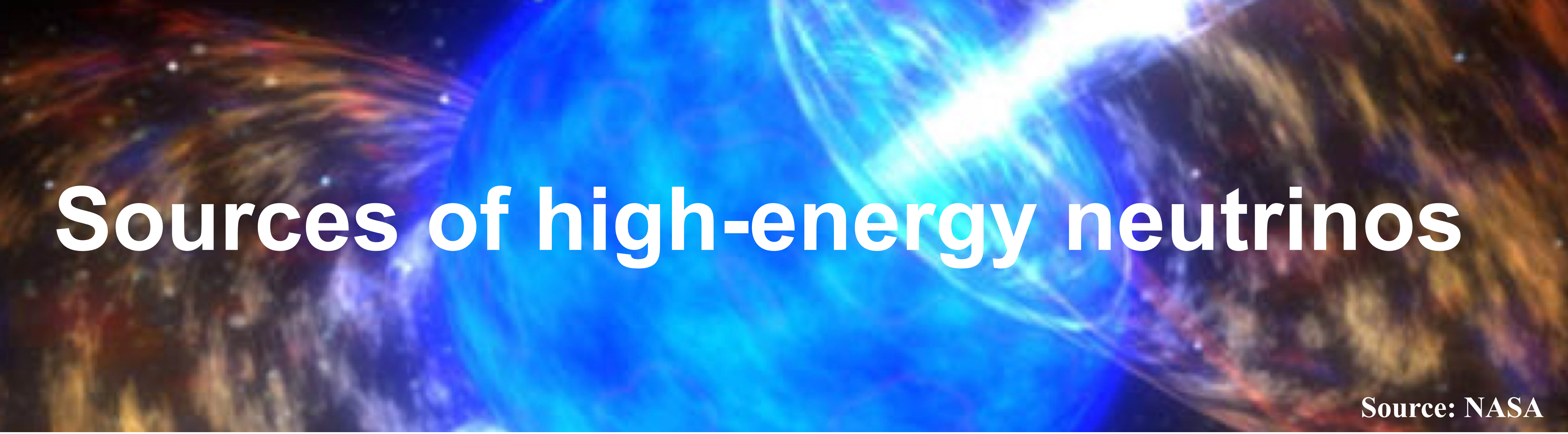
Sources of high-energy neutrinos



Source: NASA

Winter, Walter
DESY, Zeuthen, Germany

High-energy phenomena in relativistic outflows (HEPRO)

IAP Paris
Oct. 23-26, 2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

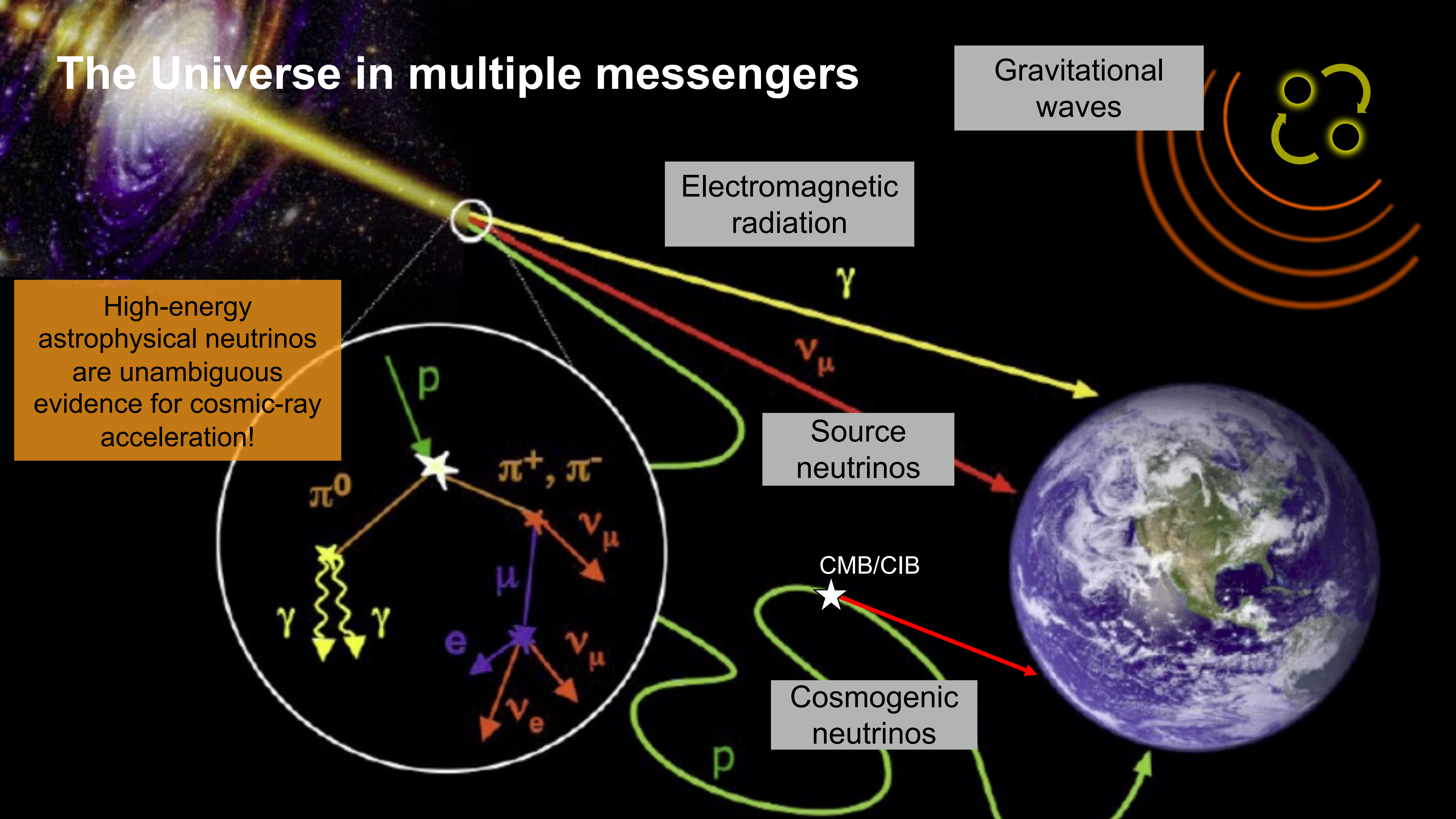
Contents

- Introduction
- Neutrinos from AGN blazars
- Neutrinos from TDE jets?
- Why are no neutrinos from GRBs seen?
- Summary

Center theme:
What can we learn about cosmic-ray acceleration in relativistic jets from neutrino observations?

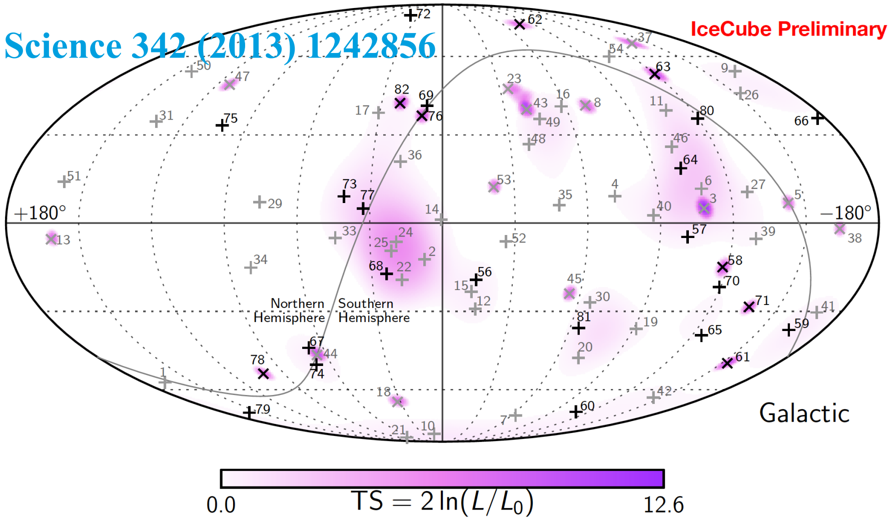
Will **not** tell you how the particles are accelerated, but give you an idea what it needs to describe neutrino and UHECR observations and what the critical issues are …

The Universe in multiple messengers



Detections of astrophysical neutrinos

A selection of results

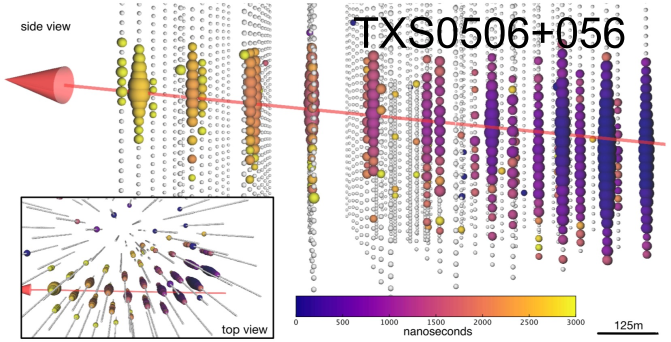


Science 342 (2013) 1242856

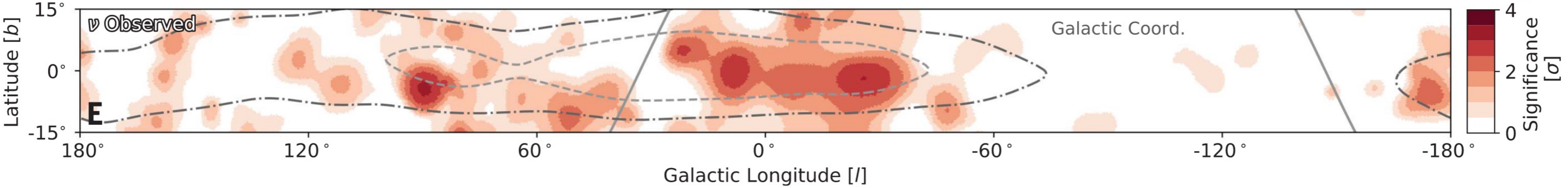
Science 378 (2022) 6619, 538

Focus of this talk: Relativistic outflows

Class	Evidence for ν	Related to relativistic jet?
AGN blazars	Widely accepted	Probably (Γ ~ 10-30)
Tidal Disruption Events	Several hints	Maybe (Γ ~ 10-100?)
Gamma-Ray Bursts	None – why?	Should be! (Γ > 100)



Science 361 (2018) 6398



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

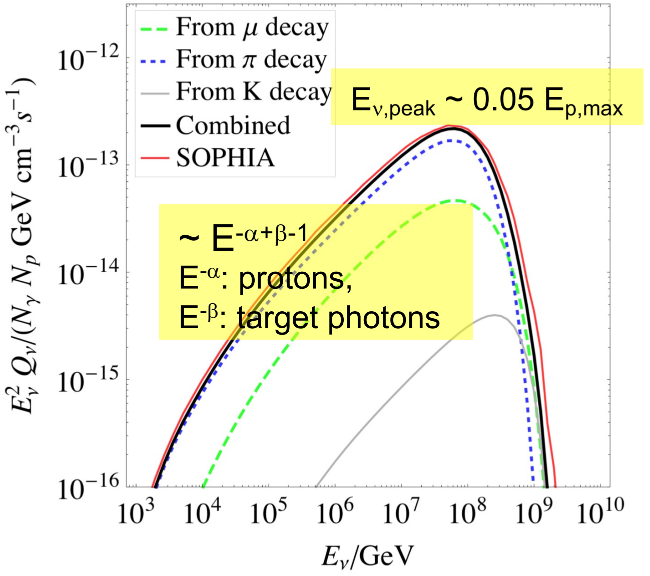
Radiation models and neutrino production

- Neutrino production e.g. through Δ-resonance (pγ)

  E_γ [keV] ~ 0.01 Γ^2/E_ν [PeV]

TeV-PeV

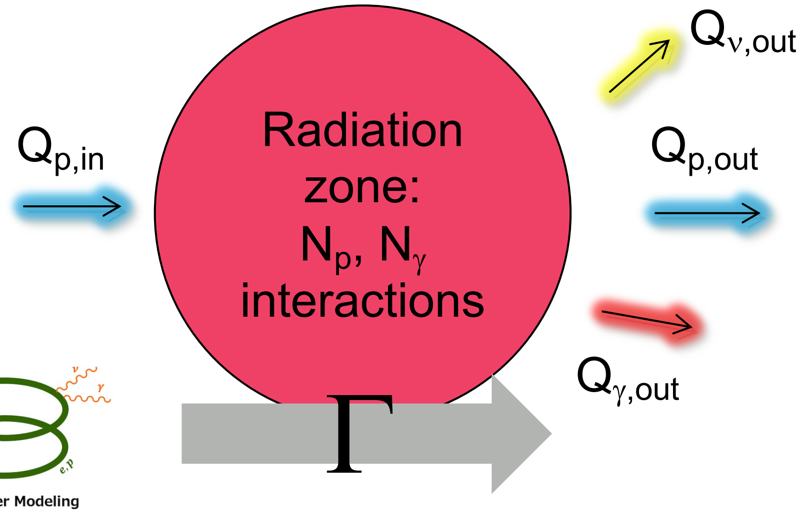
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & \rightarrow \nu \\ p + \pi^0 & \rightarrow \gamma \end{cases}$$

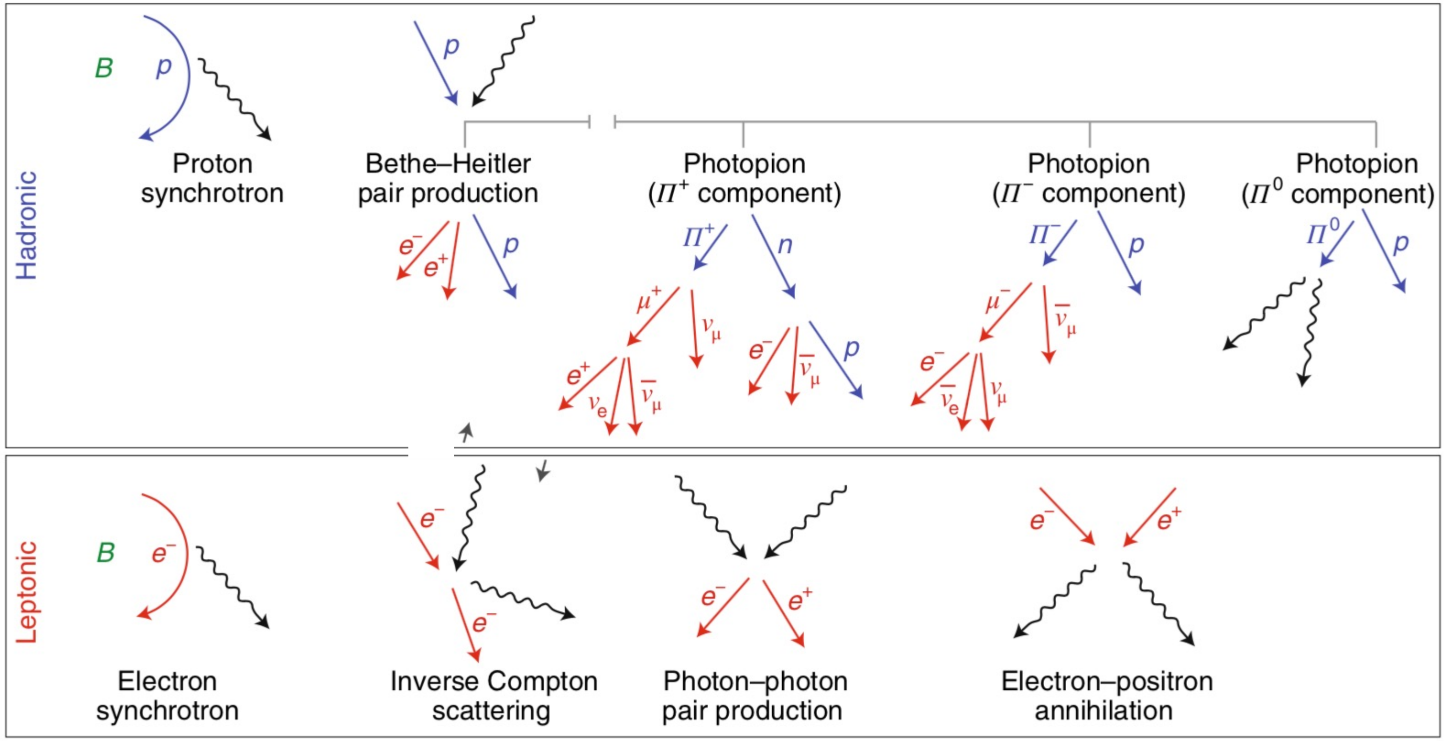


- Interaction rate ~ c **N [cm^{-3}]** σ [cm^2]
  Very sensitive to size of radiation zone!

- Interactions described by kinetic equations (one PDE per species)
- Radiation processes include interactions, escape, cooling, injection
- Numerical tool: public soon

Astrophysical Multi-Messenger Modeling

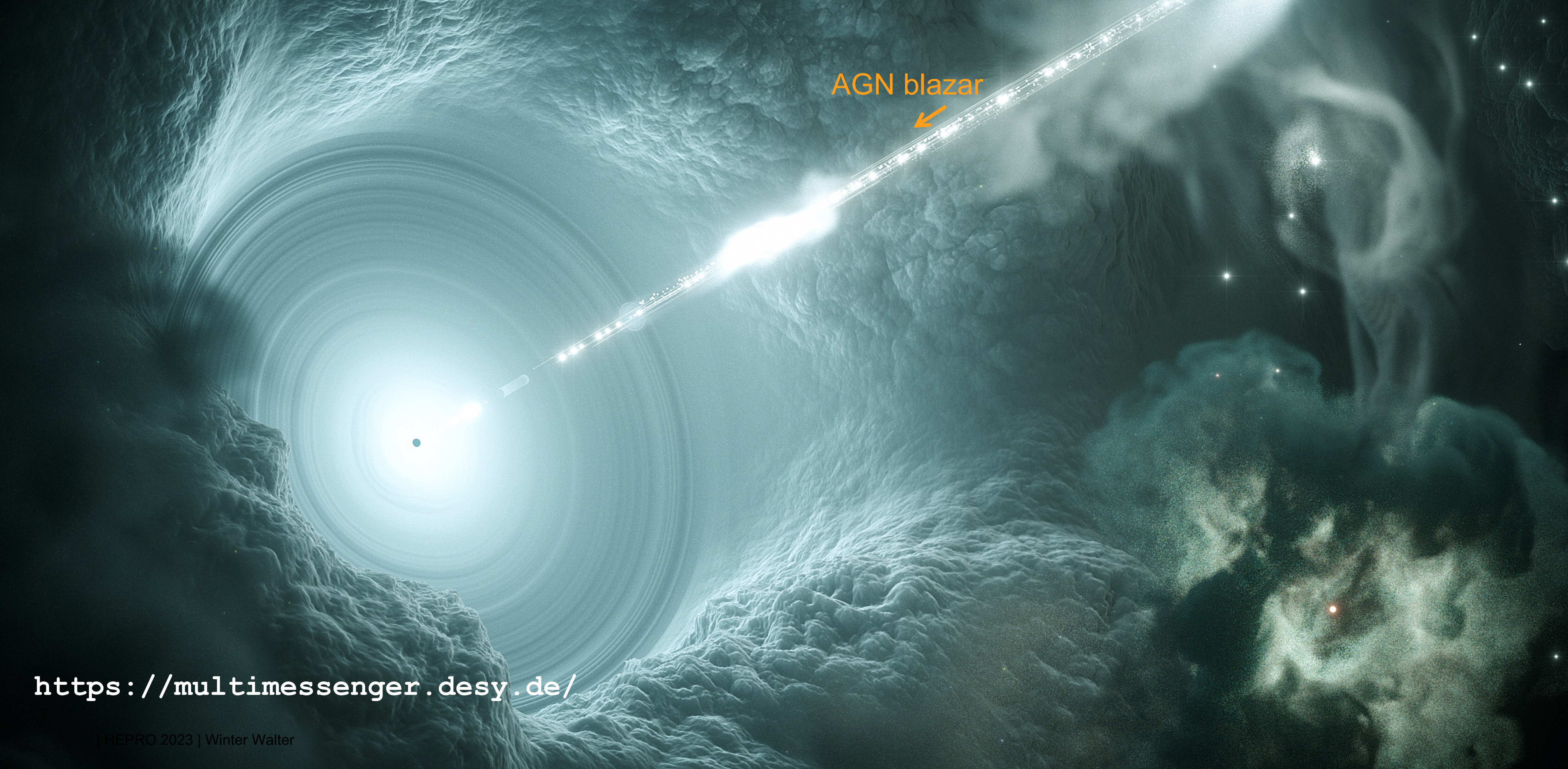




Hümmer et al, Astrophys. J. 721 (2010) 630.

Pian, Nature Astronomy 3 (2019) 24

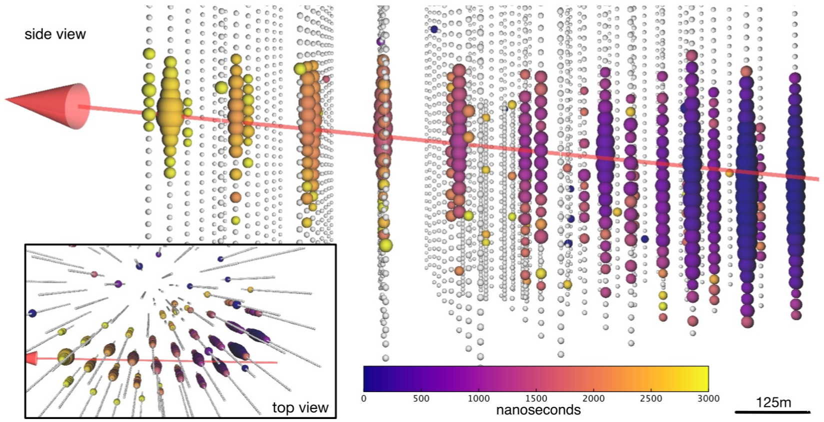
Neutrinos from AGN blazars

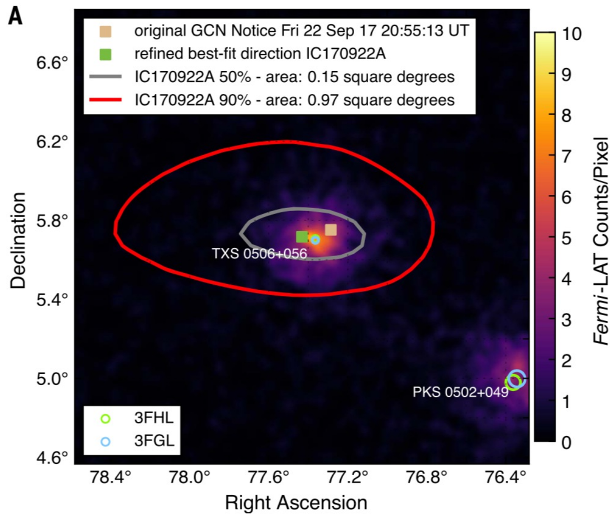


https://multimessenger.desy.de/

A neutrino from the flaring AGN blazar TXS 0506+056

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





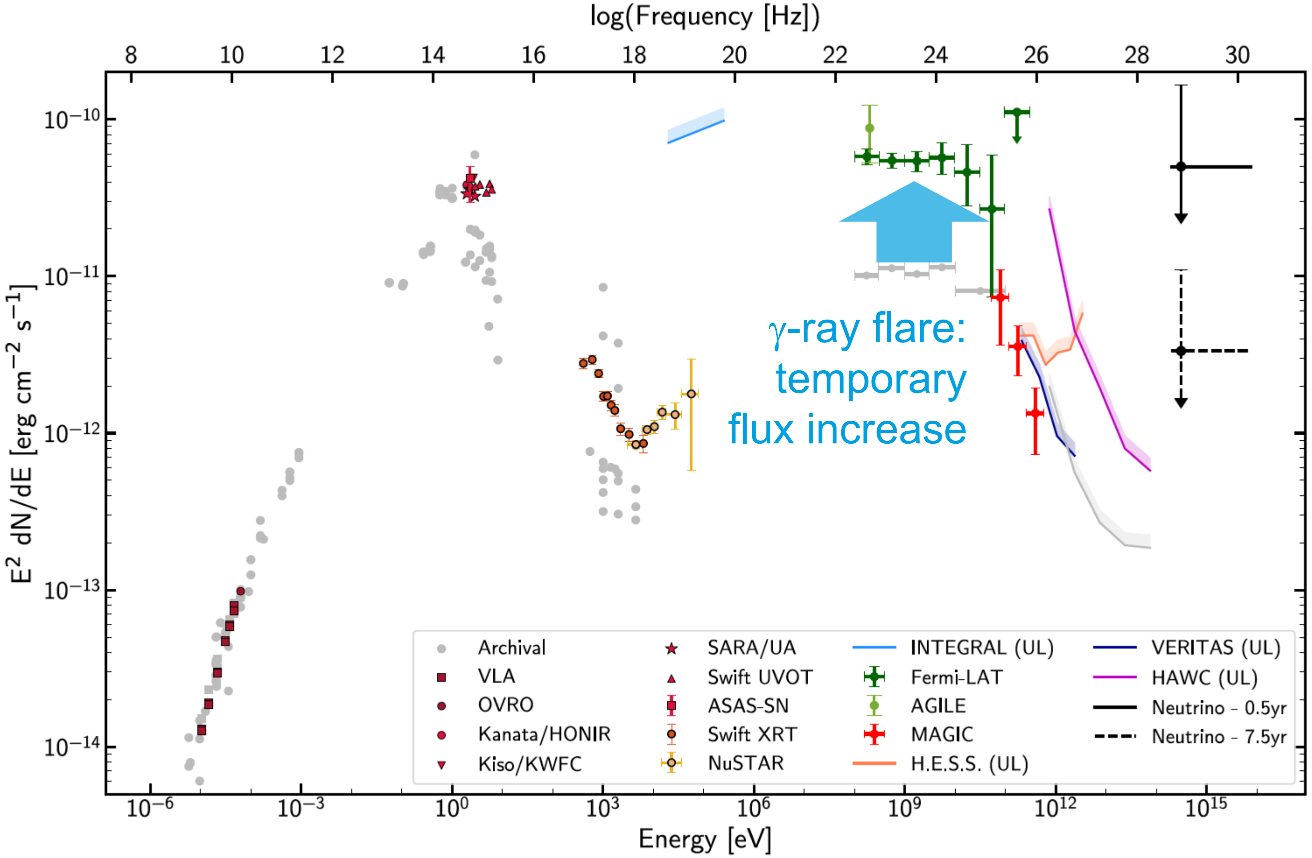
Observed by Fermi-*LAT* and MAGIC (blazar flare)

Significance for correlation: 3σ

$z = 0.3365 \pm 0.0010$

Paiano et al, 2018

SED from a multi-wavelength campaign

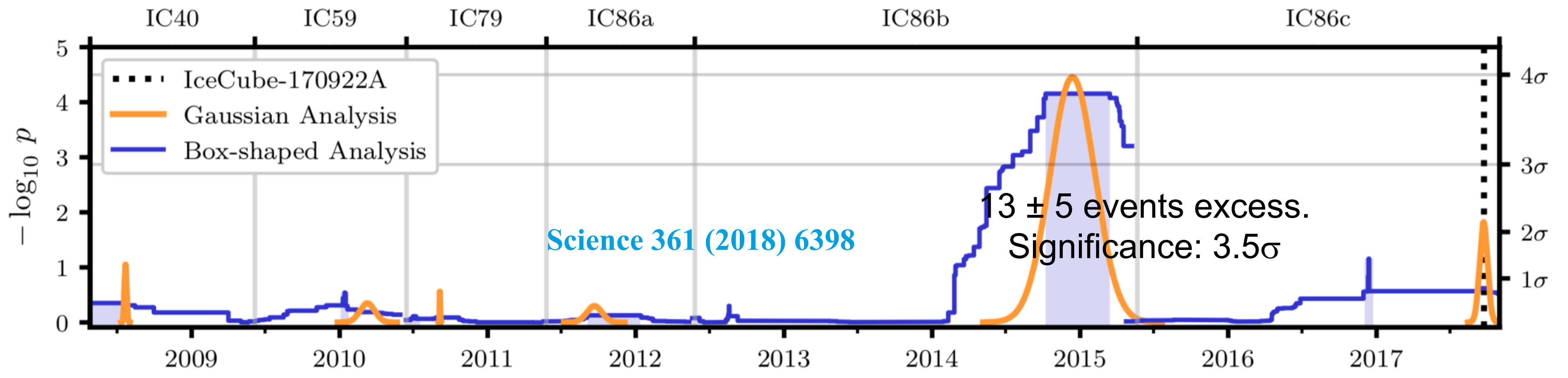


Color: coincident with neutrino; gray: archival data

Science 361 (2018) 6398

Analysis of archival neutrino (IceCube)

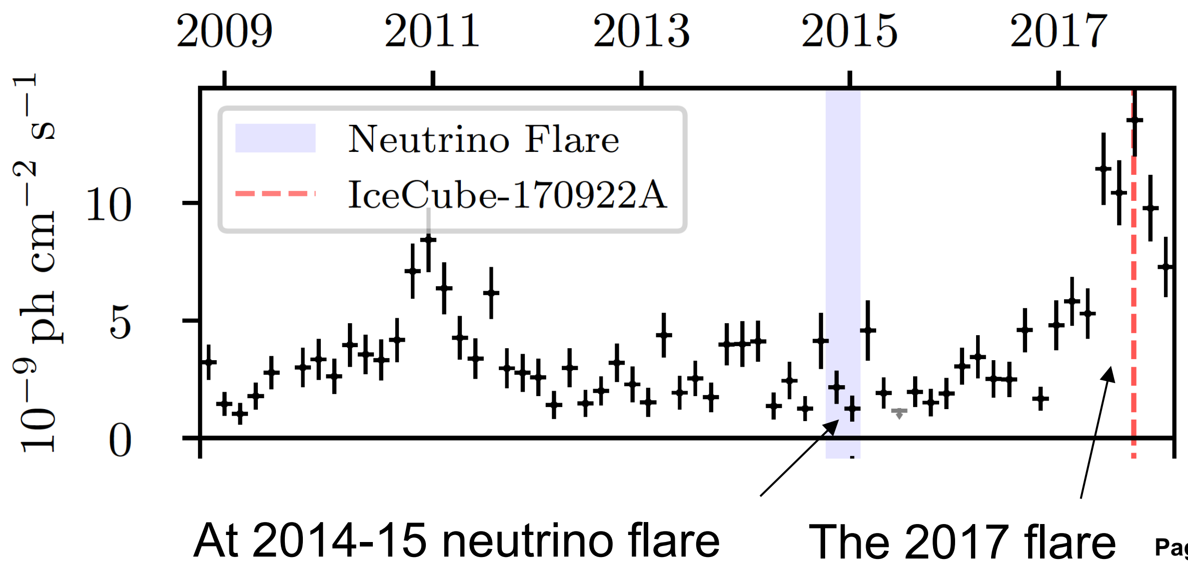
A (orphan) neutrino flare (2014-15) found from the same object in archival neutrino data



During that historical flare:

- Coincident data sparse (since no dedicated follow-up campaign)
- No significant gamma-ray activity

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

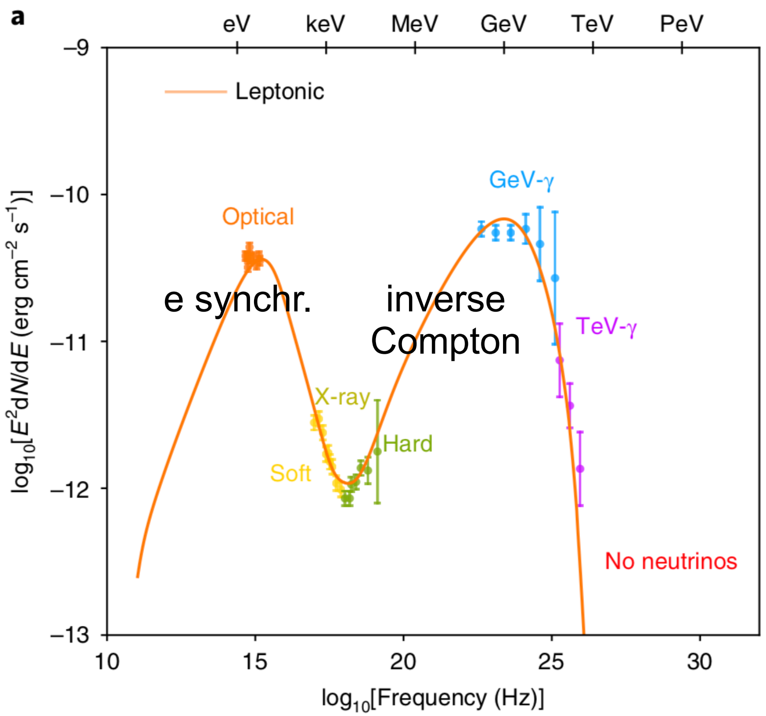


One zone model results (2017 flare)

One spherical radiation zone
Fewest assumptions

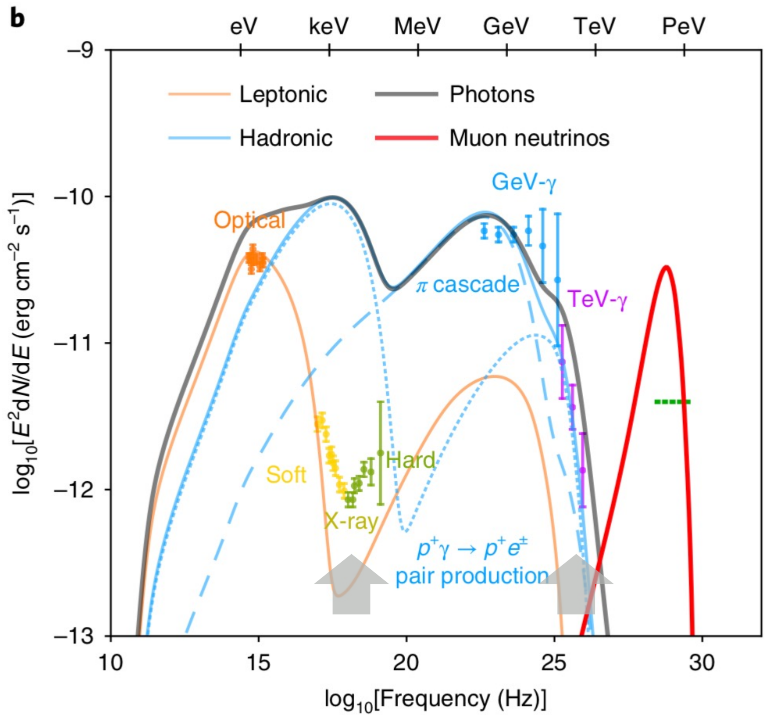
R'

Leptonic models



- No neutrinos

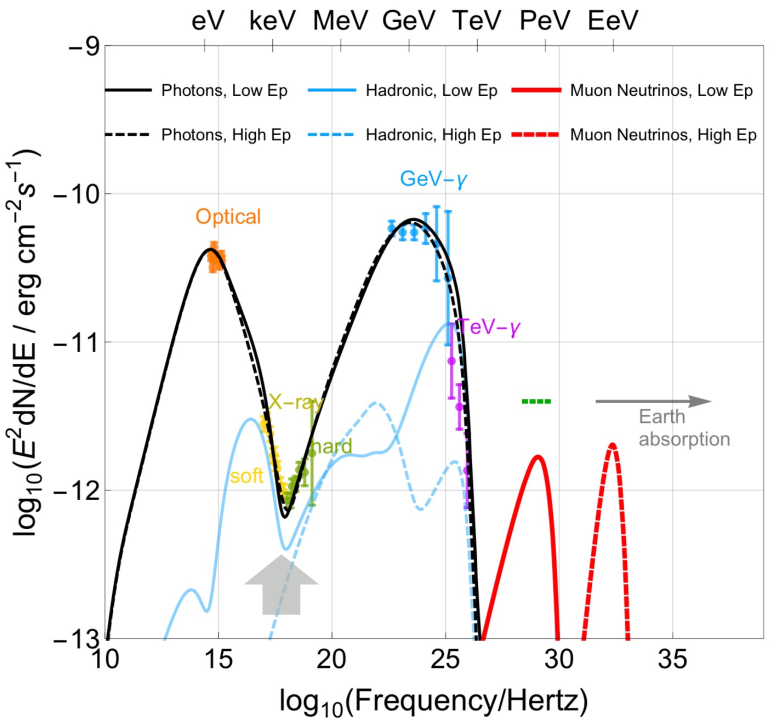
Hadronic (π cascade) models



- Violate X-ray data

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

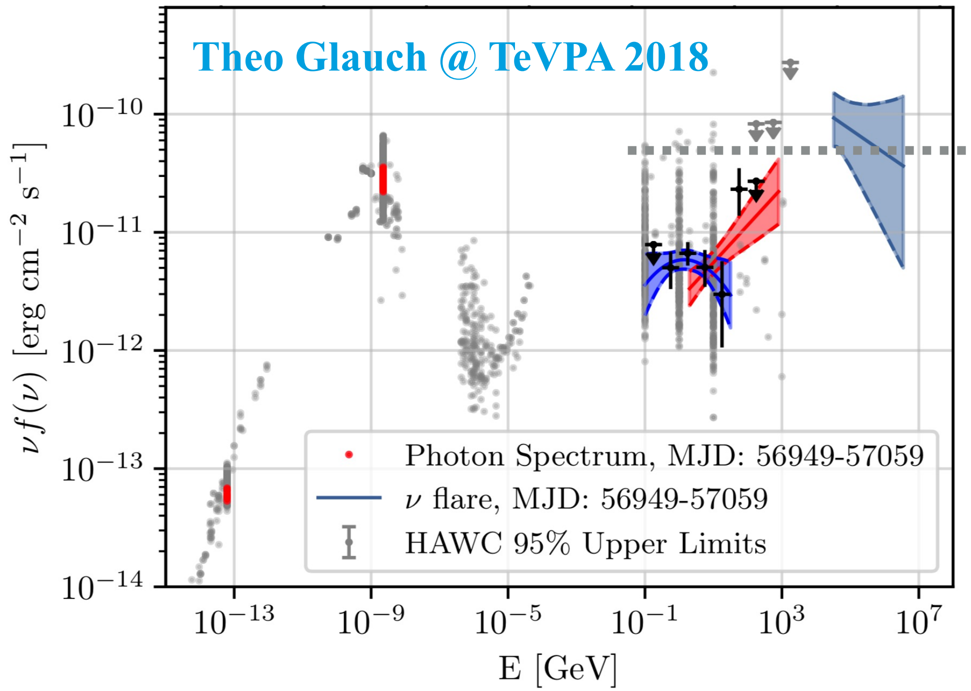
Hybrid or p synchrotron models



- **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

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?

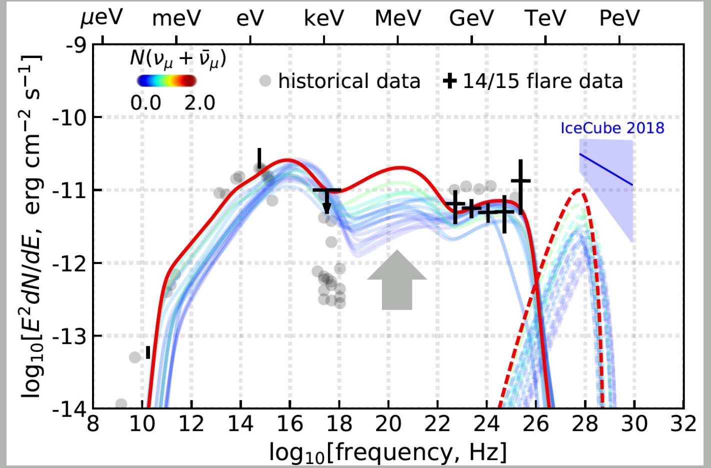
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \Rightarrow \nu \\ p + \pi^0 \Rightarrow \gamma \end{cases}$$

Comparable amounts of energy

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

- **Reprocessed** into E ranges without data during flare? (e.g. MeV range)

  Rodrigues et al, ApJL 874 (2019) L29



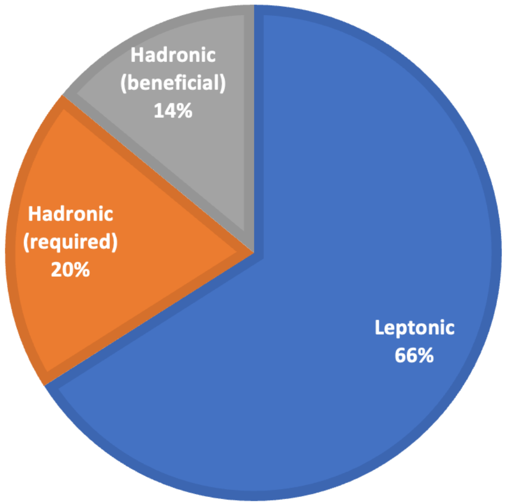
- Leave source + **dumped** into the **background light**?
  - → Implies low radiation density (γ-rays escape)
  - → Energetics more challenging
- **Absorbed or scattered** in some **opaque region**, e.g. dust/gas/radiation?
  - → Requires additional model ingredients

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

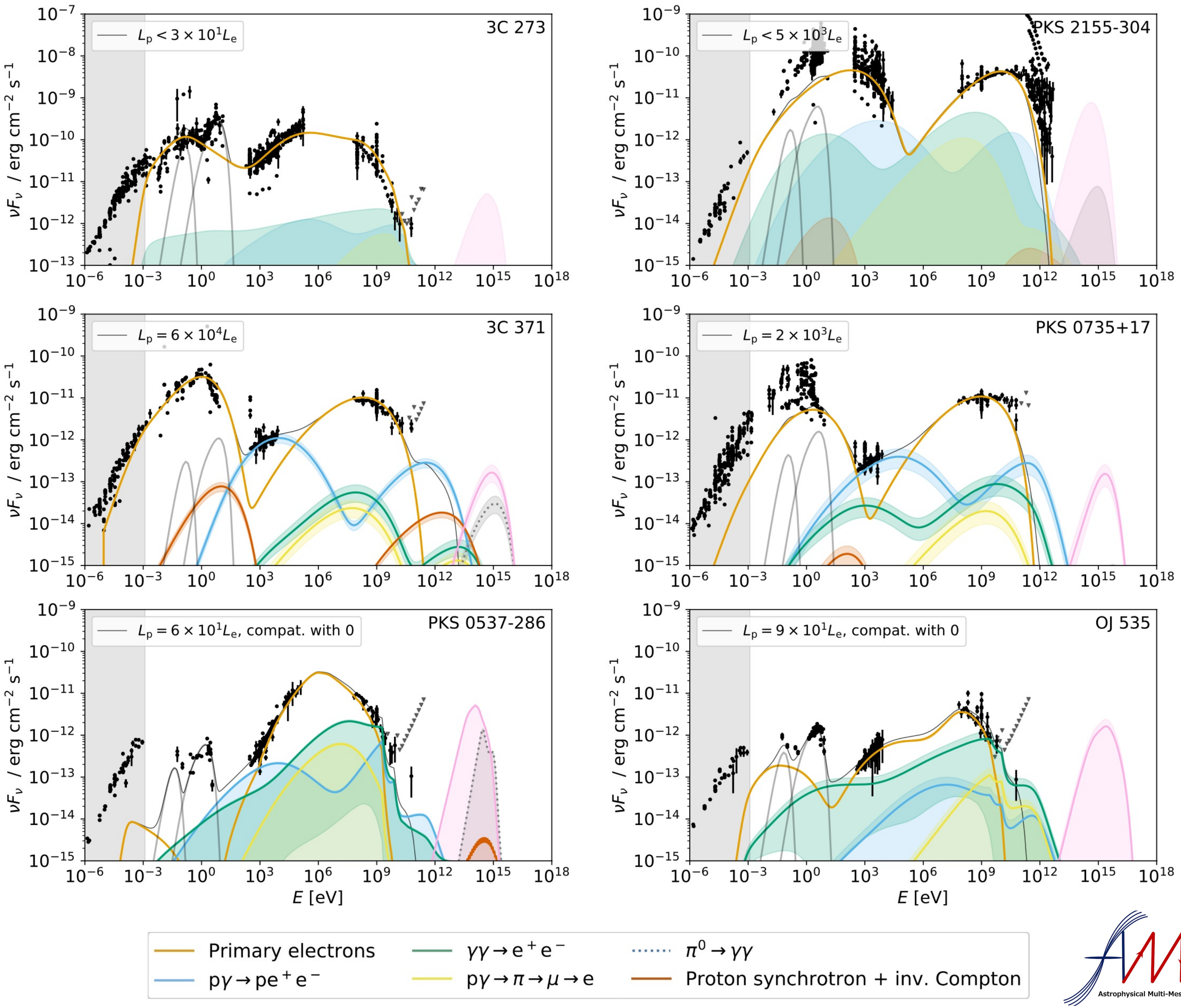
Systematic modeling

of 324 AGN blazars

Spectral energy distribution benefits from hadronic contributions in about 1/3 of all cases



Rodrigues++, A&A (to appear), 2023



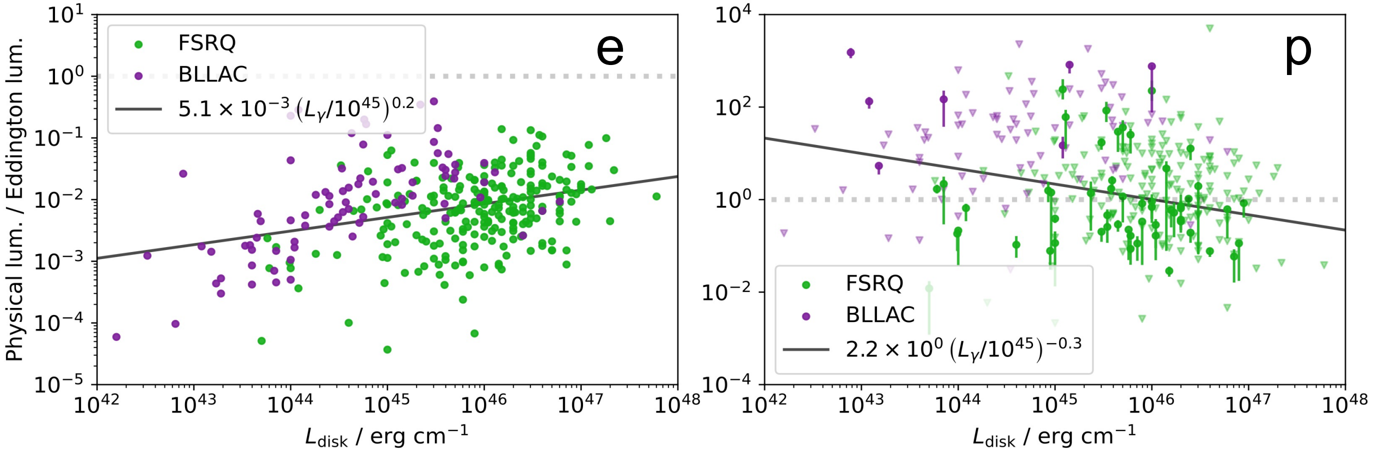
Leptonic

Hadronic (required): X-rays

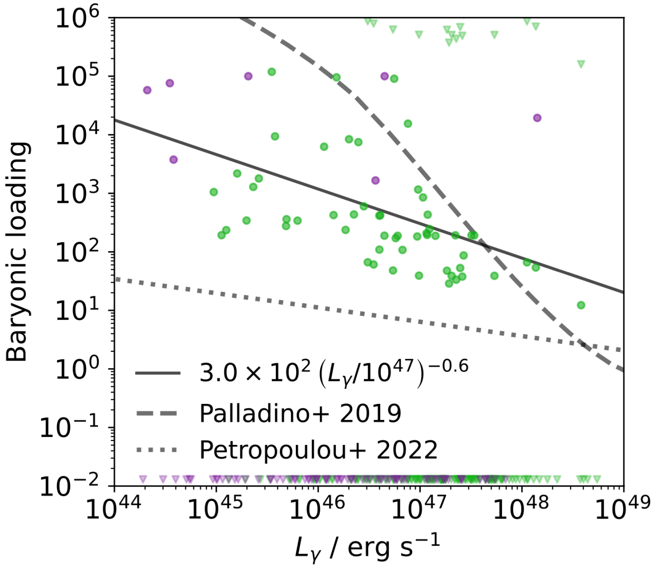
Hadronic (beneficial): compatible with zero

Energy crisis for cosmic-ray acceleration?

- Substantial fraction of Eddington luminosity has to go into non-thermal protons. In many cases super-Eddington.



- Baryonic loading (non-thermal L_p/L_e) ~ 10^1-10^5, significantly dropping with luminosity
  → No energy-equipartition!



Rodrigues++, A&A (to appear), 2023;
disk model based on Paliya et al, 2017

Theoretical comments/questions

- The electron parameters ($E_{e,min}$, $E_{e,max}$, γ_e, even escape) are often free parameters
  → Self-consistent description?
  e.g. Zech, Lemoine, 2021
- The proton parameters (esp. $E_{p,min}$, γ_p) are often chosen *ad hoc.* (l.h.s: 100 GeV, E^{-1})
  → Harder spectra and higher $E_{p,min}$ can mitigate the energy problem
  → Are $E_{e,min}$ and $E_{p,min}$ connected?
- Can such high baryonic loadings be justified from theoretical arguments?

  Are super-Eddington accretion flares somehow connected with cosmic-ray acceleration?

Neutrinos from TDEs

Tidal Disruption Events

***Is there a connection
with a relativistic outflow?***

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

How to disrupt a star

Fundamentals

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

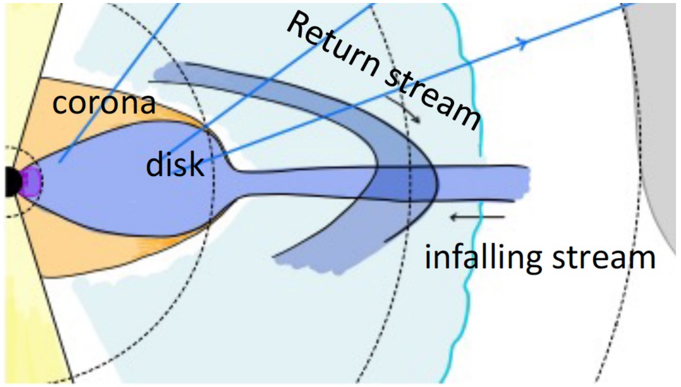
$$r_t = \left(\frac{2M}{m}\right)^{1/3} R \simeq 8.8 \times 10^{12}\,\mathrm{cm}\, \left(\frac{M}{10^6\, M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}$$

- Has to be beyond Schwarzschild radius for TDE (otherwise swallowed as a whole)

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

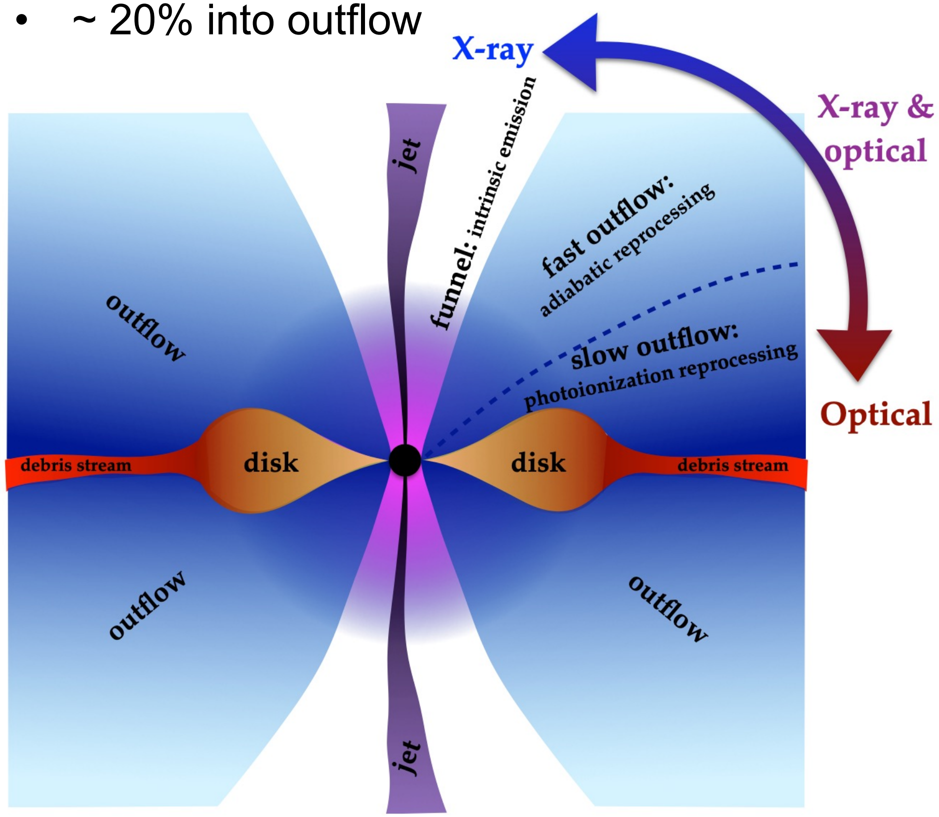
- From the comparison ($r_t > R_s$) and demographics, one obtains (theory) M <~ 2 10^7 $M_\odot$ (lower limit less certain …)

Hills, 1975; Kochanek, 2016; van Velzen 2017



Theory: A unified model?

- Supported by MHD simulations; here M_{SMBH} = 5 10^6 $M_\odot$
- Jet formation depends on SMBH spin
- Average mass accretion rate $\dot{M} \sim 10^2 L_{\mathrm{Edd}}$
  - ~ 20% of that into jet
  - ~ 3% into bolometric luminosity
  - ~ 20% into outflow

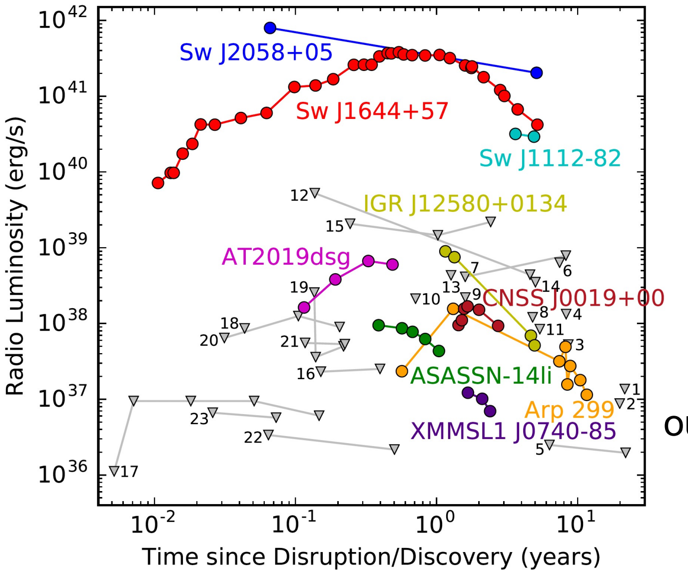


Dai, McKinney, Roth, Ramirez-Ruiz, Coleman Miller, 2018

Relativistic jets from TDEs

Radio observations

Interesting signals in about 1/3 of all cases. Evolving radio signals interpreted as outflow or jet:



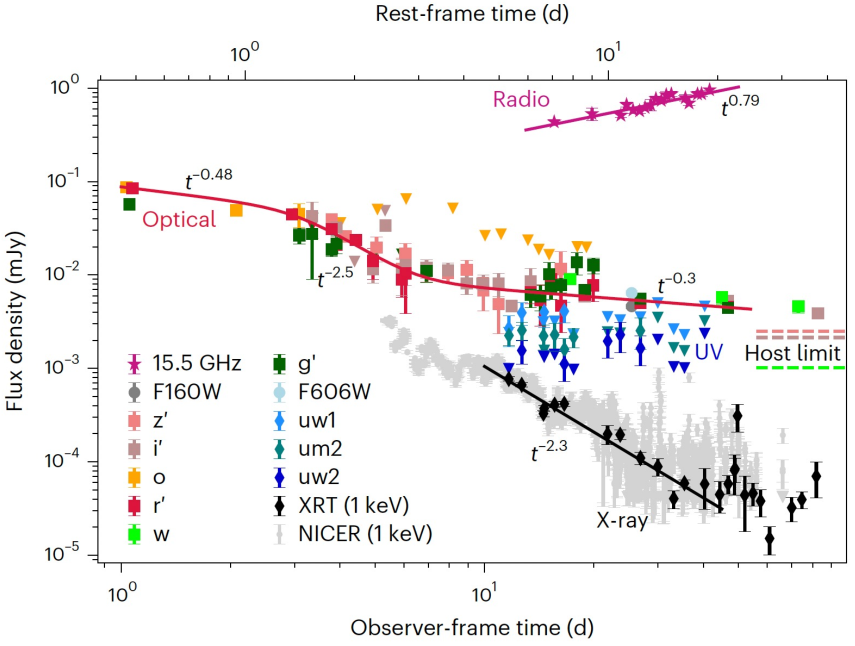
Relat. jets?

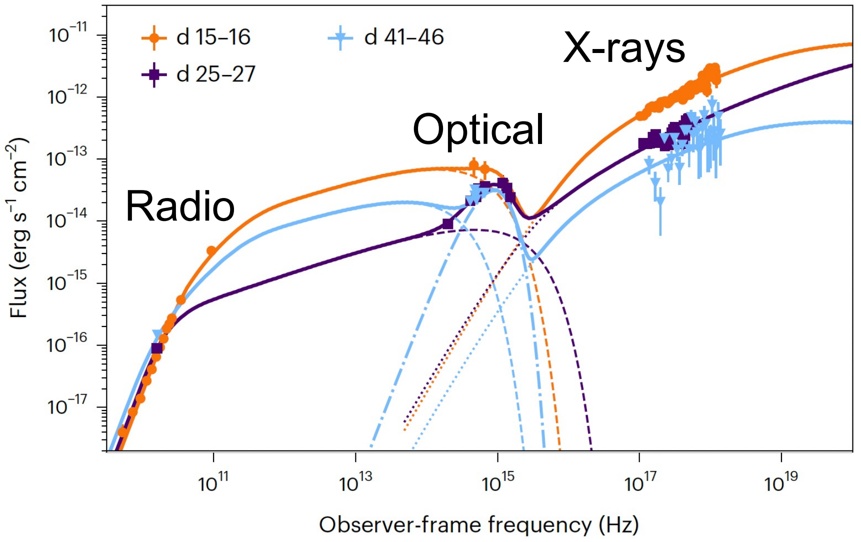
Non-relat. outflows?

Alexander, van Velzen, Horesh, Zauderer, Space Sci. Rev. 216 (2020) 5, 81

A new example: **AT2022cmc**

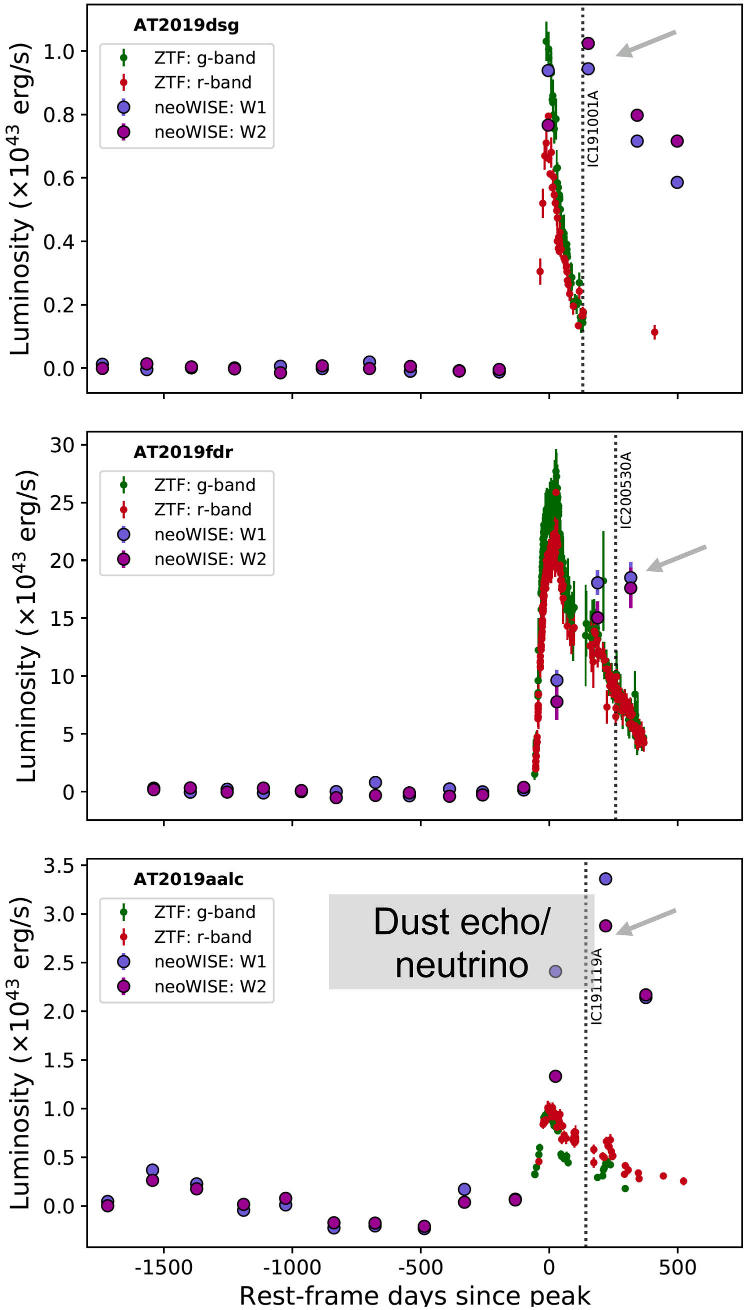
- Extremely luminous
- Non-thermal spectra in X-rays
- Associated with on-axis (or slightly off-axis) relativistic jet
- Γ ~ few to 90 (!) (one model AT2022cmc)
- Typical assumption Γ ~ 10
- Conclusion: About 1% of all TDEs have relativistic jets (not necessarily pointed in our direction, i.e., "TDE blazars")

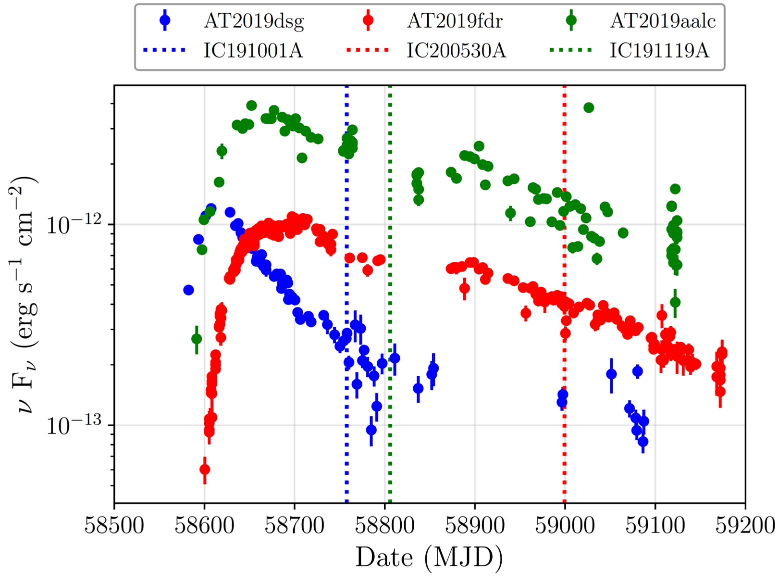




Andreoni et al, Nature 612 (2022) 7940, 430; Pasham et al, Nature Astron. 7 (2023) 1, 88

Neutrinos from TDEs





Simeon Reusch @ ECRS 2022

Analysis

- Three neutrinos associated with TDE candidates
  Stein et al, Nature Astronomy 5 (2021) 510; Reusch et al, PRL 128 (2022) 22
  van Velzen et al, arXiv:2111.09391
- Overall significance: 3.7σ
  van Velzen et al, arXiv:2111.09391

Common features:

- All three TDEs exhibit strong dust echoes in the infrared range
- All three TDEs have been detected in X-rays (not so frequent for TDEs!)
- All three TDEs exhibit neutrino time delays order 10^7 s wrt BB peak
- All three neutrinos arrived at the peak of the dust echoes

Possible interpretation:

- What if ... the dust echo itself (IR) is the target for cosmic ray interactions?
- Consequence (from pγ interactions):
  $E_p > 1.6$ EeV $(T_{IR}/0.1 \text{ eV})^{-1}$
  (for nuclei: rigidity R > 1.6 EV)
- Compatible with UHECR fits, e.g. $R_{max} \sim 1.4$-3.5 EV. Coincidence?
  Heinze et al, ApJ 873 (2019) 1, 88
- Points towards interactions of **UHECRs**
  Winter, Lunardini, ApJ 948 (2023) 1, 42

van Velzen et al, arXiv:2111.09391; two more candidates in Jiang et al, ApJL 953 (2023) 1, L12

Possible particle acceleration sites

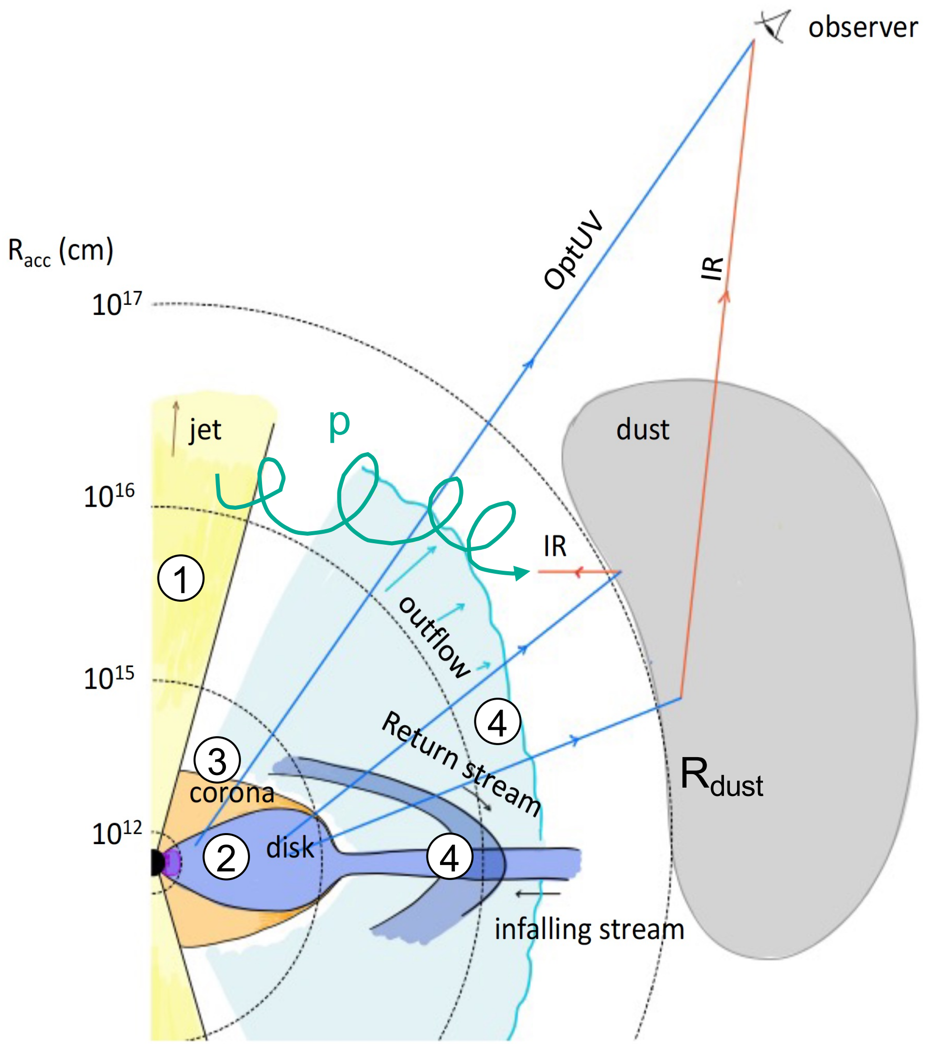
① Jets (on-axis, off-axis, choked)
Wang et al, 2011; Wang&Liu 2016;
Dai&Fang, 2016; Lunardini&Winter, 2017;
Senno et al 2017; Winter, Lunardini, 2020;
Liu, Xi, Wang, 2020; Zheng, Liu, Wang, 2022;
Mukhopadhyay et al, 2023

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

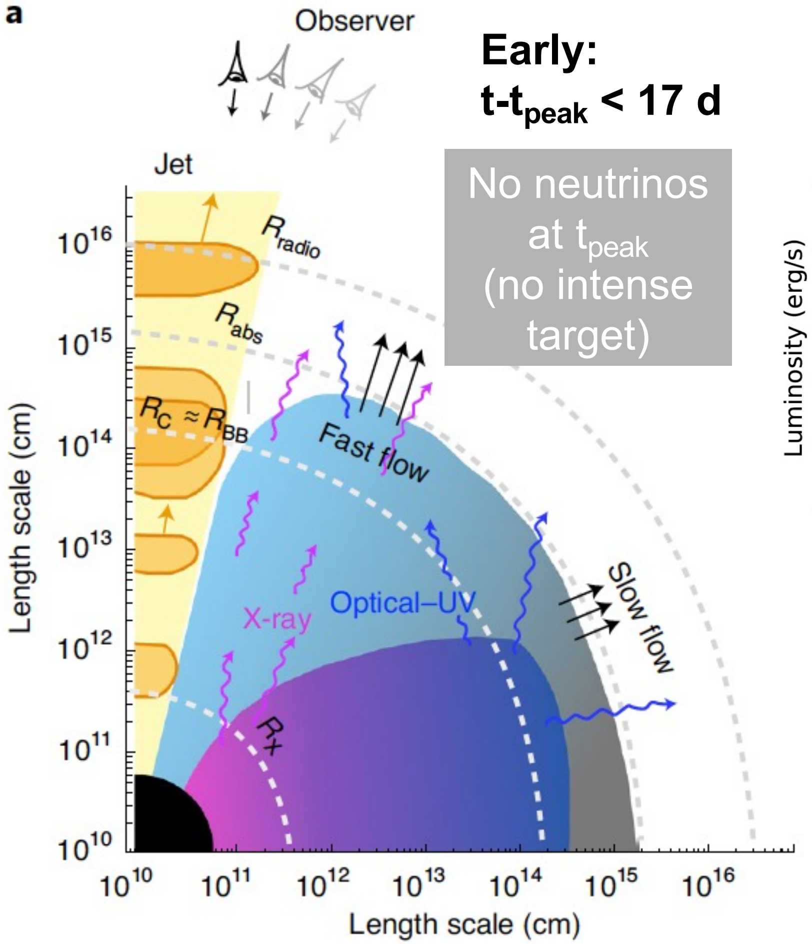
Probably neutrinos not associated with on-axis jets (constraints from radio signals).
But: hypothesis "jetted TDEs ~ neutrino-emitting TDEs" roughly consistent with neutrino diffuse flux at highest energies powered by TDEs



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

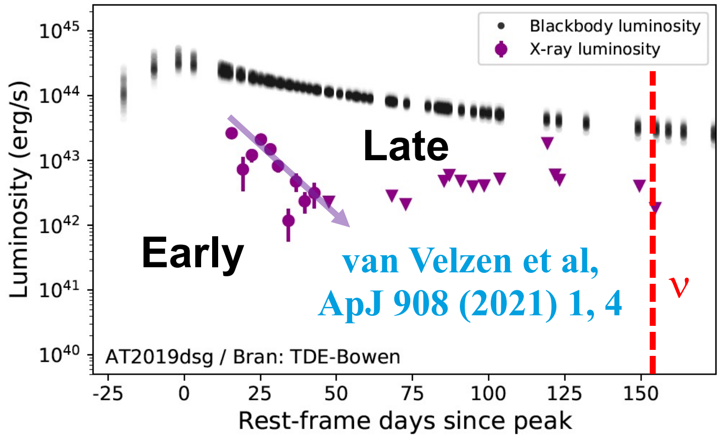
Example: A jetted concordance scenario for AT2019dsg

Addresses energetics issue, but challenged by radio observations

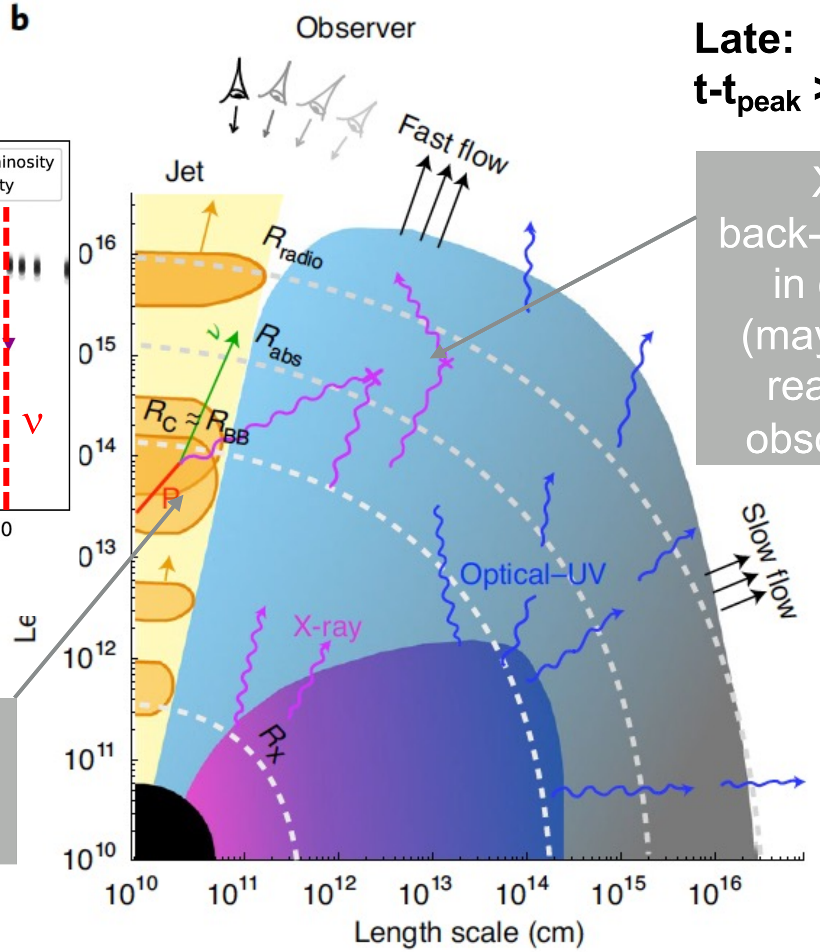


Early:
t-t_{peak} < 17 d

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



van Velzen et al, ApJ 908 (2021) 1, 4



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

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

Particle acceleration in internal shocks

Winter, Lunardini, Nature Astronomy 5 (2021) 472 [based on Dai et al, 2018];
see also Liu, Xi, Wang, 2020 for an off-axis jet; Zheng, Liu, Wang, 2022, Mukhopadhyay et al, 2023 for choked jets

Why no neutrinos from GRBs?

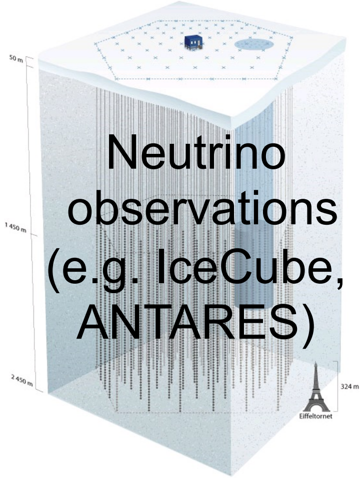
Focus on prompt phase, internal shocks

Source: NASA

Multimessenger bounds

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

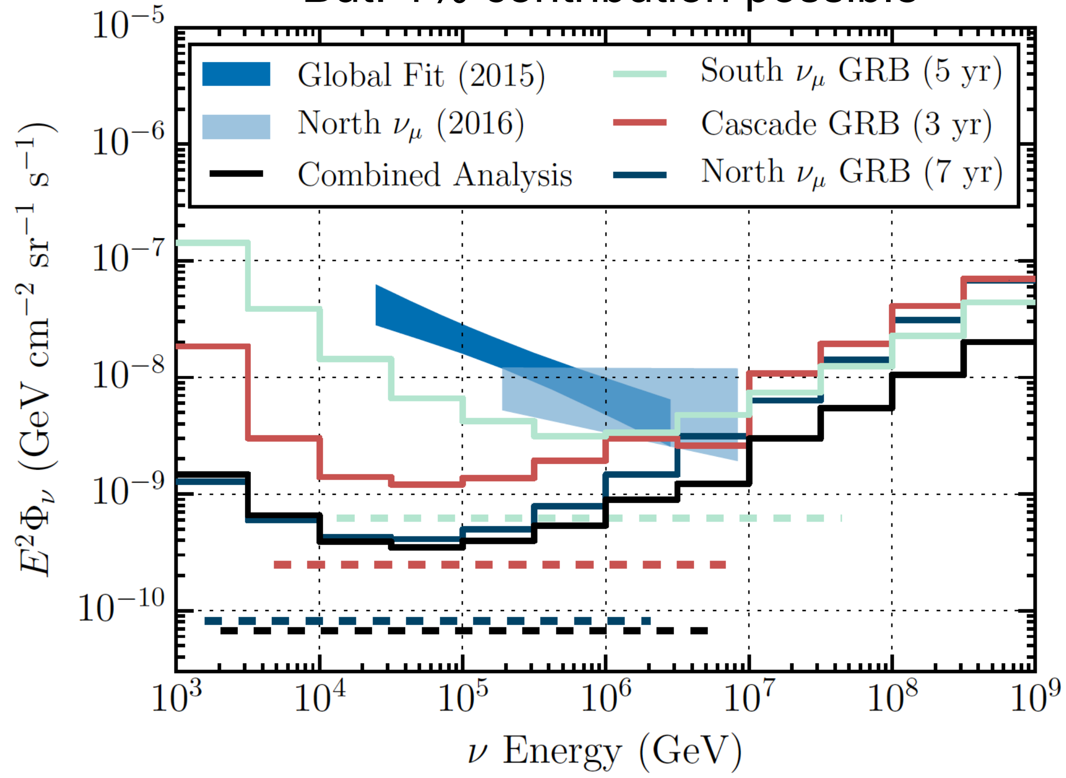
Coincidence?



Neutrino observations (e.g. IceCube, ANTARES)

Use timing, directional and energy information to reduce backgrounds

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

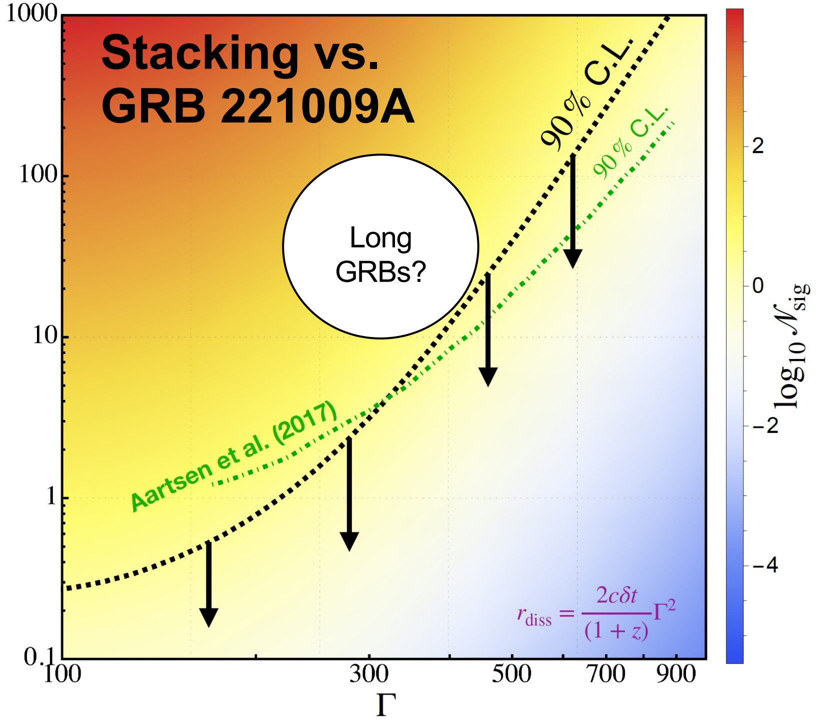


IceCube, Nature 484 (2012) 351;
Fig. from update: ApJ 843 (2017) 112

Fudge factor:
Baryonic loading $1/f_e$
(energy injected into non-thermal protons vs. electrons)

Required value to power UHECRs depends on:

- p spectrum, $E_{p,min}$ $1/f_e$
- UHECR escape mechanism
- Electron cooling efficiency
- Local GRB rate
- Peak of GRB luminosity function



Murase, Mukhopadhyay, Kheirandish, Kimura, Fang, 2022; see also Ai, Gao, 2022

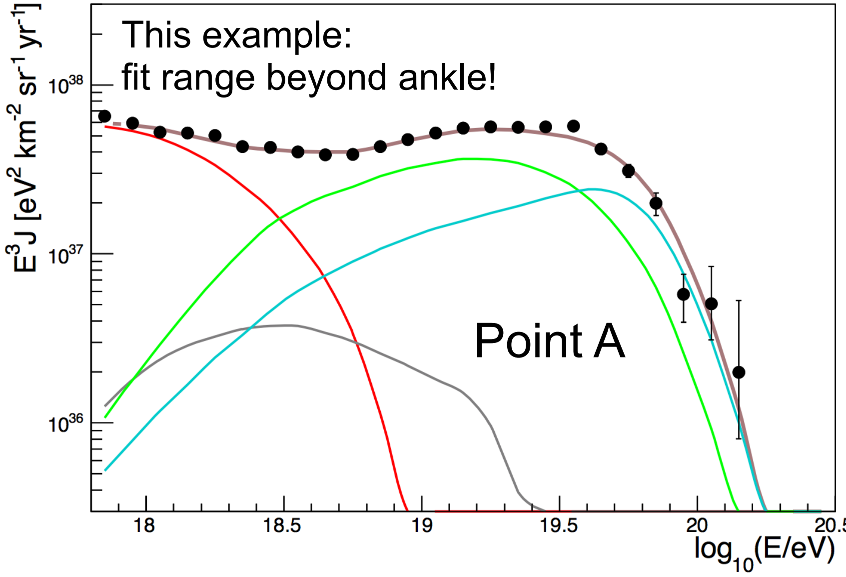
The vanilla one-zone prompt model

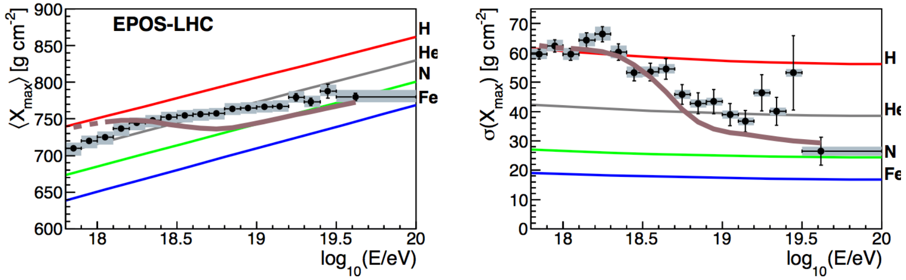
Quantitative studies require description of UHECR data (here: ankle model)

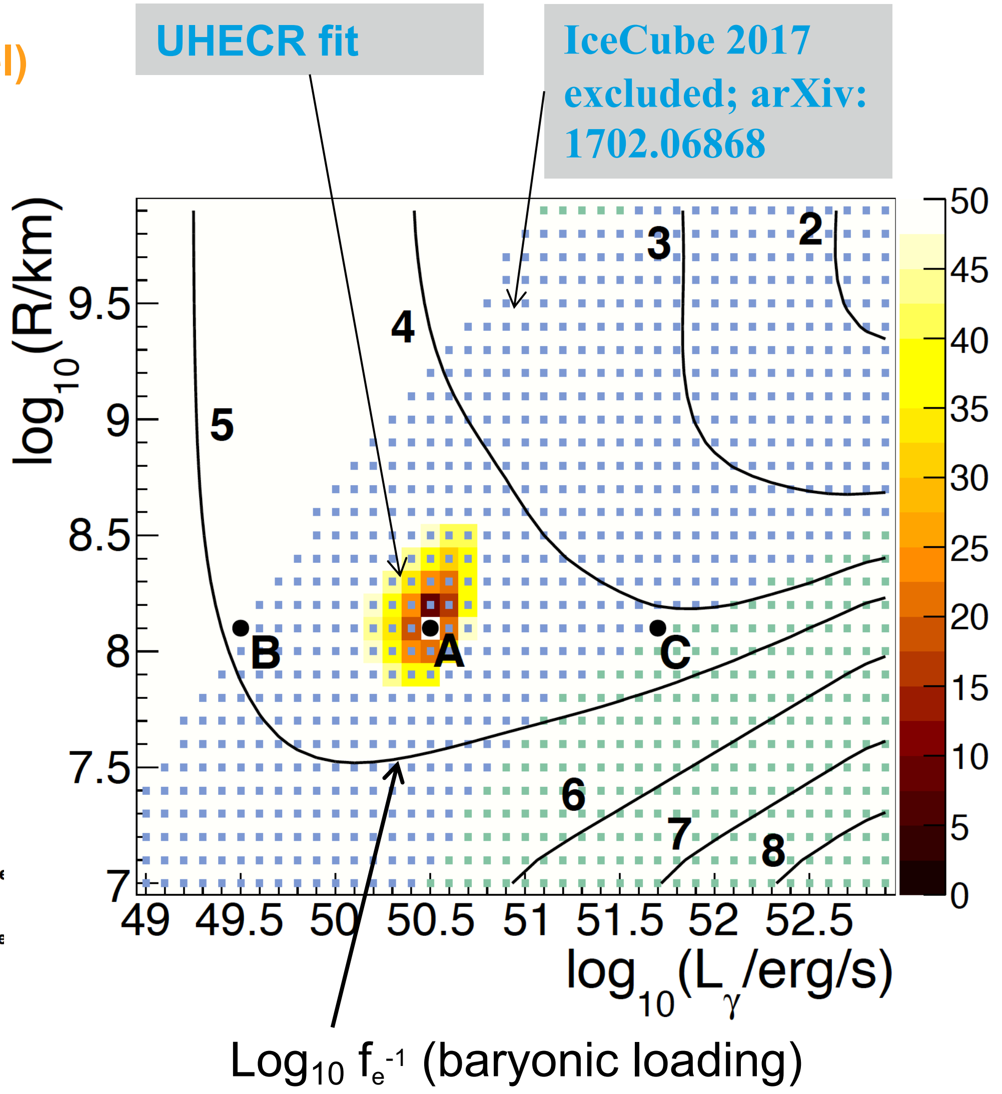
- Can describe UHECR data, but:
- Scenario is constrained by neutrino non-observatons
- Conclusion robust after extensive parameter space studies (e.g. different energy ranges)

Possible caveats:

- Low-luminosity GRBs
- Large R (magnetic reconnection?)



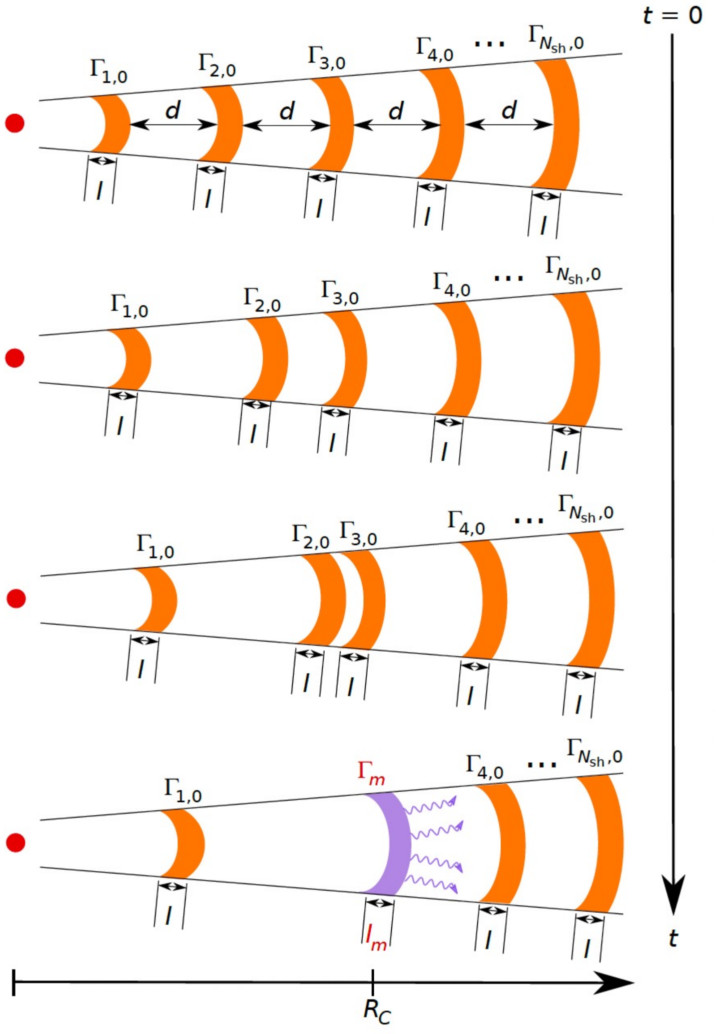




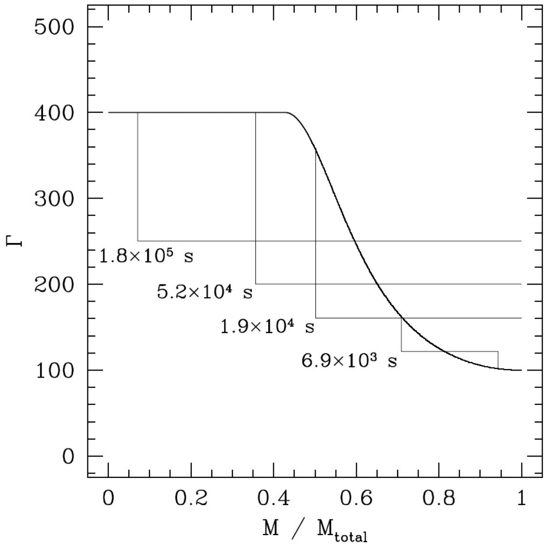
Biehl, Boncioli, Fedynitch, Winter, arXiv:1705.08909
Astron. Astrophys. 611 (2018) A101;
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

Back to the roots: Outflow models

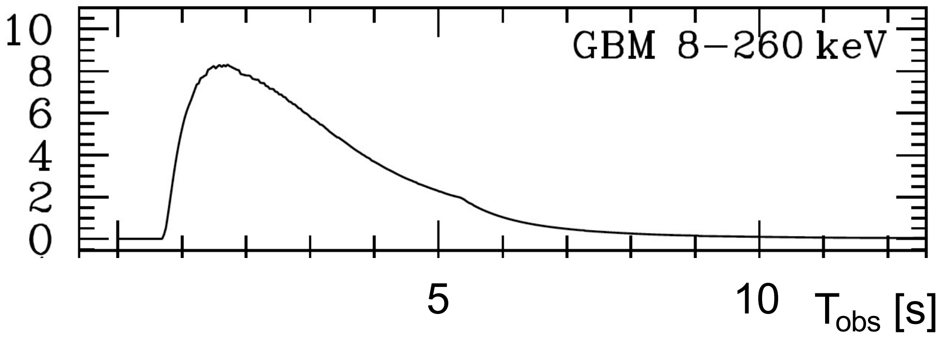
One zone approximation:
$t_v \sim l_m/c$ (variability timescale)
$R_C \sim \Gamma^2 d$ (distance to catch up)
Often: $d \sim l \rightarrow \mathbf{R_c \sim c\, \Gamma^2\, t_v}$



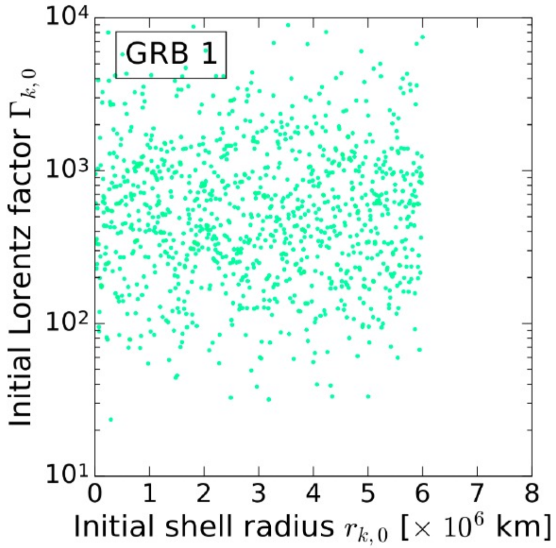
Continuous outflow: $t'_{dyn}=R_c/(c\,\Gamma)$

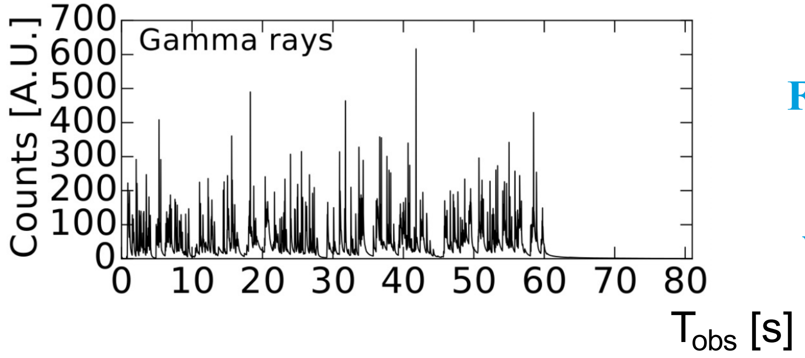


From: Bosnjak, Daigne, Dubus, A&A 498 (2009) 3



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

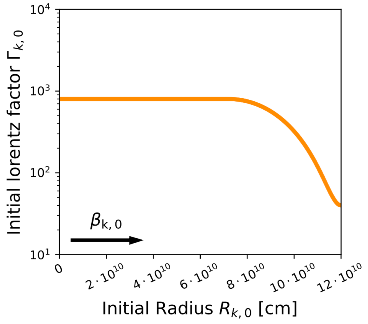
A unified engine model with free injection compositions

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

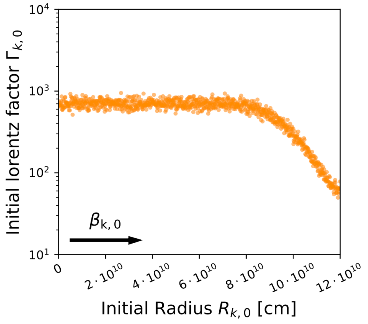
Model description

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

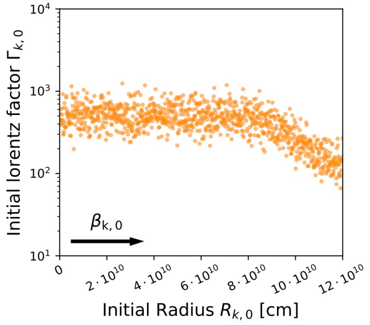
SR-0S
Strong (engine) ramp-up, no stochasticity



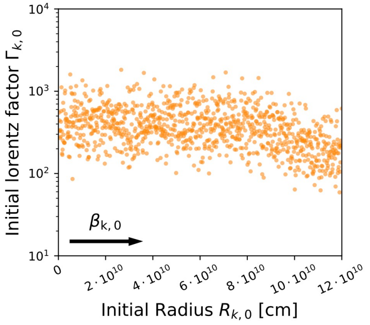
SR-LS
Strong (engine) ramp-up, low stochasticity



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



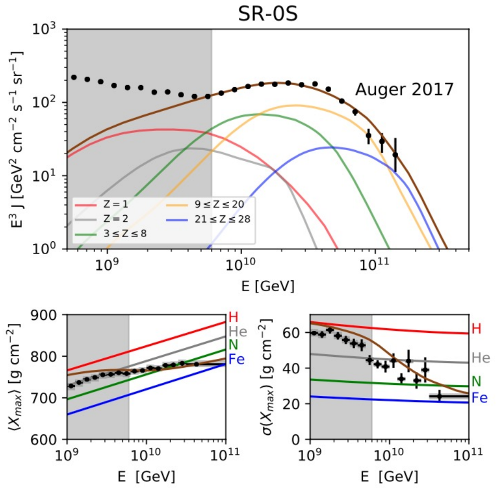
WR-HS
Weak (engine) ramp-up, high stochasticity

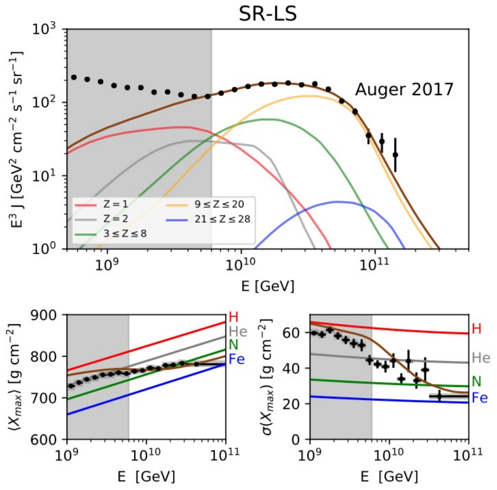


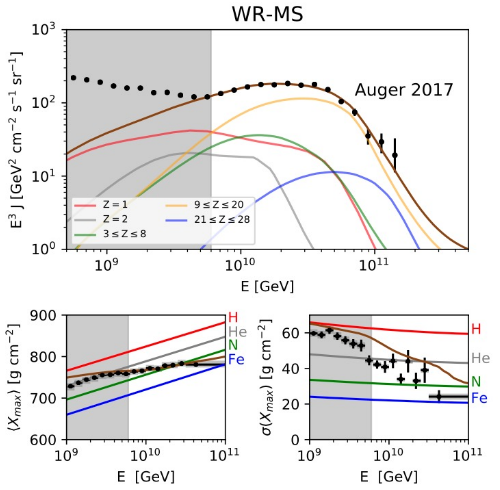
Describes UHECR data over a large range of parameters!

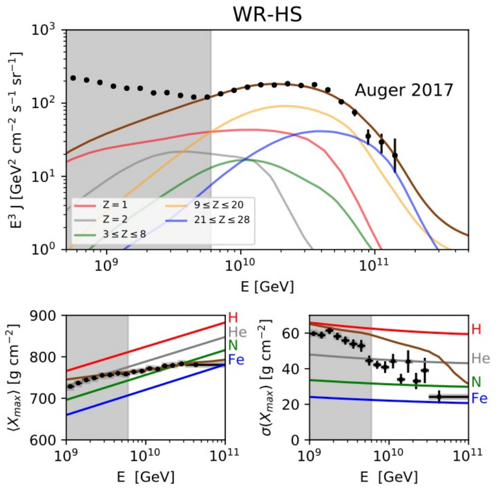
(systematically studied)

Description of UHECR data





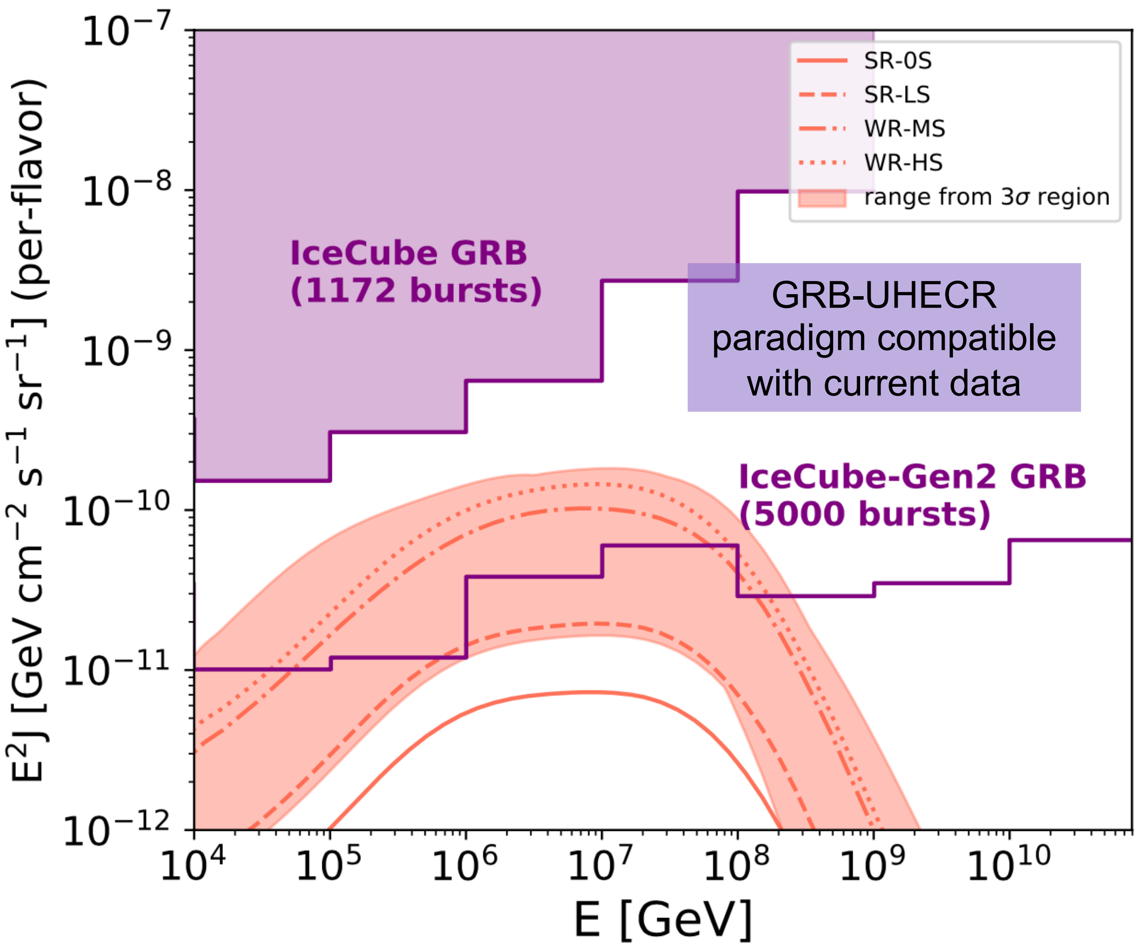


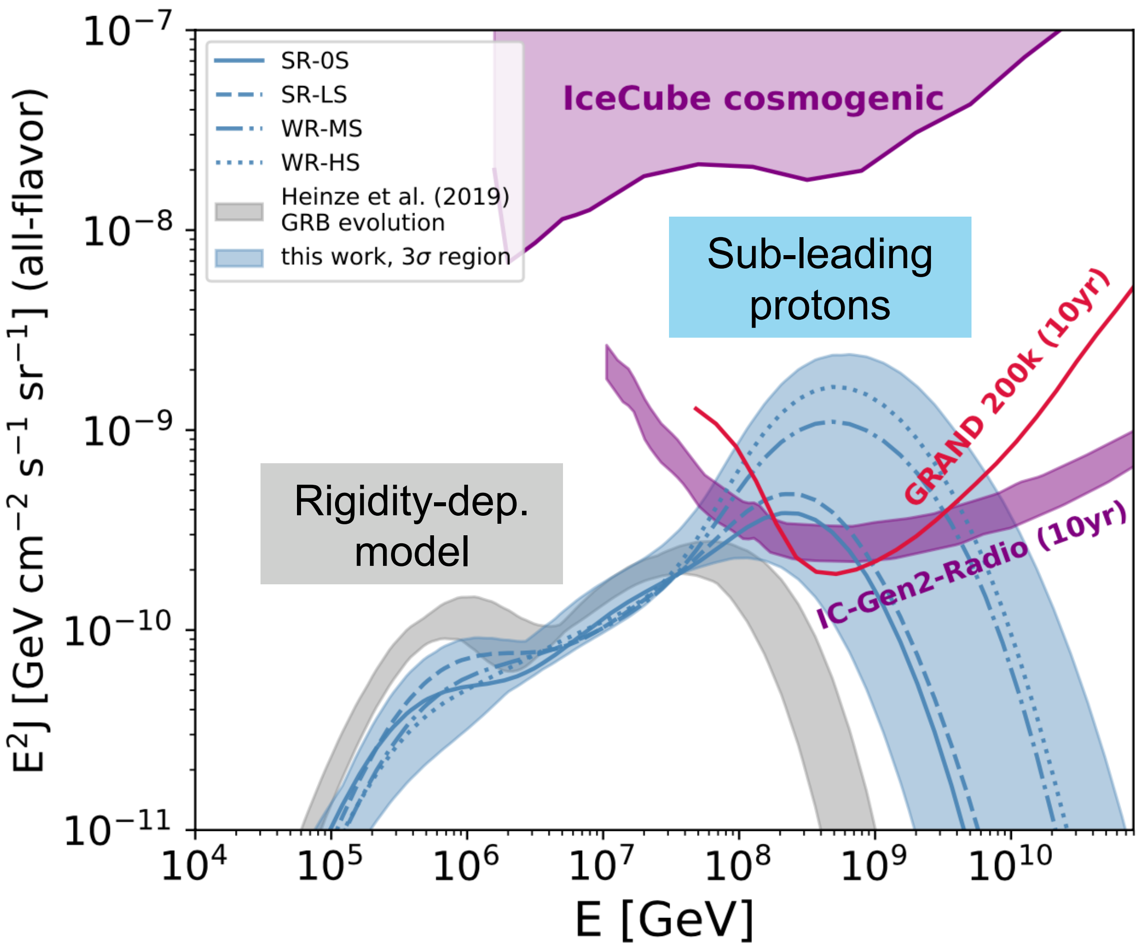


Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

Inferred neutrino fluxes from the parameter space scan

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



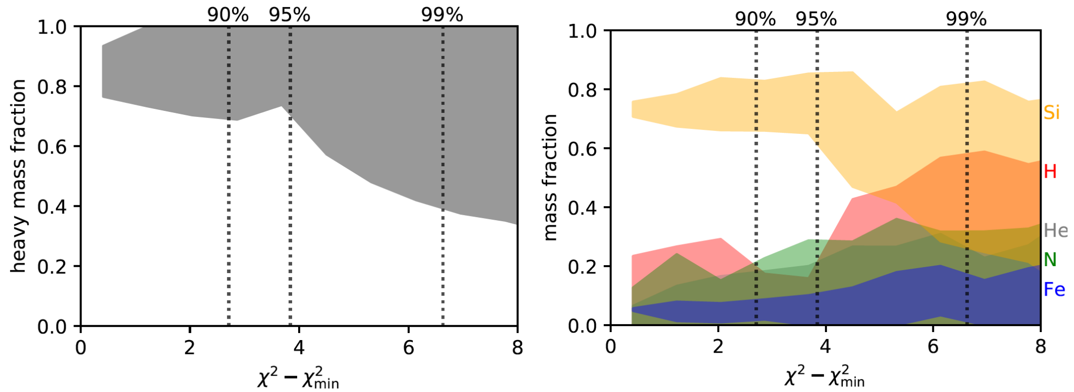


The different messengers "prefer" different production regions; one zone therefore no good approximation for neutrino production

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

Interpretation of the results and open issues

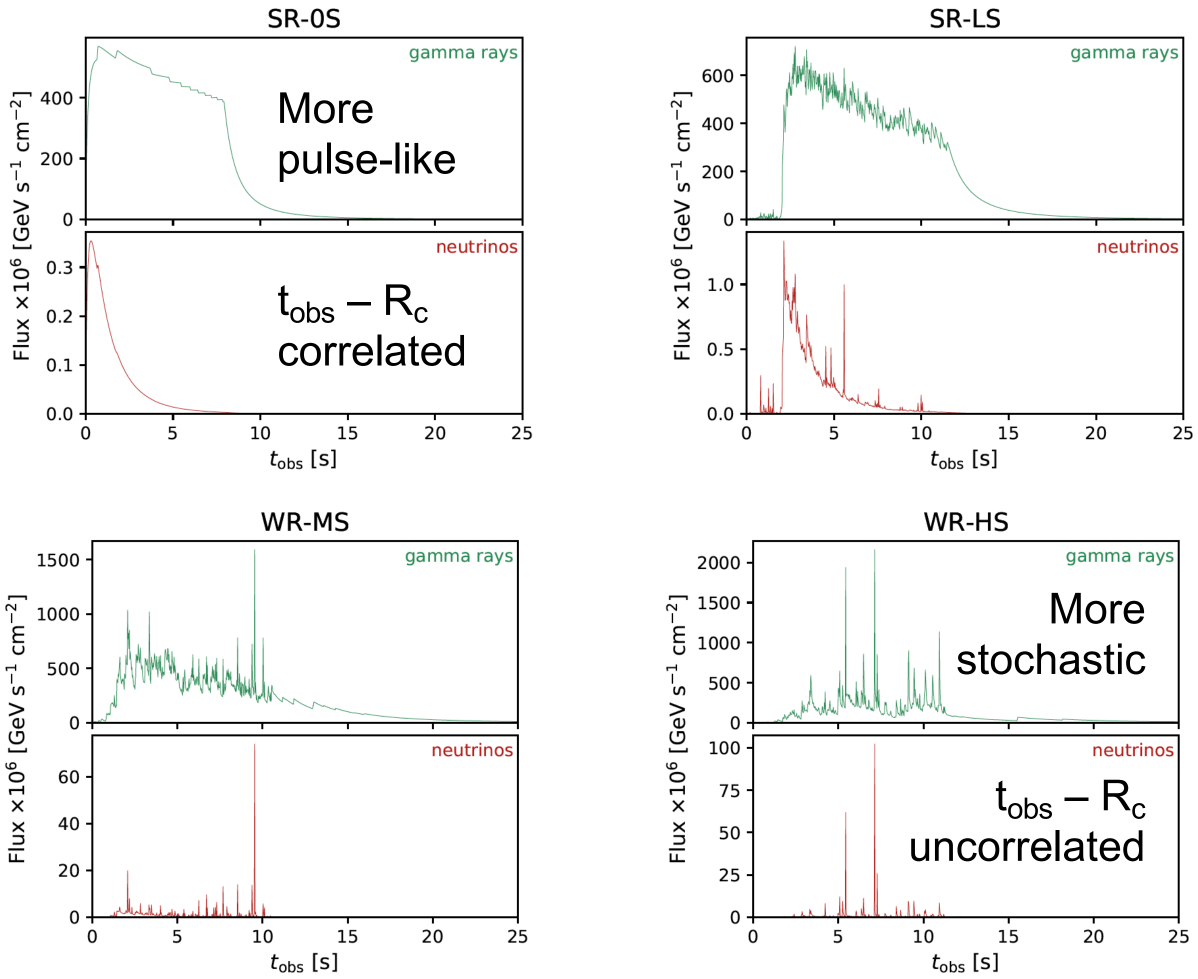
- The required injection compositon is derived: more that 70% heavy (N+Si+Fe) at the 95% CL (here: non-thermal energy fractions)



- 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^{esc}_{UHECR} (escape)	$2.01{\cdot}10^{53}$ erg	$2.10{\cdot}10^{53}$ erg	$1.85{\cdot}10^{53}$ erg	$1.69{\cdot}10^{53}$ erg
E^{src}_{CR} (in-source)	$5.11{\cdot}10^{54}$ erg	$5.13{\cdot}10^{54}$ erg	$4.62{\cdot}10^{54}$ erg	$4.36{\cdot}10^{54}$ erg
E^{src}_{UHECR} (in-source, UHECR)	$3.70{\cdot}10^{53}$ erg	$4.46{\cdot}10^{53}$ erg	$3.97{\cdot}10^{53}$ erg	$3.57{\cdot}10^{53}$ erg
E_ν	$7.81{\cdot}10^{49}$ erg	$2.18{\cdot}10^{50}$ erg	$1.28{\cdot}10^{51}$ erg	$1.79{\cdot}10^{51}$ erg
$E_{kin,init}$ (isotropic-equivalent)	$2.90{\cdot}10^{55}$ erg	$3.03{\cdot}10^{55}$ erg	$4.50{\cdot}10^{55}$ erg	$7.81{\cdot}10^{55}$ erg
Dissipation efficiency ϵ_{diss}	0.28	0.22	0.13	0.14

- Light curves may be used as engine discriminator

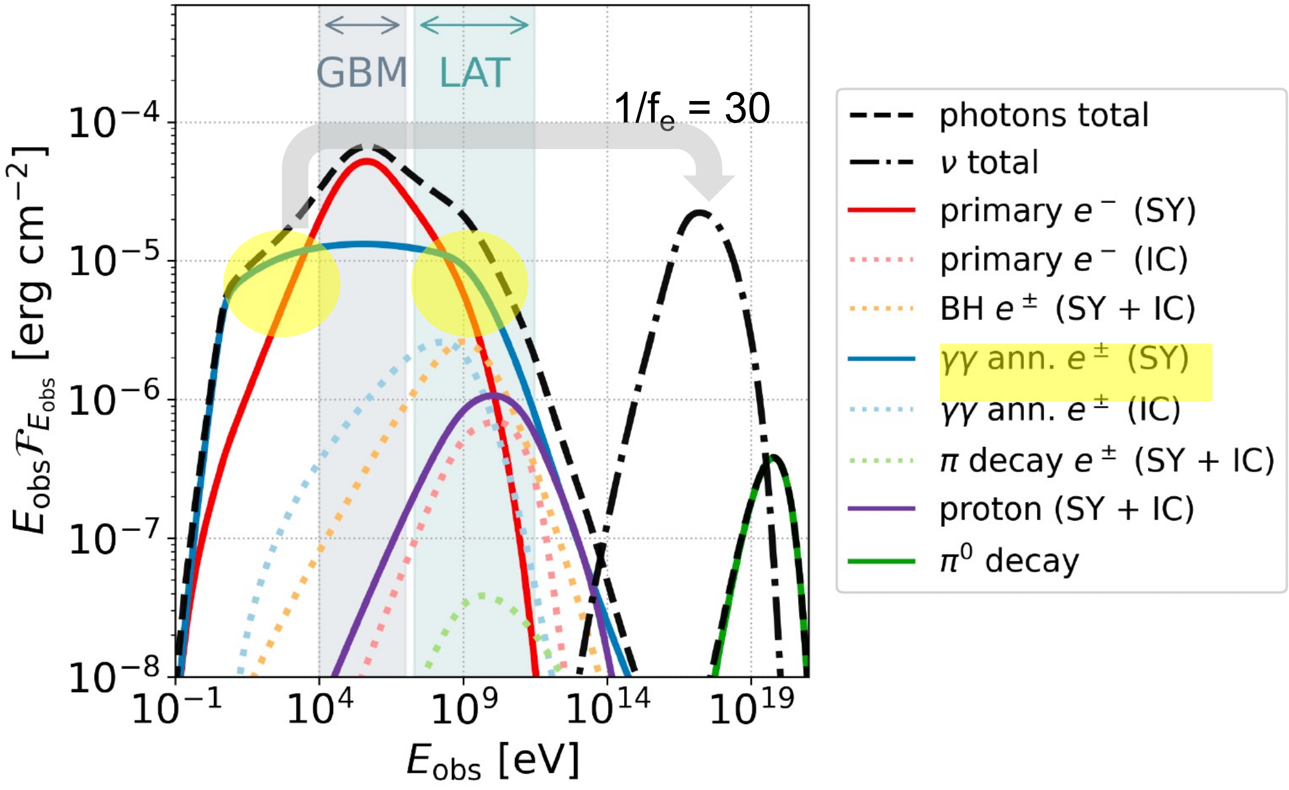


Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990

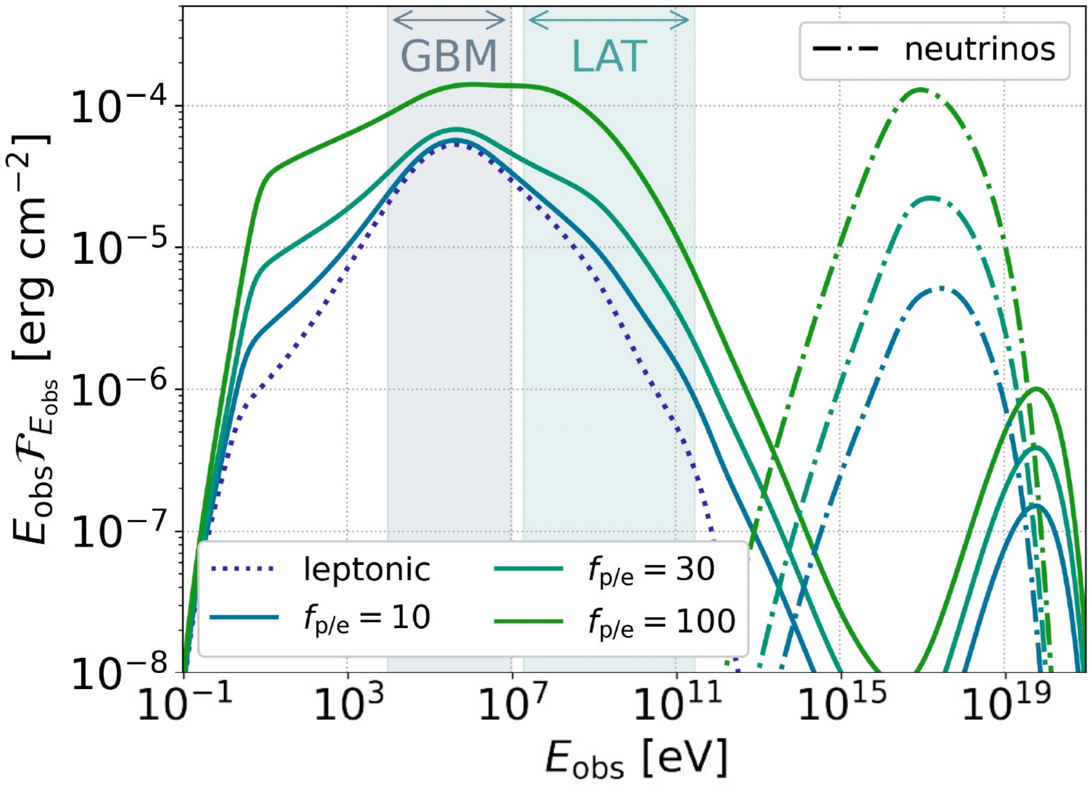
Hadronic signatures in the electromagnetic spectrum

Example: Energetic GRB with $E_{\gamma,iso}$ ~10^{54} erg, single pulse, synchrotron (fast) cooling dominated SED, large R_C ~ 10^{16} cm

Contribution from different components



Impact of baryonic loading:



→ Neutrino production dominated by low photon energies
→ Hadronic contributions enhance neutrino production
→ High peak neutrino energies

Baryonic loadings 3-10 do not modify electromagnetic spectrum at peak!

Rudolph, Petropoulou, Bosnjak, WW, ApJ 950 (2023) 1, 28.
See also Rudolph et al, ApJL 944 (2023) 2, L34 for the application to GRB 221009 and Asano, Inoue, Meszaros, ApJ 699 (2009) 953 (earlier work)

Summary and open issues

… from neutrino observations and the UHECR connection

Generic observations and open issues for acceleration models with relativistic outflows

- Neutrino production requires very efficient energy transfer into non-thermal protons. Are neutrino flares related to super-Eddington accretion events?
- Acceleration theory: Hard acceleration spectra or large $E_{p,min}$ can mitigate the energy crisis. Is there a connection with $E_{e,min}$?
- What does the required injection composition tell us about the UHECR acceleration?
- How do UHECRs escape from the source?

Neutrinos from AGN blazars

- Some convincing evidence
- Strong parameter constraints from SED on that zone
- Low neutrino production efficiency
- Certainly no energy equipartition e-p, super-Eddington accretion needed?

Neutrinos from TDE jets?

- Several hints for neutrinos from TDEs
- TDE jets interesting because they can address the energetics issue
- However, so far no clear identification of a *jetted* TDE with a neutrino

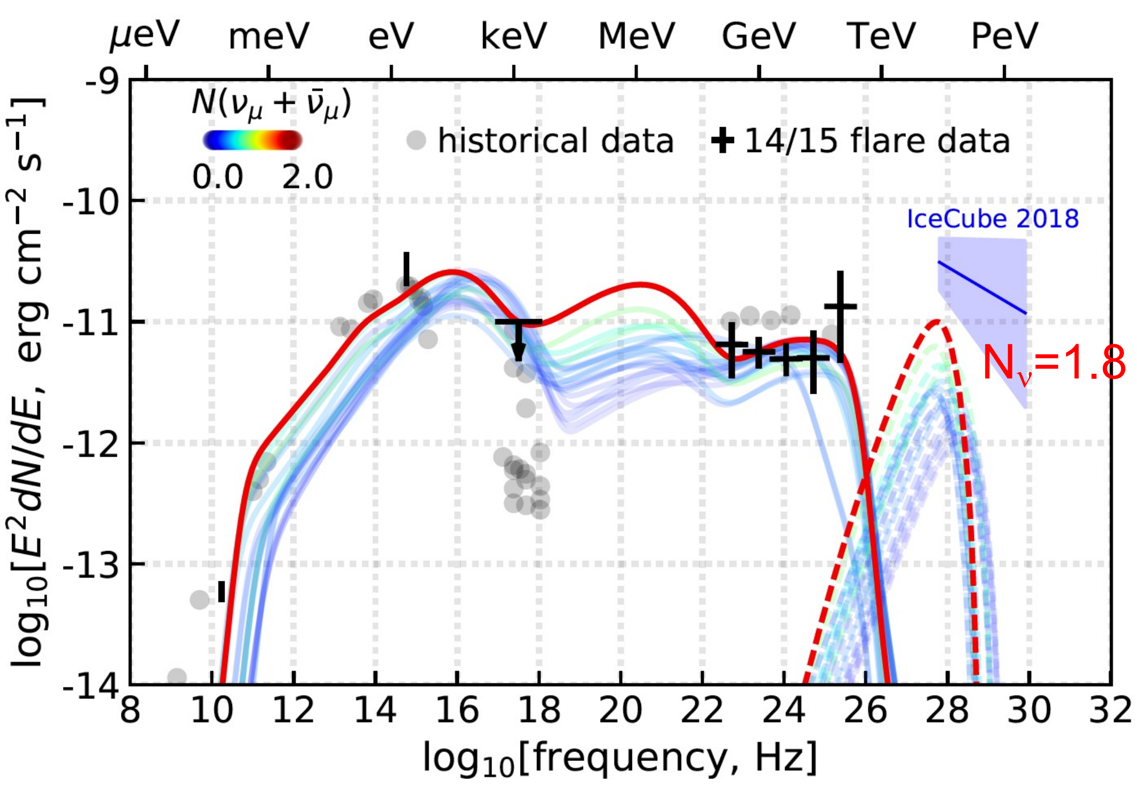
Neutrinos from GRBs

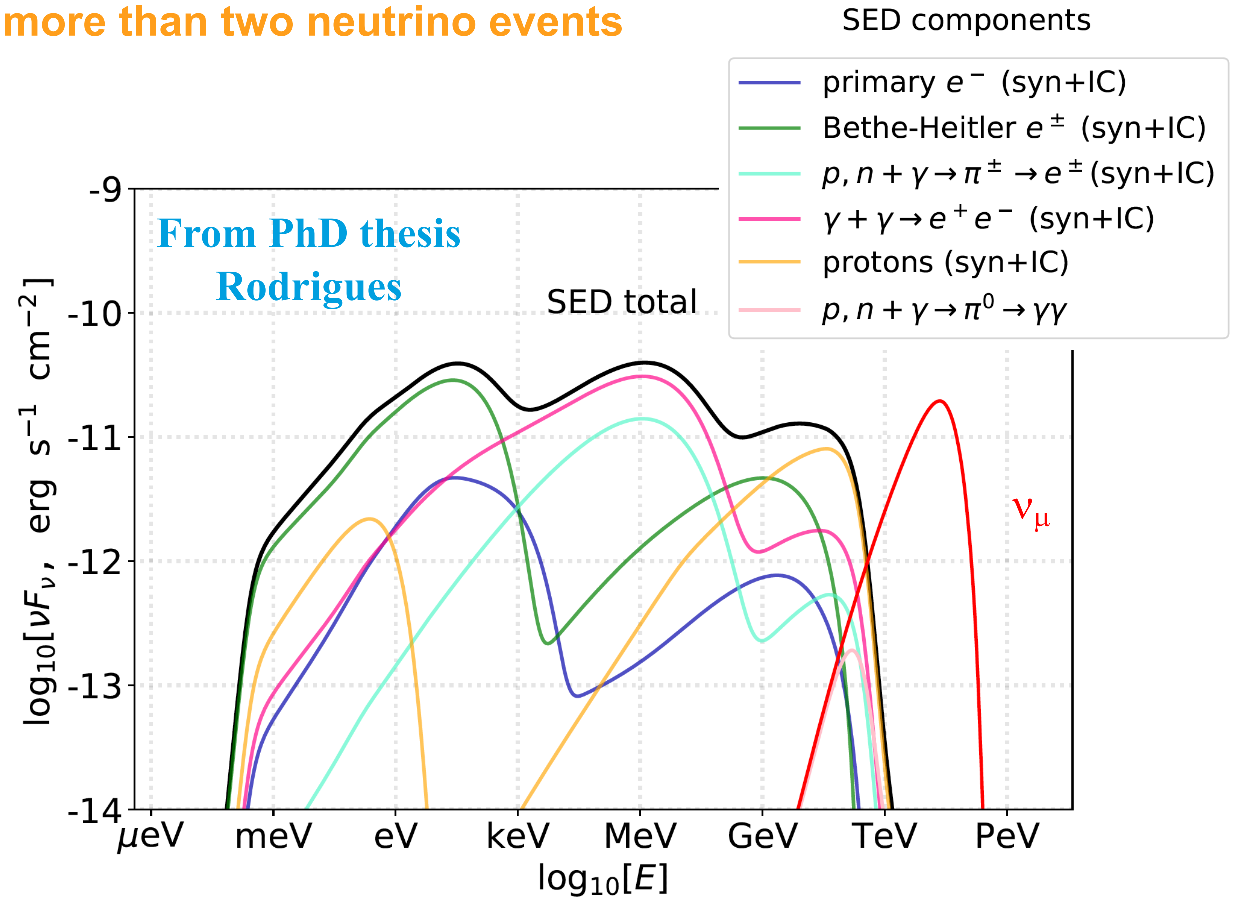
- Expected if GRBs are the sources of the UHECRs. Requires relatively high kinetic energies!
- So far no GRB neutrino seen
- One zone models constrained, but does not rule out UHECR paradigm in multi-zone models yet

BACKUP

One zone description of spectral energy distribution (AGN)

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



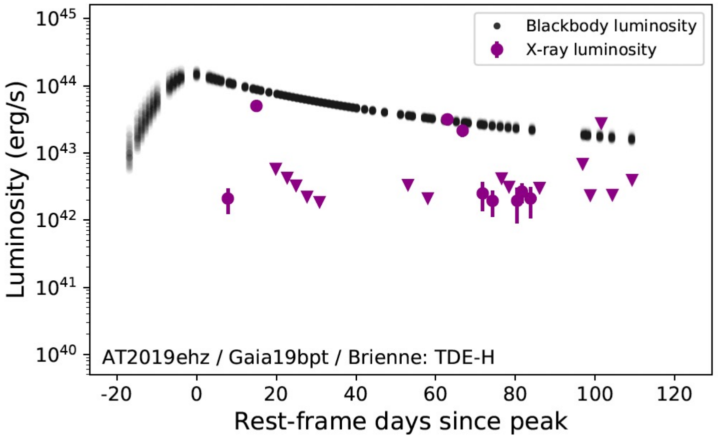


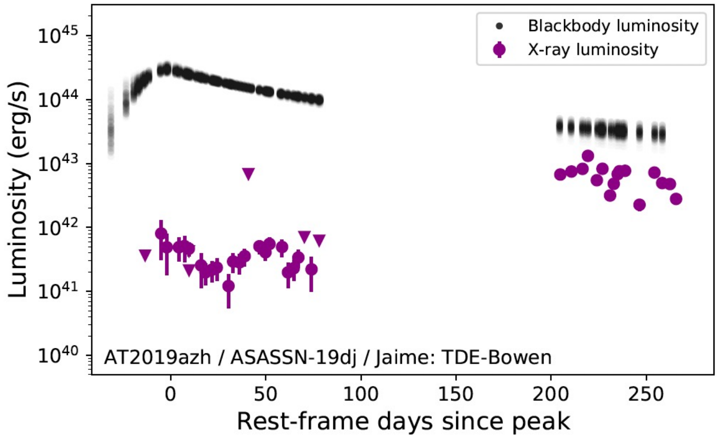
Energy deposited in MeV range and absorbed in EBL (here about 80% absorbed, 20% re-processed for E_γ > TeV)

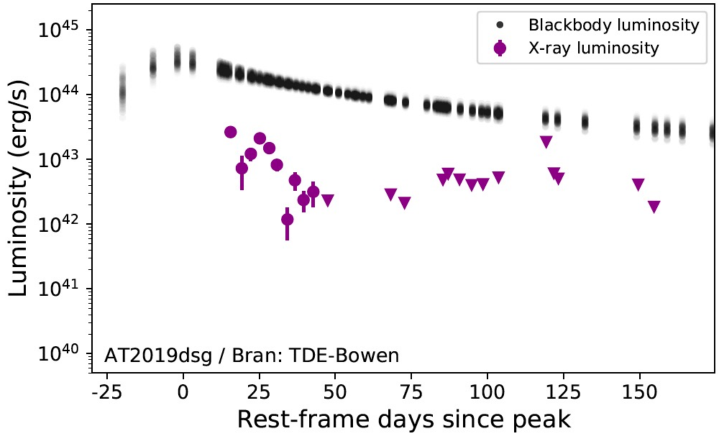
Primary electron processes (synchrotron and inverse Compton) dominate *nowhere* in this model!

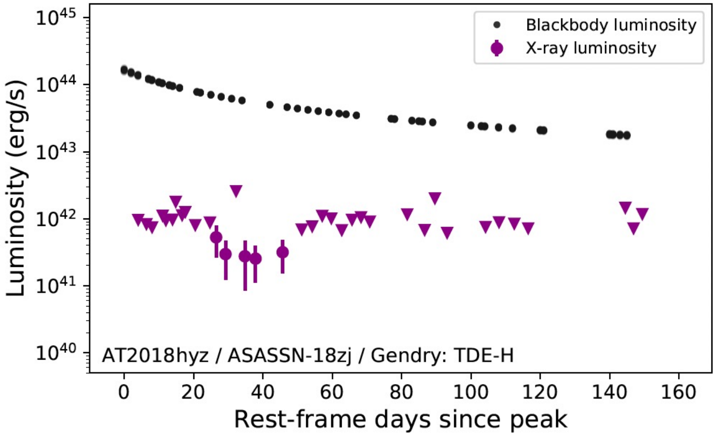
From: Rodrigues, Gao, Fedynitch, Palladino, Winter, ApJL 874 (2019) L29;
see also Halzen, et al, ApJL 874 (2019) 1, L9; Petropoulou et al, ApJ 891 (2020) 115

TDE observations (general)

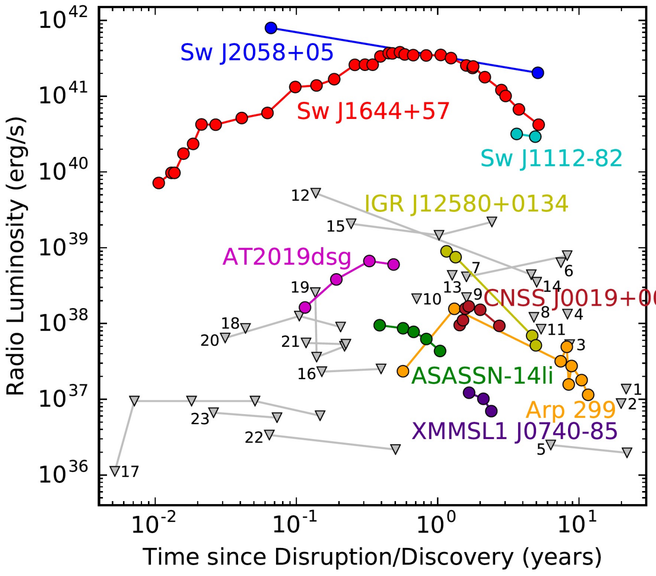








- **Optical-UV (blackbody):** Mass fallback rate typically exhibits a peak and then a ~ $t^{-5/3}$ dropoff over a few hundred days
- **X-rays:** Only observed in rare cases (here about 4 out of 17). X-ray properties very different
- **Radio:** Interesting signals in about 1/3 of all cases. Evolving radio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



Relat. jets?

Non-relat. outflows?

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

Neutrino 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:

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

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

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)

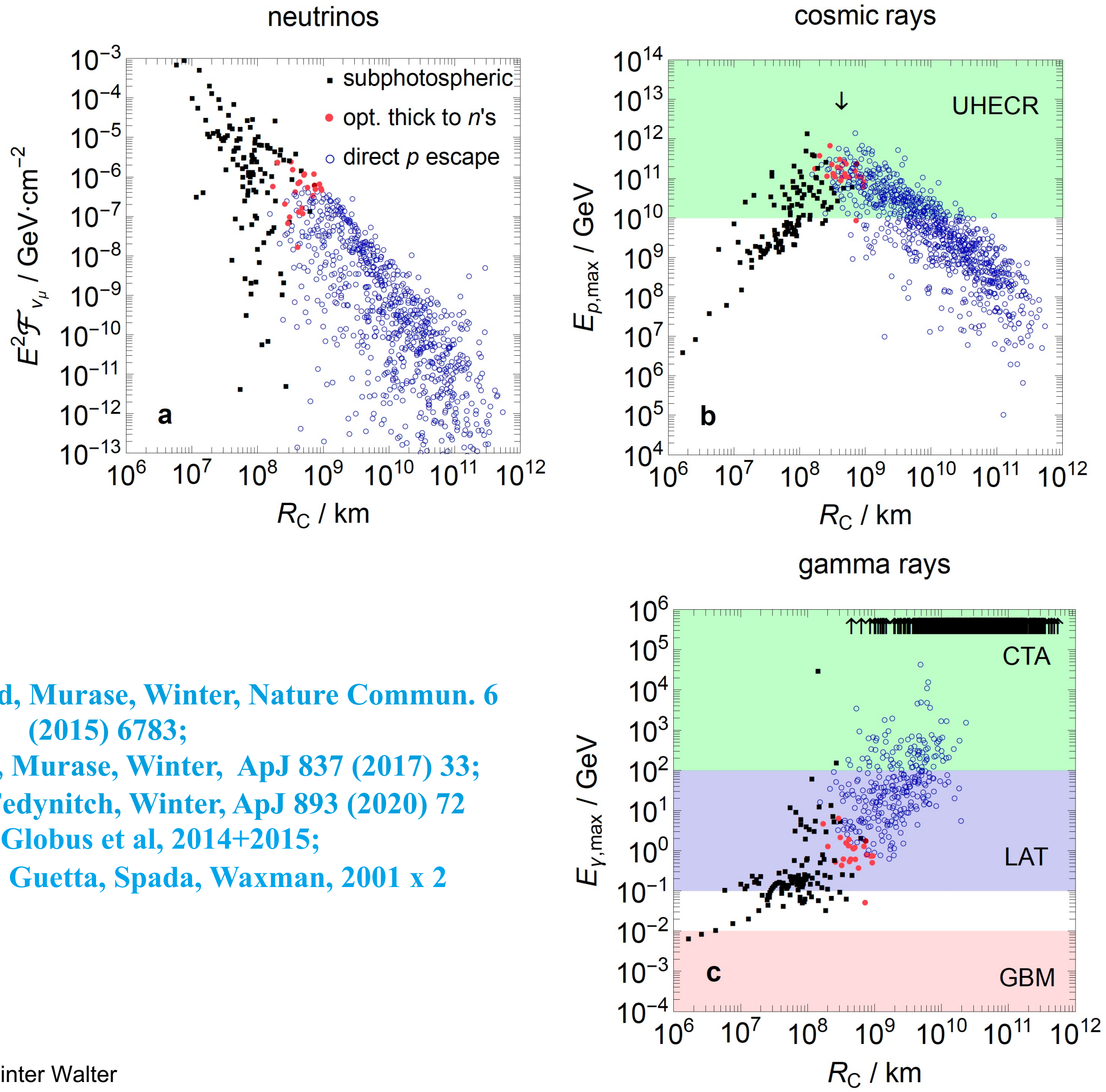
- **Production radius R and luminosity L_γ are the main control parameters for the particle interactions** [for fixed t_v] → Neutrino production, EM cascade from secondaries, nuclear disintegration, etc.

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

Back to the drawing board:

Multi-collision models

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



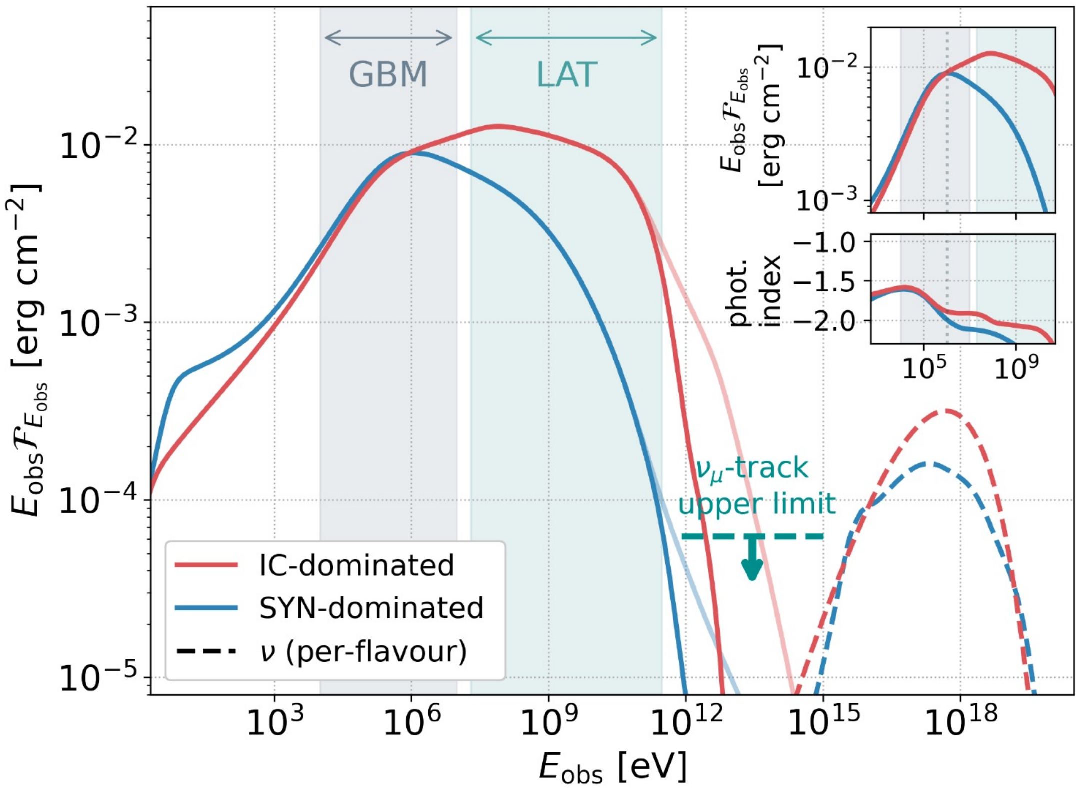
Bustamante, Baerwald, Murase, Winter, Nature Commun. 6 (2015) 6783;
Bustamante, Heinze, Murase, Winter, ApJ 837 (2017) 33;
Rudolph, Heinze, Fedynitch, Winter, ApJ 893 (2020) 72
see also Globus et al, 2014+2015;
earlier works e.g. Guetta, Spada, Waxman, 2001 x 2

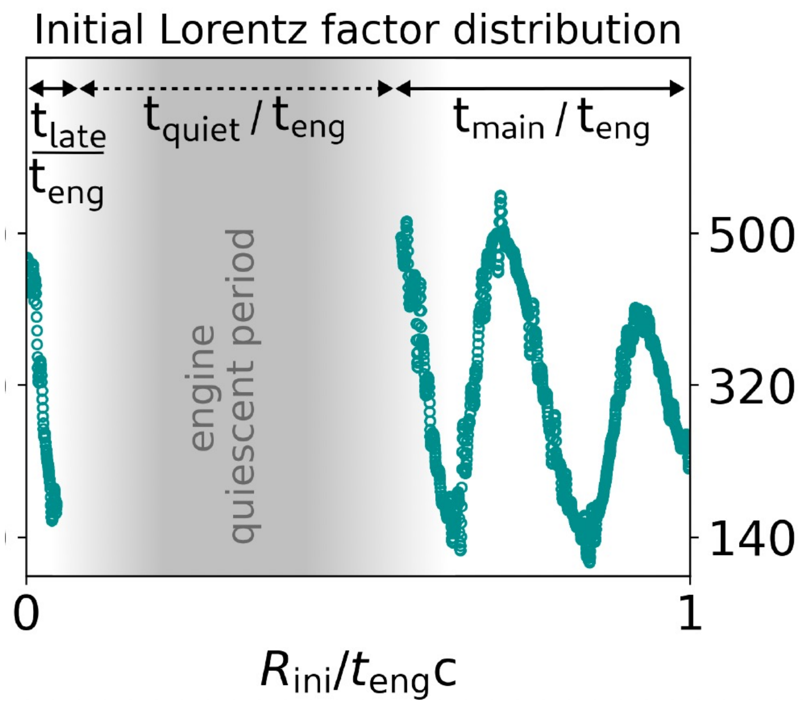
Observations

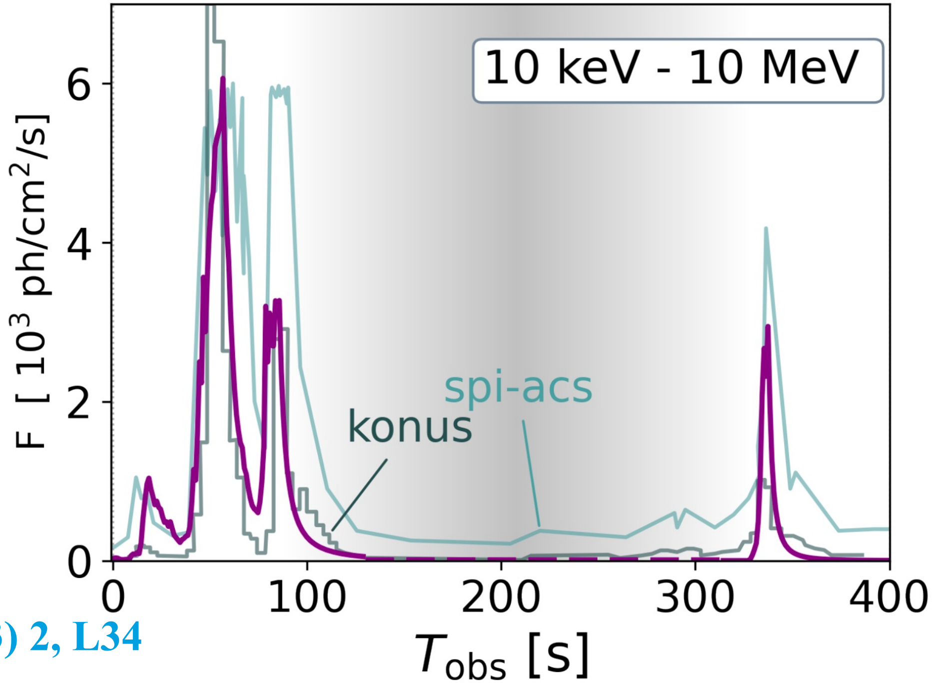
- The collision radius can vary over orders of magnitude
- The different messengers prefer different production regions; one zone therefore no good approximation
- The neutrino emission can be significantly lower
- The **engine properties** determine the nature of the (multi-messenger) light curves, and where the collisions take place
- Many aspects studied, such as impact of collision dynamics, interplay engine properties and light curves, dissipation efficiency etc.

Application to GRB 221009A

- Baryonic loading $1/f_e \sim 3$ consistent with UHECR paradigm, LHAASO photons from EBL interactions, ~energy equipartition
- Intermittent engine t_{var}~1s, quiescent period ~ 200s, $R_C \sim 10^{16}$ cm
- Spectrum does not carry significant hadronic signatures; neutrino spectra consistent with non-observation







Rudolph, Petropoulou, WW, Bosnjak, ApJL 944 (2023) 2, L34