Neutrinos from cosmic rays

https://multimessenger.desy.de/

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EuCAPT Astroneutrino workshop
Prague, Czech Republic
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Contents

- Observations of TeV-PeV neutrinos (overview of selected results)
- Physics of neutrino production (theory)

Part 1

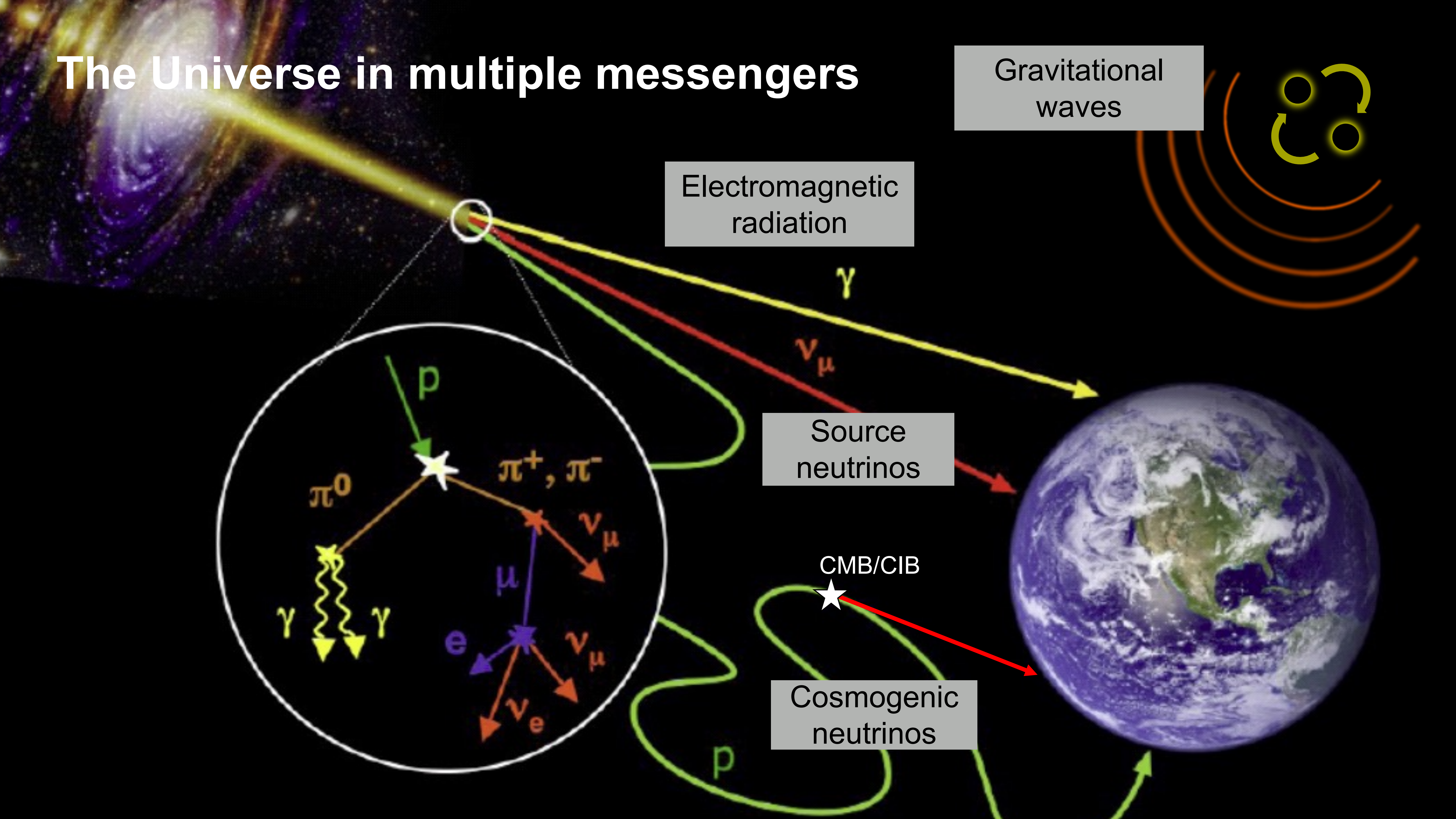
- Multi-messenger follow-ups:
  - Neutrinos from AGN blazars
  - Neutrinos from Tidal Disruption Events (TDEs)

Part 2

- The connection to Ultra-High Energy Cosmic Rays (UHECRs)
- Cosmogenic (EeV) neutrinos

Part 3

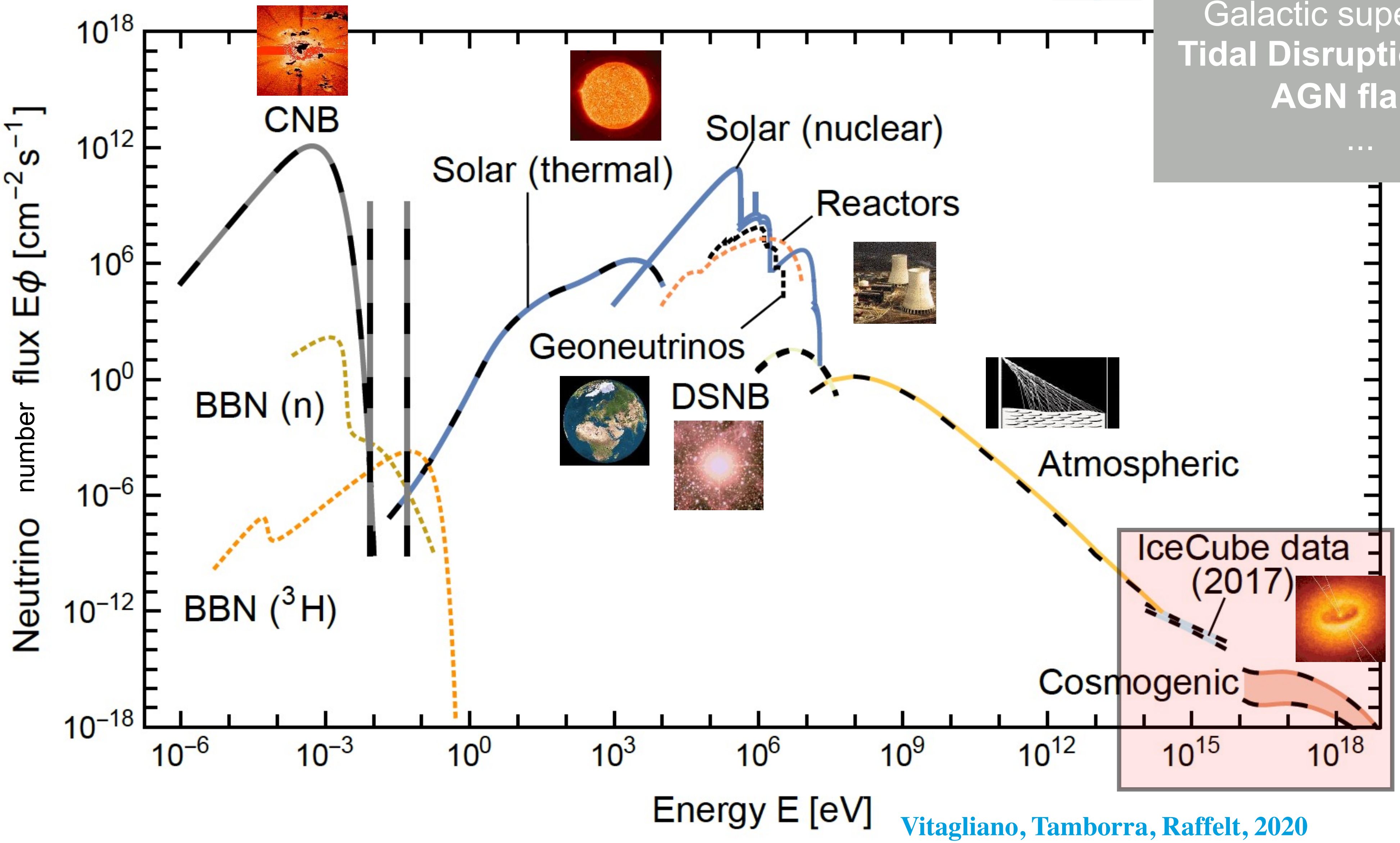
The Universe in multiple messengers



Where do the neutrinos come from?

Diffuse neutrino background (number flux)

* 0.5 m^2 ~ 10^{14} s^{-1} through a human being



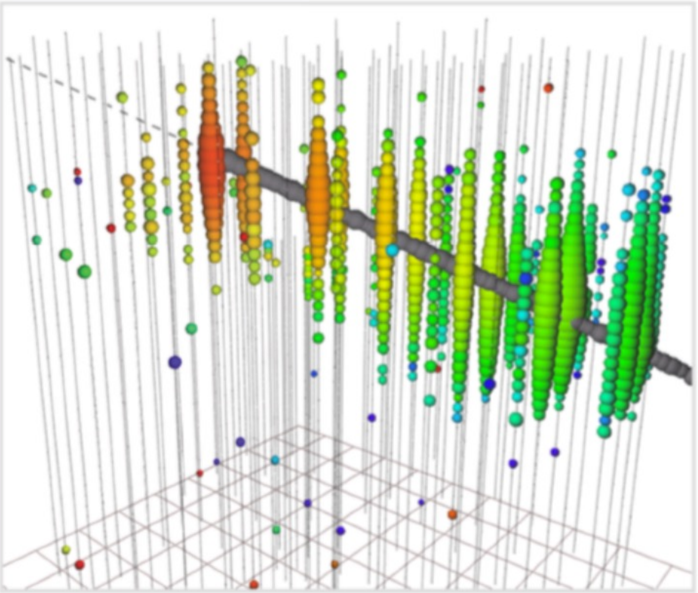
Vitagliano, Tamborra, Raffelt, 2020

Plus "transient" fluxes:
Neutrino beams (pulsed)
Galactic supernova?
Tidal Disruption Event
AGN flares
…

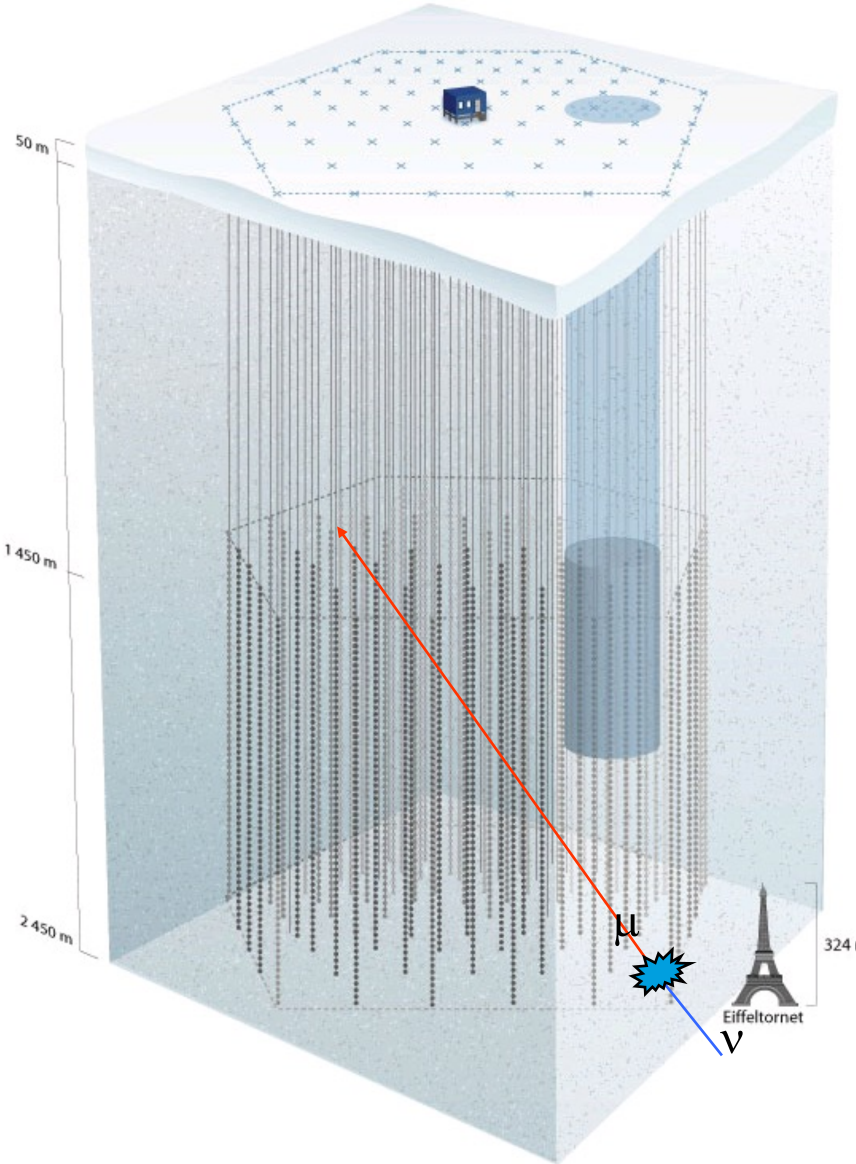
Observations of TeV-PeV neutrinos (overview)

Observing TeV-PeV neutrinos with IceCube

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

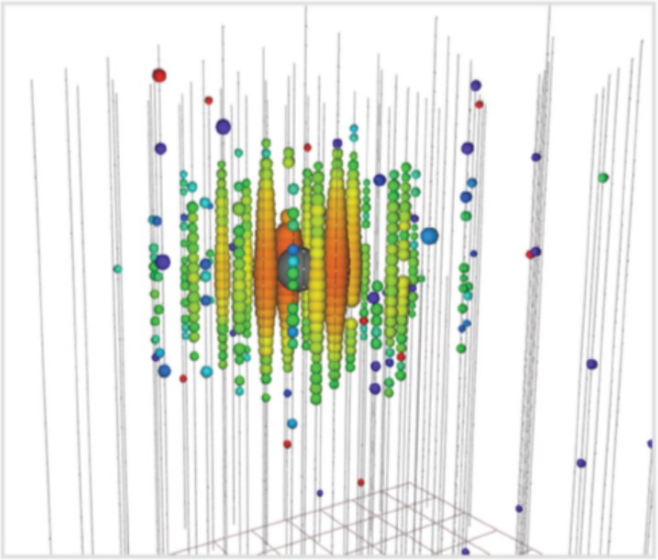


Better directional info



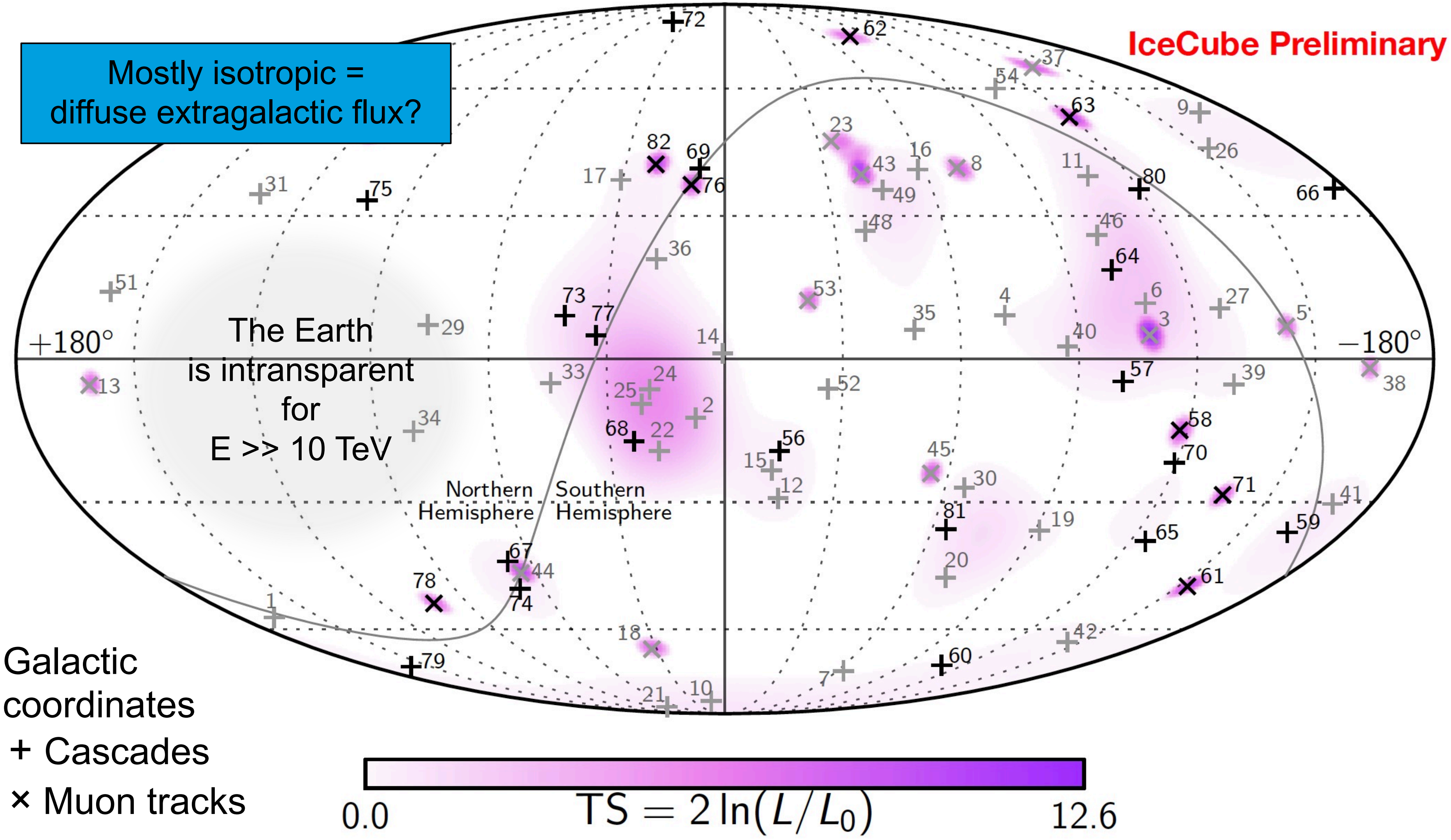
IceCube http://icecube.wisc.edu/

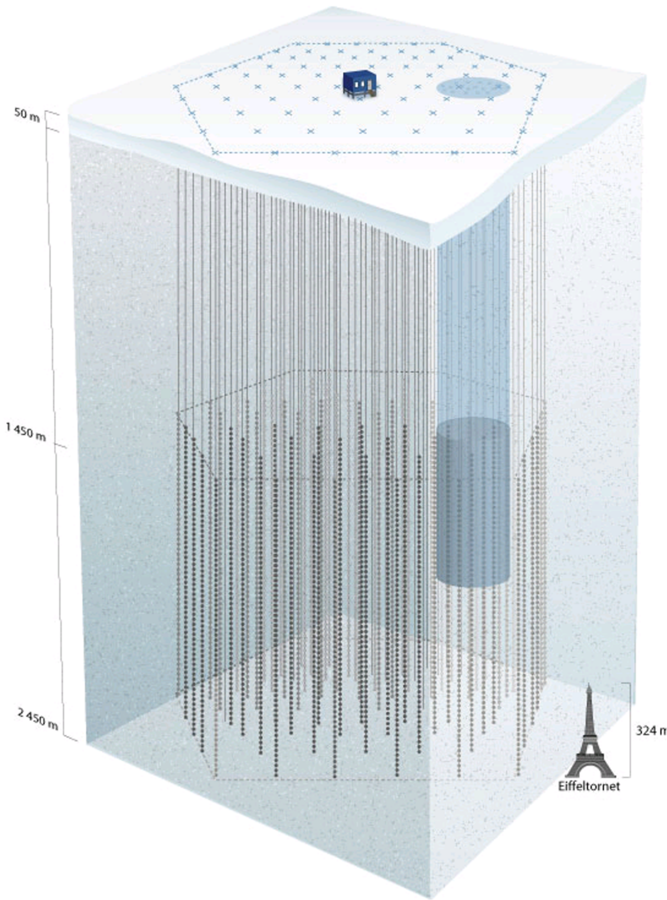
Cascade (shower):
- From ν_e
- From ν_τ
- From ν_e, ν_μ, ν_τ NC interactions



Better energy info

A flux of high-energy cosmic neutrinos

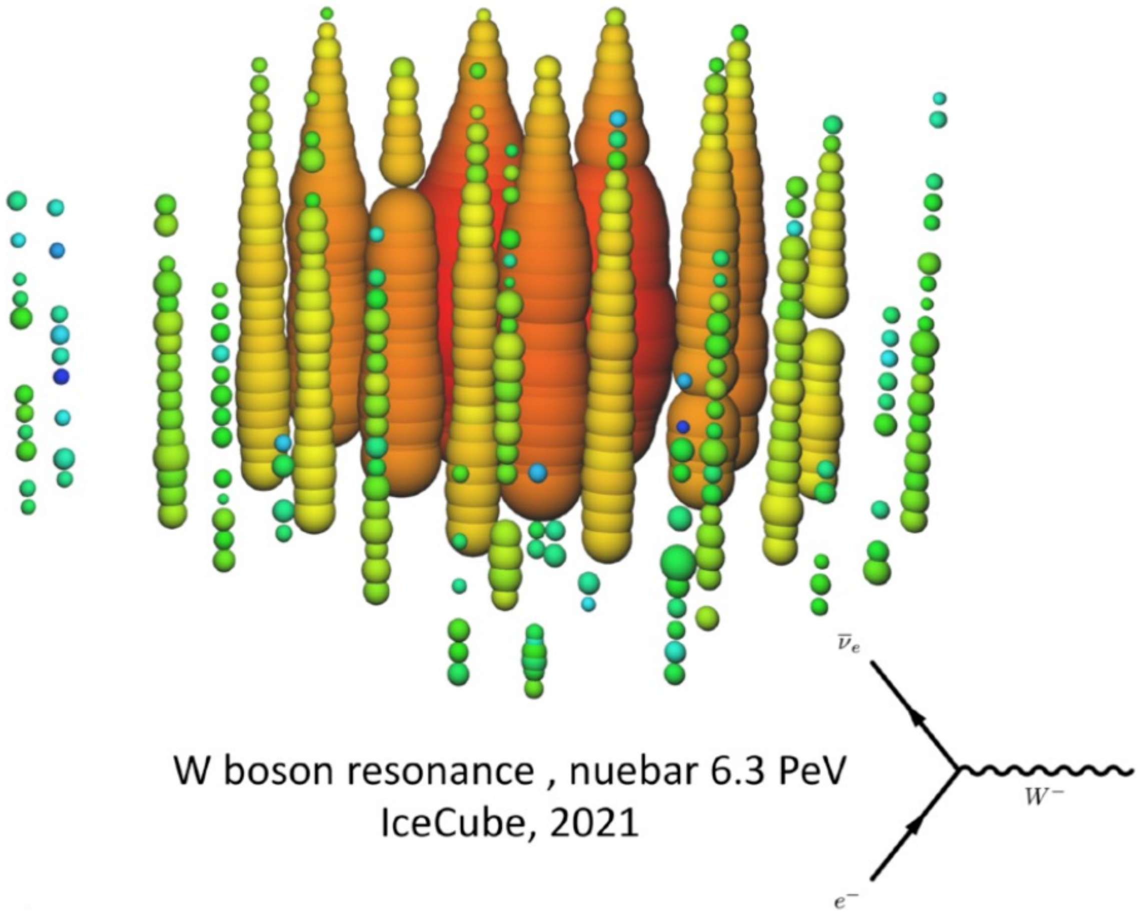




IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); update from Kopper at ICRC 2017

New event classes

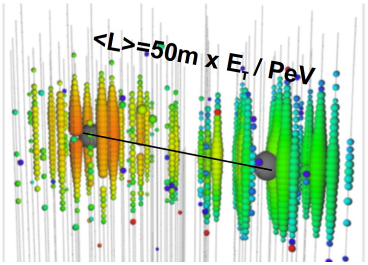
Glashow resonance

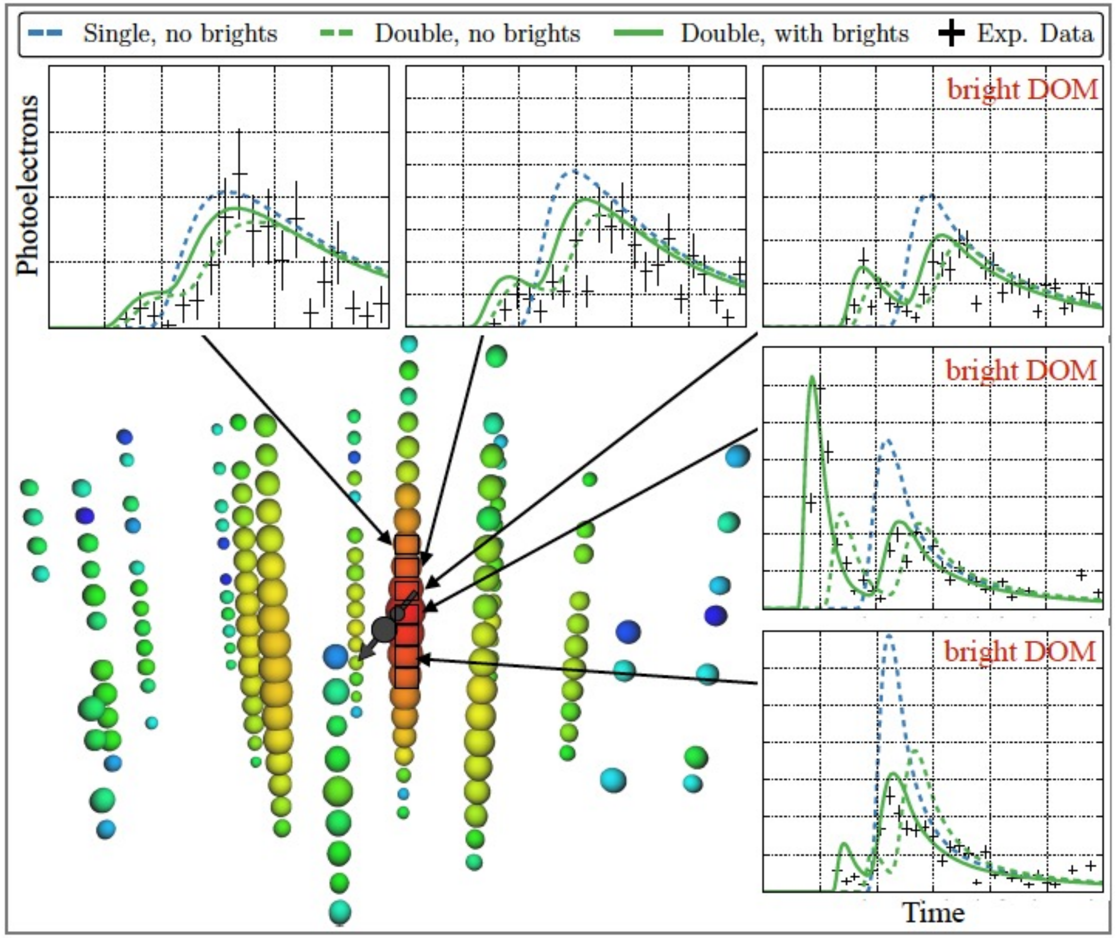


W boson resonance , nuebar 6.3 PeV
IceCube, 2021

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

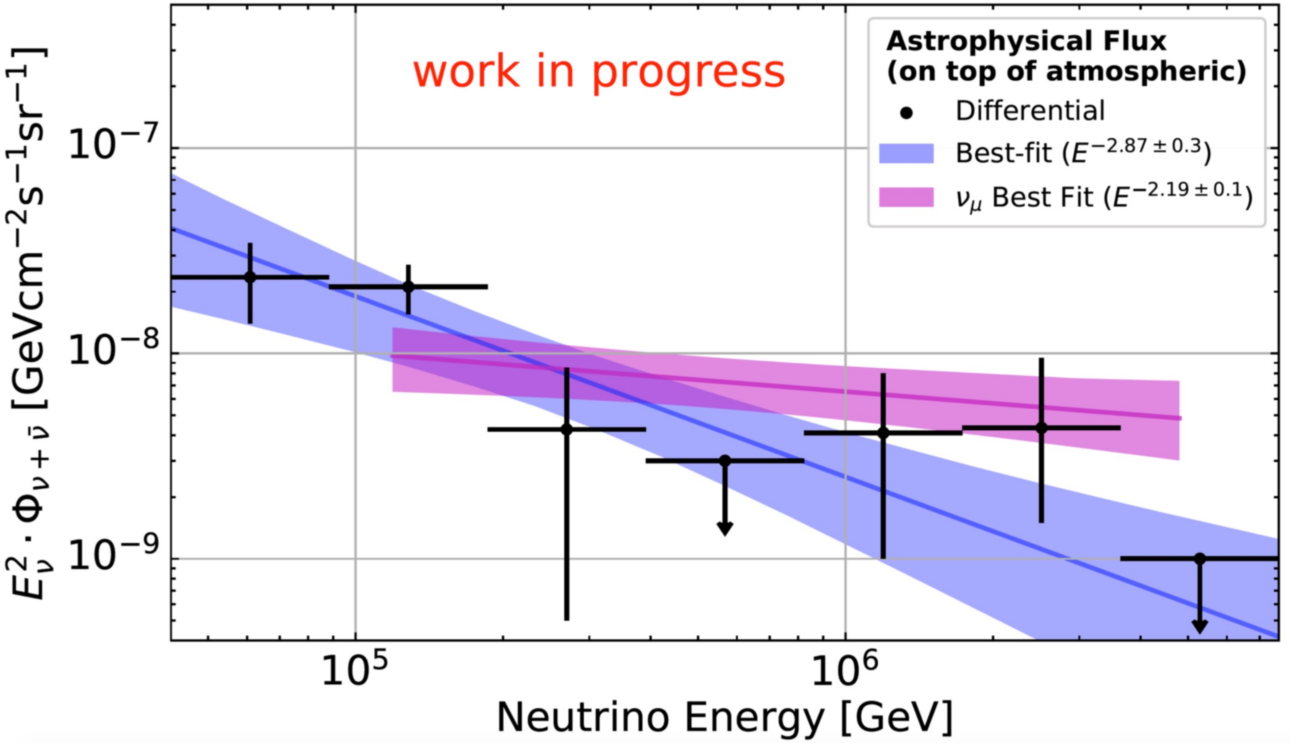
HESE = High Energy Starting Events

Interaction within detection volume

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

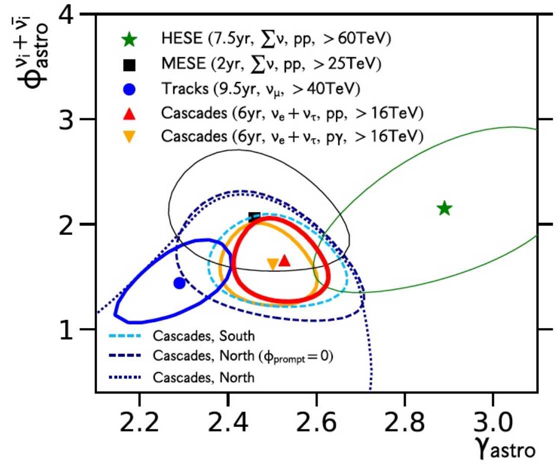
Sensitive to both hermispheres, all flavors

Lower energies = contained events



IceCube/Taboada at Neutrino 2018

PRL 125 (2020) 12, 121104 →



TGM = Through-going muons

Sensitive to ν_μ only from Northern hemisphere

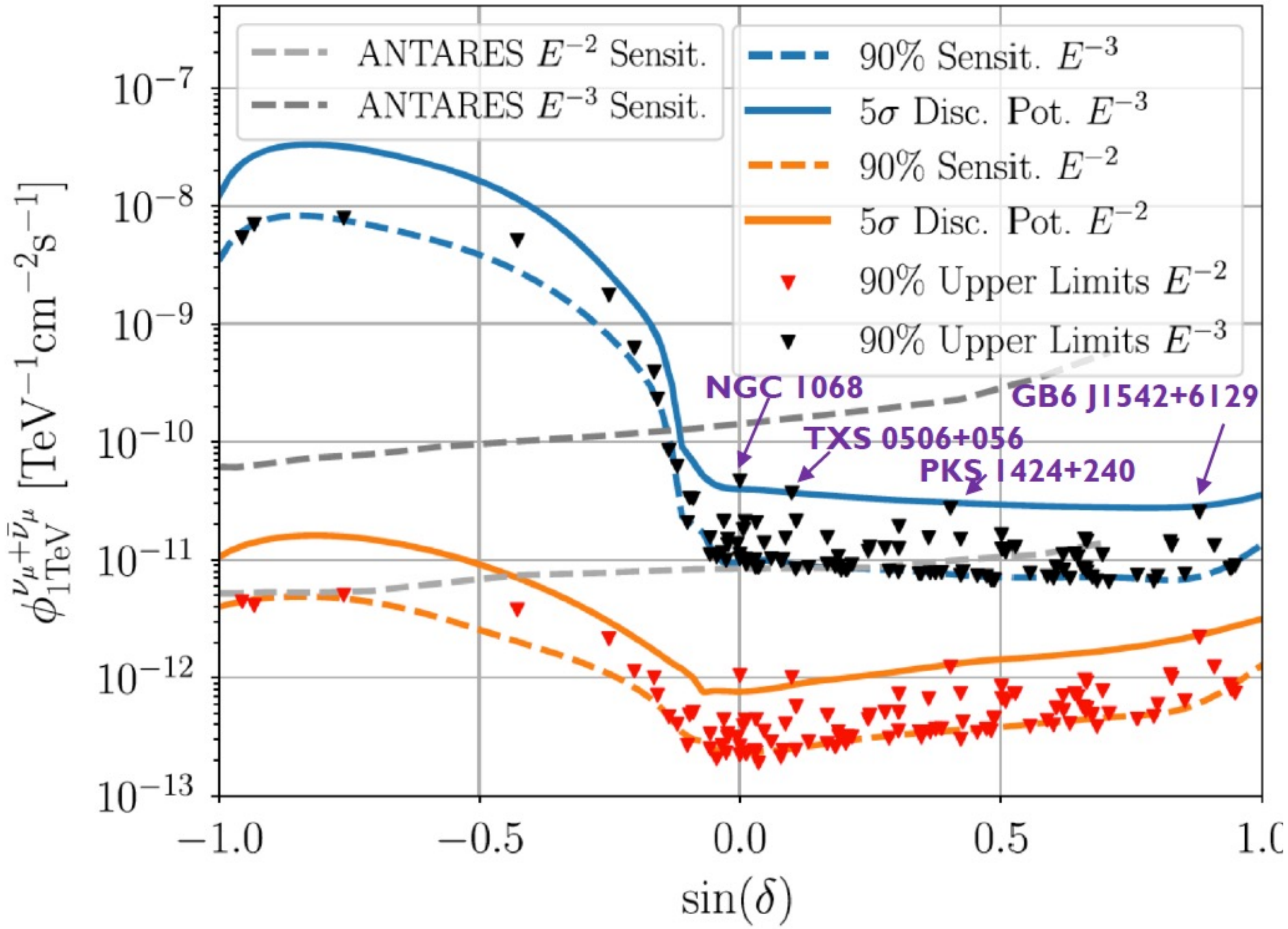
Large effective volume (interaction may be outside detector)

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

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 ...)



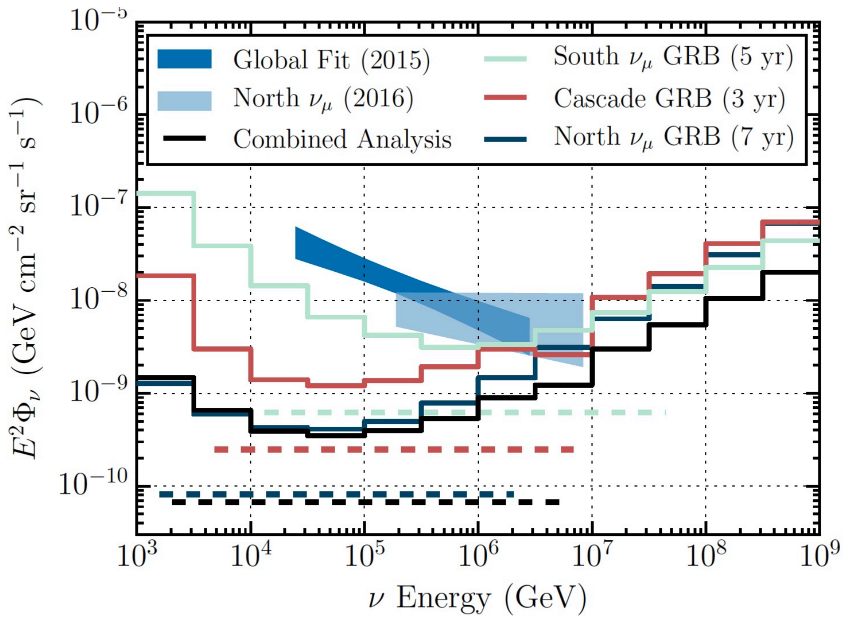
IceCube, PRL 124 (2020) 5, 051103;
from G. Illuminati @ Paris 2020

Stacking limits ...

... for the most energetic sources classes

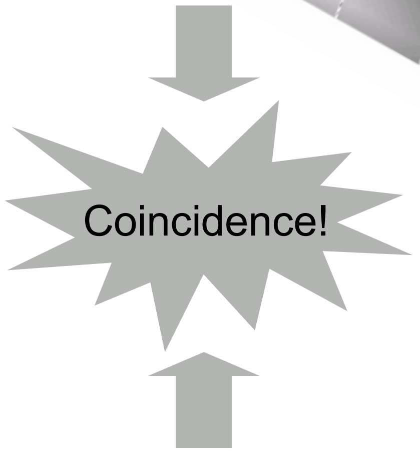
Gamma-Ray Bursts (GRBs)

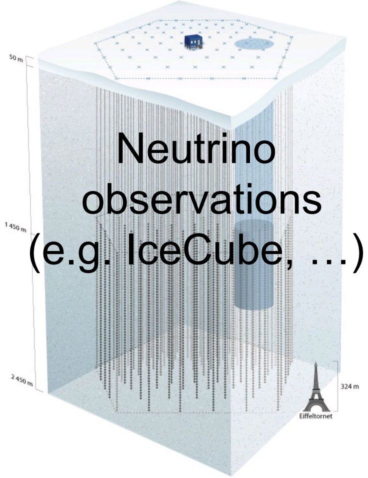
- Transients, time variability
- High luminosity over short time



- Less than ~1% of observed ν flux

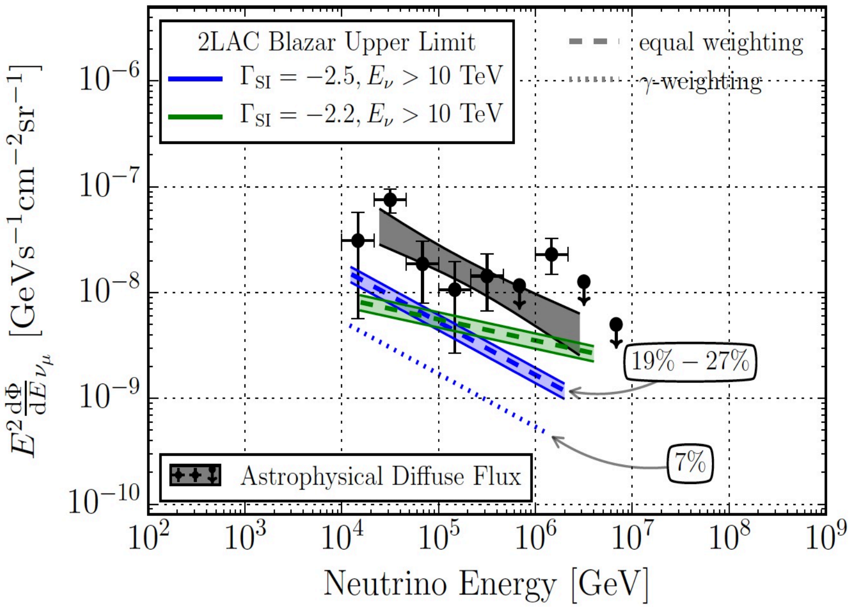
IceCube, Nature 484 (2012) 351;
Newer version: arXiv:1702.06868





Active Galactic Nuclei (AGNs)

- Steady emission with flares
- Lower luminosity, longer duration



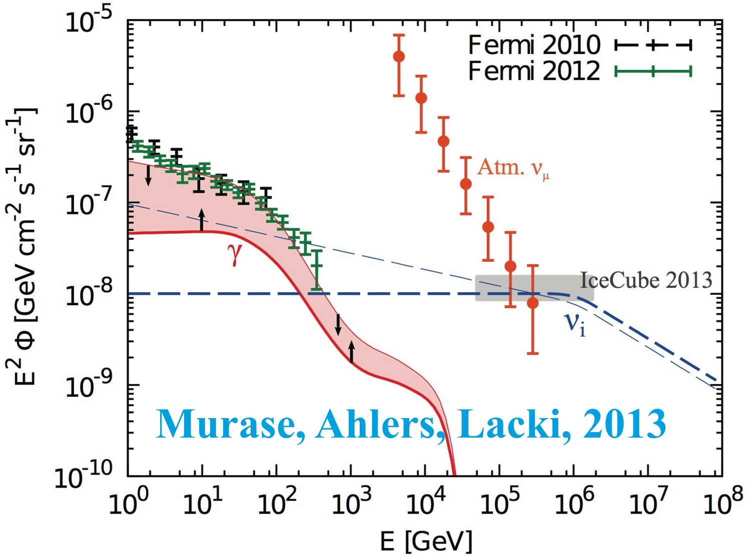
- Less than ~25% of observed ν flux?

IceCube, Astrophys. J. 835 (2017) 45

Conceptual challenges

Gamma-ray diffuse flux

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

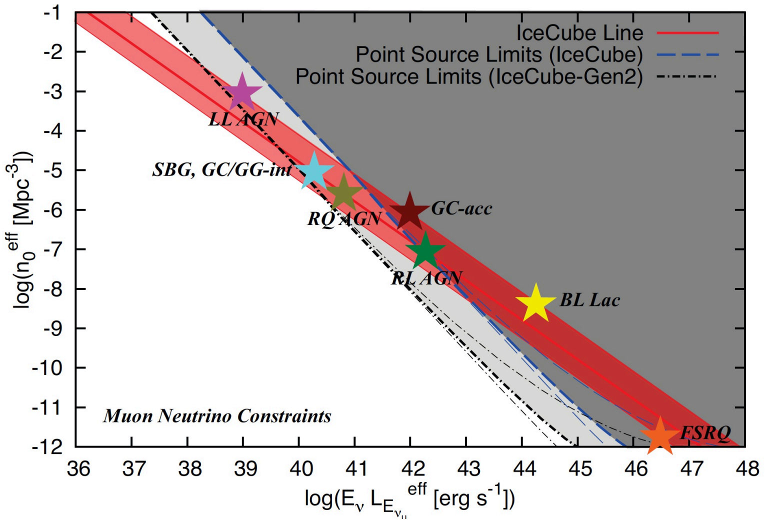


Constrains spectral index for non-AGN contributions (starburst galaxies, ...)

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



[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)?

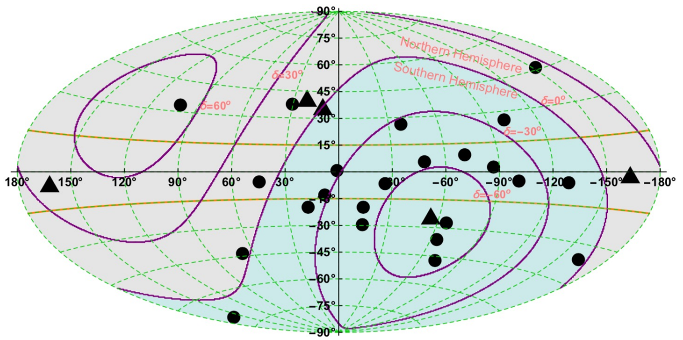
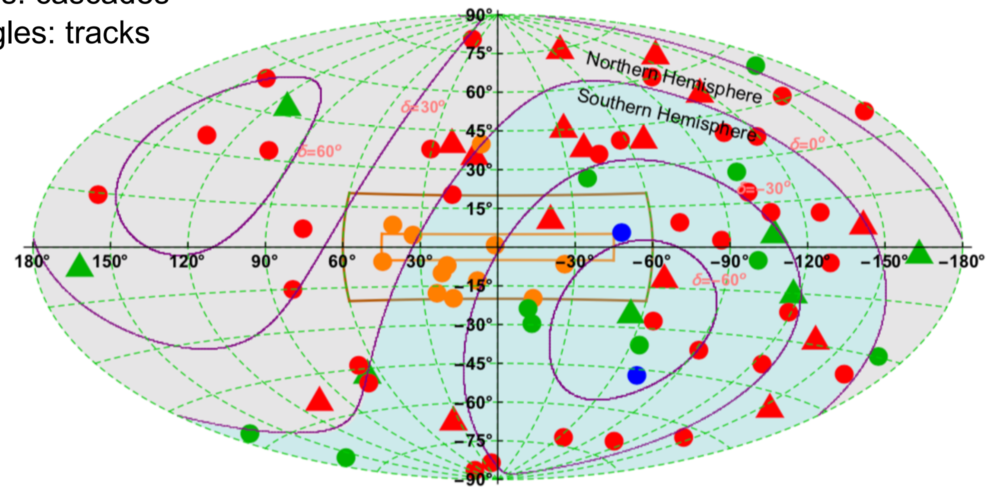


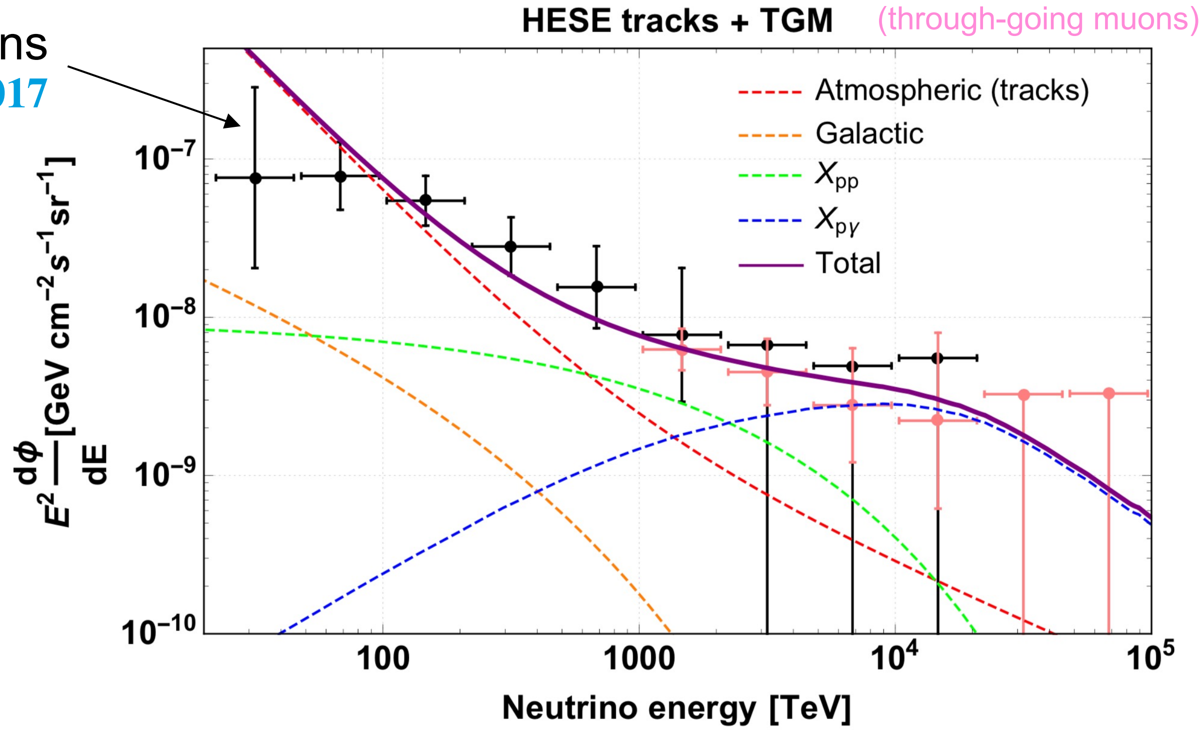
Fig. from: Palladino, Winter, A&A 615 (2018) A168

Multiple contributions to diffuse flux? A possible scenario.

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



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



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

[...]

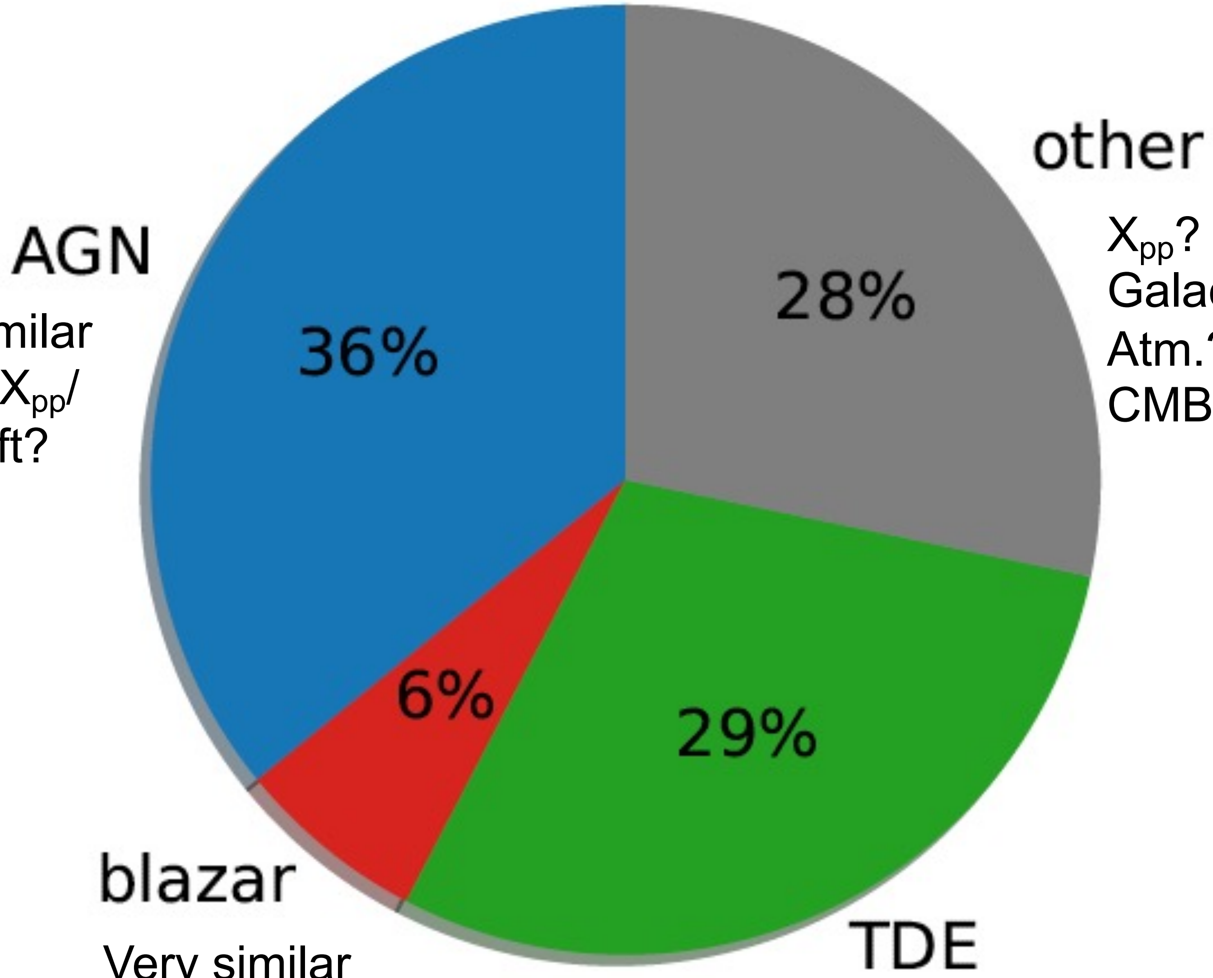
Extragalactic flux dominant
Low “background” (atm. + Galactic)

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 / ϕ_{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			$0.28^{+0.38}_{-0.25}$



Similar to X_{pp}/ soft?

X_{pp}? Galactic? Atm.? CMB???

Very similar to $X_{p\gamma}$

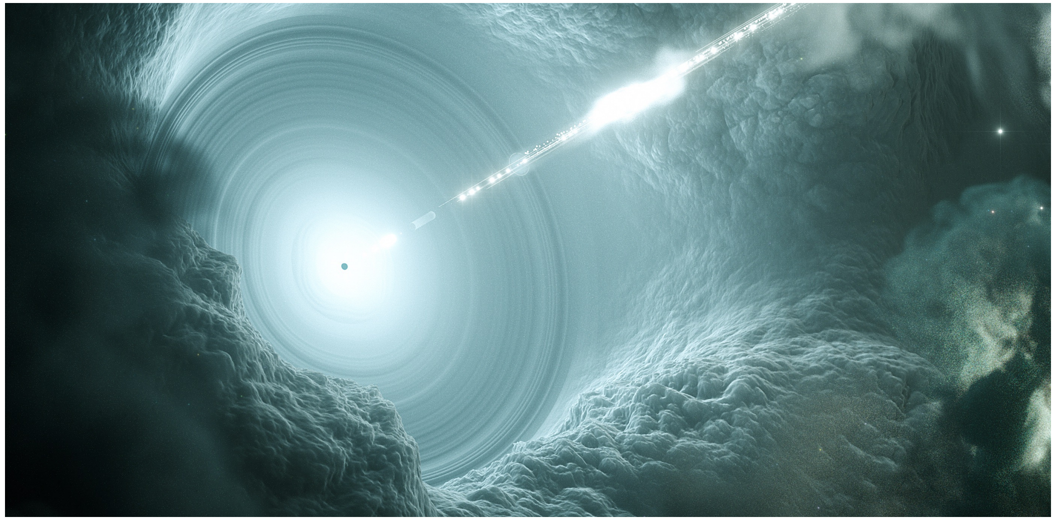
Another $X_{p\gamma}$ peaking at lower E?

Bartos et al, arXiv:2105.03792

Multi-messenger follow-ups

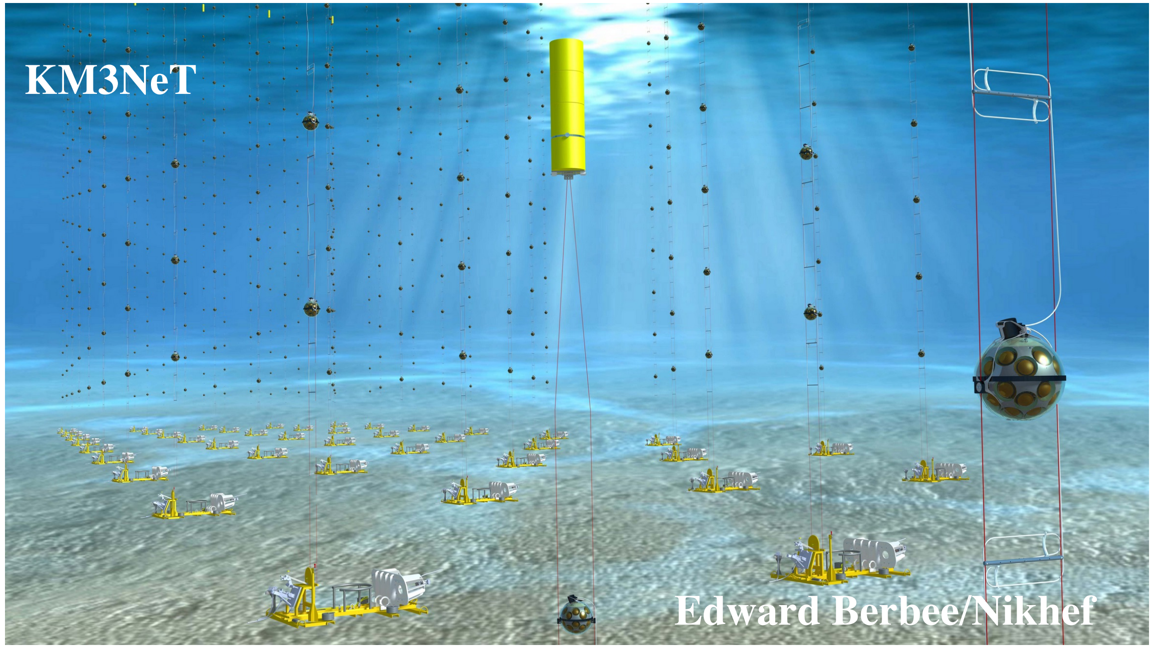
... starting the golden age of neutrino astronomy

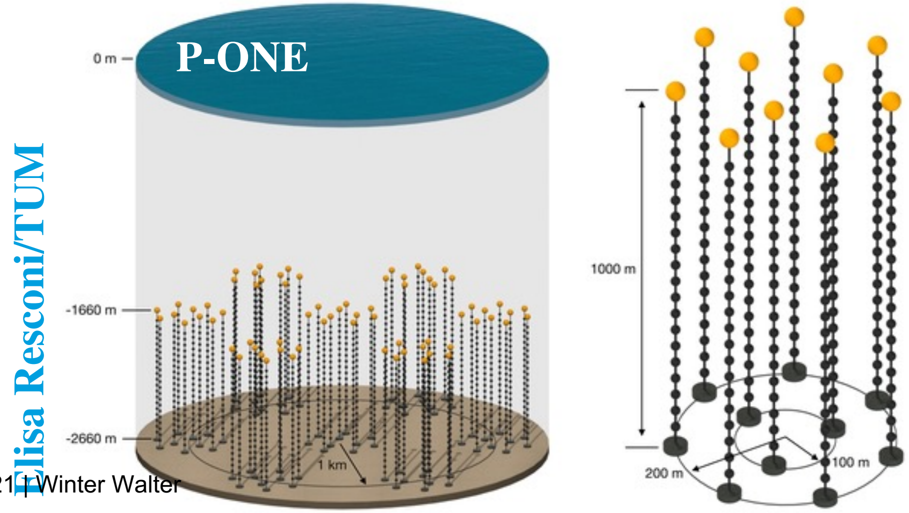
- Global alerts initiated by neutrino events
- Especially tracks with good directional information, high enough energy
- Other instruments triggered, who search for counterparts
- Prominent examples: TXS 0506+056 (AGN blazar), AT2019dsg (Tidal Disruption Events), but several other associations as well

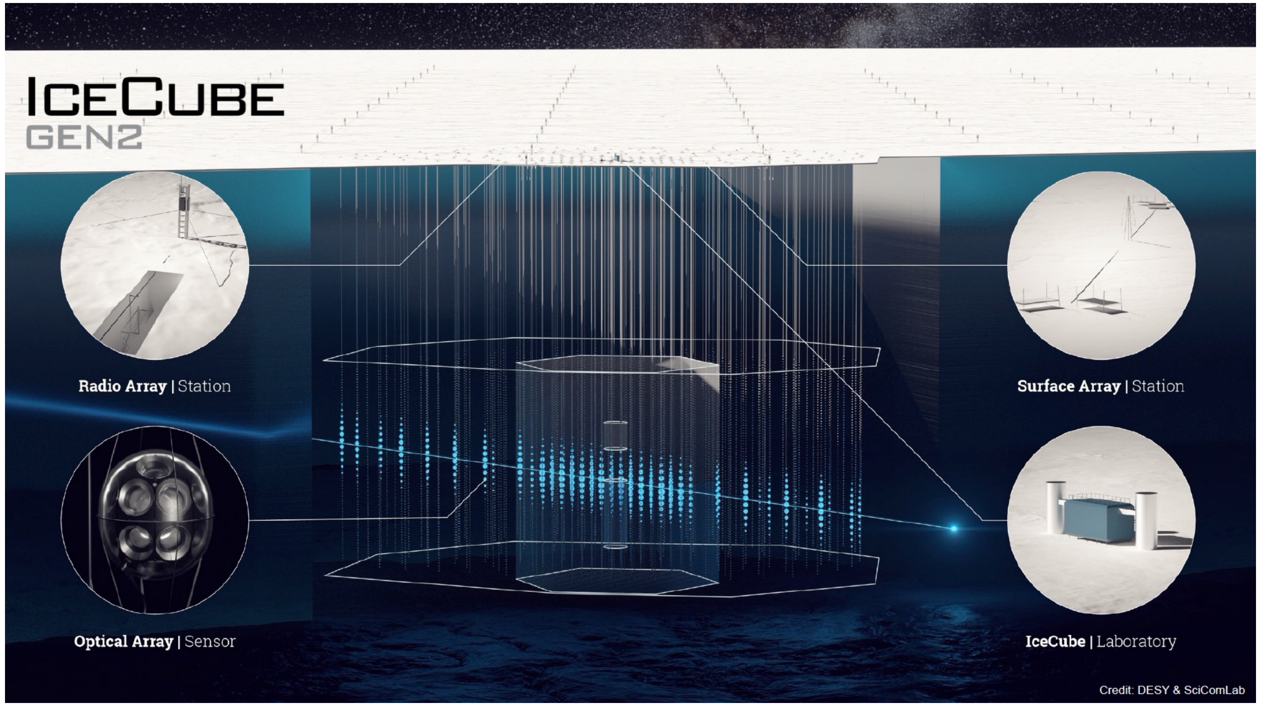


Future neutrino telescopes: PeV neutrinos

... towards a global neutrino observatory?



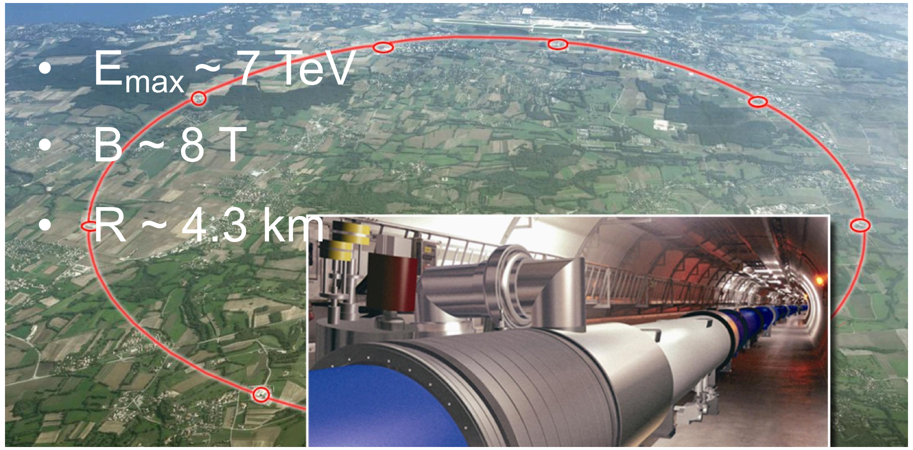




Physics of neutrino production

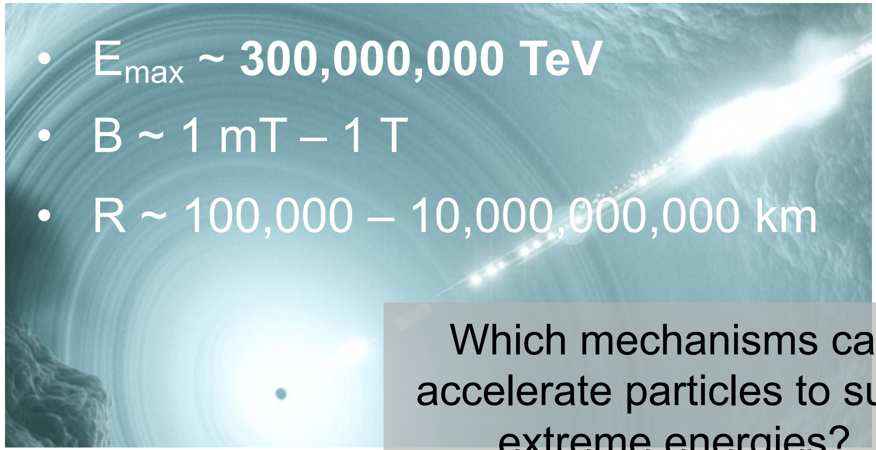
Theory

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

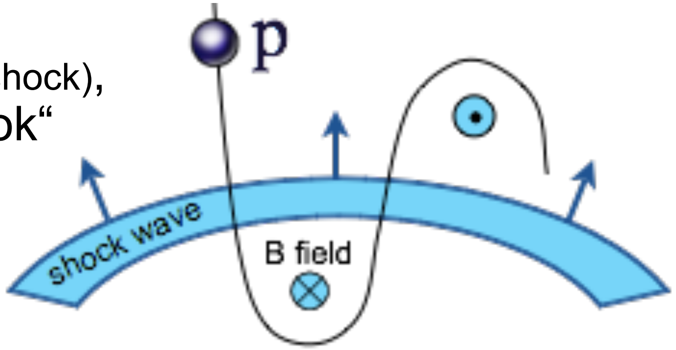


- E_{max} ~ **300,000,000 TeV**
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km

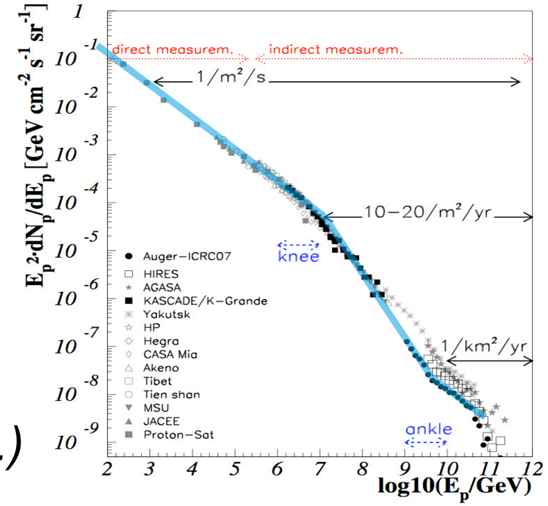
Which mechanisms can accelerate particles to such extreme energies?

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

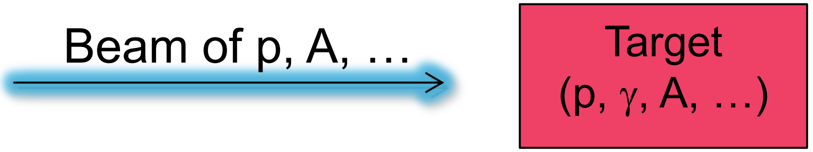


- Theory of acceleration challenging, but we **do observe** power law (= non-thermal) spectra in Nature
- For multi-messenger perspective: adopt pragmatic point of view! *(we know that it works, somehow ...)*



Secondary production: Particle physics 101?

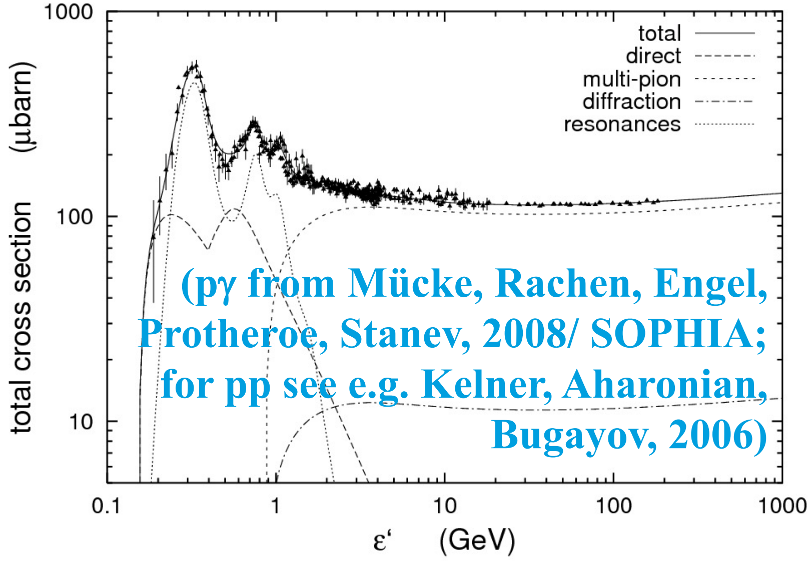
- **Beam dump picture (particle physics)**



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

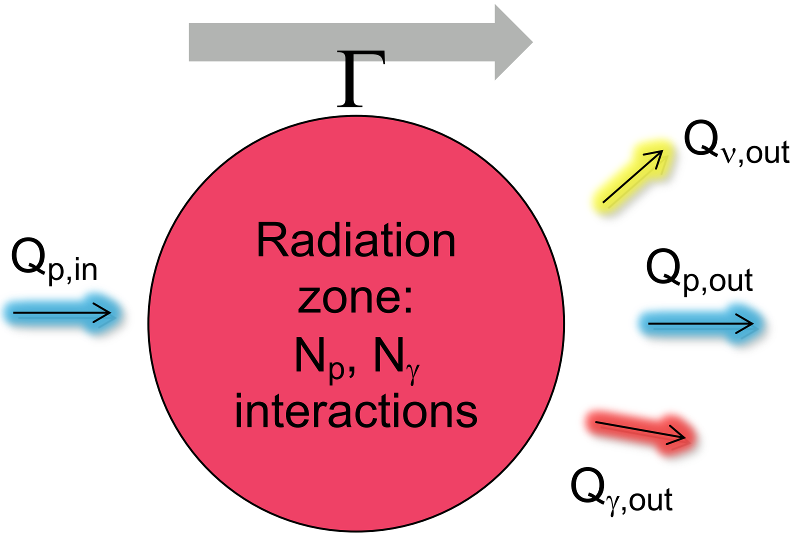
Target density (e.g. N_γ) critical for production!

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***

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

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. blob frame)

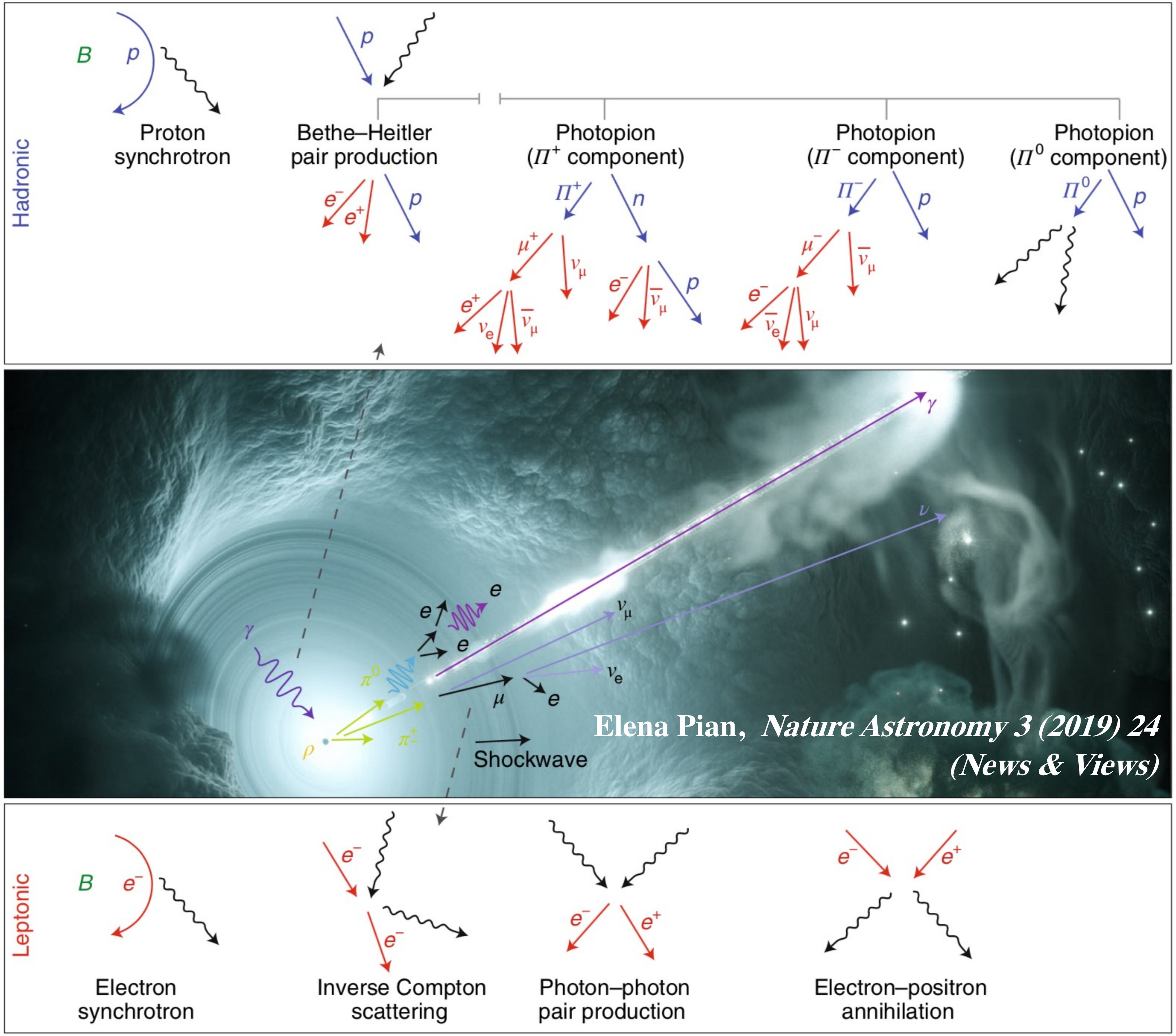
→ Re-distribution function narrow + peaked

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



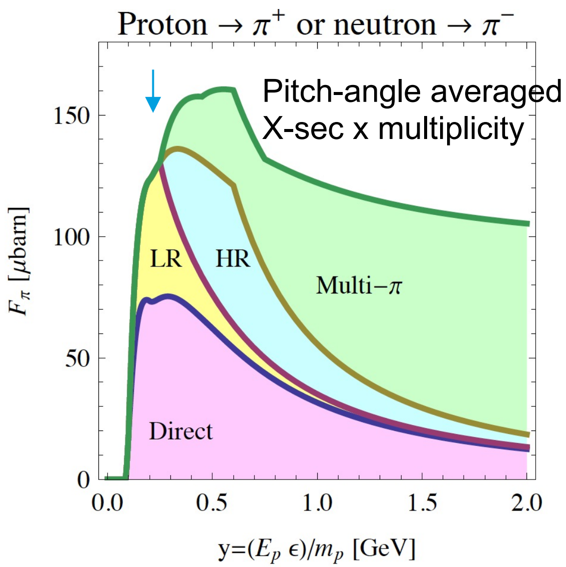
Multiple messengers from photo-pion production

- 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):

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

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

(or: $E_{\gamma,0}$ [eV] ~ 0.01 $(1+z)^{-2}/E_{\nu,0}$ [EeV])

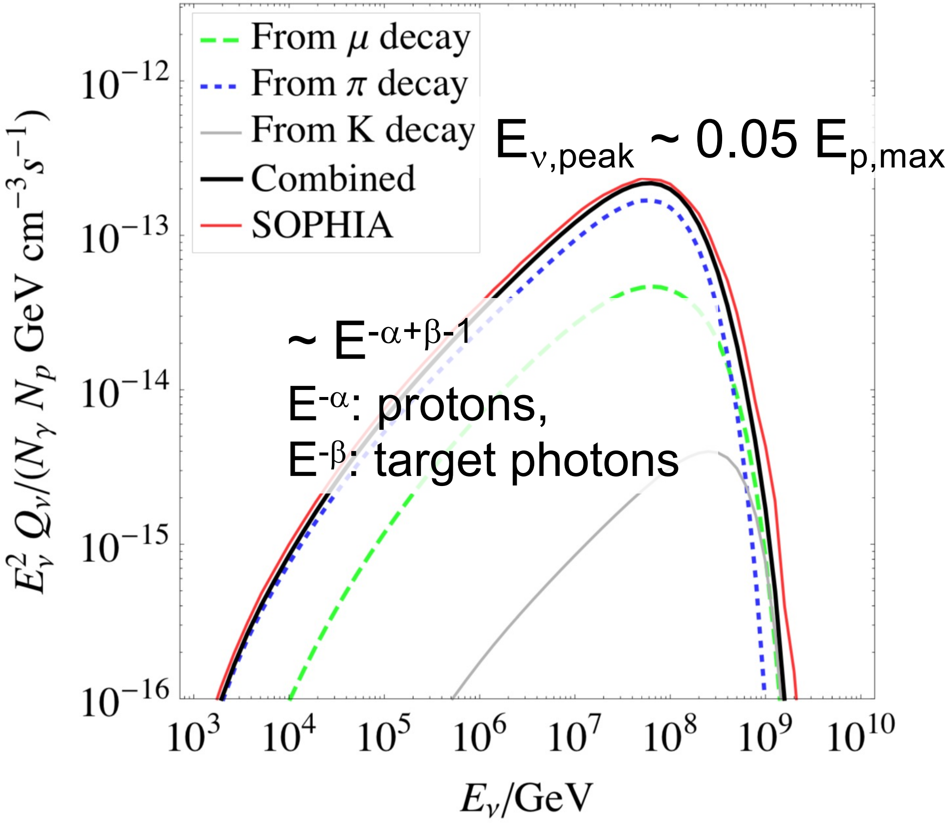


- Photons from pion decay:

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

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**

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

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 with power law larget**: more sophisticated since relativistic target

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

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

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

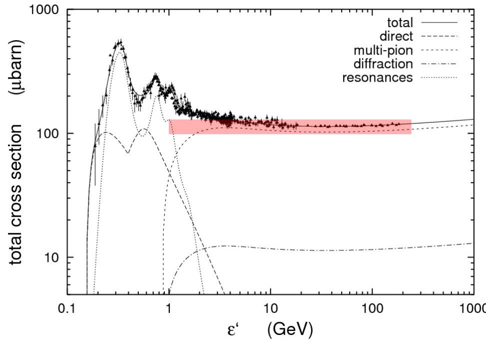
Examples: GRBs ($\beta\sim1$), AGN blazars ($\beta>1$)

- **pγ interactions with thermal target:**
Peaked (example: CMB). But: multi-pion prod. dominates if target photon T high enough.

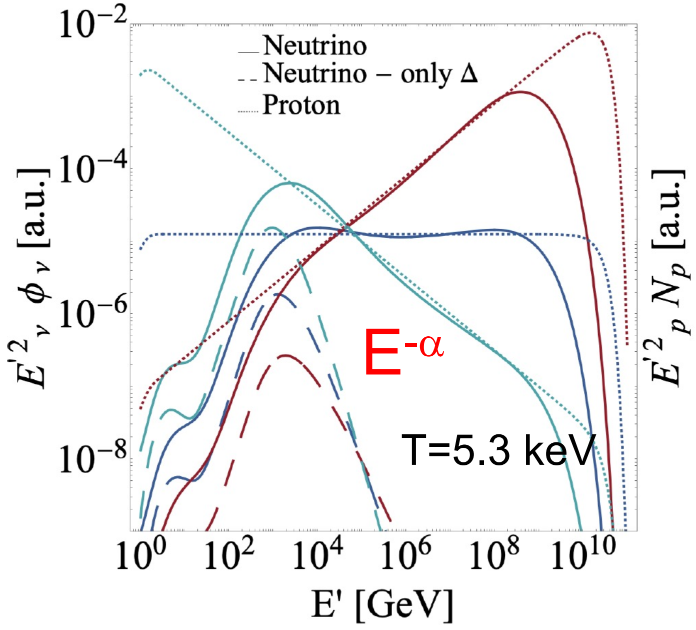
Examples: TDEs, AGN cores

$$p + \gamma$$

$E^{-\alpha}$ T



$\longrightarrow$



Fiorillo et al, JCAP 07 (2021) 028

Decouple the maximal cosmic ray and neutrino energies?

Effect of secondary cooling

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

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

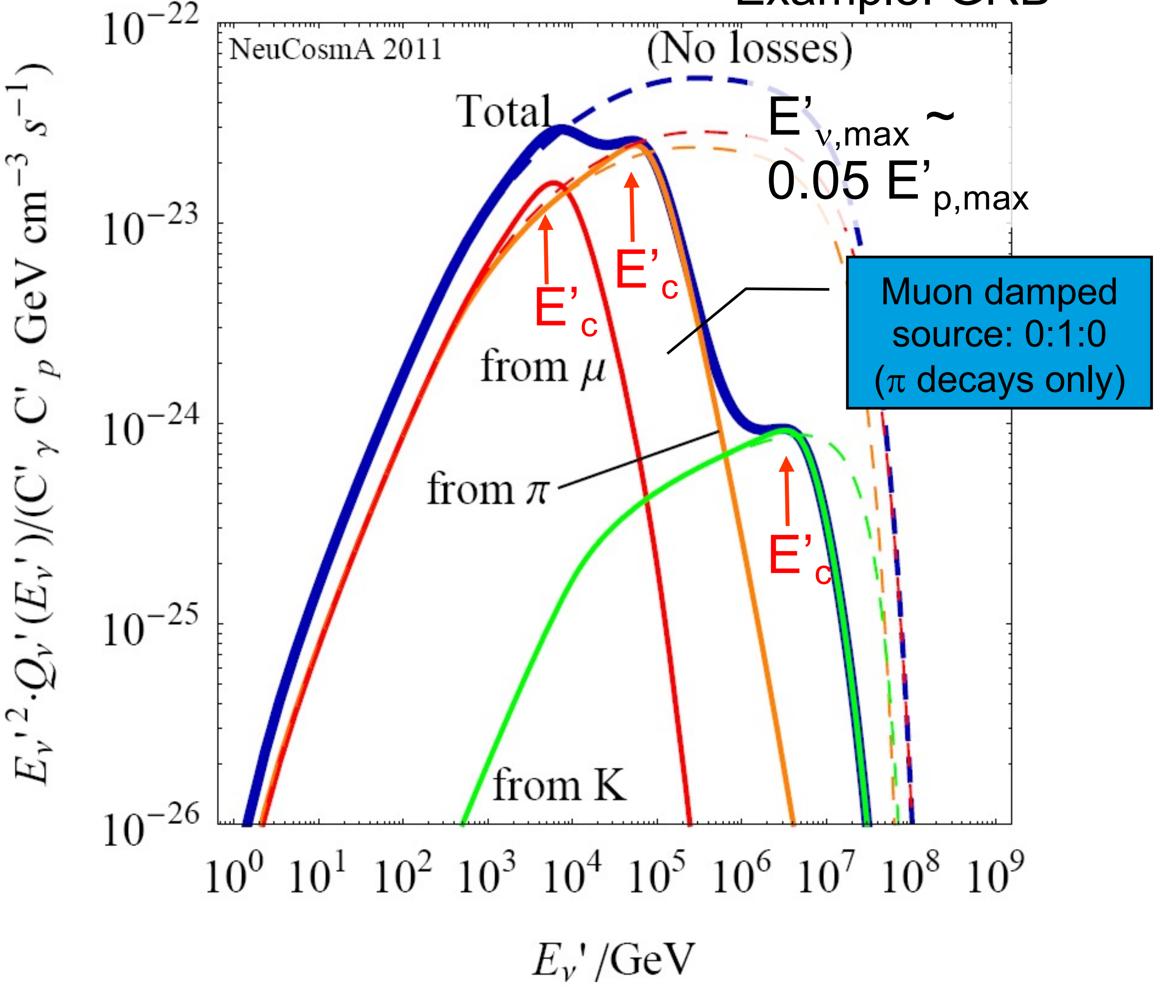
- Spectra (μ, π, K) energy loss-steepend above critical energy
(synchrotron cooling faster than decay)

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

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

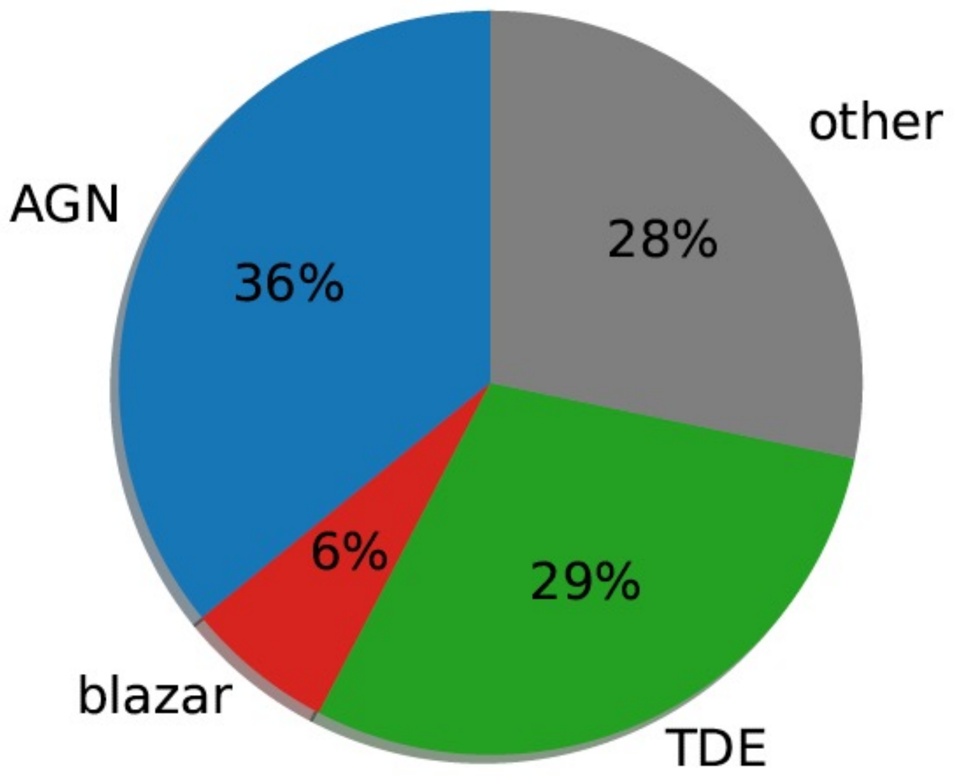


Kashti, Waxman, 2005; Lipari et al, 2007; …
Fig. from Baerwald et al, Astropart. Phys. 35 (2012) 508

Summary – part I

- A diffuse astrophysical neutrino flux in the TeV-PeV range has been detected
- There are at least 3-4 different contributions
- Several point sources become significant
- Several detections from multi-messenger follow-ups (tomorrow!)

- The neutrinos spectrum typically peaks at the primary energy $E_{\nu,peak} \sim 0.05\ E_{p,max}$
- Exceptions: sources with particular target photon shapes (E^{-1}), large T (thermal targets), pp interactions, strong magnetic fields
- In particular applicable to AGNs, CMB interactions



Bartos et al, arXiv:2105.03792

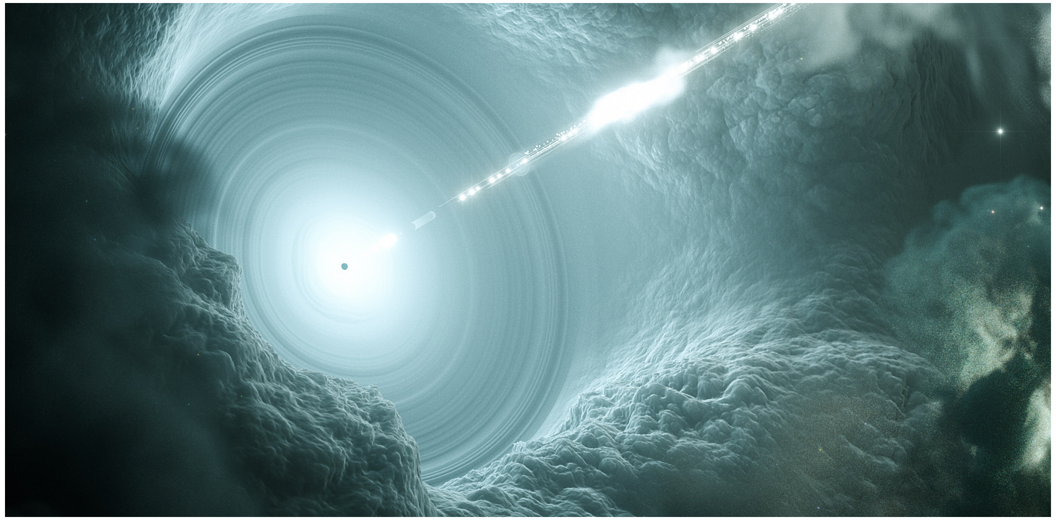
Part 2:
Multi-messenger follow-ups

... and AGN diffuse flux expectations

Recap: 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

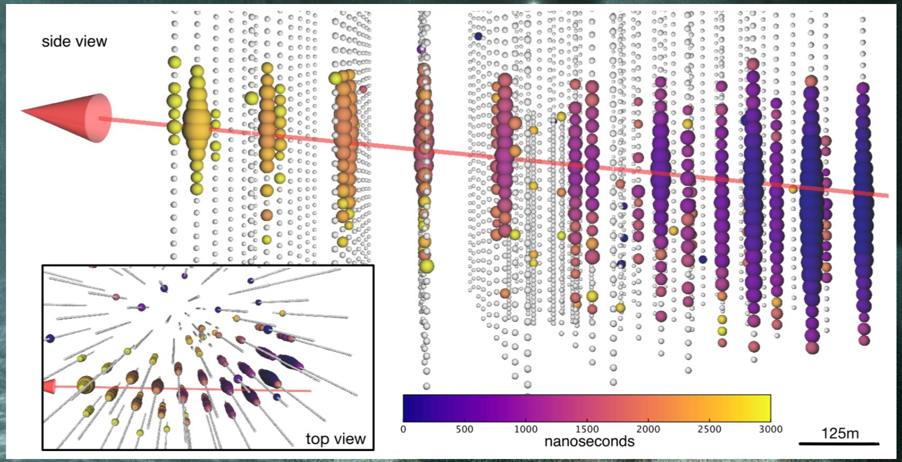


Neutrinos from AGN blazars

Overview

AGN blazar

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

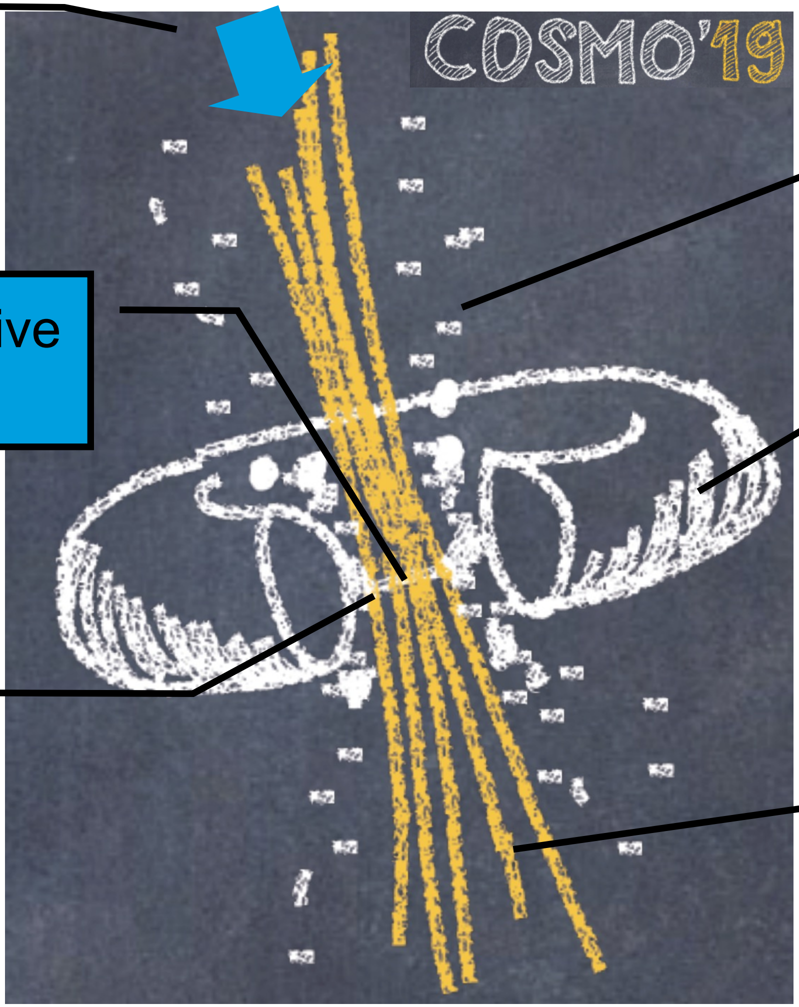
2

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

Blazar:
The observer looks into the jet

A supermassive black hole

An accretition disk



Clouds (line emissions!)

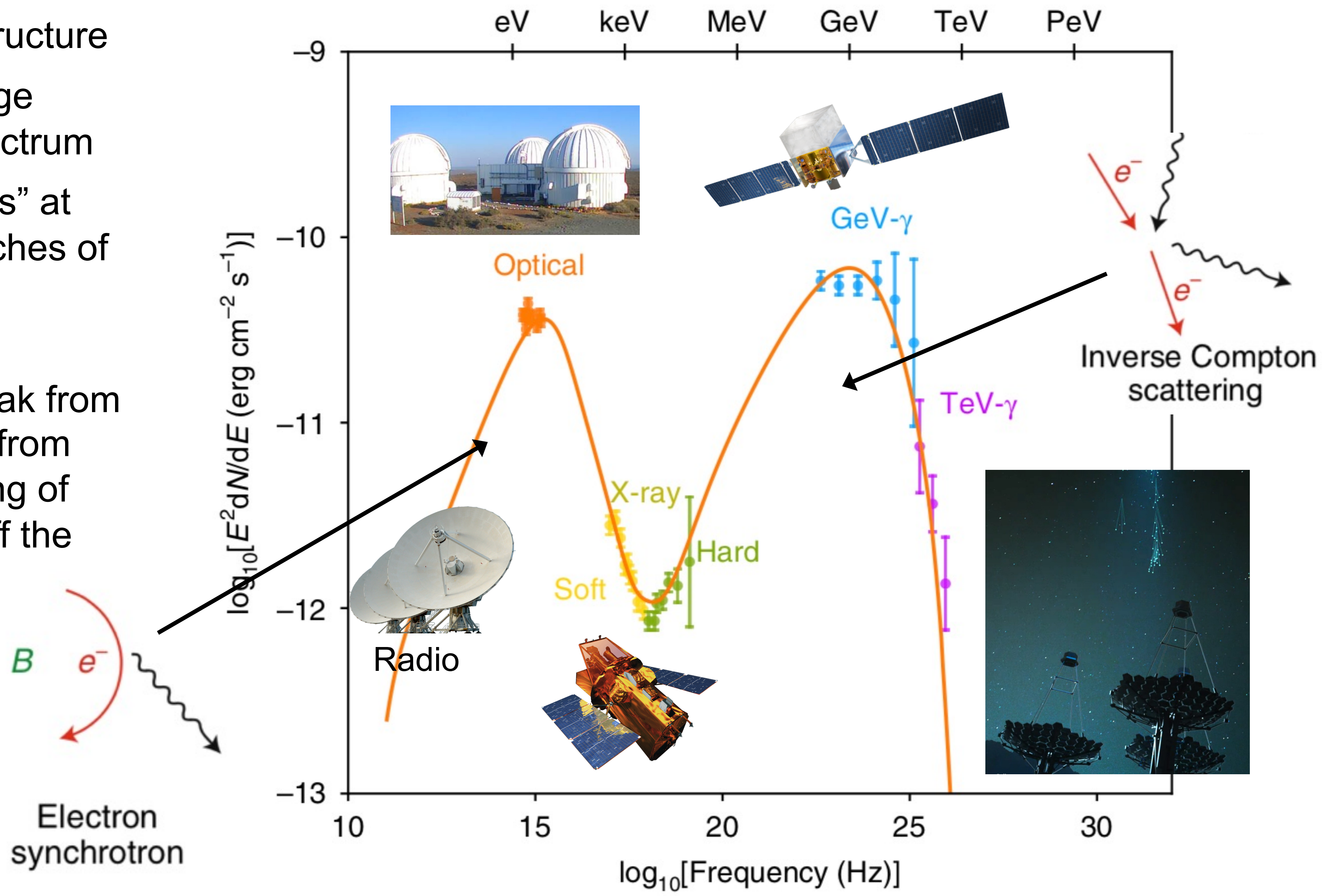
The dust torus

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”)



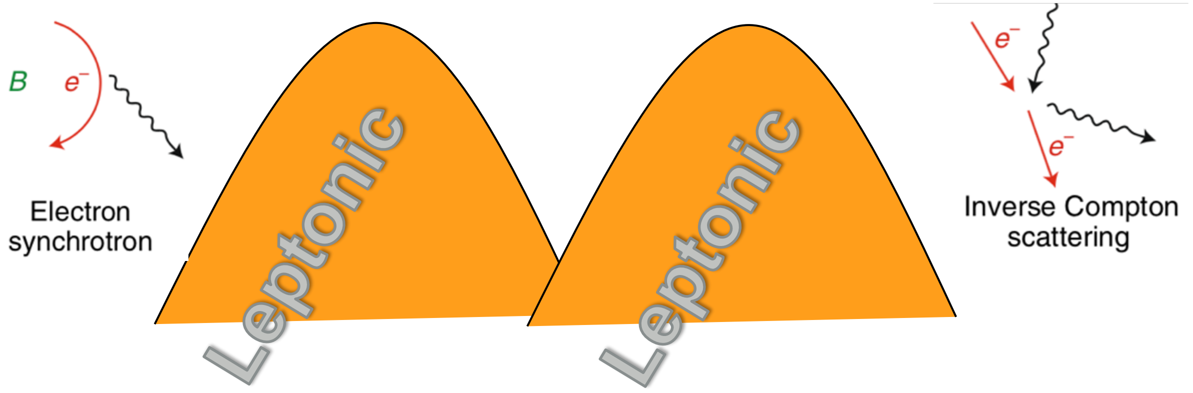
Credits: VLA, ASAS-SN, Swift, Fermi, MAGIC, DESY science comm. lab., Pian 2019, Gao et al, 2019

Typical SED models (qualitatively)

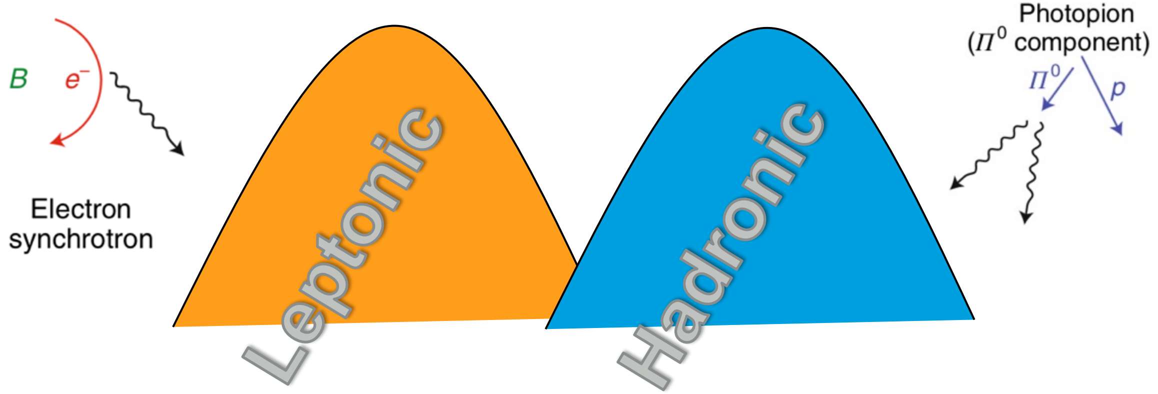
One spherical radiation zone
Fewest assumptions

R'

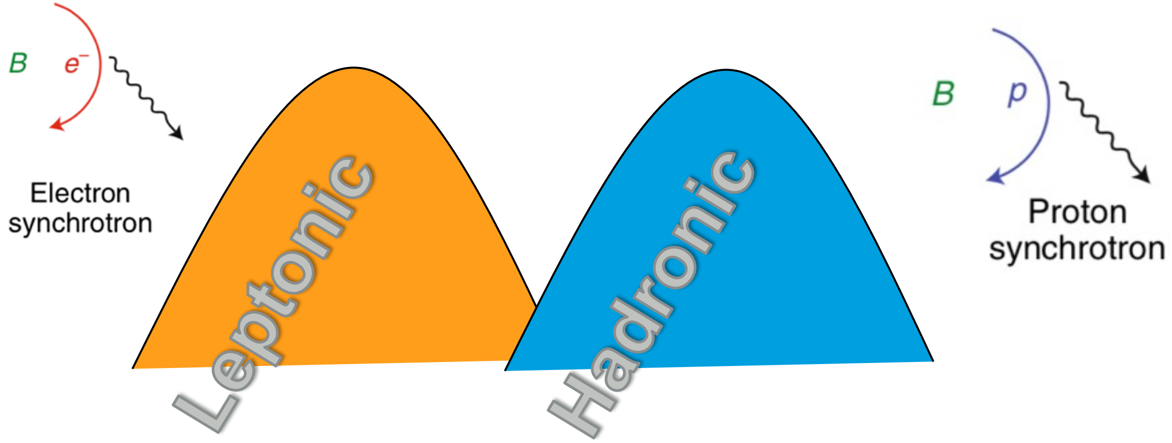
- Synchrotron self-Compton (SSC) or external Compton (EC) models



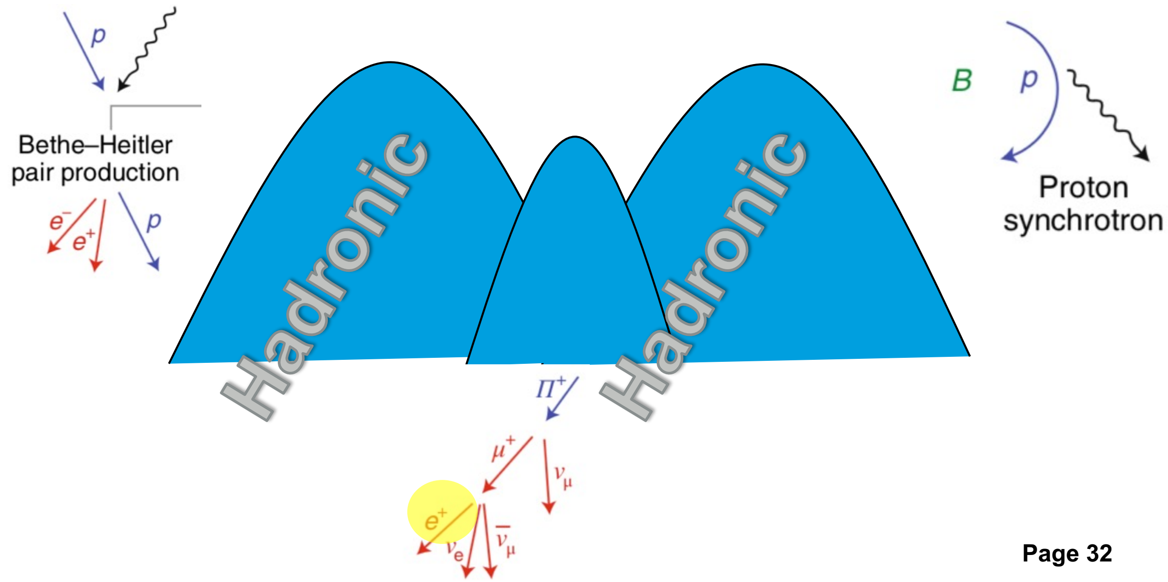
- Pion cascade models



- Proton synchrotron models (require large B')

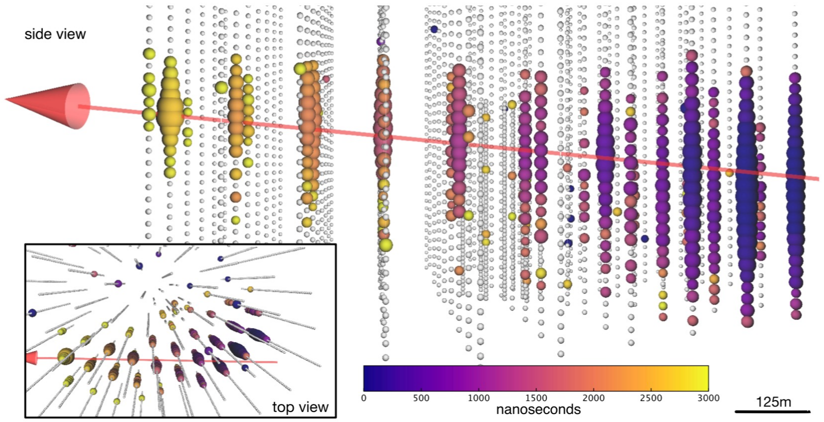


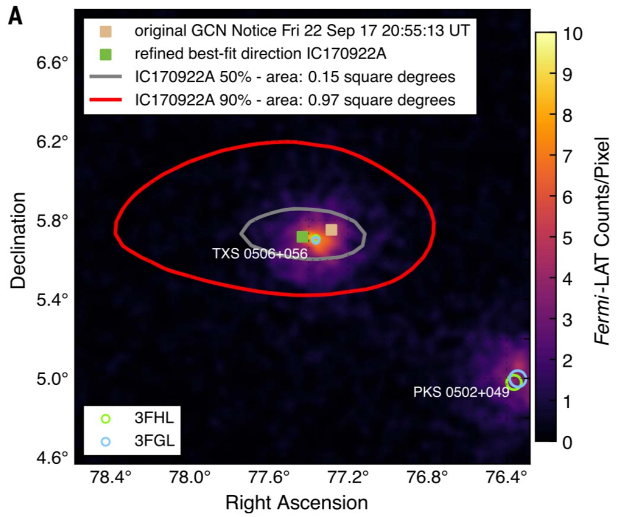
- More exotic hadronic models, for example:



A neutrino from the flaring AGN blazar TXS 0506+056

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



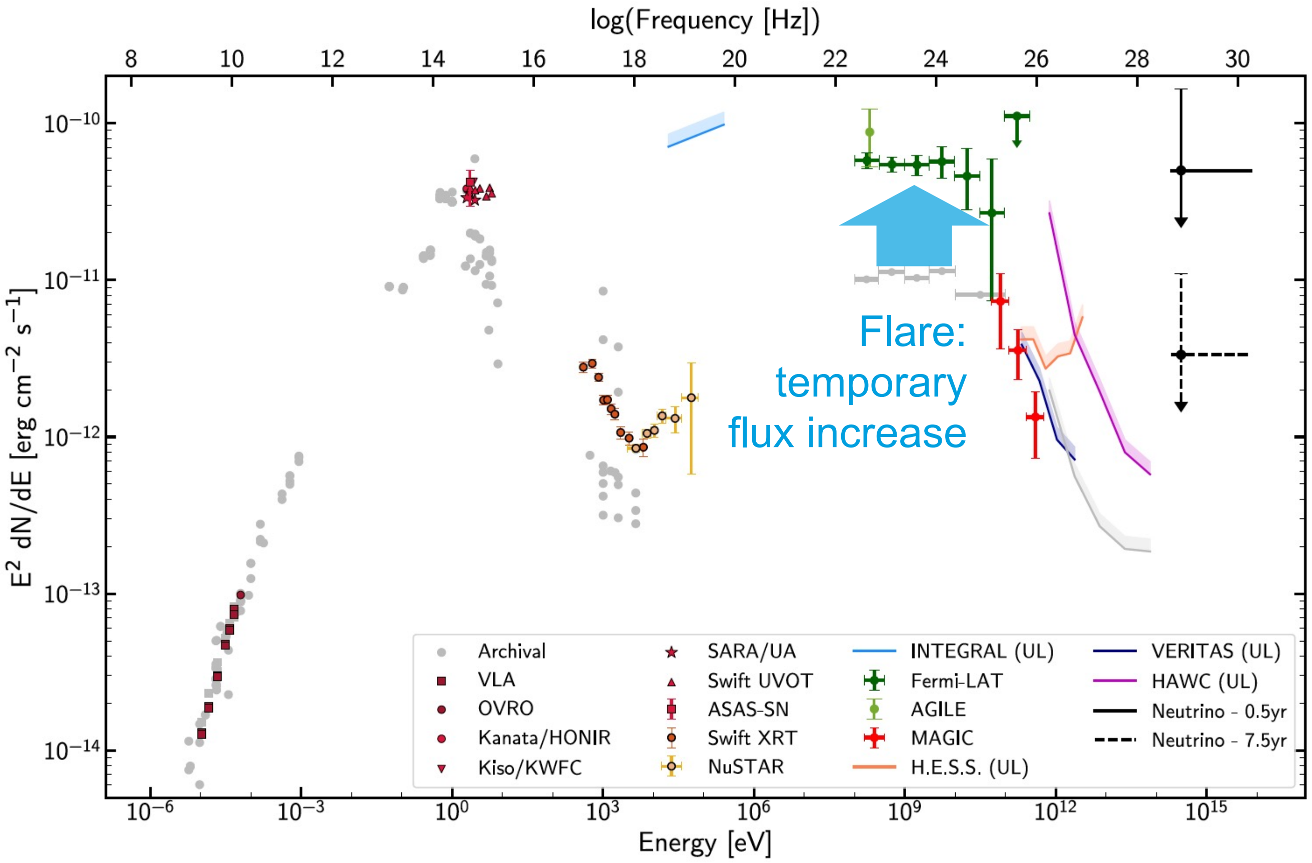


Observed by Fermi-*LAT* and MAGIC (blazar flare)

Significance for correlation: 3σ

$z = 0.3365 \pm 0.0010$
Paiano et al, 2018

SED from a multi-wavelength campaign

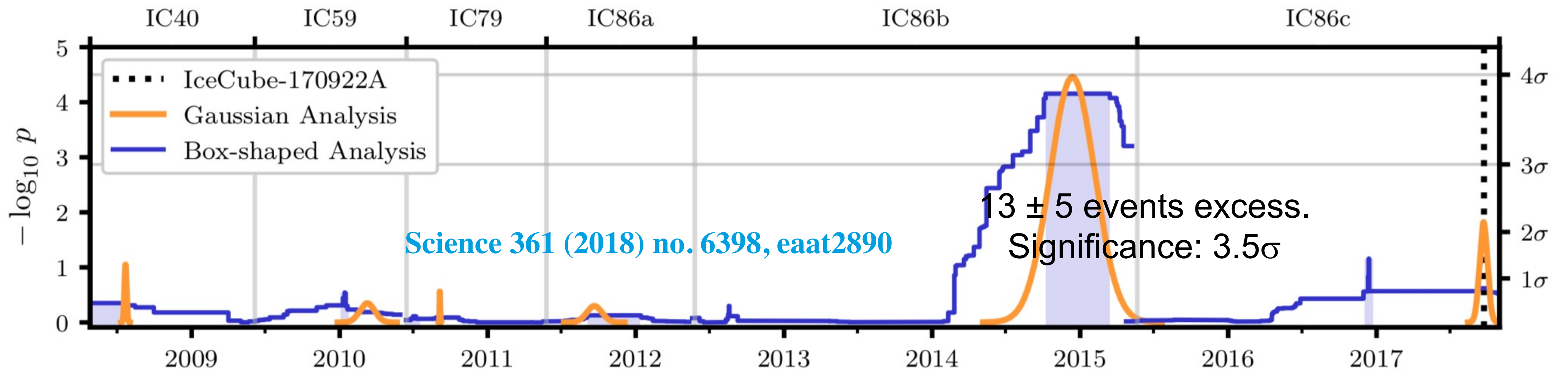


Color: coincident with neutrino; gray: archival data

Science 361 (2018) no. 6398, eaat1378

Analysis of archival neutrino (IceCube)

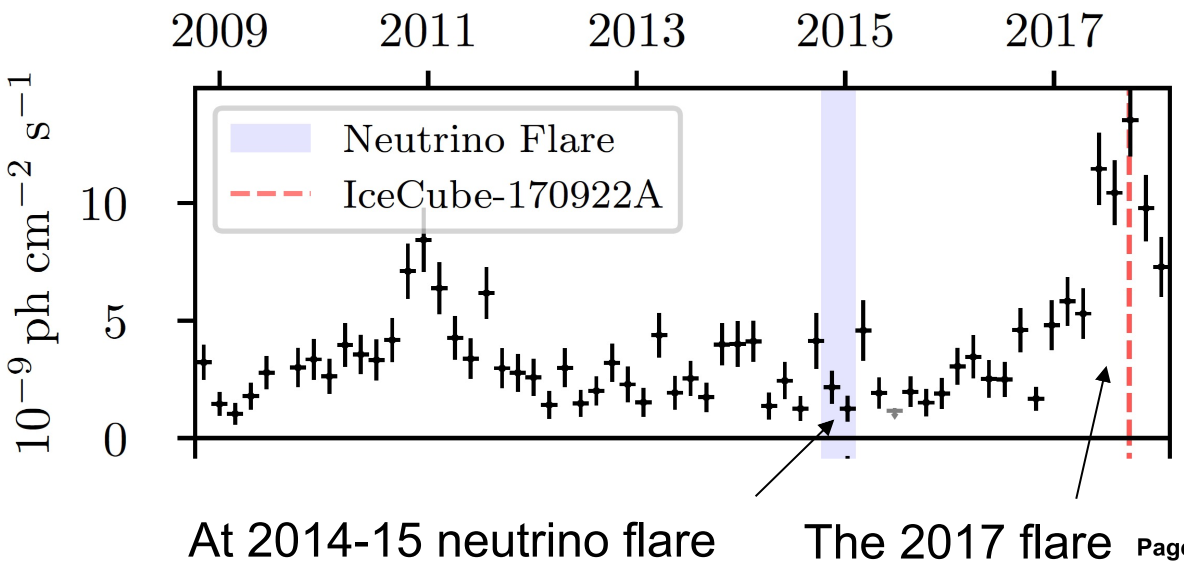
A (orphan) neutrino flare (2014-15) found from the same object in archival neutrino data



Science 361 (2018) no. 6398, eaat2890

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

Number of predicted neutrinos from a theoretical model?

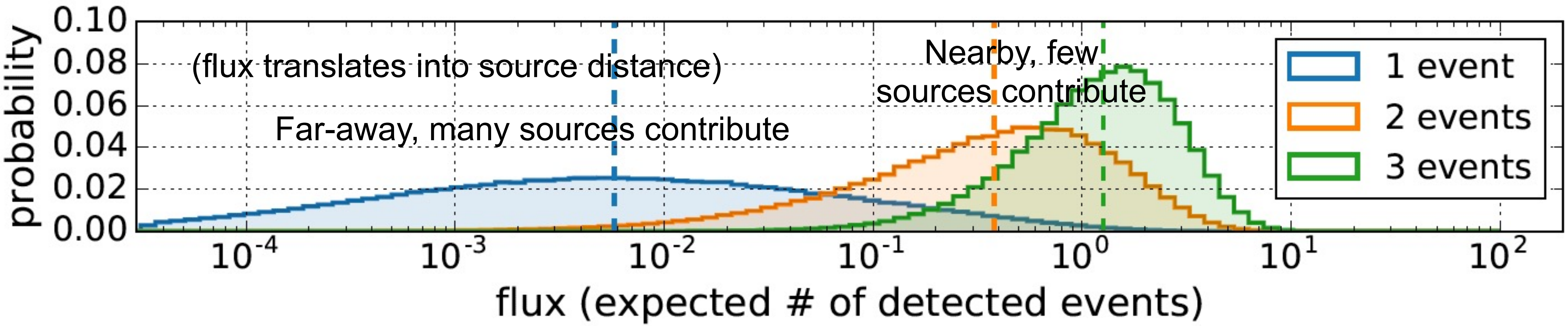
Sept. 22, 2017:
One neutrino observed

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

<u>One zone</u> model results (2017 flare)

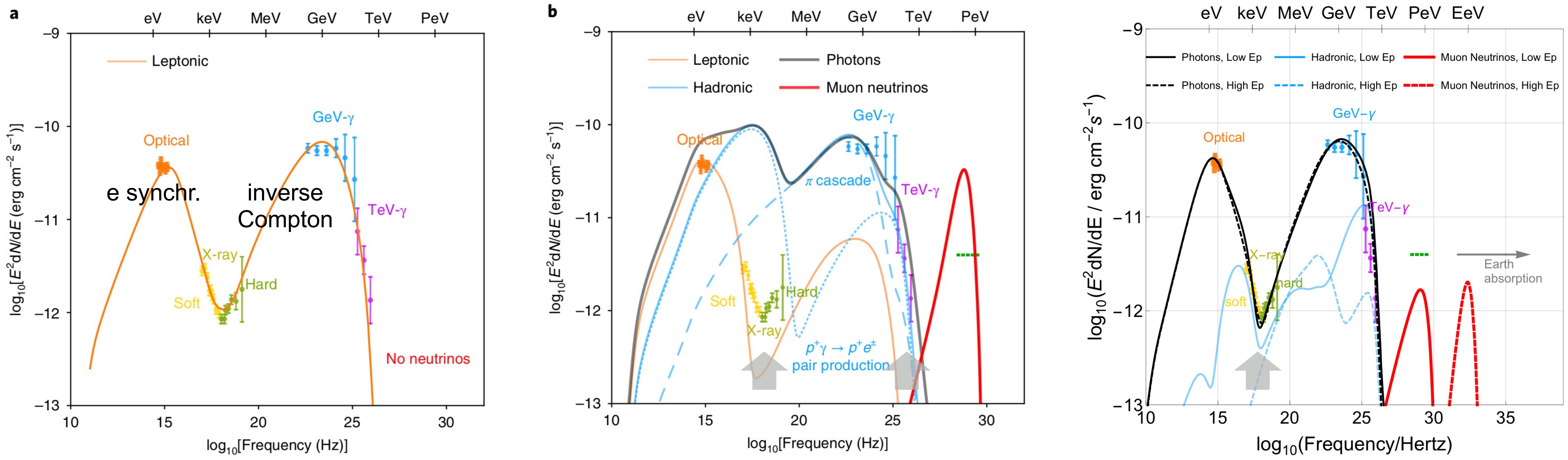
One spherical radiation zone
Fewest assumptions

R'

Leptonic models

Hadronic (π cascade) models

Hybrid or p synchrotron models



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

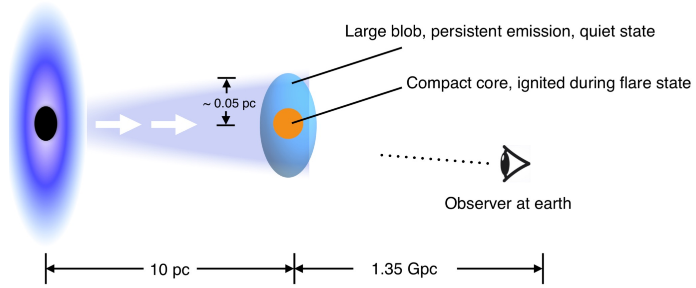
X-ray (and TeV γ-ray) data indicative for hadronic origin

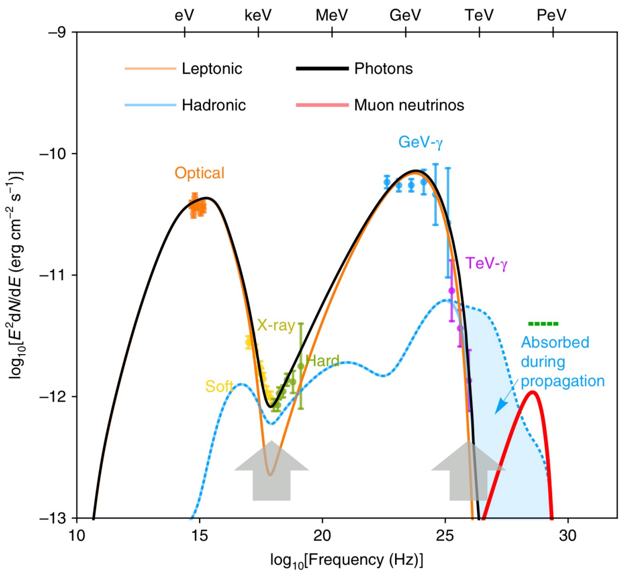
Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88;*
see also Cerutti et al, 2018; Sahakyan, 2018; Gokus et at, 2018; Keivani et al, 2018

More freedom through multiple radiation zones

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

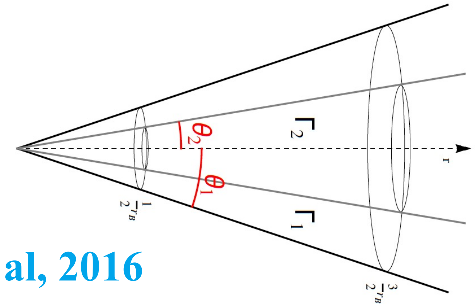
Formation of a compact core



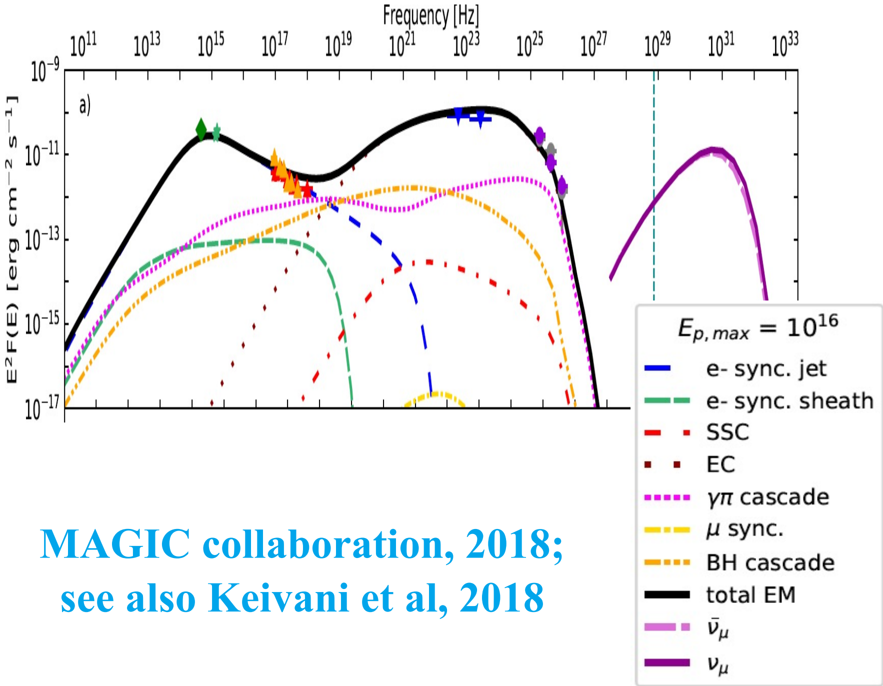


Gao et al, *Nature Astronomy 3 (2019) 88*

External radiation fields

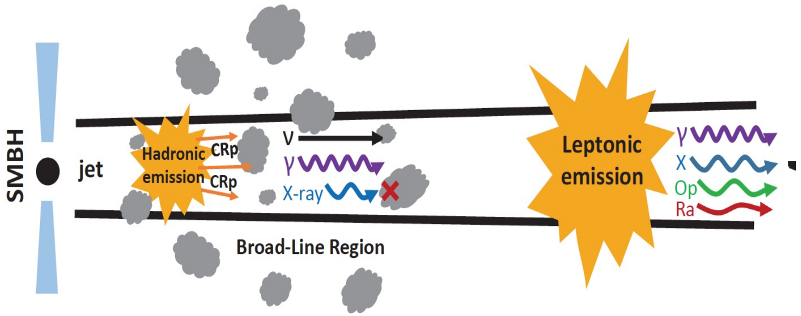


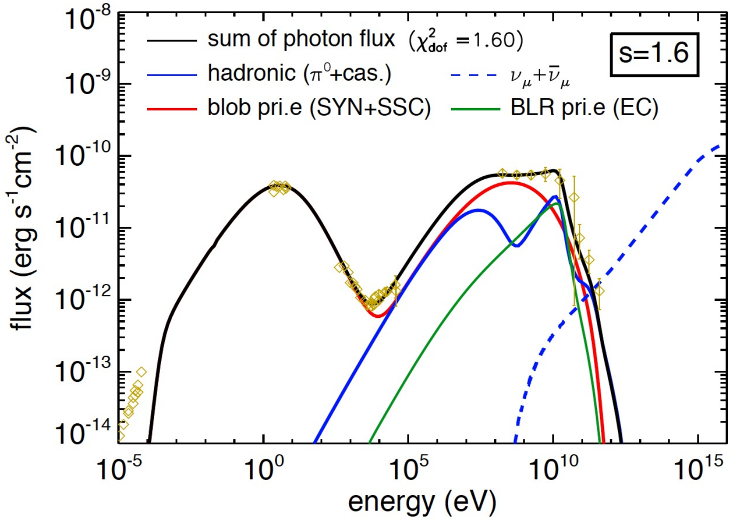
Sikora et al, 2016



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

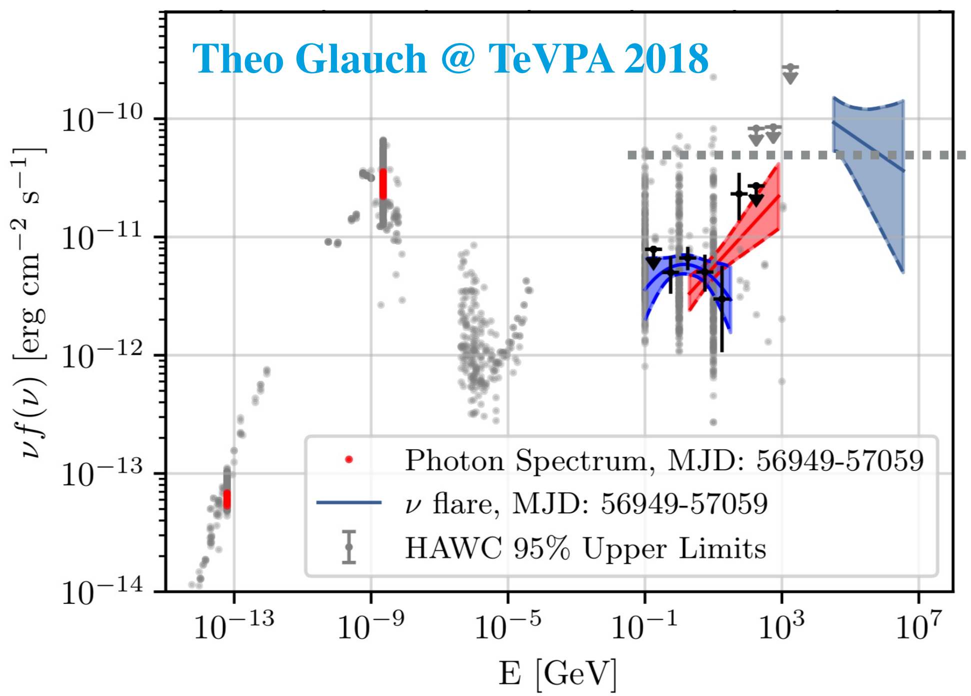
Jet-cloud interactions/ several emission zones





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

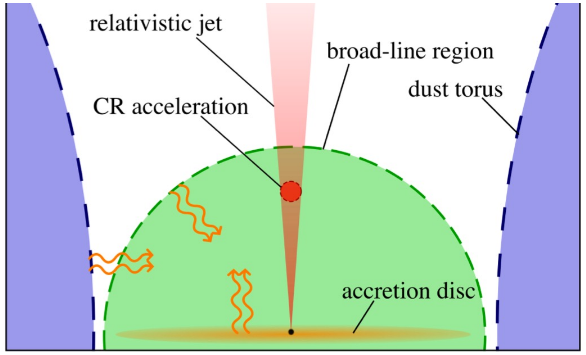
Options for hiding the gamma-rays (+electrons):

- **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

External radiation field example

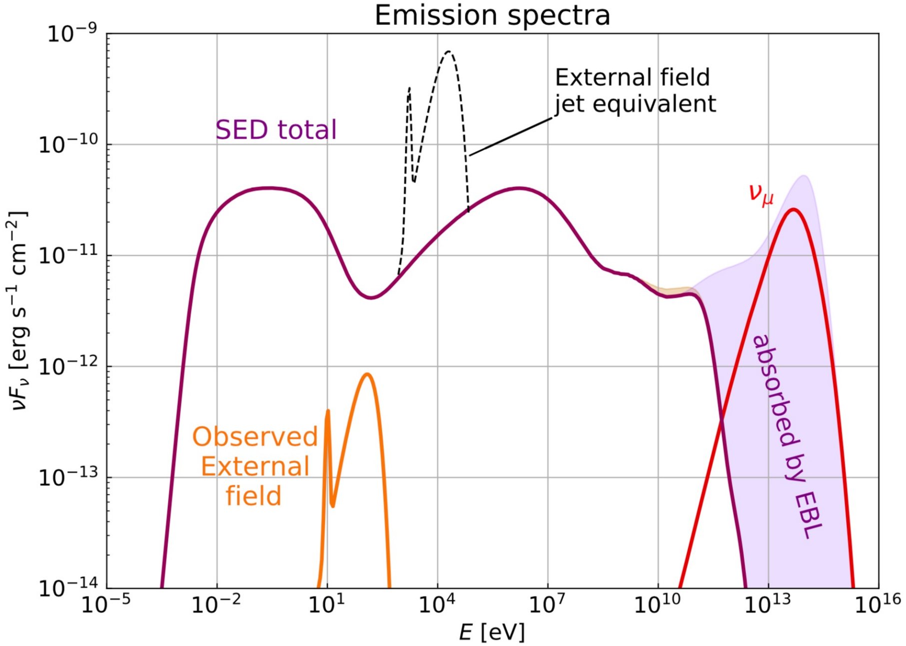
Can yield up to about five neutrino events during neutrino flare

Rodrigues et al, ApJ 854 (2018) 54



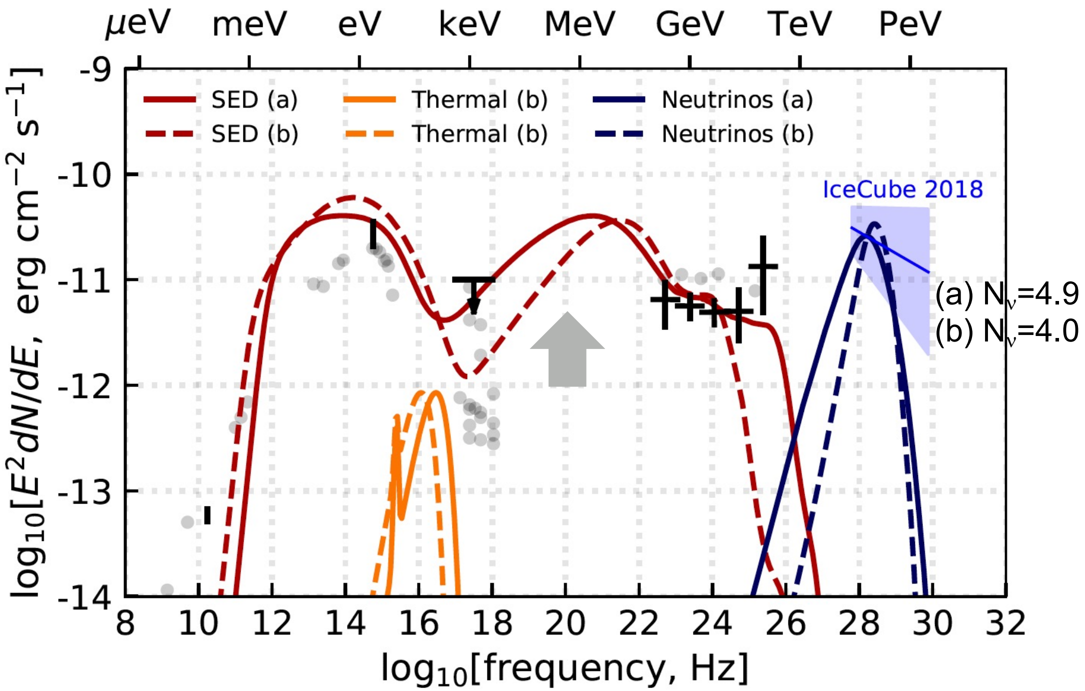
- TXS 0506+056 may be actually an FSRQ
  Padovani et al, MNRAS 484 (2019) L104

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



Courtesy X. Rodrigues

- Results for TXS 0506+056:



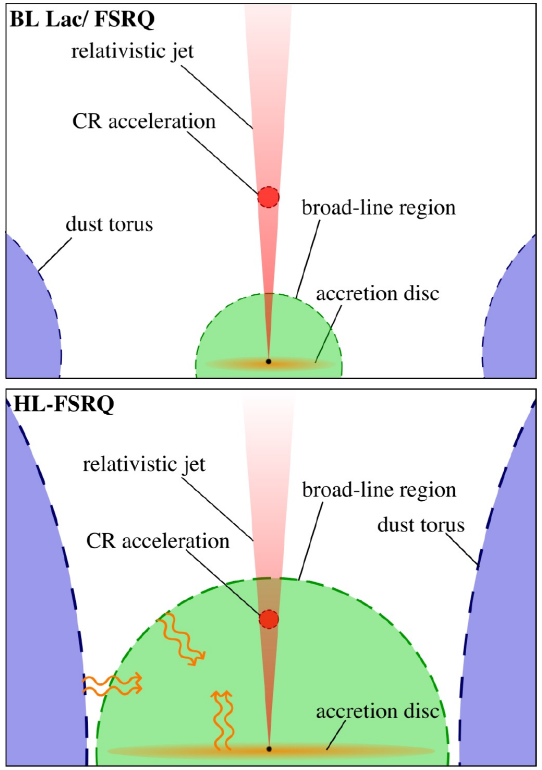
- Maximally five events; may be consistent with IceCube result if different spectral shape is assumed

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

Diffuse neutrino flux from AGN blazars?

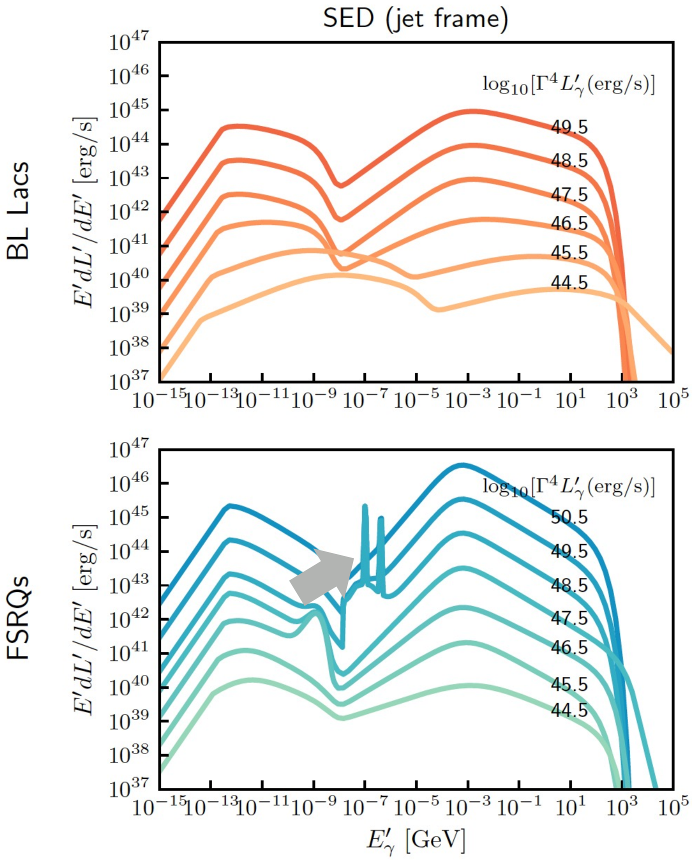
Ingredients: Neutrino production and population models

- Geometry determined by disk luminosity:

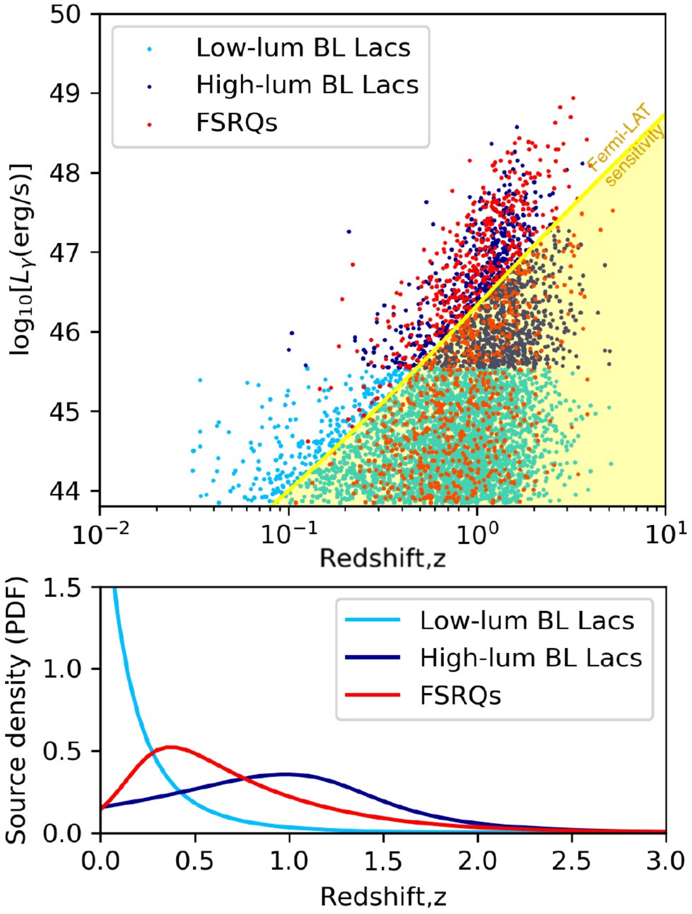


- For HL-FSRQs, the blob is exposed to boosted external fields

- SED follows "blazar sequence":



- Population model: LL-BL Lacs, HL-BL Lacs, FSRQs



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

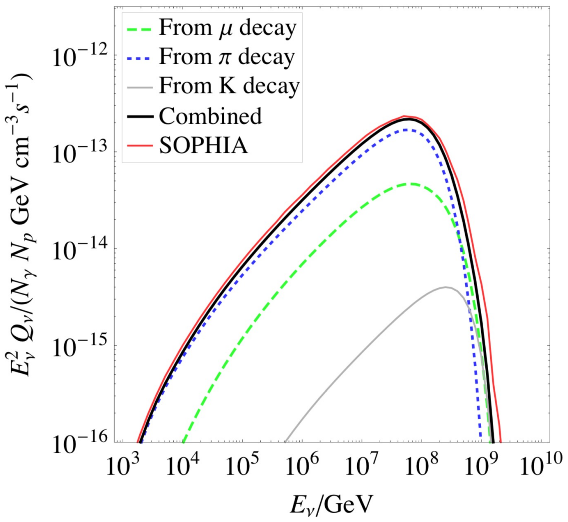
Rodrigues, Fedynitch, Gao, Boncioli, WW, ApJ 854 (2018) 54; Murase, Inoue, Dermer, PRD 90 (2014) 023007; Palladino, Rodrigues, Gao, WW, ApJ 871 (2019) 41; Rodrigues, Heinze, Palladino, van Vliet, WW, PRL 126 (2021) 191101

Describes diffuse γ-ray BG by construction!

Recap: AGN neutrino spectrum ...and two hypotheses

There is no unified (ν, γ-ray, UHECR) one zone model!

$E_{\nu,peak} \sim 0.05\ E_{p,max}$



$E_{p,max}$ ~1-10 PeV

Moderately efficient CR acclerators

1) AGN blazars describe neutrino data

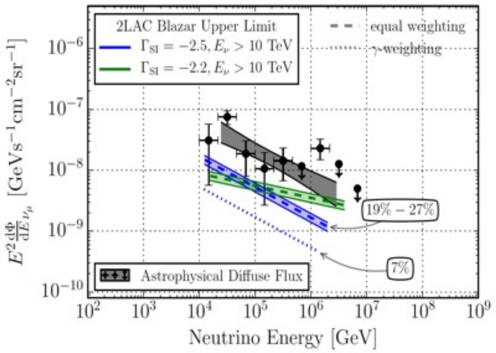
$E_{p,max}$ ~ 1-10 EeV
(R_{max} ~ 1-10 EV)

Very efficiency CR accelerators

2) AGN jets describe UHECR data

Postulate that:

1. The diffuse neutrino flux is dominated by AGN blazars (such as the extragalactic γ-ray flux!)
2. The blazar stacking limit is obeyed →
   IceCube, Astrophys. J. 835 (2017) 45



3. The baryonic loading evolves over the blazar sequence (depends on L_γ); the one of TXS 0506+056 is in the ball park of self-consistent SED models

Postulate that:

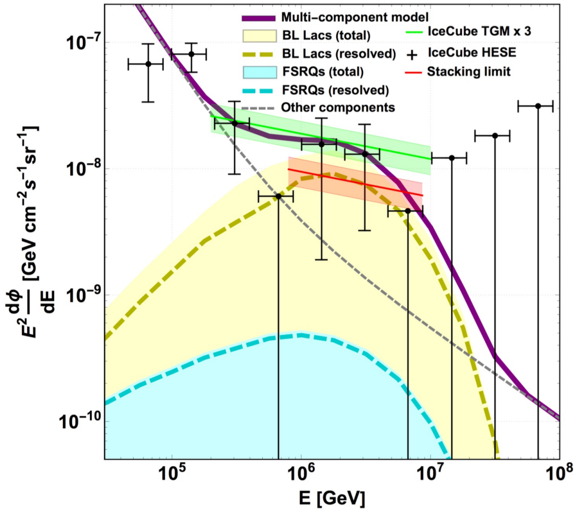
1. AGN jets (can be misaligned!) describe Auger data across the ankle
   (spectrum very well, composition observables roughly)
2. The injection compositon is roughly Galactic
3. Different classes (LL-BL Lacs, HL-BL Lacs, FSRQs) can have a different baryonic loading

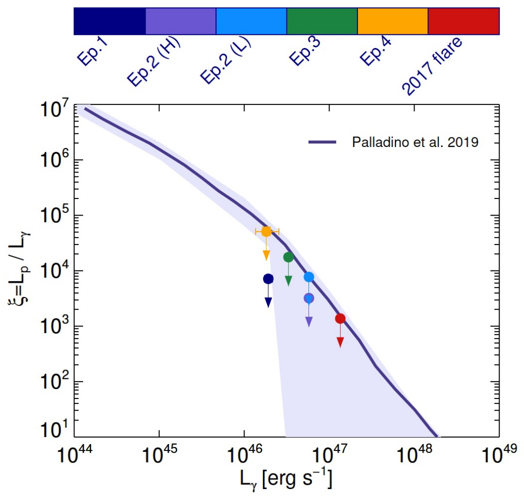
Conclusions for different hypotheses

More in part III!

1) AGN blazars describe neutrino data

1. Unresolved BL Lacs must dominate the diffuse neutrino flux
2. The baryonic loading must evolve, as otherwise efficient neutrino emitters (esp. FSRQs) stick out

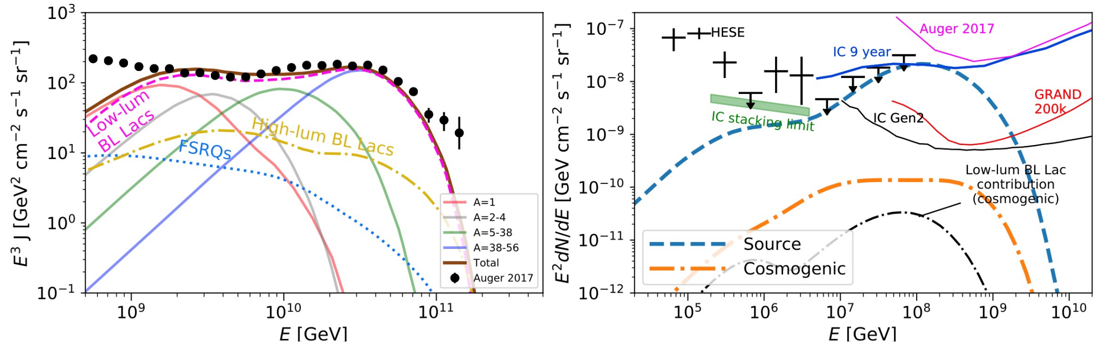




Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41;
Right Fig. from Petropoulou et al, arXiv:1911.04010: same behavior also found in multi-epoch description of TXS 0506+056

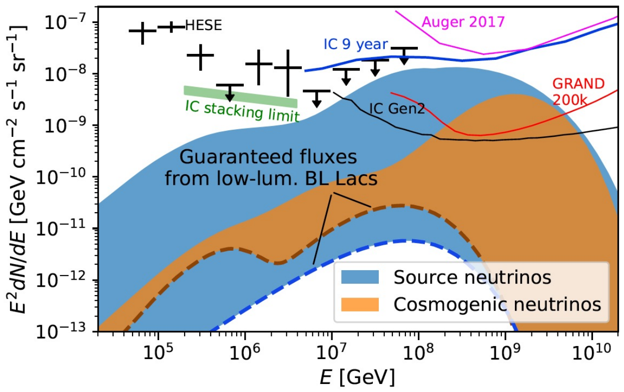
2) AGN jets describe UHECR data

1. UHECR description driven by LL-BL Lacs because of
   - Low luminosity → rigidity-dependent max. energy
   - Negative source evolution

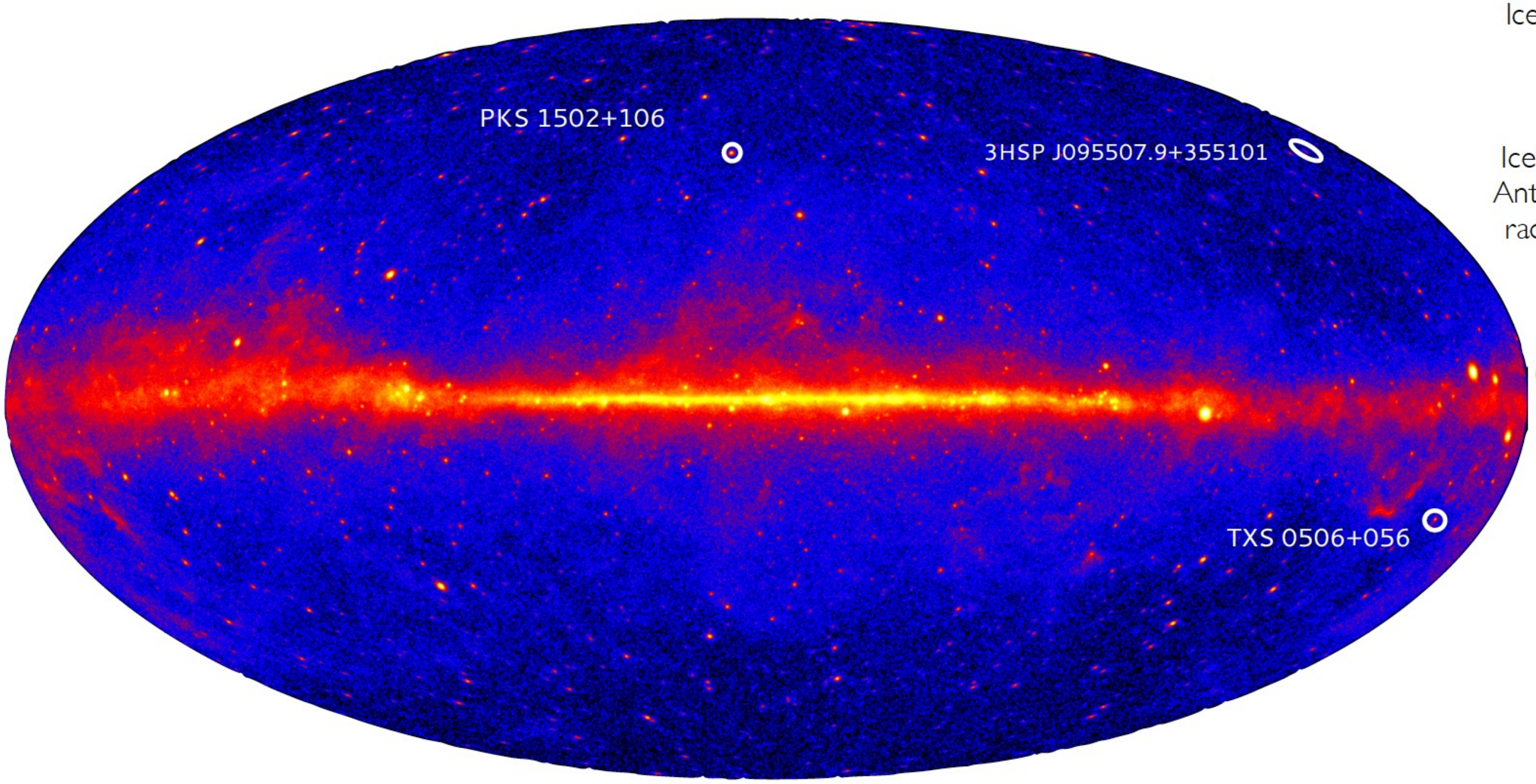


2. Neutrinos mostly come from FSRQs, peak at high energies, and may even outshine the cosmogenic flux there

Rodrigues, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021) 191101



Blazars coincident with high-energy neutrinos



Several dozen associations so far:

IceCube sends public alerts since 2016
Fermi-LAT follow up: 6 blazars in 23 follow-ups (S. Garrappa #812)
Telamon (M. Sadler #1320)
IceCube flares - X-rays (Sharma #299)
Antares flares - radio (Illuminati #1137)
radio blazars + Antares (Aublin #1240
IACTs: (Satalecka #907)

4FGL J0658.6+0636+IC201114A:
(de Menezes #296, Rosales de Leon #308)

3.3σ IceCube Coll 10yr Point-Source Analysis (3 blazars)
Franckowiak et al ApJ 893 (2020)
Giommi et al MNRAS 497 (2020)
Hovatta et al A&A 650 (2021)
Plavin et al ApJ 908 (2021)

Evaluating the significance of coincidences: Capel #1346

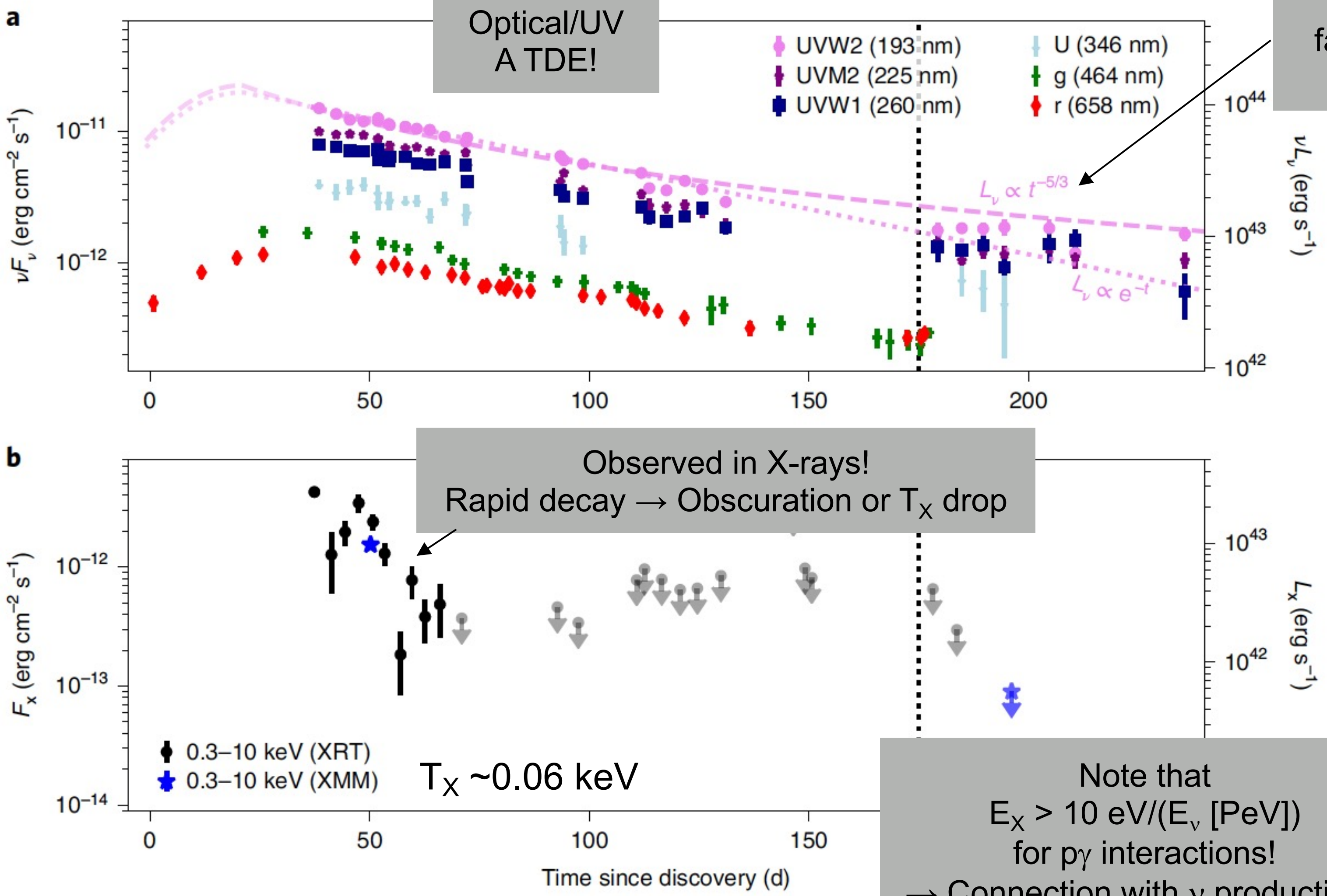
11 PKS B1424-418+IC35 Kadler, Nat Phys 12 (2016), Gao, Pohl, Winter, ApJ 843 (2017)

F. Oikonomou @ ICRC 2021

Neutrinos from TDEs

Tidal Disruption Events

Observation of a neutrino from AT2019dsg

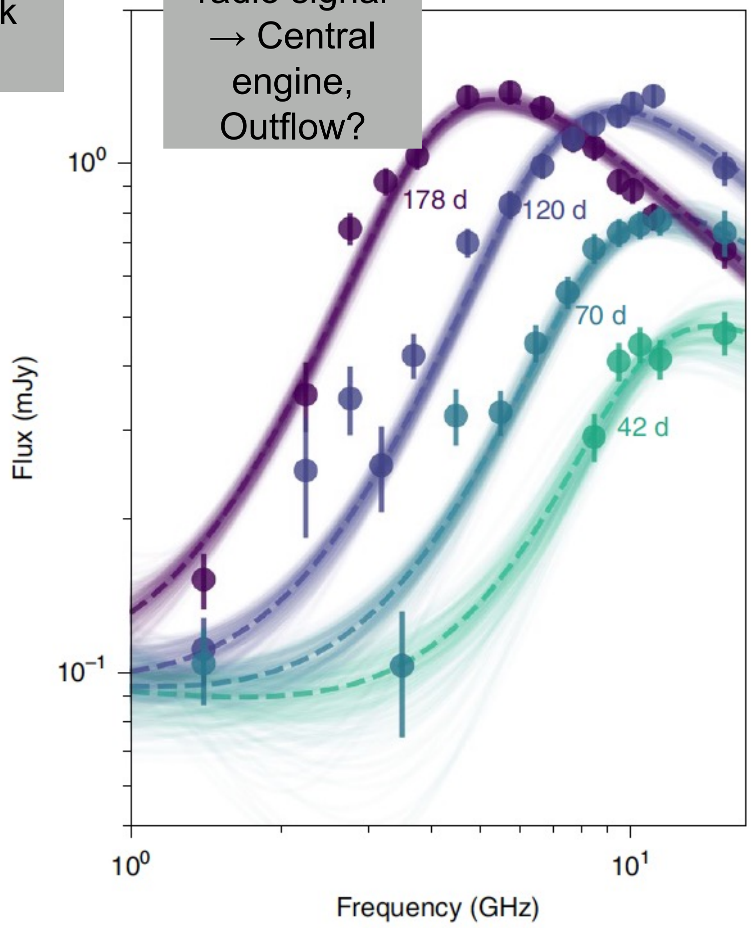


Optical/UV
A TDE!

Typical mass fallback rate

Observed in X-rays!
Rapid decay → Obscuration or T_X drop

T_X ~0.06 keV



Evolving radio signal → Central engine, Outflow?

Note that
E_X > 10 eV/(E_ν [PeV])
for pγ interactions!
→ Connection with ν production?

Stein et al, Nature Astronomy 5 (2021) 510

How to disrupt a star 101

- Force on a mass element in the star (by gravitation) ~ force exerted by the SMBH at distance

$$r_t = \left(\frac{2M}{m}\right)^{1/3} R \simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}$$

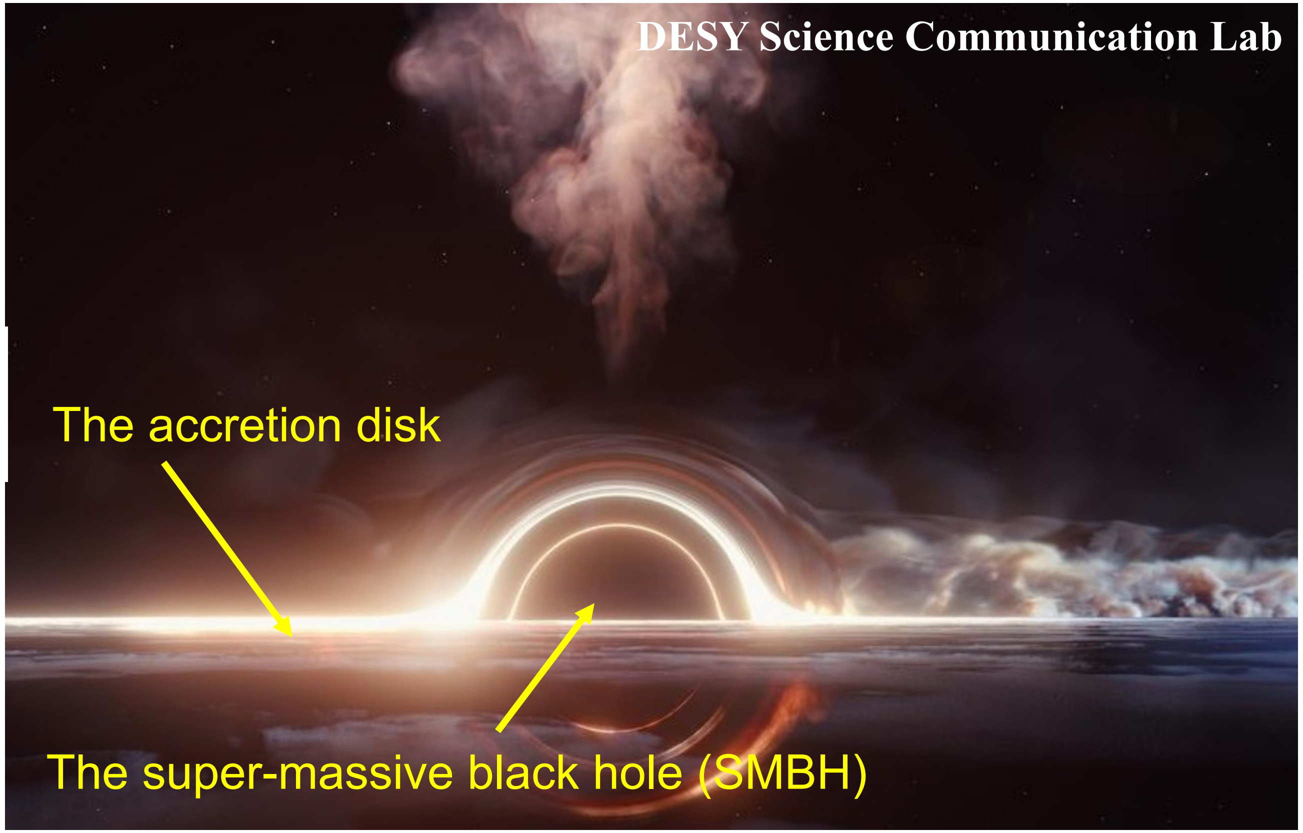
- Has to be beyond Schwarzschild radius

$$R_s = \frac{2MG}{c^2} \simeq 3 \times 10^{11}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)$$

- From the comparison ($r_t > R_s$) and TDE demographics, one obtains M <~ 10^8 $M_\odot$
  Hills, 1975; Kochanek, 2016; van Velzen 2017
- Schwarzschild time indicator for time variability of an engine?

$$\tau_s \sim 2\pi R_s/c \simeq 63\,\mathrm{s} \left(\frac{M}{10^6\ M_\odot}\right)$$

→ Fastest time variability ~ 100s



- Measure for the luminosity which can be re-processed from accretion through the SMBH: Eddington luminosity

$$L_{\mathrm{Edd}} \simeq 1.3\ 10^{44}\ \mathrm{erg/s}\,(M/(10^6\ M_\odot))$$

(TDEs are often Super-Eddington at peak)

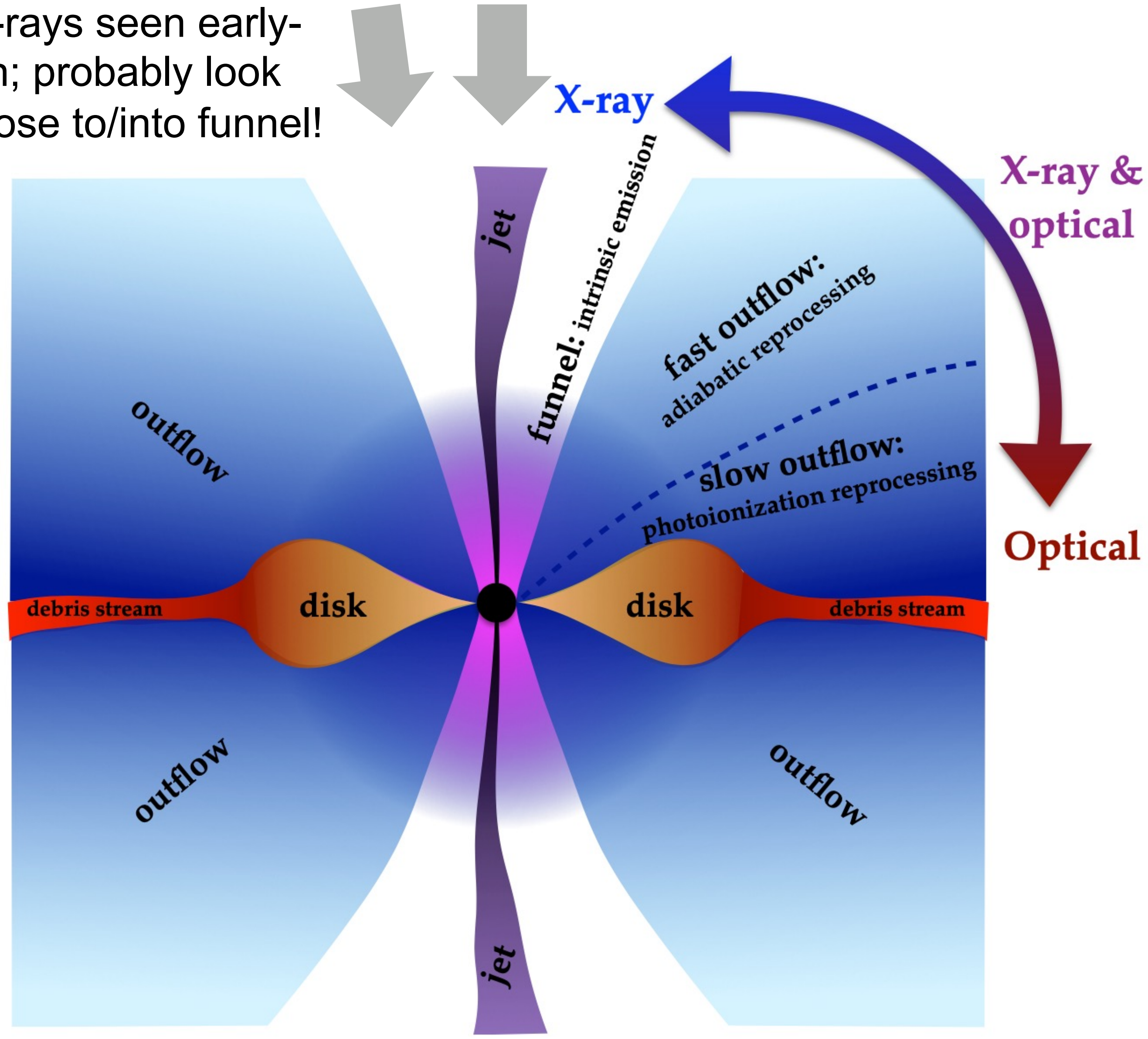
- Measure for the maximally available energy: E_{max} ~ 10^{54} erg (half a solar mass)

A TDE unified model

... used to motivate a concordance model

- Matches several aspects of AT2019dsg very well (L_{bol}, R_{BB}, X-rays/obscuration?)
- Supported by MHD sims; $M_{SMBH} = 5\ 10^6\ M_\odot$ used; we use **conservatively $M_{SMBH} = 10^6\ M_\odot$**
- A jet is optional in that model, depending on the SMBH spin
- Observations from model:
  - Average mass accretion rate $\dot{M} \sim 10^2 L_{\mathrm{Edd}}$
  - ~ 20% of that into jet
  - ~ 3% into bolometric luminosity
  - ~ 20% into outflow
  - Outflow with
    v ~ 0.1 c (towards disk) to
    v ~ 0.5 c (towards jet)

X-rays seen early-on; probably look close to/into funnel!

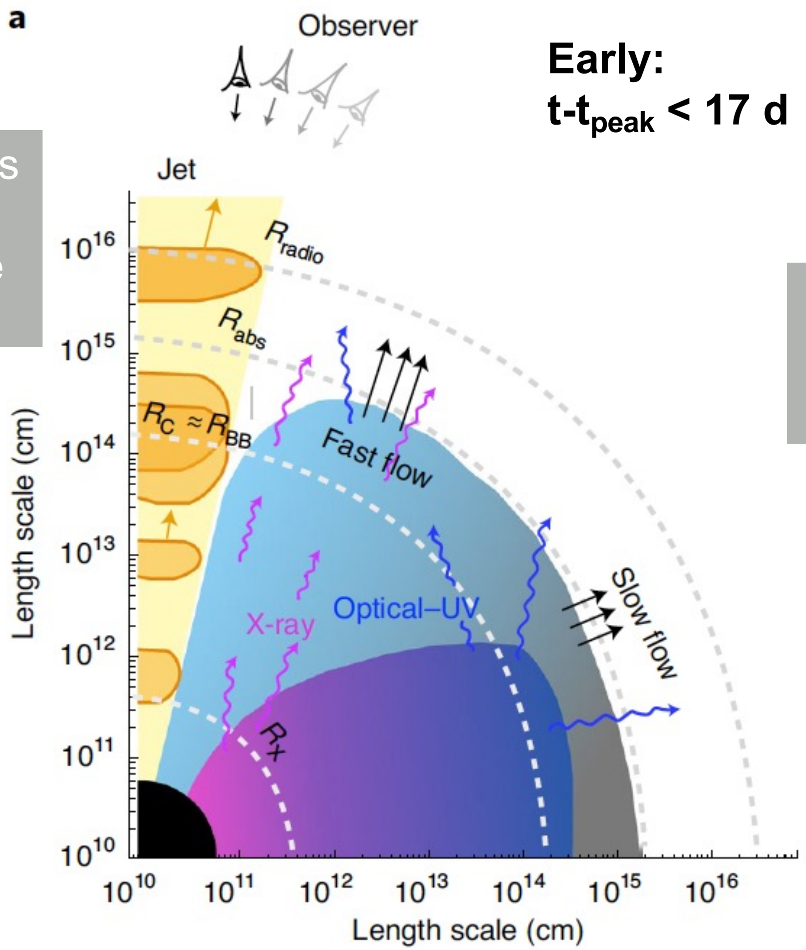


Dai, McKinney, Roth, Ramirez-Ruiz, Coleman Miller, 2018

A jetted concordance scenario

… based on TDE unified model

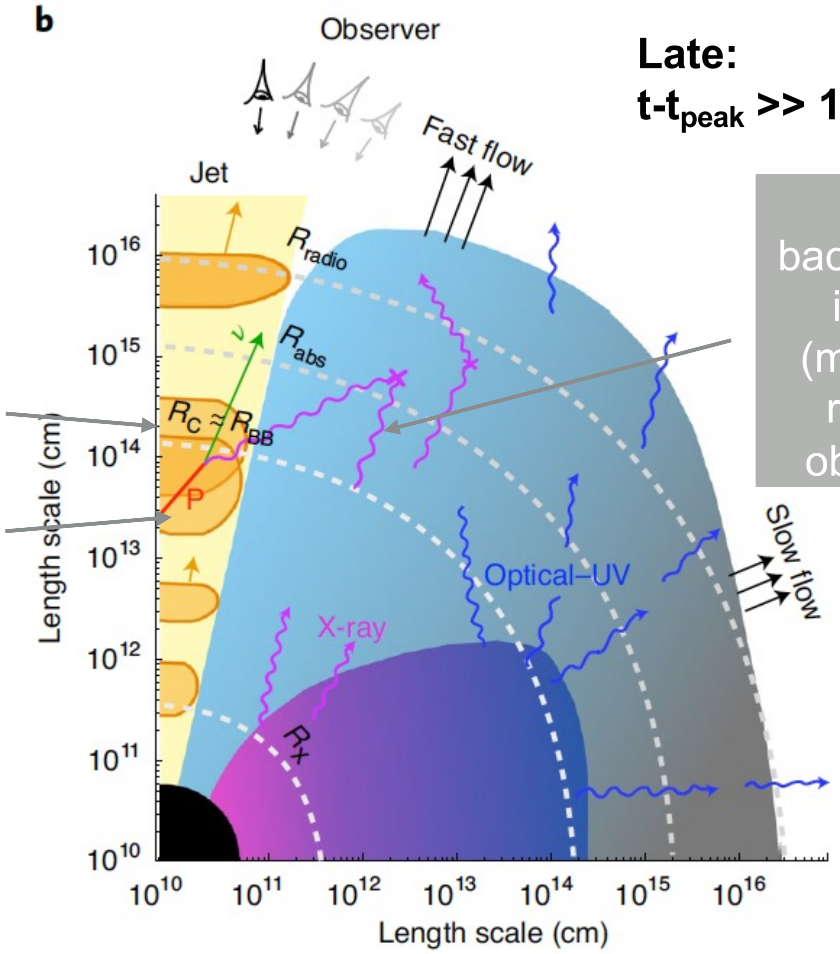
No neutrinos at t_{peak} (no intense target)



Early:
$t-t_{peak}$ < 17 d

Production radius decreases with R_{BB} (observed)

Particle acceleration in internal shocks



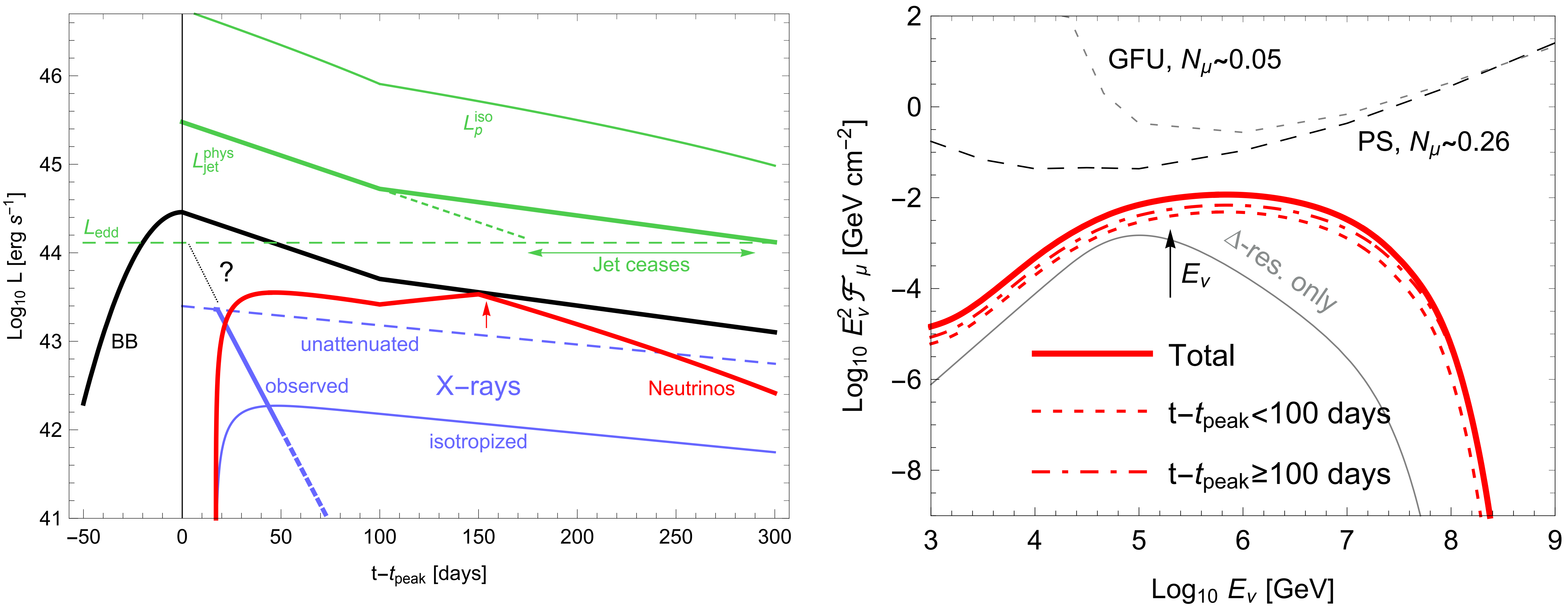
Late:
$t-t_{peak}$ >> 17 d

X-ray back-scattering in outflow (may also be reason for obscuration)

Winter, Lunardini, Nature Astronomy 5 (2021) 472;
see also Liu, Xi, Wang, 2020 for an off-axis jet

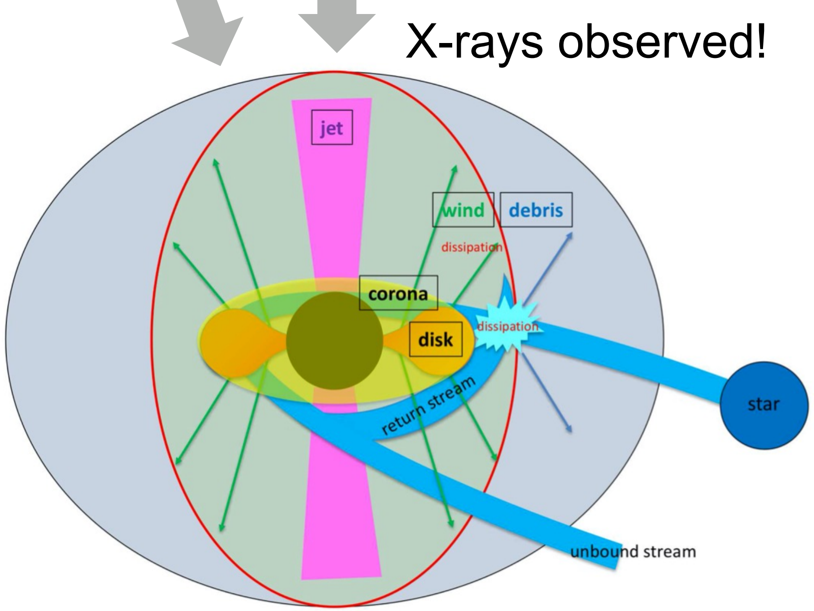
Results for neutrino luminosity lightcurve and spectrum

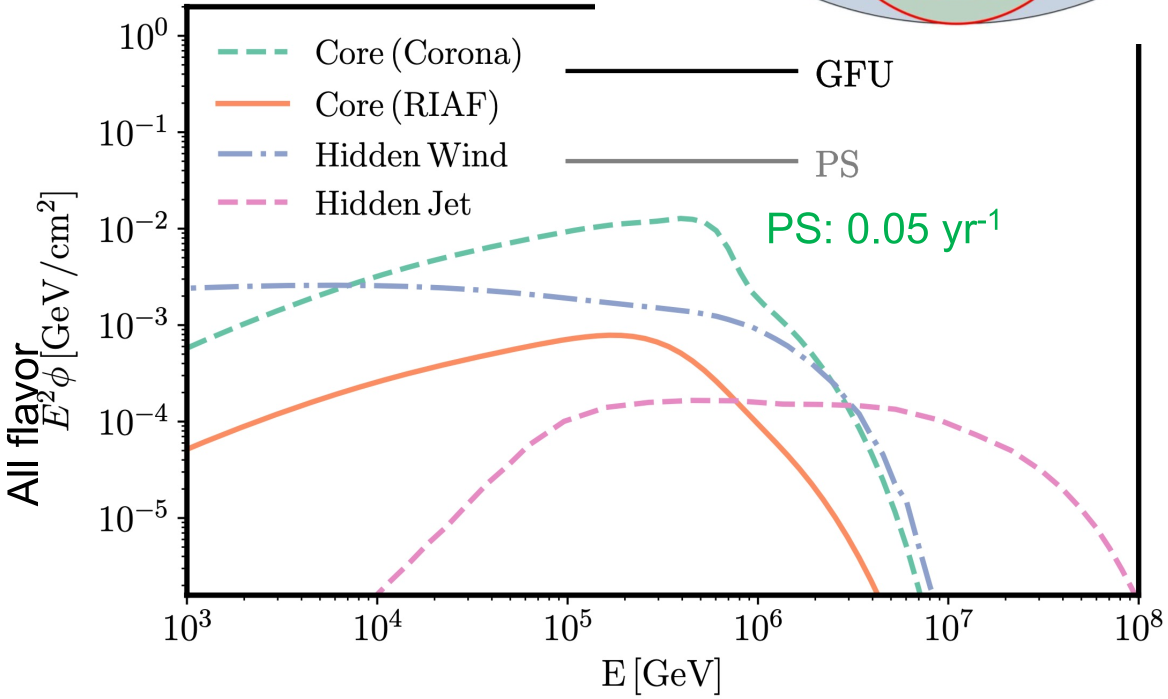
(black/thick purple: follow data; red curve: computational result; others: model ingredients)



Winter, Lunardini, Nature Astronomy 5 (2021) 472
(slightly modified figure)

Challenges and comparison to alternatives





Murase et al, arXiv:2005.08937; see also Hayasaki, Yamazaki, 2019

Jetted models

- Choked jet: probably too low luminosity
- **Jet breakout model: where are other non-thermal signatures?** (see backup)

Core models

- Corona model: parameters guesstimated from AGNs (where large assumed B for efficient stochastic acceleration is potentially in conflict with radio data ... Inoue, Khangulyan, Doi, arXiv:2105.08948)
- RIAF phase:
  typically many years after peak

Hidden wind model:

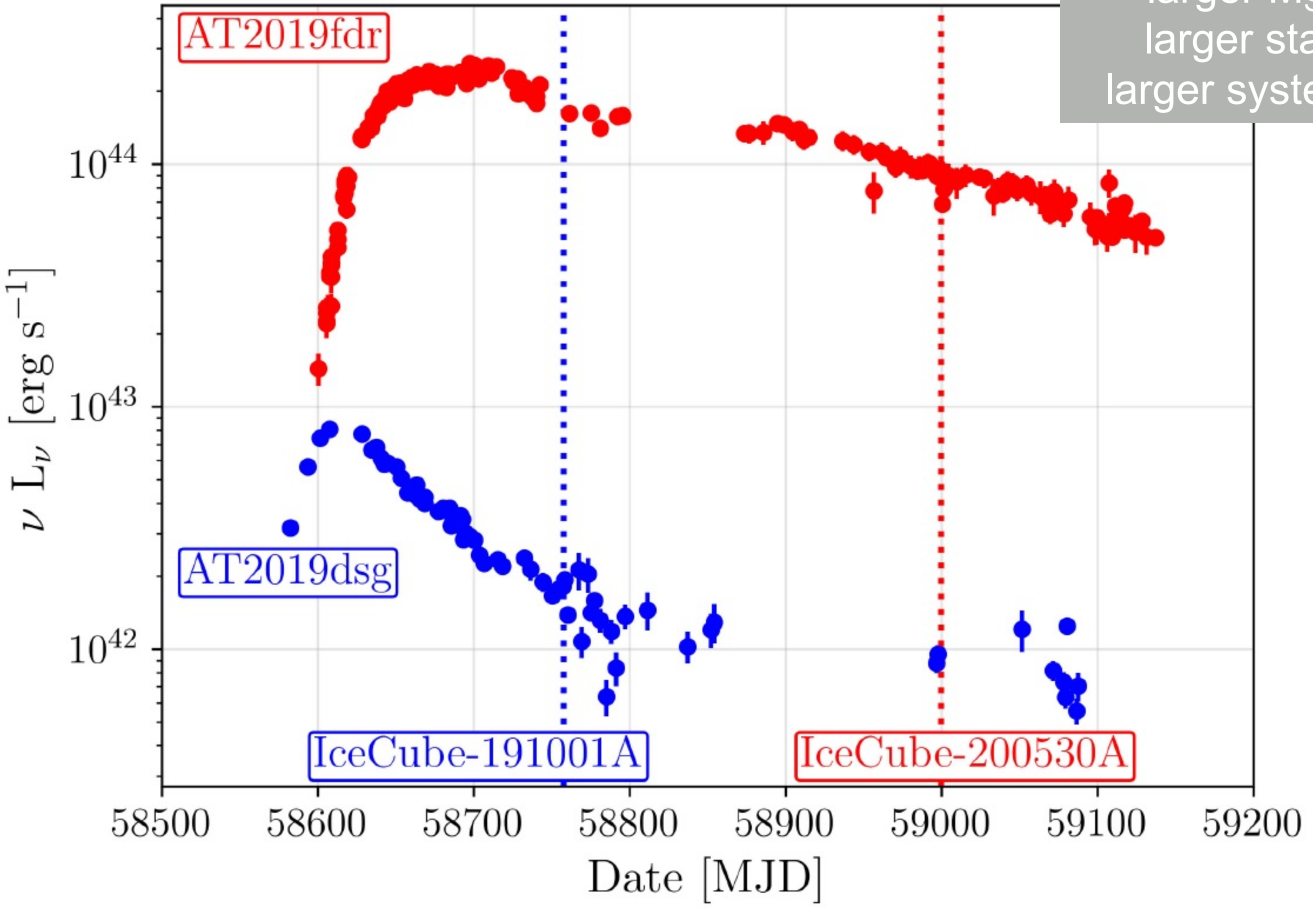
- Large uncertainties from geometry

Alternatives to jetted models have in common:

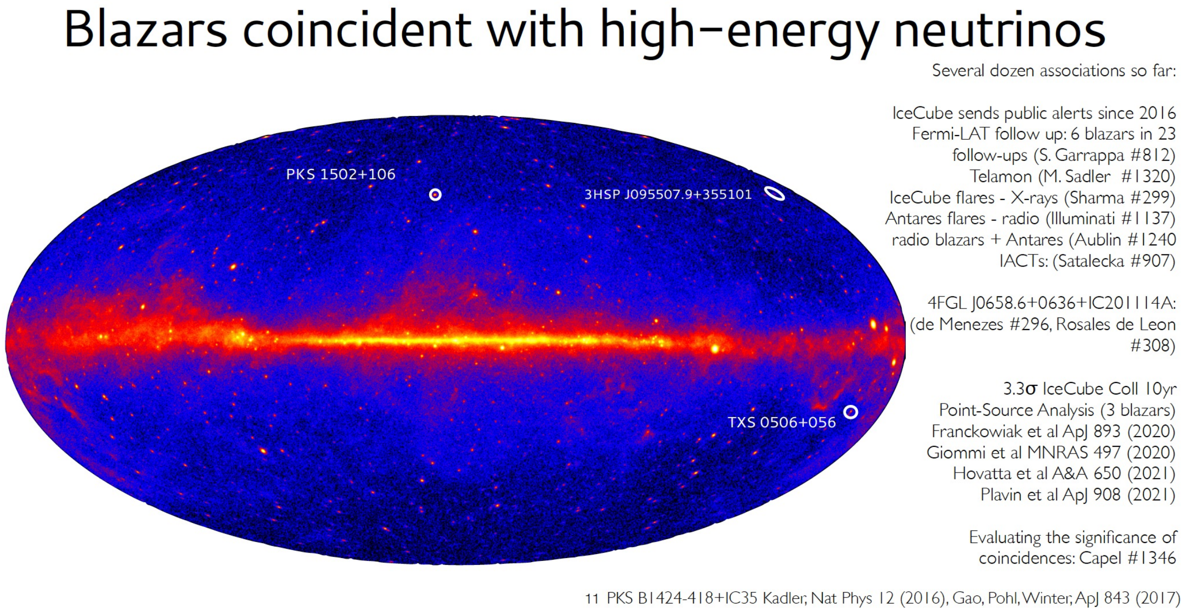
- Lower neutrino event rate
- No late-arrival prediction for neutrino
- Require large SMBH mass > $10^7\ M_\odot$ (→ energetics problem, see backup)
- Do not explain why X-rays seen

Part II: Outlook

More luminous, longer duration → larger M_{SMBH}, larger star, larger system?



F. Oikonomou @ ICRC 2021



From: Robert Stein & Simeon Reusch @
Cosmic Rays and Neutrinos in the Multi-Messenger Era, Paris, Dec. 7-11, 2020;
Reusch et al, in preparation

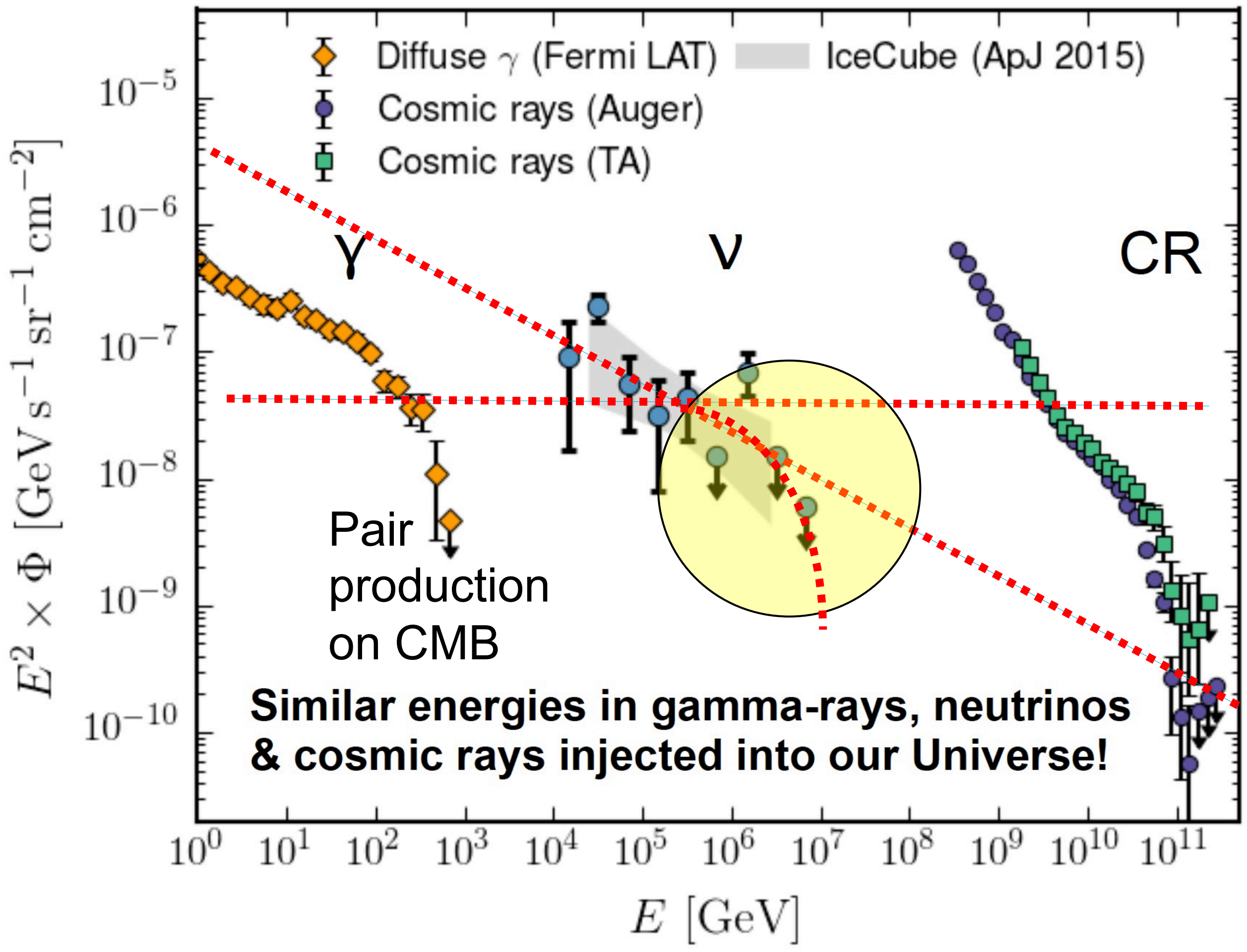
Part 3: UHECR connection

Energetics: The Waxman-Bahcall argument

- Neutrino flux matches UHECR injection
  Waxman, Bahcall,
  Phys. Rev. D59 (1999) 023002

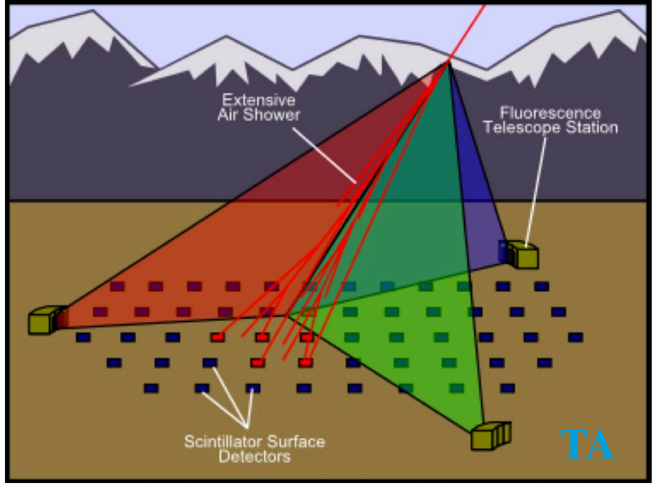
  ... and diffuse γ-rays
  see Fermi-LAT, Astrophys. J. 799 (2015) 86

- Caveats:
  - Extrapolation over many order of E
  - Energy imbalance
    if softer than E^{-2}



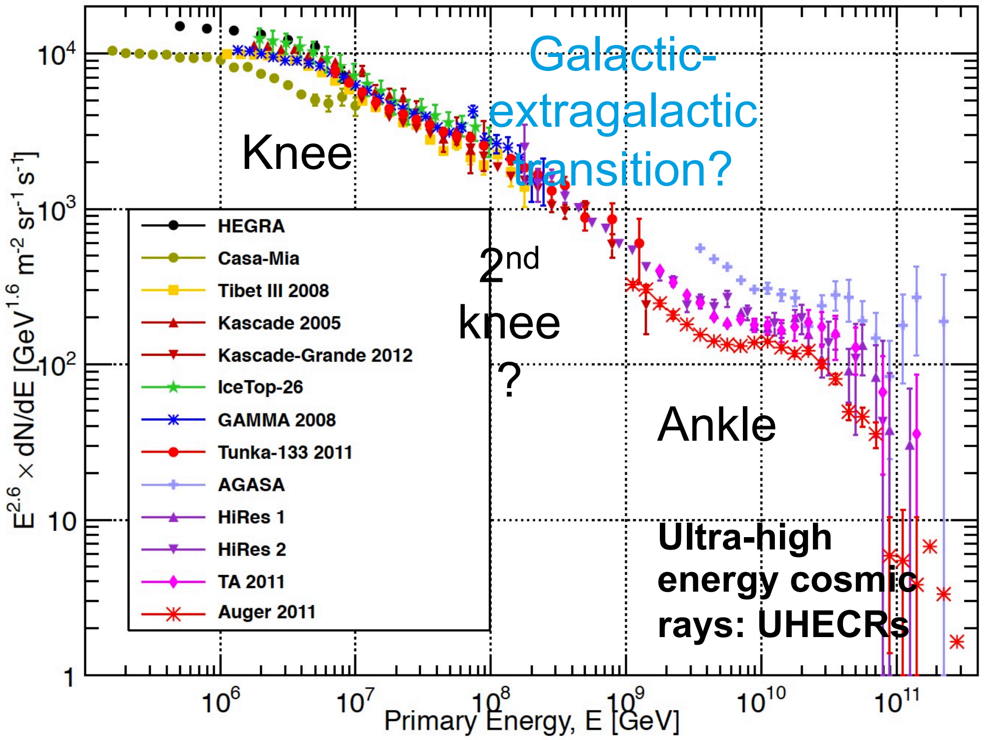
Mohrmann, Kowalski

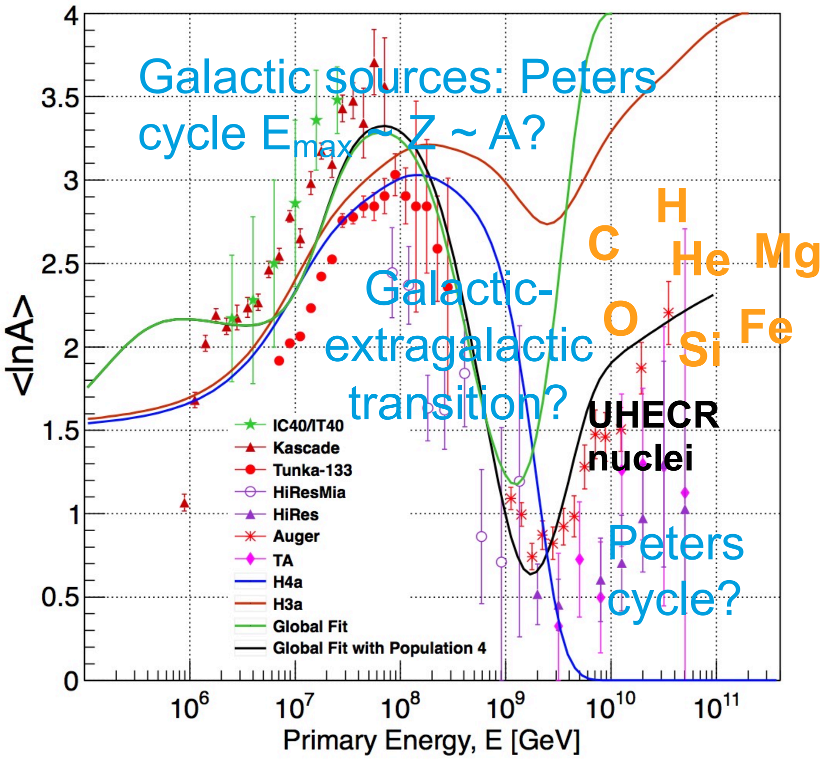
UHECRs: Spectrum and composition



- Charged particles, proton or heavier nuclei
- Spectrum with breaks (knee, 2nd knee, ankle)
- Composition non-trivial function of energy

Observables:
1) Spectrum
2) Composition: $\langle X_{max} \rangle$
3) Composition: $\sigma(X_{max})$

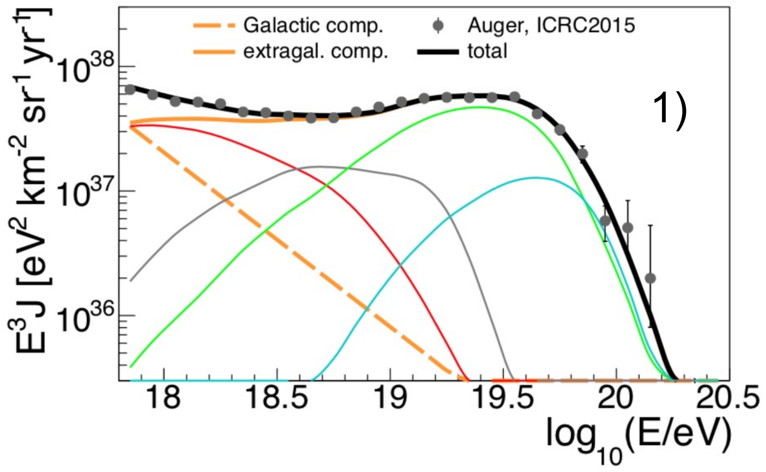


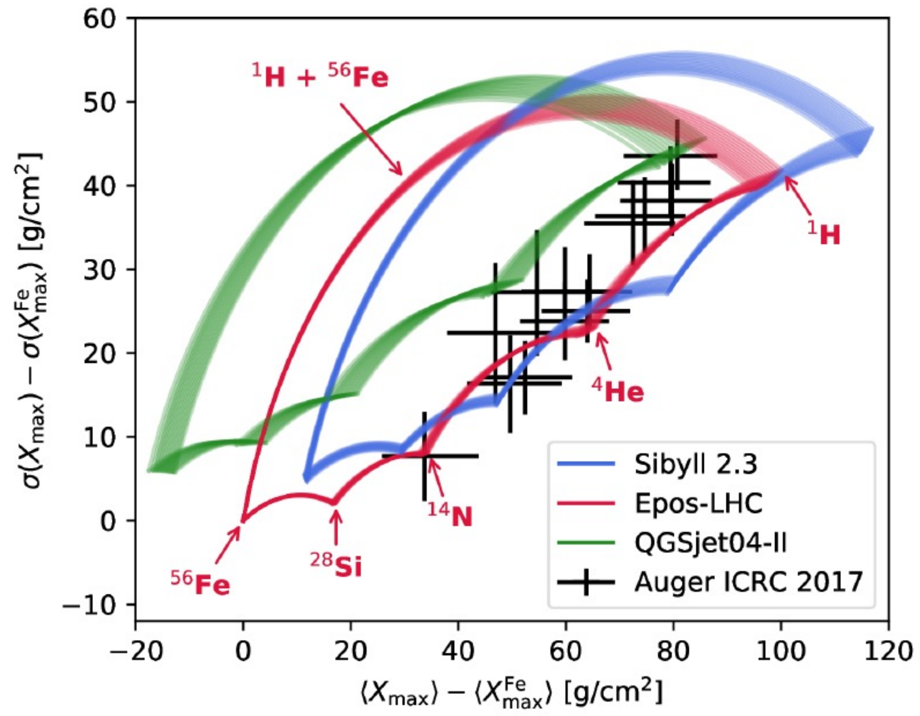


Lorentz force = centrifugal force ➔ E_{max} ~ Z c B R ~ Z (Peters cycle)

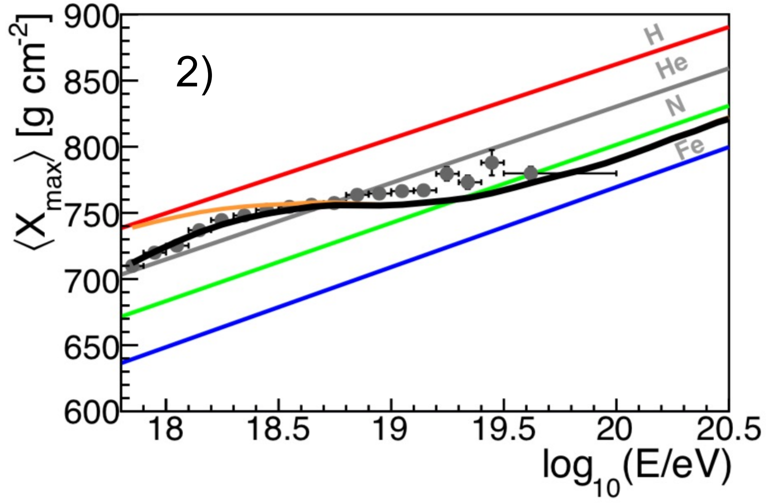
Gaisser, Stanev, Tilav, 2013

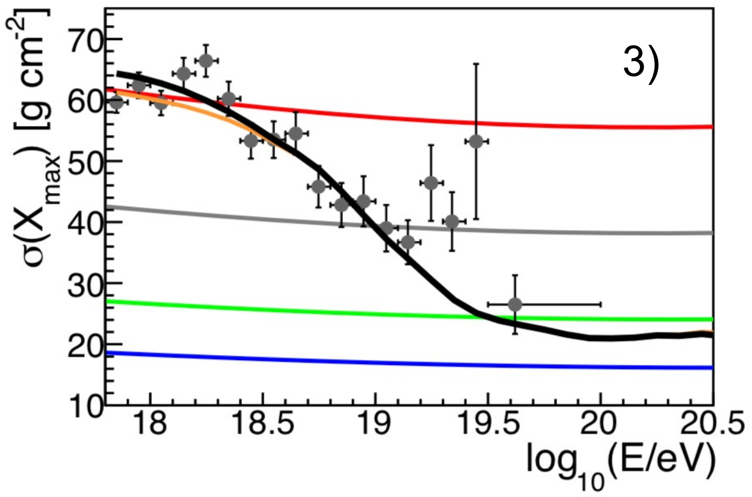
Description of observables (a typical example)





Data favor pure composition!





Observables:
1) Spectrum
2) Composition: $<X_{max}>$
3) Composition: $\sigma(X_{max})$

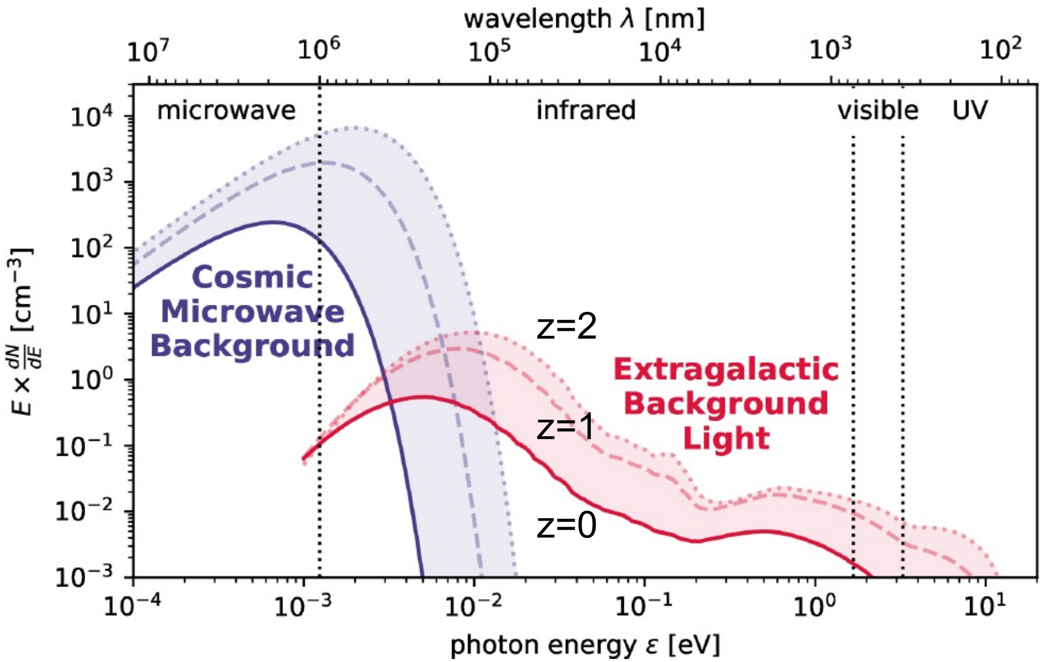
Biehl, Boncioli, Lunardini, WW, Sci. Rep. 8 (2018) 1; Upper right plot from PhD thesis Jonas Heinze, https://edoc.hu-berlin.de/handle/18452/22177

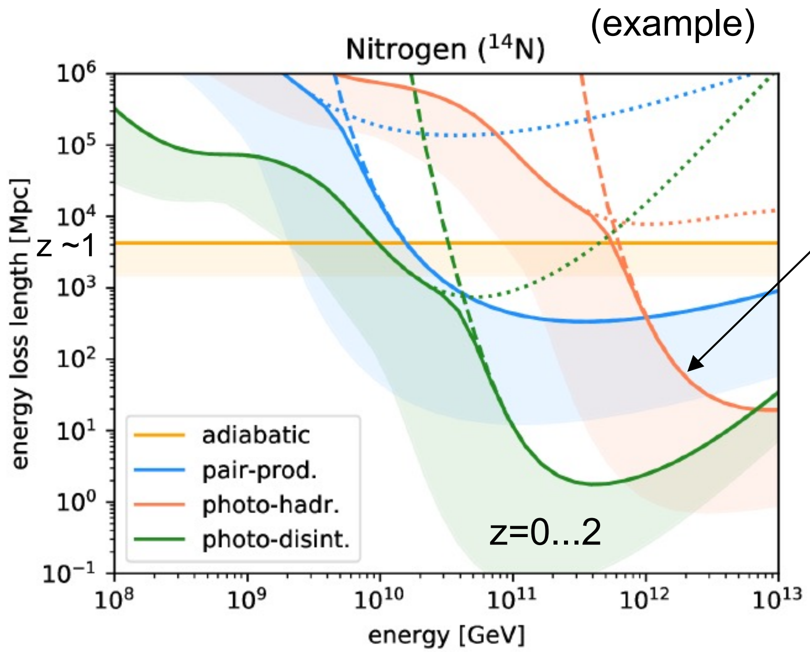
Transport of UHECRs

Transport equation similar to radiation models (solved in co-moving density Y), for species *i*:

$$\partial_t Y_i = \underbrace{-\partial_E(b_{\mathrm{ad}} Y_i)}_{\text{Adiabatic losses (expansion of Universe)}} \underbrace{- \partial_E\left(b_{e^+e^-} Y_i\right)}_{\text{Pair production losses}} \underbrace{- \Gamma_i Y_i}_{\text{Interactions (escape term)}} + \underbrace{\sum_j Q_{j\to i}(Y_j)}_{\text{Injection (interactions)}} + \underbrace{J_i}_{\text{Injection (sources)}}$$

Nuclei subject to disintegration. A nuclear cascade develops!





Neutrino production: photohadronic interactions

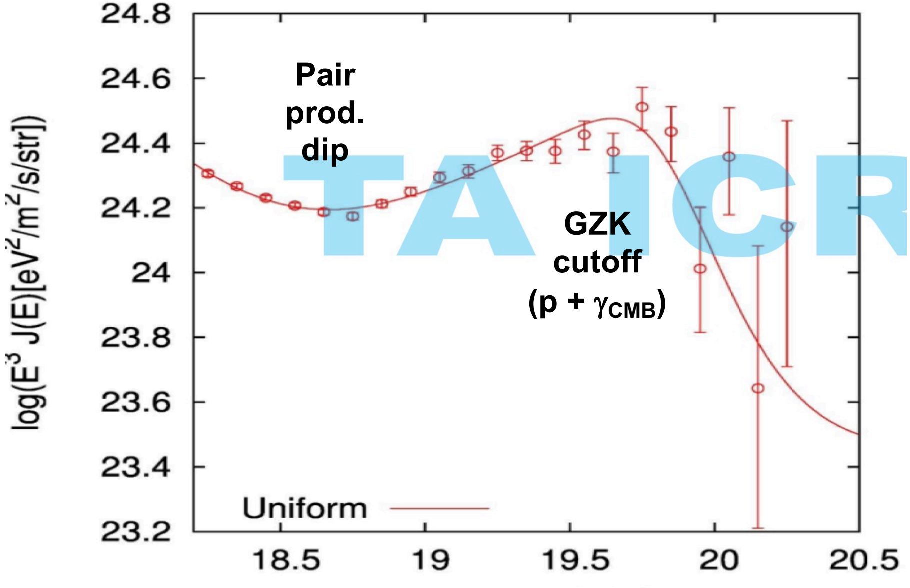
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

NB: UHECRs cannot travel further than z ~ 1

From PhD thesis Jonas Heinze, https://edoc.hu-berlin.de/handle/18452/22177

The proton only case

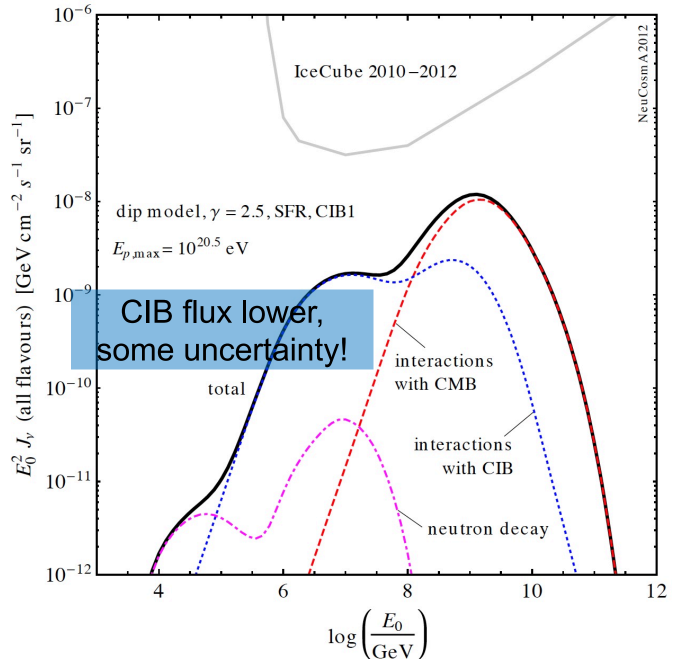
(observationally disfavored now!)

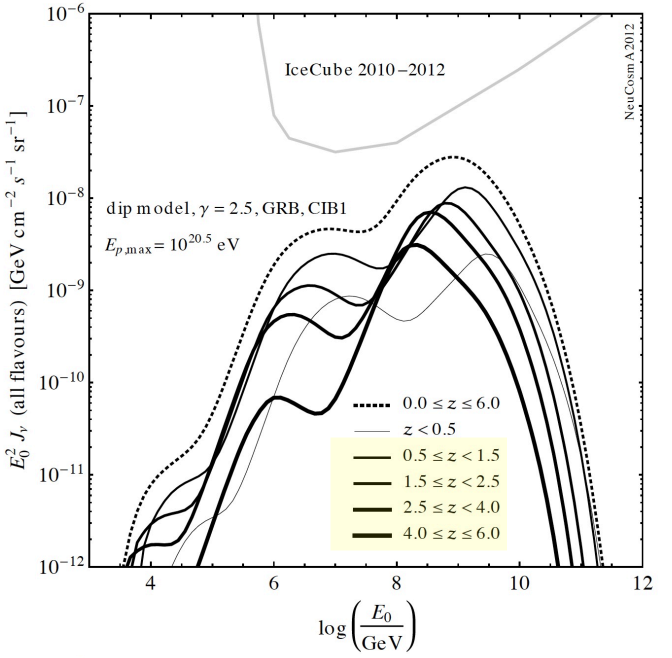


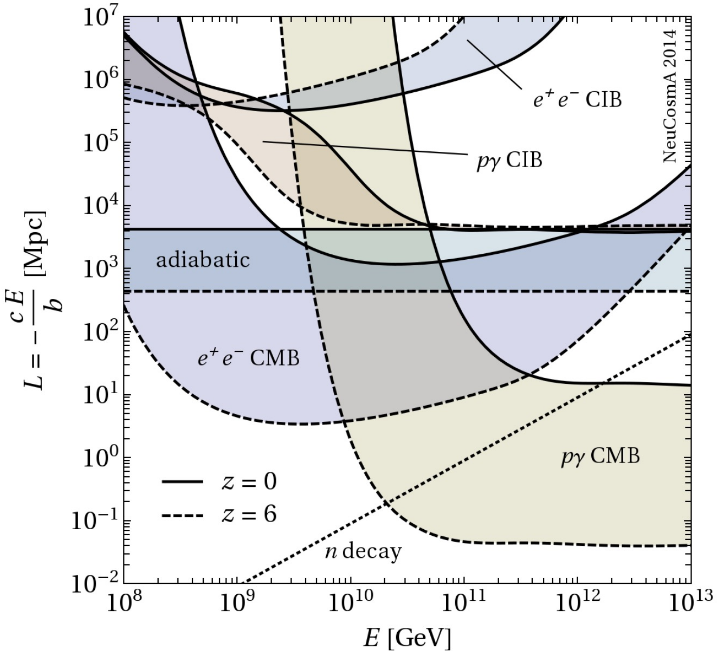
Jui @ ICRC 2015; talk by D. Ivanov

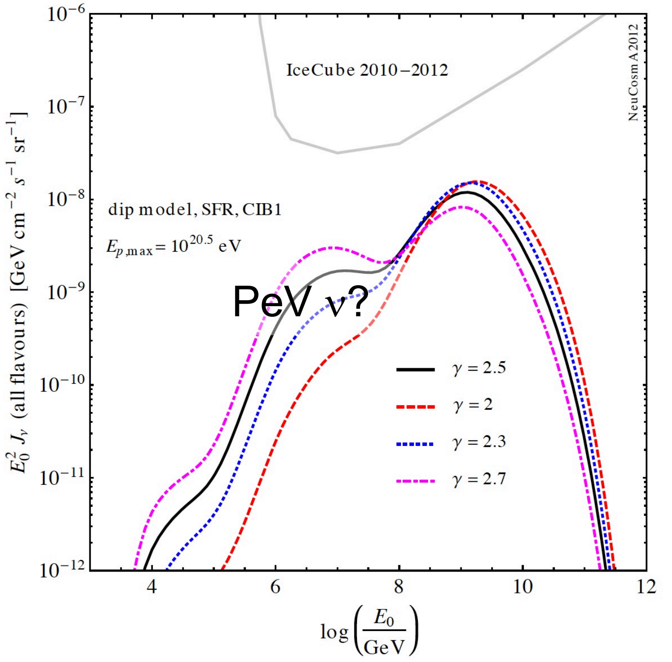
Soft spectra from sources.
Possibly hydrogen only.
Proton dip model?
Berezinsky, Gazizov, Grigorieva, 2005

$E_{\gamma,0}$ [eV] ~ 0.01 $(1+z)^{-2}/E_{\nu,0}$ [EeV]





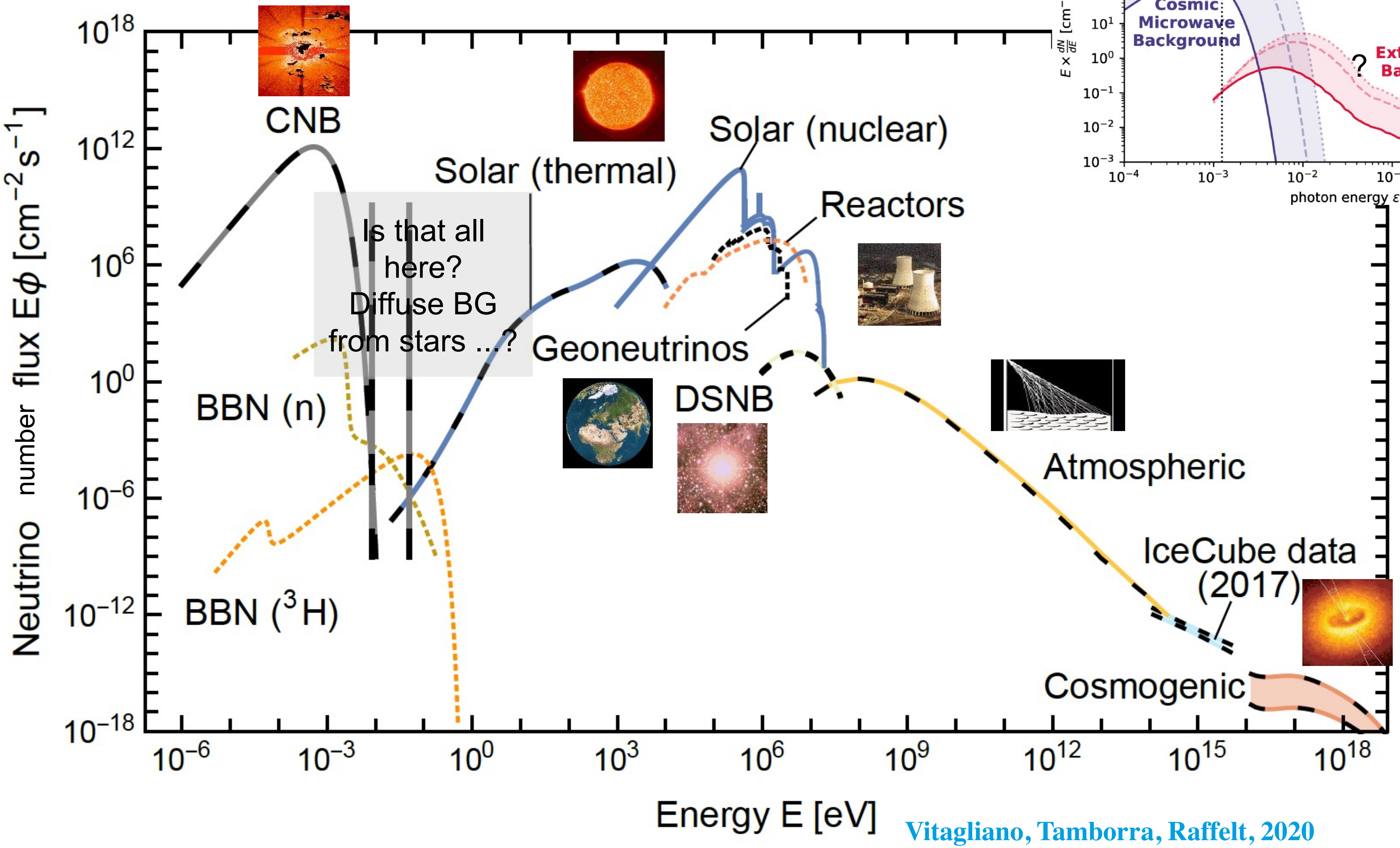


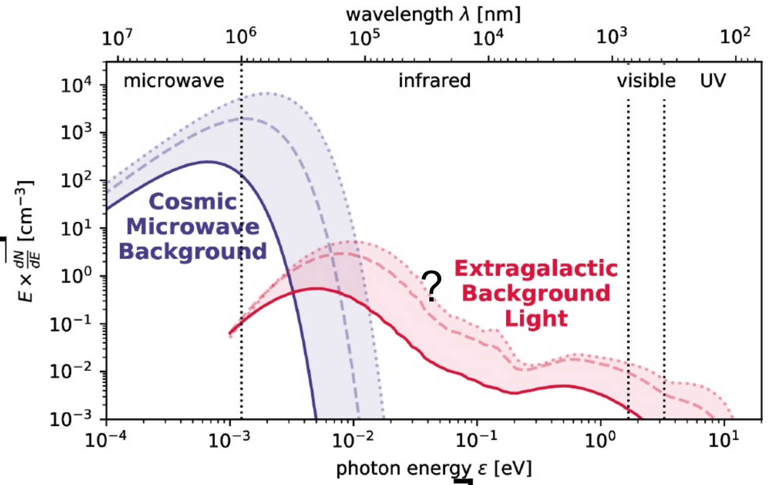


From: arXiv:1401.1820 ... and M. Bustamante

A side note on the CνB

Is our picture of low-energy astrophysical neutrinos complete?



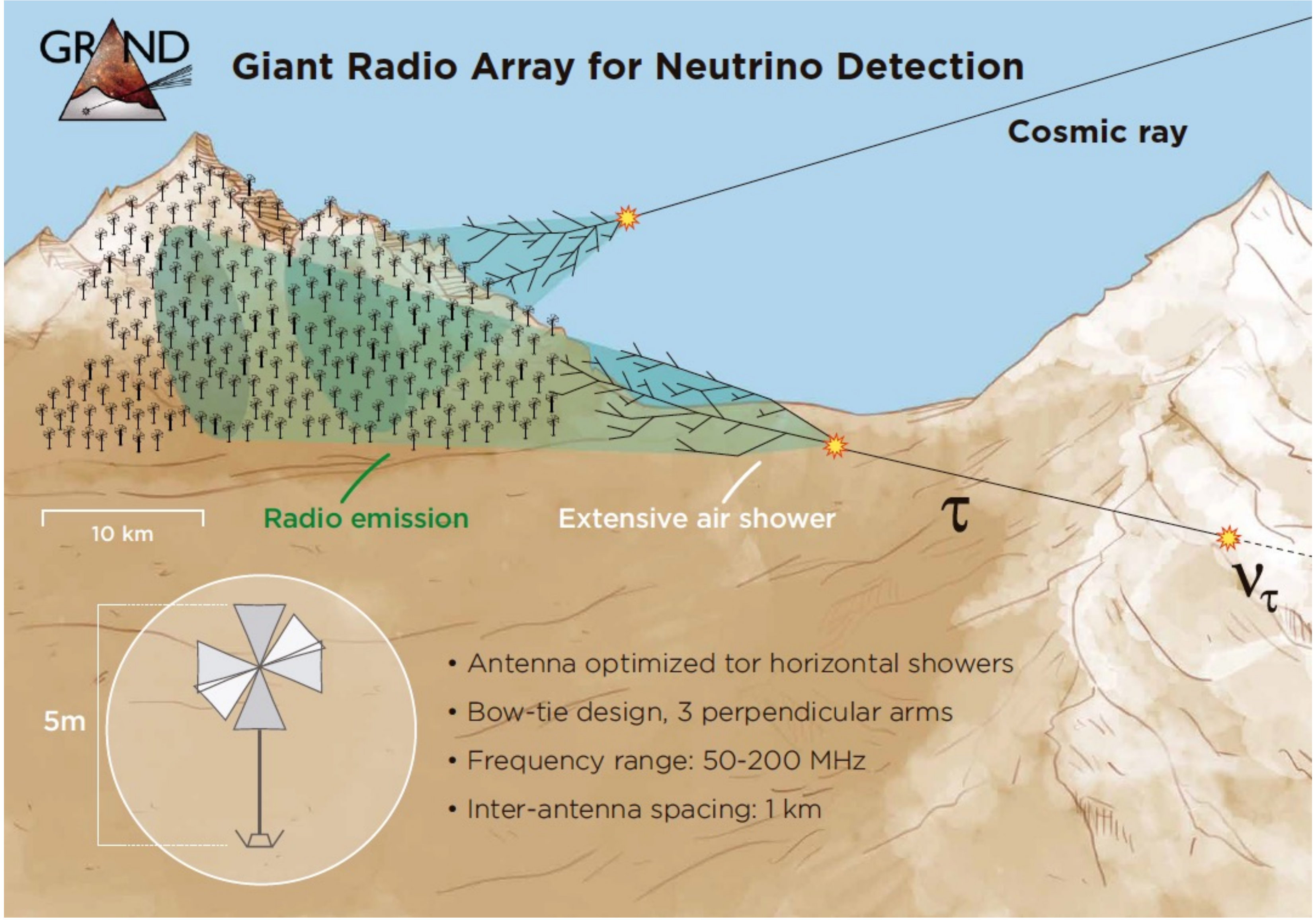


Vitagliano, Tamborra, Raffelt, 2020

The future: Radio detection of cosmogenic neutrinos

Example: GRAND

<u>Others:</u>
RNO-G
ARA/ARIANNA
IceCube-Gen2
...



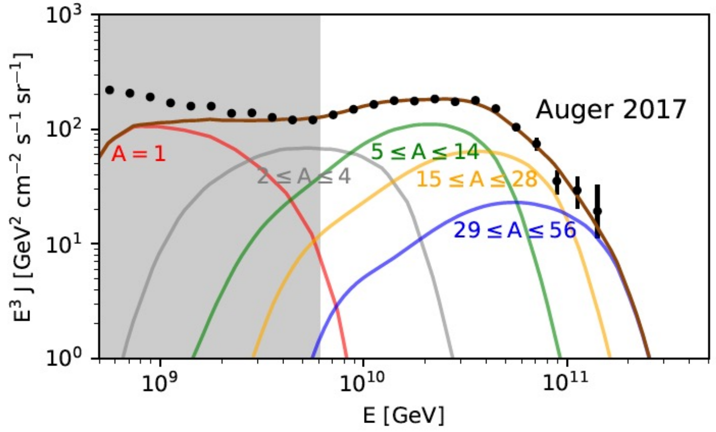
Sci. China Phys.Mech.Astron. 63 (2020) 1, 219501

Baseline UHECR transport model (Peters cycle model)

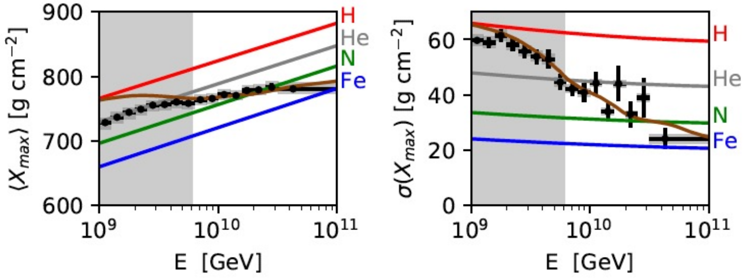
Parameters:

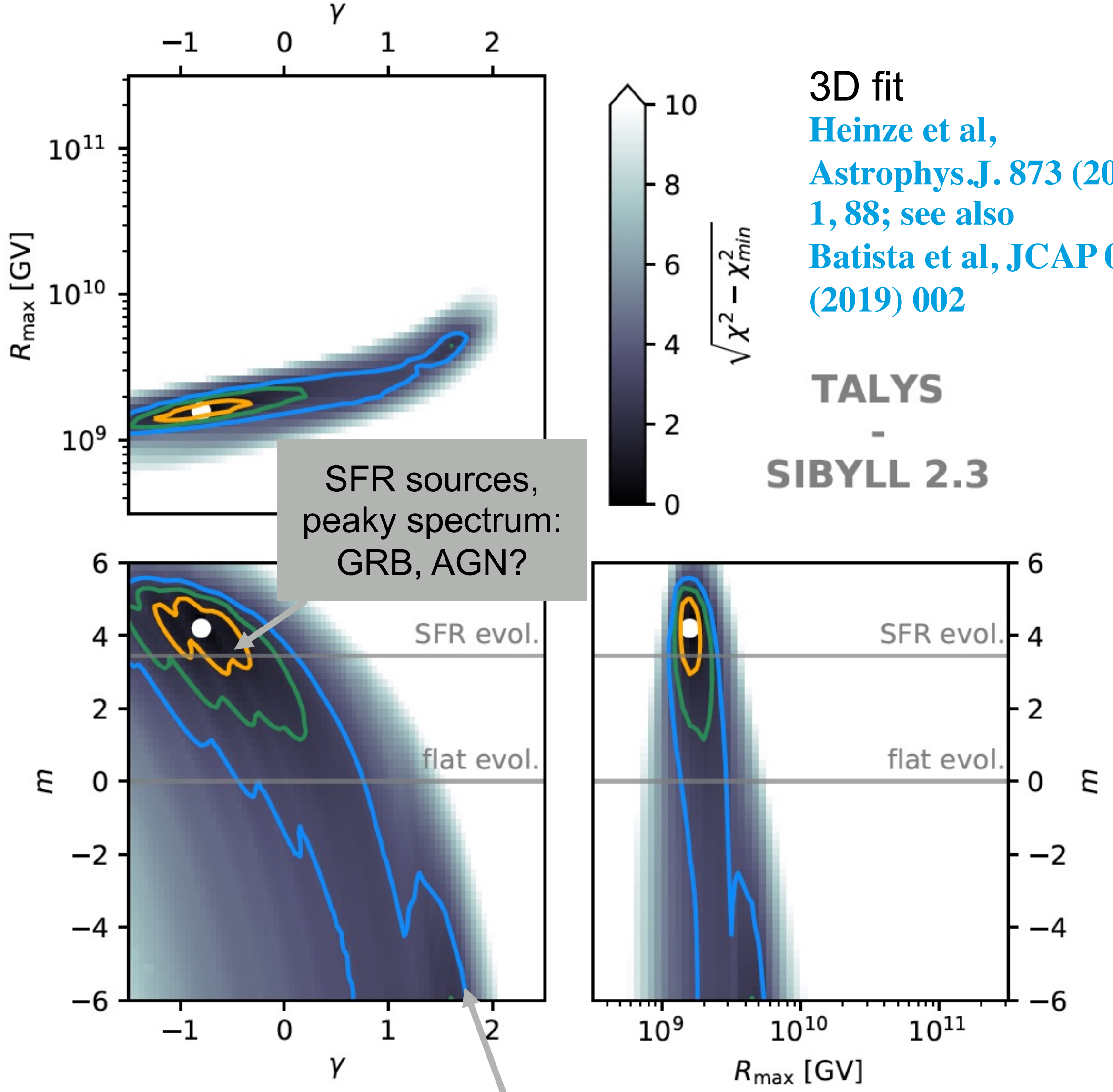
- γ: $E^{-\gamma}$ is the injection spectrum from sources
- R_{max}: Sources have $E_{max} = Z \times R_{max}$ (Peters cycle)
- m: Sources evolve $(1+z)^m$
  (SFR evolution: m ~ 3.4 for z < 1)
  (Recap: UHECRs do not travel farther than z~1)
- Free injection fractions for five mass groups:

Best-fit spectrum



Best-fit compositon





SFR sources, peaky spectrum: GRB, AGN?

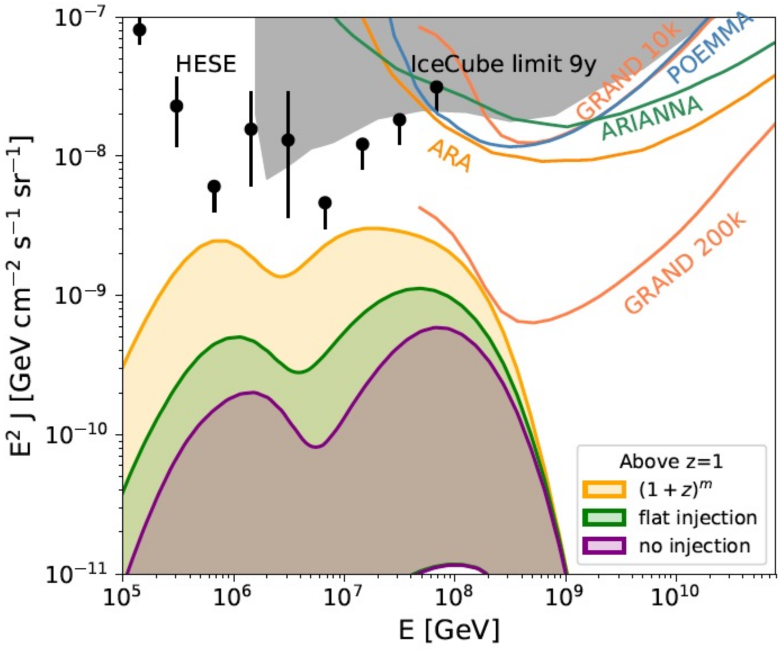
More typical acceleration spectrum, negative source evolution. TDEs?

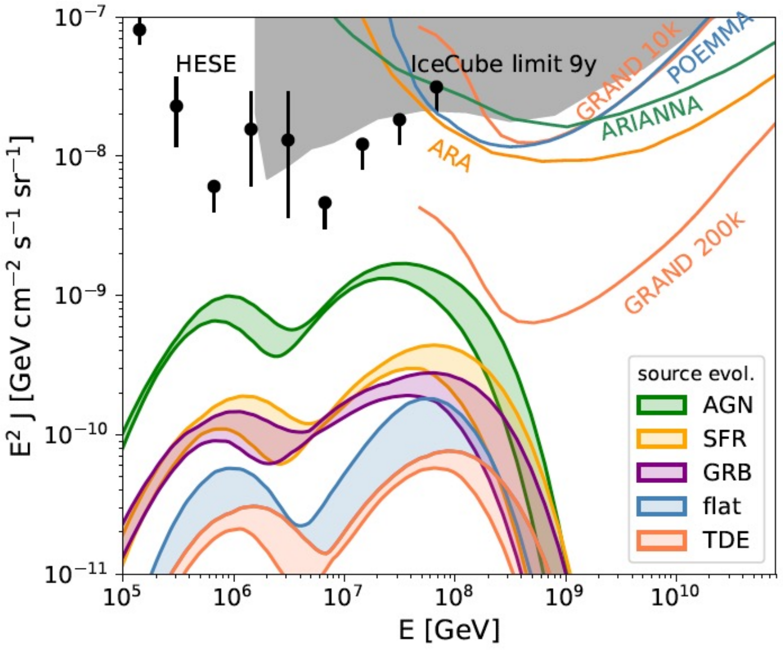
3D fit
Heinze et al, Astrophys.J. 873 (2019) 1, 88; see also Batista et al, JCAP 01 (2019) 002

TALYS - SIBYLL 2.3

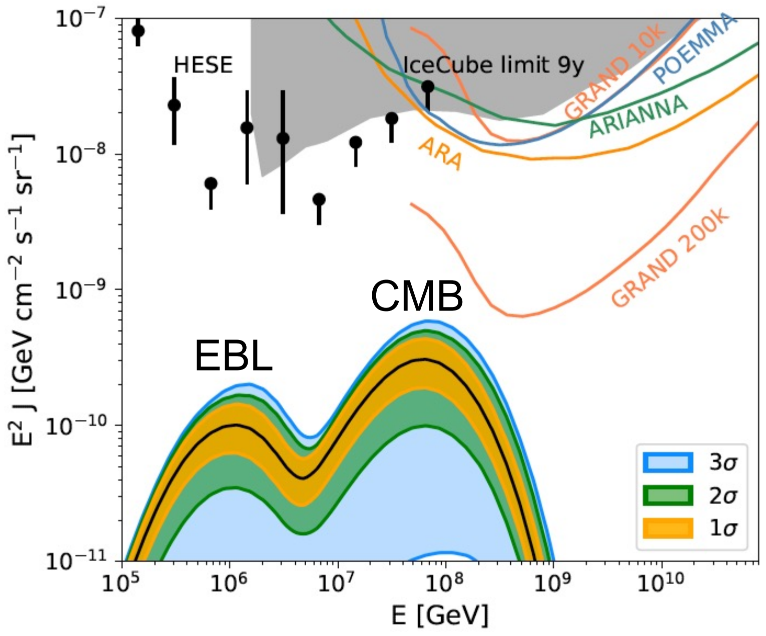
Cosmogenic neutrino flux post-diction from UHECR fit

- Cosmogenic neutrino prediction from fit to UHECR flux
- Depends on extrapolation for z>1 (UHECRs not sensitive there!)
- Conclusion: No cosmogenic neutrinos in baseline model!





Heinze et al, Astrophys. J. 873 (2019) 1, 88



However:

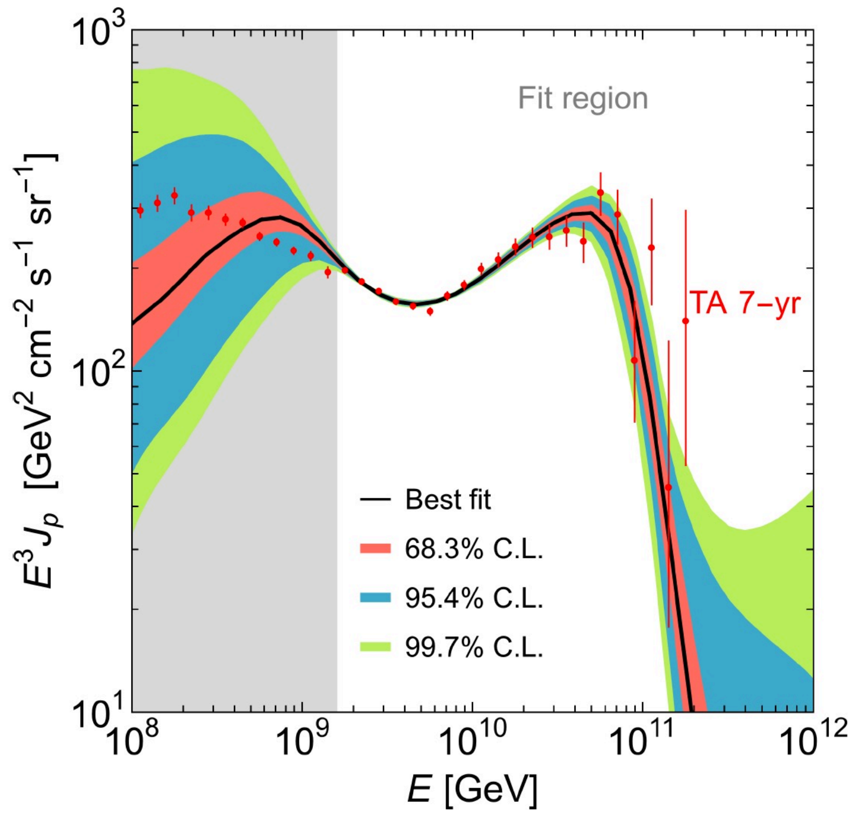
- UHECR data allow for a sub-dominant light component
- That potentially produces cosmogenic neutrinos efficiently

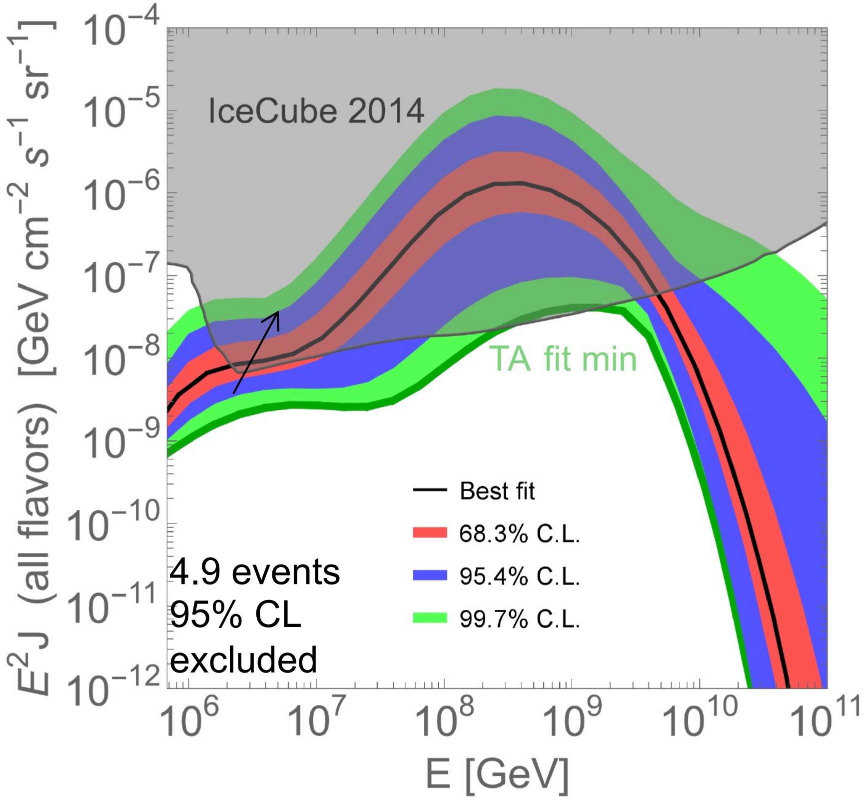
van Vliet et al, Phys. Rev. D 100 (2019) 2

How about the proton dip model?

Composition fixed to protons, fit beyond ankle

- 3D fit with fully marginalized parameters: TA 7-year meets IceCube 2014
  Heinze, Boncioli, Bustamante, Winter, Astrophysical Journal 825 (2016) 122

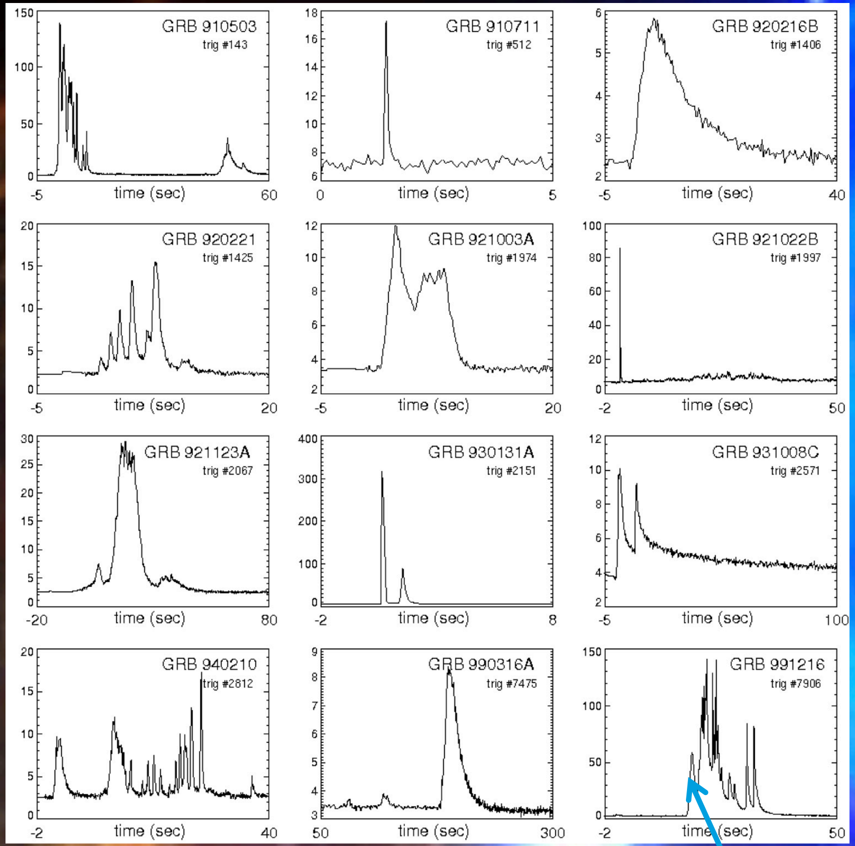




- Baseline interpretation: **The proton contribution must be constrained by cosmogenic neutrino flux!**
- **What can we learn about the cosmogenic and source neutrino fluxes for specific astrophysical source populations?**

Possible UHECR sources: Gamma-ray bursts (GRBs)

Daniel Perley

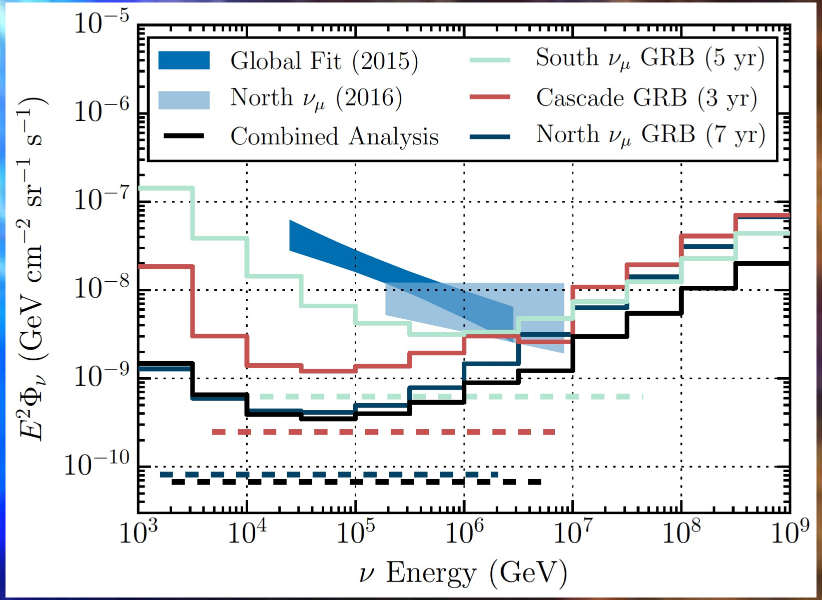


t_v: variability timescale

Several populations, such as

- **Long-duration bursts** (~10 – 100s), from collapses of massive stars? **HL-GRBs**
- Short-duration bursts (~ 0.1 – 1 s), from neutron star mergers. Low total energy output!
- Low-luminosity GRBs from intrinsically weaker engines, or shock breakout? **LL-GRBs** Potentially high rate, longer duration (but only locally observed)

- Neutrino stacking searches: <~1% of diffuse neutrino flux



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

Source: NASA

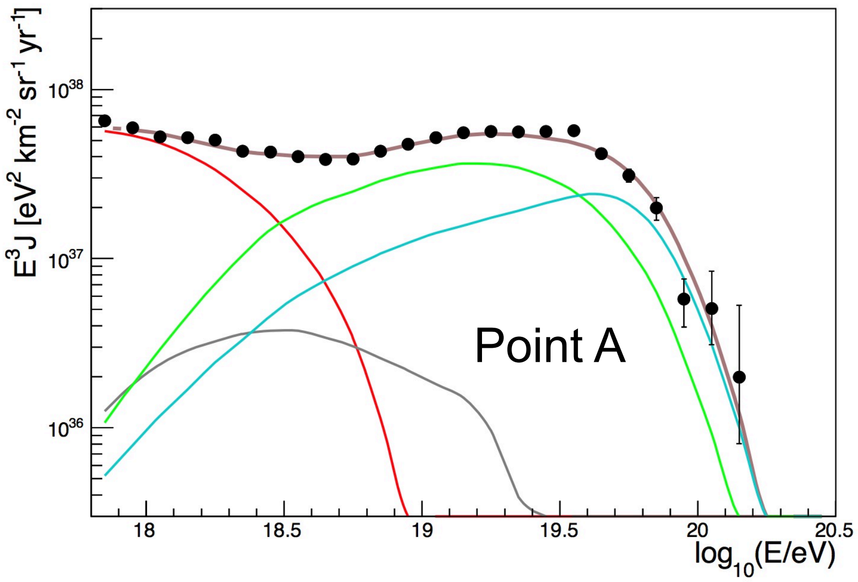
HL-GRBs: The vanilla one-zone prompt model

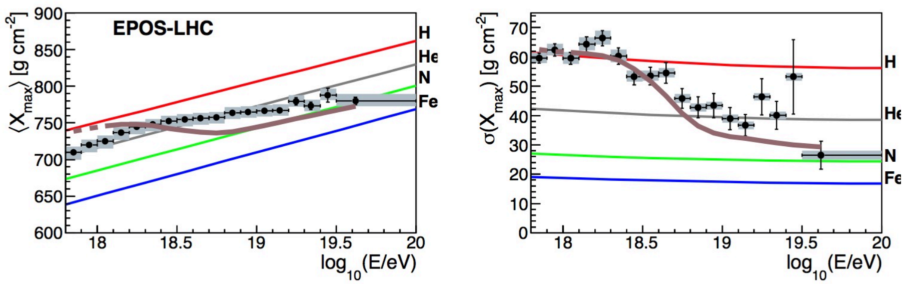
Neutrino and cosmic ray emission at same collision radius R

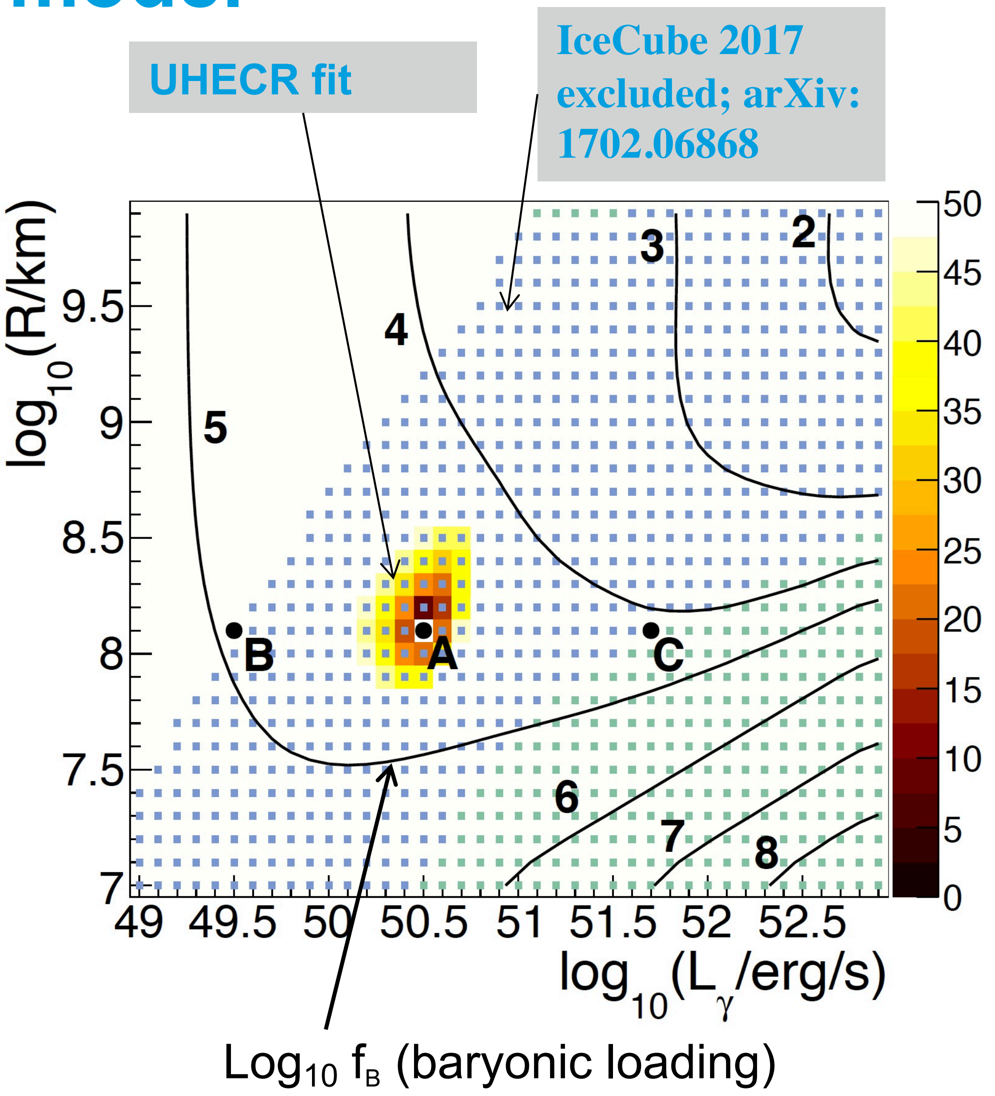
- Can describe UHECR data, roughly
- Scenario is constrained by neutrino non-observatons

<u>Recipe:</u>

- Fit UHECR data, then compute predicted neutrino fluxes
- Here only one example; extensive parameter space studies have been performed + energy cuts
- Conclusion relatively robust for parameters typically expected for HL-GRBs







Biehl, Boncioli, Fedynitch, Winter, arXiv:1705.08909
Astron. Astrophys. 611 (2018) A101;
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

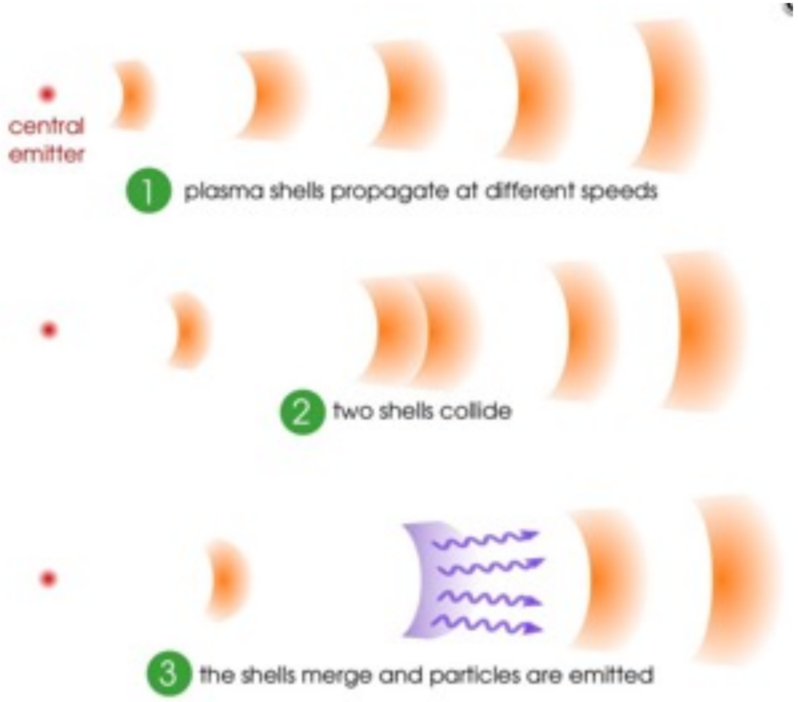
Back to the roots:

Multi-collision models

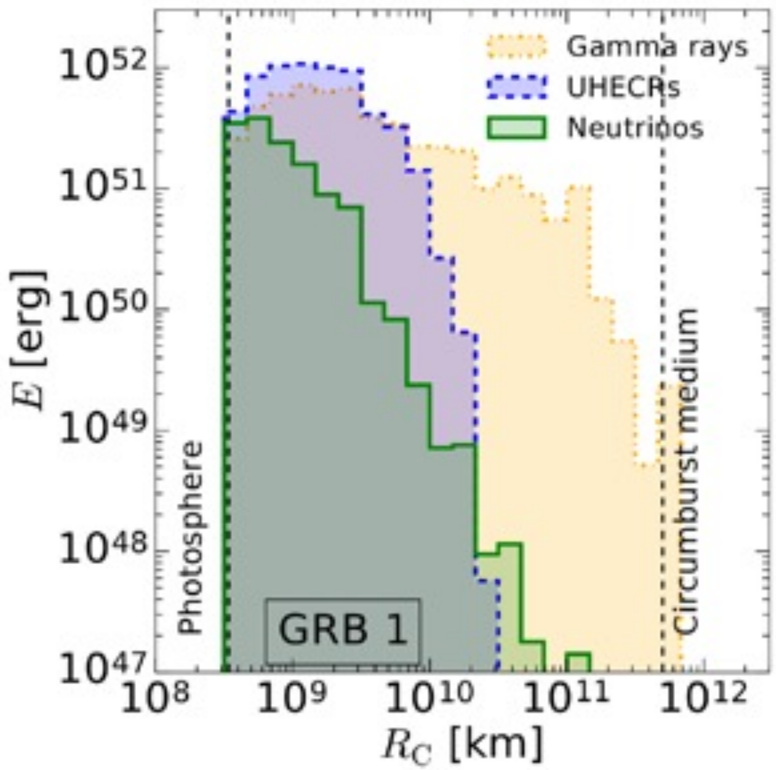
The GRB prompt emission comes from multiple zones

Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015);
Bustamante, Heinze, Murase, Winter, ApJ 837 (2017) 33;
Rudolph, Heinze, Fedynitch, Winter, ApJ 893 (2020) 72
see also Globus et al, 2014+2015;
earlier works e.g. Guetta, Spada, Waxman, 2001 x 2

Collision model, illustrated



Multi-messenger emission



Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015)

Observations

- The neutrino emission is lower (comes from a few collisions close to the photosphere)
- UHECRs and γ-rays are produced further out, where the radiation densities are lower
  - ➢ Releases tension with neutrino data
- The **engine properties** determine the nature of the (multi-messenger) light curves
- Many aspects studied, such as impact of collision dynamics, interplay engine properties and light curves, dissipation efficiency etc.

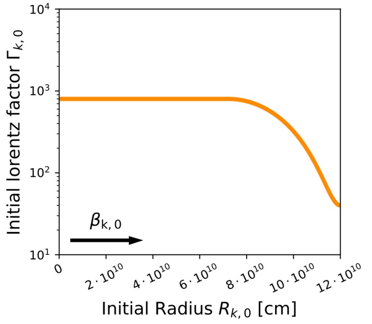
A new (unified) model with free injection compositions

Systematic parameter space study requires model which can capture stochastic and deterministic engine properties

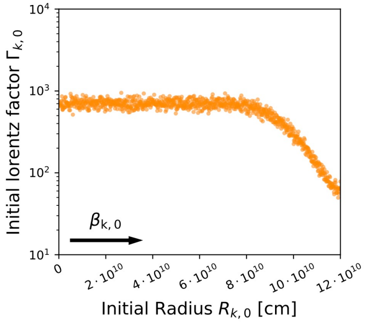
Model description

- Lorentz factor ramp-up from Γ_{min} to Γ_{max}, stochasticity (A_Γ) on top

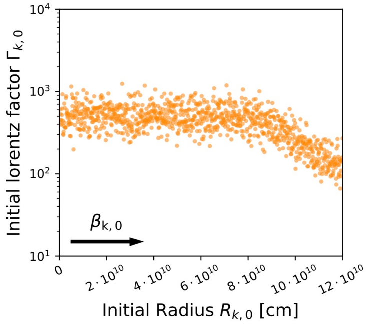
SR-0S
Strong (engine) ramp-up, no stochasticity



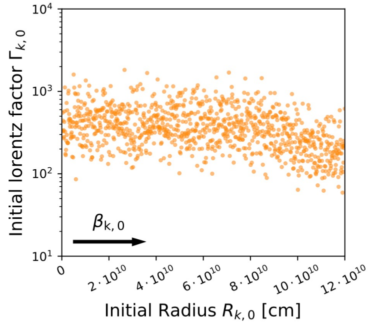
SR-LS
Strong (engine) ramp-up, low stochasticity



WR-MS
Weak (engine) ramp-up, medium stochasticity



WR-HS
Weak (engine) ramp-up, high stochasticity

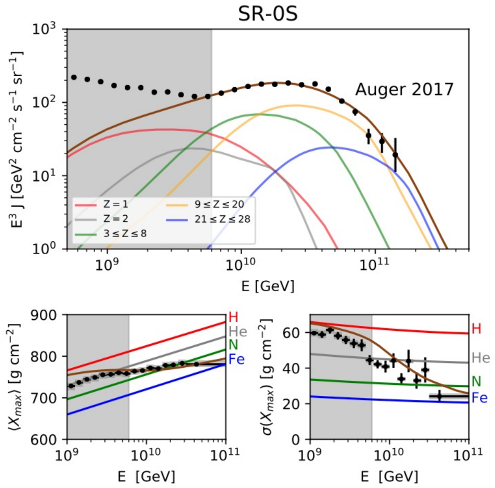


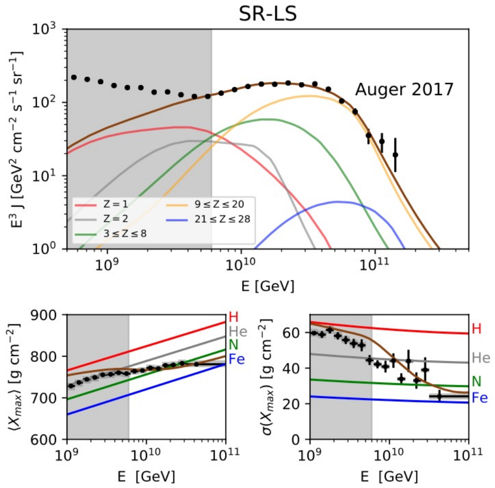
Describes UHECR data over a large range of parameters!

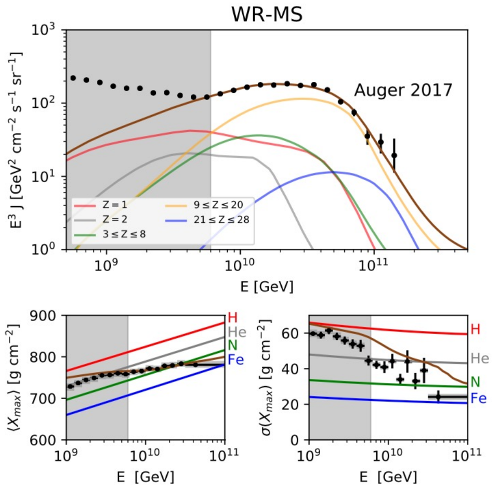
(systematically studied)

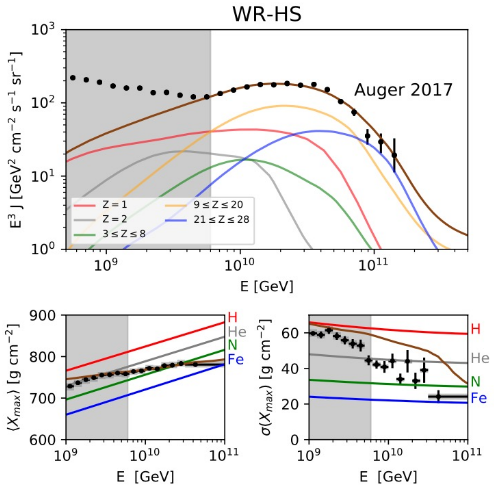
Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

Description of UHECR data



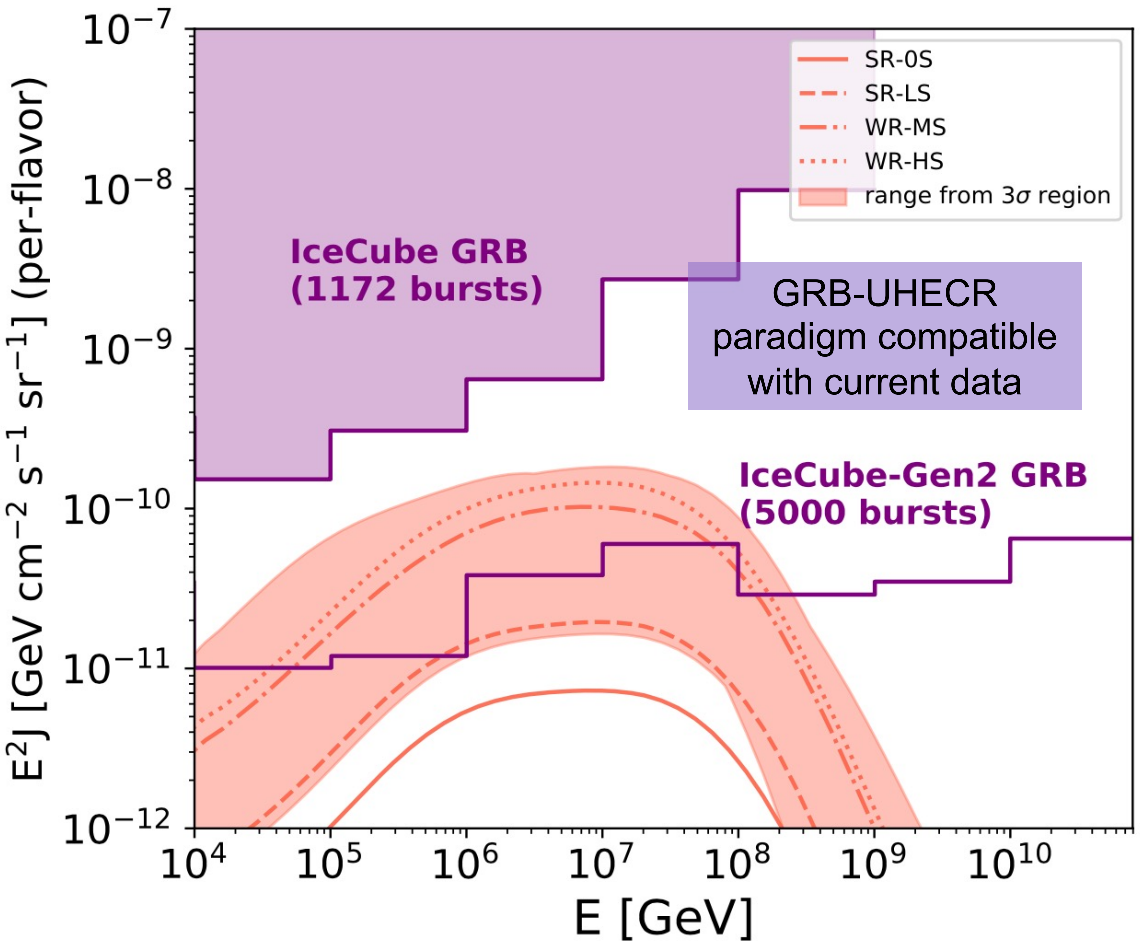


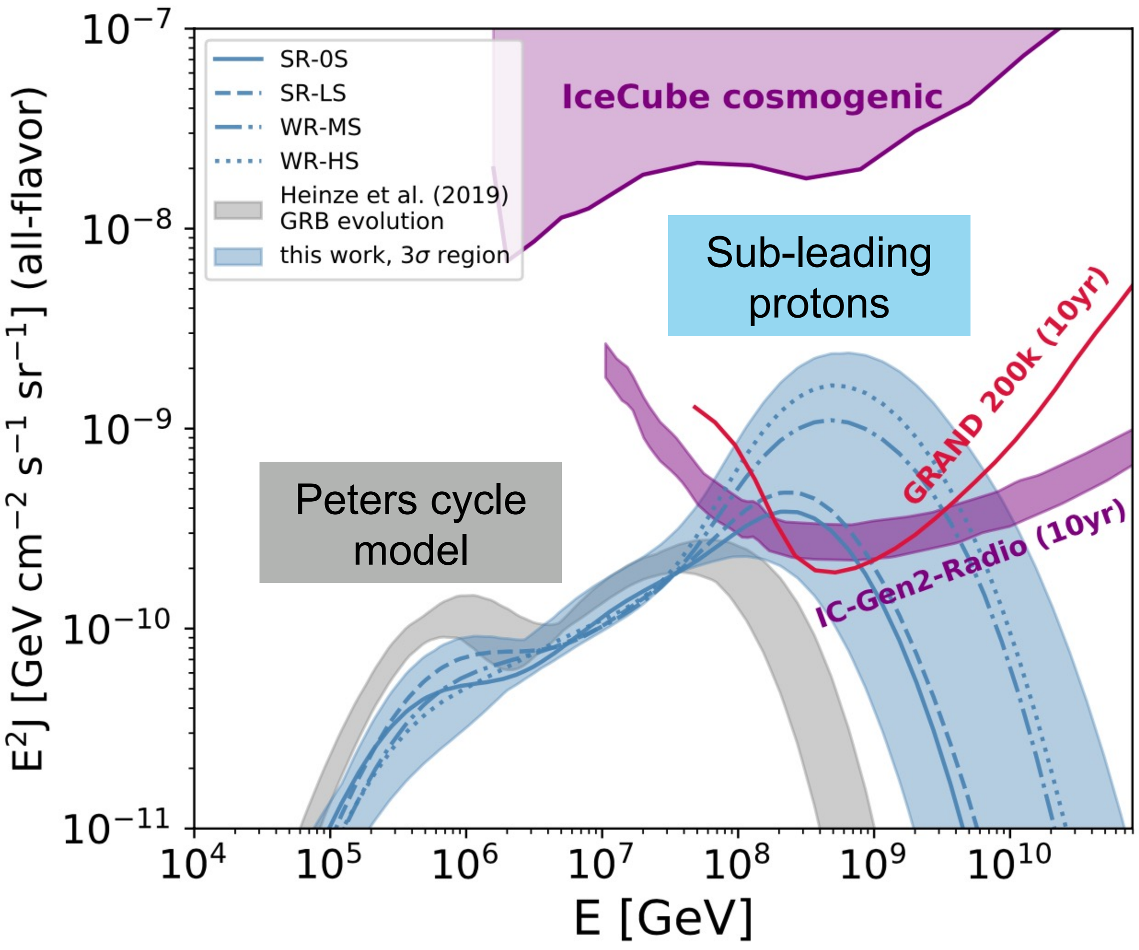




Inferred neutrino fluxes from the parameter space scan

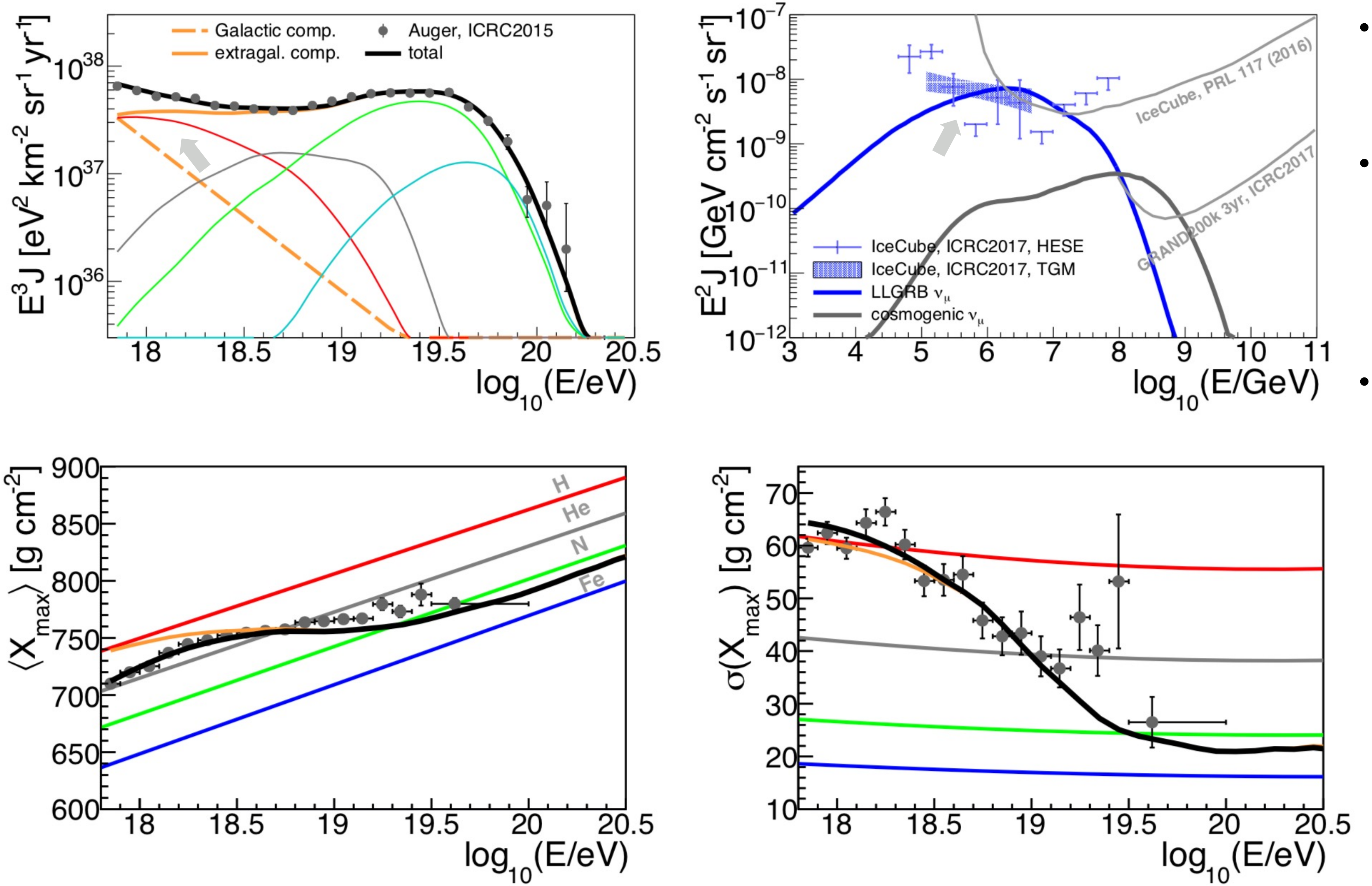
Prompt neutrino flux possibly testable with IceCube-Gen2, cosmogenic one in future radio instruments





Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

One alternative: a population of LL-GRBs



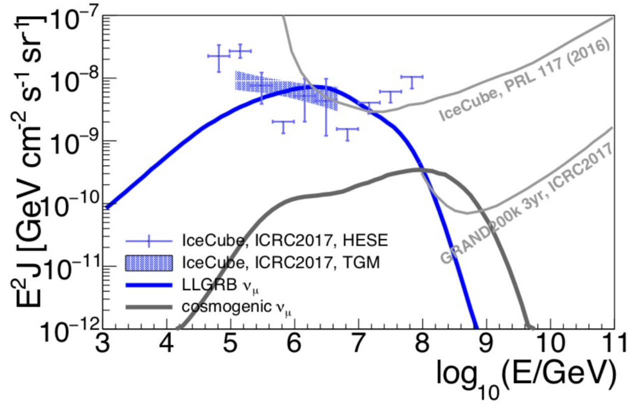
- Stacking limit does not apply, describes neutrino data at high E
- The radiation density controls the neutrino production and sub-ankle production of nucleons
- Subankle fit and neutrino flux require similar parameters

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

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

Expectations for EeV neutrinos? Summary with examples from this talk

- Low-luminosity GRBs:

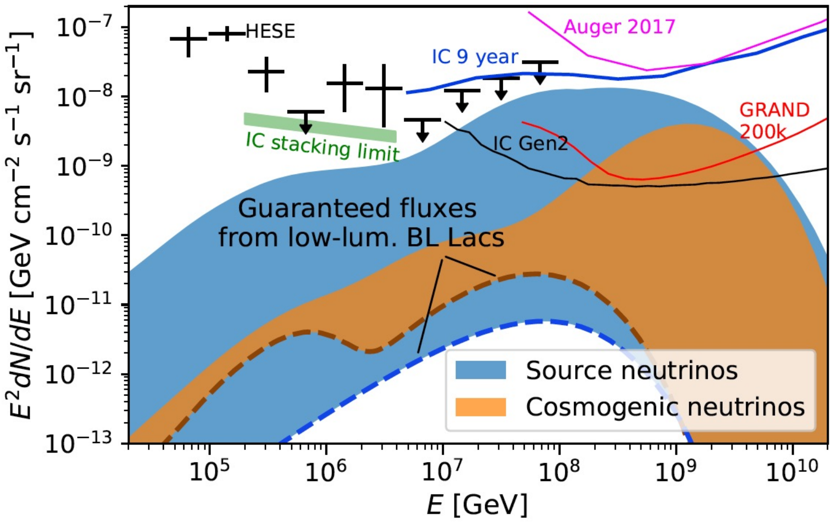


Boncioli, Biehl, Winter, ApJ 872 (2019) 110

The UHECR spectrum and composition fit, together with the source model, determine the cosmogenic flux

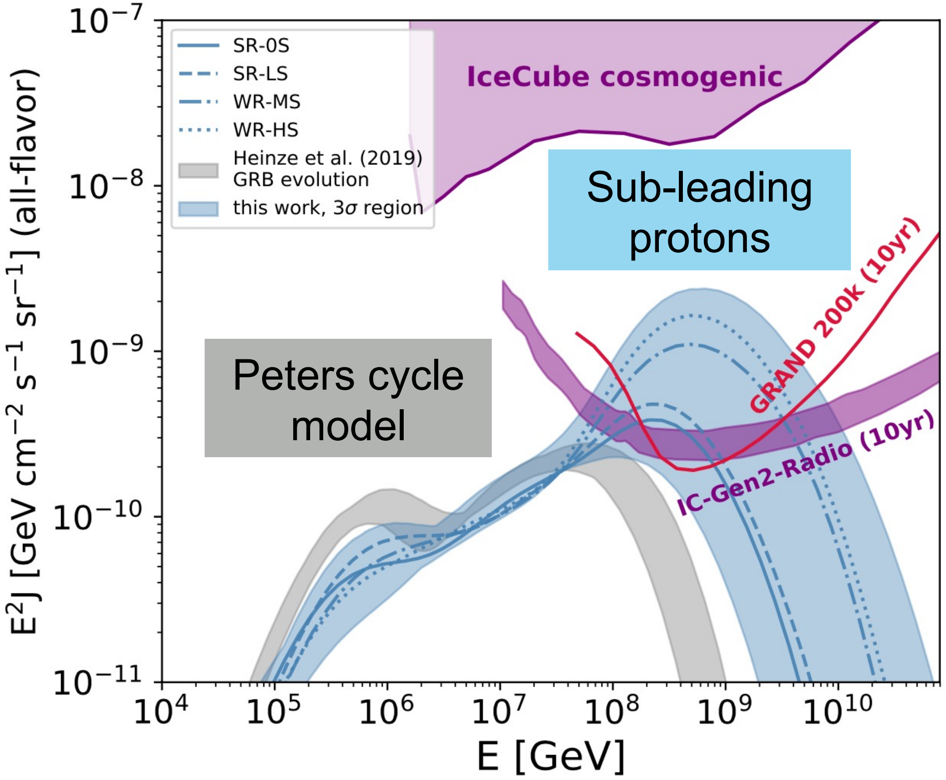
Cosmogenic neutrinos dependent on sub-leading proton component; that is plausible in many source models

- AGN jets:



Rodrigues et al PRL 126 (2021) 191101

- Standard GRBs:



Heinze et al MNRAS 498 (2020) 4, 5990

Foreground-background issue:
Is the cosmogenic neutrino flux really dominant at the highest energies, or is it outshined by sources?

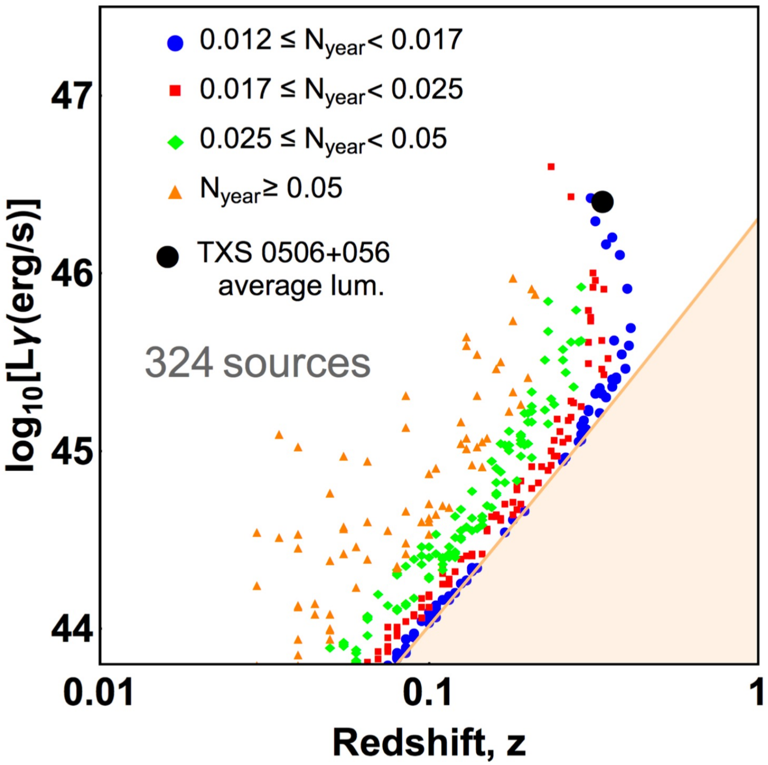
BACKUP

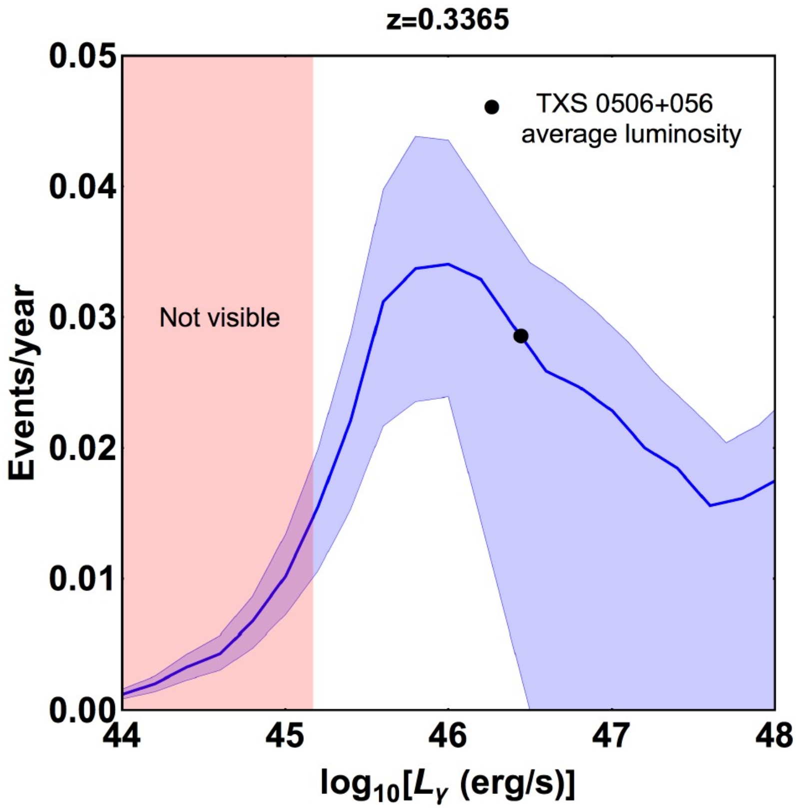
Diffuse flux model: Consequences for TXS 0506+056

$E_{p,max}$ ~1-10 PeV

- Many similar sources, each producing << 1 ν event/year
- Consistent with expect. from Eddington bias
- About 0.3 flare associations/year expected if blazars 10% of time in flaring state (duty cycle)

- TXS 0506+056 is, in that picture, not a special source, is close to the “sweet spot” (by construction)
- Archival 2014-15 flare cannot be explained (a special event?)

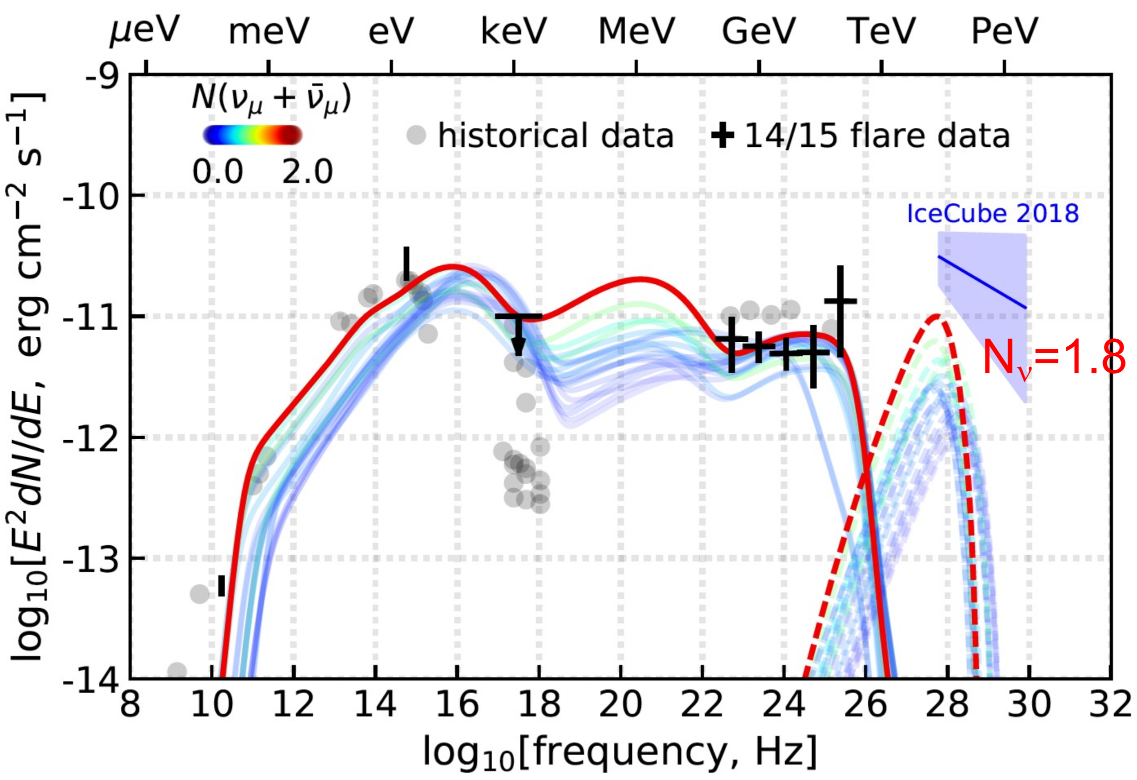


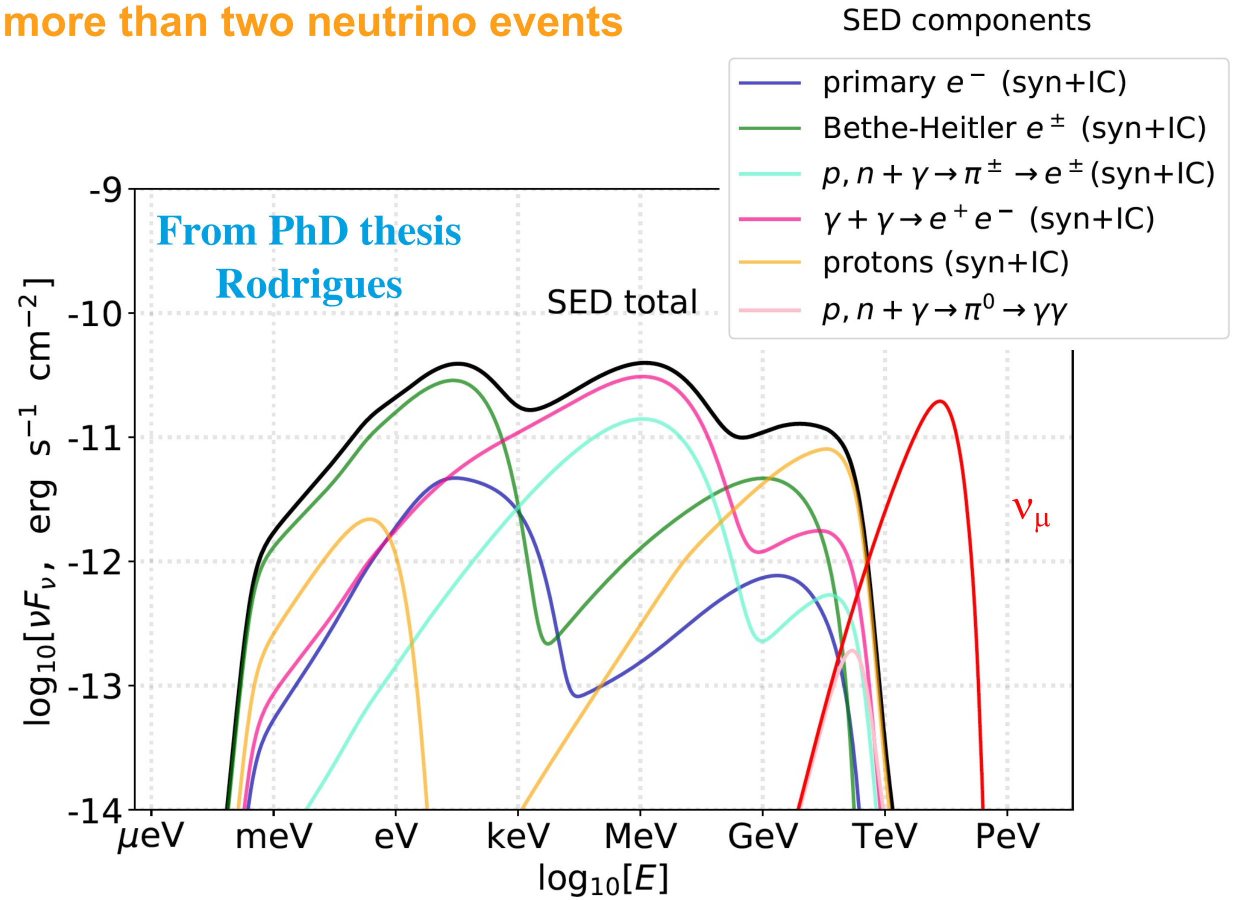


Palladino, Rodrigues, Gao, WW, ApJ 871 (2019) 41

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

Comparison: transient UHECR and neutrino sources

HL-GRBs

- Well-studied source class
- Can describe UHECR spectrum and composition X_{max}
- Multi-collision models work for a wide range of parameter sets
- Neutrino stacking limits obeyed
- Light curves may be used to further narrow down models
- Cannot describe diffuse neutrinos
- Composition variable $\sigma(X_{max})$ requires some fine-tuning
- Energetics in internal shock scenario is a challenge; more energy in afterglows than previously thought? VHE γ–rays?

LL-GRBs

- Potentially more abundant than HL-GRBs
- Can describe UHECR spectrum and composition even across the ankle
- May at the same time power the diffuse neutrino flux
- Less established/studied source class = more speculative
- Radiation modeling subject to discussions
- Progenitor model disputed
- UHECR+neutrino energetics point require relatively long "standard" LL-GRBs, may be challenged by population studies

TDEs

- The only transient class from which neutrinos have been observed from → Must accelerate cosmic rays
- Have potentially negative source evolution, which helps UHECRs
- A lot of recent activity in astrophysics; many new discoveries
- Observed TDEs are very diverse
- Models have a lot of freedom
- Local rate and demographics may have to be re-evaluated
- Energetic events, such as the jetted TDE Sw J1644+57, may be rare

Neutrino energetics for TDEs

... an upper model-independent limit

- Upper limit for average neutrino luminosity (4π solid angle emission, for pp similar):
  $L_\nu \sim 25\, L_{edd} \;\; x \;\; f_{comp} \;\; x \;\; \varepsilon_{acc} \;\; x \;\; \tau_{p\gamma} \;\; x \;\; 1/8 \;\; \mathbf{<< 0.1\, L_{edd}}$

  Average mass accretion rate

  Fraction in outflow, BB, jet, ... (0.03-0.2?)

  Accelerated fraction into non-thermal PeV (!) energy protons (<< 0.2?)

  Optical thickness <= 1, but typically << 1

  Per flavor

- Yields $E_\nu \sim 200$ days x $0.1\, L_{edd} \sim\; 2\; 10^{50}$ erg $(M_{SMBH}/10^6\, M_\odot)$
  $\rightarrow$ 0.2 events for $M_{SMBH} \sim 10^6\, M_\odot$ $\longrightarrow$

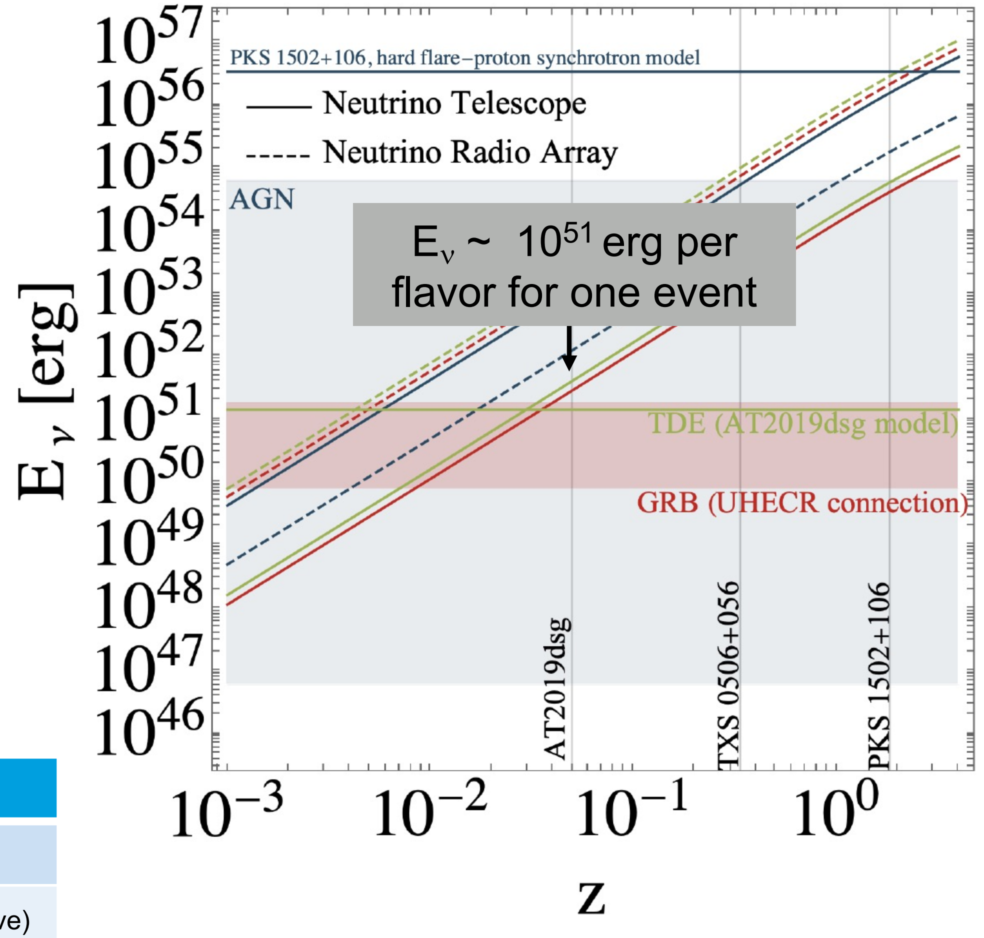
- **Conclusion:**
  either $M_{SMBH} > 10^7\, M_\odot$ and super-efficient energy conversion,
  or the outflow must be collimated with $\theta << 1$ such that $L_\nu \rightarrow L_\nu / \theta^2$

Estimates for SMBH mass

$M_{SMBH}/M_\odot$	Reference
~ 2 10^7	McConnel, Ma, 2012
3 10^5 ... 10^7	Wevers et al, 2019 (conservative)
1.2-1.4 10^6	Ryu, Krolik, Piran, 2020
2.2-8.6 10^6	Cannizzaro et al, 2021

- For a relativistic jet: second option with $\theta \sim 1/\Gamma$

(figure for all flavors, typical spectral shapes)

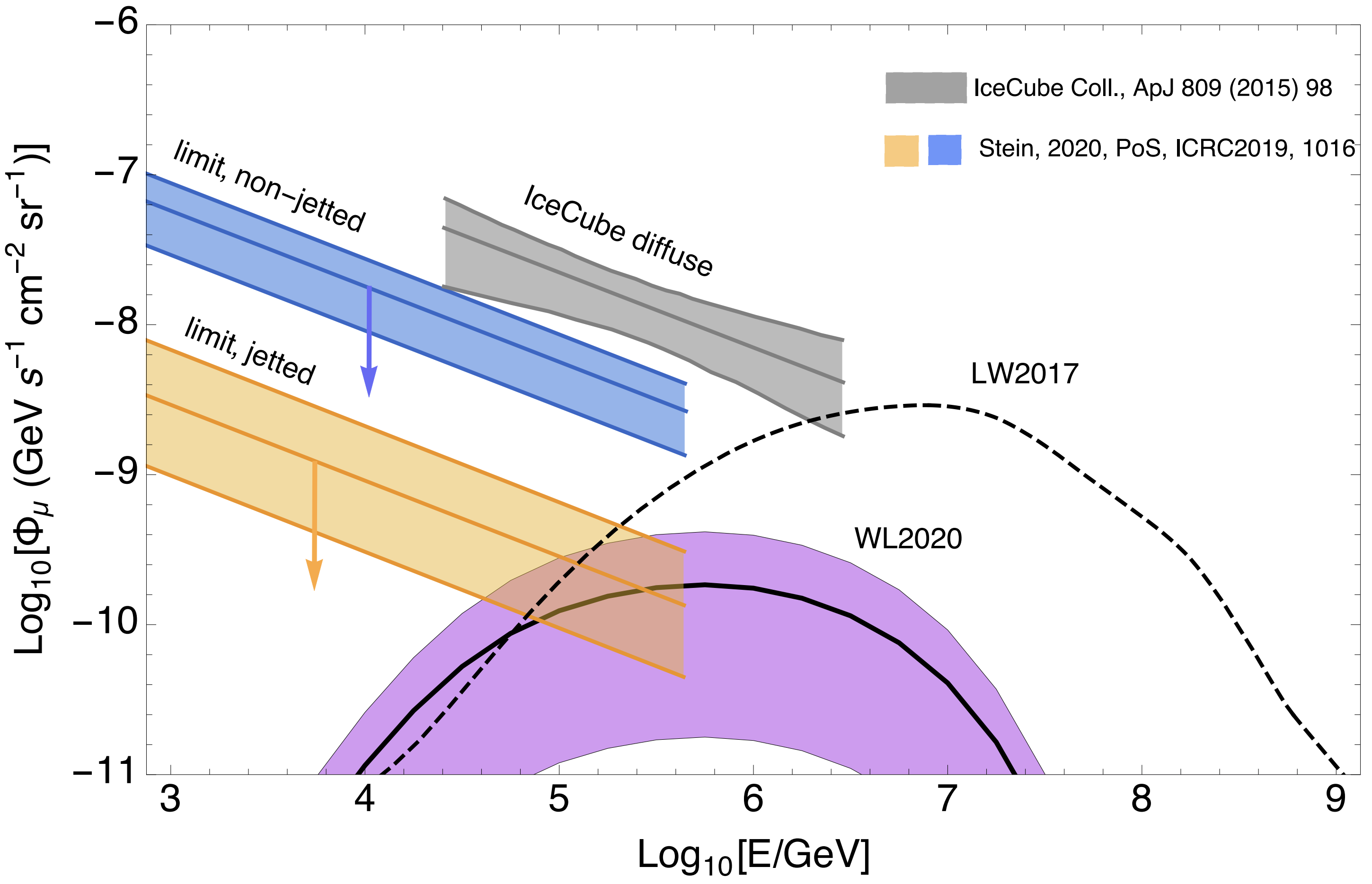


Fiorillo, van Vliet, Morisi, Winter, arXiv:2103.16577

Diffuse neutrino flux from TDEs?

- Diffuse flux from a population of AT2019dsg-like TDE consistent with current bounds
- Expected contribution to the IceCube diffuse neutrino flux at few percent level
- The typical neutrino TDE is probably less luminous than SwJ1644+47
  (used in Lunardini, Winter, Phys. Rev. D 95 (2017) 12, 123001 as prototype)

- Could neutrino-emitting TDE also power the UHECR flux?
  Biehl, Boncioli, Lunardini, Winter, Sci. Rep. 8 (2018) 1; see also Zhang et al., 2017, Guepin et al, 2018
  Note especially recent indications for under-estimated white dwarf TDE rate by factor of 50! (was most critical factor?)
  Tanikawa, Giersz, Sedda, 2021



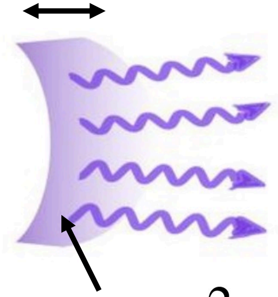
Winter, Lunardini, PoS ICRC2021 (2021) 997, arXiv:2107.14381

Neutrino production efficiency in GRBs (as example)

$$\lambda'_{\mathrm{mfp}} = \frac{1}{n'_\gamma \, \sigma_{p\gamma}}$$

... from geometry estimators; production volume determines efficiency!

$$\Delta d'$$



$$V'_{\mathrm{iso}} = 4\pi \, R^2 \cdot \Delta d'$$

- Need photon density, which can be obtained from energy density; generically:

$$u'_\gamma \equiv \int \varepsilon' \, N'_\gamma(\varepsilon') \mathrm{d}\varepsilon' = \frac{\underbrace{L_\gamma}_{L'_\gamma \Gamma^2} \Delta d'/c}{\Gamma^2 \, V'_{\mathrm{iso}}} = \frac{L_\gamma}{4\pi c \Gamma^2 R^2}$$

- Scales ~$1/R^2$ from simple geometry arguments
- *Internal shock scenario*: e.g. Guetta et al, 2004

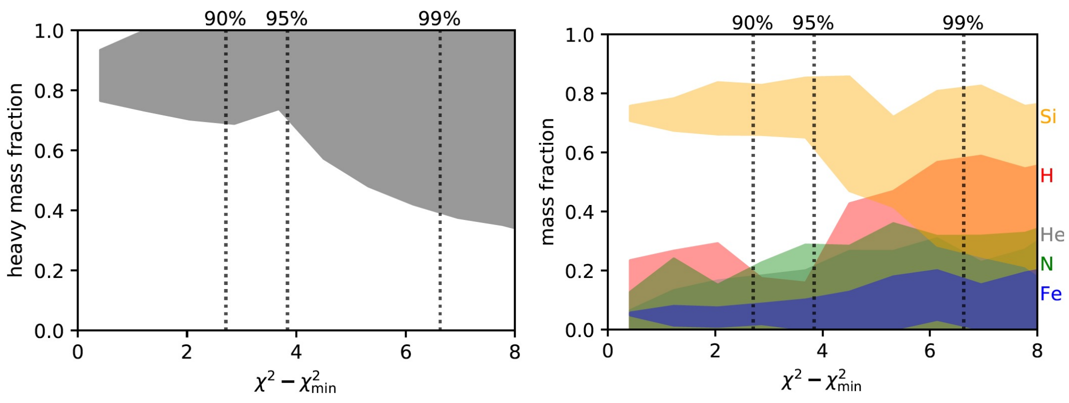
$$R \simeq 2\,\Gamma^2 \, \frac{c\, t_v}{1+z} \qquad \Delta d' \simeq \Gamma \frac{c t_v}{1+z} \quad \Rightarrow \quad f_{p\gamma} \propto L_\gamma / (\Gamma^4 t_v \epsilon_{\gamma,\mathrm{br}})$$

$$(f_{p\gamma} \propto \Delta d' / \lambda'_{\mathrm{mfp}} \sim \Delta d' \, \sigma_{p\gamma} u'_\gamma / (\epsilon_{\gamma,\mathrm{br}}/\Gamma))$$

- *Magnetic re-connection models*: est. for *R* from pulse timescale (larger)
- *Photospheric emission*: *R* corresponds to photospheric radius
- *Multi-zone models*: *R* and Δd' individually calculated for each collision
- **Production radius R and luminosity Lγ are the main control parameters for the neutrino production**
  [t_v does not vary as much as L_γ]
  e.g. He et al, 2012; Zhang, Kumar, 2013; Biehl et al, arXiv:1705.08909 (Sec. 2.5) for details

Interpretation of the results (GRB multi-collision model)

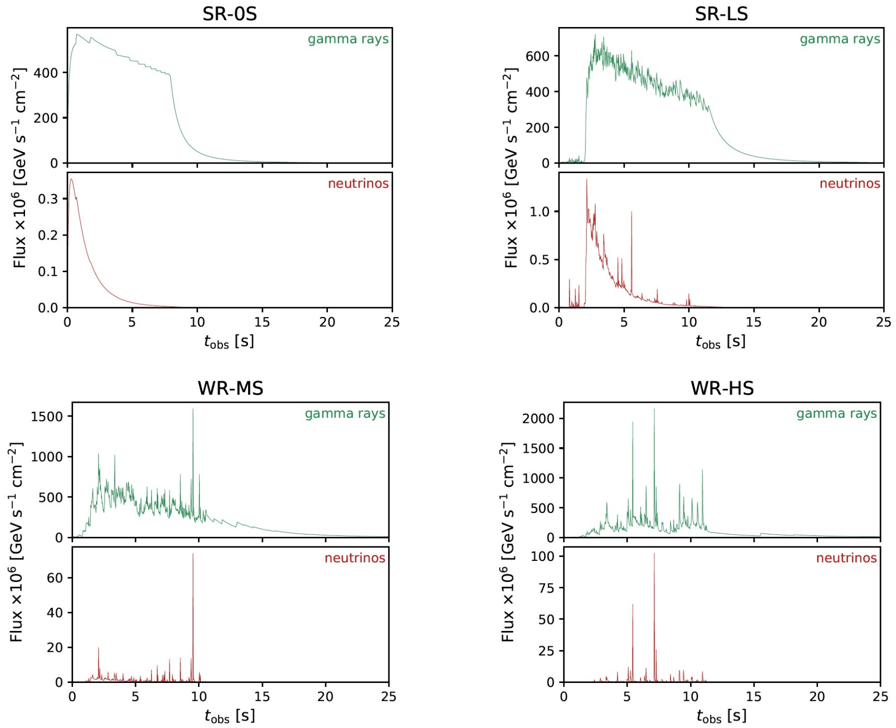
- The required injection compositon is derived: more that 70% heavy (N+Si+Fe) at the 95% CL



- Self-consistent energy budget requires kinetic energies larger than 10^{55} erg – **probably biggest challenge for UHECR paradigm**

	SR-0S	SR-LS	WR-MS	WR-HS
E_γ	$6.67 \cdot 10^{52}$ erg	$8.00 \cdot 10^{52}$ erg	$8.21 \cdot 10^{52}$ erg	$4.27 \cdot 10^{52}$ erg
E^{esc}_{UHECR} (escape)	$2.01 \cdot 10^{53}$ erg	$2.10 \cdot 10^{53}$ erg	$1.85 \cdot 10^{53}$ erg	$1.69 \cdot 10^{53}$ erg
E^{src}_{CR} (in-source)	$5.11 \cdot 10^{54}$ erg	$5.13 \cdot 10^{54}$ erg	$4.62 \cdot 10^{54}$ erg	$4.36 \cdot 10^{54}$ erg
E^{src}_{UHECR} (in-source, UHECR)	$3.70 \cdot 10^{53}$ erg	$4.46 \cdot 10^{53}$ erg	$3.97 \cdot 10^{53}$ erg	$3.57 \cdot 10^{53}$ erg
E_ν	$7.81 \cdot 10^{49}$ erg	$2.18 \cdot 10^{50}$ erg	$1.28 \cdot 10^{51}$ erg	$1.79 \cdot 10^{51}$ erg
$E_{kin,init}$ (isotropic-equivalent)	$2.90 \cdot 10^{55}$ erg	$3.03 \cdot 10^{55}$ erg	$4.50 \cdot 10^{55}$ erg	$7.81 \cdot 10^{55}$ erg

- Light curves may be used as engine discriminator



- Description of $\sigma(X_{max})$ is an instrinsic problem (because the data prefer "pure" mass groups, which are hard to obtain in multi-zone or multi-source models)

Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

Transients which can power the UHECRs

from Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66; Fit energetics: Jiang, Zhang, Murase, arXiv:2012.03122; early args: Waxman, Bahcall, ...

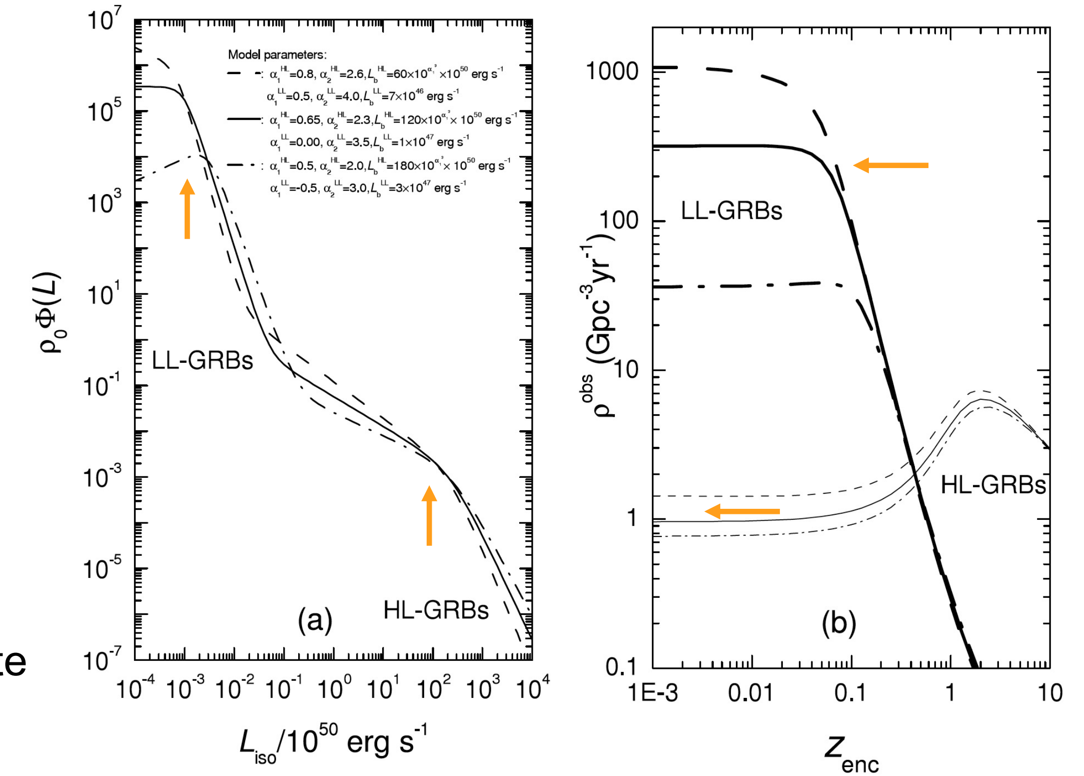
- Required energy per transient event to power UHECRs:

$$E_{\mathrm{CR}}^{[10^{10},10^{12}]} = 10^{53}\,\mathrm{erg} \cdot \frac{\dot{\varepsilon}_{\mathrm{CR}}^{[10^{10},10^{12}]}}{10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}} \; \frac{\mathrm{Gpc^{-3}\,yr^{-1}}}{\dot{n}_{\mathrm{GRB}}\big|_{z=0}}$$

Required energy output per source | Fit to UHECR data | Source density

- Connection with gamma-rays: $E_{\mathrm{CR}}^{[10^{10},10^{12}]} \sim 0.2\, f_e^{-1} E_\gamma$ if all UHECRs can escape, and 20% of the CR energy is in UHECRs (typical for E^{-2} spectrum).
f_e^{-1}: **baryonic loading** $(L_{CR}/L_\gamma)_{inj}$
- Examples in this talk: can all sustain this energy (roughly)
  - **HL-GRBs**: $E_\gamma \sim 10^{52}$ erg s^{-1} x 10 s ~ 10^{53} erg, rate ~ 1 Gpc^{-3} yr^{-1}
☞ Ok for $f_e^{-1} > 10$. *Seems widely accepted mainstream ...*
  - **LL-GRBs**: $L_\gamma \sim 10^{47}$ erg s^{-1}, rate ~ 300 Gpc^{-3} yr^{-1}
☞ Ok for Duration [s] x $f_e^{-1} > 10^5$;
duration disputed (closer to typical GRBs, rather than 10^4 s?)
  - **Jetted TDEs**: $E_\gamma \sim 10^{47}$ erg s^{-1} x 10^6 s ~ 10^{53} erg (Sw J1644+57), rate 0.1 Gpc^{-3} yr^{-1} ☞ Ok for f_e^{-1} >~ 100; *local rate + L_γ disputed*

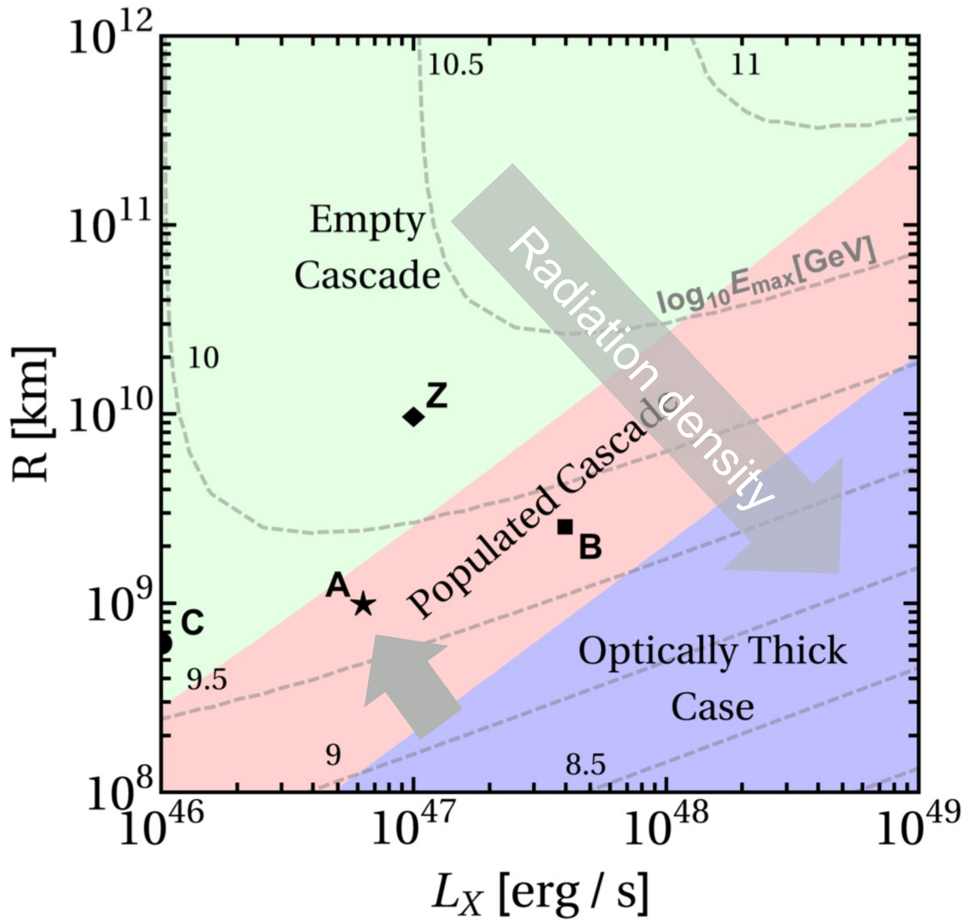
Liang, Zhang, Virgili, Dai, 2007; see also: Sun, Zhang, Li, 2015



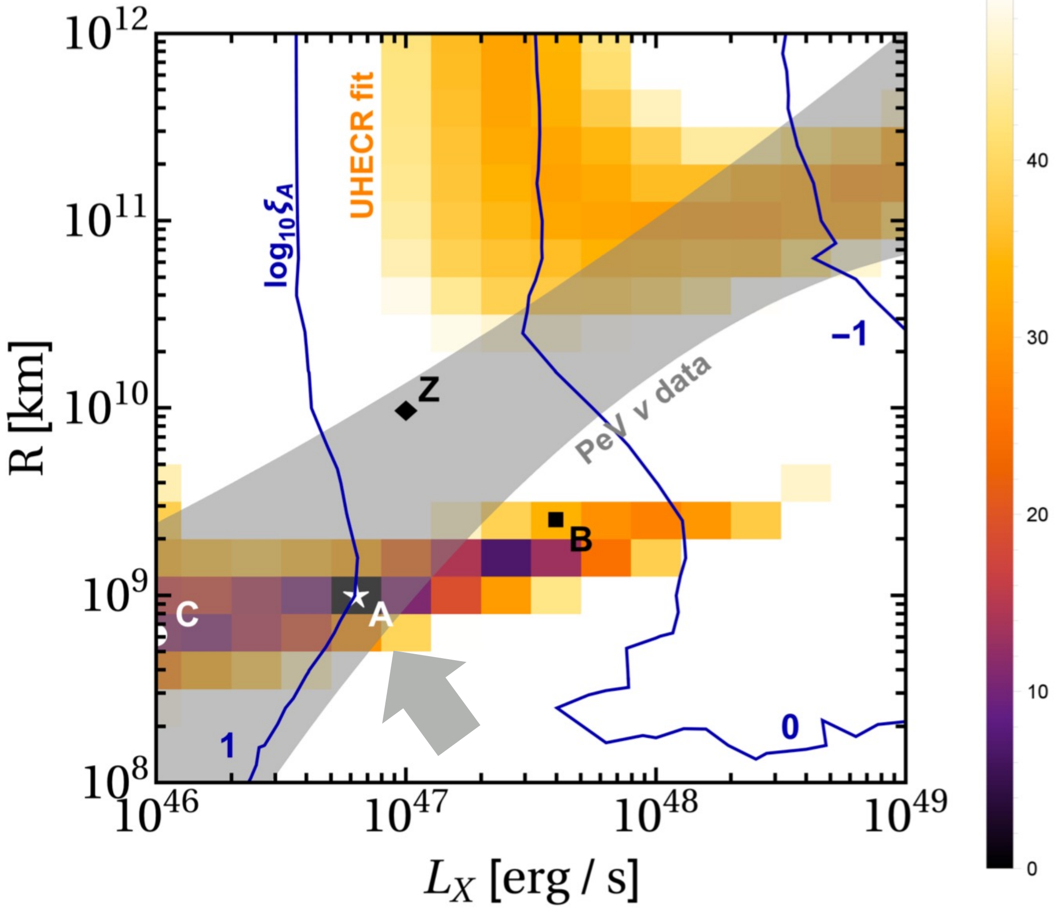
LL-GRBs: Systematic parameter space studies

What are the model parameter expectations driven by data?

Nuclear cascade and E_{max}



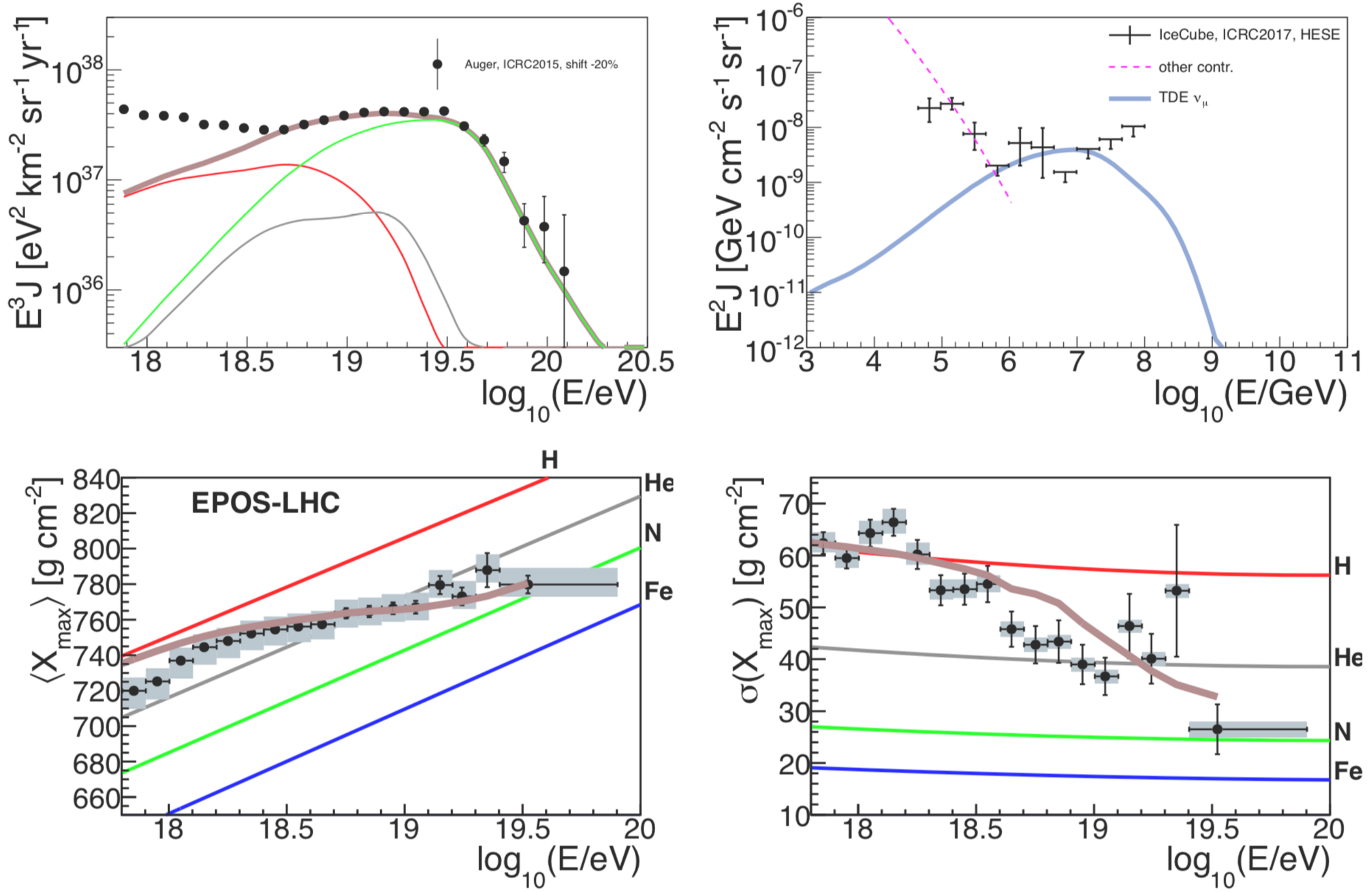
UHECR and neutrino fits



ξ_A: Baryonic loading ($\log_{10} L_{CR}/L_\gamma$)
(here: T_{90} = $2\ 10^5$ s fixed; **energetics**!)

Boncioli, Biehl, Winter, arXiv:1808.07481;
Reference point "Z": Zhang et al., 2018

Example: jetted Tidal Disruption Events (TDE)



May work for UHECRs if less luminous, more abundant sources (neutrino flux may be lower)

Biehl, Boncioli, Lunardini, WW, Sci. Rep. 8 (2018) 1; arXiv:1711.03555