Detection of Extended Galactic Sources with an Underwater Neutrino Telescope

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Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο
ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ & ΘΡΗΣΚΕΥΜΑΤΩΝ, ΠΟΛΙΤΙΣΜΟΥ & ΑΘΛΗΤΙΣΜΟΥ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης
ΕΣΠΑ 2007-2013
πρόγραμμα για την ανάπτυξη
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ

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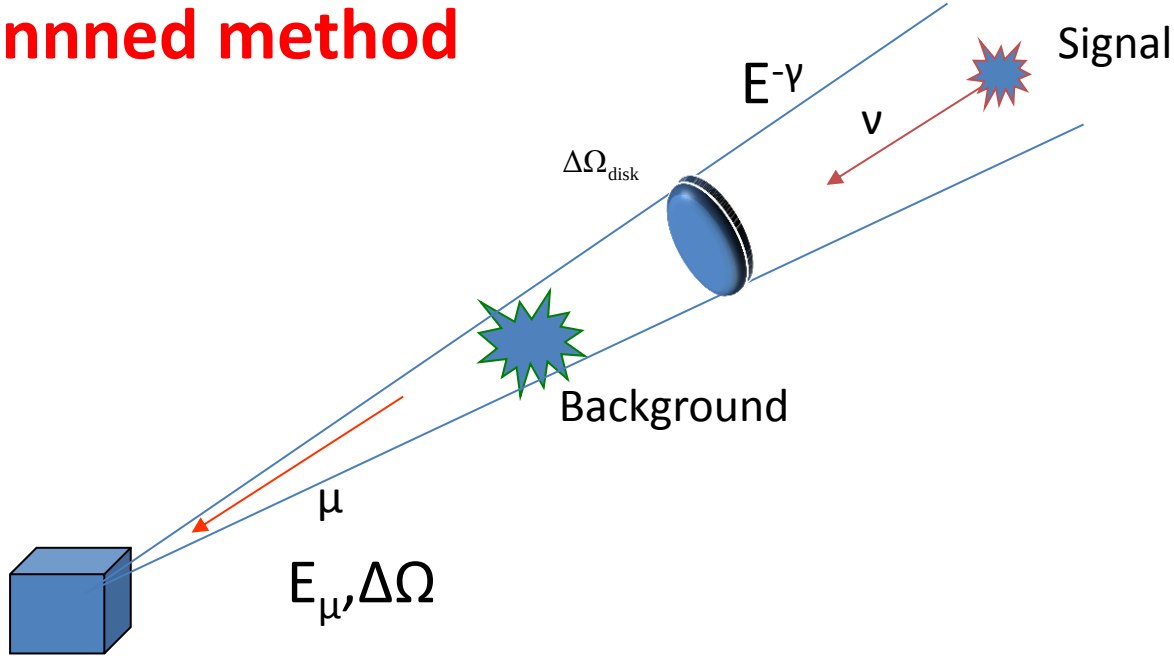
OUTLINE

- The un-binned method using the energy and the angular resolution of muon tracks
- Extended Sources Modeling
- Discovery Potential of RXJ1713-3946 using the Source Morphology
- Clusters of Galactic Plane Candidate ν-Sources
- Combined Signal of Clusters and Isolated Sources

Reminder of the Un-binnned method



$$P_{signal} = \frac{N_s}{N_{total}}$$

$$P_{bck} = \left(1 - \frac{N_s}{N_{total}}\right)$$

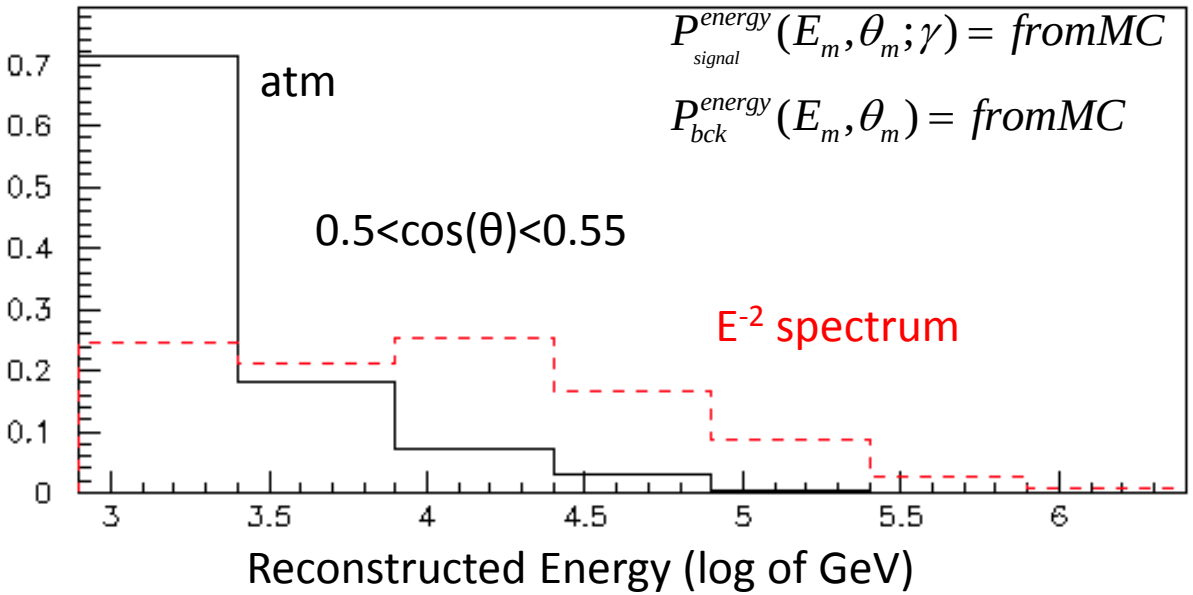
$$P(E_\mu, \Delta\Omega_{disk}) = P(E_\mu, \Delta\Omega_{disk} / signal) \cdot P_{signal} + P(E_\mu, \Delta\Omega_{disk} / bck) \cdot P_{bck}$$

$$P(E_\mu, \Delta\Omega_{disk} | signal) = P^{angle}_{signal}(\Delta\Omega_{disk}, \theta_x, \varphi_y) \cdot P^{energy}_{signal}(E_m, \theta_m; \gamma)$$

$$P(E_\mu, \Delta\Omega_{disk} | bck) = P^{angle}_{bck}(\Delta\Omega_{disk}, \theta_x, \varphi_y) \cdot P^{energy}_{bck}(E_m, \theta_m) = \frac{1}{\Delta\Omega_{disk}} \cdot P^{energy}_{atmospheric}(E_m, \theta_m)$$

Energy and Angular distributions

Reconstructed Energy Distributions for **Signal (E^{-2} spectrum)** and **Atm. Neutrino Background**



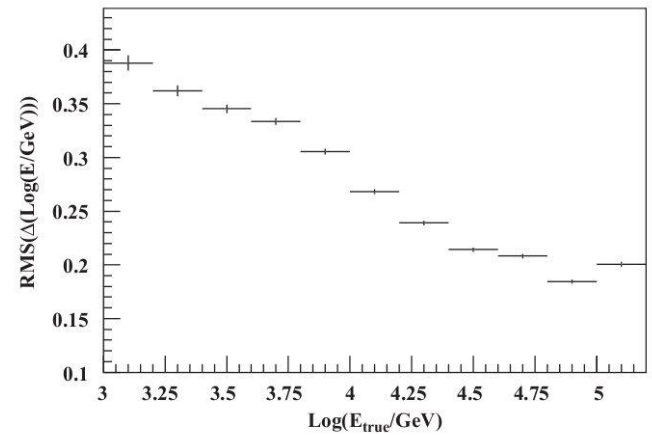
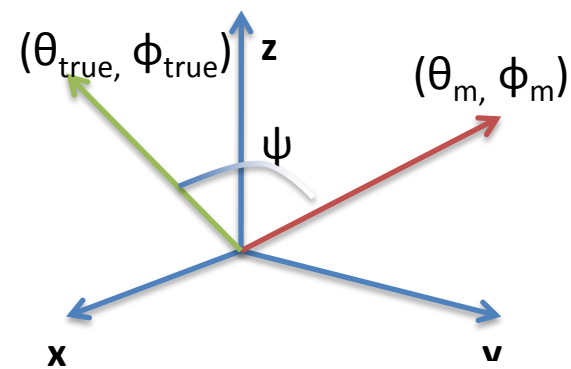


Fig. 2. The muon energy estimation resolution as a function of the true muon energy at the impact point to the center of the detector.



Estimating the angular resolution of tracks in neutrino telescopes based on a likelihood analysis

Till Neunhöffer

PDF of a reconstructed track to differ by θx and ϕx from the direction of a point source

$$P^{angle}_{signal}(\theta_x,\phi_y) = \frac{1}{1-e^{-\frac{R^2_{max}}{s_x^2+s_y^2}}}\frac{1}{2\pi s_x s_y}e^{-\frac{1}{2}\left(\frac{\theta_x^2}{s_x^2}+\frac{\phi_y^2}{s_y^2}\right)}$$

$$P^{angle}_{bck}(\theta_x,\phi_y) = \frac{1}{\Delta\Omega} = \frac{1}{\pi R^2_{max}}$$

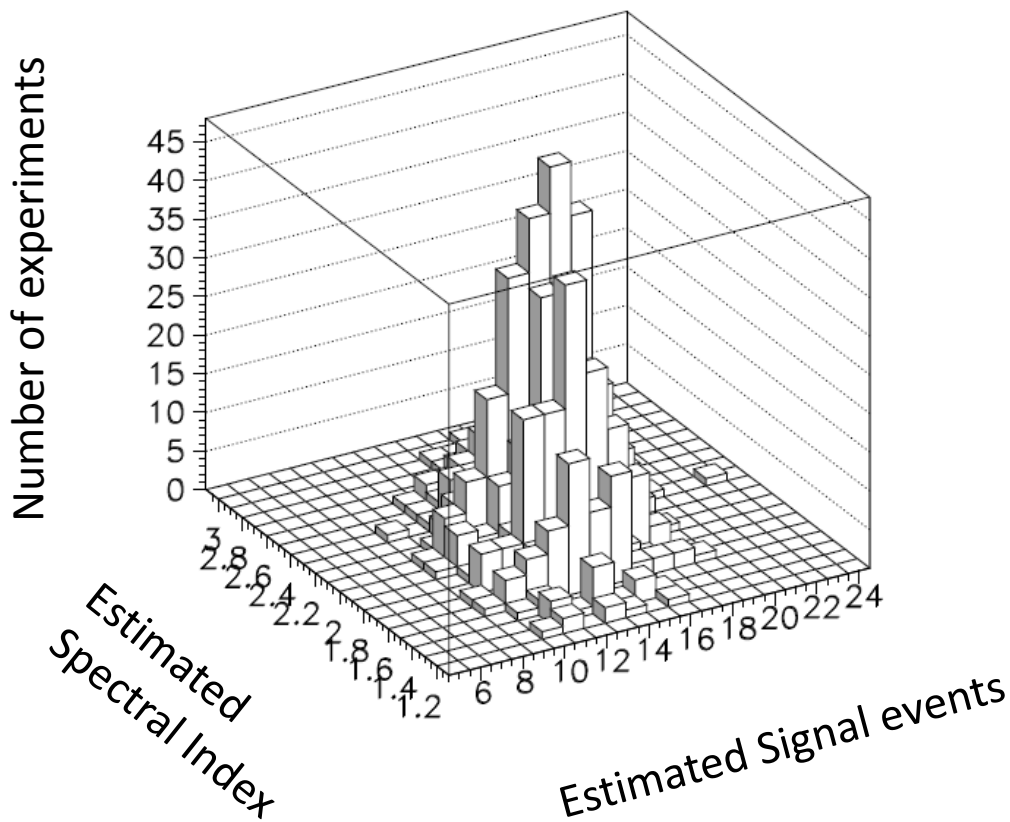
Where s_x s_y incorporate the uncertainty of the angle between the ν-μ

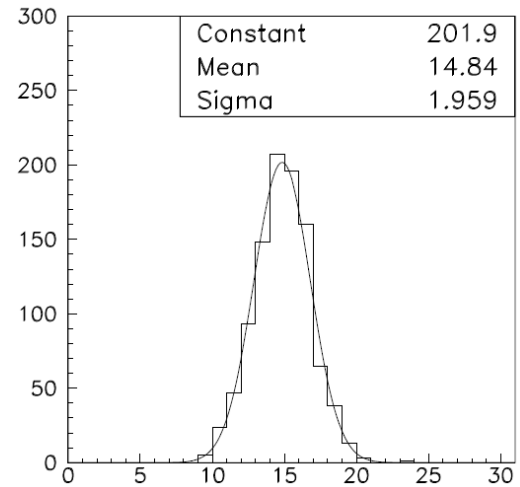
Likelihood estimations

$$L(\gamma, N_s) = \prod_{i=1}^{N_{total}} P_i\left(\theta_x, \varphi_y, E_m, \theta_m; \gamma, N_s\right)$$

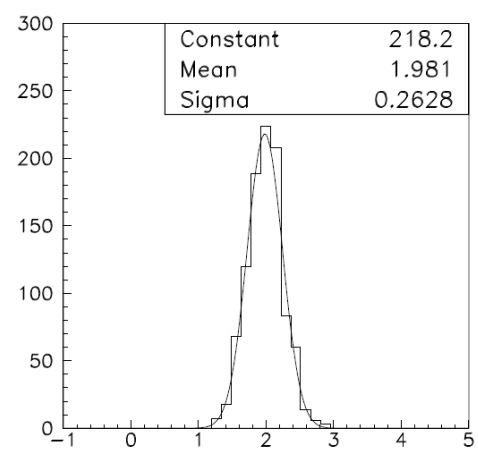
Point source δ=-60^0 and R_{max}=0.6^0 Detector: 308 Towers-180m distance

True Values: 15 Signal Events on top of 15 background events with γ=2





Estimated Signal events



Estimated Spectral Index

Discovery potential of known galactic sources

$$P_{signal}\left(\theta_x,\phi_y,E_m,\theta_m;\gamma\right)=P_{signal}^{angle}(\theta_x,\phi_y)\cdot P_{signal}^{energy}(E_m,\theta_m;\gamma)$$

$$P_{bck}=P_{bck}^{angle}(\theta_x,\phi_y)\cdot P_{bck}^{energy}(E_m,\theta_m)$$

$$P_i\left(\theta_x,\phi_y,E_m,\theta_m;\gamma,N_s\right)=\frac{N_s}{N_{total}}\cdot P_{signal}\left(\theta_x,\phi_y,E_m,\theta_m;\gamma\right)+\left(1-\frac{N_s}{N_{total}}\right)P_{bck}\left(\theta_x,\phi_y,E_m,\theta_m\right)$$

$$m=m_B+m_S=m_B+m\frac{N_s}{N_{total}}\Rightarrow m=\frac{m_B}{1-\frac{N_s}{N_{total}}}$$

$$L\left(N_s\right)=\frac{m^{N_{total}}e^{-m}}{N_{total}!}\cdot\prod_{i=1}^{N_{total}}P_i\left(\theta_x,\phi_y,E_m,\theta_m;N_s\right)$$ Extended Likelihood

Two hypotheses:

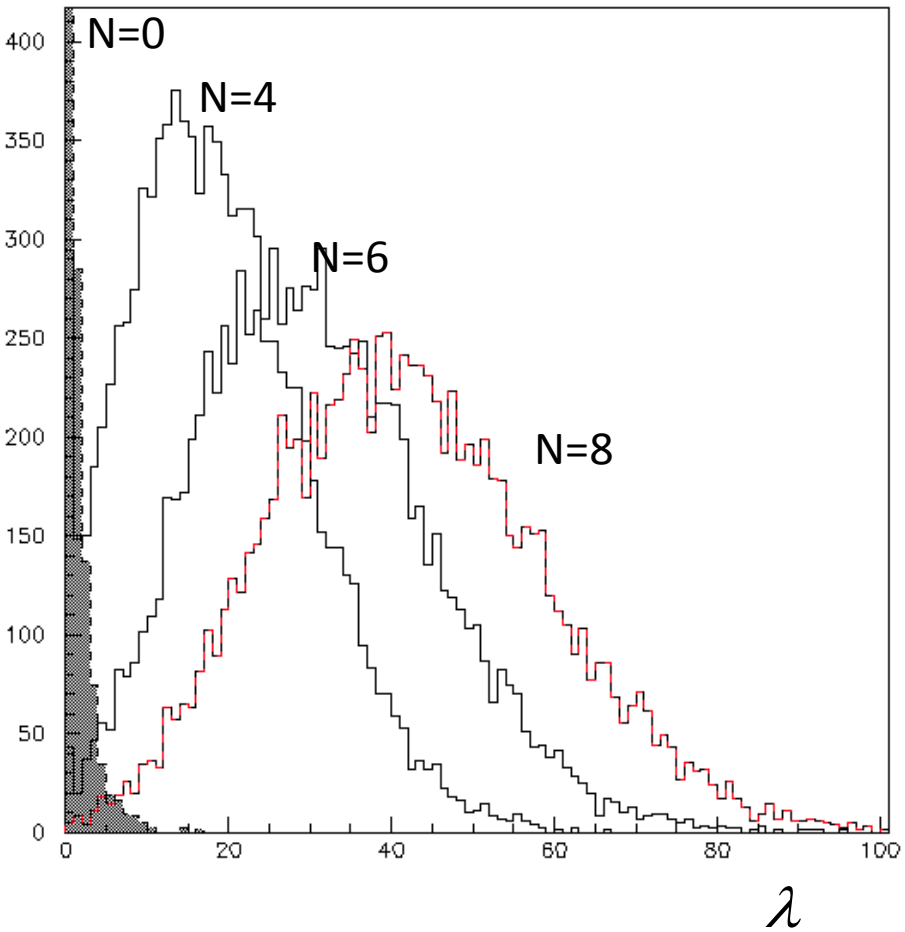
- the data sample is only background (null hypothesis)
- The data sample contains signal events (discovery)

Test statistic:

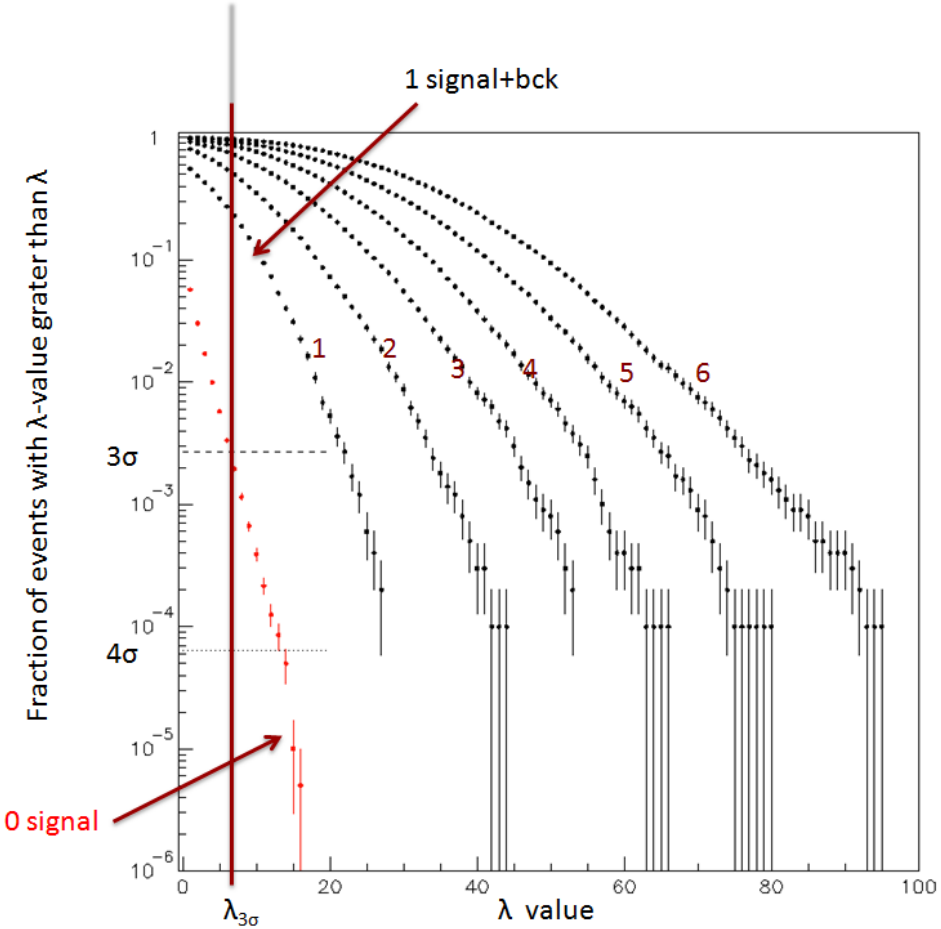
$$\lambda=-2\cdot\ln\frac{L_0\left(N_s=0\right)}{L\left(\hat{N}_s\right)}$$

Distribution of λ and Discovery probability

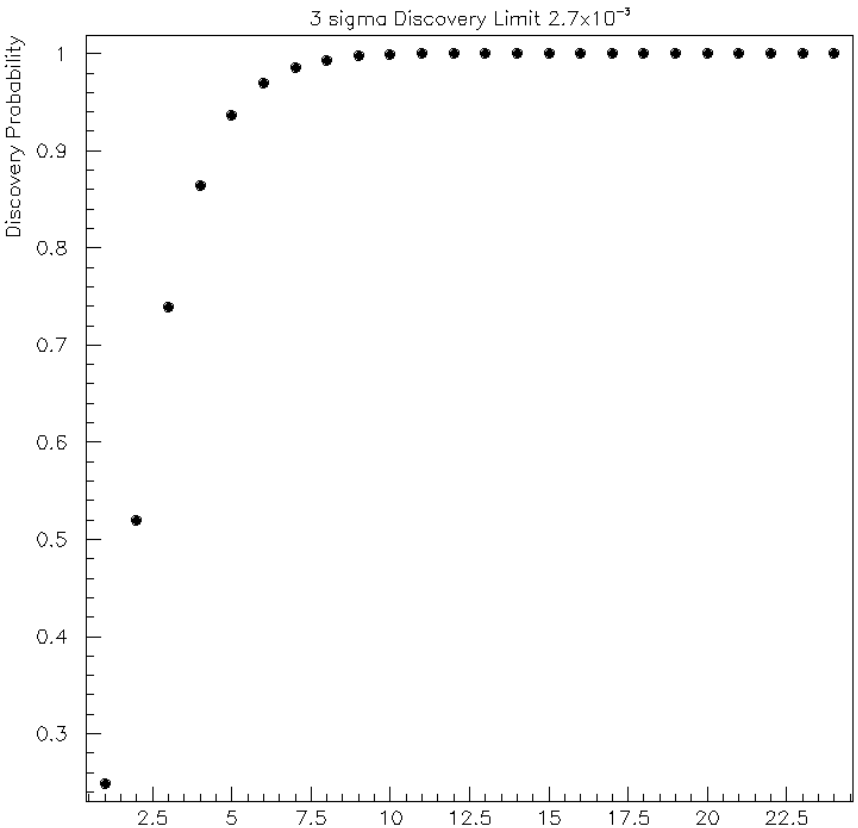
Distribution of λ when N signal events are present on top of background



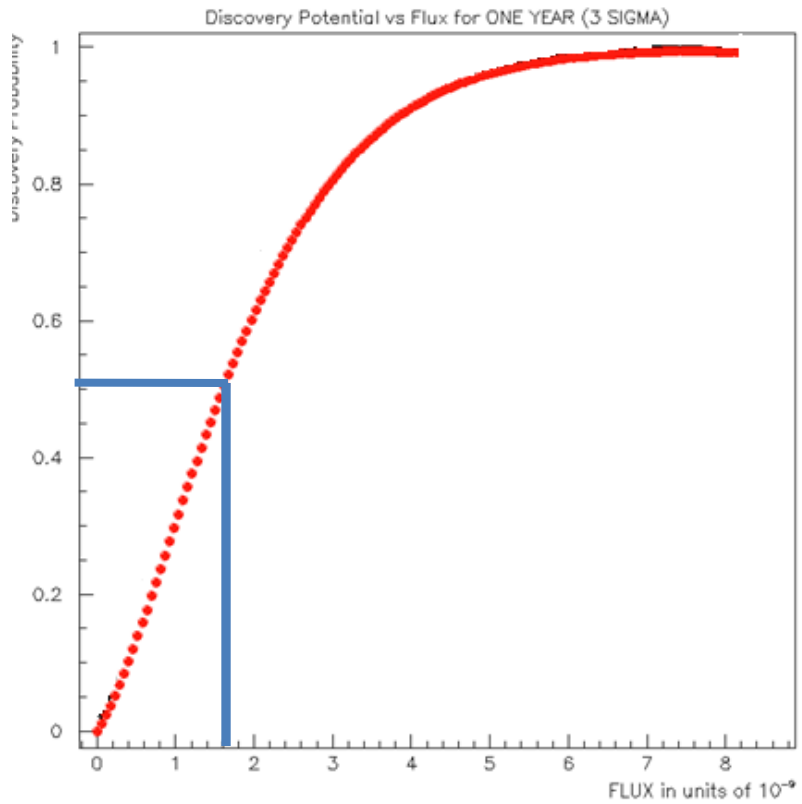
Fraction of events with λ greater than a λ value



Discovery probability and integrated flux



Number of signal events



Reference Flux

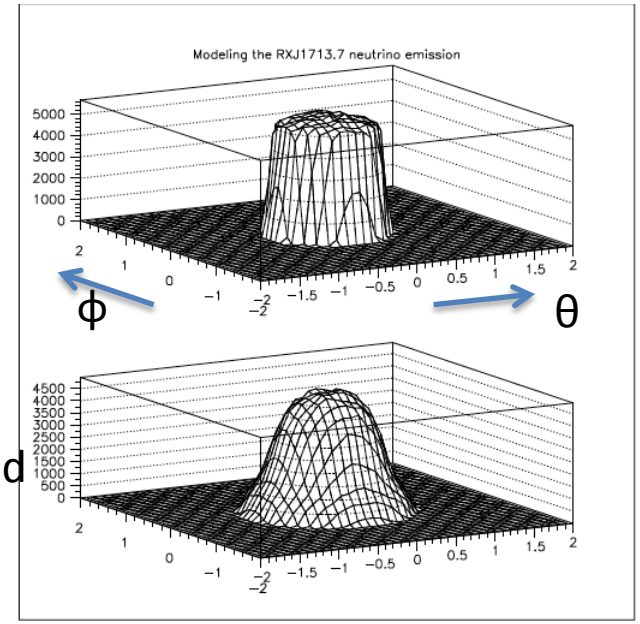
If r is the mean number of expected signal from a source then we expect 0, 1, 2, 3, 4,… tracks to be observed with probabilities according to the Poissonian probability function P(n;r).

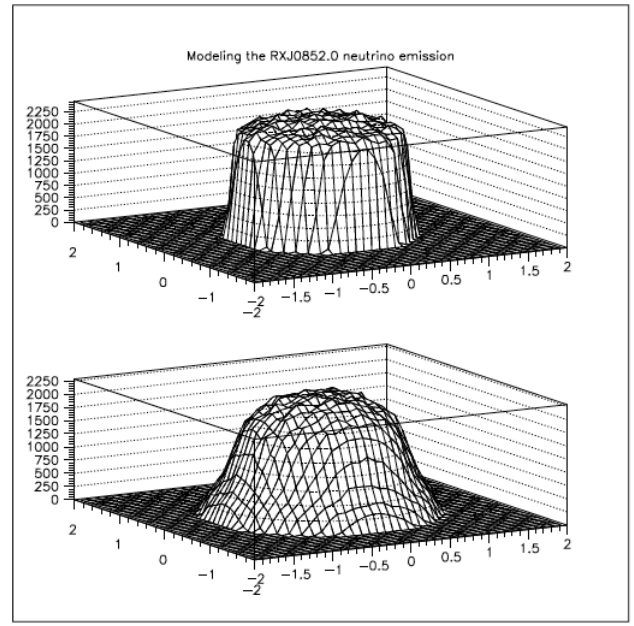
Consequently, the Discovery Potential for r expected signal tracks is the convolution of the discovery probabilities for certain number of tracks with the corresponding Poissonian probabilities for mean equals to r

Modeling the Spatial Distribution of the Sources

generated neutrinos

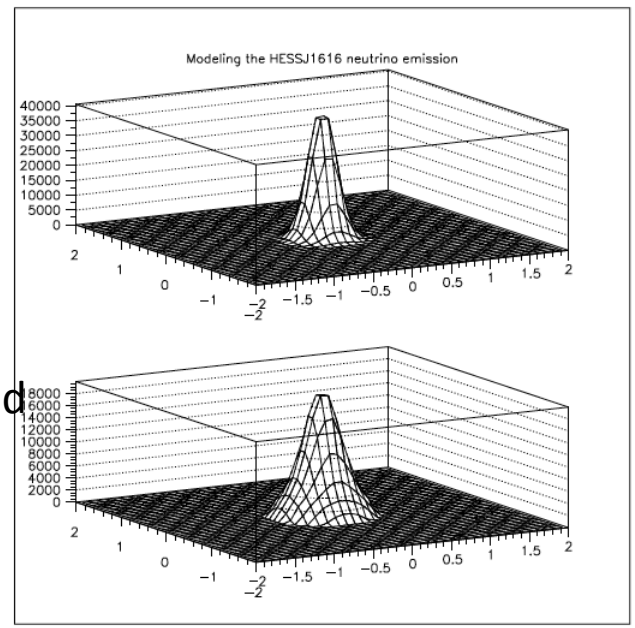
Reconstructed neutrino directions

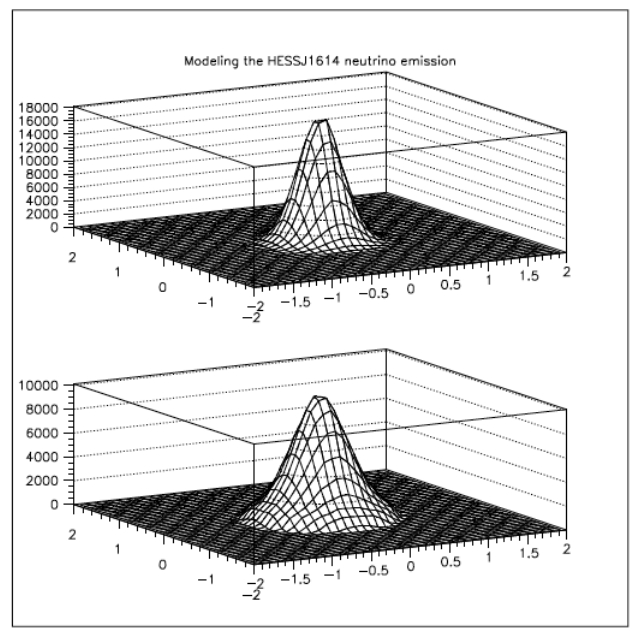




generated neutrinos

Reconstructed neutrino directions

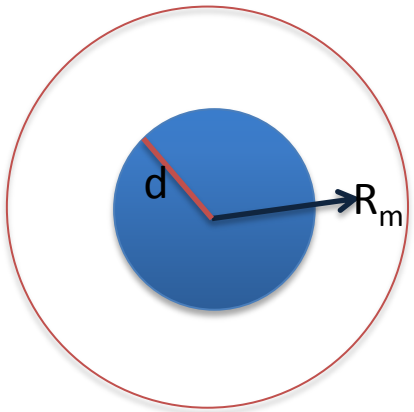




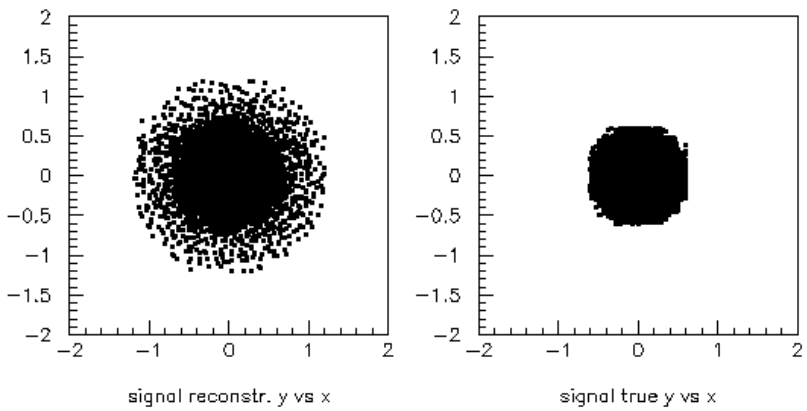
Flat disk treatment

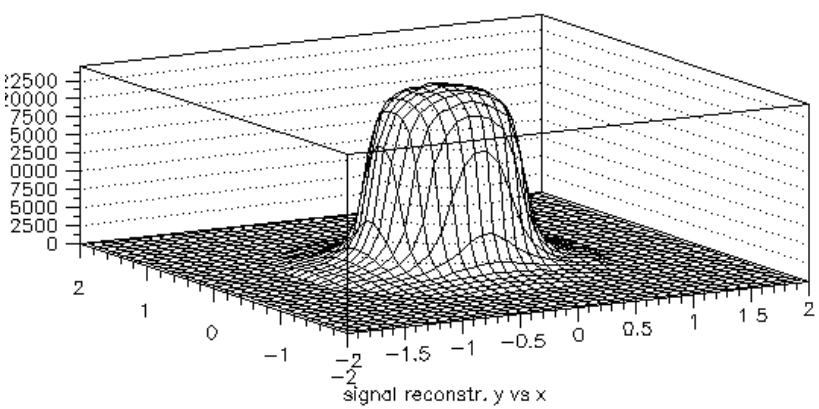
Point source →

$$P^{angle}_{signal}(\theta_x,\varphi_y)=\frac{1}{1-e^{-\frac{R_{max}}{s_x^2+s_y^2}}}\frac{1}{2\pi s_x s_y}e^{-\frac{1}{2}\left(\frac{\theta_x^2}{s_x^2}+\frac{\varphi_y^2}{s_y^2}\right)}$$

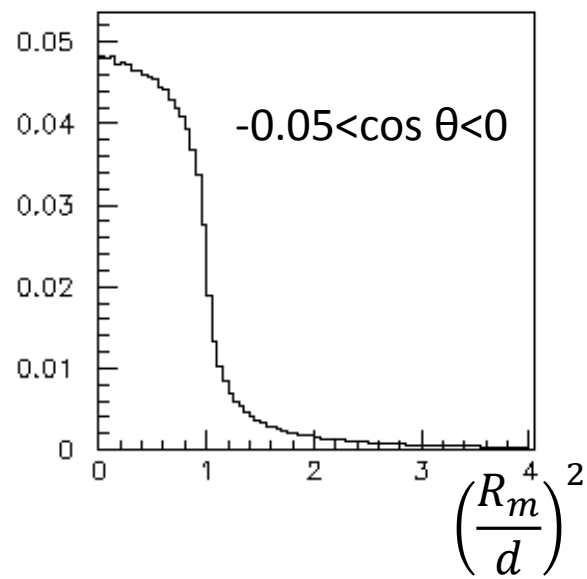


$$P^{angle}_{signal}(\theta_x,\phi_y)=\frac{1}{1-e^{-\frac{d}{s_x^2+s_y^2}}}\frac{1}{2\pi s_x s_y}\iint_{\Delta} e^{-\frac{1}{2}\left(\frac{(\theta_x-\theta_t)^2}{s_x^2}+\frac{(\phi_y-\varphi_t)^2}{s_y^2}\right)}\frac{1}{\pi d^2}d\theta_t\, d\phi_t$$

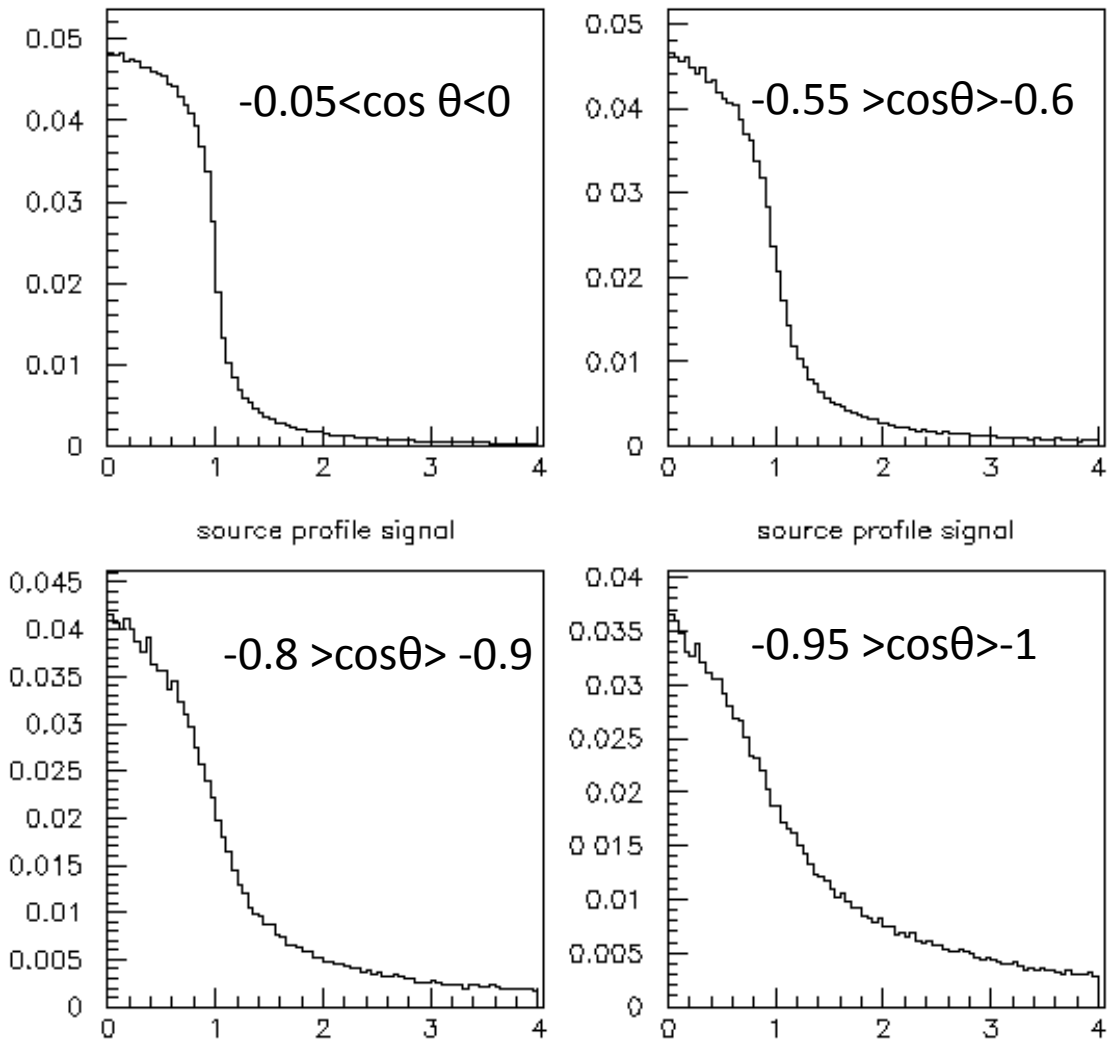




$$P^{angle}_{signal}(\theta_x,\phi_y)\rightarrow P^{angle}_{signal}\left(\left(\frac{R_m}{d}\right)^2,\cos\theta_t\right)$$



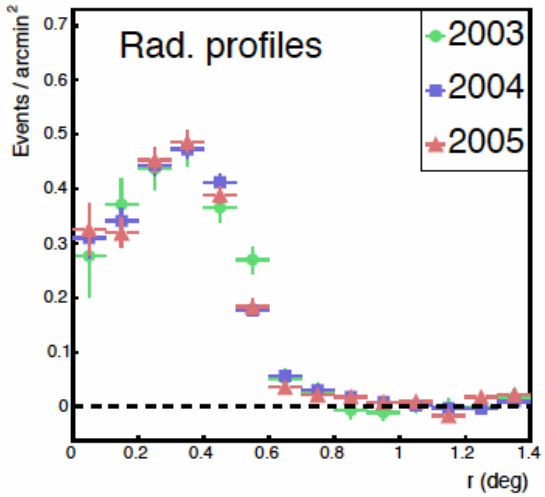
$$P^{angle}_{signal}(\theta_x,\phi_y) \rightarrow P^{angle}_{signal}\left(\left(\frac{R_m}{d}\right)^2, \cos\theta_t\right)$$

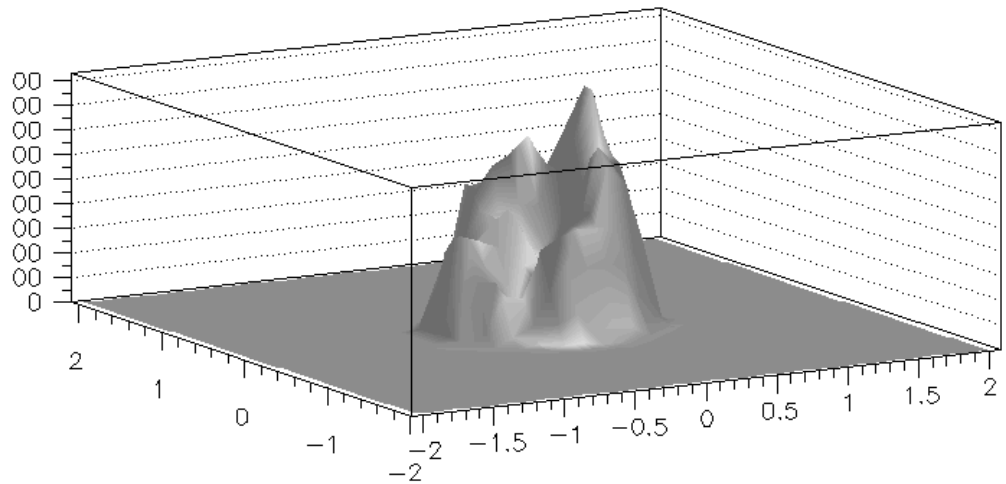


$(R_m/d)^2$

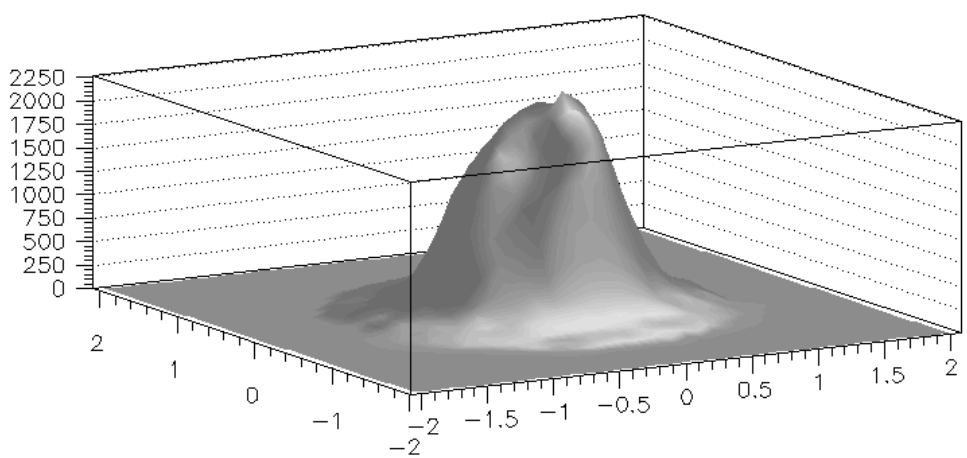
RXJ1713 Morphology

Simulate the ν emission to follow the (raw) VHE gamma emission topology

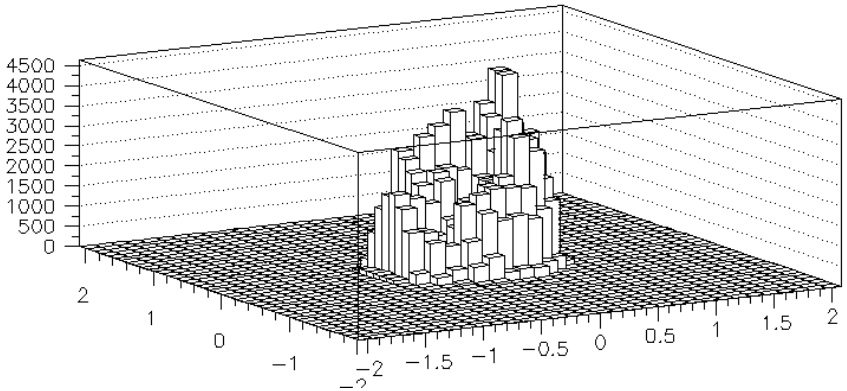




3D angular distribution of the reconstructed (ν) signal induced muons



RXJ1713



Each bin of the source-model contributes as

$$P^{angle}_{signal-bin}(\theta_x,\phi_y) = \frac{1}{1-e^{-\frac{R^2_{\max}}{s_x^2+s_y^2}}} \frac{1}{2\pi s_x s_y} \iint_{\Delta} e^{-\frac{1}{2}\left(\frac{(\theta_x-\theta_t)^2}{s_x^2}+\frac{(\phi_y-\varphi_t)^2}{s_y^2}\right)} \frac{1}{\pi d^2} d\theta_x d\phi_y$$

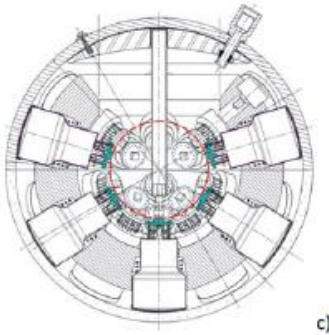
$$P_{signal}(\theta_x,\phi_y,E) = \Pi(E)\cdot \sum_{i=1}^{101} w_i \cdot P^{angle}_{signal-bin-i}(\theta_x,\phi_y)$$

$$P_{total}(\theta_x,\phi_y,E) = \frac{n_s}{N} P_{signal} + \left(1-\frac{n_s}{N}\right) P_{back}$$

Detector Geometrical Layout

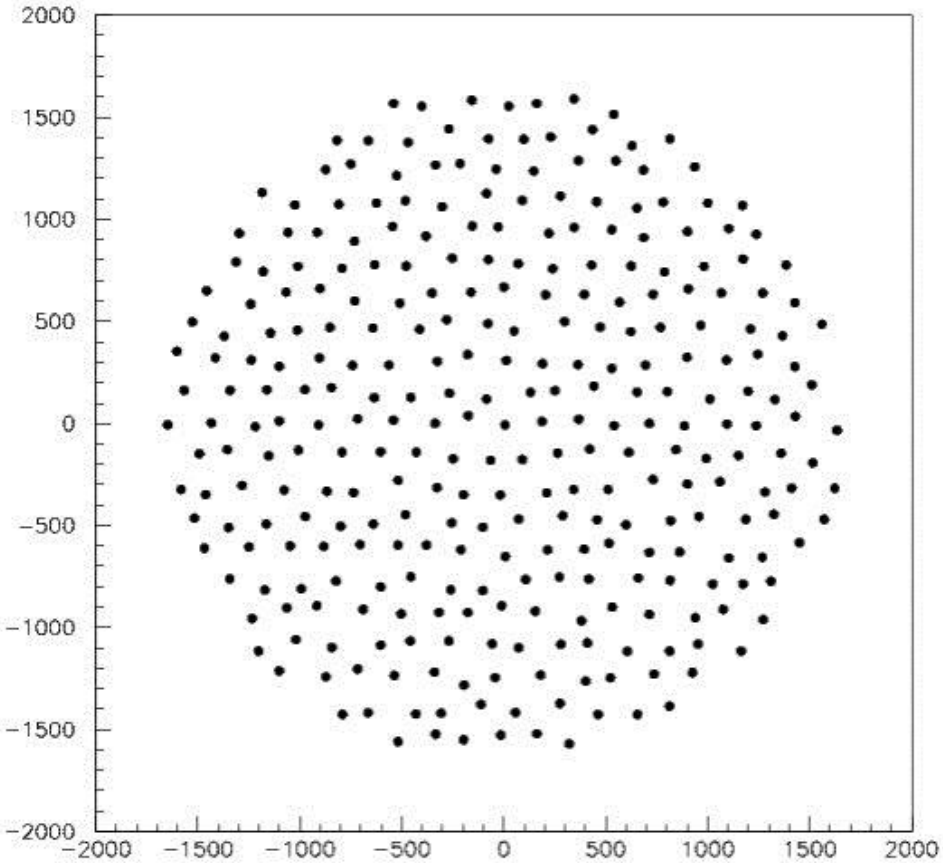
Strings: 616 strings with 100m inter string distance. Each string comprise 20 Multi PMTs, 40 m apart.

b)



a) c)

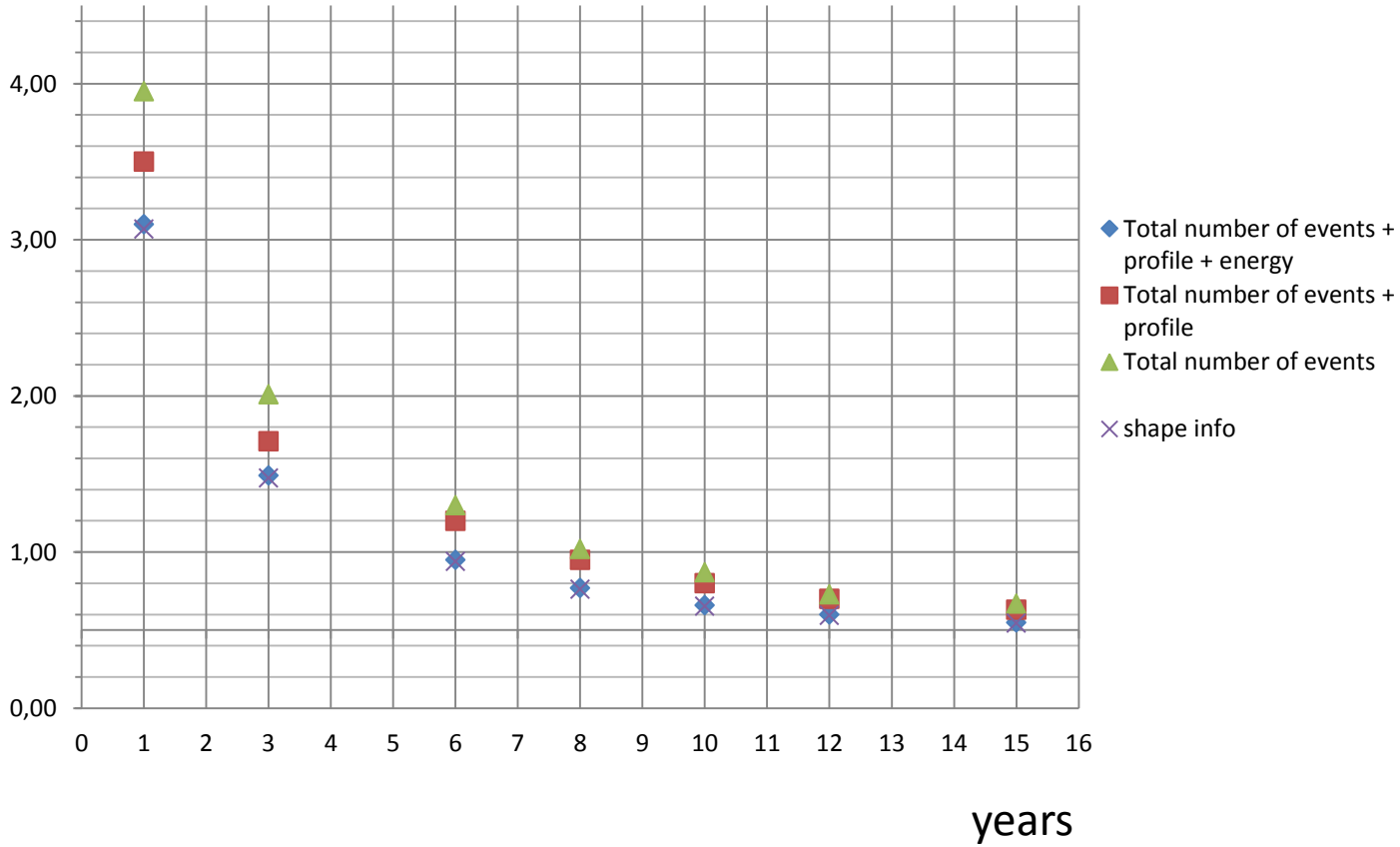
Detectors Footprint



RXJ1713

Source	Size (degrees)	Flux ($TeV^{-1}\ cm^{-2}s^{-1}$), E in TeV
RXJ1713.7-3946	Radius = 0.65°	$1.68*10^{-11}*(E^{-1.72})*exp(-sqrt(E/2.1))$

Required Flux (in units of the source flux)
for 50% discovery probability (5σ)



1% improvement in DP. 50% for 5σ discovery : 5.6 ys → 5.55 ys

Galactic Plane Sources

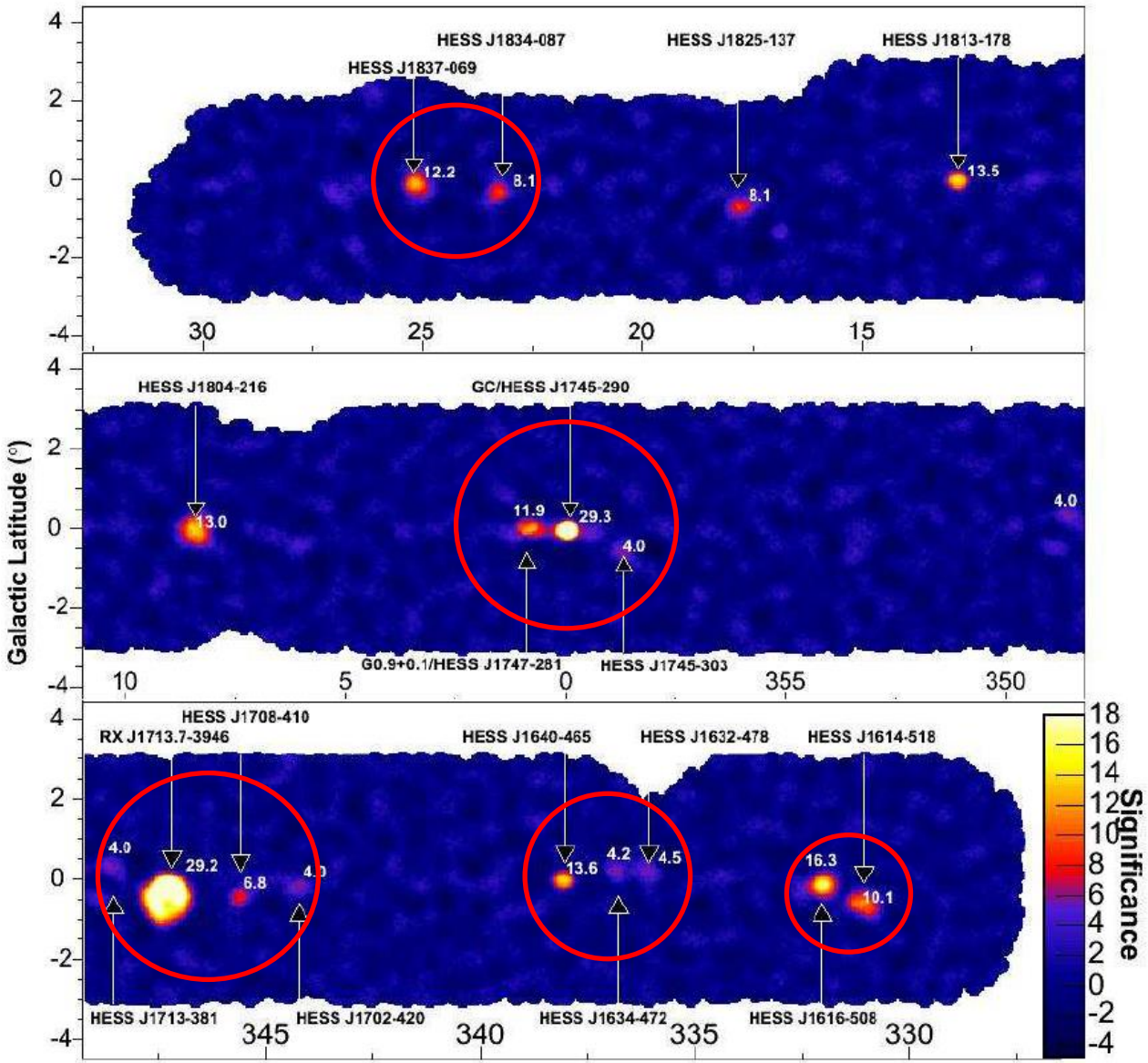
TABLE 1
H.E.S.S. Catalog Sources

Source Name	Reference	ϕ (deg)	Visibility	Spectral Parameters k_ν	Γ_ν	e_ν	$E_\nu > 1$ TeV $N_{\rm src}$	$N_{\rm sim}$	$E_\nu > 5$ TeV $N_{\rm src}$	$N_{\rm sim}$
Source Class 1 (SNRs)										
RX J1713.7−3946	1	1.3	0.74	15.52	1.72	1.35	7–14 (11)	41	2.6–6.7 (4.6)	8.2
RX J0852.0−4622	2	2.0	0.83	16.76	1.78	1.19	7–15 (11)	104	1.9–6.5 (4.2)	21
HESS J1640−465	5	0.1	0.83	0.93	2.41		0.4–3.3 (2.2)	8.7	0.0–2.1 (1.3)	1.8
HESS J1745−290[a]	4	<0.1	0.65	0.85	2.29		1.1–2.7 (2.0)	6.4	0.5–1.8 (1.3)	1.3
HESS J1834−087	5	0.2	0.54	0.80	2.45		0.2–1.7 (1.1)	6.0	0.0–1.1 (0.7)	1.2
HESS J1713−381	5	0.1	0.73	0.23	2.28		0.0–1.5 (0.6)	7.2	0.0–1.1 (0.4)	1.4
Sums for source class 1							∼27	173	∼12	35
Source Class 2 (Binary Systems)										
LS 5039 (INFC)[b]	6	0.1	0.57	2.50	1.61	1.01	0.3–0.7 (0.5)	2.5	0.1–0.3 (0.2)	0.5
LS 5039 (SUPC)[b]	6	0.1	0.57	0.26	2.51		0.1–0.3 (0.2)	3.0	0.0–0.2 (0.1)	0.6
PSR B1259−63	7	<0.1	1.00	0.34	2.72		0.1–0.9 (0.6)	9.1	0.0–0.4 (0.3)	1.7
Source Class 3 (No Counterparts at Other Wavelengths)										
HESS J1303−631	8	0.3	1.00	11.99	1.29	0.21	0.8–2.3 (1.6)	11	0.1–0.5 (0.3)	2.1
HESS J1745−303	5	0.4	0.66	1.01	1.79		0–18 (9)	9.0	0–16 (7)	1.8
HESS J1614−518	5	0.5	1.00	2.41	2.44		1–10 (6)	19	0.0–6.7 (3.7)	4.0
HESS J1837−069	5	0.2	0.53	1.65	2.27		1.2–4.5 (3.3)	5.9	0.4–3.2 (2.2)	1.2
HESS J1634−472	5	0.2	0.85	0.64	2.36		0.0–3.1 (1.7)	9.8	0.0–2.2 (1.1)	2.0
HESS J1708−410	5	0.1	0.76	0.44	2.33		0.1–1.6 (1.1)	7.6	0.0–1.1 (0.7)	1.5
Sums for source class 3							∼23	63	∼15	13
Source Class 4 (PWN)										
Vela X	9	0.8	0.81	11.75	0.98	0.84	9–23 (16)	23	5–15 (10)	4.6
HESS J1825−137	10	0.5	0.57	10.73	2.08	4.24	5–10 (8)	9.3	2.2–5.2 (3.7)	1.8
Crab Nebula	11	<0.1	0.39	22.38	2.15	1.72	4.0–7.6 (5.8)	5.2	1.1–2.7 (1.9)	1.1
HESS J1632−478	5	0.3	0.87	1.87	2.11		0–15 (9)	12	0–12 (7)	2.4
MSH 15−52	12	0.2	1.00	1.89	2.27		3.4–9.6 (7.1)	10	1.5–6.6 (4.7)	2.0
HESS J1616−508	5	0.3	1.00	2.11	2.36		2.0–9.0 (6.6)	14	0.3–5.9 (4.1)	3.0
HESS J1420−607	13	0.1	1.00	1.16	2.25		2.0–6.3 (4.6)	9.6	0.7–4.4 (3.1)	1.9
HESS J1418−609	13	0.1	1.00	0.94	2.19		1.7–6.1 (4.2)	9.6	0.8–4.5 (3.0)	1.9
HESS J1813−178	5	0.1	0.59	0.96	2.09		0.7–4.6 (3.2)	5.8	0.2–3.6 (2.4)	1.1
HESS J1702−420	5	0.2	0.77	0.82	2.32		0.5–3.3 (2.1)	8.4	0.0–2.3 (1.4)	1.7
HESS J1804−216	5	0.4	0.61	1.49	2.73		0.6–2.0 (1.5)	8.4	0.1–1.0 (0.7)	1.7
G 0.9+0.1	14	<0.1	0.65	0.27	2.31		0.1–0.9 (0.6)	6.2	0.0–0.6 (0.4)	1.2
Sums for source class 4							∼68	122	∼41	24

$$\frac{dN_{\gamma/\nu}}{dE_{\gamma/\nu}} \approx k_{\gamma/\nu}\left(\frac{E_{\gamma/\nu}}{1\ \text{TeV}}\right)^{-\Gamma_{\gamma/\nu}} \exp\left(-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}\right)$$

The Astrophysical Journal, 656:870–878, 2007 February 20

Source Grouping



H.E.S.S. Galactic Plane survey

Source Grouping Modeling

- Assume a disk large enough to contain the sources
- Collect N events for a certain experimental time
- Apply some technique like in RXJ1713 source morphology method but:
  - numbers of bins → number of sources
  - Different profile for each source
  - Different energy distribution for each source

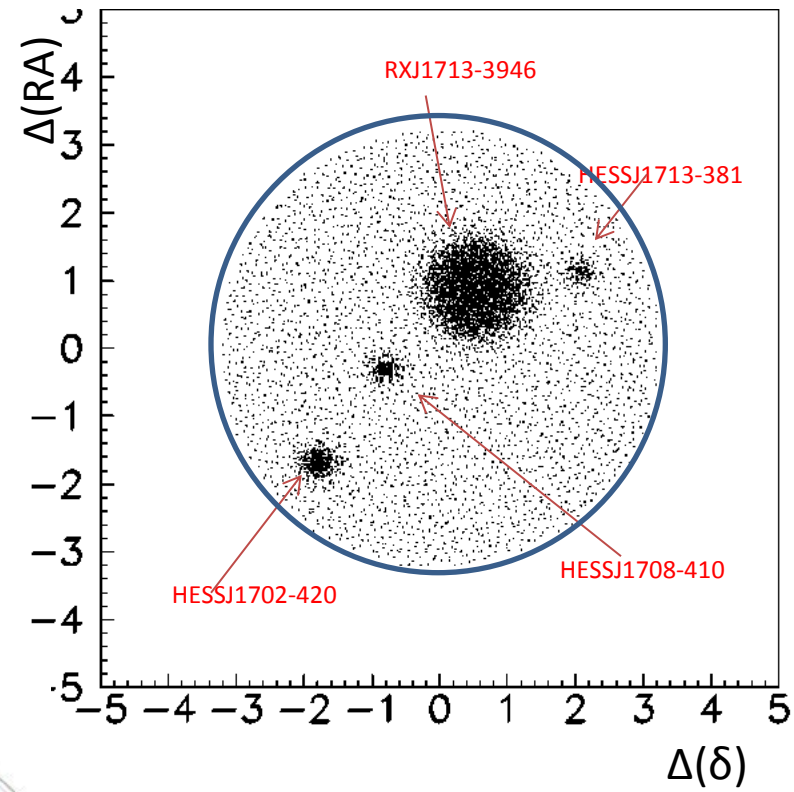
$$P_{signal}(\theta_x,\phi_y,E)=\sum_{i=1}^{Nsources} w_i \cdot P^{angle}_{signal-source-i}(\theta_x,\phi_y)\cdot \Pi_{signal-source-i}(E)$$

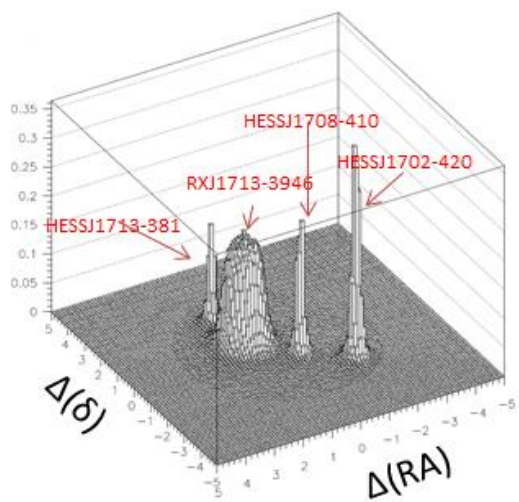
$$P_{total}(\theta_x,\phi_y,E)=\frac{n_s}{N}P_{signal}+\left(1-\frac{n_s}{N}\right)P_{back}$$

n_s: *signal events*

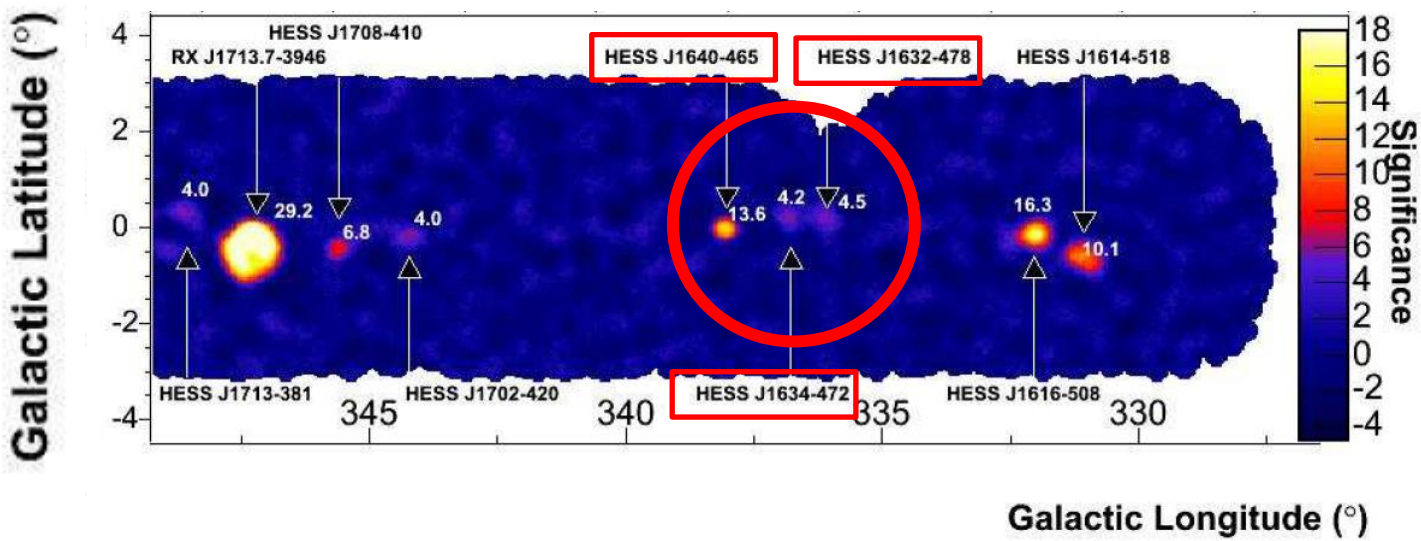
w_i : *relative strength*

Distribution of signal events inside the search disk





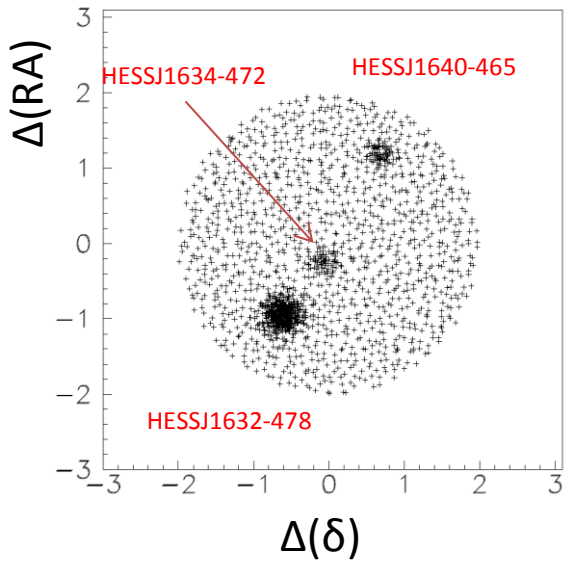
HESSJ1640-465 HESSJ1634-472 HESSJ1632-478



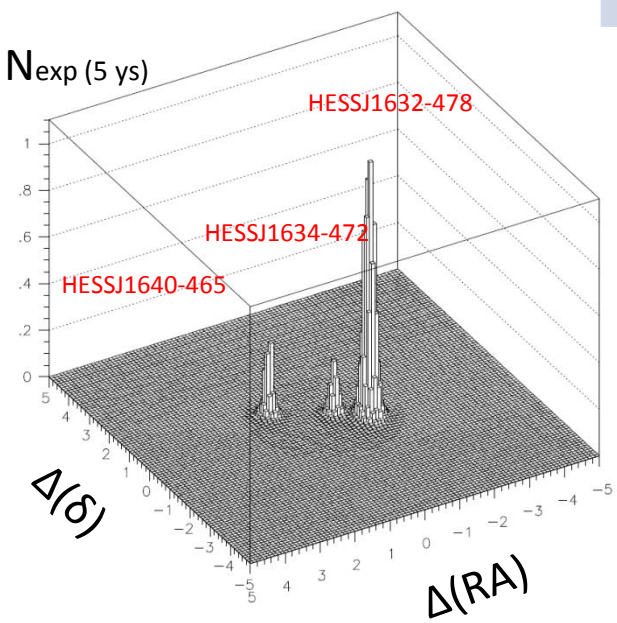
Source	R(deg)	RA	Declination	k_ν	Γ_ν	e_ν
HESSJ1640-465	0.05	16:40:43.2	-46:31:48	0.93	2.41	-
HESSJ1634-472	0.1	16:34:57.6	-47:16:12	0.64	2.36	-
HESSJ1632-478	0.15	16:32:9.6	-47:49:12	1.87	2.11	-

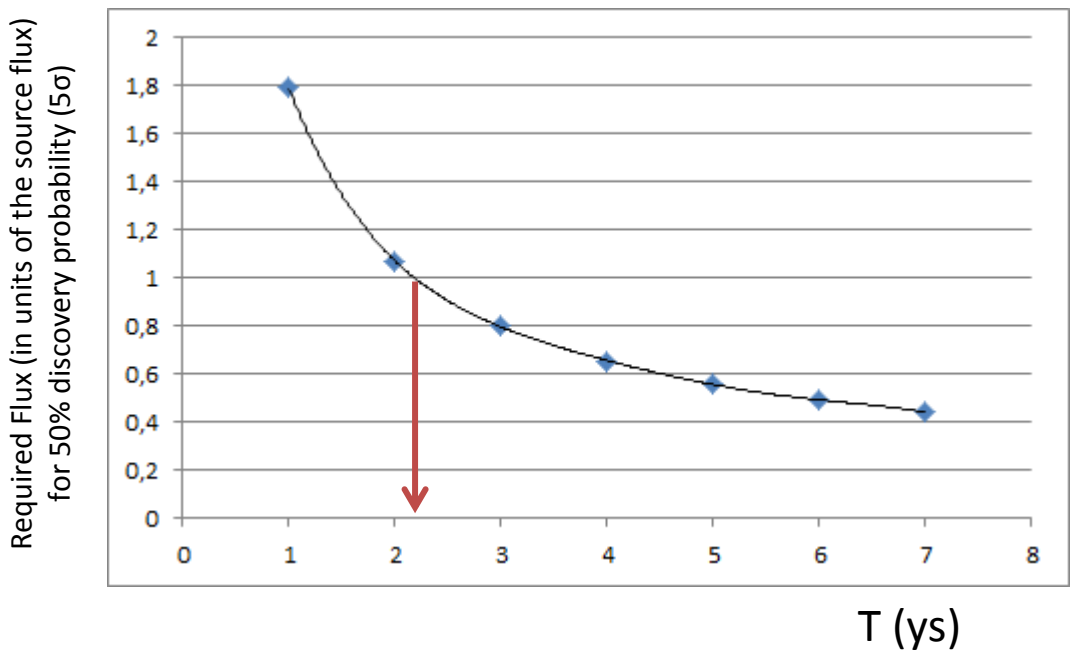
Disk center: RA=16:35:56.8 δ=-47:12:24 Radius=1.91 degrees

Expected number of background events (5 ys) = 94.8

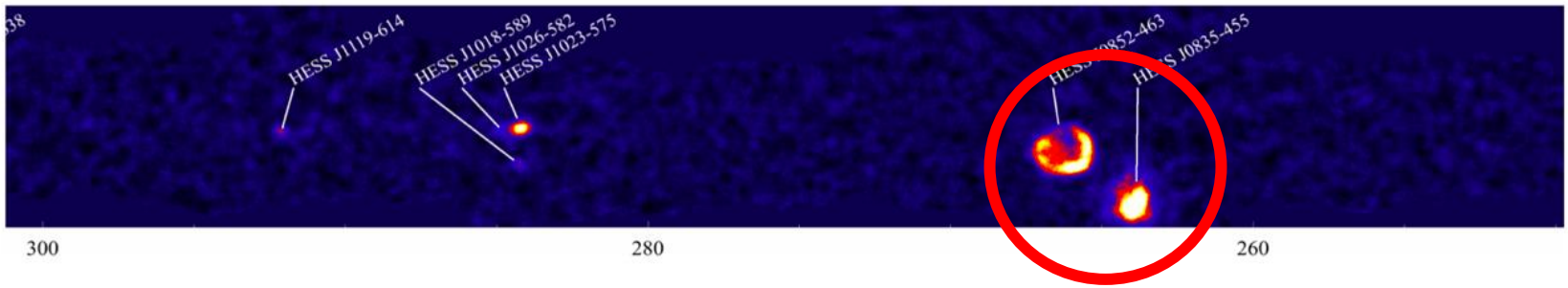


Source	Δ(RA) (with respect to disk center)	Δ(δ) (with respect to disk center)	Expected number of events (5 ys)
HESSJ1640-465	0.67	1.19	2.6
HESSJ1634-472	-0.06	-0.24	2.1
HESSJ1632-478	-0.61	-0.94	12.95





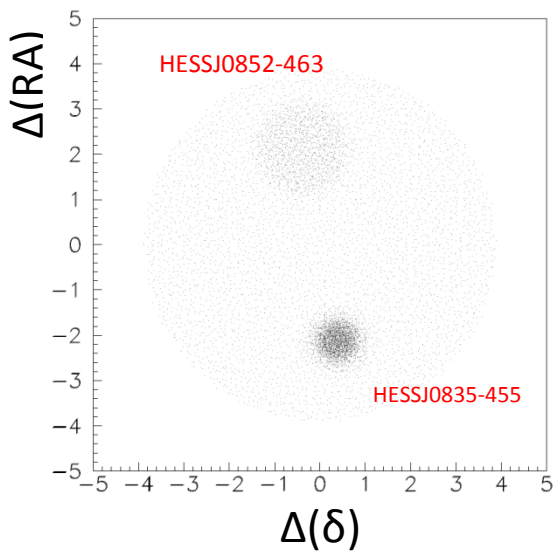
VELAX RXJ0852.0-4622



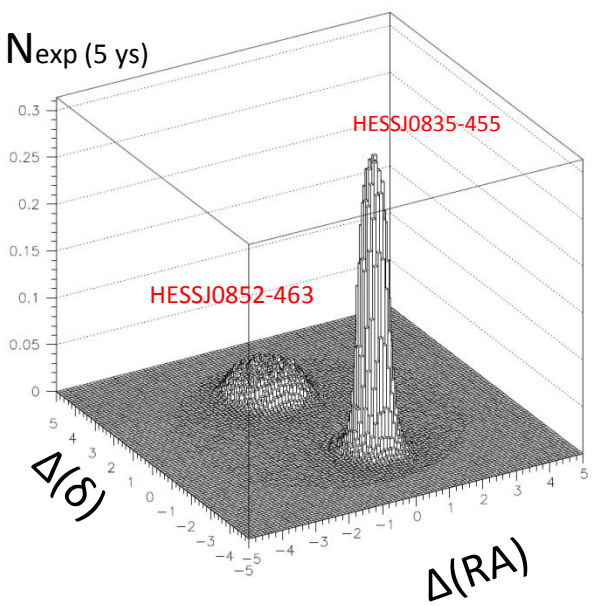
Source	R(deg)	RA	Declination	k_v	Γ_v	e_v
HESSJ0835-455	0.4	8:35:00	-45:36:00	11.75	0.98	0.84
HESSJ0852-463	1.0	8:52:00	-46:22:00	16.76	1.78	1.19

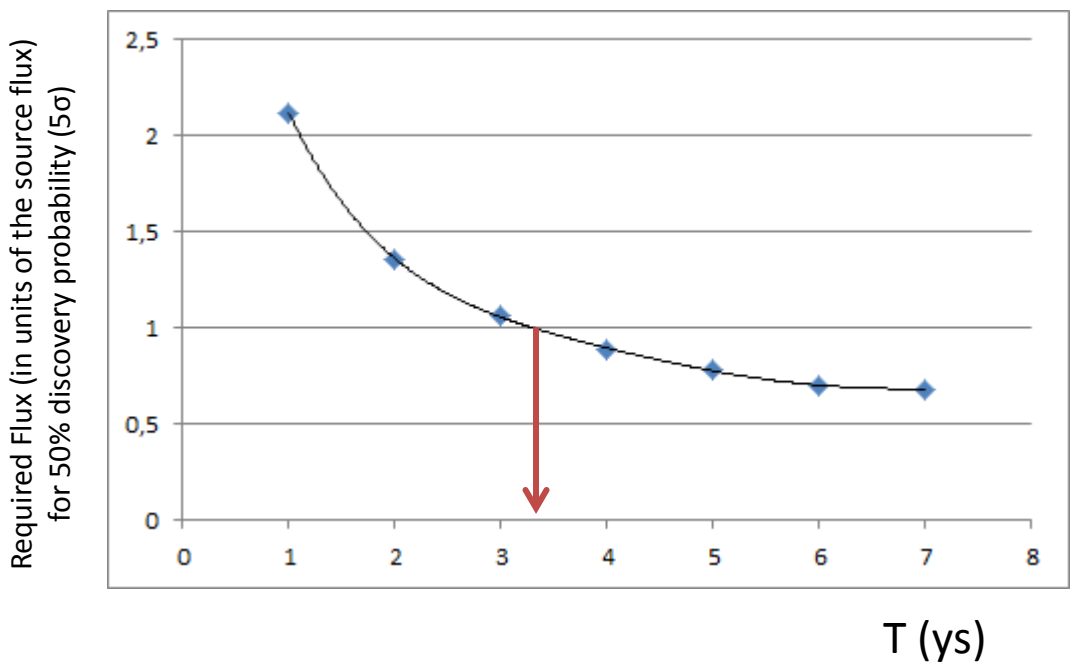
Disk center: RA=8:43:30 δ=-45:58:59 Radius=3.82 degrees

Expected number of background events (5 ys) = 364.58

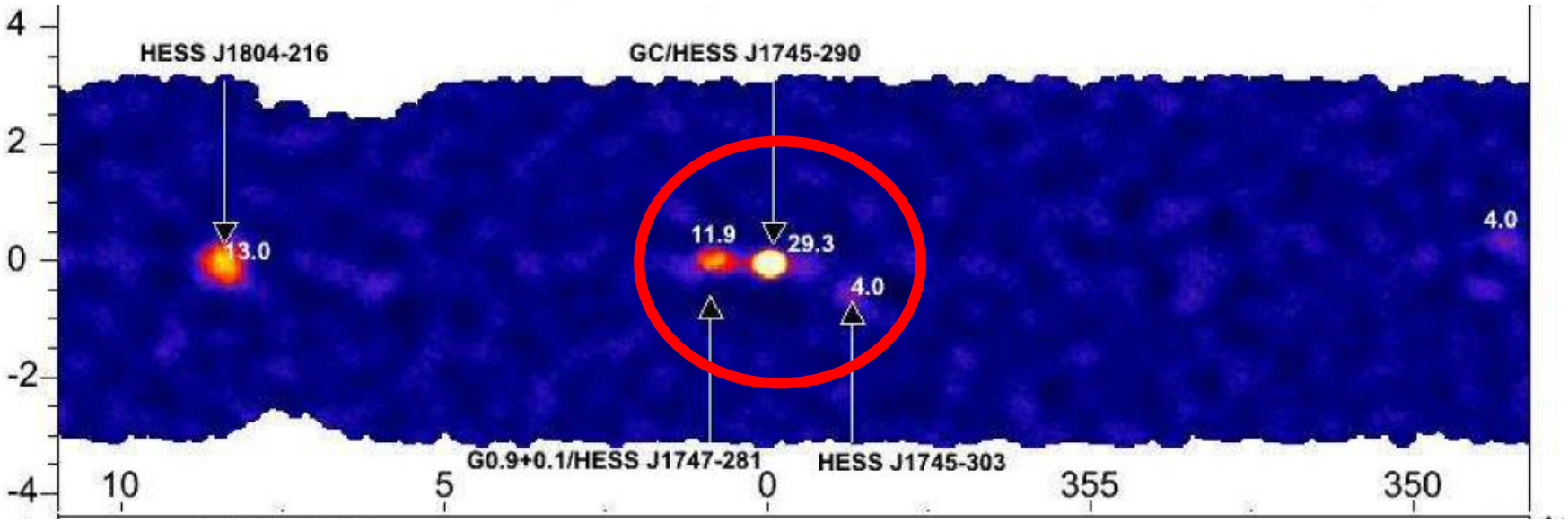


Source	Δ(RA) (with respect to disk center)	Δ(δ) (with respect to disk center)	Expected number of events (5 ys)
HESSJ0835-455	-2.12	0.38	19.5
HESSJ0852-463	2.12	-0.38	10.27





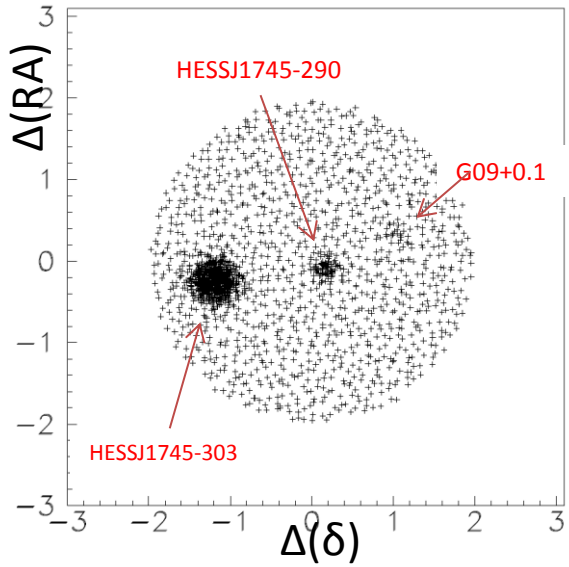
HESSJ1745-290 HESSJ1745-303 G09+01



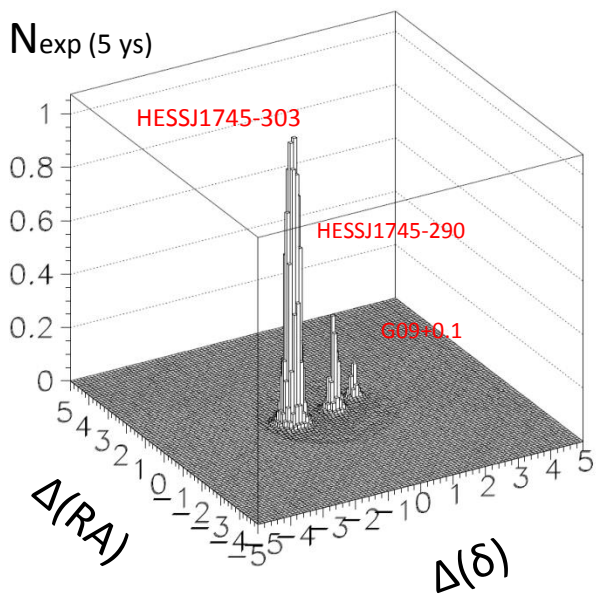
Source	R(deg)	RA	Declination	k_v	Γ_v	e_v
HESSJ1745-290	0.05	17:45:39.6	-29:00:22	0.85	2.29	-
HESSJ1745-303	0.2	17:45:2.4	-30:22:12	1.01	1.79	-
G09+0.1	0.05	17:47:23.2	-28:09:06	0.27	2.31	-

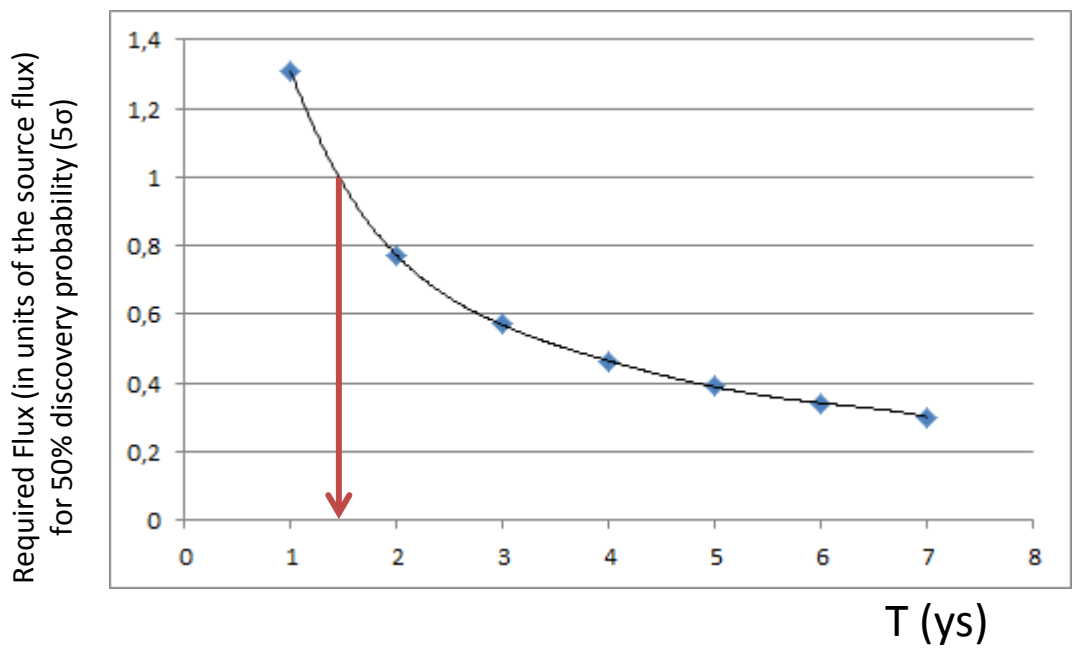
Disk center: RA=17:46:1.7 δ=-29:10:33 Radius=1.91 degrees

Expected number of background events (5 ys) = 67.57

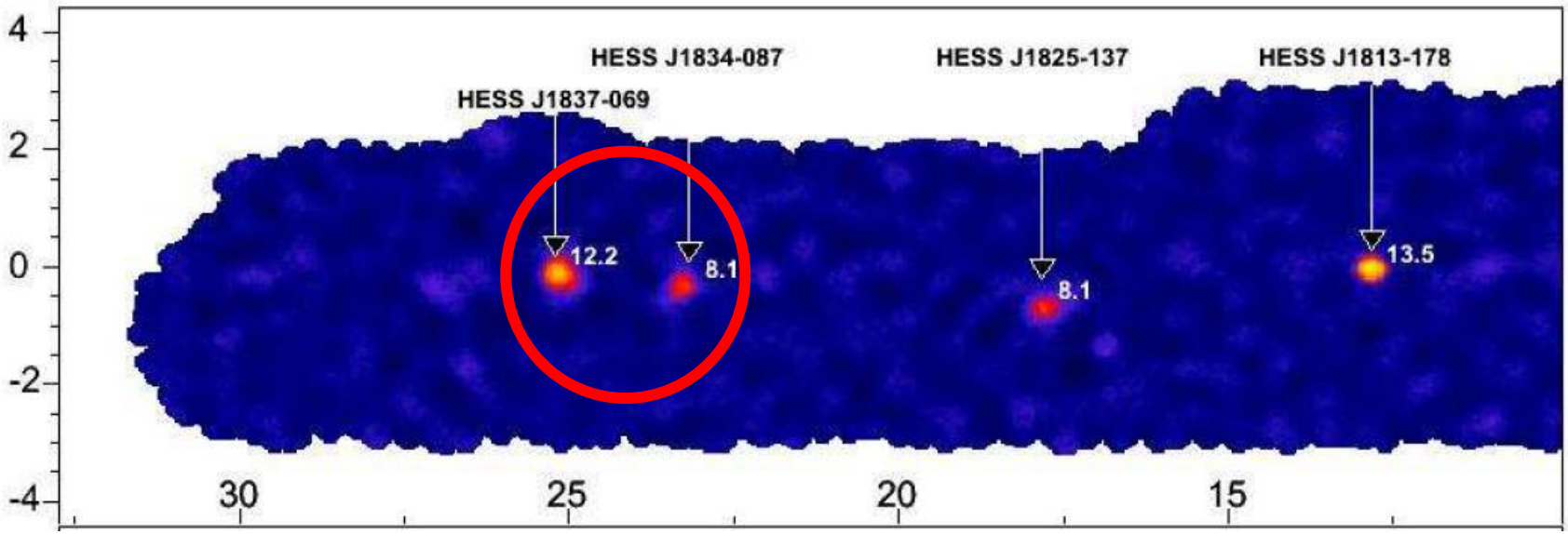


Source	Δ(RA) (with respect to disk center)	Δ(δ) (with respect to disk center)	Expected number of events (5 ys)
HESSJ1745-290	-0.09	0.17	2.64
HESSJ1745-303	-0.25	-1.19	17.28
G09+0.1	0.34	1.02	0.78





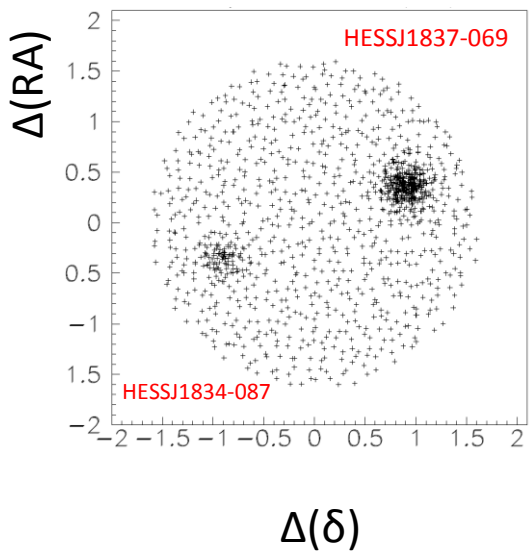
HESSJ1834-087 HESSJ1837-069



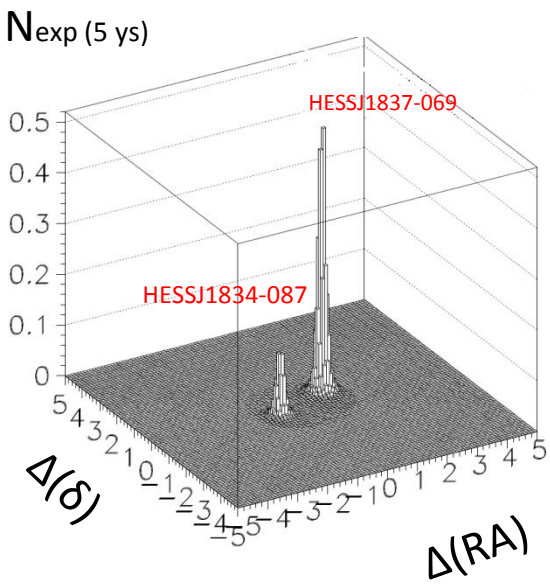
Source	R(deg)	RA	Declination	k_v	Γ_v	e_v
HESSJ1834-087	0.1	18:34:45.6	-8:45:36	0.8	2.45	-
HESSJ1837-069	0.1	18:37:38.4	-6:57:00	1.65	2.27	-

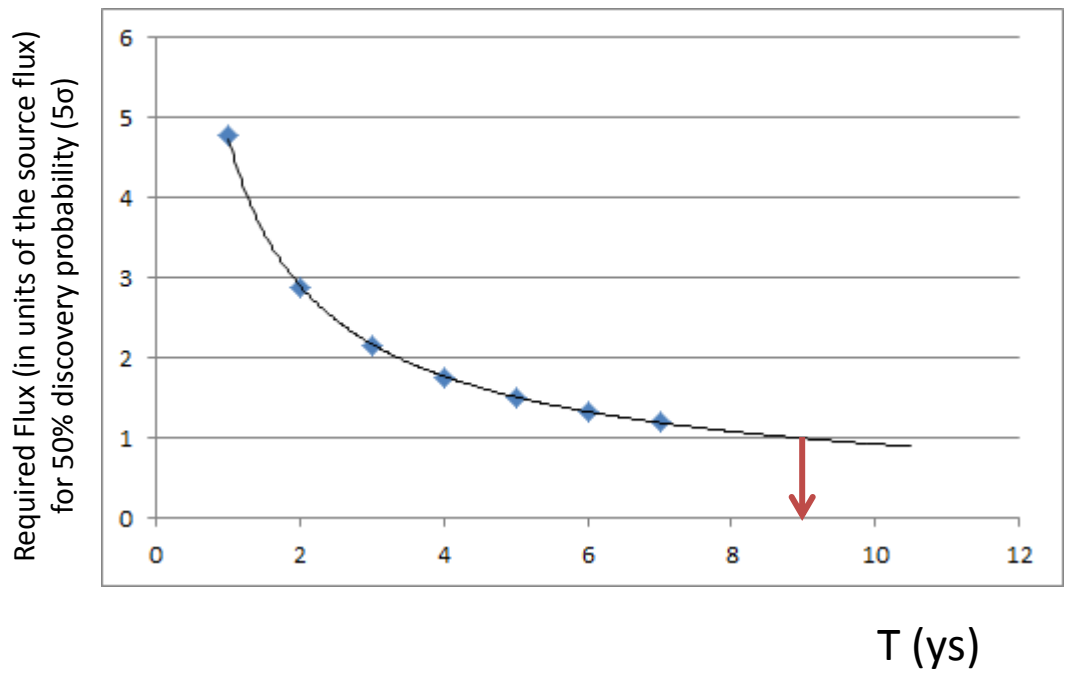
Disk center: RA=18:36:12 δ=-7:51:18 Radius=1.53 degrees

Expected number of background events (5 ys) = 39.14

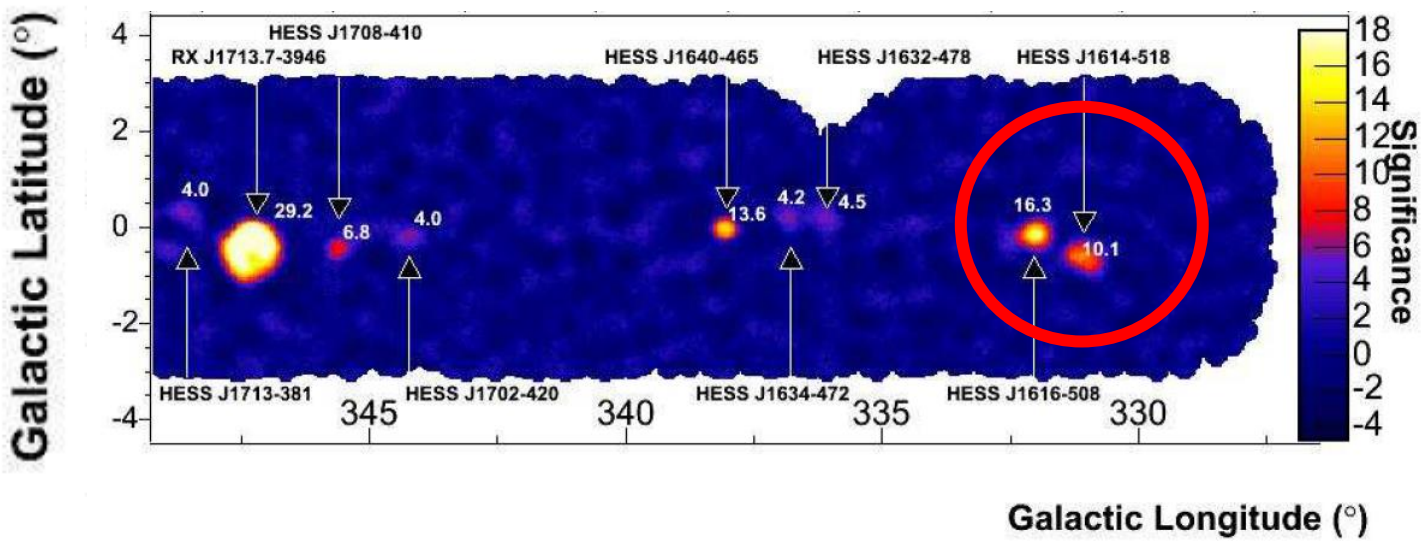


Source	Δ(RA) (with respect to disk center)	Δ(δ) (with respect to disk center)	Expected number of events (5 ys)
HESSJ1834-087	-0.36	-0.905	1.4
HESSJ1837-069	0.36	0.905	4.78

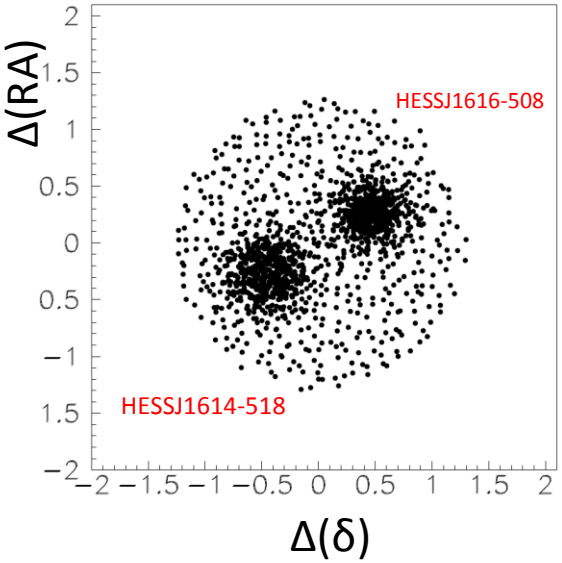




HESSJ1614-518 HESSJ1616-508



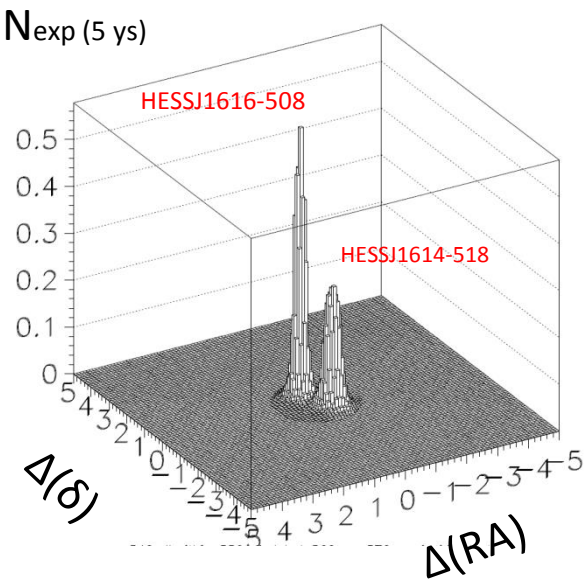
Source	R(deg)	RA	Declination	k_v	Γ_v	e_v
HESSJ1614-518	0.25	16:14:19.2	-51:49:12	2.41	2.44	-
HESSJ1616-508	0.15	16:16:24	-50:54:00	2.11	2.56	-

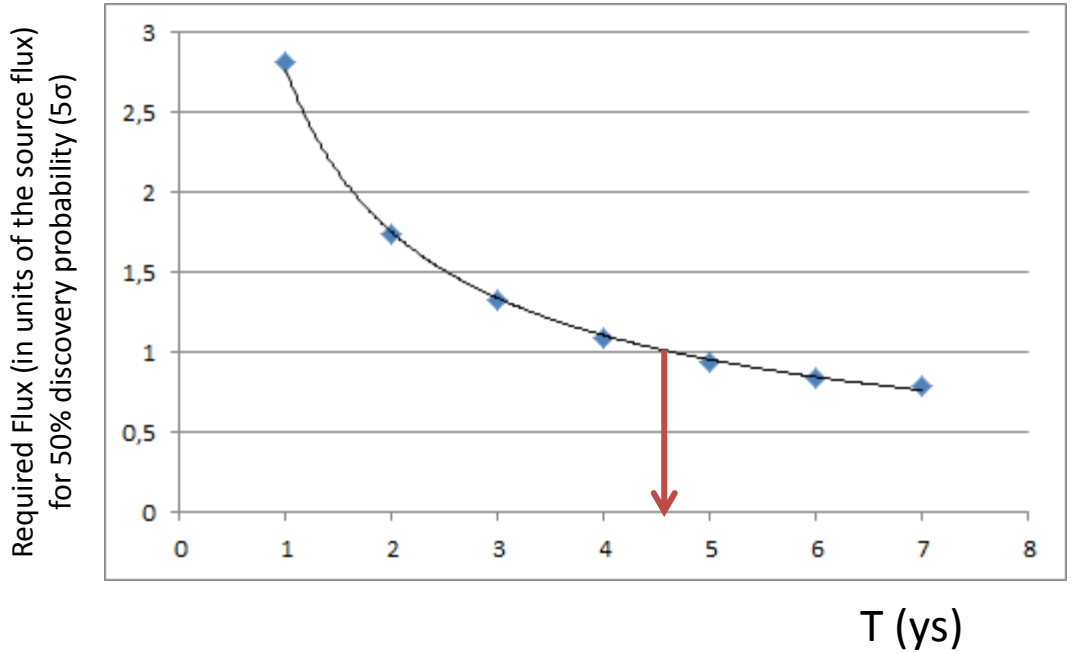


Disk center: RA=16:15:21.6 δ=-51:21:36 Radius=1.2 degrees

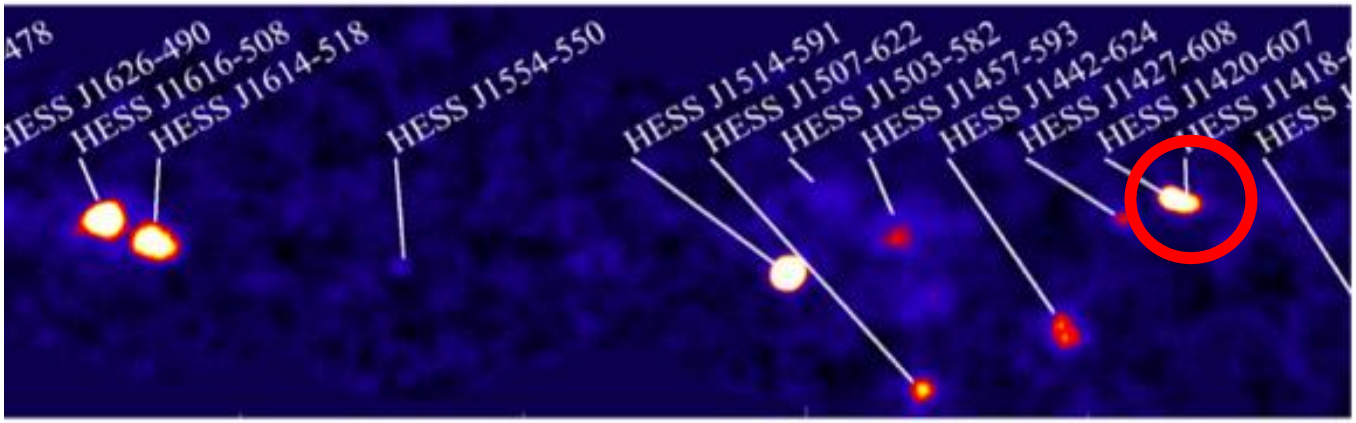
Expected number of background events (5 ys) = 45.14

Source	Δ(RA) (with respect to disk center)	Δ(δ) (with respect to disk center)	Expected number of events (5 ys)
HESSJ1614-518	-0.26	-0.46	7.12
HESSJ1616-508	0.26	0.46	7.73



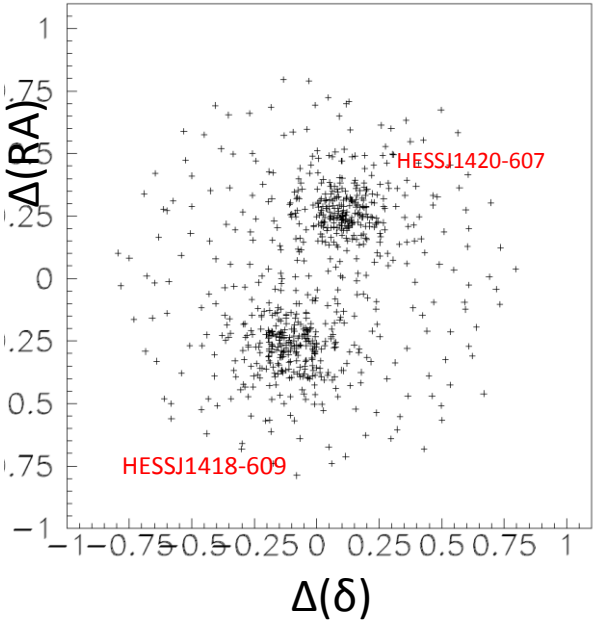


HESSJ1420-607 HESSJ1418-609



320

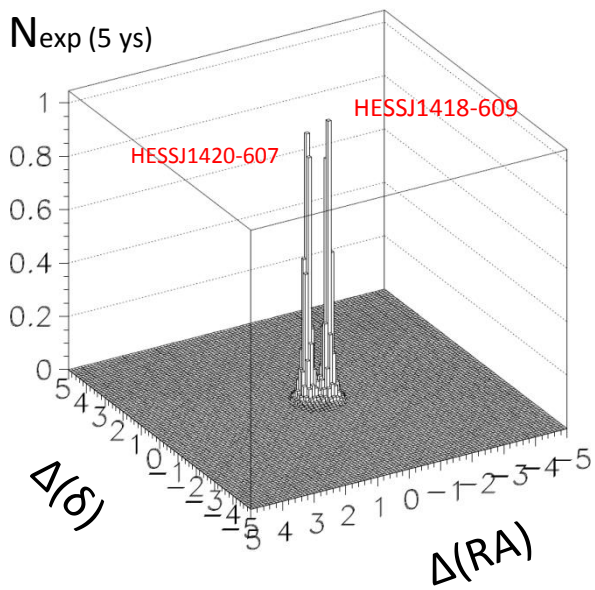
Source	R(deg)	RA	Declination	k_v	Γ_v	e_v
HESSJ1420-607	0.05	14:20:12	-60:45:32	1.16	2.25	-
HESSJ1418-609	0.05	14:18:2.4	-60:58:12	0.94	2.19	-

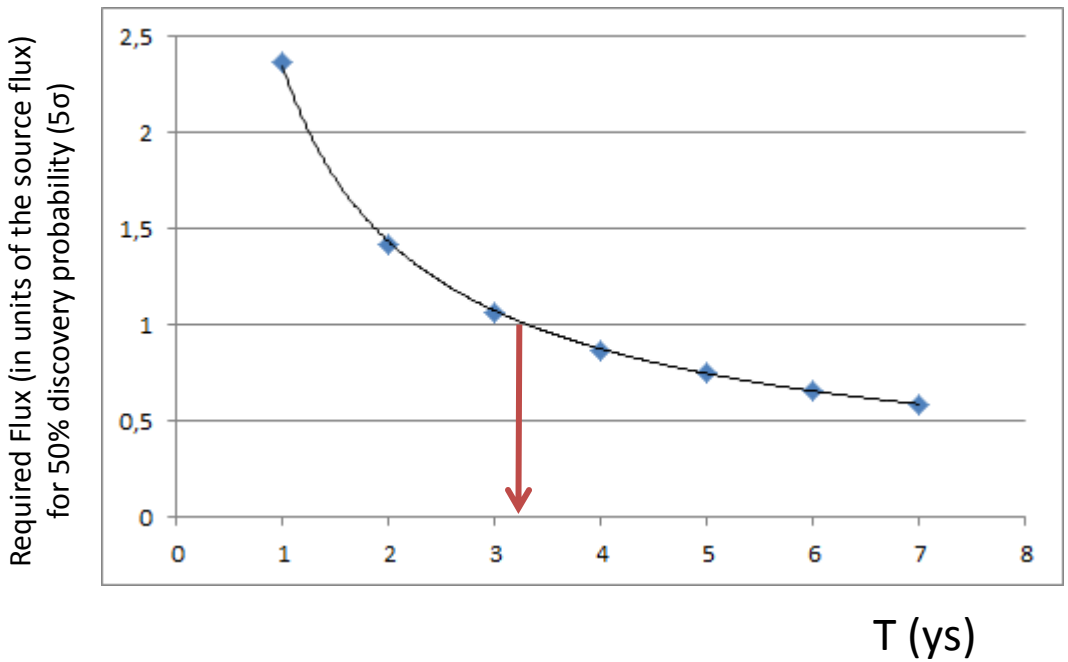


Disk center: RA=14:19:7.2 δ=-60:51:52 Radius=0.72 degrees

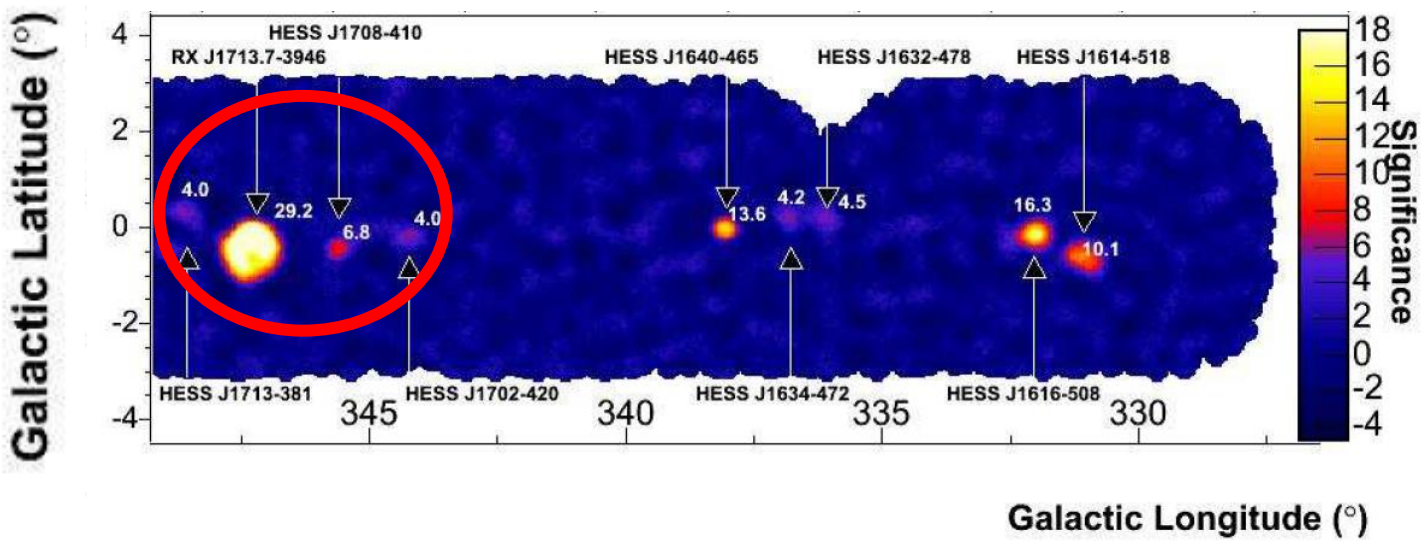
Expected number of background events (5 ys) = 17.57

Source	Δ(RA) (with respect to disk center)	Δ(δ) (with respect to disk center)	Expected number of events (5 ys)
HESSJ1420-607	0.27	0.106	9.17
HESSJ1418-609	-0.27	-0.106	8.96

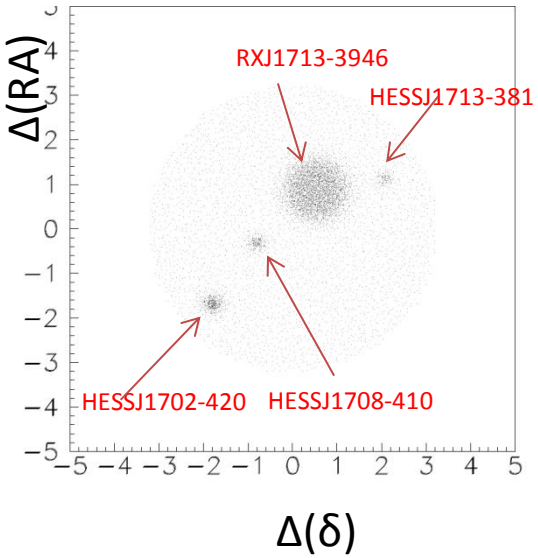




RXJ1713-3946 HESSJ1713-381 HESSJ1708-410 HESSJ1702-420



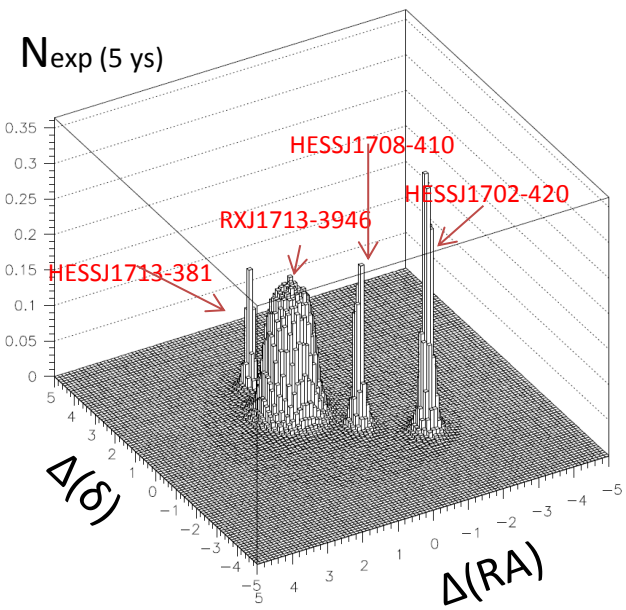
Source	R(deg)	RA	Declination	k_ν	Γ_ν	e_ν
RXJ1713-3946	0.65	17:13:00	-39:45:00	16.84	1.72	2.1
HESSJ1713-381	0.05	17:13:57.6	-38:12:00	0.23	2.28	-
HESSJ1708-410	0.05	17:8:14.4	-41:4:48	0.44	2.33	-
HESSJ1702-420	0.1	17:2:45.6	-42.4.12	0.82	2.32	-

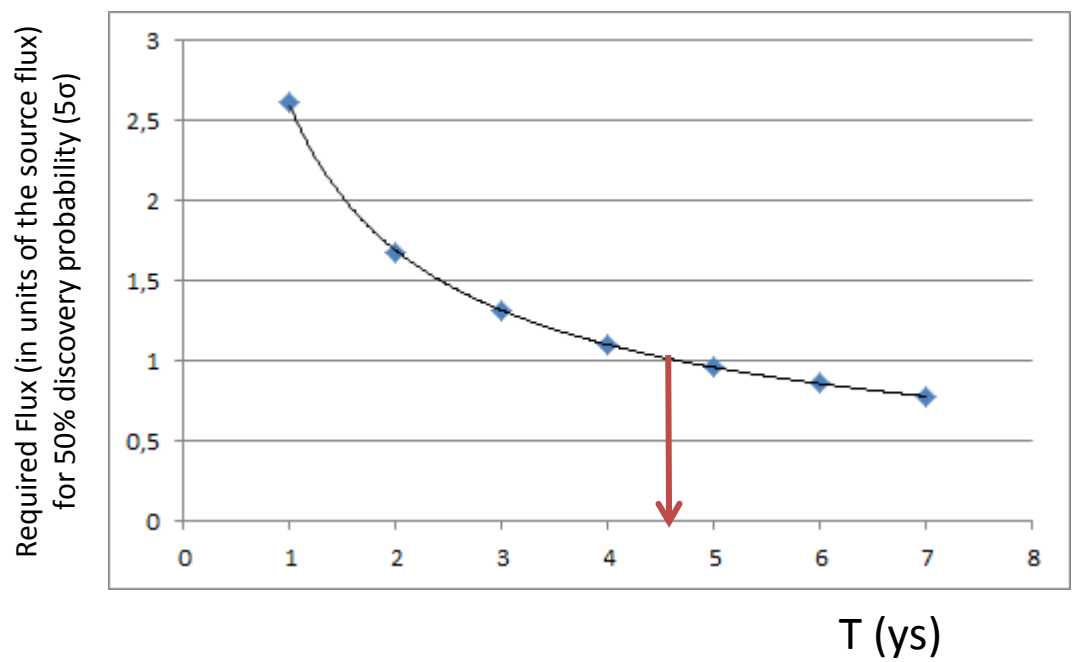


Disk center: RA=17:09:29.4 δ=-40:16:30 Radius=3.16 degrees

Expected number of background events (5 ys) = 217.9

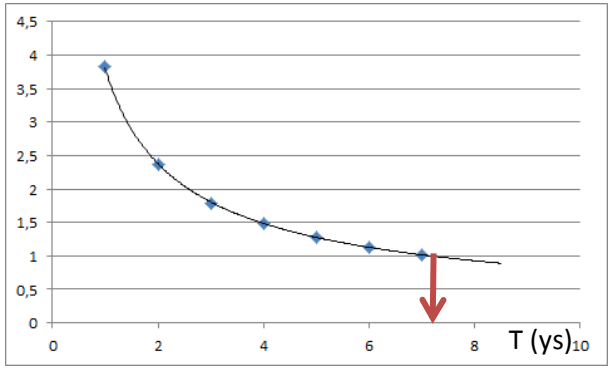
Source	Δ(RA) (with respect to disk center)	Δ(δ) (with respect to disk center)	Expected number of events (5 ys)
RXJ1713-3946	0.525	0.877	26.88
HESSJ1713-381	2.075	1.12	1.16
HESSJ1708-410	-0.805	-0.31	1.95
HESSJ1702-420	-1.795	-1.68	3.69





LS5039INFC LS5039SUPC HESSJ1825-137

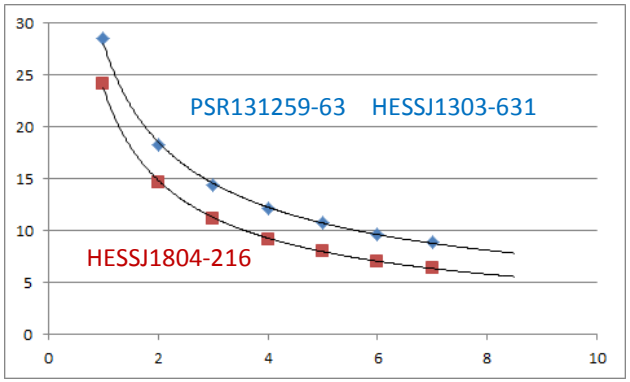
Source	R (deg)	RA	Declination	kv	Γv	ev	Nexp (5ys)
LS5039INFC	0.05	18:26:13.8	-14:50:01	2.5	1.61	1.01	1.19
LS5039SUPC	0.05	18:26:13.8	-14.50.01	0.26	2.51	-	0.41
HESSJ1825-137	0.25	18:26:2.4	-13:45:36	10.73	2.08	4.24	8.75



PSR131259-63 HESSJ1303-631

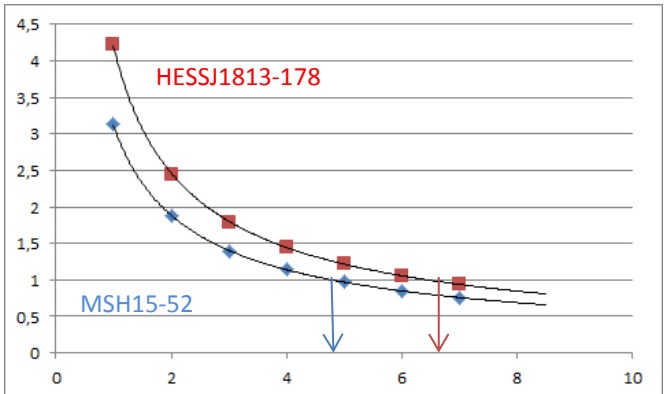
Source	R (deg)	RA	Declination	kv	Γv	ev	Nexp (5ys)
PSR131259-63	0.05	13:2:49.2	-63:50:2	0.34	2.72	-	0.59
HESSJ1303-631	0.15	13:3:0.4	-63.11.55	11.99	2.51	-	1.18

Source	R (deg)	RA	Declination	kv	Γv	ev	Nexp (5ys)
HESSJ1804-216	0.2	18:4:31	-21:42:00	1.49	2.73	-	1.42



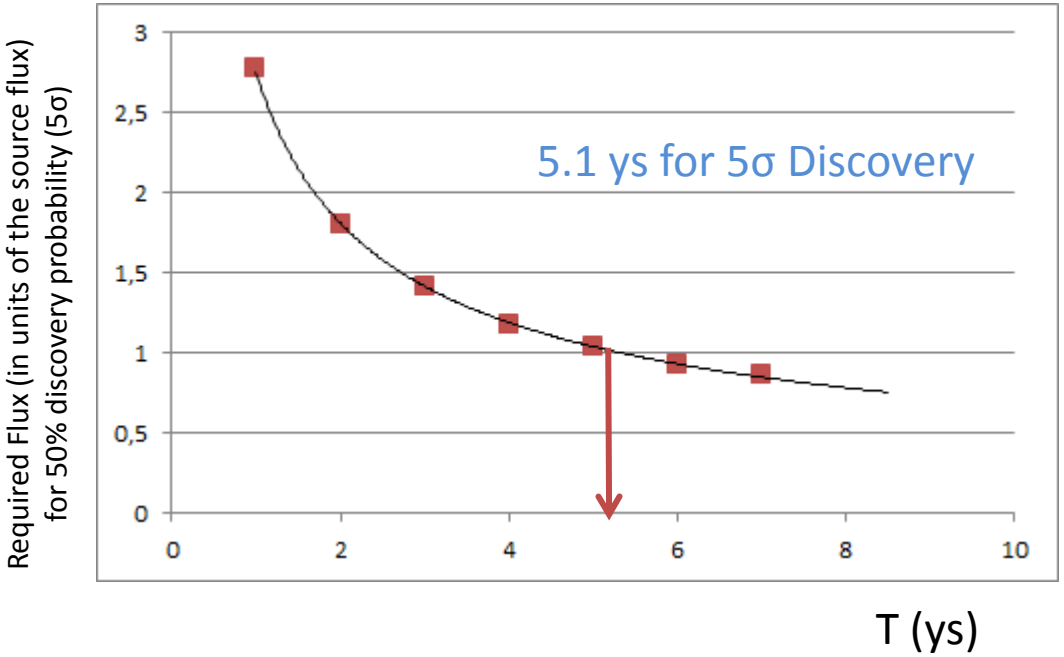
Source	R (deg)	RA	Declination	kv	Γv	ev	Nexp (5ys)
HESSJ1813-178	0.05	18:13:36	-17:50:24	0.96	2.09	-	5.08

Source	R (deg)	RA	Declination	kv	Γv	ev	Nexp (5ys)
MSH15-52	0.1	15:14:7	-59:9:27	1.89	2.27	-	10.41



Combined Results of SNRs

Source	HESSJ1640-465	HESSJ0852-463	HESSJ1745-290	HESSJ1834-087	HESSJ1303-631	RXJ1713-3946 + HESSJ1713-381
R (deg)	0.05	1.0	0.05	0.1	0.15	0.65, 0.05
Expected Signal (5ys)	2.55	9.97	2.55	1.41	1.22	19.36
Expected Background (5ys)	18.28	52.96	13.34	12.09	22.79	78.76



Combined Results of SNRs + Category 3

Source	RXJ1713-3946 + HESSJ1713-381 + HESSJ1708-410	HESSJ0852-463	HESSJ1640-465 + HESSJ1634-472	HESSJ1745-290 + HESSJ1745-303	HESSJ1834-087 + HESSJ1837-069	HESSJ1303-631	HESSJ1614-518
R (deg)	0.65, 0.05, 0.05	1.0	0.05, 0.1	0.05, 0.2	0.1, 0.1	0.15	0.25
Expected Signal (5ys)	21.13	9.97	4.63	19.88	6.2	1.25	7.22
Expected Background (5ys)	106.2	52.96	46.76	32.65	39.14	26.35	27.39