Exploring the connection between GRBs, UHECR Nuclei and Neutrinos

Cosmic Ray and Neutrino Emission from Gamma-Ray Bursts with a Nuclear Cascade

[D. Biehl, D. Boncioli, A. Fedynitch, W. Winter – arXiv:1705.08909, submitted to A&A]

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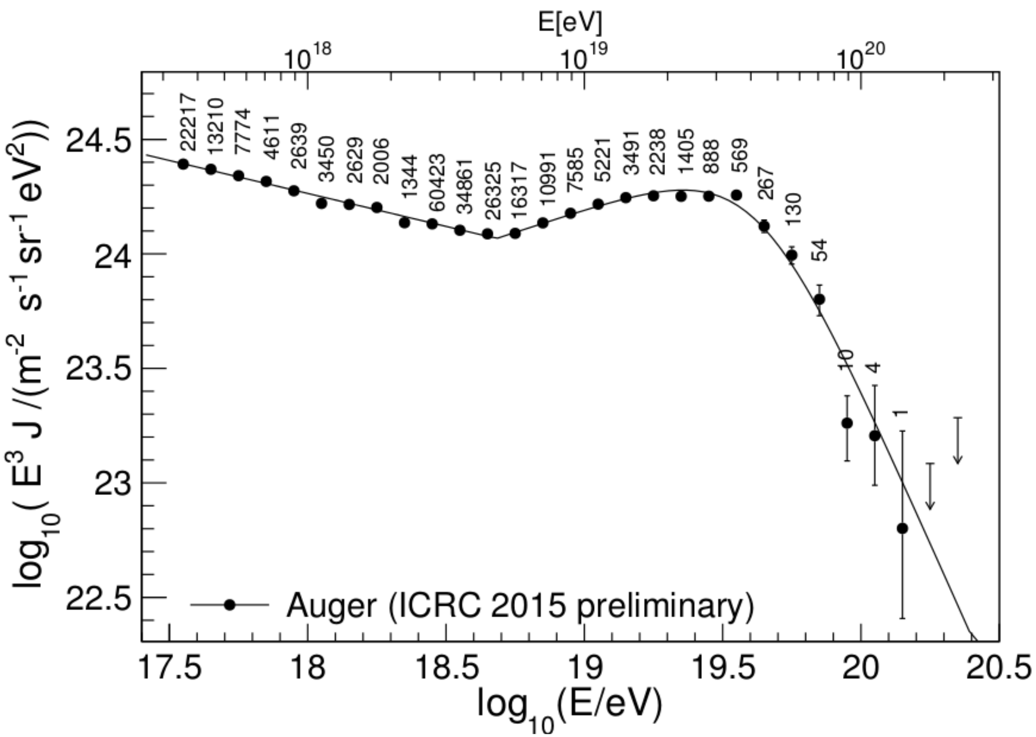
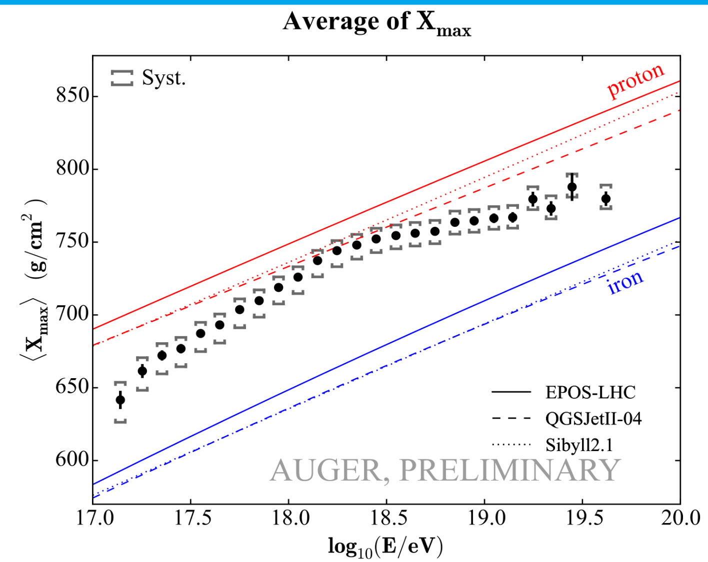
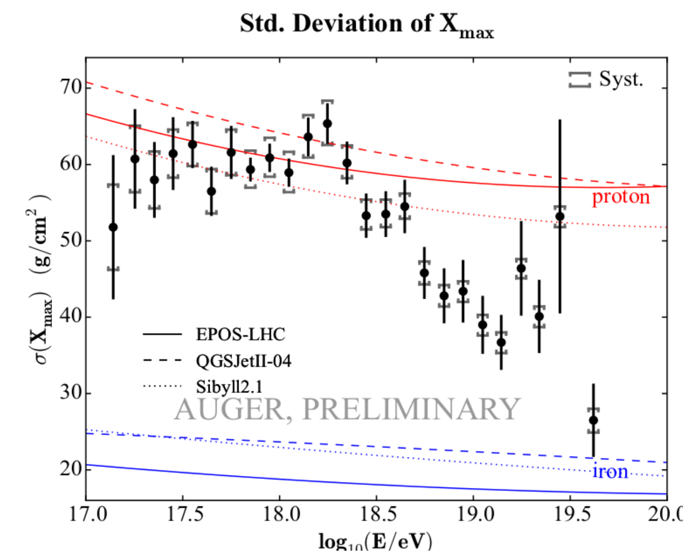
UHECR spectrum and composition



[Auger, ICRC 2015]

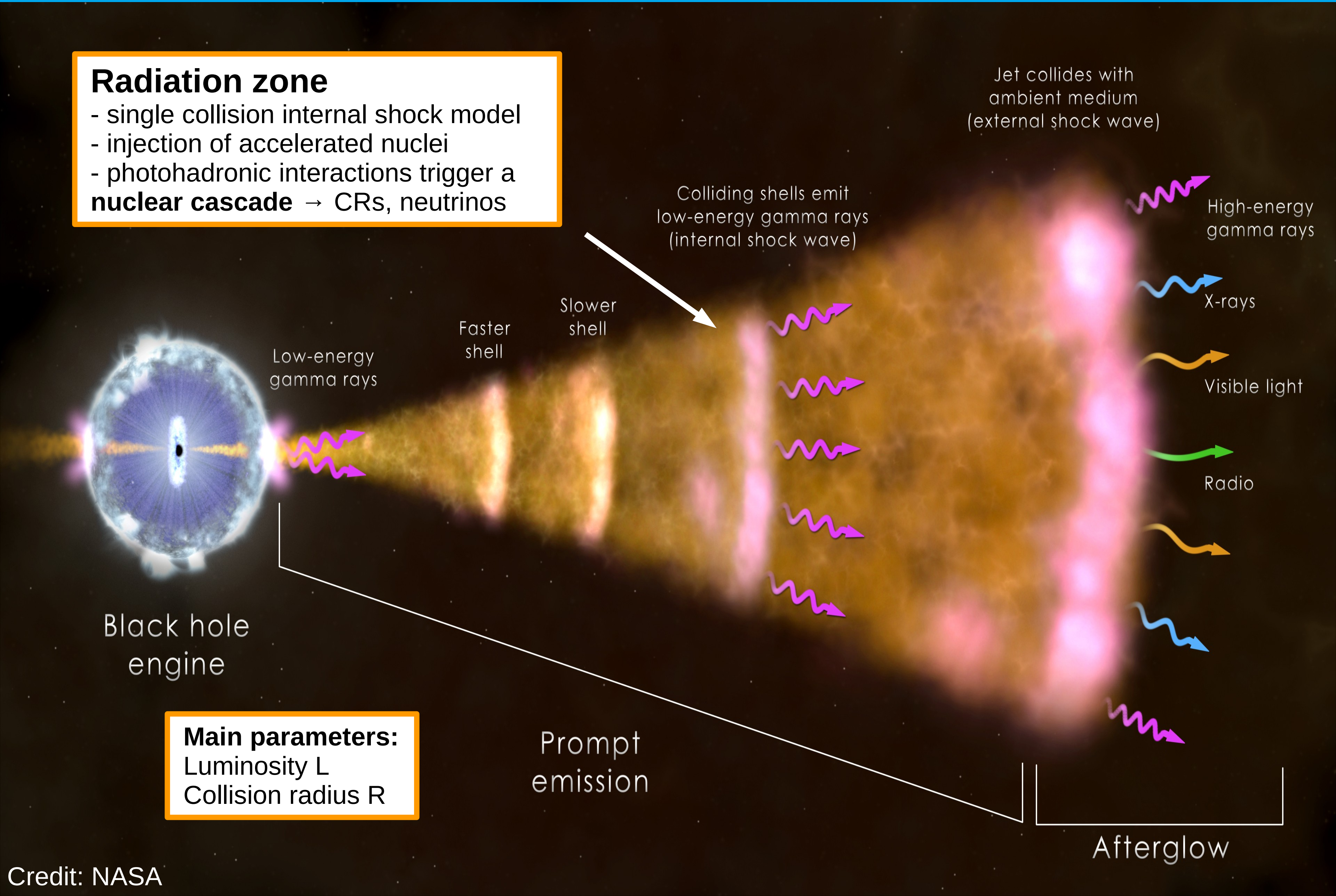




- Where do cosmic rays come from?
- What is their chemical composition?
- Can we use neutrinos to test UHECR sources?

Gamma-ray Burst phenomenology

Radiation zone
- single collision internal shock model
- injection of accelerated nuclei
- photohadronic interactions trigger a **nuclear cascade** → CRs, neutrinos

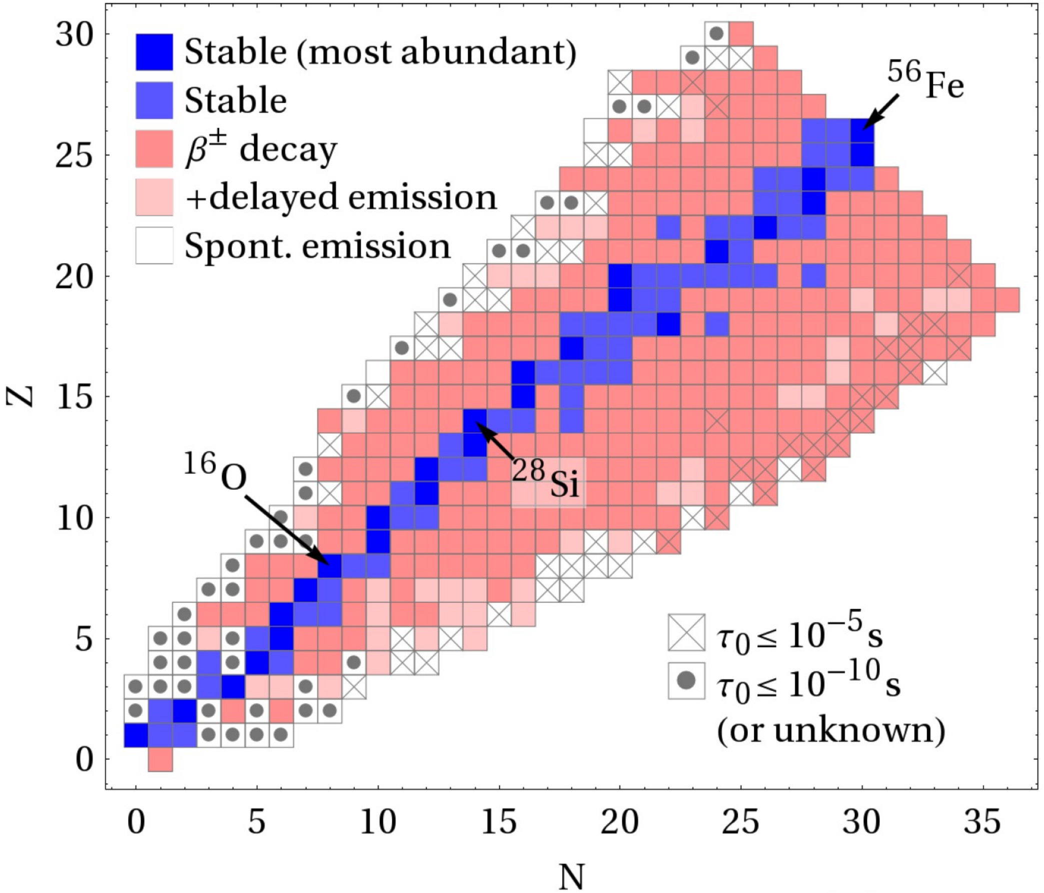


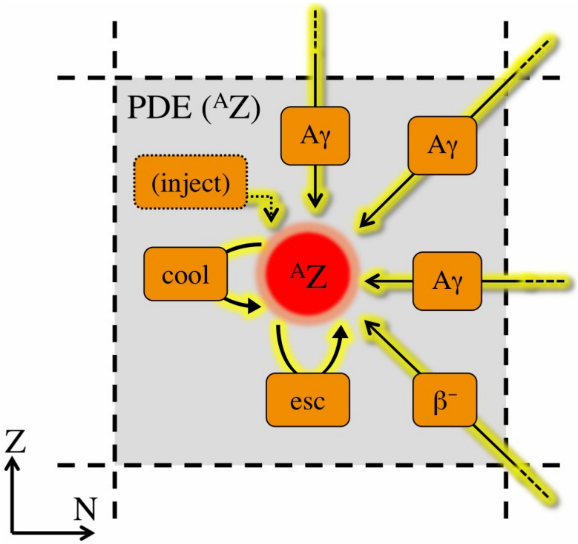
Main parameters:
Luminosity L
Collision radius R

Credit: NASA

NeuCosmA interaction model

- > **Radiation processes:**
- > Photo-meson production
- > Photo-disintegration
- > Pair-production
- > Beta decays
- > Spontaneous emission
- > Ap-/pp-collisions

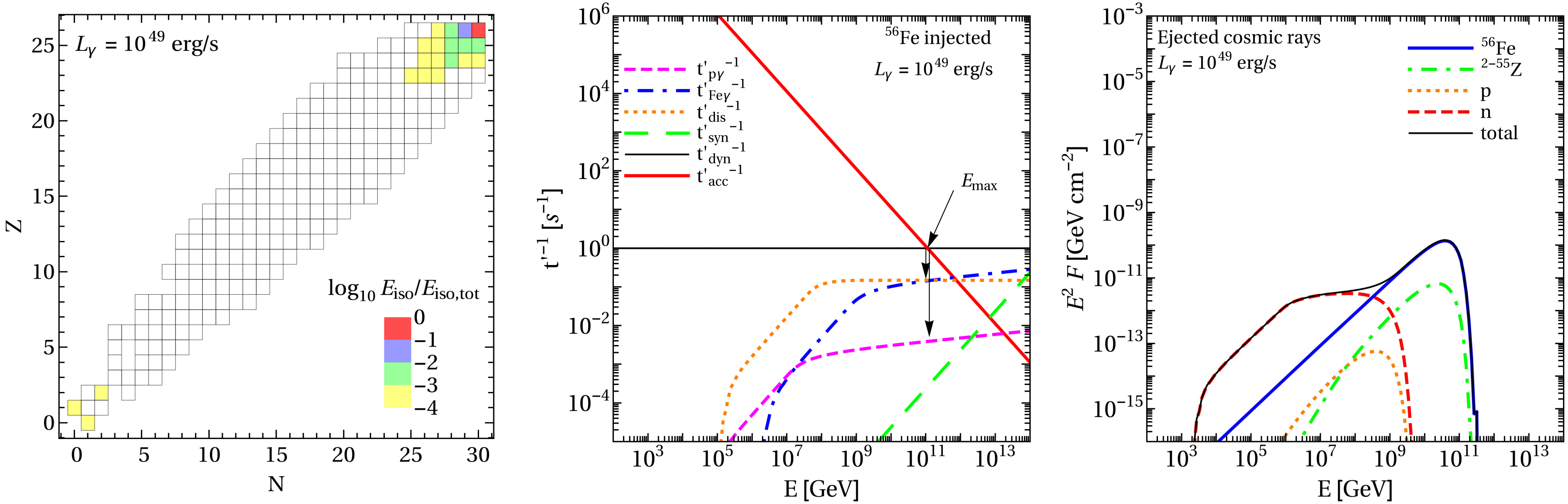




~ 500 isotopes
~ 45,000 different channels

[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

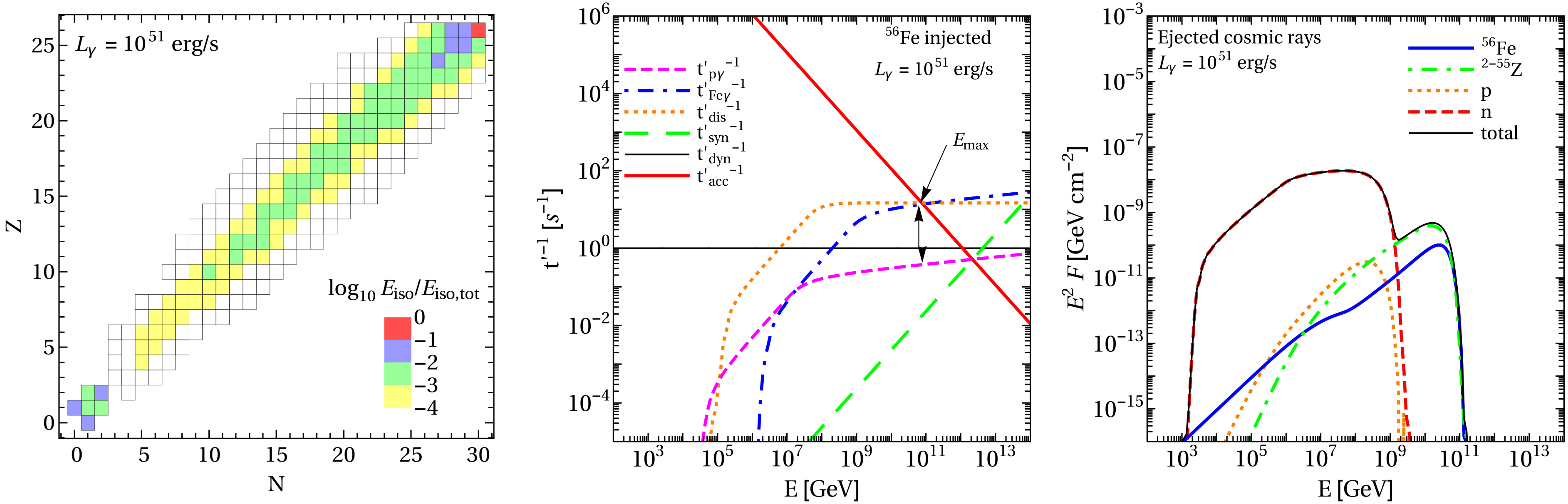
Source class I: Empty Cascade



[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

- Low target photon density
- Only a few isotopes populated relative to injected energy in primaries
- Maximum energy determined by adiabatic cooling, i.e. Peter's cycle
- Optically thin to photohadronic interactions of all species
- Nuclei stay mostly intact and escape as CR: **direct escape**

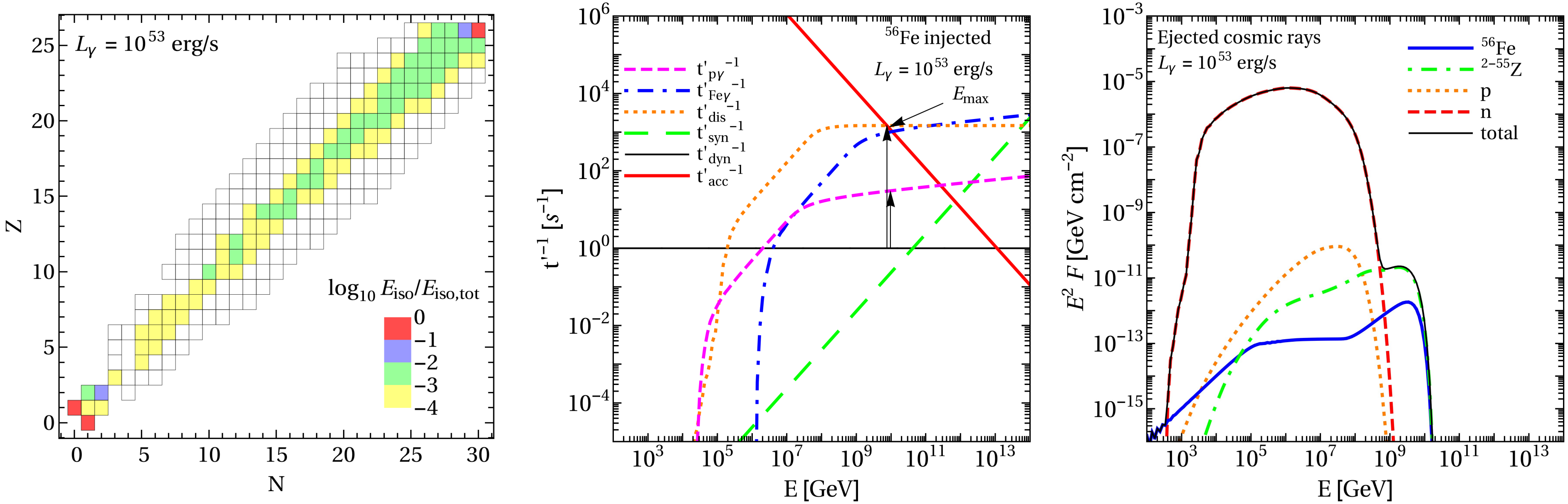
Source class II: Populated Cascade



[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

- Medium target photon density
- Cascade broadly populated along the main diagonal
- Maximum energy limited by photohadronic processes, no Peter's cycle!
- Optically thick to photohadronic interactions of heavy nuclei, still opt. thin to light nuclei
- Only a fraction of the nuclei disintegrate

Source class III: Optically Thick Case

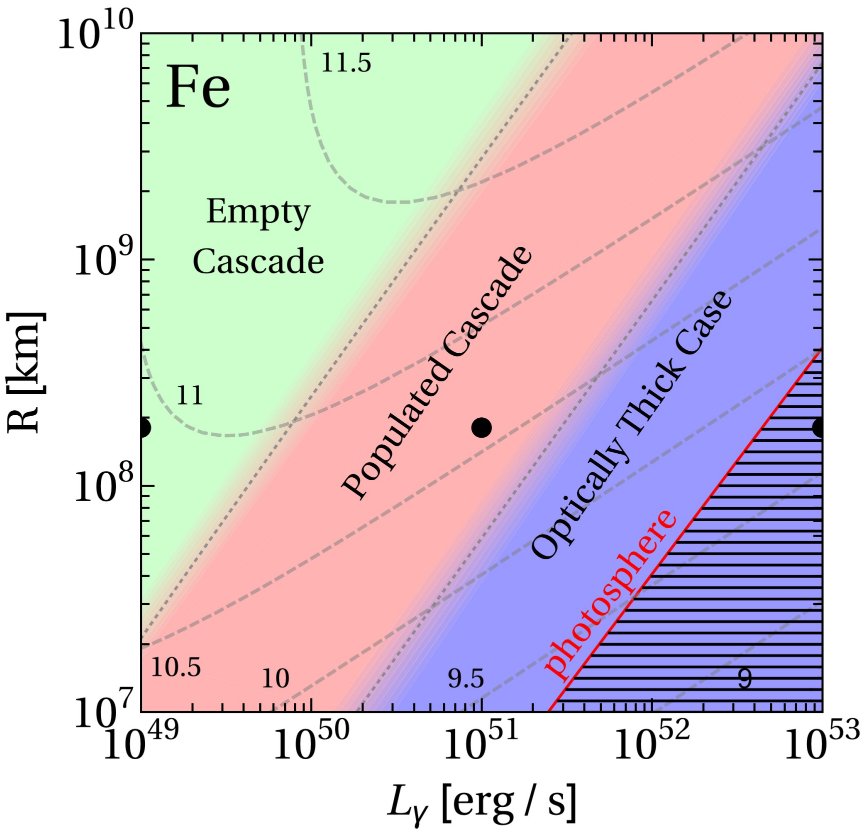


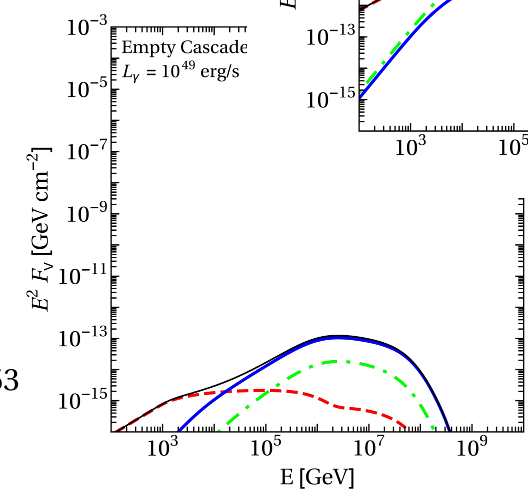
[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

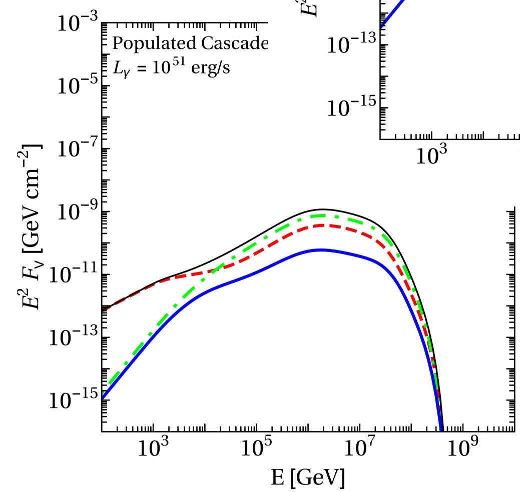
- High target photon density
- Cascade populated more narrow, most energy dumped into nucleons
- Maximum energy limited by photohadronic processes, no Peter's cycle!
- Optically thick to photohadronic interactions of all species
- Nuclei disintegrate very efficiently

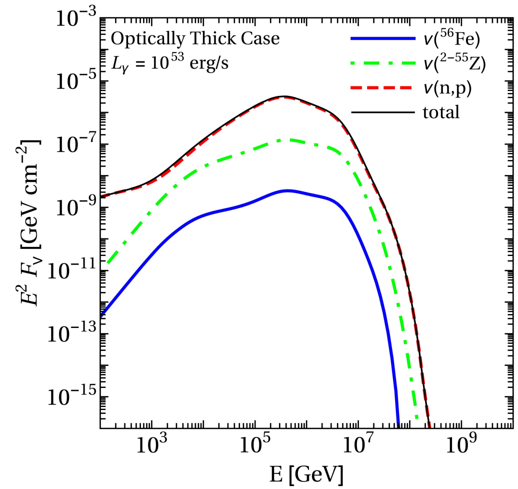
Nuclear cascade source classes: parameter space scan

- Pure iron (^{56}Fe) composition injected into a GRB shell
- Transition in optical thickness coincides with transition in neutrino production





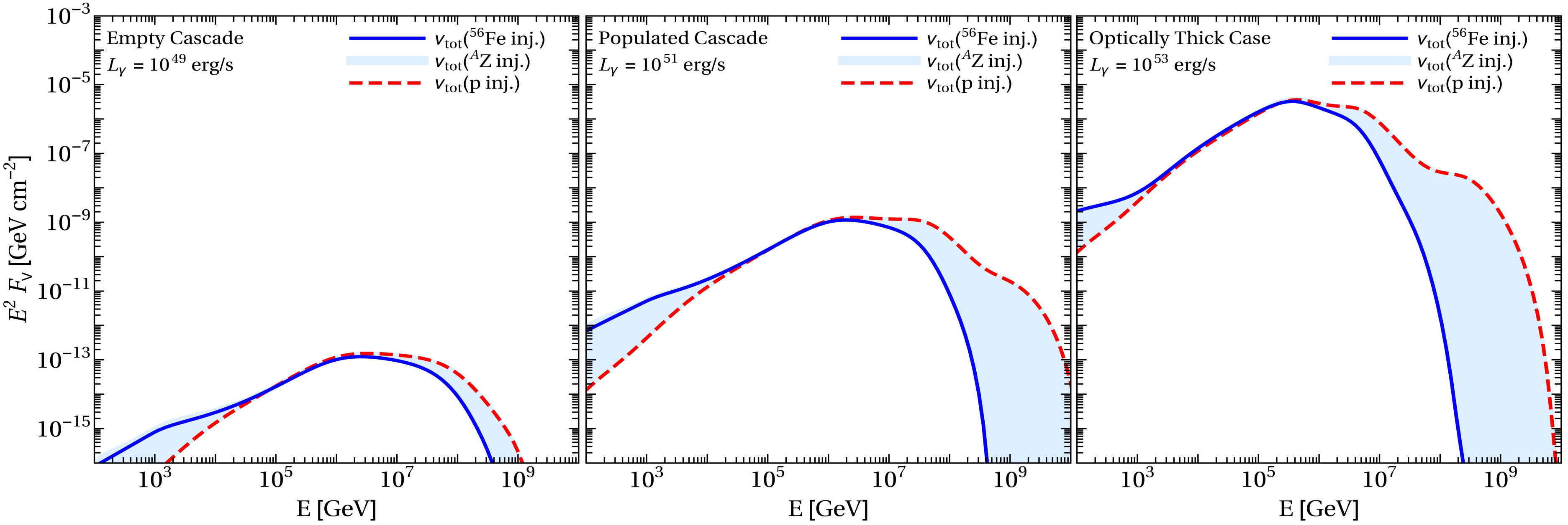




High uncertainty in cross-section of heavy isotopes!

[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

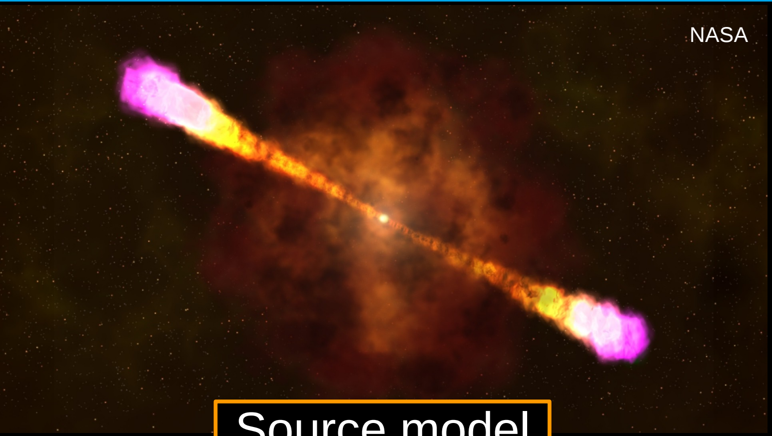
Prompt neutrinos: dependence on injection composition



[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

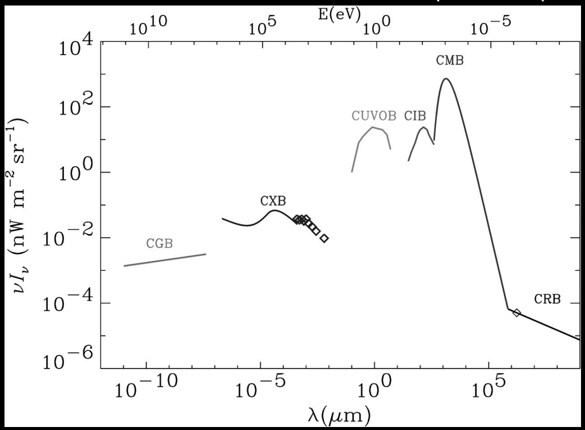
- Total all flavor neutrino fluence for arbitrary (pure) injection composition
- In energy range from ~ 10 TeV – 10 PeV weakly depending on the injected composition
- Neutrino bounds will roughly apply even if the UHECRs are nuclei

Combined source-propagation model



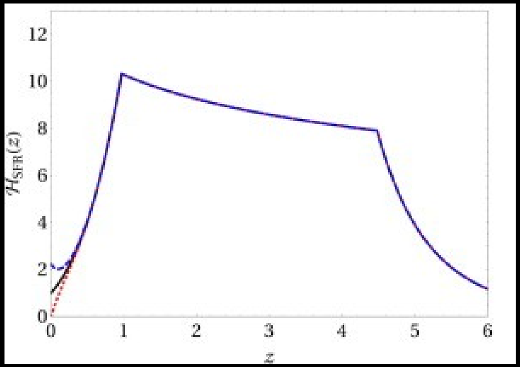
Source model

M.G. Hauser, E. Dwek, Ann. Rev. Astron. Astrop. 39, 249 (2001)

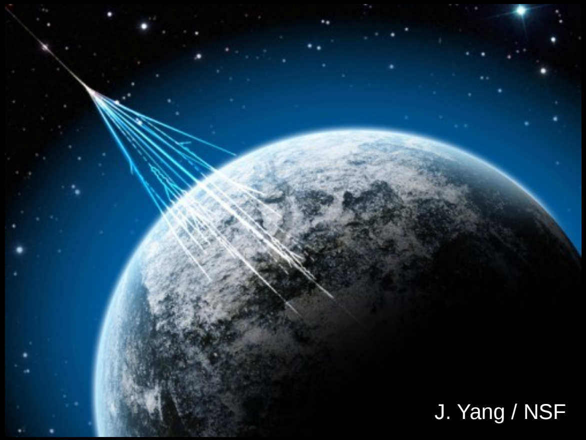


Interaction with CMB, CIB, ...

Baerwald, Bustamante, Winter, ApJ 768, 186 (2013)



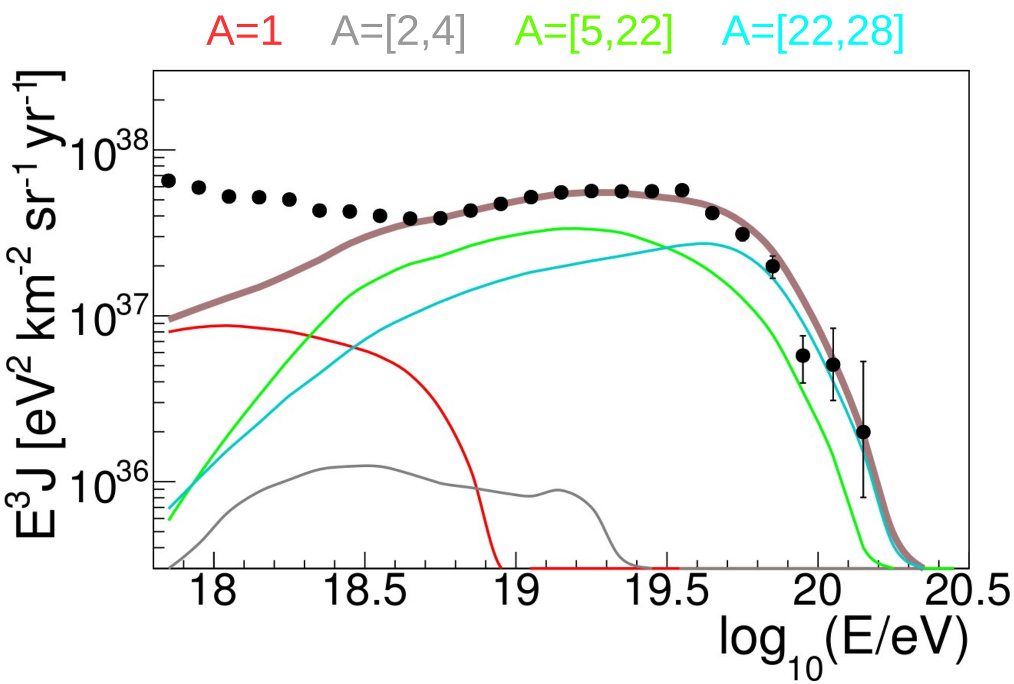
Source distribution



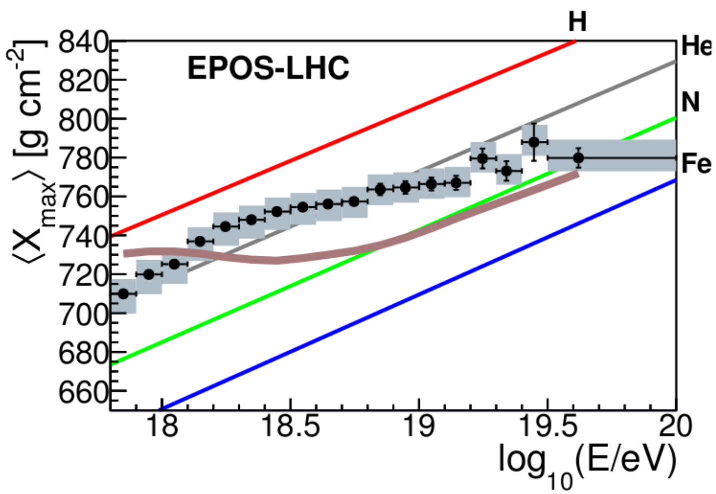
Interaction in atmosphere

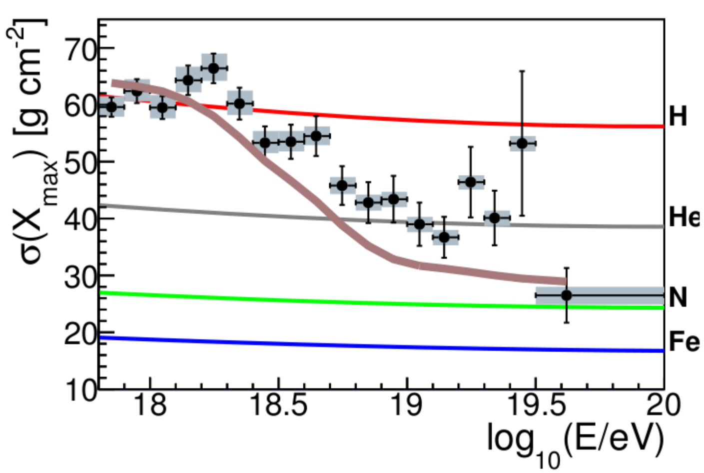
→ **UHECR spectrum & composition, neutrino fluxes**

Combined model best fit – cosmic rays



- Fit above 10^{19} eV (excluding ankle)
- Pure ^{28}Si injection at the source, $L = 10^{49}$ erg/s, $R = 10^{8.1}$ km
- Composition can be improved by a mixed injection composition





[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

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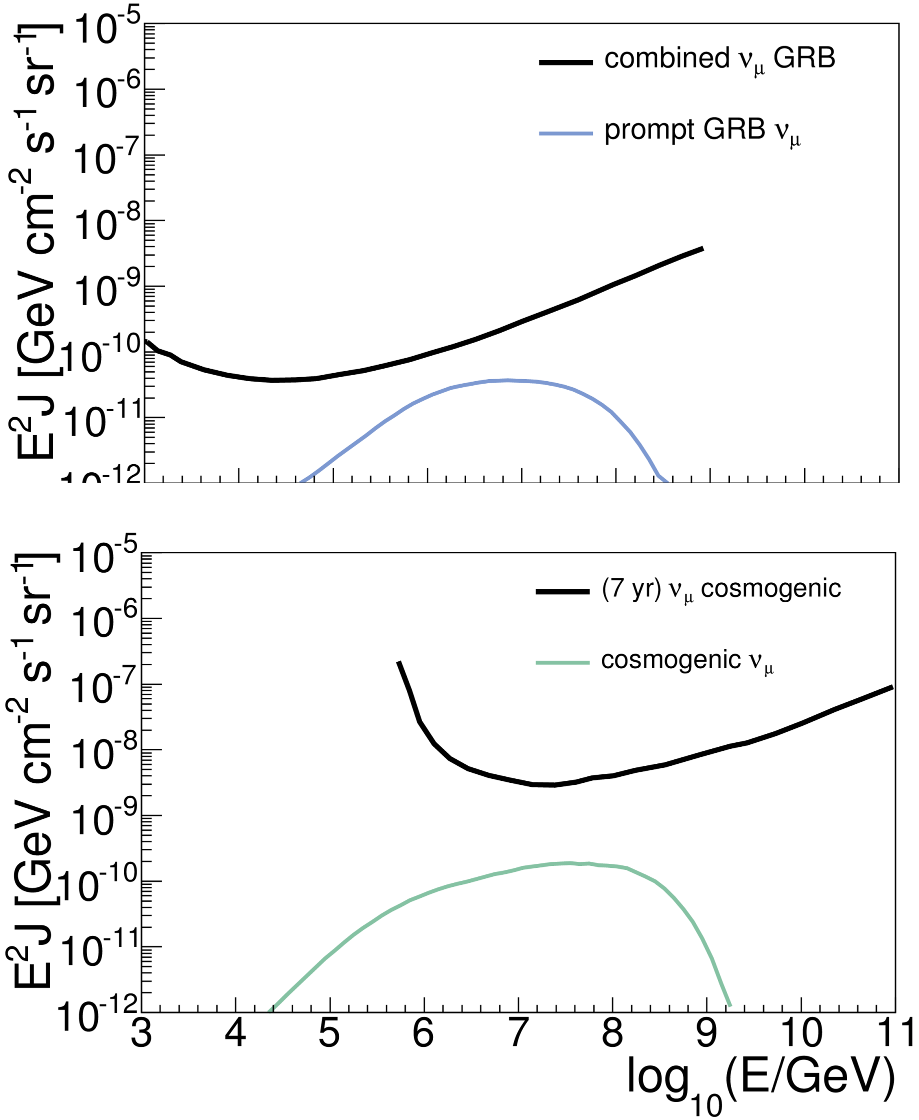
Combined model best fit – neutrinos

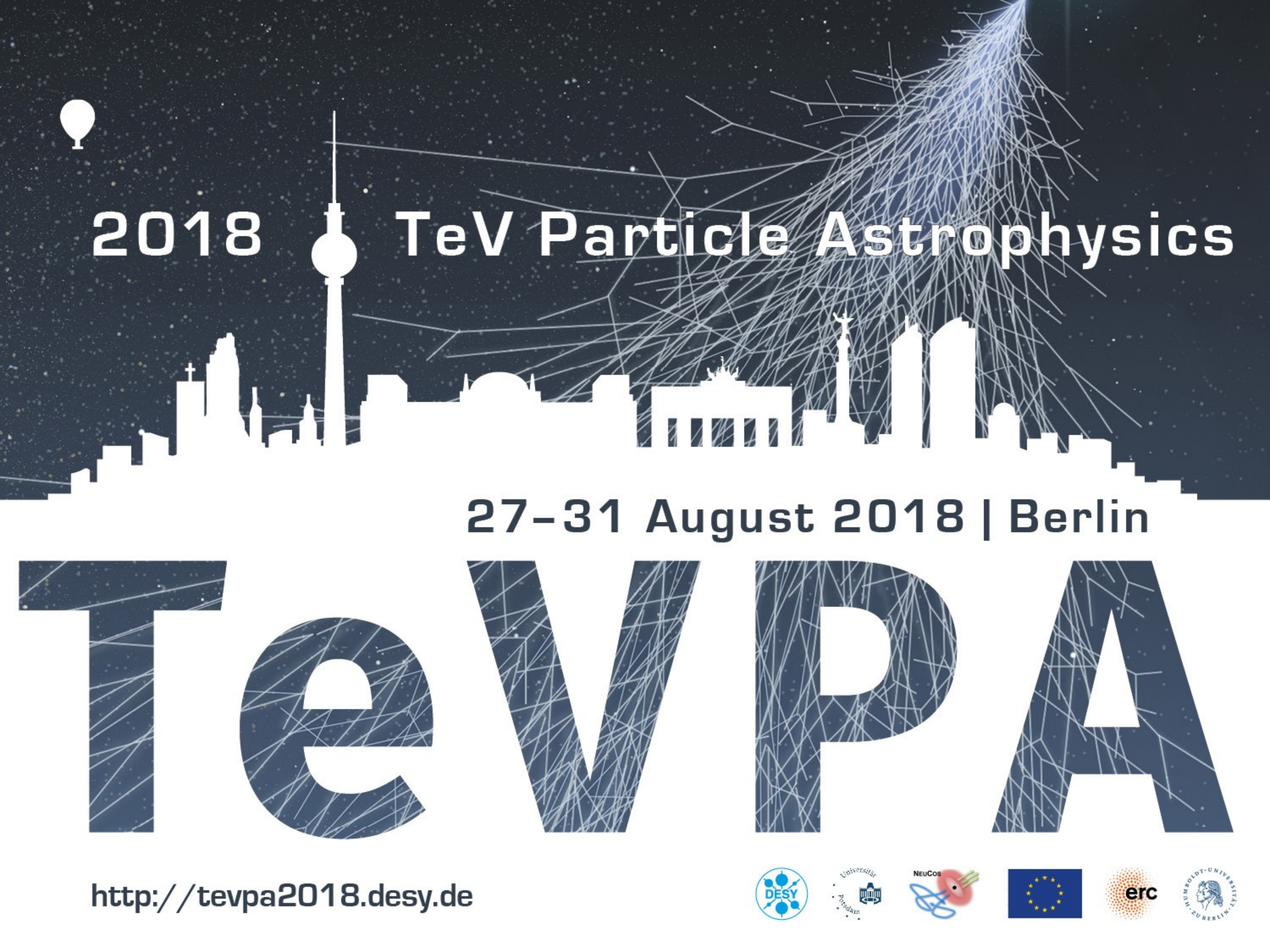


- Fit above 10^{19} eV (excluding ankle)
- Pure ^{28}Si injection at the source, L = 10^{49} erg/s, R = $10^{8.1}$ km
- Composition can be improved by a mixed injection composition
- Neutrino limits are not violated, i.e. GRBs can power both, the flux of UHECRs and neutrinos
- Prefers low gamma-ray luminosity

[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

Conclusion

- Neutrino and cosmic ray production depend on the development of the nuclear cascade – 3 different source classes:
  - Empty Cascade: source optically thin to disintegration, nuclear cascade cannot develop, primaries dominate CR and neutrino production, Peter's cycle!
  - Populated Cascade: primaries disintegrate, nuclear cascade populated, neutrino produced mainly by secondaries in disintegration chain, no Peter's cycle!
  - Optically Thick Case: all isotopes disintegrate efficiently, nuclear cascade dumped into nucleons, nucleons dominate CR escape and neutrino production
- All flavor neutrino flux depending on characteristics of the source rather than on the injected mass number (for pure composition)
  - Neutrino bounds will roughly apply even if UHECRs are nuclei!
- Ejected fluxes of cosmic rays and neutrinos are propagated to Earth, including a fit of UHECR data
  - Prompt neutrinos efficiently test the GRB-UHECR paradigm!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BACKUP

NeuCosmA interaction model

> Temporal evolution of density of particle species i:

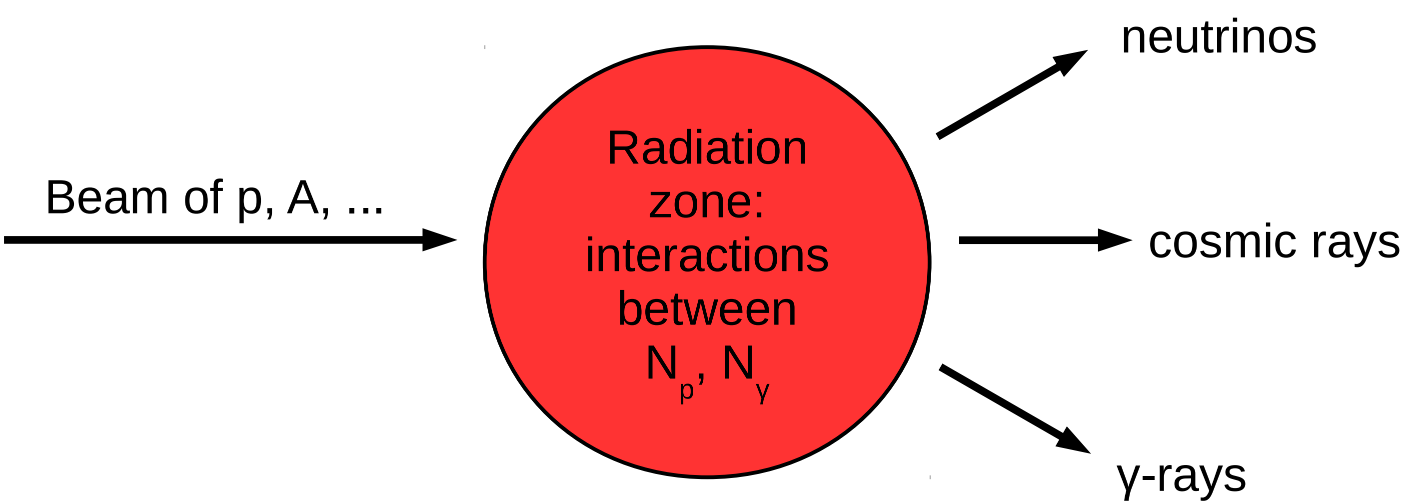
$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E) N_i(E)\right) - \frac{N_i(E)}{t_{\mathrm{esc}}} + Q(E)$$

Cooling/acceleration: synchrotron, adiabatic, ...

Escape: direct, decay, interactions

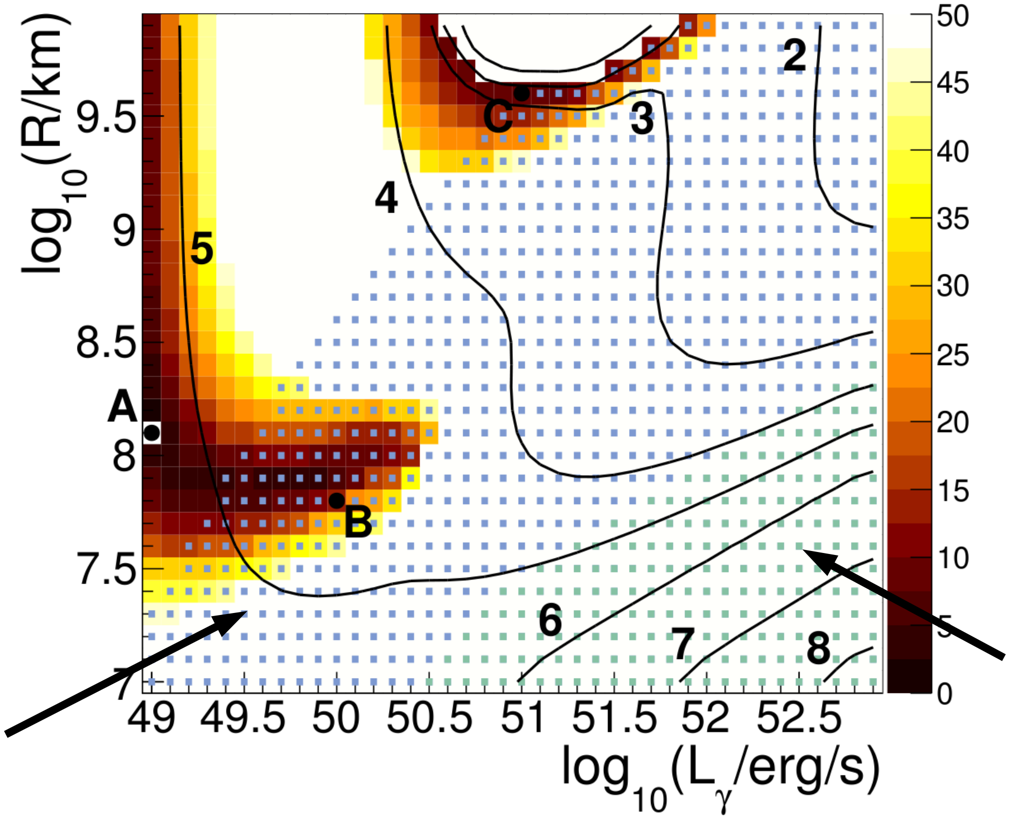
Injection: accel., other species

$$Q(E) = Q_i(E) + Q_{ji}(E)$$



Mixed composition ankle model – fit in phase space

> Fit of UHECR data above 10^{19} eV (excluding the ankle)



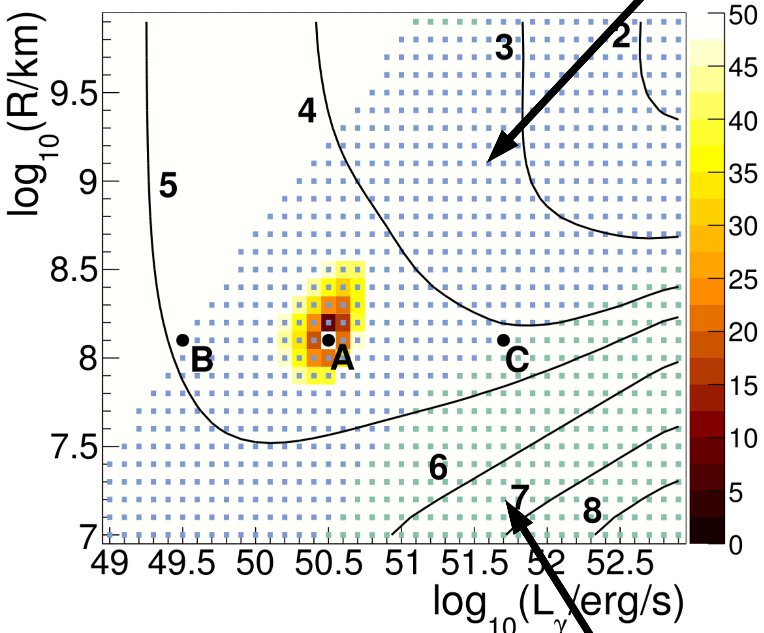
IceCube excluded region from GRB stacking analysis, Aartsen et al 2017

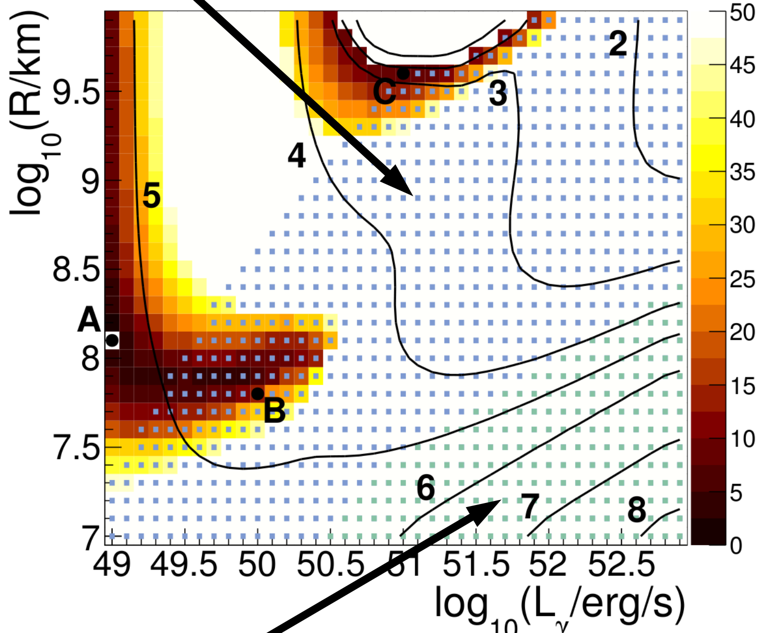
IceCube excluded region from cosmogenic neutrinos, Aartsen et al 2016

[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

Mixed composition dip vs. ankle model

IceCube excluded region
from GRB stacking analysis,
Aartsen et al 2017





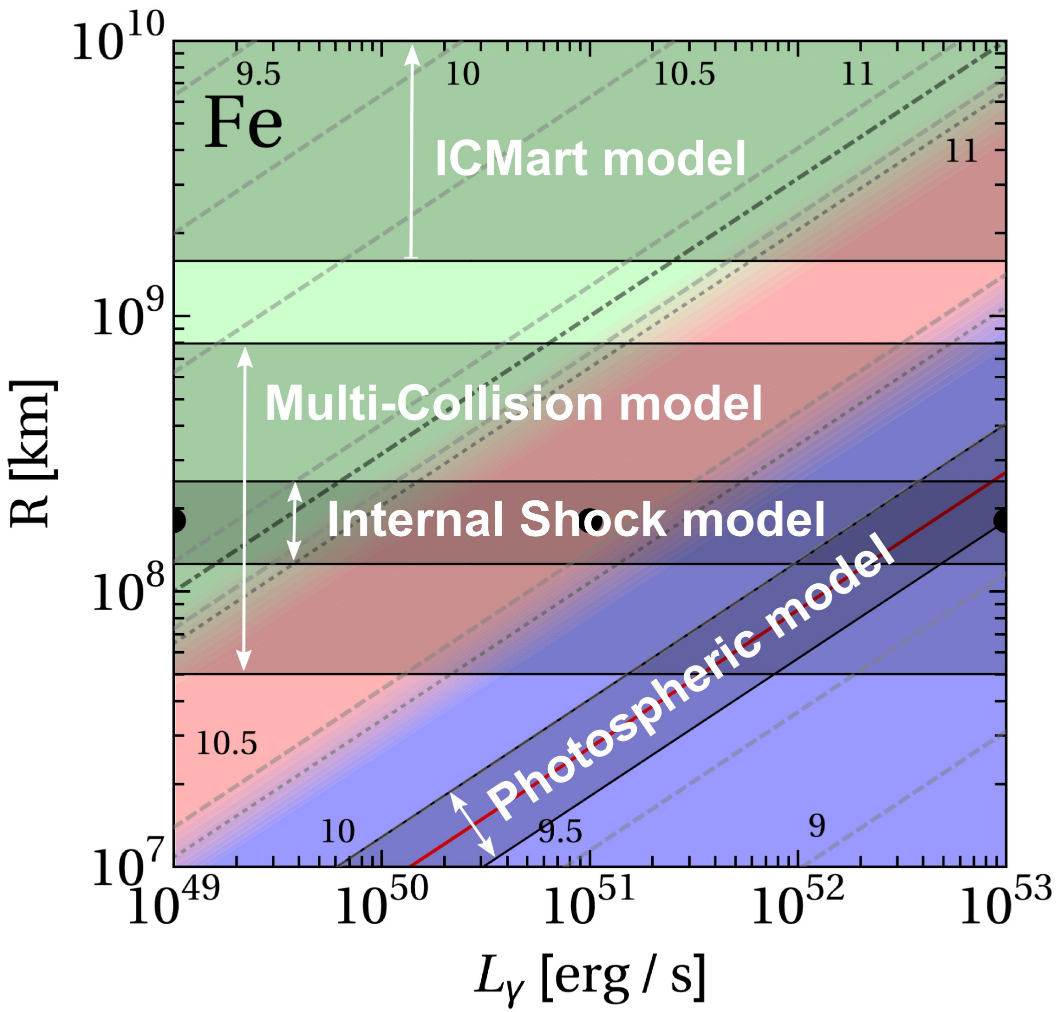
Fit of UHECR data above 10^{18} eV → including ankle

IceCube excluded region
from cosmogenic neutrinos,
Aartsen et al 2016

Fit of UHECR data above 10^{19} eV → excluding ankle

[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]

Nuclear cascade source classes: model dependency



- Fixed variability time t, R is the control parameter
- Internal shock model geometry omitted, only valid in shaded area
- Maximal energy and interaction rate scale in the same way
- No qualitative changes when moving parallel to the maximal energy contours
- Prototypes can be “translated” into other models where a similar behaviour is expected

[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909, submitted to A&A]