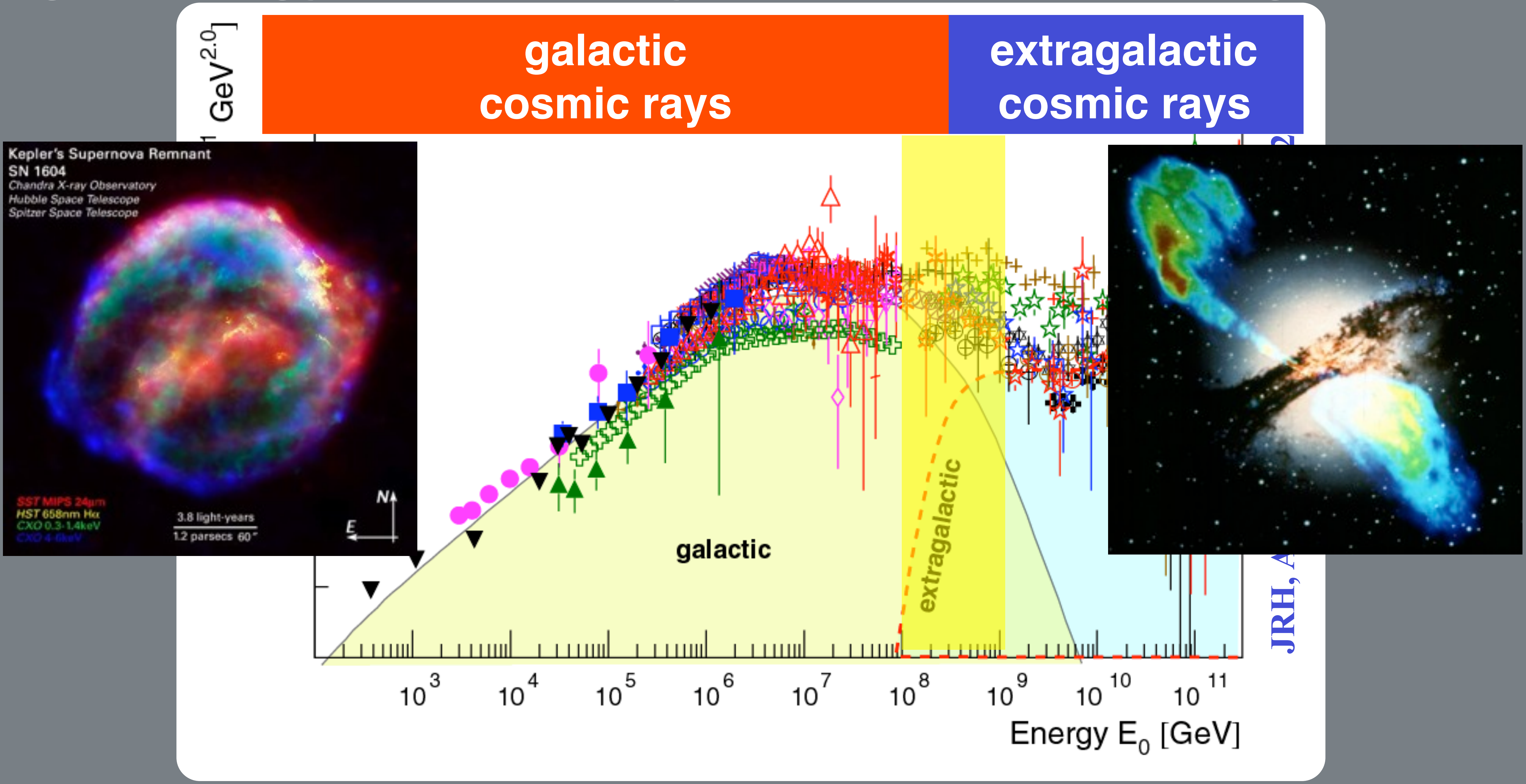
High-Energy Cosmic Rays: Galactic or Extragalactic?



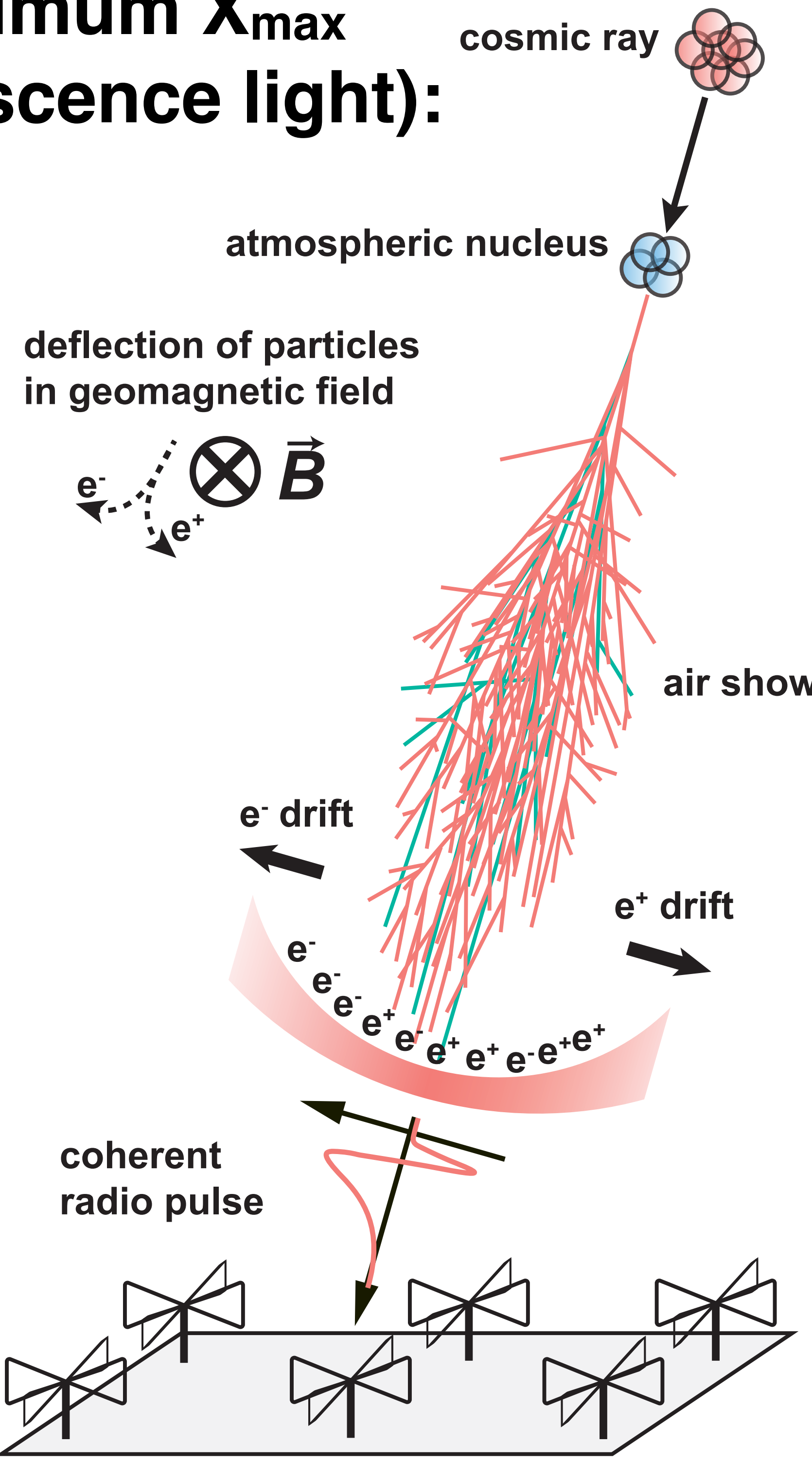
Jörg R. Hörandel **Radboud University Nijmegen, Nikhef** **http://particle.astro.ru.nl**

Transition galactic to extragalactic component of cosmic rays at E ~ 10^{17} - 10^{18} eV

need precise measurements of mass composition (particle type)

ideal: measurement of the depth of the shower maximum X_{max}

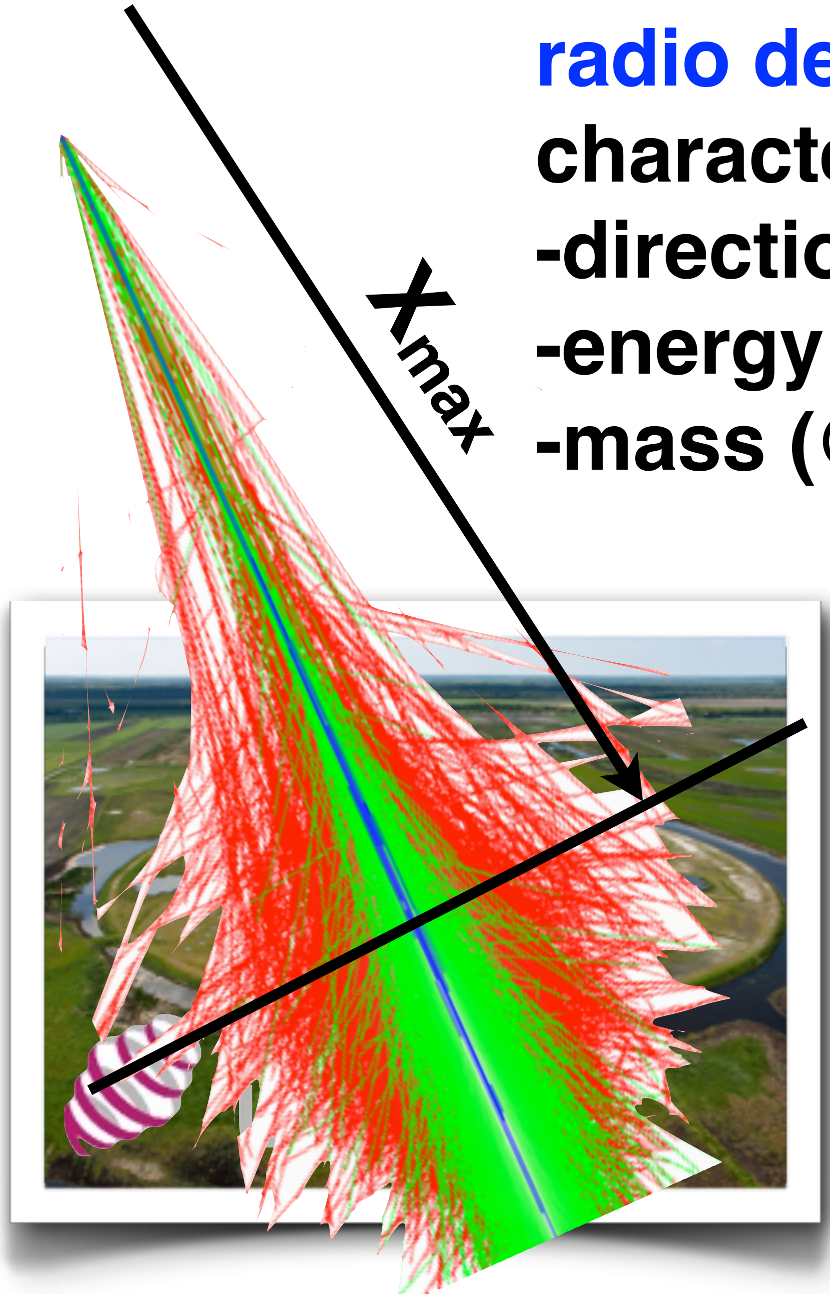
classical: optical detectors (Cherenkov light, fluorescence light): ~15% duty cycle



radio detection of air showers:

characterize cosmic rays:

- -direction ✓
- -energy ✓
- -mass (@100% duty cycle) ✓



PIERRE AUGER OBSERVATORY

Radio detection of air showers to measure..

precise shape of shower front

--> direction of cosmic ray ~0.5°

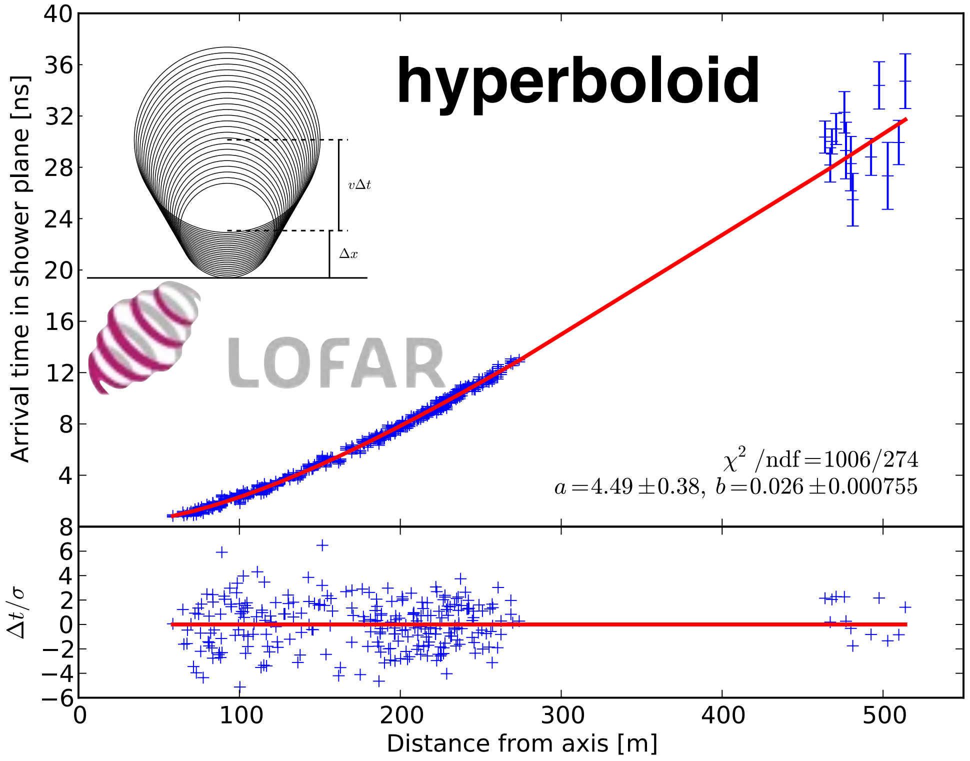
energy content of shower on ground

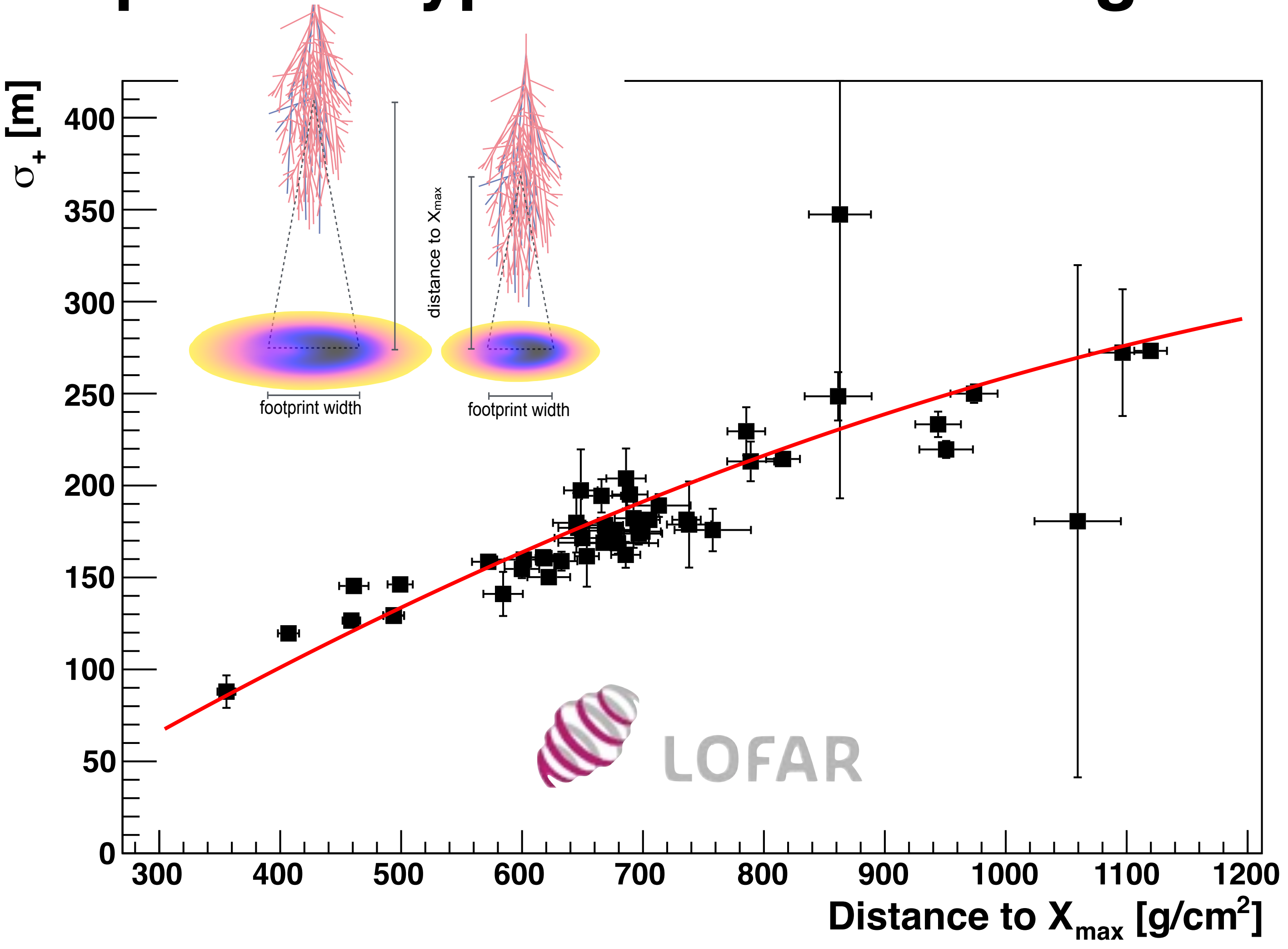
--> energy of cosmic ray AERA ~25%

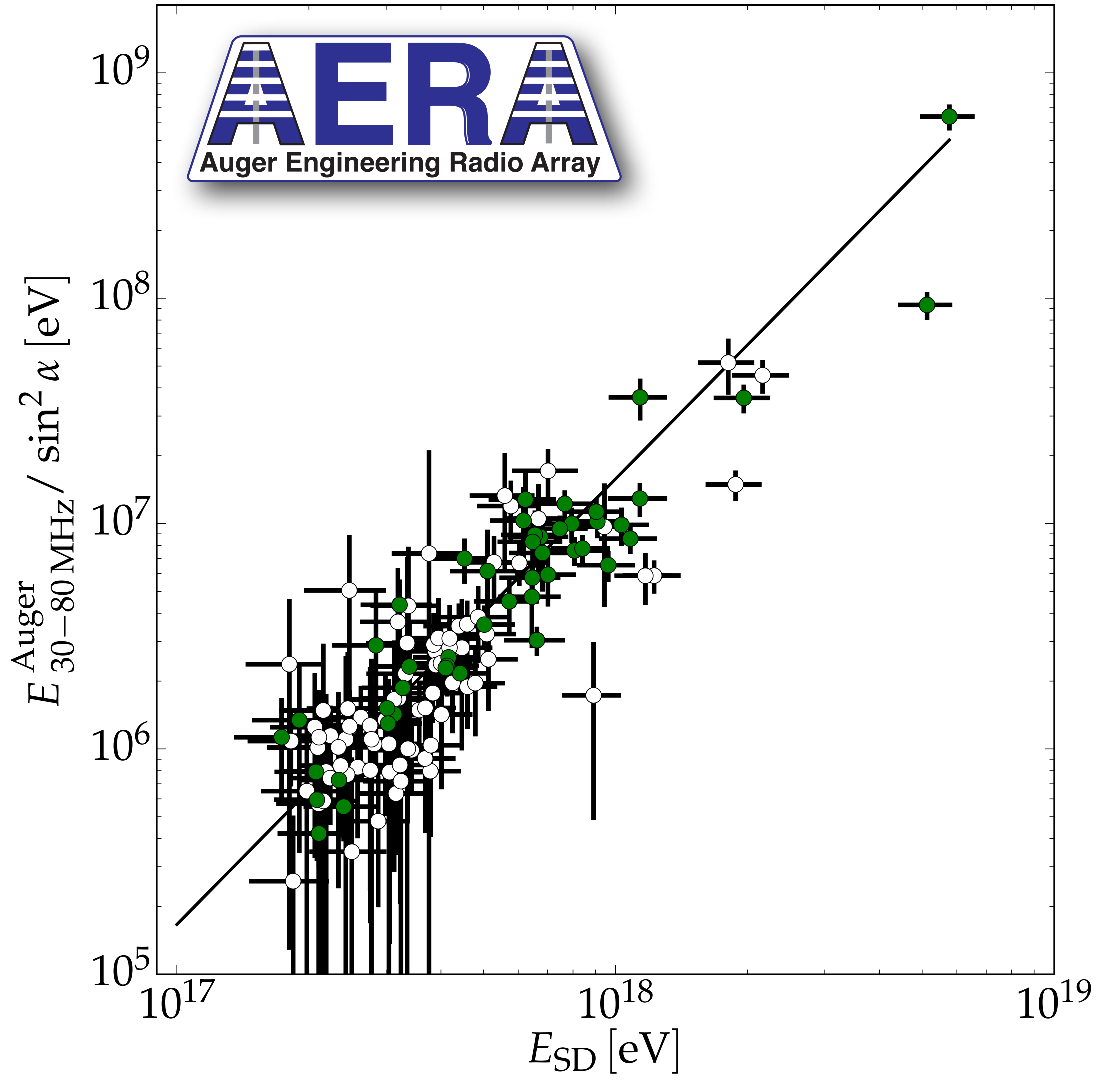
footprint of shower on ground

--> depth of shower maximum (Xmax)

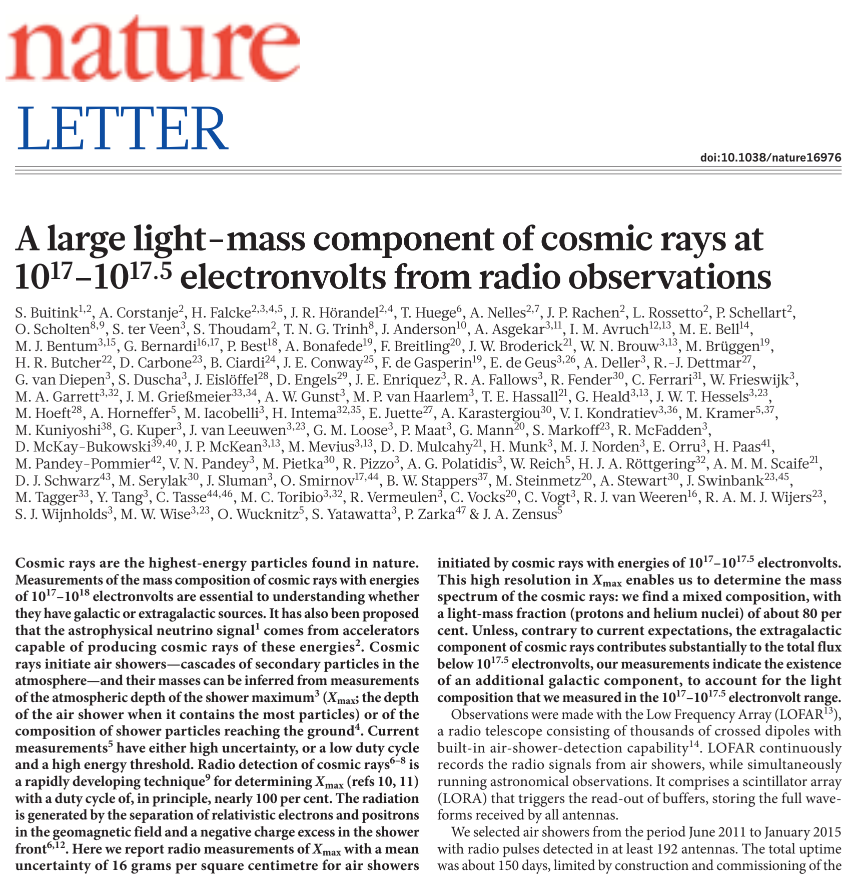
particle type LOFAR <20 g/cm²







Depth of the shower maximum



nature

LETTER

doi:10.1038/nature16976

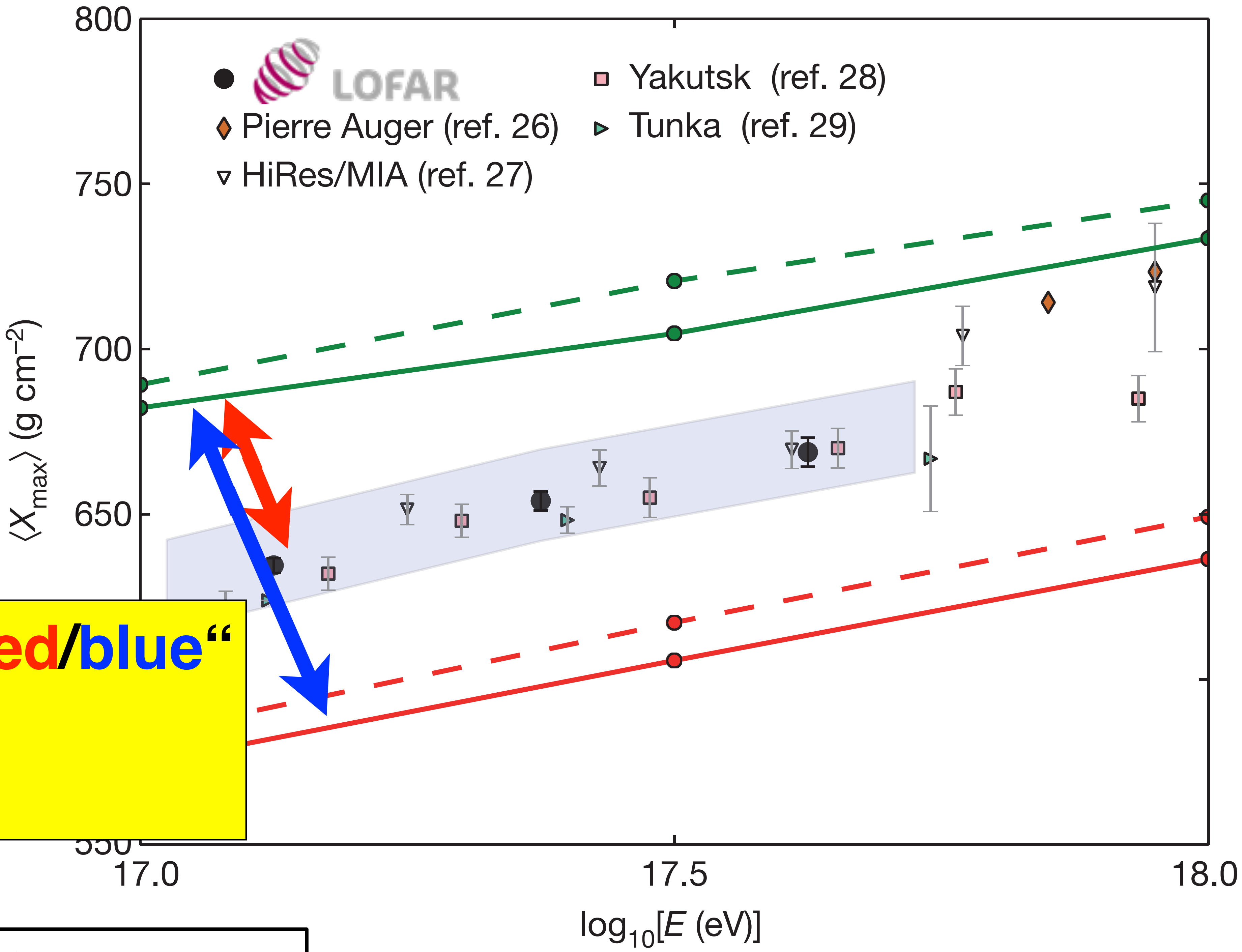
A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

S. Buitink[1,2], A. Corstanje[2], H. Falcke[2,3,4,5], J. R. Hörandel[2,4], T. Huege[6], A. Nelles[2,7], J. P. Rachen[2], L. Rossetto[2], P. Schellart[2], O. Scholten[8,9], S. ter Veen[3], S. Thoudam[2], T. N. G. Trinh[8], J. Anderson[10], A. Asgekar[3,11], I. M. Avruch[12,13], M. E. Bell[14], M. J. Bentum[3,15], G. Bernardi[16,17], P. Best[18], A. Bonafede[19], F. Breitling[20], J. W. Broderick[21], W. N. Brouw[3,13], M. Brüggen[19], H. R. Butcher[22], D. Carbone[23], B. Ciardi[24], J. E. Conway[25], F. de Gasperin[19], E. de Geus[3,26], A. Deller[3], R.-J. Dettmar[27], G. van Diepen[3], S. Duscha[3], J. Eislöffel[28], D. Engels[29], J. E. Enriquez[3], R. A. Fallows[3], R. Fender[30], C. Ferrari[31], W. Frieswijk[3], M. A. Garrett[3,32], J. M. Grießmeier[33,34], A. W. Gunst[3], M. P. van Haarlem[3], T. E. Hassall[21], G. Heald[3,13], J. W. T. Hessels[3,23], M. Hoeft[28], A. Horneffer[5], M. Iacobelli[3], H. Intema[32,35], E. Juette[27], A. Karastergiou[30], V. I. Kondratiev[3,36], M. Kramer[5,37], M. Kuniyoshi[38], G. Kuper[3], J. van Leeuwen[3,23], G. M. Loose[3], P. Maat[3], G. Mann[20], S. Markoff[23], R. McFadden[3], D. McKay-Bukowski[39,40], J. P. McKean[3,13], M. Mevius[3,13], D. D. Mulcahy[21], H. Munk[3], M. J. Norden[3], E. Orru[3], H. Paas[41], M. Pandey-Pommier[42], V. N. Pandey[3], M. Pietka[30], R. Pizzo[3], A. G. Polatidis[3], W. Reich[5], H. J. A. Röttgering[32], A. M. M. Scaife[21], D. J. Schwarz[43], M. Serylak[30], J. Sluman[3], O. Smirnov[17,44], B. W. Stappers[37], M. Steinmetz[20], A. Stewart[30], J. Swinbank[23,45], M. Tagger[33], Y. Tang[3], C. Tasse[44,46], M. C. Toribio[3,32], R. Vermeulen[3], C. Vocks[20], C. Vogt[3], R. J. van Weeren[16], R. A. M. J. Wijers[23], S. J. Wijnholds[3], M. W. Wise[3,23], O. Wucknitz[5], S. Yatawatta[3], P. Zarka[47] & J. A. Zensus[5]

Cosmic rays are the highest-energy particles found in nature. Measurements of the mass composition of cosmic rays with energies of 10^{17}–10^{18} electronvolts are essential to understanding whether they have galactic or extragalactic sources. It has also been proposed that the astrophysical neutrino signal[1] comes from accelerators capable of producing cosmic rays of these energies[2]. Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be inferred from measurements of the atmospheric depth of the shower maximum[3] ($X_{\max}$; the depth of the air shower when it contains the most particles) or of the composition of shower particles reaching the ground[4]. Current measurements[5] have either high uncertainty, or a low duty cycle and a high energy threshold. Radio detection of cosmic rays[6–8] is a rapidly developing technique[9] for determining $X_{\max}$ (refs 10, 11) with a duty cycle of, in principle, nearly 100 per cent. The radiation is generated by the separation of relativistic electrons and positrons in the geomagnetic field and a negative charge excess in the shower front[6,12]. Here we report radio measurements of $X_{\max}$ with a mean uncertainty of 16 grams per square centimetre for air showers initiated by cosmic rays with energies of 10^{17}–$10^{17.5}$ electronvolts. This high resolution in $X_{\max}$ enables us to determine the mass spectrum of the cosmic rays: we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless, contrary to current expectations, the extragalactic component of cosmic rays contributes substantially to the total flux below $10^{17.5}$ electronvolts, our measurements indicate the existence of an additional galactic component, to account for the light composition that we measured in the 10^{17}–$10^{17.5}$ electronvolt range.

Observations were made with the Low Frequency Array (LOFAR[13]), a radio telescope consisting of thousands of crossed dipoles with built-in air-shower-detection capability[14]. LOFAR continuously records the radio signals from air showers, while simultaneously running astronomical observations. It comprises a scintillator array (LORA) that triggers the read-out of buffers, storing the full waveforms received by all antennas.

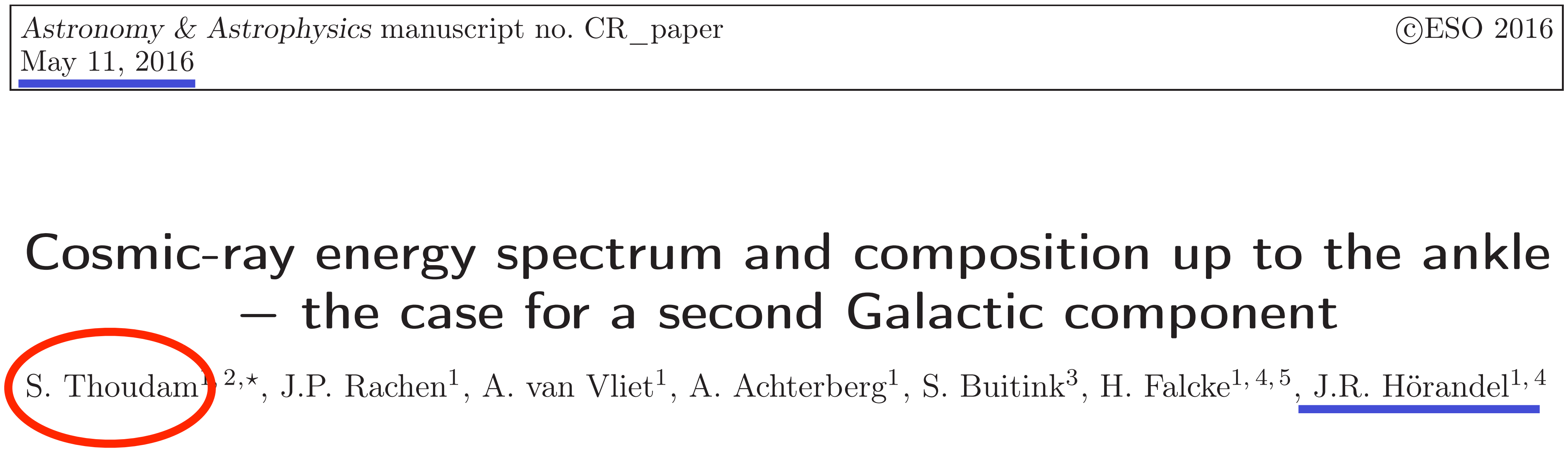
We selected air showers from the period June 2011 to January 2015 with radio pulses detected in at least 192 antennas. The total uptime was about 150 days, limited by construction and commissioning of the



relative distance “red/blue“ is measure for ln A (particle type)

$$\langle \ln \mathrm{A} \rangle = \left(\frac{X_{\max} - X^{\mathrm{p}}_{\max}}{X^{\mathrm{Fe}}_{\max} - X^{\mathrm{p}}_{\max}} \right) \times \ln A_{\mathrm{Fe}},$$

S. Buitink et al., Nature (2016)

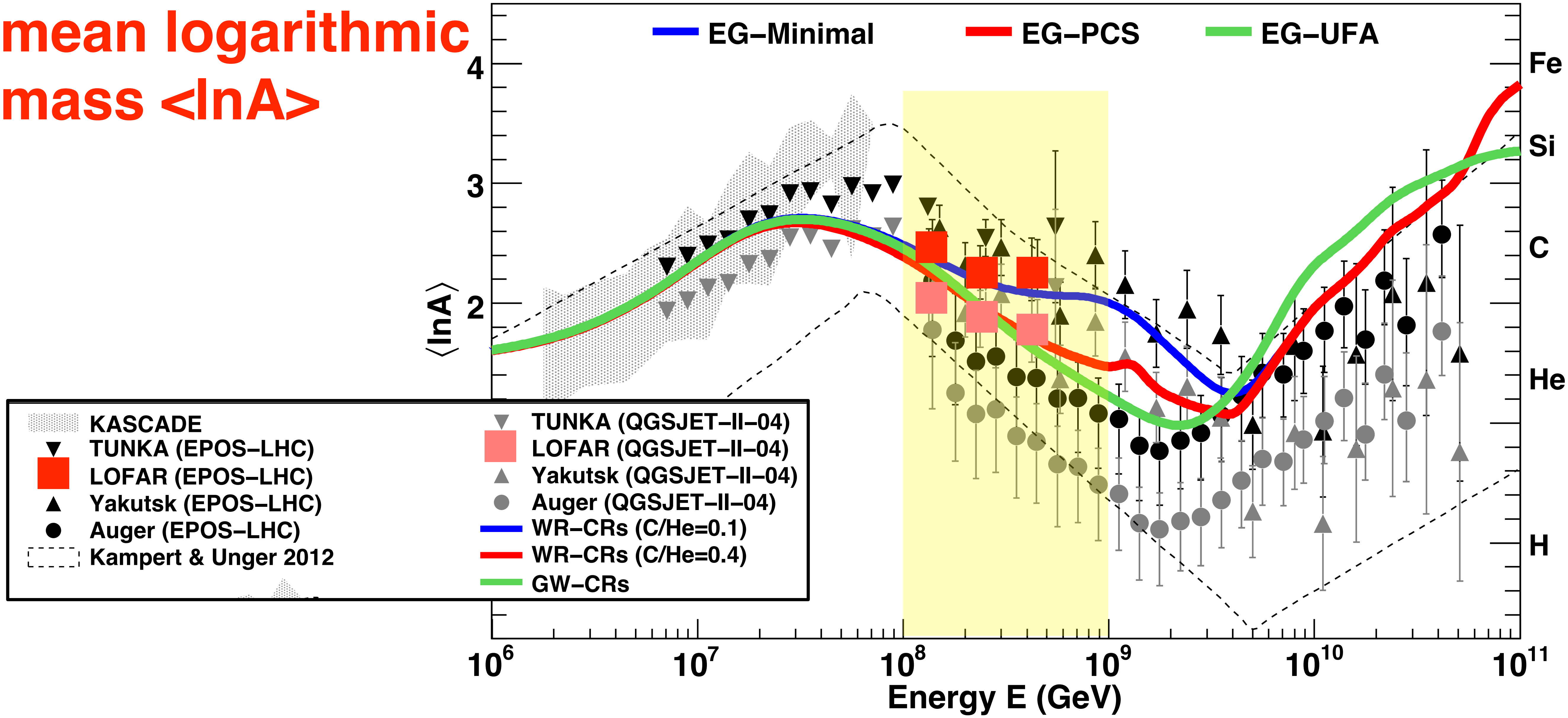


Astronomy & Astrophysics manuscript no. CR_paper ©ESO 2016
May 11, 2016

Cosmic-ray energy spectrum and composition up to the ankle – the case for a second Galactic component

S. Thoudam[1, 2,⋆], J.P. Rachen[1], A. van Vliet[1], A. Achterberg[1], S. Buitink[3], H. Falcke[1, 4, 5], J.R. Hörandel[1, 4]

mean logarithmic mass <lnA>



S. Thoudam et al., A&A submitted (2016), arXiv 1605.03111

S. Thoudam et al., ICRC Den Haag (2015)

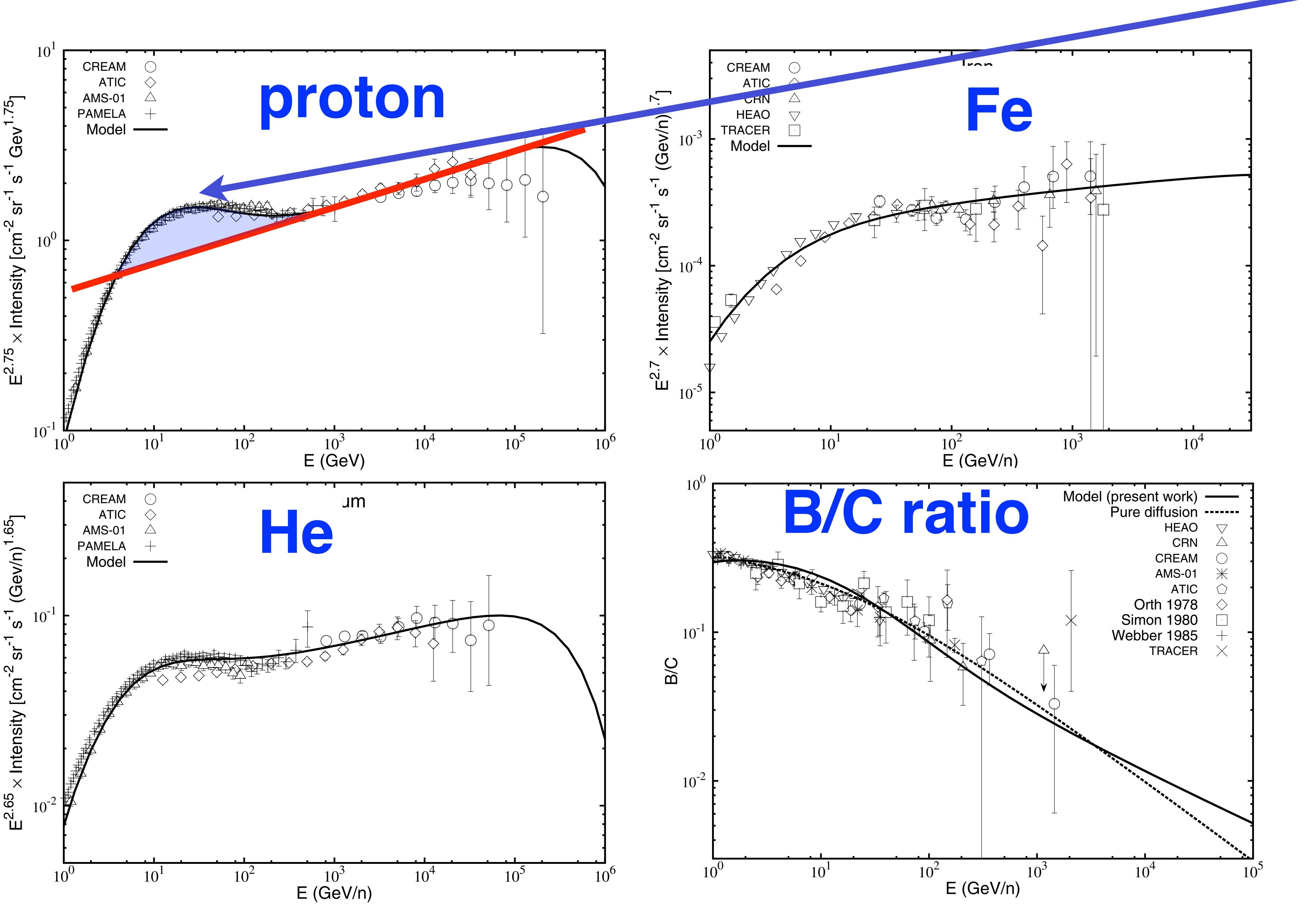
A&A 567, A33 (2014)
DOI: 10.1051/0004-6361/201322996

Astronomy & Astrophysics

GeV-TeV cosmic-ray spectral anomaly as due to reacceleration by weak shocks in the Galaxy★

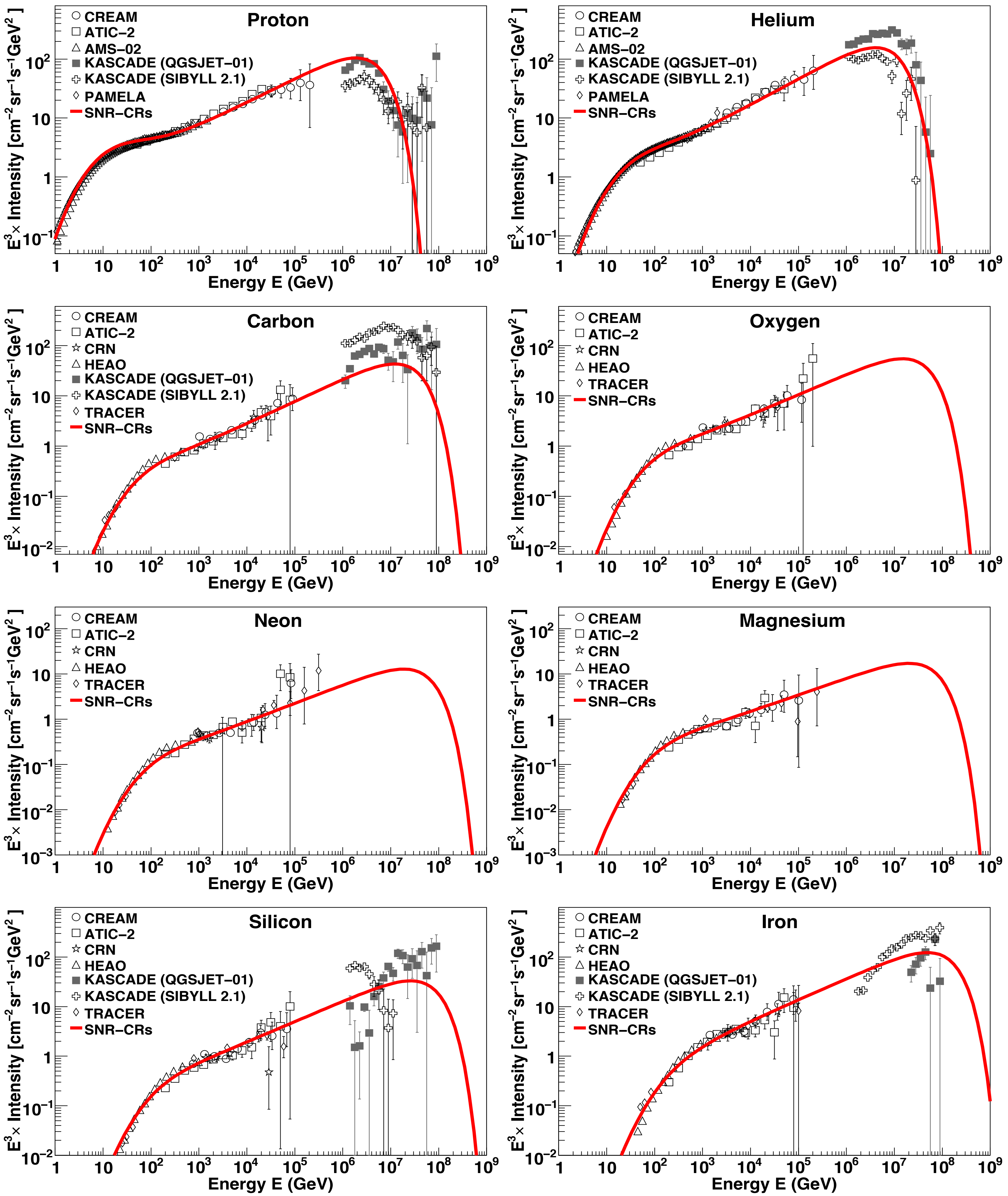
Satyendra Thoudam and Jörg R. Hörandel

bump due to reaccelertion by weak shocks in the Galaxy



✓

Contribution of (regular) SNR-CR

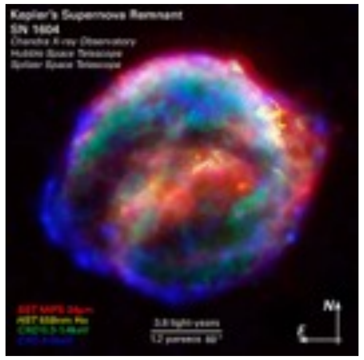


$$E_c = Z \cdot 4.5\ 10^6\ \mathrm{GeV}$$

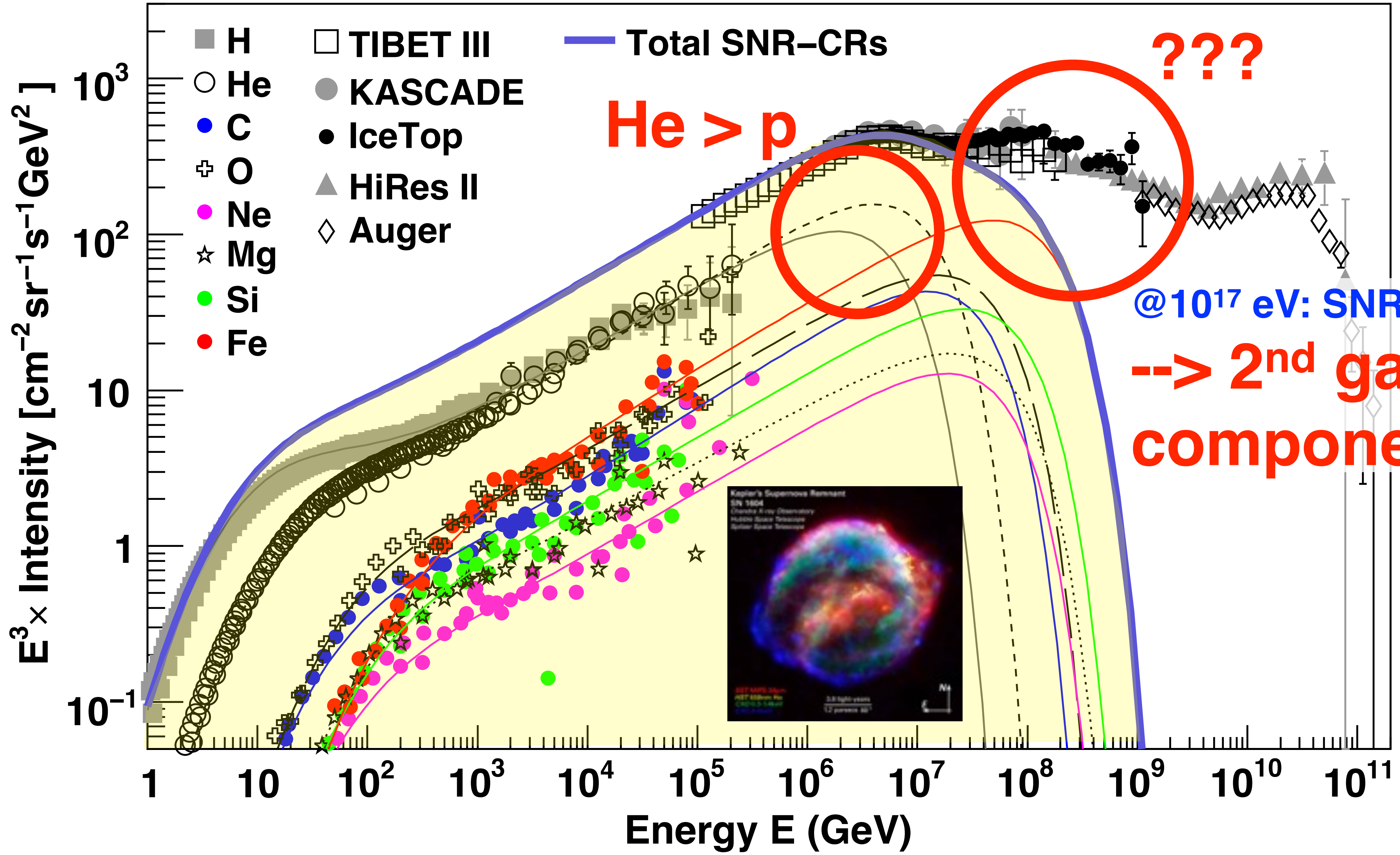
$$Q(p) = AQ_0(Ap)^{-q}\exp\left(-\frac{Ap}{Zp_c}\right),$$

Table 1. Source spectral indices, q, and energy injected per supernova, f, for the different species of cosmic rays used in the calculation of the SNR-CRs spectra shown in Figures 1 and 2.

Particle type	q	f $(\times 10^{49}$ ergs)
Proton	2.24	6.95
Helium	2.21	0.79
Carbon	2.21	2.42×10^{-2}
Oxygen	2.25	2.52×10^{-2}
Neon	2.25	3.78×10^{-3}
Magnesium	2.29	5.17×10^{-3}
Silicon	2.25	5.01×10^{-3}
Iron	2.25	4.95×10^{-3}



Contribution of (regular) SNR-CR to all-particle spectrum



He > p

???

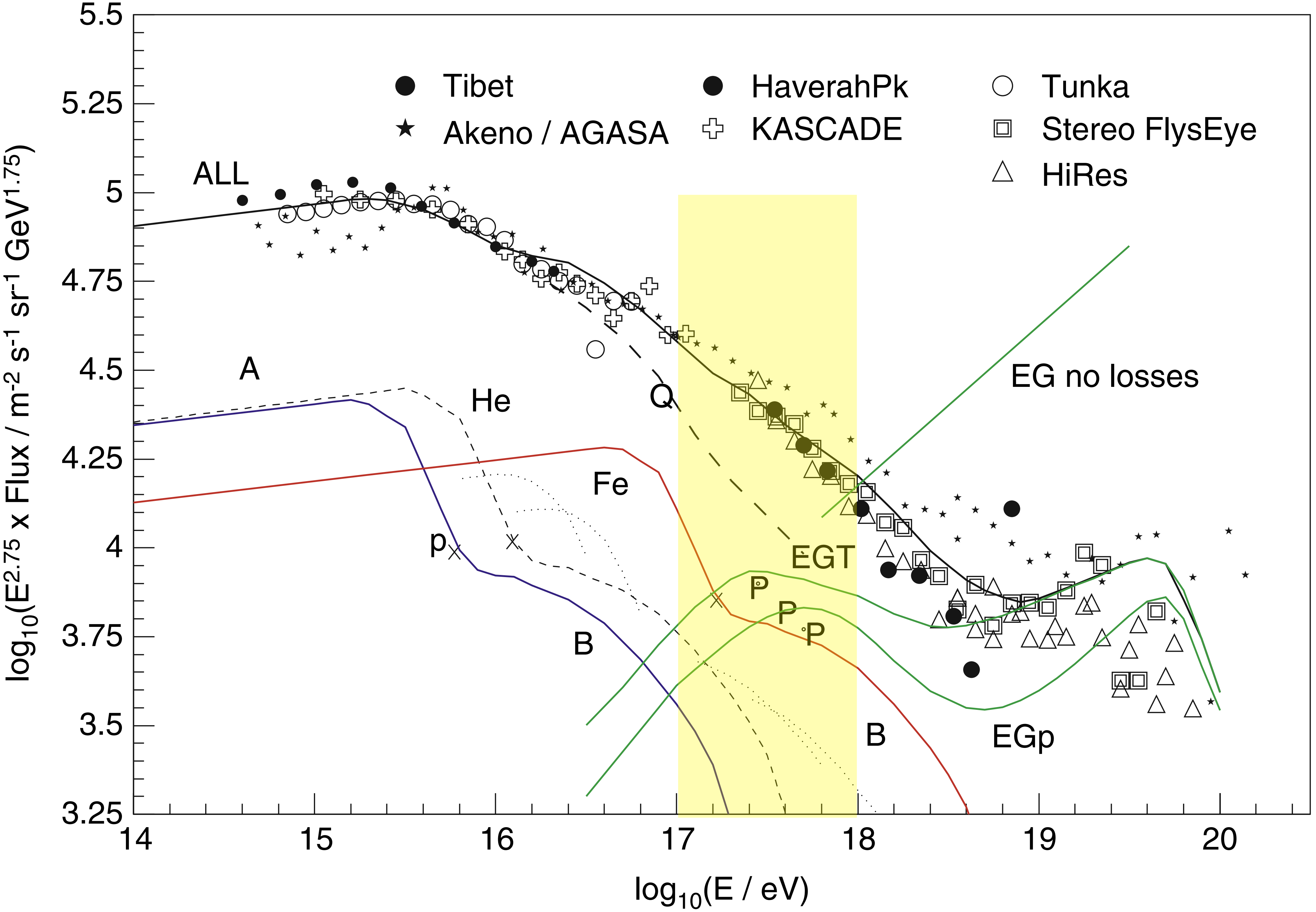
@10^{17} eV: SNR-CR ~30%

--> 2nd galactic component

Fig. 2. Contribution of SNR-CRs to the all-particle cosmic-ray spectrum. The thin lines represent spectra for the individual elements, and the thick-solid line represents the total contribution. The calculation assumes an exponential cut-off energy for protons at $E_c = 4.5 \times 10^6$ GeV. Other model parameters, and the low-energy data are the same as in Figure 1. Error bars are shown only for the proton and helium data. High-energy data: KASCADE (Antoni et al. 2005), IceTop (Aartsen et al. 2013), Tibet III (Amenomori et al. 2008), the Pierre Auger Observatory (Schulz et al. 2013), and HiRes II (Abbasi et al. 2009).

~8% of mechanical power of SN --> CRs

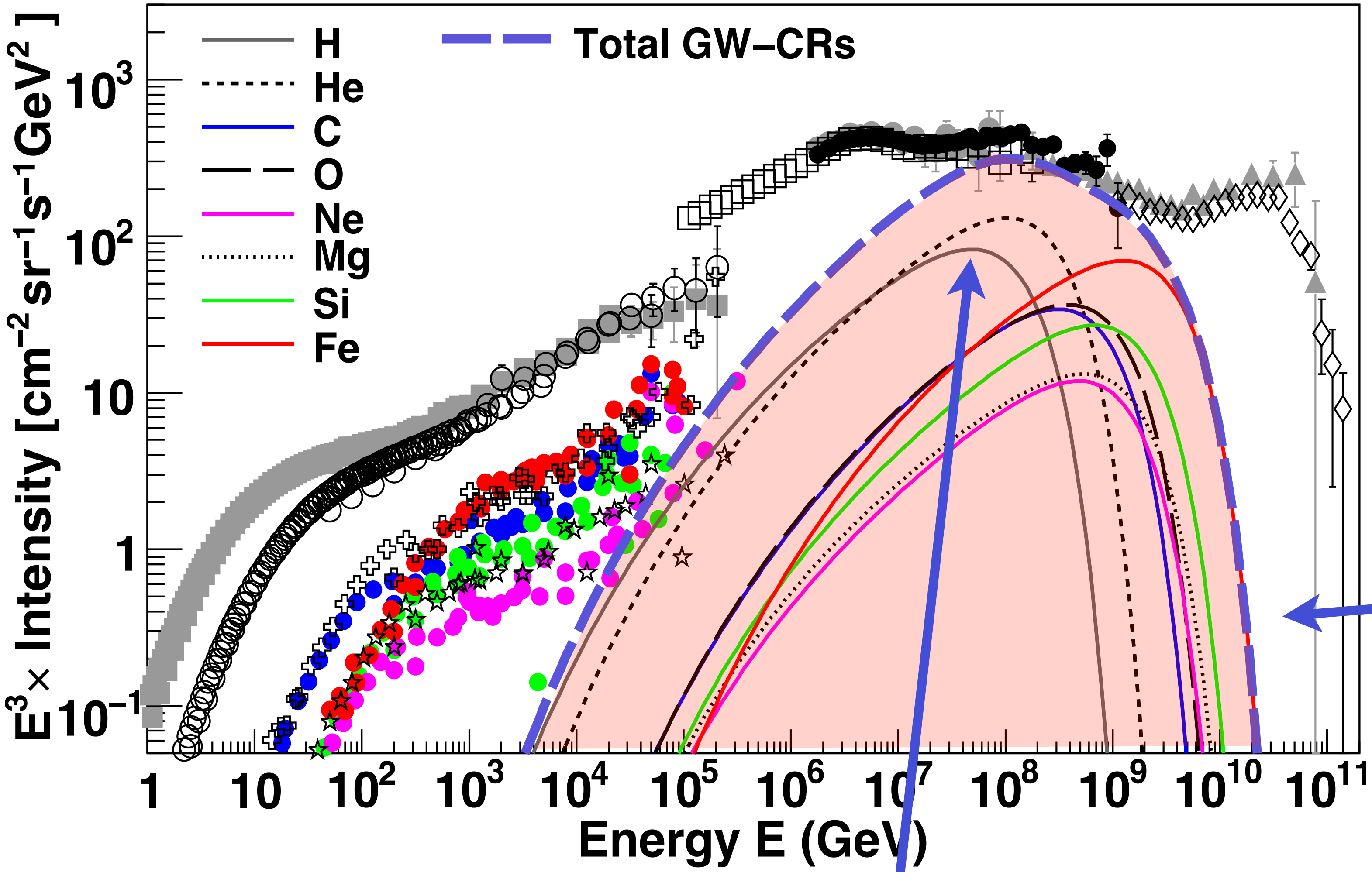
Transition to extragalactic CR component



„classical“ supernovae + additional component

M. Hillas, J. Phys. G 31 (2005) R95

Re-acceleration of SNR-CRs by Galactic wind termination shocks (GW-CRs)



fall-off due to exp fall-off in source spectra

Fig. 3. Contribution of GW-CRs to the all-particle cosmic-ray spectrum. The thin lines represent spectra for the individual elements, and the thick dashed line represents the total contribution. The injection fraction, $k_{\mathrm{w}} = 14.5\%$, and the exponential cut-off energy for protons, $E_{\mathrm{sh}} = 9.5 \times 10^7$ GeV. See text for the other model parameters. Data are the same as in Figure 2.

$$k_{sh} = 14.5\% \quad E_{sh} = 9.5 \cdot 10^7 \text{ GeV}$$

$$V = \dot{V} r \quad \dot{V} = 15 \text{ km/s/kpc}$$

Cosmic rays from Wolf-Rayet star explosions (WR-CRs)

1/210 yr = 1/7 SN

Table 2. Relative abundances of different cosmic-ray species with respect to helium for two different Wolf-Rayet wind compositions used in our model (Pollock et al. 2005).

Particle type	C/He = 0.1	C/He = 0.4
Proton	0	0
Helium	1.0	1.0
Carbon	0.1	0.4
Oxygen	3.19×10^{-2}	7.18×10^{-2}
Neon	0.42×10^{-2}	1.03×10^{-2}
Magnesium	2.63×10^{-4}	6.54×10^{-4}
Silicon	2.34×10^{-4}	5.85×10^{-4}
Iron	0.68×10^{-4}	1.69×10^{-4}

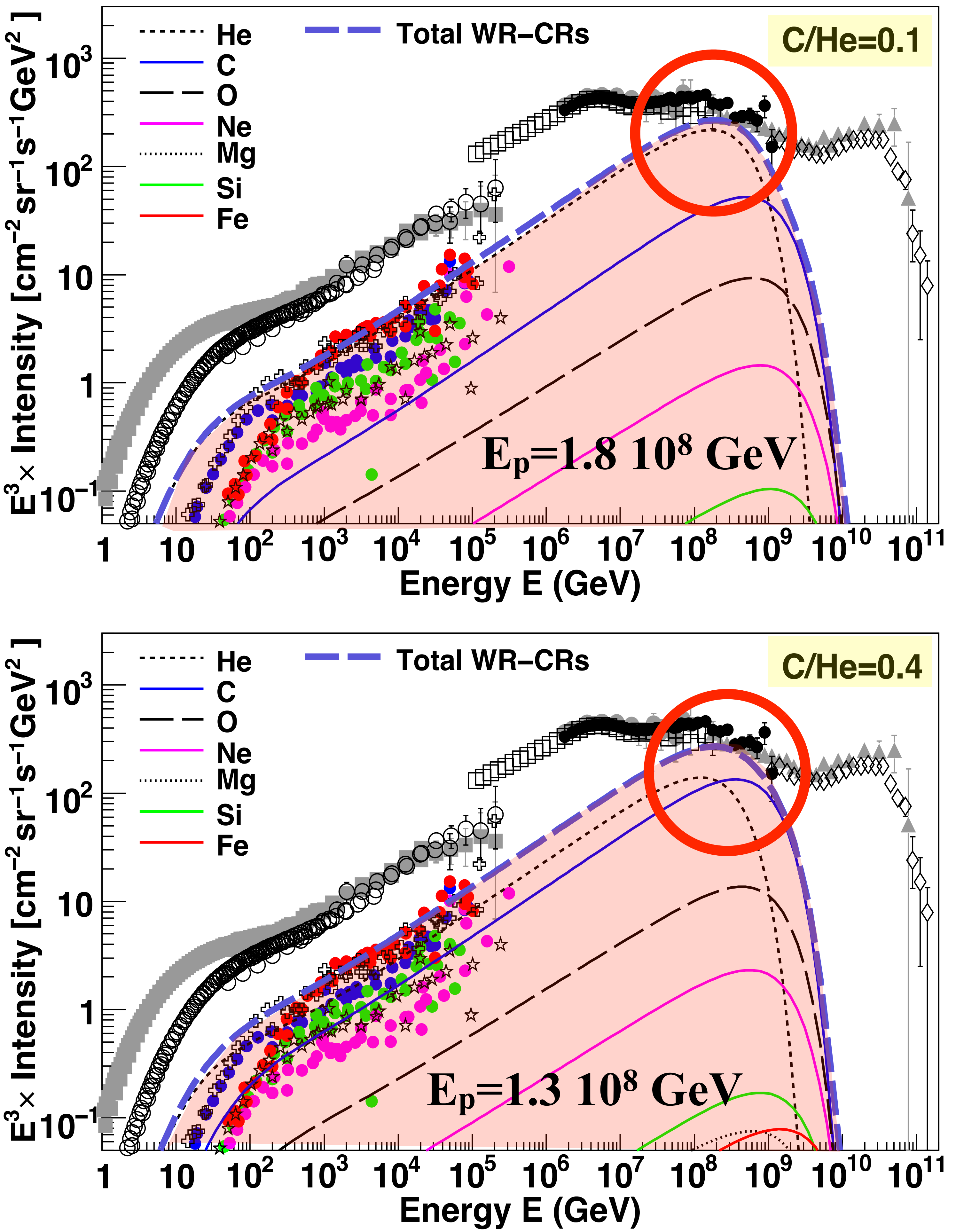
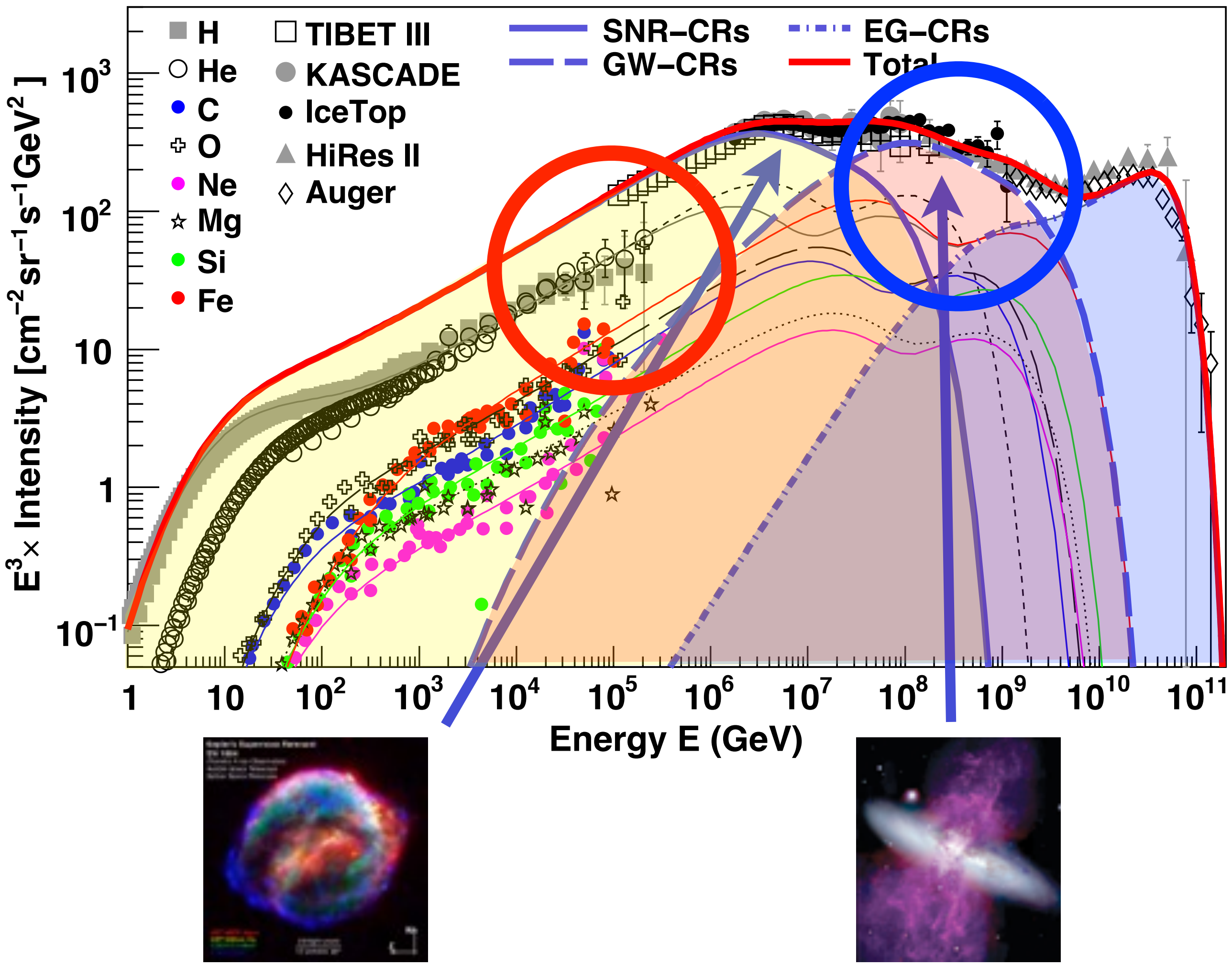


Fig. 4. Contribution of WR-CRs to the all-particle spectrum. *Top*: C/He = 0.1. *Bottom*: C/He = 0.4. The thin lines represent spectra for the individual elements, and the thick dashed line represents the total contribution. The calculation assumes an exponential energy cut-off for protons at $E_c = 1.8 \times 10^8$ GeV for C/He = 0.1, and $E_c = 1.3 \times 10^8$ GeV for C/He = 0.4. See text for the other model parameters. Data: same as in Figure 2.

all-particle spectra including 2nd galactic component



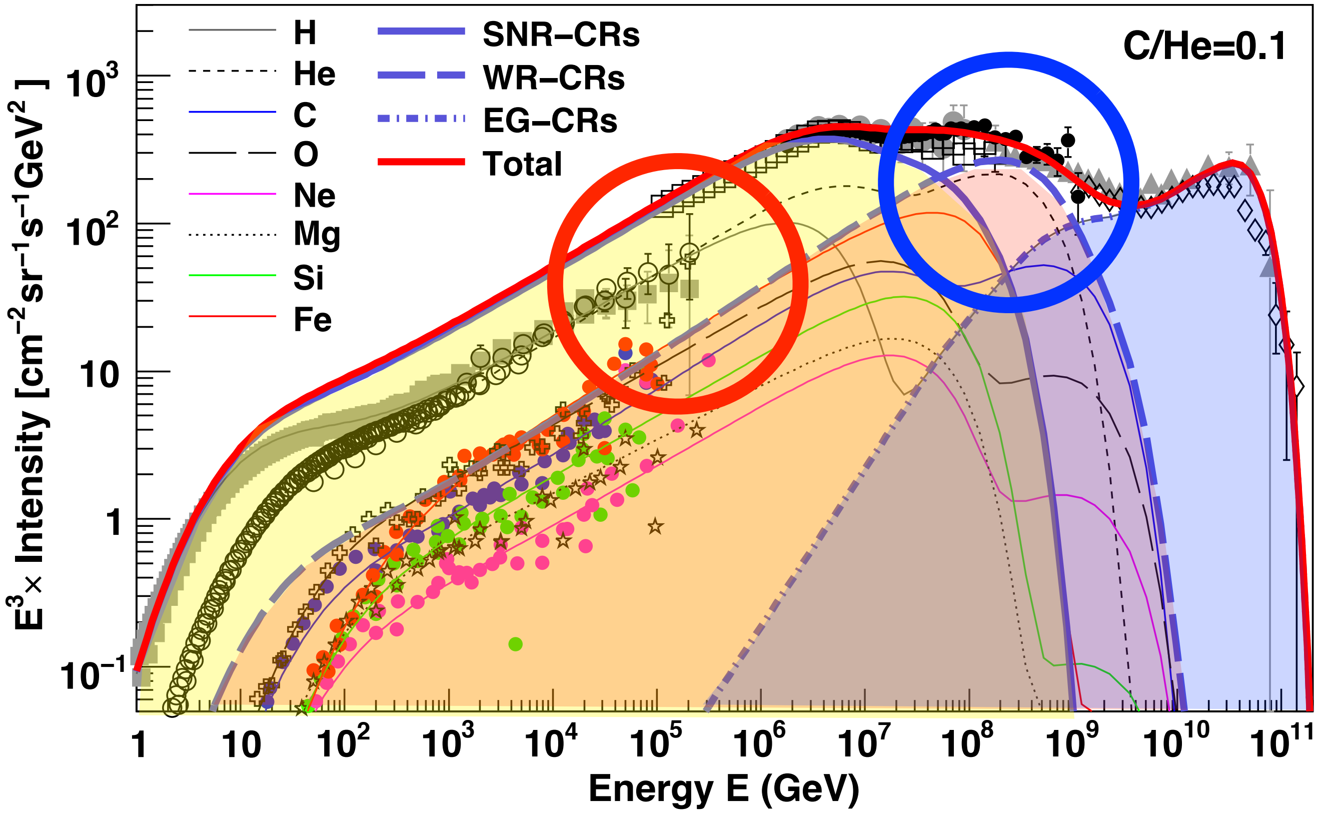
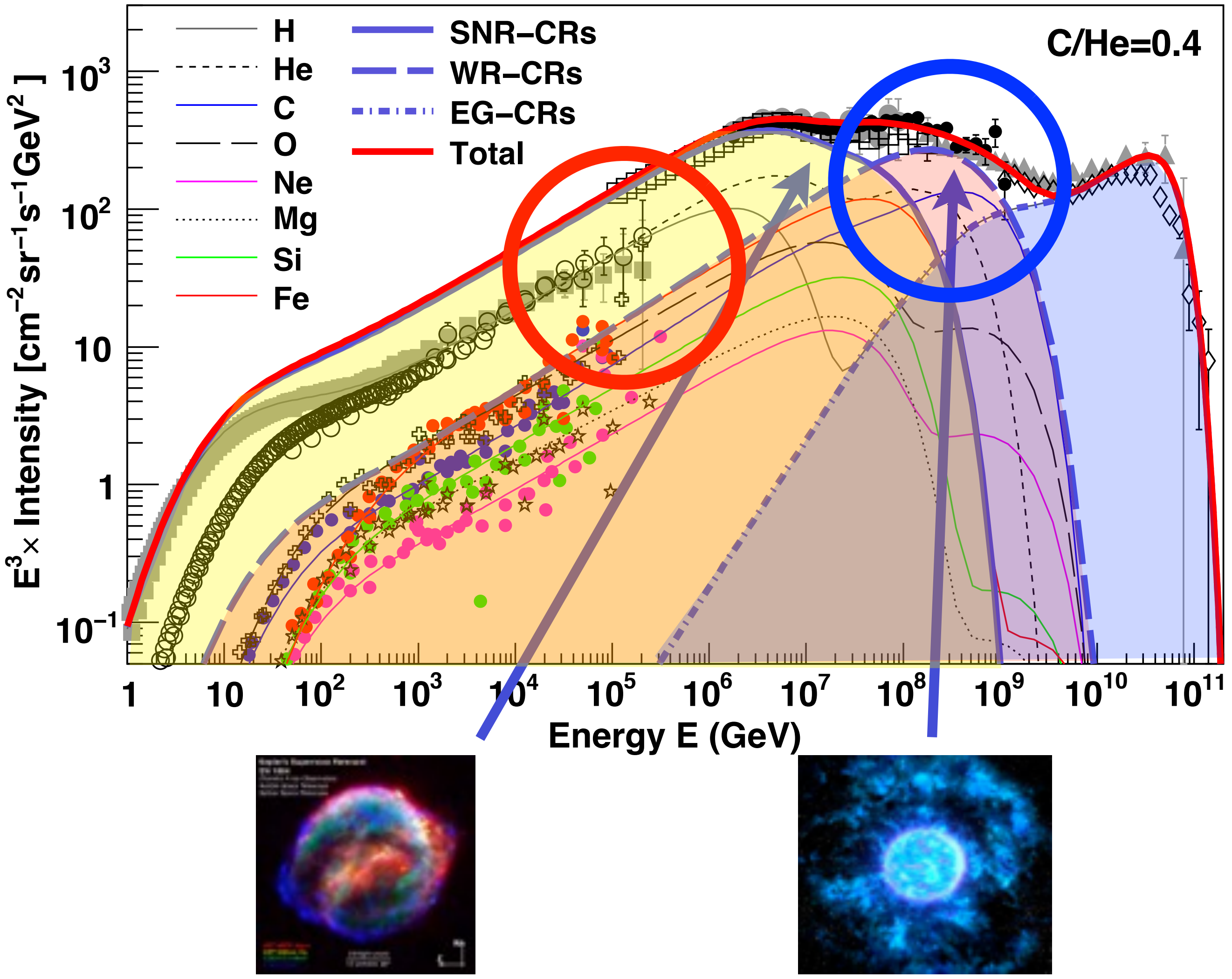


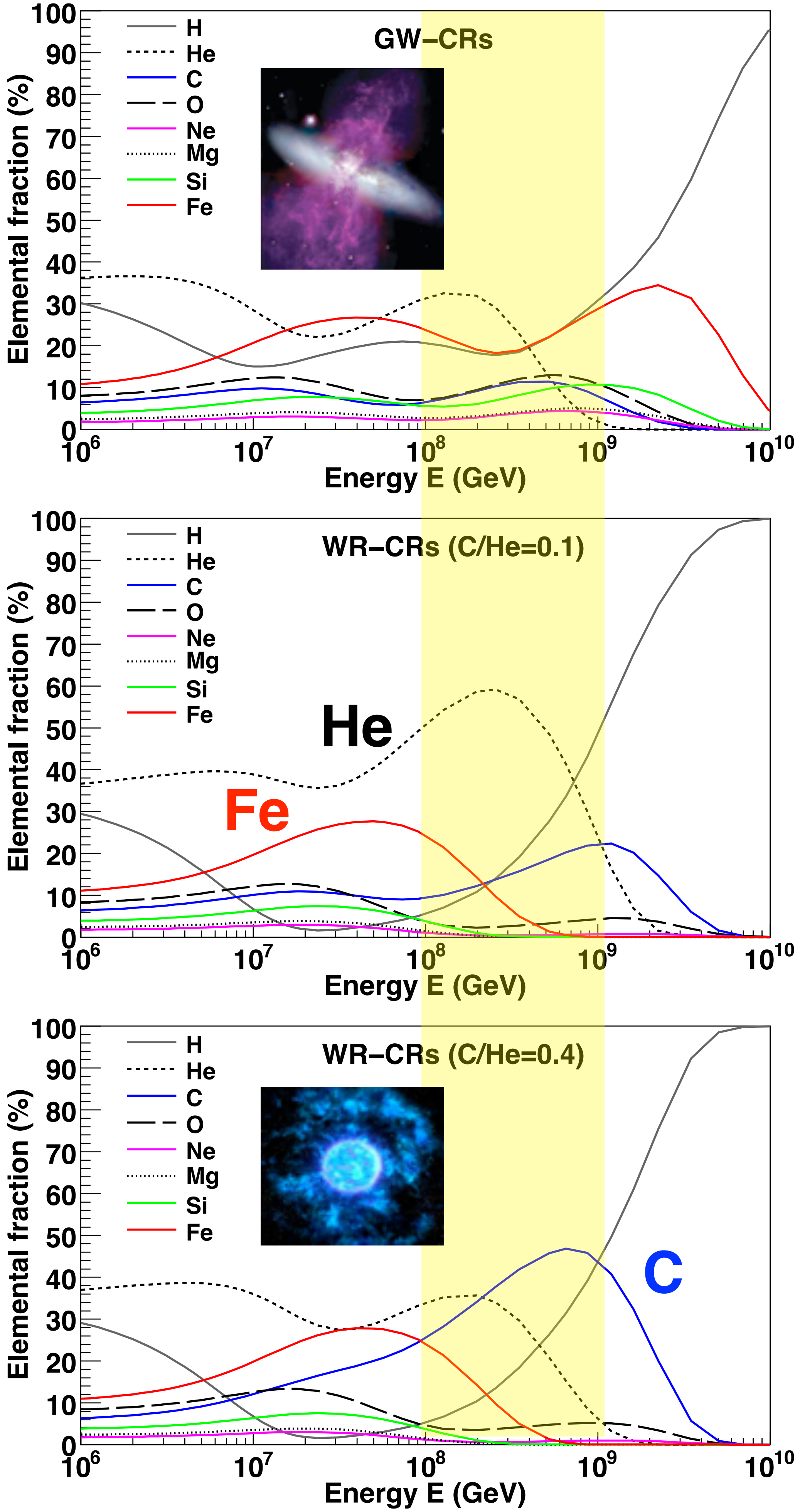
Table 3. Injection energy of SNR-CRs used in the calculation of all-particle spectrum in the WR-CR model (Figure 6).

Particle type	C/He = 0.1 $f(\times 10^{49}$ ergs)	C/He = 0.4 $f(\times 10^{49}$ ergs)
Proton	8.11	8.11
Helium	0.67	0.78
Carbon	2.11×10^{-2}	0.73×10^{-2}
Oxygen	2.94×10^{-2}	2.94×10^{-2}
Neon	4.41×10^{-3}	4.41×10^{-3}
Magnesium	6.03×10^{-3}	6.03×10^{-3}
Silicon	5.84×10^{-3}	5.84×10^{-3}
Iron	5.77×10^{-3}	5.77×10^{-3}

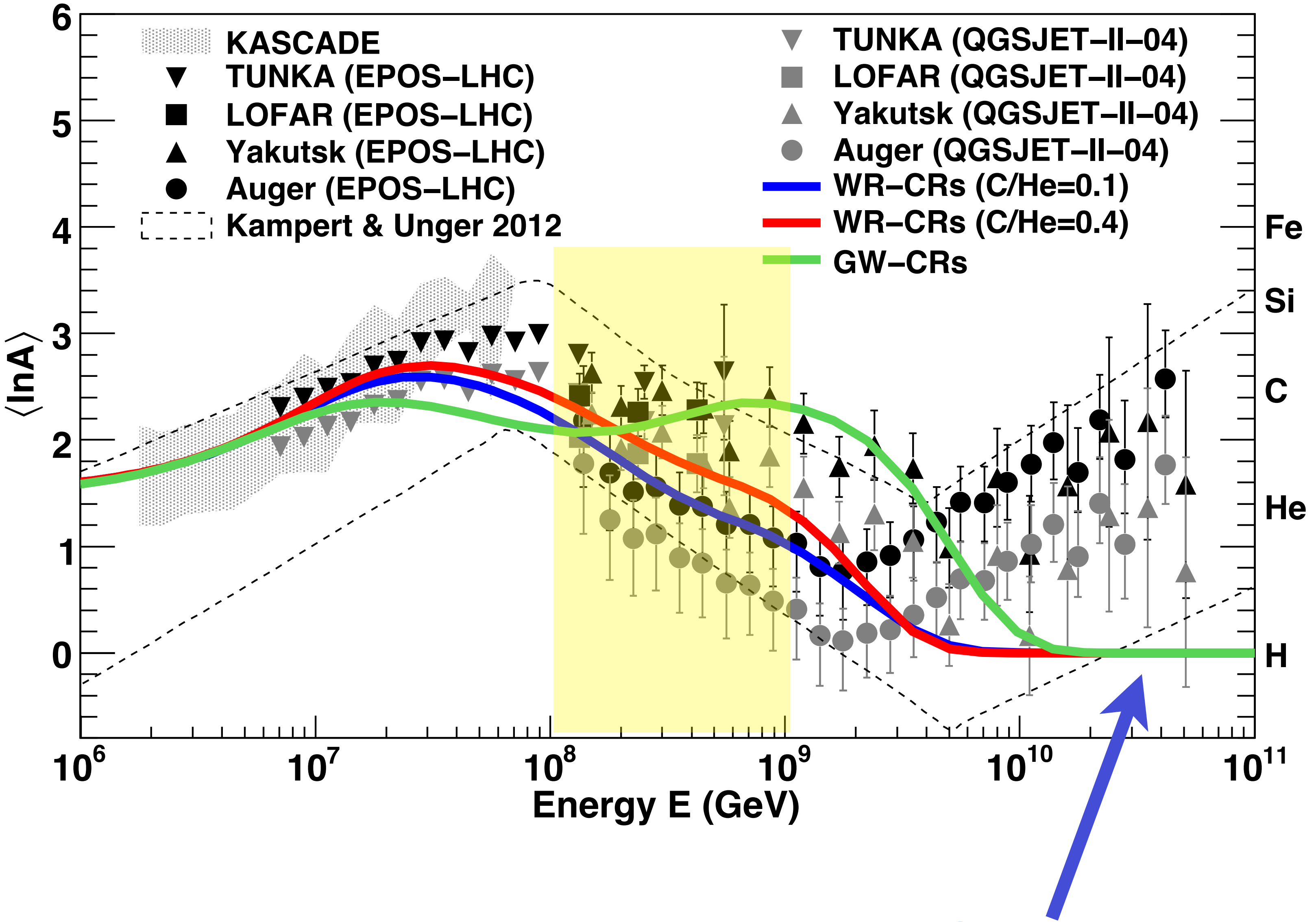


galactic CR component

elemental fraction



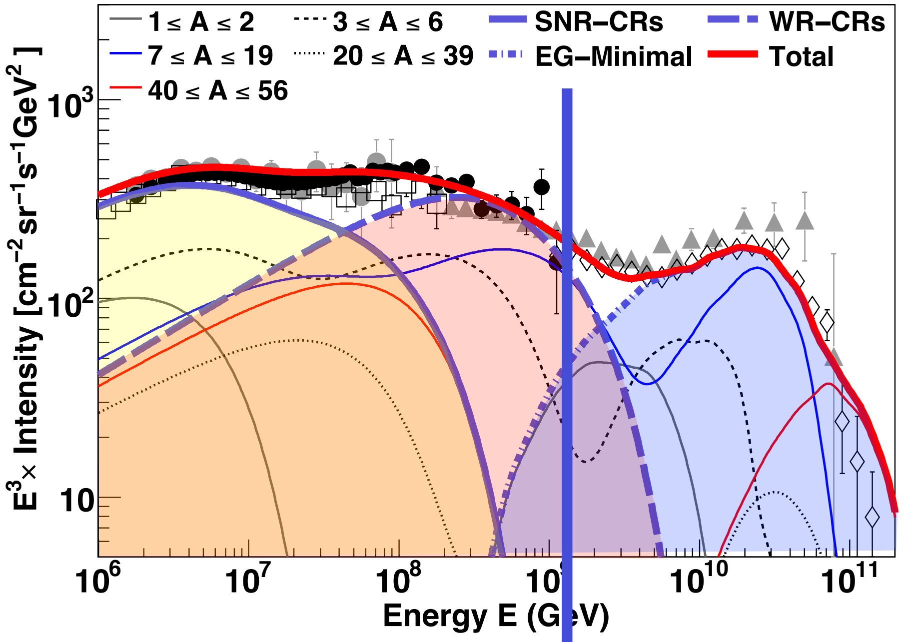
mean logarithmic mass <lnA>



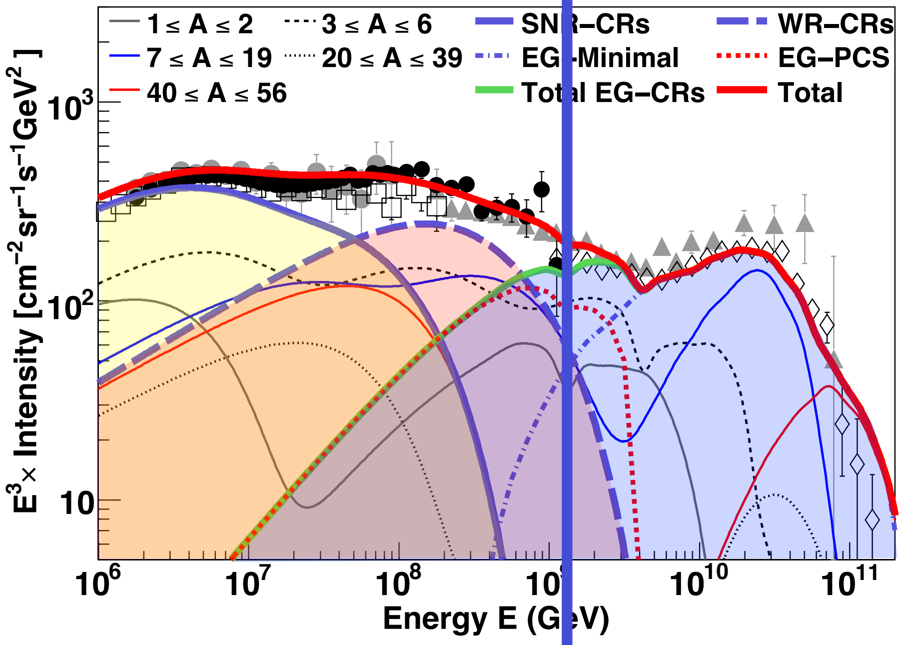
EG: p only!
~E^{-2}

Fig. 7. Elemental fraction predicted by the different models

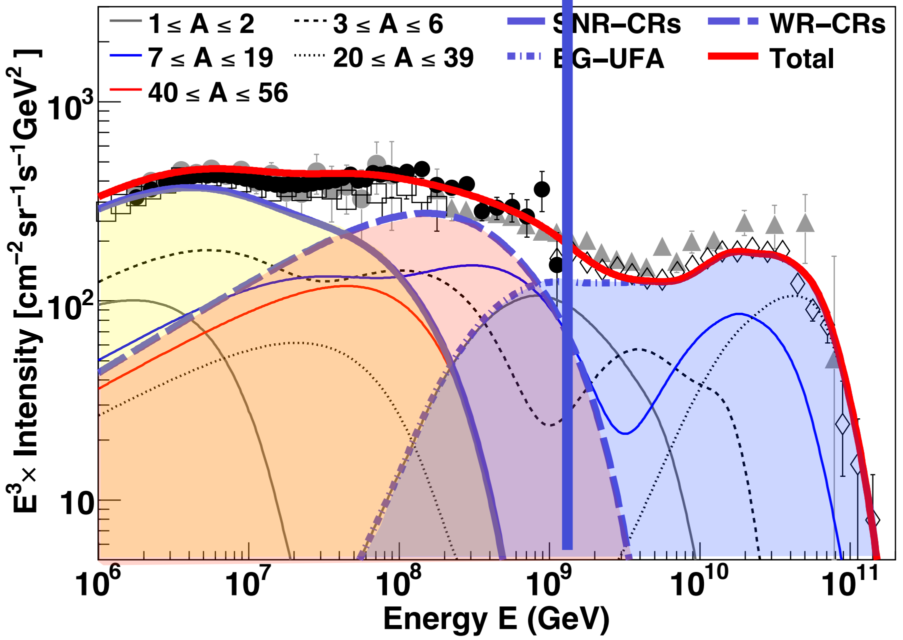
extragalactic cosmic rays



minimal model
CRPropa 3.0, uniform source distribution
sources inject p, He, N, Fe
R_c=3.8 10^9 GV

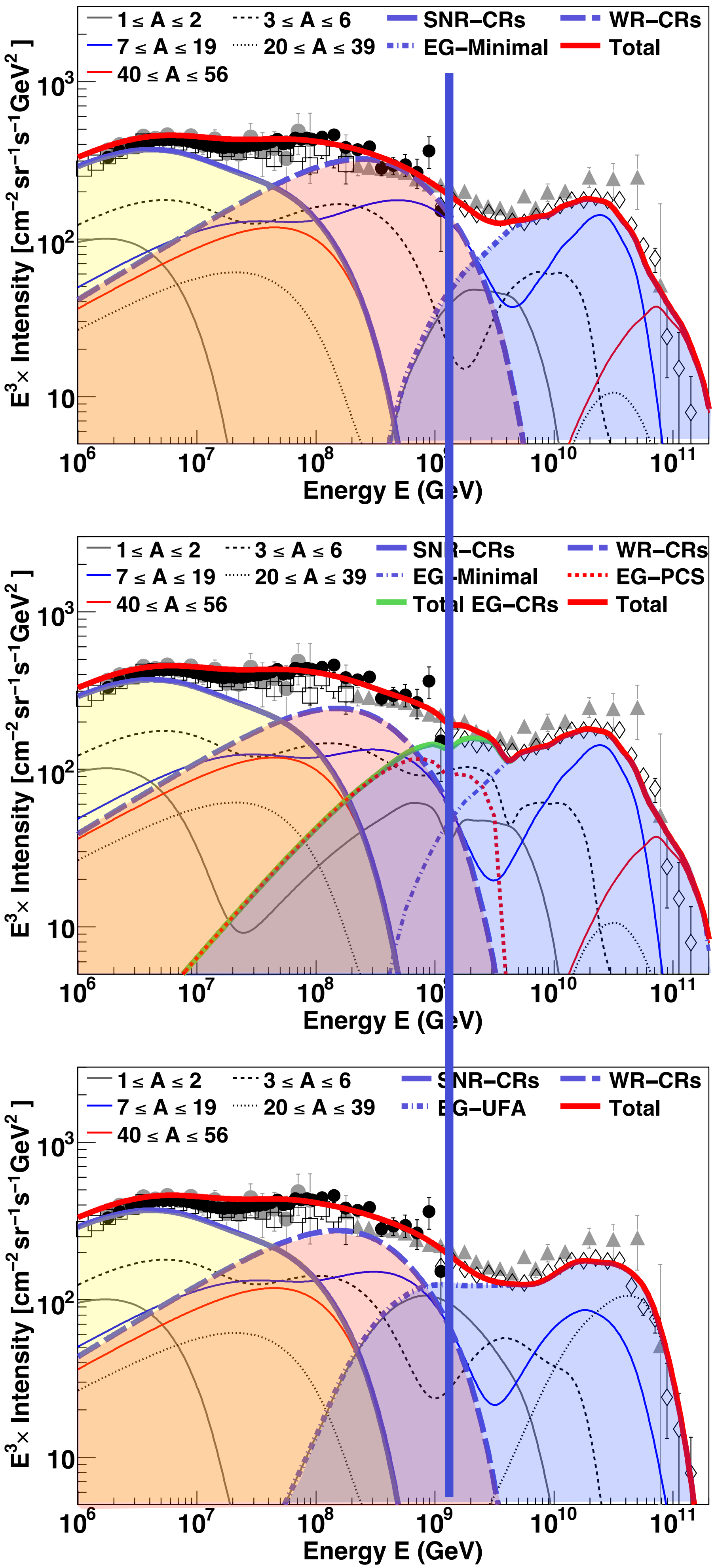


PCS model
acceleration of primordial p+He in galaxy clusters
+ minimal model from above



M. Unger, G.R. Farrar, L.A. Anchordoqui,
PRD 92 (2015) 123001

EG CRs



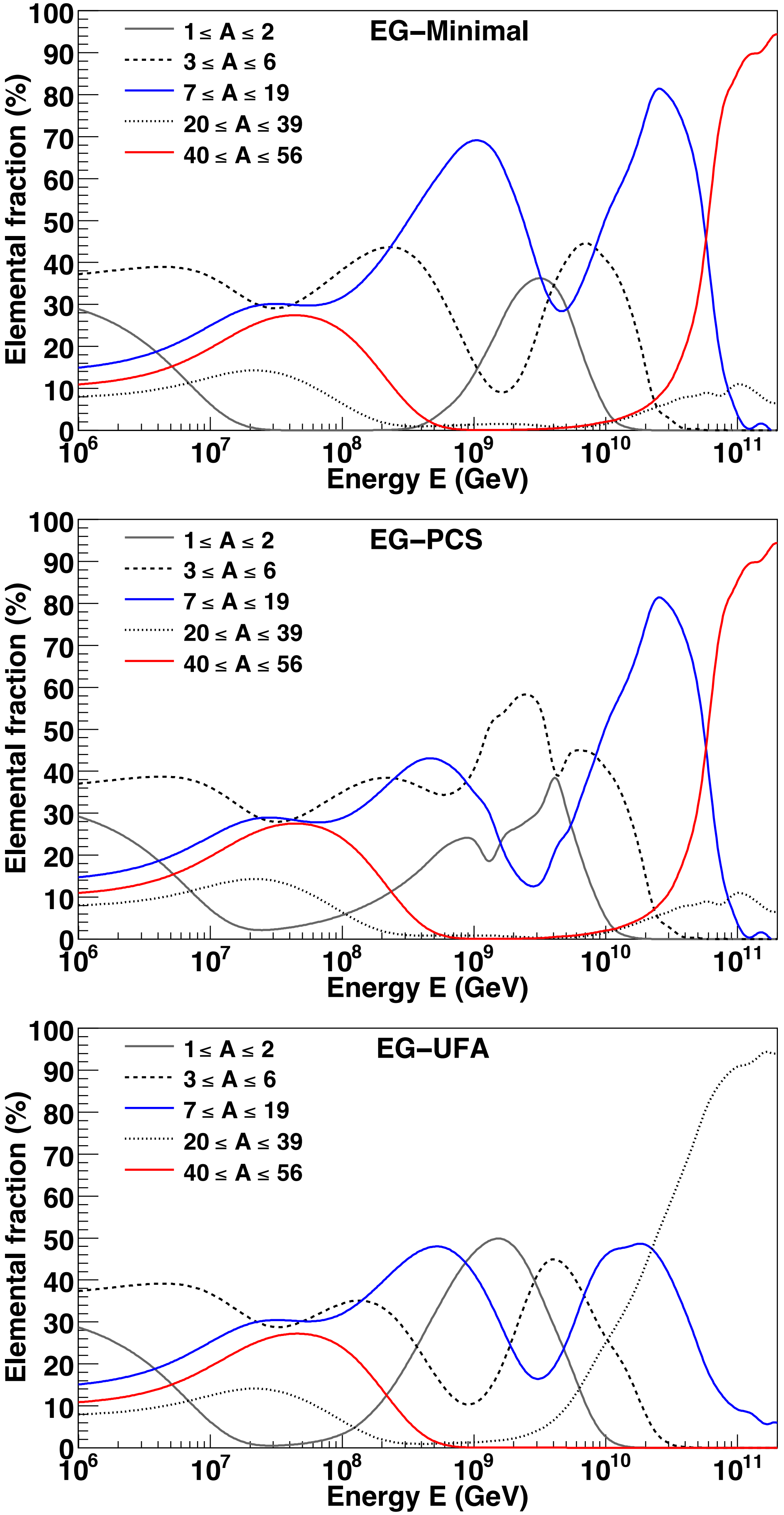


Fig. 12. — Elemental fraction of the five different mass groups

Mean logarithmic mass (lnA)

WR-CR (C/He=0.4) + EG scenarios

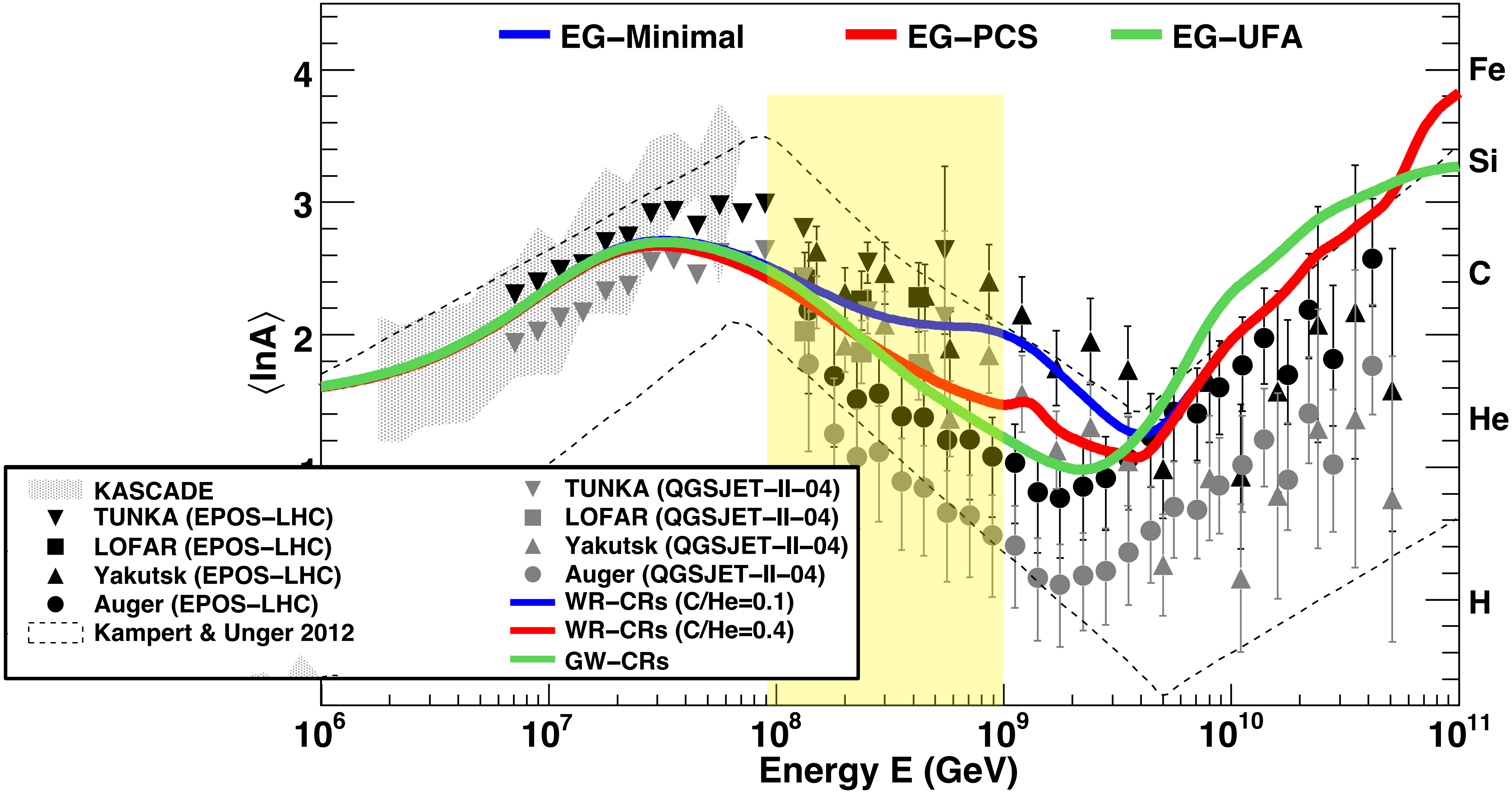
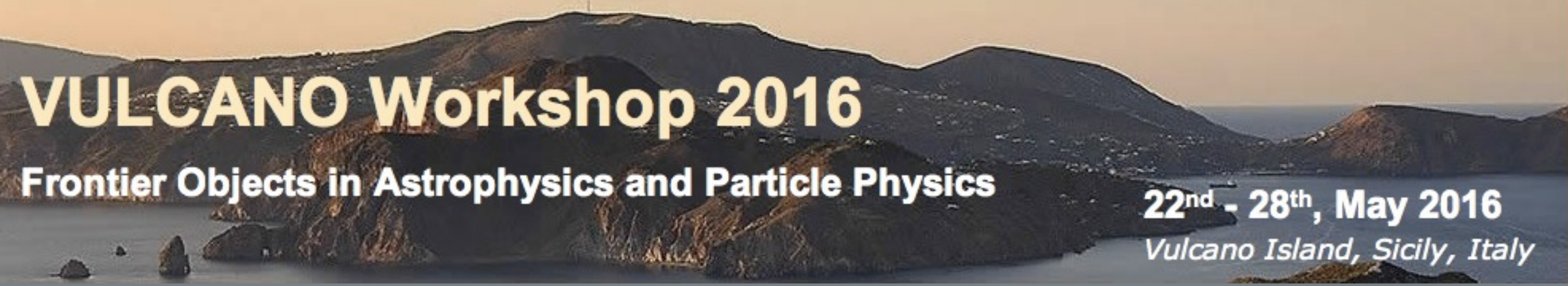
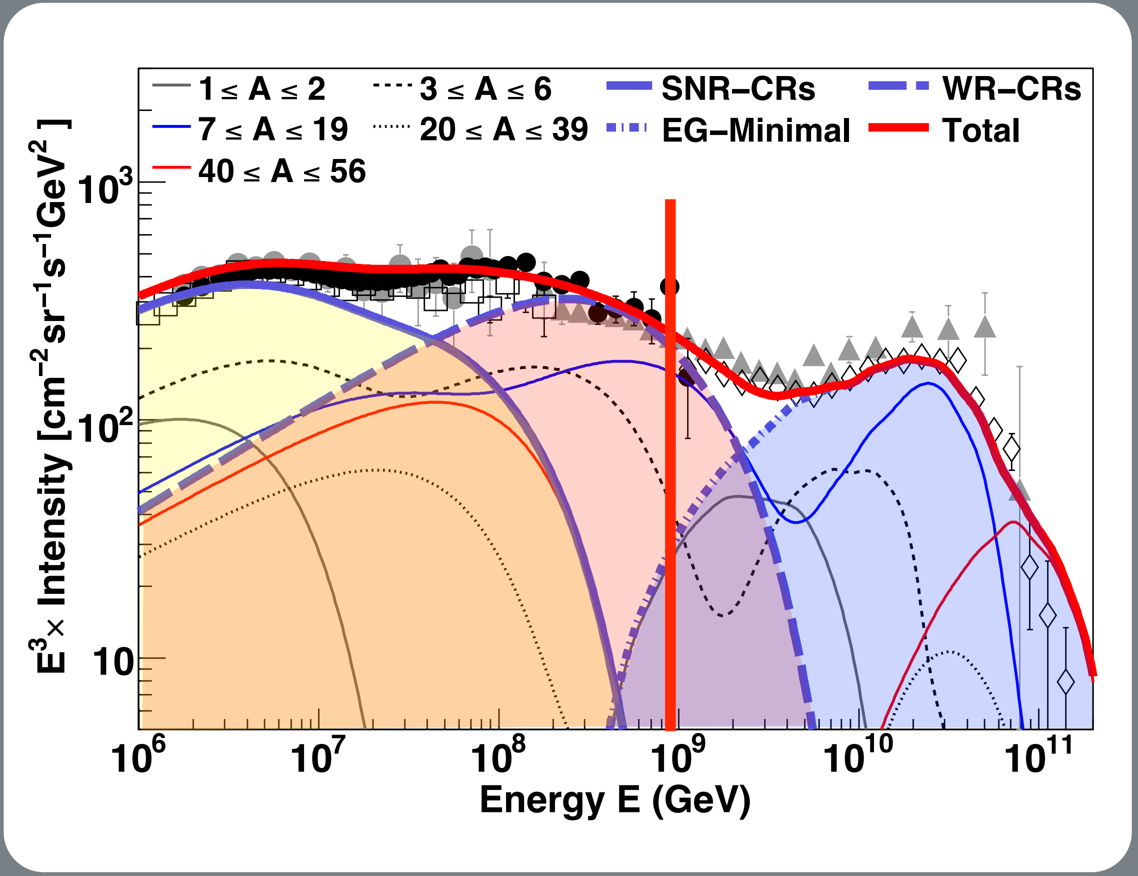


Fig. 11. Mean logarithmic mass for the three different EG-CR models combined with the WR-CR (C/He = 0.4) model. Data are the same as in Figure 8. Results obtained using WR-CR (C/He = 0.1) model are shown in Appendix B.



High-Energy Cosmic Rays: Galactic or Extragalactic?

- radio detection fo air showers is a promising new technique to measure properties of CRs above ~10^{17} eV AERA 17 km^2 --> large radio detector @ Auger
- galactic SNR accelerate CRs up to ~10^{17} eV
- 2nd galactic component at ~10^{17} - 10^{18} eV, CRs accelerated in Wolf-Rayet stars seem to be reasonable option
  --> strong contribution of He+CNO
- strong extragalactic contribution above 10^{18} eV
- three Peter‘s cycles to describe CRs from low to highest energies
  (relative contribution of elements non-trivial)



S. Thoudam et al., A&A submitted (2016), arXiv 1605.03111

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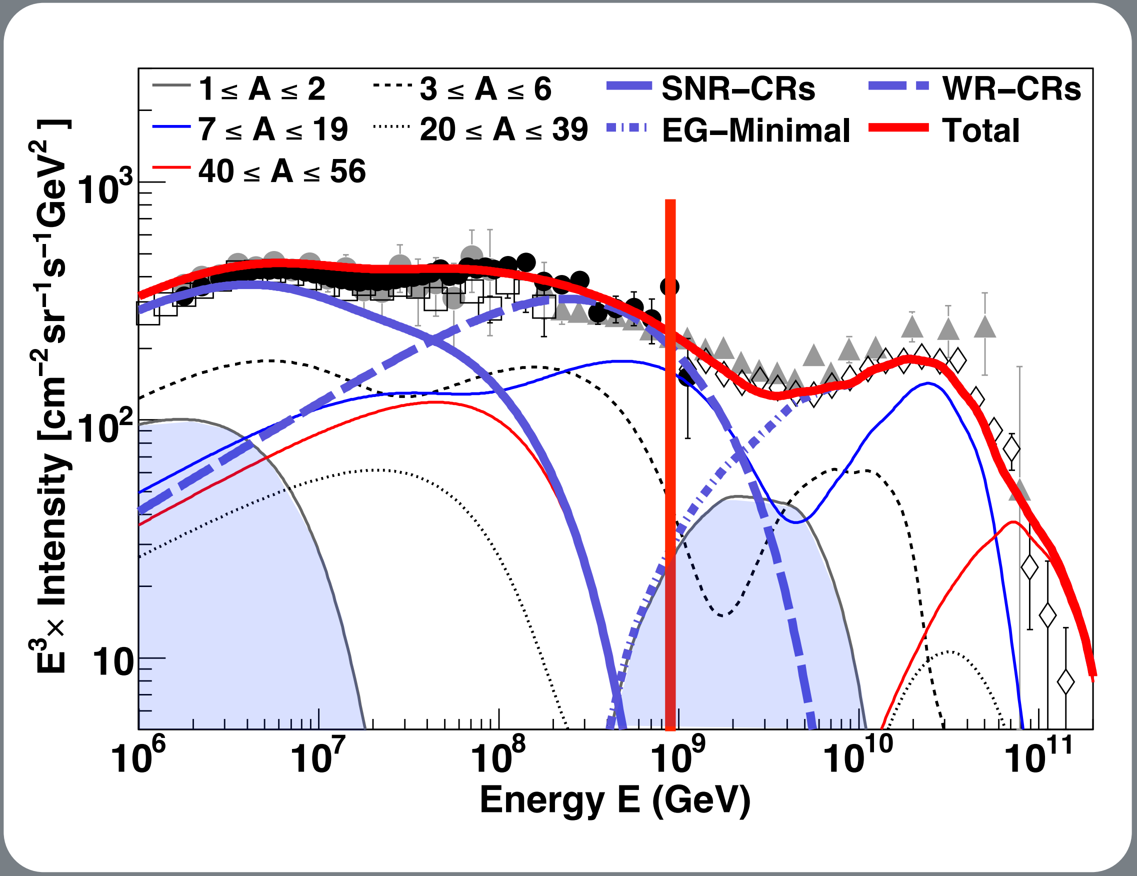

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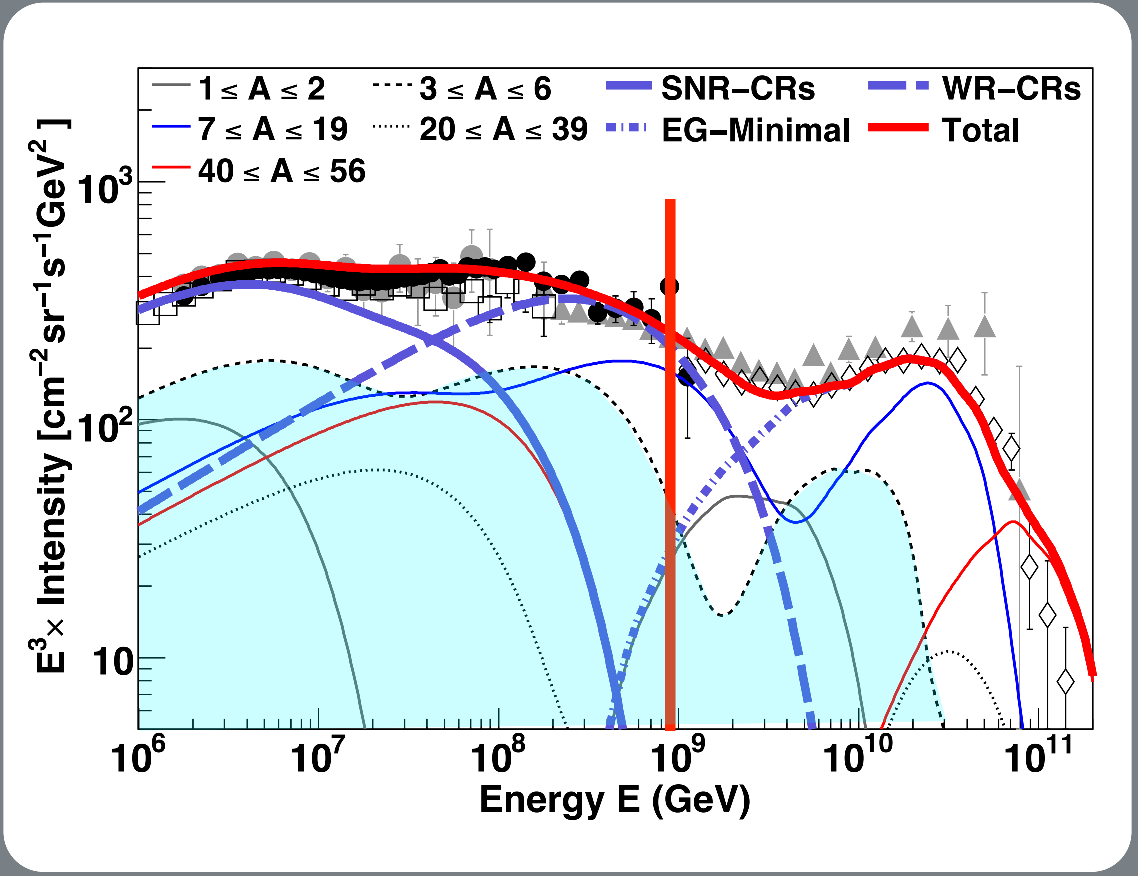

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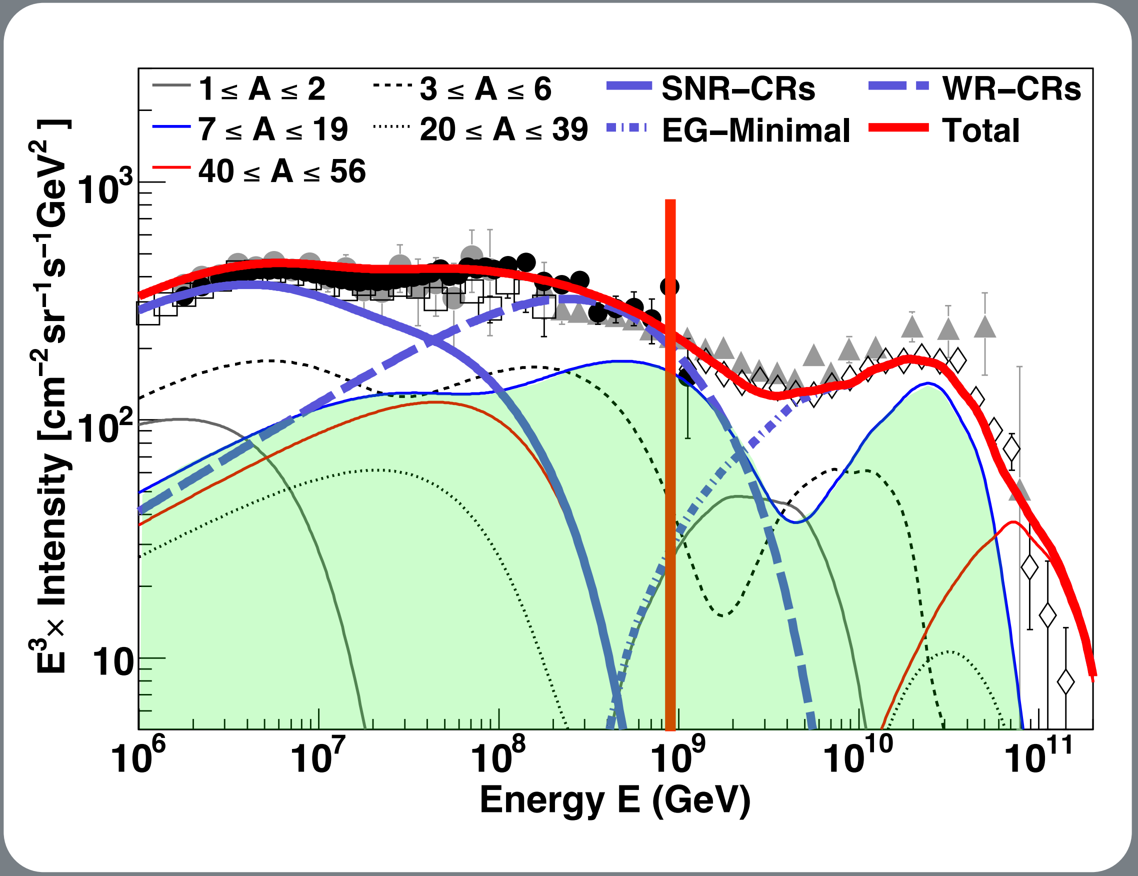

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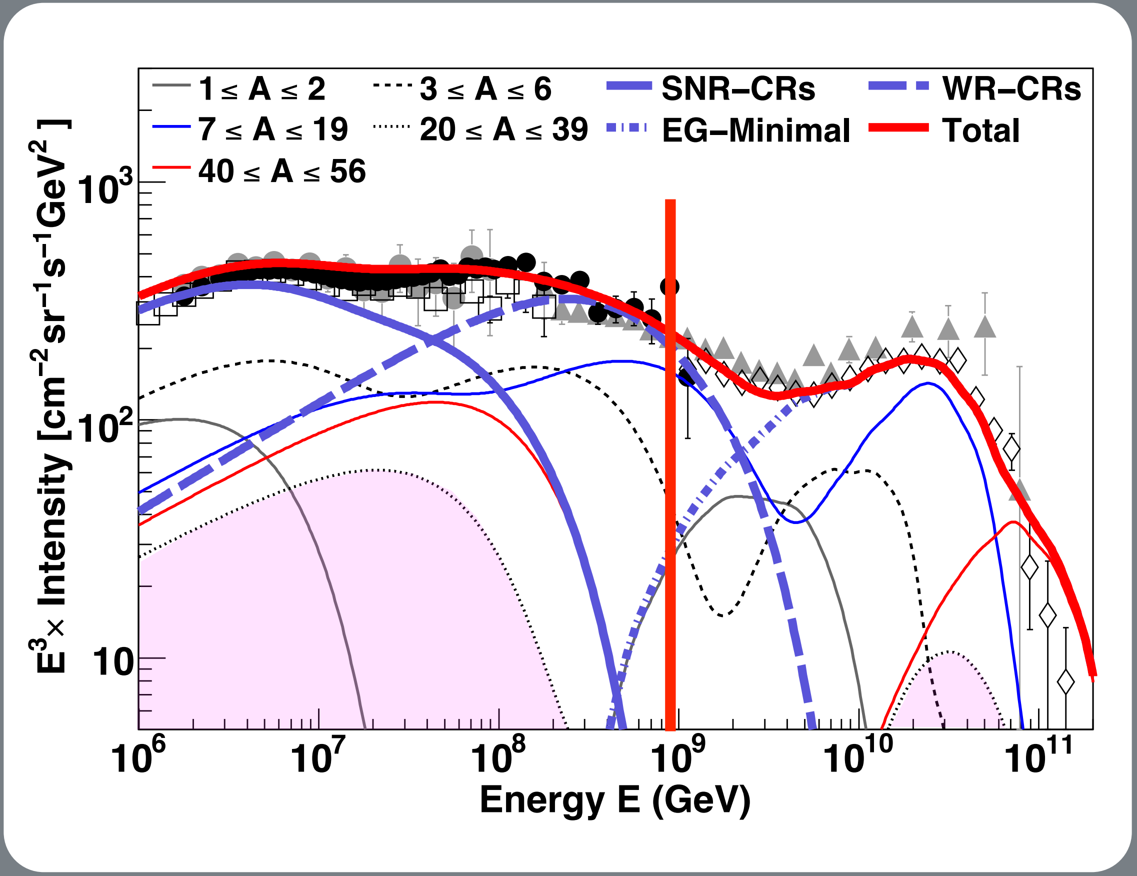
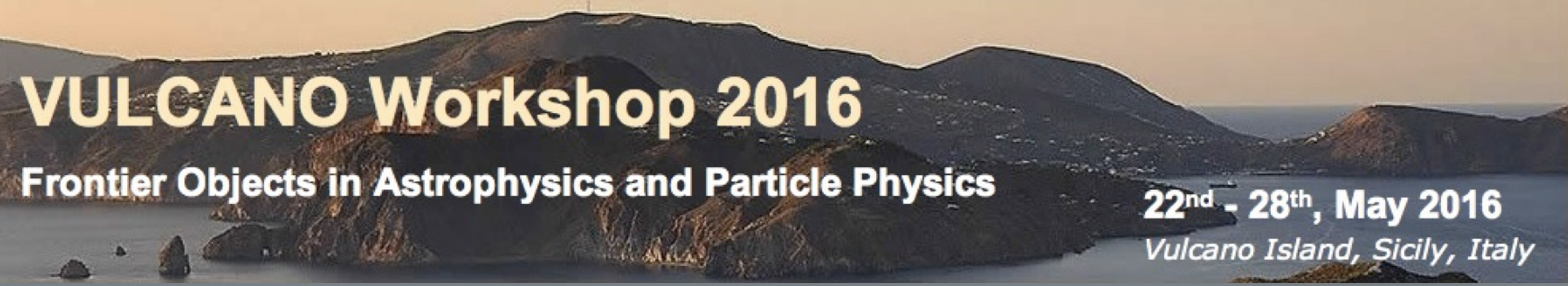
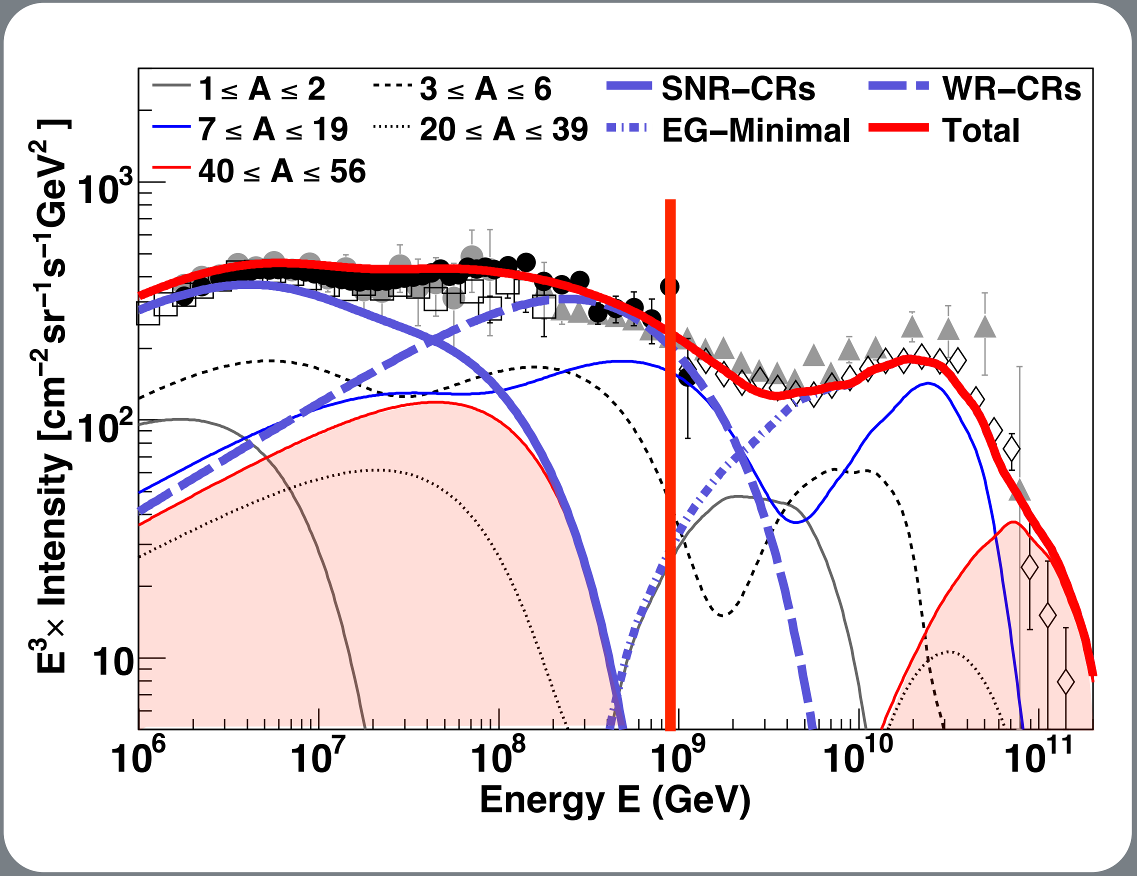


S. Thoudam et al., A&A submitted (2016), arXiv 1605.03111



High-Energy Cosmic Rays: Galactic or Extragalactic?

- radio detection fo air showers is a promising new technique to measure properties of CRs above ~10^{17} eV AERA 17 km² --> large radio detector @ Auger
- galactic SNR accelerate CRs up to ~10^{17} eV
- 2nd galactic component at ~10^{17} - 10^{18} eV,
  CRs accelerated in Wolf-Rayet stars seem to be reasonable option
  --> strong contribution of He+CNO
- strong extragalactic contribution above 10^{18} eV
- three Peter's cycles to describe CRs from low to highest energies
  (relative contribution of elements non-trivial)



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