Tidal Disruption of Stars

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

Credit: CXC/M. Weiss

Daniel Biehl
DPG spring meeting
March 22, 2018

[DB, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]
submitted to Scientific Reports

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

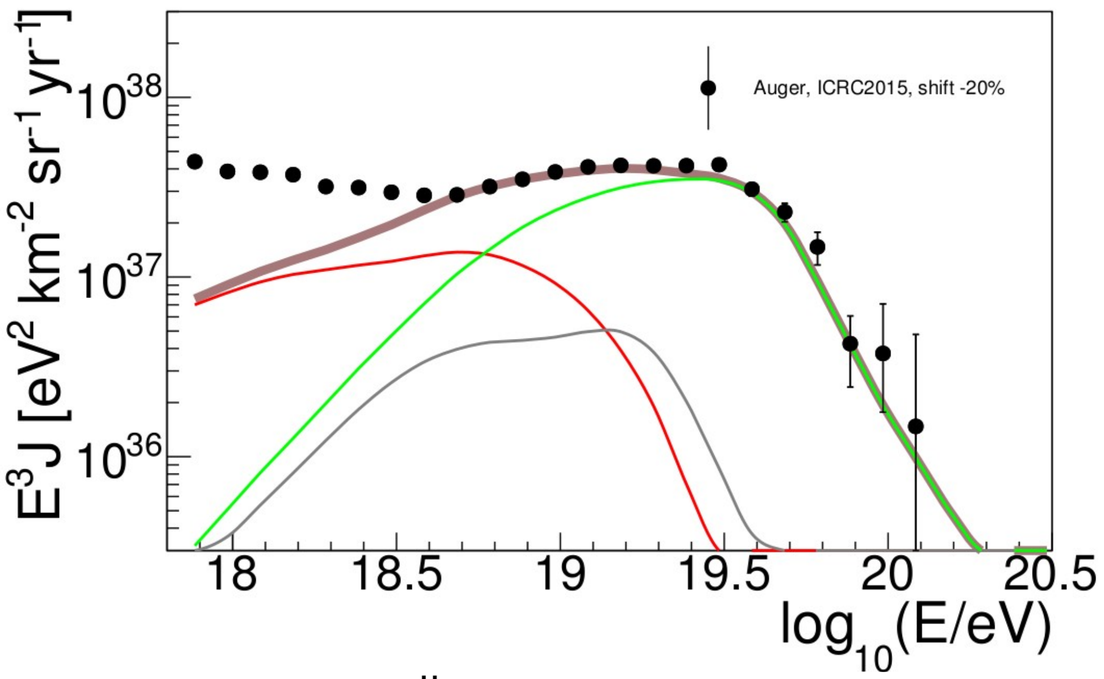
erc

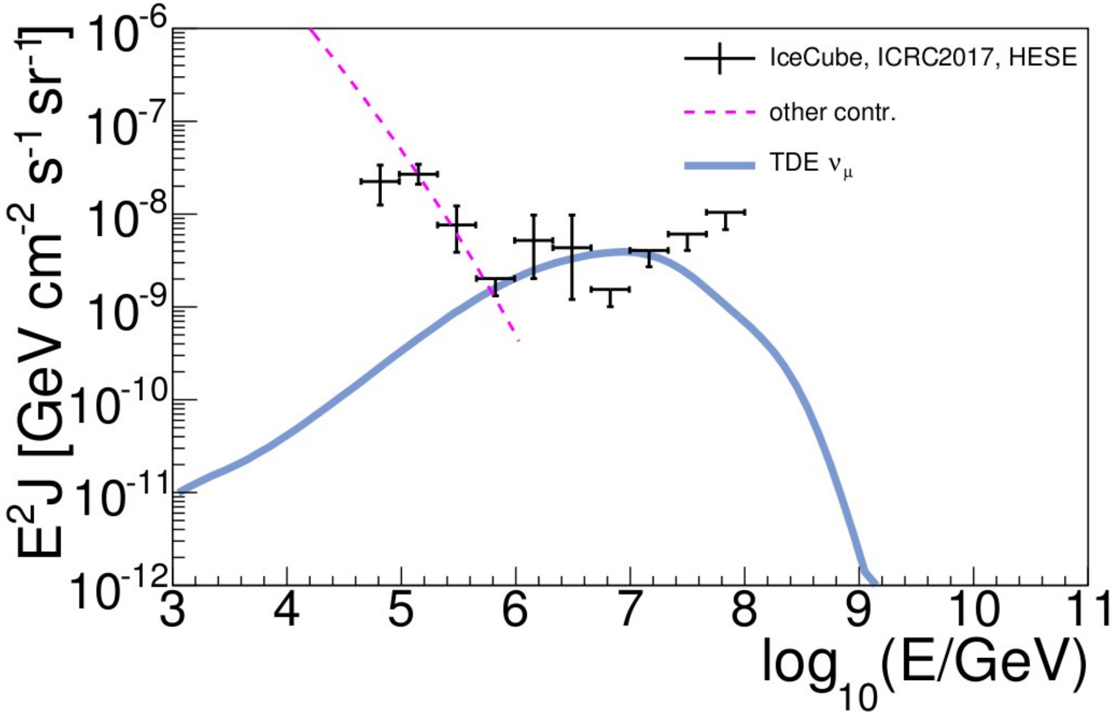
NeuCos

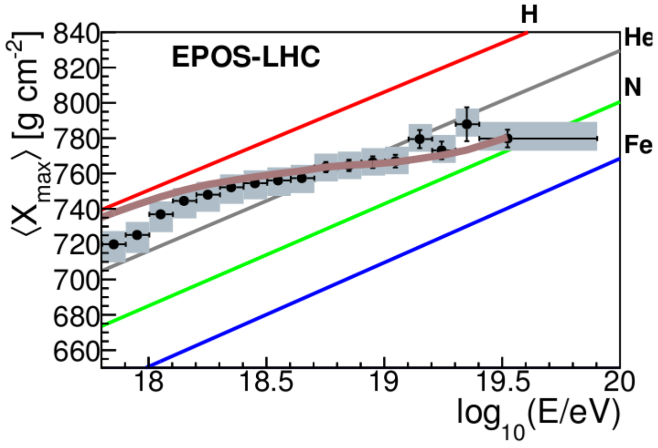
DESY

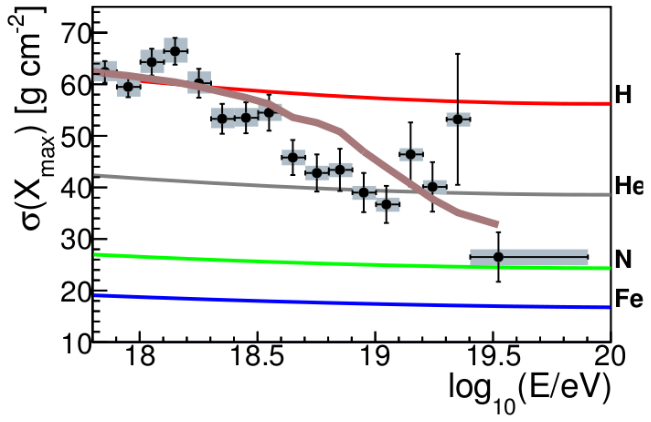
Simultaneous fit of UHECR data and PeV neutrinos

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!

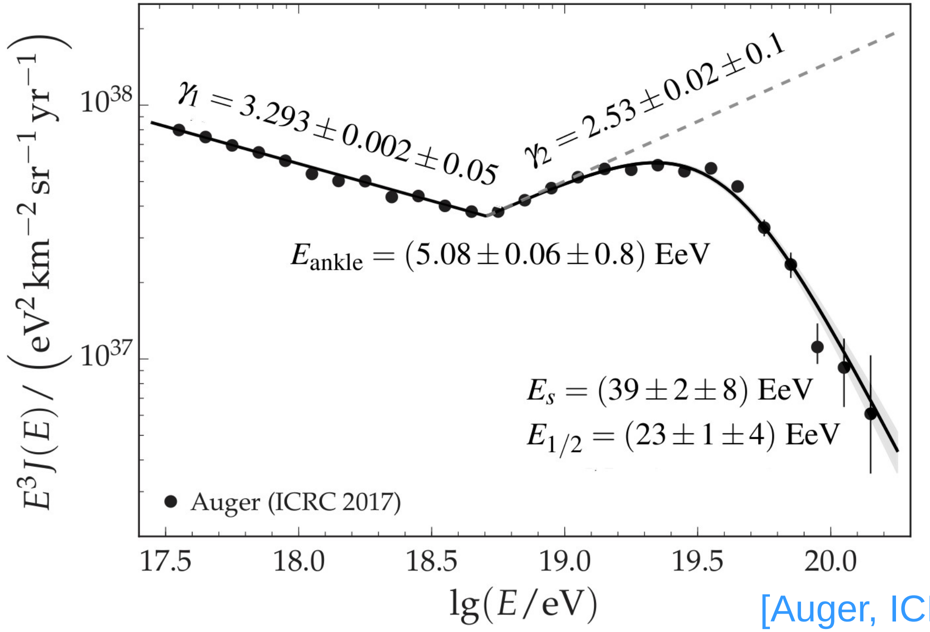
[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]

Origin of ultra-high energy cosmic rays (UHECRs)

Spectrum and composition

Facts

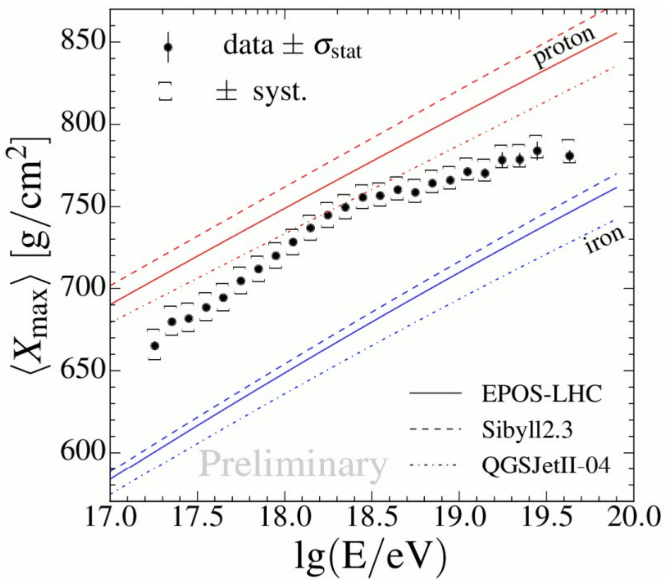
- Ultra-high energy range: E > 10^{18} eV
- Presumably of extra-galactic origin
- Change of slope (ankle) at ~ $10^{18.7}$ eV
- Suppression at ~ $10^{19.5}$ eV
- Composition tends to get heavier at the highest energies
- Energy budget to power the UHECRs ~ 10^{44} erg $\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$

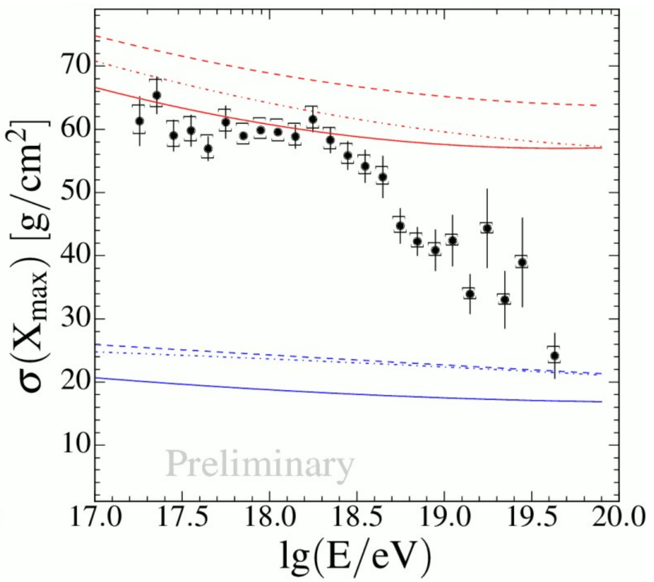


[Auger, ICRC 2017]

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, energy budget considerations

PeV neutrinos from cosmic accelerators

- Δ-resonance and subsequent pion decay

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

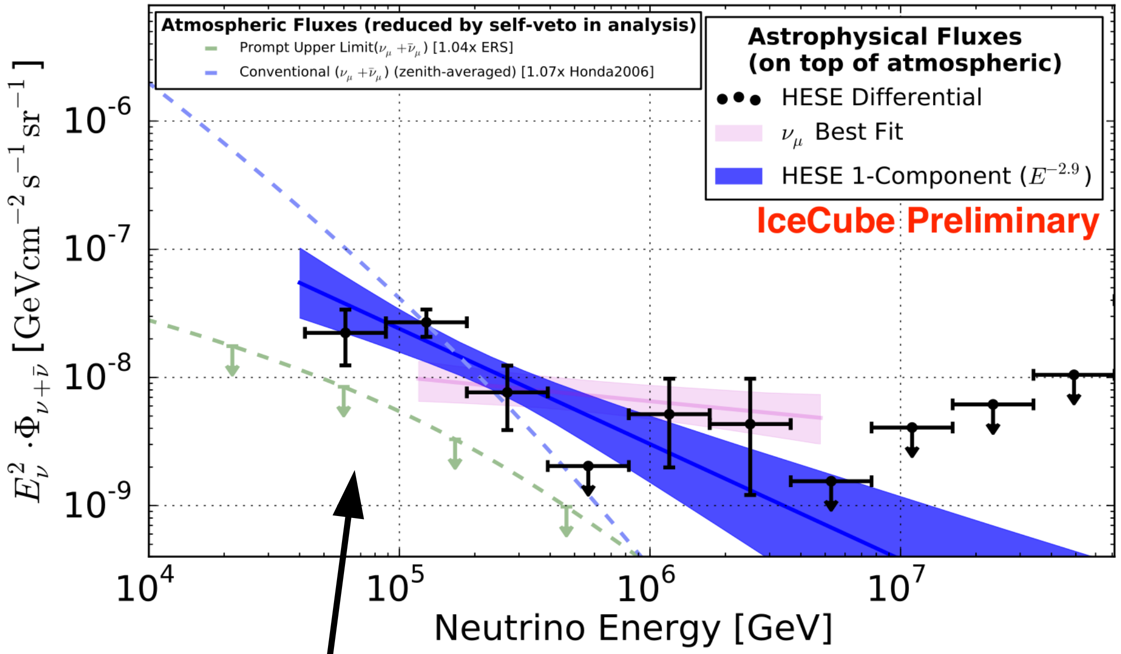
$$\begin{aligned} \pi^+ &\to \mu^+ + \nu_\mu \,, \\ & \quad\; \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \end{aligned}$$

- Highest energy neutrinos E ~ few PeV require primary energies E ~ 100 PeV

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

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

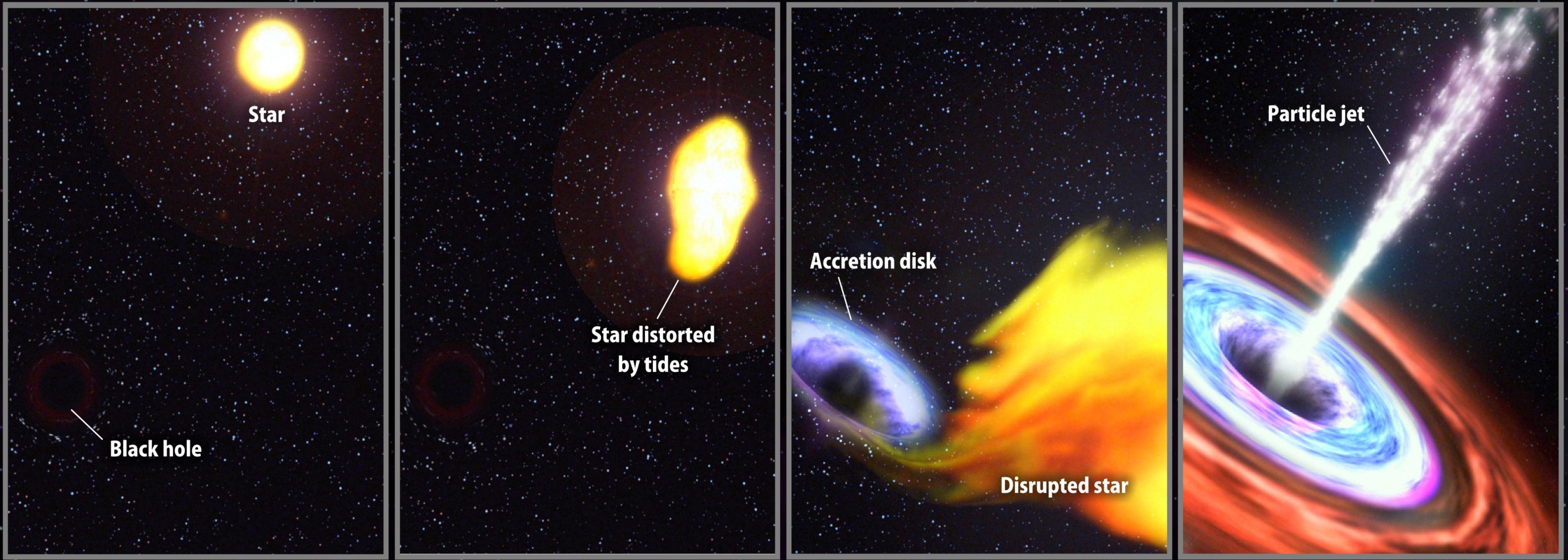
[M. Ahlers, F. Halzen (2014)]
[M. Kowalski (2014)]



[IceCube, ICRC 2017]

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

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.

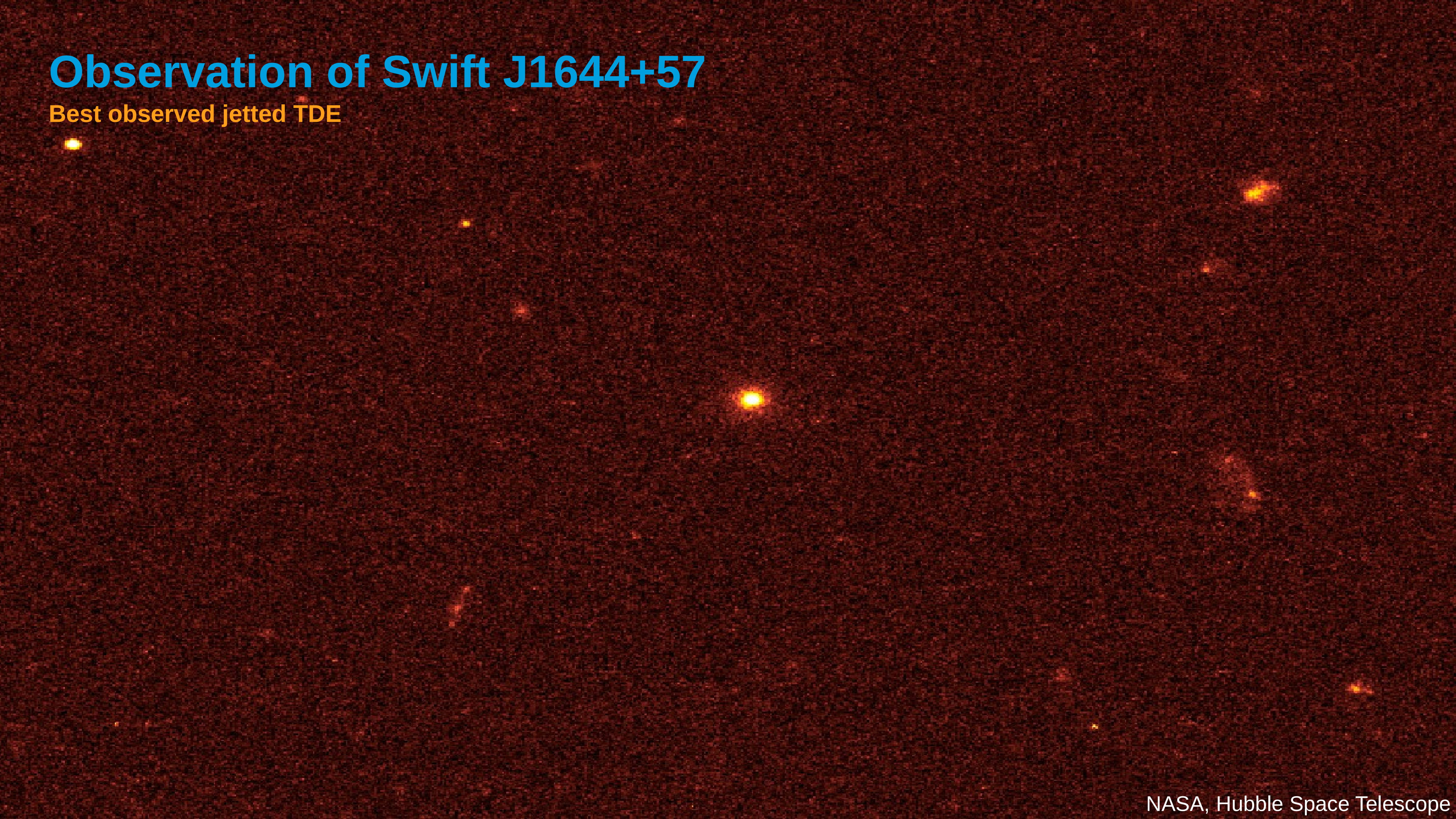
2. Strong tidal forces near the black hole increasingly distort the star. If the star passes too close, it is ripped apart.

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.

Observation of Swift J1644+57

Best observed jetted TDE



NASA, Hubble Space Telescope

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
- **Distance:** 3.9 billion light years = 1.2 Gpc

NASA, Hubble Space Telescope

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Parameters of Swift J1644+57 (considered typical)

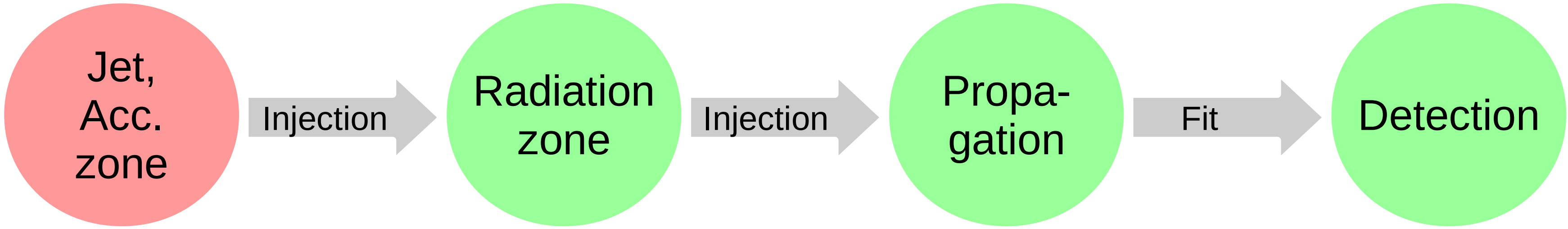
- Lorentz factor $\Gamma \sim 10$
- Isotropic equivalent energy in X-rays $E \sim 10^{53.5}$ erg
- Duration of X-ray flare $\Delta T \sim 10^6$ s
- Minimum variability time $t \sim 100$ s
- Broken power law target photon field with $\alpha = 2/3$, $\beta = 2$
- X-ray break energy $\varepsilon \sim 1$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

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

NASA, Hubble Space Telescope

The art of multi-messenger modeling

Towards a complete picture



Power law spectrum up to max. energy

Efficient calculation of the nuclear processes

Interactions with CMB, CIB, ...

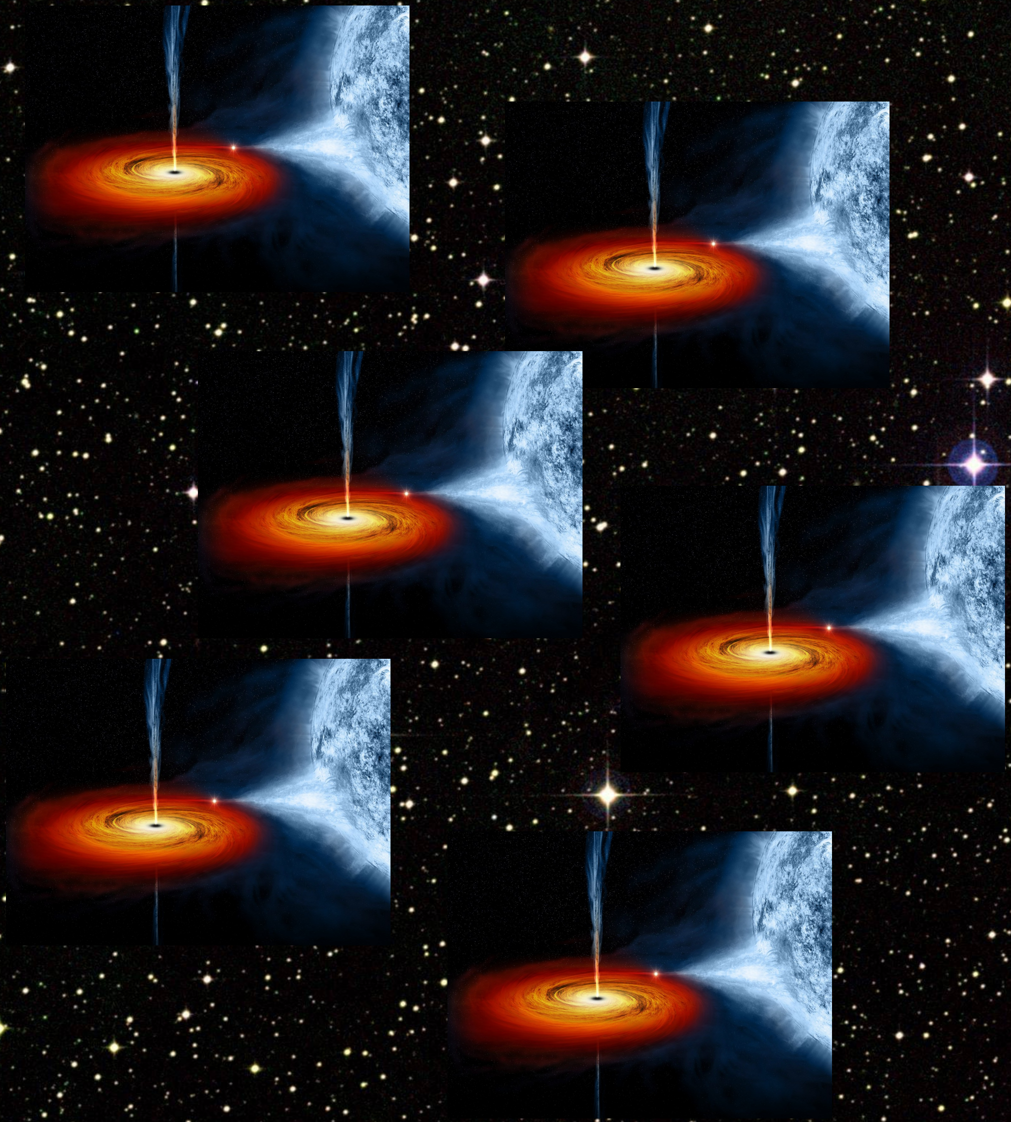
Fit to Auger data, IceCube PeV data

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

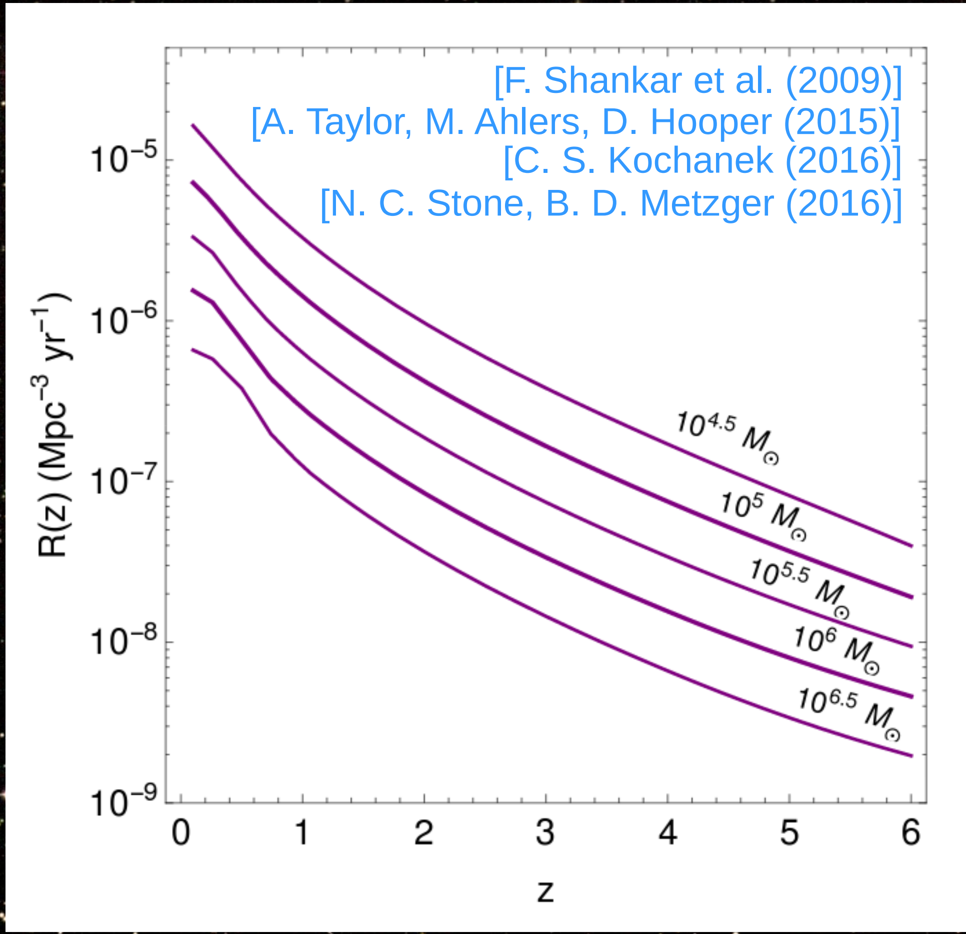
- First consistent description of neutrino **and** UHECR production in internal shocks of TDE jets
- Efficient computation of nuclear processes in the source, where photo-disintegration of nuclei **cannot** be neglected
- Interface to UHECR propagation for taking into account source evolution, interactions 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

Cosmological rate of TDEs

Evolution with redshift



Distribution in the universe



Close sources dominate, less cosmogenic neutrinos, diffuse gamma-ray photons and heavier composition

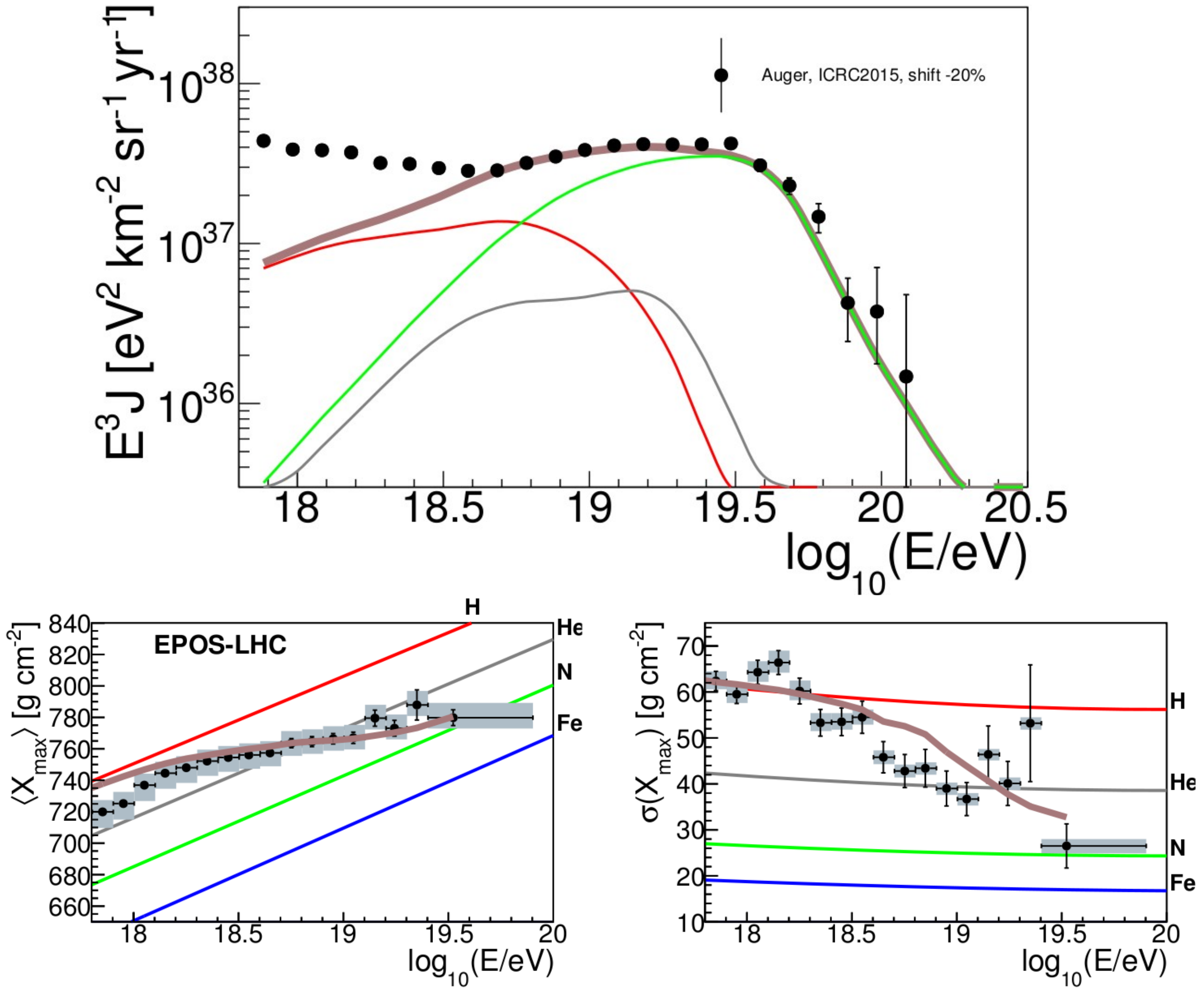
Fitting UHECR spectrum and composition

Matching the observations by Auger

Analyzing the results

- Pure nitrogen injection spectrum in the source
- Data shifted by up to 20% to account for energy scale uncertainties
- Fit only 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

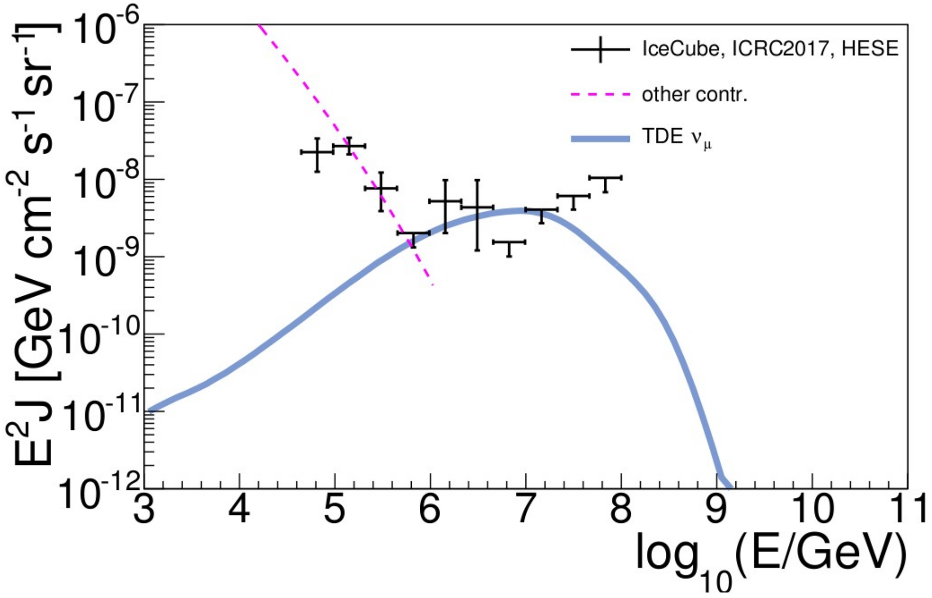
$$G \equiv \xi_A \times \frac{\tilde{R}(0)}{0.1\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}}$$



[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]

Compatibility with PeV neutrino data

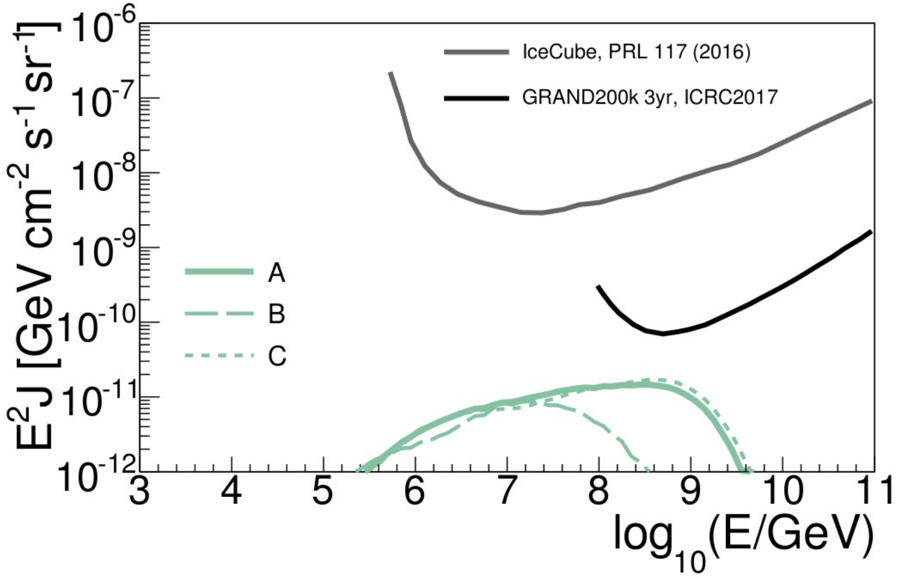
Matching the observations by IceCube



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 contribution, such as
  - atmospheric origin
  - galactic origin
  - multiple components

[A. Palladino, W. Winter, arXiv:1802.07277]



- Cosmogenic neutrino flux consistent with the limits
- Suppression of cosmogenic neutrinos mostly due to negative source evolution

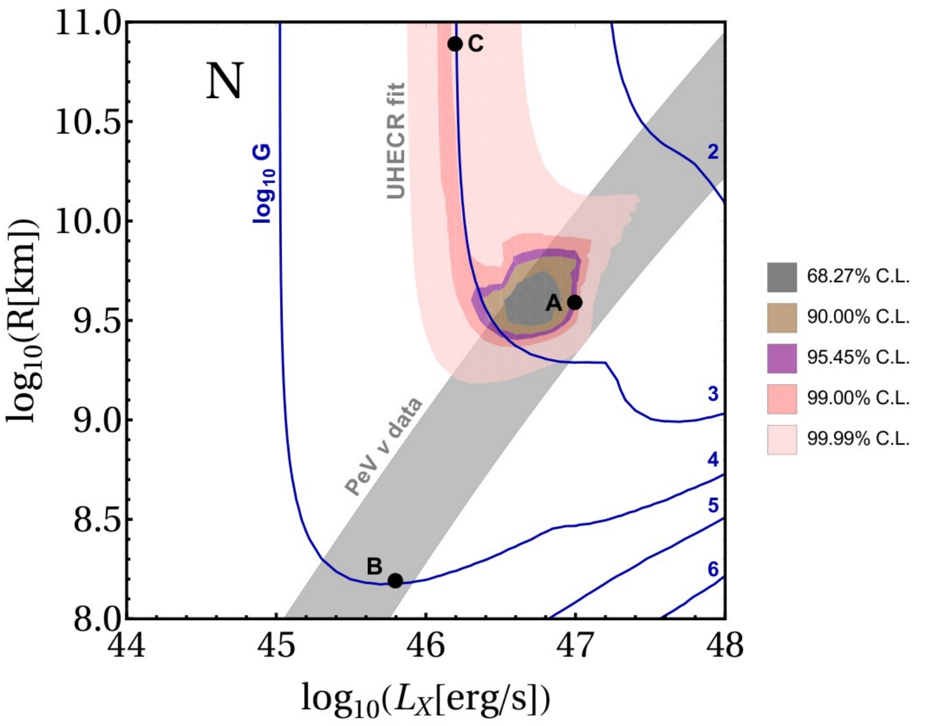
[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]

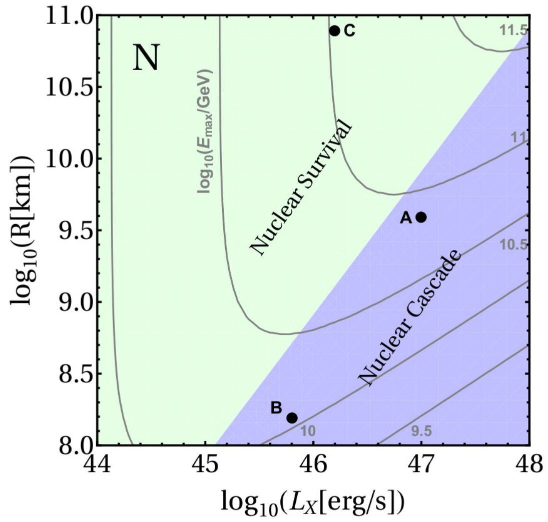
Best fit in parameter space study

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, i.e. disintegration cannot be neglected!





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

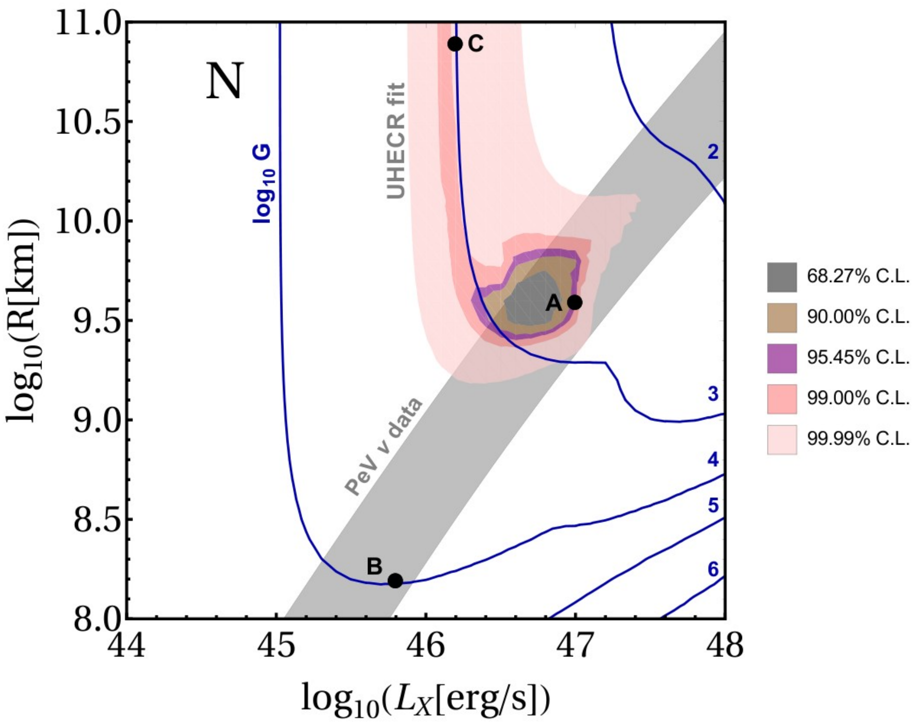
[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]

Conclusion

[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]

Tidal disruption of stars as common origin of UHECRs and neutrinos

- Tidal Disruption Events are compatible with the requirements of viable source candidates
- 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, and perform the fit over the whole parameter space in a combined source-propagation model



See also our previous work on GRBs, where we:

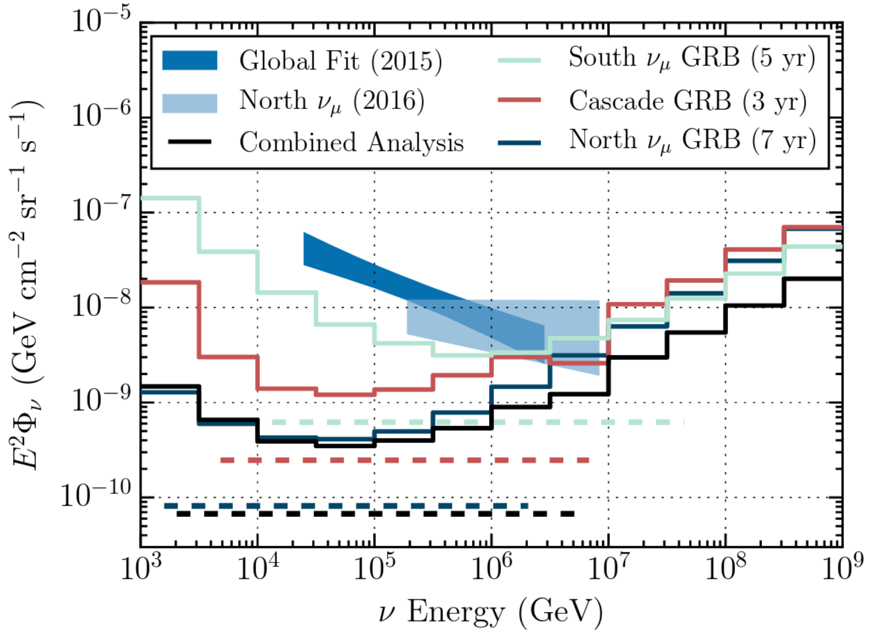
- introduce the technology
- exclude most of the parameter space
- show that a multi-messenger description naturally favors LLGRBs!

[D. Biehl et al., A&A, 2017]

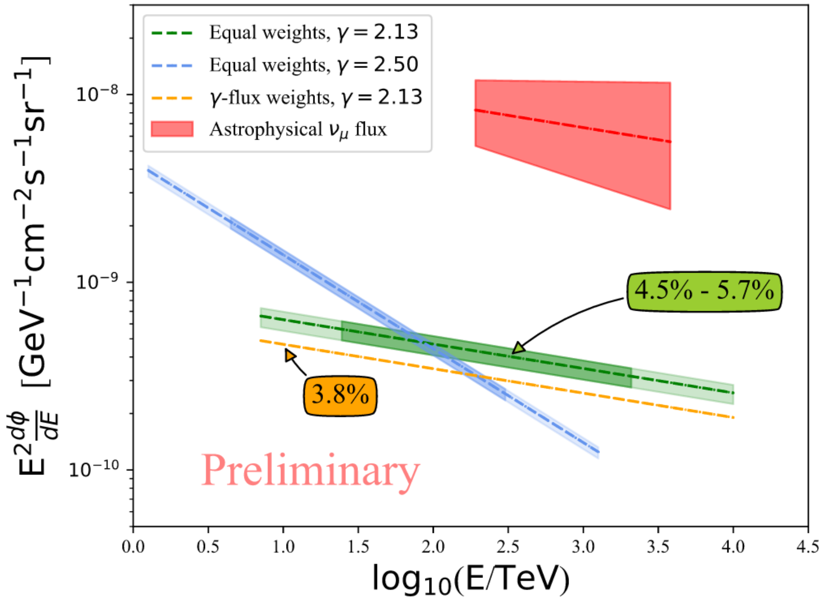
BACKUP

Prime candidates based on observations

Disfavored source classes



[IceCube, Nature 484 (2012) 351]
[IceCube, arXiv:1702.06868]



[IceCube, Astrophys. J. 835 (2017) 45]
[IceCube, ICRC 2017]

Gamma-ray bursts (GRBs)

- Transient sources, high luminosities over short times
- GRB stacking analysis: absence of temporal and spatial correlation with neutrino events → less than 1%!

Active Galactic Nuclei (AGNs)

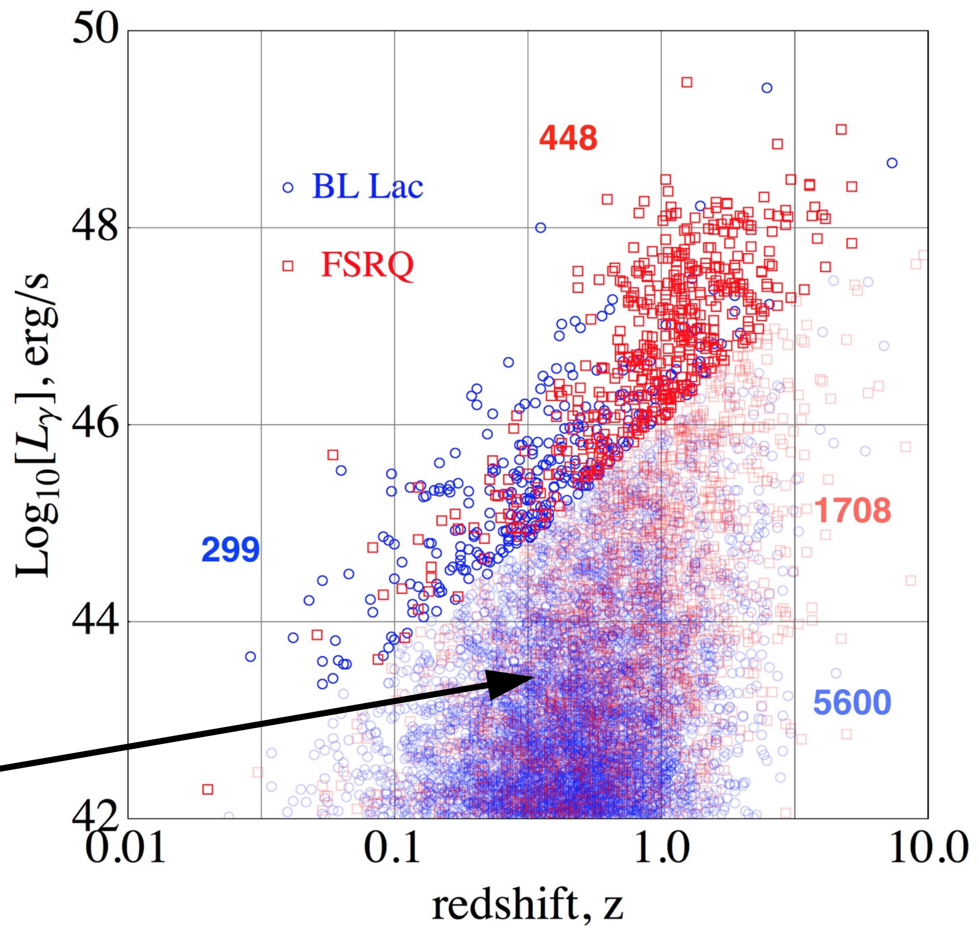
- Steady sources / flares, lower luminosities over longer times
- AGN: absence of spatial correlation with neutrino events (TXS?) → less than 10%!

Prime candidates based on observations

Viable source classes

- Lack of point sources indicates dim, abundant sources

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



Many unobserved
low luminosity objects!

[S. Gao – in preparation]

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)

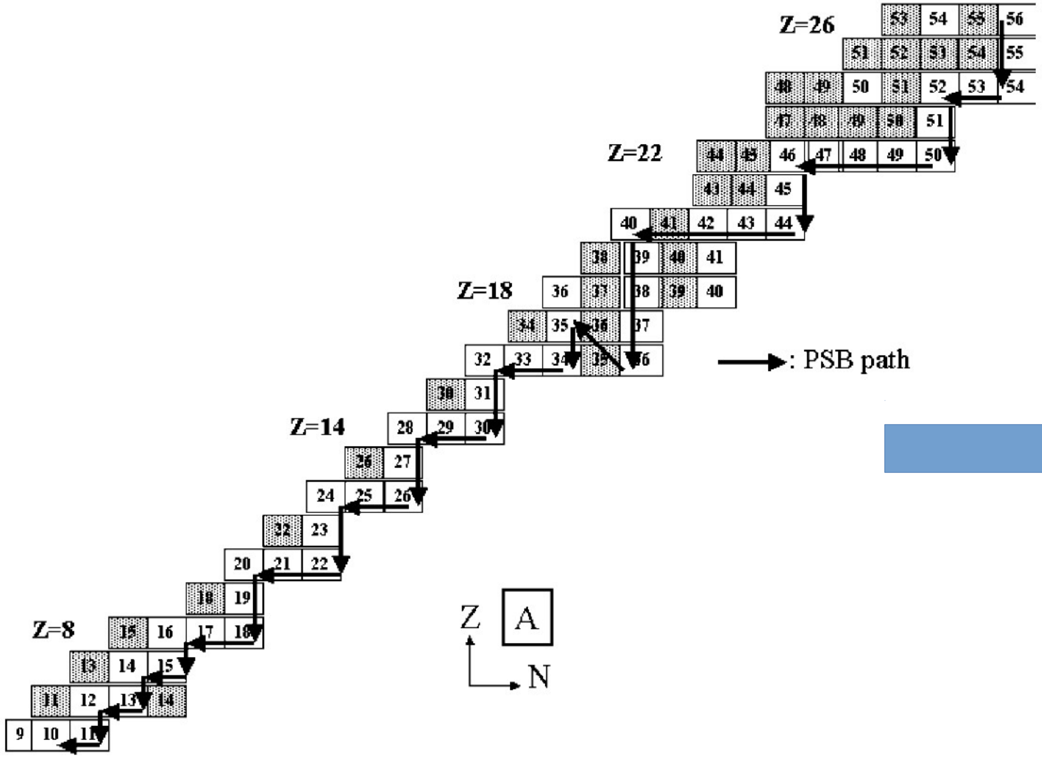
  1.) ~ 10^{54} erg for R ~ R_s

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

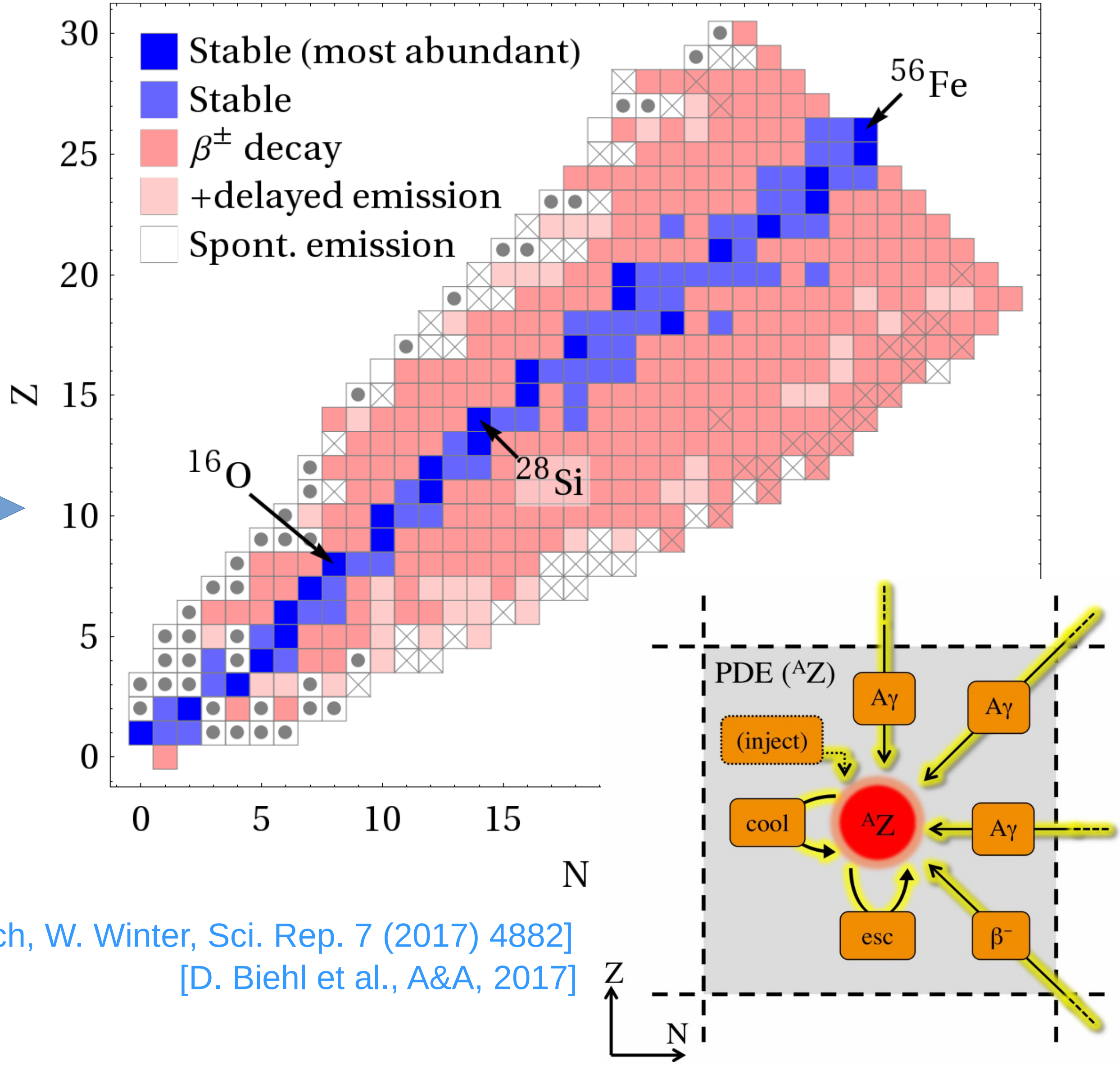
→ Sets the ball-park scale for released energy

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 et al., A&A, 2017]

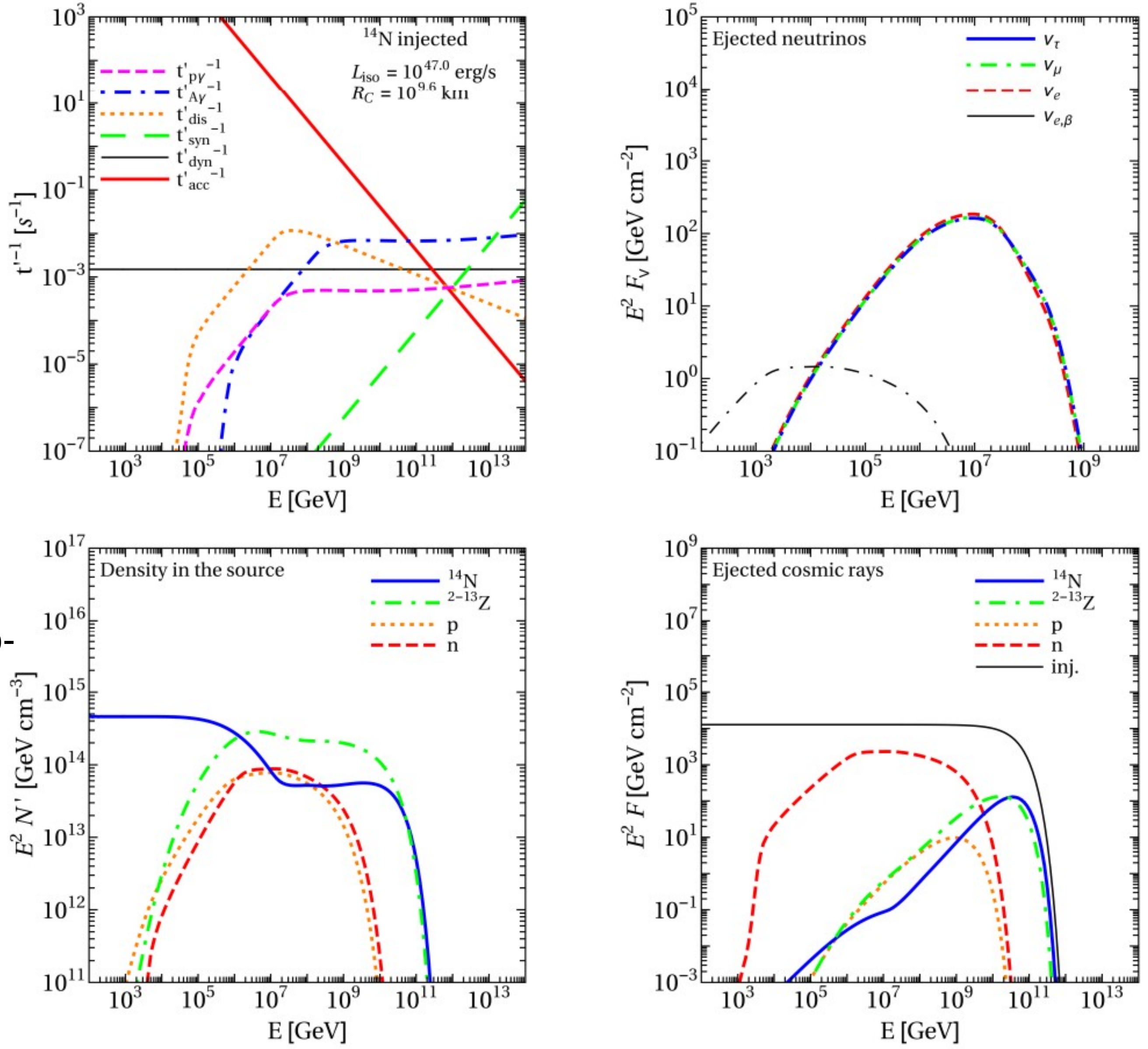
Main ingredients of our simulation

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 – arXiv:1711.03555]

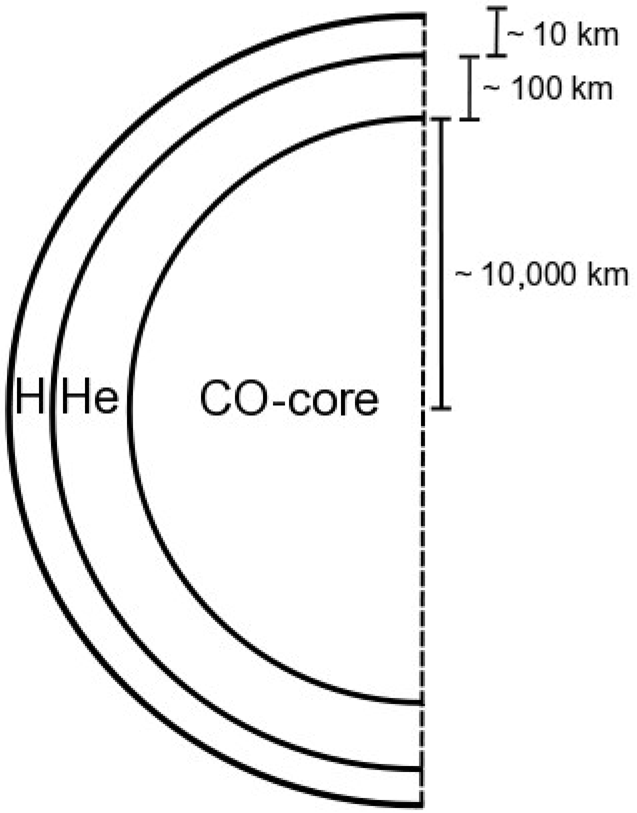
Possible scenarios for the progenitor system

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)]



Cross-section of typical white dwarf

Cosmological rate of TDEs

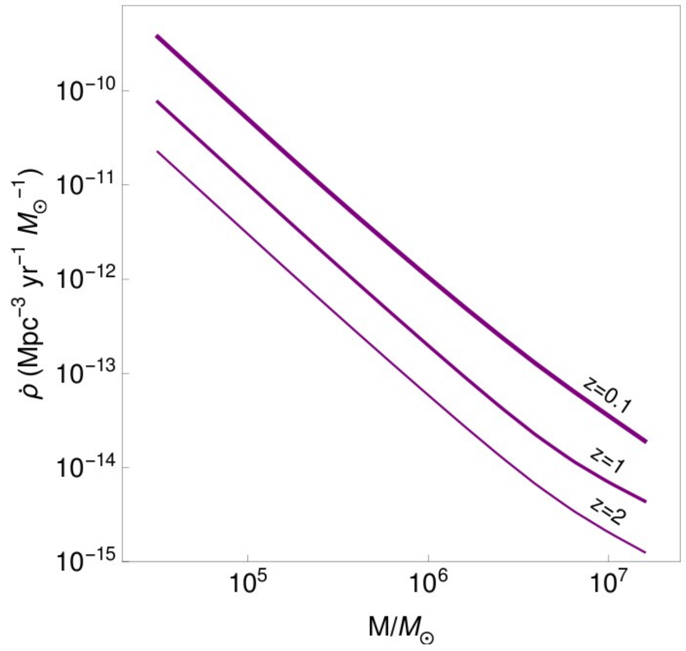
Evolution with redshift

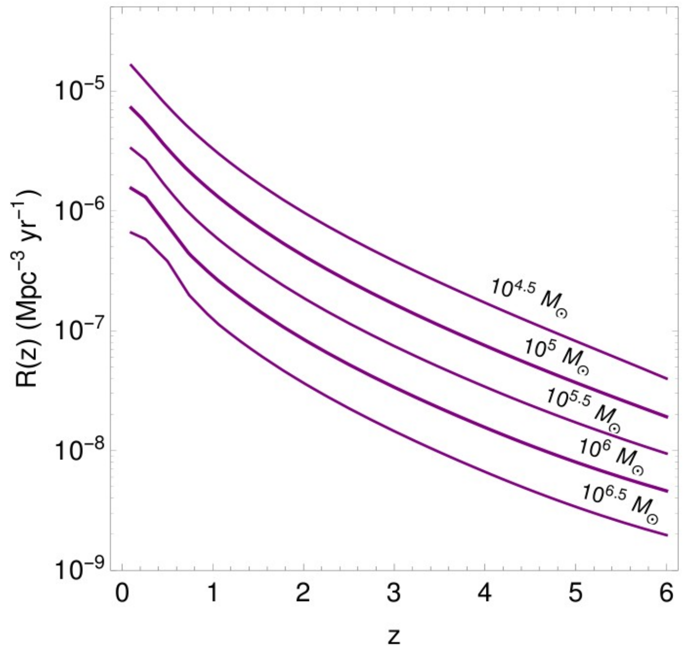
$$\dot{\rho}(z,M) = \dot{N}_{\mathrm{TD}}(M) f_{\mathrm{occ}}(M) \phi(z,M)$$

[F. Shankar et al. (2009)]
[A. Taylor, M. Ahlers, D. Hooper (2015)]
[C. S. Kochanek (2016)]
[N. C. Stone, B. D. Metzger (2016)]

Negative source evolution

- Black hole mass function Φ(z,M)
  - declines with z roughly as $(1+z)^{-3}$
  - scales like $M^{-3/2}$ for all z in considered mass range
- Occupation fraction determines minimum BH mass
- Rate of tidal disruptions per SMBH decreases weakly with increasing mass
- Rate of observable jetted TDEs suppressed by $\eta/(2\Gamma^2) \sim 5 \times 10^{-4}$
- Close sources dominate, i.e. less cosmogenic neutrinos and diffuse gamma-ray photons, heavier composition

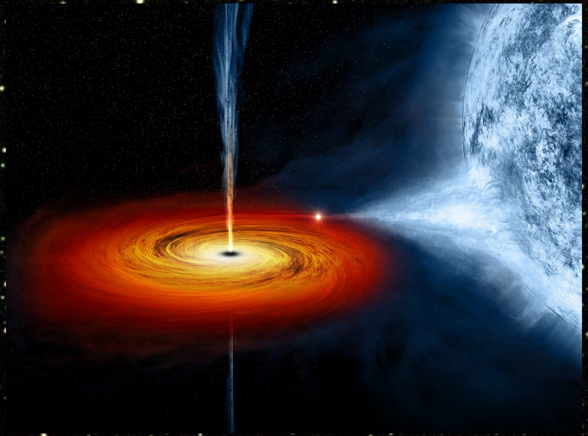




[C. Lunardini, W. Winter, PRD 95, 123001 (2017)]

Combined source-propagation model

Towards a complete picture



Source model

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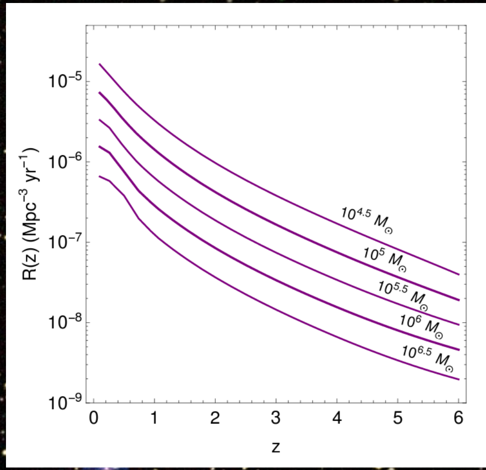

Source evolution

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)

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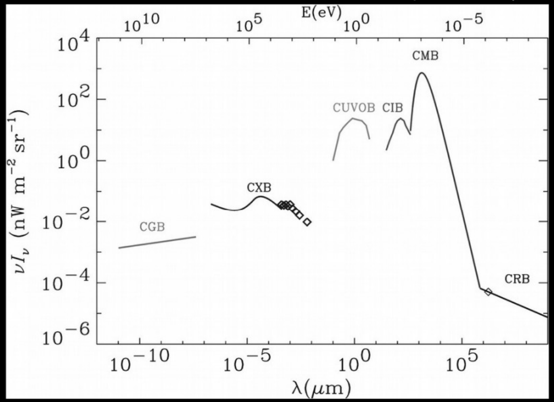

Interactions with CMB, CIB, ...

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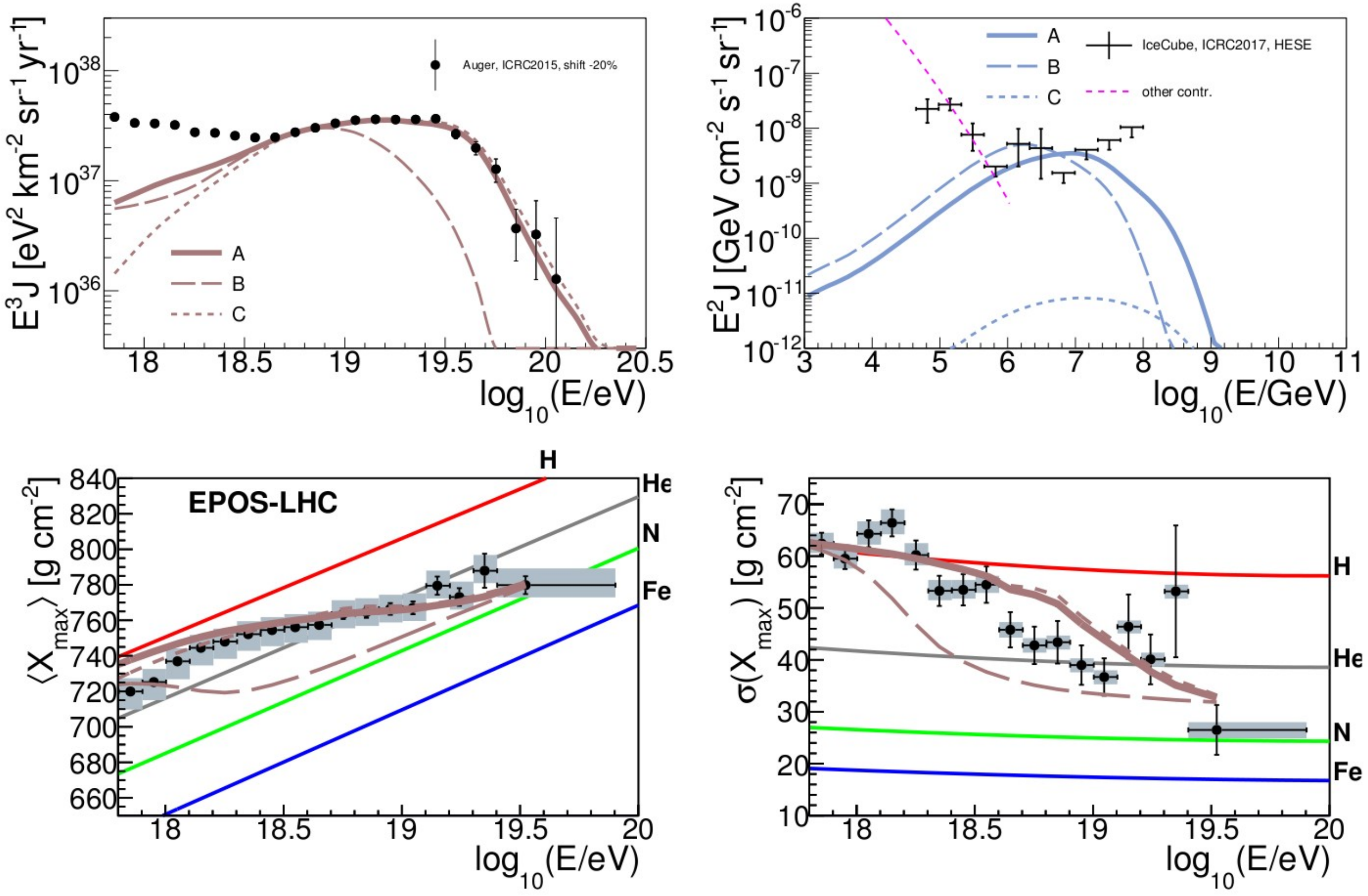
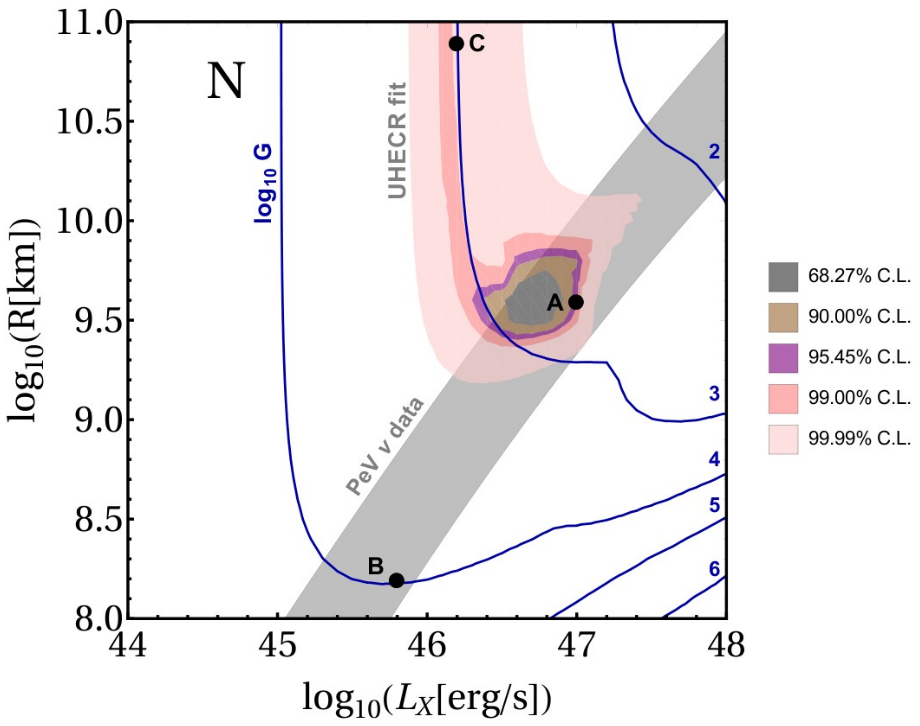
Interactions in atmosphere

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 – arXiv:1711.03555]

Prime candidates based on observations

Viable source classes

- Lack of point sources indicates dim, abundant sources

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

Starburst Galaxies (SBGs)

- Spectral index -2 ... -2.5 from Fermi shock acceleration in order to describe large energy range of neutrino spectrum
- Expected for Ap / pp-interactions
- Neutrino spectrum must not be much softer than -2 to avoid constraints from diffuse extragalactic gamma-ray background

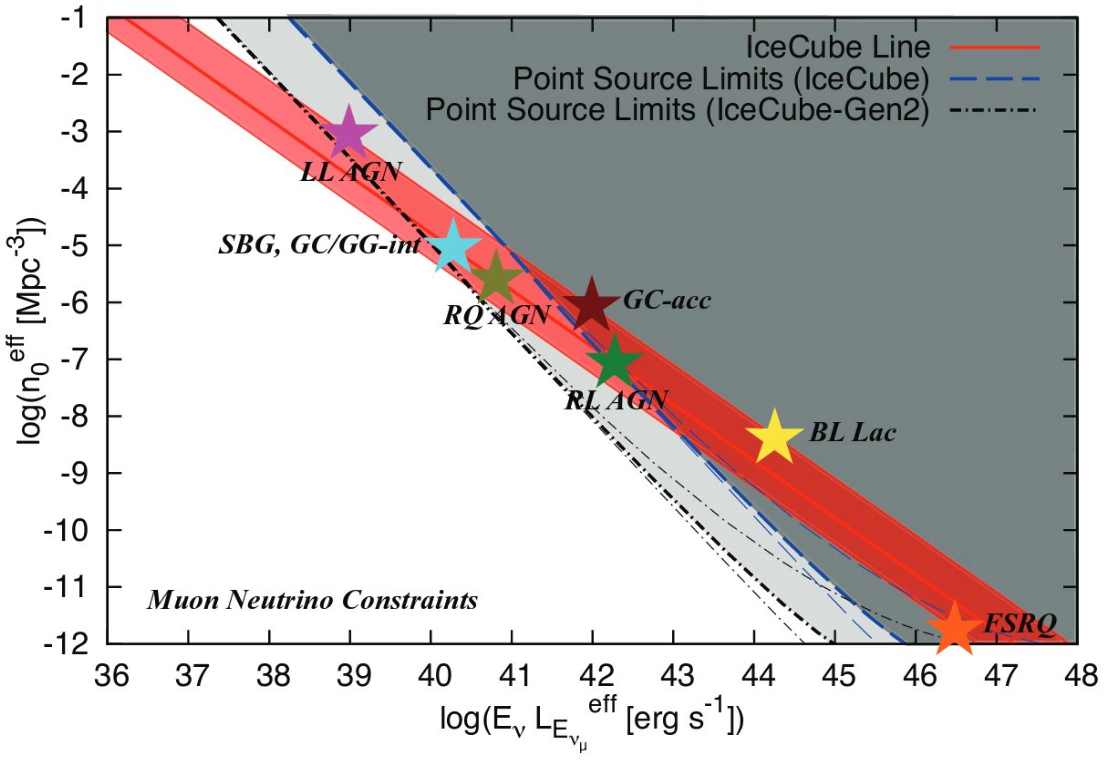
[I. Tamborra, S. Ando, K. Murase (2014)]
[X.-C. Chang, R.-Y. Liu, X.-Y. Wang (2015)]

- Maximum primary energy in SBGs not sufficient for neutrino energies much larger than PeV
- Question remains open

[K. Bechtol et al. (2015)]
[K. Murase, E. Waxman (2016)]

→ High-energy events from rare Aγ / pγ sources

Limits on source density of steady sources by non-observation of neutrino multiplets



[K. Murase, E. Waxman – PRD 94 (2016) 103006]

Experimental constraints

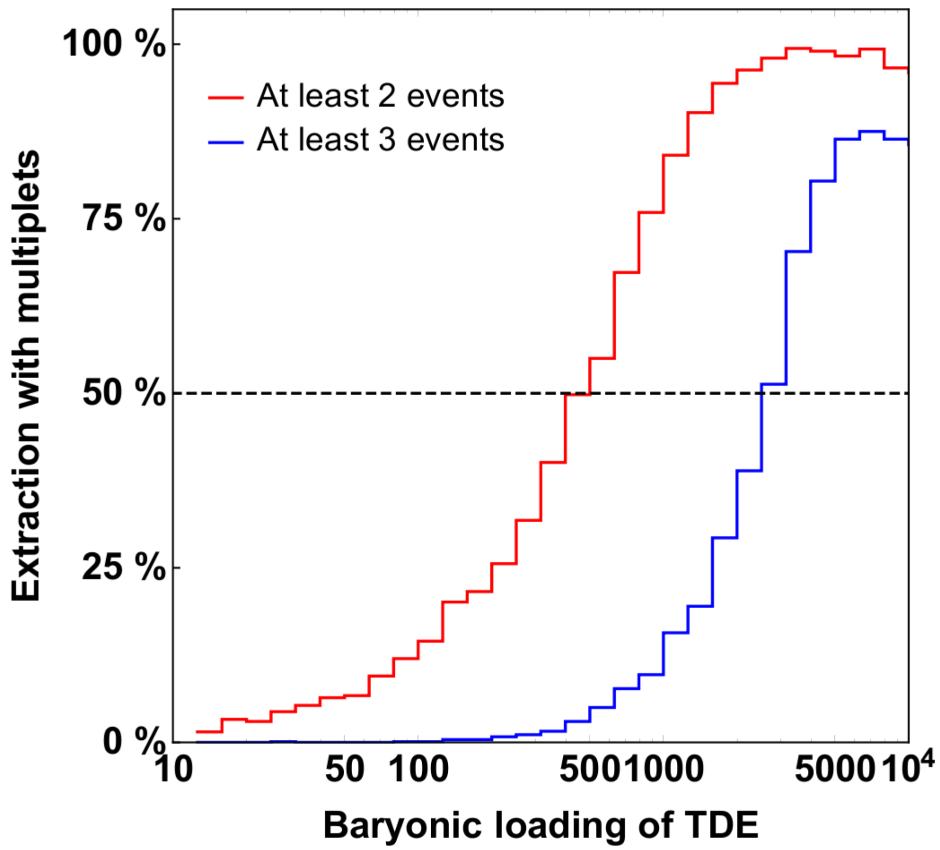
Neutrino multiplets, X-ray data, baryonic loading

Our results are consistent with current observations

- Best fit yields G ~ 540
- Disruption of a ~ 1 solar mass WD with Γ ~ 10 gives a baryonic loading of ~ 0.15 x $2\Gamma^2$ M/E ~ 525
- Matches corresponding local apparent rate ~ 0.1 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

Consistent with rate of WD disruption! If there is no tension with multiplet constraints, there is no problem with energetics and X-ray data!

- With baryonic loading ~ 500, 0.3 events are expected
- ~ 10 TDEs to account for 3 events at PeV energies
- Rough estimate of the probability to get a multiplet 1–(8/9)x(7/8) ~ 22%



[A. Palladino, W. Winter, arXiv:1802.07277]

Limitations of our model

And possible alternatives

Assumptions of the model

- Evolution of the TDE rate with redshift: intermediate / small mass BH might be less numerous than in the past
  - less negative or even positive source evolution, combined description of UHECRs and neutrinos becomes challenging

[T. Alexander, B. Bar-Or (2017)]
[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – arXiv:1711.03555]

- Expected gamma-ray flux associated with an all-flavor neutrino flux of 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} consistent with observations due to the use of a negative evolution

[M. Ackermann et al. (2016)]
[K. Bechtol et al. (2017)]

- Input parameters fixed inspired by Swift J1644+57: alternative hypotheses such as
  - Ultra-long GRBs caused by the disruption of WDs, e.g. GRB 111209A; shorter duration and variability, different X-ray spectra

[R. V. Shcherbakov et al. (2017)]

  - Tidal disruption of neutron stars associated to gravitational wave events, e.g. GW170817; the observed short GRB in the follow-up may be interpreted as a representative of a new population of jetted TDEs

[B. P. Abbott et al. (2017)]
[ongoing project with D. Boncioli, X. Rodrigues, A. Taylor]