Star formation and high energy neutrinos at IceCube: a correlation?

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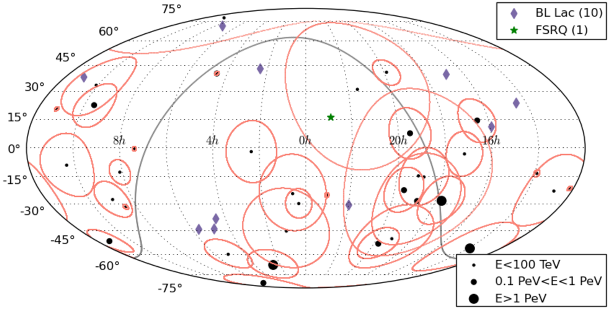
Kimberly Emig, CL and Rogier Windhorst, JCAP 1512 (2015) 029, arxiv:1507.05711 (3 years IceCube data)

Greg Vance, Kimberly Emig, CL and Rogier Windhorst, work in progress ($\geq$ 4 years IceCube data)

Spatial coincidence with astrophysical sources

Causality or randomness?



Equatorial coodinates J2000, galactic plane shown.

References:

IceCube Coll., ApJ. 796, 2014 , arXiv:1408.0634;

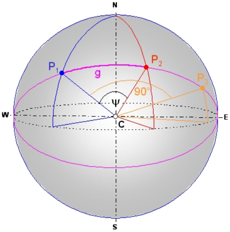
UHECR: K. Fang, T. Fujii, T. Linden, and A. V. Olinto, ApJ 794 2014 ; R. Moharana and S. Razzaque, arXiv:1501.05158 (2015); IceCube, Auger and TA coll., JCAP 1601 (2016) 01, 037, arXiv:1511.09408;

Blazars: P. Padovani and E. Resconi, MNRAS 443 2014 ; S. Sahu and L. S. Miranda, arXiv:1408.3664 ; F. Krauss, et al., Astron.Astrophys. 566 (2014) ; Fermi-LAT Coll., arXiv:1502.02147 ; Petropoulou, et al., MNRAS 448, 2015 ; ANTARES Coll., Astron. Astrophys. 576 2015 ; A. M. Brown, J. Adams, and P. M. Chadwick, arXiv:1505.00935 (2015) ; IceCube Collaboration, arXiv:1502.03104 (2015); P. Padovani et al., arXiv:1601.06550.

Star forming galaxies: L. A. Anchordoqui, et al., Phys. Rev. D 89, 2014 ; K. Emig, CL and R. Windhorst, JCAP 1512 (2015) 029

GRBs: IceCube coll., Astrophys.J. 805 (2015), arXiv:1412.651

Statistical analysis: the method



- *Normalized angular distance* between neutrino i (error σ_i) and candidate source j (error $\sigma_j \simeq 0$): $R_{ij} = \psi_{ij}/\sigma_i$
- distance of each neutrino to *nearest* candidate: $r_i = \mathrm{Min}_{\{j\}} R_{ij}$
- *coincidence* : when a neutrino overlaps with a source within the error: $r \leq 1$
- *Null* case : the candidates follow the uniform distribution

- *"Null" distribution* : the distribution of r for candidates uniformly distributed in the sky.
  - Monte Carlo: randomization of candidate positions (10^5 iterations)
  - analytics: for N νs and M candidates
    $d\mathcal{P}(r)/dr = \sum_{i=1}^{N} \sigma_i (M/2^M) \sin(r\sigma_i) \left[1 + \cos(r\sigma_i)\right]^{M-1}$

- Comparing r-distribution of data with null:
  - *p-value* : probability that the null case produces a number of coincidences ($r \leq 1$) equal or larger than the one observed in the data.

H. R. de Ruiter, A. G. Willis, and H. C. Arp, Astron. Astrophys. Suppl. Ser. 28 (1977) 211293. ; R. A. Windhorst, R. G. Kron, and D. C. Koo, Astron. Astrophys. Suppl. Ser. 58 (1984) 3987 ; W. Sutherland and W. Saunders, MNRAS 259 (1992) 413420 ; A. Virmani, et al., Astropart. Phys. 17 (2002) 489495 ; R. Moharana and S. Razzaque, arXiv:1501.05158 (2015)

Catalogs and selection criteria

- Fermi-LAT catalog (3FGL, $E \lesssim 500$ GeV) + TeVCat

  Fermi-LAT Coll., arXiv:1501.02003 ; tevcat.uchicago.edu

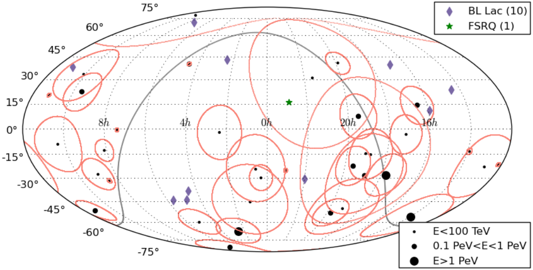
  - $E > 100$ TeV observations too sparse, strong absorption
- Infrared Astronomical Satellite (IRAS)
  - $\sim 100\mu m$ emission indicator of star formation

  Becker, et al., arXiv:0901.1775 ; Sanders, et al., Astron. J. 126, 2003 16071664

- Create a set of candidates of suitable size:
  - same class/morphology
  - brightest: $L_\gamma > L_{min}$

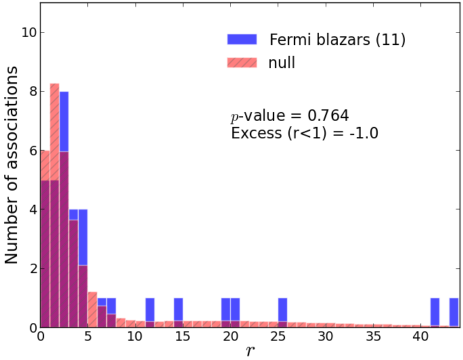
Results: Blazars

Active Galactic Nuclei (AGN), with jet pointing to Earth



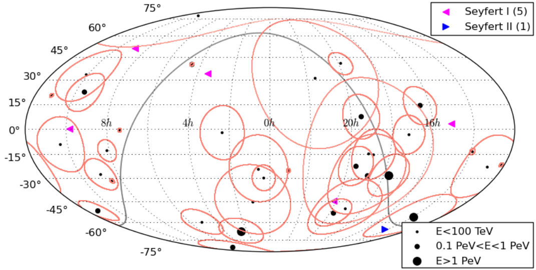
Blazar	3FGL	$F_{10-100\mathrm{GeV}} > 10^{-9}$ ph. cm^{-2} s^{-1}	11

... consistent with null



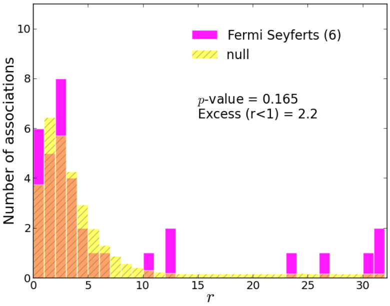
Seyfert galaxies

Weaker AGN emission; active star formation near nucleus



Seyfert	3FGL	Seyfert I & II	6

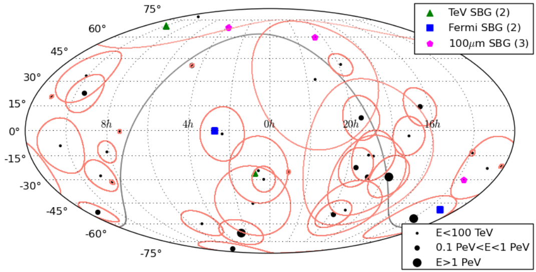
non-significant excess (first bin, $r < 1$), consistent with null



For other results consistent with null, see :
Kimberly Emig, CL and Rogier Windhorst, JCAP 1512 (2015) 029

Starburst galaxies (SBG)

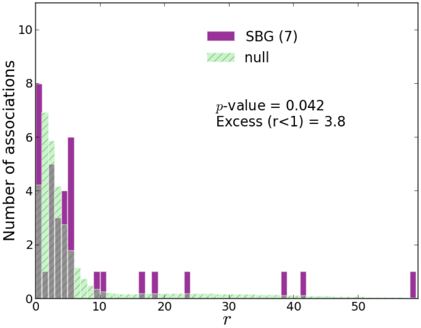
High supernova rate, CR confined by $\vec{B}$ fields



SBG	TeVCat, 3FGL IRAS 100 μm	L(100μm) $\geq$ 250 Jy	7

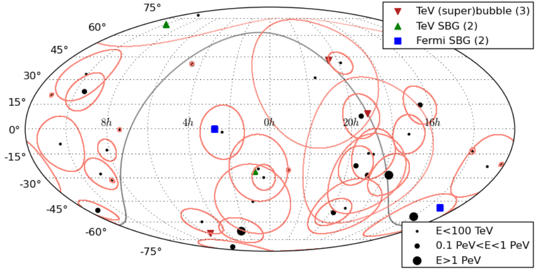
Name	RA	dec	D (Mpc)
NGC 253	00 27 34	$-$25 17 22	3.1
NGC 1068	02 42 43	$-$00 01 33	13.7
IC 342	03 46 49	+68 05 46	4.6
M 82	09 55 53	+69 40 46	3.6
NGC 4945	13 05 29	$-$49 26 03	3.9
M 83	13 37 01	$-$29 51 57	3.6
NGC 6946	20 34 52	+60 09 13	5.3

some excess of coincidences....



SBG + superbubbles+ star forming regions

$\sim 0.1 - 1$ kpc regions of extremely intense star formation activity

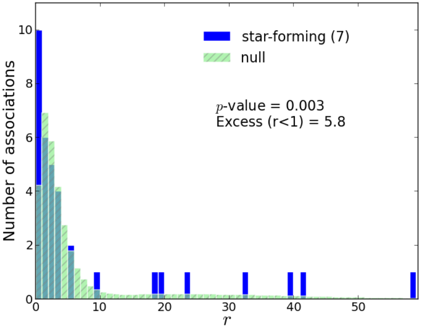


gamma-ray-observed only

Name	RA	dec	D (Mpc)
NGC 253	00 27 34	−25 17 22	3.1
NGC 1068	02 42 43	−00 01 33	13.7
30 Dor C	05 35 55	−69 11 10	0.05
M 82	09 55 53	+69 40 46	3.6
NGC 4945	13 05 29	−49 26 03	3.9
W 49 A	19 10 27	+09 11 25	0.011
Cygnus Cocoon	20 28 41	+41 10 12	0.002

Indication of correlation?

interesting excess!
0.3% probability of random occurrence ($p \lesssim 0.024$ *post-trial*)



Post-trial p-value

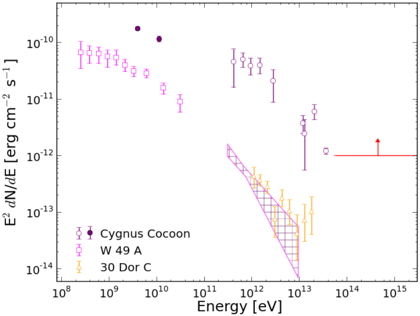
minimum pre-trial: $p_{min} = 0.003$

- J=4 independent trials:
  $P = 1 - (1 - p_{min})^J \simeq J p_{min} = 0.012$
- K=8 total trials (not independent):
  $J p_{min} \lesssim P \lesssim K p_{min} \simeq 0.024$.

G. Choudalakis, arXiv:1101.0390

Sufficient flux to produce one event ?

Compare gamma ray spectra with minimum neutrino flux needed (assume $\phi_\nu \sim \phi_\gamma$):



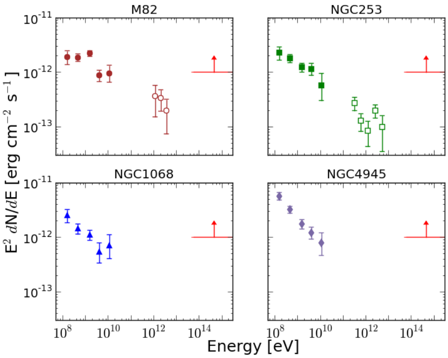
- mixed results; Cygnus cocoon a possibility

Beacom and Kistler, PRD 75 (2007) 083001 ; Gonzalez-Garcia, Halzen, and Mohapatra, Astropart. Phys. 31 (2009) 437444 ; Fox, Kashiyama, and Meszaros, ApJ. 774 (2013) 74.

Gamma ray spectra: SBG

- Comparison with required ν flux : M82, NGC253 disfavored
  - horizontal line: ~ 0.1 events for IceCube exposure

P. Padovani and E. Resconi, MNRAS 443 2014

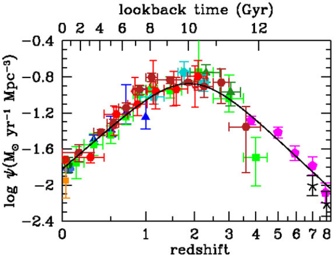


filled: Fermi-LAT ; open: HESS, VERITAS, ARGO-YBJ. *Note: intergalactic absorption subtracted!*

Local vs. cosmological

- $\frac{N_{local}}{N_{tot}} \sim \frac{3}{35-17} \sim 0.15$
- only $\sim 1-2\%$ predicted from $D < 15$ Mpc !
  - enhancement of local star formation?

    Ando, Beacom, and Yuksel, PRL95 (2005) 171101
  - selection effect?

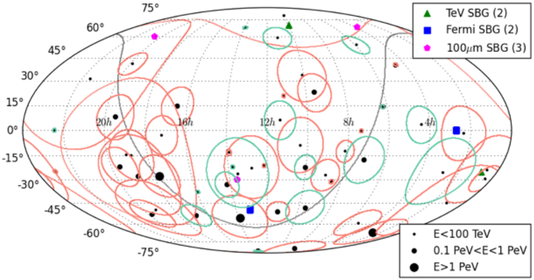


from: Madau and Dickinson,

Ann.Rev.Astron.Astrophys. 52 (2014) 415-486

Backup: update with 54 IceCube data

Starburst galaxies



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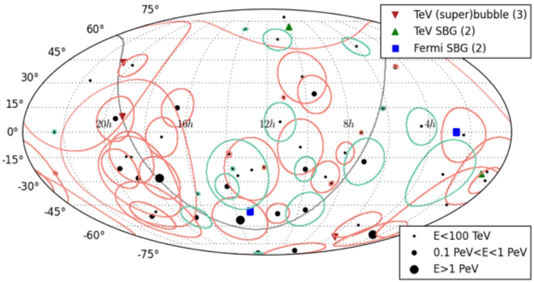
SBG + superbubbles+ star forming regions, gamma-ray-observed only



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W 49 A	19 10 27	+09 11 25	0.011
Cygnus Cocoon	20 28 41	+41 10 12	0.002

Backup: full summary table

Candidate	Catalog(s)	Selection Criteria	Cand. number	count ($r \leq 1$)	Excess	p-value ($r \leq 1$)
Blazar	3FGL	$F_{10-100\mathrm{GeV}} > 10^{-9}$ ph. cm^{-2} s^{-1}	11	5 [1]	-1.0 [-1.2]	0.764 [0.938]
Seyfert	3FGL	Seyfert I & II	6	6 [2]	2.2 [0.7]	0.165 [0.368]
Starburst	TeVCat, 3FGL	starburst	4	6 [4]	3.3 [3.1]	0.046 [0.001]
Starburst	TeVCat, 3FGL IRAS 100 μm	L(100μm) $\geq$ 250 Jy	7	8 [5]	3.8 [3.5]	0.042 [0.003]
Starburst	TeVCat, 3FGL IRAS 100 μm	same as above, randomize with $\lvert b \rvert > 10^\circ$	7	8 [5]	3.9 [3.6]	0.034 [0.002]
Star form.	TeVCat, 3FGL	starburst, superbubble, star form. region	7	10 [6]	5.8 [4.5]	0.003 [$<$0.001]

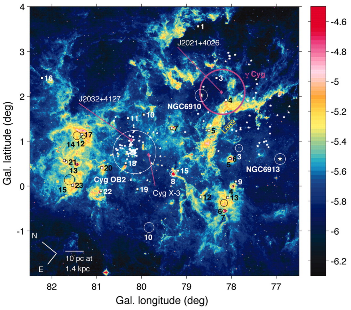
Backup: full candidates list

Name	RA (J2000)	dec (J2000)	Class	D_L [Mpc]	ν ID
NGC 253	00 27 34	−25 17 22	sbg	3.1	7, 10, 21
NGC 1068	02 42 43	−00 01 33	sbg	13.7	1
[IC 342]	03 46 49	+68 05 46	sbg	4.6	31
30 Dor C	05 35 55	−69 11 10	superbbl	0.05	19
M 82	09 55 53	+69 40 46	sbg	3.6	31
NGC 4945	13 05 29	−49 26 03	sbg	3.9	35
[M 83]	13 37 01	−29 51 57	sbg	3.6	16
W 49 A	19 10 27	+09 11 25	sfr	0.011	25, 33, 34
Cygnus C.	20 28 41	+41 10 12	superbbl	0.002	29, 34
[NGC 6946]	20 34 52	+60 09 13	sbg	5.3	34

Superbubbles and star forming regions

Very intense star formation activity

- Stellar winds and SN
- 85% of core-collapse SN
- 100s per starburst galaxy
    - some *in our galaxy :* Cygnus Cocoon, D=2 kpc



8-μm intensity map of the Cygnus X region ($W\ m^{-2}\ sr^{-1}$, in log scale). From Ackermann et al., Science 334, 2011, 11037