

BLAZARS AS NEUTRINOS FACTORIES



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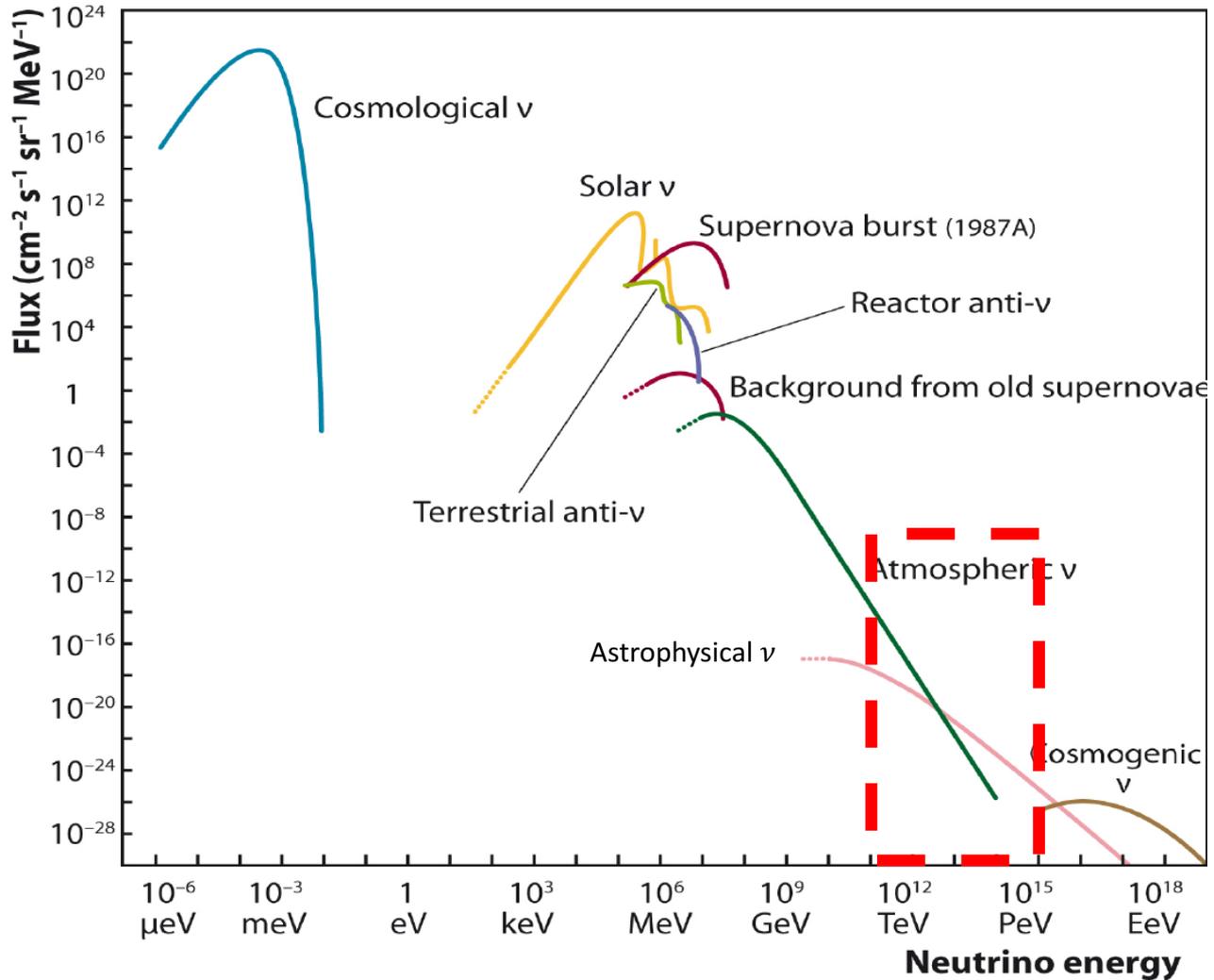
INAF - OA BRERA

INFN - GENOVA

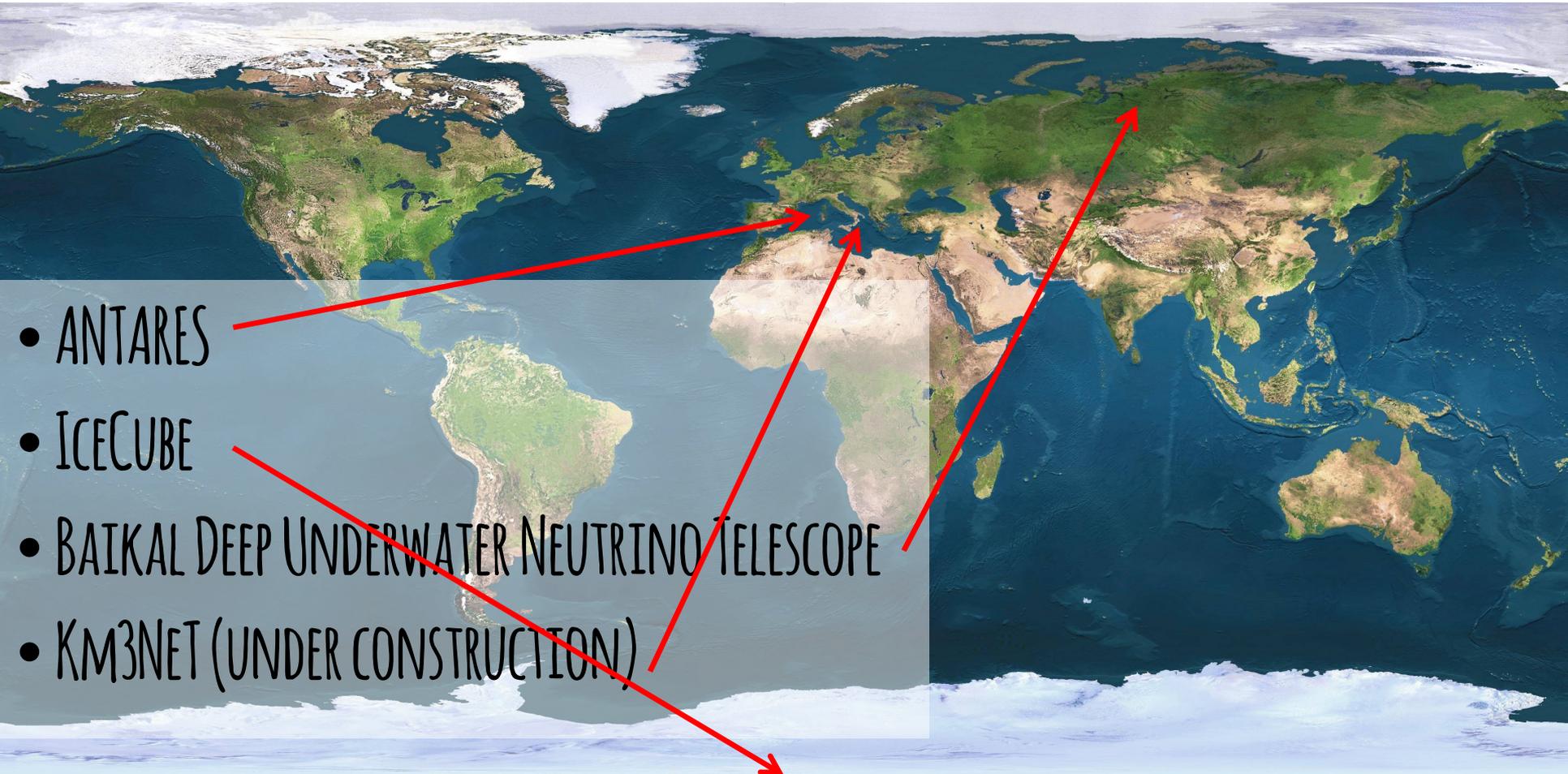
COLLABORATORS: F. TAVECCHIO, G. GHISELLINI, M. LANDONI, L. PACCIANI, S. INOUE, ...

11 DECEMBER 2018

NEUTRINO FLUX



HOW TO OBSERVE HIGH-ENERGY NEUTRINOS?

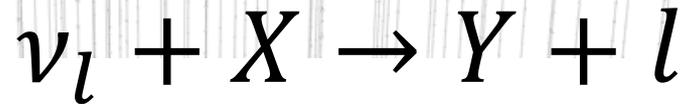
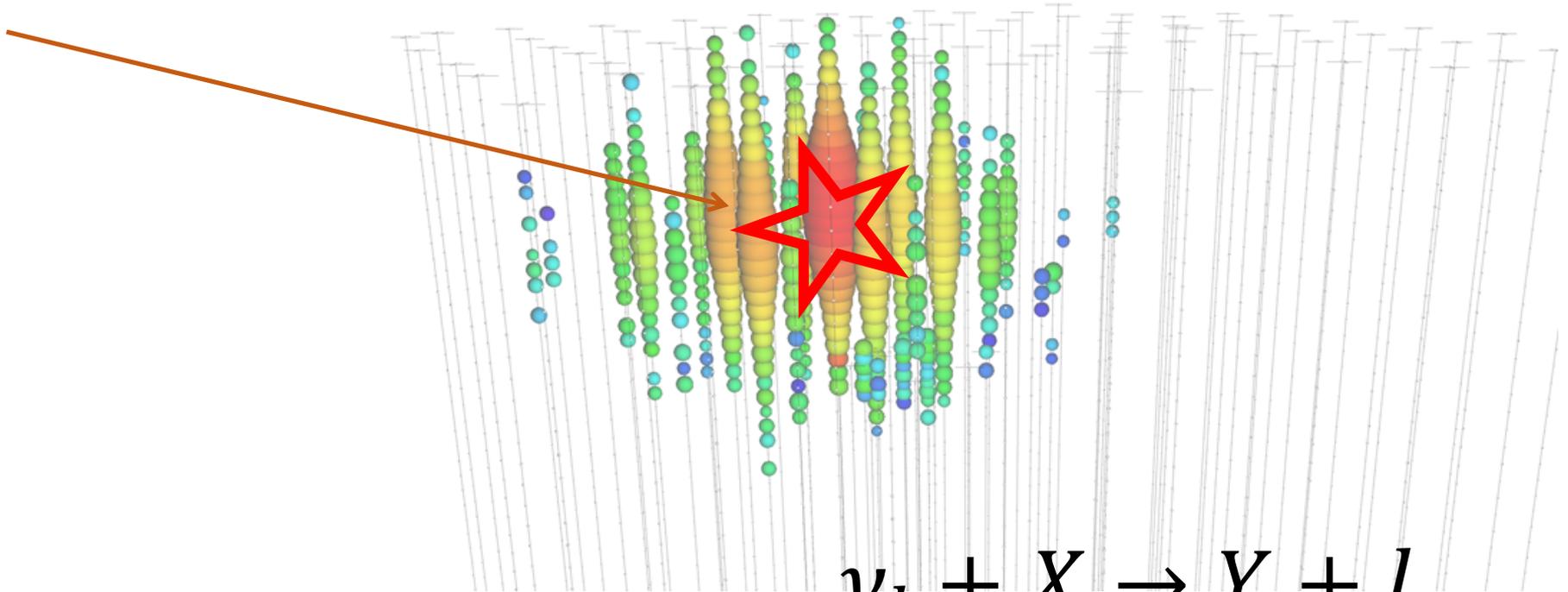


HOW TO OBSERVE HIGH-ENERGY NEUTRINOS?

INTERACTION INSIDE THE DETECTOR



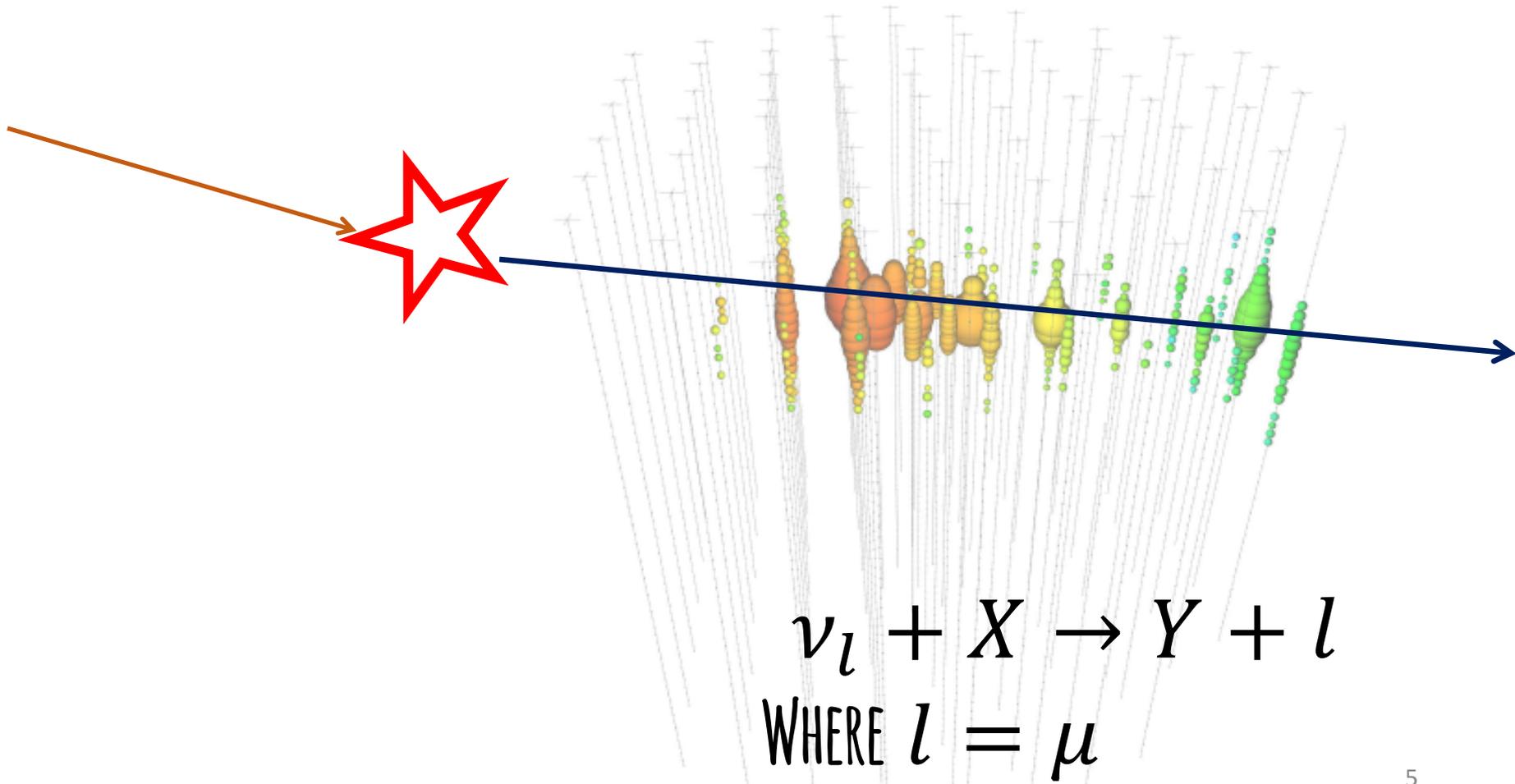
HIGH ENERGY STARTING EVENTS (HESE)



WHERE $l = e, \mu, \tau$

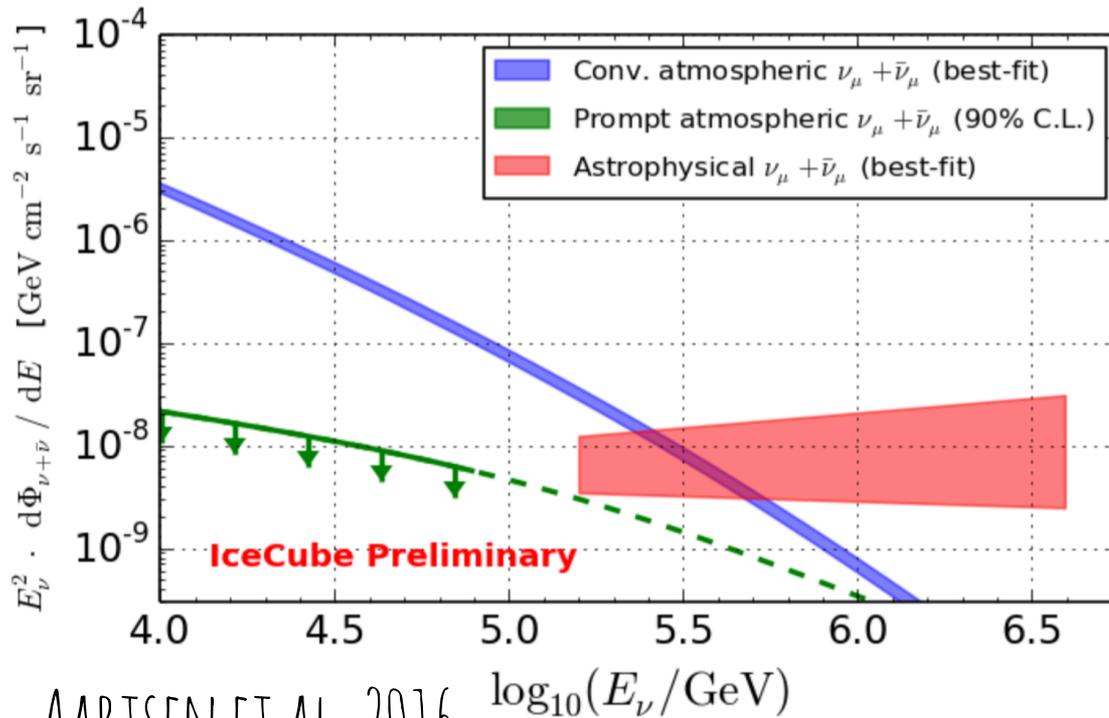
HOW TO OBSERVE HIGH-ENERGY NEUTRINOS?

INTERACTION OUTSIDE THE DETECTOR \longrightarrow THROUGHGOING MUON EVENTS



DISCOVERY OF HIGH-ENERGY NEUTRINOS BY ICECUBE

~80 EVENTS SINCE 2010 ABOVE 60TEV



~10 EVENTS PER YEAR

AARTSEN ET AL. 2016

DISCOVERY OF HIGH-ENERGY NEUTRINOS BY ICECUBE

~80 EVENTS SINCE 2010 ABOVE 60TEV

THE MUPPETS CONTINUED FROM PAGE 1



1. Kermit the frog (K)
Steadfast and true. Empathetic and smart. But let's face it, a bit of wimp.



5. Miss Piggy (P)
The original diva. Narcissistic, selfish, arrogant. But one tough cookie with a good heart underneath.



9. Cookie Monster (C)
Embraces life, and his appetite, with a verve that is both appealing and scary. Probably has substance abuse problems.



13. Elmo (M)
Communicates in baby noises and is obsessed with being touched. He is the friend of a friend whom you demand not to be left alone with.



17. Rowlf the dog (R)
Loyal, wise and pretty good at tickling the ivories. But sadly, Rowlf (and his brethren) are usually easily overlooked.



2. Fozzie Bear (F)
Good guy, horrible jokes, but his desperate pleas for approval can be a bit much. "Waka, waka!"



6. Statler and Waldorf (W)
These guys come as a team. Smart, usually correct, but, dang, they throw a lot of shade.



10. Bert (Rt)
Kind of like Oscar, only less aggressive and more whiny. Also, he doesn't live in trash.



14. Animal (A)
All id and aggression, he is the life of the party that gets on your nerves when the party is over.



18. Sam the eagle (S4)
Stic to the point of rigidity, but one suspects there is something under that reserved facade.



3. Gonzo (G)
The life of the party. Willing to do anything for a laugh. But will it ever be enough?



7. Big Bird (Bb)
Supportive, friendly and so relentlessly optimistic that you want to punch him in the face.



11. Ernie (E)
Supportive and understanding, but usually lets his friends make decisions for him.



15. Count Von Count (V)
He is happy only when he is counting things. Seriously. He is O.C.O. Not a lot of laughs, but pretty good around tax time.



19. Janice (J)
Talented, a little crazy and probably a lot stoned. She is a mystery, even to those who know her.



4. Beaker (B)
Hard-working. Tortured. Silent. Will he ever stand up for himself?



8. Oscar the Grouch (O)
A realist who has a tendency to always look at the dark side of things, but usually has a soft side he reveals only to his friends.



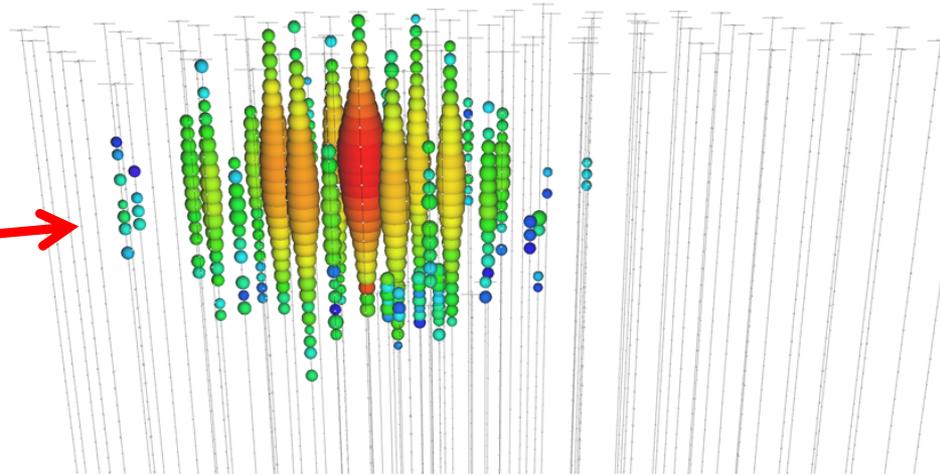
12. Scooter (S)
Organized, on top of things, but not particularly exciting or fun.



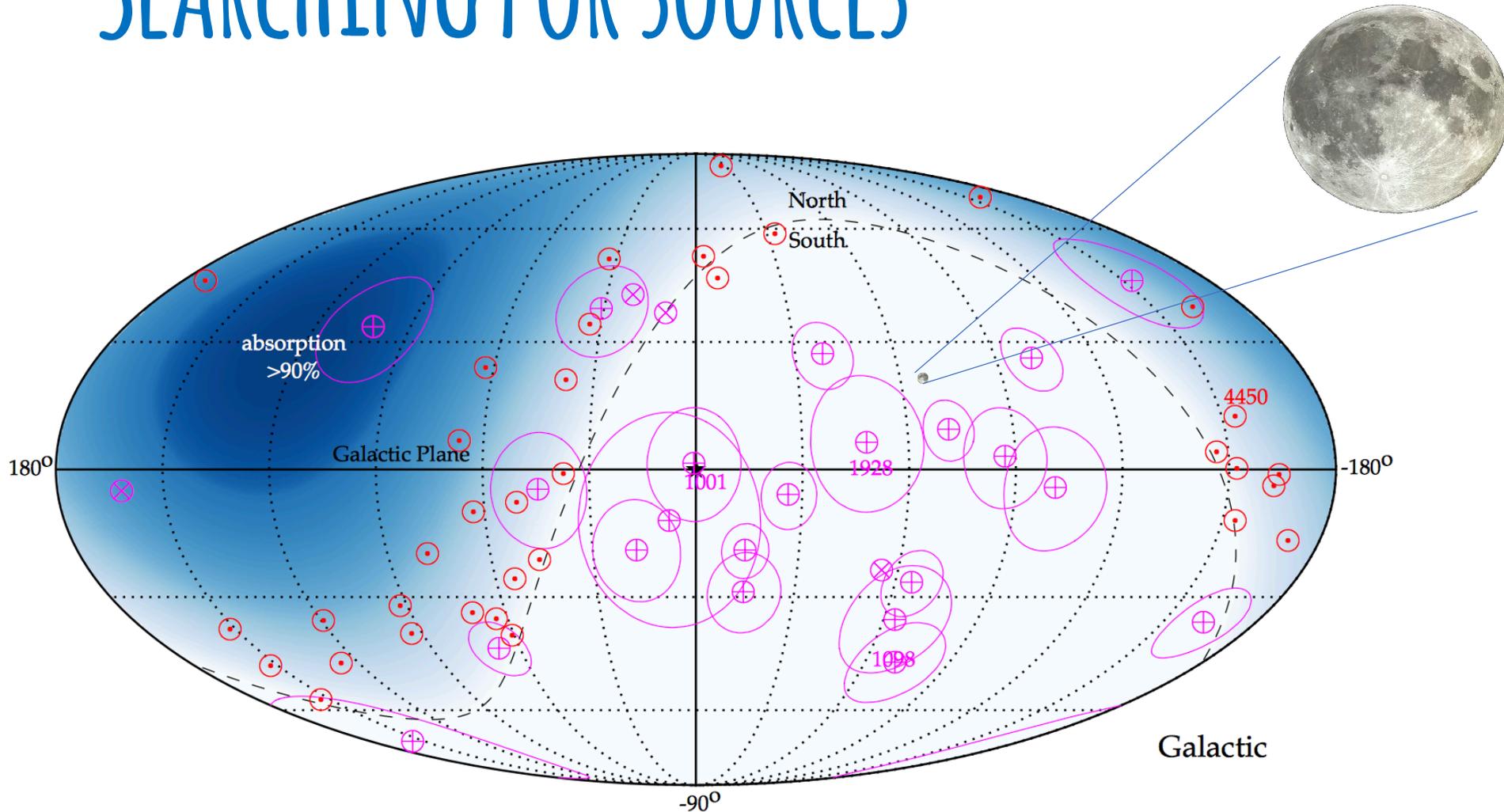
16. Dr. Bunsen Honeydew (D)
Smart, motivated and ultimately doomed to failure. Everything he does, he messes up, and others (specifically Beaker) pay for it. But he always survives.



20. Floyd Pepper (F)
Talented, like Janice and Rowlf, but tortured for his craft. Can play a mean guitar, but, yeah, man, like the scars are real.



SEARCHING FOR SOURCES



WE WILL CONSIDER ONLY THROUGHGOING MUONS!

HIGH-ENERGY NEUTRINO PRODUCTION

RELATIVISTIC PROTONS!!

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

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

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

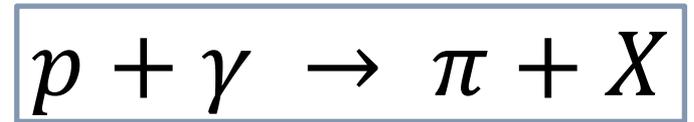
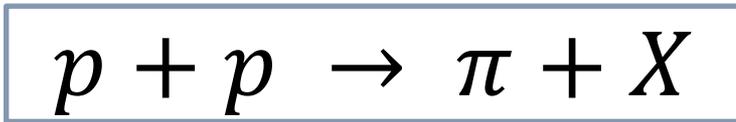
$$\pi^0 \rightarrow \gamma + \gamma$$

$$E_{\nu} \sim E_p / 20$$

1:1:1
AFTER PROPAGATION

HIGH-ENERGY NEUTRINO PRODUCTION

RELATIVISTIC PROTONS!!



OUR GALAXY

SEE M. CATALDO'S TALK

STAR-FORMING GALAXY

AGN WINDS

LOW-ENERGY RADIOGALAXIES (FRO)

HIGH-ENERGY NEUTRINO PRODUCTION

RELATIVISTIC PROTONS!!



OUR GALAXY

STAR-FORMING GALAXY

AGN WINDS

LOW-ENERGY RADIOGALAXIES (FRO)



PROTONS ACCELERATED INSIDE THE SNR ESCAPE AND INTERACT WITH INTERGALACTIC MEDIUM

HIGH-ENERGY NEUTRINO PRODUCTION

RELATIVISTIC PROTONS!!



OUR GALAXY

STAR-FORMING GALAXY

AGN WINDS

LOW-ENERGY RADIOGALAXIES (FRO)



PROTONS ACCELERATED INSIDE THE AGN WIND ESCAPE AND INTERACT WITH INTERGALACTIC MEDIUM

HIGH-ENERGY NEUTRINO PRODUCTION

RELATIVISTIC PROTONS!!



OUR GALAXY

STAR-FORMING GALAXY

AGN WINDS

LOW-ENERGY RADIOGALAXIES (FRO)



PROTONS ACCELERATED INSIDE THE JET ESCAPE AND INTERACT WITH INTERGALACTIC MEDIUM

HIGH-ENERGY NEUTRINO PRODUCTION

RELATIVISTIC PROTONS!!

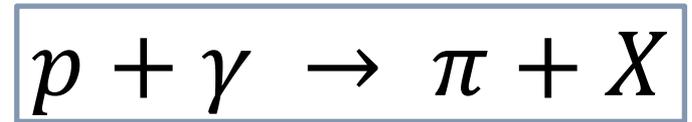


OUR GALAXY

STAR-FORMING GALAXY

AGN WINDS

LOW-ENERGY RADIOGALAXIES (FRO)



GRBS

BLAZARS

HIGH-ENERGY NEUTRINO PRODUCTION

RELATIVISTIC PROTONS!!



OUR GALAXY

STAR-FORMING GALAXY

AGN WINDS

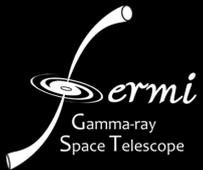
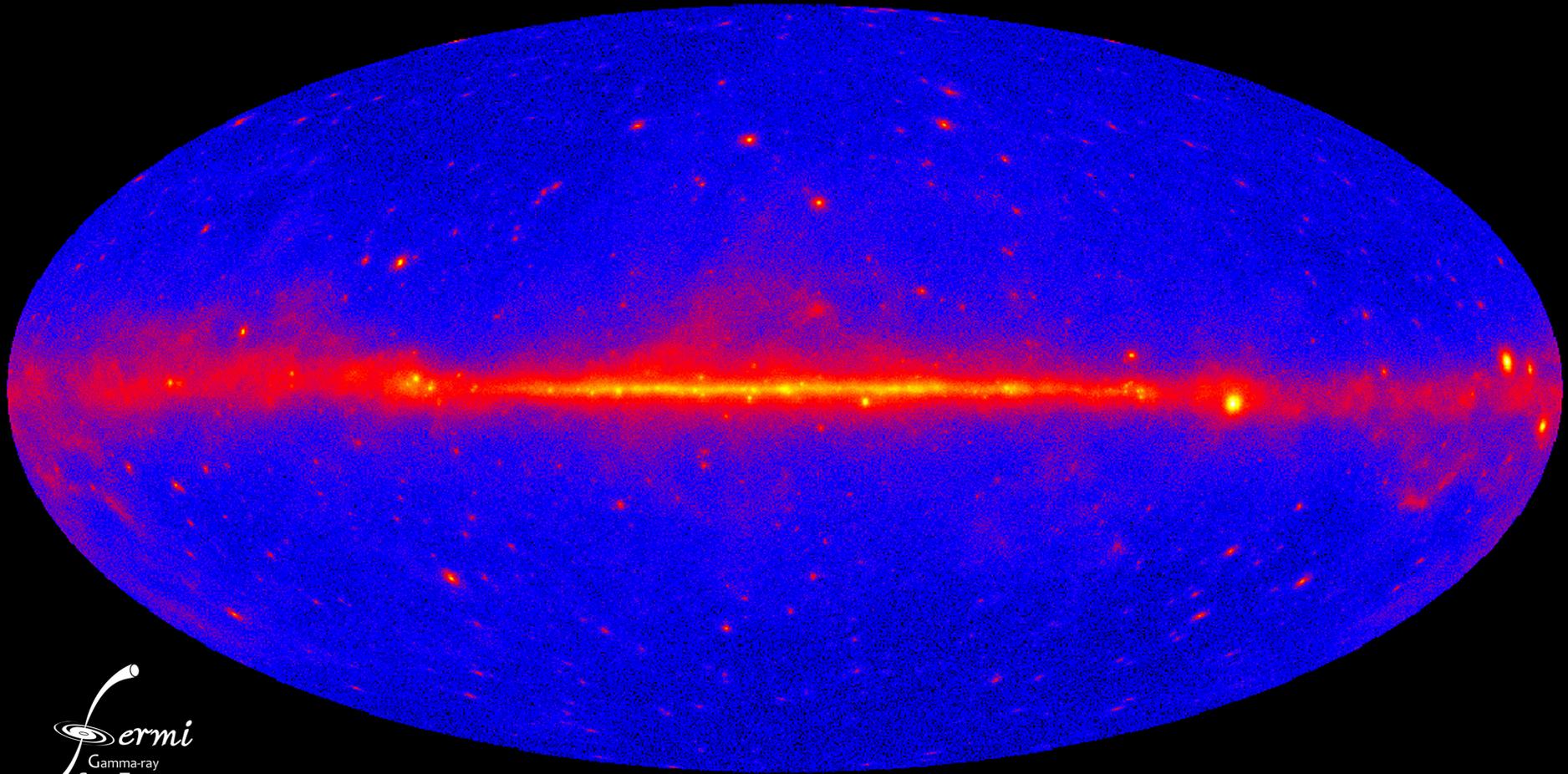
LOW-ENERGY RADIOGALAXIES (FRO)



GRBS

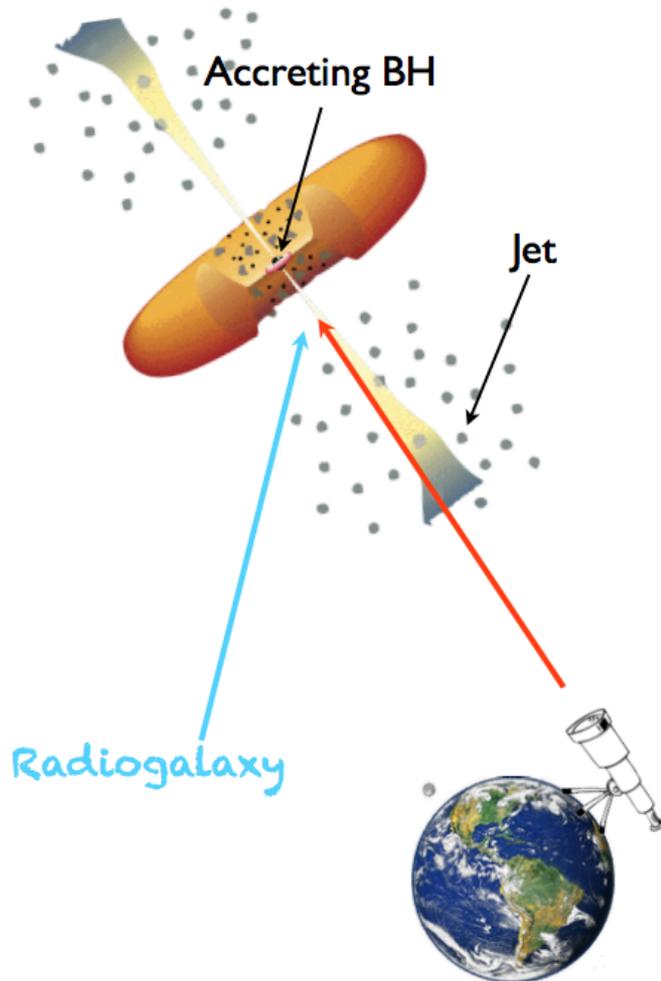
BLAZARS

HIGH-ENERGY SKY



>60% EXTRAGAL DUE TO BLAZAR!

WHAT IS A BLAZAR?



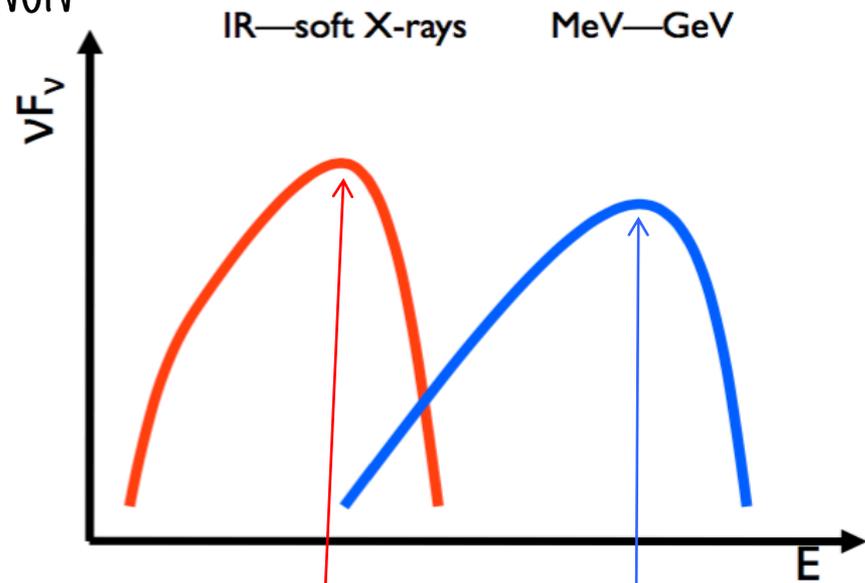
JET POINTING TO US:

OUTSHINES ANY OTHER ISOTROPIC EMISSION COMPONENT ASSOCIATED TO AGN (DISK, DUST) OR TO THE HOST GALAXY.

BLAZARS

SPECTRAL ENERGY DISTRIBUTION (SED)

DOMINATED BY THE RELATIVISTICALLY BOOSTED NON-THERMAL CONTINUUM EMISSION OF THE JET.



MODELS

LEPTONIC

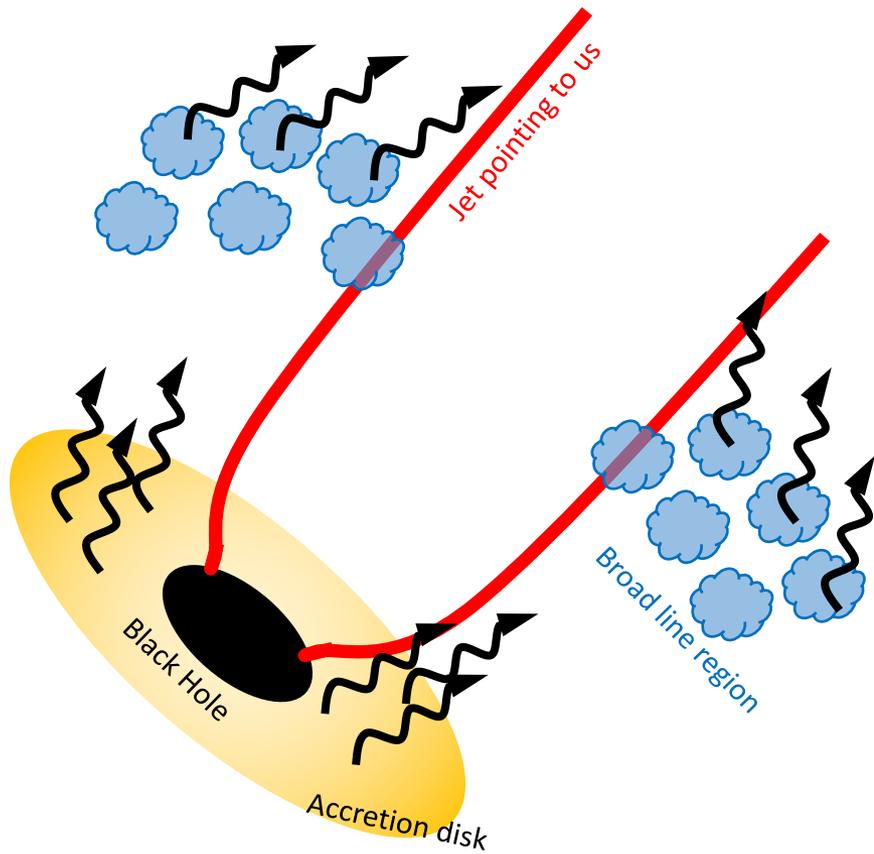
HADRONIC

SYNCHROTRON

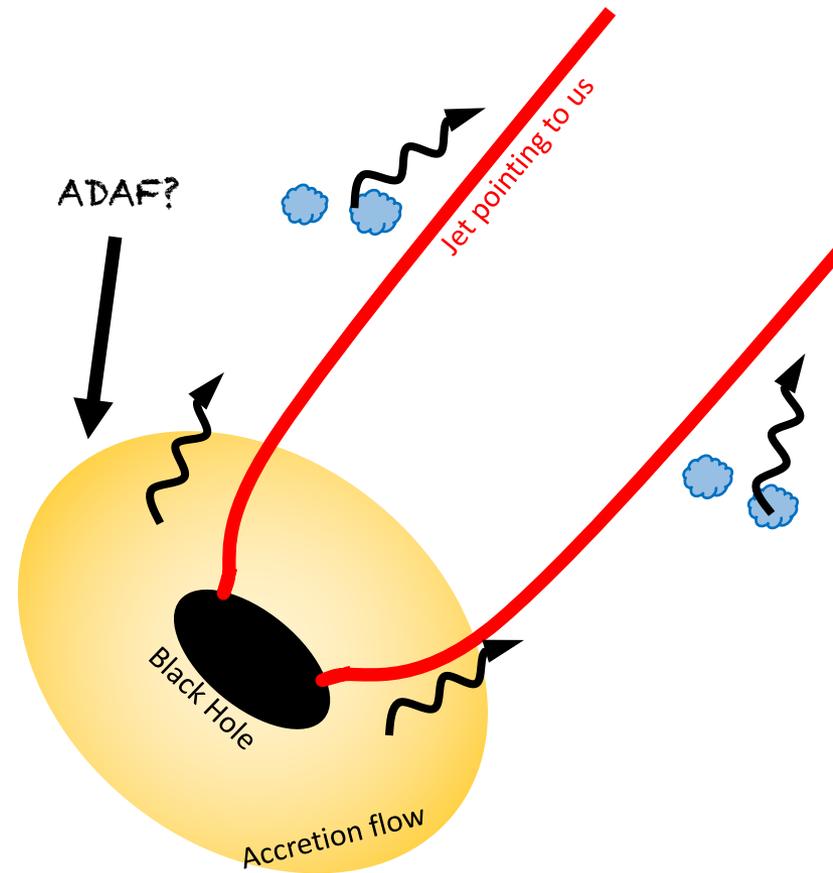
INVERSE COMPTON
REPROCESSED PHOTO-MESON PRODUCTS
OR SYNCHROTRON (PROTONS)

MY WORK

FSRQ



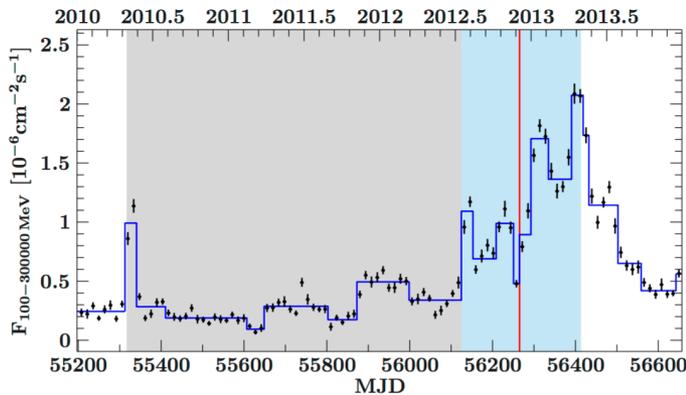
BL LAC



ARE BLAZARS DETECTABLE BY ICECUBE?

FSRQ

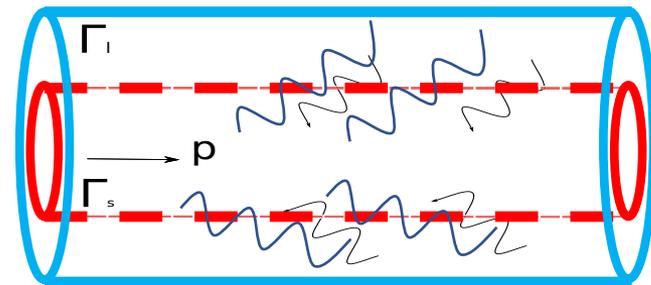
- ✓ Possible correlation between one neutrino event and a γ -ray flare of a FSRQ object (Kadler et al. 2016).



- ✗ EM- ν emission can't be exclusively hadronic (Gao et al. 2017)
- ✗ Murase and Waxman 2016
- ✗ $p+\gamma$ 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

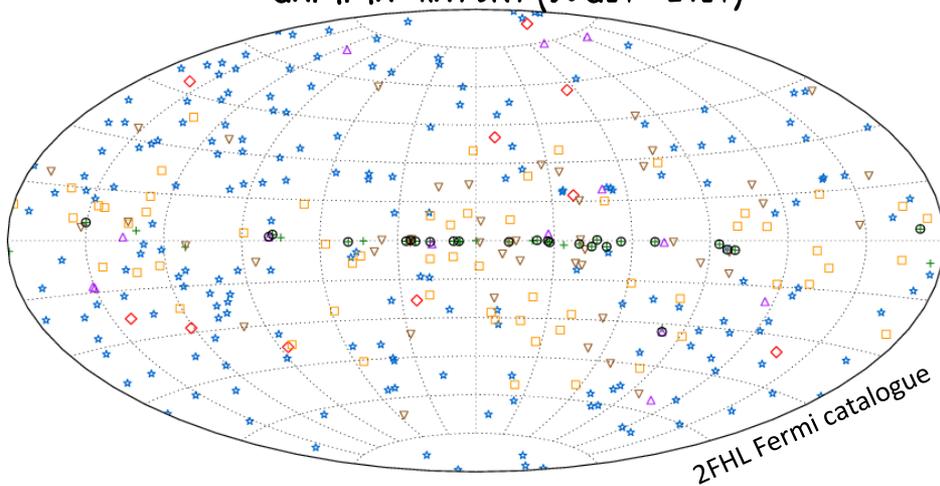
Righi et al. 2017 a

THE MODEL

ASSUMPTION 1:

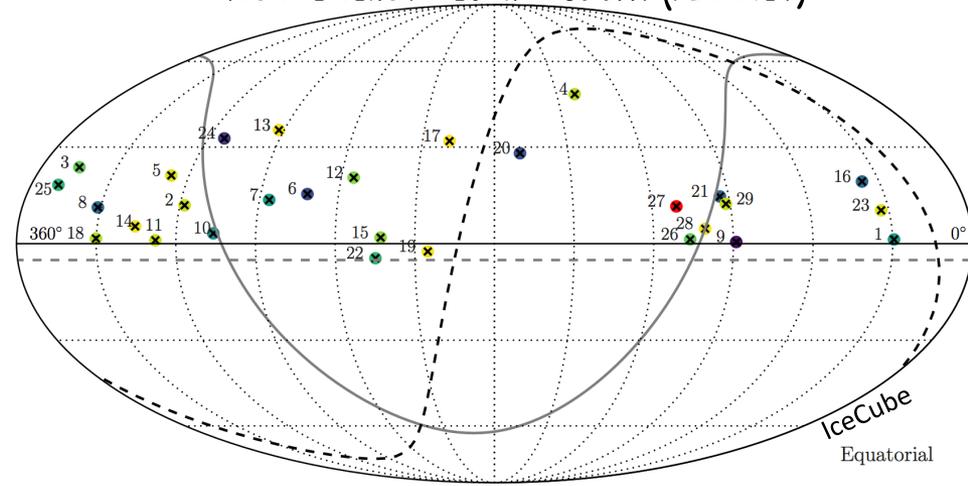
ONLY BL LAC OBJECTS OF 2FHL CATALOGUE CONTRIBUTE TO ν_μ IC EVENTS.

GAMMA-RAY SKY (50 GeV - 2 TeV)



- | | | | | | | | |
|---|---------------|---|---------|---|--------------|---|--------------|
| + | SNRs and PWNe | * | BL Lacs | □ | Unc. Blazars | ▽ | Unassociated |
| × | Pulsars | ◇ | FSRQs | △ | Others | ○ | Extended |

HIGH-ENERGY NEUTRINOS SKY (>200 TeV)



0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Muons Energy Proxy / PeV

Ackermann et al. 2015

Aartsen et al. 2016

Righi et al. 2017 a

THE MODEL

ASSUMPTION 1:

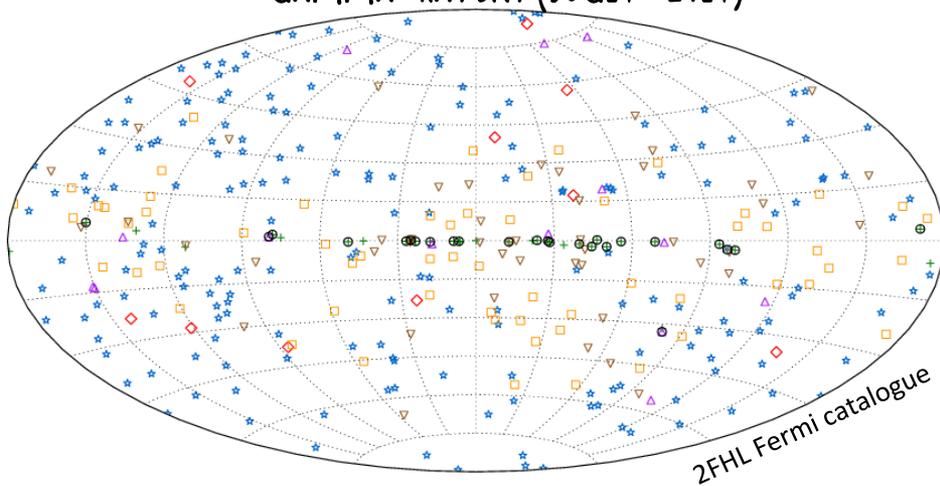
ONLY BL LAC OBJECTS OF 2FHL CATALOGUE CONTRIBUTE TO ν_μ IC EVENTS.

ASSUMPTION 2:

LINEAR RELATION BETWEEN γ -RAY EMISSION AND NEUTRINO EMISSION.

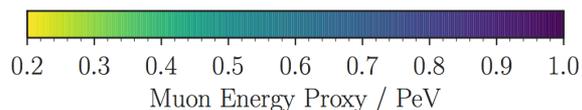
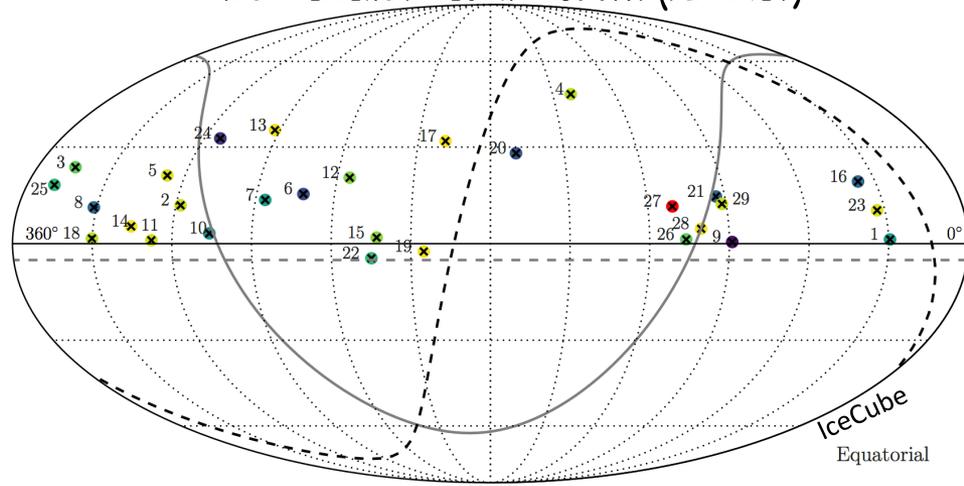
$$F_{\gamma i} = k F_{\nu i}$$

GAMMA-RAY SKY (50GeV-2TeV)



- | | | | | | | | |
|---|---------------|---|---------|---|--------------|---|--------------|
| + | SNRs and PWNe | * | BL Lacs | □ | Unc. Blazars | ▽ | Unassociated |
| × | Pulsars | ◇ | FSRQs | △ | Others | ○ | Extended |

HIGH-ENERGY NEUTRINOS SKY (>200TeV)



Aartsen et al. 2016

Ackermann 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.

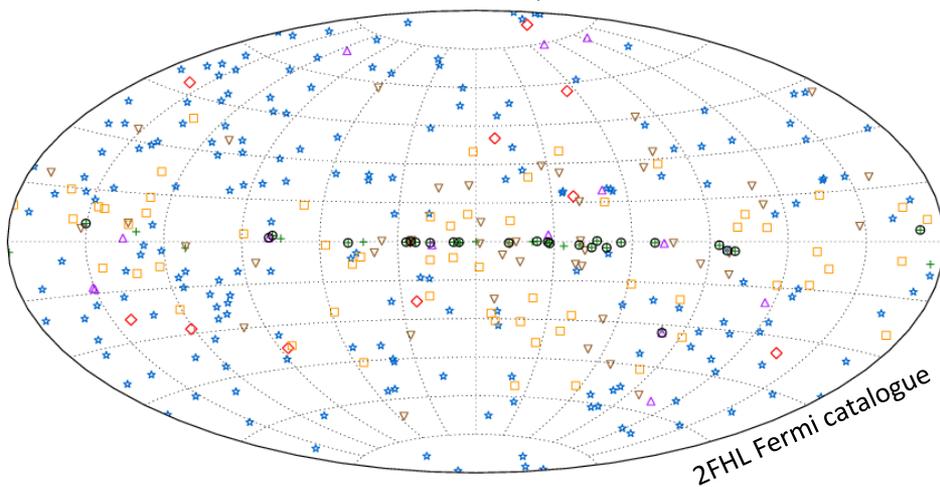
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LINEAR RELATION BETWEEN γ -RAY EMISSION AND NEUTRINO EMISSION.

$$F_{\gamma i} = k F_{\nu i}$$

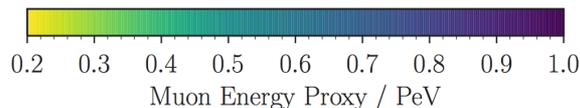
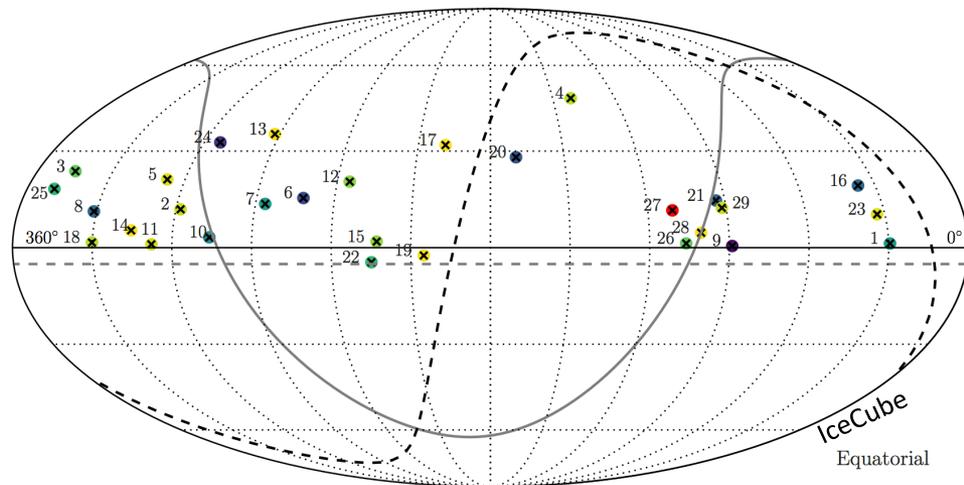
It's the same for all BL Lacs

GAMMA-RAY SKY (50GeV-2TEV)



- | | | | | | | | |
|---|---------------|---|---------|---|--------------|---|--------------|
| + | SNRs and PWNe | * | BL Lacs | □ | Unc. Blazars | ▽ | Unassociated |
| × | Pulsars | ◇ | FSRQs | △ | Others | ○ | Extended |

HIGH-ENERGY NEUTRINOS SKY (>200TEV)



Muon Energy Proxy / PeV

Aartsen et al. 2016

Ackermann et al. 2015

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

IceCube	Name	FLUX	# ν
$60^\circ < \delta < 90^\circ$			
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

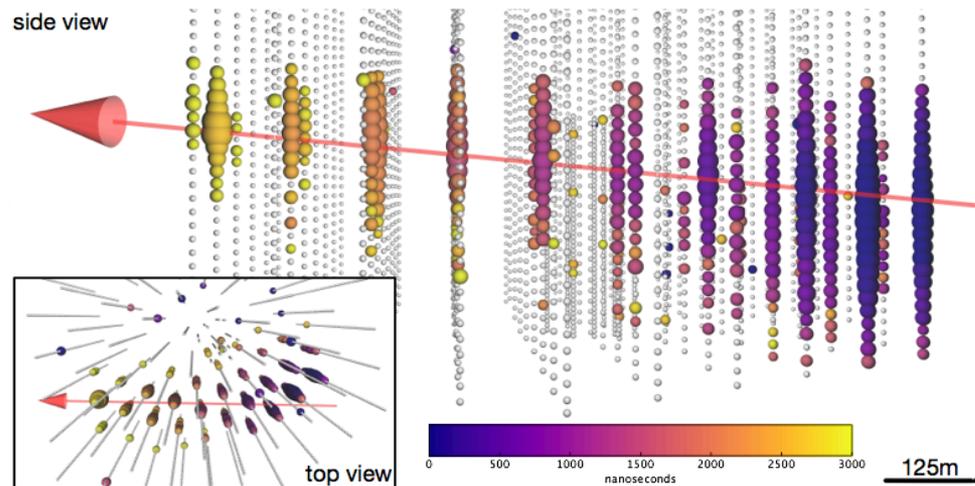
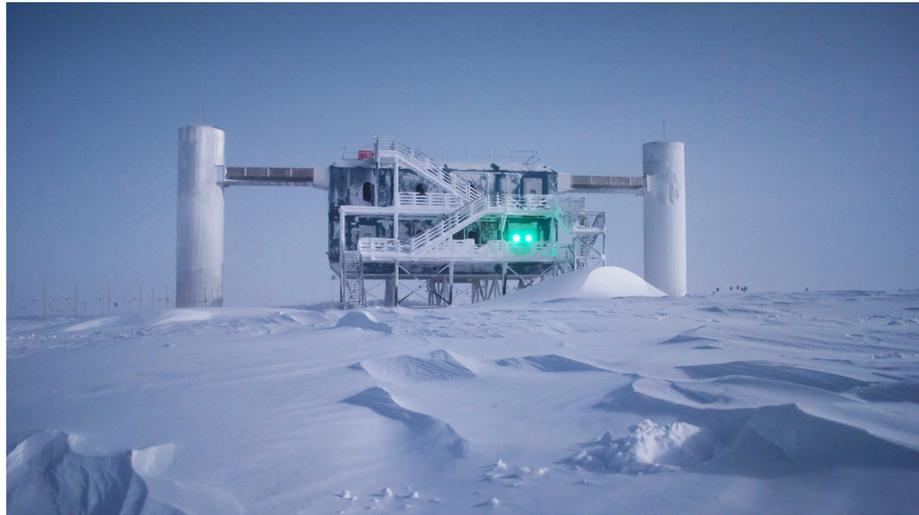
 $10^{-8} \text{ GeV/cm}^2 \text{ yr}^{-1}$

Km ³ Net (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	0.75	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	0.50	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

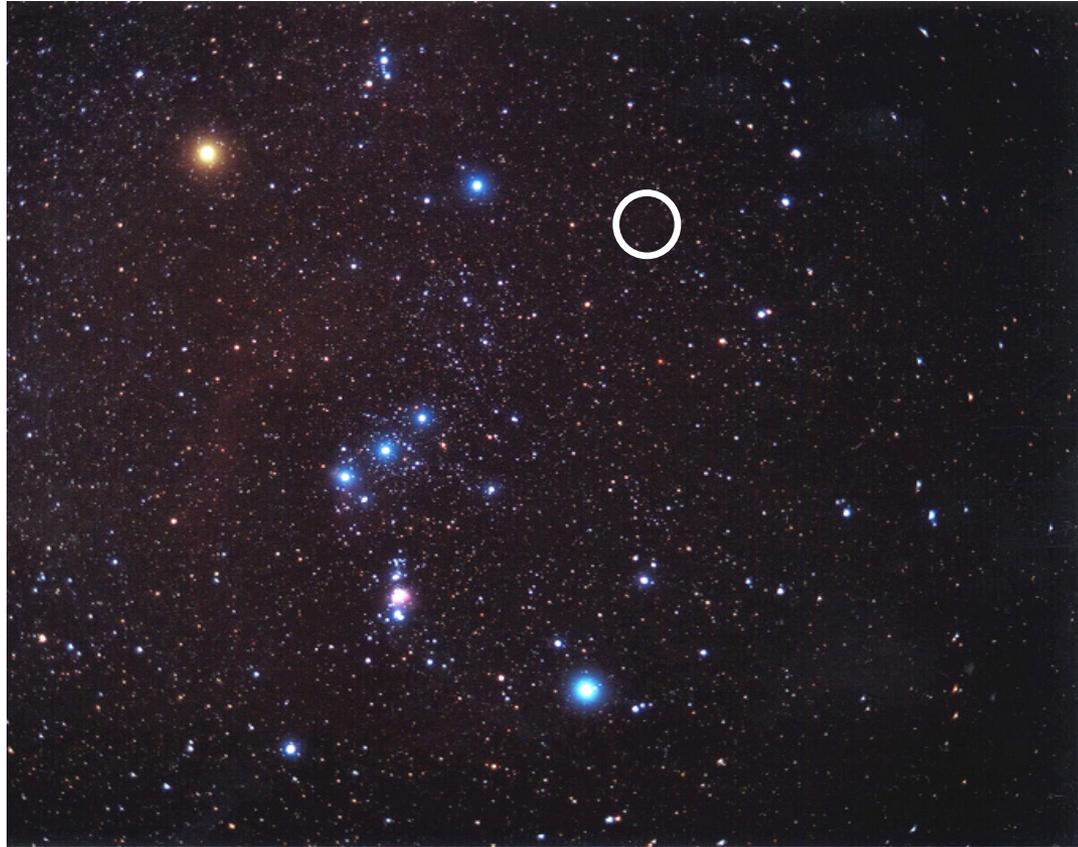
Collaboration for simulation ongoing

TXS 0506+056

22 SETTEMBRE 2017



TXS 0506+056

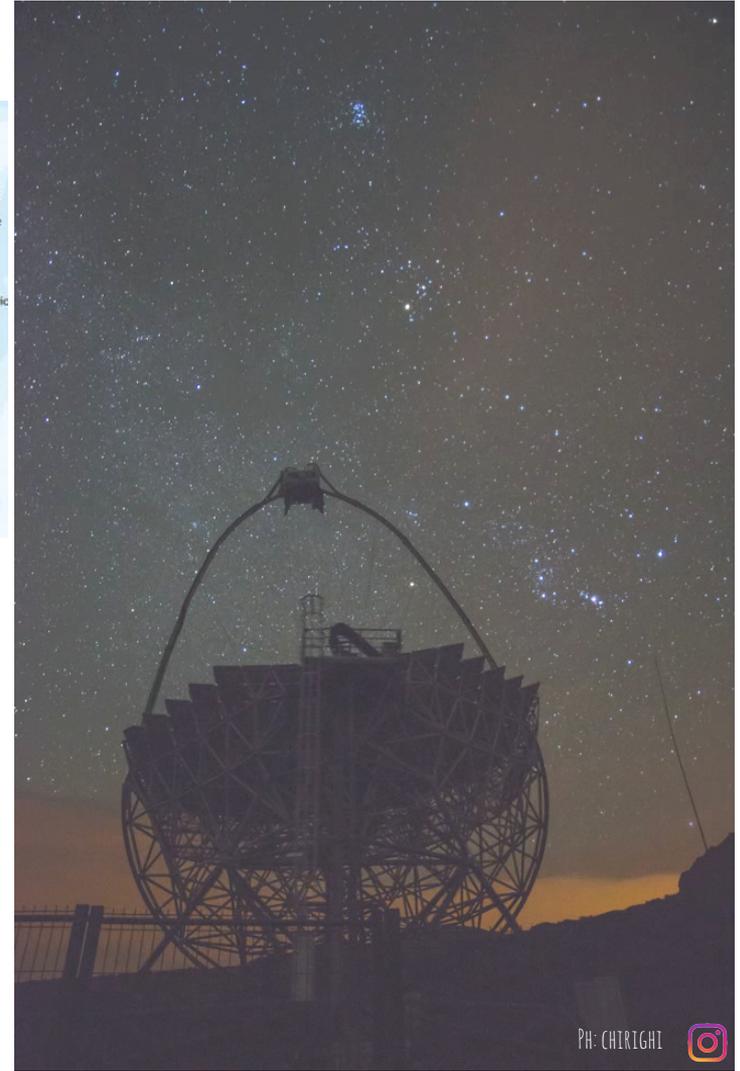


TXS 0506 + 056



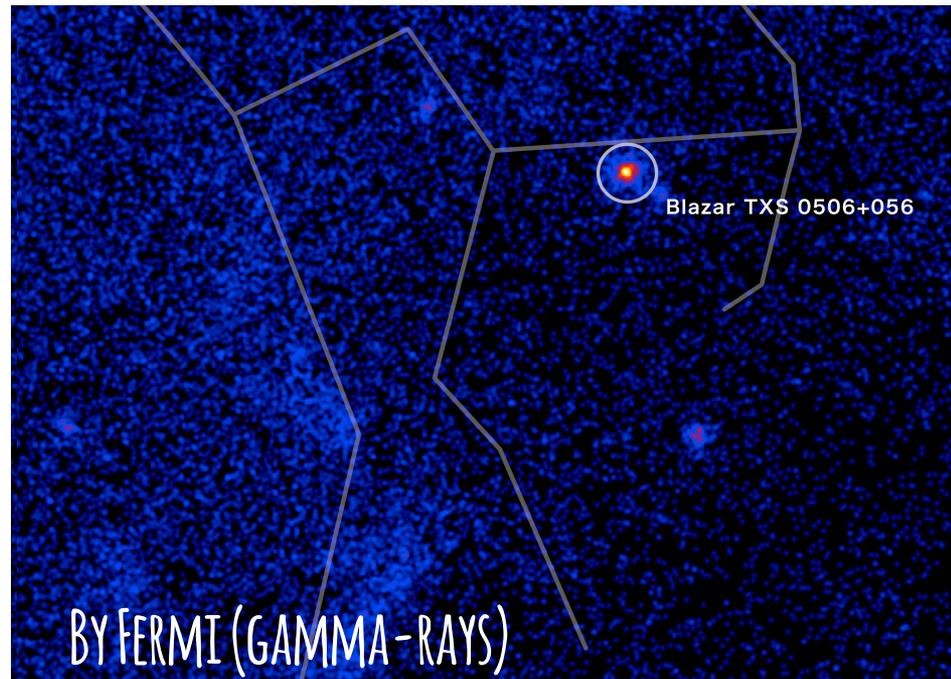
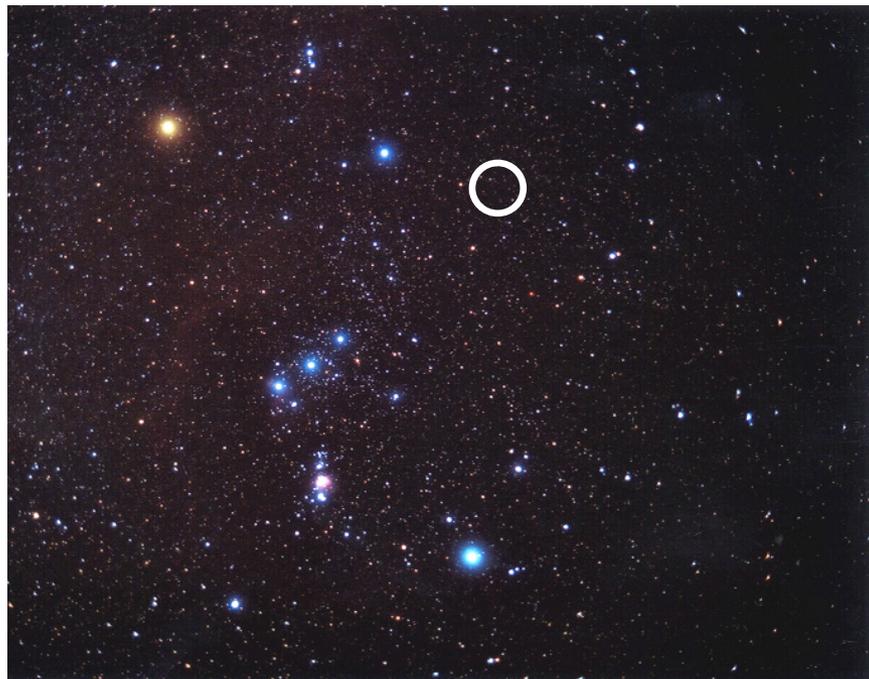
MAGIC TELESCOPES

HIGH-ENERGY GAMMA-RAY VIA CHERENKOV RADIATION



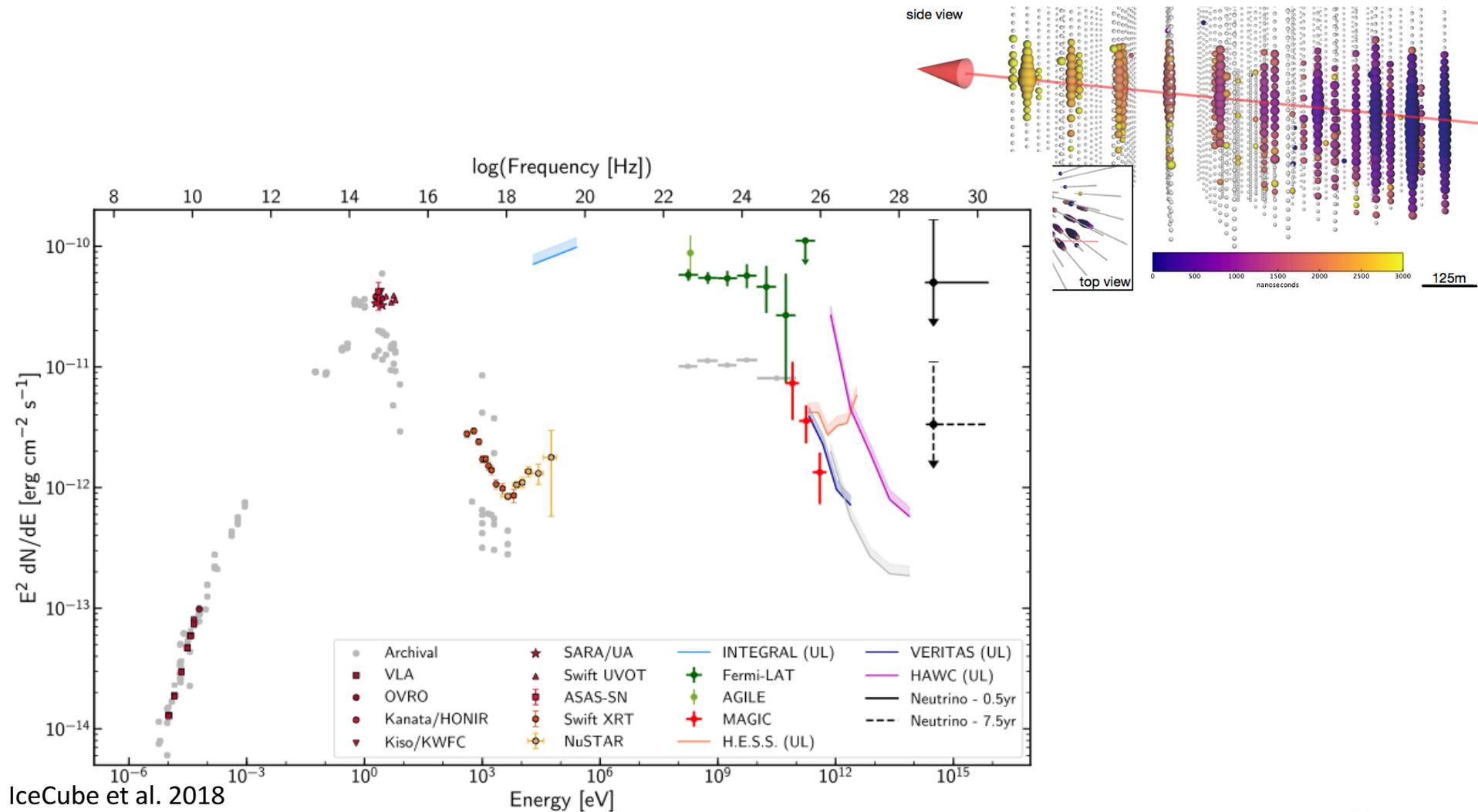
PH: CHIRIGHT 

TXS 0506+056



IC170922A AND TXS0506+056

2017 SEPTEMBER 22

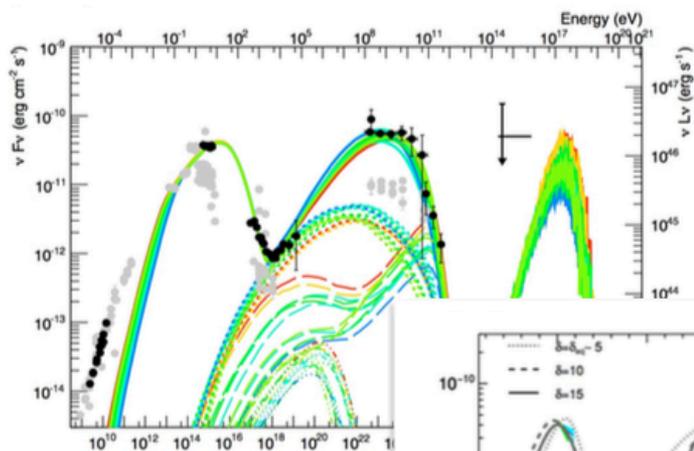


IceCube et al. 2018

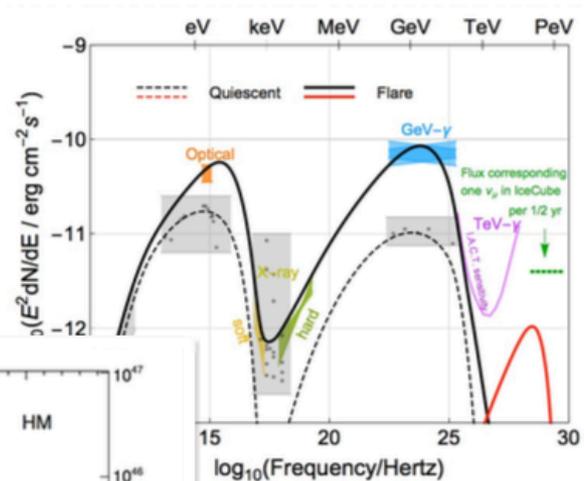
MODELS

THE COMMUNITY IS STILL WORKING ON THIS

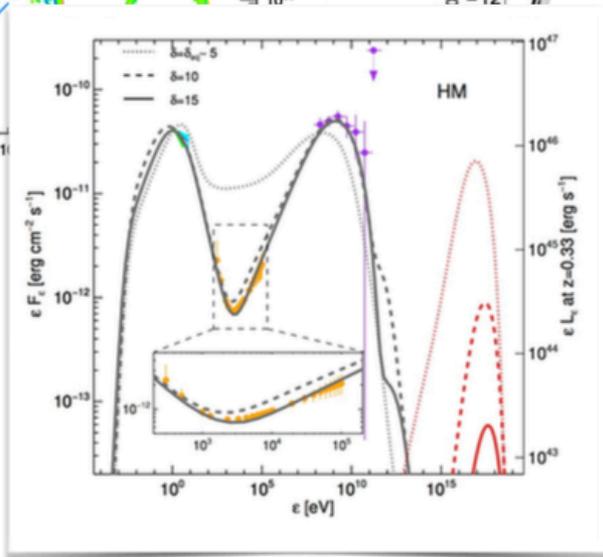
A burst of models ...



Cerruti et al. 2018



Gao et al. 2018



Keivani et al. 2018

But the jet power is very large!

TAKE HOME MESSAGES

- HIGH-ENERGY NEUTRINOS IS A FIELD TO EXPLORE
- BLAZAR ARE GOOD CANDIDATES TO PRODUCE HIGH-ENERGY NEUTRINOS (THE CASE OF TXS 0506+056)
- WAITING FOR NEW DETECTION AND NEW DETECTOR

HOW TO OBSERVE HIGH-ENERGY NEUTRINOS?

