High-energy neutrinos from the cosmos

A theoretical perspective

https://multimessenger.desy.de/

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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- Origin of the diffuse flux
- Particle physics treatment in cosmic acclerators
- A common origin of the diffuse UHECRs and neutrinos?
- Neutrinos from the AGN blazar TXS 0506+056
- Flavor composition ... and particle physics
- Summary and conclusions

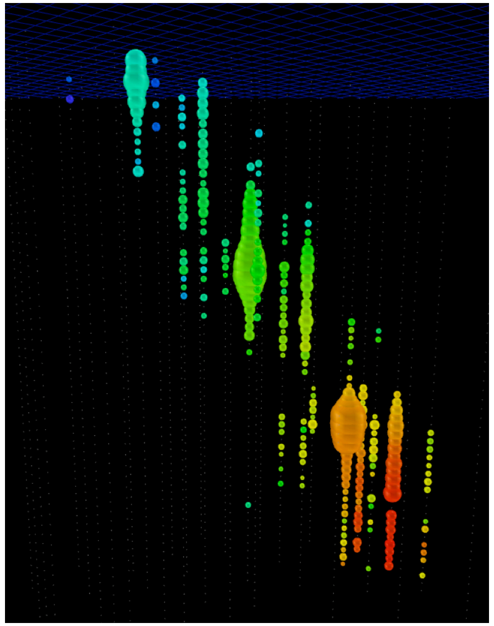
Recent results

A very short experimental summary

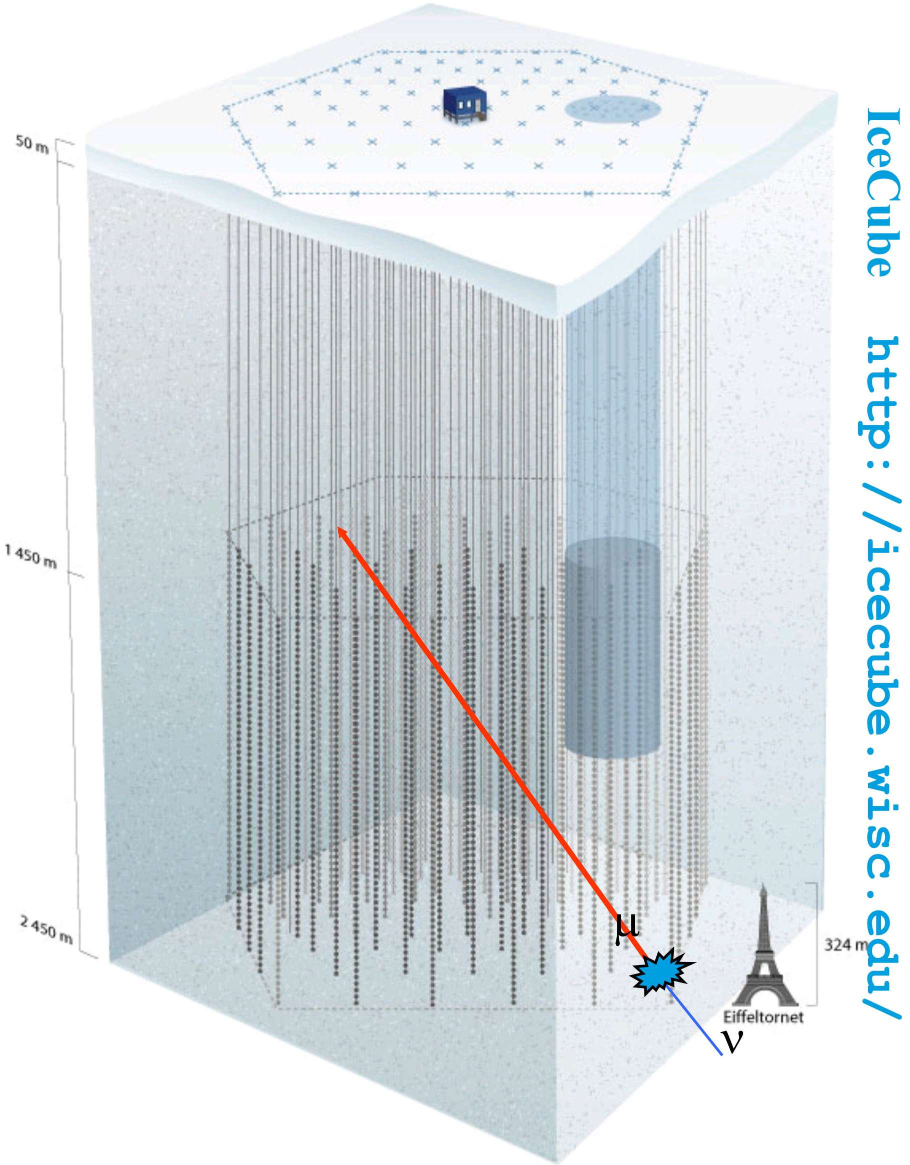
Observing TeV-PeV neutrinos with IceCube

Muon track:

- From ν_μ
- From ν_τ (17 %)

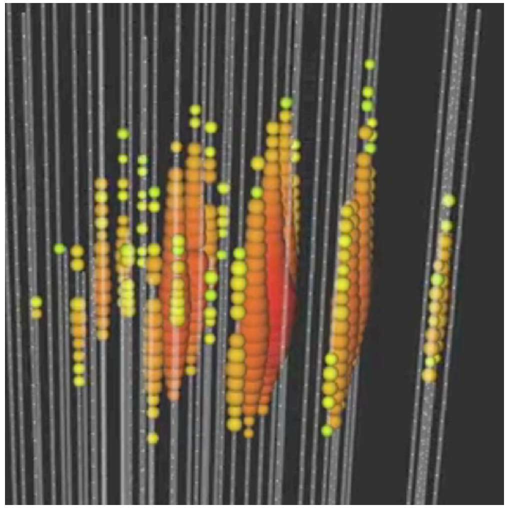


Better directional info



Cascade (shower):

- From ν_e
- From ν_τ
- From ν_e, ν_μ, ν_τ NC interactions



Better energy info

Diffuse neutrino flux – observed in different event samples

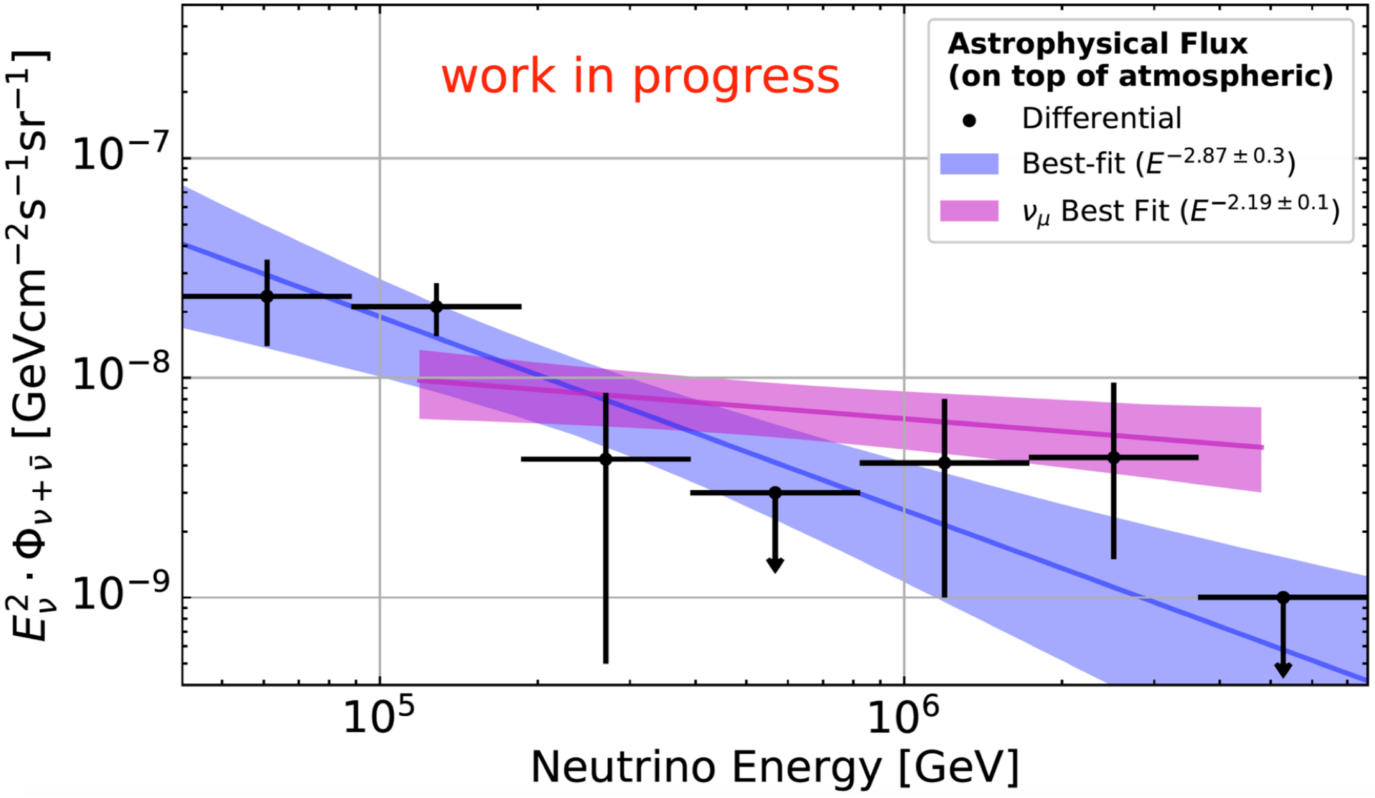
HESE = High Energy Starting Events

Interaction within detection volume

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

Sensitive to both hermispheres, all flavors

Lower energies = contained events



IceCube/Taboada at Neutrino 2018

TGM = Through-going muons

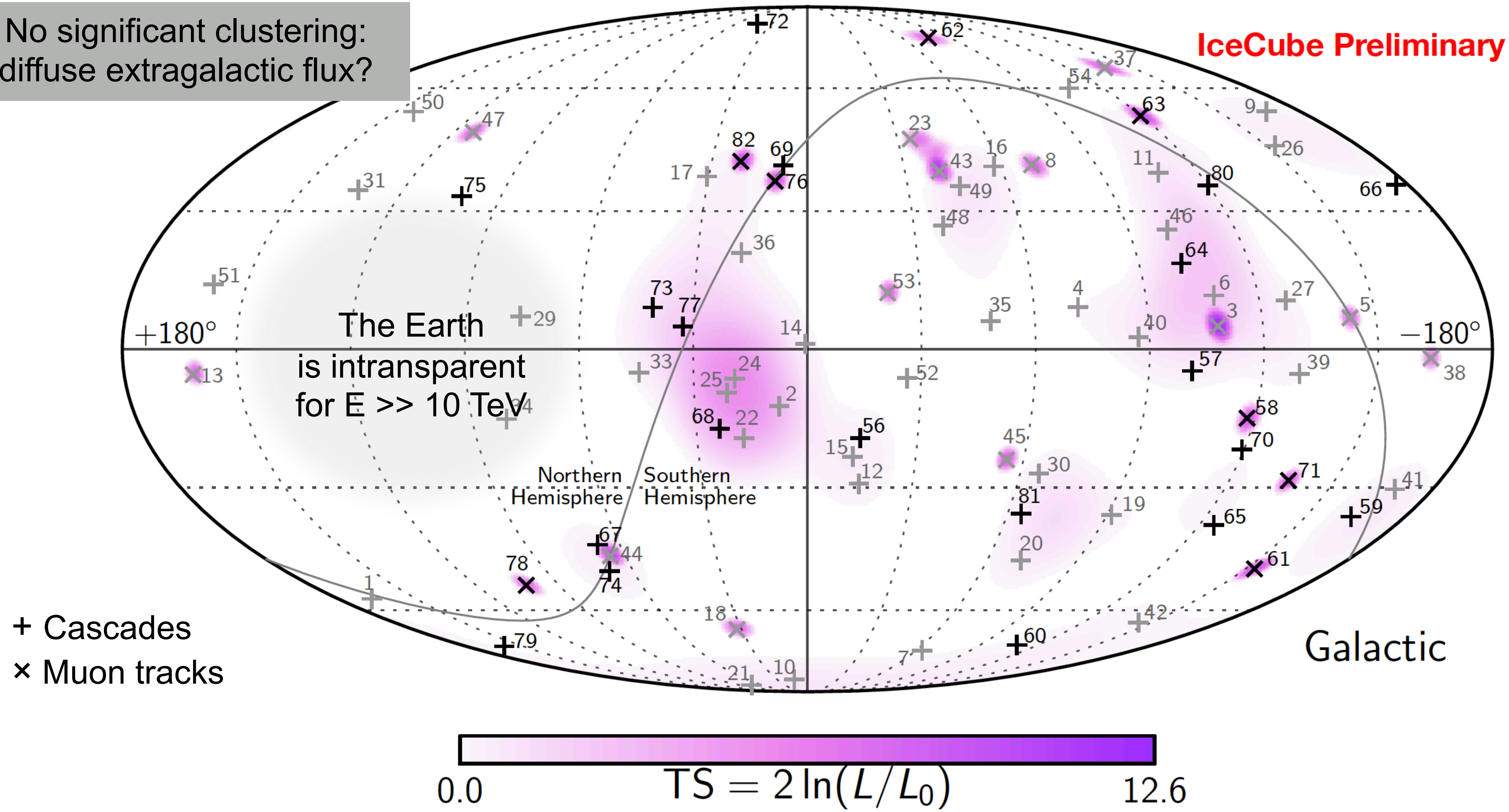
Sensitive to ν_μ only from Northern hemisphere

Large effective volume (interaction may be outside detector)

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

A flux of high energy cosmic neutrinos (HESE sample)

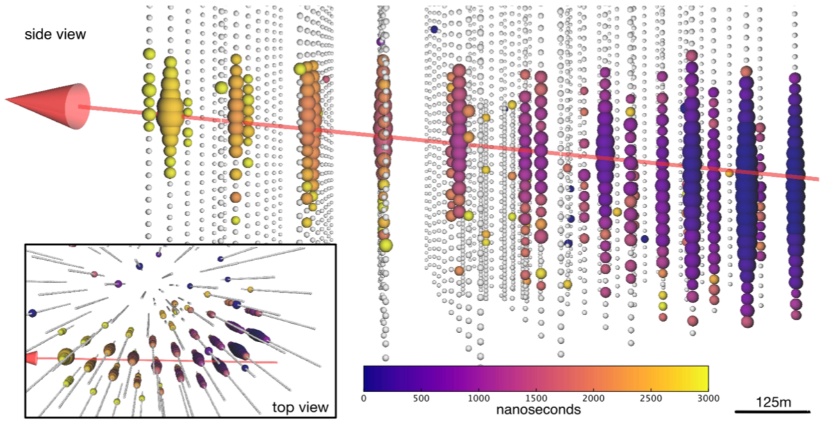
No significant clustering: diffuse extragalactic flux?

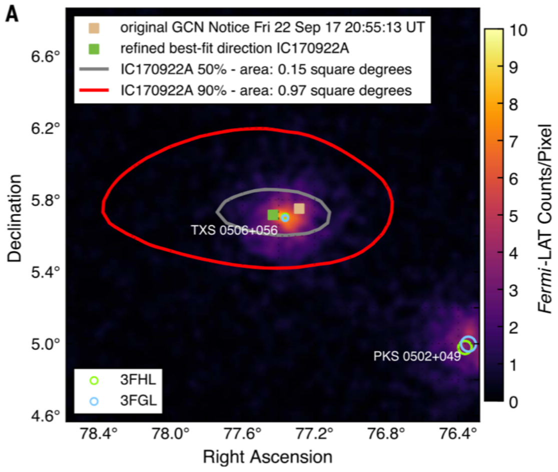


IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); update from Kopper at ICRC 2017; see also Taboada @ Neutrino 2018

Neutrinos from the AGN blazar TXS 0506+056

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



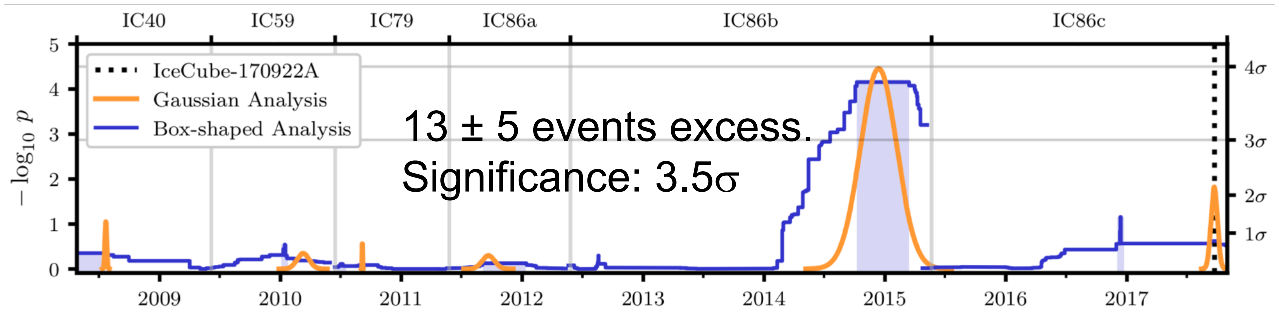


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

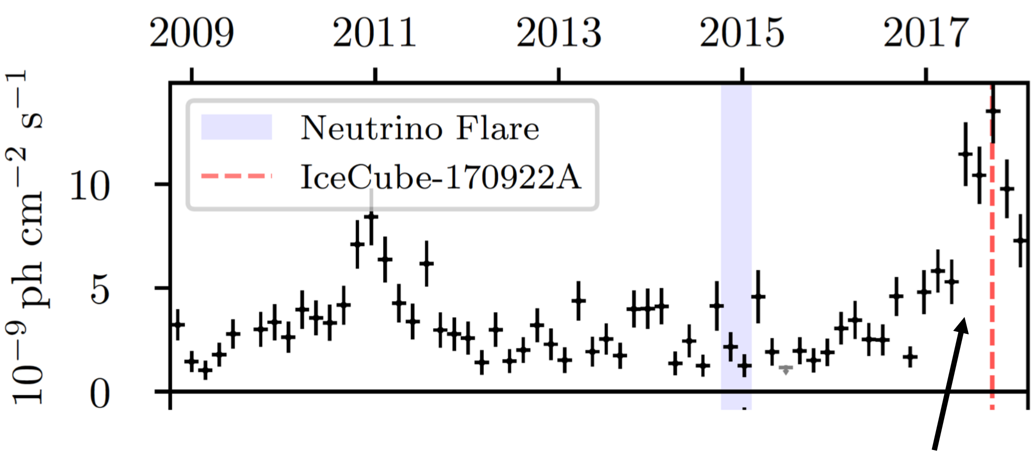
Science 361 (2018) no. 6398, eaat1378

2014-2015: A (orphan) neutrino flare found from the same object in historical data



Science 361 (2018) no. 6398, eaat2890

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



A “flare”

Origin of the diffuse flux?

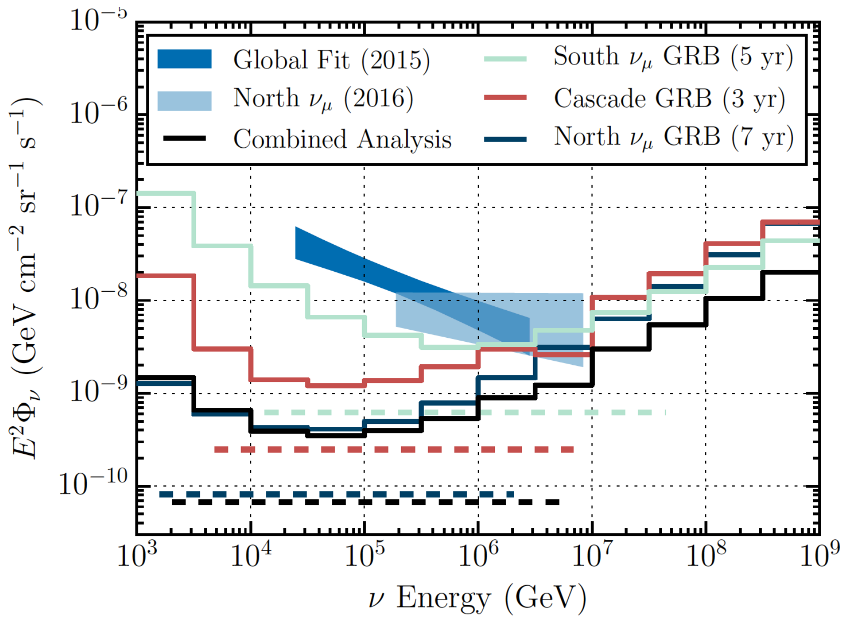
Conceptual issues and astrophysical constraints

Stacking limits ...

... for the most prominent sources populations

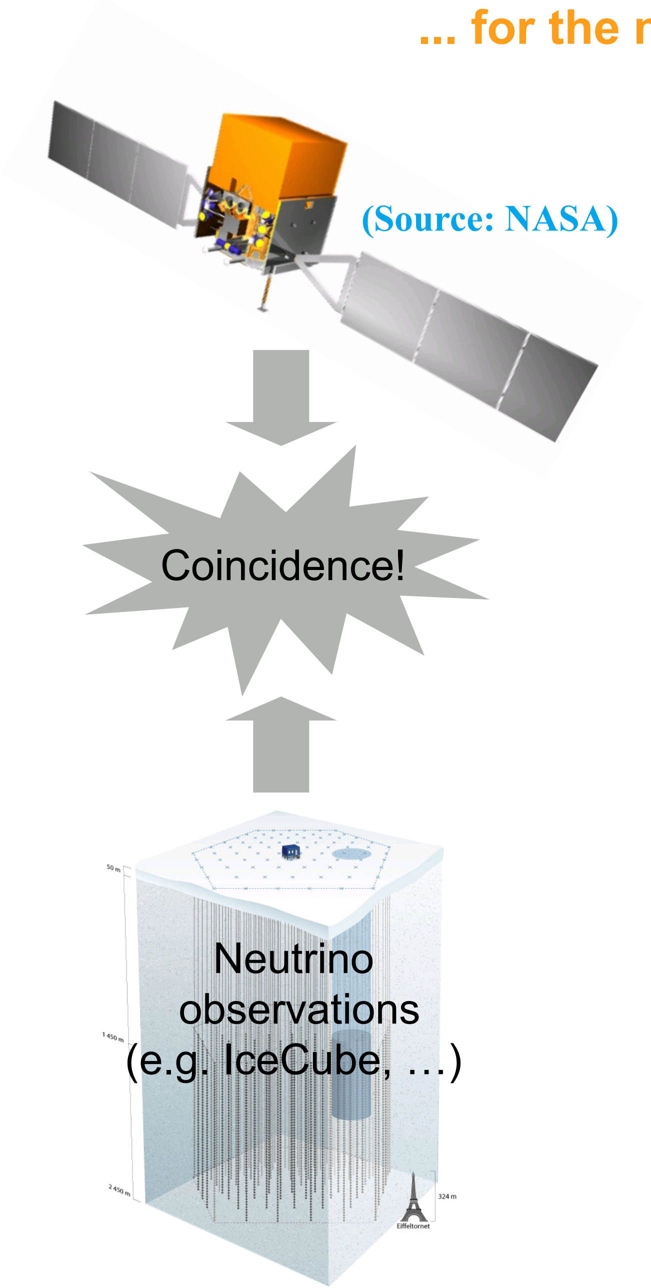
Gamma-Ray Bursts (GRBs)

- Transients, time variability
- High luminosity over short time



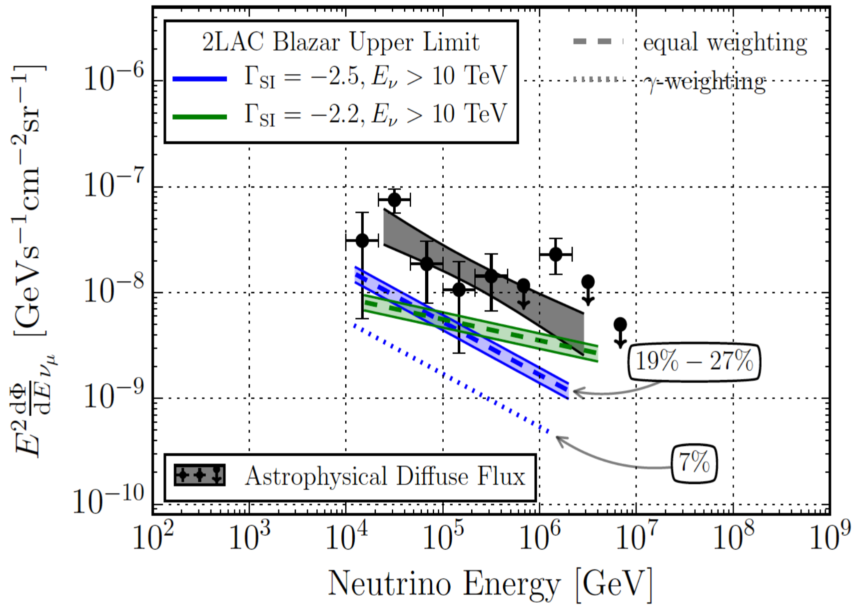
- Less than ~1% of observed ν flux

IceCube, Nature 484 (2012) 351;
Newest update: arXiv:1702.06868



Active Galactic Nuclei (AGNs)

- Steady emission with flares
- Lower luminosity, longer duration



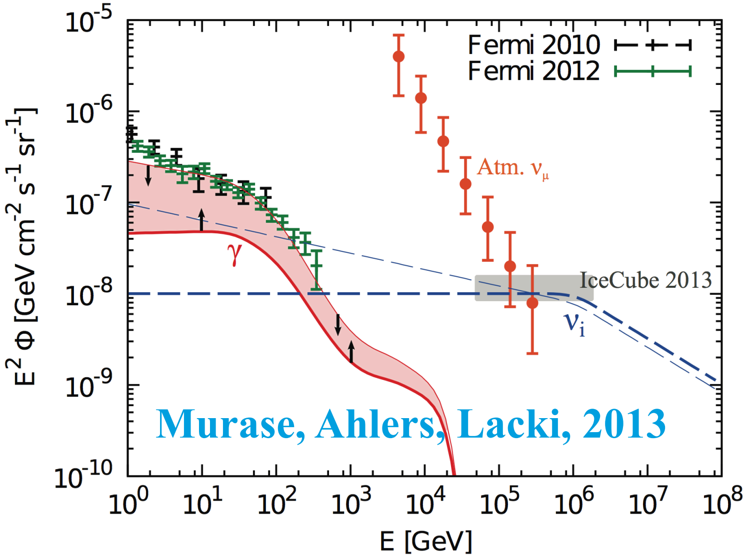
- Less than ~25% of observed ν flux

IceCube, Astrophys. J. 835 (2017) 45
(see proceedings of ICRC 2017 for updates)

Conceptual challenges

Gamma-ray diffuse flux

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



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

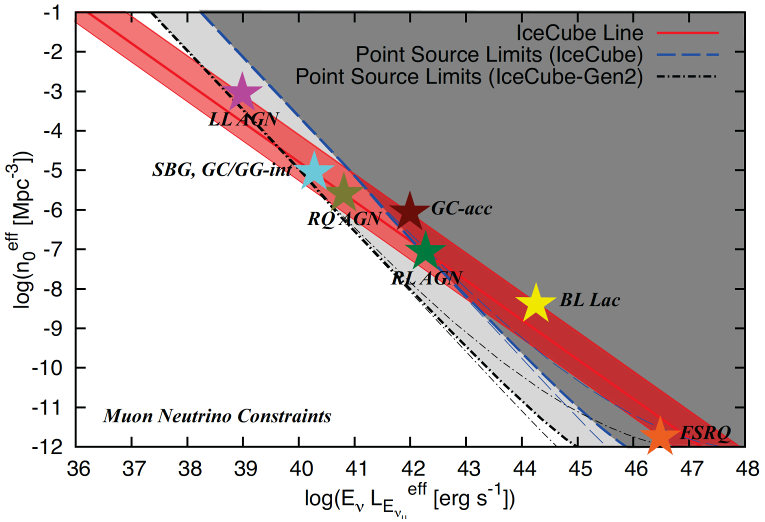


Fig. from Murase, Waxman, 2016;
see Kowalski, 2014; Ahlers, Halzen, 2014;
see also analyses performed by IceCube, arXiv:1807.11492+1811.07979 (somewhat weaker limits)

Other challenges

- Observed TGM flux harder than HESE
- A ν_μ with a reconstructed 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)?

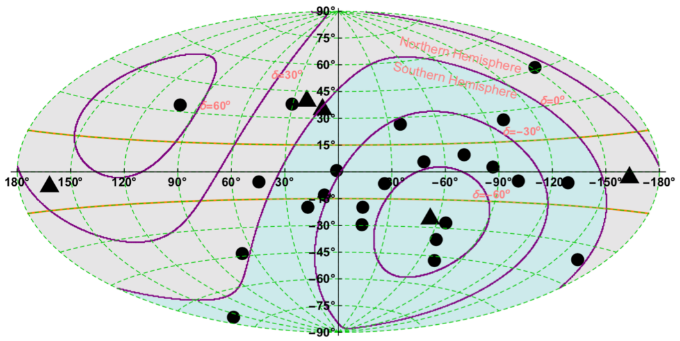
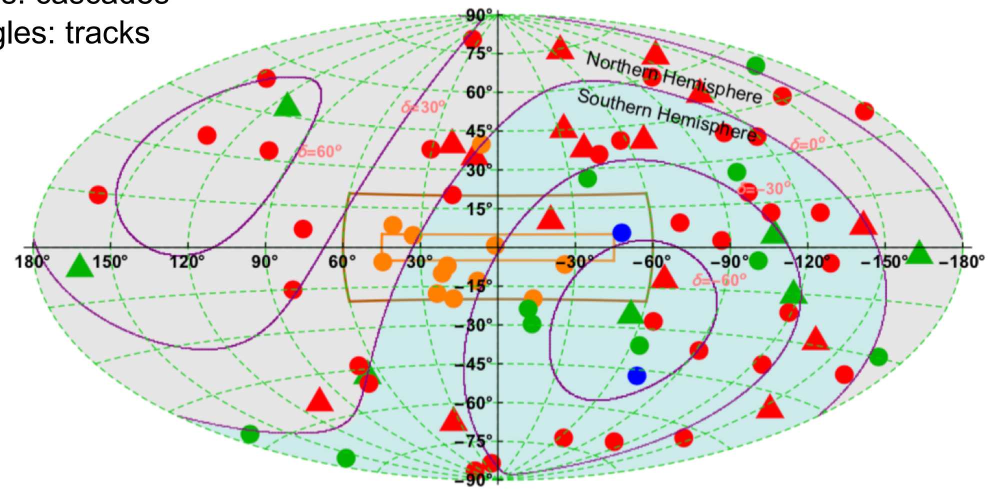


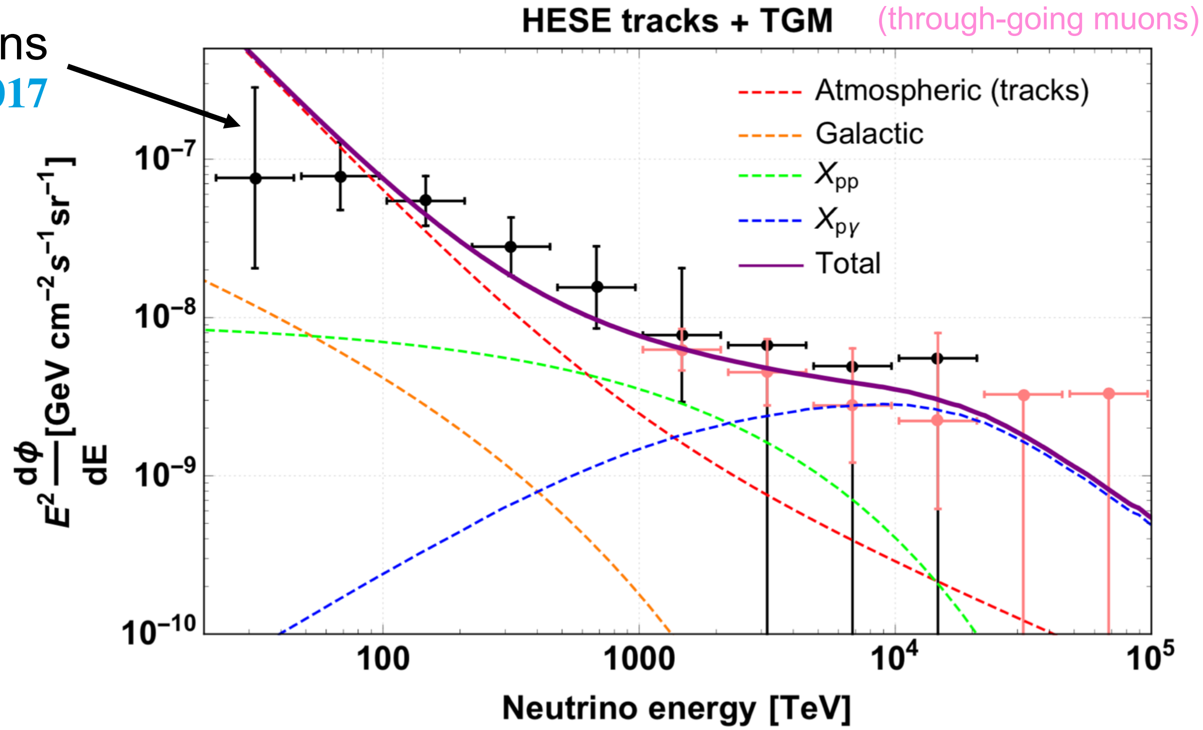
Fig. from: Palladino, Winter, A&A 615 (2018) A168

Multiple contributions to diffuse flux? A possible scenario.

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



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



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 (or Ap) int.
X_{pp}	EXtragalactic neutrinos, e.g. starburst galaxies, ~E^{-2} spectrum (Fermi acc.!)	pp (or Ap) int.
$X_{p\gamma}$	EXtragalactic ν with hard (~ E^{-1}) spectrum; highest E; UHECR connection?	pγ (or Aγ) int.

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

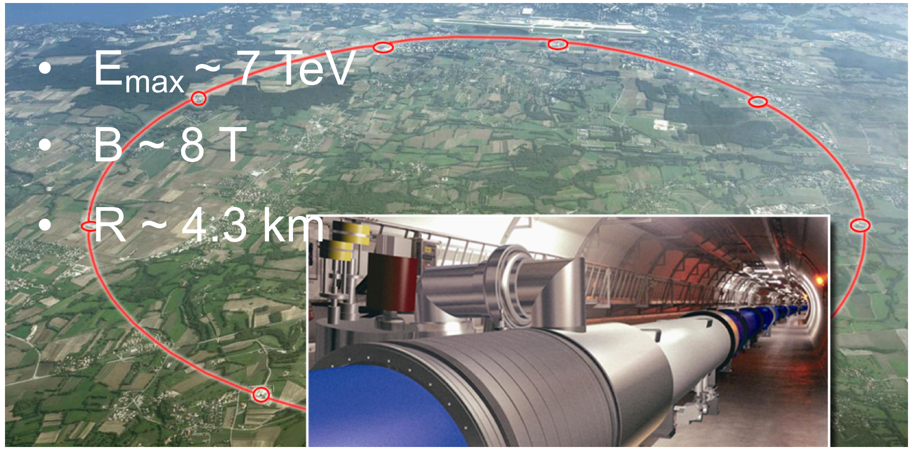
[...]

Extragalactic flux dominant
Low "background" (atm. + Galactic)

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

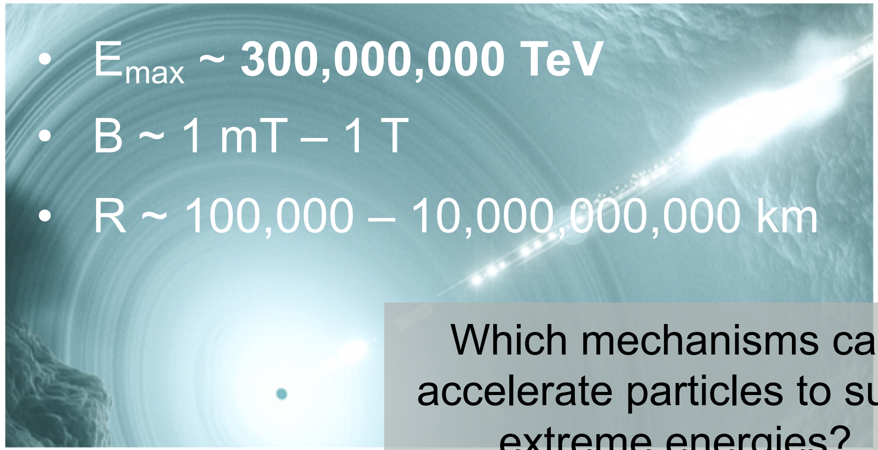
Particle physics treatment in cosmic accelerators

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

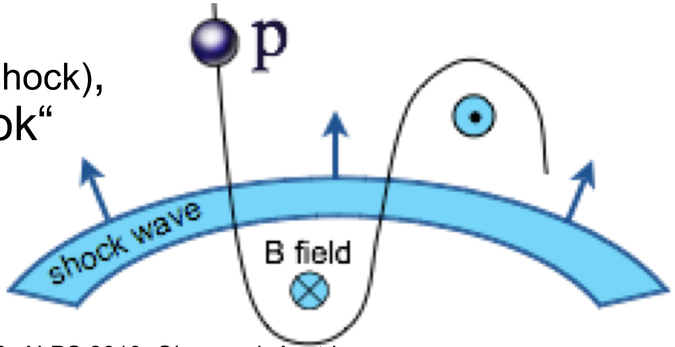


- E_{max} ~ **300,000,000 TeV**
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km

Which mechanisms can accelerate particles to such extreme energies?

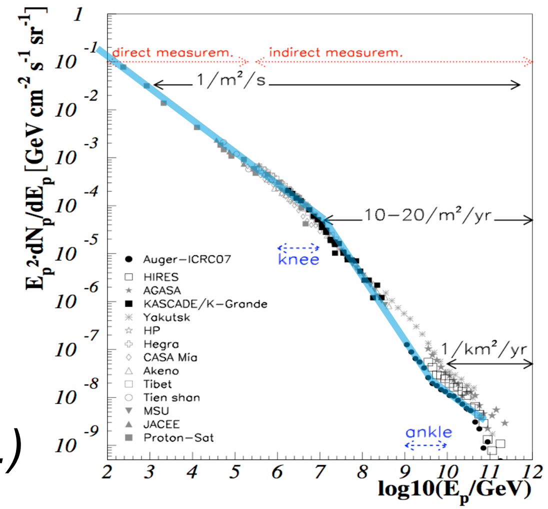
Example: *Fermi shock acceleration*

- 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



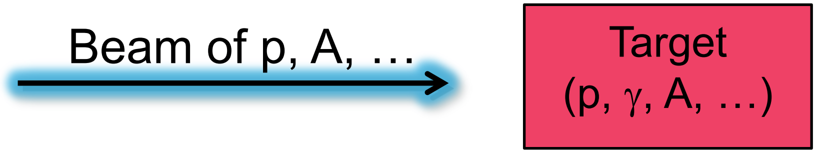
- Theory of acceleration challenging, but we **do observe** power law spectra in Nature

- For multi-messenger perspective: adopt pragmatic point of view!
  (we know that it works, somehow ...)



Secondary production: Particle physics 101?

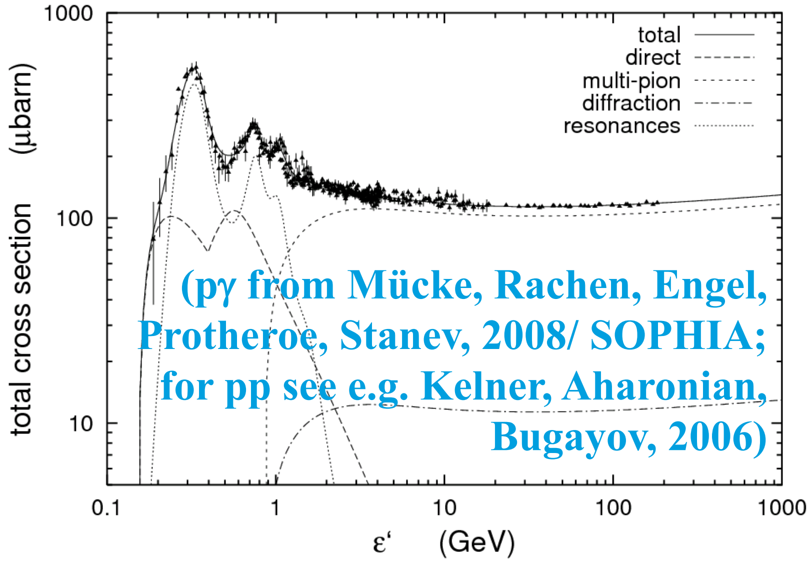
- **Beam dump picture (particle physics)**



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

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

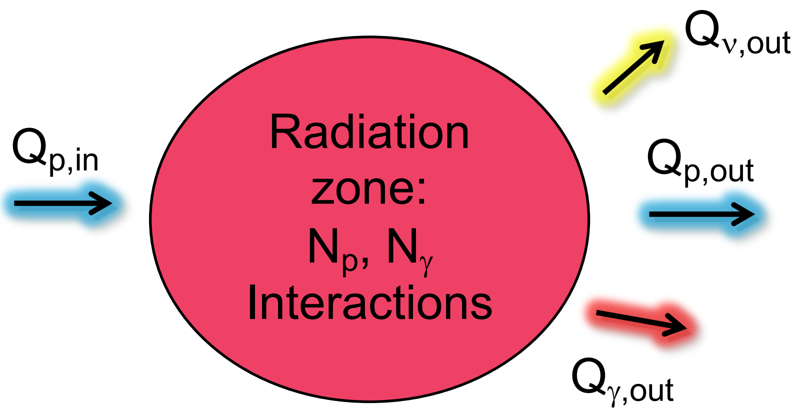
Key challenge: Need volume



(pγ from Mücke, Rachen, Engel, Protheroe, Stanev, 2008/ SOPHIA; for pp see e.g. Kelner, Aharonian, Bugayov, 2006)

(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



Global radiation models (theory)

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

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

Cooling (continuous) | Escape | Injection

"radiation processes"

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

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

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

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

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

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

→ Re-distribution function narrow + peaked

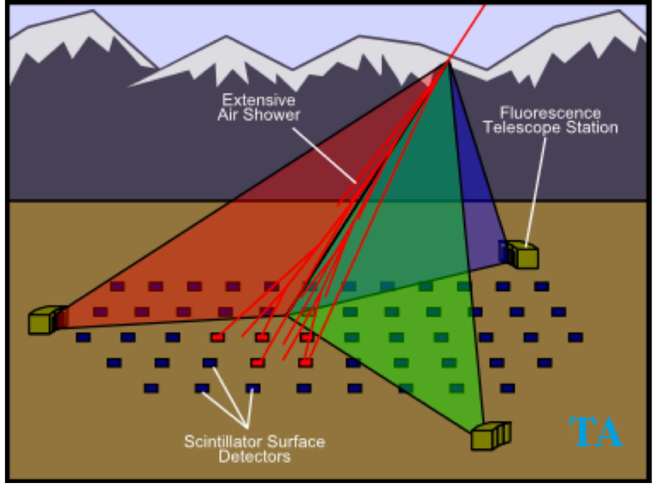
E.g. $E_\nu \sim 0.25\, E_\pi \sim 0.25 \times 0.2 \times E_p = 0.05\, E_p$

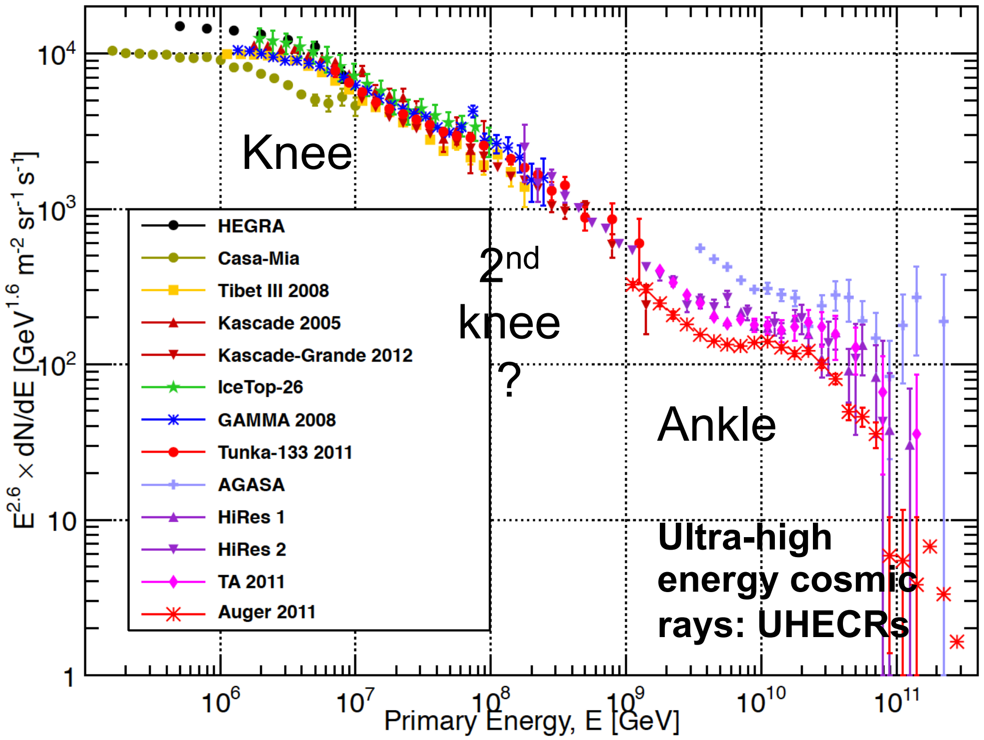
A common origin of the diffuse UHECRs and neutrinos?

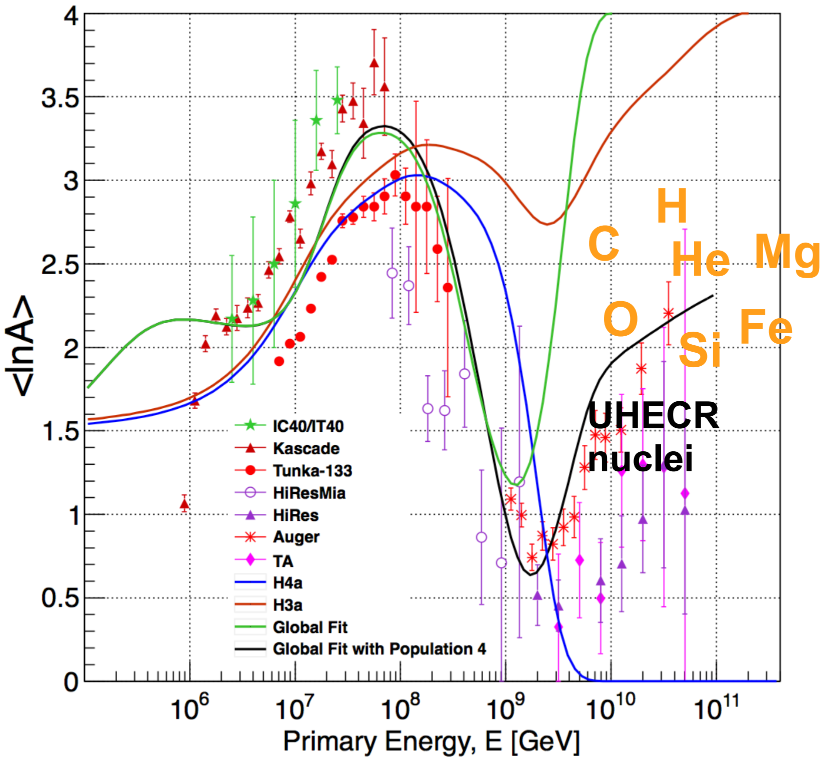
UHECRs = Ultra High-Energy Cosmic Rays > 10^{18} eV

Cosmic rays: Spectrum and composition

- Charged particles, proton or heavier nuclei
- Extragalactic origin at highest energies (just as neutrinos); transition energy to Galactic contribution subject to discussion
- Composition probably heavy (= no pure protons) at highest energies (Auger)







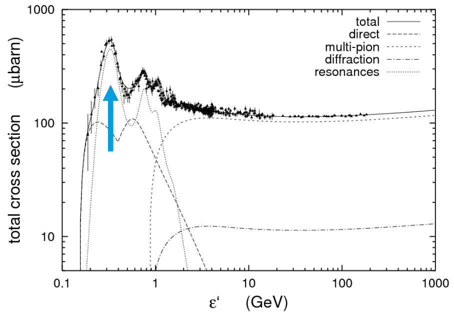
Gaisser, Stanev, Tilav, 2013

Multi-messenger connection in photohadronic models

- Neutrino peak determined by maximal cosmic ray energy
- UHECR connection typically implies
  high neutrino energy peak energy >> 10^6 GeV →
- Interaction with target photons
  (Δ-resonance approximation for C.O.M. energy):

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

E_γ [keV] ~ $0.01\ \Gamma^2/E_\nu$ [PeV]
keV energies interesting!

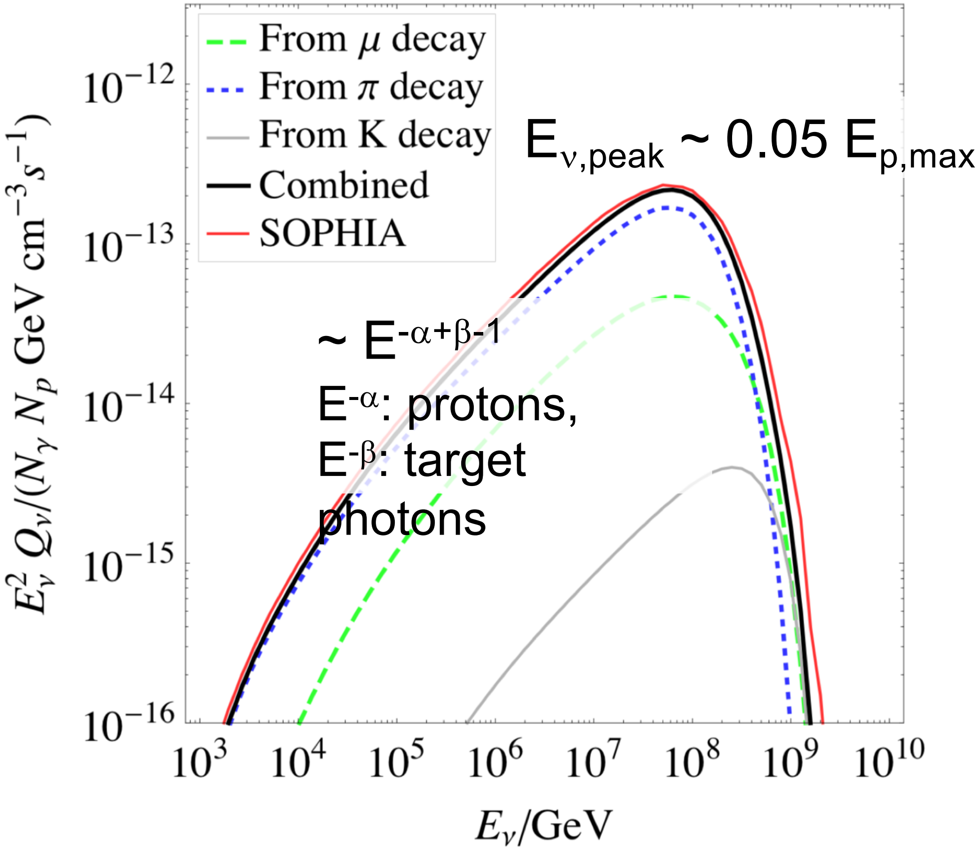


- Photons from pion decay:

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

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

AGN neutrino spectrum (example)



From: Hümmer et al, Astrophys. J. 721 (2010) 630

Decouple the maximal UHECR and neutrino energies?

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

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

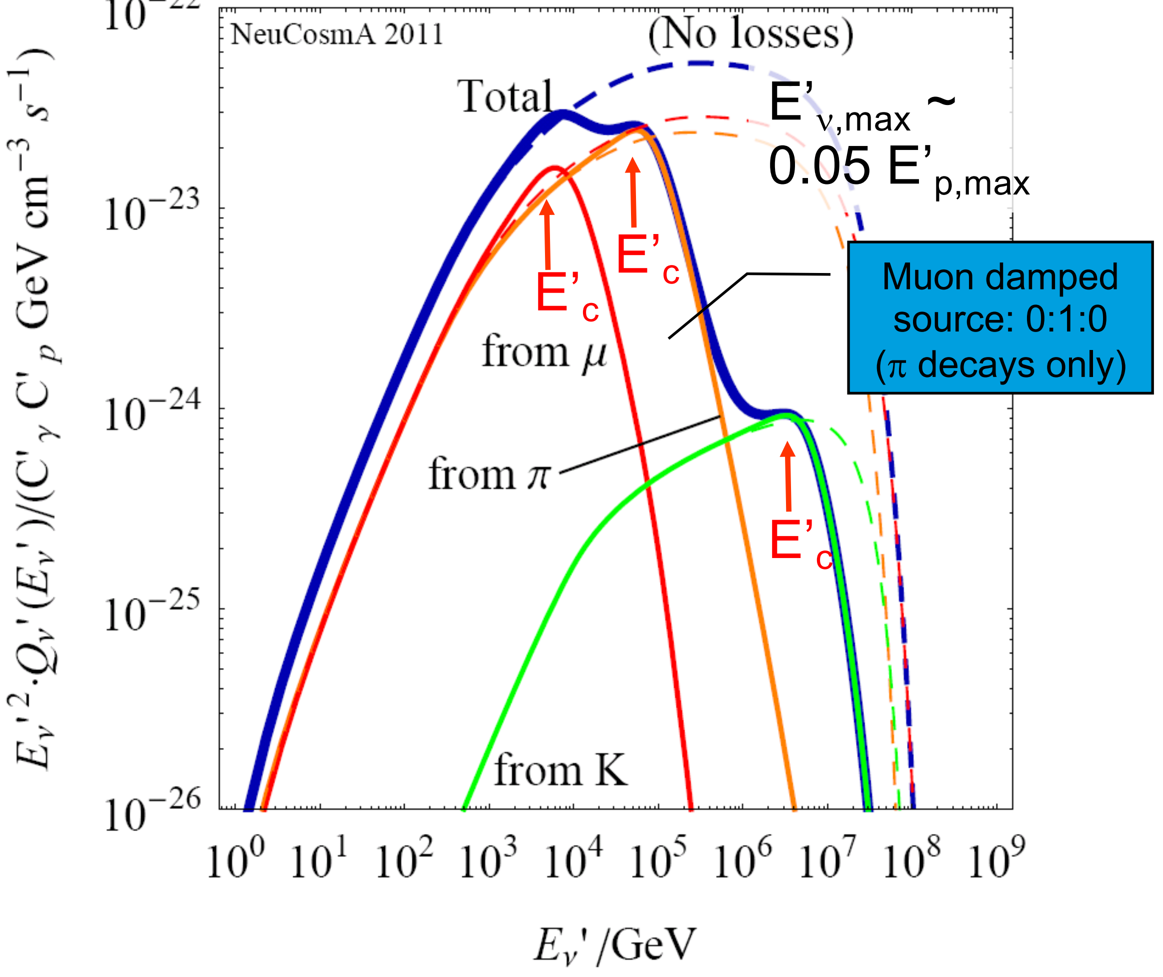
- Spectra (μ, π, K) energy loss-steepend above critical energy
(synchrotron cooling faster than decay)

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

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

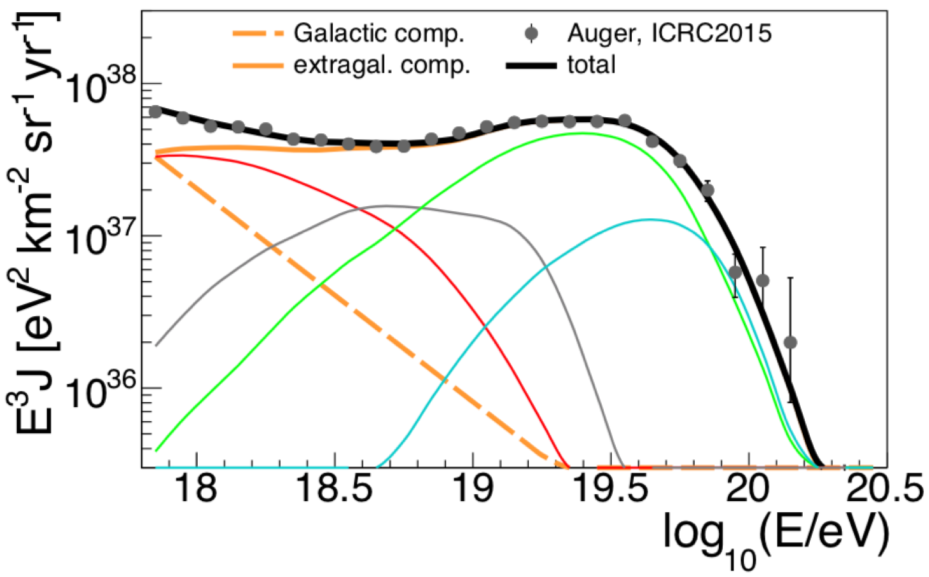
- Points towards sources with strong enough B':
Gamma-Ray Bursts, (jetted)
Tidal Disruption Events, ...

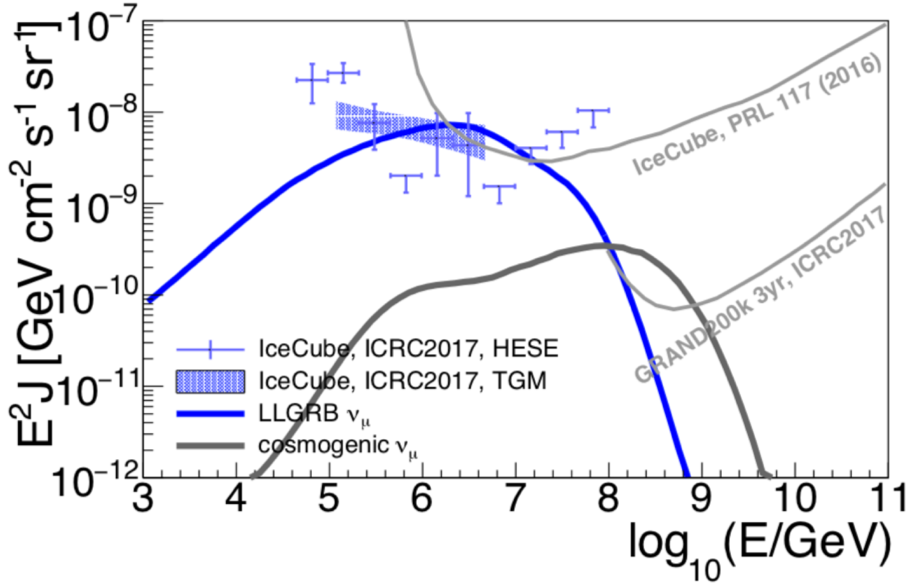
Example: GRB

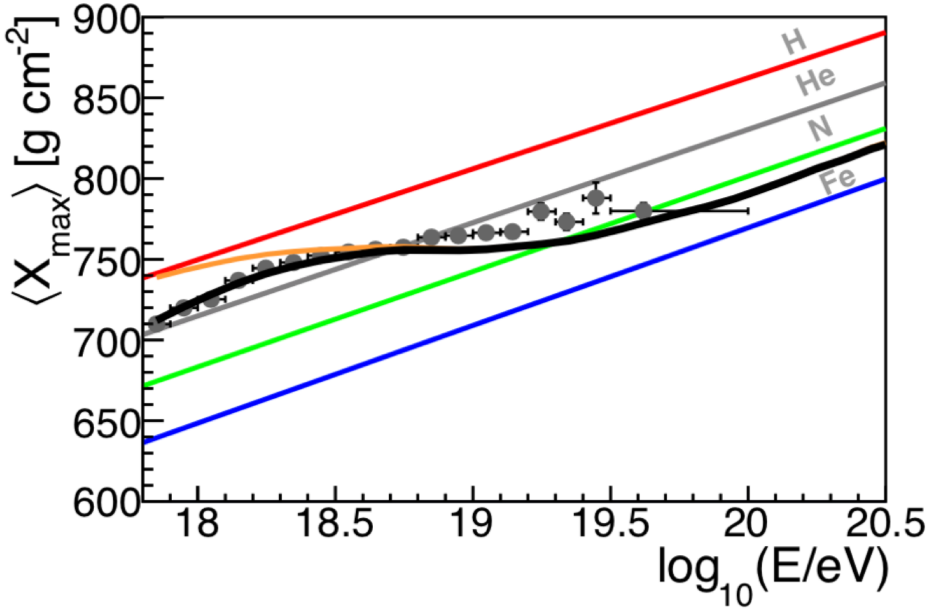


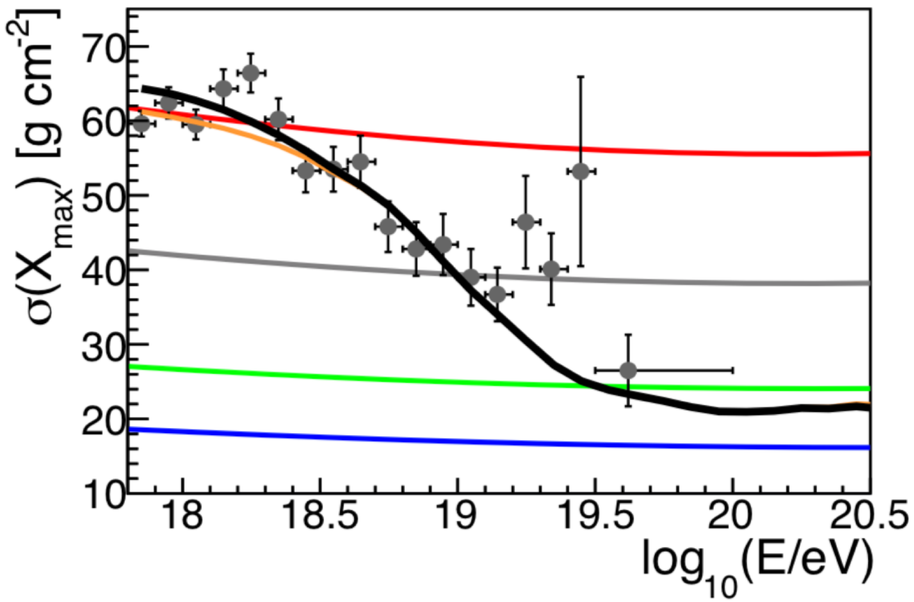
Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508;
also: Kashti, Waxman, 2005; Lipari et al, 2007; ...

Example: low-luminosity Gamma-Ray Bursts (LL-GRBs as $X_{p\gamma}$)









Boncioli, Biehl, WW, ApJ 872 (2019) 110, arXiv:1808.07481;

injection composition and escape from Zhang et al., PRD 97 (2018) 083010;

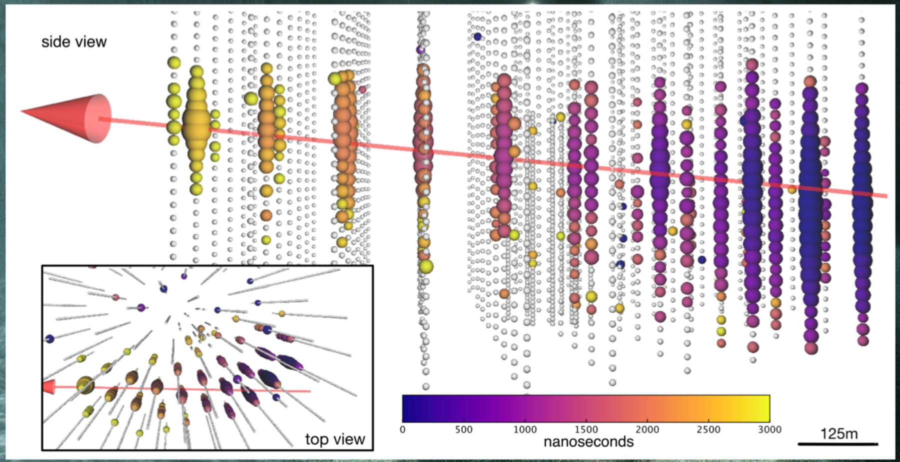
similar example (neutrinos-UHECRs): Tidal Disruption Events in Biehl, Boncioli, Lunardini, WW, Sci. Rep. 8 (2018) 10828

Neutrinos from the AGN blazar TXS 0506+056

A new era in multi-messenger astronomy?

AGN blazar

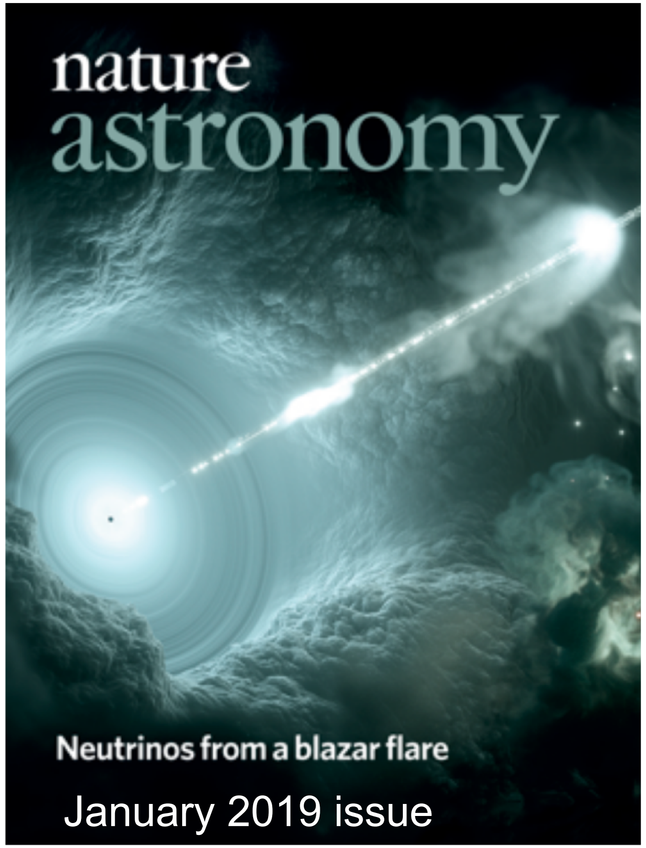
Science 361 (2018) no. 6398, eaat1378

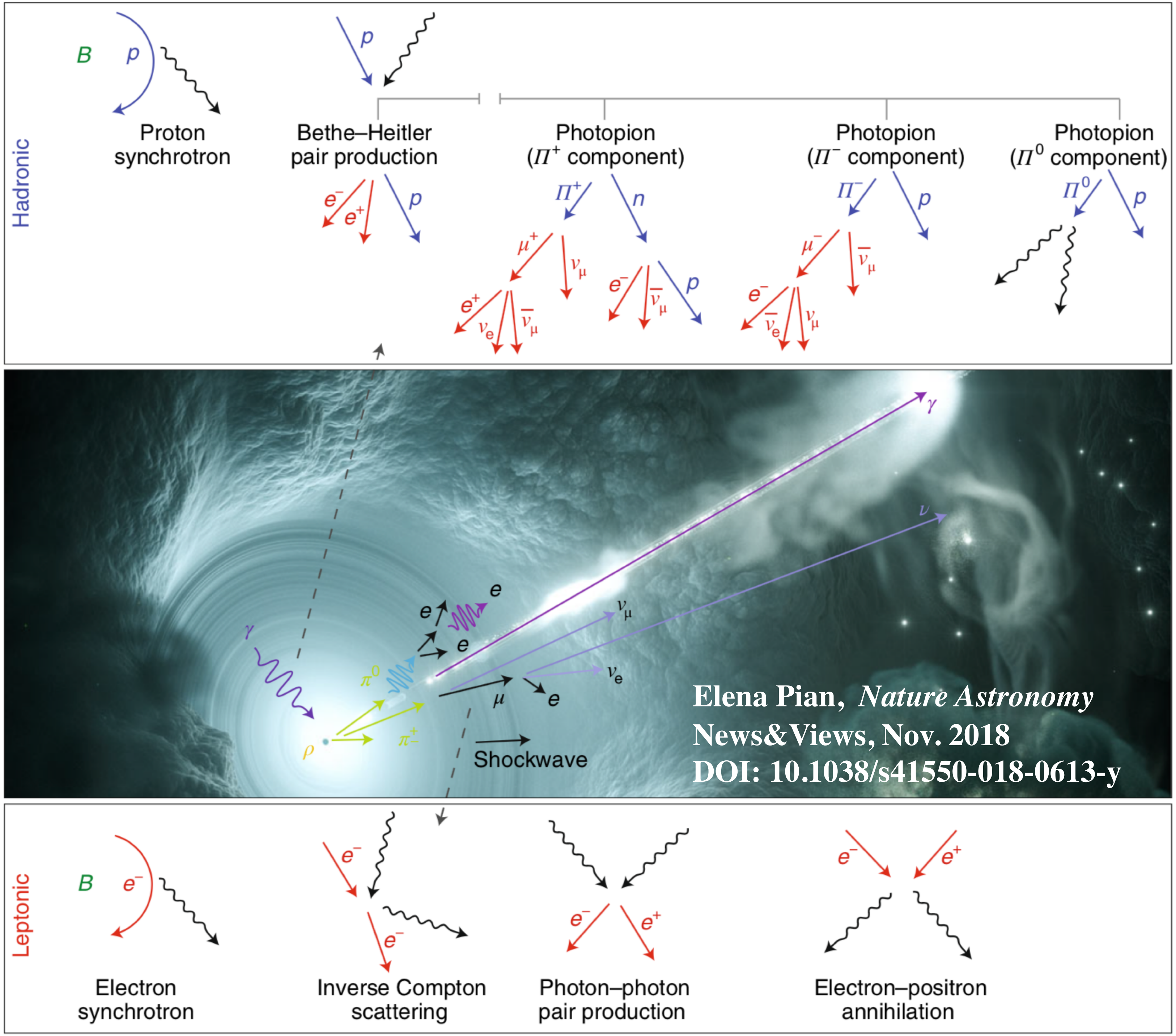


https://multimessenger.desy.de/

Multi-messenger-multi-wavelength radiation models

- Requires solving a coupled PDE system for all involved species (e^+, e^-, p, γ, ...)

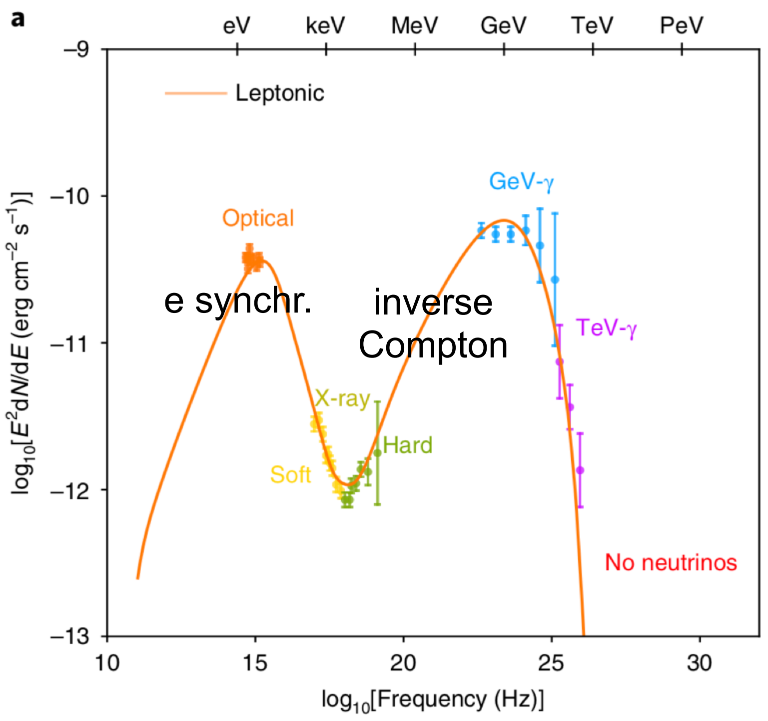




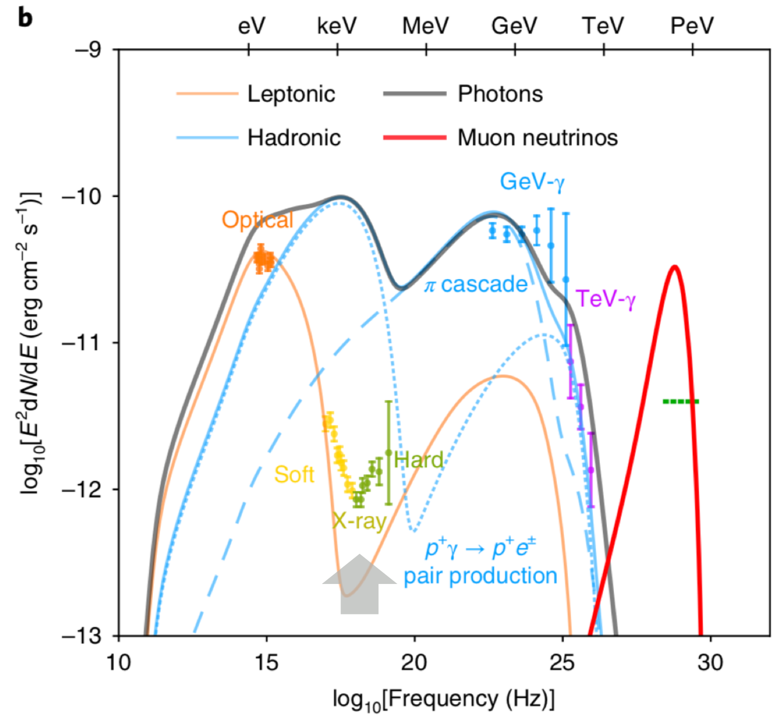
Conventional one zone model results

One radiation zone → R'

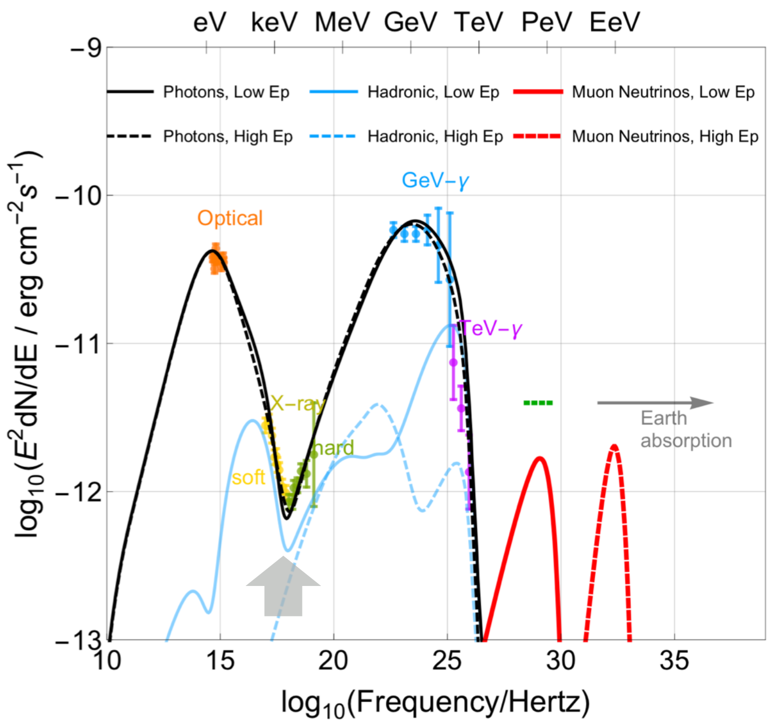
Leptonic models



Hadronic (π cascade) models



Hybrid or p synchr. models

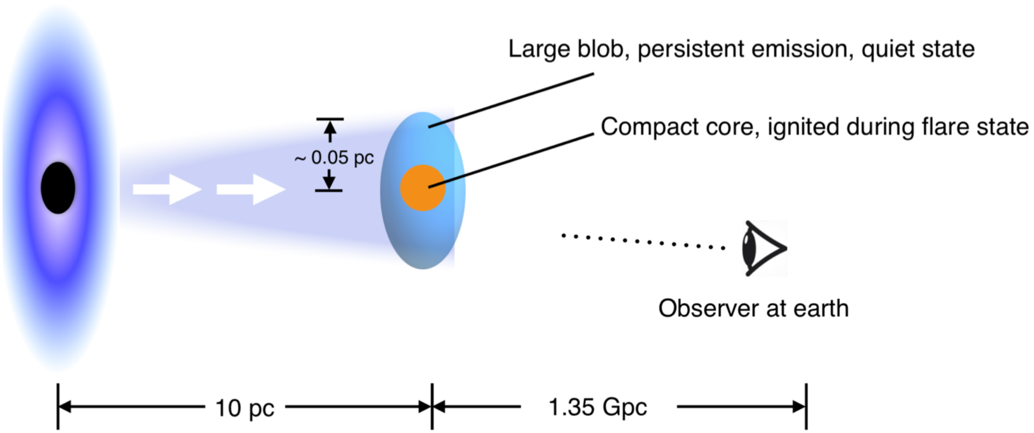


- No neutrinos
- Violate X-ray data
- Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy

Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88*

See also Keivani et al, 2018; Sahakyan, 2018; Gokus et at, 2018; MAGIC collaboration, 2018; Cerutti et al, 2018; Murase et al, 2018; Padovani et al, 2018; Zhang, Li, 2018; Liu et al, 2018; He et al, 2018; Righi, Tavecchio, Inoue, 2018 for similar conclusions/alternatives

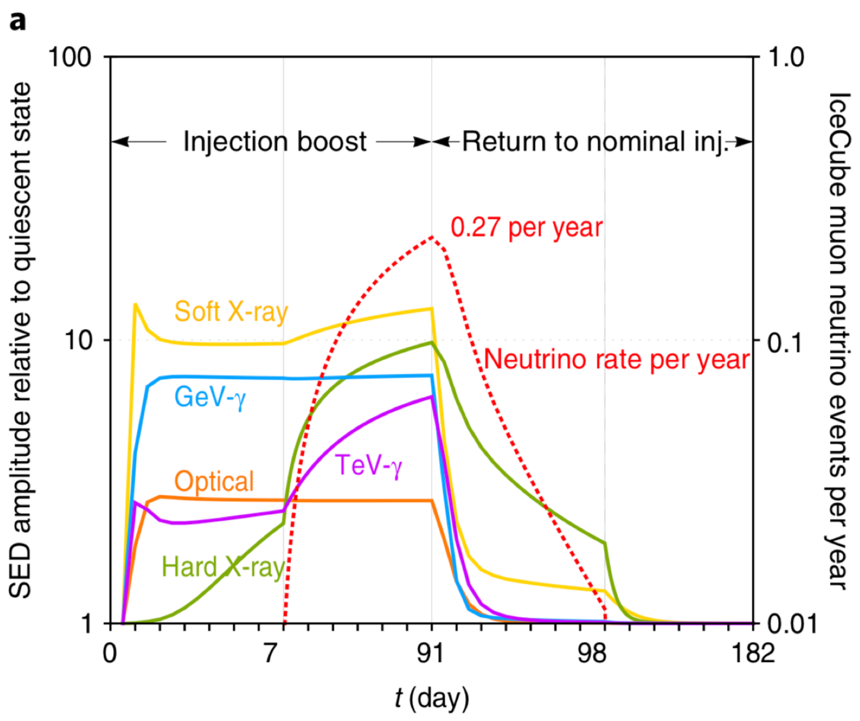
One way out: A compact core model

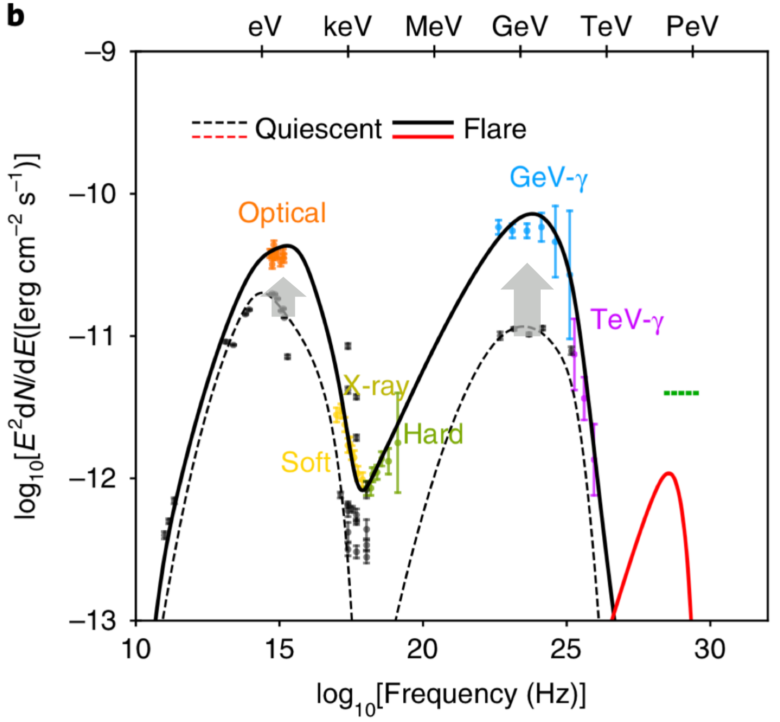


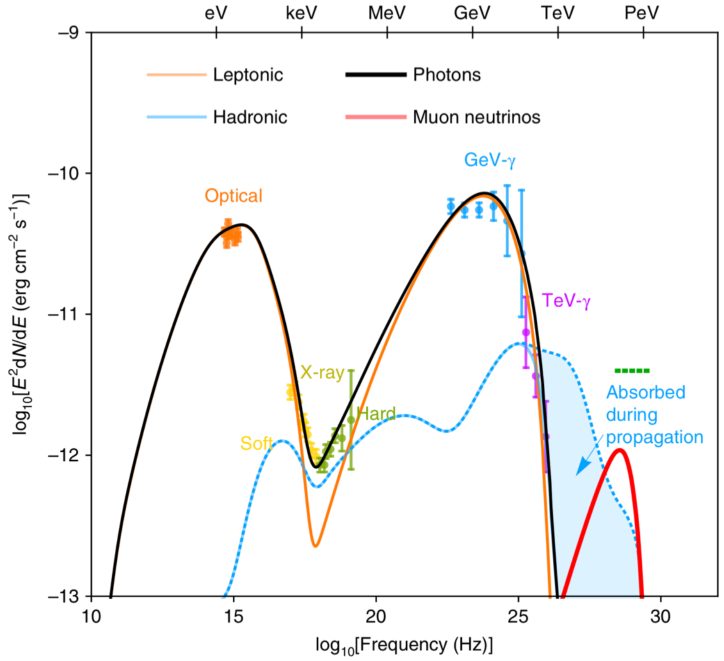
Time-dependent model:

- Formation of a compact core (size: 1/30 of blob)
- Significantly higher proton injection (factor 15)
- Increase of B-field, different properties of electron spectrum

Other alternatives: External radiation fields, hadronuclear interactions

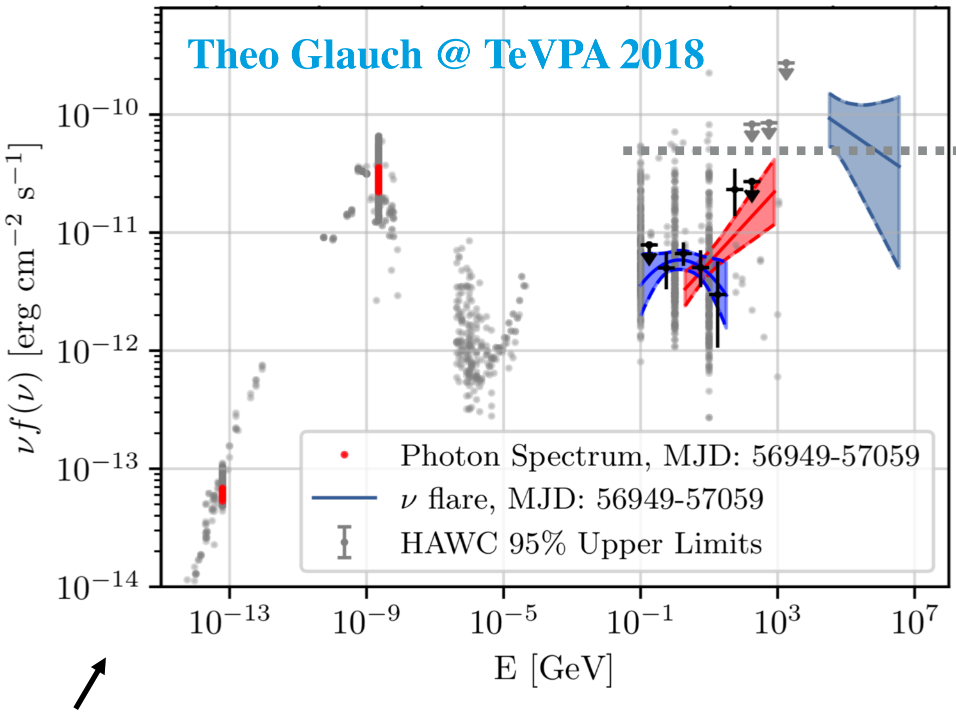






Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88*

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



Theoretical challenge: Where did all the energy go to?

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

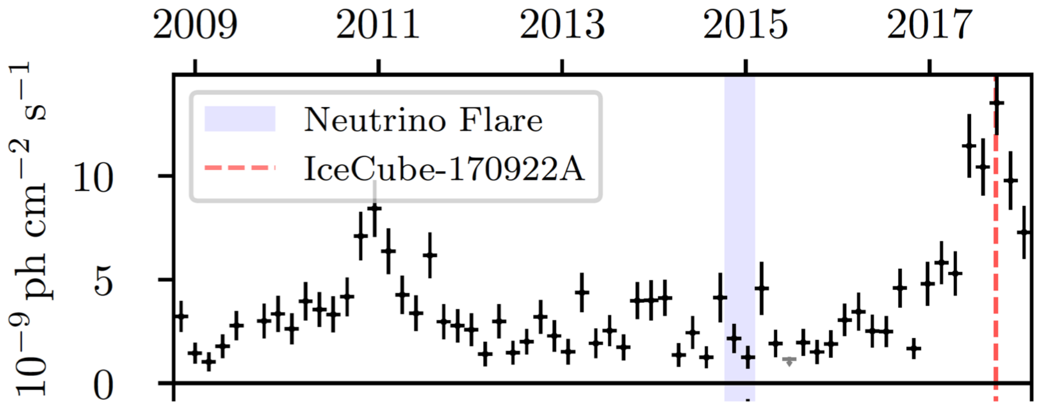
Comparable amounts of energy

Options:

- Reprocessed and "parked" in E ranges without data?
- Leave source + dumped into the background light?
- Absorbed in some opaque region, e.g. dust/gas?

- Electromagnetic data during neutrino flare sparse (colored)
- Hardening in gamma-rays? (red shaded region)
- But: overall, no significant electromagnetic flare →

Padovani et al, 2018; Garrappa et al @ Fermi 2018 + arXiv:1901.10806



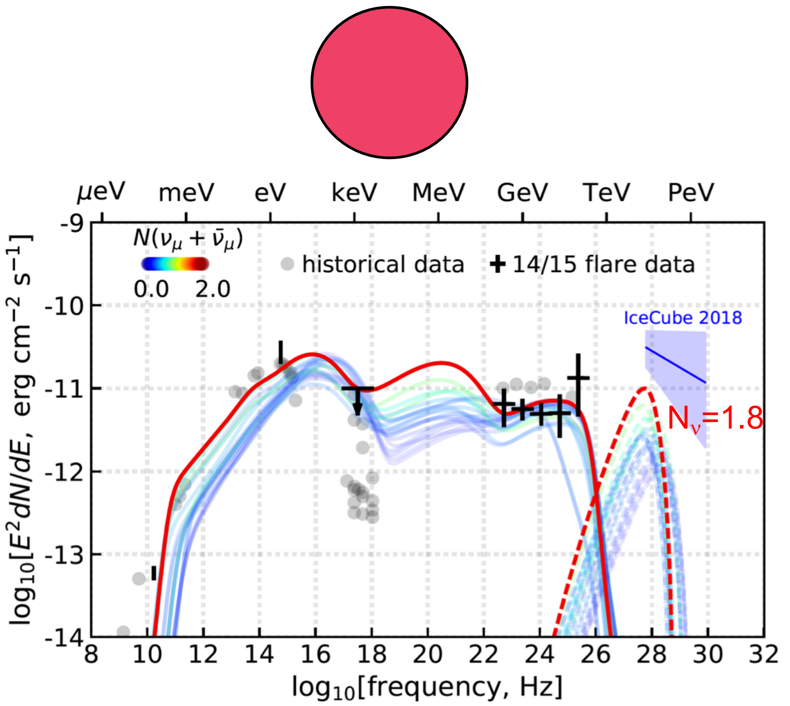
Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192

- Different origin of neutrino signal?
  Jet-cloud/star interaction? Neutron beam? Wang et al, 2018; He et al, 2018; Murase et al, 2018

Radiation models for the historical neutrino flare

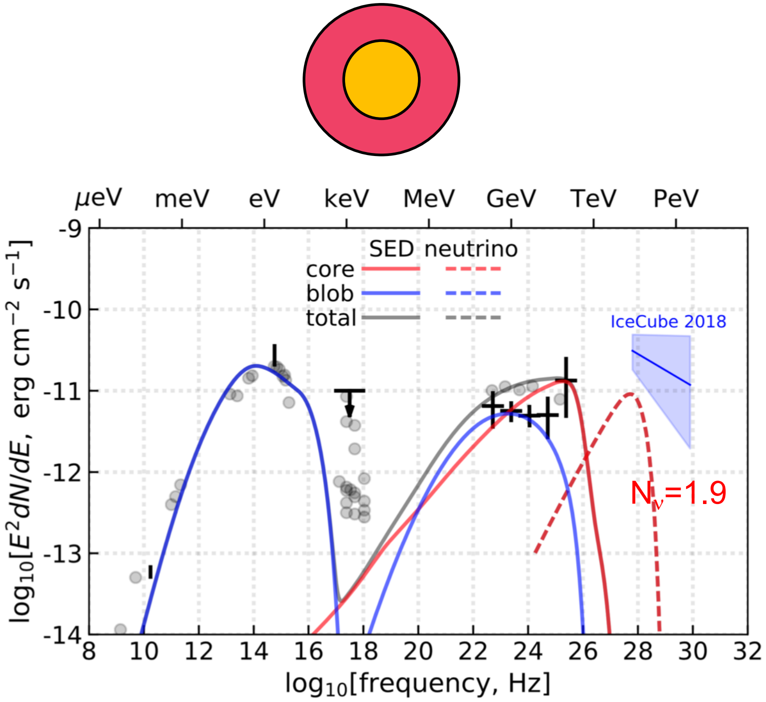
... yield at most 2-5 neutrino events without EM signature; sensitive to X-ray and VHE gamma-ray data

One zone model



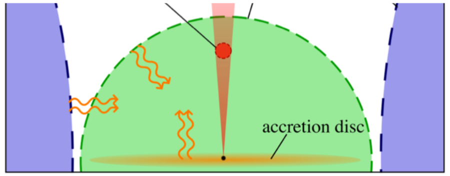
- Saturates X-ray constraint
- EM cascade hidden in MeV bump

Compact core model

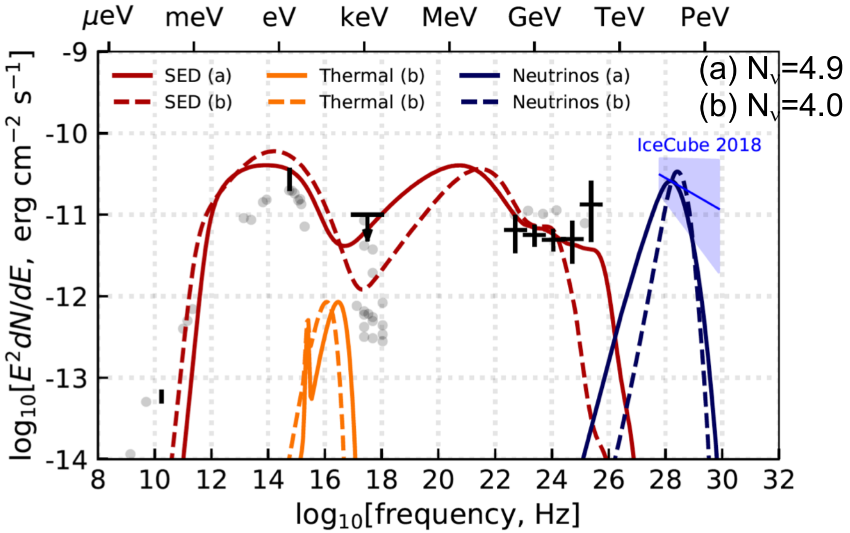


- Optical and gamma-ray emissions from different regions
- Gamma-ray hardening

External radiation field model



~colliding beams



- Spectral softening/gamma-ray absorption at highest energies
- Complicated emission spectrum

Rodrigues, WW, et al, arXiv:1812.05939, ApJL 874 (2019) L29; see also Halzen, et al, arXiv:1811.07439; Reimer et al, 1812.05654

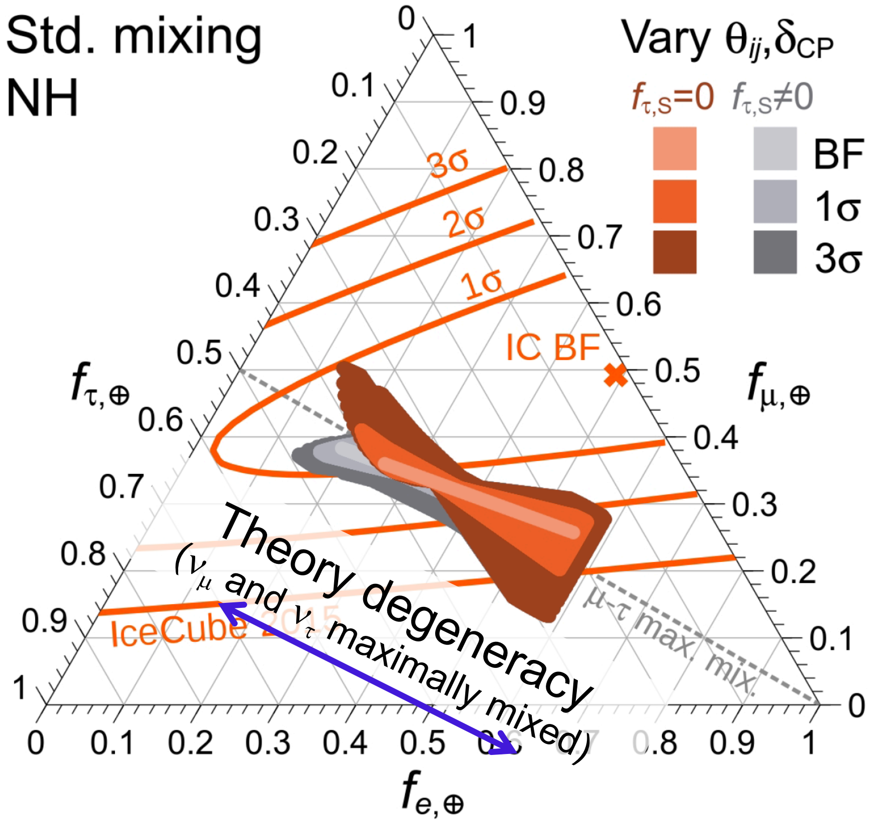
Flavor composition

... and particle physics

Flavor composition in terms of *flavor triangles*

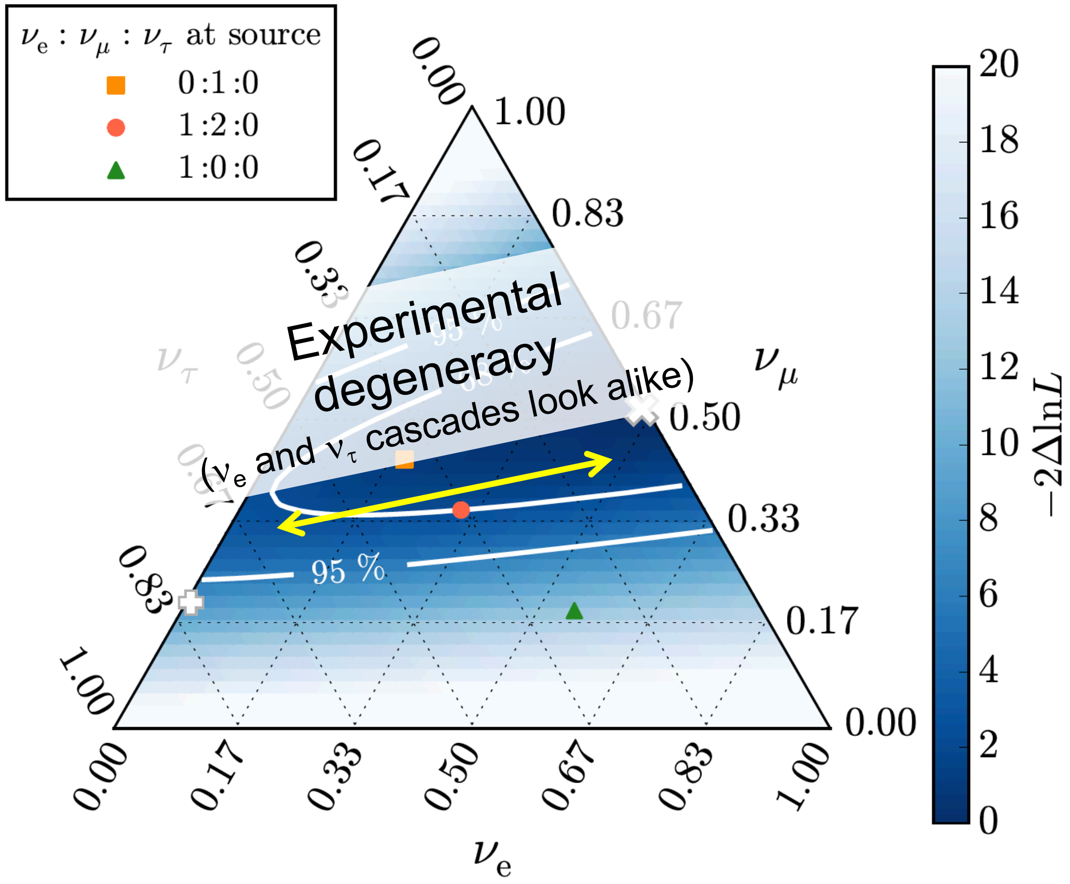
SM expectation

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$



Bustamante, Beacom, Winter, PRL 115 (2015) 16, 161302;
Arguelles, Katori, Salvado, PRL 115 (2015) 161303

Measurement

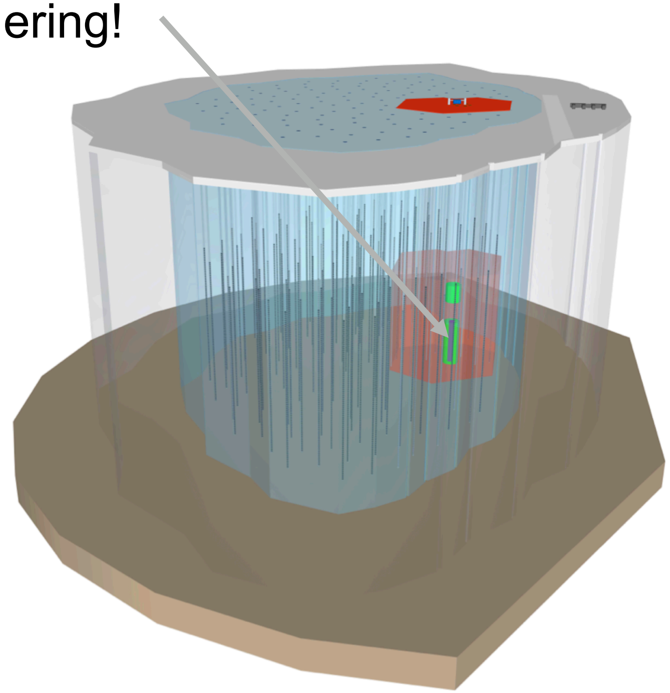


IceCube measurement
Astrophys. J. 809 (2015) 1, 98;
update: Taboada @ Neutrino 2018

Future perspectives

IceCube-Gen2

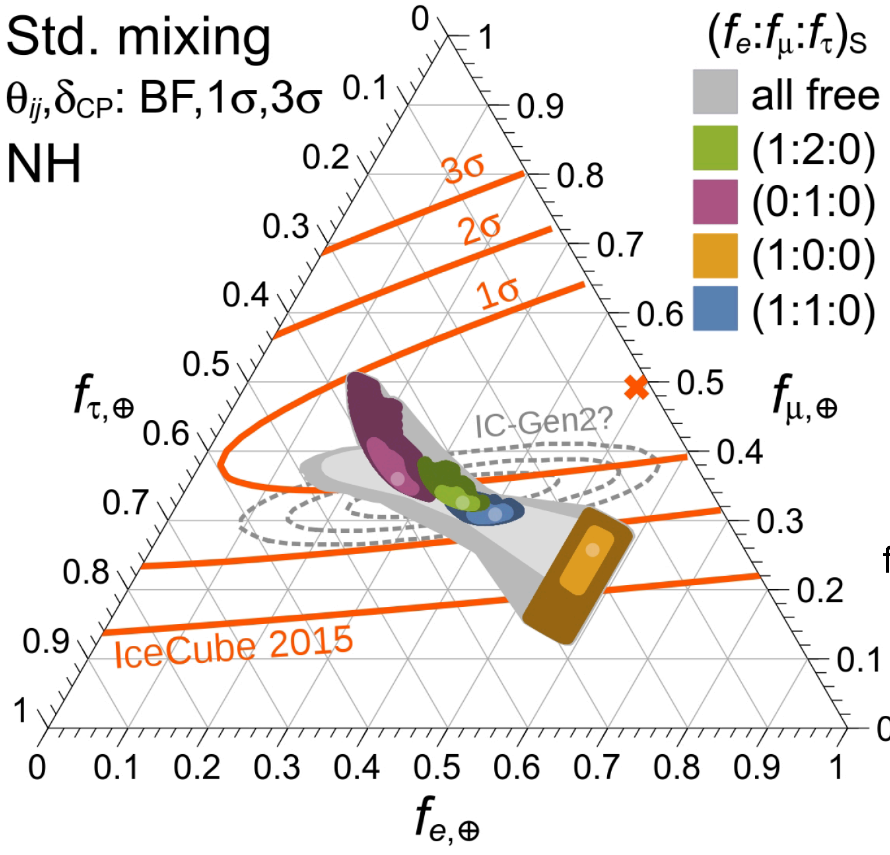
- Instrumented volume O(10) km^3
- Purpose: "deliver substantial increases in the astrophysical neutrino sample for all flavors"
- PINGU-infill for oscillation physics (about 40 strings for lower threshold in DeepCore region). Neutrino mass ordering!
- Similar ideas in sea water (KM3NeT, ARCA/ORCA)



(arXiv:1401.2046, arXiv:1412.5106)

Physics potential

- IceCube-Gen2 could exclude the current best-fit point
- Allowed regions for specific flavor compositions at source even smaller

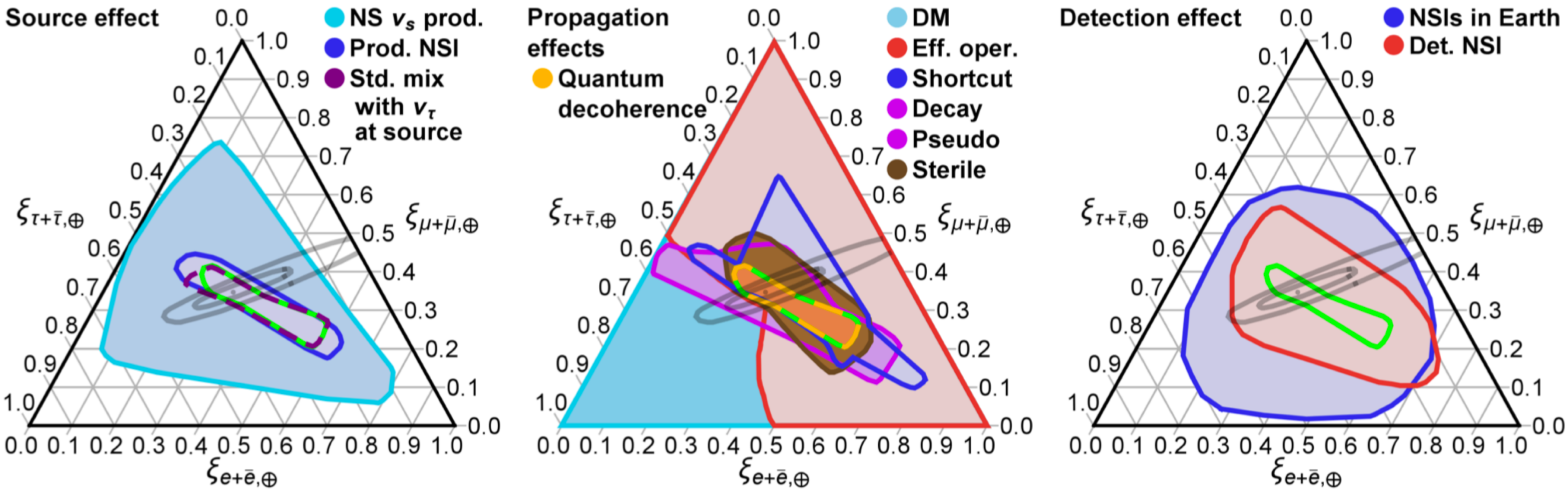


Bustamante, Beacom, Winter, PRL 115 (2015) 16, 161302

(shaded regions: current 3σ range for mixing params)

What ... if there is physics beyond the Standard Model?

Parameter space coverage including oscillation parameters and model parameters



From: Rasmussen et al, Phys. Rev. D96 (2017) 8, 083018;
long list of references therein!

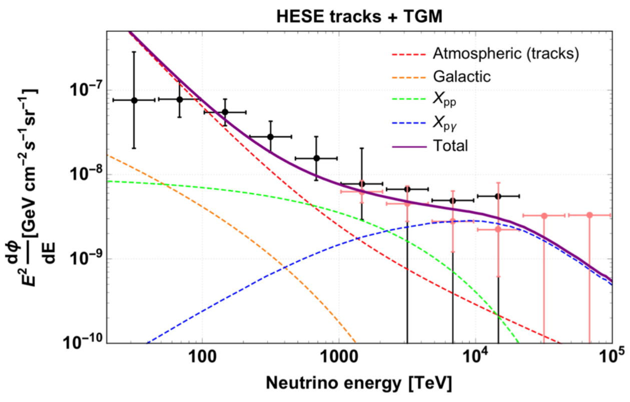
Interesting potential to discover physics BSM

Summary and conclusions

Interpretation of results on astrophysical neutrinos

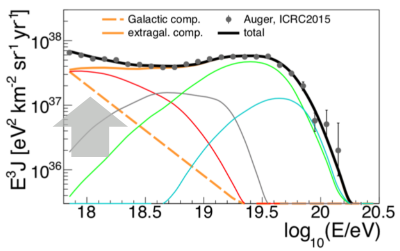
Origin of diffuse flux?

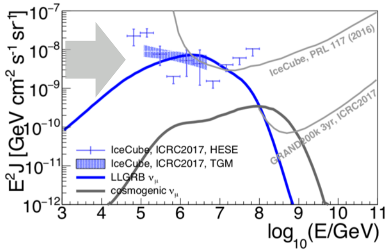
- Multiple constraints:
  Stacking limits, gamma-ray diffuse flux, multiplet constraints, anisotropy, different spectral indices in different datasets, ...
- May point towards contribution from multiple components



Common origin of diffuse neutrinos and UHECRs?

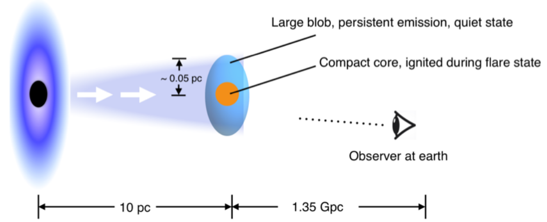
- A cutoff in the neutrino spectrum points towards sources with strong magnetic fields: LL-GRBs, jetted TDEs, ...
- High neutrino production efficiency ~ nuclear cascade develops; can be used to constrain parameter space [if sub-ankle UHECR transition to be described]





What did we learn from TXS 0506+056?

- Conventional one zone AGN models challenged, unless super-Eddington proton injection?
- Alternatives: Compact core, external radiation fields, hadronuclear interactions



- Historical flare much more challenging to describe; requires very high neutrino production efficiency accompanied by EM signatures