Cosmogenic Neutrinos challenge the Proton Dip Model

Heinze, Boncioli, Bustamante, Winter arXiv 1512.05988 , ApJ 825 (2016) no.2, 122

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DESY Zeuthen

HAP Workshop | Non-Thermal Universe
22nd September 2016

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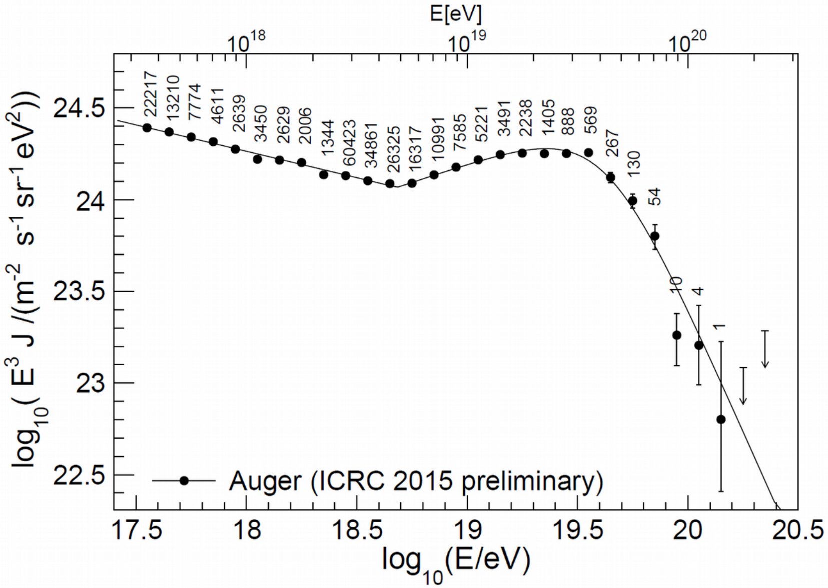
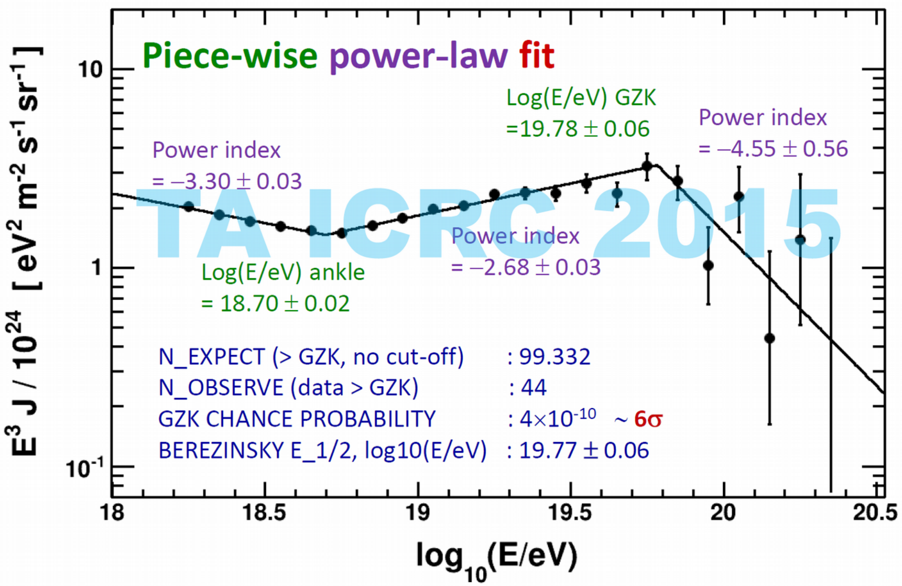
UHE Cosmic Ray spectrum

Auger Collaboration @ ICRC 2015

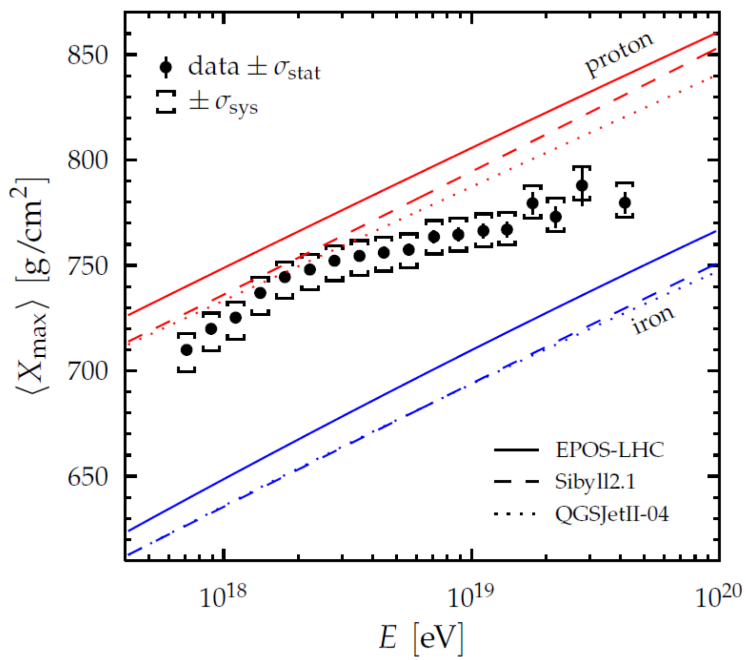


TA Collaboration @ ICRC 2015

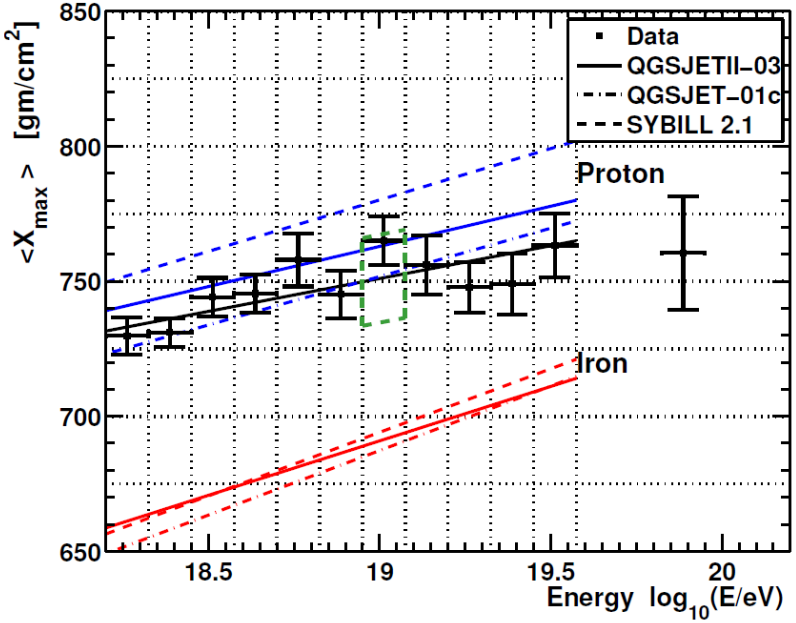


- Main spectral features: **ankle** and **cutoff**
- Interpretation ambiguous, different models viable
  - Protons or nuclei
  - Point of galactic – extragalactic transition
- **Dip model:** extragalactic and pure proton UHECRs
  - Ankle = pair - production dip
  - Cutoff = *GZK* - cutoff

UHECR mass composition



TA & Auger working group @ ICRC 2015

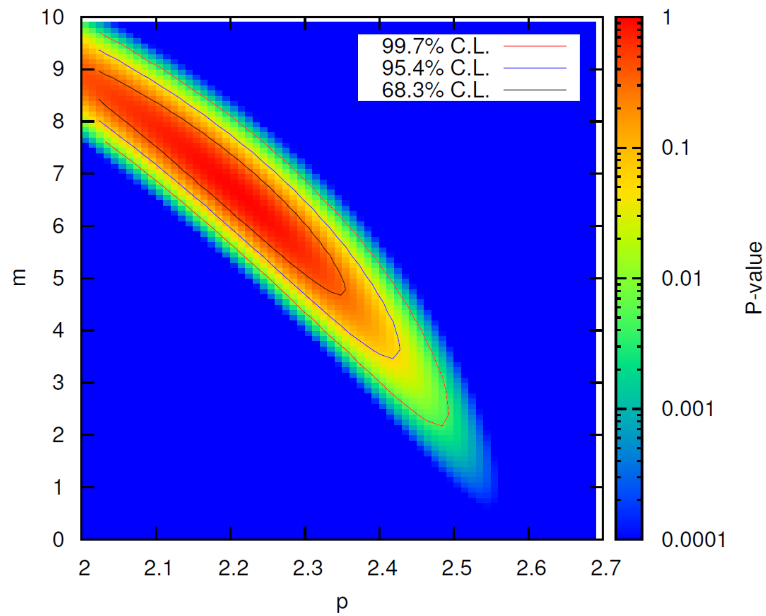


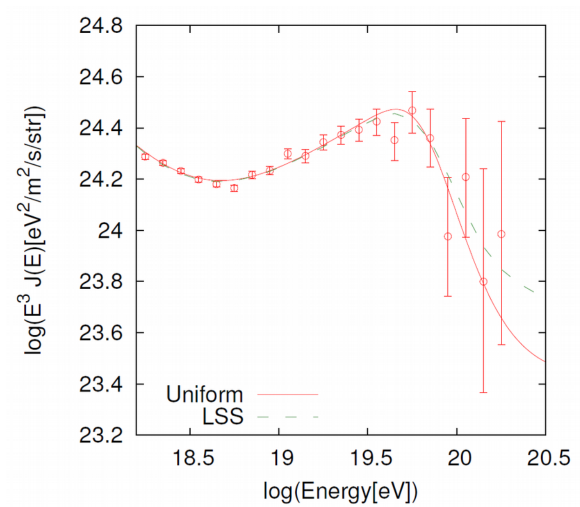
- > Auger: *heavier composition* at highest energies
- > TA: consistent with *pure proton* composition
- > High uncertainties → experiments still in agreement statistically
- > **We use TA - data:** consistent with the dip model

Interpretation of the UHECR spectrum

$$\mathcal{L}_p^{\mathrm{inj}}(E,z) \propto H(z)\, E^{-\gamma}\, \exp(-E/E_{max})$$

- Scan in 2 injection parameters
  - Source evolution $H(z) = (1 + z)^m$
  - Power law spectral index
  - **Fixed E_{max}** = 10^{12} GeV (above *GZK*-threshold)
  - Only local redshifts $z < 2$
- Best fit with:
  - Spectral index of 2 – 2.5
  - Strong source evolution
- *GZK* - interpretation implied by construction?
- What does the **strong source evolution** mean for **cosmogenic neutrinos** ?





TA Collaboration @ ICRC 2015

Model: Injection and Propagation

- Injection Model: identical, homogeneous proton sources
  - Source evolution
  - Power law at injection
  - Maximal energy

$$\mathcal{L}_p^{\mathrm{inj}}(E, z) \propto H(z)\, E^{-\gamma}\, \exp(-E/E_{max})$$

- Parametrization relative to SFR

$$H(z) = (1+z)^m \cdot \begin{cases} (1+z)^{3.44}, & z \leq 0.97 \\ 10^{1.09}(1+z)^{-0.26}, & 0.97 < z \leq 4.48 \\ 10^{6.66}(1+z)^{-7.8}, & z > 4.48 \end{cases}$$

Hopkins & Beacom astro-ph/0601463

- Energy losses during propagation:
  - Adiabatic energy losses
  - Photo-pair-production (CIB & CMB)
  - Photo-pion-production (CIB & CMB)

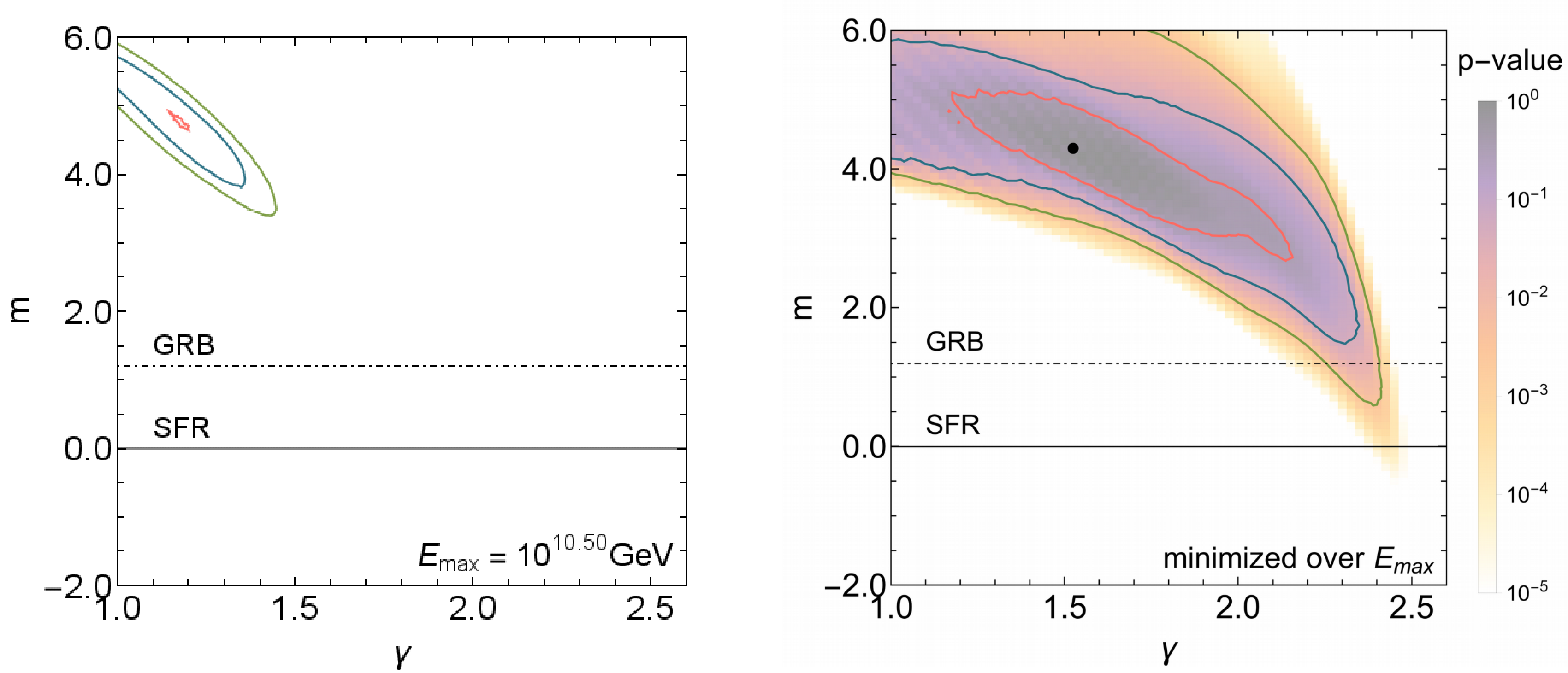
→ Computed numerically via the transport equation

Fit to TA-data

- Fit – parameters:
  - Normalization f
  - Energy shift $E' \equiv (1+\delta_E)E$

$$\chi^2 = \sum_i \frac{\left(f\, J^{\mathrm{mod}}(E_i'; \gamma, E_{\max}, m) - J^{\mathrm{TA}}(E_i)\right)^2}{\sigma_i^2} + \left(\frac{\delta_E}{\sigma_E}\right)^2$$

- 3D manifold shown as 2D projections



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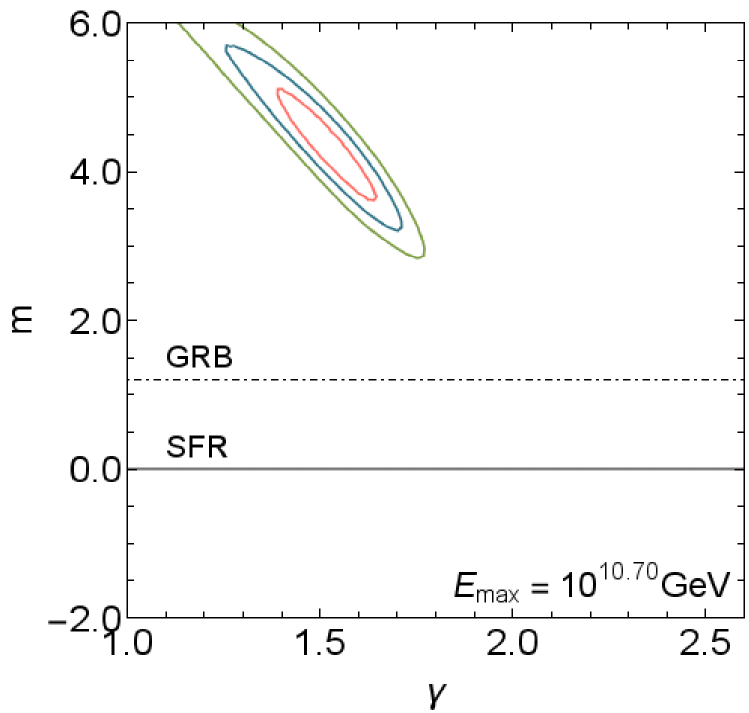

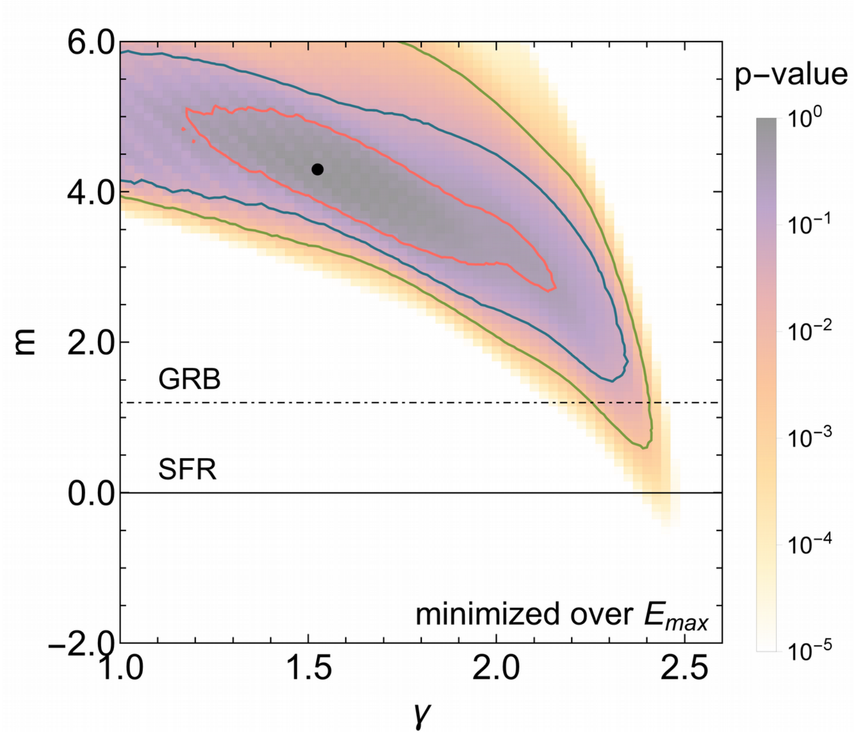

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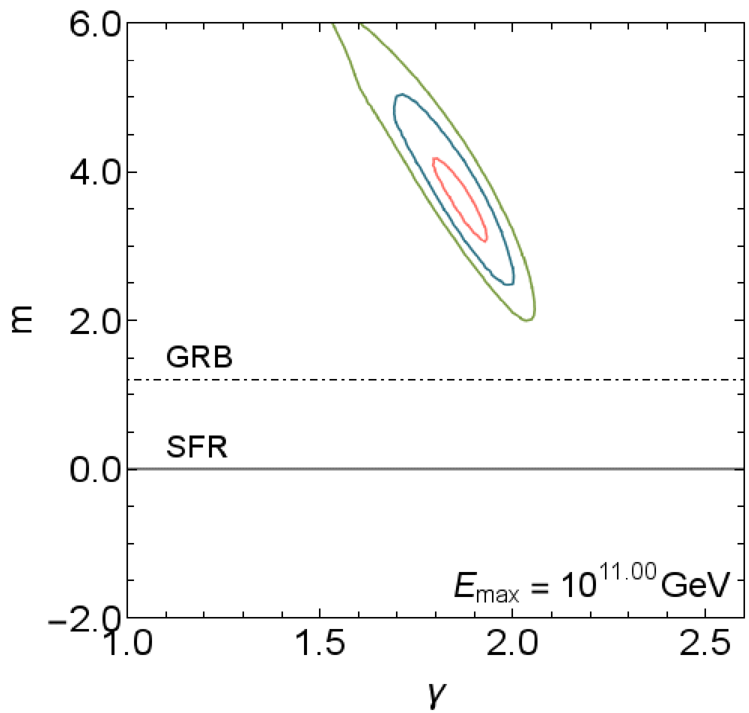

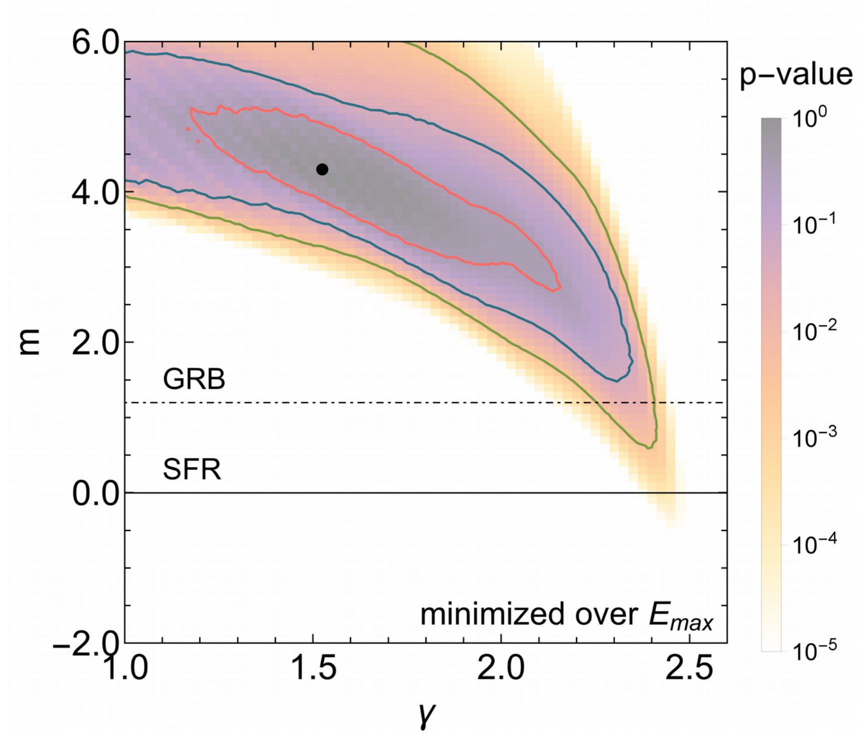

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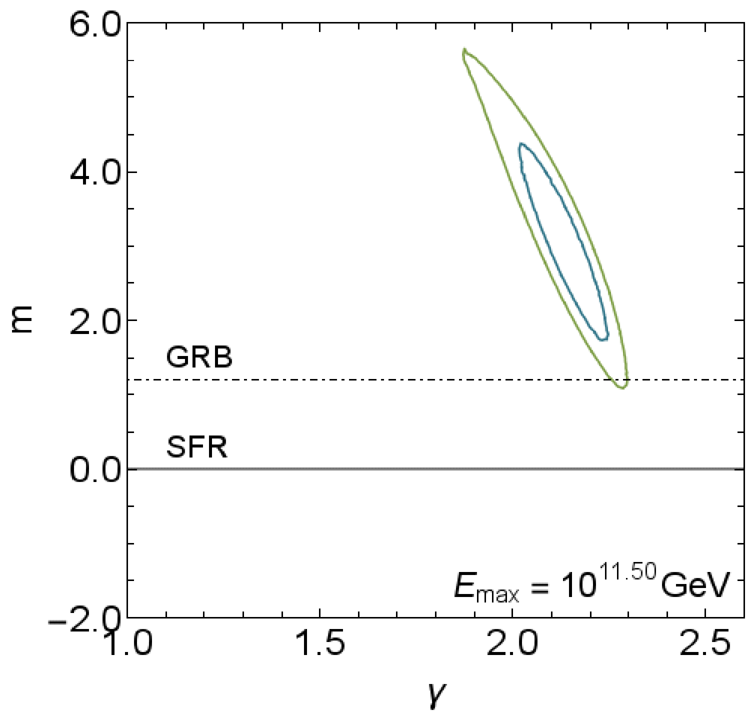

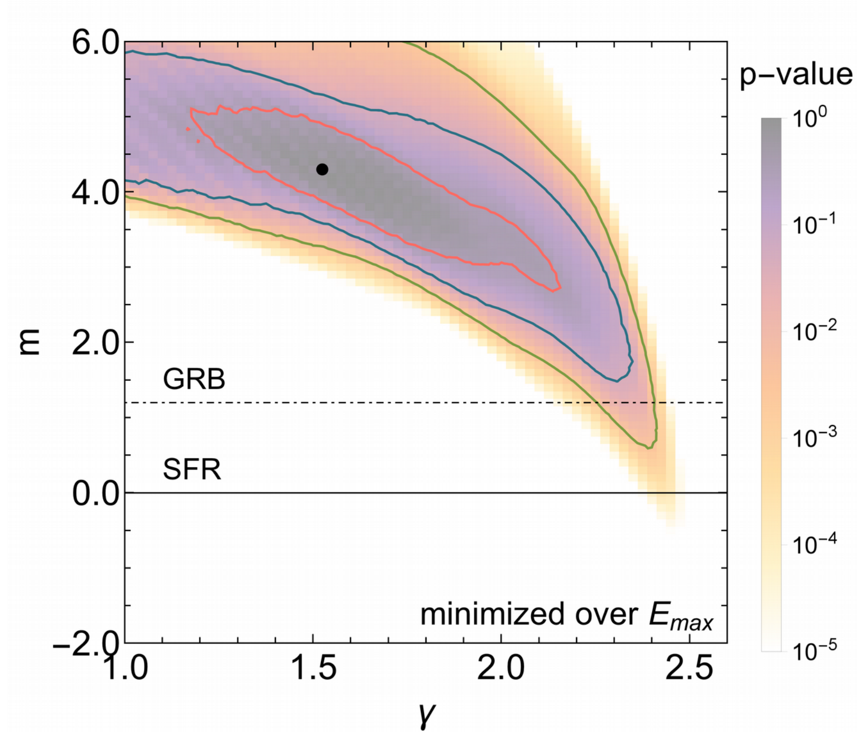

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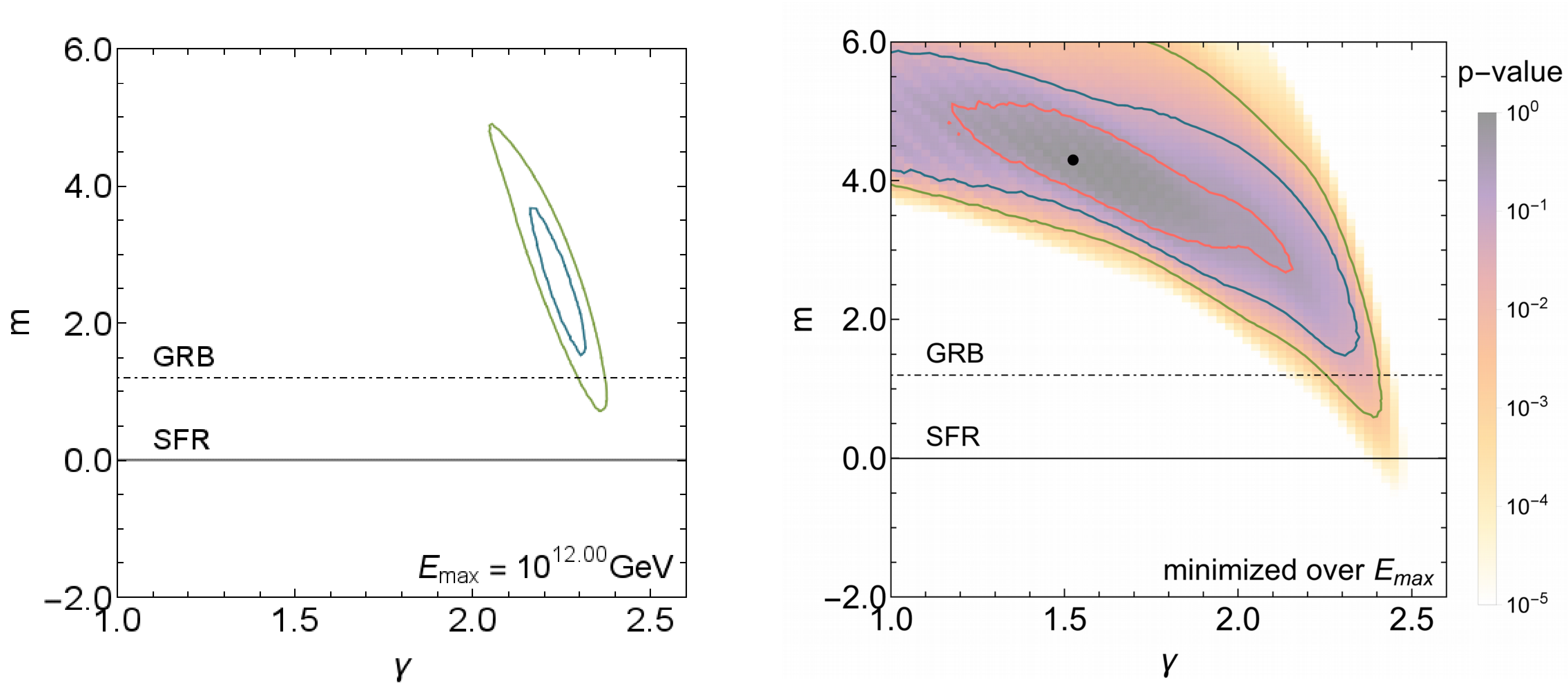

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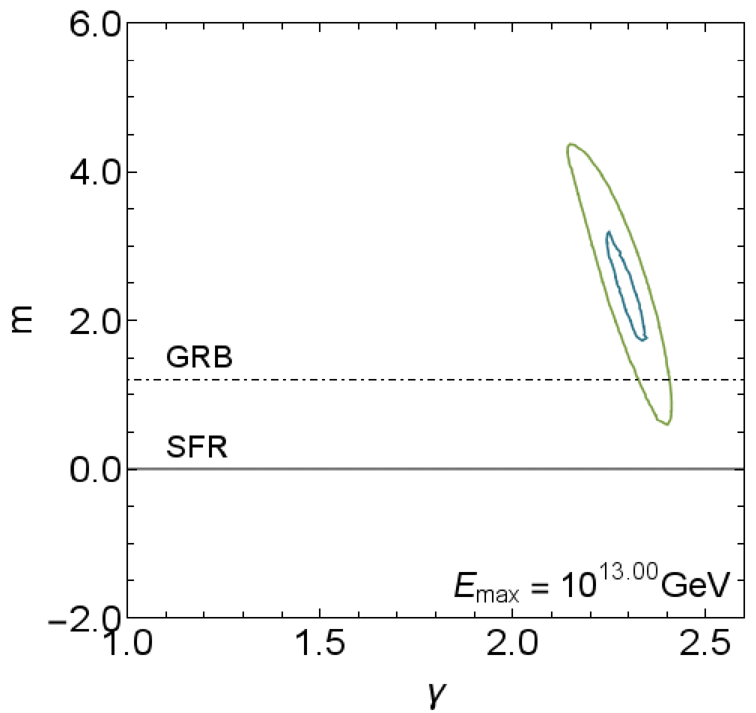
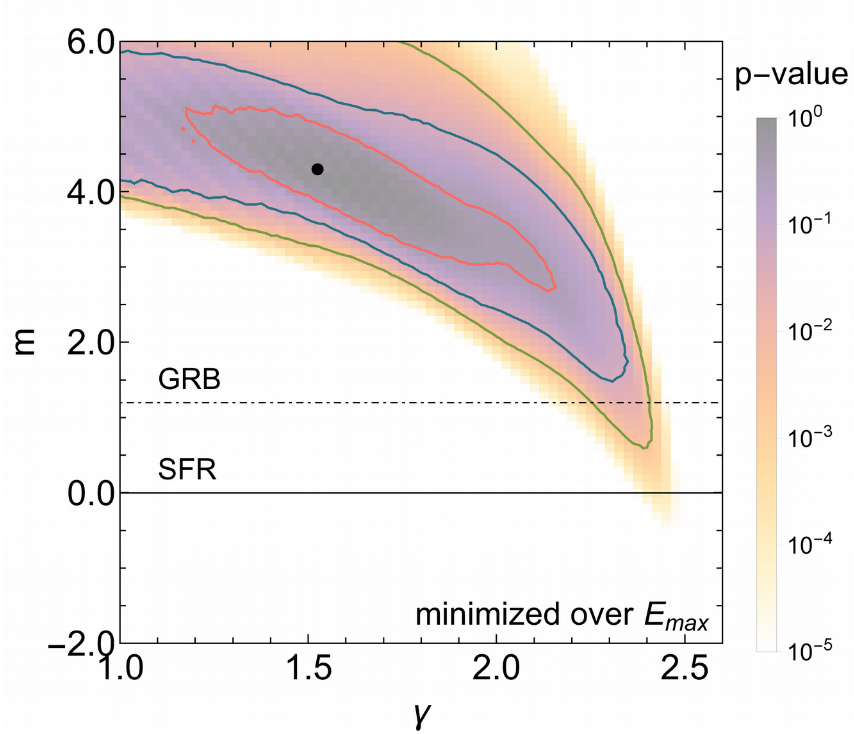
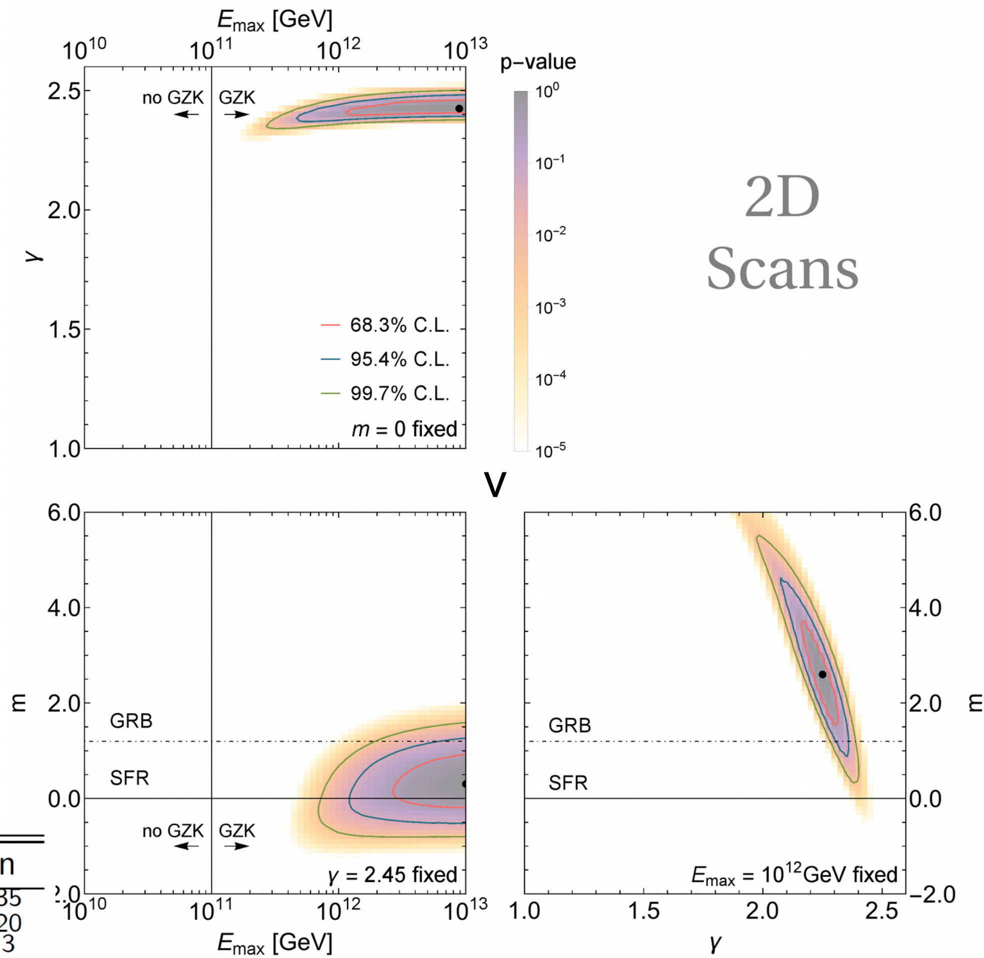




Results: Parameter space

- **>** Enlarged parameter regions compared to 2D fit
  - Multi - parameter correlation that was hidden in 2D
- **>** 3D Best fit compared to 2D:
  - Harder spectral index / stronger source evolution
  - E_{max} below *GZK* - threshold $\rightarrow$ suppression source related
  - Large energy shift (≈ 35%)

	2D scan			3D scan
γ	2.25	*2.45	2.42	$1.52^{+0.35}_{-0.20}$
$\log_{10}(E_{max}/\mathrm{GeV})$	*12.0	13.0	12.9	$10.7^{+0.3}_{-0.1}$
m	2.6	0.3	*0.0	$4.3^{+0.4}_{-0.8}$
$\chi^2_{\min}$	34.7/17	47.8/17	47.8/17	30.8/16



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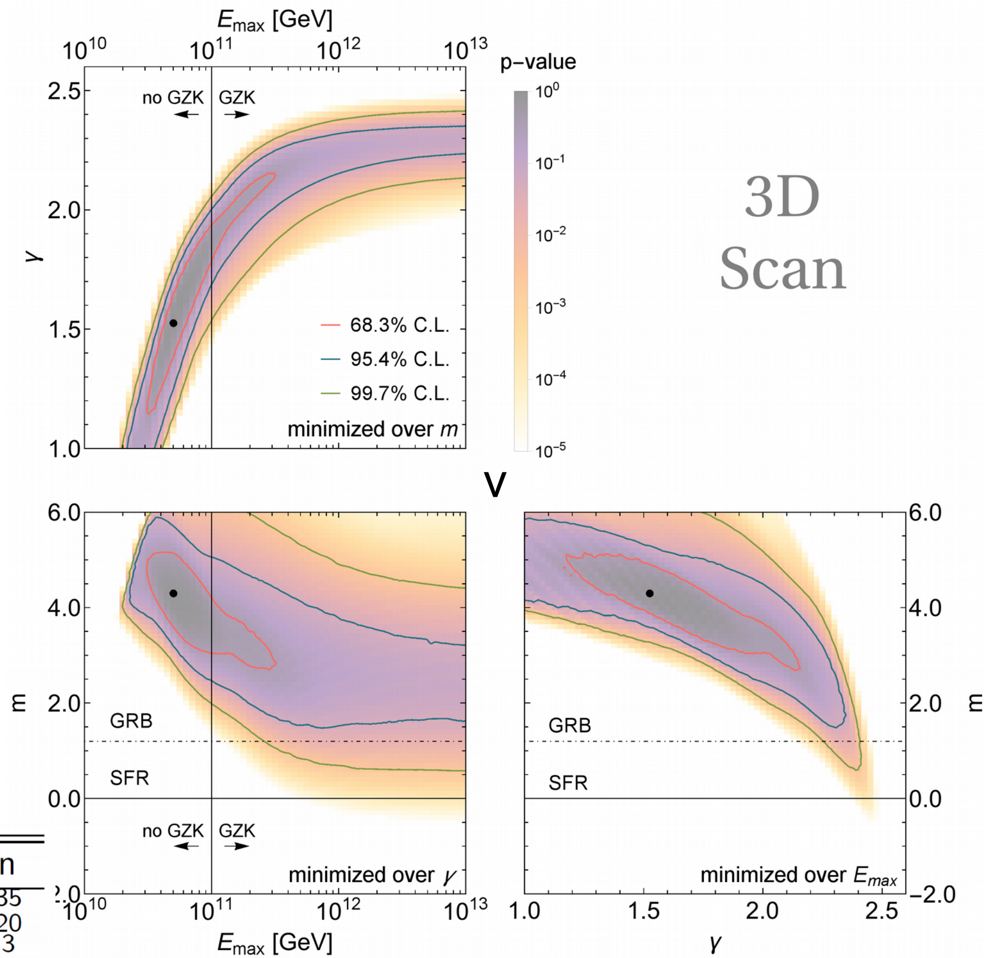

3D Scan

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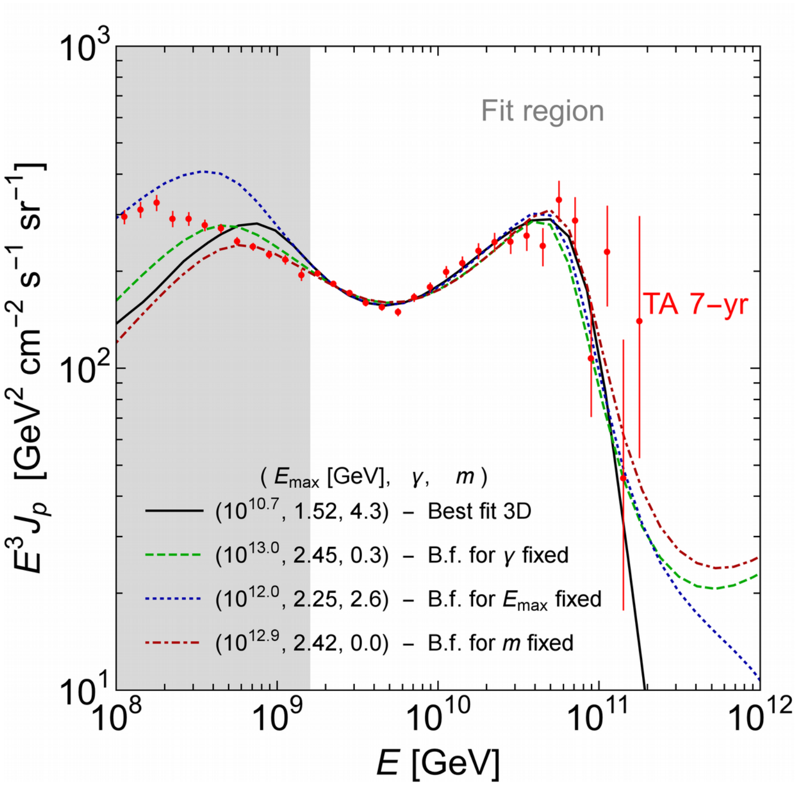
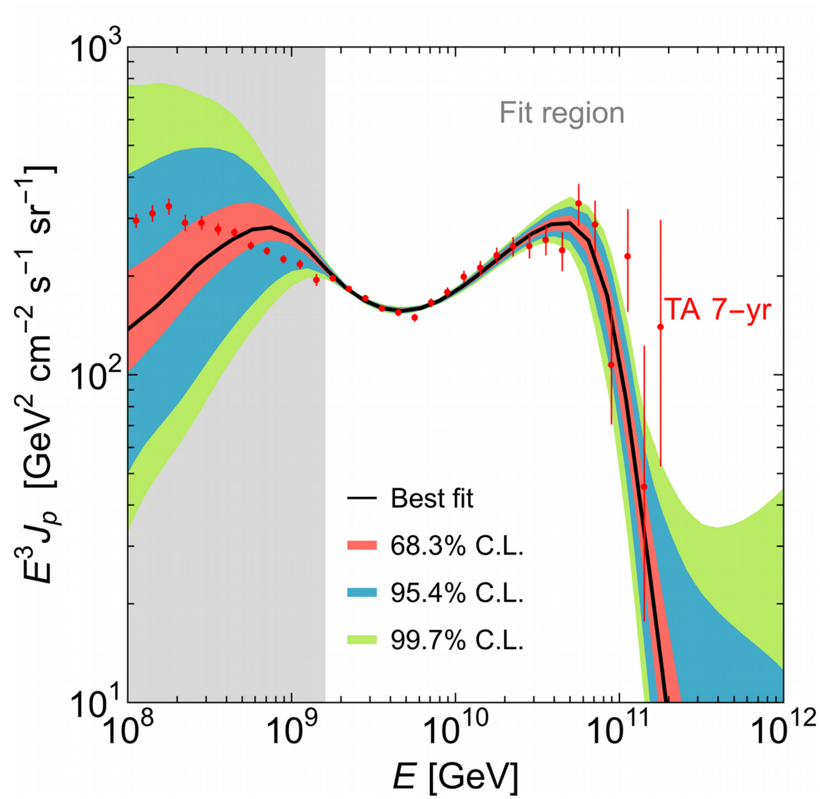
Results: Cosmic Ray Spectra

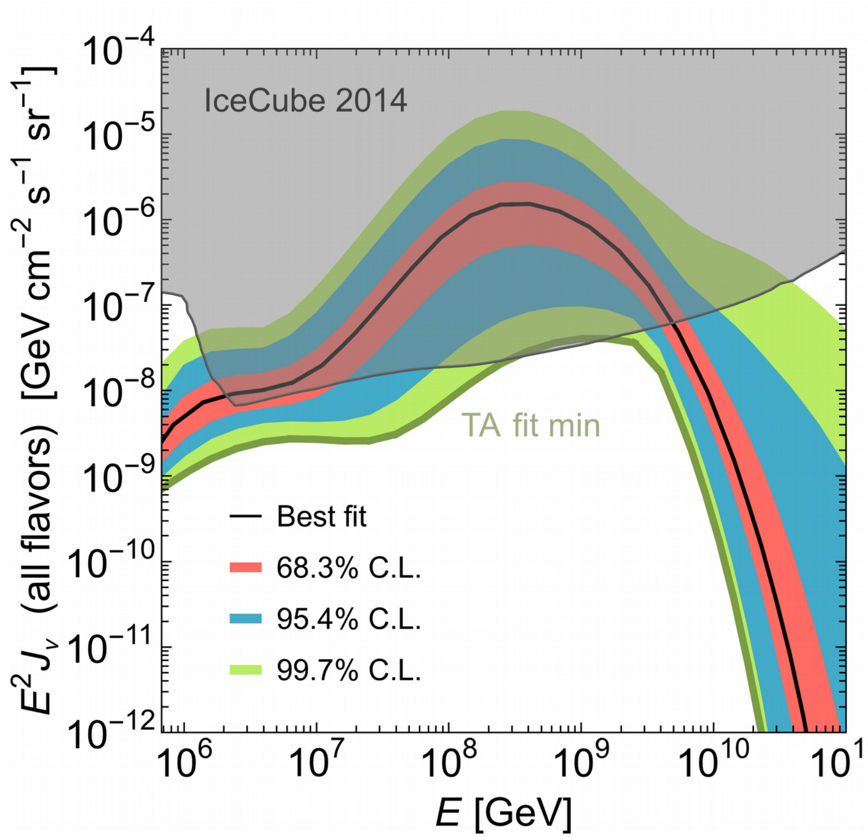




- Fit driven by ankle region (highest statistics)
- Strong overshoot below the fit range
  - Suppressed by diffusion in magn. fields
  - Low energy suppression at the sources

Results: Cosmogenic Neutrino Flux

- Neutrino flux ranges: min/max over allowed parameter space
- The lowest flux (**'TA fit min'**) exceeds the IceCube limit
- High flux mainly due to strong source evolution



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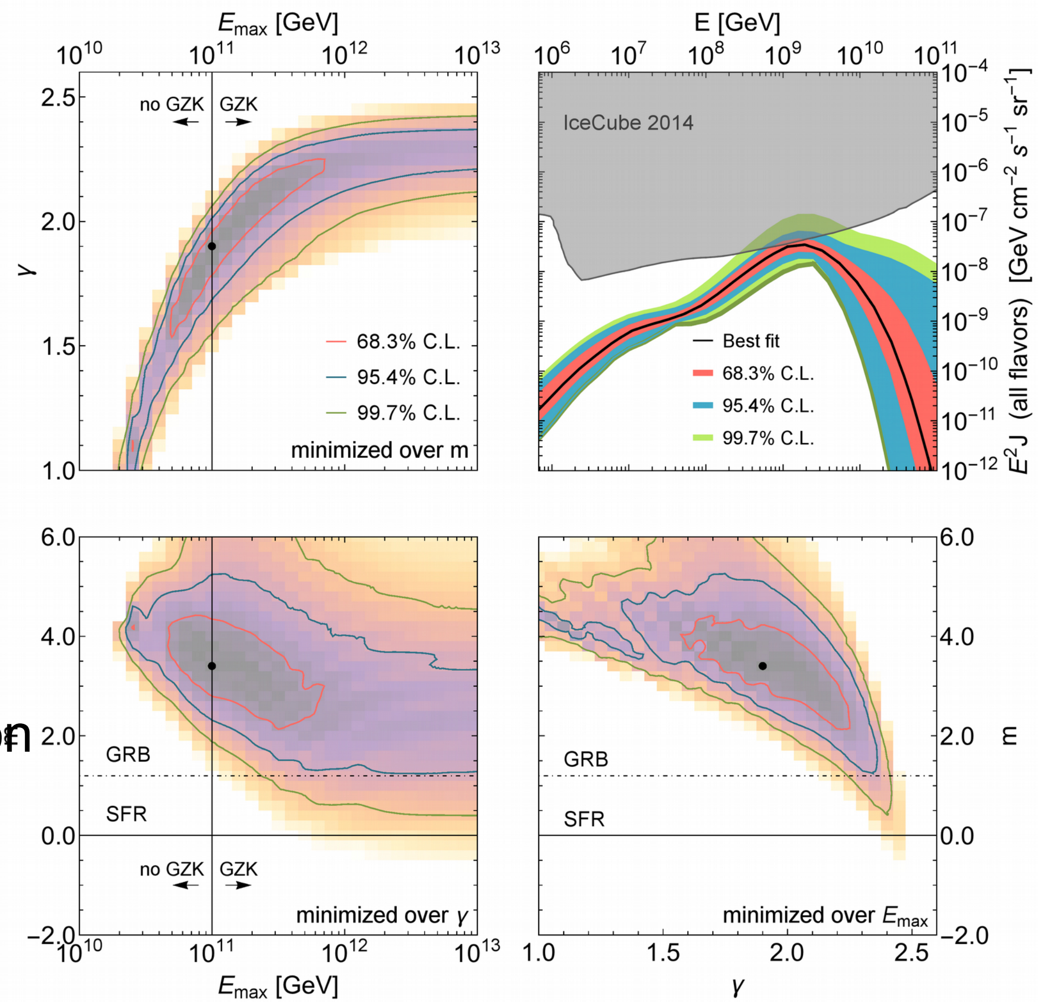
- Expected events:

	ν events
Best fit	180.6
68.3% C.L. min flux	62.7
95.4% C.L. min flux	12.4
99.7% C.L. min flux, **TA fit min**	4.9

- **Can be rejected at 95% C.L.**

Local injection (z < 1) only

- Minimal source evolution:
  - Injection only for z < 1
  - Parameter space stays qualitatively the same
- UHE cosmic rays are only sensitive to the local universe
- No contribution from high *z* → neutrino flux below limit
- *Still:* a realistic source evolution would continue to higher *z*

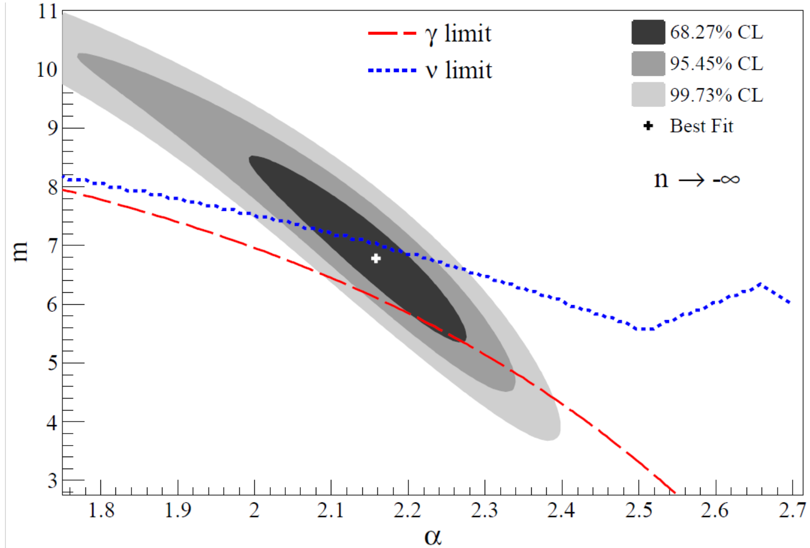


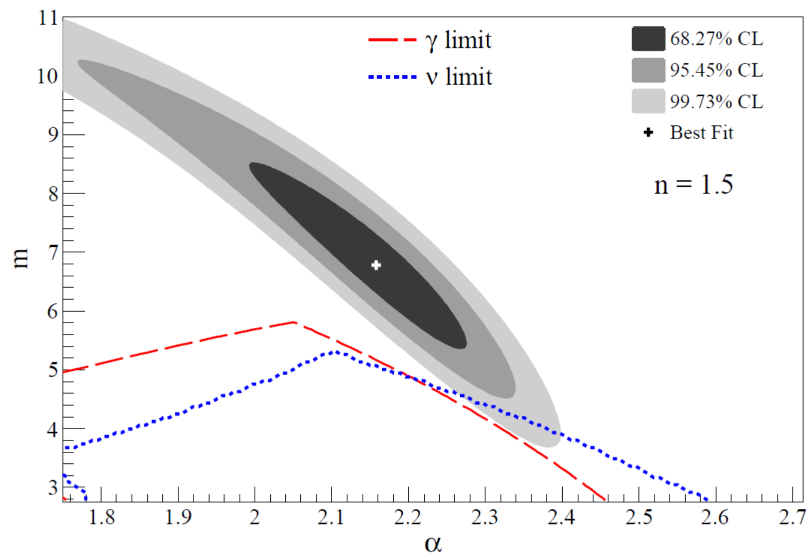
Gamma Ray Constraints on Proton dip model

- Gamma Ray and neutrino constraints for broken power law source evolution

$$S(z) = \begin{cases} (1+z)^m & z \leq 1 \\ 2^{m-n}\,(1+z)^n & z > 1 \;\&\; z \leq 6 \\ 0 & z > 6 \end{cases}$$

- Gamma ray limit stronger only for local sources
- Neutrino limit becomes stronger for distant sources





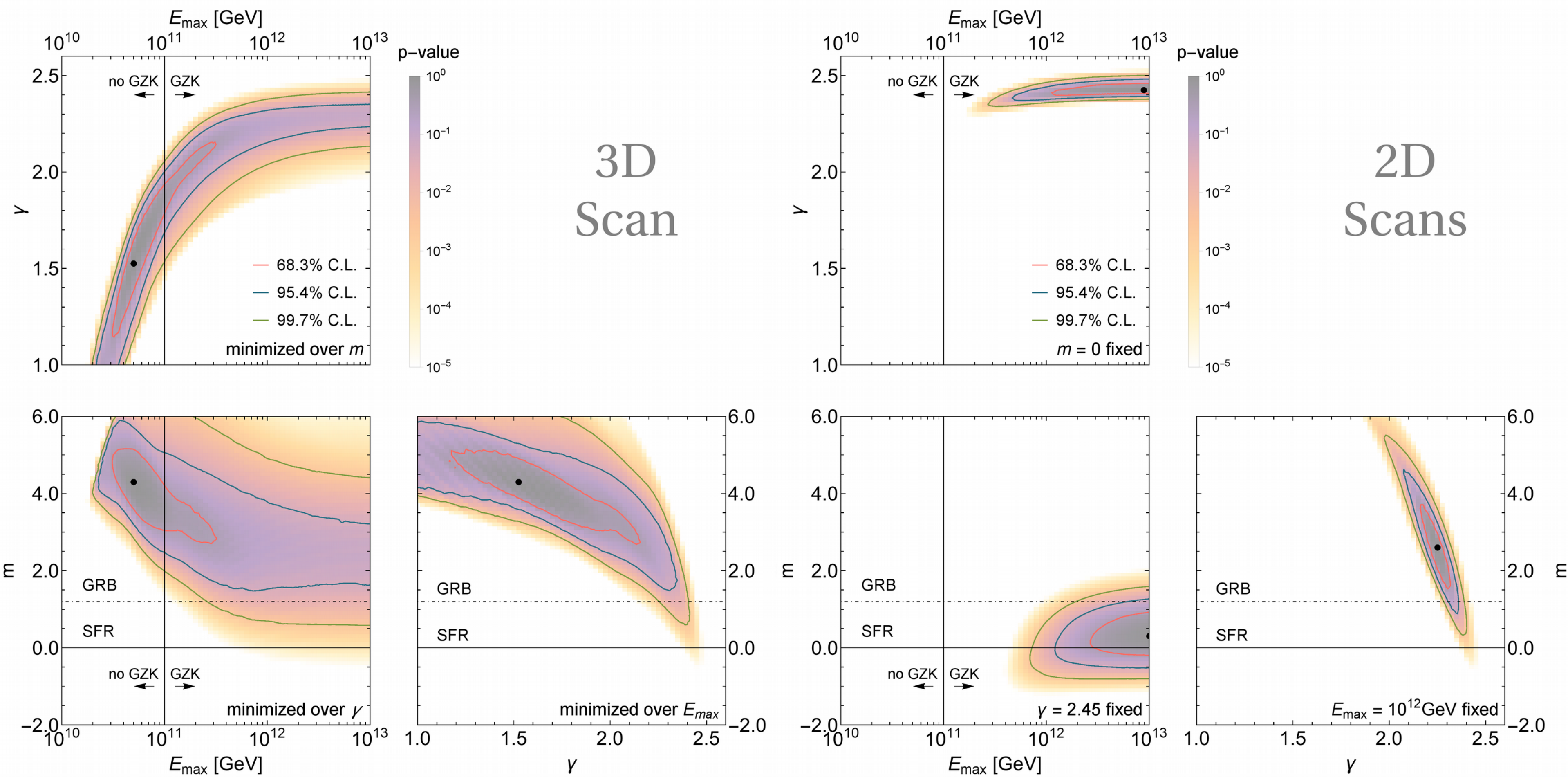
Supanitsky 1607.00290

Summary

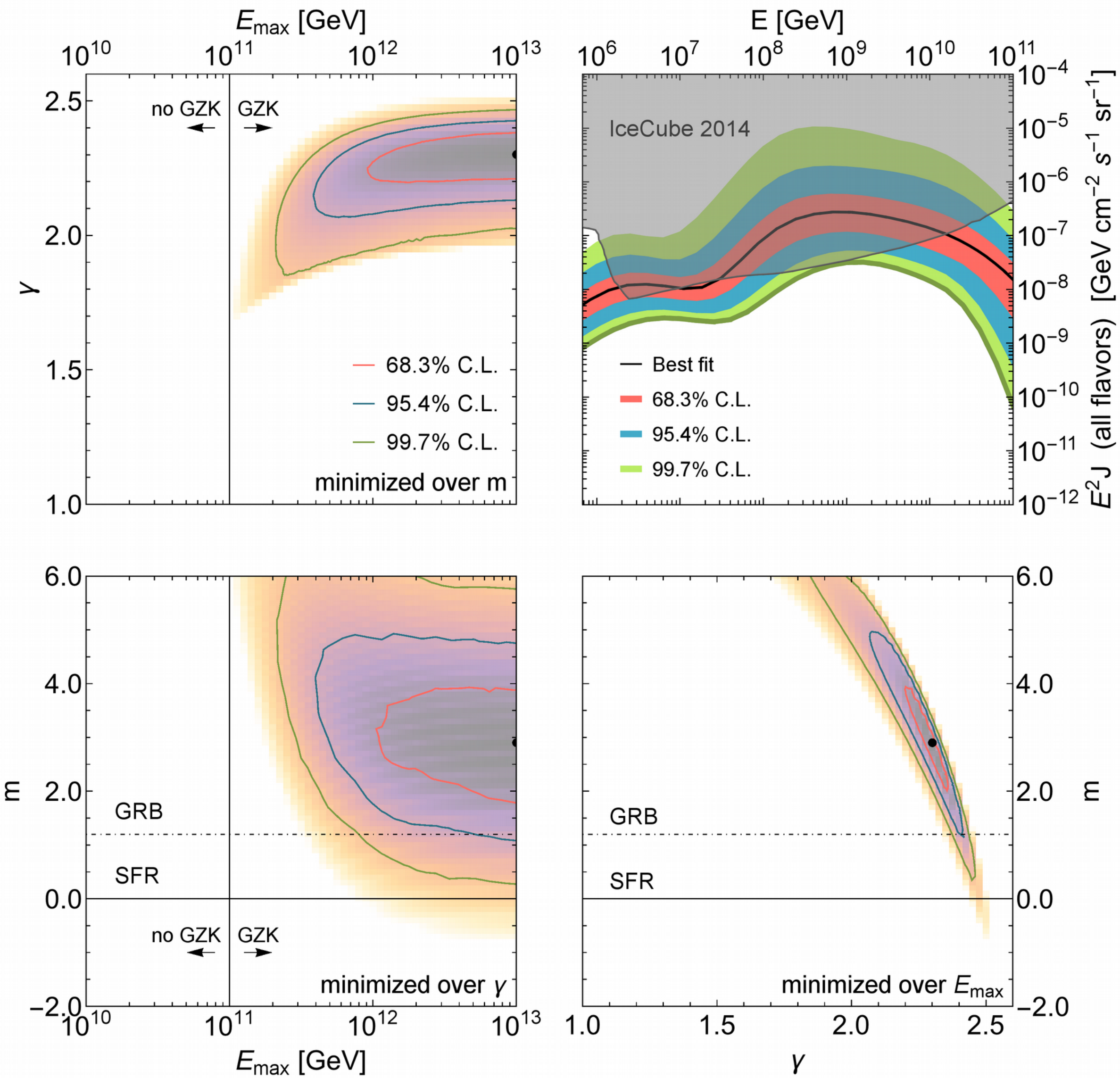
- Cosmogenic Neutrinos limit the astrophysical scenarios **independent of composition measurements**
- Fitting 3 instead of 2 astrophysical parameters enlarges the allowed parameter space
  - **Hard spectra**, **strong source evolution** and **low maximal energy** slightly favored over the *GZK* cutoff scenario
  - Fixing a high maximal energy implicitly assumes *GZK* - interpretation
- Expected **neutrino flux challenges the proton dip model**
  - Can only be compensated by cutting off injection at small redshifts
- Gamma Rays as can be additional messengers
  - Complementary to neutrinos:
    stronger limit for local, but weaker limit for distant sources

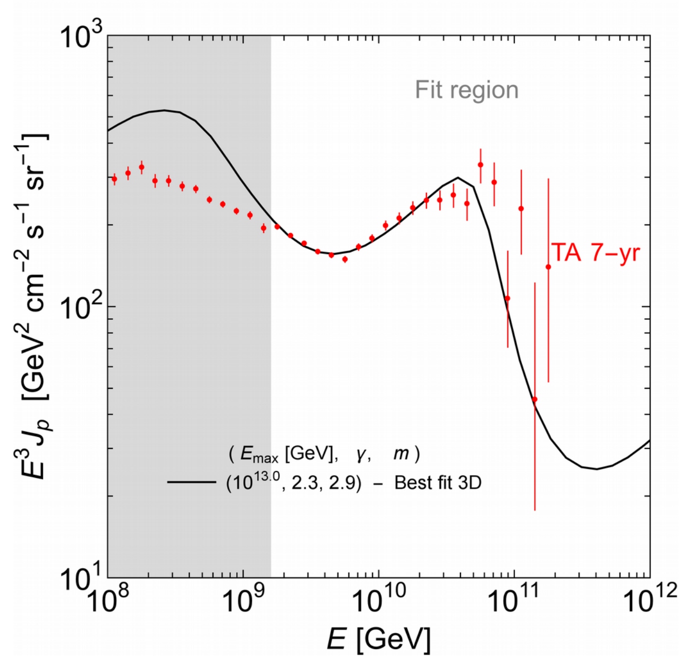
Backup Slides

2D scan vs 3D scan

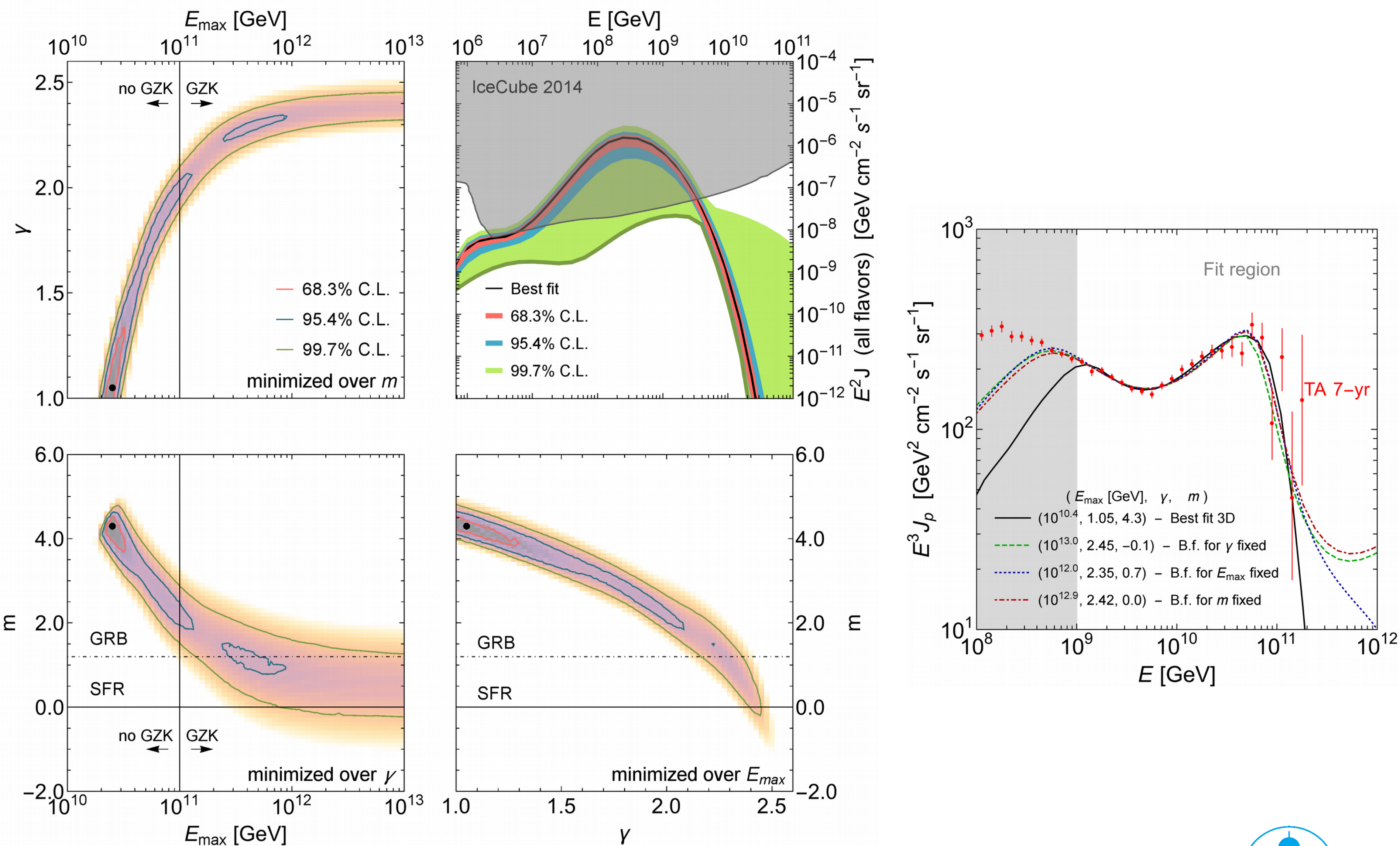


Fixed energy scale

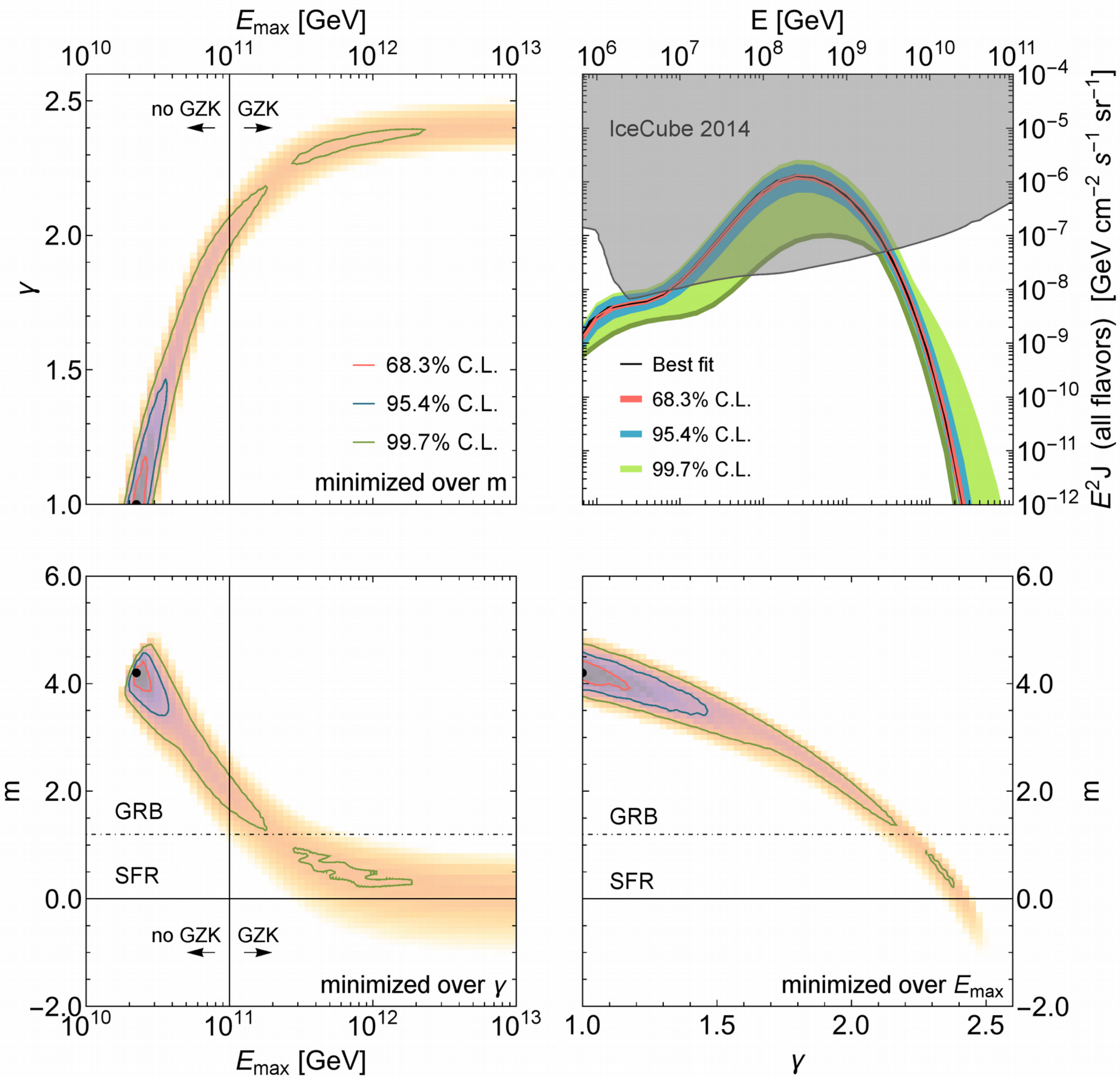


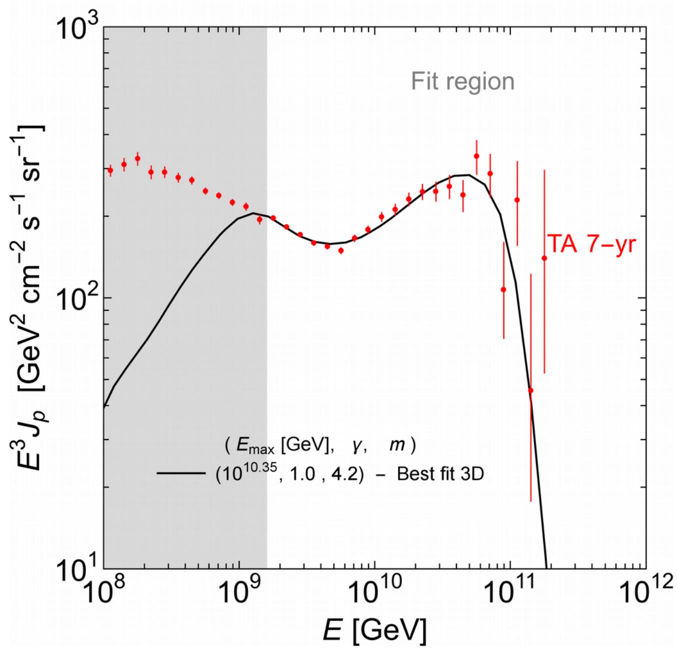


Extended fit range

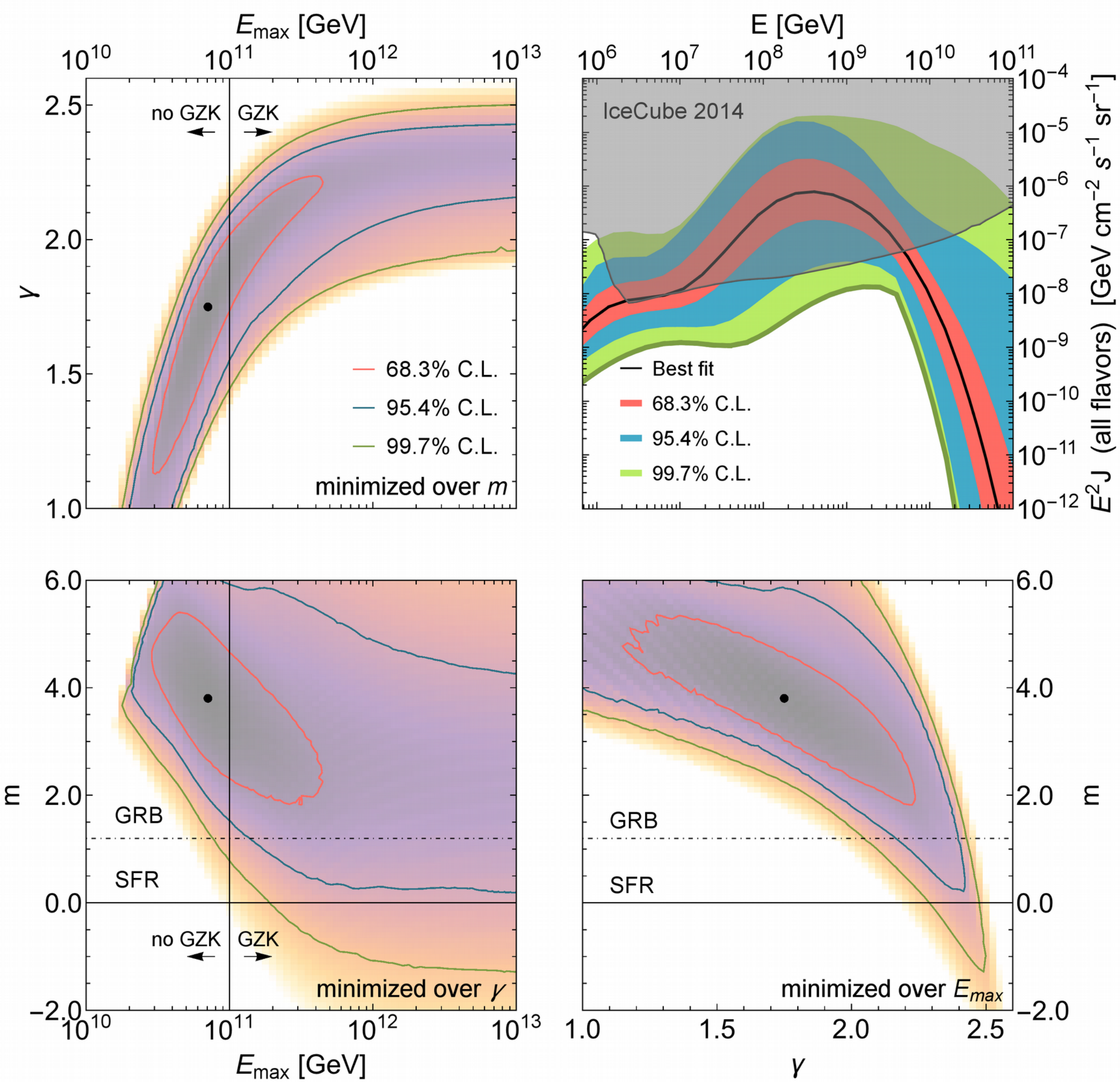


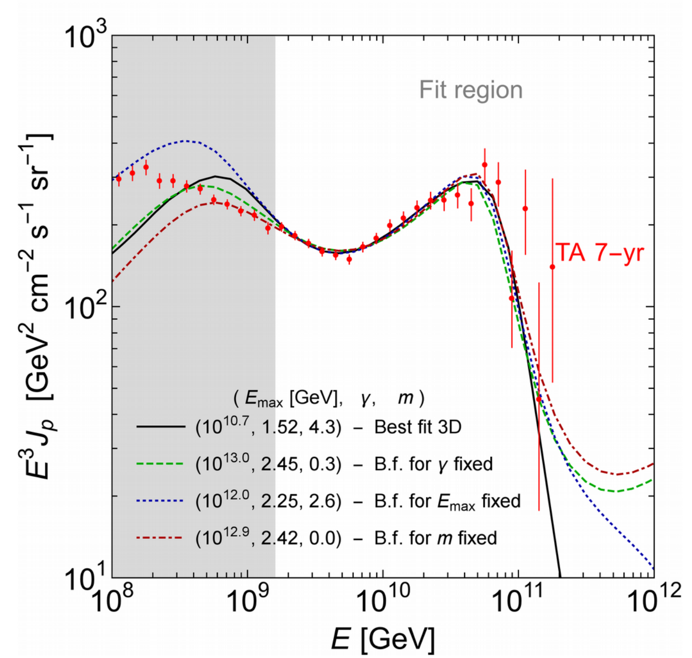
Overshoot penalty



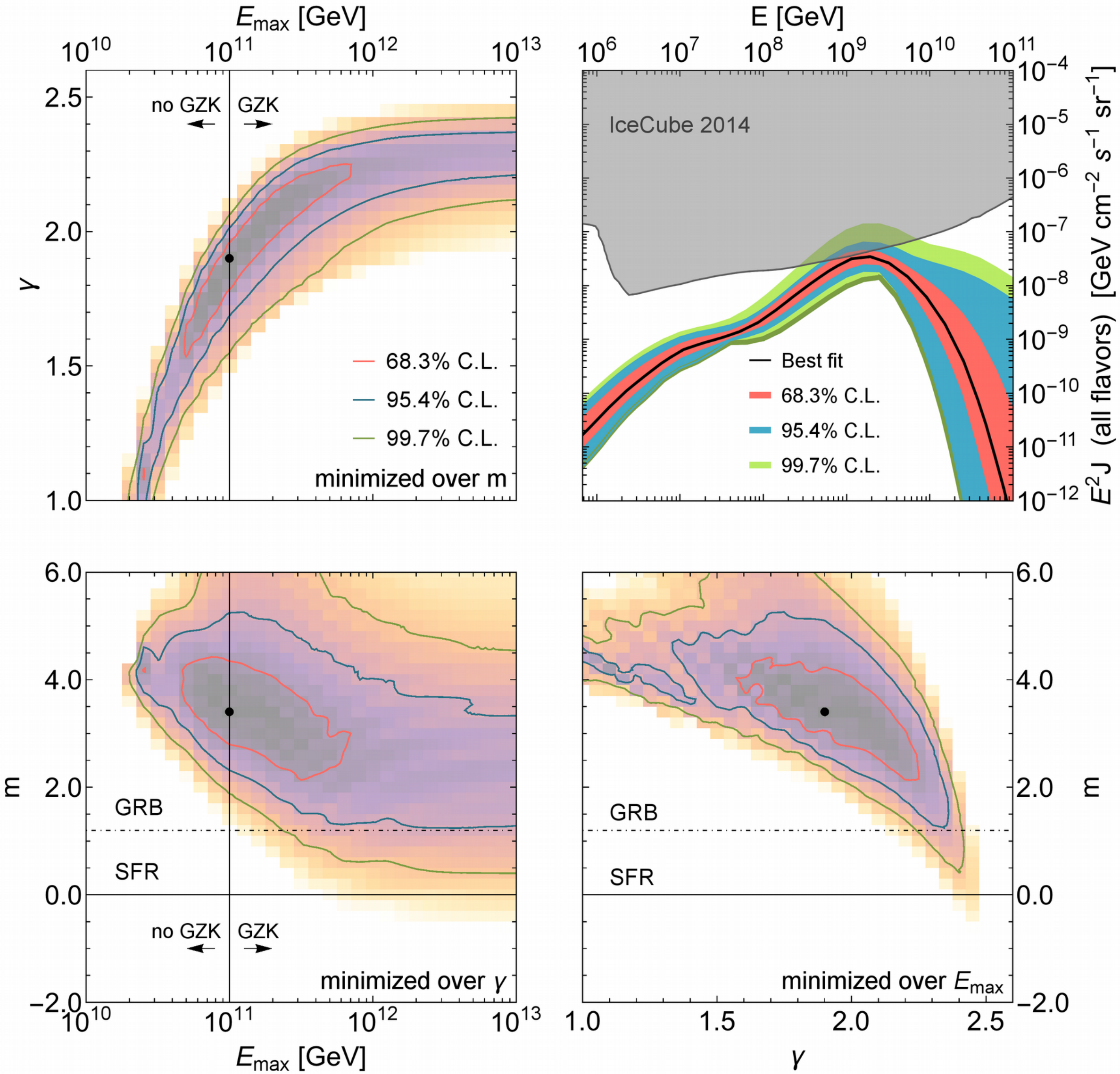


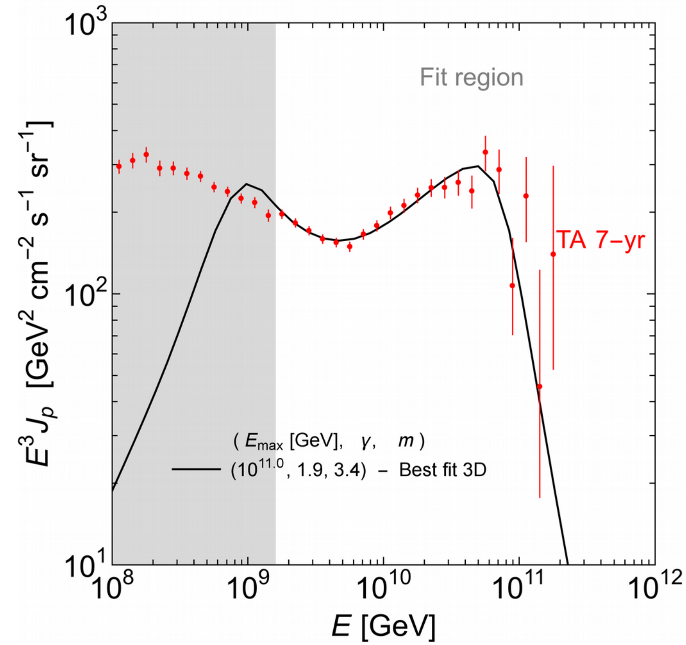
Additional 3% uncorrelated systematics



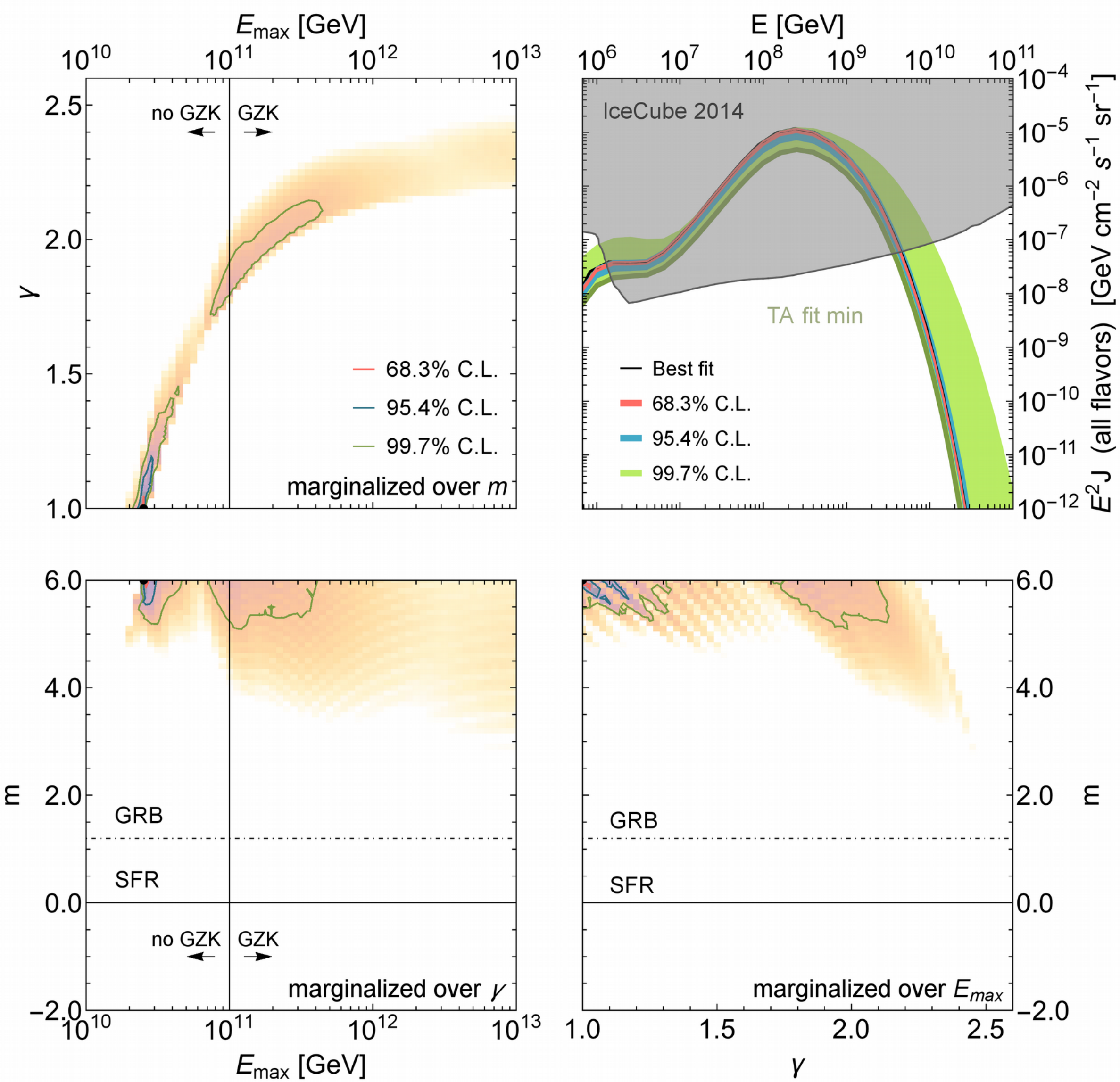


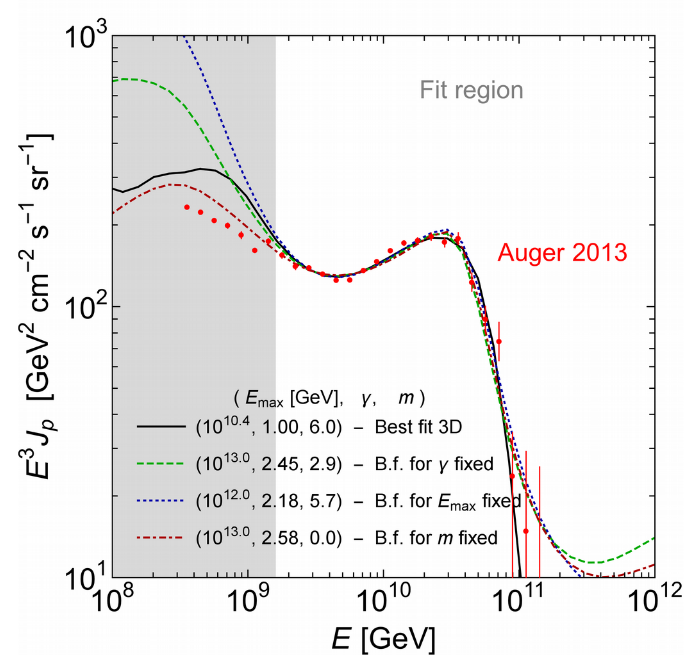
Only local injection z < 1



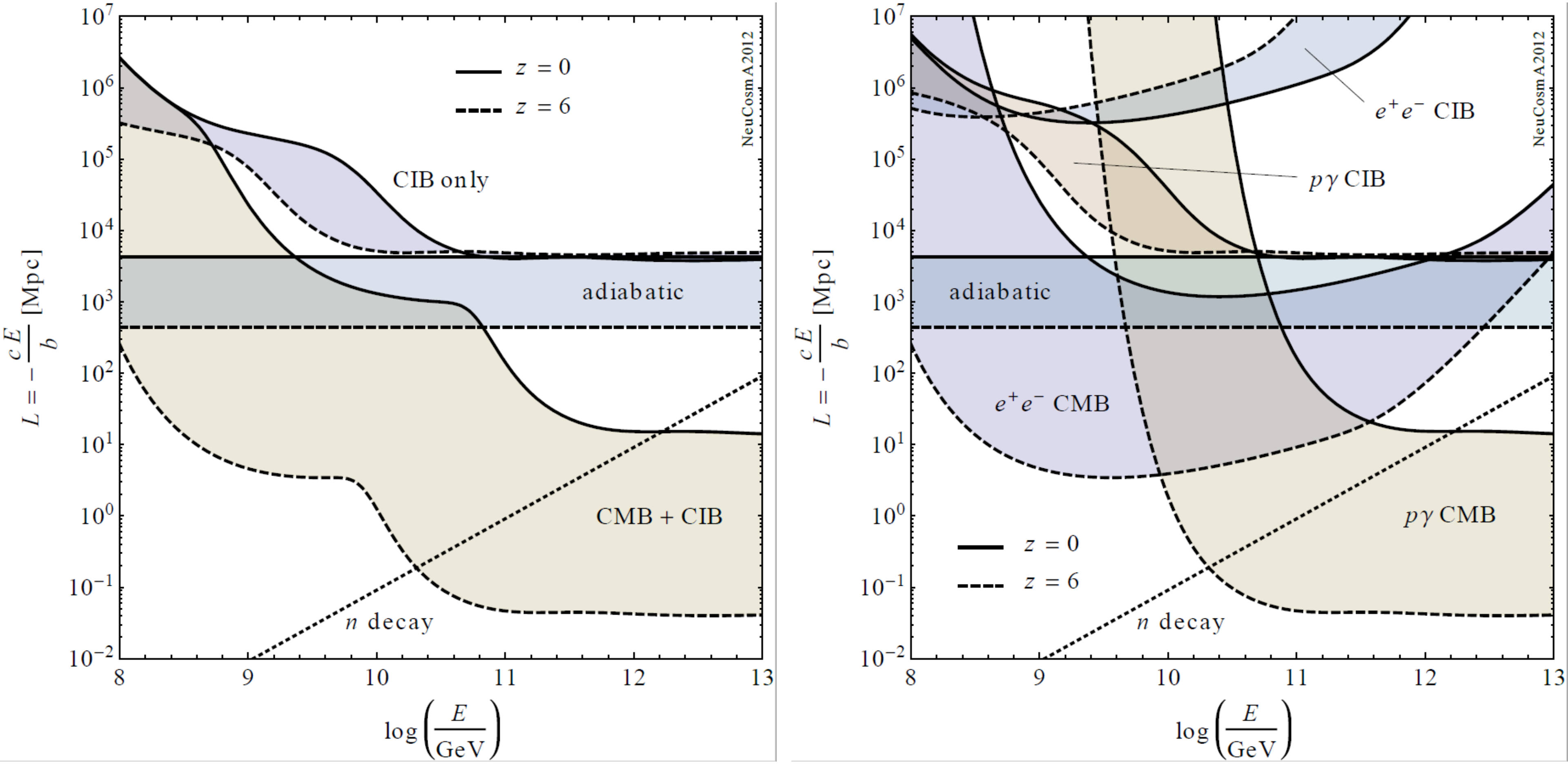


Fitting the Auger spectrum





Energy loss length



P. Baerwald, M. Bustamante, and W. Winter, Astropart. Phys. ***62****, 66 (2015)*