High-energy neutrino astronomy

... and astrophysics

https://multimessenger.desy.de/

Winter, Walter
DESY, Zeuthen, Germany

CCEPP summer school, CAS
Beijing, China
Aug. 20-21, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY

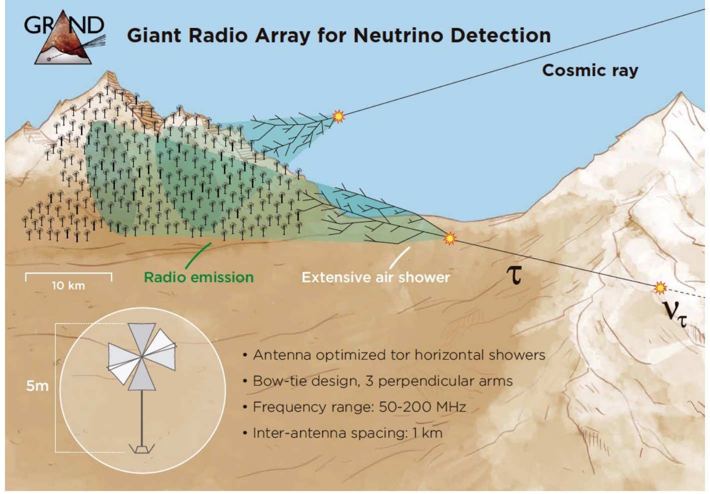
Contents

- Observations (overview of selected results)
- Physics of neutrino production (theory)
- Neutrinos from AGN blazars (overview)
- Multi-messenger interpretation of TXS 0506+056
- Diffuse neutrino flux from AGN blazars?

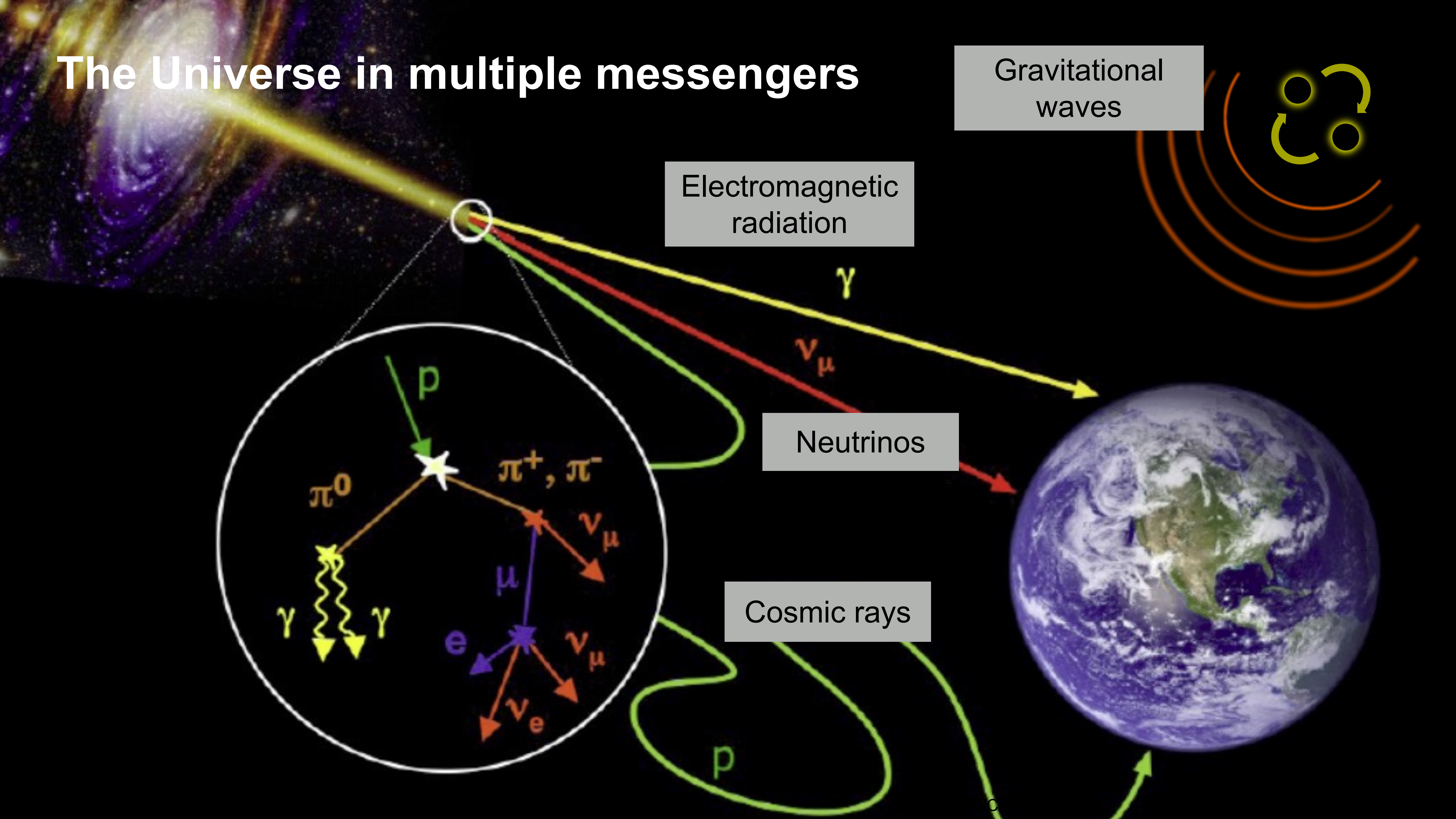
Lecture 1

- Neutrinos from Tidal Disruption Events (TDEs)
- Neutrinos and the origin of the Ultra-High Energy Cosmic Rays (UHECRs)
- The future of neutrino astronomy →
- Conclusions

Lecture 2



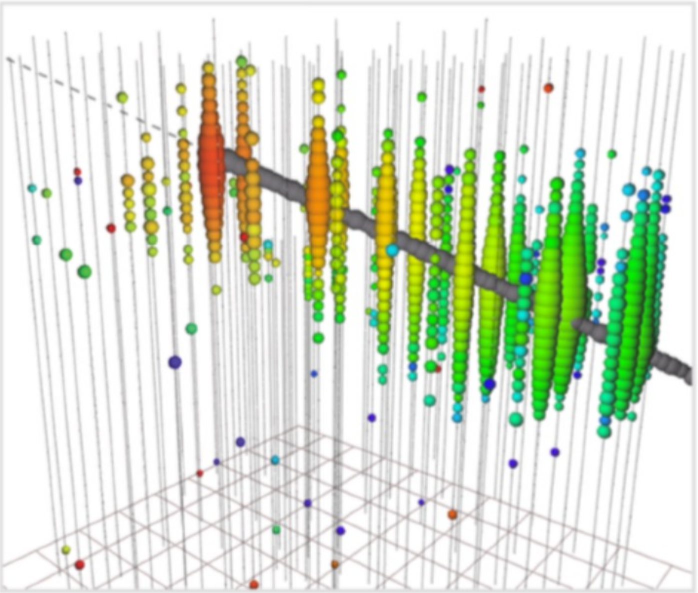
The Universe in multiple messengers



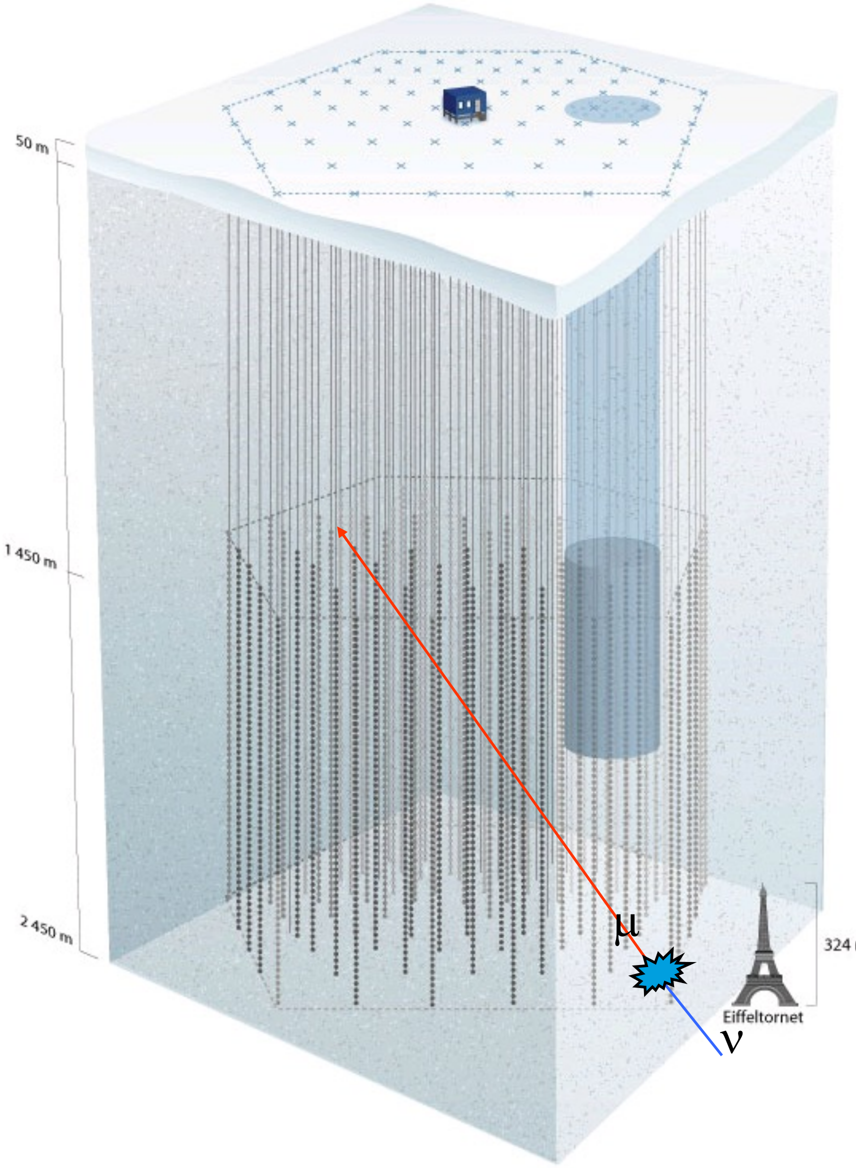
Observations (overview)

Observing TeV-PeV neutrinos with IceCube

Muon track:
- From ν_μ
- From ν_τ (17 %)

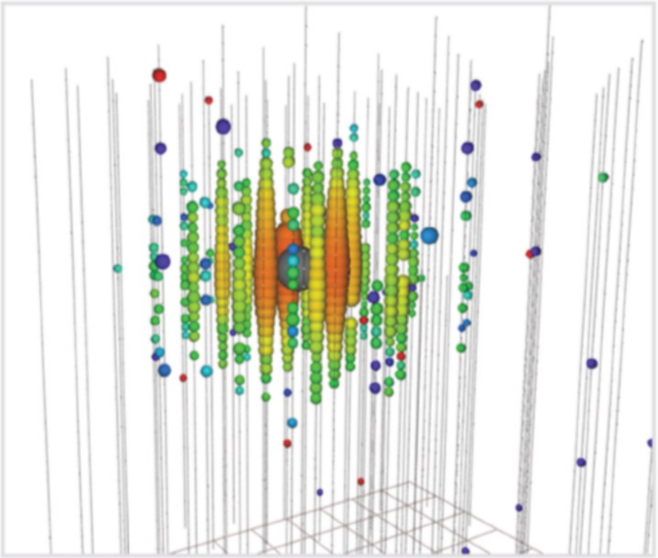


Better directional info



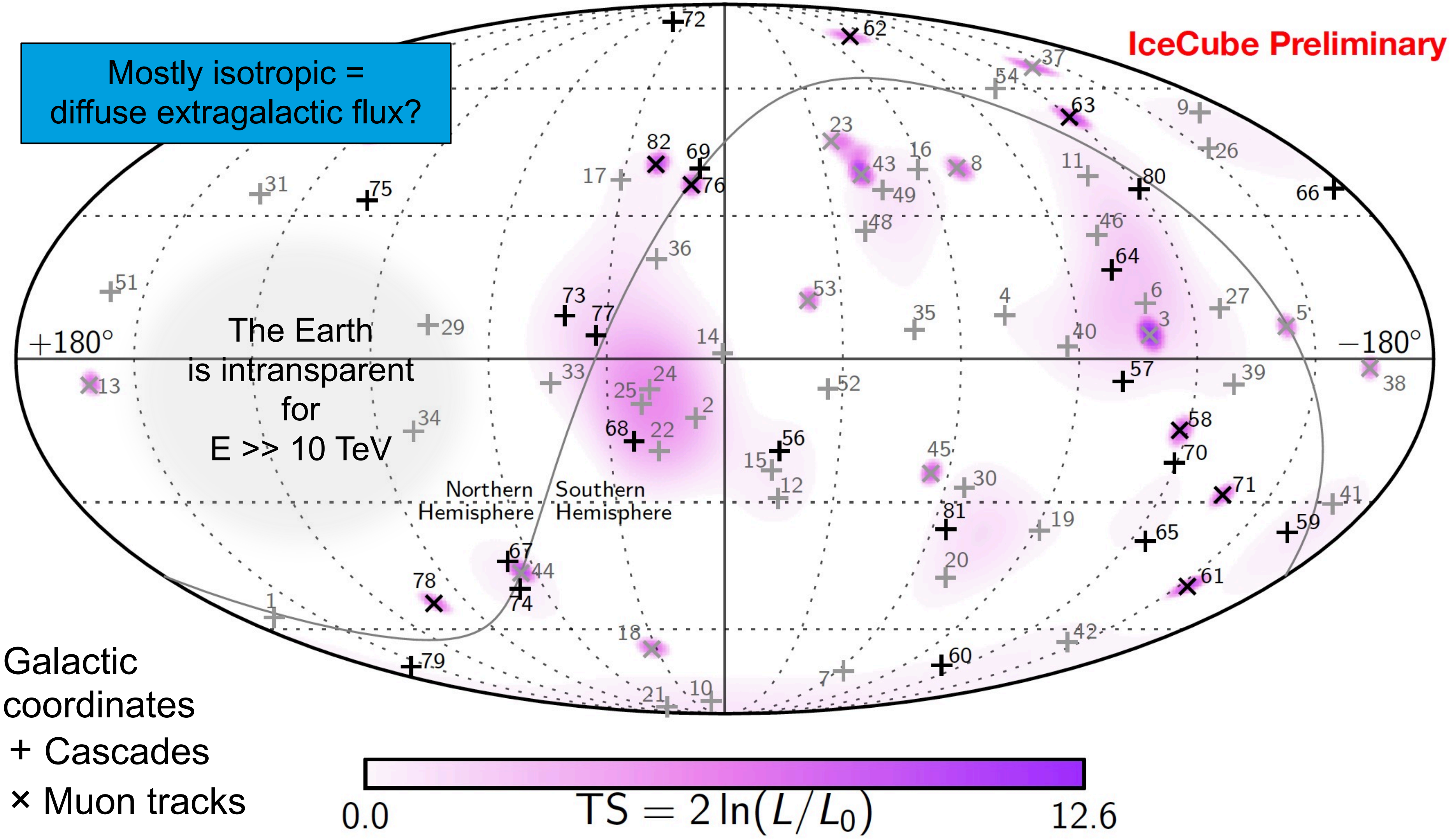
IceCube http://icecube.wisc.edu/

Cascade (shower):
- From ν_e
- From ν_τ
- From ν_e, ν_μ, ν_τ NC interactions

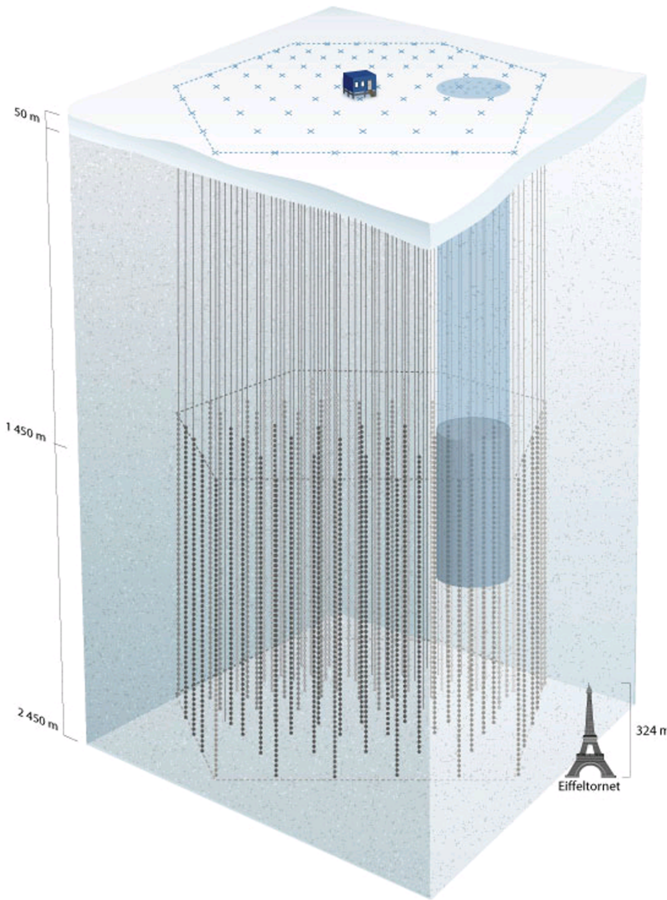


Better energy info

A flux of high-energy cosmic neutrinos

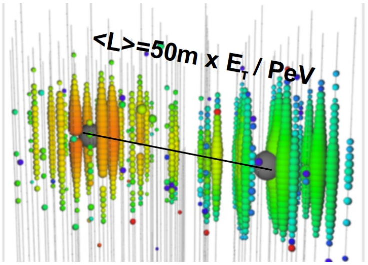


Galactic coordinates
+ Cascades
× Muon tracks

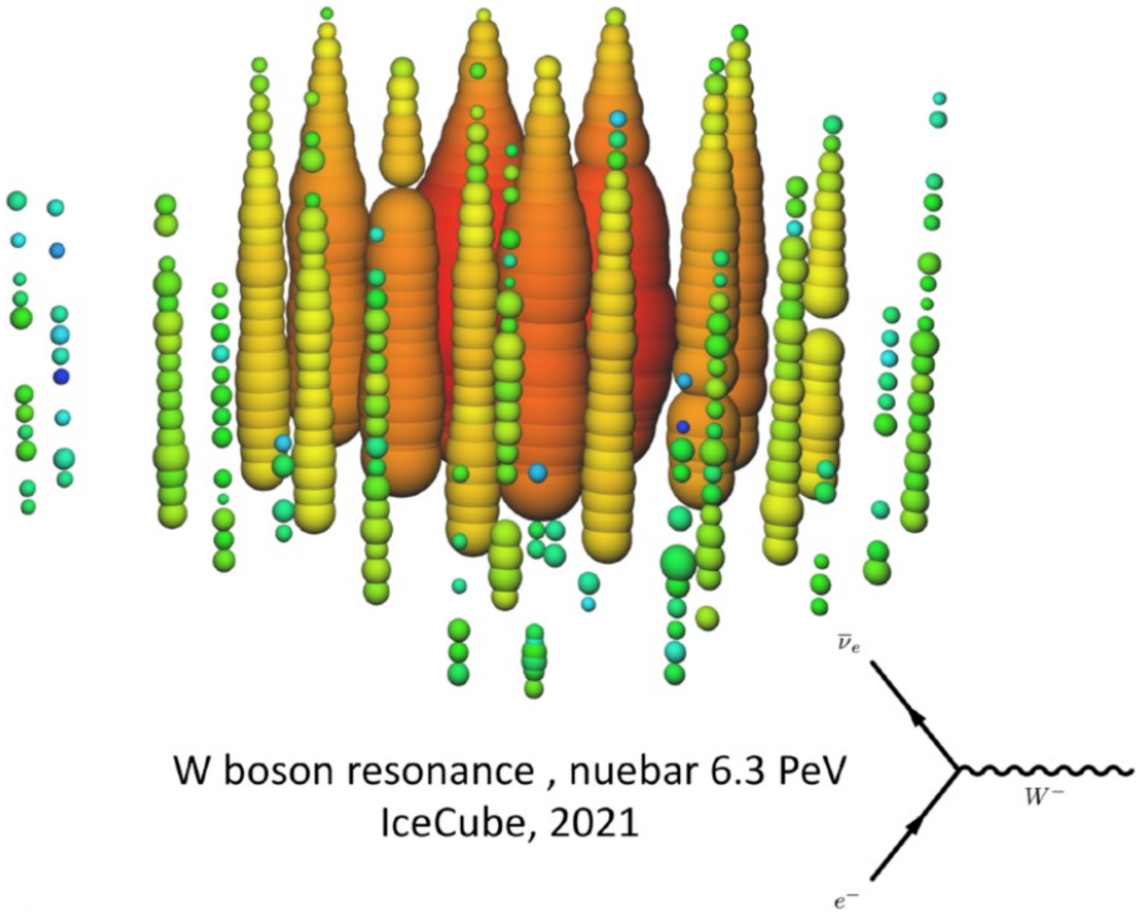


IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); update from Kopper at ICRC 2017

New event classes



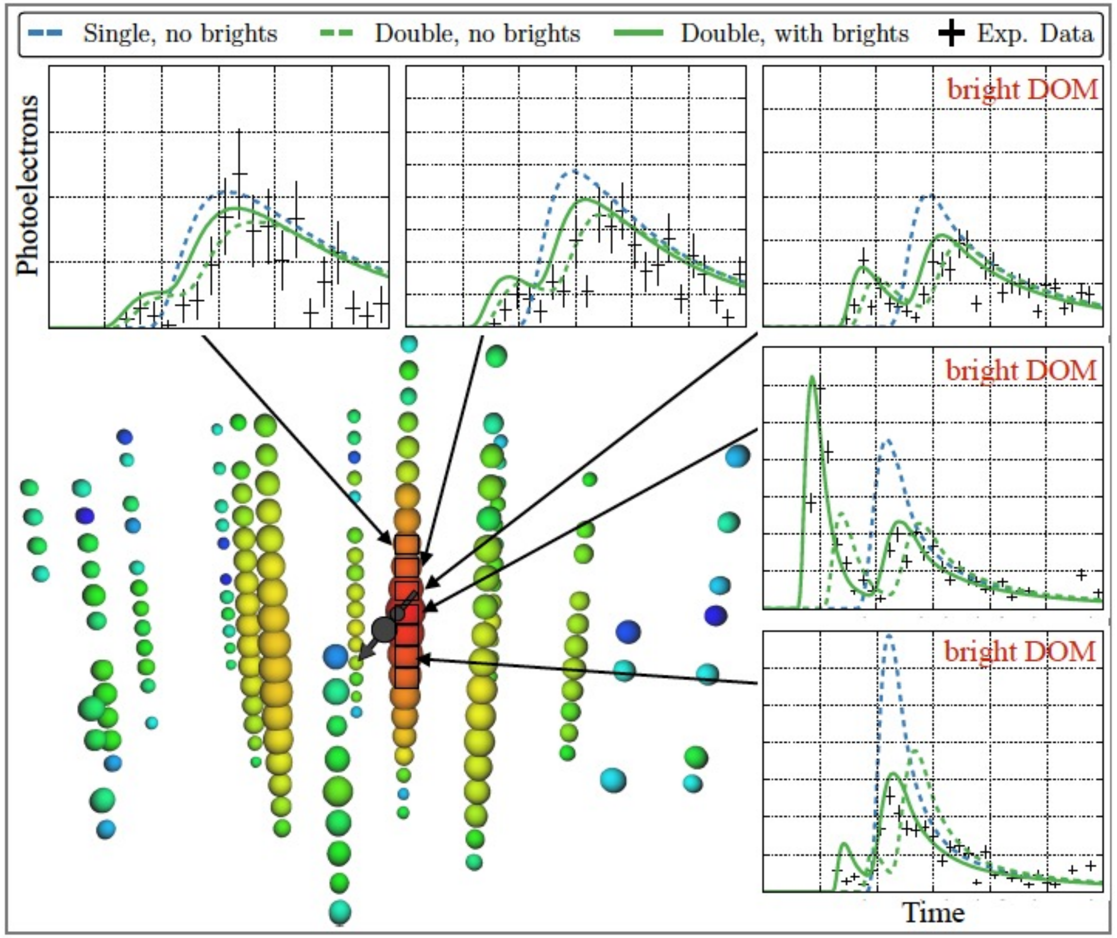
Glashow resonance



W boson resonance , nuebar 6.3 PeV
IceCube, 2021

IceCube, Nature 591 (2021) 7849, 220

Double bang (ν_τ) candidates



IceCube, arXiv:2011.03561 and PRL 125 (2020) 12, 121104

Diffuse neutrino flux – observed in different event samples

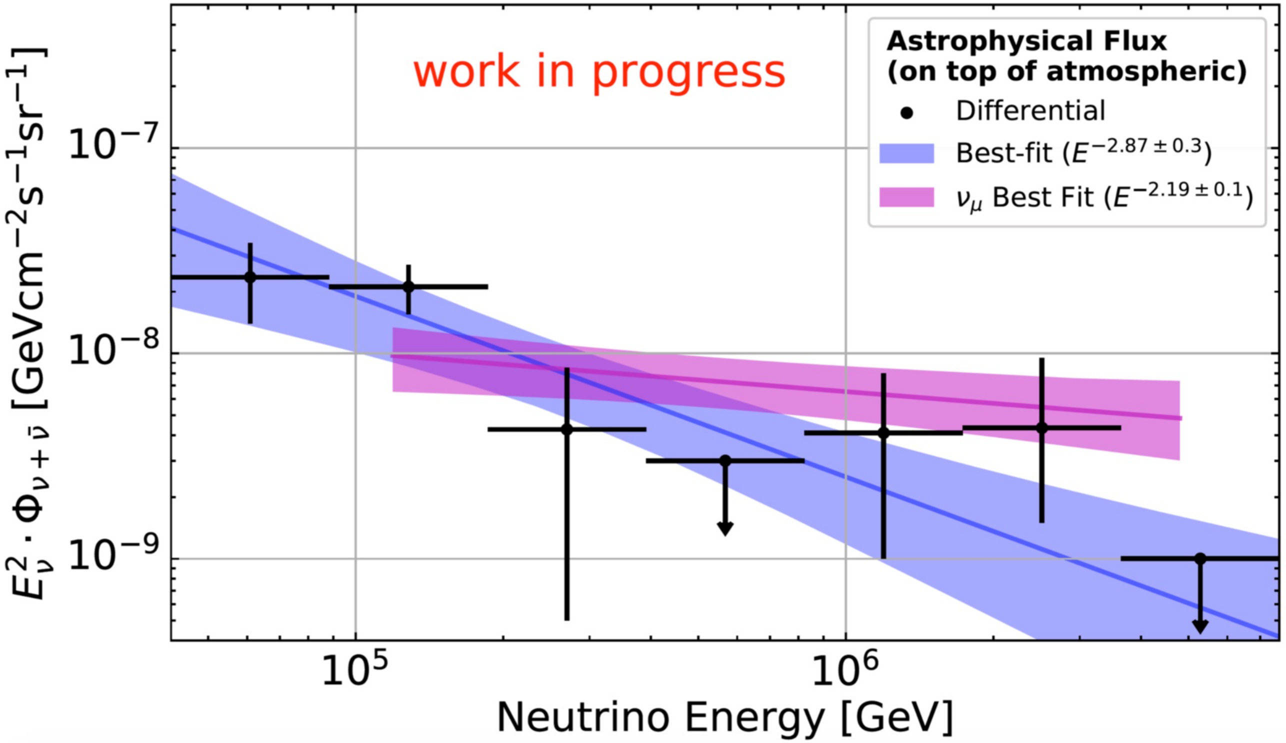
HESE = High Energy Starting Events

Interaction within detection volume

Outer layer of detector used as veto (atm. muons)

Sensitive to both hermispheres, all flavors

Lower energies = contained events



TGM = Through-going muons

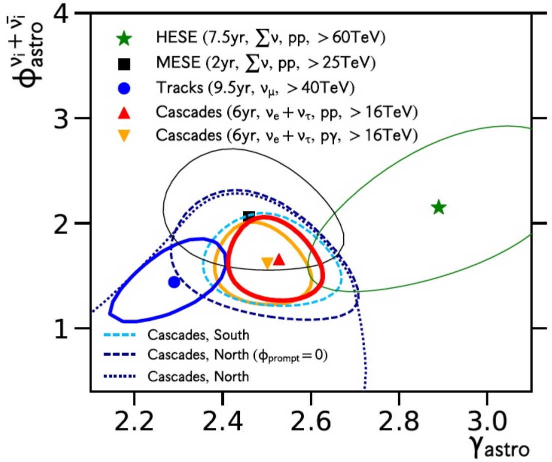
Sensitive to ν_μ only from Northern hemisphere

Large effective volume (interaction may be outside detector)

Muon energy (proxy) gives a lower limit for neutrino energy

IceCube/Taboada at Neutrino 2018

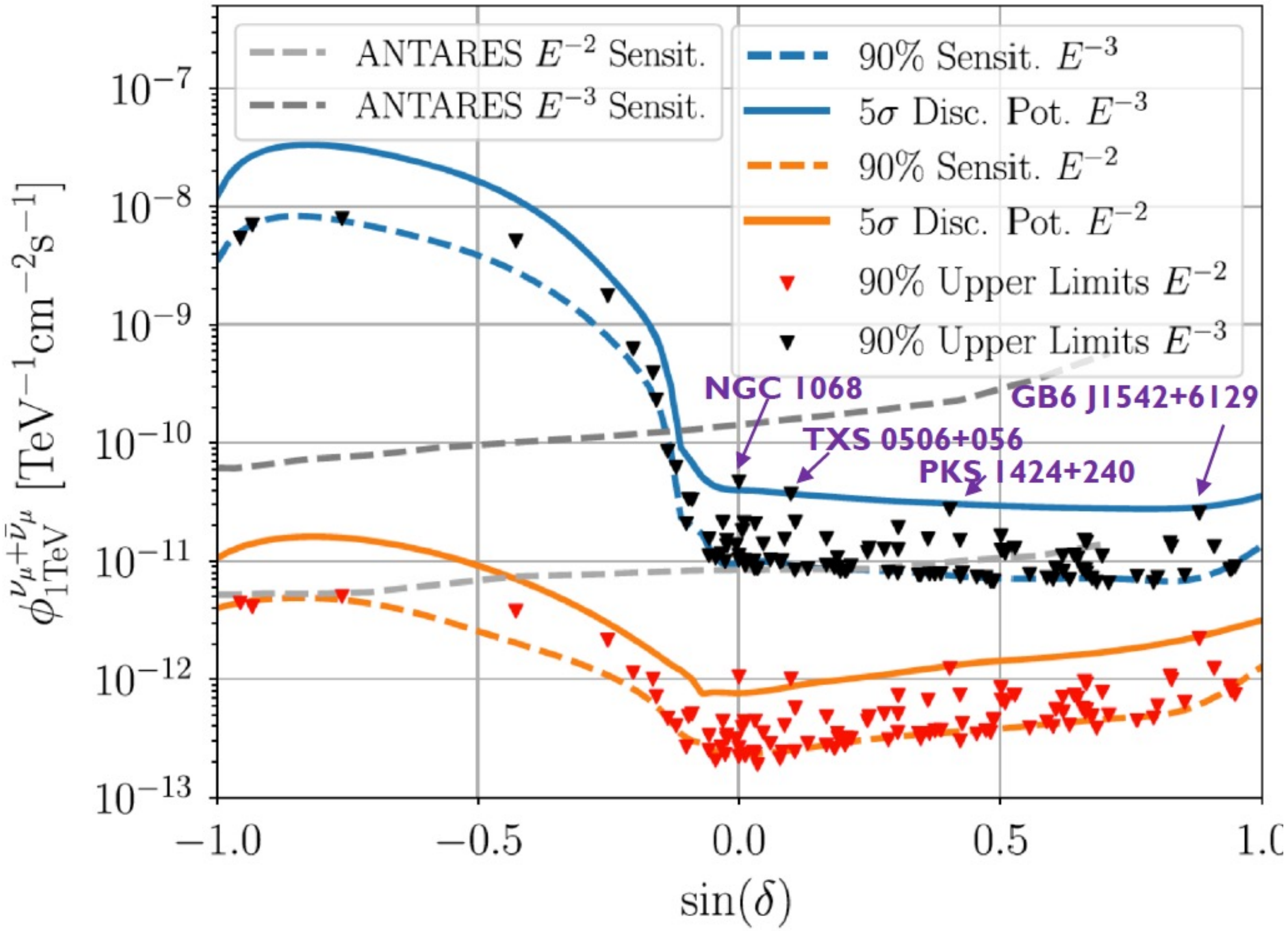
PRL 125 (2020) 12, 121104



Time-integrated 10 year point source searches

- Most significant:
  NGC 1068 (3σ post-trial)
  Starburst galaxy

- The other three are
  AGN blazars
- TXS 0506+056 is most prominent because it was found earlier through a multi-messenger follow-up (will mostly talk about that later ...)



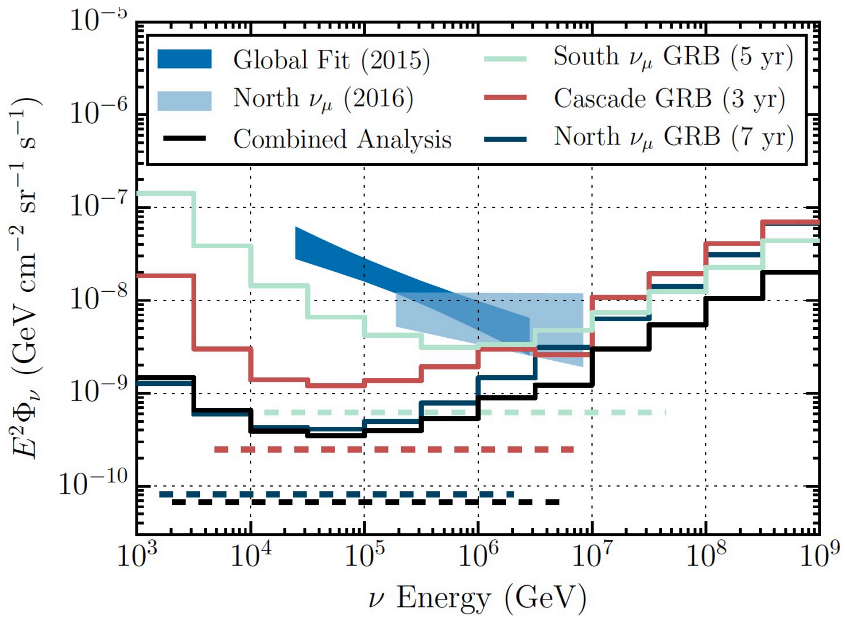
IceCube, PRL 124 (2020) 5, 051103;
from G. Illuminati @ Paris 2020

Stacking limits ...

... for the most energetic sources classes

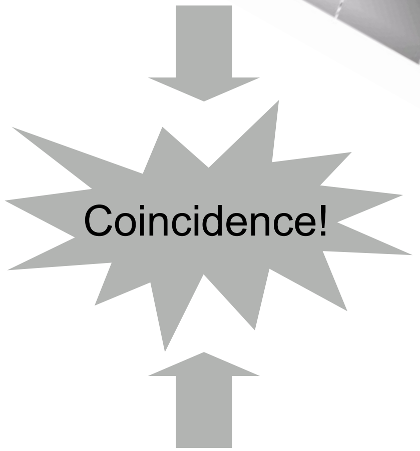
Gamma-Ray Bursts (GRBs)

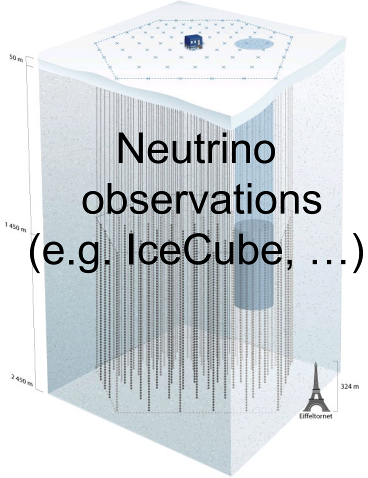
- Transients, time variability
- High luminosity over short time



- Less than ~1% of observed ν flux

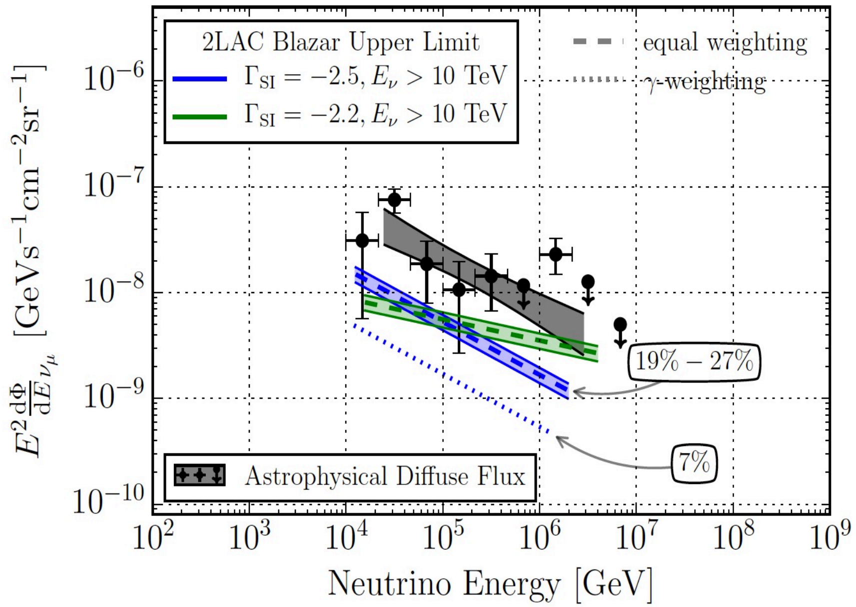
IceCube, Nature 484 (2012) 351;
Newer version: arXiv:1702.06868





Active Galactic Nuclei (AGNs)

- Steady emission with flares
- Lower luminosity, longer duration



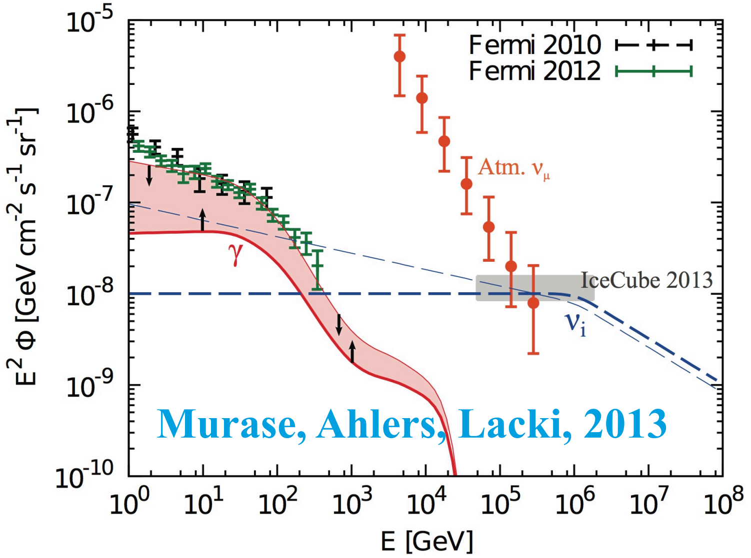
- Less than ~25% of observed ν flux?

IceCube, Astrophys. J. 835 (2017) 45

Conceptual challenges

Gamma-ray diffuse flux

$$\mathrm{p+p} \rightarrow \begin{cases} \pi^+ \\ \pi^- \\ \pi^0 \end{cases} \begin{matrix} \left.\begin{matrix} \\ \\ \end{matrix}\right\} \nu \\ \\ \gamma \end{matrix}$$

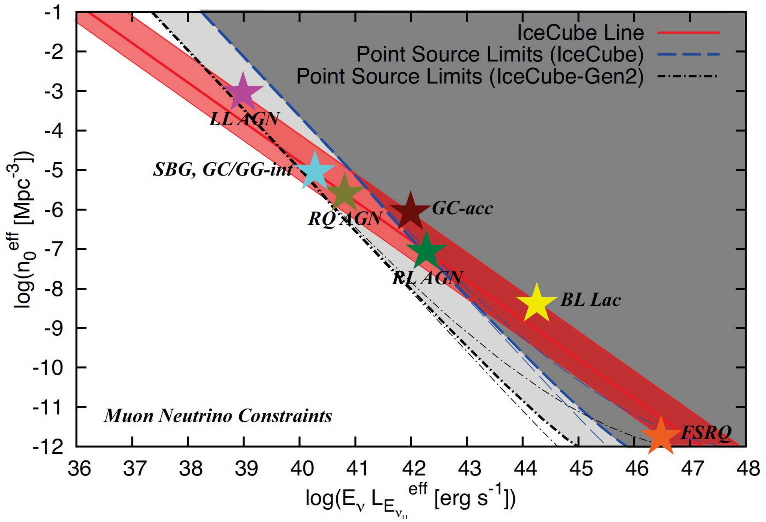


Constrains spectral index for non-AGN contributions (starburst galaxies, ...)

Bechtol et al, 2017;
Palladino et al, arXiv:1812.04685

Multiplet or point source limits

Non-observation of multiplets limits source density of powerful sources



[if they are to power the entire diffuse flux]

Kowalski, 2014; Ahlers, Halzen, 2014;
Fig. from Murase, Waxman, 2016;
see also: Dekker, Ando, 2018

Other challenges

- Observed through-going muon flux harder than HESE
- A muon track with a reconstr. muon energy of 4.5 PeV
  Aartsen et al, ApJ 833 (2016) 3
  Primaries with E > 100 PeV?
- Anisotropy for HESE events with > 100 TeV deposited energy.
  (data: Aartsen et al, arXiv:1710.01191)
  Evidence for Galactic contribution (2σ)?

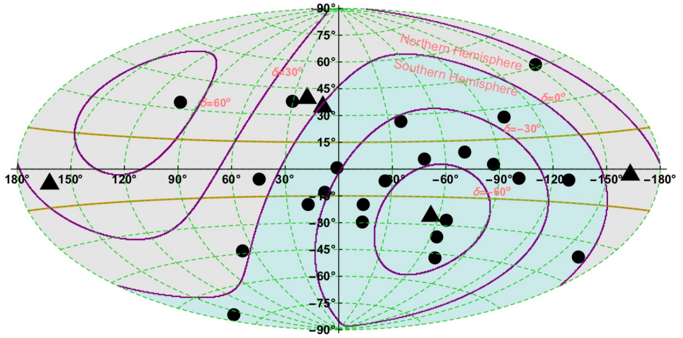
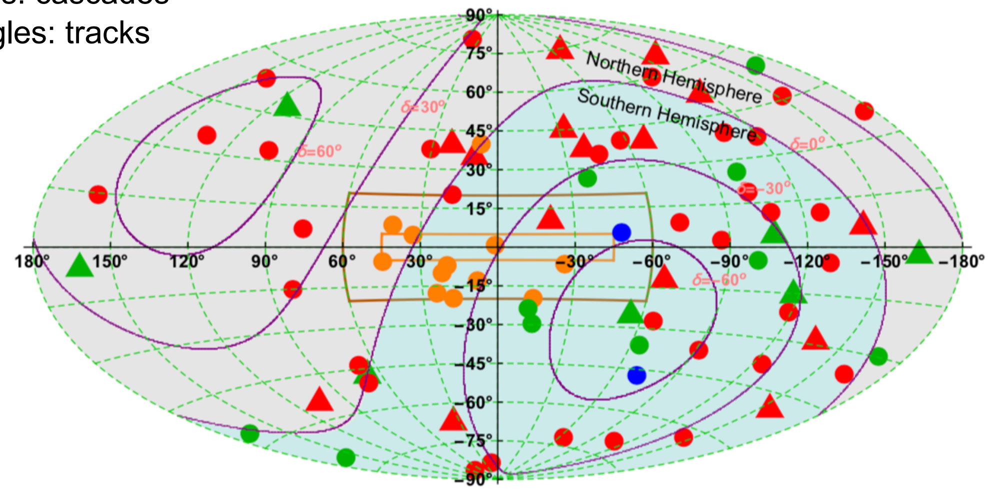


Fig. from: Palladino, Winter, A&A 615 (2018) A168

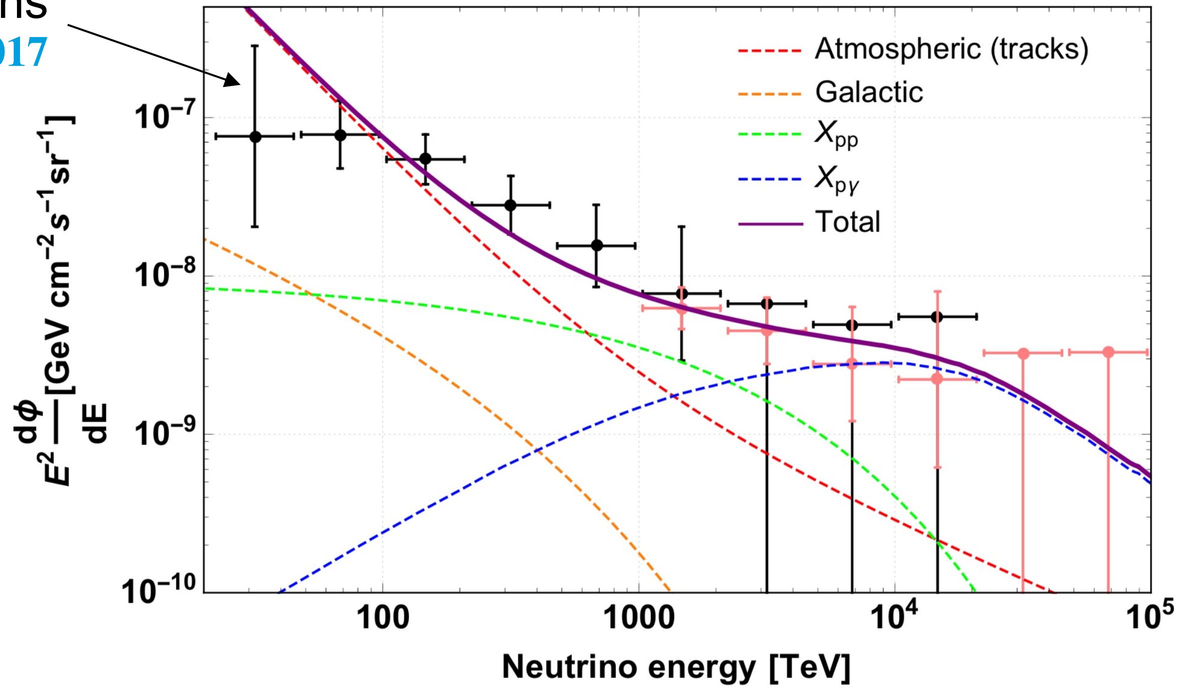
Multiple contributions to diffuse flux? A possible scenario.

Sky map (examples):
circles: cascades
triangles: tracks



Also: DM interpretations
e.g. Chianese, Miele, Morisi, 2017

HESE tracks + TGM (through-going muons)



Name	Description/examples	Neutrino prod.
Atmosph.	Residual atmospheric backgrounds (atmospheric muons or neutrinos) passing the veto systems	p, K decay, charmed mesons
Galactic	Neutrinos from Milky Way, e.g. from cosmic ray int. with gas or point sources	pp interactions
X_{pp}	EXtragalactic neutrinos, e.g. starburst galaxies, ~E^{-2} spectrum (Fermi acc.!)	pp interactions
$X_{p\gamma}$	EXtragalactic ν with hard (~ E^{-1}) spectrum; highest E; UHECR connection?	pγ interactions

Palladino, Winter, A&A 615 (2018) A168

Conclusions for different event samples

Through-going muons are most promising sample for extragalactic origin

HESE cascades

ID	Deposited energy [TeV]	Initial neutrino energy within 67% C.L. [TeV]	Galactic latitude (°)	Galactic longitude (°)	Atmospheric %	Galactic %	X-pp %	X-pγ %
1	47,6	53	-56,26	167,57	80,6	0,0	18,6	0,8
2	117	129	-12,76	7,86	25,7	53,9	18,7	1,7
4	165,4	183	8,88	-71,20	43,6	5,6	46,2	4,6
6	28,4	31	11,77	-107,66	89,2	0,0	10,4	0,4
7	34,3	38	-72,10	-64,71	86,6	0,0	12,9	0,5
9	63,2	70	54,41	-167,29	74,1	0,0	24,7	1,2
10	97,2	107	-83,32	13,88	62,1	0,0	35,5	2,3
11	88,4	98	39,03	-106,87	64,9	0,0	33,0	2,0
12	104,1	115	-29,67	-14,50	54,7	8,9	34,0	2,4
14	1040,7	1151	0,54	0,86	6,1	51,7	25,5	16,7
15	57,5	64	-23,67	-12,29	61,8	19,1	18,3	0,9
16	30,6	34	40,00	-57,18	87,6	0,7	11,3	0,4
17	199,7	221	37,33	30,67	39,8	2,7	51,4	6,0
19	71,5	79	-36,09	-91,35	70,9	0,0	27,6	1,5
20	1140,8	1261	-47,17	-71,50	12,3	0,0	53,3	34,4
21	30,2	33	-85,51	81,54	88,4	0,0	11,2	0,4
22	219,5	243	-19,66	17,64	27,4	28,2	39,2	5,3
24	30,5	34	-6,84	19,51	19,1	78,3	2,5	0,1
25	33,5	37	-9,87	21,69	30,3	65,1	4,4	0,2
26	210	232	45,77	-152,20	39,6	0,0	53,8	6,6
27	60,2	67	10,84	-126,55	75,3	0,0	23,5	1,1
29	32,7	36	6,83	76,01	84,6	3,0	11,9	0,4

[...]

Atmospheric BG dominant
Possible **Galactic** component (soft!)

HESE tracks

ID	Deposited energy [TeV]	Initial neutrino energy within 67% C.L. [TeV]	Galactic latitude (°)	Galactic longitude (°)	Atmospheric %	Galactic %	X-pp %	X-pγ %
3	78,7	295	5,18	-107,74	72,1	0,0	24,4	3,6
5	71,4	267	7,22	-142,78	74,3	0,0	22,7	3,0
8	32,6	122	40,47	-69,10	88,4	0,0	10,8	0,7
13	252,7	946	-4,84	162,19	42,3	0,0	41,0	16,7
18	31,5	118	-65,97	33,14	88,9	0,0	10,4	0,7
23	82,2	308	46,38	-33,45	71,0	0,0	25,1	3,8
28	46,1	173	-10,74	-65,56	83,1	0,0	15,5	1,4
37	30,8	115	66,30	-136,03	89,2	0,0	10,2	0,6
38	200,5	751	-1,30	-163,52	48,2	0,0	38,9	12,9
43	46,5	174	38,69	-39,88	82,9	0,0	15,7	1,4
44	84,6	317	-46,25	65,78	70,4	0,0	25,6	4,0
45	429,9	1610	-24,08	-55,18	30,5	0,0	41,9	27,5
47	74,3	278	48,67	113,12	73,4	0,0	23,4	3,2
53	27,6	103	11,53	-20,97	90,5	0,0	9,0	0,5
58	52,6	197	-14,39	-117,65	80,7	0,0	17,6	1,8
61	53,8	201	-48,57	-152,96	80,2	0,0	17,9	1,9
62	75,8	284	75,33	-73,94	72,9	0,0	23,7	3,3
63	97,4	365	52,95	-118,64	66,9	0,0	28,1	5,0
71	73,5	275	-27,92	-136,75	73,6	0,0	23,2	3,2
76	126,3	473	36,26	10,05	60,3	0,0	32,5	7,2
78	56,7	212	-53,26	103,10	79,2	0,0	18,8	2,0
82	159,3	596	40,83	21,18	54,2	0,0	36,0	9,8

Atmospheric BG dominant
Extragalactic contribution ”hidden”

Through-going muons

ID	Deposited energy [TeV]	Initial neutrino energy within 67% C.L. [TeV]	Galactic latitude (°)	Galactic longitude (°)	Atmospheric %	Galactic %	X-pp %	X-pγ %
1	480	1797,1	-56,90	155,91	18,5	0,0	48,3	33,2
2	250	936,0	-8,36	50,93	24,2	0,0	55,6	20,2
3	340	1272,9	-32,60	93,04	21,4	0,0	52,7	25,9
4	260	973,4	45,74	171,42	23,8	0,0	55,3	20,9
5	230	861,1	-10,46	63,41	25,1	0,0	56,1	18,8
6	770	2882,8	33,5268748	33,63	15,0	0,0	40,4	44,6
7	460	1722,2	20,13	38,05	18,8	0,0	48,9	32,3
8	660	2471,0	-34,56	71,33	16,1	0,0	43,2	40,8
9	950	3556,7	-11,55	-153,66	13,6	0,0	36,5	49,9
10	520	1946,8	-1,83	37,50	9,4	41,4	25,4	23,8
11	240	898,5	-21,92	46,32	24,6	0,0	55,9	19,5
12	300	1123,2	50,34	32,26	22,5	0,0	54,0	23,5
13	210	786,2	23,16	62,37	26,0	0,0	56,7	17,4
14	210	786,2	-26,38	54,90	26,0	0,0	56,7	17,4
15	300	1123,2	51,14	-2,78	22,5	0,0	54,0	23,5
16	660	2471,0	-37,84	152,62	16,1	0,0	43,2	40,8
17	200	748,8	82,75	73,54	26,5	0,0	56,9	16,6
18	260	973,4	-40,19	61,58	23,8	0,0	55,3	20,9
19	210	786,2	57,74	-32,38	26,0	0,0	56,7	17,4
20	750	2807,9	69,98	-154,13	15,2	0,0	40,9	43,9
21	670	2508,4	-1,01	-163,88	16,0	0,0	42,9	41,1
22	400	1497,6	45,21	-7,24	20,0	0,0	50,8	29,2
23	390	1460,1	-47,39	153,90	20,2	0,0	51,1	28,7
24	850	3182,3	6,12	66,95	14,3	0,0	38,6	47,1

[...]

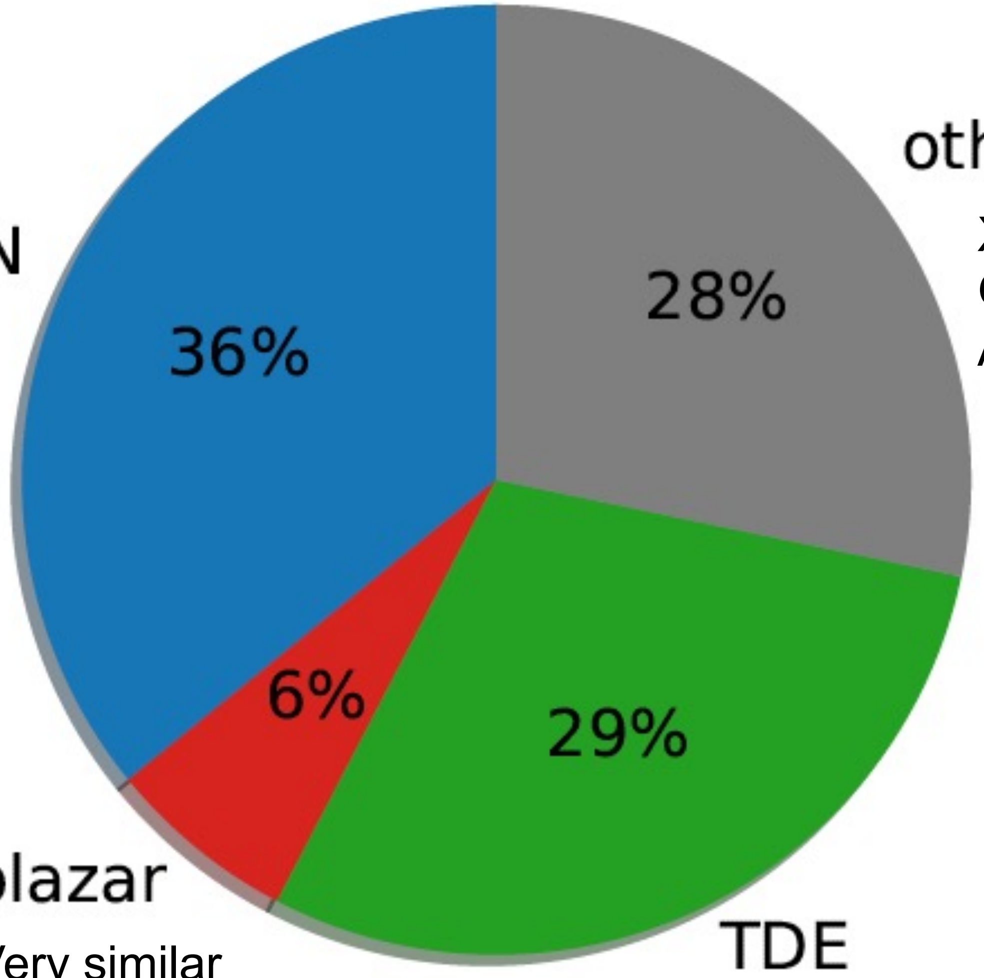
Extragalactic flux dominant
Low “background” (atm. + Galactic)

Palladino, Winter, A&A 615 (2018) A168

A different ansatz

- Take confirmed neutrino-source associations as a proxy, include redshift distributions and typical luminosities
- Large uncertainties, no spectral information, possible atm. background contamination:

Type	Flux / $\phi_{\rm IC}$		
	warm-up	simple	full
AGN		0.34	$0.36^{+0.31}_{-0.27}$
blazar	0.1	0.05	$0.06^{+0.06}_{-0.04}$
TDE	0.55	0.26	$0.32^{+0.30}_{-0.24}$
GRB		< 0.01	
CCSN		< 1.4	
other			$0.28^{+0.38}_{-0.25}$

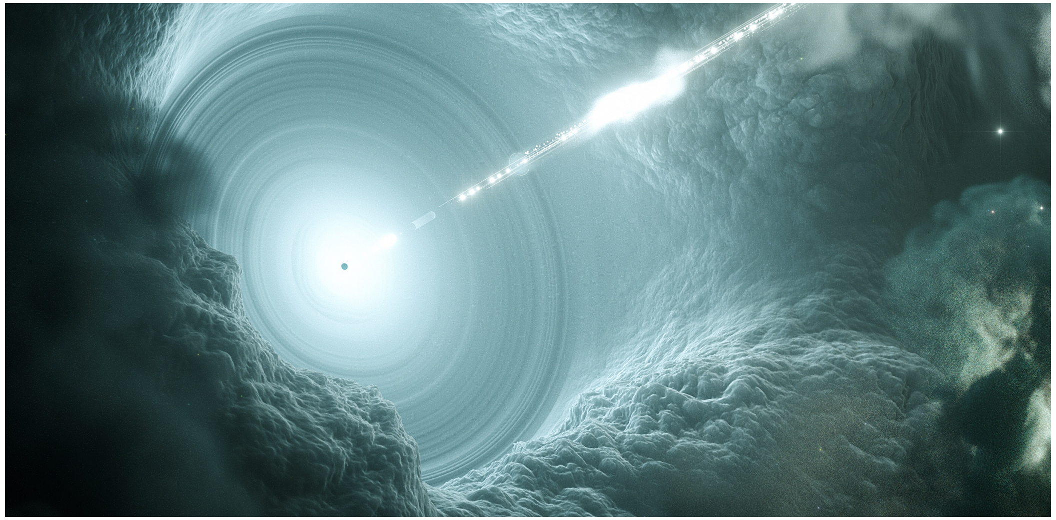


Bartos et al, arXiv:2105.03792

Multi-messenger follow-ups

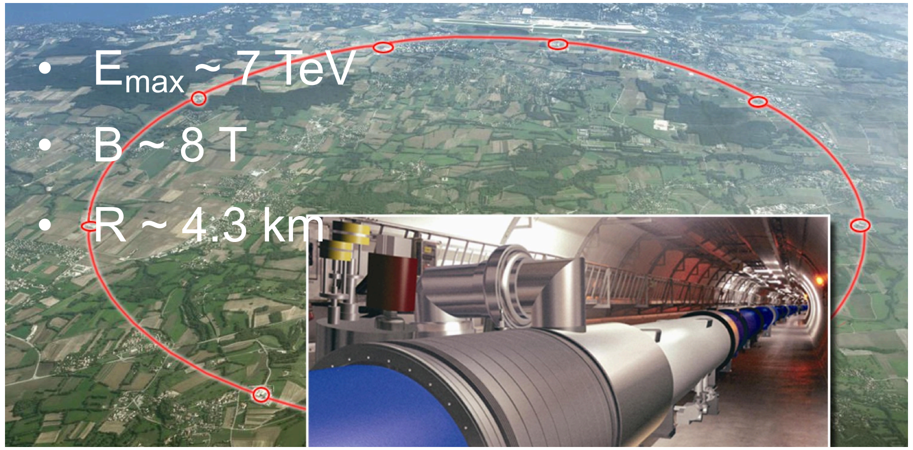
... starting the golden age of neutrino astronomy

- Global alerts initiated by neutrino events
- Especially tracks with good directional information, high enough energy
- Other instruments triggered, who search for counterparts
- Prominent examples: TXS 0506+056 (AGN blazar), AT2019dsg (Tidal Disruption Events), but several other associations as well



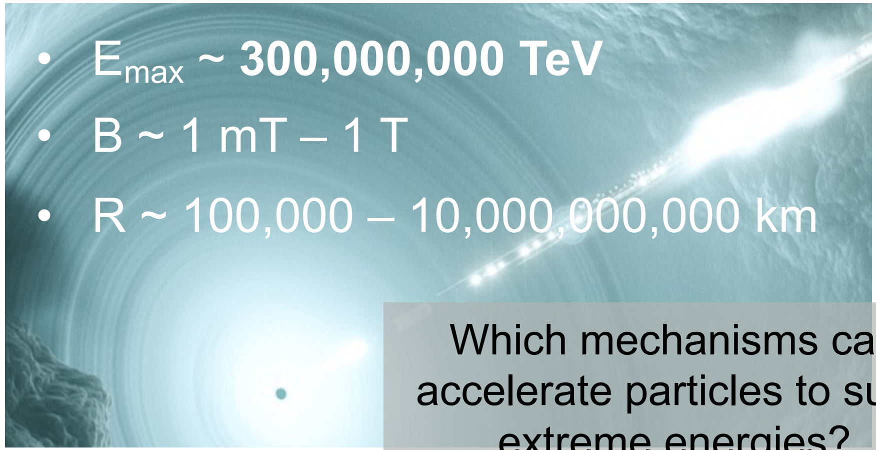
Physics of neutrino production

Particle acceleration ... a pragmatic perspective



- E_{max} ~ 7 TeV
- B ~ 8 T
- R ~ 4.3 km

Lorentz force
= centrifugal force
➔ E_{max} ~ Z c B R

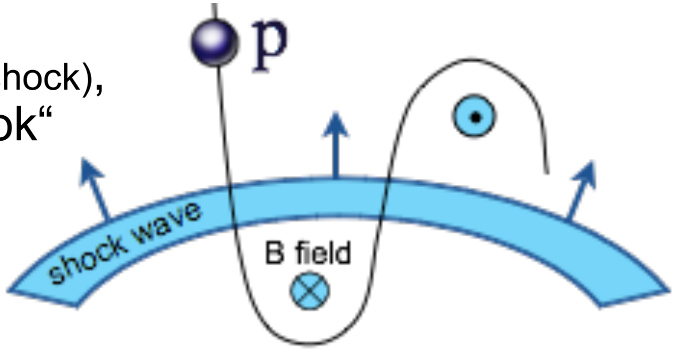


- E_{max} ~ **300,000,000 TeV**
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km

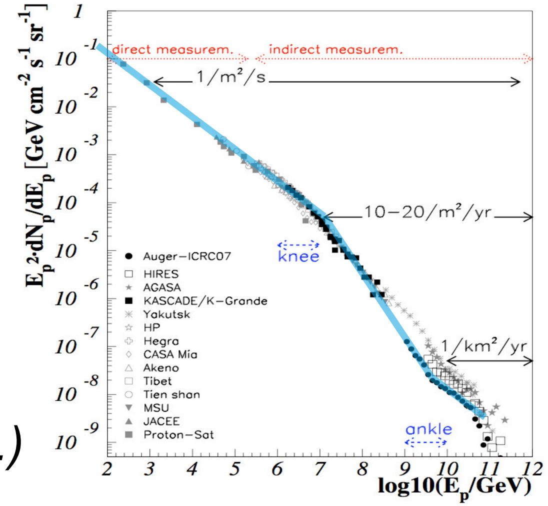
Which mechanisms can accelerate particles to such extreme energies?

Example: *Fermi shock acceleration*

- Energy gain per cycle: E ➔ η E
- Escape probability per cycle: P_{esc}
- Yields a **power law** spectrum ~ $E^{\frac{\ln P_{esc}}{\ln \eta}-1}$
- ln P_{esc}/ln η ~ -1 (from compression ratio of a strong shock), and $\mathbf{E^{-2}}$ is the typical "textbook" spectrum

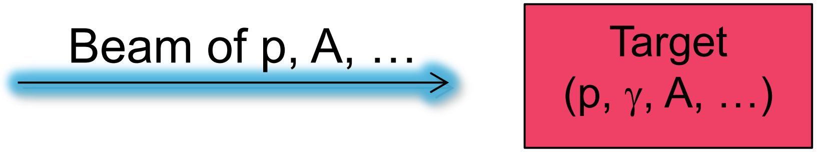


- Theory of acceleration challenging, but we **do observe** power law (= non-thermal) spectra in Nature
- For multi-messenger perspective: adopt pragmatic point of view! *(we know that it works, somehow ...)*



Secondary production: Particle physics 101?

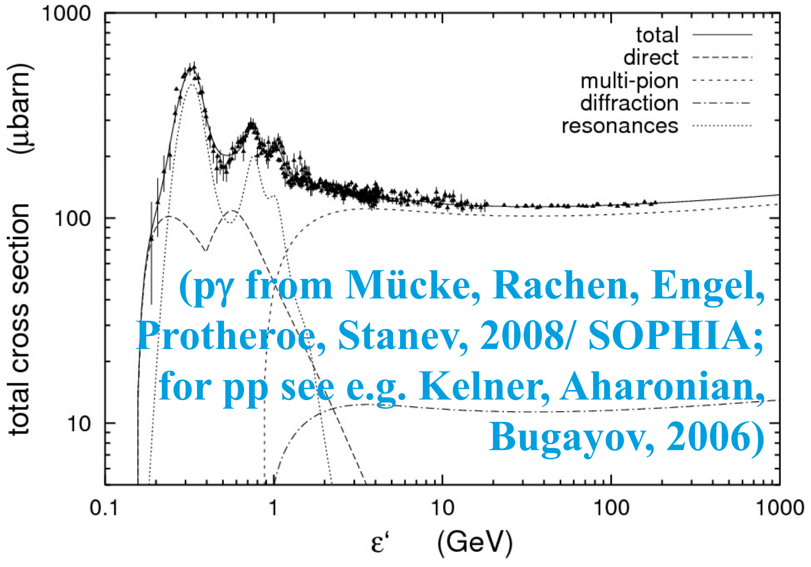
- **Beam dump picture (particle physics)**



- Interaction rate $\Gamma \sim c\ \ N\ [\mathrm{cm}^{-3}]\ \ \sigma\ [\mathrm{cm}^2]$

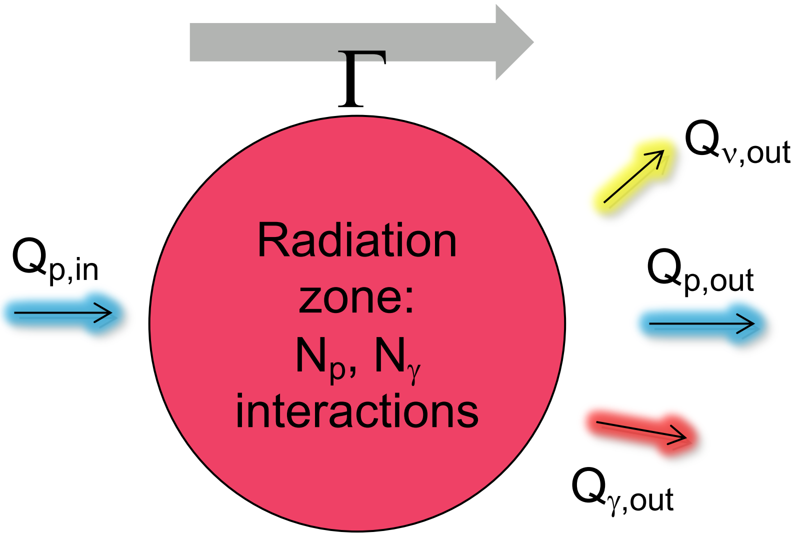
Target density (e.g. N_γ) critical for production!

Key challenge: Need volume



(Photon energy in nucleon rest frame)

- **Astrophysical challenges:**
  - Feedback between beam and target (e.g. photons from π^0 decays)
  - Need self-consistent description called **radiation model**
  - Density *in* source, in general, **not** *what you get* from the source



Here: typically a spherical blob in relativistically moving frame

Global radiation models (theory)

- Time-dependent PDE system, one PDE per **particle species *i***

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)N_i(E)\right) - \frac{N_i(E)}{t_{\mathrm{esc}}} + Q(E)$$

Cooling (continuous) Escape Injection

"radiation processes"

$b(E)=-E\, t^{-1}_{loss}$
$Q(E,t)$ [GeV^{-1} cm^{-3} s^{-1}]
$N(E,t)$ [GeV^{-1} cm^{-3}] particle spectrum including spectral effects

- Injection: species *i* from acceleration zone, and from other species *j*:

$$Q(E) = Q_i(E) + Q_{ji}(E)$$

$$Q_{ji}(E_i) = \int dE_j\, N_j(E_j)\, \Gamma_j^{\mathrm{IT}}(E_j)\, \frac{dn^{\mathrm{IT}}_{j\to i}}{dE_i}(E_j, E_i)$$

Density other species	Inter-action rate	Re-distribution function +secondary multiplicity

Strongly forward peaked spectra in interaction frame (e.g. blob frame)

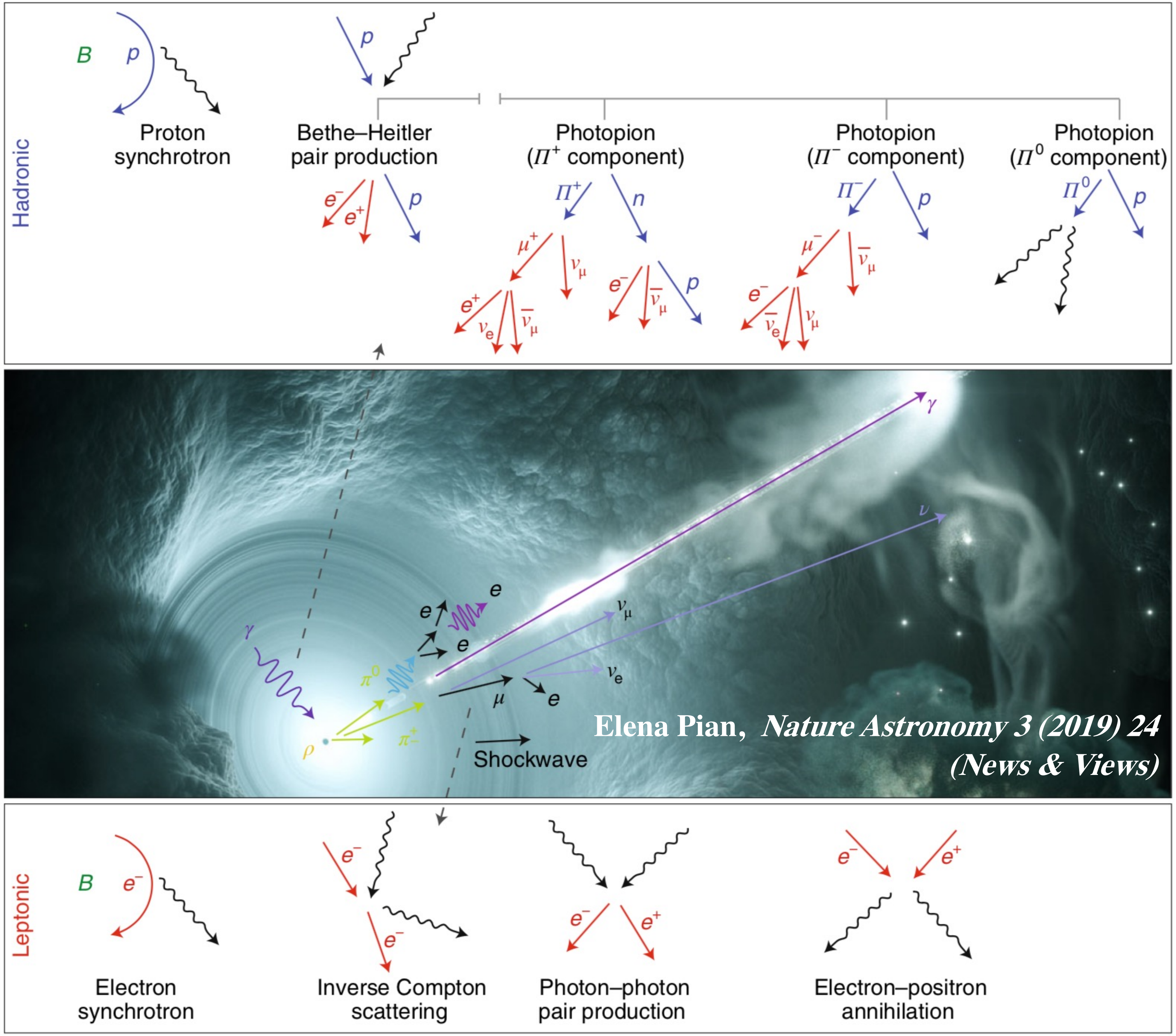
→ Re-distribution function narrow + peaked

E.g. $E_\nu \sim 0.25\, E_\pi \sim 0.25 \times 0.2 \times E_p = 0.05\, E_p$

Radiation processes

Examples for e and p

- These processes lead to cooling, escape (→ leave species), and re-injection terms
- Other processes relevant for neutrinos: synchroton cooling of muons, pions

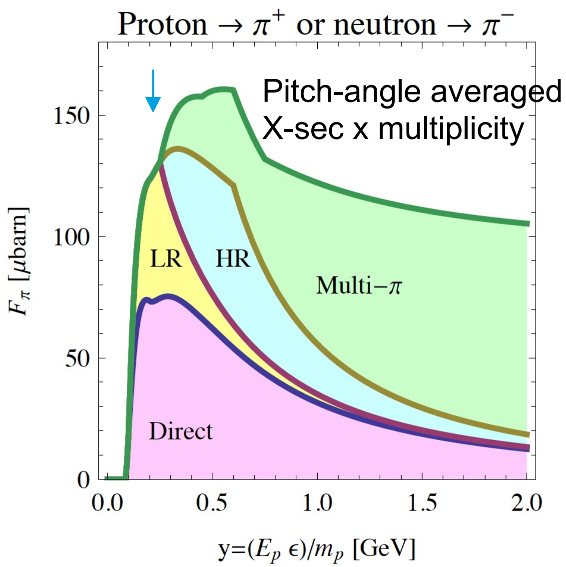


Multiple messengers from photo-pion production

- Neutrino peak determined by maximal cosmic ray energy
  [conditions apply: for target photons steeper (softer) than ε^{-1} (and low enough ε_{min})]
- Interaction with target photons
  (Δ-resonance approximation for C.O.M. energy):

$$p + \gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} n + \pi^+ & \to \nu \\ p + \pi^0 & \to \gamma \end{cases}$$

E_γ [keV] ~ 0.01 Γ^2/E_ν [PeV]
keV energies interesting!
(computed for Δ-res, yellow) →

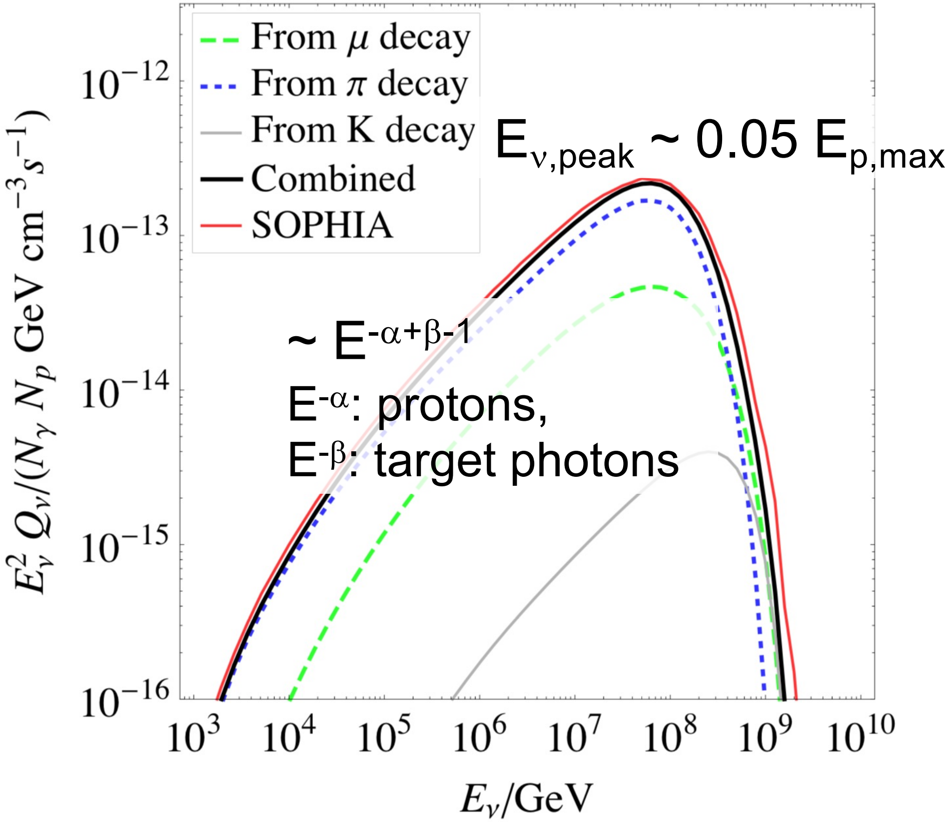


- Photons from pion decay:

$$\pi^0 \longrightarrow \gamma + \gamma$$

Injected at $E_{\gamma,peak}$ ~ 0.1 $E_{p,max}$
TeV–PeV energies interesting!
(but: electromagnetic cascade in source!)

AGN neutrino spectrum (example)



From: Hümmer et al, Astrophys. J. 721 (2010) 630; for a more complete view of possible cases, see Fiorillo et al, JCAP 07 (2021) 028

pp versus pγ interactions

When do the neutrinos follow the primary spectrum?

- **pp interactions**

$$\mathrm{p}+\mathrm{p} \rightarrow \begin{cases} \pi^{+} + \text{anything} & 1/3 \text{ of all cases} \\ \pi^{-} + \text{anything} & 1/3 \text{ of all cases} \\ \pi^{0} + \text{anything} & 1/3 \text{ of all cases} \end{cases}$$

Spectrum: $E^{-\alpha}$ non-rel. $E^{-\alpha}$

(Branchings actually not exactly 1/3; see **JCAP 1701 (2017) 033**)

Examples: starburst galaxies, environments with gas/dust

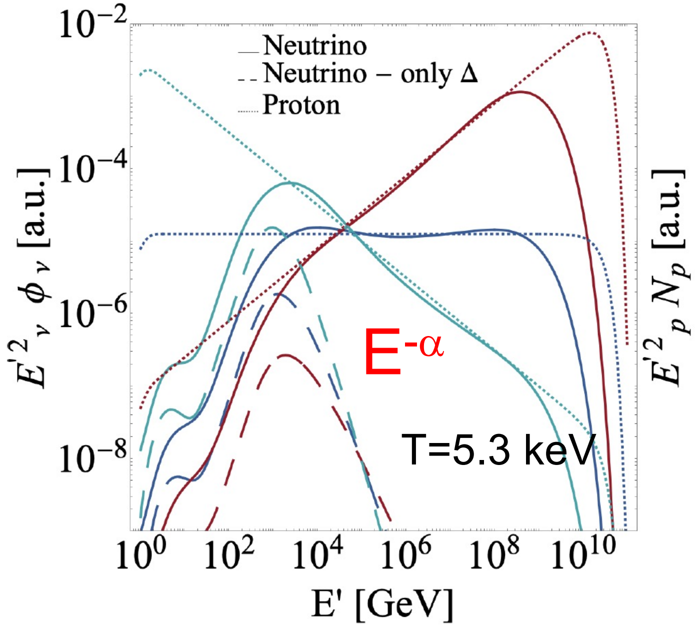
- **pγ interactions**: more sophisticated, as relativistic target (power law)

$$p+\gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} n+\pi^{+} & 1/3 \text{ of all cases} \\ p+\pi^{0} & 2/3 \text{ of all cases} \end{cases}$$

$E^{-\alpha}$ $E^{-\beta}$ $E^{-\alpha+\beta-1}$

$E^{-\alpha}$ only if $\beta=1$!

Examples: GRBs (β~1), AGN blazars (β>1)

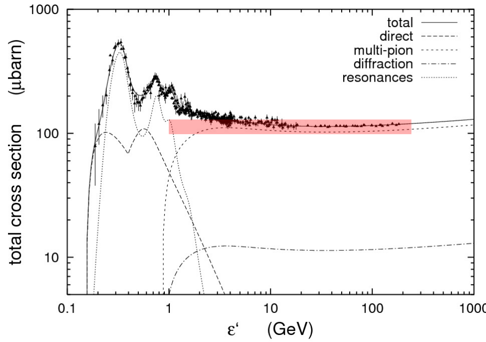


Fiorillo et al, JCAP 07 (2021) 028

- **Effect of multi-pion production (pγ):** Dominates if target photon temperature high enough (thermal target).
  Examples: TDEs, AGN cores

$$p+\gamma$$

$E^{-\alpha}$ T



→

Decouple the maximal cosmic ray and neutrino energies?

Effect of secondary cooling

- Synchrotron cooling of secondaries (μ, π, K) in neutrino production chain:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \, ,$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

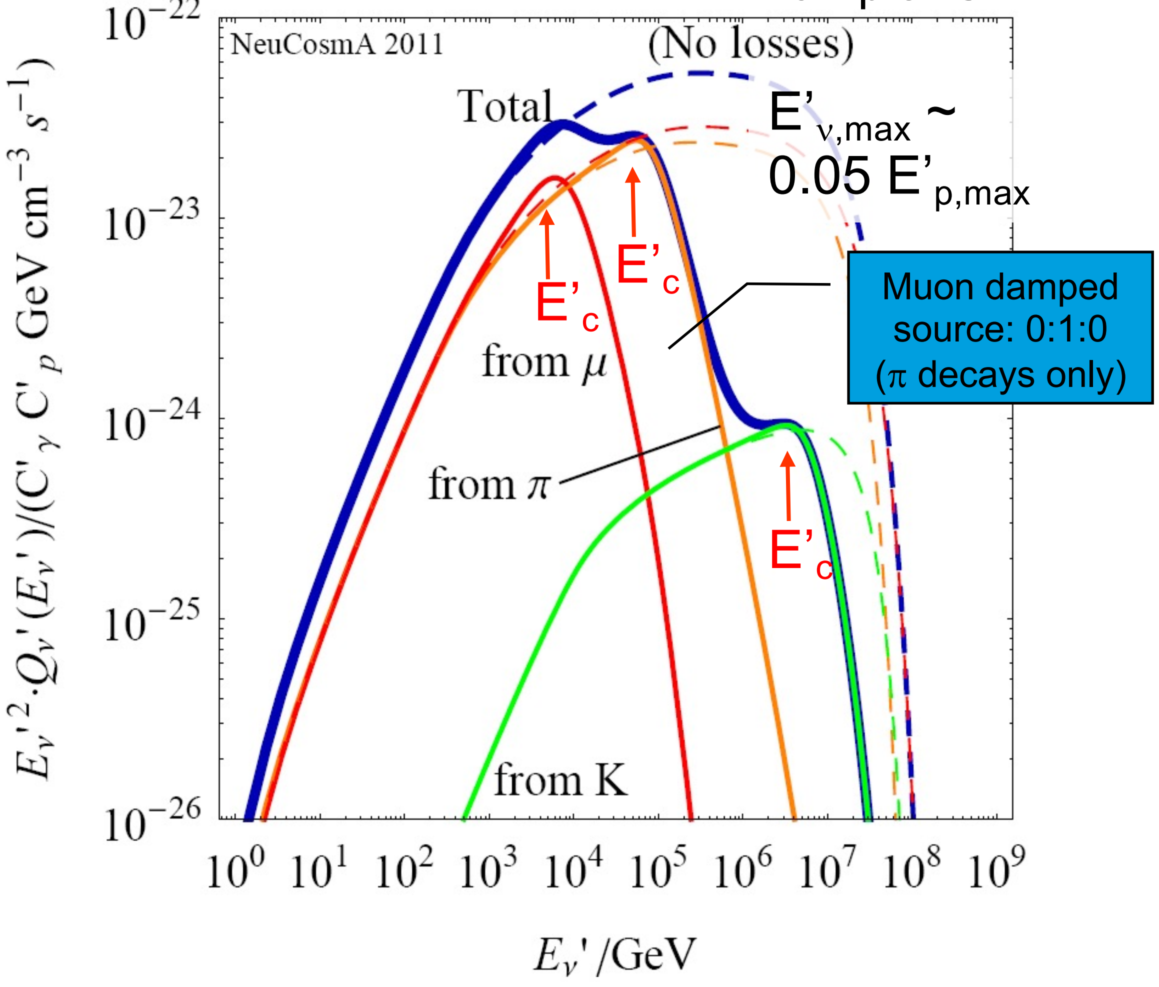
- Spectra (μ, π, K) energy loss-steepend above critical energy
(synchrotron cooling faster than decay)

$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

Depends on particle physics only (m, τ_0 of secondary), and **B'**

- Points towards sources with strong enough B' if UHECR connection:
Gamma-Ray Bursts, (jetted)
Tidal Disruption Events, ...

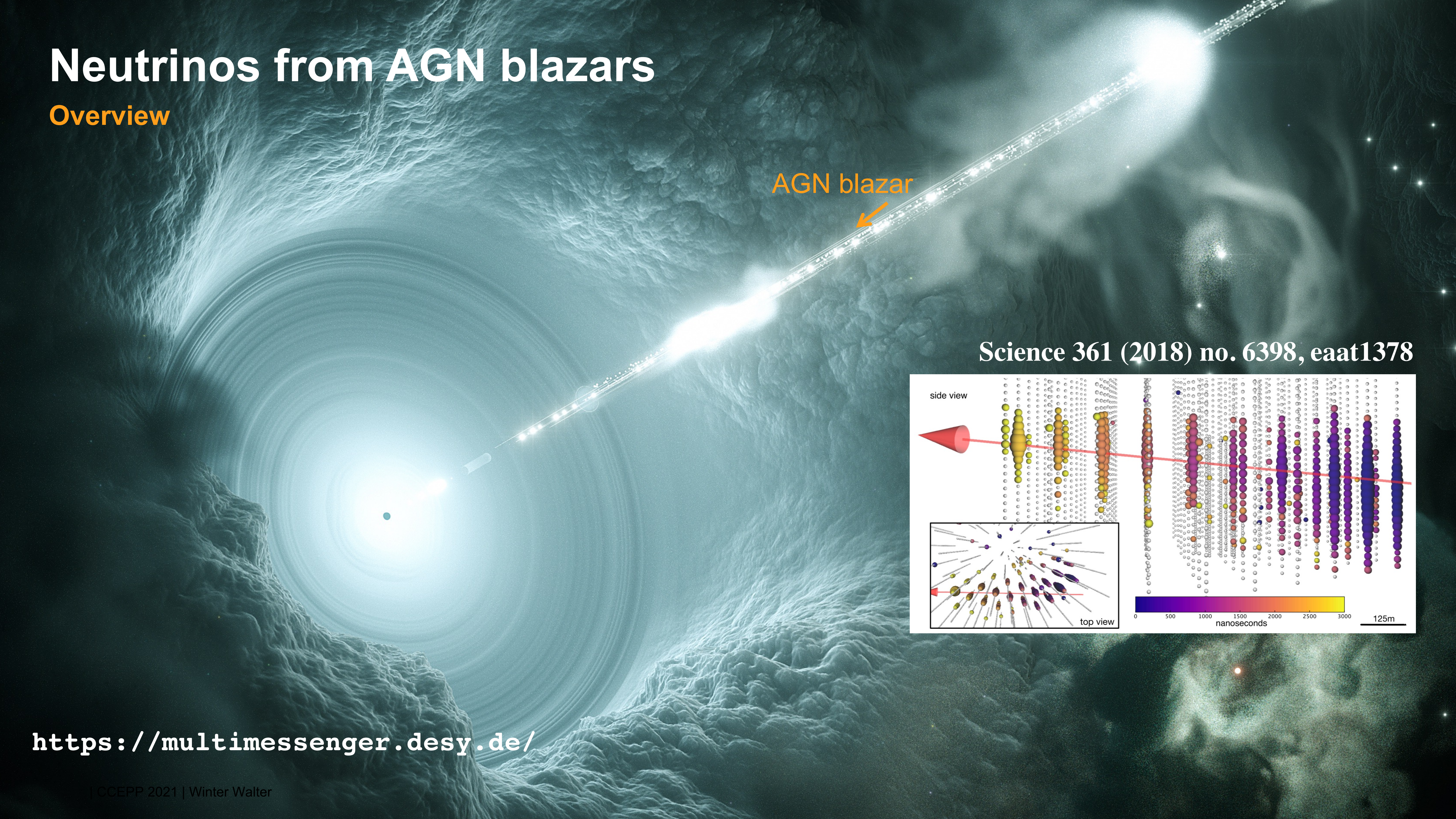
Example: GRB



Kashti, Waxman, 2005; Lipari et al, 2007; ...
Fig. from Baerwald et al, Astropart. Phys. 35 (2012) 508

Neutrinos from AGN blazars

Overview



Science 361 (2018) no. 6398, eaat1378

https://multimessenger.desy.de/

What is an AGN blazar?
(AGN = Active Galactic Nucleus)

Theory basics:

1

Angular momentum determines geometry

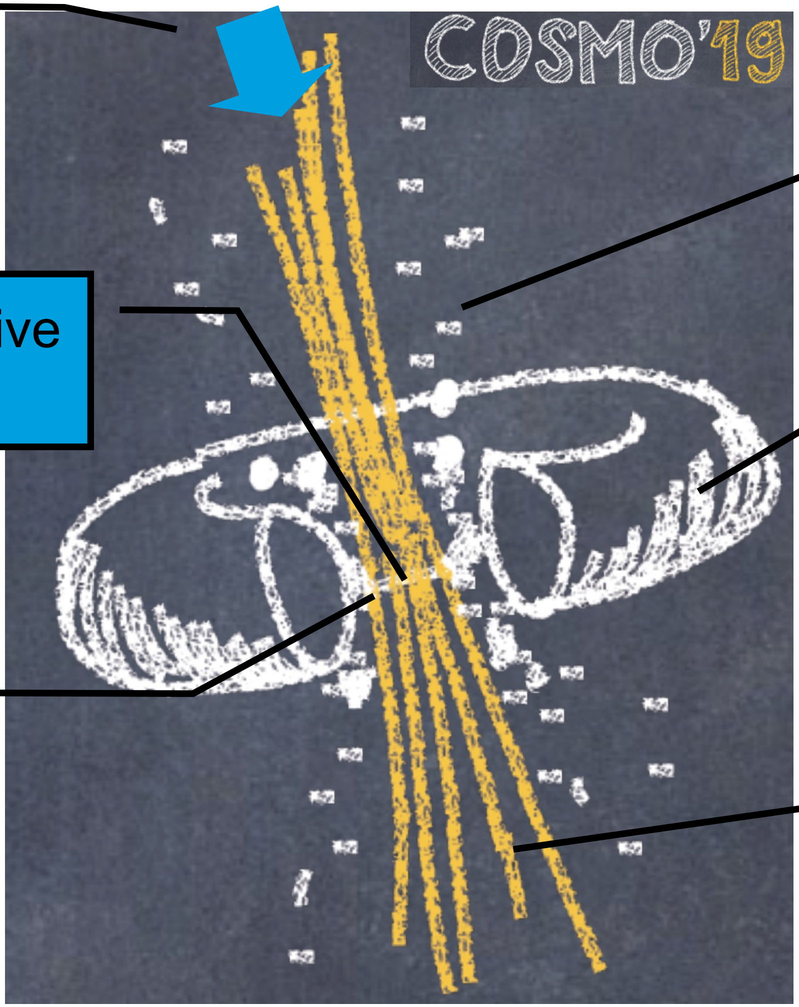
2

Estimate for accretion power ~ phys. jet power:
Eddington luminosity
$L_{edd} \sim 10^{47}$ erg s^{-1}
x $M_{BH}/(10^9\ M_{sun})$

Blazar:
The observer looks into the jet

A supermassive black hole

An accretition disk



Clouds (line emissions!)

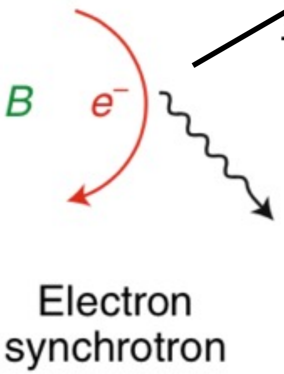
The dust torus

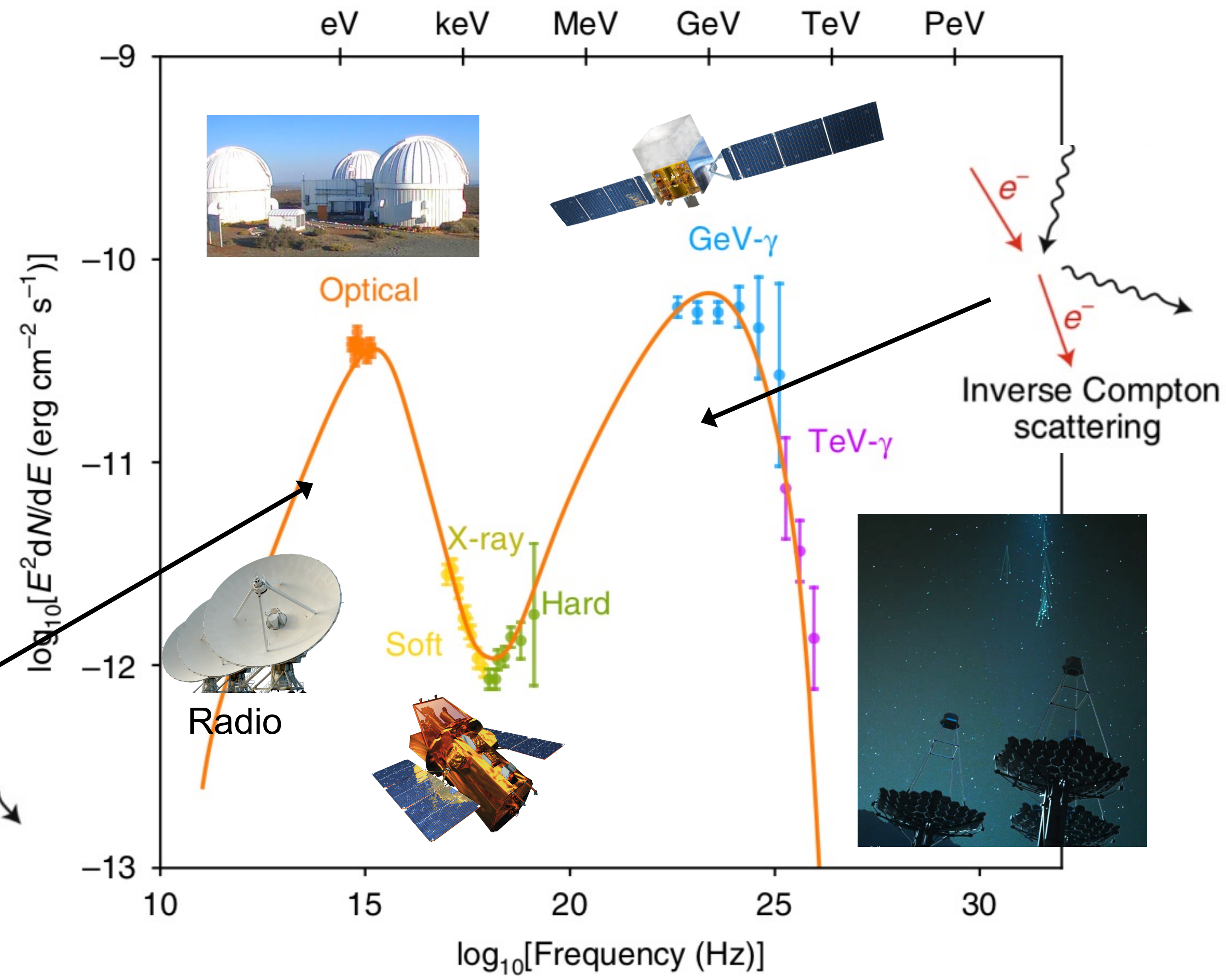
The jet(s)

Electromagnetic picture of blazars

- Exhibit a typical two-hump structure
- Measured over extremely large range of electromagnetic spectrum
- Often observation “campaigns” at same time, or follow-up searches of neutrinos

- Simplest explanation: first peak from electron synchroton, second from inverse Compton up-scattering of these synchrotron photons off the same electrons (= SSC – “synchrotron self-Compton model”)





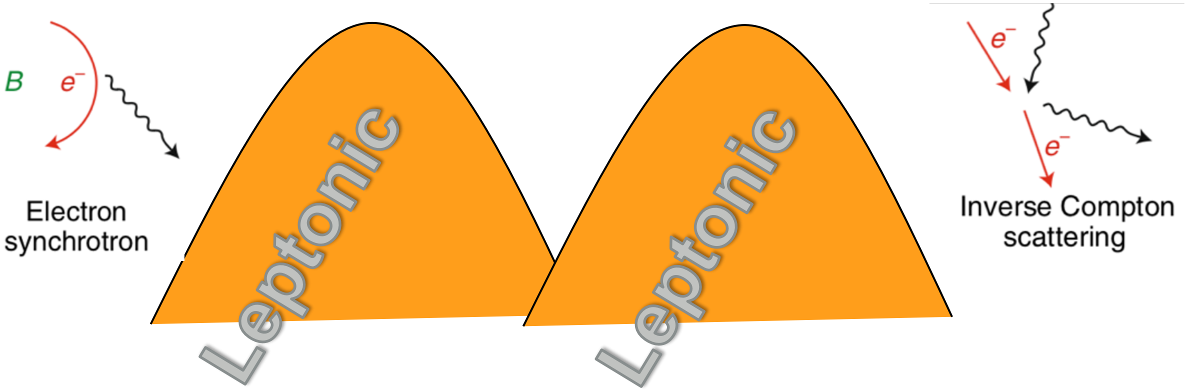
Credits: VLA, ASAS-SN, Swift, Fermi, MAGIC, DESY science comm. lab., Pian 2019, Gao et al, 2019

Typical SED models (qualitatively)

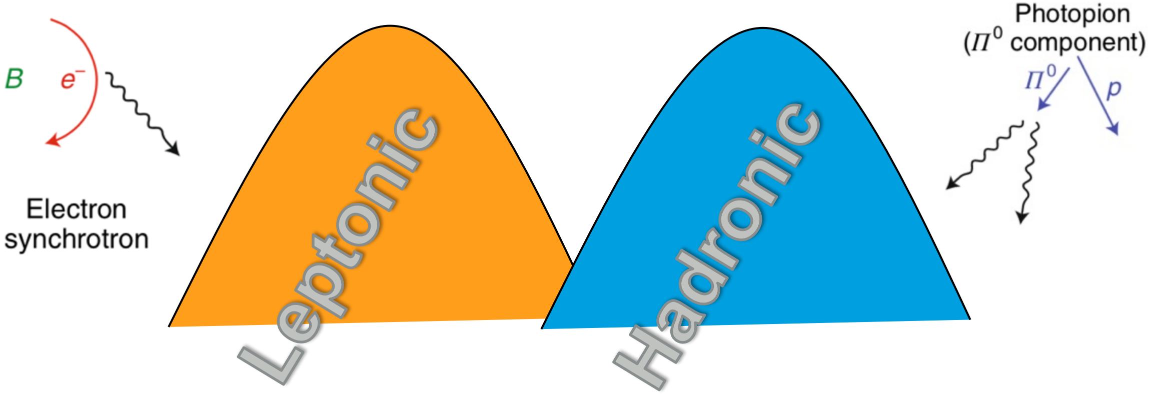
One spherical radiation zone
Fewest assumptions

R’

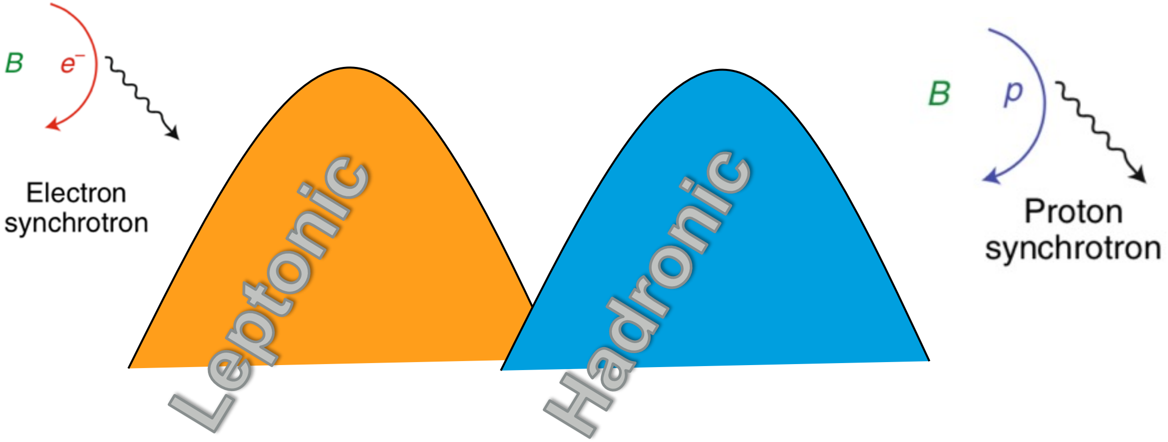
- Synchrotron self-Compton (SSC) or external Compton (EC) models



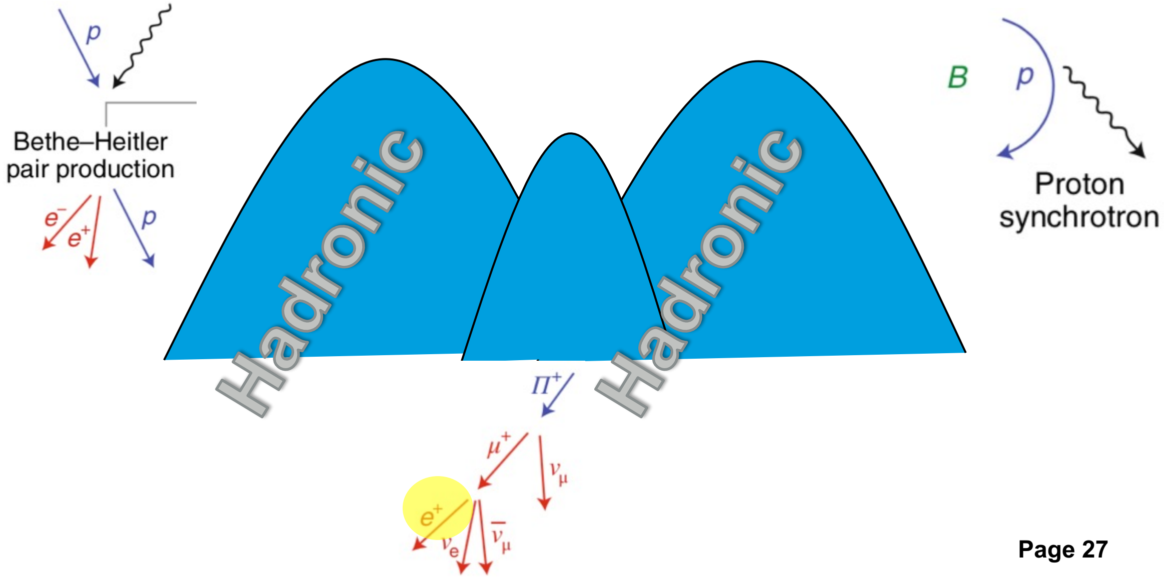
- Pion cascade models



- Proton synchrotron models (require large B’)



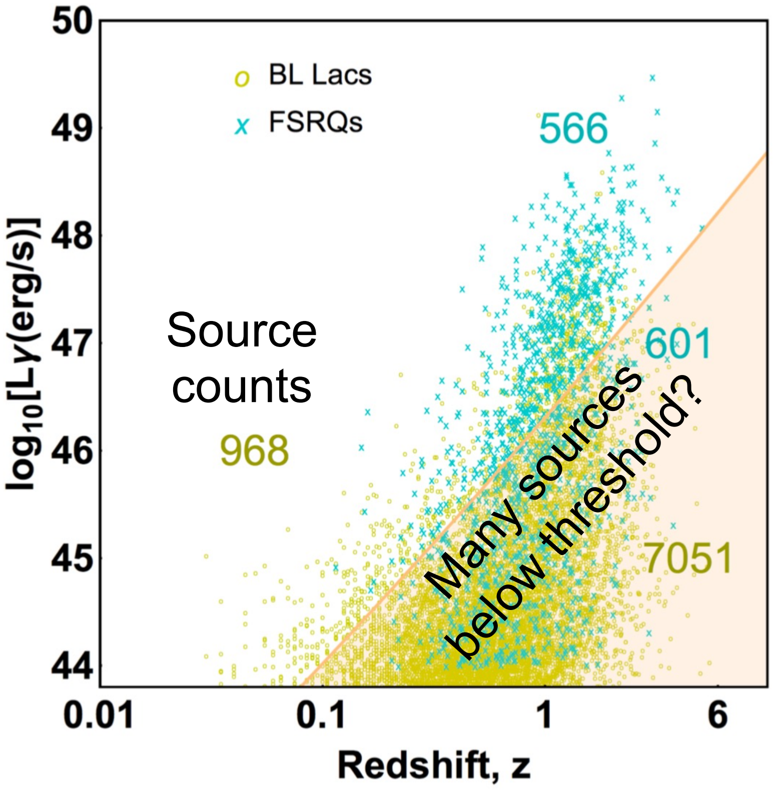
- More exotic hadronic models, for example:

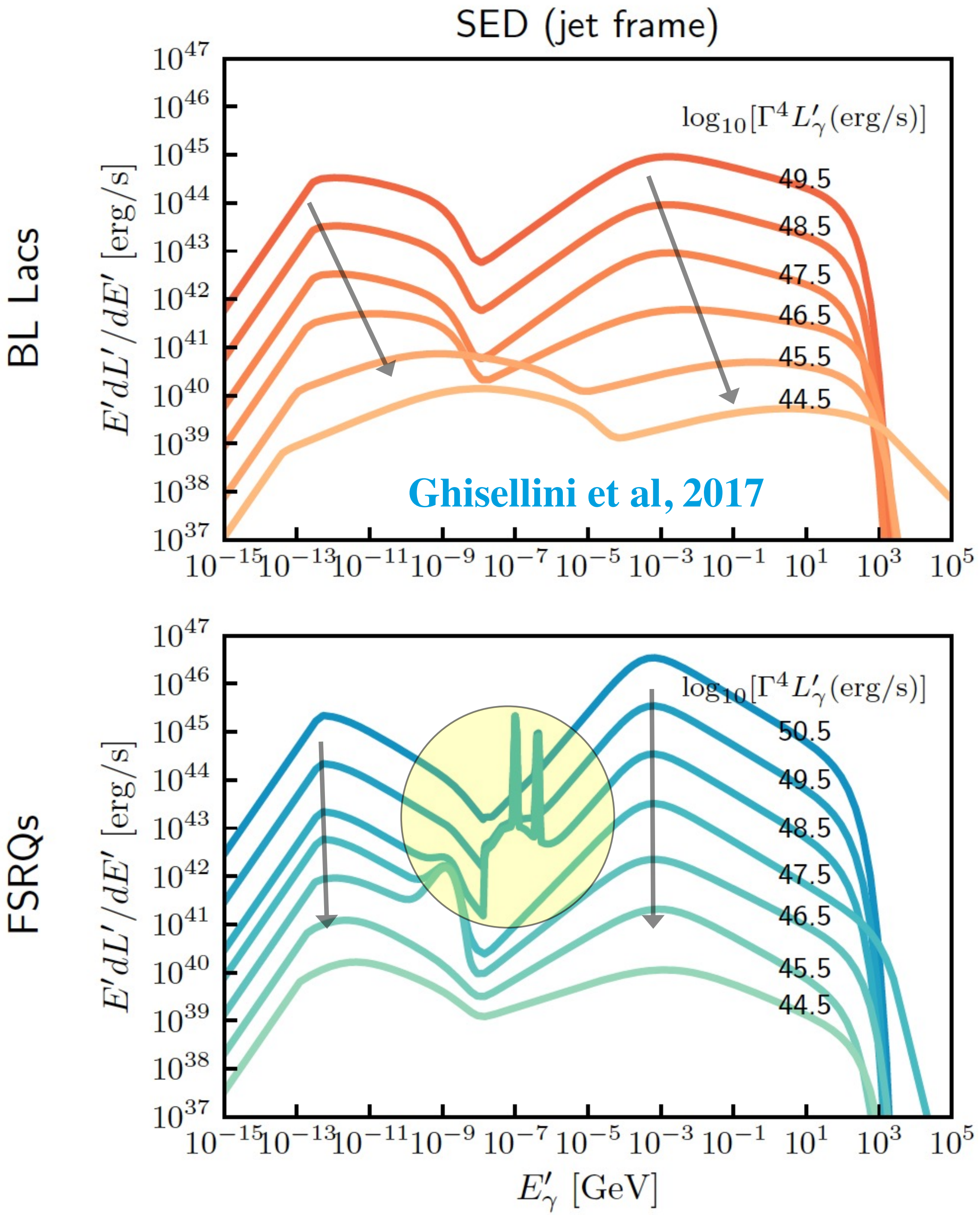


A population of blazars

- **FSRQs** (Flat Spectrum Radio Quasars): higher luminosities and additional spectral features compared to **BL Lacs**
- There is a (empirical, disputed) relationship between luminosity and spectral energy distribution (SED) aka the "blazar sequence" →

Population model by Ajello et al, 2012+2014; sources from 3LAC catalogue

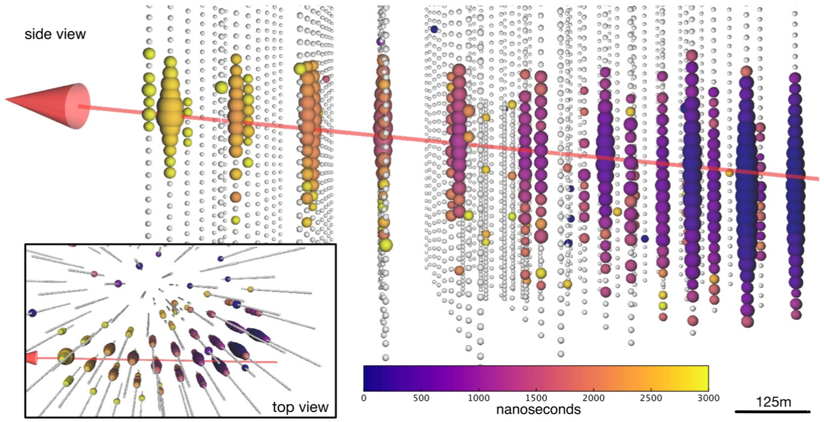


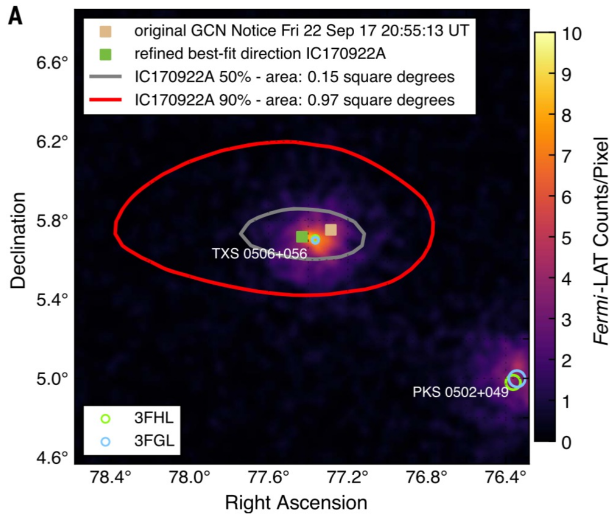


Figs. from Palladino, Rodrigues, Gao, WW, ApJ 871 (2019) 41

A neutrino from the flaring AGN blazar TXS 0506+056

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare



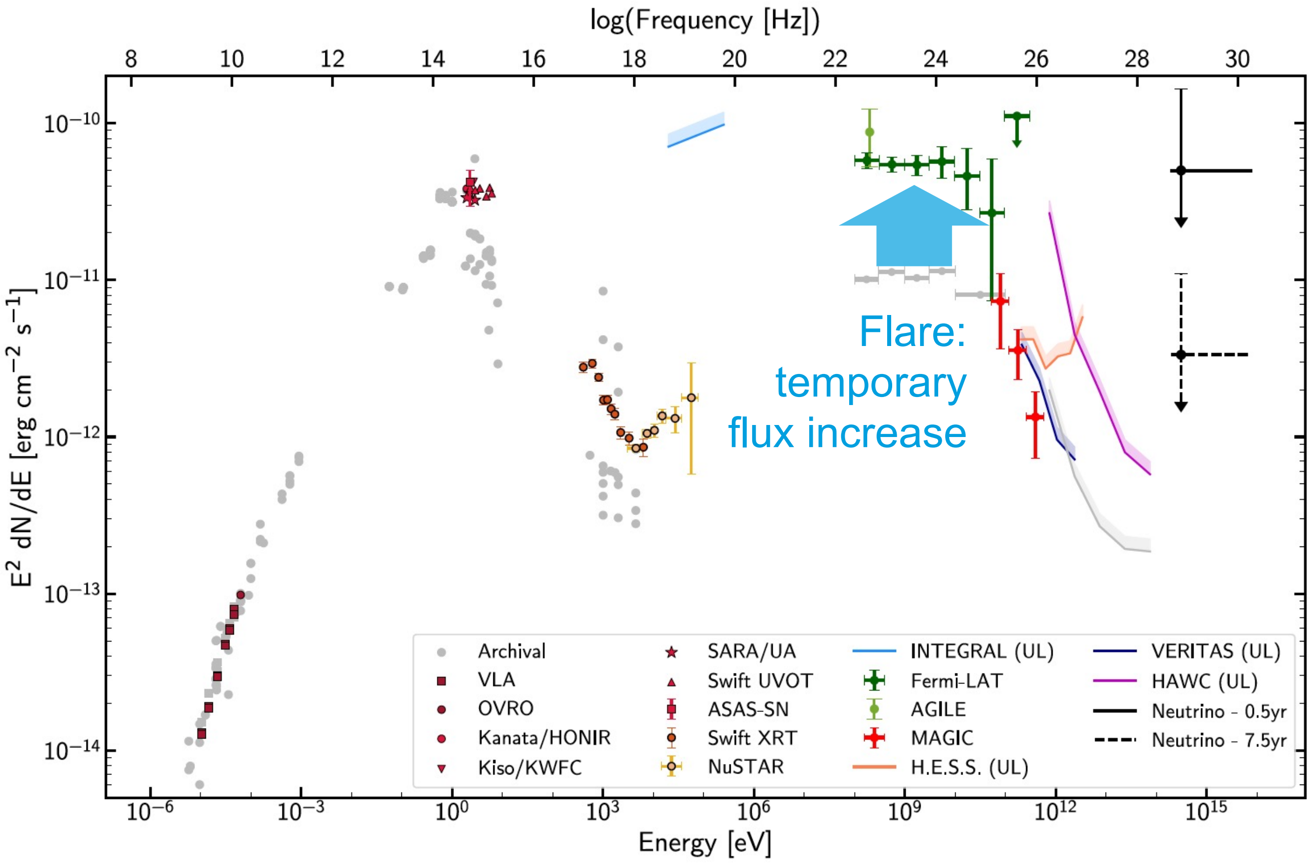


Observed by Fermi-*LAT* and MAGIC (blazar flare)

Significance for correlation: 3σ

z = 0.3365 ± 0.0010
Paiano et al, 2018

SED from a multi-wavelength campaign

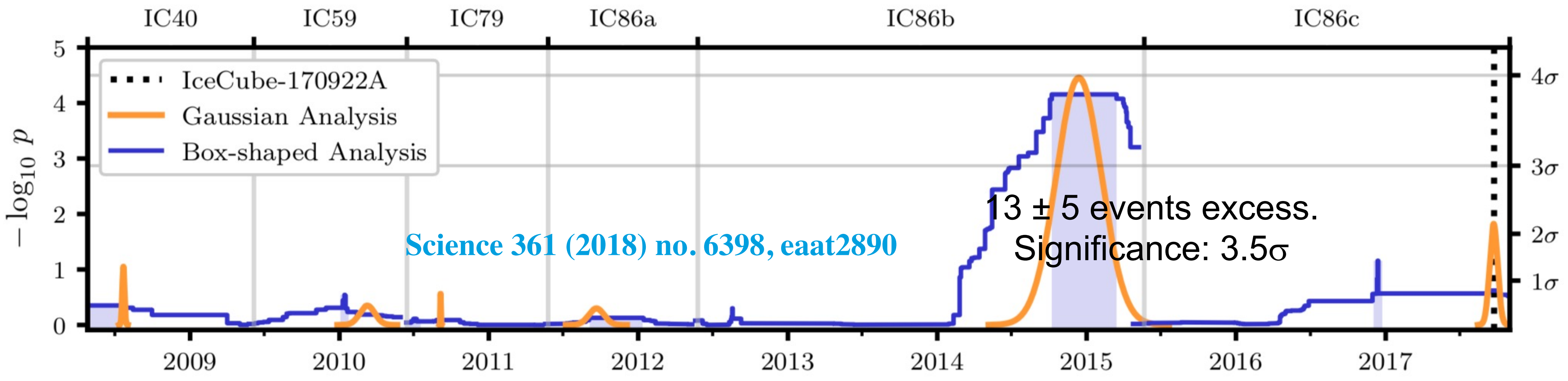


Color: coincident with neutrino; gray: archival data

Science 361 (2018) no. 6398, eaat1378

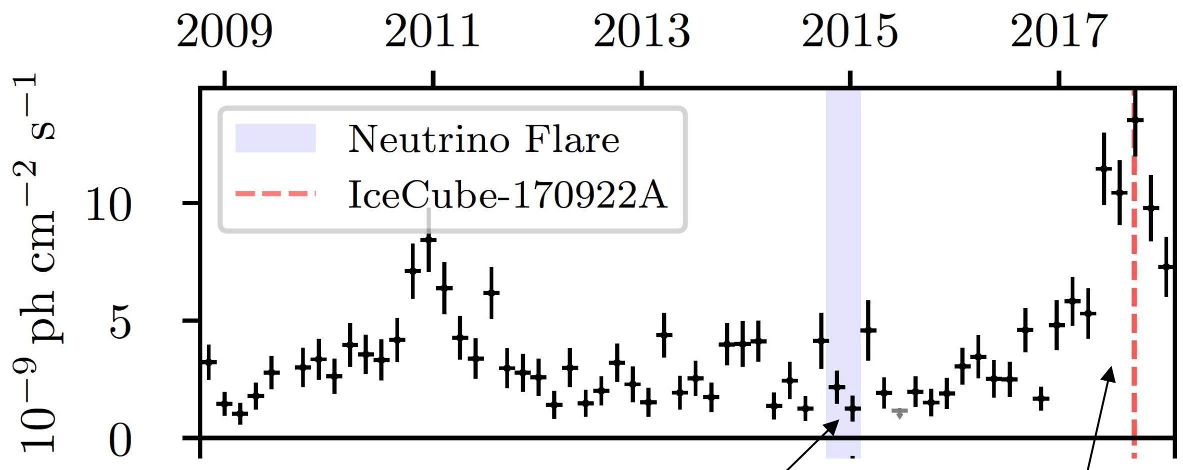
Analysis of archival neutrino (IceCube)

A (orphan) neutrino flare (2014-15) found from the same object in archival neutrino data



During that historical flare:
- Coincident data sparse (since no dedicated follow-up campaign)
- No significant gamma-ray activity

Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192



At 2014-15 neutrino flare

The 2017 flare

Number of predicted neutrinos from a theoretical model?

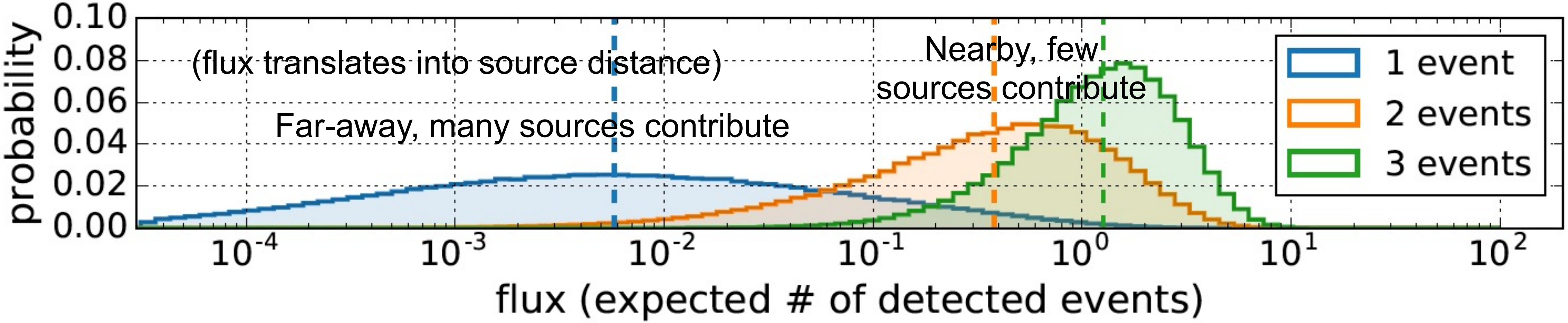
Sept. 22, 2017:
One neutrino observed

Good reasons to expect that the *predicted* model neutrino flux should be significantly lower

2014-2015:
13 ± 5 neutrinos observed

Relatively high number, Gaussian statistics
→ Model prediction of similar order needed

- **Eddington bias:**
  Trial factor for numerous faint sources (here 10^4 equal-lumi BL Lacs z-distributed within z<4, 10 events total)



Strotjohann, Kowalski, Frankowiack, A&A 622 (2019) L9;
see also Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41

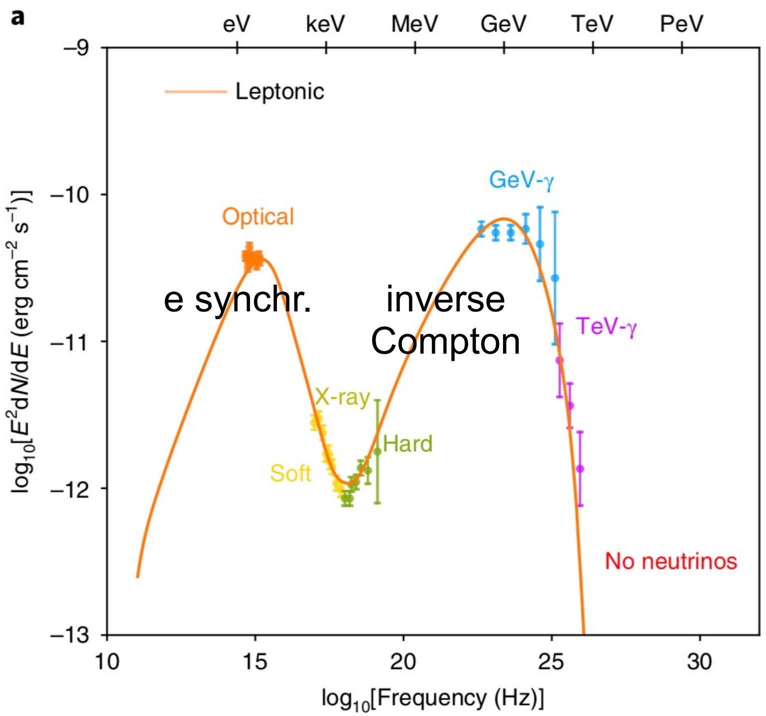
Multi-messenger interpretation of TXS 0506+056

One zone model results (2017 flare)

One spherical radiation zone
Fewest assumptions

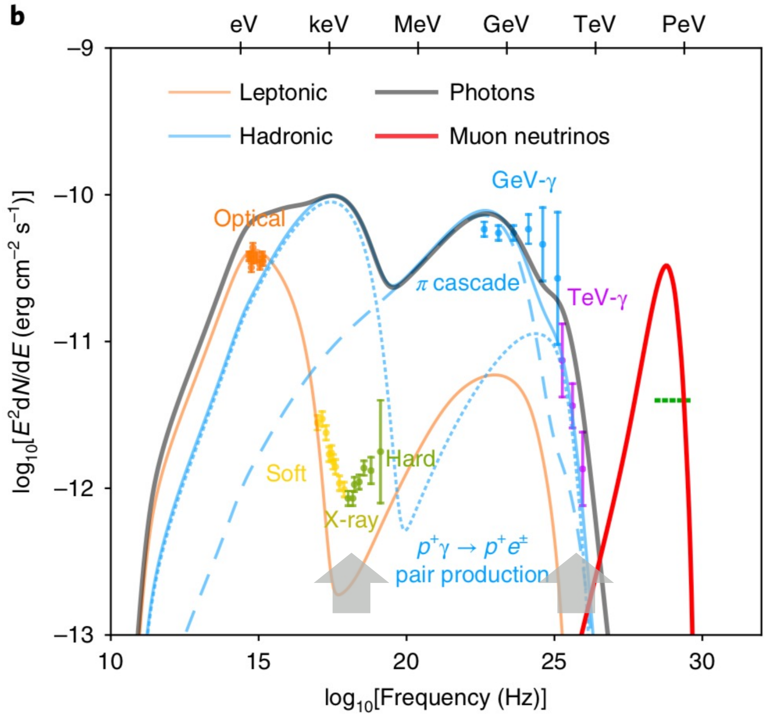
R'

Leptonic models



- No neutrinos

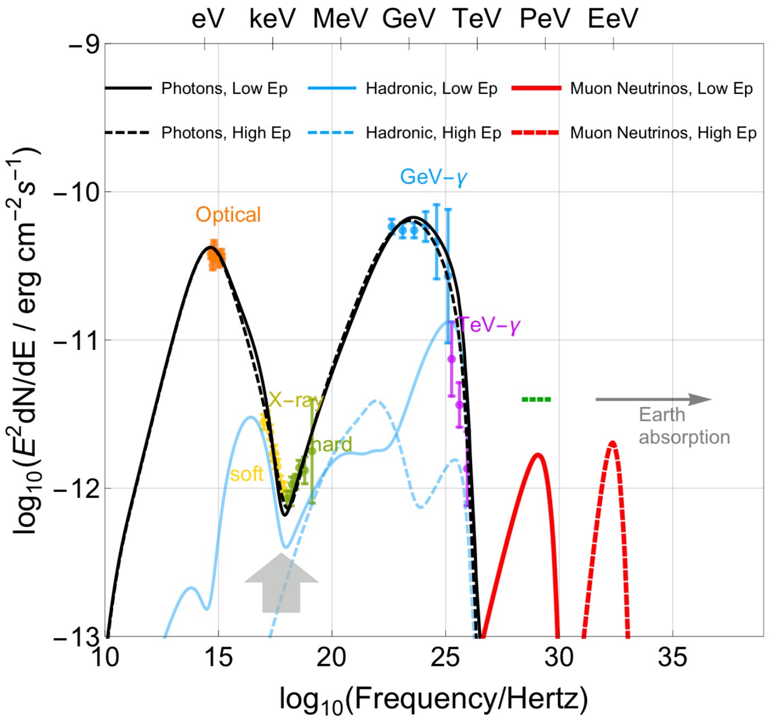
Hadronic (π cascade) models



- Violate X-ray data

X-ray (and TeV γ-ray) data indicative for hadronic origin

Hybrid or p synchrotron models



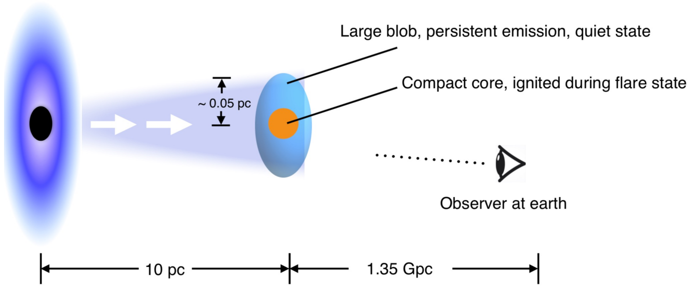
- **Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy**

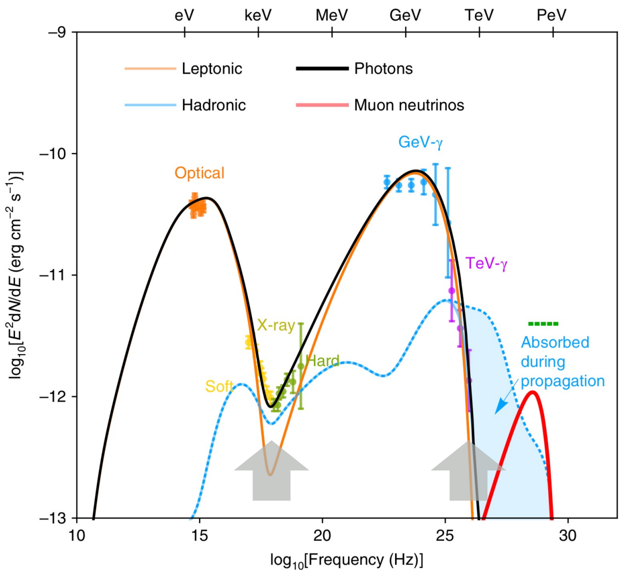
Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88;*
see also Cerutti et al, 2018; Sahakyan, 2018; Gokus et at, 2018; Keivani et al, 2018

More freedom through multiple radiation zones

... to solve energetics problem (examples). At the expense of more parameters.

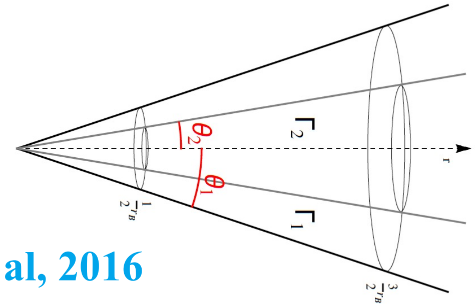
Formation of a compact core



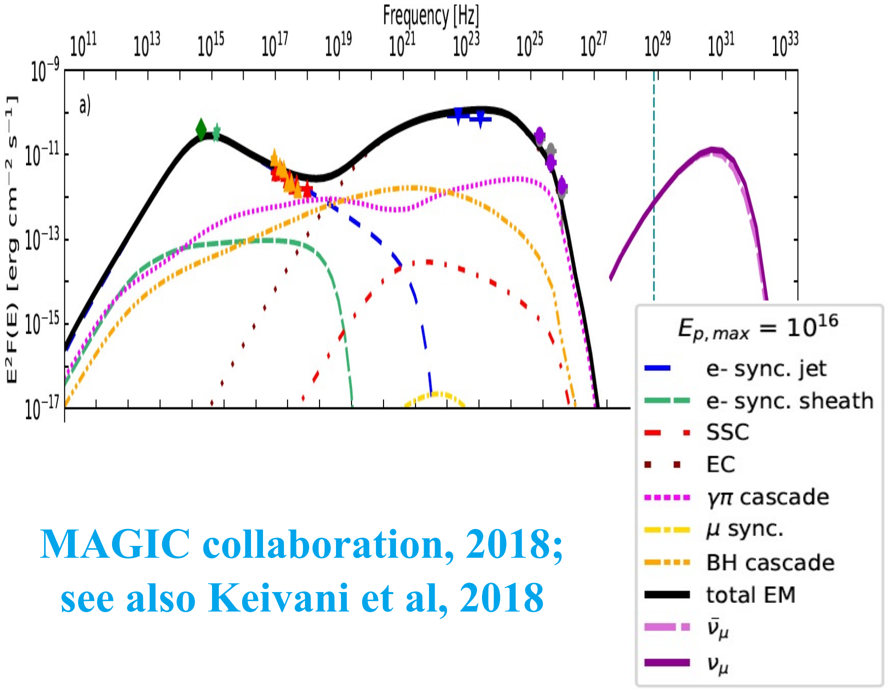


Gao et al, *Nature Astronomy 3 (2019) 88*

External radiation fields

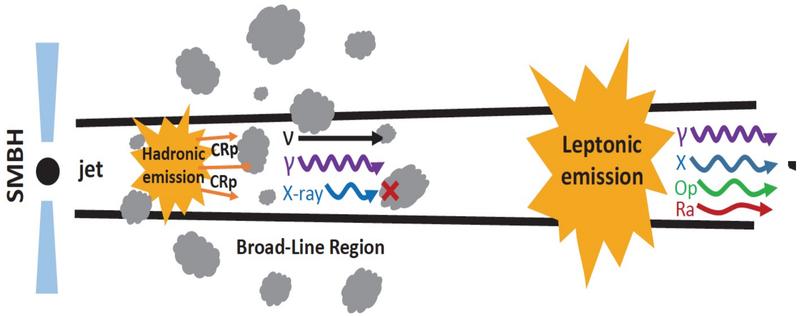


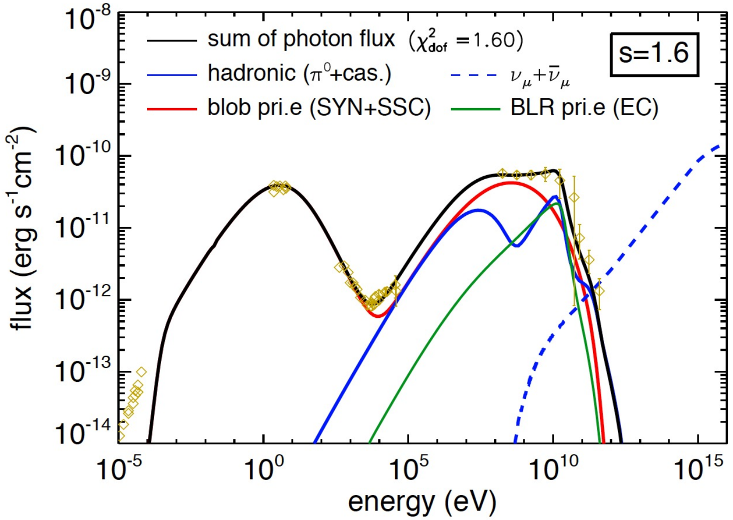
Sikora et al, 2016



MAGIC collaboration, 2018;
see also Keivani et al, 2018

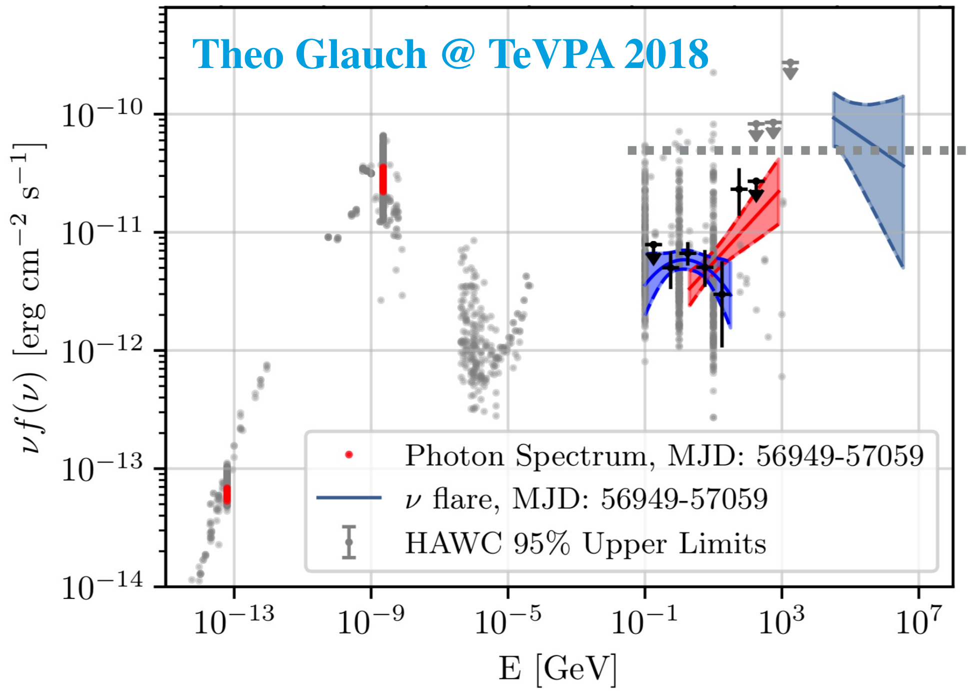
Jet-cloud interactions/ several emission zones





Liu et et al, 2018;
see also Xue et al, 2019

The archival (2014-15) neutrino flare of TXS 0506+056



- Electromagnetic data during neutrino flare sparse (colored)
- Hardening in gamma-rays? (red shaded region)

Padovani et al, 2018; Garrappa et al, arXiv:1901.10806

Theoretical challenge: Where did all the energy go to?

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

Comparable amounts of energy

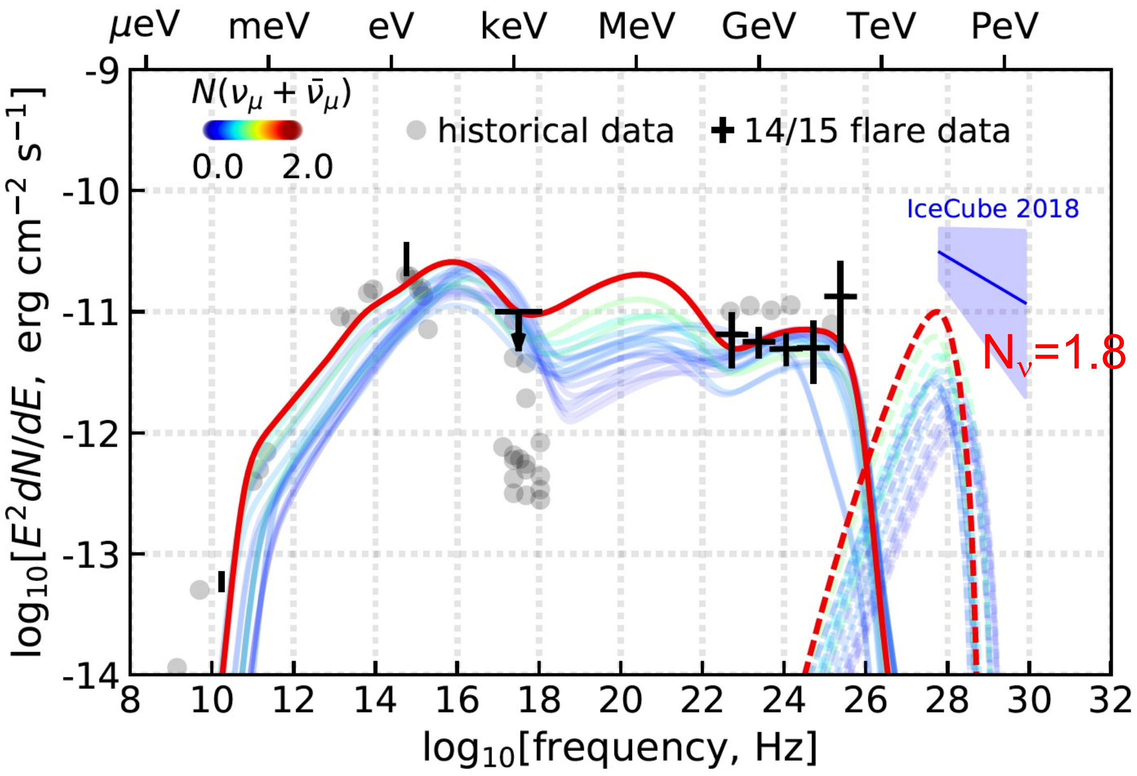
Options for hiding the gamma-rays (+electrons):

- **Reprocessed** and "parked" in E ranges without data during flare? (e.g. MeV range, sub-eV range)
  - → Can this be accommodated in a self-consistent model (next slide)? Fine-tuned during flare?
  - → Requires monitoring in all wavelength bands
- Leave source + **dumped** into the **background light**?
  - → Implies low radiation density to have gamma-rays escape
  - → Difficult to accommodate energetics if sole solution (low neutrino production efficiency!)
- **Absorbed or scattered** in some **opaque region**, e.g. dust/gas/radiation?
  - → Requires additional model ingredients

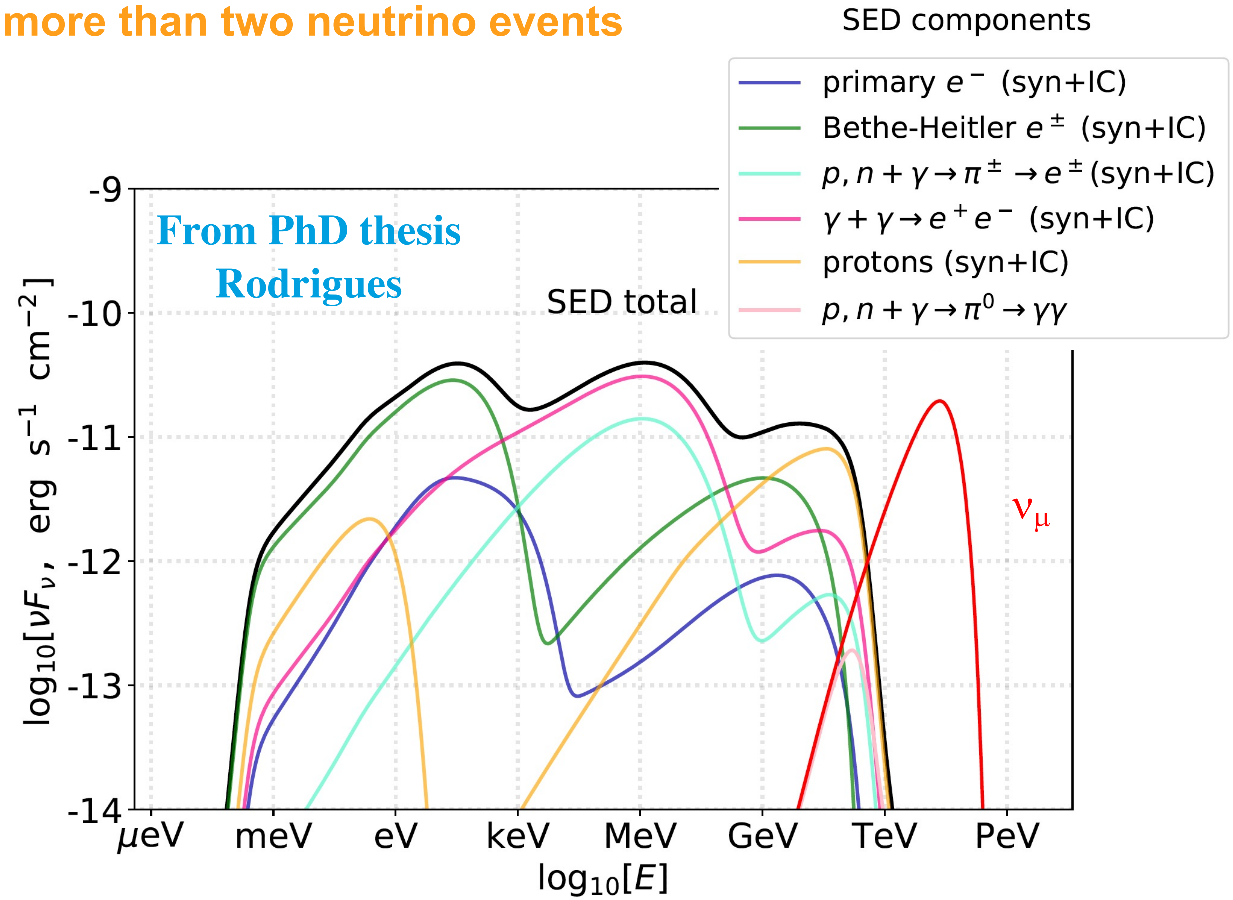
    see e.g. Wang et al, 2018; Murase et al, 2018

One zone description of spectral energy distribution

.... can describe SED (with significant excess of L_{edd}), but no more than two neutrino events



Energy deposited in MeV range and absorbed in EBL
(here about 80% absorbed, 20% re-processed for E_γ > TeV)



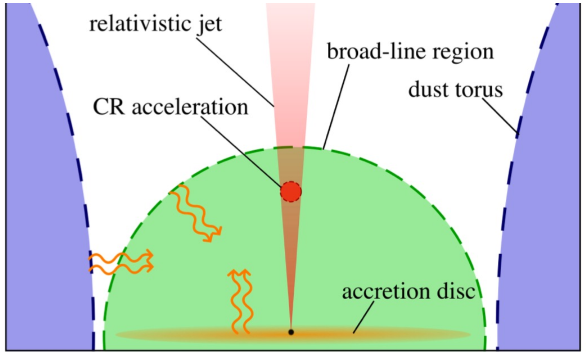
Primary electron processes (synchrotron and inverse Compton) dominate *nowhere* in this model!

From: Rodrigues, Gao, Fedynitch, Palladino, Winter, ApJL 874 (2019) L29; see also Halzen, et al, arXiv:1811.07439

External radiation field example

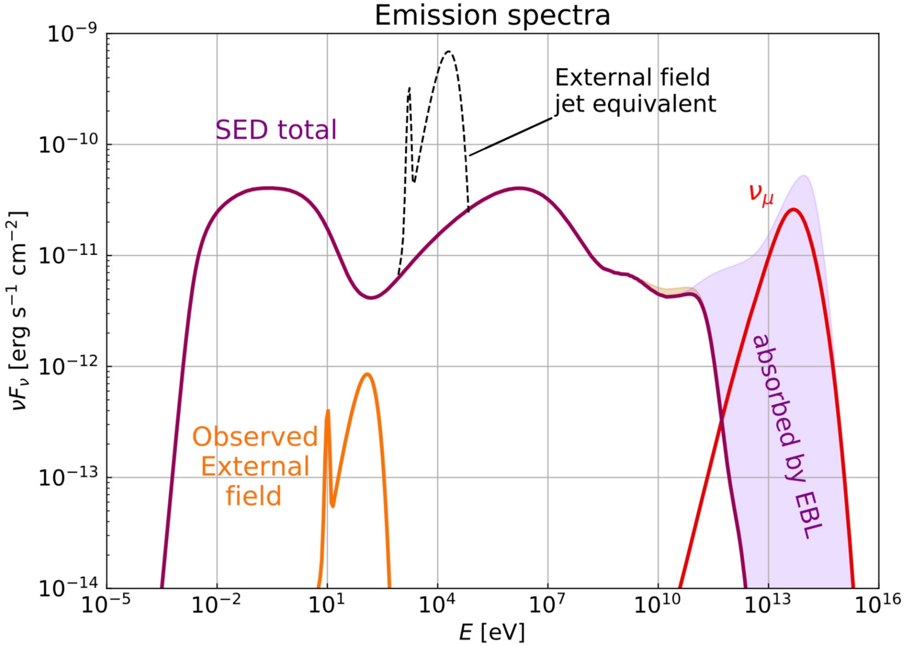
Can yield up to about five neutrino events during neutrino flare

Rodrigues et al, ApJ 854 (2018) 54



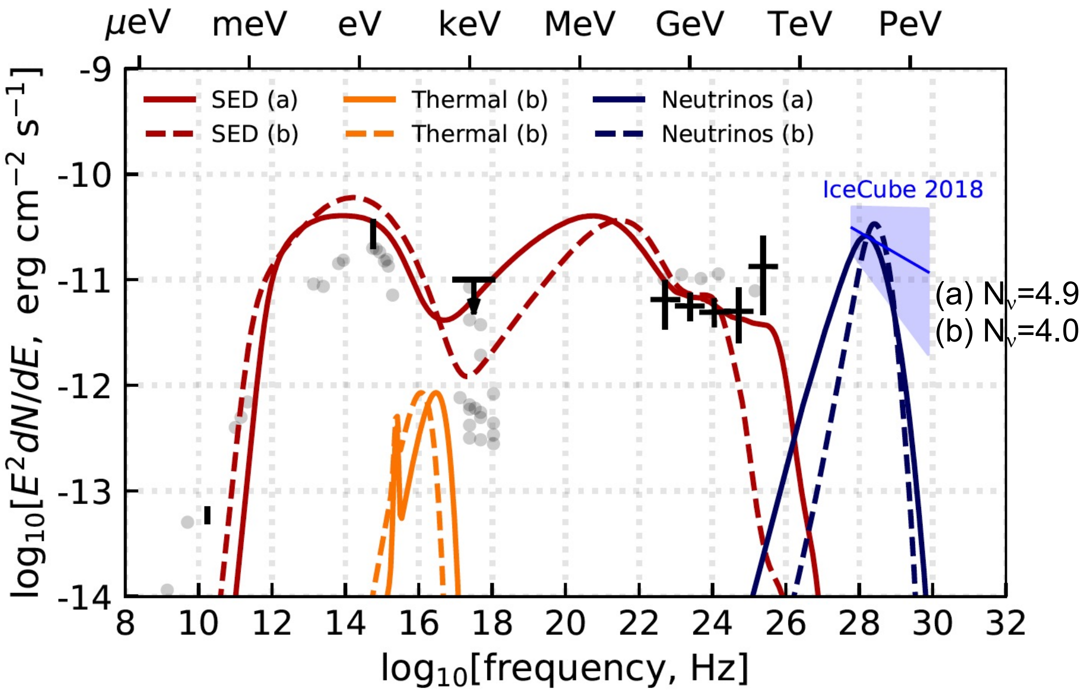
- TXS 0506+056 may be actually an FSRQ
  Padovani et al, MNRAS 484 (2019) L104

- These can be back-scattered into the jet frame. Example:



Courtesy X. Rodrigues

- Results for TXS 0506+056:

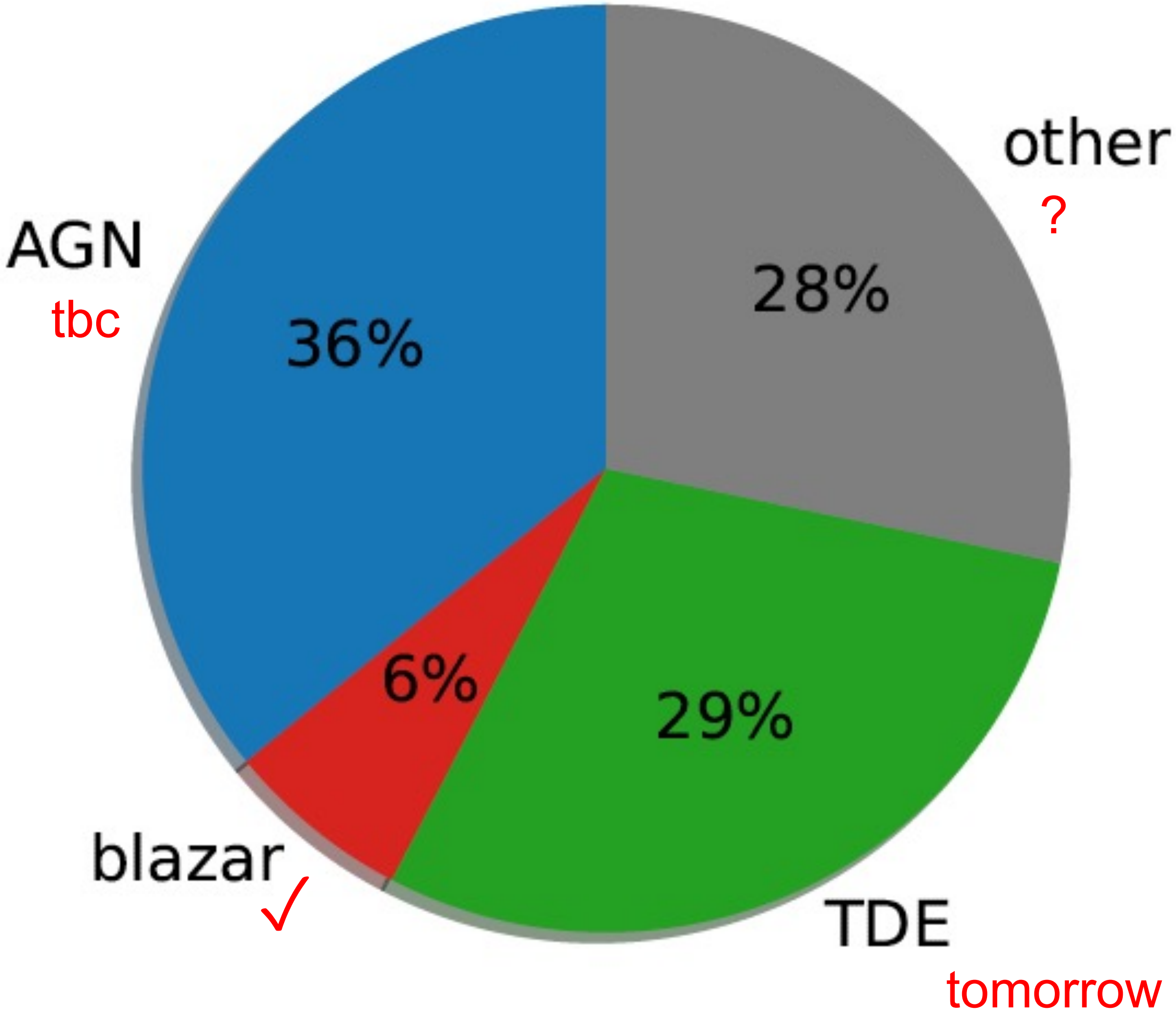


- Maximally five events; may be consistent with IceCube result if different spectral shape is assumed

Rodrigues, et al, ApJL 874 (2019) L29; see also Reimer et al, 1812.05654

Summary (part I)

- Several source associations of neutrinos, and a diffuse flux of astrophysical neutrinos
- AGN blazars established a likely source of neutrinos, but probably not the dominant contribution to the diffuse flux (stacking limit!)
- AGN cores, starburst galaxies possible contenders (abundant, less luminous)
- Better statistics needed for firm conclusions
- Open issue: Galactic sources? Probably to be addressed by KM3NeT/ANTARES in future.



Bartos et al, arXiv:2105.03792