Cosmogenic neutrinos challenge the proton dip model

arXiv:1512.05988v2, accepted for publication in ApJ

Jonas Heinze, Denise Boncioli, Mauricio Bustamante and Walter Winter

Trieste, "Perspectives on the Extragalactic Frontiers: from Astrophysics to Fundamental Physics", May 2nd – 6th, 2016

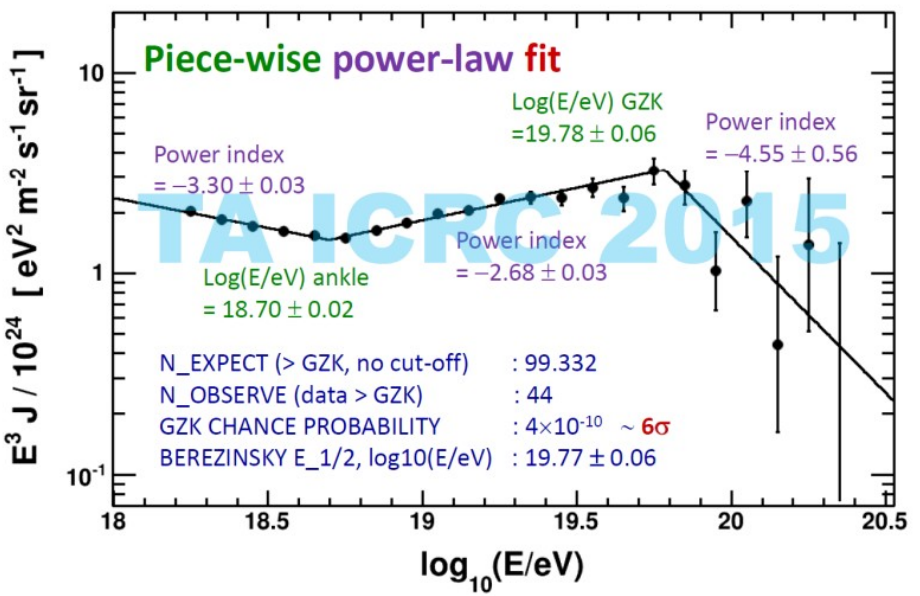
HELMHOLTZ | ASSOCIATION

DESY

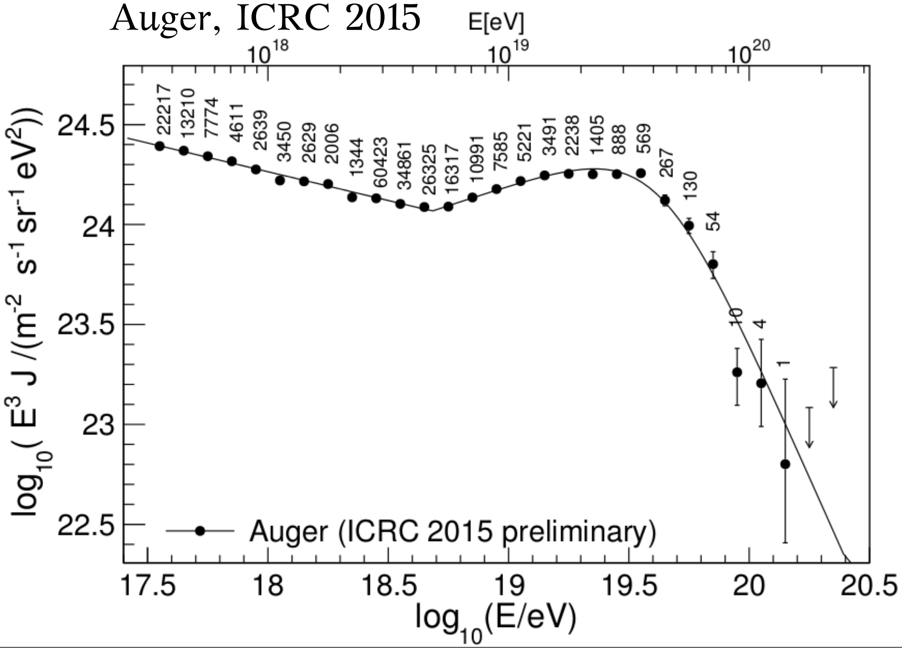
The UHECR energy spectrum

- The UHECR energy spectrum shows features

TA, ICRC 2015



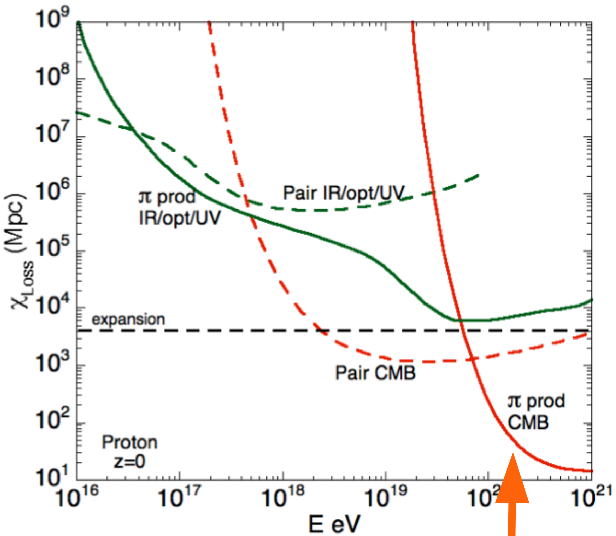
Auger, ICRC 2015



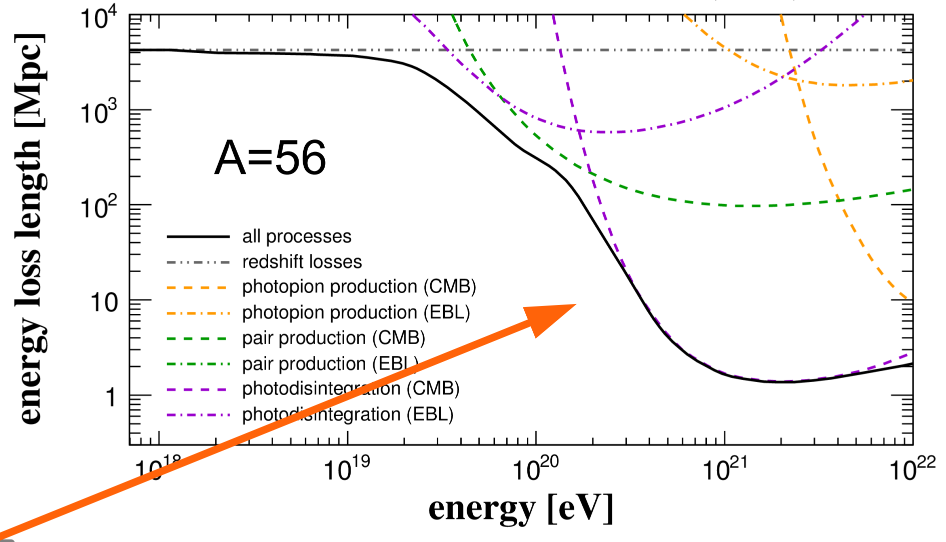
- The origin of these features is not yet clear → their interpretations depend on the UHECR composition and on characteristics of the sources and propagation through extragalactic space

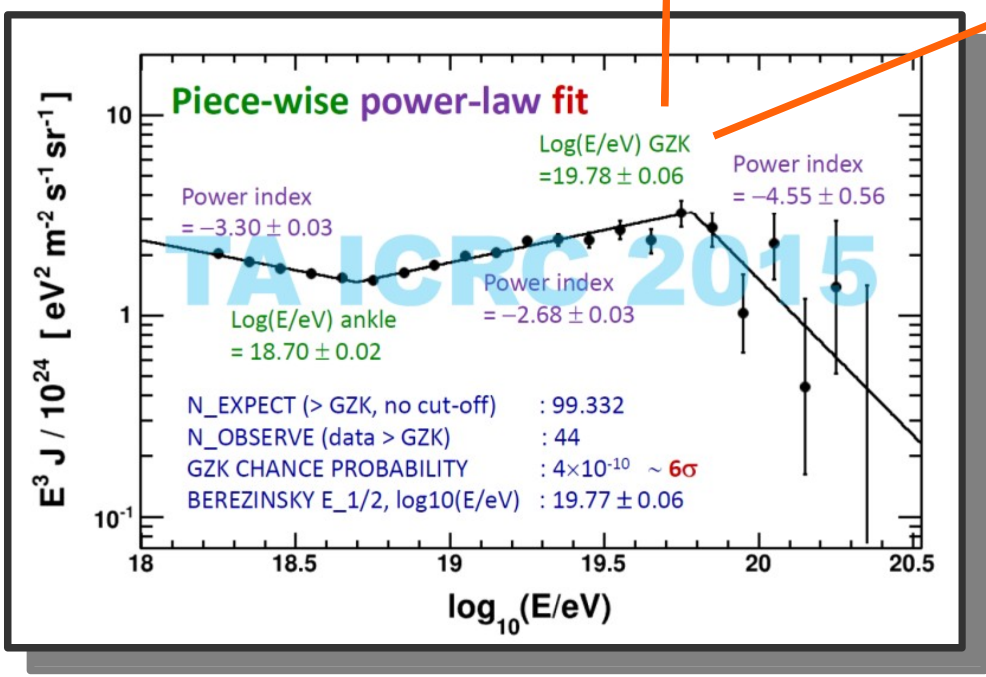
Spectrum features: suppression of the flux

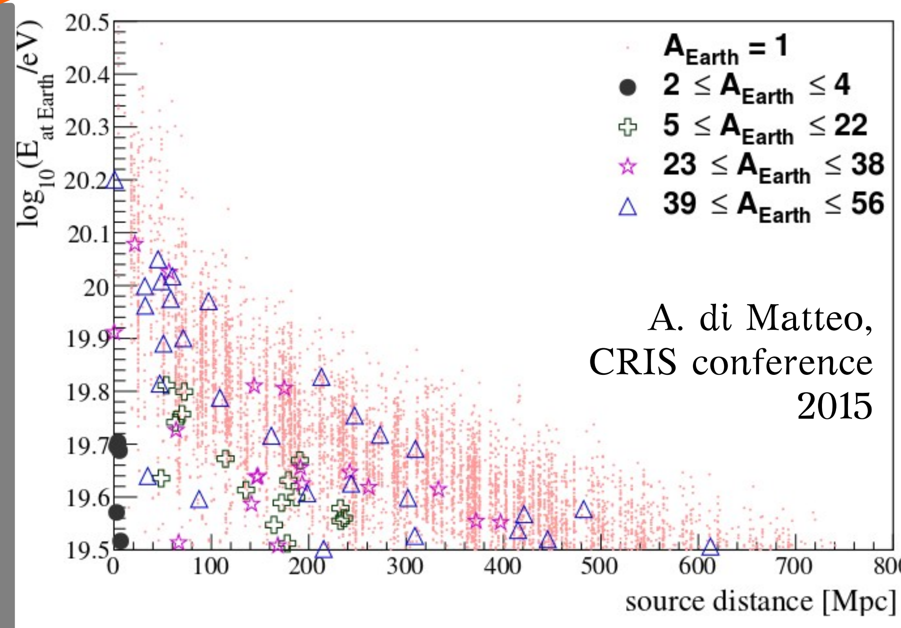
D. Allard, Astropart. Phys. 39-40 (2012) 33-43



R. Alves Batista, DB, A. di Matteo, A. van Vliet and D. Walz, JCAP 1510 (2015) 10, 063

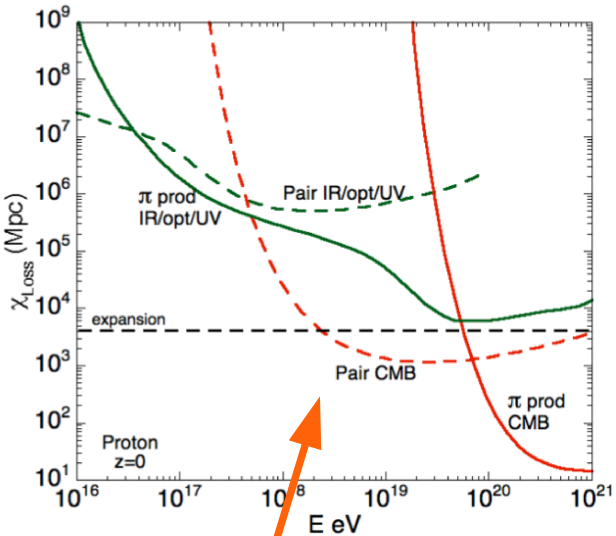






A. di Matteo, CRIS conference 2015

Spectrum features: the "Ankle"



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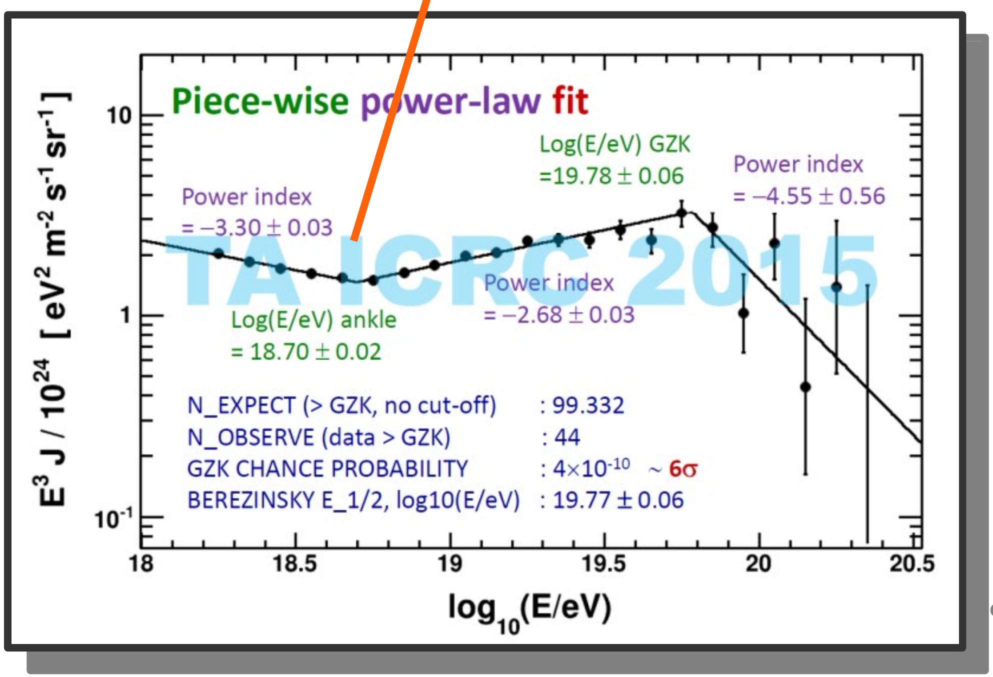
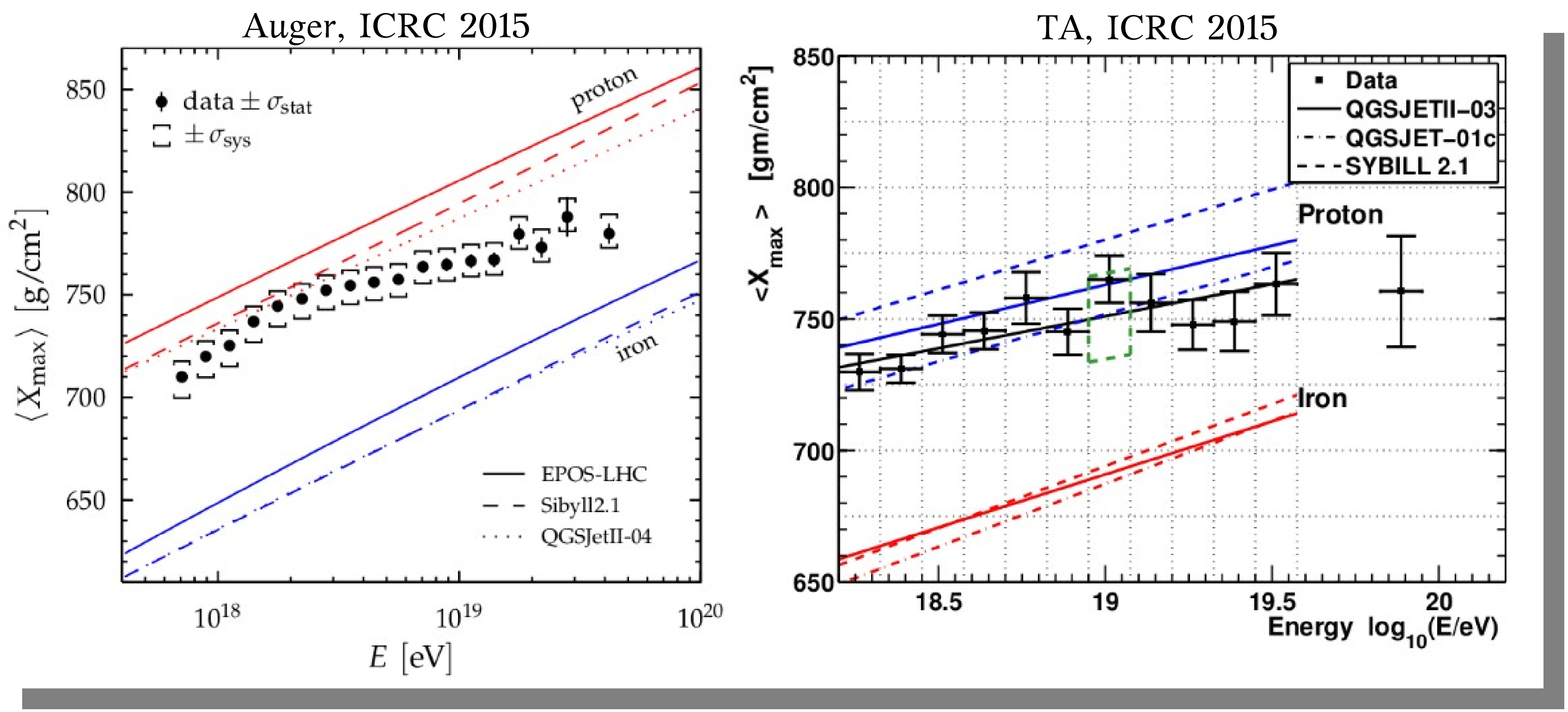


- If UHECRs above 1 EeV are mainly extragalactic protons, the features are mainly due to interactions with the CMB → "**dip model**"
- In the context of the "**ankle model**", the "ankle" is due to the transition between galactic and extragalactic cosmic rays
- A **mixed composition** complicates the scenario...

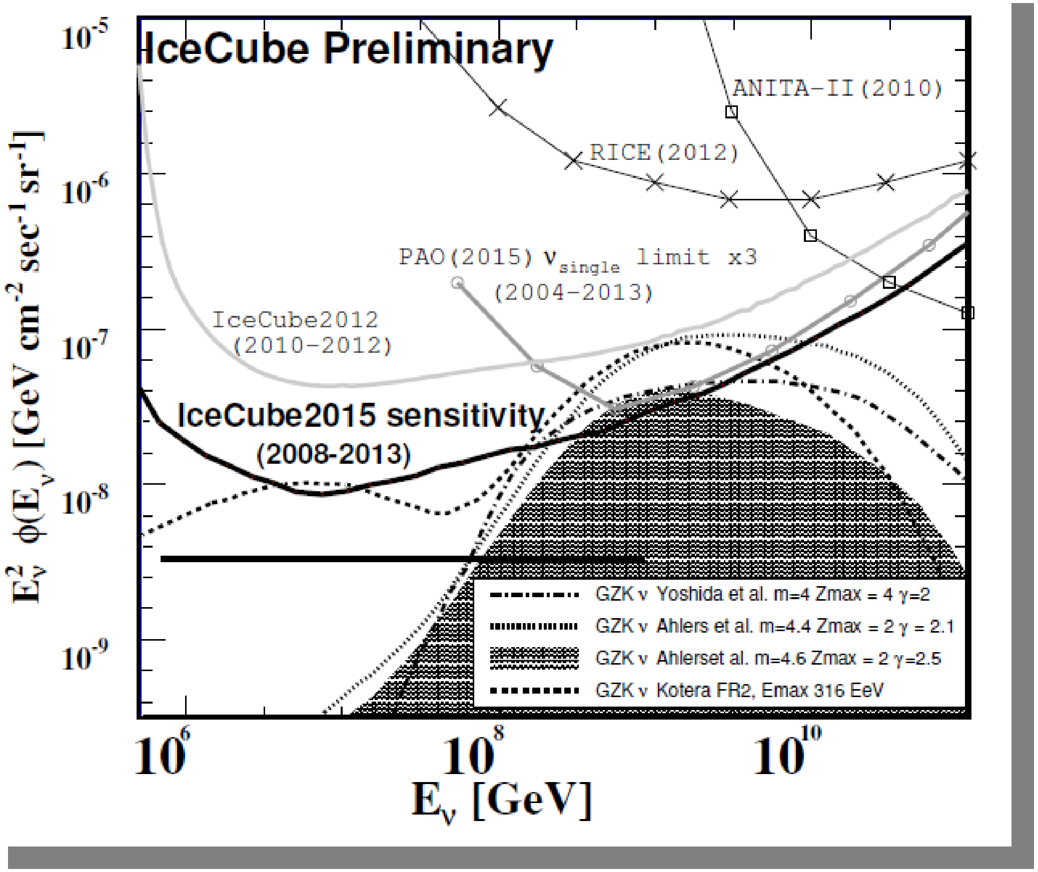
Composition observables



- Auger results could be interpreted as evindence against the dip model
- After accounting for the different resolutions, acceptances and analysis strategies of the two experiments, the results are found in good agreement within systematics → see TA and Auger working group @ ICRC 2015
- Uncertainties in the interactions of different primaries and shower development → no strong conclusions

Information from secondary particles

IceCube, ICRC 2015



- Secondary particles produced during propagation add information to the aim of understanding the UHECR properties
- Is the neutrino flux able to limit astrophysical models for UHECRs?

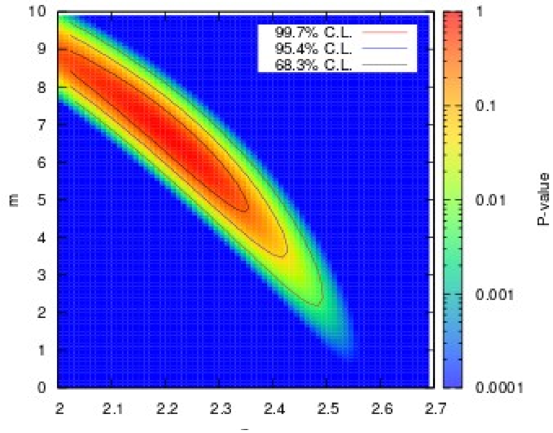
TA spectrum fit presented @ ICRC 2015

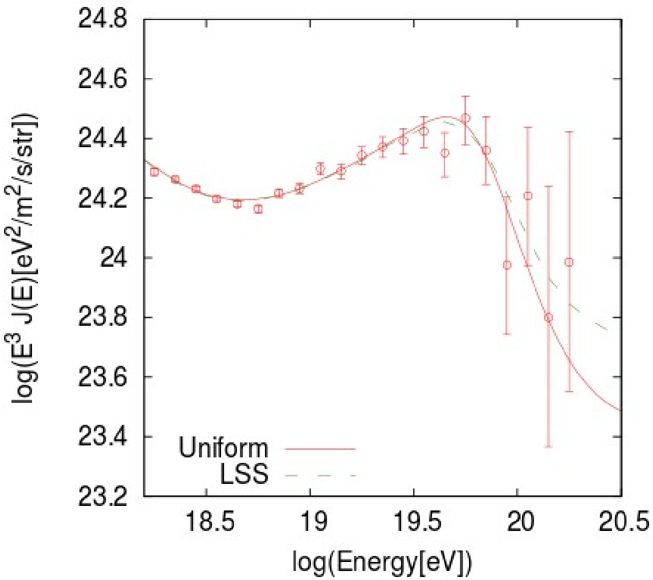
- A fit of the UHECR energy spectrum was presented at ICRC on behalf of the TA collaboration, with the assumption of a **pure proton composition**:

$$Q(E,z) = \alpha E^{-p}(1+z)^{3+m},\ E < E_{\max},\ z < z_{\max},$$

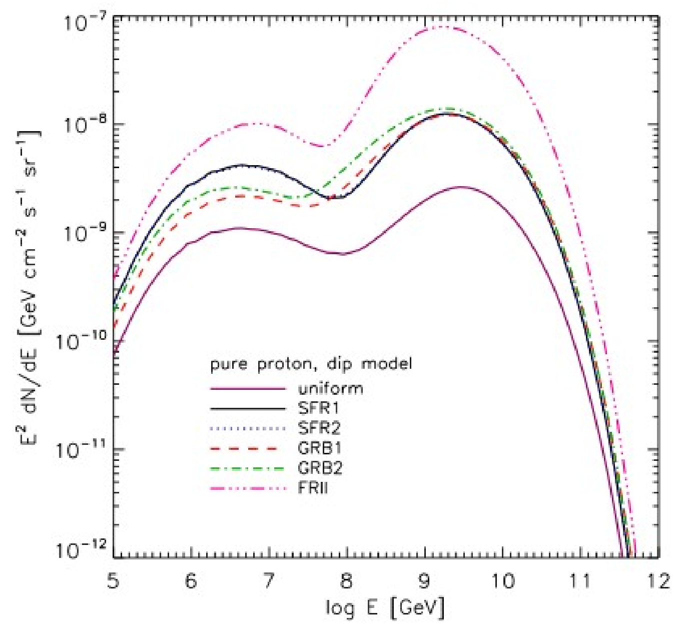
$$(\gamma, m) = (2.21^{+0.10}_{-0.15}, 6.7^{+1.7}_{-1.4})$$

TA, ICRC 2015





- What are the consequences of the best fit parameters from the point of view of the neutrino flux?



Kotera, Allard, Olinto, JCAP10(2010)013

Simulation of UHECR propagation and fit - protons

Sources

- Sources assumed to be identical, homogeneously distributed (up to z=6), with proton injection:

$$J_p^{\rm inj}(E) \propto H(z) E^{-\gamma} \exp(-E/E_{\max})$$

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

SFR, as in Hopkins & Beacom (2006)

Propagation

- Propagation computed numerically including:

  - adiabatic energy losses due to the expansion of the Universe
  - pair production
  - photopion production

  → as computed in Baerwald et al (2015), using the CIB from Franceschini et al. (2008)

- Resulting <u>neutrino flux</u> is also computed

Simulation of UHECR propagation and fit - protons

- The most recent combined spectrum (surface and fluorescence detectors) of the TA collaboration is used – 7 years of data taking

Data

- A scan is performed over the model parameters:

  - spectral injection index
  - maximal injected energy
  - source redshift evolution

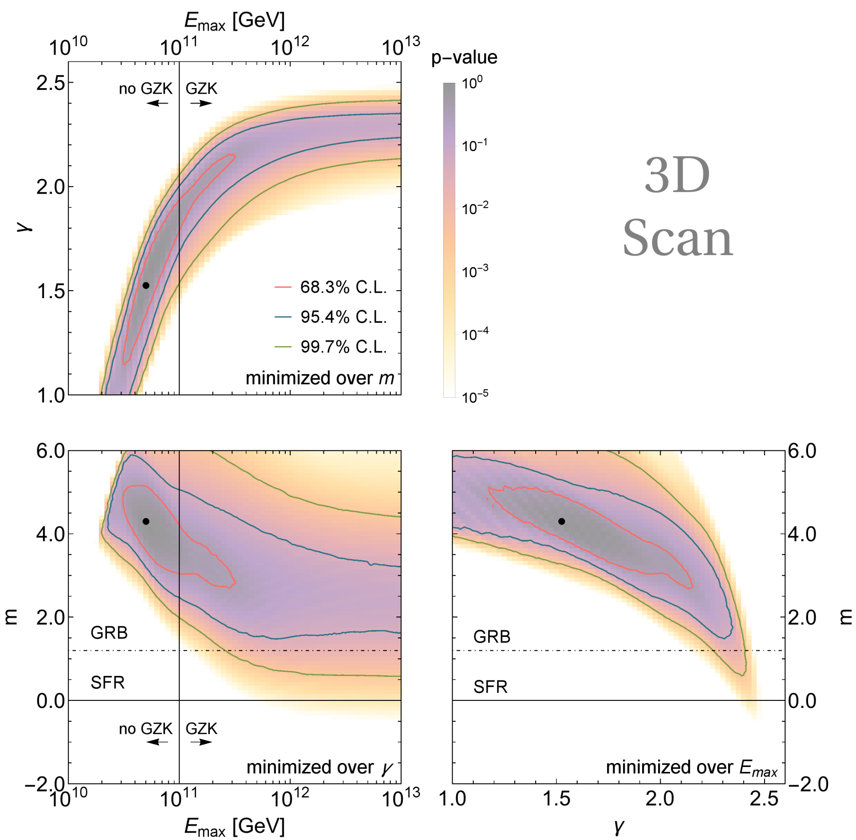
Fit

3 astrophysical parameters!

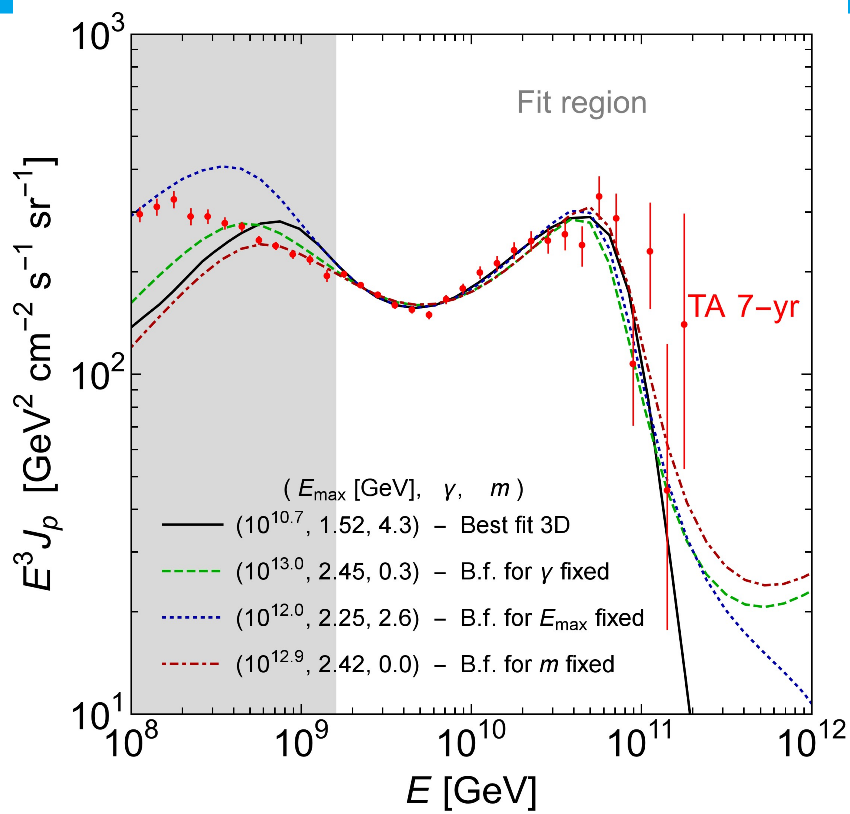
- For each combination, the normalization and the shift in the energy scale are computed

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

Simulation of UHECR propagation and fit - protons



3D Scan



- Hard spectra, strong source evolution and low maximal proton energy at the source are slightly favored over the conventional GZK scenario

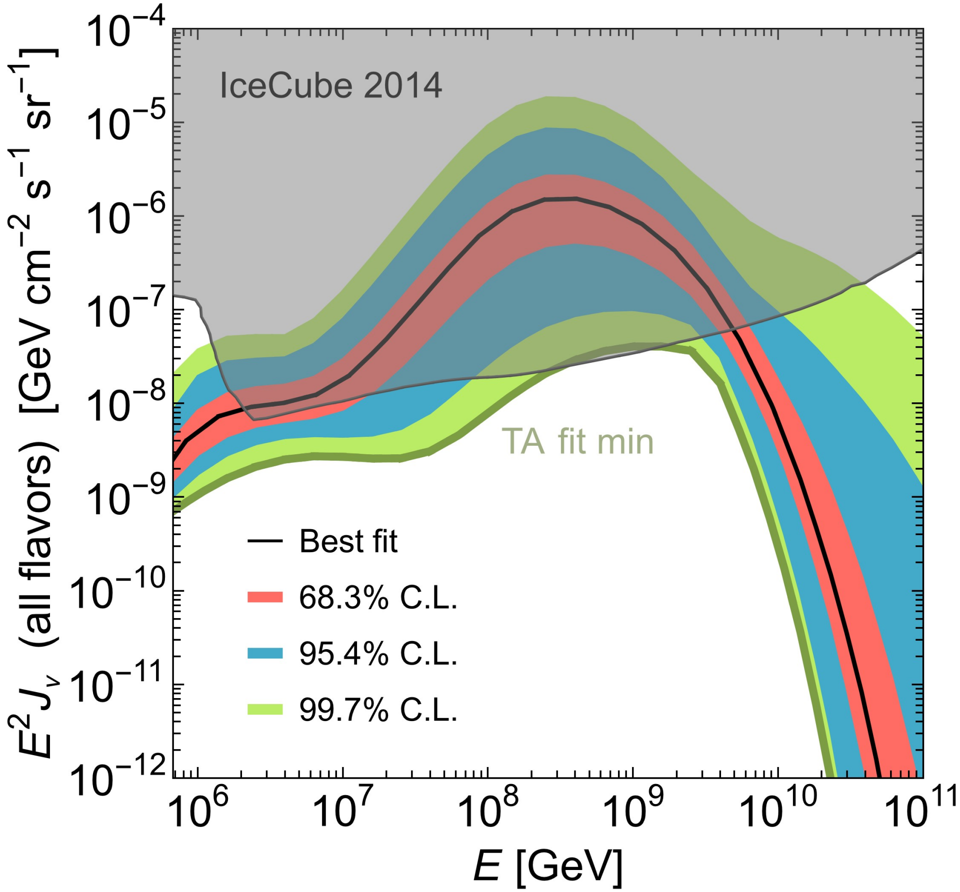
γ	$1.52^{+0.35}_{-0.20}$
$\log_{10}(E_{max}/\text{GeV})$	$10.7^{+0.3}_{-0.1}$
m	$4.3^{+0.4}_{-0.8}$
δ_E	-0.35
$\chi^2_{min}/\text{d.o.f.}$	$30.8/16$

UHECR propagation and neutrino flux

- Expected numbers of events after 6 years in IceCube:

	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

Only 1 event was observed
→ this flux can be excluded at 95% CL



- Evidence against dip model independent of mass composition measurement

Summary and Conclusions

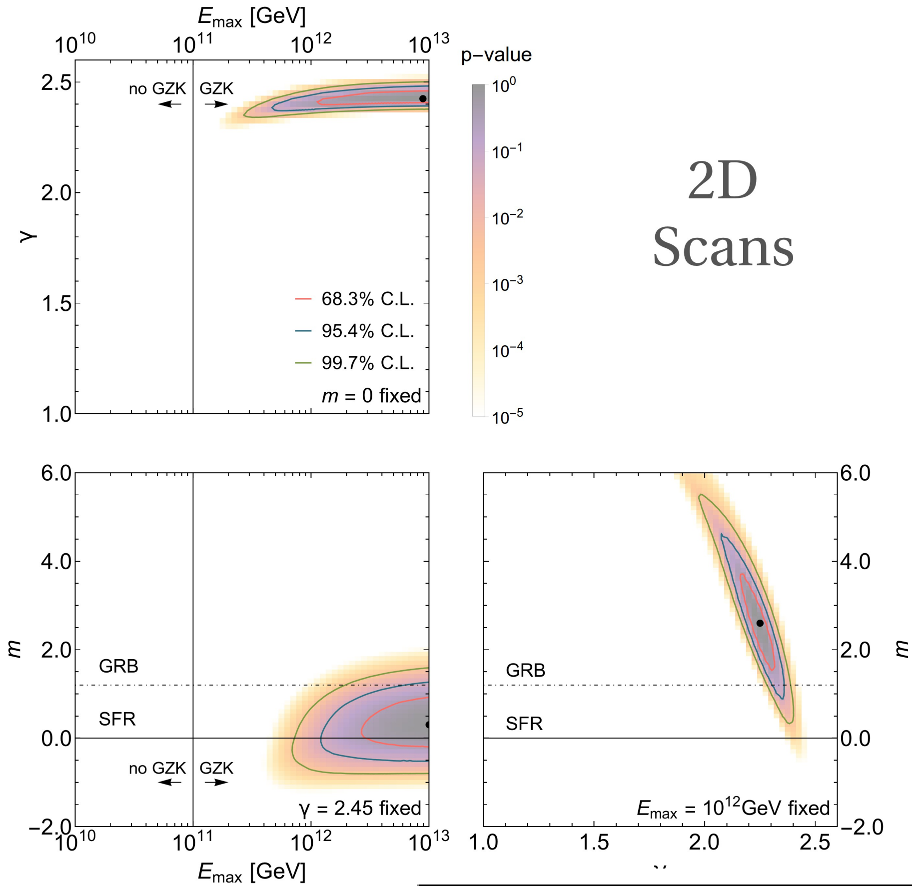
- Features of the UHECR spectrum are measured, but their origin is not clear
- The sensitivity of the neutrino flux can be used as a tool to limit the astrophysical scenarios that are compatible with the interpretations of the measured UHECR spectrum → can be done **independently from the composition measurements**
- Fit of the energy spectrum in terms of **3 astrophysical parameters**: spectral injection index, maximal proton energy and source redshift evolution, with the hypothesis of a pure proton composition → **hard spectra, strong source evolution and low maximal energy favored wrt GZK cutoff scenario**
- The expected neutrino flux from the best fit solution limits the possible scenarios: the "degeneracy" of the spectrum alone is broken!
- **The conventional proton dip model is challenged!**
- See **arXiv:1512.05988v2** (submitted to ApJ) for details

  - effects of systematics

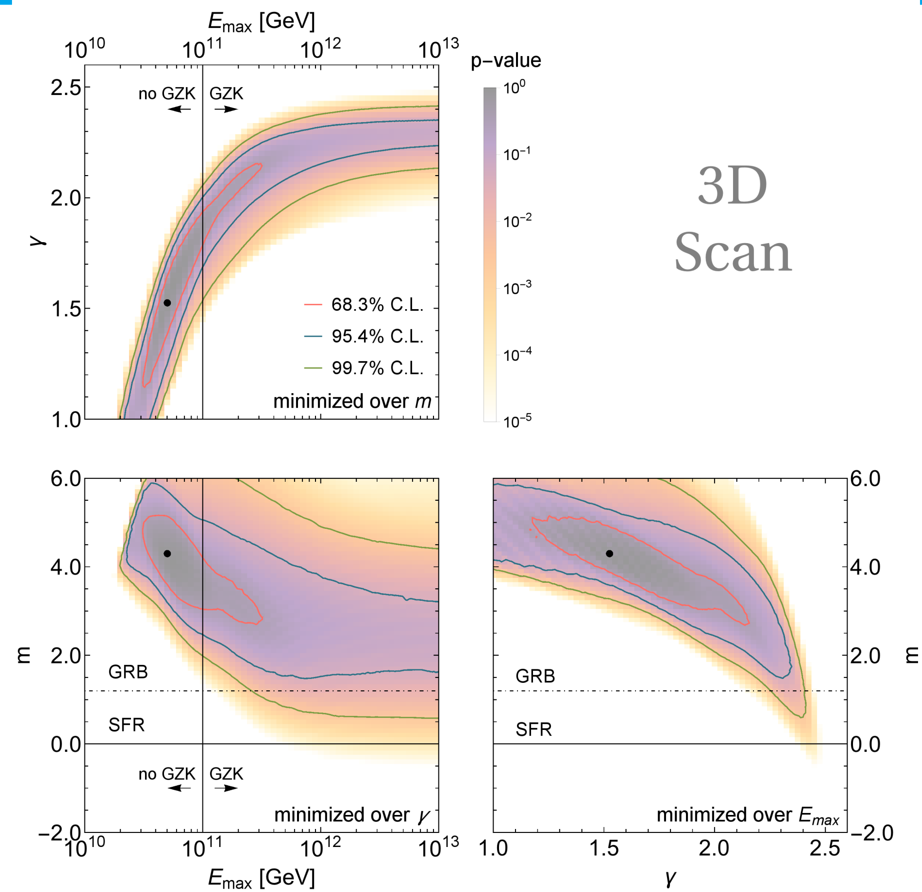
  - effect of changing some astrophysical assumptions

Backup slides

2D scans vs 3D scan



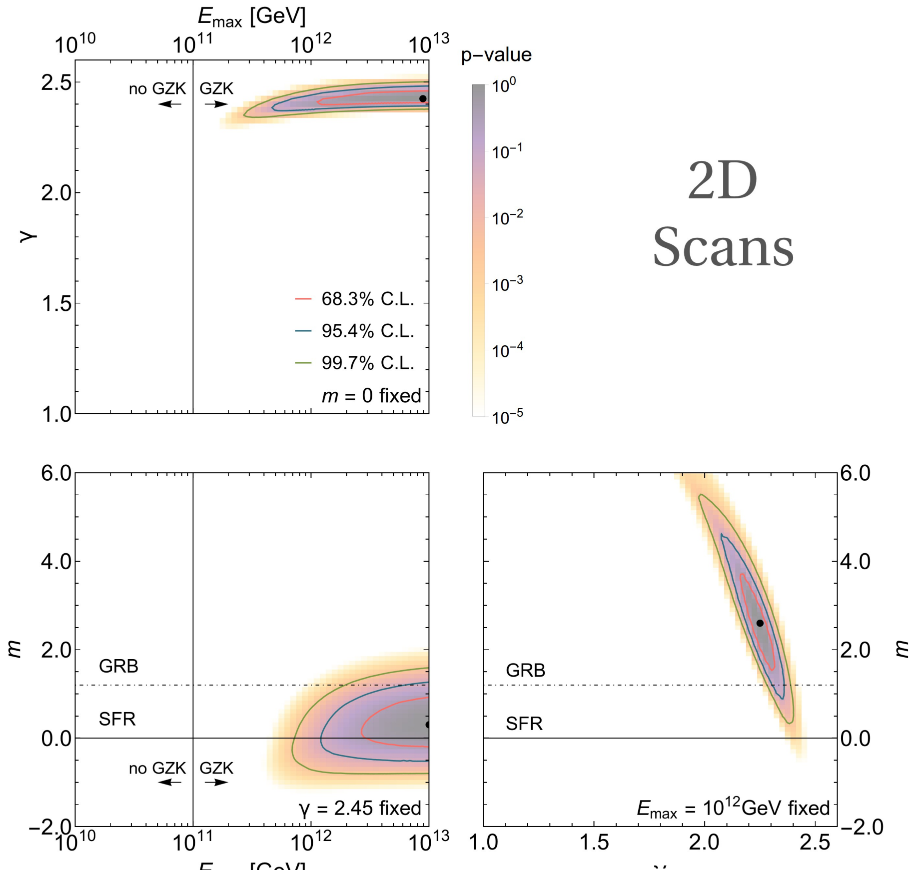
2D Scans



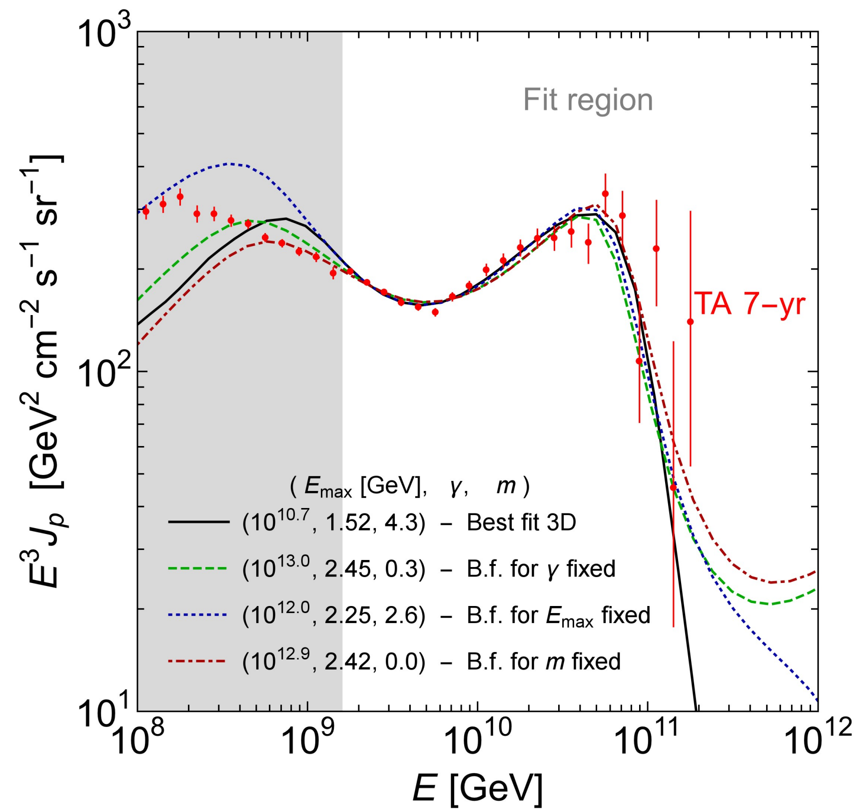
3D Scan

	2D scans			3D scan
γ	2.25	*2.45	2.42	$1.52^{+0.35}_{-0.20}$
$\log_{10}(E_{max}/\text{GeV})$	*12.0	13.0	12.9	$10.7^{+0.3}_{-0.1}$
m	2.6	0.3	*0.0	$4.3^{+0.4}_{-0.8}$
δ_E	–0.11	–0.06	–0.16	–0.35
χ^2_{min}/d.o.f.	34.7/17	47.8/17	47.8/17	30.8/16

2D scans



2D Scans



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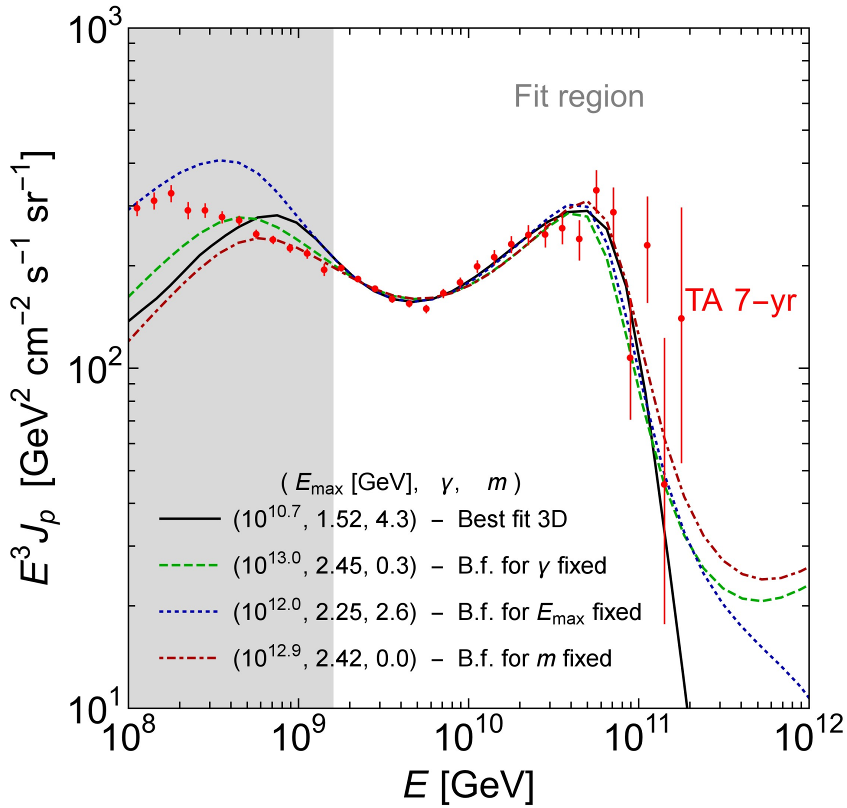
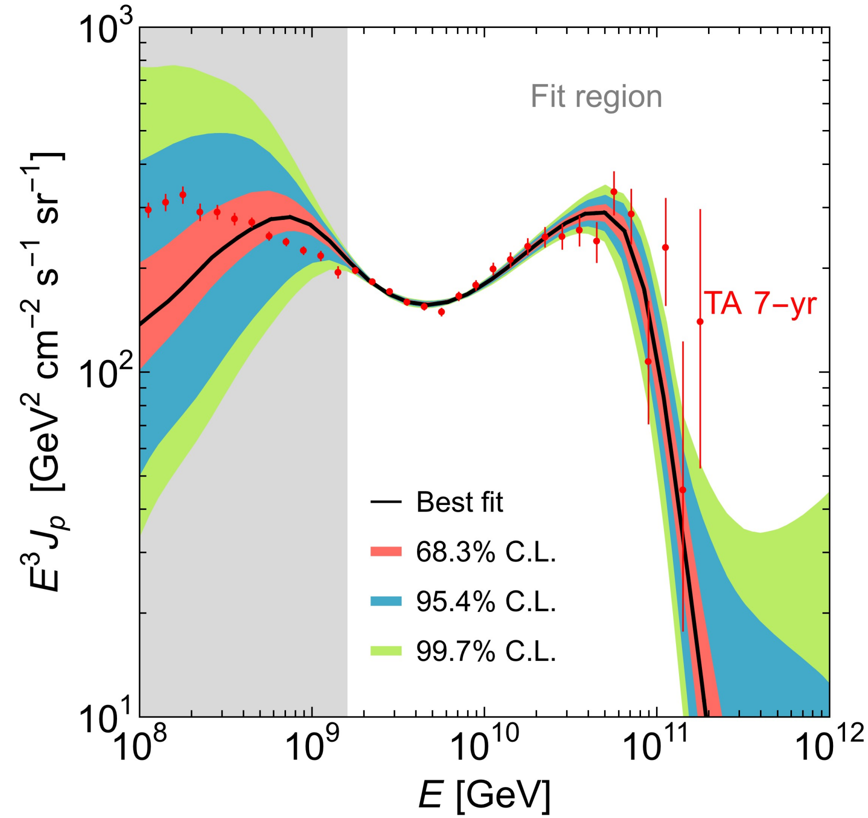
Proton spectra





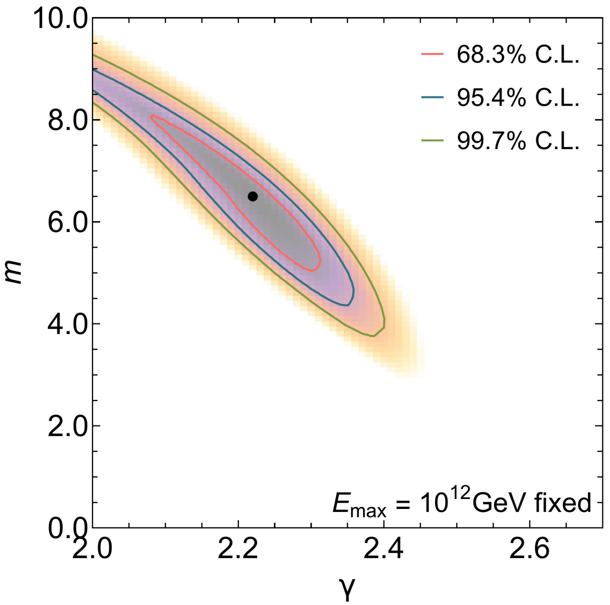
- The minimal and maximal proton spectra at each energy are set by the lower and upper edges of the shaded regions at each energy
- The maximal proton flux below the fit region has to be ascribed to the highest allowed values for m within the 99.7% CL, connected with the lowest allowed values for Emax, responsible for the minimal proton flux at the highest energies

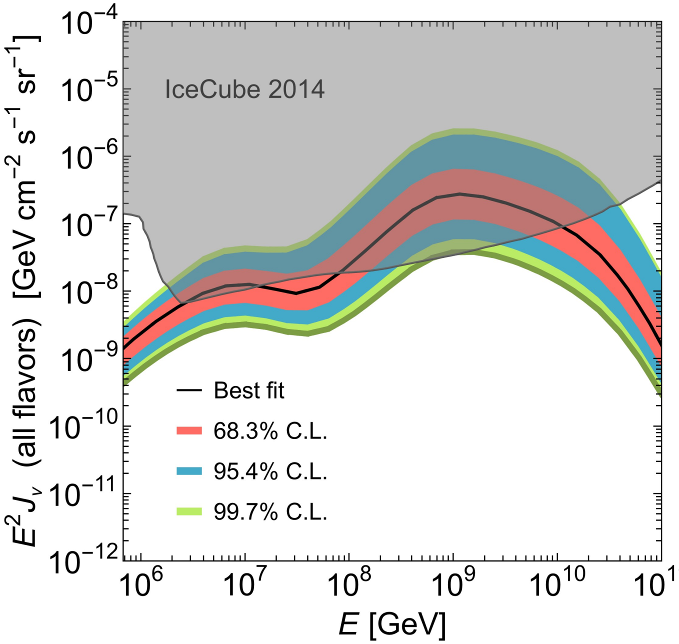
Fits using the astrophysical TA assumptions

- TA assumptions and results (using SD spectrum after 5 years, with syst+stat)

source evolution of the form $(1+z)^m$ and injected protons up to $z=2$, with fixed $E_{max} = 10^{12}$ GeV.

$$(\gamma, m) = (2.21^{+0.10}_{-0.15}, 6.7^{+1.7}_{-1.4}) \quad \delta_E = -0.03, \text{ with } \chi^2_{min}/\text{d.o.f.} = 12.4/17$$





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3D fit with low-energy penalty	1.00	10.3	4.1	−0.51	37.8/16	145.1	124.4	74.4	**12.1**
3D fit starting from 10^9 GeV	1.05	10.4	4.3	−0.49	40.2/18	173.4	111.0	58.8	**2.5**
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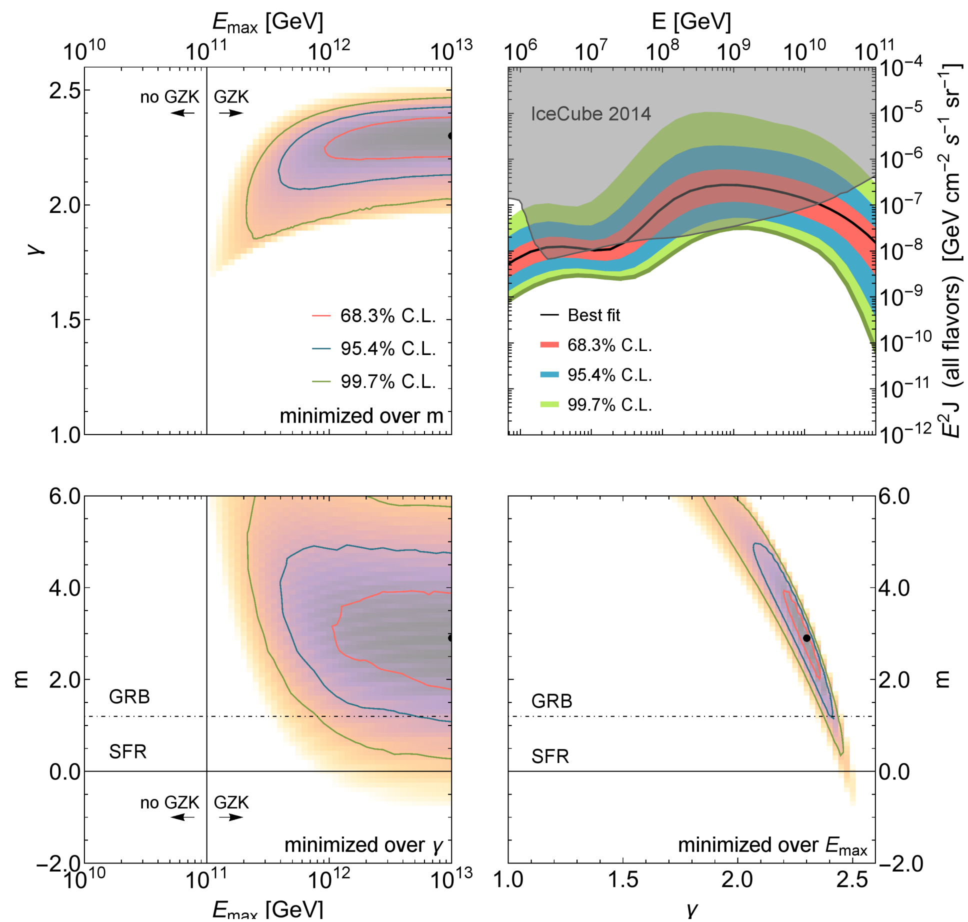
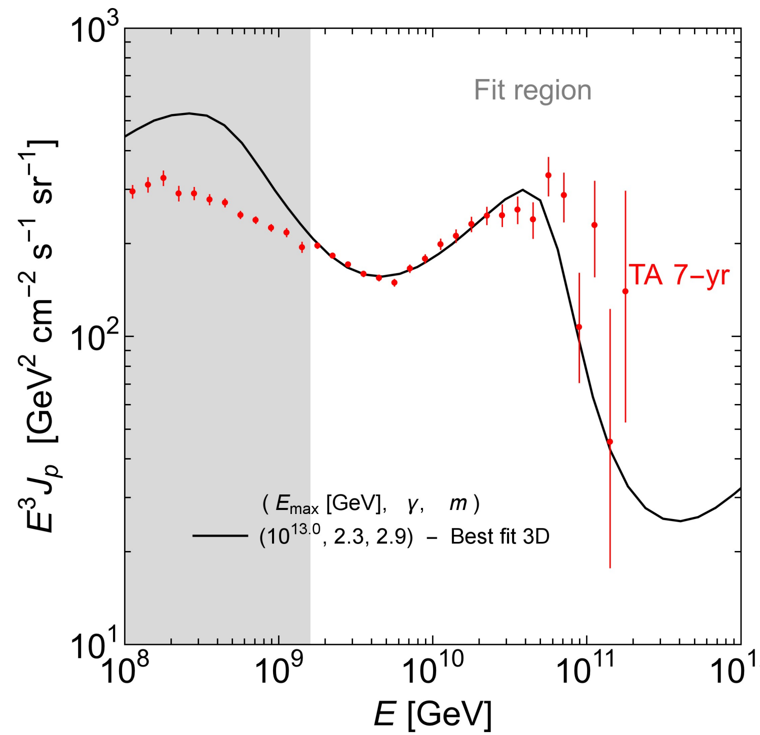
Effect of the energy scale uncertainty





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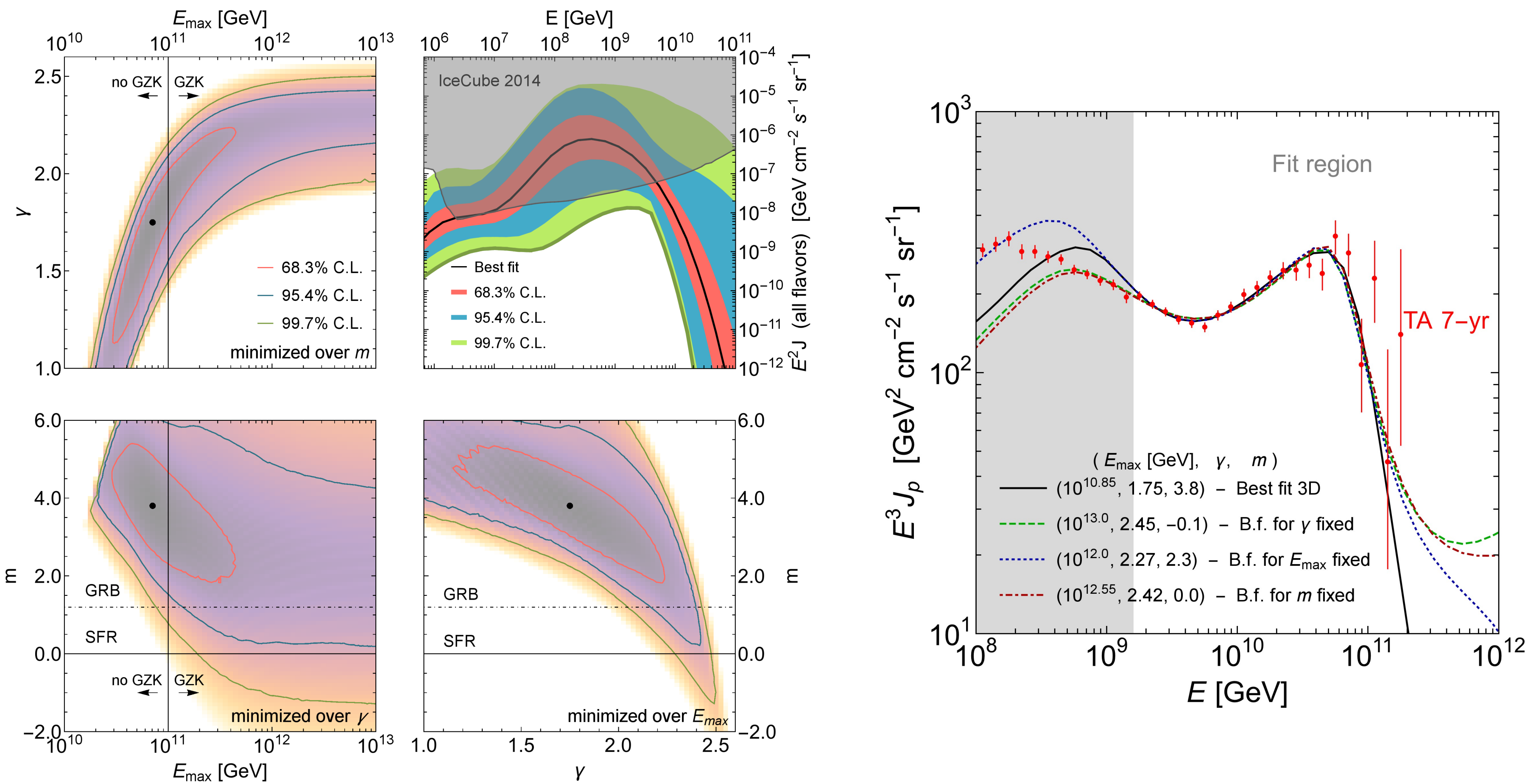
Effect of an uncorrelated bin-to-bin systematic error



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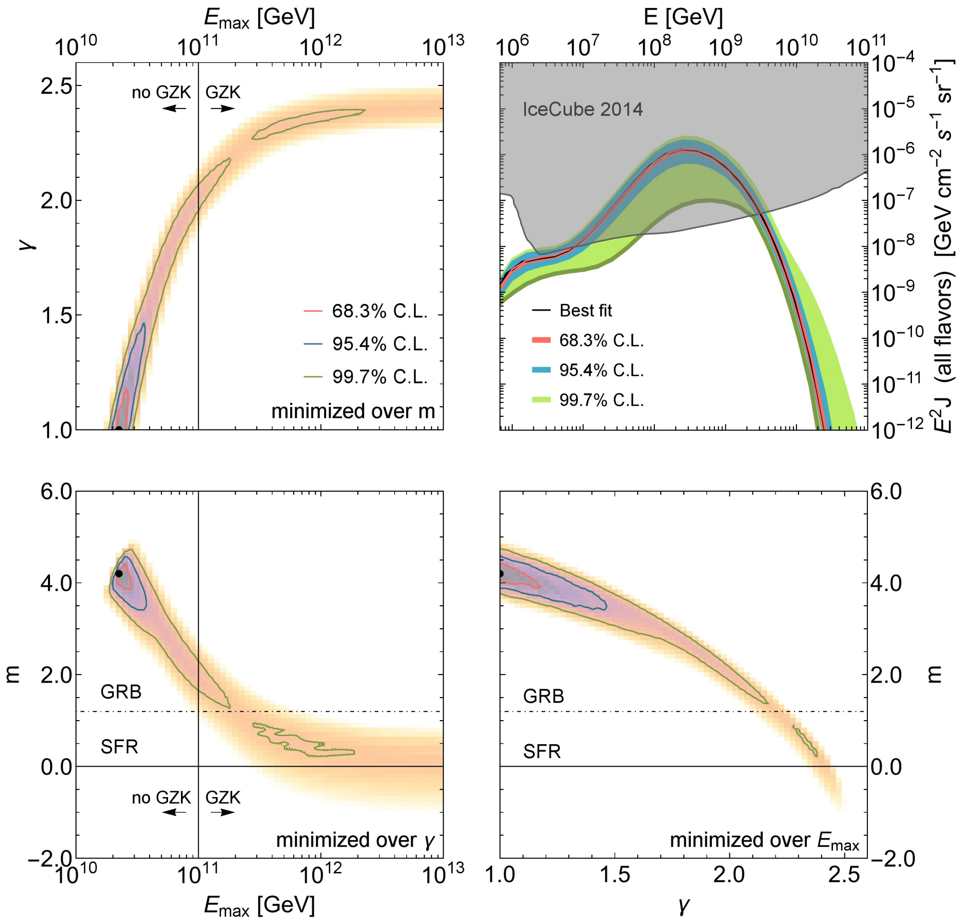
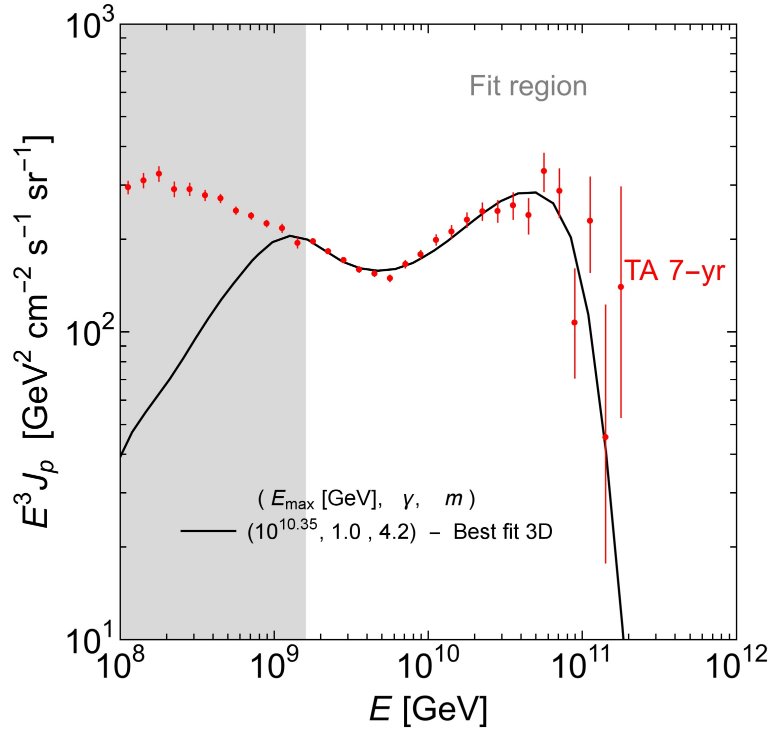
Overshoot penalty at low energies





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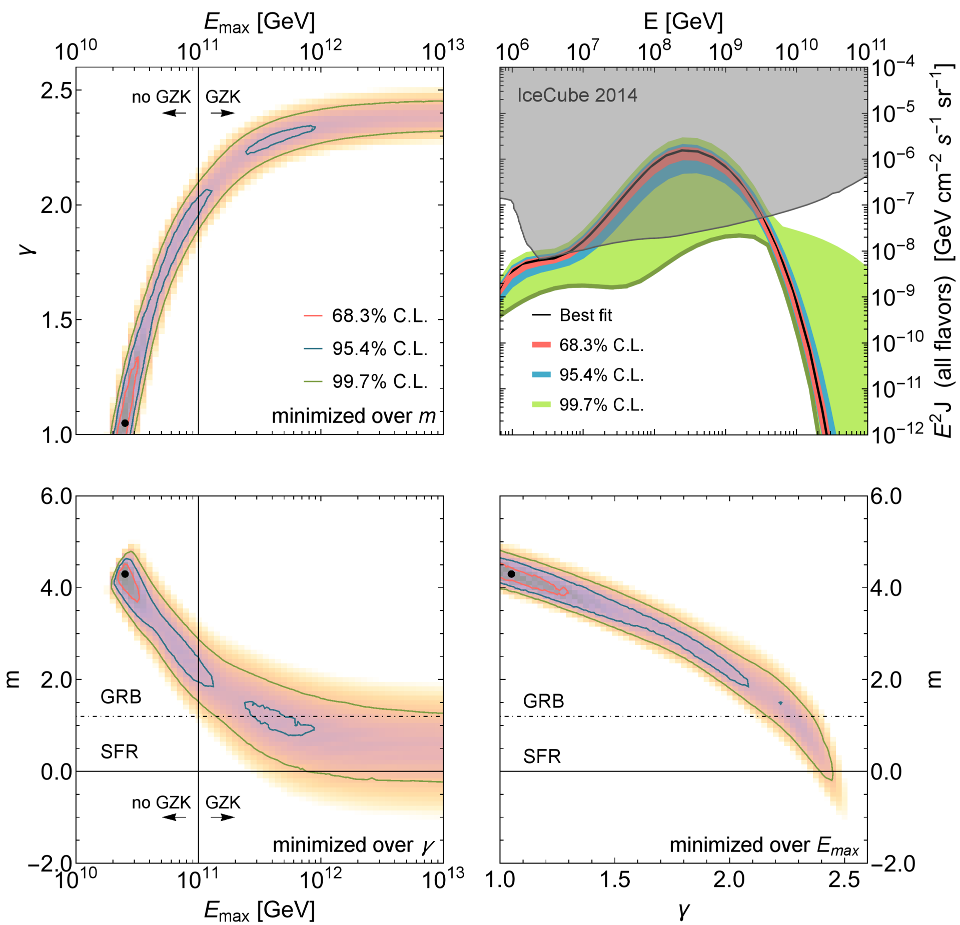
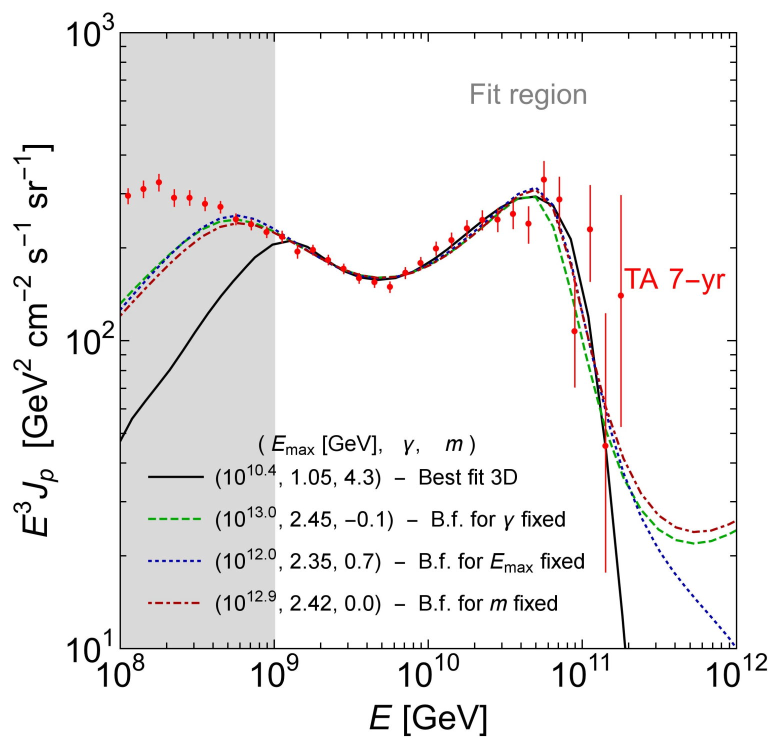
Effect of changing the starting energy of the fit





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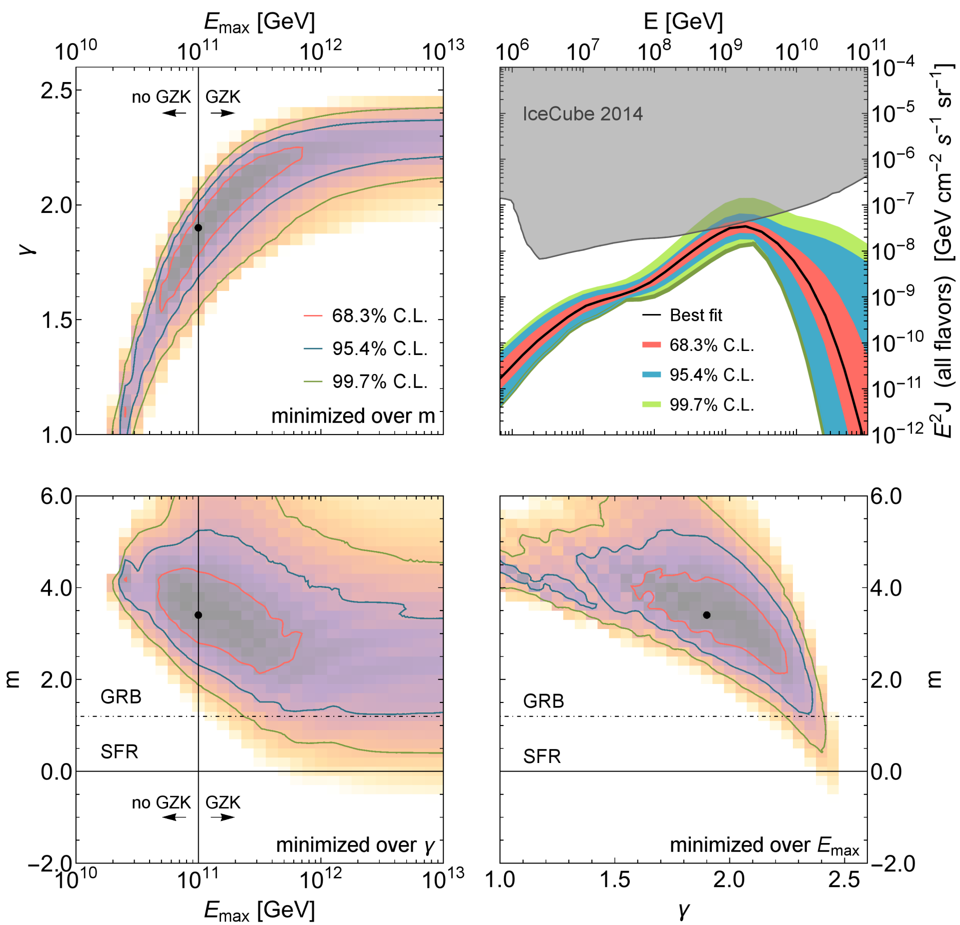
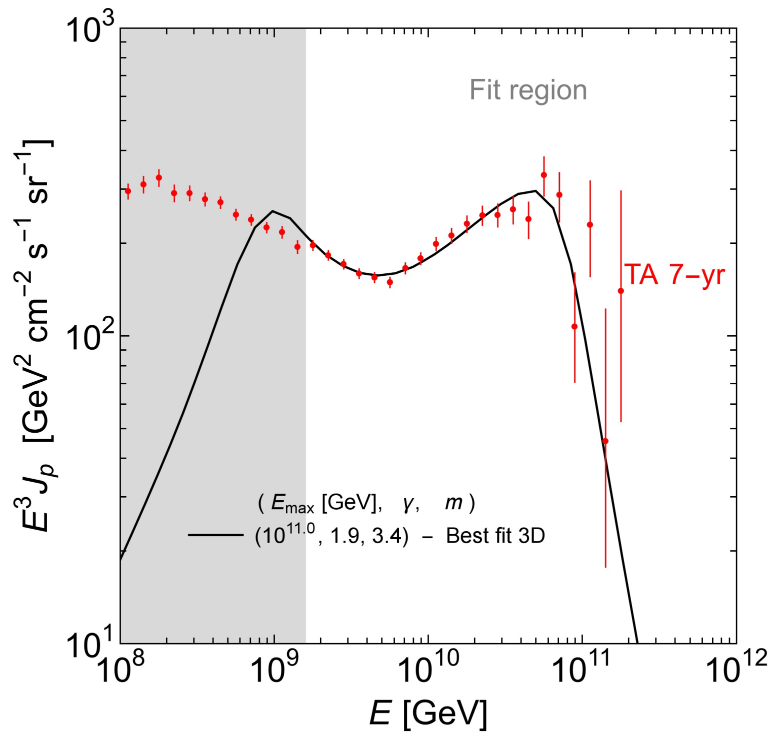
Maximal redshift injection cutoff





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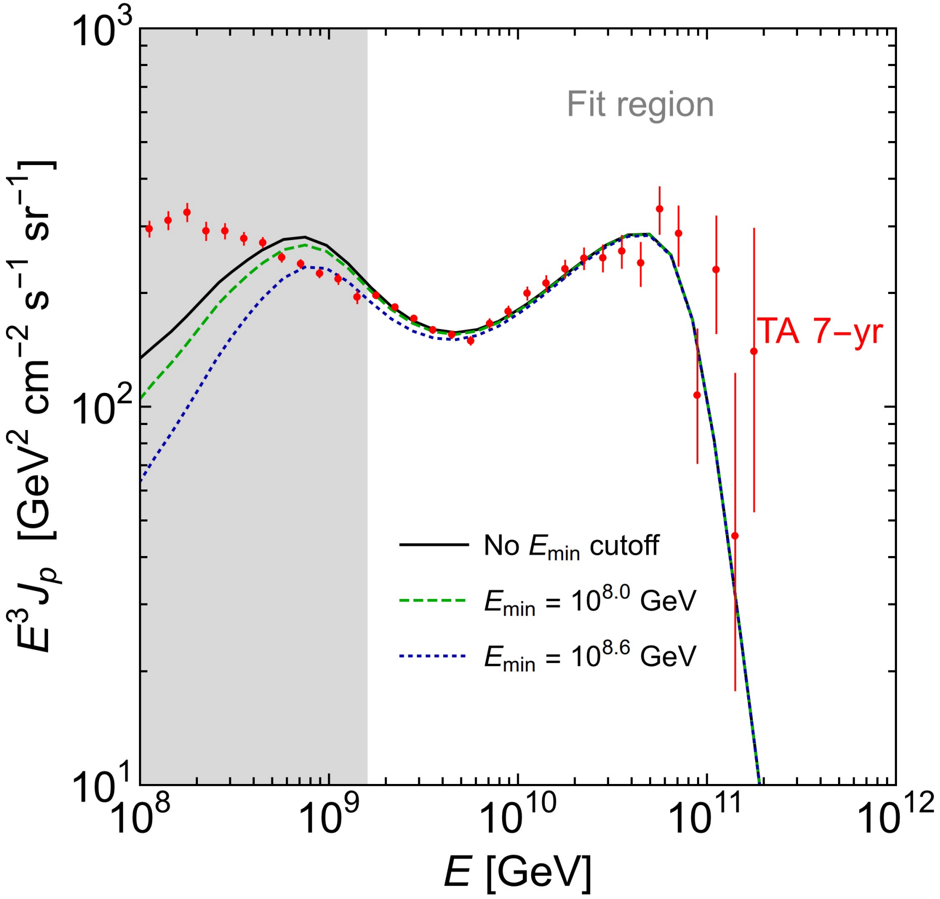
2D fit with TA assumptions	2.22	*12.0	**6.5	−0.10	34.2/17	27.8	12.9	6.9	**4.4**
3D fit with fixed energy scale	2.30	13.0	2.9	*0.00	39.4/17	40.5	17.8	7.8	**4.4**
3D fit with 3% syst. added in quadrature	1.75	10.8	3.8	−0.31	22.4/16	94.0	30.0	5.0	**1.5**
3D fit with low-energy penalty	1.00	10.3	4.1	−0.51	37.8/16	145.1	124.4	74.4	**12.1**
3D fit starting from 10^9 GeV	1.05	10.4	4.3	−0.49	40.2/18	173.4	111.0	58.8	**2.5**
3D fit with $z = 1$ cutoff	1.90	11.0	3.4	−0.29	32.3/16	2.5	1.9	1.3	**0.9**

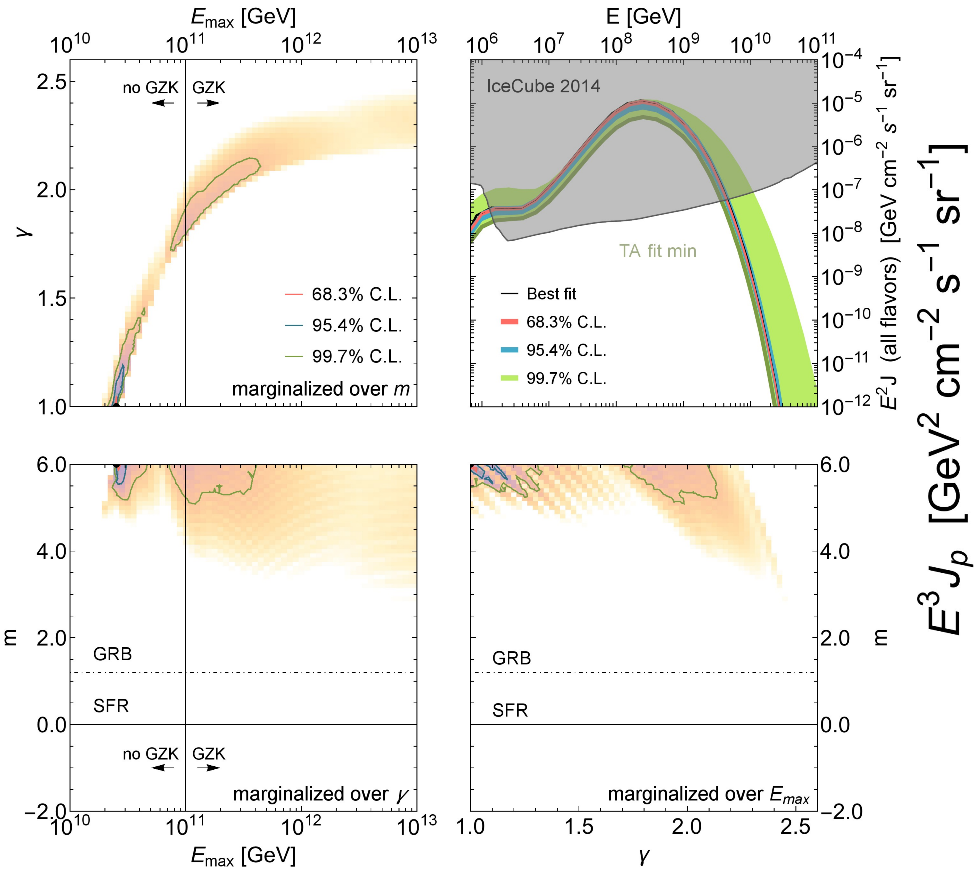
Effect of minimal injection energy

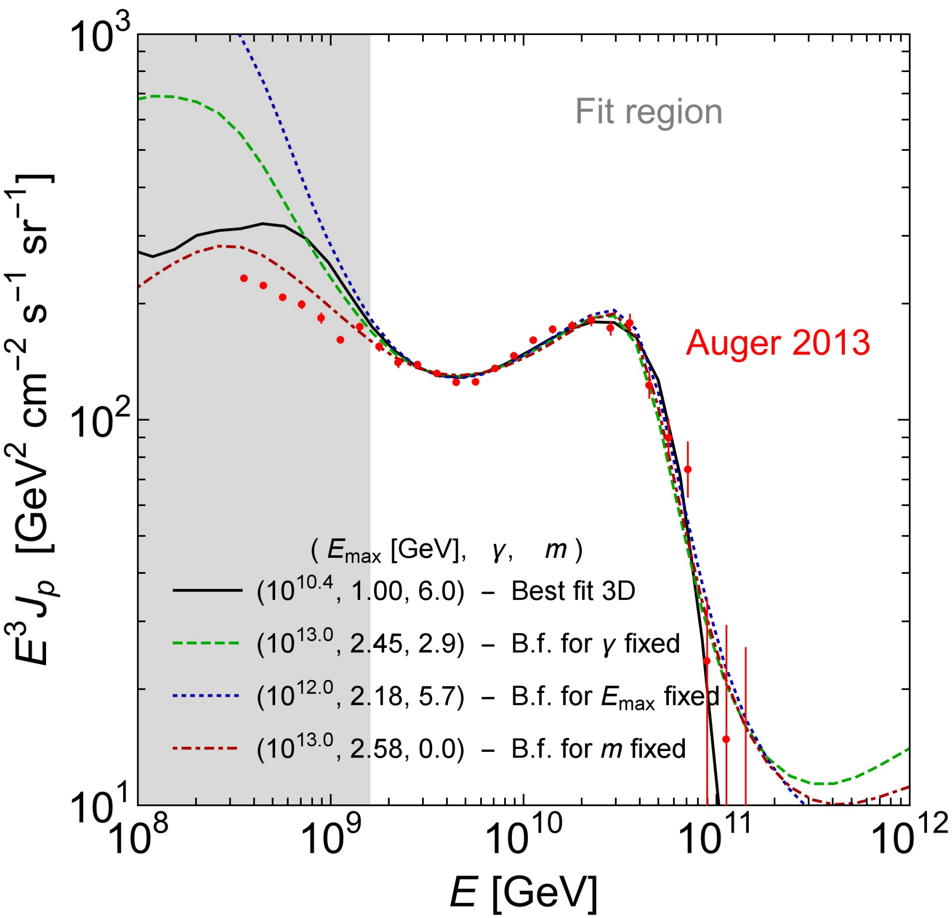
$$J_p^{\rm inj}(E) \propto H(z) E^{-\gamma} \exp(-E/E_{\rm max}) \longrightarrow \exp(-E_{\rm min}/E)$$

$E_{\rm min} = 10^8, 10^{8.6}$ GeV



Fit of the Auger spectrum





Chi2/dof=95.5/16

Number of expected neutrino events

$$N_\nu = \Delta\Omega \cdot t_{\mathrm{exp}} \int dE\, J_\nu(E) \cdot A_{\mathrm{eff}}(E) ,$$

- Aeff = (declination averaged) effective area for the chosen neutrino flavor(s), including thresholds and Earth matter effects
- t_exp = time of exposure

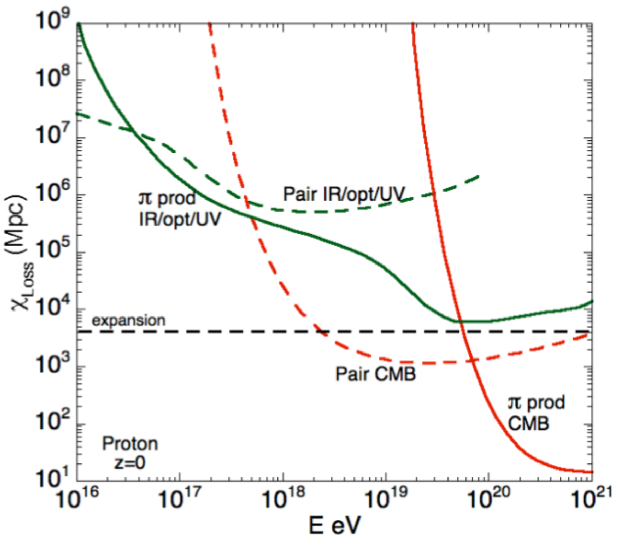
- If no significan flux is observed, the number N can be interpreted in terms of the confidence level of a limit

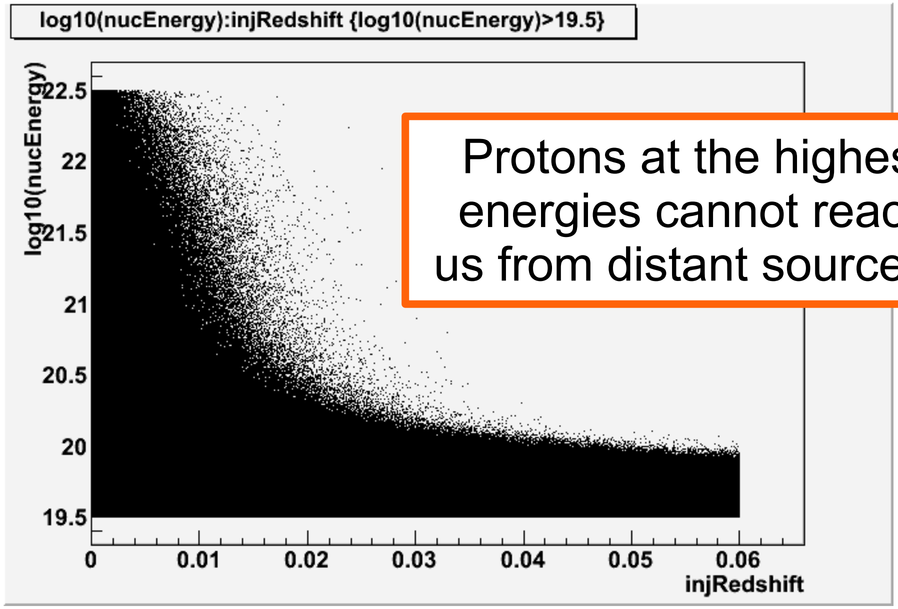
- We estimated the number of expected neutrino events in IceCube from the differential upper limit given in Ishihara (2015), obtaining the normalization constant by cross checking the benchmark models here shown, with the corresponding event rates.

Interactions and energy losses for protons

- Loss mechanisms and their relevance for propagation of protons pointed out early after the discovery of the cosmic microwave background (CMB) in 1965

D. Allard, Astropart. Phys. 39-40 (2012) 33-43





Protons at the highest energies cannot reach us from distant sources !

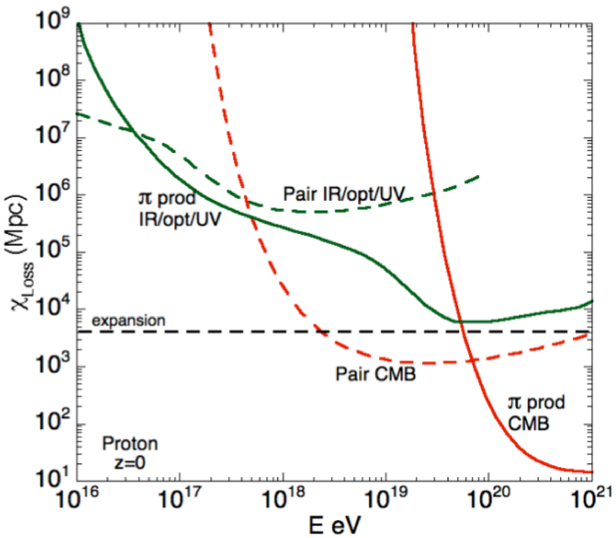
- Greisen, Zatsepin and Kuzmin estimated the opacity of the universe for CR protons above 100 EeV and predicted the existence of the suppression of the flux at the highest energies (GZK cut-off)

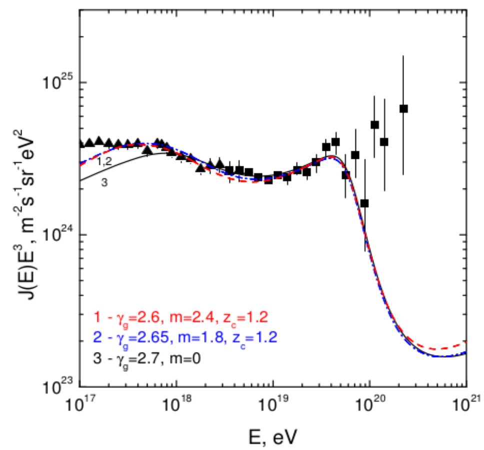
→ K. Greisen, PRL 16 748 (1966), G.T. Zatsepin and V.A. Kuzmin, Sov. Phys. JETP Lett. 4 78 (1966)

Interactions and energy losses for protons

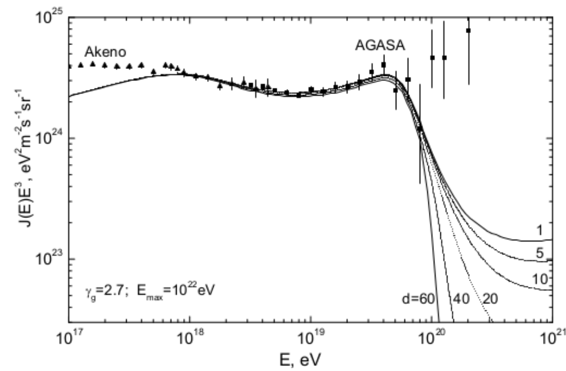
- Around 10^18.7 eV the spectrum exhibits a hardening: the “ankle”
- In the context of the dip model, the intermediate energy range is dominated by pair production

D. Allard, Astropart. Phys. 39-40 (2012) 33-43





Berezinsky, Gazizov and Grigorieva, Phys.Rev.D 74 (2006)



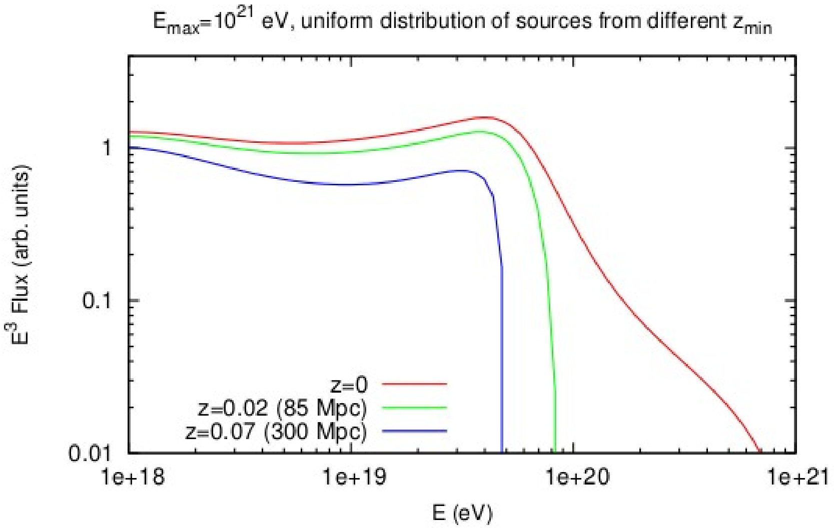
- Due to the interaction length of the process, this feature is less sensitive to details of the distribution of sources wrt the suppression
- Hillas and Blumenthal studied the effect of pair production on protons above 1 EeV → Hillas, Phys. Lett. 24A 677 (1967), Blumenthal, Phys. Rev. D Vol 1 1596 (1970)

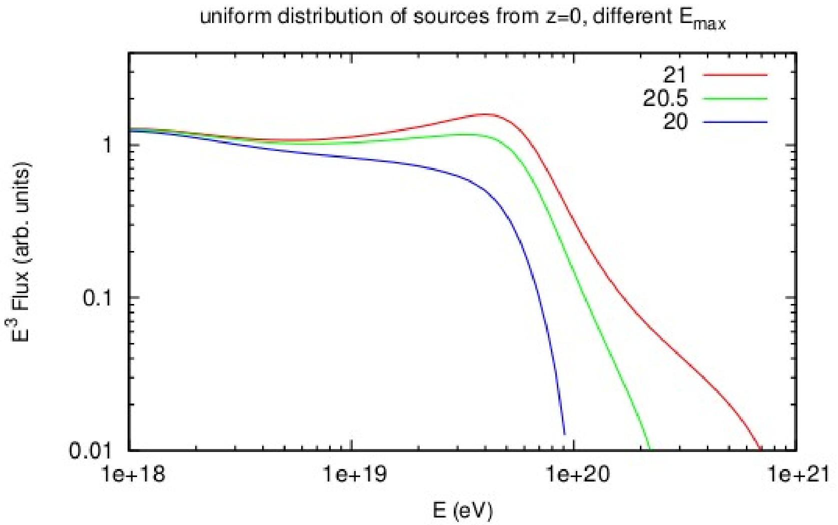
Propagated spectrum – pure protons at injection

- Suppression due to propagation: CR interactions with the photon background, effect of the minimum distance of the sources

- Suppression due to properties of the sources: maximum energy of acceleration of injected protons

R. Aloisio & DB, Astrop. Phys. 35 (2011) 152-160



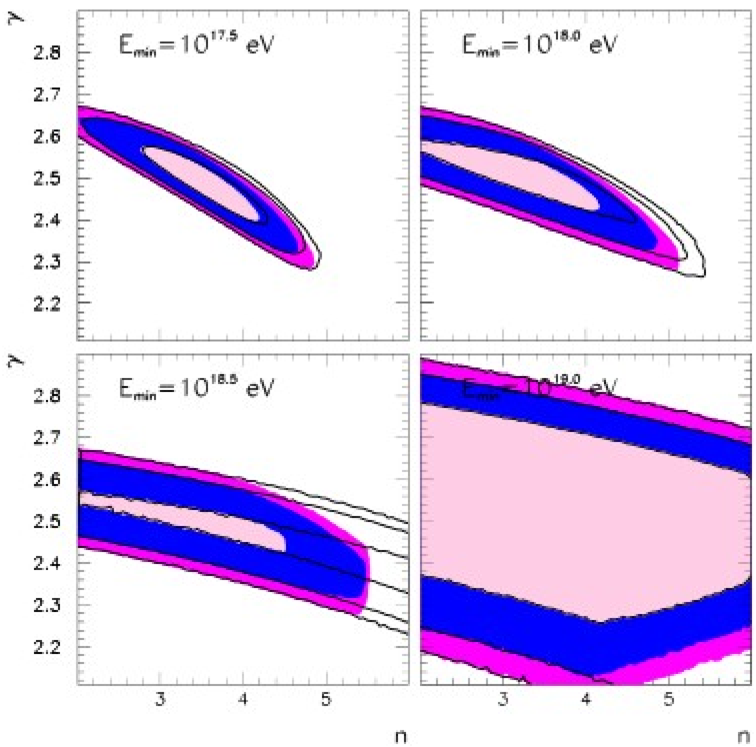


- Even in the simple case of a pure proton composition, the suppression can be due to different aspects or to a combination of them.

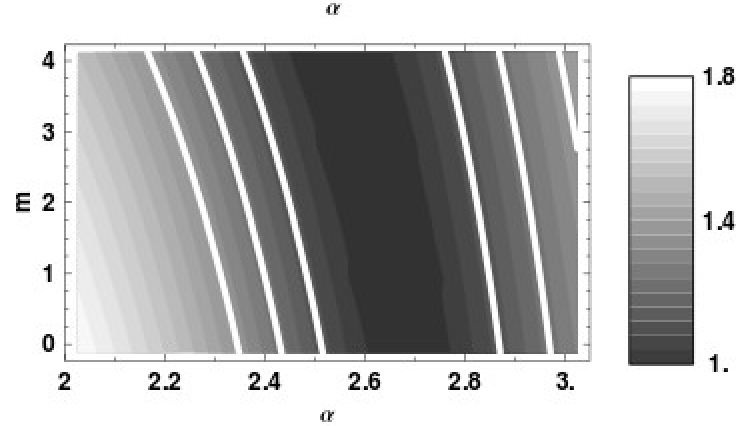
- With the assumption of pure proton composition, how can the spectrum features be investigated?

2D scans

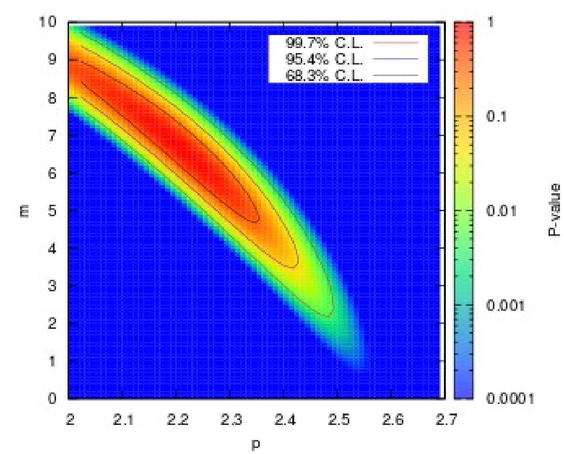
Ahlers, Anchordoqui, Gonzalez-Garcia, Halzen, Sarkar, Astropart. Phys. 34 (2010)



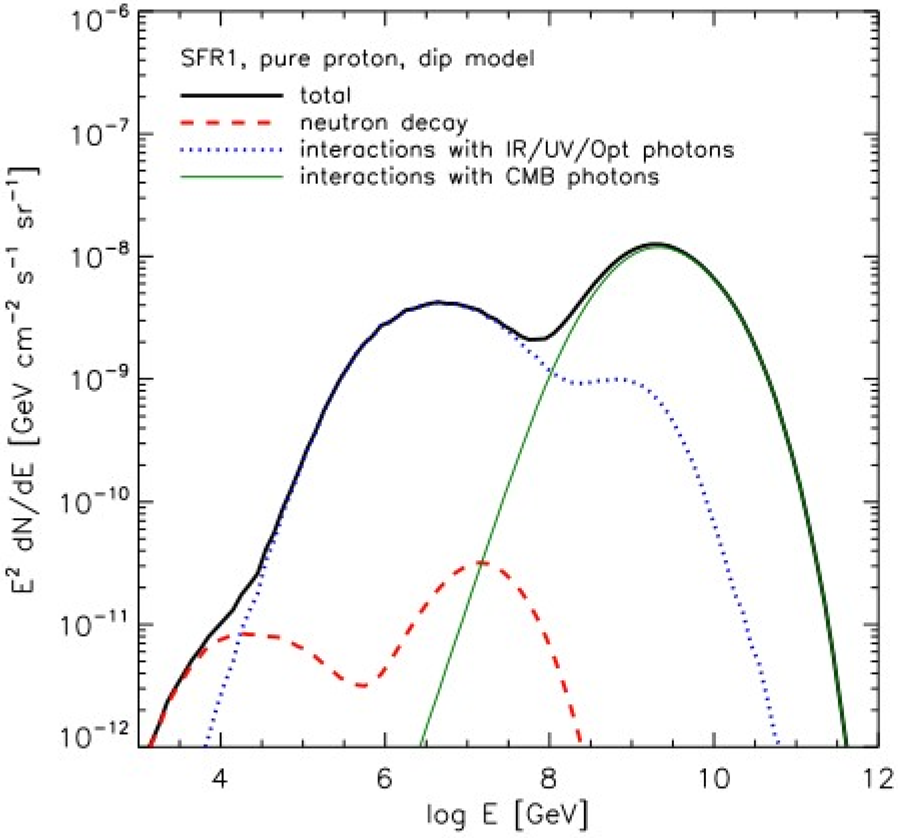
De Marco & Stanev, Phys. Rev. D72 (2005)



TA, ICRC 2015

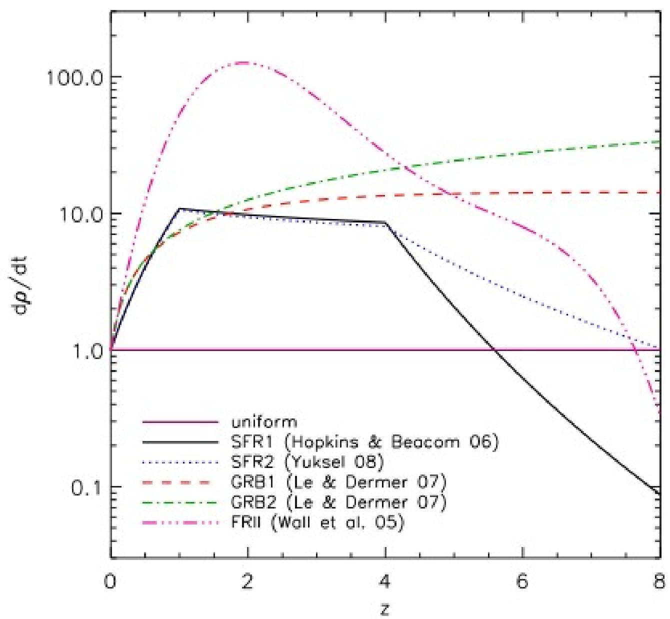


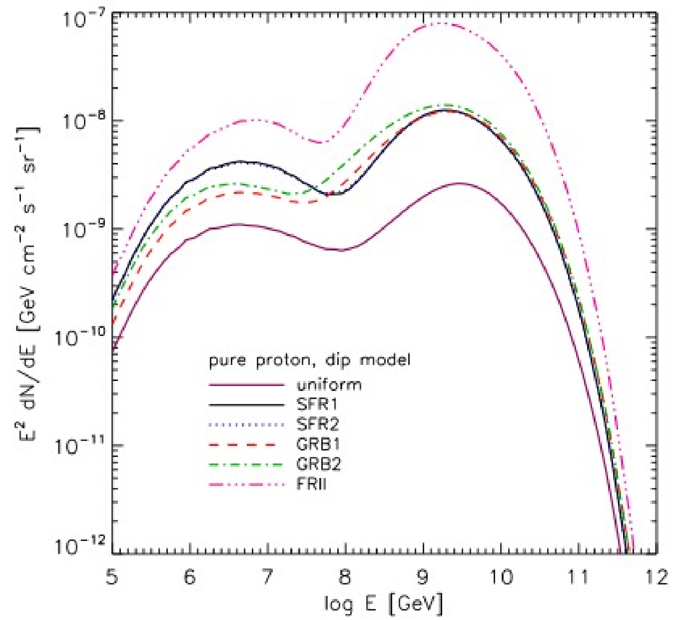
Neutrino flux



Kotera, Allard, Olinto, JCAP10(2010)013

Neutrino flux → source evolution





Kotera, Allard, Olinto, JCAP10(2010)013

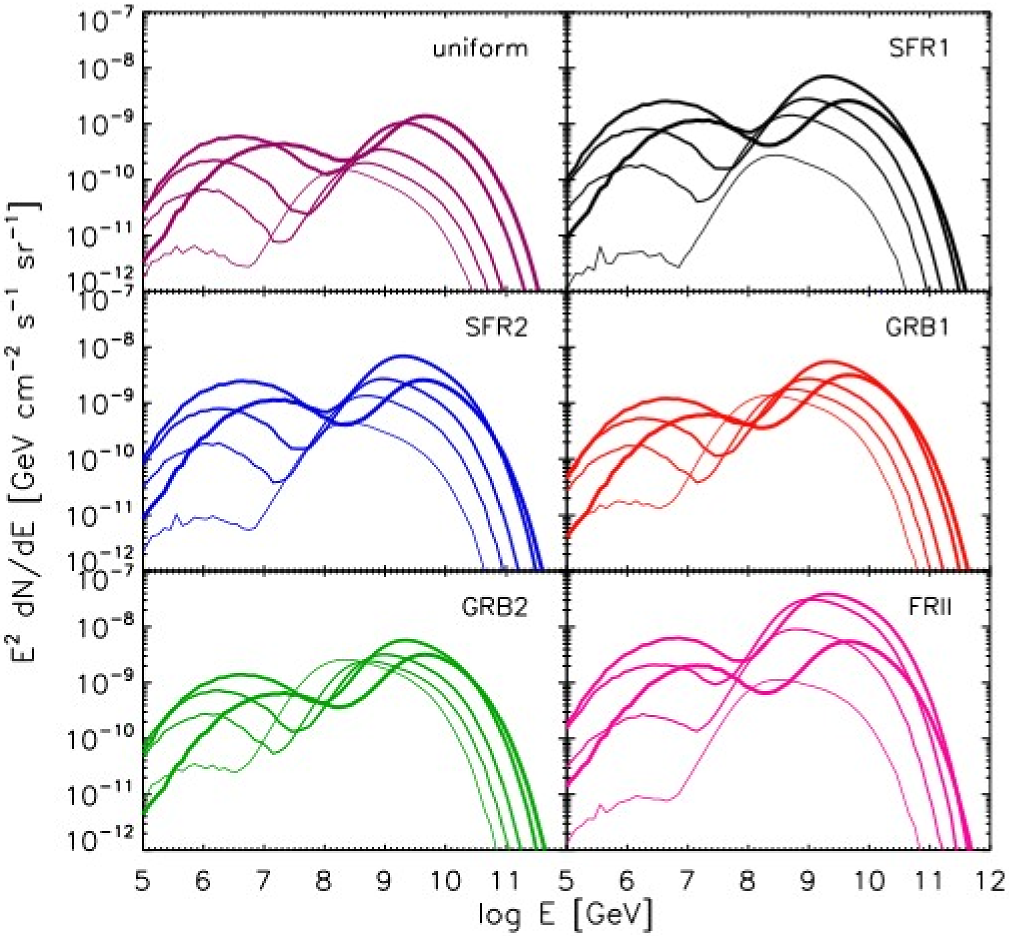
SFR 1 $(1+z)^{3.4}$ for $z<1$, then $(1+z)^{-0.26}$ for $1\leq z<4$ and $(1+z)^{-7.8}$ for $z\geq 4$.

SFR 2 $(1+z)^{3.4}$ for $z<1$, $(1+z)^{-0.3}$ for $1\leq z<4$ and $(1+z)^{-3.5}$ for $z\geq 4$.

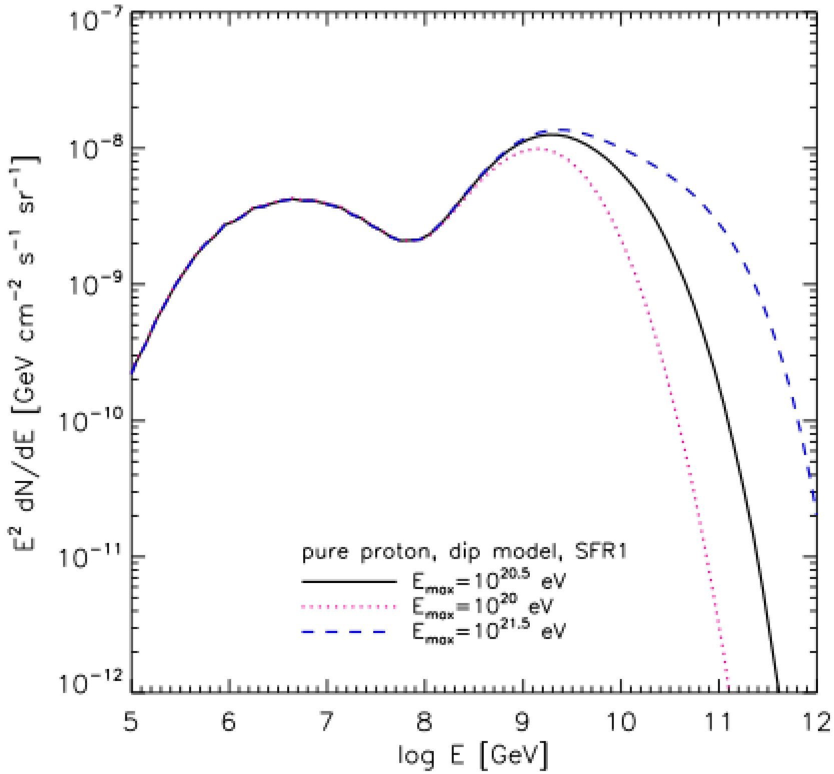
GRB 1, 2 $(1+8z)/[1+(z/3)^{1.3}]$ for GRB1 and as $(1+11z)/[1+(z/3)^{0.5}]$ for GRB2.

FR II $\log\dot{\rho} = 2.7z + 1.45z^2 + 0.18z^3 - 0.01z^4$

Neutrino flux → distance of the sources

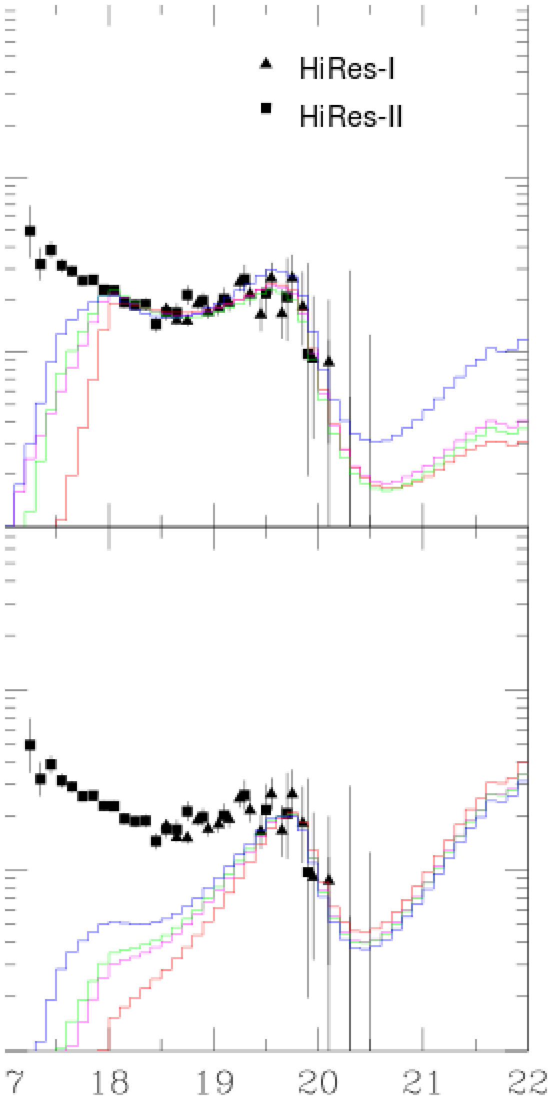


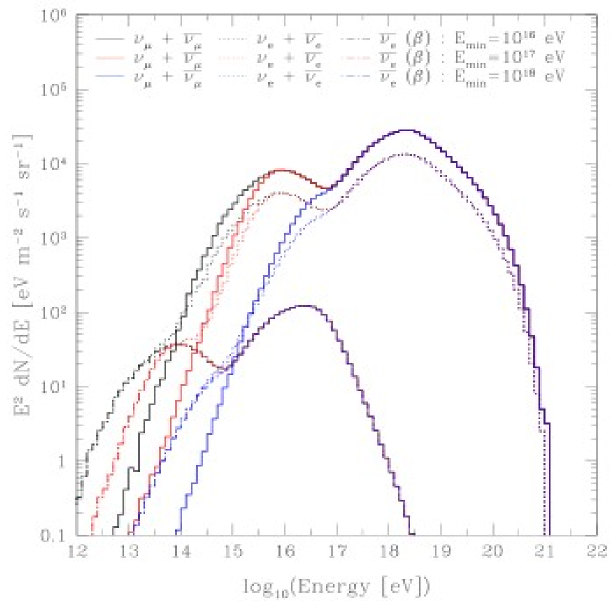
Neutrino flux → maximal energy of protons

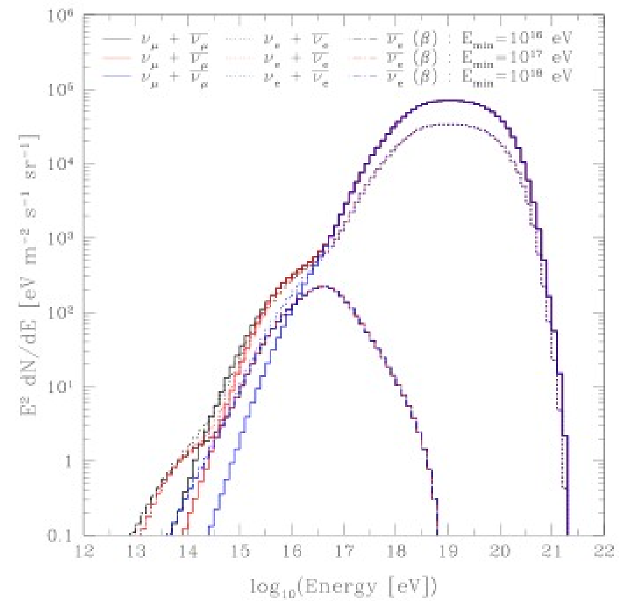


Kotera, Allard, Olinto, JCAP10(2010)013

Neutrino flux: dip model vs ankle model







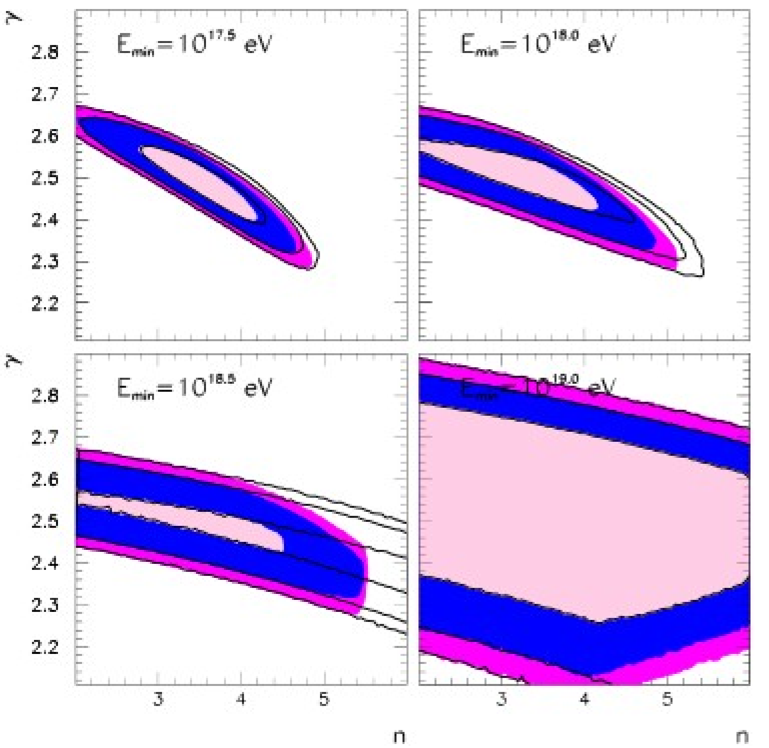
Takami, Murase, Nagataky, Sato,
Astropart. Phys. 31 (2009)

Constraints from gamma rays

Ahlers, Anchordoqui, Gonzalez-Garcia, Halzen, Sarkar, Astropart. Phys. 34 (2010)

$$\mathcal{L}_p(0,E) \propto (E/E_0)^{-\gamma} \times \begin{cases} f_-(E/E_{\rm min}) & E < E_{\rm min}\,, \\ 1 & E_{\rm min} < E < E_{\rm max}\,, \\ f_+(E/E_{\rm max}) & E_{\rm max} < E\,. \end{cases}$$

$$f_\pm(x) \equiv x^{\pm 2} \exp(1 - x^{\pm 2})$$



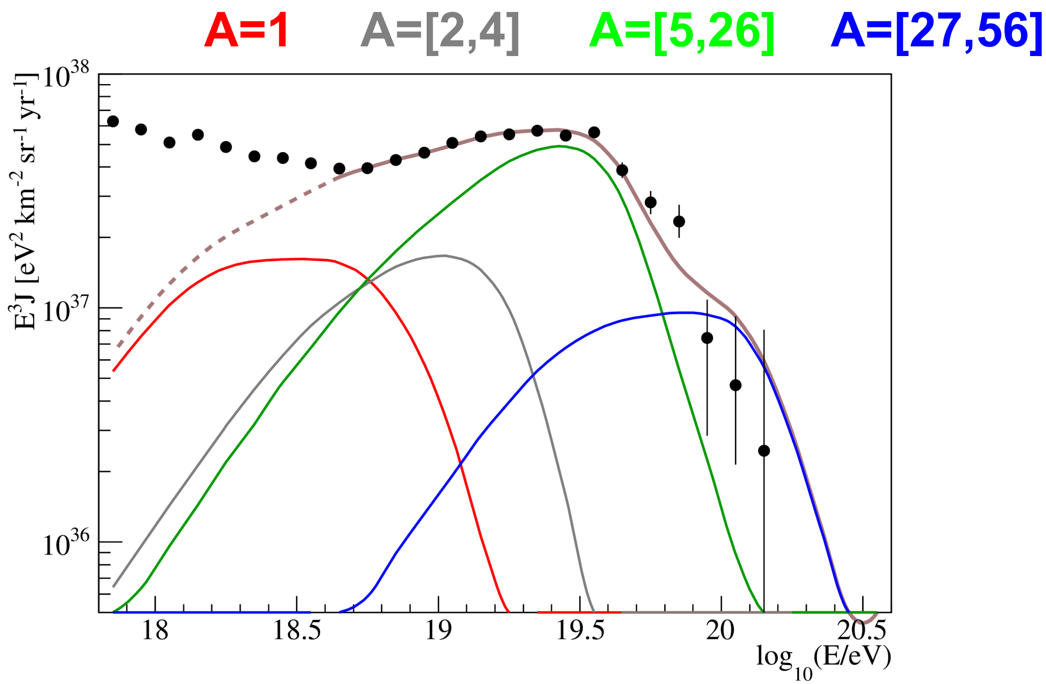
- Production of π0 and π± are correlated → injections in electromagnetic cascades and neutrinos
- Constraints in the parameter space from the diffuse gamma-ray data → limits on the maximal neutrino flux (especially from the allowed source evolution)
- We do not take into account the Fermi bound, but we are interested in the minimal allowed neutrino flux

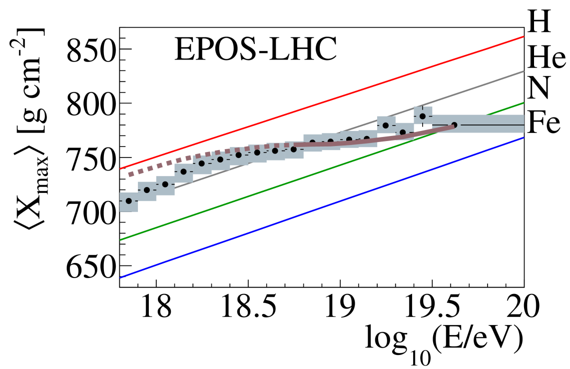
Fit results

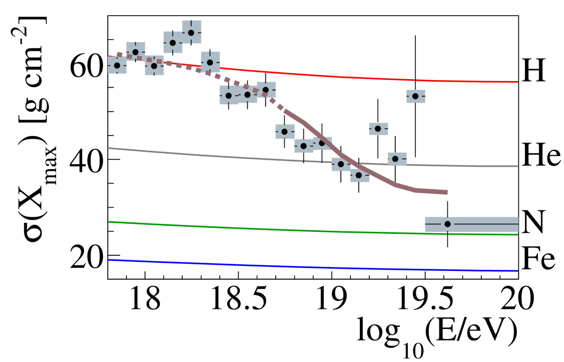
MODEL

- *SimProp* propagation
- PSB cross sections
- Gilmore EBL
- EPOS-LHC air interactions

	parameters
Rcut	18.67
gamma	0.94
H	0.0
He	62.0
N	37.2
Fe	0.8
Dmin	178.5/119





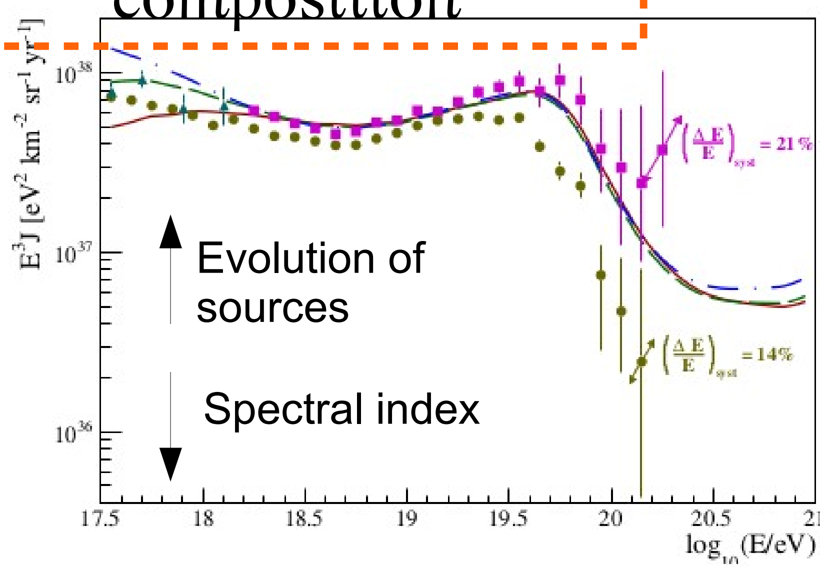


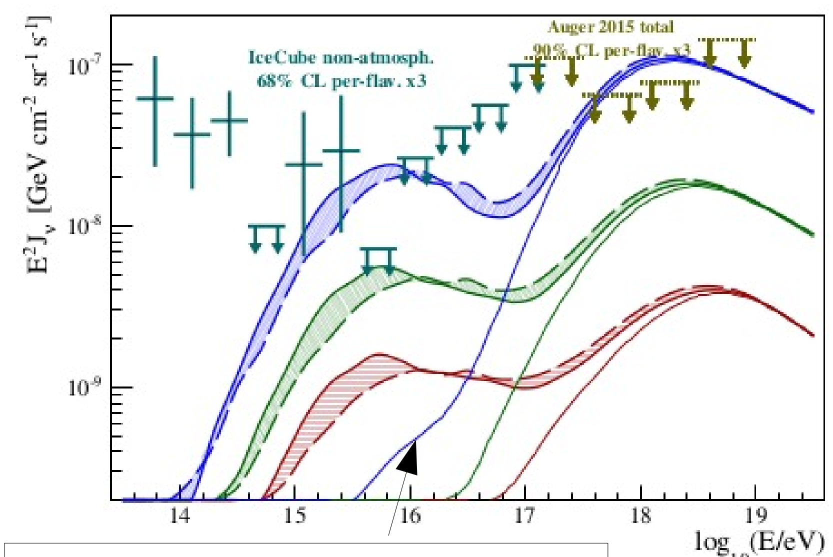
Constraining source models with secondary messengers

- Neutrinos produced by interactions of UHECRs, because of their extremely low interaction rate, arrive on Earth unmodified except for redshift energy losses and flavor oscillations, with the overall universe contributing to their flux
- This makes neutrinos a viable probe for
  - the chemical composition of UHECR
  - the cosmological evolution of sources

Pure proton composition

R. Aloisio, DB, A. di Matteo, A.F. Grillo, S. Petrera and F. Salamida, arXiv:1505.04020 [astro-ph.HE], JCAP 1510 (2015)



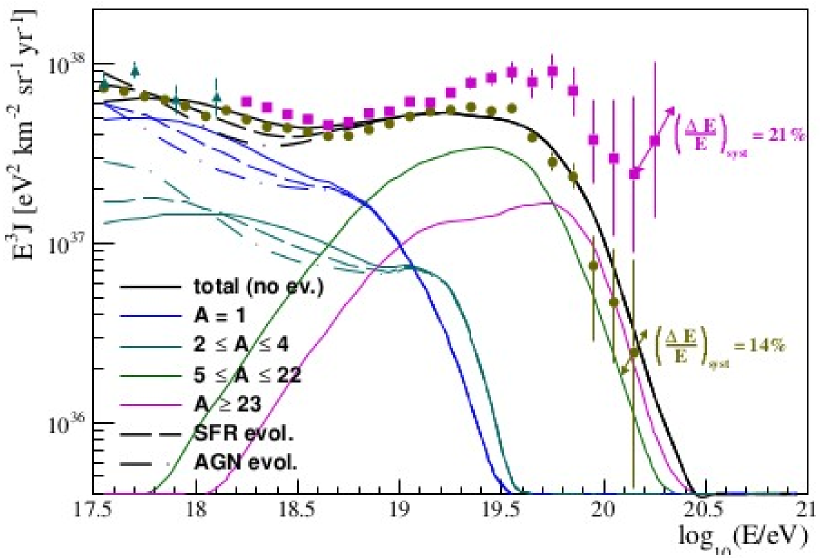


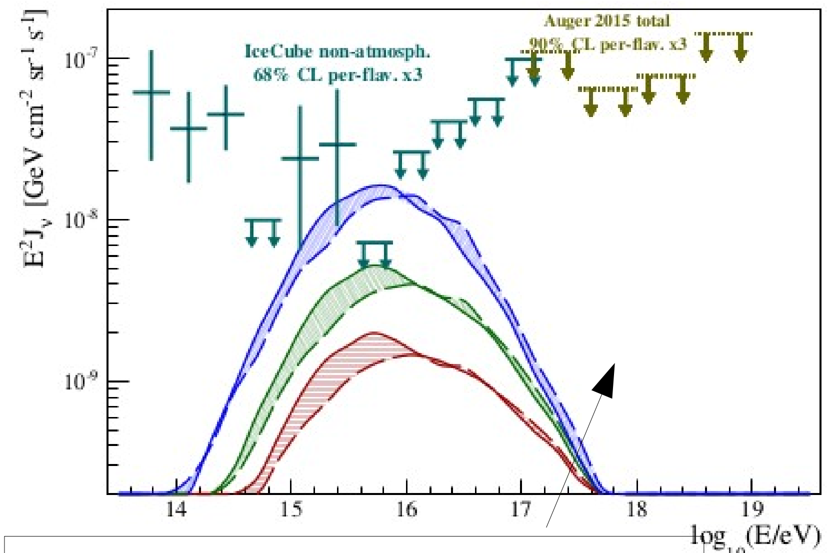
Taking into acccount only CMB

Constraining source models with secondary messengers

Mixed composition

R. Aloisio, DB, A. di Matteo, A.F. Grillo, S. Petrera and F. Salamida, arXiv:1505.04020 [astro-ph.HE], JCAP 1510 (2015)





No contribution from pion production

For the mixed composition, we have chosen two different population of sources:

- first class: light masses with low energy cutoff and soft spectral index
- second class: all masses with hard spectral index and higher energy cutoff wrt first class

Constraining source models with secondary messengers

Mixed composition

R. Aloisio, DB, A. di Matteo, A.F. Grillo, S. Petrera and F. Salamida, arXiv:1505.04020 [astro-ph.HE], JCAP 1510 (2015)