Blazars as neutrino factories

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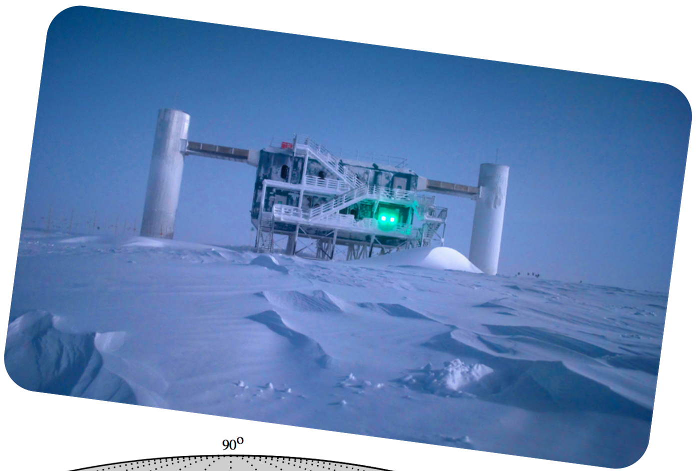
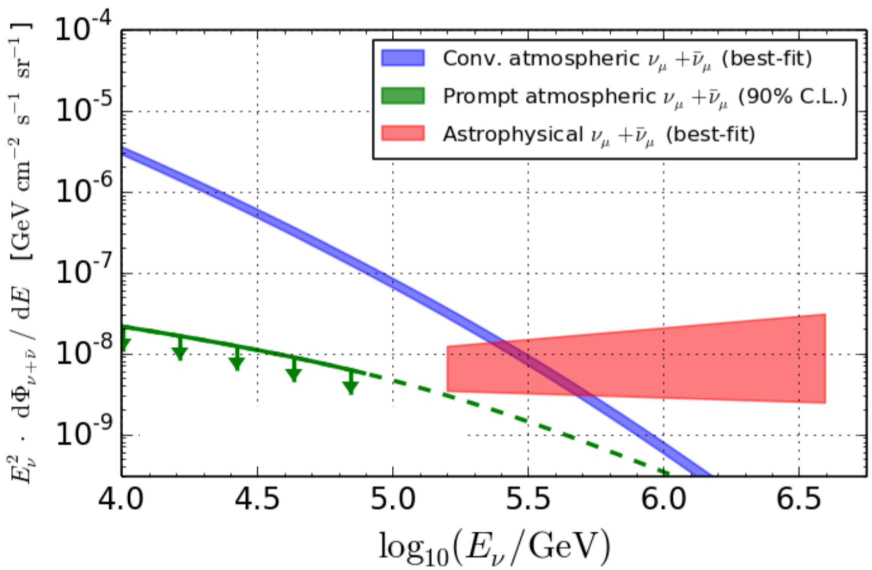
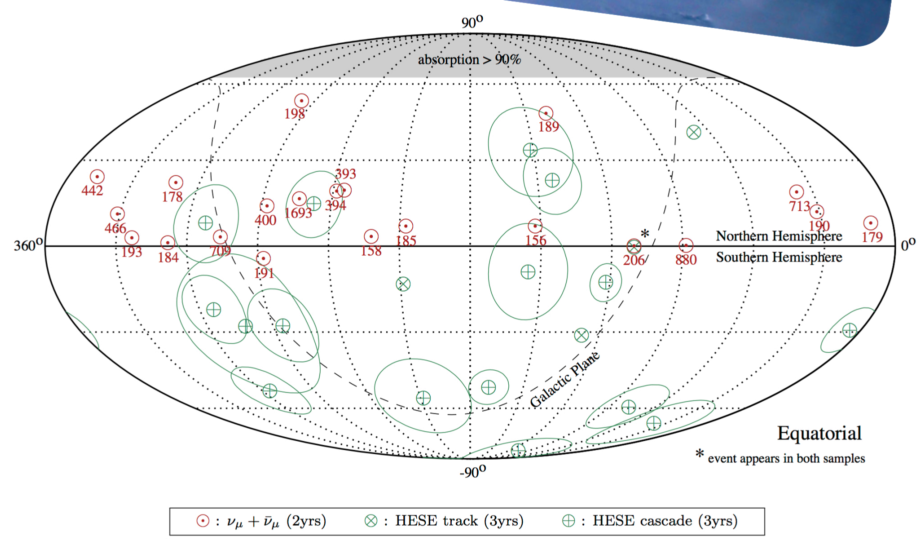
Discovery of high-energy neutrinos by IceCube



~60 events since 2010 above 60TeV

Aartsen et al. 2016

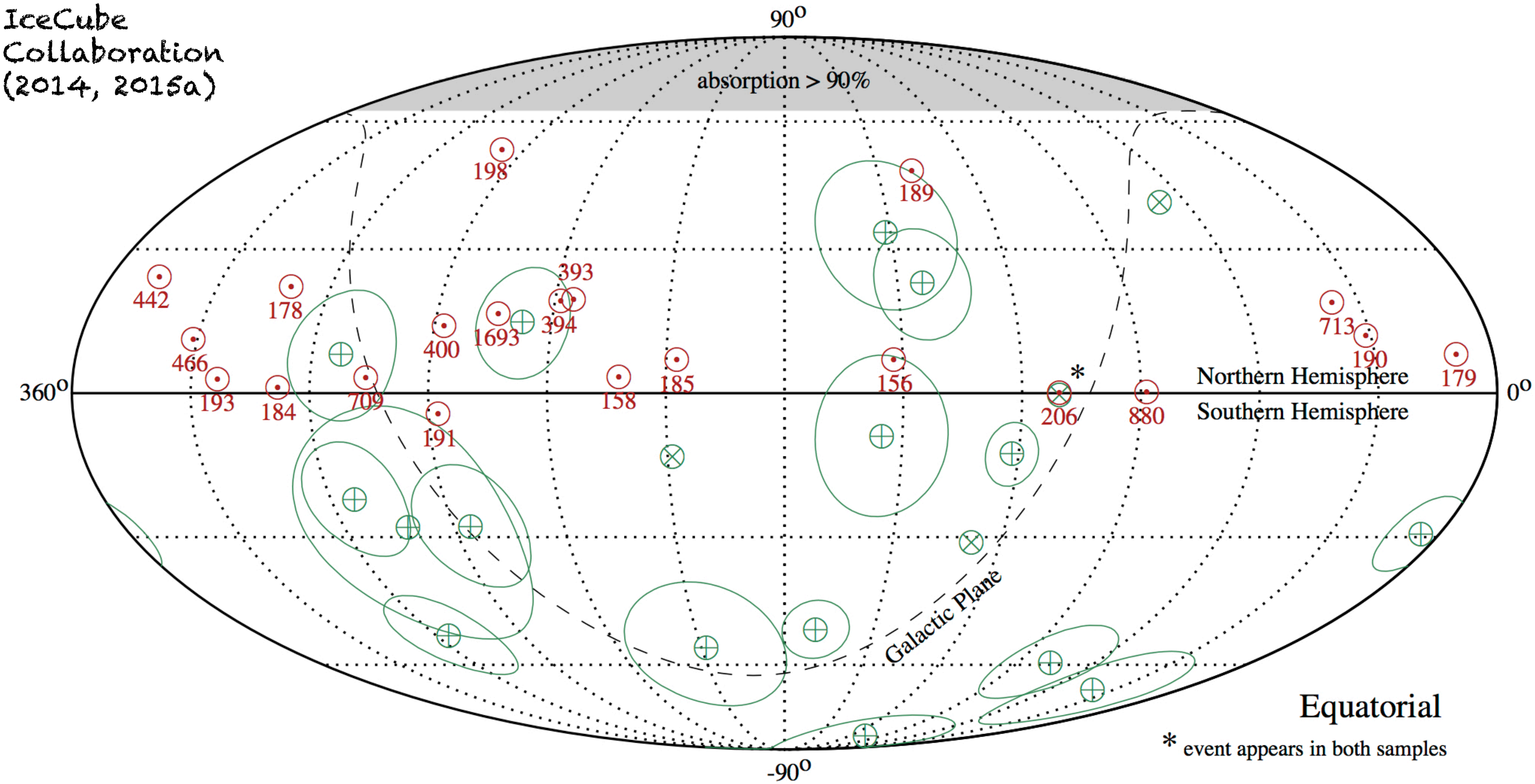




Who is producing these neutrinos?

Searching for sources

IceCube Collaboration (2014, 2015a)



$\odot$: $\nu_\mu + \bar{\nu}_\mu$ (2yrs) $\otimes$: HESE track (3yrs) $\oplus$: HESE cascade (3yrs)

High-energy neutrino production

Relativistic protons!!

$$p + p \rightarrow \pi + X$$

$$p + \gamma \rightarrow \pi + X$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu} \rightarrow e^{\pm} + \nu_{e} + 2\,\nu_{\mu}$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

1:1:1
after propagation

$$\boldsymbol{E_{\nu} \sim E_{p}/20}$$

High-energy neutrino production

Relativistic protons!!

$$p + p \rightarrow \pi + X$$

$$p + \gamma \rightarrow \pi + X$$

Our galaxy
Star-forming Galaxy
AGN winds
Low-energy radiogalaxies (FR0)

e.g. Ahlers and Murase 2014
Vissani and Palladino 2015

High-energy neutrino production

Relativistic protons!!

$$p + p \rightarrow \pi + X$$

$$p + \gamma \rightarrow \pi + X$$

Our galaxy
Star-forming Galaxy
AGN winds
Low-energy radiogalaxies (FR0)

Protons accelerated inside the SNR escape and interact with intergalactic medium

e. g. Loeb and Waxman 2006
Tamborra et al. 2014

High-energy neutrino production

Relativistic protons!!

$$p + p \rightarrow \pi + X$$

$$p + \gamma \rightarrow \pi + X$$

Our galaxy
Star-forming Galaxy
AGN winds
Low-energy radiogalaxies (FR0)

Protons accelerated inside the AGN wind escape and interact with intergalactic medium

e.g. Lamastra et al. 2016
Lamastra et al. 2017

High-energy neutrino production

Relativistic protons!!

$$p + p \rightarrow \pi + X$$

$$p + \gamma \rightarrow \pi + X$$

Our galaxy
Star-forming Galaxy
AGN winds
Low-energy radiogalaxies (FR0)

Protons accelerated inside the jet escape and interact with intergalactic medium

e.g. Tavecchio et al. 2018

High-energy neutrino production

Relativistic protons!!

$$p + p \rightarrow \pi + X$$

$$p + \gamma \rightarrow \pi + X$$

Our galaxy
Star-forming Galaxy
AGN winds
Low-energy radiogalaxies (FR0)

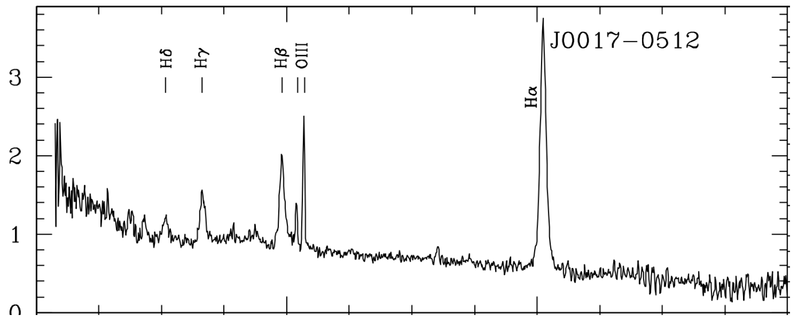
Jets
GRBs
Blazars

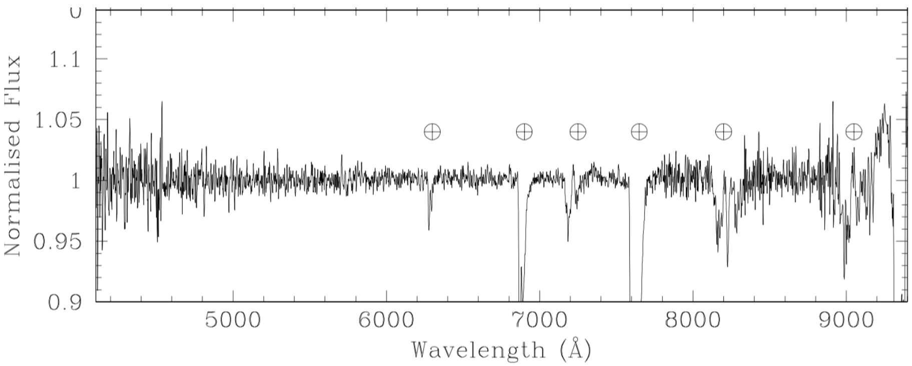
e.g. Waxman and Bachall 1997
Atoyan and Dermer 2003
Tavecchio at al. 2014

Blazars

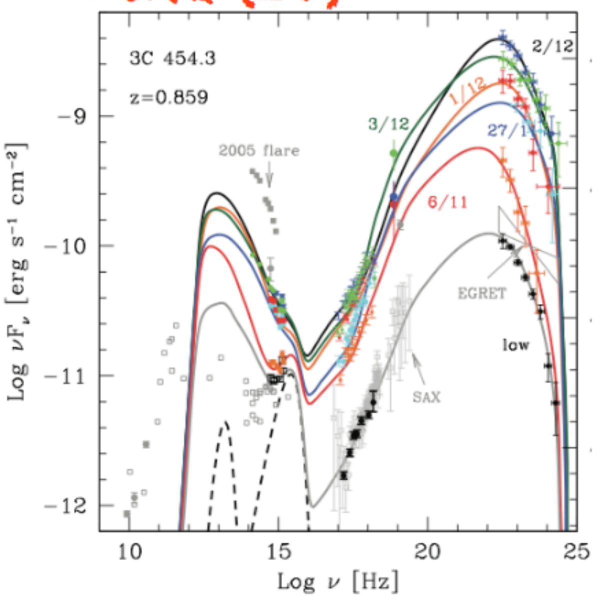
FSRQ

BL Lac

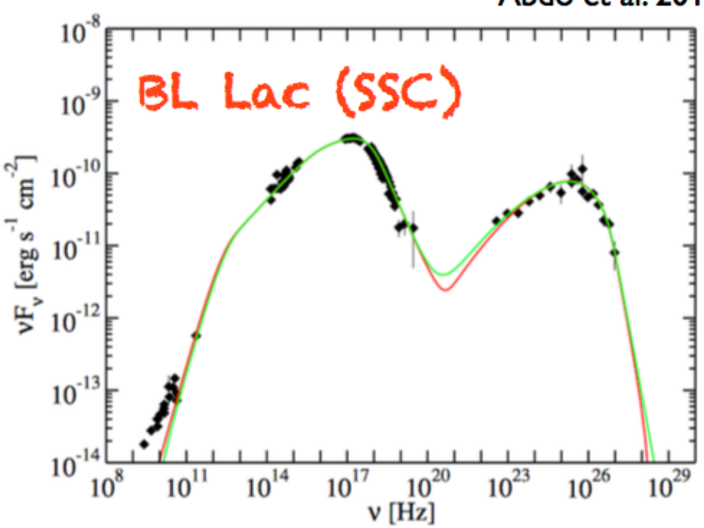




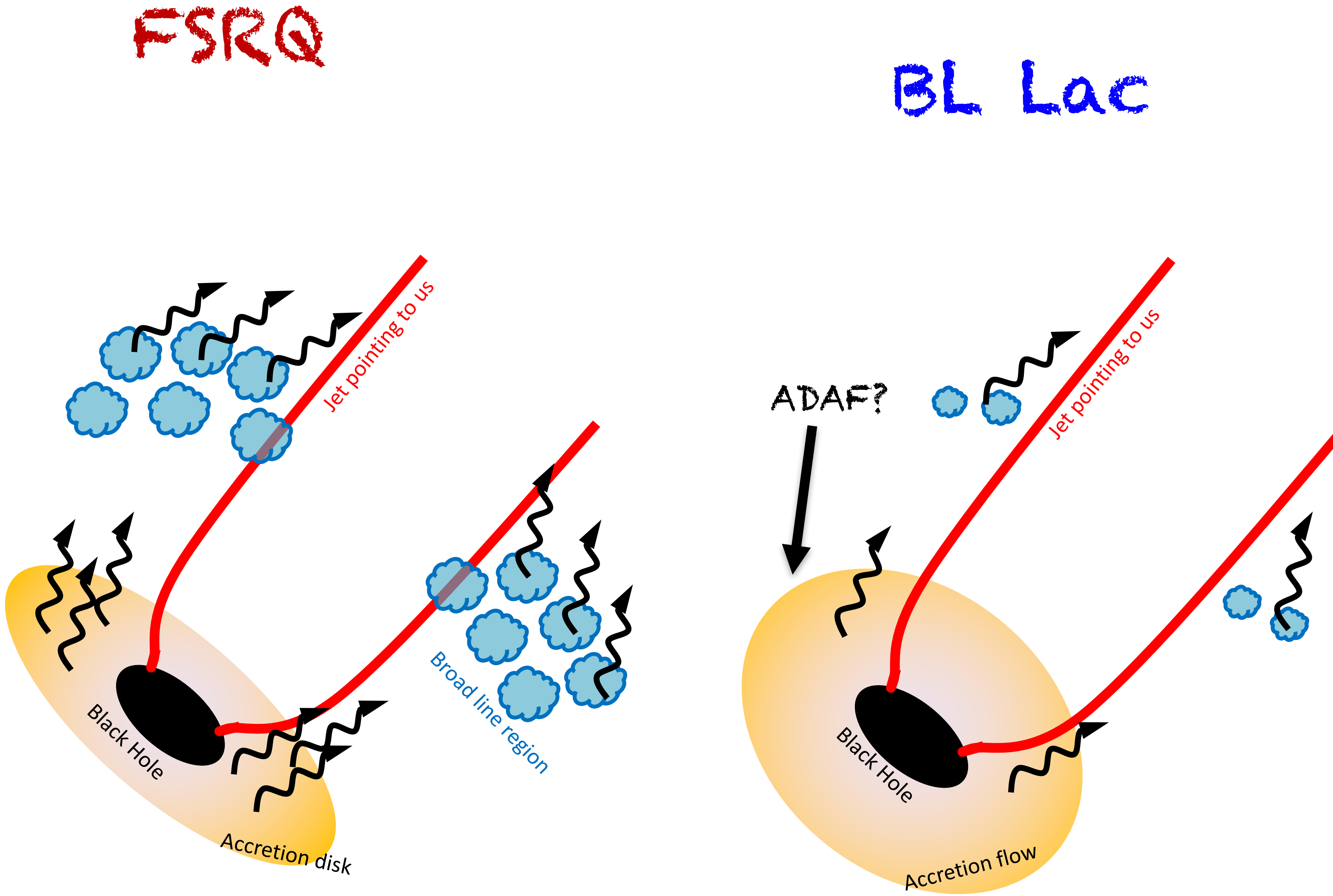
FSRQ (EC) Bonnoli et al. 2011



Abdo et al. 2011



Blazars

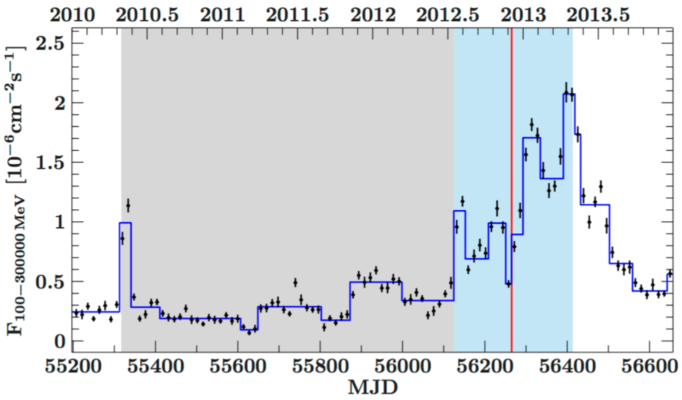


FSRQ
BL Lac
Jet pointing to us
Black Hole
Accretion disk
Broad line region
ADAF?
Jet pointing to us
Black Hole
Accretion flow

Are Blazars detectable by IceCube?

FSRQ

✔ Possible correlation between one neutrino event and a γ-ray flare of a FSRQ object (Kadler et al. 2016).



✗ EM-ν emission can't be exclusively hadronic (Gao et al. 2017)

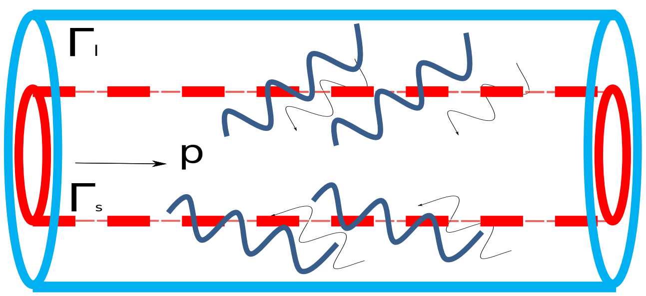
✗ Murase and Waxman 2016

✗ p+γ reaction with UV photons of BLR produce neutrino spectra harder than that "IceCube spectrum"

BL Lac

✔ Padovani et al. 2016 (spatial correlation with γ -ray BL Lacs detected above 50GeV)

✔ Tavecchio et al. 2014 efficient neutrino production (spine-layer model only for high-energy emitting BL Lacs)



Ghisellini et al. 2005

Fermi 2FHL catalogue (sources emitting above 50GeV) is a good representation of these sources

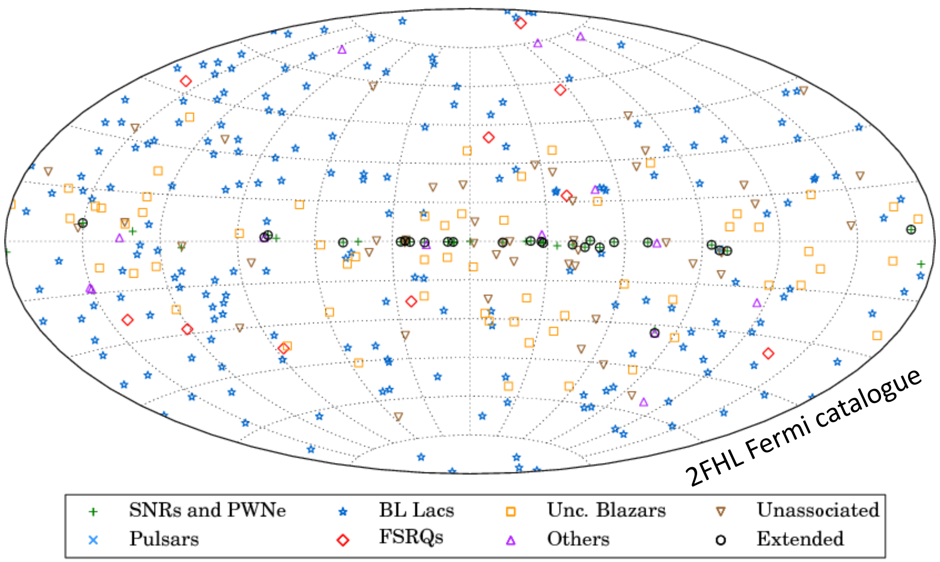
Righi et al. 2017 a

The model

Assumption 1:

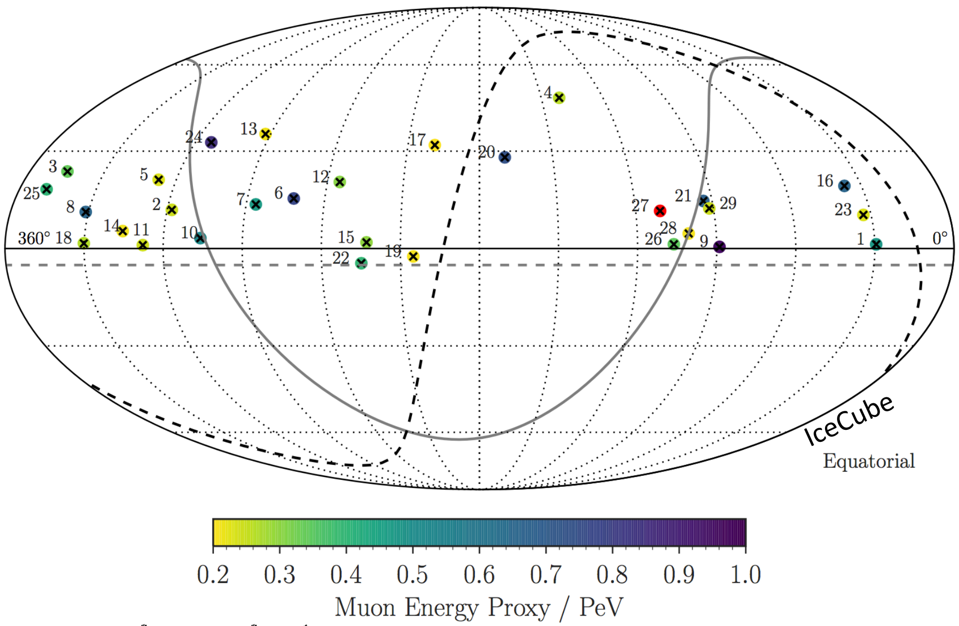
Only BL Lac objects of 2FHL catalogue contribute to ν_μ IC events.

Gamma-ray sky (50GeV-2TeV)



Ackermann et al. 2015

High-energy neutrinos sky (>200TeV)



Aartsen et al. 2016

The model

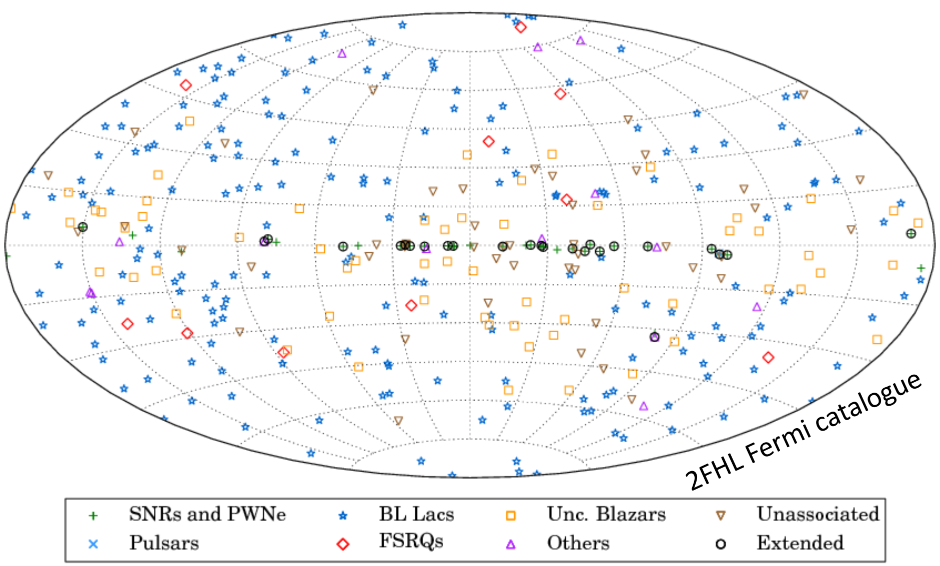
Righi et al. 2017 a

Assumption 1:
Only BL Lac objects of 2FHL catalogue contribute to ν_μ IC events.

Assumption 2:
Linear relation between γ-ray emission and neutrino emission.

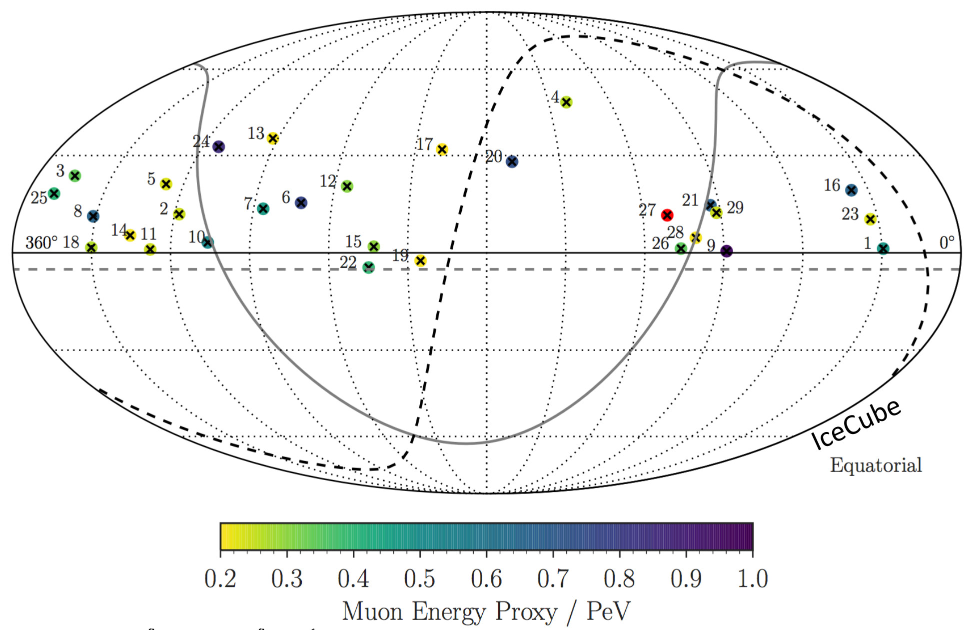
$$F_{\gamma_i} = k F_{\nu_i}$$

Gamma-ray sky (50GeV-2TeV)



Ackermann et al. 2015

High-energy neutrinos sky (>200TeV)



Aartsen et al. 2016

Righi et al. 2017 a

The model

Assumption 1:

Only BL Lac objects of 2FHL catalogue contribute to ν_μ IC events.

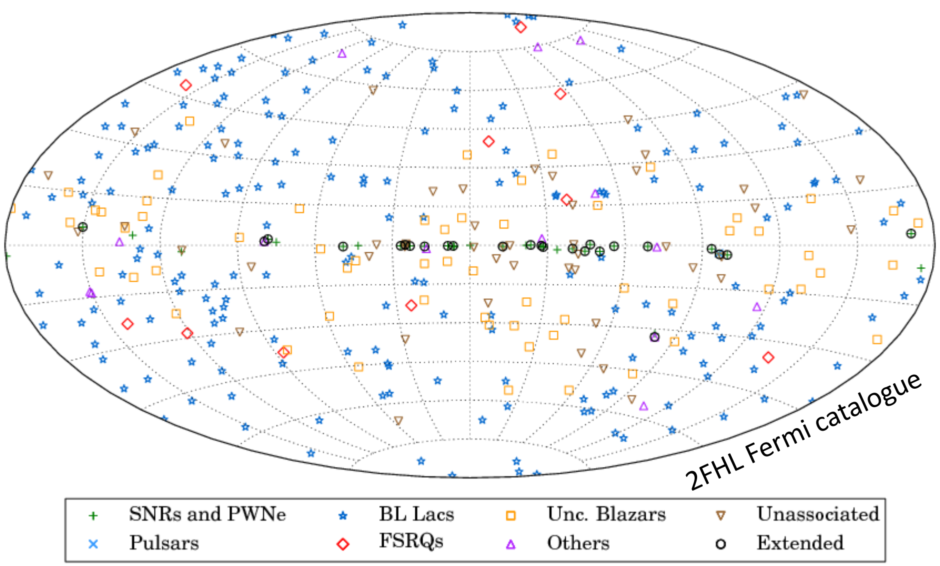
Assumption 2:

Linear relation between γ-ray emission and neutrino emission.

$$F_{\gamma_i} = k F_{\nu_i}$$

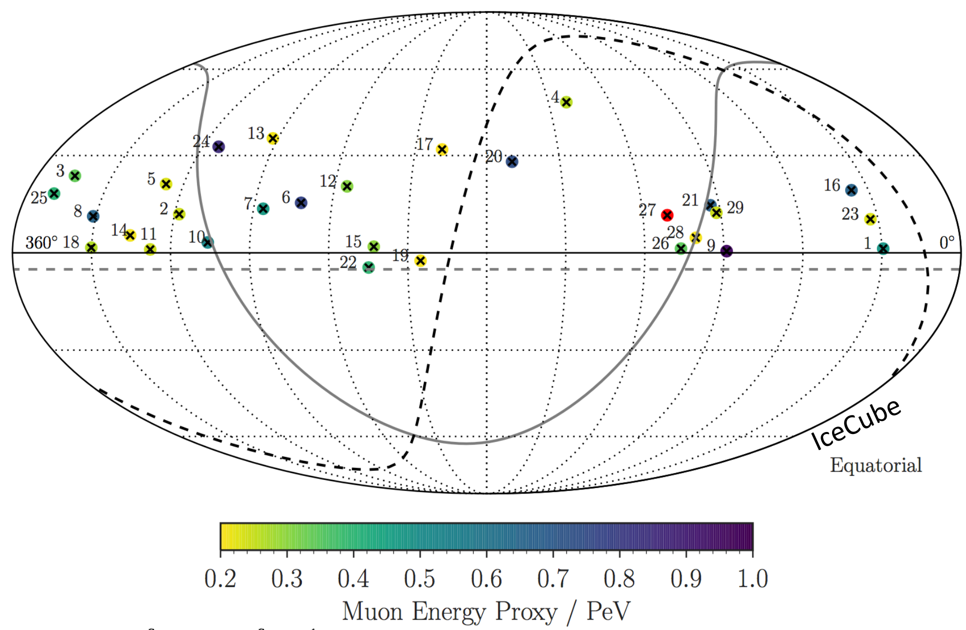
It's the same for all BL Lacs

Gamma-ray sky (50GeV-2TeV)



Ackermann et al. 2015

High-energy neutrinos sky (>200TeV)



Aartsen et al. 2016

Results

Righi et al. 2017 a

$$N_\nu = \dot{N}_\nu T_{\rm exp} = T_{\rm exp} \int_{E_1}^{E_2} A_{\rm eff}(E_\nu)\Phi_i(E_\nu)dE_\nu$$

IceCube

	Name	FLUX	$\#\nu$
	$60^\circ < \delta < 90^\circ$		
1	1ES1959+650	1.38	0.27
2	1ES0502+675	1.14	0.22
3	S50716+71	0.44	0.08
4	1RXSJ013106.4+61203	0.25	0.05
5	4C+67.04	0.25	0.05
6	Mkn180	0.24	0.05
7	MS0737.9+7441	0.13	0.02
8	RXJ0805.4+7534	0.08	0.02
9	S40954+65	0.07	0.01
10	S41749+70	0.07	0.01
	$30^\circ < \delta < 60^\circ$		
11	Mkn421	8.77	4.89
12	Mkn501	3.41	1.90
13	PG1218+304	0.92	0.52
14	3C66A	0.87	0.49
15	1H1013+498	0.87	0.49
16	1ES0033+595	0.82	0.46
17	1ES2344+514	0.69	0.39
18	1ES1215+303	0.52	0.29
19	B32247+381	0.37	0.21
20	B30133+388	0.35	0.19
	$0^\circ < \delta < 30^\circ$		
21	PG1553+113	1.89	2.47
22	PKS1424+240	1.00	1.30
23	PG1218+304	0.92	1.20
24	TXS0518+211	0.87	1.14
25	1ES0647+250	0.75	0.99
26	1ES1215+303	0.52	0.69
27	RXJ0648.7+1516	0.45	0.59
28	1RXSJ194246.3+10333	0.41	0.54
29	RBS0413	0.32	0.42
30	1H1720+117	0.25	0.33
		10^{-8} GeV/cm^{2}s	yr^{-1}

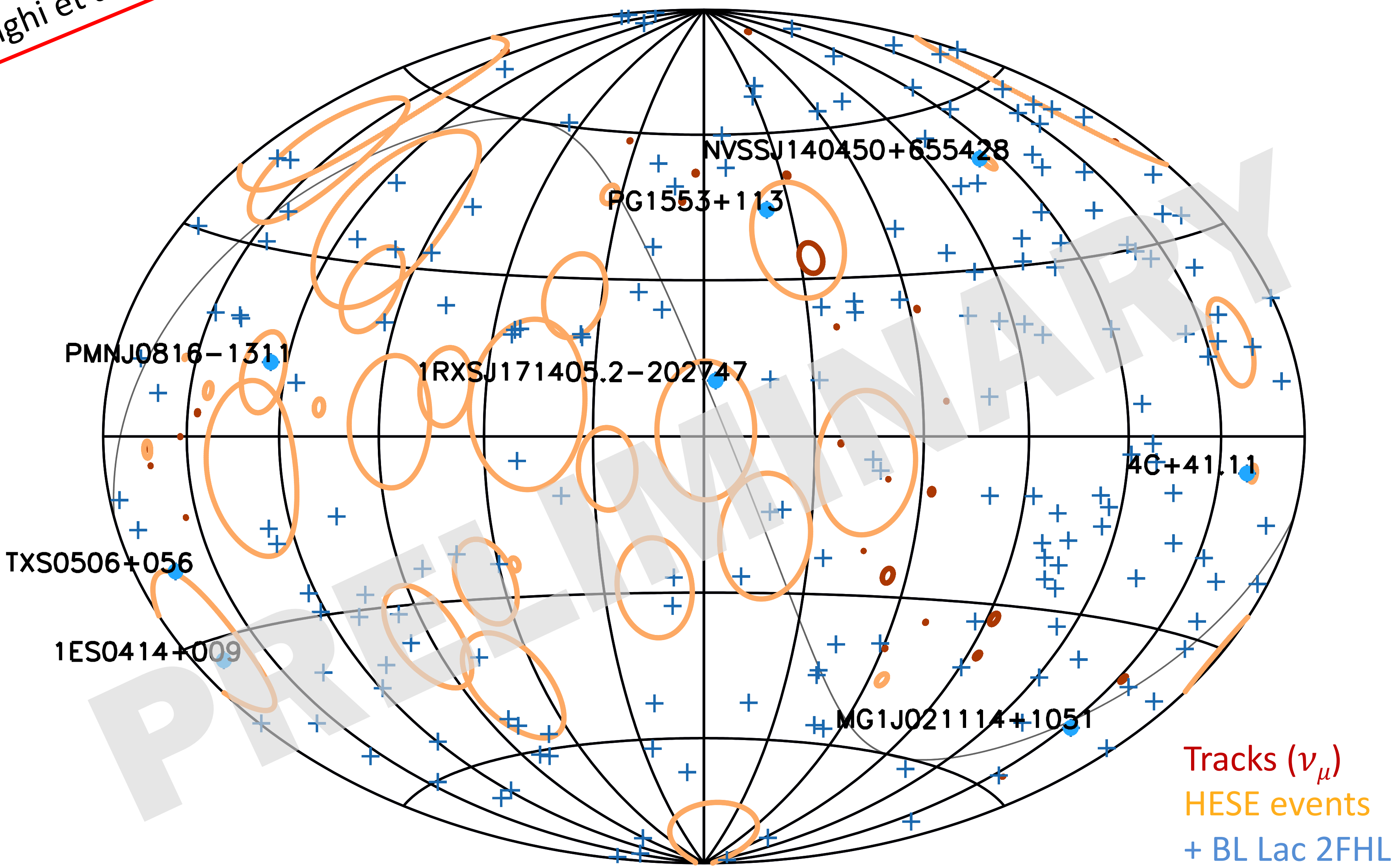
Km3NeT (prediction)

	Name	F_ν	R_ν	Visibility at horizon	R_ν	Visibility at 10°
1	Mkn421	8.77	4.59	0.30	5.80	0.39
2	PKS2155-304	2.15	2.23	0.60	2.53	0.69
3	Mkn501	3.41	1.65	0.28	2.26	0.39
4	PG1553+113	1.89	1.42	0.44	1.66	0.51
5	PKS0447-439	0.76	0.87	0.67	1.02	0.79
6	PKS1424+240	1.00	0.67	0.39	0.79	0.46
7	PKS2005-489	0.51	0.63	0.72	[illegible]	0.86
8	TXS0518+211	0.87	0.59	0.39	0.72	0.48
9	PG1218+304	0.92	0.55	0.34	0.69	0.44
10	1ES0647+250	0.75	0.47	0.36	0.60	0.46
11	3C66A	0.87	0.38	0.25	0.54	0.36
12	1RXSJ054357.3-55320	0.30	0.40	0.78	0.52	1.00
13	PKS0301-243	0.43	0.44	0.59	0.49	0.66
14	1H1914-194	0.45	0.44	0.57	0.49	0.63
15[a]	1H1013+498	0.87	-	-	0.48	0.32
15[b]	1RXSJ194246.3+10333	0.41	0.32	0.45	-	-
16	PKS1440-389	0.36	0.41	0.66	0.47	0.76
17	1ES0347-121	0.39	0.35	0.53	0.40	0.60
18	1ES1215+303	0.52	0.31	0.34	0.39	0.44
19	1RXSJ101015.9-31190	0.32	0.34	0.60	0.39	0.69
20	RXJ0648.7+1516	0.45	0.33	0.42	0.38	0.49

Collaboration for simulation ongoing

Righi et al. submitted

BL Lacs candidates

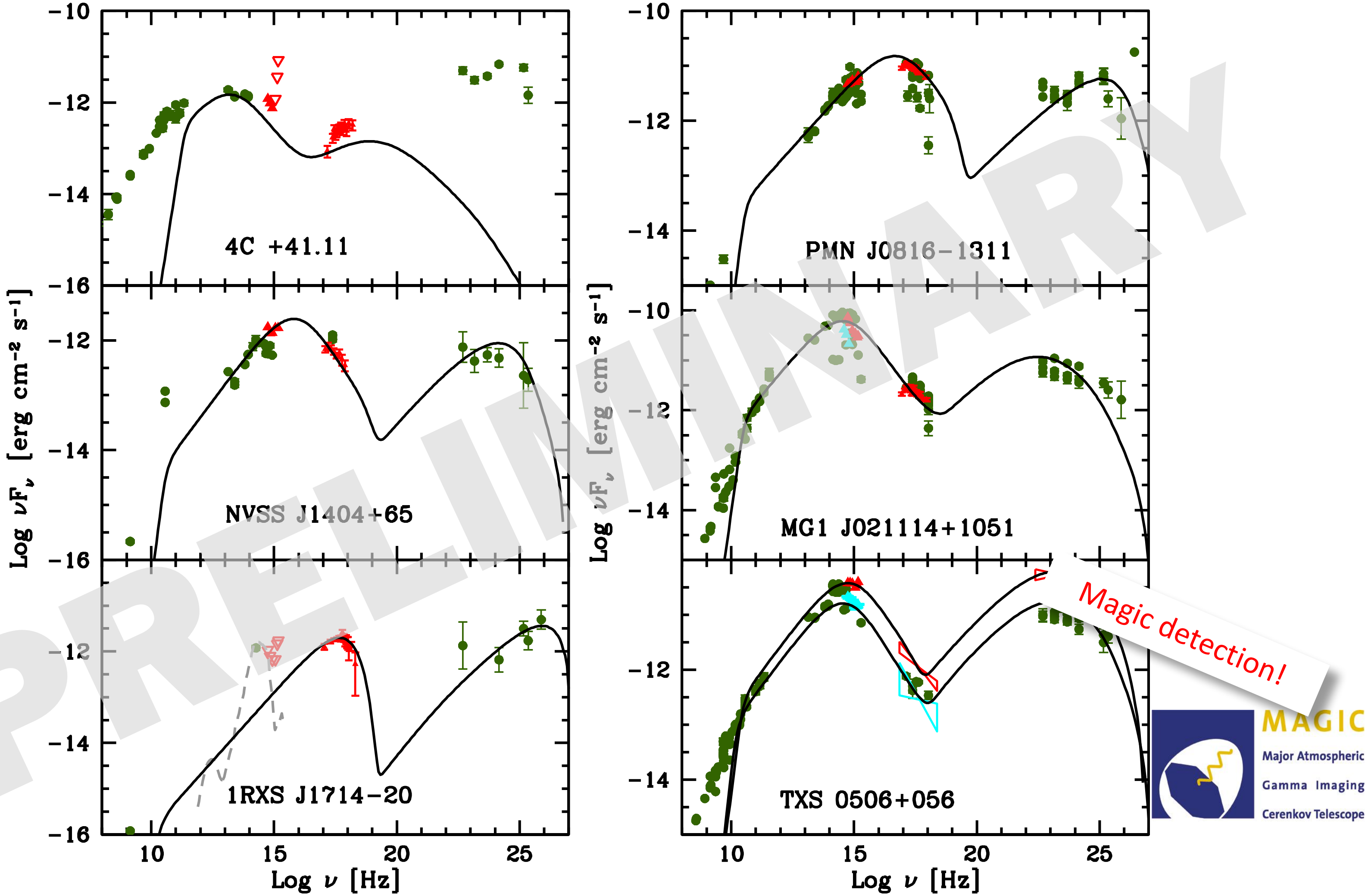


8 BL Lac object with a spatial correlation with a track or an HESE event.

BL Lacs candidates

Righi et al. submitted

Data analysis: REM Swift



Work in progress

Righi et al. in prep

Why IceCube haven't detect the brightest Mkn421 or Mkn501 yet?

They are proto-typical HSP with indications for the existence of Spine-Layer structure…

…TXS0506+056 is ISP (for which SL structure is not yet convincingly proven)…

Take home messages

- Blazar are good candidates to produce high-energy neutrinos!
- TXS 0506+056 is very intriguing... Stay tuned!
- The "problem of Mkn421" is a question which have yet to be resolved.

THANKS!

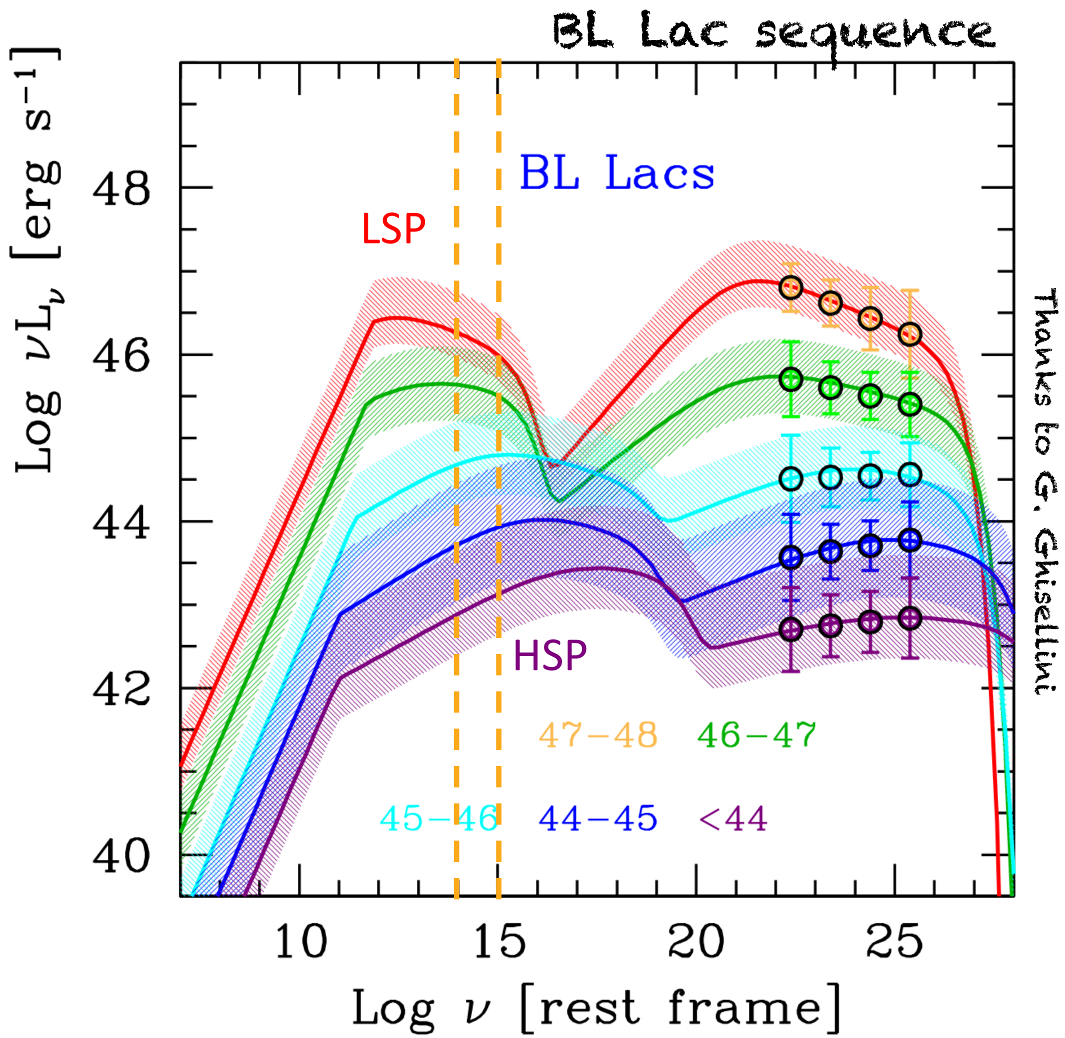
Work in progress

LSP: $\nu^S_{peak} < 10^{14}$Hz

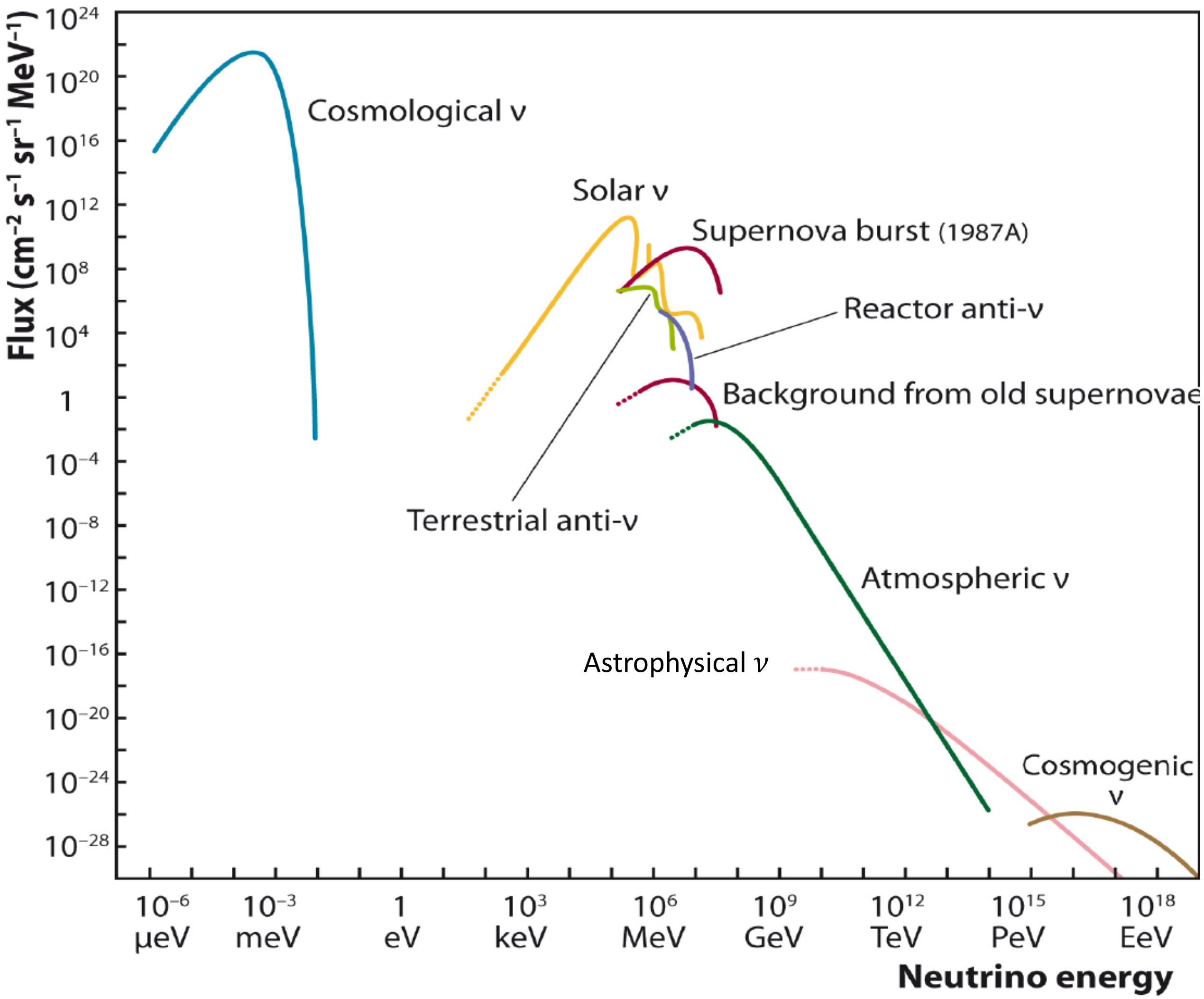
ISP: $10^{14}\text{Hz} < \nu^S_{peak} < 10^{15} Hz$

HSP: $\nu^S_{peak} > 10^{15}$Hz

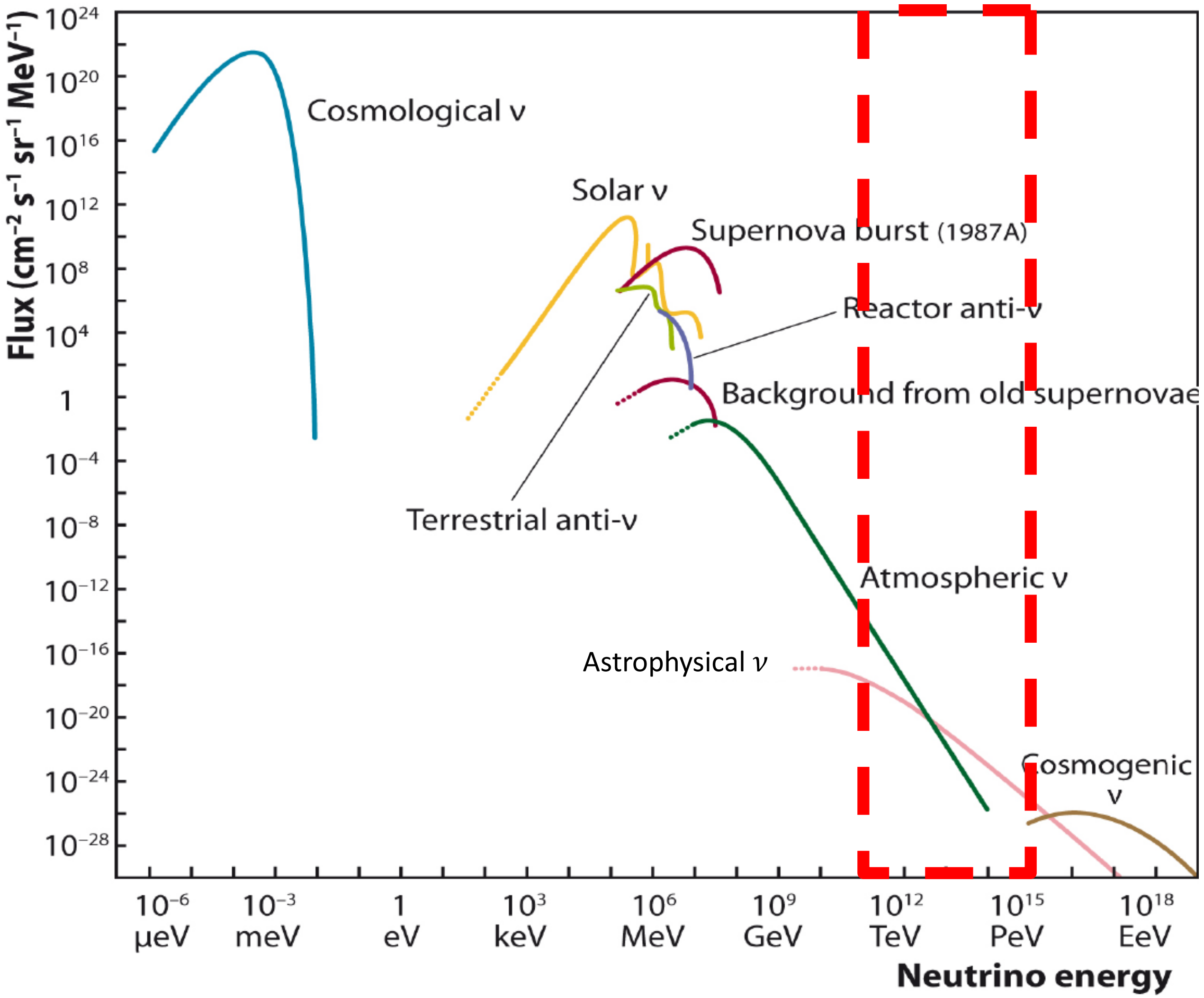
Ackermann et al. 2015 - 3LAC



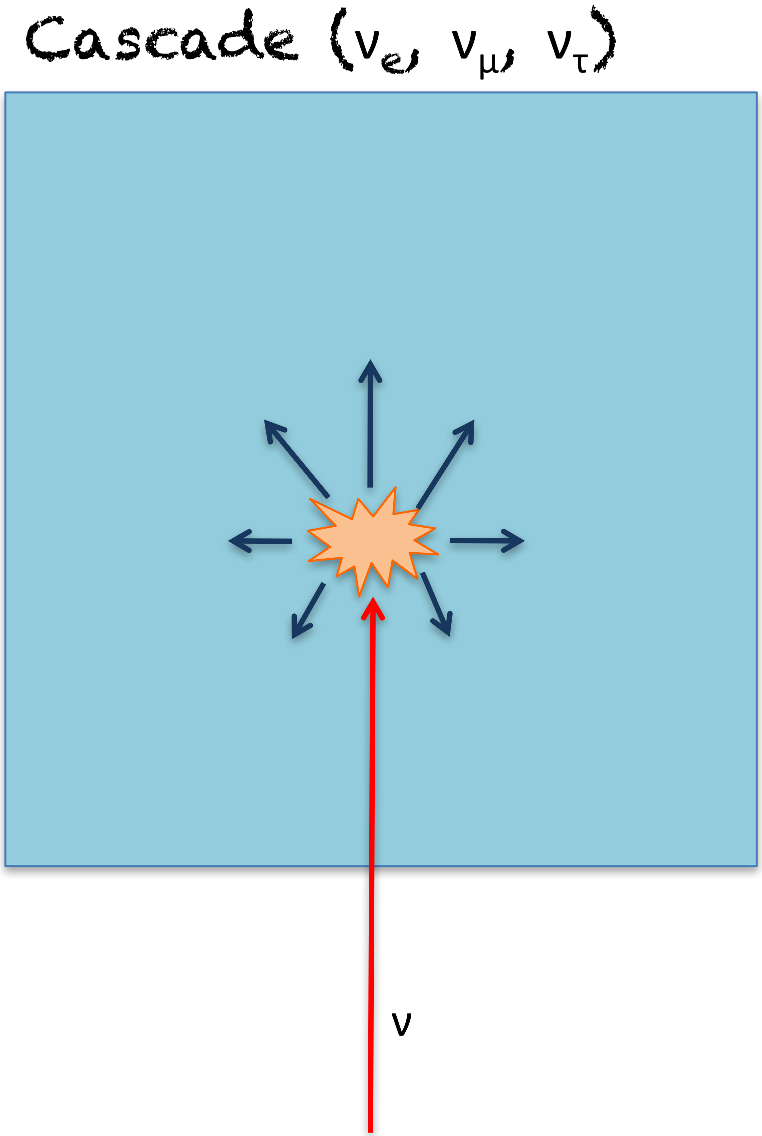
Neutrino flux

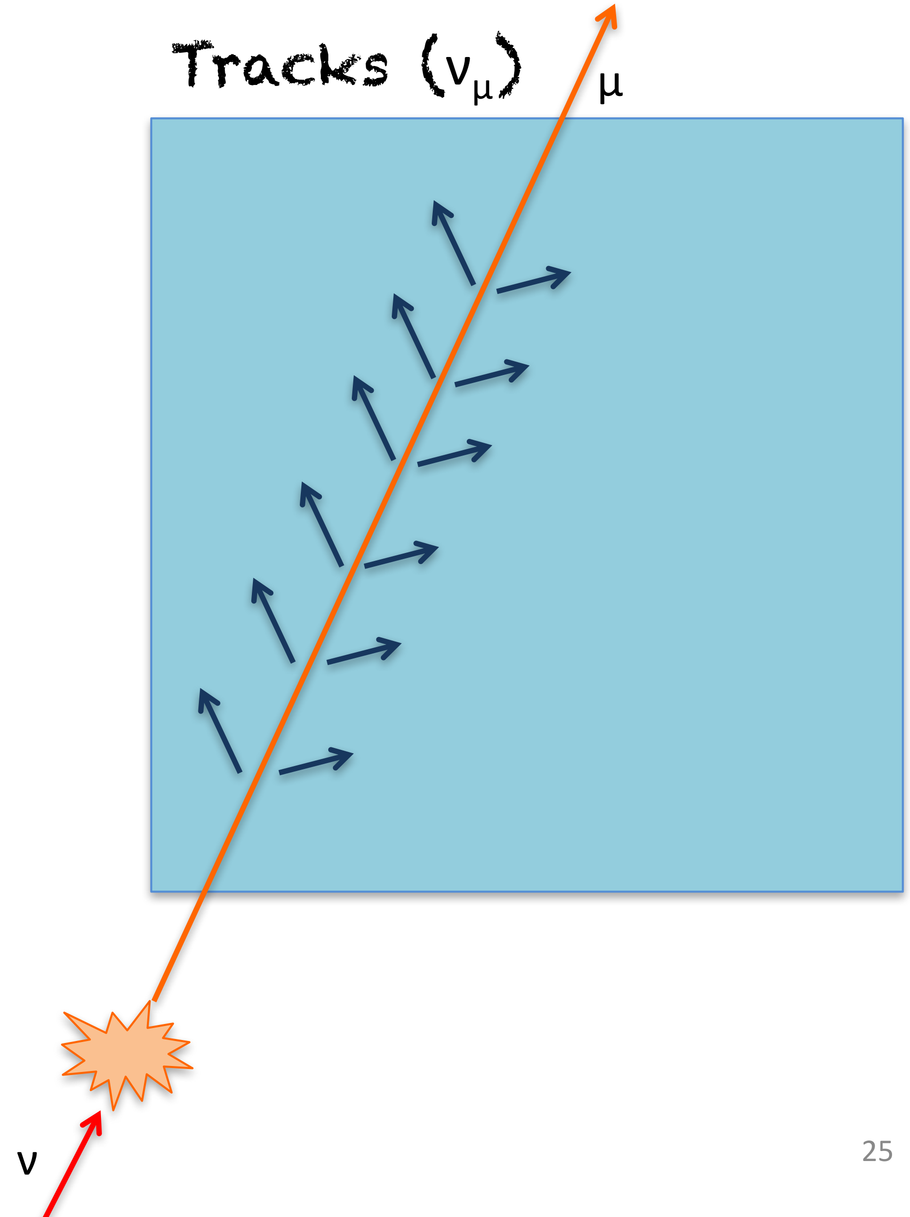


Neutrino flux



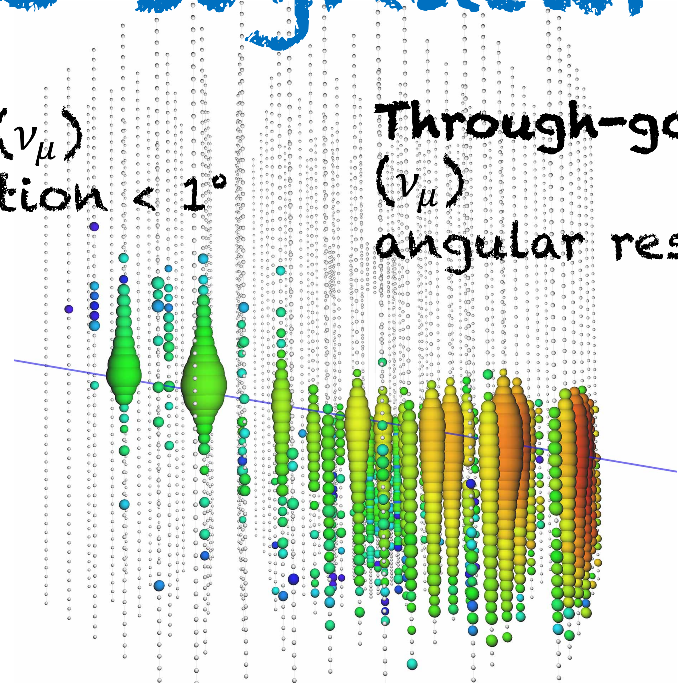
Different signature





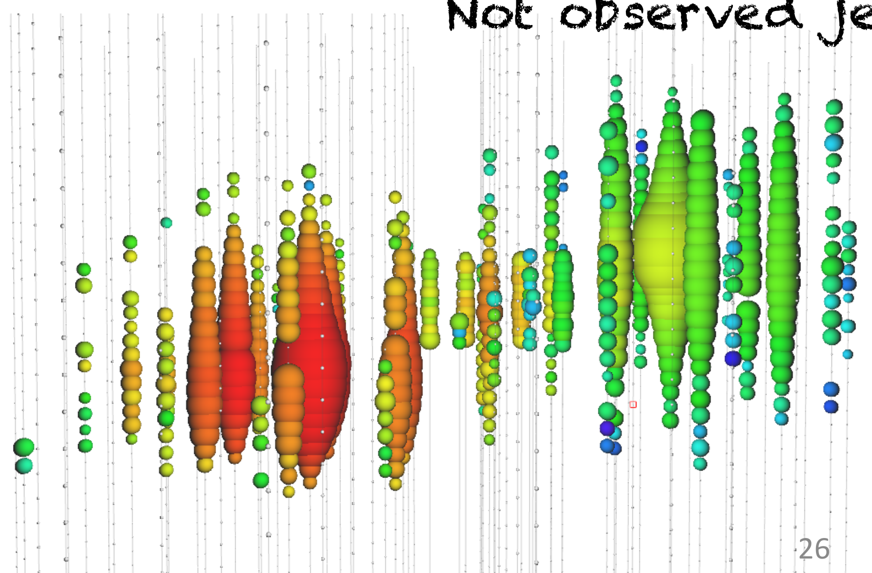
Neutrino signature in ice

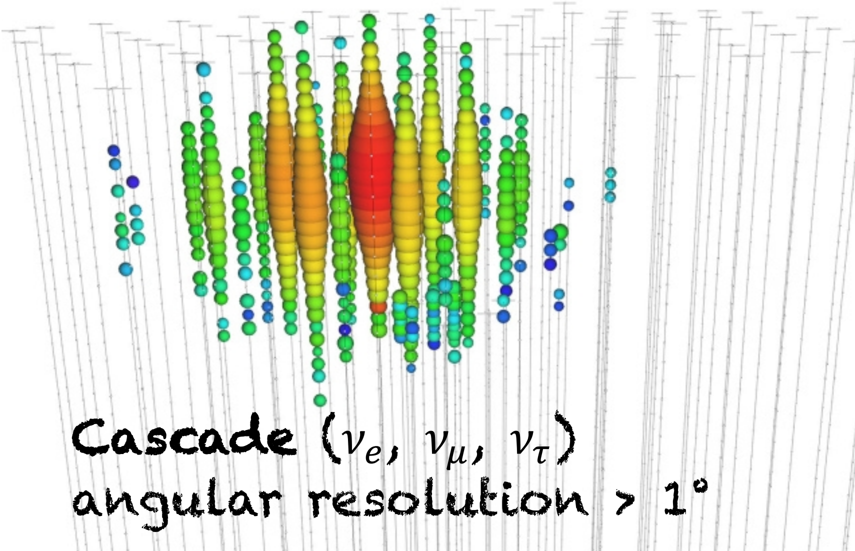
Starting track (ν_μ)
angular resolution < 1°



Through-going track (ν_μ)
angular resolution < 1°

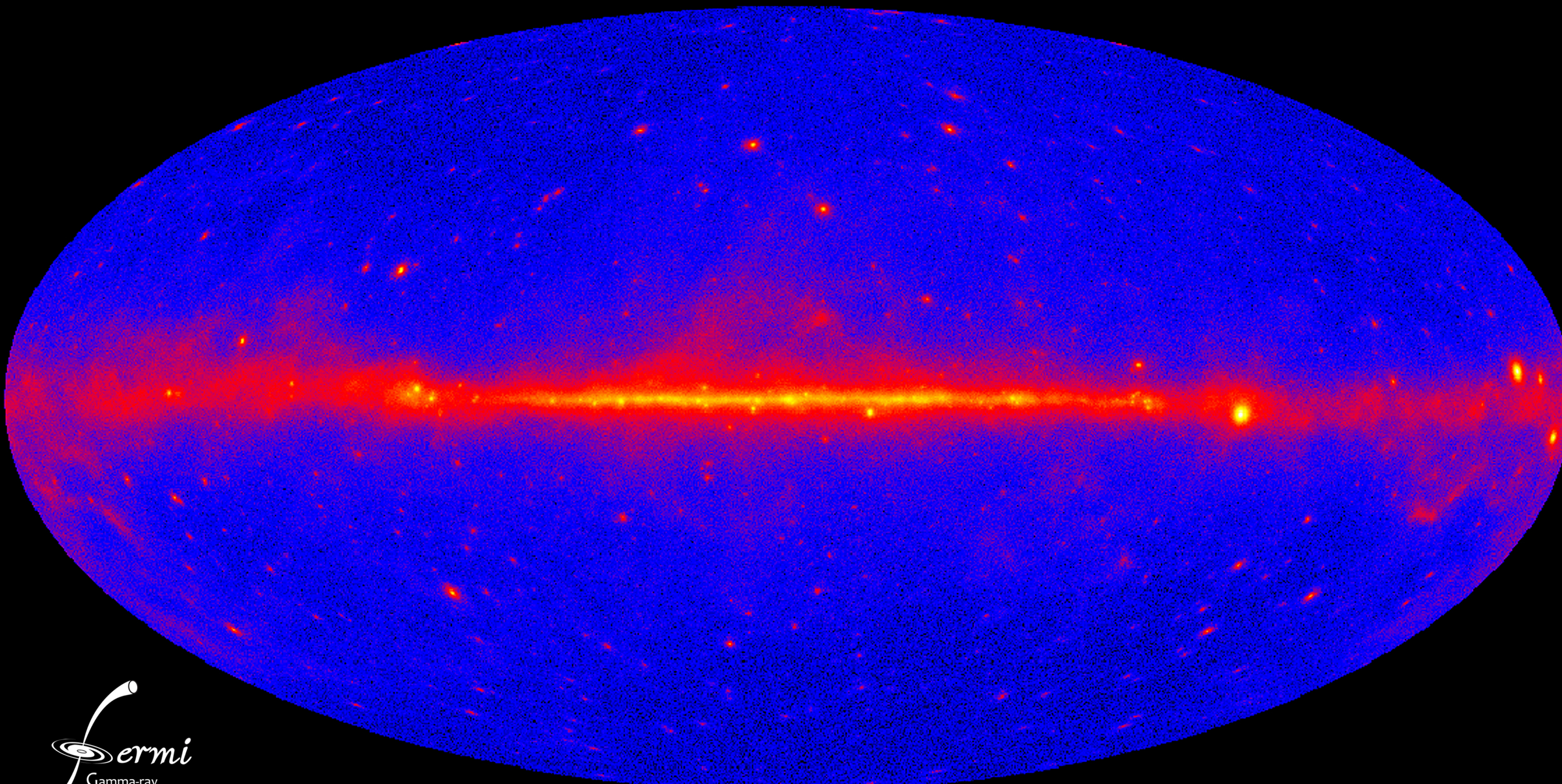
Double bang (ν_τ)
Not observed jet





Cascade (ν_e, ν_μ, ν_τ)
angular resolution > 1°

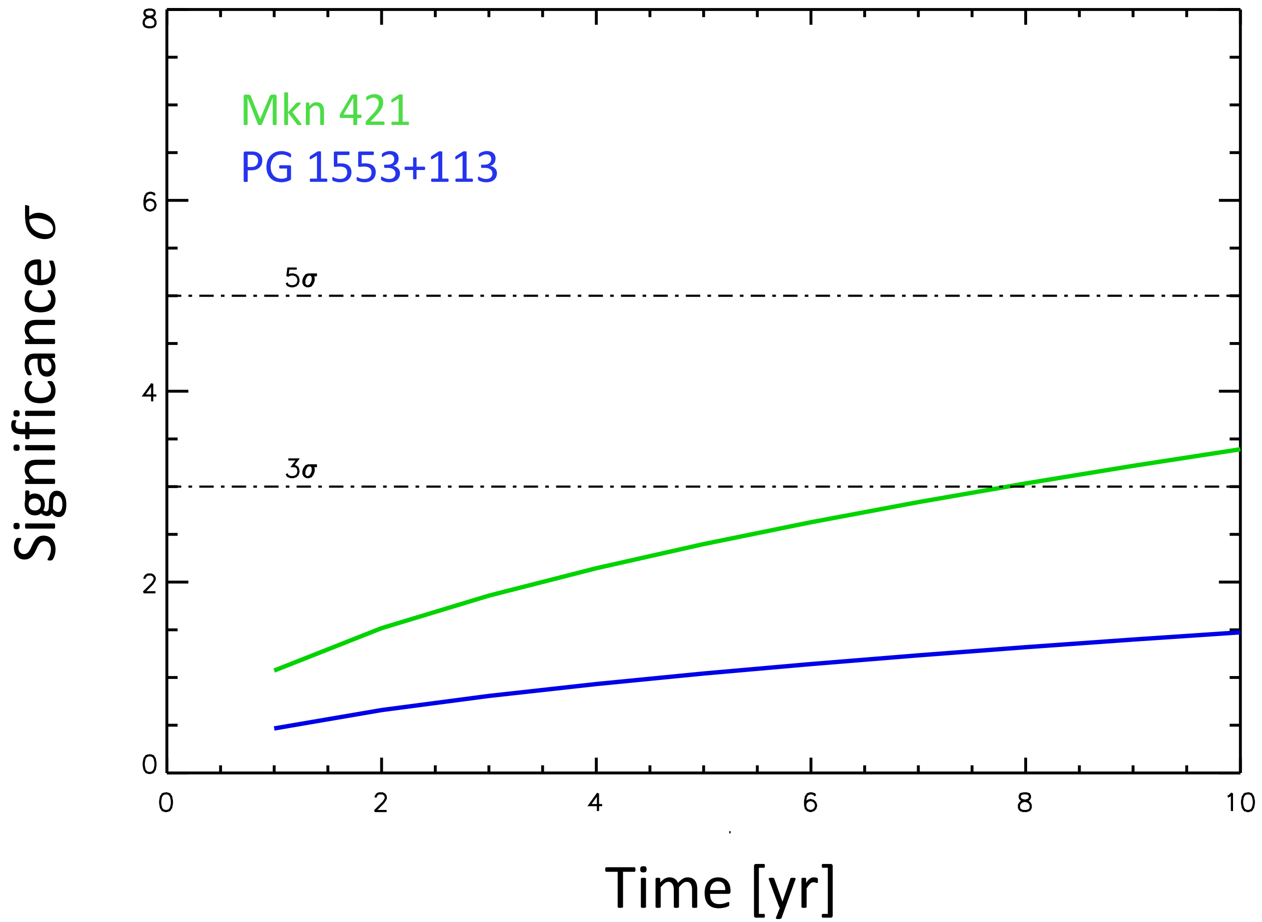
>60% extragal due to Blazar!



Fermi
Gamma-ray
Space Telescope

Righi et al. 2017 b

Detectability



Assuming 30% efficiency of the detector

This analysis includes the background!

Righi et al. 2017 b

Detectability

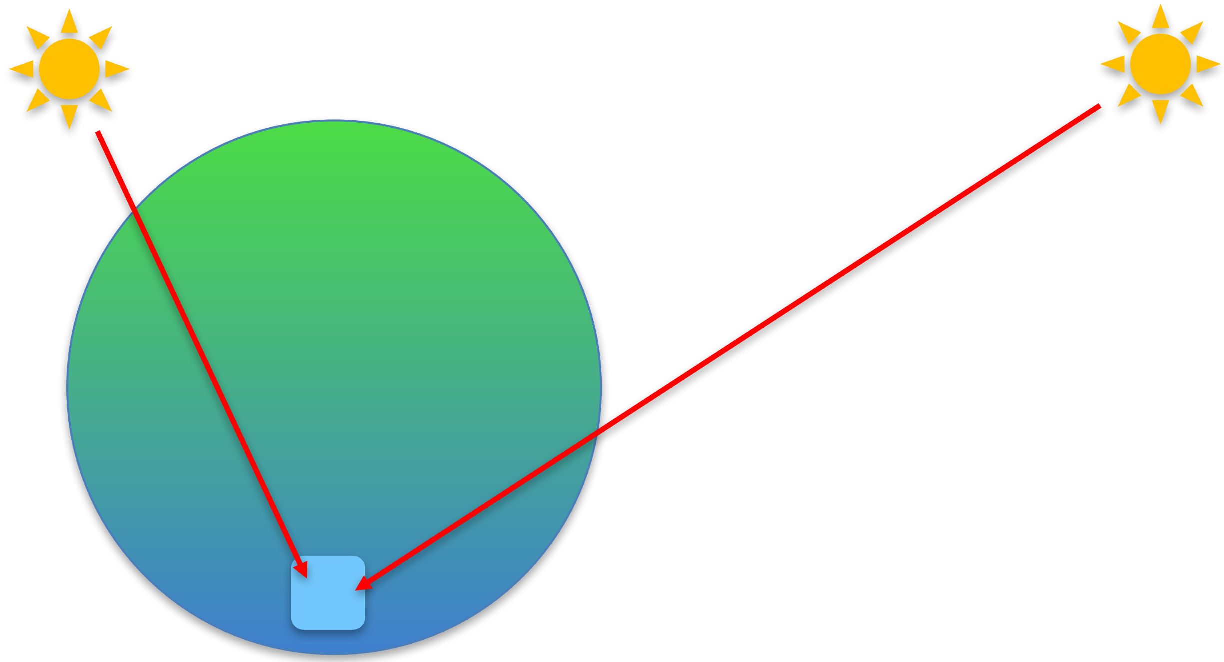
average muon energy-loss rate

Neutrino flux for each source

Charge current cross section

Attenuation due to Earth

$$\frac{d\dot{N}}{dE_\mu} = \frac{1}{\alpha + \beta E_\mu}\frac{A}{m_p}\int_{E_\mu}^{E_{\nu max}} \phi(E_\nu)\sigma_{CC}(E_\nu)e^{-\tau(x,E_\nu)}dE_\nu$$

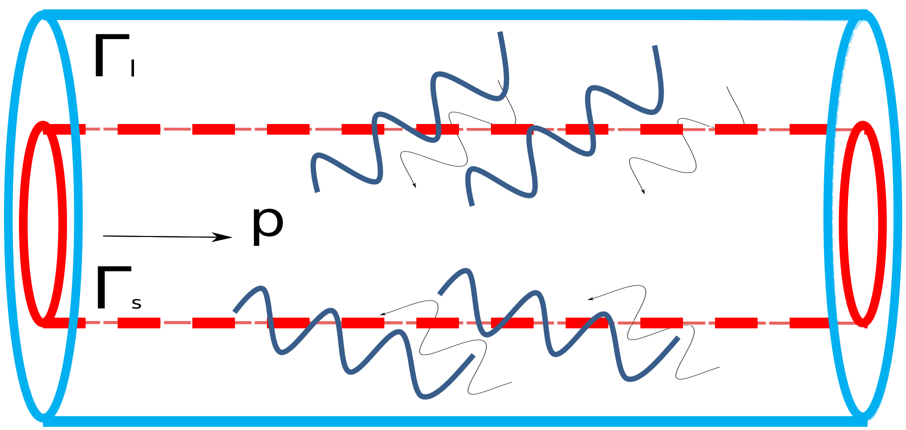


Spine-layer model

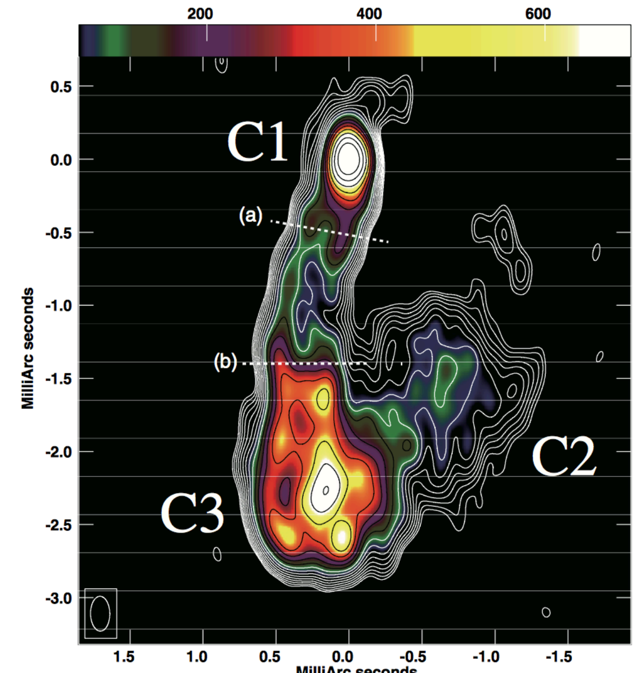
$\Gamma_s = 15 - 20$

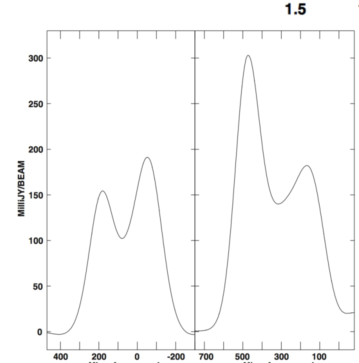
$\Gamma_l = 3 - 5$

The relative motion of the two components leads to the amplification of the radiation field of the layer as observed in the spine reference frame.



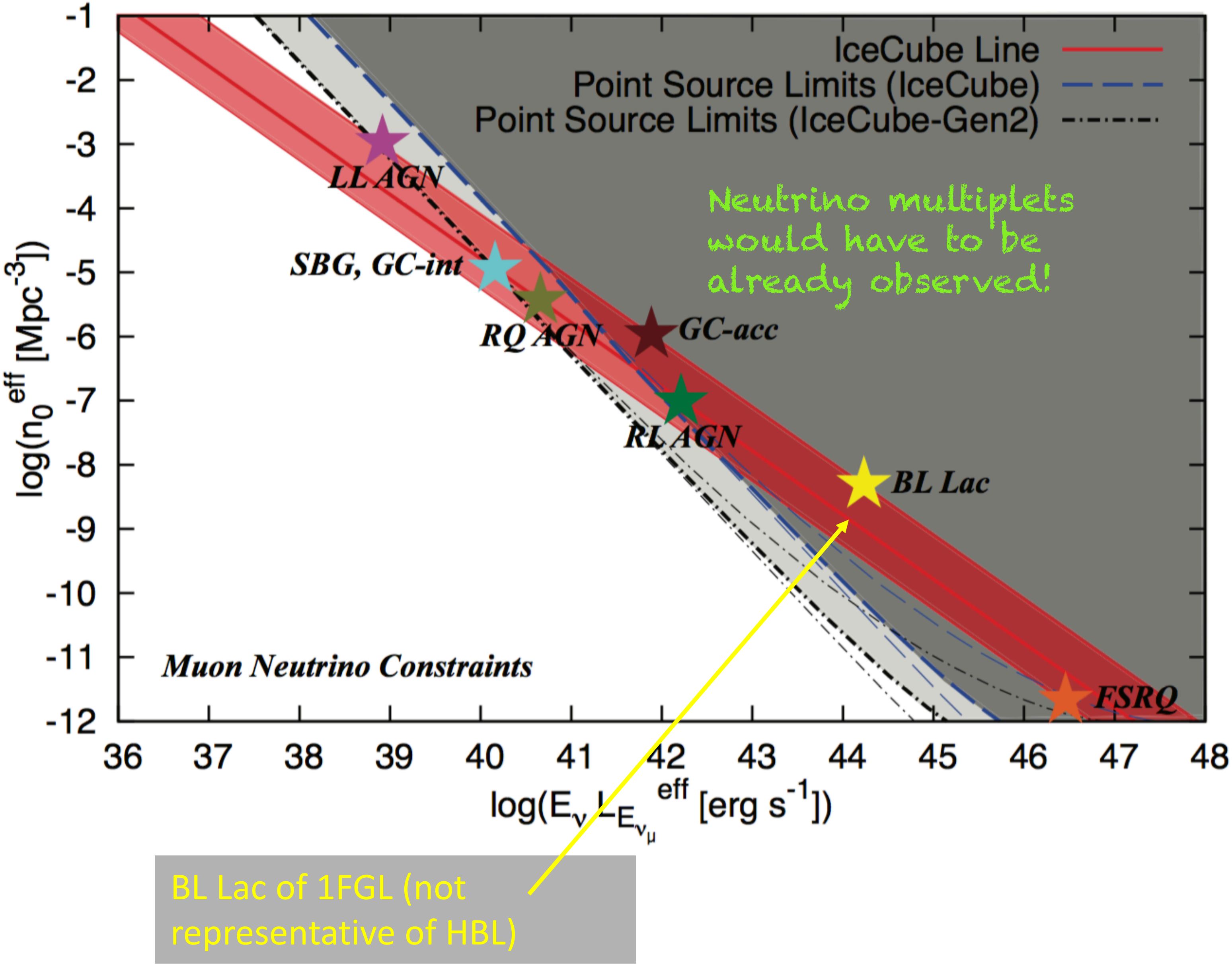
Ghisellini et al. 2005
Tavecchio & Ghisellini 2008, 2014





Nagai et al. 2014
Giovannini et al. 2015

the weakly beamed emission of the layer could dominate the emission from misaligned radiogalaxies



Murase and Waxmann, 2016

Righi et al. 2017 a

Theoretical framework

- → Leptonic scenario for the SED
- → EM and ν outputs derive from two different (but not indepentent!) channels
- → Neutrino luminosity: $L_\nu = \varepsilon_p Q'_p \delta_s^4$
- → IC luminosity: $L_\gamma = \varepsilon_e Q'_e \delta_s^4$
- → $\frac{F_\nu}{F_\gamma} = \frac{L_\nu}{L_\gamma} = \frac{\varepsilon_p Q'_p}{\varepsilon_e Q'_e}$
- → ε_p and ε_e depend on the same photon field
- → Q'_p and Q'_e depend on the total power P_{jet}
- → $\frac{F_\nu}{F_\gamma} \approx const.$ the same in all HBL.

$Q'_{p,e}$ CR, electrons injected power

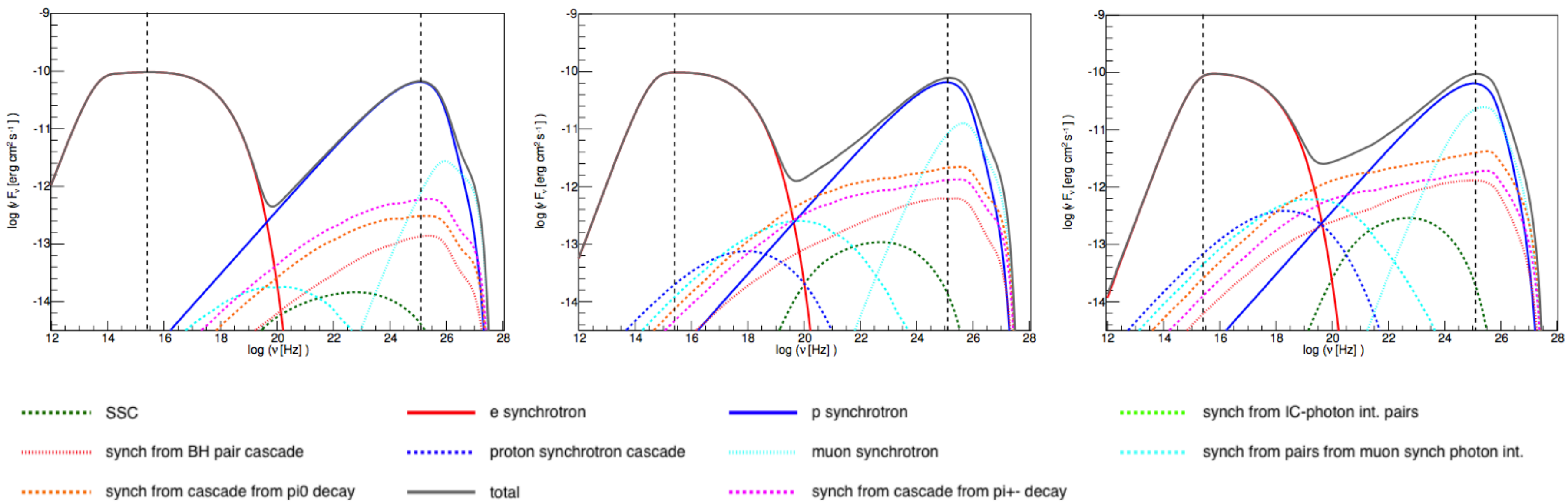
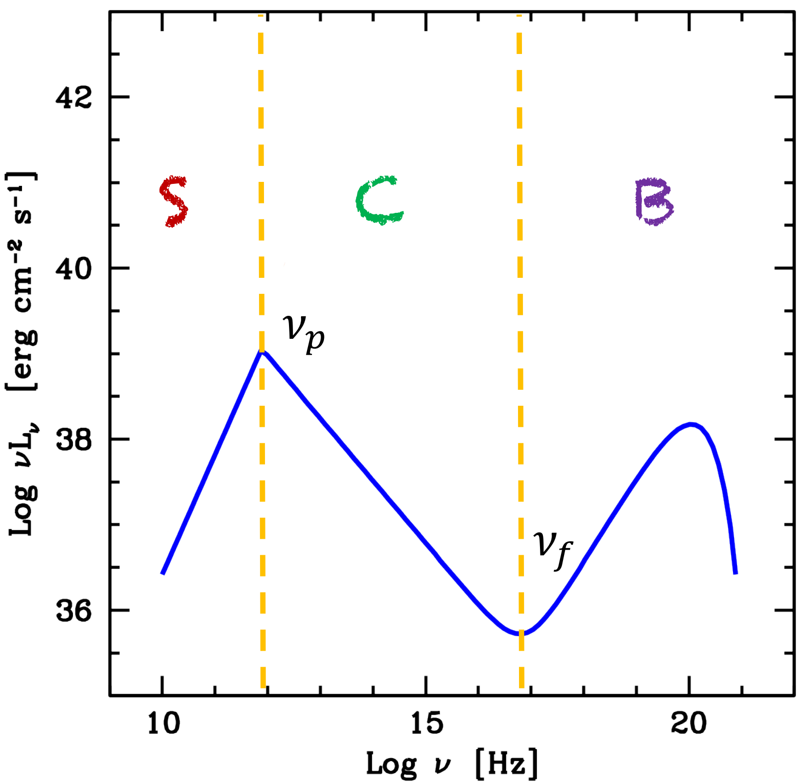


Fig. 2. Variation in the modelled SED when moving along the diagonal in log R-log B space. From left to right, models with log $B[G]$ = 0.5,1.5,2.0 are shown. Particle densities are adjusted to maintain the same overall flux level between the different models. Solid red and blue lines indicate the electron and proton synchrotron emission. The dotted and dashed lines show muon-synchrotron emission at the highest energies, and the SSC and muon-synchrotron cascade components at lower energies, as indicated in the legend. The VHE spectrum is absorbed by the EBL, assuming a redshift of 0.116, corresponding to the source PKS 2155-304. The spectral index n_1 is chosen to be 1.9. The two dashed vertical lines are there to guide the eye by marking the approximate peak postitions of the model in the central figure.

Zech et al. 2017

Advection Dominated Accretion Flow (ADAF)



2-temperature structure, with hot ions holding most of the energy and transferring it inefficiently to the electrons that produce most of the radiation.

S: $\nu < \nu_p$ ciclo-synchrotron emission

C: $\nu_p < \nu < \nu_f$ comptonisation of S

B: $\nu > \nu_f$ bremsstrahlung emission

After ν_p the synchrotron spectrum falls exponentially

Average energy of a photon for saturated componization in the Wien regime $h\nu_f = 3kT_e$

MAHADEVAN 97
Naranyan & Yi 95a,95b

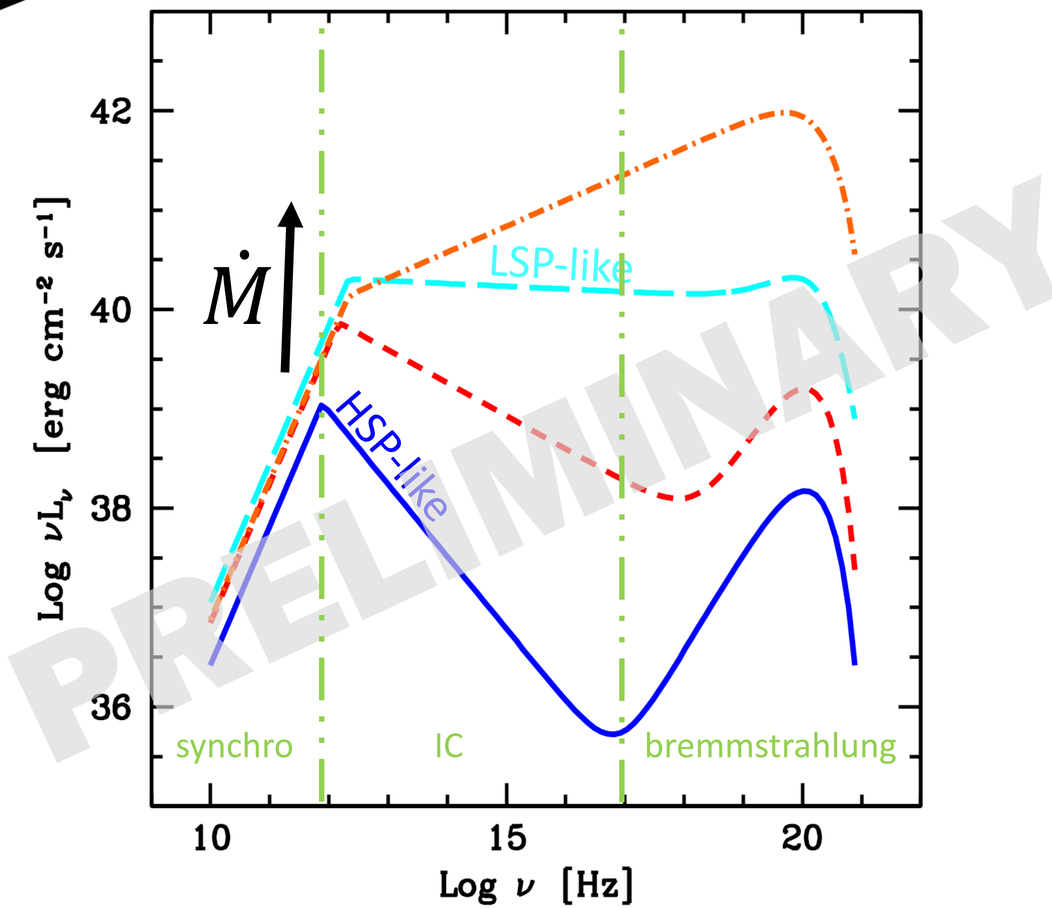
Righi et al. in prep

Work in progress

ADAF model

Naranyan & Yi 95a,95b
MAHADEVAN 97

$$L_{jet} \propto L_{disk}$$
$$L_{disk} \propto \dot{M}^2$$



The ADAF spectrum depends on $\dot{M}$.

LSP: red peak -> high accretion rate

HSP: blue peak -> low accretion rate

Work in progress

Righi et al. in prep

ADAF model

Pound for CR luminosity, the neutrino luminosity decrease drastically in case of HSP!

This lack can explain the potential detection of TXS0506+056 and the non-detection of Mkn421.