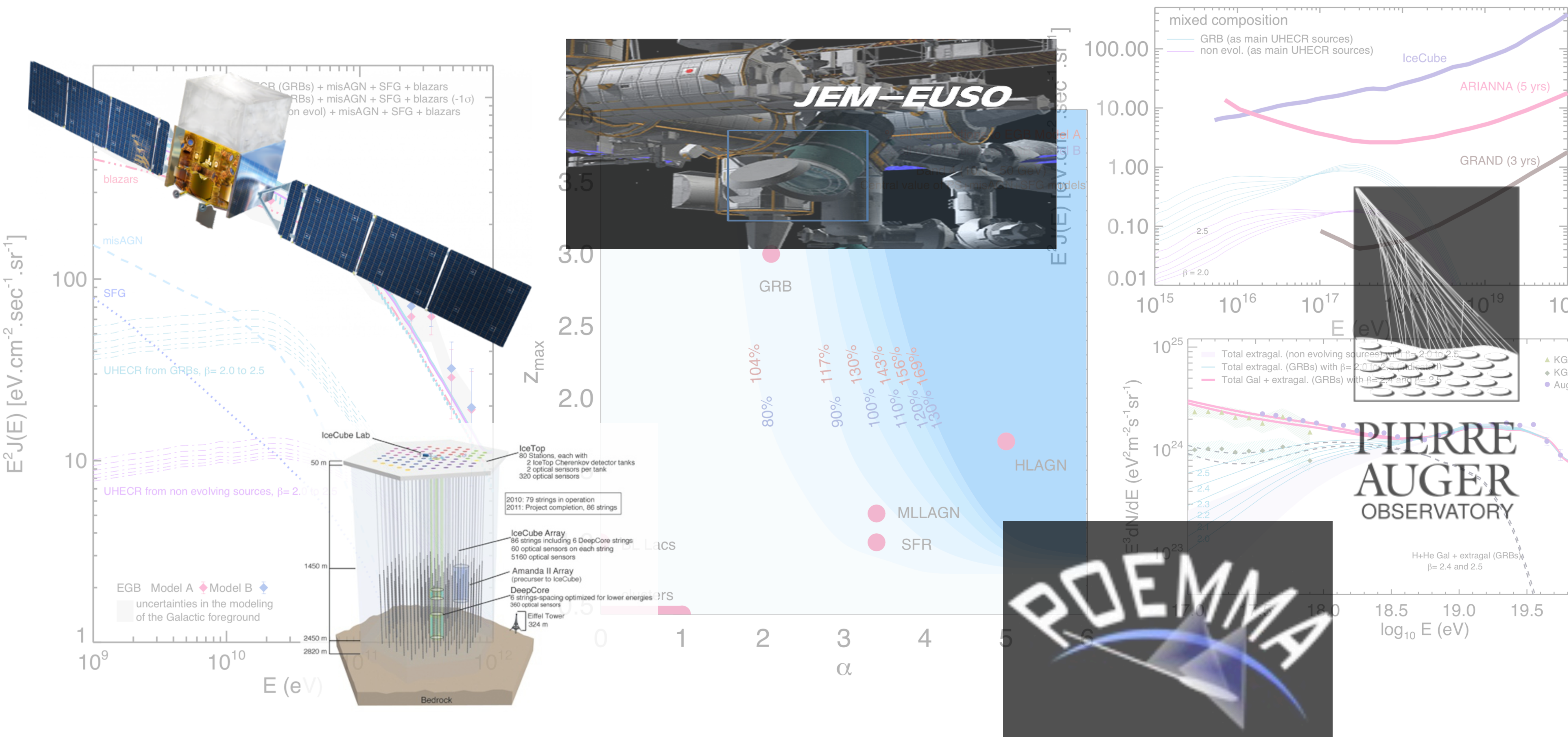
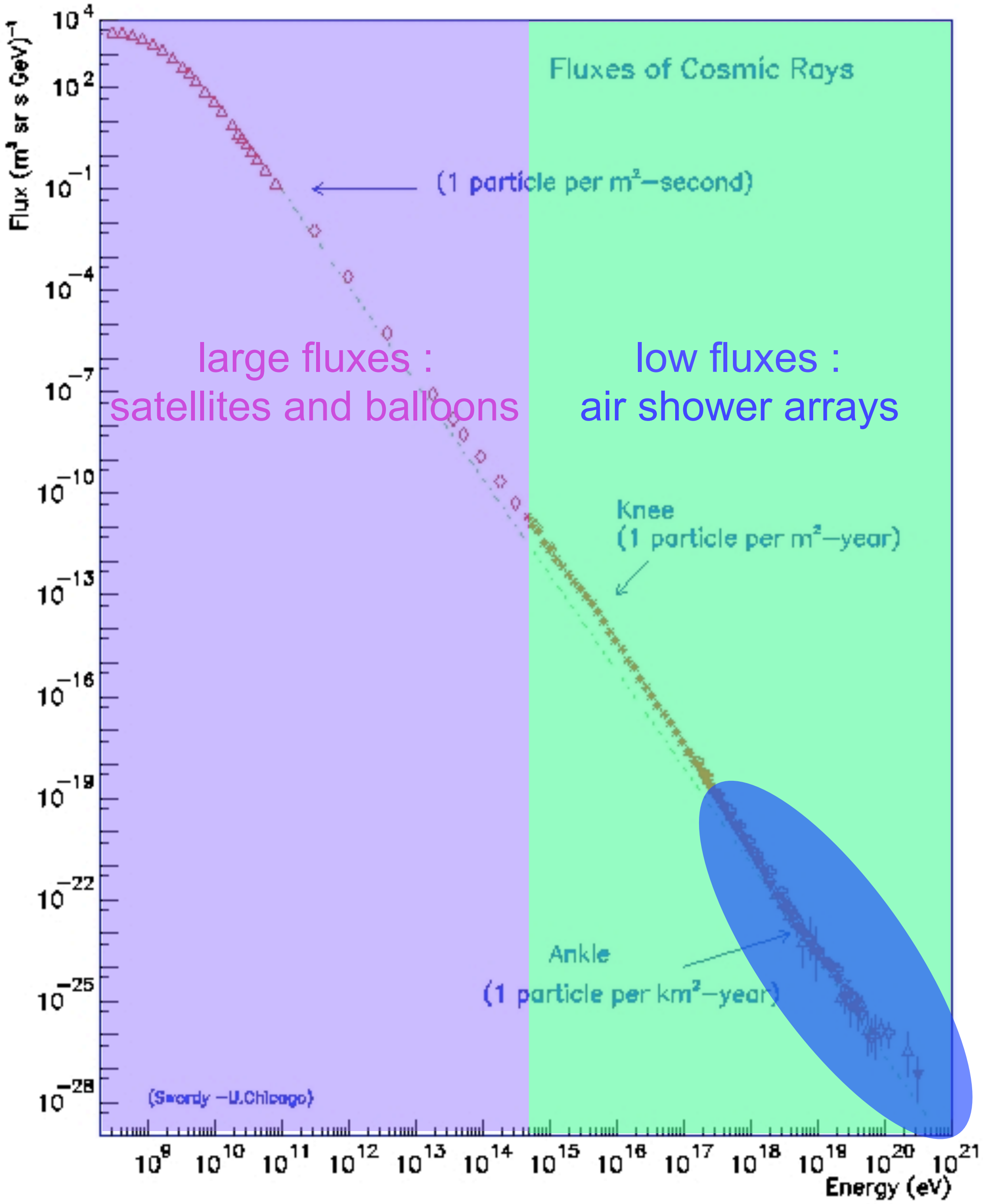
Multimessenger contraints on the origin of ultra-high-energy cosmic-rays



Denis Allard in collaboration with

Noemie Globus, E. Parizot, T. Piran, G.Decerprit, R. Mochkovitch et al.

The cosmic-ray spectrum
(a wonder of high-energy astrophysics)



Spectrum measured on 12 orders of magnitude in energy and 32 in flux

- At low energy (<10^{13-14} eV) the fluxes are large
-> domain of satellite and atmospheric balloons

- At high energies (low fluxes) one uses air shower properties to detect cosmic-ray
-> domain of air shower arrays and fluorescence detector

- At the highest energies (~10^{20} eV), extremely low fluxes (<1 CR.km^{-2}.century^{-1})
-> domain of giant air shower detectors
NB : these particles are simply the most energetic particles known to exist in the universe

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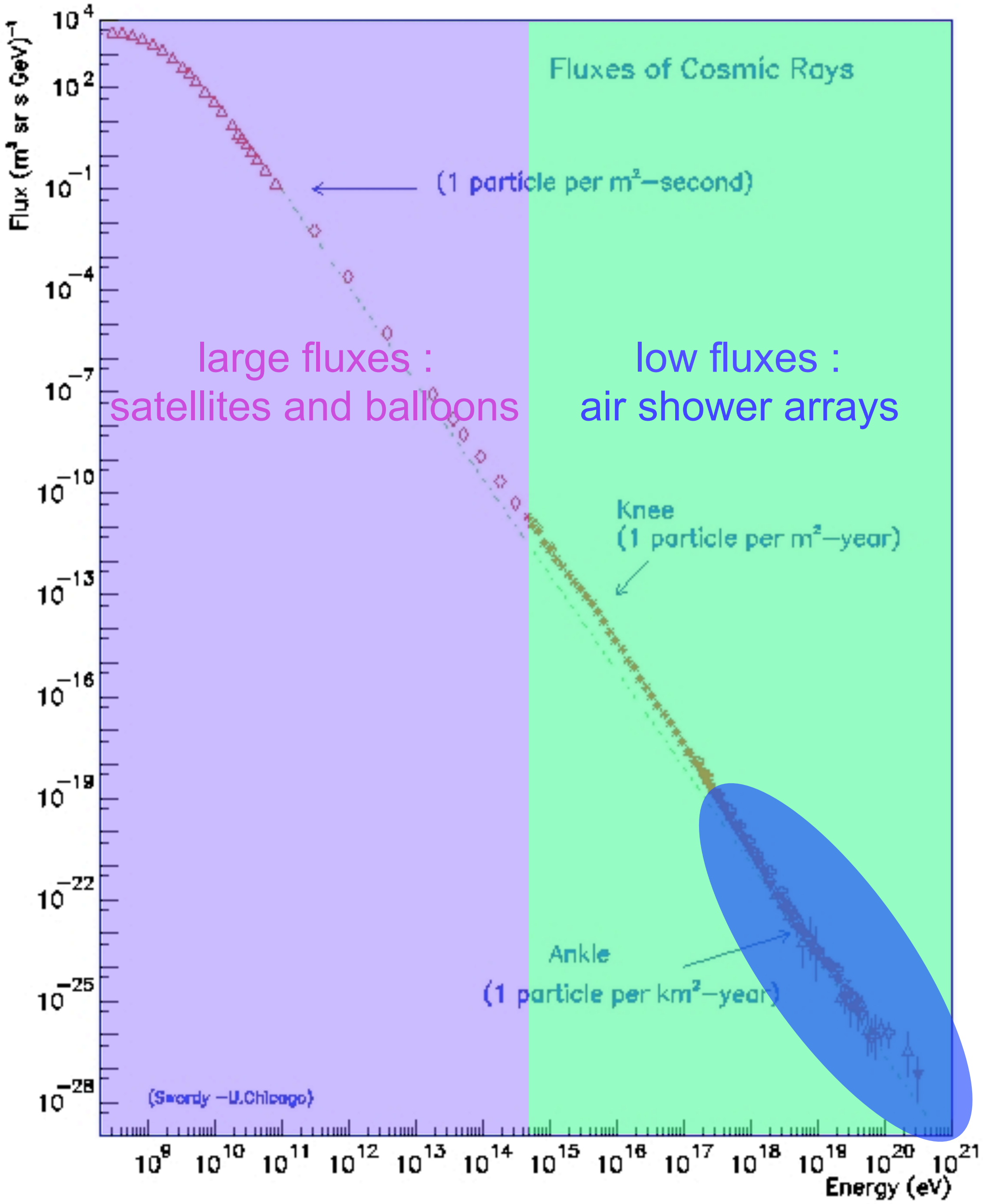

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NB : these particles are simply the most energetic particles known to exist in the universe

We know cosmic-rays are accelerated in astrophysical sources but we do not know much more about their origin (long standing question for high-energy astrophysics)

3 key observables to understand the origin of cosmic-rays

1. Angular spectrum → Arrival directions
2. Energy spectrum → Flux as a function of the energy
3. Mass spectrum → composition

Detection of VHE and UHE cosmic-rays

Above ~10^{14} eV, fluxes are too low for satellites and balloons detection

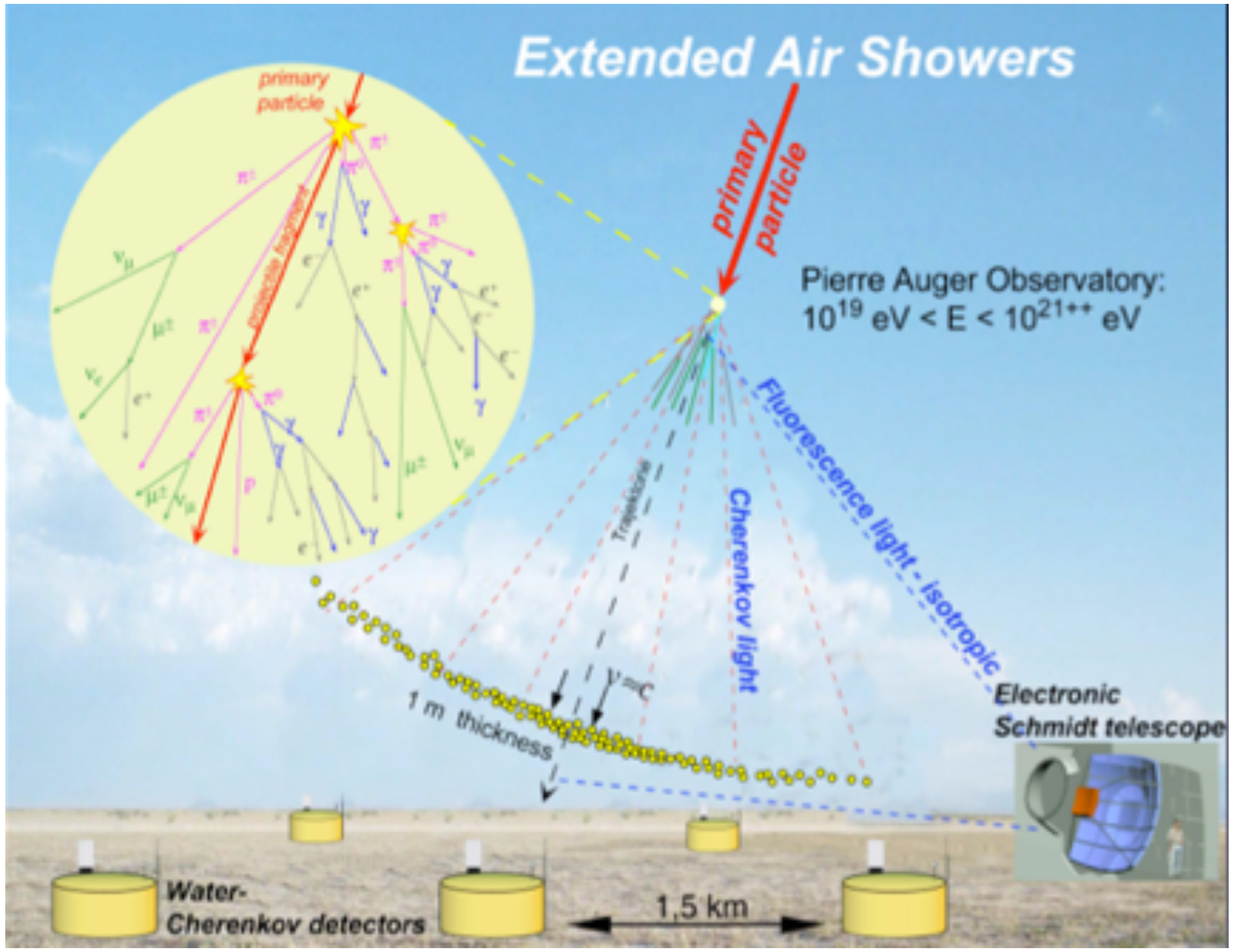
Ground based observatory detect atmospheric air showers

Principle : detect secondary particles in order to reconstruct the properties of the primary cosmic-ray

Mainly two detection methods :

- Ground arrays
- Fluorescence telescope

KASCADE (Germany; ~10^{15} to 10^{18} eV) and Auger (argentina; >10^{17} eV) are two examples of ground based cosmic-ray observatories



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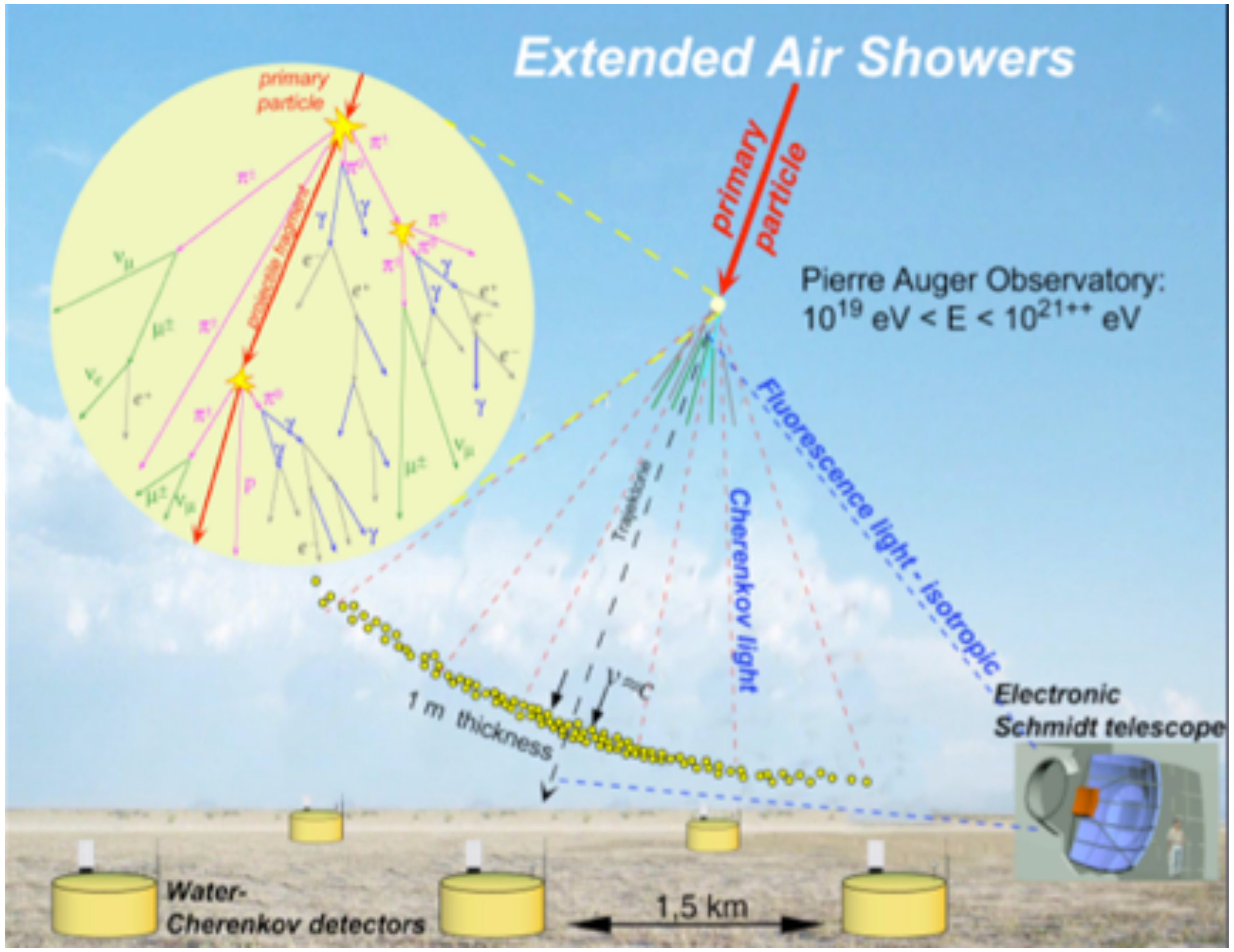
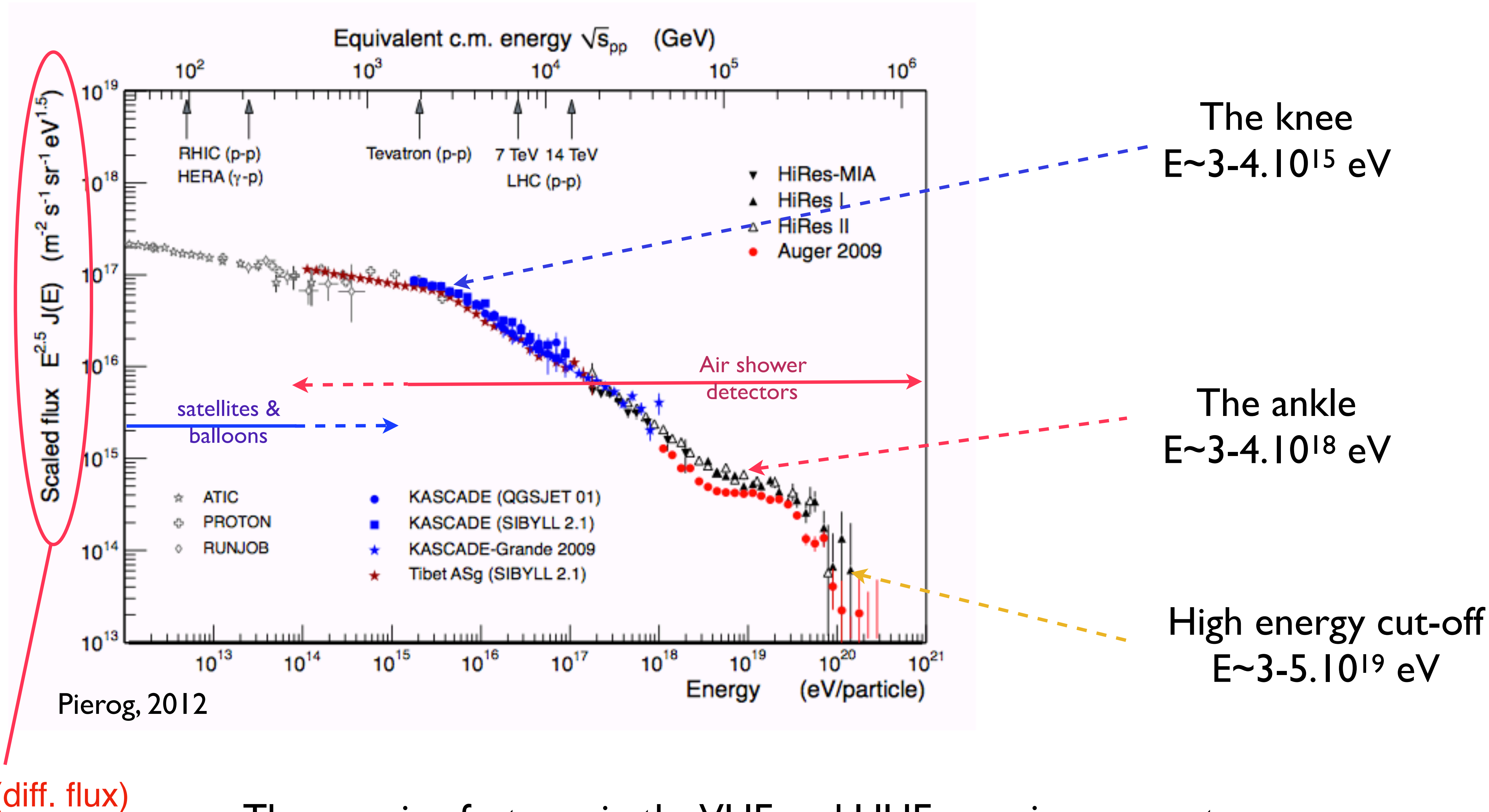
Energy and direction reconstruction of the primary cosmic-ray is well mastered

The composition cannot be reconstructed on an event by event basis (unlike with balloons and satellites)

The best that can be done for CR composition is to separate large datasets into light/intermediate/heavy CR components

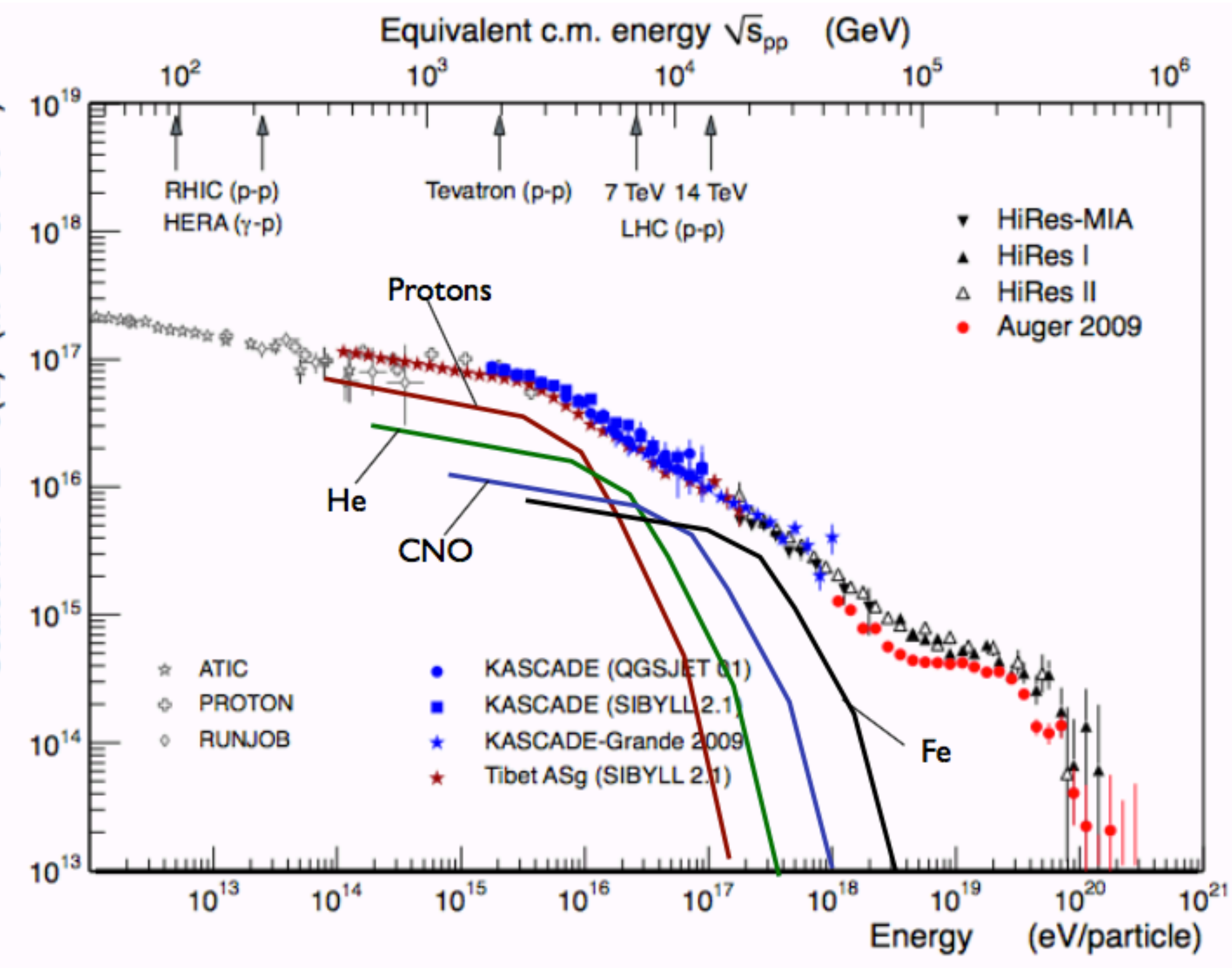


Let us come back to the cosmic-ray spectrum



Three major features in the VHE and UHE cosmic-ray spectrum :
The knee and the ankle (known for a long time)
A high energy cut-off (established only a few years ago)

The knee and above

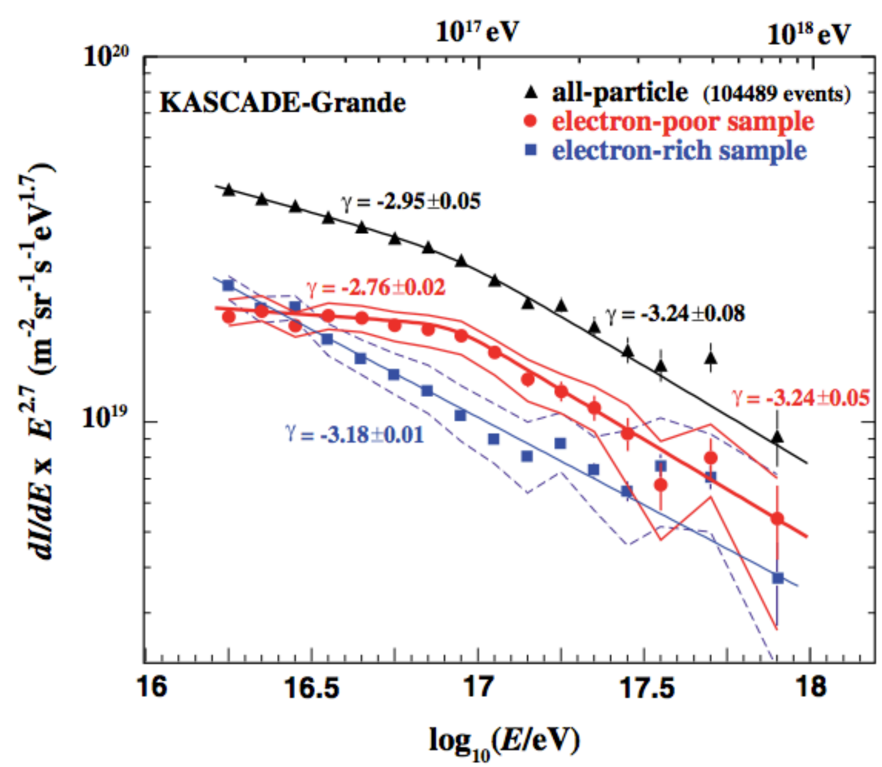


The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

One of the most popular physical explanation of the knee : maximum energy of Galactic accelerators is reached ==> knees of the different species expected at energies proportional to their charge (other explanations with similar implications for the composition exist)

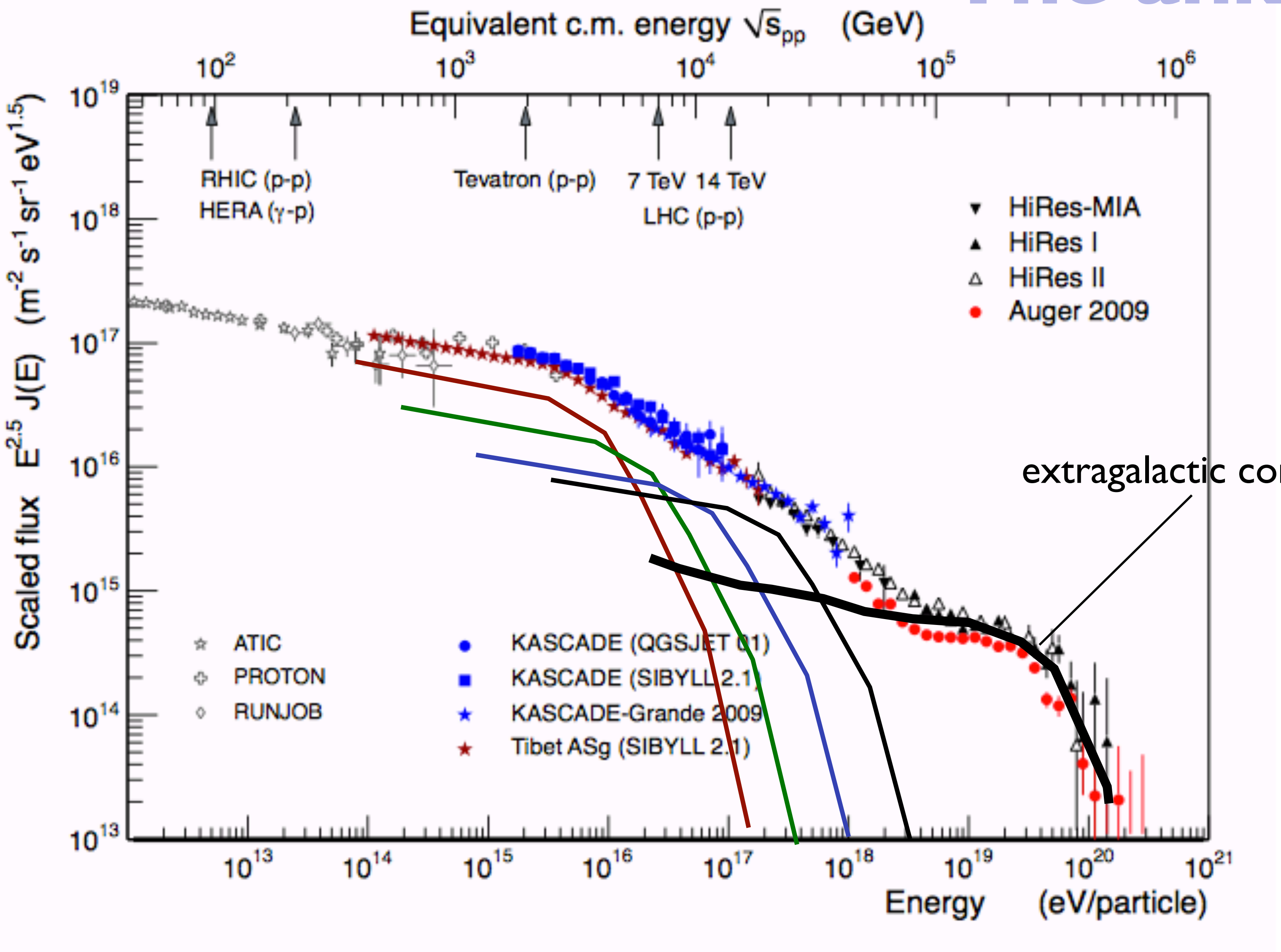
==> composition getting heavier in the energy decade following the knee confirmed by most experiments

==> knee of the heavy elements at ~10^{17} eV observed as expected by the Kascade-Grande experiment (compatible with an energy 26 time higher than the "proton" knee)



KG collab, Phys. Rev. Lett., 2011

The ankle



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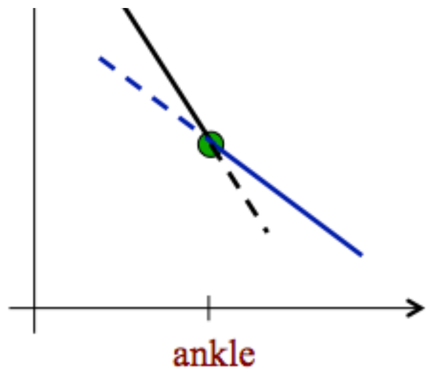
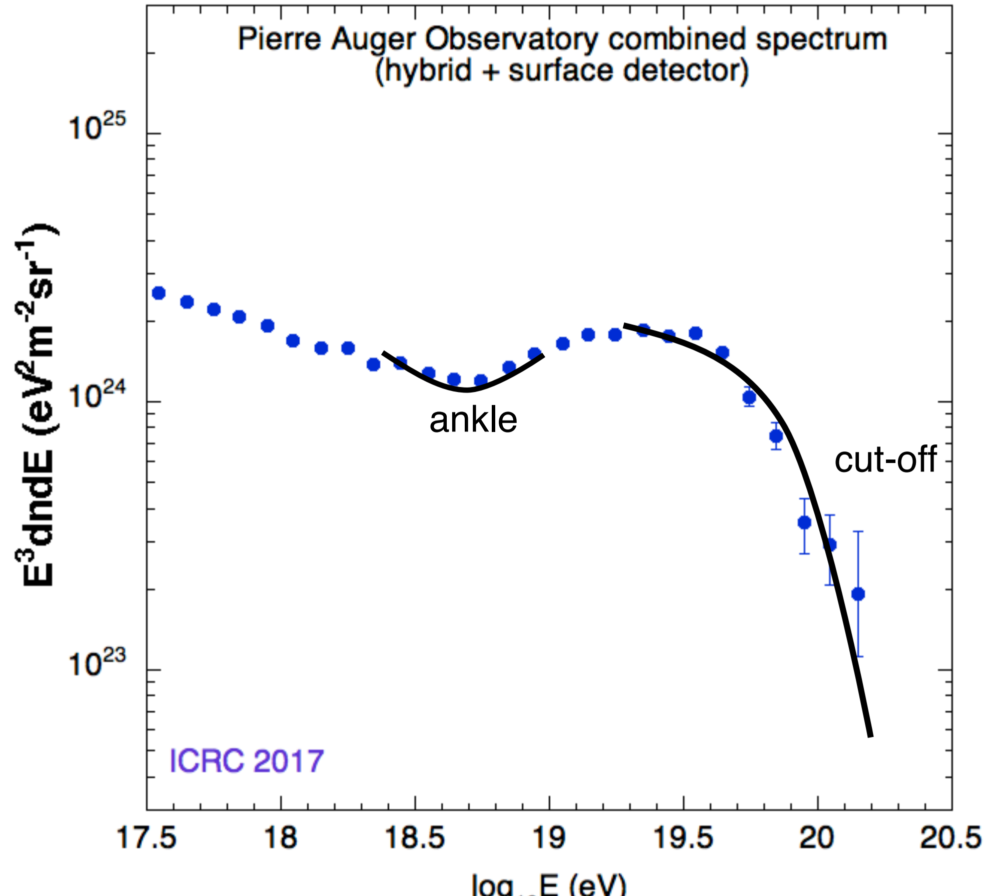


ankle : transition from a softer to a harder component

==> very natural feature for the transition from galactic to extragalactic cosmic-ray



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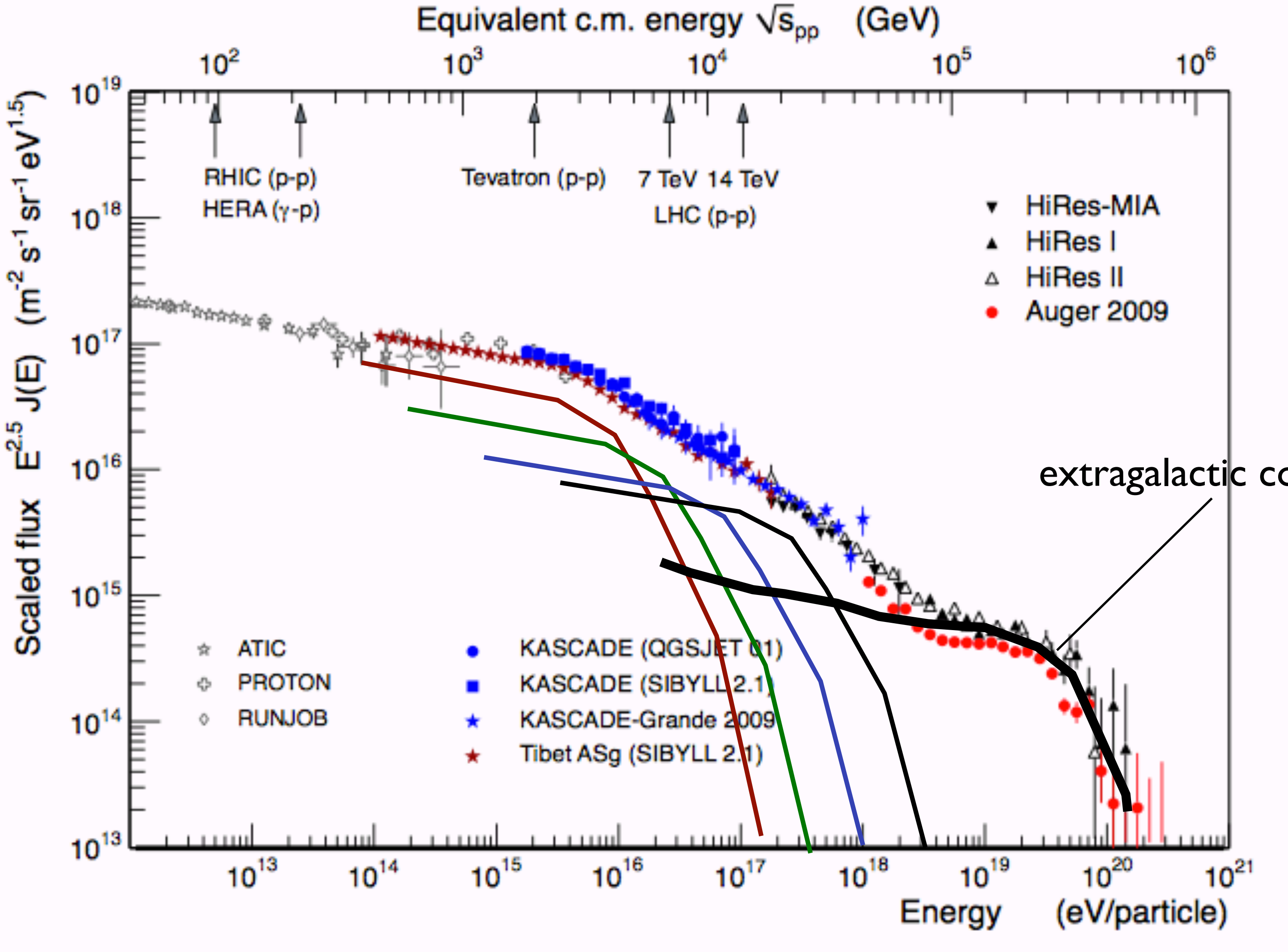


The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

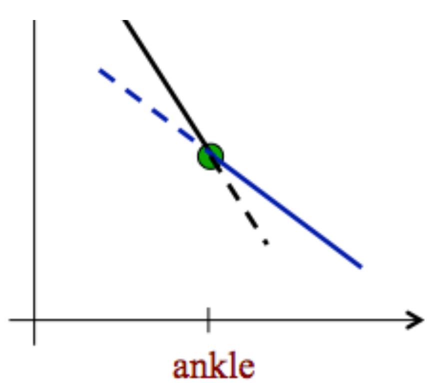
Why should the component taking over be extragalactic?

Several argument are usually invoked :

- No galactic accelerator expected to be powerful enough to reach the highest energies
- Anisotropies in the direction of the galactic disk would be naively expected

➡ Strong belief that the highest energy cosmic-ray are of extragalactic origin but there is no definitive proof of it

➡ we will assume the UHECR are extragalactic in the following



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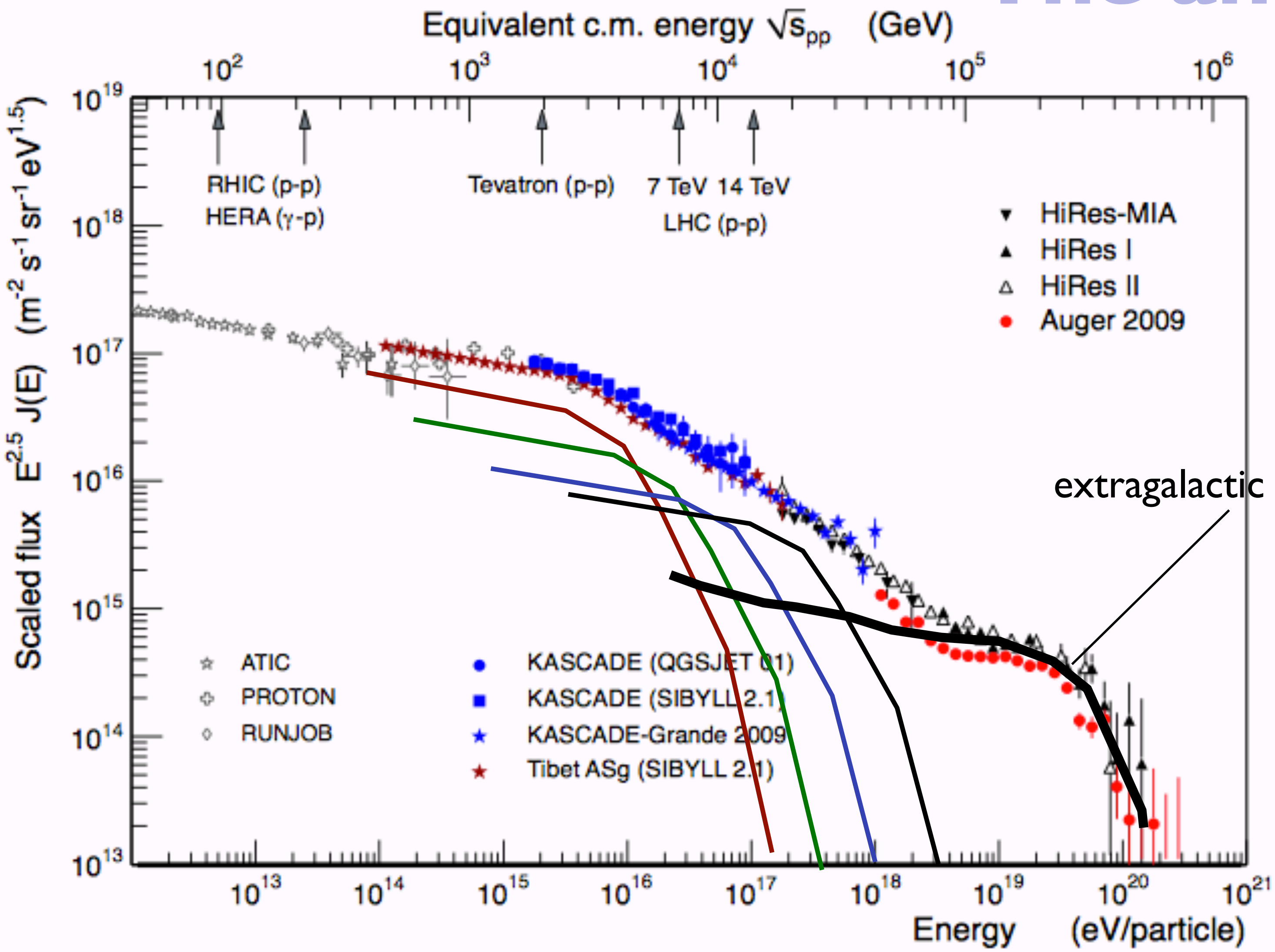

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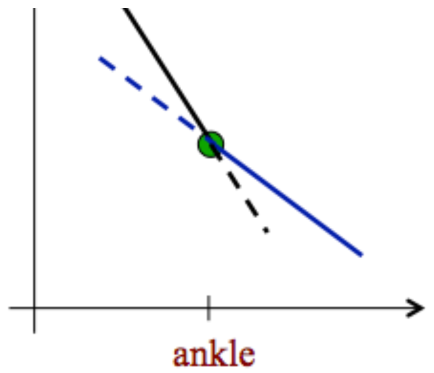
Galactic sources :
Galactic cosmic-ray origin probably related to the end of the life or the explosion of massive stars (stellar winds, supernova remnants, superbubbles, pulsars)
Galactic center?

Extragalactic sources :
AGNs, GRBs, galaxy clusters, young neutron stars which are "on top" of the Hillas diagram often mentioned



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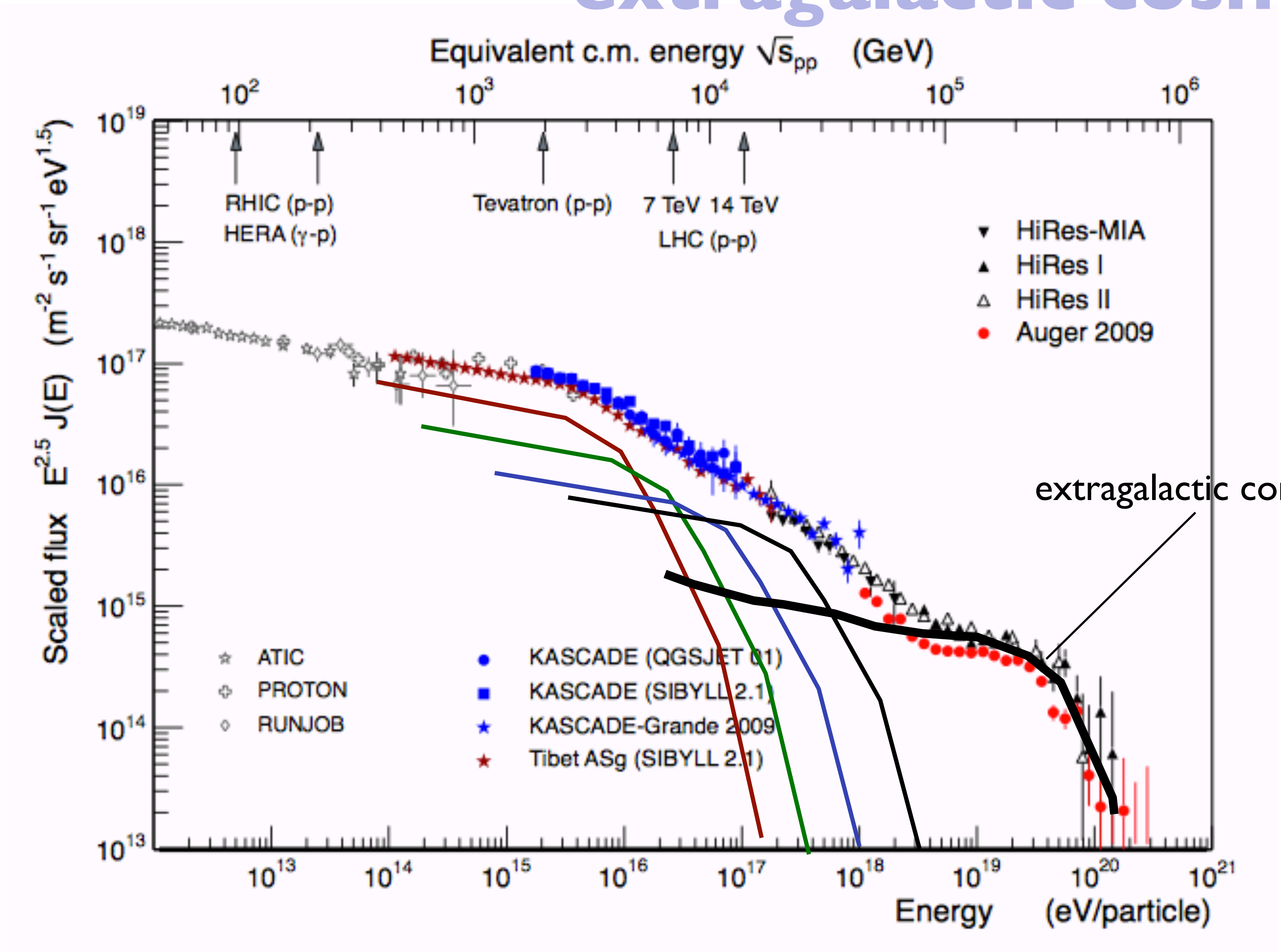
A consistent picture of the transition from galactic to extragalactic cosmic-rays?



Pierog, 2012

Tantalizing picture ! What UHECR data (Auger) have to say about it?
Can we bring additional constraints with other messengers (photons, neutrinos)

3 key observables to understand the origin of cosmic-rays

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4 key observables to understand the origin of cosmic-rays

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4. **Multi-messenger counterparts** → cosmogenic γ and ν

4 key observables to understand the origin of cosmic-rays

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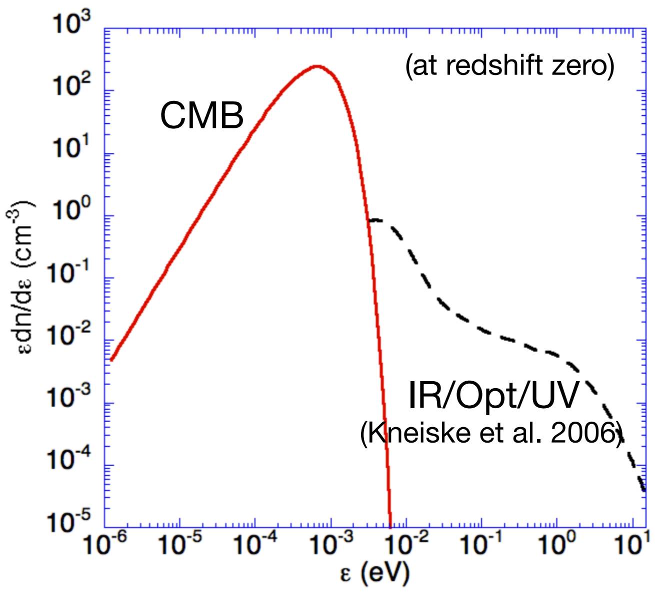
4 — Multi-messenger counterparts → cosmogenic γ and ν

We are going to consider not only Auger data (UHECR) but also Fermi (γ-ray) and IceCube (neutrino) data

Ultra-high-energy cosmic-rays (UHECR), neutrinos and photons : the multi-messenger link

UHECR (E>10^{17} eV) are strongly suspected to be of extragalactic origin

Extragalactic ultra-high-energy cosmic-rays must loose energy and produce secondary (cosmogenic) neutrinos and gamma-rays during their propagation interacting with the extragalactic background light (UV-optical-IR, CMB)



- pair production: $N+\gamma \rightarrow N+e^+/e^-$ $==> secondary\ e^{+/-}$

Threshold with CMB photons ~10^{18} eV per nucleon (at z=0)

- Pion and meson production :

$\pi^0 \rightarrow 2\gamma$

$\pi^+ \rightarrow \mu^+ + \nu_\mu,\ \mu^+ \rightarrow \overline{\nu_\mu} + e^+ + \nu_e$ $==> secondary\ e^{+/-}, \gamma\ and\ \nu$

$\pi^- \rightarrow \mu^- + \overline{\nu_\mu},\ \mu^- \rightarrow \nu_\mu + e^- + \overline{\nu_e}$

Threshold with CMB photons ~10^{20} eV per nucleon (at z=0)

mechanism responsible for the GZK cut-off at least for UHECR protons

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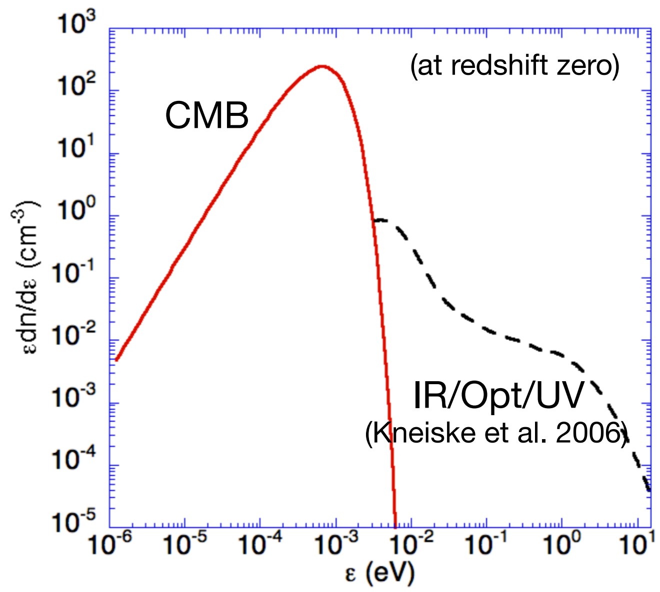

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$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu},\ \mu^- \rightarrow \nu_\mu + e^- + \overline{\nu_e}$$

νs do not interact while propagating in the extragalactic medium
while the universe is opaque to VHE e^+/e^- and γ which cascade down to sub-TeV energies

Diffuse UHECR (E>10^{17} eV) flux
➡ diffuse ν flux in the PeV-EeV range
➡ diffuse γ-ray flux in the GeV-TeV range

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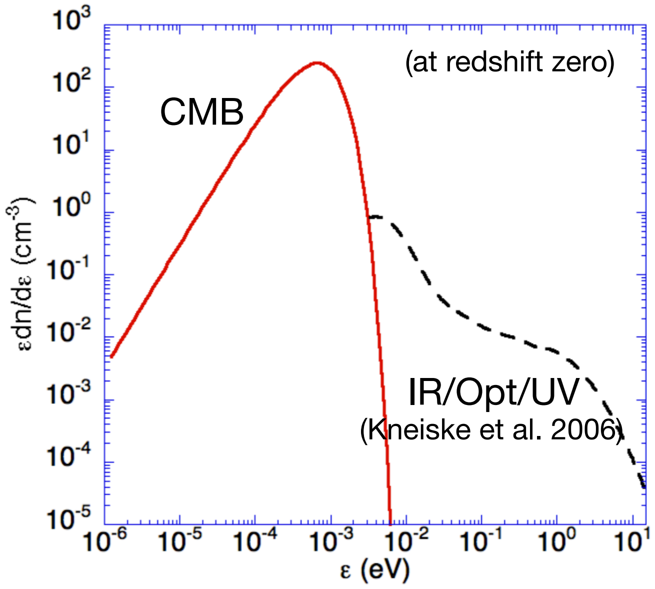

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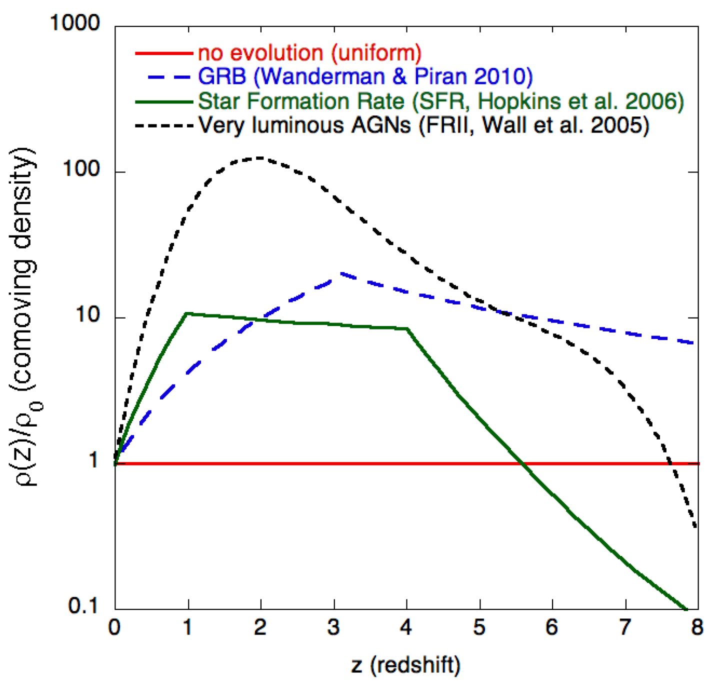
The extragalactic photon backgrounds evolve with time, they are hotter and denser as the redshift increases

➡ cosmological evolution of the sources is expected to have a strong impact on cosmogenic photons and neutrino fluxes

4 different hypotheses on the source evolution in the following :

- A very strong evolution such as that of very luminous AGNs (hereafter labeled FR-II)
- 2 "intermediate" evolutions following the "star formation rate" (SFR) and the evolution of GRB sources
- A baseline case with no evolution (often labeled "uniform")



Calculations of cosmogenic neutrino and photon fluxes what do we do ?

We assume a given extragalactic UHECR phenomenological model which relies on :

- source spectrum (usually a power law)
- source composition
- maximum energy at the sources
- cosmological evolution of the sources (distribution of initial redshifts)

Particles propagation from the sources to the Earth is simulated (energy losses, secondary particles productions)

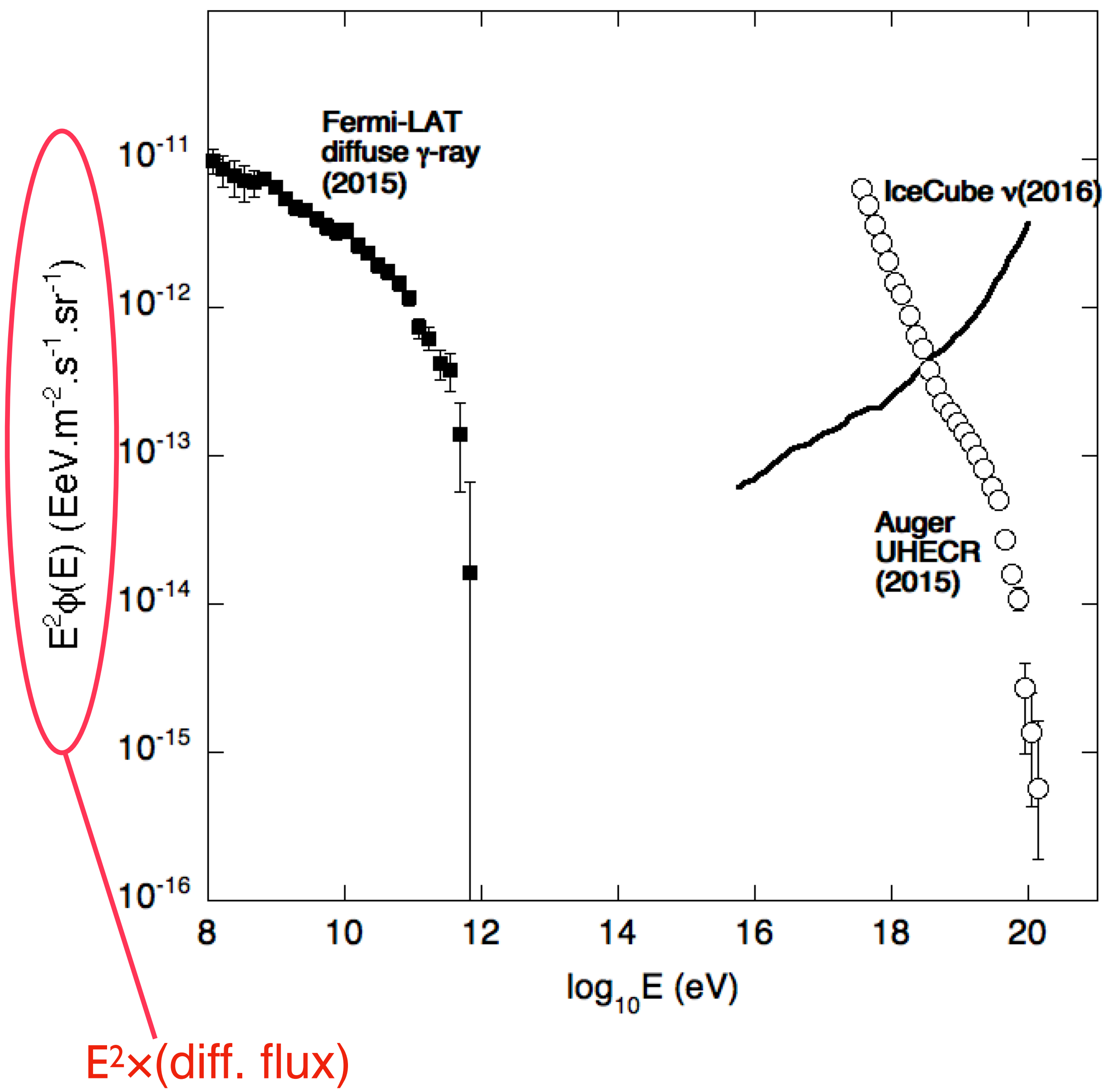
A "good" model should reproduce the measured UHECR spectrum

➡ normalisation for the secondary ν and γ fluxes

➡ νs and γs must not overshoot IceCube UHEν sensitivity and Fermi-LAT isotropic gamma-ray background (IGRB)

NB : it should also reproduce the observed UHECR composition

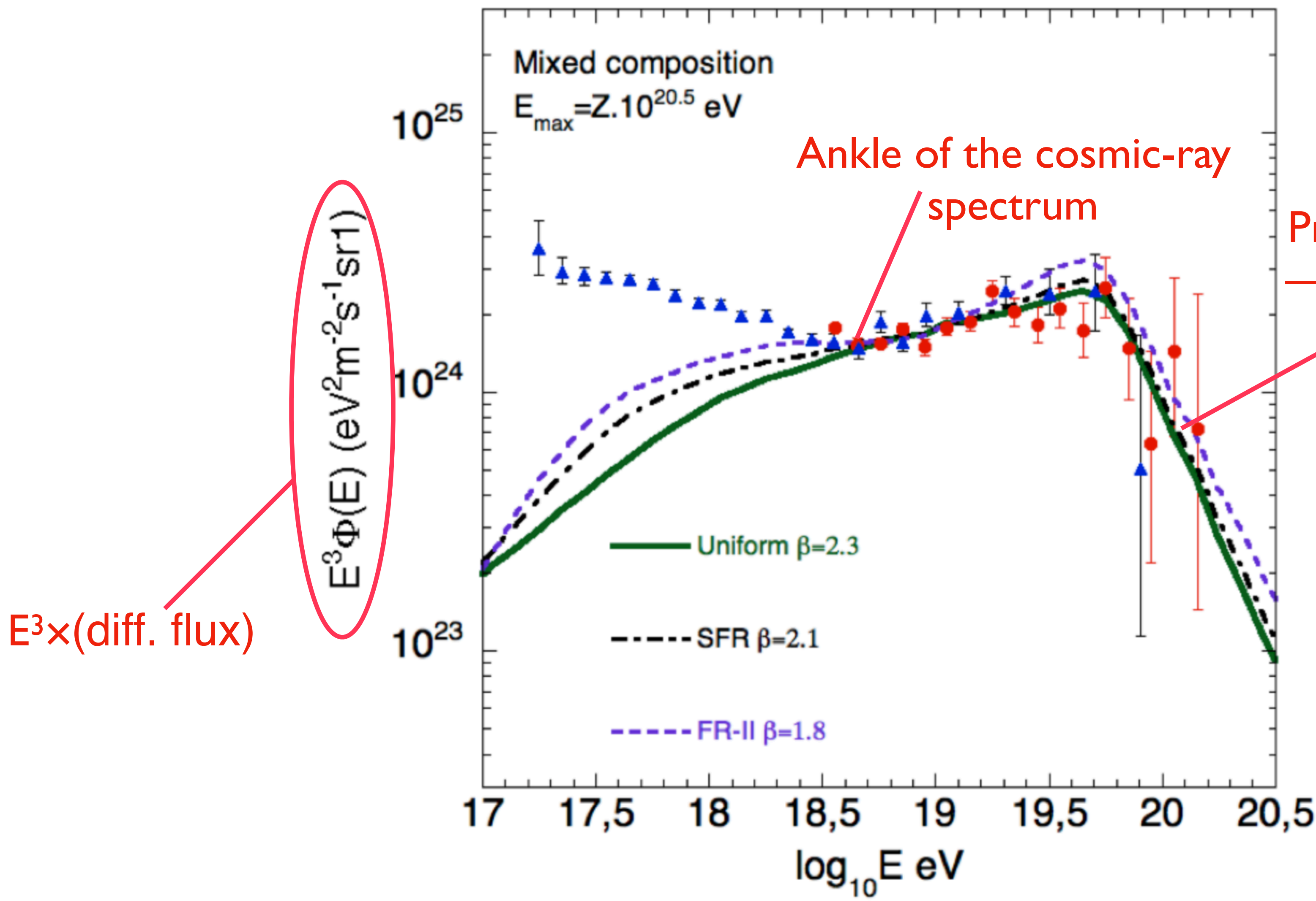
Aartsen et al. 2016, Phys. Rev. Lett. 117 (24)
Ackermann et al. 2015, ApJ 799:86
Auger Collaboration 2015 (ICRC)



One example : mixed composition assumed at UHECR sources

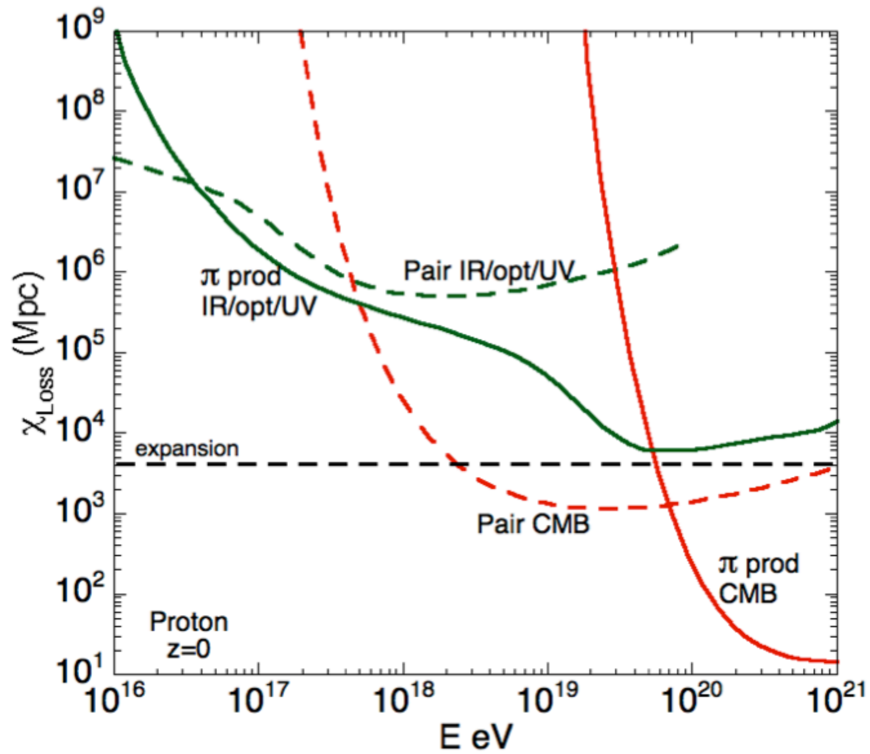
Assuming the maximum energy per nucleon is above 10^{20} eV (what most people thought until ~2010) mixed composition similar to that of low energy galactic cosmic-rays :

$N(E) \propto E^{-\beta}$, $E_{max}(Z)=Z\times E_{max}^{proton}$, $E_{max}^{proton}=10^{20.5}$ eV



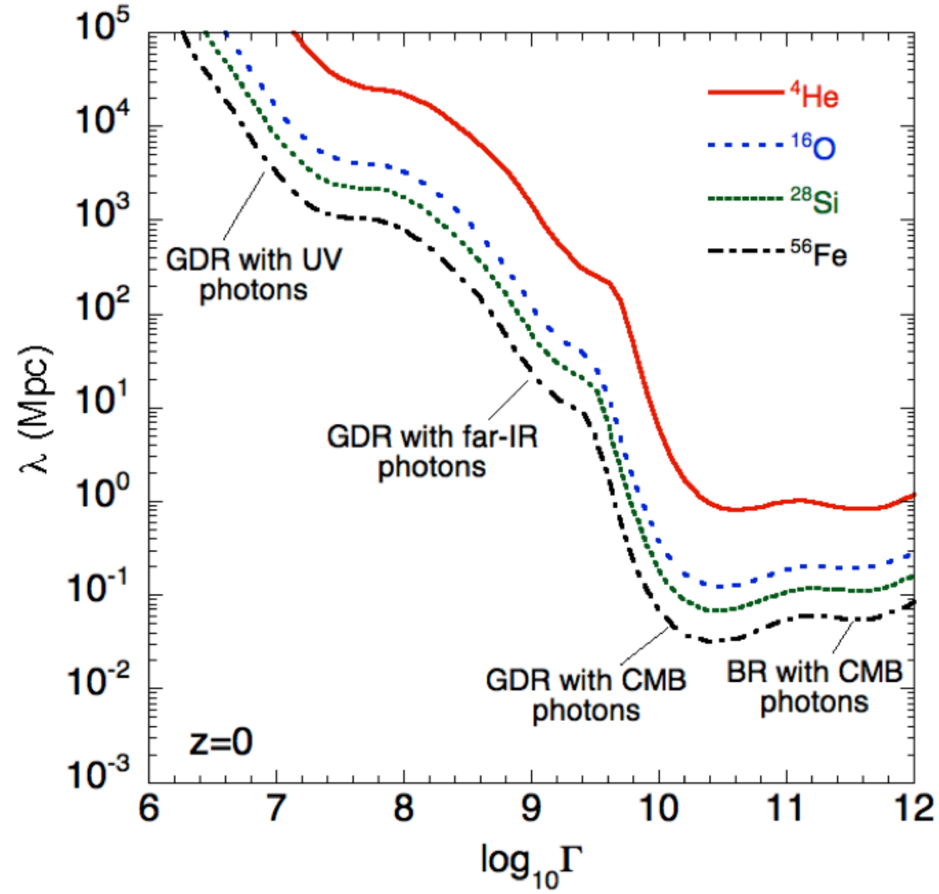
The UHECR spectrum can be well reproduced above the ankle
—> the ankle is interpreted in this case as a signature of the transition between Galactic and extragalactic cosmic-rays (more precisely the end of the transition)

The GZK effect for protons and nuclei



proton attenuation length as a function of the energy :
Strong decrease above ~10^{20} eV due to pion production with CMB photons
—> Horizon of UHE proton gets reduced above this energy
—> GZK cut-off for protons

nuclei mean free path for giant dipole resonance (photodisintegration) as a function of the Lorentz factor :
Strong decrease above $\Gamma \sim 4.10^9$ due to GDR interaction with CMB photons
—> Horizon of UHE nuclei get reduced an energy ~ A×4-5.10^{18} eV
—> GZK cut-off for nuclei



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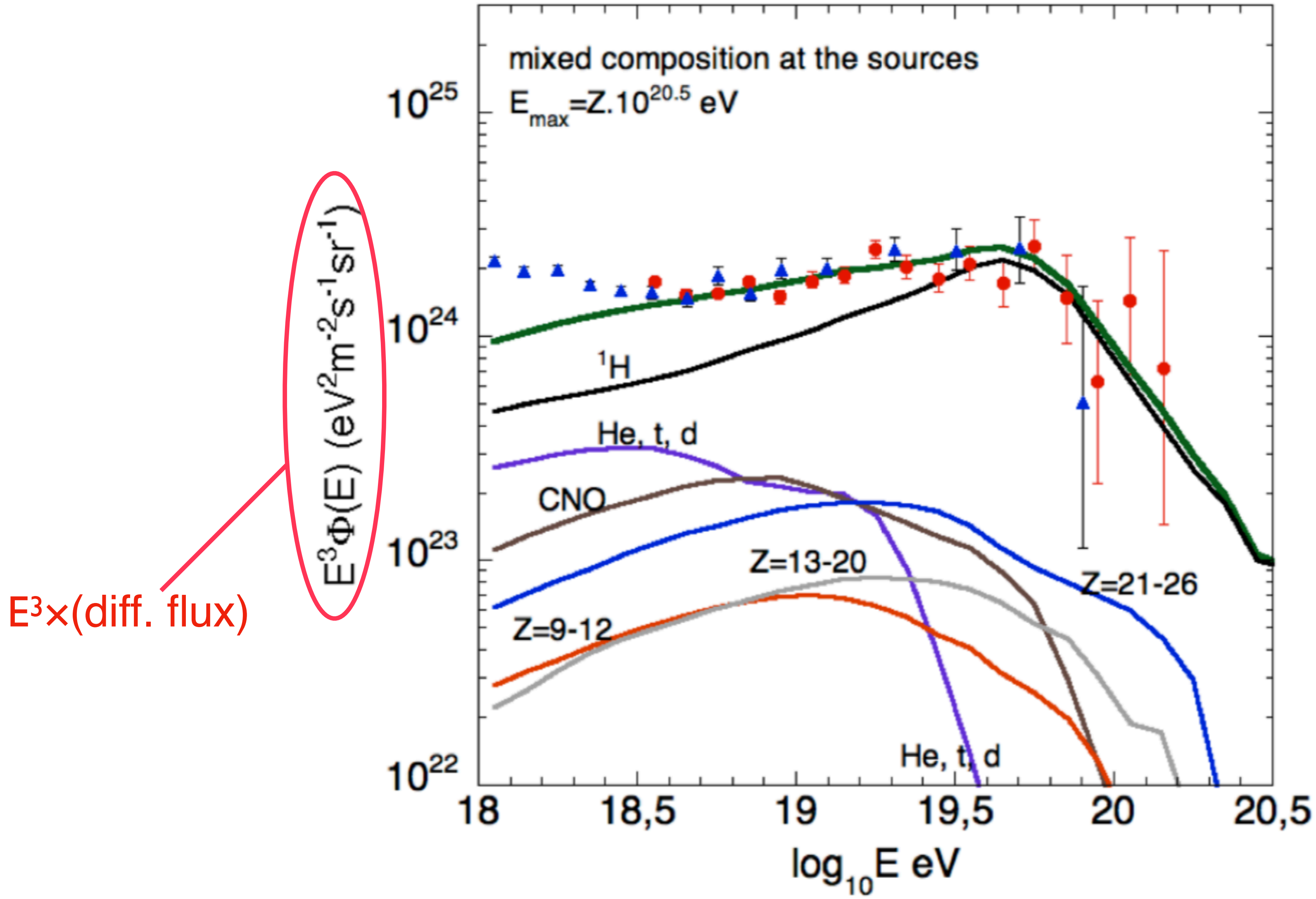

When all the species are assumed to be accelerated above 10^{20} eV, the composition is expected to get lighter (i.e proton richer) above 10^{19} eV (photodisintegration of composed species)

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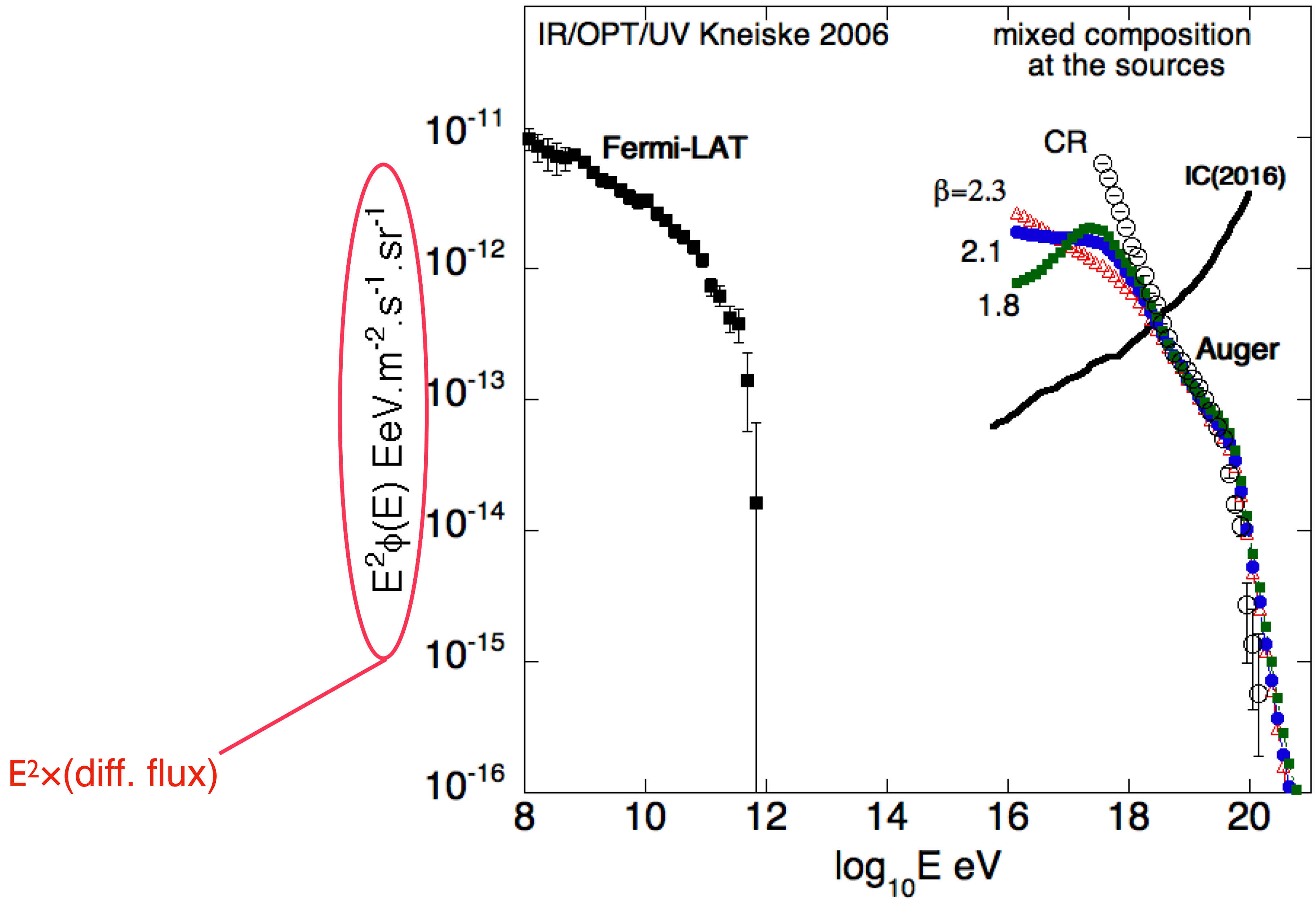

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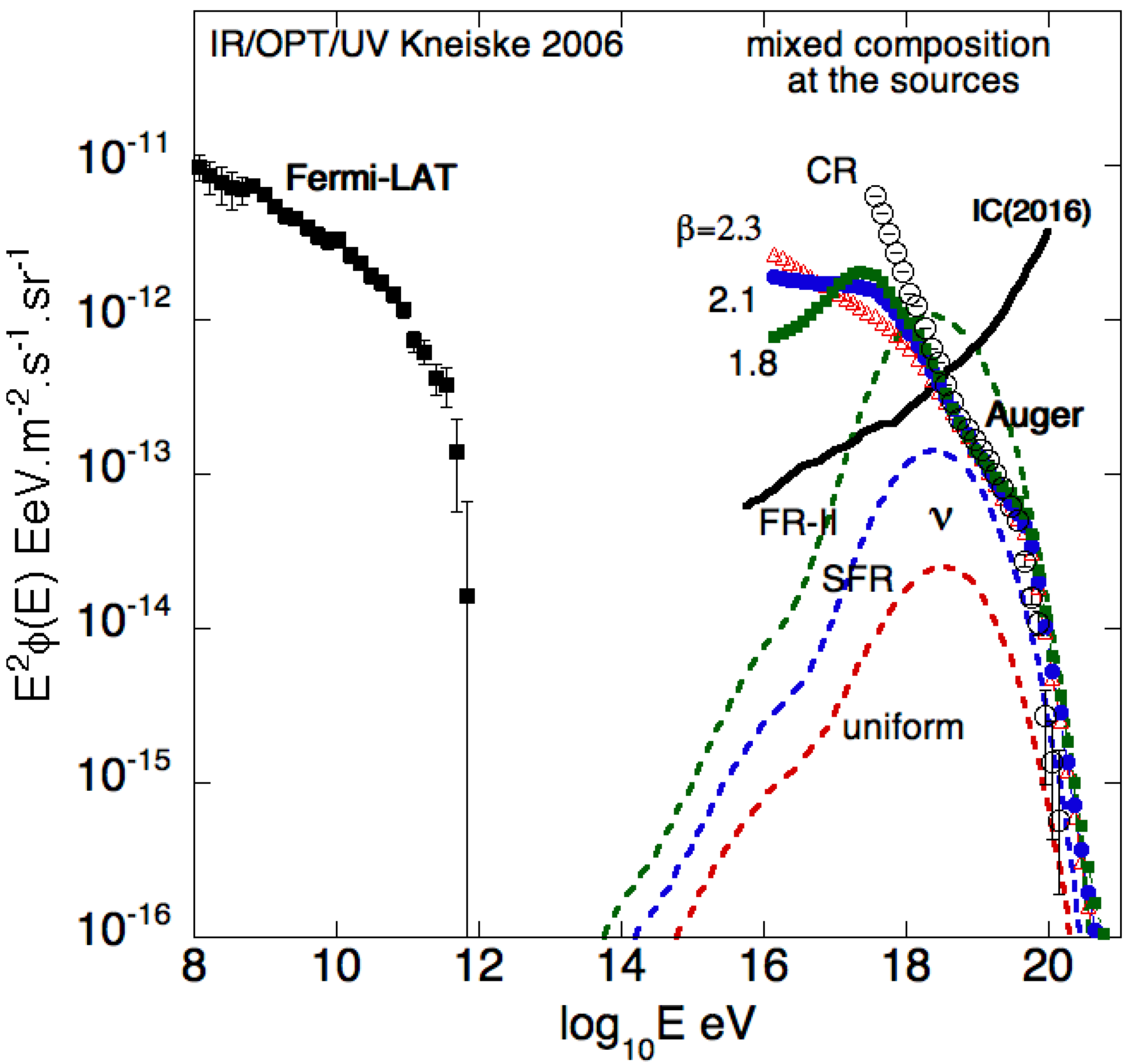
Neutrino "bumps" peaking around 10^{18} eV —> produced by UHECR >>10^{19} eV per nucleon —> π-photoproduction on CMB photons



Strong impact of the cosmological evolution of the sources on the cosmogenic ν fluxes —> evolutions significantly stronger than SFR constrained by IceCube

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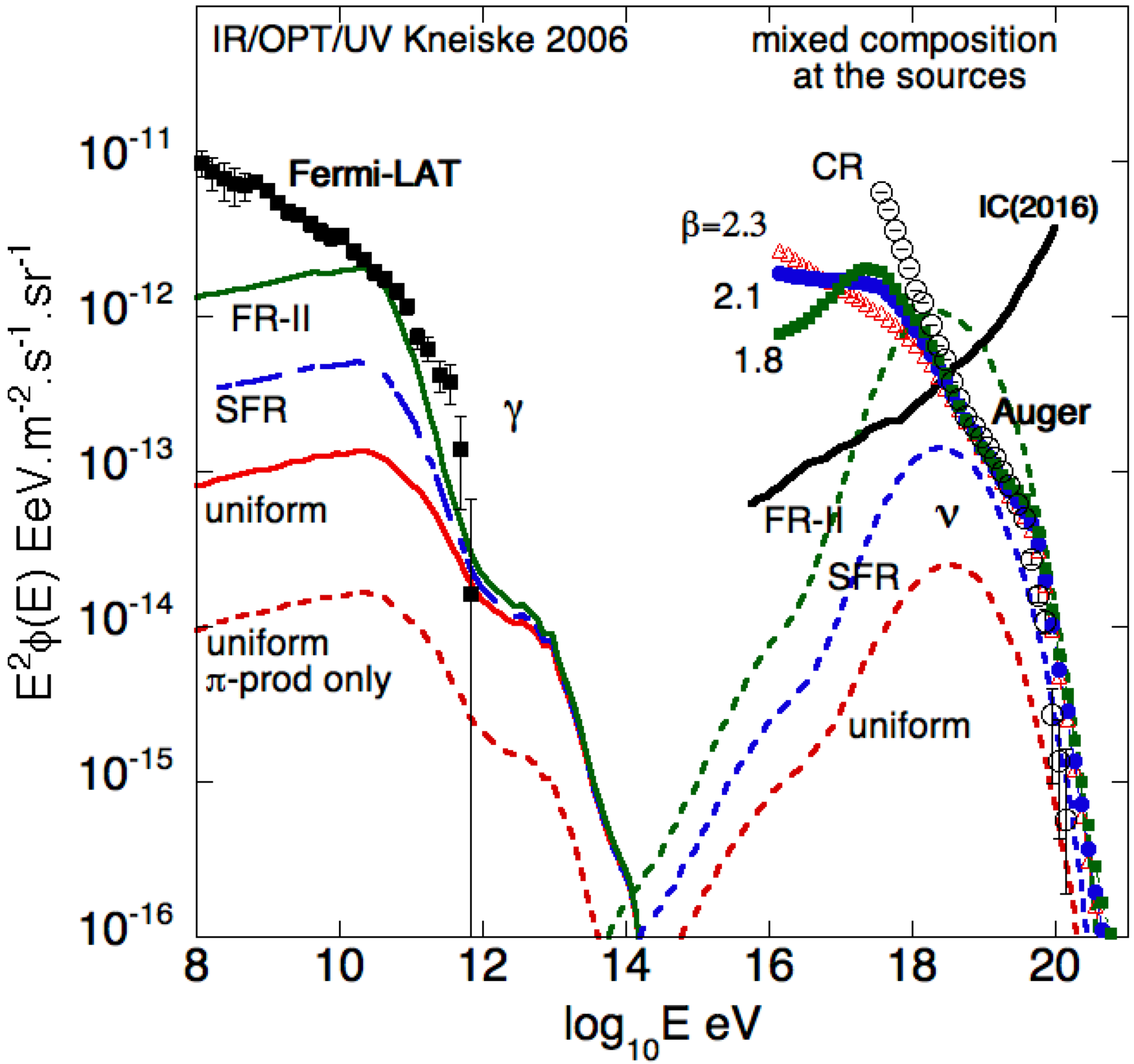
(i) All the energy released in γ and e^+e^- piles up in the subTeV range

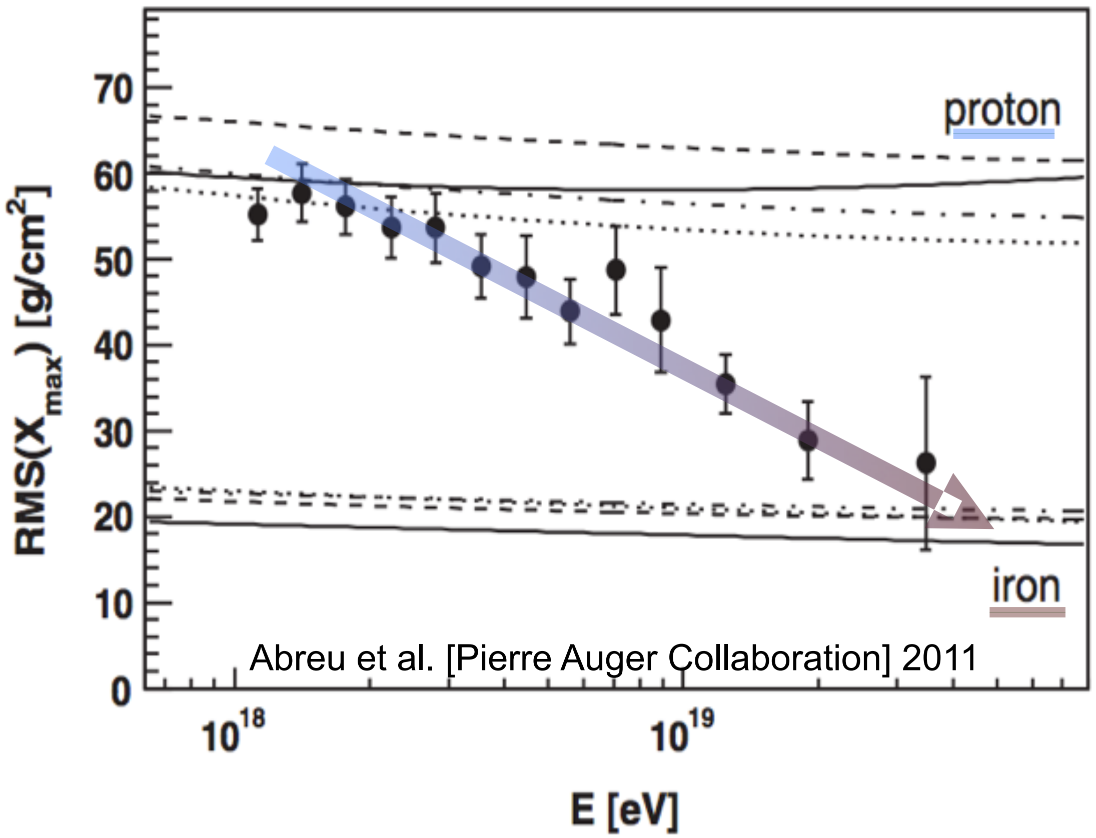
(ii) Strong impact of the cosmological evolution of the sources on the cosmogenic γ fluxes —> strongest evolution also ruled out by Fermi-LAT IGRB

(Adapted from Decerprit and Allard, A&A, 2011)



(iii) subdominant contribution of π-photoproduction to cosmogenic γs —> dominant contribution of the e^+e^- pair production —> unlike cosmogenic νs, cosmogenic γs are not mostly produced by the highest energy particles

Implications of Auger composition measurements



The evolution of the composition implied by Auger composition analyses strongly suggest that the composition is light at the ankle and becoming heavier as the energy increases

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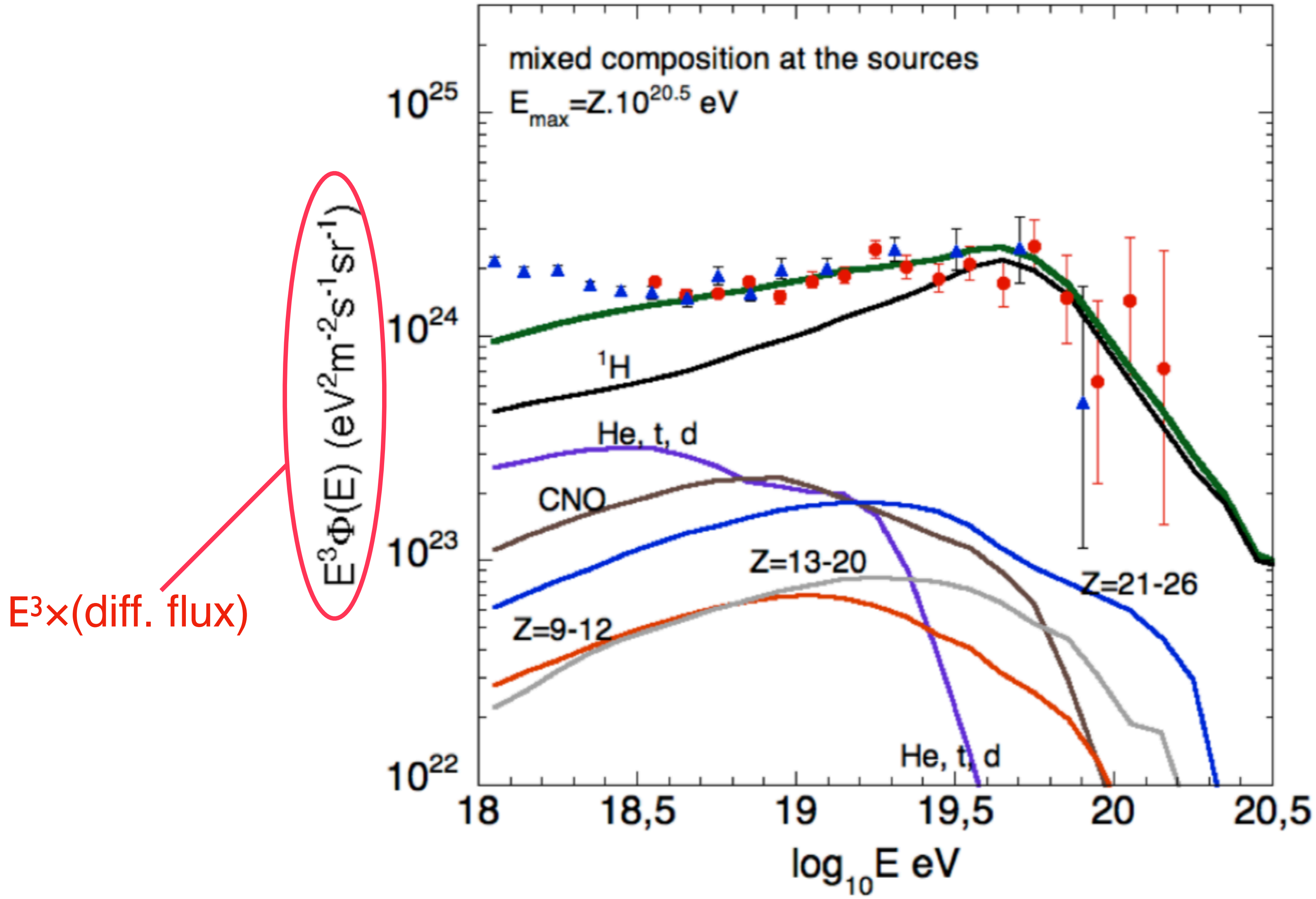

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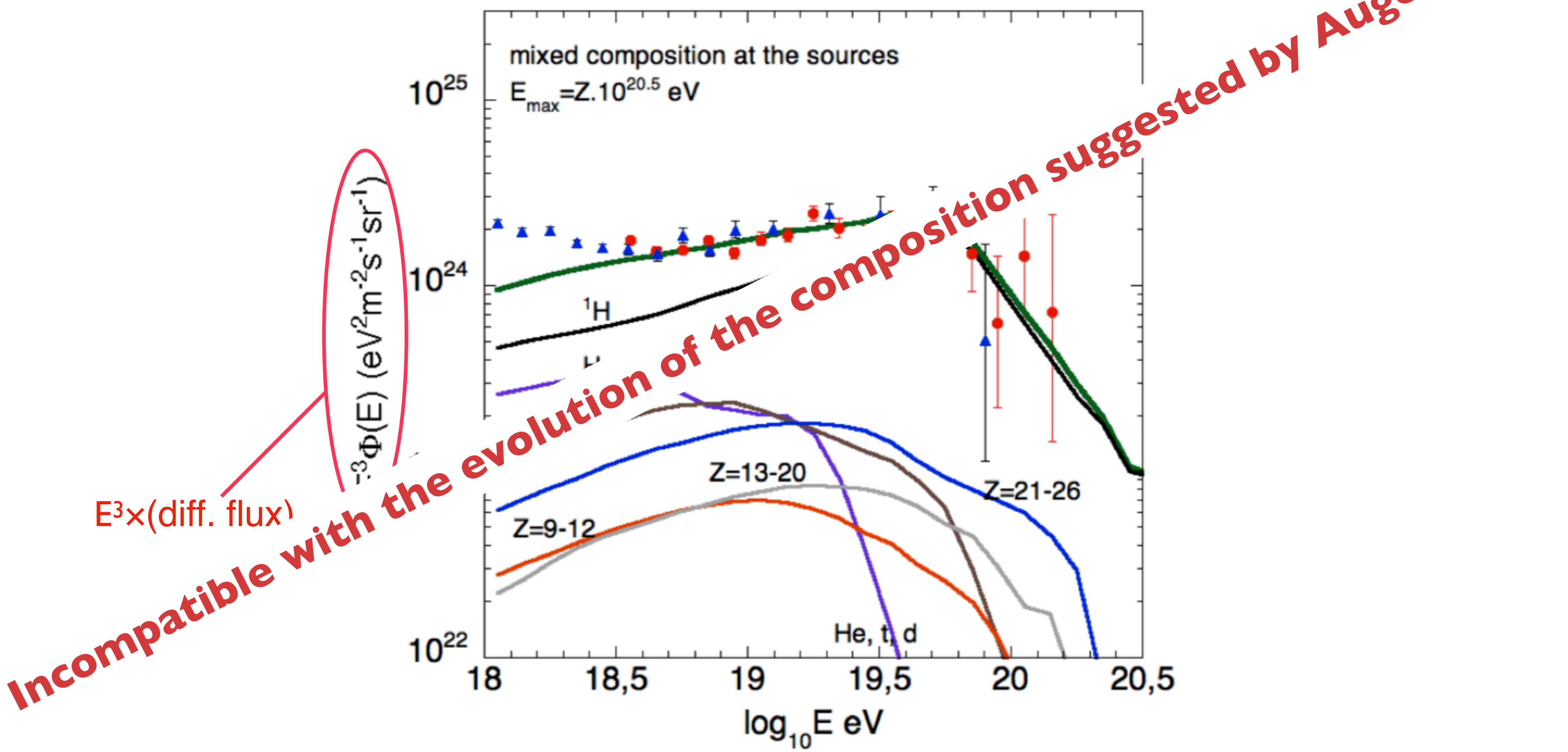

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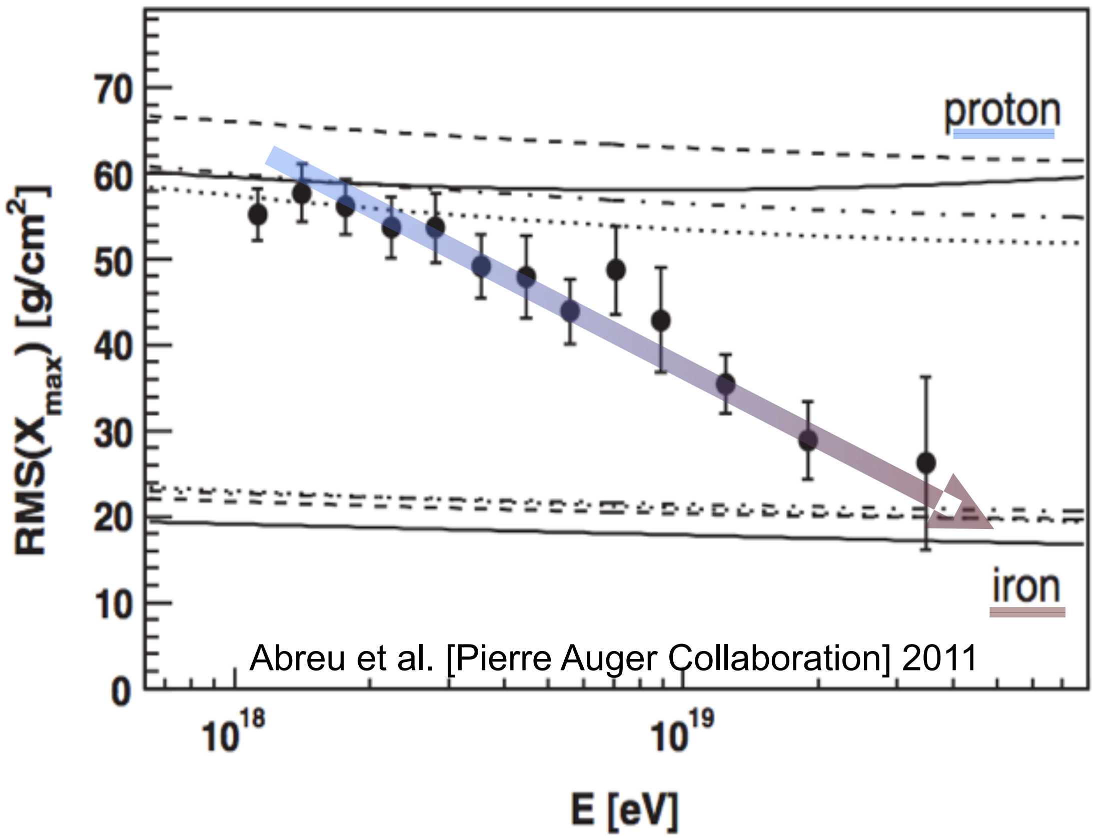
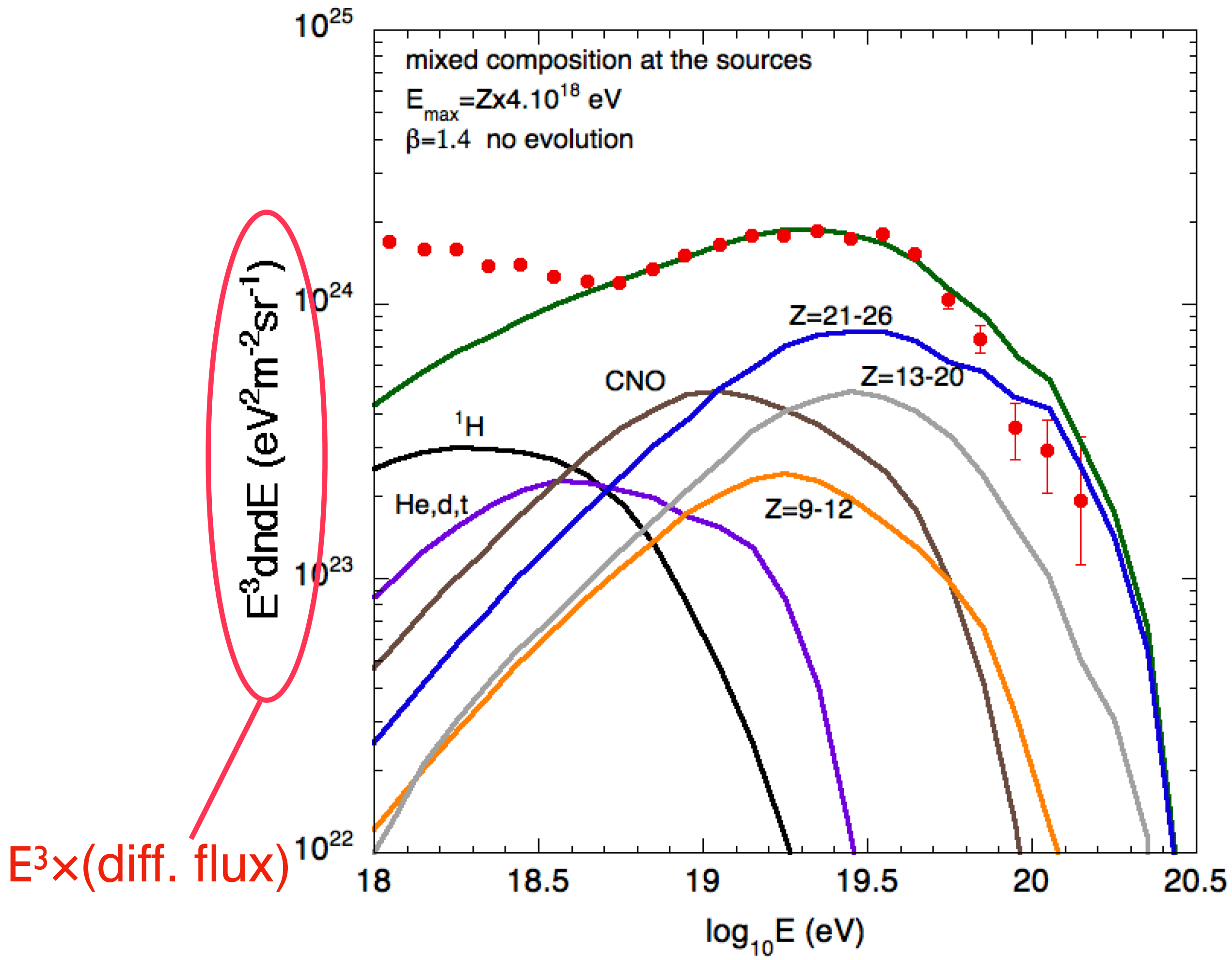




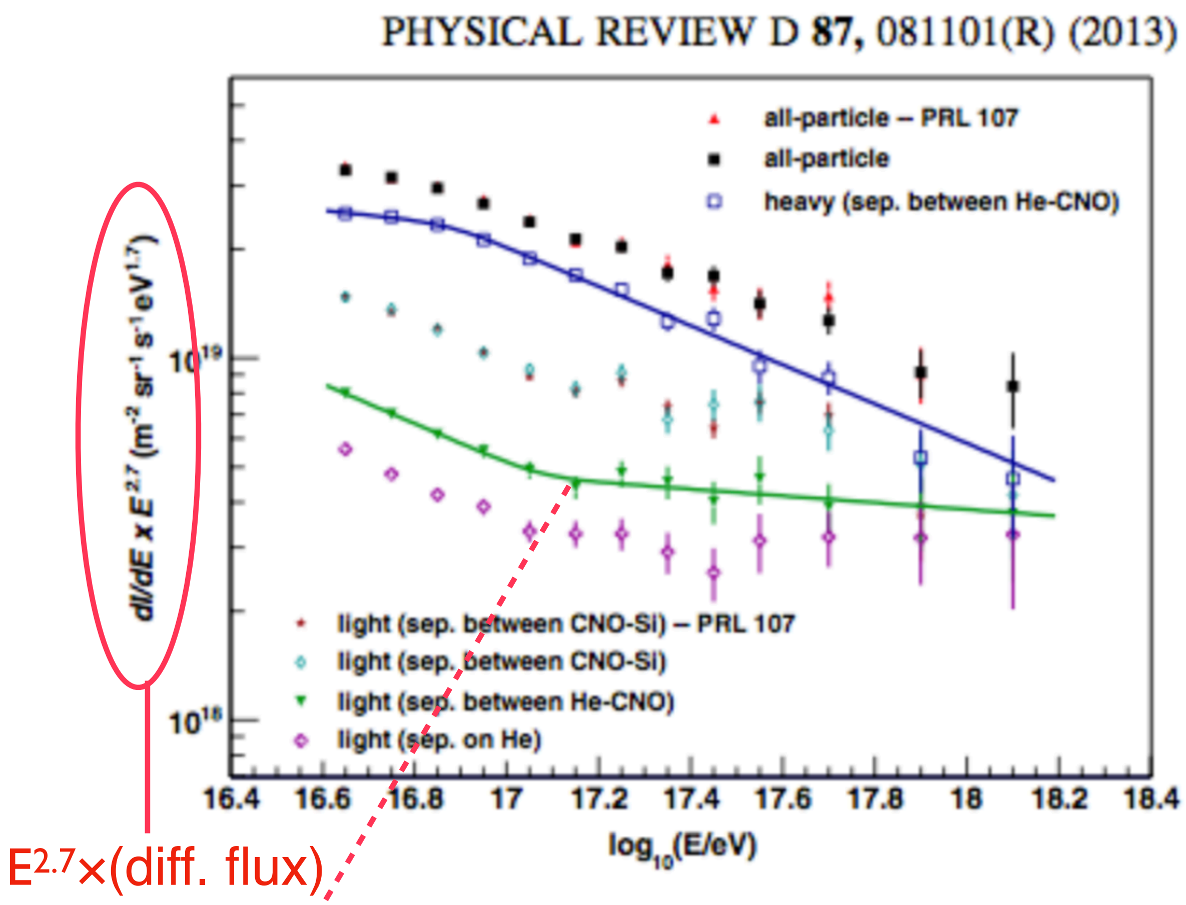
The evolution of the composition implied by Auger composition analyses strongly suggest that the composition is light at the ankle and becoming heavier as the energy increases
—> dominant sources of UHECR do not accelerate protons to the highest energies

Low maximum energy per nucleon (a few EeV to 10^{19} eV, well below the pion production threshold with CMB photons) and hard source spectral indexes required

here $N(E) \propto E^{-\beta}$, $\beta=1.4$, $E_{max}(Z)=Z\times E_{max}^{proton}$, $E_{max}^{proton}=4.10^{18}$ eV

obviously not a good news for UHE cosmogenic neutrinos predictions

KASCADE-Grande's light ankle



KASCADE-Grande's light ankle, equivalent to the ankle of the cosmic-ray spectrum but for the light component (H-He), around 10^{17} eV

—> most probably implies that extragalactic light component starts to be significant already at 10^{17} eV

—> light component quite soft above 10^{17} eV (~2.7)

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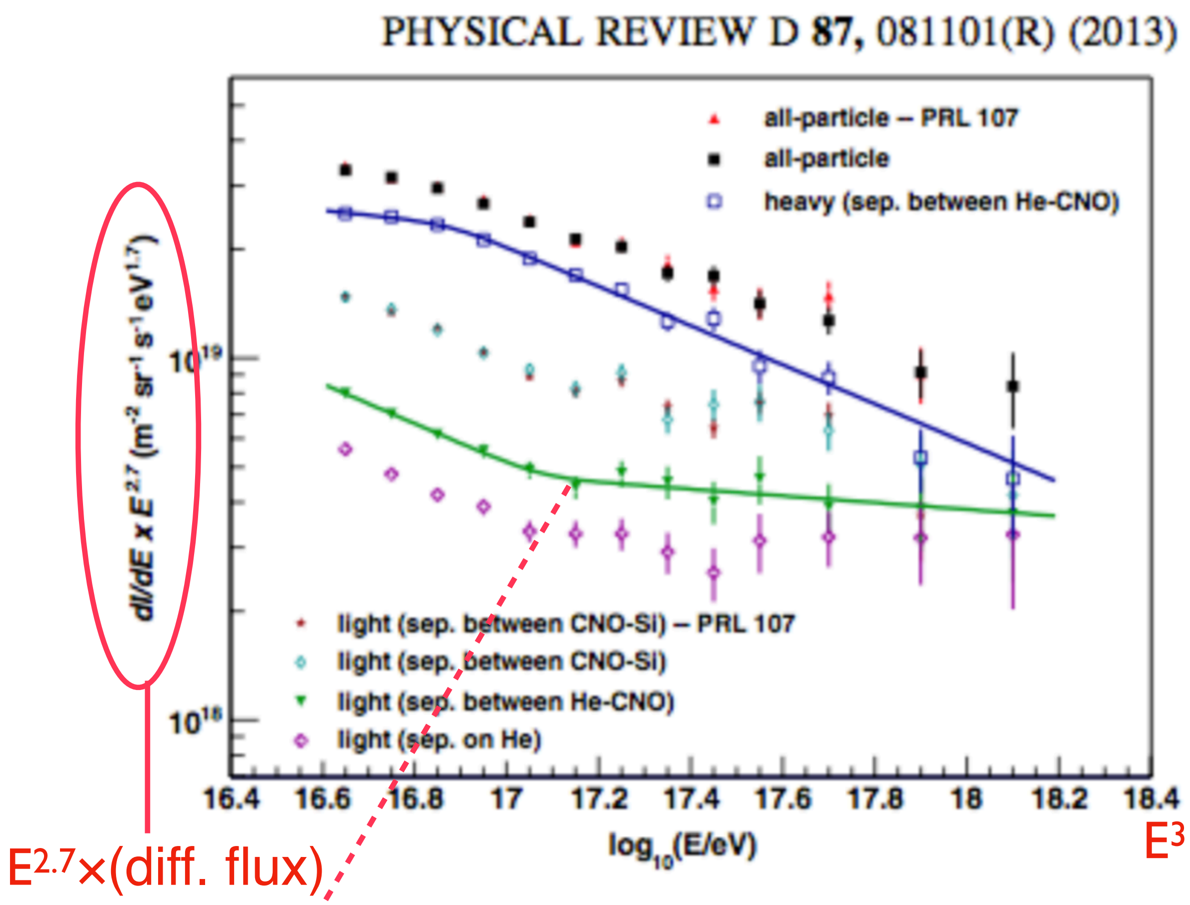

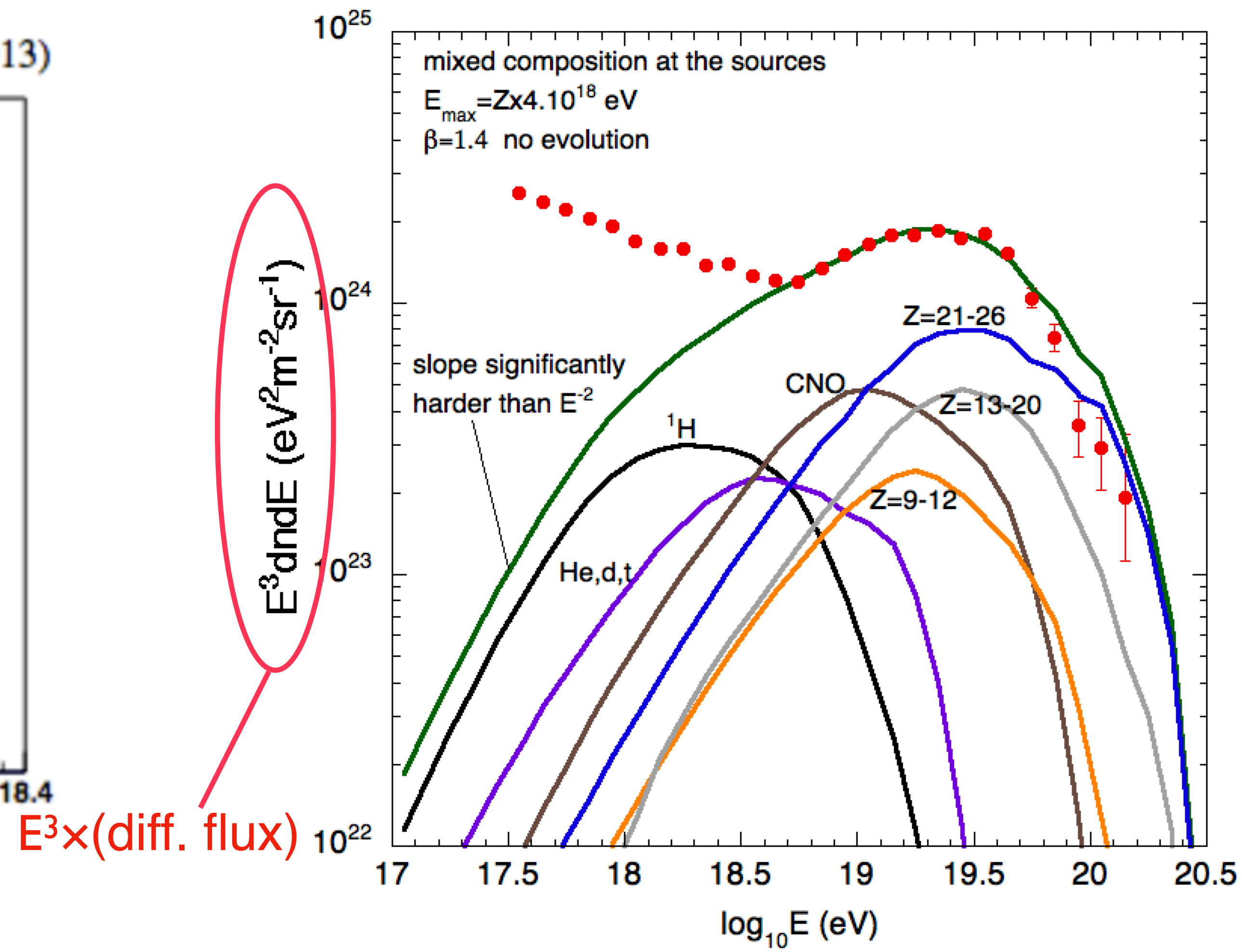

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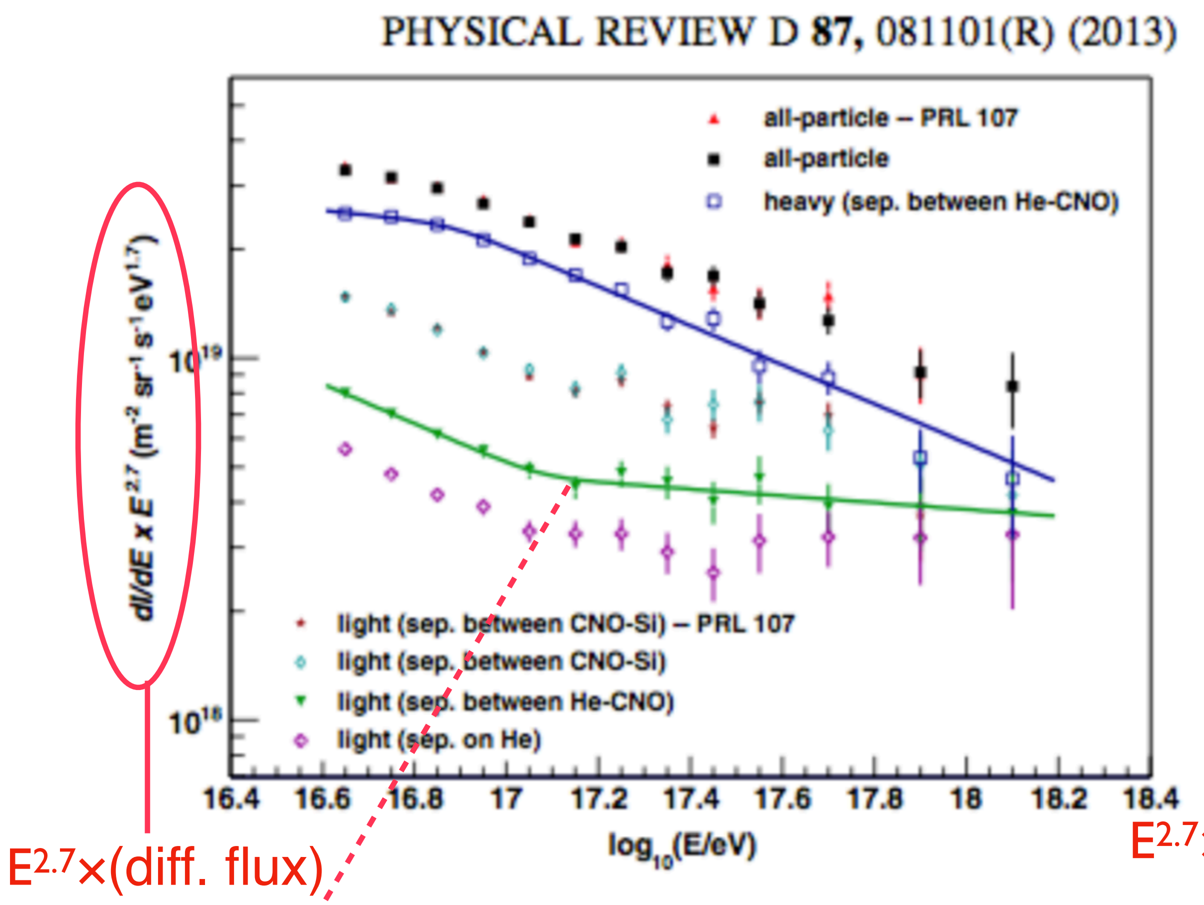
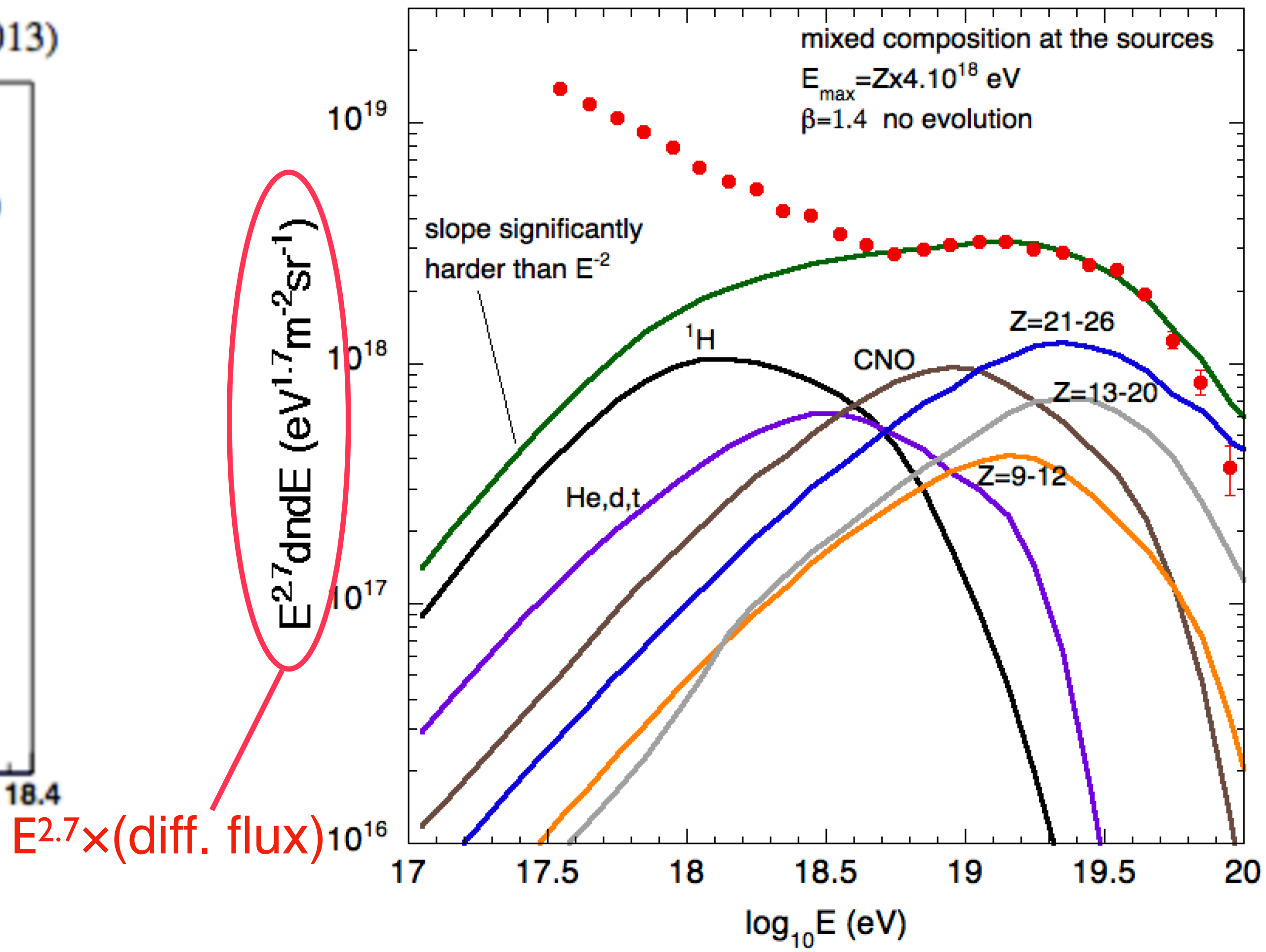
Difficult to make a consistent picture of the Auger composition + the light ankle with the above phenomenological model

One would need a much softer spectrum for the light nuclei

KASCADE-Grande's light ankle





KASCADE-Grande's light ankle, equivalent to the ankle of the cosmic-ray spectrum but for the light component (H-He), around 10^{17} eV

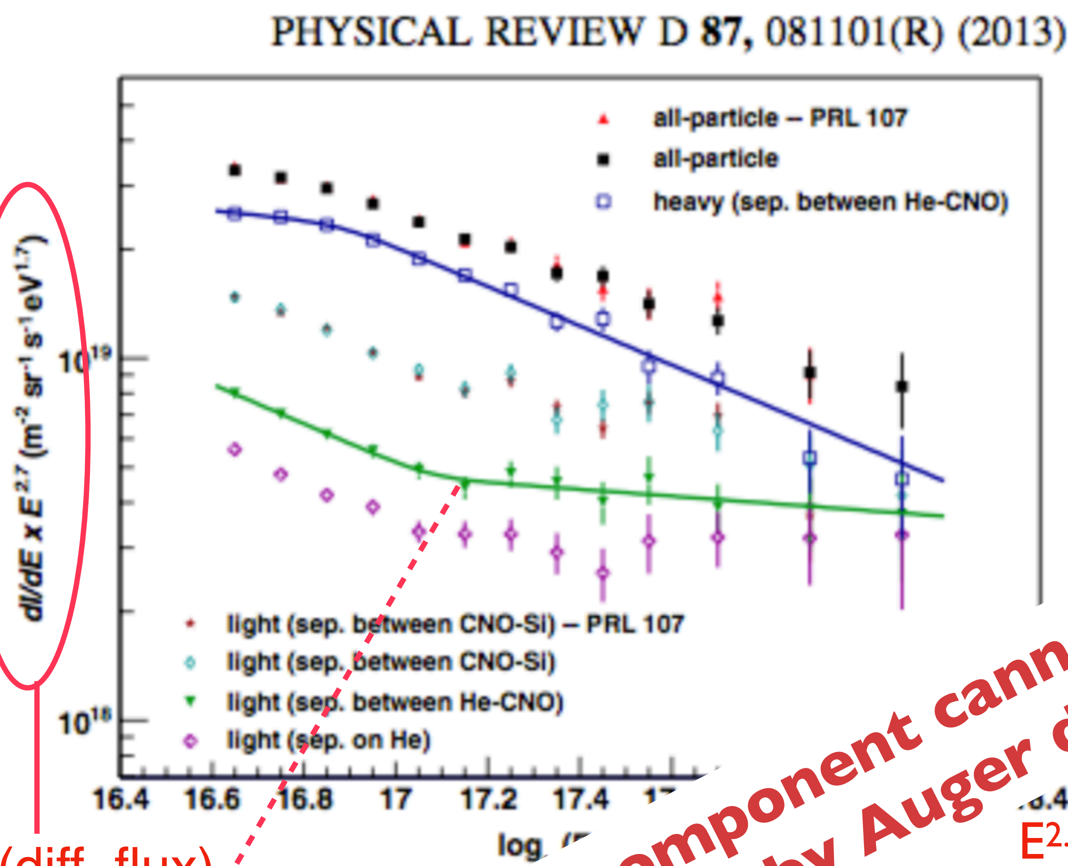
—> most probably implies that extragalactic light component starts to be significant already at 10^{17} eV

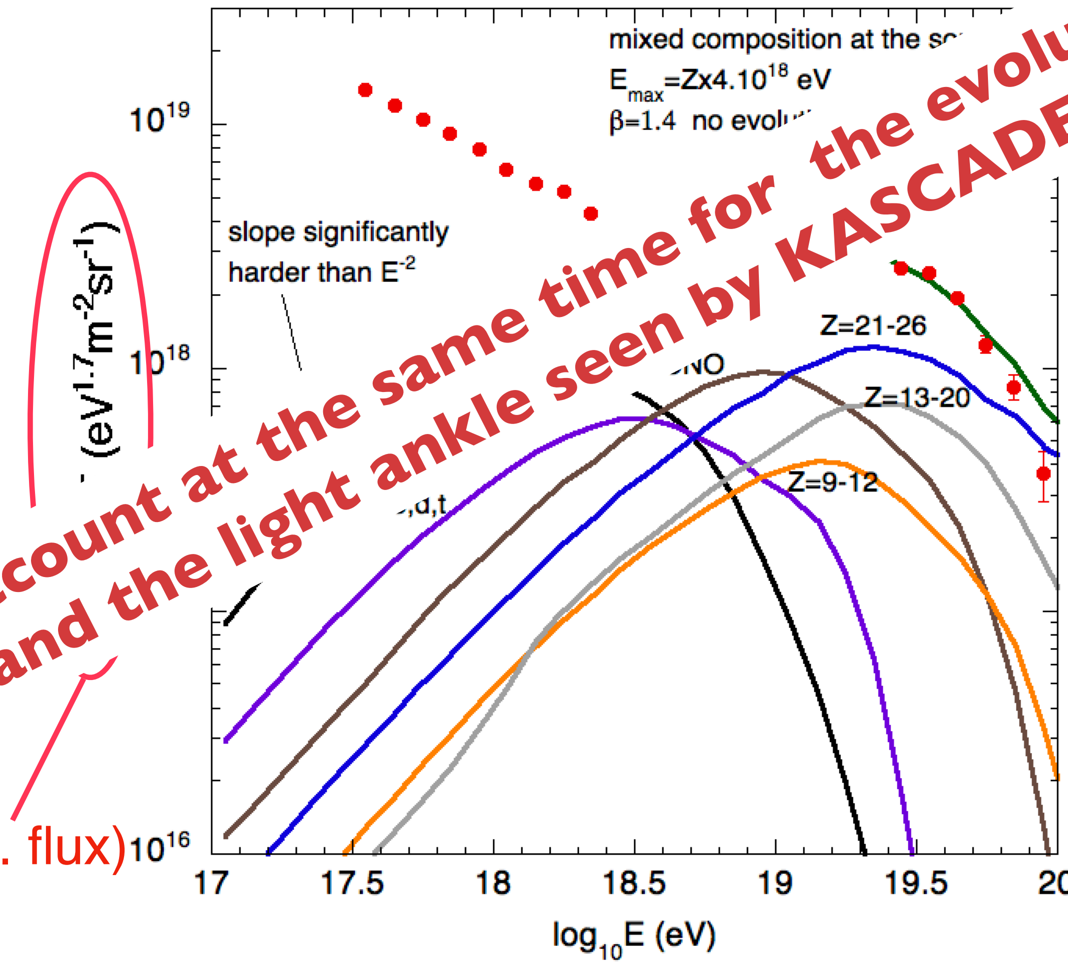
—> light component quite soft above 10^{17} eV (~2.7)

Difficult to make a consistent picture of the Auger composition + the light ankle with the above phenomenological model

One would need a much softer spectrum for the light nuclei

KASCADE-Grande's light ankle





Such an extragalactic component cannot account at the same time for the evolution of the composition suggested by Auger data and the light ankle seen by KASCADE-Grande

KASCADE ... ankle, equivalent to the ankle of the cosmic-ray spectrum but for the light comp... , around 10^{17} eV

- ...bably implies that extragalactic light component starts to be significant already at 10^{17} eV
- ... component quite soft above 10^{17} eV (~2.7)

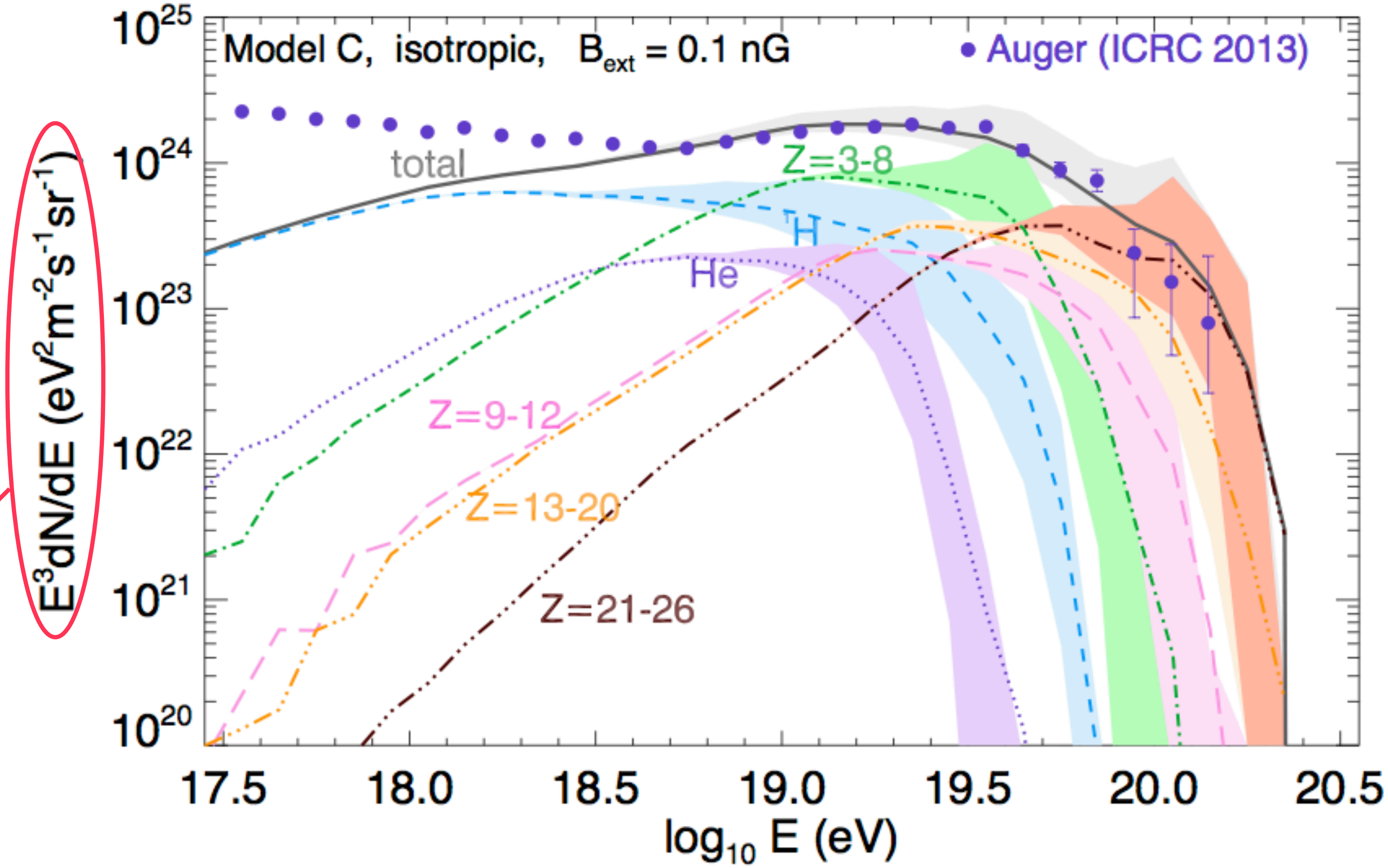
Phenomenological model of UHECR acceleration as a solution to the soft proton spectrum issue

Model of UHECR acceleration at GRB internal shocks (Globus et al. 2015) can reproduce UHECR data (Auger spectrum and composition)

- if most of the energy dissipated is communicated to accelerated cosmic-rays
- the composition injected at the shock has ~ 10 times galactic CR metallicity

NB : Spectrum on earth, sum of the contributions of all GRB after propagation in the extragalactic medium

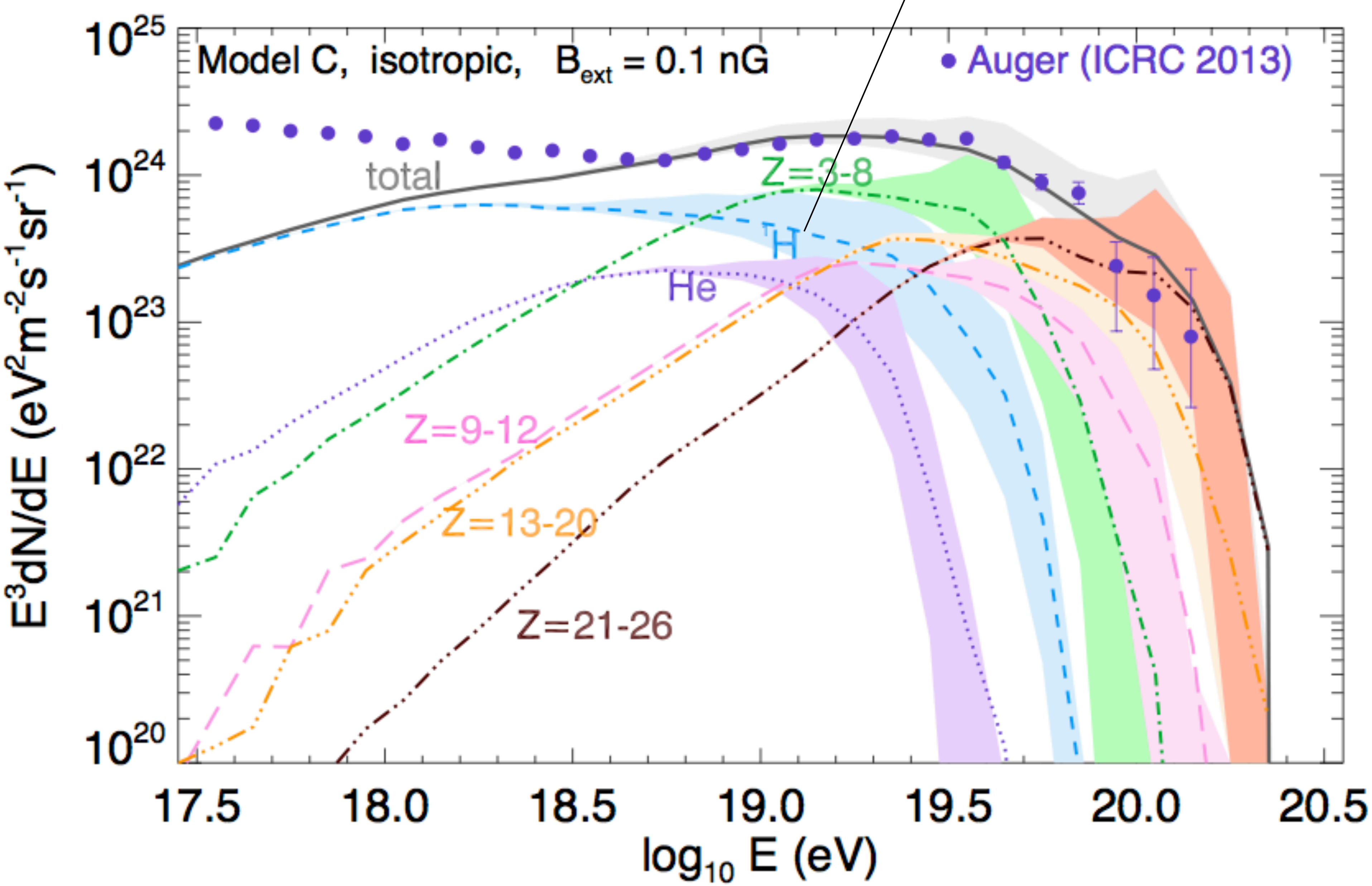
E³×(diff. flux)



N. Globus, D. Allard, R. Mochkovitch, E. Parizot, MNRAS, 2015

Phenomenological model : implications for the GCR to EGCR transition

low proton maximum energy
—> composition getting heavier as the energy increases



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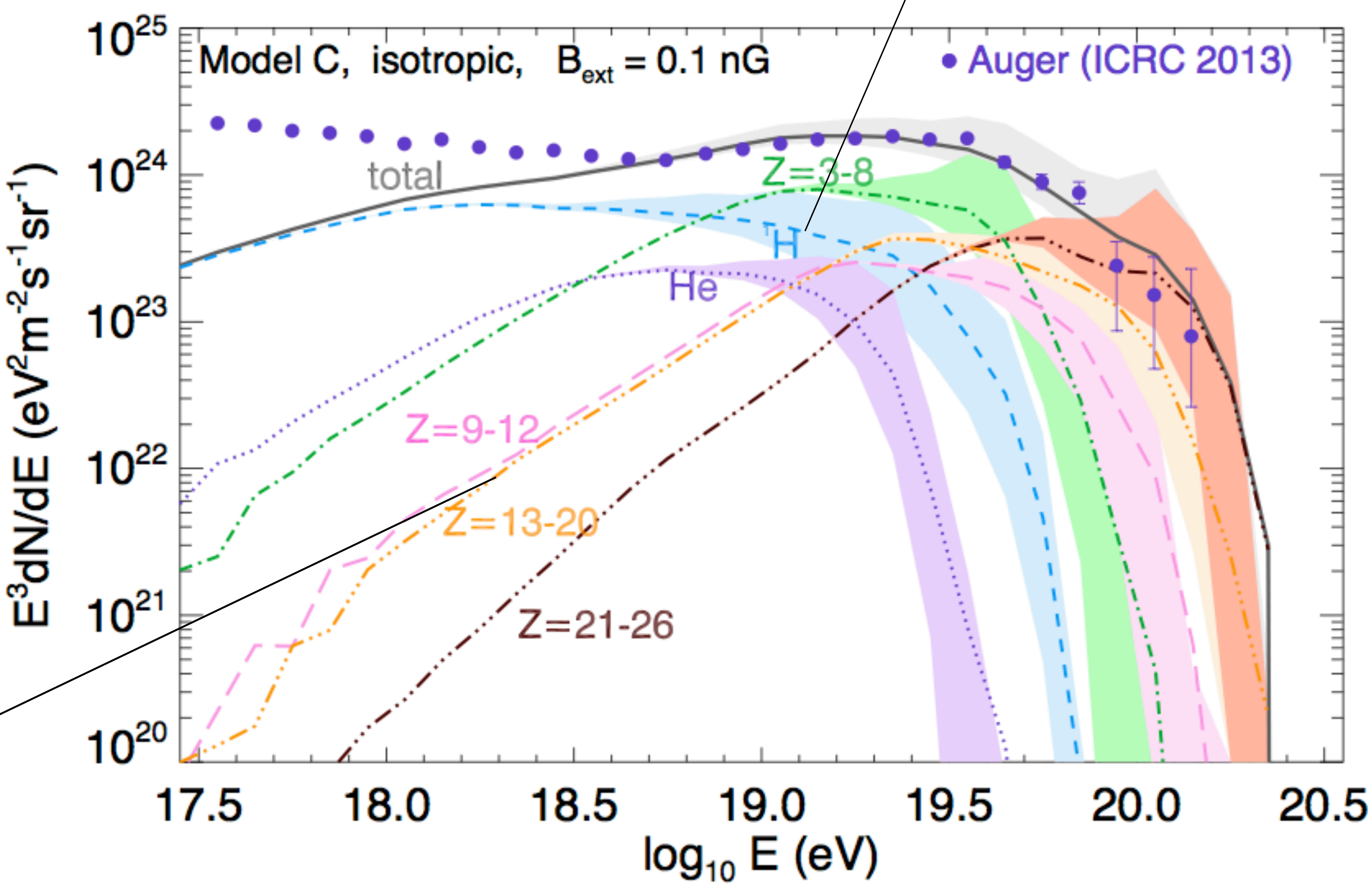


Heavier nuclei spectrum : Very hard due to the high-pass filter effect of the escape process
—> Hard nuclei spectrum required to fit Auger composition at high energy

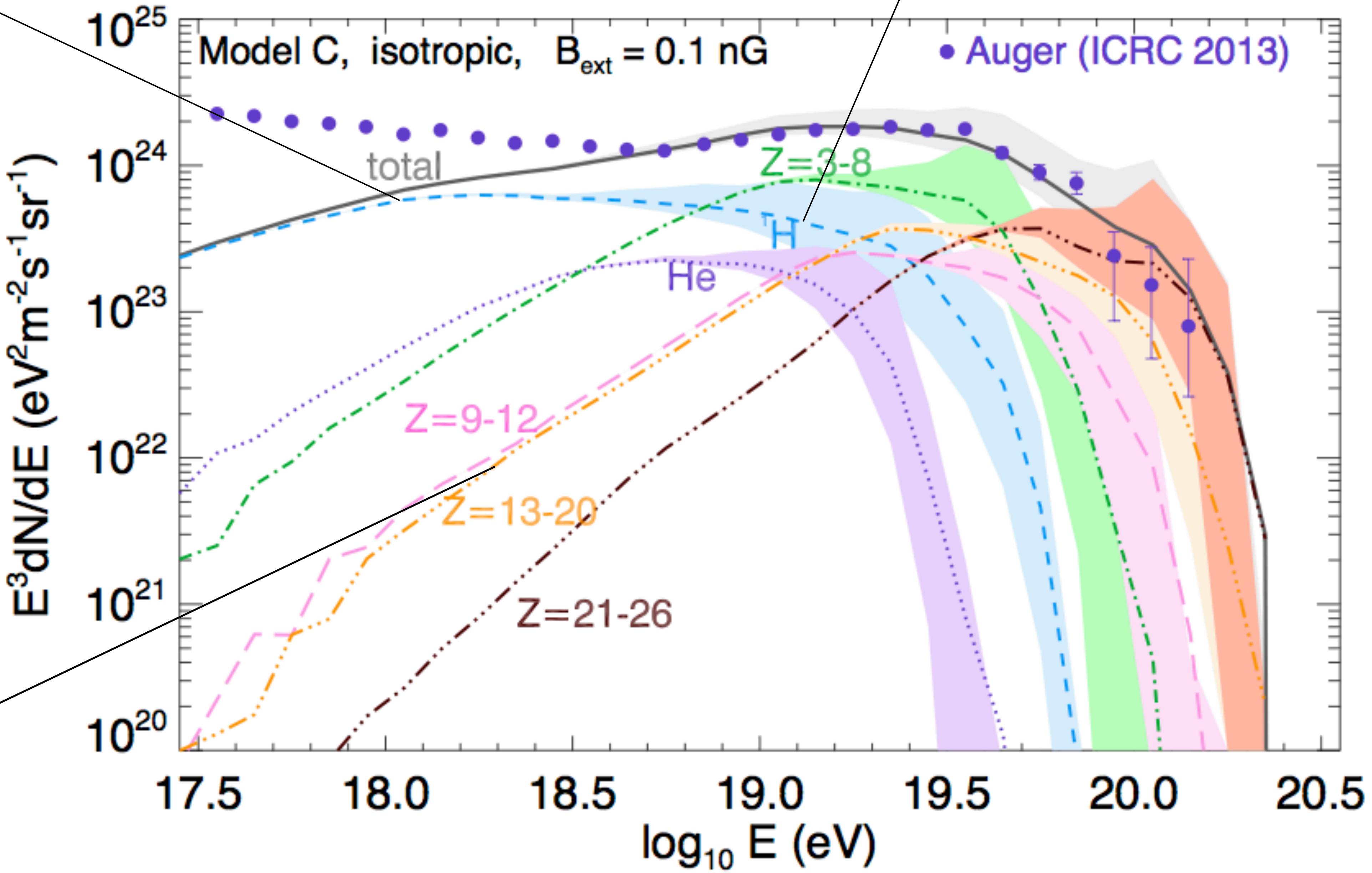
Phenomenological model : implications for the GCR to EGCR transition

Proton spectrum : Soft due to the efficient escape of neutrons from the source (secondary neutron from the photodisintegration of nuclei within the source)

—> Allows the proton component to extend down to the light ankle seen by KASCADE-Grande

low proton maximum energy

—> composition getting heavier as the energy increases



Heavier nuclei spectrum : Very hard due to the high-pass filter effect of the escape process

—> Hard nuclei spectrum required to fit Auger composition at high energy

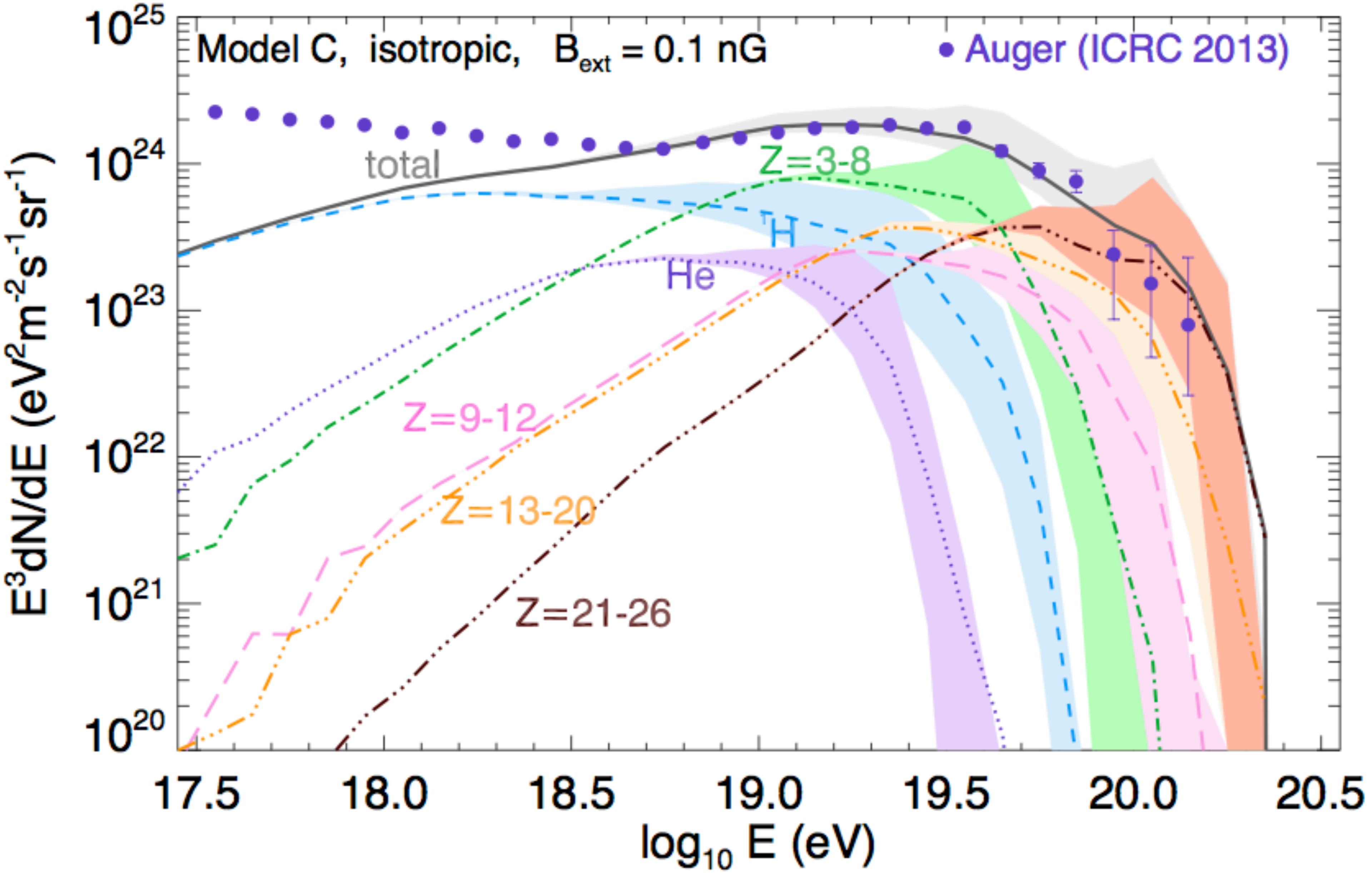
Phenomenological model : implications for the GCR to EGCR transition

The difference in shape between the proton and nuclei spectra arises from the fact that the source environment is strongly magnetized and harbours dense radiation fields

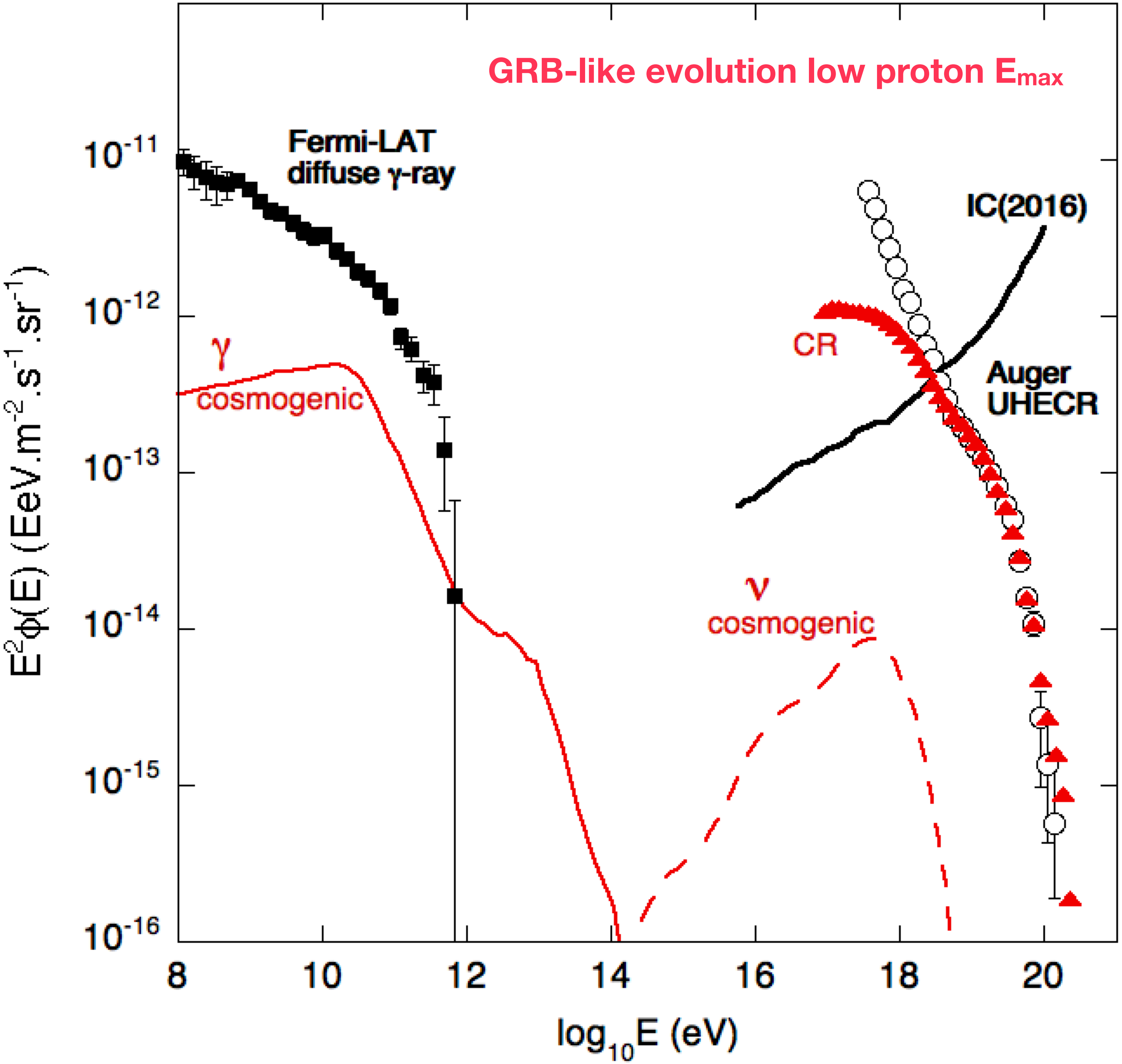
—> should not be a distinctive feature of GRB sources

We showed that an extragalactic component presenting these spectral features was able to account for the light ankle and the evolution of the composition measured by Auger

Globus, Allard & Parizot, 2015, PRD rapid com.



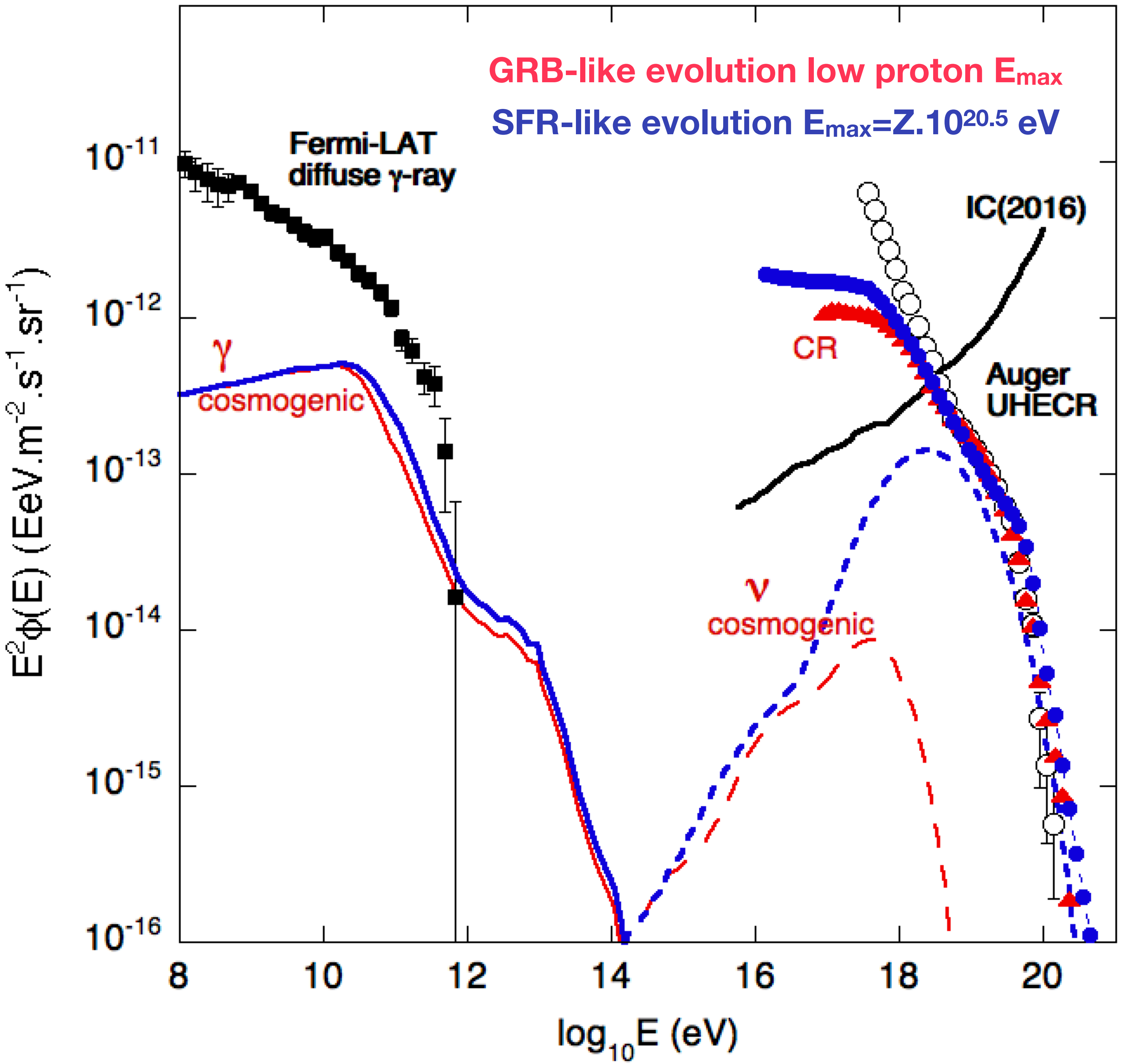
Phenomenological model : multi-messenger implications



The impact is, as expected, very strong on the predicted cosmogenic neutrino fluxes

Despite the low maximum energy per nucleon, the diffuse γ-ray flux is very similar to that of previous mixed composition case

Phenomenological model : multi-messenger implications



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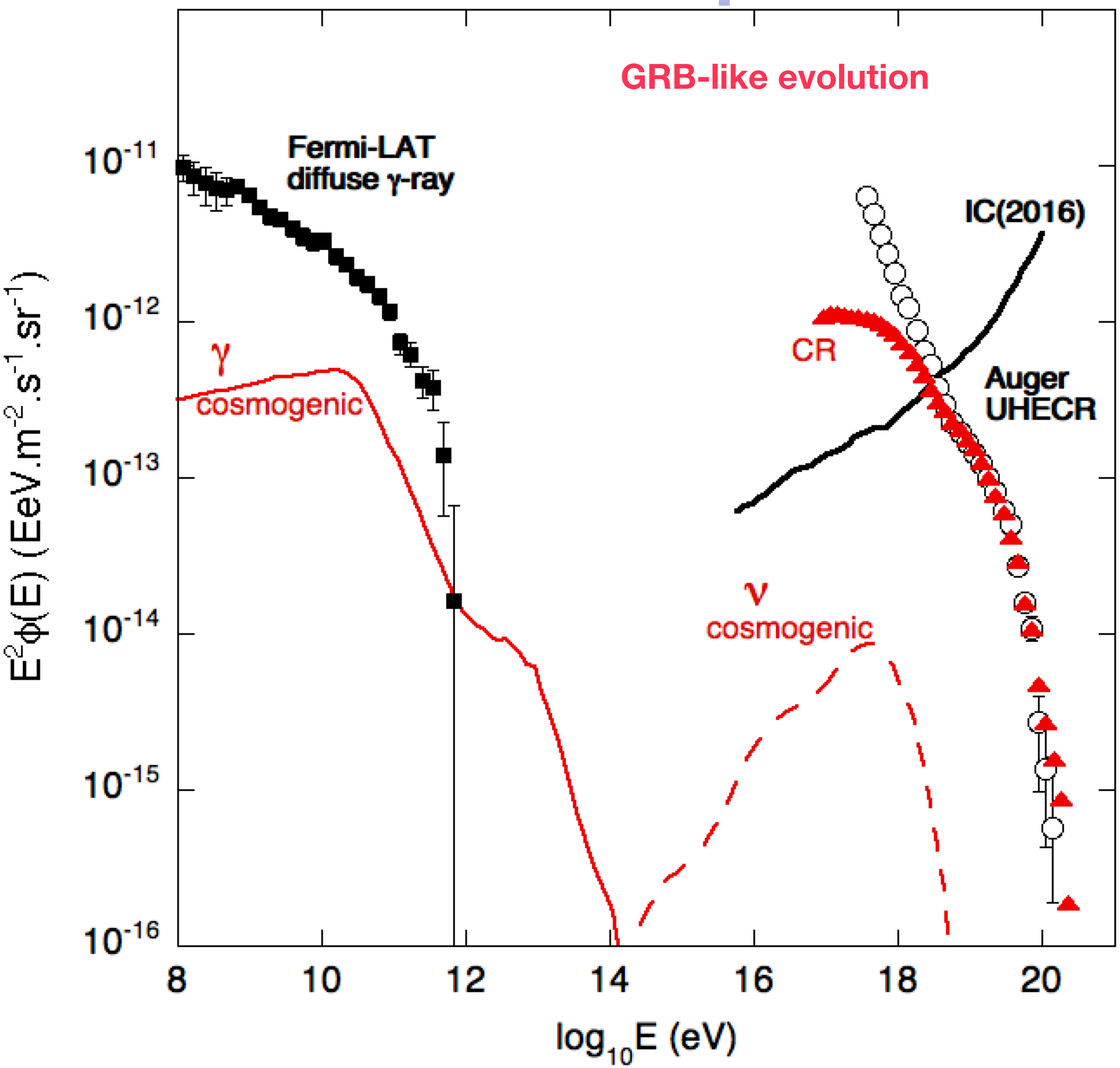
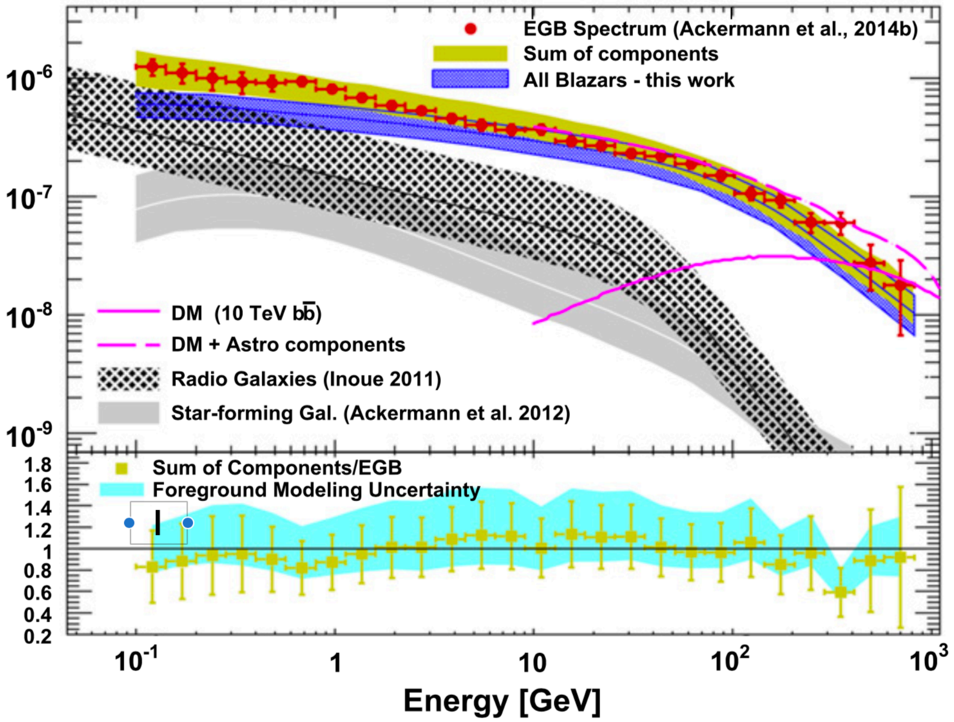


The impact is, as expected, very strong on the predicted cosmogenic neutrino fluxes

Despite the low maximum energy per nucleon, the diffuse γ-ray flux is very similar to that of previous mixed composition case

This scenario looks completely unconstrained from the point of view of cosmogenic neutrinos and photons
But Fermi-LAT data contain more informations than what we just discussed

Composition of the extragalactic γ-ray background



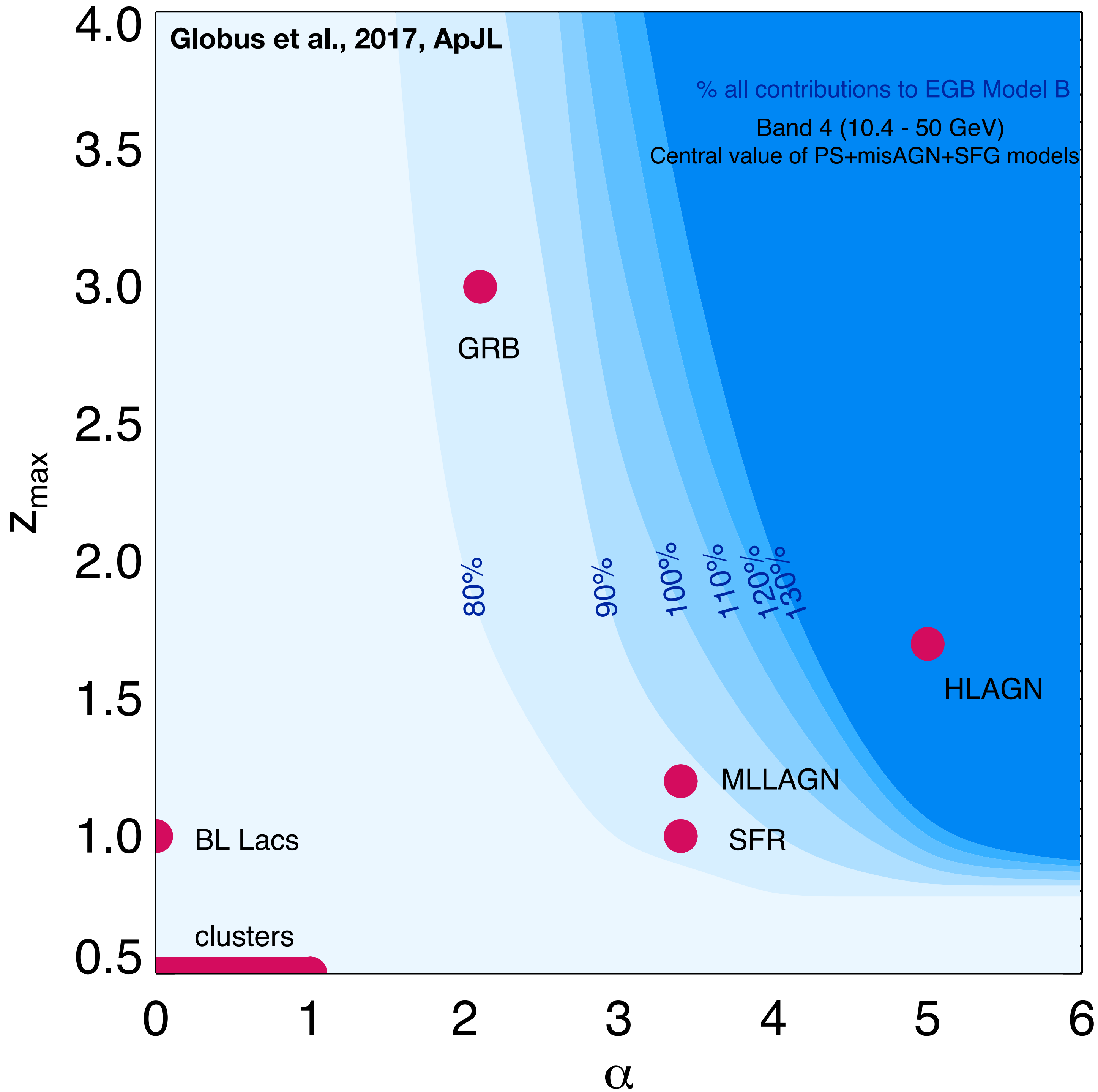
Ajello et al., ApJ, 2015

➡ different astrophysical sources are known to contribute to the total γ-ray background and must be accounted for :

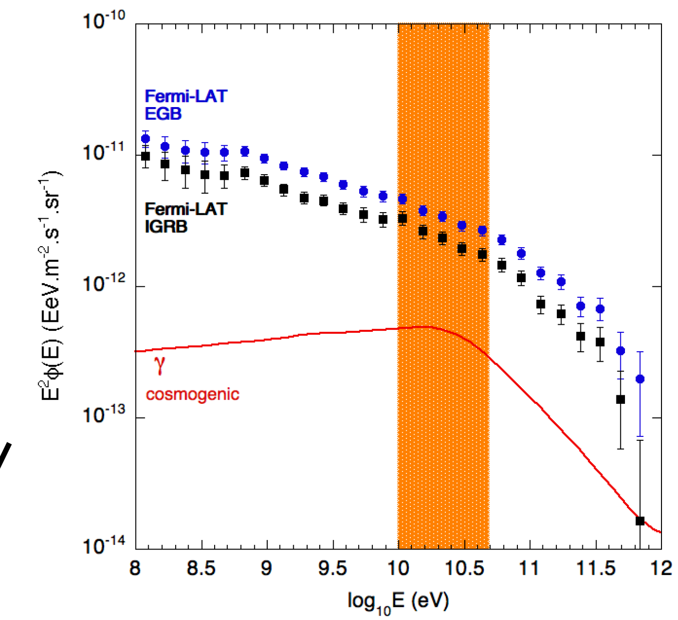
- Blazars (dominant contribution) estimated from Fermi data by Ackermann et al. , PRL, 2016 and Zechlin et al., ApJ, 2016
- Star forming galaxies estimated from Fermi data by Ackermann et al. , 2012
- Misaligned AGNs estimated by Inoue, 2011

The contribution of UHECR must added to those to check whether or not a given UHECR astrophysical model is viable.
We use the UHECR output obtained from our calculations for GRB sources (soft spectrum for protons and hard for composed species) and run our calculation for different hypotheses on the cosmological evolution to see which ones are disfavoured by Fermi data

Summary plot on the allowed cosmological evolutions



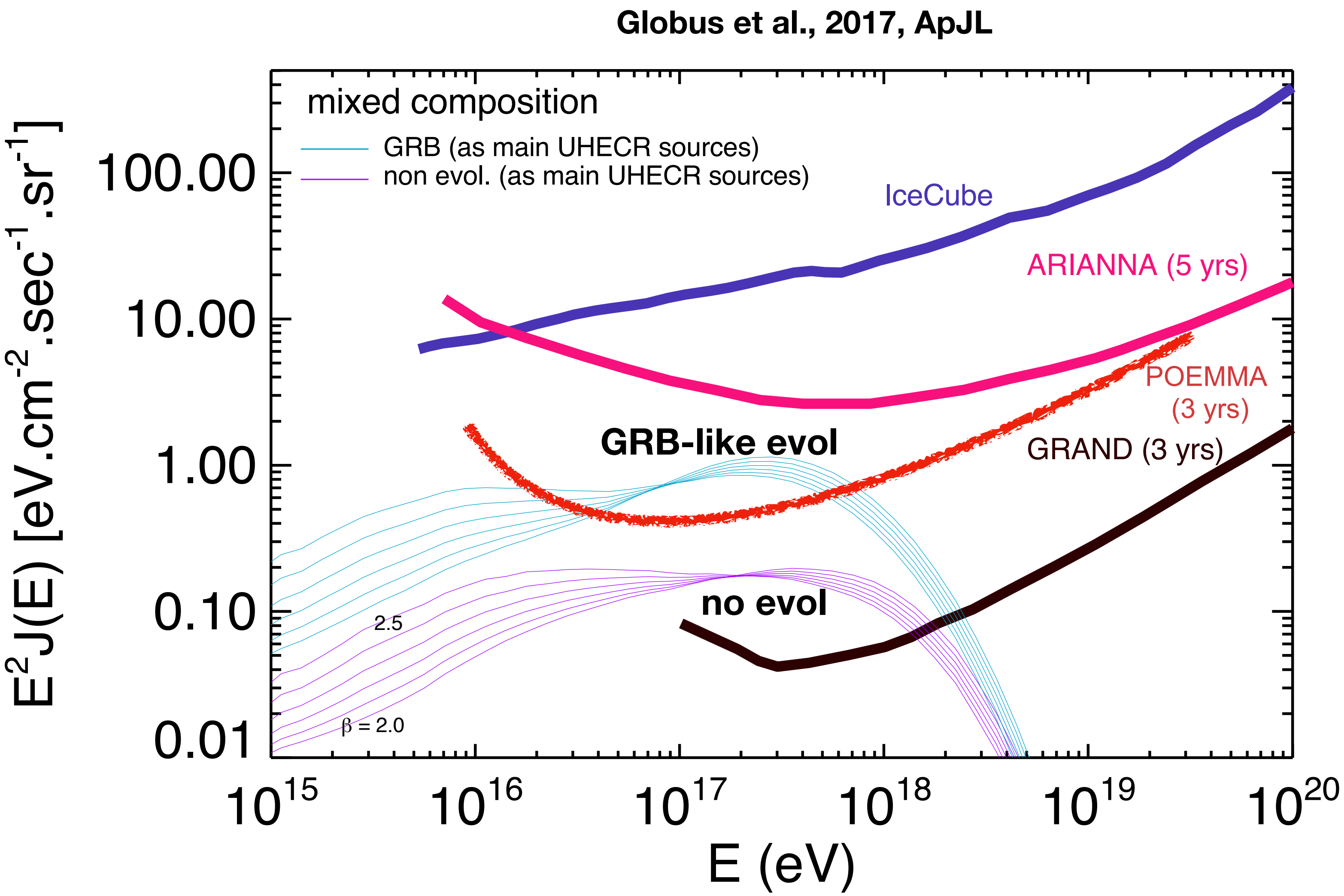
Astrophysical sources evolution usually parametrised as : $(1+z)^{\alpha}$ up to a redshift $\mathbf{z_{max}}$



In the 10-50 GeV band, where the UHECR contribution to the EGRB is the largest

In the case of our UHECR model (light ankle and low Emax), only very strong evolutions such as that of very luminous AGNs are clearly disfavoured

Discussion of the resulting cosmogenic neutrino fluxes

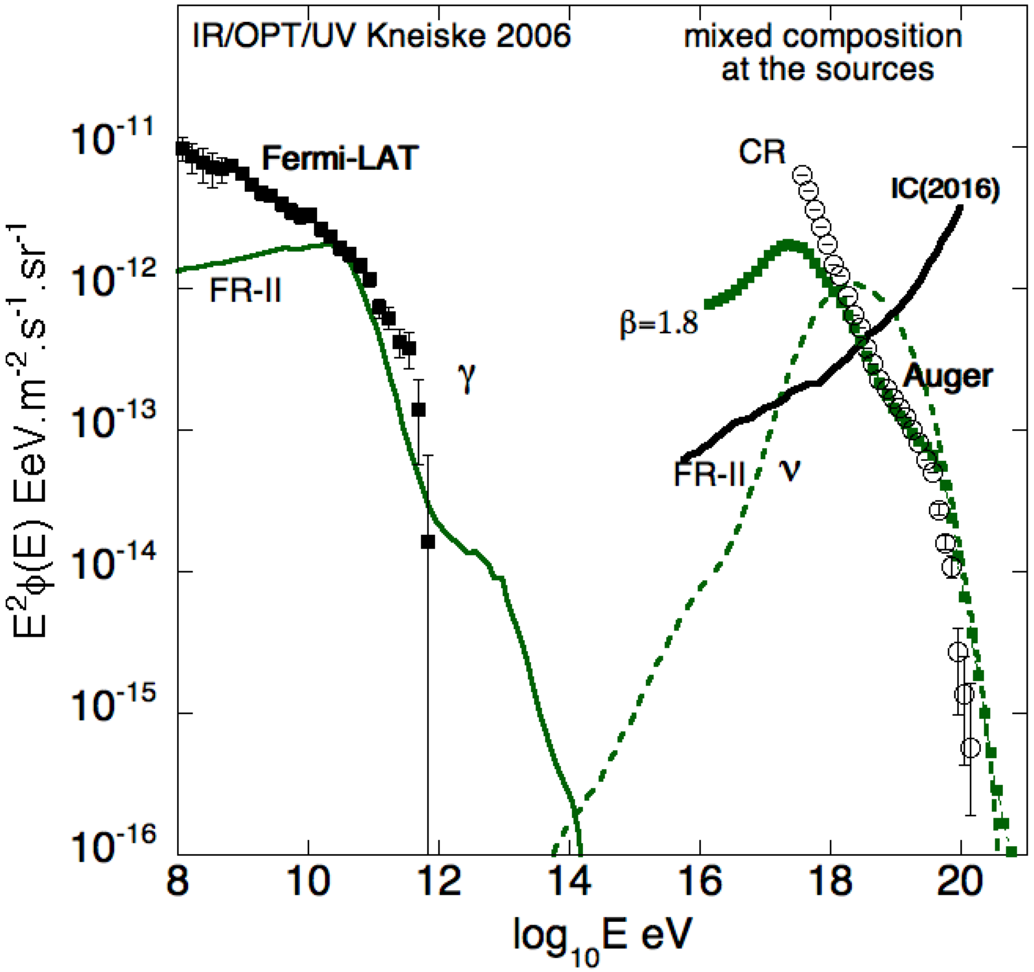


The range of cosmogenic neutrino fluxes predicted in the framework of our model are low (mostly due to the low value of the maximum energy per nucleon)

Not observable by current and mid-term experiments
GRAND and possibly POEMMA could see some neutrinos for GRB or SFR-like evolutions

However there is possibly more to observe than just the cosmogenic neutrinos from the dominant contribution to UHECRs

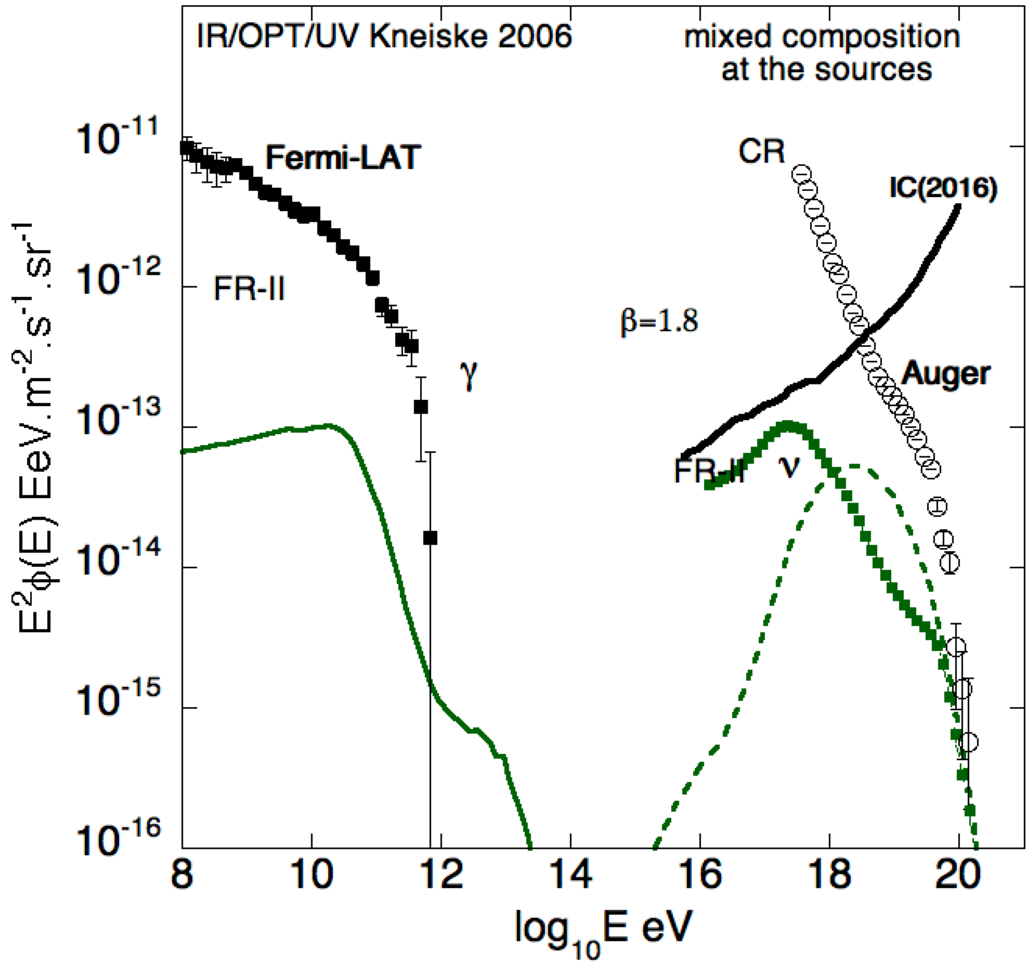
Constraining the presence of powerful protons accelerators in the universe



Let us consider proton accelerators (above 10^{20} eV) with a strong source evolution

- ➡ green curve is ruled out by Fermi, IceCube and Auger (composition)
- ➡ Let us instead assume it is a subdominant part of the spectrum, say 5% at 10^{19} eV

Constraining the presence of powerful protons accelerators in the universe



Let us consider proton accelerators (above 10^{20} eV) with a strong source evolution

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- ➡ Then it is not ruled out anymore by any experimental constraint

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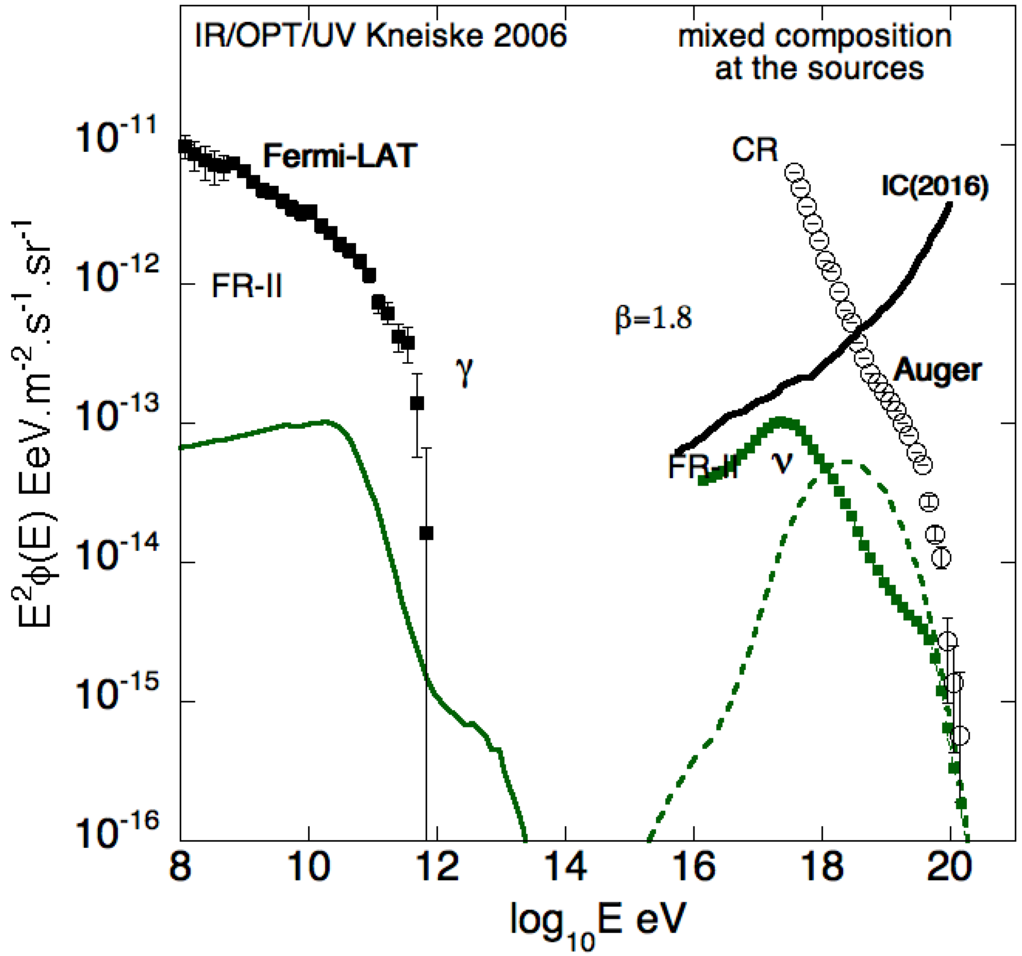

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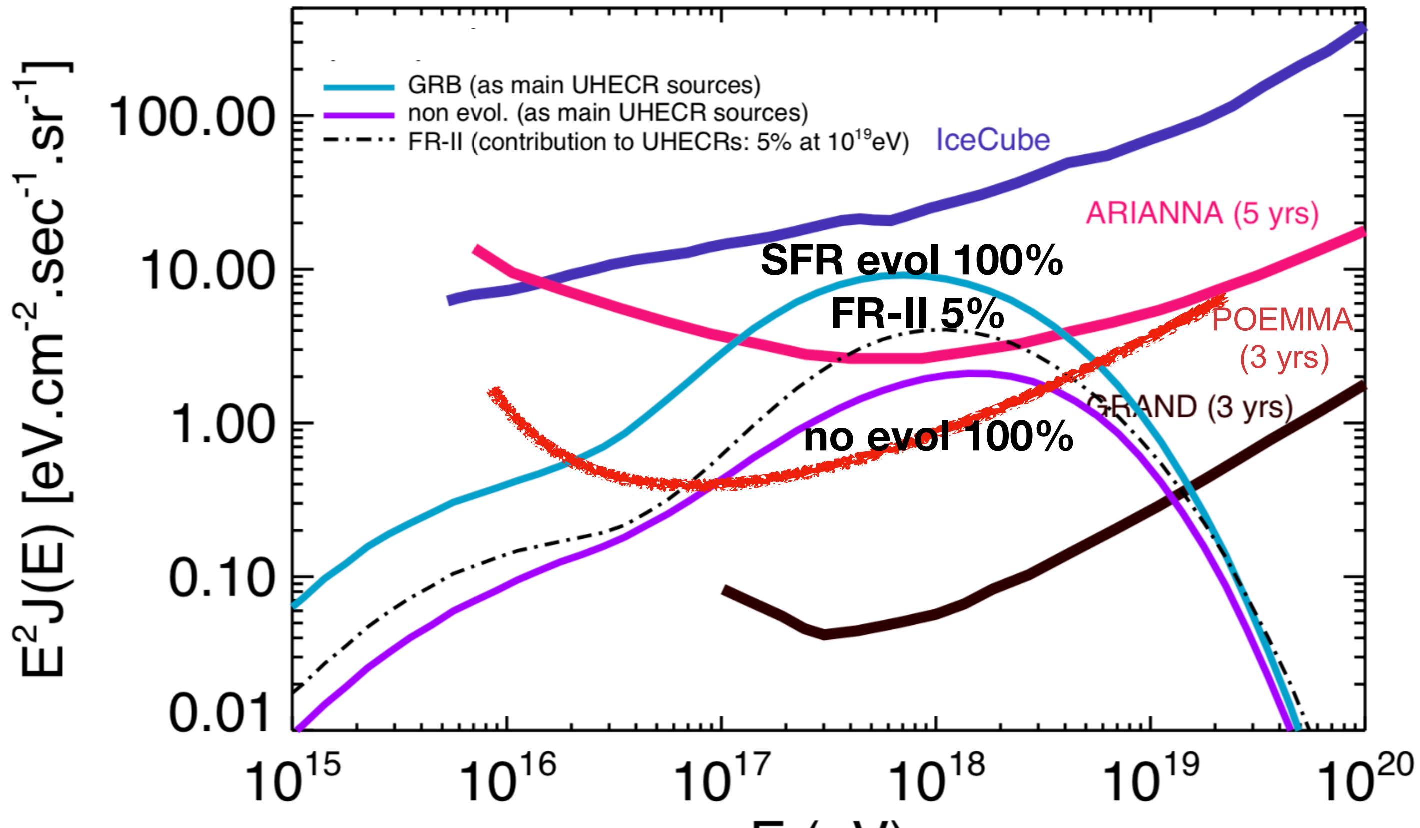
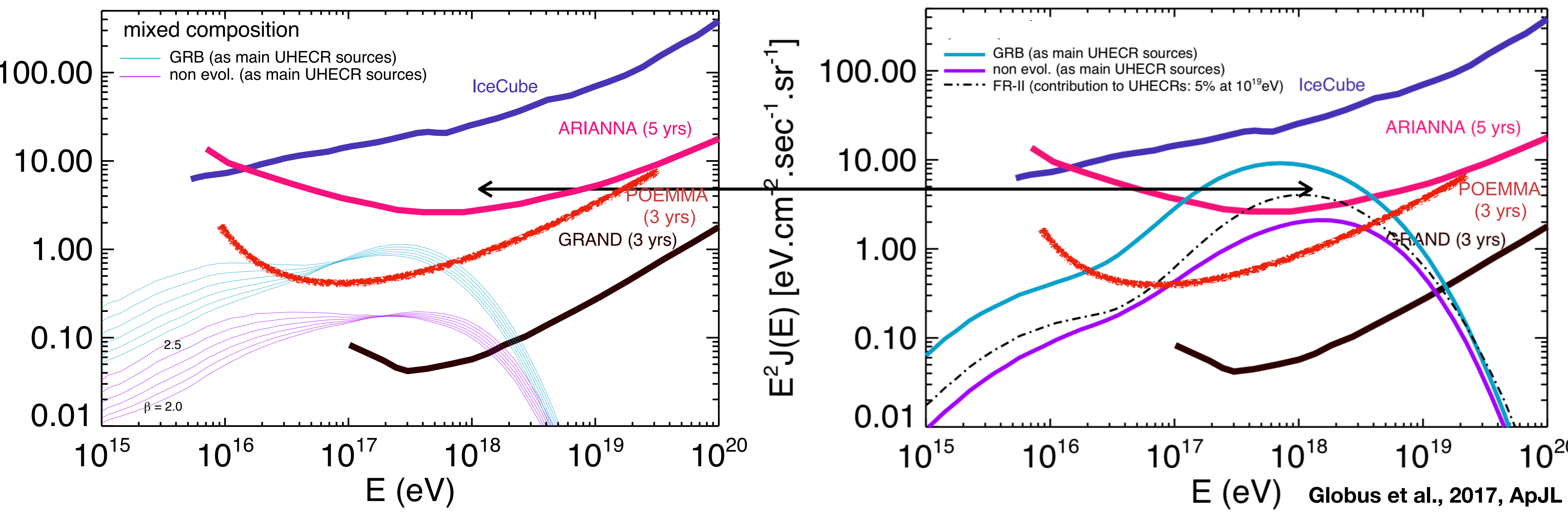


Globus et al., 2017, ApJL

The resulting neutrino flux is larger than that of a non evolving source scenario and 100% contribution to the UHECR spectrum

Constraining the presence of powerful protons accelerators in the universe

The resulting neutrino flux is significantly larger than that of the main UHECR component



Globus et al., 2017, ApJL

Real window to constrain the presence of proton accelerator in the universe
(and not only within the GZK horizon)

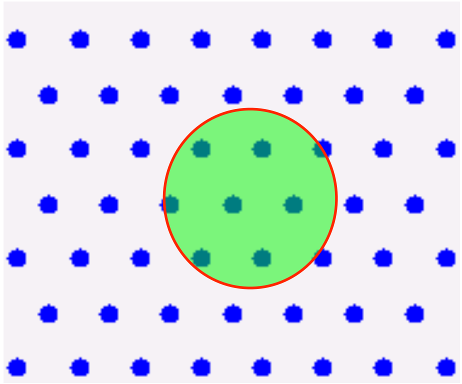
THE END

THANK YOU FOR YOUR ATTENTION!!!

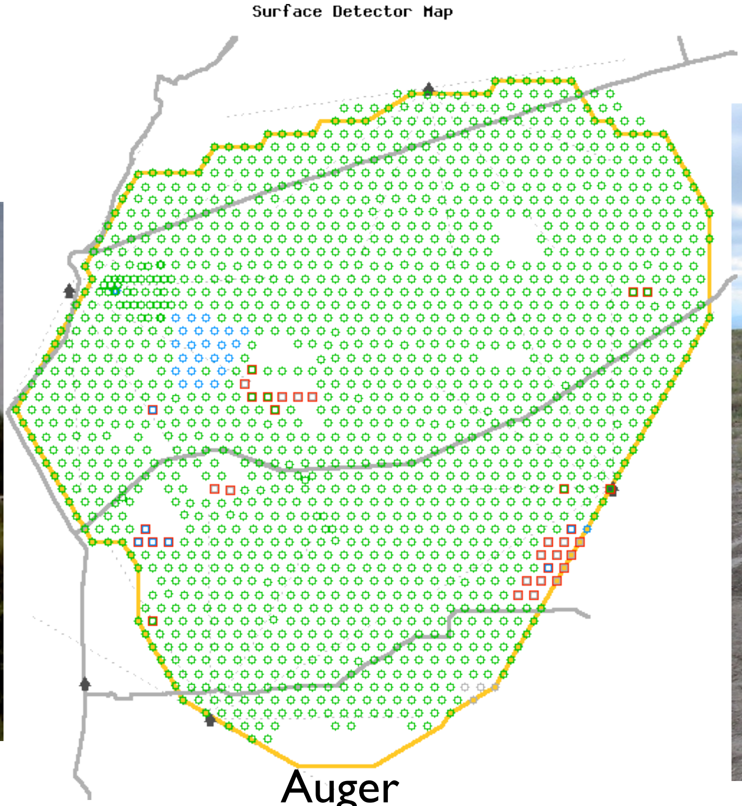
Ground array detectors

- Sampling air shower particles at ground level
- Surface covered and detector spacing depends on the targeted energy range :
  - Kascade (10^{15}-10^{17} eV) : surface 40000 m^2, 252 detectors, spacing 13m
  - Kascade Grande (10^{16}-10^{18} eV) : surface 0.5 km^2, 37 detectors, spacing 130m
  - Auger ($10^{18.5}$- >10^{20} eV) : surface 3000 km^2, 1600 detectors, spacing 1500 m

- Different type of detectors :
  - Scintillators (KASCADE) (==> electrons)
  - Shielded scintillators (KASCADE) (==> muons)
  - Water Cerenkov Tanks (Auger) (==> all particles)



Kascade



Auger