Tidal Disruption of Stars

as a possible origin of ultra-high energy cosmic ray and neutrinos

Credit: CXC/M. Weiss

[DB, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

Daniel Biehl
TeVPA 2018
August 28, 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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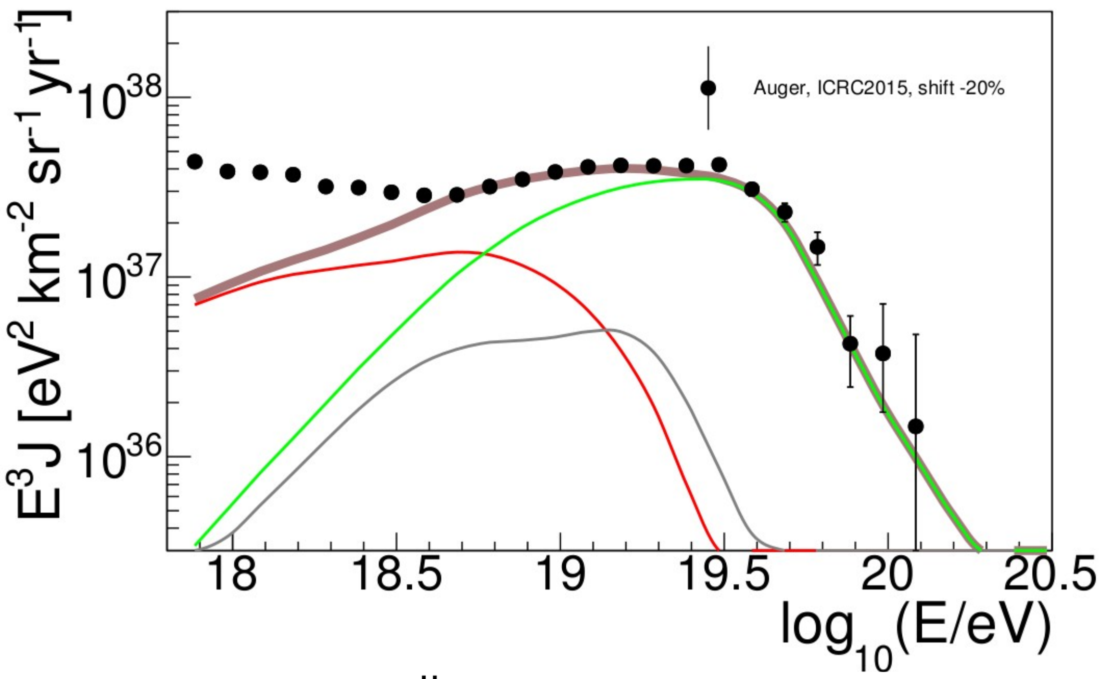
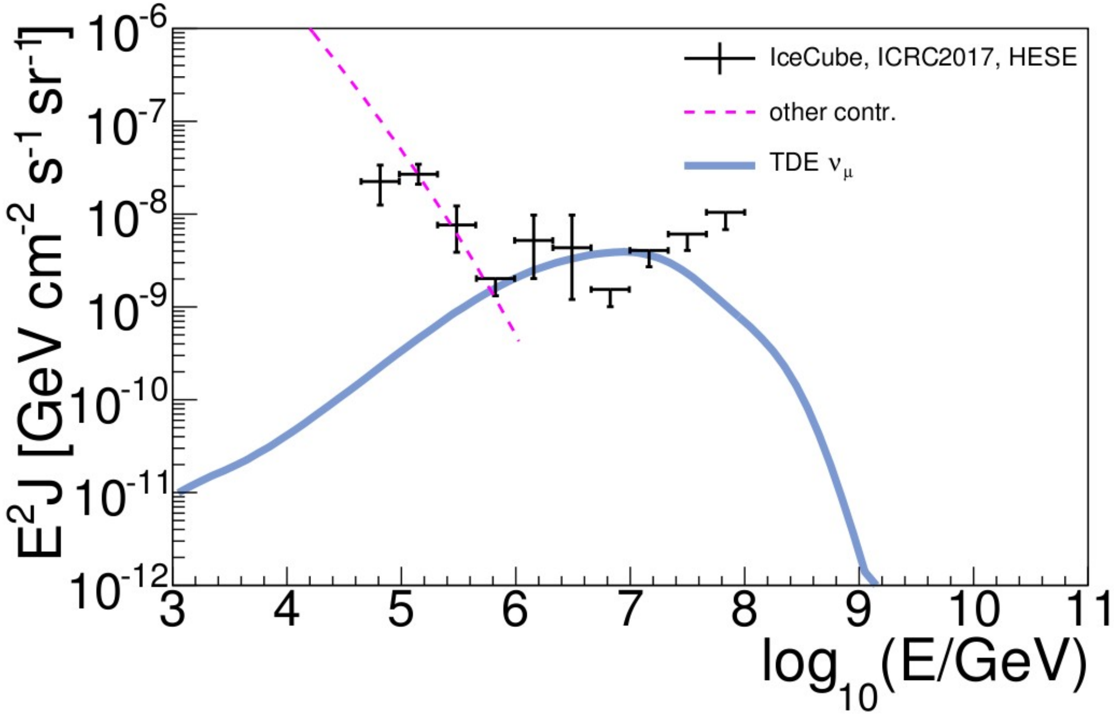
NEUCOS

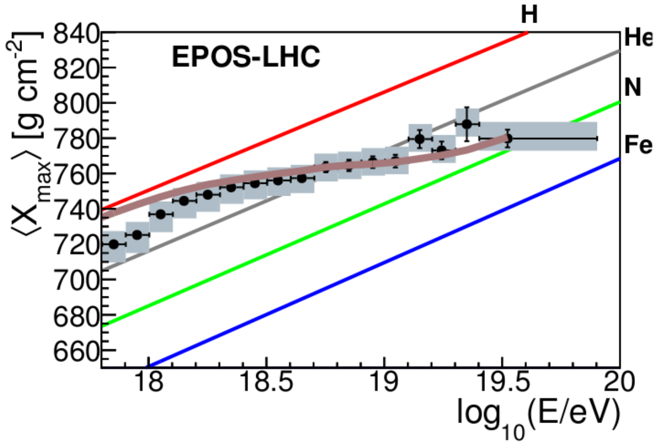
DESY

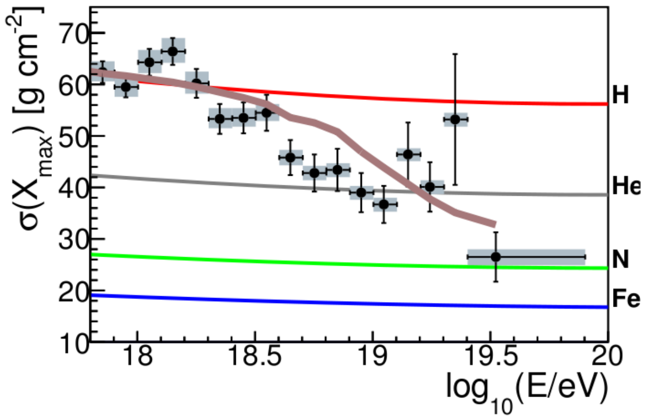
Simultaneous fit of UHECR data and PeV neutrinos

A complete, self-consistent multi-messenger picture for tidal disruption events









We can describe the UHECRs and PeV neutrinos simultaneously in a combined source-propagation model!

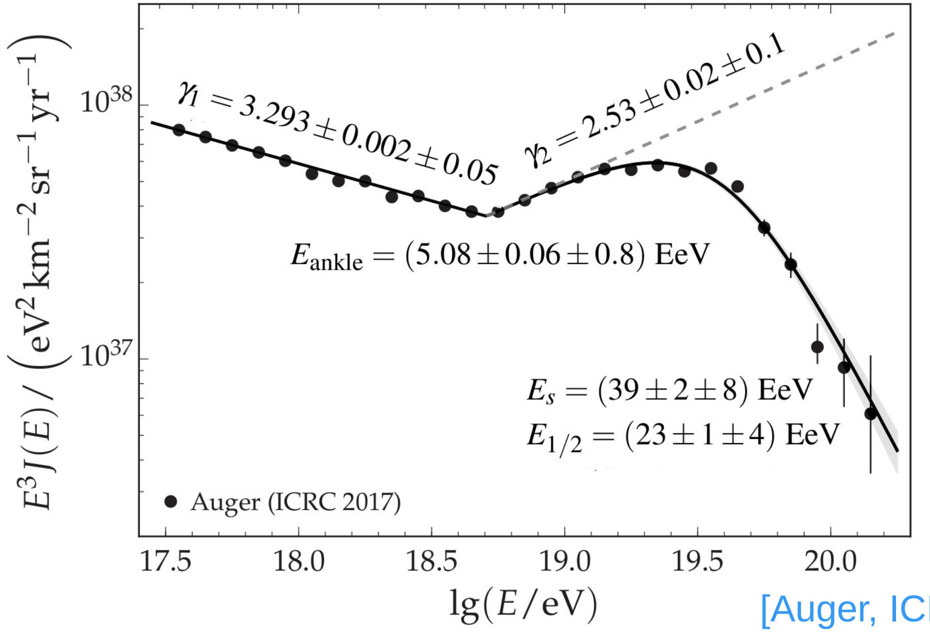
[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

Origin of ultra-high energy cosmic rays

Spectrum and composition as measured by Auger

Facts

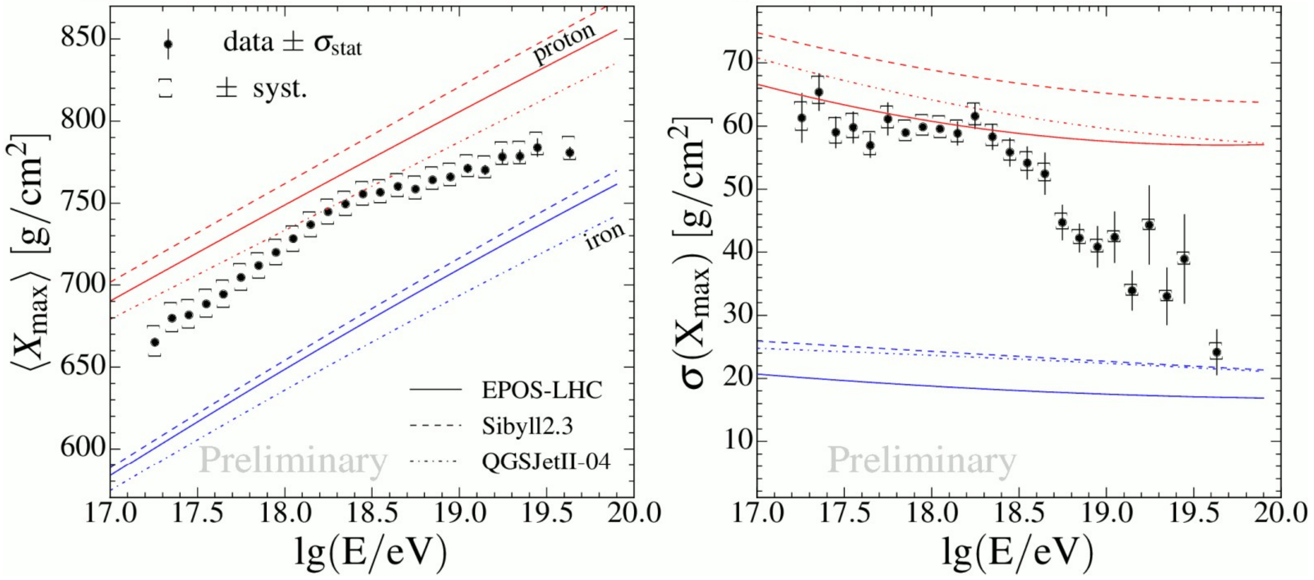
- Ultra-high energy range: E > 10^{18} eV
- Presumably of extra-galactic origin
- Change of slope (ankle) at ~ $10^{18.7}$ eV
- Suppression at ~ $10^{19.5}$ eV
- Composition tends to get heavier at the highest energies
- Energy budget to power the UHECRs ~ 10^{44} erg Mpc^{-3} yr^{-1}



[Auger, ICRC 2017]

Questions

- What are the sources of the UHECRs?
- What is their chemical composition?
- What is the connection to different messengers, such as neutrinos, gamma-rays, gravitational waves?



Neutrinos as by-products of UHECRs

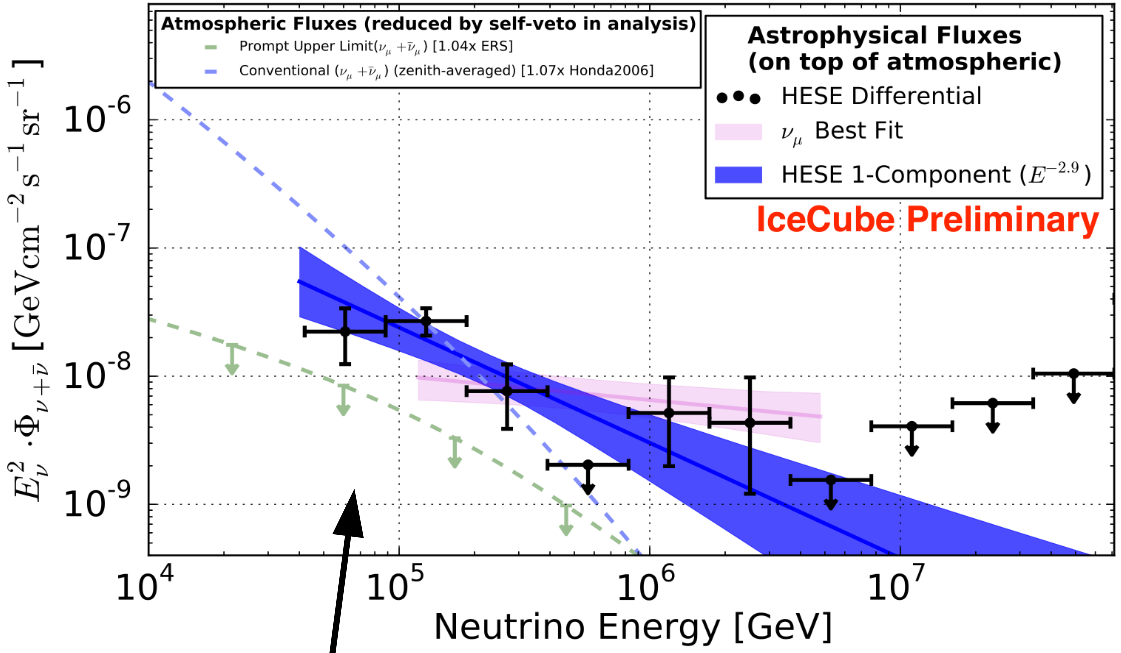
Hadronic processes and estimated spectrum

PeV neutrinos from cosmic accelerators

- Δ-resonance and subsequent pion decay

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

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



[IceCube, ICRC 2017]

- Neutrinos take ~ 5% of primary energy, i.e. highest energy neutrinos E ~ few PeV require primary energies E ~ 100 PeV

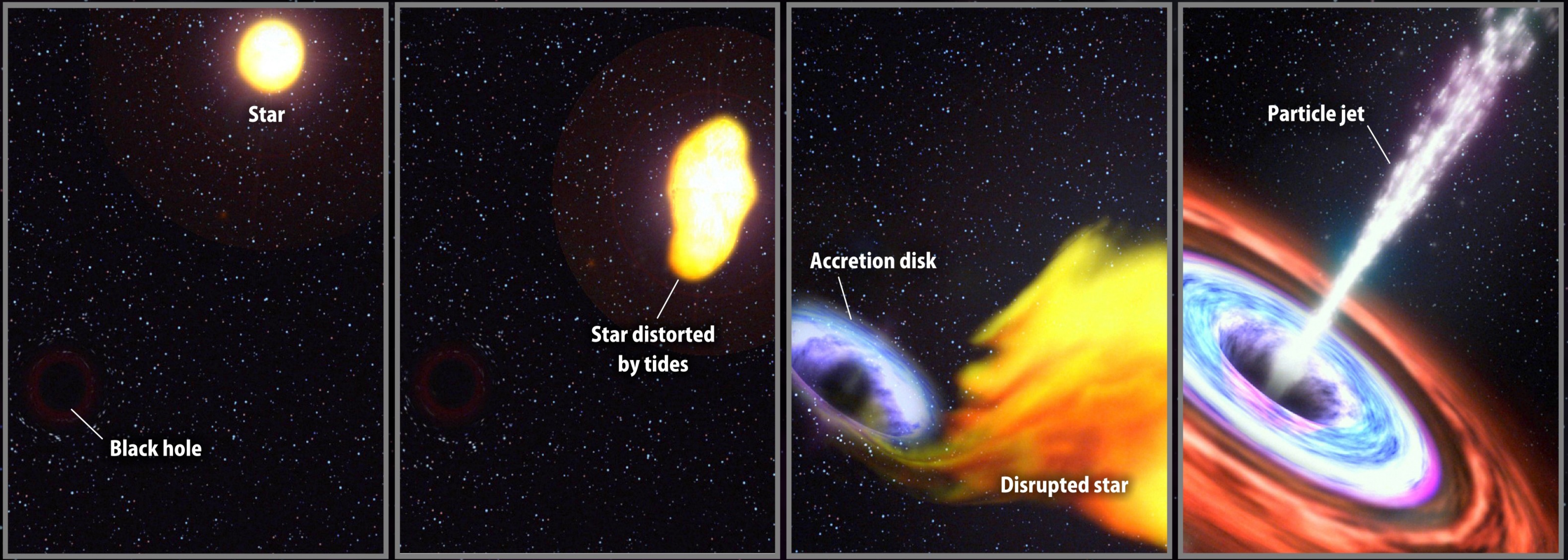
$$E_\nu^2 \phi_\nu \sim (1/4) f_{p\gamma} E_p^2 (dN_p^{\mathrm{iso}}/dE_p)$$

Sub-PeV neutrinos could come from other component, not yet statistically evident!

- Lack of point sources indicates dim, abundant sources
  → High-energy events from rare Aγ / pγ sources

[M. Ahlers, F. Halzen (2014)]
[M. Kowalski (2014)]

Swift J1644+57: Onset of a relativistic jet



1. A sun-like star on an eccentric orbit plunges toward the supermassive black hole in the heart of a distant galaxy.

2. Strong tidal forces near the black hole increasingly distort the star. If the star passes too close, it is ripped apart.

3. The part of the star facing the black hole streams toward it and forms an accretion disk. The remainder of the star just expands into space.

4. Near the black hole, magnetic fields power a narrow jet of particles moving near the speed of light. Viewed head-on, the jet is a brilliant X-ray and radio source.

Credit: NASA/Goddard Space Flight Center/Swift

Development of the nuclear cascade

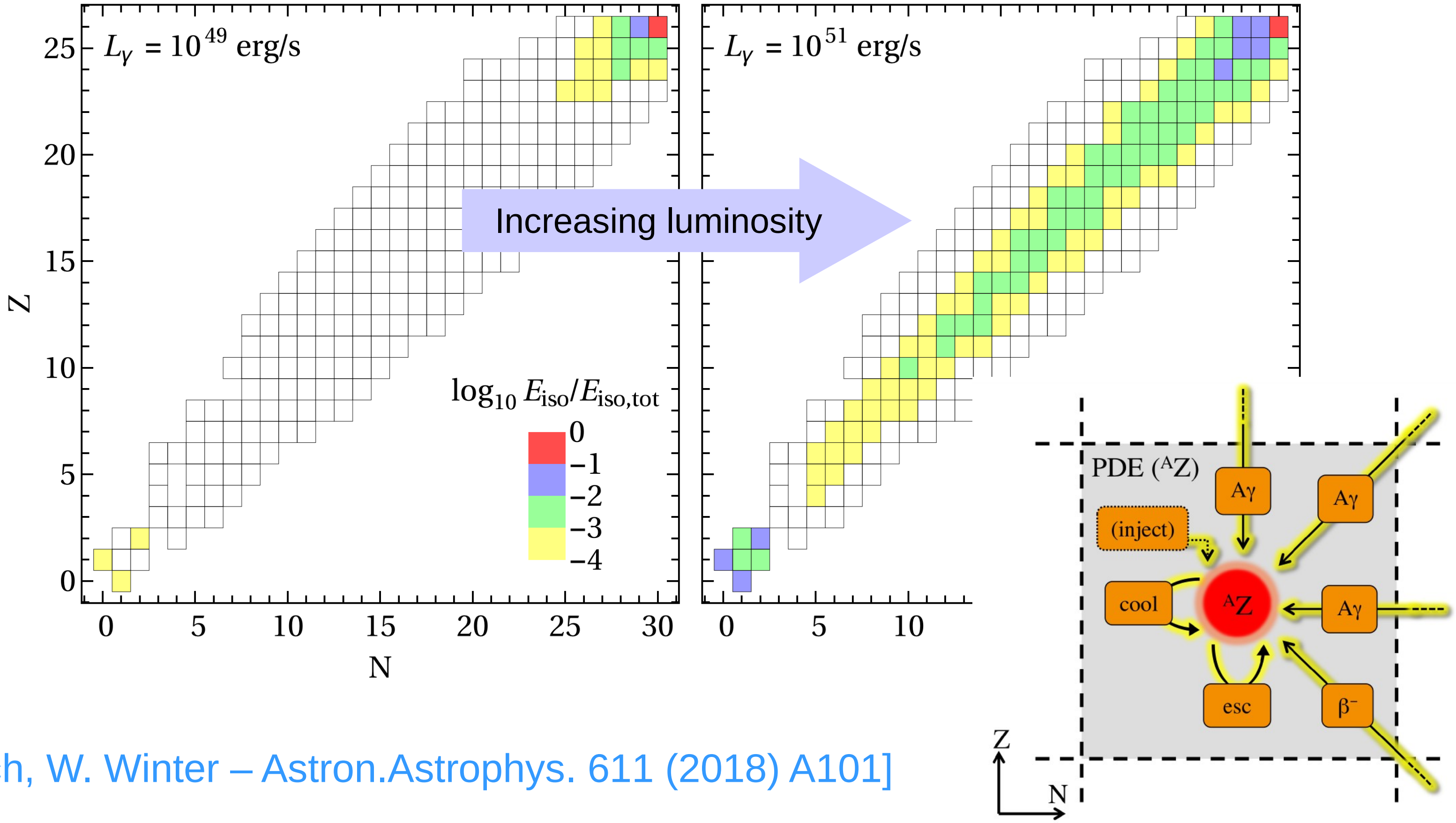
A qualitative and quantitative representation of interactions

$$\frac{\partial N_i'}{\partial t} = \frac{\partial}{\partial E'}\left(-b'(E')N_i'(E')\right) - \frac{N_i'(E')}{t'_{\mathrm{esc}}} + \tilde{Q}'_{ji}(E)$$

Triggering the nuclear cascade

- Solve coupled partial differential equation including all interactions, energy losses, escape, injection, feedback, ...
- Example: pure iron injected in a GRB shell, different luminosities
- Up to ~ 500 different particle species with up to ~ 45,000 competing channels
- Development of the nuclear cascade and neutrino production efficiency scales with the photon density

→ **Production radius R and luminosity L are the main control parameters for the nuclear cascade and neutrino production**



[D. Biehl, D. Boncioli, A. Fedynitch, W. Winter – Astron.Astrophys. 611 (2018) A101]

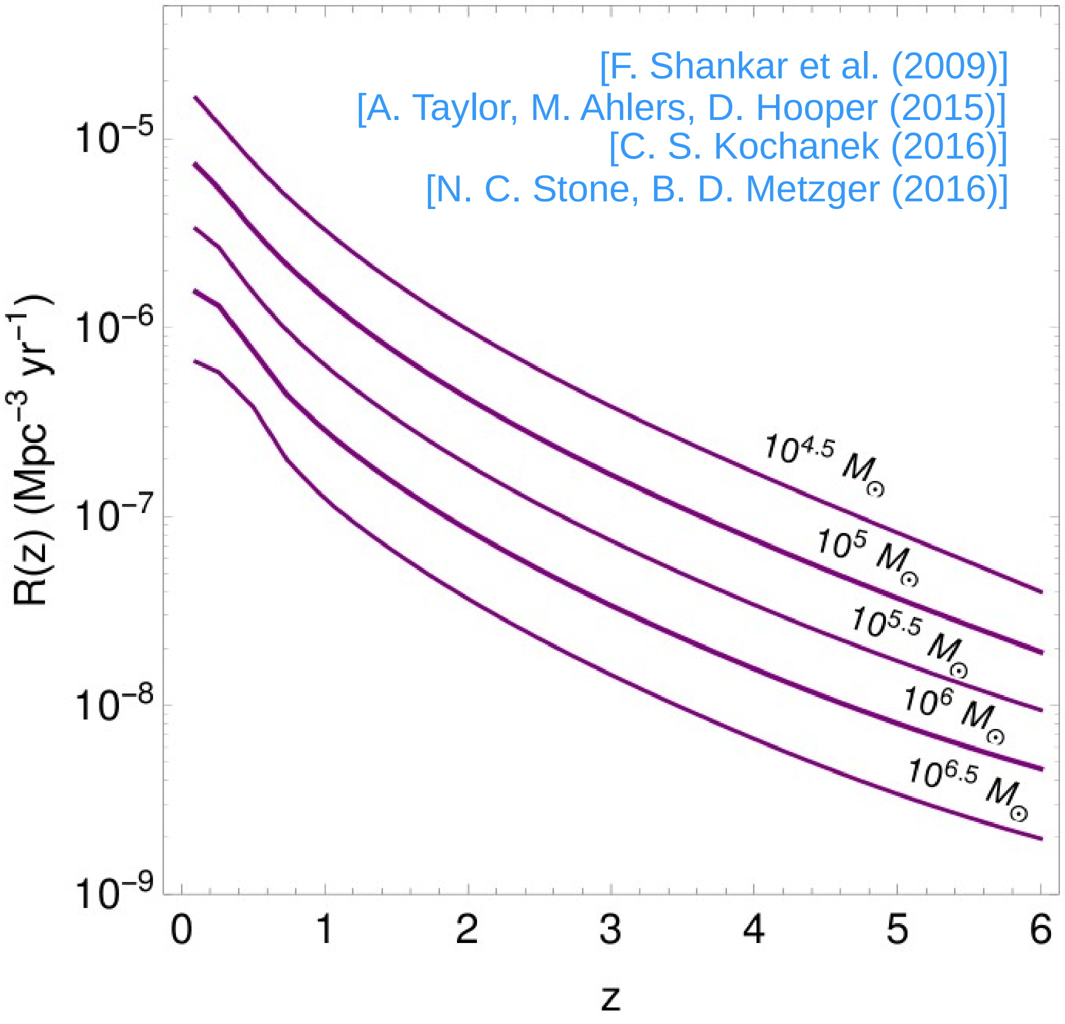
Population model in a nutshell

Cosmological rate of TDEs

$$\dot{\rho}(z, M) = \dot{N}_{\mathrm{TD}}(M) f_{\mathrm{occ}}(M) \phi(z, M)$$

Negative source evolution

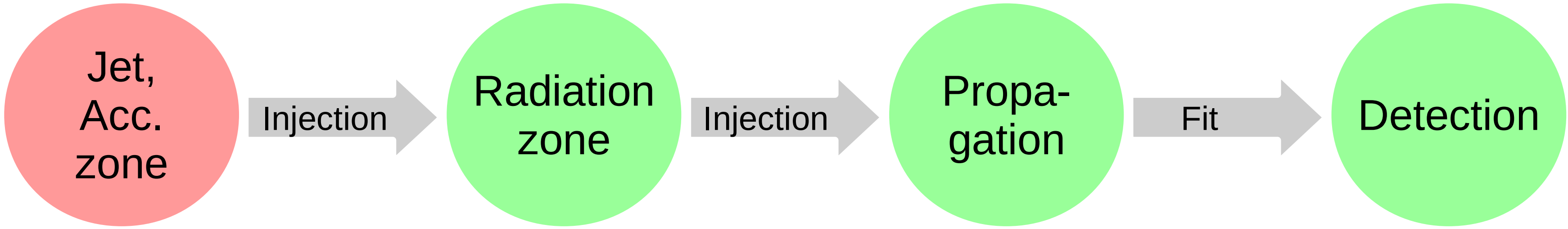
- Follows mainly black hole mass function Φ(z,M)
  - declines with z roughly as $(1+z)^{-3}$
- Rate of observable jetted TDEs suppressed by $\eta/(2\Gamma^2) \sim 5 \times 10^{-4}$ → rougly around ~ 0.1 – 10 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Same luminosity in cosmologically co-moving frame
- Close sources dominate, i.e. less cosmogenic neutrinos and diffuse gamma-ray photons, heavier composition



[C. Lunardini, W. Winter, PRD 95, 123001 (2017)]

Connecting the components of our model

Towards a complete picture



Power law spectrum up to max. energy

Efficient calculation of the nuclear processes

Interactions with CMB, CIB, ...
[R. Aloisio et al., JCAP (2012)]

Fit to Auger data, IceCube PeV data

Going beyond the state-of-the-art with NeuCosmA

- Consistent description of neutrino **and** UHECR production in internal shocks of TDE jets
- Efficient computation of nuclear processes in the source, where photo-disintegration of nuclei cannot be neglected
- Interface to UHECR propagation for taking into account source evolution, interactions with atmosphere, CMB, CIB, ...
- Fit to spectrum and composition measured by Auger, compatibility check with PeV neutrino data by IceCube
- Systematic parameter space study unveiling the potential of TDEs being the sources of UHECRs **and** PeV neutrinos

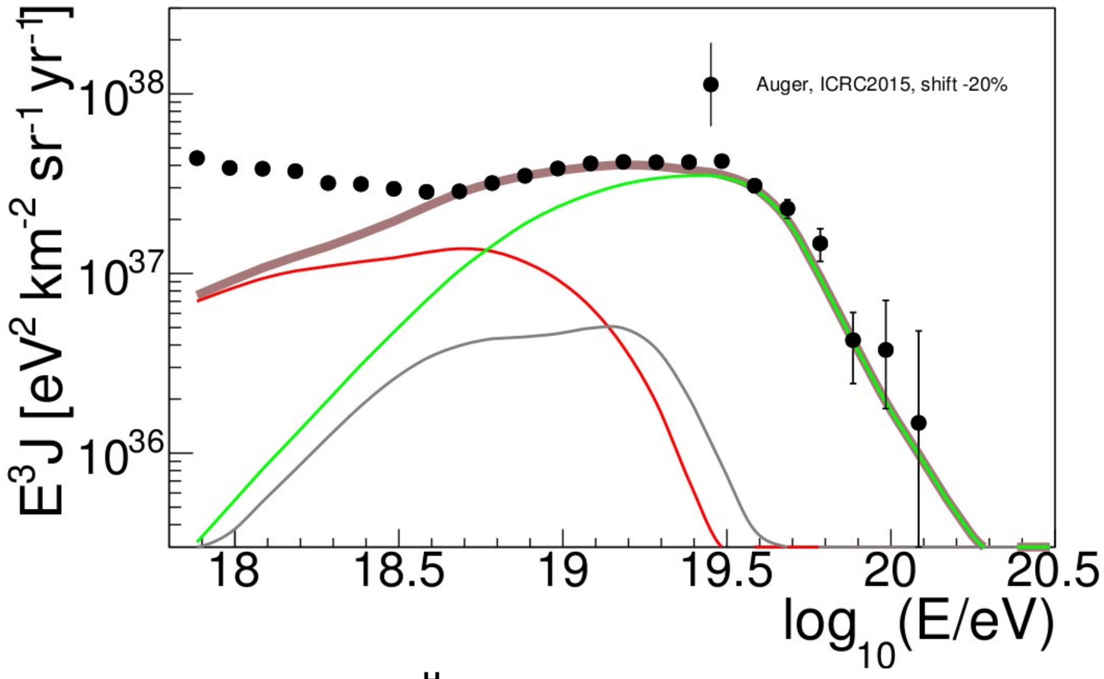
Fitting UHECR spectrum and composition

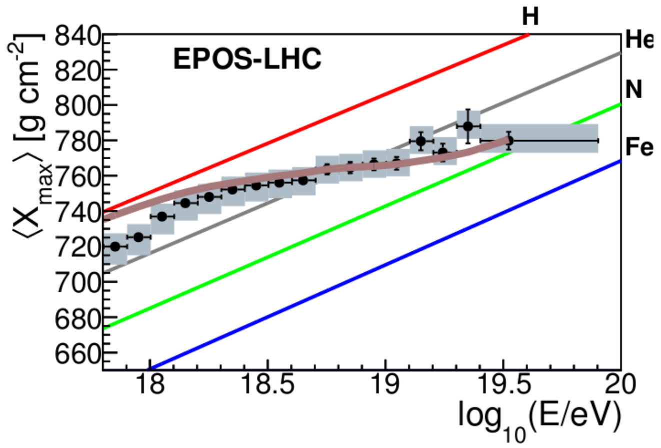
Matching the observations by Auger

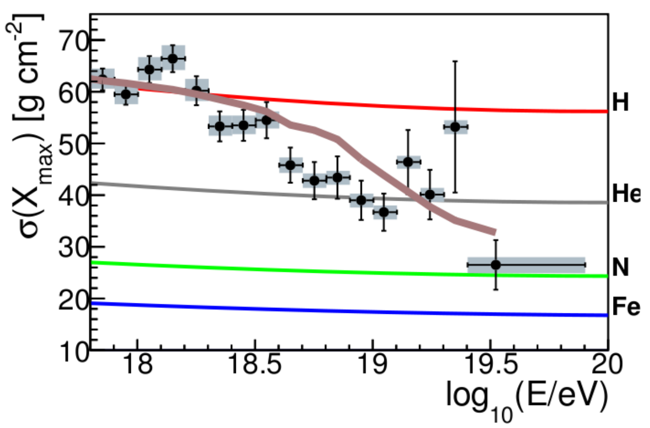
Analyzing the results

- Pure nitrogen injection spectrum in the source motivated by the disruption of white dwarfs
- Fit above the ankle ~ $10^{18.7}$ eV
- Maximum-likelihood method in three fit parameters:
  - production radius R
  - X-ray luminosity L
  - normalization parameter G
- G is degenerate in baryonic loading and event rate

$$G \equiv \xi_A \times \frac{\tilde{R}(0)}{0.1\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}}$$







[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

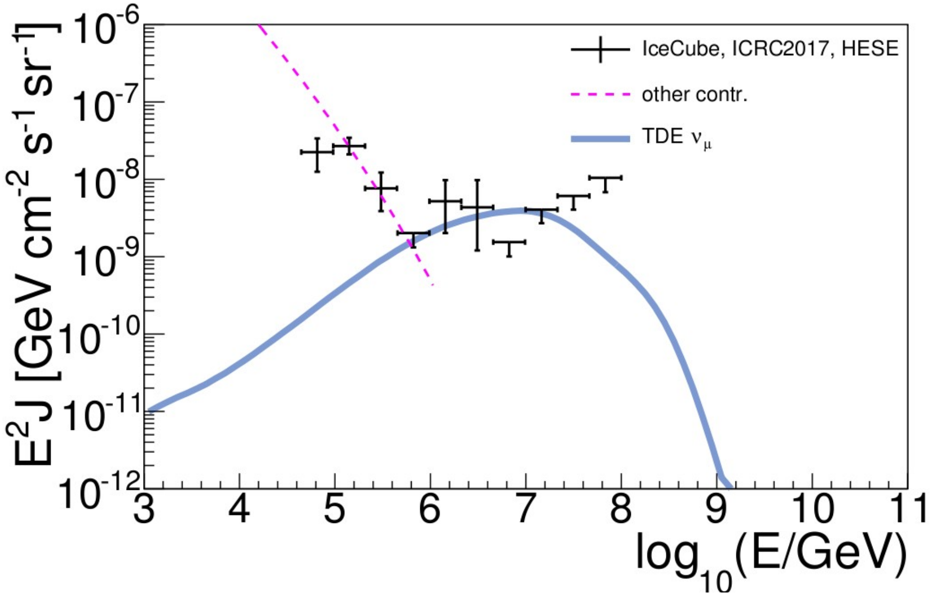
Compatibility with PeV neutrino data

Matching the observations by IceCube

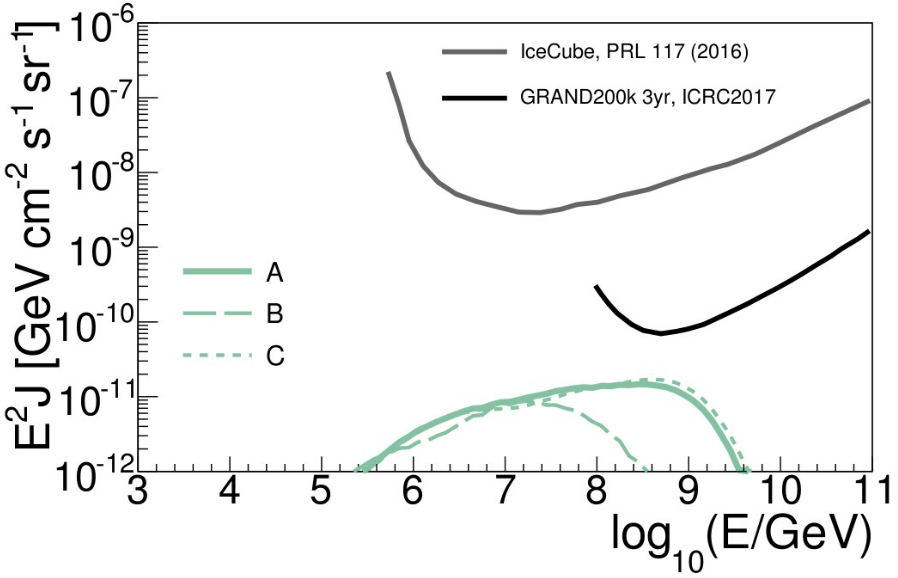
Neutrino flux from prompt emission

- Applying the same normalization results in a neutrino flux consistent with the two PeV data points in IceCube
- Data points below PeV energies assumed to come from other / multiple component

[A. Palladino, W. Winter, Astron.Astrophys. 615 (2018) A168]



- Upper limit at 6 – 10 PeV (Glashow resonance) consistent with our flux as flavor ratio is different
- Suppression of cosmogenic neutrinos mostly due to negative source evolution
- No detection of cosmogenic neutrinos expected even in GRAND



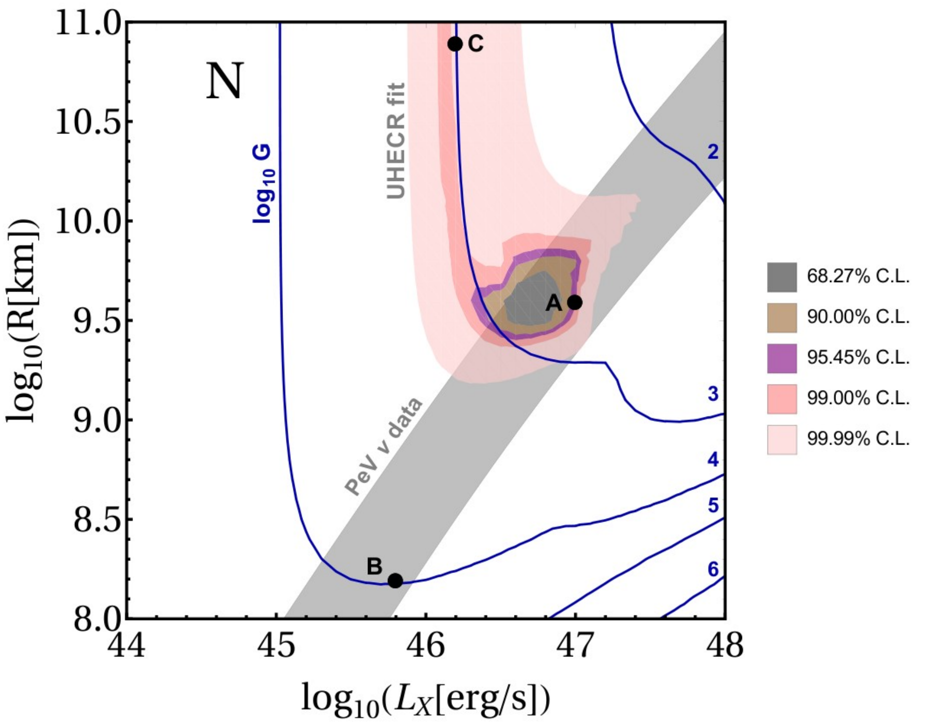
[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

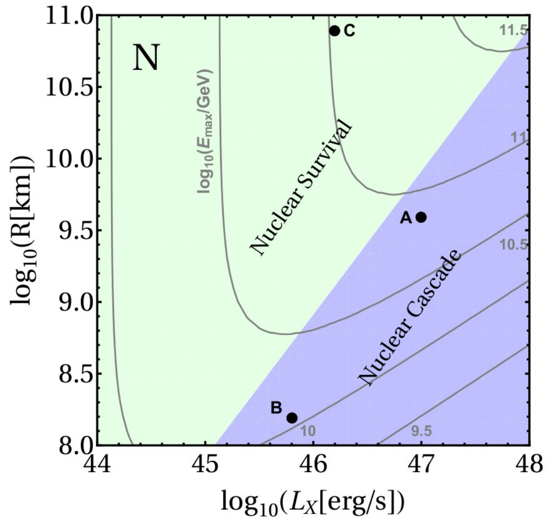
Best fit in parameter space study

The importance of nuclear disintegration

Common region in parameter space

- Best fit corresponds to the minimum χ^2 for joint description
- Confidence levels for cosmic rays follow mainly the maximum energy contour at ~ $10^{10.8}$ GeV
- PeV neutrino data band corresponds to the 1σ region from the two PeV data points in IceCube
- Neutrino band follows the required radiation density
- Region preferred by neutrinos clearly coincides with the region of efficient photo-meson production





It is possible to fit both within 1 σ of each other!

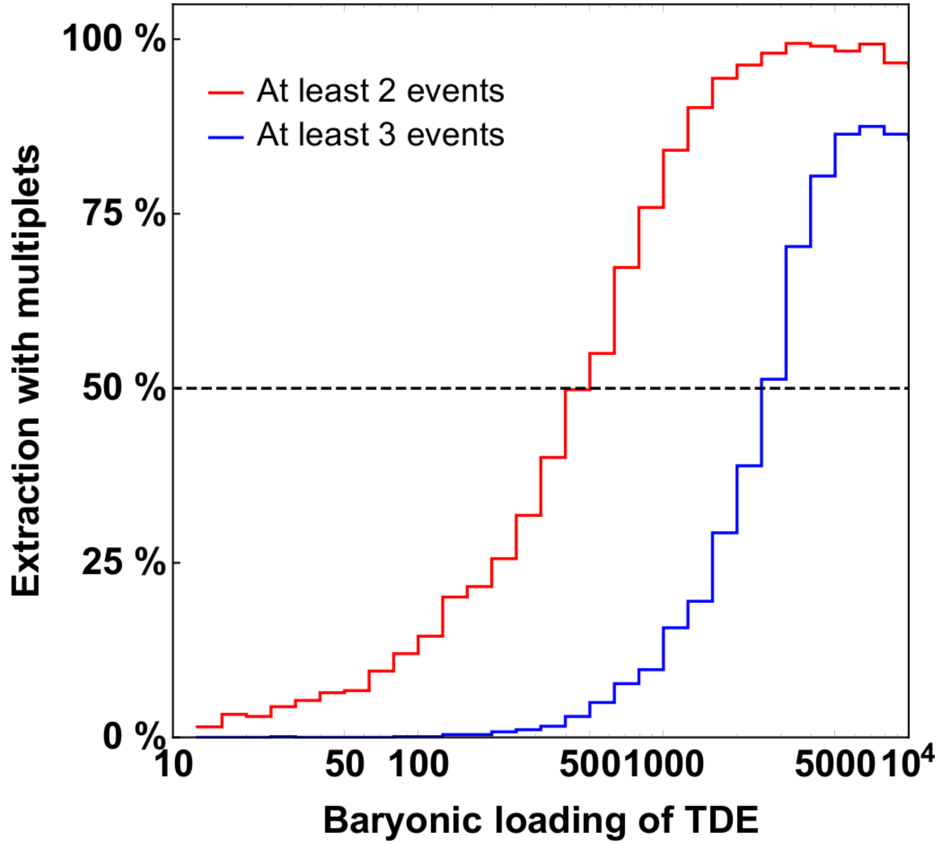
[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

Neutrino multiplets from jetted TDEs

Multiplet constraints in the context of our model

Our results are consistent with current observations

- Neutrino multiplets can test this model, as the baryonic loading and the rate both cannot be too high
- Main difference: we describe only PeV data, where statistics are low (~ 3 events), spectral shape different
- Best fit yields G ~ 540, varying the baryonic loading and randomly drawing from a set of sources corresponding to the resulting rate gives a probability < 50%



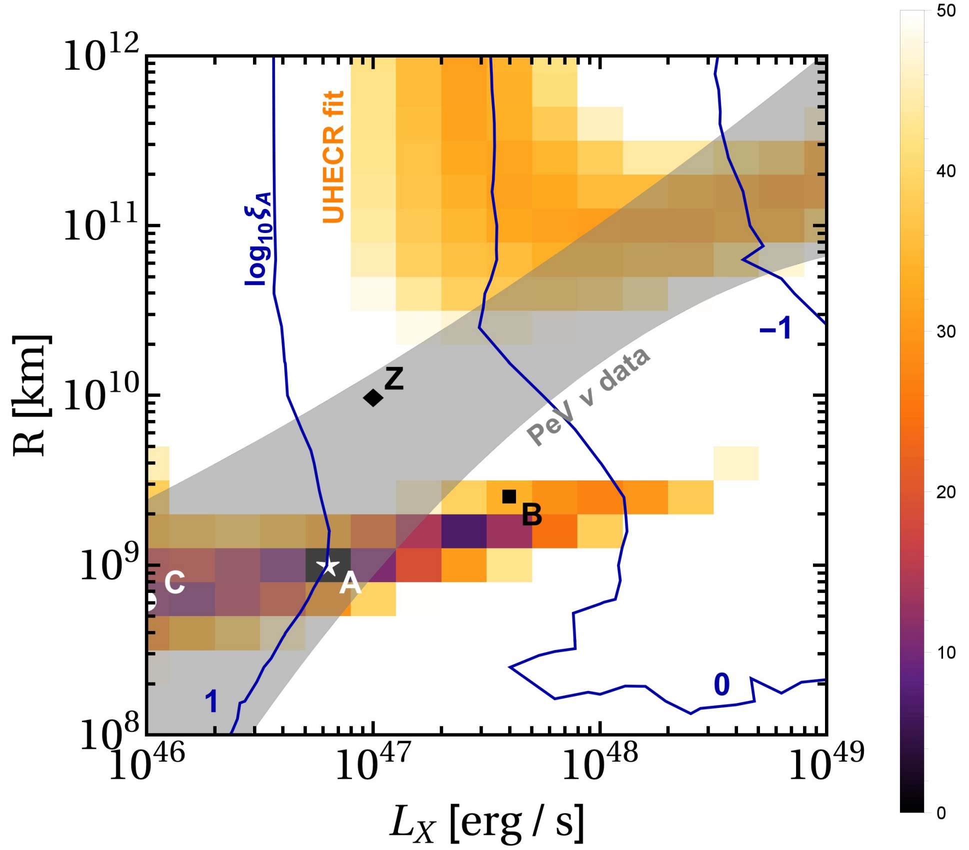
[A. Palladino, W. Winter, Astron.Astrophys. 615 (2018) A168]

A quick look at low-luminosity GRBs

[D. Boncioli, D. Biehl, W. Winter – arXiv:1808.07481]

LL-GRBs as a distinct population from conventional GRBs

- Stacking limits excludes most of the parameter space for conventional GRBs, pointing towards low luminosities which are unconstrained [D. Biehl et al., A&A (2018)]
- With a similar approach it is possible to fit UHECR and neutrino data simultaneously while getting a detectable signal in cosmogenic neutrinos
- … and the nuclear cascade controls the sub-ankle region, data can be described even across the ankle!
- Could be interesting objects for next-generation telescopes like CTA as gamma-rays up to TeV energies are expected



Color code: χ^2

[D. Boncioli, D. Biehl, W. Winter, arXiv:1808.07481]

Check it out to see the fit results!

Conclusion

[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

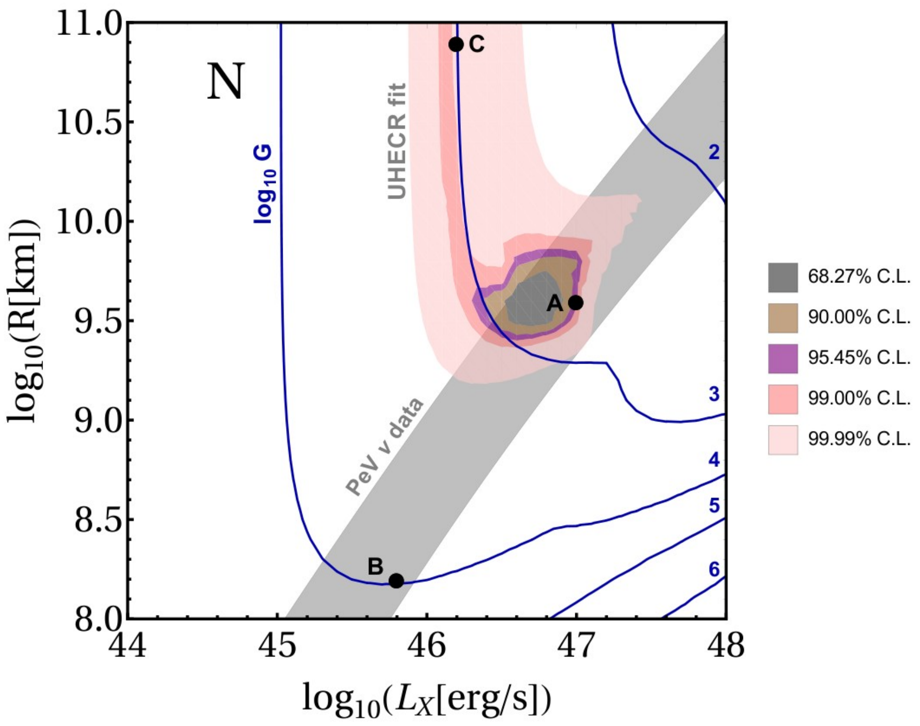
Tidal disruption of stars as common origin of UHECRs and neutrinos

- Tidal Disruption Events are compatible with the requirements of viable source candidates for UHECRs and PeV neutrinos

- Our model gives a full self-consistent picture of TDEs as common source of the measured UHECR spectrum and composition in Auger and the PeV neutrino data in IceCube

- We fully describe the nuclear processes in the source, which cannot be neglected in a joint description, and perform the fit over the whole parameter space in a combined source-propagation model

- See also our previous work on GRBs, where we introduce the technology, exclude most of the parameter space and show that a multi-messenger description naturally favors LL-GRBs



[D. Biehl, D. Boncioli, A. Fedynitch, W. Winter – Astron.Astrophys. 611 (2018) A101]

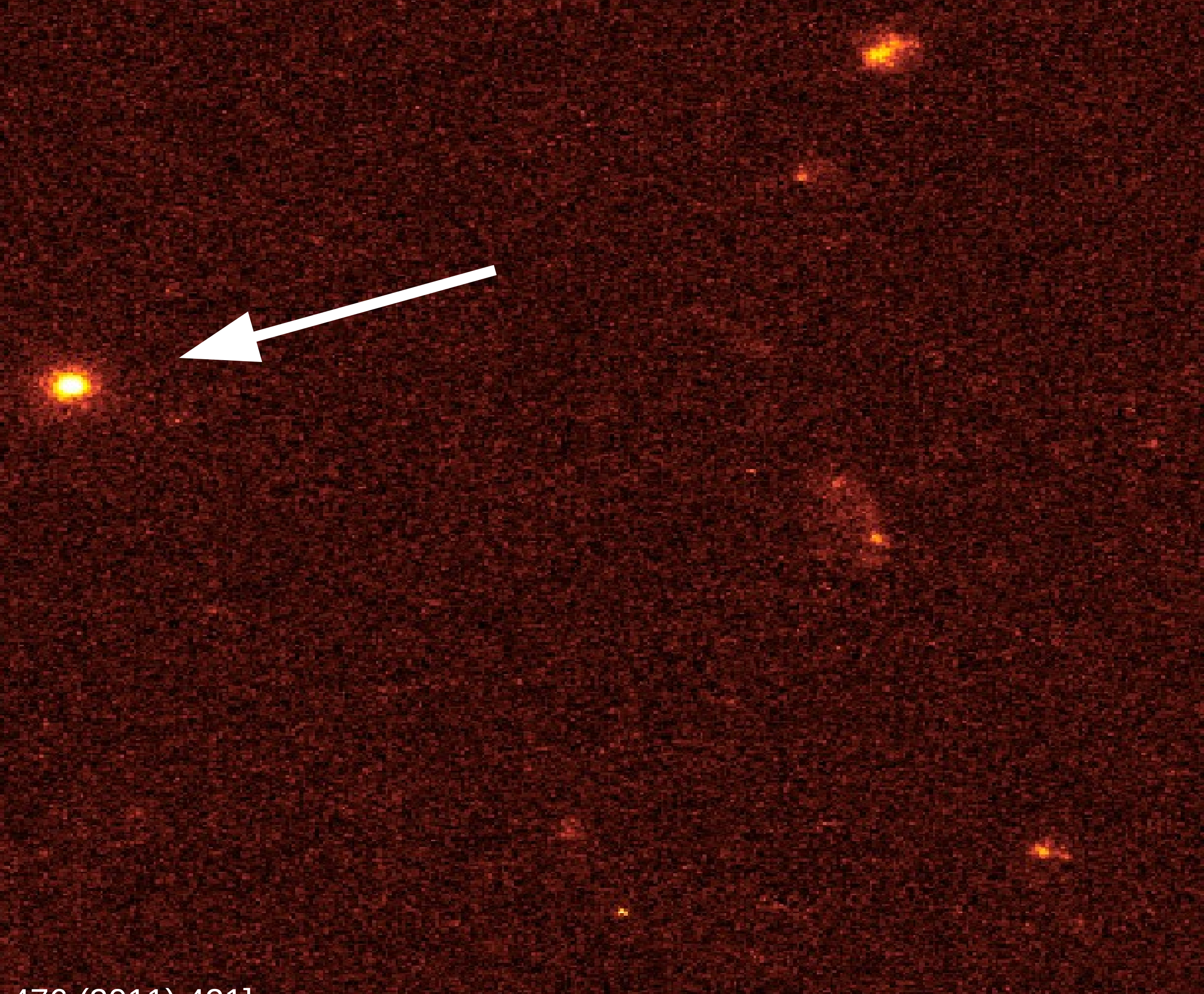
BACKUP

Observation of Swift J1644+57

Best observed jetted TDE

Stats for Swift J1644+57

- **Discovery:** March 28, 2011, NASA's Swift Satellite
- **Event:** supermassive black hole (SMBH) actived by tidal breakup of passing star
- **Mass: ~** 5 million solar masses
- **Luminosity distance:** 1.88 Gpc (z = 0.354)



Parameters of Swift J1644+57 (considered typical)

- Lorentz factor $\Gamma \sim 10$
- Isotropic equivalent energy in X-rays $E \sim 10^{53.5}$ erg
- Duration of X-ray flare $\Delta T \sim 10^{6}$ s
- Minimum variability time t ~ 100 s
- Broken power law target photon field with $\alpha = 2/3$, $\beta = 2$
- X-ray break energy $\varepsilon \sim 1$ keV

[D. N. Burrows et al. – Nature 476 (2011) 421]

NASA, Hubble Space Telescope

Tidal disruption and jet formation

Physics of Swift J1644+57

Parameter estimates

- Comparing the tidal radius r_t with the Schwarzschild radius R_s of the black hole gives an upper limit on its mass
  → conservative value of maximum M ~ $10^{7.2}$ solar masses

[C. S. Kochanek (2016)]

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

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

- Eddington luminosity of this black hole ~ 1.3 x 10^{44} erg/s, observed peak luminosity ~ $10^{47.5}$ erg/s
  → super-Eddington scenario, requires strongly anisotropic radiation pattern with relativistic jet pointed towards us

[D. N. Burrows et al. (2011)]

- Maximum energy potentially released via accretion E ~ $Mc^2/2 * (R_s / R)$

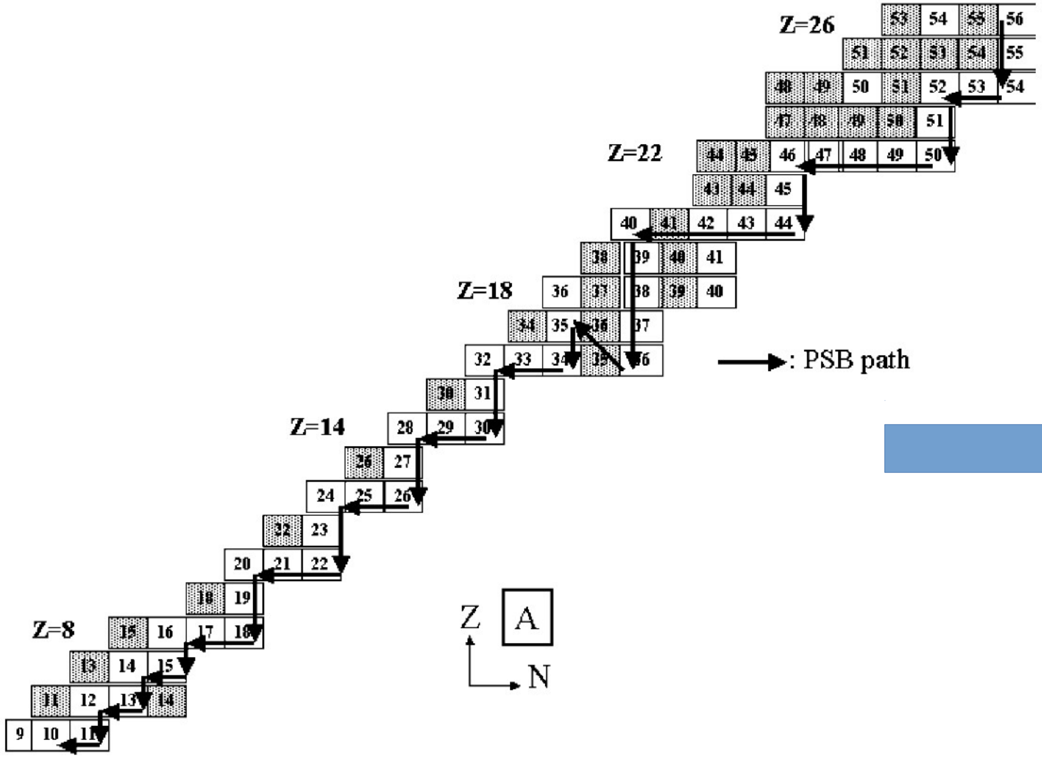
  1.) ~ 10^{54} erg for R ~ R_s

  2.) ~ 10^{52} erg for R ~ r_t

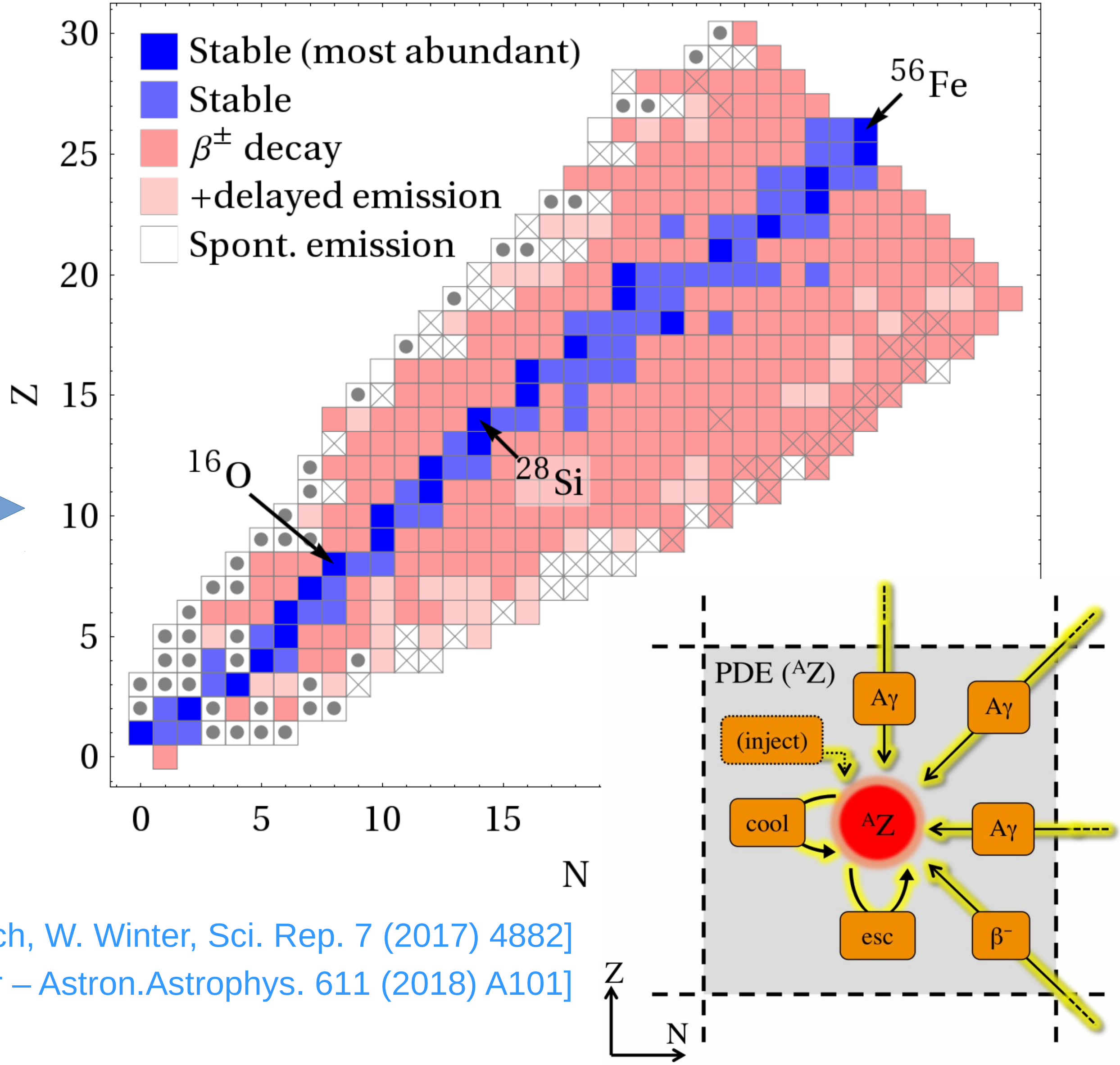
  → Sets the ball-park scale for released energy

Modeling nuclear interactions with NeuCosmA

Efficient computation of the nuclear cascade



[Khan et al, Astropart. Phys. 23 (2005), 191-201]



[D. Boncioli, A. Fedynitch, W. Winter, Sci. Rep. 7 (2017) 4882]

[D. Biehl, D. Boncioli, A. Fedynitch, W. Winter – Astron.Astrophys. 611 (2018) A101]

Possible scenarios for the progenitor system

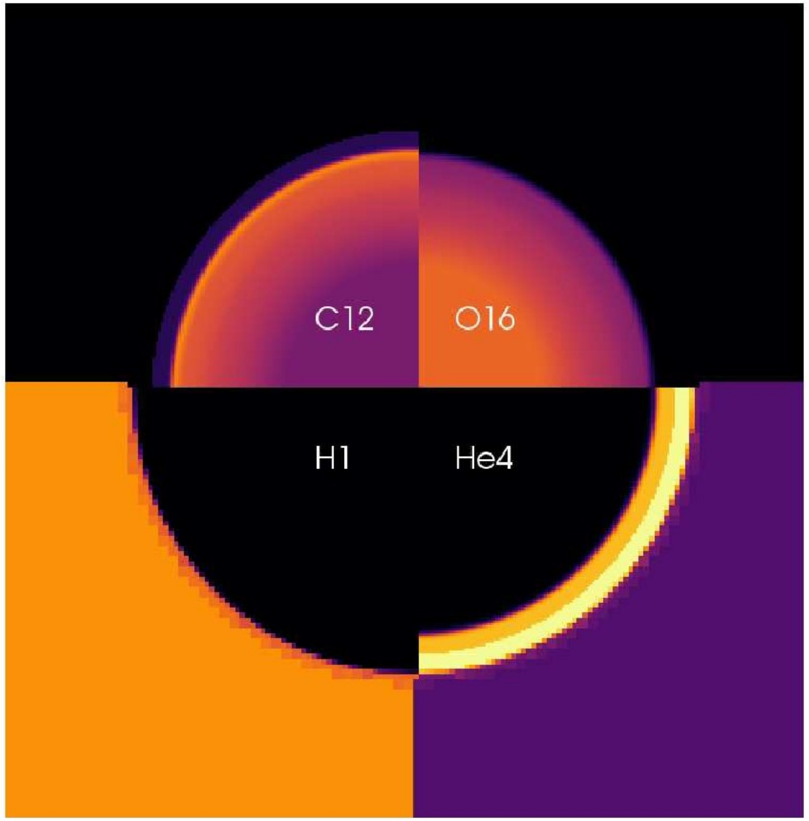
A diverse population of TDEs

Binaries of black holes and stars

- Three jet-hosting TDEs have been identified so far, the observations are consistent with [D. N. Burrows et al. (2011)] [S. B. Cenko et al. (2012)]
  - Supermassive black hole, M > 10^5 solar masses, disrupting main sequence star [J. S. Bloom et al. (2012)]
  - Intermediate mass black hole, 10^3 > M > 10^5 solar masses, disrupting white dwarf (WD)
- Other scenarios are possible as well, e.g. tidal forces triggering the burning of elements which may normally not happen due to the mass of the star [R. Alves Batista, J. Silk (2017)]
- Presence of intermediate mass isotopes motivated by the disruption of white dwarfs, ONeMg white dwarfs from past supernovae or explosive nuclear burning

[B. T. Zhang, K. Murase, F. Oikonomou, Z. Li (2017)]

[P. Anninos et al. (2018)]



Cross-section of typical white dwarf

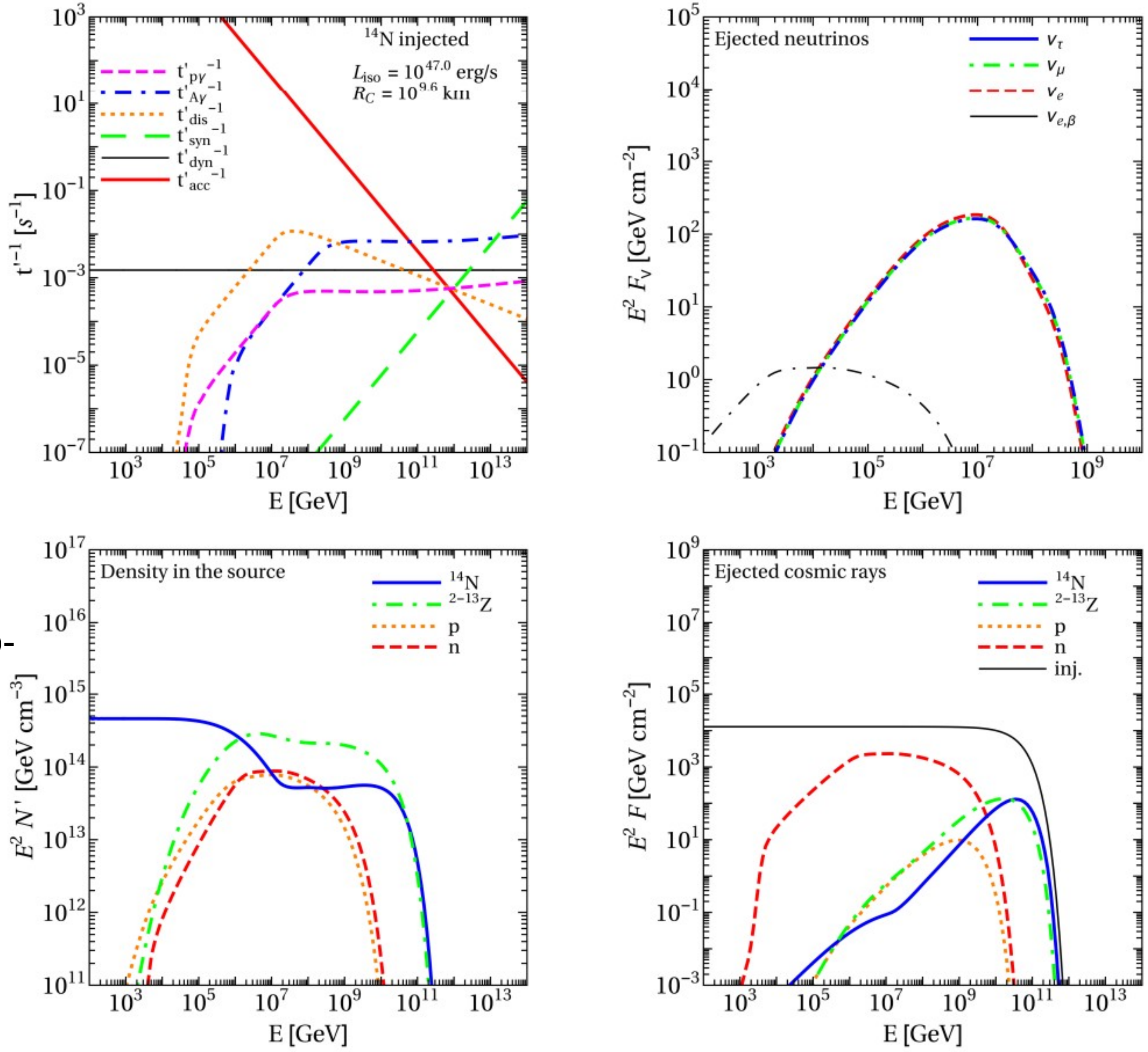
Main ingredients of our simulation

Parameters, assumptions, composition

Details on the model

- Internal shock scenario connecting radius and time variability by $R \sim 2\Gamma^2 ct$
- Static broken power law target photon field assumed
- Efficient Fermi shock acceleration of nuclei, injection follows spectral index ~ 2 up to a maximum energy
- Direct UHECR escape mechanism leads to harder escaping spectra with respect to the injection
- Photo-disintegration based on TALYS + CRPropa, Photo-Meson production based on SOPHIA
- Pure nitrogen injection motivated by the disruption of carbon-oxygen white dwarfs and the observation of nitrogen emission lines

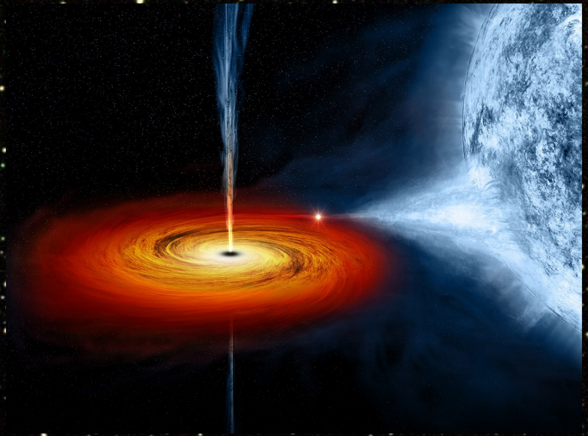
[S. B. Cenko et al. (2016)]
[J. S. Brown et al. (2017)]



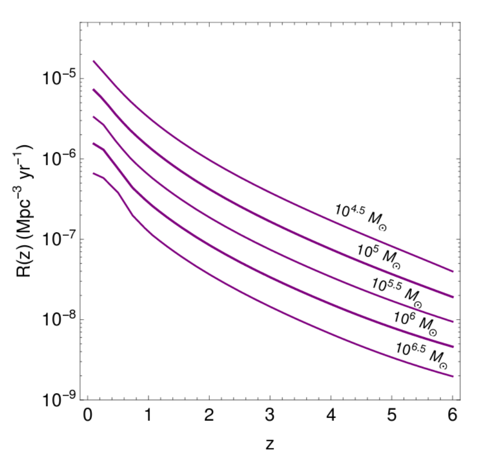
[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

Combined source-propagation model

Towards a complete picture



Source model



Source evolution

Energy of single TDE ~ LΔT ~ 10^{53} erg

Local rate of TDEs ~ 2 x 10^{-6} Mpc^{-3} yr^{-1}

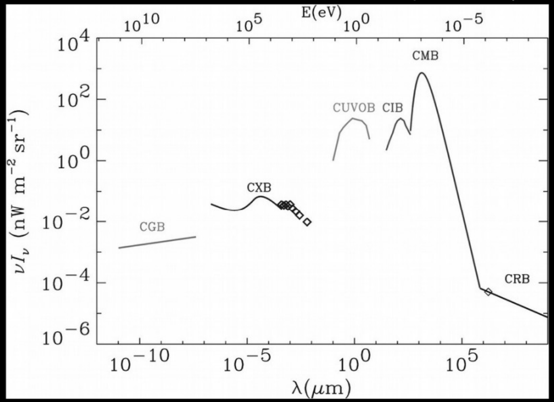
Beaming factor ~ $1/(2\Gamma^2)$ ~ 5 x 10^{-3}

Fraction of jetted TDEs ~ 0.1

Energy Budget? ~ 10^{44} erg Mpc^{-3} yr^{-1}

Rough estimate matches!

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

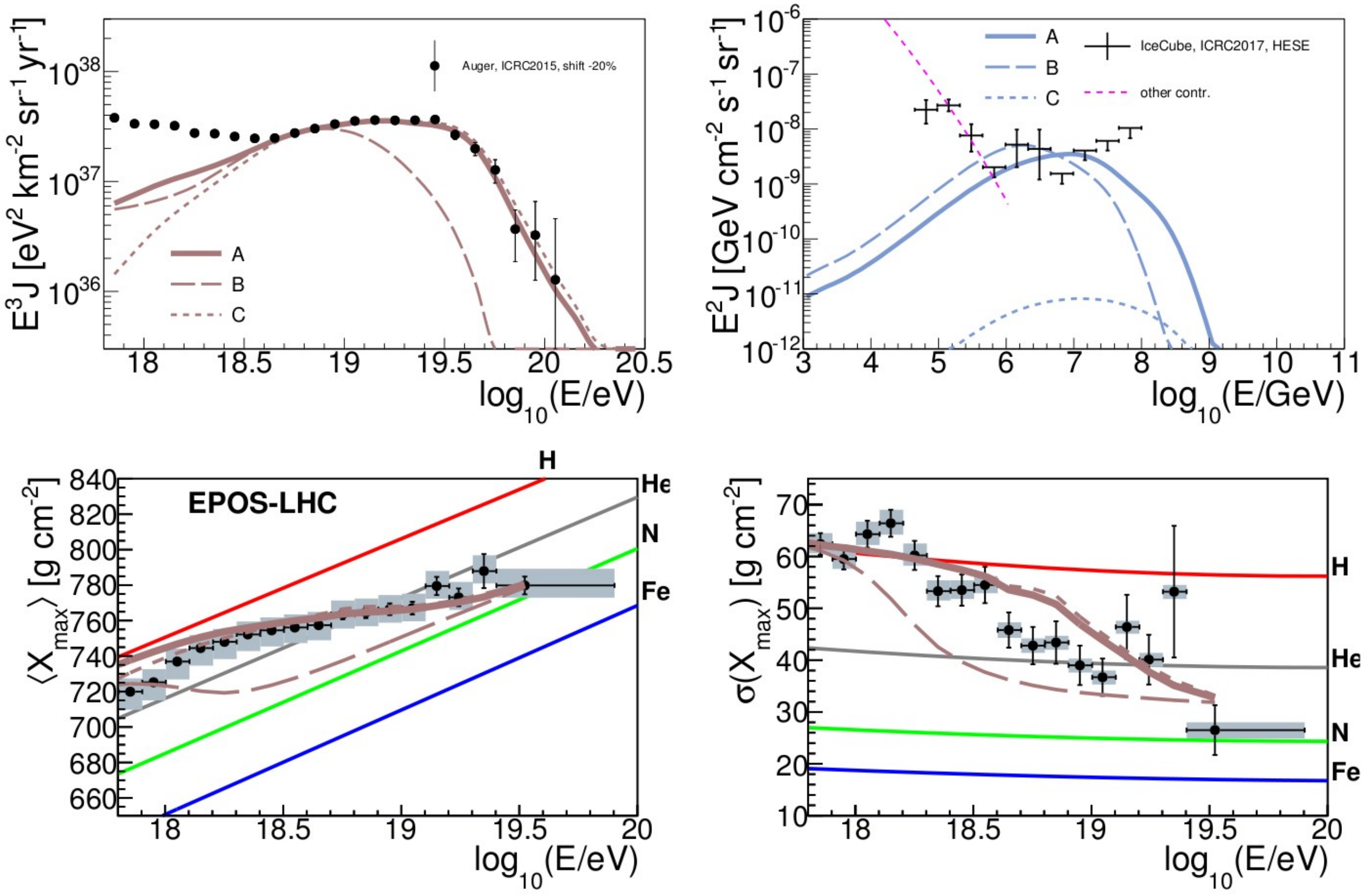


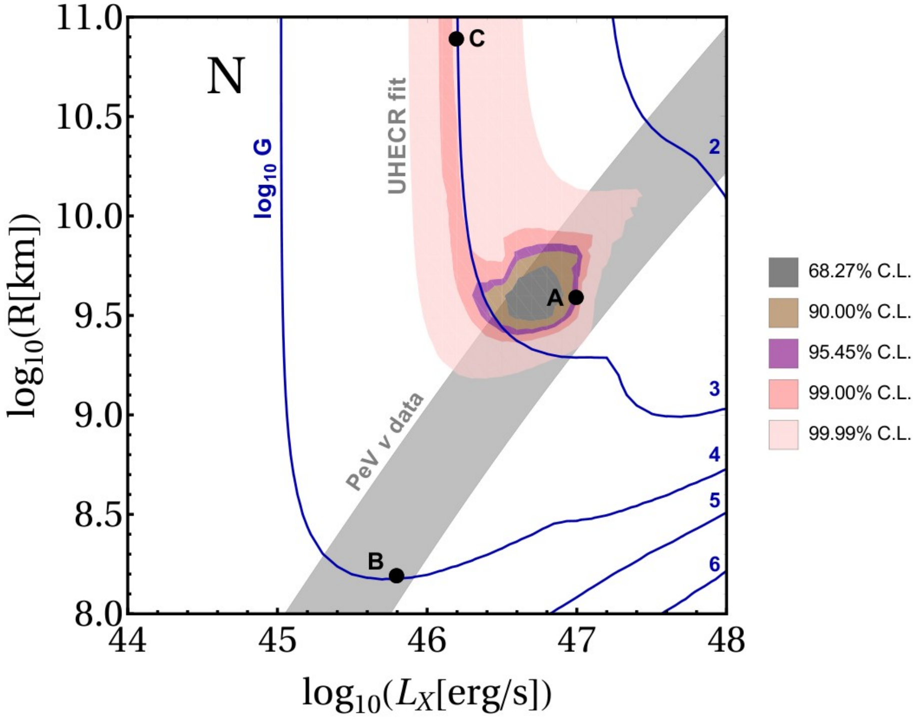
Interactions with CMB, CIB, ...

Interactions in atmosphere

Single messenger best fit points

Fitting either cosmic ray or neutrino data





It is possible to fit both within the 1σ region of each other!

[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]