



The hunt for cosmic sources (of ν 's) with IceCube

Elisa Bernardini

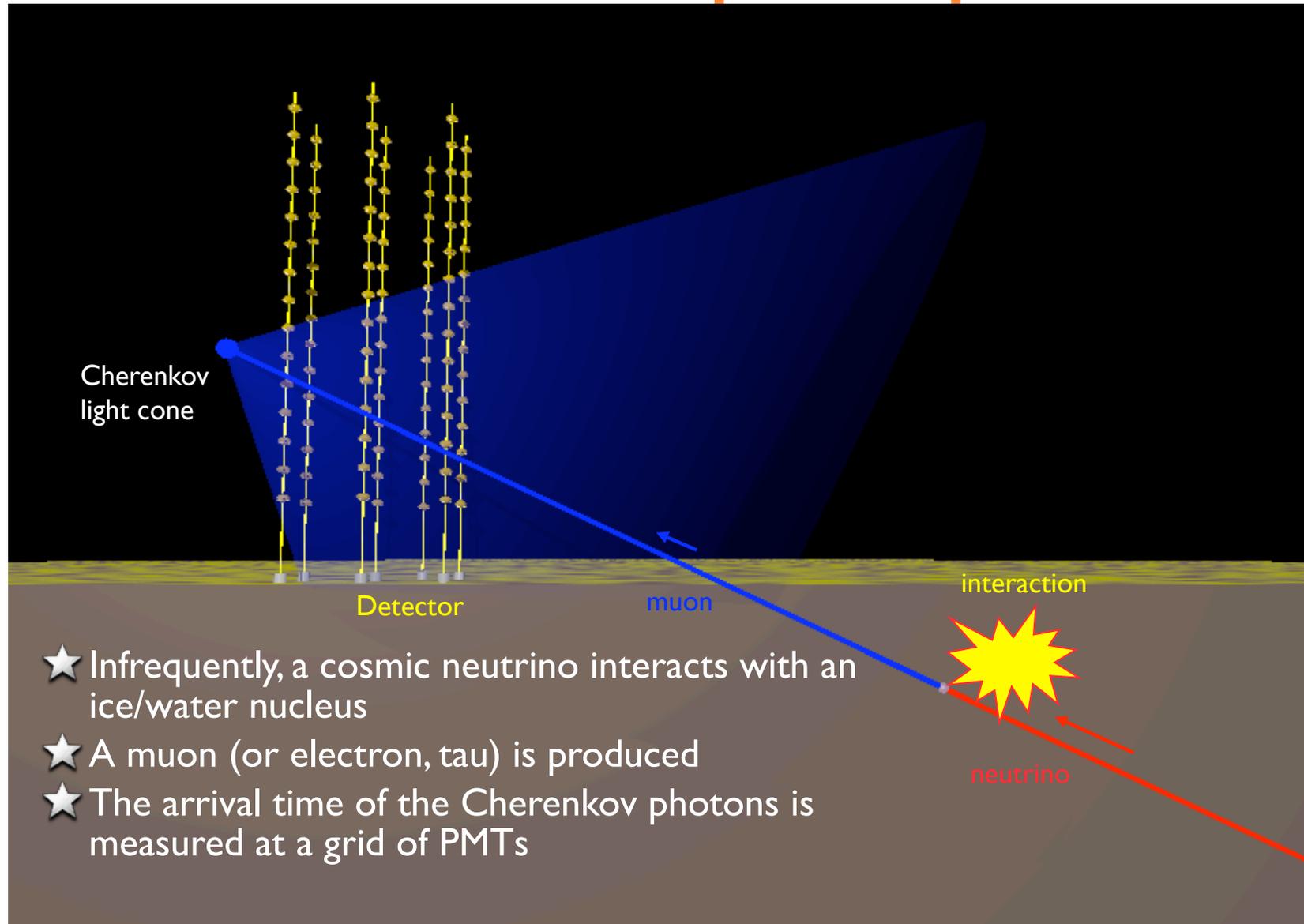
for the IceCube Collaboration

Scineghe08

Science with the New Generation of
High Energy Gamma-Ray Experiments
Padova, Italy

The IceCube telescope & Operation principles

Detection principle



The detector

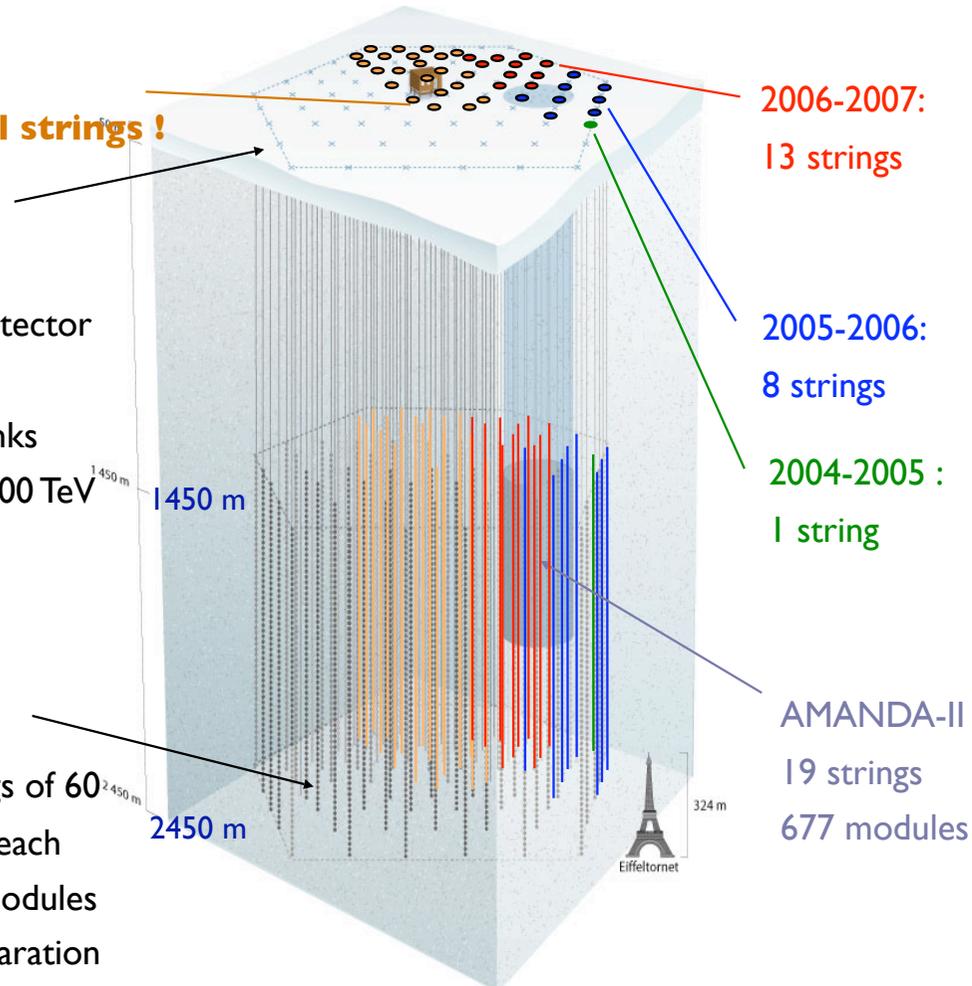
**2007-2008:
18 additional strings !**

IceTop

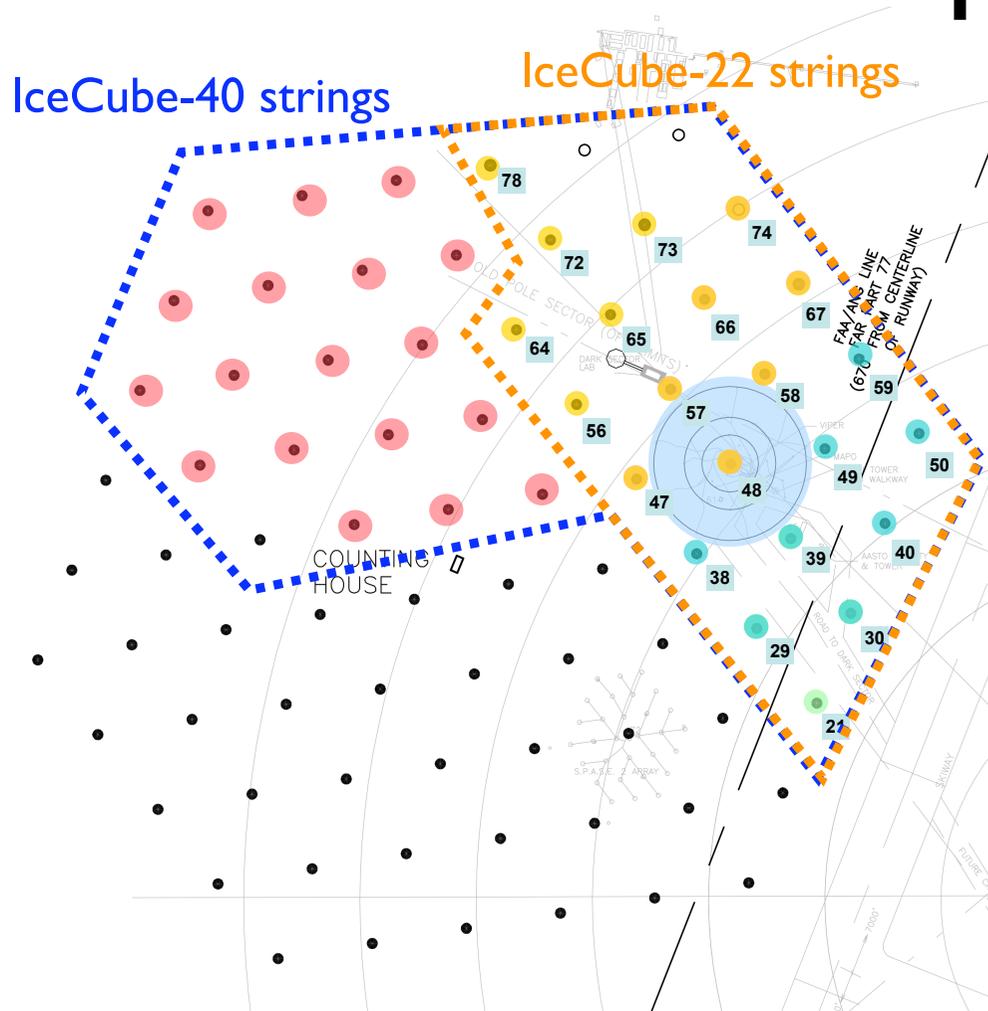
Air shower detector
80 pairs of ice
Cherenkov tanks
Threshold ~ 300 TeV

IceCube

Goal of 80 strings of $60^{2450\text{ m}}$
optical modules each
17 m between modules
125 m string separation



Construction progress



2005: 1 String

2006: 9 Strings

2007: 22 Strings

2008: 40 Strings
+ 40 surface stations

+ 19 AMANDA strings

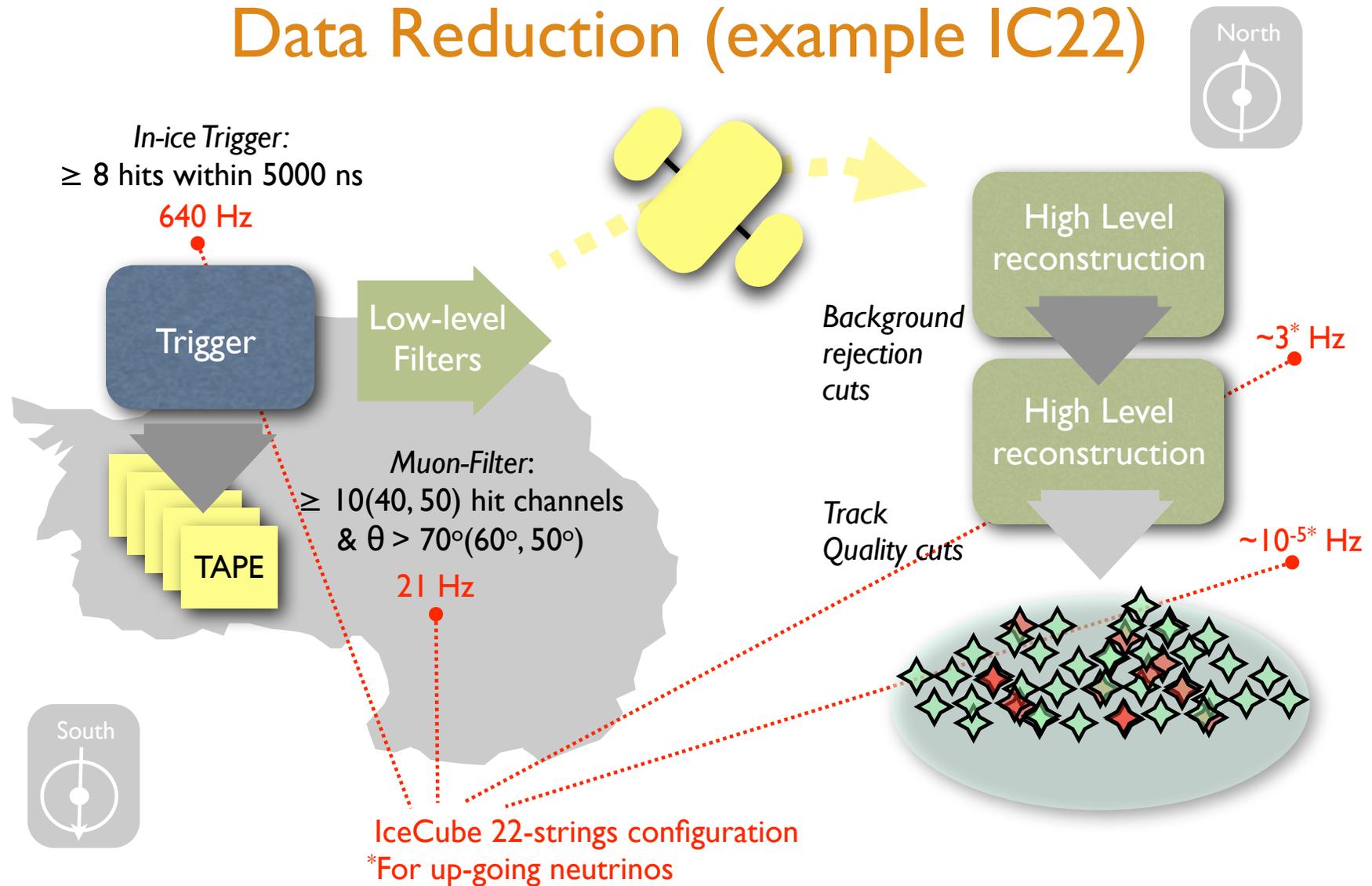
2009: 50 Strings

2010: 64 Strings

2011: 75+ Strings

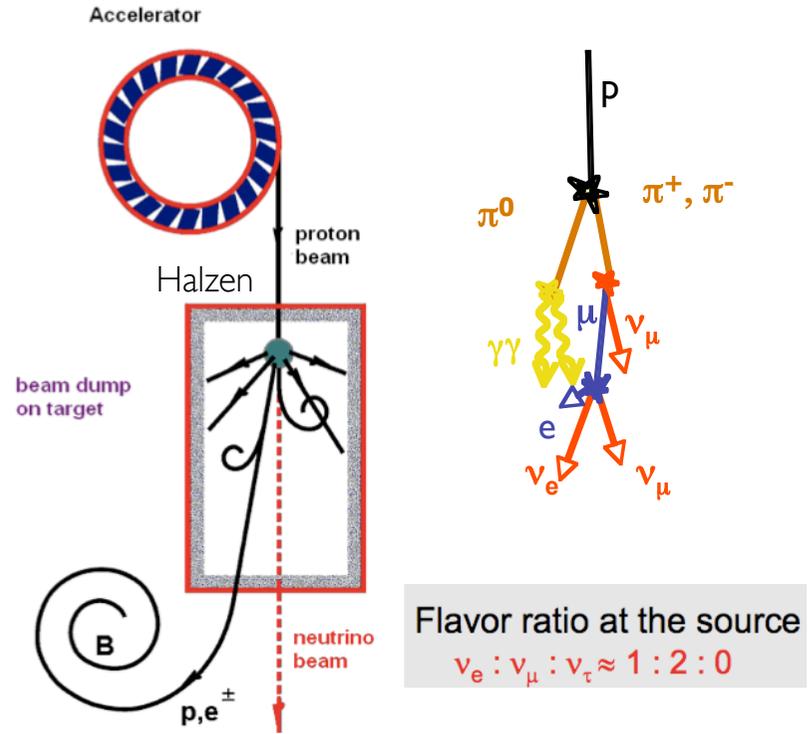
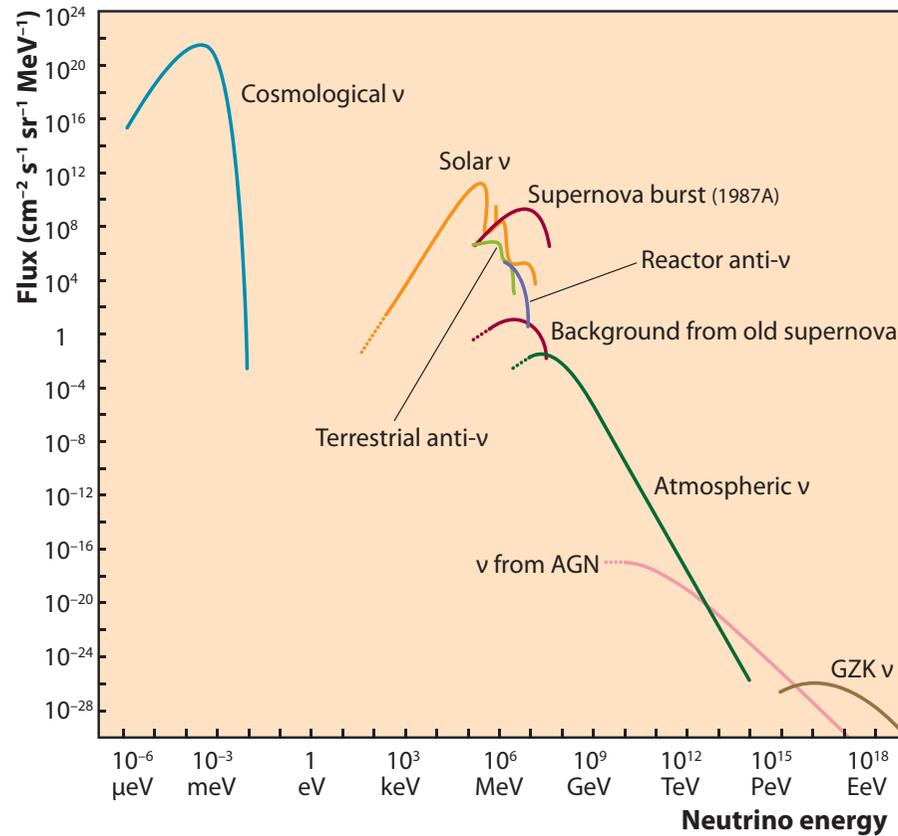
Search for point sources

Data Reduction (example IC22)



Searching for cosmic sources of ν 's

Cosmic neutrinos

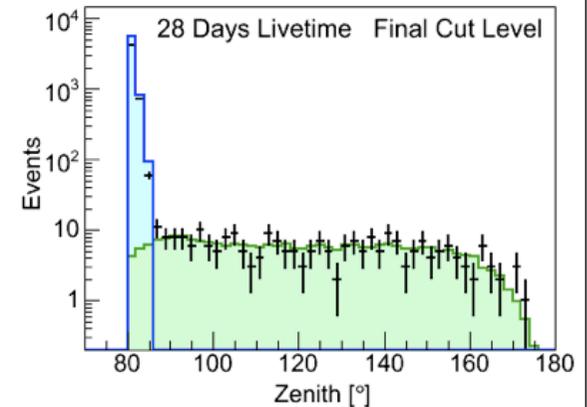
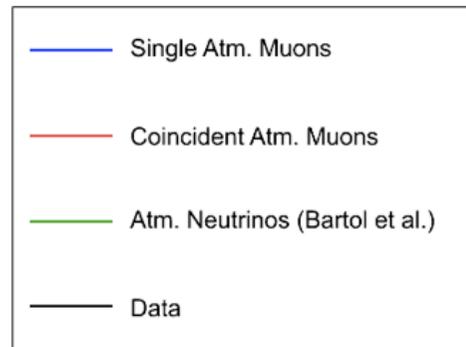
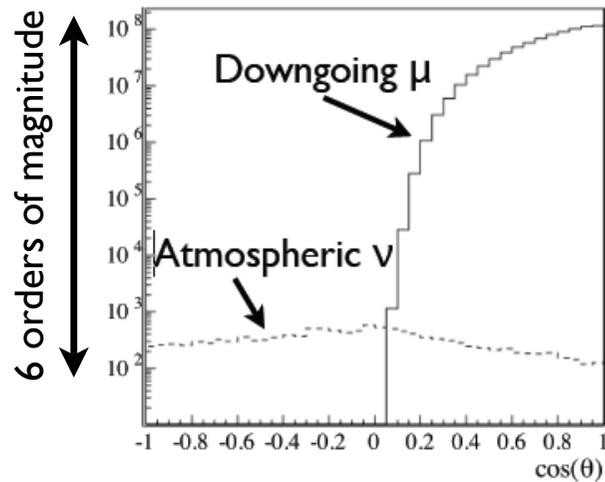
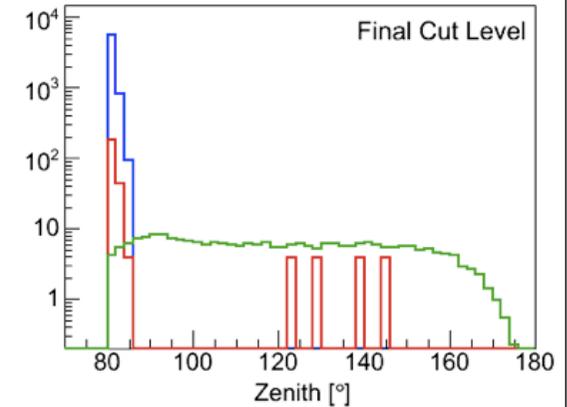
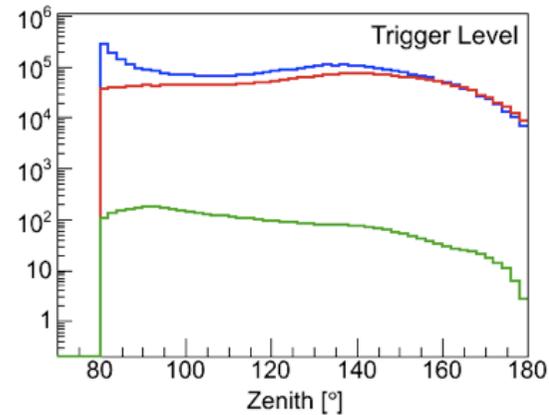
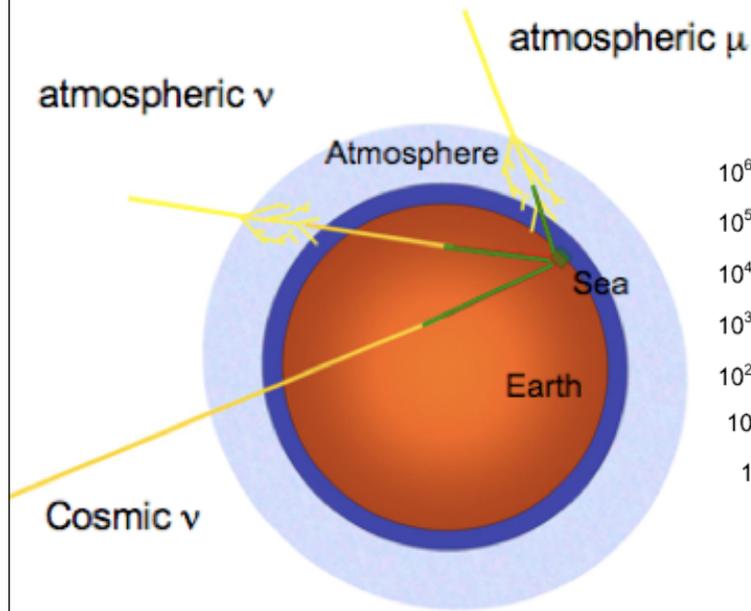


Flavor ratio at the source
 $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 2 : 0$

Neutrino oscillation length:
 $\lambda_{23} \approx 10^{11} (E_\nu / \text{TeV}) \text{ cm}$

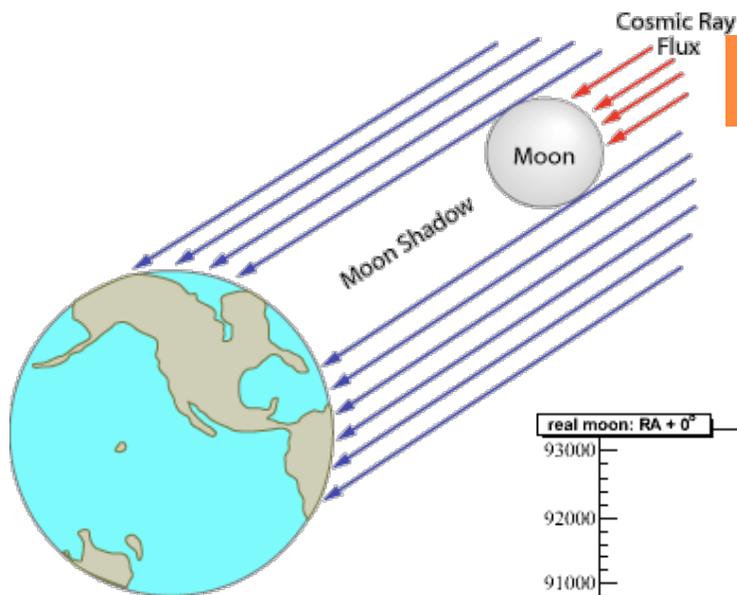
Flavor ratio at the Earth:
 $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

Signal and backgrounds

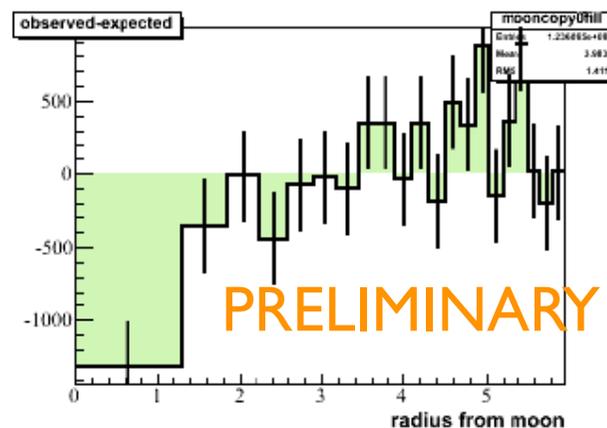
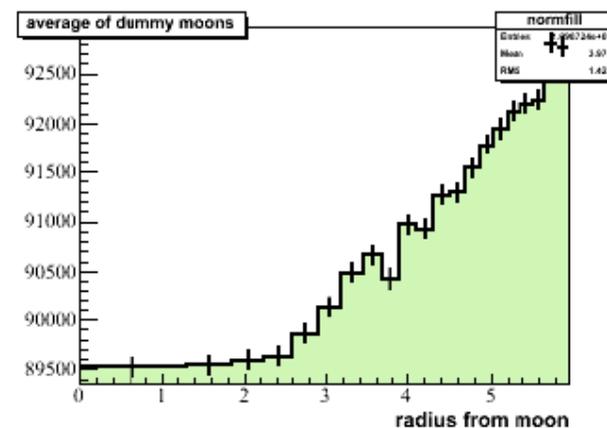
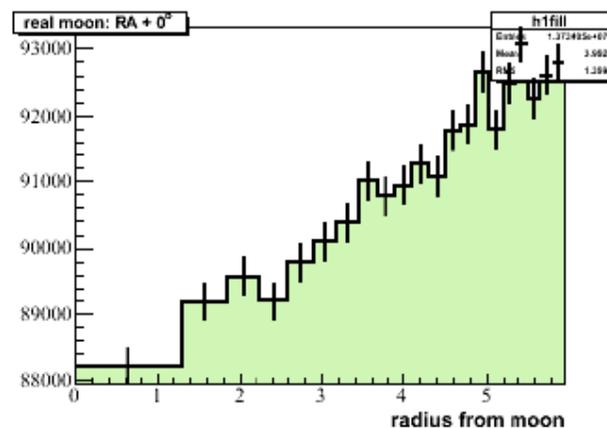


IC22 detector, for illustration tighter cuts are being used, compared to point-source search cuts

IceCube-40 strings: Moon shadow



IceCube-40 strings
Moon shadow analysis
(3 months of data): the
Moon provides a down-
going standard candle
for neutrino telescopes



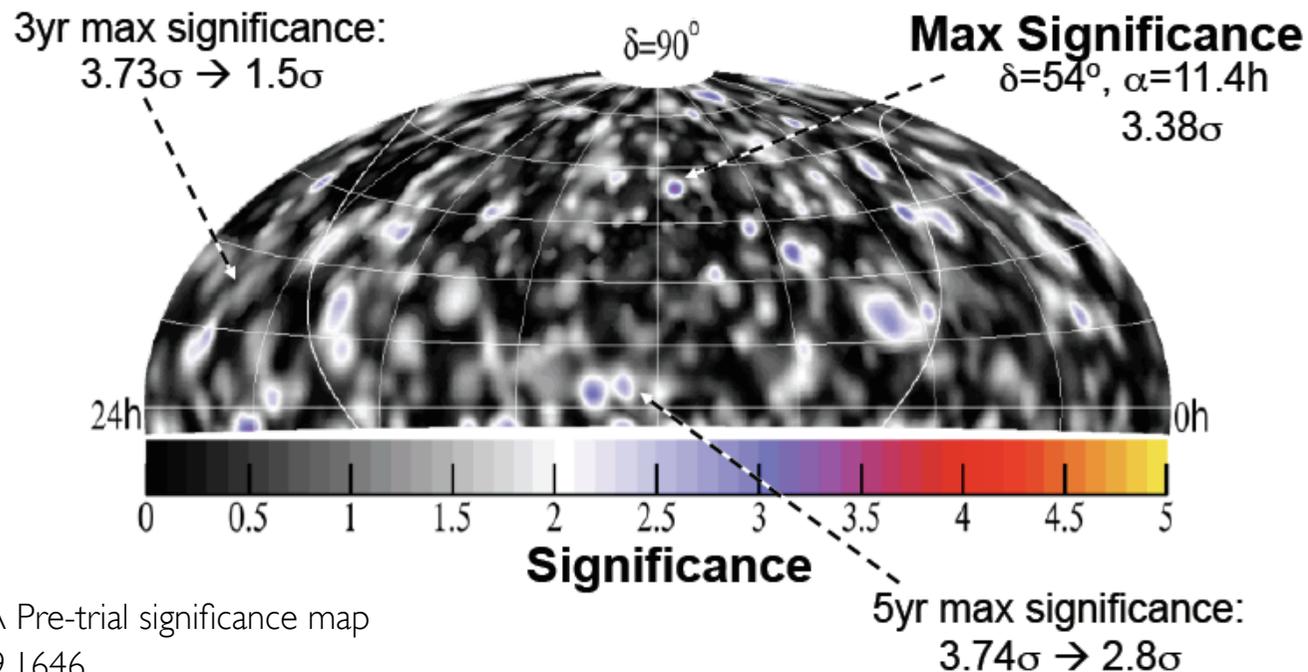
PRELIMINARY

observed: 88202 events
expected: 89521.6 events
deficit: -1319.62 events
error: 315.265 events
significance: -4.18576 σ

Search for point sources

State of the Art (I)

- ★ 7 years (2000-2006, 3.8 yrs effective, 6595 selected \uparrow -going events) with AMANDA
- ★ 95% of RA-randomized skymaps have maximum significance $> 3.38 \sigma$
→ Not significant

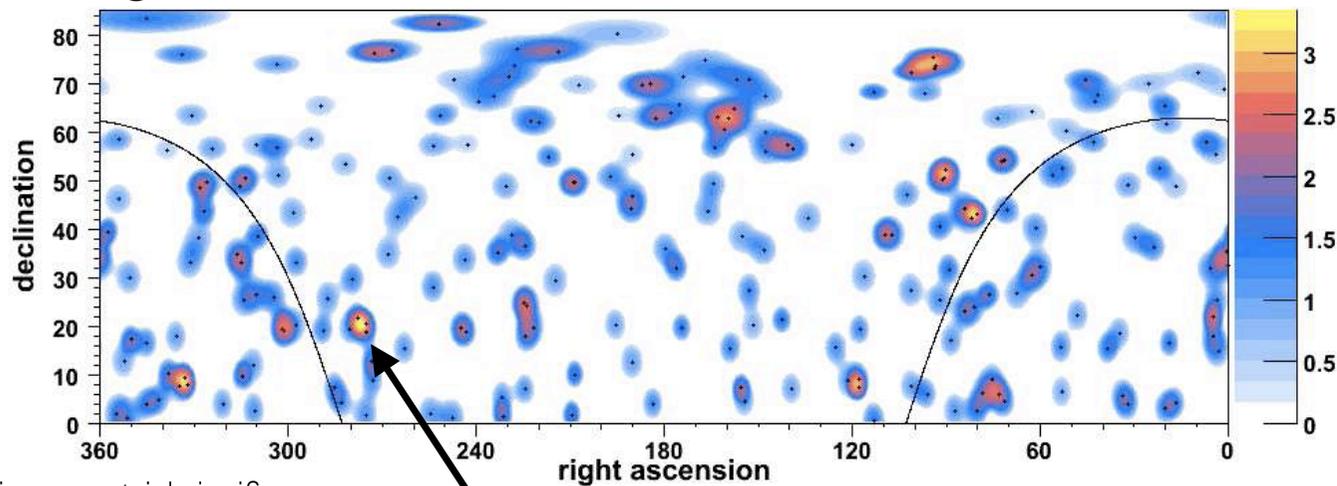


AMANDA Pre-trial significance map
arXiv:0809.1646

Search for point sources

State of the Art (II)

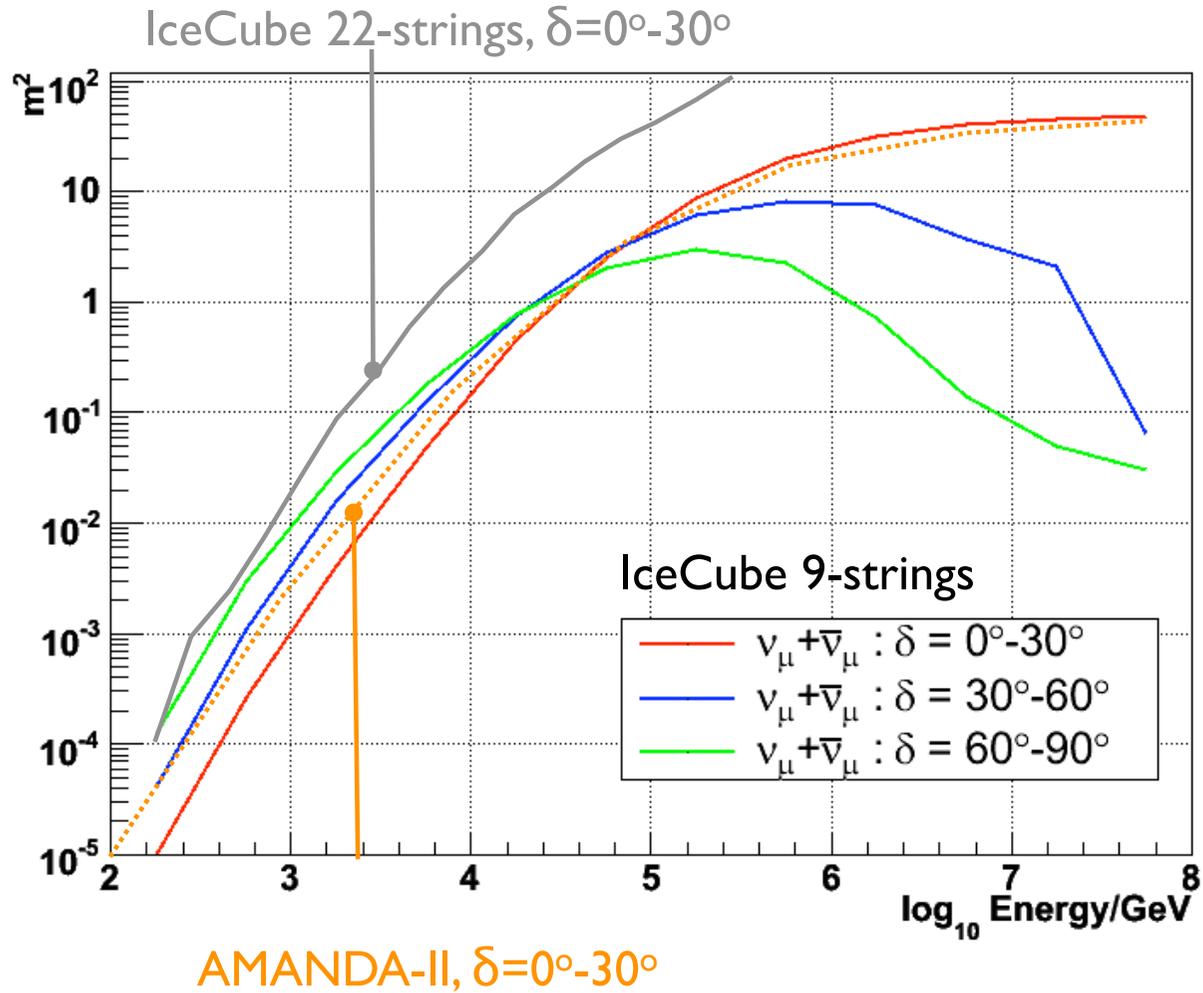
- ★ 1 year (2006, 0.4 yr effective, 233 selected \uparrow -going events) with IceCube (9-strings)
- ★ 26 a-priori source locations also searched, none is significant
- ★ 60% of RA-randomized skymaps have maximum significance $> 3.35\sigma$
→ Not significant



IceCube-9 strings pre-trial significance map
arXiv:0711.0353

Max significance 3.4σ @ $\delta=20.4^\circ$, $\alpha=276.6^\circ$

Effective Area



Search for point sources

State of the Art (III)

★ 1 year (2007, 0.8 yr effective, 5114 selected ↑-going events) with IceCube (22-strings)

★ Un-binned max. likelihood method: compare ratio of source likelihood (for signal events n_s) to background likelihood ($n_s=0$)

$$\mathcal{L}(n_s) = \prod_{i=1}^N \left(\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right)$$

★ Add energy estimator to PDF (hit channels N_{Chan}) to improve separation of hard signal spectrum and softer background spectrum

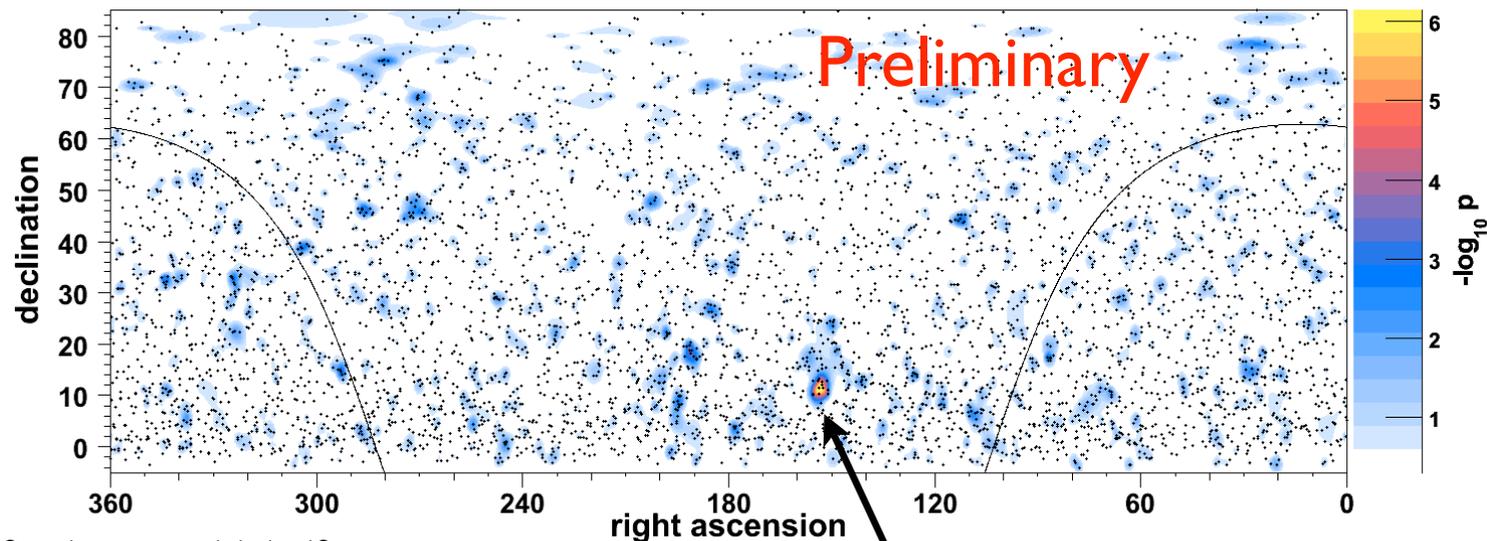
$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-r_i^2/2\sigma_i^2} \cdot P(E_i|\gamma) \quad \mathcal{B}_i = B_{\text{zen}} \cdot P_{\text{atm}}(E_i)$$

★ Source hypothesis uses event-wise uncertainty on track direction and energy estimators from MC; Background hypothesis based on distribution of declination and energy estimator for experimental events

Search for point sources

State of the Art (IV)

- ★ Most-sensitive analysis (max. likelihood): 0.7% of RA-randomized sky maps have maximum significance $> 4.8 \sigma$ → Not significant
- ★ No evidence of time structure and none of the events are closer than 10 days



IceCube-22 strings pre-trial significance
map max. likelihood analysis

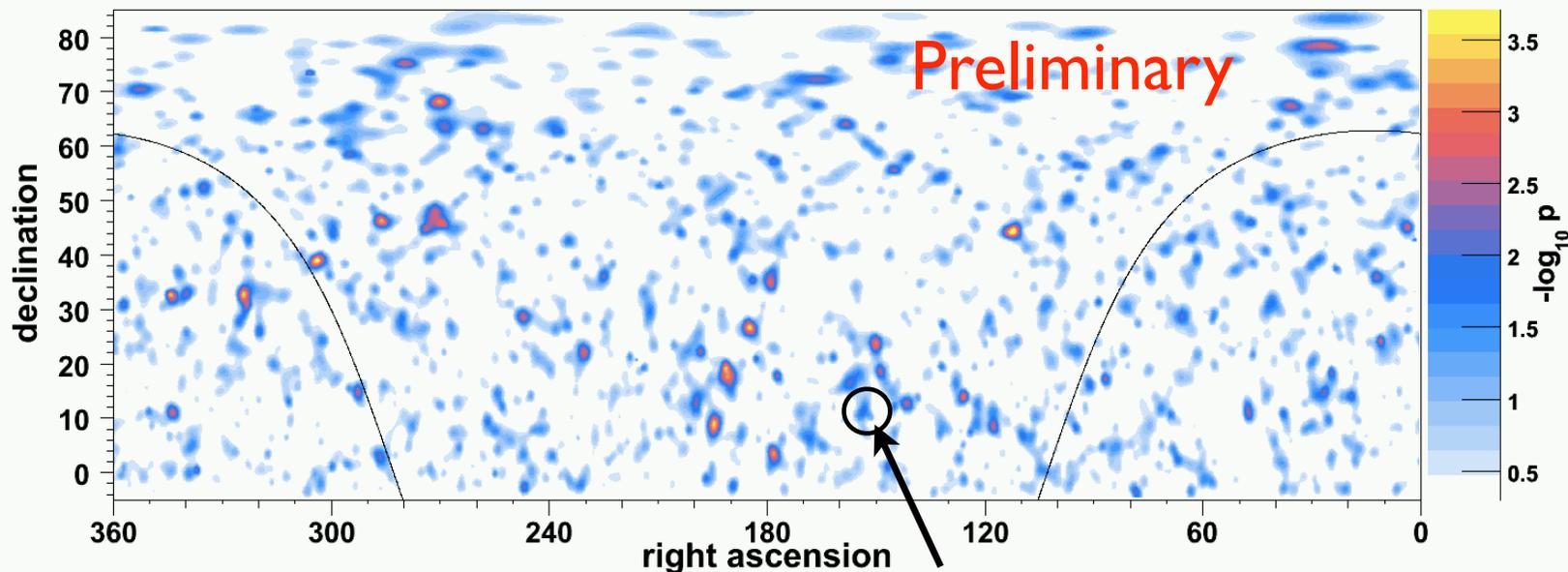
pre-trial p-value: $-\log_{10}(p)$: 6.14 (4.8σ)

post-trial: 1.3% (2.2σ , incl. additional trial factor 2 from catalog search)

Search for point sources

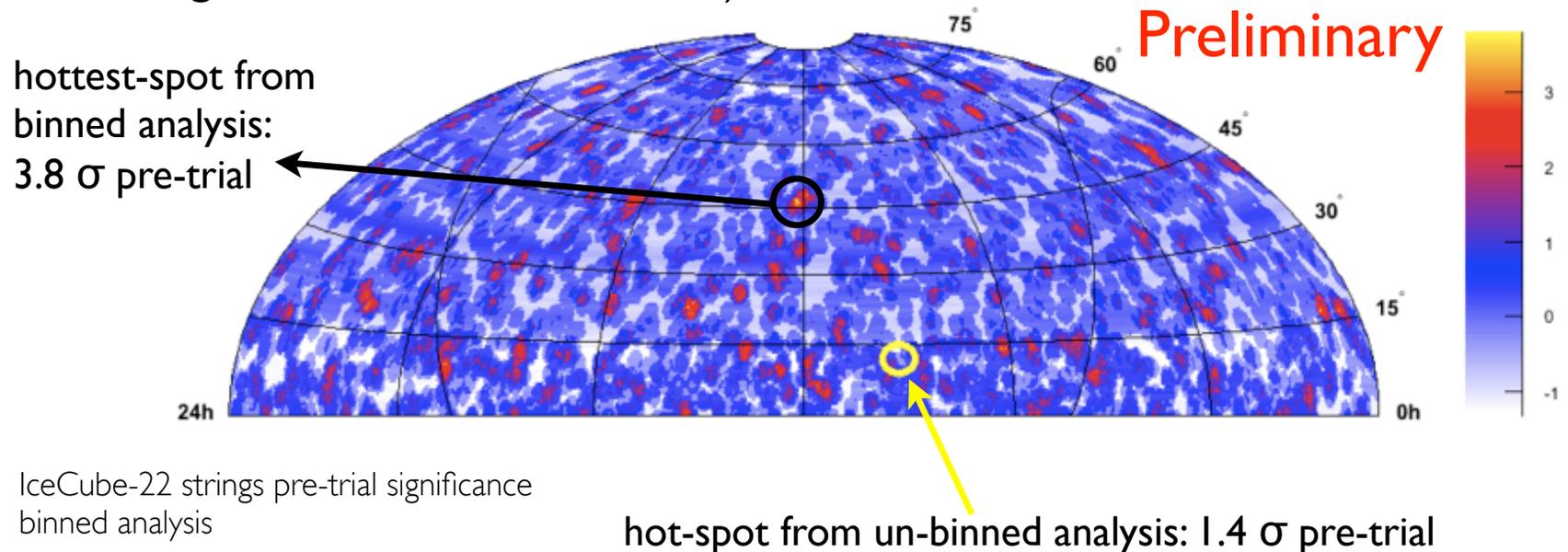
State of the Art

- ★ If the un-binned analysis is performed without the energy / N_{Chan} term, the original hottest spot is still an excess, but no longer significant at all (Note that the scale has changed and no spot is significant after trials) => The significance at this spot depends on distribution of high N_{Chan} events
- ★ Systematic uncertainty under study



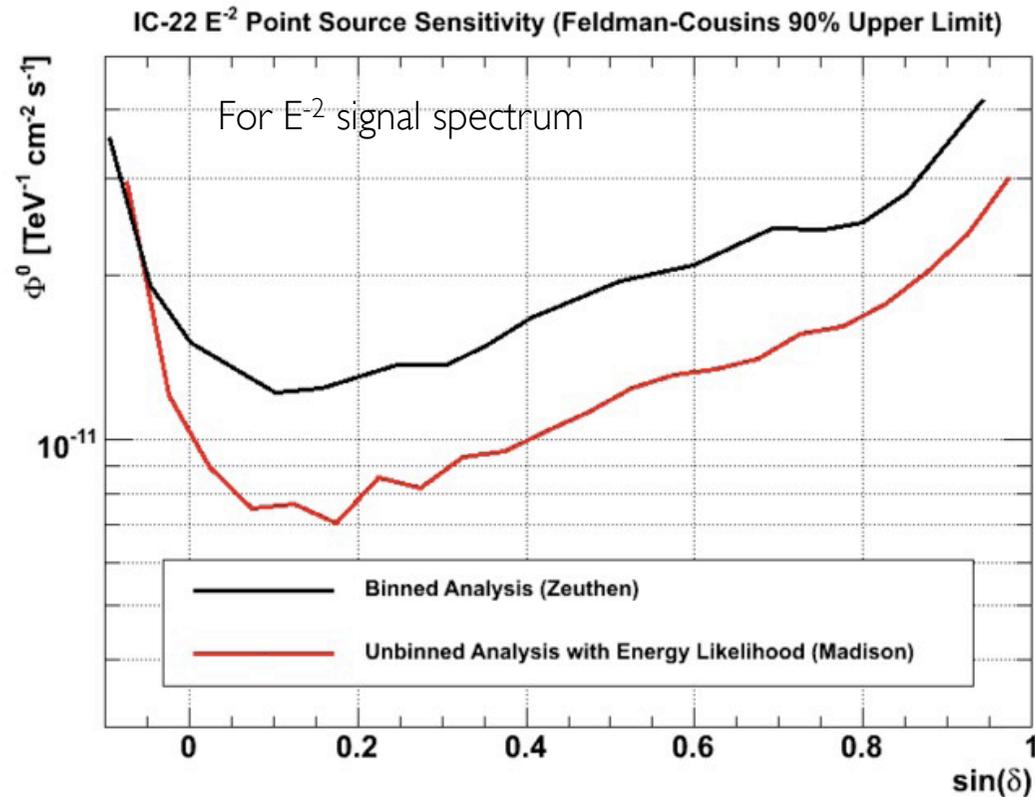
Independent analyses (I)

- ★ 1 year (2007, 0.8 yr effective, 2956 selected \uparrow -going events) with IceCube (22-strings)
- ★ binned analysis, 20-30% less sensitive, but more robust, based on a different reconstruction with $\sim 0.5^\circ$ better angular resolution at hot-spot declination and better for high N_{Chan} events, 1.4σ @ hot-spot (3.8σ if using the same reconstruction)



Sensitivity (F&C)

- ★ AMANDA (7yrs) avg sensitivity unbinned: 5.2×10^{-11} ($\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$)
- ★ IceCube22 (1yr) avg sensitivity unbinned: 1.3×10^{-11} ($\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$)
- ★ IceCube22 (1yr) avg sensitivity binned: 2.0×10^{-11} ($\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$)



Pre-defined catalog

- ★ Test on a-priori source list:
- ★ no excess is significant after trials (28 from # sources plus additional trial factor from all-sky analysis)

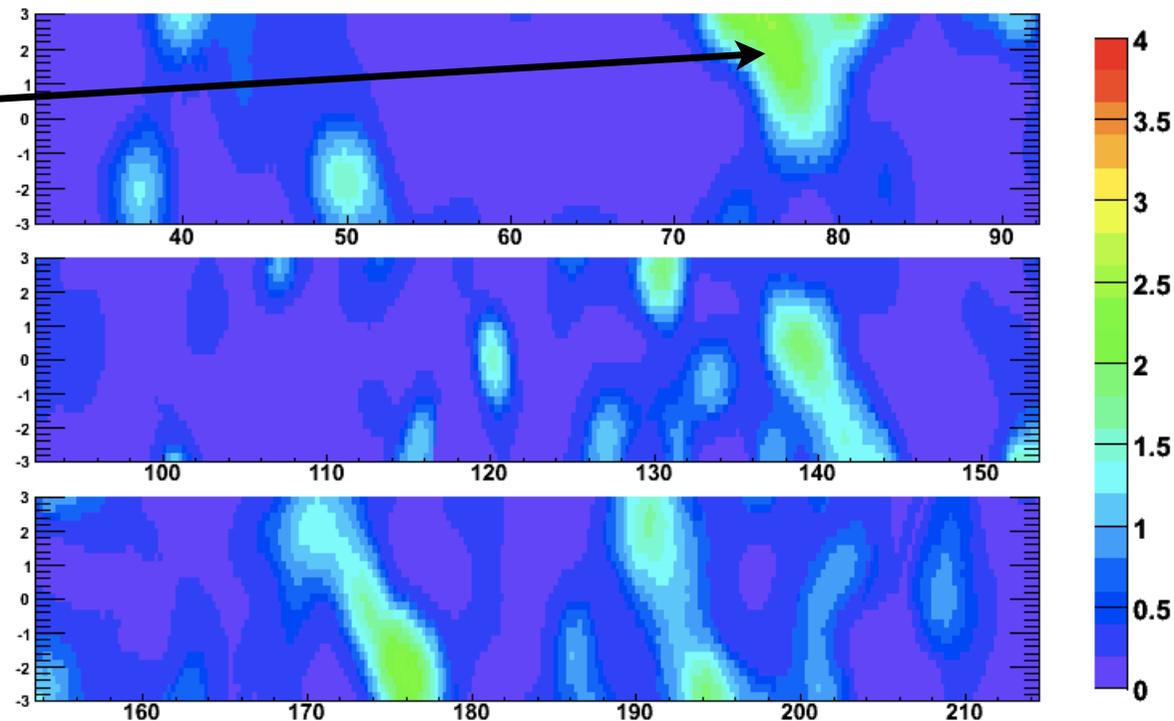
Name	max. likelihood p-value	binned analysis p-value
MGRO J2019+37	0.42	0.51
MGRO J1908+06	---	0.90
TeV J2032+4130	---	0.81
SS 433	0.24	0.66
Cyg X-1	---	1.00
LS I +61 303	0.49	0.80
GRS 1915+105	---	0.20
XTE J1118+480	0.07	1.00
GRO J0422+32	---	0.15
Geminga	---	0.51
Crab Nebula	---	0.10
Cas A	---	0.54
Mrk 421	---	0.82
Mrk 501	---	0.48
1ES 1959+650	0.04	0.57
1ES 2344+514	---	0.19
H 1426+428	---	1.00
1ES 0229+200	---	0.81
BL Lac	0.34	0.80
S5 0716+71	0.27	0.62
3C66A	0.33	0.77
3C 454.3	0.17	0.13
4C 38.41	---	0.51
PKS 0528+134	---	1.00
3C 273	0.36	0.88
M87	---	0.68
NGC 1275	0.19	0.49
Cyg A	---	0.19

IceCube-22 strings pre-trial significance for a catalog of pre-defined sources
 blue: most sensitive analysis (for E^{-2} spectrum)
 black: binned analysis
 ---: are negative excesses

Independent analyses (II)

- ★ 1 year (2007, 0.8 yr effective) with IceCube (22-strings) & AMANDA
- ★ optimized for softer spectra (e.g. Crab-like, with cut-off @ few TeV)
- ★ 1.8σ @ hot-spot (same reconstruction as max. likelihood analysis)

Maximum excess:
p-value=0.0037
expected for 95%
background cases

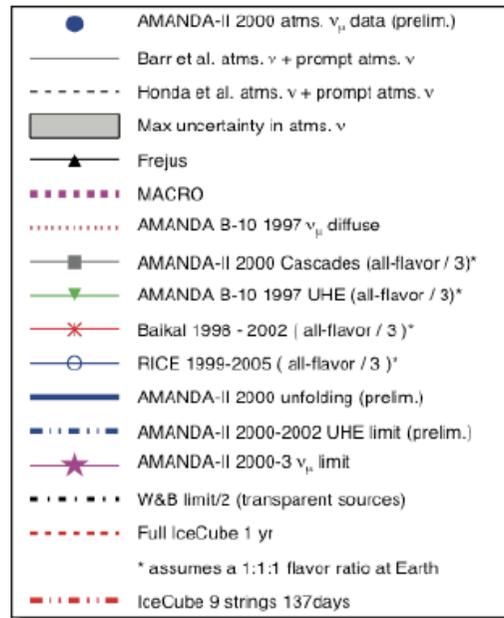
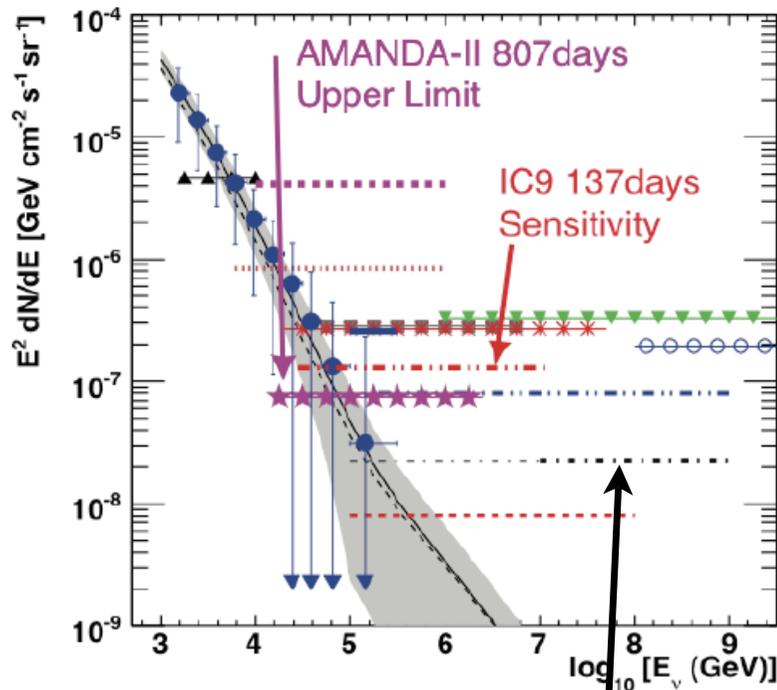
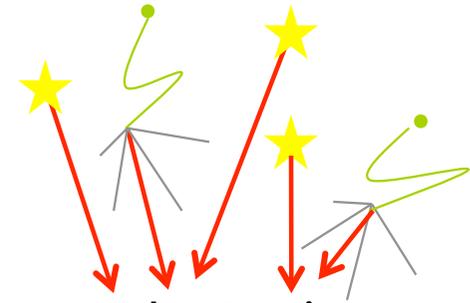


IceCube-22 +
AMANDA pre-trial
significance for scan of
the Galactic Plane

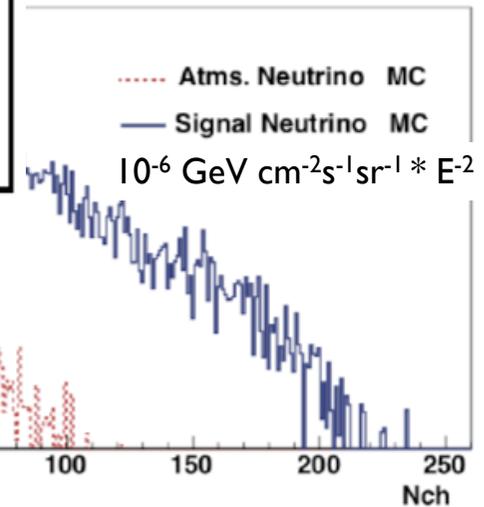
Diffuse fluxes

★ Search for cumulative effect of many weak sources

★ Exploit the different energy spectrum compared to atmospheric ν 's



Waxman & Bahcall
(PRD59, 1999)
corresponds to
about 50 ev/yr/km^2

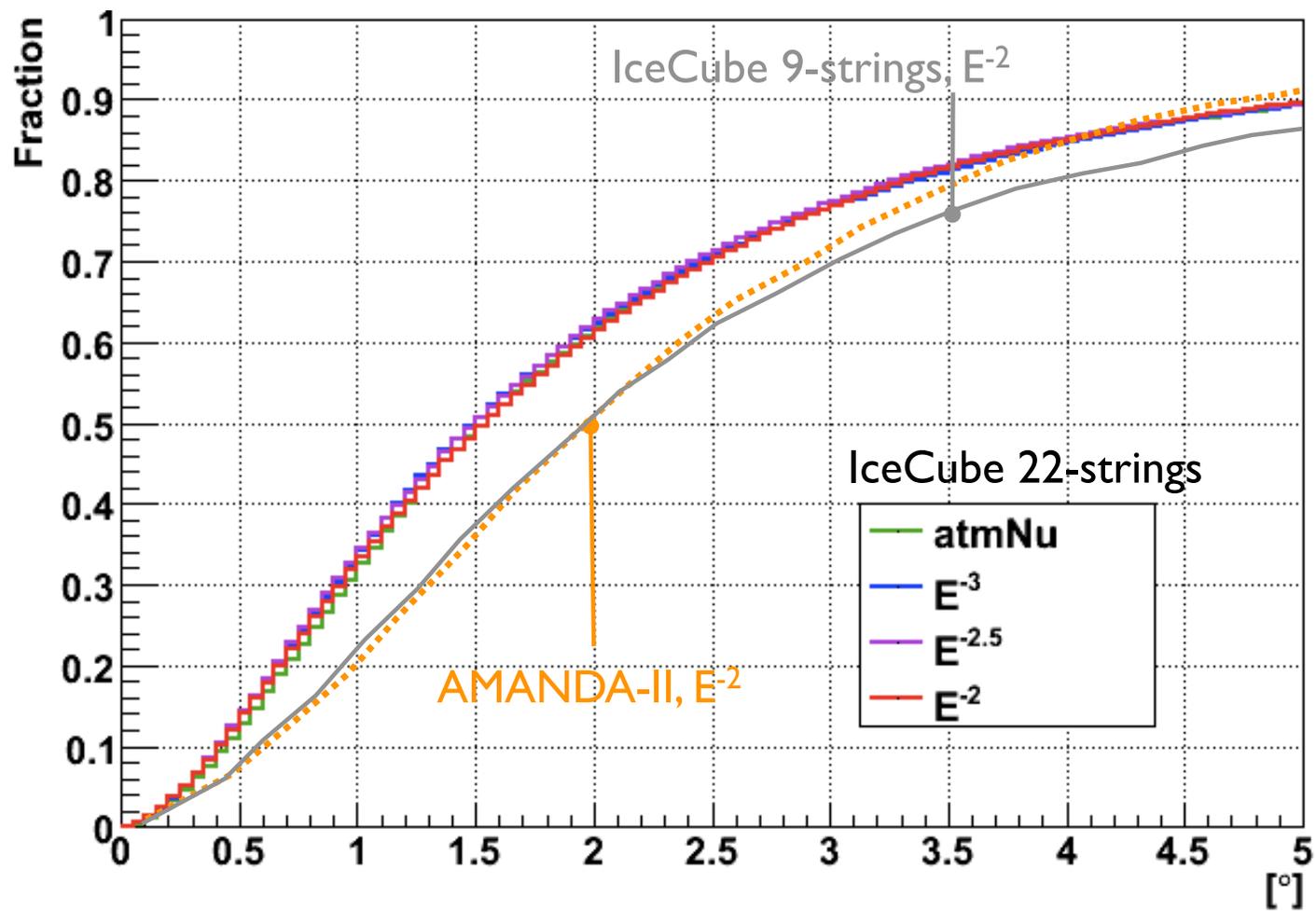


Summary & Outlook

- ★ Half of the IceCube detector installed!
- ★ First results presented at ICRC, several analyses performed on last year data (IceCube 22 and IceCube22 combined with AMANDA)
- ★ No cosmic signal found, yet
- ★ Correlation studies of high energy neutrinos with photons are a fundamental input to tune the search strategies and to increase the discovery chance
- ★ Several projects are being developed to exploit this potential
- ★ On-line analyses scheme are also being worked out for γ -ray and optical follow-up studies (pioneering effort by the cooperation with AMANDA/MAGIC NT₀O!)
- ★ Stay tuned!

Extra slides

Point Spread Function



Discovery potential (5σ with 50% probability)

