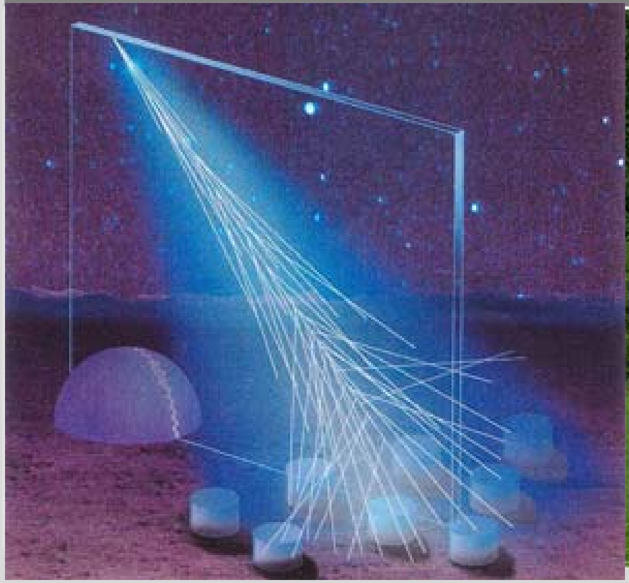
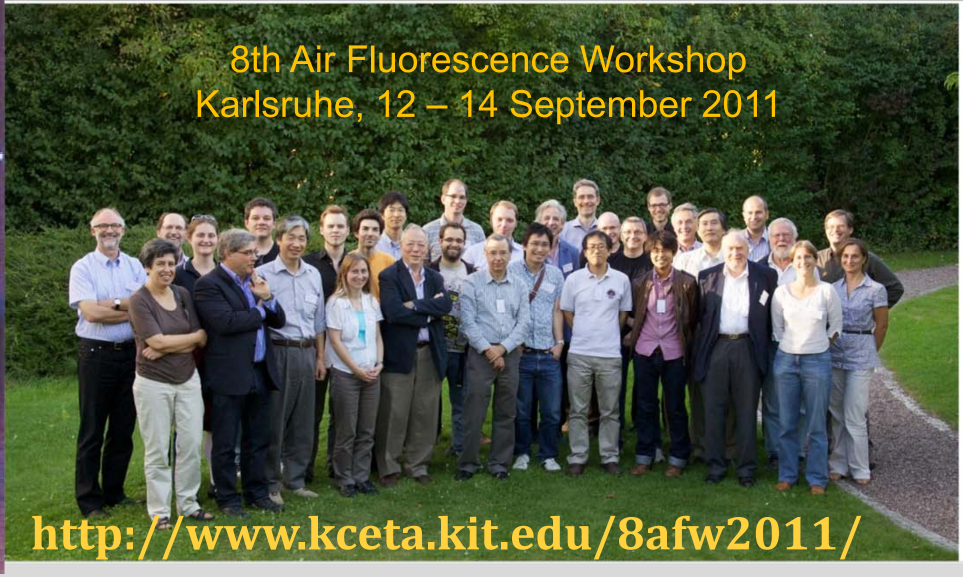
Nitrogen fluorescence in air for observing extensive air showers

B. Keilhauer

AtmoHEAD: Atmospheric Monitoring for High-Energy Astroparticle Detectors, Saclay, 10 – 12 June 2013

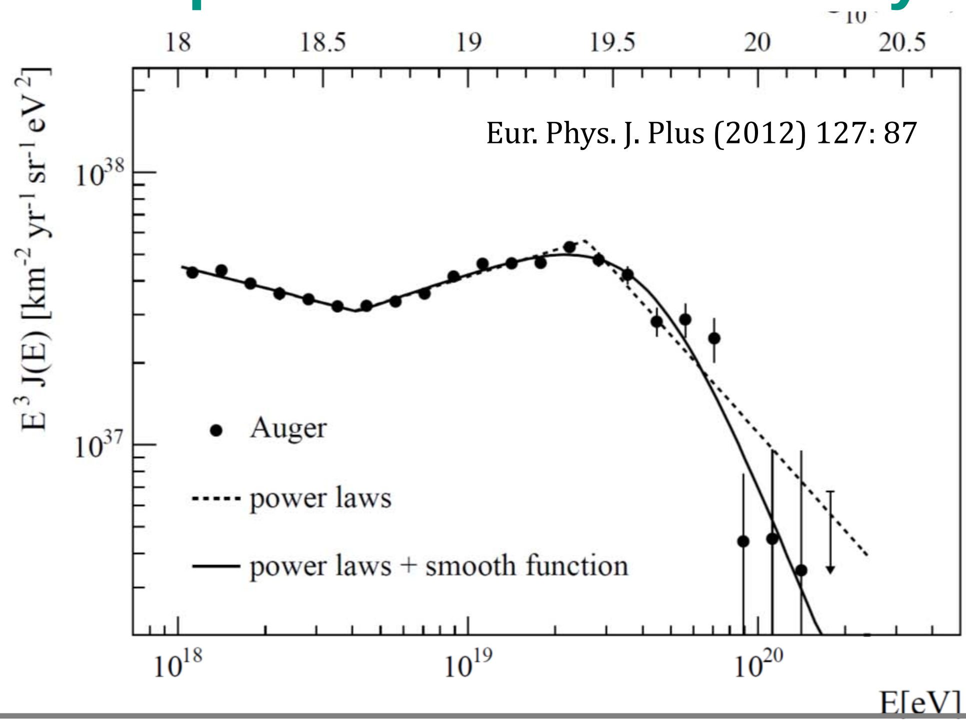




Delegation of the workshop:

M. Bohacova
M. Fraga
B. Keilhauer
J. Matthews
N. Sakaki
Y. Tameda
Y. Tsunesada
A. Ulrich

Interpretation of Cosmic Rays



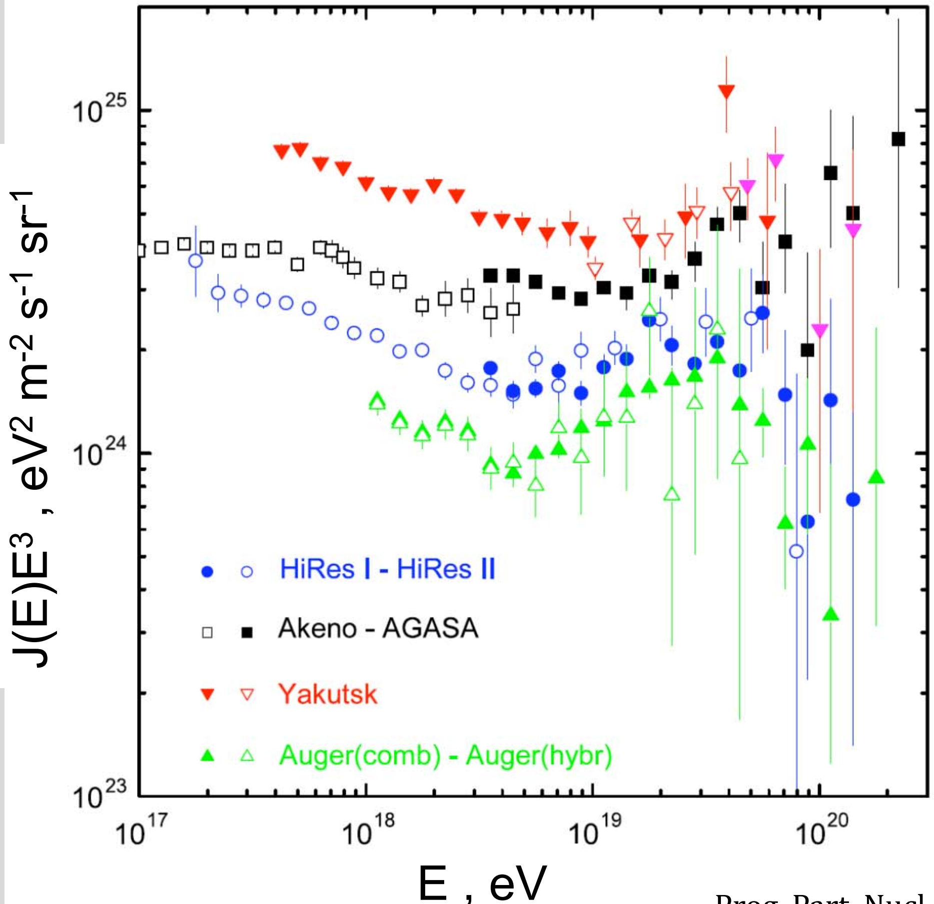
UHECR MODELS V. Berezinsky, UHECR2012

for description of spectra, mass composition, sources, transition.

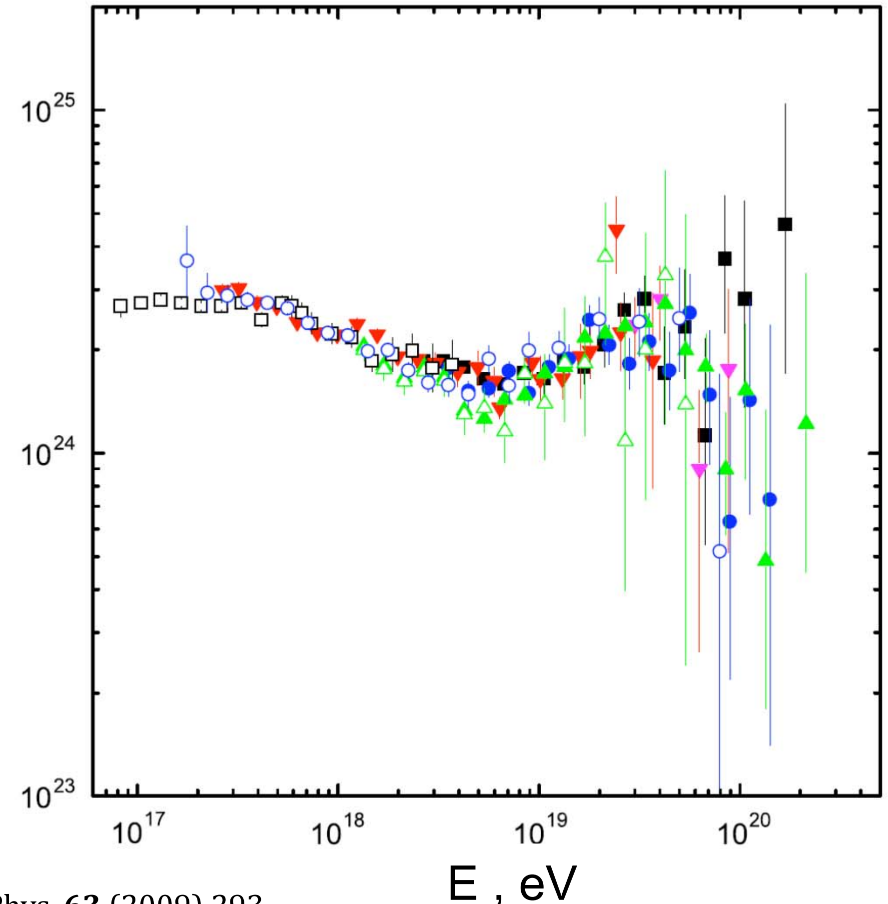
- **Dip model** (transition at the second knee $E_{\mathrm{tr}} \sim (5-7) \times 10^{17}$ eV).
- **Ankle models** (transition at ankle $E_{\mathrm{tr}} \sim (0.3-1.0) \times 10^{19}$ eV).
- **Mixed composition models** (arbitrary transition).
- **Models based on Auger mass composition.**

Interpretation of Cosmic Rays
- scaling of the absolute energy -

direct data of the experiments



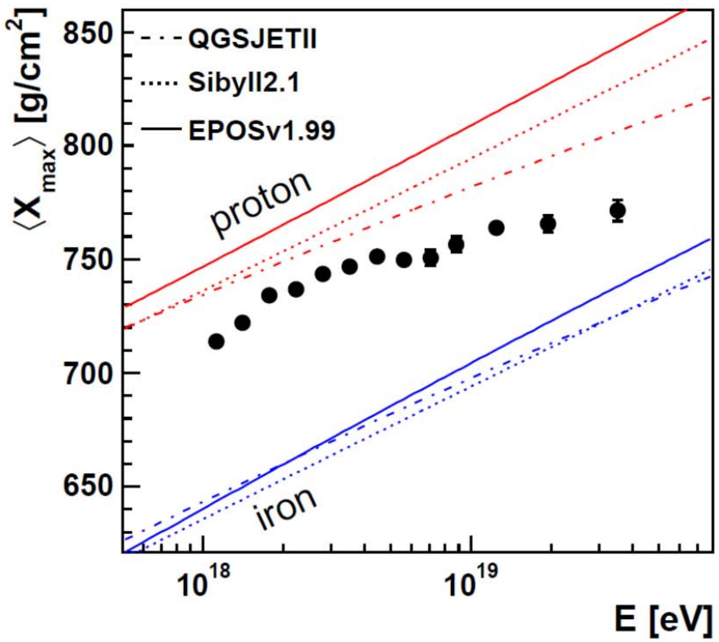
re-scaled data

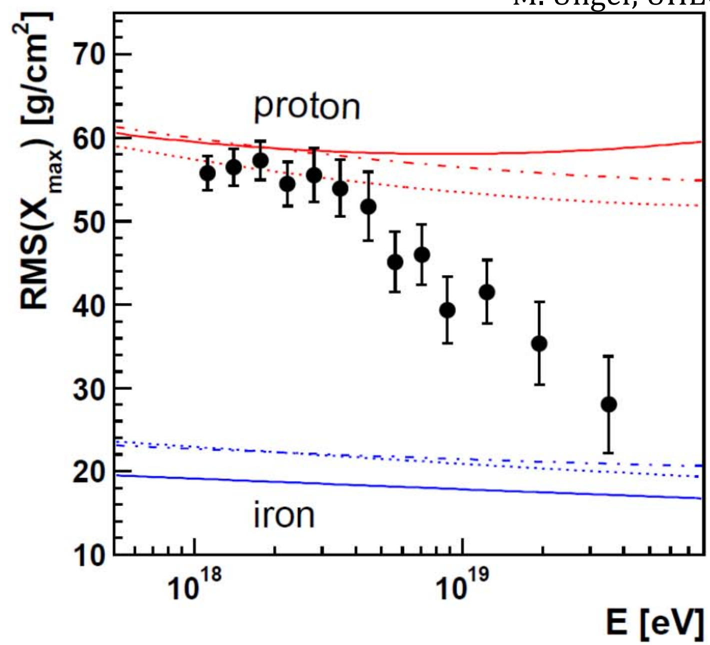


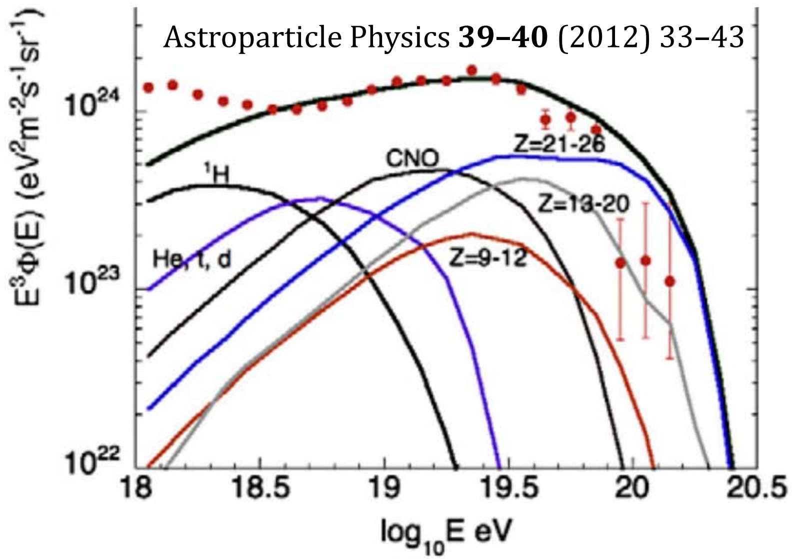
Prog. Part. Nucl. Phys. **63** (2009) 293

Interpretation of Cosmic Rays
- determination of the composition -

M. Unger, UHECR2012

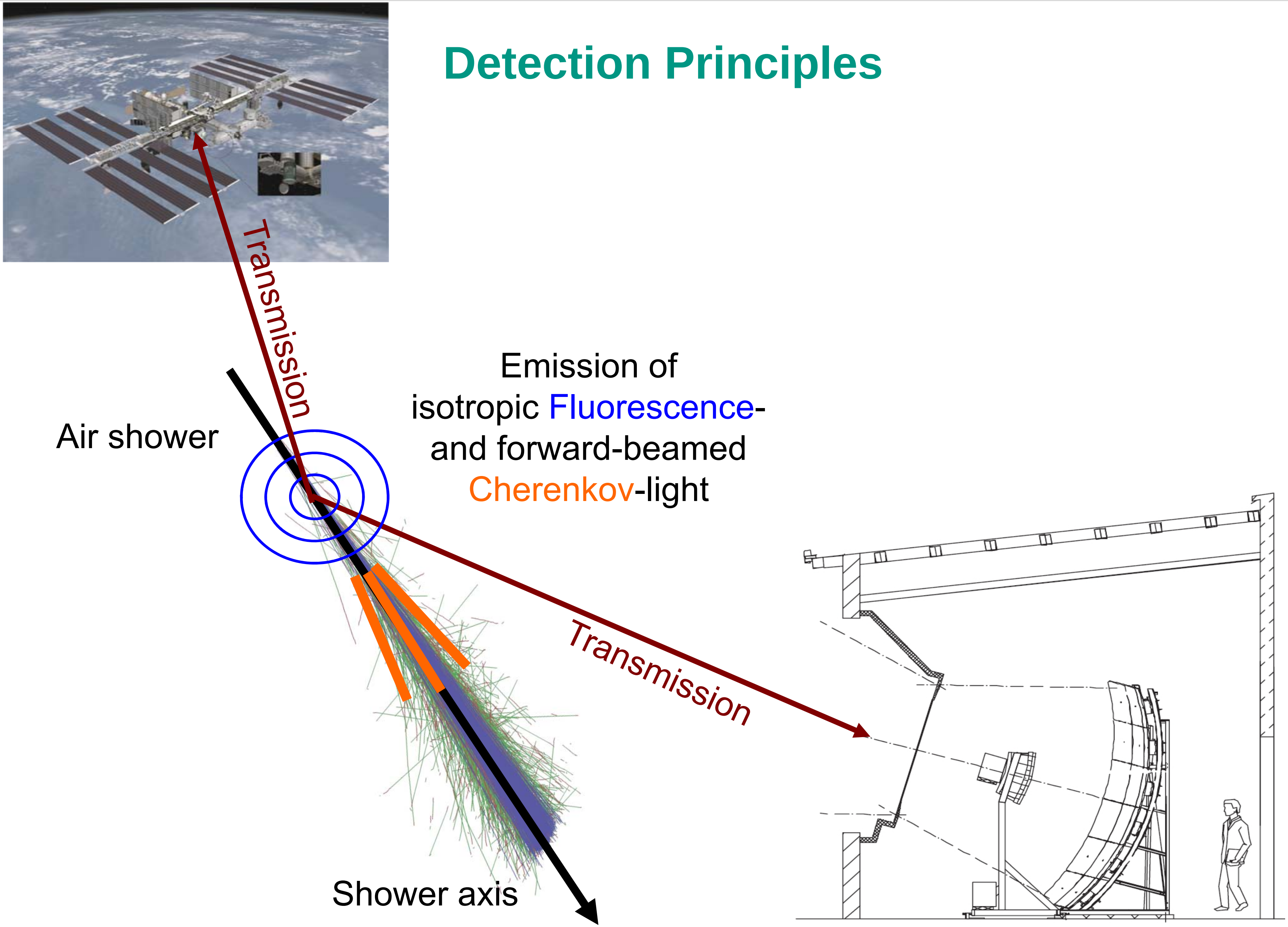






Astroparticle Physics **39–40** (2012) 33–43

Detection Principles



Fluorescence Light Production

- excitation of **nitrogen** in air because of energy deposit from EAS
  - direct excitation of 1N via ionization

$$N_2 + e^- \rightarrow N_2^{+\star} + e^- + e^-$$

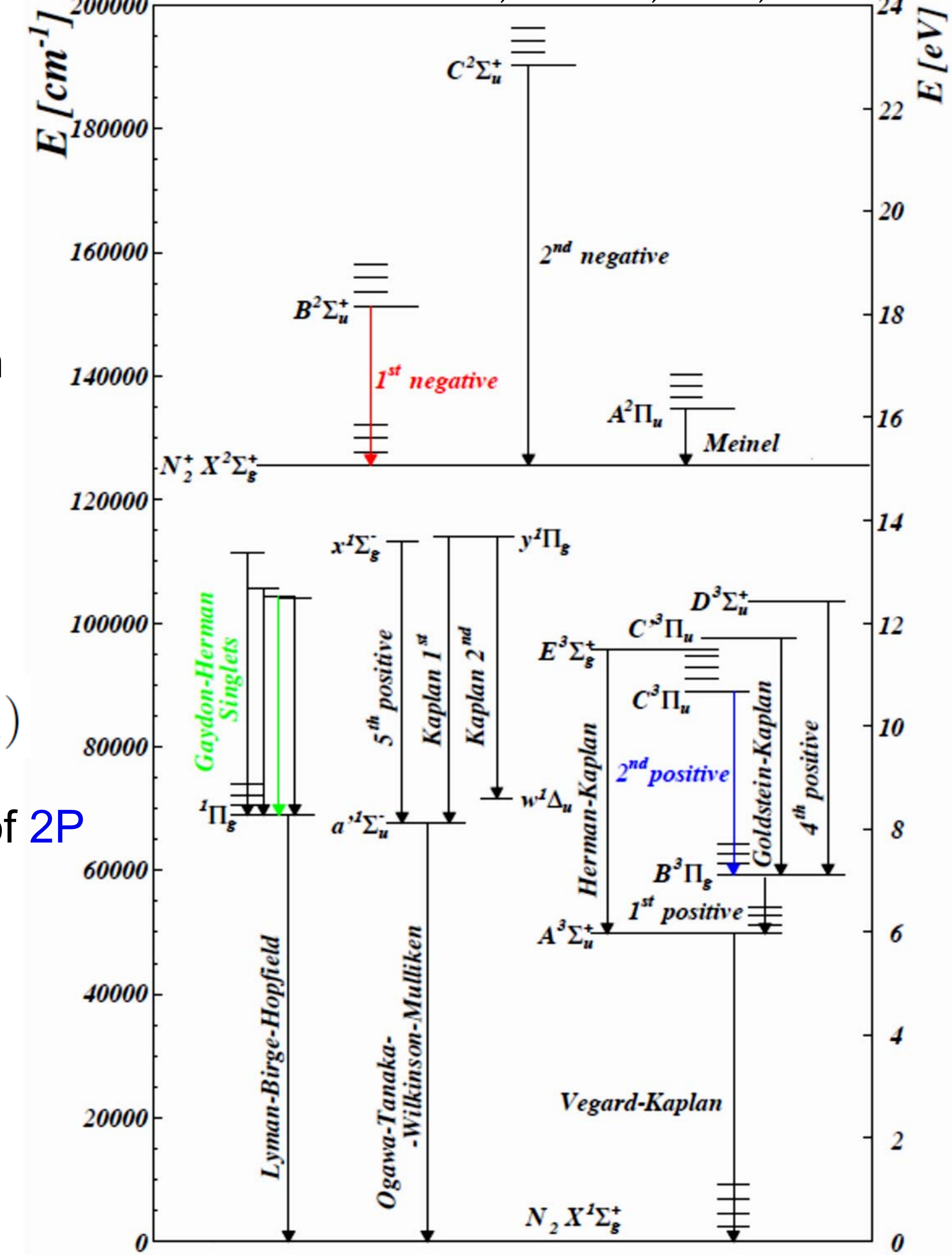
  - collisions with low energy electrons with spin change for 2P

$$N_2 + e(\uparrow) \rightarrow N_2^\star(C^3\Pi_u) + e(\downarrow)$$

  - down cascading from higher level of 2P

$$N_2^+ + e \rightarrow N_2^\star(C^3\Pi_u)$$

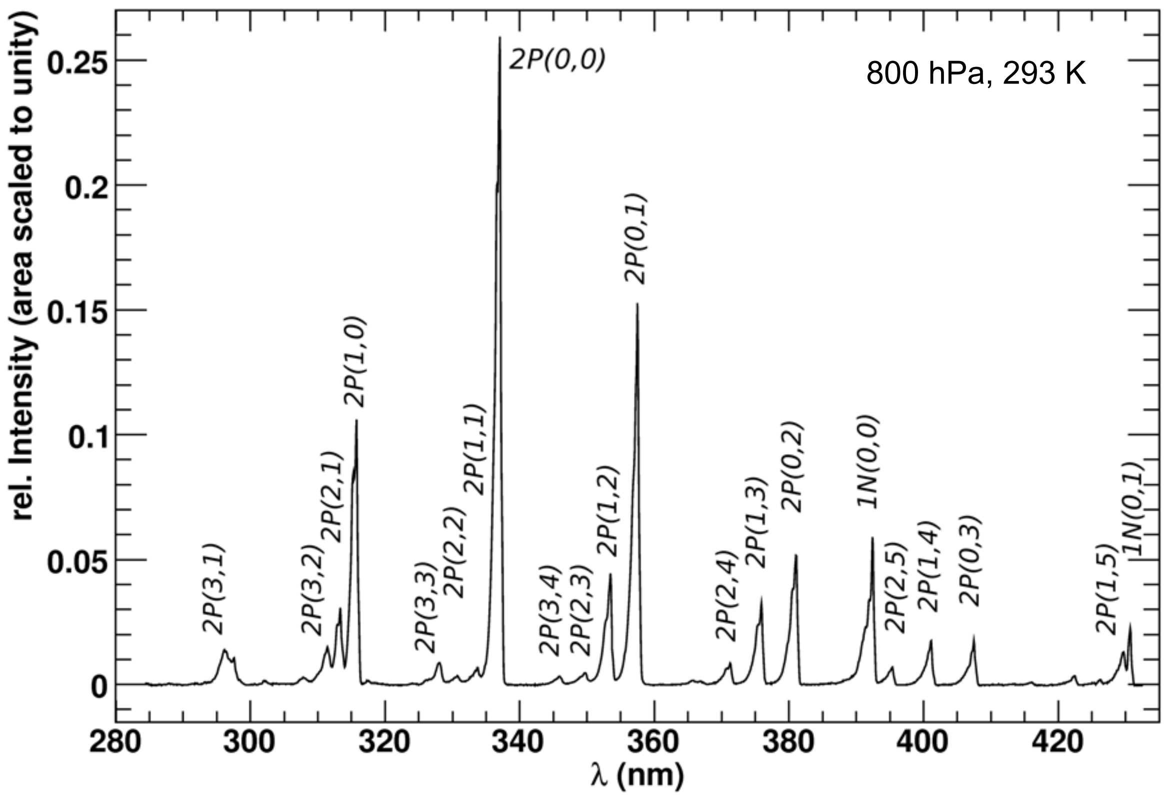
- spontaneous de-excitation → fluorescence light



A.N. Bunner, PhD thesis, Cornell, 1967

Fluorescence Light Production

- excitation of nitrogen in air because of energy deposit from EAS
- spontaneous de-excitation → fluorescence light
- atmosphere dependence because of quenching



NIM **A597**(2008)41

Formulas for a Fluorescence Description

$$Y_{\mathrm{air}}(\lambda, p, T) = Y_{\mathrm{air}}(337\ \mathrm{nm}, p_0, T_0) \cdot I_\lambda(p_0, T_0) \cdot \frac{1 + \dfrac{p_0}{p'_{\mathrm{air}}(\lambda, T_0)}}{1 + \dfrac{p}{p'_{\mathrm{air}}(\lambda, T_0) \cdot \sqrt{\frac{T}{T_0}} \cdot \frac{H_\lambda(T_0)}{H_\lambda(T)}}}$$

Formulas for a Fluorescence Description

$$Y_{\mathrm{air}}(\lambda, p, T) = \boxed{Y_{\mathrm{air}}(337\ \mathrm{nm}, p_0, T_0)} \cdot I_\lambda(p_0, T_0) \cdot \frac{1 + \dfrac{p_0}{p'_{\mathrm{air}}(\lambda, T_0)}}{1 + \dfrac{p}{p'_{\mathrm{air}}(\lambda, T_0) \cdot \sqrt{\dfrac{T}{T_0}} \cdot \dfrac{H_\lambda(T_0)}{H_\lambda(T)}}}$$

a) absolute yield value of a reference transmission:

fluorescence yield in photons emitted per MeV of energy deposited at given experimental conditions p_0 and T_0

Formulas for a Fluorescence Description

$$Y_{\mathrm{air}}(\lambda, p, T) = Y_{\mathrm{air}}(337\ \mathrm{nm}, p_0, T_0) \cdot I_\lambda(p_0, T_0) \cdot \frac{1 + \dfrac{p_0}{p'_{\mathrm{air}}(\lambda, T_0)}}{1 + \dfrac{p}{p'_{\mathrm{air}}(\lambda, T_0) \cdot \sqrt{\dfrac{T}{T_0}} \cdot \dfrac{H_\lambda(T_0)}{H_\lambda(T)}}}$$

a) absolute yield value of a reference transmission

b) wavelengths-dependent spectrum:

ratio of individual transitions of the spectrum between about 280 and 430 nm to the strength of the transitions at 337.1 nm

Formulas for a Fluorescence Description

$$Y_{\mathrm{air}}(\lambda, p, T) = Y_{\mathrm{air}}(337\ \mathrm{nm}, p_0, T_0) \cdot I_\lambda(p_0, T_0) \cdot \frac{1 + \dfrac{p_0}{\boxed{p'_{\mathrm{air}}(\lambda, T_0)}}}{1 + \dfrac{p}{\boxed{p'_{\mathrm{air}}(\lambda, T_0)} \cdot \sqrt{\dfrac{T}{T_0}} \cdot \dfrac{H_\lambda(T_0)}{H_\lambda(T)}}}$$

a) absolute yield value of a reference transmission

b) wavelengths-dependent spectrum

c) pressure dependence in dry air:

characteristic pressure of dry air at experimental conditions T_0

Formulas for a Fluorescence Description

$$Y_{\rm air}(\lambda, p, T) = Y_{\rm air}(337\ {\rm nm}, p_0, T_0) \cdot I_\lambda(p_0, T_0) \cdot \frac{1 + \dfrac{p_0}{p'_{\rm air}(\lambda, T_0)}}{1 + \dfrac{p}{\boxed{p'_{\rm air}(\lambda, T_0)} \cdot \sqrt{\dfrac{T}{T_0}} \cdot \dfrac{H_\lambda(T_0)}{H_\lambda(T)}}}$$

a) absolute yield value of a reference transmission

b) wavelengths-dependent spectrum

c) pressure dependence in dry air

d) humidity quenching: $\dfrac{1}{p'_{\rm air}} \rightarrow \dfrac{1}{p'_{\rm air}}\left(1 - \dfrac{p_h}{p}\right) + \dfrac{1}{p'_{\rm H_2O}} \dfrac{p_h}{p}$

$p'_{H2O}(\lambda, T_0)$ - characteristic pressure of water vapor at experimental conditions T_0

Formulas for a Fluorescence Description

$$Y_{\mathrm{air}}(\lambda, p, T) = Y_{\mathrm{air}}(337\ \mathrm{nm}, p_0, T_0) \cdot I_\lambda(p_0, T_0) \cdot \frac{1 + \dfrac{p_0}{p'_{\mathrm{air}}(\lambda, T_0)}}{1 + \dfrac{p}{p'_{\mathrm{air}}(\lambda, T_0) \cdot \sqrt{\dfrac{T}{T_0}} \cdot \boxed{\dfrac{H_\lambda(T_0)}{H_\lambda(T)}}}}$$

a) absolute yield value of a reference transmission

b) wavelengths-dependent spectrum

c) pressure dependence in dry air

d) humidity quenching

e) temperature-dependent collisional cross sections: $\dfrac{H_\lambda(T)}{H_\lambda(T_0)} = \left(\dfrac{T}{T_0}\right)^{\alpha_\lambda}$

α_λ- exponent of the power law describing the T-dependent collisional cross sections for each λ

Formulas for a Fluorescence Description

$$Y_{\mathrm{air}}(\lambda, p, T) = Y_{\mathrm{air}}(337\ \mathrm{nm}, p_0, T_0) \cdot I_\lambda(p_0, T_0) \cdot \frac{1 + \dfrac{p_0}{p'_{\mathrm{air}}(\lambda, T_0)}}{1 + \dfrac{p}{p'_{\mathrm{air}}(\lambda, T_0) \cdot \sqrt{\dfrac{T}{T_0}} \cdot \dfrac{H_\lambda(T_0)}{H_\lambda(T)}}}$$

a) absolute yield value of a reference transmission

b) wavelengths-dependent spectrum

c) pressure dependence in dry air

d) humidity quenching

e) temperature-dependent collisional cross sections

} Non-radiative de-excitation of excited nitrogen molecules
$\Rightarrow$ **only 1 value for each band system**

Strategy

1. Describing the spectrum and the dependences on atmospheric conditions:

   b) wavelengths-dependent spectrum

   c) pressure dependence in dry air

   d) humidity quenching

   e) temperature-dependent collisional cross sections

$\Rightarrow$ **common altitude-dependent shape**
$\Rightarrow$ **requires adequate knowledge of atmospheric profiles**

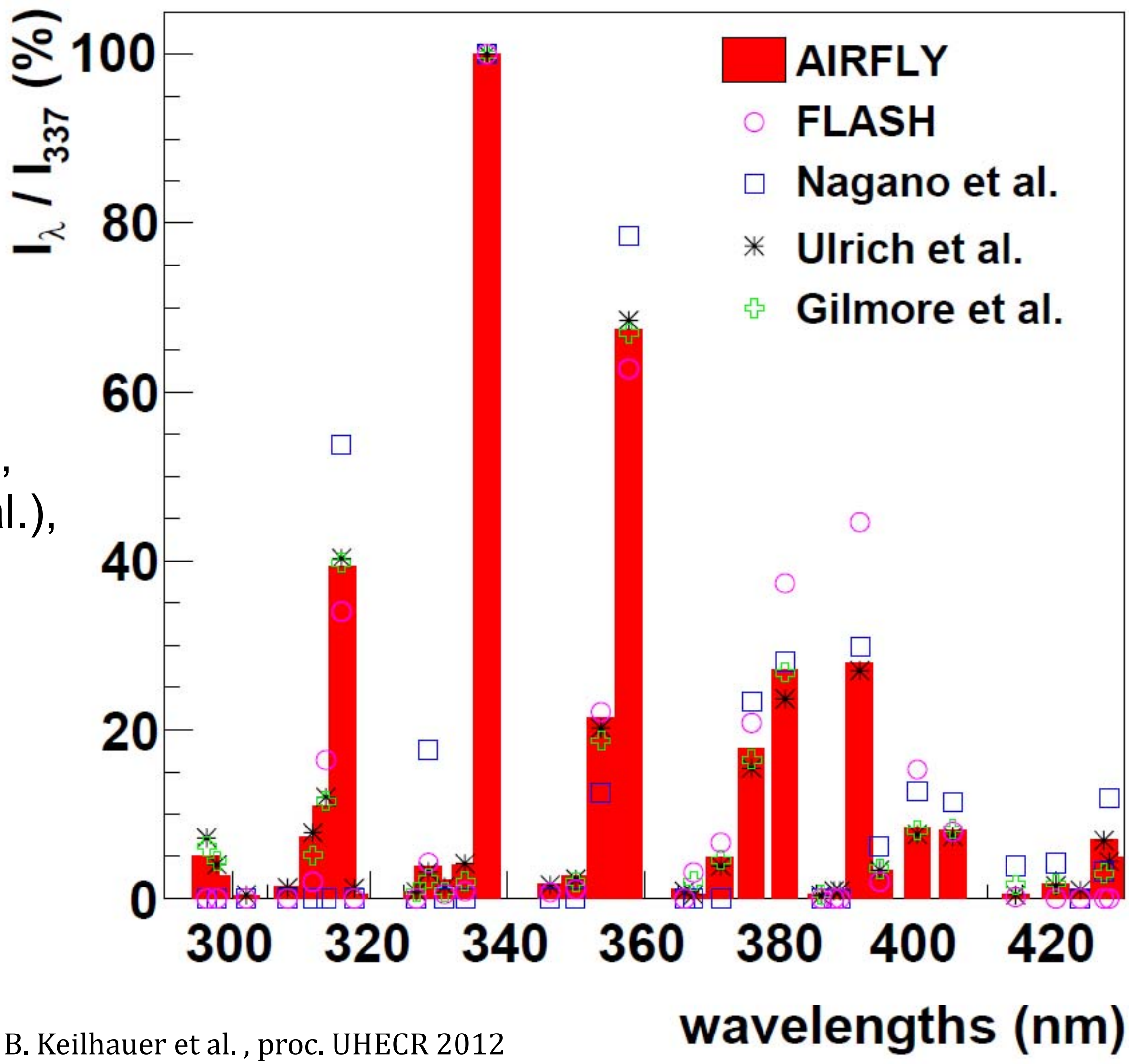
2. Finding the absolute scaling:

$\Rightarrow$ **direct shift of reconstructed primary E of air showers**

Suggested Reference Fluorescence Description - spectral intensities -

spectral intensities I_λ as measured by AIRFLY; 34 transitions between 296 and 428 nm

The sum of the yield differs by
-1.66% (Ulrich et al.),
+2.08% (Nagano et al.),
-1.70% (FLASH).



B. Keilhauer et al. , proc. UHECR 2012

Suggested Reference Fluorescence Description - pressure dependence-

p'_{air} :

- one value for each band system;
- weighted averages for 2P(0,x), (1,x), (2,x), (3,x), 1N (0,x), (1,x), GH (0,x) derived from AIRFLY measurements;
- for weak transitions, as 2P(4,x), further GH, estimates from their publicatation

system	band	λ (nm)	I_λ/I_{337} (%)	p'_{air} (hPa)
N_2 2P	0-0	337.1	100	15.83 ± 0.80
	0-1	357.7	67.4 ± 2.4	
	0-2	380.5	27.2 ± 1.0	
	0-3	405.0	8.07 ± 0.29	

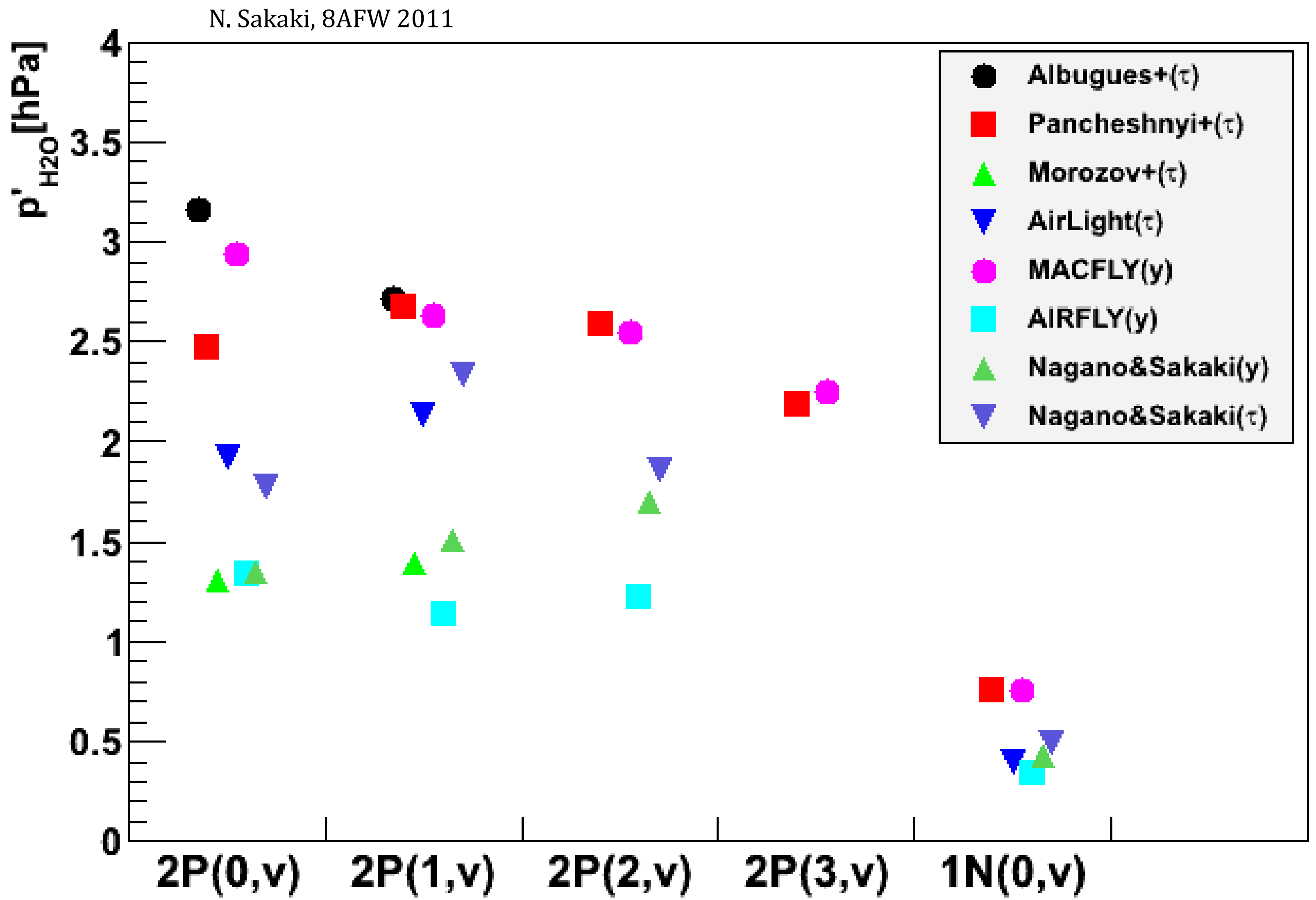
Suggested Reference Fluorescence Description - humidity dependence-

p'_{H2O} :

- one value for each band system;
- weighted averages for 2P (0,x), (1,x), (2,x), 1N (0,x) derived from Sakaki et al. measurements using the **photon yield** and the **lifetime technique**
- for weak transitions of 2P(3,x) and 2P(4,x) use weighted average of p'_{H2O} of 2P (1,x) and (2,x) bands (4.8% of the total emission at p_0, T_0)
- for all others set to Zero (2.1% of the total emission at p_0, T_0)

system	band	λ (nm)	I_λ/I_{337} (%)	p'_{air} (hPa)	p'_{H_2O} (hPa)
N_2 2P	0-0	337.1	100	15.83 ± 0.80	1.46 ± 0.05
	0-1	357.7	67.4 ± 2.4		
	0-2	380.5	27.2 ± 1.0		
	0-3	405.0	8.07 ± 0.29		

Systematic study from Sakaki et al.
- humidity dependence-



Suggested Reference Fluorescence Description - temp.-dep. collisional cross sections -

α-coefficient :

- one value for each band system;
- weighted average for 2P(0,x) and 1N(0,x) derived from AIRFLY measurements
- for weak transitions of 2P(3,x) and 2P(4,x) use weighted average of p'_{H2O} of 2P (1,x) and (2,x) bands (4.8% of the total emission at p_0, T_0)
- for all others set to Zero (2.1% of the total emission at p_0, T_0)

system	band	λ (nm)	I_λ/I_{337} (%)	p'_{air} (hPa)	p'_{H_2O} (hPa)	α
N_2 2P	0-0	337.1	100			
	0-1	357.7	67.4 ± 2.4	15.83 ± 0.80	1.46 ± 0.05	-0.35 ± 0.08
	0-2	380.5	27.2 ± 1.0			
	0-3	405.0	8.07 ± 0.29			

Parameter Set for the Reference Fluorescence Description

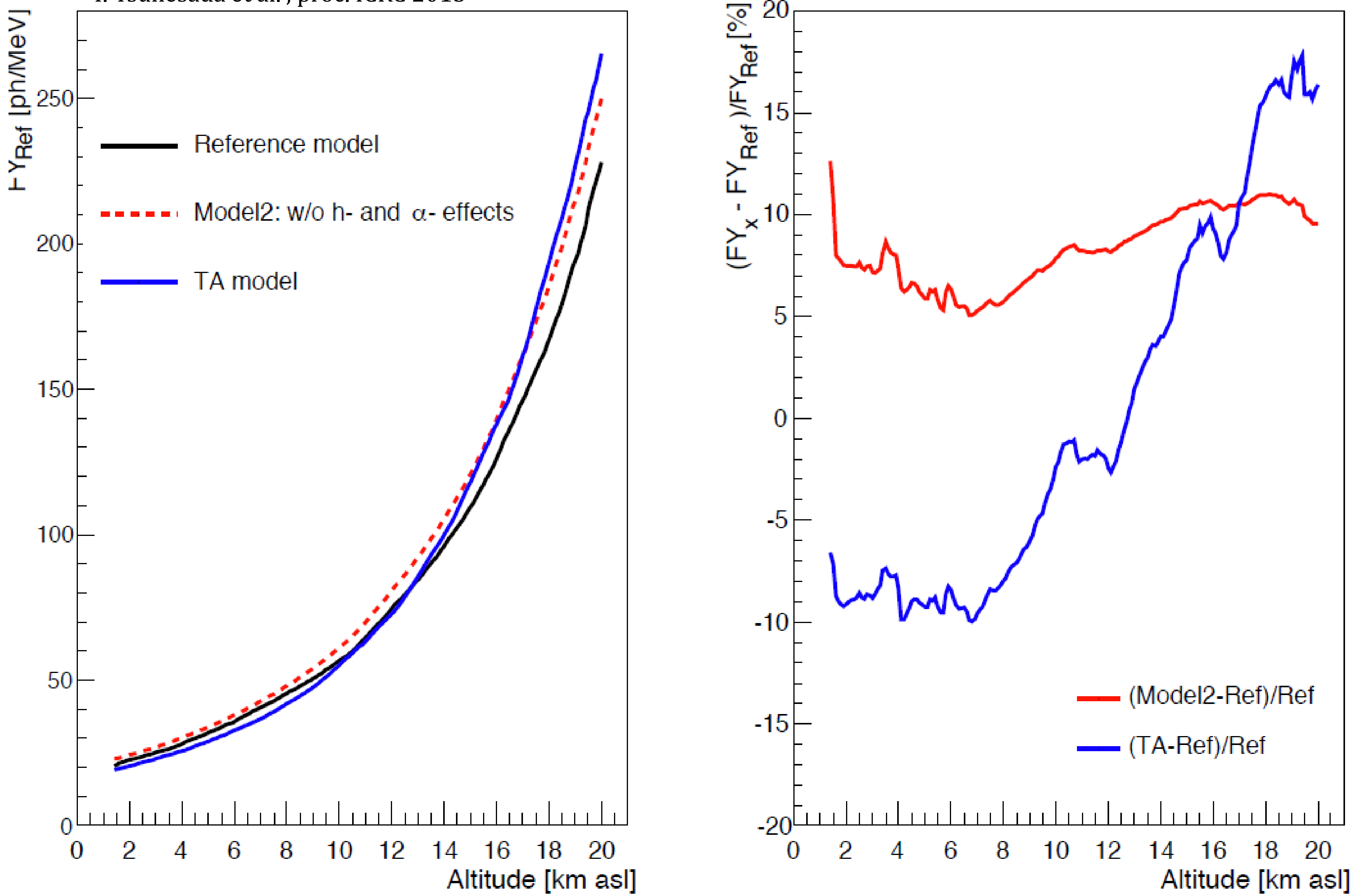
system	band	λ (nm)	I_λ/I_{337} (%)	p'_{air} (hPa)	p'_{H_2O} (hPa)	α
N_2 2P	0-0	337.1	100	15.83 ± 0.80	1.46 ± 0.05	-0.35 ± 0.08
	0-1	357.7	67.4 ± 2.4			
	0-2	380.5	27.2 ± 1.0			
	0-3	405.0	8.07 ± 0.29			
	1-0	315.9	39.3 ± 1.4	12.03 ± 0.66	1.90 ± 0.18	-0.20 ± 0.08
	1-1	333.9	4.02 ± 0.18			
	1-2	353.7	21.35 ± 0.76			
	1-3	375.6	17.87 ± 0.63			
	1-4	399.8	8.38 ± 0.29			
	1-5	427.0	7.08 ± 0.28			
	2-0	297.7	2.77 ±0.13	13.12 ± 0.71	1.80 ± 0.14	-0.17 ± 0.08
	2-1	313.6	11.05 ± 0.41			
	2-2	330.9	2.15 ± 0.12			
	2-3	350.0	2.79 ± 0.11			
	2-4	371.1	4.97 ± 0.22			
	2-5	394.3	3.36 ± 0.15			
	2-6	420.0	1.75 ± 0.10			
	3-1	296.2	5.16 ± 0.29	19.88 ± 0.86	1.84 ± 0.2	-0.19 ± 0.08
	3-2	311.7	7.24 ± 0.27			
	3-3	328.5	3.80 ± 0.14			
	3-5	367.2	0.54 ± 0.04			
	3-7	414.1	0.49 ± 0.07			
	4-4	326.8	0.80 ± 0.08	19 ± 5.0	1.84 ± 0.2	-0.19 ± 0.08
	4-7	385.8	0.50 ± 0.08			
N_2^+ 1N	0-0	391.4	28.0 ± 1.0	2.94 ± 0.33	0.47 ± 0.02	-0.76 ± 0.08
	0-1	427.8	4.94 ± 0.19			
	1-1	388.5	0.83 ± 0.04	3.92 ± 0.32	0	0
	1-2	423.6	1.04 ± 0.11			
N_2 GH	0-4	346.3	1.74 ± 0.11	7.98 ± 0.56	0	0
	0-5	366.1	1.13 ± 0.08			
	0-6	387.7	1.17 ± 0.06			
	5-2	308.0	1.44 ± 0.10	21 ± 10.0	0	0
	6-2	302.0	0.41 ± 0.06	21 ± 10.0	0	0
	6-3	317.6	0.46 ± 0.06			

B. Keilhauer et al. , proc. UHECR 2012

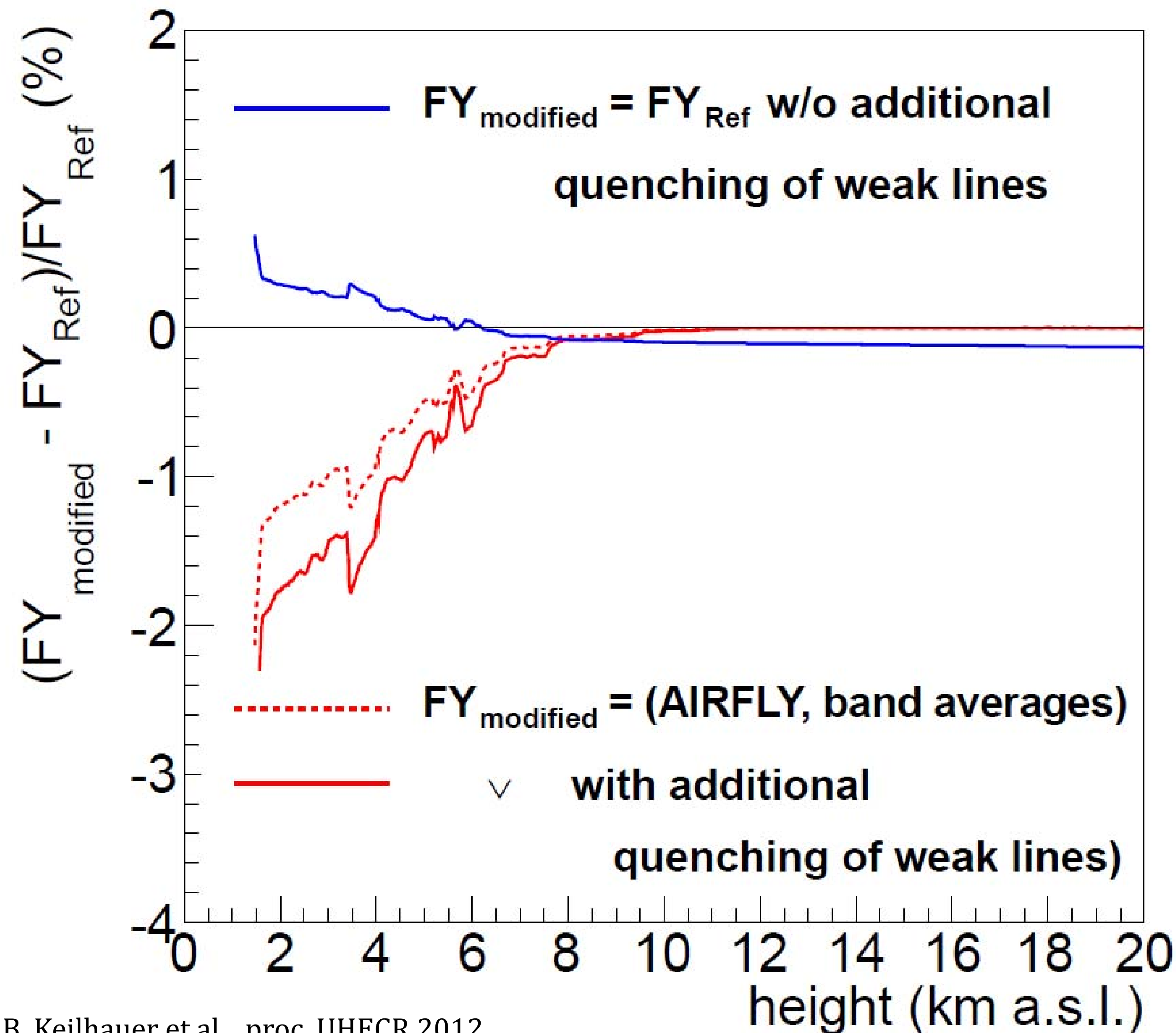
„academic“ fluorescence yield

- scaling according Nagano et al. (2004) -

Y. Tsunesada et al. , proc. ICRC 2013

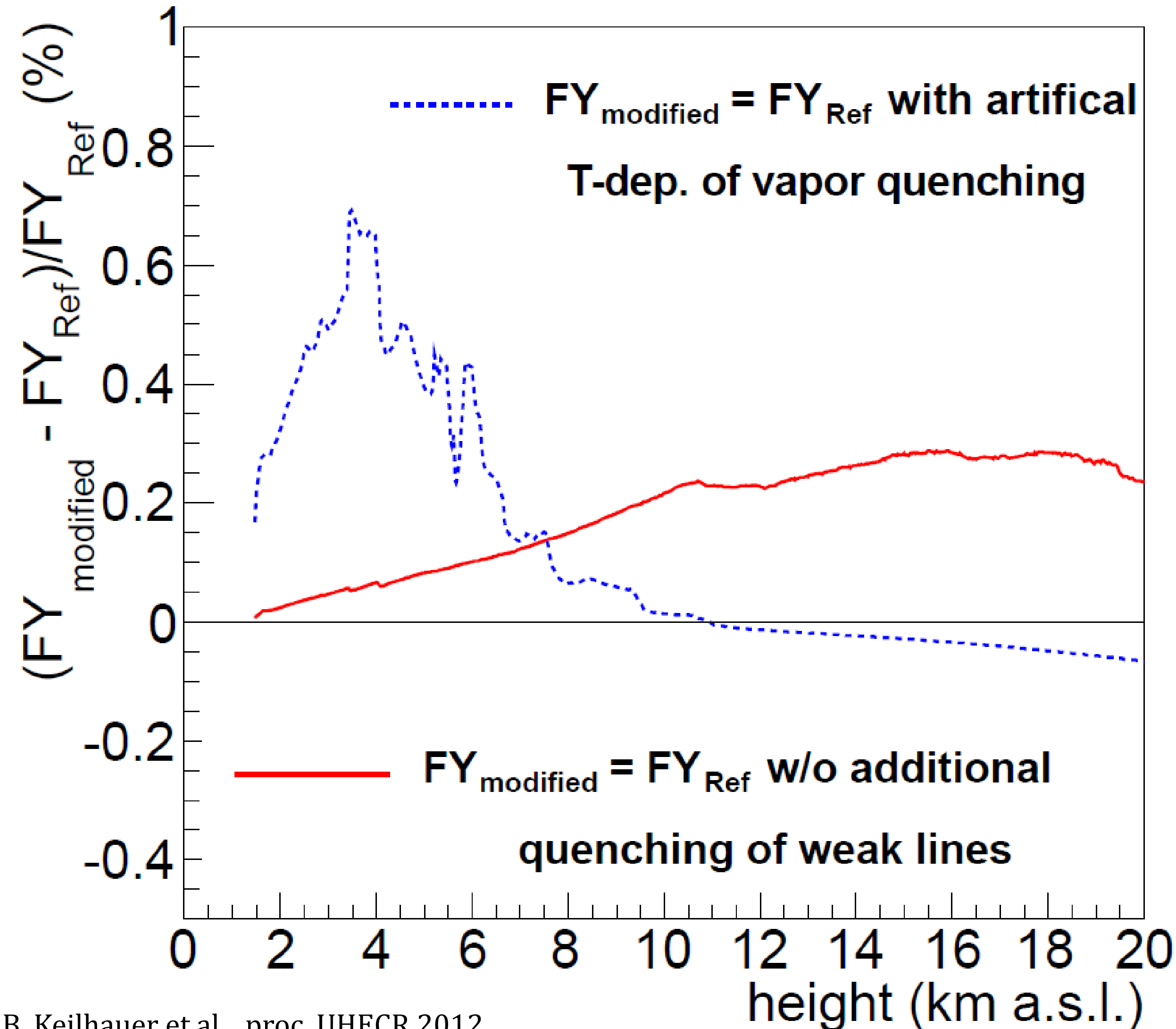


„academic“ fluorescence yield - variations of p'_{H2O} -



B. Keilhauer et al. , proc. UHECR 2012

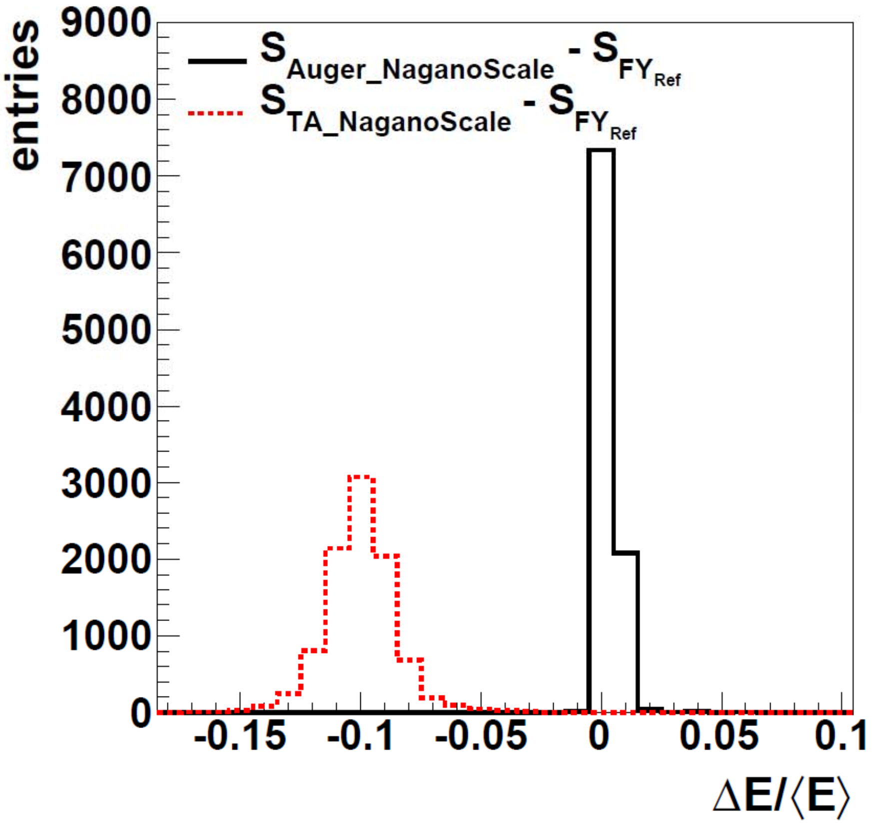
„academic“ fluorescence yield
- variations of α -

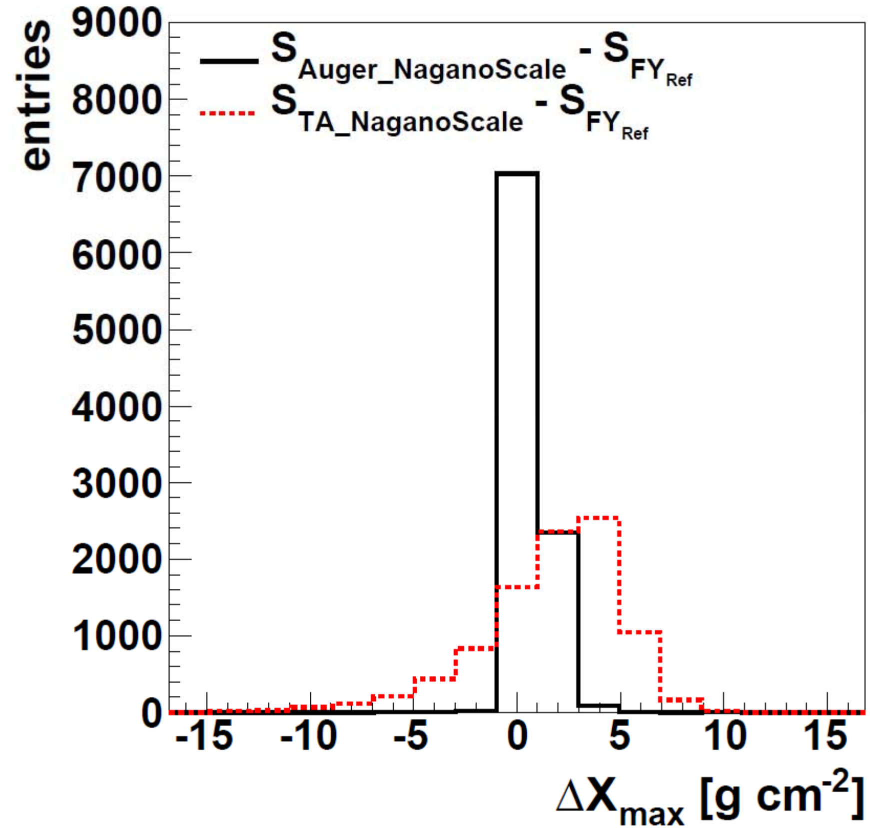


B. Keilhauer et al. , proc. UHECR 2012

Application to air shower reconstruction

- same absolute scaling, Auger reconstruction framework -



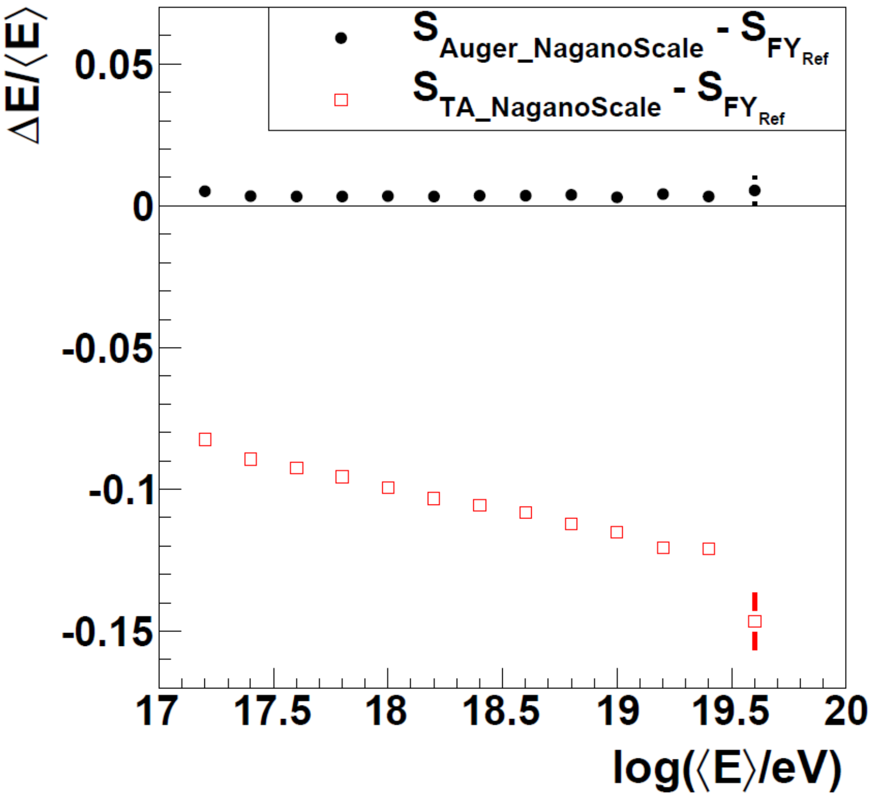


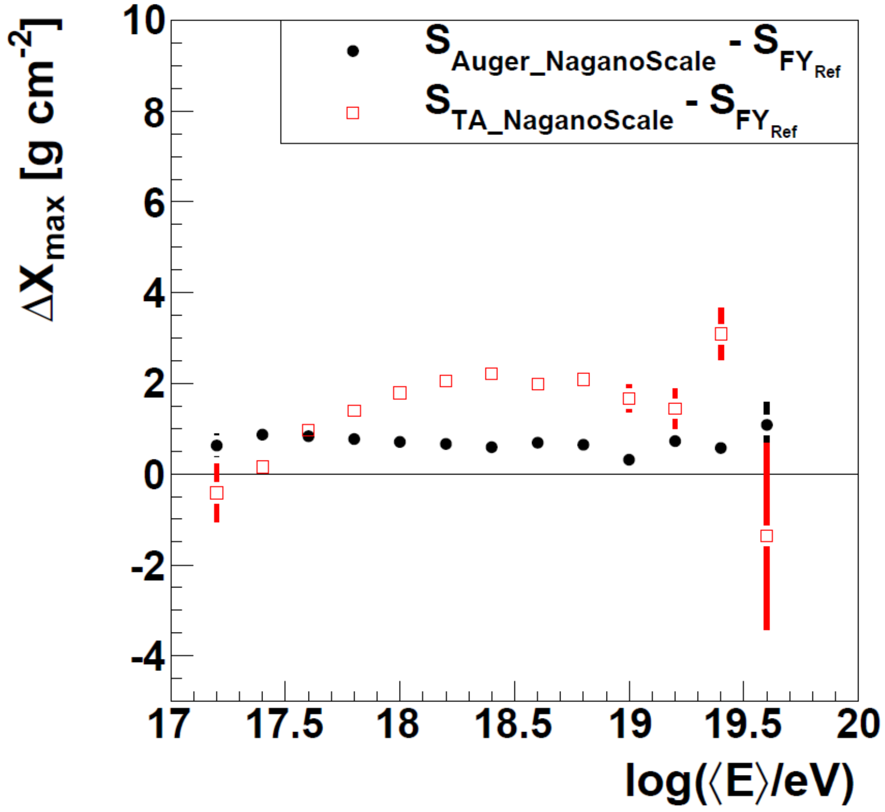
Mean:	-9.98 %	0.34 %	0.71 g cm^{-2}	1.63 g cm^{-2}
RMS:	1.76 %	1.22 %	1.25 g cm^{-2}	3.56 g cm^{-2}

B. Keilhauer et al. , proc. UHECR 2012

Systematics in air shower reconstruction

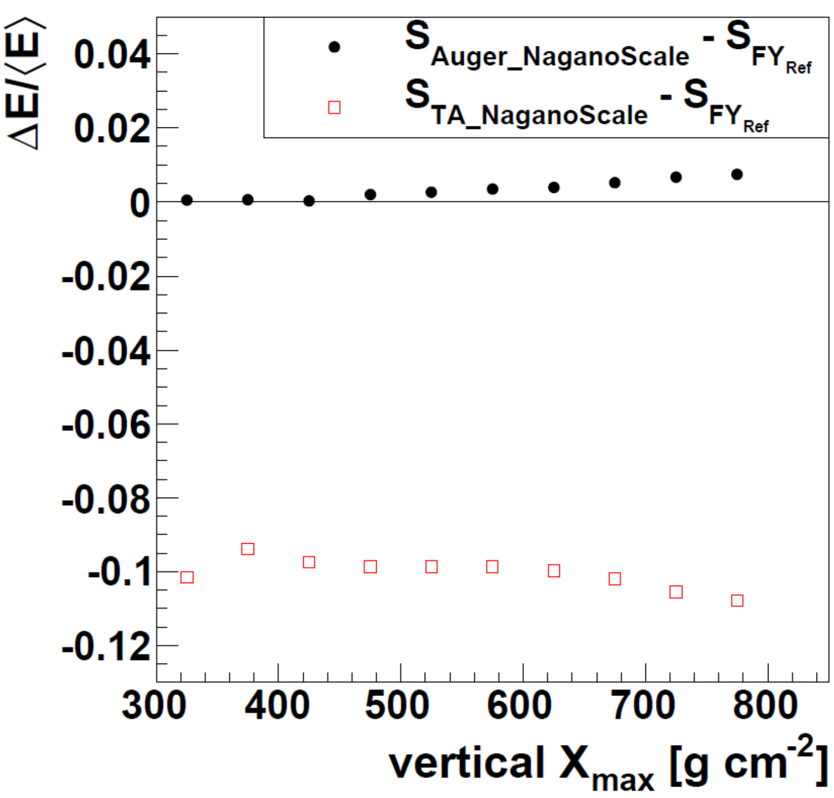
- same absolute scaling, Auger reconstruction framework -

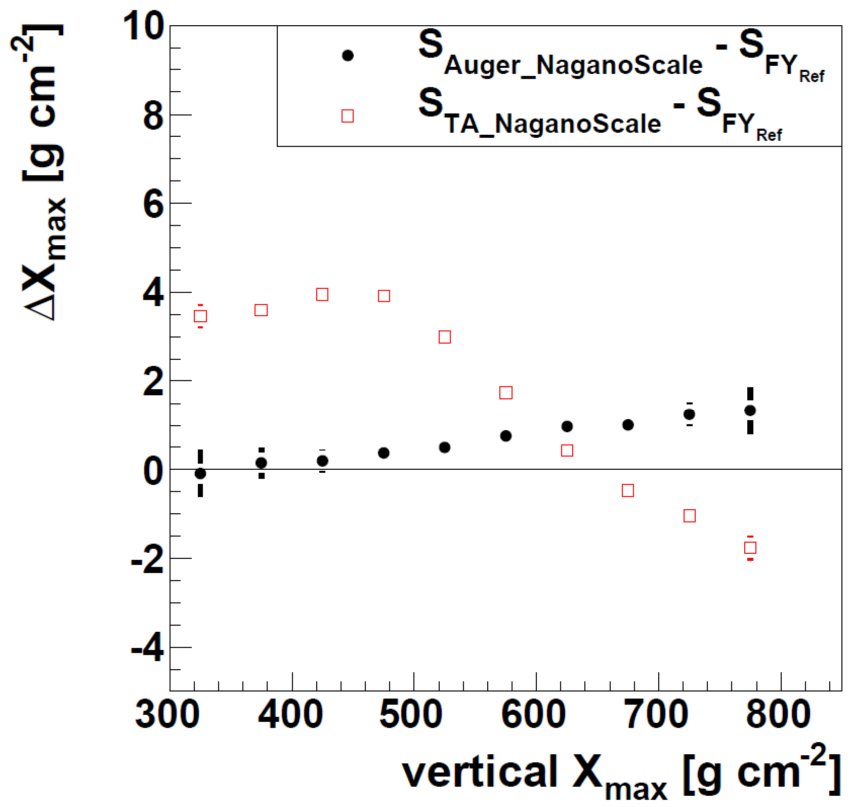




B. Keilhauer et al. , proc. UHECR 2012

Systematics in air shower reconstruction
- same absolute scaling, Auger reconstruction framework -

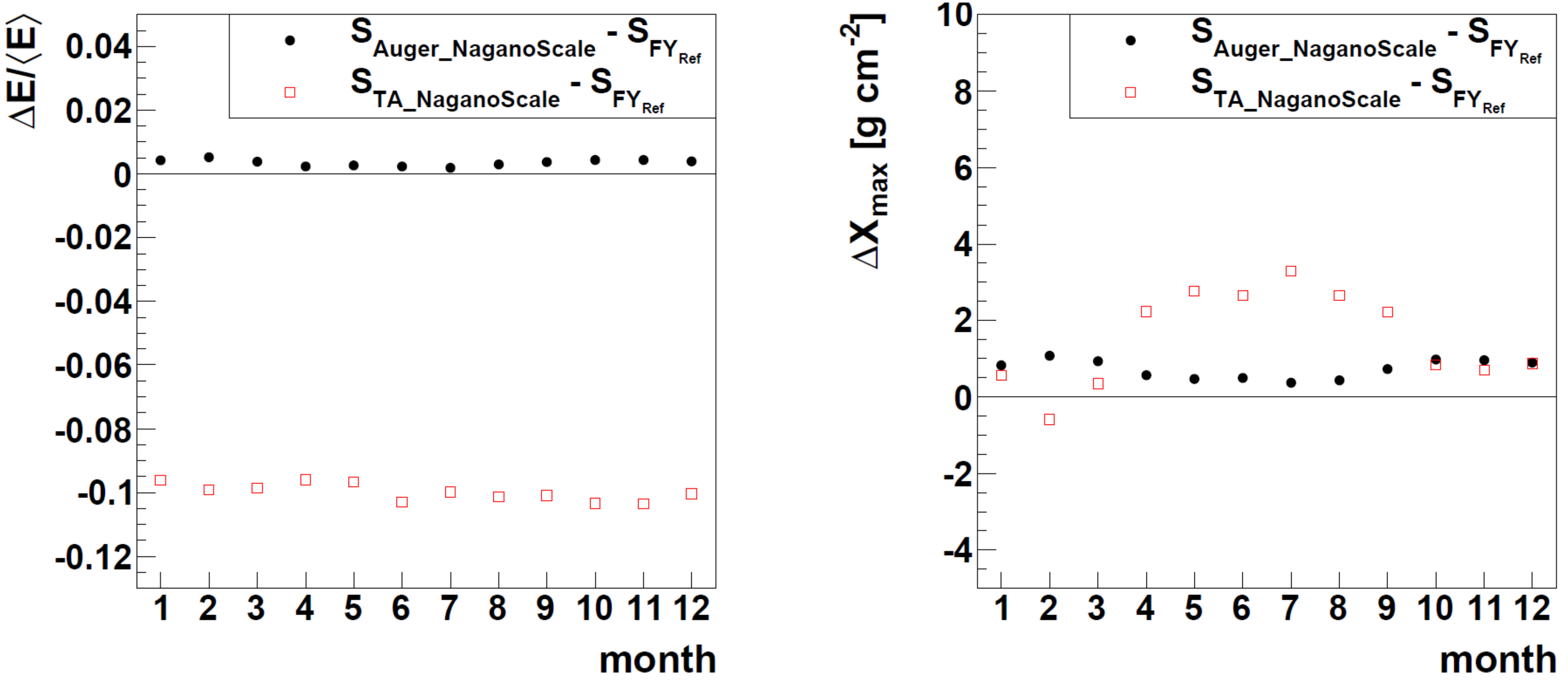




B. Keilhauer et al. , proc. UHECR 2012

Systematics in air shower reconstruction

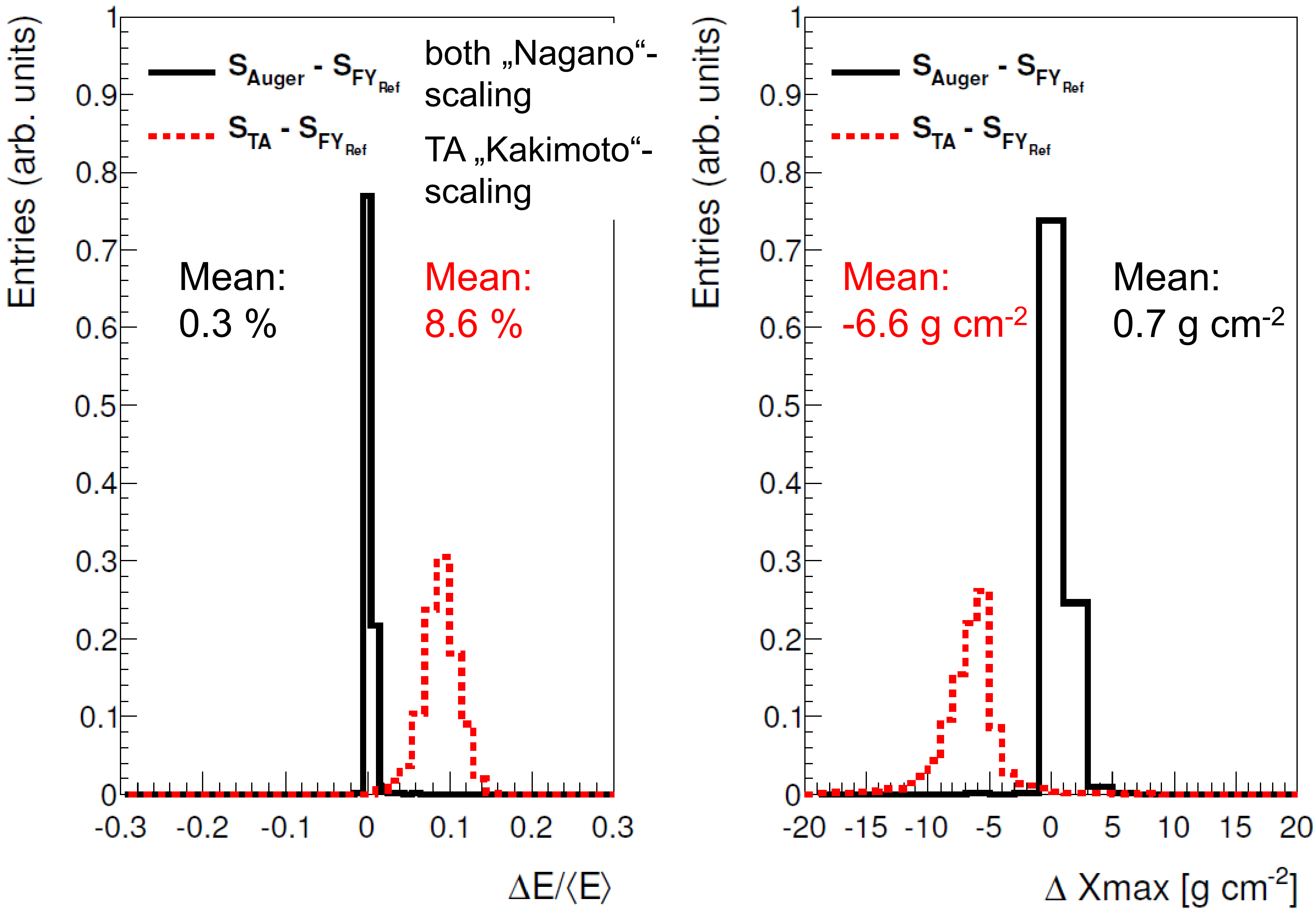
- same absolute scaling, Auger reconstruction framework -



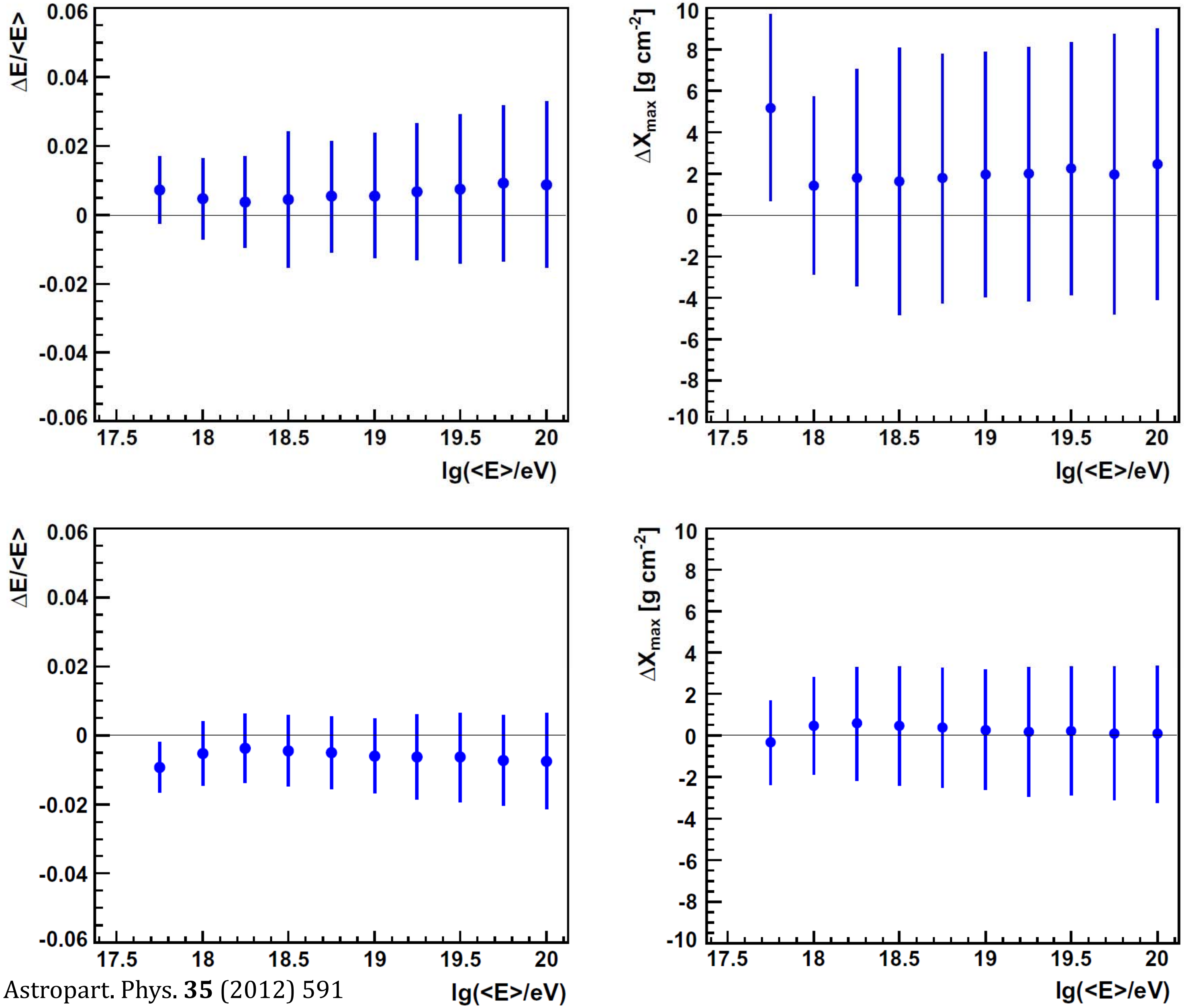
B. Keilhauer et al. , proc. UHECR 2012

Application to air shower reconstruction

- different absolute scaling -



Influence of atmospheric profiles



monthly models

GDAS

Conclusion

- a reference fluorescence description has been developed
- all known atmospheric effects are implemented
- application to air shower reconstructions are done for Auger and TA, but not used in the official experiments‘ reconstructions yet

➢ first details are published in the proc. of UHECR2012

➢ more in the proc. of ICRC 2013