GRBs and TDEs as sources of UHECRs and neutrinos

GRB: Gamma-Ray Burst
TDE: Tidal Disruption Event

https://multimessenger.desy.de/

Winter, Walter
DESY, Zeuthen, Germany

CRPHYS2020
Connecting high-energy astroparticle physics
for origins of cosmic rays and future perspectives

YITP Kyoto, Japan (hybrid)
Dec. 7-10, 2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Contents

Transients which can power the UHECRs

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

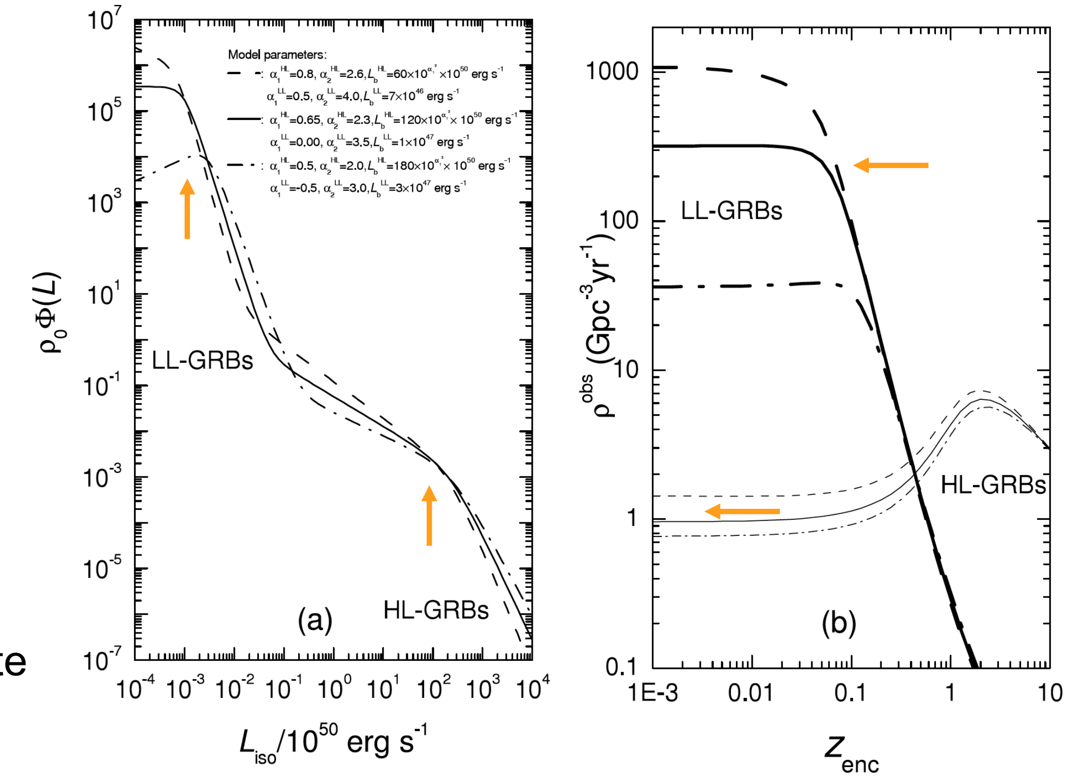
- Required energy per transient event to power UHECRs:

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

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

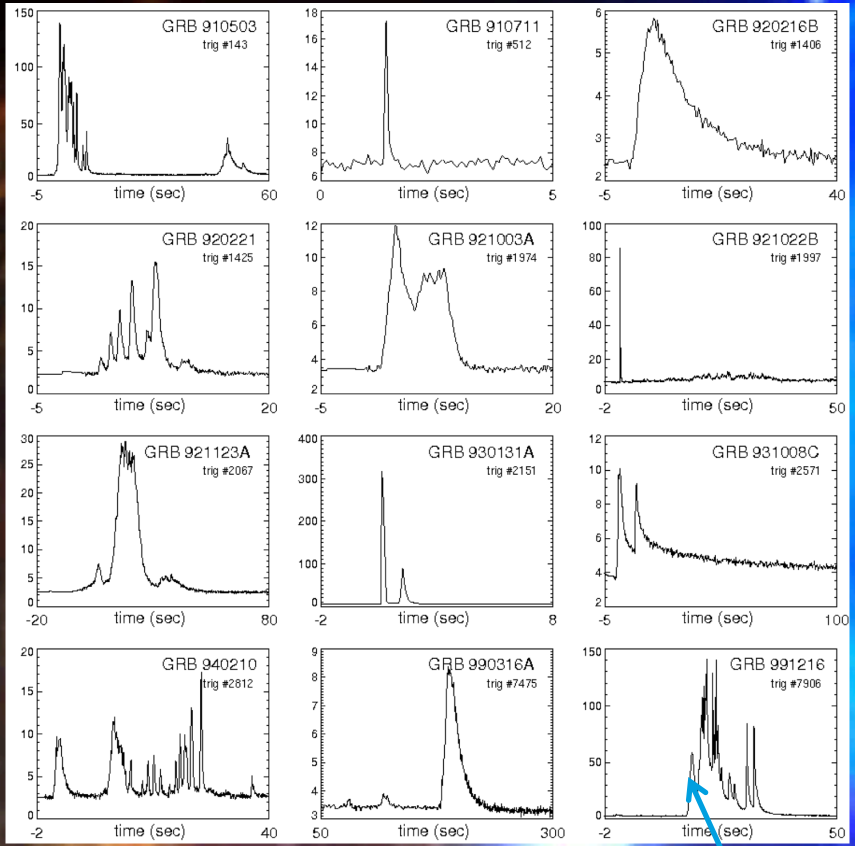
- Connection with gamma-rays: $E_{\rm CR}^{[10^{10},10^{12}]} \sim 0.2\, f_e^{-1} E_\gamma$ if all UHECRs can escape, and 20% of the CR energy is in UHECRs (typical for E^{-2} spectrum).
  f_e^{-1}: **baryonic loading** $(L_{CR}/L_\gamma)_{inj}$
- Examples in this talk: can all sustain this energy (roughly)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

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



Gamma-ray bursts (GRBs)

Daniel Perley

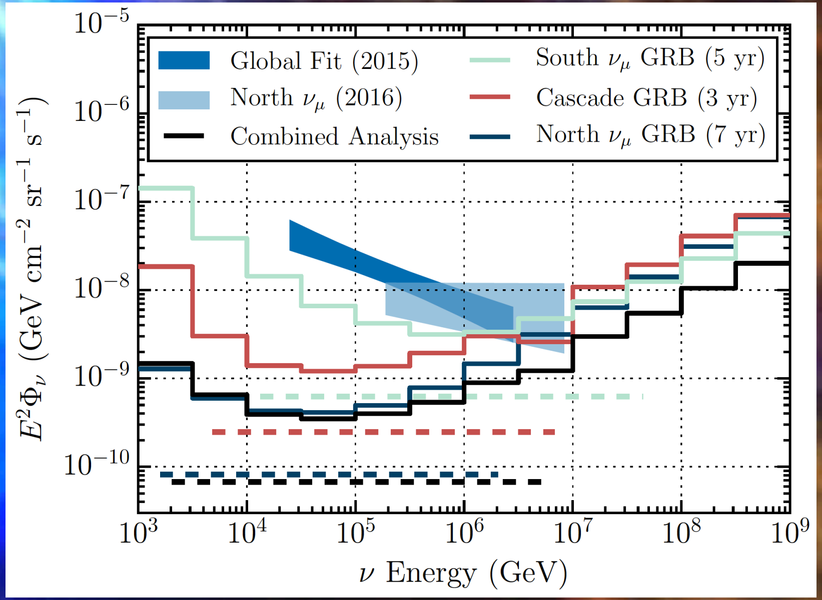


t_V: variability timescale

Several populations, such as

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

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



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

Source: NASA

HL-GRBs

... as UHECR and neutrino sources

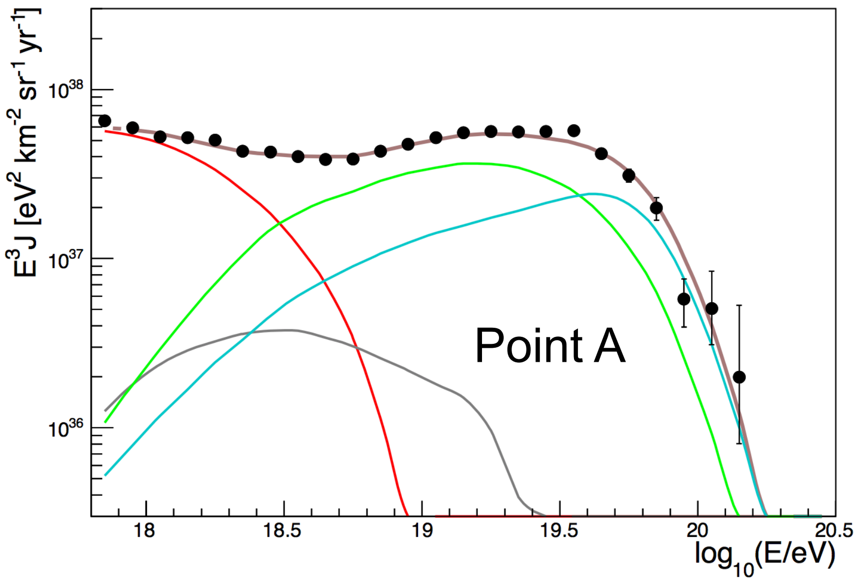
The vanilla one-zone prompt model

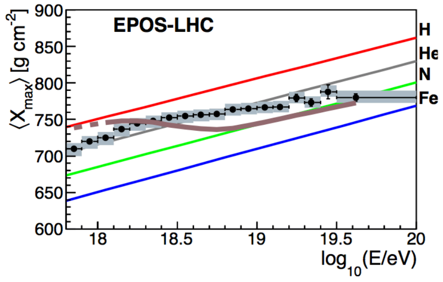
Neutrino and cosmic ray emission at same collision radius R

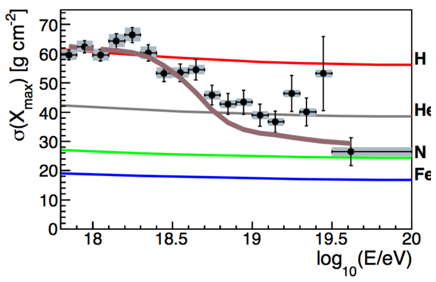
- Can describe UHECR data, roughly
- Scenario is constrained by neutrino non-observatons

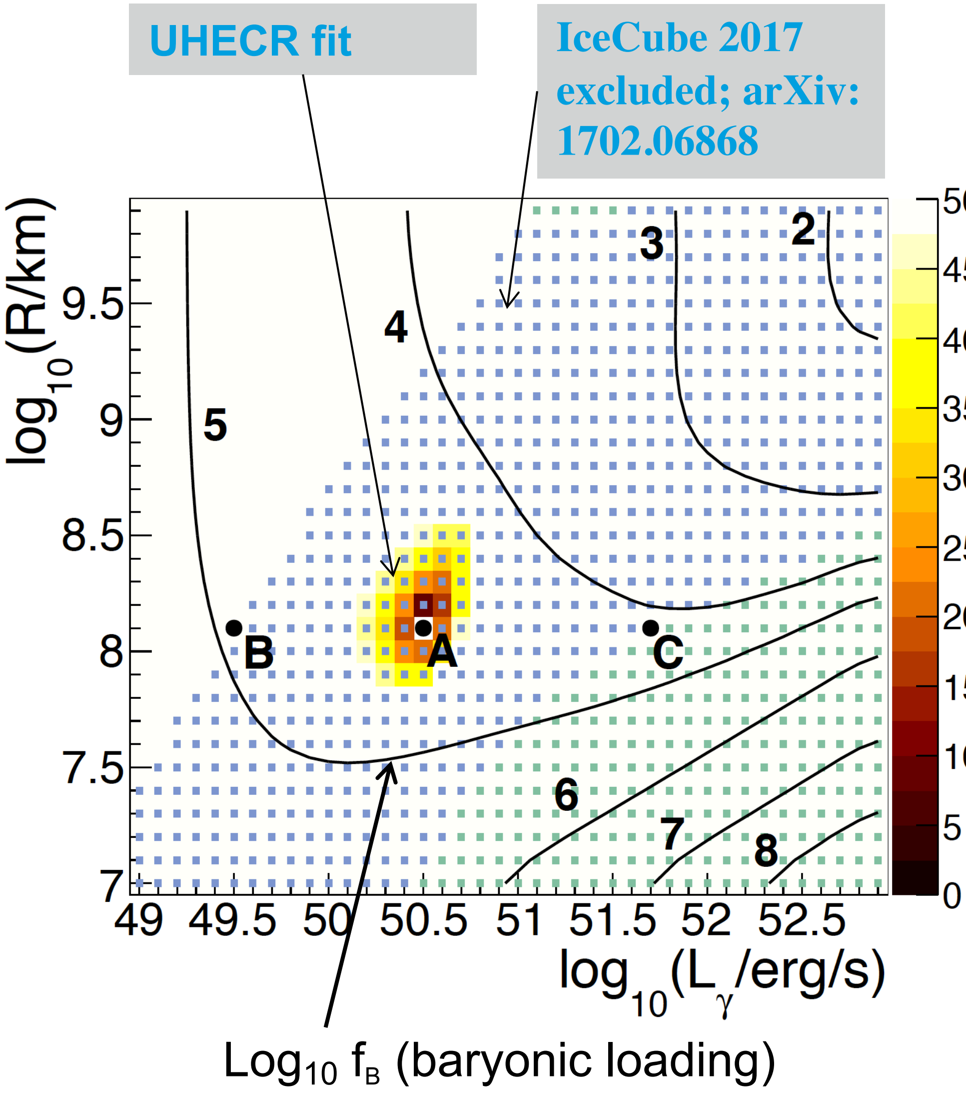
Recipe:

- 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









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

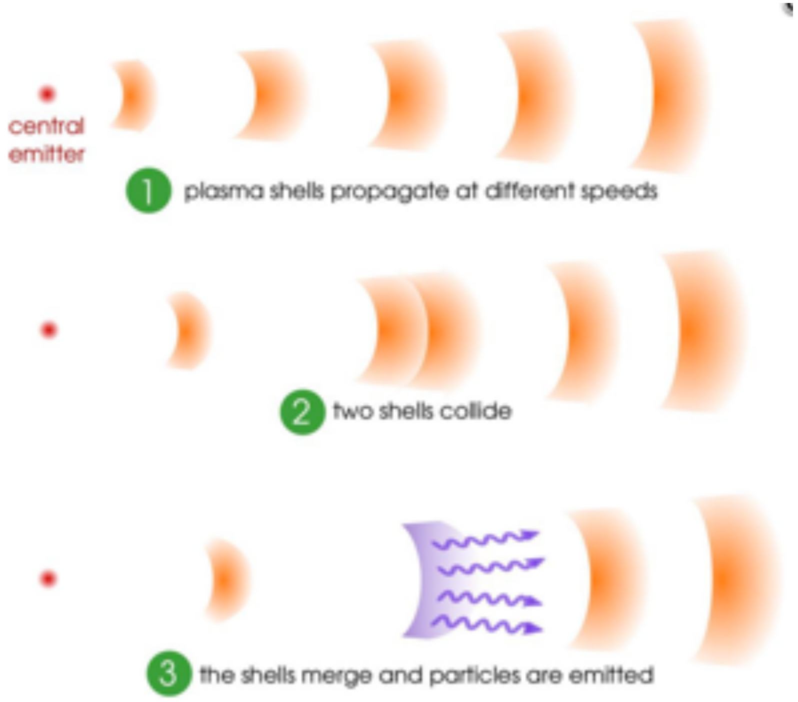
Back to the roots:

Multi-collision models

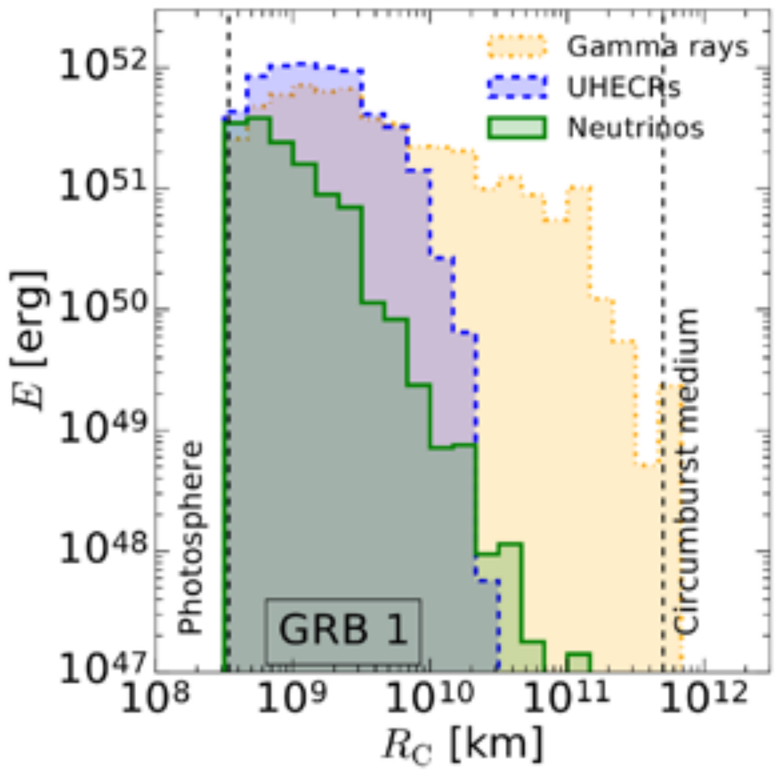
The GRB prompt emission comes from multiple zones

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

Collision model, illustrated



Multi-messenger emission



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

Observations

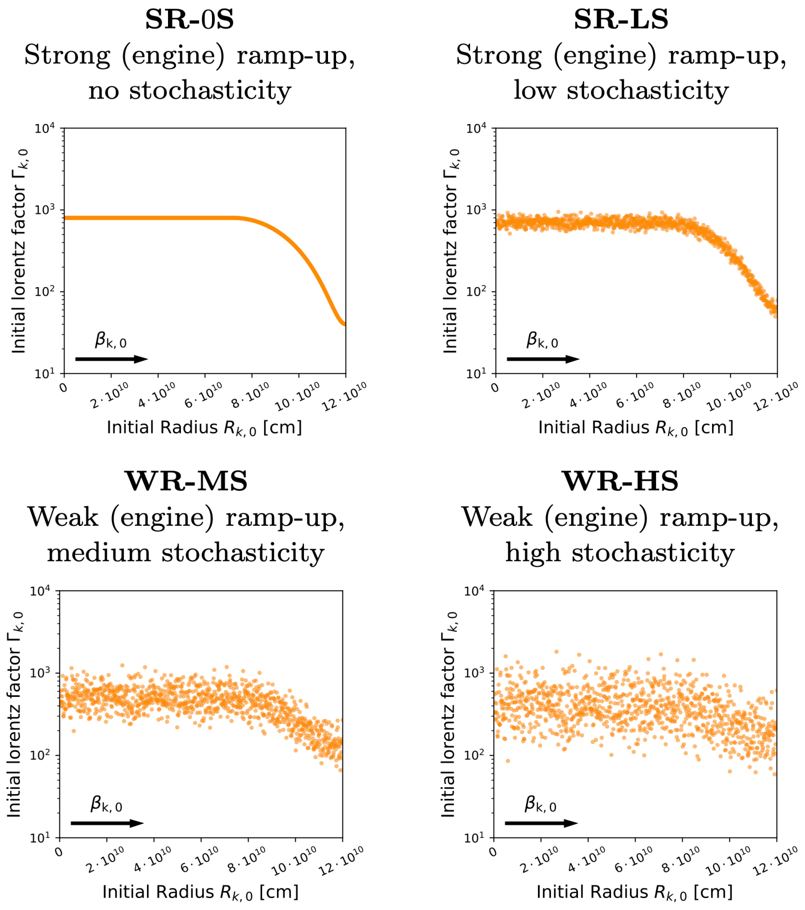
- The neutrino emission is lower (comes from a few collisions close to the photosphere)
- UHECRs and γ-rays are produced further out, where the radiation densities are lower
  - ➢ Releases tension with neutrino data
- The **engine properties** determine the nature of the (multi-messenger) light curves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

A new (unified) model with free injection compositions

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

Model description

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

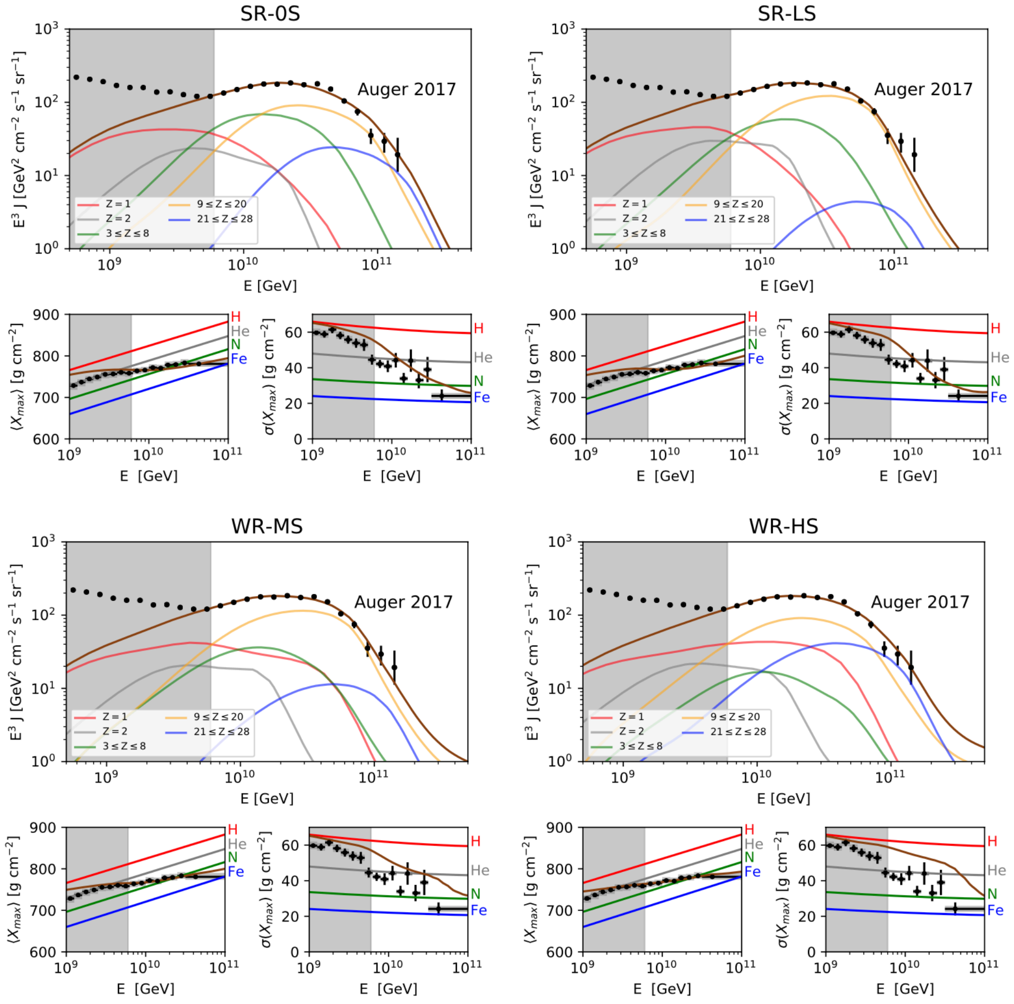


Describes UHECR data over a large range of parameters!

(systematically studied)

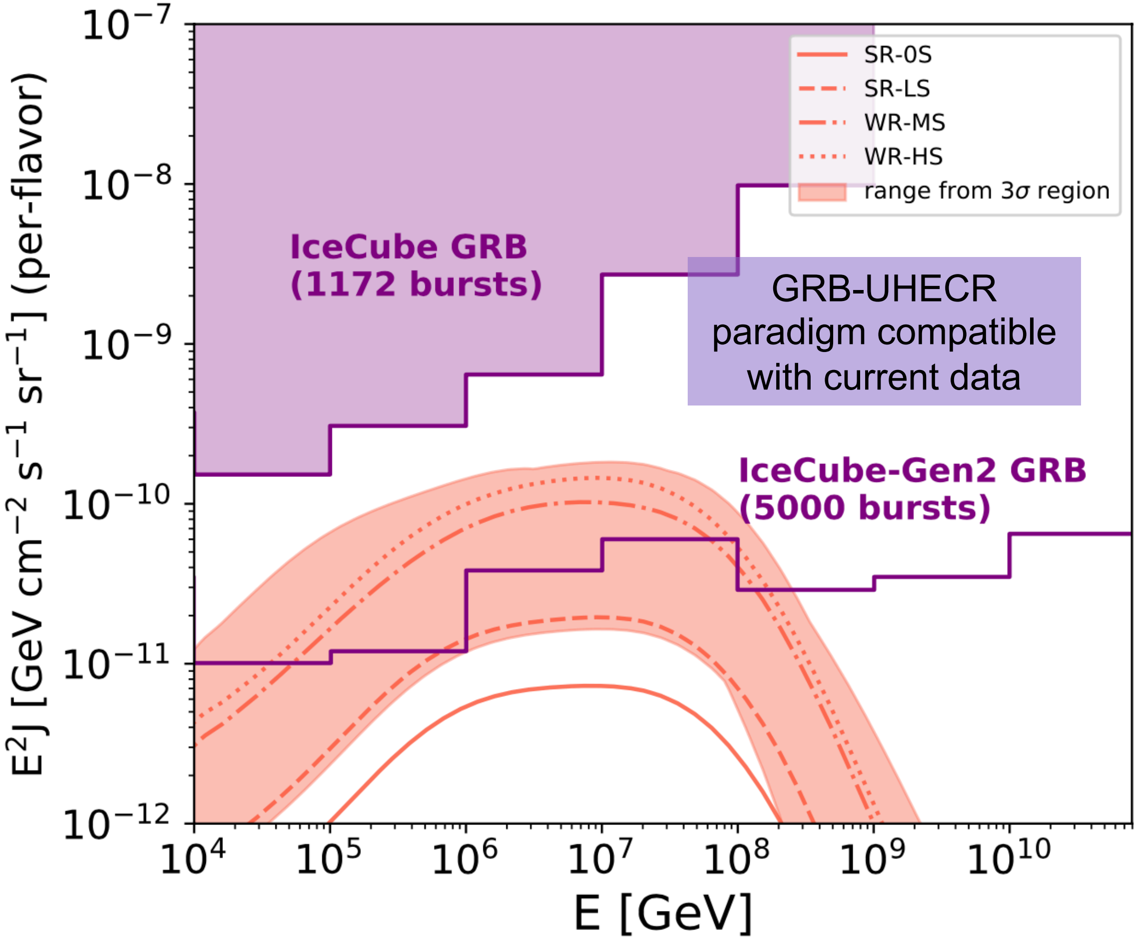
Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

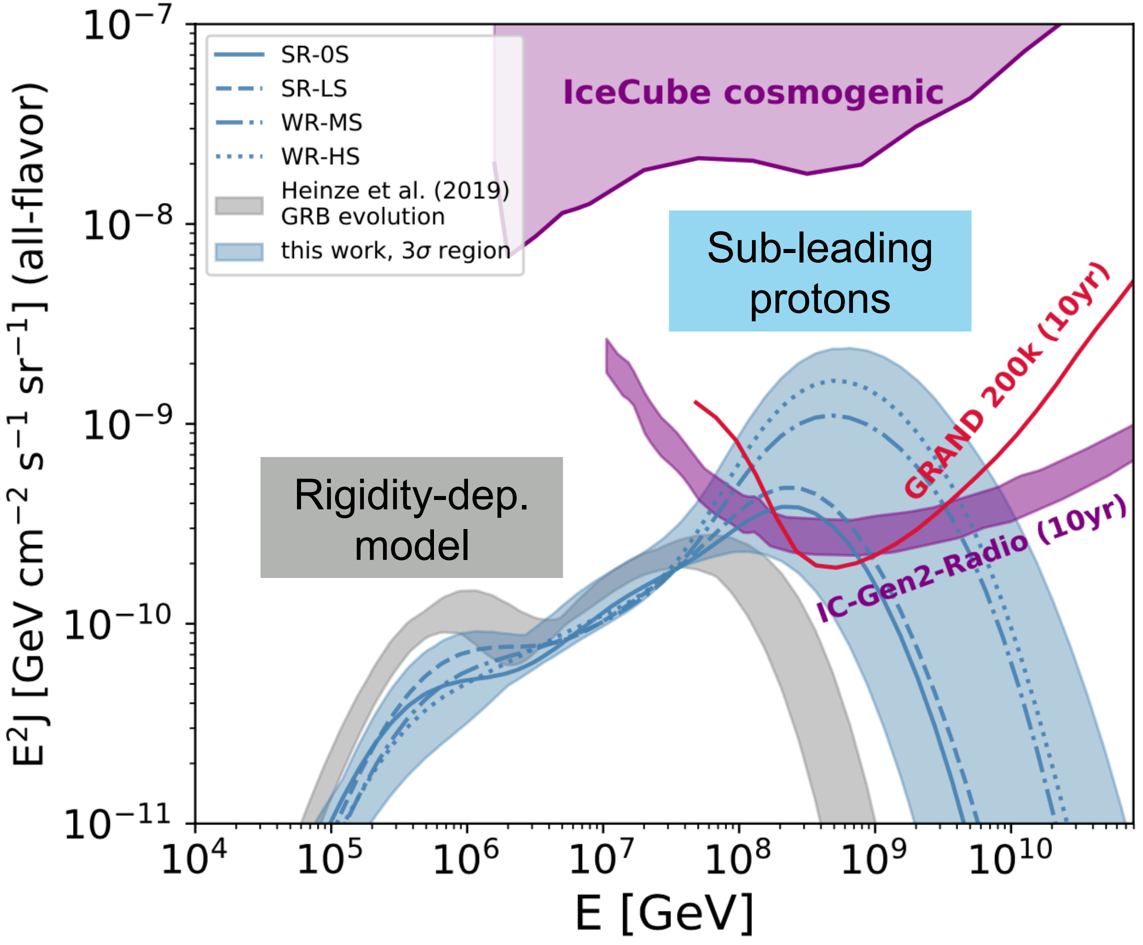
Description of UHECR data



Inferred neutrino fluxes from the parameter space scan

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

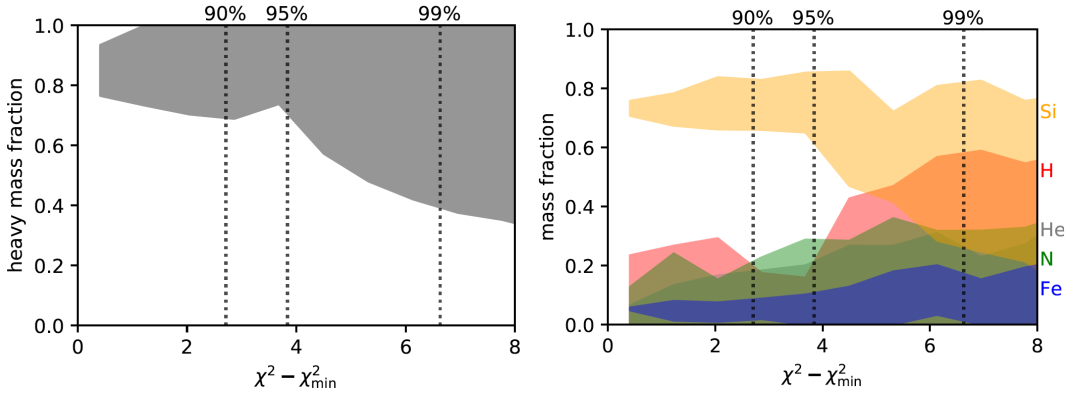




Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

Interpretation of the results

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

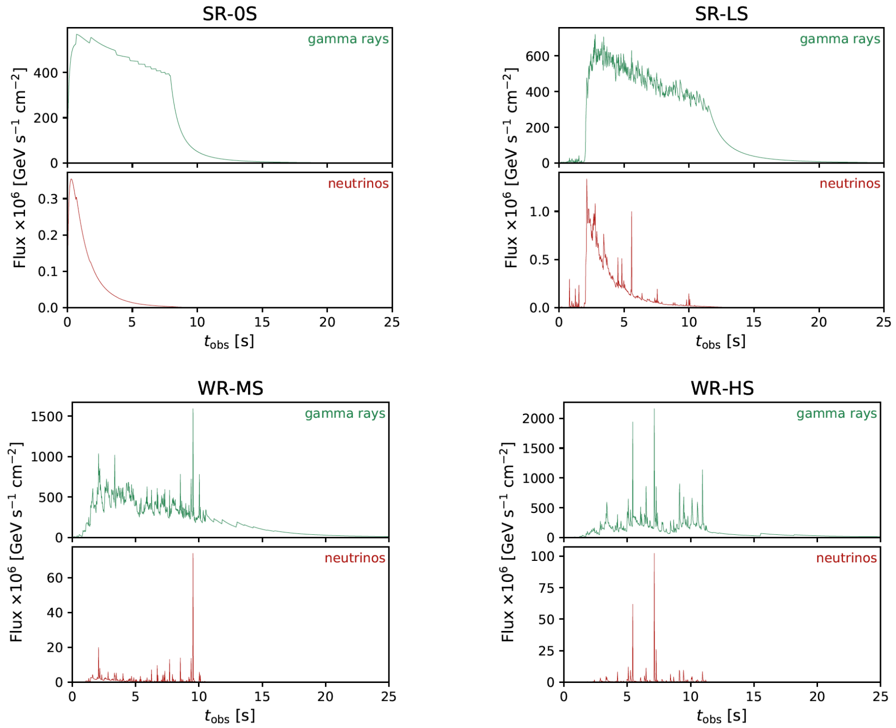


- Self-consistent energy budget requires kinetic energies larger than 10^{55} erg – **probably biggest challenge for UHECR paradigm**

	SR-0S	SR-LS	WR-MS	WR-HS
E_γ	$6.67{\cdot}10^{52}$ erg	$8.00{\cdot}10^{52}$ erg	$8.21{\cdot}10^{52}$ erg	$4.27{\cdot}10^{52}$ erg
$E^{\rm esc}_{\rm UHECR}$ (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

p. 3

- Light curves may be used as engine discriminator



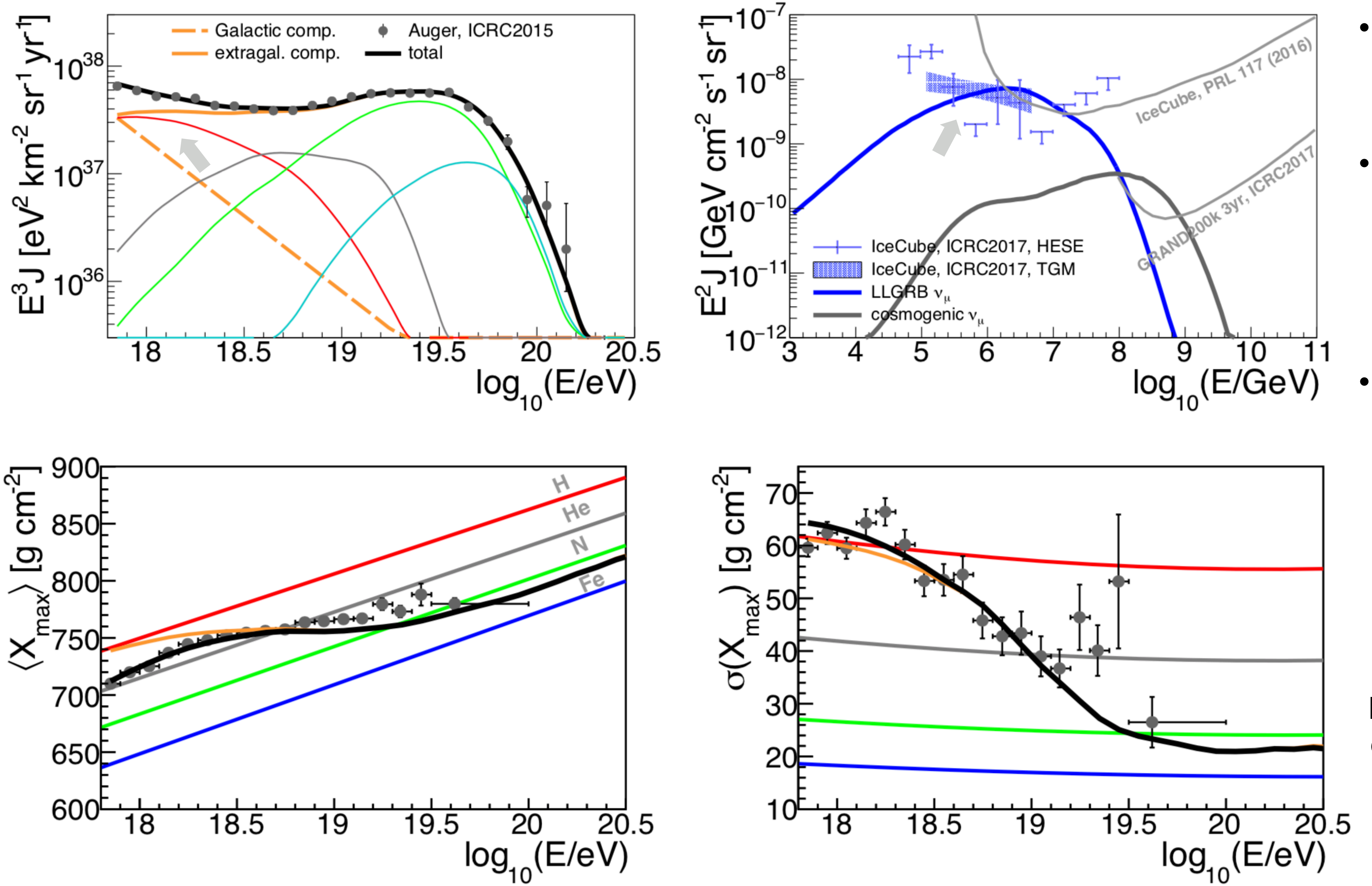
- Description of σ(X_{max}) is an instrinsic problem (because the data prefer "pure" mass groups, which are hard to obtain in multi-zone or multi-source models)

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

LL-GRBs

A population of low-luminosity GRBs?

Describing UHECRs and neutrinos with LL-GRBs



- Can be simultaneously described
- The radiation density controls the neutrino production and sub-ankle production of nucleons
- Subankle fit and neutrino flux require similar parameters

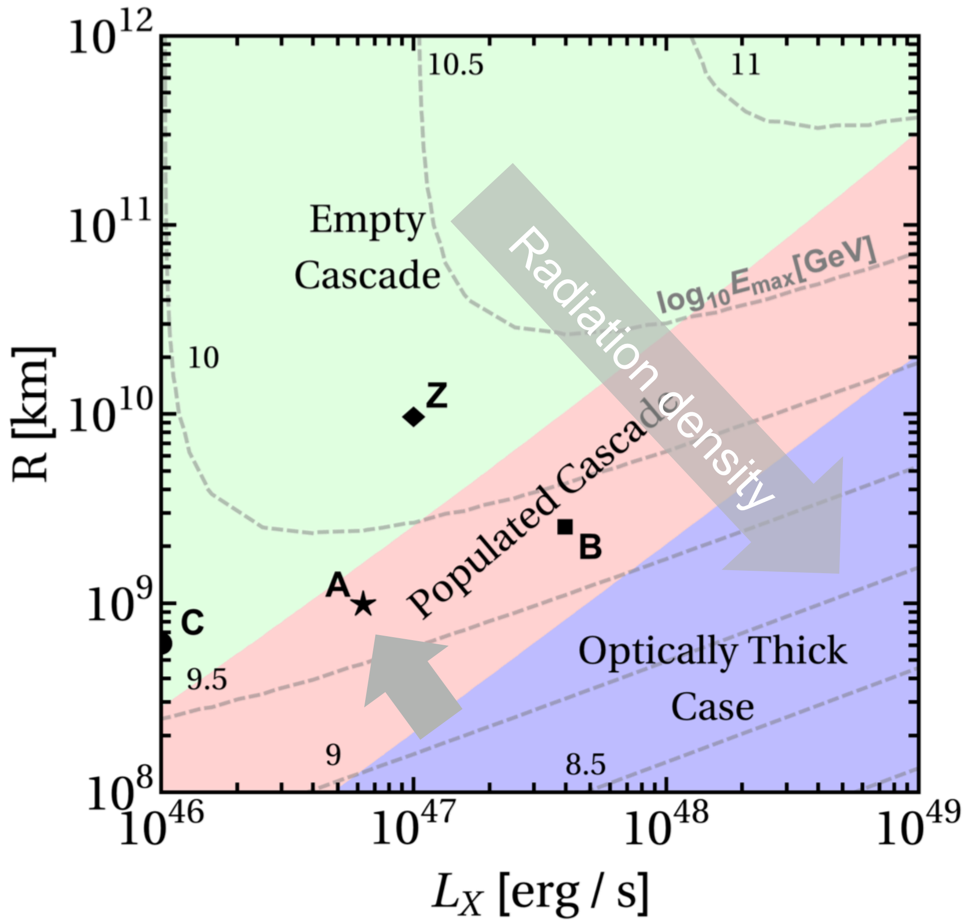
Boncioli, Biehl, Winter, ApJ 872 (2019) 110; arXiv:1808.07481

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

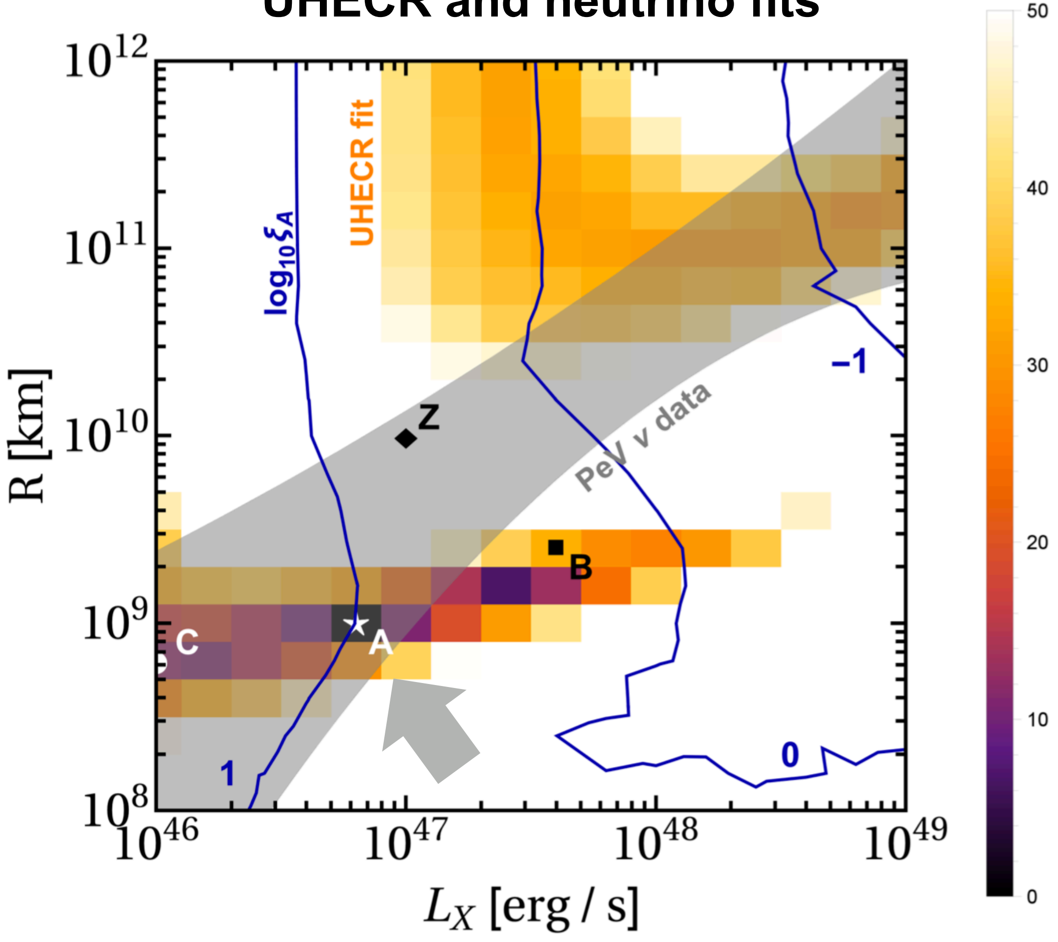
Systematic parameter space studies

What are the model parameter expectations driven by data?

Nuclear cascade and E_{max}



UHECR and neutrino fits

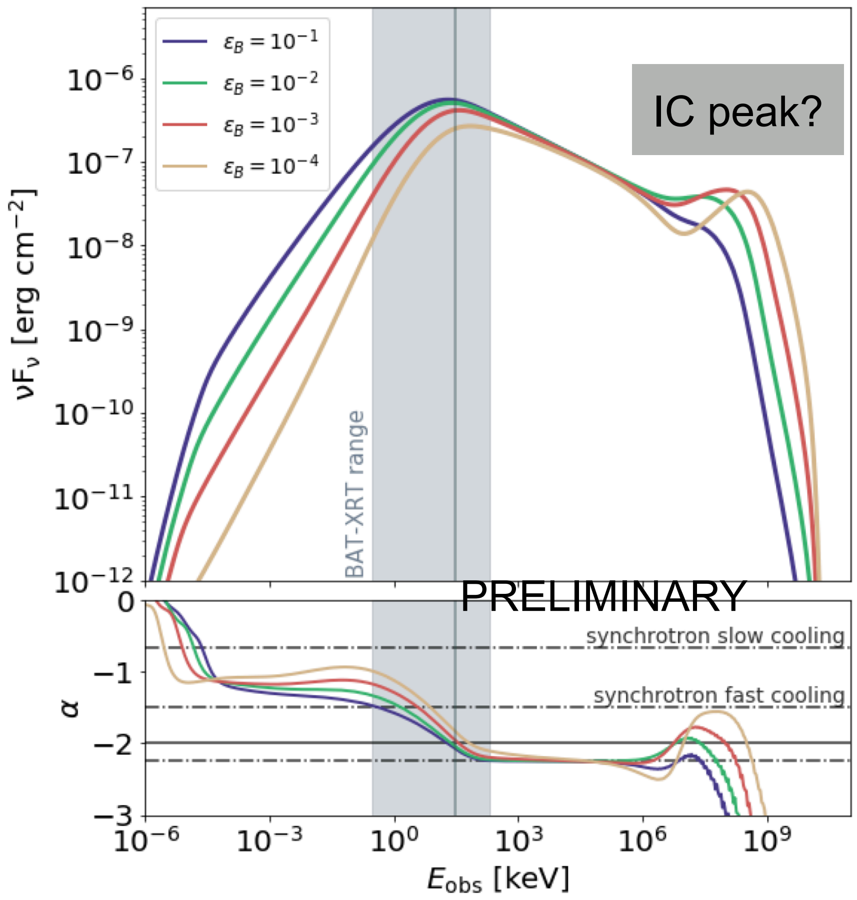


Boncioli, Biehl, Winter, arXiv:1808.07481;
Reference point "Z": Zhang et al., 2018

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

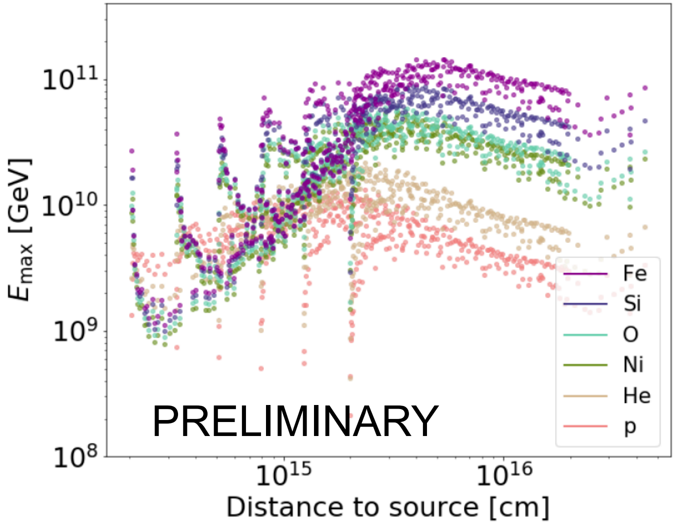
Open issues for LL-GRBs

Towards self-consistent SED radiation models



Rudolph, Bosnjak, Palladino, Sadeh, Winter, to appear;
see also discussions in Samuelsson et al, 2019+2020 for one zone model

- Can the necessary maximal energies be reached?



Conclusion: yes, because in multi-collision models the X-rays and UHECRs come from different regions

- What can we learn about the typical parameters?
- T_{90} <~ 10^5 s (from EGB contribution). Still **too large?**
- Necessary baryonic loading >~ 10
- OK in that ballpark, but unclear how large it can be from hadronic feedback in radiation modeling

Tidal Disruption Events

How to disrupt a star 101

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

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

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

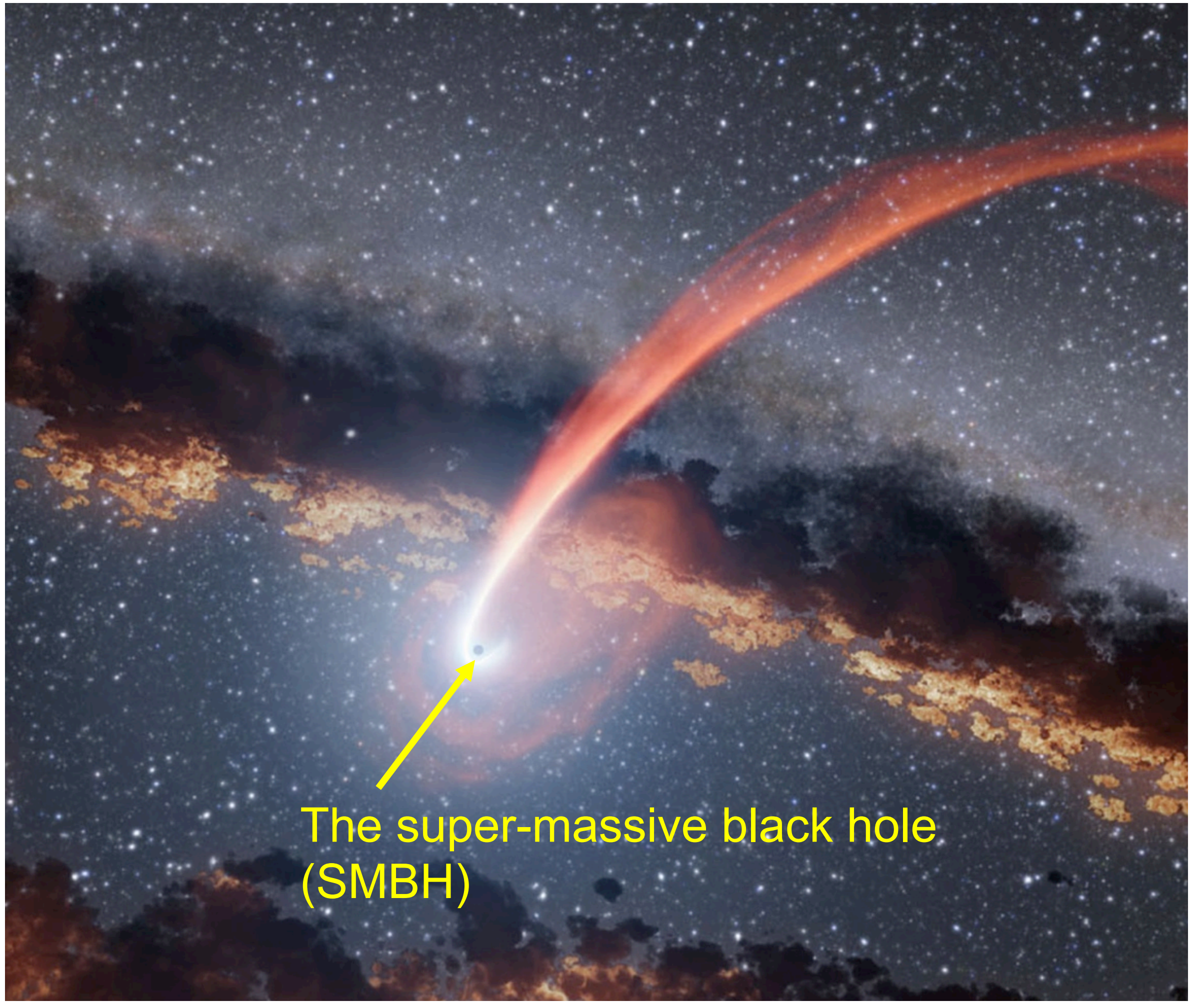
$$R_s = \frac{2MG}{c^2} \simeq 3 \times 10^{11}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)$$

- From the comparison ($r_t > R_s$) and TDE demographics, one obtains M <~ 2 x 10^7 $M_\odot$
  Hills, 1975; Kochanek, 2016; van Velzen 2017

- Schwarzschild time indicator for time variability?

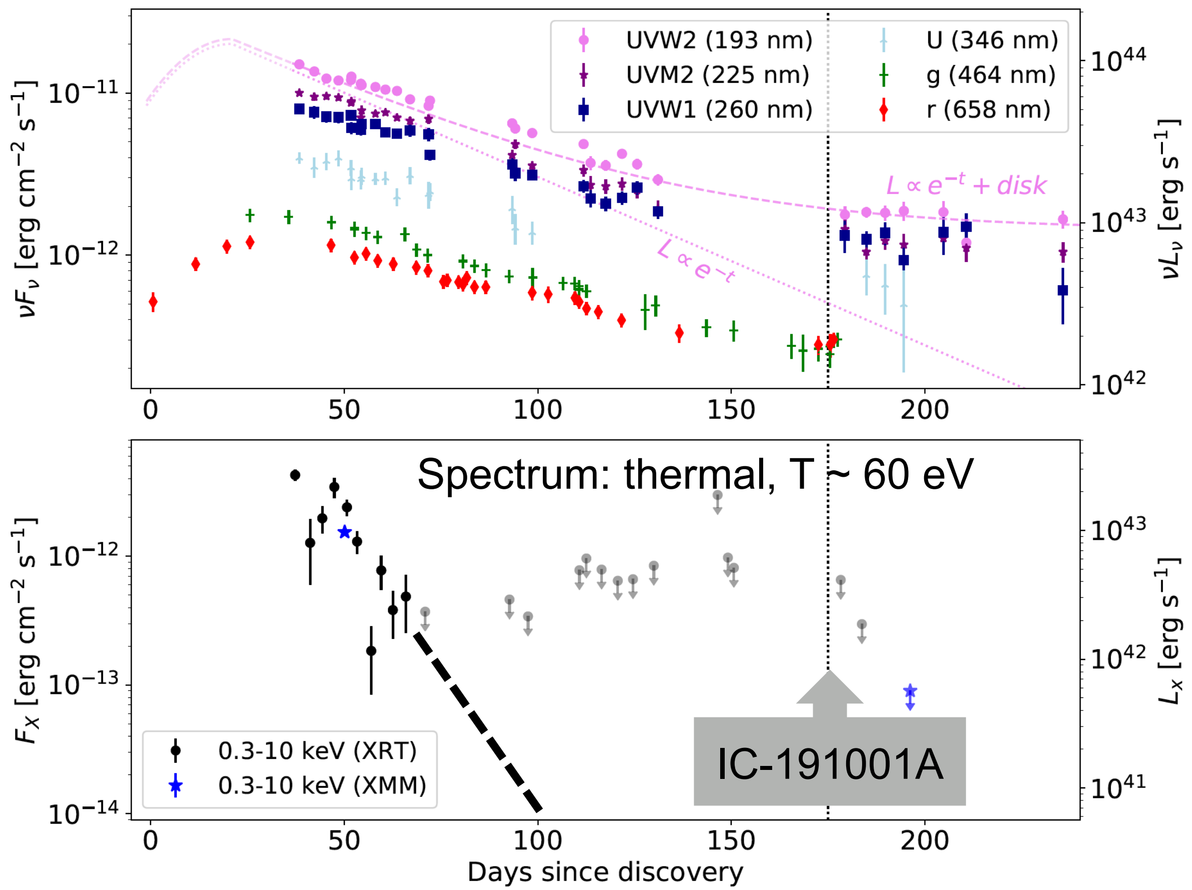
$$\tau_s \sim 2\pi R_s/c \simeq 63\,\mathrm{s} \left(\frac{M}{10^6\ M_\odot}\right)$$

→ Fastest time variability ~ 100s (assumption)



Observation of a neutrino from a Tidal Disruption Event

The TDE AT2019dsg was discovered as counterpart of the neutrino IC-191001A about 150 days after peak



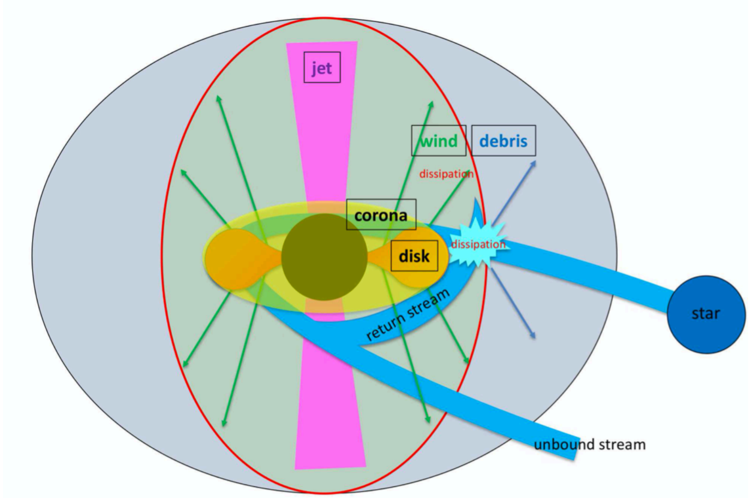
Stein et al, arXiv:2005.05340

- First association of a neutrino with a TDE
- The radio emission of the TDE showed sustained engine activity over that long time
- Quickly decaying X-rays have been observed. Possibly effect of obscuration

Questions:

- Where was the neutrino produced? In a jet? In the core? In a hidden wind?
- Why did the neutrino come 150 days after the peak?
- Is there a connection to the X-ray emission?

Fig. from Murase et al, arXiv:2005.08937; see also Hayasaki, Yamazaki, 2019 →

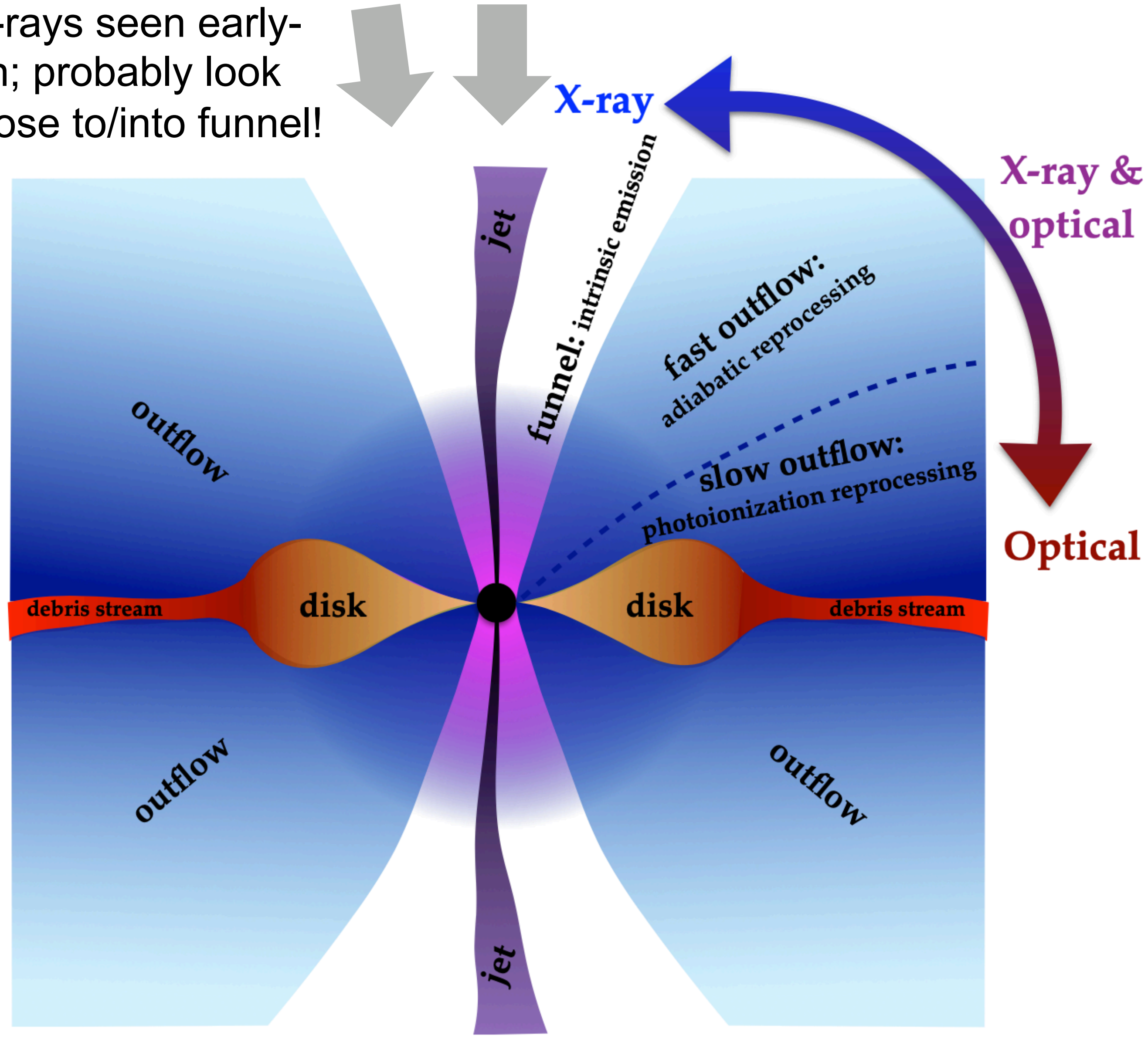


TDE unified model

... used to motivate a concordance model

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

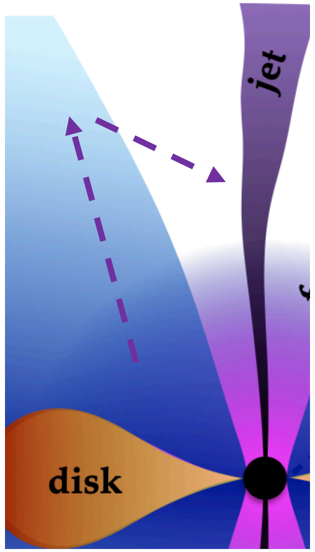
X-rays seen early-on; probably look close to/into funnel!



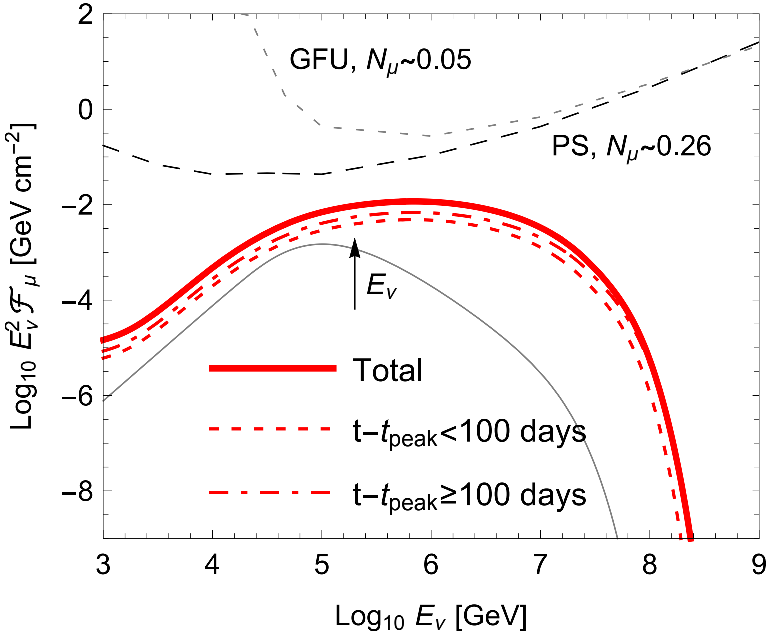
Dai, McKinney, Roth, Ramirez-Ruiz, Coleman Miller, 2018

A jetted concordance model

- Same effect which causes X-ray obscuration leads to isotropized X-rays backscattered into jet frame →

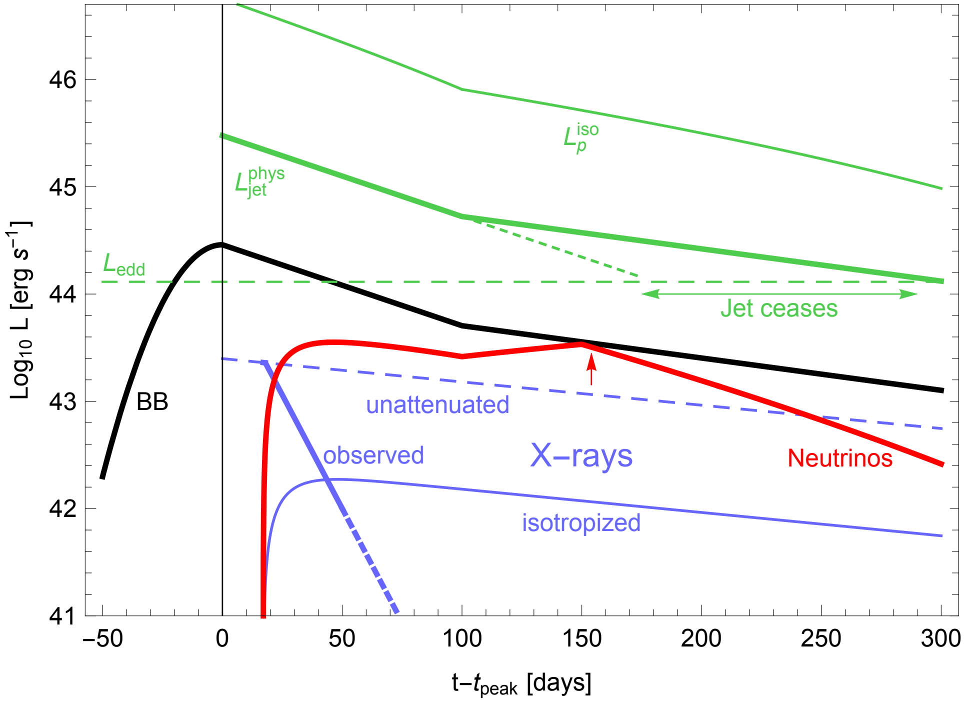


Dai et al, 2018



- Number of events: 0.05-0.26, depending on effective area
- Multi-pion production dominated neutrino flux (Δ-resonance: gray)

- Neutrino production peaks at ~ 150 days because of competition between decreasing production radius and proton luminosity ($L_\nu \sim R_C^{-2}$)
- **Prediction for future observations**: Neutrinos come significantly after t_{peak} (target needs to isotropize, which leads to delay)

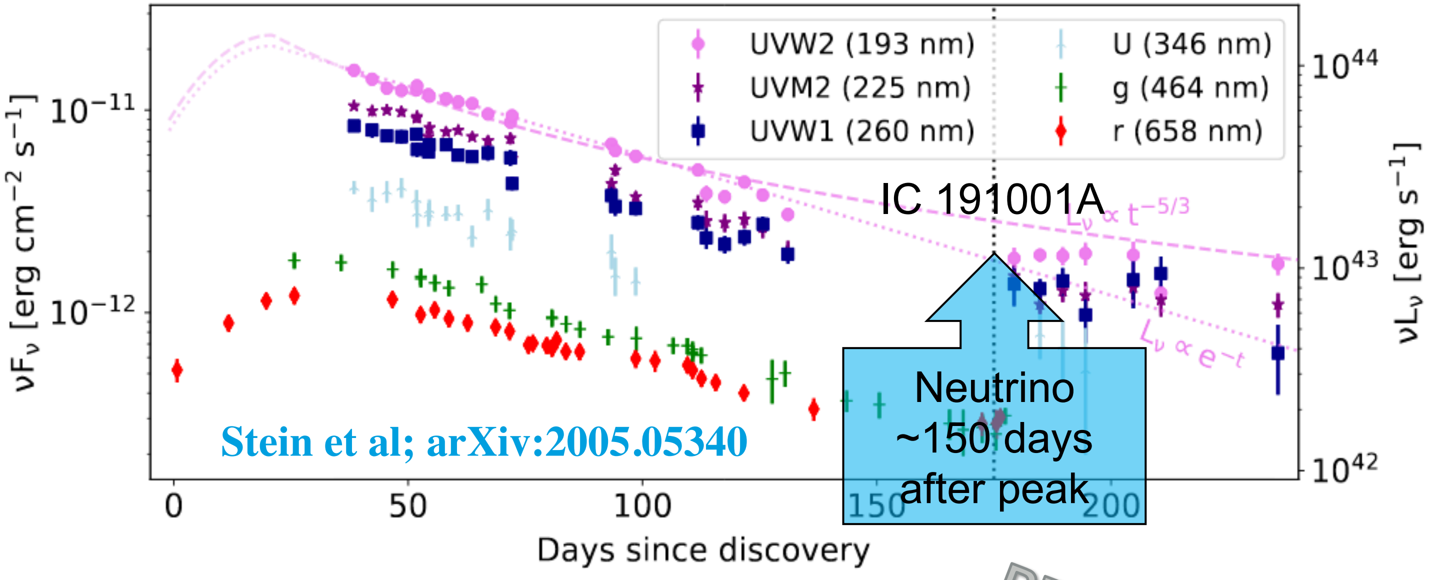


Winter, Lunardini, arXiv:2005.06097;
see also Liu et al, arXiv:2011.03773

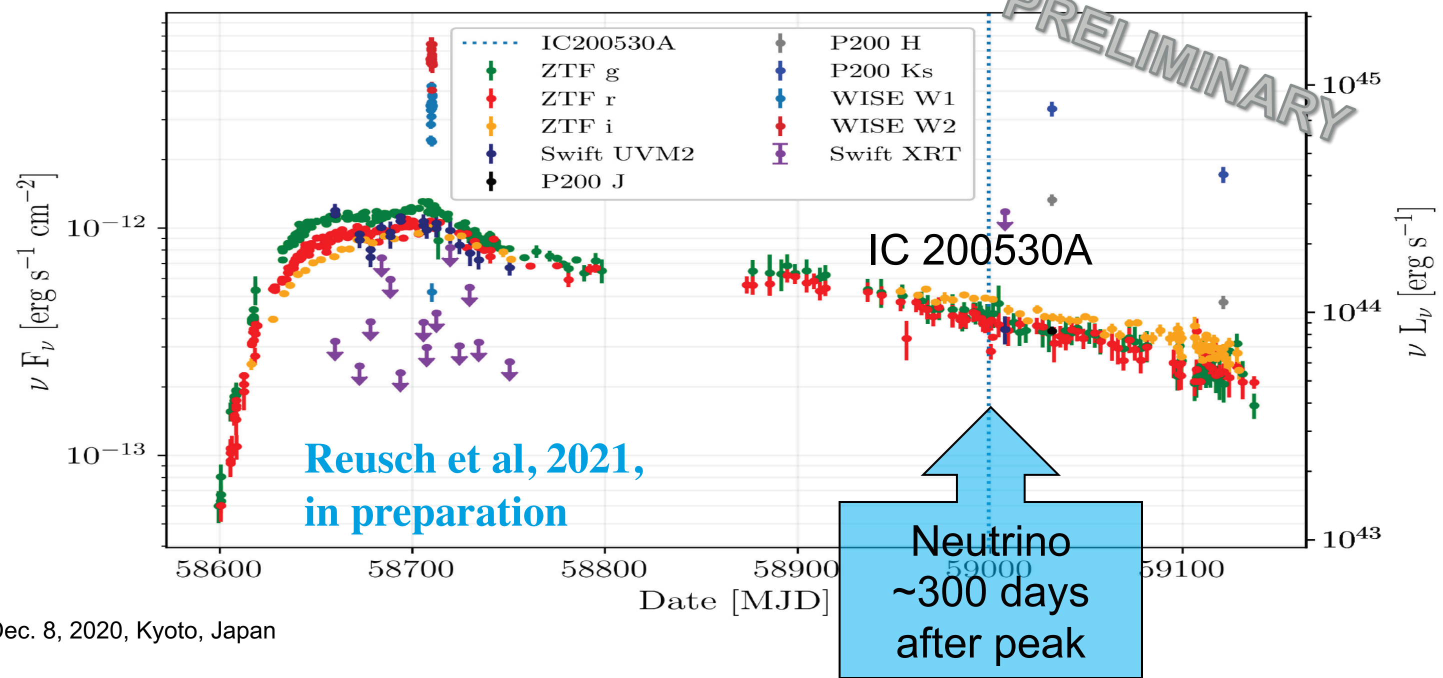
Is that the end of the story?

From: van Velzen et al, 2001.01409

AT2019dsg
aka **Bran Stark**



AT2019fdr
aka **Tywin Lannister**



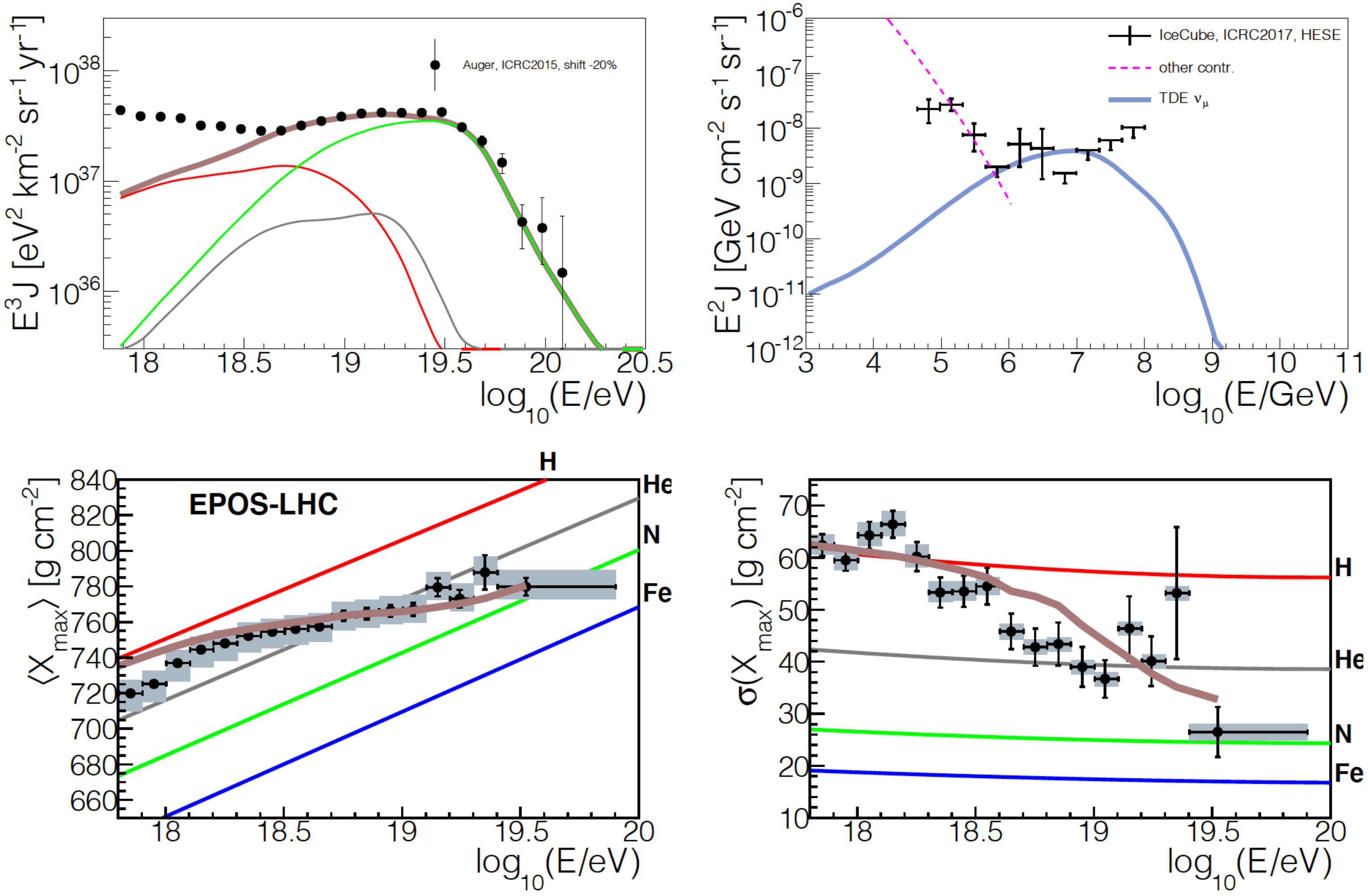
AT 2019fdr: More luminous, longer; probably larger star disrupted, larger SMBH mass, larger system

Ongoing data analysis and theoretical modeling.

Why do these neutrinos come 150-300 days after the peak?

Diffuse UHECRs and neutrinos from TDE?

- Can potentially describe neutrinos and UHECRs at the highest E
- TDEs may have negative source evolution (helps UHECR fit)
- Requires very luminous (Sw J1644+57-like) TDEs disrupting C-O white dwarfs or similar at high enough local rate
- Tension with neutrino stacking searches and multiplet limits
  e.g Stein, PoS ICRC2019 (2020) 1016
- Subject may require further study in light of recent TDE discoveries ...



Biehl, Boncioli, Lunardini, Winter,
Sci. Rep. 8 (2018) 1, 10828, arXiv:1711.03555;
see also Zhang, Murase, Oikonomou, Li, arXiv:1706.00391;
Guepin et al, arXiv:1711.11274

Summary

Different transient classes in the light of UHECR and neutrino observations

HL-GRBs

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

LL-GRBs

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

TDEs

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

Final slide: Personal opinion

Questions from the organizers

- **What's your targeted physics in next decades?**
  - HL-GRBs: Scrutinize energetics; afterglows (including VHE emission) seem key issue; neutrino discoveries?
  - LL-GRBs: More complete population studies/samples; neutrino stacking searches
  - TDEs: More neutrino discoveries from TDEs?
    Population studies, simulations, systematics

WINTER IS HERE
van Velzen et al, 2001.01409

- **What we need to accomplish?**
  - Theoretical side: connection to GW events and with jet physics, particle acceleration at relativistic shocks
  - Observational side: wider/longer+deeper surveys, coverage of multiple wavelengths. Neutrino telescope upgrades. Improved UHECR composition data.

- **Take-home messages**
  - See previous slide