Multi-Messenger views on Transient Phenomena

DESY/Science Communication Lab

Walter Winter
DESY, Zeuthen, Germany

Cosmic Rays and Neutrinos in the Multi-Messenger Era

Dec. 8-13, 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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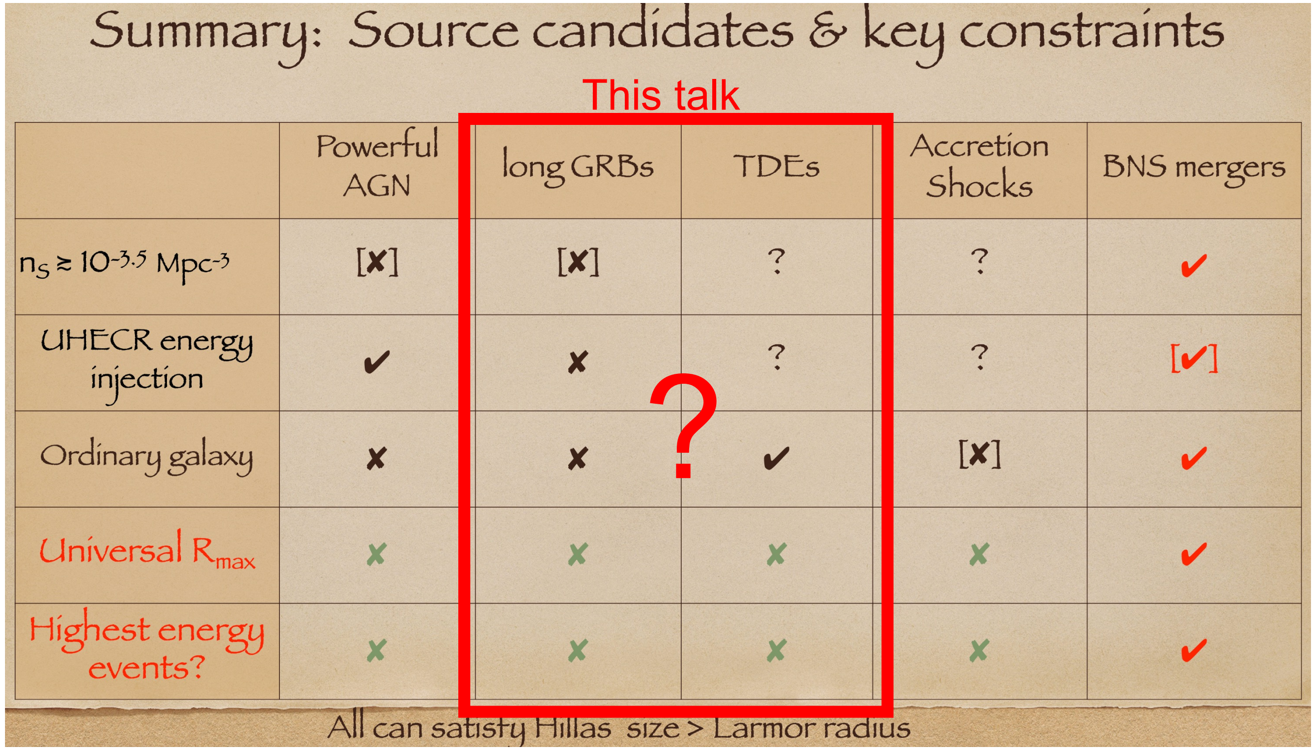
- **GRBs** and the UHECR paradigm
  - Introduction
  - Neutrino constraints on one-zone models
  - Outflow models
  - Can UHECRs and neutrinos be described?
  - Hadronic signatures in prompt phase and afterglow
- Neutrinos and UHECRs from **TDEs**?
  - Neutrino-TDE observations
  - Dust echo (IR) as target for UHECRs?
  - From a few associations to an UHECR-emitting population
  - What do we learn from UHECRs?
  - Gamma-ray constraints
- Summary

Why UHECRs from transients? See e.g. talks **Bister, Farrar, Unger**



Summary: Source candidates & key constraints

This talk

	Powerful AGN	long GRBs	TDEs	Accretion Shocks	BNS mergers
$n_S \gtrsim 10^{-3.5}$ Mpc^{-3}	[✘]	[✘]	?	?	✔
UHECR energy injection	✔	✘	?	?	[✔]
Ordinary galaxy	✘	✘	✔	[✘]	✔
Universal R_{max}	✘	✘	✘	✘	✔
Highest energy events?	✘	✘	✘	✘	✔

?

All can satisfy Hillas size > Larmor radius

From: Glennys Farrar's talk on Tuesday

GRBs and the UHECR paradigm

Source: NASA

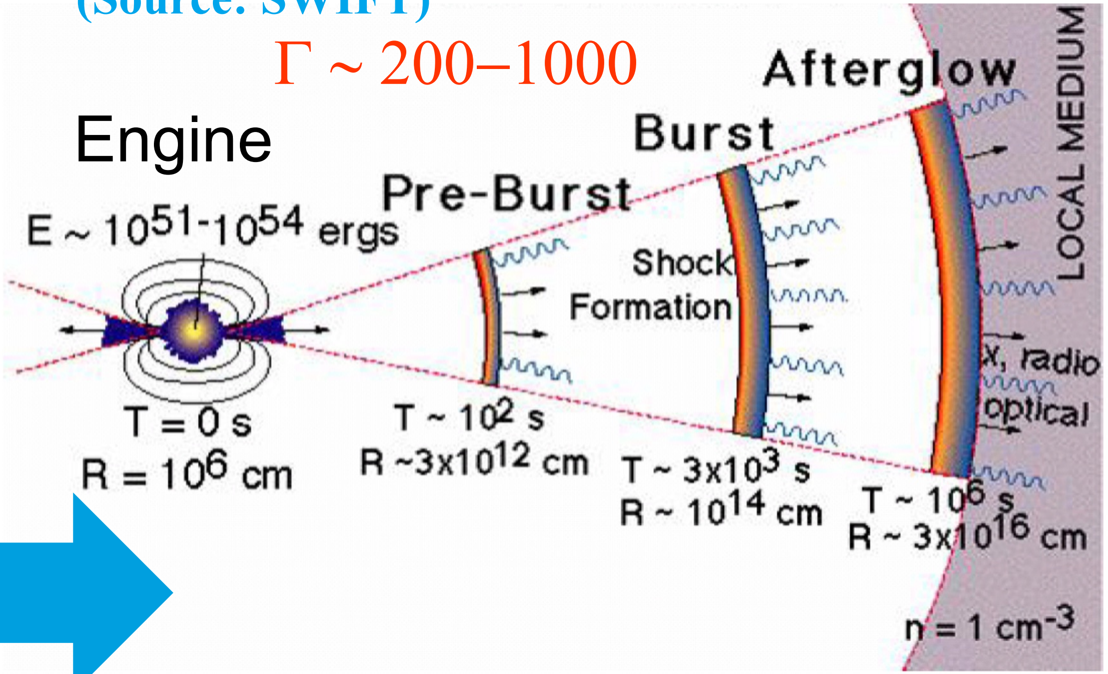
GRBs: Different regimes

Prompt phase

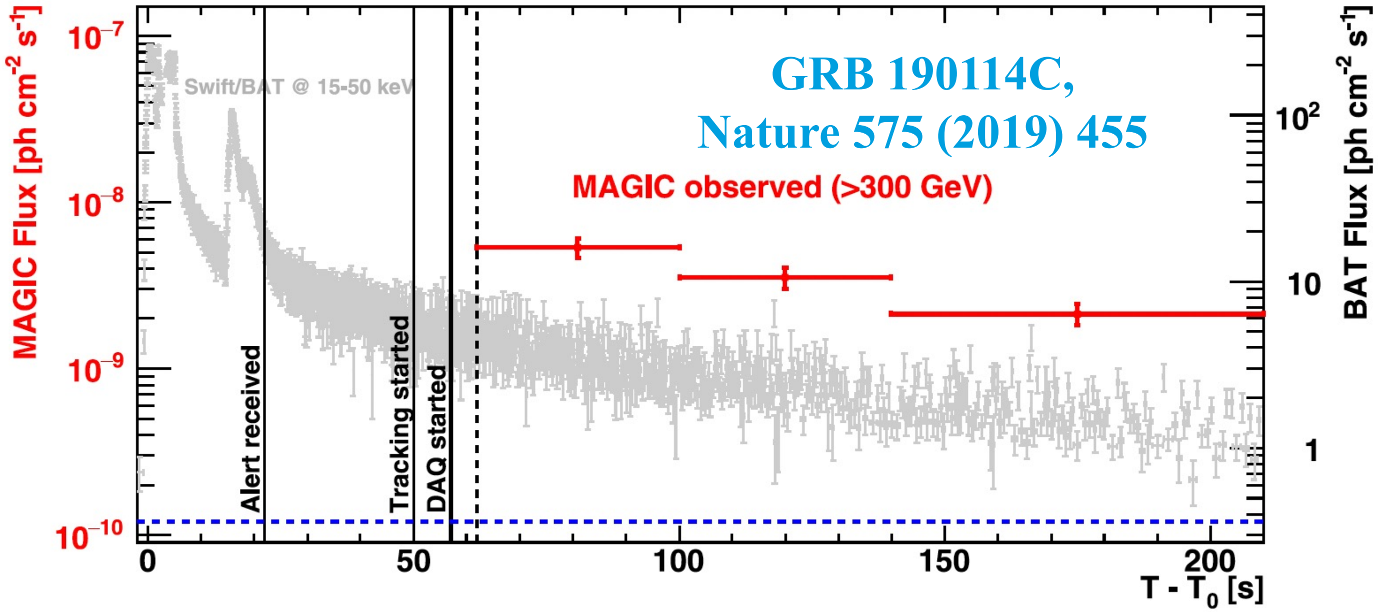
Prompt phase: Highest flux ⇨ Energetics

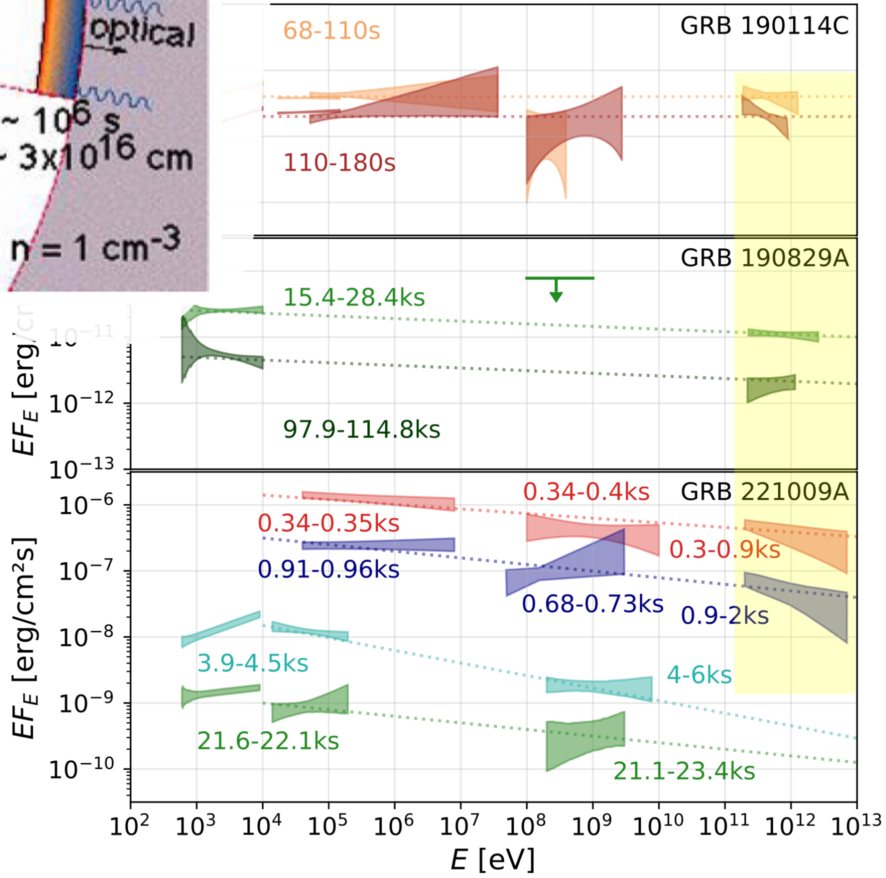
Afterglow

(Source: SWIFT)



Recently: Afterglow observations in VHE range





From: Klinger et al, ApJ accepted, arXiv:2403.13902

UHECR energetics and the Waxman-Bahcall paradigm

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

GeV

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

Required energy output per source

Fit to UHECR data

Source density

Rough estimate: Baryonic loading $1/f_e$ ~10 if E_γ ~10^{53} erg and about 10% in UHECR range

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

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

But: Required (in source) injection luminosity depends on:

- Injection spectrum, $E_{p,min}$
- Cosmic ray composition
- UHECR escape mechanism
- UHECR fit range
- Electron cooling efficiency
- Local GRB rate
- Peak of GRB luminosity function

Dedicated theoretical modeling needed
Source-propagation-(population) models

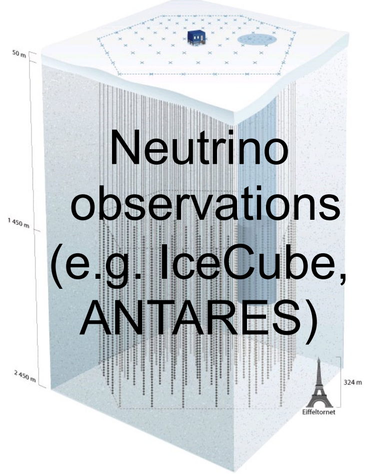
Purpose:
Baryonic loading/energetics derived from UHECR fit (instead of *ad hoc* fix), self-consistent picture

Neutrino stacking bounds

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

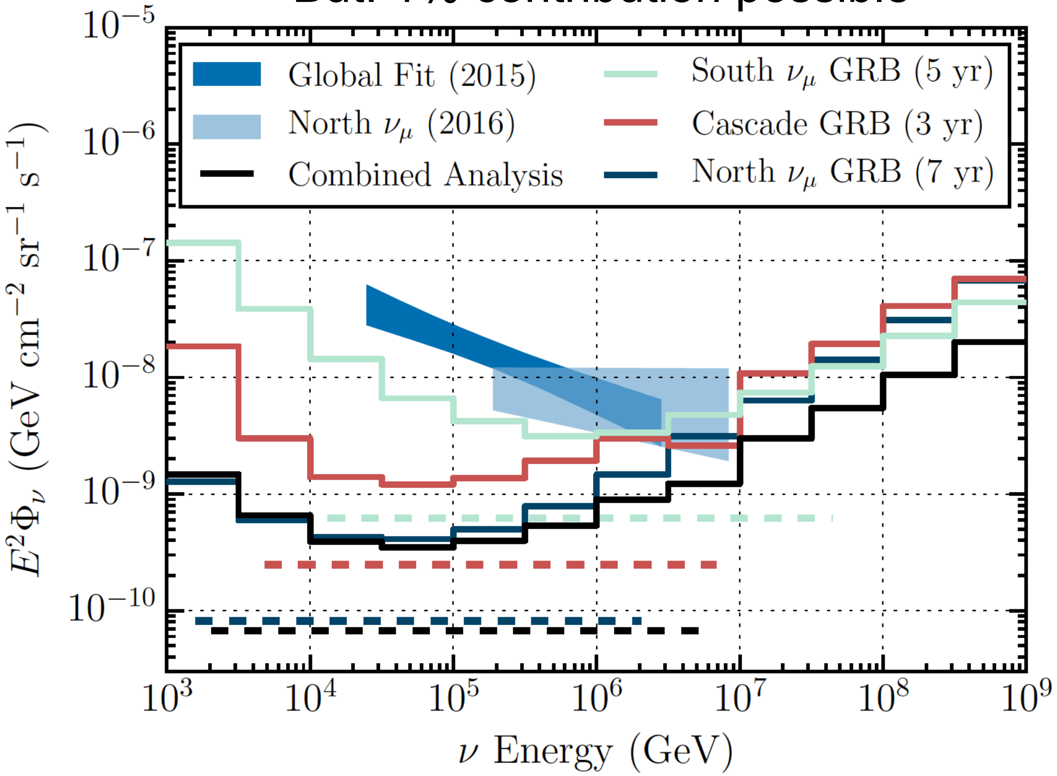
Coincidence?

Neutrino observations (e.g. IceCube, ANTARES)



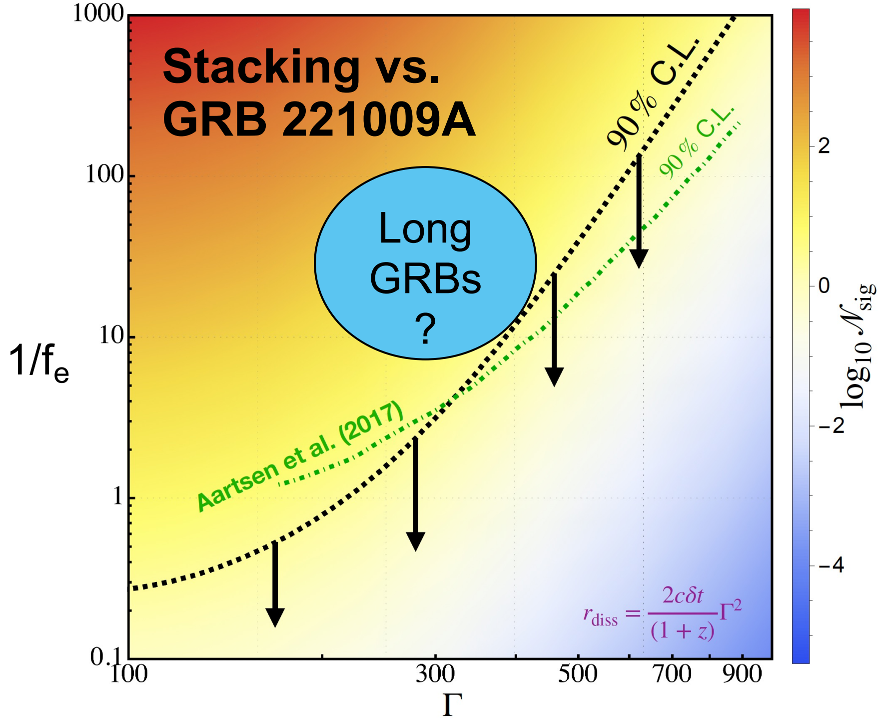
Use timing, directional and energy information to reduce backgrounds

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



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

Are GRBs the sources of the UHECRs?

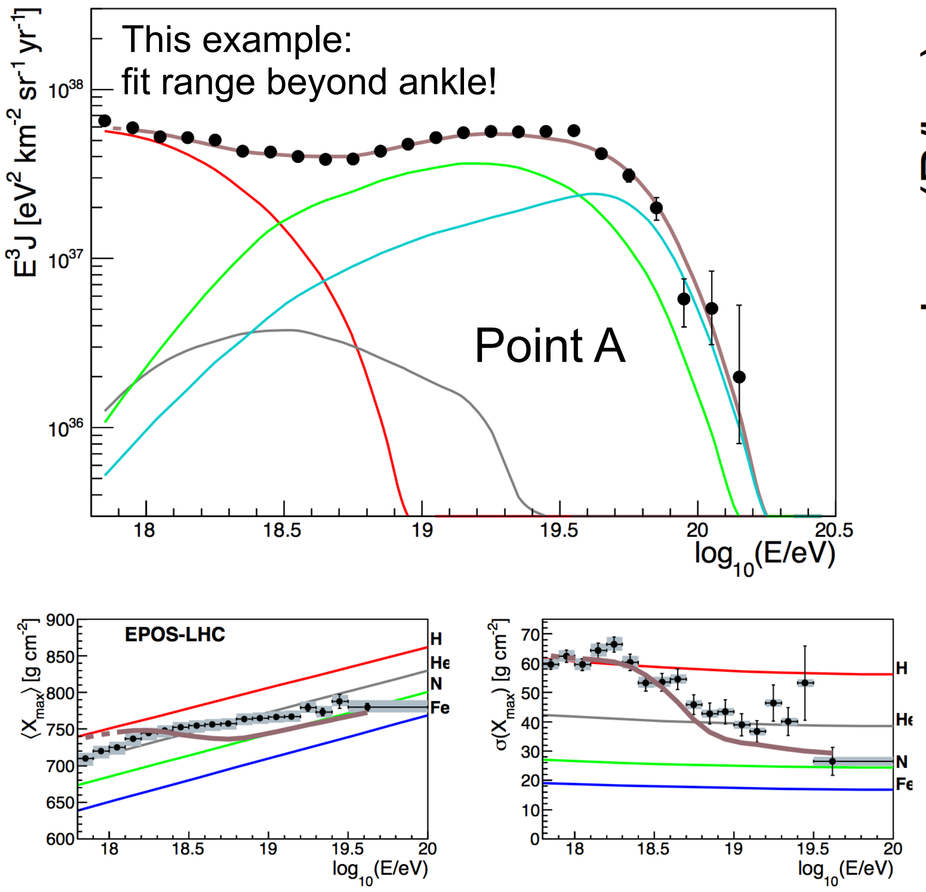


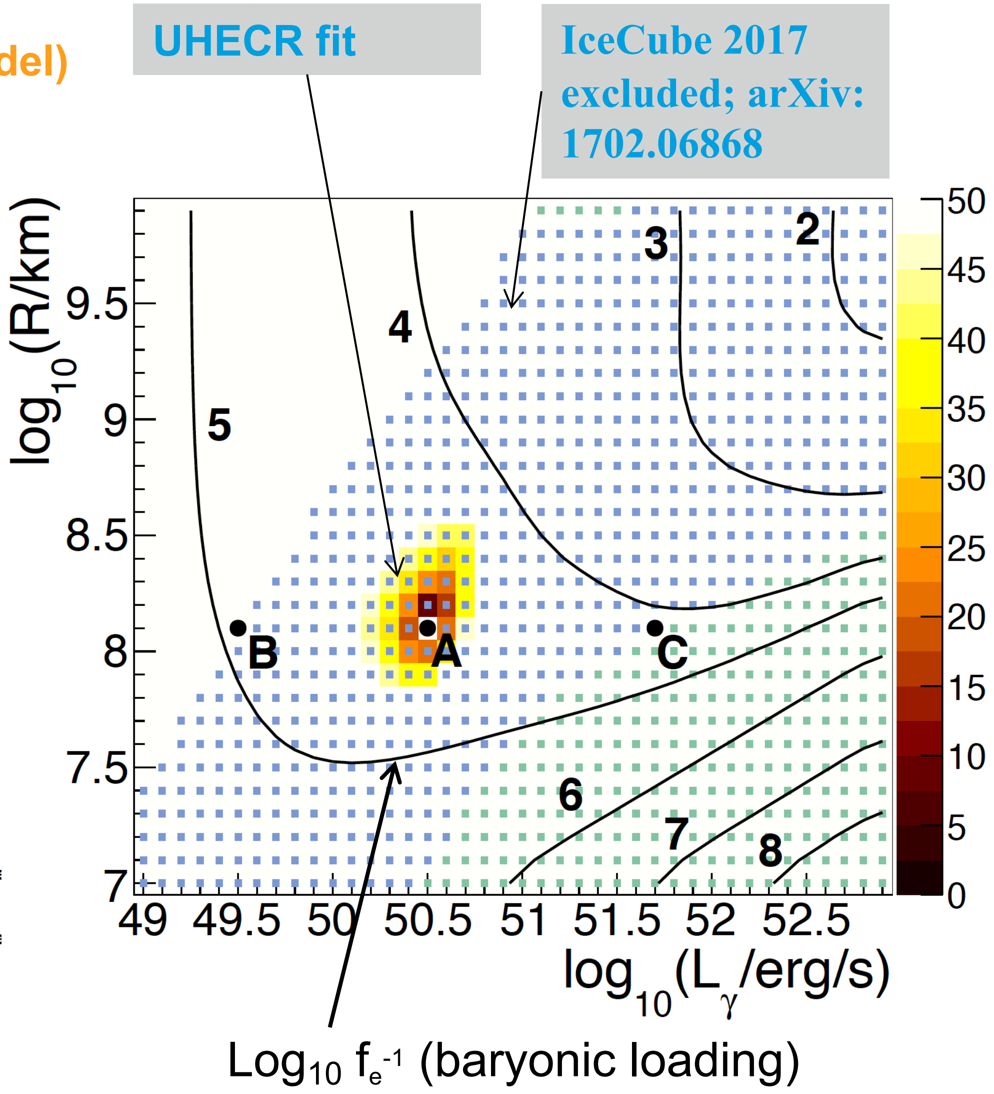
Murase, Mukhopadhyay, Kheirandish, Kimura, Fang, 2022; see also Ai, Gao, 2022

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?)

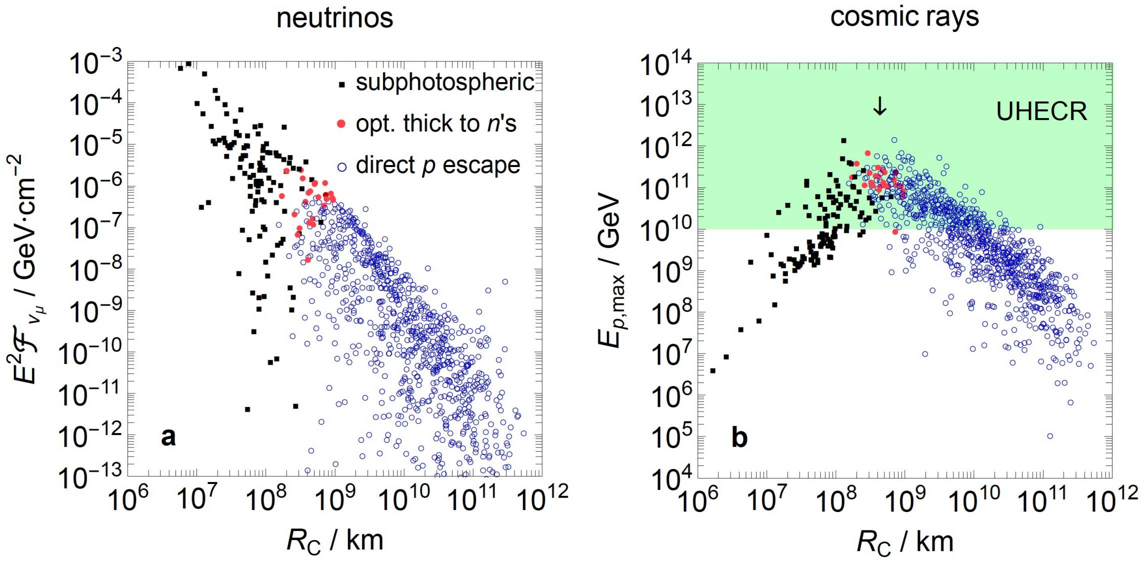


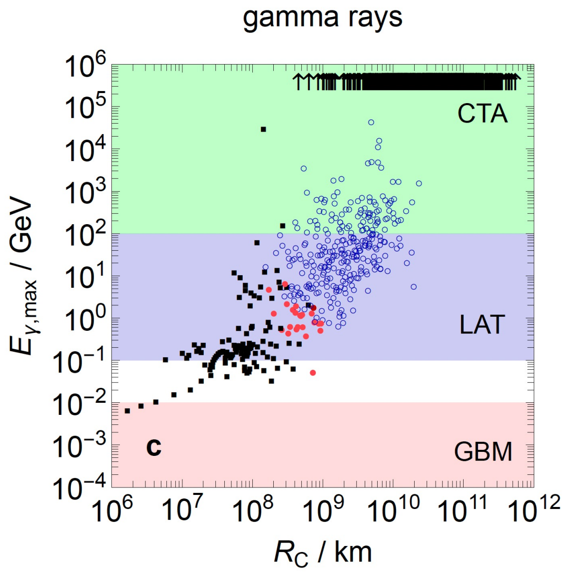


Biehl, Boncioli, Fedynitch, Winter, A&A 611 (2018) A101;
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

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

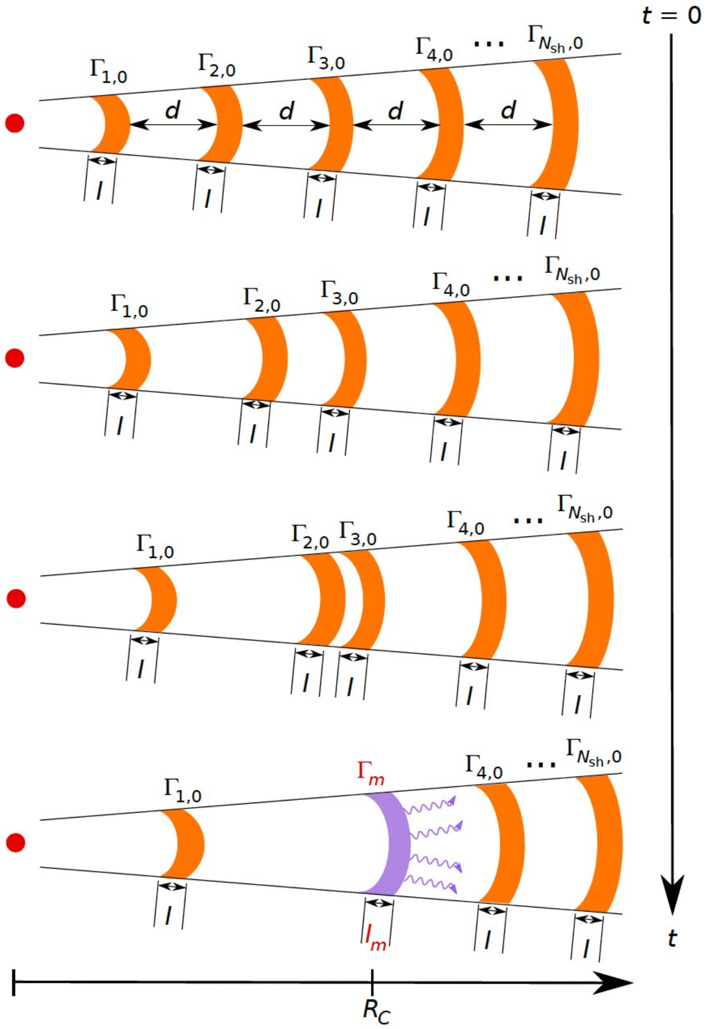
Observations

- The collision radius can vary over orders of magnitude
- Different messengers prefer different production regions
- 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.

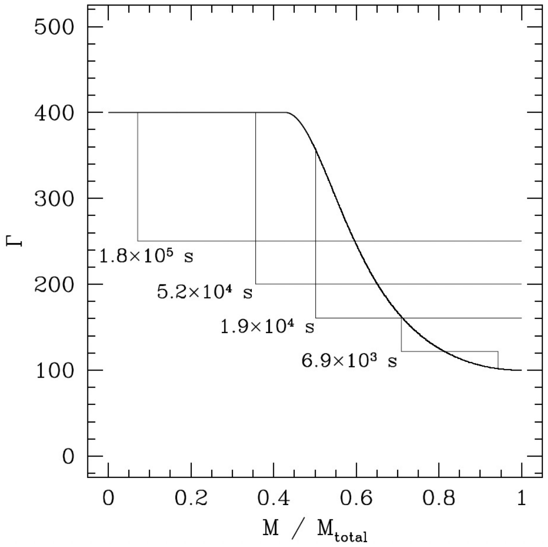
Outflow models

Continuous versus discrete

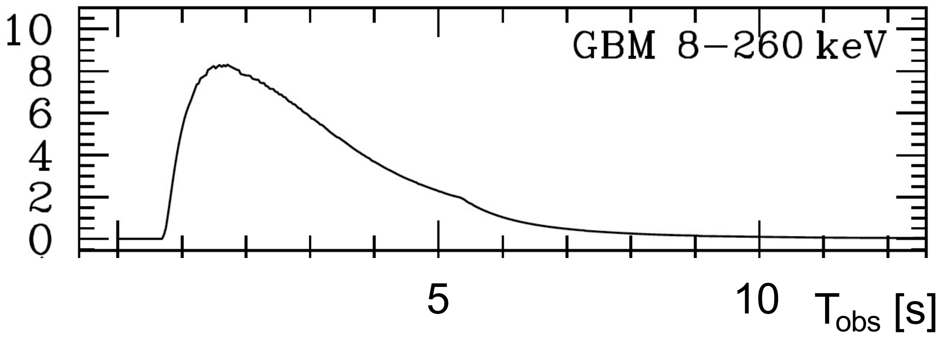
One zone approximation:
$t_v \sim l_m/c$ (variability timescale)
$R_C \sim \Gamma^2 d$ (distance to catch up)
Often: $d \sim l \rightarrow \mathbf{R_c \sim c\, \Gamma^2\, t_v}$



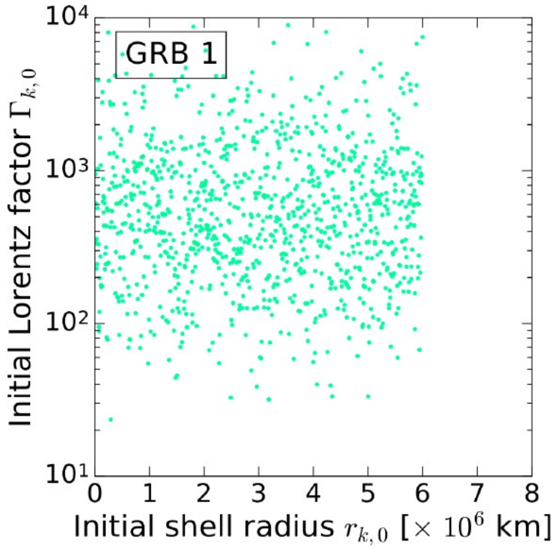
Continuous outflow: $t'_{dyn}=R_c/(c\,\Gamma)$

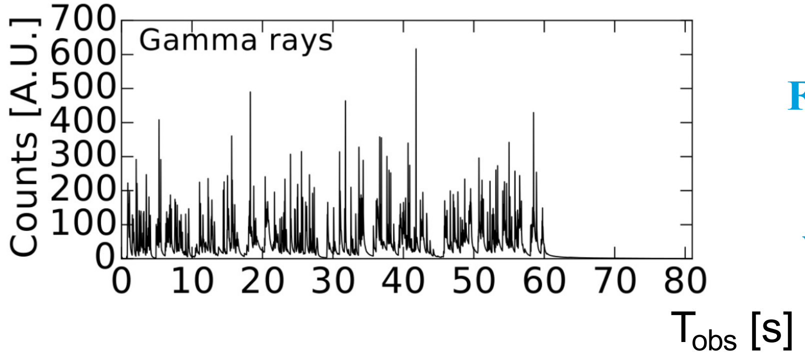


From: Bosnjak, Daigne, Dubus, A&A 498 (2009) 3



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





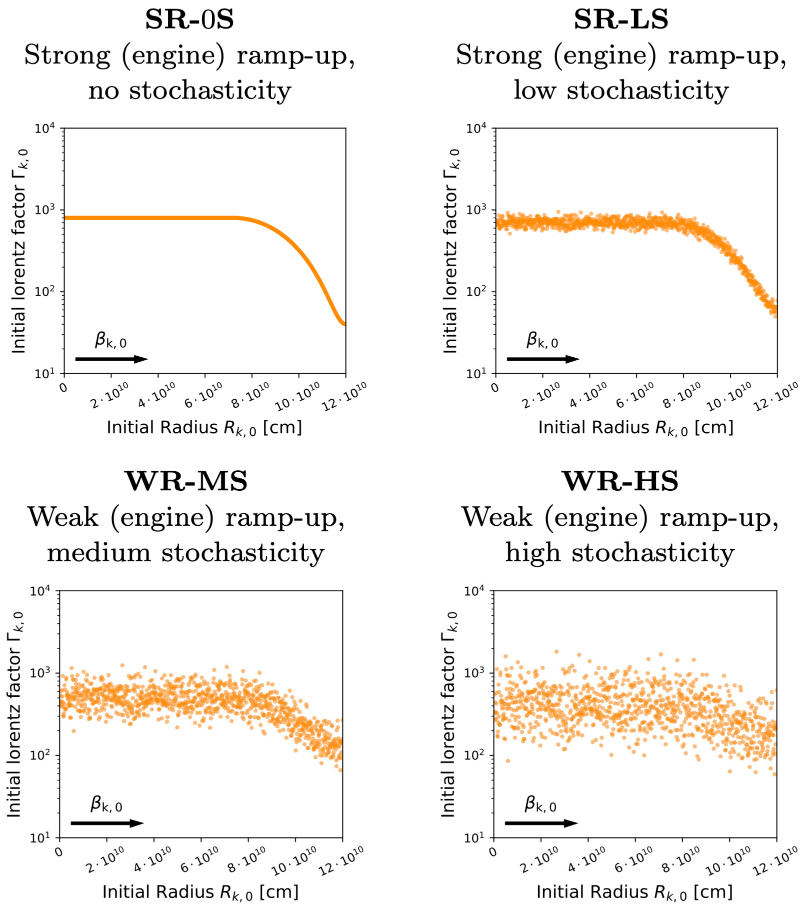
From: Bustamante, Heinze, Murase, Winter, ApJ 837 (2017) 33; Bustamante, Baerwald, Murase, Winter, Nature Commun. 6 (2015) 6783

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

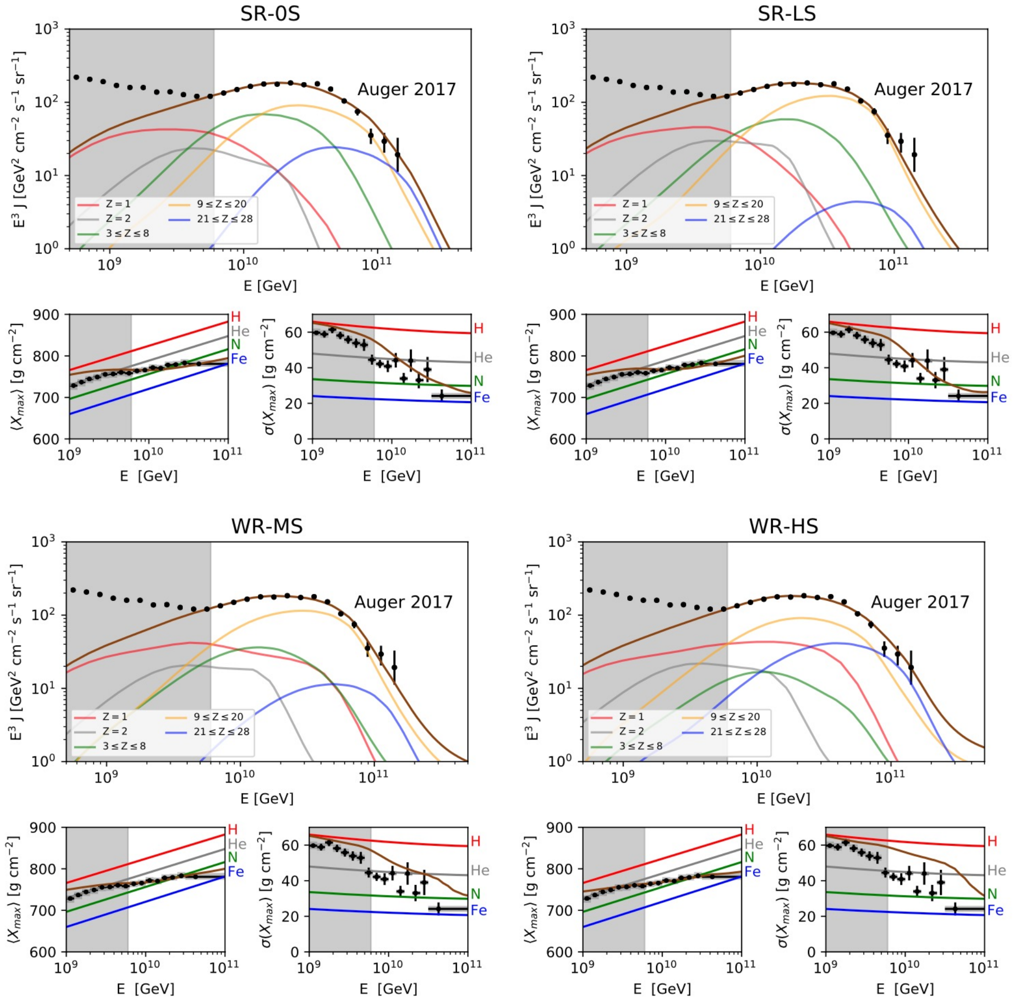


Describes UHECR data over a large range of parameters!

(systematically studied)

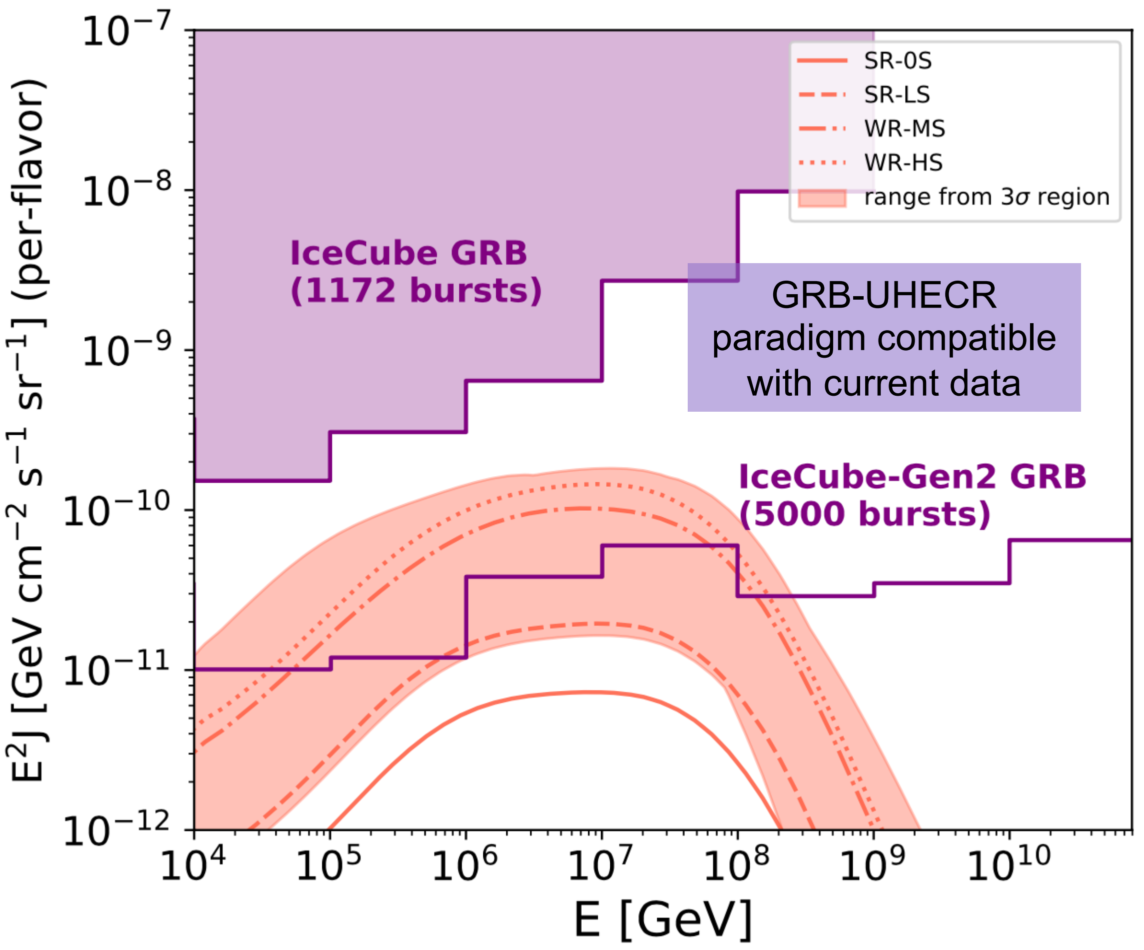
Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

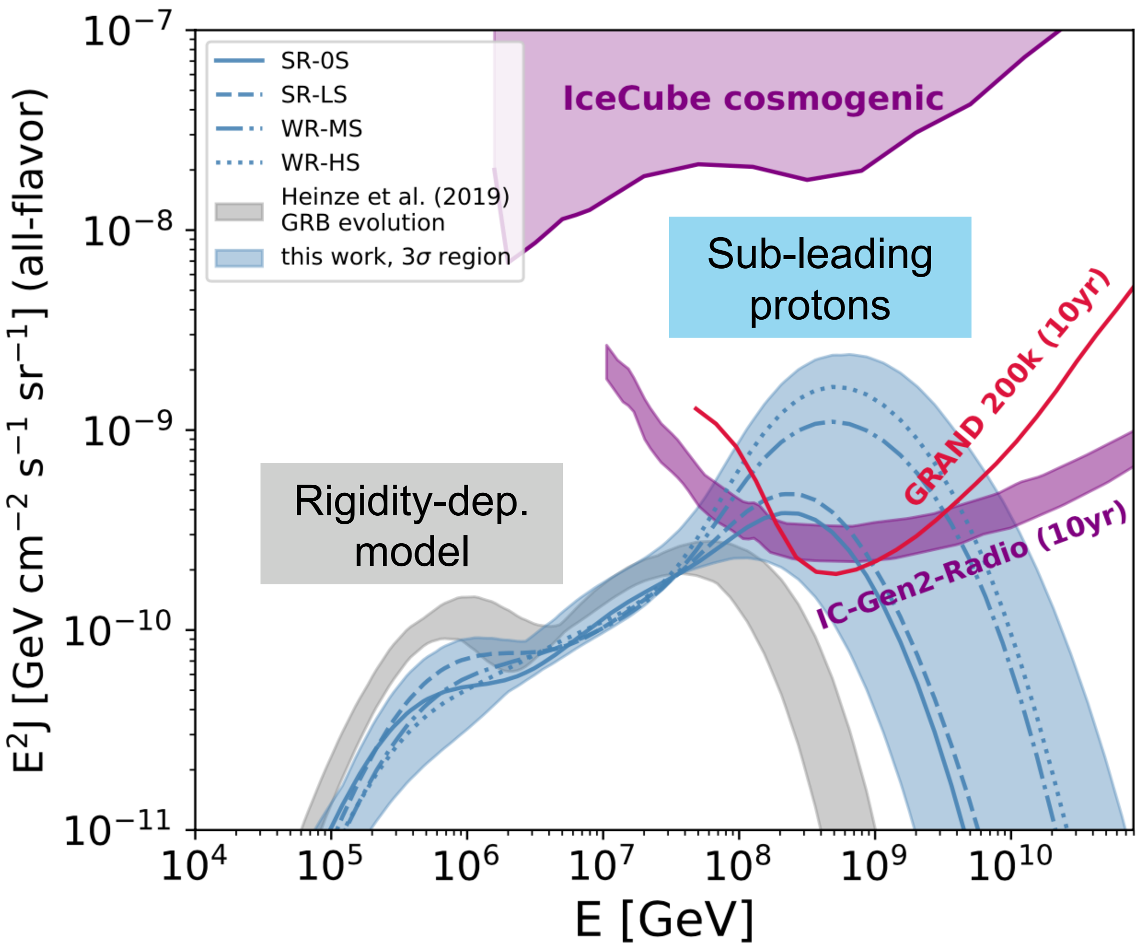
Description of UHECR data



Inferred neutrino fluxes from the parameter space scan

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

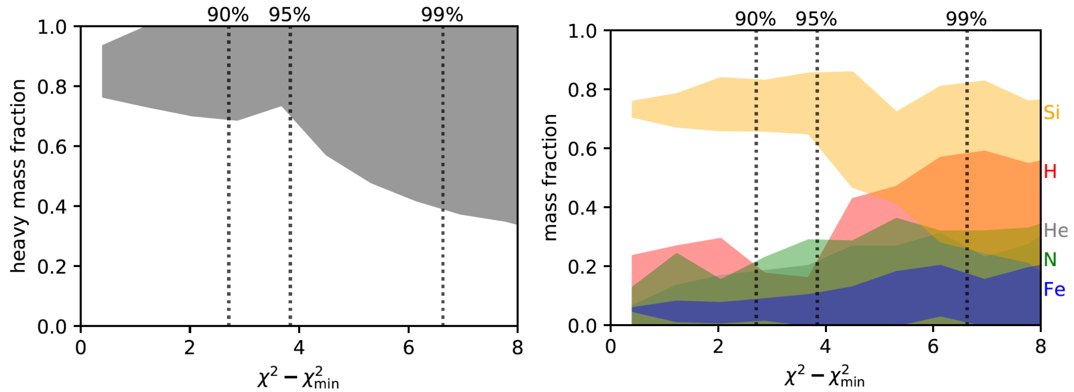




Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990

Interpretation of the results and open issues

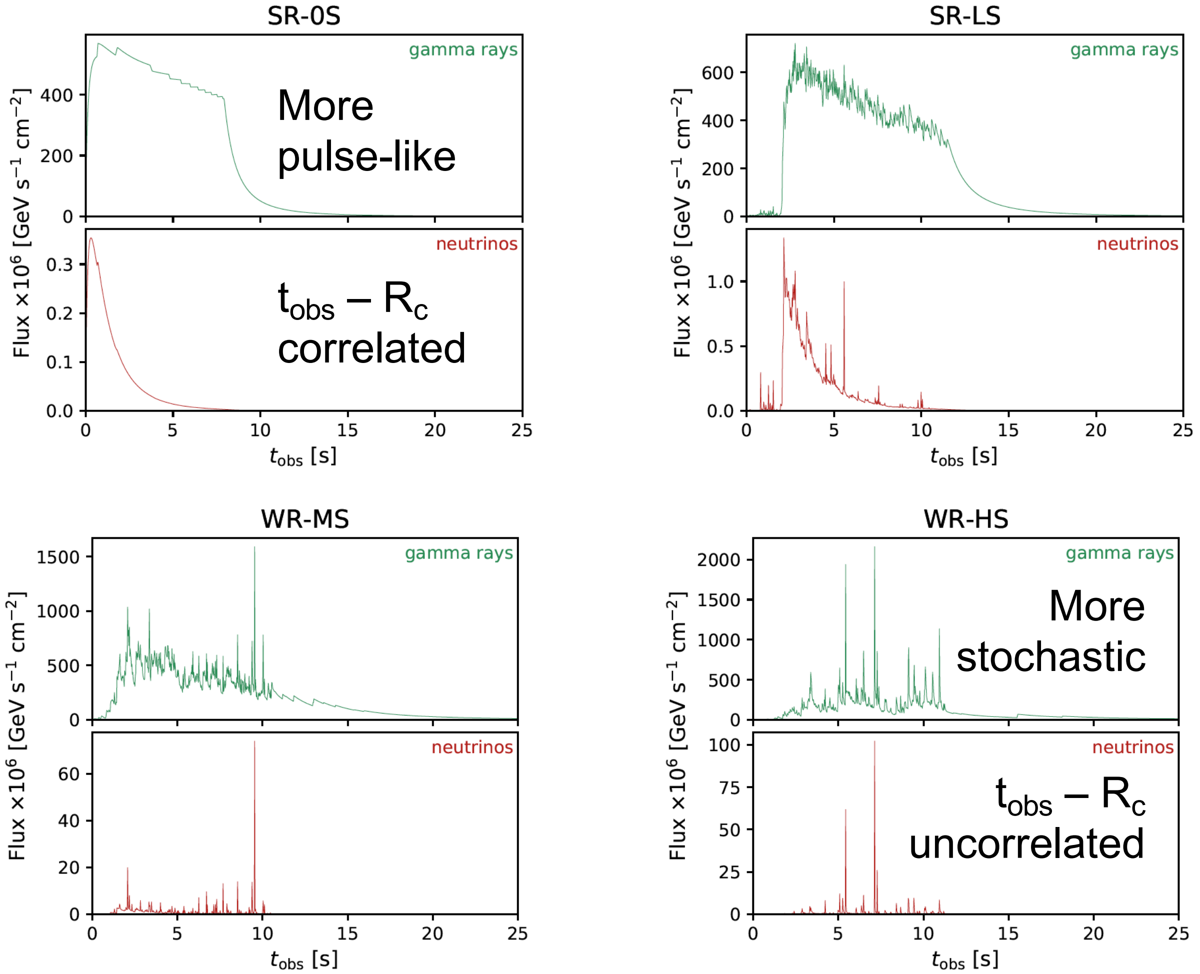
- The required injection compositon is derived: more that 70% heavy (N+Si+Fe) at the 95% CL (here: non-thermal energy fractions)



- 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

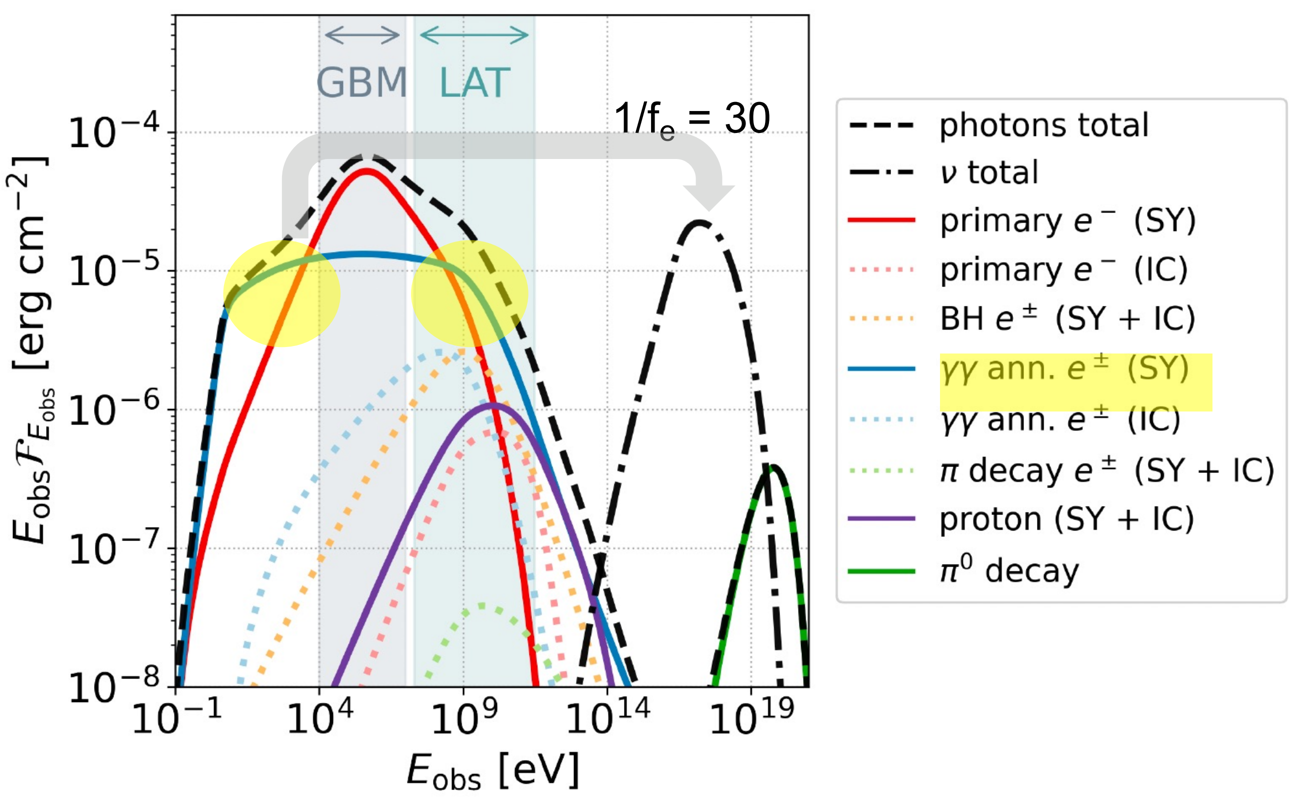


Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990

Hadronic signatures in the prompt electromagnetic spectrum

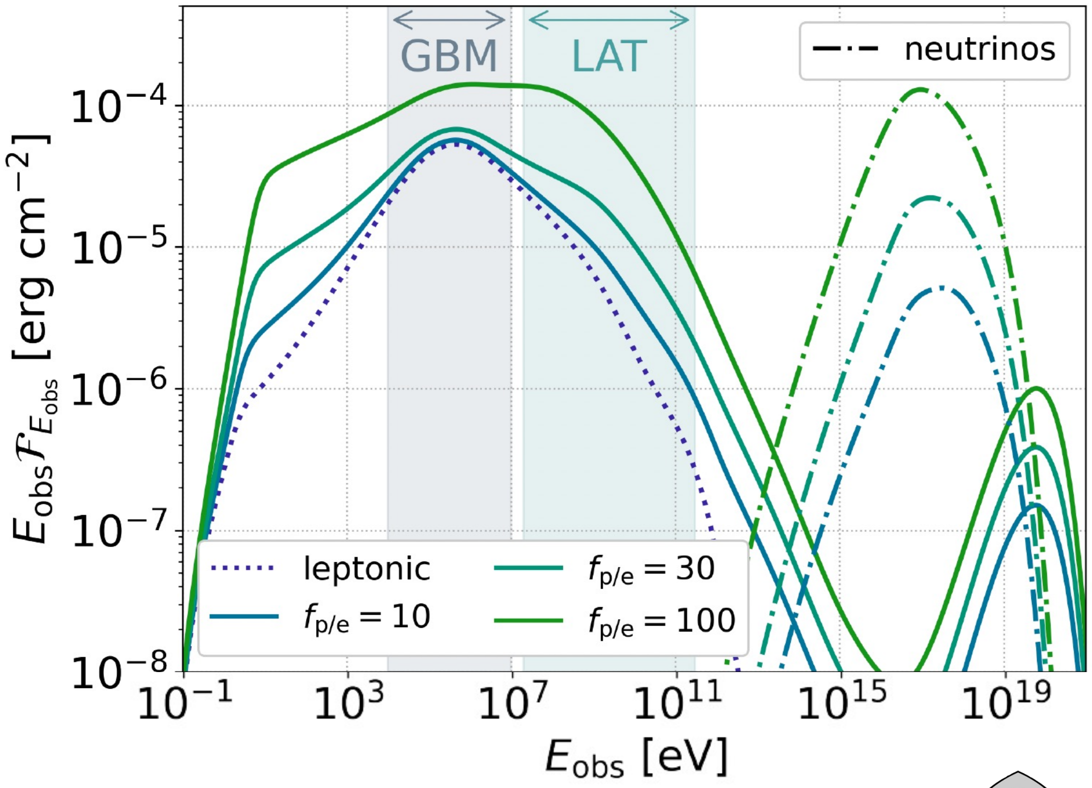
Example: Energetic GRB with $E_{\gamma,iso} \sim 10^{54}$ erg, single pulse, synchrotron (fast) cooling dominated SED, large $R_C \sim 10^{16}$ cm

Contribution from different components



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

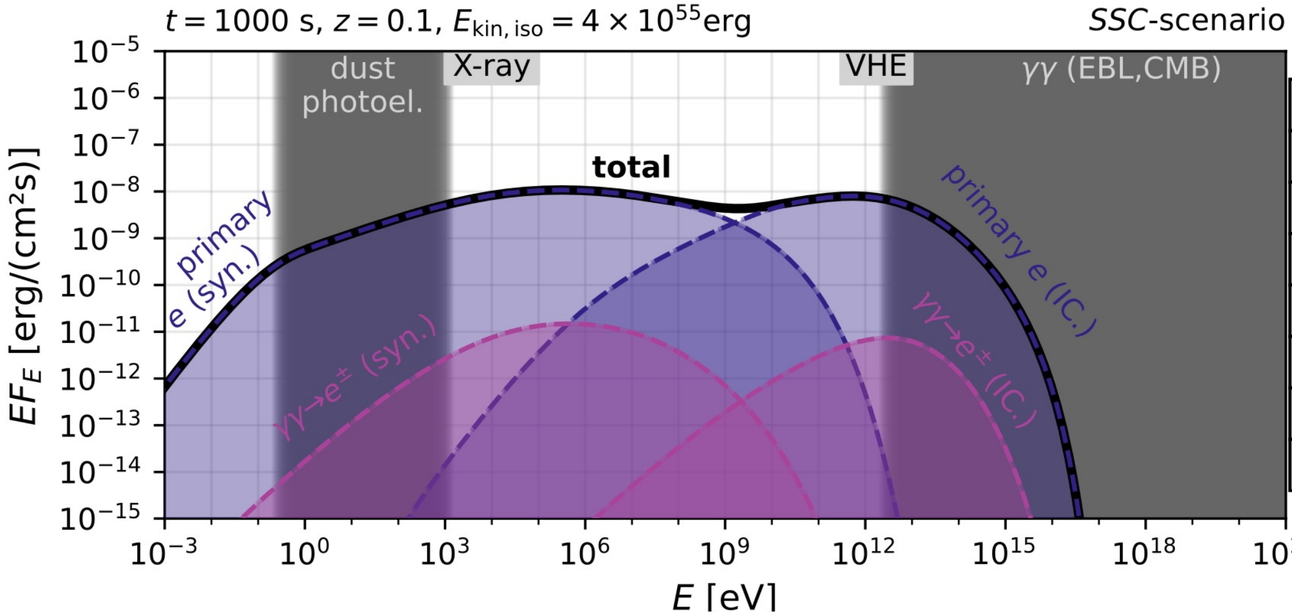
Impact of baryonic loading:



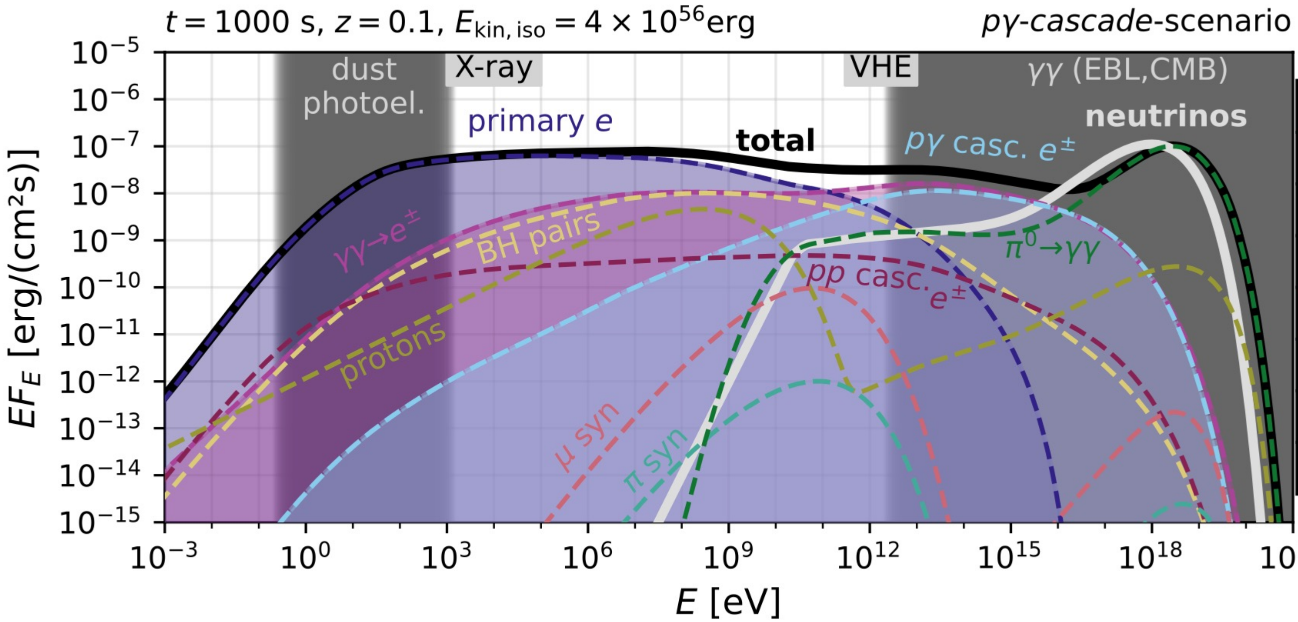
Baryonic loadings 3-10 do not modify electromagnetic spectrum at peak!

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)

Hadronic signatures in the afterglows?

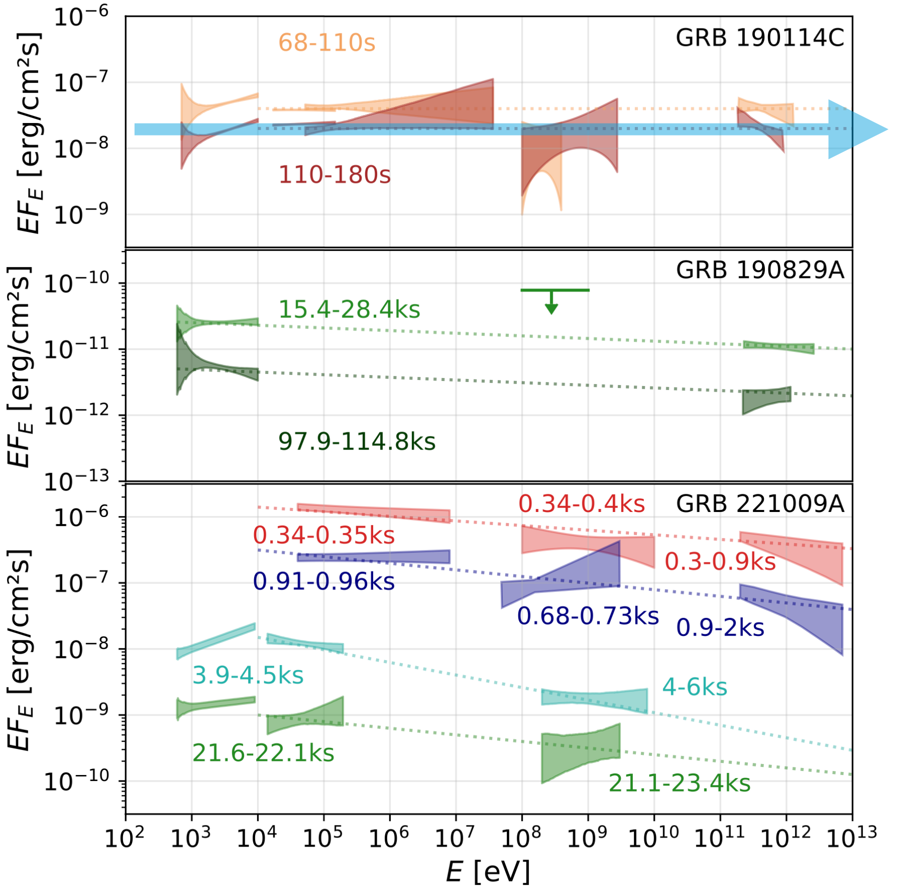


Γ	50
n	1
ε_B	10^{-4}
ε_e	$10^{-1.5}$
ε_p	0
E'_{min}	$10^{9.0}$
η	1
s_{inj}	2.3



Γ	50
n	10^3
ε_B	10^{-5}
ε_e	$10^{-4.5}$
ε_p	10^0
E'_{min}	$10^{9.5}$
η	1
s_{inj}	2

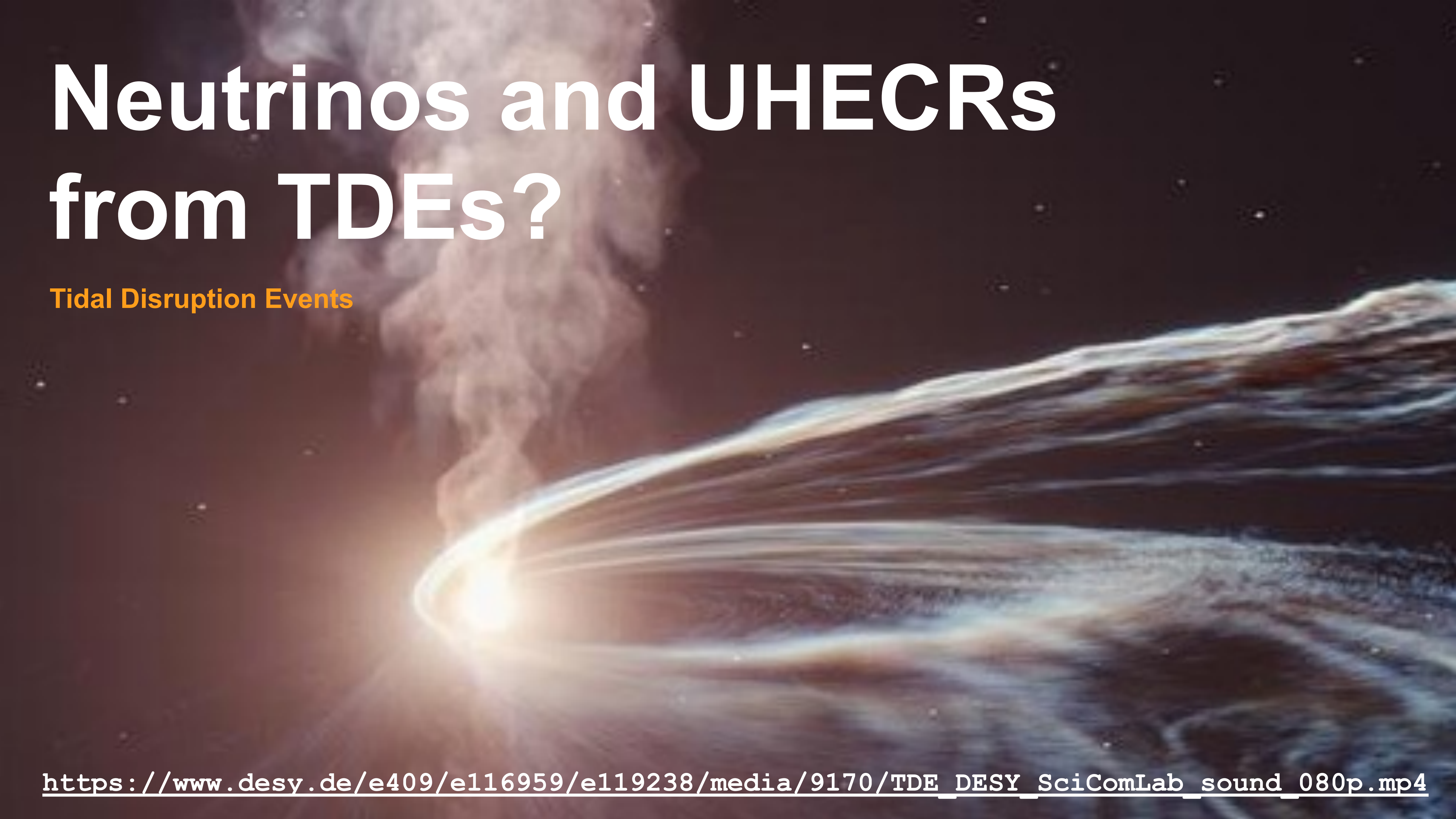
What drives these "quasi-flat" spectra over many orders of E?



From: Klinger, Yuan, Taylor, WW, ApJ accepted, arXiv:2403.13902

Neutrinos and UHECRs 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)

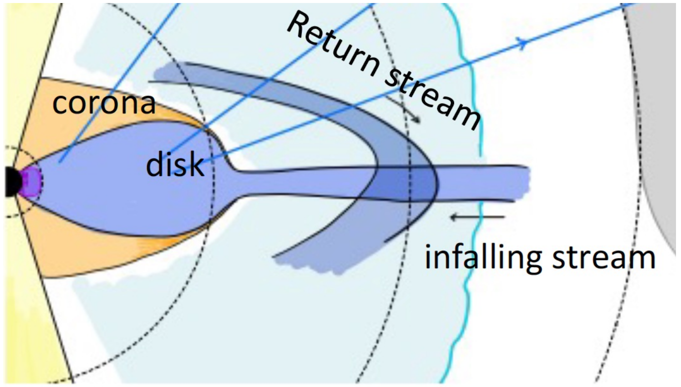
$$r_t = \left(\frac{2M}{m}\right)^{1/3} R \simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\, M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}$$

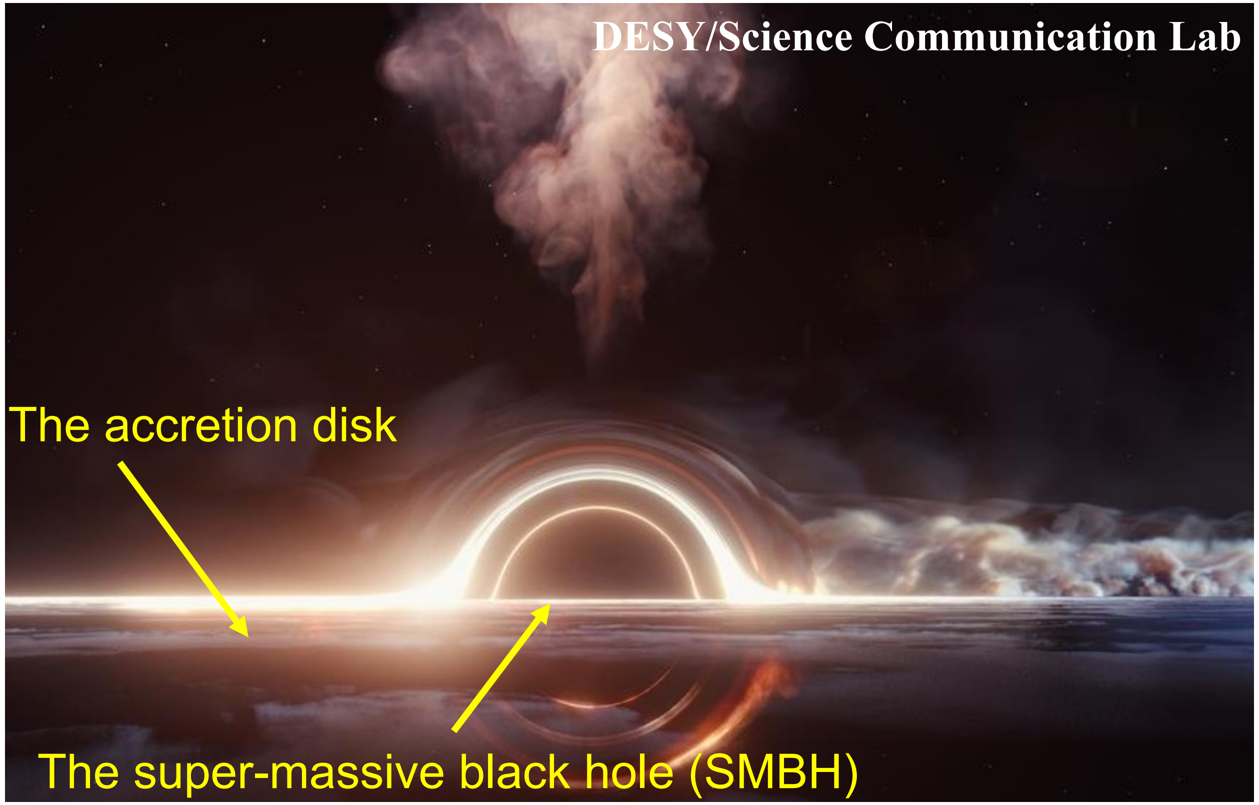
- Has to be beyond Schwarzschild radius for TDE

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

- 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





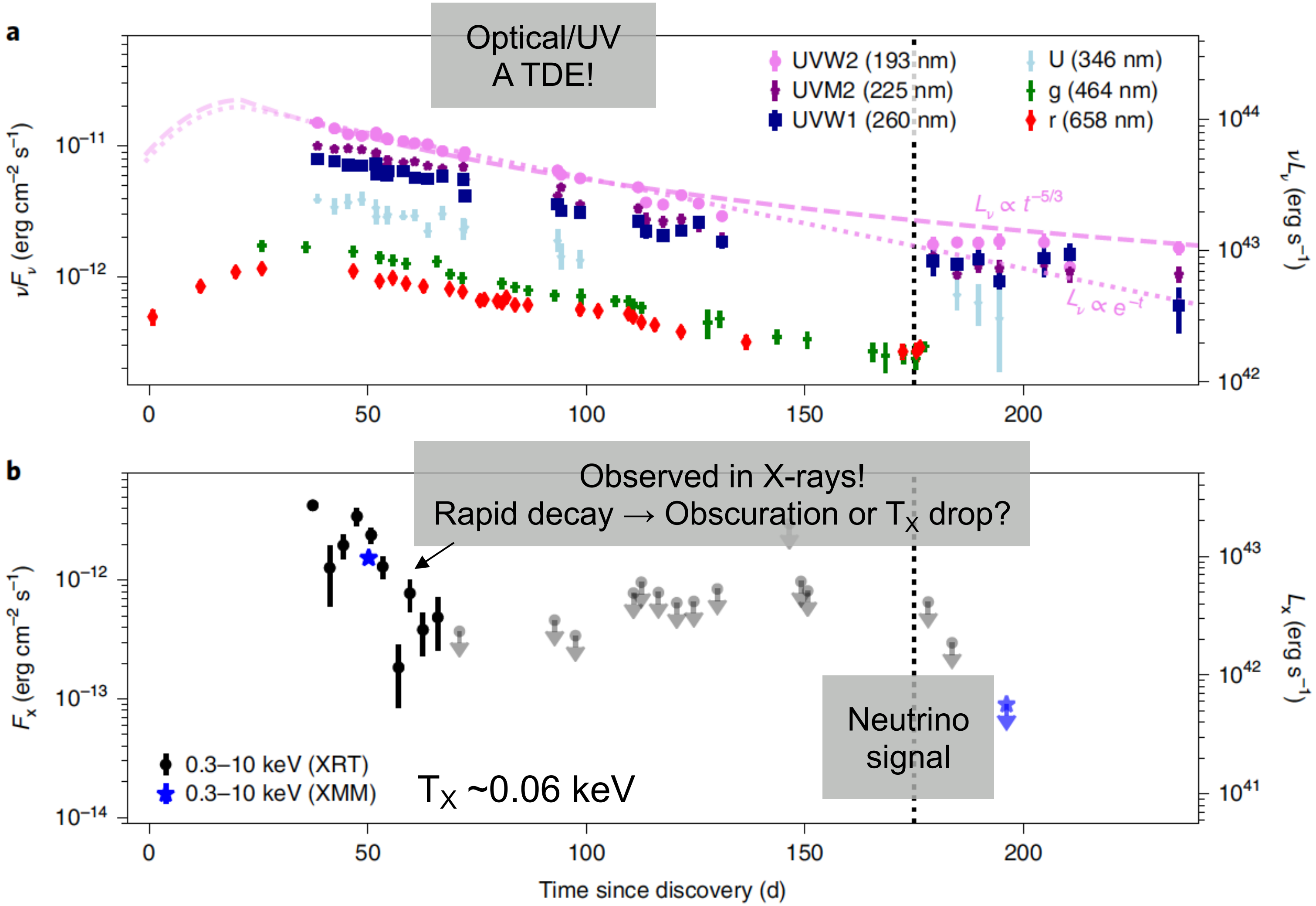
Energetics

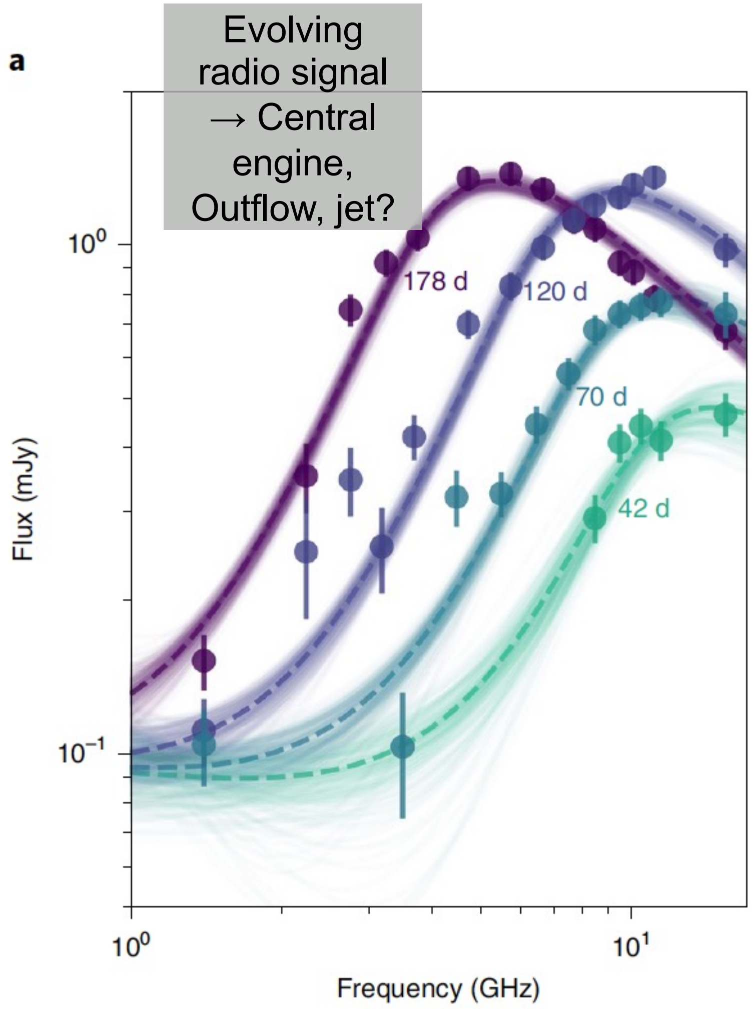
- Measure for the luminosity which can be re-processed from accretion through the SMBH: **Eddington luminosity**

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

- 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
  Luminosity into non-thermal CRs related to that?

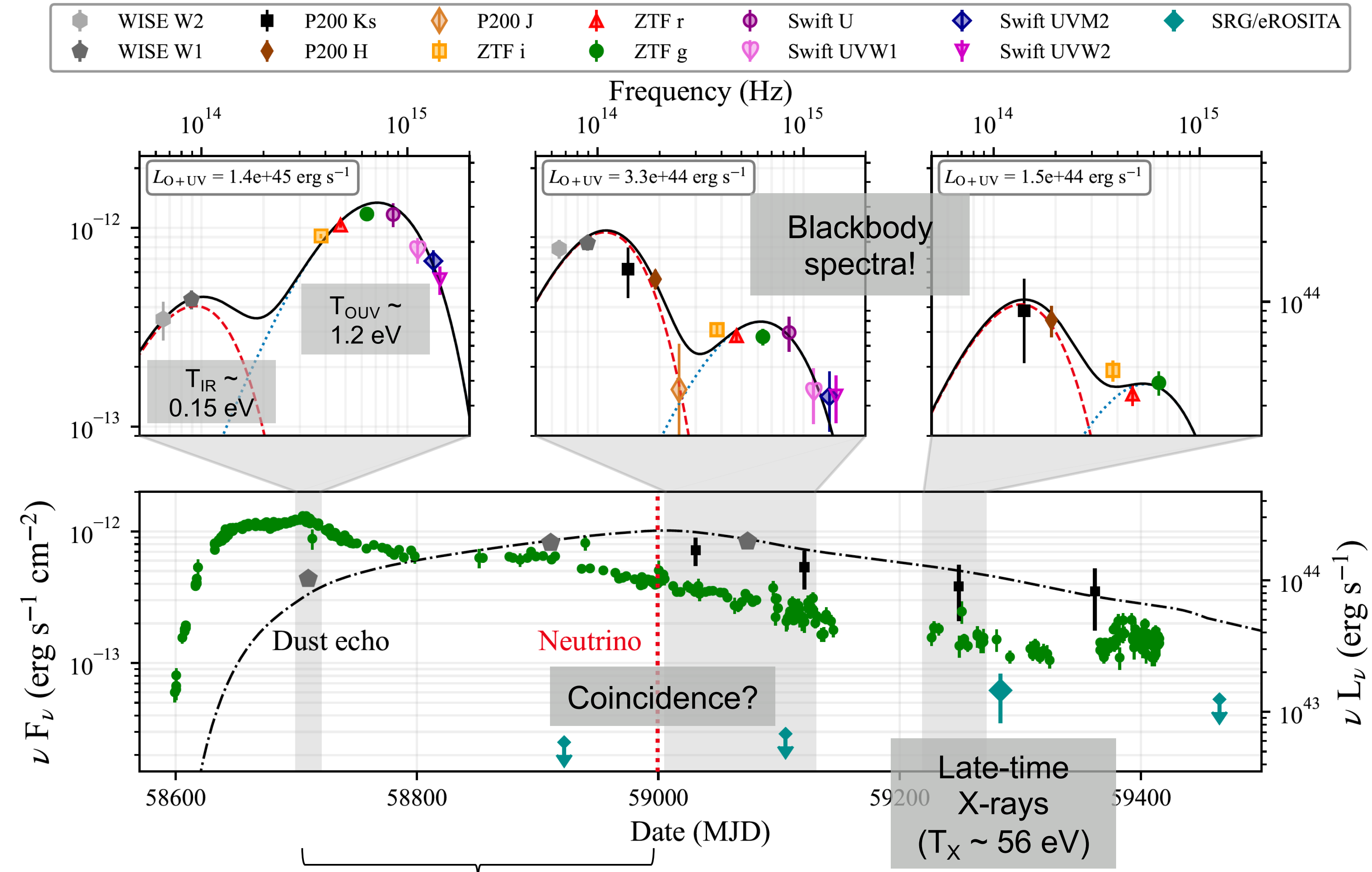
A neutrino from AT2019dsg





Stein et al, Nature Astronomy 5 (2021) 510

Another neutrino from the TDE candidate AT2019fdr



Dust echo "convolved" over 2 Δt

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

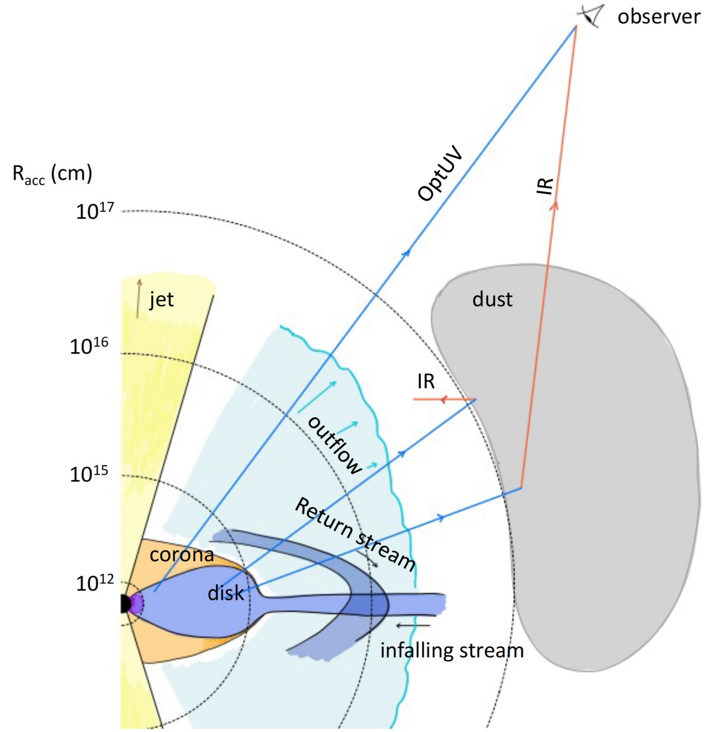


Fig. from arXiv:2205.11538

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

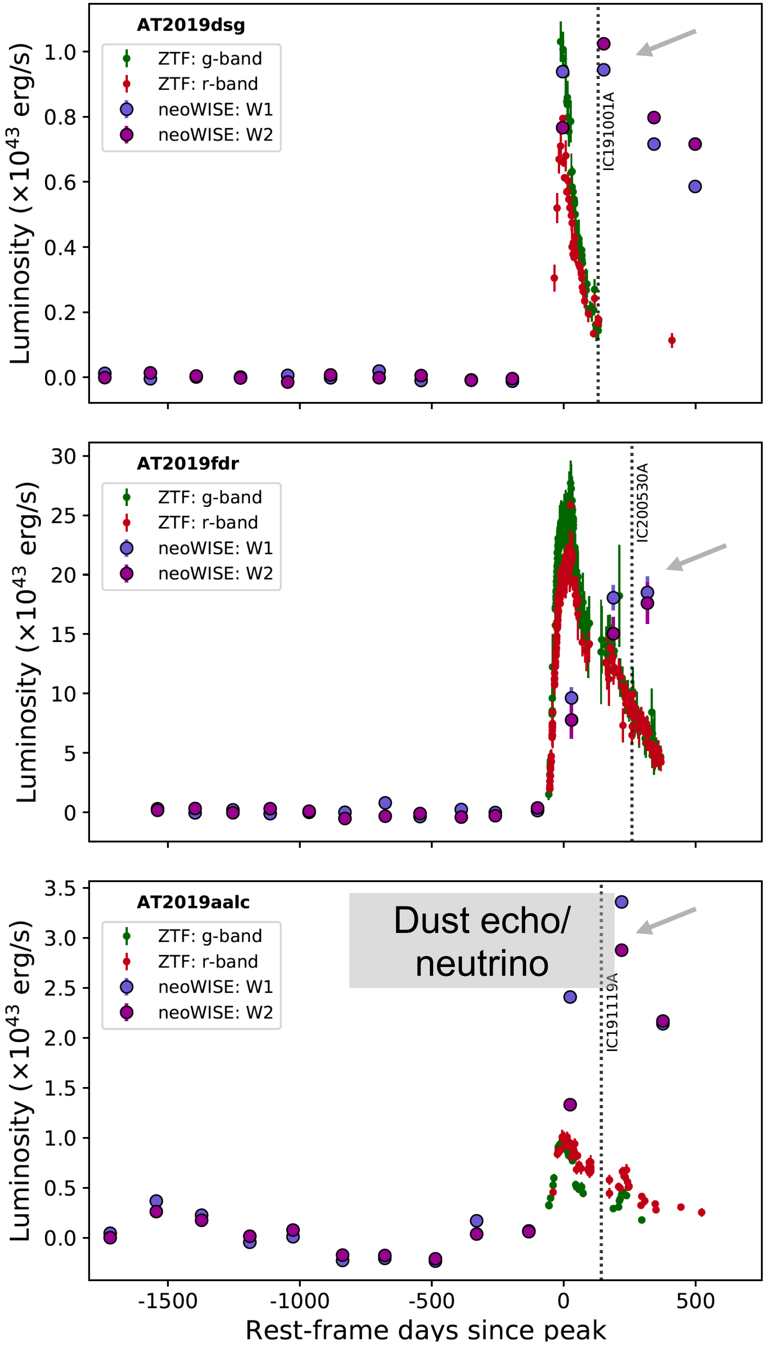
AT2019aalc

Analysis

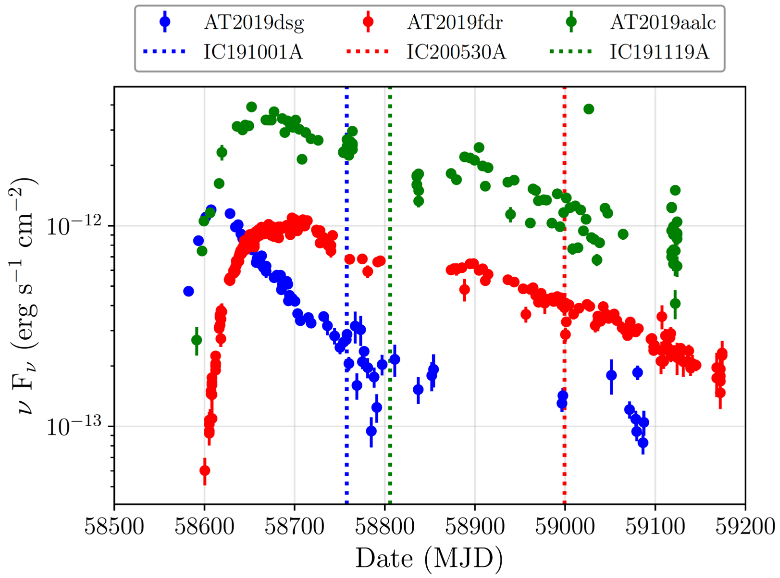
- Selected a sample of 1732 accretion flares with properties similar to AT2019dsg and AT2019fdr (dust echo)
- Found another TDE candidate: AT2019aalc with a similar neutrino time delay
- Overall significance: 3.7σ **van Velzen et al, arXiv:2111.09391**

Further possible associations

- Two obscured TDEs? **Jiang et al, 2023.** One with a strong X-ray flare **Li et al, 2024.** One (AT2021lwx) outside 90% CL **Yuan et al, 2024.** One (AT2021loi) associated with BFF **Milan Veres et al, 2024**



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

(probably incomplete list…)

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; Winter, Lunardini, 2023

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)

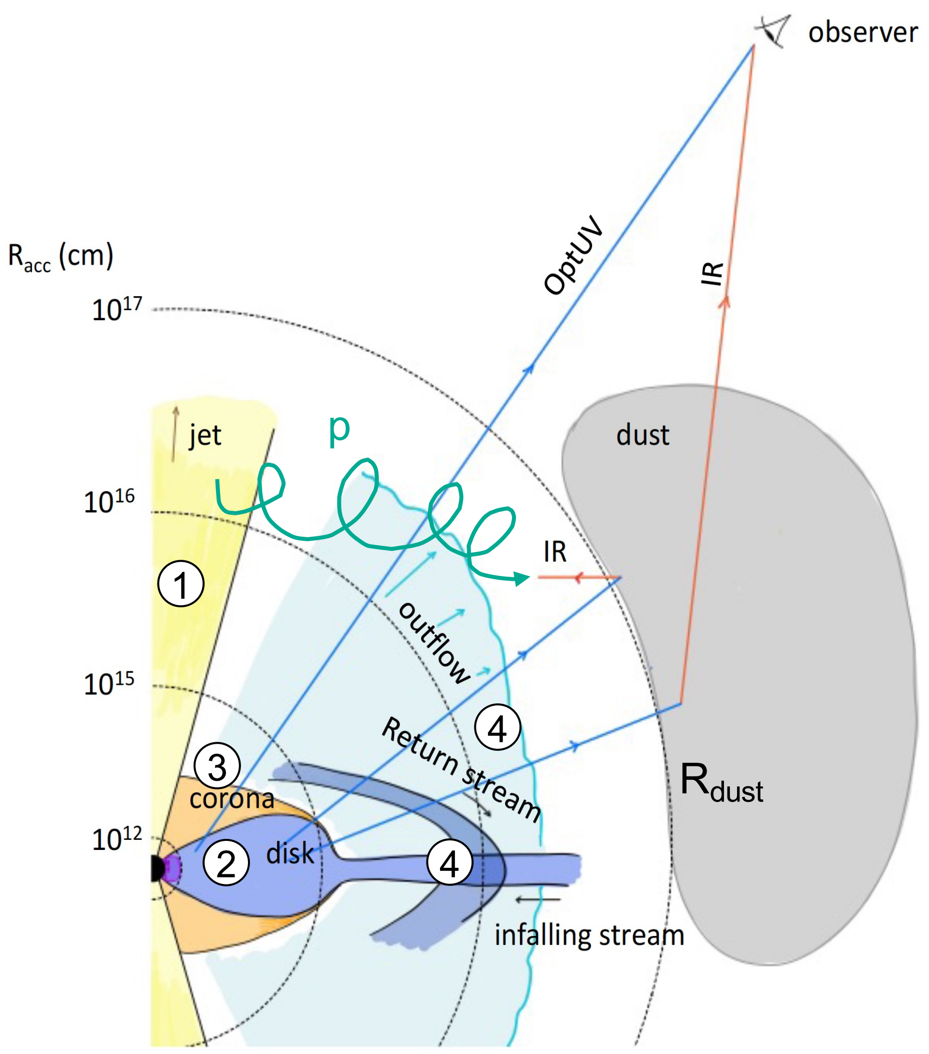
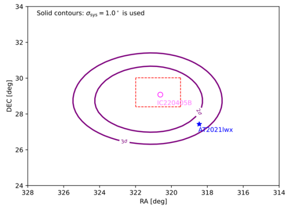


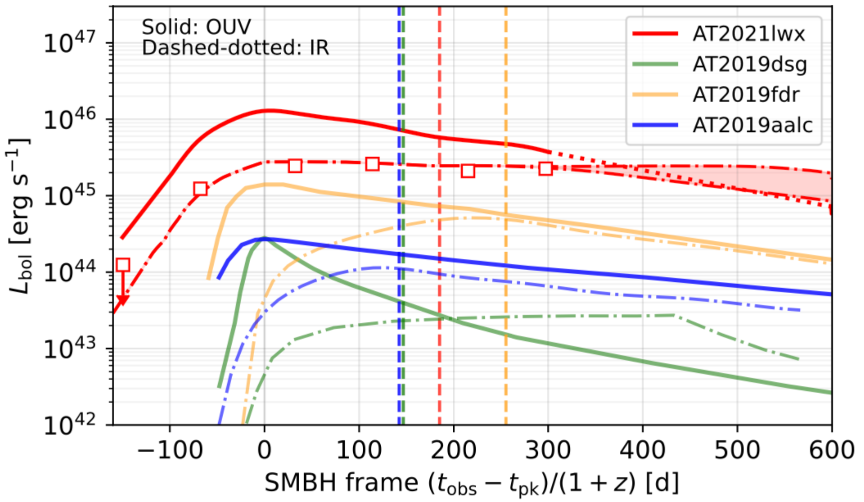
Fig: Winter, Lunardini, ApJ 948 (2023) 1, 42

Direct connection with dust echo?

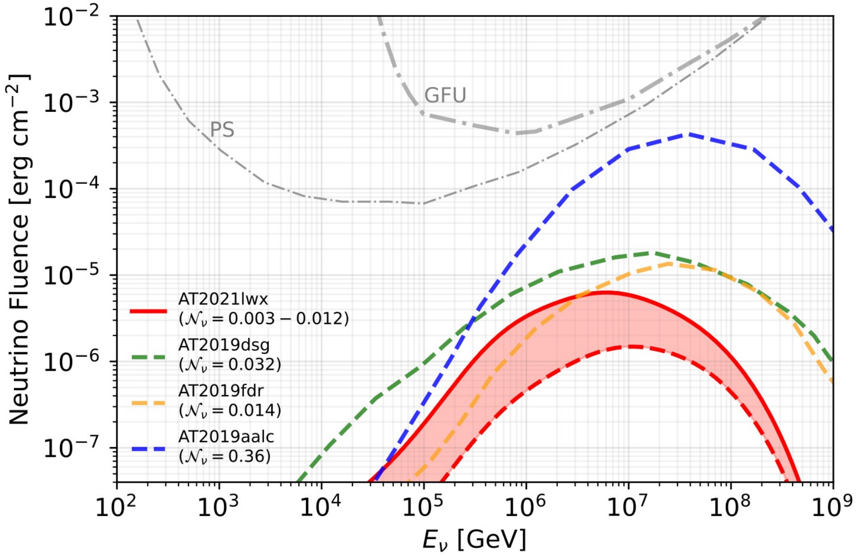


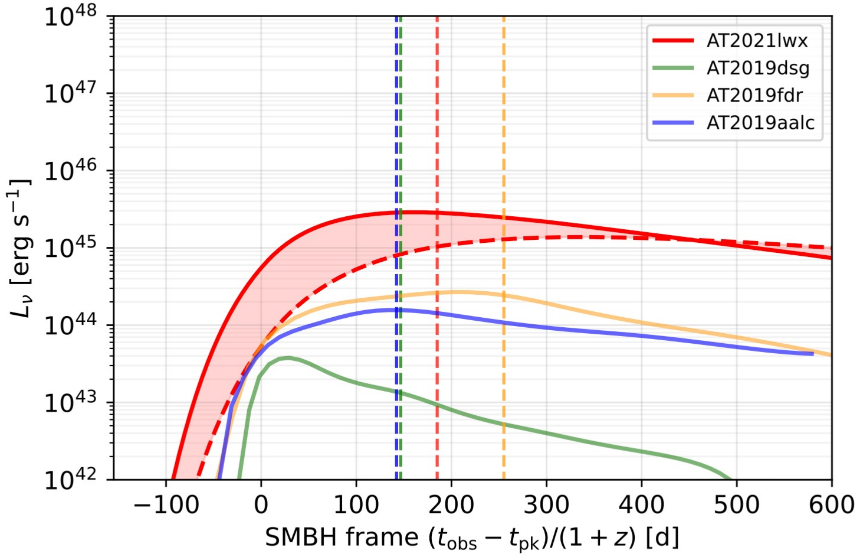
AT2021lwx ("Scary Barbie"): Another Neutrino-Coincident TDE with a Strong Dust Echo?

- Neutrino arrival seems to be correlated with dust echo
- **What if ... the dust echo itself (IR) is the target?**
- Consequence (from pγ interactions): $E_p > 1.6$ EeV $(T_{IR}/0.1\ \mathrm{eV})^{-1}$. (for nuclei: **rigidity R > 1.6 EV**)
- Compatible with UHECR fits, e.g. R_{max} ~ 1.4-3.5 EV. Coincidence? e.g. Heinze et al, ApJ 873 (2019) 1, 88
- Points towards interactions of **UHECRs → UHE neutrinos**



The direct connection between the neutrino production (incl. time delay) and the dust echo could be a **smoking gun signature for the acceleration of UHECRs** in TDEs



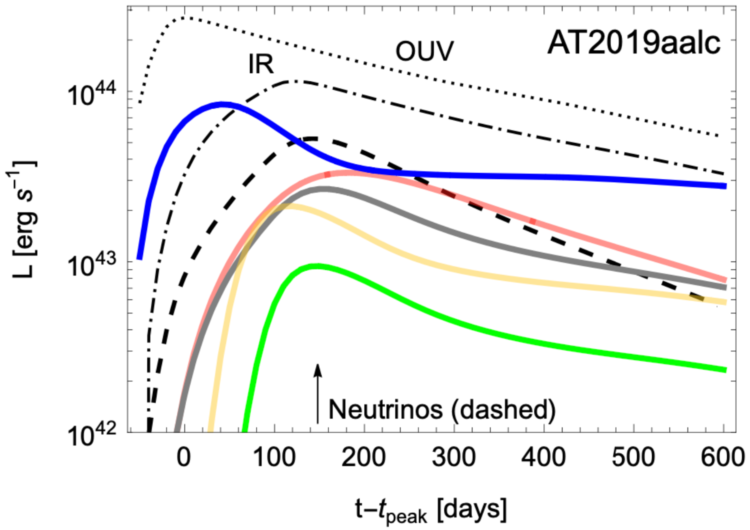


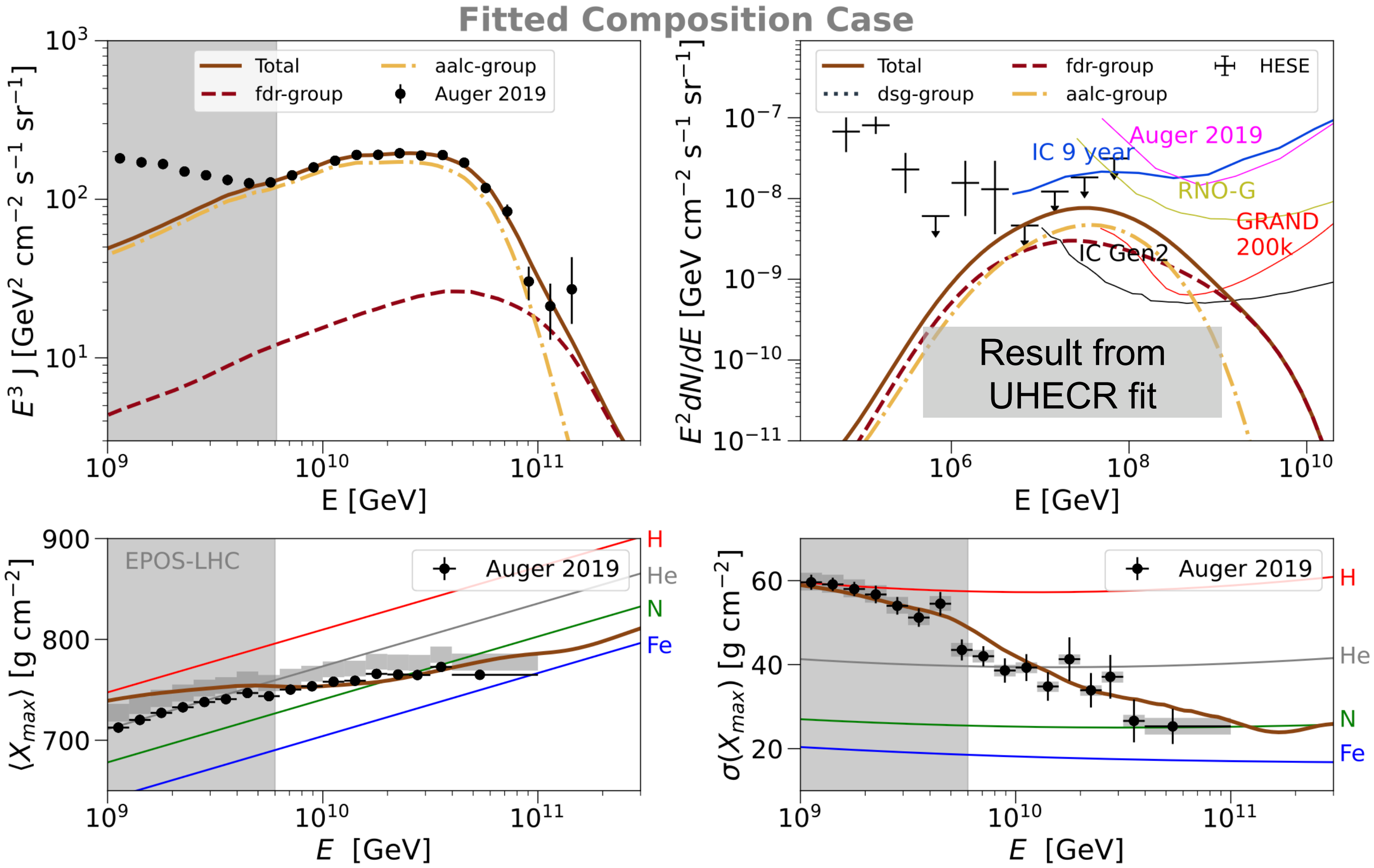
Figs. from Yuan, Winter, Lunardini, ApJ 969 (2024) 136

UHECR connection and diffuse neutrino flux

Requires description of UHECR data (spectrum and composition)

- Idea: Extrapolate from a few neutrino-associated TDEs to a population, main params fitted
- Produces a diffuse neutrino flux at sub-EeV energies
- Simulate time-dependent UHECR production. Different mass groups vs νs ↓

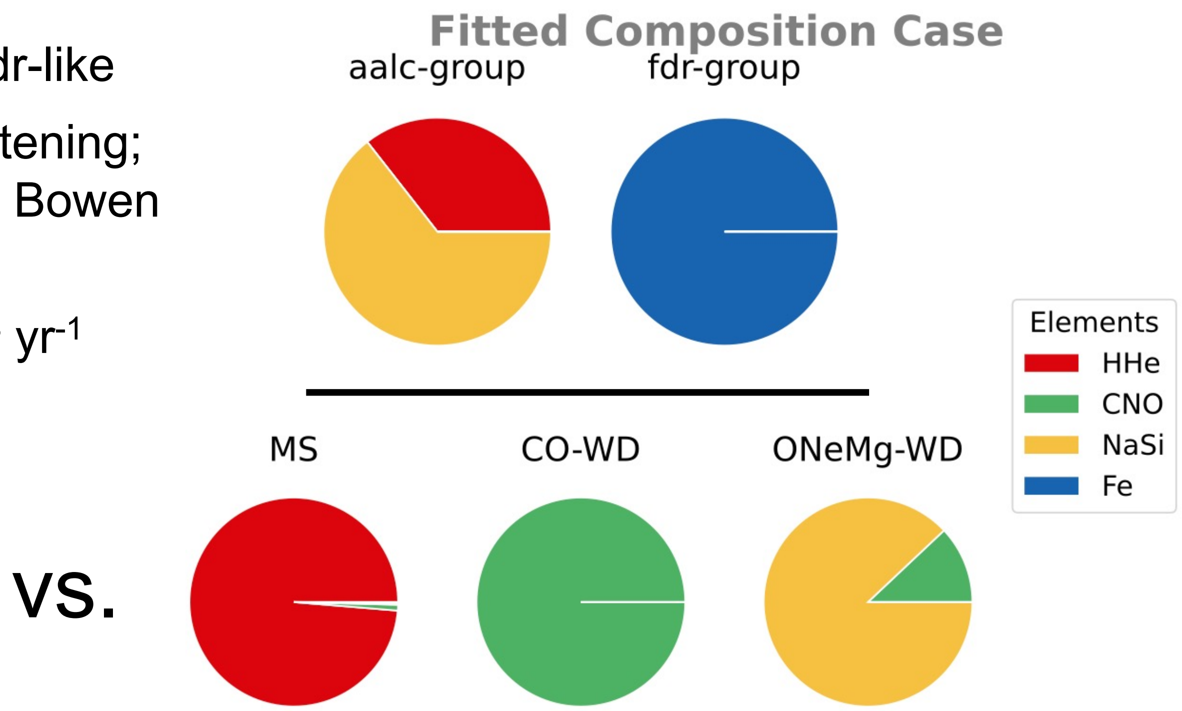


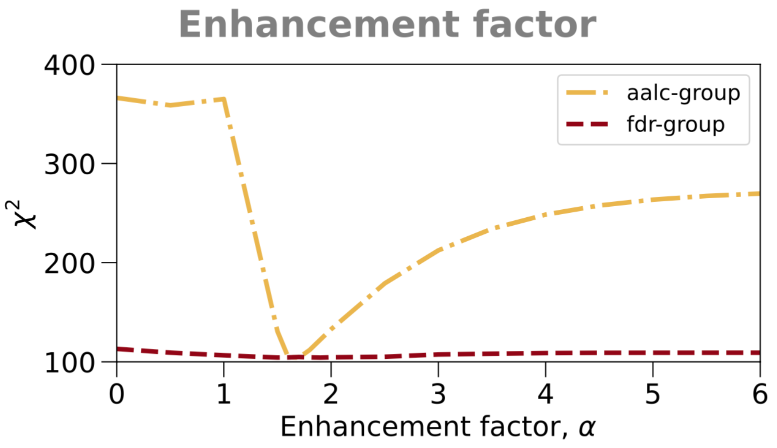


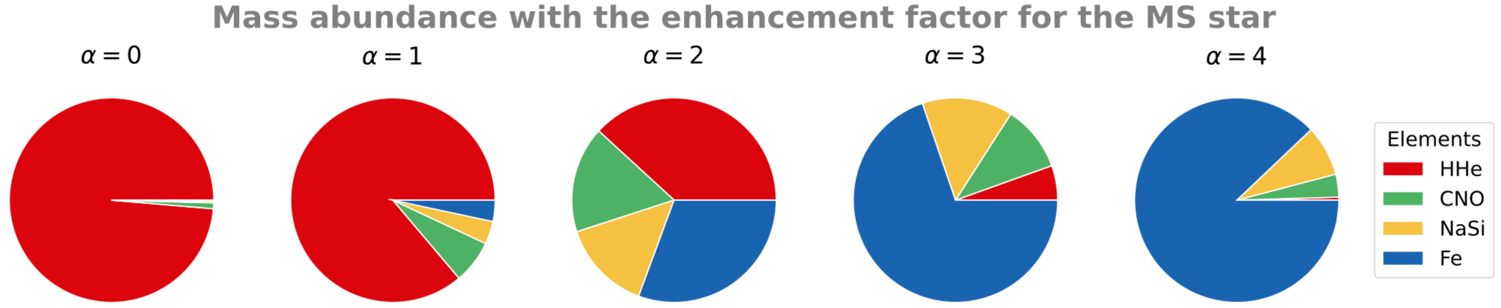
Plotko, Winter, Lunardini, Yuan, 2024;
see also: Biehl, Boncioli, Lunardini, Winter, Sci. Rep. 8 (2018) 1, 10828; Farrar, Piran, 2014;
Zhang et al, PRD 96 (2017) 6; Guepin et al, A&A616 (2018) A179; …

What do we learn about UHECRs from TDEs?

- Need at least two populations: AT2019aalc-like, AT2019fdr-like
- Interesting: AT2019aalc recently exhibited a huge rebrightening; AT2019aalc-like TDEs special population associated with Bowen Fluoresence Flares? Milan Veres et al, 2024
- Required local UHECR-emitting TDE rate ~ 10-100 $Gpc^{-3}\ yr^{-1}$ → Main sequence (MS) star disruptions?
- Composition not directly compatible with any of the progenitor candidates →
- Possible way out: heavier elements are easier accelerated/picked up. Enhancement factor? Define $(A/Z)^{\alpha}$
  e.g. Caprioli et al. (2017), Hanusch et al. (2019)



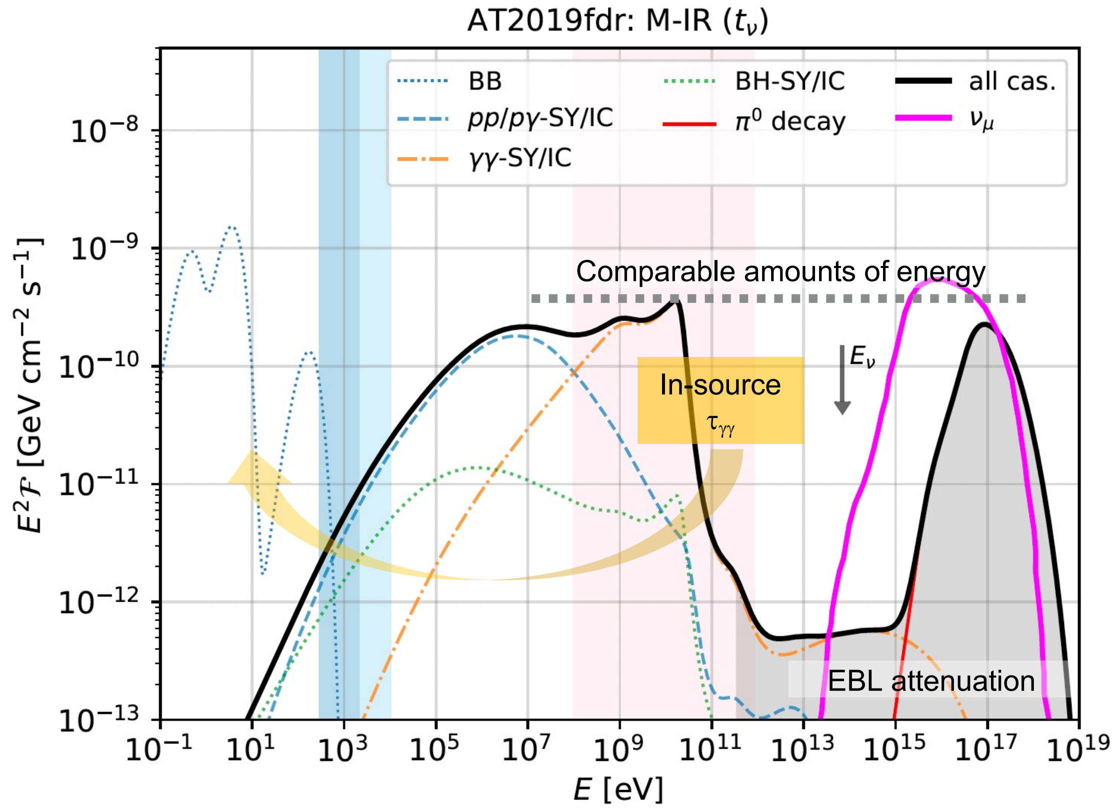


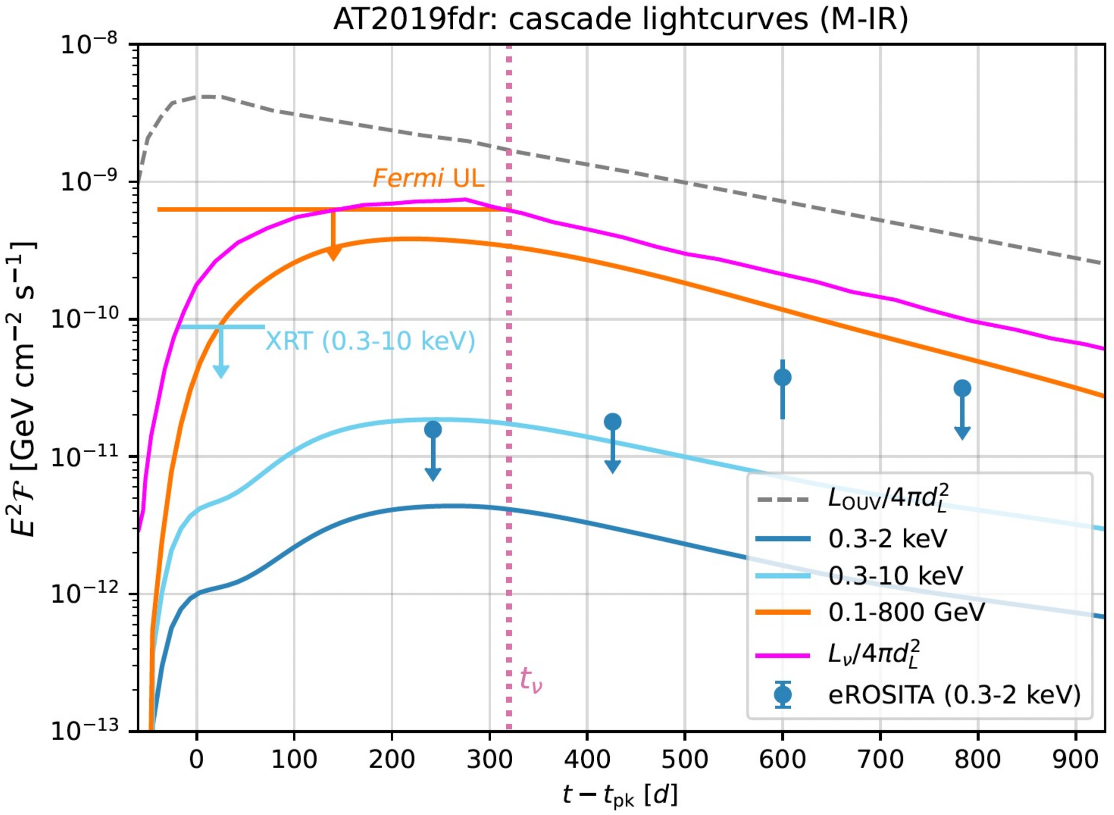


Plotko, Winter, Lunardini, Yuan, 2024

Predictions for gamma rays

- Gamma-ray attenuation expected at the highest energies; gamma-rays and neutrinos correlated
- Very compact production regions excluded from gamma-ray limits
- Constrain predicted neutrino event rate to 0.01-0.1 events per TDE





Yuan, Winter, ApJ 956 (2023) 30
(based upon model M-IR in Winter, Lunardini, ApJ 948 (2023) 42)

Summary: multi-messenger signal from GRBs and TDEs

GRBs

UHECRs
- Potentially sufficient power, but high E_{kin}
- Description of UHECR data for various outflow scenarios (except for $\sigma(X_{max})$)
- Heavy injection composition needed

Neutrinos
- Compatible with stacking bounds in multi-collision/outflow models
- Contribution to diffuse neutrino flux <1%

Electromagnetic radiation
- Peak in gamma-ray range
- Large energy output (long GRBs)

Gravitational waves
- Possible association with short GRBs
- Energy output (GRB) quite small?

TDEs

UHECRs
- Potentially sufficient power, pop. uncertain
- Local rate compatible with MS disruptions
- Heavy injection composition needed, enhancement at injection?

Neutrinos
- Several candidates for associations
- Possible contribution to diffuse flux at highest energies, radio detection?

Electromagnetic radiation
- Observed in optical/UV/IR
- Sometimes X-ray, radio detection

Gravitational waves
- No detection yet
- However, similar models for BNS mergers

e.g. Decoene, Guepin et al, 2020; Rossoni, Boncioli, Sigl, 2024; Farrar 2024
(fraction of mass fallback luminosity accelerated)

BACKUP

Example: Nuclear cascade from photo-disintegration

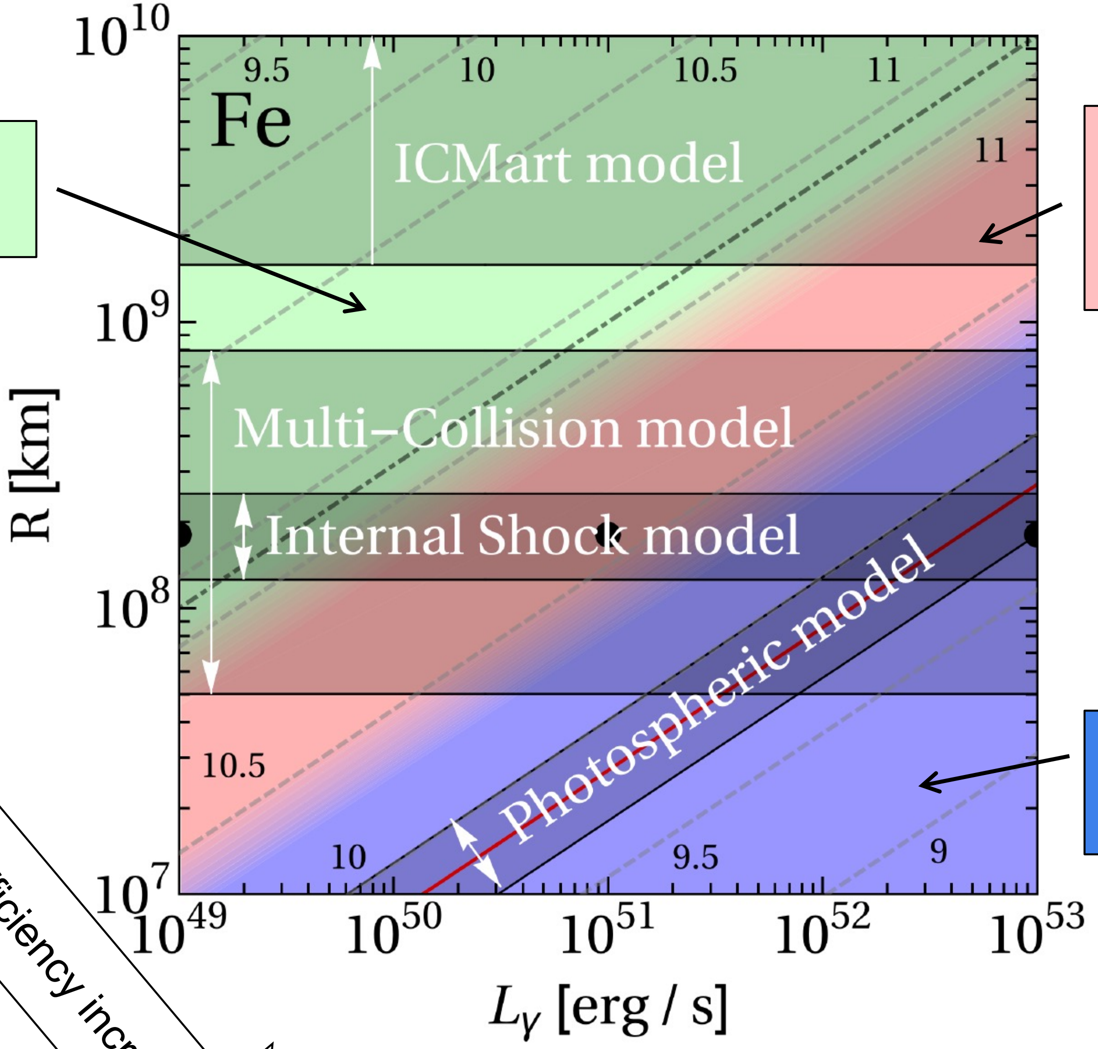
t_v=0.01s
(here fixed)

Nuclear survival

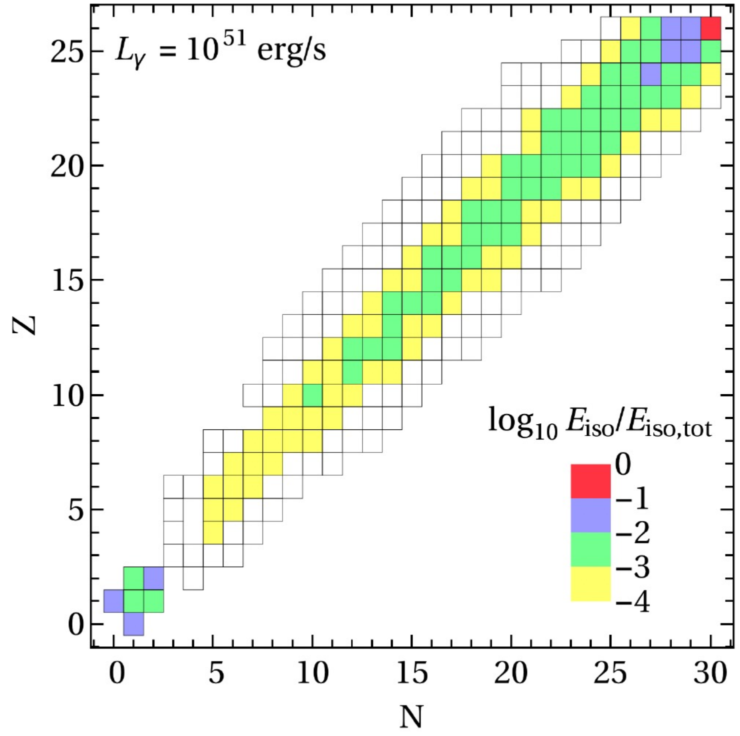
Populated nuclear cascade

Optically thick for all nuclei

Pion production efficiency increases



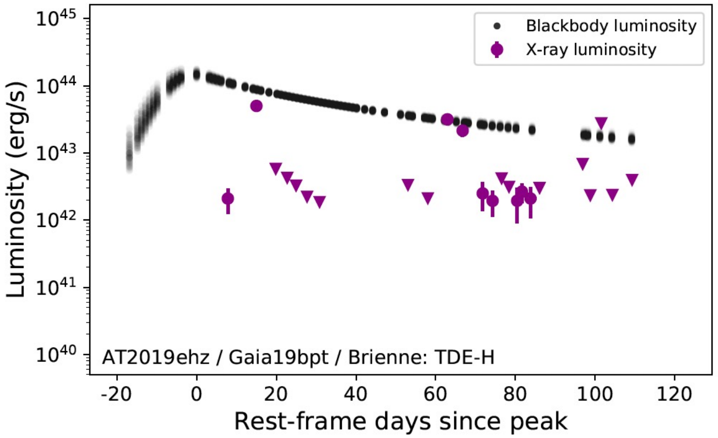
Disintegration of ^{56}Fe ***within*** a GRB shell collision

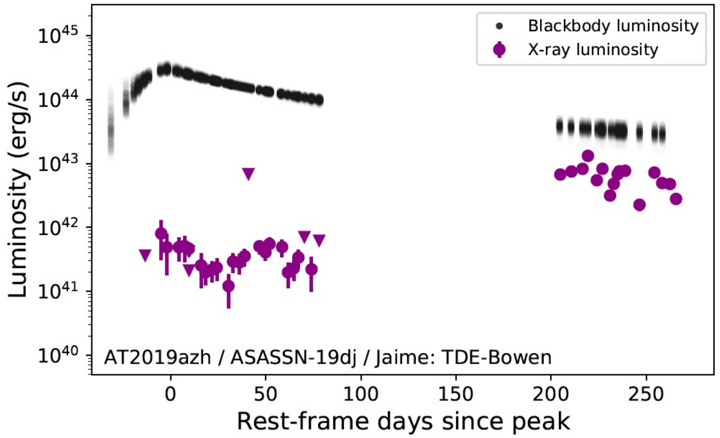


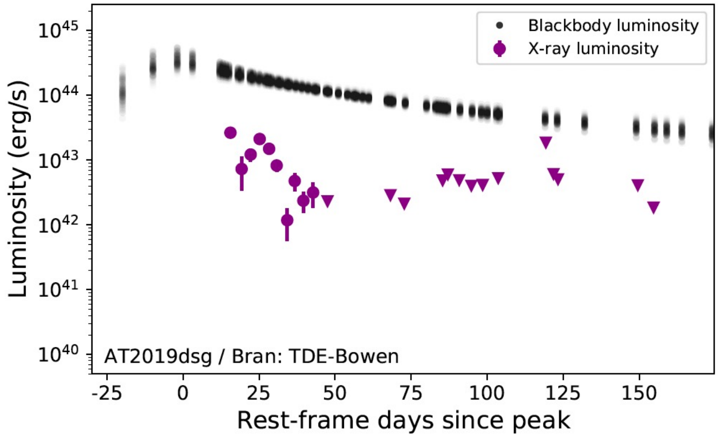
(middle dot in left panel)

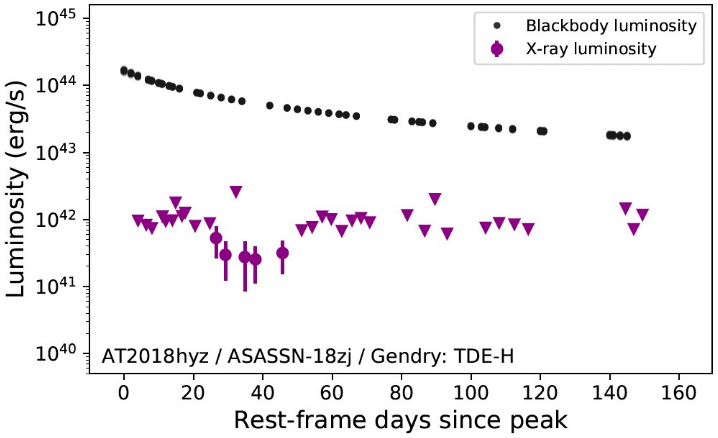
Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909;
see also Murase et al, 2008; Anchordoqui et al, 2008; De Lia, Tamborra, 2024

TDE observations (general)



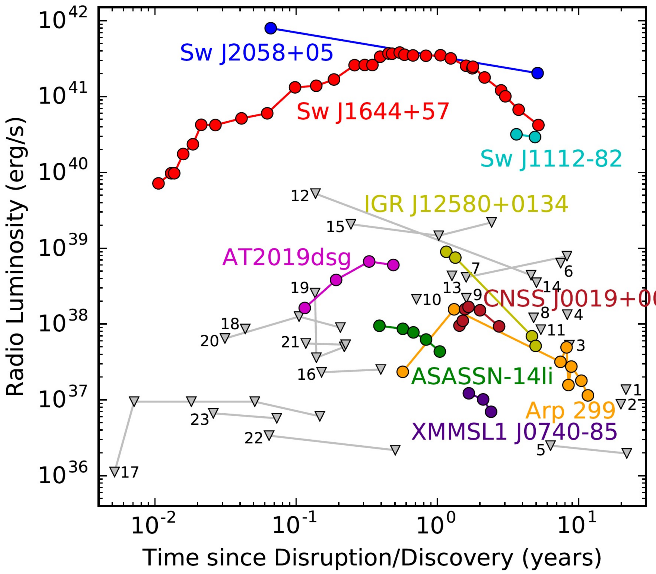






van Velzen et al, Astrophys. J. 908 (2021) 1, 4;
Alexander, van Velzen, Horesh, Zauderer, Space Sci. Rev. 216 (2020) 5, 81

- **Optical-UV (blackbody):**
  Radiation 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?