# The impact of the cross sections on the outcome of the propagation studies

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# Outline

- Comparison of Photoabsorption Cross Sections
- Simulations of Propagation of UHECRs
- Summary

# Comparison of Photoabsorption Cross Sections

- T. Inakura *et al.*, *PHYSICAL REVIEW C* **80**, 044301 (2009) and T. Inakura *et al.*, *PHYSICAL REVIEW C* **84**, 021302(R) (2011).
  - $\sigma_{GDR}$ (GDR: Giant Dipole Resonance)
  - 12 nuclei (4He 12C 16O 20Ne 24Mg 28Si 32S 36Ar 40Ca 48Ti 52Cr 56Fe)
  - Different interaction models
    - SkM* : J. Bartel *et al., Nucl. Phys.* ***A*** **386**, 79 (1982).
    - SLy4 : E. Chanbanat, P. Bonche, P. Haensel, J. Mayer, and R. Schaeffer, *Nucl. Phys.* **A627**, 710 (1997).
    - UNEDF1 : M. Kortelainen *et al., Phys. Rev. C* **85**, 024304 (2012).
  - Photoabsorption cross sections below the proton or neutron separation energies were removed or replaced by the discrete cross sections of another model.
  - Energy scales of the cross sections of 4He were corrected.
- TALYS-1.95 https://tendl.web.psi.ch/tendl_2019/talys.html
  - $\sigma_{GDR} + \sigma_{QD}$ (QD: Quasi Deuteron)
  - Default : 11 nuclei
    (12C 16O 20Ne 24Mg 28Si 32S 36Ar 40Ca 48Ti 52Cr 56Fe)
  - Restored (E1-strength function was changed for CRPropa and SimProp) )
    : 5 nuclei (12C 16O 24Mg 28Si 40Ca)

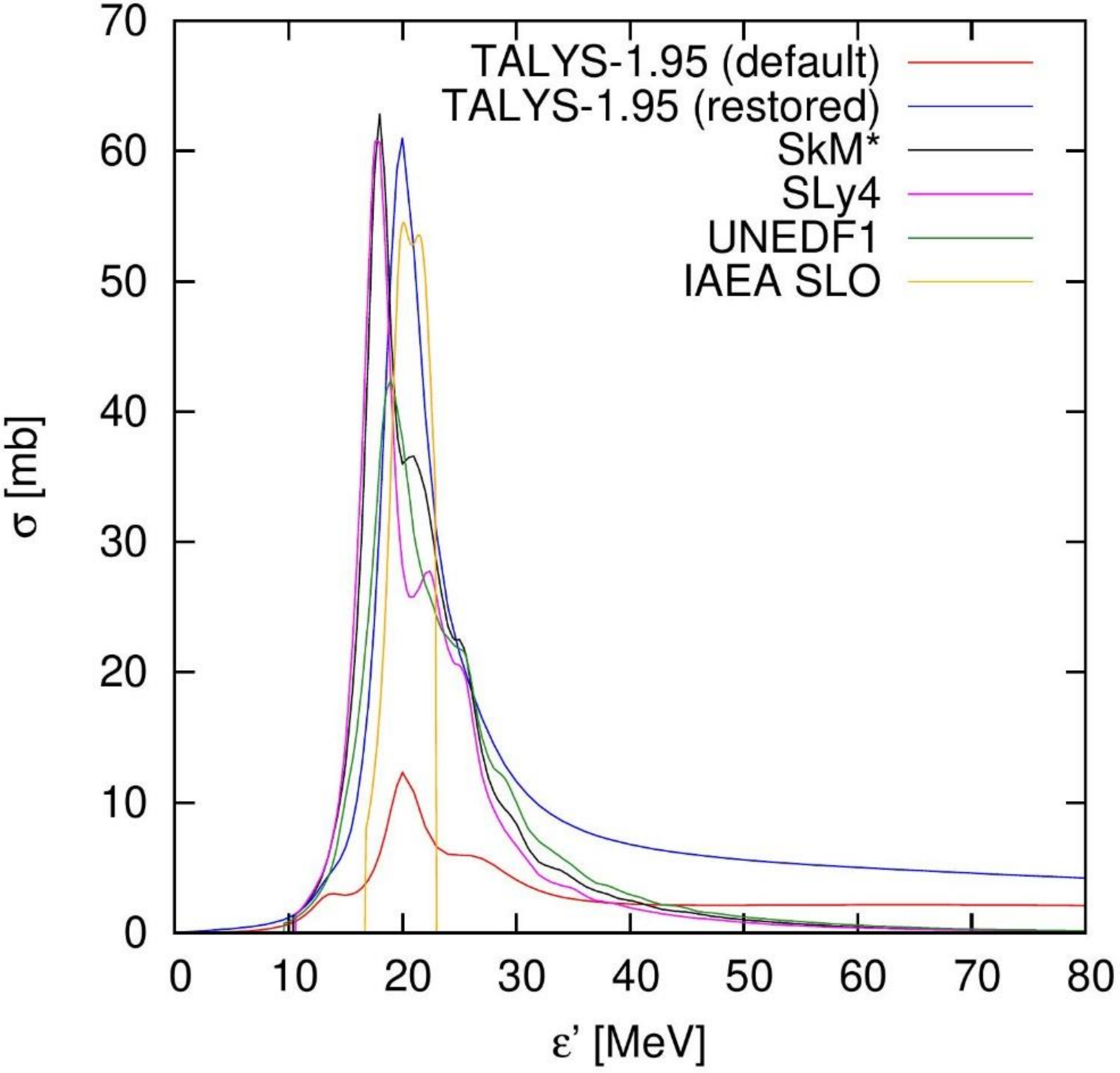
# Data for Comparison

- IAEA Photonuclear  Data Library 2019
- T. Kawano *et al.*, *Nuclear Data Sheets* **163**, 109–162 (2020).
- Table III Recommended Experimental GDR parameters
- Standard Lorentzian (SLO):

$$\sigma_{\mathrm{GDR}}(E_\gamma) = \sigma_R \frac{E_\gamma^2 \Gamma_R^2}{(E_R^2 - E_\gamma^2)^2 + E_\gamma^2 \Gamma_R^2}$$

$\sigma_R$ : peak cross section
$E_R$: resonance energy
$\Gamma_R$: resonance width

# $^{28}$Si Photoabsorption Cross Sections

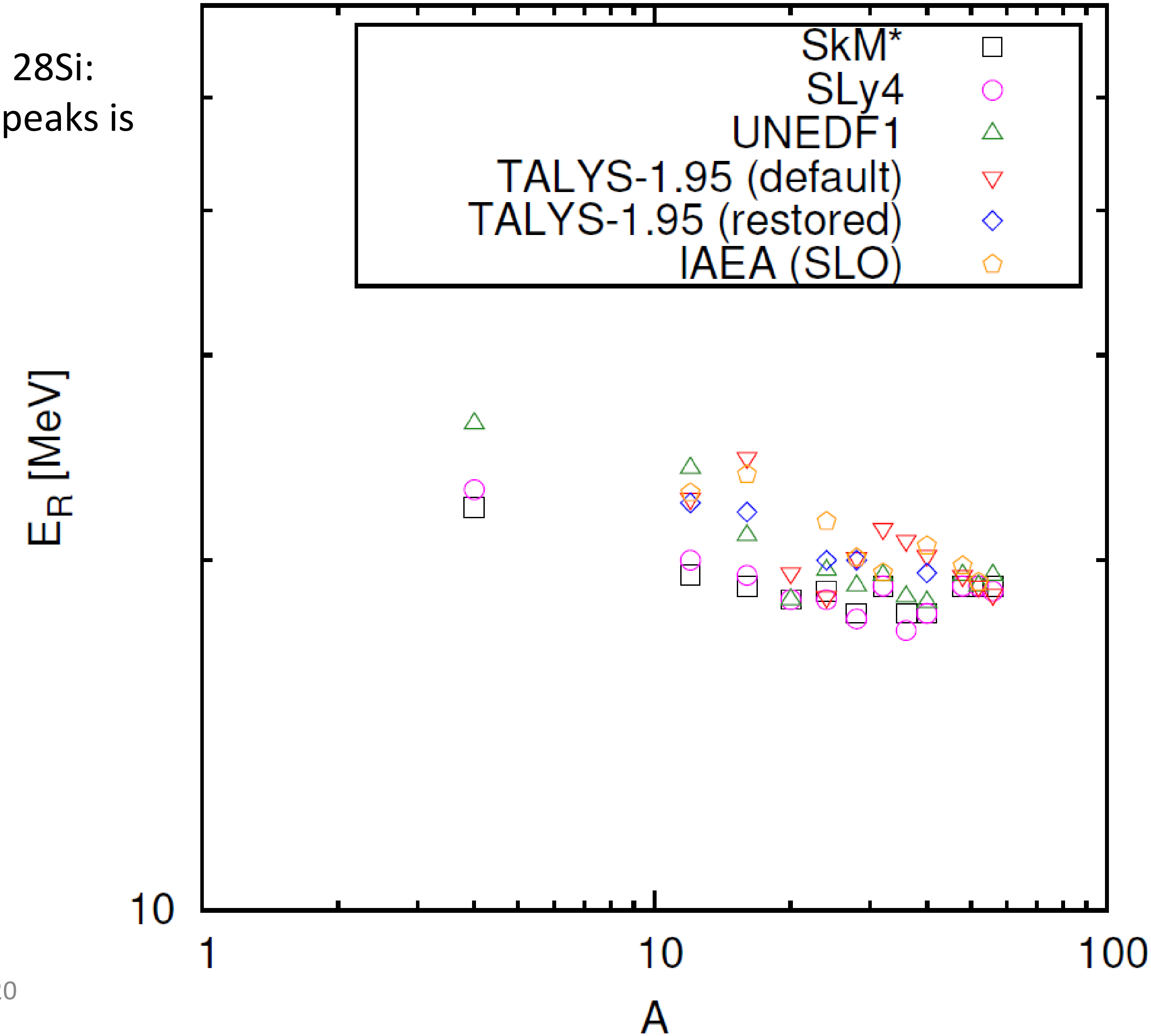


# GDR Peak Energies in MeV

| | IAEA (SLO) | SkM* | SLy4 | UNEDF1 | TALYS default | TALYS restored |
|---|---|---|---|---|---|---|
| 4He | NONE | 22.2 | 23.0 | 26.2 | NONE | NONE |
| 12C | 22.9 | 19.4 | 20.0 | 24.0 | 22.6 | 22.4 |
| 16O | 23.7 | 19.0 | 19.4 | 21.0 | 24.5 | 22.0 |
| 20Ne | NONE | 16.0, 21.0 | 16.0, 21.0 | 16.0, 21.0 | 15.2, 23.8 | |
| 24Mg | 19.7, 23.5 | 16.0, 21.6 | 16.0, 21.0 | 17.6, 21.6 | 14.4, 22.8 | 20.0 |
| 28Si | 20.1 | 18.0 | 17.8 | 19.0 | 20.1 | 20.0 |
| 32S | 19.5 | 19.0 | 19.0 | 19.4 | 21.3 | |
| 36Ar | NONE | 18.0 | 17.4 | 18.6 | 20.8 | |
| 40Ca | 20.6 | 18.0 | 18.0 | 18.4 | 20.2 | 19.5 |
| 48Ti | 19.8 | 19.0 | 19.0 | 19.4 | 19.4 | |
| 52Cr | 19.2 | 19.0 | 19.0 | 19.0 | 19.0 | |
| 56Fe | NONE | 19.0 | 18.8 | 19.4 | 18.7 | |

# GDR Peak Energies

20Ne, 24Mg, 28Si: average of 2 peaks is plotted.

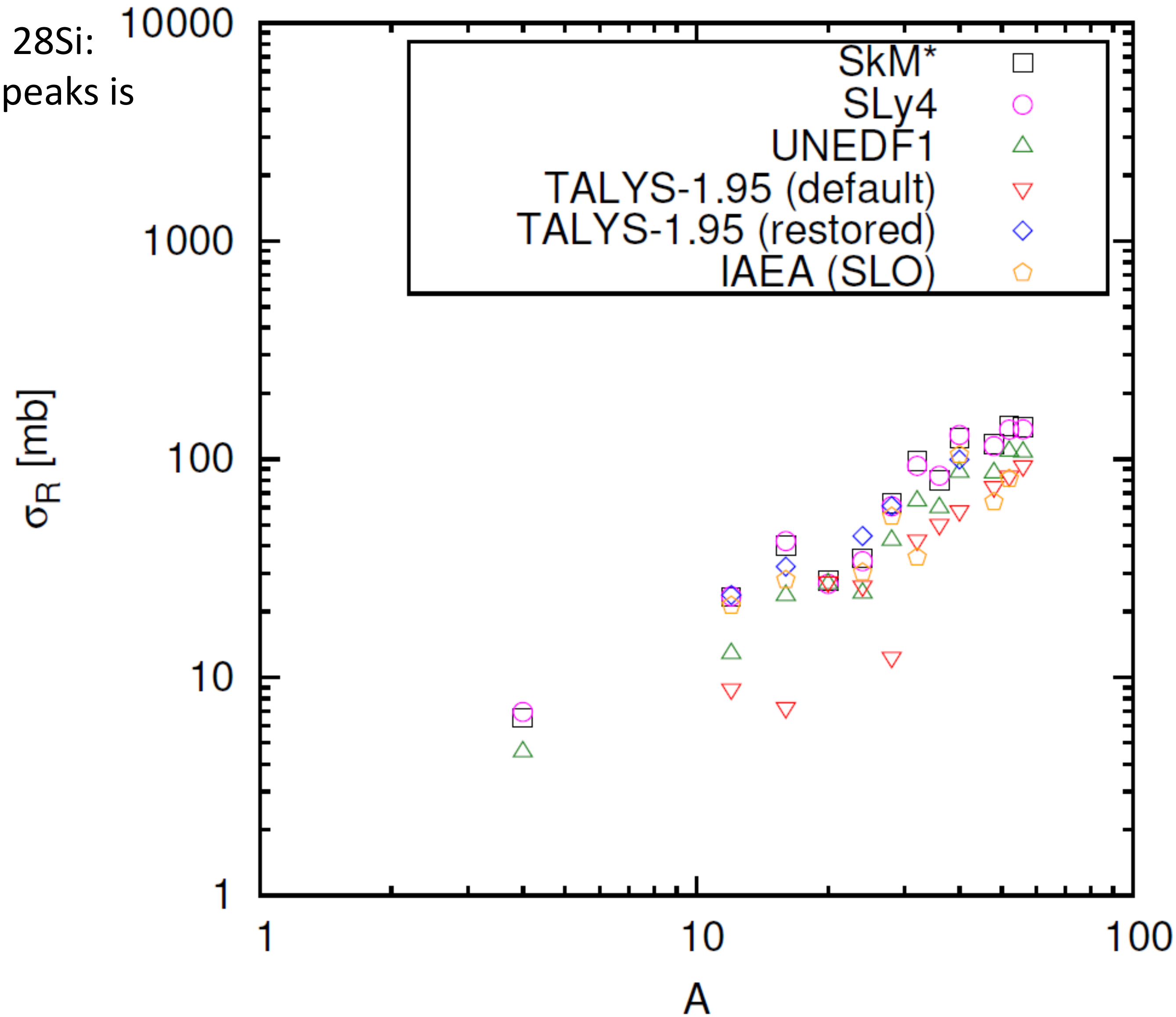


# GDR Peak Cross Sections in mb

| | IAEA (SLO) | SkM* | SLy4 | UNEDF1 | TALYS default | TALYS restored |
|---|---|---|---|---|---|---|
| 4He | NONE | 6.5 | 6.9 | 4.5 | NONE | NONE |
| 12C | 21.30 | 23.3 | 23.5 | 12.8 | 8.9 | 23.8 |
| 16O | 27.96 | 40.2 | 42.1 | 23.7 | 7.3 | 32.2 |
| 20Ne | NONE | 24.1, 31.3 | 23.4, 30.2 | 23.4, 30.2 | 27.9, 27.1 | |
| 24Mg | 33.05, 27.60 | 34.4, 35.7 | 30.9, 37.3 | 21.9, 26.7 | 23.9, 28.7 | 44.5 |
| 28Si | 54.52 | 62.9 | 60.8 | 42.4 | 12.4 | 61.0 |
| 32S | 35.43 | 97.7 | 93.0 | 64.1 | 42.6 | |
| 36Ar | NONE | 80.0 | 83.8 | 59.7 | 50.2 | |
| 40Ca | 104.78 | 124.4 | 128.9 | 86.8 | 58.2 | 99.5 |
| 48Ti | 63.74 | 117.4 | 114.8 | 86.3 | 74.8 | |
| 52Cr | 81.34 | 141.7 | 136.5 | 108.3 | 83.9 | |
| 56Fe | NONE | 140.3 | 137.0 | 107.2 | 93.3 | |

# GDR Peak Cross Sections

20Ne, 24Mg, 28Si: average of 2 peaks is plotted.



# Calculation of the mean free path of photodisintegration

Mean free path λ (Stecker 1969)

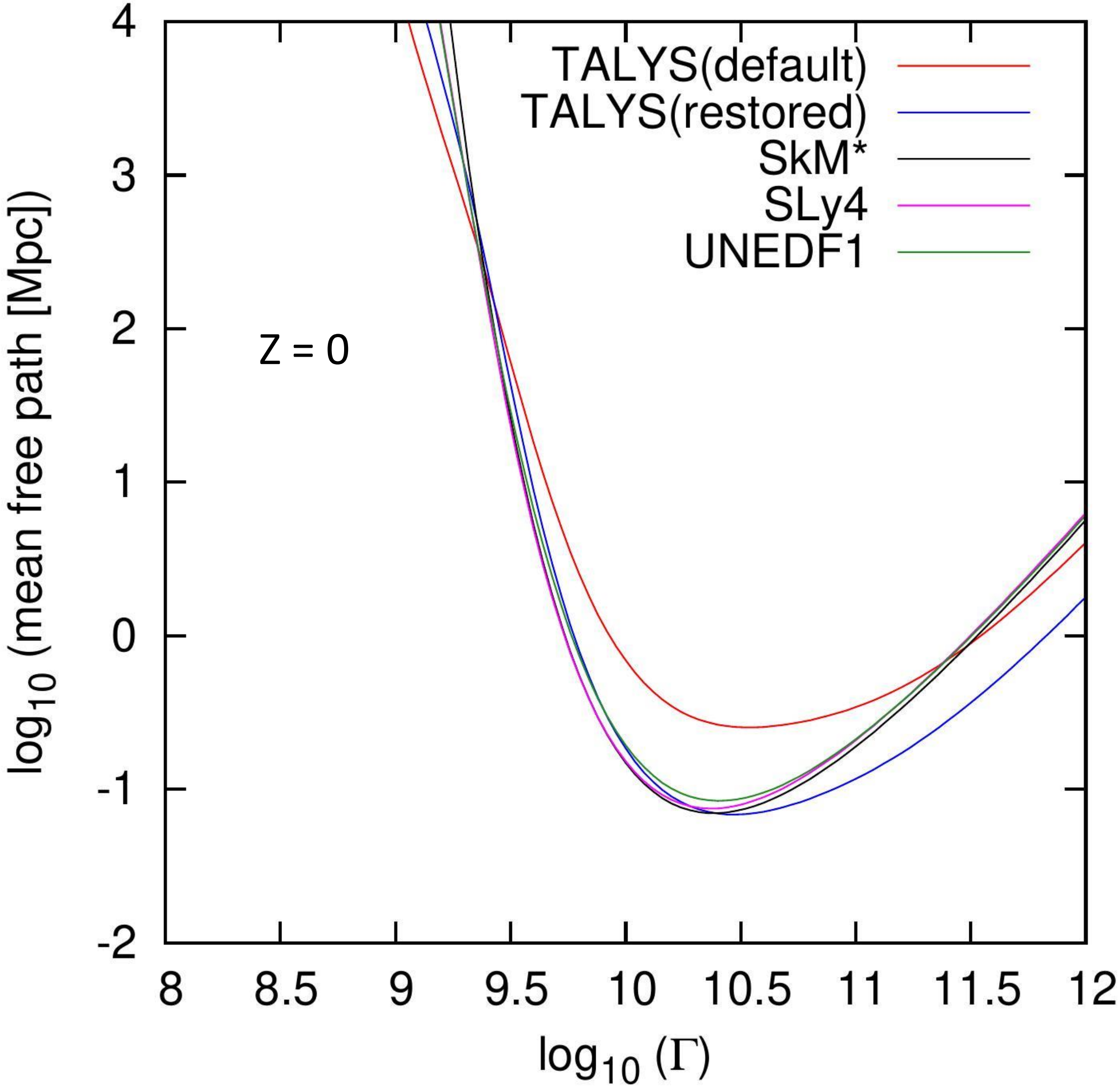
$$\lambda^{-1}(\Gamma, z) = \frac{1}{2\Gamma^2}\int_0^\infty \int_0^{2\Gamma\epsilon} n(\epsilon, z)\frac{1}{\epsilon^2}\epsilon'\sigma(\epsilon')\, d\epsilon' d\epsilon,$$

- n: spectral number density of background photons (CMB, IRB(Gilmore+, 2012))
- Γ : Lorentz factor of the nucleus
- ε : photon energy
- ε' = Γ ε (1 – cos Θ) : photon energy in the nucleus's rest frame
- Θ : opening angle between the photon and the nucleus momenta
- σ : non-elastic cross section (replaced with $\sigma_{GDR}$ for SkM*, SLy4 & UNEDF1 models)

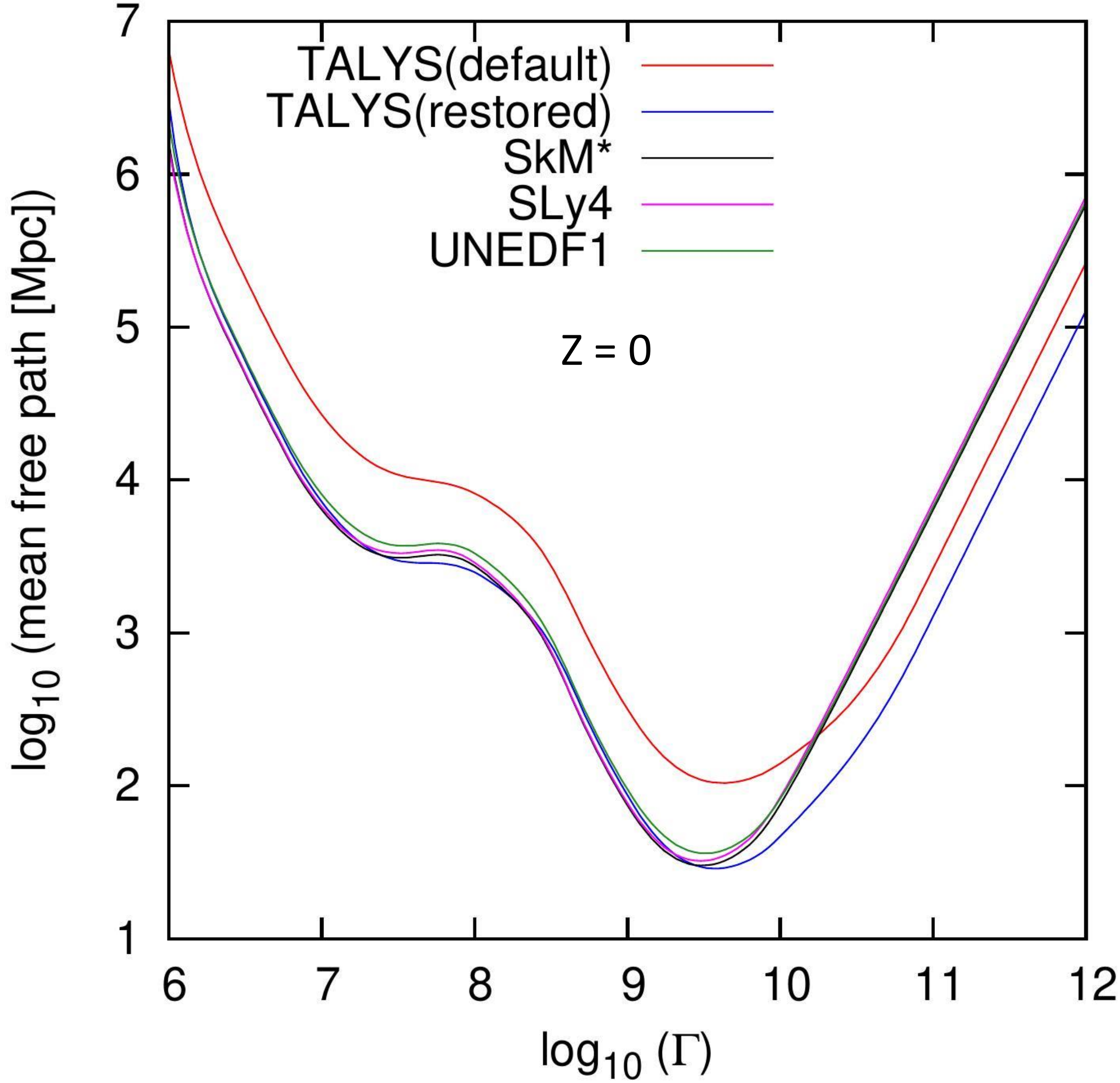
$$\sigma_{non-el} = \sum_Z \sum_N \sigma_{prod}(Z, N).$$

$$\sigma_{prod}(Z,N) = \sum_{i_n=0}^{\infty}\sum_{i_p=0}^{\infty}\sum_{i_d=0}^{\infty}\sum_{i_t=0}^{\infty}\sum_{i_h=0}^{\infty}\sum_{i_\alpha=0}^{\infty} \sigma^{ex}(i_n, i_p, i_d, i_t, i_h, i_\alpha)\delta_N\delta_Z,$$

# $^{28}$Si mean free path of photodisintegration with the CMB photons



# $^{28}$Si mean free path of photodisintegration with the IRB(Gilmore+, 2012) photons



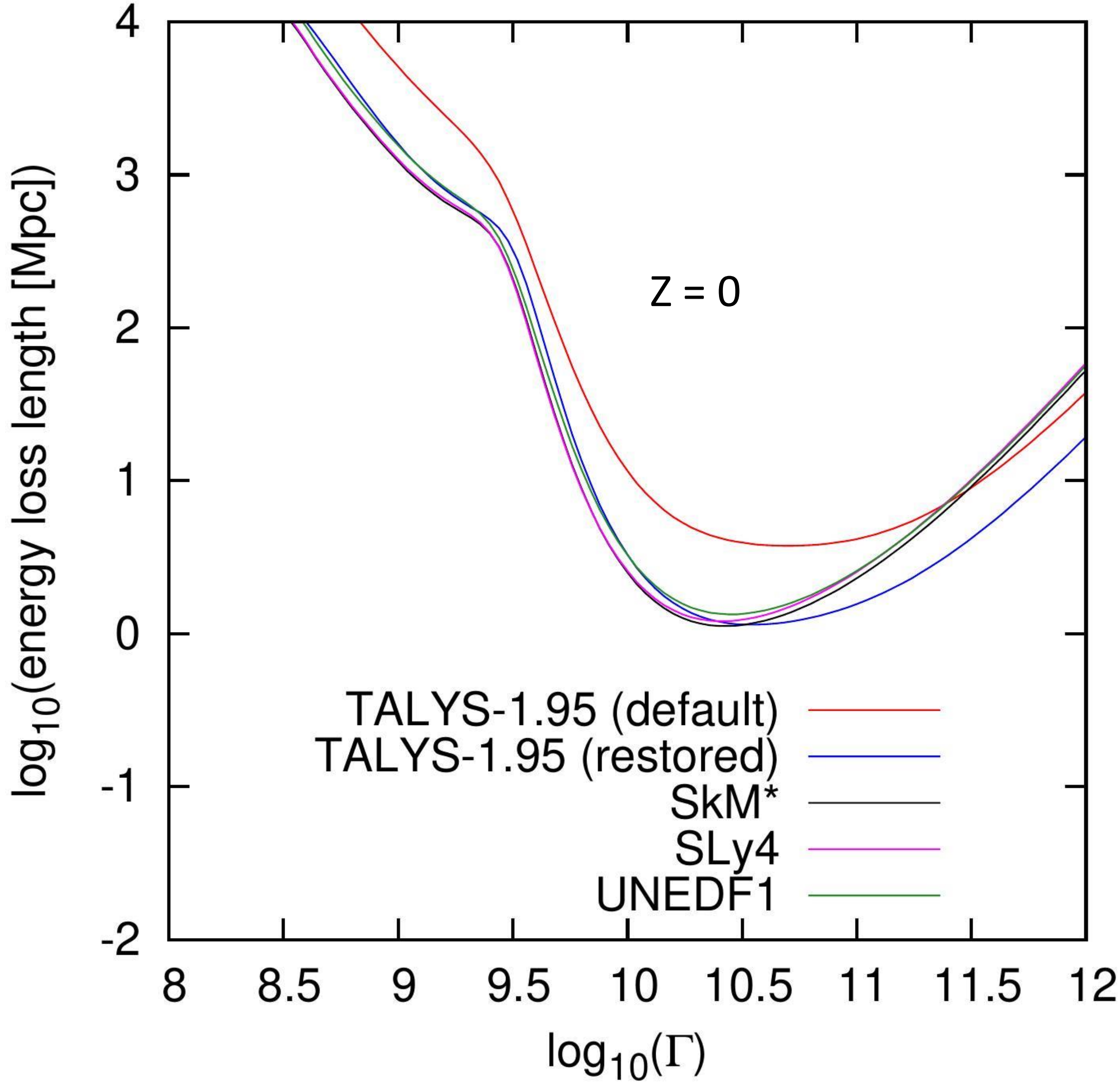
# Simulations of Propagation of UHECRs

$$dN/dE \propto E_{\rm inj}^{-\gamma} \exp(-E_{\rm inj}/ZR_{\rm cut})$$

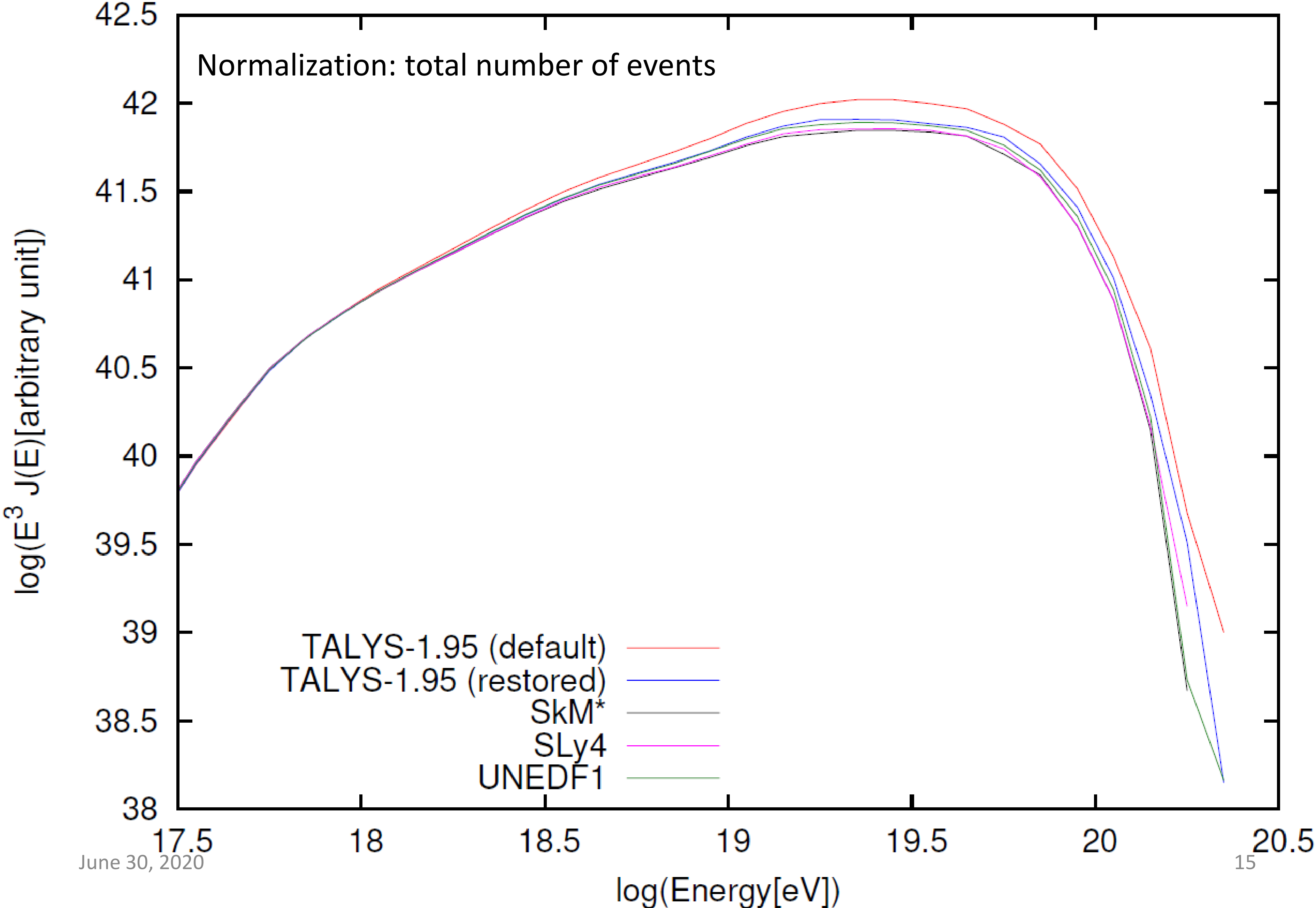
$$0 < z < 1$$

- $\gamma = 1$, $R_{\rm cut} = 5\times10^{18}$ V
- Sources are uniformly distributed in comoving volume.
- CRPropa3
- IRB: Gilmore+ 2012
- 1 dimensional propagation
- We replaced the default mean free path tables (TALYS (restored)) with other models (TALYS (default), SkM*, SLy4, UNEDF1).
- We did not change the tables of the branching ratios.

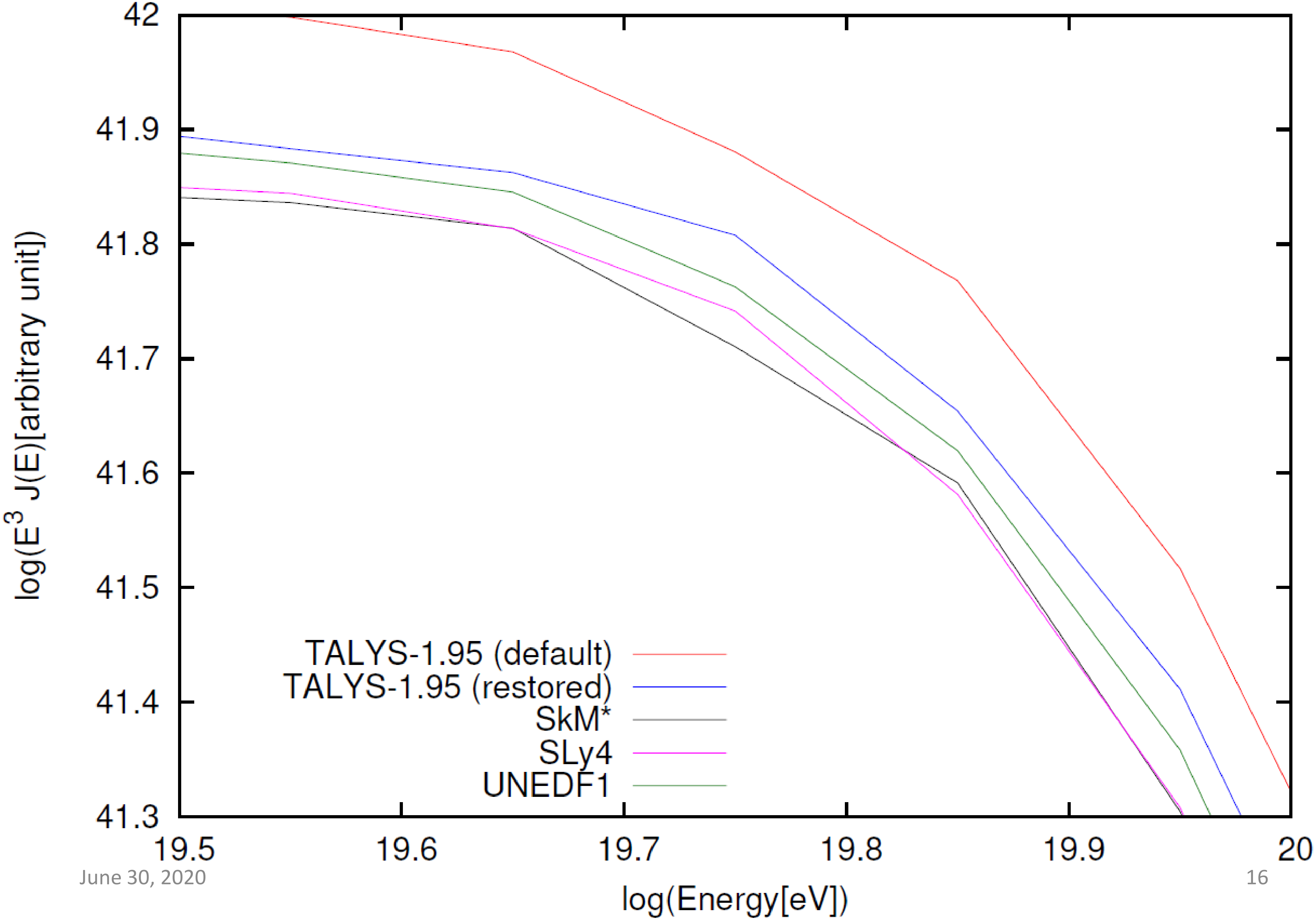
# $^{28}$Si Energy Loss Length of Photodisintegration (CMB + IRB(Gilmore+, 2012))



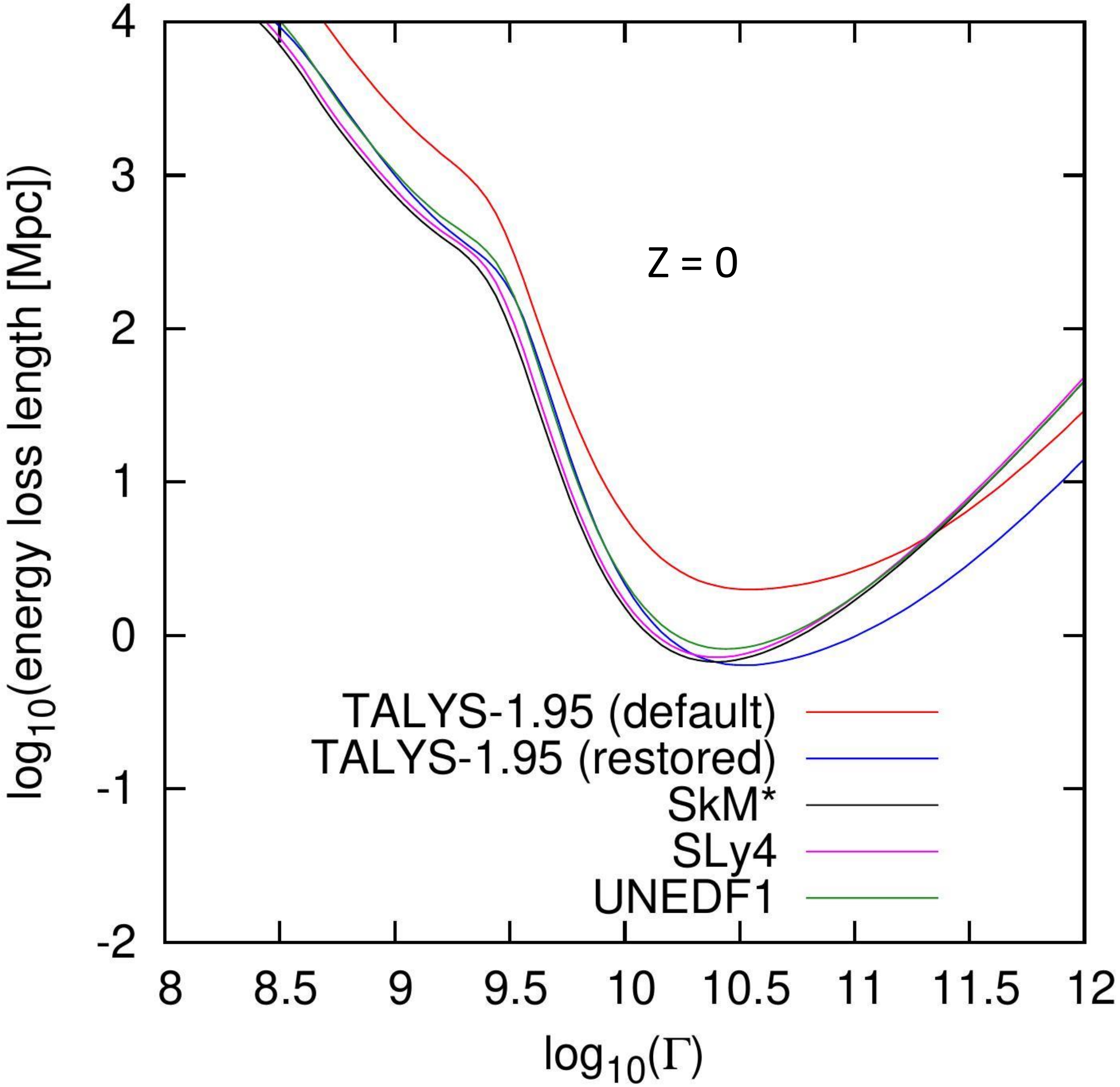
# Energy Spectrum from 28Si source



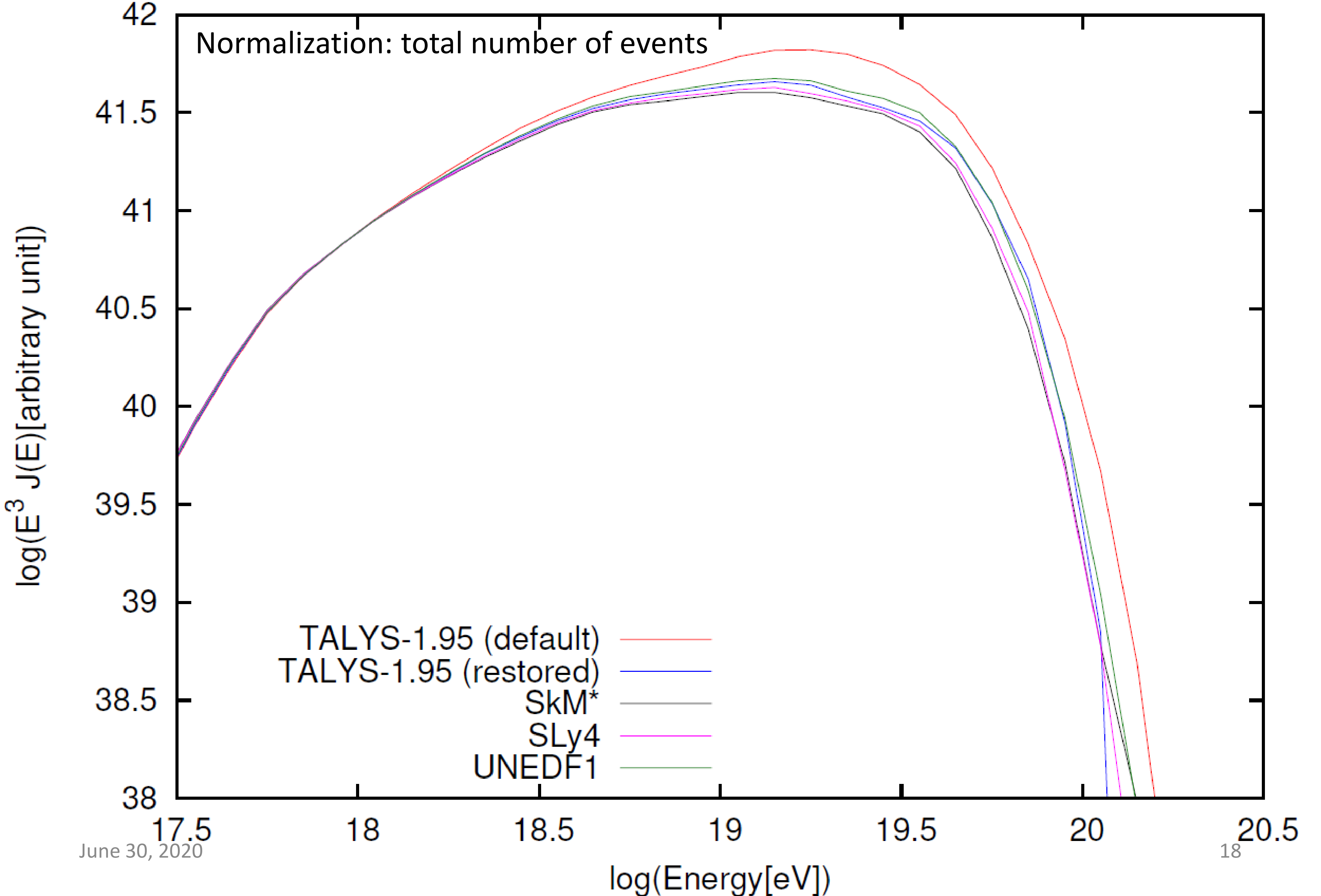
# Energy Spectrum from 28Si source



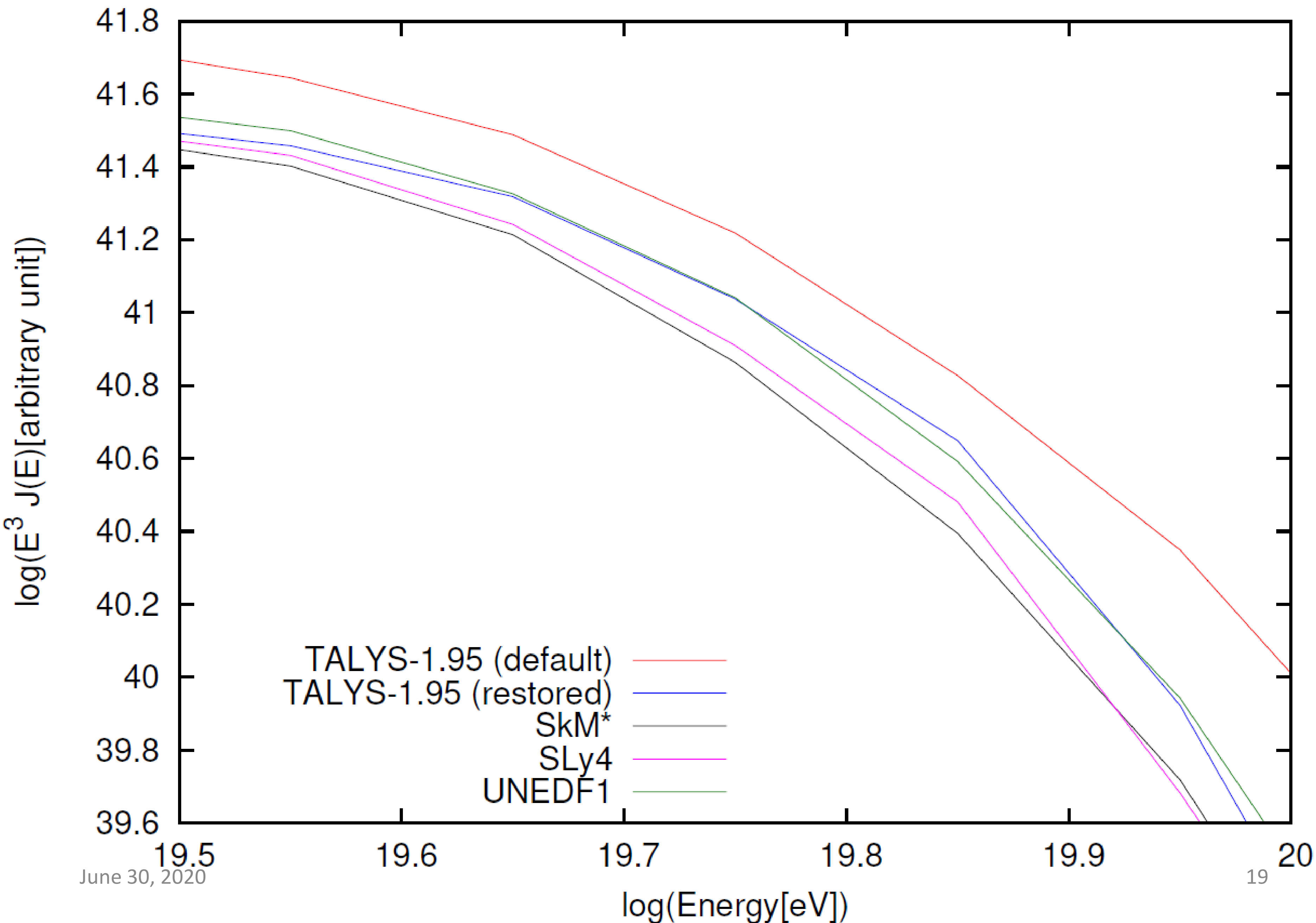
# $^{16}O$ Energy Loss Length of Photodisintegration (CMB + IRB(Gilmore+, 2012))



# Energy Spectrum from 16O source



# Energy Spectrum from 16O source



# Summary

- We compared 5 models (T. Inakura *et al.* and TALYS) of photoabsorption cross sections of 12 nuclei (4He 12C 16O 20Ne 24Mg 28Si 32S 36Ar 40Ca 48Ti 52Cr 56Fe).
  – Max. difference of the GDR peak energies: about 29% (16O)
  – Max. difference of the GDR cross sections: about 580% (16O)
- We simulated the propagation of UHECRs using these photoabsorption cross sections and CRPropa3.
  – Assumption of the UHECR sources:
    $dN/dE \propto E_{\rm inj}^{-\gamma} \exp(-E_{\rm inj}/ZR_{\rm cut})$
    $R_{\rm cut}$ = 5x$10^{18}$ V, 0<z<1 uniform distribution
  – Cutoff energies are shifted mainly depending on the GDR peak energies.