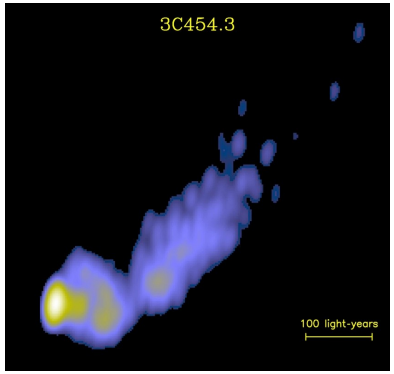
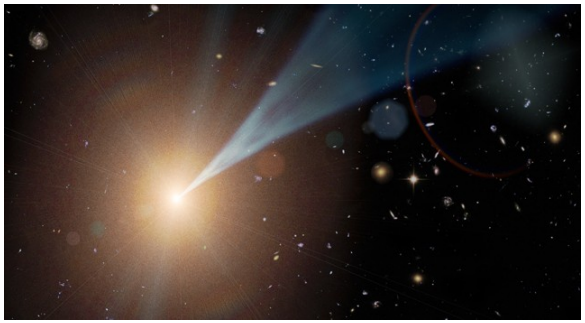
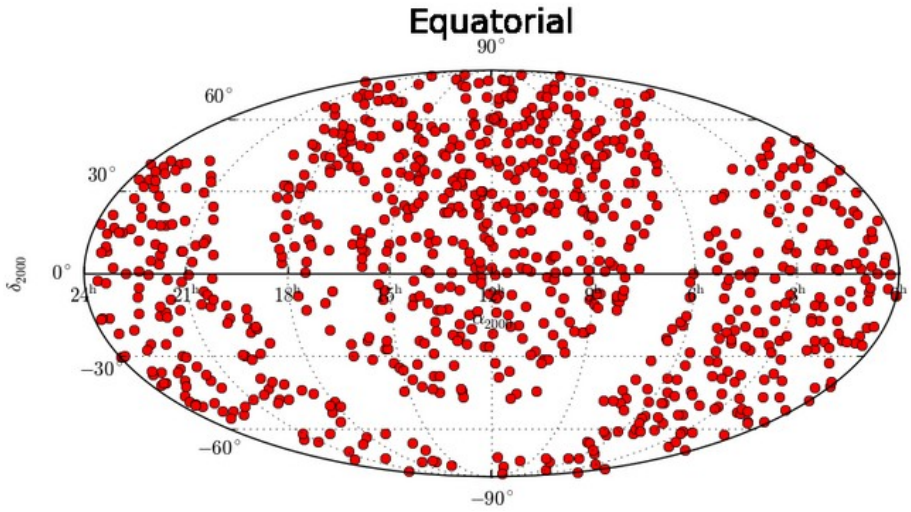
Analysis of the cumulative neutrino flux from FERMI-LAT blazar populations using 3 years of IceCube data





All blazars from *2-LAC* – 862 objects



Thorsten Glüsenkamp for the IceCube Collaboration

RICAP-14

October 1st, 2014

HELMHOLTZ ASSOCIATION

IceCube

DESY

Blazars: Possible candidate for HE-Neutrinos

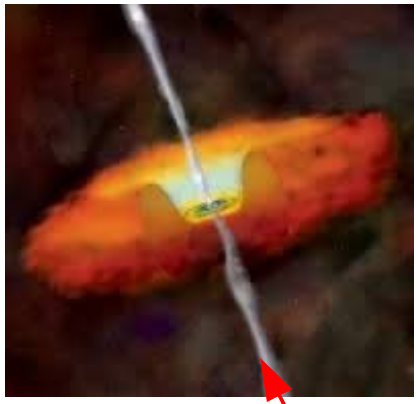
> Blazars: Active Galactic Nuclei **(AGN)** with jets

- Line of sight close to jet axis

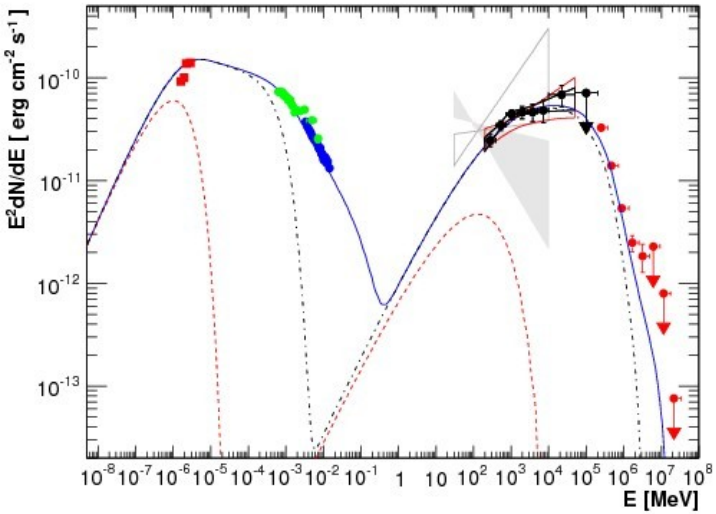
Blazars: Possible candidate for HE-Neutrinos

> Blazars: Active Galactic Nuclei **(AGN)** with jets

- Line of sight close to jet axis



"Double Hump" spectrum



"Synchroton Peak"

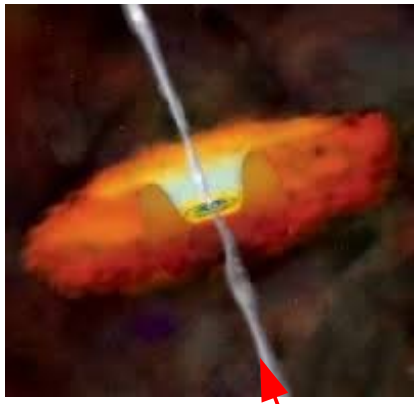
"Gamma Peak"

Which processes create the "gamma peak"?

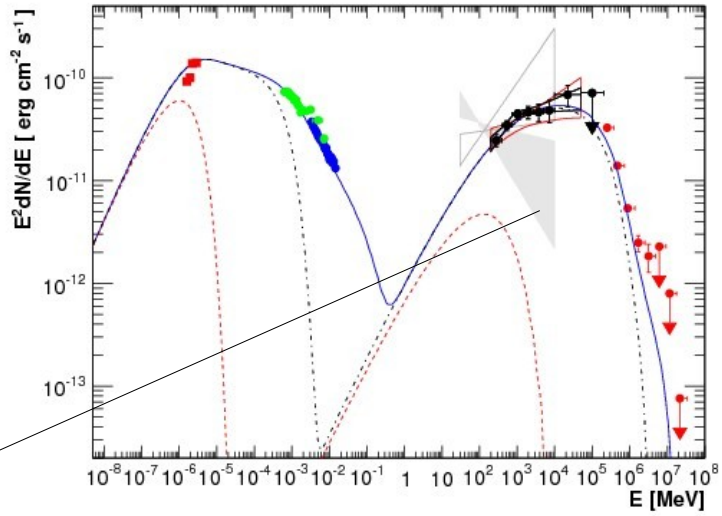
Blazars: Possible candidate for HE-Neutrinos

> Blazars: Active Galactic Nuclei **(AGN)** with jets

- Line of sight close to jet axis

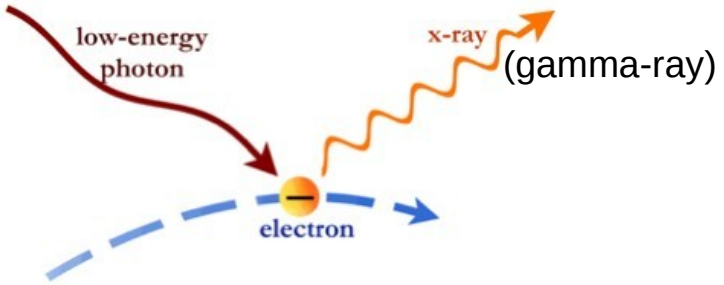


"Double Hump" spectrum



Which processes create the "gamma peak"?

If leptonic:



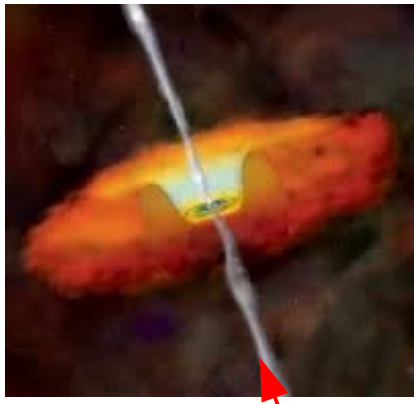
Inverse compton

DESY

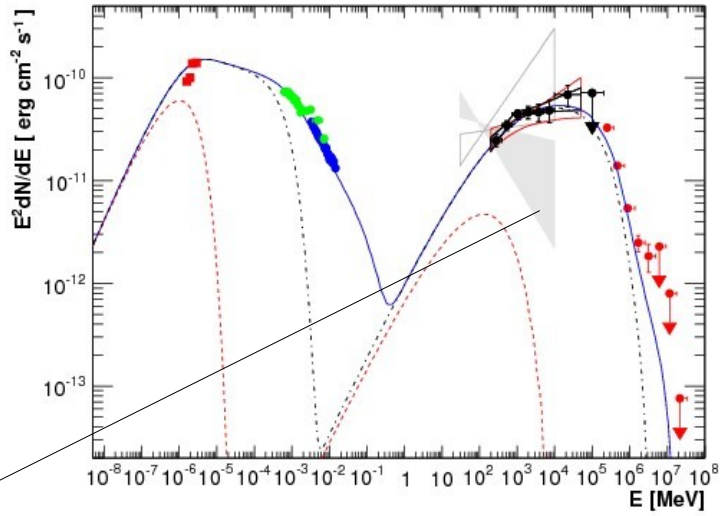
Blazars: Possible candidate for HE-Neutrinos

> Blazars: Active Galactic Nuclei **(AGN)** with jets

- Line of sight close to jet axis



"Double Hump" spectrum



Which processes create the "gamma peak"?

If hadronic:

Proton/Proton $p + \text{nucleus} \rightarrow \pi + X \quad (\pi = \pi^{\pm}, \pi^0)$

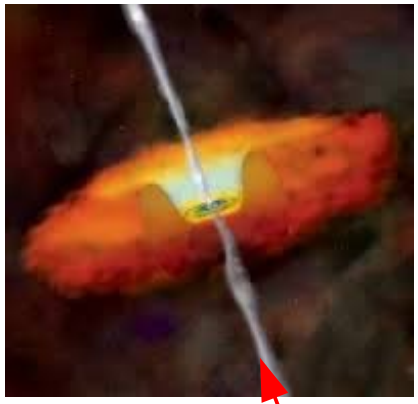
Photomeson $p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^0 + p \\ \pi^+ + n \end{cases},$

DESY

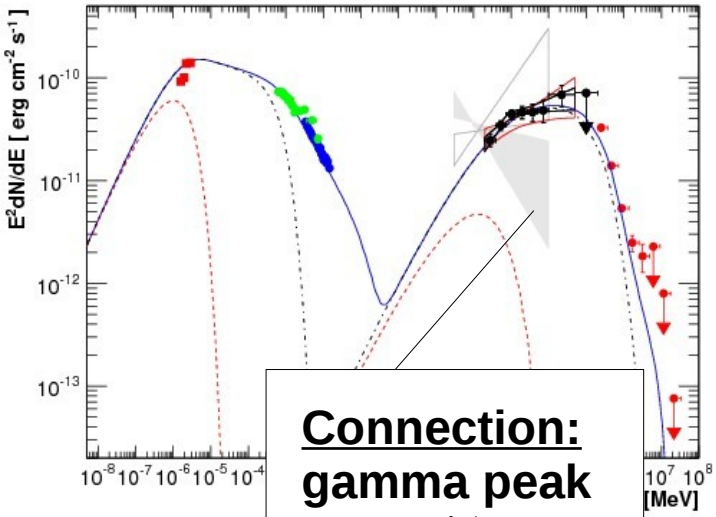
Blazars: Possible candidate for HE-Neutrinos

> Blazars: Active Galactic Nuclei **(AGN)** with jets

- Line of sight close to jet axis



"Double Hump" spectrum



Which processes create the "gamma peak"?

Connection:
gamma peak

⇕

Neutrinos

If hadro

Proton/Proton $p + \mathrm{nucl} \quad (= \pi^{\pm}, \pi^{0})$

Photomeson

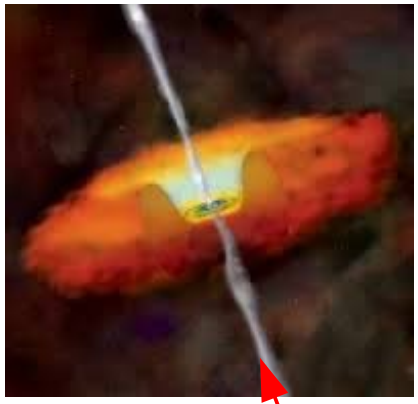
$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} \pi^{0} + p \\ \pi^{+} + n \end{cases},$$

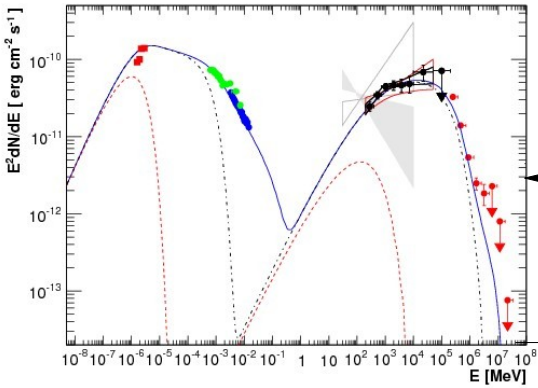
DESY

Blazars: Possible candidate for HE-Neutrinos

> Blazars: Active Galactic Nuclei **(AGN)** with jets

- Line of sight close to jet axis





Generation spectrum neutrinos

$E^{-\Gamma}$

Gammas reprocess to lower energies

100 GeV

~ PeV or higher

If

Connection: gamma peak

Neutrinos

Correlation between different energy ranges possible

Proton/Proton

Photomeson

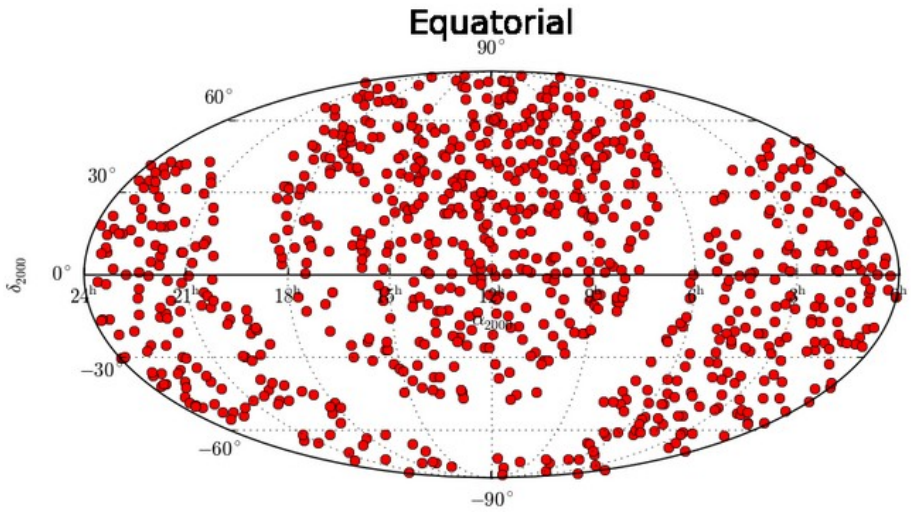
$$p \qquad X \qquad (\pi = \pi^{\pm}, \pi^{0})$$

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} \pi^{0} + p \\ \pi^{+} + n \end{cases},$$

DESY

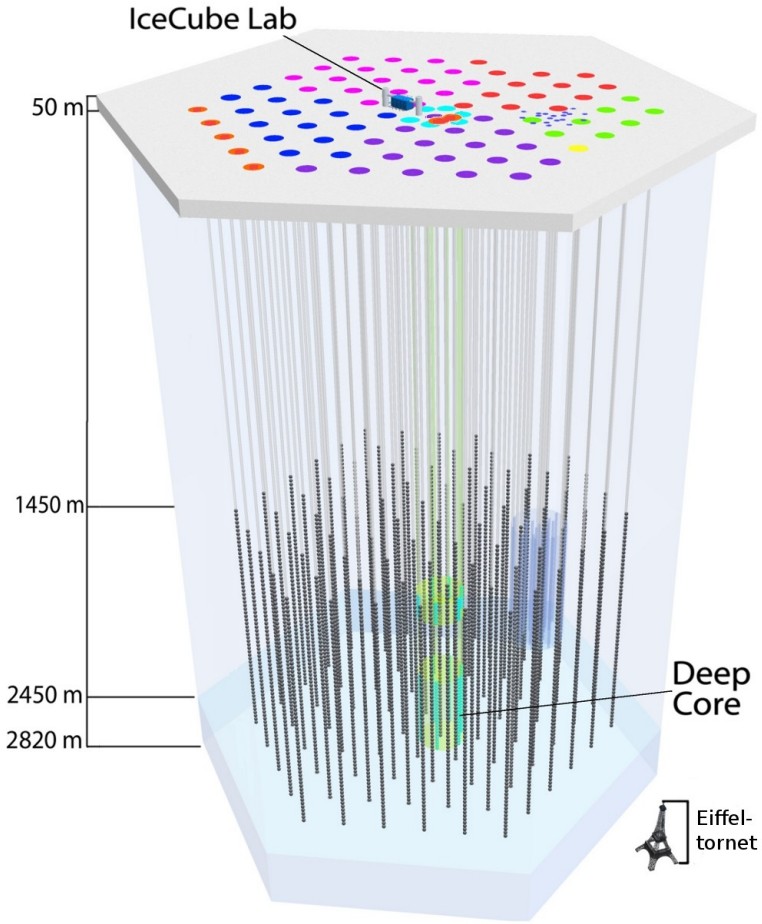
The General idea of this analysis

All Blazars in 2-LAC



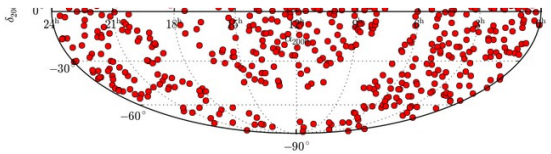
Look for cumulative faint flux with IceCube muon track data

As few assumptions as possible



The General idea of this analysis

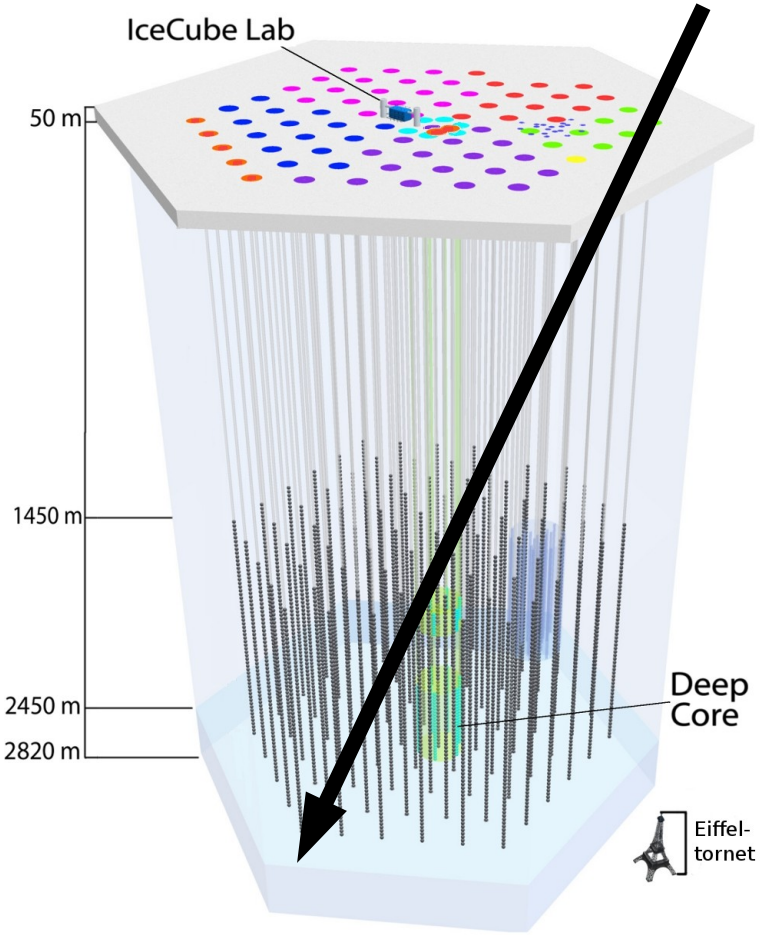
All Blazars in 2-LAC



Track event selection -> Good pointing (~ 1 deg)
(Muon tracks)

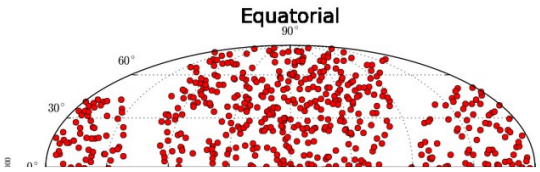
Southern sky (downgoing)
- Need high energy cut to reduce muon background
- Only sensitive to high energies (> 100 TeV)

Main Background: Atmospheric Muons

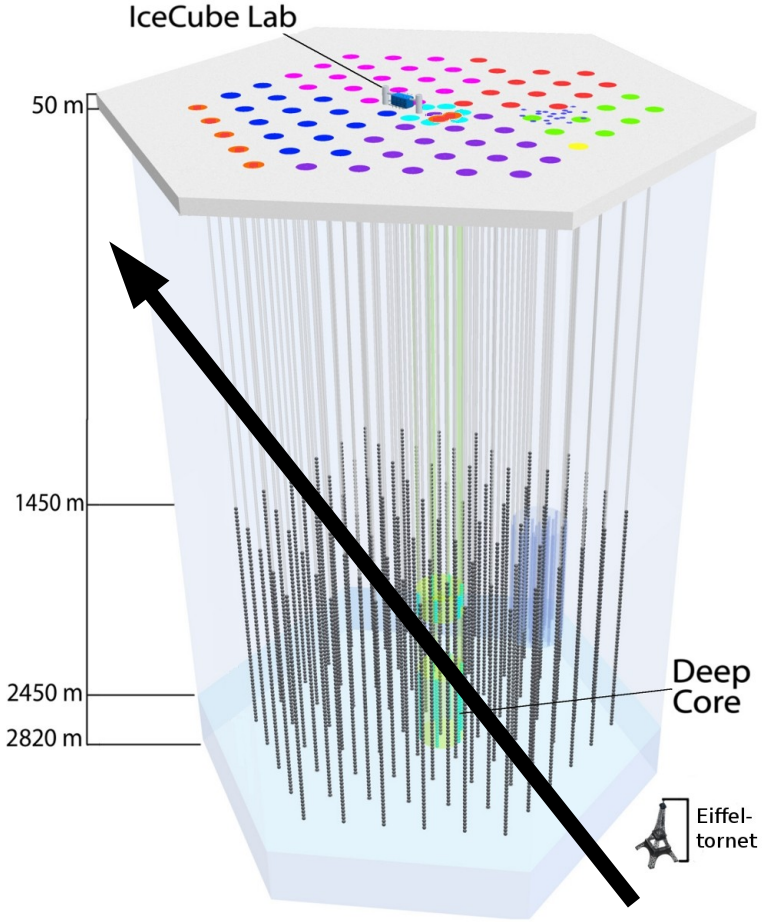


The General idea of this analysis

All Blazars in 2-LAC



Main Background: Atmospheric μ-Neutrinos



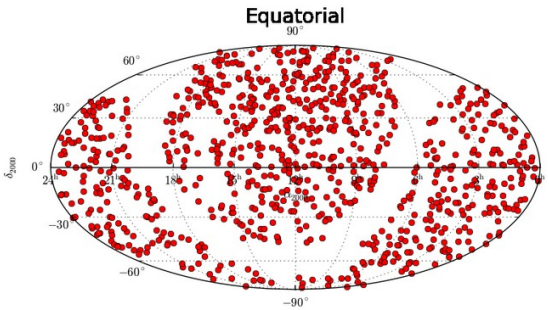
Track event selection -> Good pointing (~ 1 deg)
(Muon tracks)

Southern sky (downgoing)
- Need high energy cut to reduce muon background
- Only sensitive to high energies

Northern sky (upgoing)
- Can go to lower energies
- High energies (~ PeV) mostly absorbed in earth

The General idea of this analysis

All Blazars in 2-LAC

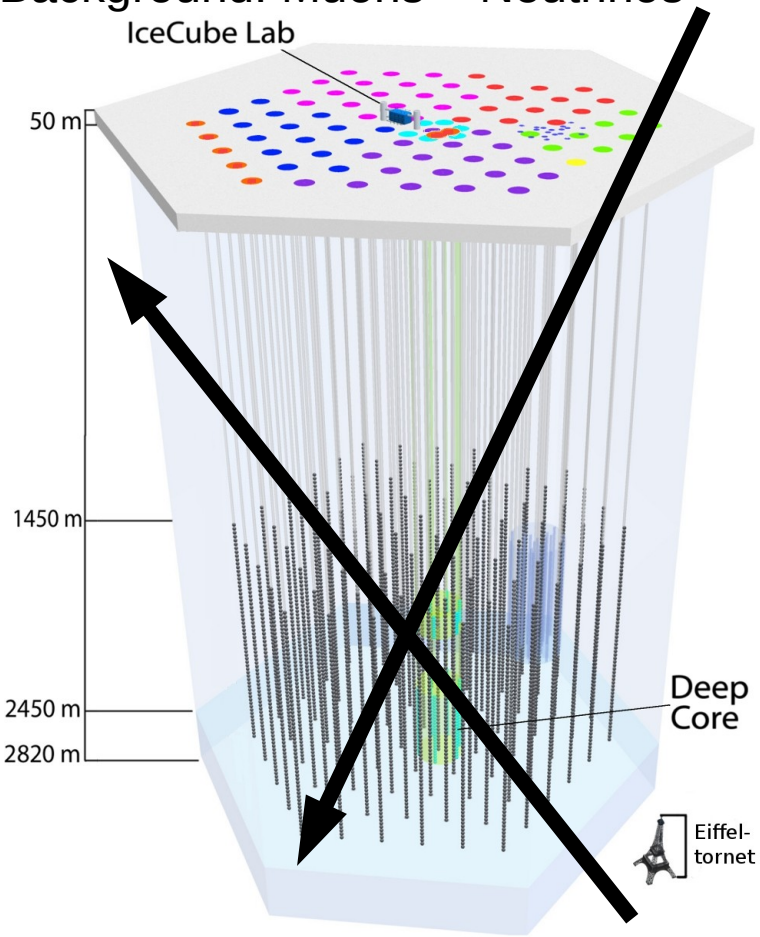


Track event selection -> Good pointing (~ 1 deg)
(Muon tracks)

Southern sky (downgoing)
- Need high energy cut to reduce muon background
- Only sensitive to high energies

Northern sky (upgoing)
- Can go to lower energies
- High energies (~ PeV) mostly absorbed in earth

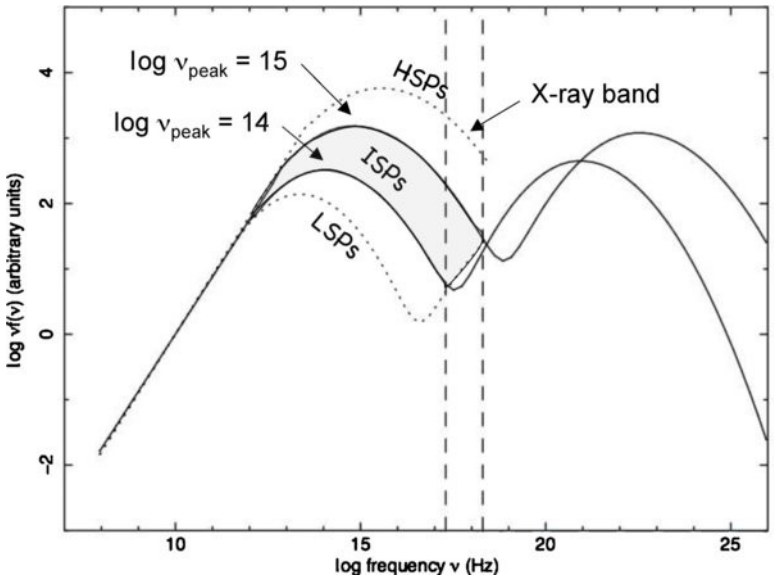
Background: Muons + Neutrinos



Complementary!

Classification of blazars used in this work

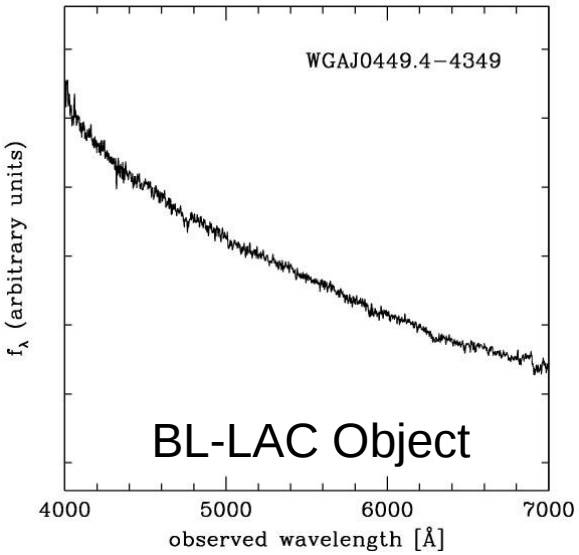
> 1) position of the synchroton peak

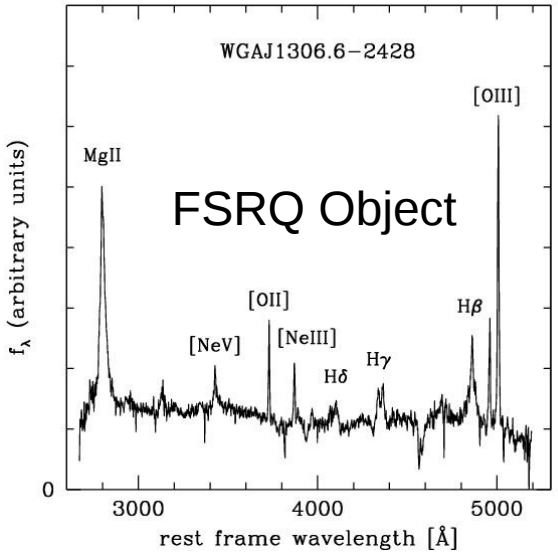


LSP < 10^{14} Hz < **ISP** < 10^{15} Hz < **HSP**
(**L**ow/**I**ntermediate/**H**igh **S**ynchroton **P**eaked)

Classification of blazars used in this work

> 2) rest frame width of optical emission lines





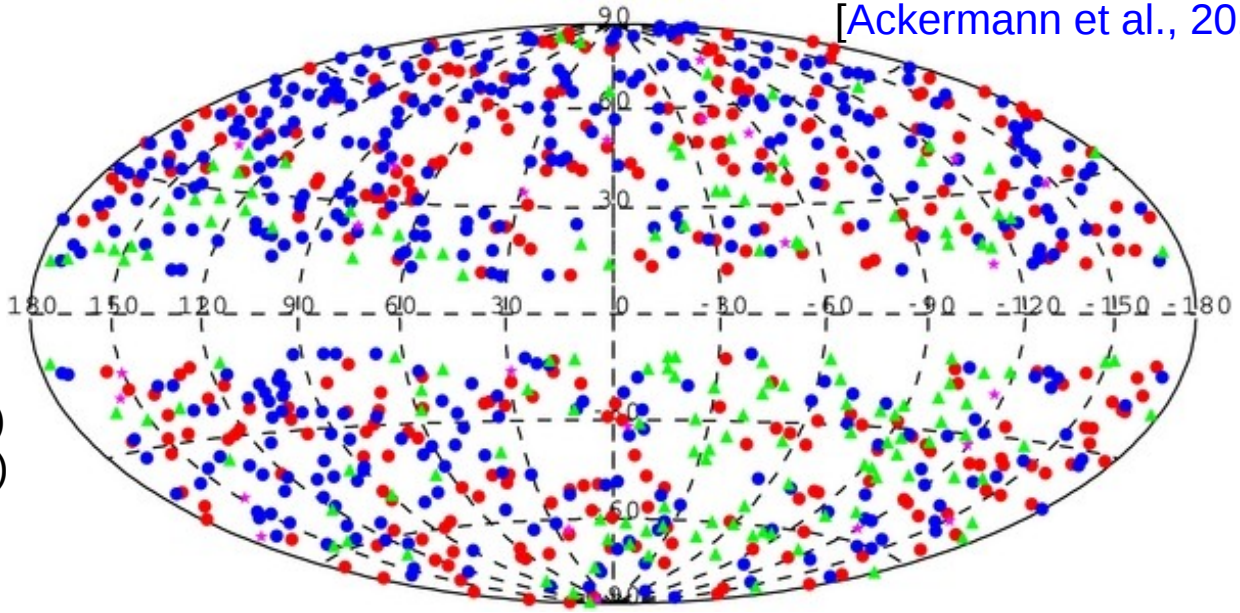
BL-LAC: emission lines with width < 5 Å

FSRQ: emission lines with width > 5 Å
(**F**lat **S**pectrum **R**adio **Q**uasar)

Fermi-LAT AGN catalogue (2-LAC)

FERMI-LAT AGN SKYMAP (|b| > 10)

[Ackermann et al., 2011]

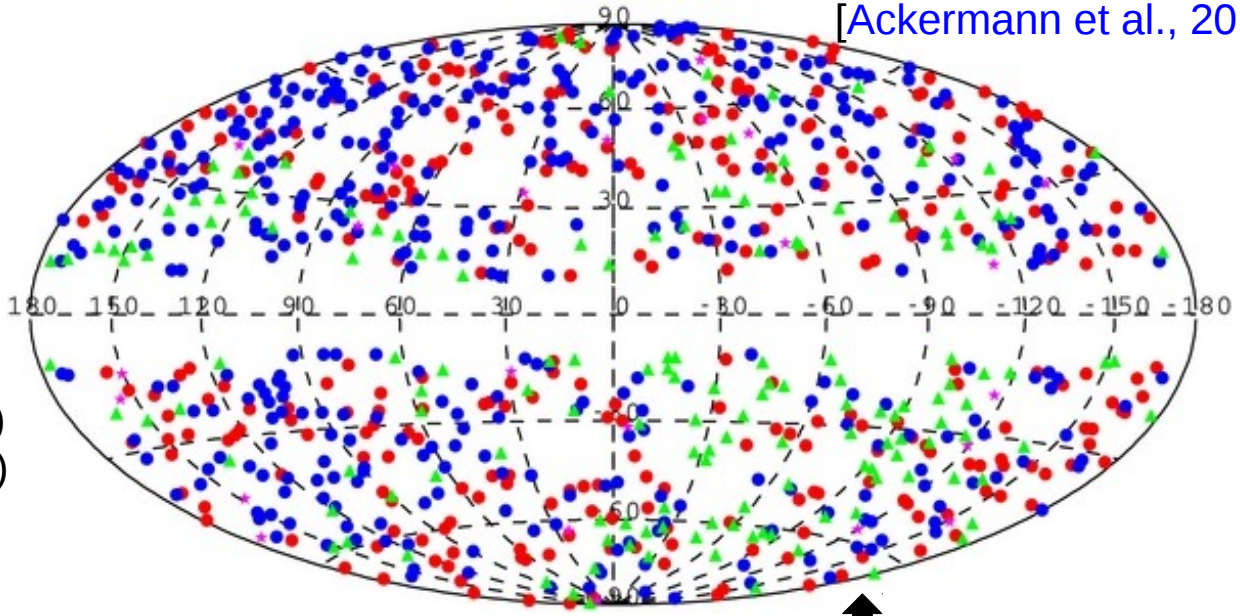


Total sources: 886
Magenta: Non-Blazar AGN (24)
Everything else: Blazars! (862)

Fermi-LAT AGN catalogue (2-LAC)

FERMI-LAT AGN SKYMAP (|b| > 10)

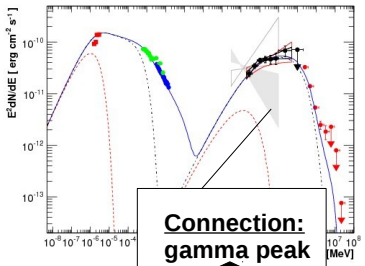
[Ackermann et al., 2011]



Total sources: 886
Magenta: Non-Blazar AGN (24)
Everything else: Blazars! (862)

> Largest 4-π (almost) flux limited sample

> For subpopulations (FSRQs), > 70% (85%) of total γ-emission is resolved [Ajello et al. 2012, ApJ, 751, 108 / Zeng et al. 2013, 10.1093/mnras/stt223]



Connection: gamma peak

Neutrinos

Entire Population study possible

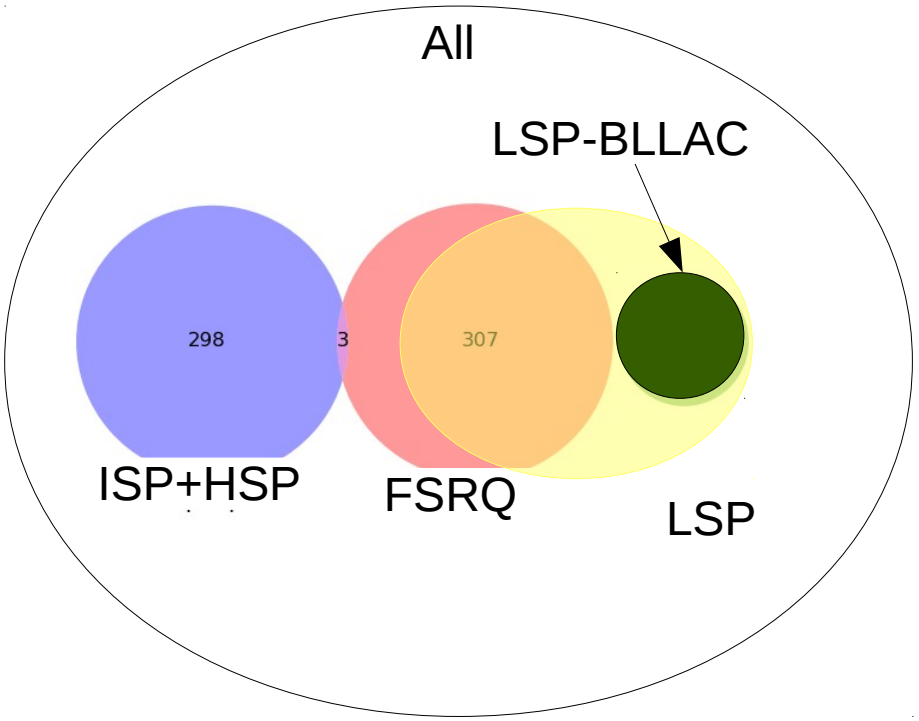
Overview

> Stacking analysis

- **5 populations (defined with FERMI-LAT)**
- ***FSRQ, LSP-BLLAC, ISP+HSP***

  LSP, ALL
- 3 years of IceCube track data (2009-2012)
- 2 weighting schemes
- 100s of sources per population

(862 sources total)
Overlap between populations



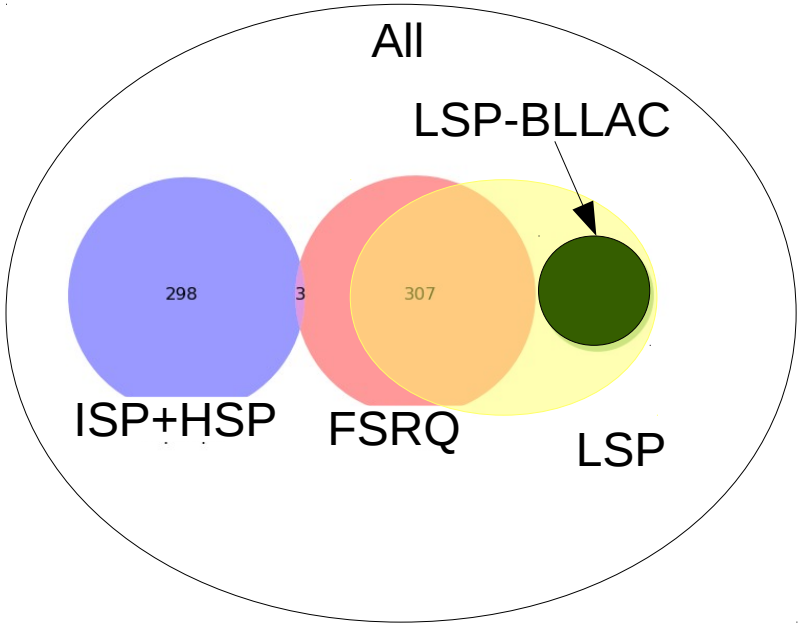
Overview

> Stacking analysis

- **5 populations (defined with FERMI-LAT)**
- ***FSRQ, LSP-BLLAC, ISP+HSP***

  LSP, ALL
- 3 years of IceCube track data (2009-2012)
- 2 weighting schemes
- **100s of sources per population**

(862 sources total)
Overlap between populations



Diffuse Search (100% of the sky)

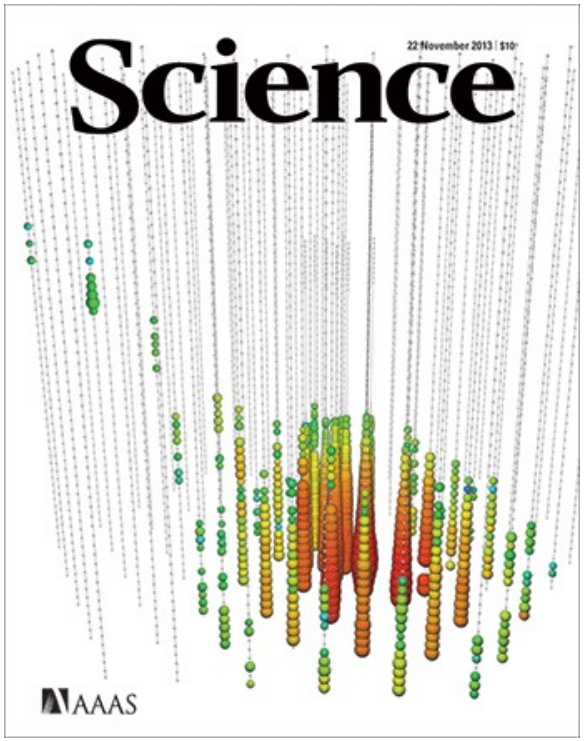
Mass stacking/ population search (1-10% of the sky)

Stacking/Extended sources (<< 1% of the sky)

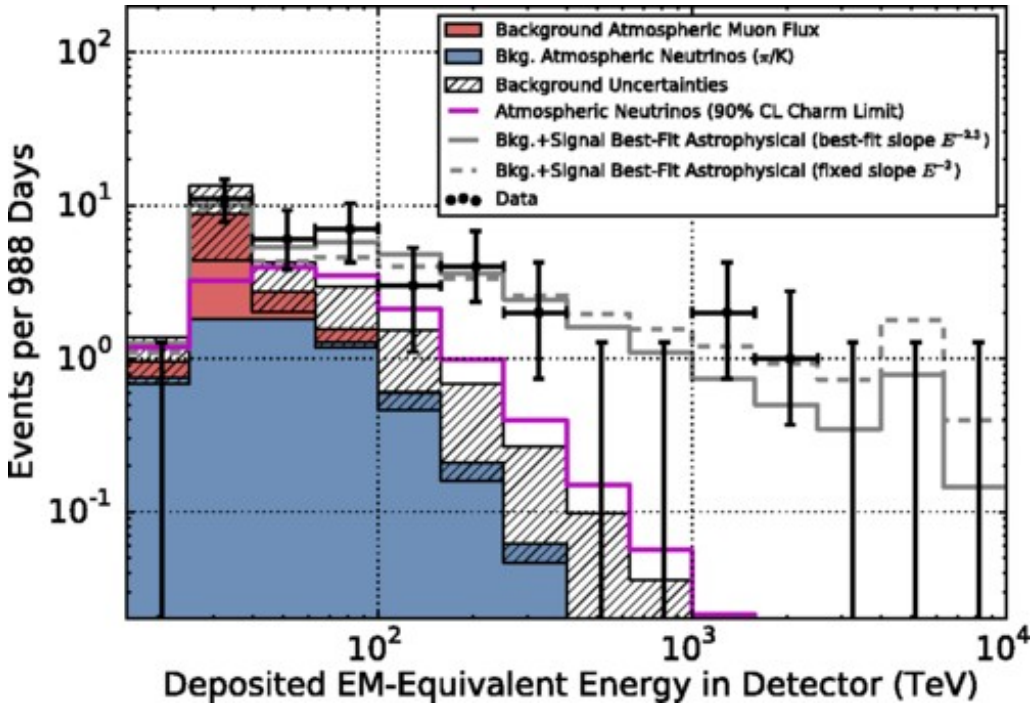
Individual Point sources

DESY

After discovery of the diffuse flux...



[IceCube Coll. 2013, IceCube Coll. 2014]



> Natural question:
How much do (FERMI-LAT) blazars (or a certain sub-population like FSRQs) contribute to the diffuse signal?

The Analysis

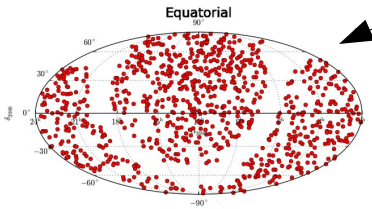
> Stacking: Test the **combined** emission of all sources

$$\ln(L) = \sum_{i}^{NEvents} \ln\left(\frac{n_s}{N_{tot}} \cdot S_i + \left(1 - \frac{n_s}{N_{tot}}\right) \cdot B_i\right)$$

The Analysis

> Stacking: Test the **combined** emission of all sources

$$\ln(L) = \sum_{i}^{NEvents} \ln\left(\frac{n_s}{N_{tot}} \cdot S_i + \left(1 - \frac{n_s}{N_{tot}}\right) \cdot B_i\right)$$



Composite
of many gaussian PSF's *

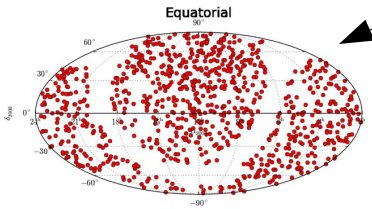
Almost flat distribution *
over the sky (from data)

*) + an energy term

The Analysis

> Stacking: Test the **combined** emission of all sources

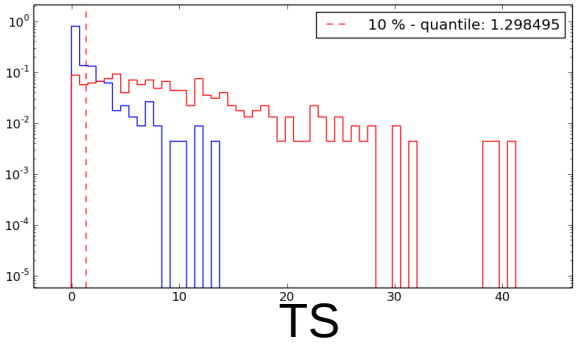
$$\ln(L) = \sum_{i}^{NEvents} \ln\left(\frac{n_s}{N_{tot}} \cdot S_i + \left(1 - \frac{n_s}{N_{tot}}\right) \cdot B_i\right)$$



Composite
of many gaussian PSF's

Almost flat distribution
over the sky (from data)

> LLH-Ratio defines test statistic



Blue: No Signal

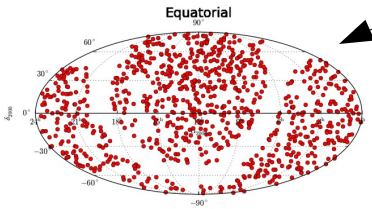
Red: Some Signal

> Use CL_s method to calculate limits (see e.g. [Zech '89])

The Analysis

> Stacking: Test the **combined** emission of all sources

$$\ln(L) = \sum_{i}^{NEvents} \ln\left(\frac{n_s}{N_{tot}} \cdot S_i + \left(1 - \frac{n_s}{N_{tot}}\right) \cdot B_i\right)$$



Composite
of many gaussian PSF's

Almost flat distribution
over the sky (from data)

“weight taking into account effective area at particular direction”

$$S_i = \sum_{j=1}^{N_{sources}} w_j \cdot S_{i,j}$$

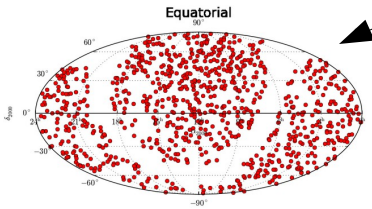
$$w_j = w_{\theta,j} * w_{relative,j}$$

“expected contribution to total neutrino flux from this source”

The Analysis

> Stacking: Test the **combined** emission of all sources

$$\ln(L) = \sum_{i}^{NEvents} \ln\left(\frac{n_s}{N_{tot}} \cdot S_i + \left(1 - \frac{n_s}{N_{tot}}\right) \cdot B_i\right)$$



Composite
of many gaussian PSF's

Almost flat distribution
over the sky (from data)

"weight taking into account effective area at particular direction"

$$S_i = \sum_{j=1}^{N_{sources}} w_j \cdot S_{i,j}$$

"fixed"

$$w_j = w_{\theta,j} * w_{relative,j}$$

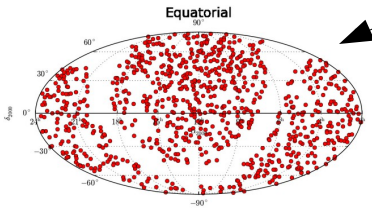
"expected contribution to total neutrino flux from this source"

DESY

The Analysis

> Stacking: Test the **combined** emission of all sources

$$\ln(L) = \sum_{i}^{NEvents} \ln\left(\frac{n_s}{N_{tot}} \cdot S_i + \left(1 - \frac{n_s}{N_{tot}}\right) \cdot B_i\right)$$



Composite
of many gaussian PSF's

Almost flat distribution
over the sky (from data)

"weight taking into account effective area at particular direction"

$$S_i = \sum_{j=1}^{N_{sources}} w_j \cdot S_{i,j}$$

"fixed"

$$w_j = w_{\theta,j} \cdot w_{relative,j}$$

"put in by hand"

"expected contribution to total neutrino flux from this source"

Relative weight is crucial in any stacking analysis

Weighting schemes

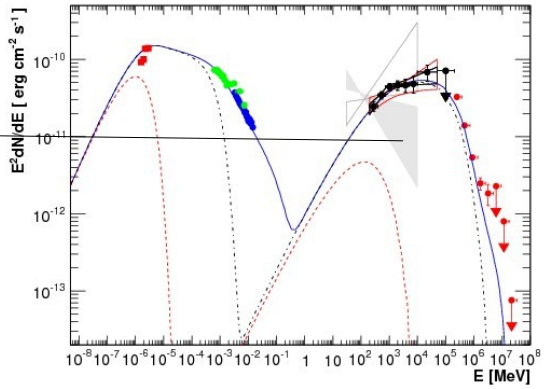
2 stacking weighting schemes

1)

$$\left(w_{relative,\,j} \propto \frac{\gamma_{lum.,\,j}}{4\pi \times d^2} \right)$$ [Energyflux in gammas at earth]

> The traditional approach

Connection:
gamma peak
⇕
Neutrinos



Weighting schemes

2 stacking weighting schemes

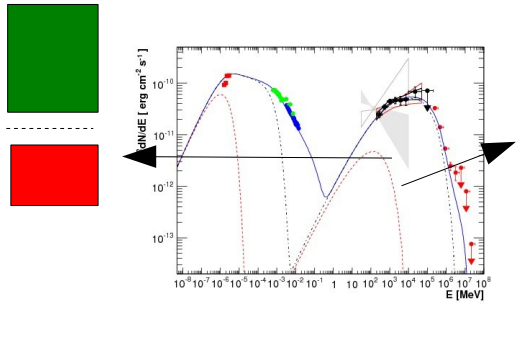
2)

All sources are equal

$$\left(w_{relative,j}=1\right)$$

Source 1

Source 2



Hadronic

Leptonic

Muon/Proton Synchroton

...

> The unbiased approach:

- What if hadronic contribution is sub-dominant?
- What if there is scatter in hadronic contribution?

DESY

One word on bias

2 stacking weighting schemes

2)

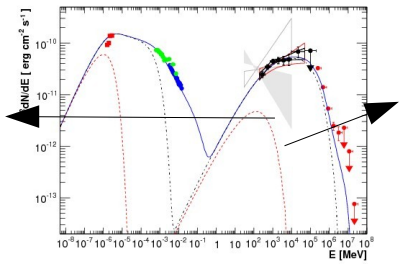
All sources are equal

$$\left(w_{relative,j}=1\right)$$

> The unbiased approach:

Source 1

Source 2



Hadronic

Leptonic

Muon/Proton Synchroton

...

Gamma emission is only used as a tracer for hadronic sites

Equal weighting + 100's of sources explores new parameter space

DESY

Results

Results

Preliminary

No of sources

Gamma (E-flux) Weighting

Name	n_s	Γ_{SI}	p-val
All Blazars	19	-2.8	36%
FSRQ	14	-2.6	34%
LSP	13	-2.6	36%
ISP+HSP	0		(>50%)
LSP-BLLAC	38	-3.2	13%

862
310
308
301
68

Equal Weighting

Name	n_s	Γ_{SI}	p-val
All Blazars	175	-3.0	6%
FSRQ	30	-2.7	34%
LSP	41	-2.8	28%
ISP+HSP	103	-3.3	11%
LSP-BLLAC	56	-3.0	7%

- n_s : best fit normalization parameter of signal pdf
- Γ_{SI}: best fit spectral index (~ +/- 0.4)

DESY

Results

Preliminary

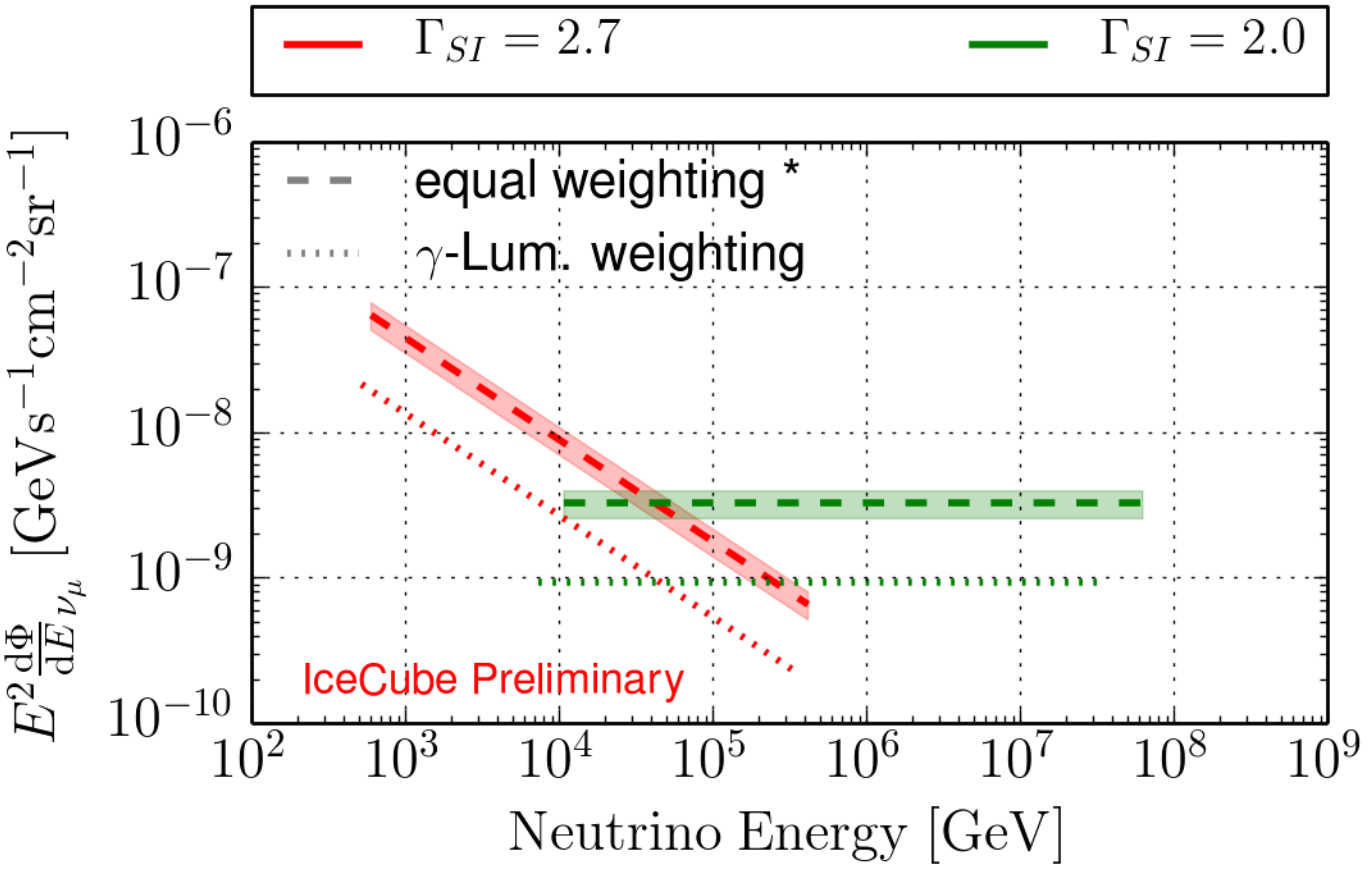
Gamma (E-flux) Weighting				No of sources	Equal Weighting			
Name	n_s	Γ_{SI}	p-val		Name	n_s	Γ_{SI}	p-val
All Blazars	19	-2.8	36%	862	All Blazars	175	-3.0	6%
FSRQ	14	-2.6	34%	310	FSRQ	30	-2.7	34%
LSP	13	-2.6	36%	308	LSP	41	-2.8	28%
ISP+HSP	0		(>50%)	301	ISP+HSP	103	-3.3	11%
LSP-BLLAC	38	-3.2	13%	68	LSP-BLLAC	56	-3.0	7%

- n_s : best fit normalization parameter of signal pdf
- Γ_{SI}: best fit spectral index (~ +/- 0.4)

DESY

Limit on ν_μ-Flux from all 2LAC Blazars

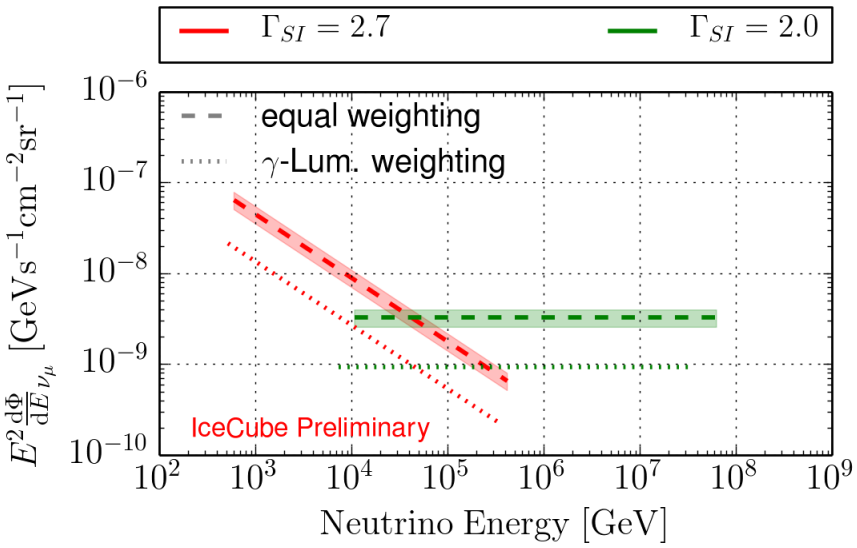
Preliminary



* Band denotes outcomes of random realizations of the luminosity function (source count distribution)

Explanation of limits

Preliminary

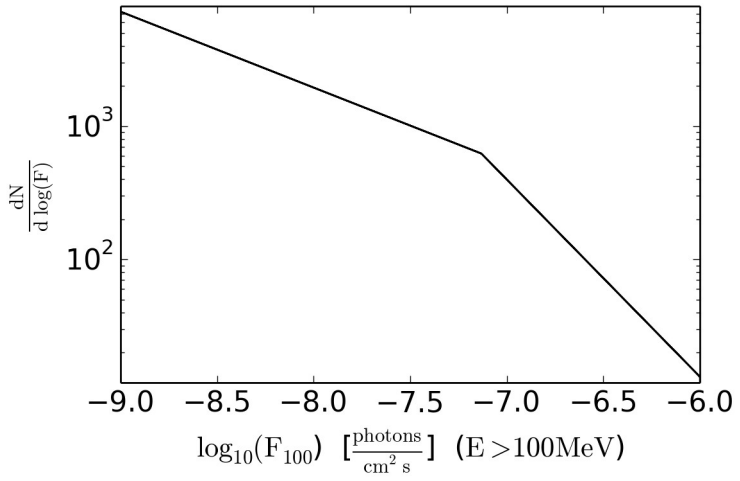


Step 1)

Take some source count distribution (here from Fermi-Blazars

[Abdo et al 2010, 10.1088/0004-637X/720/1/435])

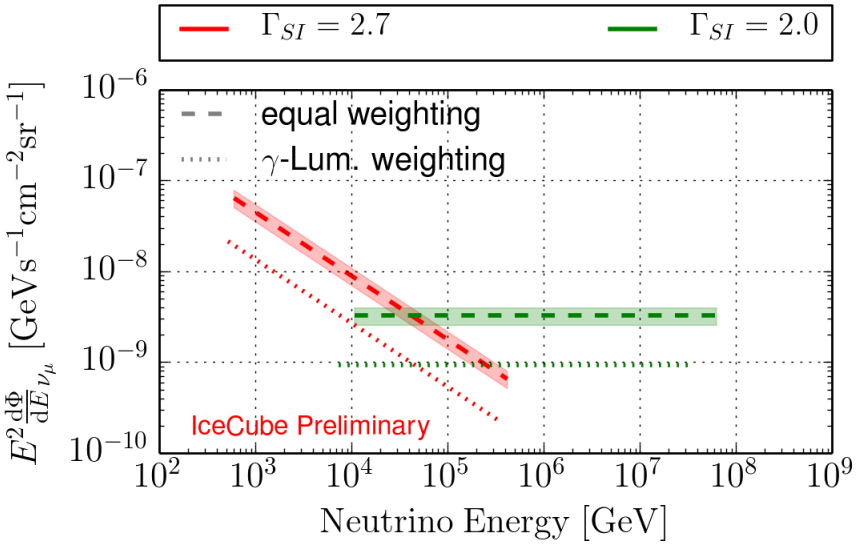
“distribution of sources with a given flux as measured on earth”



DESY

Explanation of limits

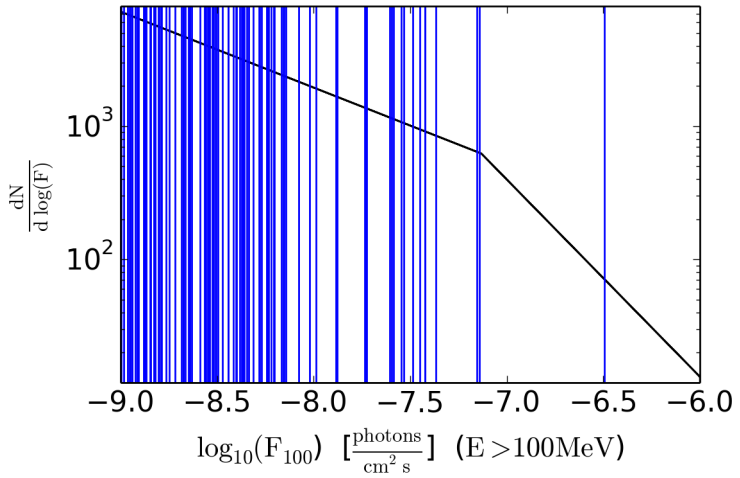
Preliminary



Step 2)

Sample from this source count distribution

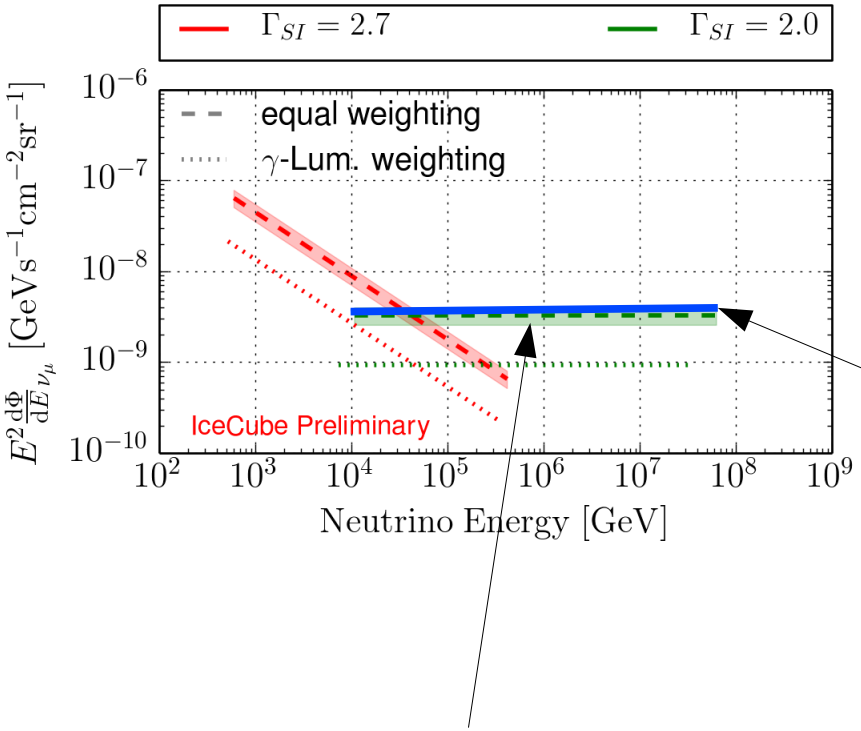
Sample points used as weights for neutrino emission among the sources



Explanation of limits

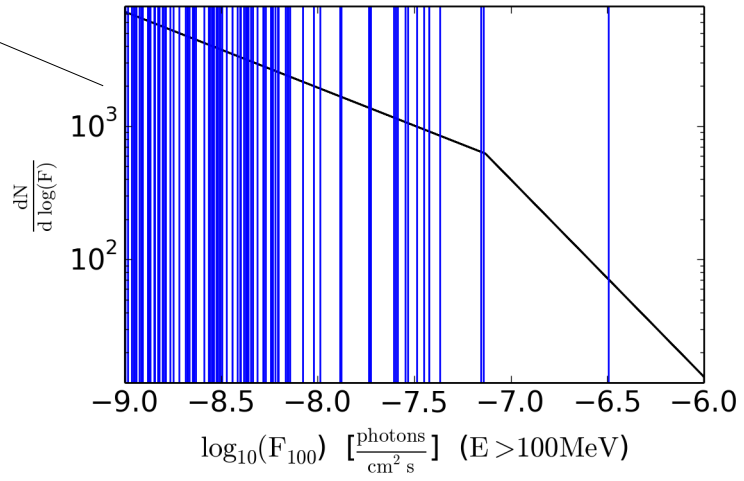
Preliminary

Step 3)



Point source analysis with sampled points giving neutrino emission among sources

Use equal weights in likelihood

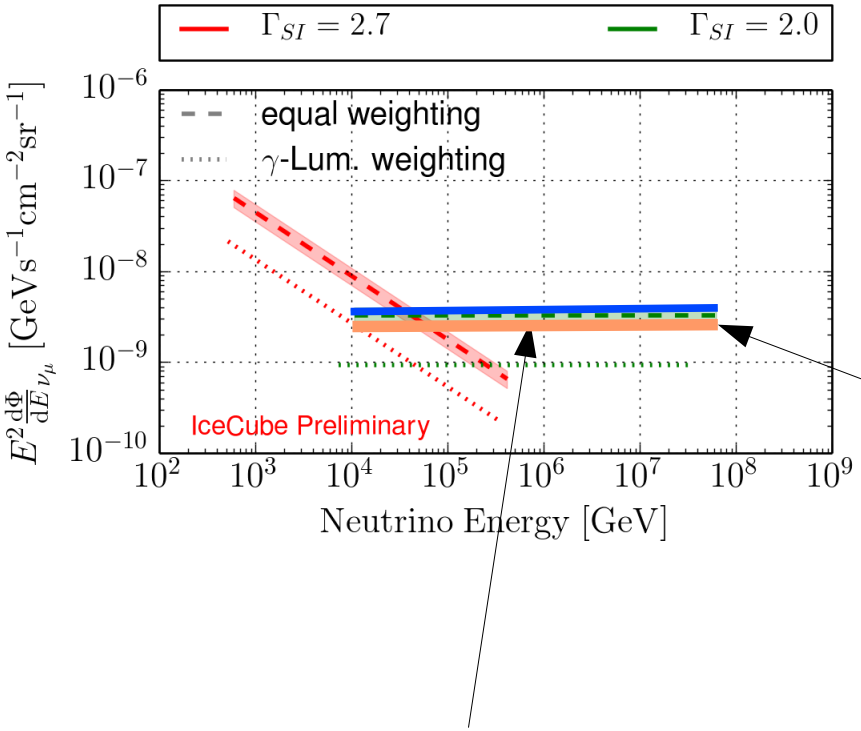


One limit for one particular realization of neutrino emission

Explanation of limits

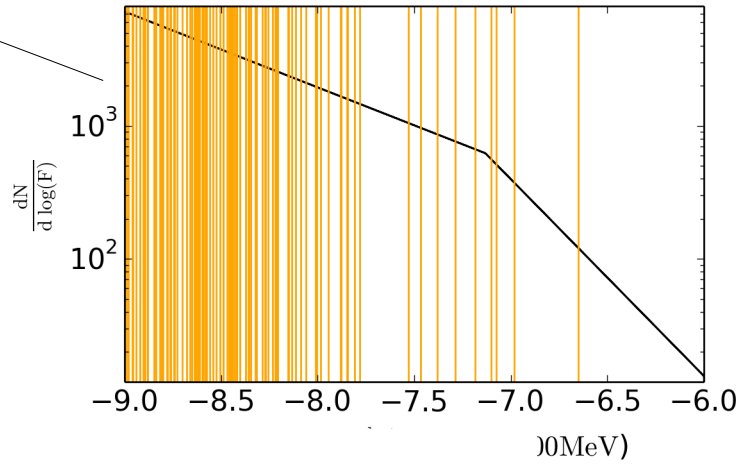
Preliminary

Repeat steps 1-3)



Point source analysis with sampled points giving neutrino emission among sources

Use equal weights in likelihood

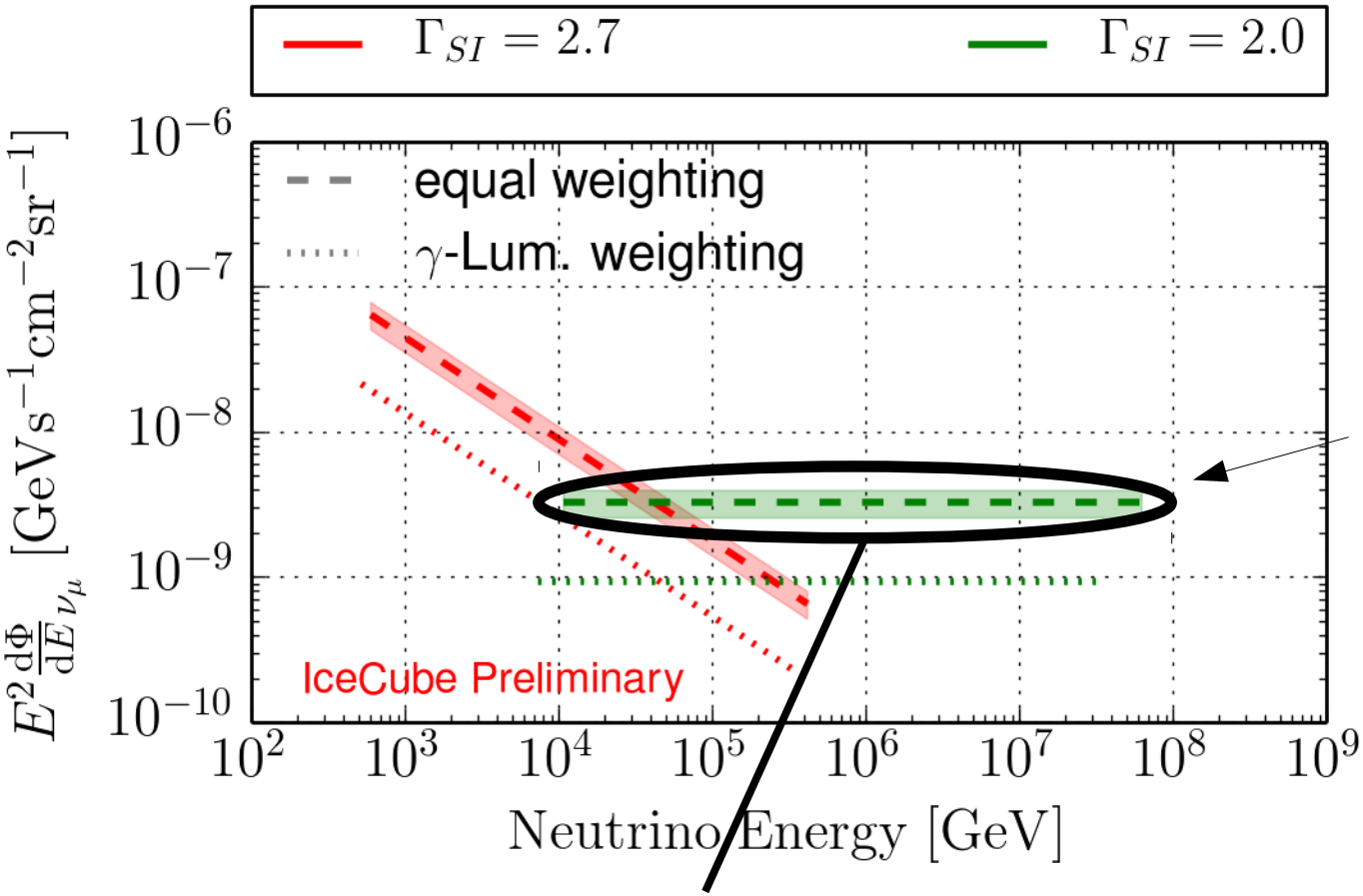


A second limit for another realization of neutrino emission

DESY

Explanation of limits

Preliminary

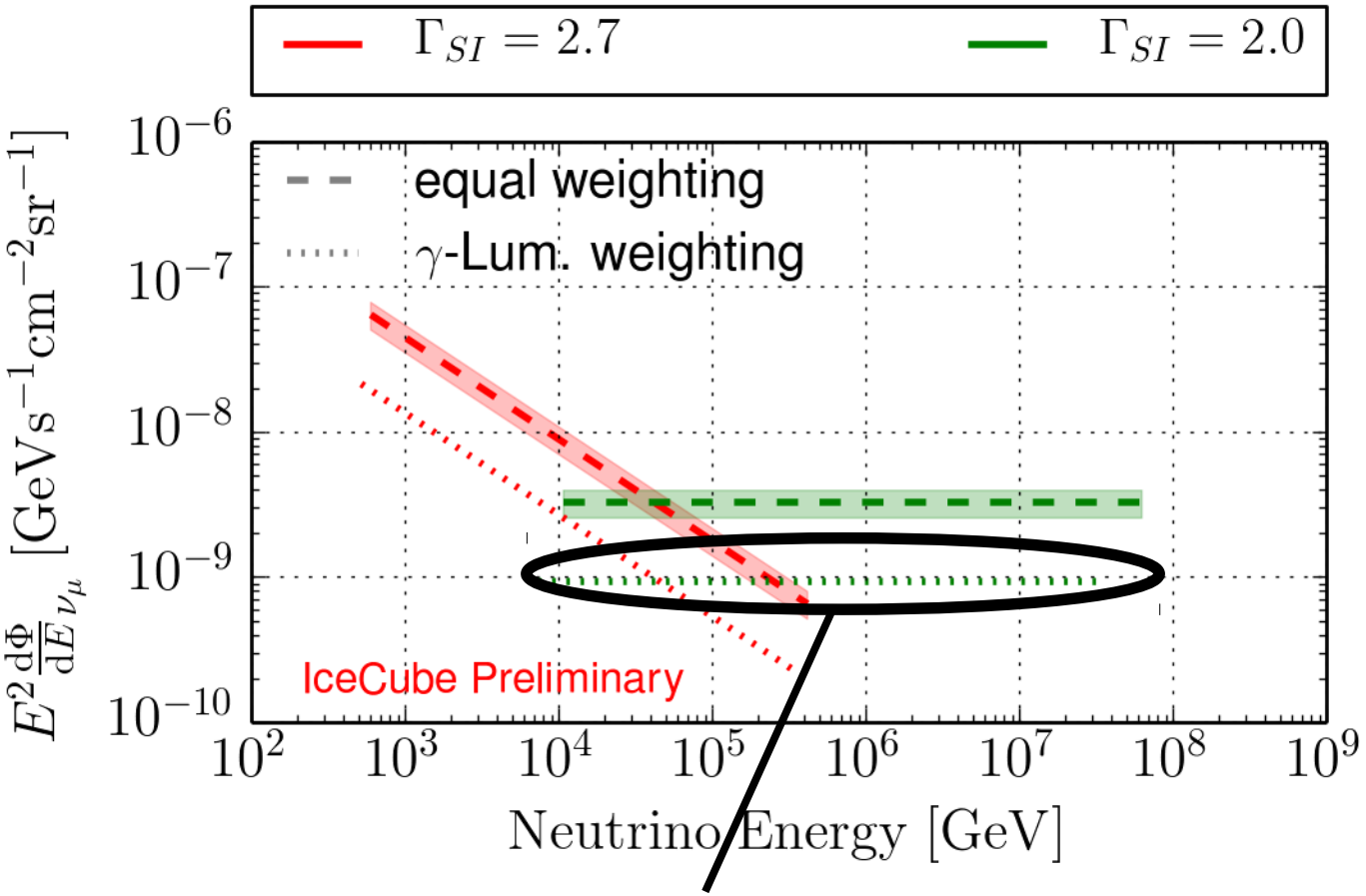


Do it many many times, one gets a band of limits

In fact, limit valid for all (quasi-)diffuse subpopulations using “realistic” source count distributions
-> conservative

Explanation of limits

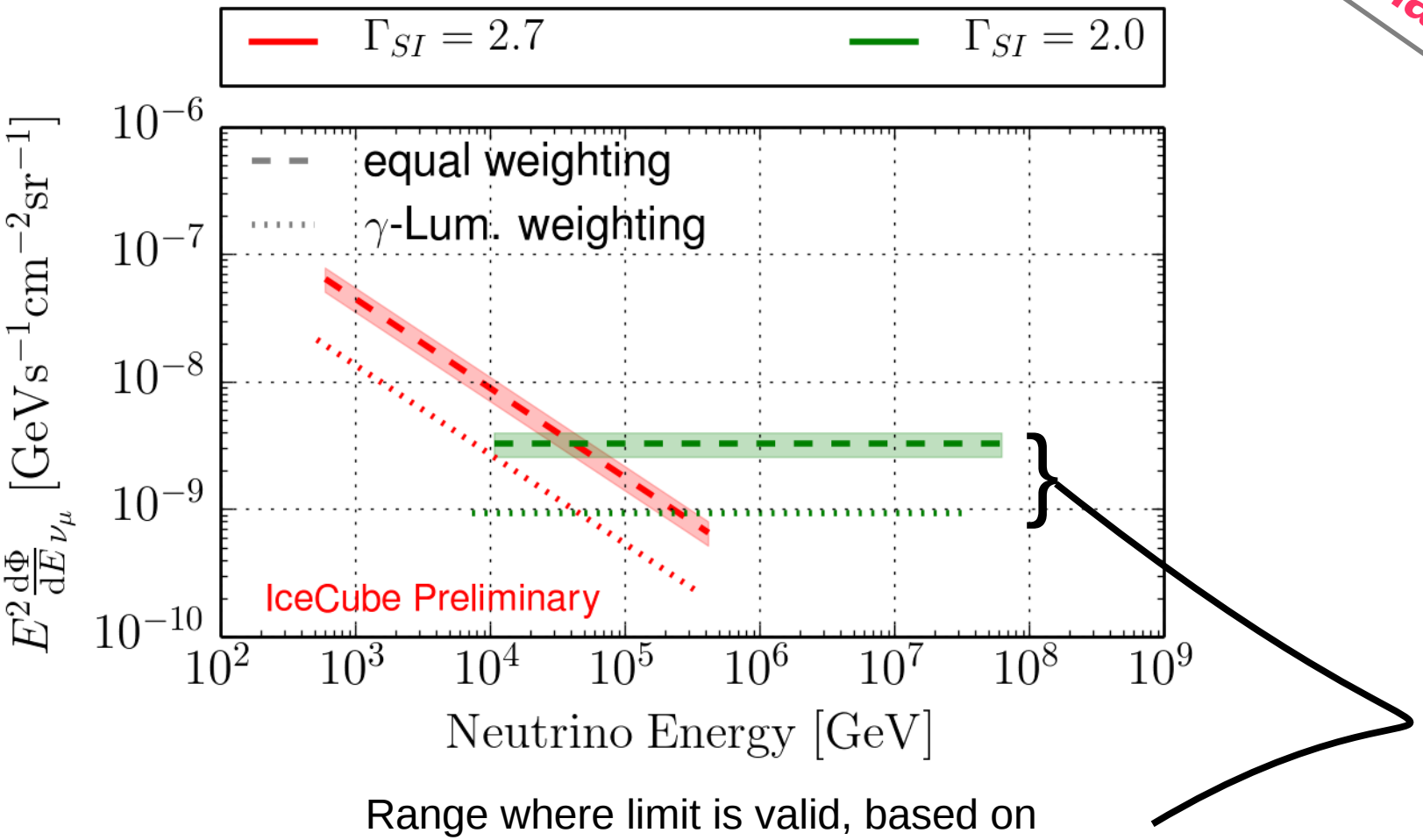
Preliminary



Limit valid assuming neutrino flux follows gamma (energy-)flux at earth
-> optimistic

Explanation of limits

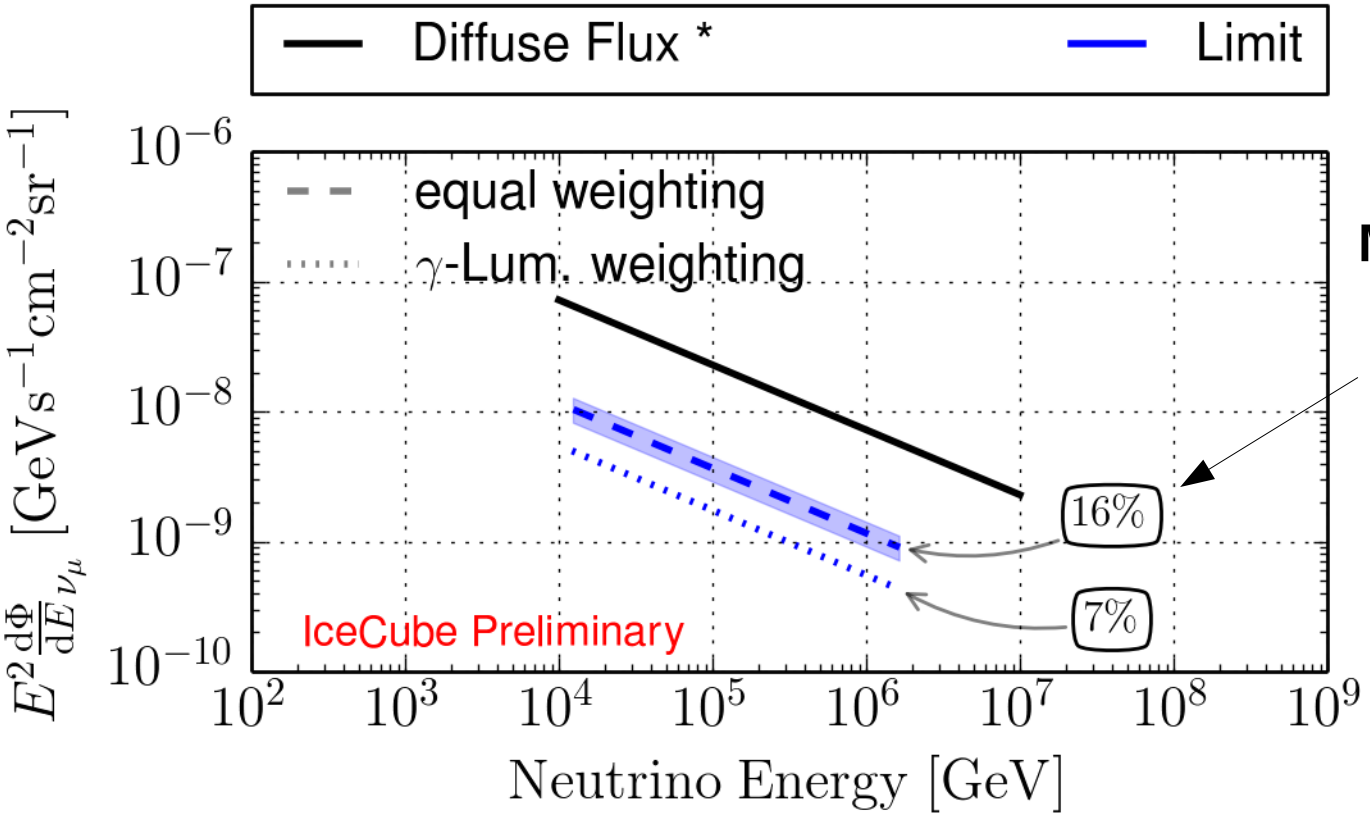
Preliminary



Range where limit is valid, based on optimistic / conservative assumptions about nature

Limit on ν_μ-Flux from all 2LAC Blazars

Preliminary



Max. contribution to best fit diffuse flux ($E^{-2.5}$)

*** new result** (~ $E^{-2.5}$), **shown at ISVHECRI 2014, see talk by J. van Santen**

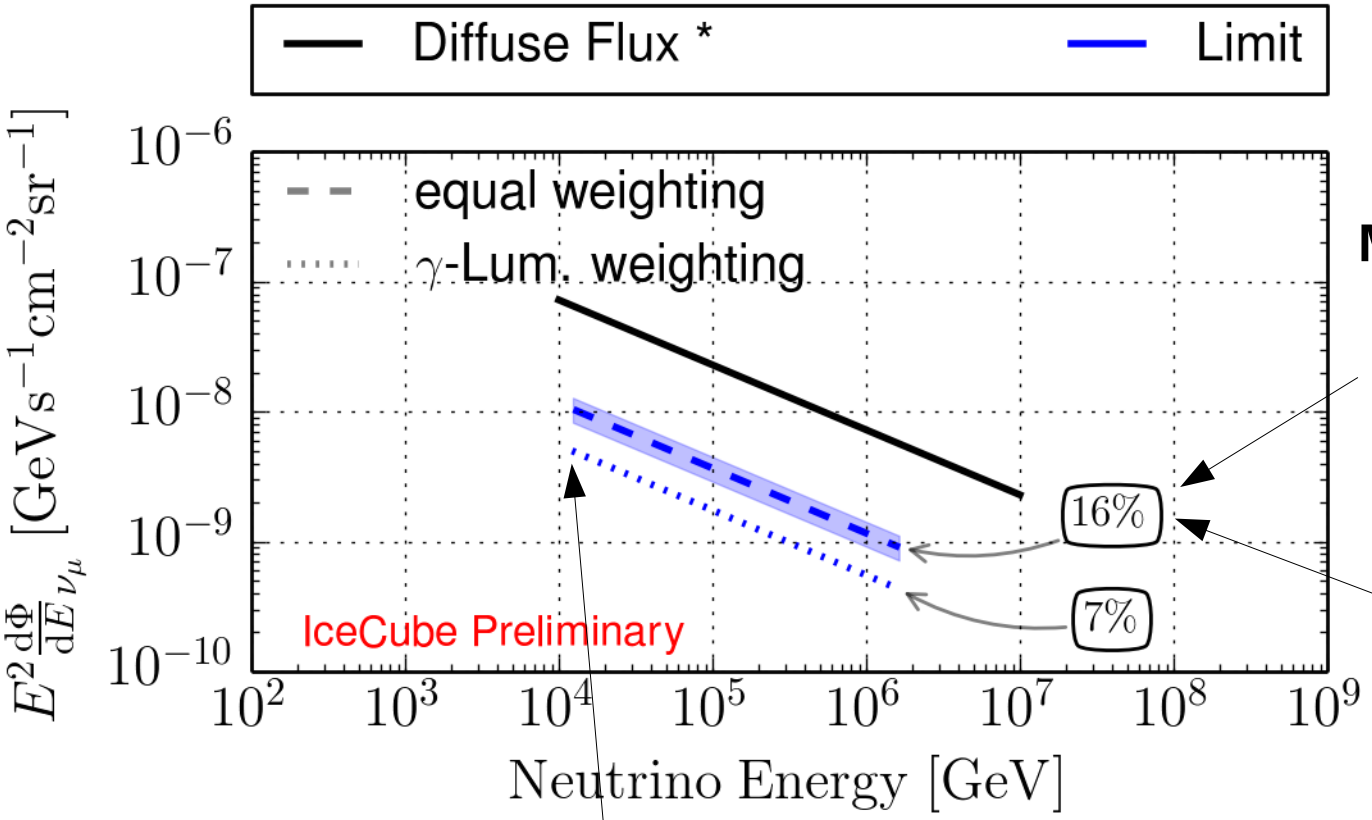
Assumptions:

· 1:1:1 ratio of flavors

DESY

Limit on ν_μ-Flux from all 2LAC Blazars

Preliminary



Max. contribution to best fit diffuse flux ($E^{-2.5}$)

Valid for (quasi-)isotropic subpopulations, e.g. **TeVCat sources** in the catalogue

* **new result** (~ $E^{-2.5}$), **shown at ISVHECRI 2014, see talk by J. van Santen**

Assumptions:

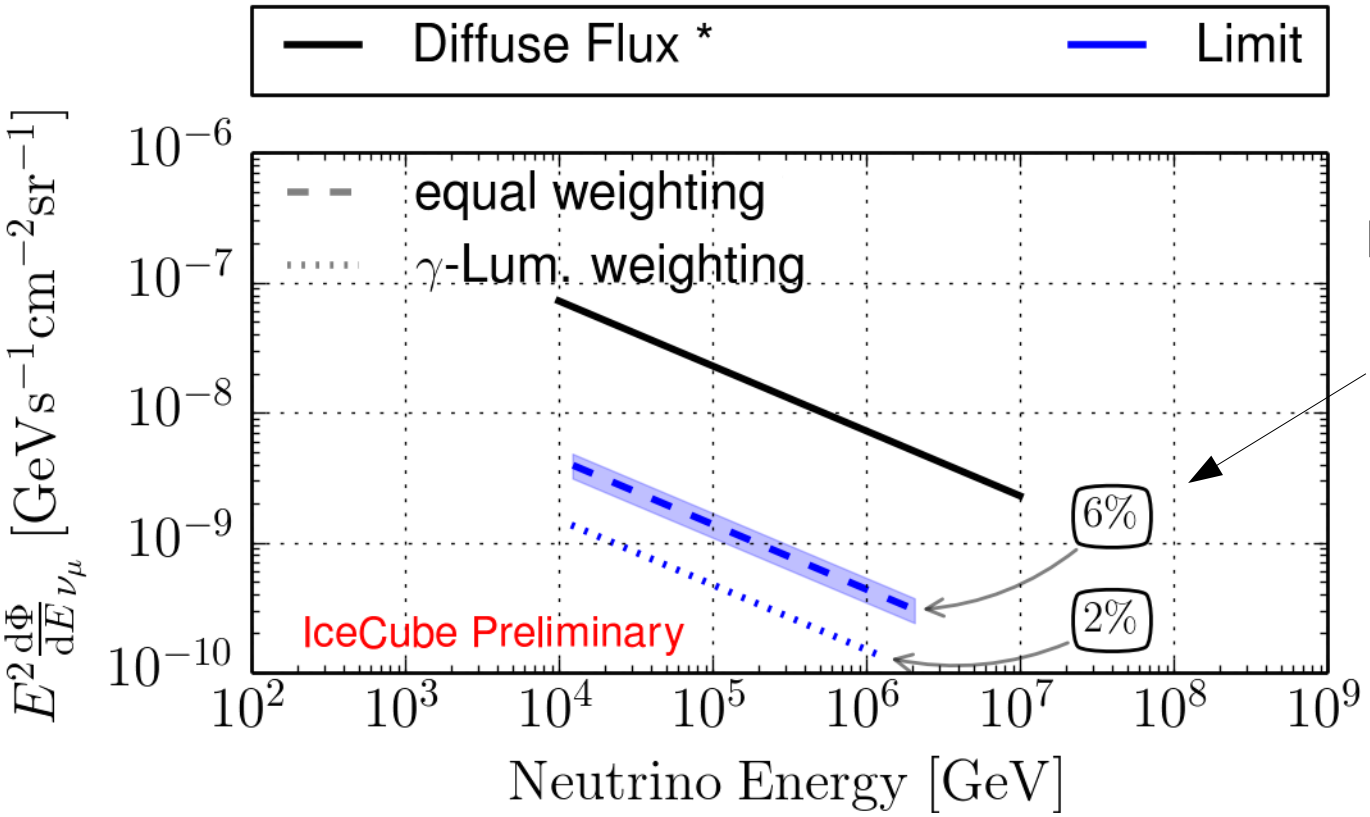
· 1:1:1 ratio of flavors

Starting at 10 TeV (conservative) to be comparable to measurement

DESY

Limit on ν_μ-Flux from all 2LAC FSRQ's

Preliminary



Max. contribution to best fit diffuse flux ($E^{-2.5}$)

*** new result** (~ $E^{-2.5}$), **shown at ISVHECRI 2014, see talk by J. van Santen**

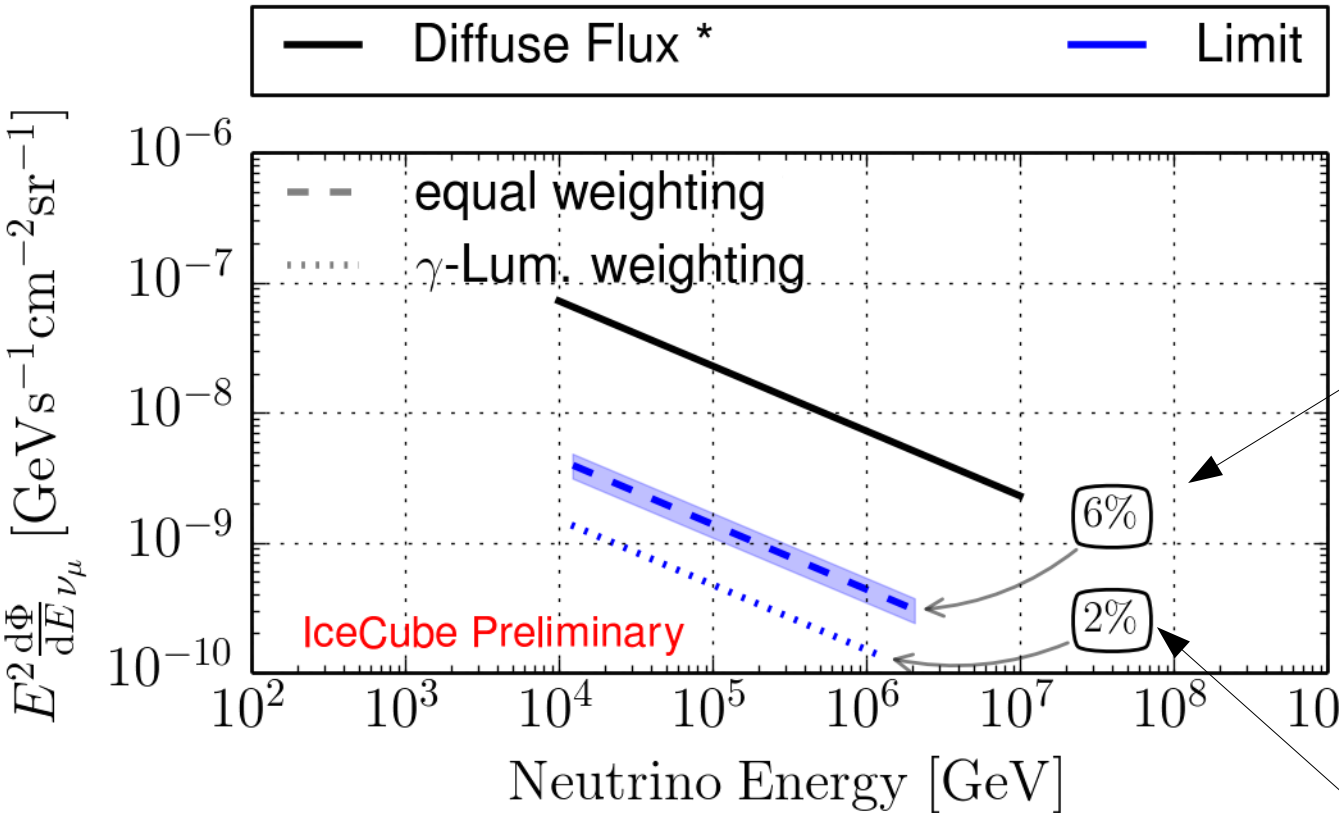
Assumptions:

· 1:1:1 ratio of flavors

DESY

Limit on ν_μ-Flux from all 2LAC FSRQ's

Preliminary



Max. contribution to best fit diffuse flux ($E^{-2.5}$)

Limit extendable to all FSRQs in observable universe

* **new result** (~ $E^{-2.5}$), **shown at ISVHECRI 2014, see talk by J. van Santen**

Assumptions:
- 1:1:1 ratio of flavors
- $\nu \propto \gamma$ + 70 % of gamma resolved

DESY

Conclusions

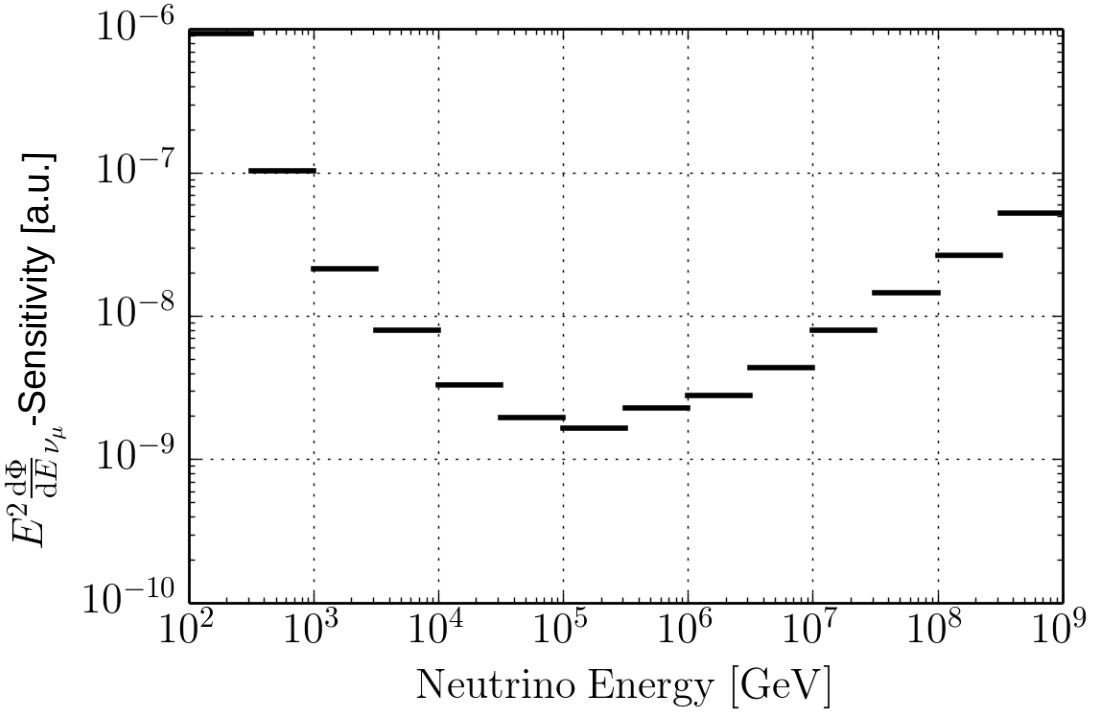
- Nothing significant observed
  - Best p-value: 6% (all blazars, equal weighting)
- The diffuse neutrino flux is not dominantly produced by FERMI-LAT blazars or any subpopulation (e.g. majority of TeVCat blazars)
  - Contribution < ~ 15 % (astrophysical S.I. ~ 2.5)
- For specific blazar samples (e.g. FSRQs) this constraint can be tighter
  - FSRQs: Contribution < ~ 5 % (astrophysical S.I. ~ 2.5)
- More years of data will tell in the future if the mild overfluctuation (6%) was only a fluke or not (**almost 3 more years of data taken already**)

Backup

Determination of energy range

Preliminary

Energy range determined from differential sensitivity

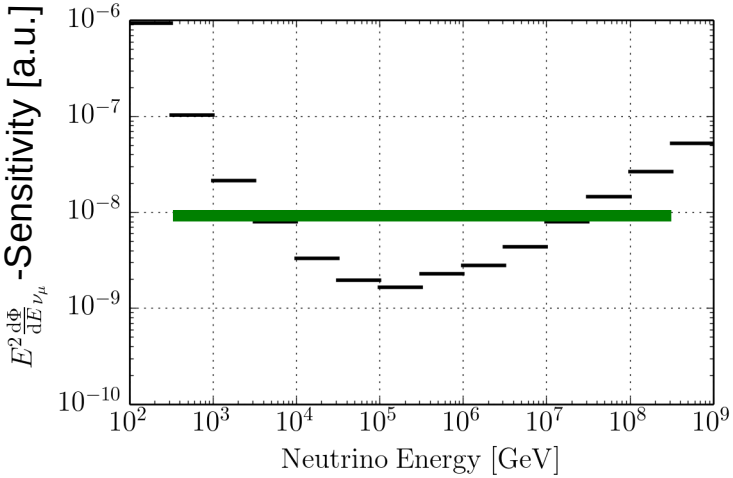


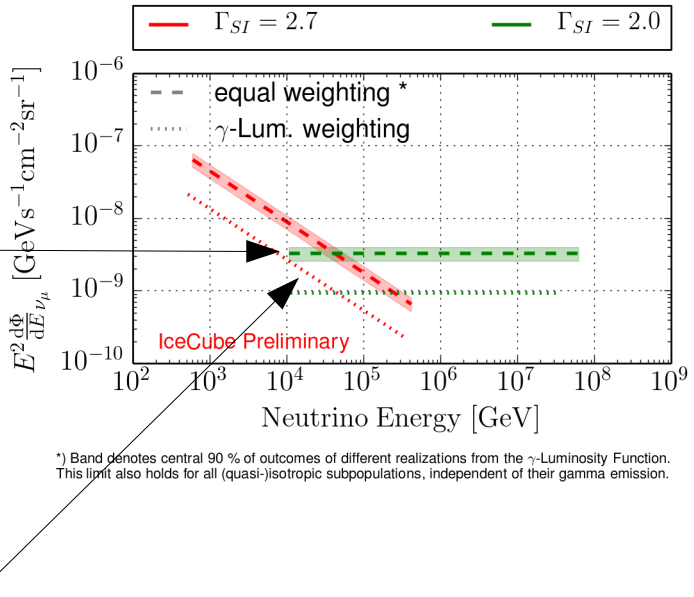
Determination of energy range

Preliminary

Energy range determined from differential sensitivy

Hard flux: E^-2





*) Band denotes central 90 % of outcomes of different realizations from the γ-Luminosity Function. This limit also holds for all (quasi-)isotropic subpopulations, independent of their gamma emission.

The energy region, where 90 % of the contribution to the limit comes from, is shown in this plot

-> validity region of the limit

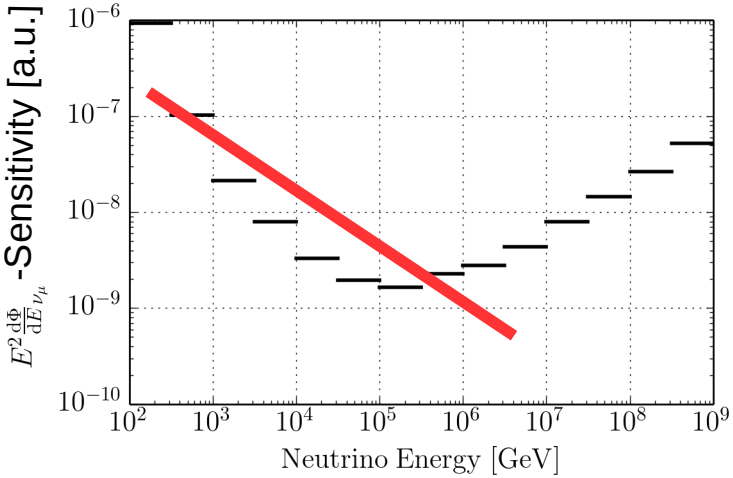
DESY

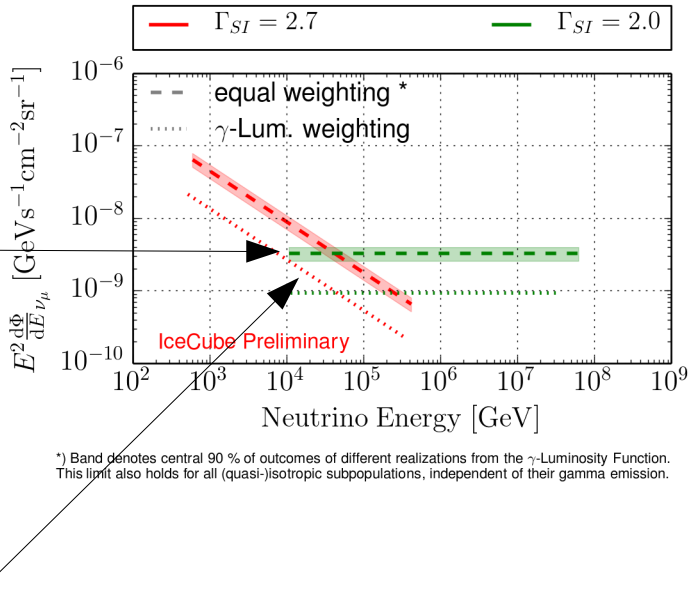
Determination of energy range

Preliminary

Energy range determined from differential sensitivy

Soft flux: E^-2.7





The energy region, where 90 % of the contribution to the limit comes from, is shown in this plot

-> validity region of the limit

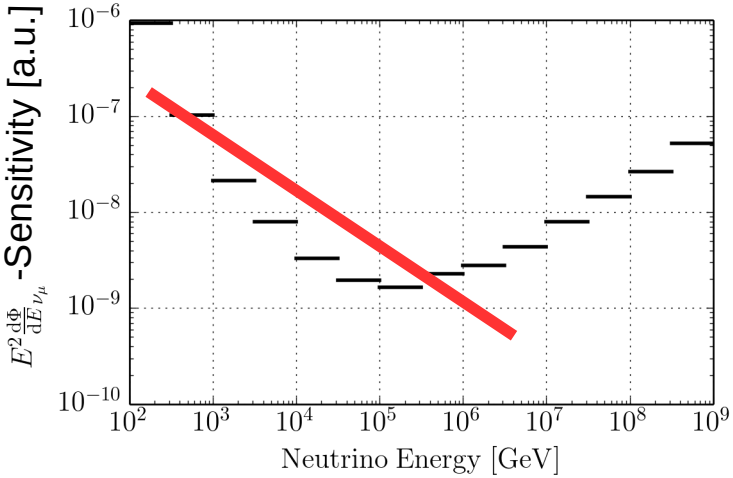
DESY

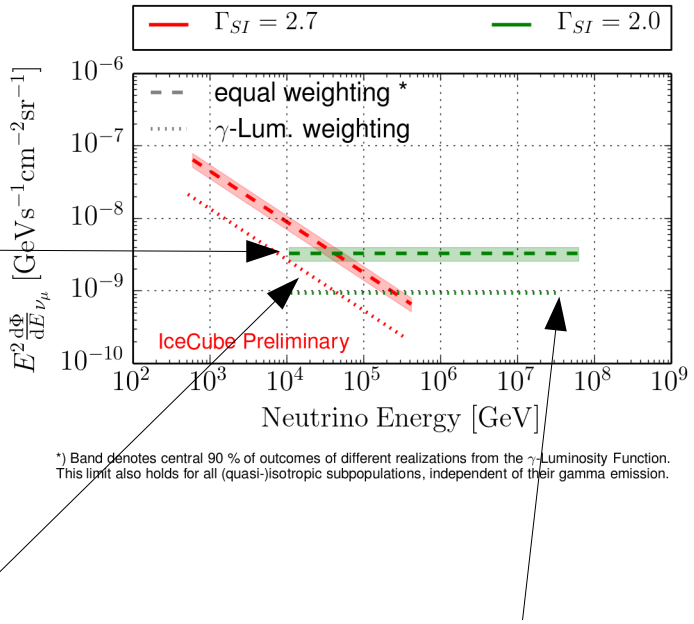
Determination of energy range

Preliminary

Energy range determined from differential sensitivy

Soft flux: E^-2.7





The energy region, where 90 % of the contribution to the limit comes from, is shown in this plot

-> validity region of the limit

Minor differences because of weighting

DESY