Simulations of Ultra High Energy Cosmic Rays propagation

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Outline

- Motivation
- Comparison between propagation codes
- Fit results of TA SD energy spectrum

Motivation

Accurate observation of the energy flux

: statistical error ～1% of the flux

→ Check the accuracy using different propagation codes to calculate model energy flux

1) CRPropa (Astropart. Phys. **42**, 41 (2013) etc.) : MC approach

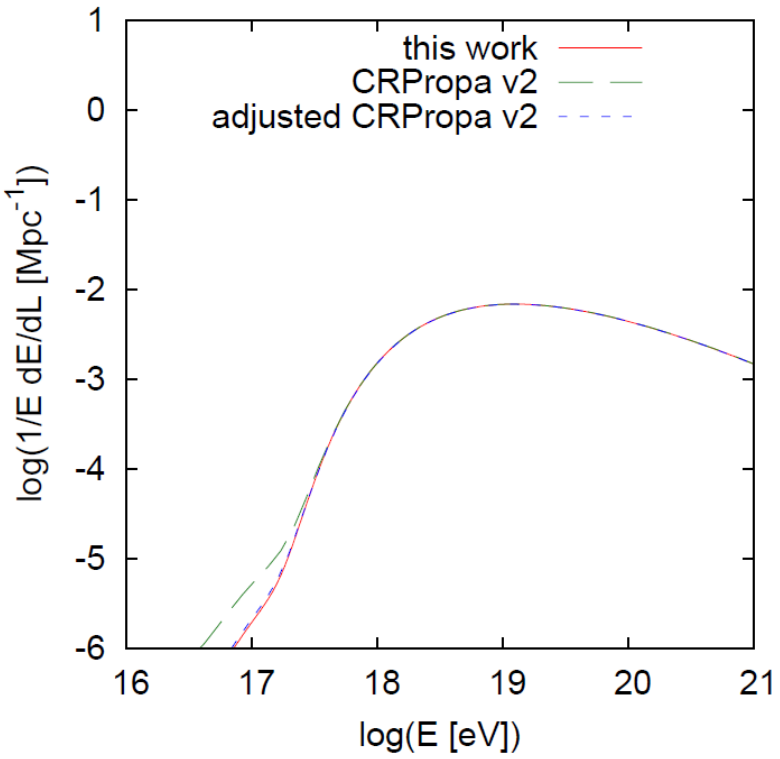
2) TransportCR (developed by O. Kalashev (JCAP **1201**, 044 (2012) etc.))

based on solving transport equations

Model Conditions

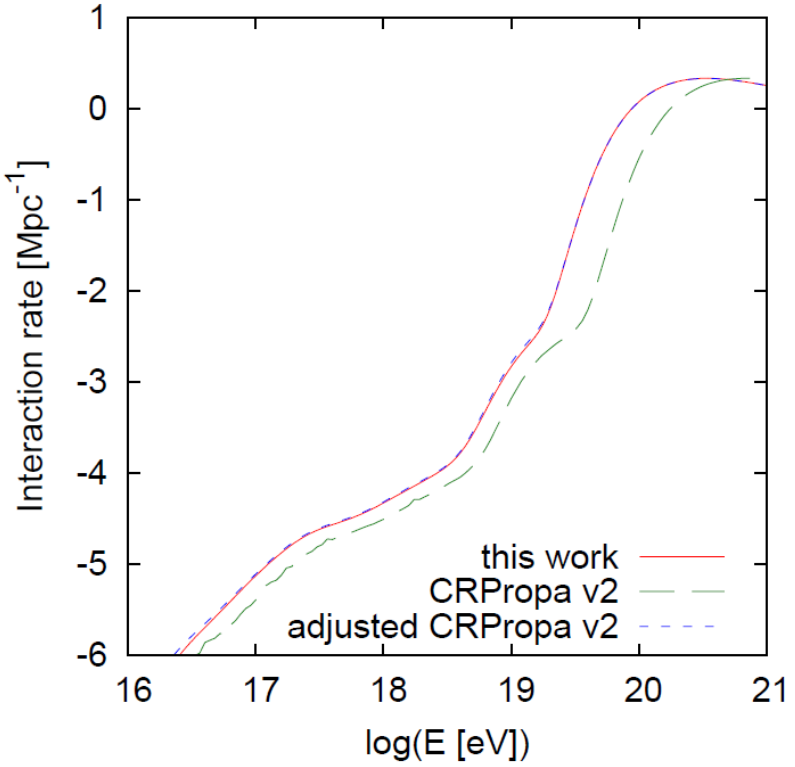
- Pure proton
- Injection spectrum $\mathbf{E^{-p}}$, Emax =10^{21} eV
- Source density $\propto$ $\mathbf{(1 + z)^{m}}$ (per comoving unit volume)
- Energy losses with CMB and IRB: Kneiske 2004 (best fit model) are considered.
- Propagation without considering magnetic fields

Comparison of interaction rates



(a) Pair production energy loss rate at $z = 1$

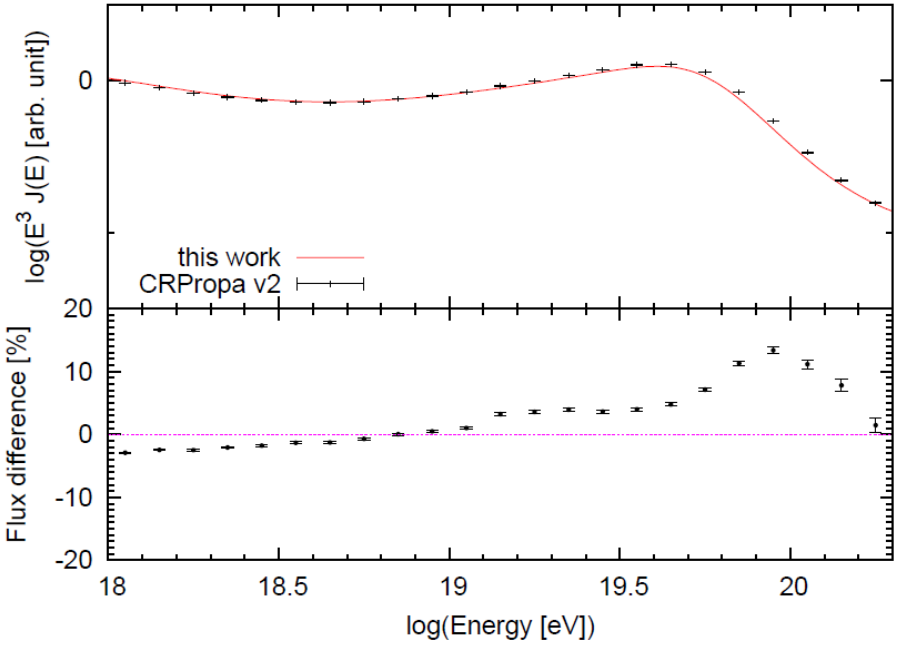
Evolution of IRB is implemented in CRPropa v3



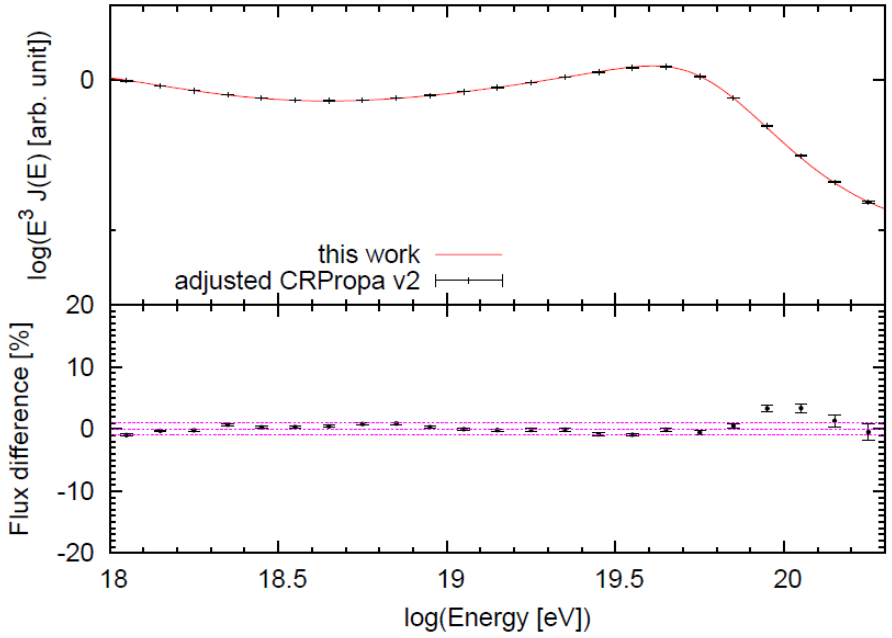
(b) Photopion production rate at $z = 1$

Modification of this pion production rate was included in CRPropa.

Comparison of energy spectra



Injection: $\mathbf{E^{-2.4}}$
Source density: $\mathbf{(1+z)^4}$



With the modifications
Injection: $\mathbf{E^{-2.4}}$
Source density: $\mathbf{(1+z)^4}$

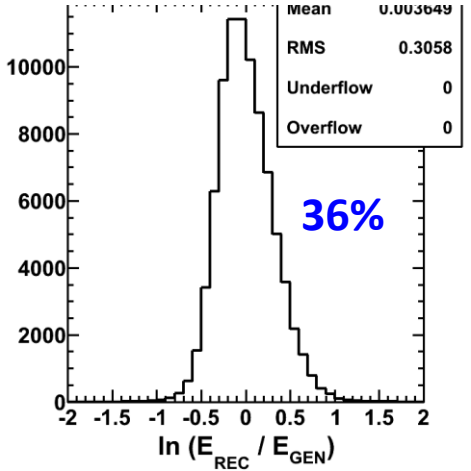
- Mainly modification of the pion production rate

→ Maximum difference of the flux ～1 %

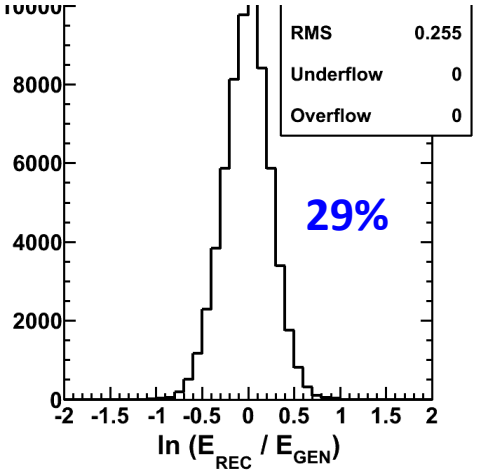
Data set of TA SD

- TA SD data for 6 years
- 17763 events above $10^{18.2}$ eV
- Zenith angle cut : 45 deg
- Boundary $\geqq$1.2km
- Energy resolution:

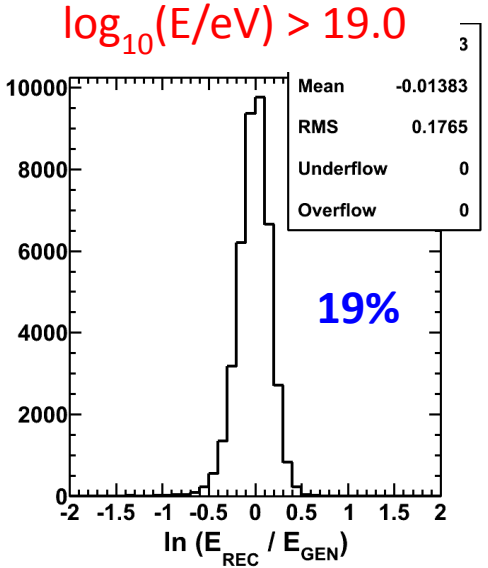
$18.0 < \log_{10}(E/eV) < 18.5$



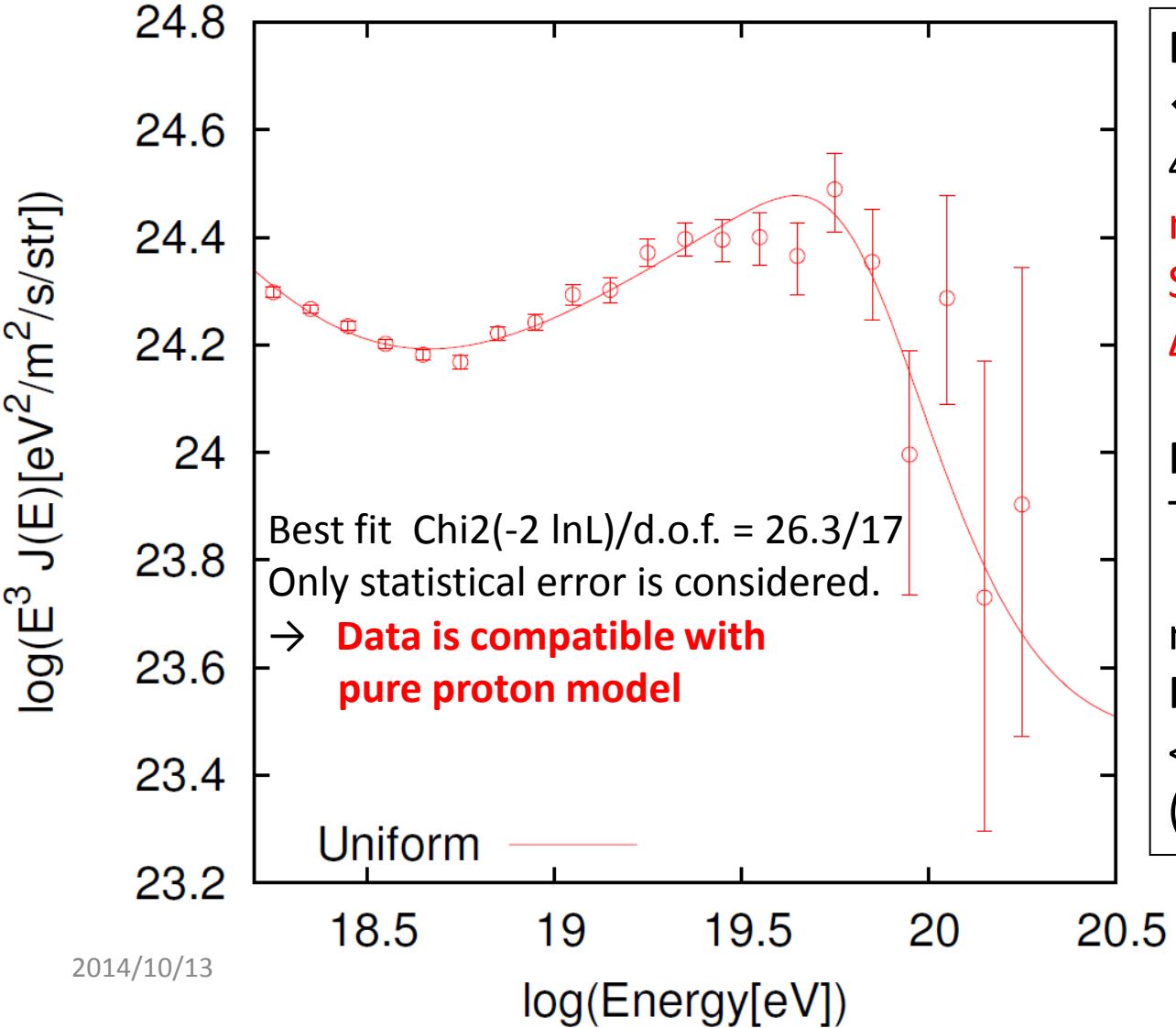
$18.5 < \log_{10}(E/eV) < 19.0$



$\log_{10}(E/eV) > 19.0$



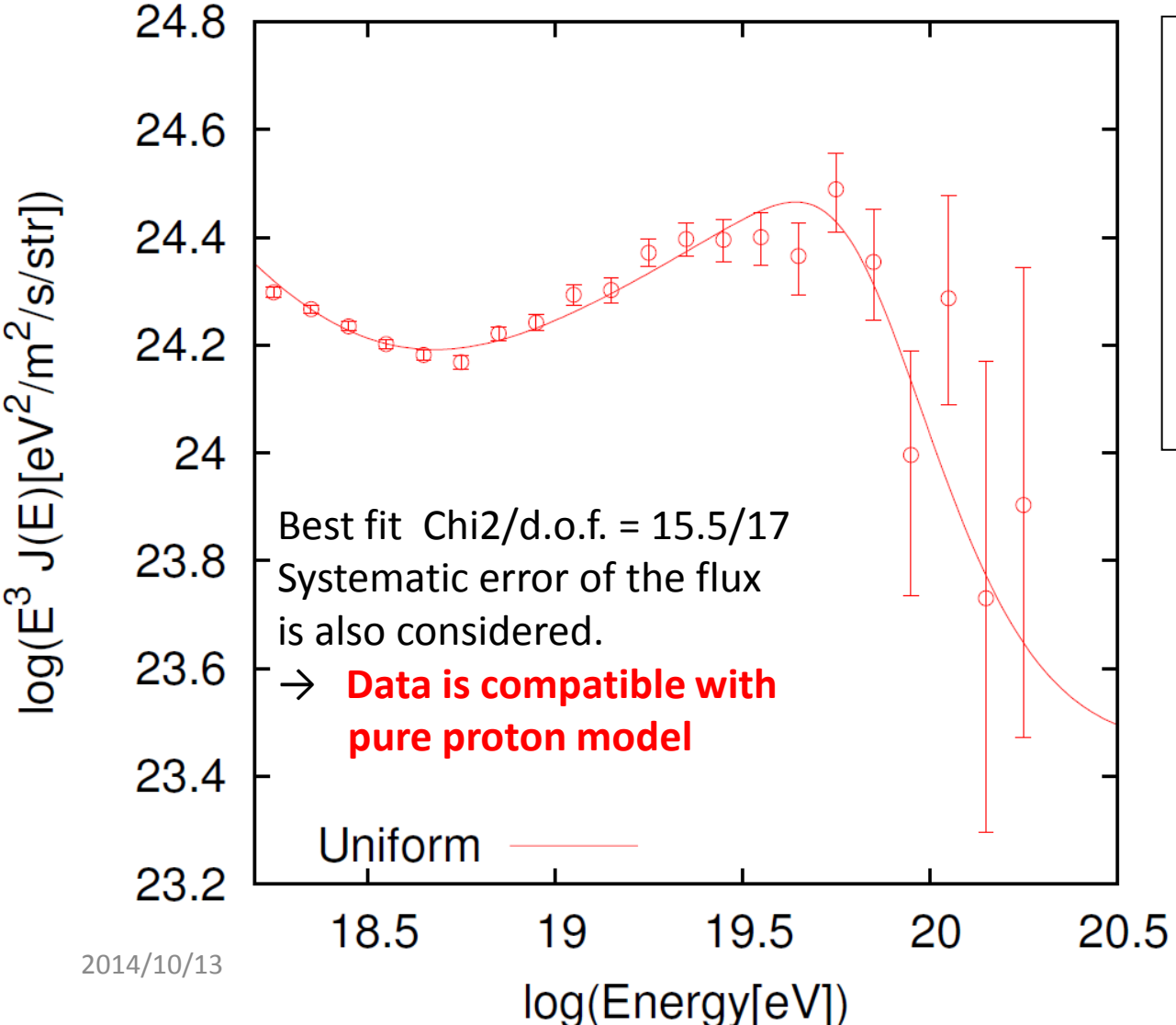
Best fit energy spectrum with 6 year TA SD energy spectrum



E > $10^{18.2}$ eV
⇔ Most distant Z～0.7
4 free parameters:
normalization constant,
Shift of energy scale:
$\Delta \log_{10} E$, E^{-p} and $(1+z)^m$.

Propagation:
TransportCR
(checked by
modified CRPropa)
Field strength of IGM
<～ 0.1 nG
(Berezinsky et al. 2007)

Best fit energy spectrum with 6 year TA SD energy spectrum

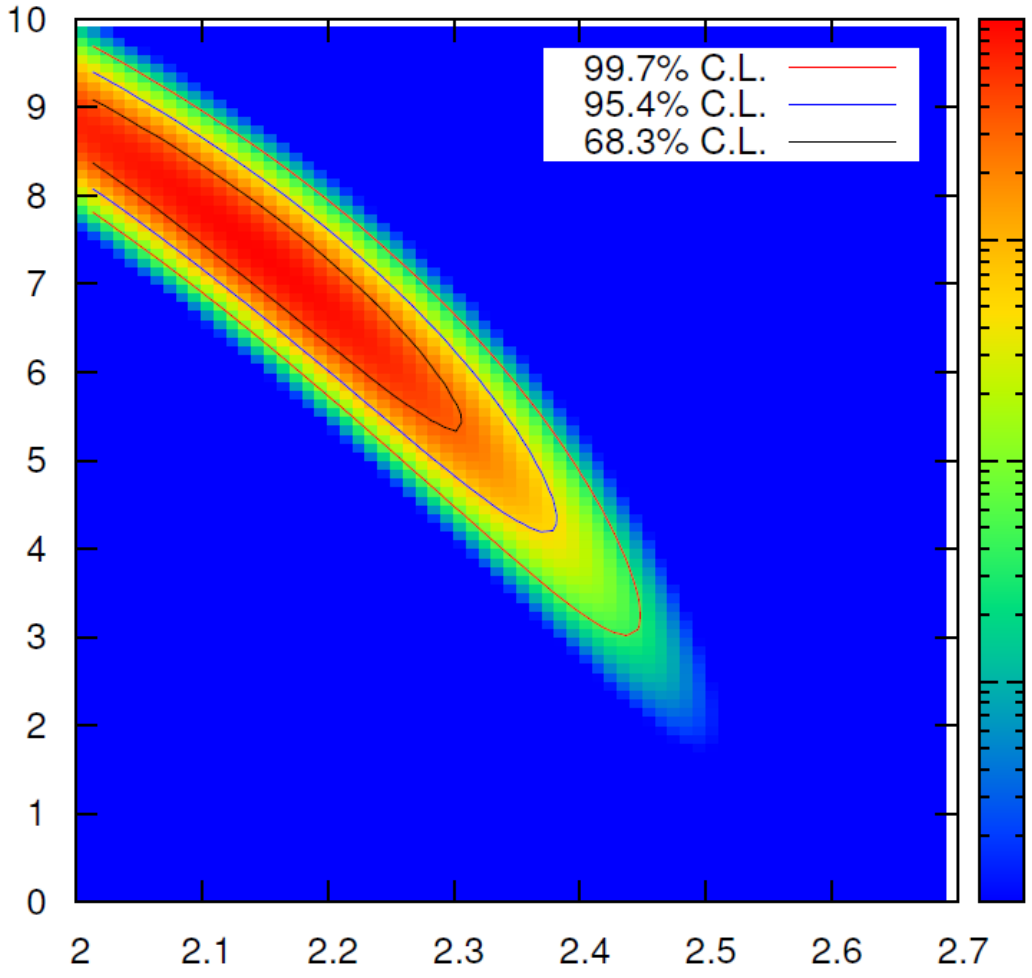


$\sigma^{SYS} \sim 3\%$ of the flux for all energies. Mainly from the calculation of the acceptance

$\sigma_{TOT} = \mathrm{Sqrt}(\sigma_{STAT}^2 + \sigma_{SYS}^2)$

:Gaussian distribution

Joint confidence region of E^{-p} and $(1+z)^m$



m of
$(1 + z)^m$

p of
E^{-p}

5 %
Compatibility

0.3 %
Compatibility

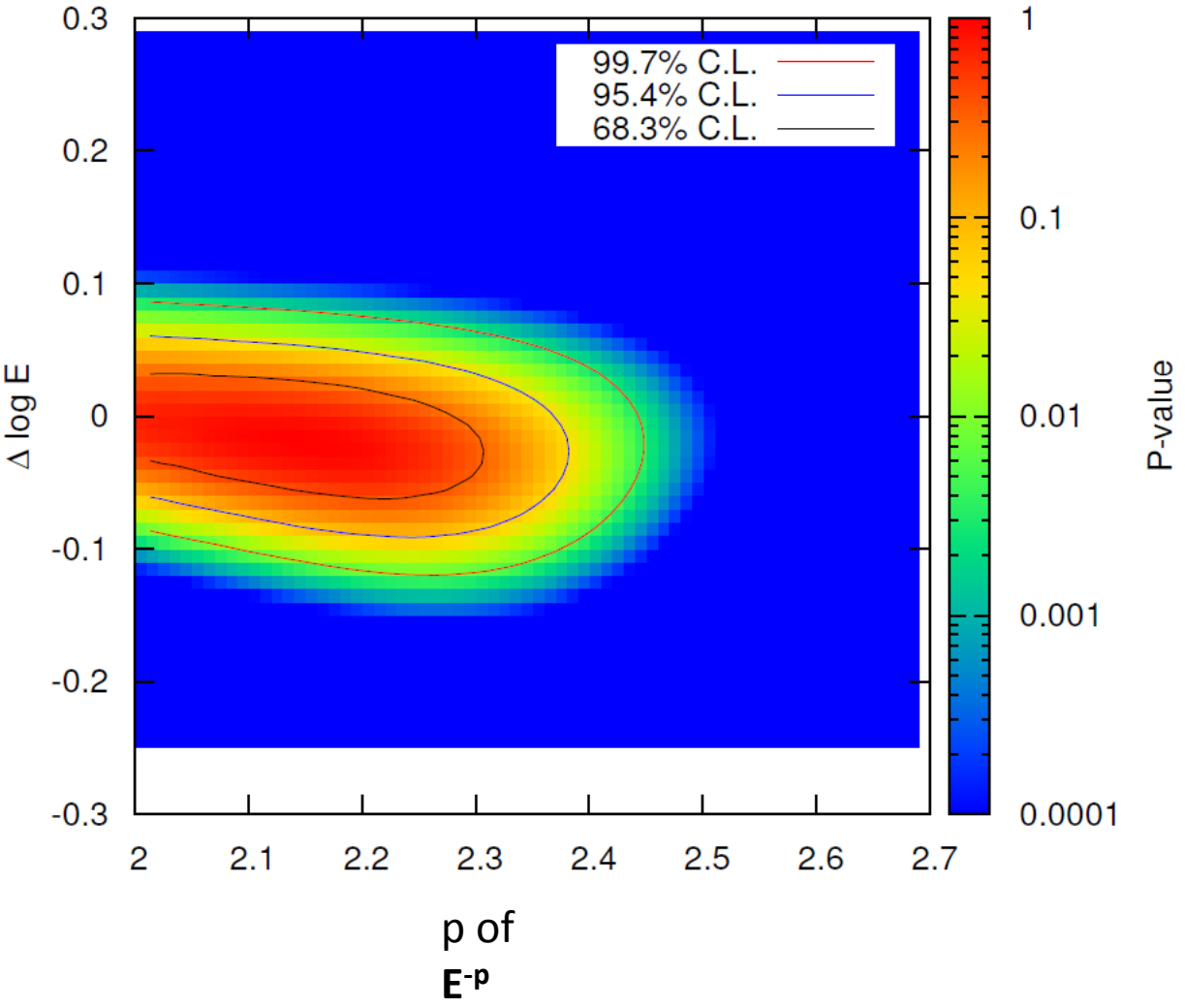
$\chi^2 - \chi^2_{\min}$

is evaluated as P-values.

Joint confidence region of E^{-p} and $\Delta \log_{10} E$

ΔE/E～ 26 % →

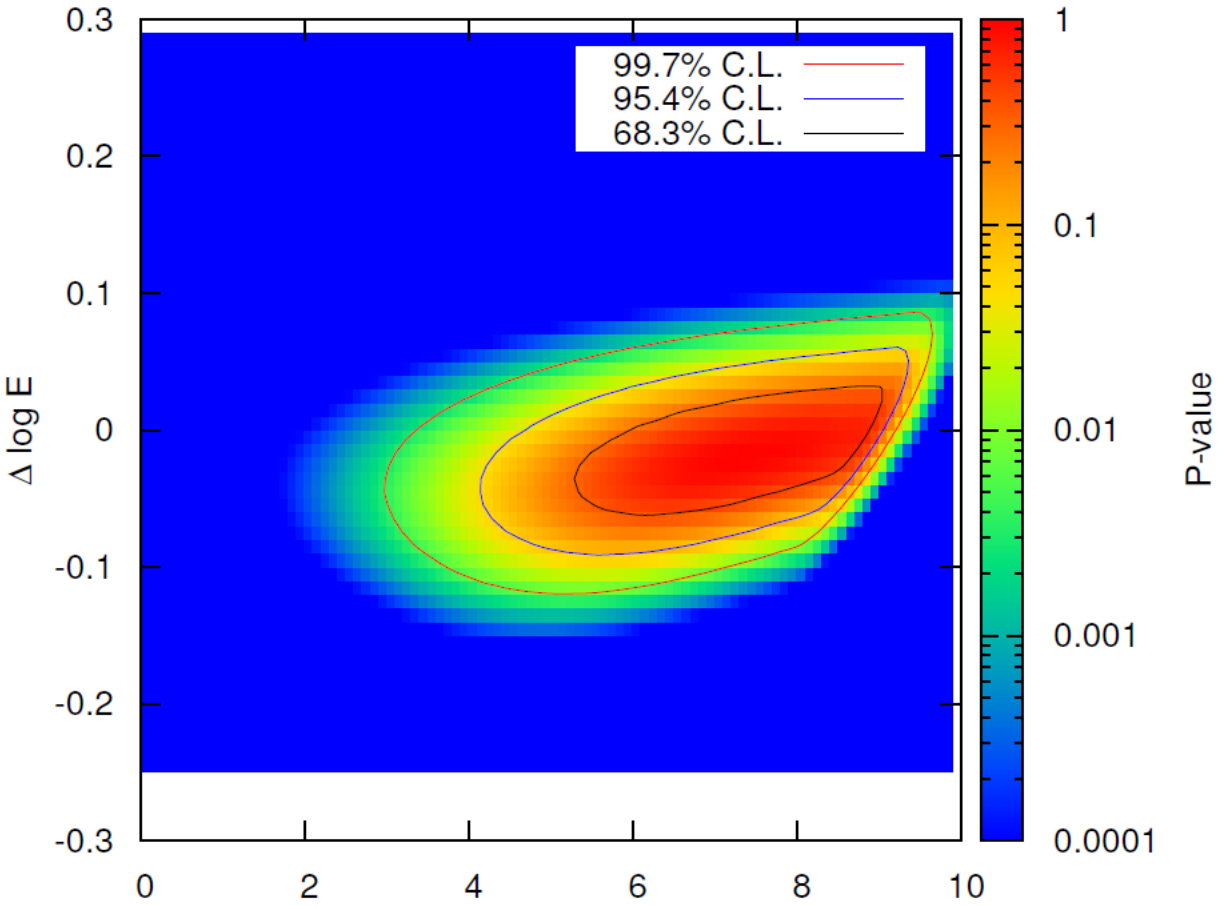
ΔE/E ～ -21 % →



Joint confidence region of $(1+z)^m$ and $\Delta \log_{10} E$

ΔE/E～ 26 % →

ΔE/E ～ -21 % →



Summary and conclusions

- We compared 2 propagation codes.

→ Consistency of model energy flux of pure proton ～**1%**

- We analyzed SD energy spectrum with the 6-year data.
- We searched compatibilities between data and pure proton model for $E > 10^{18.2}$ eV.
- TA SD data is **compatible** with **pure proton model**.

We obtained the constraint of the fit parameters

injection energy spectrum $\mathbf{E^{-p}}$, evolution parameter $\mathbf{(1+z)^{m}}$

and the shift of the energy scale $\Delta \log_{10} E$

if pure proton model is assumed.