

ASTROPHYSICAL HIGH ENERGY NEUTRINO POINT SOURCES SEARCH WITH A FDR CONTROLLING PROCEDURE APPLIED ON AMANDA-II 2000-2006 DATA

IceCube Neutrino Observatory

Point Source Search with AMANDA/IceCube

What's / why using the False Discovery Rate ?

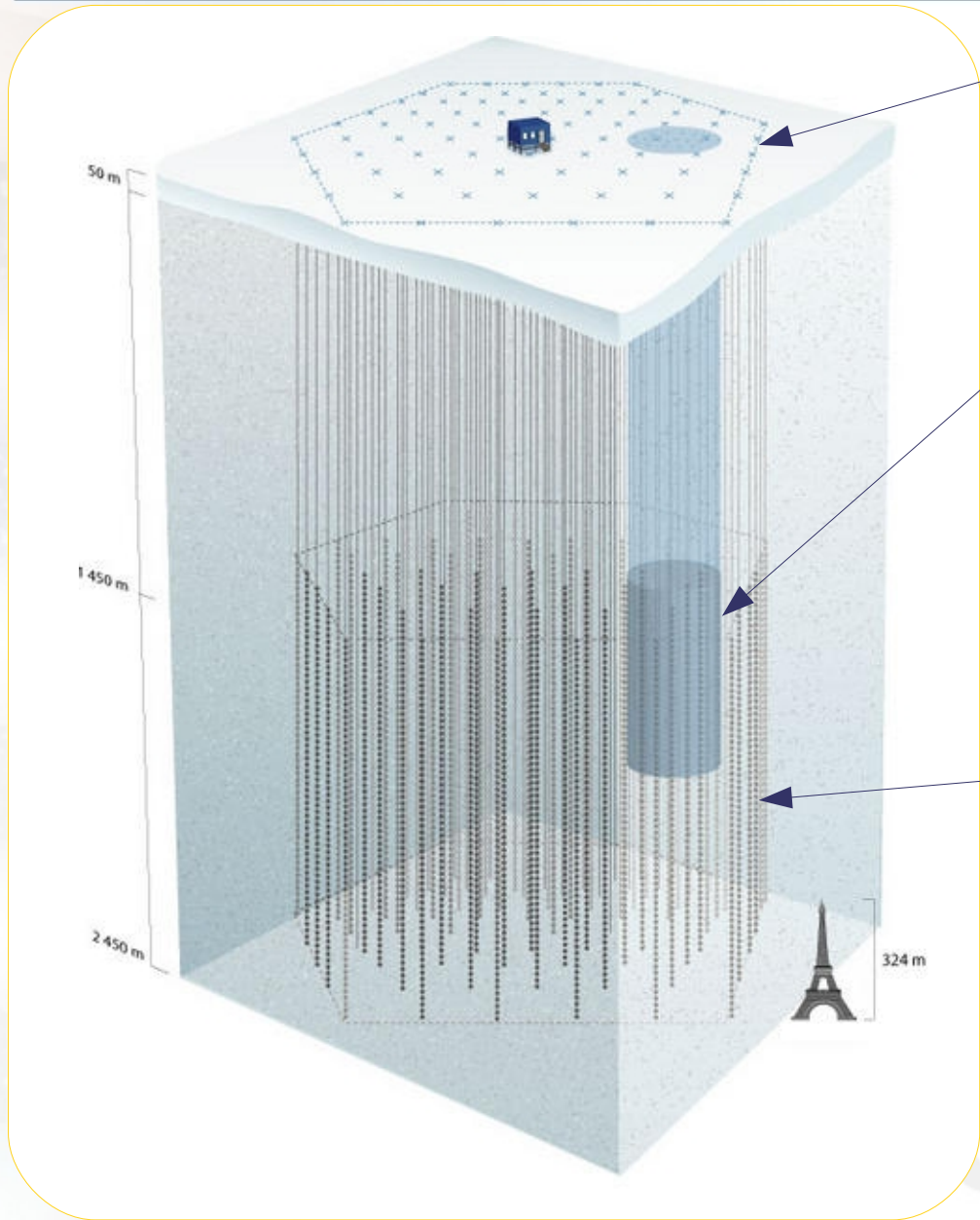
FDR controlling procedure for PS search

Results on AMANDA-II 2000-2006 data

Conclusions

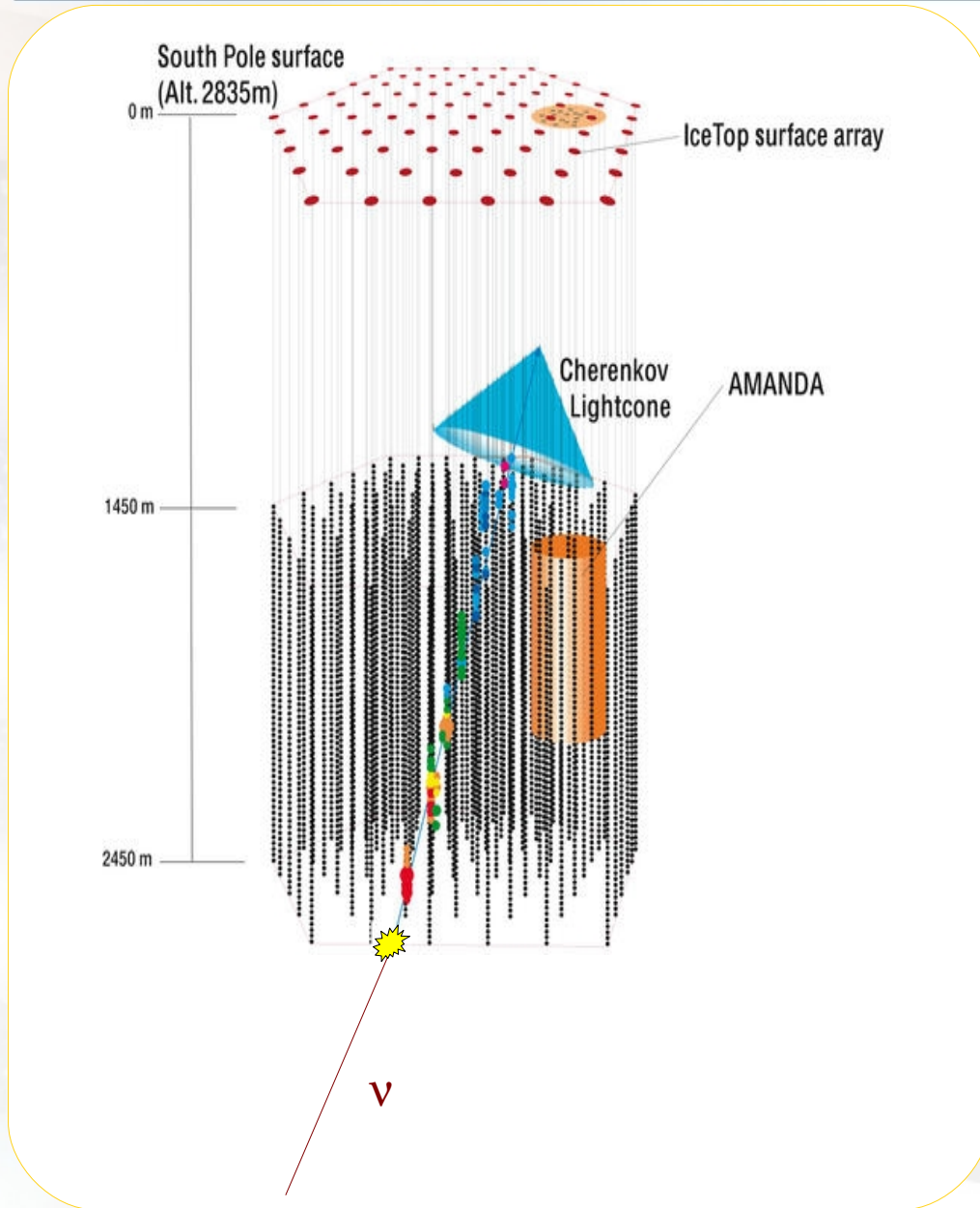
IceCube

IceCube Neutrino Observatory

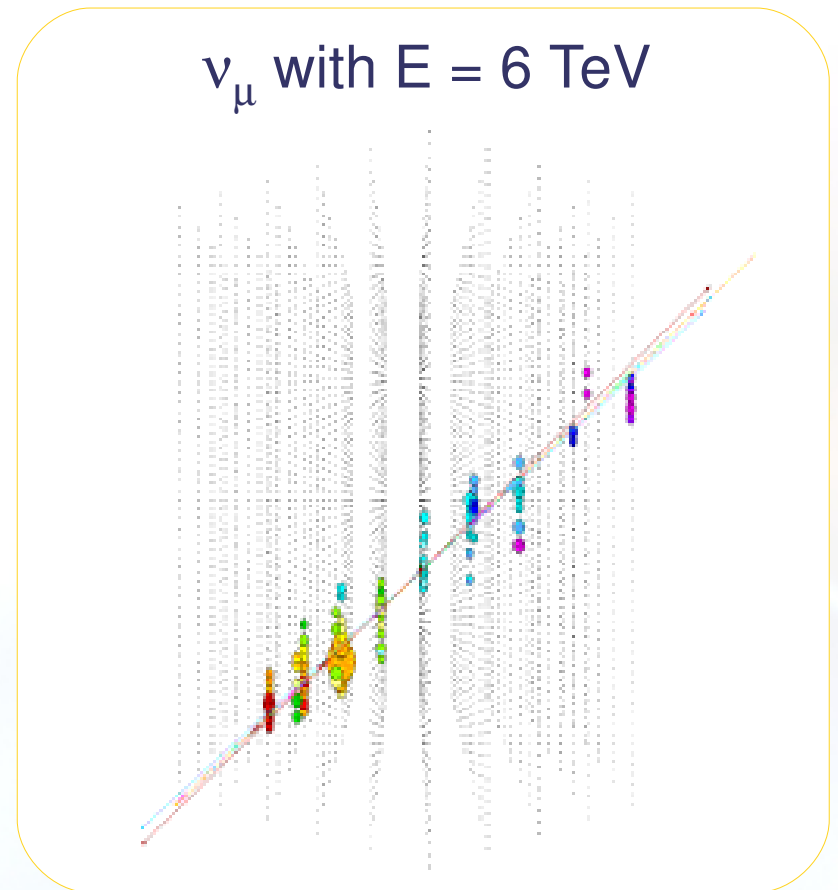


- **IceTop Air Shower Array**
 - 160 Cherenkov Tanks (2DOMs)
 - Used for calibration, bg study,...
- **AMANDA**
 - Completed in 2000
 - 677 OM – 19 strings
 - \varnothing : 200 m – 1.5 - 2.0 km depth
 - Extension to low energies
- **IceCube**
 - Completion in 2011
 - 4800 DOM – 80 strings
 - 1 km x 1km²
 - First fully funded cubic kilometer sized neutrino detector

IceCube Neutrino Observatory



Optimized to detect muon tracks induced by c.c. interactions of neutrinos with $E > 100$ GeV



Background vs. Signal

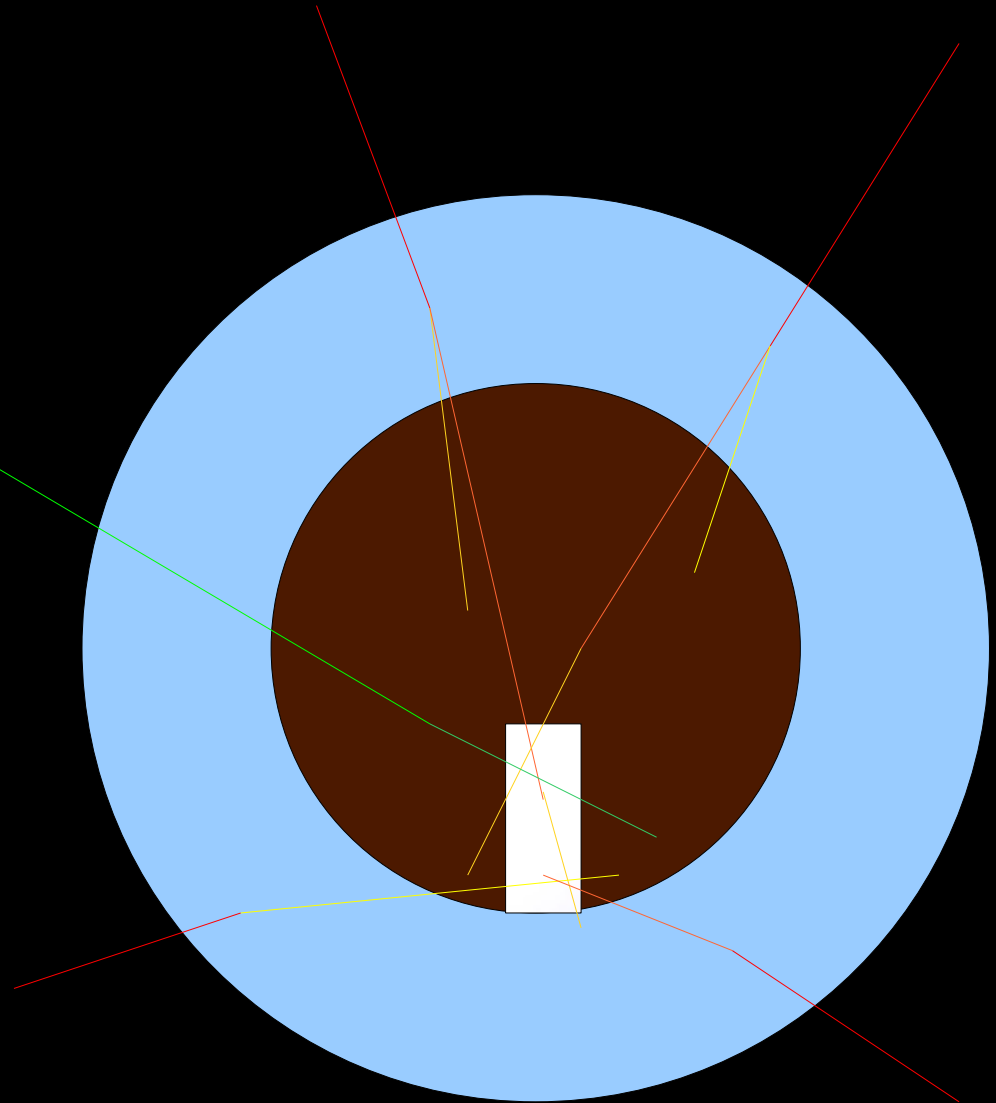
Interaction of cosmic rays in the earth's atmosphere



ν

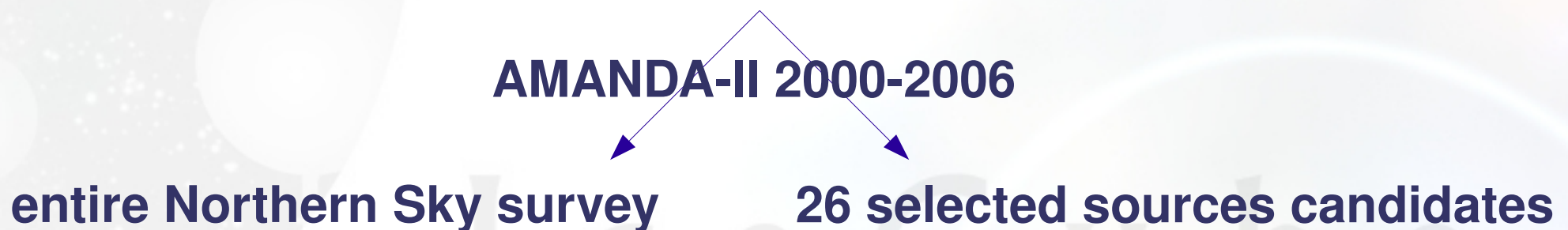
For 1 cosmic neutrino :

- 10^9 atmospheric muons
 - Northward coming stopped by the earth
- 10^3 atmospheric neutrinos
 - Downward going rejected



Philosophy of Point Source Search

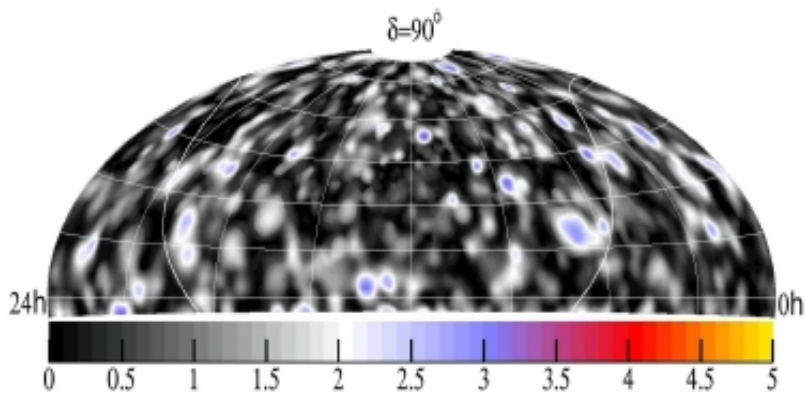
- Localized excess of events over background
 - Background : uniformly distributed in right ascension
 - Signal : detector Point Spread Function
- Final event selection : from $\sim 10^9$ to $\sim 10^3$ events per year
 - Blind approach (randomized r.a.)
 - $< 5\%$ wrongly reconstruction down-going μ
 - $\sim 1.5^\circ - 2.5^\circ$ angular resolution $f(E, \delta)$



Unbinned maximum likelihood search method

entire Northern Sky survey

- $0.25^\circ \times 0.25^\circ$ grid
- $-5^\circ < \delta < 83^\circ$
- **Maximal Significance**
 3.38σ @ $\delta = 54^\circ$; $\alpha = 11.4h$
- **Proba in random sky : 95%**



- $E^2\Phi_{\mu\tau} \leq 5.2 \times 10^{-11} \text{ TeV cm}^{-2} \text{ s}^{-1}$

26 selected sources candidates

Candidate	$\delta(^{\circ})$	$\alpha(h)$	Φ_{90}	p	$\Psi(^{\circ})$
3C 273	2.05	12.49	8.71	0.081	2.1
SS 433	4.98	19.19	3.21	0.64	2.2
GRS 1915+105	10.95	19.25	7.76	0.11	2.3
M87	12.39	12.51	4.49	0.41	2.1
PKS 0528+134	13.53	5.52	3.26	0.64	2.3
3C 454.3	16.15	22.90	2.58	0.73	2.3
Geminga	17.77	6.57	12.77	0.0086	2.3
Crab Nebula	22.01	5.58	9.27	0.18	2.3
GRO J0422+32	32.91	4.36	2.75	0.76	2.2
Cyg X-1	35.20	19.97	4.00	0.57	2.1
MGRO J2019+37	36.83	20.32	9.67	0.077	2.1
4C 38.41	38.14	16.59	2.20	0.85	2.1
Mrk 421	38.21	11.07	2.54	0.82	2.1
Mrk 501	39.76	16.90	7.28	0.22	2.0
Cyg A	40.73	19.99	9.24	0.095	2.0
Cyg X-3	40.96	20.54	6.59	0.29	2.0
Cyg OB2	41.32	20.55	6.39	0.30	2.0
NGC 1275	41.51	3.33	4.50	0.47	2.0
BL Lac	42.28	22.05	5.13	0.38	2.0
H 1426+428	42.68	14.48	5.68	0.36	2.0
3C66A	43.04	2.38	8.06	0.18	2.0
XTE J1118+480	48.04	11.30	5.17	0.50	1.8
1ES 2344+514	51.71	23.78	5.74	0.44	1.7
Cas A	58.82	23.39	3.83	0.67	1.6
LS I +61 303	61.23	2.68	14.74	0.034	1.5
1ES 1959+650	65.15	20.0	6.76	0.44	1.5

trial factor correction

20%

Search for Point Sources of High Energy Neutrinos with Final Data from AMANDA-II
Phys.Rev.D79:062001,2009

Unbinned maximum likelihood search method

- **Hypothesis on the signal**

$$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_{i=1}^N \left(\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right) \quad \mathcal{S}_i = \frac{1}{2\pi\sigma^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma^2}} \int P(N_{ch}|E_\nu) P(E_\nu|\gamma) dE_\nu$$

- **Maximal Significance**

3.38 σ @ $\delta = 54^\circ$; $\alpha = 11.4\text{h}$

- **Proba in random sky : 95%**

→ p-value correction *a posteriori*

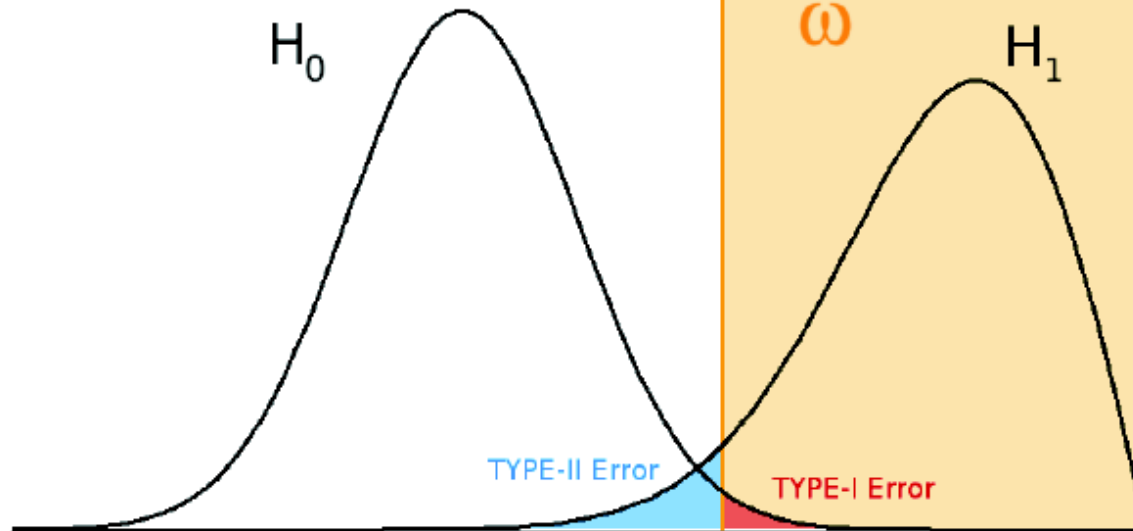
« blind analysis » on pure background sky with

- **randomized right ascensions**
- **declinations preserved**

→ Not dedicated to multiple source detection

STATISTICAL ESTIMATORS & FDR

Simple Test



H_0 : Null Hypothesis

→ Background

H_1 : Alternative Hyp.

→ Signal

Errors

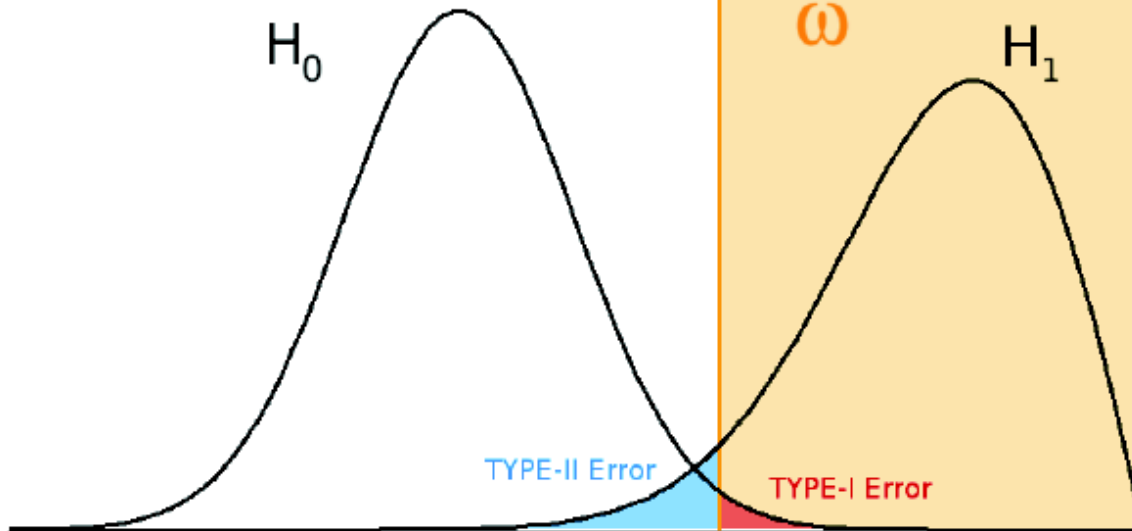
type-I : False rejection

type-II : No detection

IceCube

STATISTICAL ESTIMATORS & FDR

Simple Test



H_0 : Null Hypothesis

→ Background

H_1 : Alternative Hyp.

→ Signal

Errors

type-I : False rejection

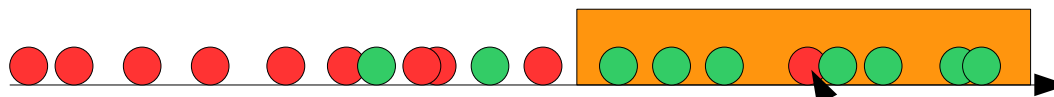
type-II : No detection

Multiple Tests (n)

$$p(x \in \omega | H_0) = 1 - (1 - p)^n$$

$$= 0.40$$

rejections : $R = 8$



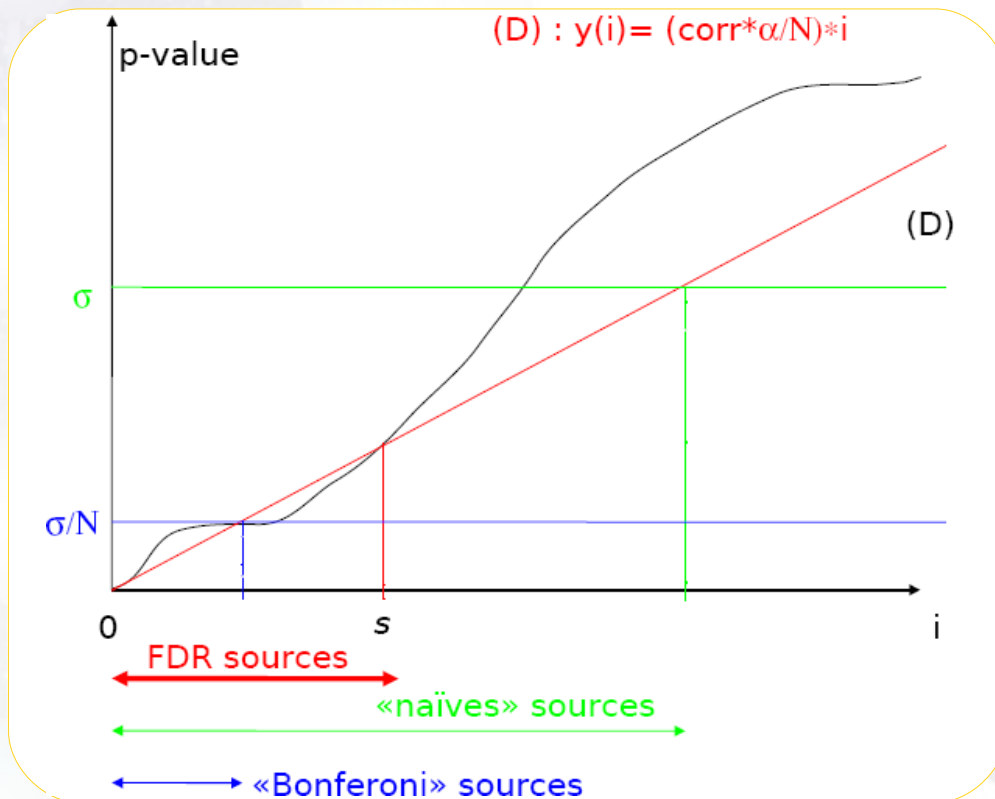
False rejection : $U = 1$

	H_0	H_1	Total
rejected	U	T	R
non rejected	V	S	$m - R$
Total	m_0	$m - m_0$	m

$$FDR = E \left(\frac{U}{R \vee 1} \right)$$

FALSE DISCOVERY RATE CONTROLLING PROC.

- Maximise Detection Potential while controlling detection CL using multiple hypothesis H_0 (background) testing procedure
- Method independant of source flux model
- No need of MC check *a posteriori*



- Set of N pvalues (probability to be bg v)
→ order in increasing order
- Find the last crossing (s) with **the line (D)**
- Reject H_0 for $i < s$ with a Confidence Level $1 - \alpha$
- If H_0 is rejected → Signal

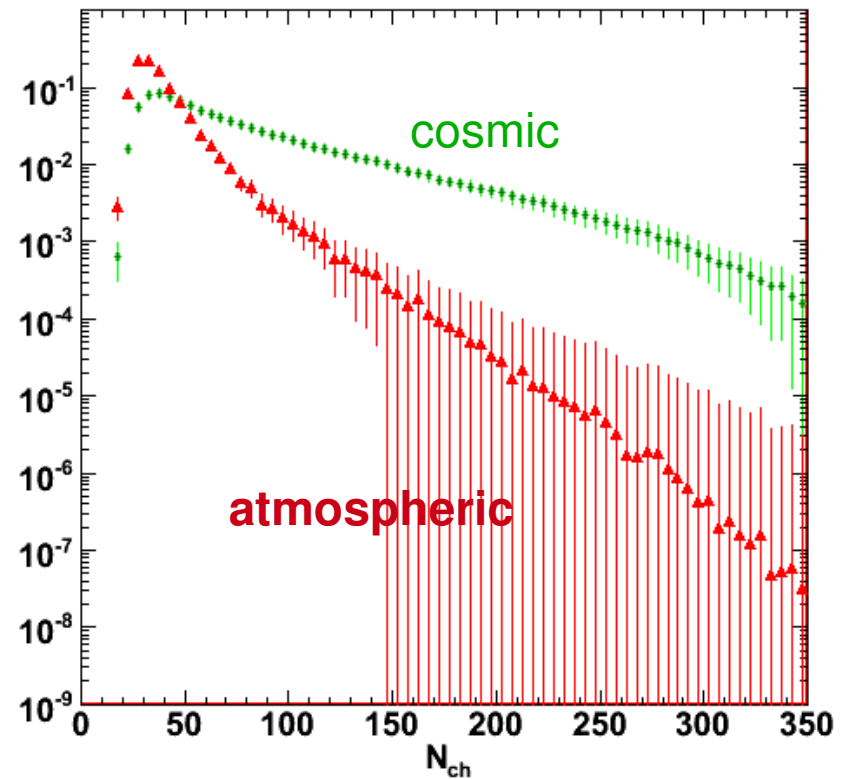
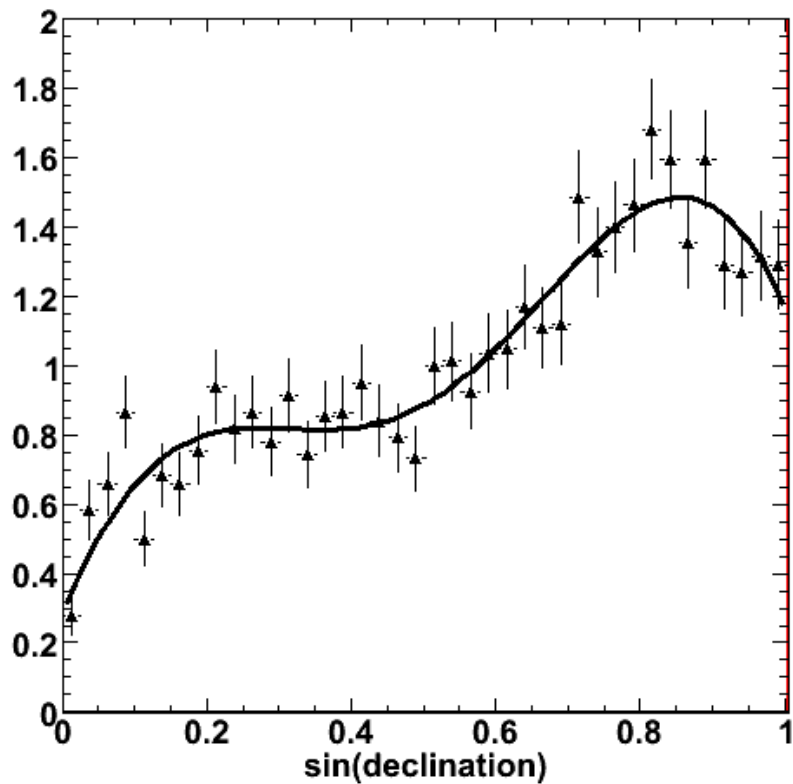
FDR PROCEDURE FOR POINT SOURCE SEARCH

Final set of neutrinos : $N \nu \rightarrow N$ p-values

depending on :

- ν density (position)

- energy (N_{ch})

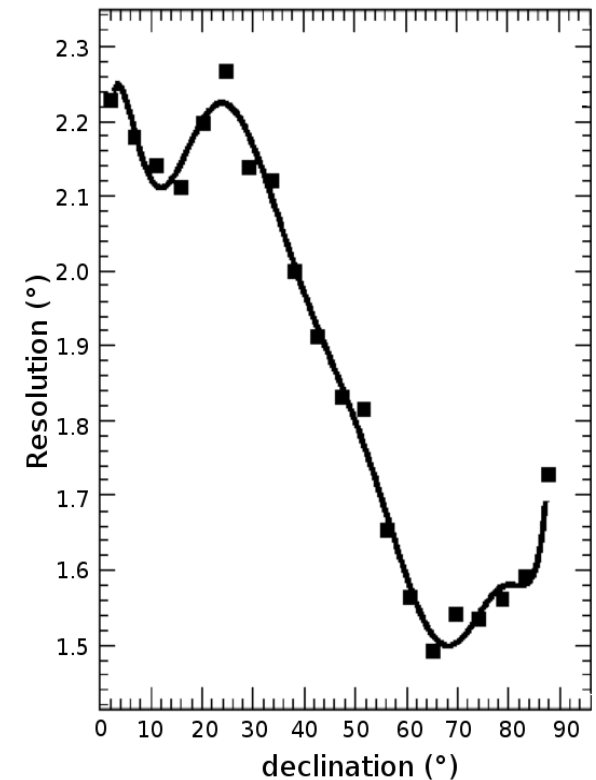
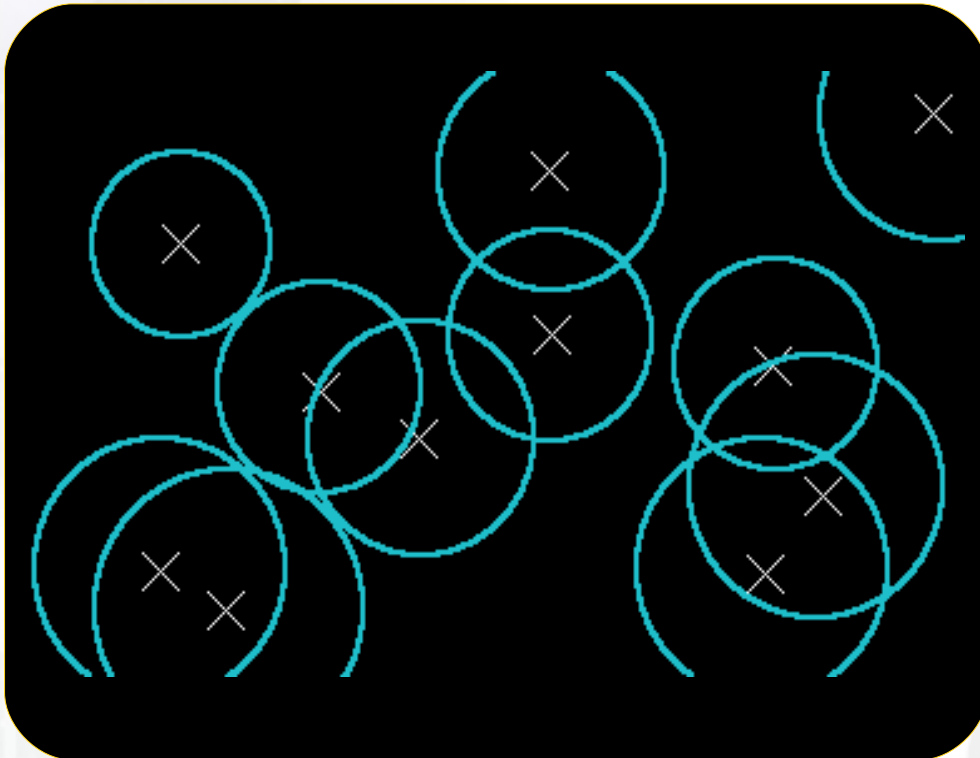


FDR PROCEDURE FOR POINT SOURCE SEARCH

Hypothesis tested for each ν

1. Definition of a search bin around each neutrino

Optimal bin size : $1.585 * \text{Resolution}(\delta)$



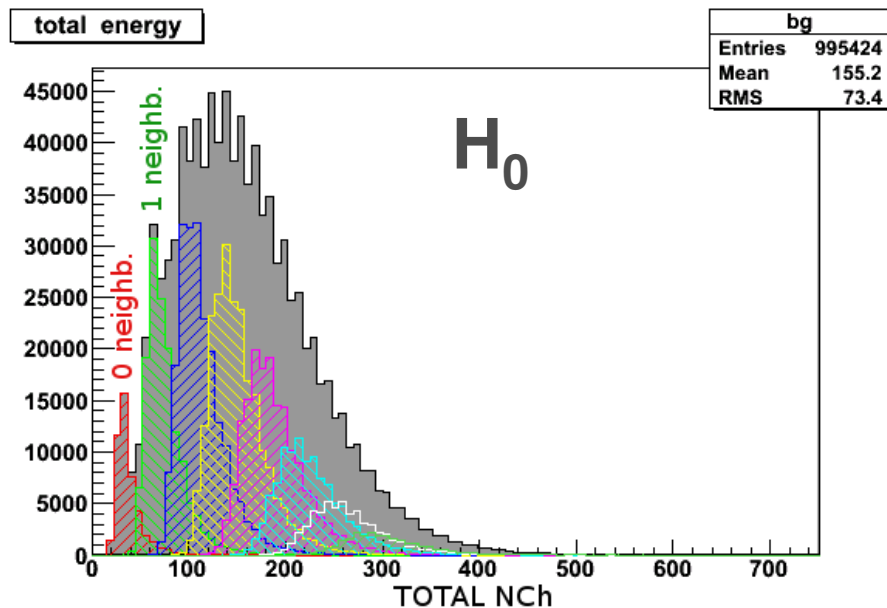
FDR PROCEDURE FOR POINT SOURCE SEARCH

Hypothesis tested for each v

2. Definition of variable that takes into account both **density** and **energy** criteria → **TOTAL ENERGY (NCh)**

$$P(i, n_{bg}) = \frac{e^{-n_{bg}} n_{bg}^i}{i!}$$

$$E_{TOT}(x) = \sum_{i=0}^{\infty} P(i, n_{bg}) E_i(x)$$



with :

$$E_0(x) = \frac{1}{1+e^{p_5(x-p_5)}} e^{\sum_{i=0}^4 p_i \ln(x)} \frac{1}{1+e^{p_7(x-p_8)}} + \frac{p_9 e^{p_{10}x}}{1+e^{-p_7(x-p_8)}}$$

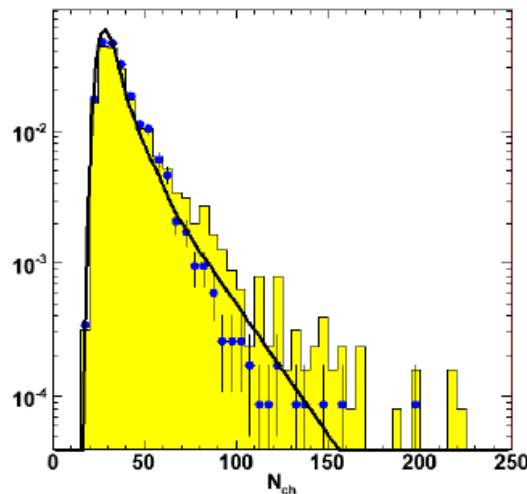
$$E_1(x) = \int_0^x E_0(a) E_0(x-a) da$$

$$E_n(x) = \int_0^x E_0(a) E_{n-1}(x-a) da$$

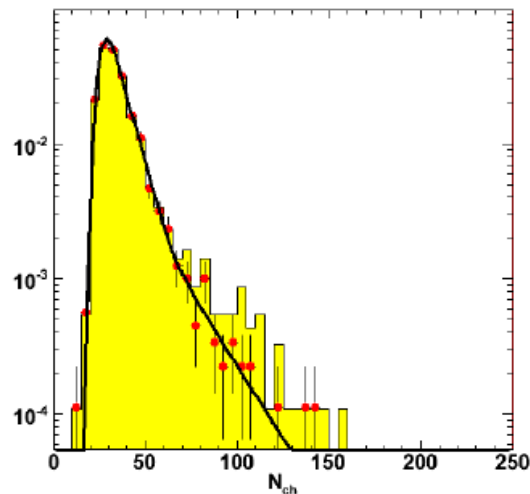
ENERGY PDF'S FROM SIMULATIONS (NUSIM)

A good knowledge of the distribution at high energy is crucial.

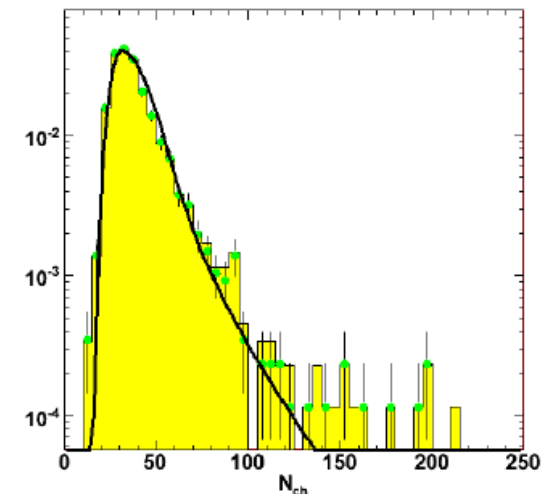
- Few events out of data → large uncertainties
- Use of simulations → check of reliability → better statistics



(a) $\delta < 32.5^\circ$



(b) $32.5^\circ \leq \delta \leq 52.5^\circ$



(c) $\delta > 52.5^\circ$

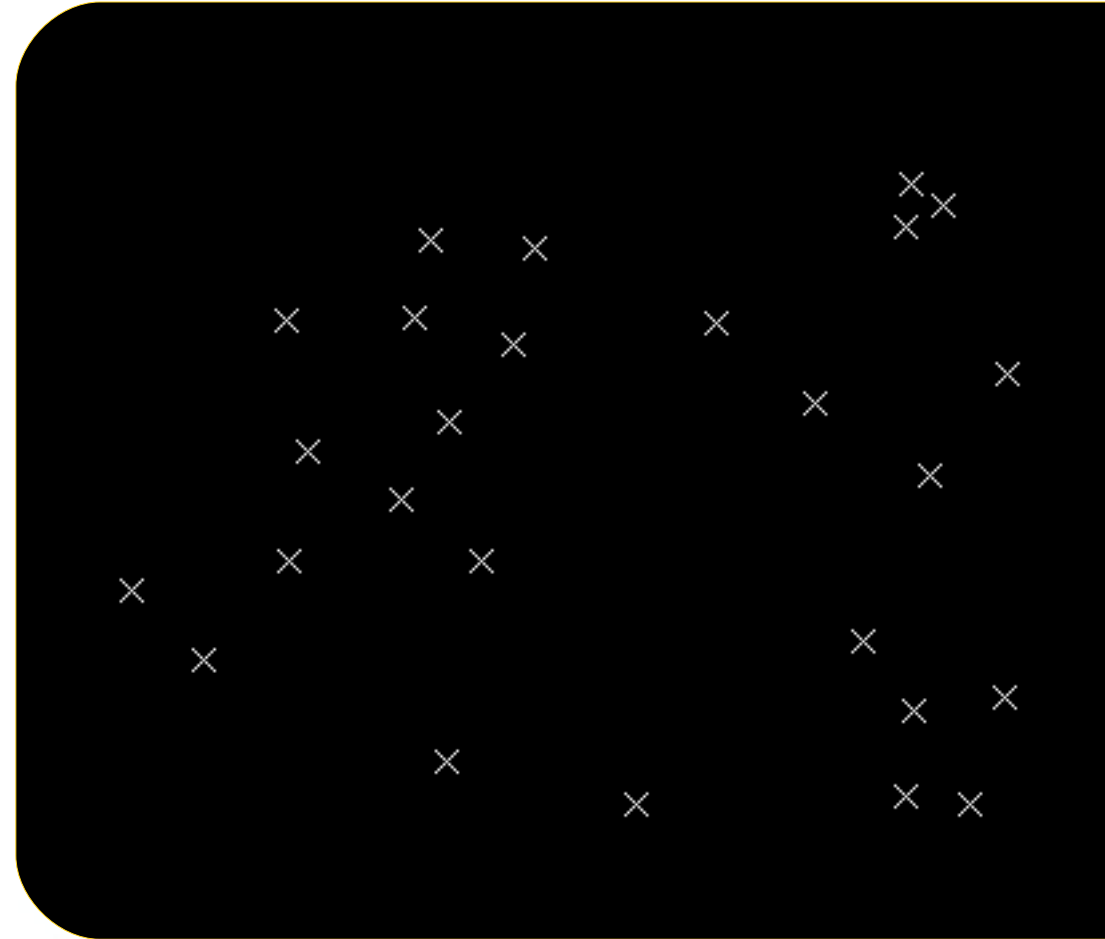


Better estimation of the energy PDF's.

FDR PROCEDURE FOR POINT SOURCE SEARCH

Hypothesis tested for each v

Set of p-values



FDR PROCEDURE FOR POINT SOURCE SEARCH

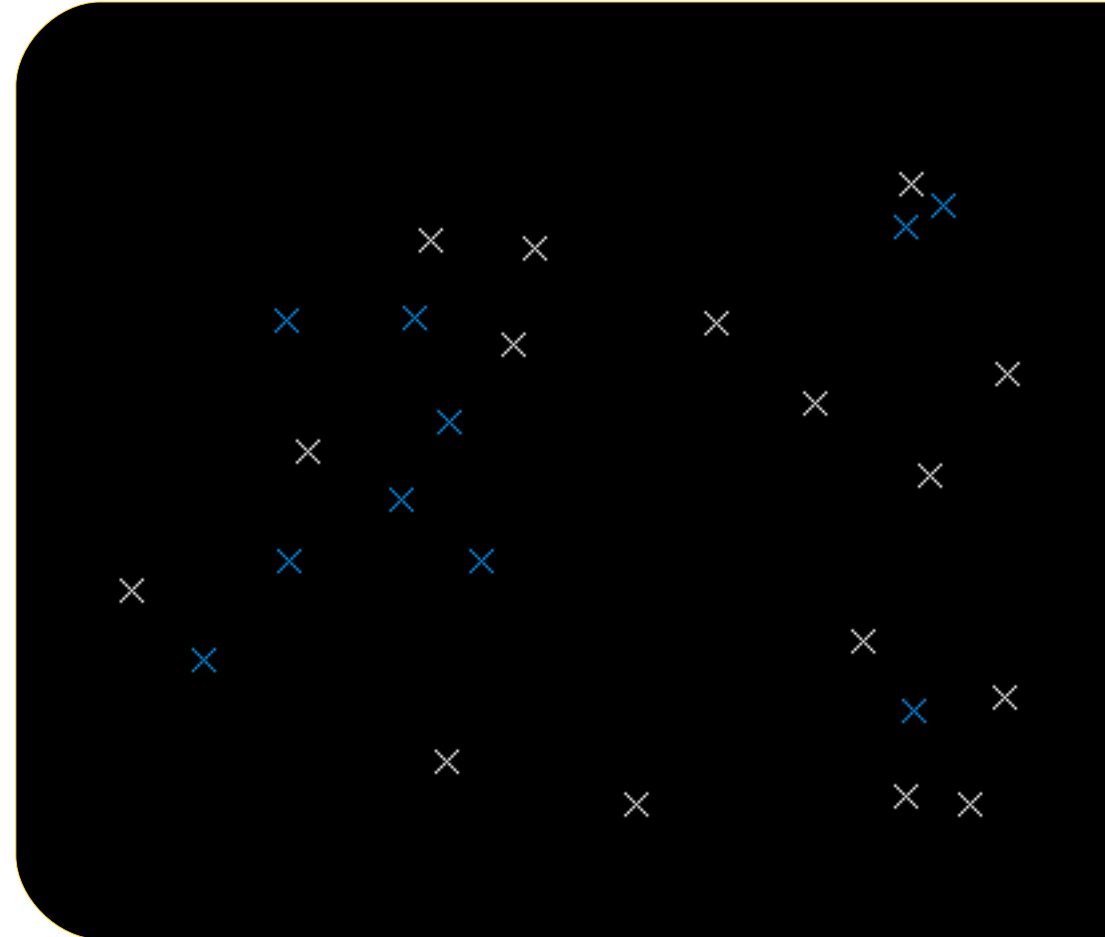
Hypothesis tested for each v

Set of p-values



FDR Procedure

Set of rejected
p-values



FDR PROCEDURE FOR POINT SOURCE SEARCH

Hypothesis tested for each v

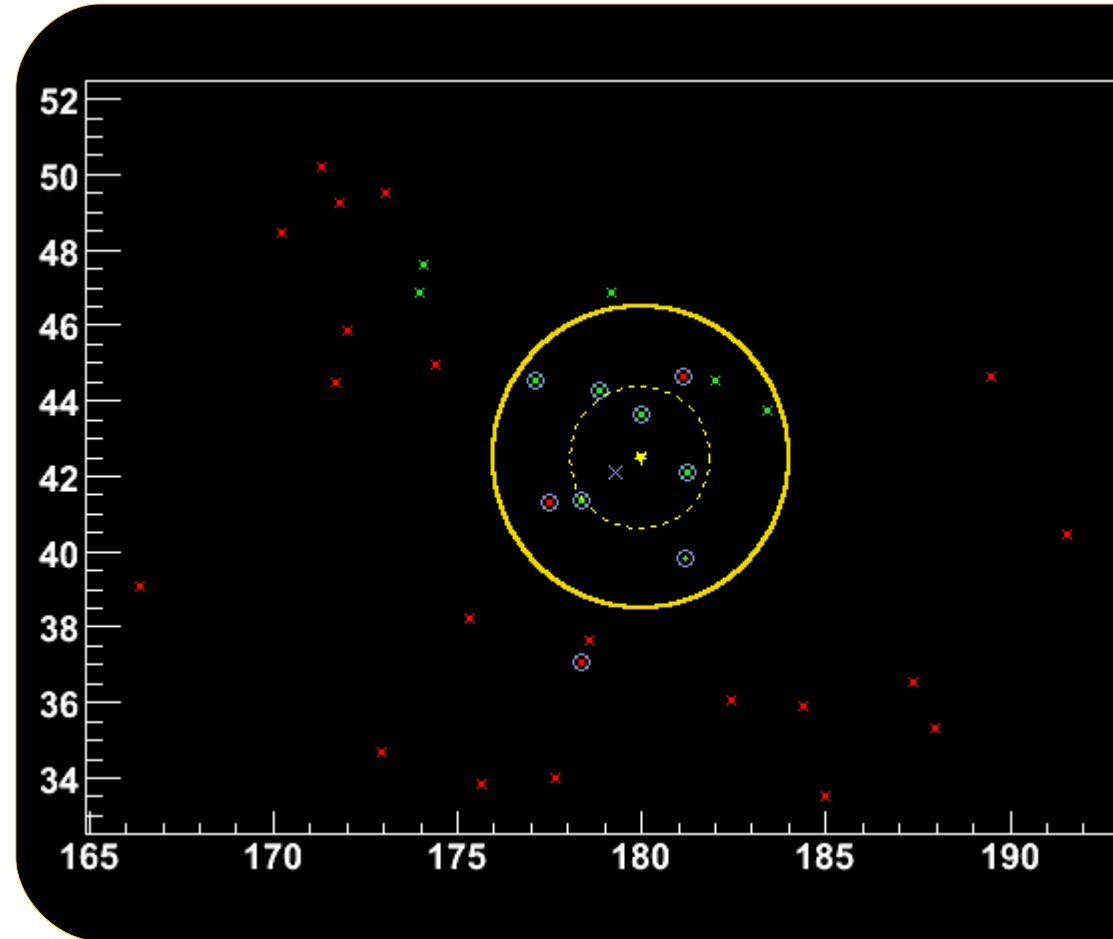
Set of p-values

FDR Procedure

Set of rejected
p-values

!! FDR NOT CONTROLLED !!

- Bg neutrino (1000v)
- Source neutrino (12v)
- Detected neutrino
- ★ True Source Position
- × Source Reco. Position



FDR PROCEDURE FOR POINT SOURCE SEARCH

Hypothesis tested for each v

Set of p-values

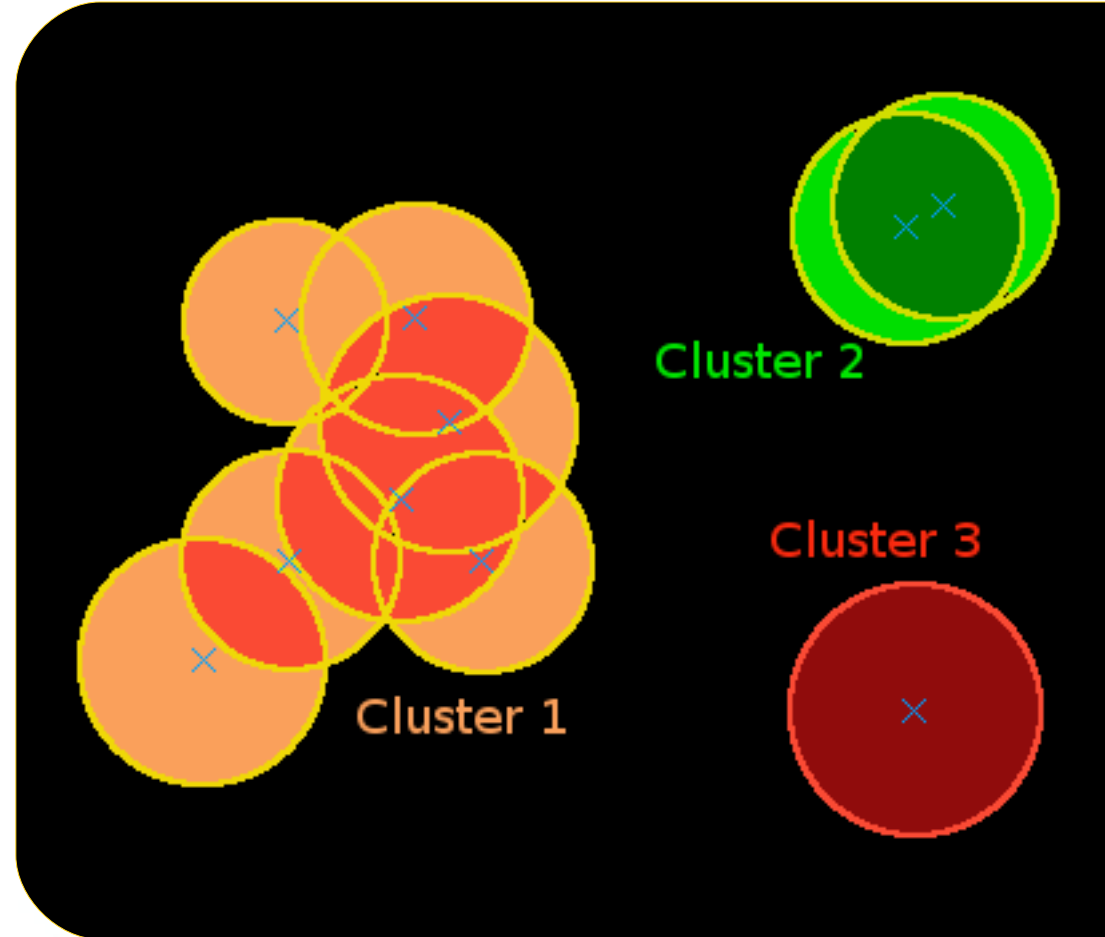
FDR Procedure

Set of rejected
p-values

Hierarchical Clustering

Set of clusters

FDR OF CLUSTERS



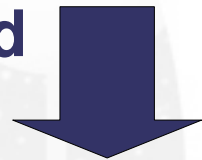
FDR PROCEDURE FOR POINT SOURCE SEARCH

Hypothesis tested for each v



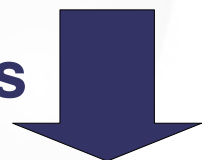
Set of p-values

FDR Procedure



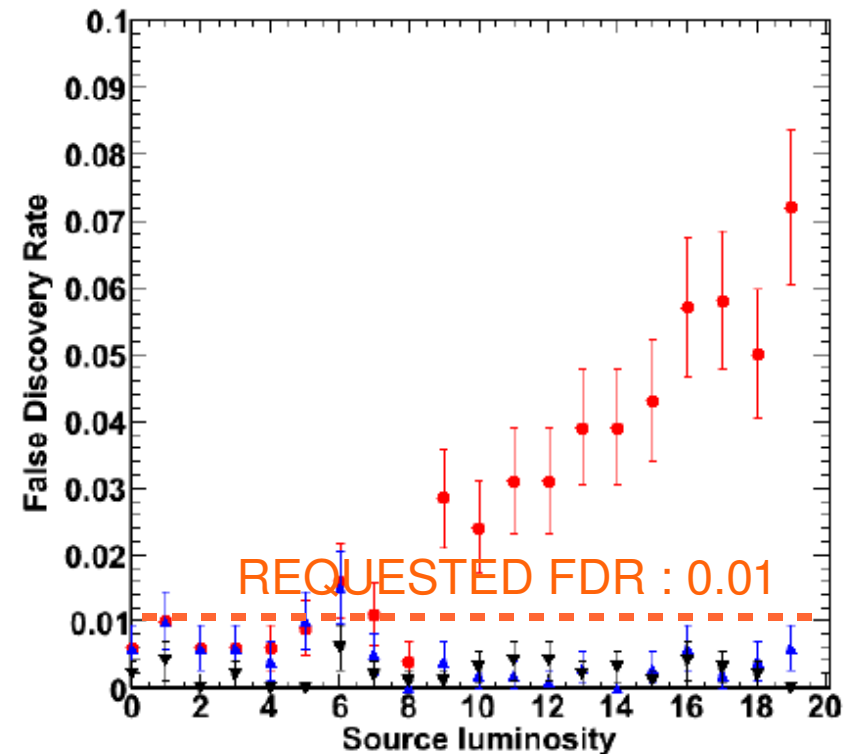
Set of rejected p-values

Hierarchical Clustering



Set of clusters

**FDR OF CLUSTERS
NOT CONTROLLED**



FDR PROCEDURE FOR POINT SOURCE SEARCH

Hypothesis tested for each v

Set of p-values

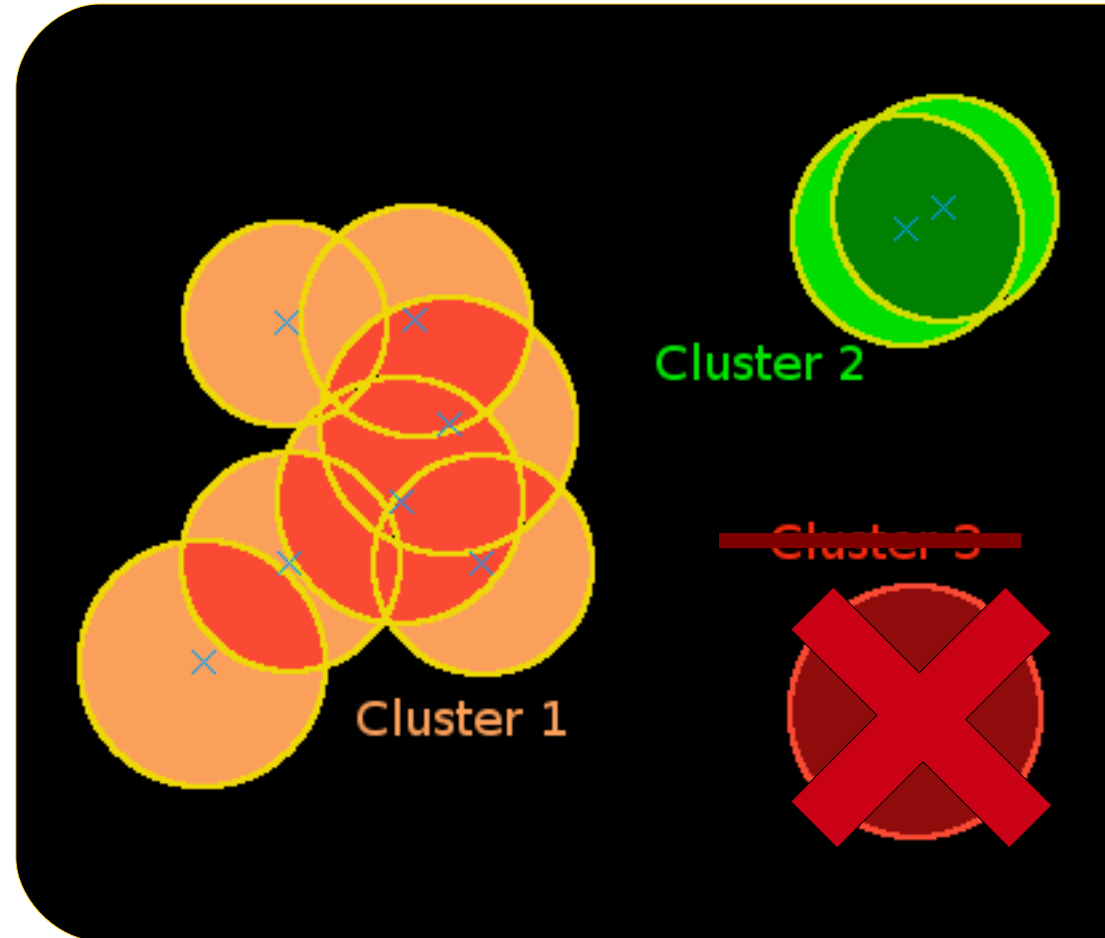
FDR Procedure

Set of rejected
p-values

Hierarchical Clustering

Set of clusters

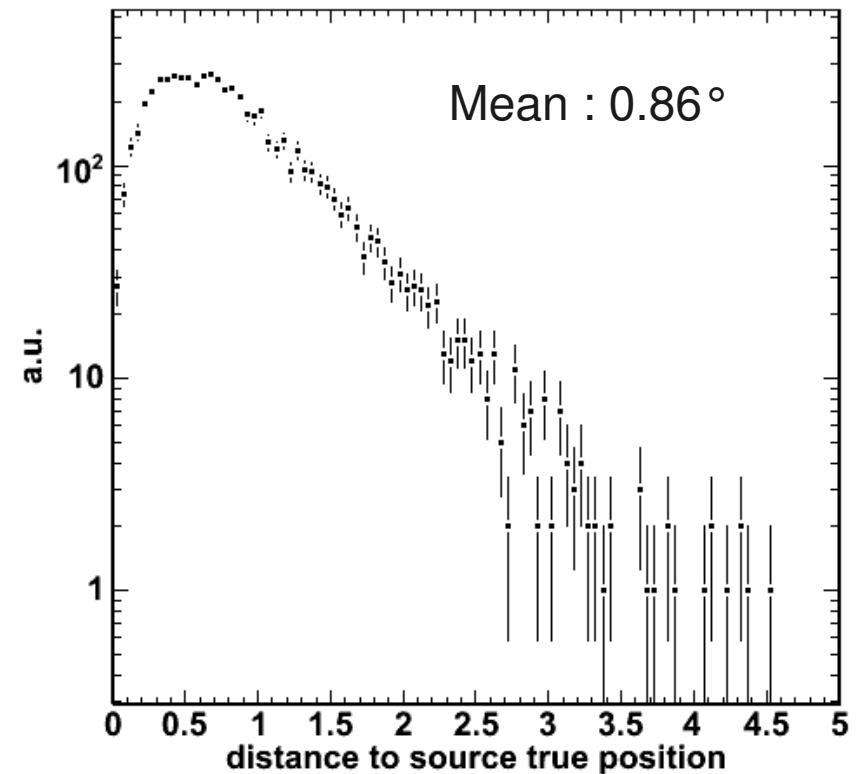
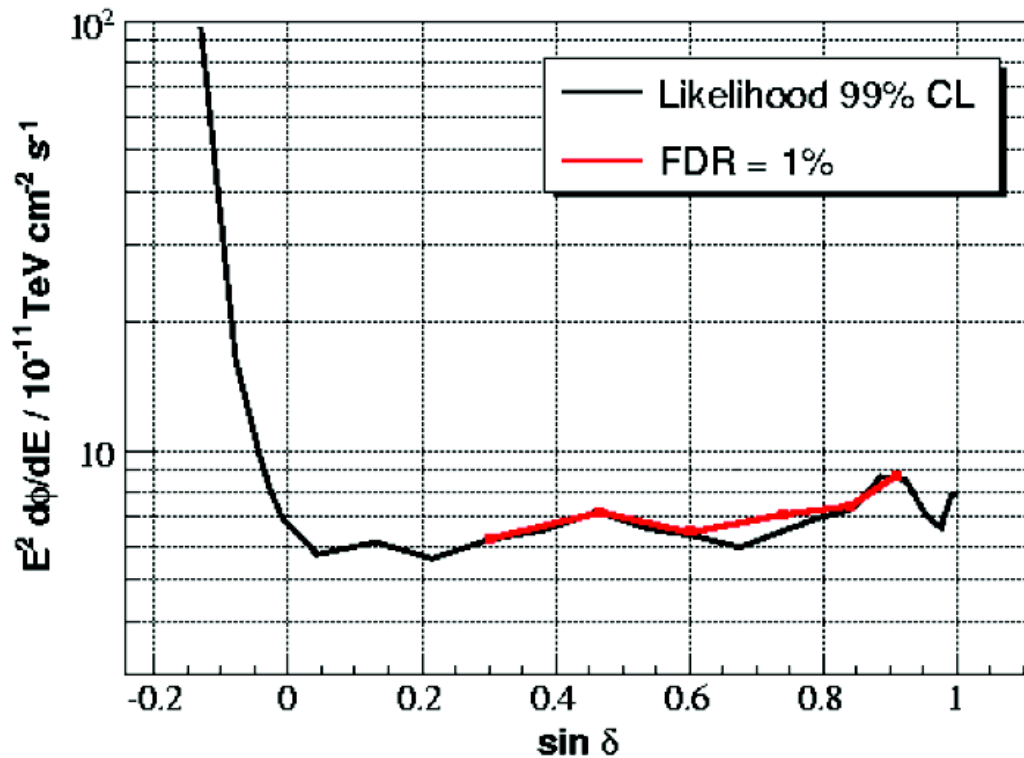
If more than 1 cluster
& at least 1 cluster with more than 1 v
→ cut 1 v clusters



FALSE DISCOVERY RATE DISCOVERY @ 99%CL

CHECK OF THE PROCEDURE WITH « DATA CHALLENGE »

- 17442 blind tests : no knowledge on source location or luminosity

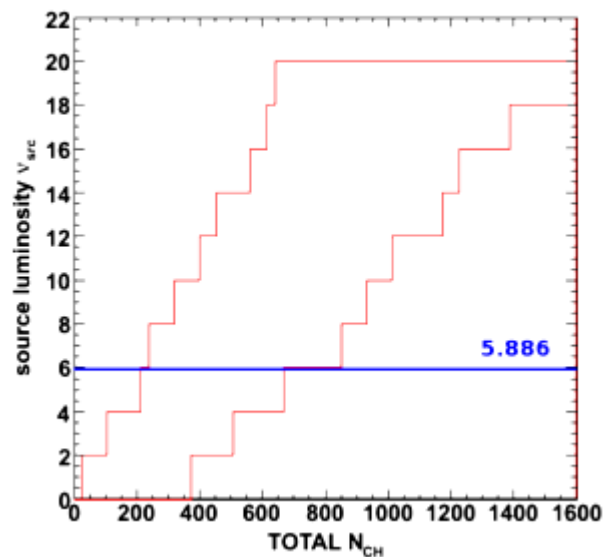


FALSE DISCOVERY RATE DISCOVERY @ 99%CL

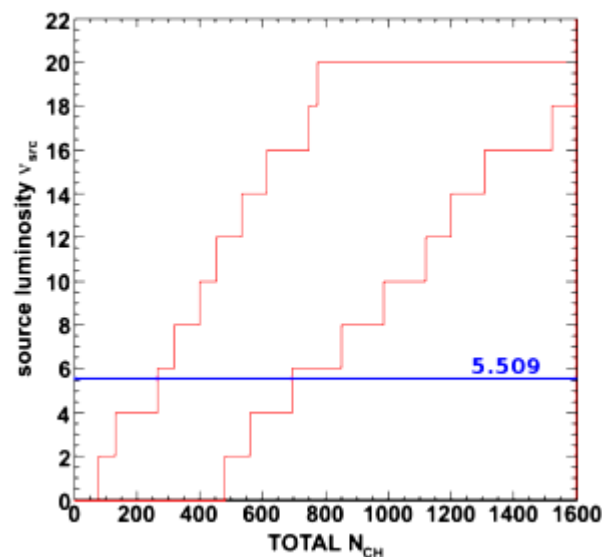
CHECK OF THE PROCEDURE WITH « DATA CHALLENGE »

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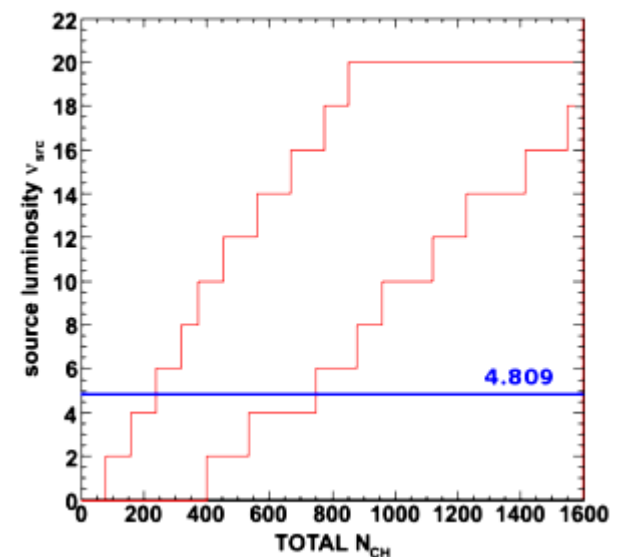
Feldman-Cousins 90%CL at low declination



Feldman-Cousins 90%CL at mid declination



Feldman-Cousins 90%CL at high declination



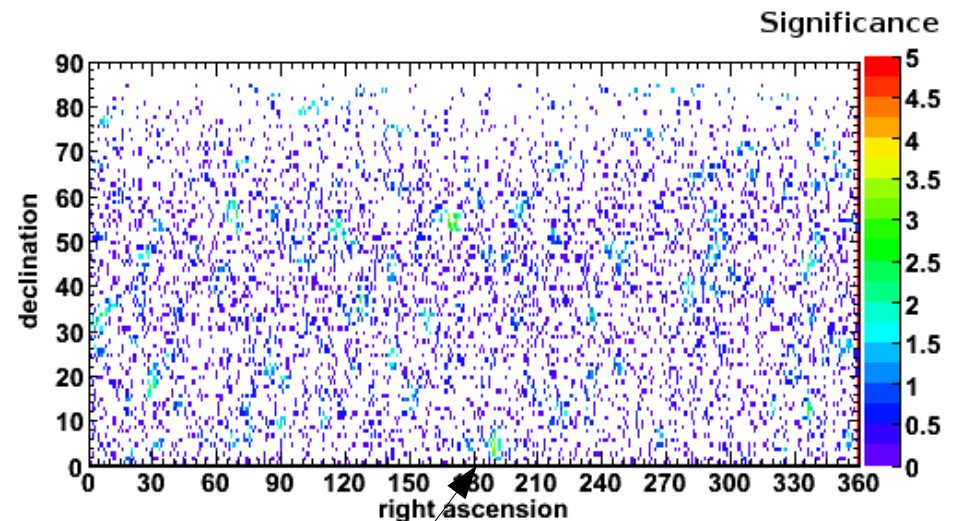
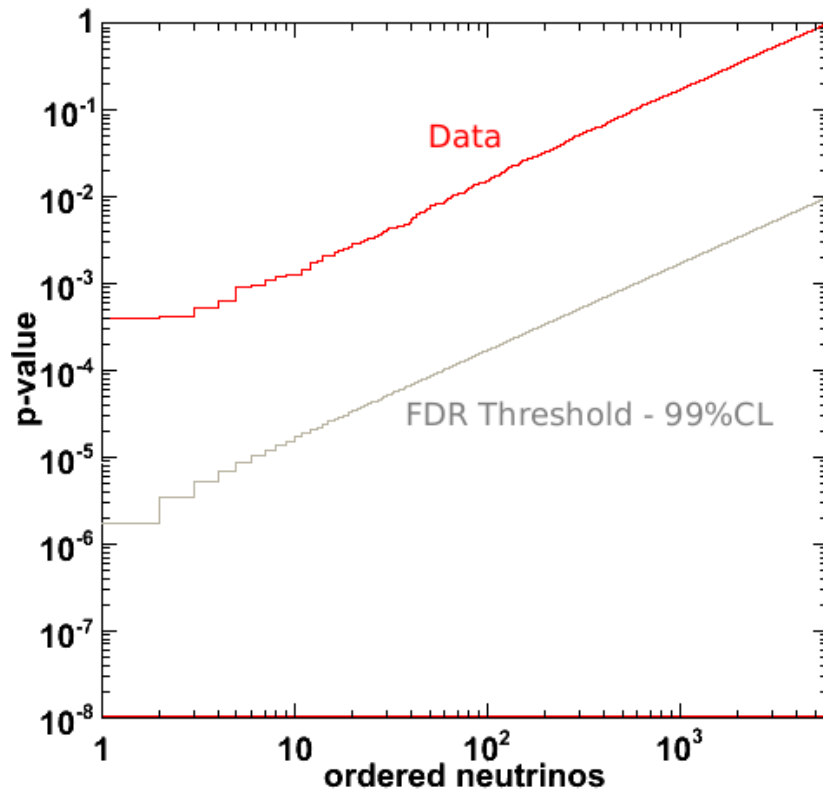
Sensitivity 90%CL : $2.5 - 3.0 \times 10^{-11} \text{ TeV cm}^{-2}\text{s}^{-1}$

FALSE DISCOVERY RATE DISCOVERY @ 99%CL

Results on AMANDA 2000-2006 neutrinos candidate events

- No event has rejected the Null Hypothesis : **NO DISCOVERY**

AMANDA - 7 YEARS : FDR results



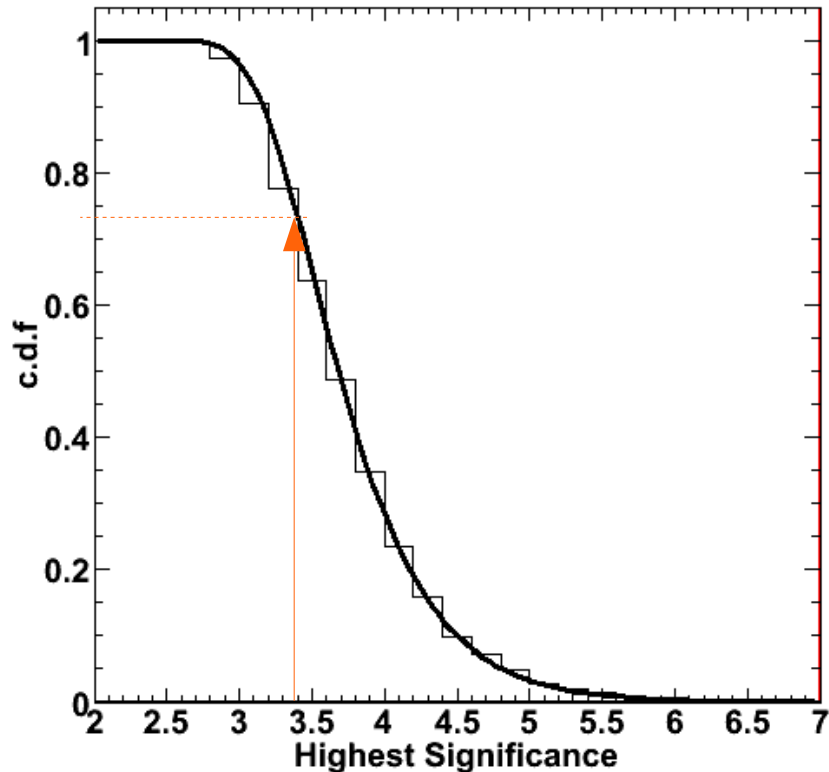
(190.93 ; 4.74) p-value : $4.07 \cdot 10^{-4}$
(sign. : 3.39)

ALL SKY SURVEY

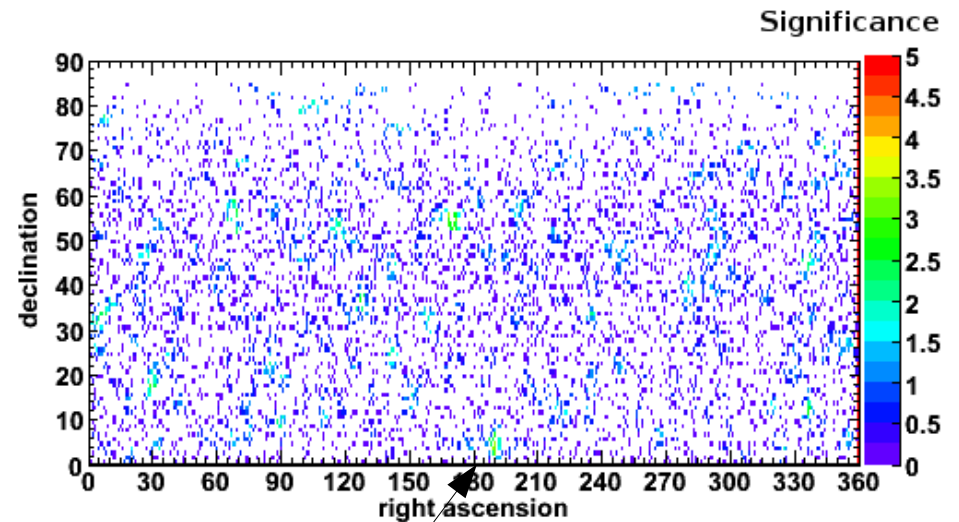
Results

- Highest Significance : 3.39 (p-value : $4.07 \cdot 10^{-4}$)

IN BACKGROUND SKY



From Data Challenge background skies



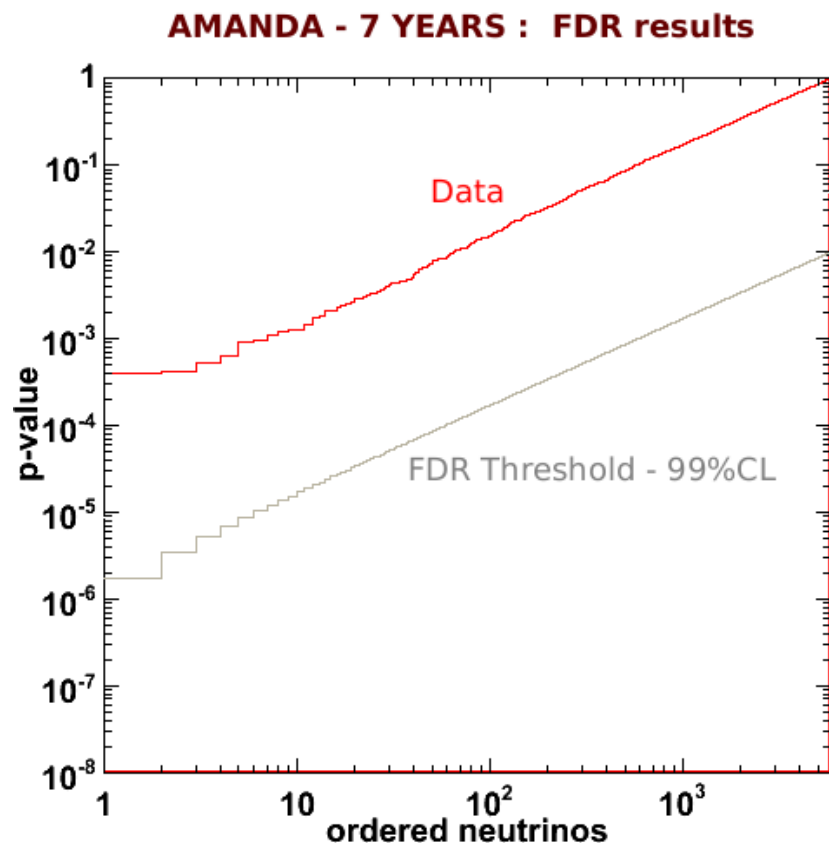
(190.93 ; 4.74) p-value : $4.07 \cdot 10^{-4}$
(sign. : 3.39)

74.4 % of background skies

ALL SKY SURVEY

Results

- 10 lowest p-values

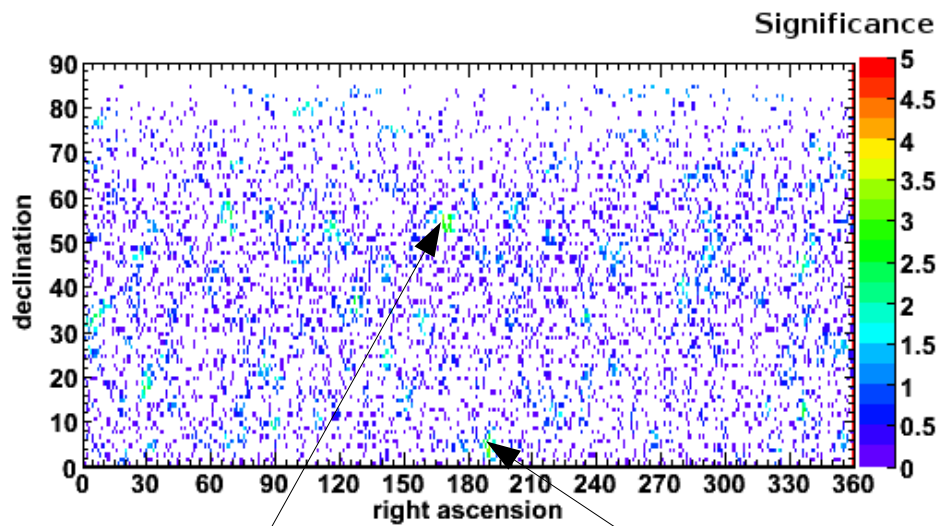


	R.A.(°)	Decl(°)	P-value
1	190.93	4.74	4.05 10 ⁻⁴
2	168.32	55.08	4.26 10 ⁻⁴
3	189.55	3.90	5.34 10 ⁻⁴
4	172.67	54.66	6.33 10 ⁻⁴
5	190.44	3.36	9.36 10 ⁻⁴
6	190.26	2.64	9.39 10 ⁻⁴
7	171.94	53.46	1.10 10 ⁻³
8	168.89	53.60	1.22 10 ⁻³
9	29.21	17.31	1.26 10 ⁻³
10	168.41	54.60	1.45 10 ⁻³

ALL SKY SURVEY

Results

- 10 lowest p-values



5

4

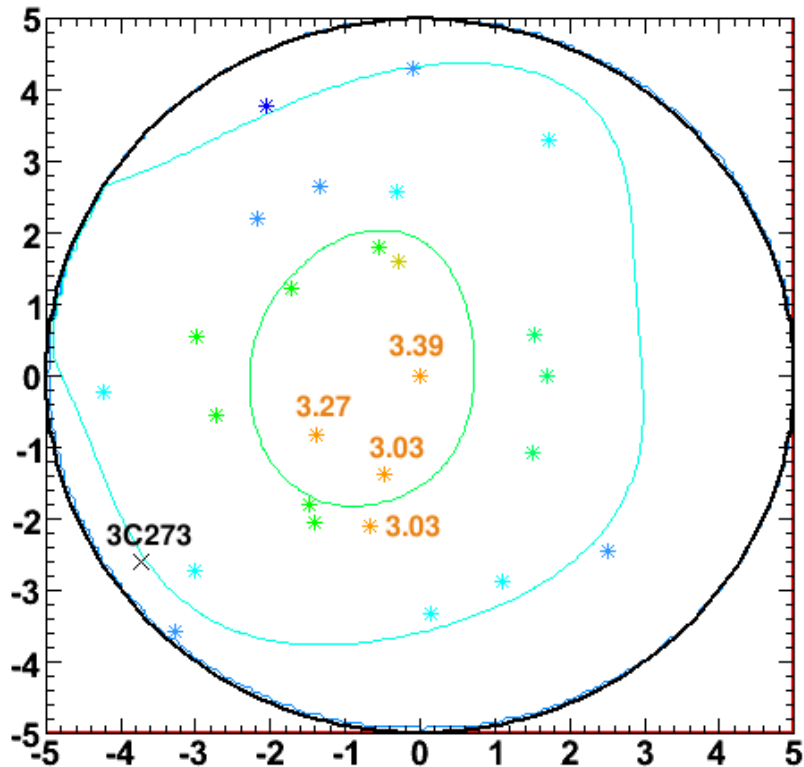
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1	190.93	4.74	$4.05 \cdot 10^{-4}$
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9	29.21	17.31	$1.26 \cdot 10^{-3}$
10	168.41	54.60	$1.45 \cdot 10^{-3}$

ALL SKY SURVEY : HOT SPOT

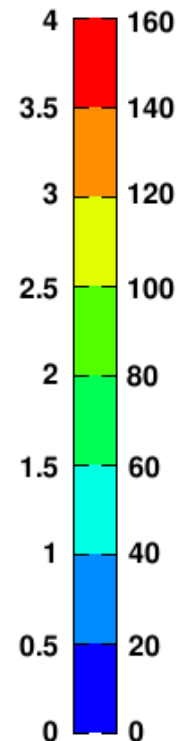
Results

- Around the « Hot Spot » : 3C273 at distance of 4.52°

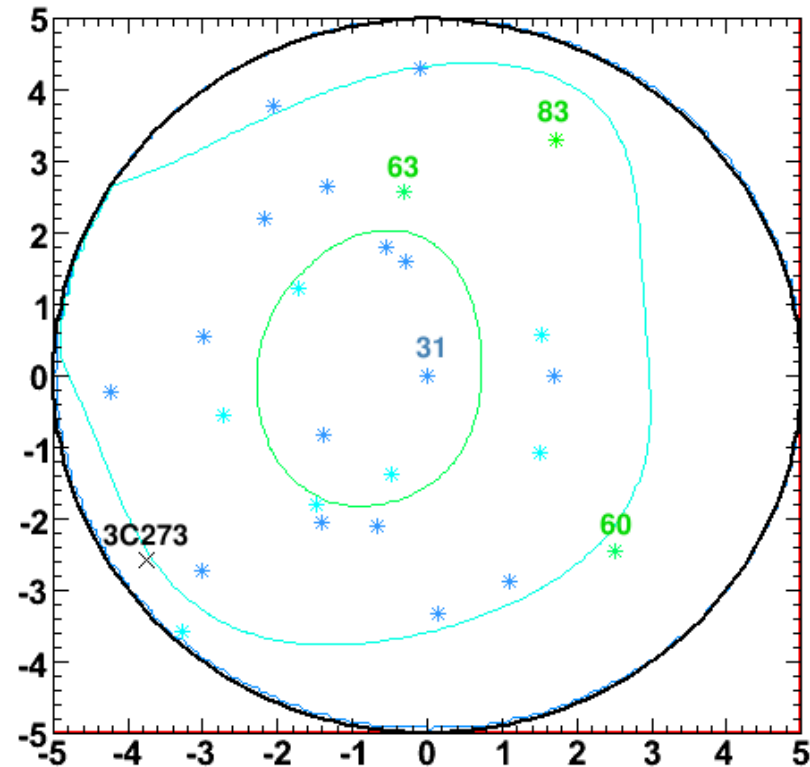
7 YEARS AMANDA



Significance NCh



FDR HOT SPOT- (RA 190.93° ; Dec 4.74°)

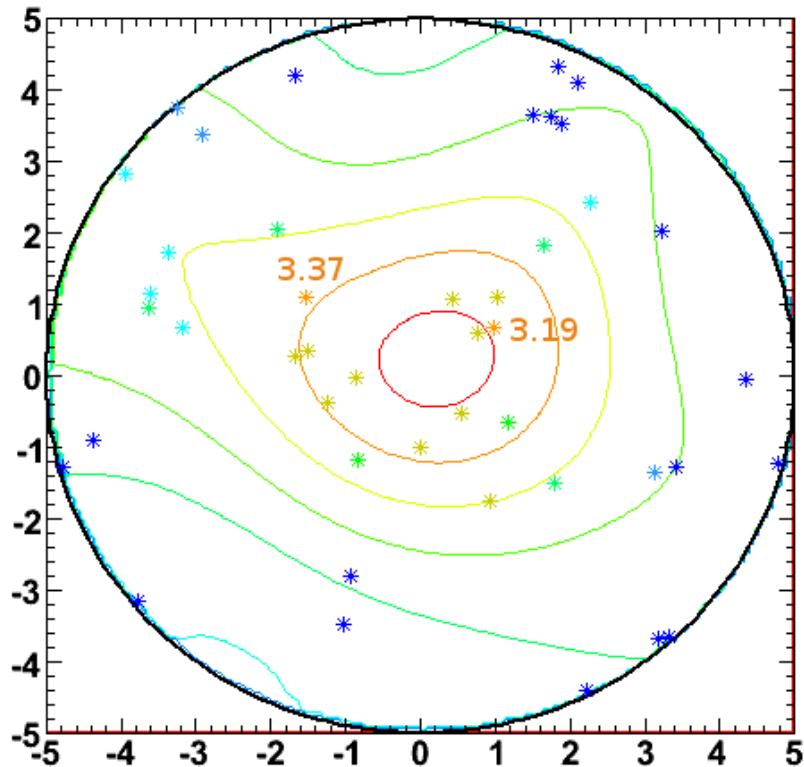


ALL SKY SURVEY : 2nd HOT SPOT

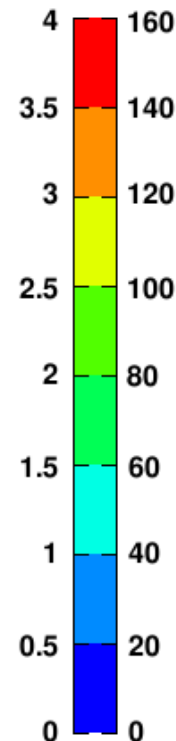
Results

- 2nd FDR « Hot Spot » = Likelihood Method Hot Spot

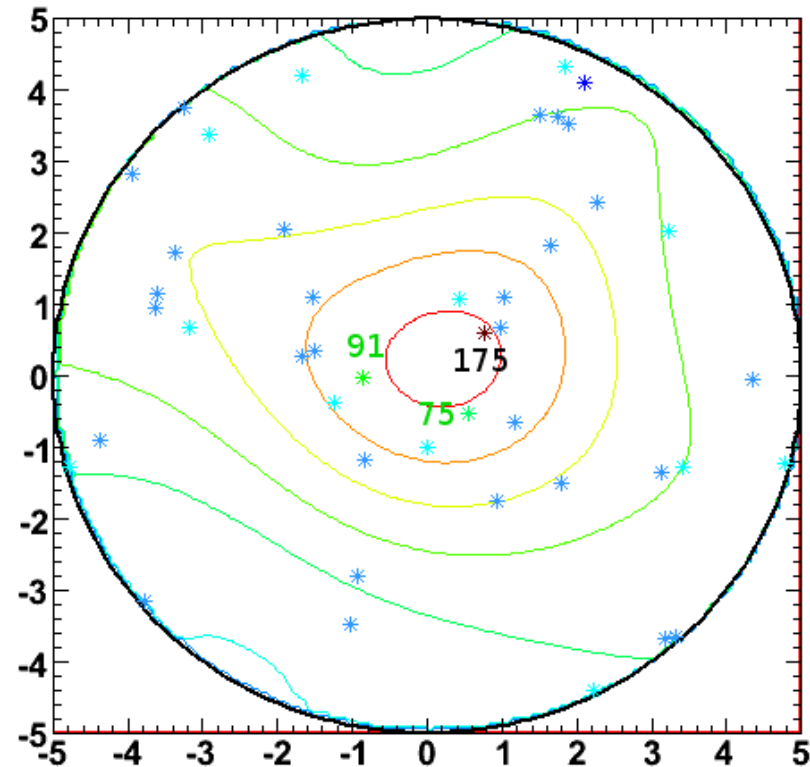
7 YEARS AMANDA



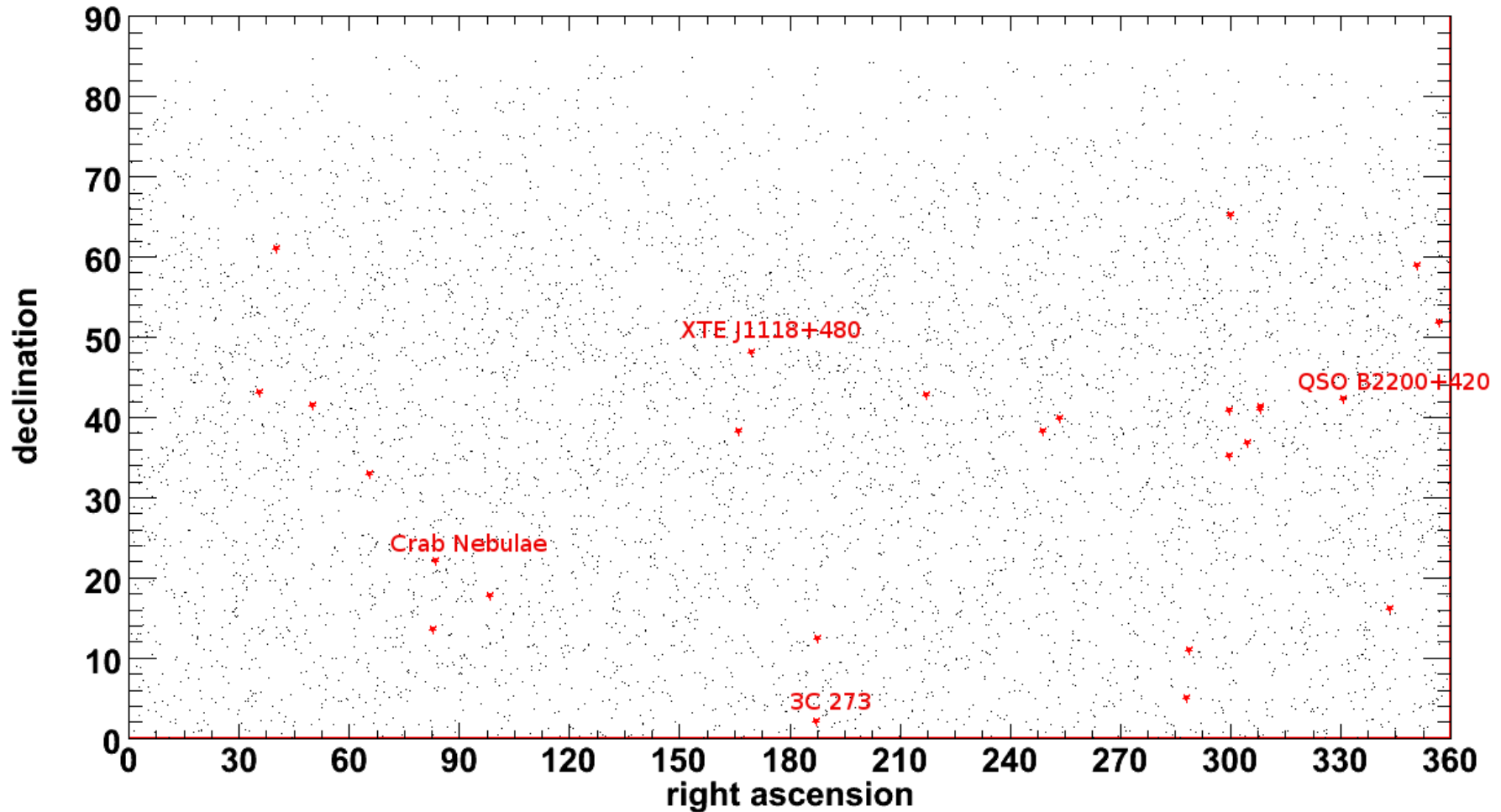
Significance NCh



LLH HOT SPOT- (RA 171° ; Dec 54°)

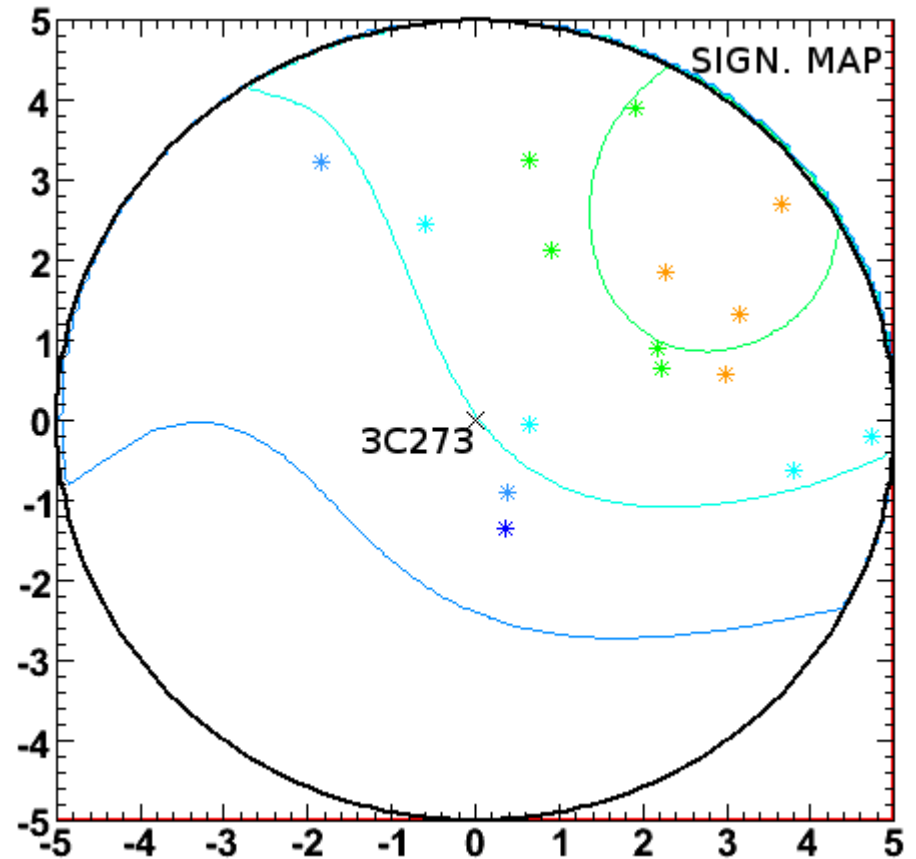


FROM SOURCE CATALOGUE



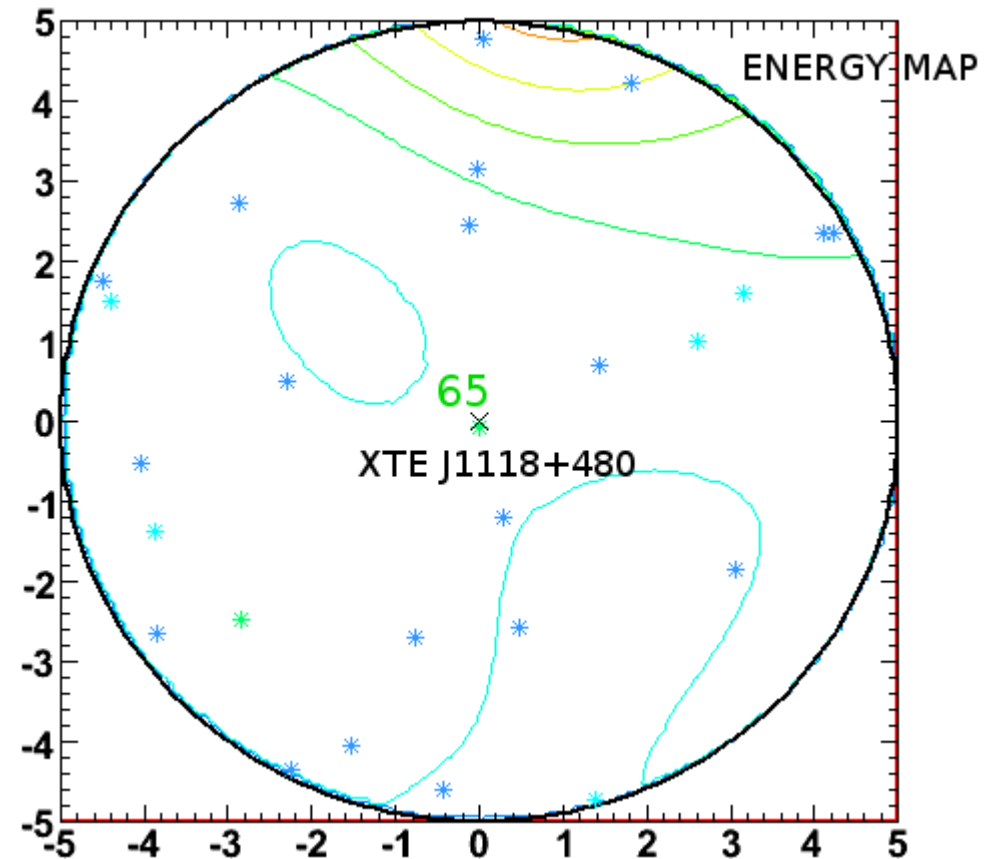
FROM SOURCE CATALOGUE

<u>Object</u>	<u>R.Asc.(°)</u>	<u>Decl.(°)</u>	<u>Significance</u>
3C 273	187.28	2.05	3.39
XTE J1118+480	169.55	48.04	2.61
BL Lac (QSO B2200+420)	330.68	42.28	2.31
Crab Nebulae	83.63	22.01	2.03
Cyg X-1	299.59	35.2	1.34
Cyg A	299.87	40.73	1.34
1ES 1959+650	300.00	65.15	1.20
Geminga	98.48	17.77	1.08
Cas A	350.85	58.82	1.07
1ES 2344+514	356.77	51.71	0.93
Mrk 501	253.47	39.76	0.92
4C 38.41	248.82	38.14	0.92



FROM SOURCE CATALOGUE

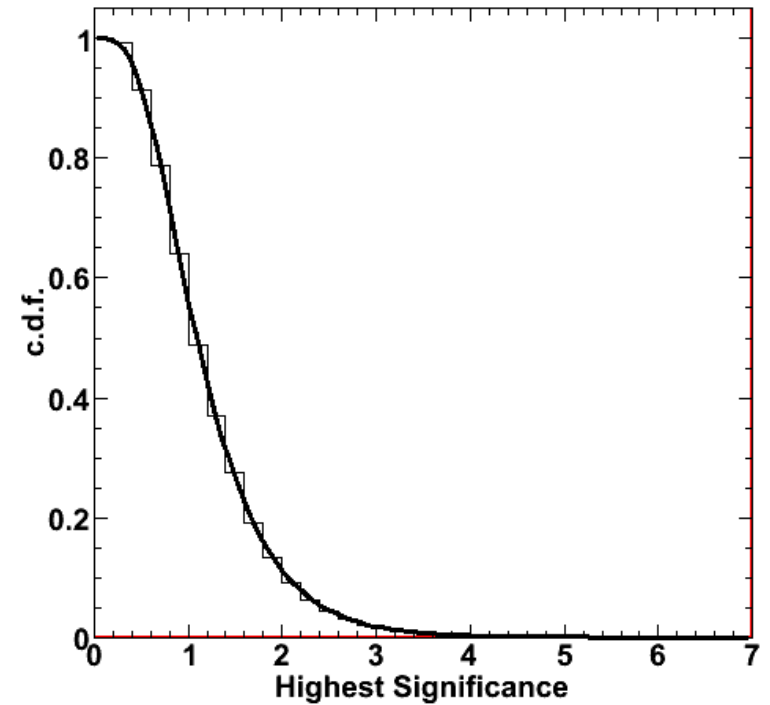
<u>Object</u>	<u>R.Asc.(°)</u>	<u>Decl.(°)</u>	<u>Significance</u>
3C 273	187.28	2.05	3.39
XTE J1118+480	169.55	48.04	2.61
BL Lac (QSO B2200+420)	330.68	42.28	2.31
Crab Nebulae	83.63	22.01	2.03
Cyg X-1	299.59	35.2	1.34
Cyg A	299.87	40.73	1.34
1ES 1959+650	300.00	65.15	1.20
Geminga	98.48	17.77	1.08
Cas A	350.85	58.82	1.07
1ES 2344+514	356.77	51.71	0.93
Mrk 501	253.47	39.76	0.92
4C 38.41	248.82	38.14	0.92



FROM SOURCE CATALOGUE

<u>Object</u>	<u>R.Asc.(°)</u>	<u>Decl(°)</u>	<u>Significance</u>	<u>Proba.</u>
3C 273	187.28	2.05	3.39	$8.5 \cdot 10^{-3}$
XTE J1118+480	169.55	48.04	2.61	0.036
BL Lac (QSO B2200+420)	330.68	42.28	2.31	0.063
Crab Nebulae	83.63	22.01	2.03	0.105
Cyg X-1	299.59	35.2	1.34	0.346
Cyg A	299.87	40.73	1.34	0.346
1ES 1959+650	300.00	65.15	1.20	0.424
Geminga	98.48	17.77	1.08	0.505
Cas A	350.85	58.82	1.07	0.514
1ES 2344+514	356.77	51.71	0.93	0.617
Mrk 501	253.47	39.76	0.92	0.628
4C 38.41	248.82	38.14	0.92	0.628

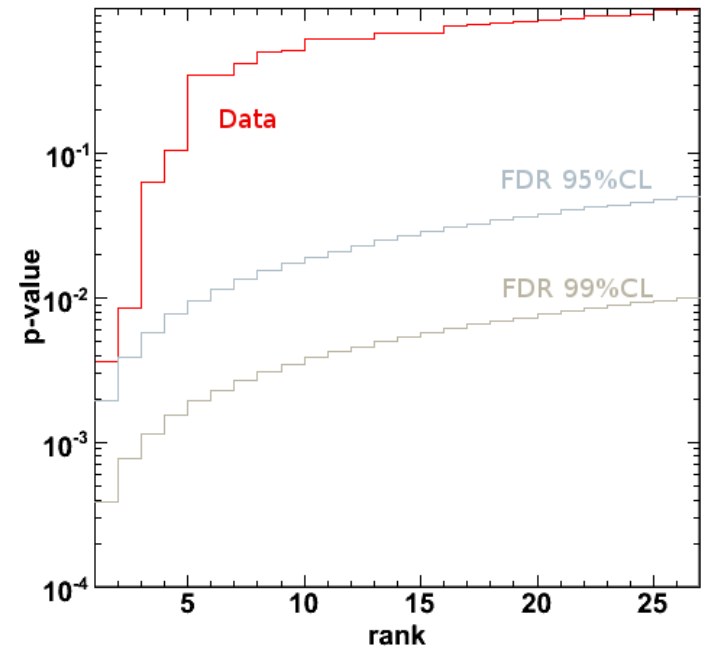
5° AROUND SOURCE



From Data Challenge
background skies

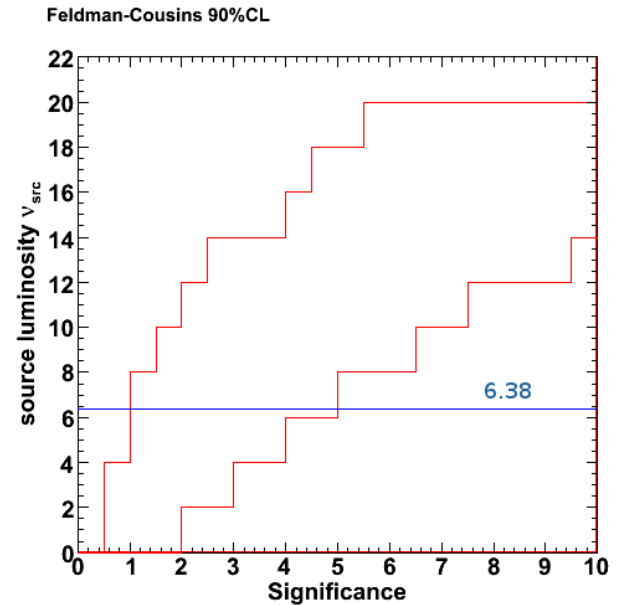
FROM SOURCE CATALOGUE

<u>Object</u>	<u>R.Asc.(°)</u>	<u>Decl(°)</u>	<u>Significance</u>	<u>Proba.</u>
3C 273	187.28	2.05	3.39	$8.5 \cdot 10^{-3}$
XTE J1118+480	169.55	48.04	2.61	0.036
BL Lac (QSO B2200+420)	330.68	42.28	2.31	0.063
Crab Nebulae	83.63	22.01	2.03	0.105
Cyg X-1	299.59	35.2	1.34	0.346
Cyg A	299.87	40.73	1.34	0.346
1ES 1959+650	300.00	65.15	1.20	0.424
Geminga	98.48	17.77	1.08	0.505
Cas A	350.85	58.82	1.07	0.514
1ES 2344+514	356.77	51.71	0.93	0.617
Mrk 501	253.47	39.76	0.92	0.628
4C 38.41	248.82	38.14	0.92	0.628



FROM SOURCE CATALOGUE

<u>Object</u>	<u>R.Asc.(°)</u>	<u>Decl.(°)</u>	<u>Significance</u>	<u>Proba.</u>	<u>Limits (*)</u>
3C 273	187.28	2.05	3.39	$8.5 \cdot 10^{-3}$	6.58
XTE J1118+480	169.55	48.04	2.61	0.036	8.81
BL Lac (QSO B2200+420)	330.68	42.28	2.31	0.063	7.27
Crab Nebulae	83.63	22.01	2.03	0.105	5.93
Cyg X-1	299.59	35.2	1.34	0.346	4.82
Cyg A	299.87	40.73	1.34	0.346	4.82
1ES 1959+650	300.00	65.15	1.20	0.424	6.30
Geminga	98.48	17.77	1.08	0.505	3.91
Cas A	350.85	58.82	1.07	0.514	5.60
1ES 2344+514	356.77	51.71	0.93	0.617	2.63
Mrk 501	253.47	39.76	0.92	0.628	2.40
4C 38.41	248.82	38.14	0.92	0.628	2.38



From Data Challenge skies

FROM SOURCE CATALOGUE

<u>Object</u>	<u>R.Asc.(°)</u>	<u>Decl(°)</u>	<u>Significance</u>	<u>Proba.</u>	<u>Limits (*)</u>	<u>Closest nu</u>	
						<u>Sign.</u>	<u>Distance</u>
3C 273	187.28	2.05	3.39	$8.5 \cdot 10^{-3}$	6.58	1.11	0.653
XTE J1118+480	169.55	48.04	2.61	0.036	8.81	0.11	0.069
BL Lac (QSO B2200+420)	330.68	42.28	2.31	0.063	7.27	0.29	0.617
Crab Nebulae	83.63	22.01	2.03	0.105	5.93	1.34	0.699
Cyg X-1	299.59	35.2	1.34	0.346	4.82	0.007	0.533
Cyg A	299.87	40.73	1.34	0.346	4.82	0.57	0.824
1ES 1959+650	300.00	65.15	1.20	0.424	6.30	0.32	0.497
Geminga	98.48	17.77	1.08	0.505	3.91	0.13	2.162
Cas A	350.85	58.82	1.07	0.514	5.60	0.04	0.905
1ES 2344+514	356.77	51.71	0.93	0.617	2.63	0.31	0.309
Mrk 501	253.47	39.76	0.92	0.628	2.40	0.37	0.971
4C 38.41	248.82	38.14	0.92	0.628	2.38	0.11	1.196

FROM SOURCE CATALOGUE – Cont'd

<u>Object</u>	<u>R.Asc.(°)</u>	<u>Decl(°)</u>	<u>Significance</u>	<u>Proba.</u>	<u>Limits (*)</u>	<u>Closest nu</u>	
						<u>Sign.</u>	<u>Distance</u>
Cyg X-3	308.11	40.96	0.85	0.682	2.41	0.61	0.510
Cyg OB2	308.29	41.32	0.85	0.682	2.42	0.61	0.135
MGRO J2019+37	304.83	36.83	0.84	0.688	2.36	0.15	0.184
M87	187.71	12.39	0.73	0.771	1.71	0.05	1.748
PKS 0528+134	82.74	13.52	0.72	0.775	1.75	0.09	2.420
NGC 1275	49.95	41.51	0.68	0.805	2.42	0.11	0.190
H1426+428	217.14	42.68	0.65	0.829	2.43	0.10	1.425
LS I +61 303	40.13	61.23	0.63	0.839	2.94	0.06	0.485
GRO J0422+32	65.43	32.91	0.59	0.866	2.26	0.15	0.991
GRS 1915+105	288.8	10.95	0.54	0.897	1.76	0.53	0.462
SS 433	287.96	4.98	0.52	0.905	1.85	0.001	1.435
3C 454.3	343.49	16.45	0.50	0.918	-	0.15	1.034
3C66A	35.67	43.04	0.27	0.990	-	0.08	0.111

SUMMARY

FDR

- Maximise Detection Potential while controlling C.L.
- No need of source flux model neither MC check *a posteriori*
- Take naturally into account the trial factor of multiple tests
- Convenient for multiple sources detections

From Data Challenge

- Sensitivity 90%CL : $2.5 - 3.0 \times 10^{-11} \text{ TeV cm}^{-2}\text{s}^{-1}$
- Discovery Potentiel 50% (99%CL) : $6.0 - 8.9 \times 10^{-11} \text{ TeV cm}^{-2}\text{s}^{-1}$

On AMANDA-II 2000-2006 data

- No discovery – Hot Spot @ $[\alpha=190.9^\circ ; \delta= 4.7^\circ]$ (Bg proba : 74.4%)
- Second Hot Spot is LLH Method Hot Spot
- Selected source : HS near ($<5^\circ$) 3C273 (Bg proba : 0.85%)