Cosmogenic neutrinos challenge the proton dip model

NEUCOS-Workshop

JH, Boncioli, Bustamante, Winter
ApJ 825:122 (2016) [arXiv:1512.05988]

Jonas Heinze
THAT
Zeuthen, 1.6.2017

HELMHOLTZ ASSOCIATION

NEUCOS

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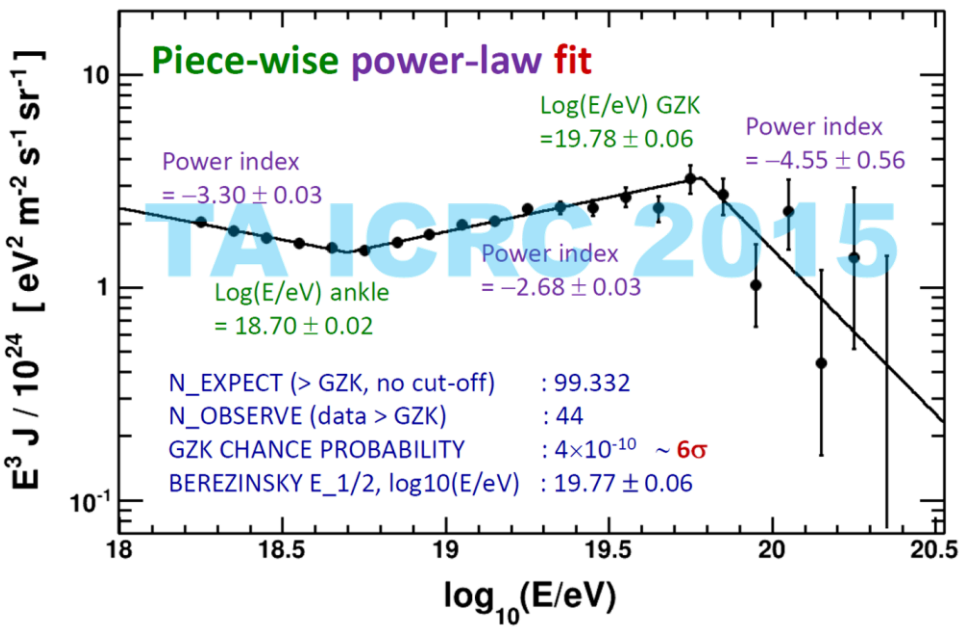
DESY

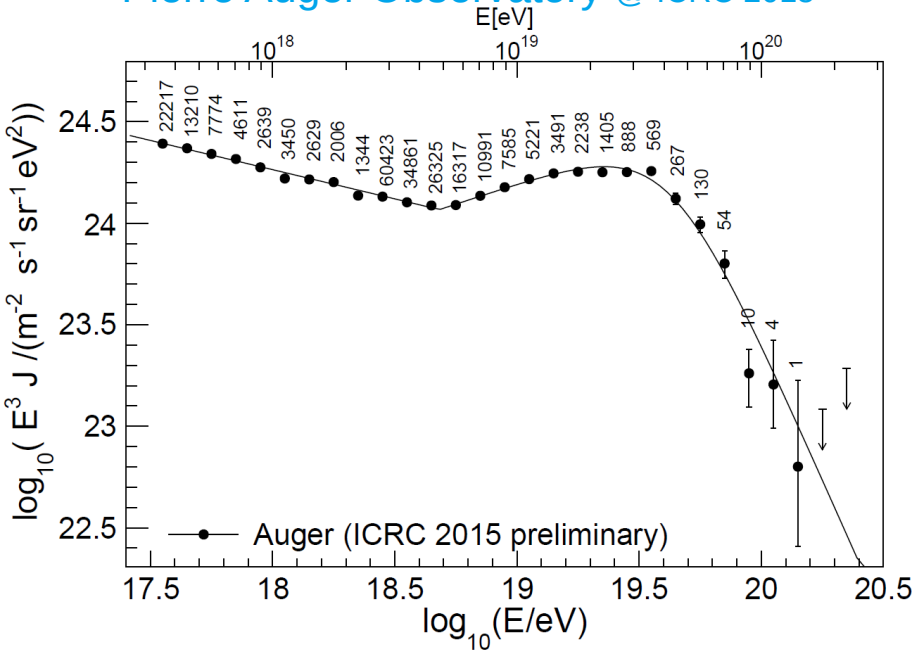
Observations: Spectrum

- Very low flux → needs extensive air shower experiments

Telescope Array @ ICRC 2015



Pierre Auger Observatory @ ICRC 2015

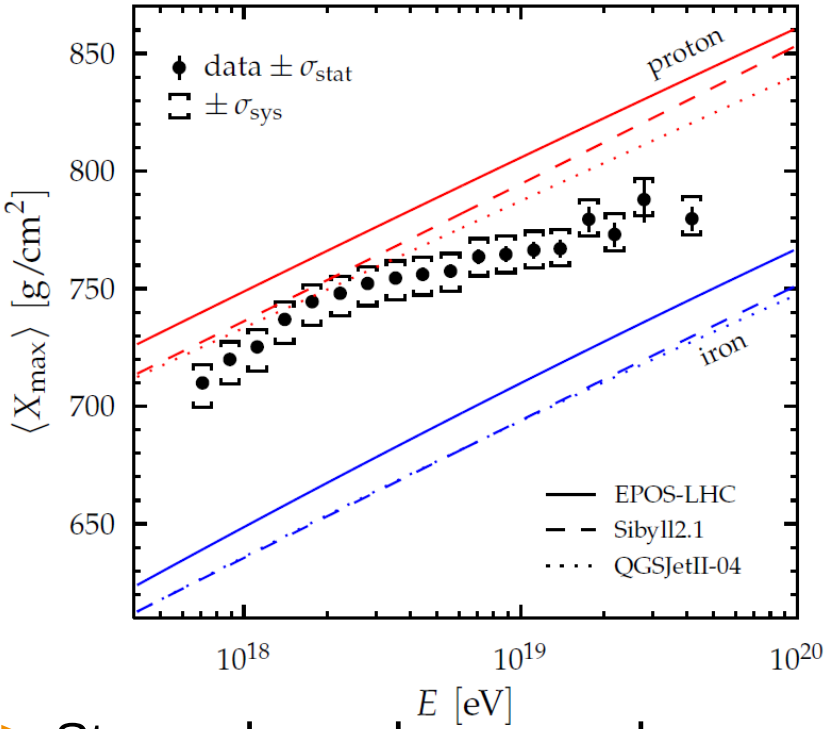


- Important features: Ankle at $5 \cdot 10^{18}$ and suppression at $5 \cdot 10^{19}$
  - Source properties? or propagation effects?
- Large energy scale uncertainties → spectra in agreement (except cutoff region)

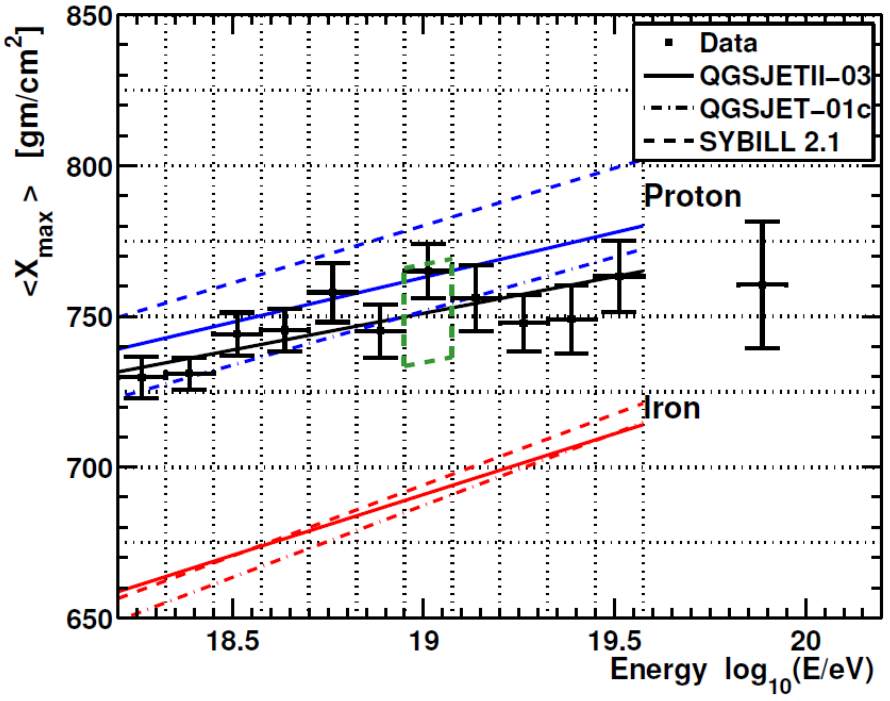
Observations: Mass composition

- Observable: Average depth of shower maximum $< X_{max} >$

Pierre Auger Observatory @ ICRC 2015



Telescope Array @ ICRC 2015



- Strong dependence on shower models
  - Auger: trend toward heavier nuclei
  - TA: compatible with protons or light nuclei
  - In agreement when compared to same model

Settle the argument by independent observable

Different Models

- **Dip Model:** UHECRs are extragalactic protons
  - Ankle due to pair production and suppression due to GZK effect
  - Simple but convenient model: all features due to propagation

- **Ankle Model:** gal. - extragal. transition at the ankle
  - Protons at the highest energies: GZK effect

- **Mixed composition models:**
  - Motivated by Auger data
  - Usually transition at the ankle as in the Ankle model
  - E.g. rigidity dependent injection cut-off at the source

Secondary messengers can help disentangle this!

Assumptions

1. Pure Proton composition as in Dip Model
2. Simple injection model: power – law with energy cutoff

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

   - Source Evolution relative to star formation rate

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

3. Normalization by χ^2 - fit to TA-spectrum (proton composition)
   - Fit parameters: E_{max} (max. Energy) γ (spectral index) m (source evol.)
   - Energy scale shift allowed (20% exp. uncertainty, penalty on large shifts)

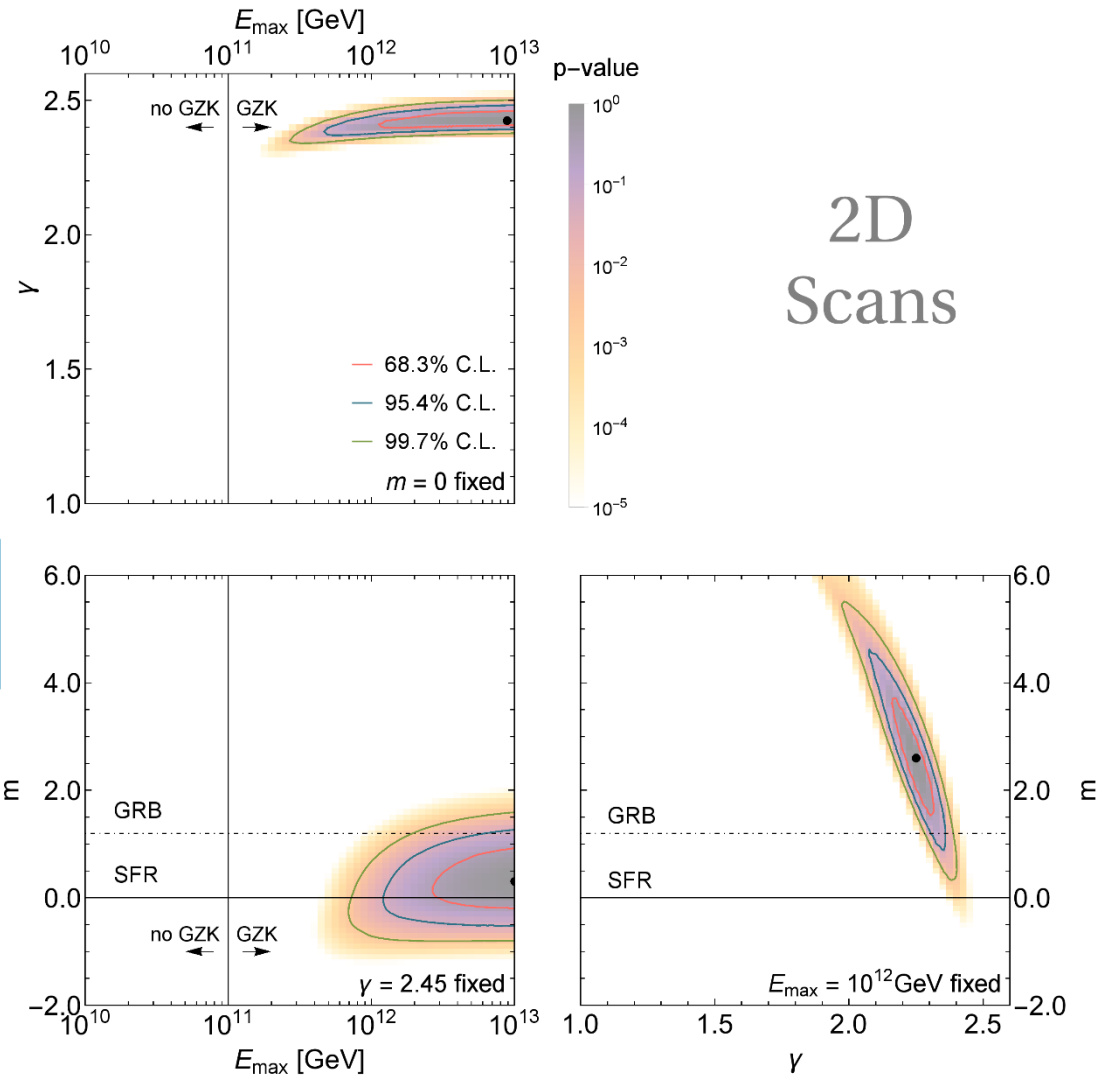
Has to satisfy IceCube upper limit on cosmogenic neutrinos! (none detected)

IceCube Collaboration, Phys. Rev. Lett. 117 (2016)

2D scan

- Typically found in literature
- Allowed parameter space
  - High E_{max} → GZK – effect
  - Strong γ – m correlation
  - Small energy scale shifts <10%

Choice of fixed 3rd parameter resonable, but biased?



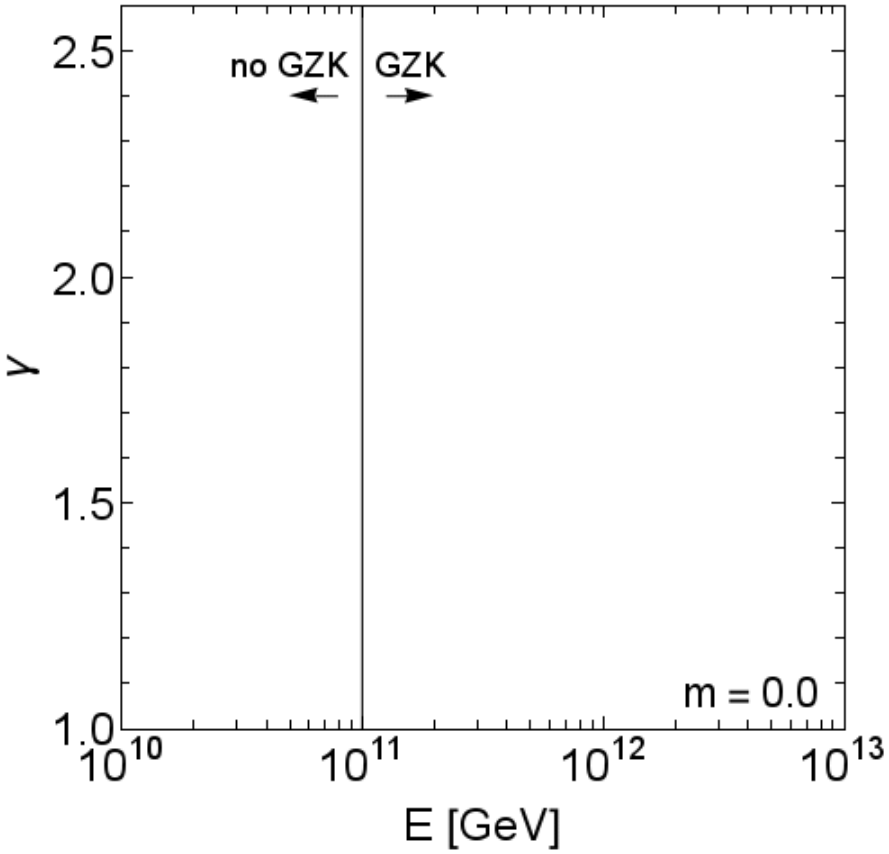
2D Scans

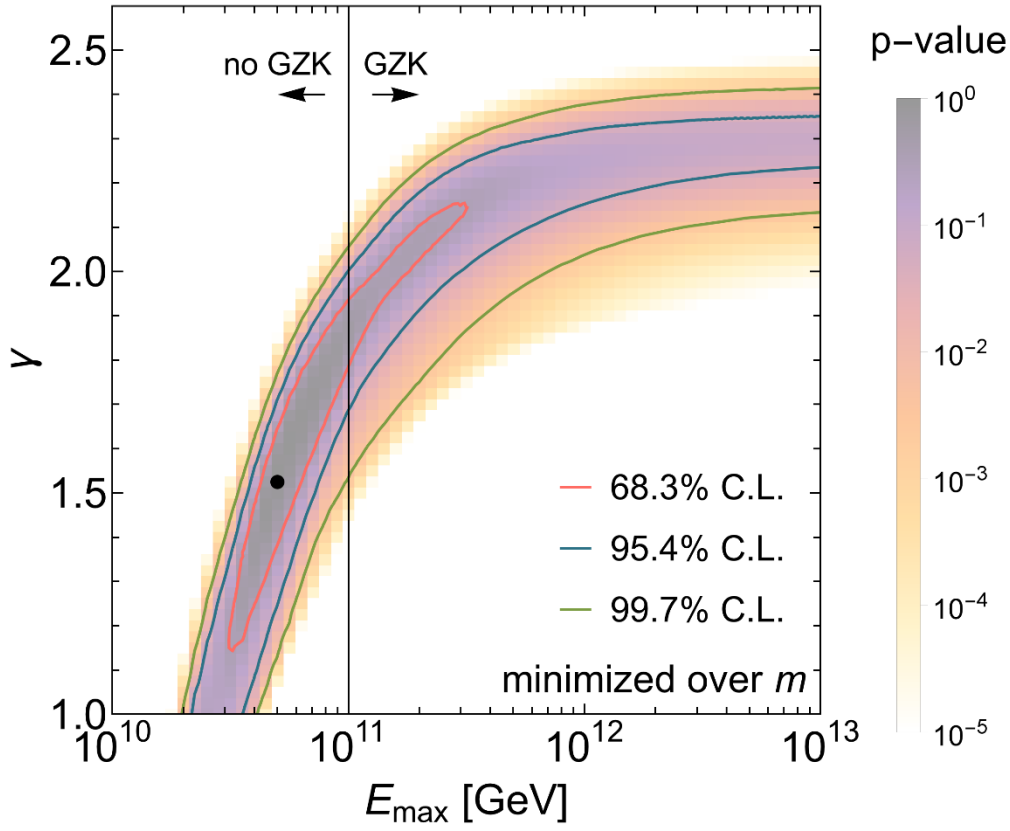
Best fits:

	2D scan		
γ	2.25	*2.45	2.42
$\log_{10}(E_{max}/\mathrm{GeV})$	*12.0	13.0	12.9
m	2.6	0.3	*0.0
χ^2_{min}	34.7/17	47.8/17	47.8/17

3D scan

- Three dimensional “banana”-shape
- Shown as two dimensional projections





3D scan

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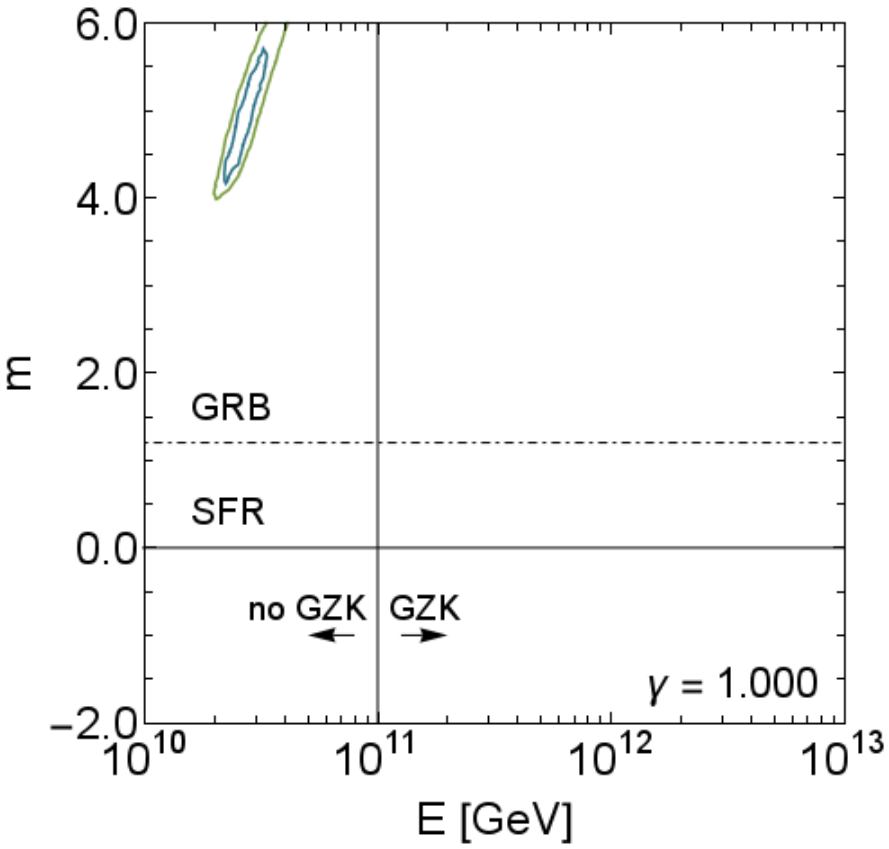

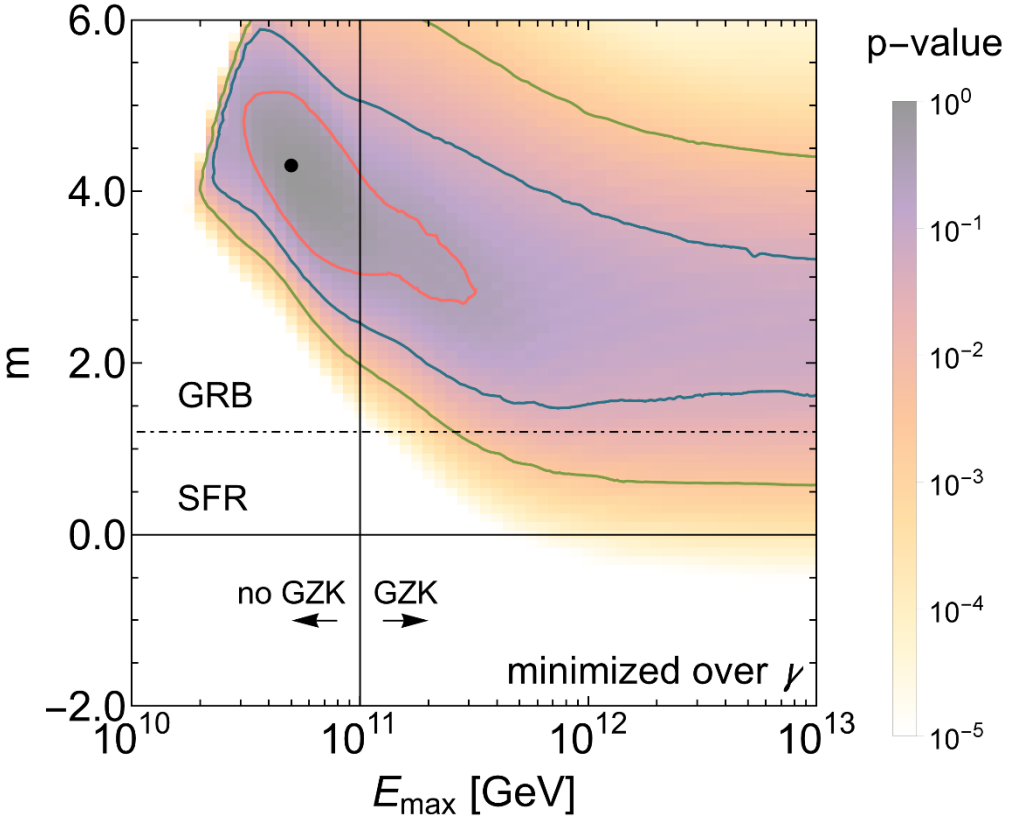

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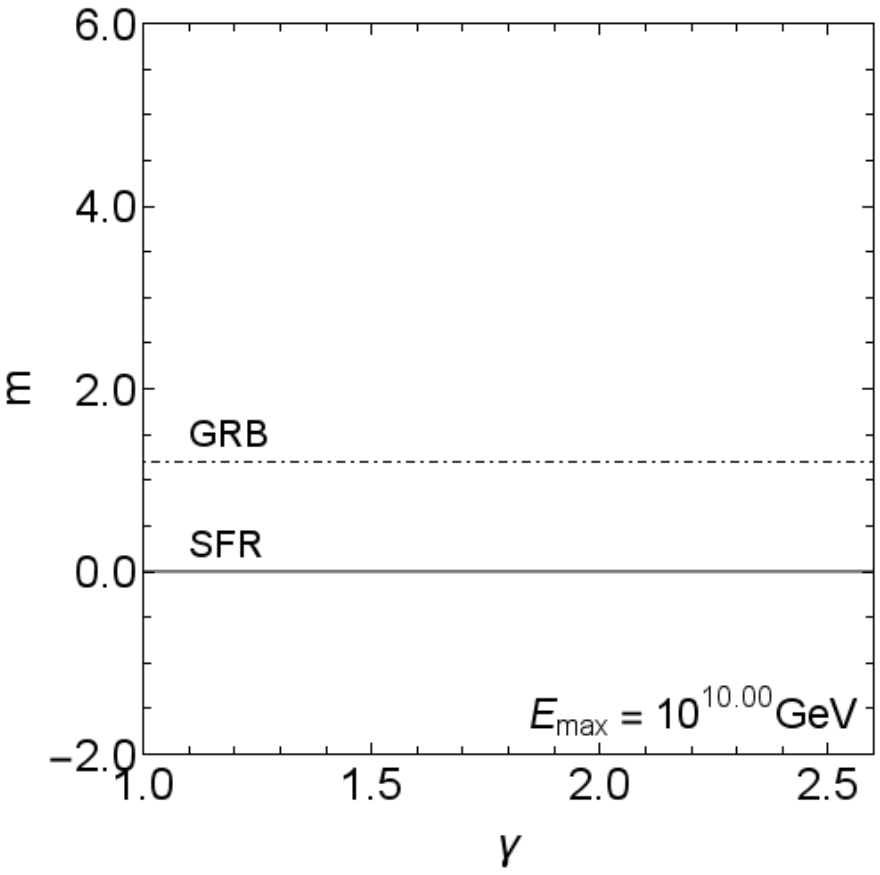
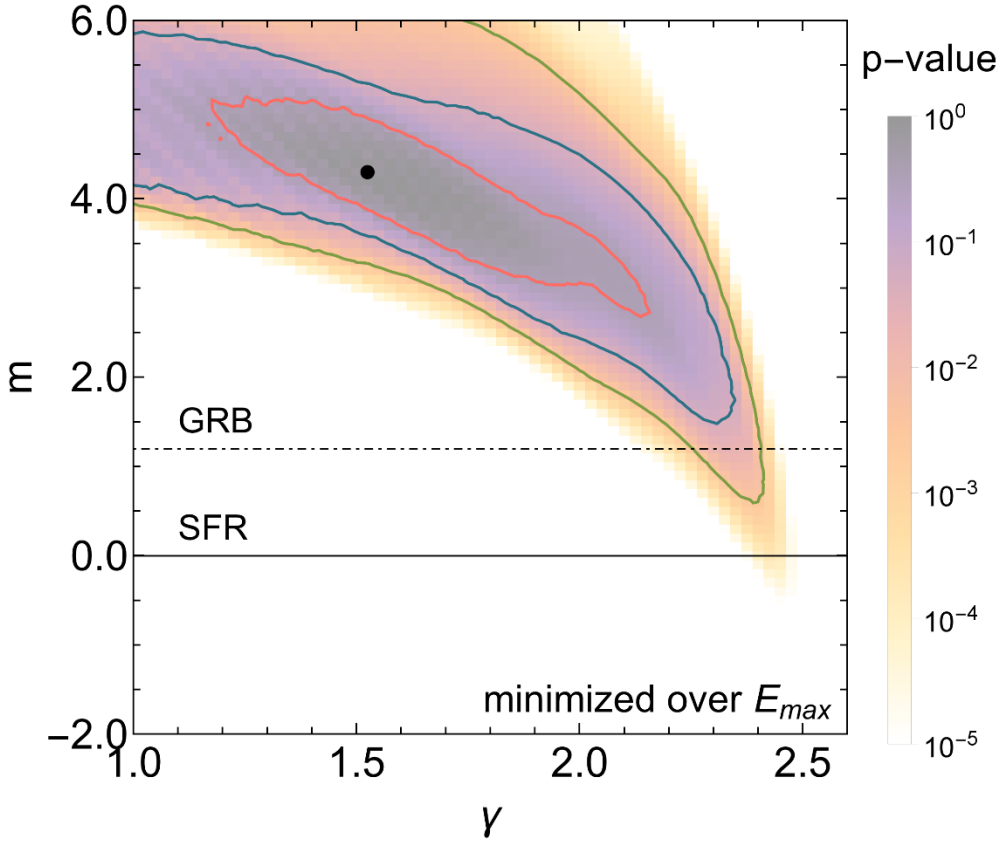
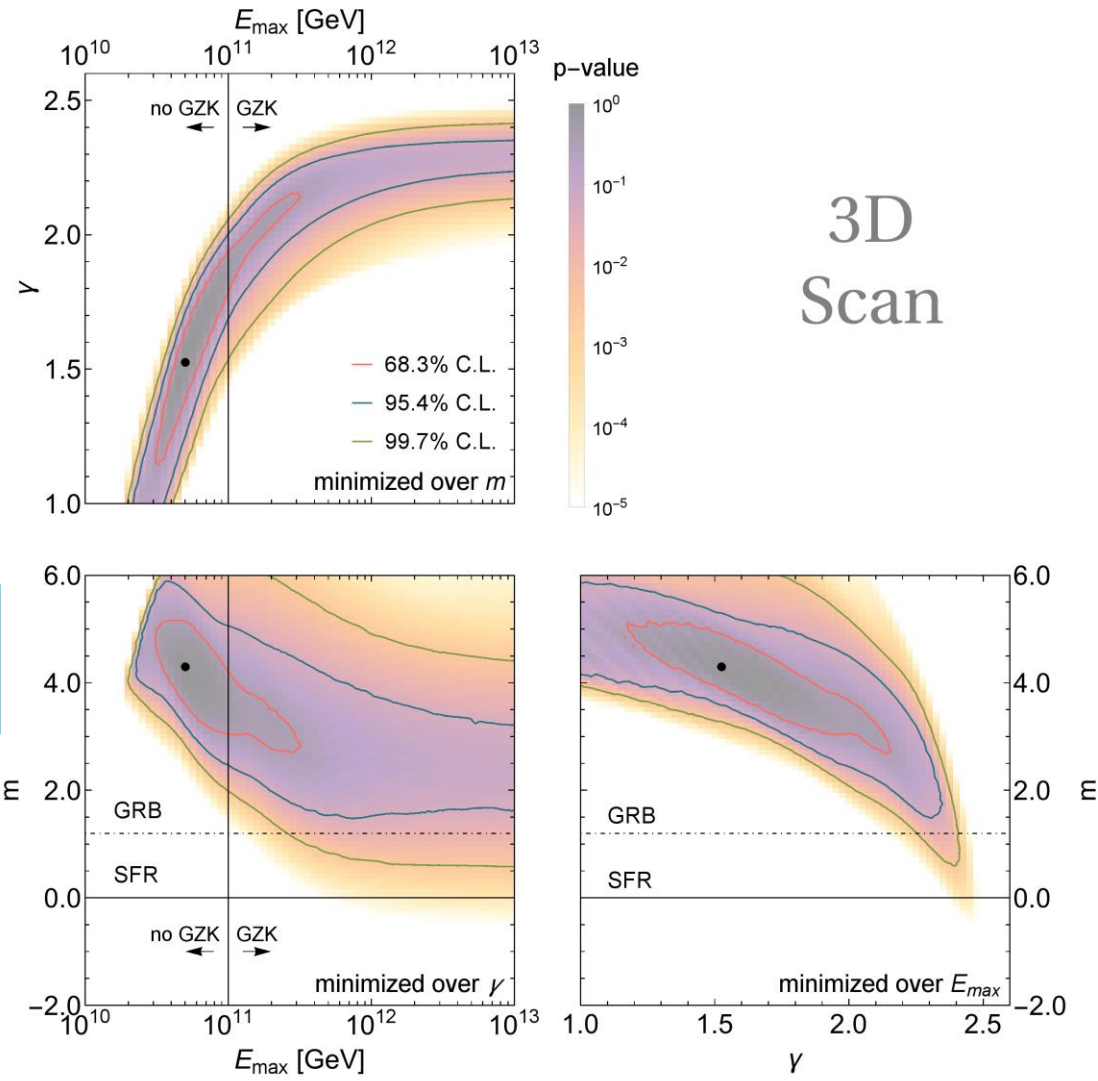




3D scan

- Parameter space enlarged compared to 2D scan
  - Multi-parameter correlations
  - Harder spectrum and stronger evolution
  - Low max. energy allowed → suppression as source effect

Problem: large energy shift needed for low cutoff energies

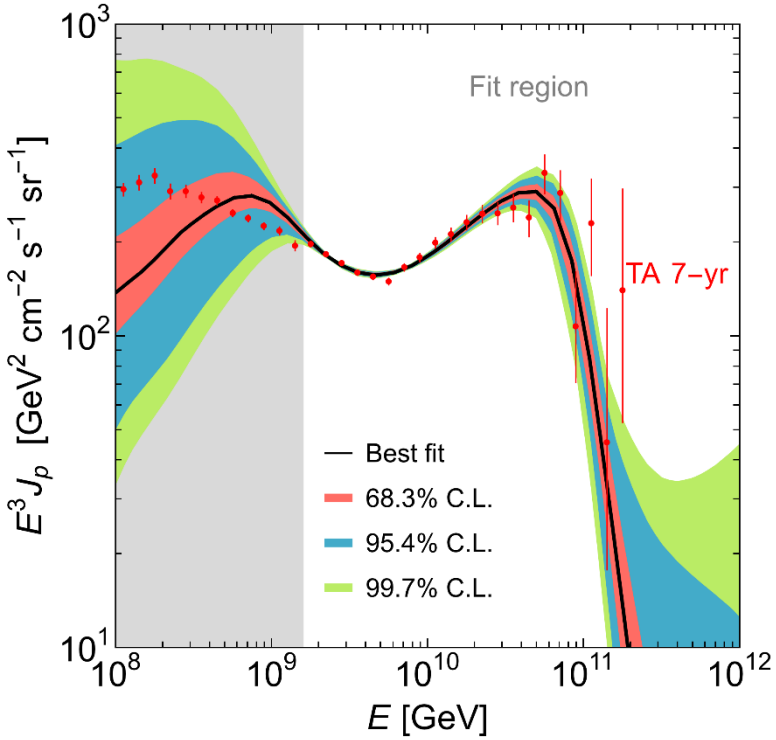


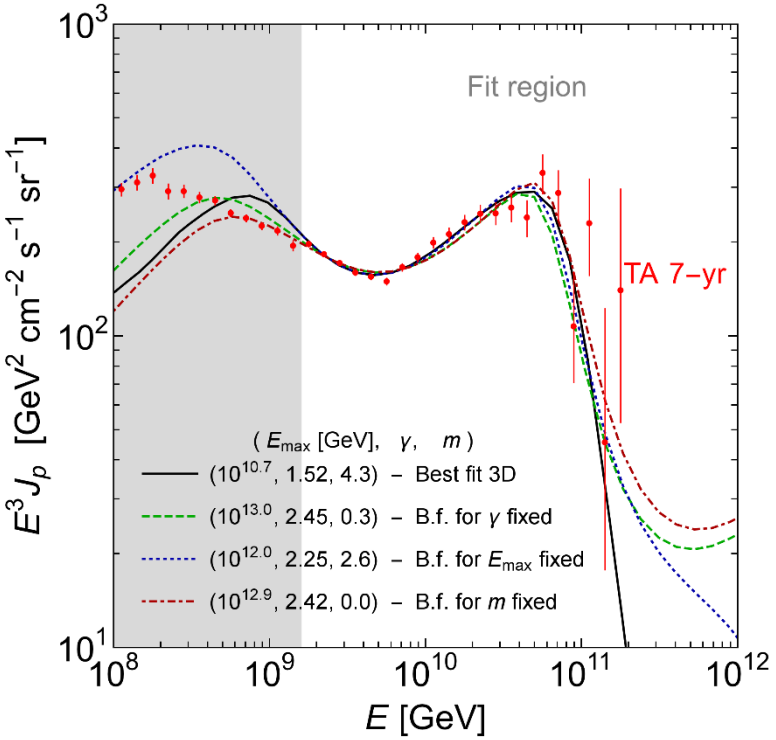
3D Scan

Best fits:

	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	$4.3^{+0.4}_{-0.8}$
χ^2_{min}	34.7/17	47.8/17	47.8/17	30.8/16

Best fit spectra

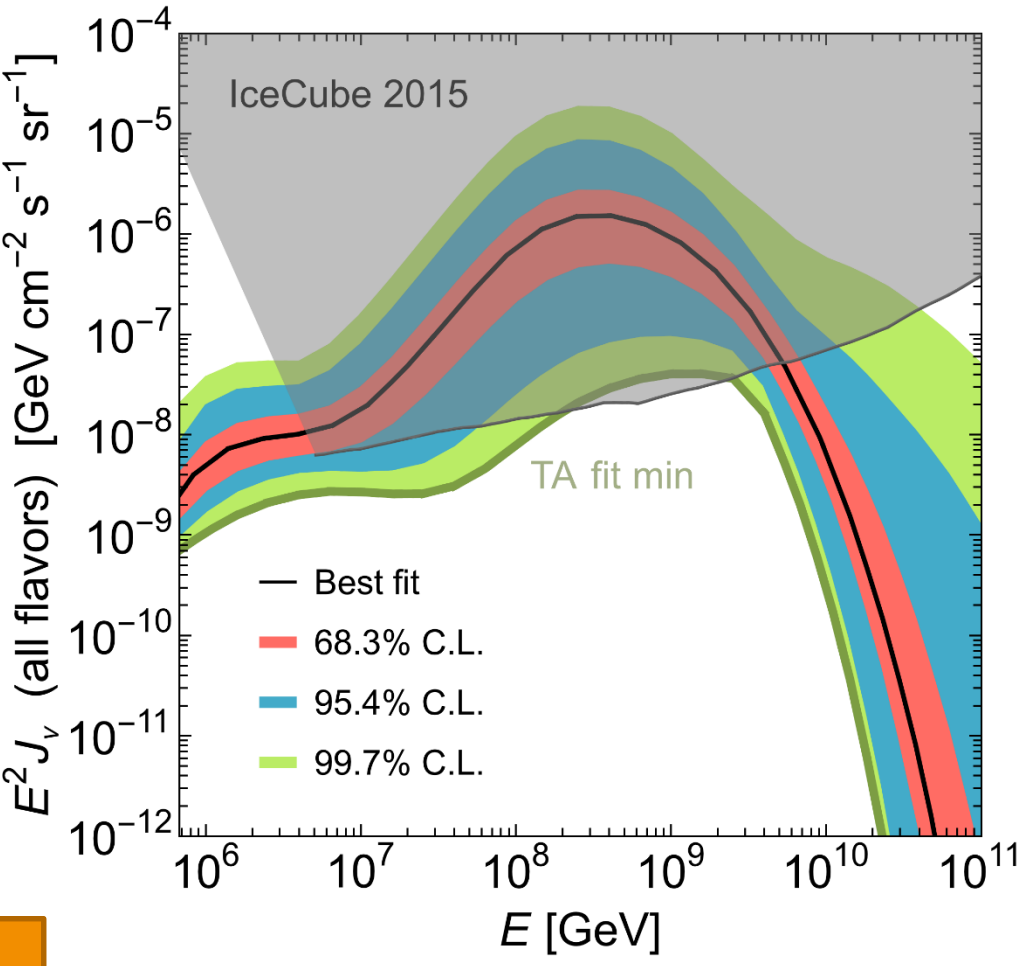




- Low statistics cannot distinguish source- or GZK effect
- Fit driven by ankle region
  - Favours hard spectra....
  - …and strong source evolution
- Overshoot: below fit range
  - Minimal escape energy?
  - Magnetic field diffusion?
  - Or further constraint on Dip model?

Cosmogenic Neutrinos

- Ranges: min/max over allowed parameter space
- Exceeds recent IceCube upper limit
  - Mainly due to high source evol.
- Minimal number of expected events: 5.4
  - Challenged at more than 95% C.L.
  - … already in stress with TA data

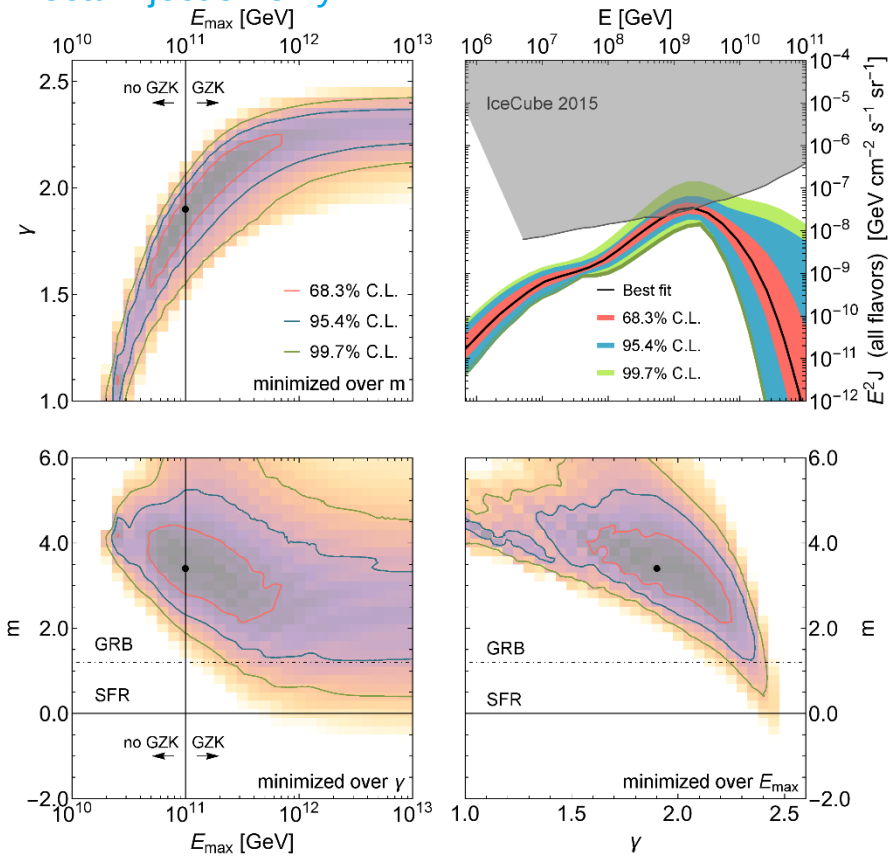


Dip model excluded for reasonable source evolution!

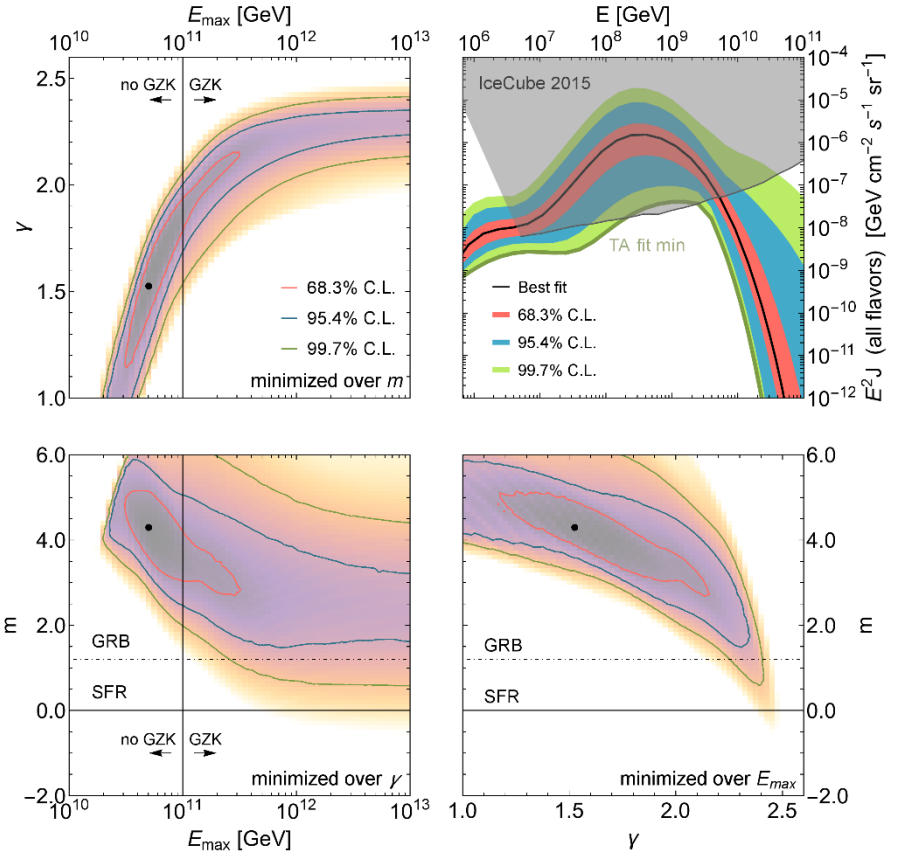
Extreme test case

- No injection above redshift z = 1
- UHECRs only sensitive to local universe
  → fit not qualitatively changed!

Local injection only

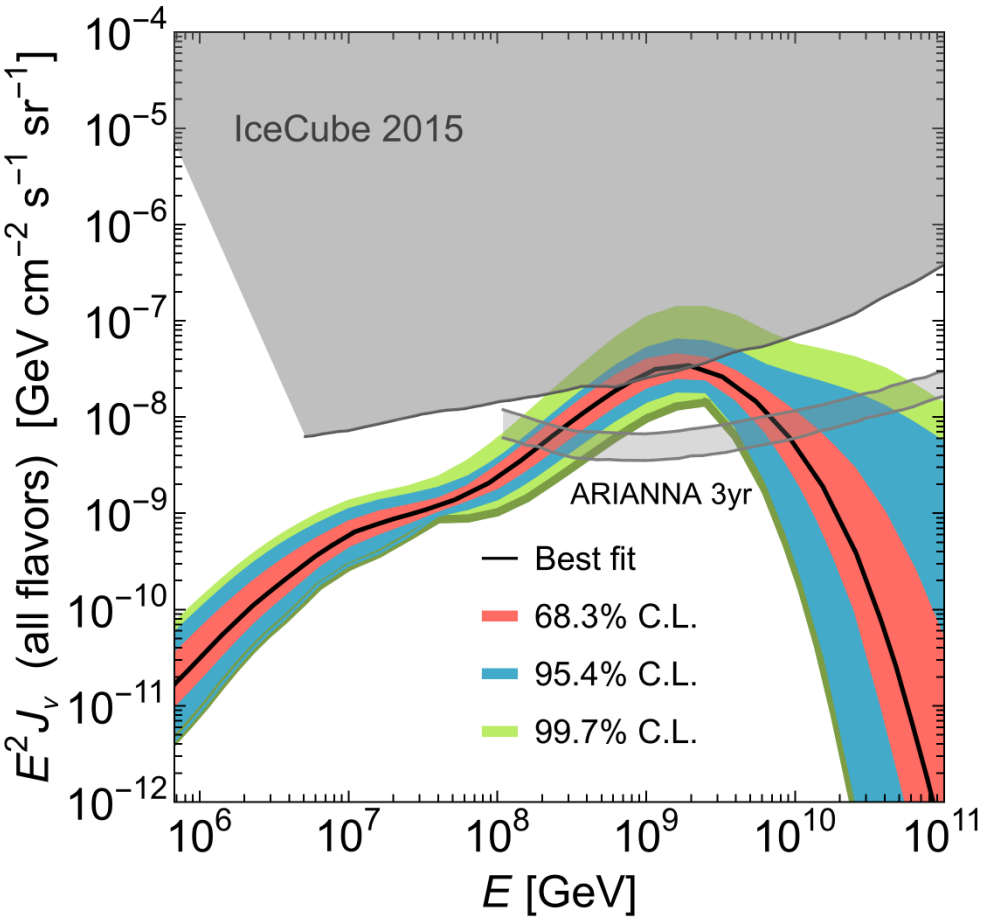


Standard evolution



Extreme test case

- Much lower neutrino flux
- … but cutoff at z = 1
  is an unrealistic test case
- Any more realistic source evol.
  within reach of IceCube
- ARIANNA 3 years sensitivity
  will settle any doubt!



Constraints from cosmogenic gamma rays!

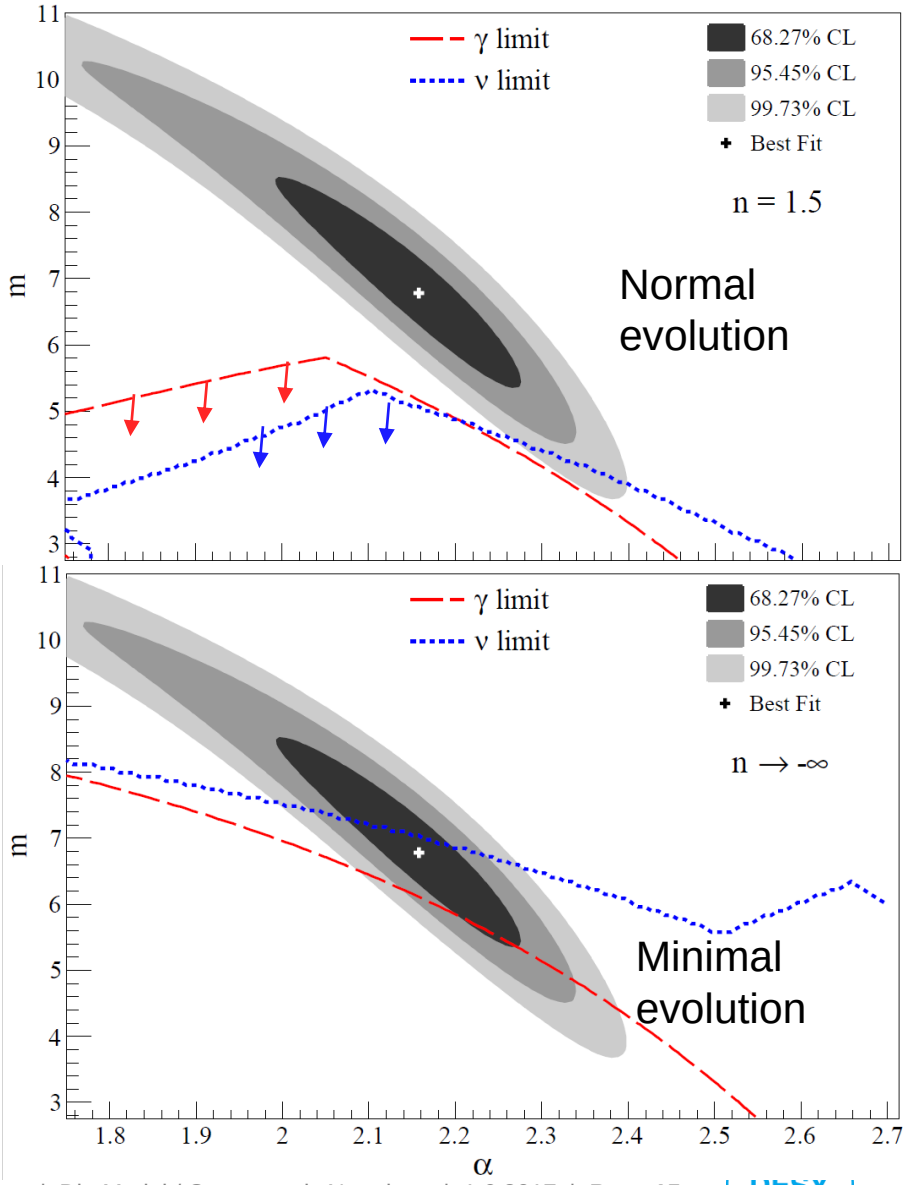
Supanitsky Phys. Rev. **D94** (2016)

- Fixed $E_{max} = 10^{19.5}$ eV
- Source evolution broken at z = 1

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

- Neutrino constraints consistent with ours

Gamma-ray constraints strong for local sources!



Conclusion

- Extending UHECR-fit to three parameters yields new insight
  - Hard spectra, strong source evolution and low maximal energy favoured
  - … but still includes parameters from 2D-scan
  - Large energy scale norm (TA) favoured by fit
- Expected neutrino events from Dip model above IceCube limit
  - Holds even for changed assumptions (fixed energy scale, changed fit range…)

Dip model strongly challenged!
Complementary to composition measurements

- Additional support for Auger like composition of UHECRs

Backup slides

Injection Model

- Use simple injection model as test case:

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

- Three main model parameters
  - E_{max} : Maximal Energy
  - γ : Spectral index
  - H(z) : Redshift source evolution
- Source evolution relative to star formation rate

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

- Propagation computed numerically

Statistical analysis

- Fit each set of parameters to the observed flux:

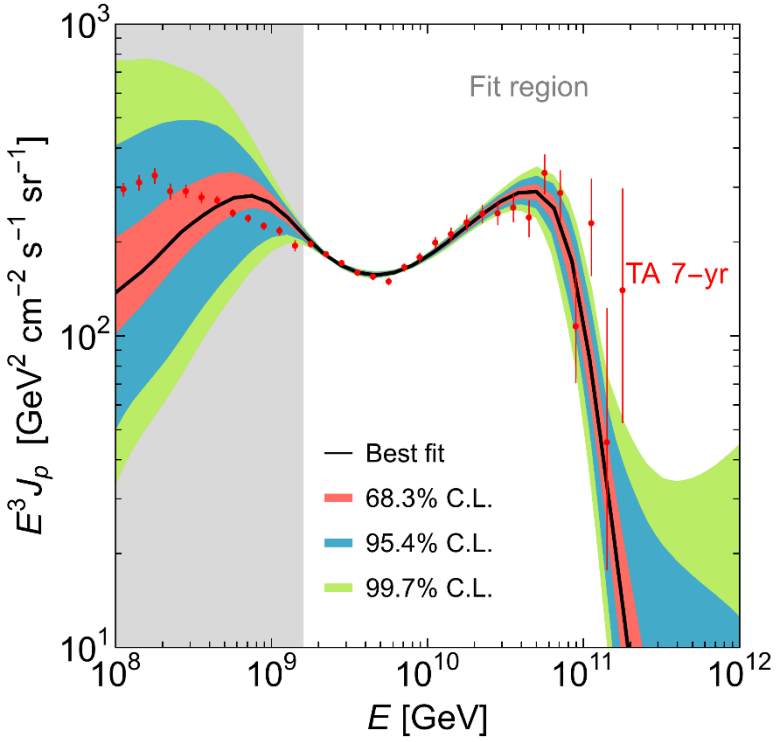
$$\chi^2 = \sum_i \frac{\left(f\, J^{\mathrm{mod}}(E_i'; \gamma, E_{\mathrm{max}}, m) - J^{\mathrm{TA}}(E_i)\right)^2}{\sigma_i^2} + \left(\frac{\delta_E}{\sigma_E}\right)^2$$

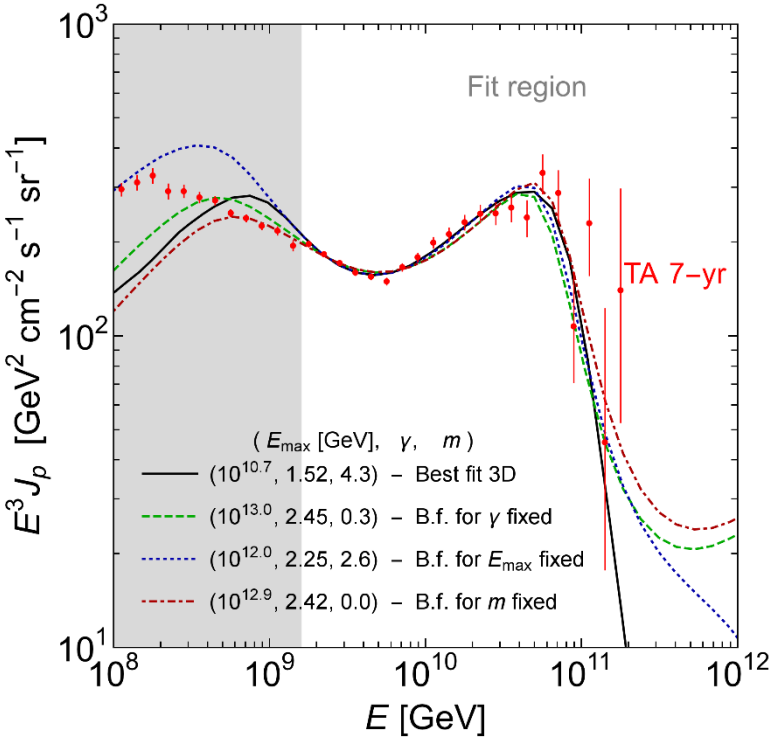
- Fit parameters:
  - f normalization — free parameter related to source luminosity and density
  - δ_E energy scale shift — systematic uncertainty 20% for TA

- Allowed regions from $\Delta\chi^2$

$$\Delta\chi^2(\gamma, E_{\mathrm{max}}, m) = \chi^2(\gamma, E_{\mathrm{max}}, m) - \chi^2_{\mathrm{min}}$$

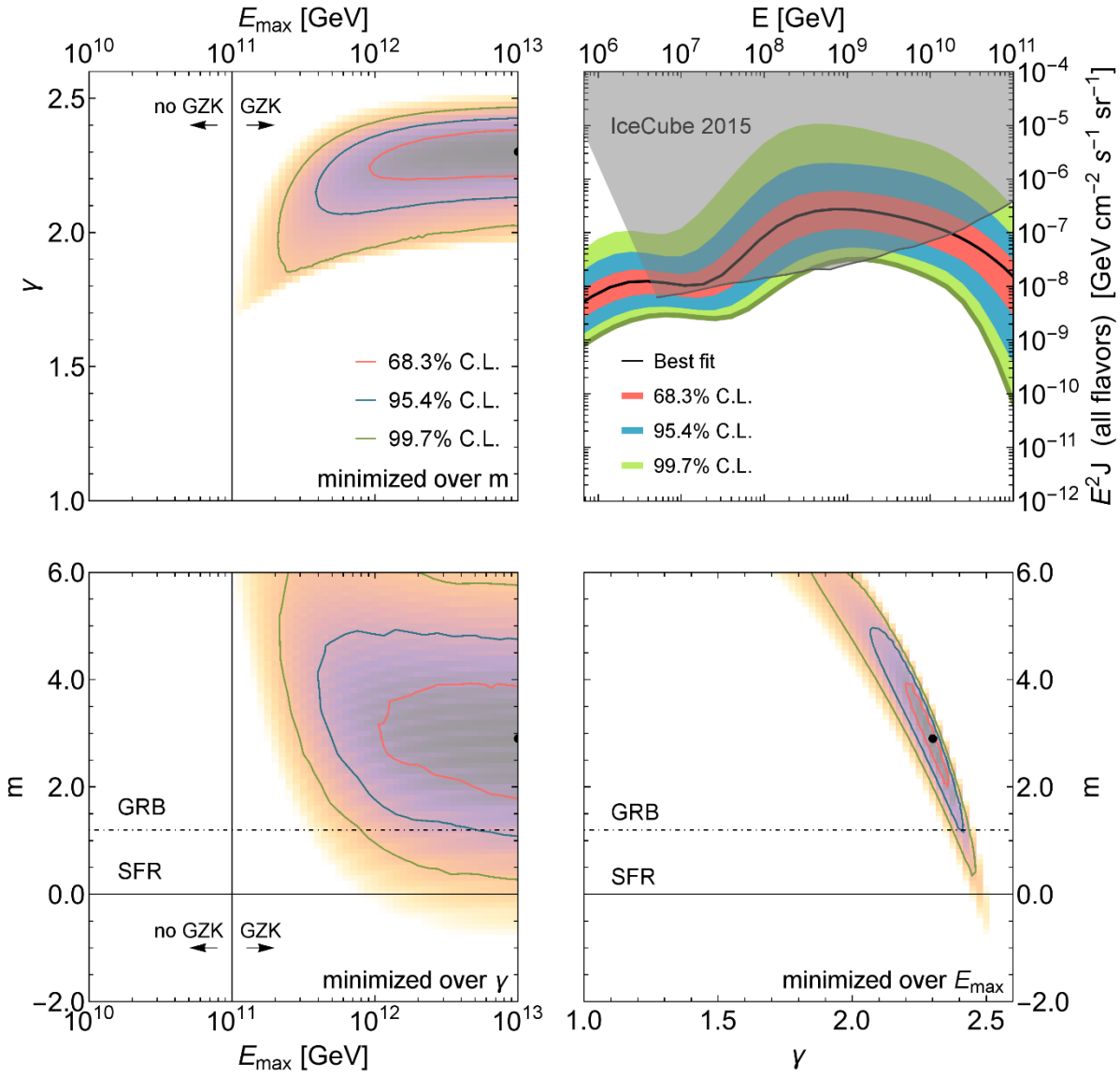
UHECR - Spectra



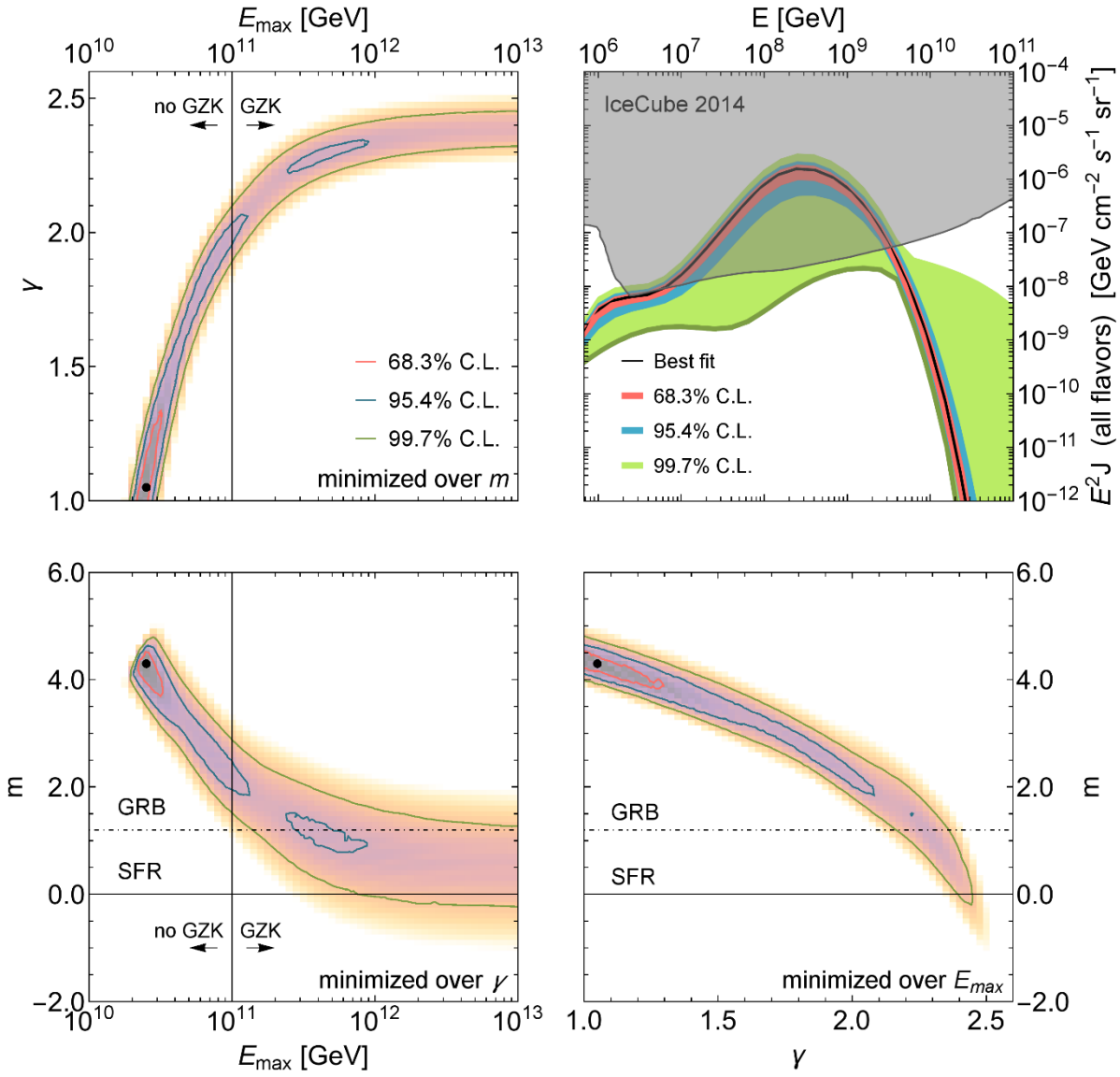


- Fit is driven by ankle region due high statistics
- Cutoff statistics too low to distinguish source- or GZK-effect
- Strong overshoot below fit range (due to high source evolution)

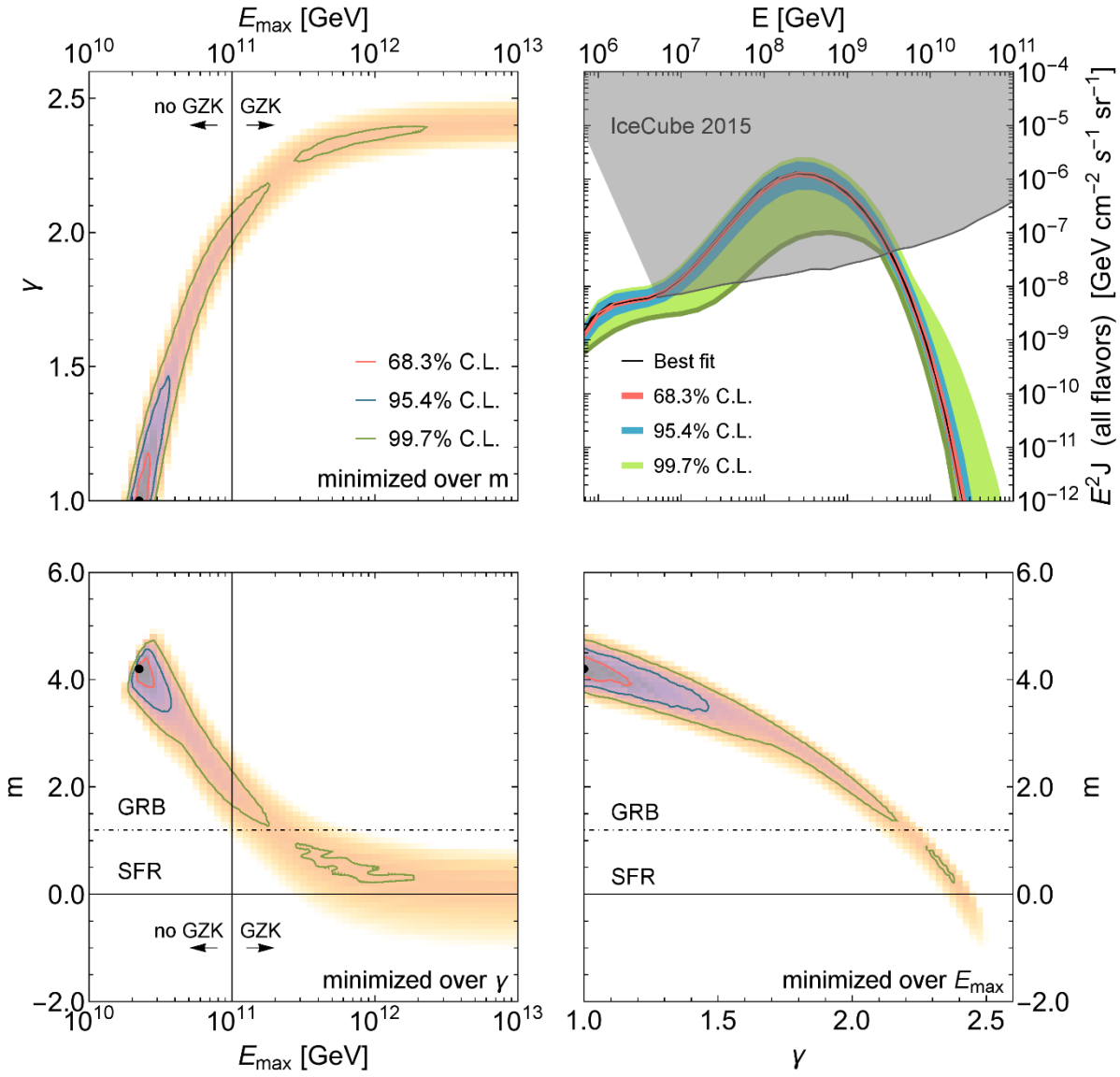
Fixed energy scale



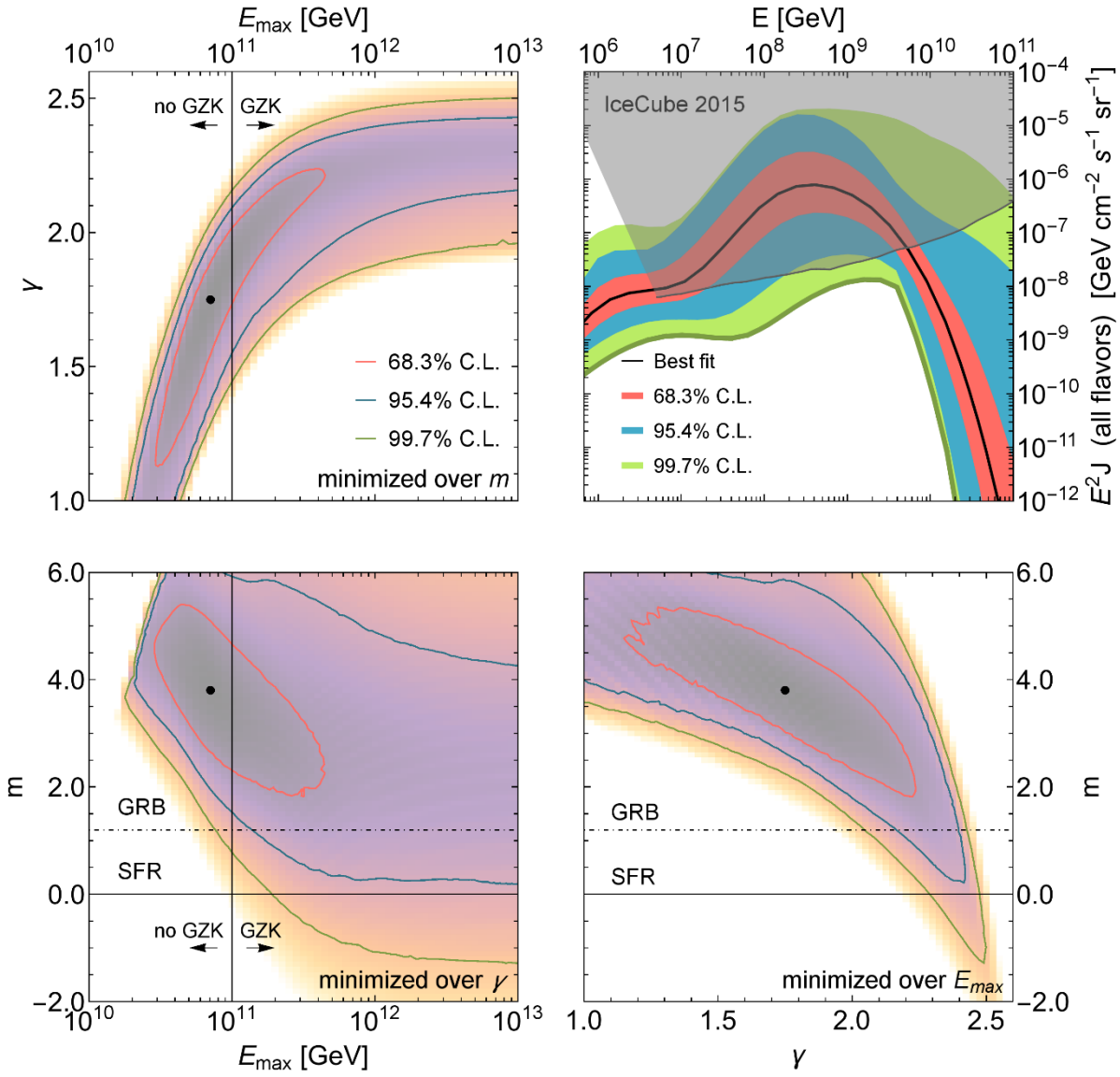
Extended fit range



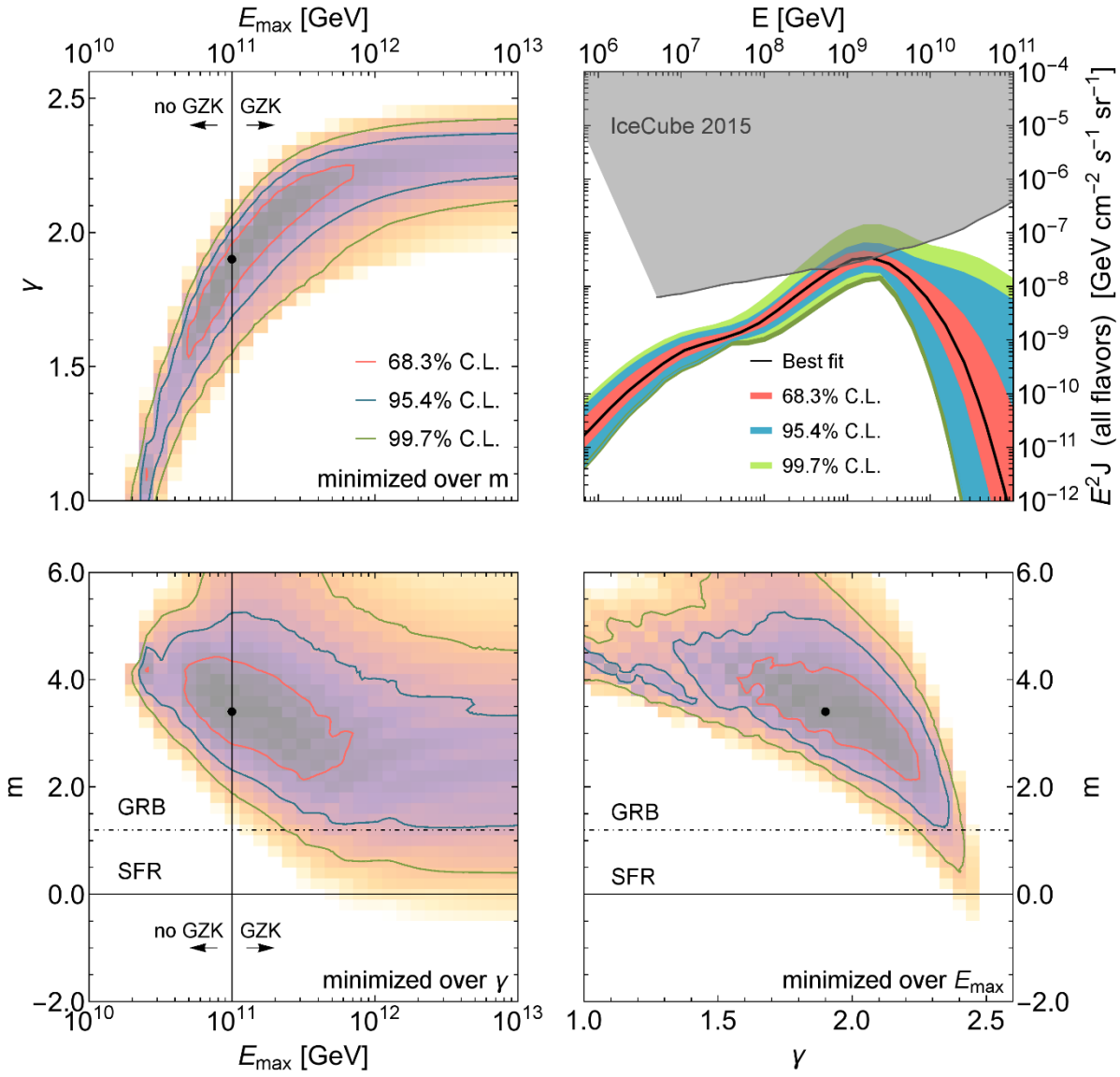
Overshoot penalty



Additional 3% systematics



Only local injection z < 1

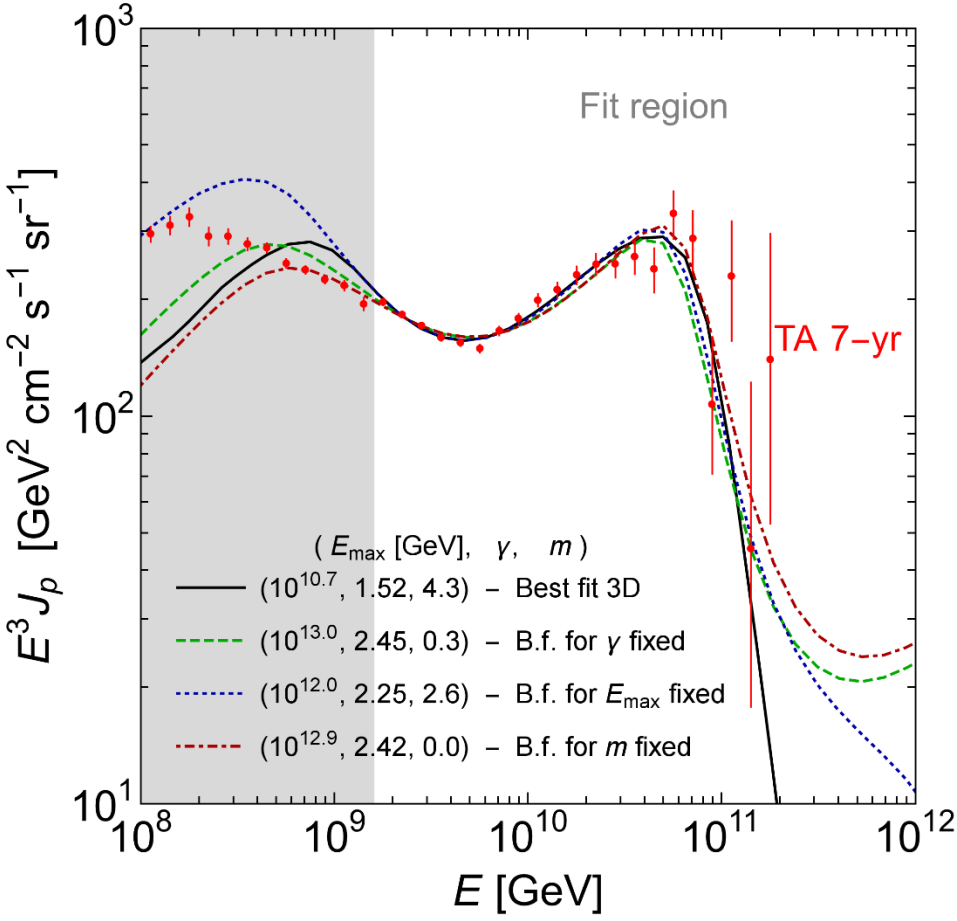


Best fit spectra for 2D and 3D

- High energy cutoff:
  Low statistics cannot distinguish source- or GZK effect

- Ankle region:
  - 3D: due to hard injection and pile up from high redshift …
  - … **not** classical pair-prod.-dip
  - 2D: classical pair-prod.-dip

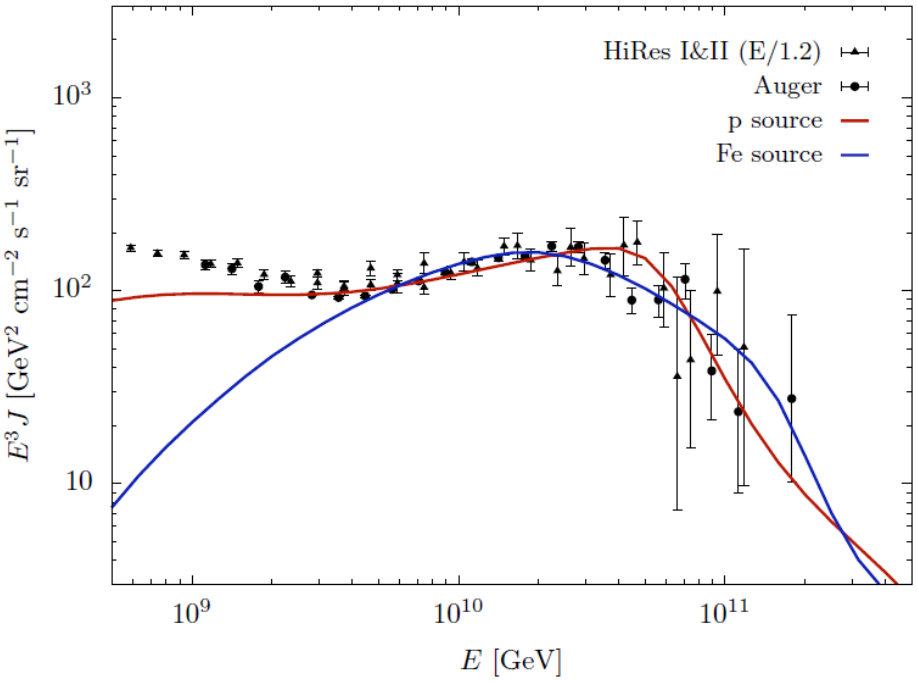
- Overshoot: below fit range
  - Minimal escape energy?
  - Magnetic field diffusion?
  - Or further constraint on Dip model?

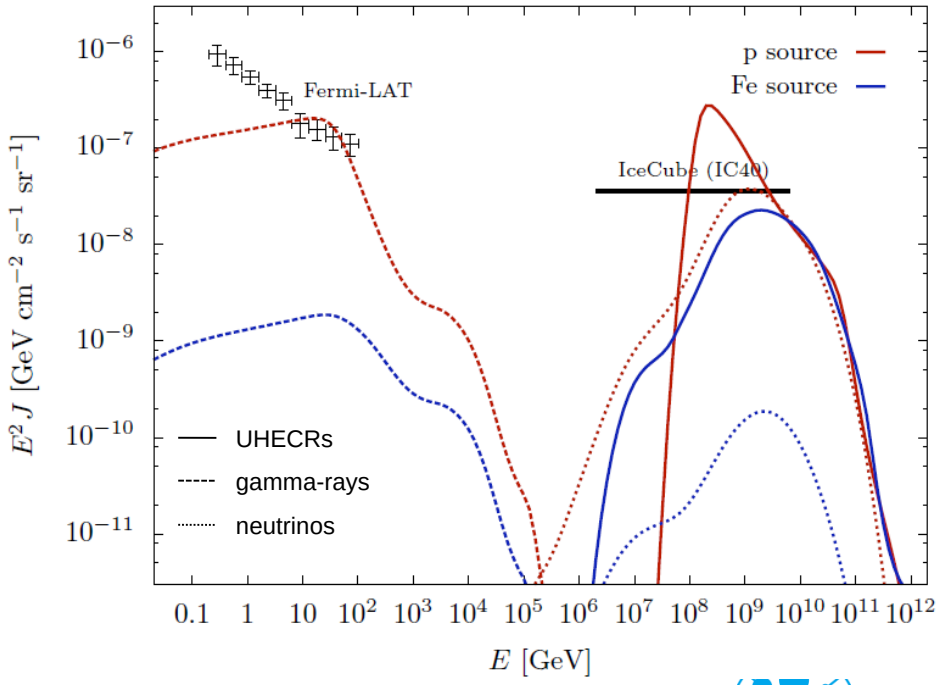


Alternative model: mixed composition

- Favoured by Auger composition data
- Lots of degrees of freedom
  → need to make assumptions about injected composition
- Pion production suppressed
  → cosmogenic neutrinos and gamma-rays suppressed

Ahlers, Salvado
Phys. Rev. **D84**, 085019 (2011)





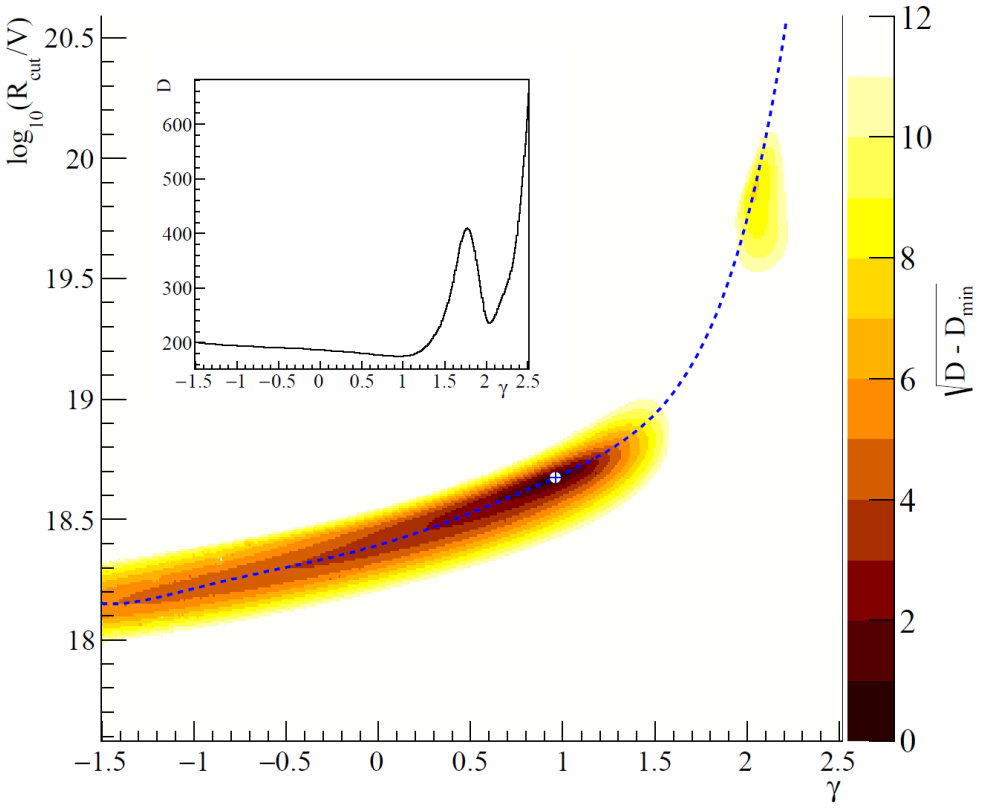
Combined fit to spectrum and composition

Pierre Auger Collaboration, arXiv: 1612.07155

- Auger approach:
  - Rigidity depended cutoff

$$f_{\rm cut}(E, Z_A R_{\rm cut}) = \begin{cases} 1 & (E < Z_A R_{\rm cut}) \\ \exp\left(1 - \frac{E}{Z_A R_{\rm cut}}\right) & (E > Z_A R_{\rm cut}) \end{cases}$$

  - Combined fit to composition



- Good fit to primary UHECR spectrum and composition
  - …but only above the ankle
- Secondary messengers not (yet) included

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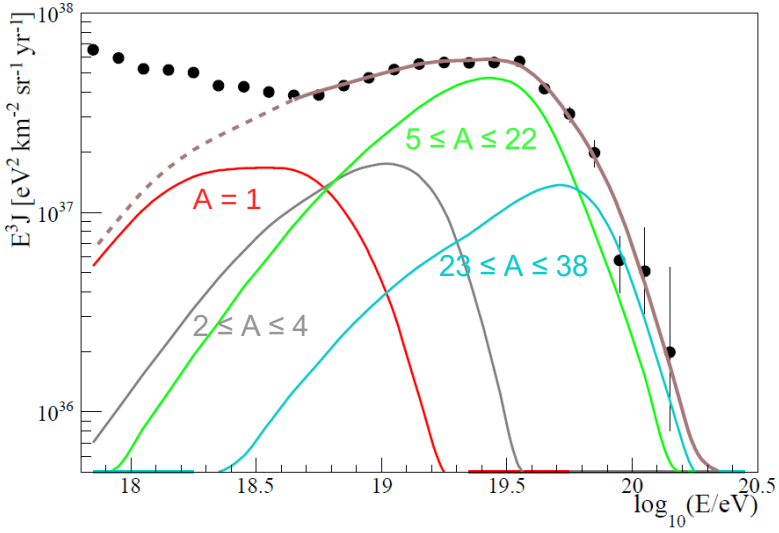

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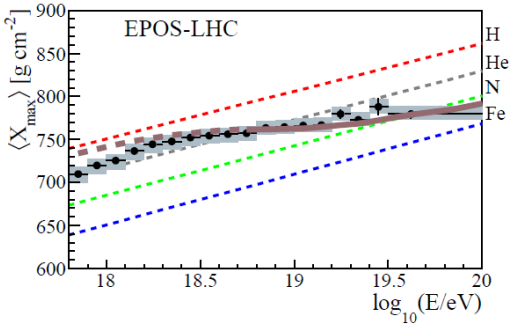
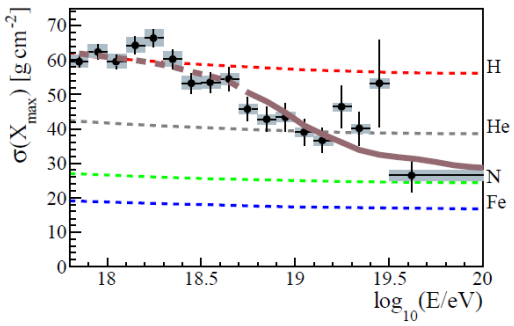
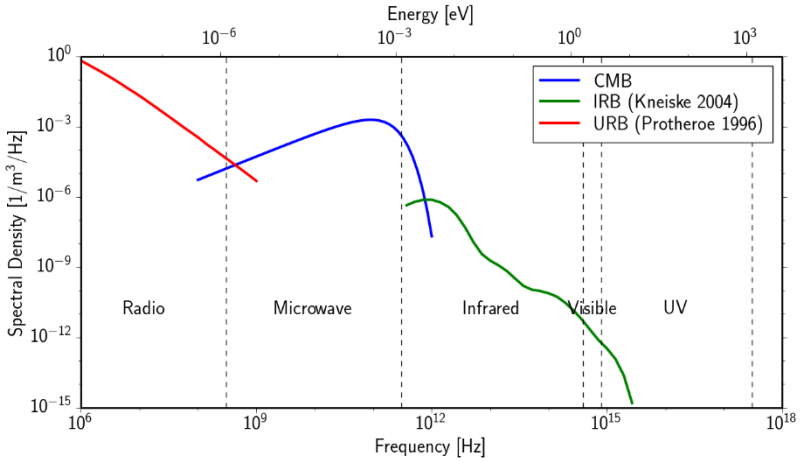




DESY

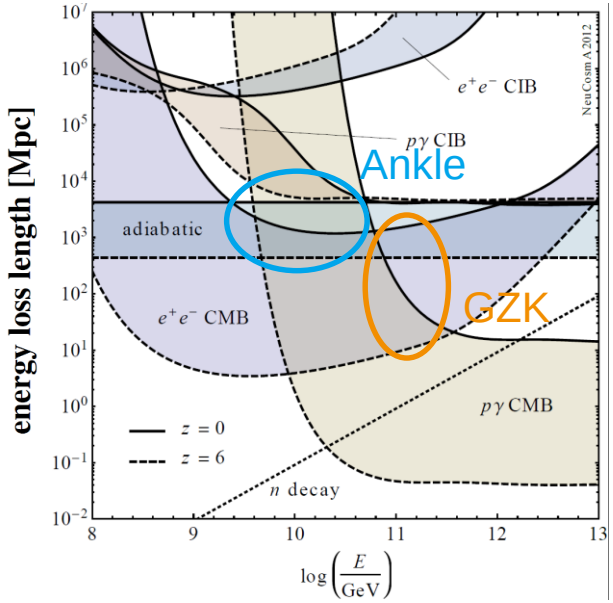
Extragalactic propagation of UHECR-Protons

- Flux suppression
  - Photo-pion-prod.
  - “GZK” - cutoff at $6.8 \cdot 10^{19}$ eV
  - … or source effect ?



Kuempel arXiv:1409.3129

- Ankle
  - Pair production dip or…
  - … gal. – extragal. Transition



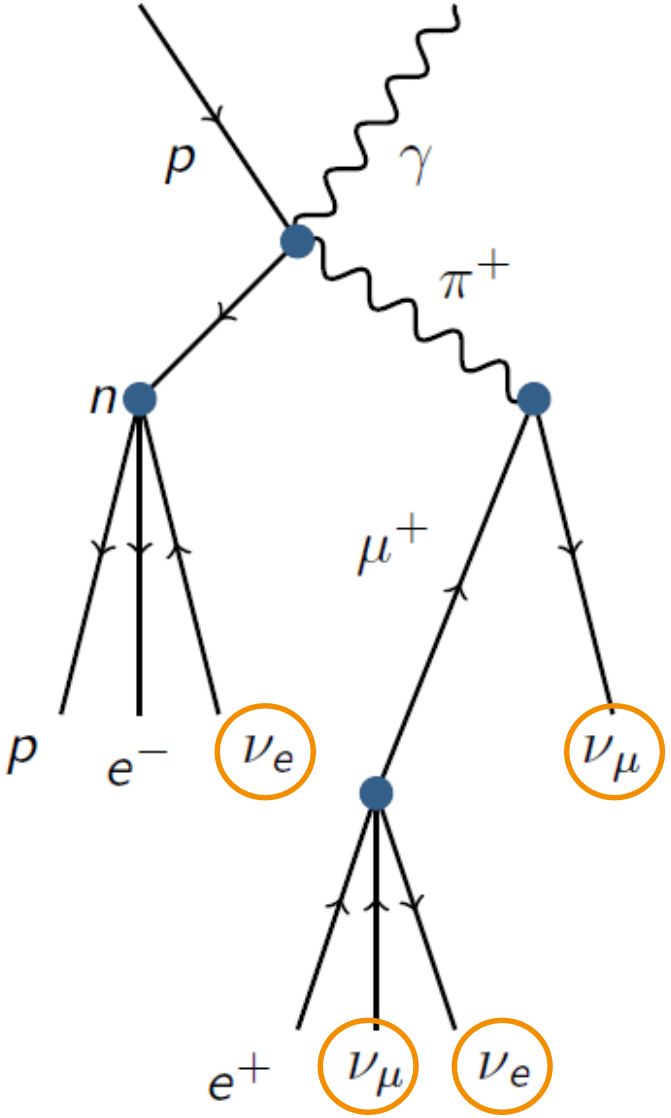
Baerwald, Bustamante, Winter Astropart. Phys. **62**, 66 (2015),

- Dip Model
  - UHECRs are extragalactic protons
  - Simple but convenient model: all features due to propagation

Cosmogenic Neutrinos

- Photo-pion-production: Delta resonance

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+, & \frac{1}{3}\,\mathrm{BR} \\ p + \pi^0, & \frac{2}{3}\,\mathrm{BR} \end{cases}$$



- Neutrinos only from π^+ decay-channel
  - Average energy: $E_\nu = E_p / 20$
  - Different thresholds for CMB and CIB…
  - …peaks at different neutrino energies

Constraints from cosmogenic gamma rays?

- Cosmogenic gamma-rays: produced in π^0 – decay

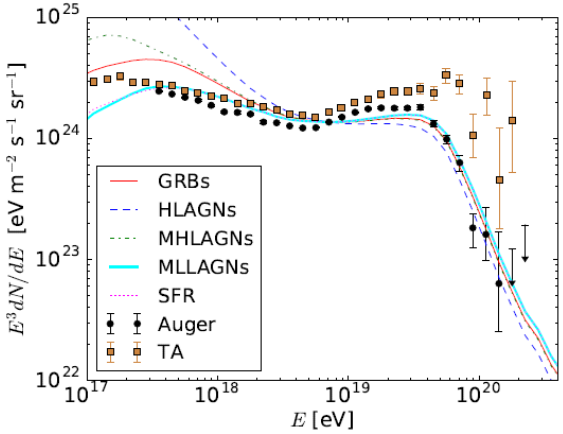
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+, & \frac{1}{3}\,\mathrm{BR} \\ p + \pi^0, & \frac{2}{3}\,\mathrm{BR} \end{cases}$$

→ Cosmogenic neutrinos

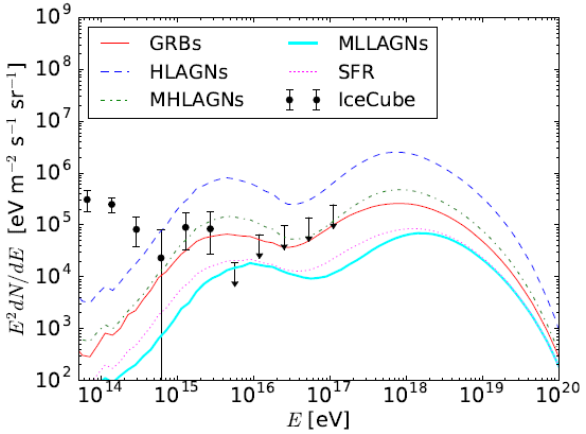
→ Cosmogenic gamma-rays

- E.M. cascade → detected at lower energies
- Third messenger, can also restrict UHECRs

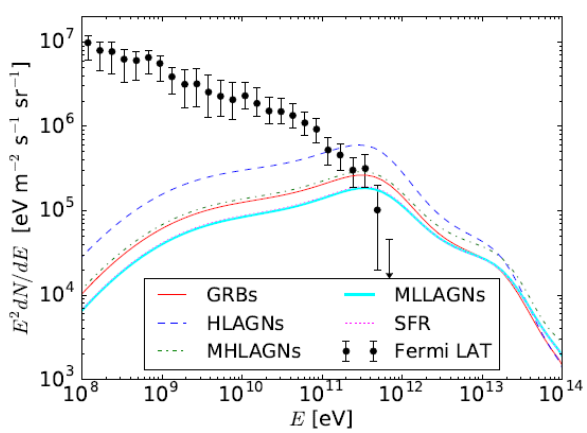
van Vliet
arXiv: 1609.03336



(a) Cosmic rays



(b) Neutrinos



(c) Photons

Extragalactic cosmic rays

- Cosmic Rays
  - Charged particles
  - Approximate E^{-3} spectrum
  - Little distinct features
- Ultra High Energies
  - Above 10^9 GeV
  - Low anisotropy
  - Large Lamour radius
  - → extragalactic!

Origin?

Composition?

Transition?

Blumer, Engel, Horandel,
Prog. Part. Nucl. Phys. **63**, 293 (2009)