High energy neutrino emission from obscured sources through the pp channel

Matthias Vereecken

Vrije Universiteit Brussel

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Outline

Introduction & Motivation

Obscured flat spectrum radio AGN

Neutrino modelling

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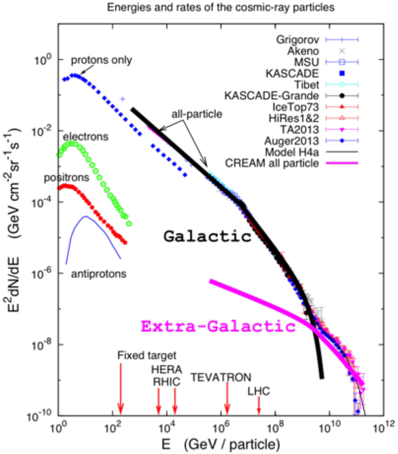
Cosmic rays

Observed cosmic rays

- Galactic
- Extragalactic

Composition unknown

Sources?



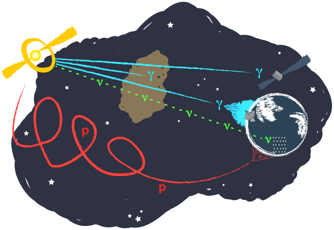
(Blasi 2014)

Multimessenger paradigm

Multimessenger astronomy

Combine information from different messengers to learn more about the sources

- Photons (IR, optical, x-ray, γ)
- Cosmic rays
- **Neutrinos**
- Gravitational waves



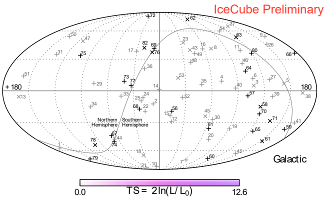
(J. A. Aguilar & J. Yang, IceCube/WIPAC)

Astrophysical neutrino flux

Observed astrophysical neutrino flux

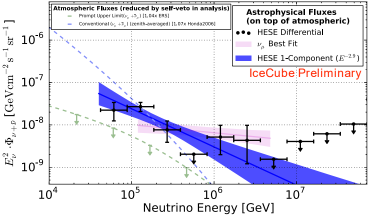
$$E^2\phi_\nu(E) \propto 10^{-8}\left(\frac{E}{100\ \mathrm{TeV}}\right)^{2-\alpha}$$

with



(PoS (ICRC2017) 981)

HESE $\alpha = -2.92^{+0.33}_{-0.29}$



(PoS (ICRC2017) 981)

Muons $\alpha = -2.19 \pm 0.10$

(PoS (ICRC2017) 1005)

Neutrinos and UHECRs

Estimation neutrino flux

UHECR energy production rate
$E_{cr} Q_{E_{cr}} = 0.5 \times 10^{44} \ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}$

Typical targets

Waxman-Bahcall bound
$E_\nu^2 \phi_i \approx 10^{-8} \ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$

Coincidence with measured flux

$\Rightarrow$ Energy production rate

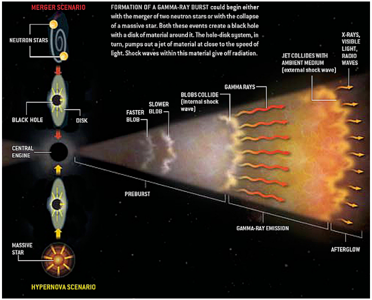
$$\text{UHECR } (> 10^{19} \text{ eV}) \approx \text{neutrinos } (\sim 0.1 - 1 \text{ PeV})$$

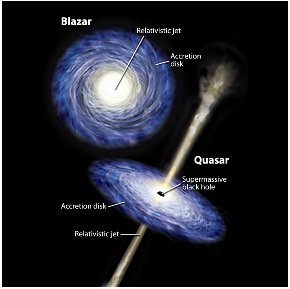
Searching for the sources of high energy neutrinos/UHECRs

CR accelerator Gamma-ray bursts, active galactic nuclei

- $p\gamma$ channel
- Lower cut-off: pion production threshold

$$E_{\rm min} \sim \Gamma^2 m_p m_\pi c^4 / E_\gamma \rightarrow E_\nu \sim 0.05 E_{\rm min}$$



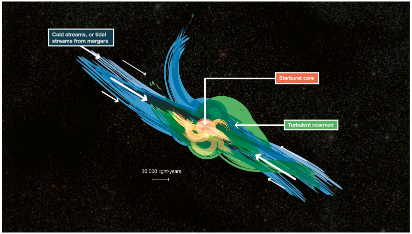


(Aurore Simonnet)

Searching for the sources of high energy neutrinos/UHECRs

CR reservoir Starburst galaxies

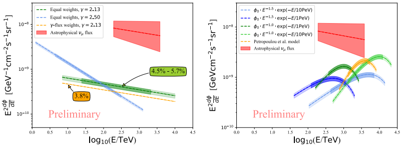
- *pp* channel
- Down to GeV energies
- Calorimetric environment for $50 - 100\ \mathrm{PeV}$ cosmic rays



(NASA/ESA)

Searches for typical sources

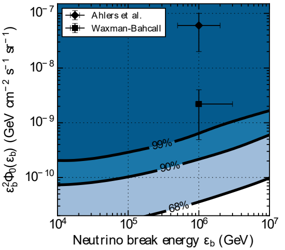
AGN



(PoS(ICRC2017)994)

Up to ∼30% of total diffuse flux

GRBs



*(APJ **843** (2017) no.2, 112)*

Also other searches:

- General point source searches
- Coincident with transient optical/x-ray/gamma
- ...

Searching for the sources of high energy neutrinos

General constraints on *steady* neutrino sources

Characterise source population

- $L^{\mathrm{eff}}_{E_{\nu_\mu}}$ from $L_{\nu_\mu} \propto L^{\alpha}_{ph}$
- n^{eff}_0 dominating flux

Constrain using

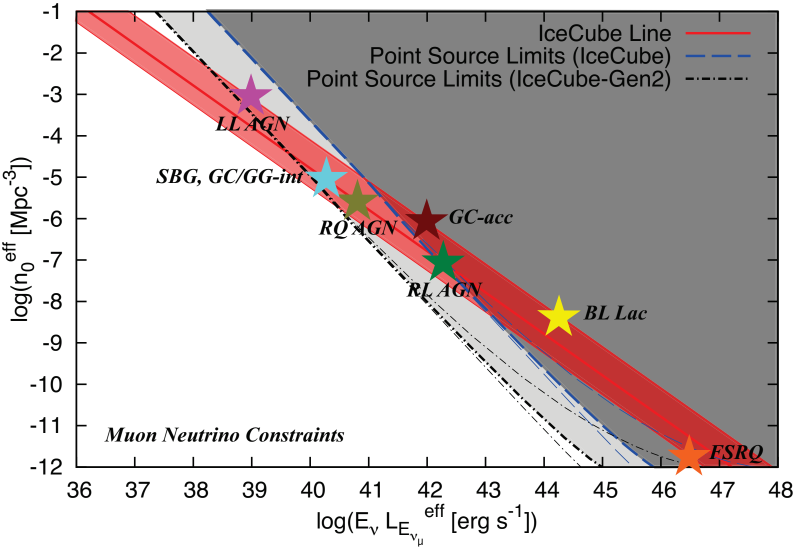
- No multiplets detected
- Responsible for astrophysical neutrino flux

Resulting limits

$$n^{\mathrm{eff}}_0 \gtrsim 10^{-7}\ \mathrm{Mpc}^{-3}$$

$$E_\nu L^{\mathrm{eff}}_{E_{\nu_\mu}} \lesssim 10^{42}\ \mathrm{erg\ s}^{-1}$$

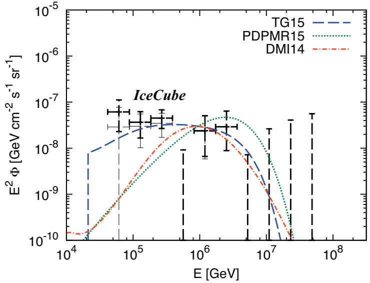
Searching for the sources of high energy neutrinos



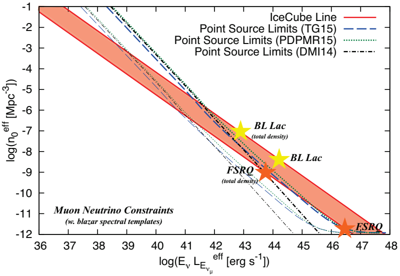
(Murase and Waxman 2016)

Searching for the sources of high energy neutrinos

Even for corrected models of AGN neutrino emission



(Murase and Waxman 2016)

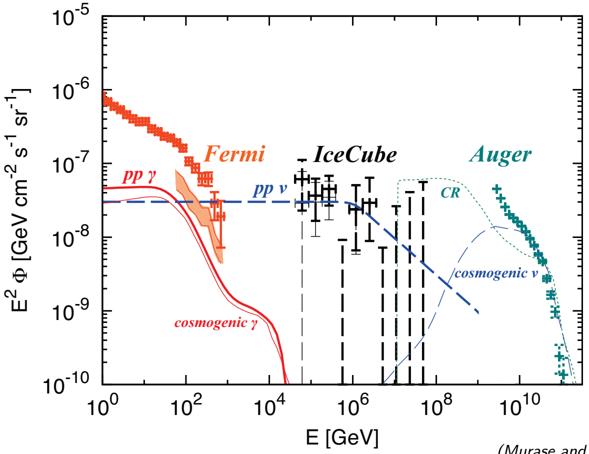


(Murase and Waxman 2016)

Starburst galaxies

Starburst galaxies are good candidates:

- Self-consistently explain CR, γ and neutrino fluxes
- Almost calorimetric source for $E_{\rm cr} \leq 50 - 100\,\mathrm{PeV}$



(Murase and Waxman 2016)

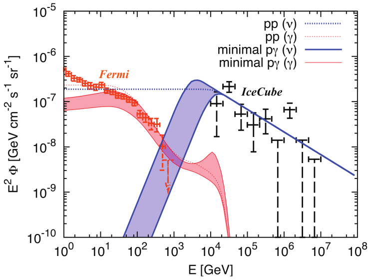
Combining gamma ray and neutrino data

Gamma ray-neutrino connection

$$\varepsilon_\nu Q_{\varepsilon_\nu} \approx \frac{3K}{4(1+K)}\min[1, f_{pp/p\gamma}]\varepsilon_p Q_{\varepsilon_p}\,,$$

$$\varepsilon_\gamma Q_{\varepsilon_\gamma} \approx \frac{4}{3K}(\varepsilon_\nu Q_{\varepsilon_\nu})\Big|_{\varepsilon_\nu=\varepsilon_\gamma/2}\,,$$

$$K = \frac{N_{\pi^\pm}}{N_{\pi^0}} \approx \begin{cases} 1 & (p\gamma) \\ 2 & (pp) \end{cases}$$



(Murase, Guetta and Ahlers 2016)

Conclusions:

- Assuming transparency gives tension
- Extension with $s \geq 2.1 - 2.2$ of $E_\nu \geq 100$ TeV to lower energies incompatible with Fermi γ-ray background

Hidden sources?

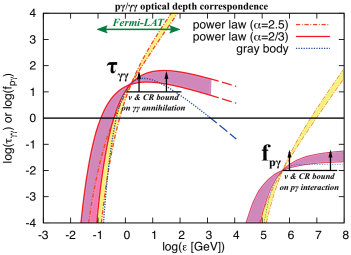
Estimating non-transparancy

$p\gamma$ efficiency

$$f_{p\gamma}(\varepsilon_p) \approx \eta_{p\gamma}(\alpha)\hat{\sigma}_{p\gamma}(r/\Gamma)(\varepsilon'_t n_{\varepsilon'_t})$$

$\gamma\gamma$ optical depth

$$\tau_{\gamma\gamma}(\varepsilon_\gamma) \approx \eta_{\gamma\gamma}(\alpha)\sigma_T(r/\Gamma)(\varepsilon'_t n_{\varepsilon'_t})$$



(Murase, Guetta and Ahlers 2016)

$$\tau_{\gamma\gamma}(\varepsilon_\gamma^c) \sim 10\left(\frac{f_{p\gamma}(\varepsilon_p)}{0.01}\right)$$

$$\varepsilon_\gamma^c \sim \mathrm{GeV}\ \left(\frac{\varepsilon_\nu}{25\ \mathrm{TeV}}\right)$$

Implies sources with *X-ray or MeV γ-ray counterparts*

$$\varepsilon_t \sim 20\ \mathrm{keV}(\Gamma/10)^2(\varepsilon_\nu/30\ \mathrm{TeV})^{-1}$$

Obscured sources

Investigate alternative:

Obscuration by matter

- pp interaction instead of $p\gamma$
  - Enough matter to produce neutrinos
  - Obscures γ-rays
- Distinct from starburst galaxies:
  p **not** trapped in gas environment

$\rightarrow$ Specialise to one set of such objects:

Obscured flat spectrum radio AGN

- If subset blazars: can not be main source of neutrino flux
- Very clean object
- Able to probe blazar content in new way
- Mechanism is general

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Active Galactic nuclei

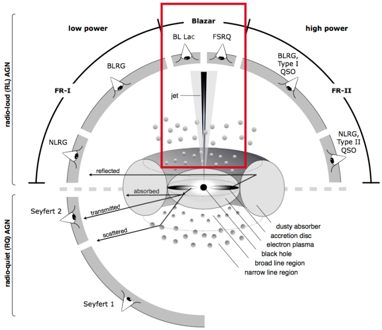
Active galactic nuclei

Sufficient non-thermal output

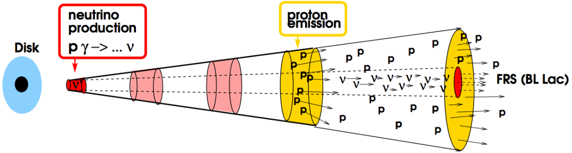
If sources of cosmic rays

$$p + \gamma \rightarrow \Delta^+$$

$$\rightarrow \begin{cases} p\pi^0 \rightarrow p\gamma\gamma \\ n\pi^+ \rightarrow ne^+\nu_e\bar{\nu}_\mu\nu_\mu \end{cases}$$



(Abdo et al. 2011)



(Becker and Biermann 2008)

Processes for non-thermal photon emission

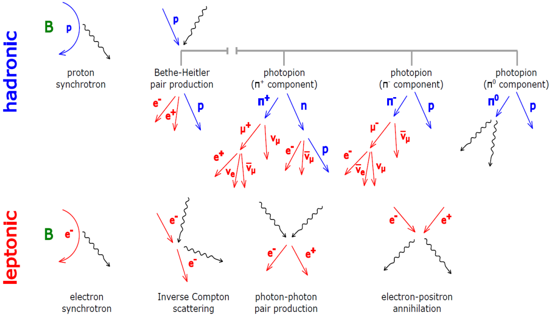
AGN emission

Leptonic

Can explain most spectra

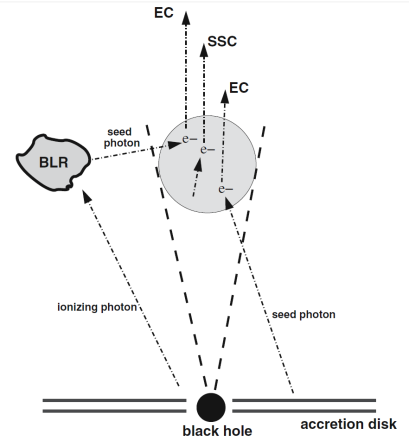
Hadronic

Attractive if want to explain cosmic rays



(Mastichiadis 2016)

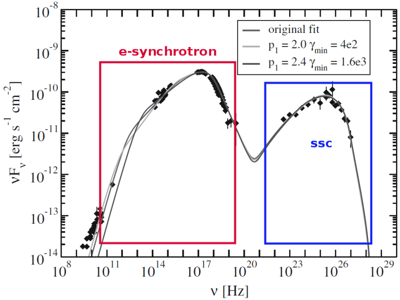
Emission in leptonic models



(Beckman and Shrader 2012)

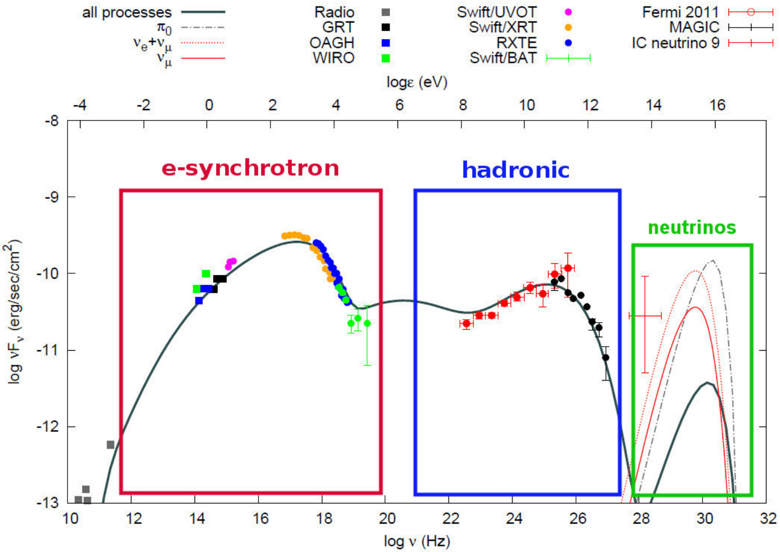
Spectral energy distribution

- Dominated by non-thermal
- 2 bumps



(Abdo et al. 2011)

Emission in hadronic models



(Petropoulou et al. 2015)

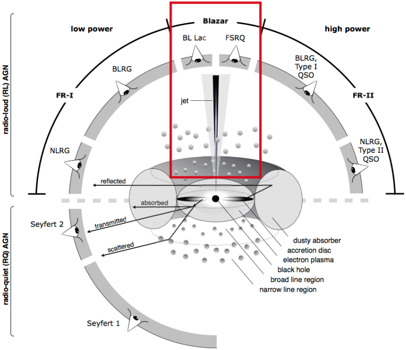
Obscured sources

Obscuration by matter

Gas & dust in front of jet
$\rightarrow$ beam dump

Note: not same as CR reservoir!

$$p + p \rightarrow \begin{cases} pp\pi^0 \\ pn\pi^+ \end{cases}$$



(Abdo et al. 2011)

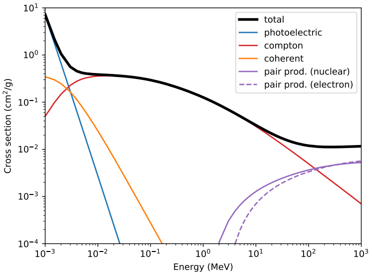
$$\sigma_{pp} \approx 2 \times 10^{-26}\ \text{cm}^2 \Rightarrow \text{require } N_H \approx 10^{26}\ \text{cm}^{-2}$$

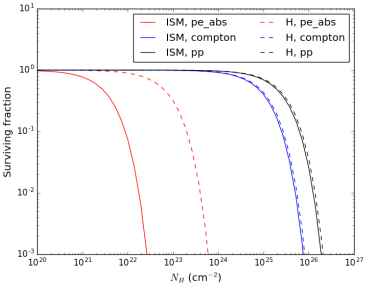
Probing obscuration

Obscuration

- In γ-rays
- In X-rays!

$$\frac{I_X^{obs}}{I_X^0} = e^{-X_{tot}/\lambda_X}$$





Protons

$$\frac{I_p^{int}}{I_p^0} = 1 - e^{-X_{tot}/\lambda_{p-N}}$$

Full beamdump: $X_{tot} = 4\lambda_{p-N}$

Photoelectric or compton?

Which process dominates attenuation of X-rays?

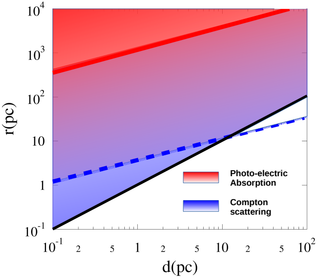
$$\frac{I_X^{obs}}{I_X^0} = e^{-X_{tot}/\lambda_X}.$$

Estimate ionisation parameter

$$U_X = \int_{E_1}^{E_2} \frac{L_E/E}{4\pi r^2 c\ n_N} dE$$

Quasar broad line clouds

$$\frac{N_{H^+}}{N_H} \simeq 10^{5.3} U$$



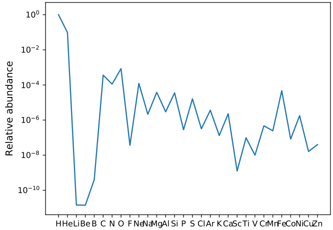
(Maggi et al. 2016)

$\Rightarrow$ **Compton**

Composition

Relation *pp* and X-ray attenuation

$$\frac{I_p^{int}}{I_p^0} = 1 - \left(\frac{I_X^{obs}}{I_X^0}\right)^{\lambda_X/\lambda_{p-N}}$$



Depends on composition!

Dust composition	λ_{p-N} (g cm^{-2})	λ_X (g cm^{-2})	λ_{p-N}/λ_X
H(A=1)	23	14	1.6
C(A=12)	53	55	1.0
N(A=14)	56	62	0.9
O(A=16)	59	80	0.7
Si(A=28)	71	55	1.3
Fe(A=56)	89	84	1.1

(Maggi et al. 2016)

Object selection

Starting point: two catalogs

<u>Van Velzen</u>

- Radio catalog
- Close universe
- Possible sources UHECRs

<u>Fermi 2LAC</u>

- γ-ray sources
- Detected by Fermi
- High energy sources

Select for

- Point source
- Flat radio spectrum
- Reduced X-ray emission

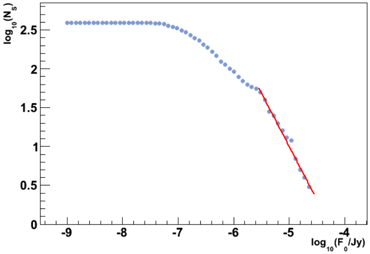
Source attenuation

Avoid diminished X-ray due to

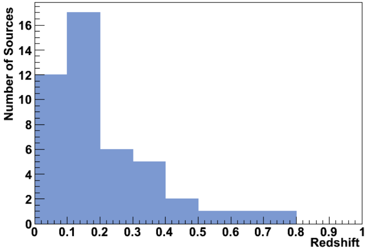
- Intergalactic medium
- Redshift effect
- Selection effect

$\rightarrow$ construct unbiased sample

$$N(F_m > F_0) \propto (F_0)^{-3/2}$$



(Maggi et al. 2016)



(Maggi et al. 2016)

Restrict sample to

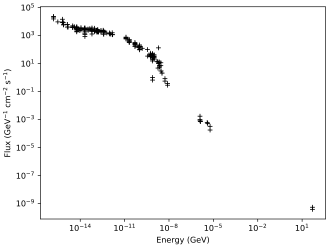
$$z < 0.17$$

Flat radio spectrum

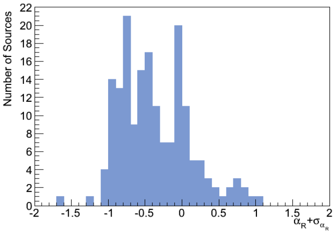
Criterion:

$$\alpha_R + \sigma_{\alpha_R} > -0.5$$

3C371



(Maggi et al. 2016)



(Maggi et al. 2016)

Distribution of fitted indices

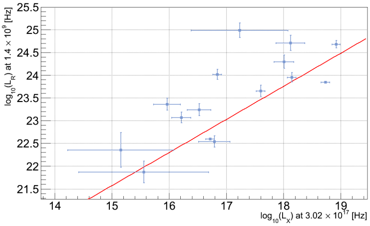
Resulting objects:

- BL Lac
- FSRQ
- ULIRG

Radio - X-ray correlation

Diminished X-rays: divide out power of internal engine!

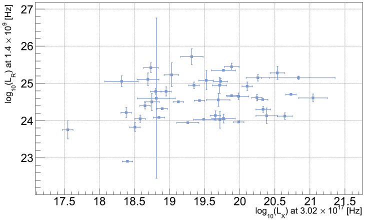
FSRQ/ULIRG



(Maggi et al. 2016)

$$L_R = L_X^{0.73}$$

BL Lac



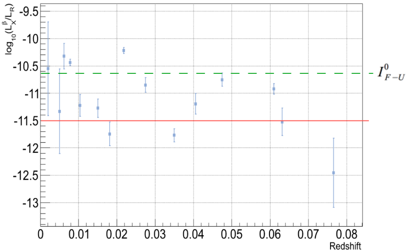
(Maggi et al. 2016)

No relation

Obscured X-ray

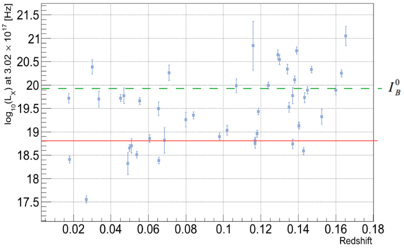
Determining a baseline and obscured sources

FSRQ/ULIRG



(Maggi et al. 2016)

BL Lac



(Maggi et al. 2016)

Intensity ratio $L_X^{0.73}/L_R$

Resulting objects

Object name (NED ID)	H	C	N	O	Si	Fe
Class: FSRQ						
2MASXJ05581173+5328180	0.79	0.93	0.94	0.97	0.87	0.91
CGCG186-048	0.71	0.88	0.90	0.94	0.79	0.85
MRK0668	0.92	0.99	0.99	1.00	0.96	0.98
Class: ULIRG						
ARP220	0.79	0.93	0.94	0.97	0.86	0.91
Class: BLLac						
3C371	0.84	0.95	0.96	0.98	0.90	0.94
B21811+31	0.81	0.94	0.95	0.98	0.88	0.92
SBS0812+578	0.87	0.97	0.98	0.99	0.93	0.96
GB6J1542+6129	0.82	0.95	0.96	0.98	0.89	0.93
RGBJ1534+372	0.86	0.97	0.97	0.99	0.92	0.95
SBS1200+608	0.89	0.98	0.98	0.99	0.94	0.97
PKS1349-439	0.85	0.96	0.97	0.98	0.91	0.95
4C+04.77	0.97	1.00	1.00	1.00	0.99	1.00
1H1720+117	0.89	0.98	0.98	0.99	0.94	0.97
APLibrae	0.90	0.98	0.99	0.99	0.95	0.97
PKS1717+177	0.83	0.95	0.96	0.98	0.89	0.93

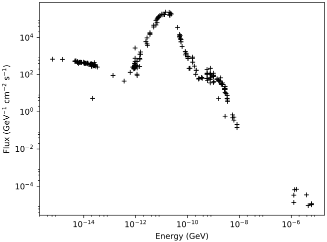
(Maggi et al. 2016)

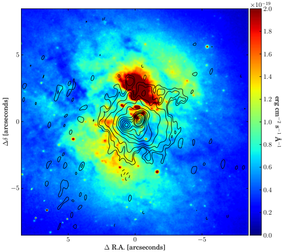
ULIRG

Potentially interesting class:
Ultraluminous infrared galaxies

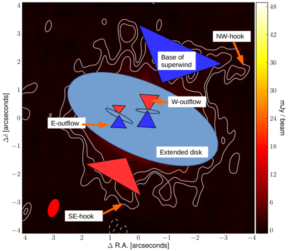
- Huge infrared bump
- Flat radio spectrum

ARP 220





(A&A 593, A86 (2016))



(A&A 593, A86 (2016))

IceCube search: results

IceCube analysis performed by Giuliano
Data from 2012-2015

Name	RA (°)	dec (°)	TS	p-value	n_s	γ	ϕ^{90}
1H1720+117	261.27	11.87	0.0	1.0	0.0	3.11	6.95E-13
2MASX	89.55	53.47	3.63	0.037	16.12	2.73	1.08E-12
3C371	271.71	69.82	0.82	0.242	5.35	4.0	1.18E-12
4C+04.77	331.07	4.67	0.12	0.412	0.73	2.05	6.50E-13
ARP220	233.74	23.50	0.0	1.0	0.0	4.0	7.46E-13
B21811+31	273.40	31.74	2.51	0.076	11.93	2.85	8.50E-13
CGCG186-048	176.84	35.02	0.0	1.0	0.0	2.88	8.56E-13
GB6J1542+6129	235.74	61.50	0.0	1.0	0.0	2.68	1.07E-12
MRK0668	211.75	28.45	0.24	0.300	2.48	3.76	8.79E-13
NGC3628	170.07	13.59	3.93	0.034	6.88	2.21	7.19E-13
PKS1717+177	259.80	17.75	1.44	0.142	7.81	2.97	7.54E-13
RGBJ1534+372	233.70	37.27	0.30	0.318	3.95	3.05	8.99E-13
SBS0812-578	124.09	57.65	0.11	0.386	1.70	3.84	1.09E-12
SBS1200+608	180.76	60.52	0.0	1.0	0.0	2.46	1.09E-12

(PoS(ICRC2017)1000)

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Neutrino spectrum

Model neutrino emission from above sources

- Obscuration (*pp*-interaction) is universal
- Normalisation depends on source class

Neutrinos from *pp*-interactions: need Monte Carlo generation
Analytical fits exist for ν and γ

$$\phi_\nu(E_\nu) = \int_{E_{\min}}^{E_{\max}} \left[1 - \exp\left(n_H \sigma_{\mathrm{inel}}(E_p)\right)\right] J_p(E_p) F_\nu\left(\frac{E_\nu}{E_p}, E_p\right) \frac{\mathrm{d}E_p}{E_p}$$

However

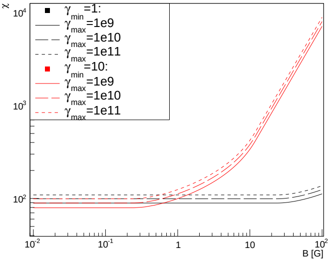
- Ignores possible **multiple interactions**
- Newer version of generators exist

$\Rightarrow$ Simulate in SIBYLL

Electron luminosity

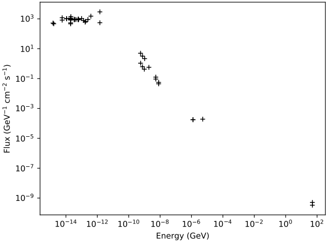
Need normalisation proton spectrum!
Use **radio emission**

$$L_e = \chi L_R, \quad \chi \geq 1$$



(Becker et al. 2014)

PKS1717+177



Electron synchrotron

↓

Radio emission

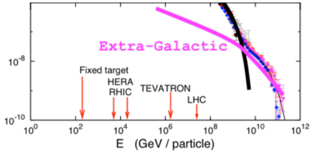
Calculated analytically

- Power law e
- Magnetic field

Electron-proton ratio

Relating electron and proton luminosity

$$\boxed{L_e = f_e L_p}$$



(Blasi 2014)

Theory

Assumptions

- Acceleration p, e similar
- $N_p = N_e$

Highly uncertain, but surely $f_e \ll 1$

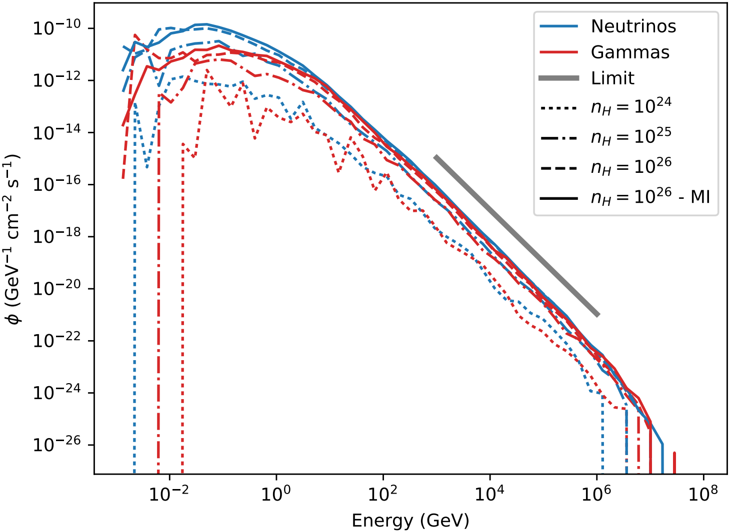
Observation

Estimate

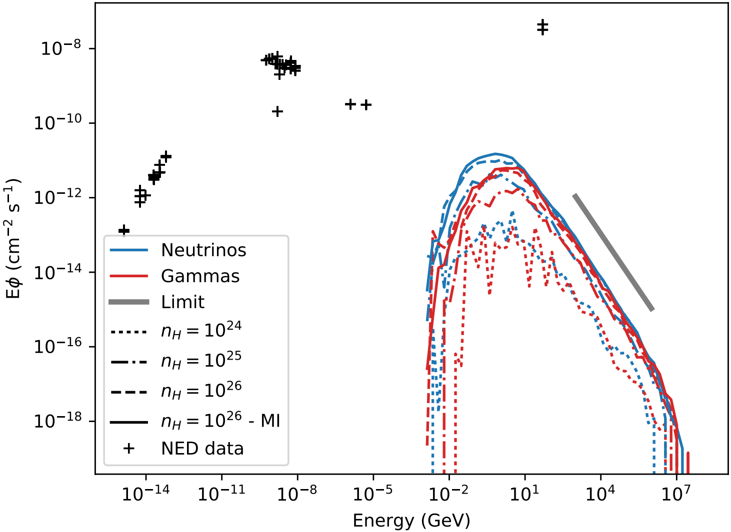
- UHECR flux
- Synchrotron emission

Benchmark: $f_e \approx 0.1$ (extragalactic)

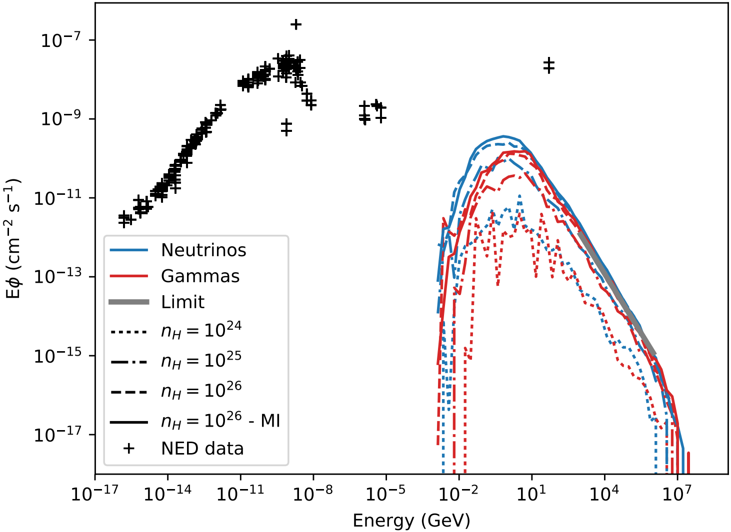
Results: GB6J1542+6129



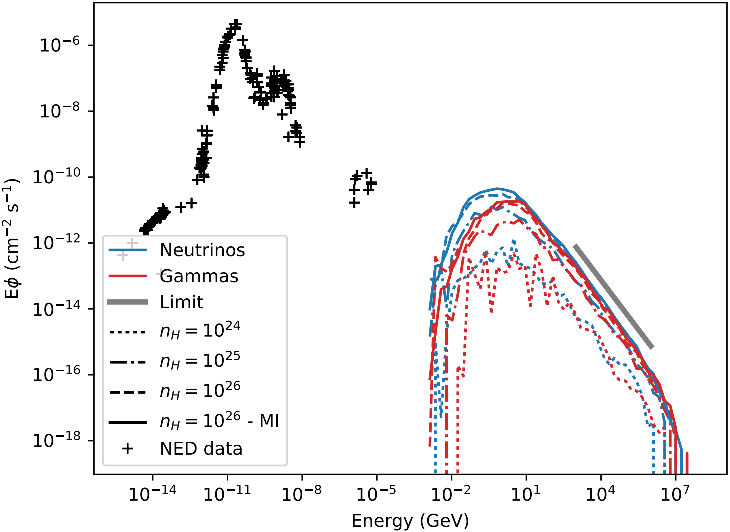
Results: GB6J1542+6129



Results: 3C371



Results: ARP220



Results

Summarising:

- No fluxes above limit
- Most can be probed with improved sensitivity!
- Multiple interactions negligible

Blazar	Limit	Prediction
1H1720+117	6.95e-10	4.76e-11
2MASXJ05581173+5328180	1.08e-09	2.54e-10
3C371	1.18e-09	1.80e-09
4C+04.77	6.50e-10	6.42e-10
ARP220	7.46e-10	2.21e-10
B21811+31	8.50e-10	1.11e-10
CGCG186-048	8.56e-10	3.54e-10
GB6J1542+6129	1.07e-09	7.44e-11
MRK0668	8.79e-10	1.22e-09
NGC3628	7.19e-10	3.55e-10
PKS1717+177	7.54e-10	4.60e-10
RGBJ1534+372	8.99e-10	1.42e-11
SBS0812+578	1.09e-09	6.61e-11
SBS1200+608	1.09e-09	9.06e-11

Outlook

- Handling neutrons
- γ-ray attenuation (almost done)
- Constraints on population
  - Obscured flat spectrum AGN
  - General dense *pp* channel sources
- Write paper
- Investigate closer ULIRG (Pablo)

Summary and conclusions

- Typical sources high energy neutrinos (GRBs, AGN) strongly constrained by IceCube limits
- General constraints on source population
  - Lower limit on source density
  - Upper limit on neutrino luminosity
- Gamma-ray background constrains sources: suggests hidden source
- Gas and dust can provide obscuration and beam dump environment
- Selected obscured flat spectrum radio AGN & put limits
- Modelling neutrino emission: under limits and within reach
- ULIRG deserve further study