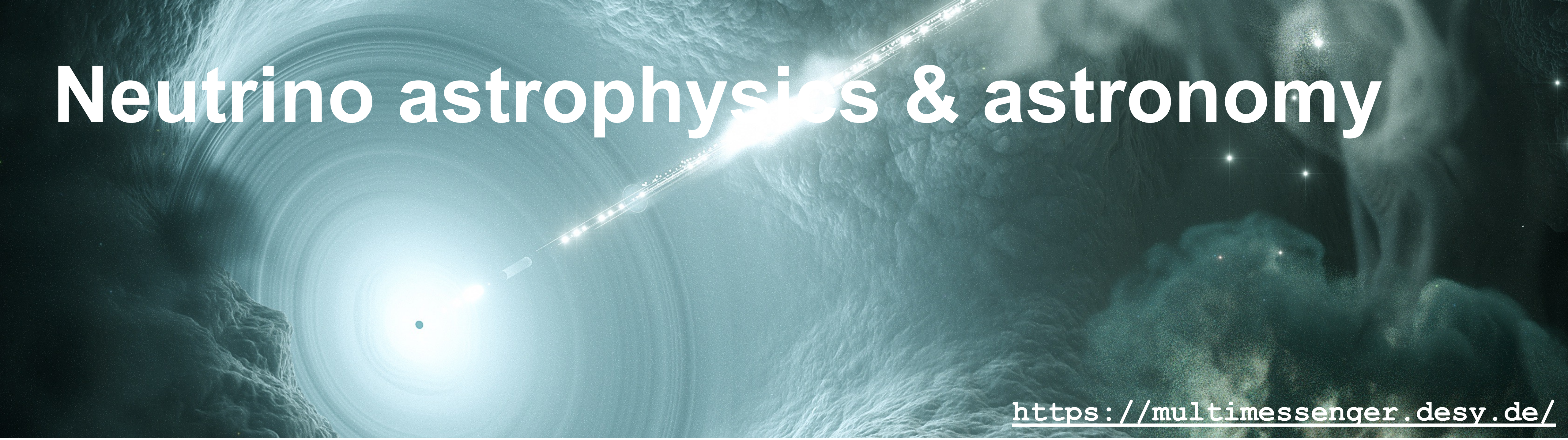


Neutrino astrophysics & astronomy

https://multimessenger.desy.de/

Winter, Walter
DESY, Zeuthen, Germany

Here,
There &
Everywhere

PhD Summer School on Neutrinos
July 17-21, 2023
Niels Bohr Institute, Copenhagen

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Contents

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

Lecture I
(Monday)

- Multi-messenger follow-ups / astrophysical objects:
  - Neutrinos from AGN blazars
  - Neutrinos from Tidal Disruption Events (TDEs)
  - Neutrinos from Gamma-Ray Bursts (GRBs)

Lecture II
(Tuesday)

Talk Rudolph
(Wednesday)

- The connection to Ultra-High Energy Cosmic Rays (UHECRs)
  - Cosmogenic (EeV) neutrinos
  - Source models – example GRBs

Lecture III
(Thursday)

Disclaimer: Bear in mind that some of the results presented here will be updated in the next two weeks at ICRC 2023 (July 26-Aug 3) **https://www.icrc2023.org/**

Lecture I: Introduction/overview

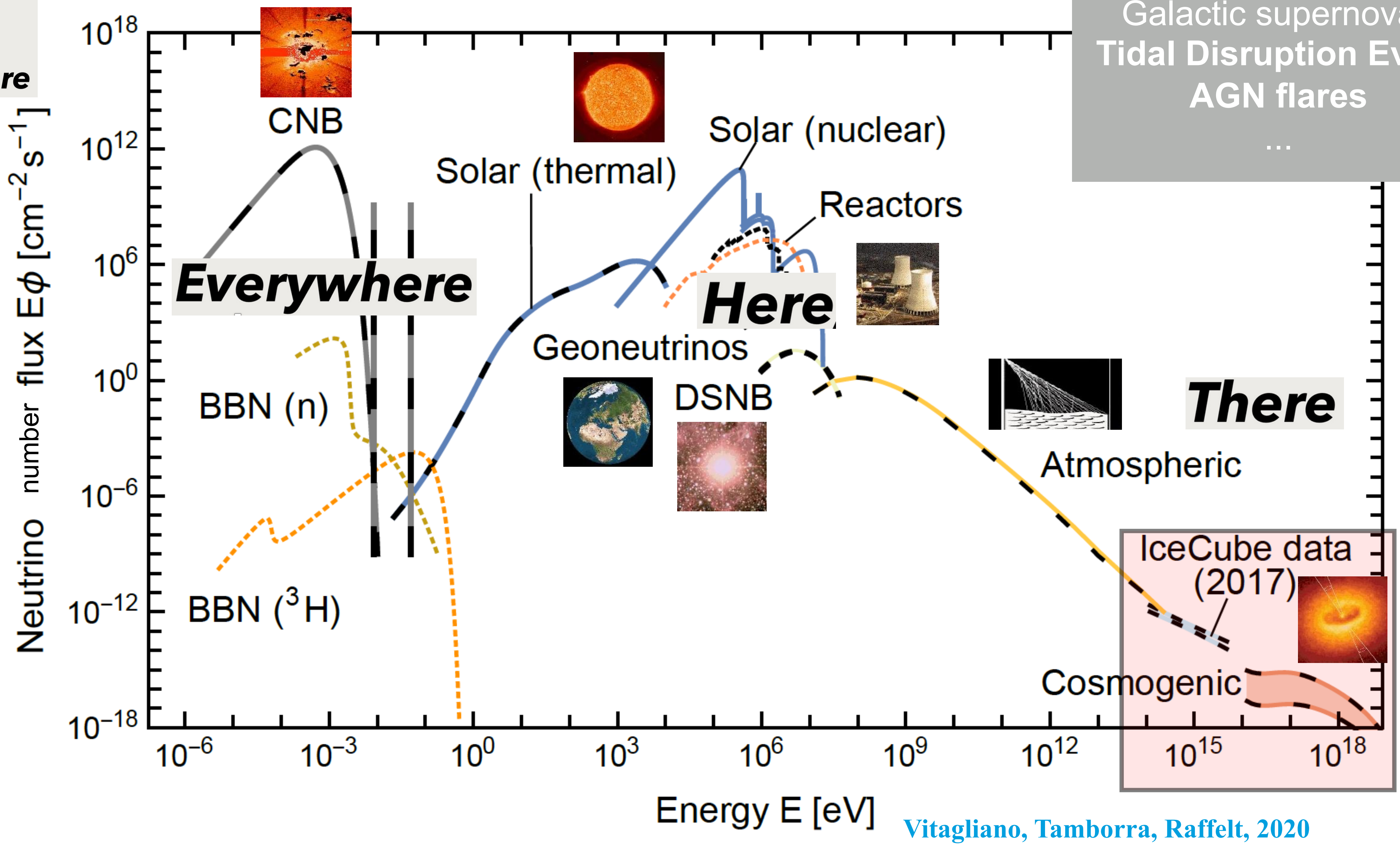
Observations and physics of neutrino production

Where do the neutrinos come from?

Diffuse neutrino background (number flux)

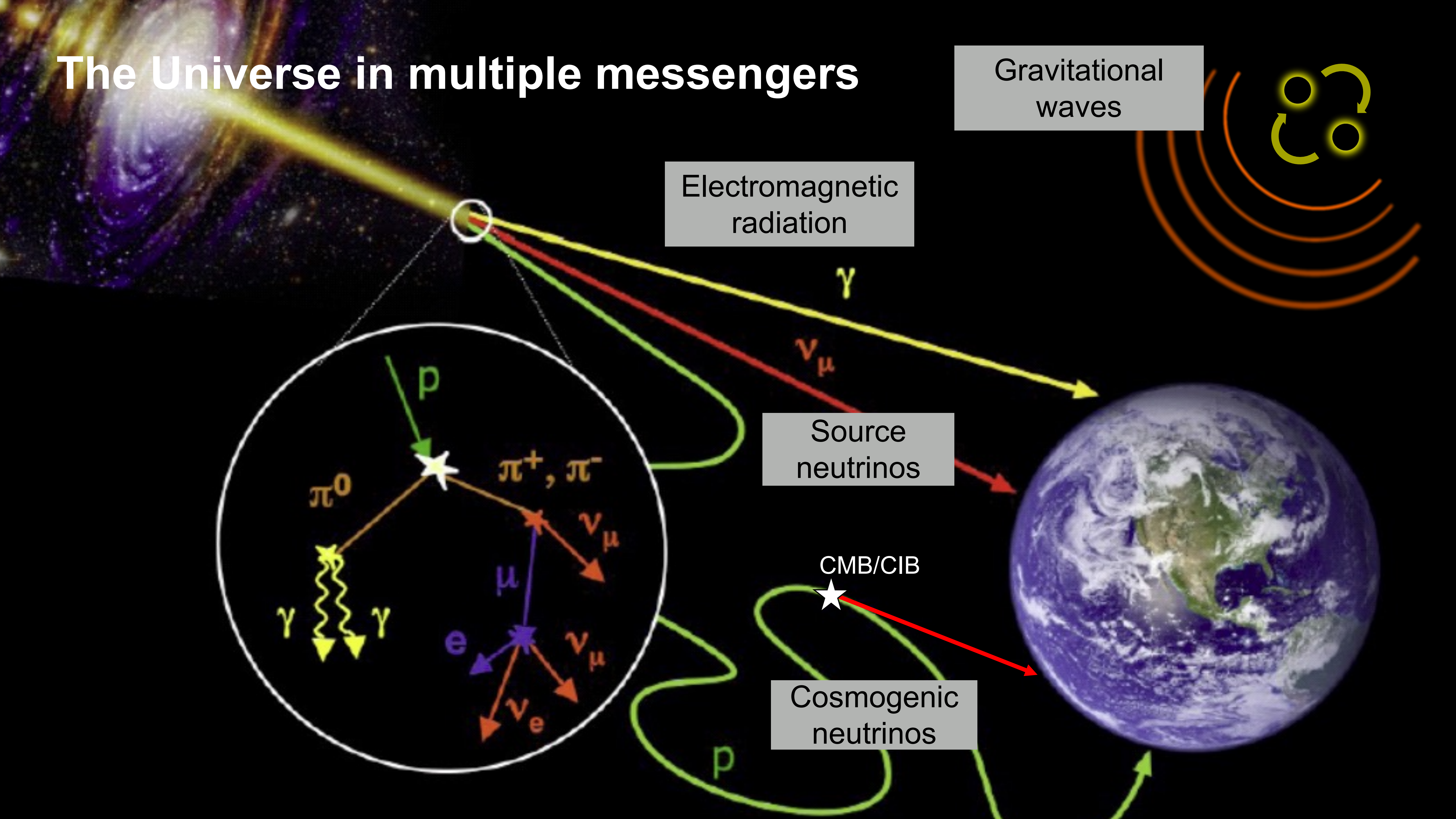
Here,
There &
Everywhere

Plus “transient” fluxes:
Neutrino beams (pulsed)
Galactic supernova?
Tidal Disruption Event
AGN flares
...



Vitagliano, Tamborra, Raffelt, 2020

The Universe in multiple messengers



Gravitational waves

Electromagnetic radiation

Source neutrinos

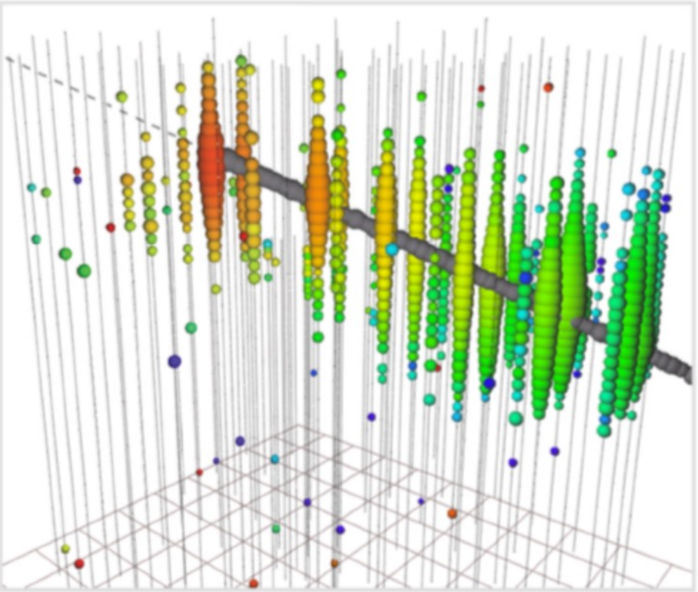
Cosmogenic neutrinos

CMB/CIB

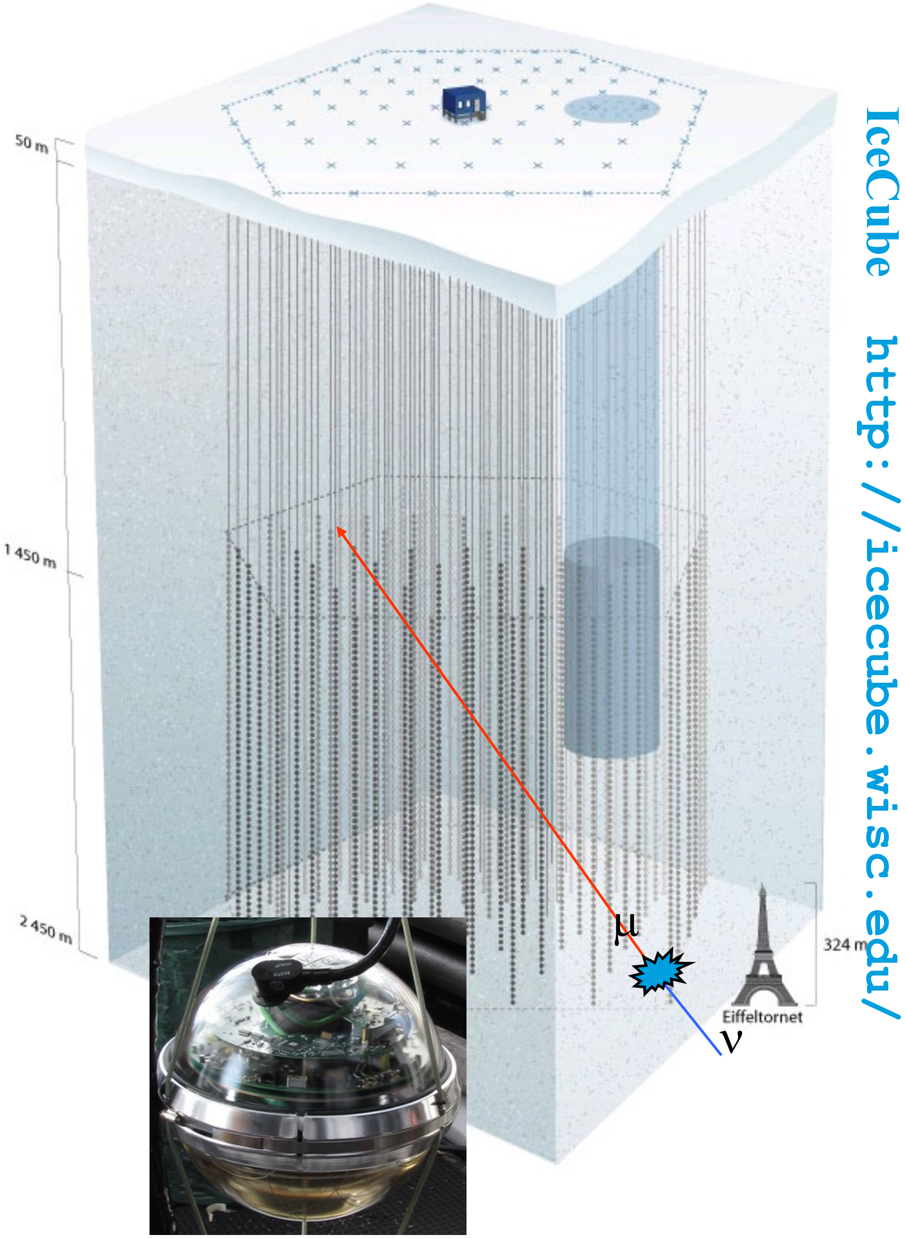
Observations of TeV-PeV neutrinos (overview)

Observing TeV-PeV neutrinos with IceCube

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

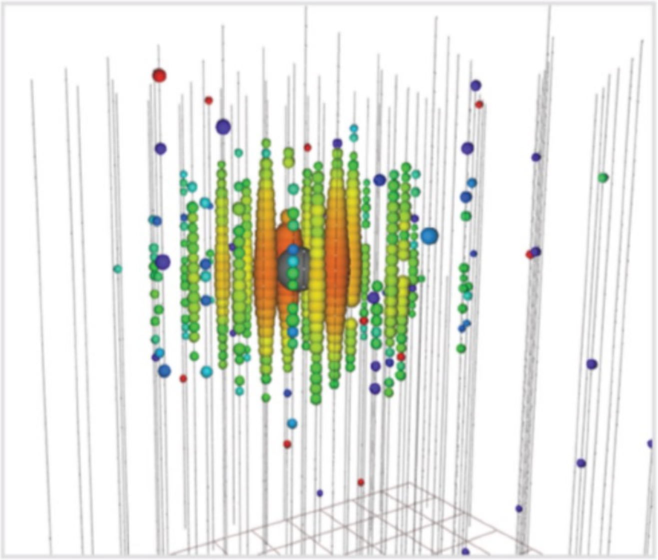


Better directional info



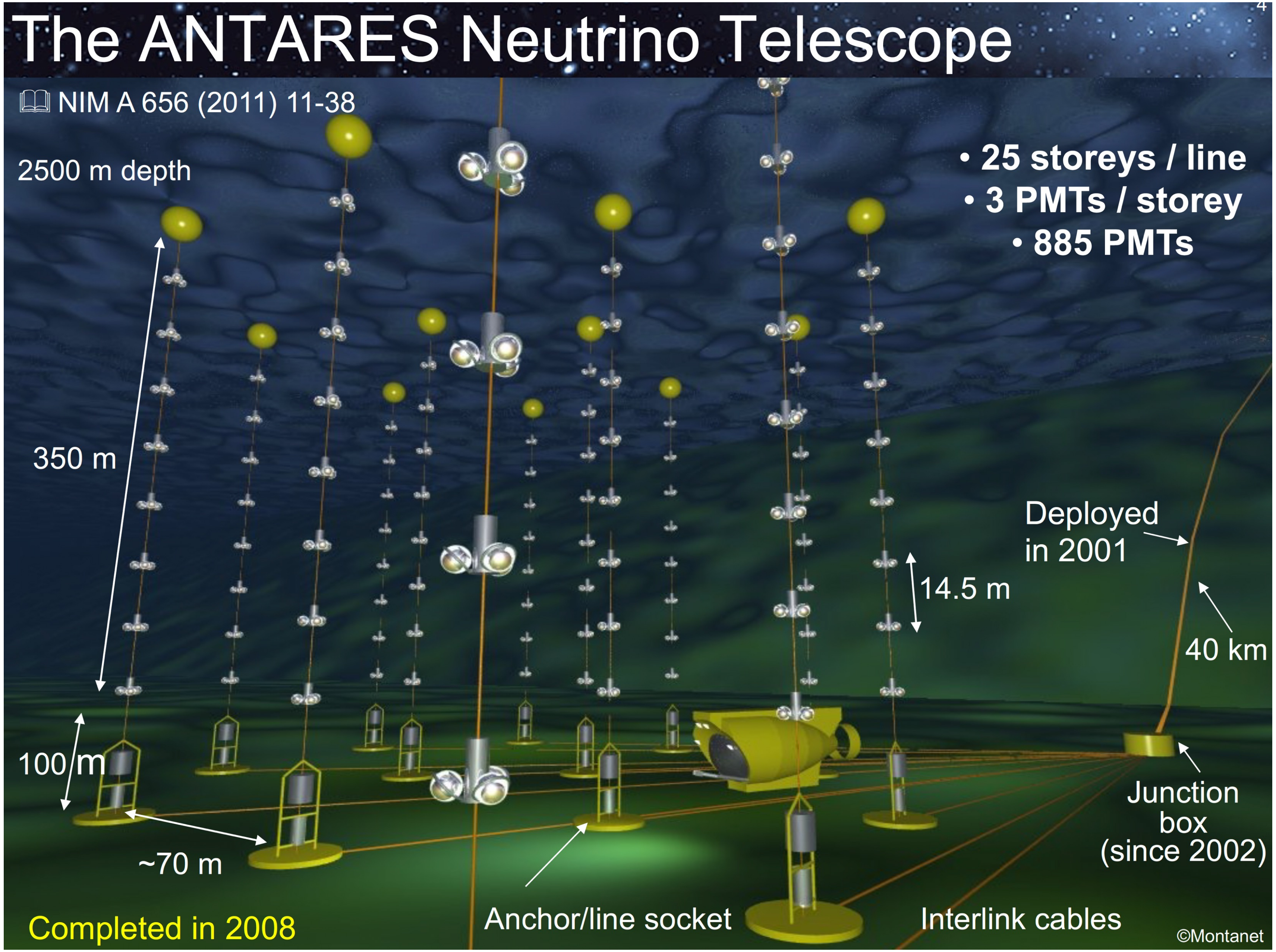
IceCube http://icecube.wisc.edu/

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



Better energy info

ANTARES



The ANTARES Neutrino Telescope

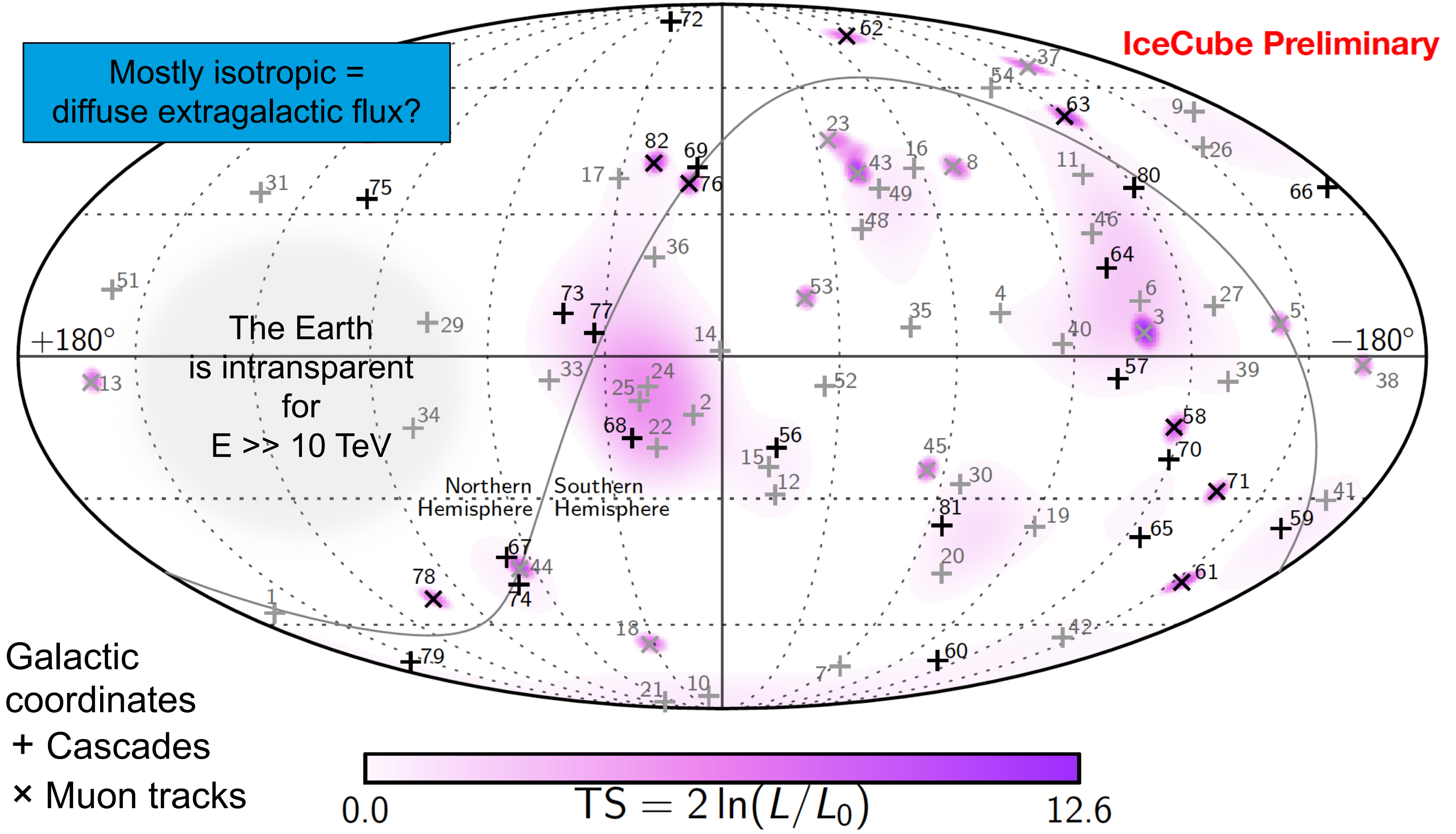
📖 NIM A 656 (2011) 11-38

- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

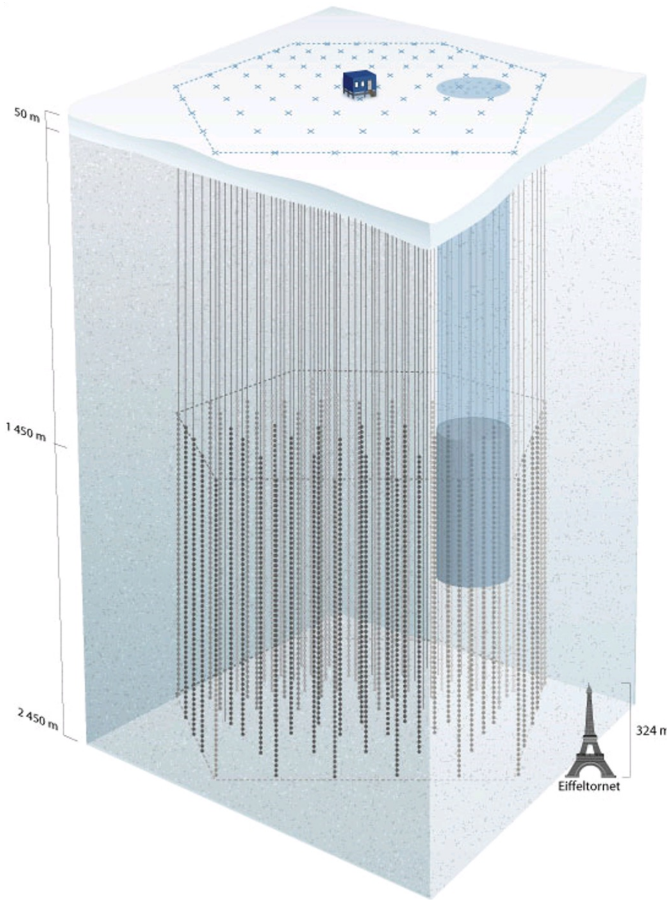
A. Kouchner

A flux of high-energy cosmic neutrinos

Mostly isotropic = diffuse extragalactic flux?

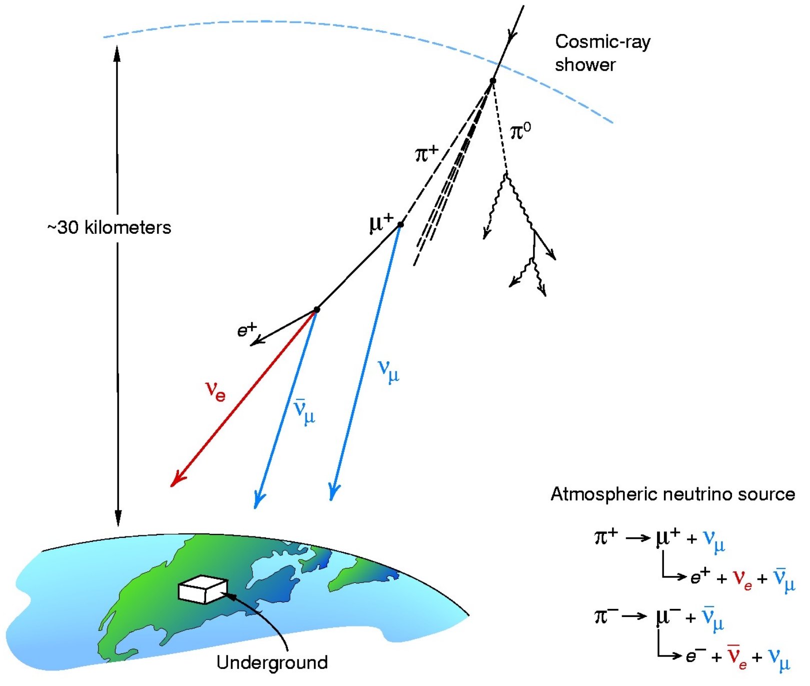


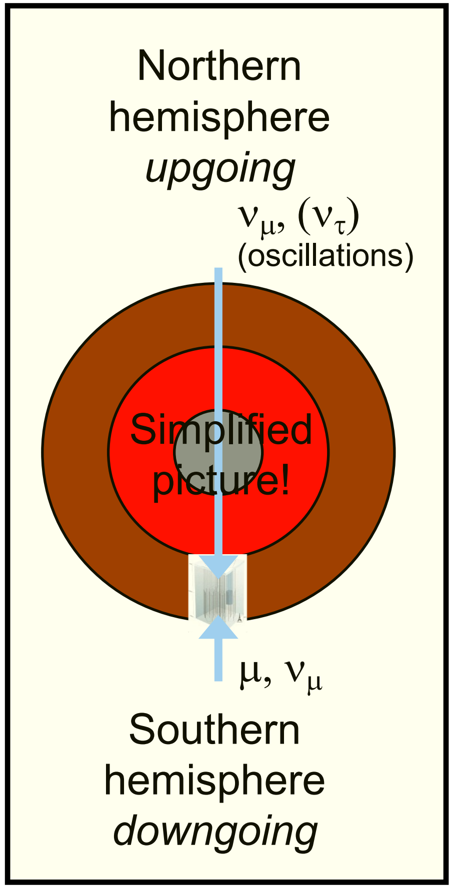
Galactic coordinates
+ Cascades
× Muon tracks

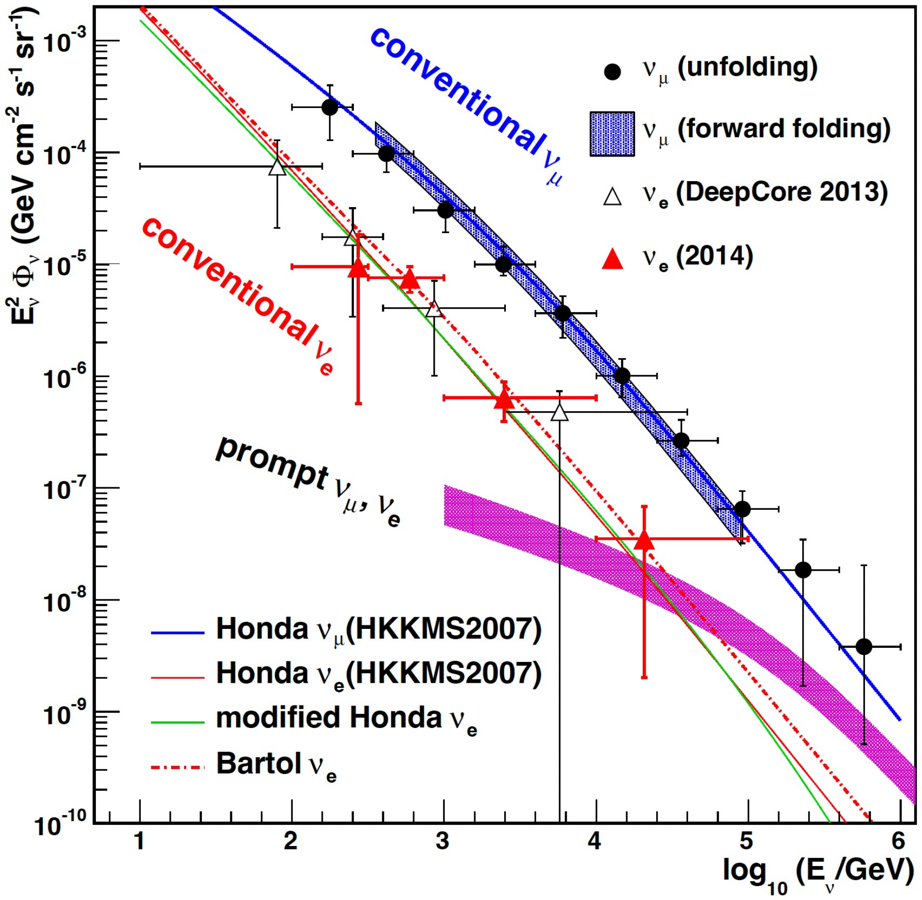


IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); update from Kopper at ICRC 2017

Backgrounds: Neutrinos and muons from the atmosphere







Muon lifetime: 2 10^{-6} s (~ 600 m) x E/m_0.
In addition: muons lose energy.

Consequence: Atmospheric neutrino and muon backgrounds at Earth

For transport computations, see Gaisser, Engel, Resconi: Cosmic rays and particle physics, Cambridge, 2016

IceCube, Phys. Rev.D 91 (2015) 122004

Diffuse neutrino flux – observed in different event samples

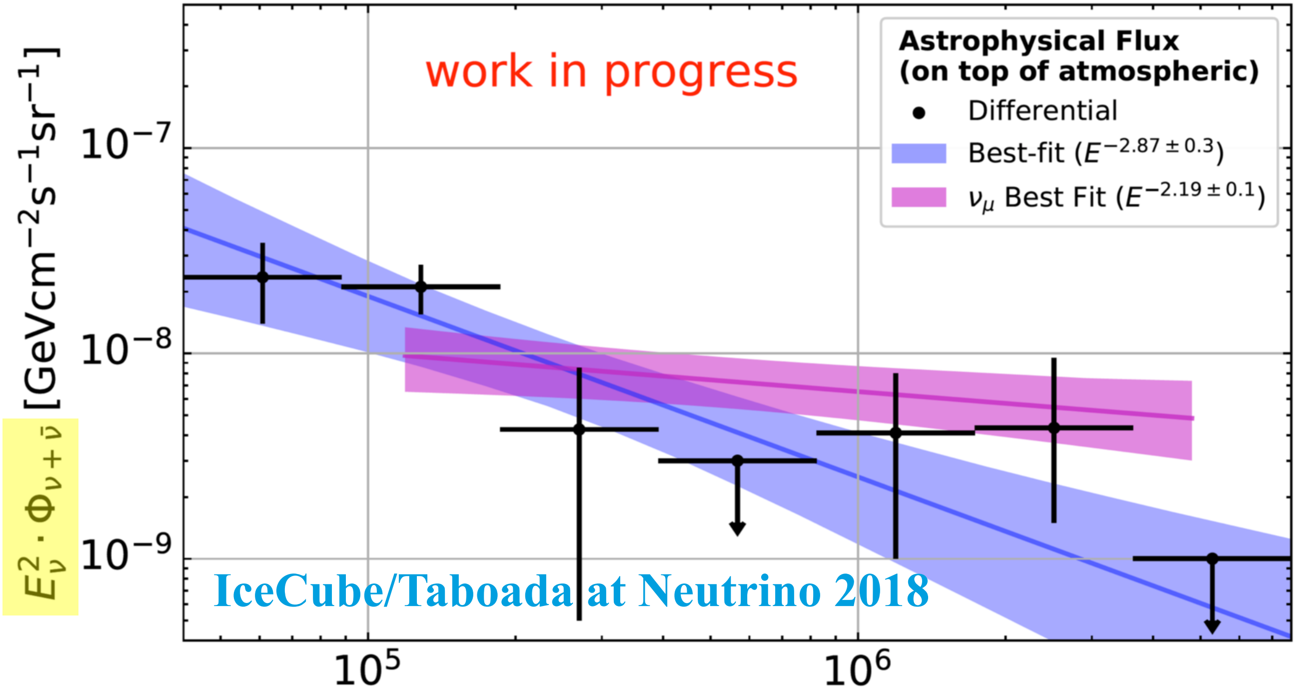
HESE = High Energy Starting Events

Interaction within detection volume

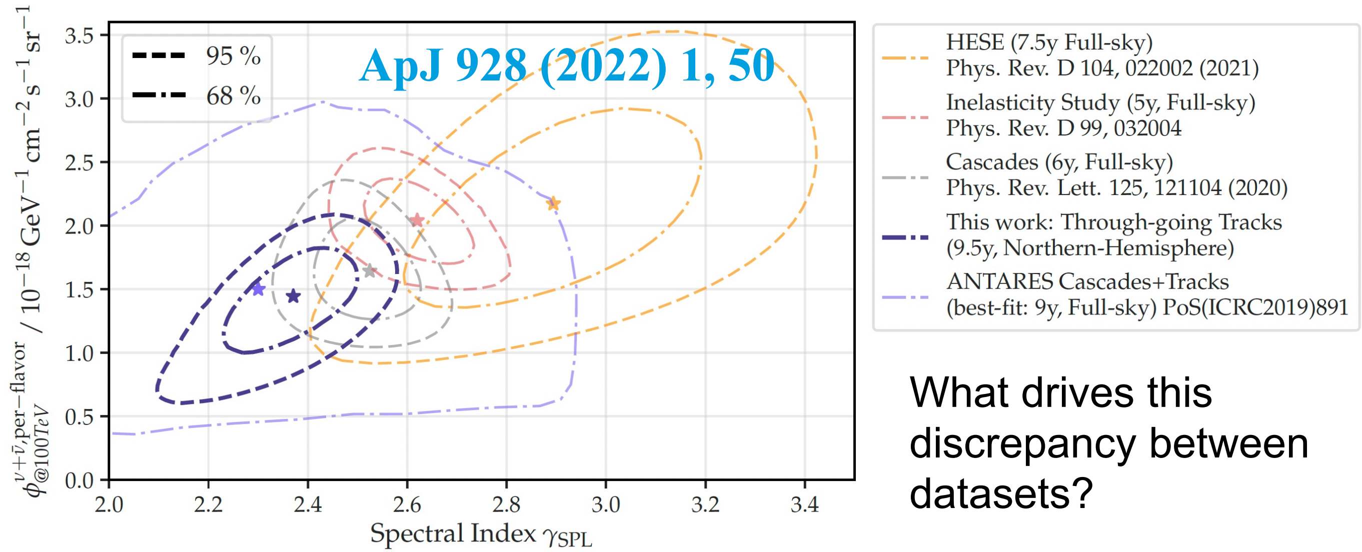
Outer layer of detector used as veto (atm. muons)

Sensitive to both hermispheres, all flavors

Lower energies = contained events



IceCube/Taboada at Neutrino 2018



ApJ 928 (2022) 1, 50

What drives this discrepancy between datasets?

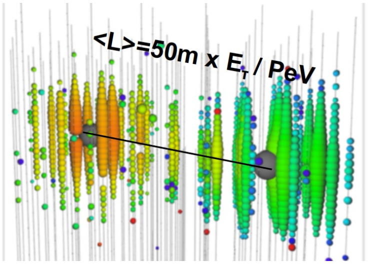
Through-going muon tracks

Sensitive to ν_μ only from Northern hemisphere

Large effective volume (interaction may be outside detector)

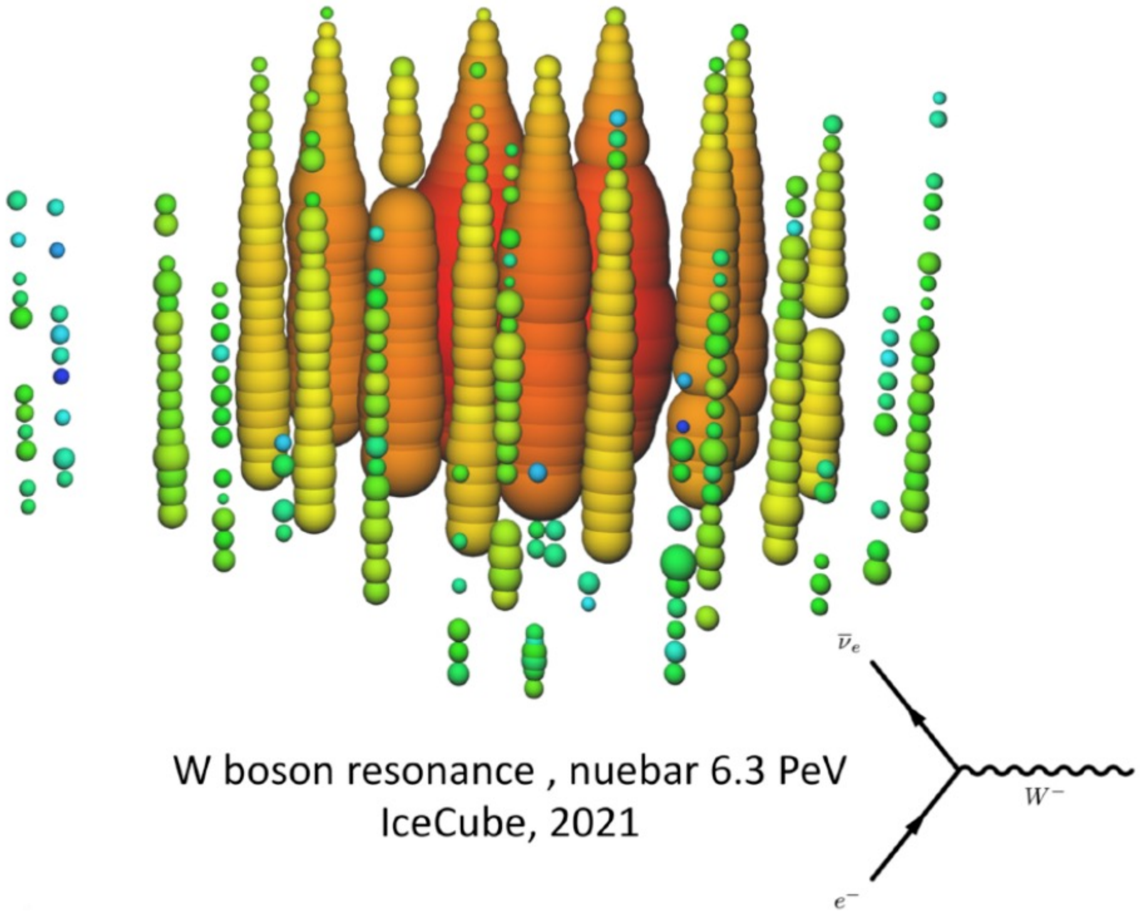
Muon energy gives a lower limit for neutrino energy

New event classes

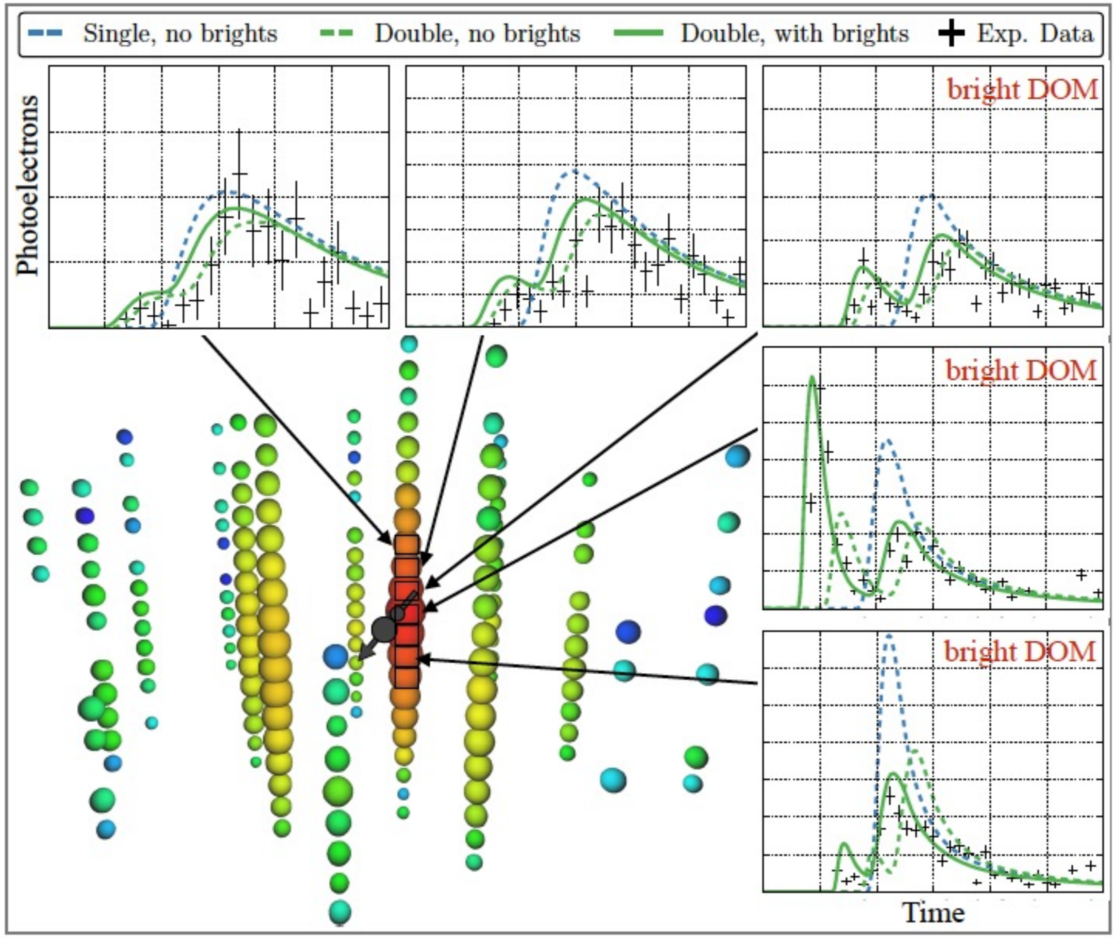


Glashow resonance

Double bang (ν_τ) candidates



W boson resonance , nuebar 6.3 PeV
IceCube, 2021



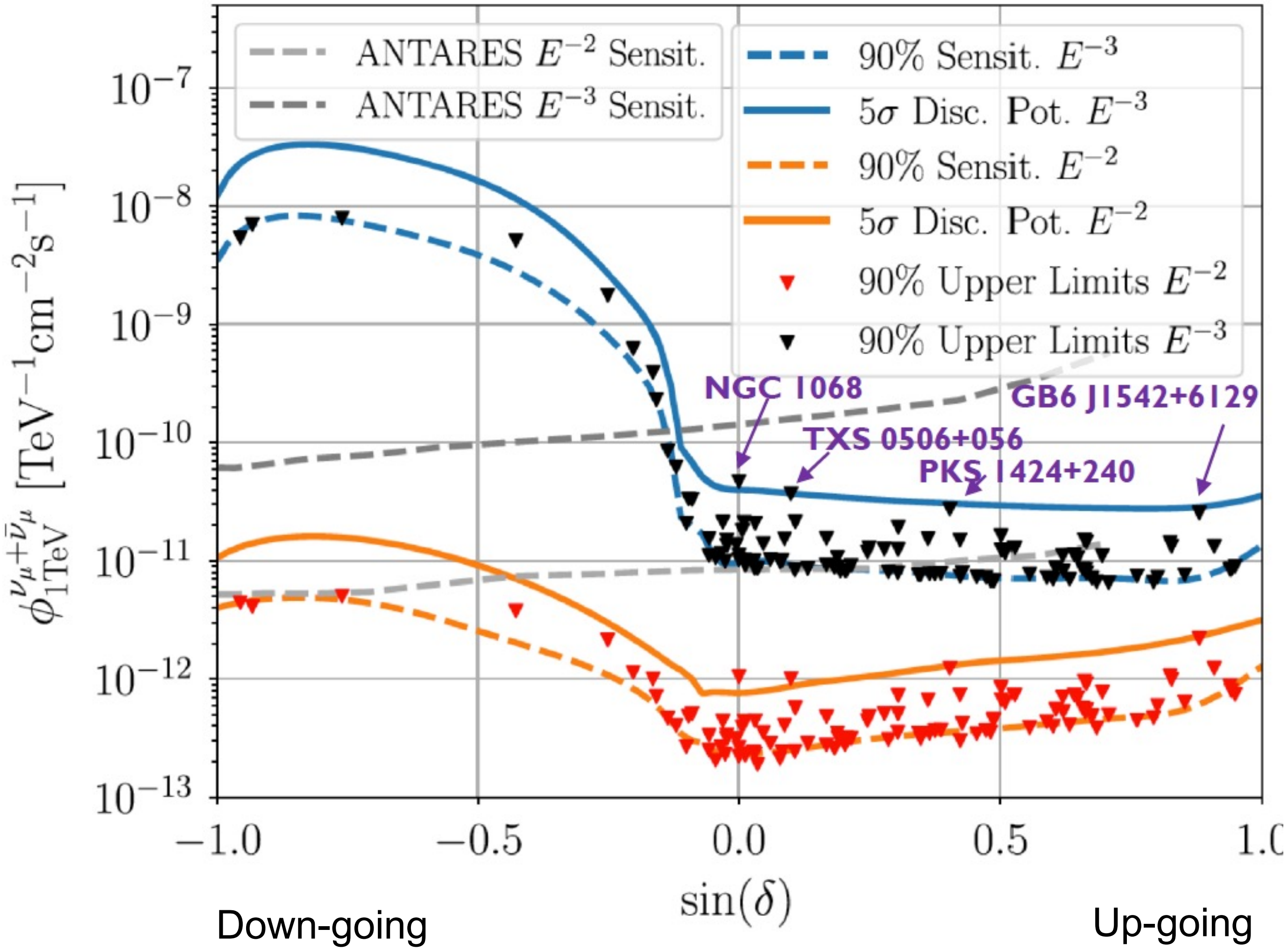
IceCube, Nature 591 (2021) 7849, 220

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

Time-integrated 10 year point source searches

- Most significant:
  NGC 1068 (3σ post-trial)
  Active galaxy, Seyfert 2, starburst

- The other three are AGN blazars
- TXS 0506+056 is prominent because it was found earlier through a multi-messenger follow-up



Down-going

Up-going

→ Exercises

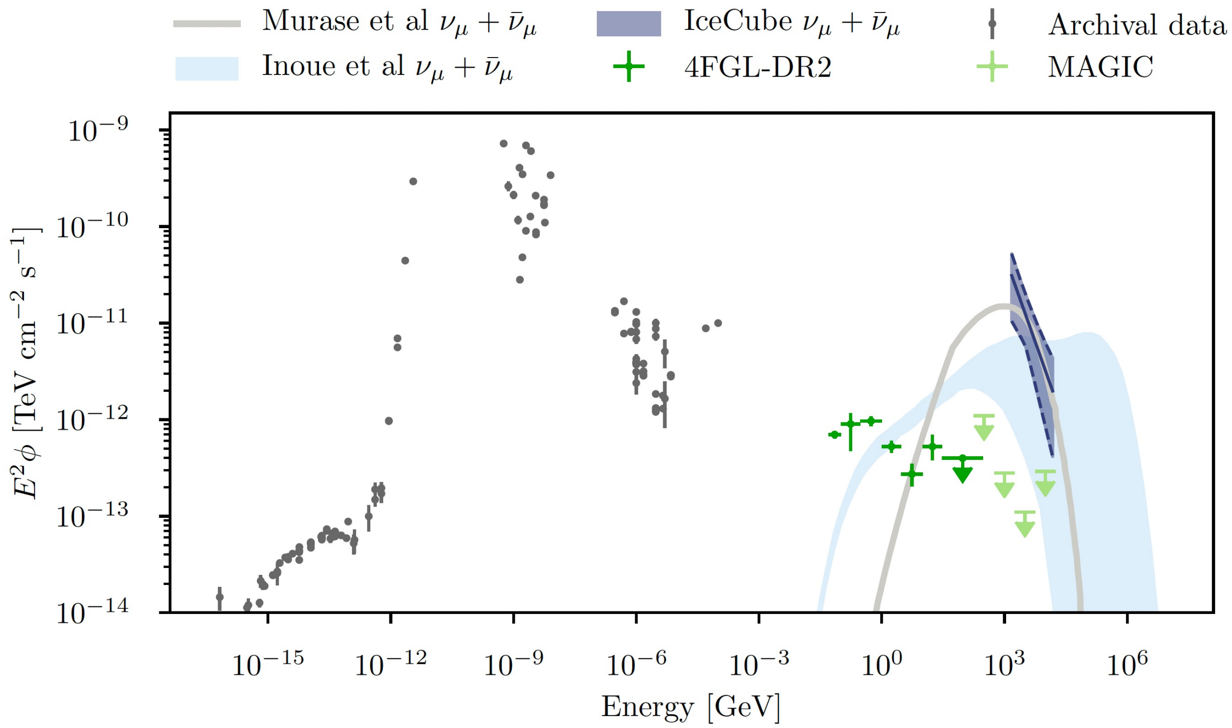
IceCube, PRL 124 (2020) 5, 051103; from G. Illuminati @ Paris 2020

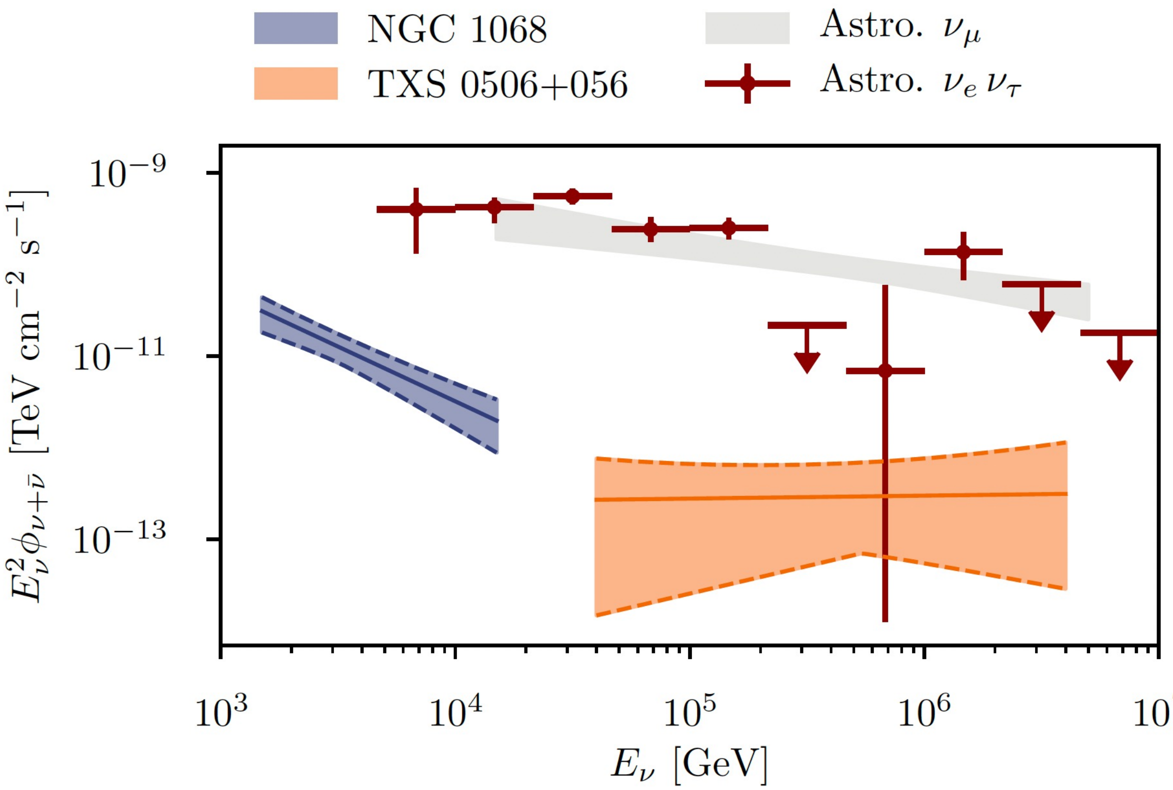
Neutrinos from NGC 1068

→ Talk Salvatore


Credits: NASA, ESA & A. van der Hoever

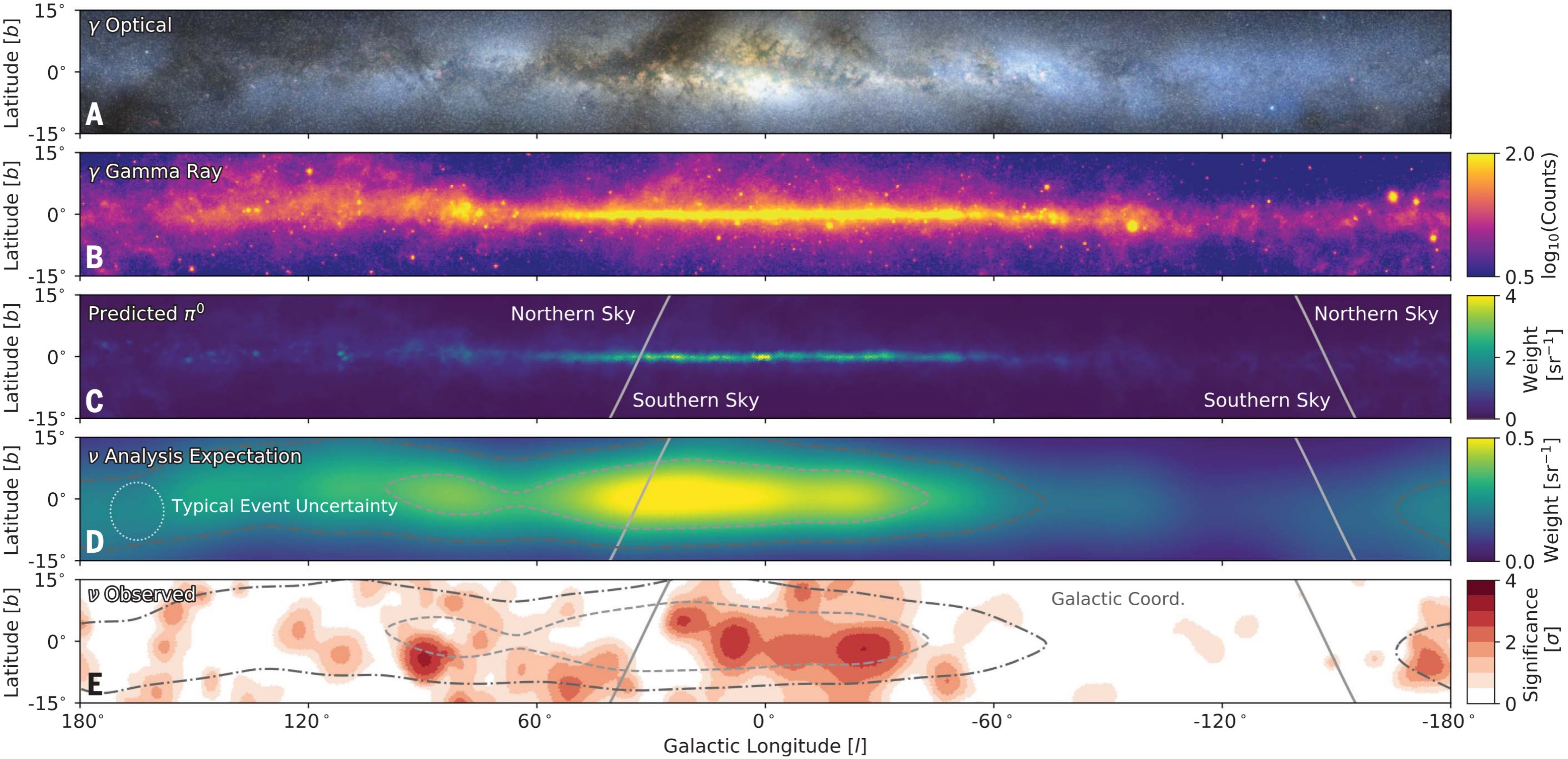
- Excess of 79 (+22 -20) events, leading to 4.2σ significance
- Strongest point source, soft spectrum, z=0.004
- Obscured in very-high energy gamma-rays; kind-of expected if neutrino production is efficient, e.g. **Murase, Guetta, Ahlers, PRL 116 (2016) 071101**





IceCube, Science 378 (2022) 6619, 538

Galactic plane seen in neutrinos at 4.5σ



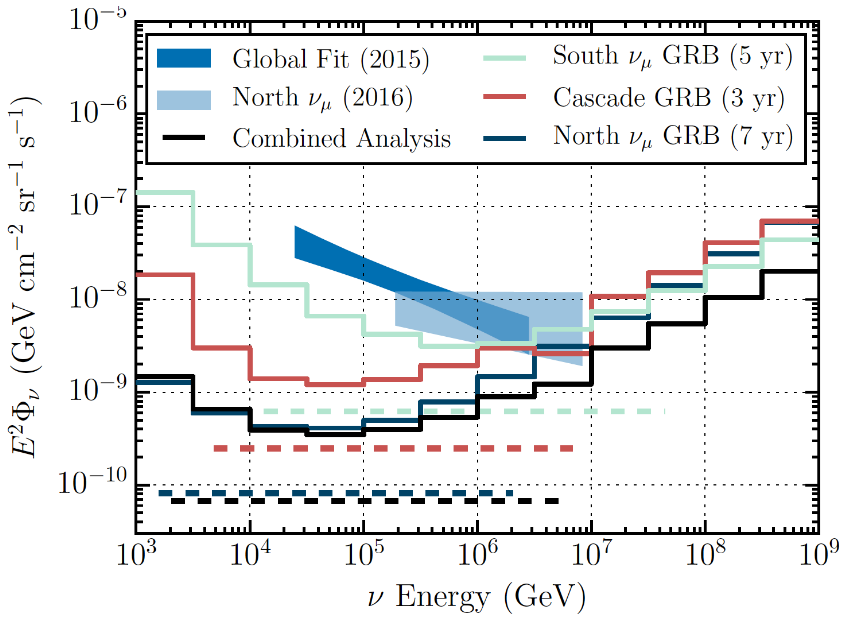
IceCube, Science 380 (2023) 1338;
see also ANTARES, Phys. Lett. B 841 (2023) 137951

Stacking limits ...

... for the most energetic sources classes

Gamma-Ray Bursts (GRBs)

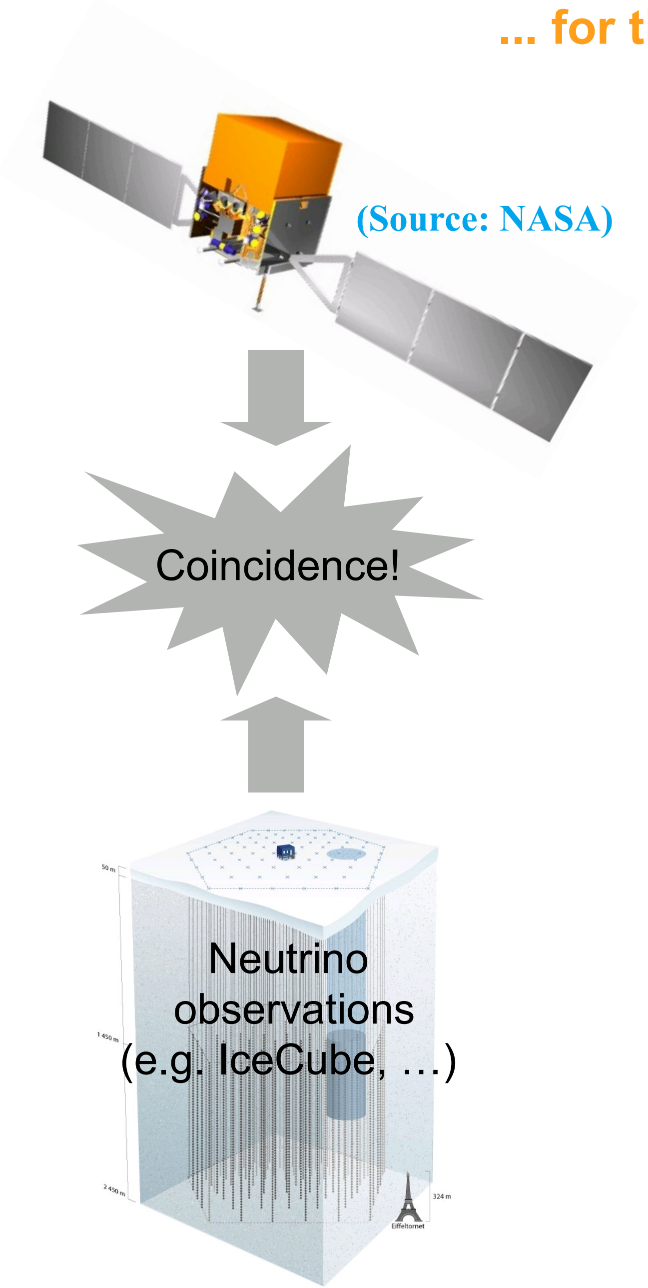
- Transients, time variability
- High luminosity over short time



- Less than ~1% of observed ν flux

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

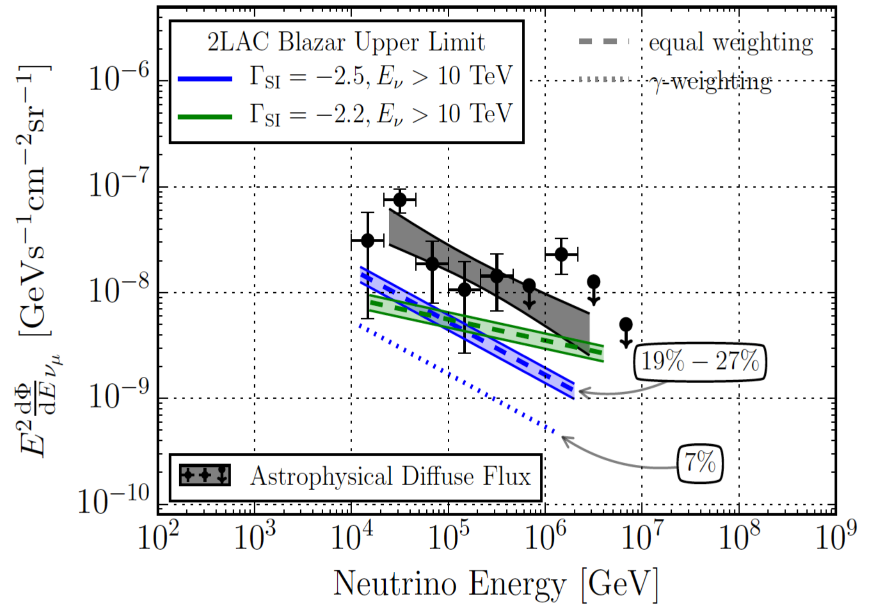
→ Talk Rudolph, exercise



(Source: NASA)

Active Galactic Nuclei (AGN) blazars

- Steady emission with flares
- Lower luminosity, longer duration



- Less than ~25% of observed ν flux?

IceCube, Astrophys. J. 835 (2017) 45

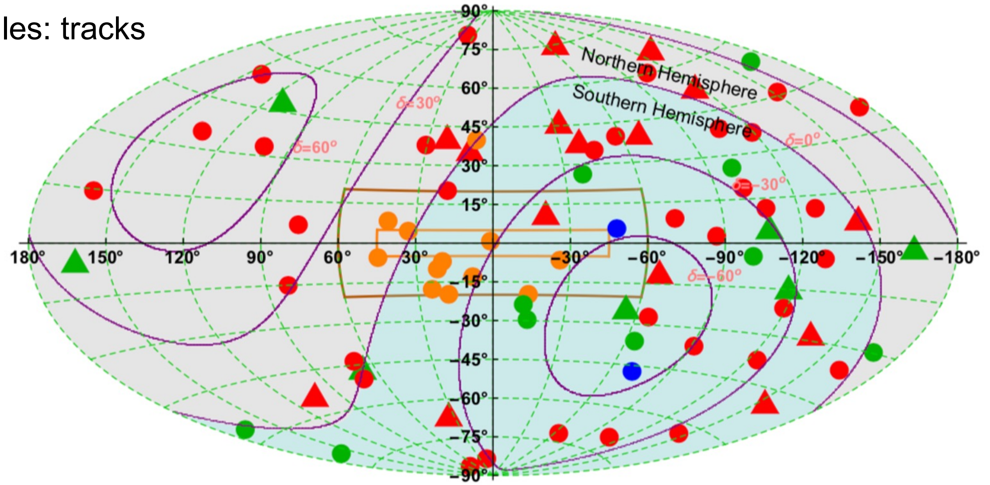
→ Lecture 2

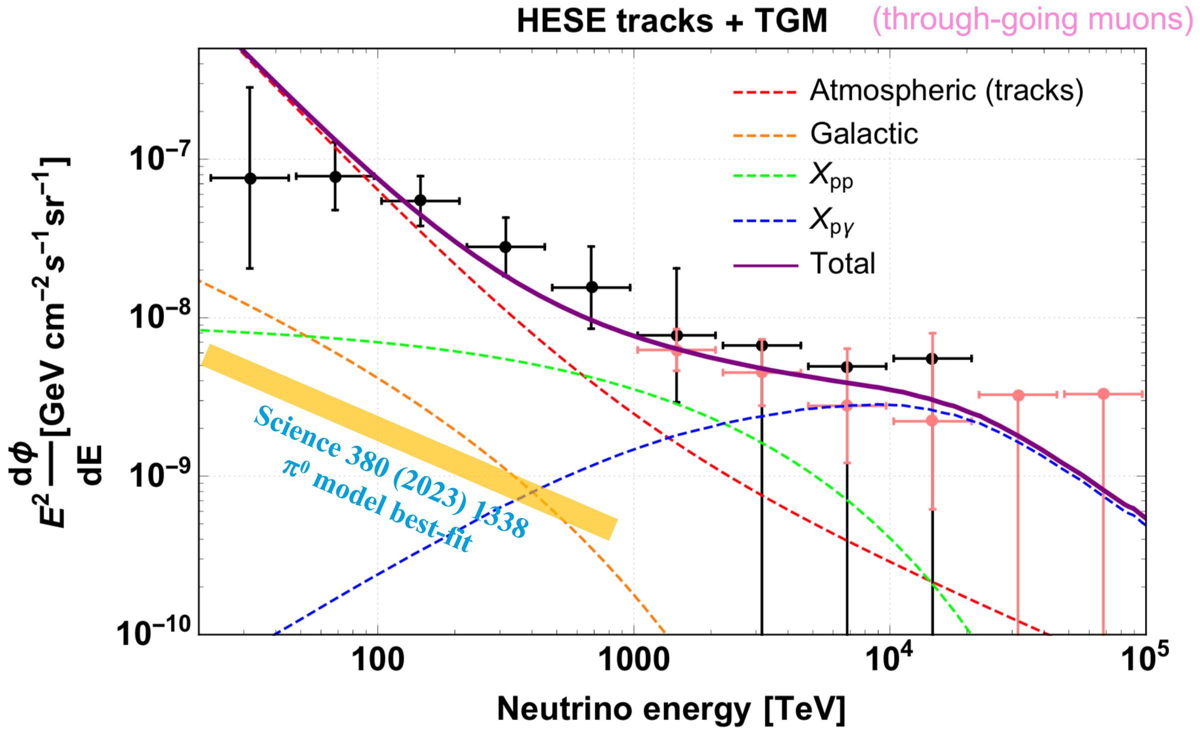
Multiple contributions to diffuse flux? A possible scenario.

Sky map (Galactic coordinates, examples):

circles: cascades

triangles: tracks





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?	$p\gamma$ 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 for Galactic νs

HESE **cascades**

Science 380 (2023) 1338:
uses 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

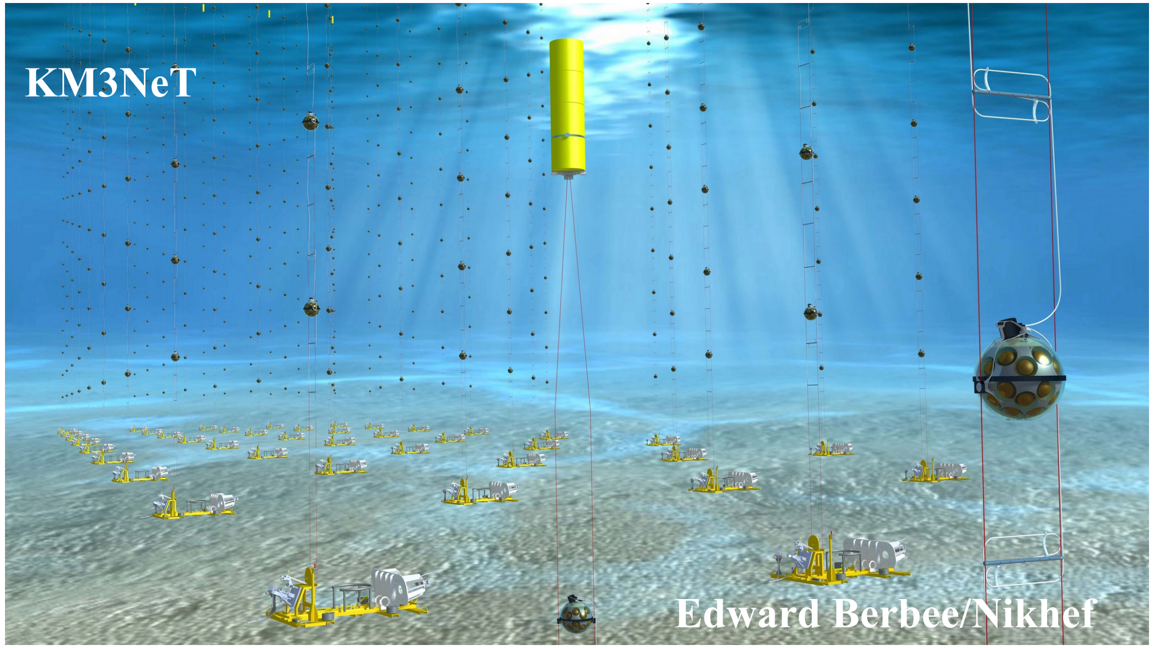
[…]

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

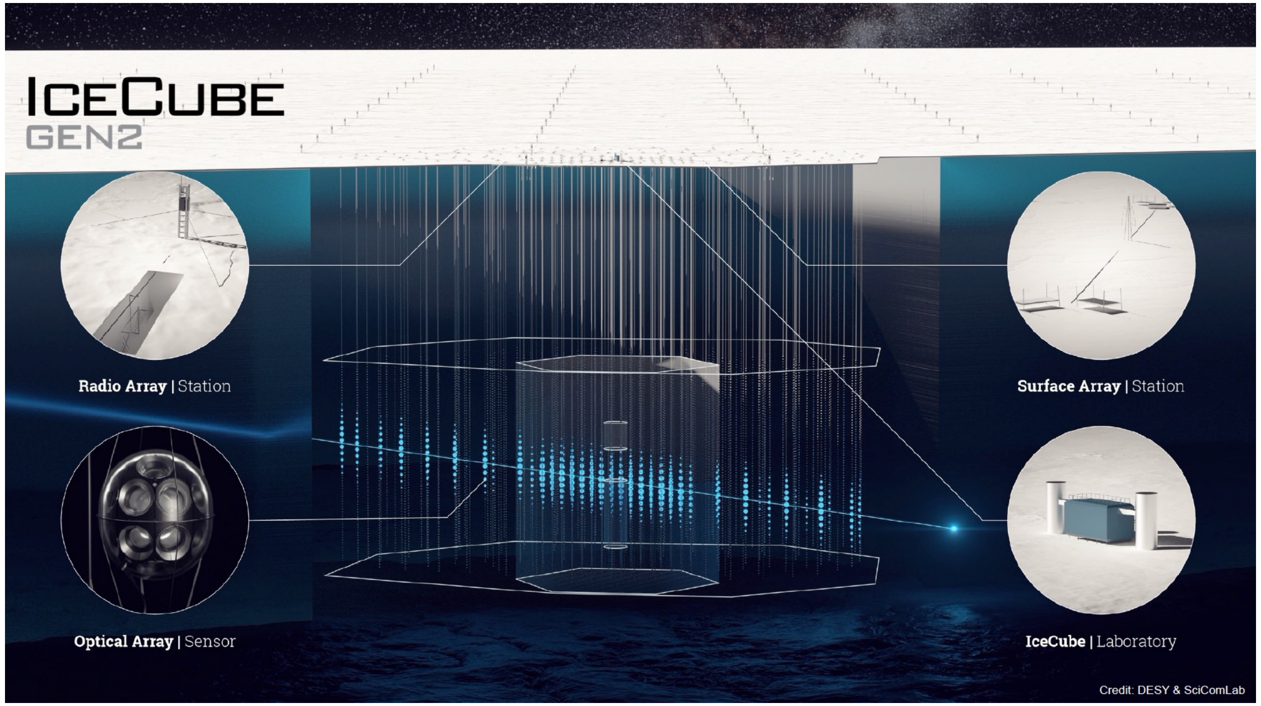
Palladino, Winter, A&A 615 (2018) A168

Future neutrino telescopes: PeV neutrinos

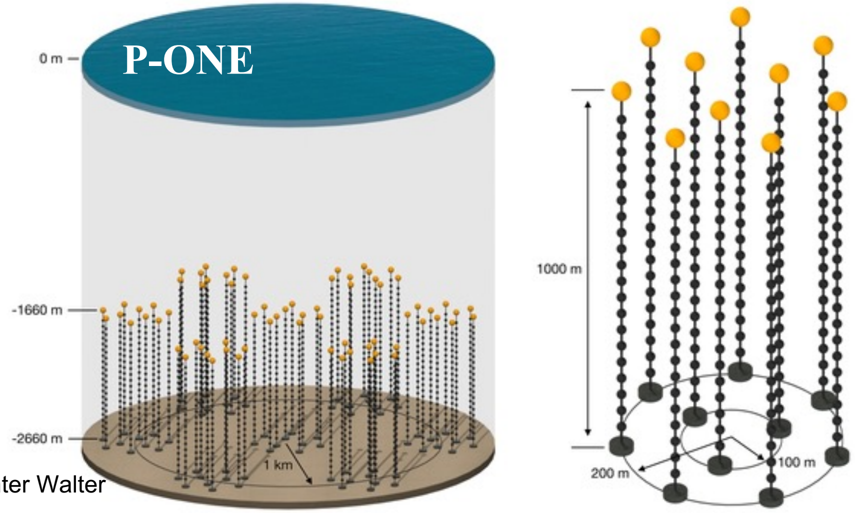
… towards a global neutrino observatory?



Edward Berbee/Nikhef



Credit: DESY & SciComLab

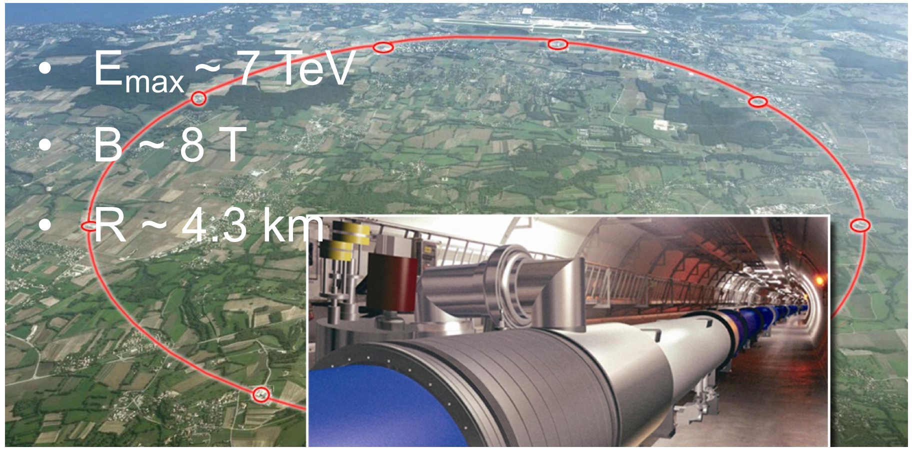


Elisa Resconi/TUM

Physics of neutrino production

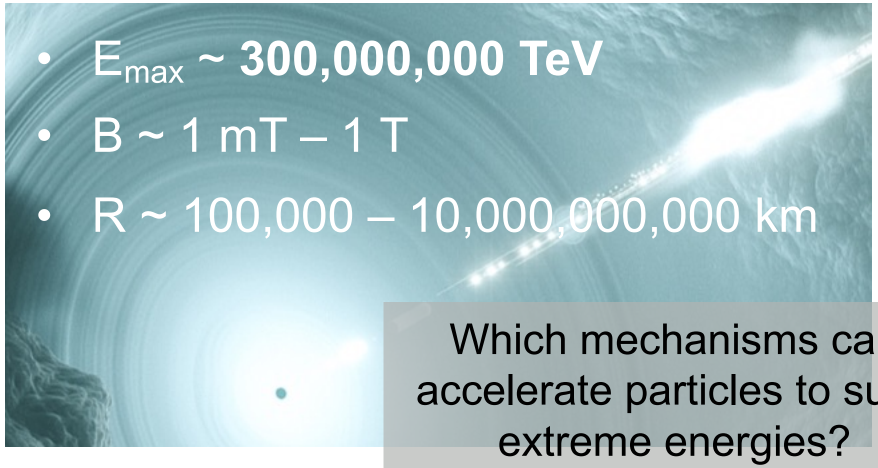
(theoretical background)

Particle acceleration ... a pragmatic perspective



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

Lorentz force
= centrifugal force
➔ $E_{max} \sim Z\,c\,B\,R$



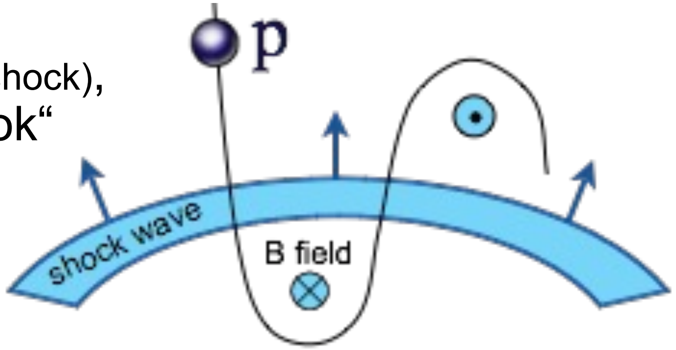
- E_{max} ~ **300,000,000 TeV**
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km

Which mechanisms can accelerate particles to such extreme energies?

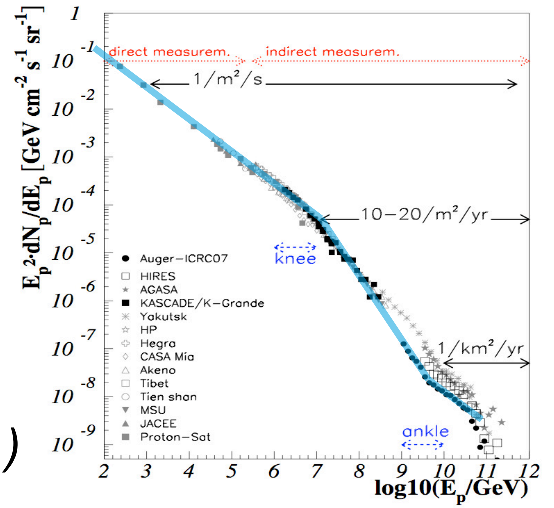
Example: *Fermi shock acceleration*

- 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 **E^{-2}** is the typical “textbook“ spectrum

→ Talk Peretti

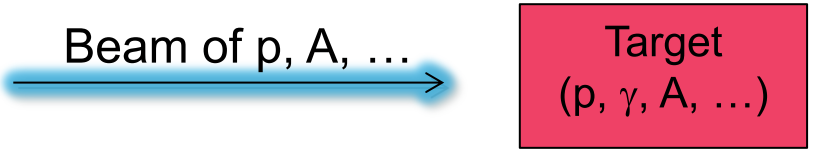


- Theory of acceleration challenging, but we **do observe** power law (= non-thermal) spectra in Nature
- For multi-messenger perspective: adopt pragmatic point of view!
  (we know that it works, somehow ...)



Secondary production: Particle physics 101?

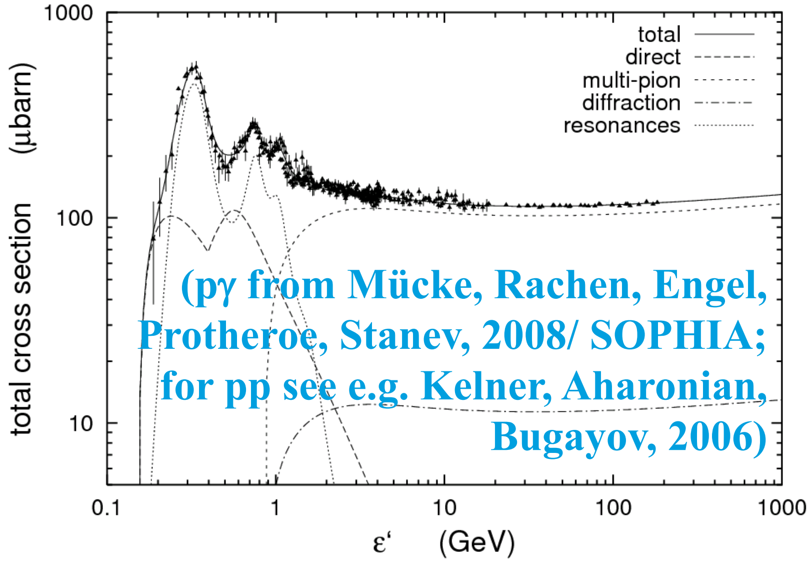
- **Beam dump picture (particle physics)**



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

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

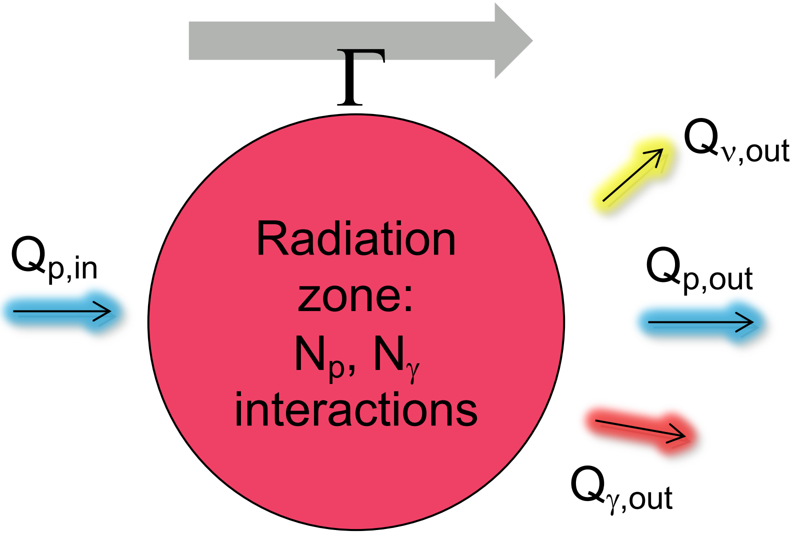
Key challenge:
Need volume



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

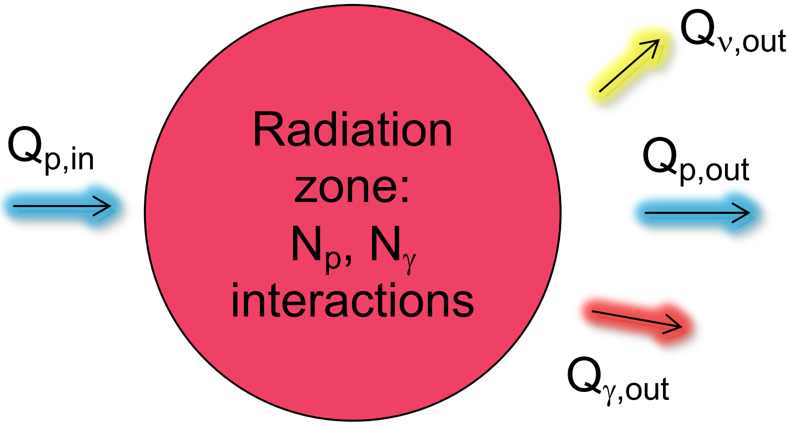
(Photon energy in nucleon rest frame)

- **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



Here: typically a spherical blob in relativistically moving frame

Global radiation models (theory)



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

$$\frac{\partial N_i}{\partial t} = \underbrace{\frac{\partial}{\partial E}\left(-b(E)N_i(E)\right)}_{\text{Cooling (continuous)}} - \underbrace{\frac{N_i(E)}{t_{\mathrm{esc}}}}_{\text{Escape}} + \underbrace{Q(E)}_{\text{Injection}}$$

$b(E) = -E\, t^{-1}_{\mathrm{loss}}$

"radiation processes"

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

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

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

$$Q_{ji}(E_i) = \int dE_j\, \underbrace{N_j(E_j)}_{\text{Density other species}}\, \underbrace{\Gamma_j^{\mathrm{IT}}(E_j)}_{\text{Inter-action rate}}\, \underbrace{\frac{dn_{j\to i}^{\mathrm{IT}}}{dE_i}(E_j, E_i)}_{\text{Re-distribution function +secondary multiplicity}}$$

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

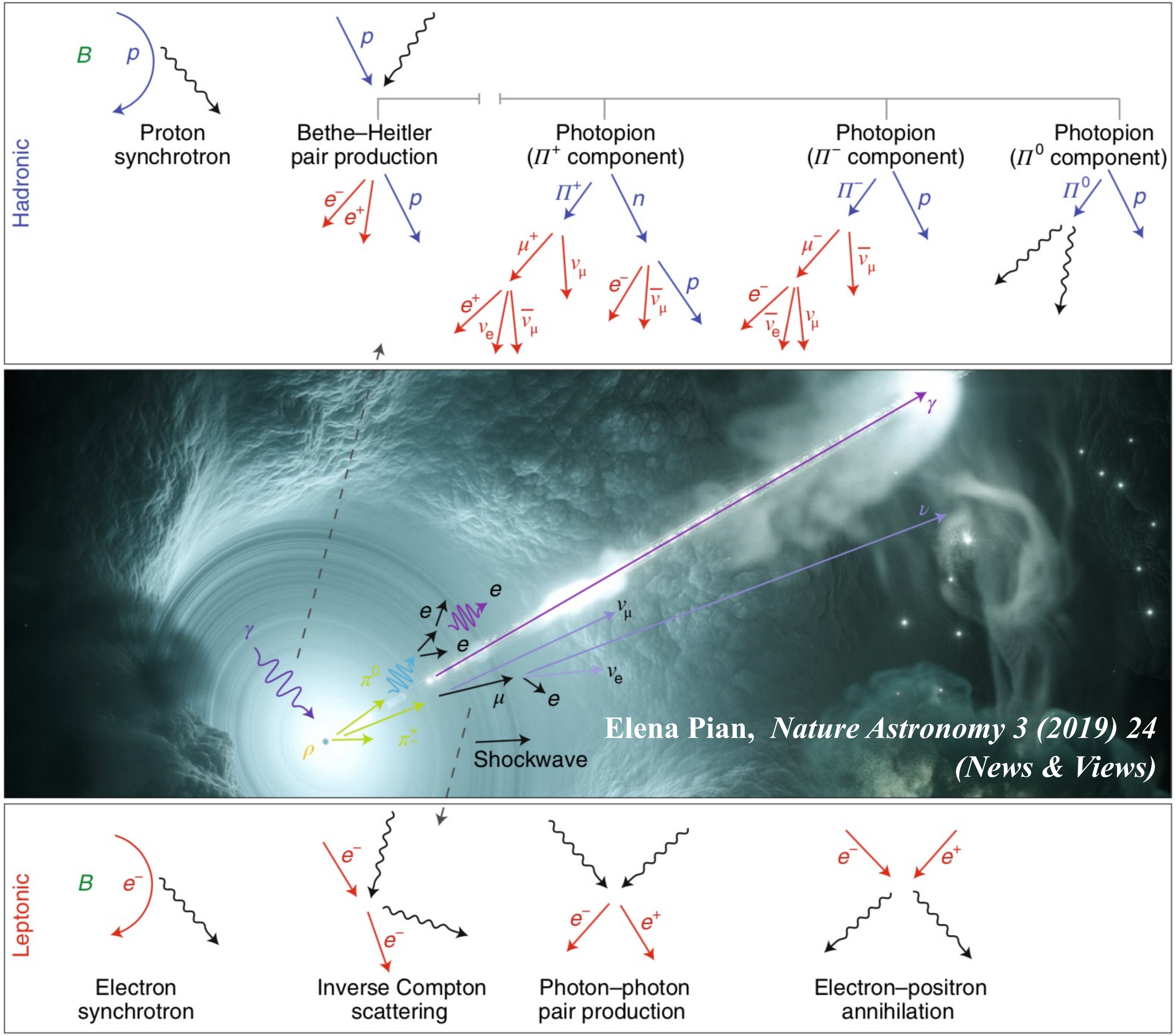
→ Re-distribution function narrow + peaked

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



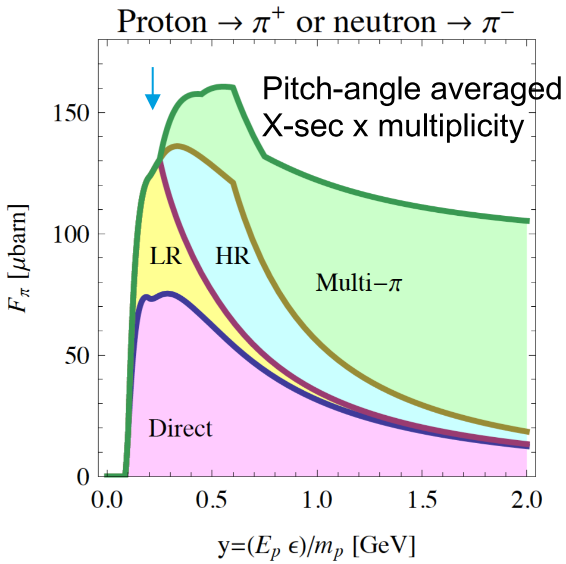
Elena Pian, *Nature Astronomy 3 (2019) 24 (News & Views)*

Photo-pion production in the multi-messenger context

- Neutrino peak determined by maximal cosmic ray energy →
  [conditions apply: for target photons steeper (softer) than ε^{-1} (and low enough $\varepsilon_{\min}$)]
- 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) →



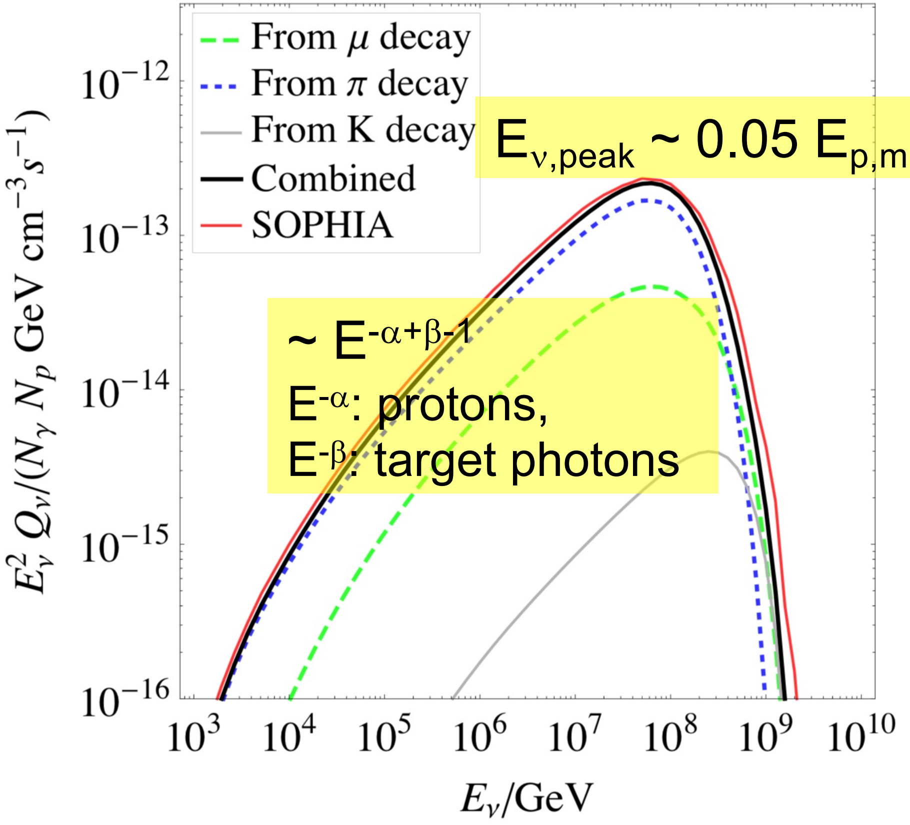
Pitch-angle averaged X-sec x multiplicity

- Photons from pion decay:

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

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

AGN neutrino spectrum (example)



$E_{\nu,\mathrm{peak}}$ ~ 0.05 $E_{p,\max}$

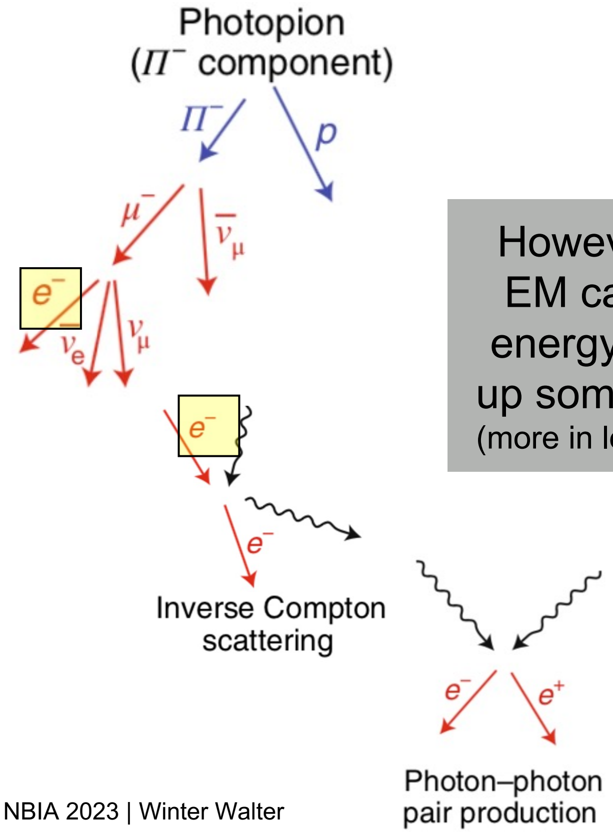
~ $E^{-\alpha+\beta-1}$
$E^{-\alpha}$: protons,
$E^{-\beta}$: target photons

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

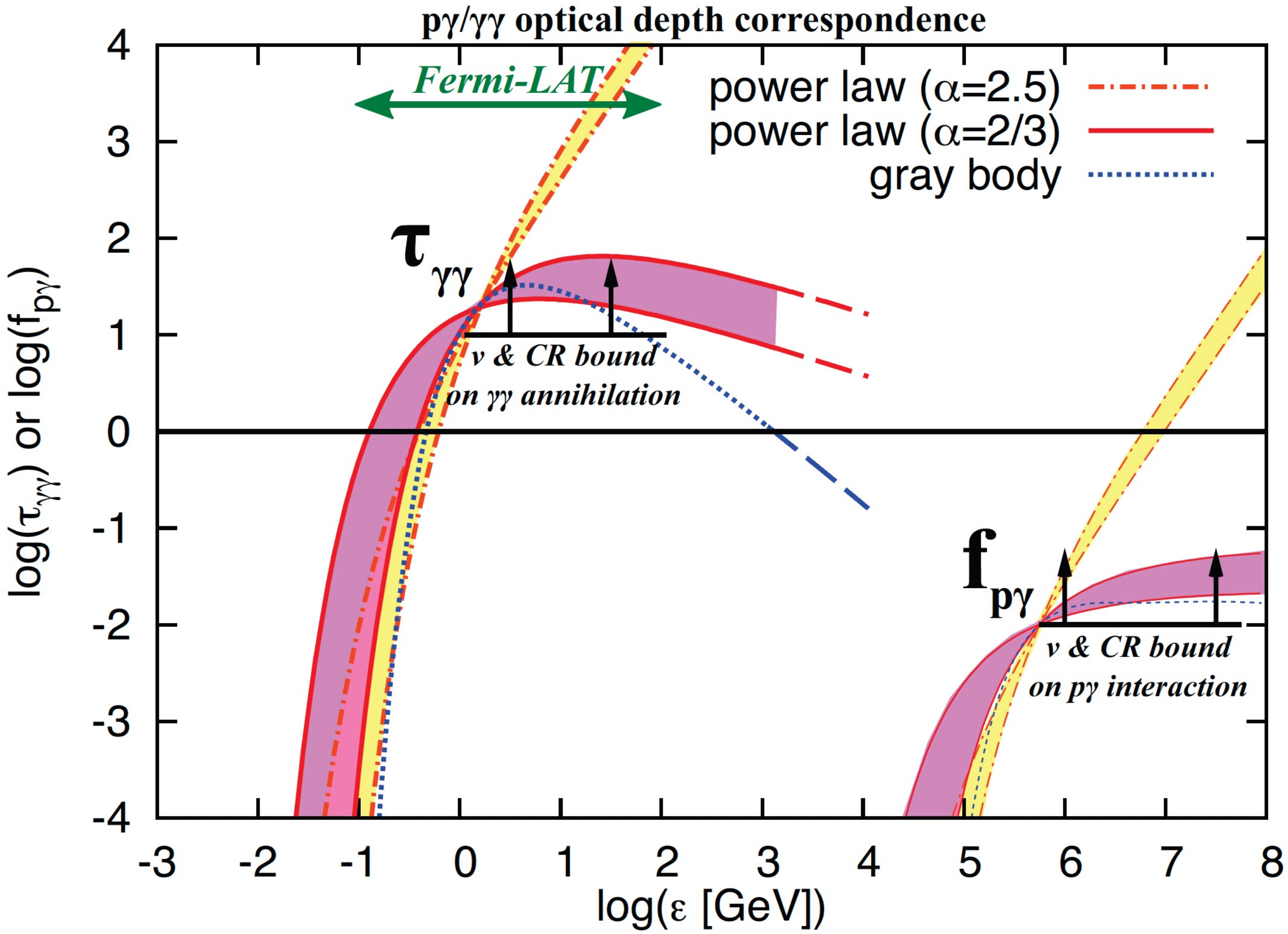
Fate of the very-high-energy gamma rays $\pi^0 \rightarrow \gamma + \gamma$

Are neutrino sources gamma-ray dark?

- Efficient neutrino production implies $\gamma\gamma$-annihilation
- Other electromagnetic products are affected by these processes as well, e.g.



However, the EM cascade energy shows up somewhere!
(more in lecture 2…)



τ: optical thickness (=R/λ_{mfp})

Murase, Guetta, Ahlers, PRL 116 (2016) 071101

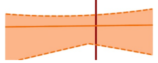
pp versus pγ interactions

When do the neutrinos follow the primary spectrum? When E^{-2}?

- **pp interactions**

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

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



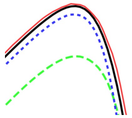
(Branchings actually not exactly 1/3; see **JCAP 1701 (2017) 033**)

Examples: starburst galaxies, environments with gas/dust

- **pγ interactions with power-law target**: more sophisticated since relativistic target

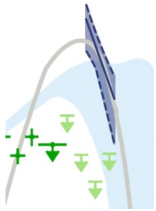
$$p + \gamma \to \Delta^+ \to \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

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



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

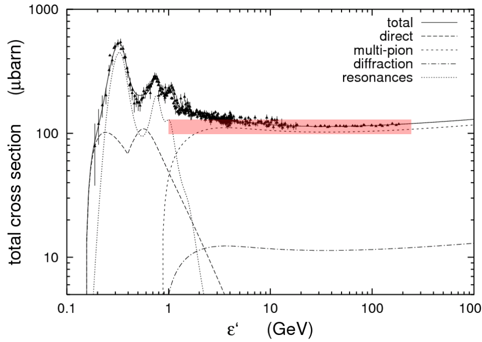
Examples: GRBs (β~1), AGN blazars (β>1)



- **pγ interactions with thermal target:**
Peaked (example: CMB). But: multi-pion prod. dominates if C.O.M. energy high enough.

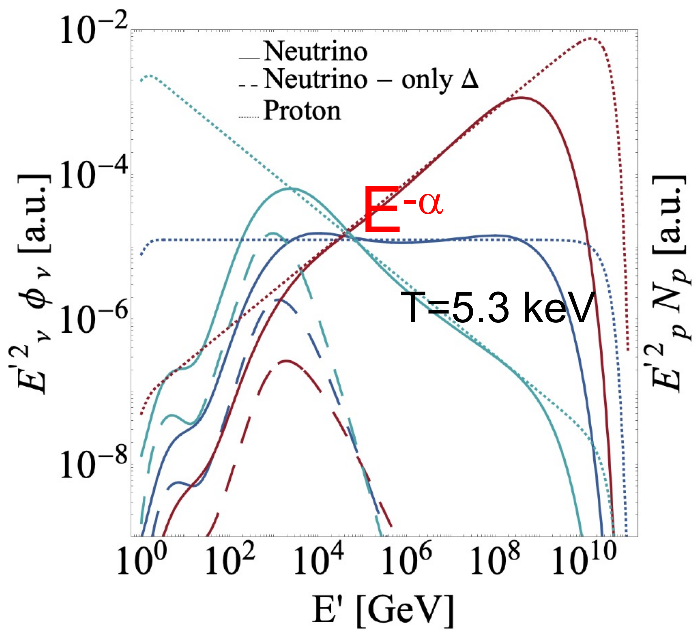
Examples: TDEs, AGN cores

$$\underset{E^{-\alpha}}{p} + \underset{T}{\gamma}$$



→

Fiorillo et al, JCAP 07 (2021) 028



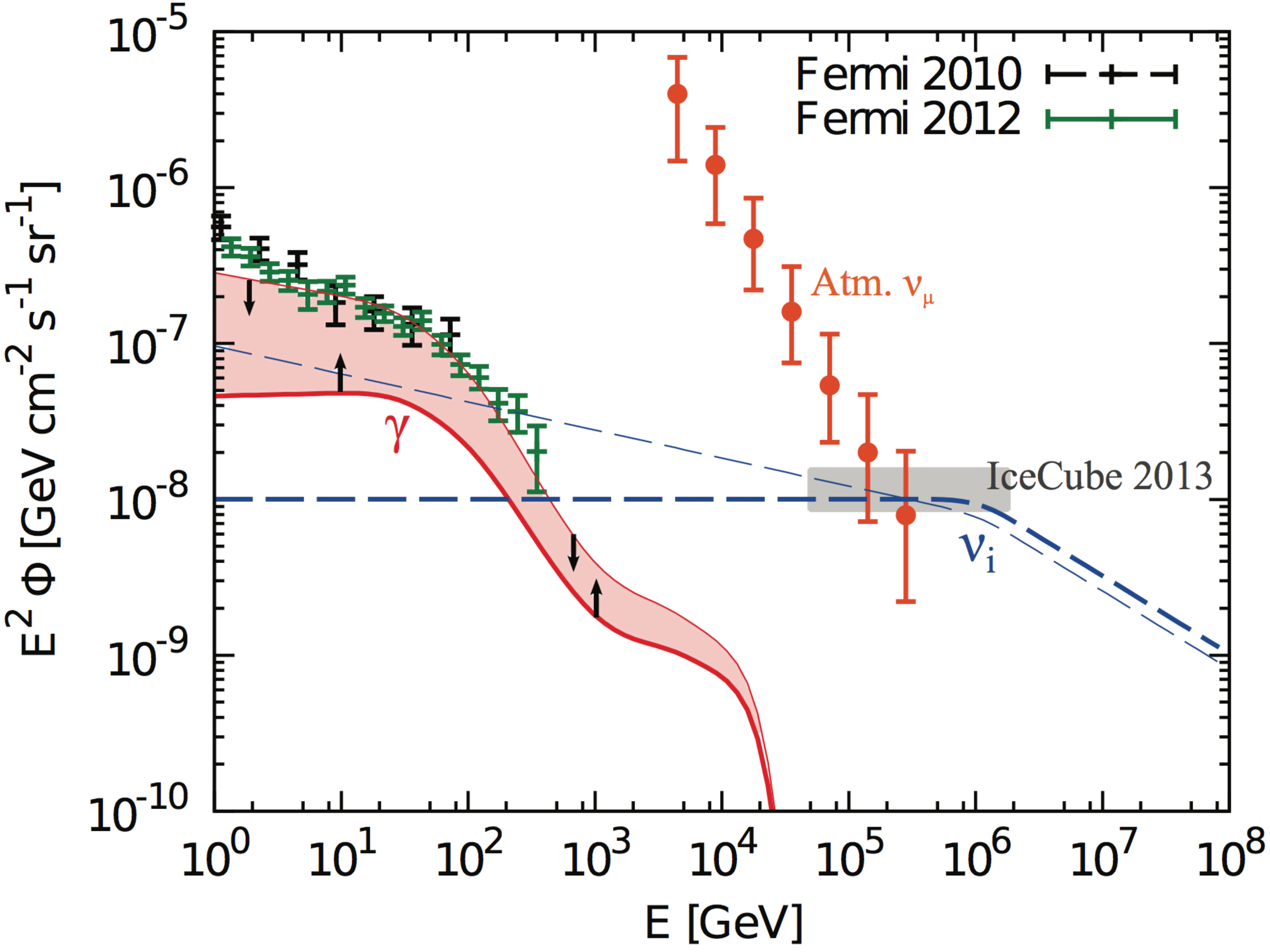
Application for pp interactions: Starburst galaxies

Gamma-ray diffuse flux

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

- Neutrinos and gamma-rays follow primary E^{-2} spectrum
- Diffuse gamma-ray background dominated by AGN; non-AGN contributions sub-leading
- Constrains spectral index for non-AGN contributions (starburst galaxies, ...)

Bechtol et al, 2017;
Palladino et al, arXiv:1812.04685;
Peretti et al, 2020; …



Murase, Ahlers, Lacki, 2013

Decouple the maximal cosmic ray and neutrino energies?

Effect of secondary cooling, change of flavor composition

- 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)

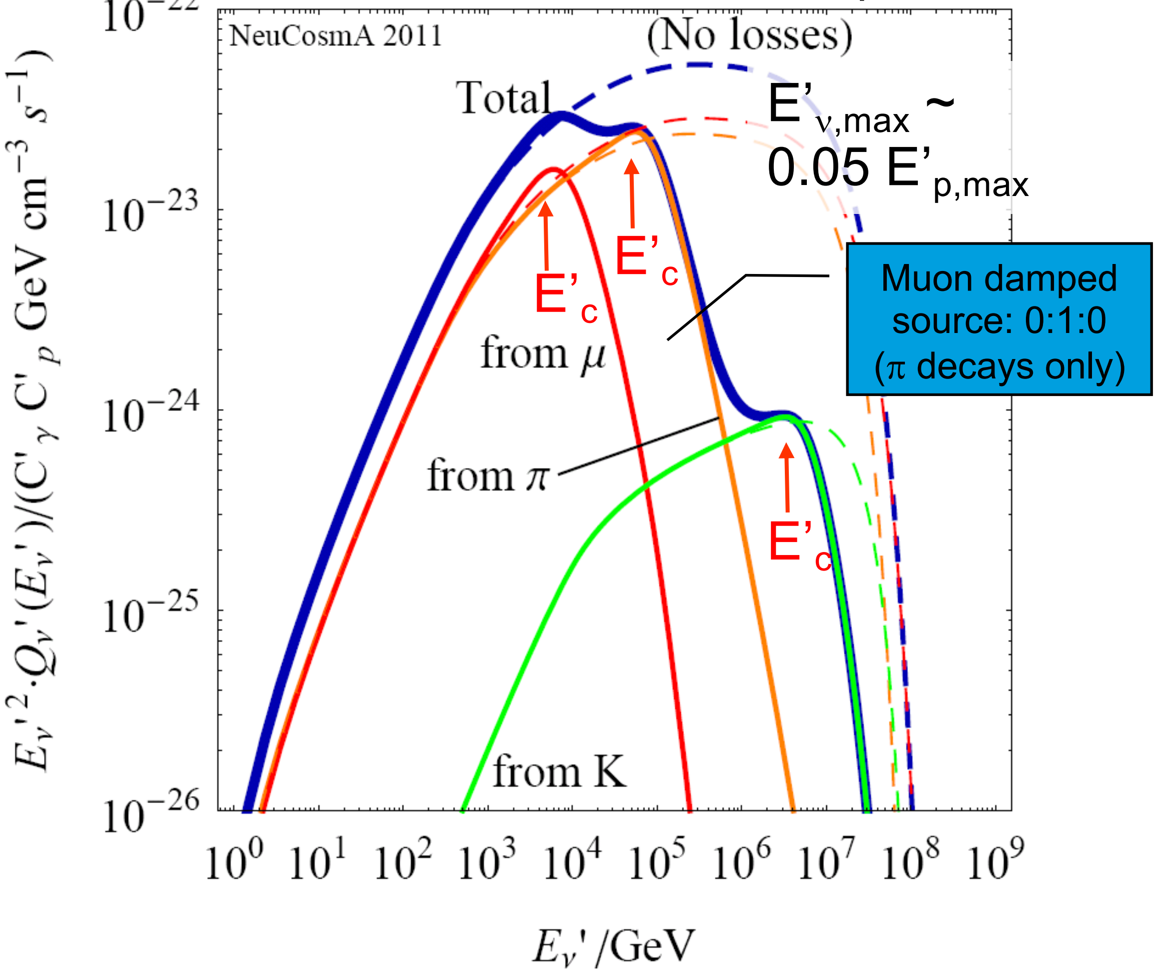
$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

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, ...

→ Talk Rudolph

Example: GRB



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

Flavor composition in terms of *flavor triangles*

→ Talk Telalovic

Theoretical expectations

- Standard model expectation for flavor mixing (averaged neutrino oscillations):

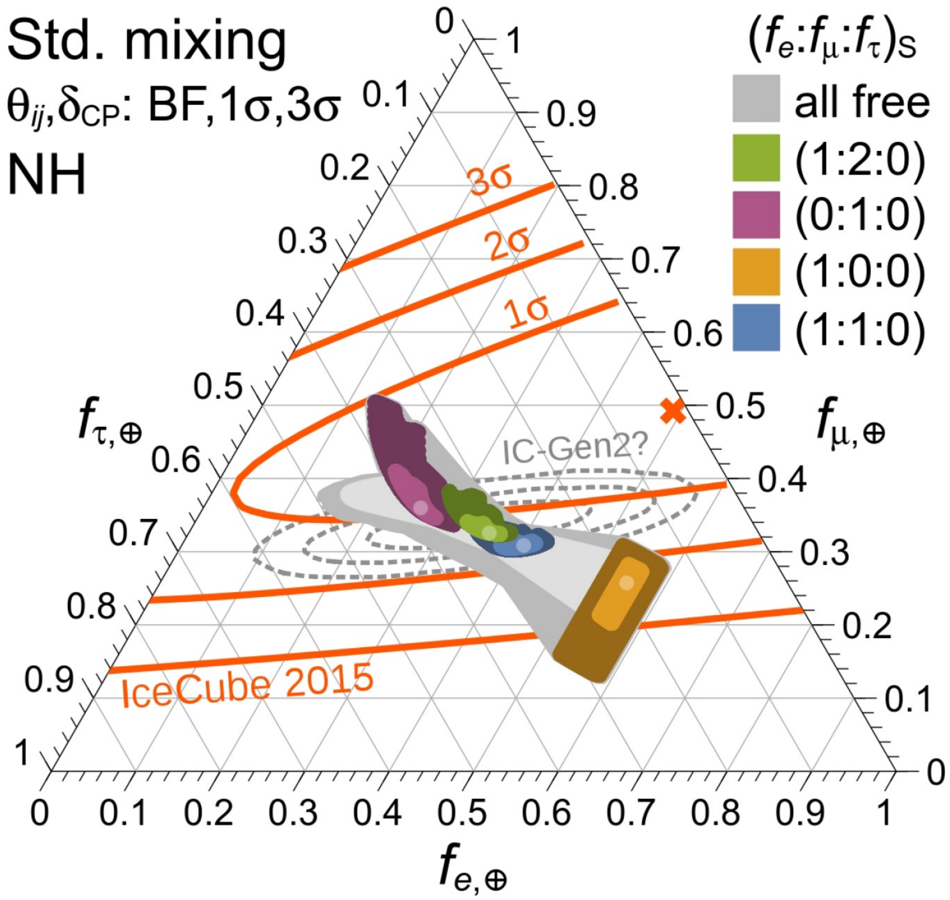
$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

- Flavor compositons at source $(f_e:f_\mu:f_\tau)_S$:
    - Pion decay chain: (1:2:0)
    - Muon damped source: (0:1:0) – previous slide
    - Neutron decays: (1:0:0)
    - Charmed meson decays or muon pile-up: (1:1:0)

for a comprehensive picture of energy-dependent flavor compositions, see Hümmer et al, Astropart. Phys. 34 (2010) 205

- Small region of flavor triangle occupied by SM physics, but BSM may cause deviations! →

Physics potential



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

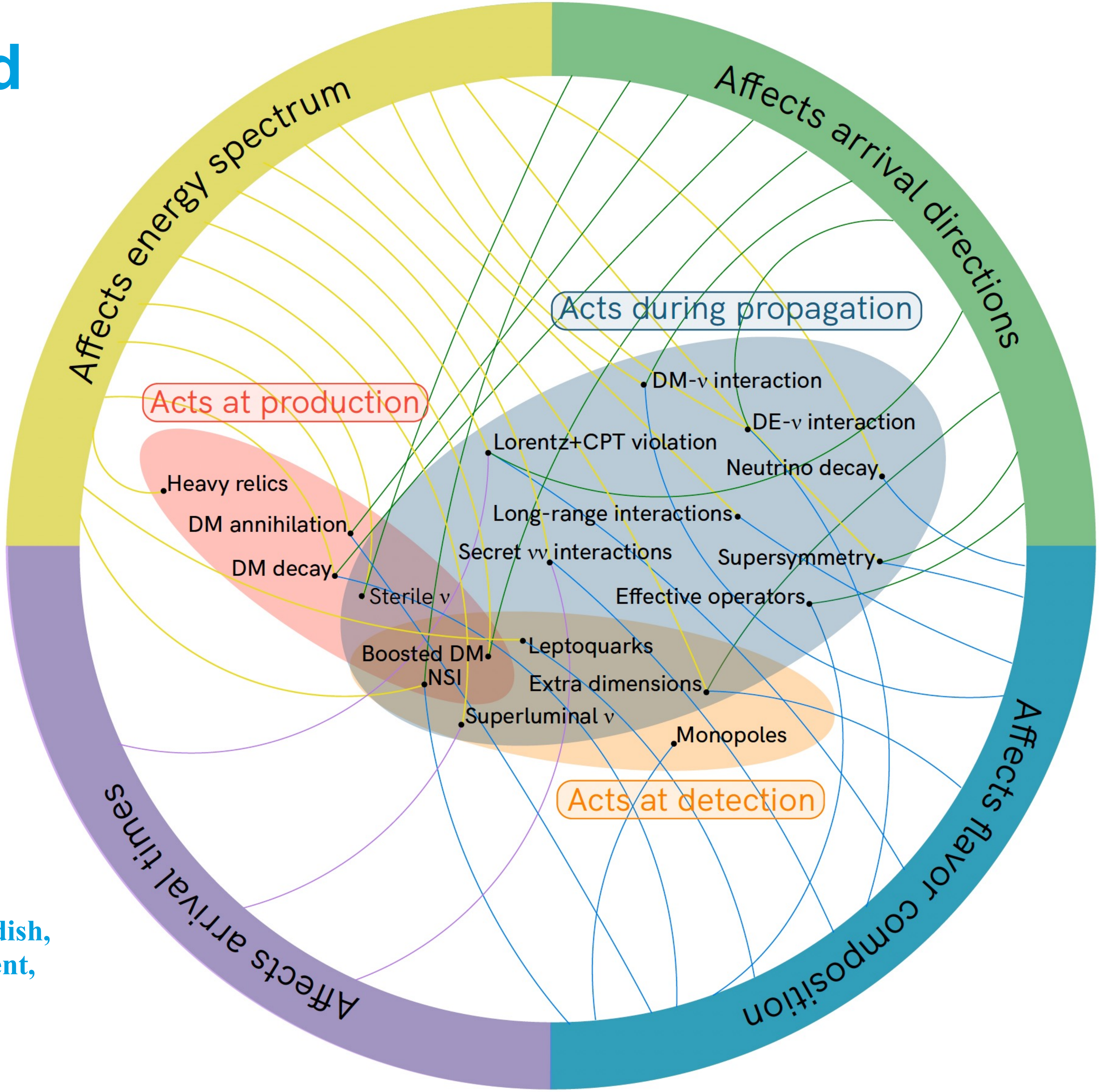
dates back to: Barenboim, Quigg, 2003

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

IceCube measurement Astrophys. J. 809 (2015) 1, 98; update: Eur. Phys. J. C 82 (2022) 11, 1031

Beyond the Standard Model tests

with astrophysical neutrinos



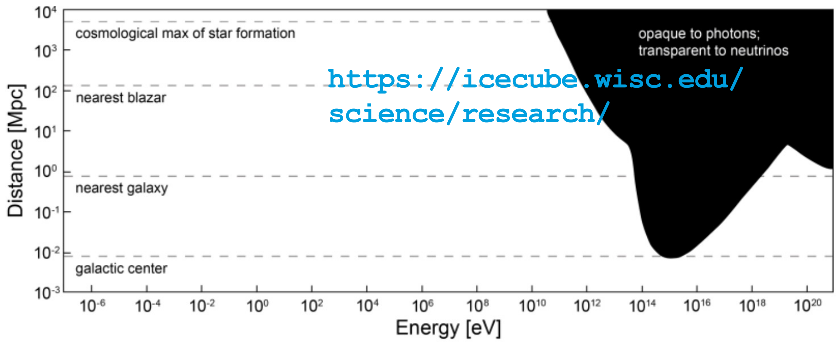
Argüelles, Bustamante, Kheirandish, Palomares-Ruiz, Salvado, Vincent, ICRC 2019

Energetics

- $E_\nu \sim \varepsilon_{th} \times E_p \times \overbrace{\min(0.2\,\tau_{p\gamma}, 1)}^{\text{Often: } f_\pi} \times \overbrace{1/8}^{½\,(\pi^+ \text{ only}) \times ¼\,(4 \text{ leptons})}$ **<< 0.01 E_p** (typically)
  $\tau_{p\gamma}$: optical thickness ($=R/\lambda_{mfp}$) to pγ interactions
  ε_{th}: fraction of proton luminosity beyond pγ threshold
- For $E_p \sim 1/f_e \times E_\gamma$ ($1/f_e$: **baryonic loading**):
  $E_\nu << 0.01\ 1/f_e\ E_\gamma$
- Consequence: Need baryonic loading $1/f_e >> 100$ for energy in neutrinos comparable to gamma-rays

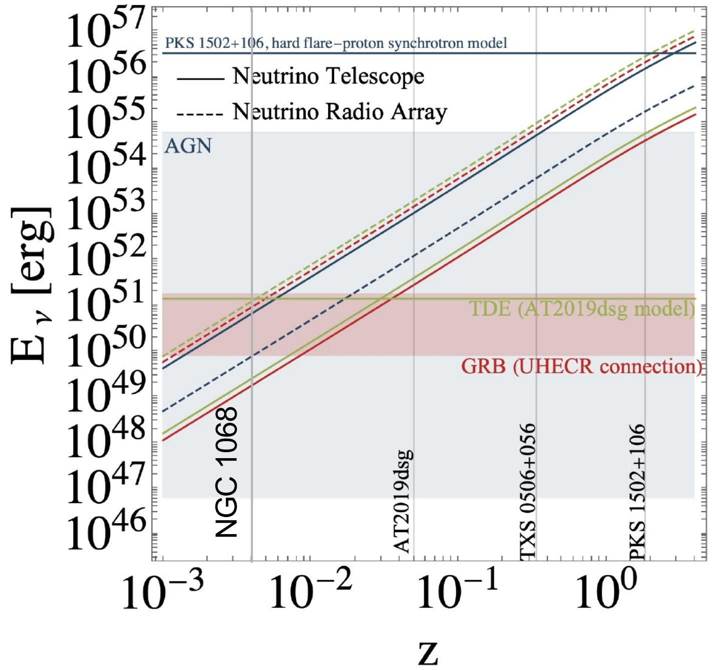
- **Qualitative consequences:** →
  - Justifying PeV neutrinos from AGN blazars (distant!) require extremely high $1/f_e >> 100$ for the models → Lecture 2
  - GRBs are expected to have $1/f_e \sim 10$-100 from UHECR connection/ Since there are few nearby, they are not seen in νs … → Talk Rudolph, Lecture 3
  - TDEs can be quite nearby and luminous → Lecture 2
  - Other sources (e.g. NGC 1068, Milky Way) detected if very nearby
- *Although neutrinos can travel through the whole universe, it is only realistically possible to see nearby or bright sources …*

How far can neutrinos versus gamma-rays travel?



https://icecube.wisc.edu/science/research/

vs. How much energy do I have to emit from the source into neutrinos of all flavors to observe one event?



(typical spectral shapes assumed)

Fiorillo, van Vliet, Morisi, Winter, JCAP 07 (2021) 028

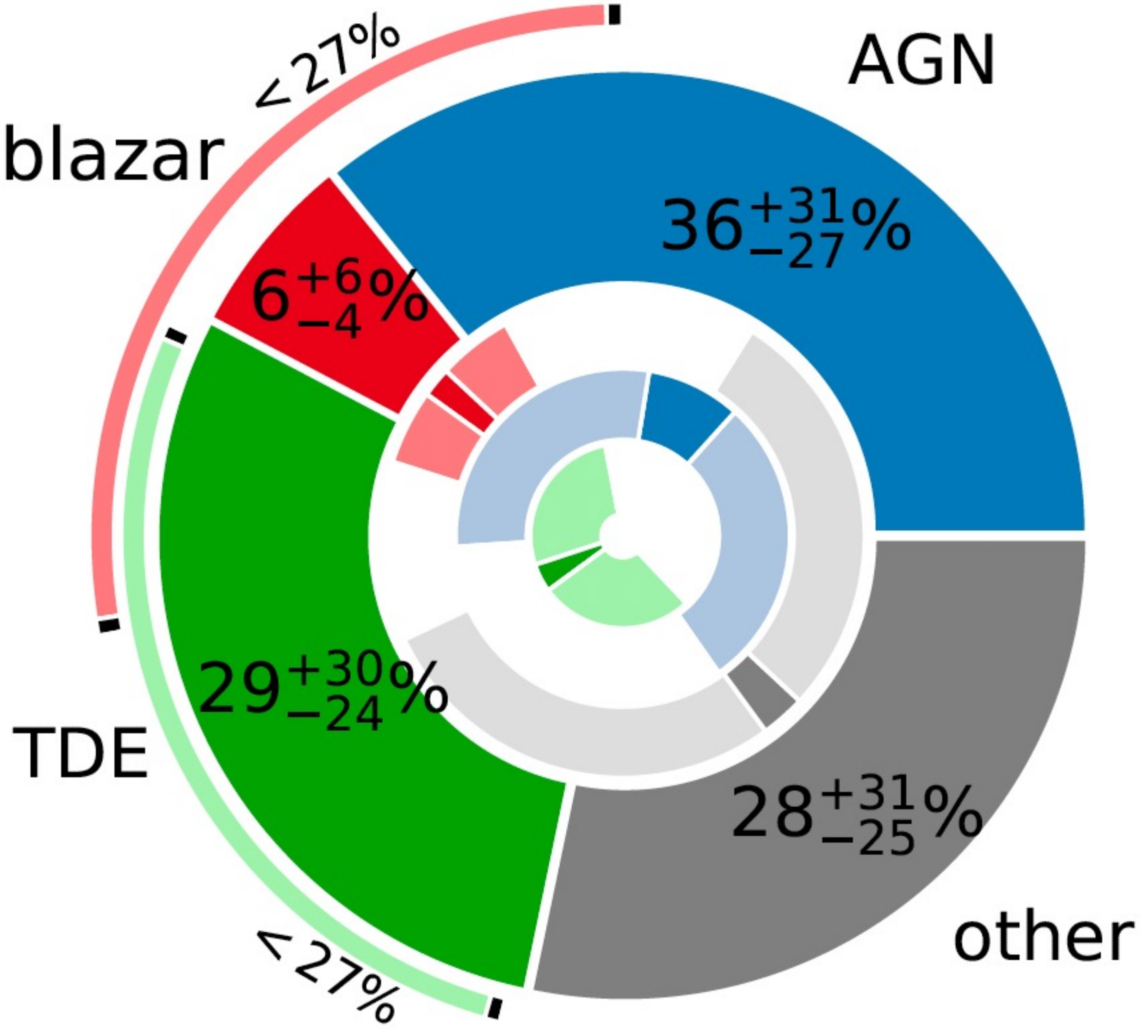
Summary and outlook – lecture I

Evidence for multiple individual neutrino source populations emerging

- AGN blazars
- TDE
- AGN cores?
- Galactic
- Other

Neutrino production

- The neutrinos spectrum typically peaks at the primary energy $E_{\nu,\mathrm{peak}} \sim 0.05\, E_{p,\mathrm{max}}$. Exception: strong B (secondary cooling)
- The neutrino spectrum follows the primary spectrum for pp interactions and thermal targets with high C.O.M. energies
- Neutrinos can be only seen from very nearby or very luminous individual sources



Bartos et al, arXiv:2105.03792

Lecture II:
Multi-messenger follow-ups

Videos

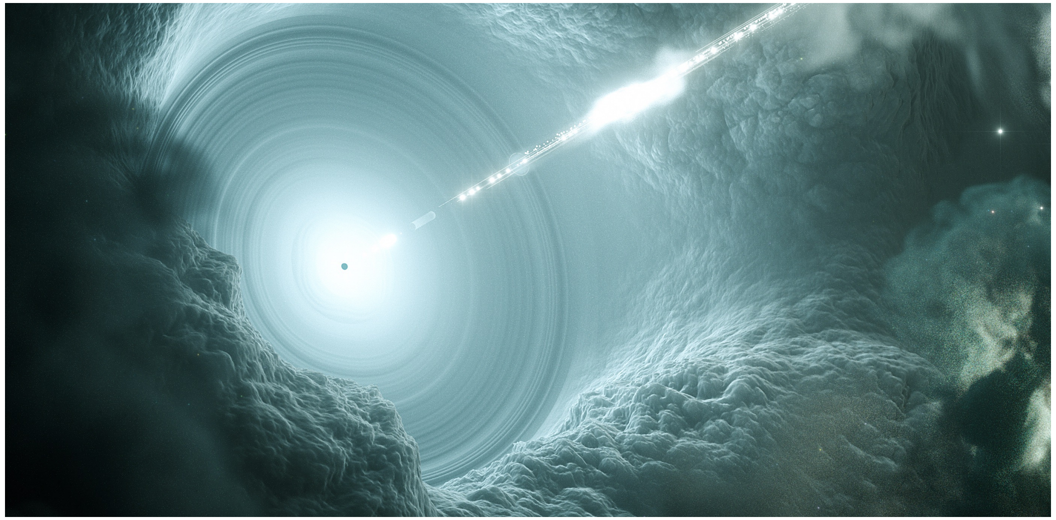
https://multimessenger.desy.de/

https://www.desy.de/e409/e116959/e119238/media/9170/TDE_DESY_SciComLab_sound_080p.mp4

Multi-messenger follow-ups

... starting the golden age of neutrino astronomy

https://multimessenger.desy.de/



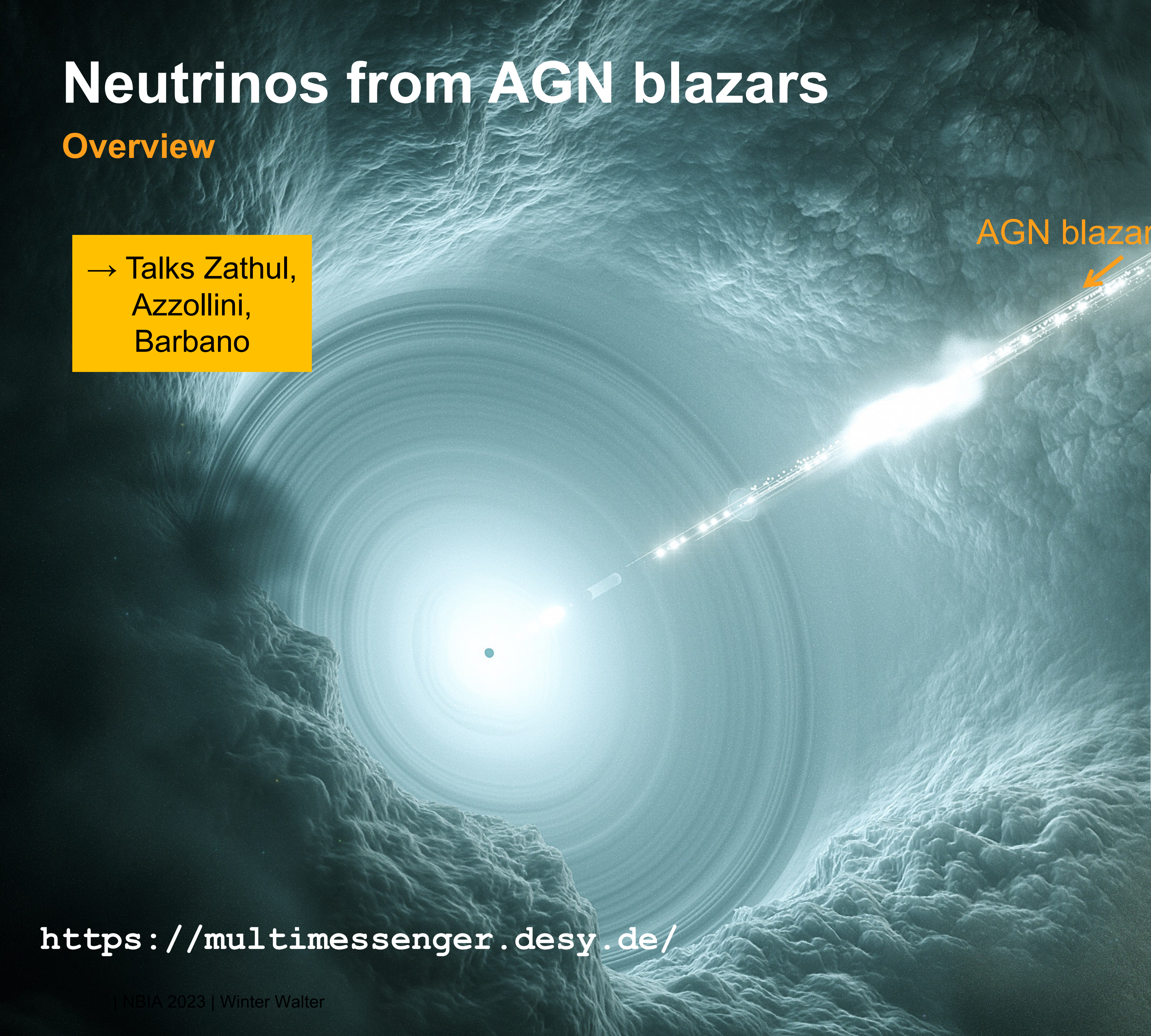
- Global alerts initiated by neutrino events
- Especially tracks with good directional information, high enough energy
- Other instruments triggered, who search for counterparts
- Prominent examples: TXS 0506+056 (AGN blazar), AT2019dsg, AT2019fdr (Tidal Disruption Events), but several other associations as well

https://www.desy.de/e409/e116959/e119238/media/9170/TDE_DESY_SciComLab_sound_080p.mp4

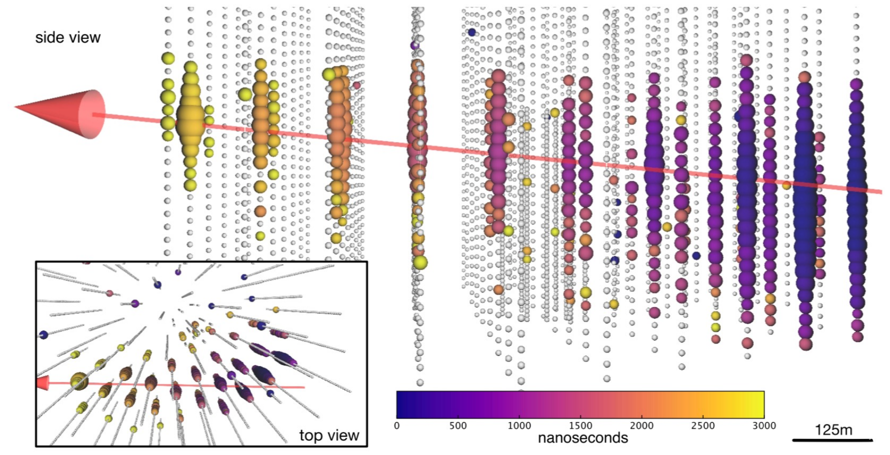
Neutrinos from AGN blazars

Overview

→ Talks Zathul, Azzollini, Barbano



Science 361 (2018) no. 6398, eaat1378



https://multimessenger.desy.de/

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

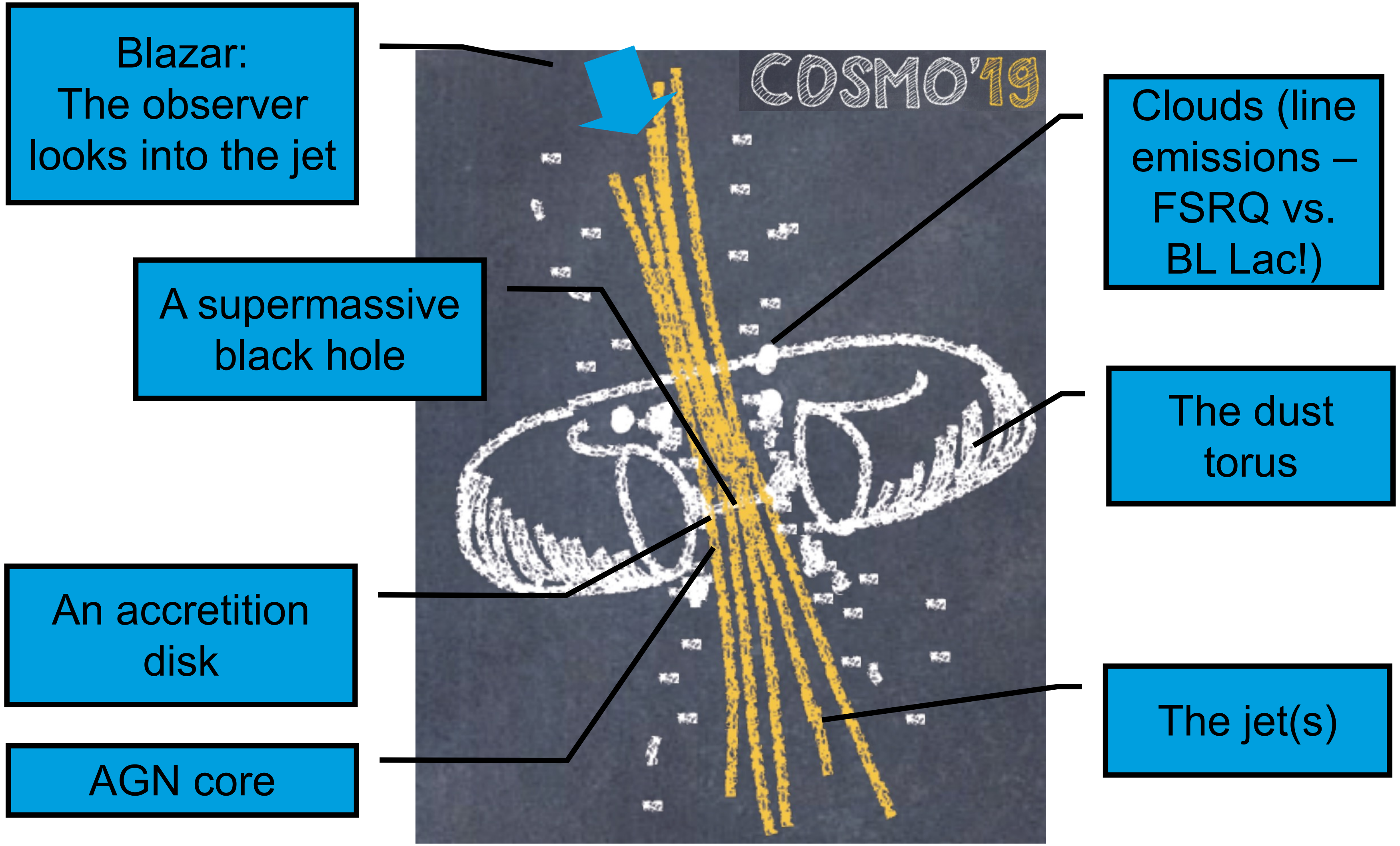
Theory basics:

1

Angular momentum determines geometry

2

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



Blazar:
The observer looks into the jet

A supermassive black hole

An accretition disk

AGN core

Clouds (line emissions – FSRQ vs. BL Lac!)

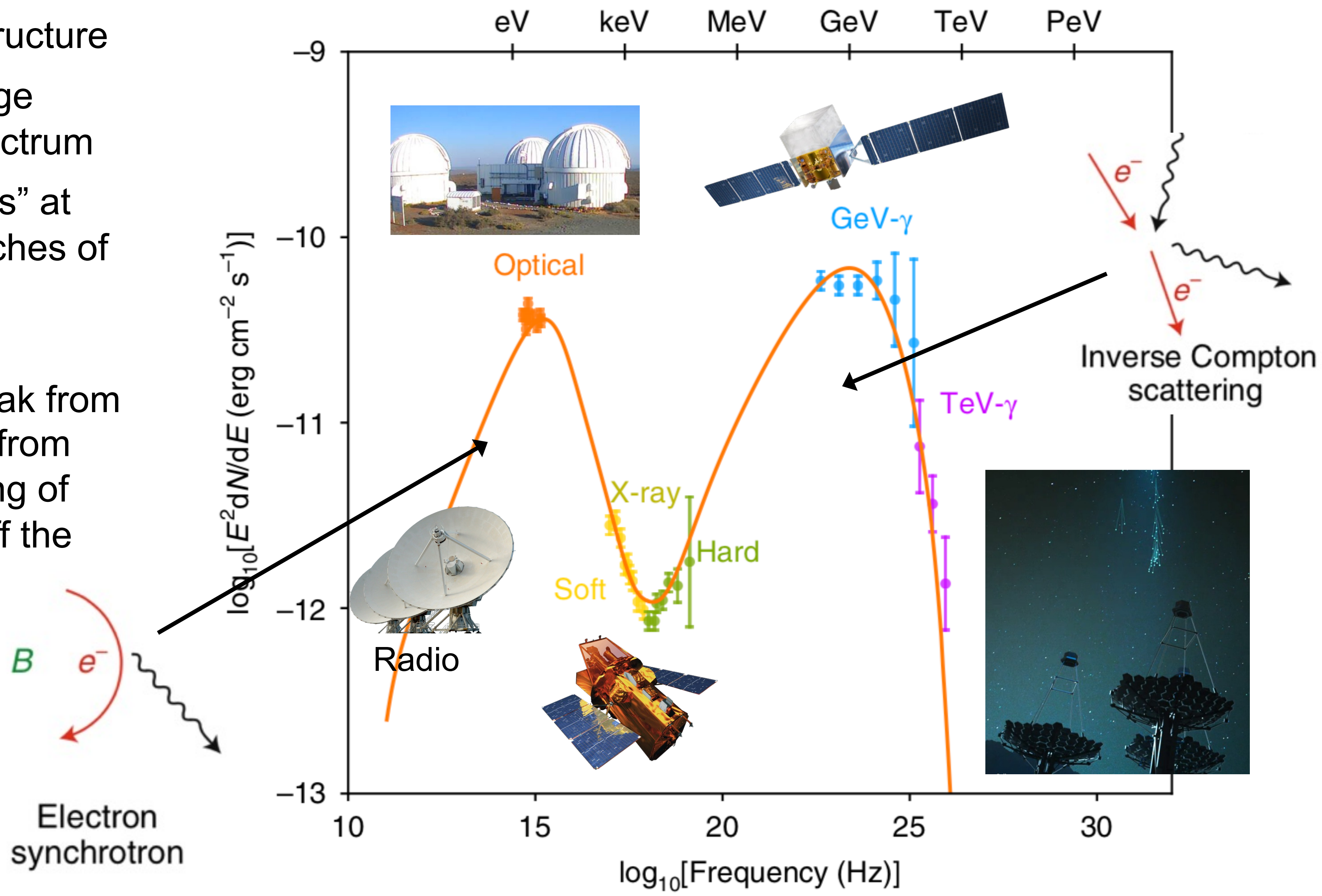
The dust torus

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

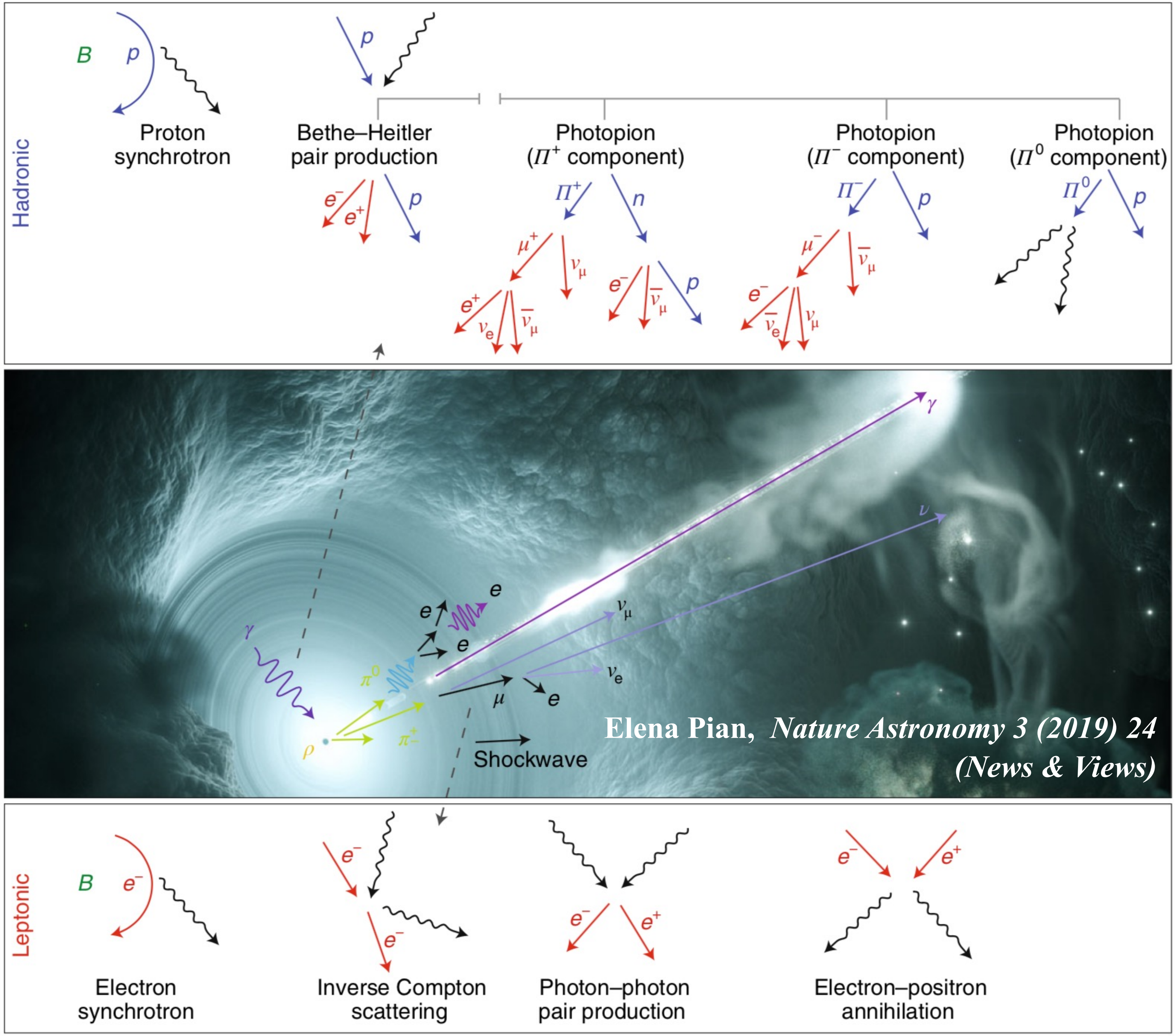
- Simplest explanation: first peak from electron synchrotron, second from inverse Compton up-scattering of these synchrotron photons off the same electrons
(= SSC – “synchrotron self-Compton model”)



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

Radiation processes

Examples for e and p - recap



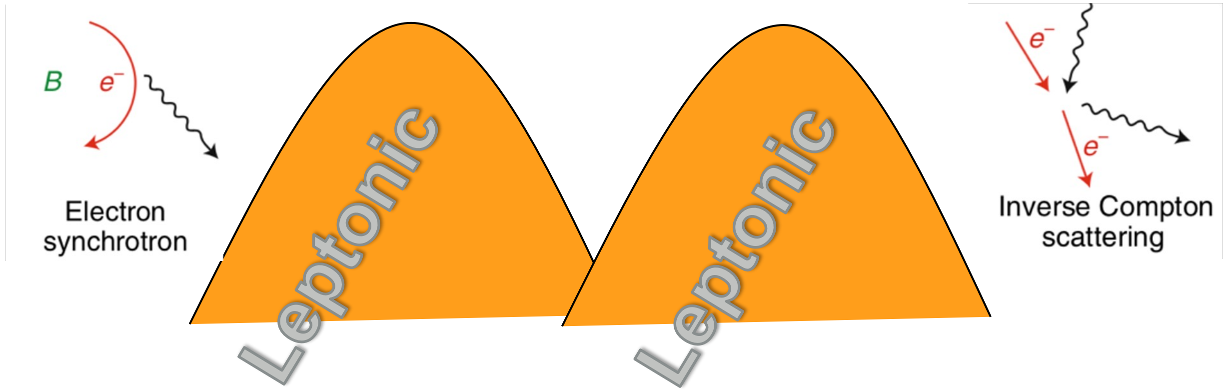
Elena Pian, *Nature Astronomy 3 (2019) 24 (News & Views)*

Typical SED models (qualitatively)

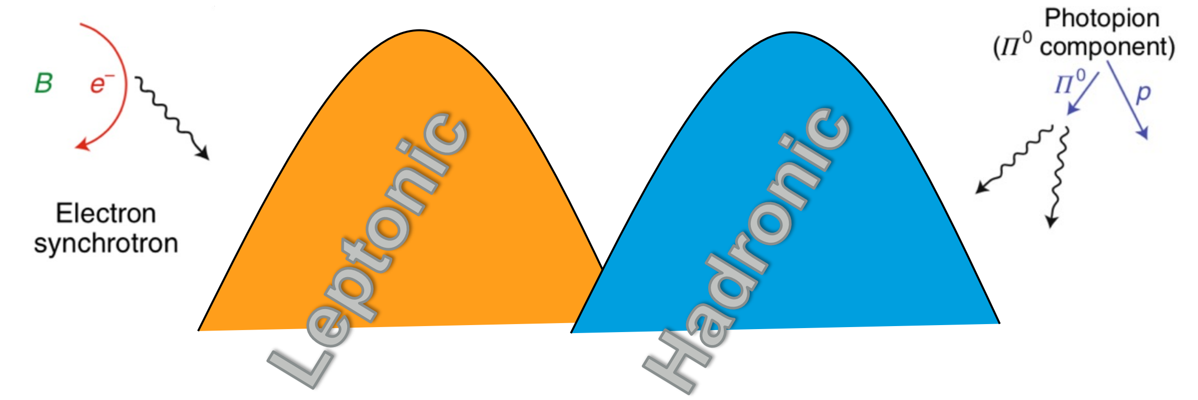
One spherical radiation zone
Fewest assumptions

R’

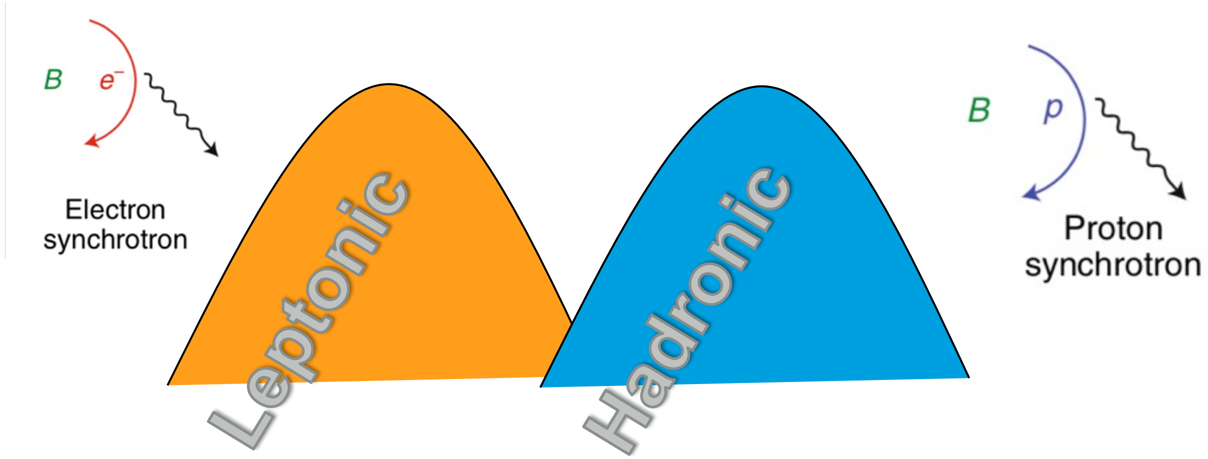
- Synchrotron self-Compton (SSC) or external Compton (EC) models



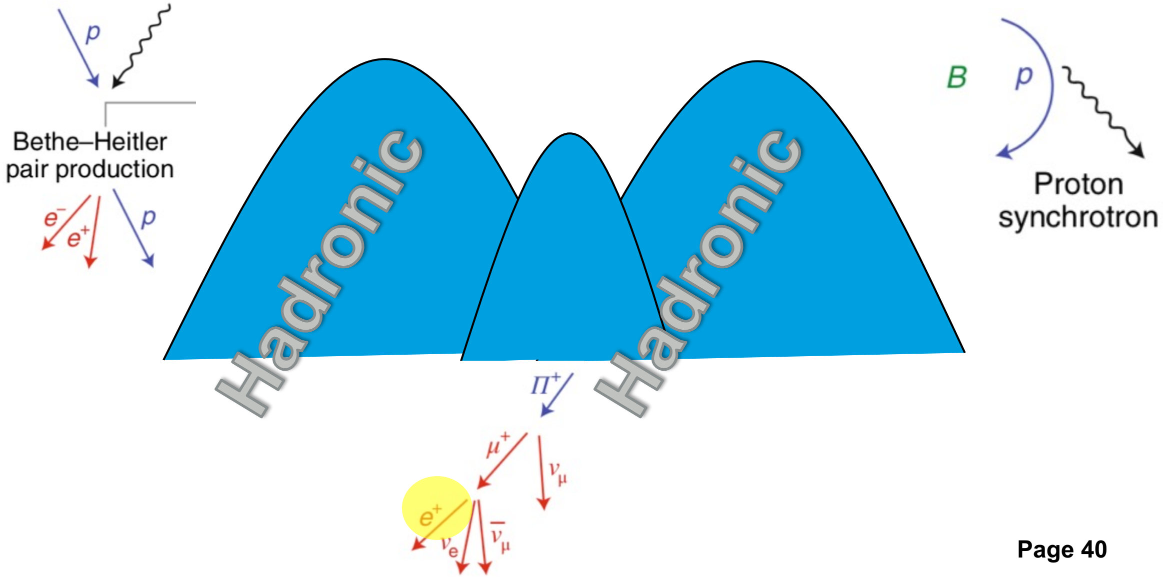
- Pion cascade models



- Proton synchrotron models (require large B’)

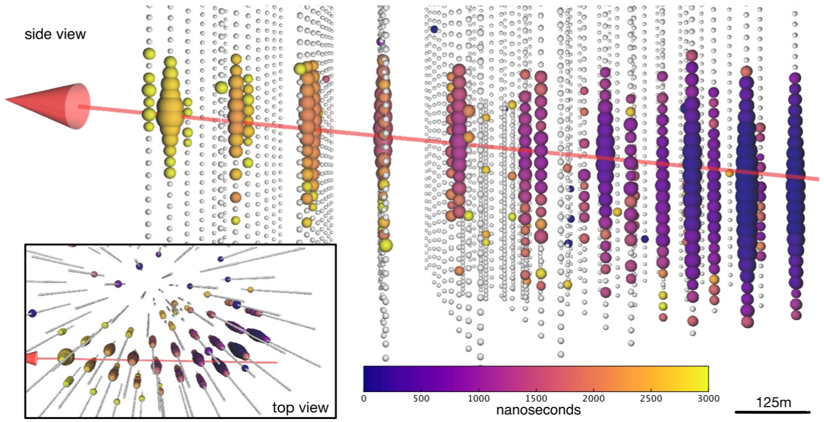


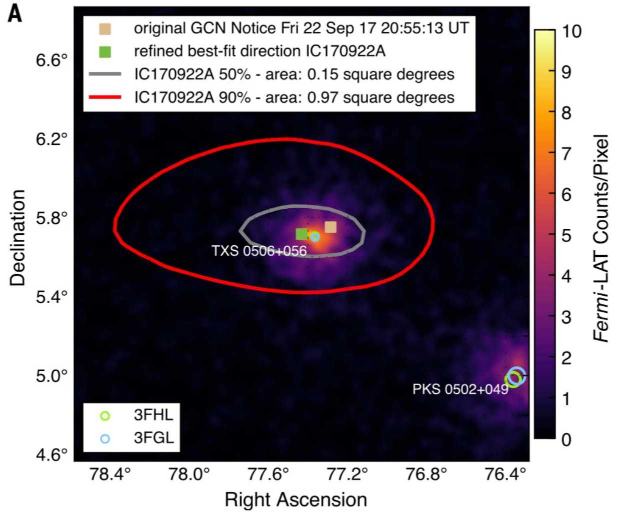
- More exotic hadronic models, for example:



A neutrino from the flaring AGN blazar TXS 0506+056

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



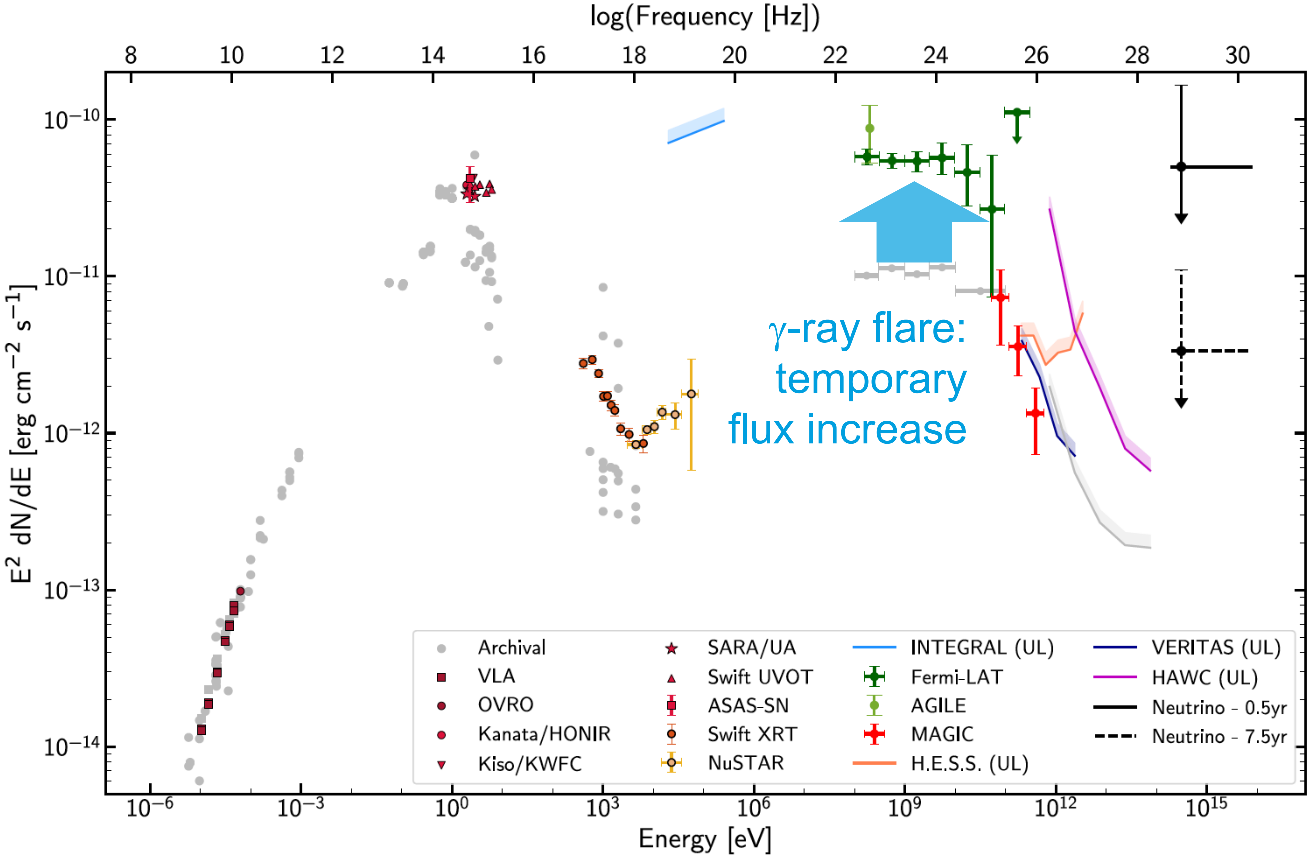


Observed by Fermi-*LAT* and MAGIC (blazar flare)

Significance for correlation: 3σ

z = 0.3365 ± 0.0010
Paiano et al, 2018

SED from a multi-wavelength campaign



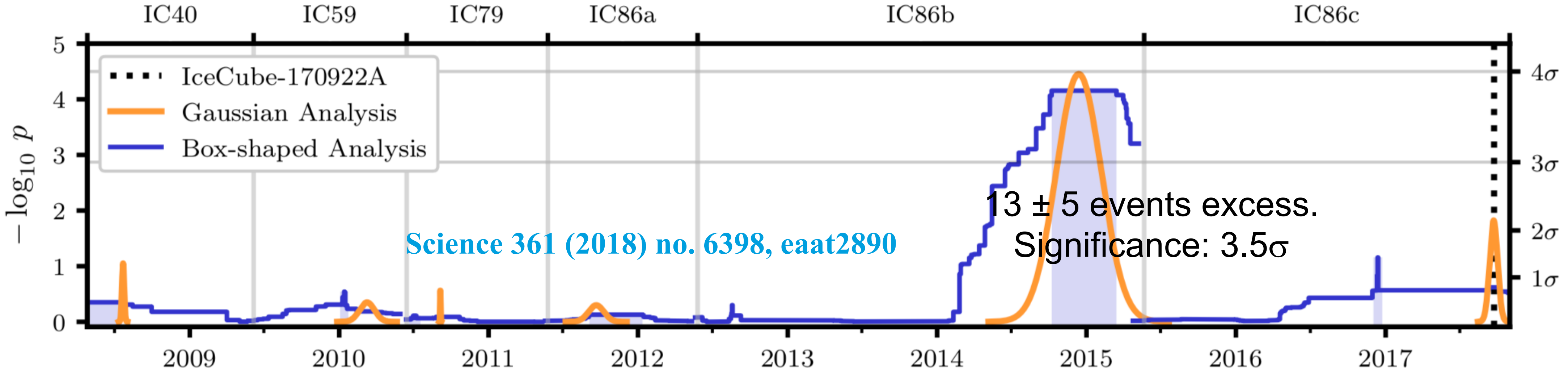
γ-ray flare: temporary flux increase

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



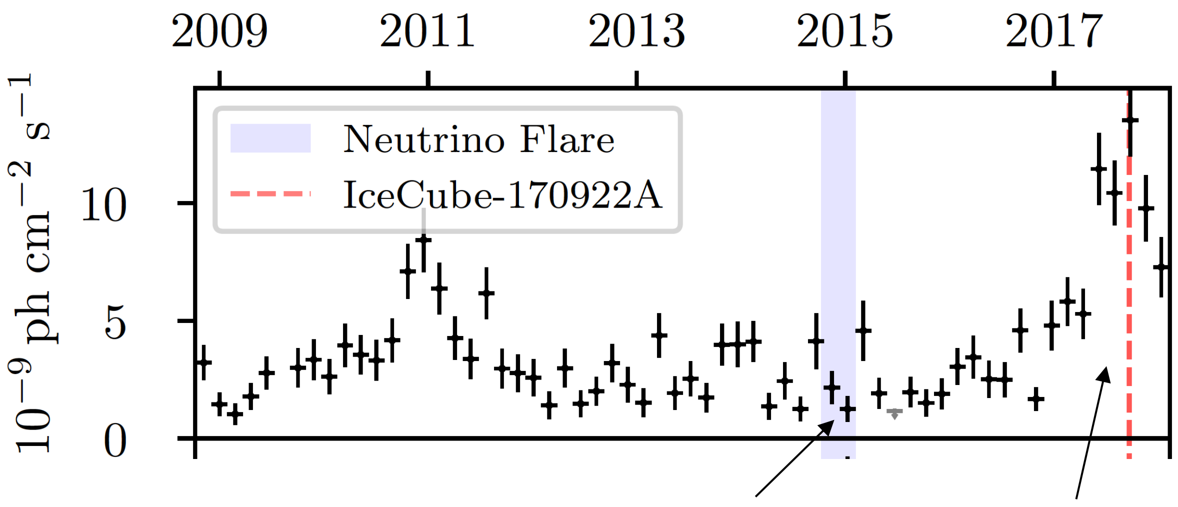
13 ± 5 events excess.
Significance: 3.5σ

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



At 2014-15 neutrino flare

The 2017 flare

Number of predicted neutrinos from a theoretical model?

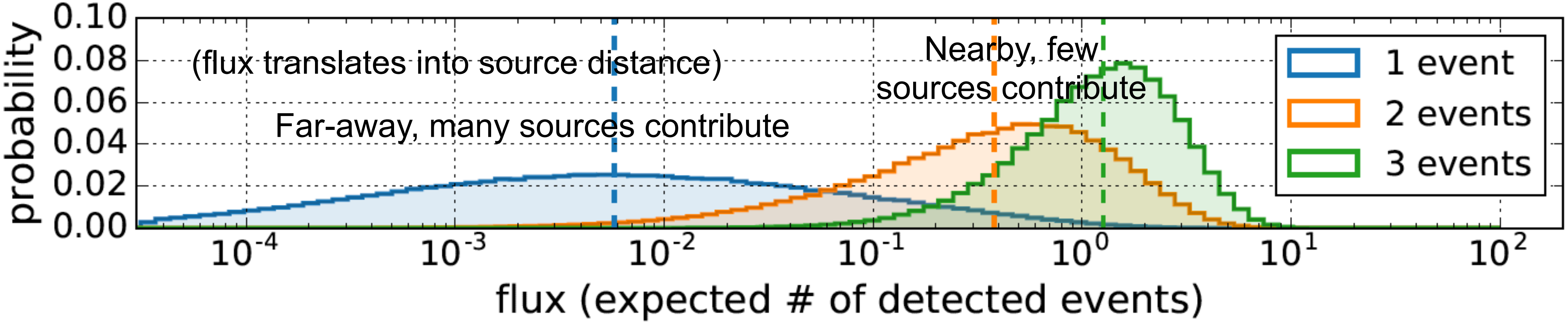
Sept. 22, 2017:
One neutrino observed

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

2014-2015:
13 ± 5 neutrinos observed

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

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



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

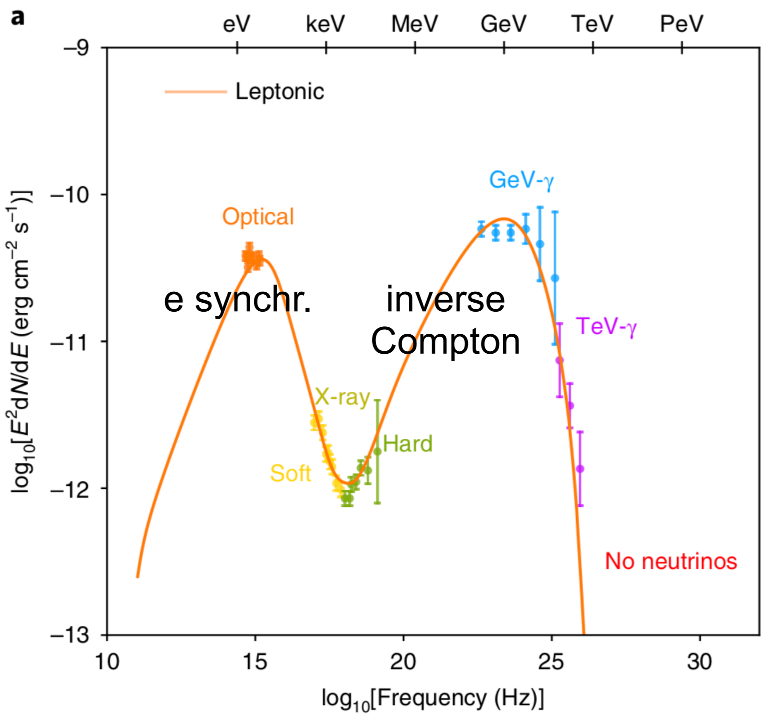
Multi-messenger interpretation of TXS 0506+056

One zone model results (2017 flare)

One spherical radiation zone
Fewest assumptions

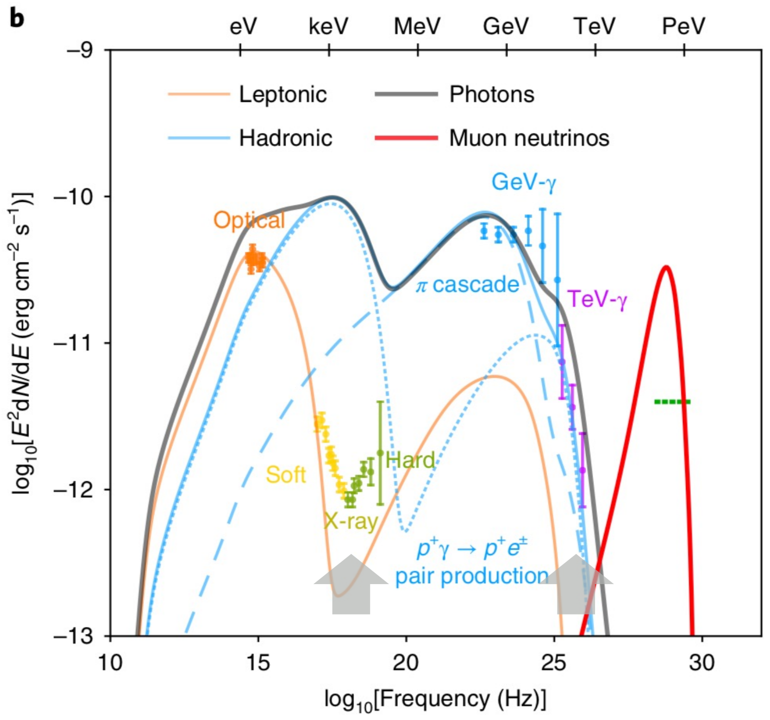
R’

Leptonic models



- No neutrinos

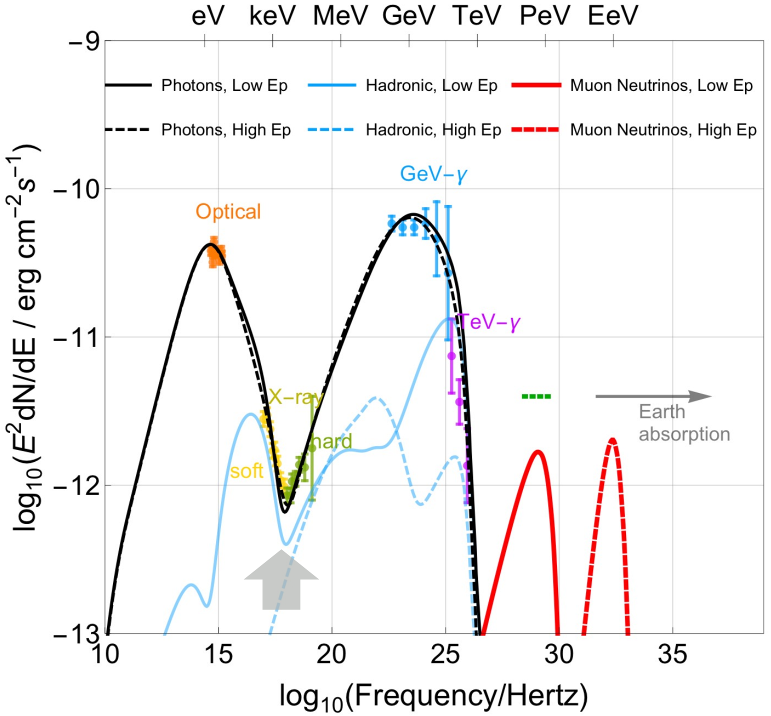
Hadronic (π cascade) models



- Violate X-ray data

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

Hybrid or p synchrotron models



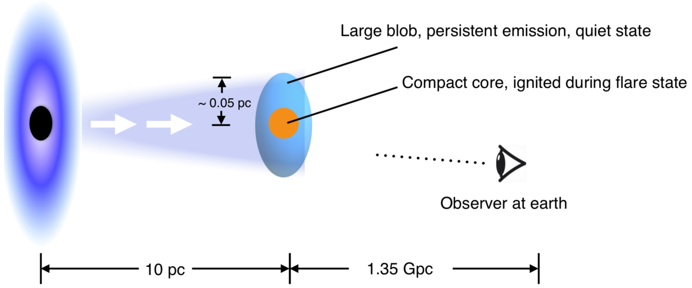
- **Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy**
  Baryonic loading $1/f_e > 10^4$

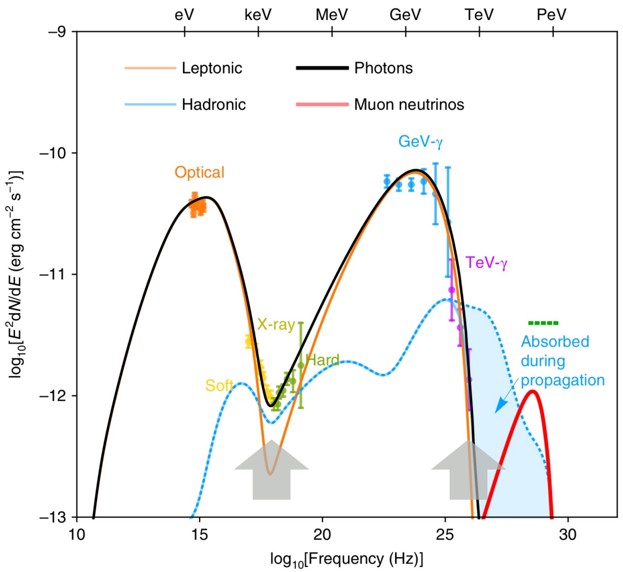
Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88;*
see also Cerutti et al, 2018; Sahakyan, 2018; Gokus et at, 2018; Keivani et al, 2018

More freedom through multiple radiation zones

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

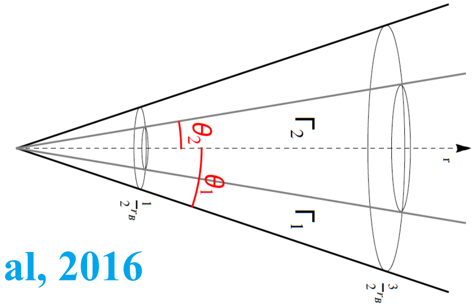
Formation of a compact core



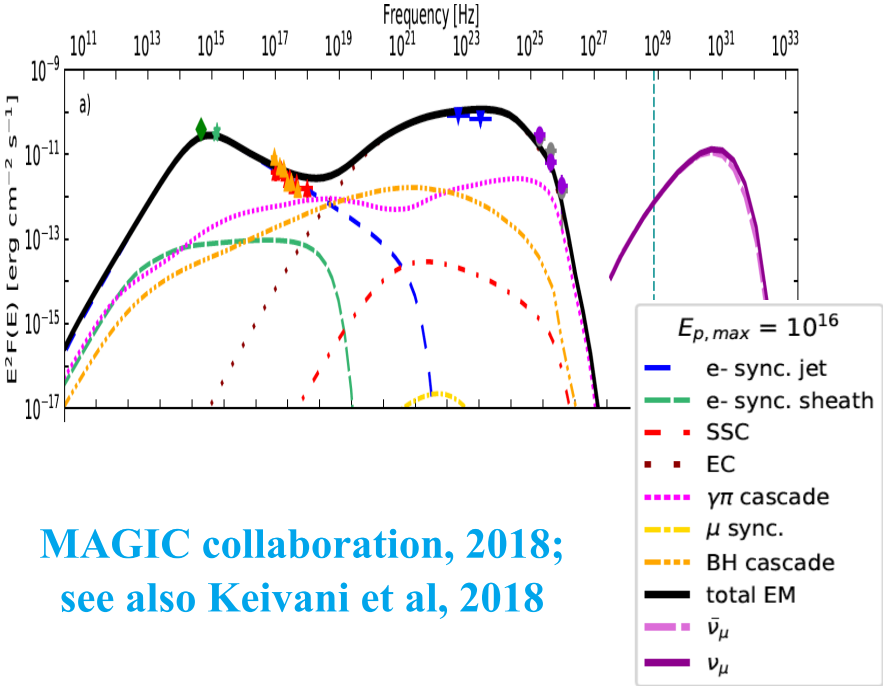


Gao et al, *Nature Astronomy 3 (2019) 88*

External radiation fields

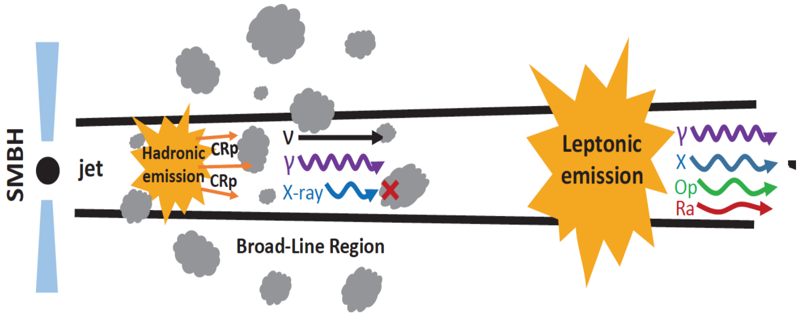


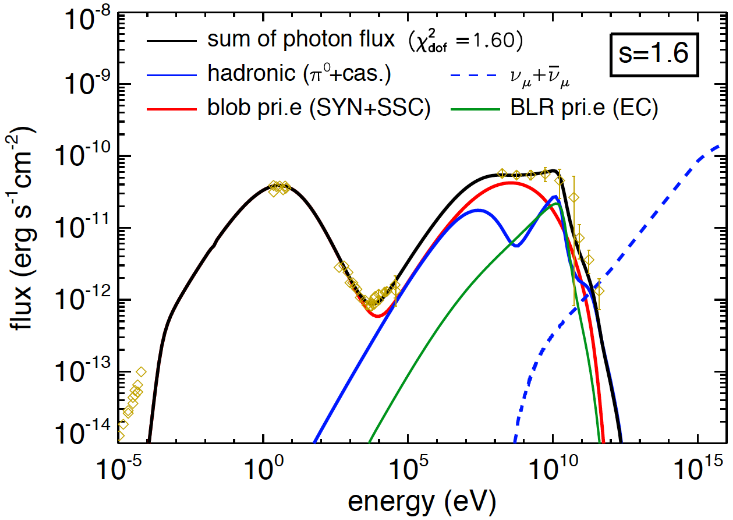
Sikora et al, 2016



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

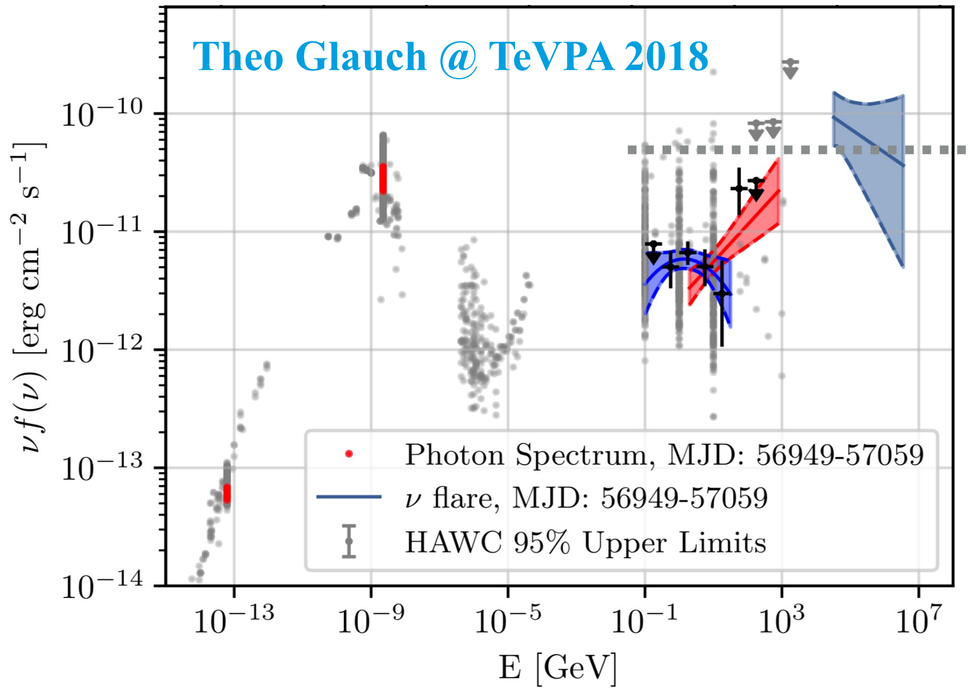
Jet-cloud interactions/ several emission zones





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

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



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

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

Theoretical challenge: Where did all the energy go to?

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

Comparable amounts of energy

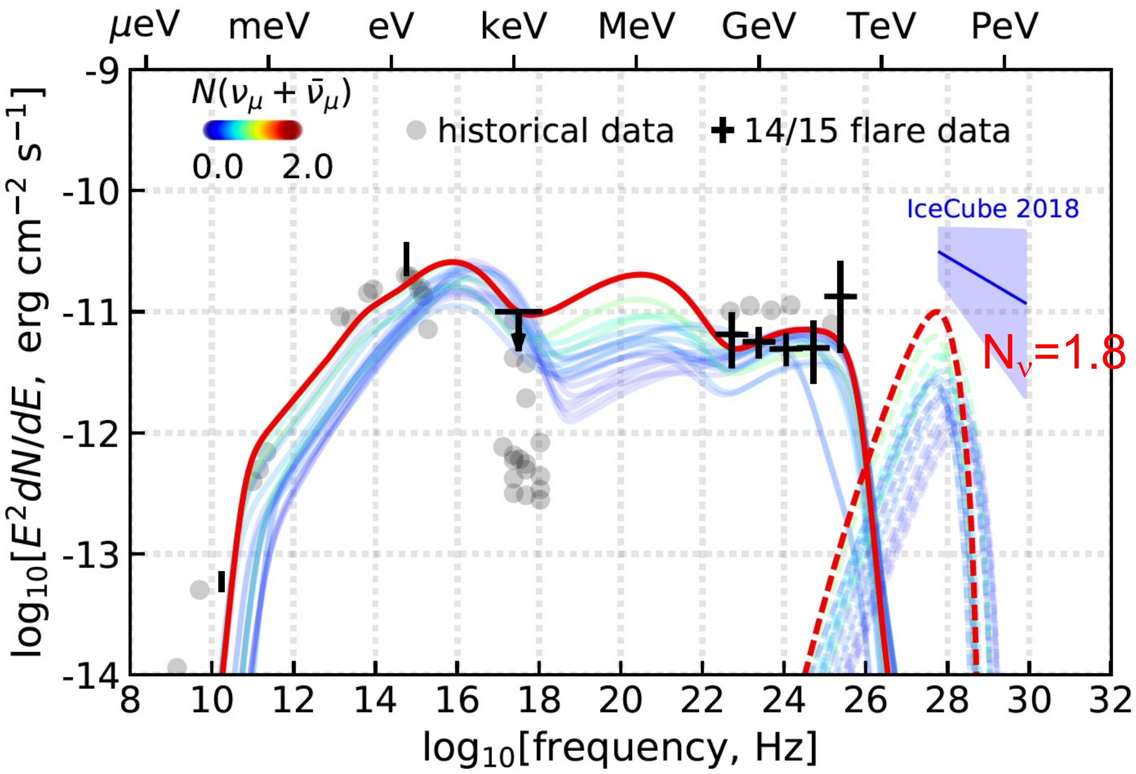
Options for hiding the gamma-rays (+electrons):

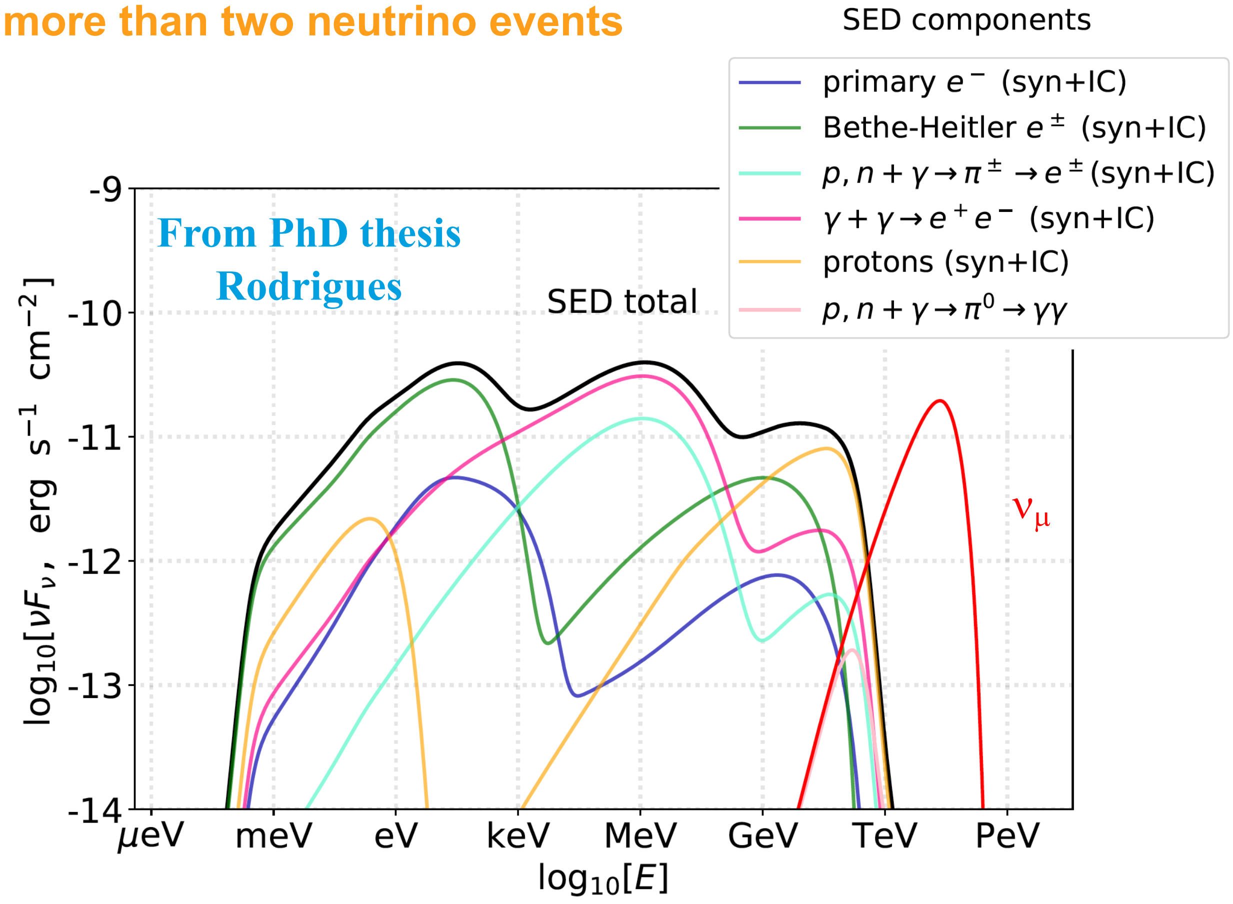
- **Reprocessed** and ”parked” in E ranges without data during flare? (e.g. MeV range, sub-eV range)
  - → Can this be accommodated in a self-consistent model (next slide)? Fine-tuned during flare?
  - → Requires monitoring in all wavelength bands
- Leave source + **dumped** into the **background light**?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

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

One zone description of spectral energy distribution

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





From PhD thesis Rodrigues

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

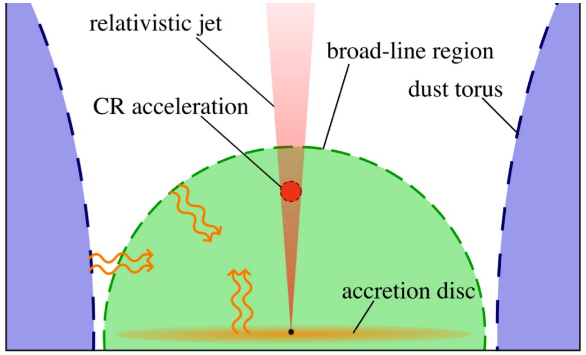
Primary electron processes (synchrotron and inverse Compton) dominate *nowhere* in this model!

From: Rodrigues, Gao, Fedynitch, Palladino, Winter, ApJL 874 (2019) L29; see also Halzen, et al, ApJL 874 (2019) 1, L9; Petropoulou et al, ApJ 891 (2020) 115

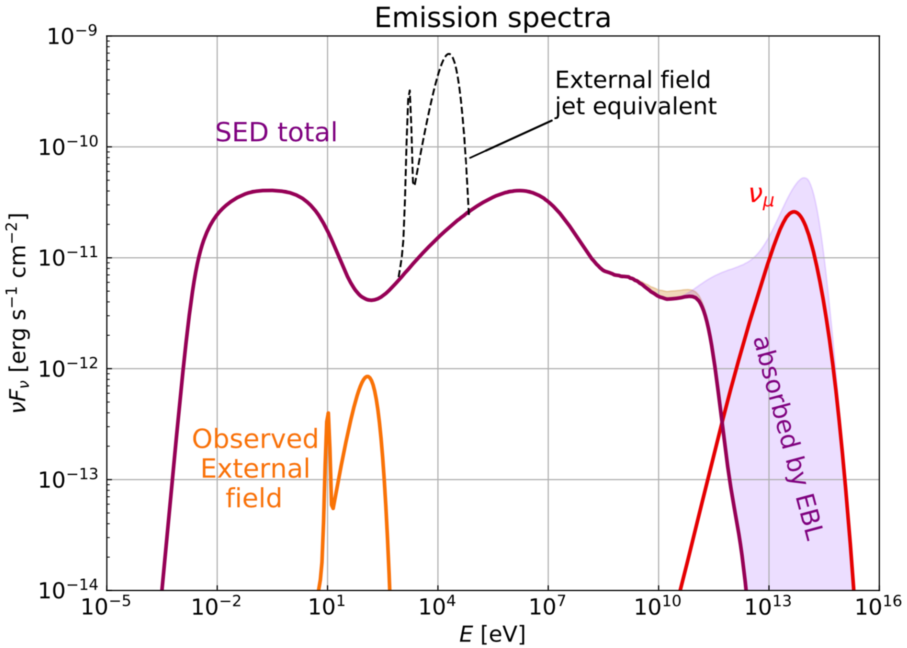
External radiation field example

Can yield up to about five neutrino events during neutrino flare

Rodrigues et al, ApJ 854 (2018) 54

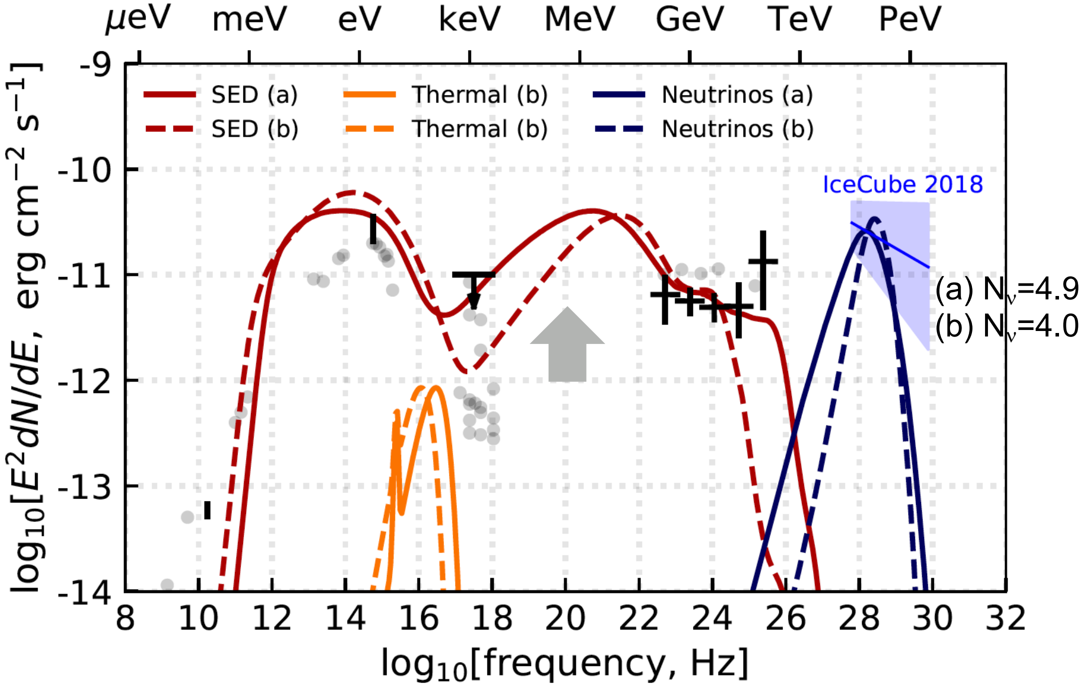


- TXS 0506+056 may be actually an FSRQ
  Padovani et al, MNRAS 484 (2019) L104
- These can be back-scattered into the jet frame. Example:



Courtesy X. Rodrigues

- Results for TXS 0506+056:



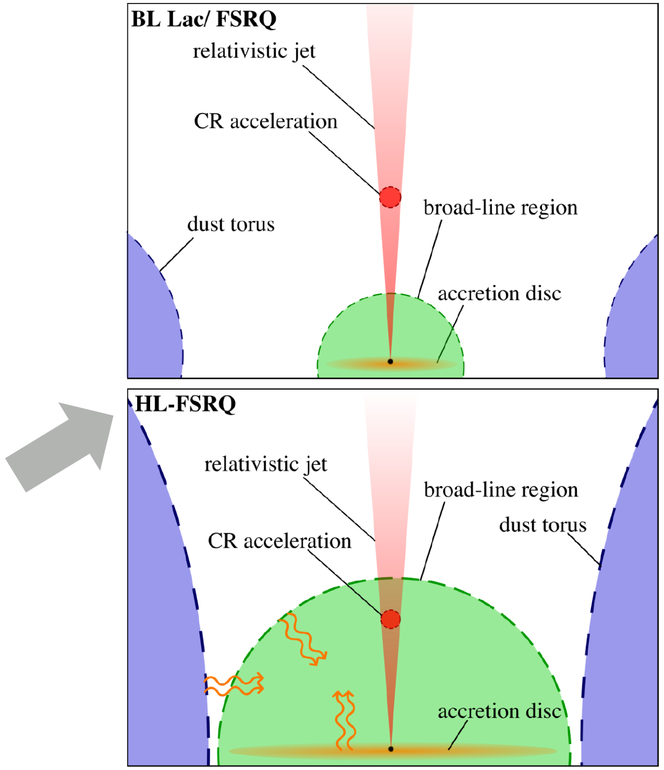
- Maximally five events; may be consistent with IceCube result if different spectral shape is assumed

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

Diffuse neutrino flux from AGN?

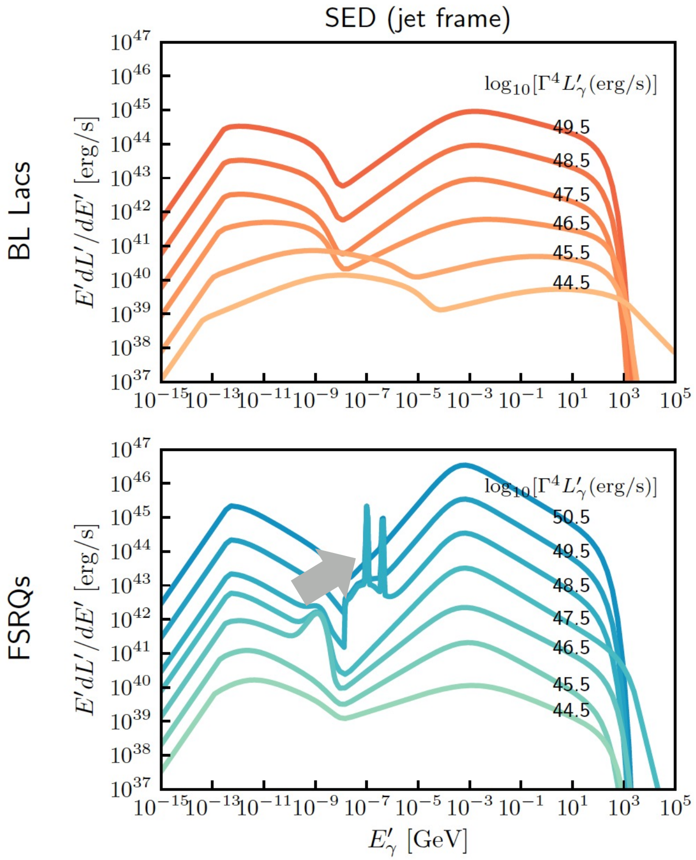
Ingredients: Neutrino production and population models

- Geometry determined by disk luminosity:

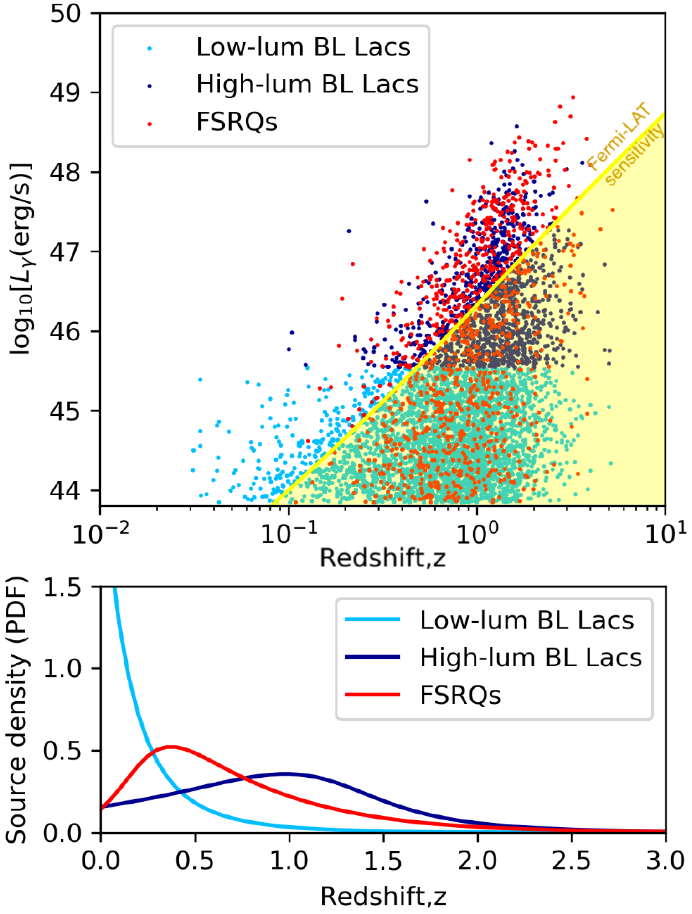


- For HL-FSRQs, the blob is exposed to boosted external fields

- 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!

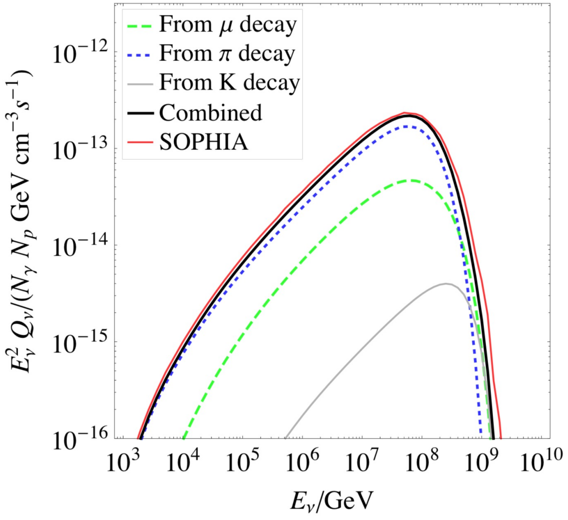
Recap: AGN neutrino spectrum ...and two hypotheses

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

Moderately efficient CR acclerators

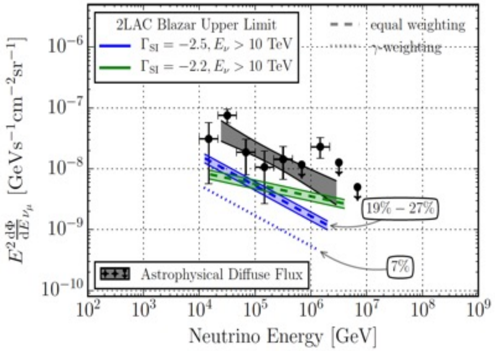
1) AGN blazars describe neutrino data

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



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

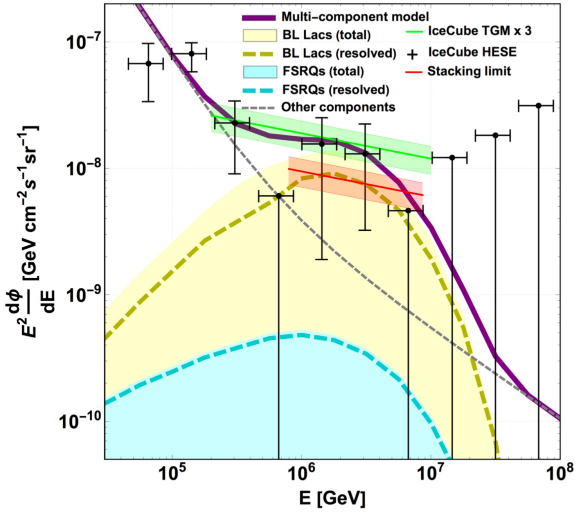


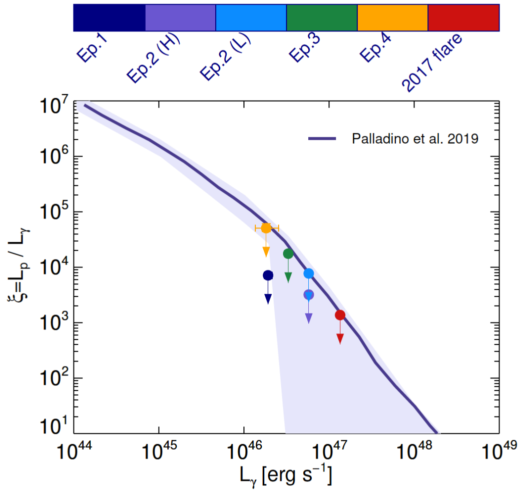
3. The baryonic loading evolves over the blazar sequence (depends on L_γ); the one of TXS 0506+056 is in the ball park of self-consistent SED models

Conclusions for different hypotheses

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

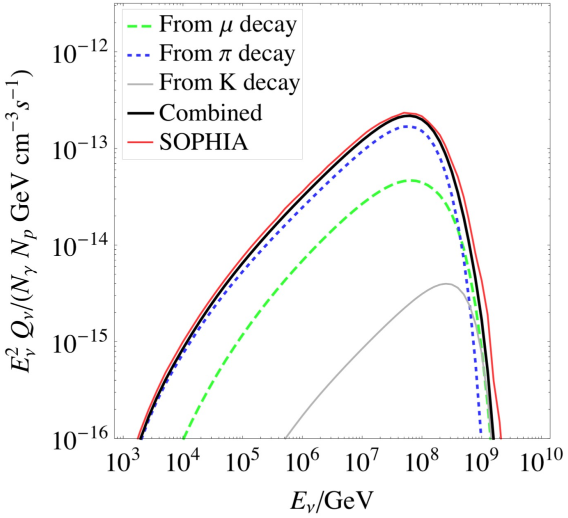
Recap: AGN neutrino spectrum ...and two hypotheses

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

Moderately efficient CR acclerators

1) AGN blazars describe neutrino data

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



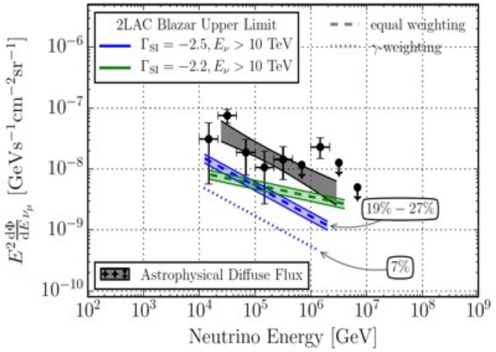
$E_{p,max}$ ~ 1-10 EeV
(R_{max} ~ 1-10 EV)

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

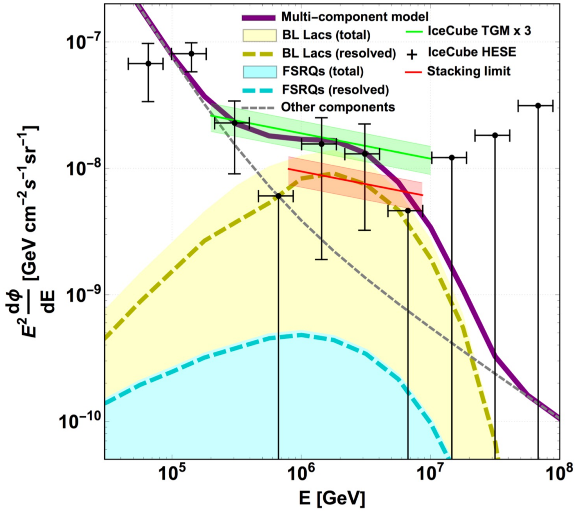
Postulate that:

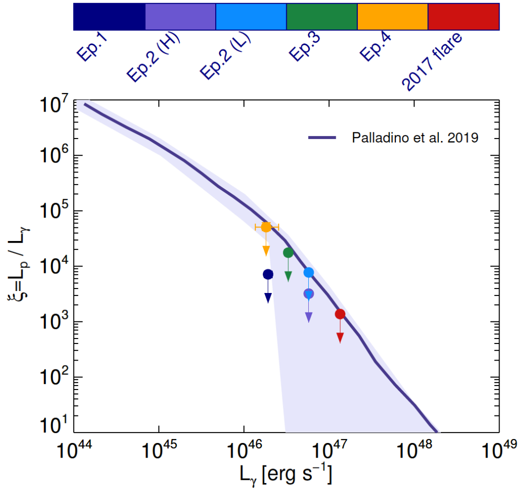
1. AGN jets (can be misaligned!) describe Auger data across the ankle
   (spectrum very well, composition observables roughly)
2. The injection compositon is roughly Galactic
3. Different classes
   (LL-BL Lacs, HL-BL Lacs, FSRQs)
   can have a different baryonic loading

Conclusions for different hypotheses

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

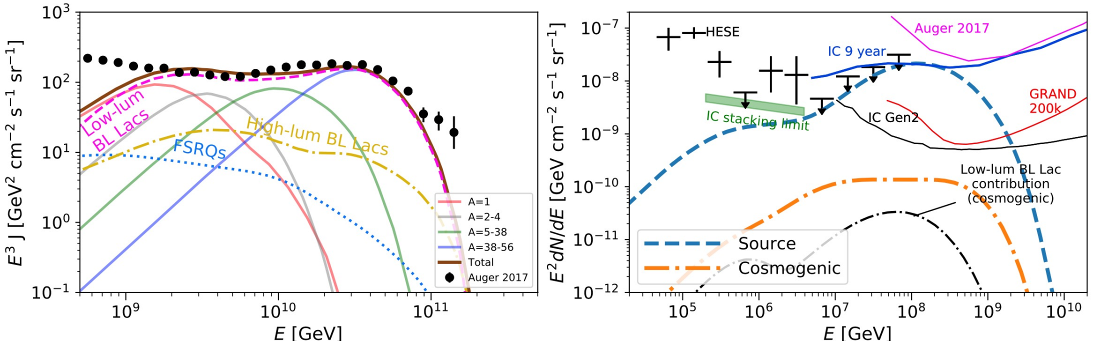




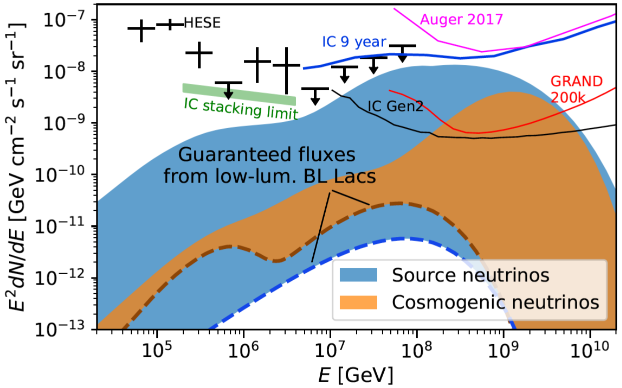
Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41;
Right Fig. from Petropoulou et al, arXiv:1911.04010: same behavior also found in multi-epoch description of TXS 0506+056

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



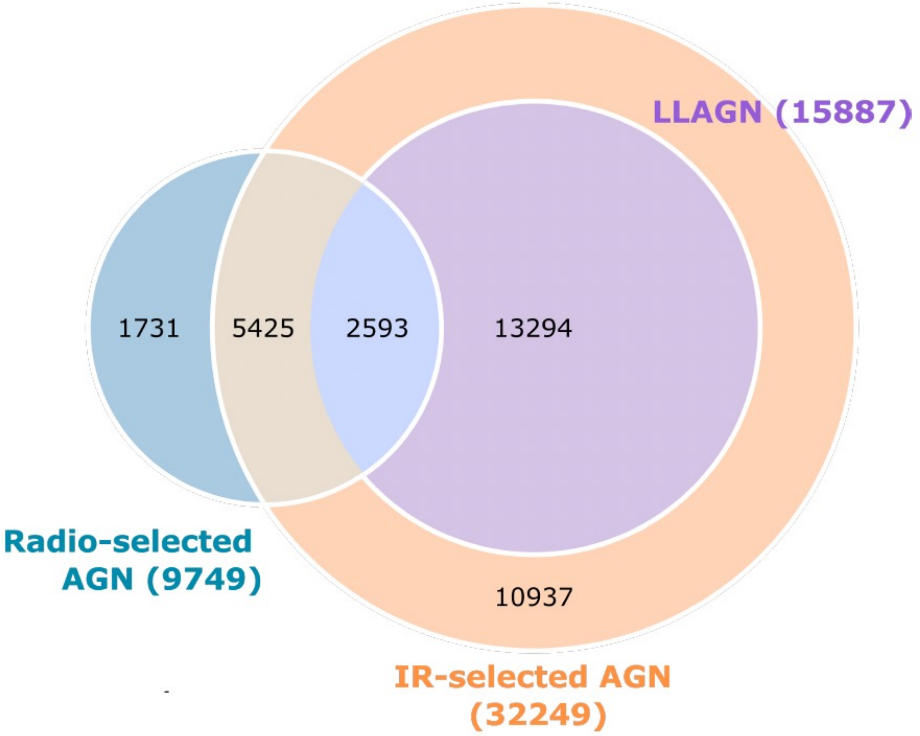
Rodrigues, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021) 191101

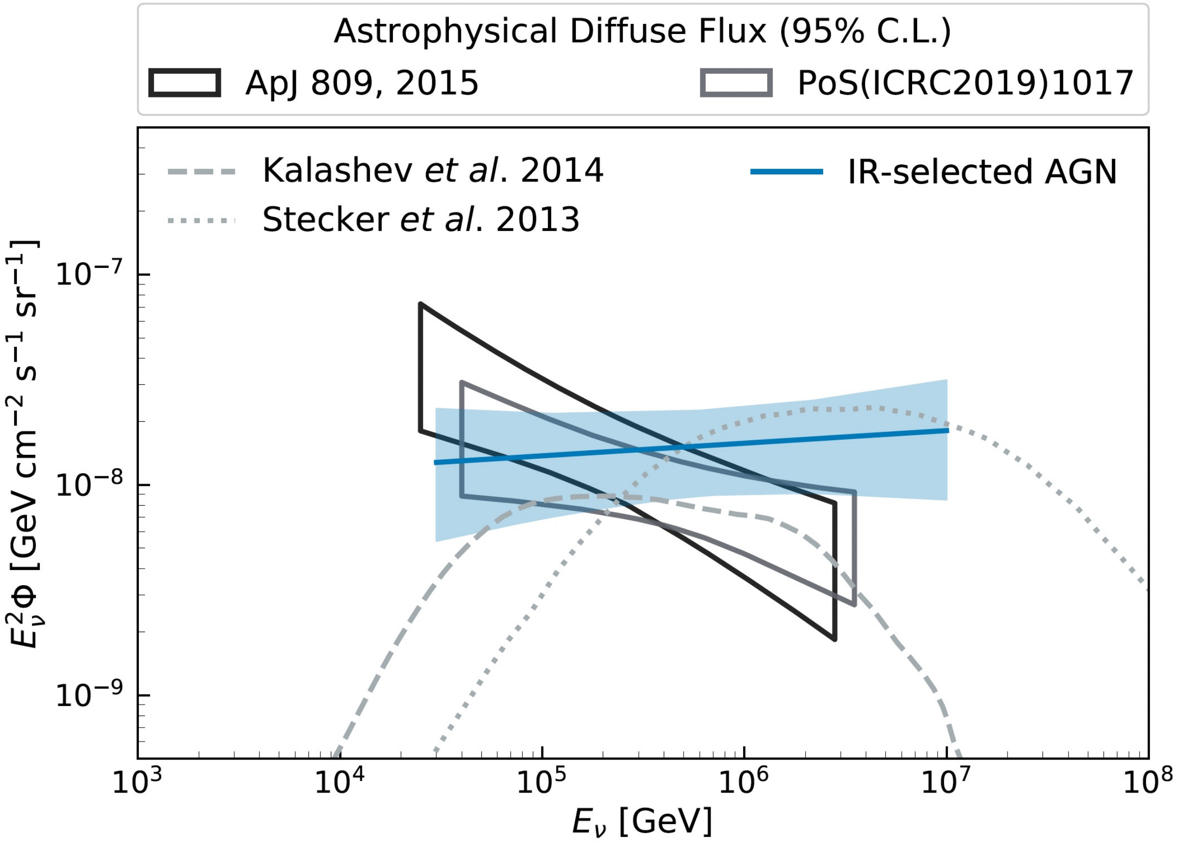
→ Talk Fiorillo, lecture 3

Neutrinos from AGN cores

- Large AGN (core) samples tested in stacking search; IR-selected largest sample (in comb. with X-rays) largest

- 2.6σ evidence for correlation mit IR-selected sample





IceCube, Phys. Rev.D 106 (2022) 2, 022005

Neutrinos from TDEs

Tidal Disruption Events

https://www.desy.de/e409/e116959/e119238/media/9170/TDE_DESY_SciComLab_sound_080p.mp4

How to disrupt a star 101

Gravity

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

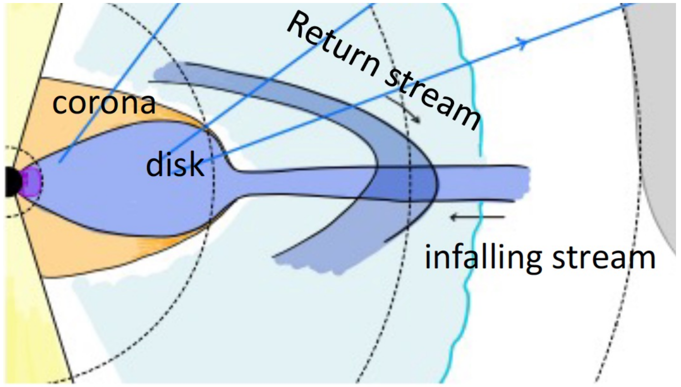
$$r_t = \left(\frac{2M}{m}\right)^{1/3} R \simeq 8.8 \times 10^{12}\,\mathrm{cm}\,\left(\frac{M}{10^6\,M_\odot}\right)^{1/3}\frac{R}{R_\odot}\left(\frac{m}{M_\odot}\right)^{-1/3}$$

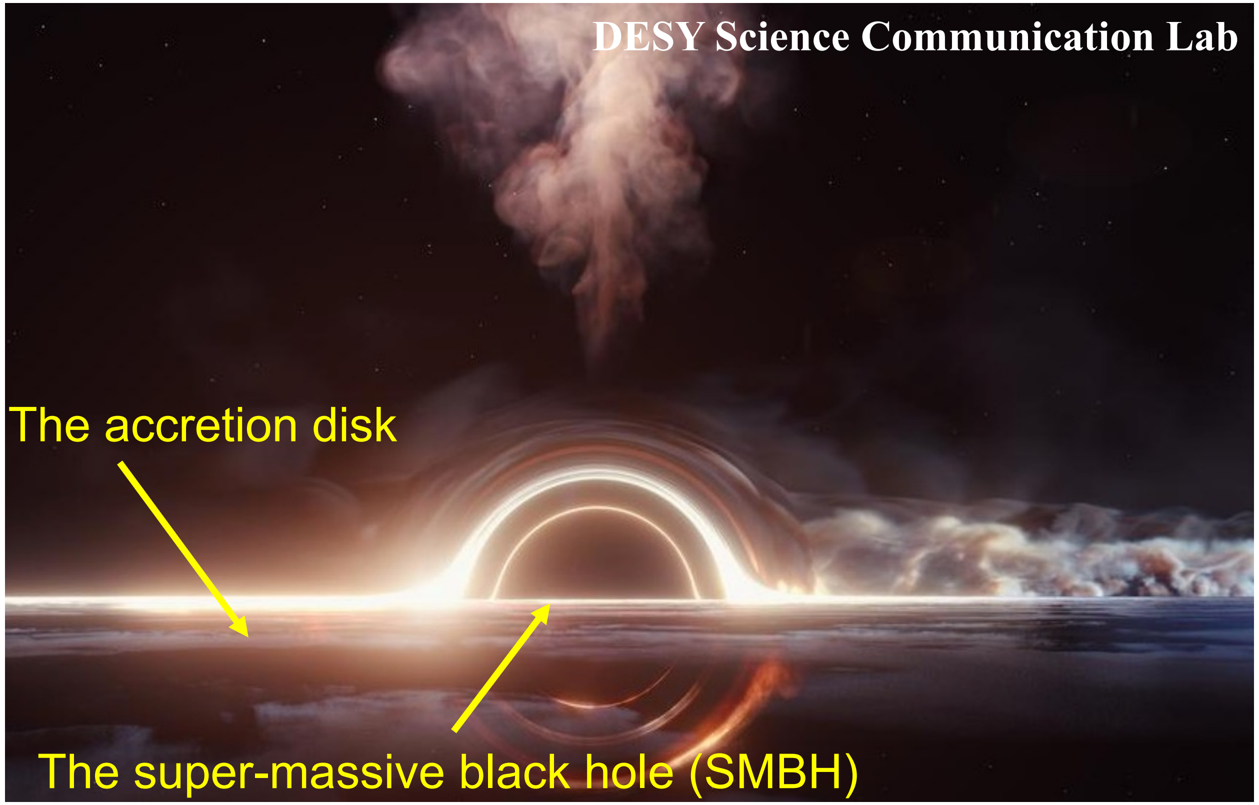
- Has to be beyond Schwarzschild radius for TDE

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

- From the comparison ($r_t > R_s$) and demographics, one obtains (theory) M <~ 2 10^7 $M_\odot$ (lower limit less certain …)

  Hills, 1975; Kochanek, 2016; van Velzen 2017





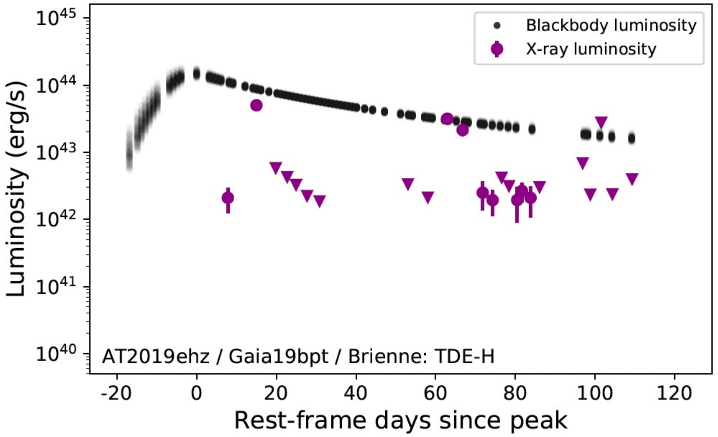
Energetics

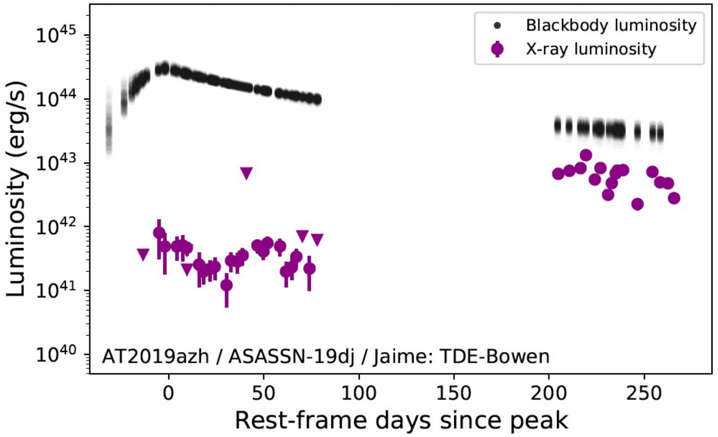
- Measure for the luminosity which can be re-processed from accretion through the SMBH: **Eddington luminosity**

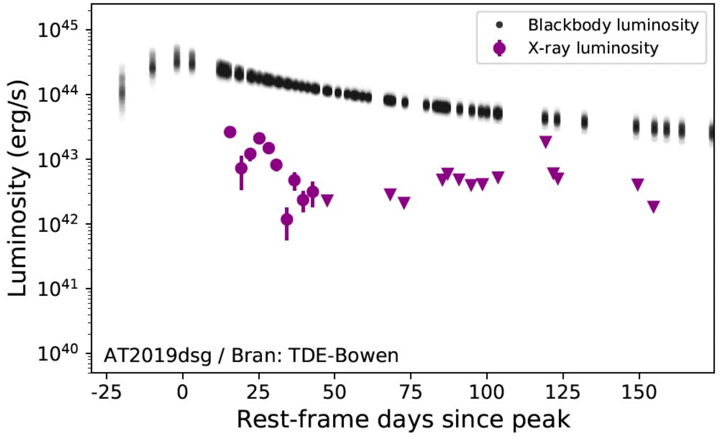
$$L_{\mathrm{Edd}} \simeq 1.3\ 10^{44}\ \mathrm{erg/s}\,(M/(10^6\ M_\odot))$$

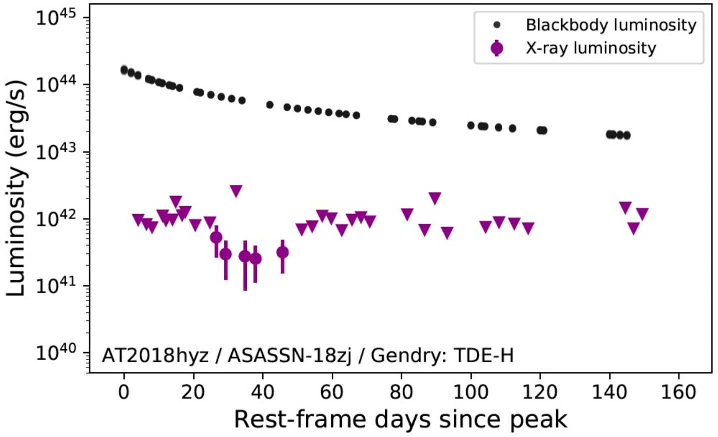
- Energy to be re-processed: about half of a star's mass E ~ 10^{54} erg (half a solar mass)
- Super-Eddington **mass fallback rate** expected at peak to process that amount of energy

TDE observations (general)



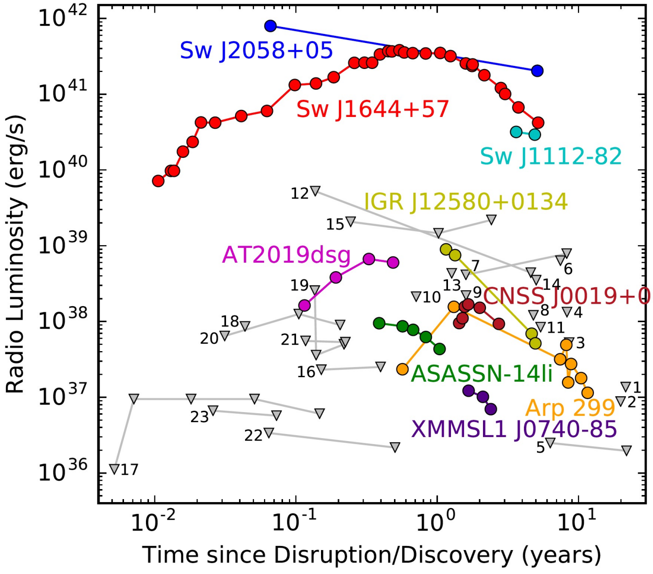






van Velzen et al, Astrophys. J. 908 (2021) 1, 4;
Alexander, van Velzen, Horesh, Zauderer, Space Sci. Rev. 216 (2020) 5, 81

- **Optical-UV (blackbody):** Mass fallback rate typically exhibits a peak and then a ~ $t^{-5/3}$ dropoff over a few hundred days
- **X-rays:** Only observed in rare cases (here about 4 out of 17). X-ray properties very different
- **Radio:** Interesting signals in about 1/3 of all cases. Evolving radio signals interpreted as outflow or jet



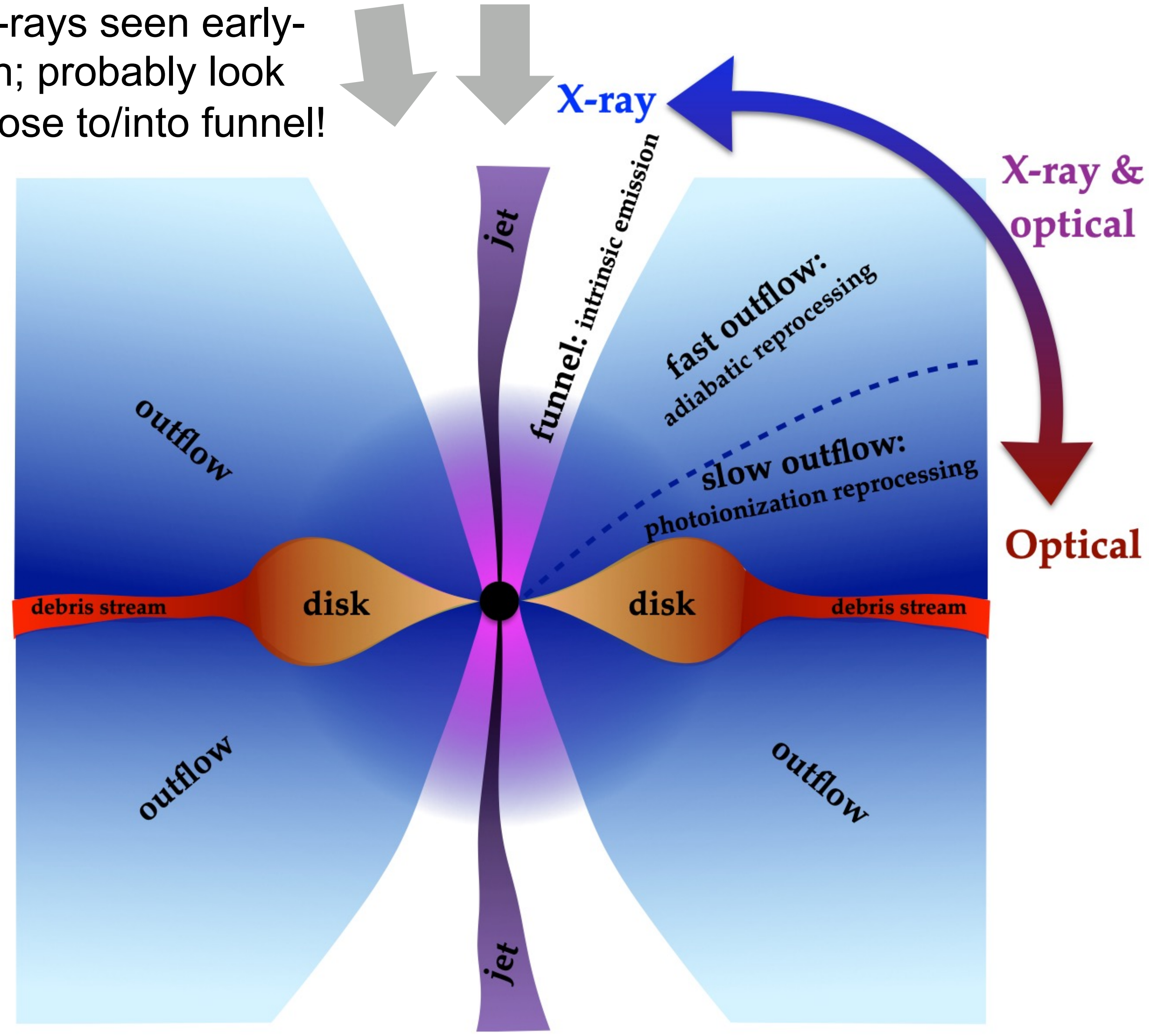
Relat. jets?

Non-relat. outflows?

A TDE unified model

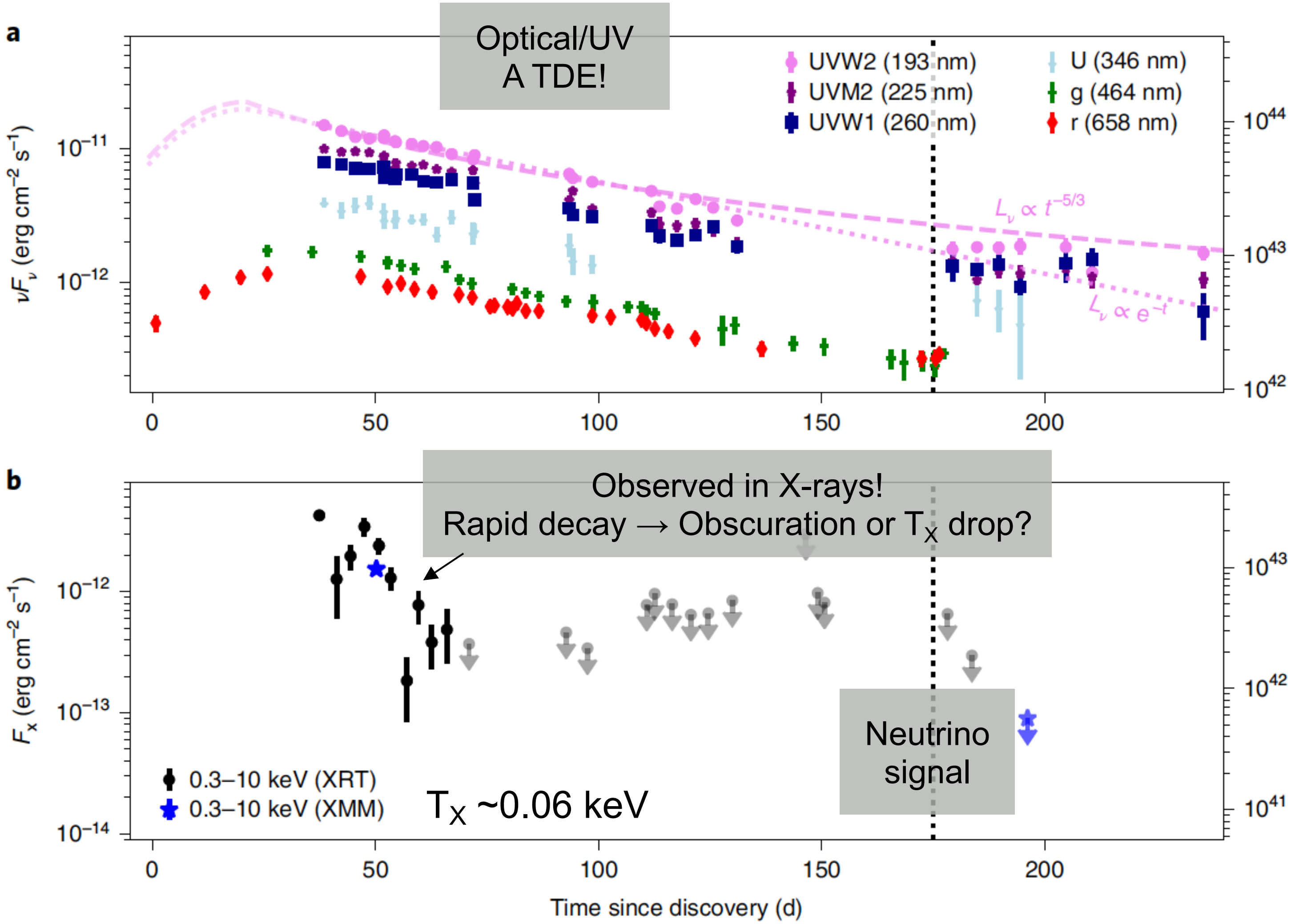
- Supported by MHD simulations; here $M_{\mathrm{SMBH}} = 5\ 10^6\ M_\odot$
- A jet is optional in that model, depending on the SMBH spin
- Observations from model:
  - Average mass accretion rate $\dot{M} \sim 10^2 L_{\mathrm{Edd}}$
  - ~ 20% of that into jet
  - ~ 3% into bolometric luminosity
  - ~ 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 neutrino from AT2019dsg

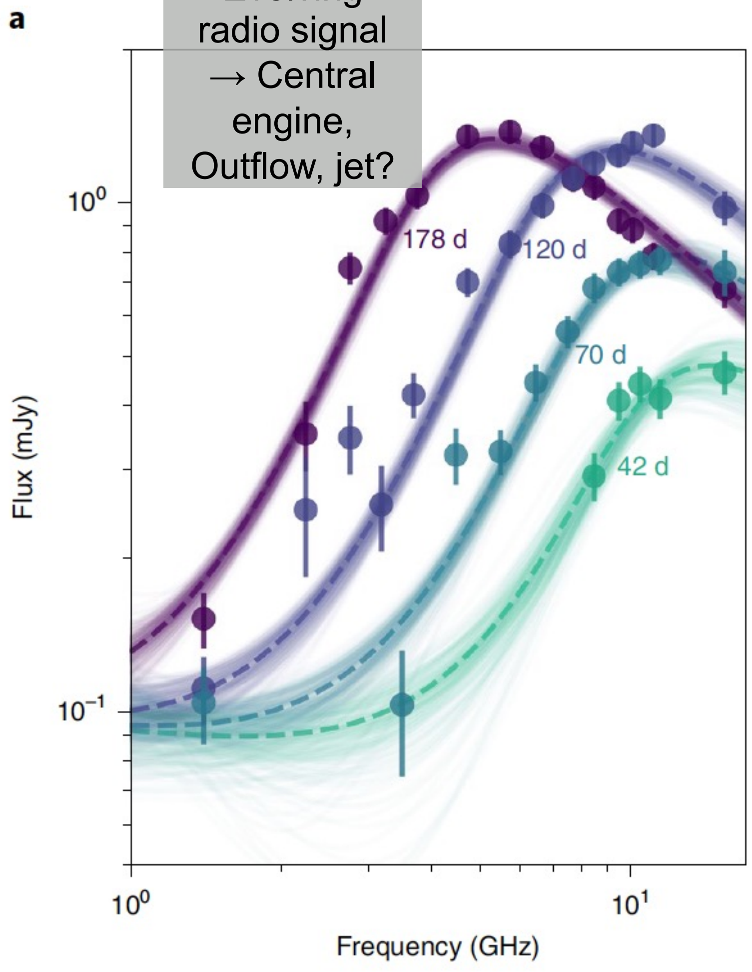


Optical/UV
A TDE!

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

T_X ~0.06 keV

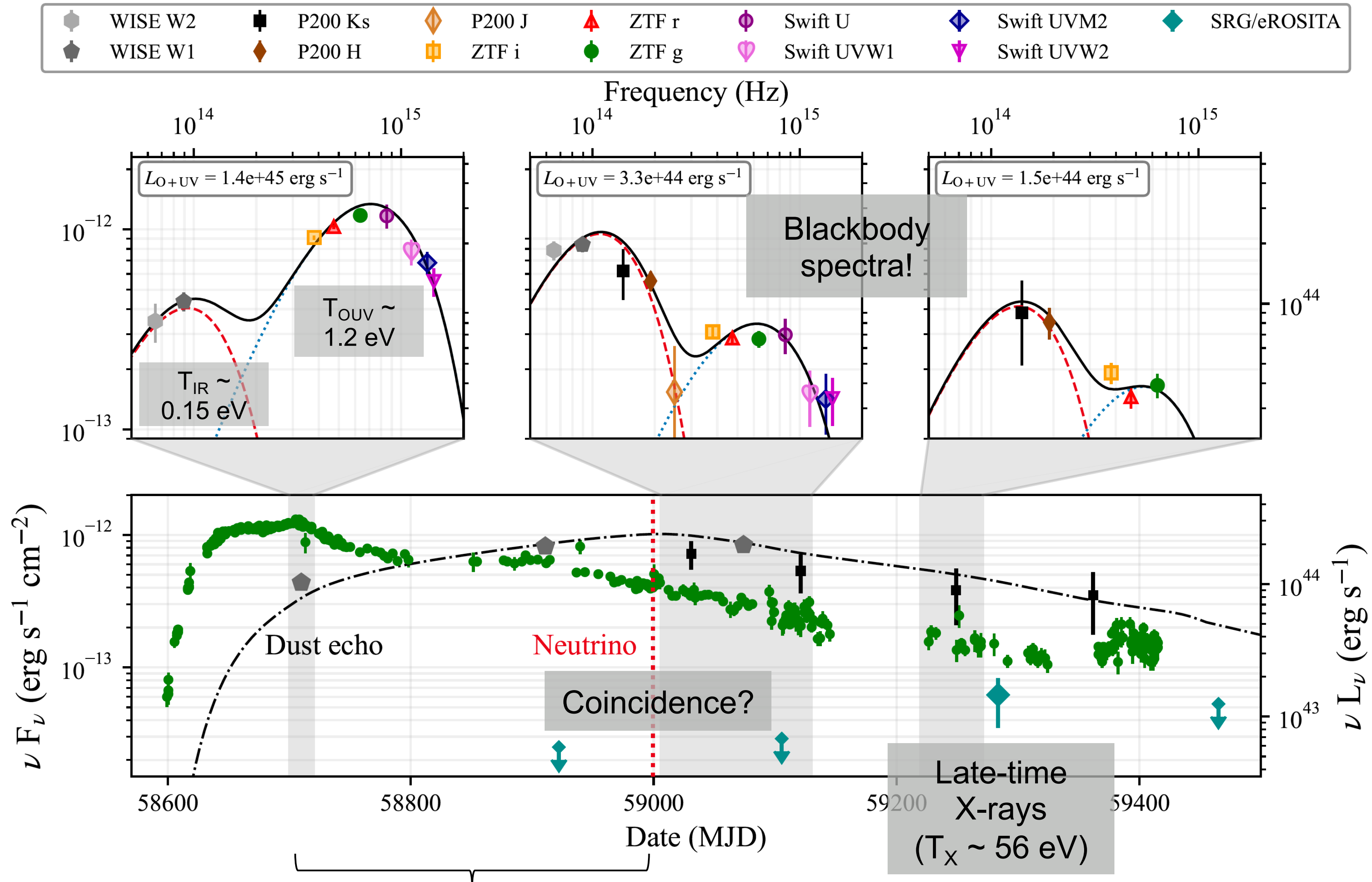
Neutrino
signal



Evolving
radio signal
→ Central
engine,
Outflow, jet?

Stein et al, Nature Astronomy 5 (2021) 510

Another neutrino from the TDE candidate AT2019fdr



T_{OUV} ~ 1.2 eV

T_{IR} ~ 0.15 eV

Blackbody spectra!

Coincidence?

Late-time X-rays (T_X ~ 56 eV)

Dust echo "convolved" over 2 Δt

- Dust echo (IR): Median time delay Δt ~ 150 days ~ 4 10^{17} cm ~ R_{dust}

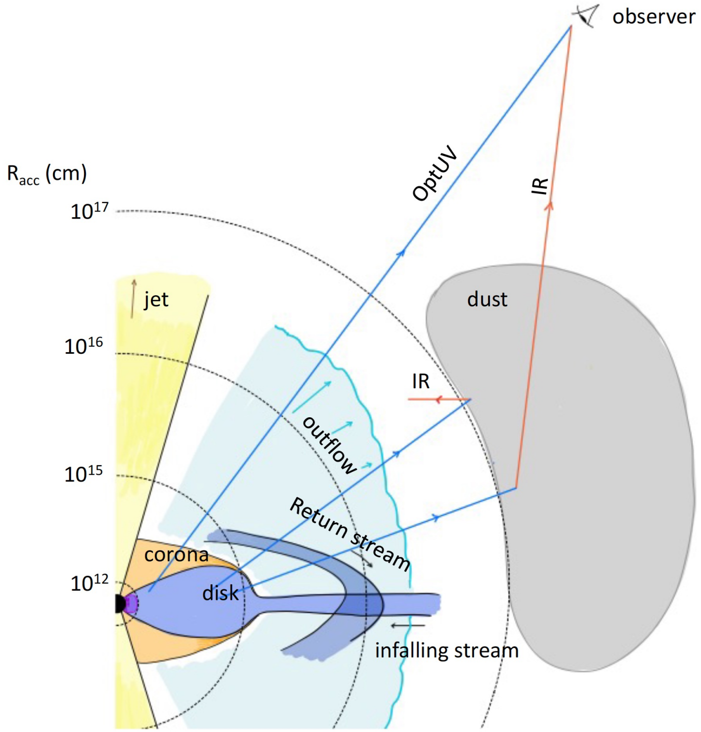


Fig. from arXiv:2205.11538

Reusch, WW et al, PRL 128 (2022) 22; see Pitik et al, 2022 for SN interpretation

AT2019aalc

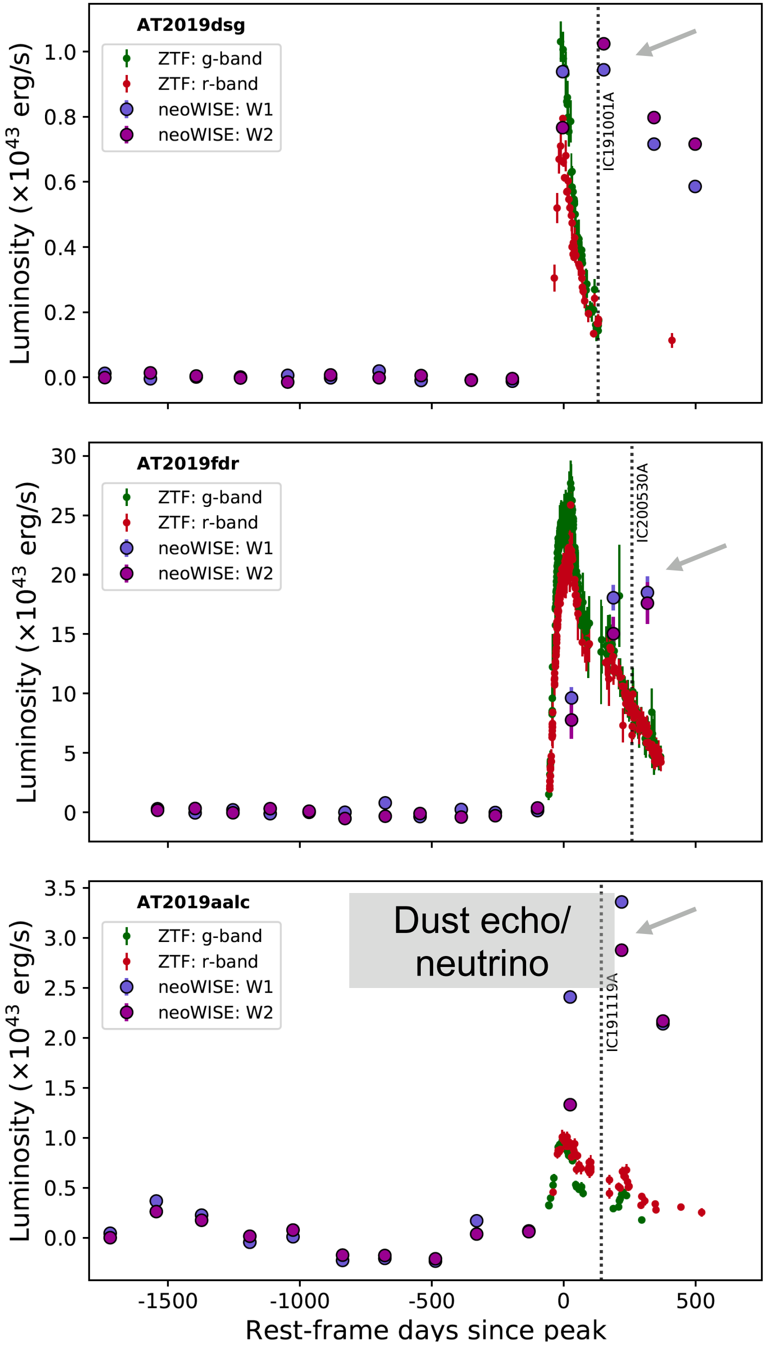
… as third neutrino-TDE association

Analysis

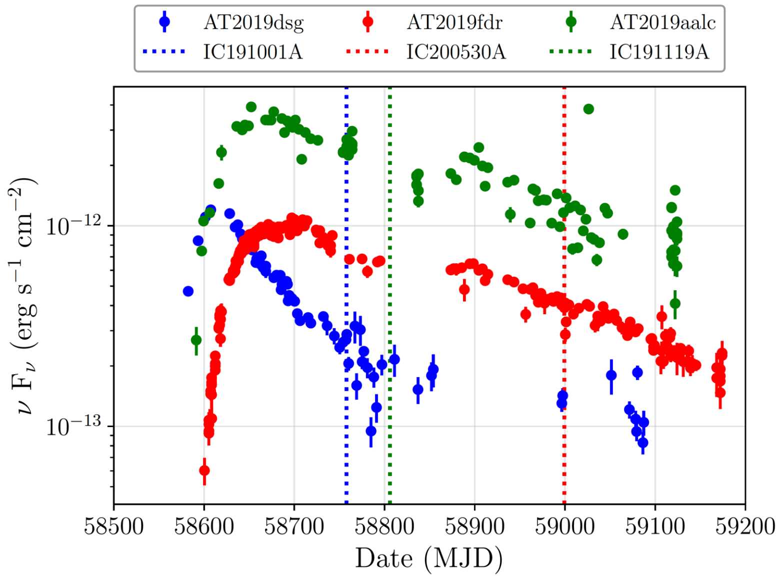
- Selected a sample of 1732 accretion flares with properties similar to AT2019dsg and AT2019fdr (dust echo)
- Found another TDE candidate: AT2019aalc with a similar neutrino time delay
- Overall significance: 3.7σ
  van Velzen et al, arXiv:2111.09391

Caveats

- AT2019aalc also exhibited a late-time X-ray signal
- AT2019fdr and AT2019aalc not uniquely identified as TDEs;
  e.g. Pitik et al, Astrophys. J. 929 (2022) 2, 163
  happened in pre-existing AGN;
  no evolving radio signals



van Velzen et al, arXiv:2111.09391



Simeon Reusch @ ECRS 2022

Common features of these three "TDEs":

- Detected in X-rays (but X-ray signals qualitatively different)
- Large BB luminosities
- Strong dust echoes in IR
- Neutrinos all delayed wrt peak by order 100 days (close to dust echo peak)

Possible particle acceleration sites

① Jets (on-axis, off-axis, choked)
Wang et al, 2011; Wang&Liu 2016; Dai&Fang, 2016; Lunardini&Winter, 2017; Senno et al 2017; Winter, Lunardini, 2020; Liu, Xi, Wang, 2020; Zheng, Liu, Wang, 2022

② Disk
Hayasaki&Yamazaki, 2019

③ Corona
Murase et al, 2020

④ Winds, outflow, stream-stream collisions
Murase et al, 2020; Fang et al, 2020; Wu et al, 2021

Based on the experimental evidence, it is difficult to establish a particular particle accelerator!

However: probably the accelerator is "TDE-particular" (otherwise other sources would outshine the TDE neutrino flux)

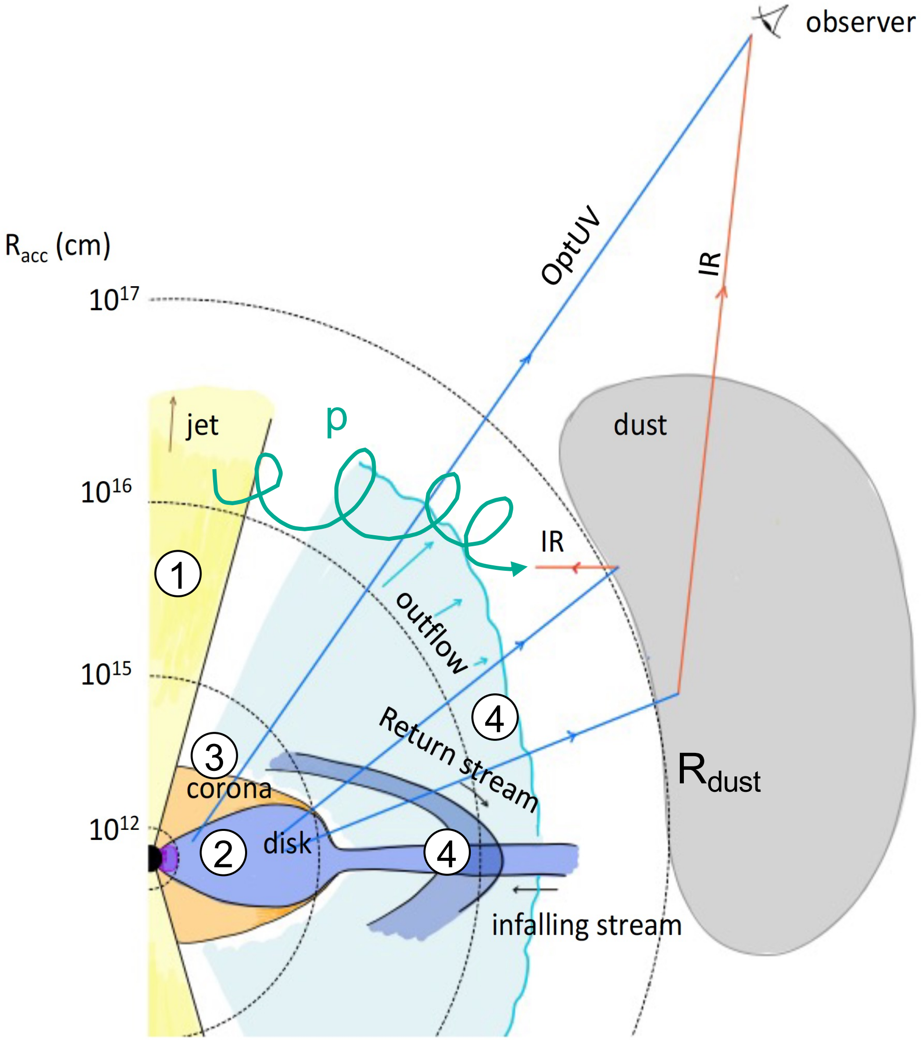
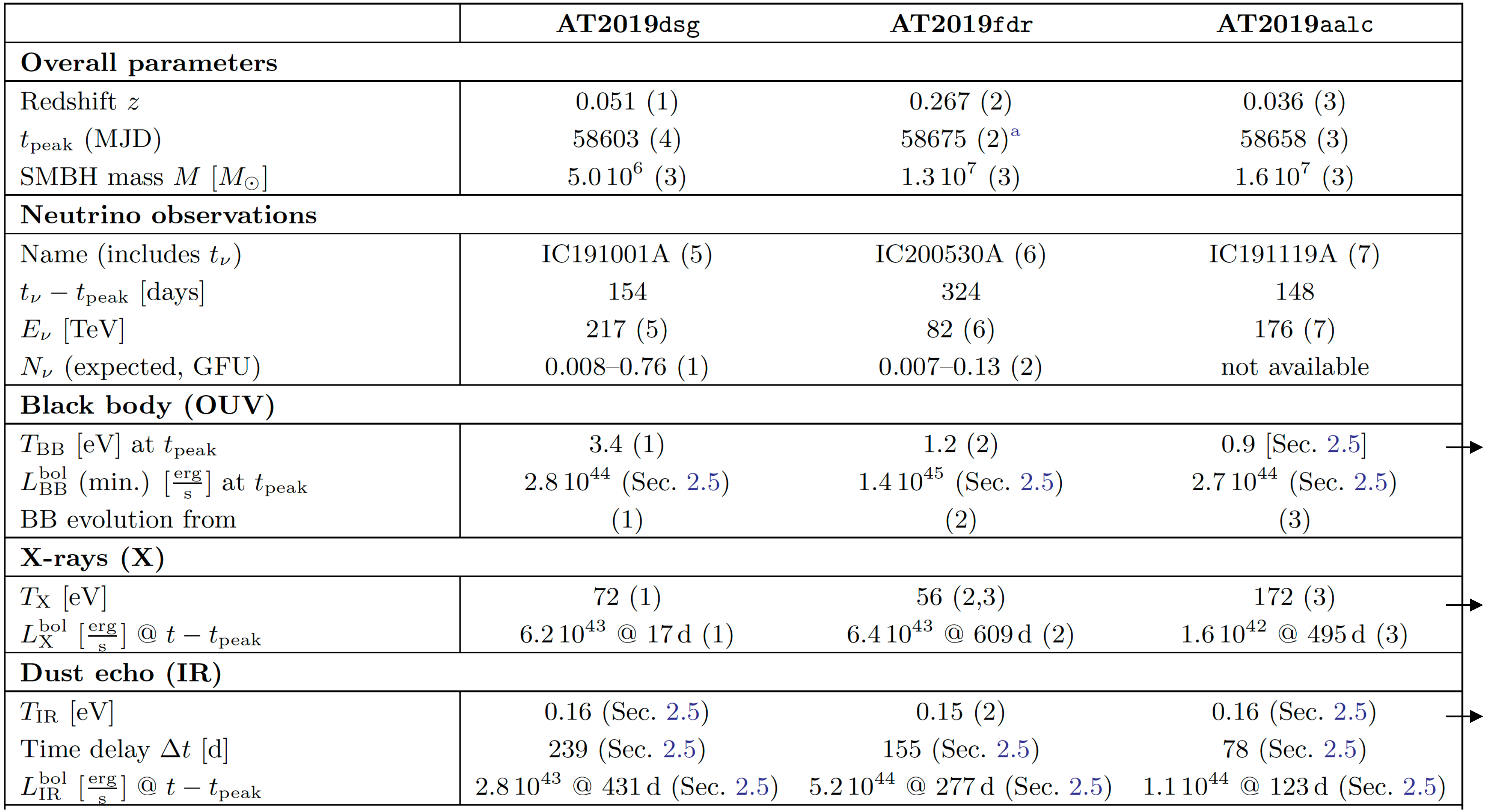


Fig: Winter, Lunardini, ApJ 948 (2023) 1, 42

Possible target photons and required proton energies



	AT2019dsg	**AT2019fdr**	**AT2019aalc**
Overall parameters			
Redshift z	0.051 (1)	0.267 (2)	0.036 (3)
$t_{\rm peak}$ (MJD)	58603 (4)	58675 (2)[a]	58658 (3)
SMBH mass M $[M_\odot]$	$5.0\,10^6$ (3)	$1.3\,10^7$ (3)	$1.6\,10^7$ (3)
Neutrino observations			
Name (includes t_ν)	IC191001A (5)	IC200530A (6)	IC191119A (7)
$t_\nu - t_{\rm peak}$ [days]	154	324	148
E_ν [TeV]	217 (5)	82 (6)	176 (7)
N_ν (expected, GFU)	0.008–0.76 (1)	0.007–0.13 (2)	not available
Black body (OUV)			
$T_{\rm BB}$ [eV] at $t_{\rm peak}$	3.4 (1)	1.2 (2)	0.9 [Sec. 2.5]
$L_{\rm BB}^{\rm bol}$ (min.) $[\frac{\rm erg}{\rm s}]$ at $t_{\rm peak}$	$2.8\,10^{44}$ (Sec. 2.5)	$1.4\,10^{45}$ (Sec. 2.5)	$2.7\,10^{44}$ (Sec. 2.5)
BB evolution from	(1)	(2)	(3)
X-rays (X)			
$T_{\rm X}$ [eV]	72 (1)	56 (2,3)	172 (3)
$L_{\rm X}^{\rm bol}$ $[\frac{\rm erg}{\rm s}]$ @ $t - t_{\rm peak}$	$6.2\,10^{43}$ @ 17 d (1)	$6.4\,10^{43}$ @ 609 d (2)	$1.6\,10^{42}$ @ 495 d (3)
Dust echo (IR)			
$T_{\rm IR}$ [eV]	0.16 (Sec. 2.5)	0.15 (2)	0.16 (Sec. 2.5)
Time delay Δt [d]	239 (Sec. 2.5)	155 (Sec. 2.5)	78 (Sec. 2.5)
$L_{\rm IR}^{\rm bol}$ $[\frac{\rm erg}{\rm s}]$ @ $t - t_{\rm peak}$	$2.8\,10^{43}$ @ 431 d (Sec. 2.5)	$5.2\,10^{44}$ @ 277 d (Sec. 2.5)	$1.1\,10^{44}$ @ 123 d (Sec. 2.5)

Winter, Lunardini, arXiv:2205.11538

Required target photon temperature (pγ):

$$T \simeq 80\,\mathrm{eV} \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-1}$$

Translates into:

$$E_{p,\max} \gtrsim 20\,E_\nu \simeq 160\,\mathrm{PeV} \left(\frac{T}{\mathrm{eV}} \right)^{-1}$$

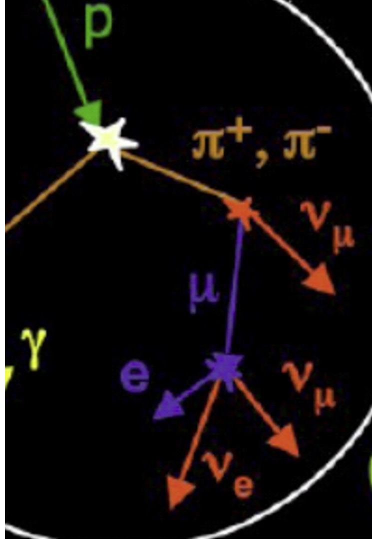
→ $E_{p,max}$ > 100 PeV

→ $E_{p,max}$ > 2 PeV

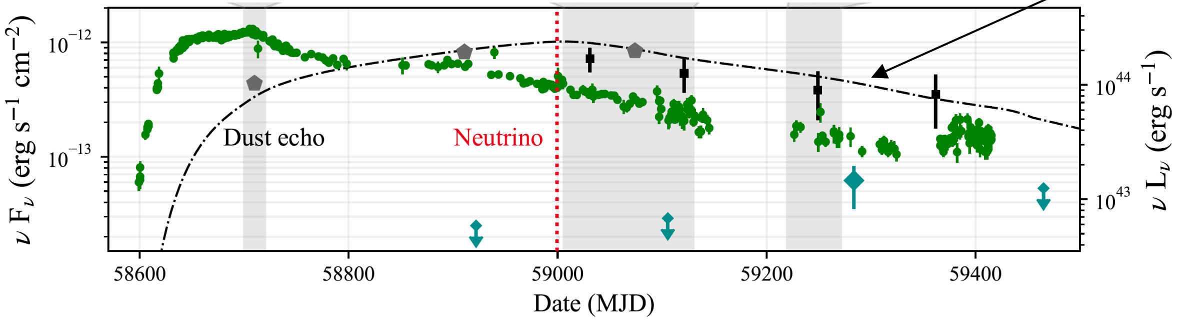
→ $E_{p,max}$ > 1 EeV. **UHECRs?**

$E_{p,max}$ controls the available photon targets!

Origin of neutrino time delay?



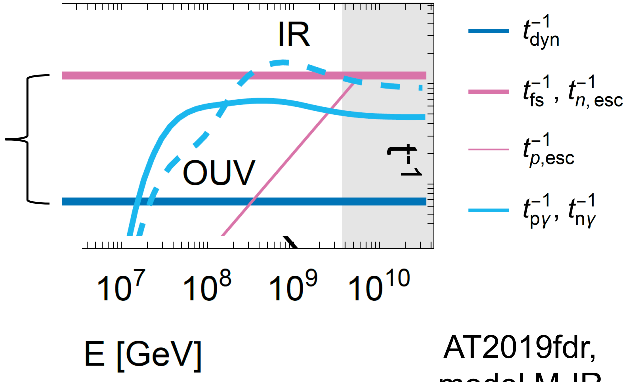
1. Target builds up over time (e.g. through evolution of outflow, dust echo). Apparently related to size of (newly formed) system



From: Reusch et al, PRL 128 (2022) 22

2. Accelerator appears delayed (transition in accretion disk state, circularization time, …)
3. Protons are magnetically confined (calorimeter), i.e., do not interact immediately.

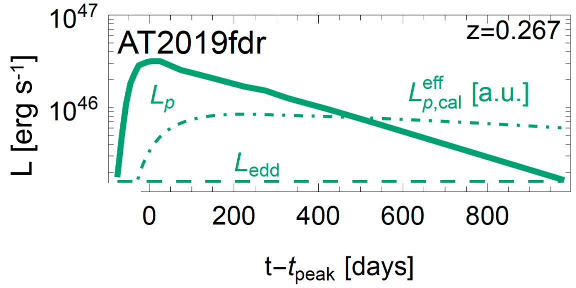
Magnetically confined protons interact over t_{dyn}, but not t_{fs}



AT2019fdr, model M-IR

Displacement over dynamical timescale (Bohm-like diffusion assumed):

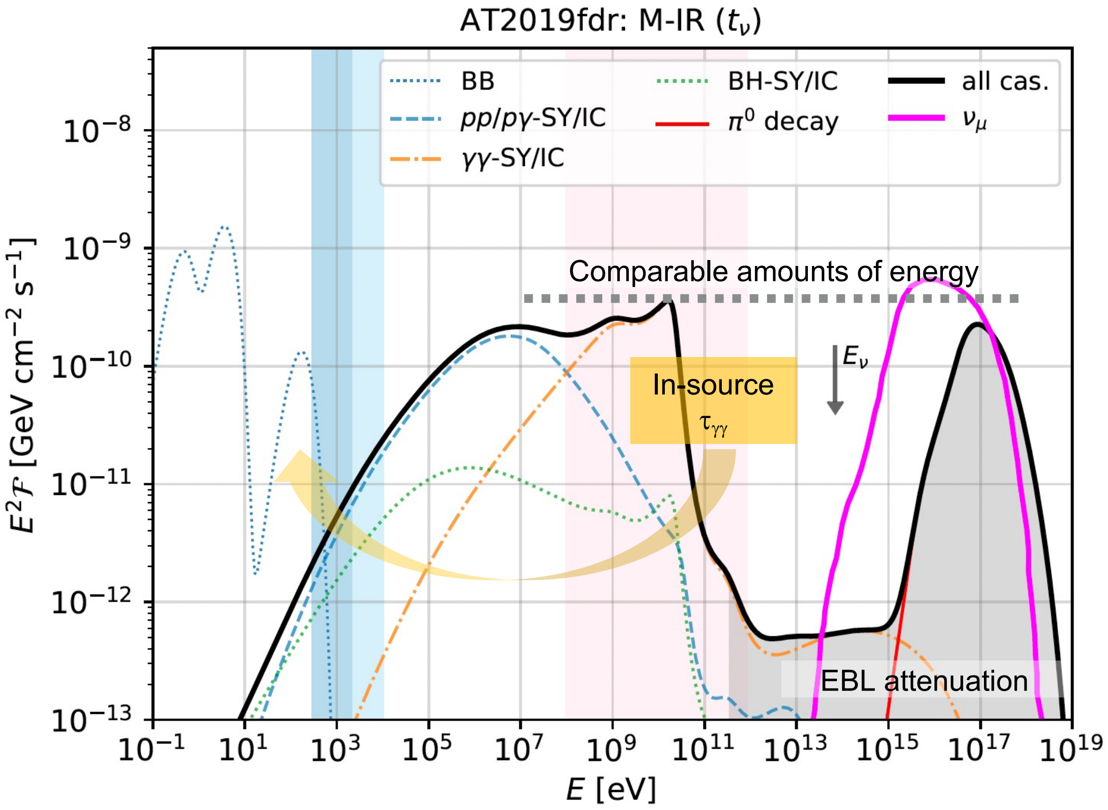
$$R \simeq \sqrt{D\, t_{p,\mathrm{diff}}} = 3\, 10^{15}\, \mathrm{cm} \left(\frac{E_p}{\mathrm{PeV}}\right)^{1/2} \left(\frac{B}{\mathrm{G}}\right)^{-1/2} \left(\frac{t_{\mathrm{dyn}}}{1000\,\mathrm{days}}\right)^{1/2}$$

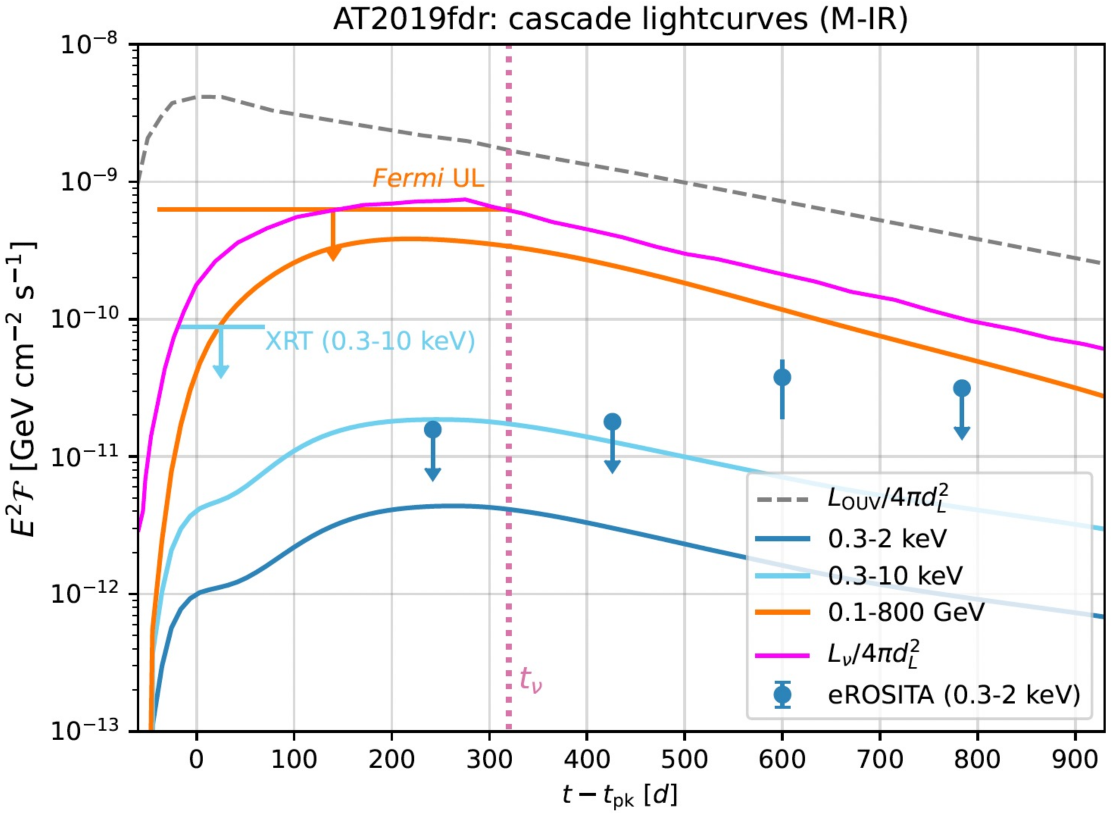


Winter, Lunardini, ApJ 948 (2023) 1, 42

An example with high proton energies – dust echo as target

- Gamma-ray and predicted neutrino signals tend to be correlated; here calorimetric system
- Too compact production regions excluded; limits predicted neutrino event rate to 0.01-0.1 events per TDE

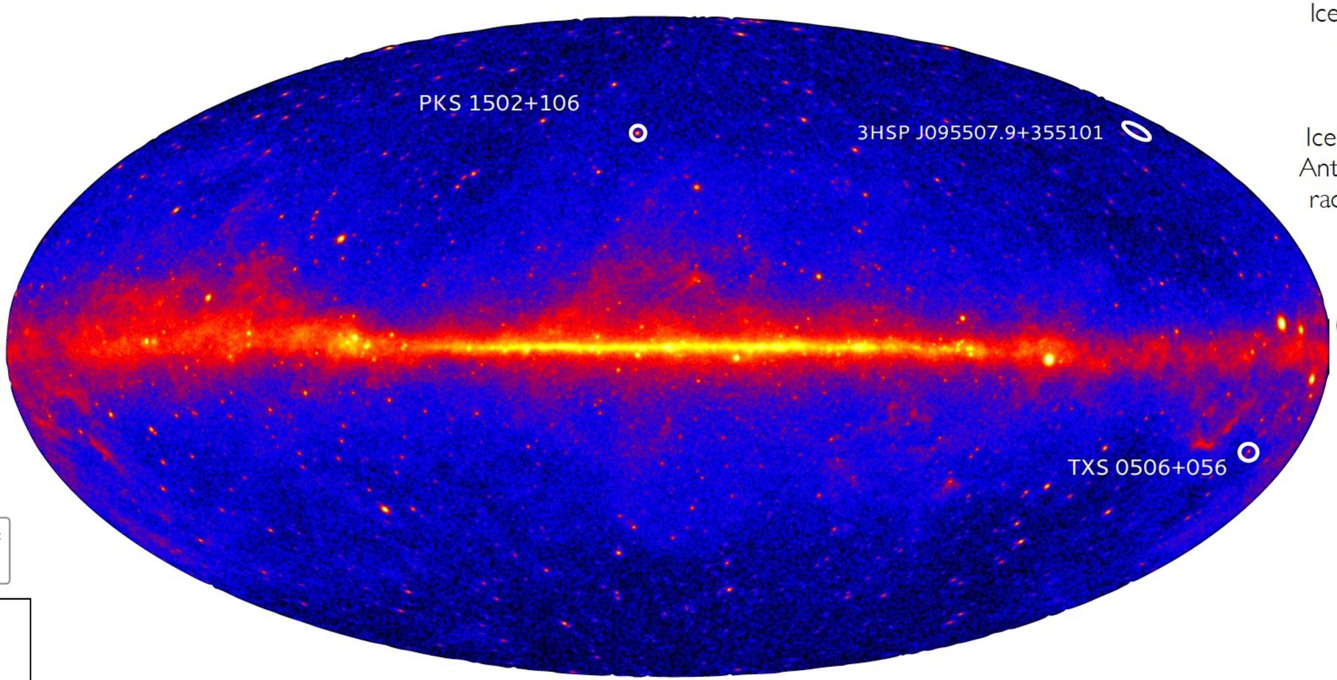

AT2019fdr: M-IR (t_ν)


AT2019fdr: cascade lightcurves (M-IR)

Yuan, Winter, 2023; based upon model in Winter, Lunardini, ApJ 948 (2023) 1, 42

Summary lecture II

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)

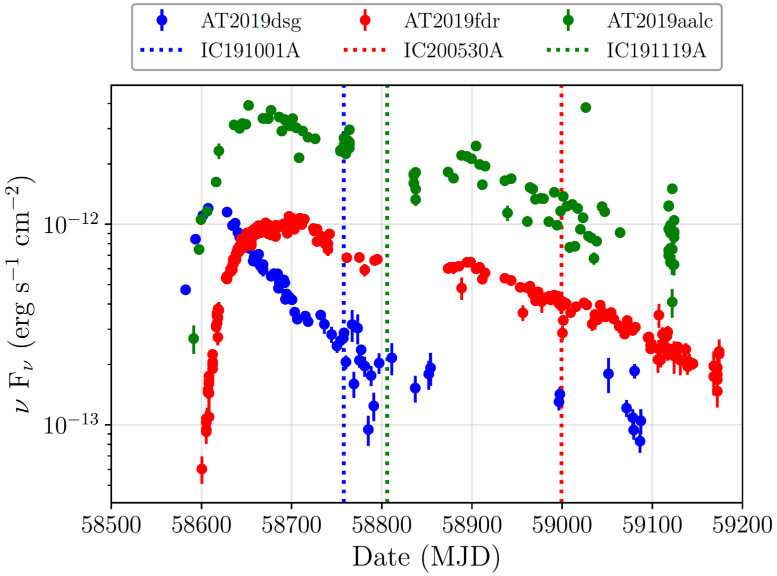
4FGL J0658.6+0636+IC201114A:
(de Menezes #296, Rosales de Leon
#308)

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



Simeon Reusch @ ECRS 2022

Lecture III: Neutrinos and the origin of the UHECRs

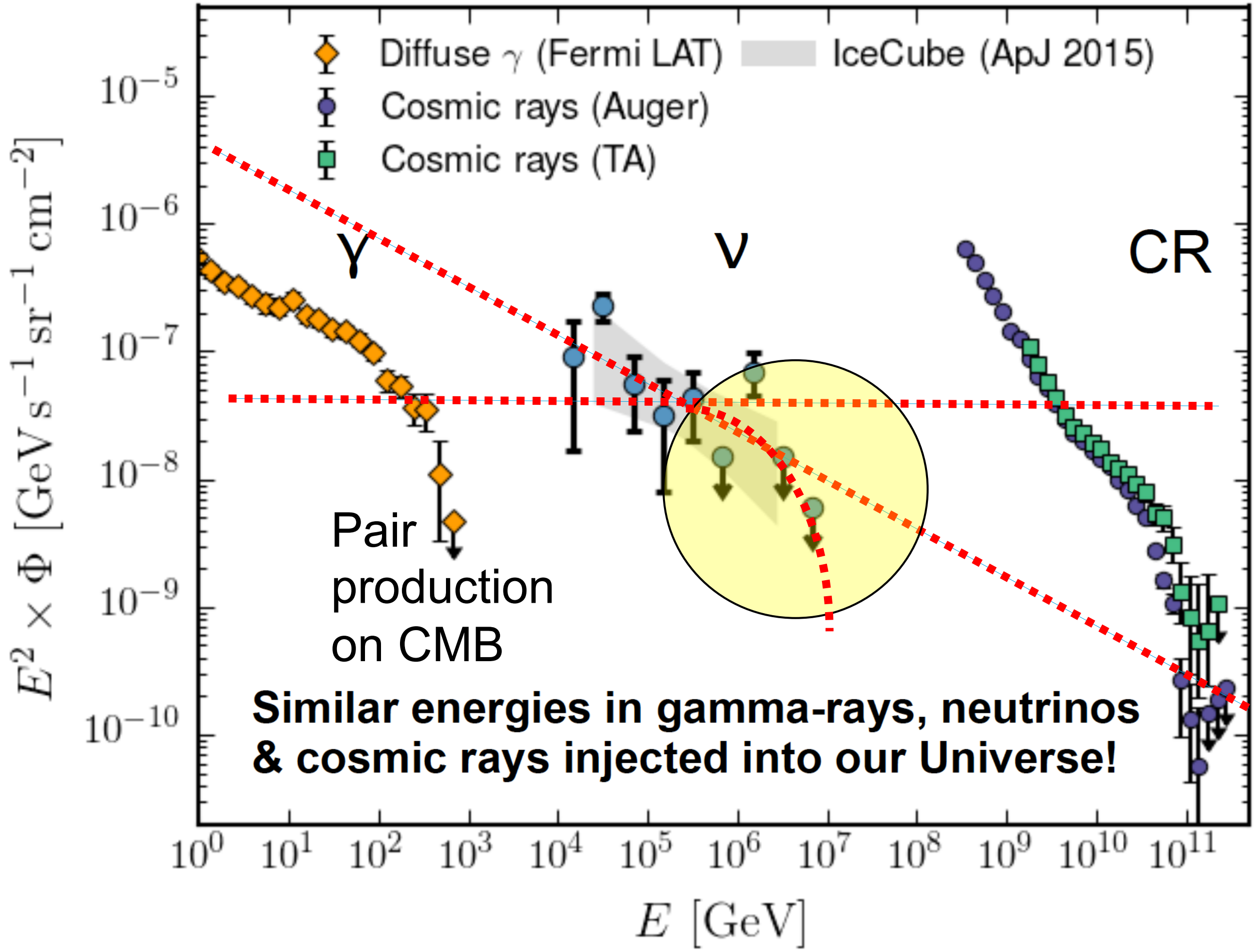
UHECR: Ultra-high energy cosmic rays

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}



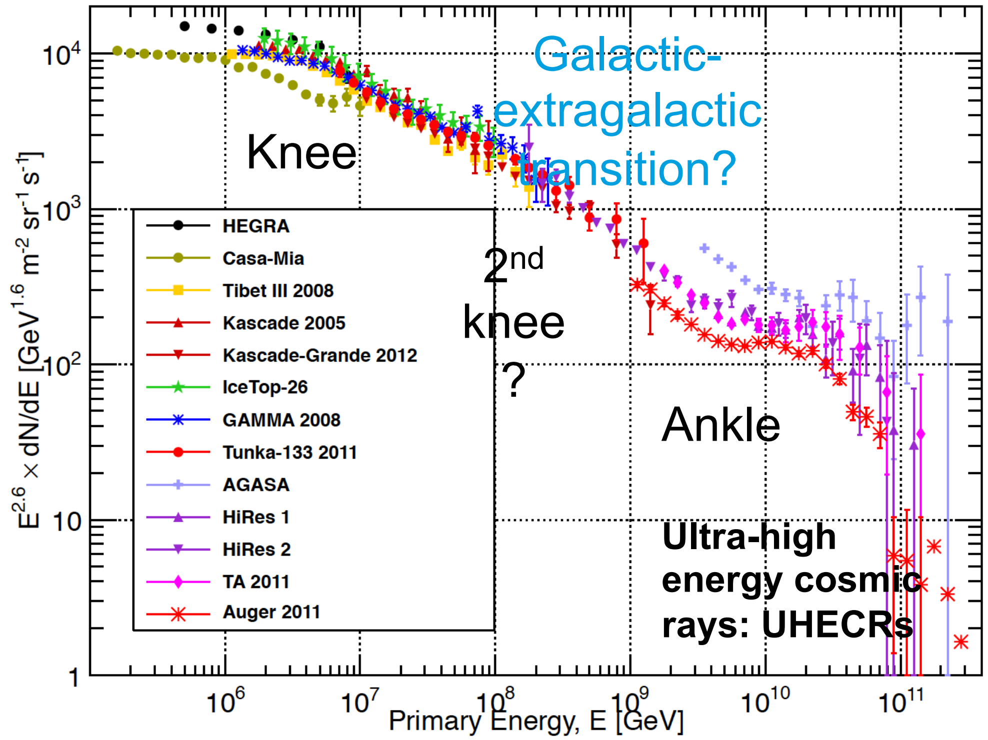
Similar energies in gamma-rays, neutrinos & cosmic rays injected into our Universe!

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

Lorentz force =
centrifugal force
➔ $E_{max} \sim Z\, c\, B\, R \sim Z$
(Peters cycle)



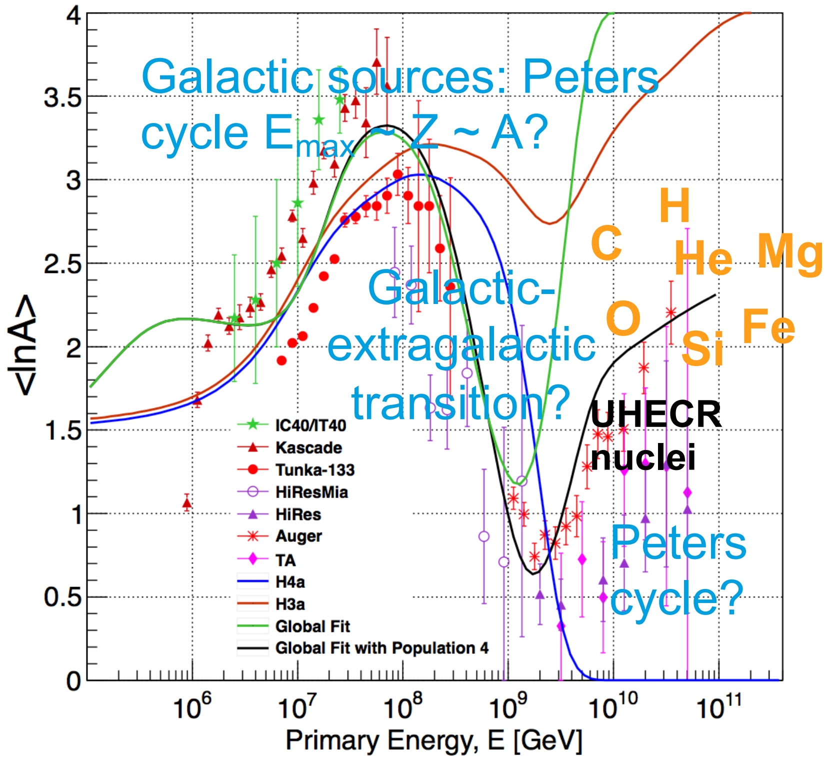
Knee

Galactic-extragalactic transition?

2nd knee ?

Ankle

Ultra-high energy cosmic rays: UHECRs



Galactic sources: Peters cycle $E_{max} \sim Z \sim A$?

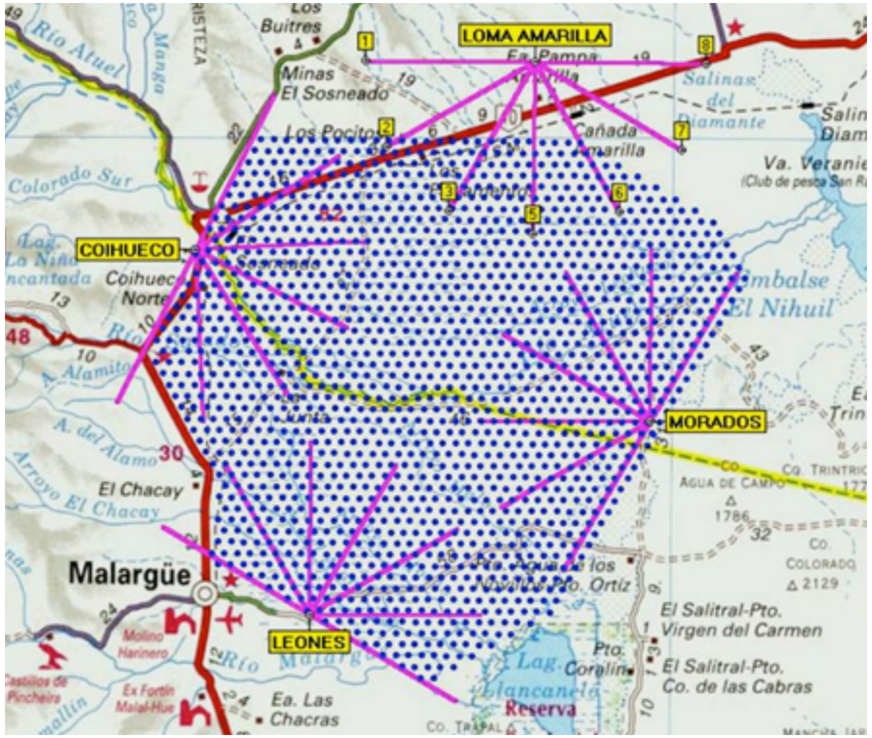
Galactic-extragalactic transition?

UHECR nuclei

Peters cycle?

Gaisser, Stanev, Tilav, 2013

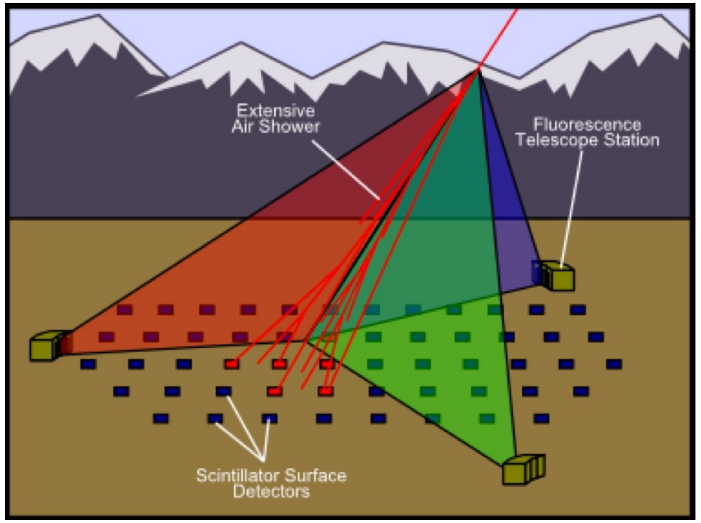
UHECR observatories

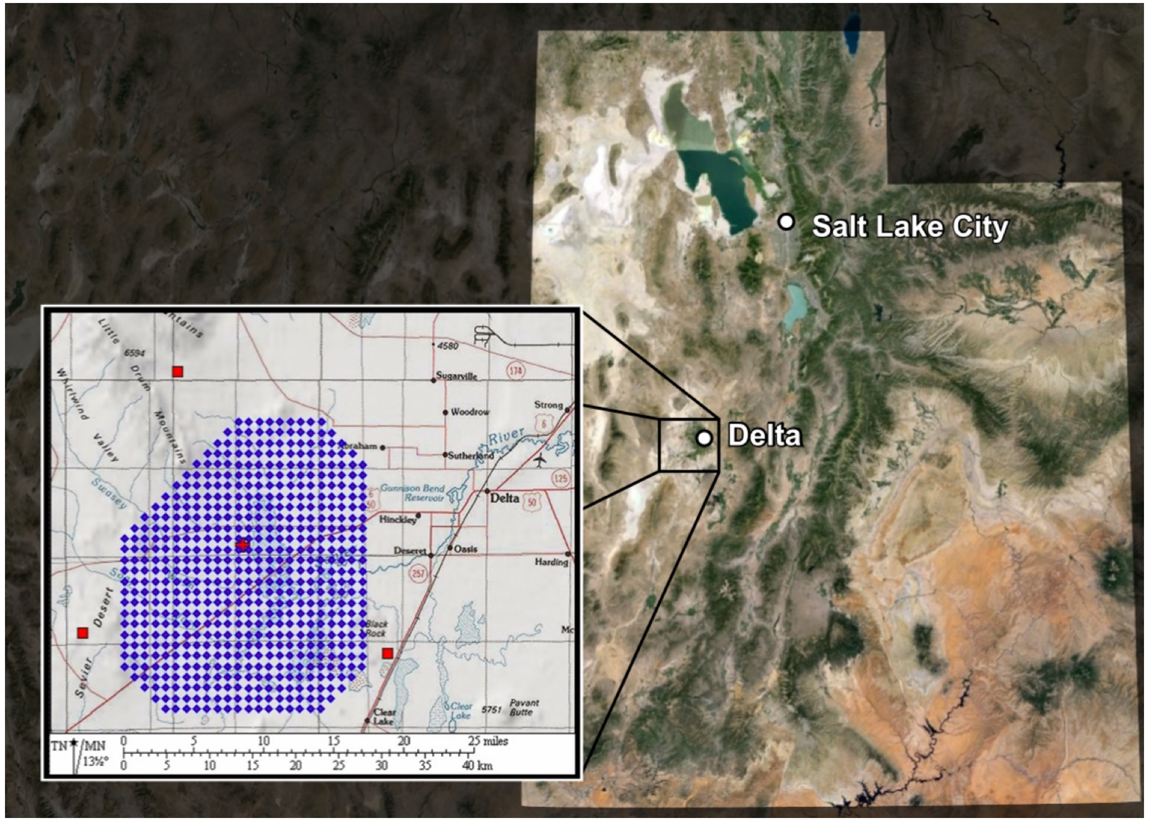


Auger

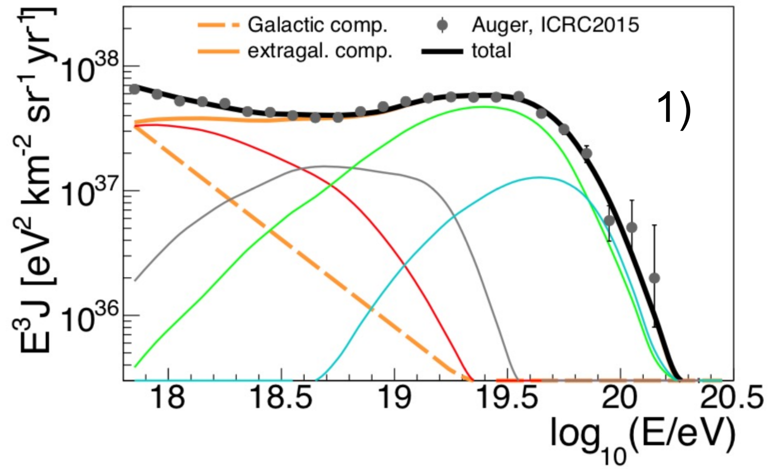
Observables:
1) Spectrum
2) Composition: $<X_{max}>$
3) Composition: $\sigma(X_{max})$

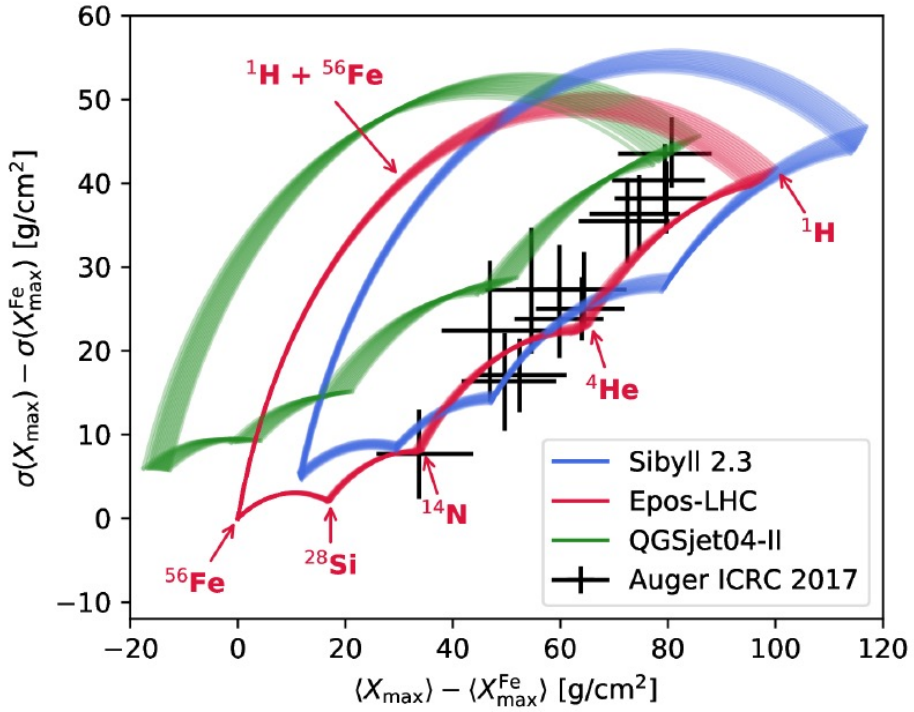
Telescope Array (TA)



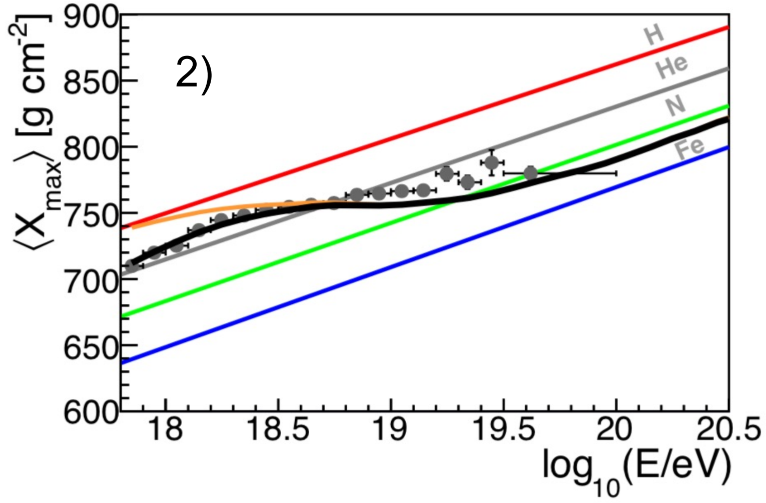


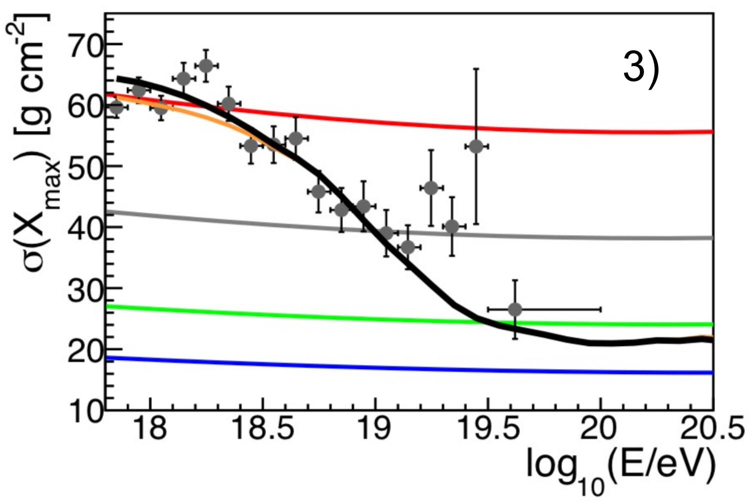
Description of observables (a typical example)





Data favor
pure composition!





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

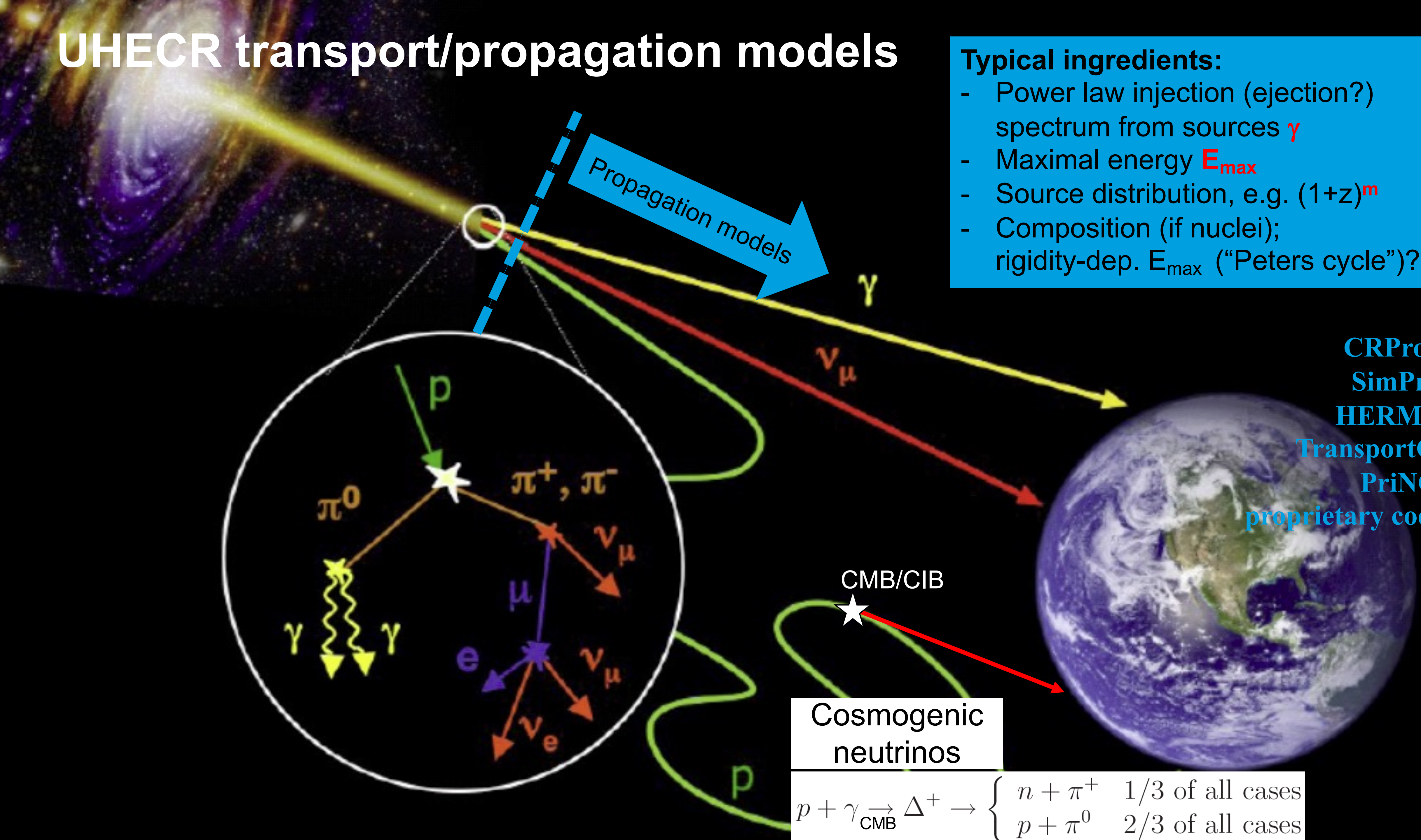
Biehl, Boncioli, Lunardini, WW, Sci. Rep. 8 (2018) 1; Upper right plot from PhD thesis Jonas Heinze, https://edoc.hu-berlin.de/handle/18452/22177

UHECR transport

… and the expectations for cosmogenic neutrinos

UHECR transport/propagation models

Typical ingredients:
- Power law injection (ejection?) spectrum from sources γ
- Maximal energy E_{max}
- Source distribution, e.g. $(1+z)^m$
- Composition (if nuclei); rigidity-dep. E_{max} (“Peters cycle”)?



CRPropa,
SimProp,
HERMES,
TransportCR,
PriNCE,
proprietary codes,
…

Cosmogenic neutrinos

$$p+\gamma \xrightarrow[\text{CMB}]{} \Delta^+ \to \begin{cases} n+\pi^+ & 1/3 \text{ of all cases} \\ p+\pi^0 & 2/3 \text{ of all cases} \end{cases}$$

Transport of UHECRs

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

$$\partial_t Y_i = -\partial_E(b_{\mathrm{ad}} Y_i) - \partial_E\left(b_{e^+e^-} Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i}(Y_j) + J_i$$

Adiabatic losses (expansion of Universe)

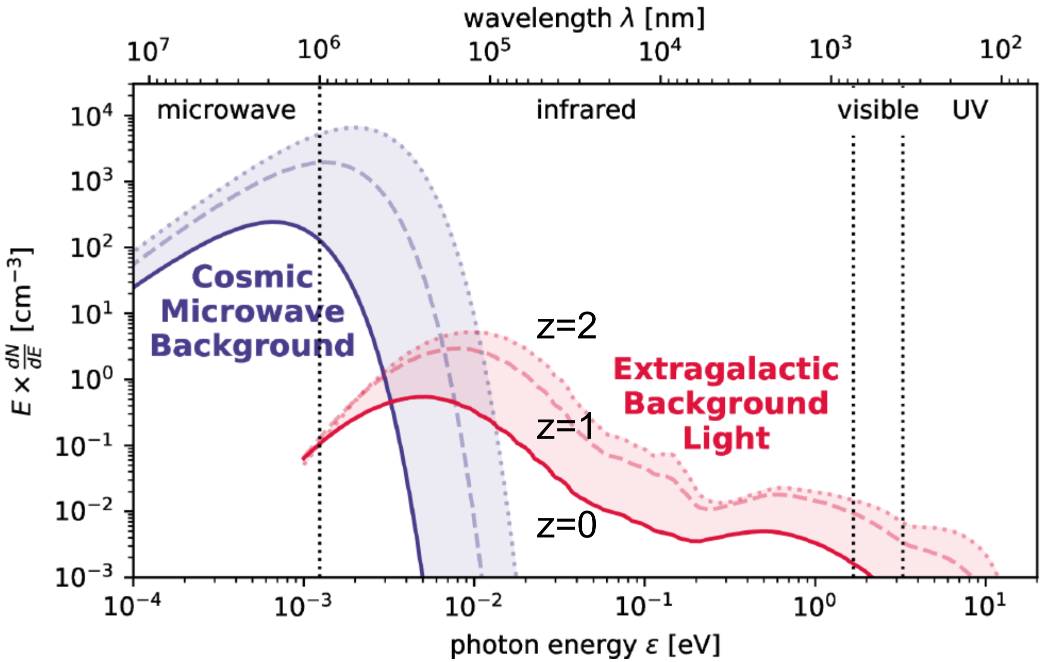
Pair production losses

Interactions (escape term)

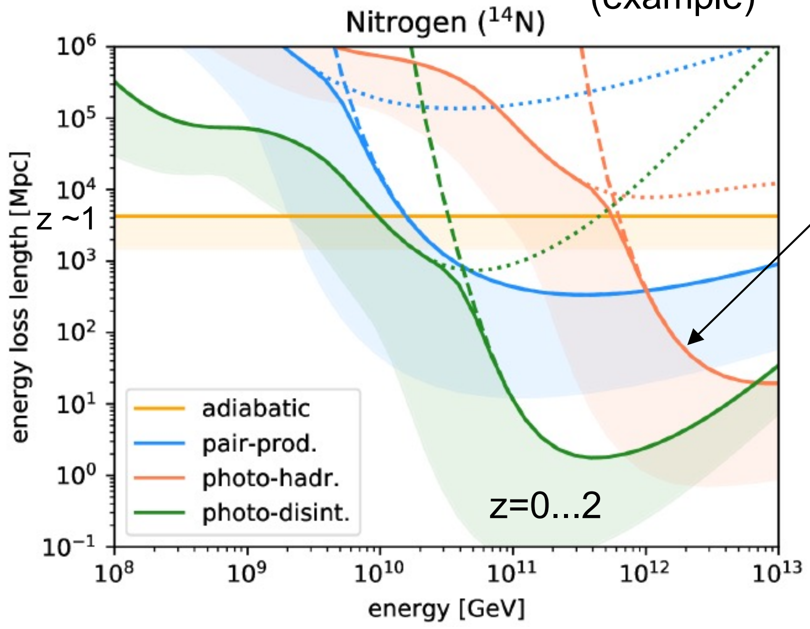
Injection (interactions)

Injection (sources)

Nuclei subject to disintegration. A nuclear cascade develops!



(example)



Neutrino production: photohadronic interactions

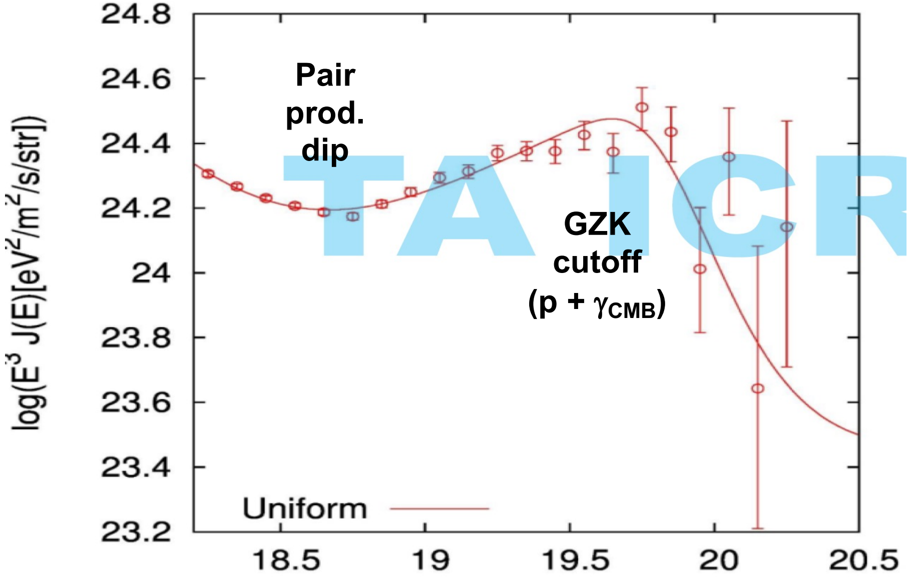
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

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

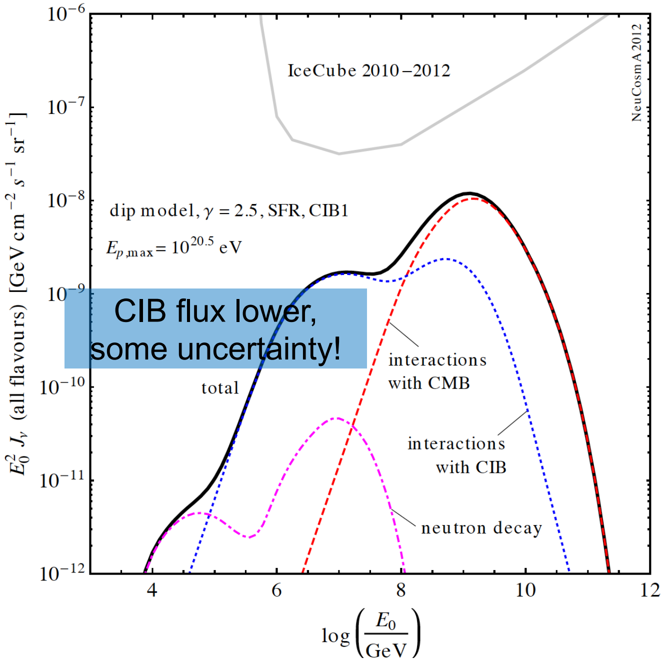
(observationally disfavored now!)



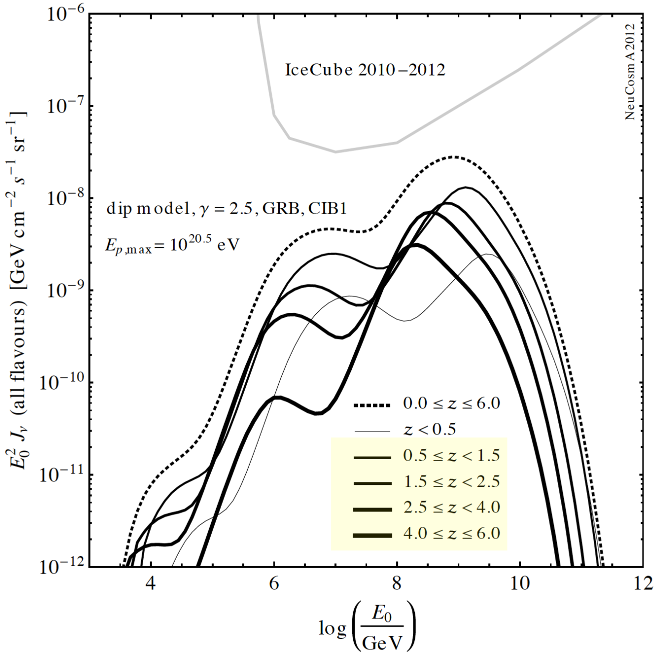
Jui @ ICRC 2015; talk by D. Ivanov

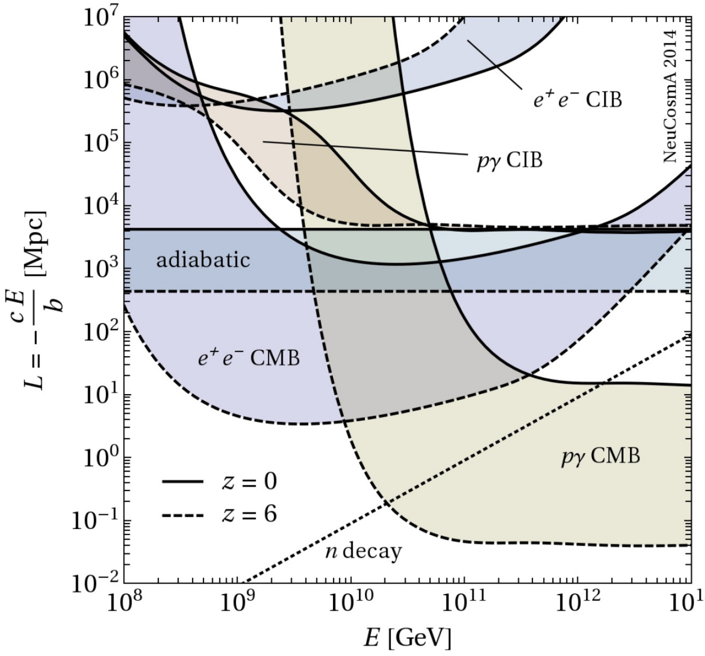
Soft spectra from sources.
Possibly hydrogen only.
Proton dip model
Berezinsky, Gazizov, Grigorieva, 2005

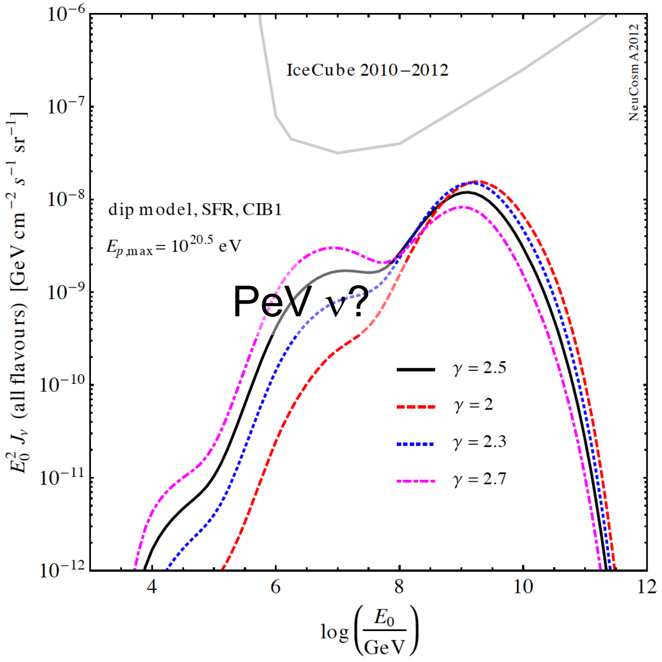
$E_{\gamma,0}$ [eV] ~ 0.01 $(1+z)^{-2}/E_{\nu,0}$ [EeV]



CIB flux lower, some uncertainty!







PeV ν?

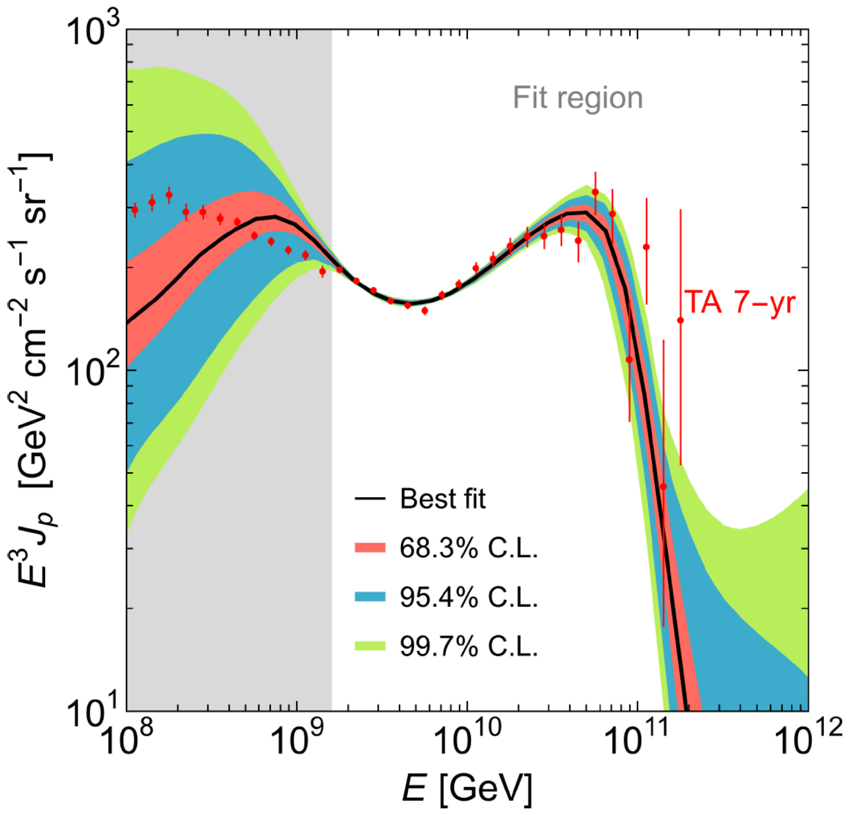
From: arXiv:1401.1820

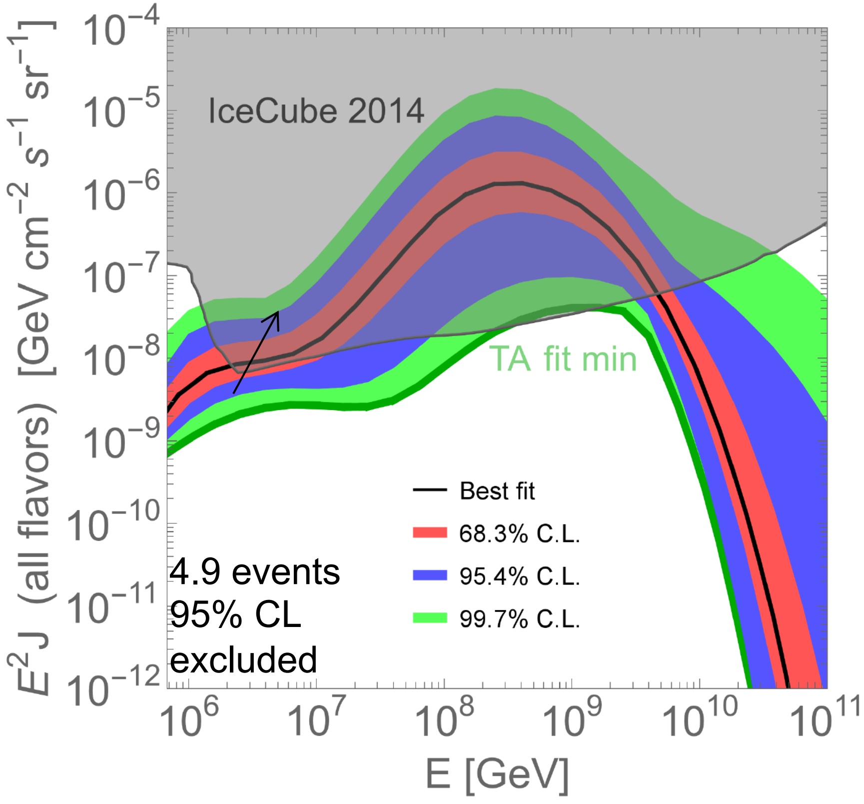
... and M. Bustamante

How about the proton dip model?

Composition fixed to protons, fit beyond ankle

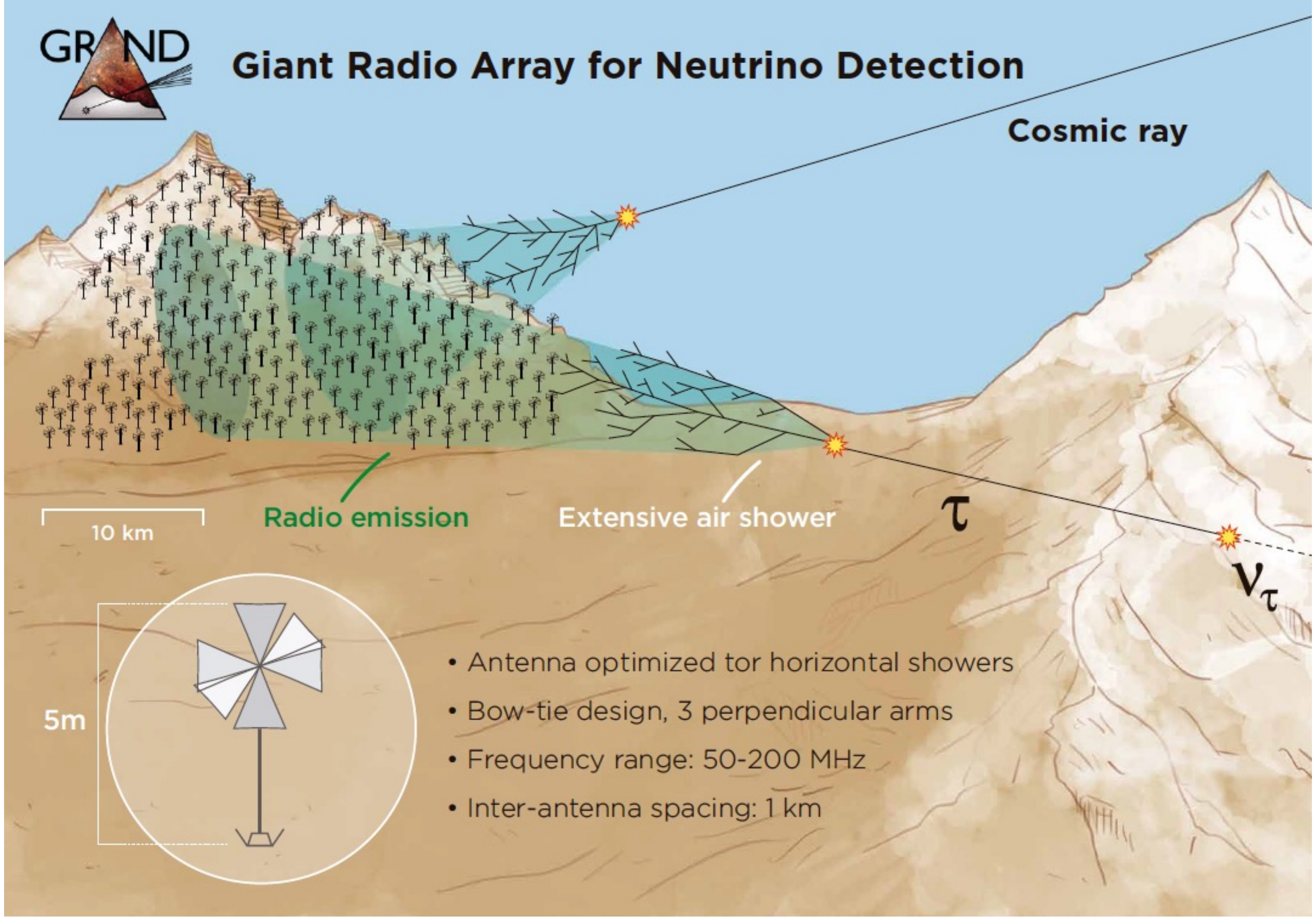
- 3D fit with fully marginalized parameters: TA 7-year meets IceCube 2014
  Heinze, Boncioli, Bustamante, Winter, Astrophysical Journal 825 (2016) 122



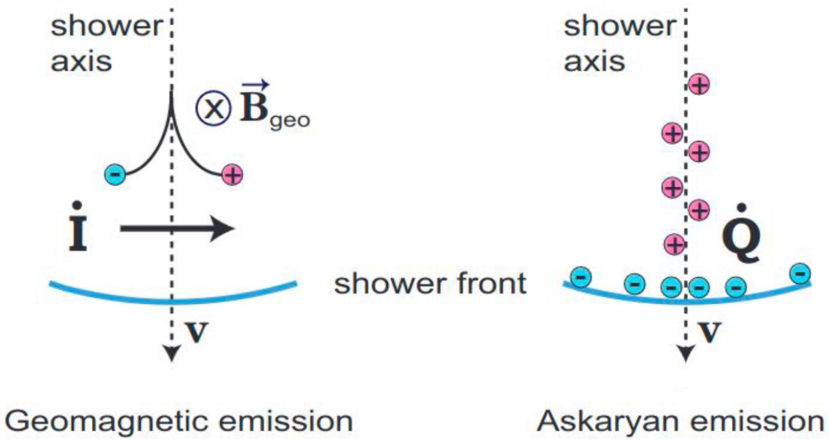


- Baseline interpretation: **The proton contribution must be constrained by cosmogenic neutrino flux!**

The future: Radio detection of cosmogenic neutrinos



- Antenna optimized tor horizontal showers
- Bow-tie design, 3 perpendicular arms
- Frequency range: 50-200 MHz
- Inter-antenna spacing: 1 km



Schröder, Nucl. & Part. Phys. Proc. (2017) 1

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

Another example: RNO-G

RNO-G

Radio Neutrino observatory - Greenland

STATION DEPLOYMENT

Warm deployment sled movable by snowmobile

...or people!

Shallow antennas deployed in trenches

Shallow:
LPDAs

Deep channels lowered by hand

Vpol:
Fat dipoles

Hpol:
Wide quad-slots

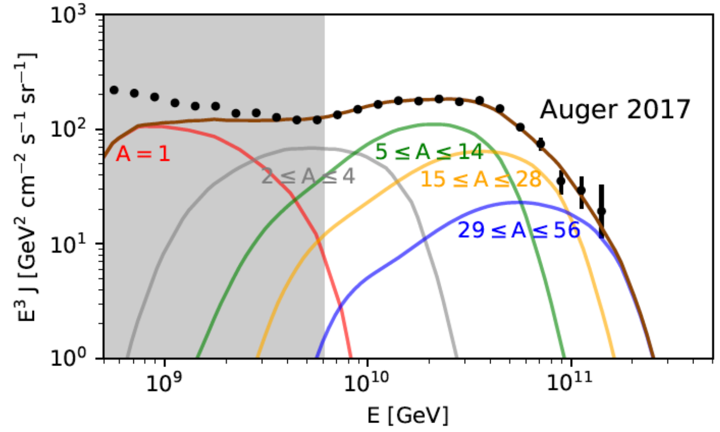
A. Vieregg @ TeVPA 2022

Baseline UHECR transport model (Peters cycle model)

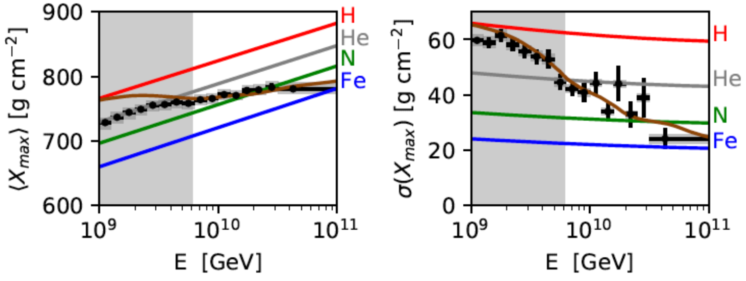
Parameters:

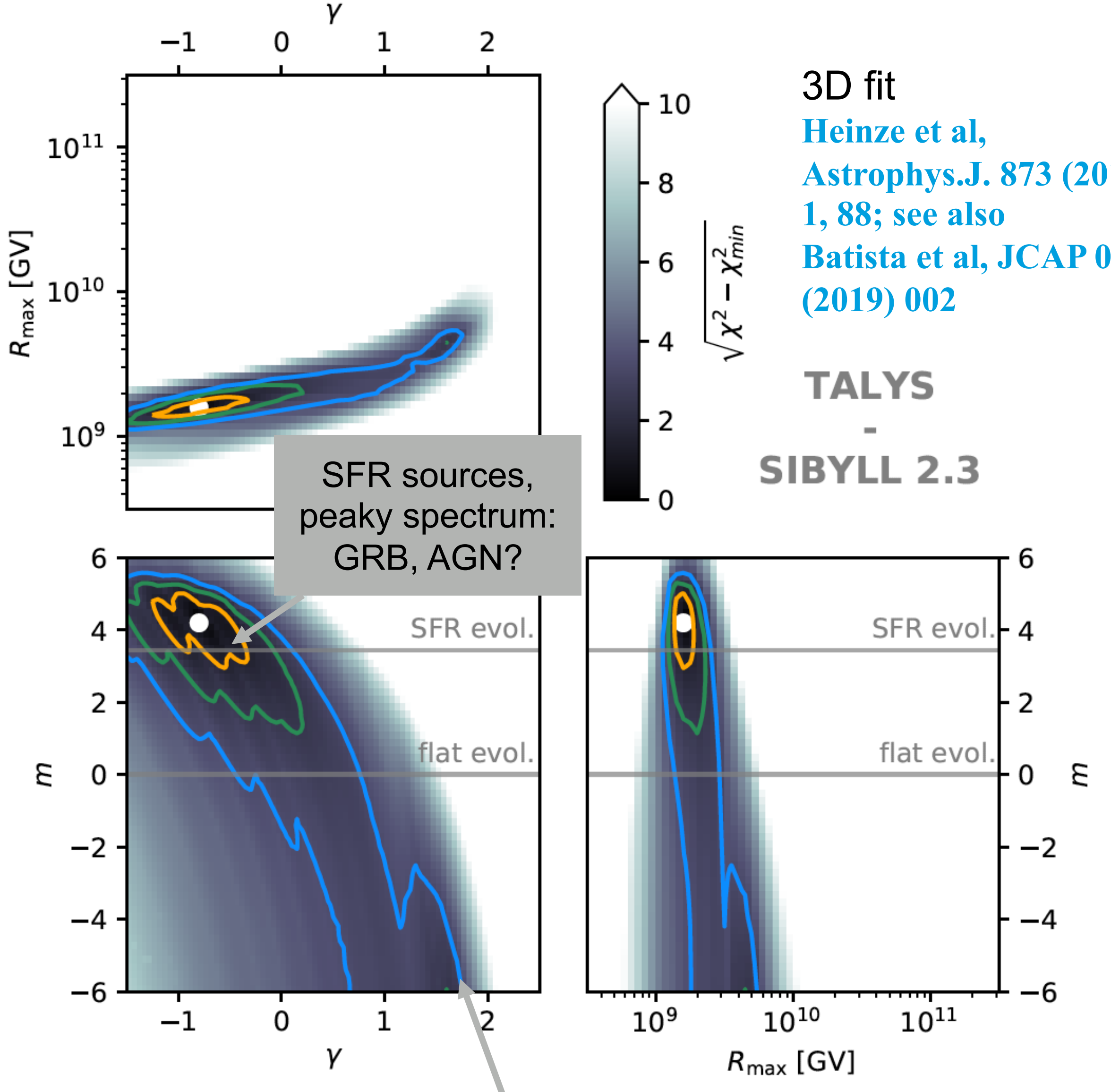
- γ: $E^{-\gamma}$ is the injection spectrum from sources
- R_{max}: Sources have $E_{max}=Z \times R_{max}$ (Peters cycle)
- **m**: Sources evolve $(1+z)^m$
  (SFR evolution: $m \sim 3.4$ for $z < 1$)
  (Recap: UHECRs do not travel farther than z~1)
- Free injection fractions for five mass groups:

Best-fit spectrum



Best-fit compositon





3D fit

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

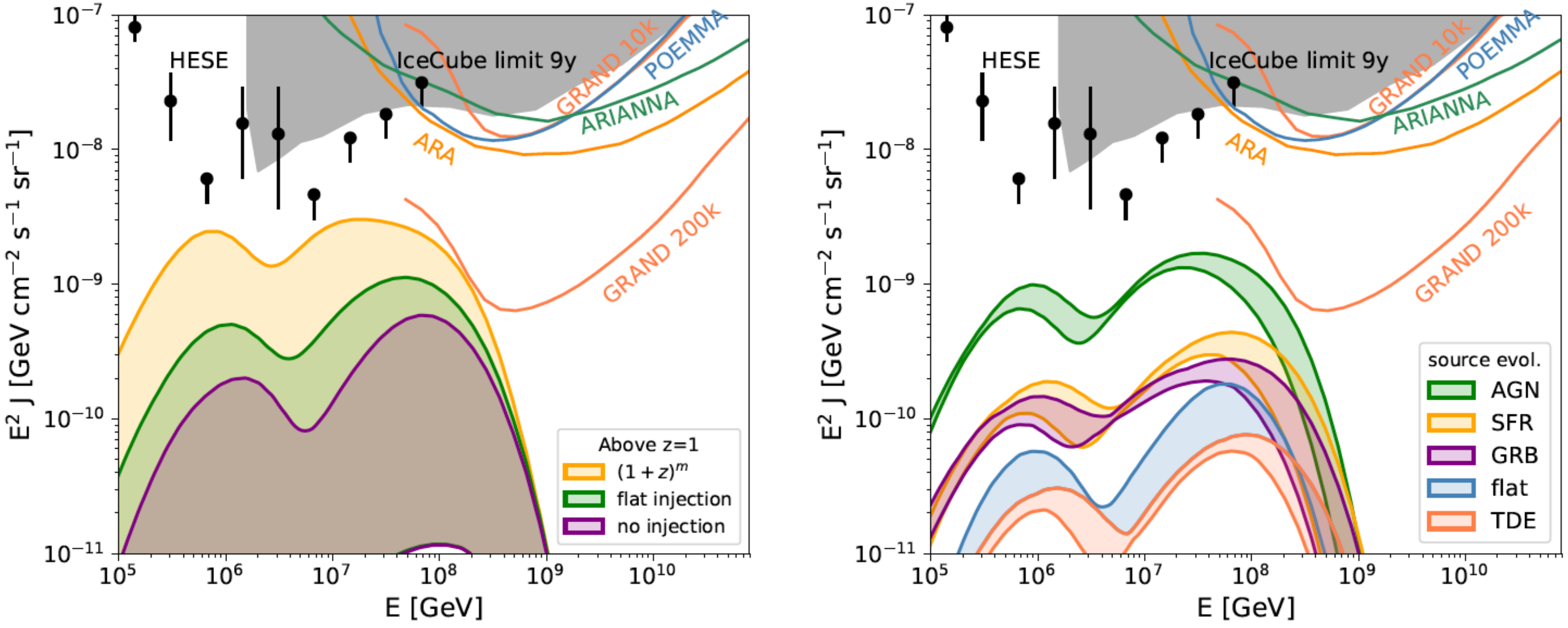
TALYS - SIBYLL 2.3

SFR sources, peaky spectrum: GRB, AGN?

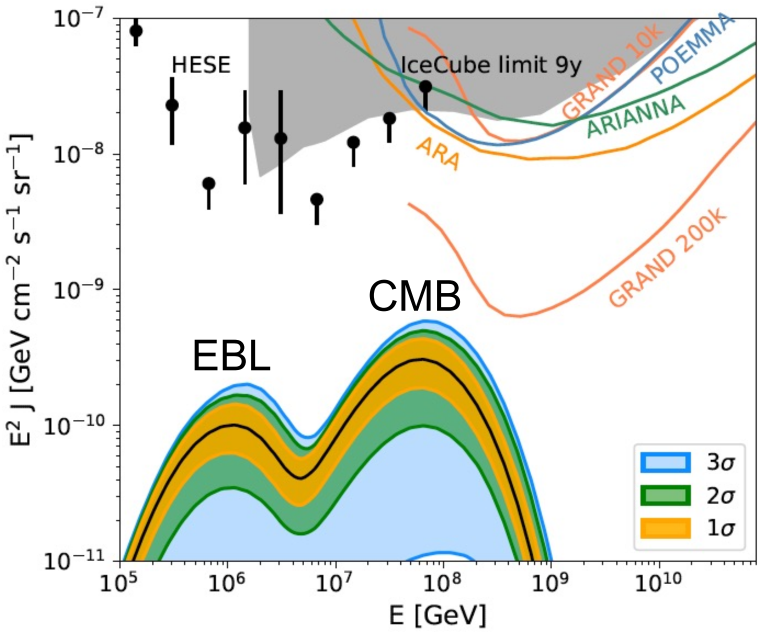
More typical acceleration spectrum, negative source evolution. TDEs?

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



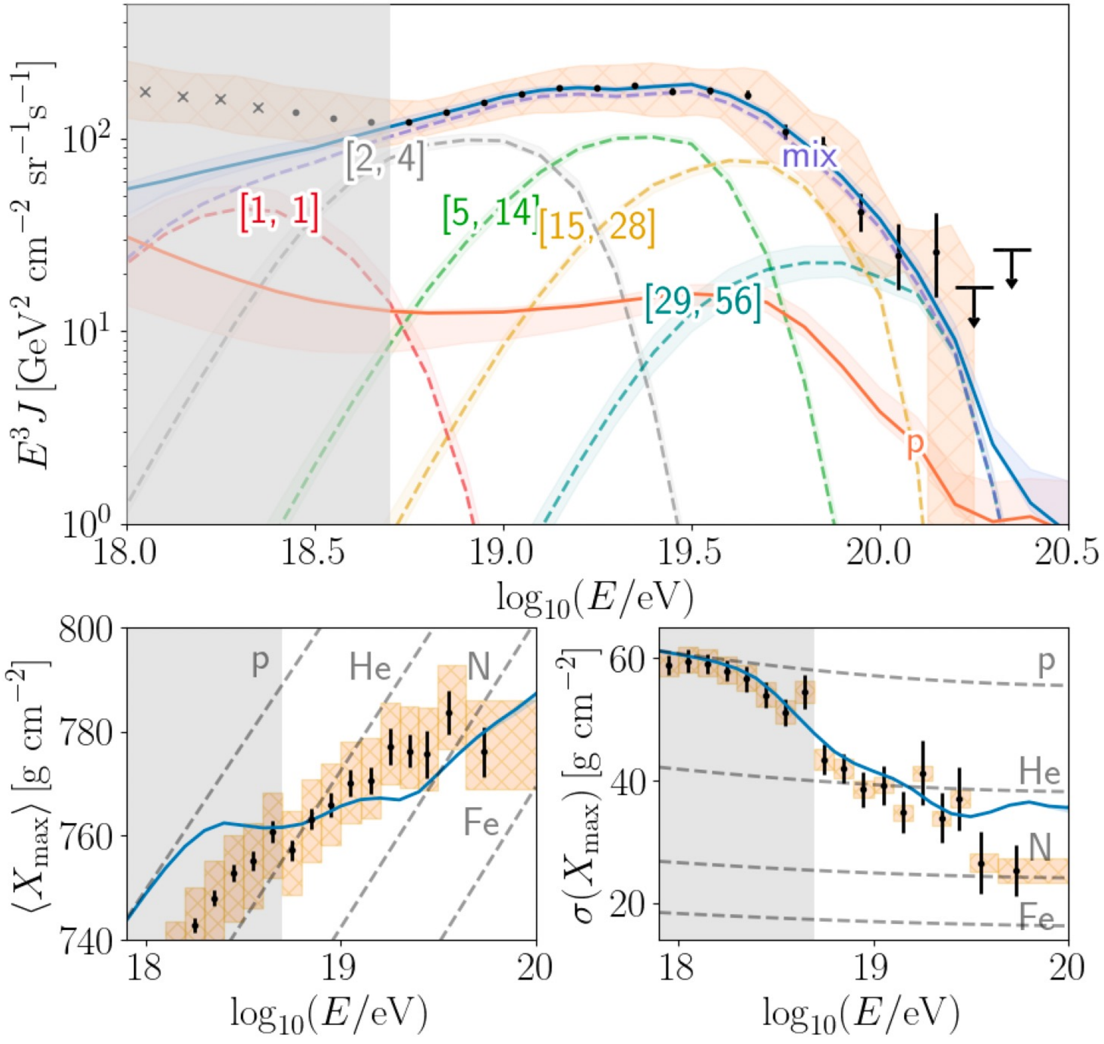
However:

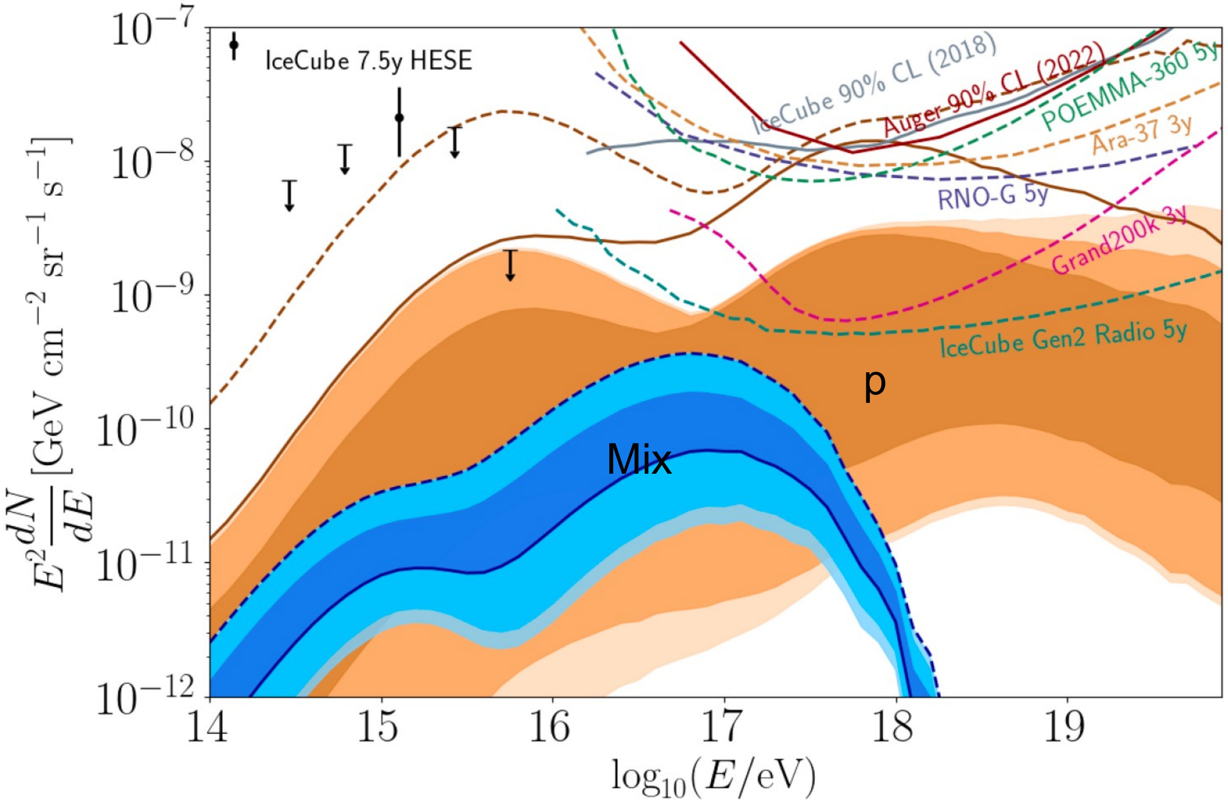
- UHECR data allow for a sub-dominant light component
- That potentially produces cosmogenic neutrinos efficiently

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

Cosmogenic neutrinos in two-component models

Here: Sub-leading "proton dip" model, which dominates the cosmogenic neutrino flux





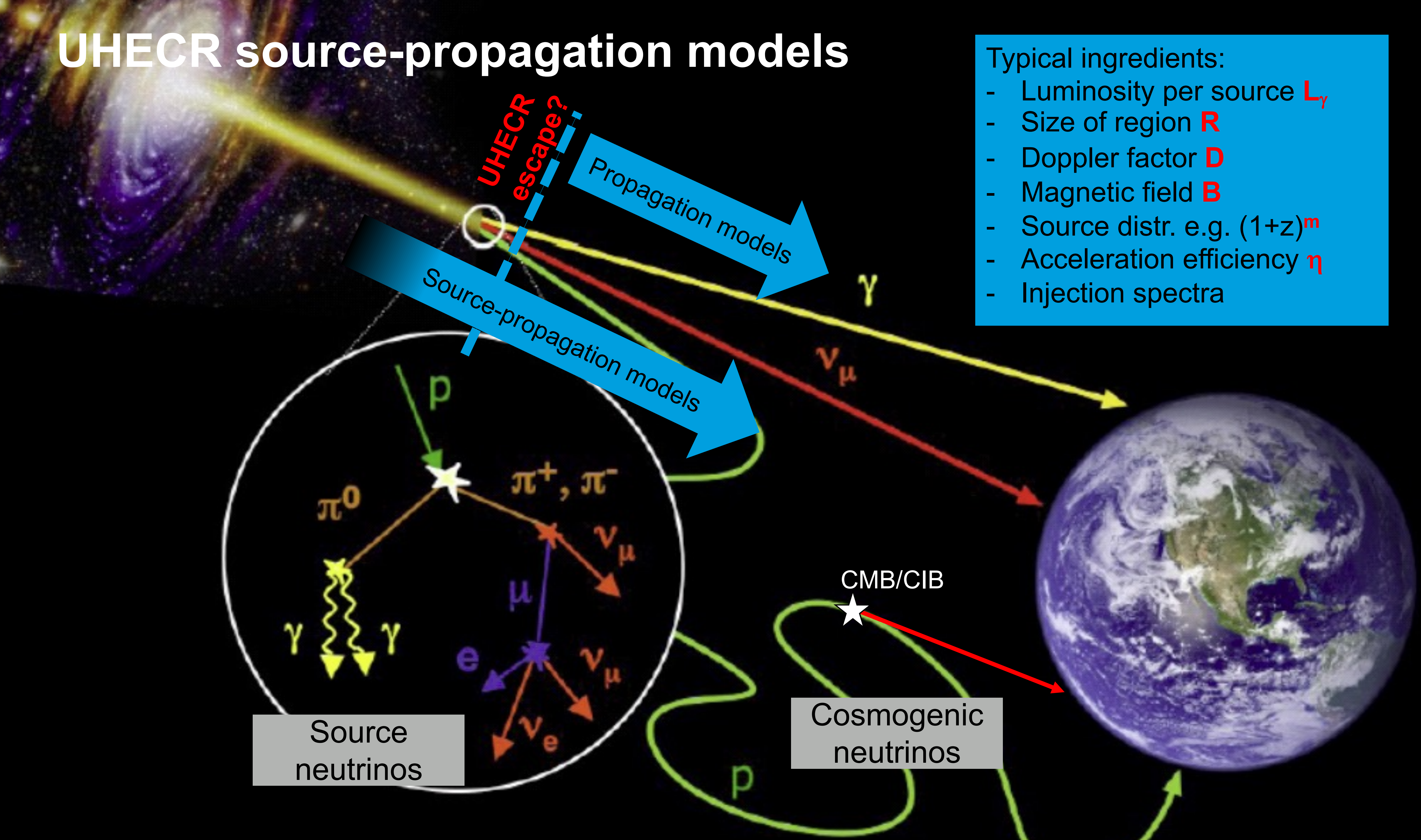
Ehlert, van Vliet, Oikonomou, Winter, arXiv:2304.07321; see also: Muzio et al. 2019+2023; Das et al. 2021

Source neutrinos from UHECR sources

Example: Gamma-Ray Bursts

UHECR source-propagation models

Typical ingredients:
- Luminosity per source **L_γ**
- Size of region **R**
- Doppler factor **D**
- Magnetic field **B**
- Source distr. e.g. $(1+z)^m$
- Acceleration efficiency η
- Injection spectra



Source neutrinos

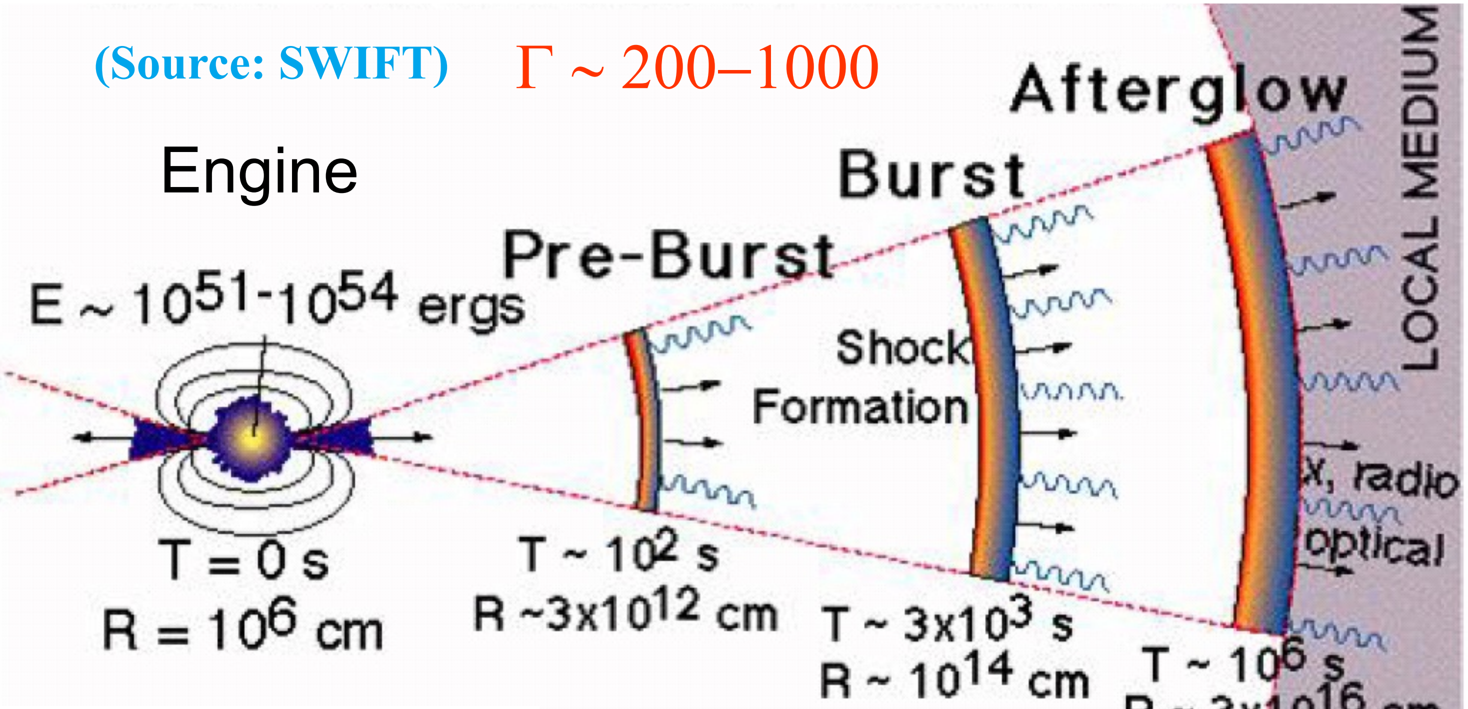
Cosmogenic neutrinos

GRB – different regions

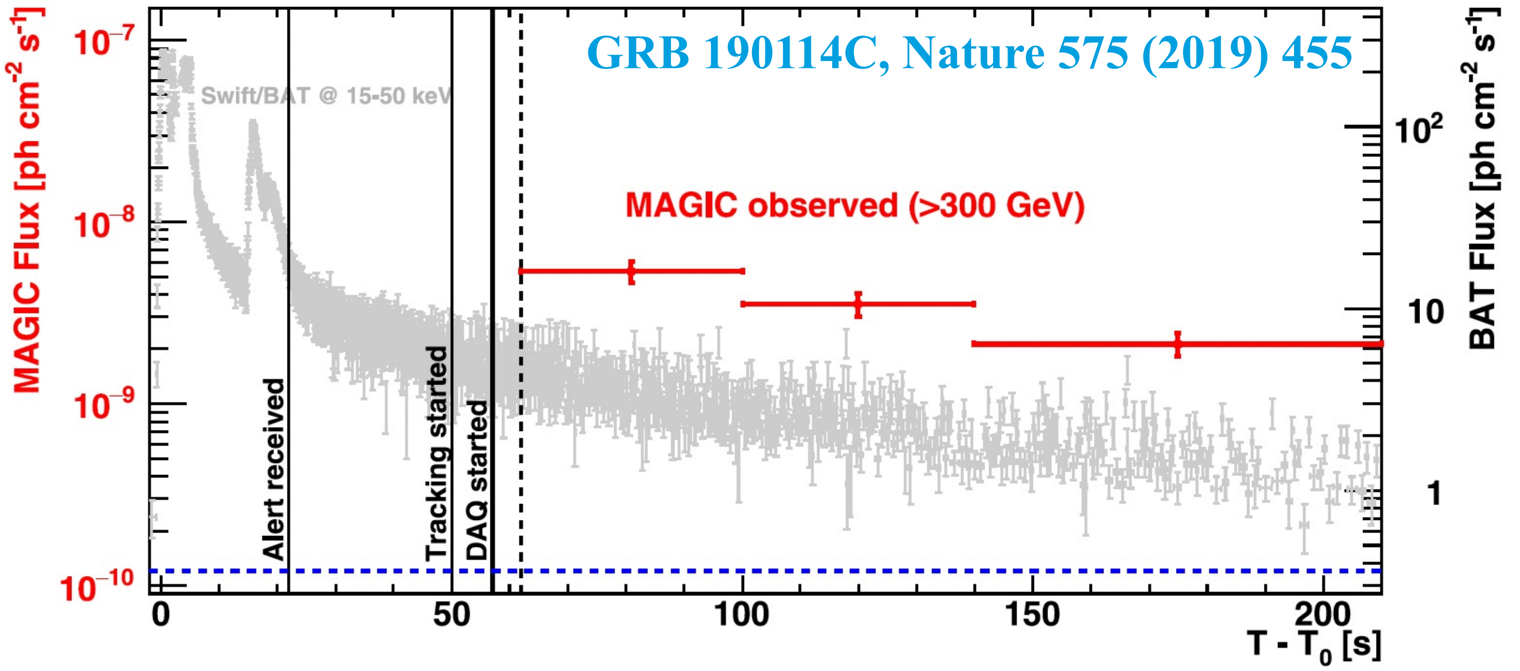
→ Talk Rudolph

Prompt phase

Afterglow


(Source: SWIFT)

$\Gamma \sim 200–1000$


GRB 190114C, Nature 575 (2019) 455

Focus on
prompt phase
Highest flux
⇨ Energetics

Pion production efficiency in GRBs

(redshift neglected
for simplicity!
Primed quantities:
shock rest frame)

- Pion production efficiency f_π (~ 0.2 $\tau_{p\gamma}$) from photon energy density:

$$u'_\gamma \equiv \int \varepsilon' N'_\gamma(\varepsilon') \mathrm{d}\varepsilon' = \frac{L_\gamma}{4\pi c \Gamma^2 R^2}$$

$$f_\pi \propto \frac{c\, t'_{\mathrm{dyn}}}{\lambda'_{\mathrm{mfp}}} \sim c\, t'_{\mathrm{dyn}}\, \sigma_{p\gamma} \frac{u'_\gamma}{\hat{\epsilon}_\gamma/\Gamma}$$

Typical photon energy (where photon number density peaks): $\hat{\epsilon}_\gamma \sim \epsilon_{\gamma,\mathrm{br}}$ for spectra ϵ^{-1} or harder below break
(not achievable for synchrotron emission …)

$$f_\pi \propto \frac{t'_{\mathrm{dyn}}\, L_\gamma}{\hat{\epsilon}_\gamma\, R^2\, \Gamma} \sim \underbrace{\frac{L_\gamma\, t_v}{\hat{\epsilon}_\gamma\, R^2}}_{t'_{\mathrm{dyn}} \simeq \Gamma\, t_v} \sim \underbrace{\frac{L_\gamma}{\hat{\epsilon}_\gamma\, R\, \Gamma^2}}_{t'_{\mathrm{dyn}} \simeq R/\Gamma} \sim \underbrace{\frac{L_\gamma}{\hat{\epsilon}_\gamma\, \Gamma^4\, t_v}}_{R \propto \Gamma^2\, t_v}$$

Internal shock model
(multi-zone, discrete outflow).
Magnetic reconnection models
(two different scales)

Internal
shock model
(cont. outflow).
Photospheric
models?

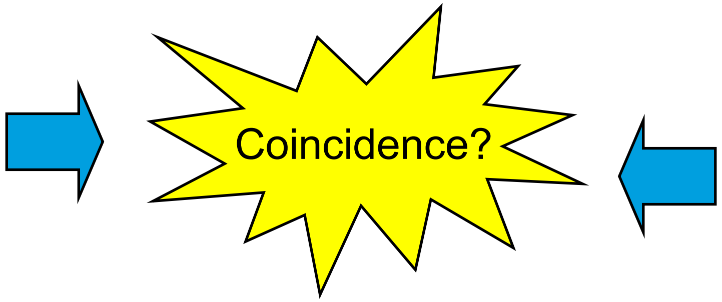
Internal
shock model
(one zone)

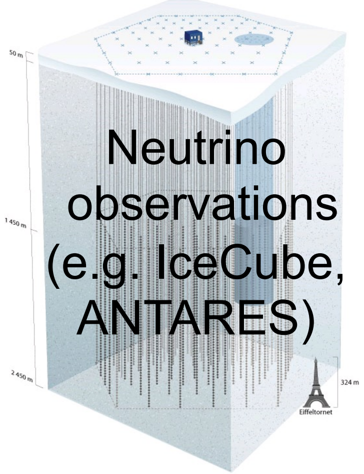
- **Production radius R and luminosity L_γ are the main control parameters for the particle interactions** [for fixed t_v] → Neutrino production, EM cascade from secondaries, nuclear disintegration, etc.

e.g. Guetta et al, 2003; He et al, 2012; Zhang, Kumar, 2013; Biehl et al, arXiv:1705.08909 (Sec. 2.5); Pitik et al, 2021

Multimessenger stacking bounds

Gamma-ray observations (e.g. Fermi, Swift, etc)

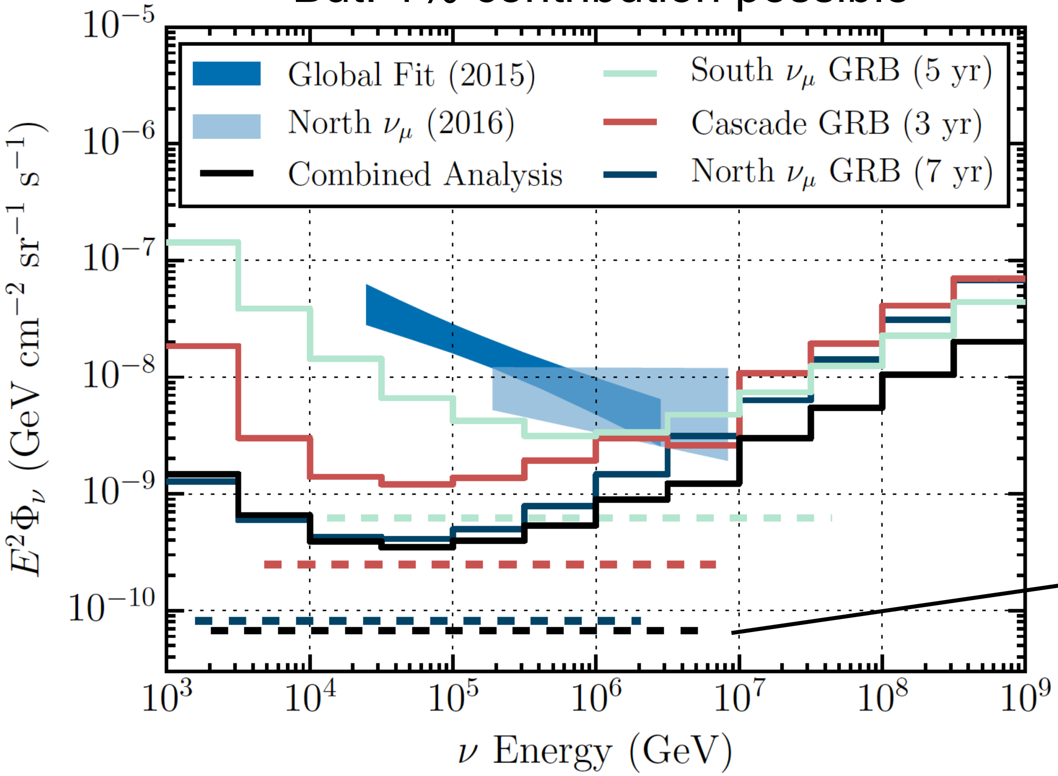


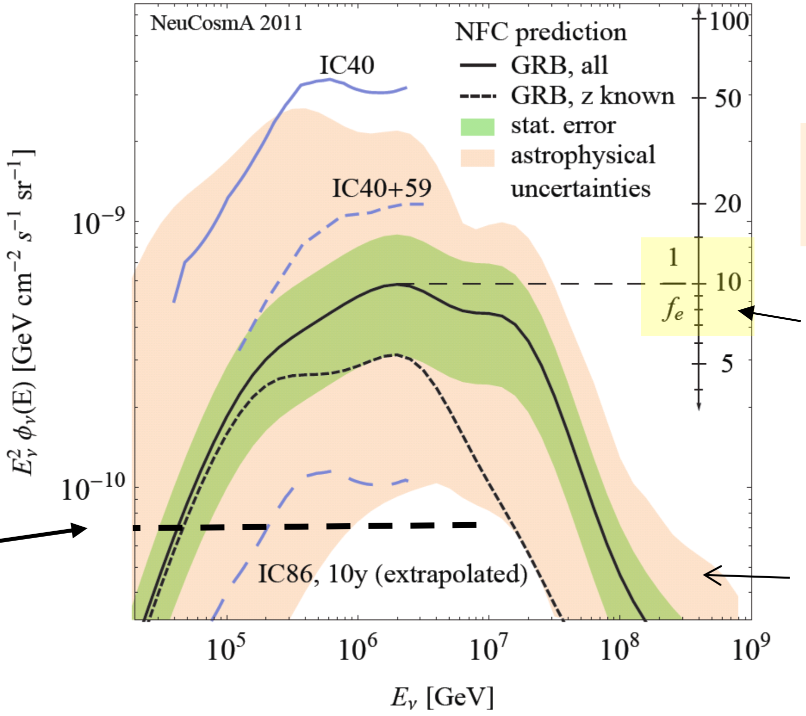


Neutrino observations (e.g. IceCube, ANTARES)

Use timing, directional and energy information to reduce backgrounds

Cannot power observed diffuse flux!
But: 1% contribution possible





Neutrino production
E_ν α E_γ x $1/f_e$ x f_π

Baryonic loading:
Ad hoc assumption (estimate from UHECRs)

Uncertainty from geometry estimators (→ pion prod. efficiency f_π)

IceCube, Nature 484 (2012) 351;
Fig. from update: ApJ 843 (2017) 112

Hümmer et al PRL 108 (2012) 231101;
Waxman, Bahcall, 1997; Guetta et al, 2003; He et al, 2012

The Waxman-Bahcall paradigm and possible interpretations

- Required ejected UHECR energy per transient event to power UHECRs:

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

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

Required energy output per source

Fit to UHECR data

Source density

Baryonic loading ~10 if E_γ ~10^{53} erg and about 10% in UHECR range + efficient escape?

Possible interpretation of non-observation of neutrinos:

- The one zone model is an over-simplification. **Different messengers come from different regions.**
- The parameters of the UHECR-emitting GRBs are very different.
  Do only very energetic GRBs accelerate UHECRs? How about low-luminosity GRBs?
- The UHECR acceleration takes place in very different zones, e.g. in magnetic reconnection areas (large R), in the afterglow etc, where the neutrino production is less efficient
- The baryonic loading is wrong. What do we expect from/need for UHECR data?
  What is allowed from hadronic signatures in the electromagnetic spectrum?
- GRBs simply do not accelerate/power the UHECRs

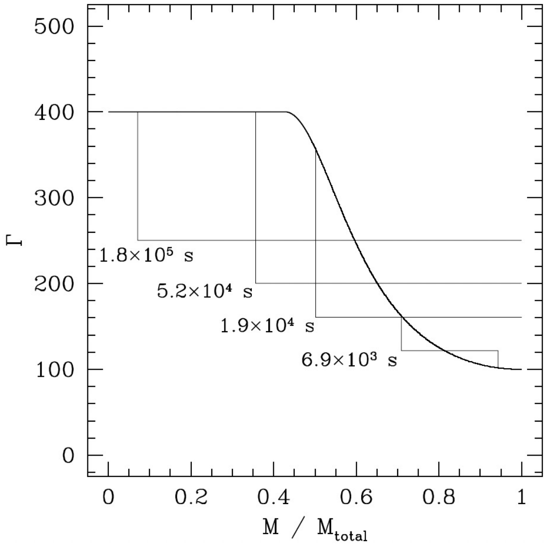
Multi-zone models for the prompt phase emission

Outflow models

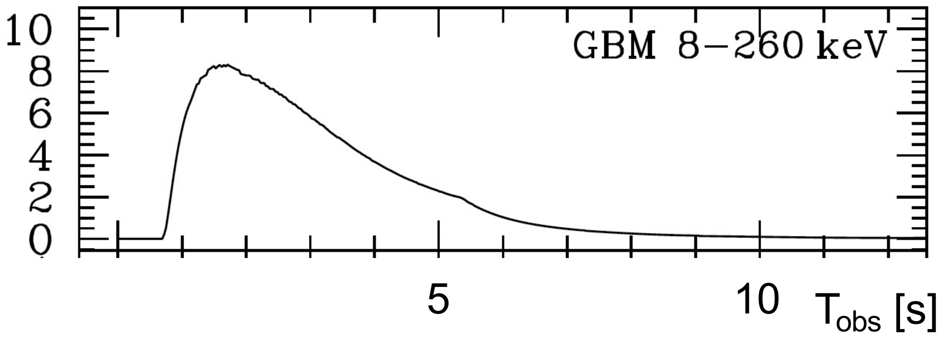
Applied to internal shocks

One zone approximation:
$t_v \sim l_m/c$ (variability timescale)
$R_C \sim \Gamma^2 d$ (distance to catch up)
Often: $d \sim l \rightarrow \mathbf{R_c \sim c\, \Gamma^2\, t_v}$

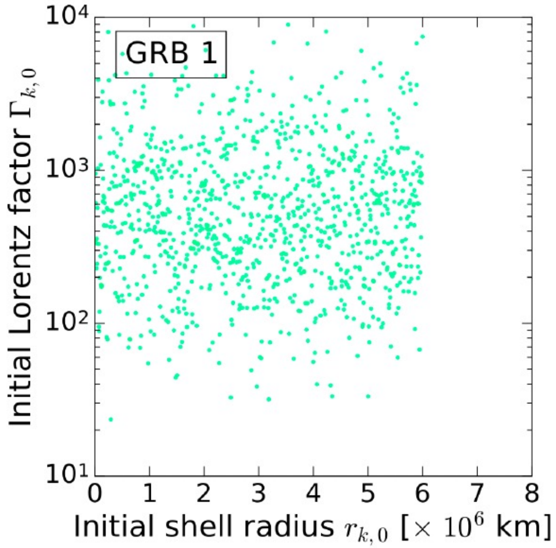
Continuous outflow: $t'_{dyn}=R_c/(c\,\Gamma)$

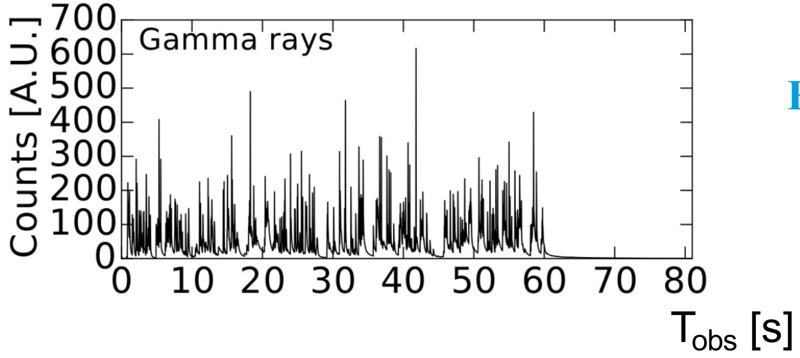


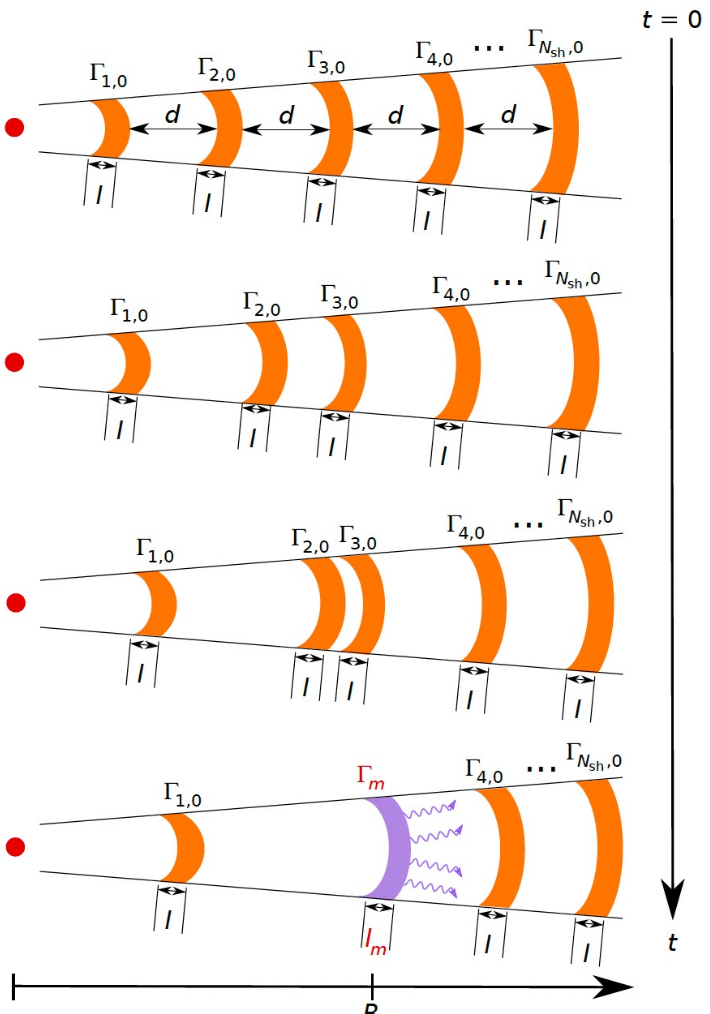
From: Bosnjak, Daigne, Dubus, A&A 498 (2009) 3



Discrete outflow: $t'_{dyn}=\Gamma\, l_m/c$







From: Bustamante, Heinze, Murase, Winter, ApJ 837 (2017) 33; Bustamante, Baerwald, Murase, Winter, Nature Commun. 6 (2015) 6783

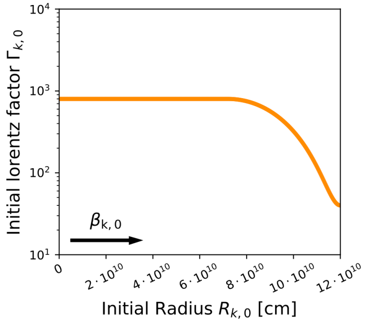
A unified engine model with free injection compositions

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

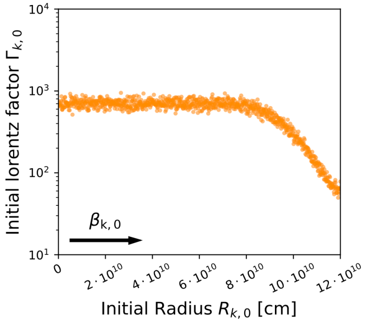
Model description

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

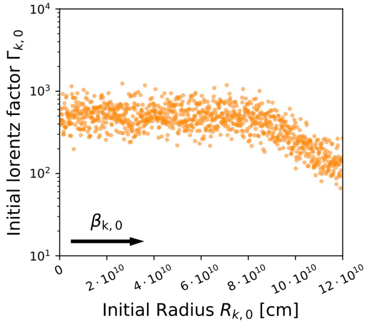
SR-0S
Strong (engine) ramp-up,
no stochasticity



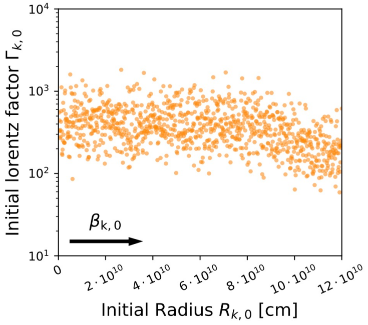
SR-LS
Strong (engine) ramp-up,
low stochasticity



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



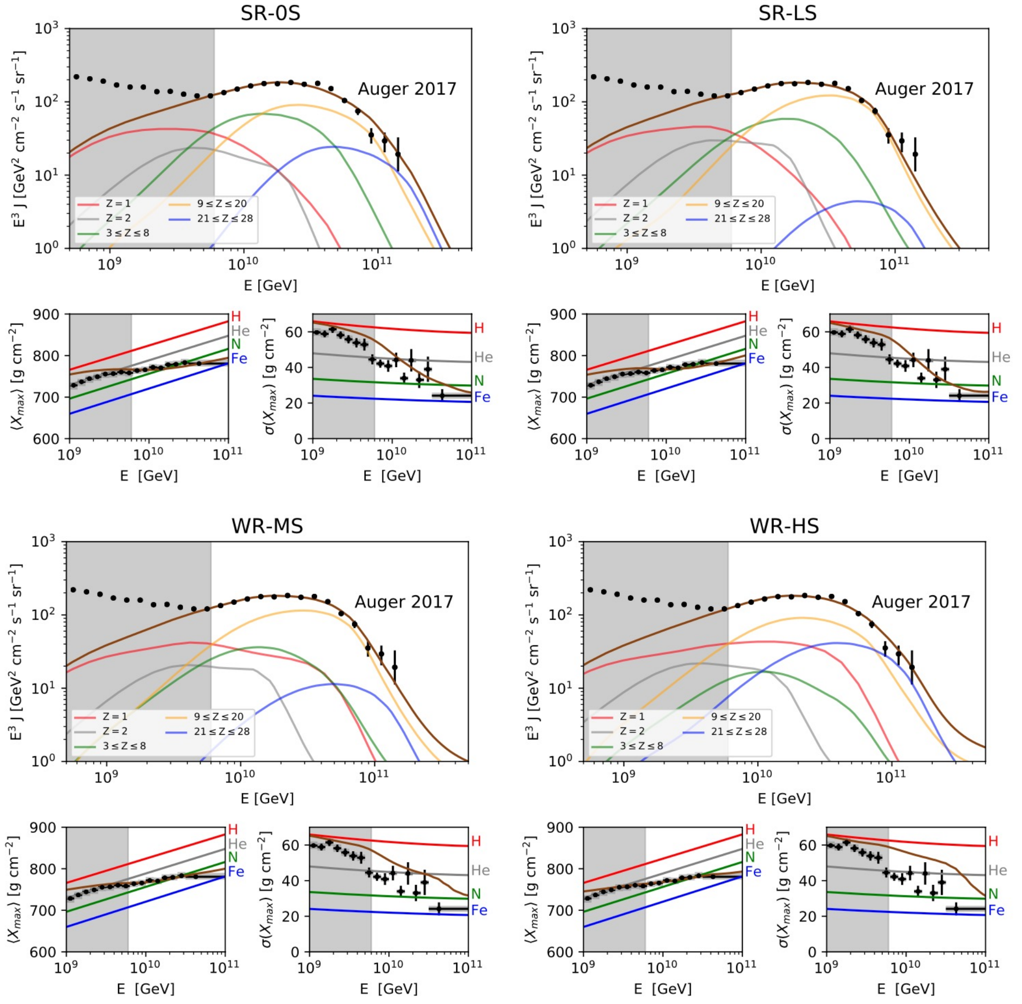
WR-HS
Weak (engine) ramp-up,
high stochasticity



Describes UHECR data over a large range of parameters!

(systematically studied)

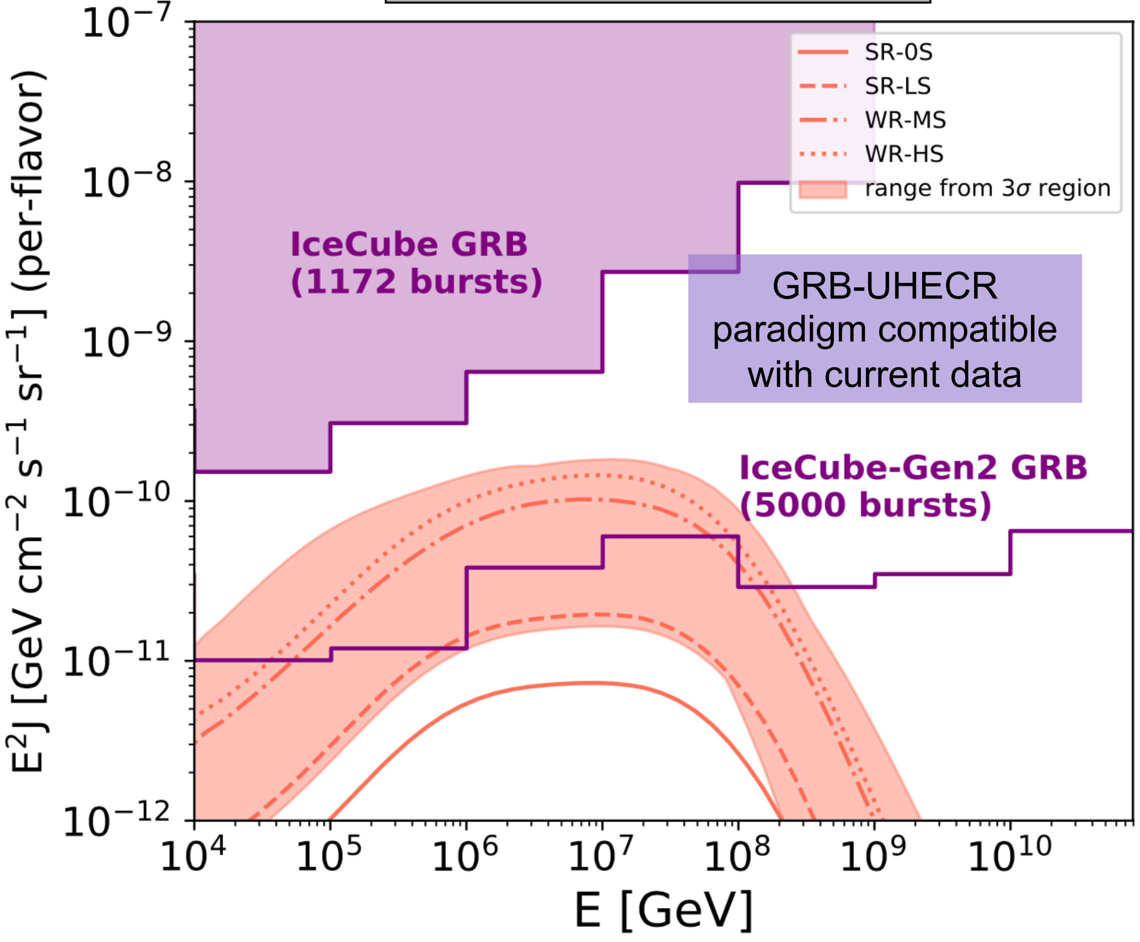
Description of UHECR data



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

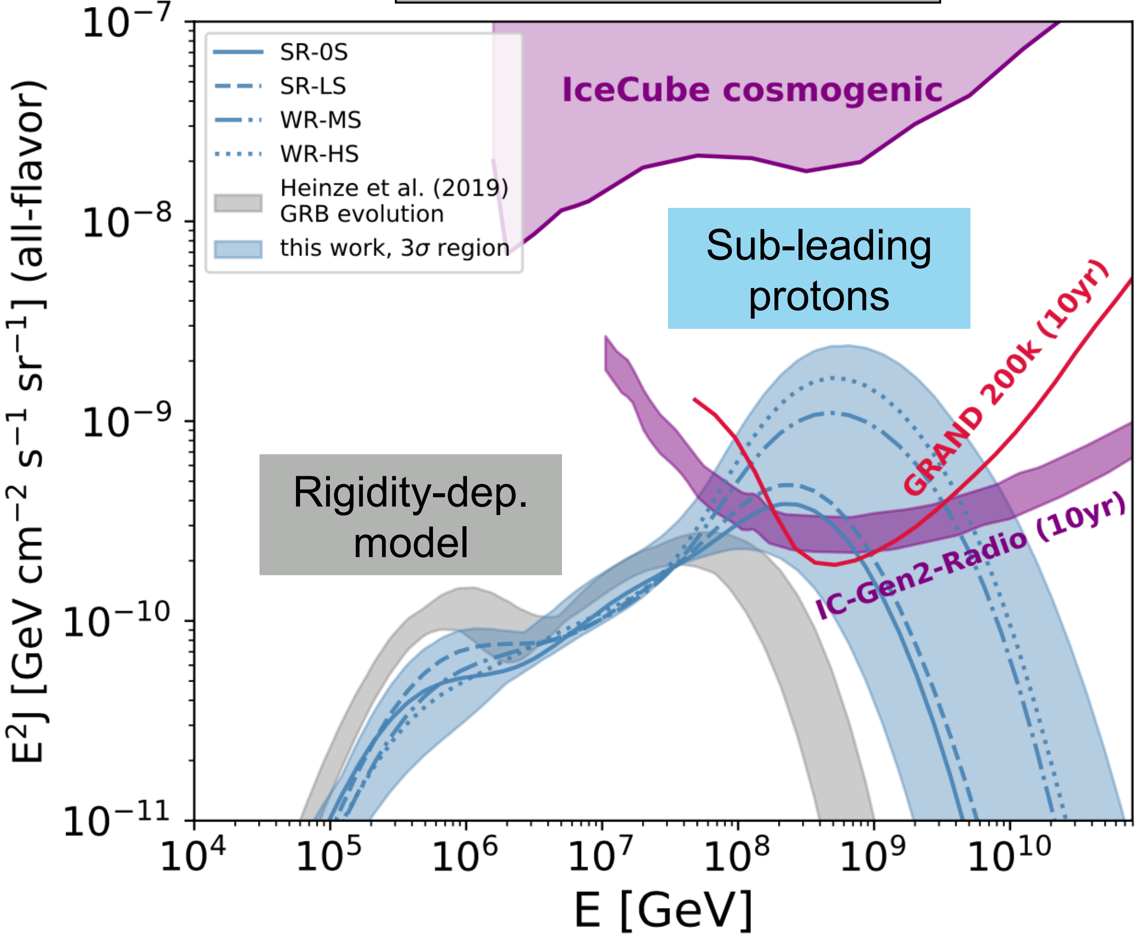
Inferred neutrino fluxes from the parameter space scan

Source neutrinos



GRB-UHECR paradigm compatible with current data

Cosmogenic neutrinos



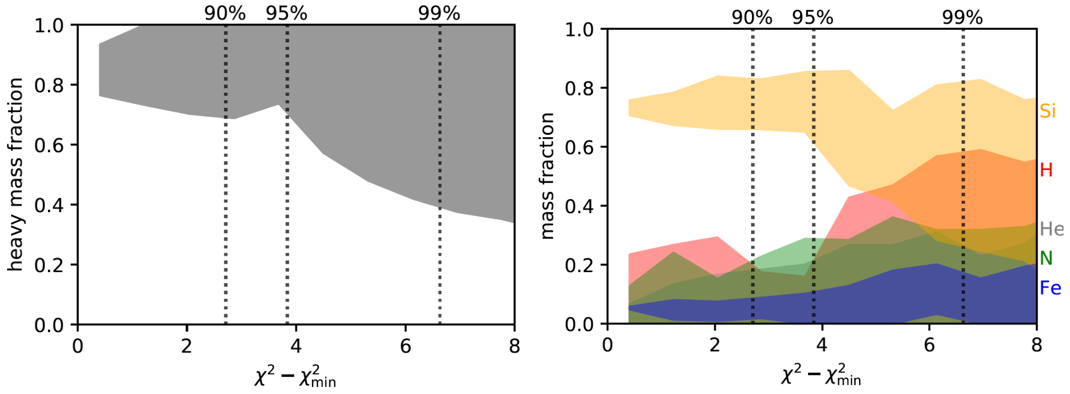
Sub-leading protons

Rigidity-dep. model

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

Interpretation of the results

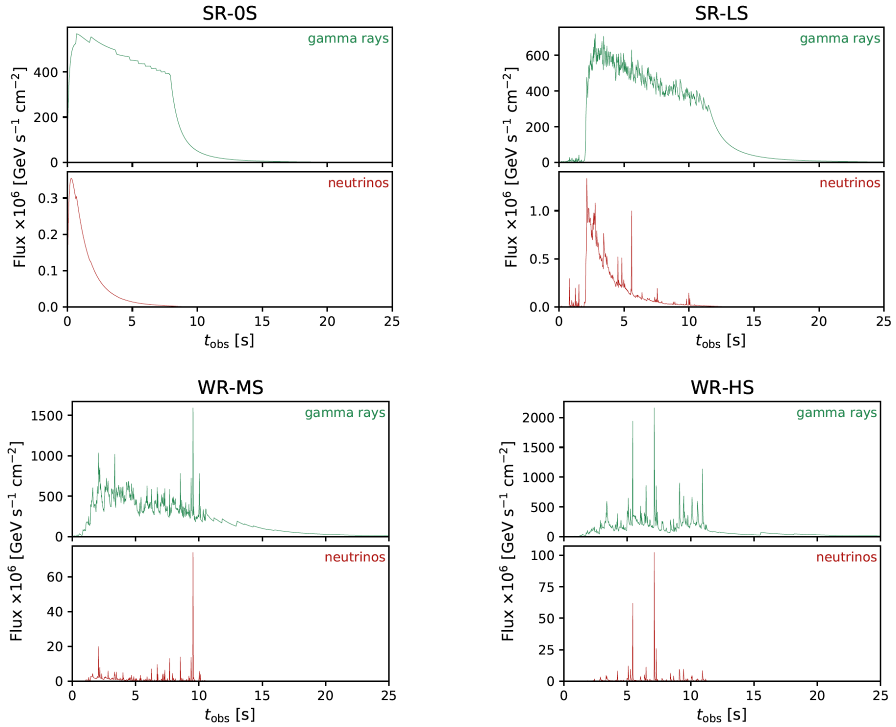
- The required injection compositon is derived: more that 70% heavy (N+Si+Fe) at the 95% CL



- Self-consistent energy budget requires kinetic energies larger than 10^{55} erg – **perhaps 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
$E^{\rm esc}_{\rm UHECR}$ (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
$E^{\rm src}_{\rm CR}$ (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
$E^{\rm src}_{\rm UHECR}$ (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
$E_{\rm kin,init}$ (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
Dissipation efficiency $\epsilon_{\rm diss}$	0.28	0.22	0.13	0.14
Baryonic loading $1/f_e$	80.1	67.1	59.5	108.4

- Light curves may be used as engine discriminator

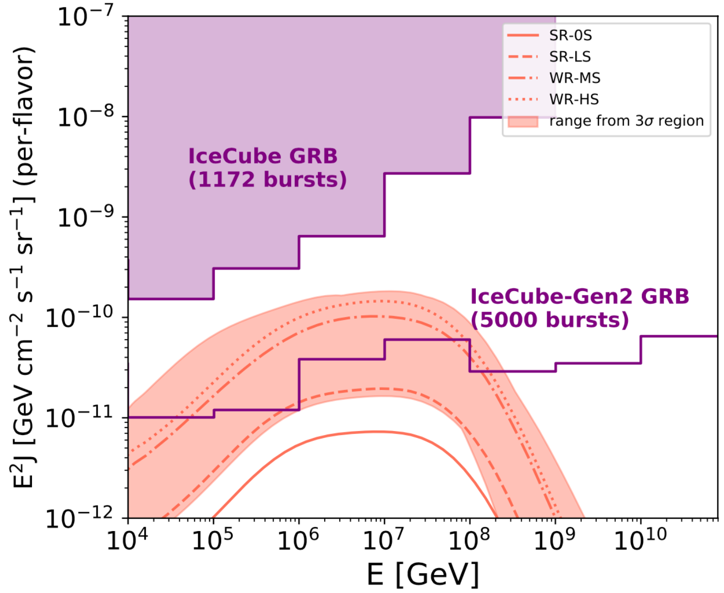


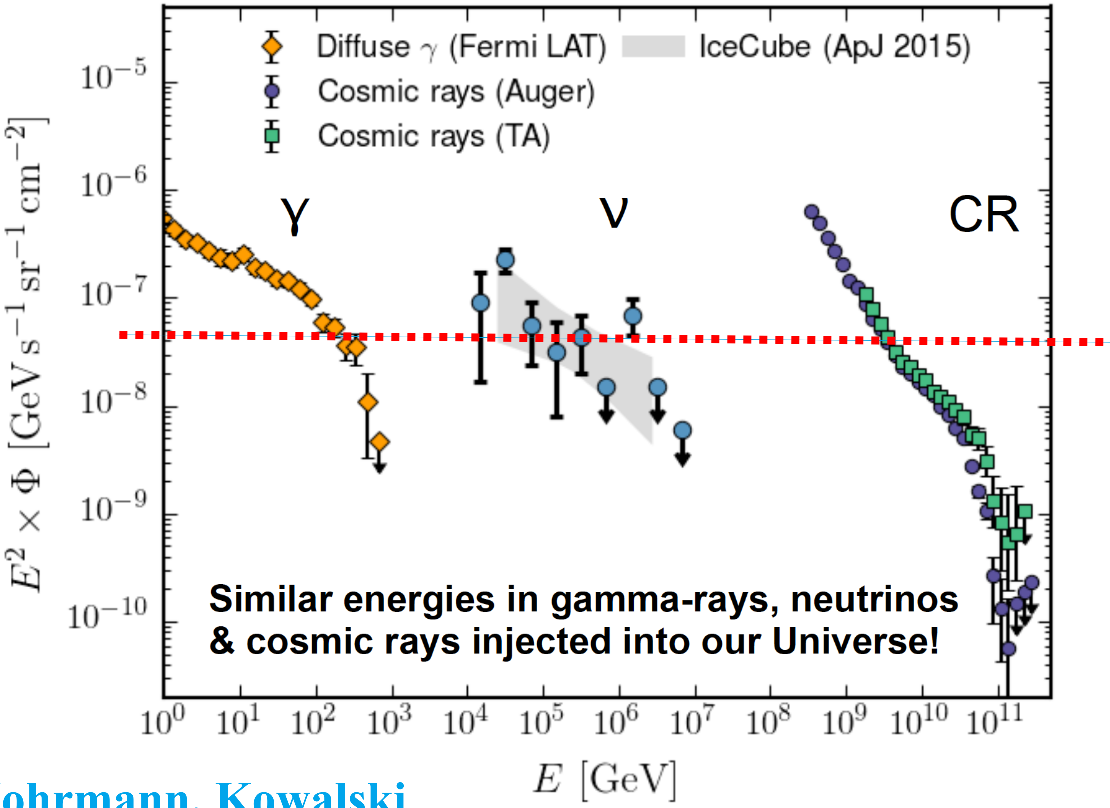
- Description of $\sigma(X_{\max})$ is an instrinsic problem (because the data prefer “pure” mass groups, which are hard to obtain in multi-zone or multi-source models)

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

Summary lecture III

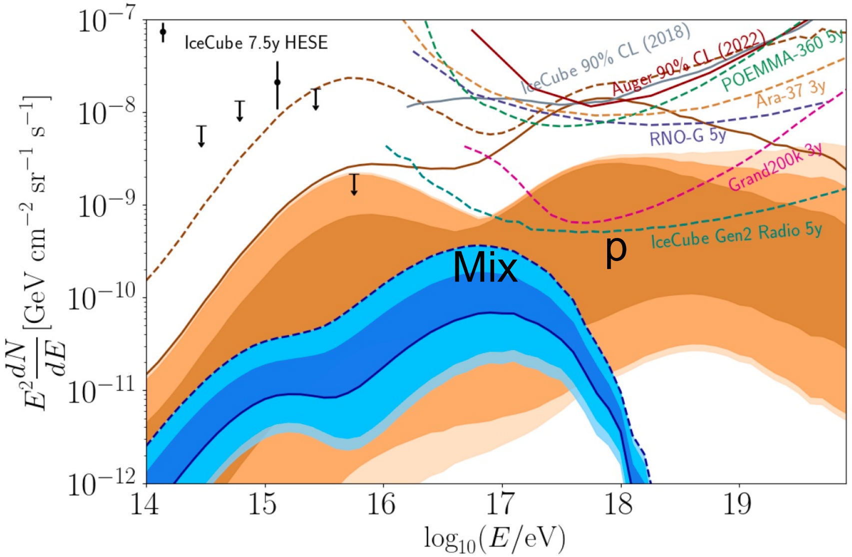
If GRBs are the UHECR sources, neutrinos should be ultimately seen. Could be also AGN, TDE …





Similar energies in gamma-rays, neutrinos & cosmic rays injected into our Universe!

Mohrmann, Kowalski

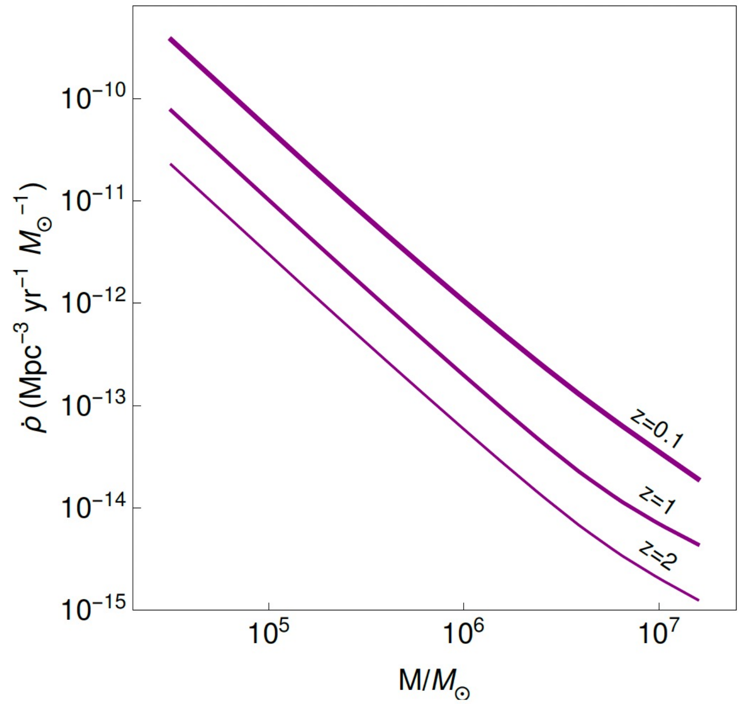


The detection of cosmogenic neutrinos depends on populations subleading in UHECRs

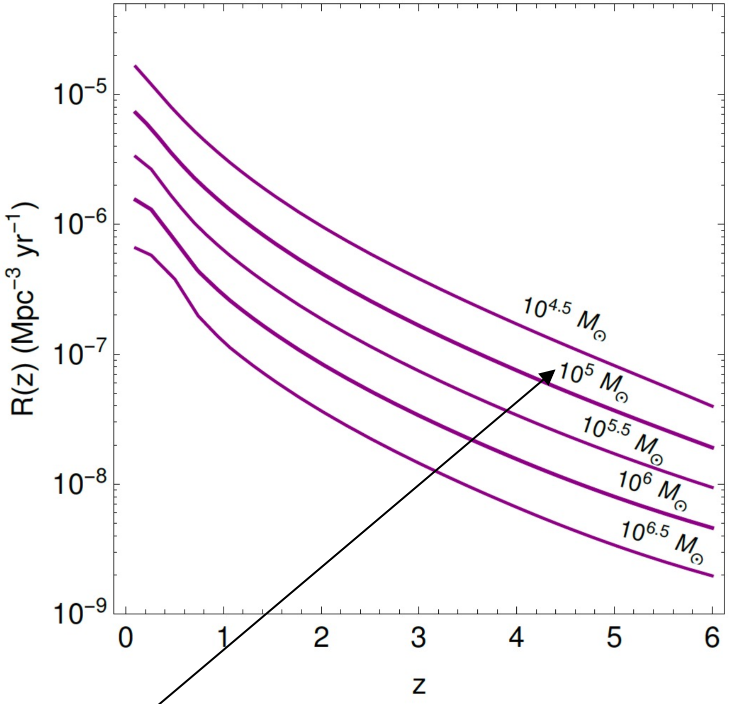
BACKUP

Notes on TDE demographics

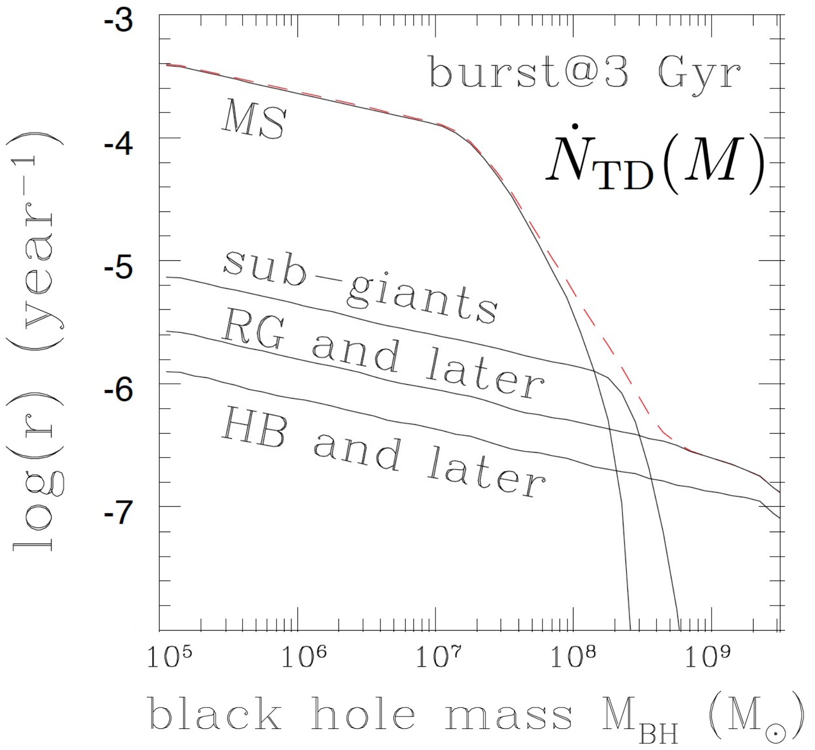
- **SMBH evolution**



- **Source evolution**



- **Dependence on progenitor**



$$\dot{\rho}(z,M) = \dot{N}_{\rm TD}(M)\, f_{\rm occ}(M)\, \phi(z,M)$$

Volumetric TDE rate

TDE rate per SMBH

Occup. factor. Threshold?

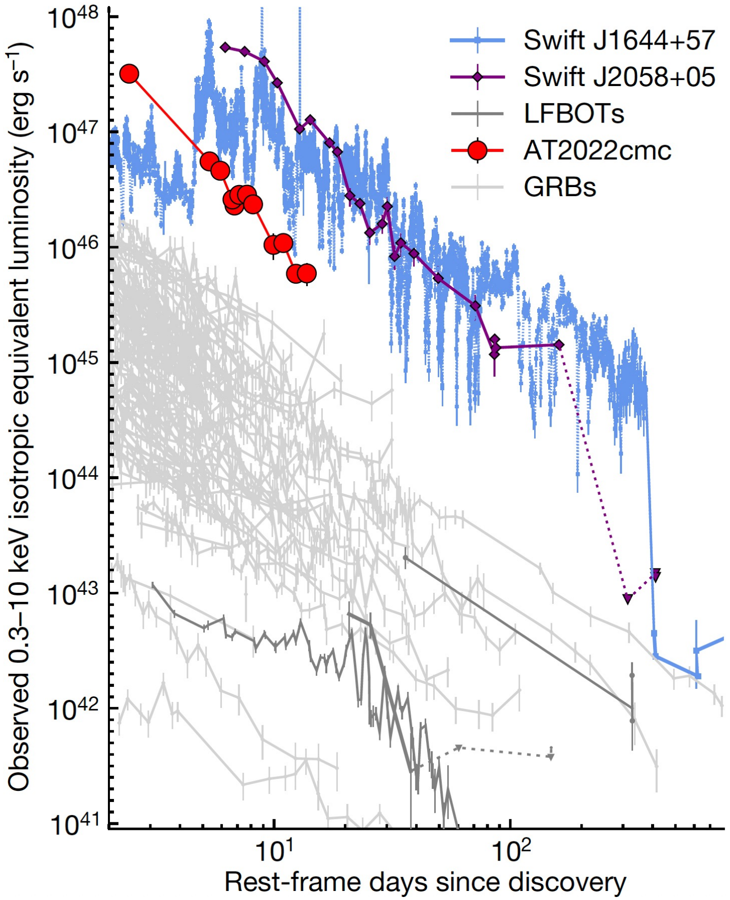
SMBH mass function. Strong M, z-dep.

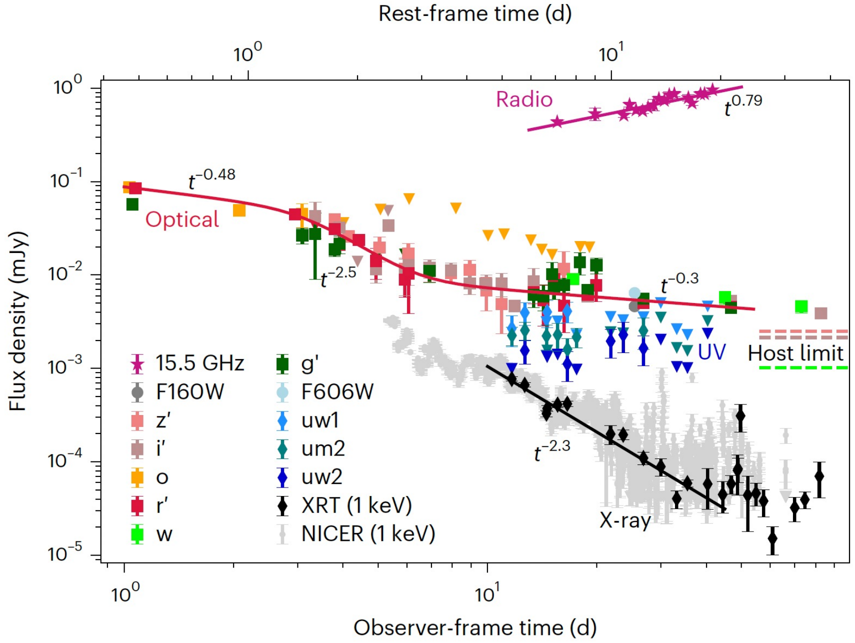
Shankar et al, 2009; Konchanek 2016 (Fig. r.h.s.), Stone, Metzger, 2016; Lunardini, Winter, 2017 (Figs. l.h.s)

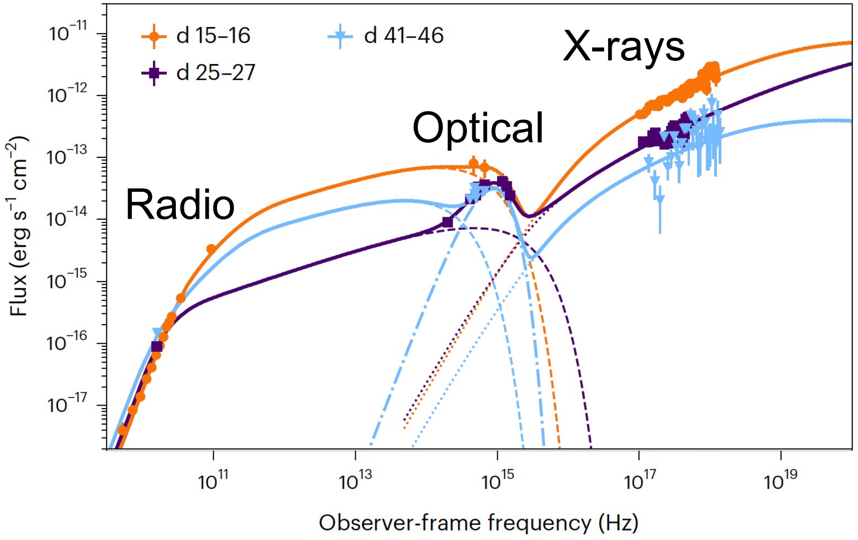
Jetted TDEs

A brand-new example: AT2022cmc

- Extremely luminous
- Non-thermal spectra in X-rays
- Associated with on-axis (or slightly off-axis) relativistic jets
- $\Gamma \sim$ few to 90
  (one model AT2022cmc)
- Typical assumption $\Gamma \sim 10$
- Conclusion: About 1% of all TDEs have relativistic jets (not necessarily pointed in our directions)



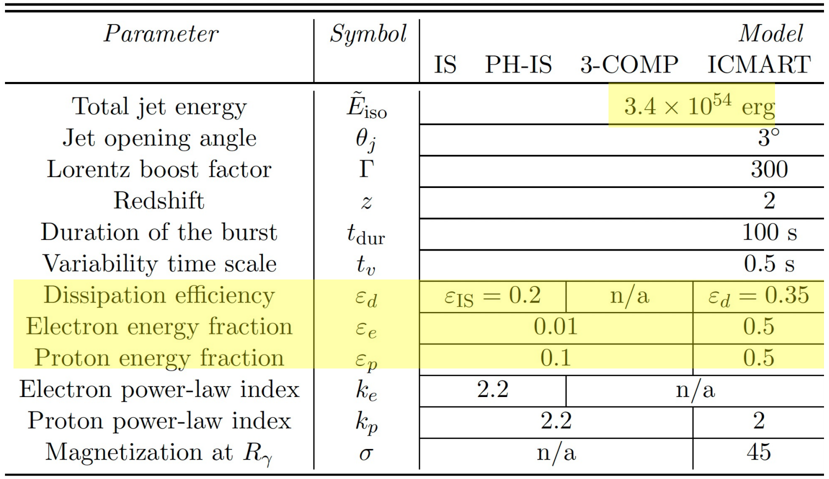




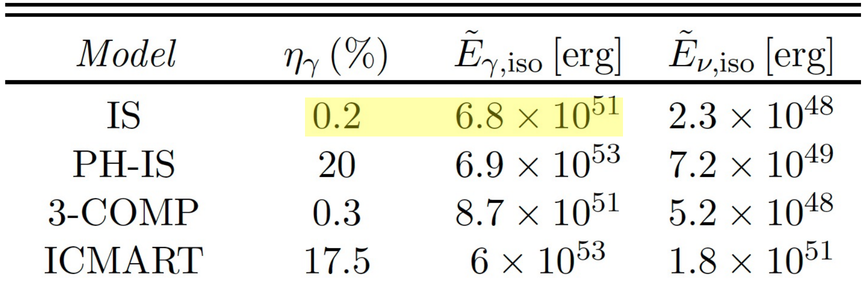
Andreoni et al, Nature 612 (2022) 7940, 430; Pasham et al, Nature Astron. 7 (2023) 1, 88

Model dependence of prompt neutrino flux? (one zone models)

Similar neutrino fluxes under the assumption of similar total jet energy and certain dissipation efficiencies.



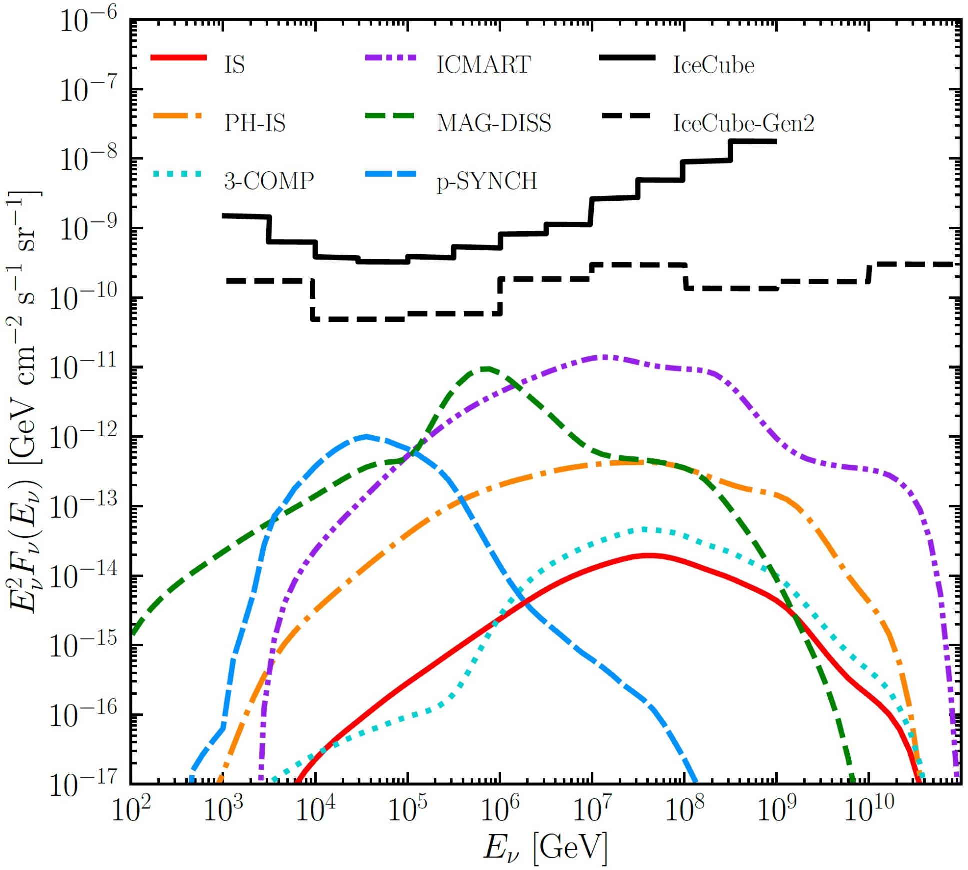
Parameter	Symbol	IS	PH-IS	3-COMP	ICMART
					Model
Total jet energy	$\tilde{E}_{\rm iso}$	3.4×10^{54} erg			
Jet opening angle	θ_j	3°			
Lorentz boost factor	Γ	300			
Redshift	z	2			
Duration of the burst	$t_{\rm dur}$	100 s			
Variability time scale	t_v	0.5 s			
Dissipation efficiency	ε_d	$\varepsilon_{\rm IS} = 0.2$		n/a	$\varepsilon_d = 0.35$
Electron energy fraction	ε_e	0.01			0.5
Proton energy fraction	ε_p	0.1			0.5
Electron power-law index	k_e	2.2		n/a	
Proton power-law index	k_p	2.2			2
Magnetization at R_γ	σ	n/a			45



Model	η_γ (%)	$\tilde{E}_{\gamma,\rm iso}$ [erg]	$\tilde{E}_{\nu,\rm iso}$ [erg]
IS	0.2	6.8×10^{51}	2.3×10^{48}
PH-IS	20	6.9×10^{53}	7.2×10^{49}
3-COMP	0.3	8.7×10^{51}	5.2×10^{48}
ICMART	17.5	6×10^{53}	1.8×10^{51}

$\eta_\gamma = \varepsilon_d \, \varepsilon_e$

Pitik, Tamborra, Petropoulou, JCAP 05 (2021) 034



However:

- Radiative efficiency of IS model low ($E_{\gamma,\rm iso}$ does not describe typical GRB)
- Not clear if jet power is sufficient to power UHECRs
- Efficiencies and partition parameters somewhat *ad hoc*

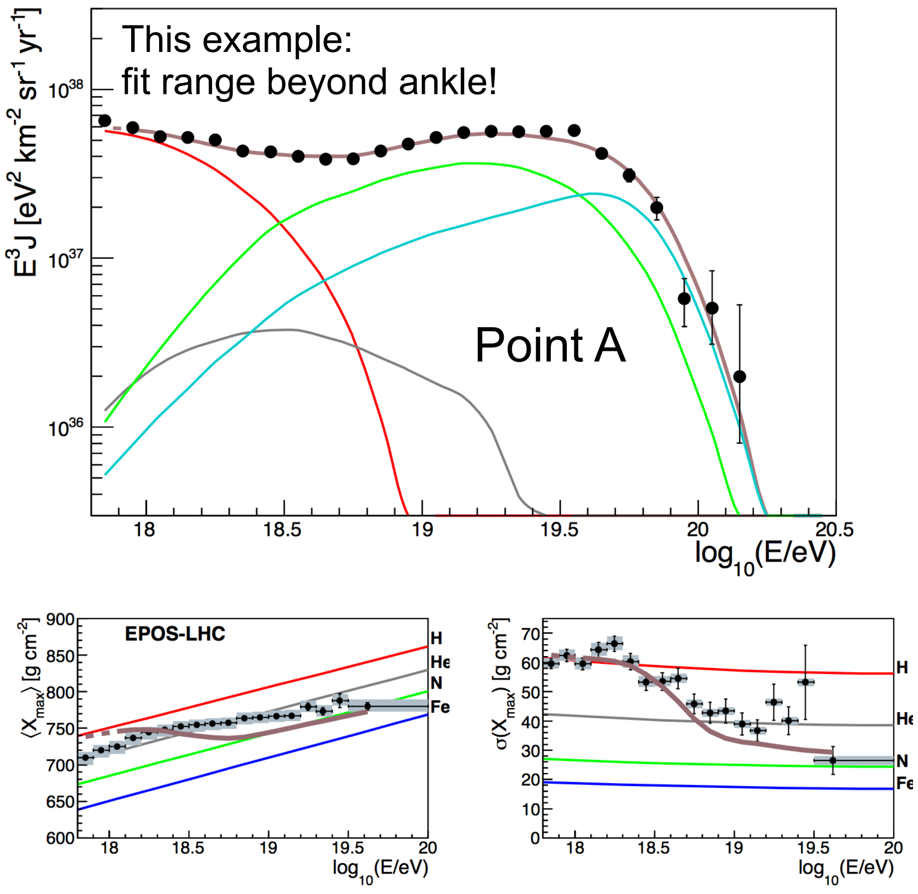
The vanilla one-zone prompt model

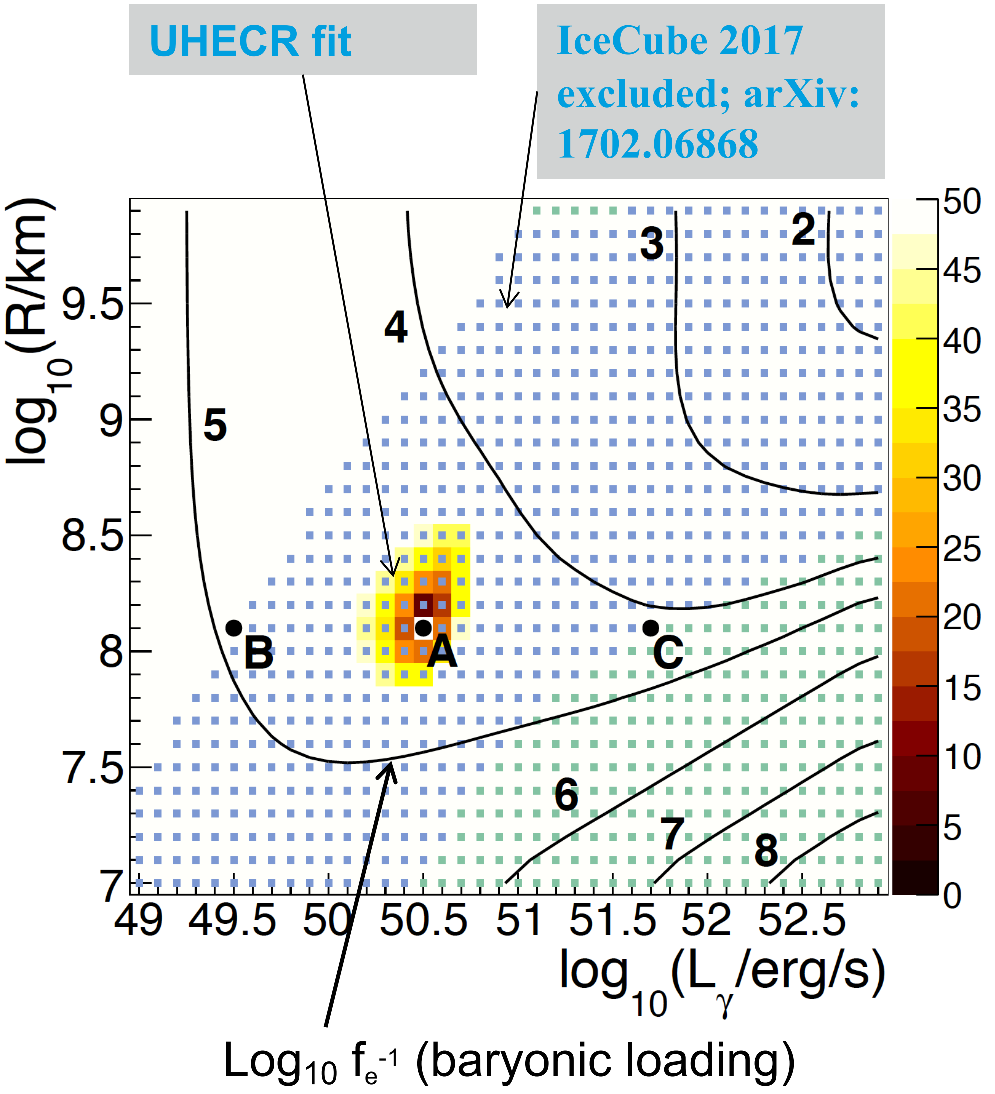
Neutrino and cosmic ray emission at same collision radius R

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

Recipe:

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


This example:
fit range beyond ankle!


UHECR fit

IceCube 2017 excluded; arXiv: 1702.06868

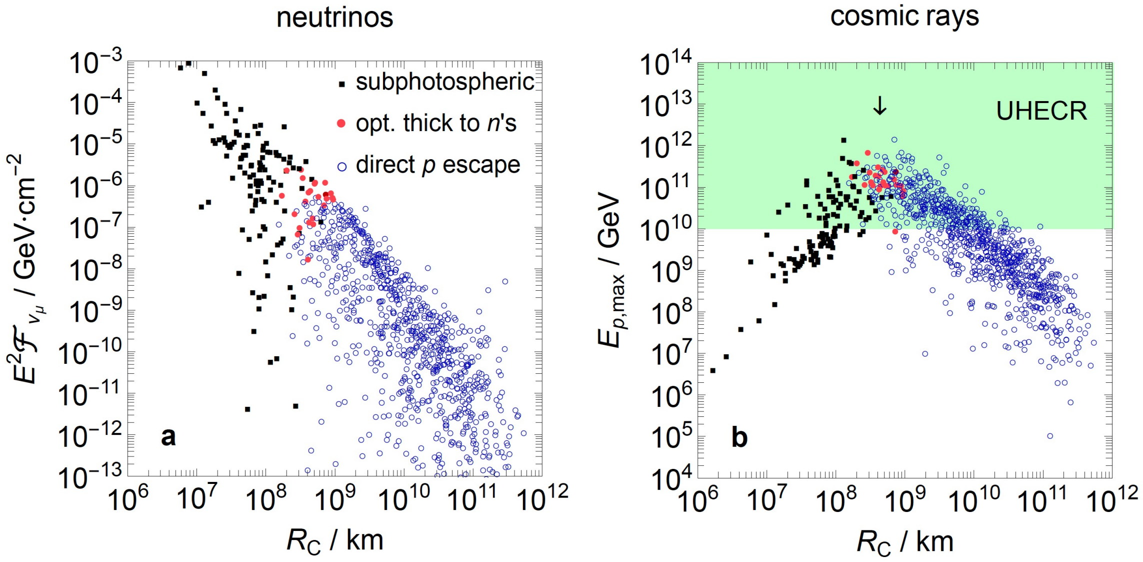
$\text{Log}_{10}\, f_e^{-1}$ (baryonic loading)

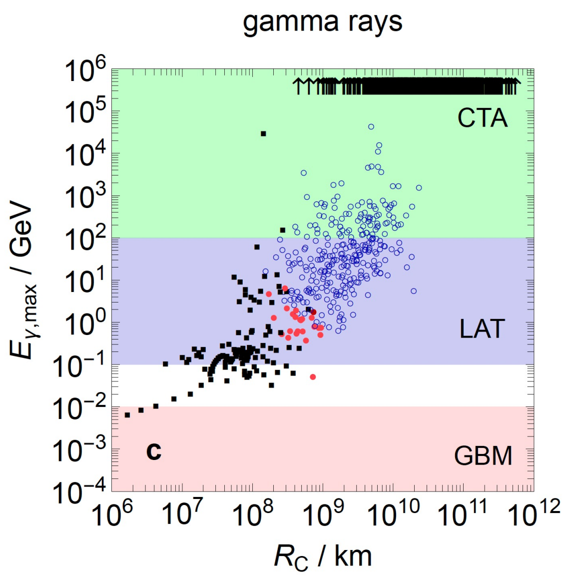
Biehl, Boncioli, Fedynitch, Winter, arXiv:1705.08909
Astron. Astrophys. 611 (2018) A101;
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

Back to the roots:

Multi-collision models

The GRB prompt emission comes from multiple zones (one GRB)





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

Observations

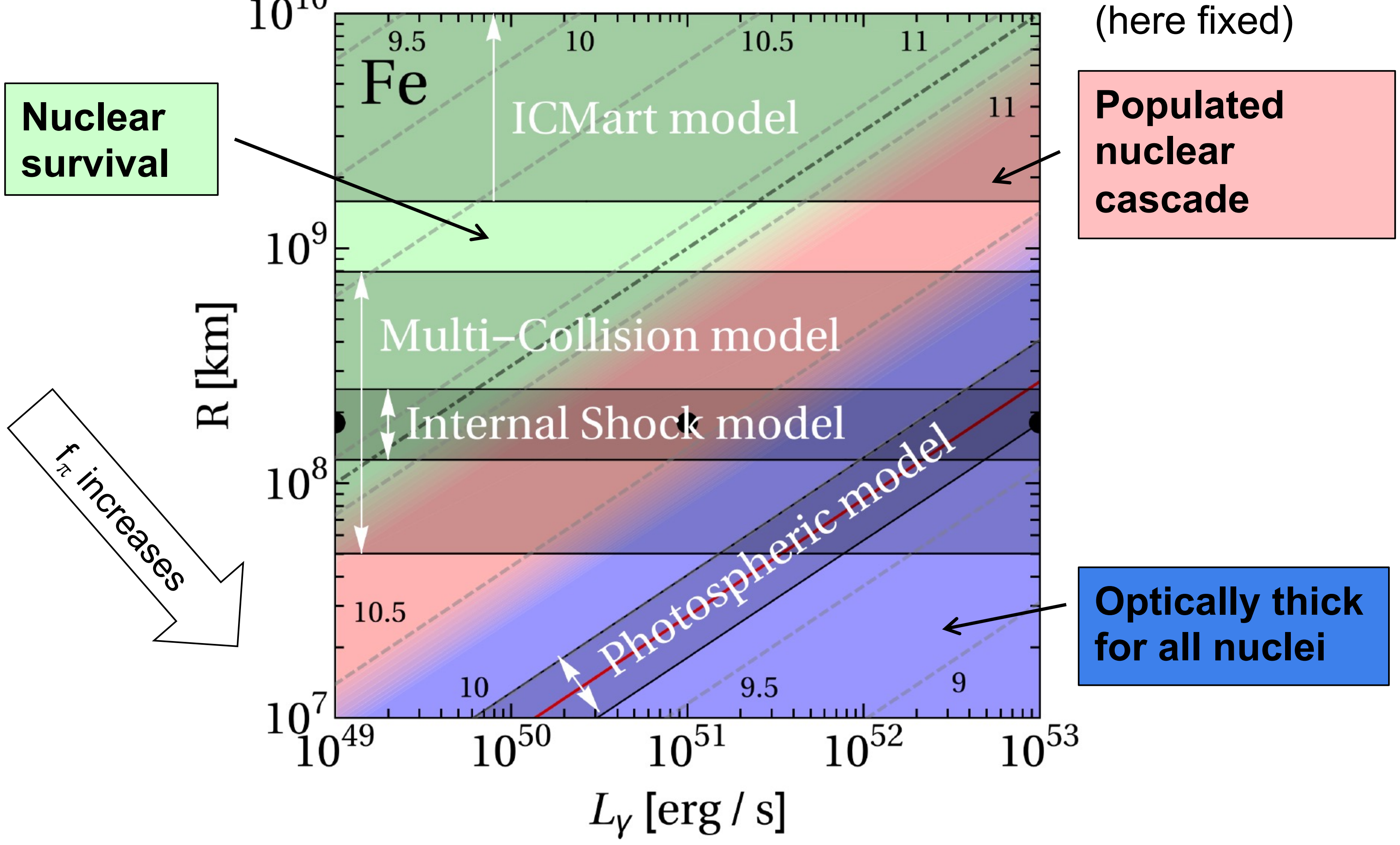
- The collision radius can vary over orders of magnitude
- The different messengers prefer different production regions; one zone therefore no good approximation
- The neutrino emission can be significantly lower

- The **engine properties** determine the nature of the (multi-messenger) light curves, and where the collisions take place

- Many aspects studied, such as impact of collision dynamics, interplay engine properties and light curves, dissipation efficiency etc.

Related example: Nuclear cascade (UHECR iron nuclei)

t_v=0.01s
(here fixed)

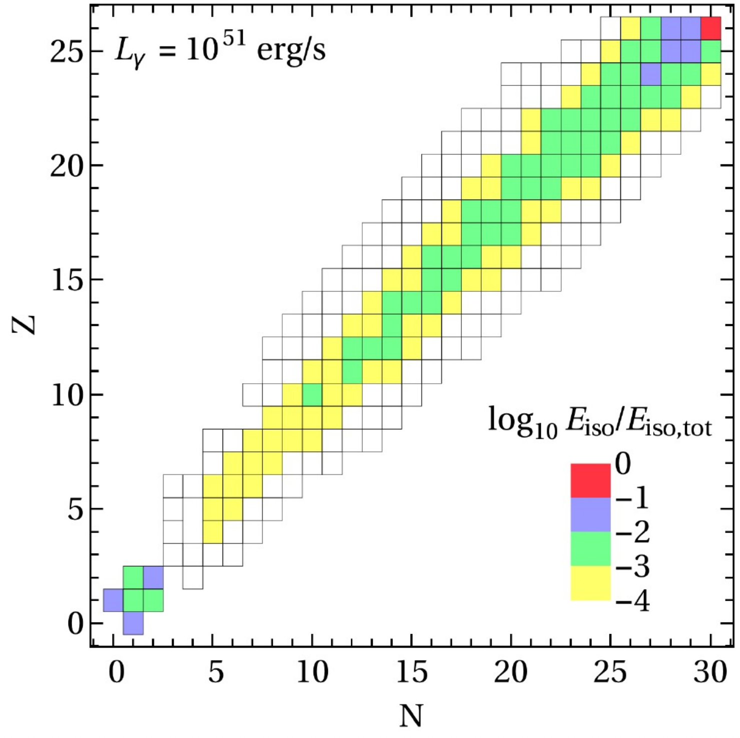


Nuclear survival

Populated nuclear cascade

Optically thick for all nuclei

Disintegration of ^{56}Fe ***within*** a GRB shell collision



(middle dot in left panel)

Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909;
see also Murase et al, 2008; Anchordoqui et al, 2008