Are Starburst Galaxies Neutrino Calorimeters?

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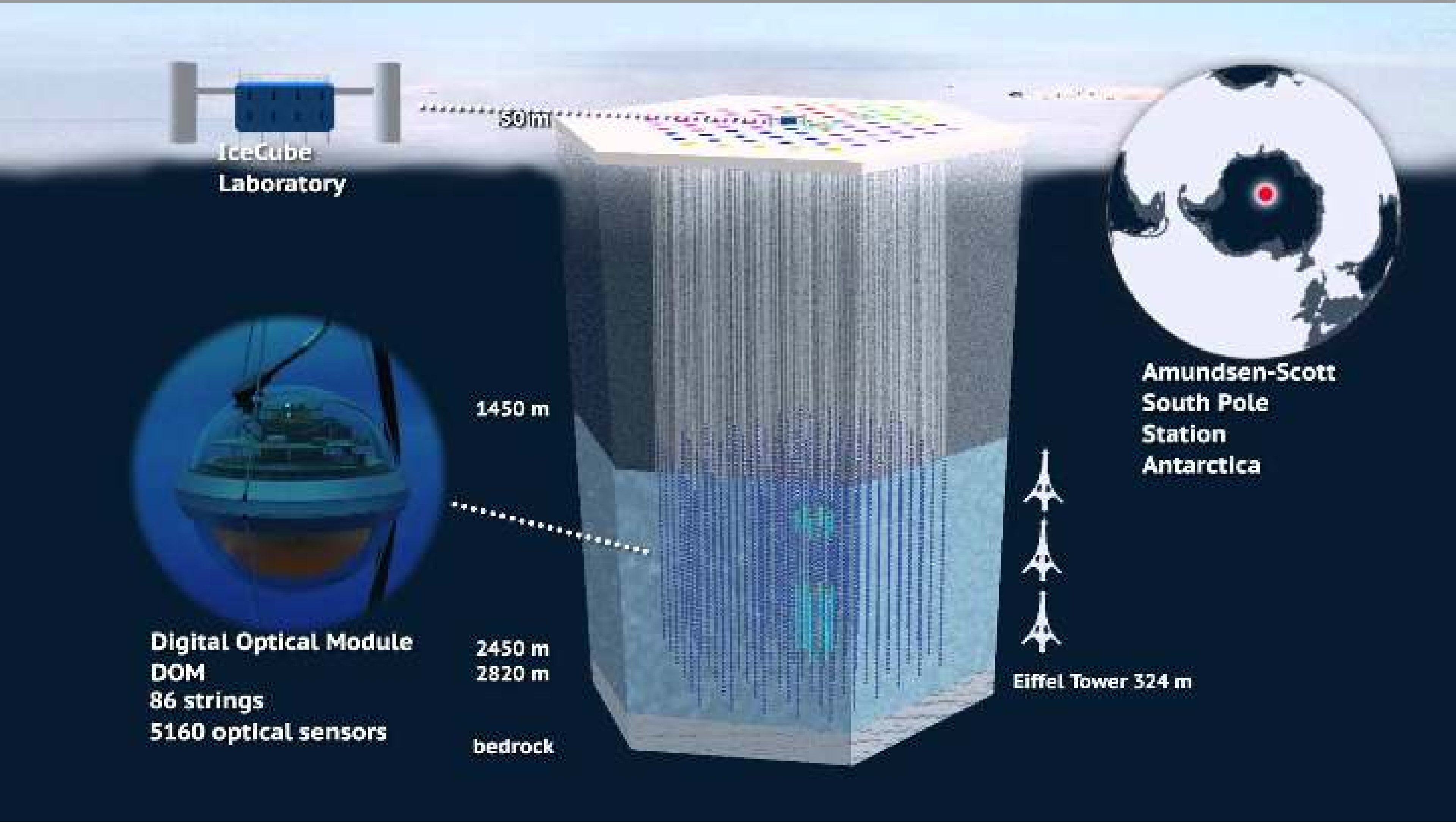
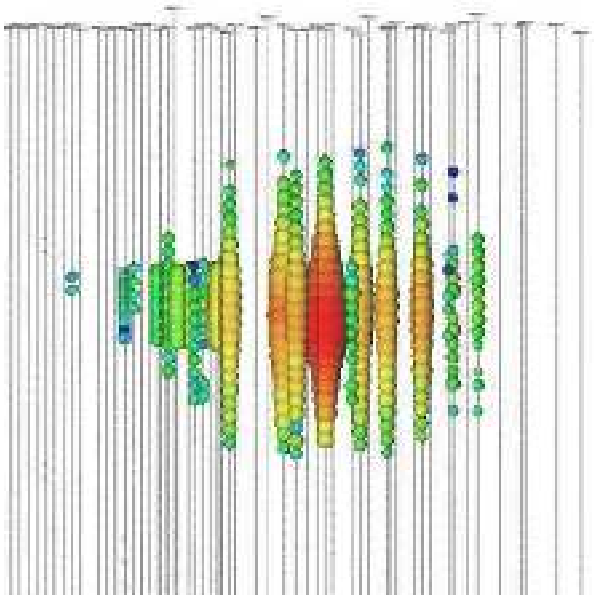
13/07/2017

IceCube Neutrino Observatory



Event Morphology



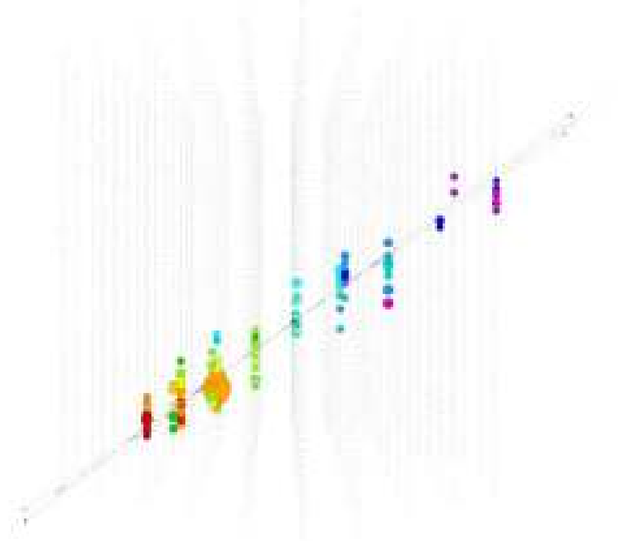
Cascades

- Caused by CC-interactions by ν_e & ν_τ & NC-interactions across all flavours.
- Cherenkov emission propagates in almost spherically (some directional information remains).
- Excellent energy reconstruction (in starting events) $\Delta E < 0.2E$
- Angular resolution limited by ice models $\Delta\theta$ = 10-15 degrees

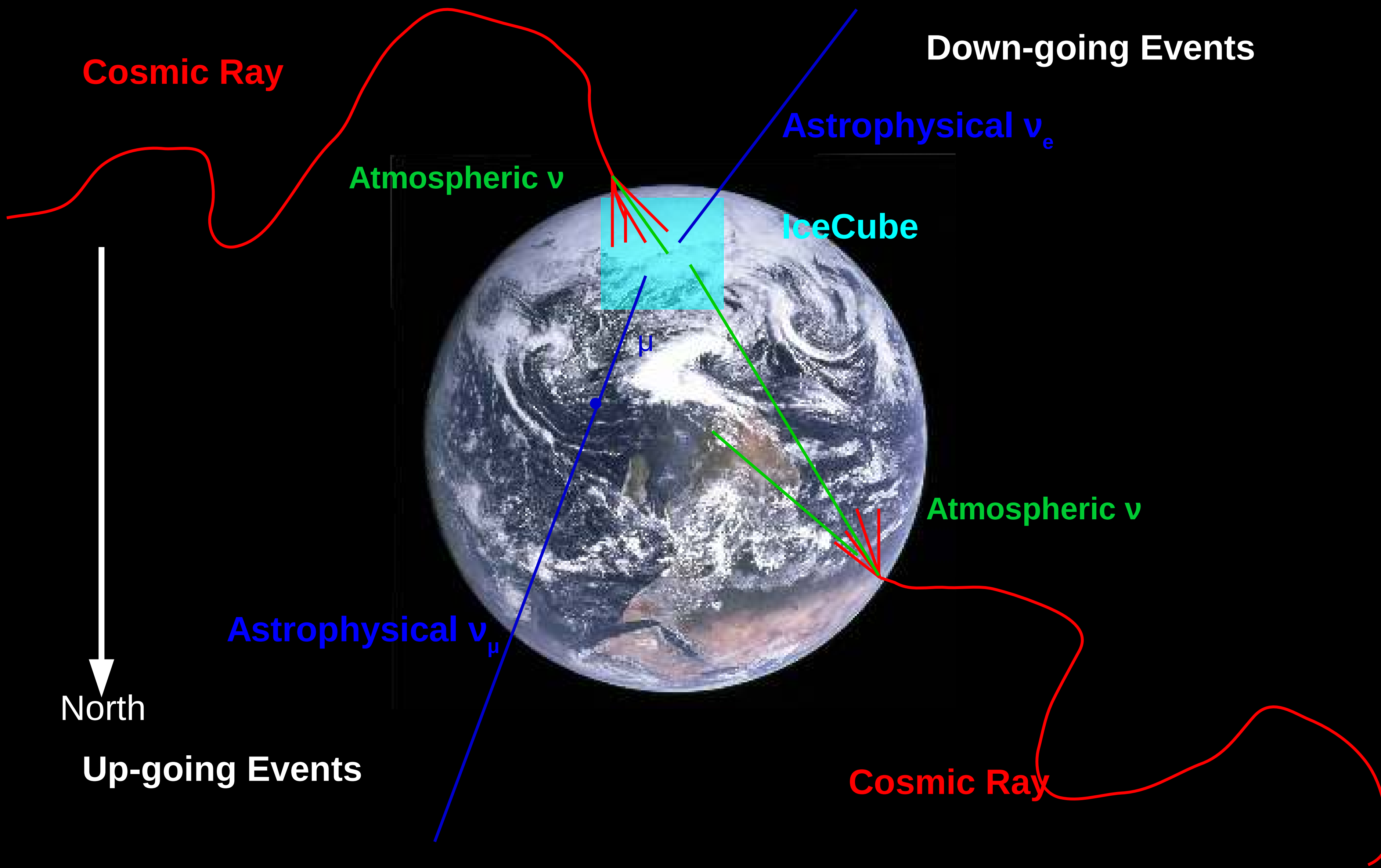
Tracks (muons)

Muons are generated by cosmic-ray air-showers
+
CC-interaction of $\nu_\mu \rightarrow$ muon
(astrophysical & atmospheric neutrinos)

Excellent angular resolution $\Delta\theta < 0.7$ degrees

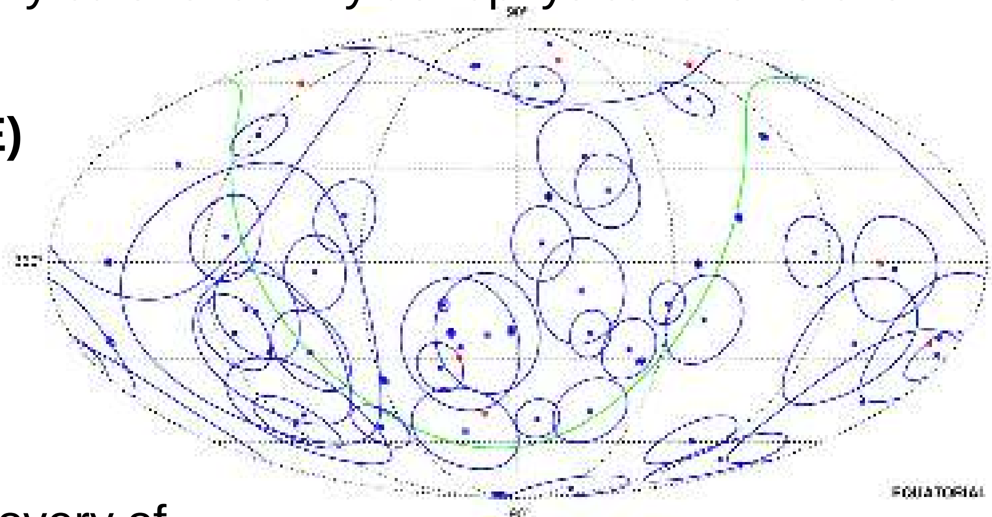


What IceCube Observes...



Astrophysical Samples

Diffuse analyses utilise various quality cuts to identify astrophysical events over the atmospheric background.



High Energy Starting Events (HESE)

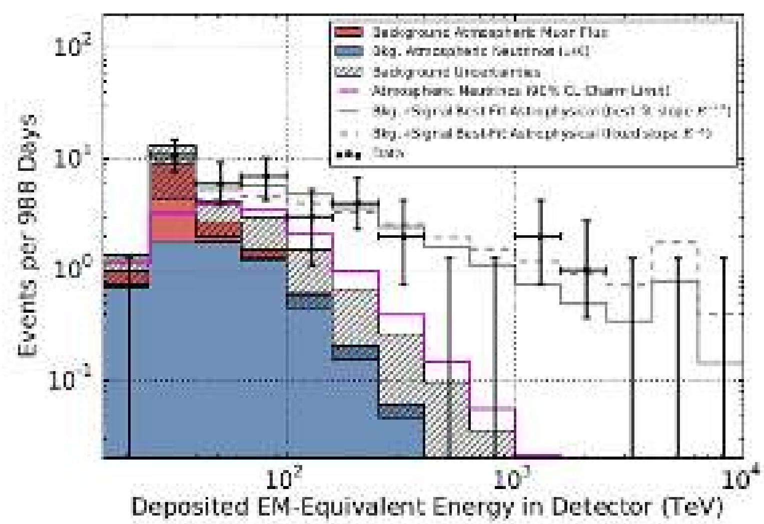
Surface veto

Q_{tot} > 6000 PE

Events must start inside detector

Sample was used to announce discovery of astrophysical flux (2013)

Composed of mostly of cascades with some tracks



Medium Energy Starting Events (MESE)

Lower energy threshold Q_{tot} > 4500 PE

- Progressive volume cuts

Astrophysical Samples

Diffuse up-going sample:
Earth absorbs air-shower muons & atmospheric neutrinos (to a lesser extent)

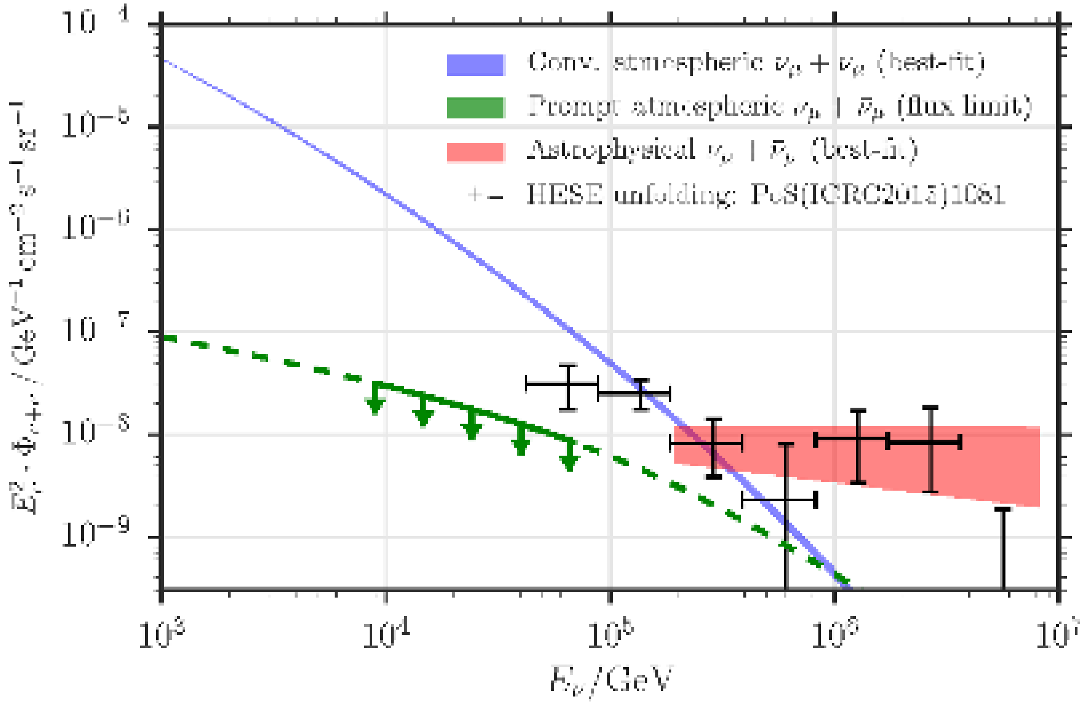
Sample consists of track events with good angular resolution (0.2-0.7 degrees)

Energy spectrum:

$$E^2\Phi(E) = 2.06^{+0.35}_{-0.26} \times E^{-0.46\pm0.12} 10^{-8} \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

Sample contains 100,000s of atmospheric events + 100s of astrophysical events

Sample is more useful for point source searches – particularly stacked likelihood searches



Point Source Searches

Multiple point source searches have been done using HESE, MESE & up-going muon samples

Searches utilise a maximum likelihood function to identify the position of the most likely source.

No significant results found so far

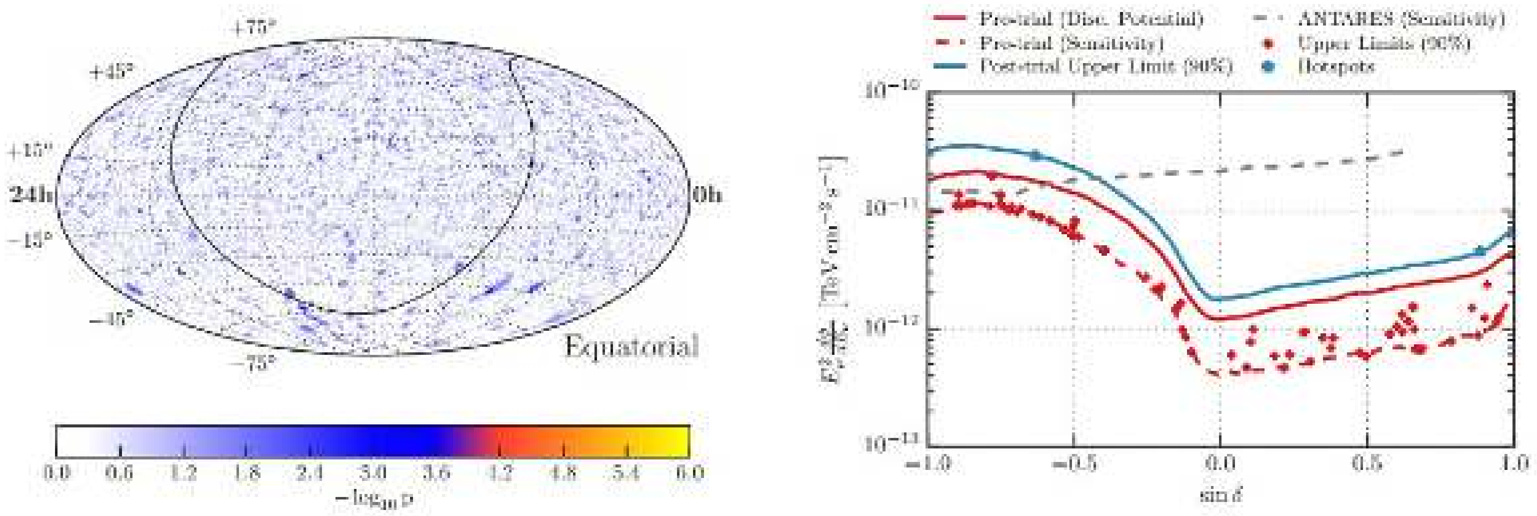
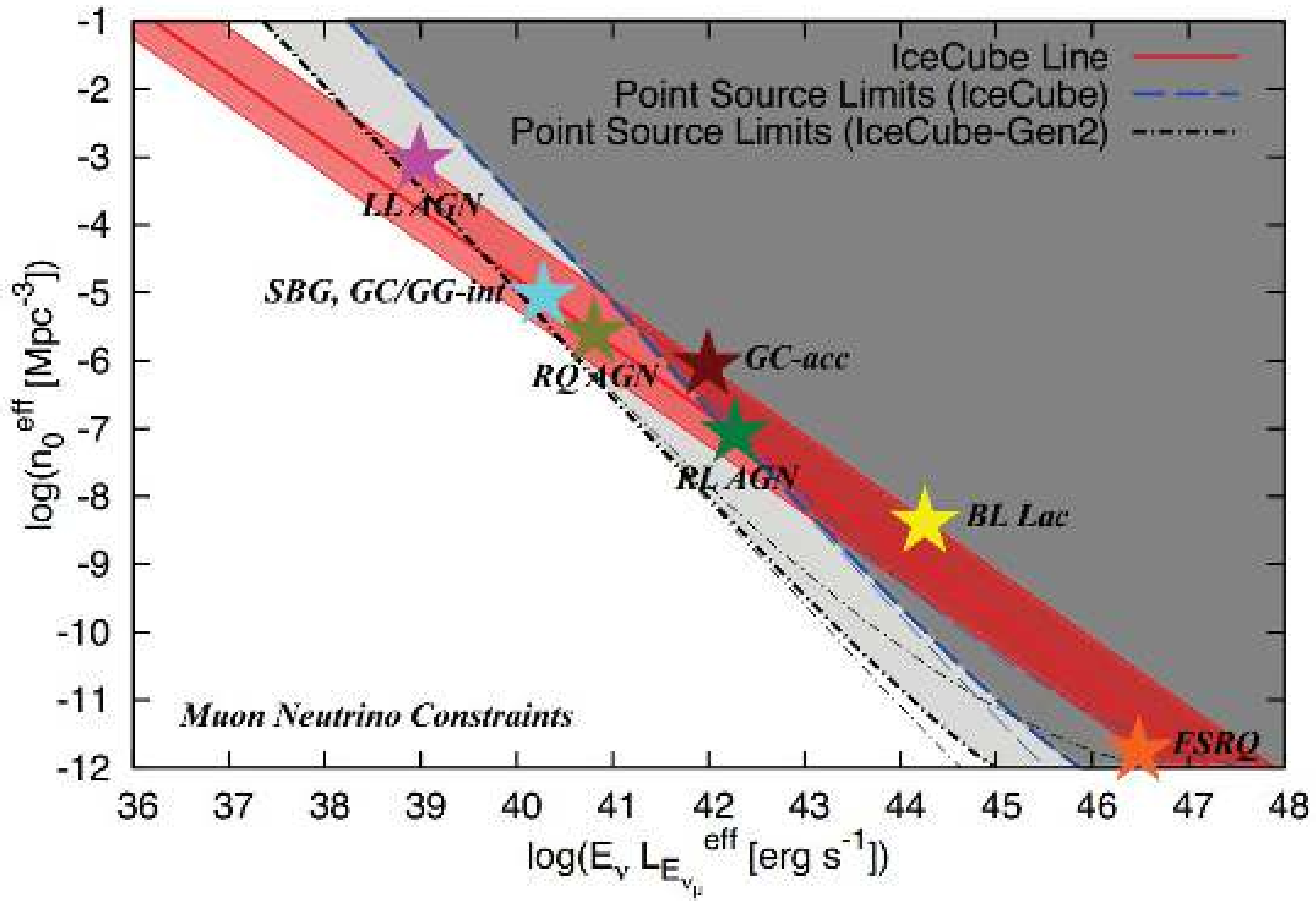


Figure 4: Left: results of all-sky time-independent clustering search in logarithmic pre-trial p-values. Right: sensitivity (dashed red) at 90% C.L., 5σ discovery potential (solid red) and 90% C.L. upper limit (blue) assuming a $\nu_\mu + \bar{\nu}_\mu$ unbroken E^{-2} energy spectrum [12].

Astrophysical Sources



Local Density $\log(n_{0,eff}/Mpc^{-3})$

Luminosity per object $\log(E_\nu L_\nu/erg\ s^{-1})$

Blazars

Thorsten’s Blazar Stacking Analysis (Glusenkamp et al. 2016) placed upper limits on the blazar contribution to astrophysical flux (< 21%)

They used a stacked likelihood analysis → evaluated the locations of blazars, FSQR & BL LAC objects from the Fermi 2LAC catlaogue, weighting each source using their gamma-ray flux

$$\log L(n_s,\gamma) = min \sum_{i=1}^{N_\nu} \log\left(\frac{n_s}{N_\nu} S(E_i,\alpha_i,\delta_i) + \left(1-\frac{n_s}{N_\nu}\right) B(E_i,\sin\delta_i)\right)$$

$$S(E_i,\alpha_i,\delta_i) = \frac{1}{\sum w_j}\sum_{j}^{N_{src}} \frac{w_j}{2\pi\sigma_i^2}\exp\left(\left(\frac{\Delta\theta_{ij}}{\sigma_i}\right)^2\right) g(E_i,\gamma)$$

$$w_j = \varphi_{\nu,j} \times \int_{E_{\nu,min}}^{E_{\nu,max}} h(E_\nu) \times A_{eff}(\theta_j,E_\nu)\, dE_\nu = C\varphi_{IR,j} \times w_{acc} = w_{src} \times w_{acc}$$

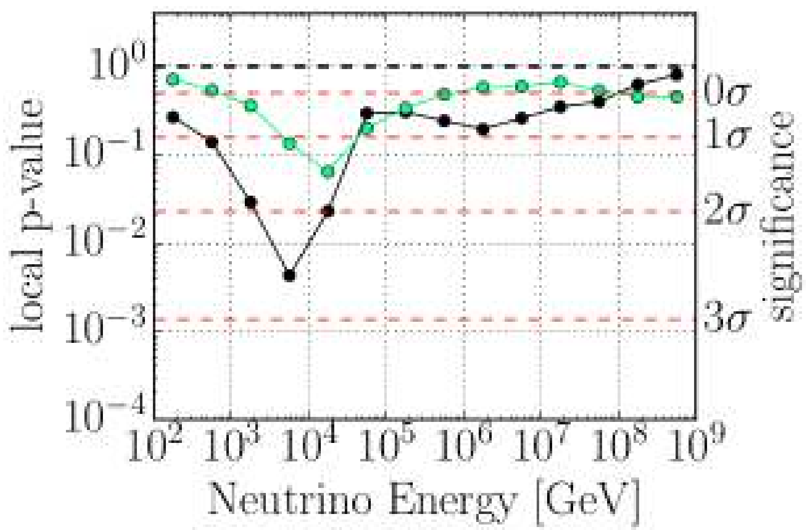
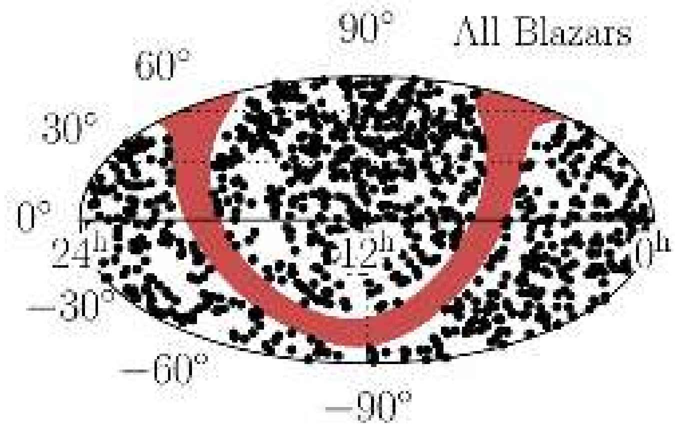


Figure 3. Local p-values for the sample containing all 2LAC blazars using the equal-weighting scheme (black) and gamma-weighting scheme (green) in the differential test.



Starburst Galaxies

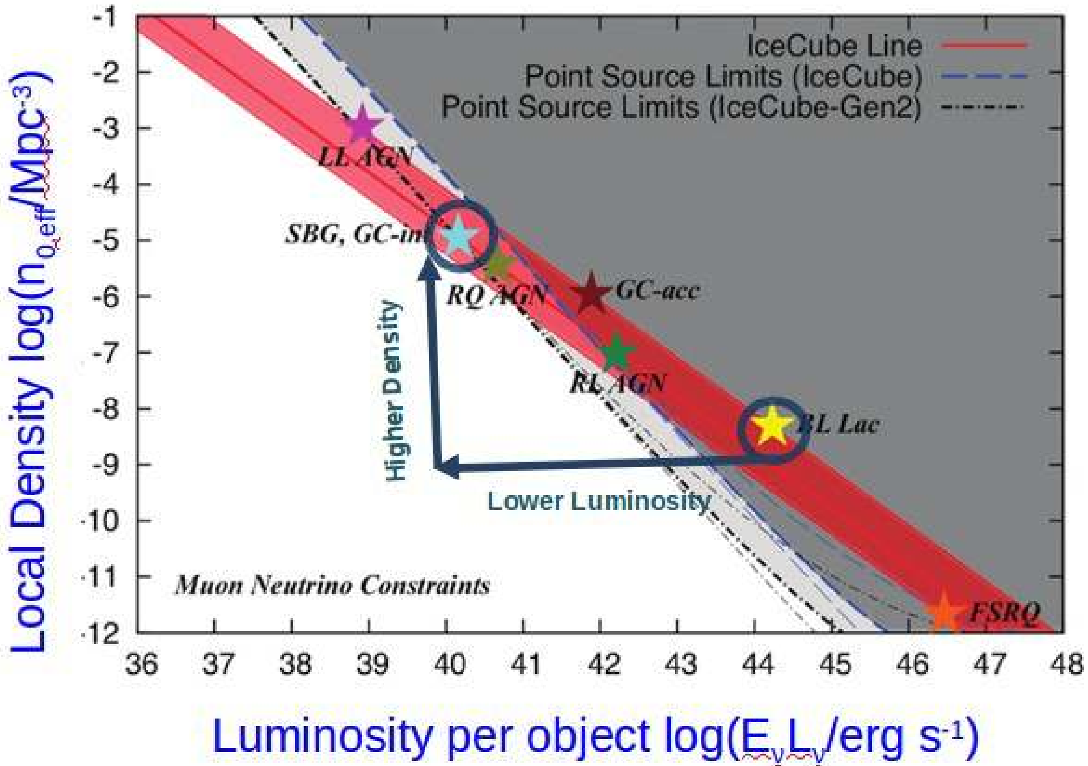
Galaxies with a local SFR > 10 M_{sol}/yr

High SFR → High rate of Supernova & GRBs → Large proportion of Supernova Remnants

Abundant sites for cosmic ray acceleration

High density of target gas & ambient radiation →

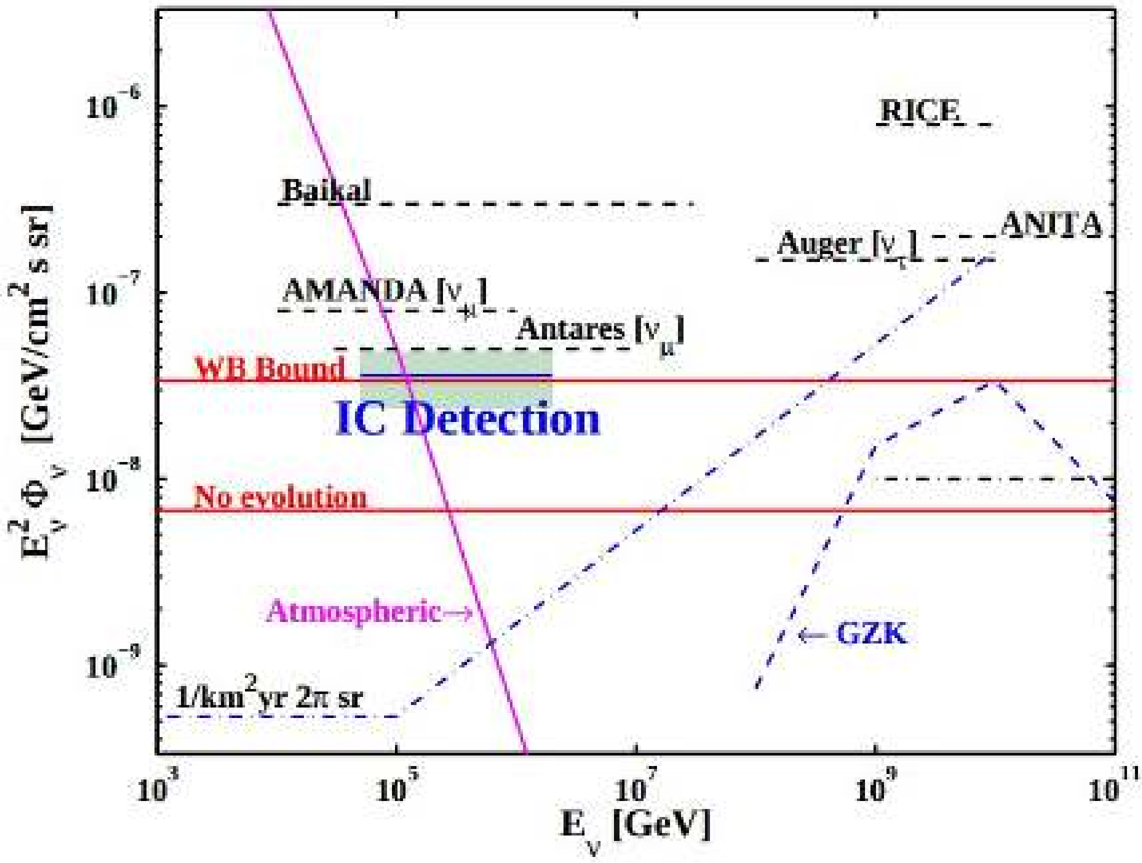
Starbursts act as CR calorimeters → neutrino emission proportional to total CR power.



Starburst Galaxies

Waxman (2016)

Starbursts and star-forming galaxies may dominate diffuse flux (Waxman-Bahcall Bound)



Starburst Galaxies

Neutrino emission should be accompanied by hadronic gamma-rays

Only 2 local Starbursts galaxies (M82 & NGC 253) have measured F_γ (Fermi-LAT, HESS & Veritas)

However, models predict that Starbursts are also host to large numbers of Pulsar Wind Nebulae (PWNe).

Ground based γ-ray telescopes don't have the resolution to distinguish leptonic & hadronic γ-ray emission in Starburst galaxies (but CTA probably could)

Nevertheless, γ-ray observations can be help resolve our question.

Starburst Energetics

Infrared Flux → neutrino Flux ($F_{IR} \rightarrow F_{\nu}$):

Star-formation rate $\Psi = 10^{-44}\, L_{IR}(8\text{-}1000\mu m)\, M_{*} yr^{-1}$ (IRAS 1986)

SN rate:

CR Luminosity: $L_{CR} = E_{SN} R_{SN} f_{CR}$ erg s^{-1}

Neutrino Luminsoity $L_{\nu} = f_{\nu} L_{CR} = f_{\gamma}\, L_{CR}$

If the Starbursts' γ-ray flux is primarily hadronic in nature, then we can assume: $f_{\gamma} \approx f_{\nu}$

Only two starburst galaxies; M82 & NGC 253, have observed γ-ray emission at relevent energies (E ~ 10-100 TeV).

Infrared Flux of Starburst Galaxies

In lieu of γ-ray emission, we use Far Infrared emission to estimate the neutrino flux

High Star-formation rate leads to larger population of hot OB-type stars.

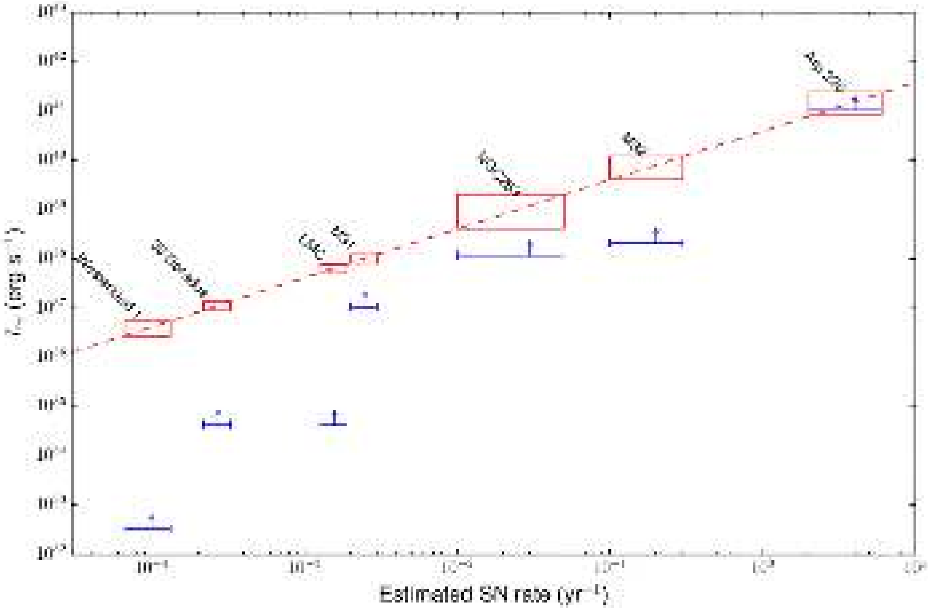
Their UV emission dominates the Spectral Energy Distribution

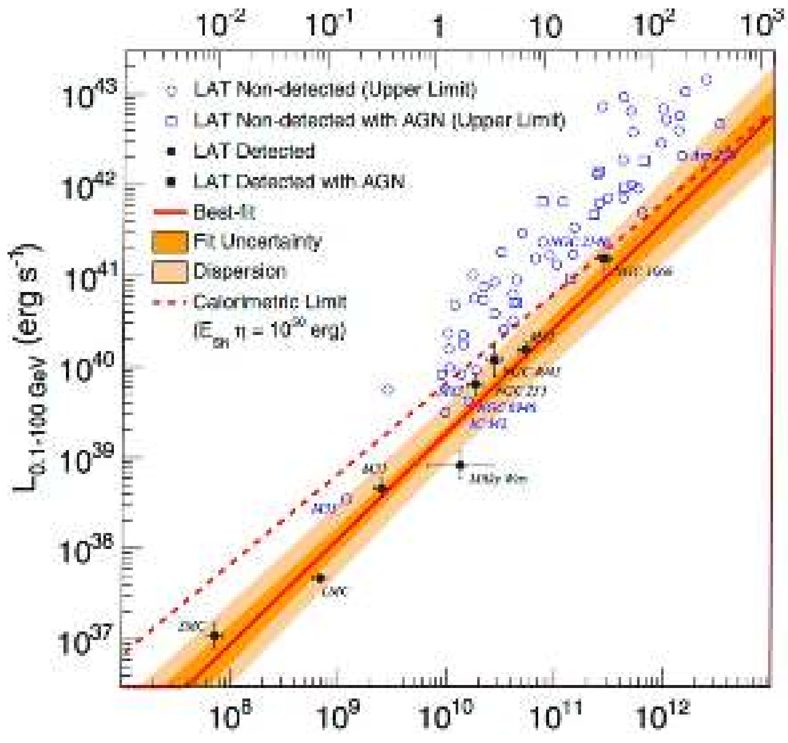
UV emission warms up dust particles, which cool by radiating IR photons (1-1000 microns).

If Neutrino emission is proportional to the star-formation rate, we can use IR to construct a model

Starburst Energetics

	L_{IR} [10^{10} L_{sol}]	F_{γ} (E_{γ}> 100 TeV) [10^{-11} GeV/cm^2]	D [Mpc]	f_{γ}	L_{ν} (L_{γ}) [10^{37} erg/s]
M82	4.1 (IRAS)	1 (Inoue et al.)	3.53	0.002	2.41
NGC 253	2.5 (IRAS)	2 (Inoue et al.)	3.56	0.007	4.9





Starburst Energetics

Applying this to the SFR:
Derive Starburst distribution over redshift using SFR
(around 10% of star-formation occurs in Starburst)

Assuming $L_{\nu,0}$ of M82 or NGC 253, we find that:

$F_{\nu,M82} / F_{\nu,tot} = 0.01$, 1 %

$F_{\nu,M82} / F_{\nu,tot} = 0.035$, 3.5 %

Fraction of flux accounted for Starbursts under this model

Cosmic SFR
Madau, Dickinson 2015
Beacom, Hopkins 2006

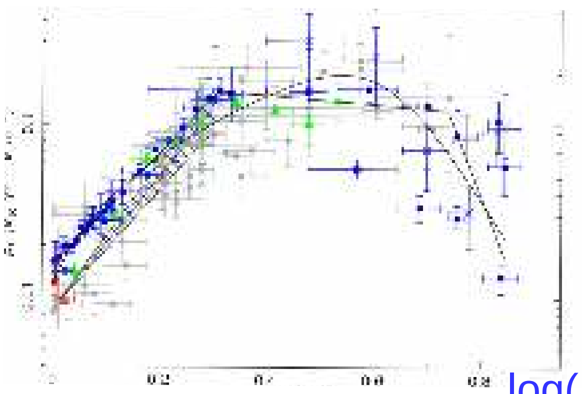
Fraction of star-formation by Starburst (~10 % for 1 < z < 2)
Lamastra, Menci et al. 2013

$$n_{SB}(z) = \frac{\psi(z) f_{SB}(z)}{\psi_0}$$

SFR per SB
> 10 M_{sol}/yr

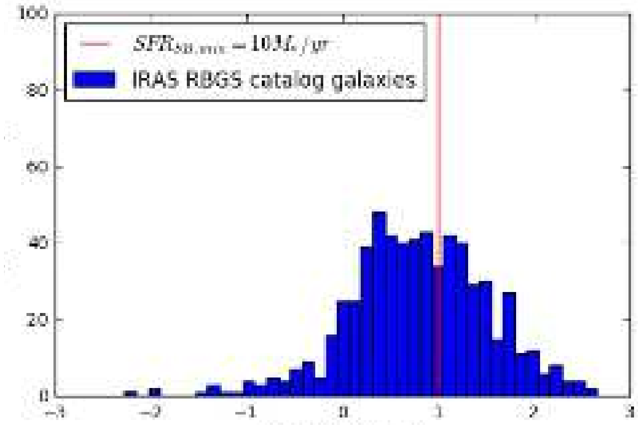
$$E_\nu^2 F_{\nu,SB} = L_{\nu,0} \int_0^{z_{max}} \frac{n_{SB}(z)}{4\pi D_c^2 (1+z) E(z)} \frac{dV_c(z)}{dz} dz$$

Cosmic SFR (Hopkins 2006)



$\rho_{SFR}(z)$ SFR density per redshift

log(1+z)



N_{IRAS} Galaxies per bin

ψ_0 :Local SFR [M_{sol}/yr]

Starburst Energetics

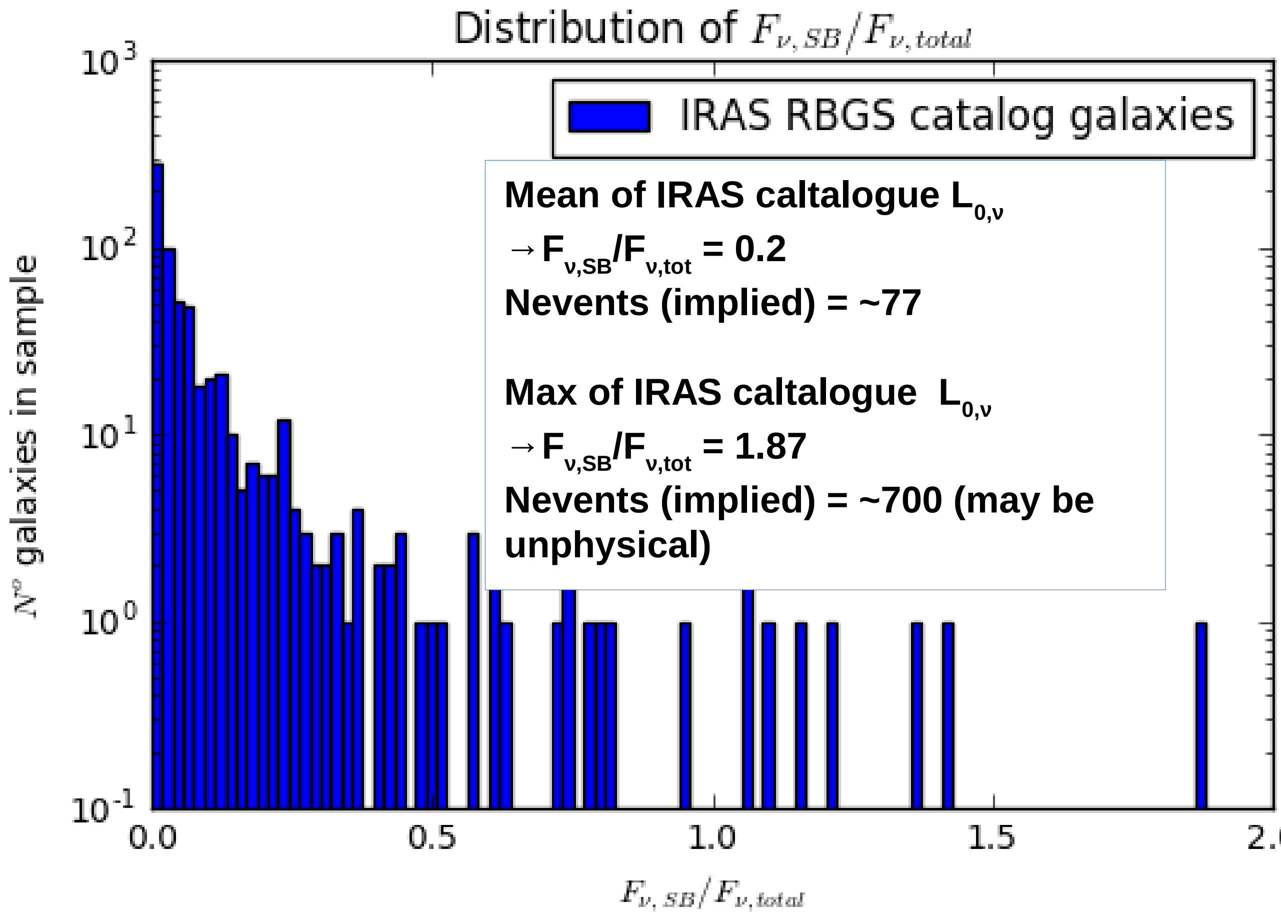
Apply results to IR luminosities of IRAS sample of bright IR galaxies

Catalogue average luminosity → $F_{\nu,SB}/F_{\nu,tot} \approx 0.2$

20 % of the flux accounted for by Starbusts under optimistic assumptions (γ-ray flux 100 % hadronic)

8 % from nearest galaxies (reperesented in IRAS sample)

$F_{tot,iras}/F\nu,tot = \sum F_{i,iras} =$ 0.08, 8 %
30 astrophysical events



Summary (part 1)

Results so far:
IR – Neutrino model suggests that Starburst are not the dominant contribution to the astrophysical flux observed by IceCube

Starbursts unlikely to produce easily identifiable muon multiplets

However some Starburst contribution may be identifiable using a stacked likelihood analysis (a la the Blazar analysis) to constrain the Starburst contribution to the spectrum.

Results are in agreement with Ahlers et al. Starbursts unlikely to dominate neutrino flux

Stacking Analysis

Neutrino Data:

IC86 3 year diffuse up-going sample (muons)

- Good angular resolution
- Dominated by northern sky
- Background estimated with simulations

Source Data:

IRAS Revised Bright Galaxy Catalogue (initial)

~ 643 galaxies (323 in northern sky)

- Cuts being considered to filter out AGN

Spitzer IR catalogue more modern, 1000s of galaxies in catalogue

Stacking Analysis

Log-likelihood analysis
- minimize for signal event number n_s and power index γ

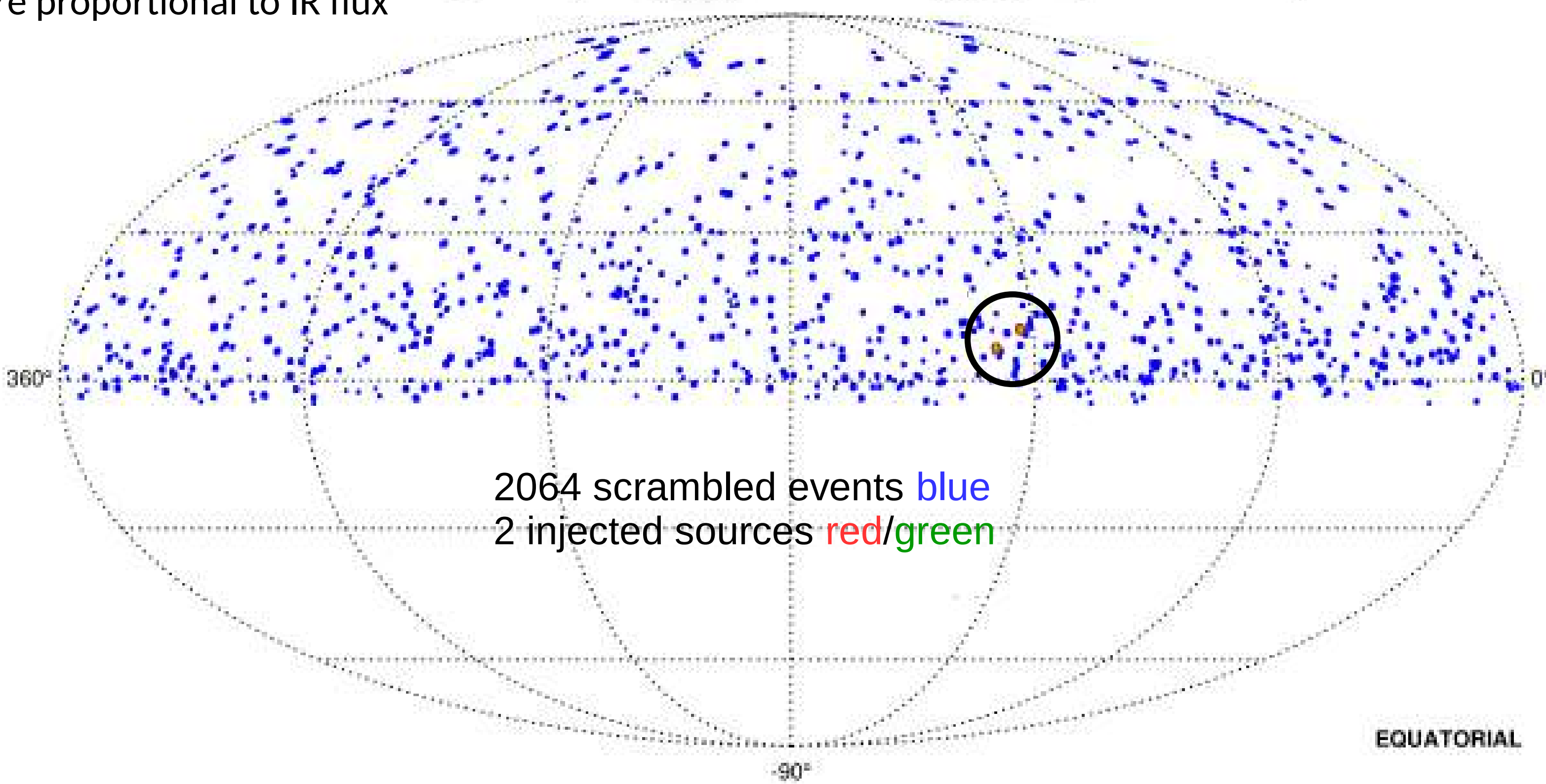
$$\log L(n_s,\gamma) = min \sum_{i=1}^{N_\nu} \log\left(\frac{n_s}{N_\nu} S(E_i,\alpha_i,\delta_i) + \left(1-\frac{n_s}{N_\nu}\right) B(E_i,\sin\delta_i)\right)$$

Source positions defined usign catalogue coordinates

$$S(E_i,\alpha_i,\delta_i) = \frac{1}{\sum w_j} \sum_j^{N_{src}} \frac{w_j}{2\pi\sigma_i{}^2} \exp\left(\left(\frac{\Delta\theta_{ij}}{\sigma_i}\right)^2\right) g(E_i,\gamma)$$

Weights are proportional to IR flux

$$w_j = \varphi_{\nu,j} \times \int_{E_{\nu,min}}^{E_{\nu,max}} h(E_\nu) \times A_{eff}(\theta_j,E_\nu)\, dE_\nu = C\varphi_{IR,j} \times w_{acc} = w_{src} \times w_{acc}$$



Summary (part 2)

Developed point source code to implement stacking analysis
(Diagnostic phase)

Need to establish sensitivity to Starburst point sources

Future Work:
Allow for optimisation of power spectrum

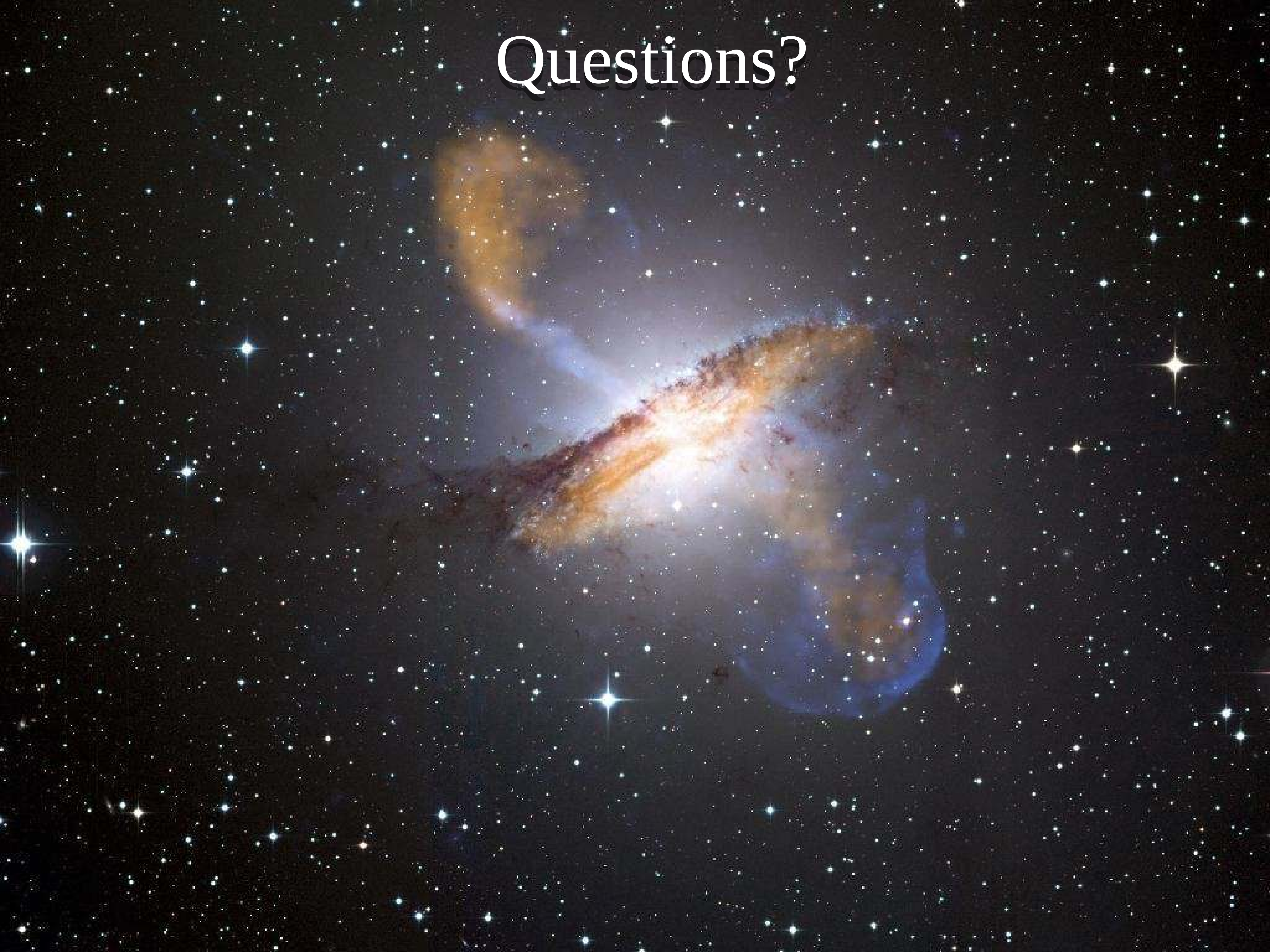
Implement code on un-blinded events

Compare results to Blazar stacking analysis

Goal:
Place constraints on Starburst contribution to neutrino flux

→ move toward ruling out Starbursts as source candidates

Questions?




Thank you!