Connection between UHECRs and astrophysical neutrinos

in astrophysical source models

https://multimessenger.desy.de/

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The Paris Saclay AstroParticle Symposium 2021

Oct. 25-29, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY

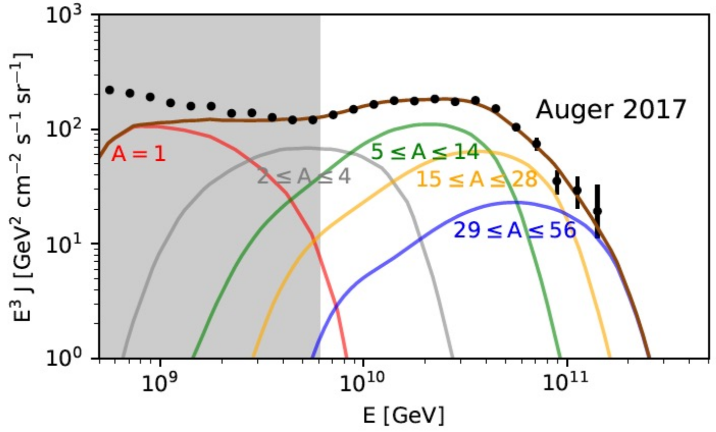
Contents

Lessons from UHECR transport model (Peters cycle model)

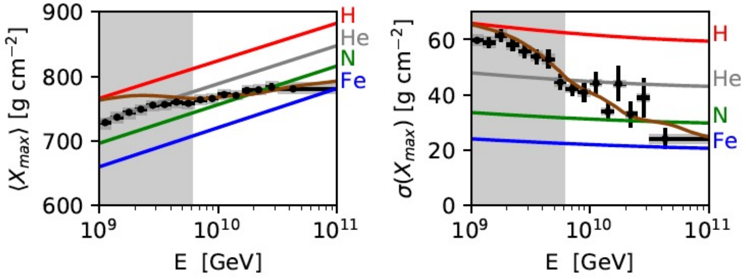
Parameters:

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

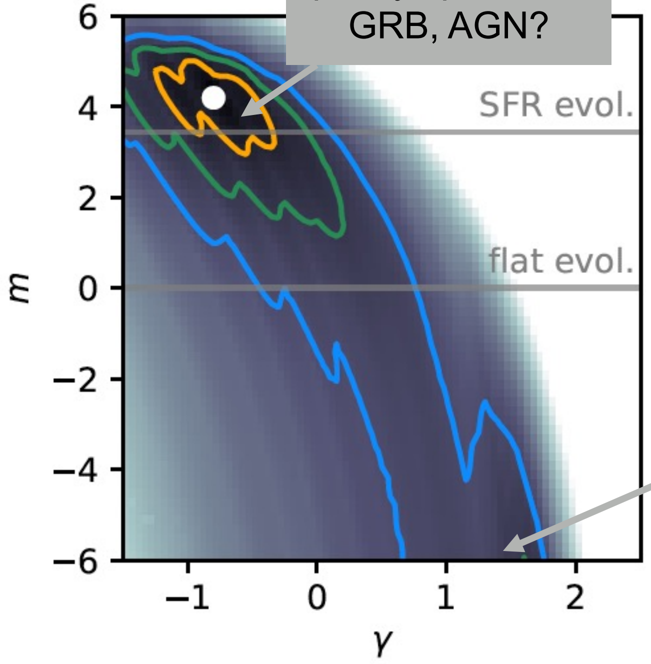
Best-fit spectrum



Best-fit compositon



SFR sources, peaky spectrum: GRB, AGN?



3D fit
Heinze et al, Astrophys.J. 873 (2019) 1, 88; see also Batista et al, JCAP 01 (2019) 002

Closer to typical acceleration spectrum, negative source evolution. TDEs? LL-BL Lacs?

Conclusions for sources:

- Peters cycle describes UHECR data well; limits:
  - Disintegration in source
  - Addl. light component (→ cosmogenic neutrinos)
- Need hard escape spectra for SFR evolution; negative source evolution helps
- X_{max}-$\sigma(X_{max})$ interplay requires relatively pure composition (from light to heavy)

The grand challenges

... to describe UHECRs and neutrinos at the highest energies

Note that 1) and 4) are also UHECR challenges!

1. **The UHECR escape mechanism challenge**
   How do UHECRs escape from their sources? Are the in-source spectra and escape spectra different? How do we obtain hard escape spectra?

2. **The maximal neutrino energy challenge**
   The maximal neutrino energy follows the primary energy. But: neutrinos are observed in the TeV-PeV range! How can we connect UHECRs and the IceCube neutrinos then?

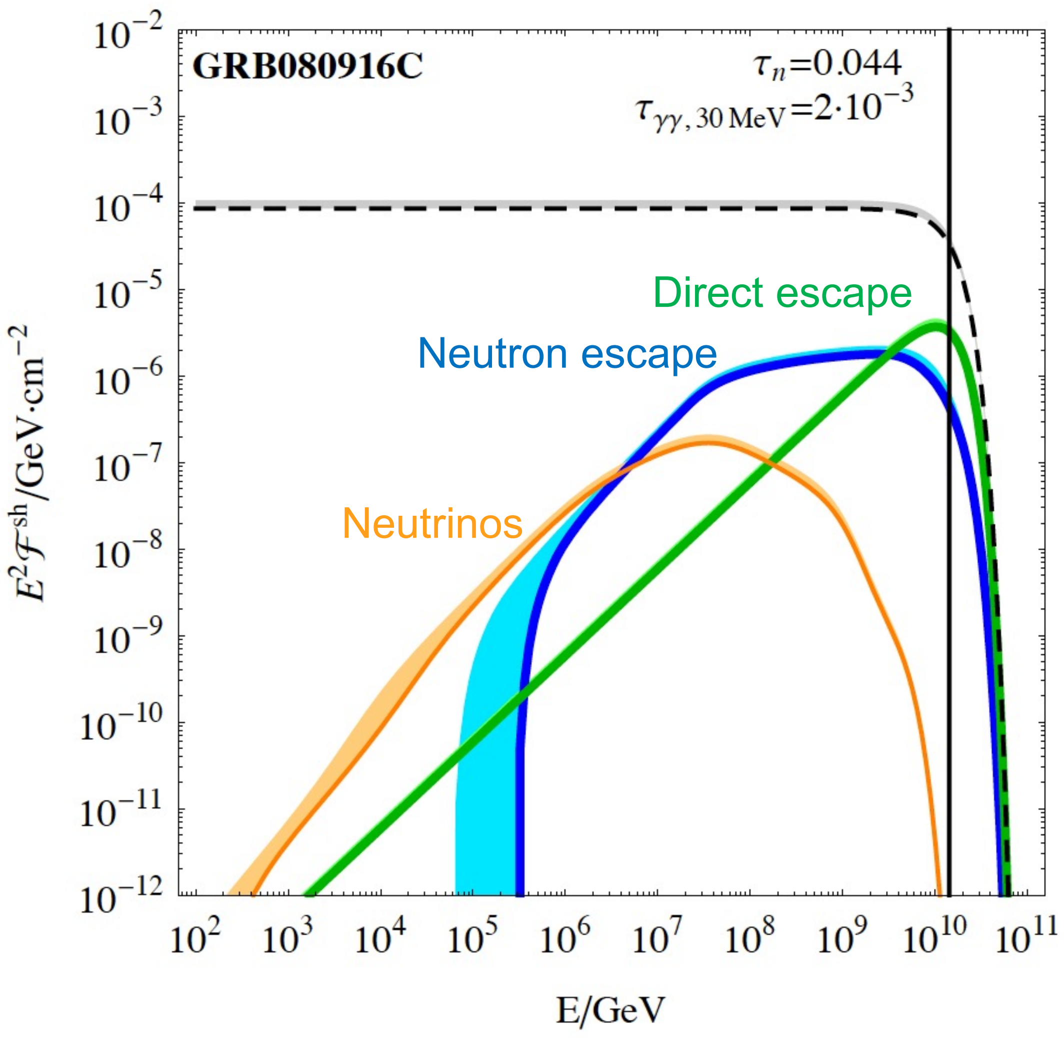
3. **The efficient neutrino production – nuclear cascade challenge**
   High target photon densities (required for neutrino production) will trigger nuclear cascade in source (... but: that destroys the Peters cycle needed to describe UHECR data!)

4. **The energy budget challenge**
   Typically relatively high **escaping** UHECR energies per source needed.
   Requires sufficient kinetic energy at first place!

1. The escape mechanism challenge

Baerwald, Bustamante, Winter, Astrophys. J. 768 (2013) 186

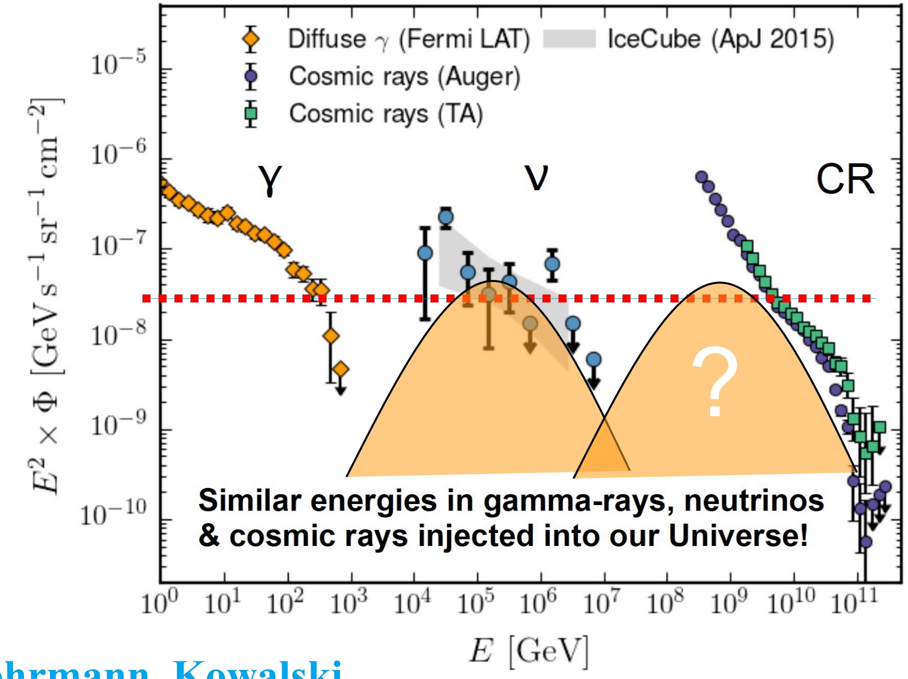
- Non-trivial question, depends on acceleration mechanism and source environment
- Cosmic ray can (depending on parameters) escape through different mechanisms, such as
  - As neutrons (if efficiently produced)
  - By diffusion, depending on the turbulent spectrum
  - At the highest energies (if R_L > Region) directly; hard!
- Example: GRBs. Neutron and direct escape compete depending on the pγ timescale. (direct esape also works for an expanding shell, depending on the adiabatic index) →
- Other discussions include e.g. interplay disintegration/escape in environment of source Unger, Farrar, Anchordoqui, PRD 92 (2015) 12, 123001; escape from shocks may act as high-pass filter Globus, Allard, Mochkovitch, Parizot, MNRAS 451 (2015) 1, 751; see also Sec. IIIB for a summary of escape mechanisms Zhang et al, PRD 96 (2017) 6, 063007



Most source models require/imply assumption for hard escape mechanism!

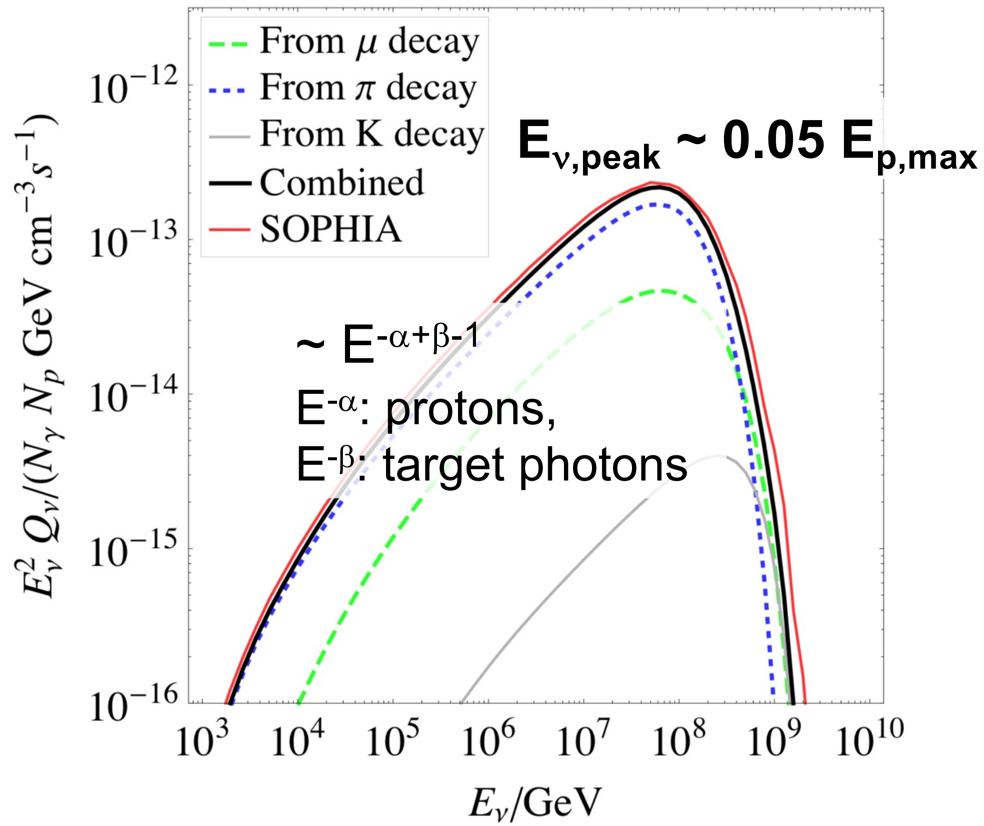
2. The neutrino peak energy challenge

- Neutrinos observed in TeV-PeV range



Mohrmann, Kowalski

AGN neutrino spectrum (example)



From: Hümmer et al, Astrophys. J. 721 (2010) 630; for a more complete view of possible cases, see Fiorillo et al, JCAP 07 (2021) 028

- The maximal or peak neutrino energy will follow the primary energy
- Consequence: neutrinos should be observed up to EeV energies!

Decouple the maximal cosmic-ray and neutrino energies?

Secondary cooling as a possible solution

- Synchrotron cooling of secondaries (μ, π, K) in neutrino production chain:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu ,$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

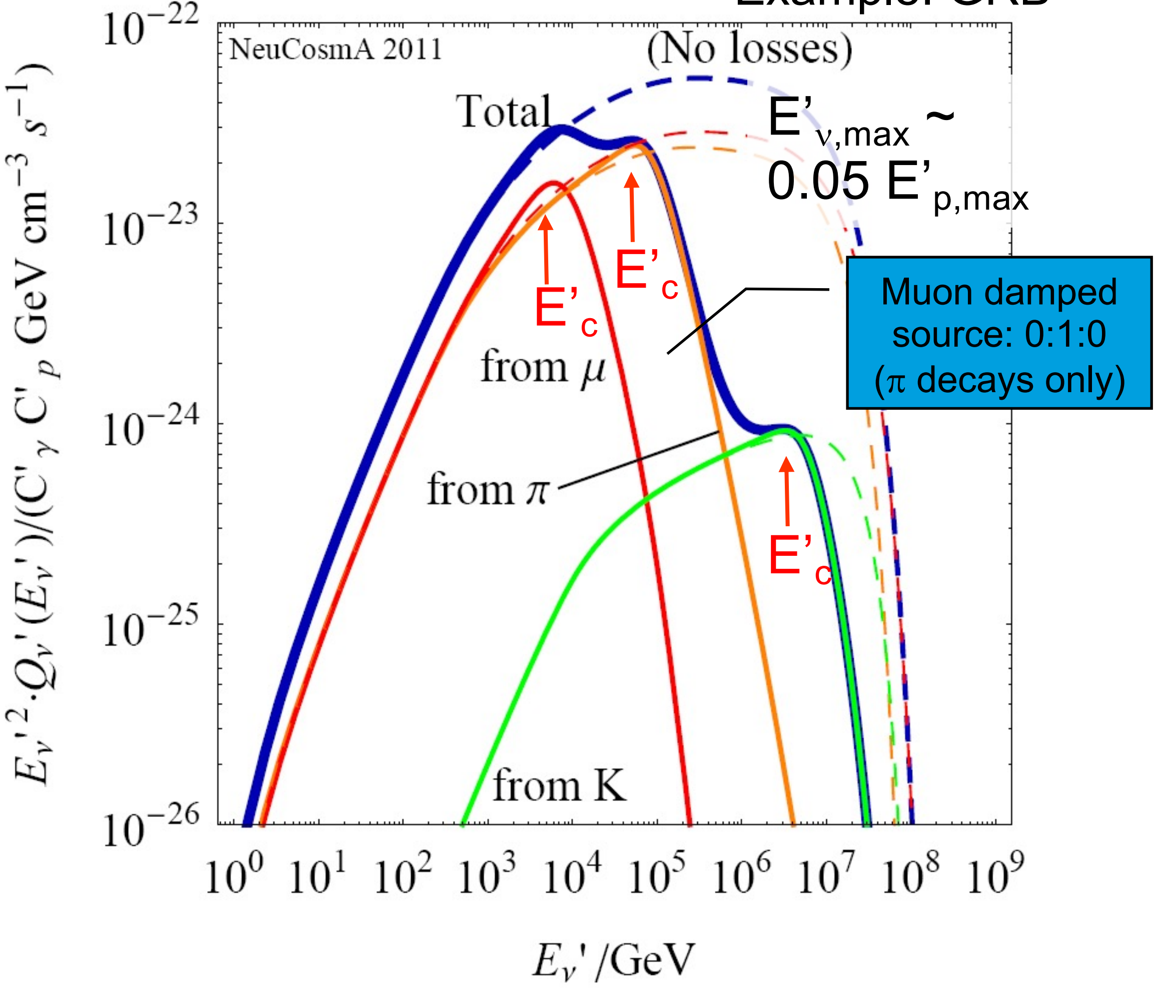
- Spectra (μ, π, K) energy loss-steepend above critical energy
  (synchrotron cooling faster than decay)

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

  Depends on particle physics only (m, τ_0 of secondary), and **B'**

- Points towards sources with strong enough B' if UHECR connection:
  Gamma-Ray Bursts, (jetted)
  Tidal Disruption Events, ...

Example: GRB



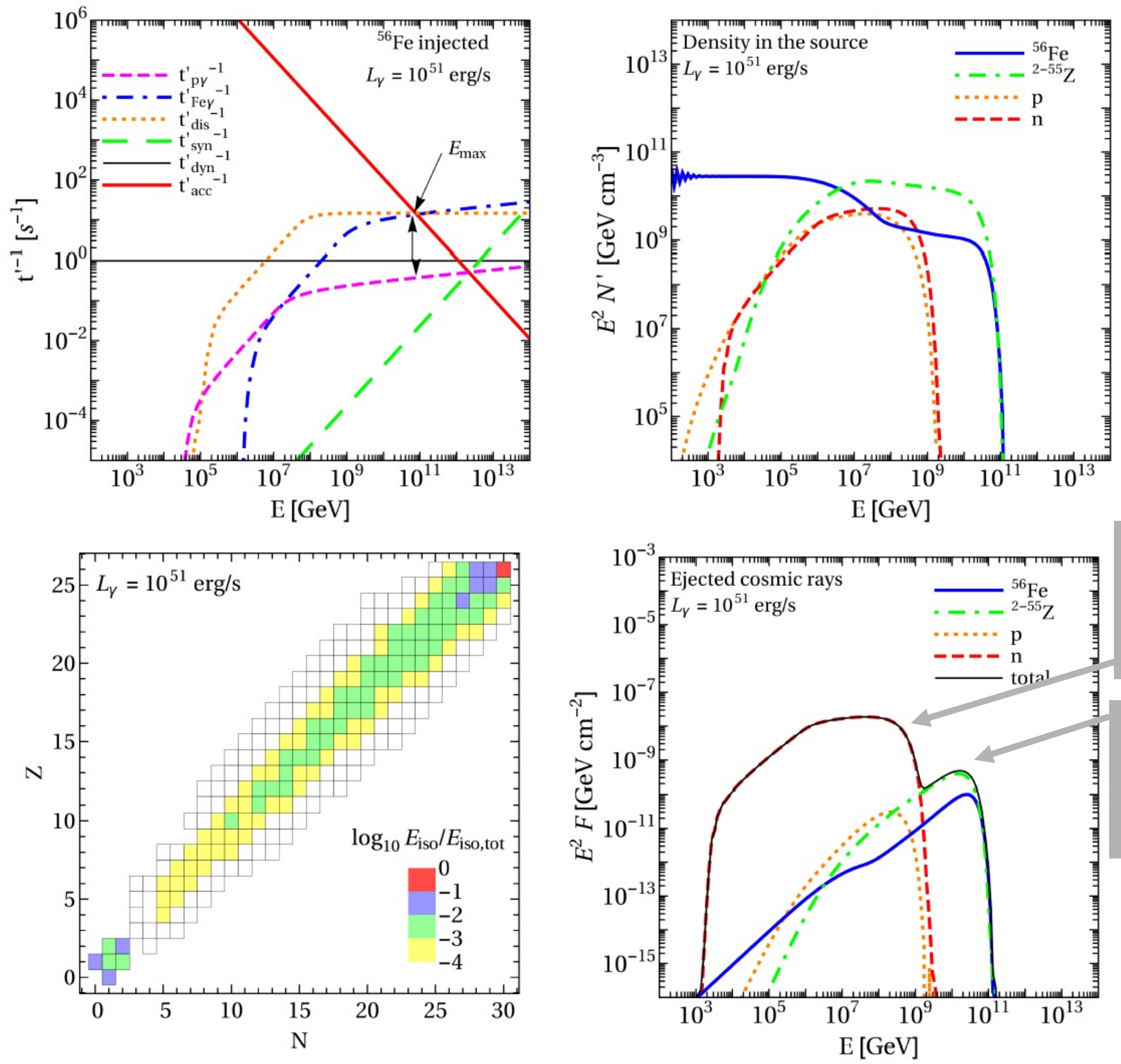
Kashti, Waxman, 2005; Lipari et al, 2007; ...
Fig. from Baerwald et al, Astropart. Phys. 35 (2012) 508

3. The neutrino production – nuclear cascade challenge

- Efficient neutrino production requires high enough target densities
  → trigger disintegration as well

- The maximal energy is constrained by interactions
  → the Peters cycle model breaks
  → UHECRs interact cannot efficiently escape

- Conclusions:
  - UHECRs may not come from the same sources or regions where the neutrinos are produced
  - However: there are interesting cases where the disintegration products can improve the ankle description (→ LL-GRBs)



Efficient neutron production

$R_L \ll R$ at highest E

Example: Gamma-Ray Burst with nuclear cascade in-source; from Biehl, Boncioli, Fedynitch, Winter, A&A 611 (2018) A101

4. The energetics challenge – example: transients

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:

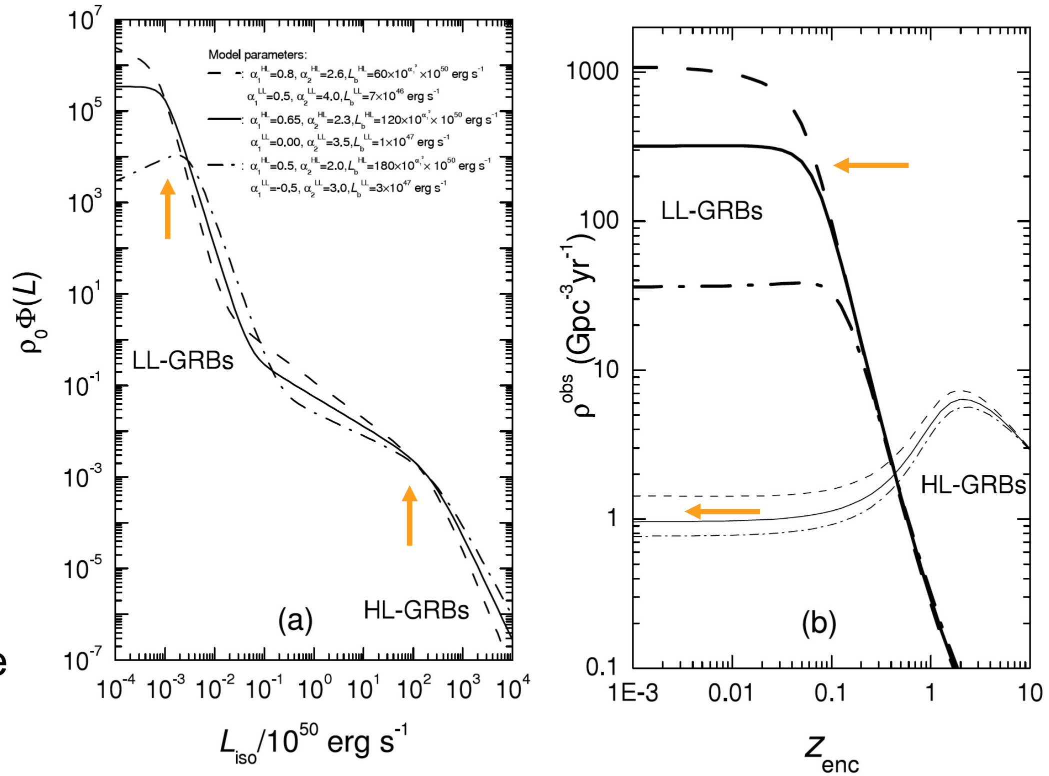
$$E_{\rm CR}^{[10^{10},10^{12}]} = 10^{53}\,{\rm erg} \cdot \frac{\dot{\varepsilon}_{\rm CR}^{[10^{10},10^{12}]}}{10^{44}\,{\rm erg\,Mpc^{-3}\,yr^{-1}}} \, \frac{\rm Gpc^{-3}\,yr^{-1}}{\dot{n}_{\rm GRB}\big|_{z=0}}$$

(GeV)

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

- Connection with gamma-rays: $E_{\rm CR}^{[10^{10},10^{12}]}$ ~ 0.2 f_e^{-1} E_γ
  if UHECRs can escape efficiently, and 20% of the CR energy is transferred to 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_γ ~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_γ ~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_γ ~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*

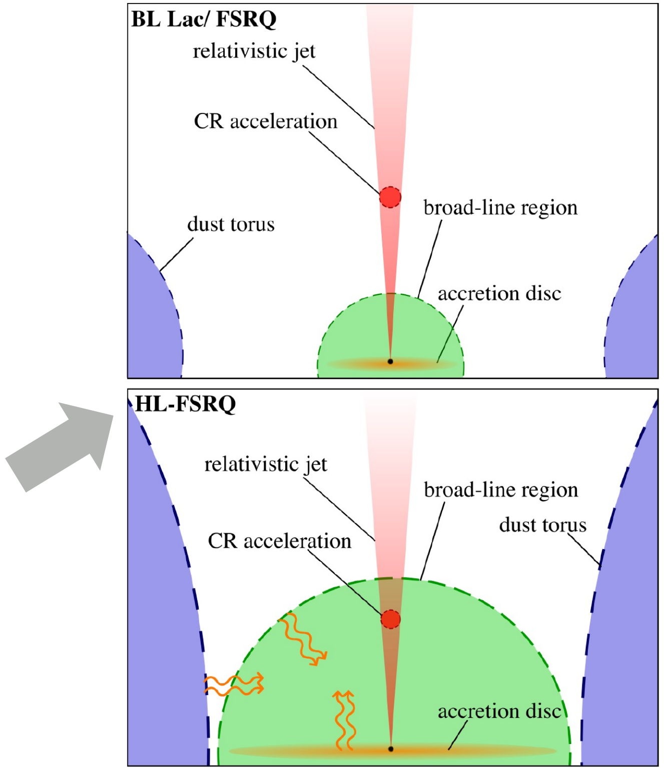
Liang, Zhang, Virgili, Dai, 2007; see also: Sun, Zhang, Li, 2015



Test case: AGN

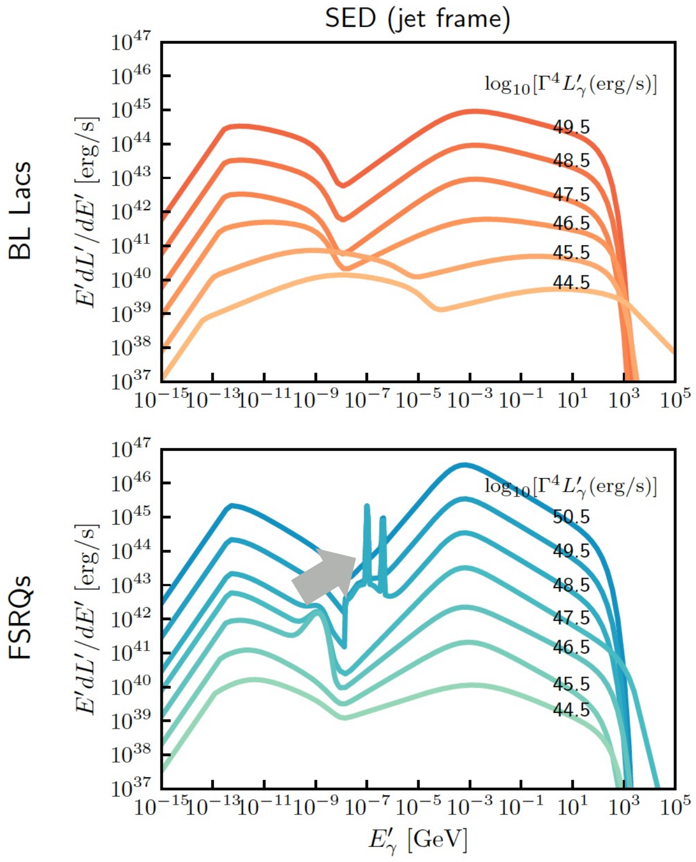
Ingredients: Neutrino production and population models

- Geometry determined by disk luminosity:



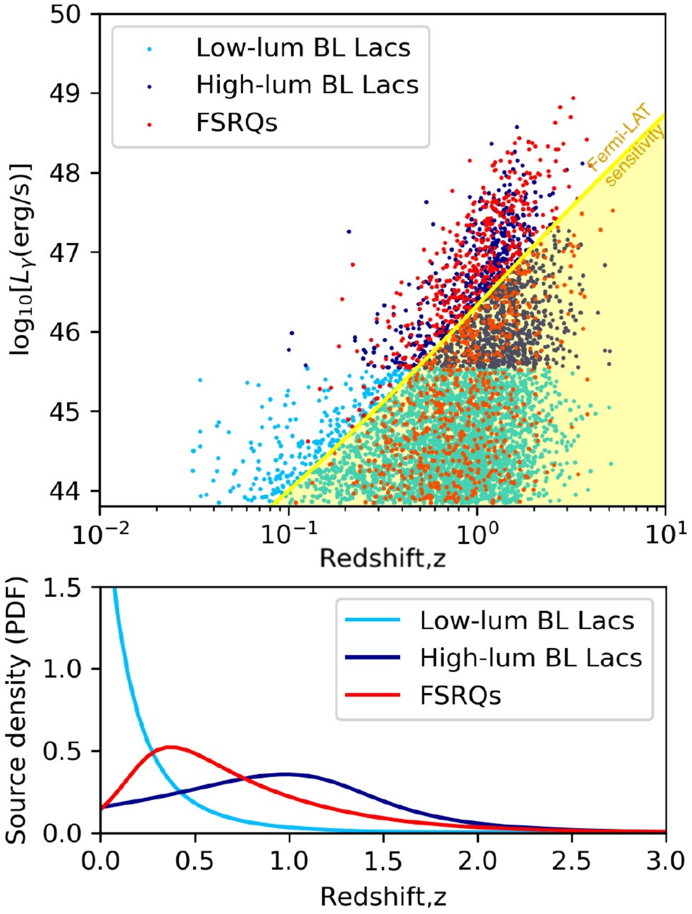
- For HL-FSRQs, the blob is exposed to boosted external fields

- SED follows "blazar sequence":



Rodrigues, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) 54; Murase, Inoue, Dermer, PRD 90 (2014) 023007; Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41; Rodrigues, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021) 191101

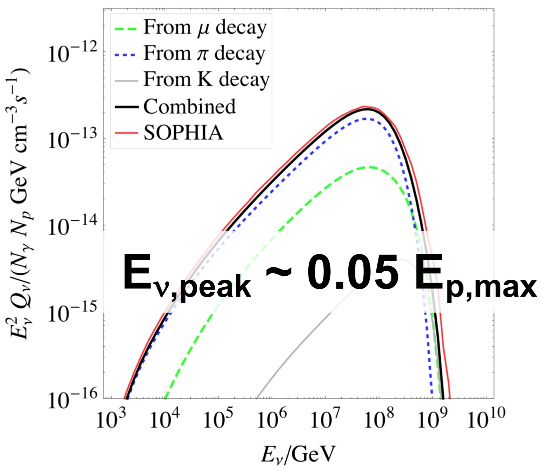
- Population model: LL-BL Lacs, HL-BL Lacs, FSRQs



Population model by Ajello et al, 2012+2014; sources from Fermi's 3LAC catalogue

Describes diffuse γ-ray BG by construction!

Consequences for AGN

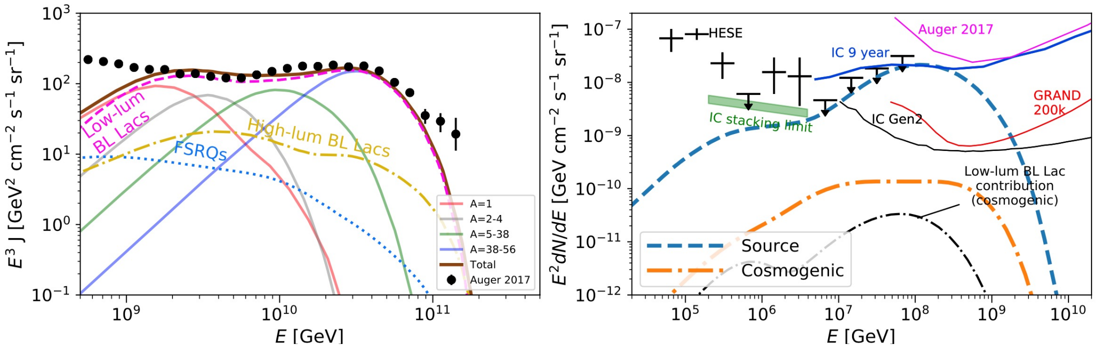


$E_{\nu,peak} \sim 0.05\ E_{p,max}$

→ Challenge 2: neutrinos have to peak at high E

→ Challenge 3: neutrinos and UHECRs from different populations

1. UHECR description driven by LL-BL Lacs because of
   - Low luminosity → rigidity-dependent max. energy
   - Negative source evolution → Challenge 1

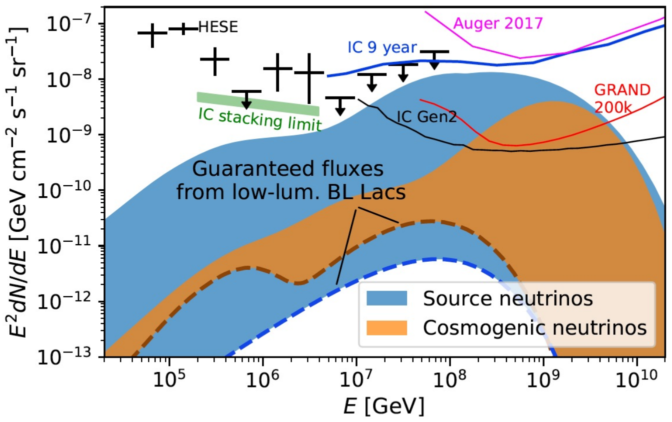


Postulate that:

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

2. Source neutrinos mostly come from FSRQs, peak at high energies, and may even outshine the cosmogenic flux there

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

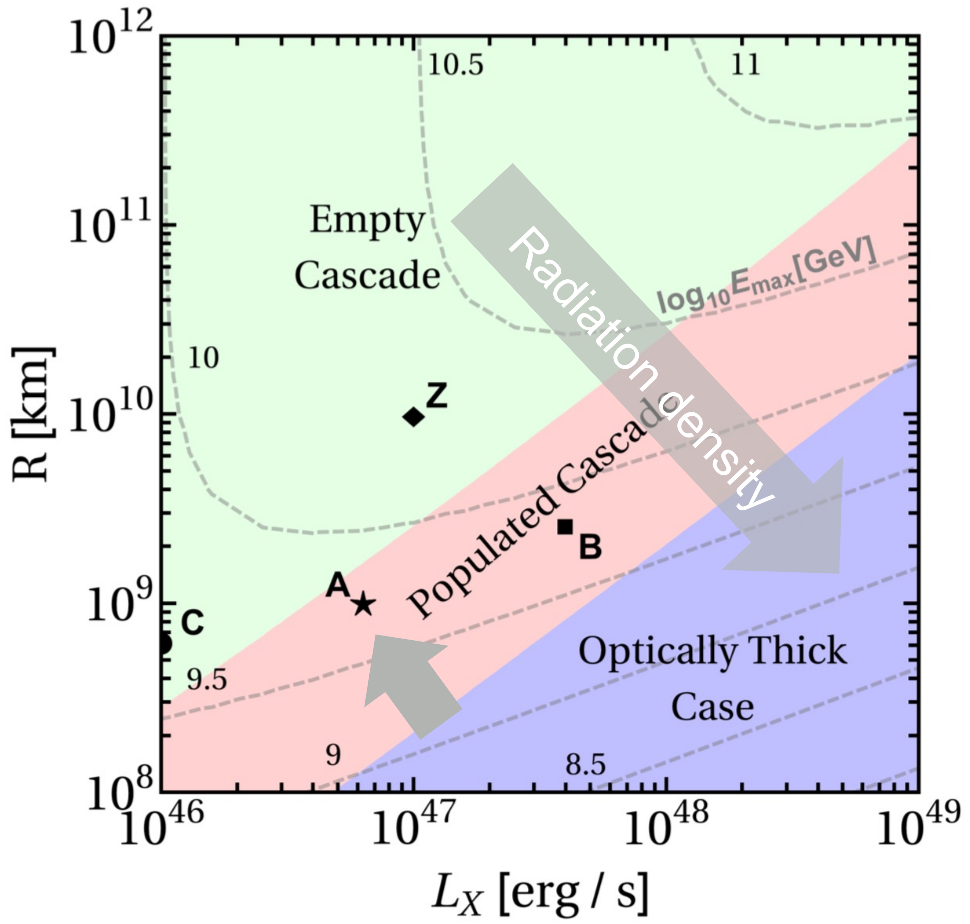


Test case: LL-GRBs

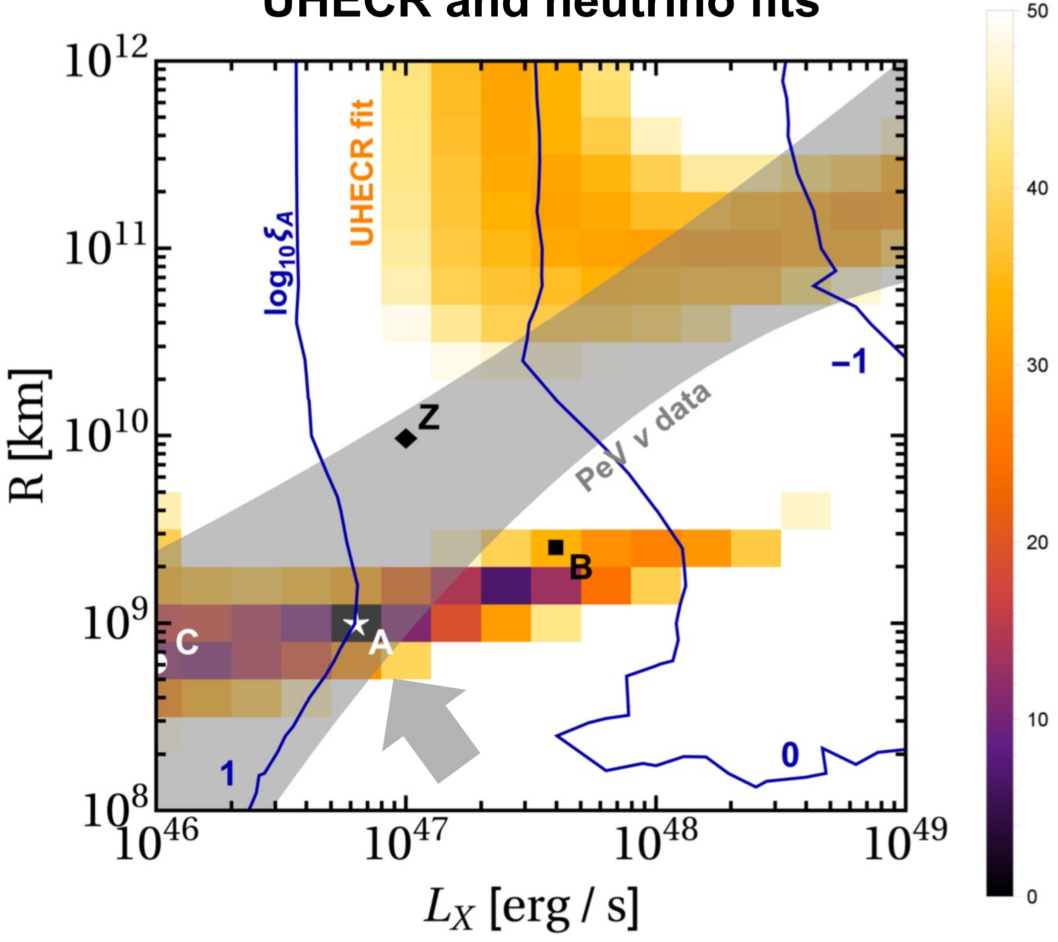
LL-GRBs: Systematic parameter space studies

Idea: describe UHECRs and neutrinos at same time

Nuclear cascade and E_{max}



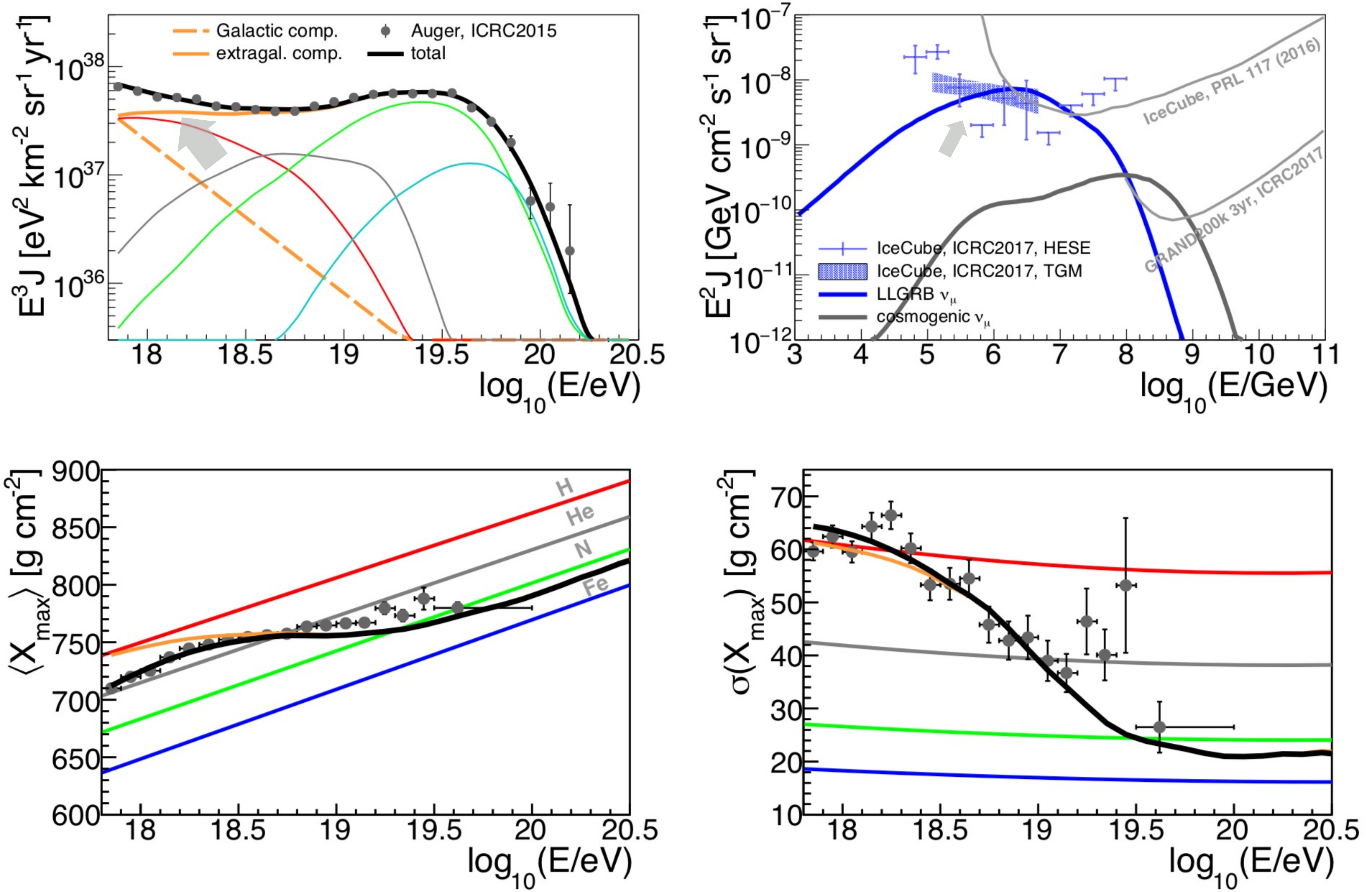
UHECR and neutrino fits



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; **energetics**!)

One alternative: a population of LL-GRBs



→ Challenge 2: Secondary cooling decouples neutrinos and UHECRs

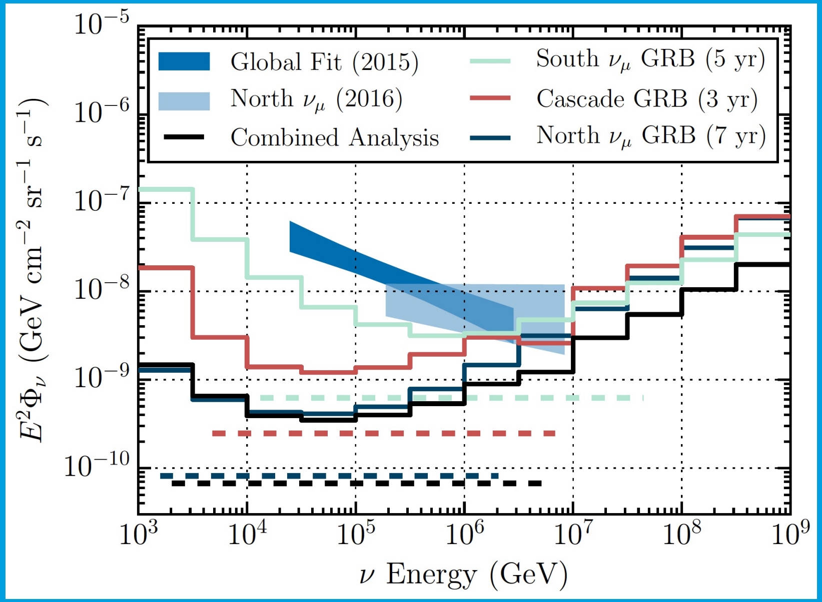
→ Challenge 3: neutrino production and ankle description require similar parameters (interesting!)

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

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

Test case: HL-GRBs

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



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

→ Challenges 2/3: TeV-PeV neutrinos not observed, but production efficient!

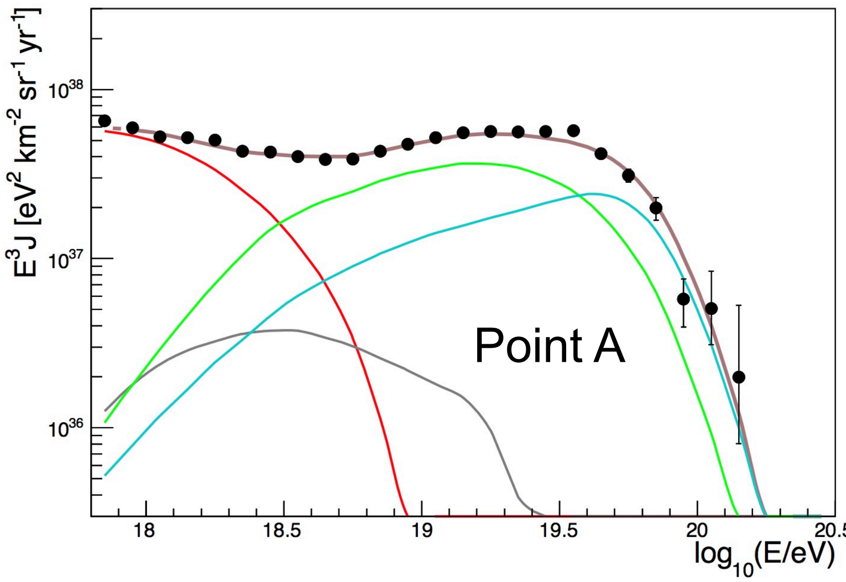
HL-GRBs: The vanilla one-zone prompt model

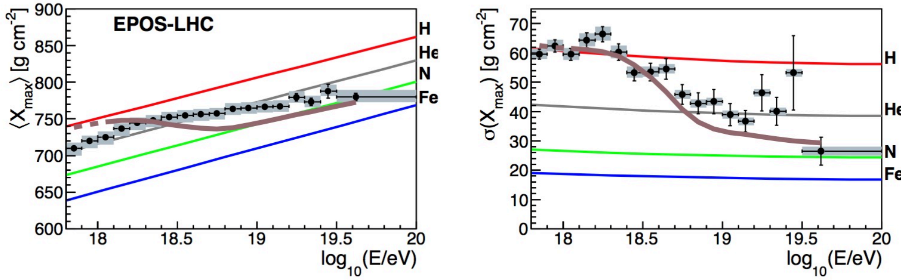
Neutrino and cosmic ray emission at same collision radius R

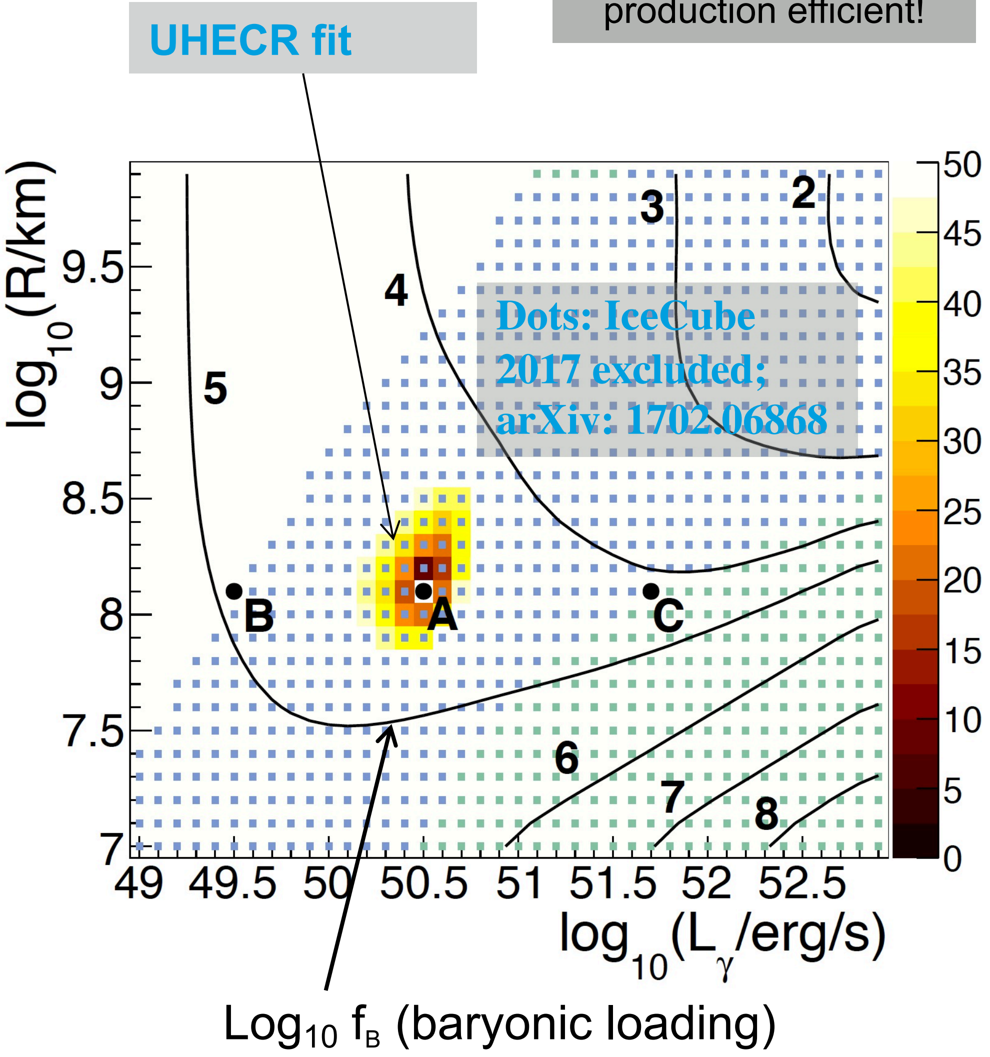
- Can describe UHECR data, roughly
- Scenario is constrained by neutrino non-observatons

Recipe:

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







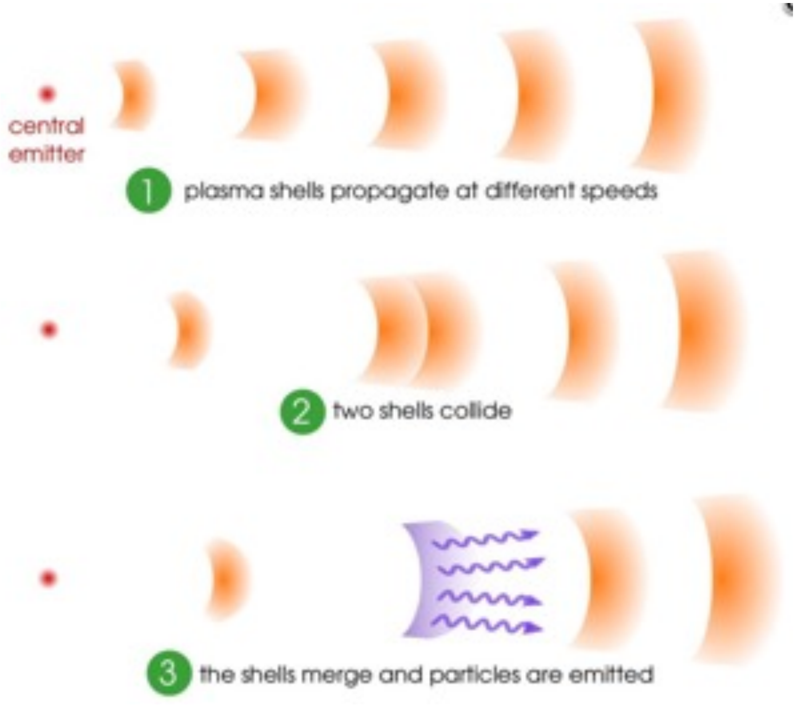
Biehl, Boncioli, Fedynitch, Winter, arXiv:1705.08909
Astron. Astrophys. 611 (2018) A101;
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

Back to the roots:
Multi-collision models

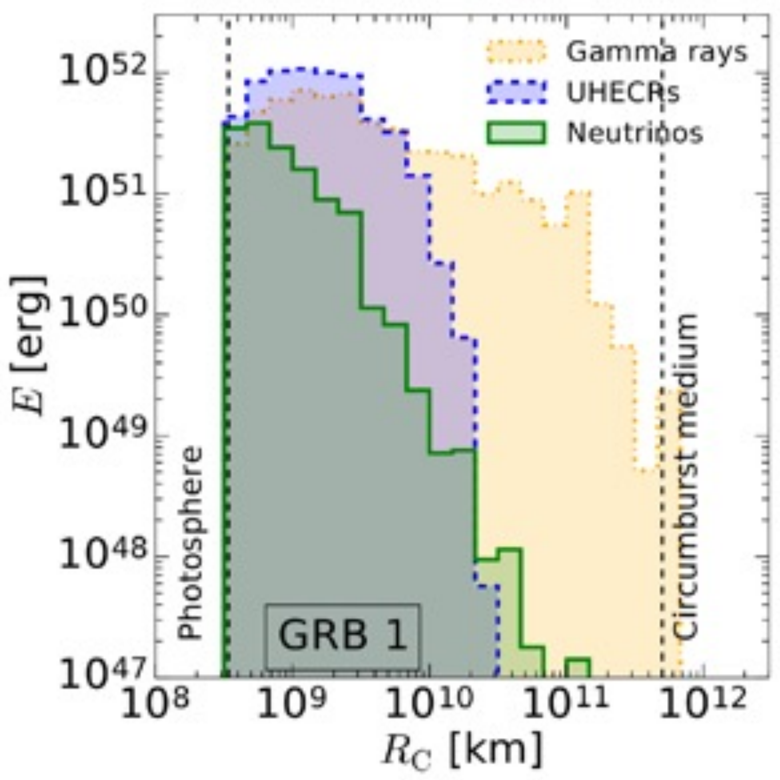
The GRB prompt emission comes from multiple zones

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

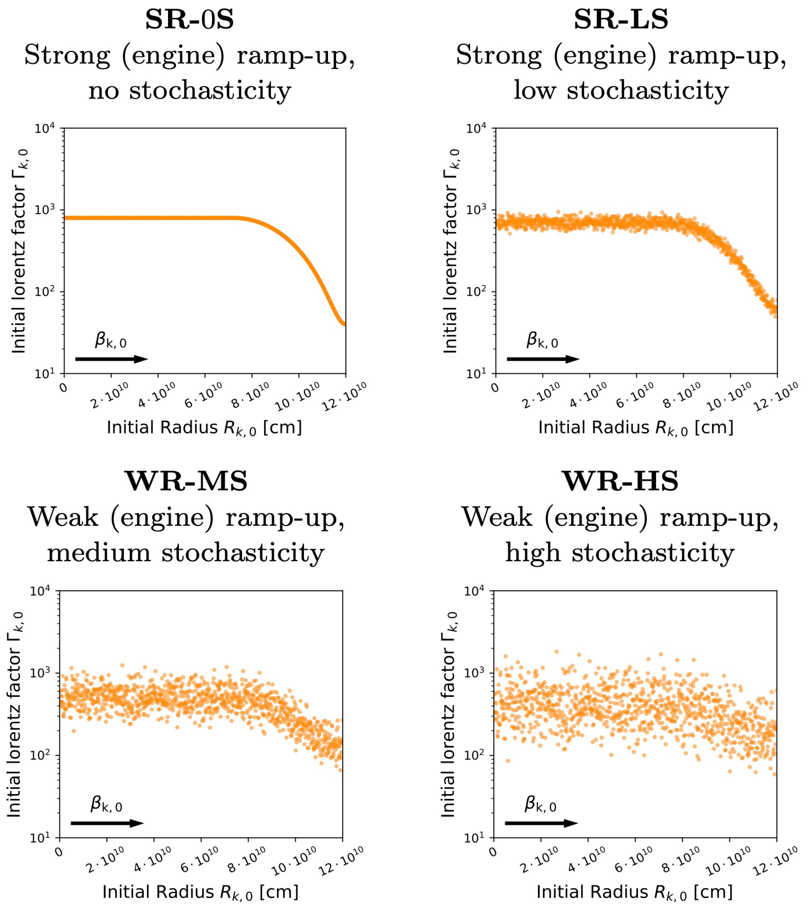
- The neutrino emission is lower (comes from a few collisions close to the photosphere)
- UHECRs and γ-rays are produced further out, where the radiation densities are lower
- The **engine properties** determine the nature of the (multi-messenger) light curves
- Many aspects studied, such as impact of 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

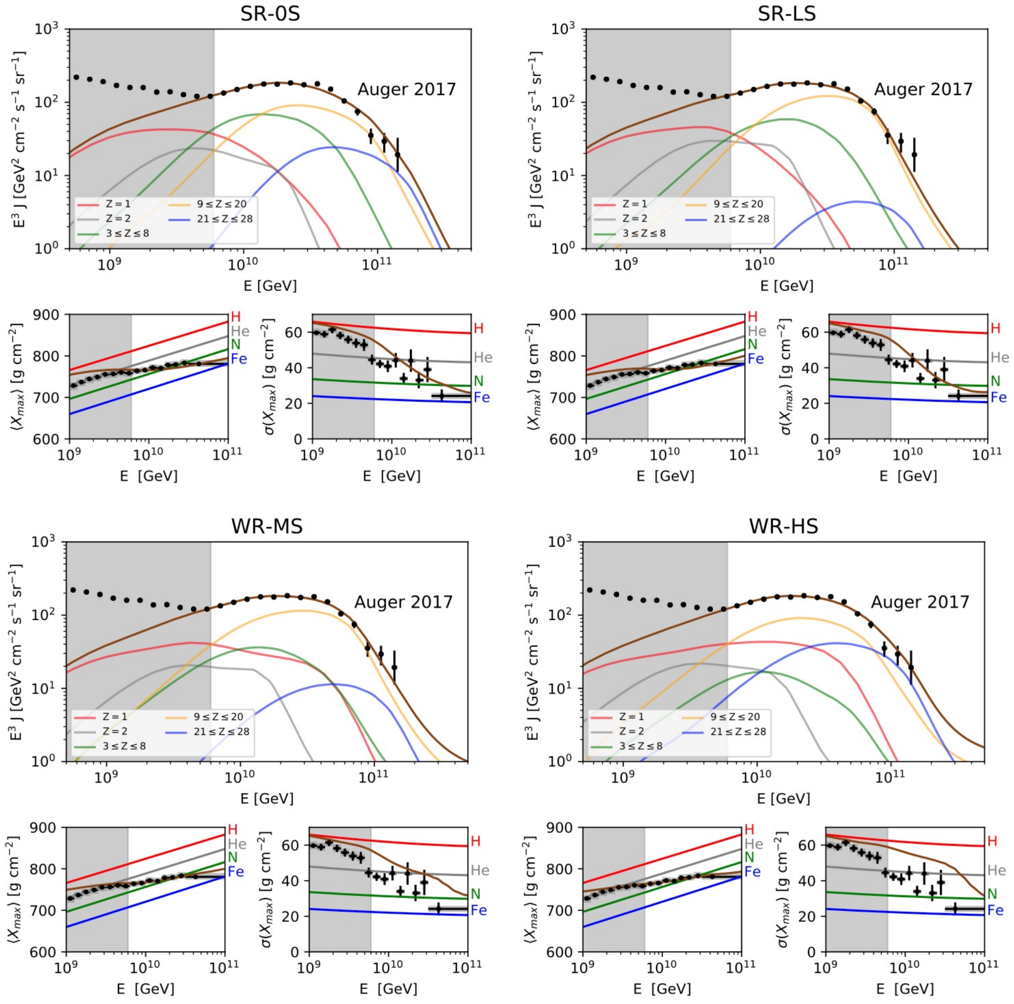


Describes UHECR data over a large range of parameters!

(systematically studied)

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

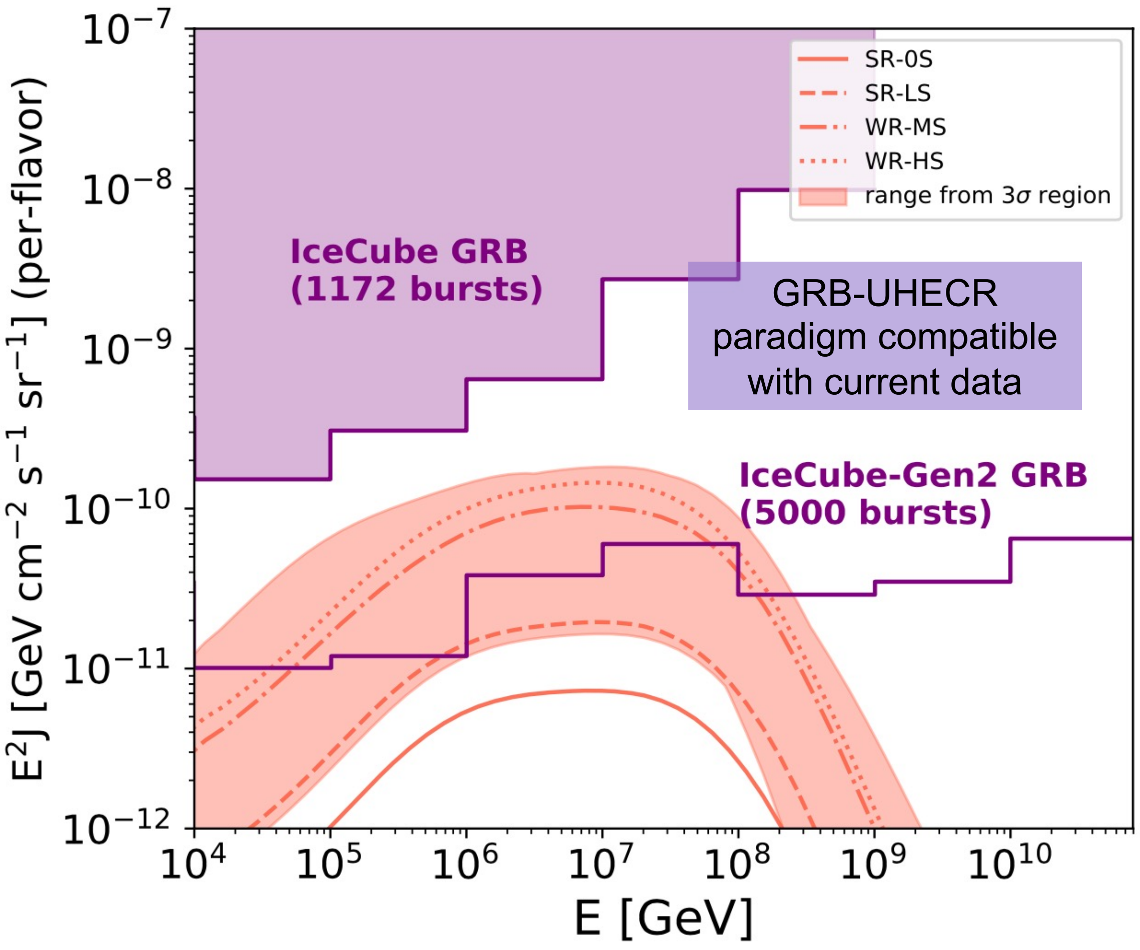
Description of UHECR data

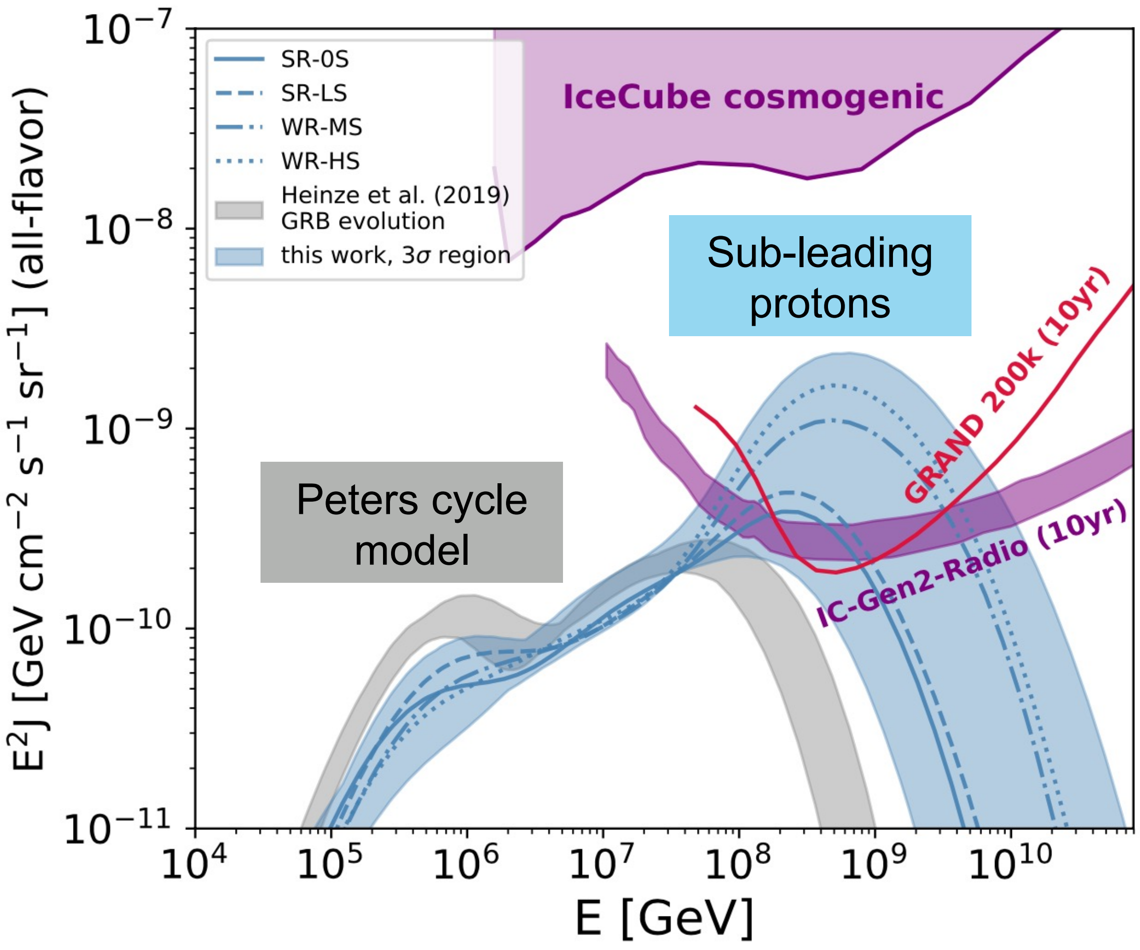


But: $\sigma(X_{max})$!

Inferred neutrino fluxes from the parameter space scan

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

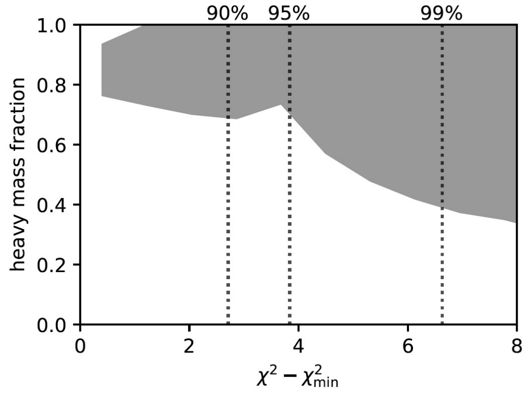


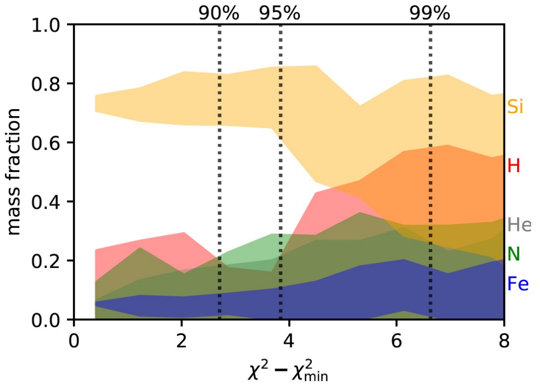


Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990

Interpretation of the results (GRB multi-collision model)

- The required (in source) injection compositon is derived *by free parameters*:
  more that 70% heavy (N+Si+Fe) at the 95% CL



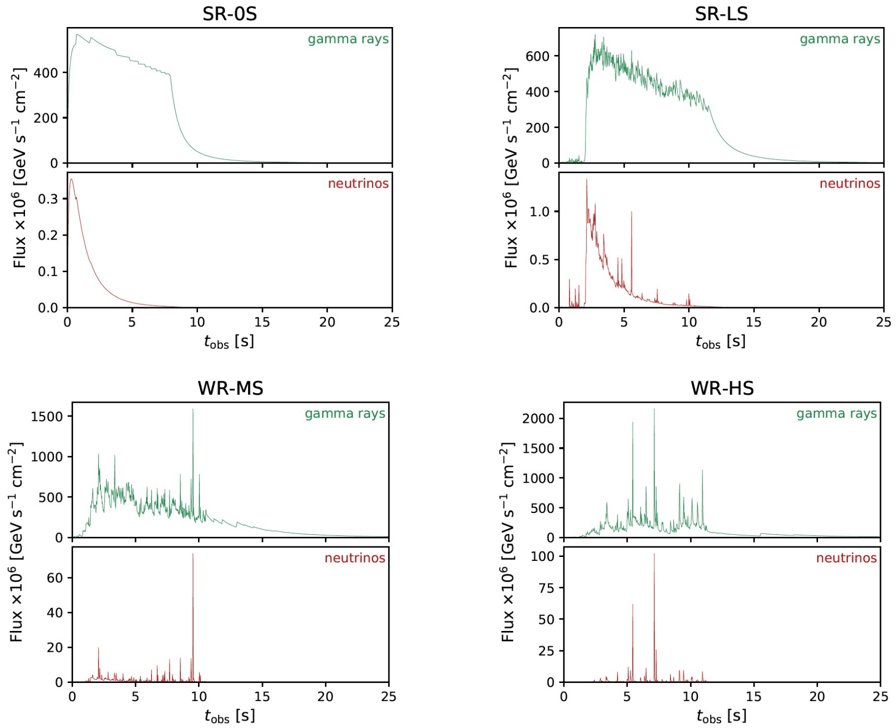


- Self-consistent energy budget requires kinetic energies larger than 10^{55} erg – **probably biggest challenge for UHECR paradigm**

→ Challenge 4!

	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

- Light curves may be used as engine discriminator

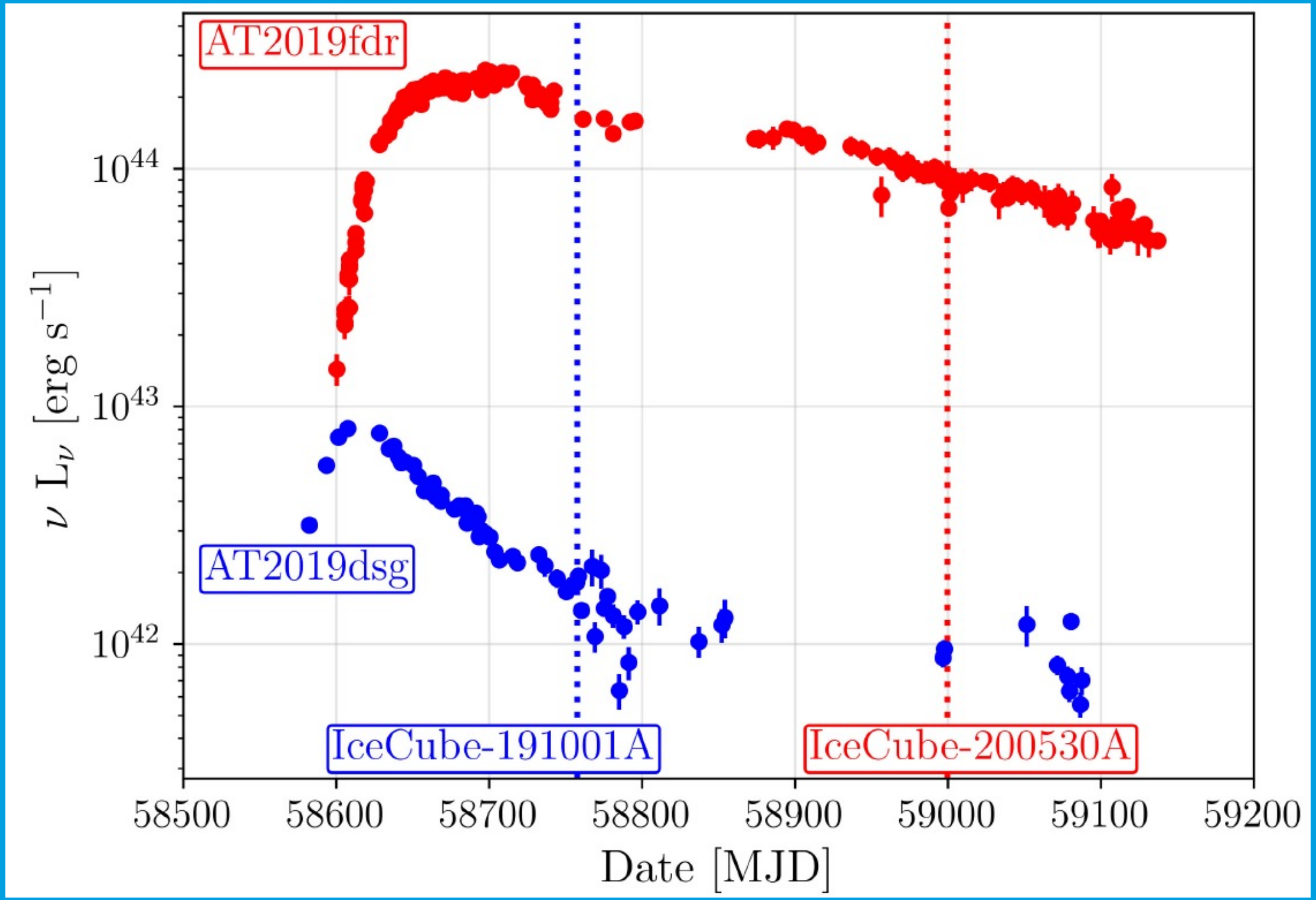


- Description of $\sigma(X_{max})$ is an instrinsic problem
  (because the data prefer “pure” mass groups, which are hard to obtain in multi-zone or multi-source models)

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

Test case: TDEs

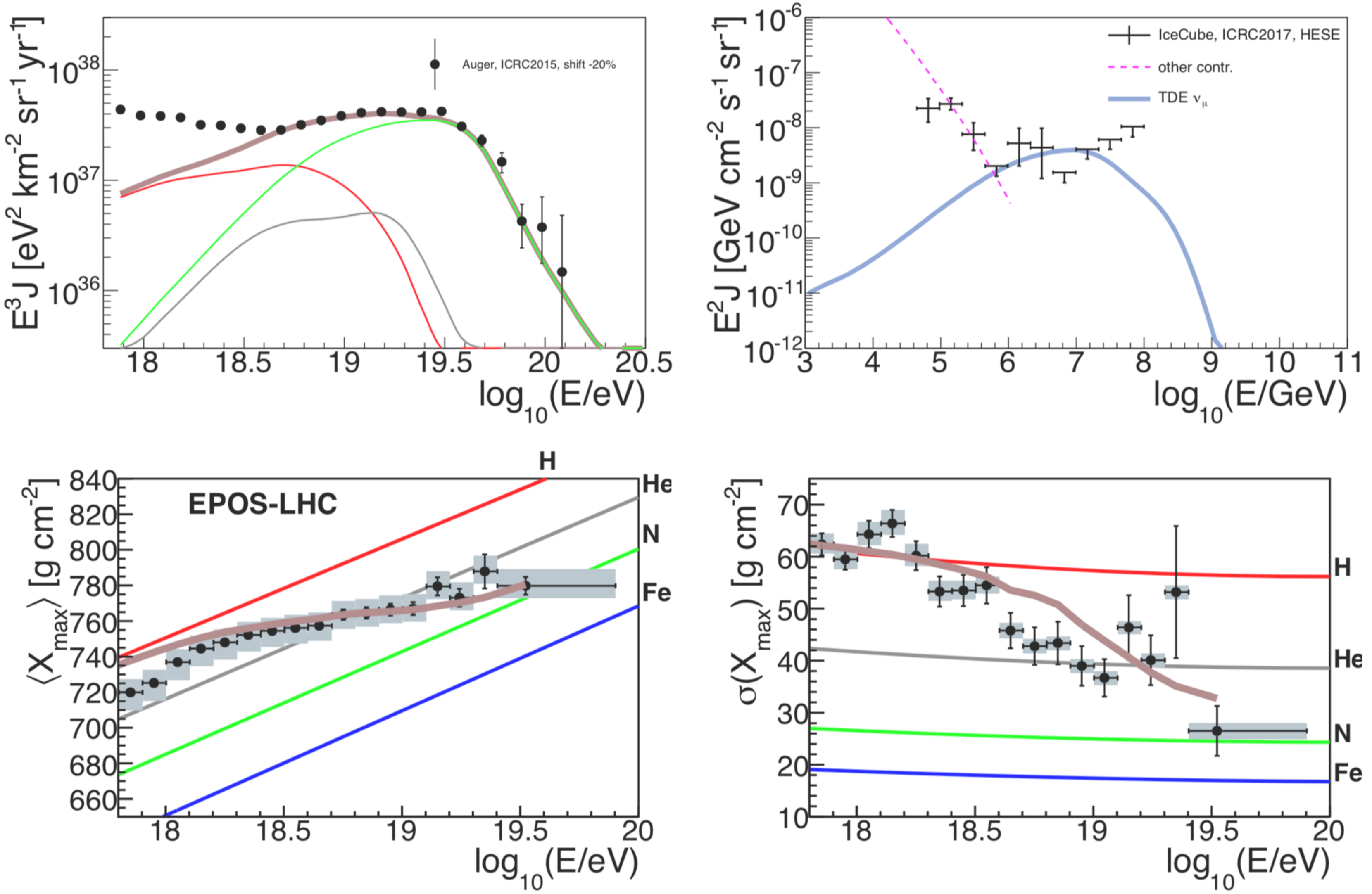
Tidal Disruption Events



From: Robert Stein & Simeon Reusch @
Cosmic Rays and Neutrinos in the Multi-Messenger Era, Paris, Dec. 7-11, 2020;
Reusch et al, in preparation

Example: jetted Tidal Disruption Events (TDE)

→ Challenge 2: Secondary cooling decouples neutrinos and UHECRs



Here for luminous jetted TDEs (some challenges …)

May work for UHECRs if less luminous, more abundant sources (neutrino flux may be lower)

Biehl, Boncioli, Lunardini, Winter, Sci. Rep. 8 (2018) 1; see also Guepin et al, A&A 616 (2018) A179

Summary and conclusion

1. **The UHECR escape mechanism challenge**
   Typically a very hard escape spectrum from the sources is postulated.
   Negative source evolution helps → LL-GRBs, TDEs

2. **The maximal neutrino energy challenge**
   If the TeV-PeV neutrinos and UHECRs need to be described simultaneously, strong magnetic fields are required (secondary cooling) → LL-GRBs, jetted TDEs

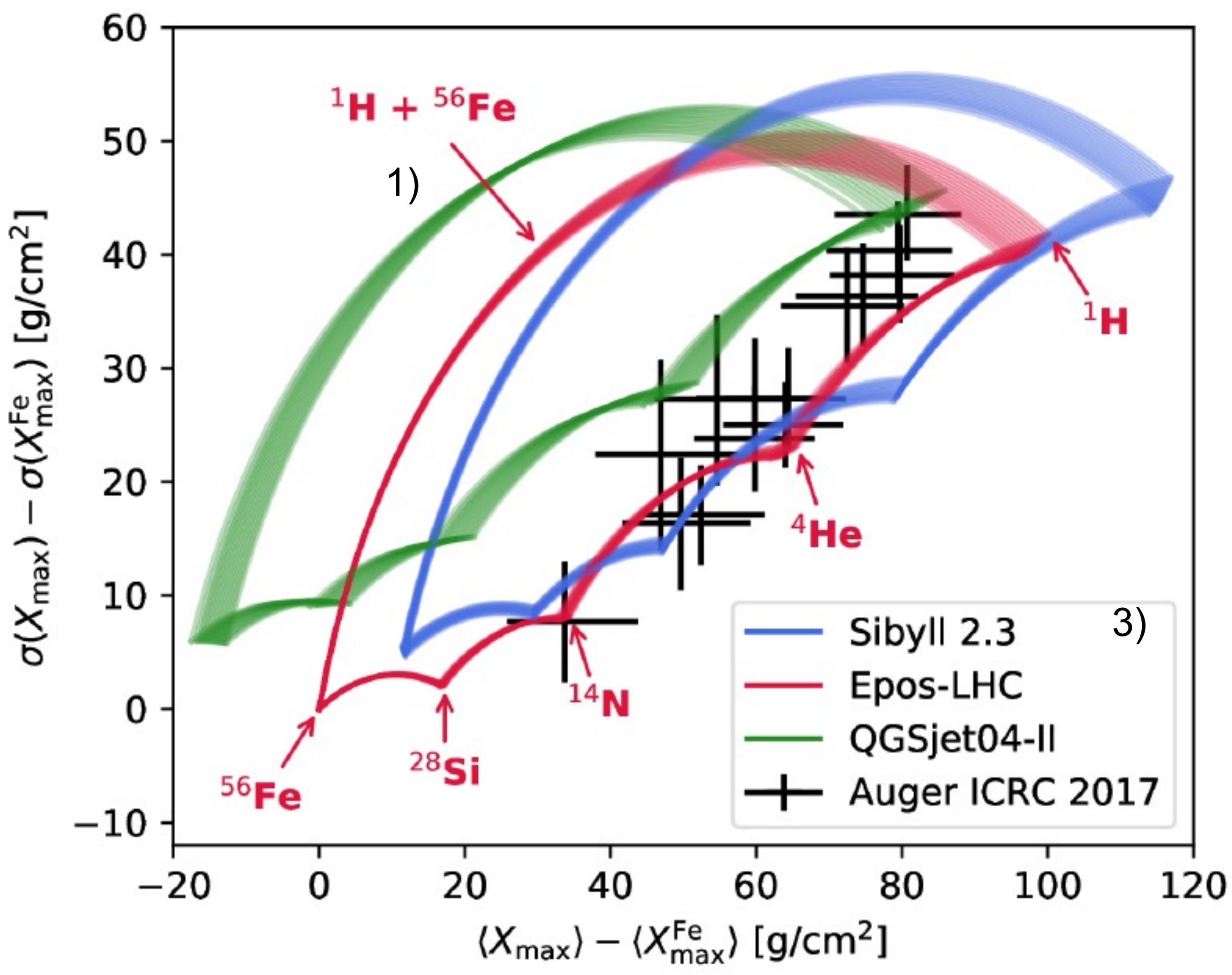
3. **The efficient neutrino production – nuclear cascade challenge**
   High target photon densities (required for neutrino production) will trigger nuclear cascade in source
   Neutrinos and UHECRs from different source populations (→ AGN) or production regions (→ HL-GRBs); effect sometimes useful to describe ankle by disintegration products (→ LL-GRBs)

4. **The energy budget challenge**
   Typically relatively high **escaping** UHECR energies per source needed.
   Kinetic energy in UHECR source classes previously underestimated (→ HL-GRBs) or indications for super-Eddington accretion (→ AGN)?

5. **The $\sigma(X_{max})$ (BONUS!) challenge**
   Any UHECR source model with multiple sources or production regions will likely produce mixed composition

BACKUP

5. The σ(X_{max}) challenge



Data favor
pure composition!

PhD thesis Jonas Heinze, https://edoc.hu-berlin.de/handle/18452/22177

pp versus pγ interactions

When do the neutrinos follow the primary spectrum?

- **pp interactions**

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

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

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

Examples: starburst galaxies, environments with gas/dust

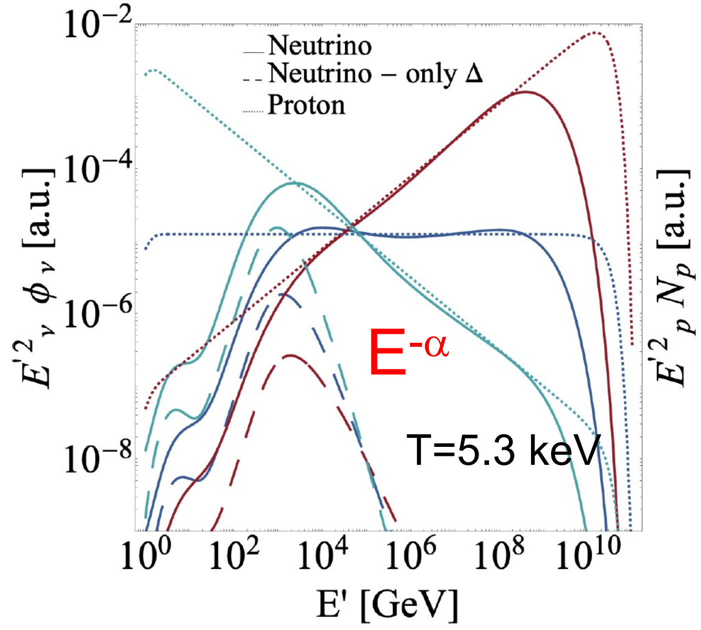
- **pγ interactions with power law target**: more sophisticated since relativistic target

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

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

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

Examples: GRBs ($\beta \sim 1$), AGN blazars ($\beta > 1$)



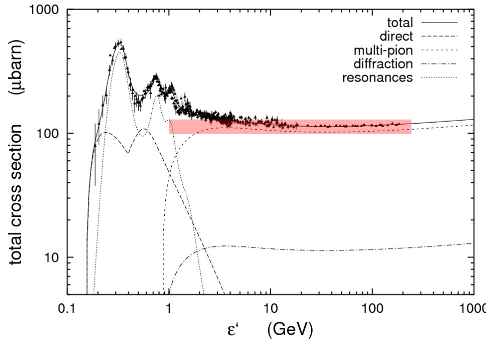
Fiorillo et al, JCAP 07 (2021) 028

- **pγ interactions with thermal target:**
Peaked (example: CMB). But: multi-pion prod. dominates if target photon T high enough.

Examples: TDEs, AGN cores

$$p + \gamma$$

$E^{-\alpha}$ T

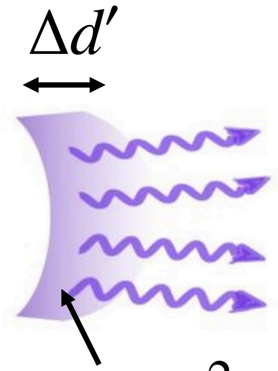


→

Neutrino production efficiency in GRBs (as example)

... from geometry estimators; production volume determines efficiency!

$$\lambda'_{\rm mfp} = \frac{1}{n'_\gamma \, \sigma_{p\gamma}}$$



- Need photon density, which can be obtained from energy density; generically:

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

L'_γ

$$V'_{\rm iso} = 4\pi R^2 \cdot \Delta d'$$

- Scales ~$1/R^2$ from simple geometry arguments
- *Internal shock scenario*: e.g. Guetta et al, 2004

$$R \simeq 2\Gamma^2 \frac{c\, t_v}{1+z} \qquad \Delta d' \simeq \Gamma \frac{c t_v}{1+z} \quad \Rightarrow \quad f_{p\gamma} \propto L_\gamma / (\Gamma^4 t_v \epsilon_{\gamma,\rm br})$$

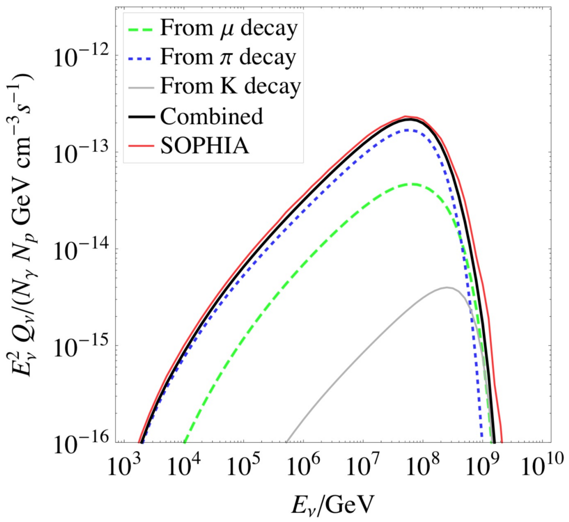
$$\left(f_{p\gamma} \propto \Delta d' / \lambda'_{\rm mfp} \sim \Delta d' \, \sigma_{p\gamma} u'_\gamma / (\epsilon_{\gamma,\rm br}/\Gamma)\right)$$

- *Magnetic re-connection models*: est. for *R* from pulse timescale (larger)
- *Photospheric emission*: *R* corresponds to photospheric radius
- *Multi-zone models*: *R* and Δd' individually calculated for each collision
- **Production radius R and luminosity Lγ are the main control parameters for the neutrino production** [t_v does not vary as much as L_γ]
  e.g. He et al, 2012; Zhang, Kumar, 2013; Biehl et al, arXiv:1705.08909 (Sec. 2.5) for details

Recap: AGN neutrino spectrum ...and two hypotheses

There is no unified (ν, γ-ray, UHECR) one zone model!

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



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

Moderately efficient CR acclerators

1) AGN blazars describe neutrino data

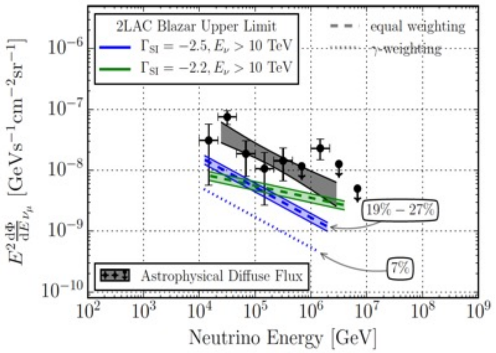
$E_{p,max}$ ~ 1-10 EeV
(R_{max} ~ 1-10 EV)

Very efficiency CR accelerators

2) AGN jets describe UHECR data

Postulate that:

1. The diffuse neutrino flux is dominated by AGN blazars (such as the extragalactic γ-ray flux!)
2. The blazar stacking limit is obeyed → IceCube, Astrophys. J. 835 (2017) 45



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

Postulate that:

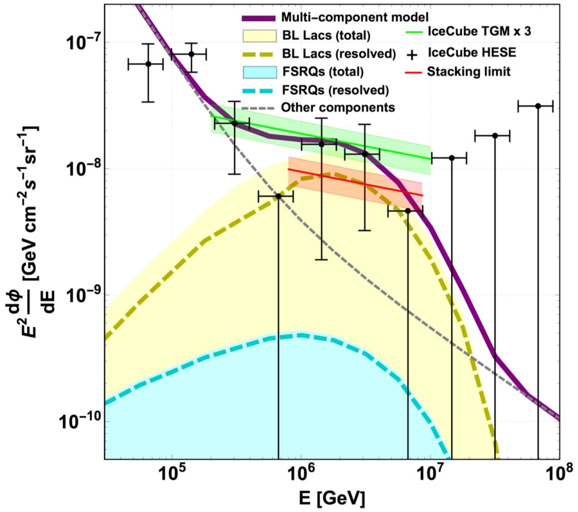
1. AGN jets (can be misaligned!) describe Auger data across the ankle
(spectrum very well, composition observables roughly)
2. The injection compositon is roughly Galactic
3. Different classes
(LL-BL Lacs, HL-BL Lacs, FSRQs)
can have a different baryonic loading

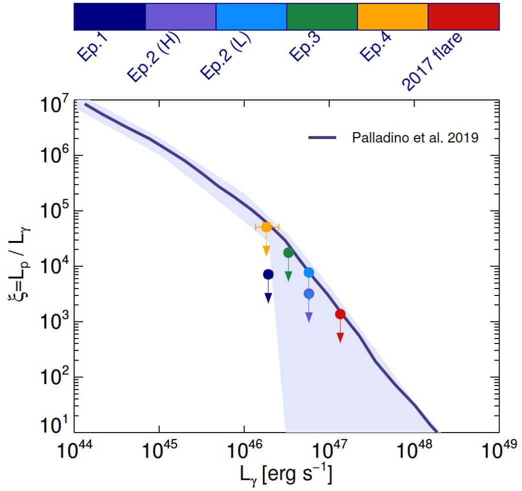
Conclusions for different hypotheses

More in part III!

1) AGN blazars describe neutrino data

1. Unresolved BL Lacs must dominate the diffuse neutrino flux
2. The baryonic loading must evolve, as otherwise efficient neutrino emitters (esp. FSRQs) stick out

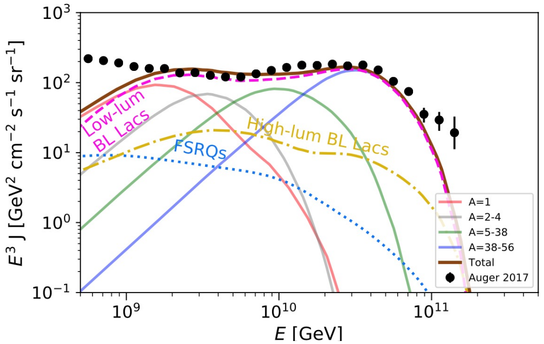


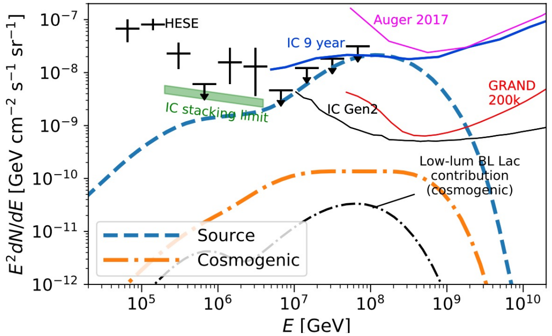


Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41;
Right Fig. from Petropoulou et al, arXiv:1911.04010: same behavior also found in multi-epoch description of TXS 0506+056

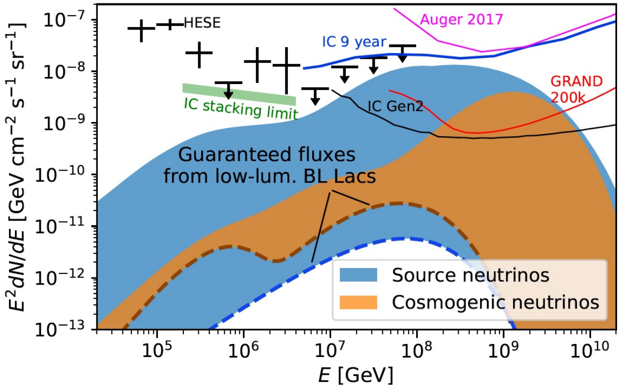
2) AGN jets describe UHECR data

1. UHECR description driven by LL-BL Lacs because of
   - Low luminosity → rigidity-dependent max. energy
   - Negative source evolution





2. Neutrinos mostly come from FSRQs, peak at high energies, and may even outshine the cosmogenic flux there



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