

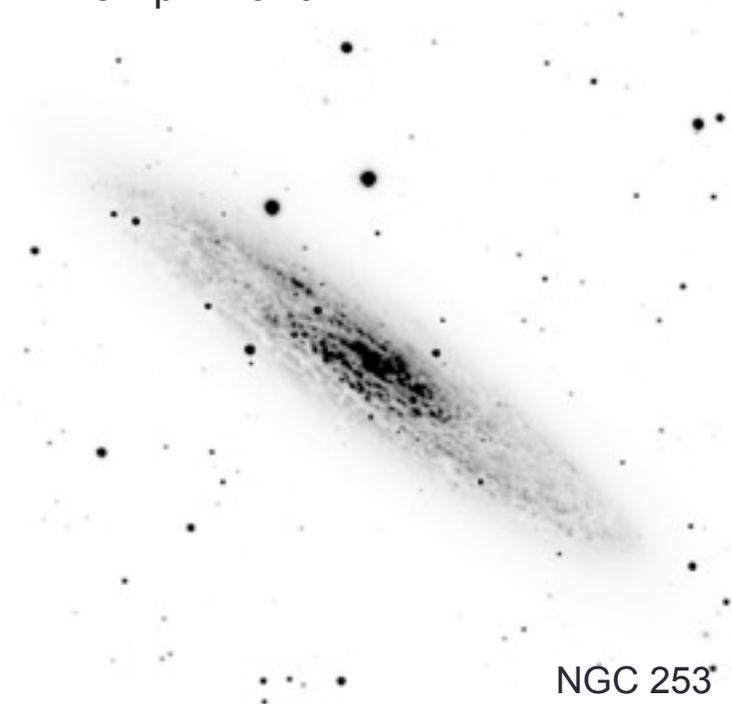
Do high-energy astrophysical neutrinos trace star formation?

Kimberly Emig

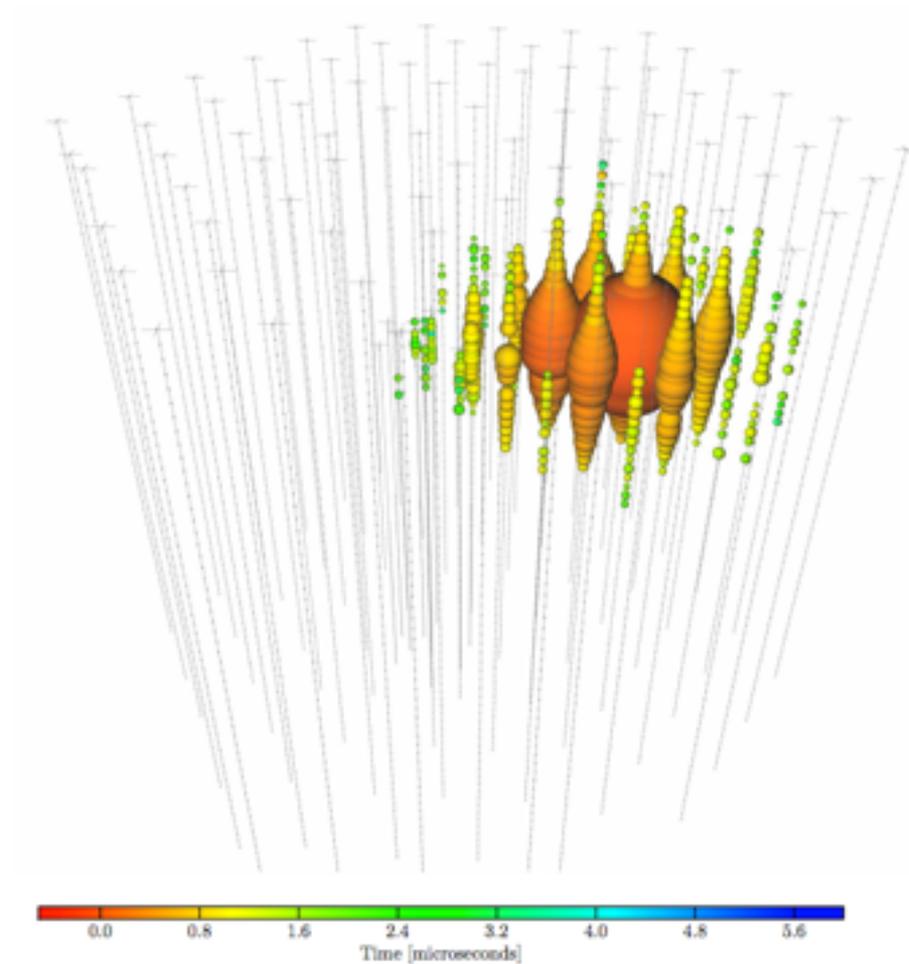
Cecilia Lunardini, Rogier Windhorst

Unveiling the Anisotropic Universe (2)

13 April 2016



NGC 253^{*}

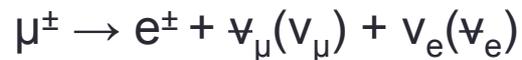
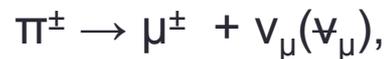
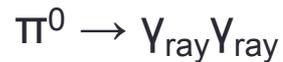


Outline

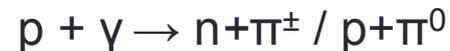
- Introduction
- Method: spatial associations
- Results of possible counterparts
 - Blazars
 - Seyferts
 - Star formation

High-energy neutrino production

PP: Inelastic collision between CRp and thermal protons in ISM



P γ : interaction of a CRp with a photon



Neutrino kinetic energy

~5% CRp energy

~50% γ_{ray} energy

(IceCube: 30—3000 TeV)

Astrophysical significance

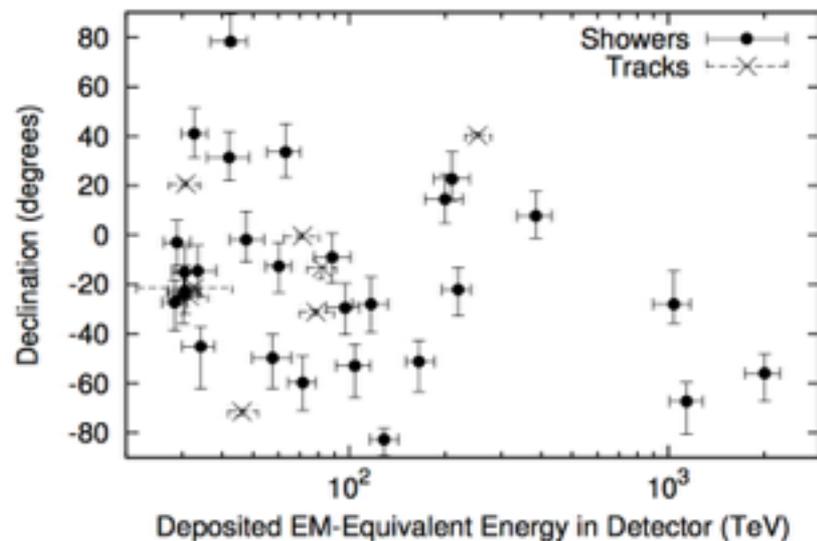
- Cosmic rays
- Gamma rays
- **Neutrinos**
 - Hadronic particle accelerators
CRe vs CRp
 - reliable directional information
CRs absorbed or B deflected
 - Identify obscured high energy activity
CR, γ_{ray} absorption

IceCube: 3 year results

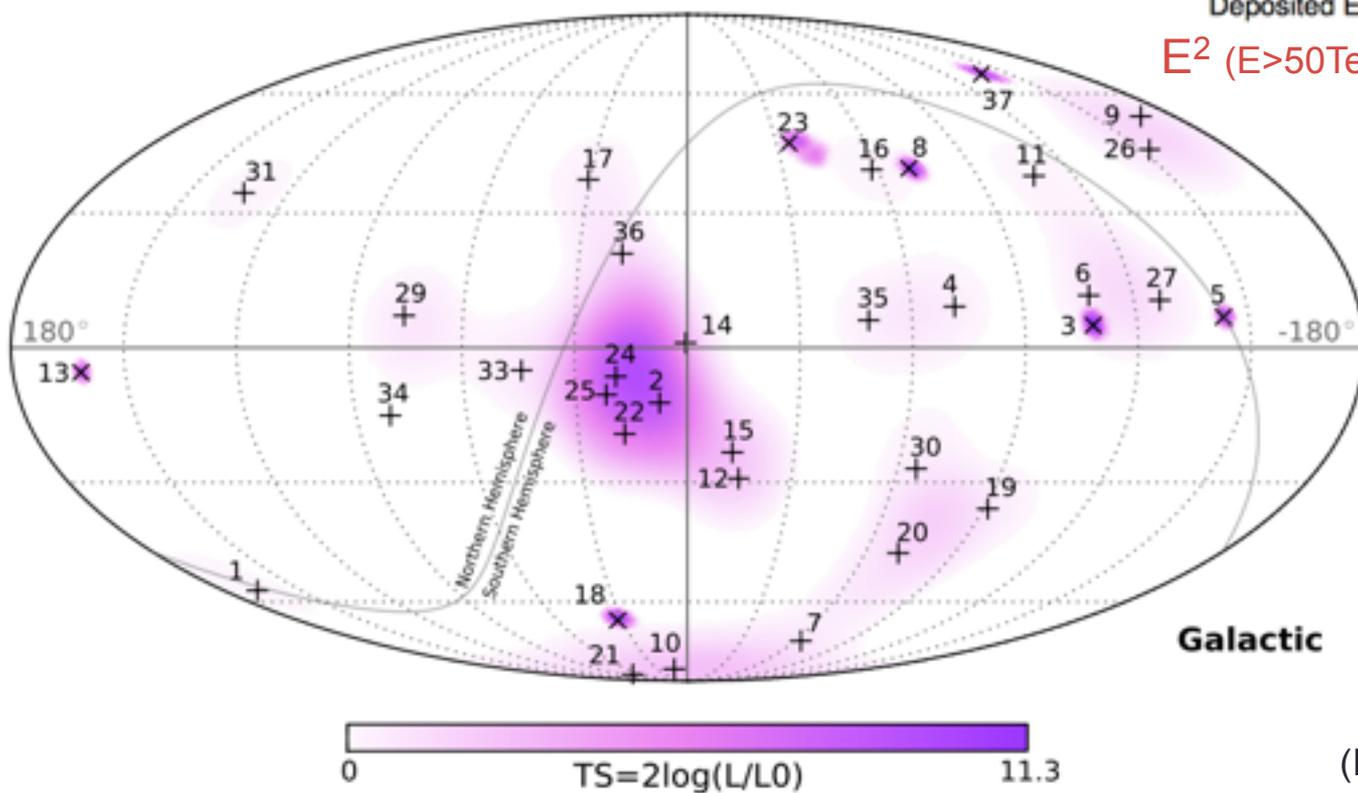
$E \sim 30 \text{ TeV} - 3 \text{ PeV}$

9 track (x) [$8.4 \pm 4.2 \text{ CR muons}$]

28 shower (+) [$6.6^{+5.9}_{-1.6} \text{ atmosphere}$]



$E^2 (E > 50 \text{ TeV}) \sim 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$



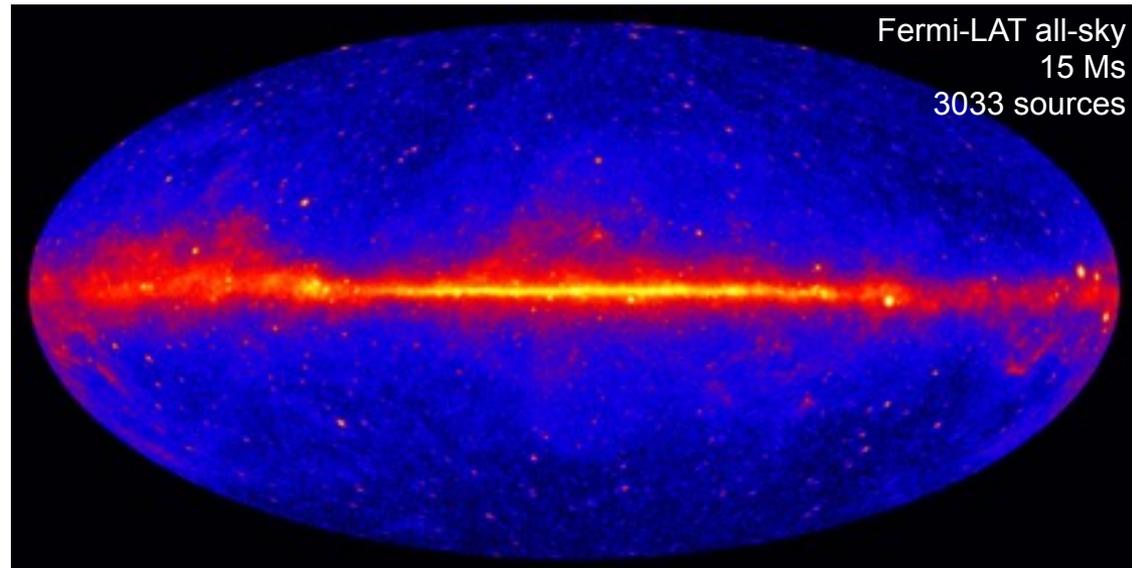
(IceCube Collaboration 2014)

Catalogs of possible counterparts

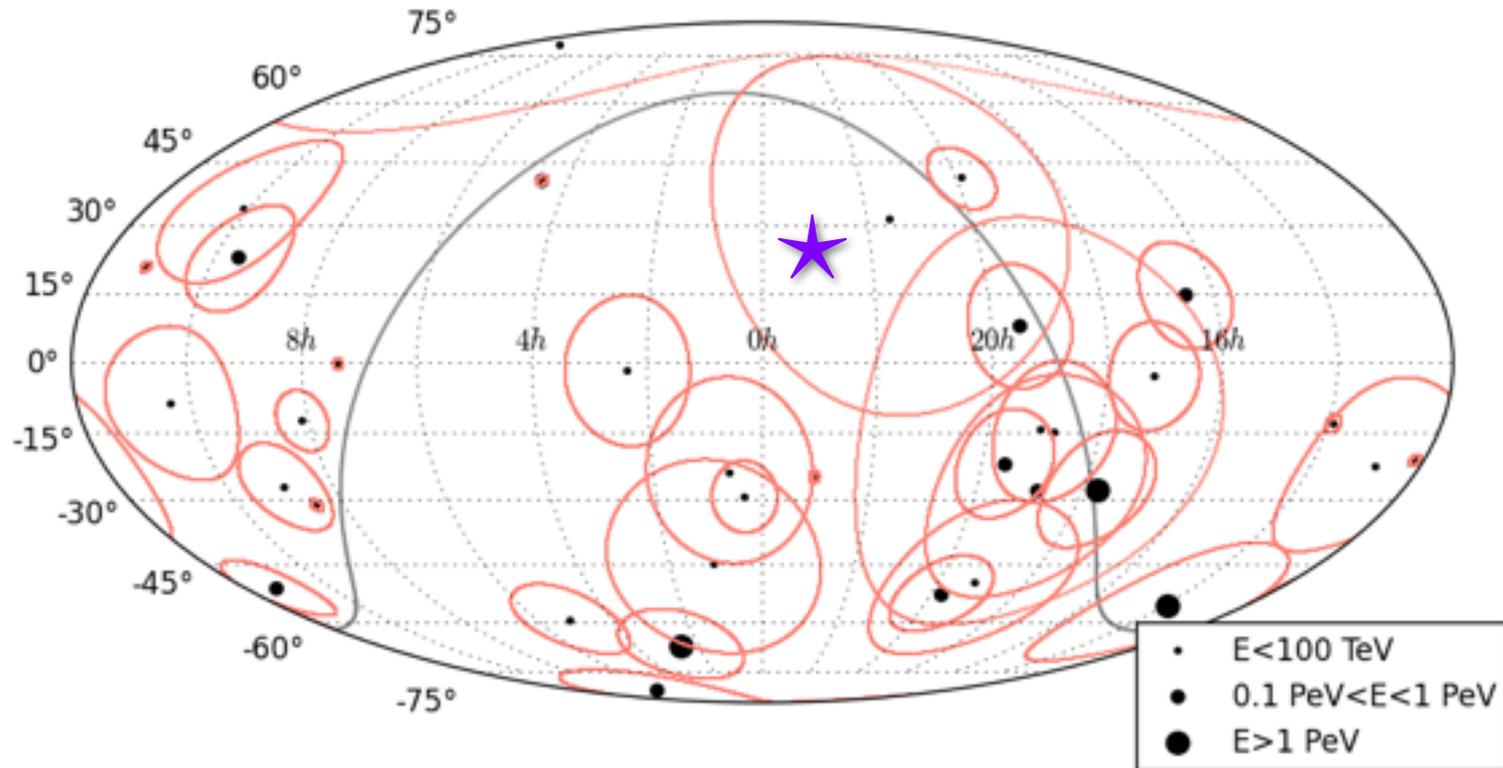
Ideal source associations $E > 50$ TeV

$$E_\nu \sim \frac{1}{2} E_\gamma$$

- **EGB absorption** of >100 GeV photons
 - **CMB interaction** with $>$ PeV photons
 - 10s TeV detectors, **non-uniform sky coverage**
-
- **Fermi 3FGL** (4 year)
Acerro+ 2015
 - **TeVCat** tevcad.uchicago.edu



Method



$P_1 = (\alpha_1, \delta_1)$ Neutrino event

$P_2 = (\alpha_2, \delta_2)$ Possible counterpart

$$s = \cos^{-1} (\sin (\delta_1) \sin (\delta_2) + \cos (\delta_1) \cos (\delta_2) \cos (\Delta\alpha))$$

Weighted distance: $r = \frac{s}{\sigma_\nu}$

If $r < 1$ source lies within median angular error

deRutier+ 1977
Windhorst+ 1984
Sutherland+ 1992
Virmani+ 2002
Moharana+ 2015
Padovani+ 2016

Blazars (AGN)

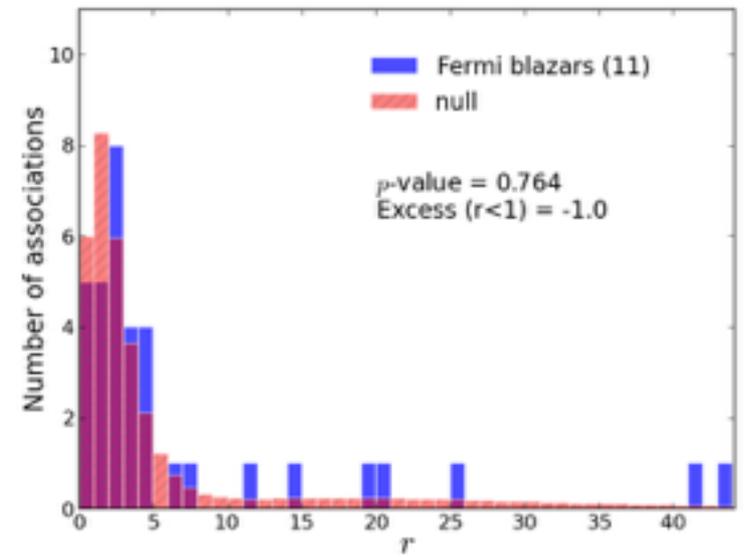
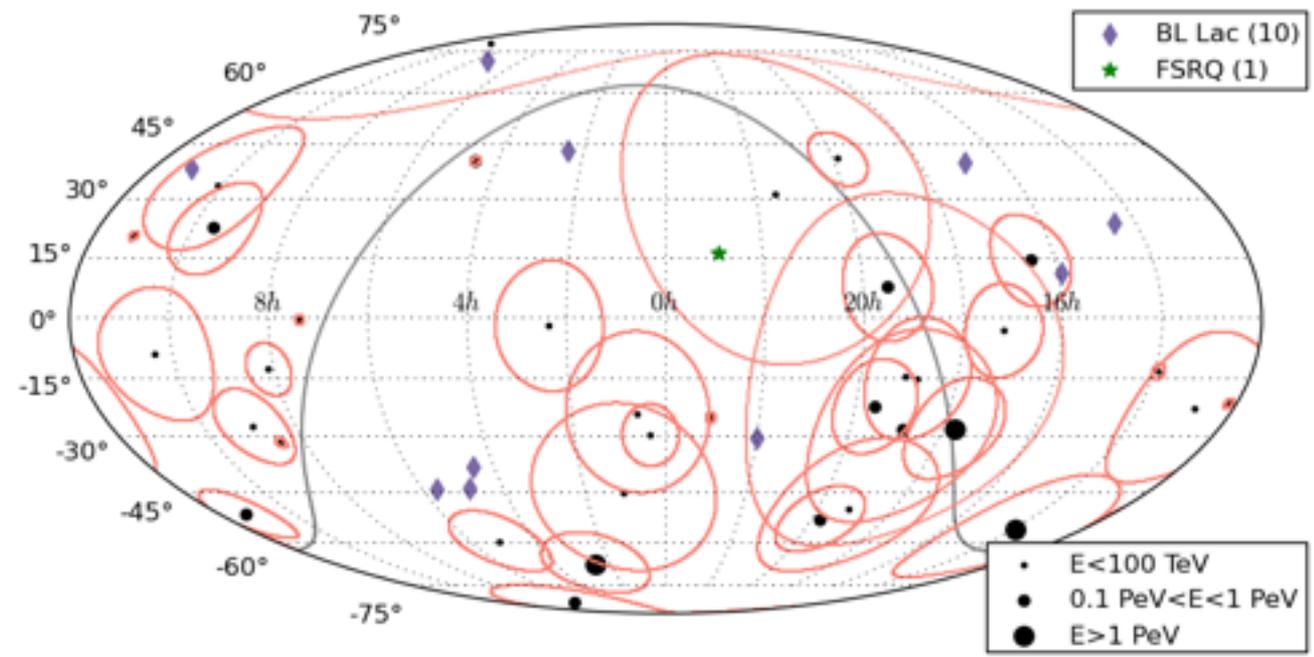
Selection:

Uniform 3FGL sample,
search all AGN types:
 $L_{10-100\text{GeV}} > 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1}$

Result:

P-value = 0.764
Excess ($r < 1$) = -1

Consistent with null hypothesis
and previous claims
Gluskamp+ 2015, Brown+ 2015



Seyfert Galaxies

- Local
- Less luminous quasars
- Emission from AGN & star formation at core
- **Neutrino emission:**
 - AGN impacts surrounding dusty region?
 - star formation?
 - high H column density

Circinus Galaxy



Correlations with IceCube neutrinos

- Cross-matching positions with UHECRs and Swift-BAT 70 month catalog revealed Seyferts Moharana+ 2015

Seyferts

Selection:

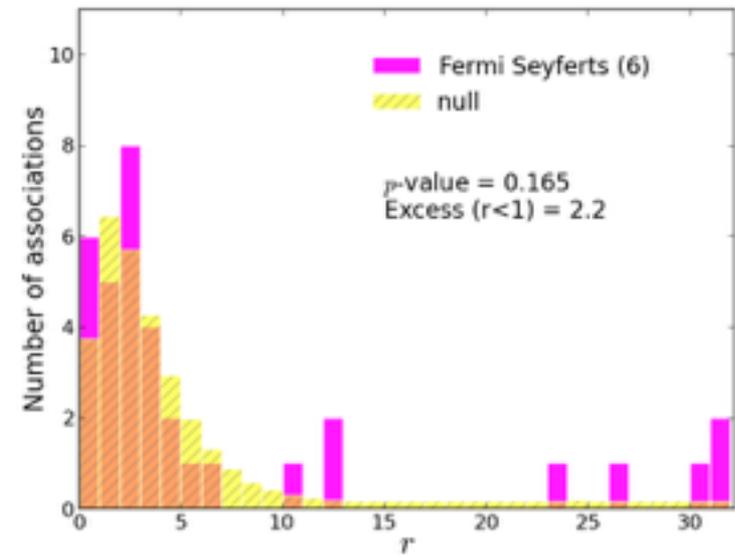
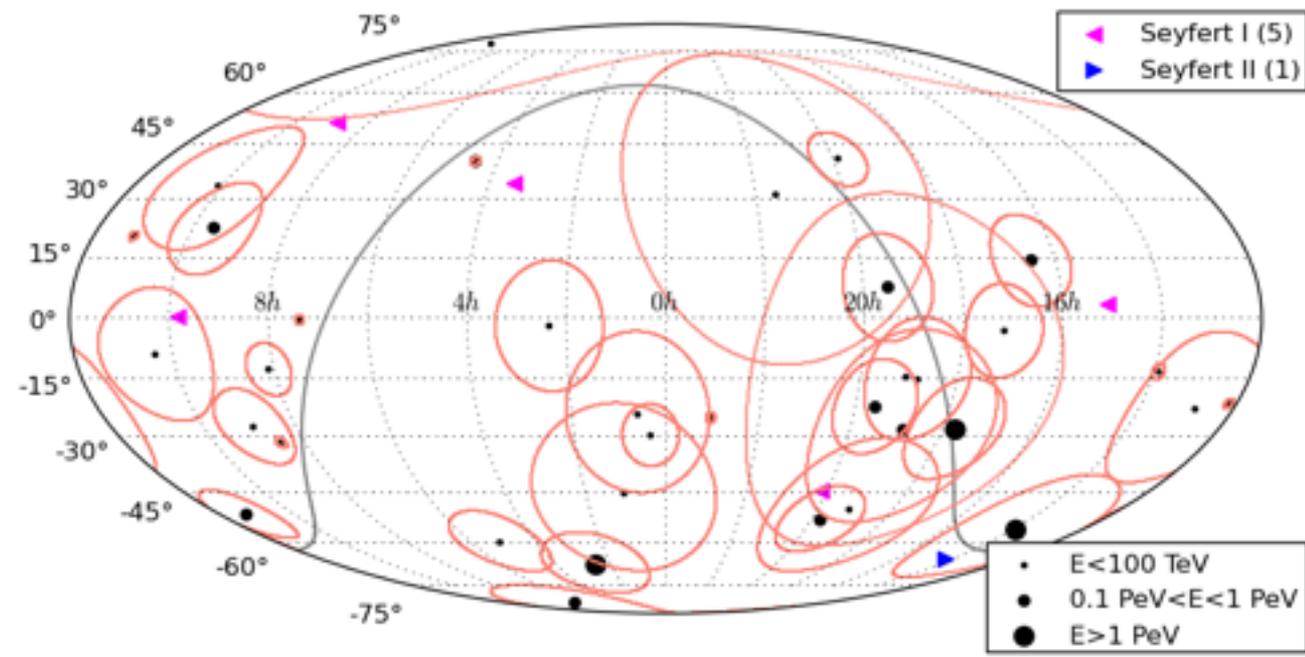
Fermi 3FGL Seyferts

Result:

P-value = 0.165

Excess ($r < 1$) = 2.2

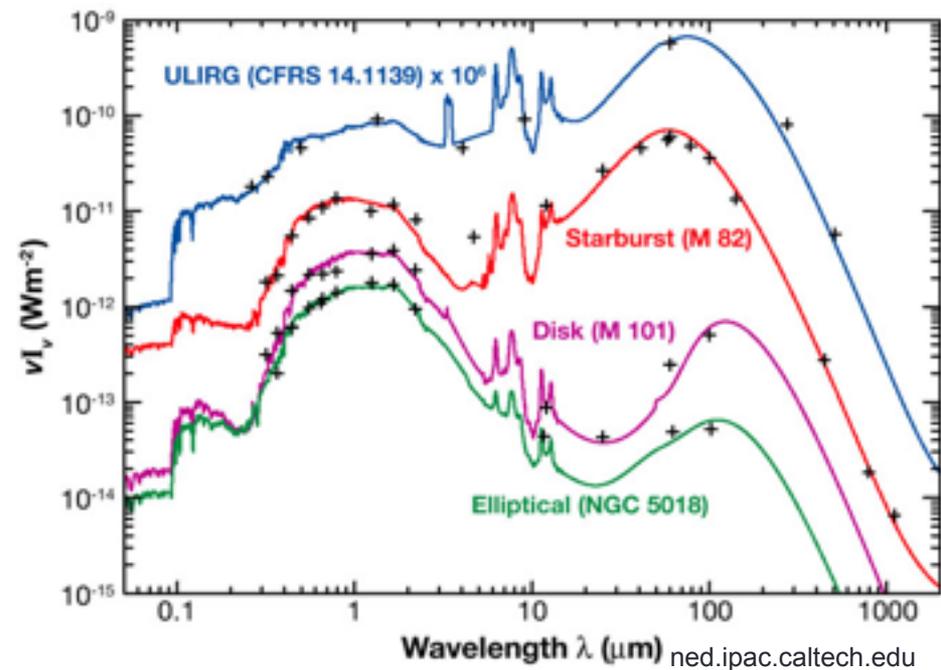
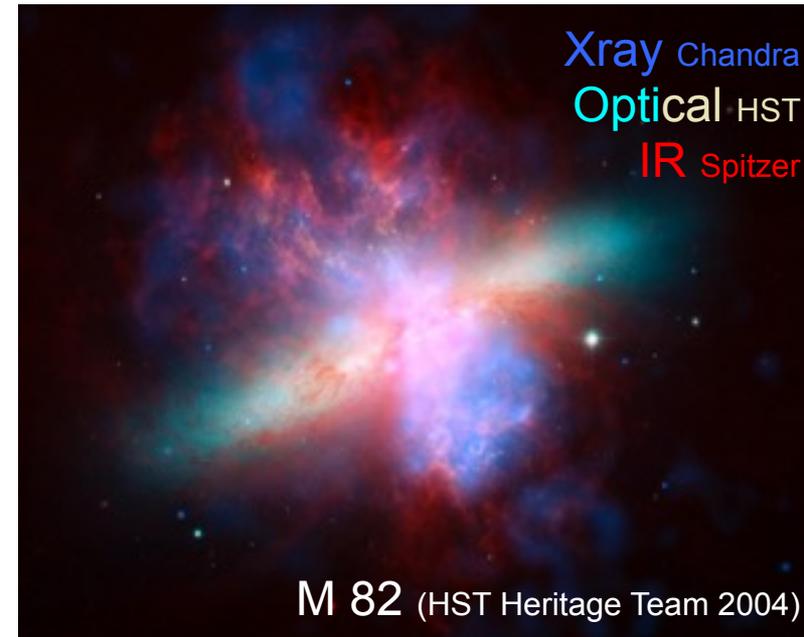
Not statistically significant, but may warrant further investigations



Starburst Galaxies

- Emission of galaxy dominated by star forming activity
- $\text{SFR} > 1 M_{\text{sun}} \text{ yr}^{-1}$
 - SN rate $\geq 0.3 \text{ yr}^{-1}$
- **Neutrino emission:**
 - Host collections of SN remnants, PWN, SN, superbubbles
 - CRs confined by B fields

Loeb+ 2006, Murase 2013,2014, Liu+ 2014,
Tamborra+ 2014, Fang+ 2014, Anchrodoqui+ 2014,
Chang+ 2015
- SED peak shortward of $100 \mu\text{m}$



Starbursts

Selection:

$S(100\mu\text{m}) > 250 \text{ Jy}$

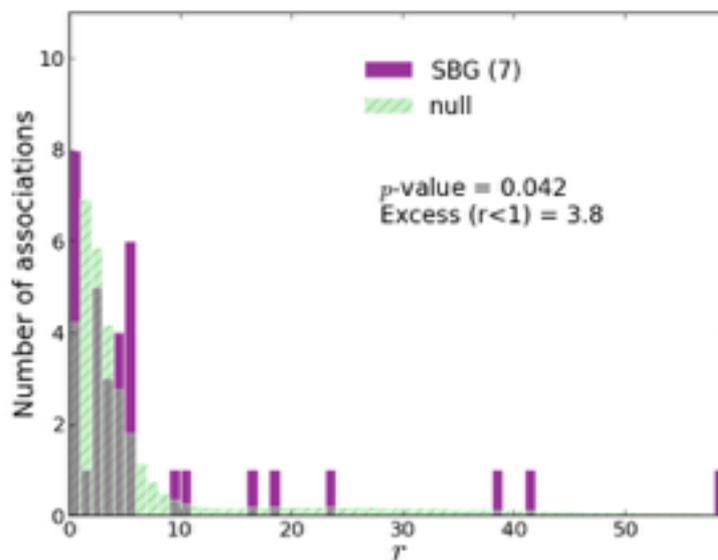
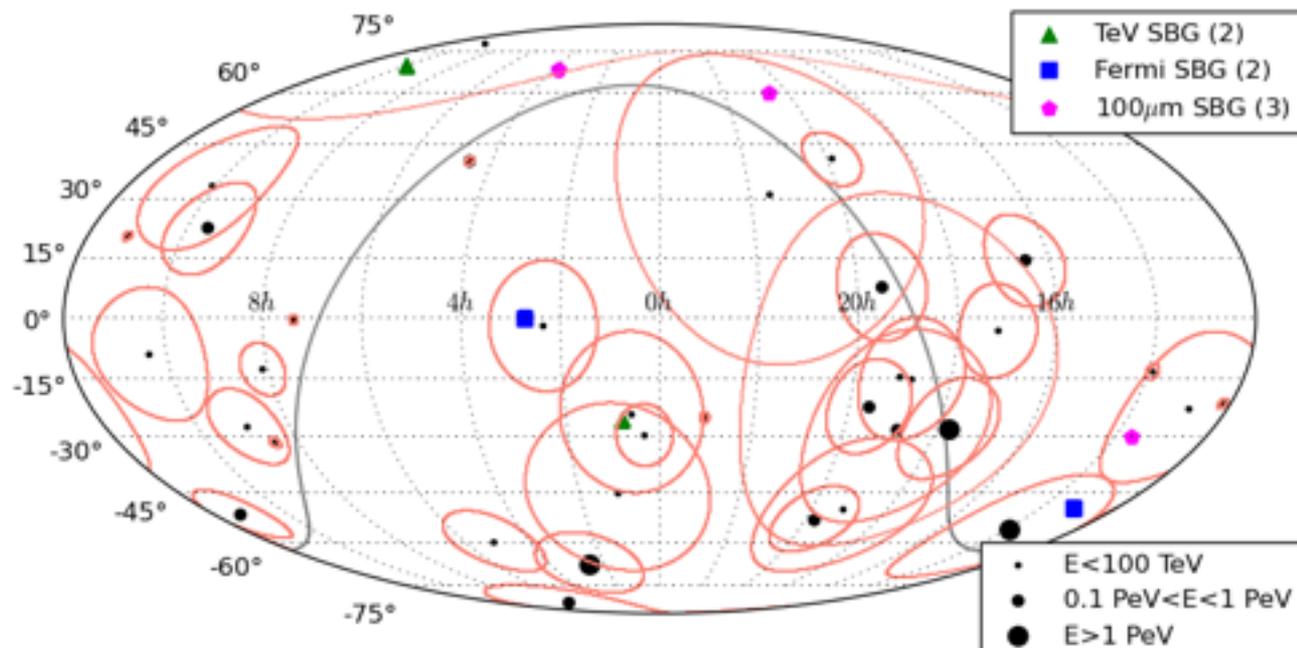
Becker+ 2009

Result:

P-value = 0.042

Excess ($r < 1$) = 3.8

Source	RA	dec	D_L [Mpc]
NGC 253	11.9	-25.2	3.1
NGC 1068	40.7	-0.0	13.7
IC 342	56.7	+68.1	4.6
M 82	149.0	+69.7	3.6
NGC 4945	196.3	-49.5	3.9
M 83	204.3	-29.9	3.6
NGC 6946	308.7	+60.2	5.3



Starbursts: Additional Tests

Randomize $|b| > 10^\circ$:

P-value = 0.034

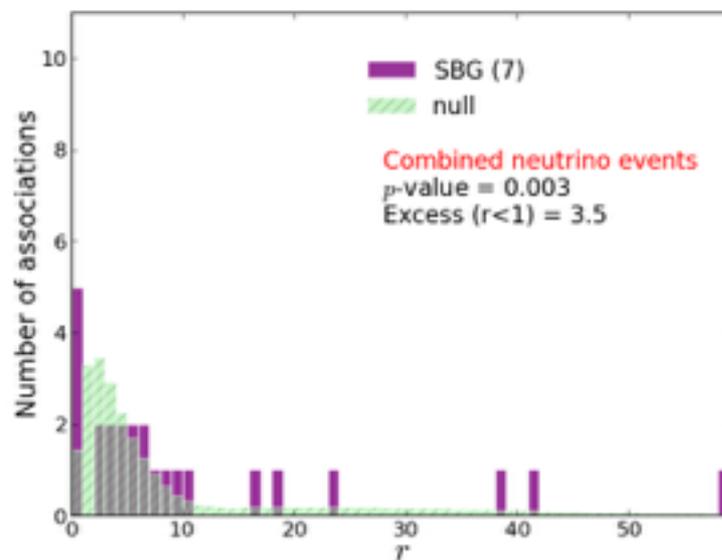
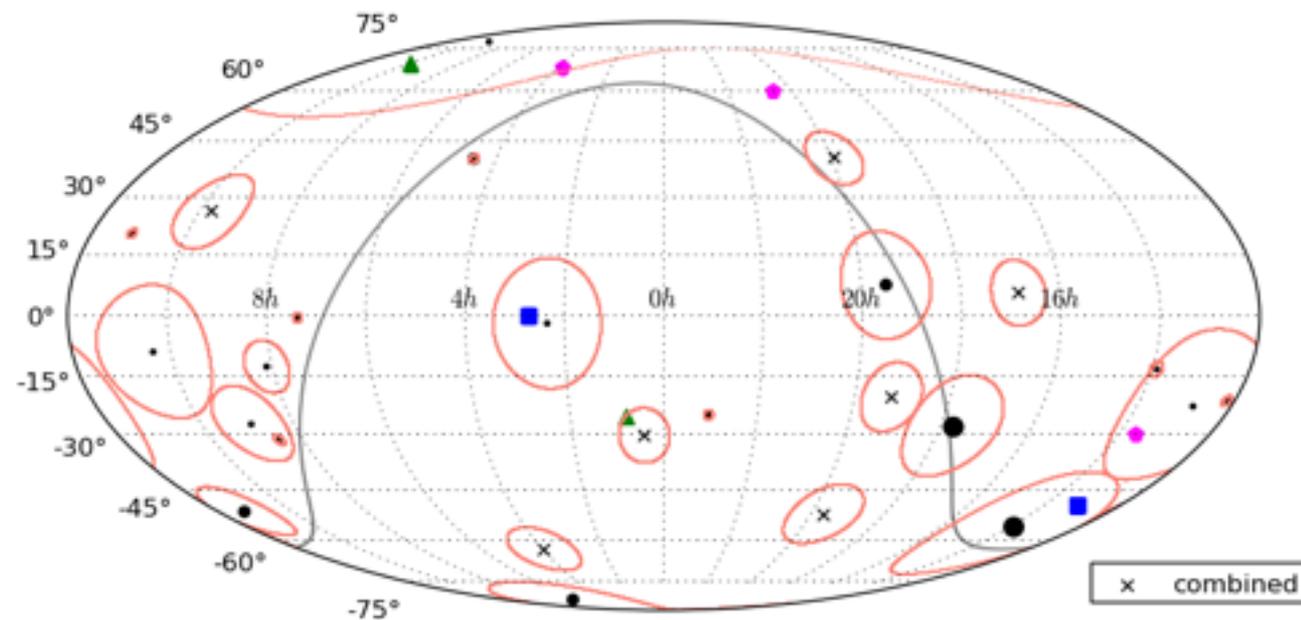
3FGL starbursts (4):

P-value = 0.046

Combined neutrinos
(right):

P-value = 0.003

Source	RA	dec	D_L [Mpc]
NGC 253	11.9	-25.2	3.1
NGC 1068	40.7	-0.0	13.7
IC 342	56.7	+68.1	4.6
M 82	149.0	+69.7	3.6
NGC 4945	196.3	-49.5	3.9
M 83	204.3	-29.9	3.6
NGC 6946	308.7	+60.2	5.3



Star formation

Massive stars



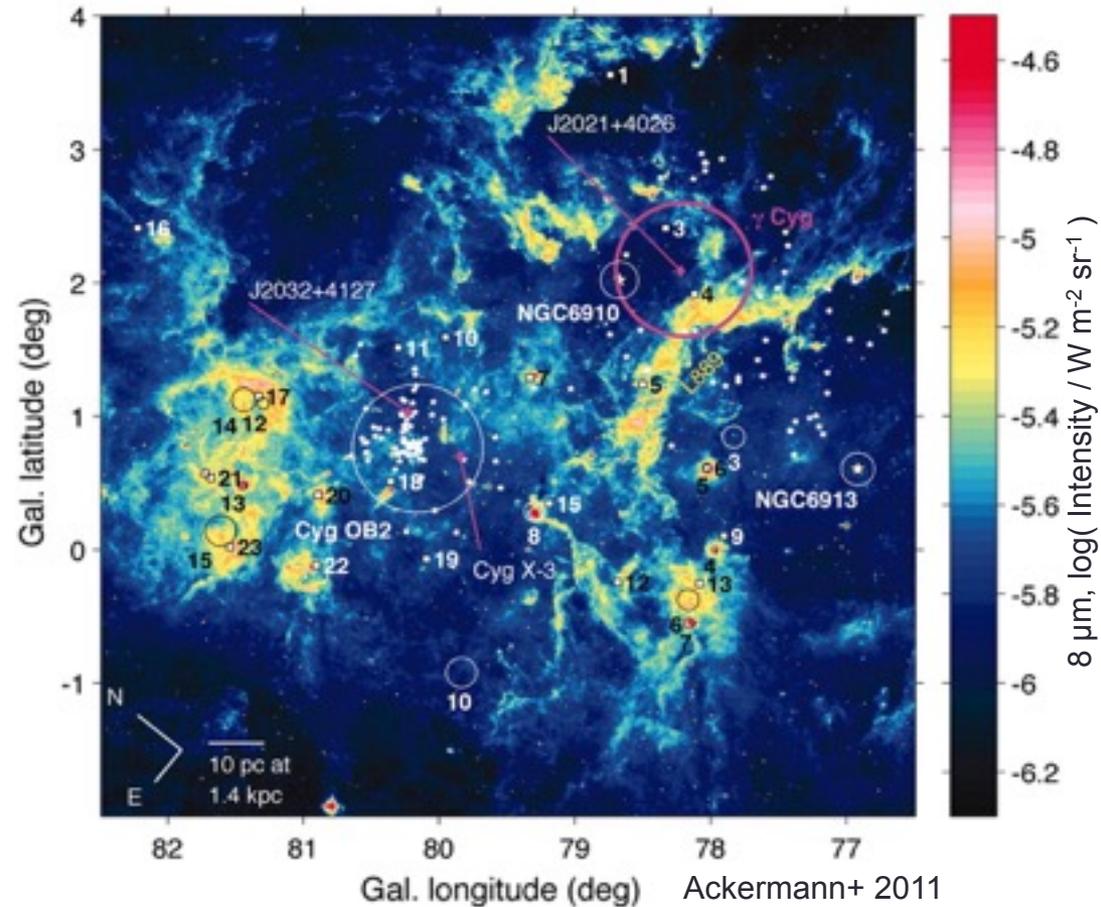
OB associations



Superbubbles

- Stellar winds and SN
- 85% of core-collapse SN
- 100s per starburst galaxy

Cygnus X Cocoon



Star forming regions

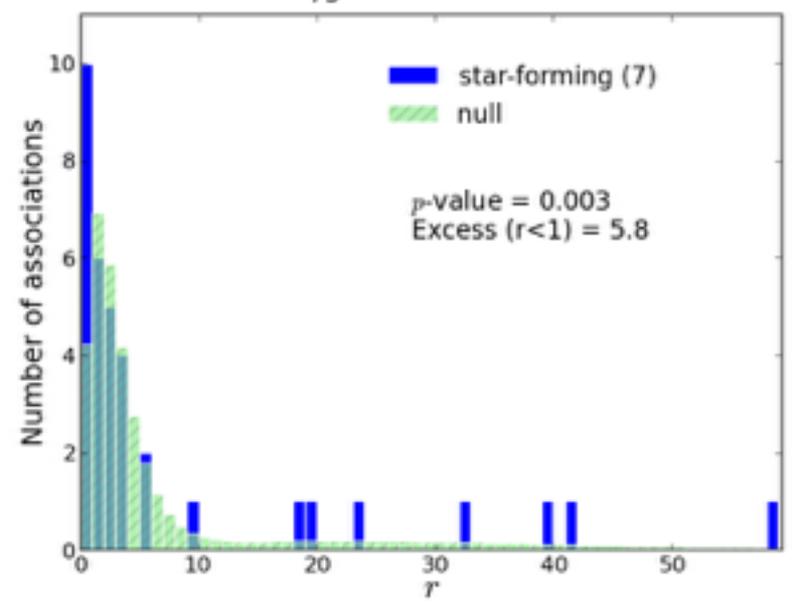
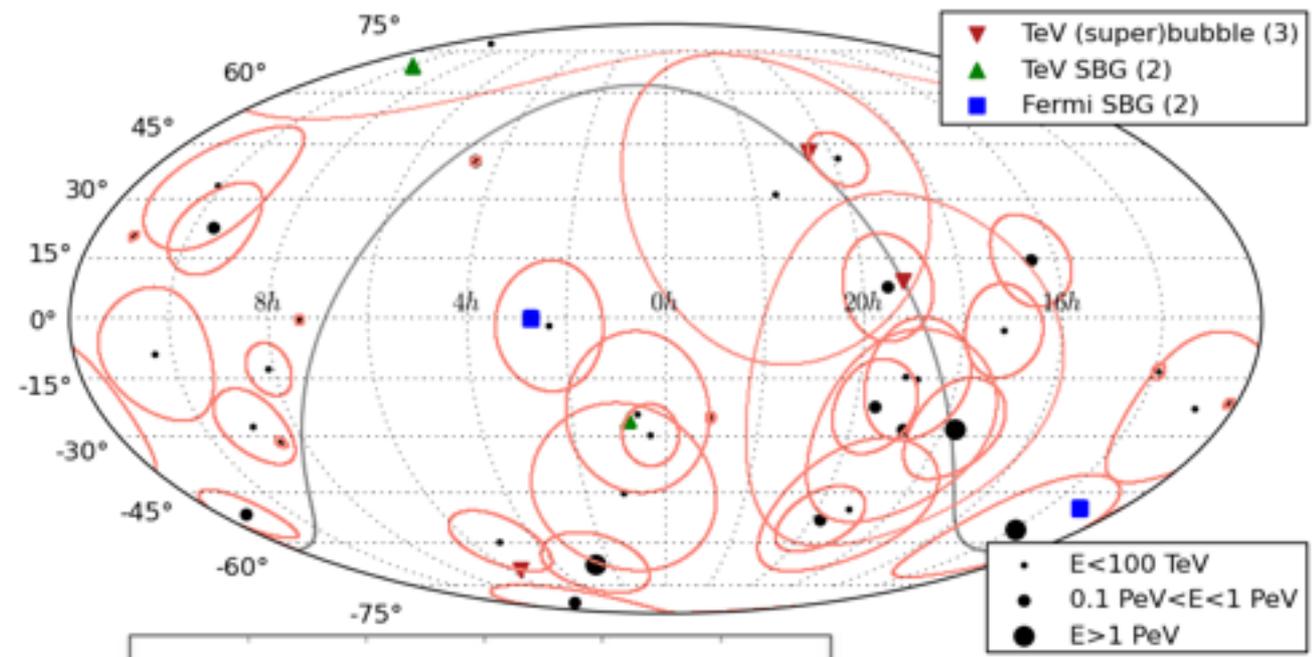
Selection:

3FGL Starbursts
 TeV Superbubble &
 Starform region

Result:

P-value = 0.003
 Excess ($r < 1$) = 5.8

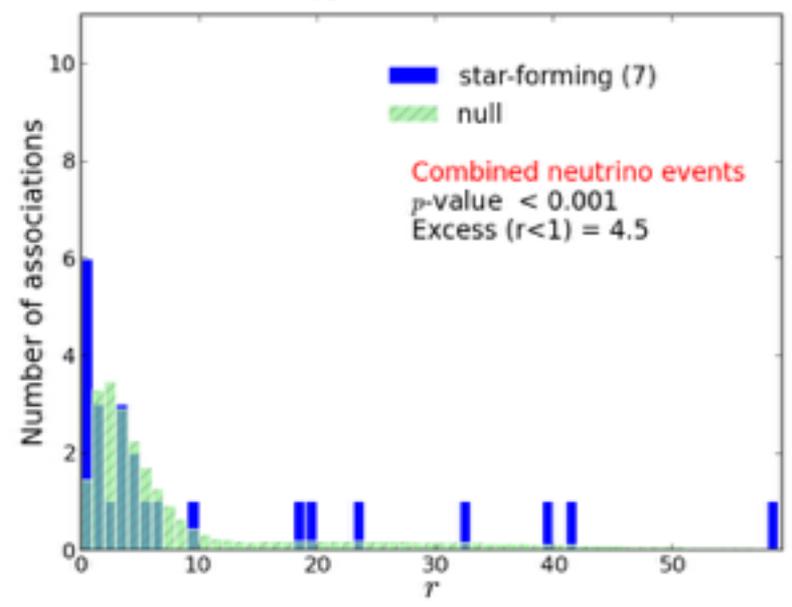
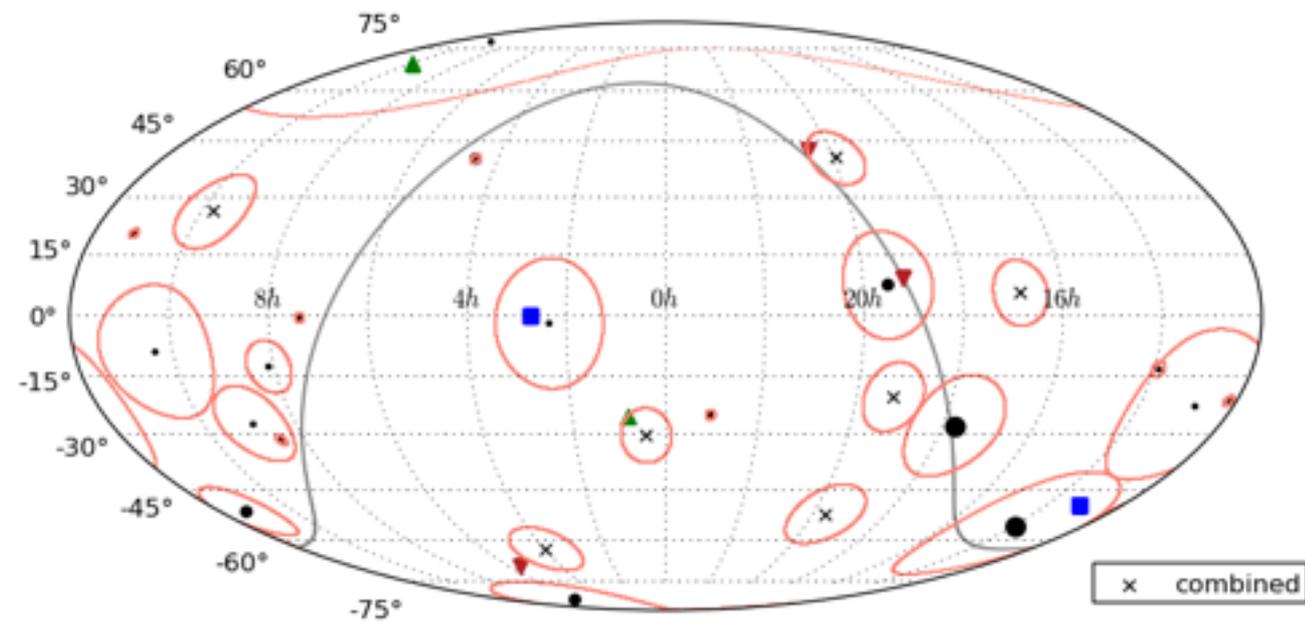
Source	RA	dec	D_L [Mpc]
NGC 253	11.9	-25.2	3.1
NGC 1068	40.7	-0.0	13.7
30 Dor C	84.0	-69.2	0.05
M 82	149	+69.7	3.6
NGC 4945	196	-49.5	3.9
W 49 A	288	+9.2	0.011
Cyg Cocoon	307	+41.2	0.002



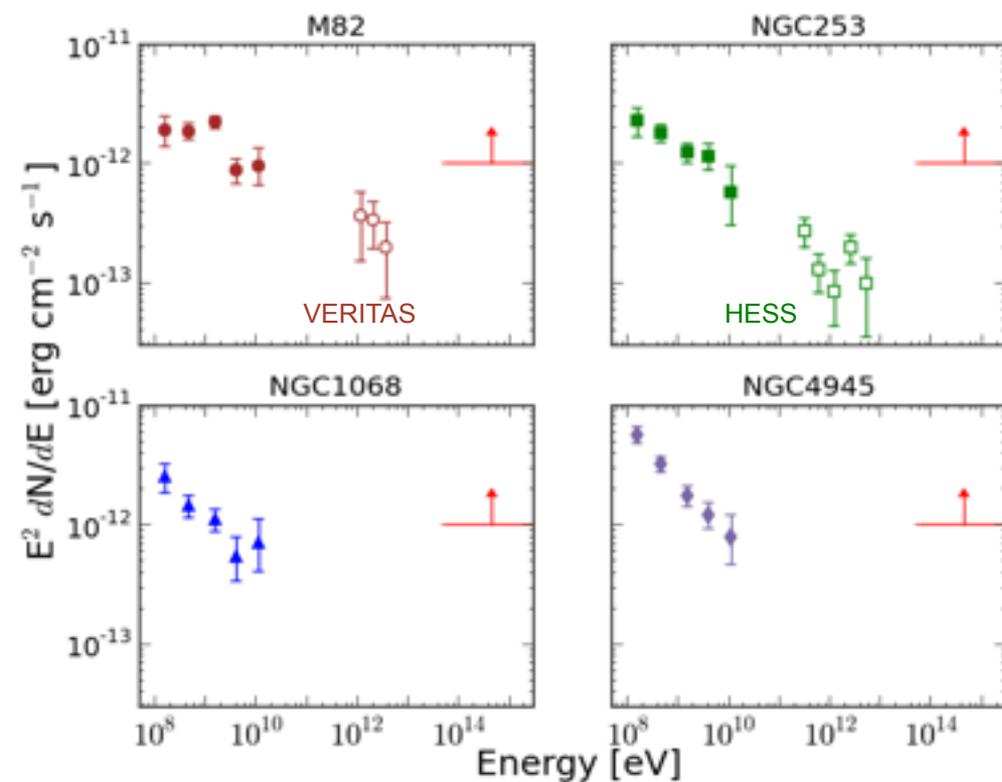
Star forming regions: Additional tests

Combined neutrinos:
 P-value < 0.001
 Excess (r<1) = 4.5

Source	RA	dec	D _L [Mpc]
NGC 253	11.9	-25.2	3.1
NGC 1068	40.7	-0.0	13.7
30 Dor C	84.0	-69.2	0.05
M 82	149	+69.7	3.6
NGC 4945	196	-49.5	3.9
W 49 A	288	+9.2	0.011
Cyg Cocoon	307	+41.2	0.002



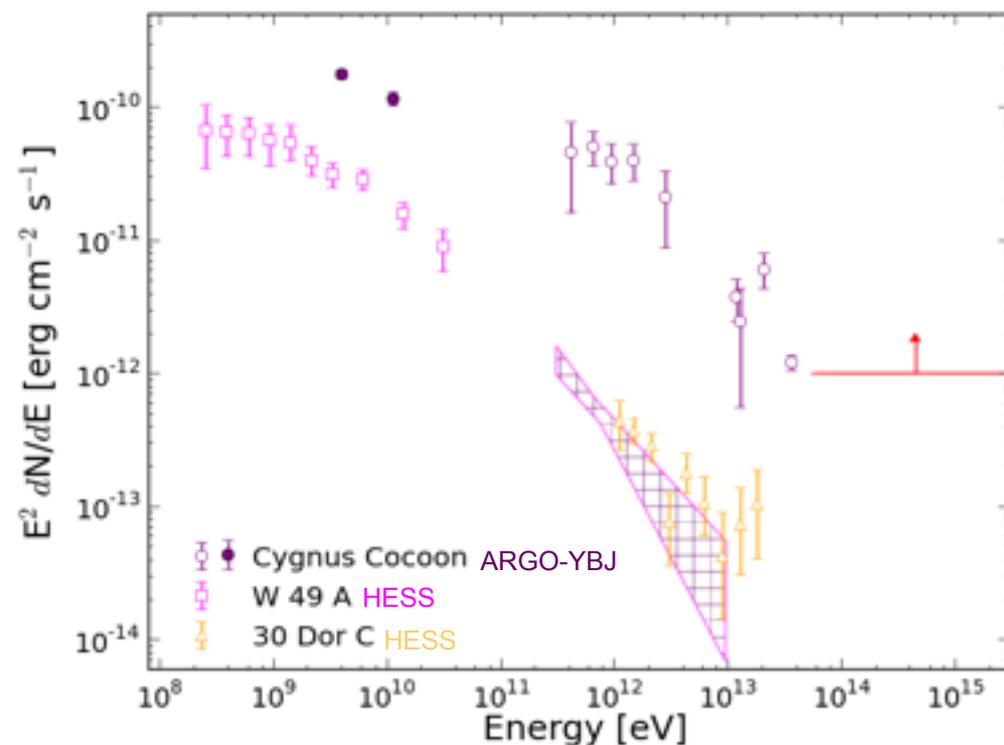
Gamma-ray spectra: Starbursts



IceCube point source sensitivity to neutrino emission

Gamma-rays don't trace neutrinos?
Further investigation needed!

Gamma-ray spectra: Superbubbles



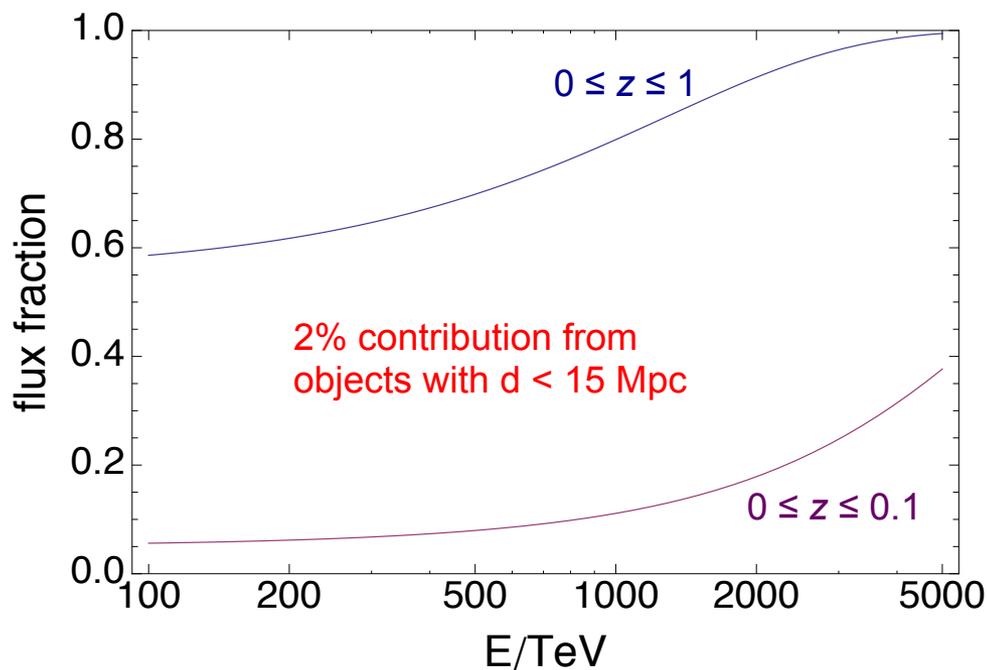
↑ IceCube point source sensitivity to neutrino emission

Cygnus cocoon passes energetics test!

Evolving contributions to neutrino flux

Peak of star-form activity $z \sim 1-3$

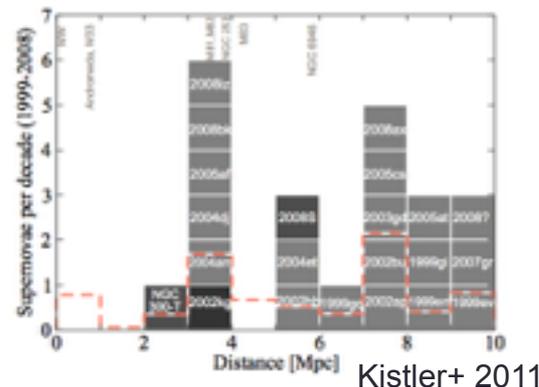
supernova rate evolution



- Assume 3-4 associations
- Accounts for 15% events
- Would over predict neutrino flux from high z population

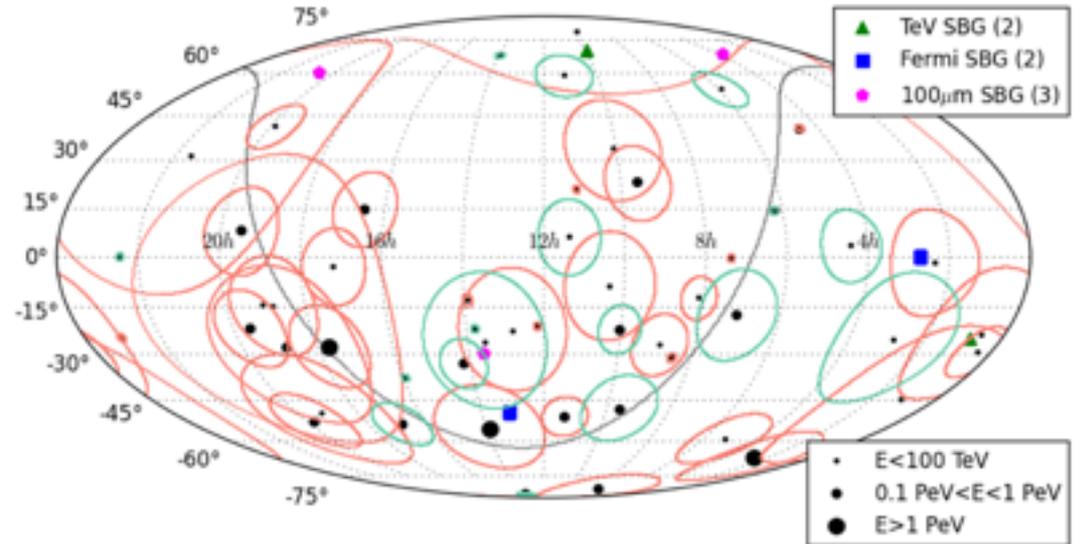
Possibilities

- local fluctuation in star forming activity w/in $d < 15$ Mpc Ando+ 2005



- Further investigation into SFH
- orientation effect?

Conclusions



Blazars & Seyferts: consistent with a null distribution

Star-forming activity:

- Brightest starburst galaxies: **p-value = 0.042**
- Gamma-ray star forming regions: **p-value = 0.003**

Further investigation:

- Gamma-ray emission characteristics from SF activity
- Better constrain star formation history of local universe
- Possible orientation effects

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