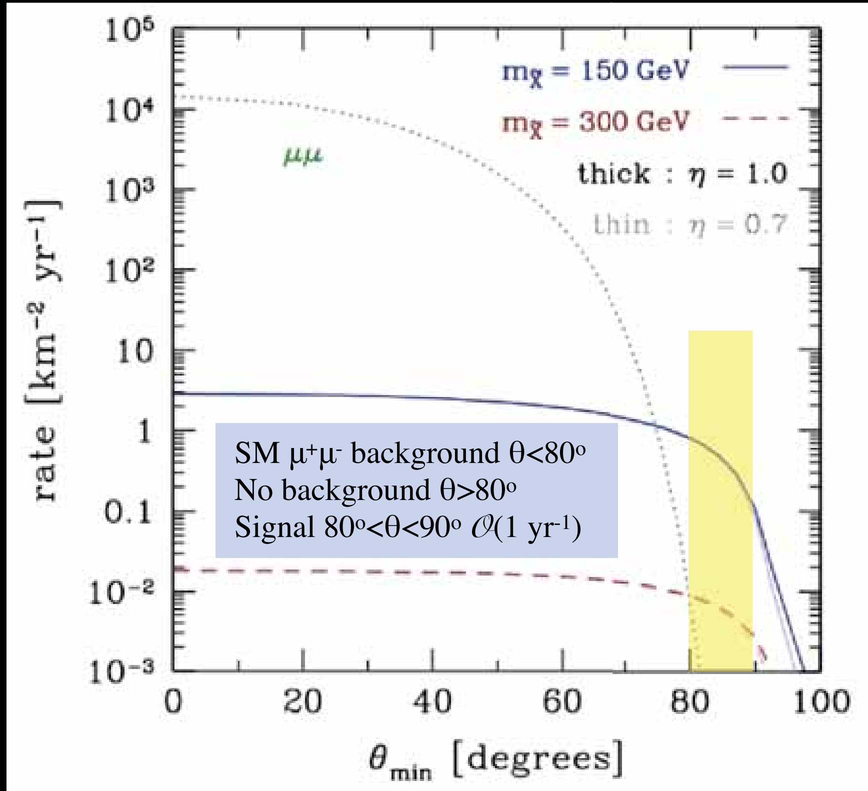
How they are produced?

1. UHE CR produce SUSY particles
2. SUSY particles cascade to NLSP
3. Meta-stable NLSP travels to IceCube

stau ($\tilde{\tau}$) will look **very** similar to a muon in IceCube

SUSY searches in IceCube





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arXiv:0705.3782v1 [hep-ph]

Signature

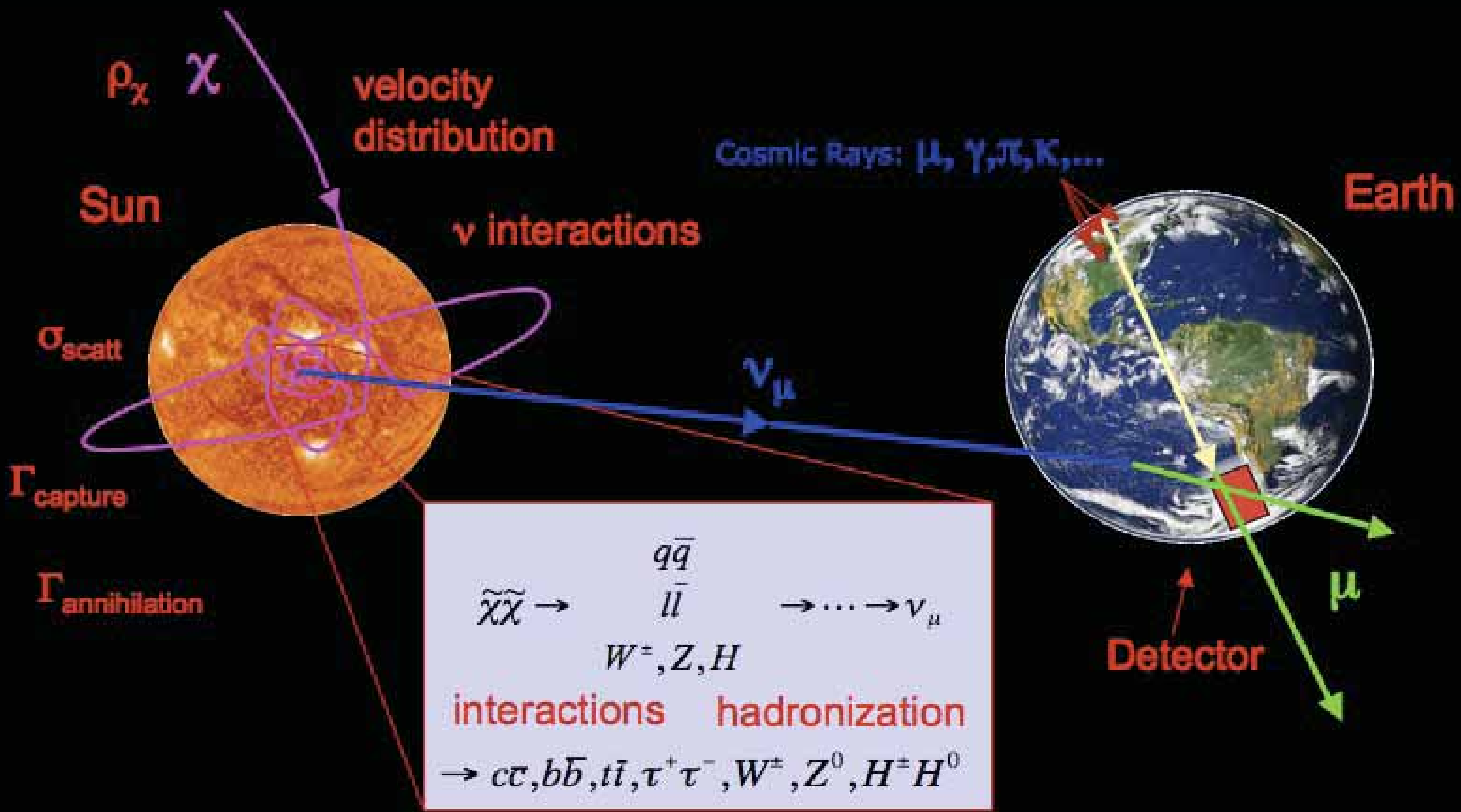
- Two nearly parallel **μ-like** tracks near the horizon separated by more than 100m
- Above the horizon dominated by SM $\mu^+\mu^-$ background

Other stau sources via ν-N

Cosmic HE (unknown diffuse flux) ← I.F.M.Albuquerque, G. Burdman, Z. Chacko arXiv:0711.2908v1 [hep-ph] — 6-0.1 yr^{-1} @ WB limit, 20-1 yr^{-1} @ MPR limit

Atmospheric prompt charm decay ← S.Ando, J.F. Beacom, S. Profumo, D. Rainwater arXiv:0711.2908v1 [hep-ph] — <1 yr^{-1} & dominates over cosmic ν

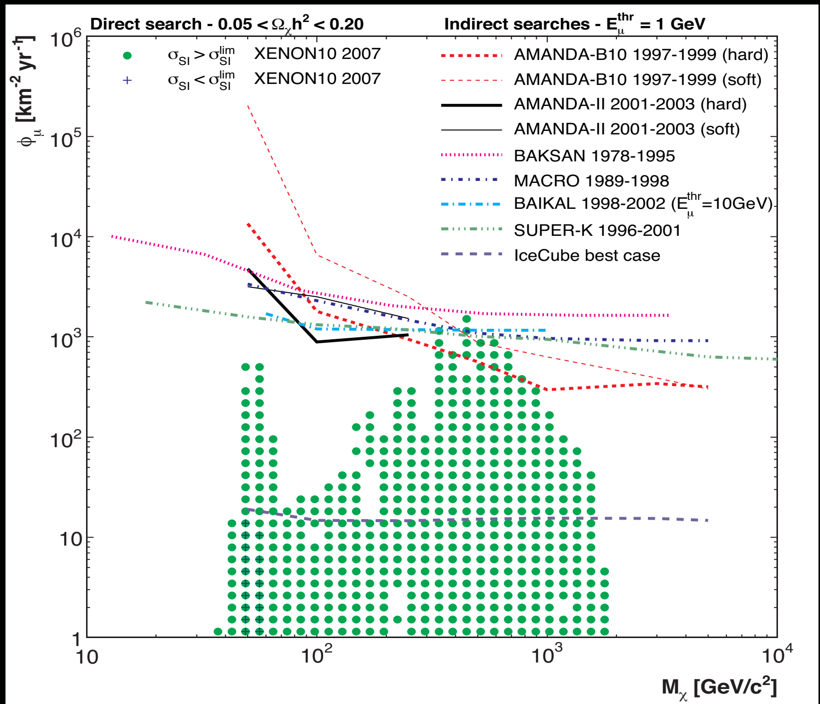
WIMPs searches



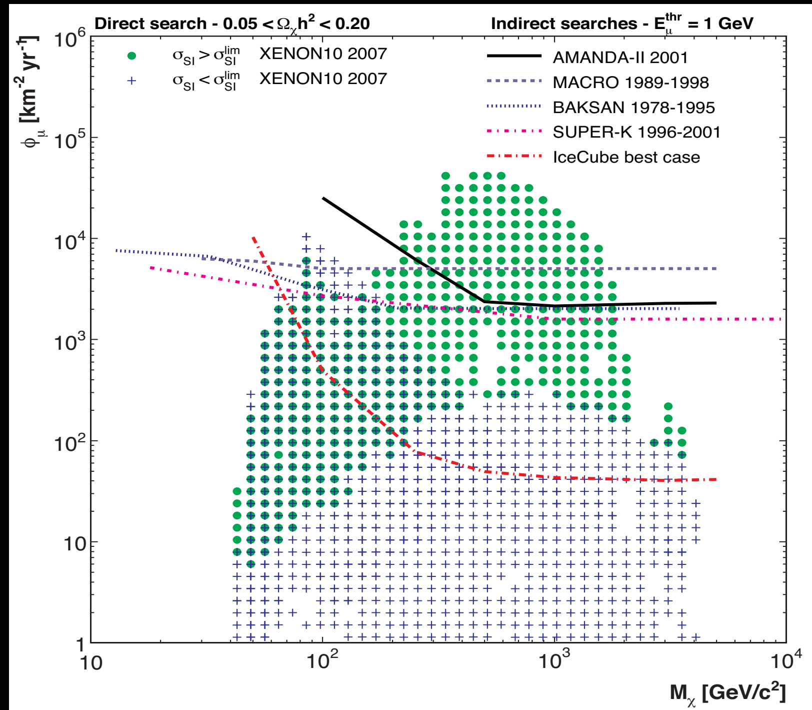
WIMPs are trapped in gravity wells :
The center of Earth and Sun appear as sources of **ν**

WIMPs searches with AMANDA & IceCube

muon flux from Earth center



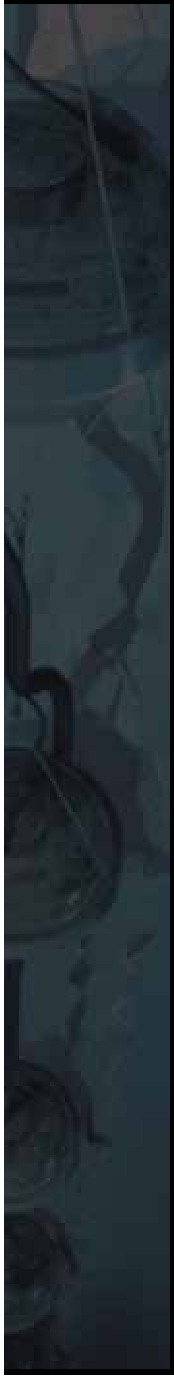
muon flux from the Sun

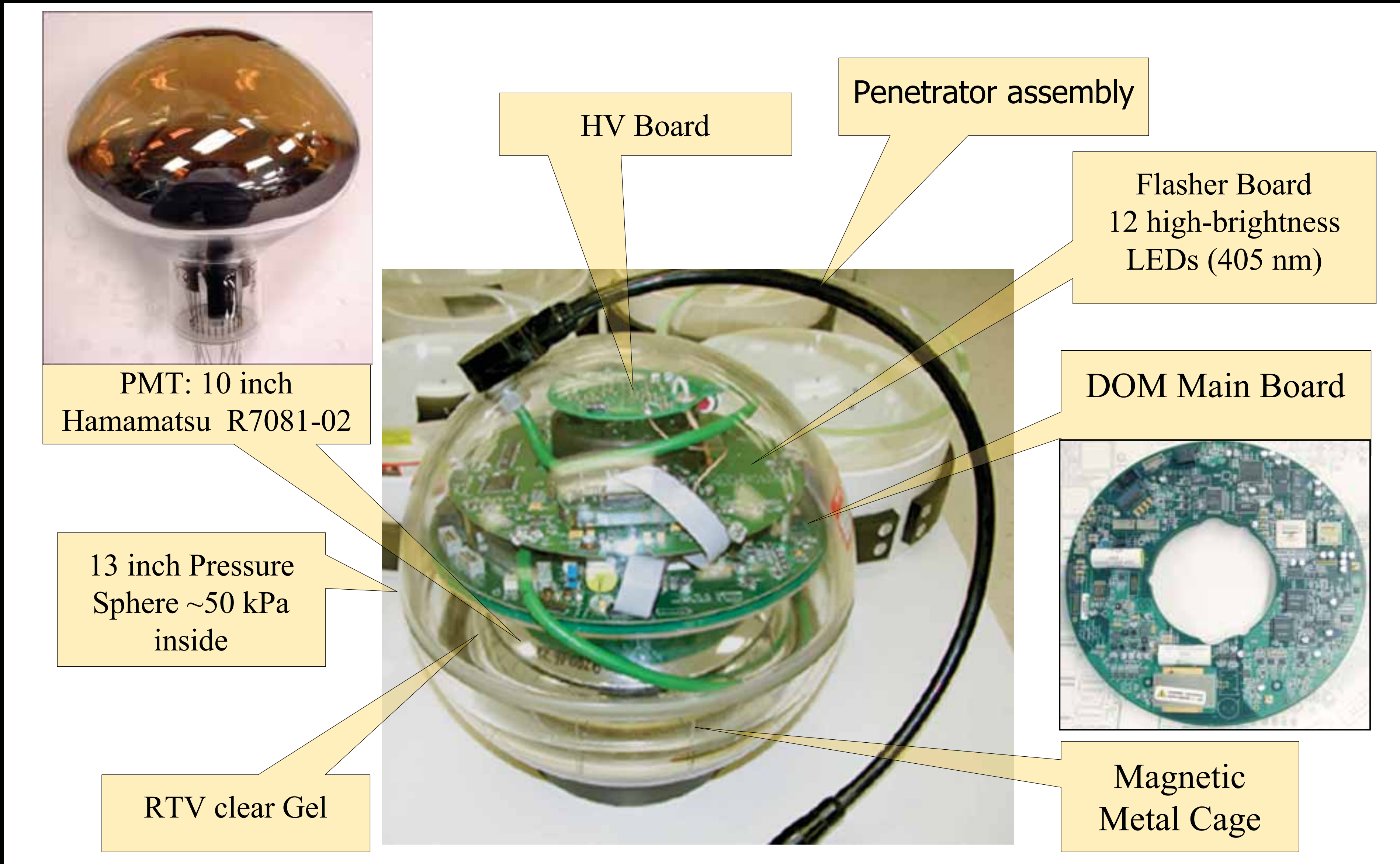


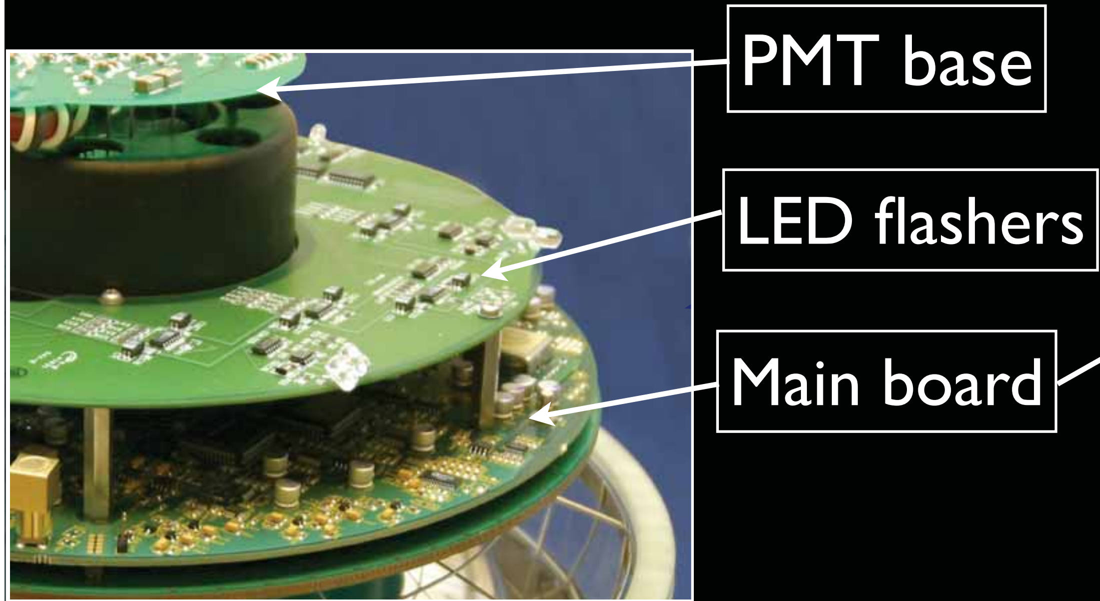
Work ongoing with AMANDA 2000-2006
We can use AMANDA/IceCube 22 combined data (veto from IceCube)

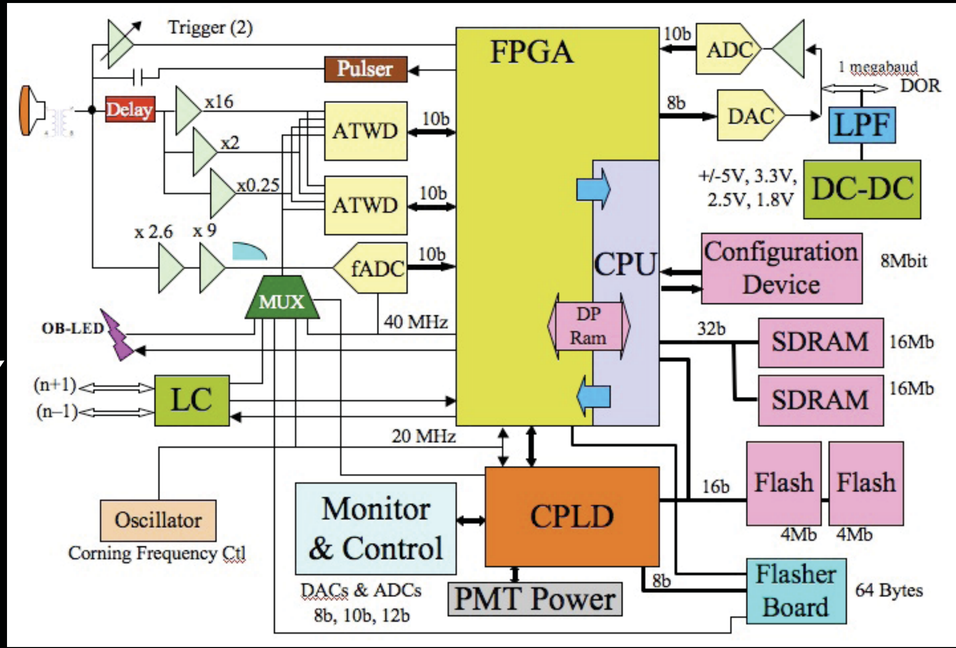
Future > Deep Core (first lines in 2009)

The DOMs : the eyes of IceCube







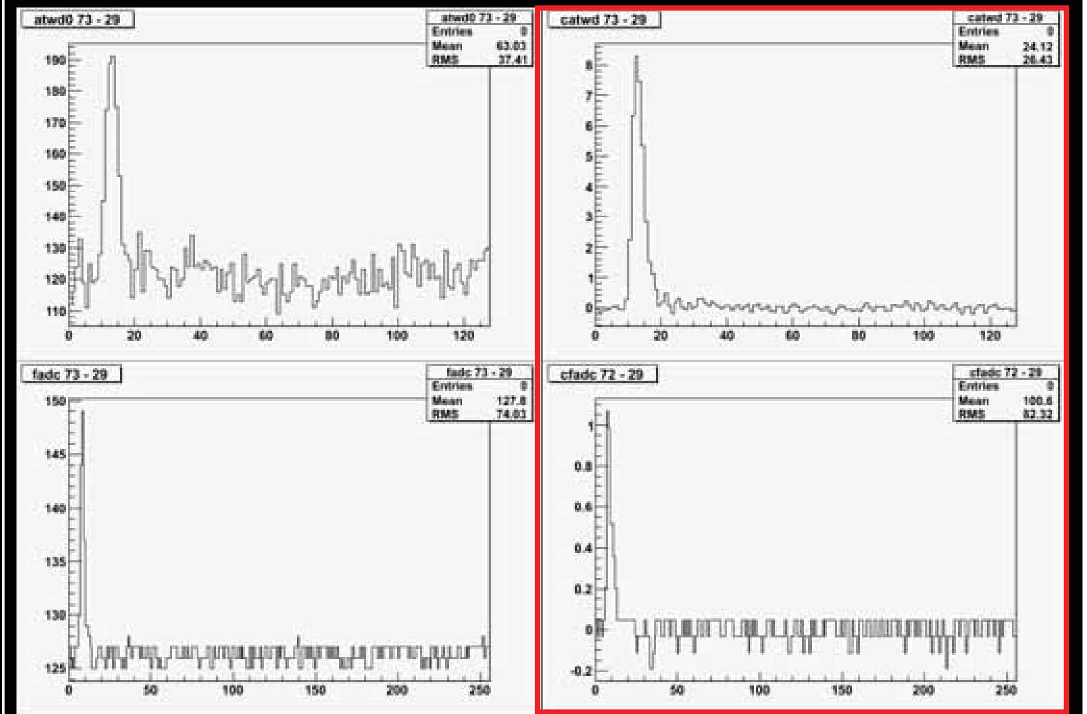


- 2 ATWD @ 300 MHz on 400ns
- FADC @ 40MHz on 6.4μs

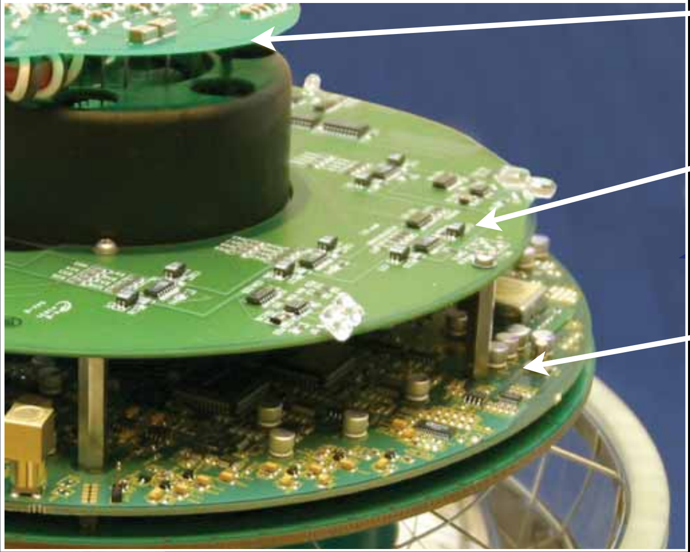
- Dynamic range 500pe/15ns 25000pe/6.4μs
- Send all data to surface : data + time stamp

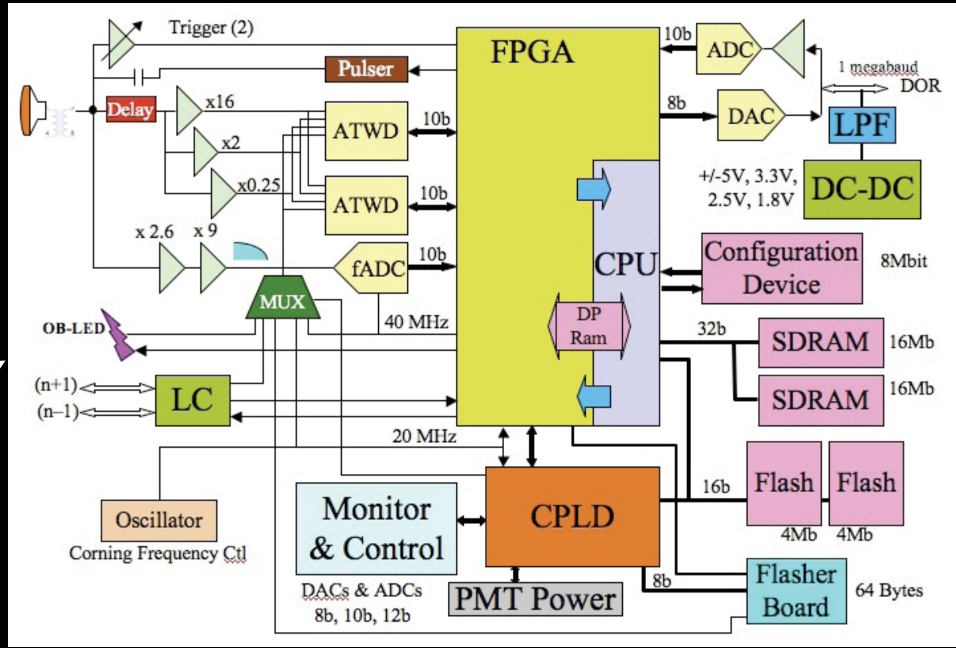
- Dark noise rate ~ 400 Hz
- Local coincidence rate ~ 15 Hz
- Timing resolution ≤ 2-3 ns

- Data rate IC-80 : 120 Gb/day (raw)
- Satellite bandwidth : 30 Gb/day



IC22 real waveforms





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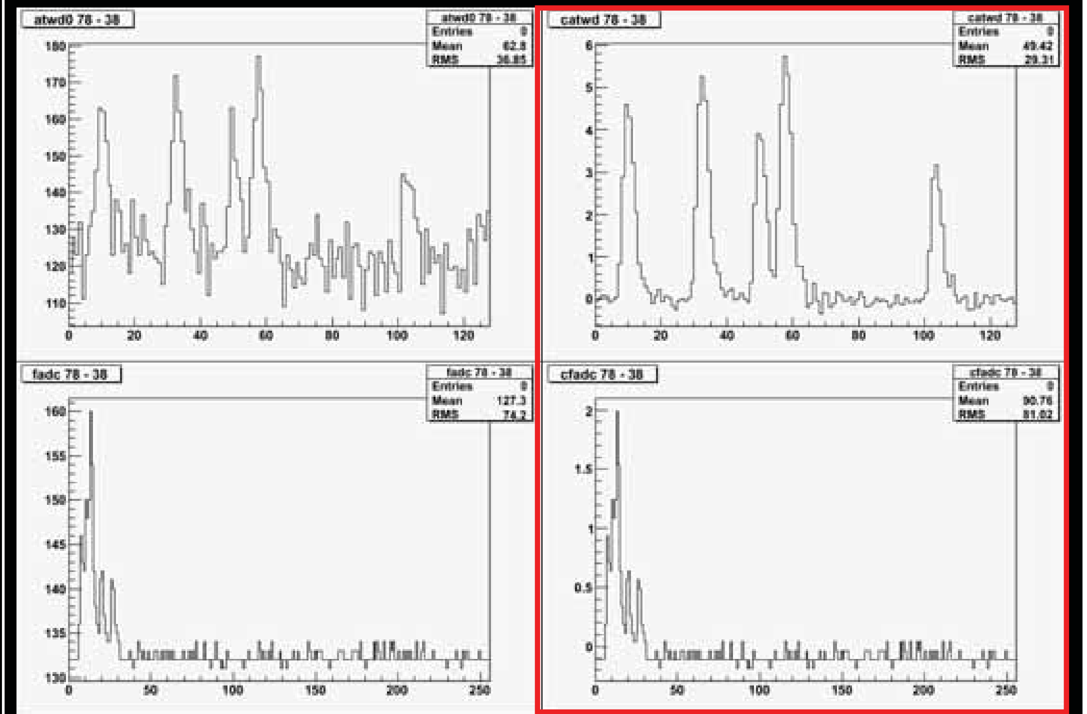
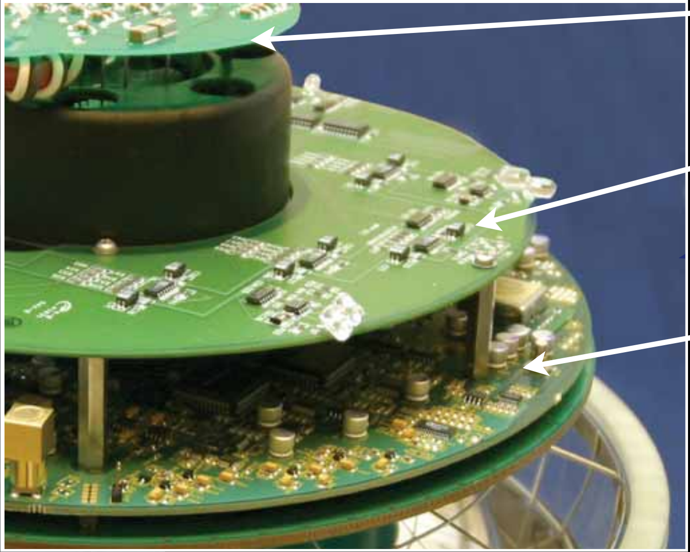
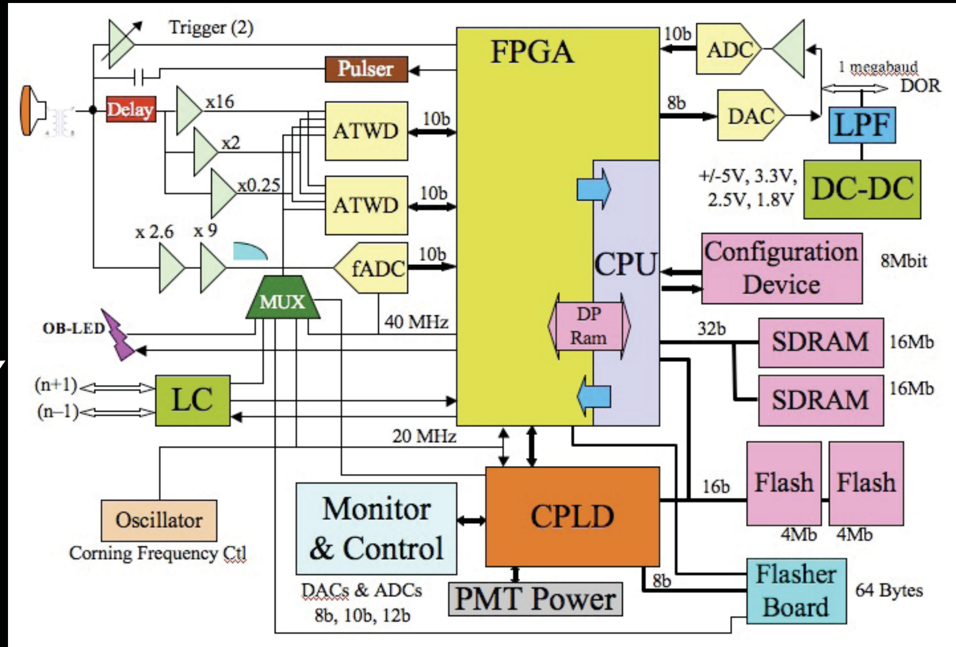


IC22 real waveforms





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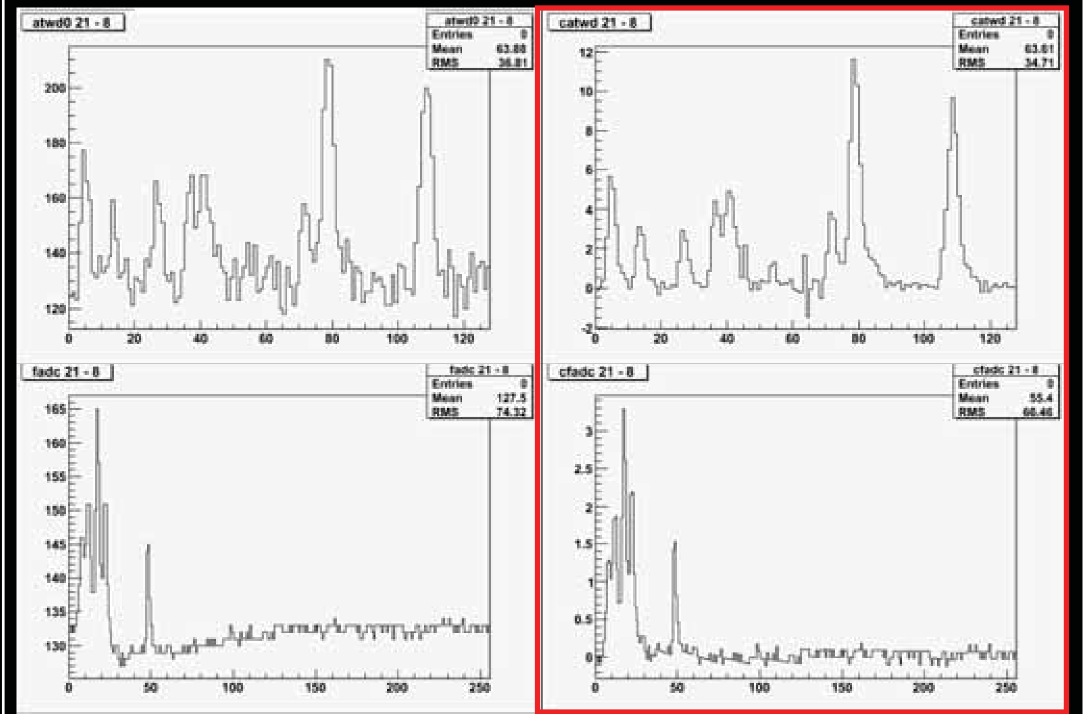
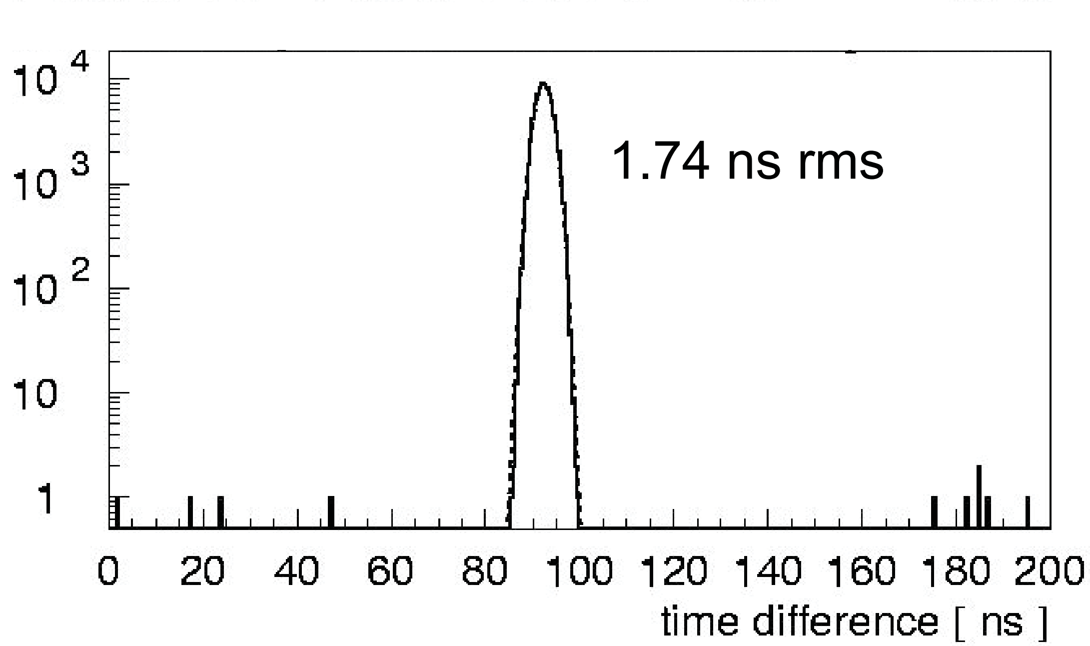
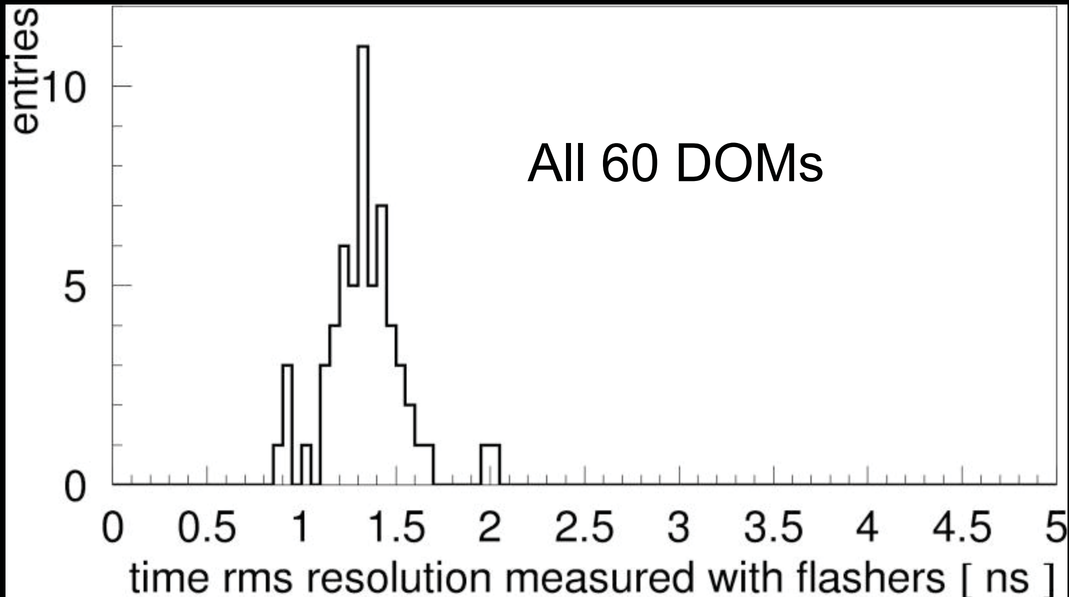
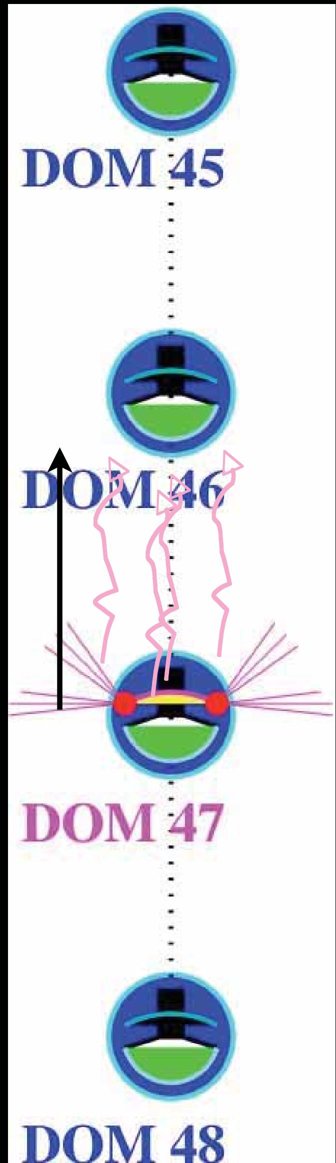


IC22 real waveforms

Timing verification with flashers







Confirmation of the precision of time synchronisation procedure