Multi-messenger signal from Gamma-Ray Bursts

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Neutrinos in the multi-messenger era

Louvain-la-Neuve, Belgium
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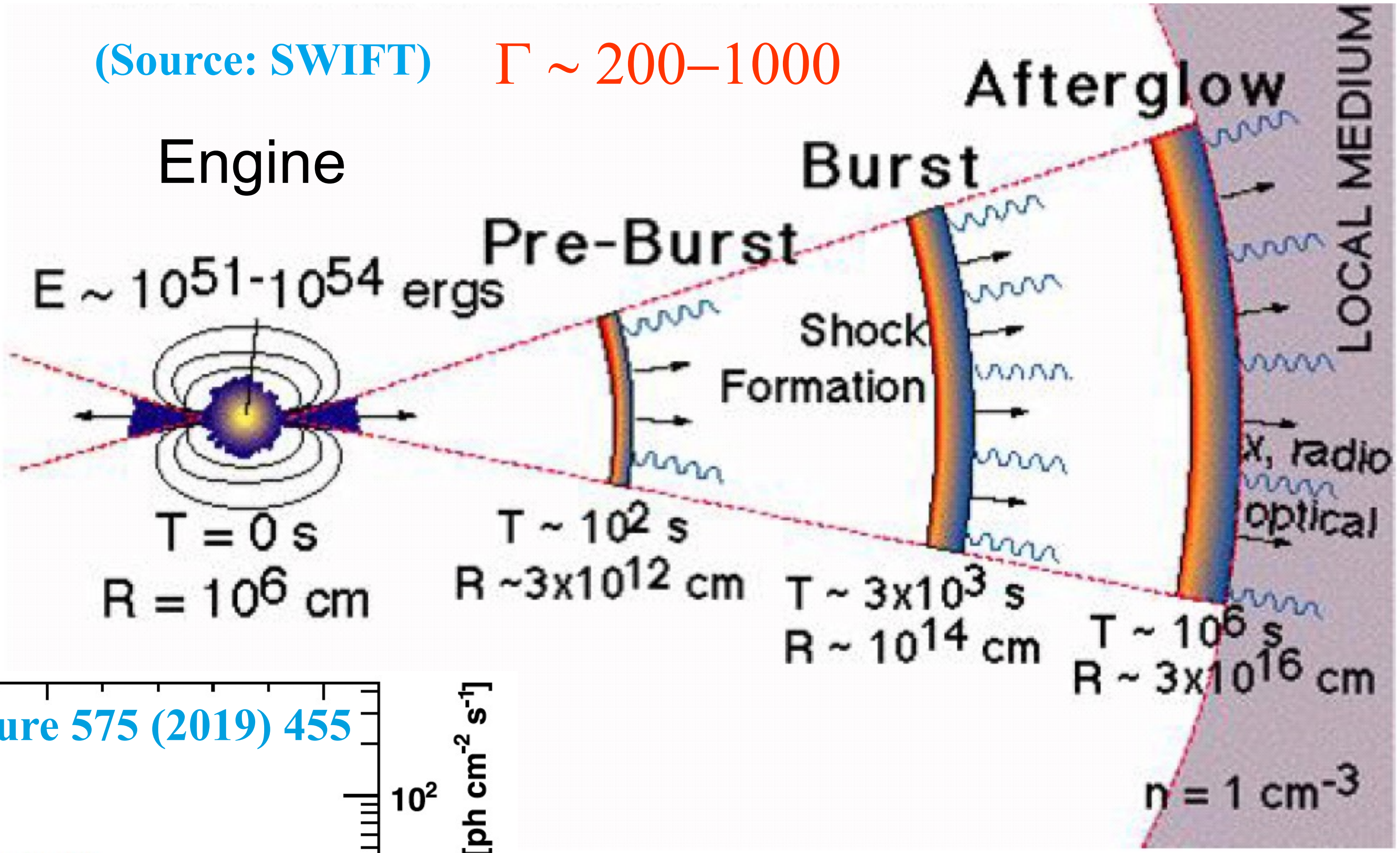
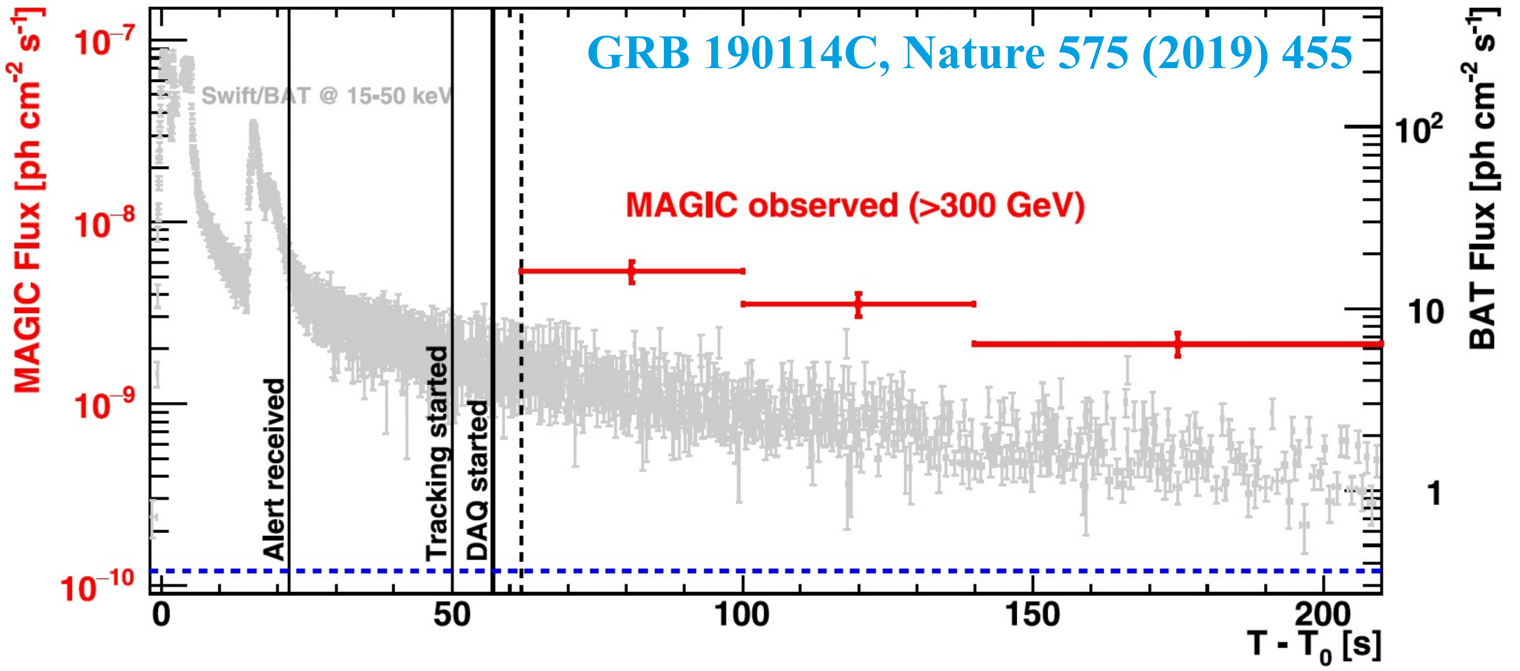
Contents

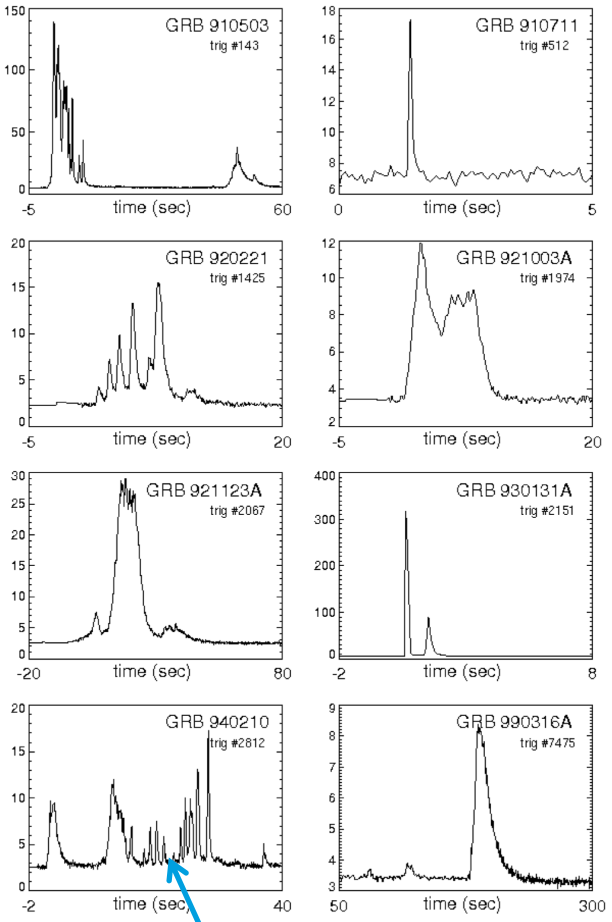
GRB – different regions





Focus on
prompt phase
Highest flux
⇨ Energetics

GRB prompt emission … and different populations



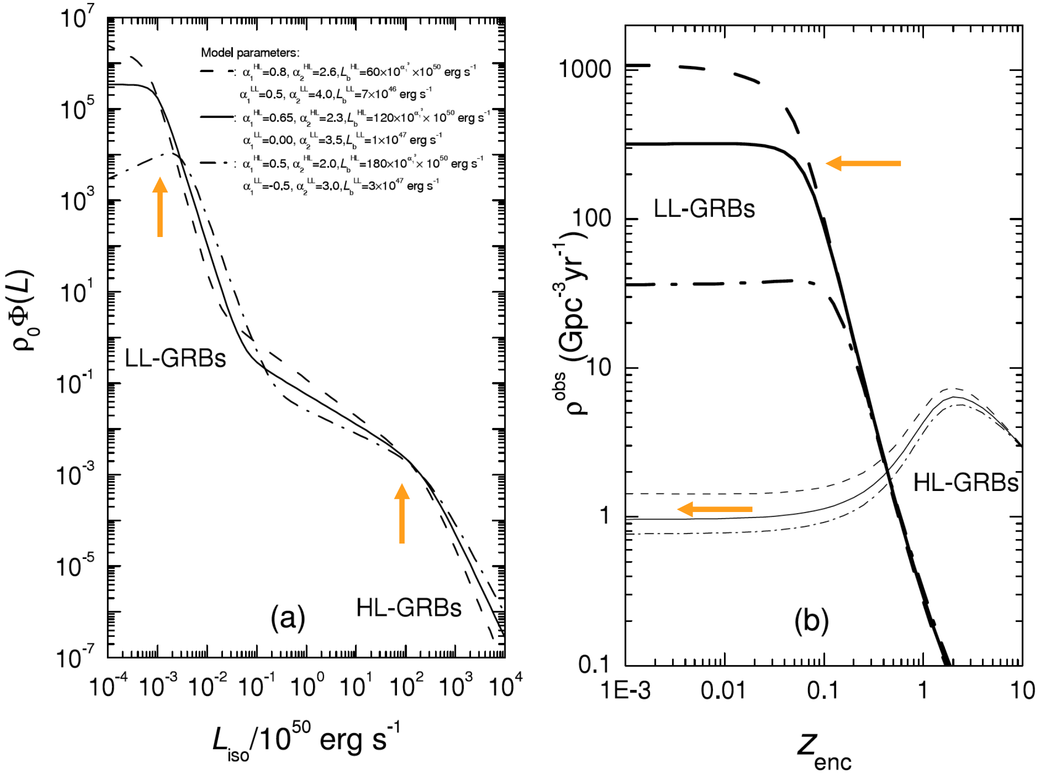
t_v: variability timescale

Daniel Perley

Several populations, such as

- **Long-duration bursts** (~2 – 100s), from collapses of massive stars? **HL-GRBs**
- **Short-duration bursts** (~ 0.1 – 2 s) **sGRBs**, from neutron star mergers? Can have high luminosity, but low total energy output!
- **Low-luminosity GRBs** from intrinsically weaker engines, or shock breakout? **LL-GRBs** Potentially high rate, longer duration

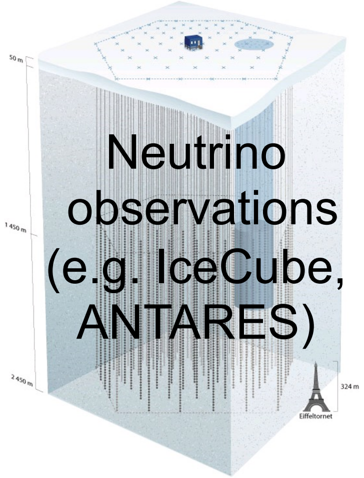
Liang, Zhang, Virgili, Dai, 2007; see also: Sun, Zhang, Li, 2015



Multimessenger stacking bounds

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

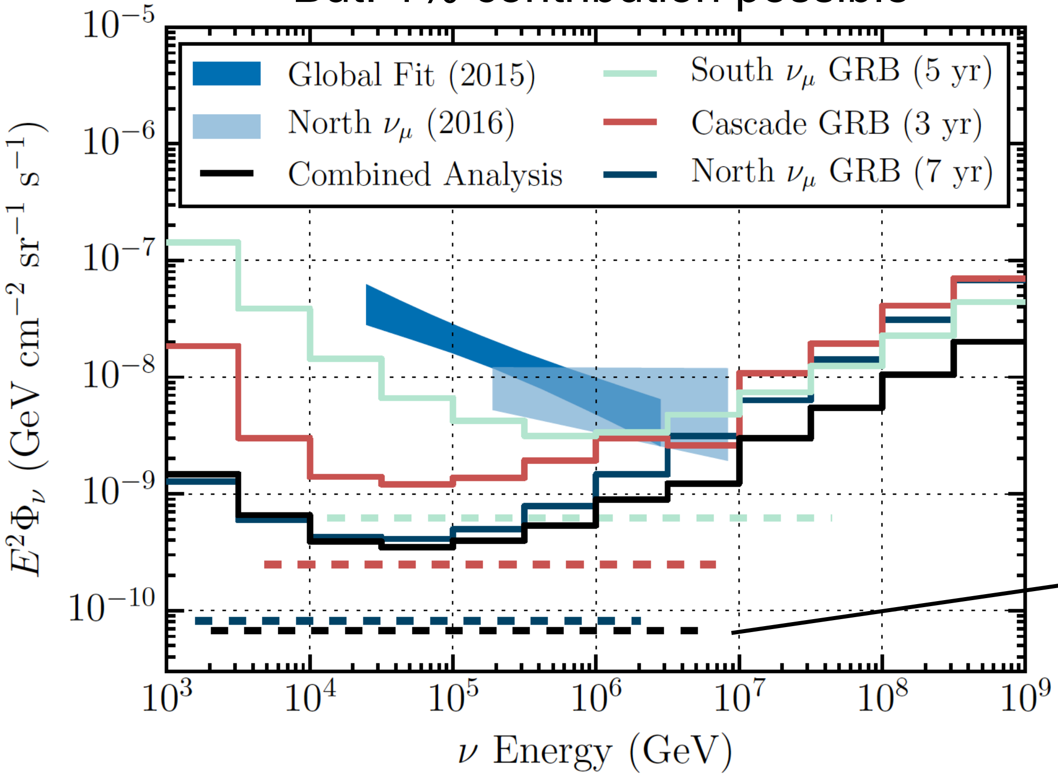
Coincidence?

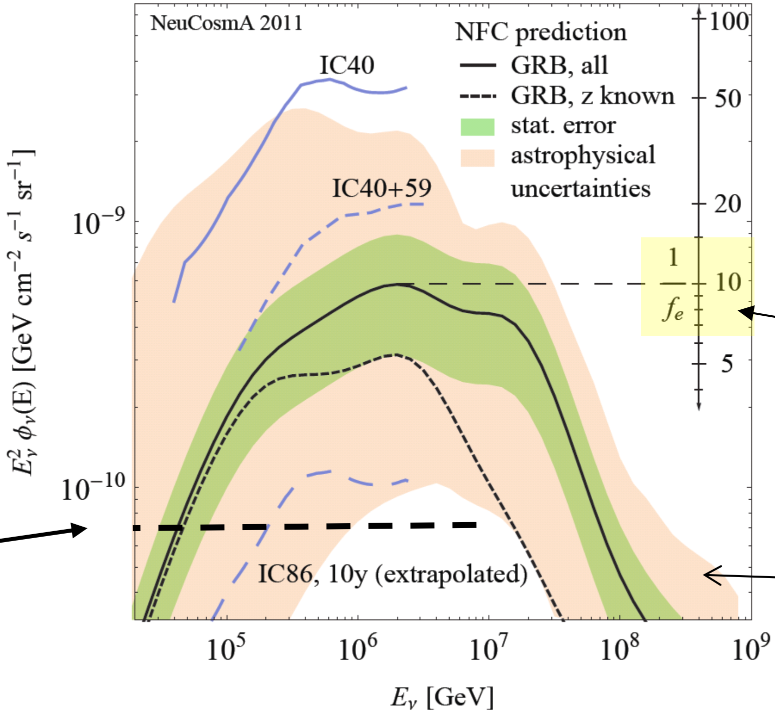


Neutrino observations (e.g. IceCube, ANTARES)

Use timing, directional and energy information to reduce backgrounds

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





Neutrino production
$E_\nu \sim E_\gamma \times 1/f_e \times f_\pi$

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:

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

Required energy output per source

Fit to UHECR data

Source density

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

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

Possible interpretation of non-observation of neutrinos:

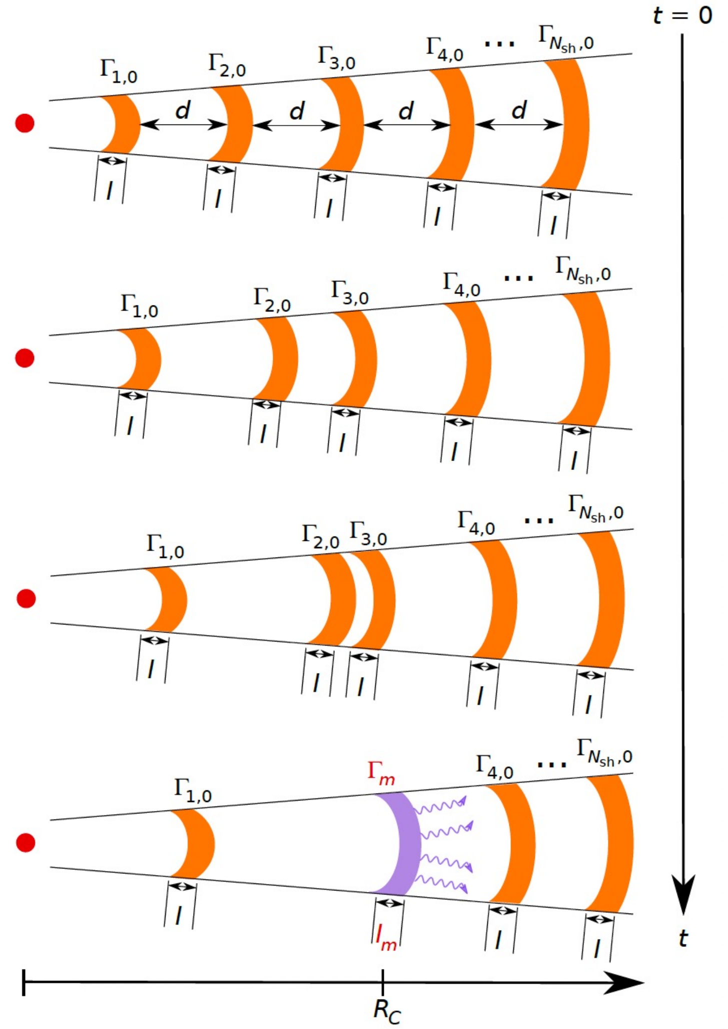
- The one zone model is an over-simplification. Different messengers come from different regions.
- The parameters of the UHECR-emitting GRBs are very different.
  Do only very energetic GRBs accelerate UHECRs? How about low-luminosity GRBs?
- The UHECR acceleration takes place in very different zones, 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

Models for the prompt phase emission

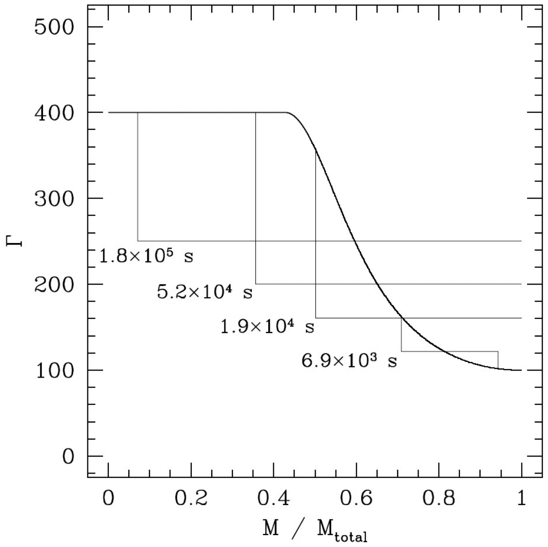
Outflow models

Applied to internal shocks

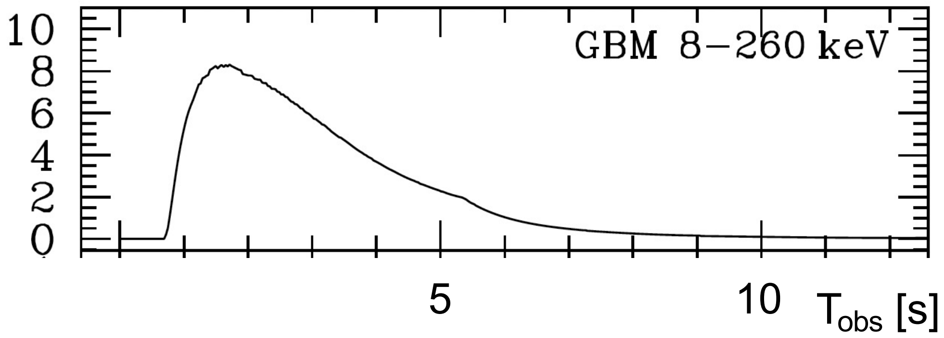
One zone approximation:
$t_v \sim l_m/c$ (variability timescale)
$R_C \sim \Gamma^2 d$ (distance to catch up)
Often: $d \sim l \rightarrow \mathbf{R_c \sim c\, \Gamma^2\, t_v}$



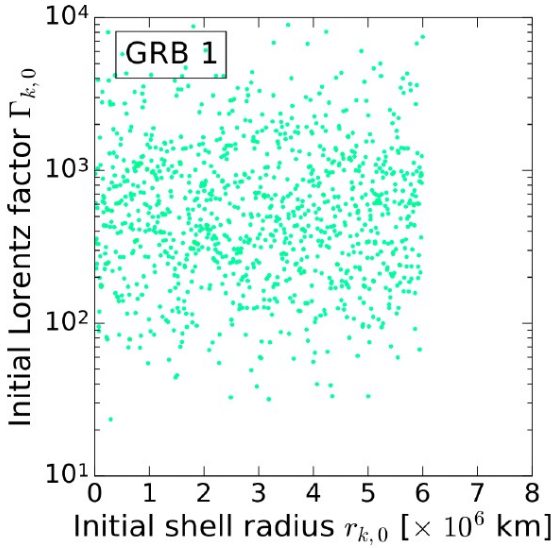
Continuous outflow: $t'_{dyn}=R_c/(c\,\Gamma)$

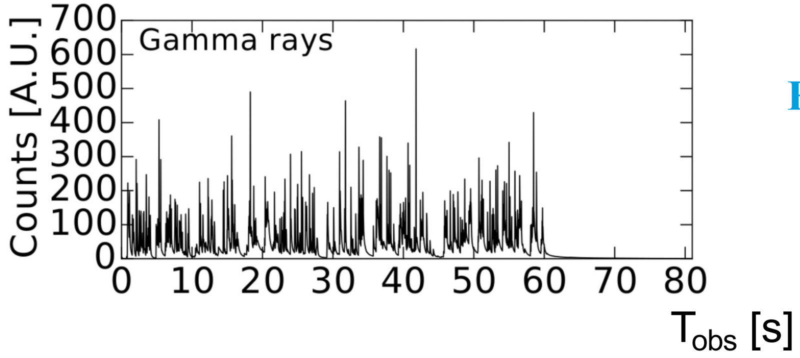


From: Bosnjak, Daigne, Dubus, A&A 498 (2009) 3



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

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:

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

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

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

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 …)

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

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

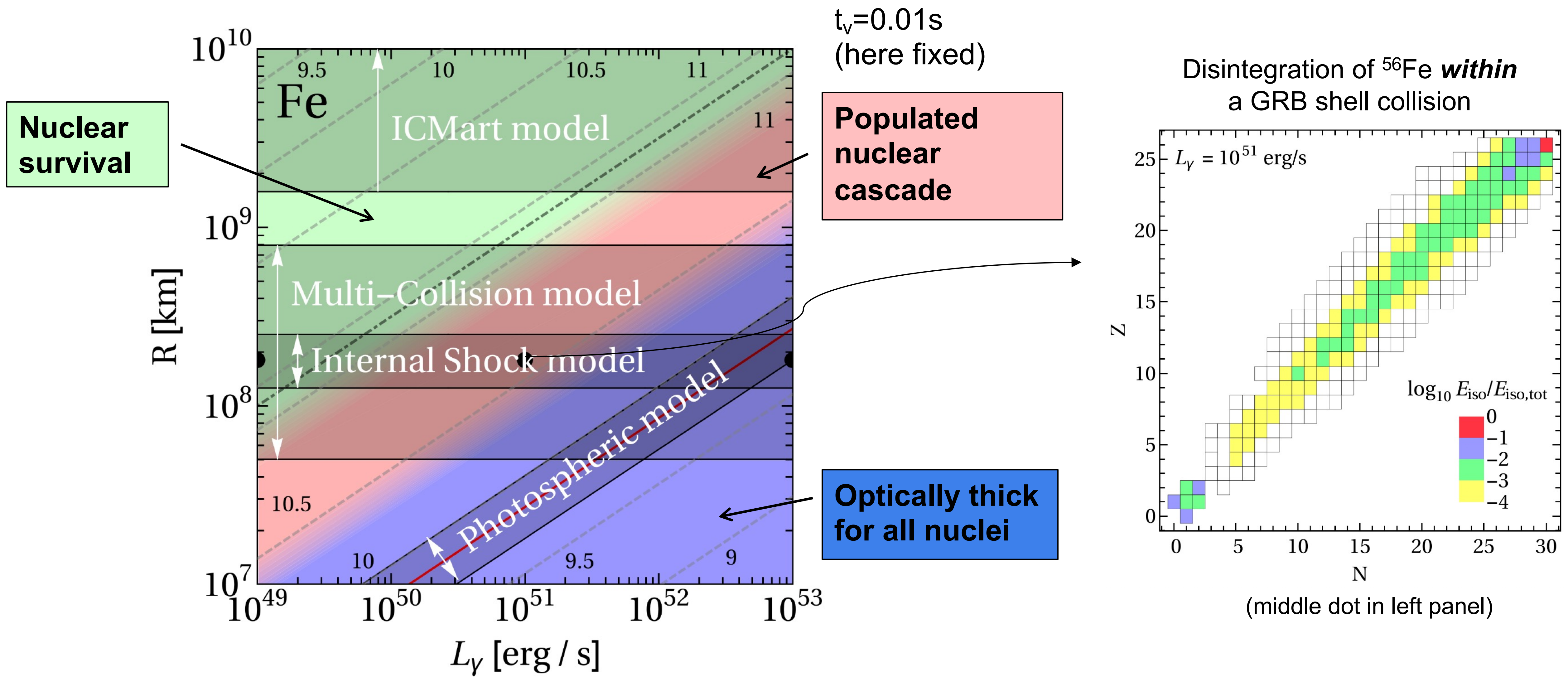
Internal shock model (one zone)

- **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

Example: Nuclear cascade (UHECR iron nuclei)

t_v=0.01s
(here fixed)



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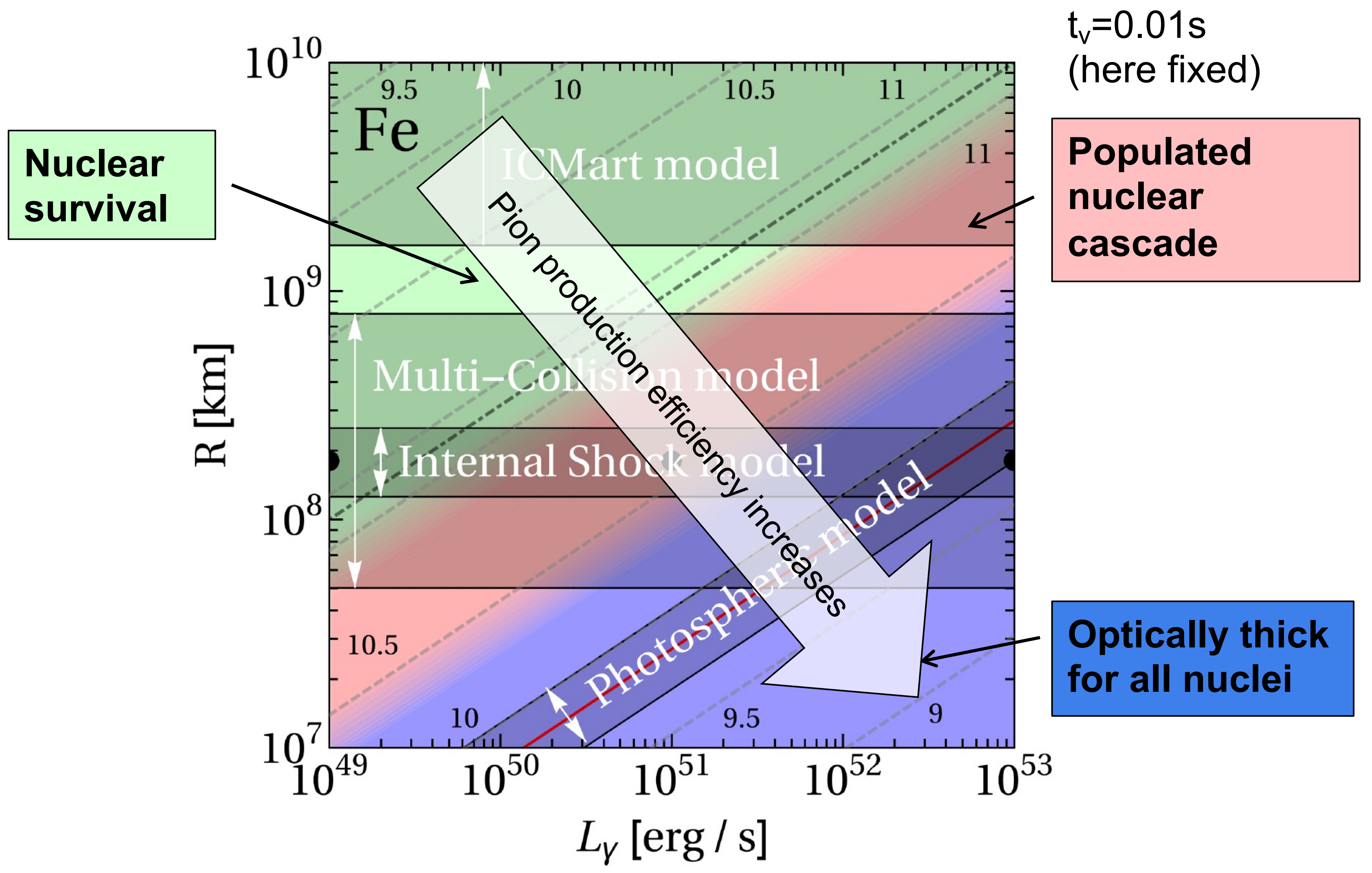
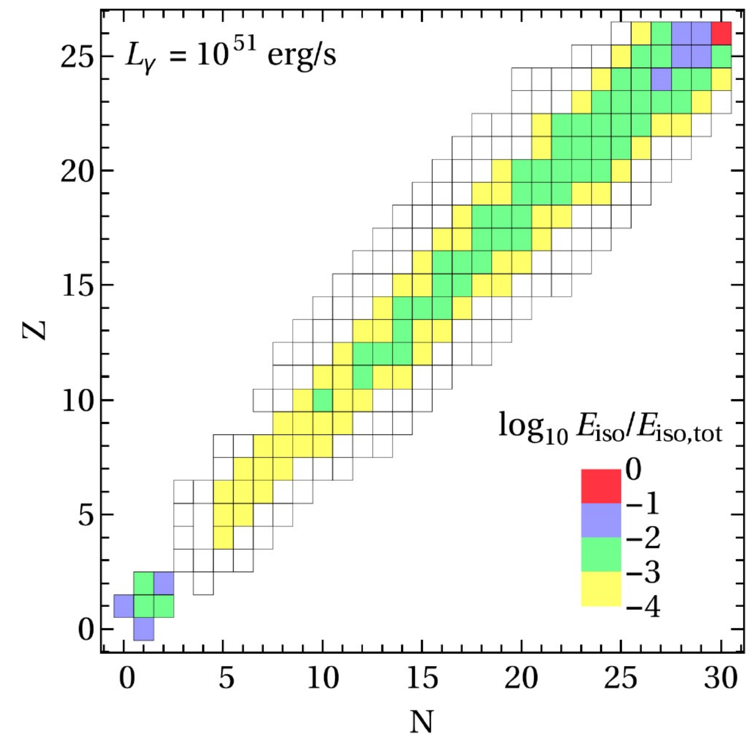
Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909;
see also Murase et al, 2008; Anchordoqui et al, 2008

Example: Nuclear cascade



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



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Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909;
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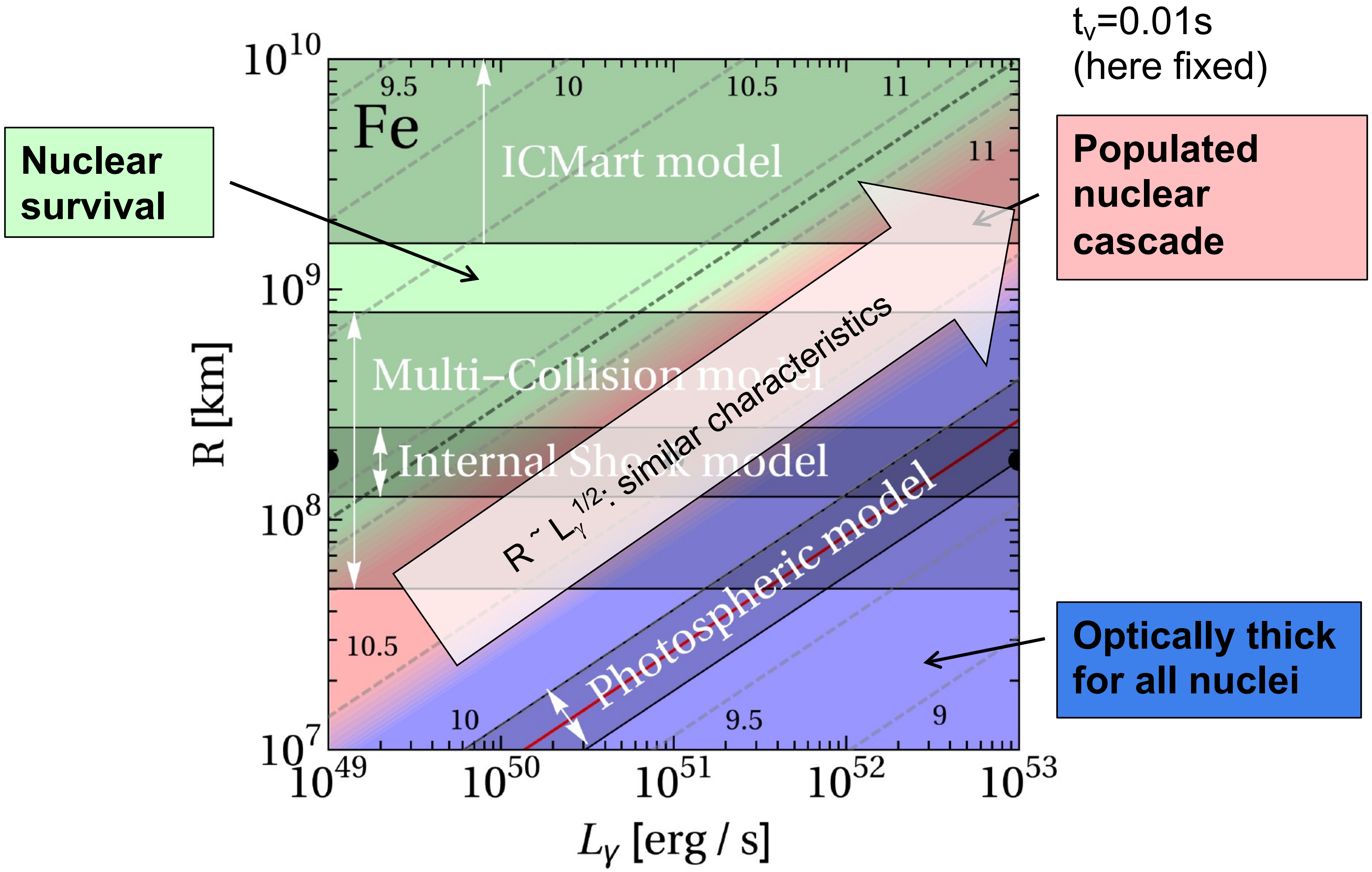
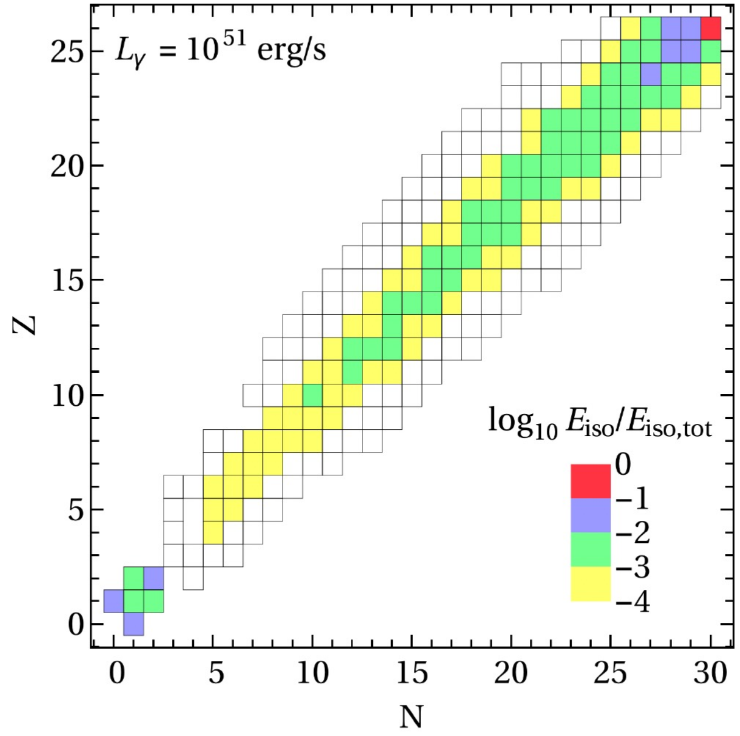
Example: Nuclear cascade





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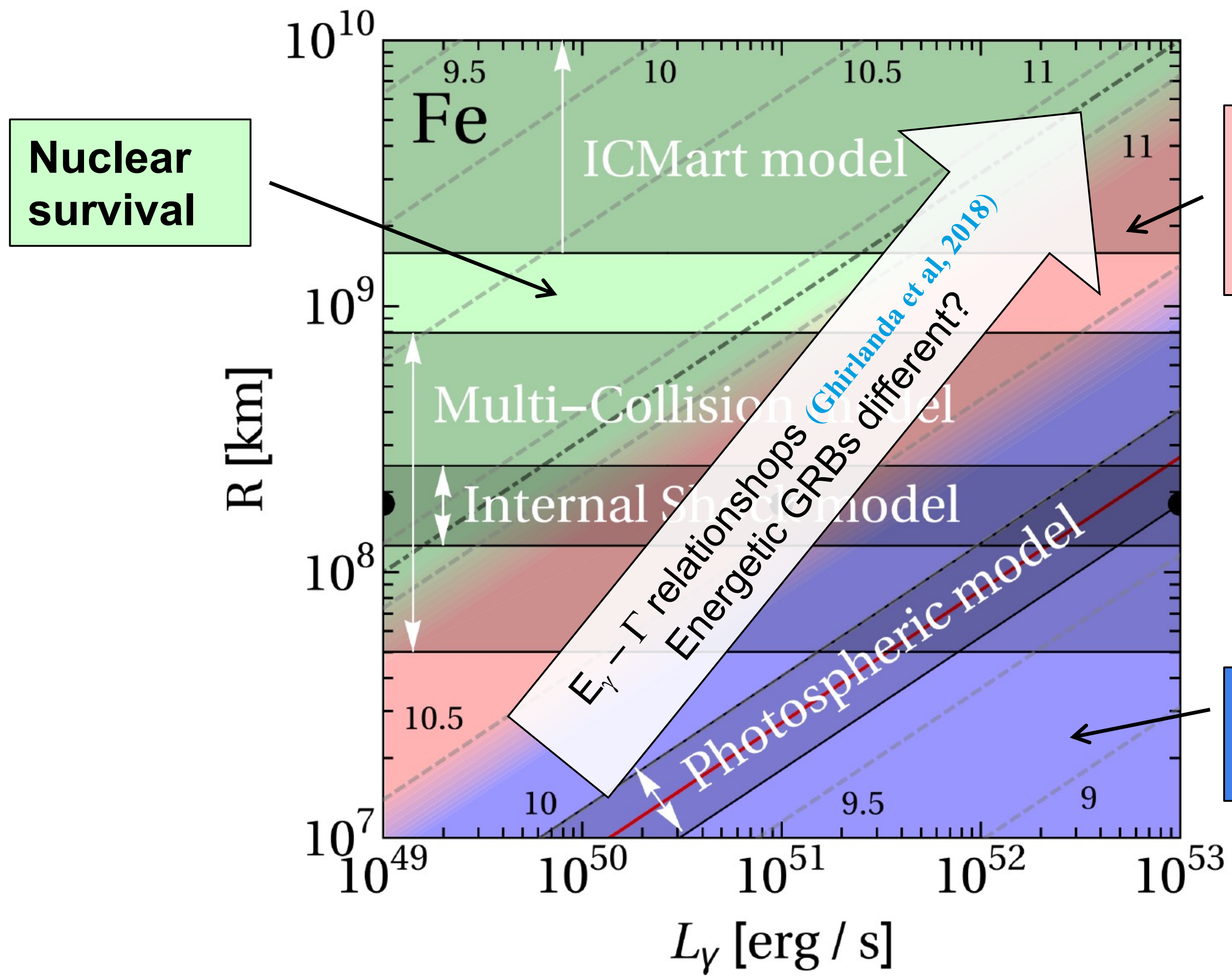
Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909; see also Murase et al, 2008; Anchordoqui et al, 2008

Example: Nuclear cascade

t_v=0.01s
(here fixed)



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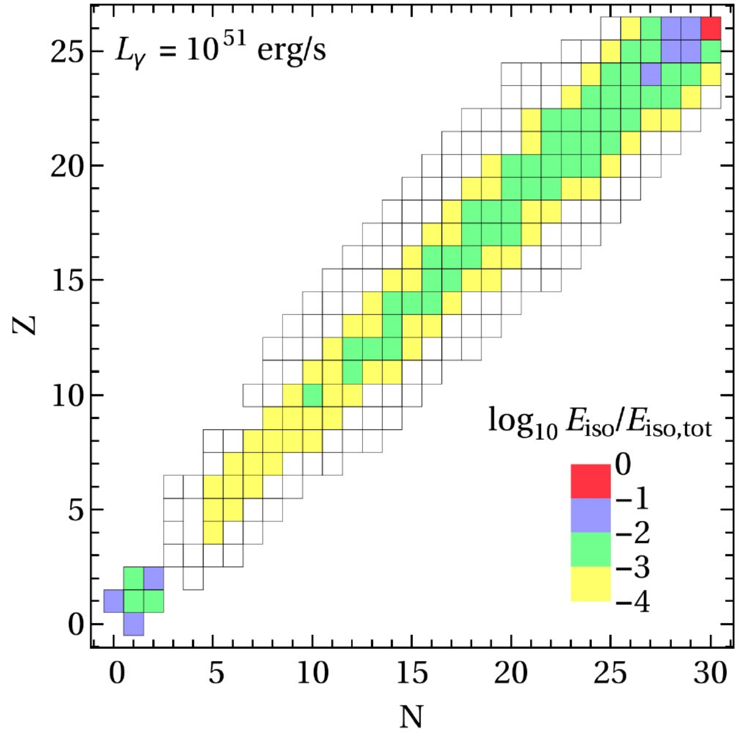


(middle dot in left panel)

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

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

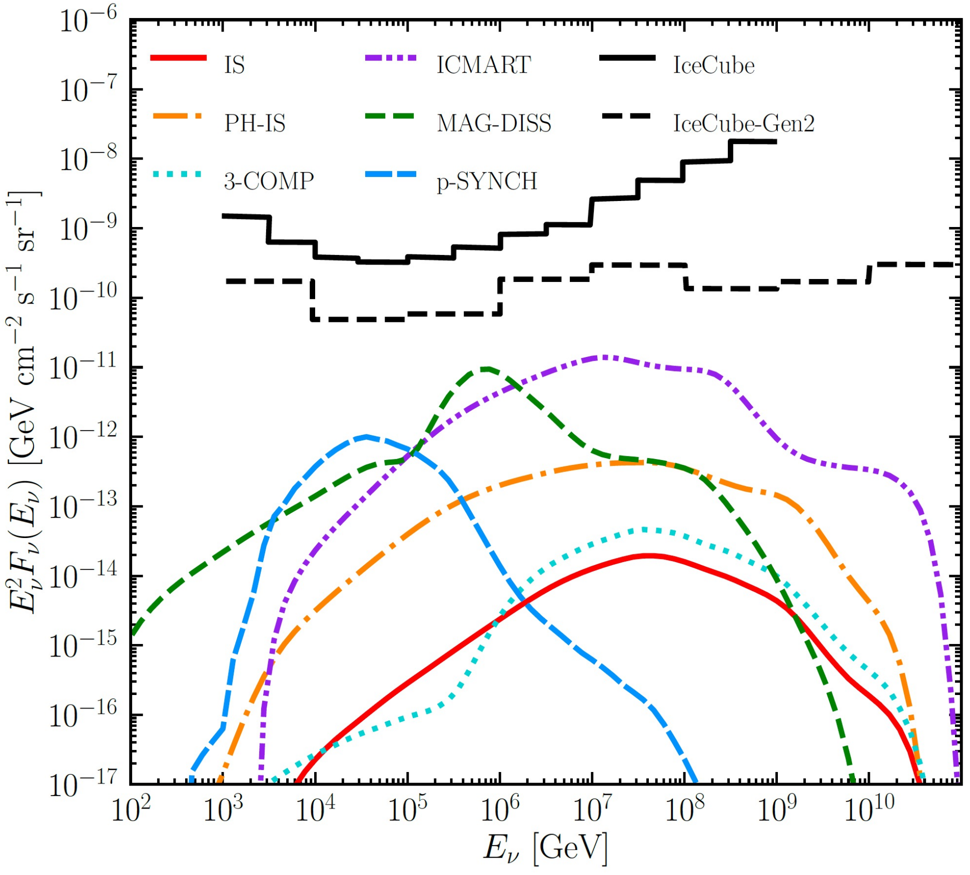
Similar neutrino fluxes under the assumption of similar total jet energy and certain dissipation efficiencies.

Parameter	Symbol	IS	PH-IS	3-COMP	ICMART
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*

Multi-messenger tests of the UHECR paradigm

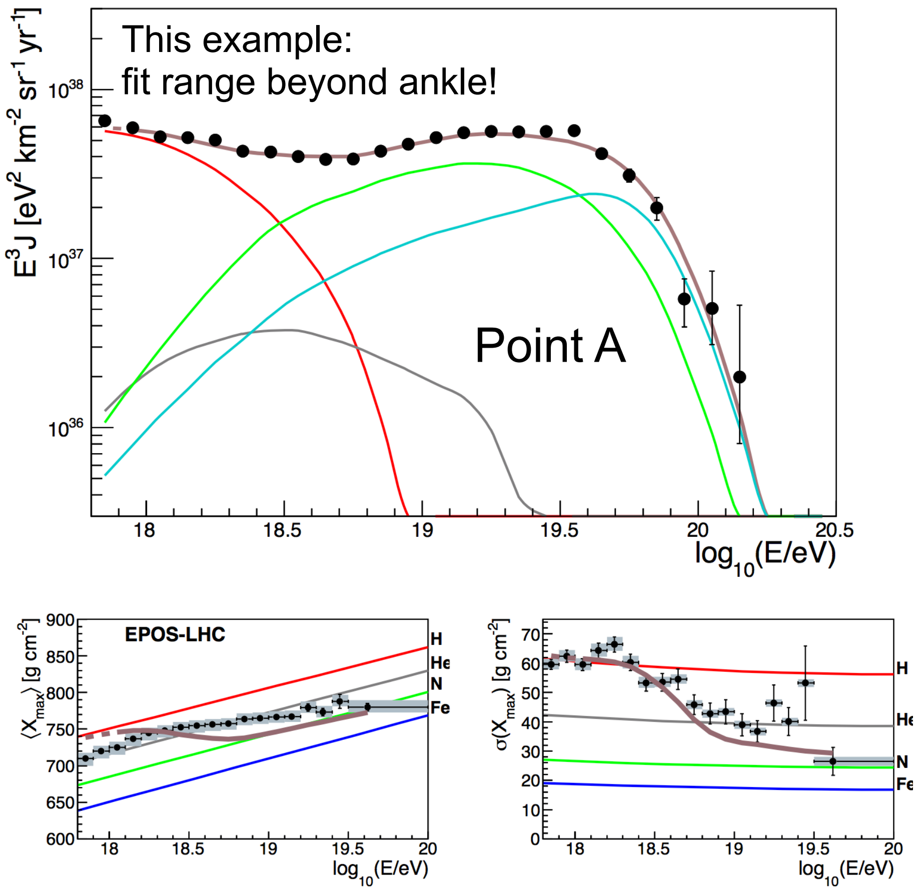
The vanilla one-zone prompt model

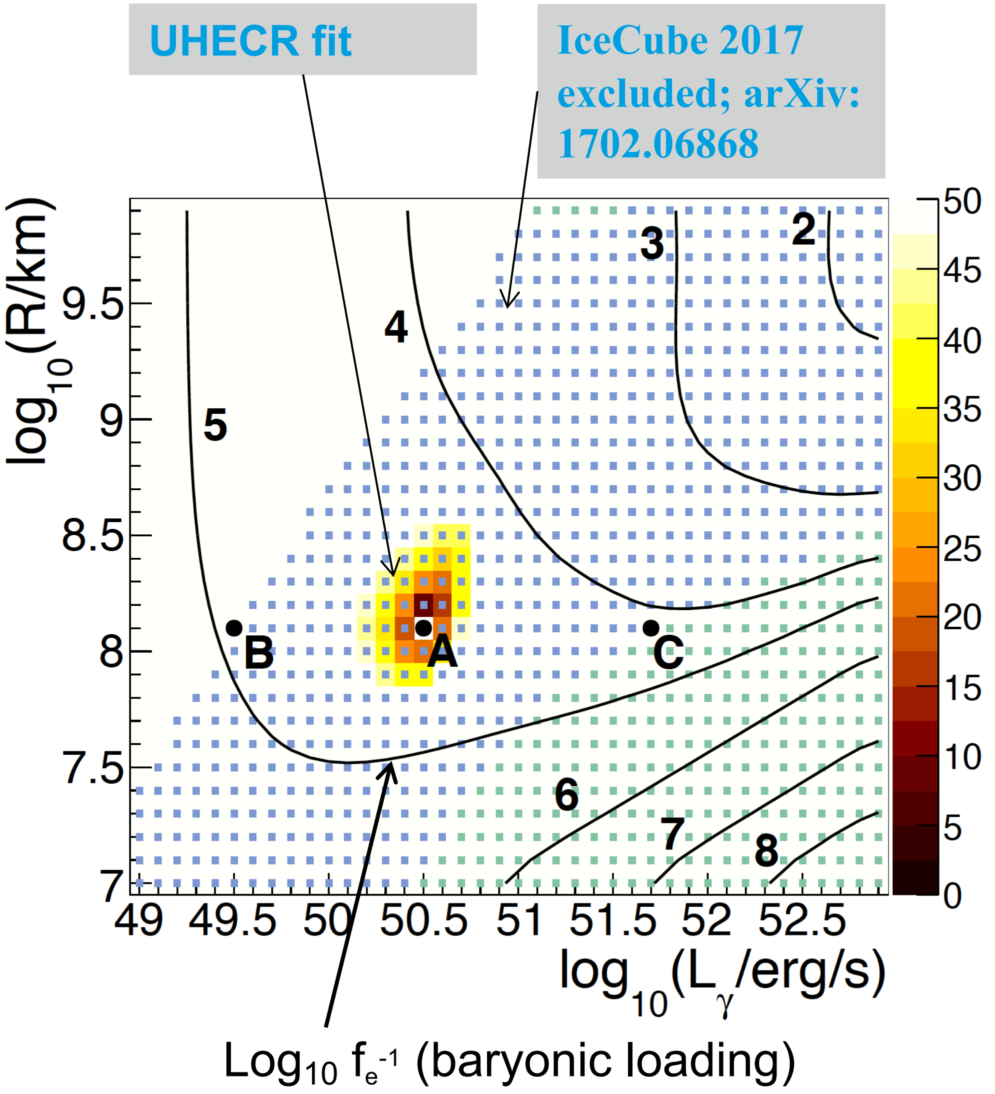
Neutrino and cosmic ray emission at same collision radius R

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

<u>Recipe:</u>

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

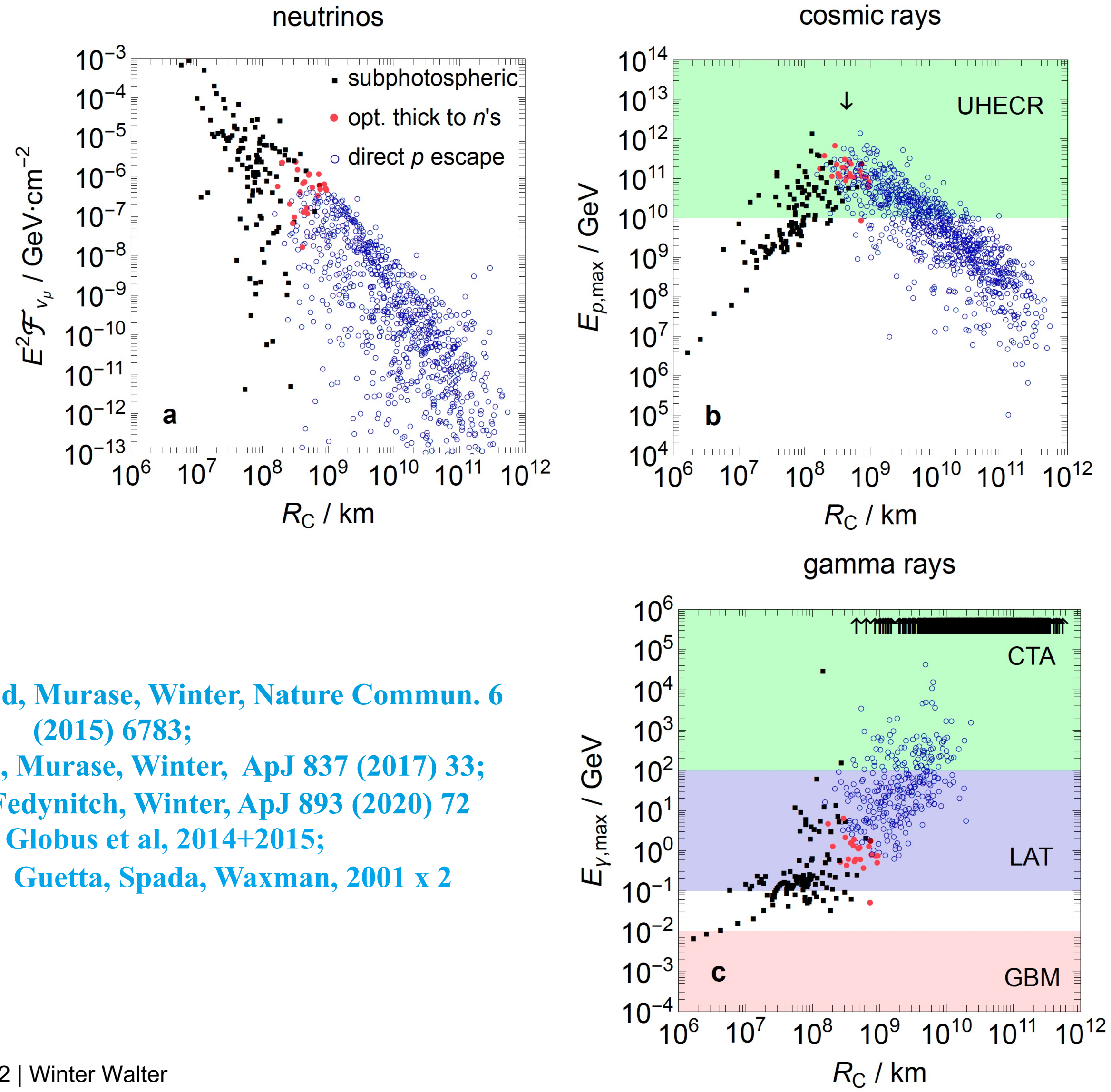




Biehl, Boncioli, Fedynitch, Winter, arXiv:1705.08909
Astron. Astrophys. 611 (2018) A101;
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

Back to the roots:
Multi-collision models

The GRB prompt emission comes from multiple zones (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.

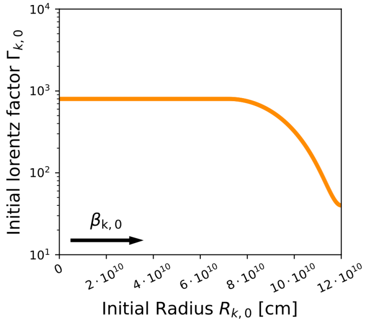
A unified engine model with free injection compositions

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

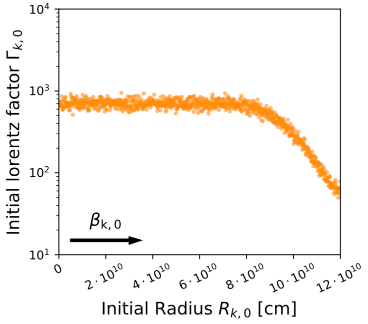
Model description

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

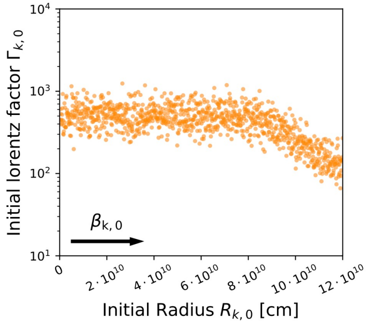
SR-0S
Strong (engine) ramp-up, no stochasticity



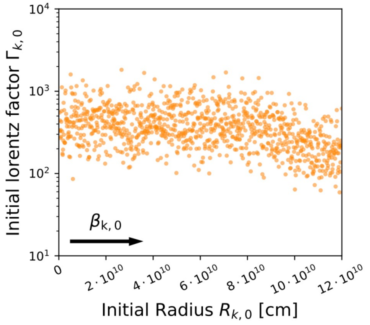
SR-LS
Strong (engine) ramp-up, low stochasticity



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



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

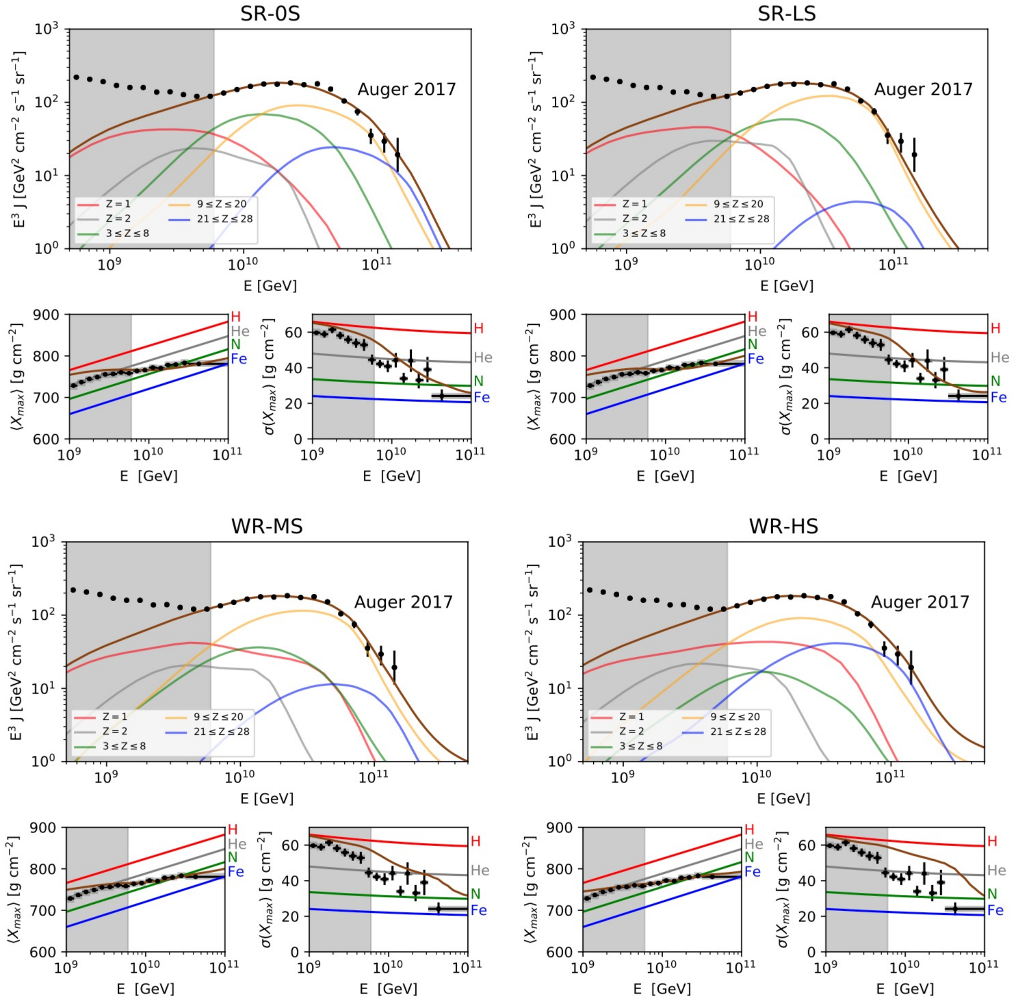


Describes UHECR data over a large range of parameters!

(systematically studied)

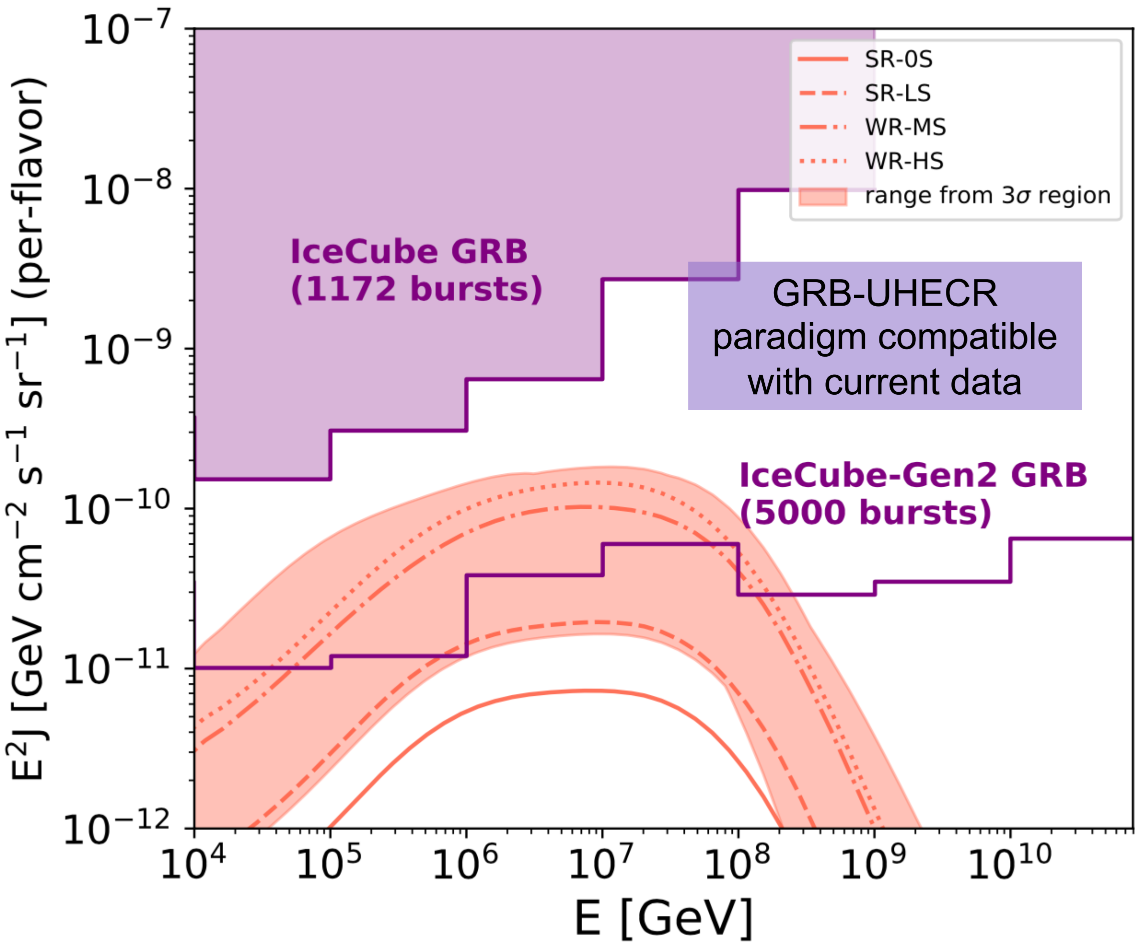
Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

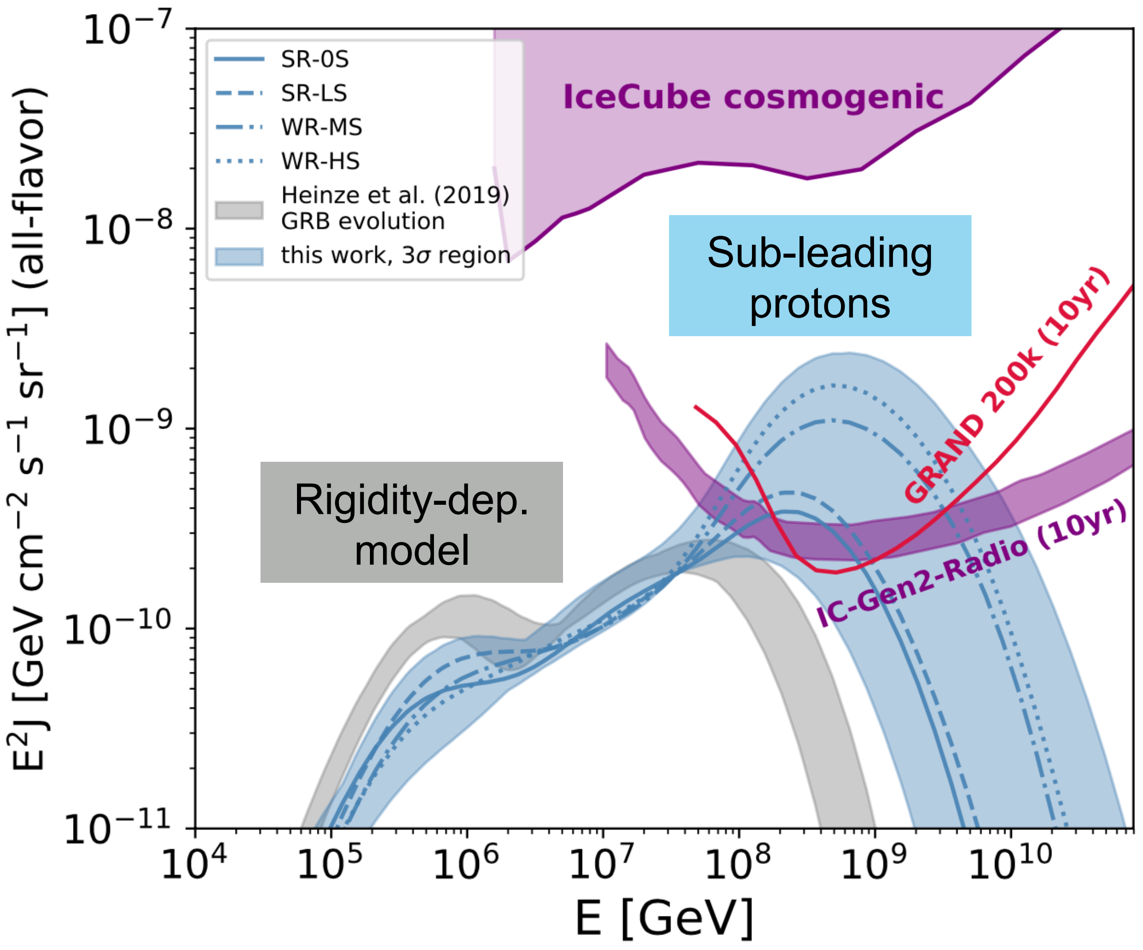
Description of UHECR data



Inferred neutrino fluxes from the parameter space scan

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

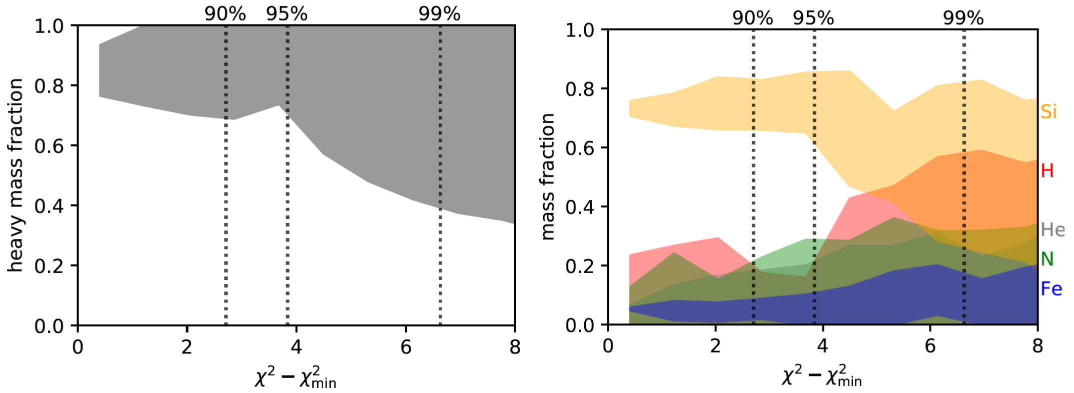




Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

Interpretation of the results

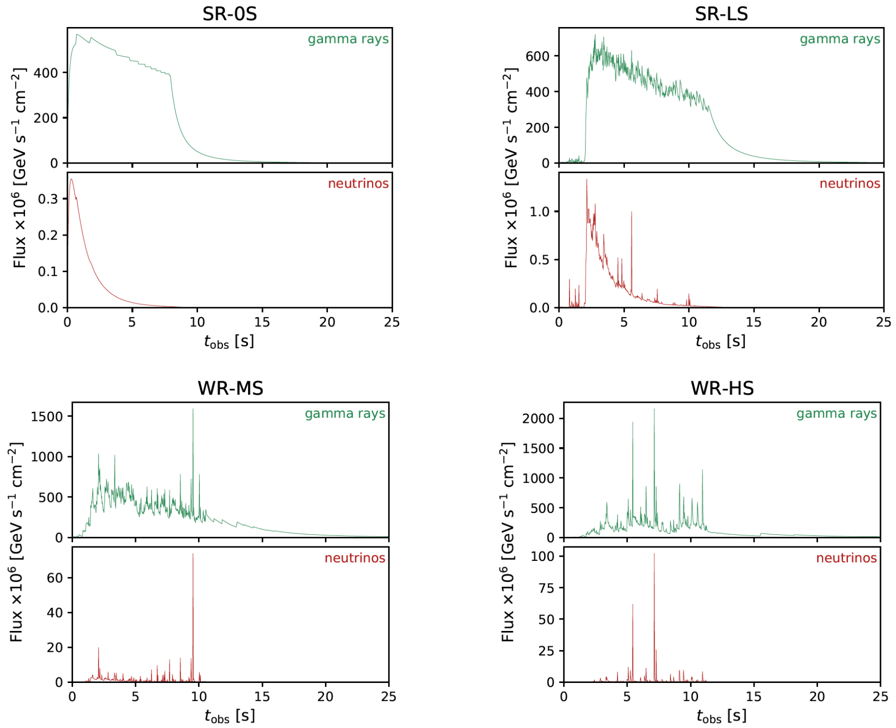
- The required injection compositon is derived: more that 70% heavy (N+Si+Fe) at the 95% CL



- Self-consistent energy budget requires kinetic energies larger than 10^{55} erg – **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

- Light curves may be used as engine discriminator



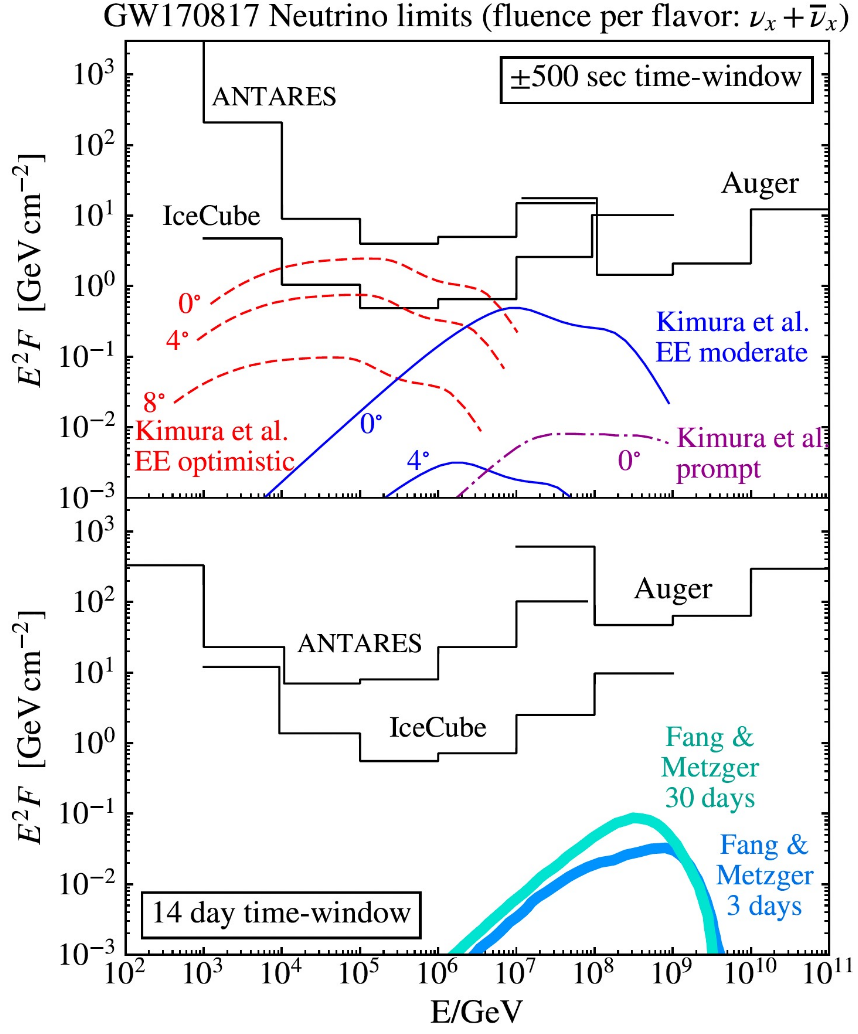
- Description of σ(X_{max}) is an instrinsic problem (because the data prefer "pure" mass groups, which are hard to obtain in multi-zone or multi-source models)

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

Multi-messenger tests of the gravitational wave connection

Neutrinos from sGRB 170817A? associated with the BNS merger

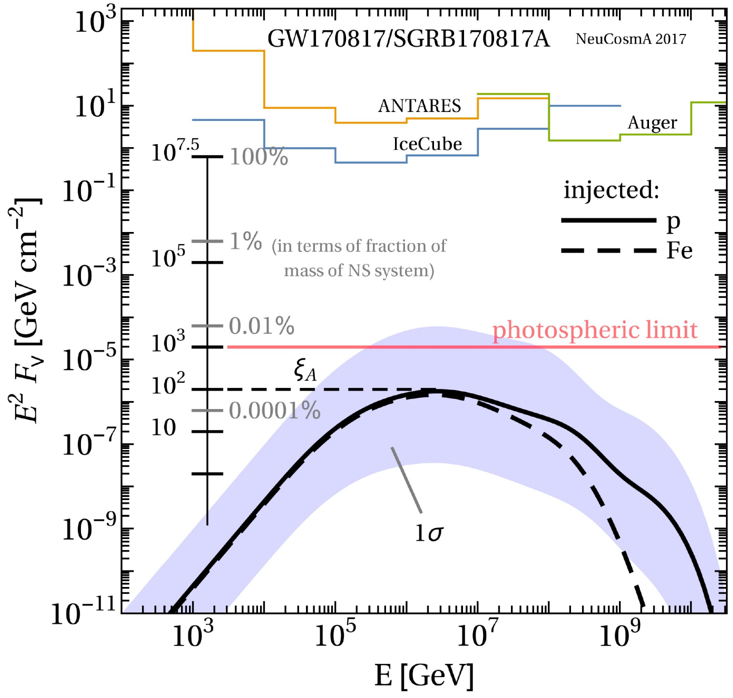
Experimental result



ANTARES, IceCube, Auger, LIGO, VIRGO, 2017

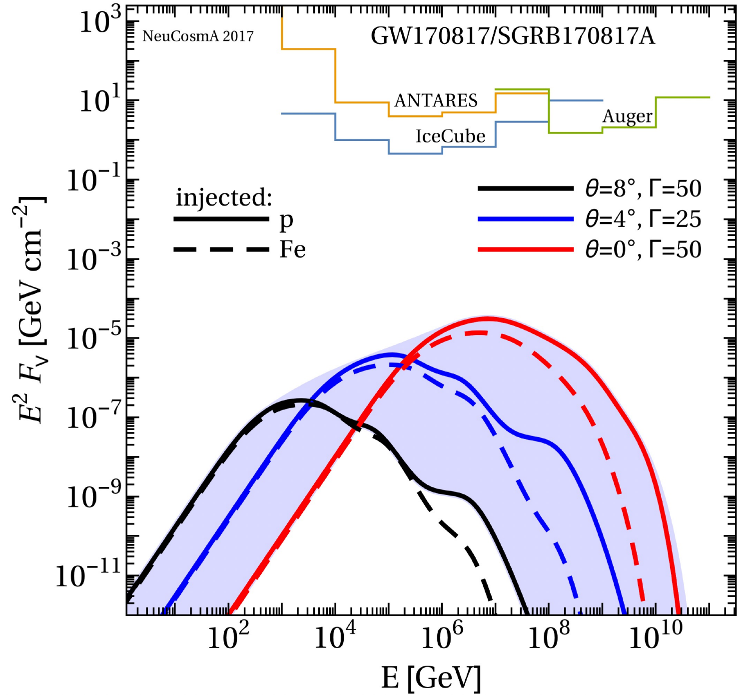
Neutrino fluence prediction for this sGRB (one zone)

Structured jet



Shaded: parameter uncertainties

Off-axis jet



Shaded: θ_{obs}: 0-8°, Γ: 5-50

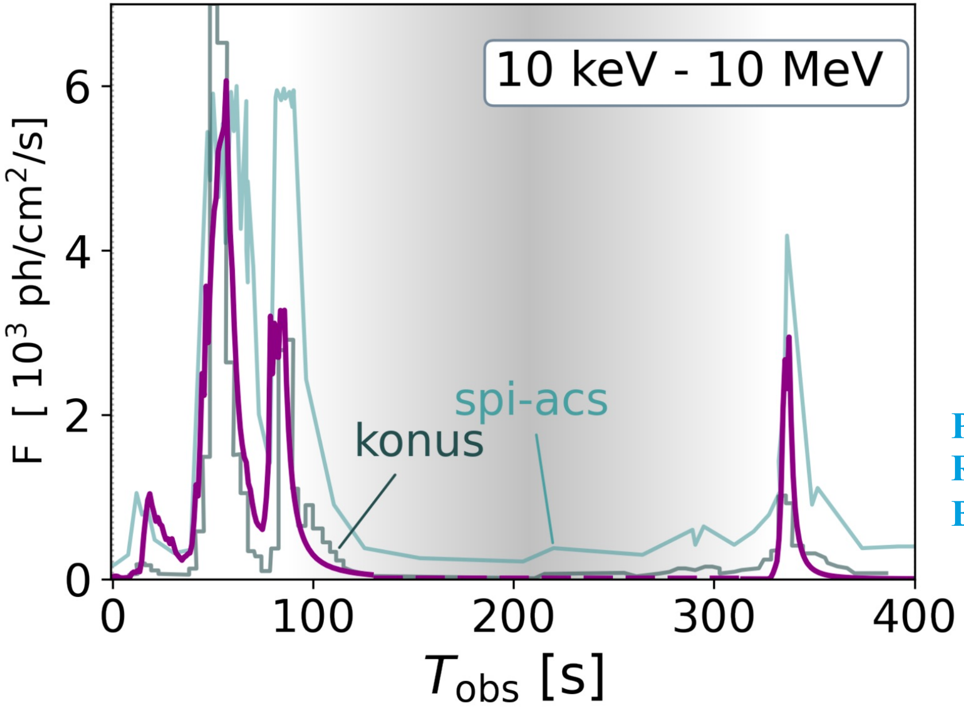
The baryonic loading is constrained by the Thomson optical depth – which must be higher for higher OA (since measured γ-ray flux fixed!)

Biehl, Heinze, Winter, MNRAS 476 (2018) 1, 1191;
see also Ahlers, Halser, 2019

Energetic GRBs

Example: GRB 221009A

- $E_\gamma \sim 3\ 10^{54}$ erg at z ~ 0.151
- Observations of photons up to 18 TeV (LHAASO) [?]
- Can be interpreted as signature of UHECRs interacting with the extragalactic background light (if the EGMF is extremely tiny…)
  Das, Razzaque, 2022; Alves Batista, 2022; Mirabal 2022
  Evidence for UHECR acceleration?
  (most alternative explanations are even more exotic…)



Purple: modeled curve.
Rudolph, Petropoulou, Bosnjak, WW, to appear.

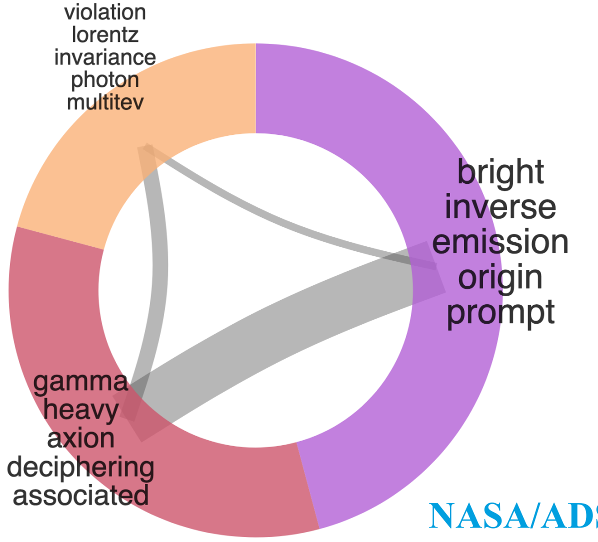
https://www.space.com/most-powerful-gamma-ray-burst-ever-seen. From 08.11.2022

Astronomers just spotted the most powerful flash of light ever seen

By Tereza Pultarova published 25 days ago

The gamma-ray burst was also the nearest ever detected.

Gamma-ray bursts are the most energetic flashes of light known to exist in the universe. (Image credit: NASA, ESA and M. Kornmesser)



NASA/ADS
17.11.2022

Why are energetic GRBs interesting?

A case study with GRB 221009A

- Assume that $E_0 \sim M_\odot \sim 2\ 10^{54}$ erg available as initial energy (→ progenitor/collapsor models, rot. energy …)

$$E_{\rm iso}^{\rm kin} \simeq \varepsilon_{\rm jet} \, \frac{4\pi}{\Omega} \, E_0 \simeq 0.2\, 536\, E_0 \; \simeq 100\, E_0 \simeq 2\, 10^{56} \, {\rm erg}$$

Here: 20% of energy into jet assumed, jet opening angle 3.5° from measured jet break **(GCN 32755)**

- Consequence: Radiative efficiency

$$\frac{E_{\gamma,\rm iso}}{E_{\rm iso}^{\rm kin}} \simeq 0.01 \sim \varepsilon_e \, \varepsilon_{\rm diss}$$

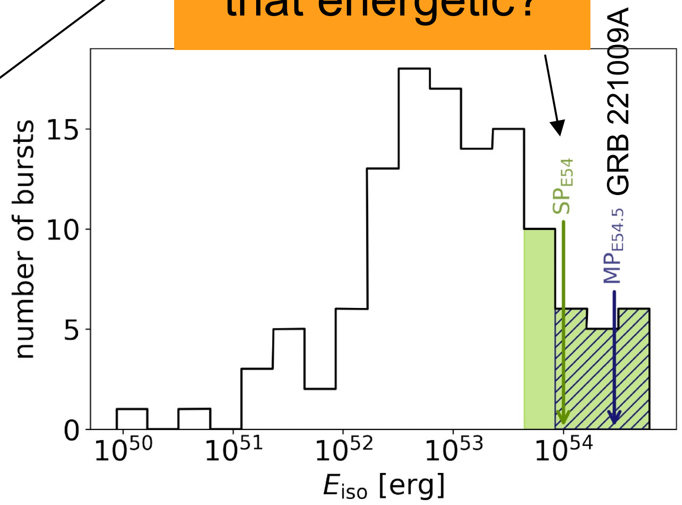
>0.1? <0.1?

The baryonic loading $f_e^{-1} < 10$
Energy equipartition?

- Required baryonic loading to power the UHECRs:

$$f_e^{-1} \simeq 3 \cdot \frac{E_{\gamma,\rm iso}}{3\, 10^{54}\,{\rm erg}} \cdot \frac{\dot{\varepsilon}_{\rm UHECR}}{10^{44}\,{\rm erg\,Mpc^{-3}\,yr}} \cdot \frac{0.1\,{\rm Gpc^{-3}\,yr^{-1}}}{\dot{n}_0}$$

10% of all GRBs that energetic?

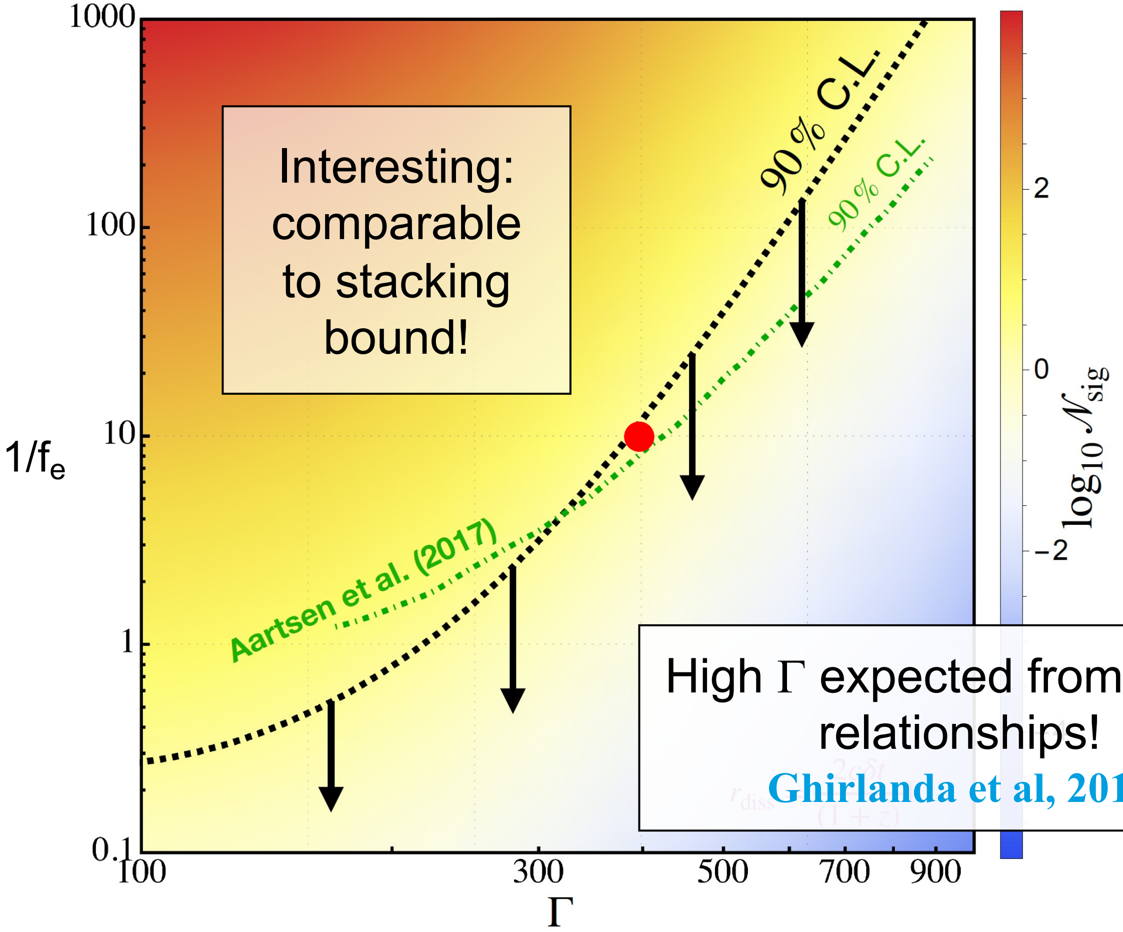


- Energy equipartition attractive: Hadronic secondary signatures cannot exceed the peak flux even if efficient secondary production!

Rudolph, Petropoulou, Bosnjak, WW, to appear.
Based on GBM catalogue Poolakkil et al., 2021

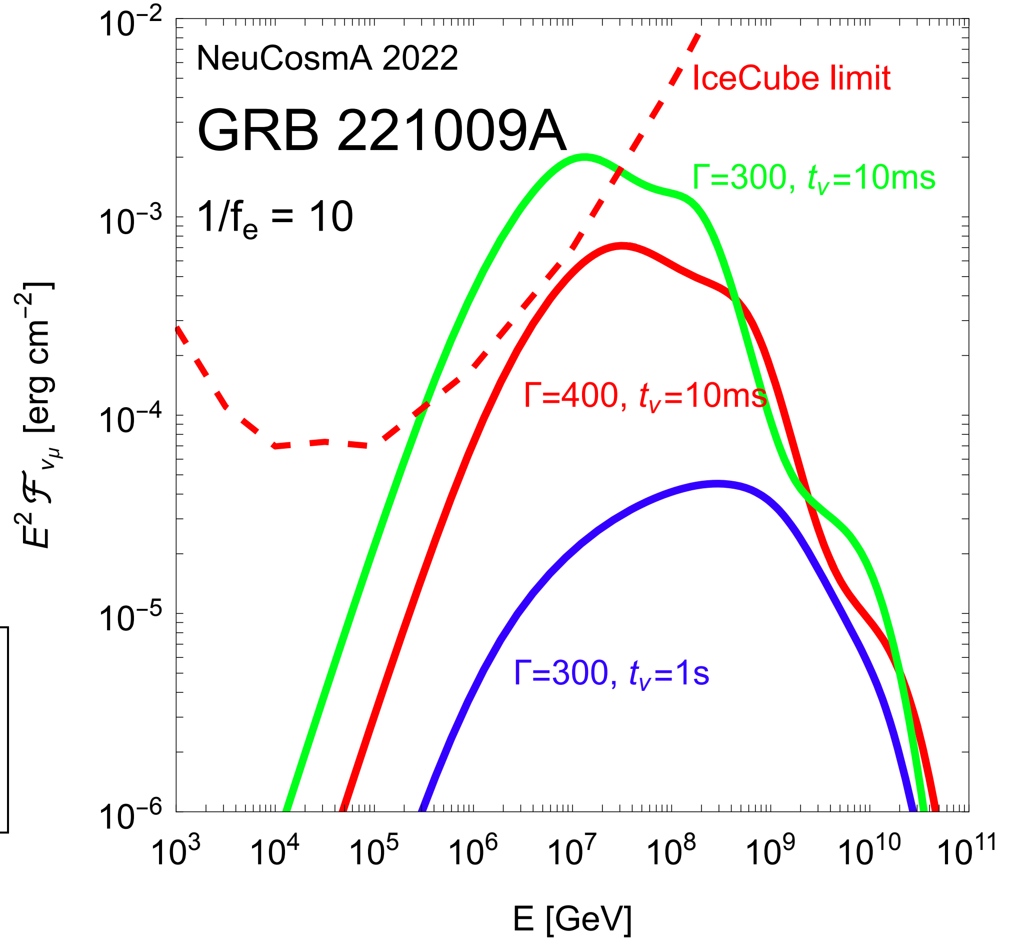
GRB 201009A – why have no neutrinos been seen?

Example: Internal shock model, one zone model



High Γ expected from E_{iso}-Γ relationships!
Ghirlanda et al, 2018

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



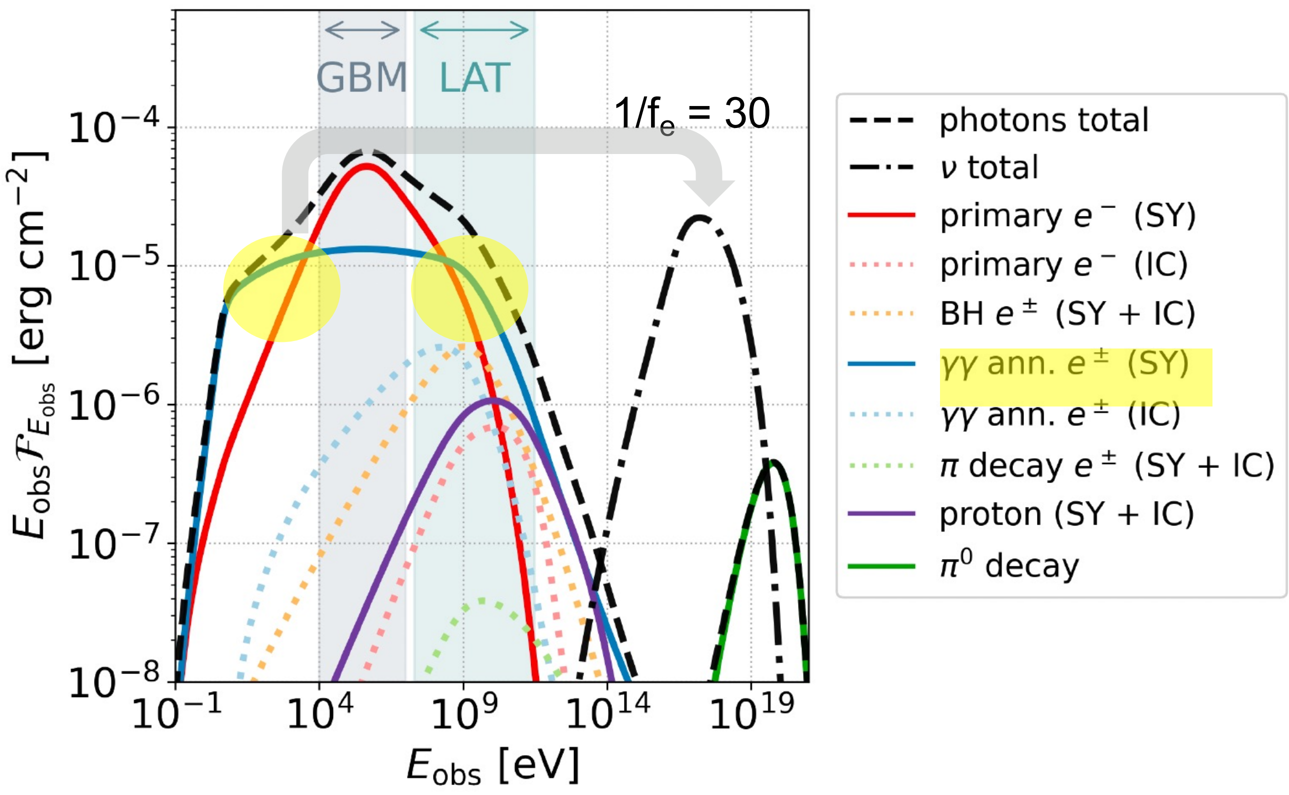
WW, preliminary

Expectation strongly depends on parameters!

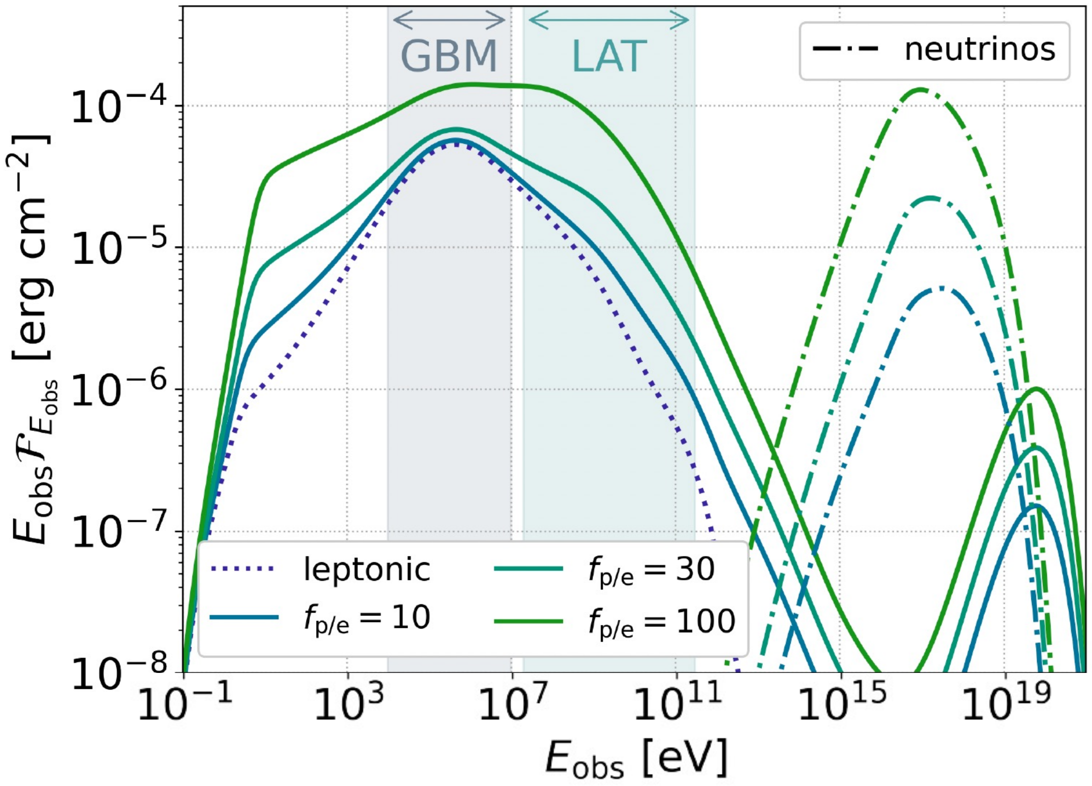
Hadronic signatures in the electromagnetic spectrum

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:



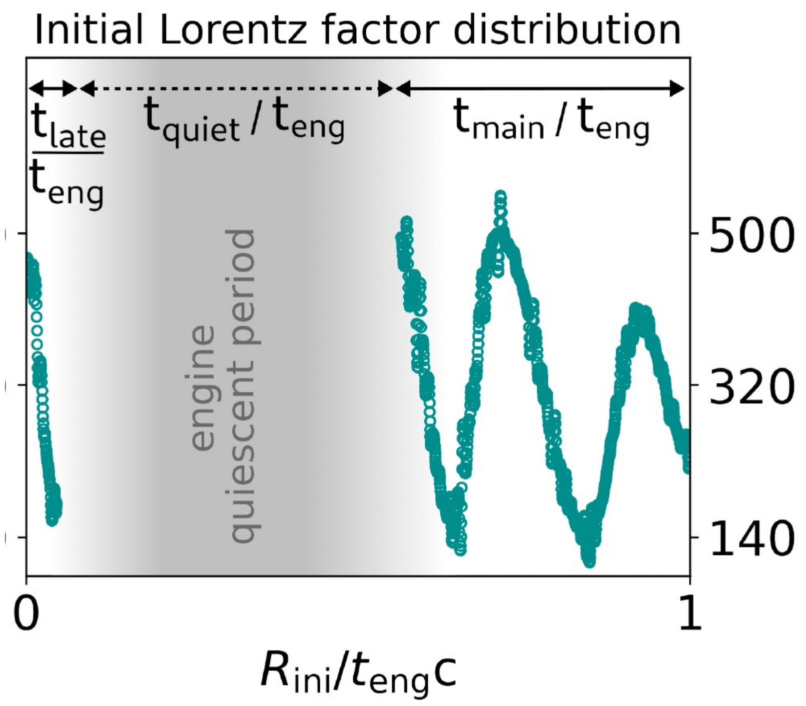
Spectral index -1.5 in fast cooling regime
→ Neutrino production dominated by low photon energies
→ Hadronic contributions enhance neutrino production
→ High peak neutrino energies

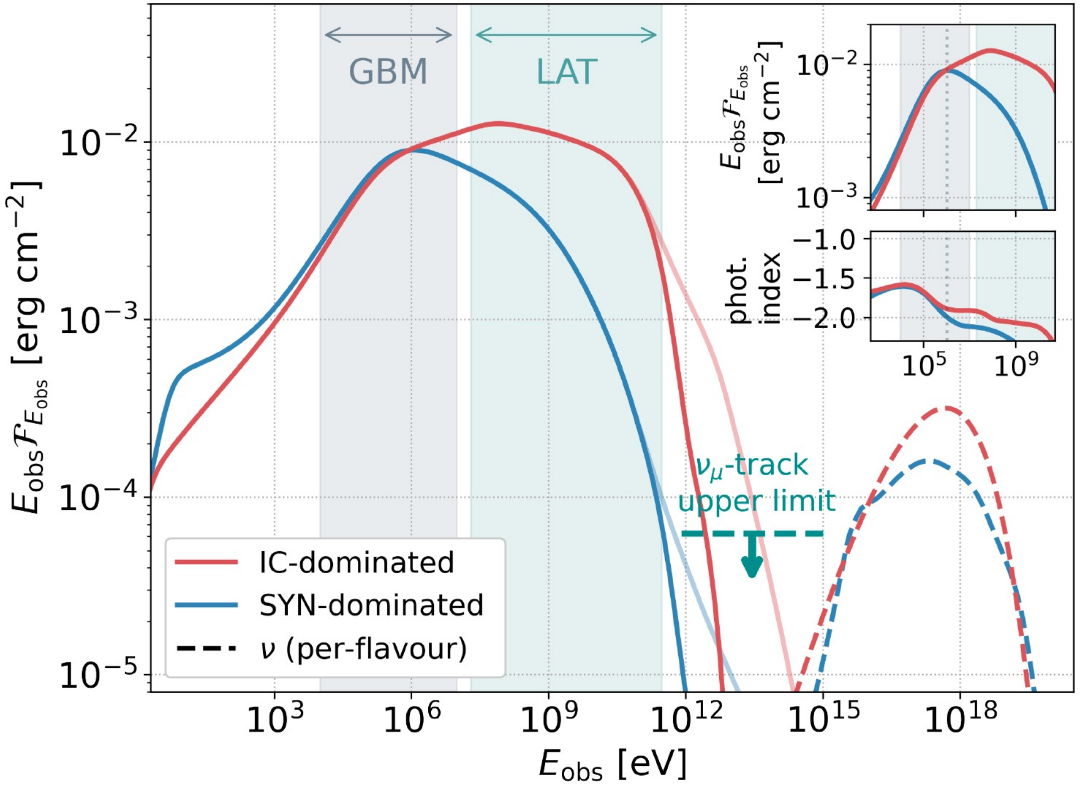
Baryonic loading 3-10 do not modify electromagnetic spectrum at peak!

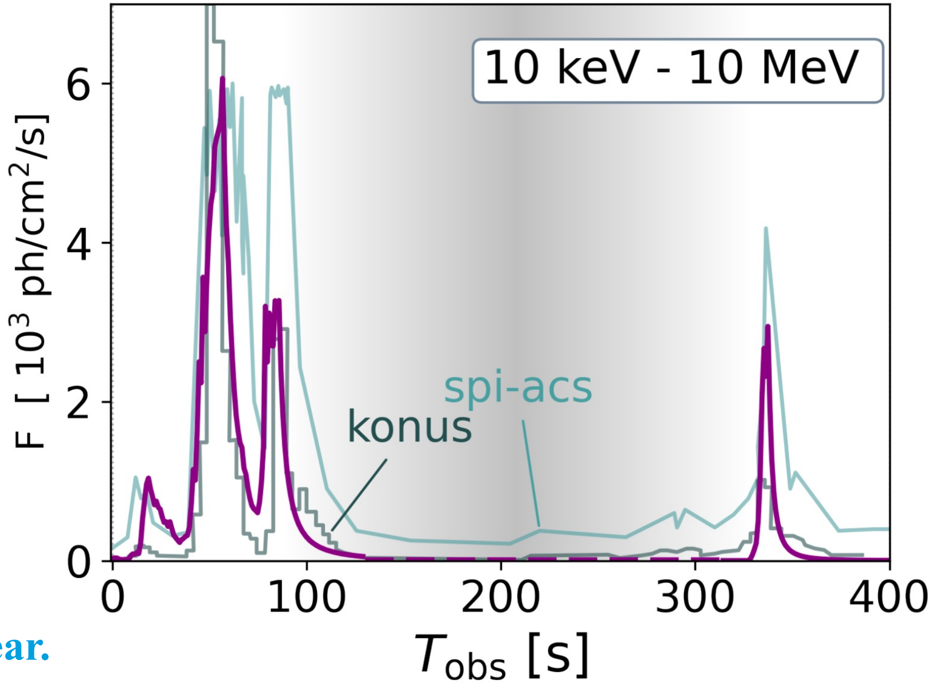
Rudolph, Petropoulou, Bosnjak, WW, to appear. See also Asano, Inoue, Meszaros, 2009

Application to GRB 221009A (1)

- 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, to appear.

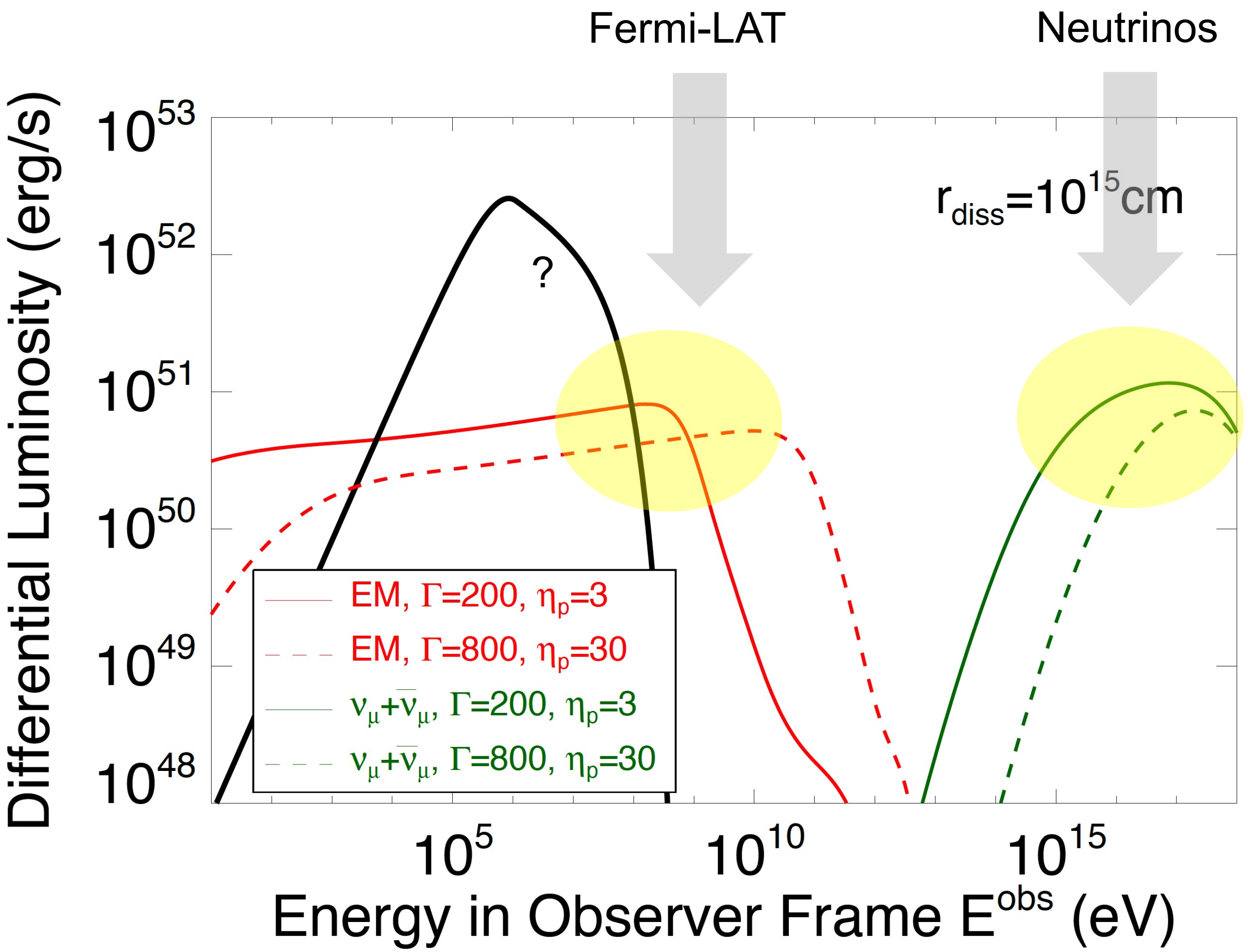
Application to GRB 221009A (2)

Example with smaller $R_C \sim 10^{14}$ to 10^{15} cm

- Hadronic signatures expected for low enough R_C, high enough baryonic loading
- Constraints from Fermi-*LAT* vs. neutrino data?

Challenges:

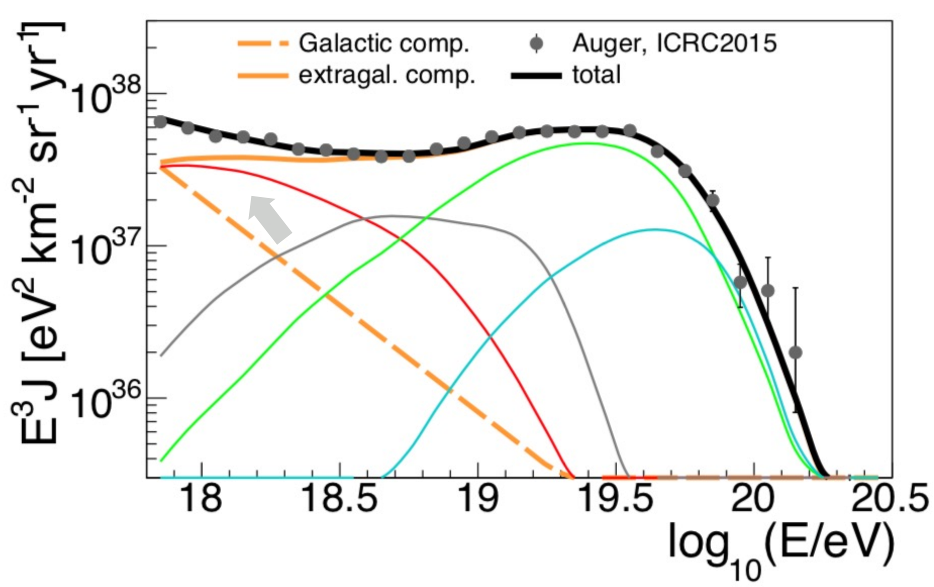
- Effects of pile-up in LAT data?
- Baryonic loading 30 can be excluded on energetics grounds (see earlier)
  Rudolph, Petropoulou, WW, Bosnjak, to appear.
- Small R_C challenged by stacking limit if all energetic GRBs are alike (self-consistent radiation model)
  Rudolph, Petropoulou, Bosnjak, WW, to appear.
- Nonlinear feedback from EM cascade on SED/neutrino production?

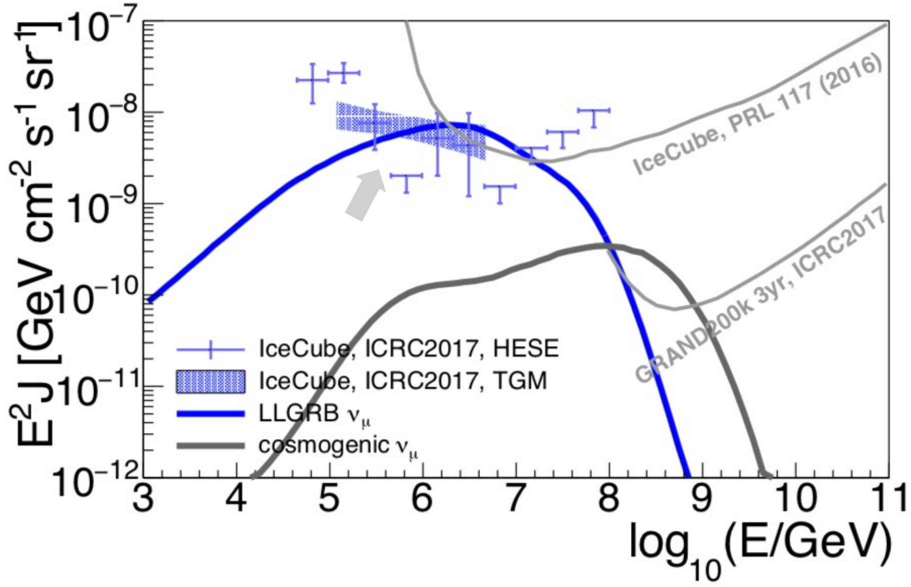


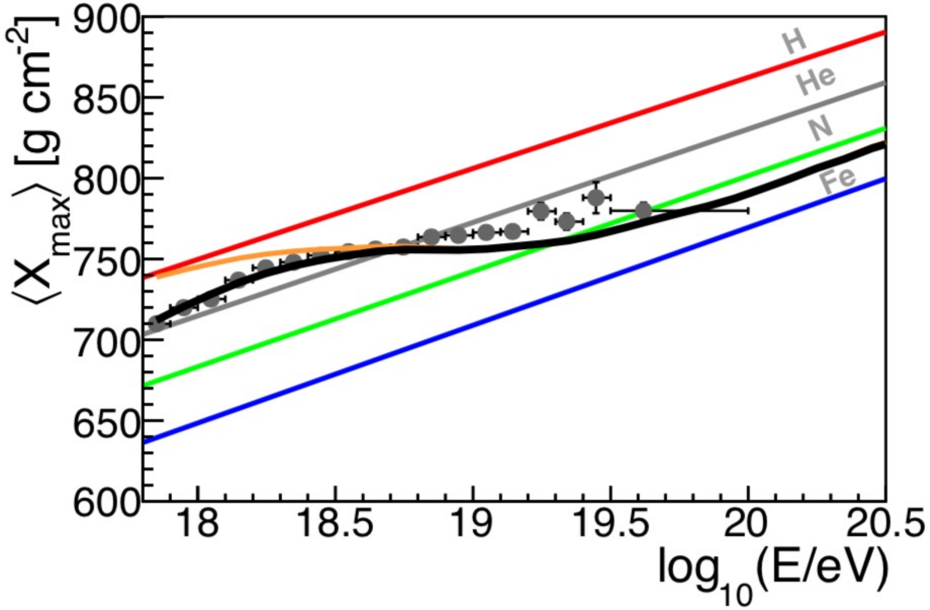
Riu, Zhang, Wang, arXiv:2211.14200

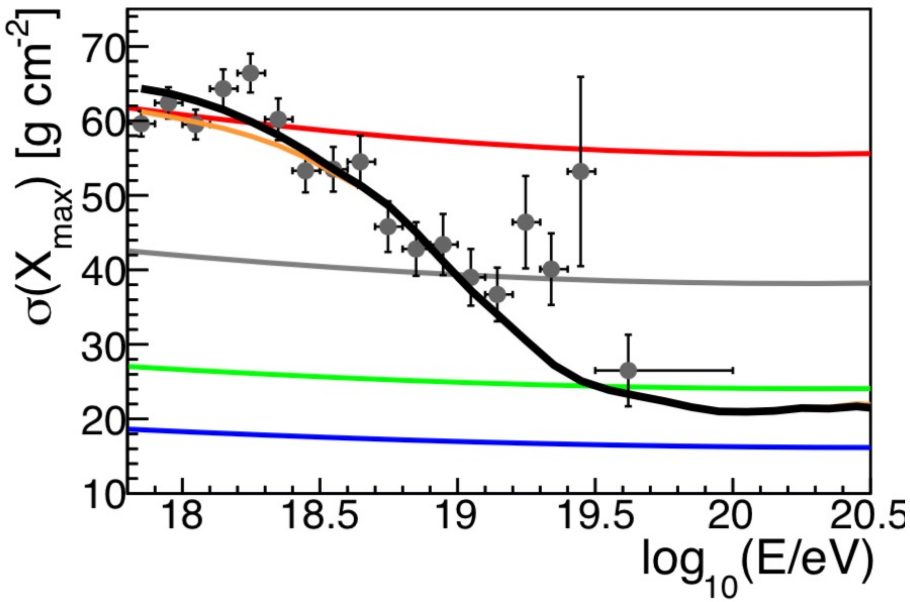
Low-luminosity GRBs

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

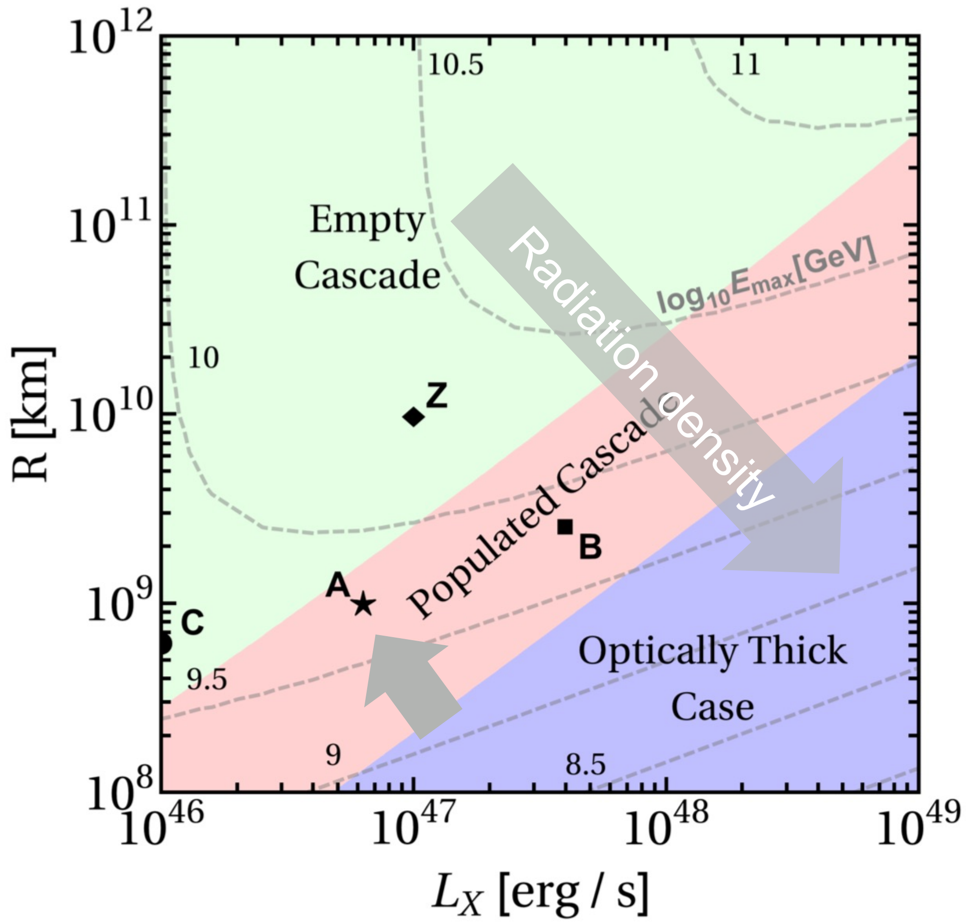
Boncioli, Biehl, Winter, ApJ 872 (2019) 110; arXiv:1808.07481; see also Murase et al, 2006

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

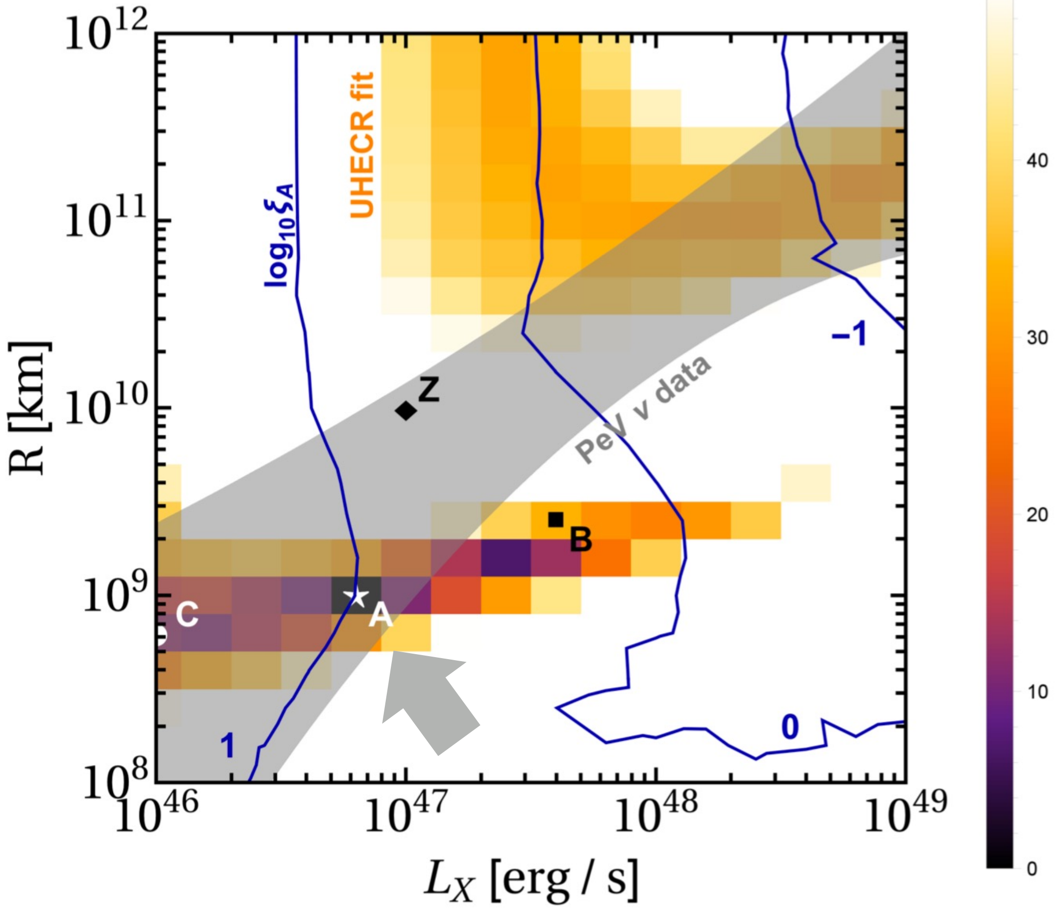
Systematic parameter space studies

What are the model parameter expectations driven by data?

Nuclear cascade and E_{max}



UHECR and neutrino fits

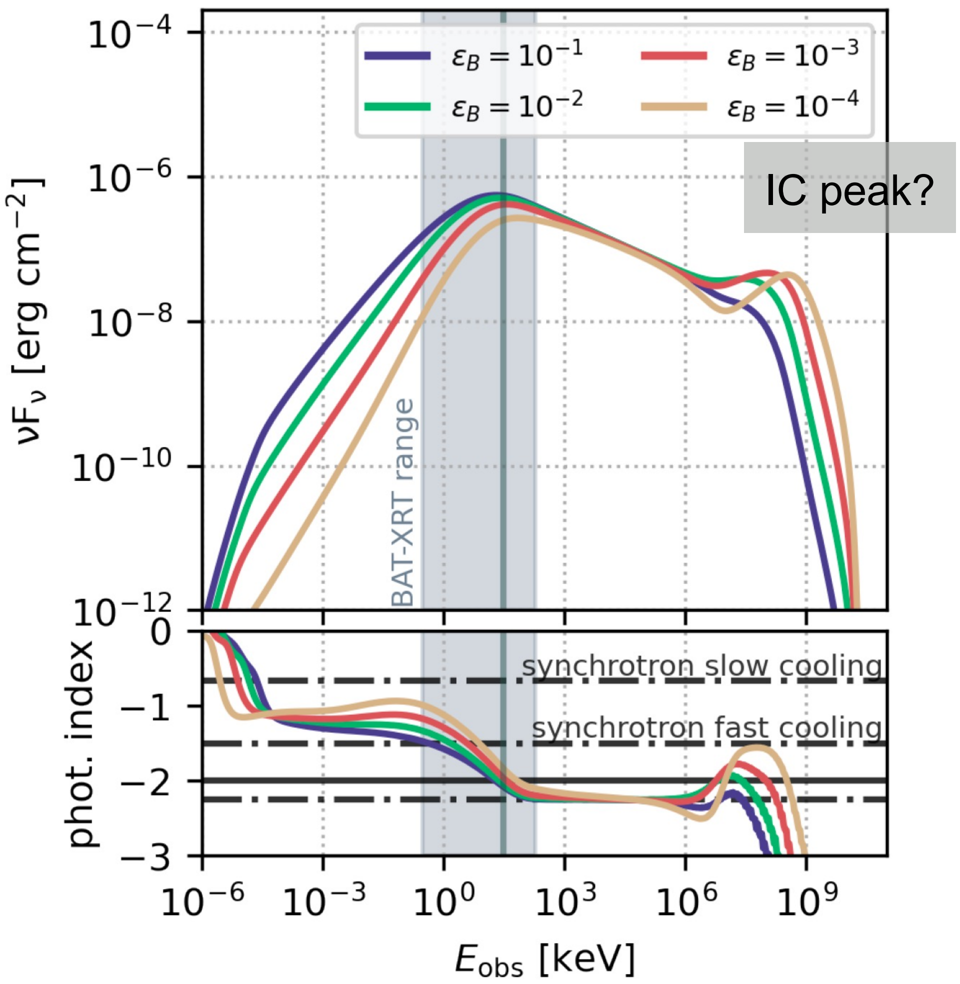


ξ_A: Baryonic loading ($1/f_e$)
(here: $T_{90} = 2\ 10^5$ s fixed)

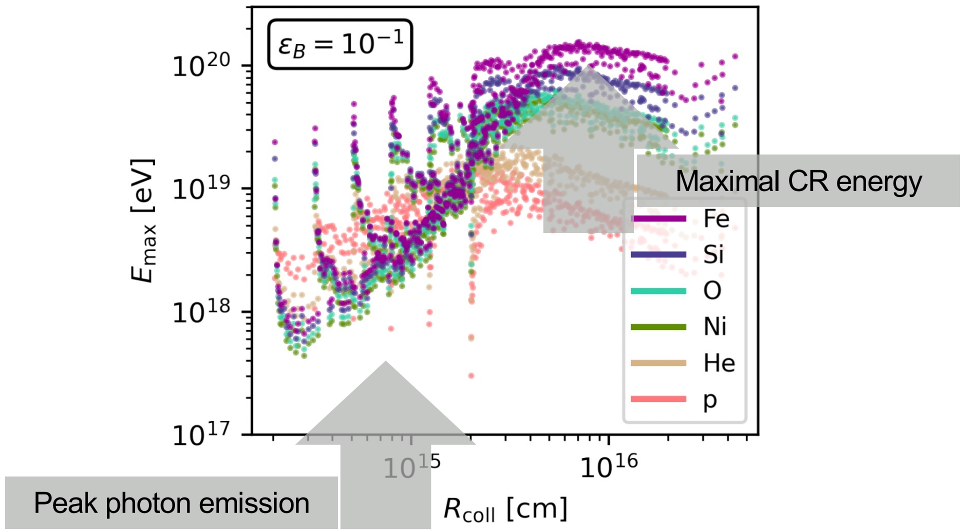
Boncioli, Biehl, Winter, arXiv:1808.07481;
Reference point "Z": Zhang et al., 2018

Open issues for LL-GRBs

Continuous outflow model, Γ ~ 10-40



- 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). Are the typical LL-GRB ultra-long?
  - Necessary baryonic loading ~ 10; allowed by SED!

Rudolph, Bosnjak, Palladino, Sadeh, WW, MNRAS 511 (2022) 4, 5823; see also discussions in Samuelsson et al, 2019+2020 for one zone model

Summary

UHECR paradigm for different GRB classes (prompt emission), and the implications for neutrino production

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 across the ankle
- May at the same time power the diffuse neutrino flux
- Less established/studied source class = more speculative
- Progenitor model disputed
- Energetics require relatively long "standard" LL-GRBs

sGRBs

- Connection with GW physics
- Energy budget low for UHECR/ neutrino signals

Energetic GRBs

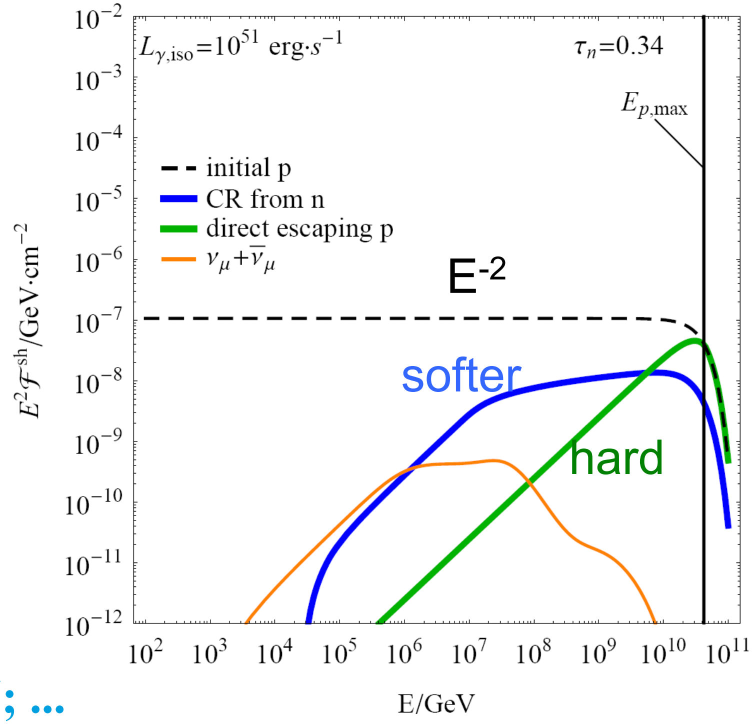
- Do not require very large baryonic loadings, energy equipartion between electrons and protons?
- Will have a new, well studied prototype (GRB 221009A)
- Synchrotron fast-cooling regime and hadronic SED components may enhance neutrino production; typical neutrino energies higher than previously thought? Radio detection?
- Unclear if a separate population and how large the local rate is
- Energetics may scrutinize conventional internal shock models
- Neutrino (per GRB) fluence not as high as one may have hoped for

BACKUP

Challenge: How do cosmic rays escape from the source?

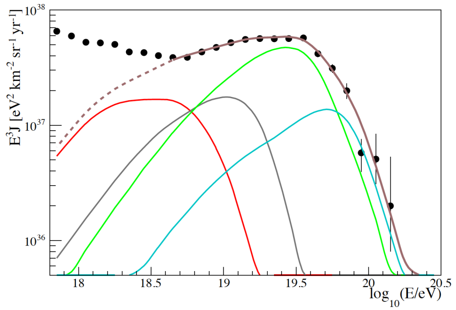
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

- **Neutron model**
  Only neutrons can escape
  Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87
- **Direct escape** (aka "high pass filter", "leakage", …)
  Charged *cosmic rays can efficiently escape*
  if Larmor radius reaches size of region
  (conservative escape contribution, green curve, hard) →
  (predicted in: Baerwald et al, ApJ 768 (2013) 186)



(GRB, protons, without propagation effects)

- **All escape**, advective/free-streaming escape
  (most aggressive scenario, dashed curve, ~ E^{-2})
- **Diffusive escape:** e. g. Escape rate ~ $(R_L)^\alpha$
  (compromise, but highly assumption dependent)
  e.g. Unger et al, 2015; Kachelrieß et al, 2017; Fang, Murase, 2017; …
- Current Auger best-fit supports
  direct escape hypothesis
  (requires E^{-1} from sources);
  possibly neutrons below ankle?
  (e. g. Unger, Farrar, Anchordoqui, 2015)



Auger