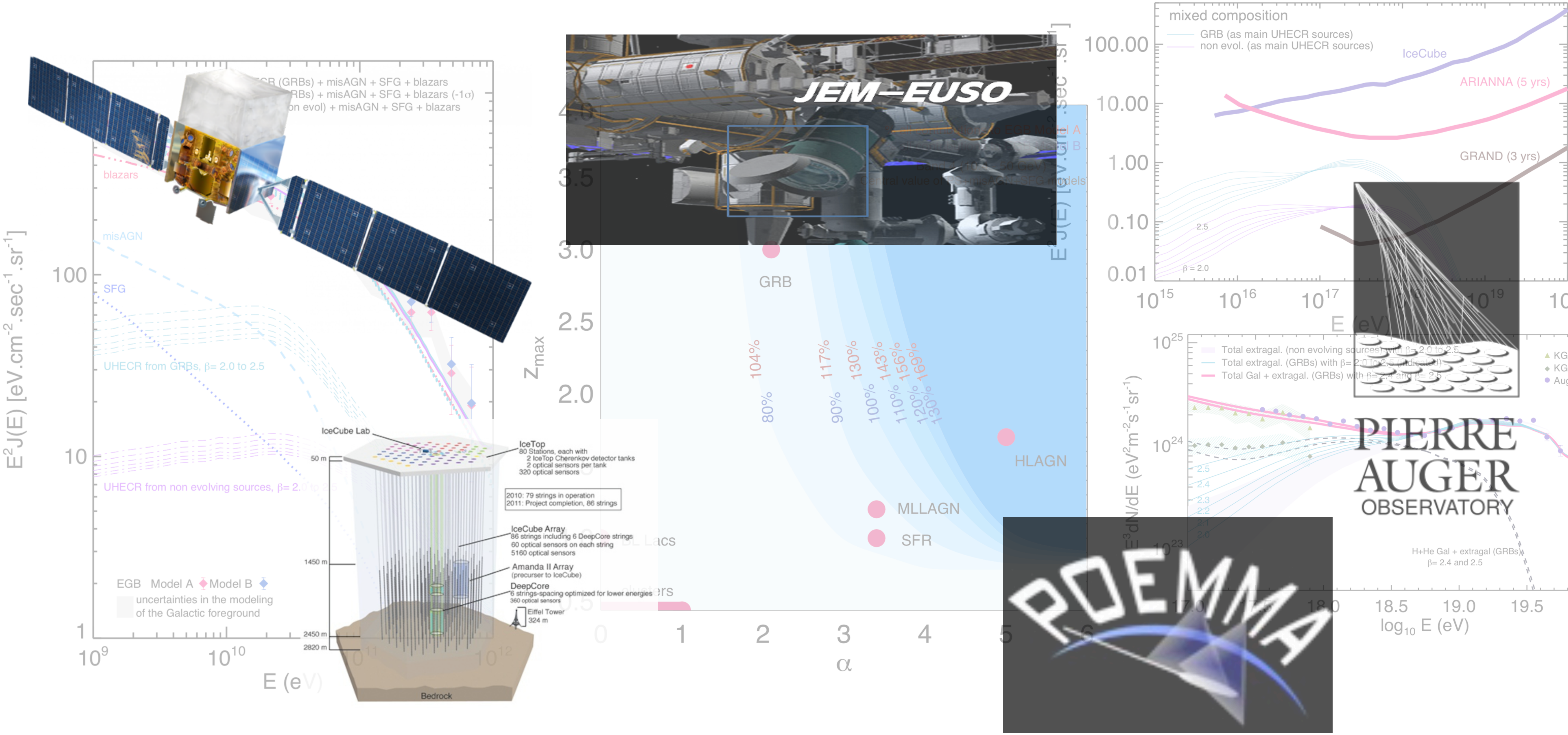
Multimessenger contraints on the origin of ultra-high-energy cosmic-rays



Denis Allard in collaboration with

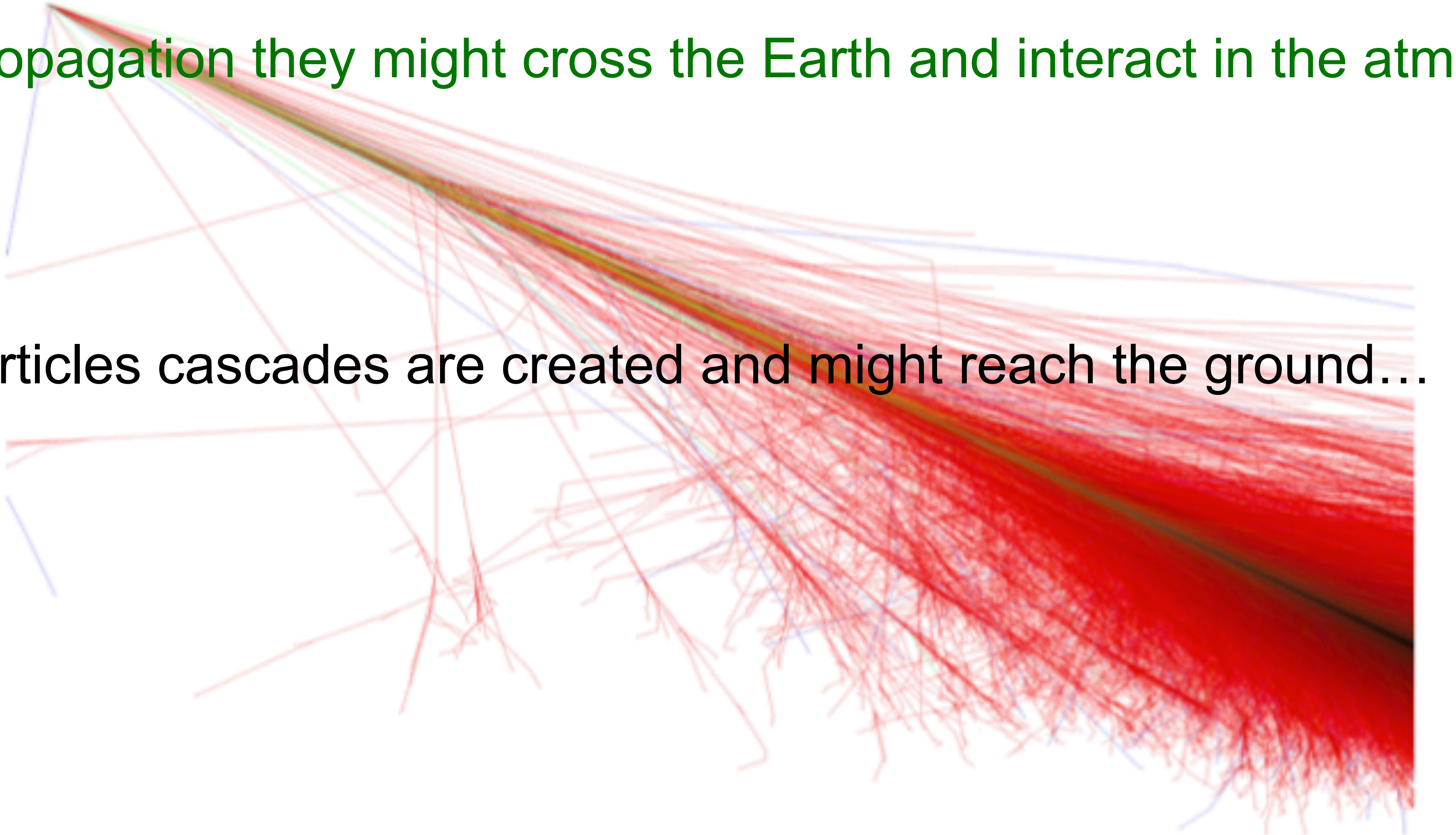
Noemie Globus, E. Parizot, T. Piran, G.Decerprit, R. Mochkovitch et al.

What are cosmic-rays?

★ High energy particles “traveling” throughout the Galaxy and even throughout the intergalactic space

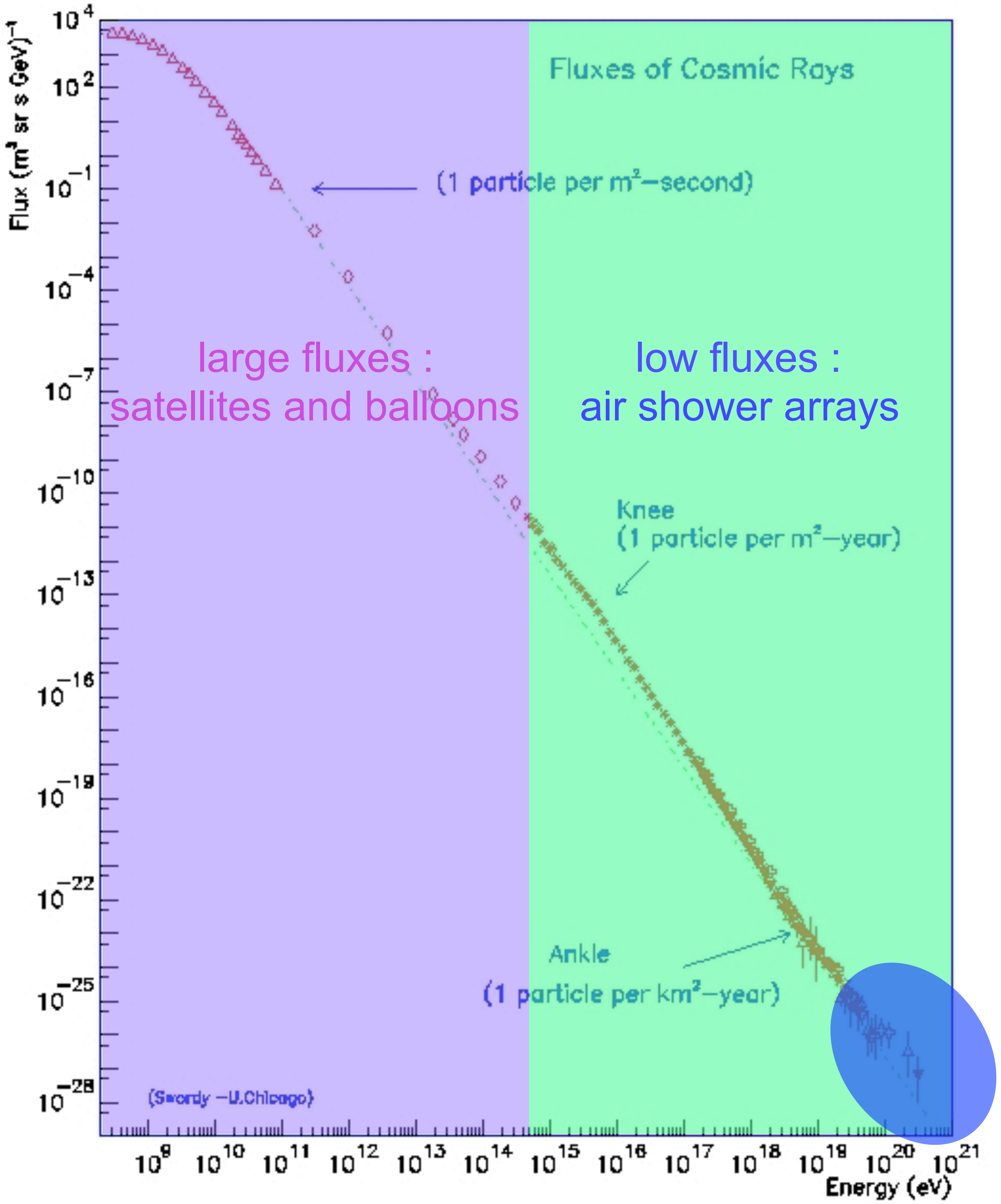
★ Protons, various atomic nuclei and some electrons with various energies
(Helium, Carbon, Oxygene, Iron, mostly very small abundances of heavier nuclei)

★ During their propagation they might cross the Earth and interact in the atmosphere



★ Secondary particles cascades are created and might reach the ground…
---> Air showers

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

The cosmic-ray spectrum
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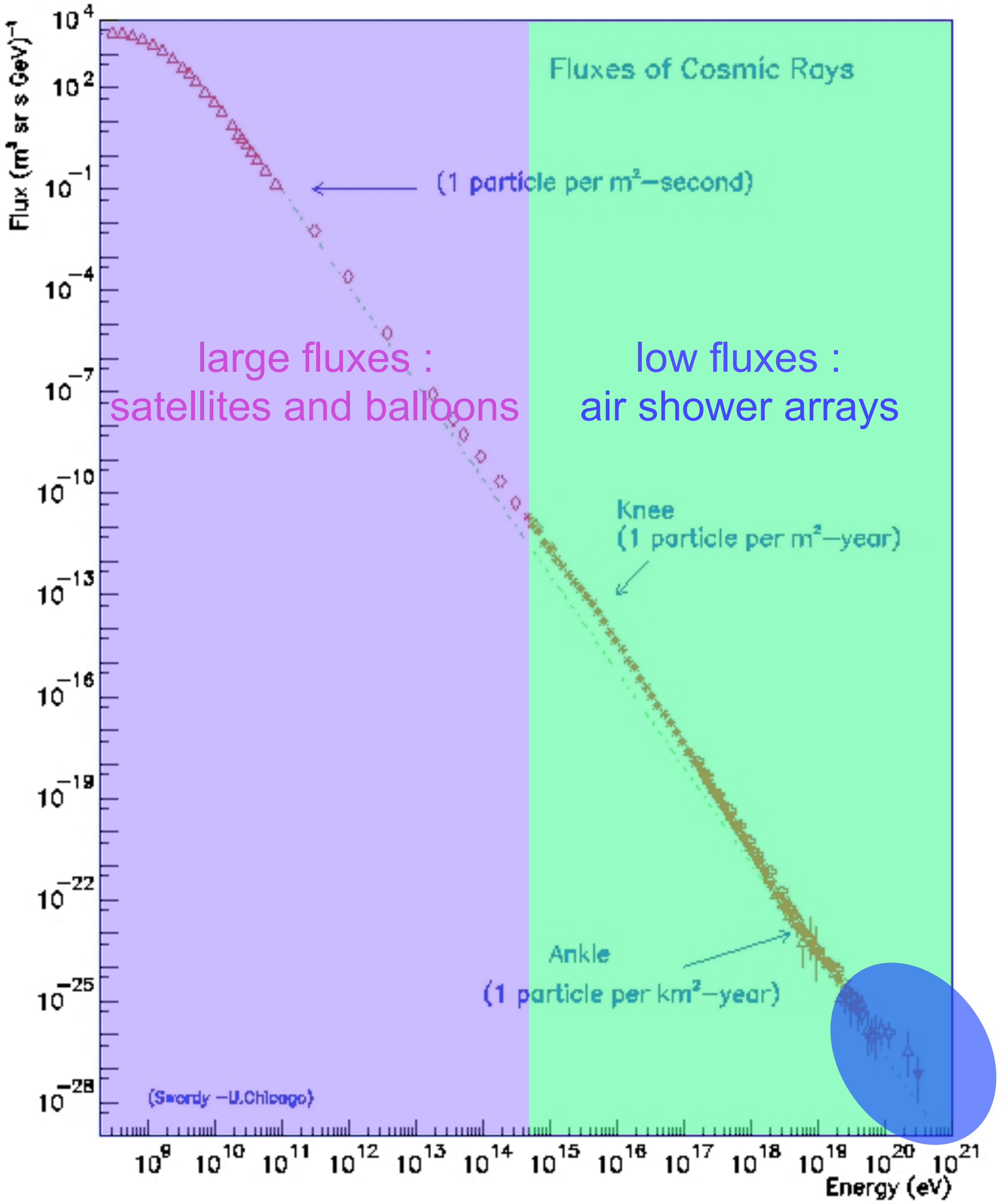


It's been know for many decades that cosmic-rays of extraordinary energies are produced in the universe far beyond the reach of men-build accelerators

How are they produced/accelerated, how energetic can they become ? What are their sources in the Galaxy? What are their sources outside of the Galaxy?

What role do they play in the galactic ecology, in the intergalactic ecology, in the terrestrial ecology?

About their production we know they are accelerated in astrophysical sources…

However we do not know for sure what are the main sources of cosmic-rays in the different energy ranges of the spectrum.

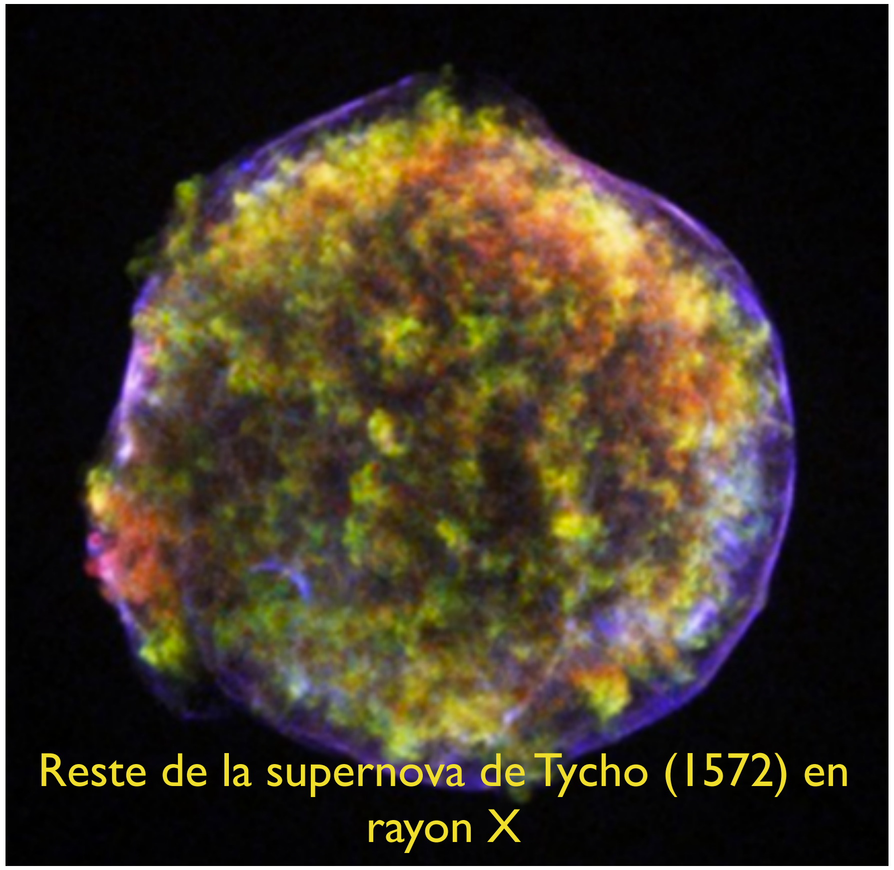
We do not know either the details of the acceleration mechanism(s)… Although we have some ideas

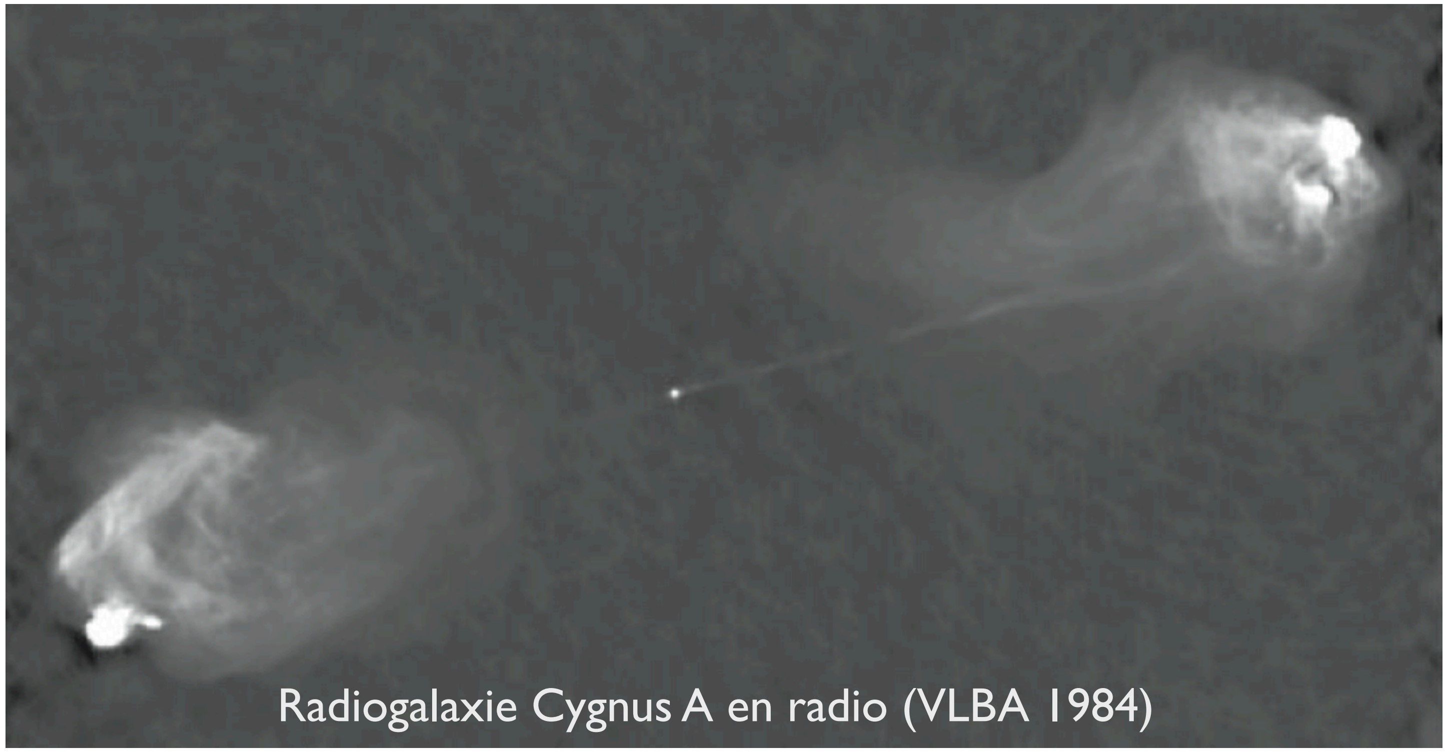
Cosmic-ray acceleration and astrophysical shock wave

Diffuse shock acceleration or first order Fermi acceleration is the most studied acceleration mechanism

shock waves are very common in astrophysics they can be found in supernova remnants, active galactic nuclei, even in the solar system

they form as soon a supersonic wind/plasma propagates in an ambient medium


Reste de la supernova de Tycho (1572) en rayon X


Radiogalaxie Cygnus A en radio (VLBA 1984)

Two necessary ingredients : the shock wave and turbulent magnetic fields on both sides of the shock

➡ Charged particles can perform upstream -> downstream -> upstream cycles and gain energy at each cycle (key role of the isotropization of the particles by the magnetic fields)

➡ Acceleration mechanism

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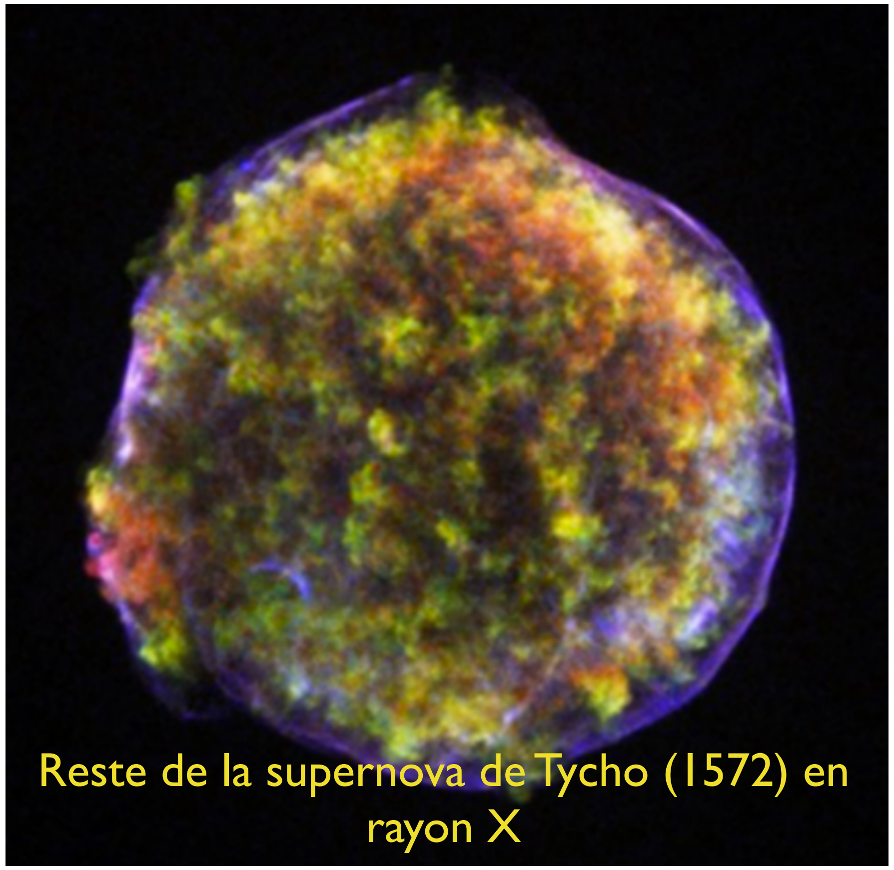

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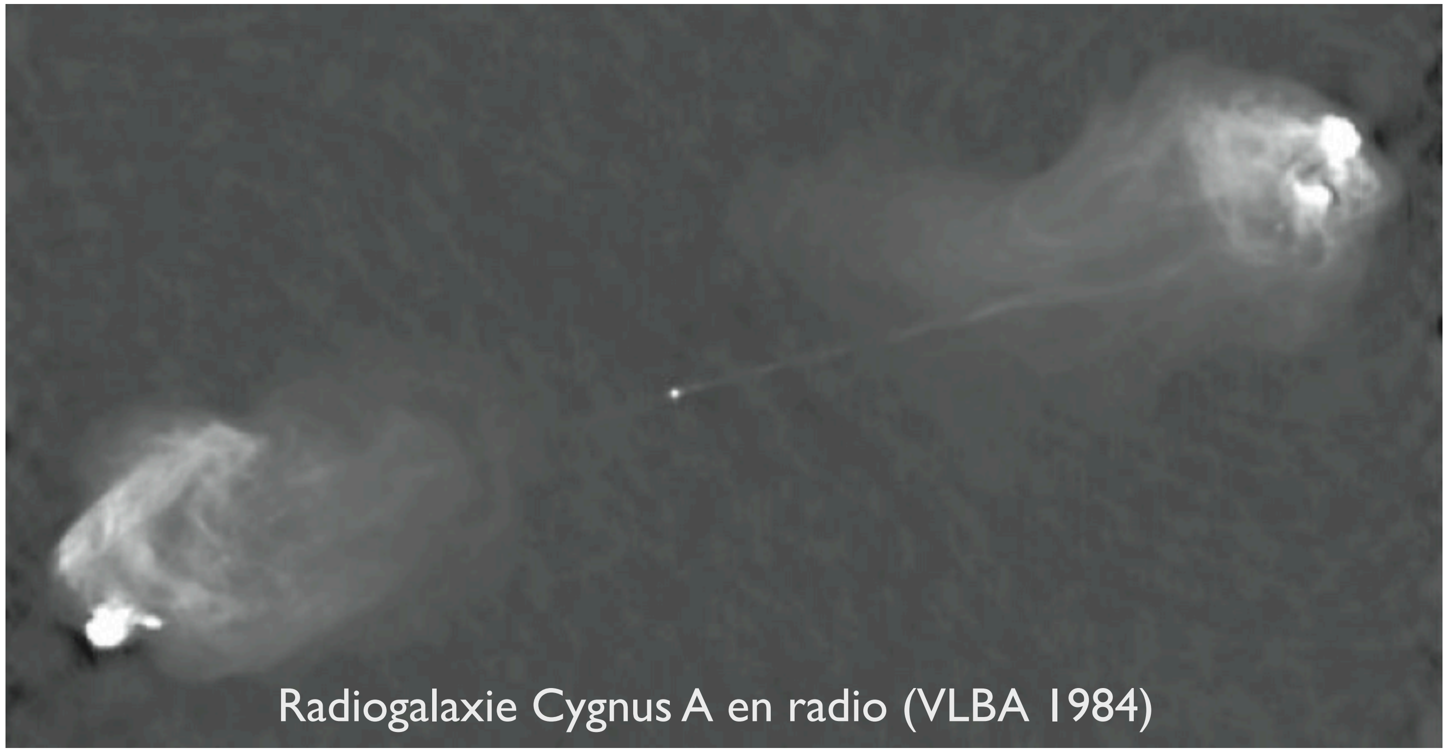

Radiogalaxie Cygnus A en radio (VLBA 1984)

Two necessary ingredients : the shock wave and turbulent magnetic fields on both sides of the shock

➡ Particles have a certain probability not to recross the shock after a cycle

➡ The larger the number of cycles performed, the higher the energy, the lower the number of particles

➡ Natural prediction of a power law spectrum (with index 2 for the simplest version)

Cosmic-ray acceleration and astrophysical shock wave

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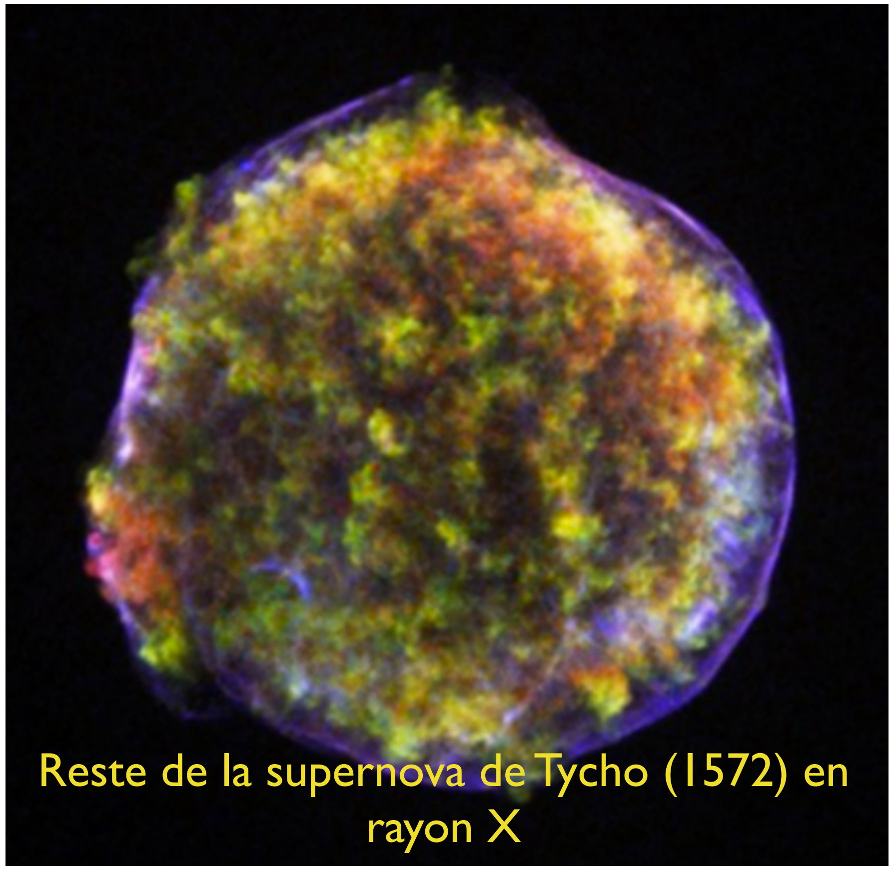

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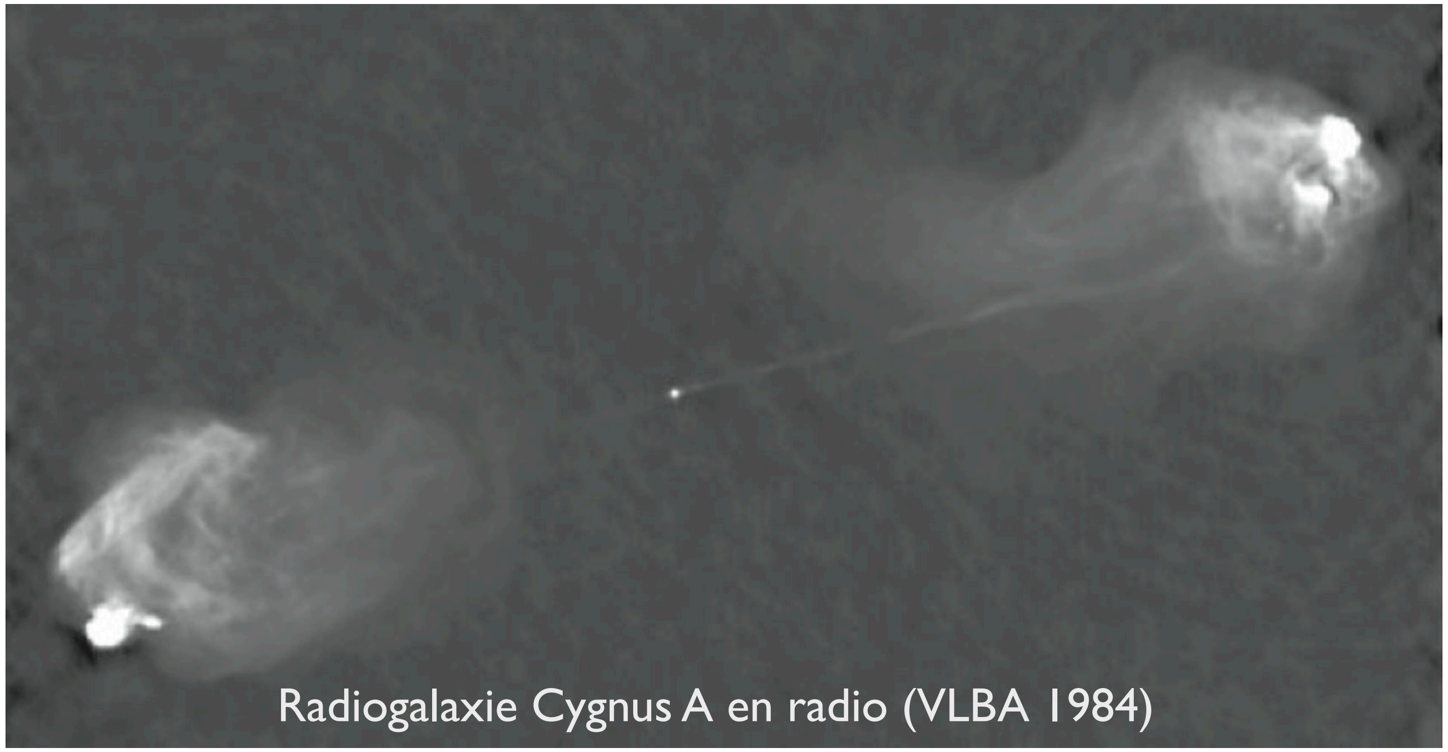


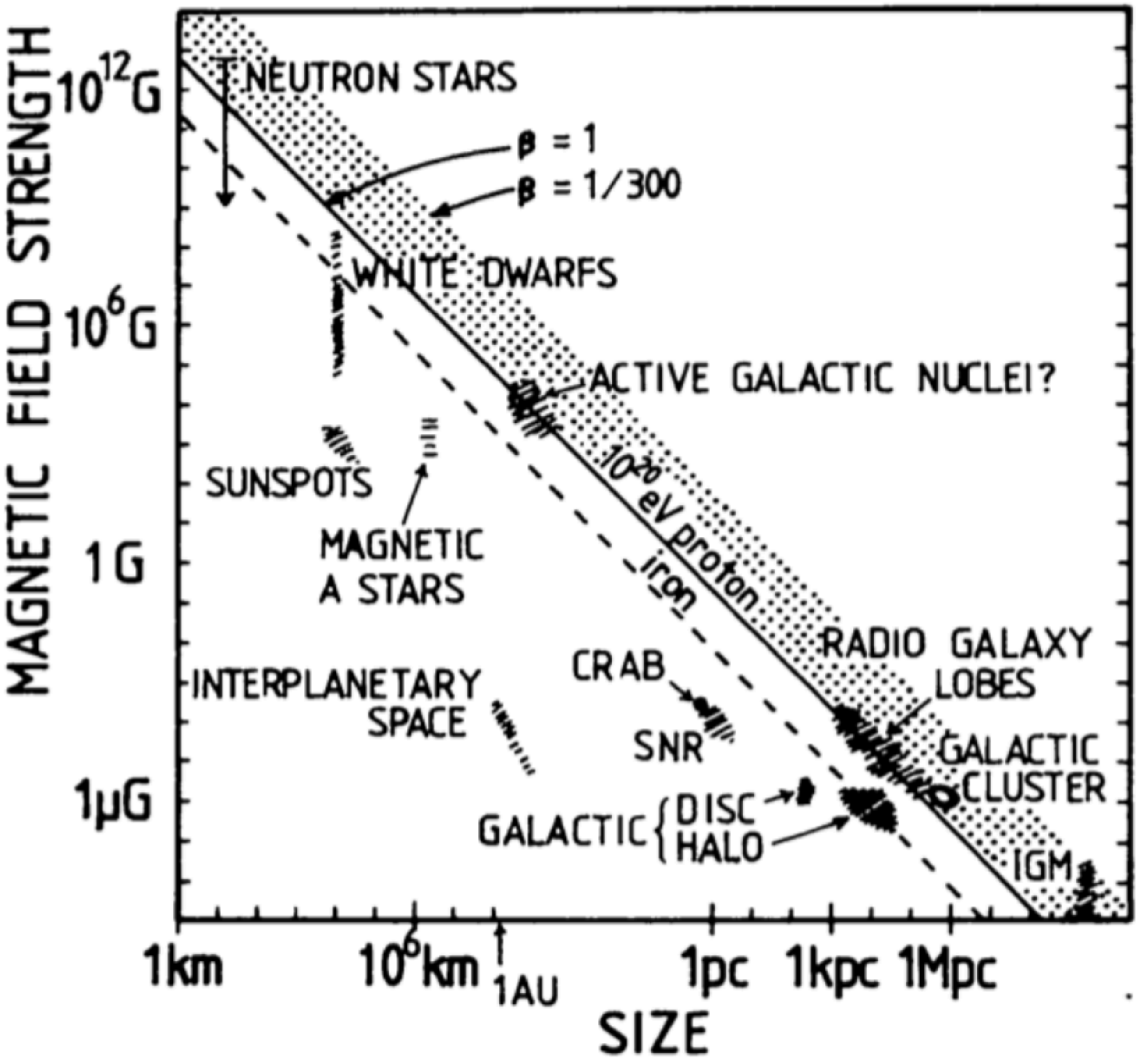
Radiogalaxie Cygnus A en radio (VLBA 1984)

Two necessary ingredients : the shock wave and turbulent magnetic fields on both sides of the shock

➡ Energy reachable limited by the capacity of the magnetic field to confine the particles or by energy losses

➡ In the confinement limited case, the maximum energy is expected to be proportional to the charge Z of the species (26 times larger for Fe than for protons)

Hillas diagram



➡ The maximum energy depends on the capacity of the source to confine particles : one can use the criterion R_L<$Size_{source}$ to give a rough estimate of E_{max}

➡ more or less the argument used to build the famous Hillas diagram :

Sources are put in the B Vs Size plane

➡ possible candidates for the acceleration of UHECR lie above the dashed (for Fe cosmic-rays) or the continuous line (for protons)

However :

➡ Over-optimistic estimate

➡ necessary but not sufficient condition

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

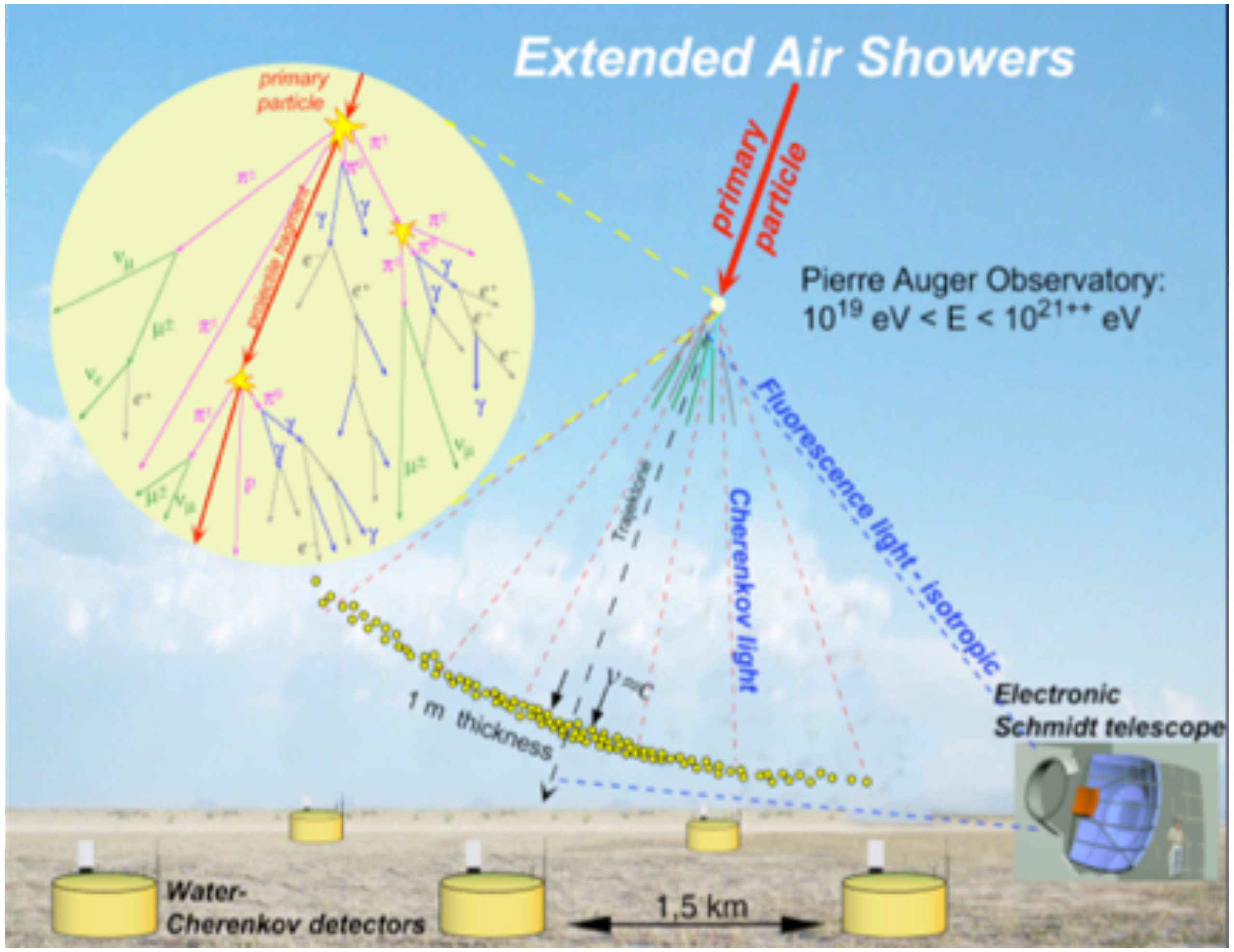
3

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



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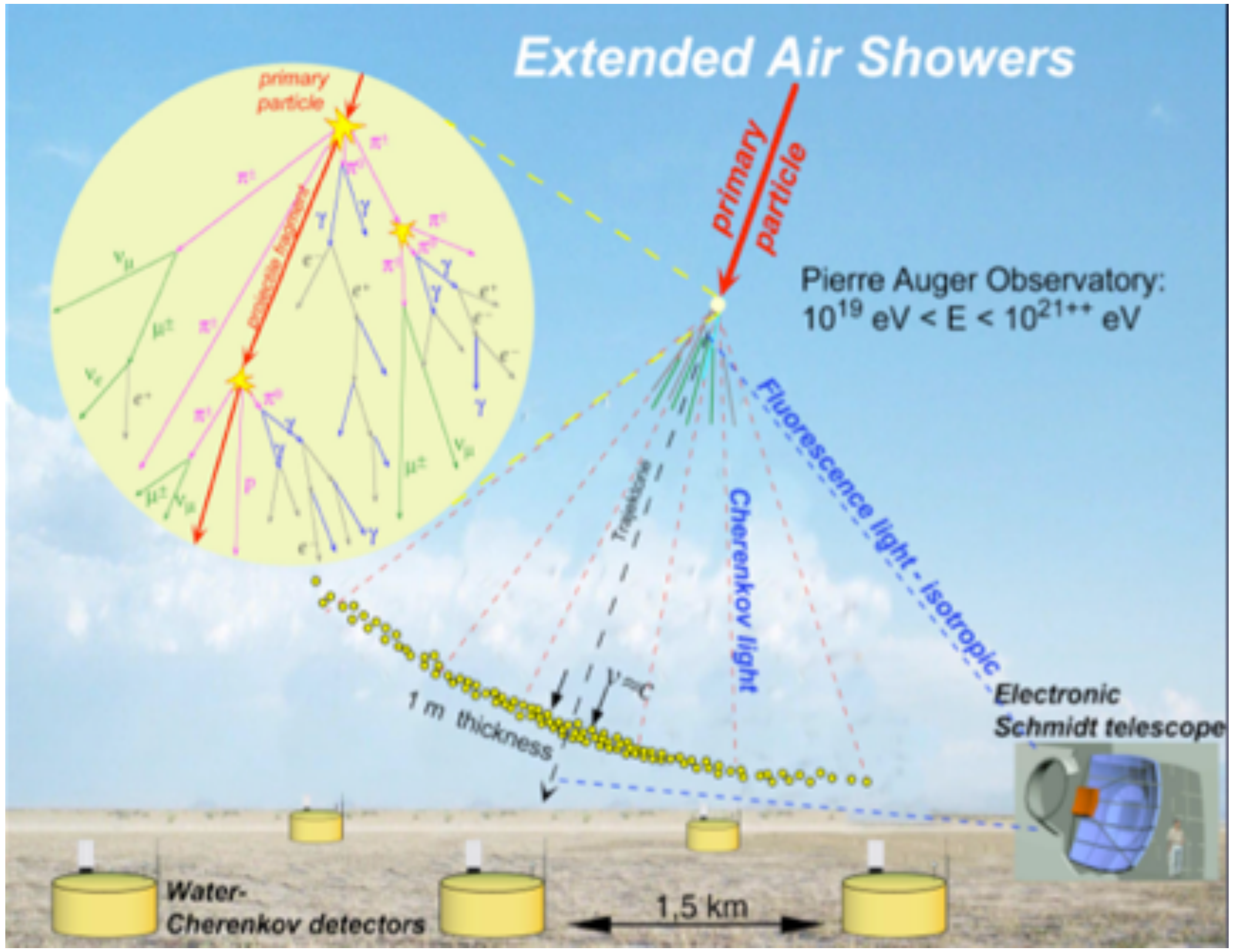
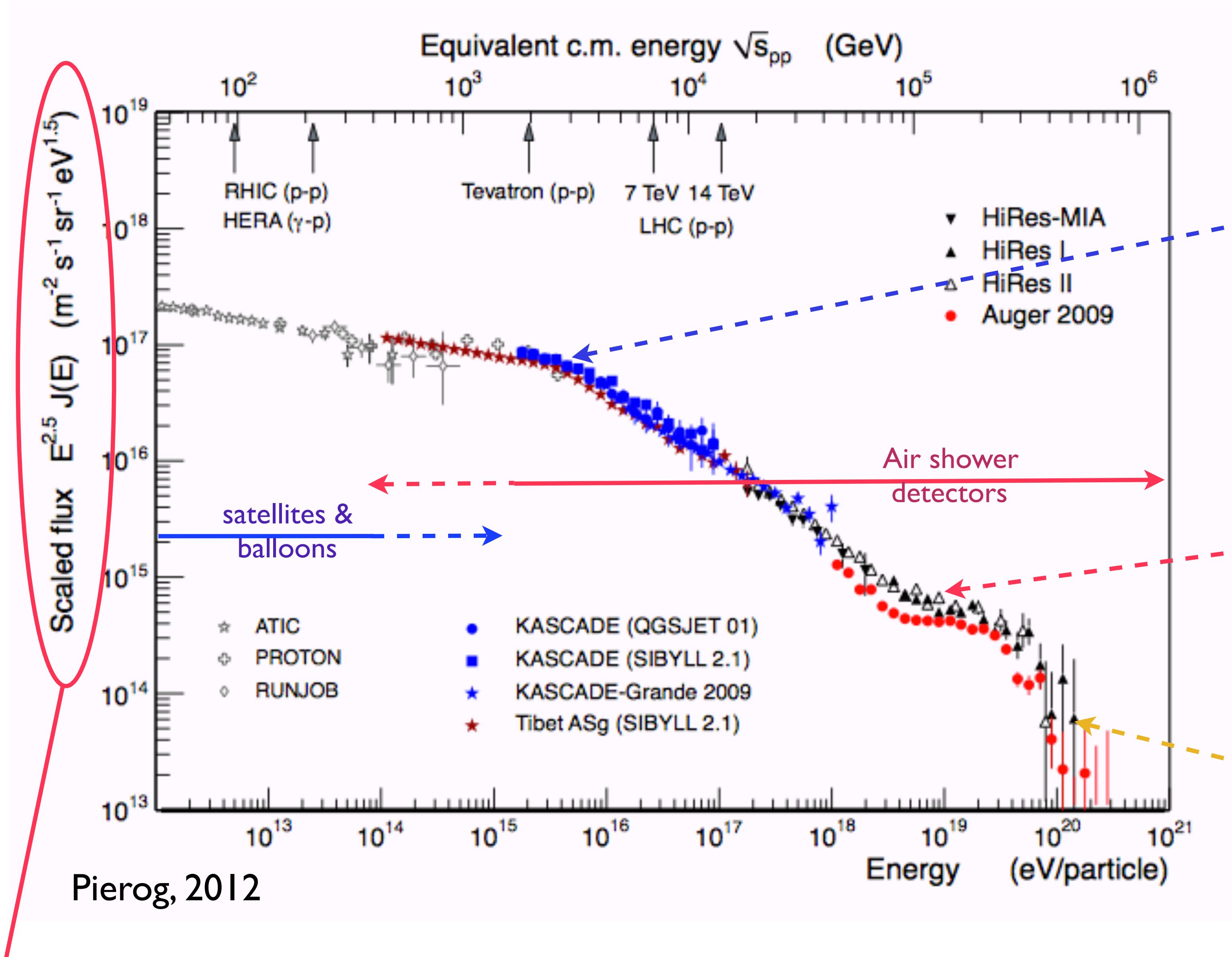
Energy and direction reconstruction of the primary cosmic-ray is well mastered

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



Pierog, 2012

$E^{2.5}\times$(diff. flux)

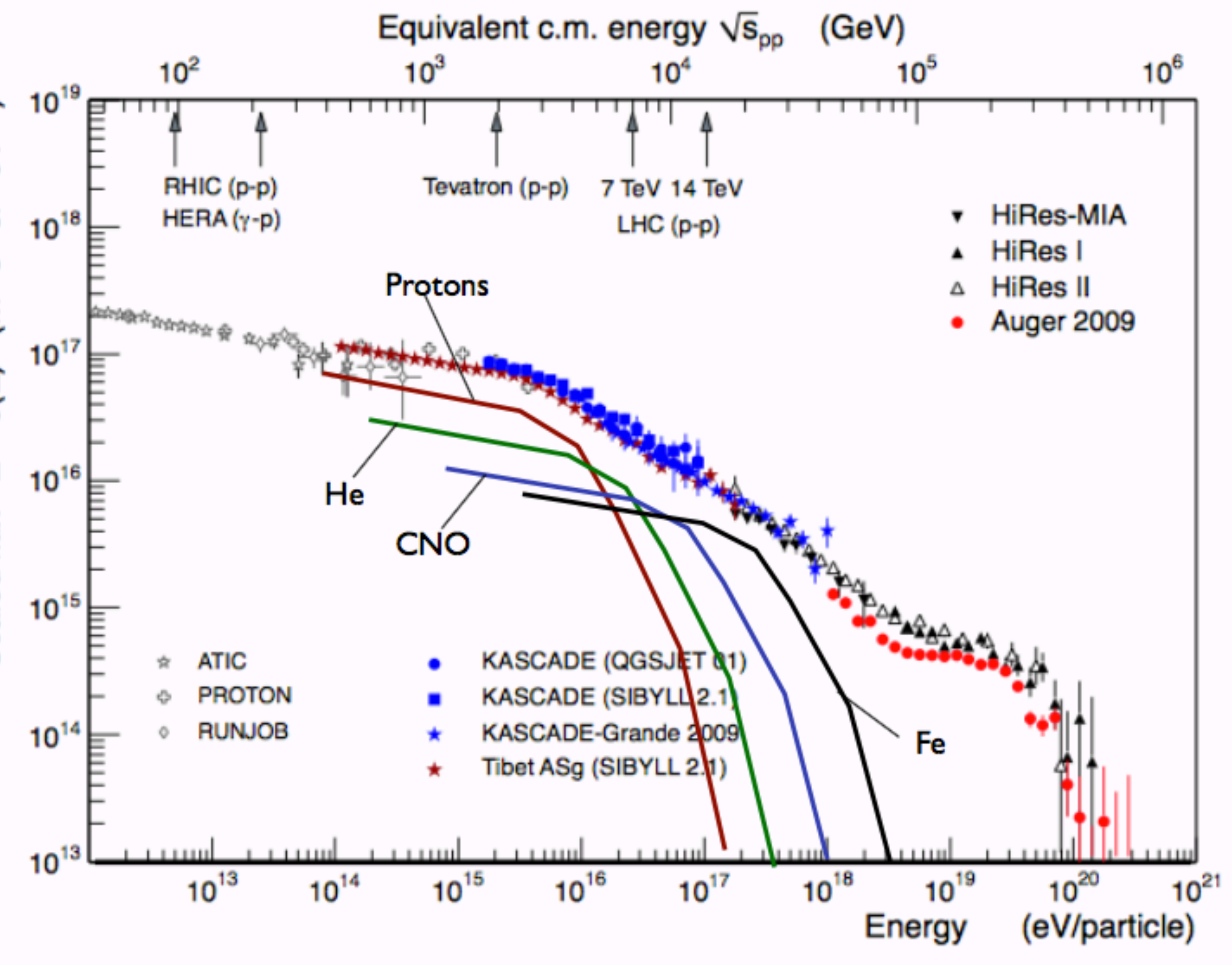
The knee
$E\sim3\text{-}4.10^{15}$ eV

The ankle
$E\sim3\text{-}4.10^{18}$ eV

High energy cut-off
$E\sim3\text{-}5.10^{19}$ eV

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

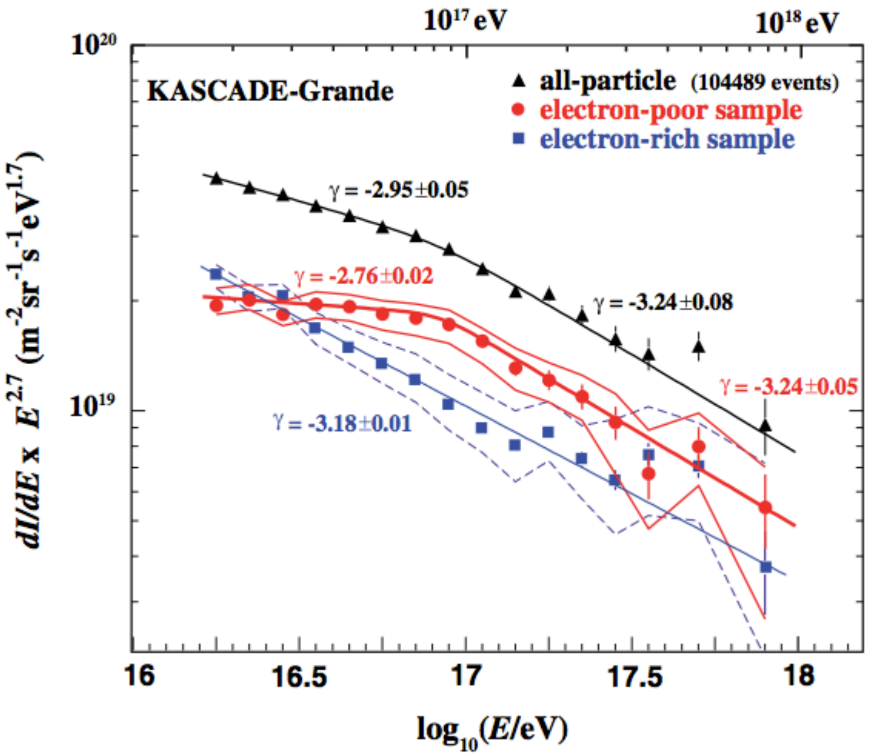


==> composition getting heavier in the energy decade following the knee confirmed by most experiments

==> 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)

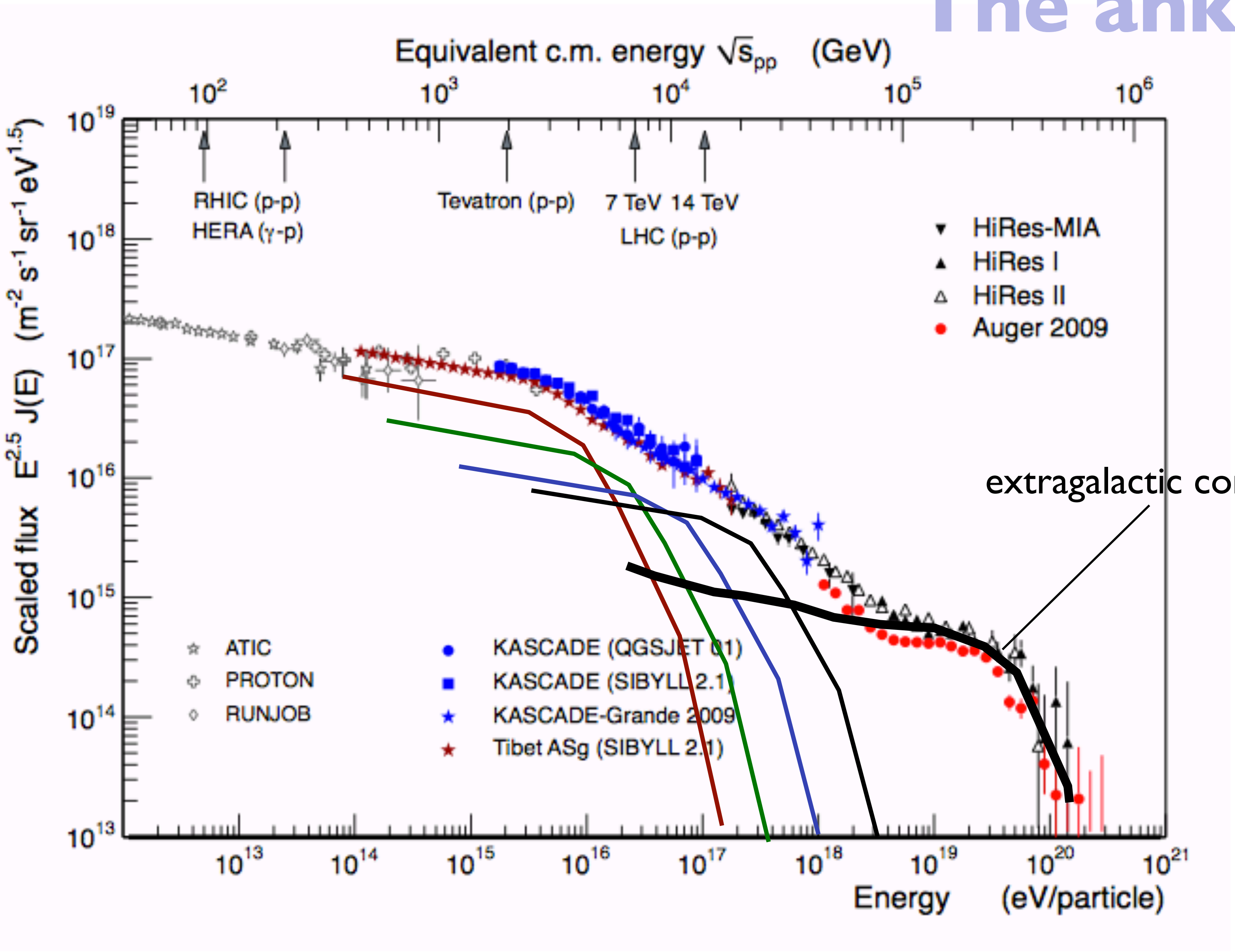
The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

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)



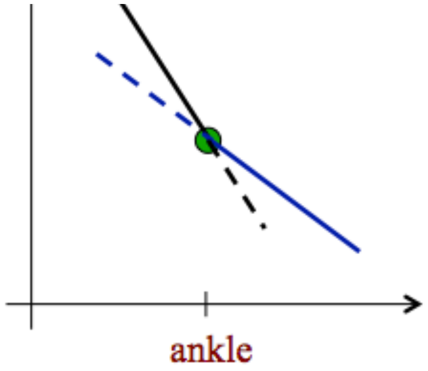
KG collab, Phys. Rev. Lett., 2011

The ankle



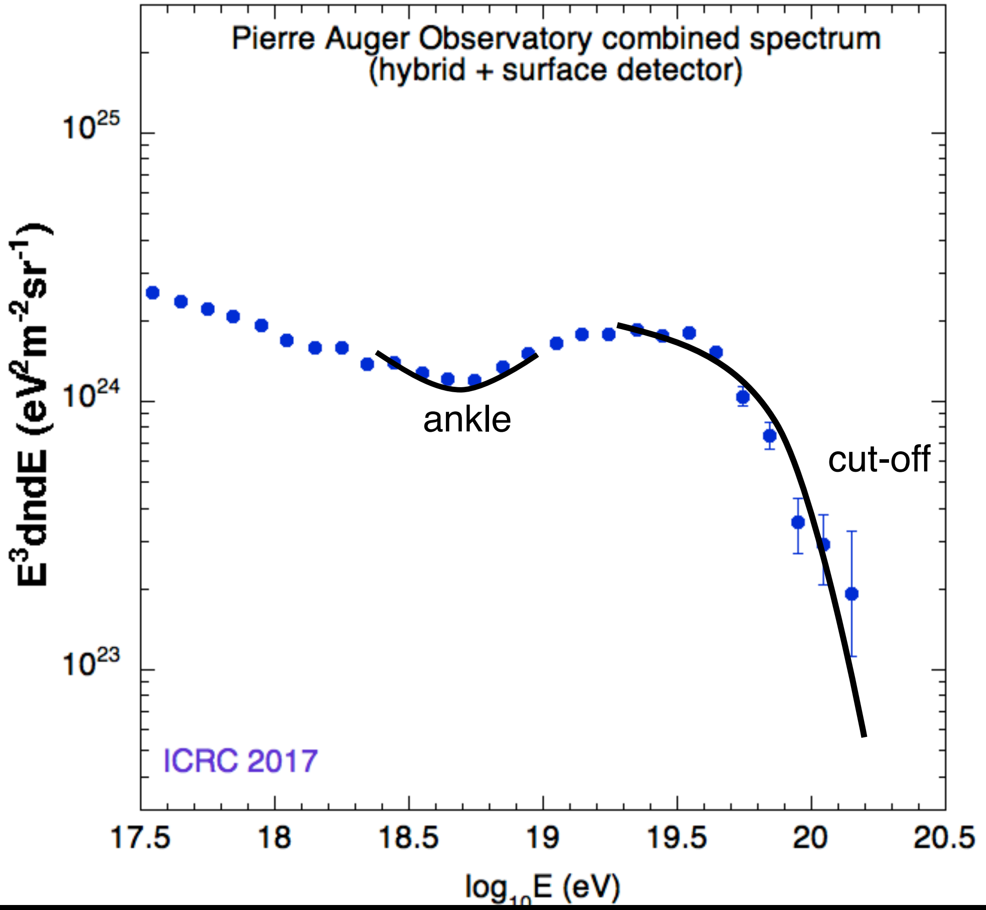
extragalactic component

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

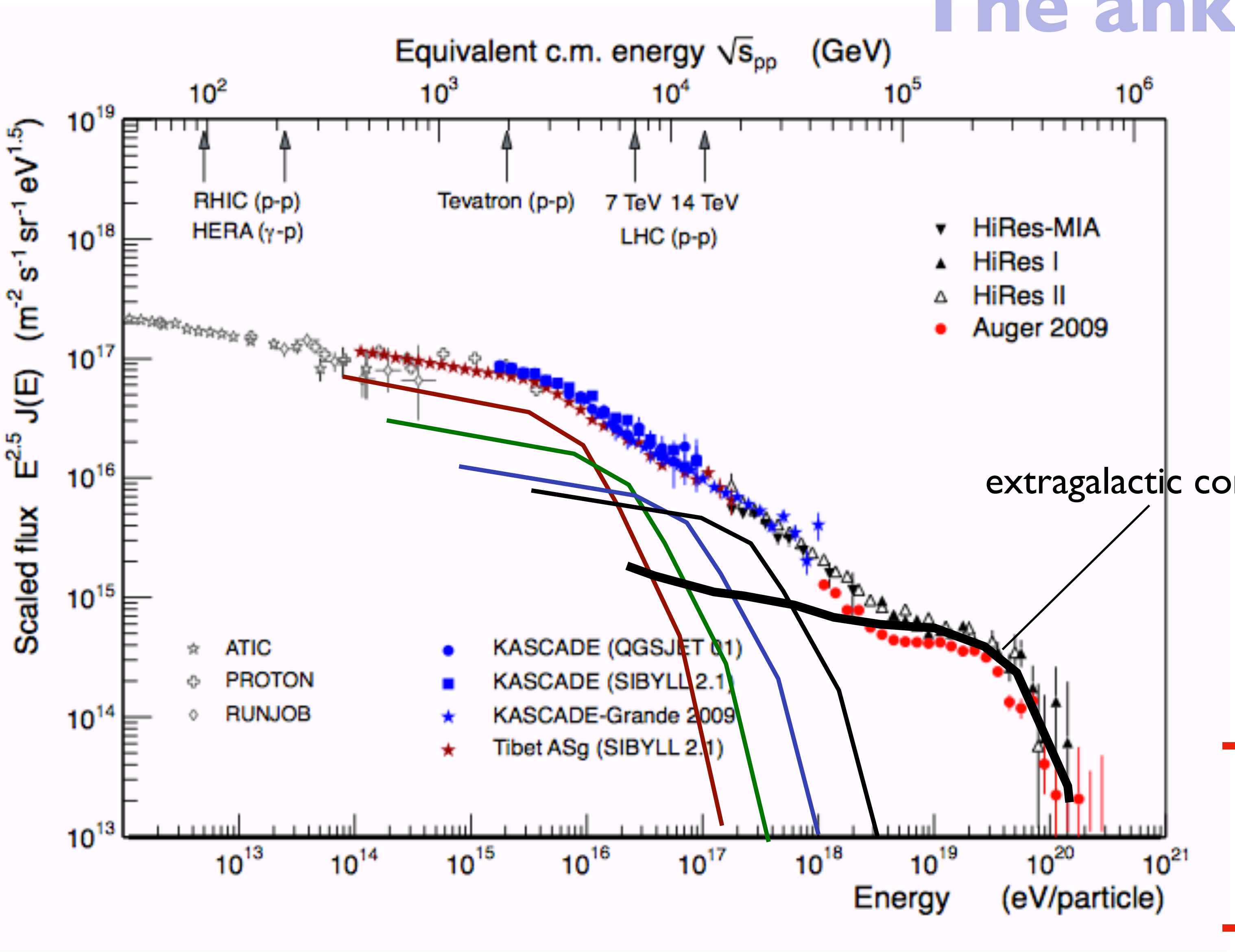


ankle : transition from a softer to a harder component

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



The ankle



extragalactic component

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

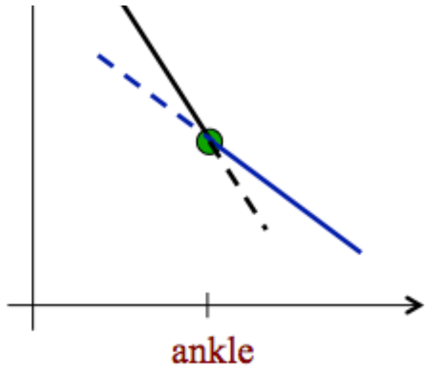
Why should the component taking over be extragalactic?

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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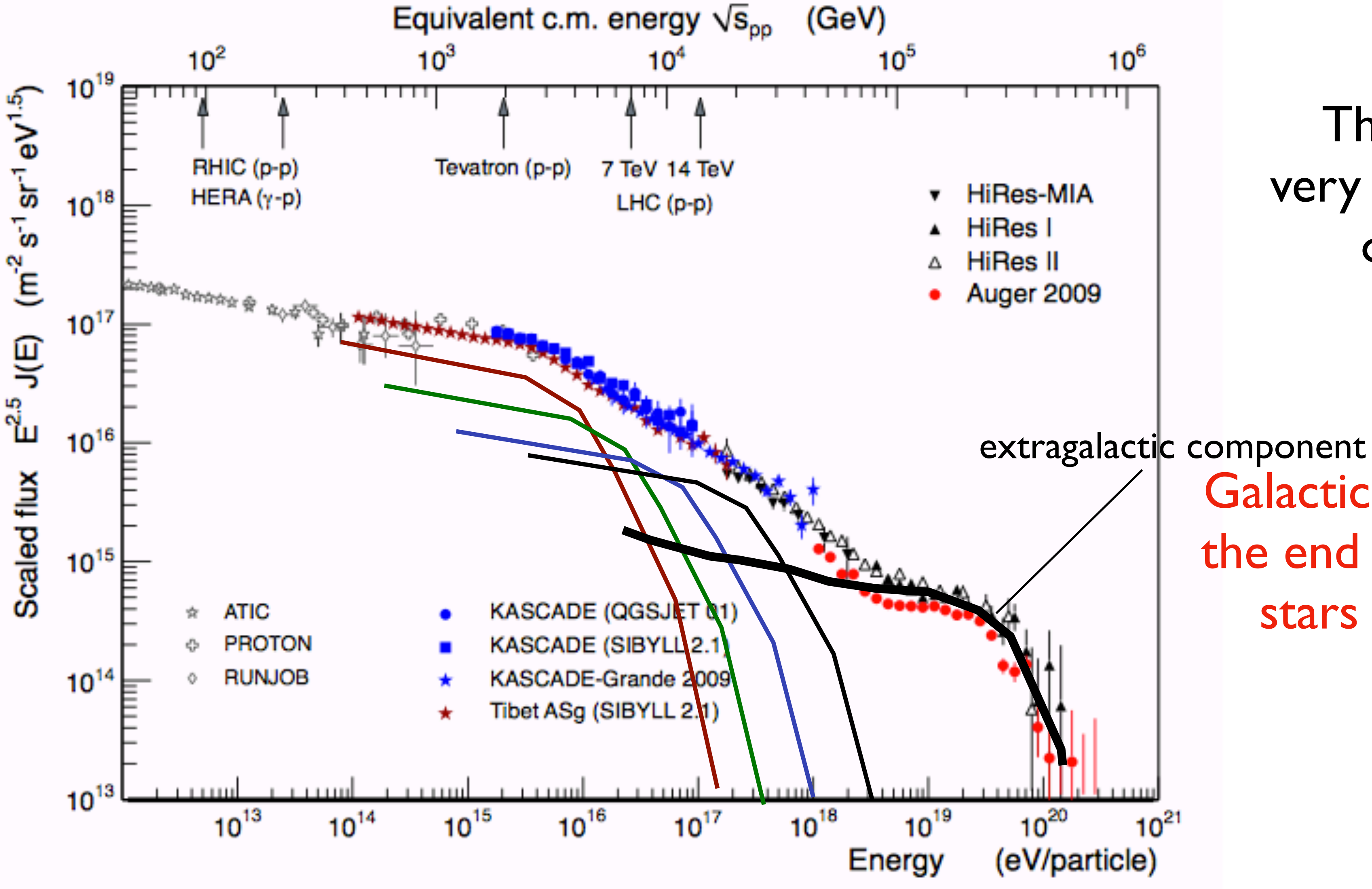
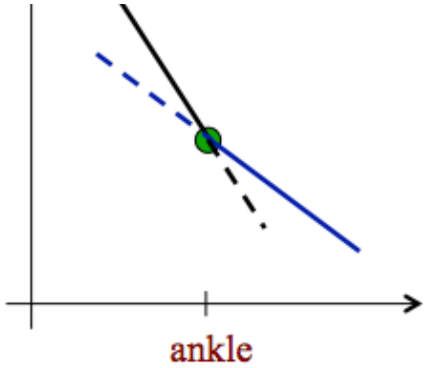


The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

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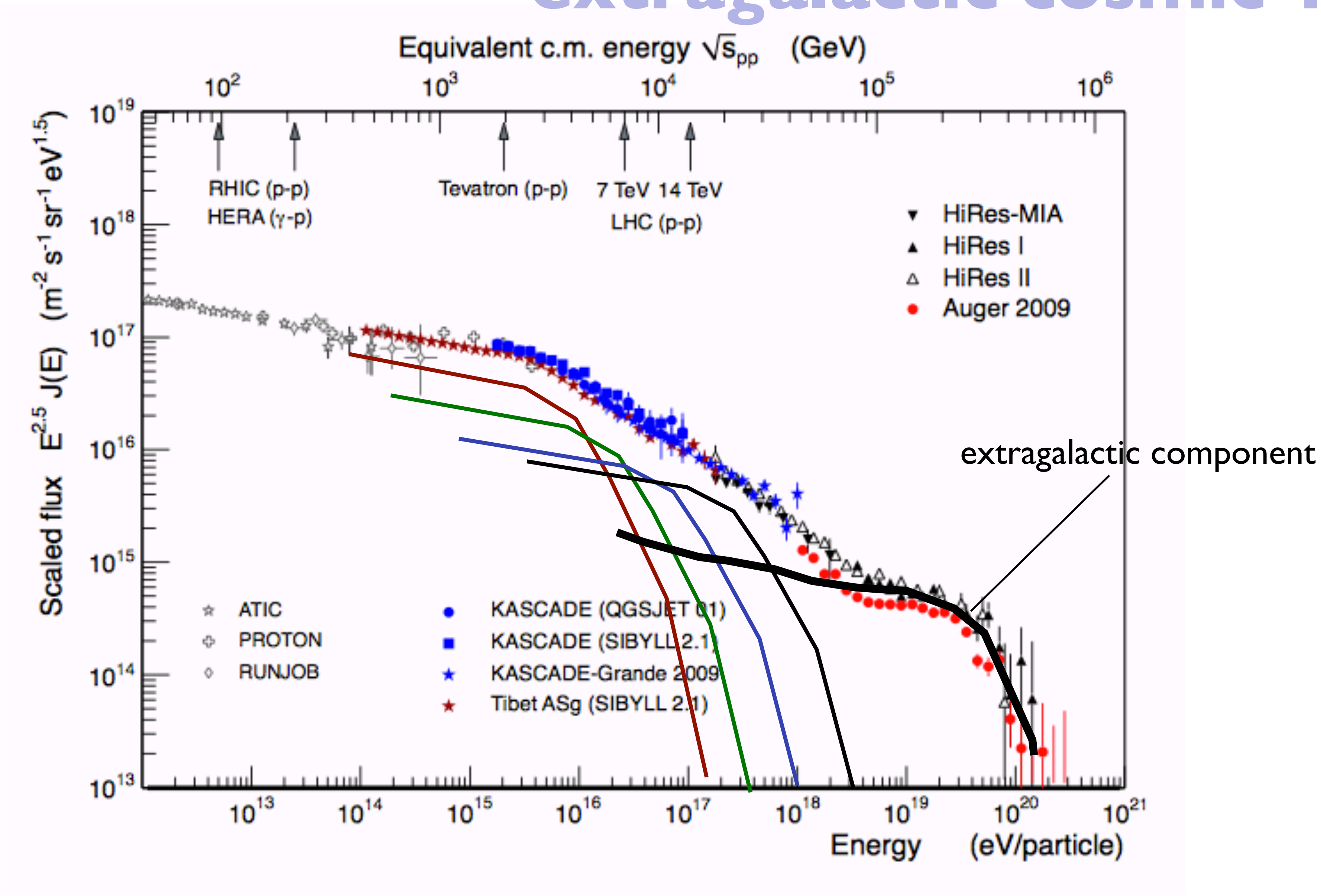
A consistent picture of the transition from galactic to extragalactic cosmic-rays?



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

1

Angular spectrum

Arrival directions

2

Energy spectrum

Flux as a function of the energy

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Mass spectrum

composition

4 key observables to understand the origin of cosmic-rays

1

Angular spectrum

Arrival directions

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Energy spectrum

Flux as a function of the energy

3

Mass spectrum

composition

4

Multi-messenger counterparts

cosmogenic γ and ν

4 key observables to understand the origin of cosmic-rays

1

Angular spectrum

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Flux as a function of the energy

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Mass spectrum

composition

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Multi-messenger counterparts

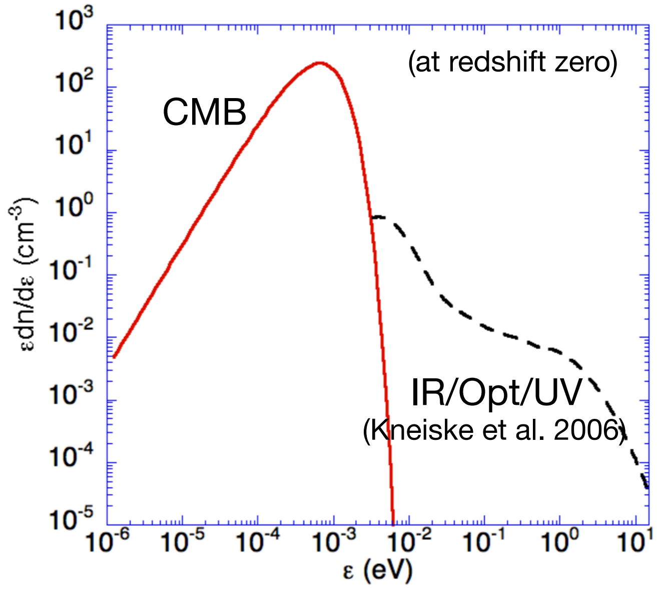
cosmogenic γ and ν

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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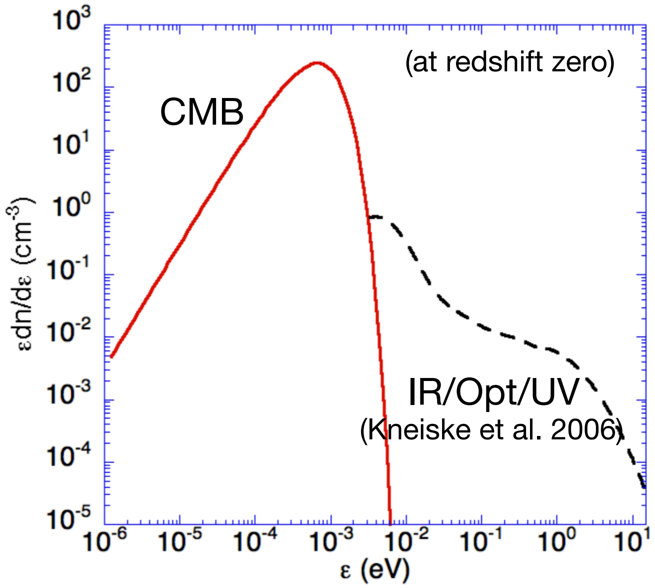

νs do not interact while propagating in the extragalactic medium
while the universe is opaque to VHE e^+/e^- and γ which cascade down to sub-TeV energies

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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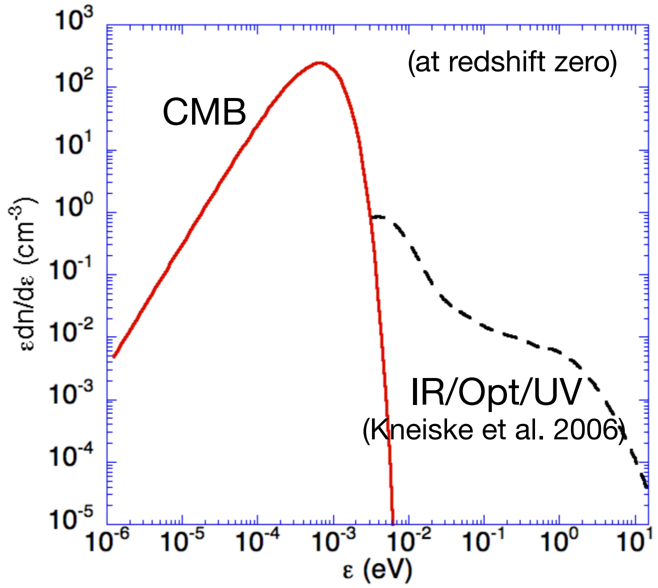
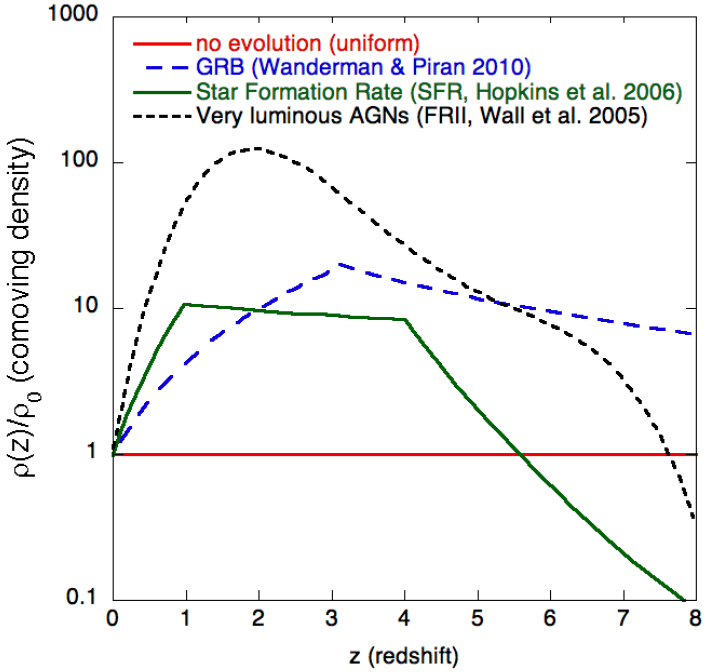


The extragalactic photon backgrounds evolve with time, they are hotter and denser as the redshift increases

➡ 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)

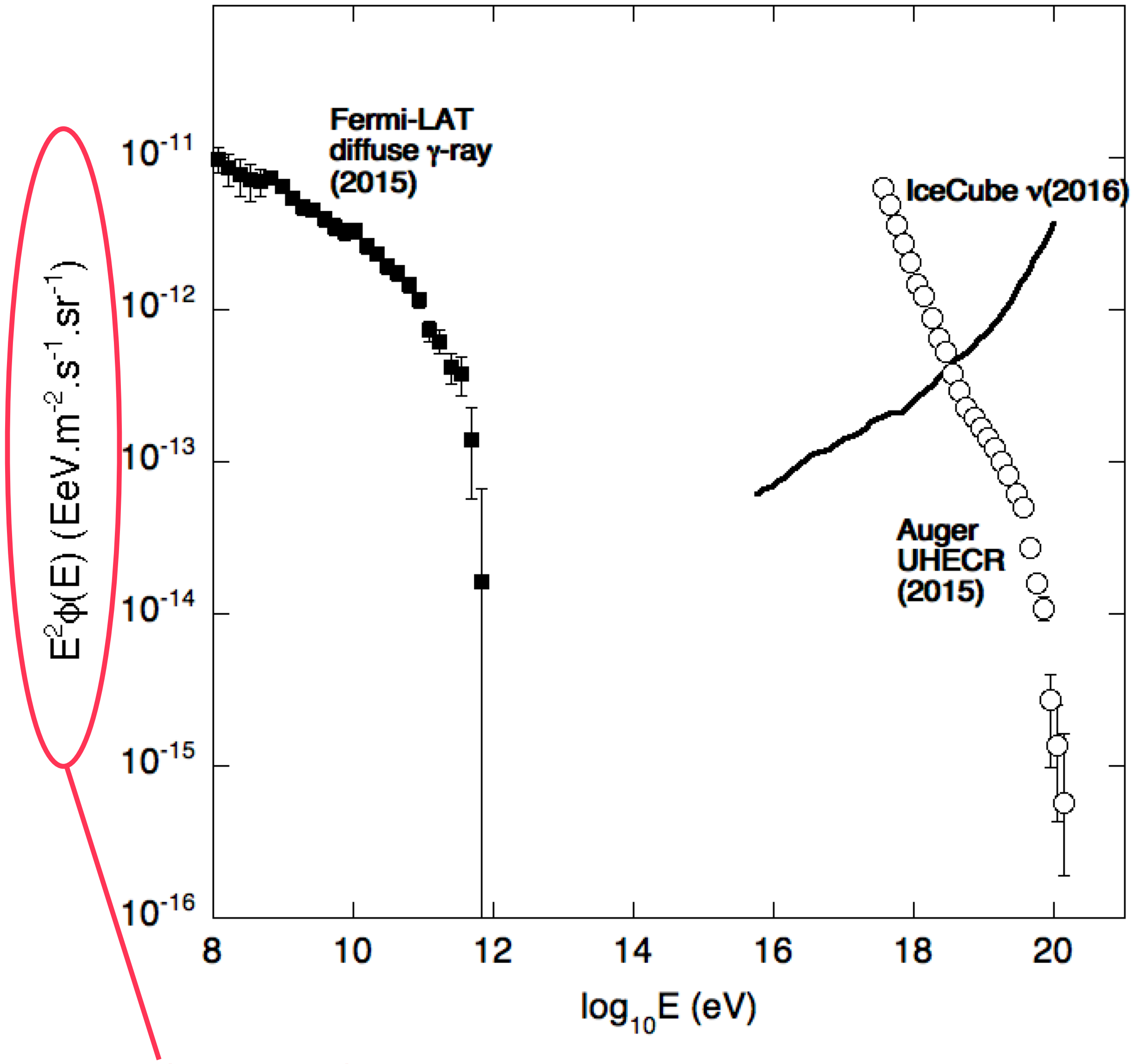
A “good” model should reproduce the measured UHECR spectrum

➡ 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)

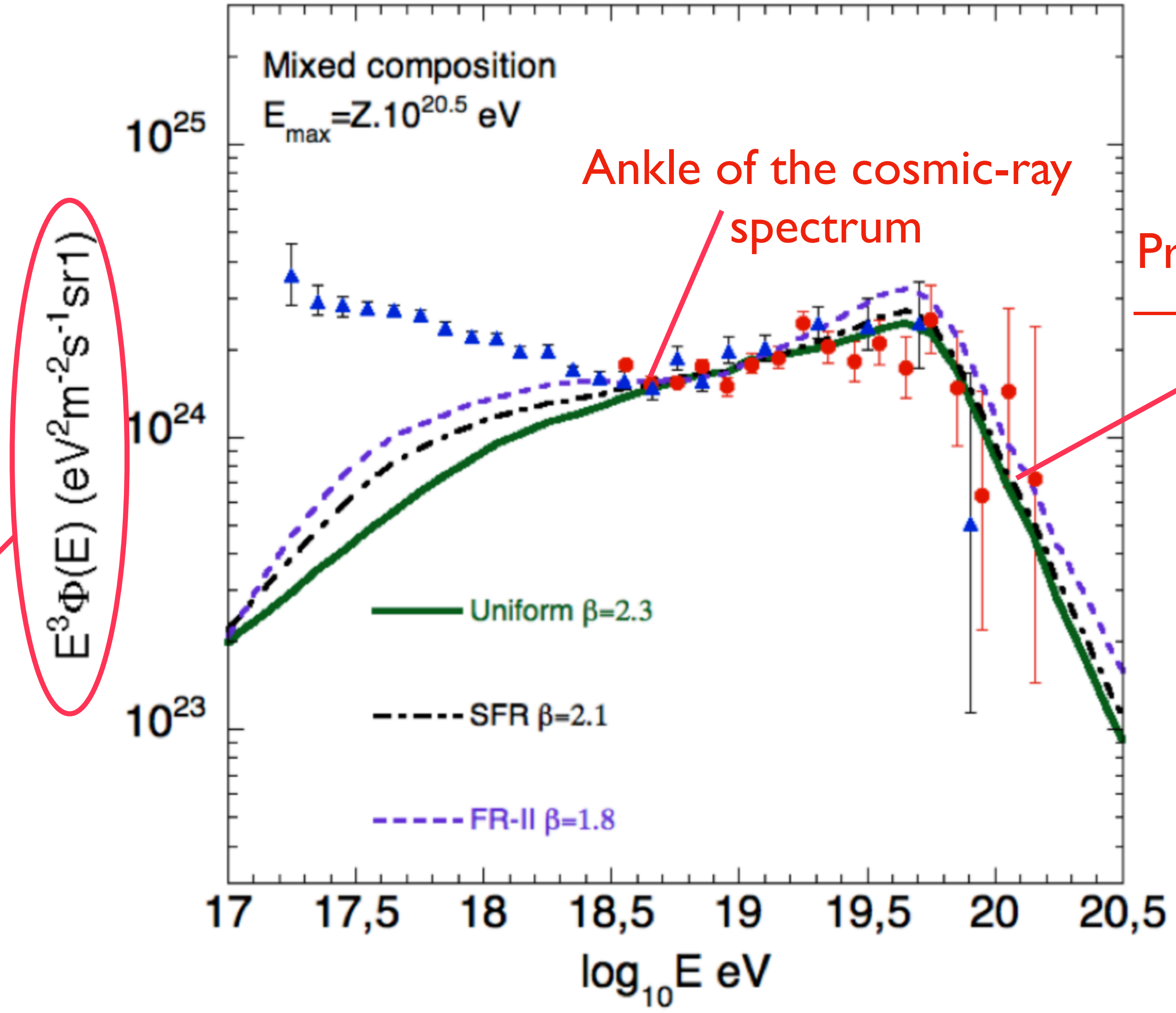


E^2×(diff. flux)

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



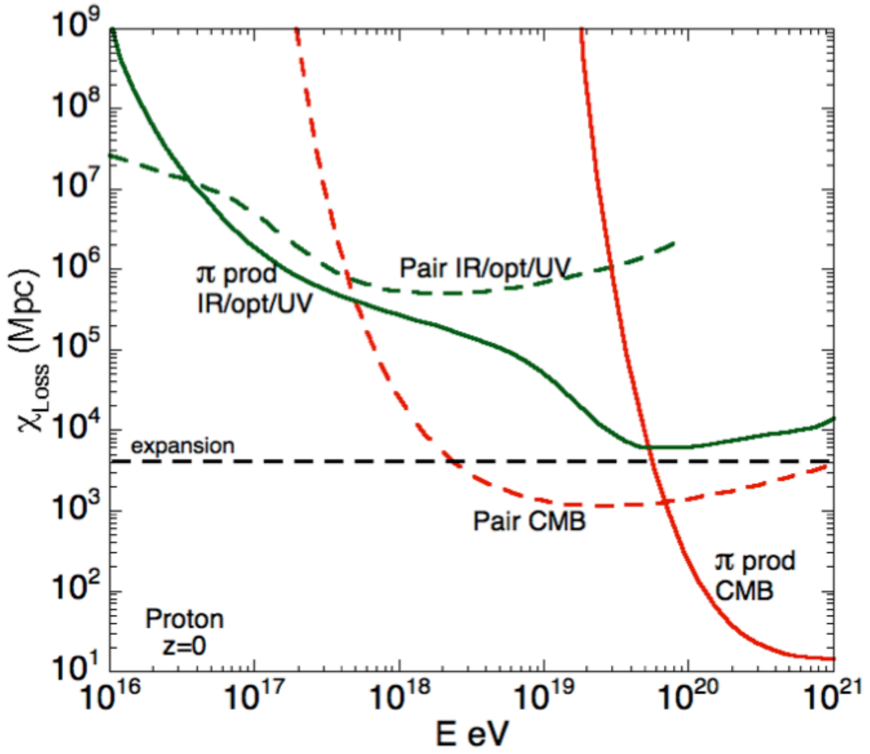
Ankle of the cosmic-ray spectrum

Predicted suppression above 5.10^{19} eV
—> unrelated to the maximum energy at the sources
—> GZK effect

$E^3 \times$(diff. flux)

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

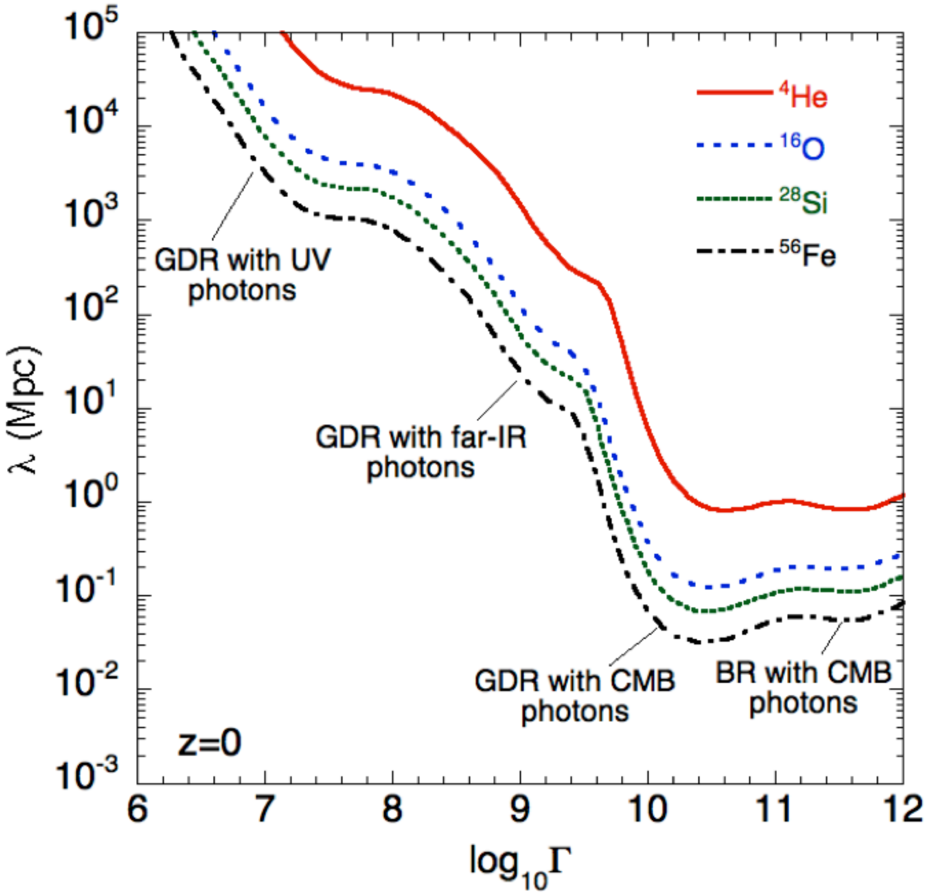
—> GZK cut-off for protons

nuclei mean free path for giant dipole resonance (photodisintegration) as a function of the Lorentz factor :

Strong decrease above Γ~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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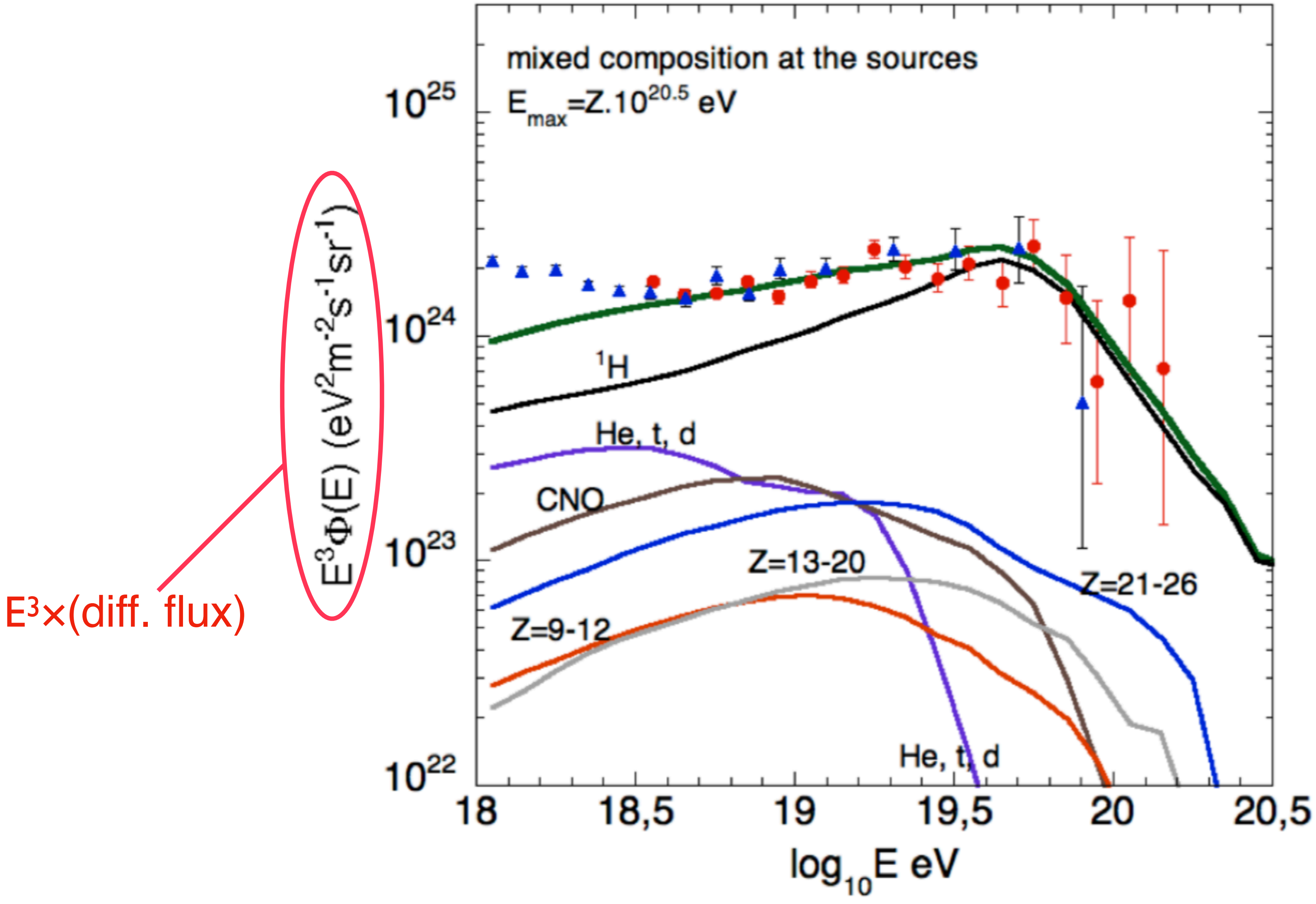

When all the species are assumed to be accelerated above 10^{20} eV, the composition is expected to get lighter (i.e proton richer) above 10^{19} eV (photodisintegration of composed species)

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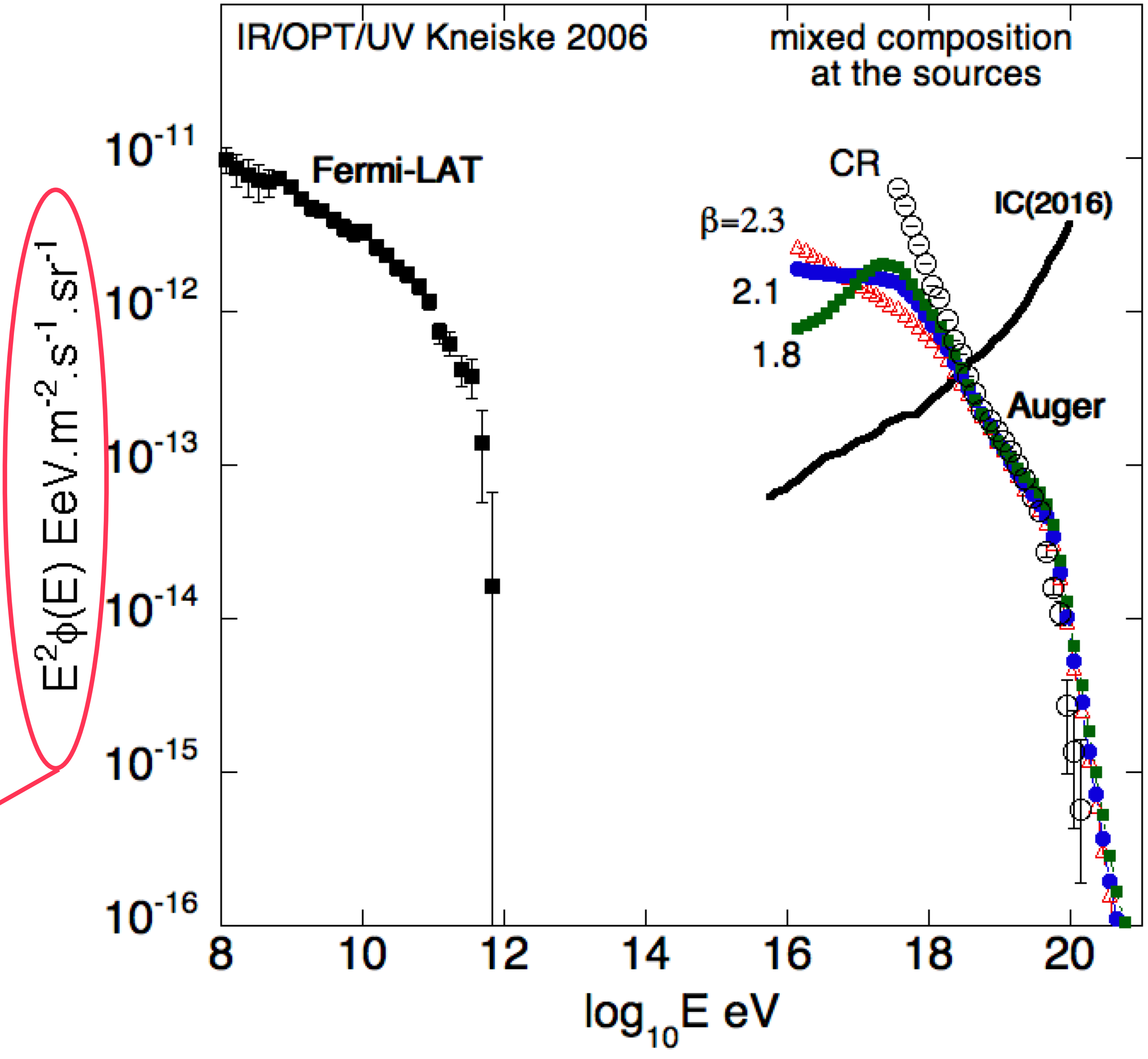

E²×(diff. flux)

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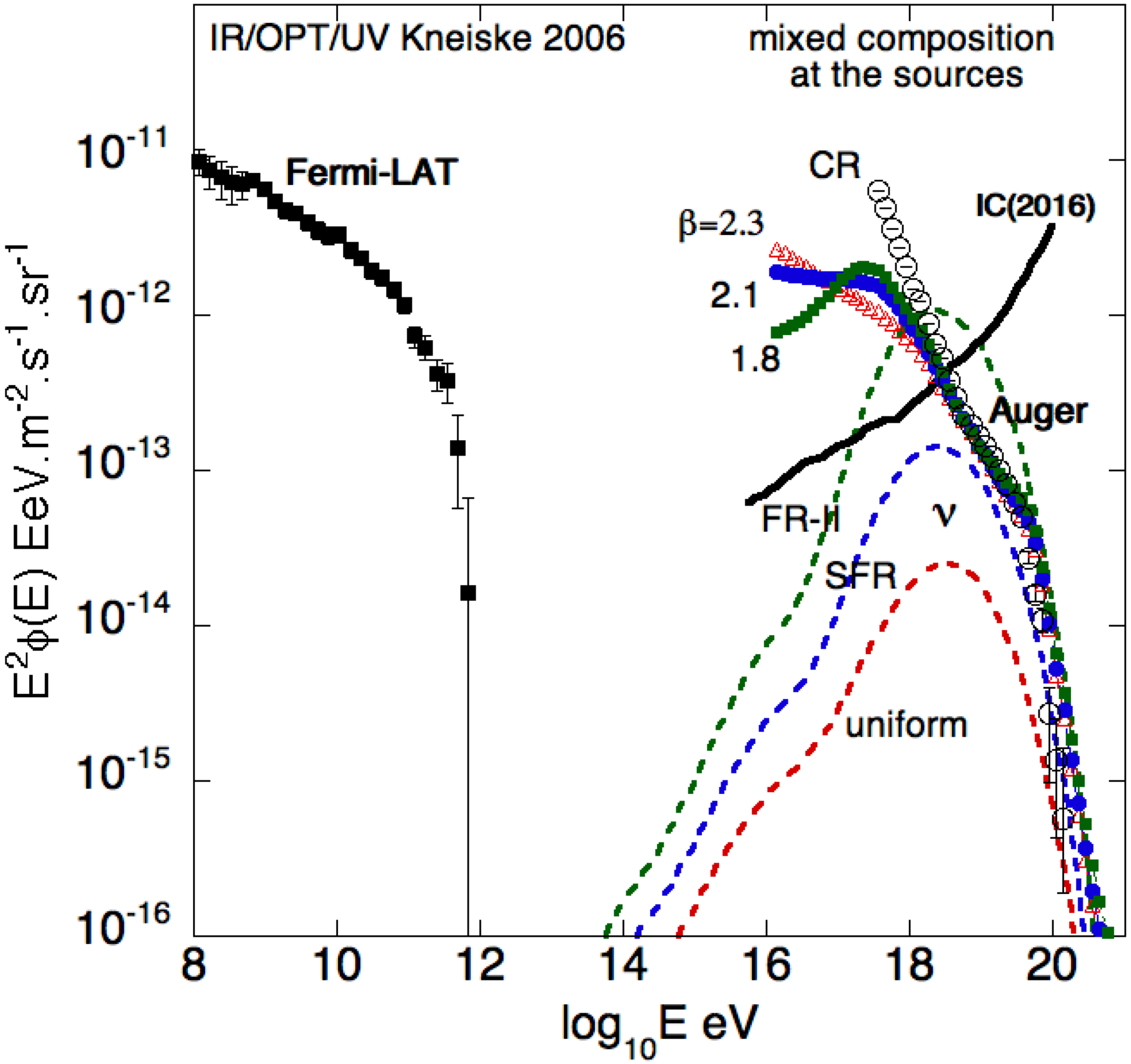
Neutrino "bumps" peaking around 10^{18} eV
—> produced by UHECR >>10^{19} eV per nucleon
—> π-photoproduction on CMB photons



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

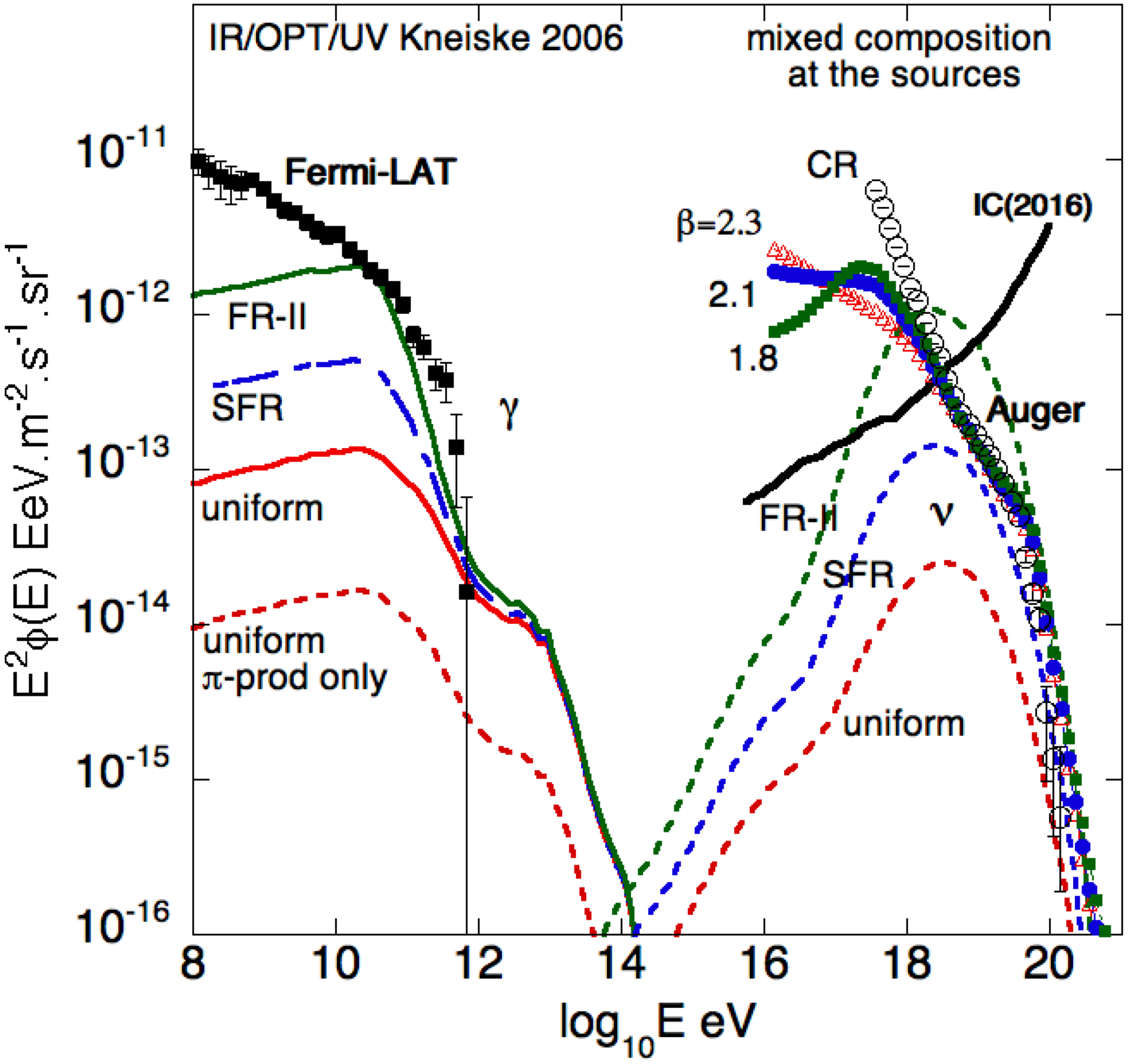
One example : mixed composition assumed at UHECR sources

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

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

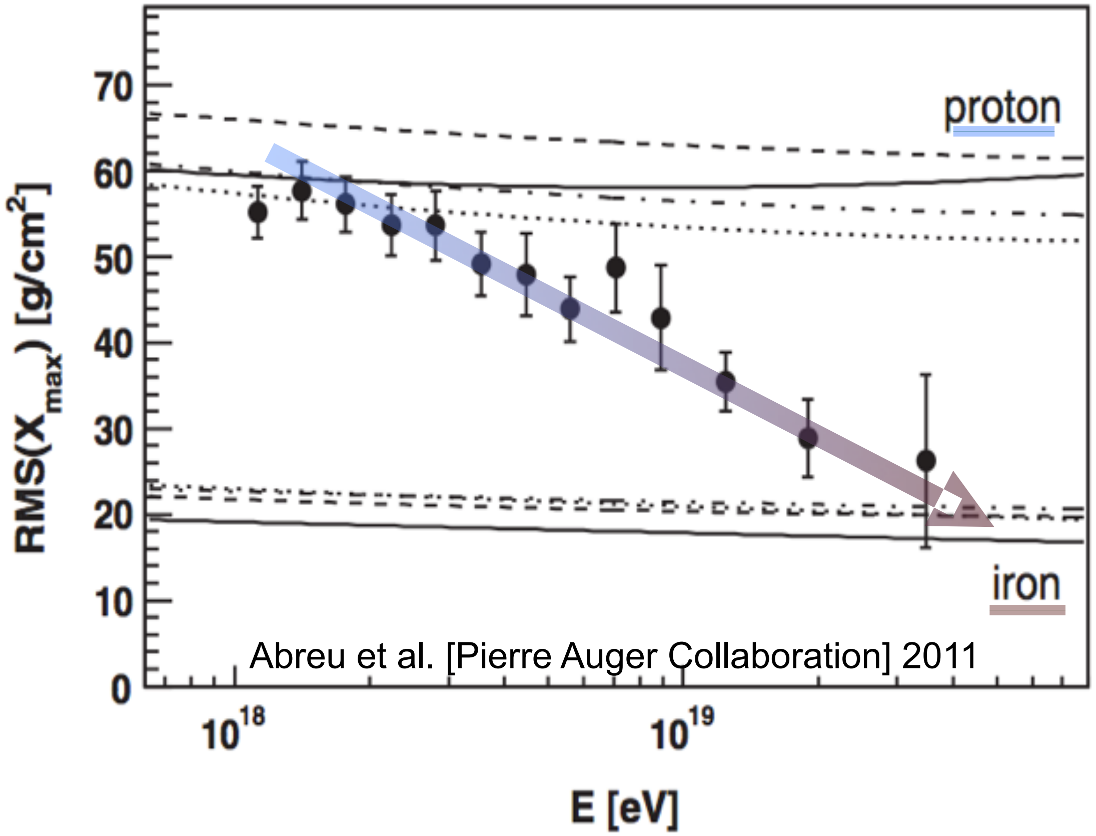
(ii) Strong impact of the cosmological evolution of the sources on the cosmogenic γ fluxes —> strongest evolution also ruled out by Fermi-LAT IGRB

(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



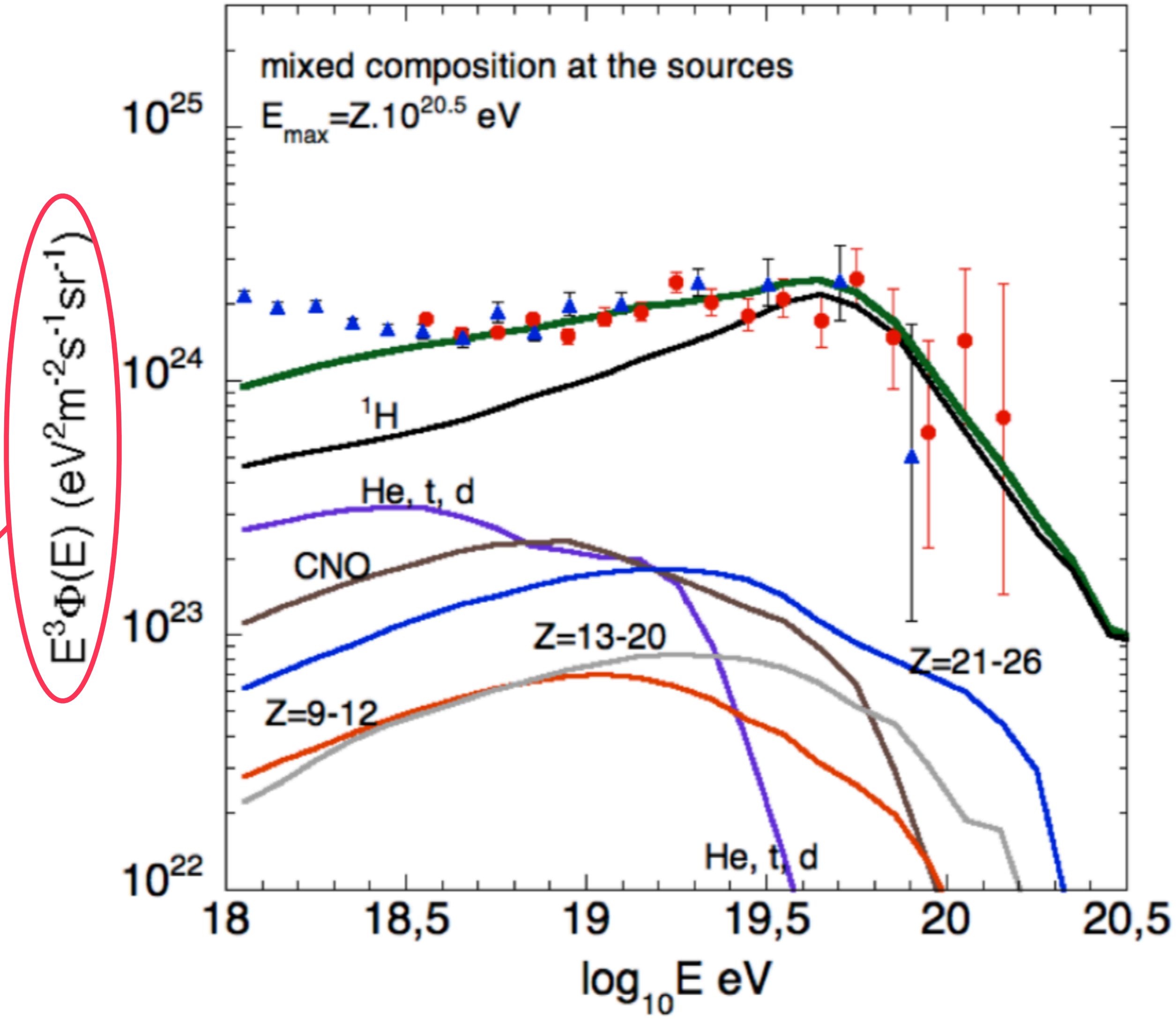
Abreu et al. [Pierre Auger Collaboration] 2011

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

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



E³×(diff. flux)

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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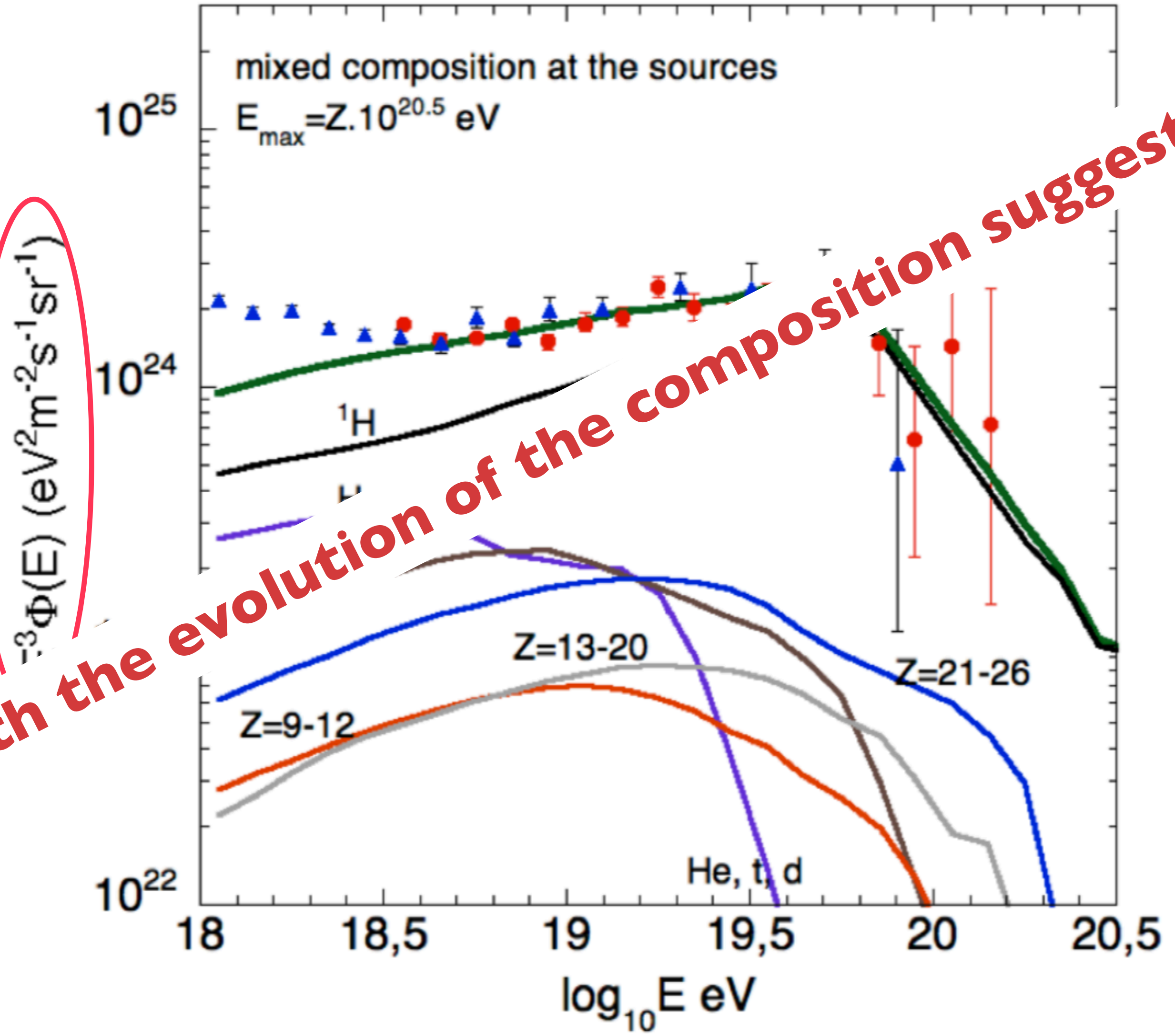

$E^3\times$(diff. flux)

Incompatible with the evolution of the composition suggested by Auger data !

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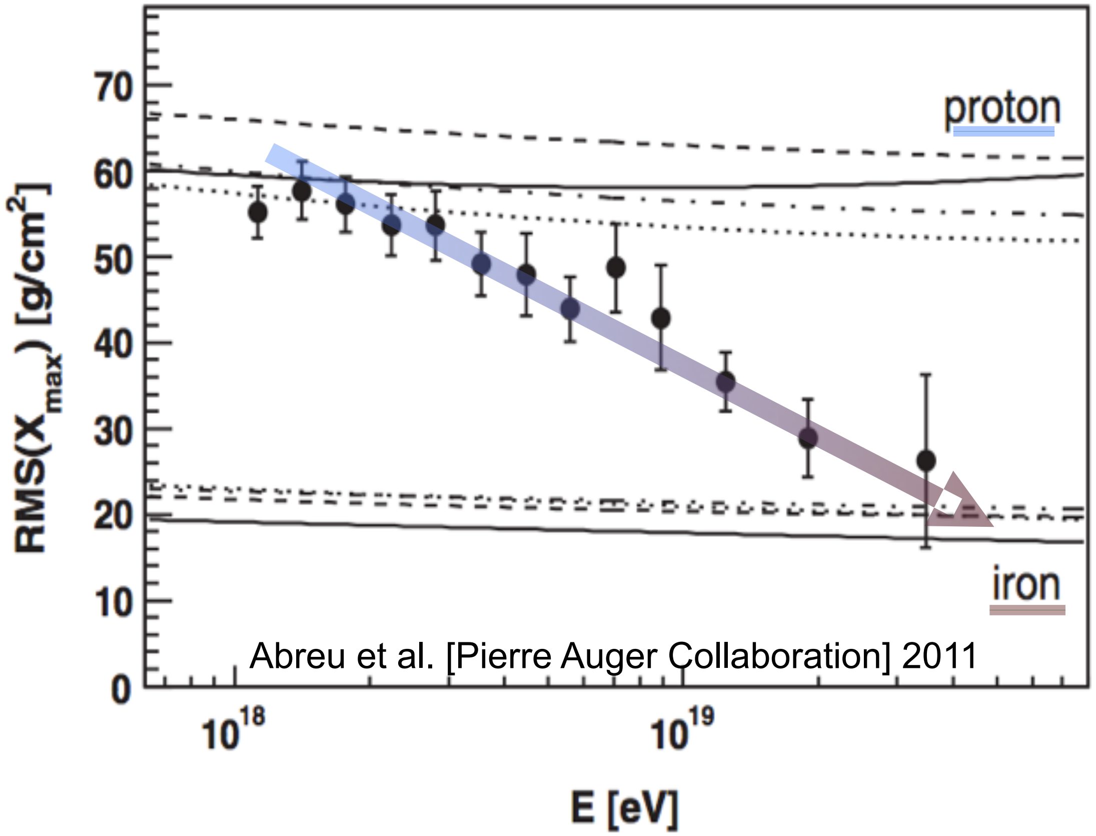
Implications of Auger composition measurements



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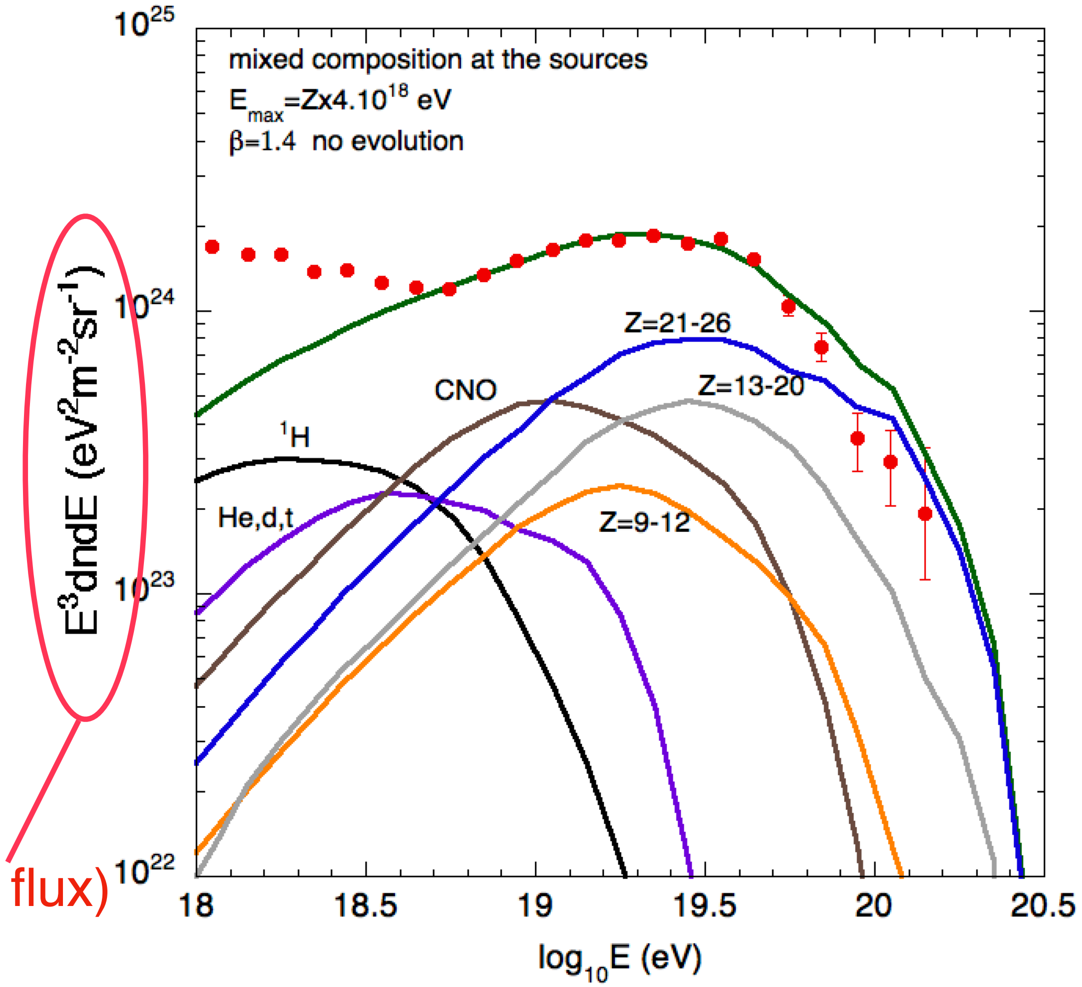


$E^3\times$(diff. flux)

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

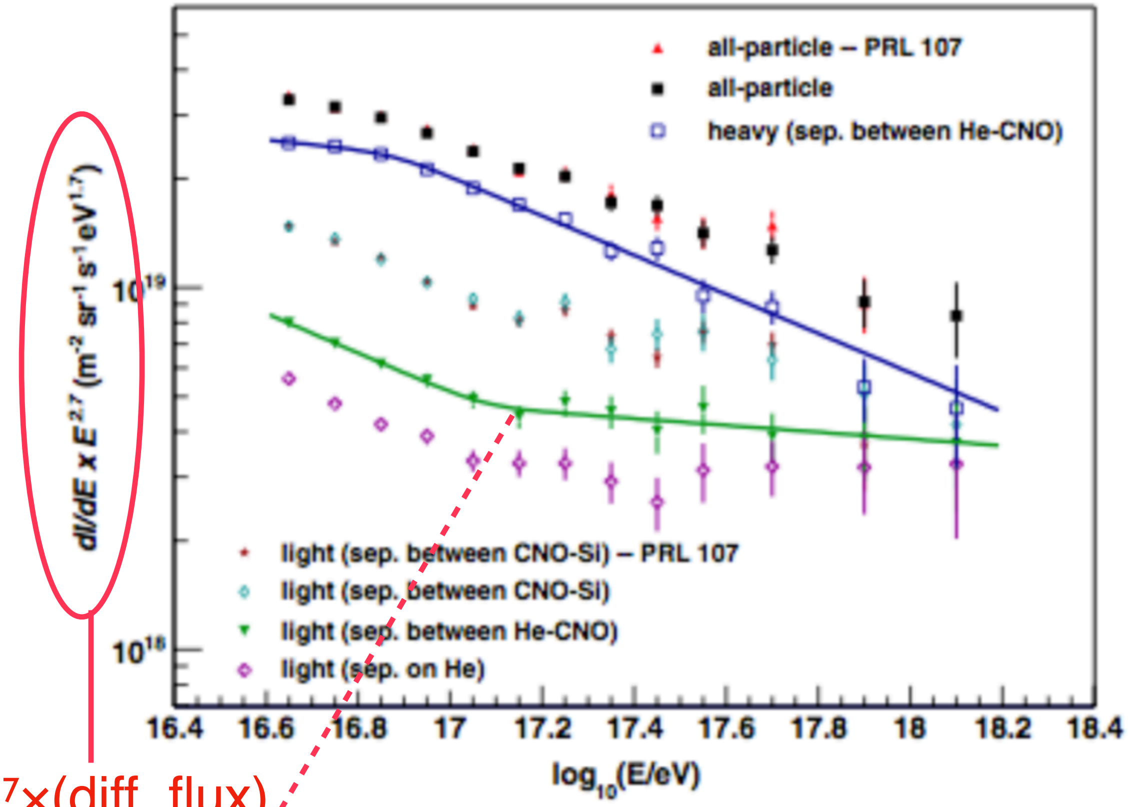
Low maximum energy per nucleon (a few EeV to 10^{19} eV, well below the pion production threshold with CMB photons) and hard source spectral indexes required

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

PHYSICAL REVIEW D **87**, 081101(R) (2013)



$E^{2.7}$×(diff. flux)

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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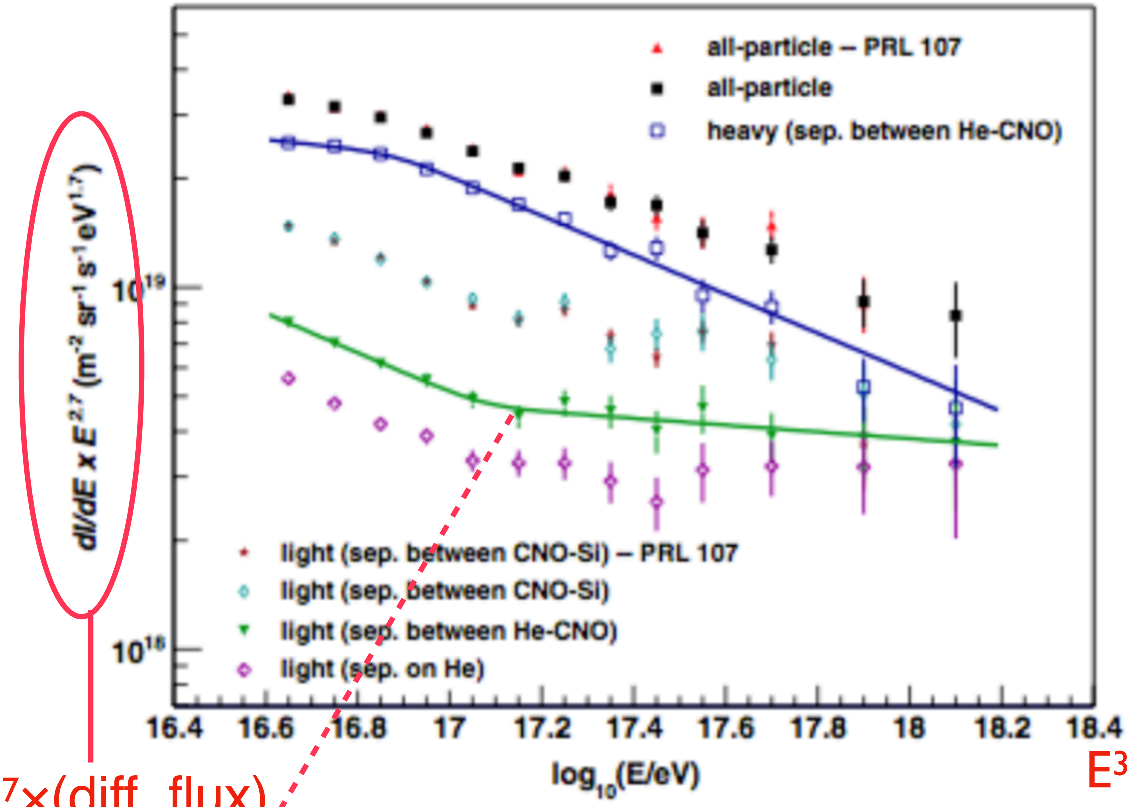

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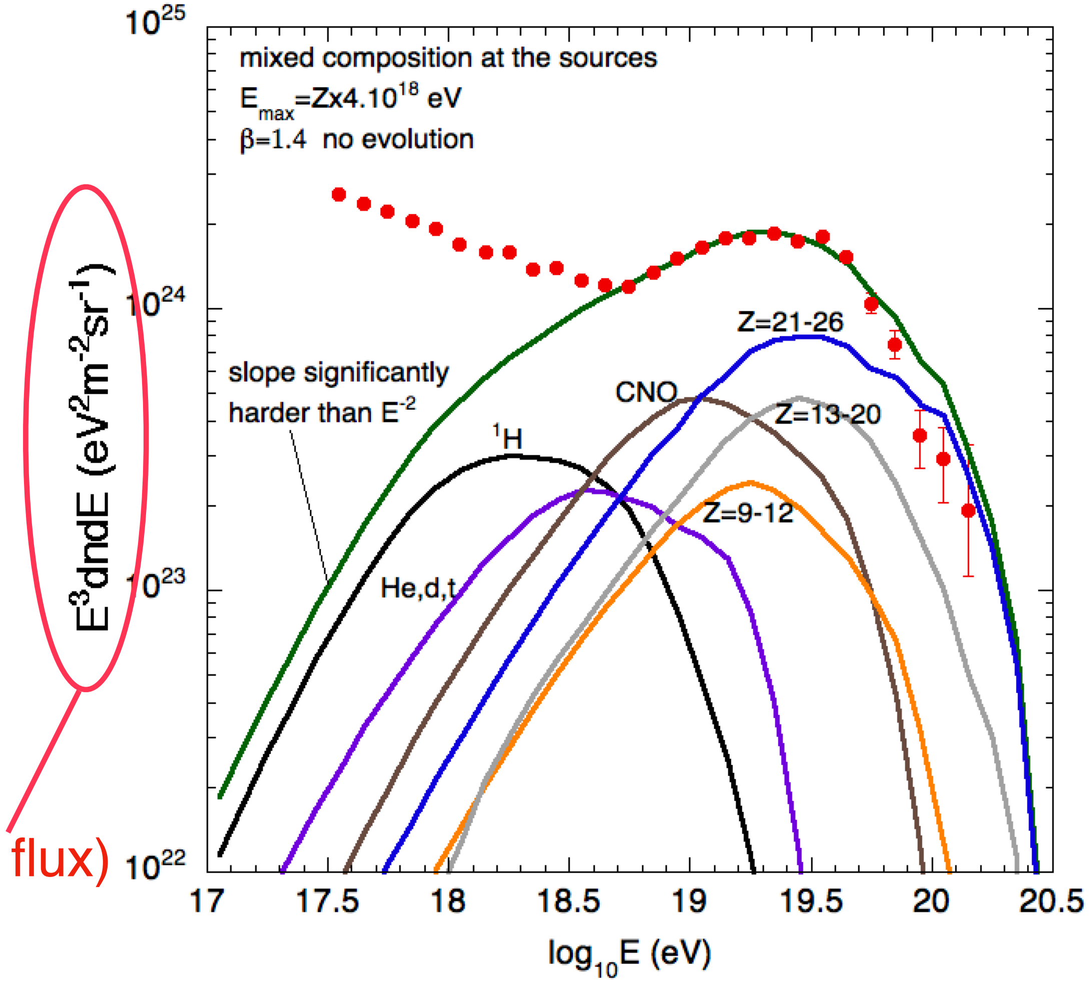

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Difficult to make a consistent picture of the Auger composition + the light ankle with the above phenomenological model

One would need a much softer spectrum for the light nuclei

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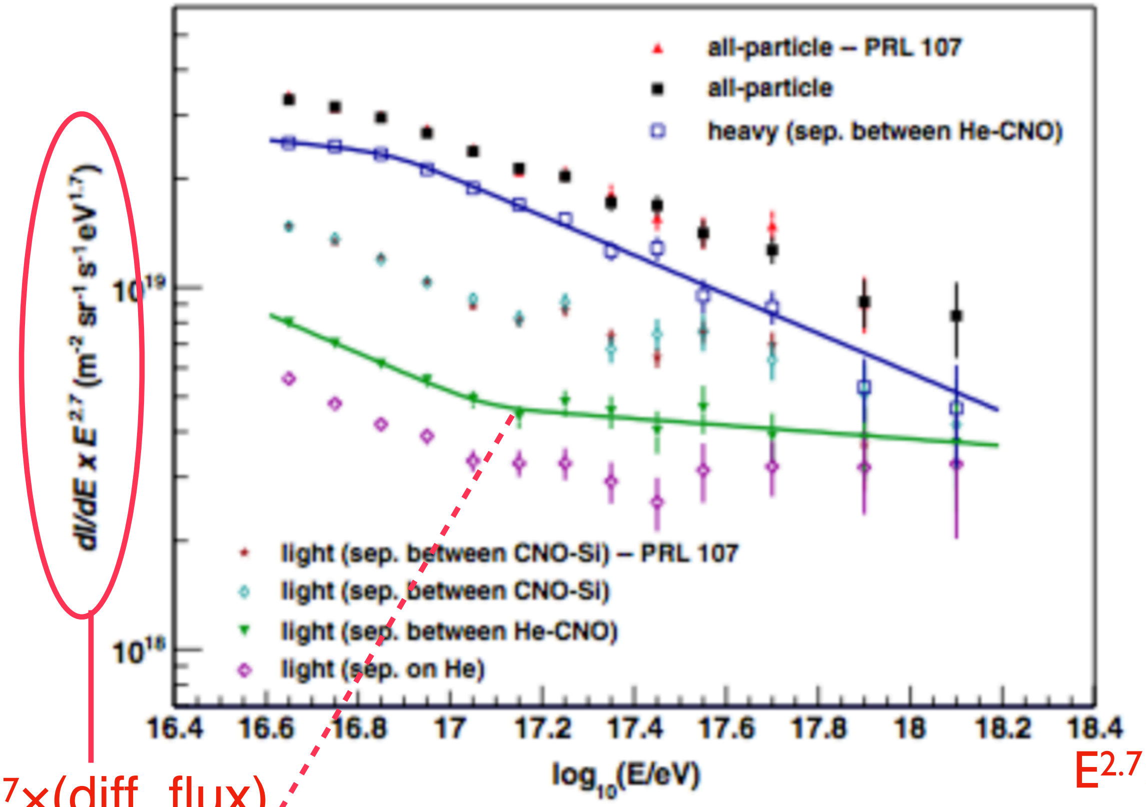

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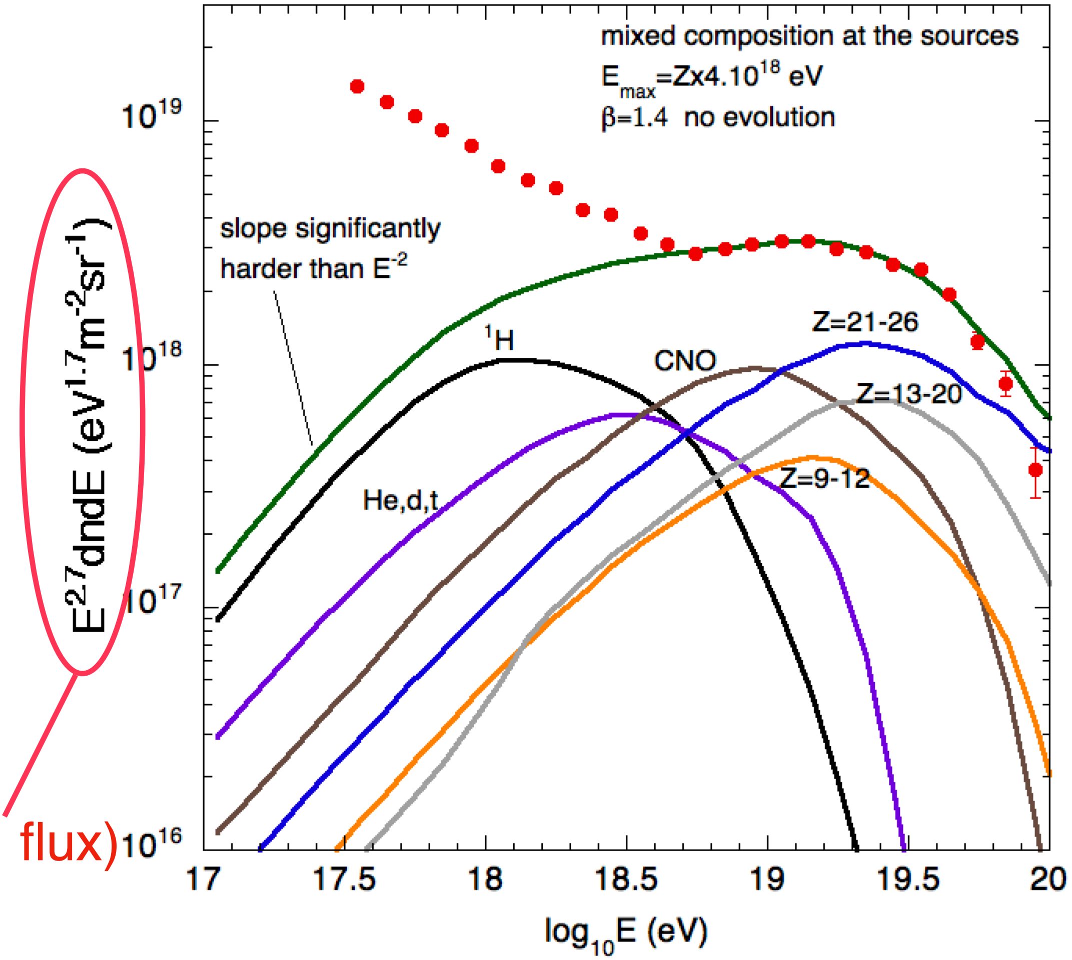

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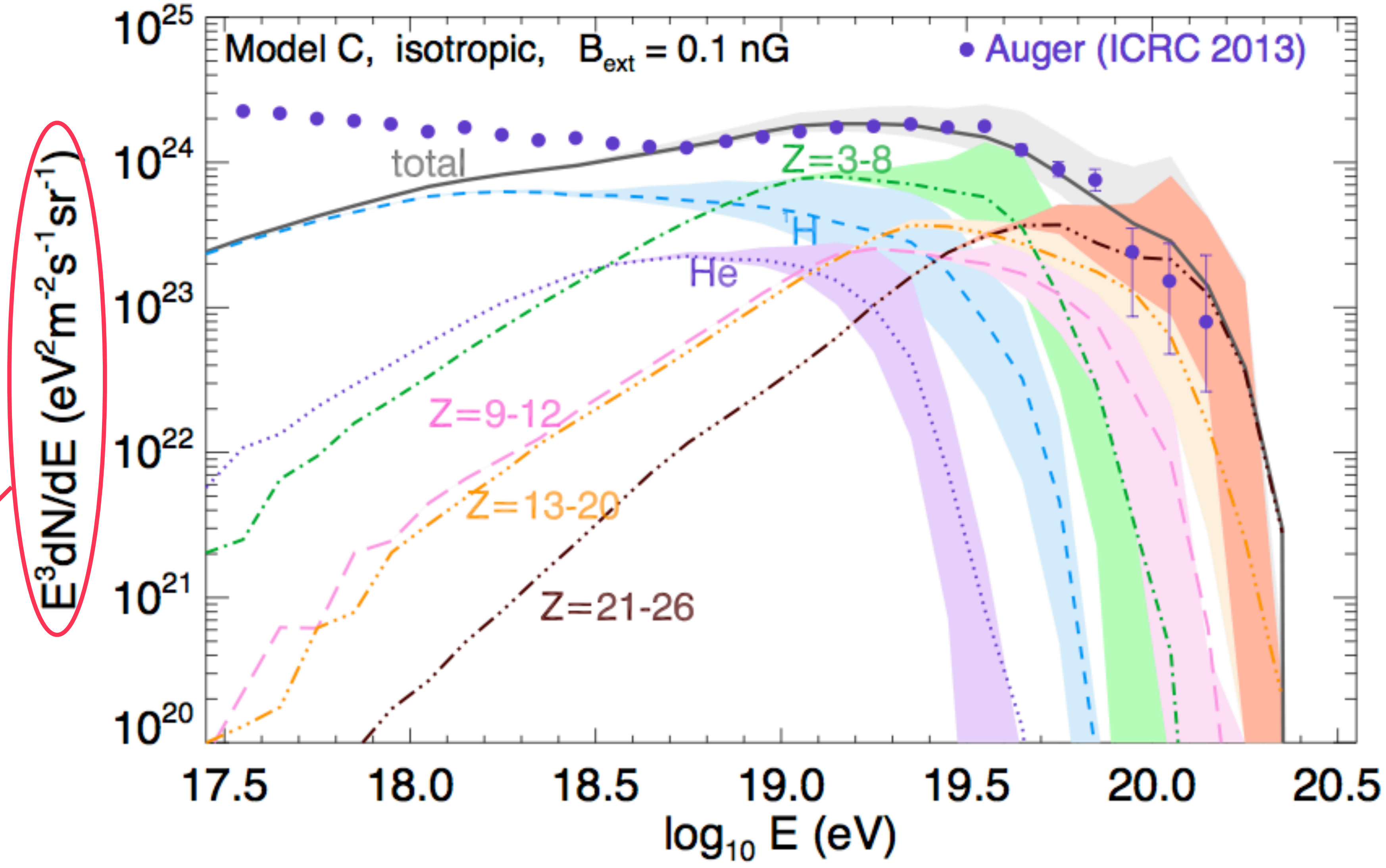
Phenomenological model of UHECR acceleration as a solution to the soft proton spectrum issue

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



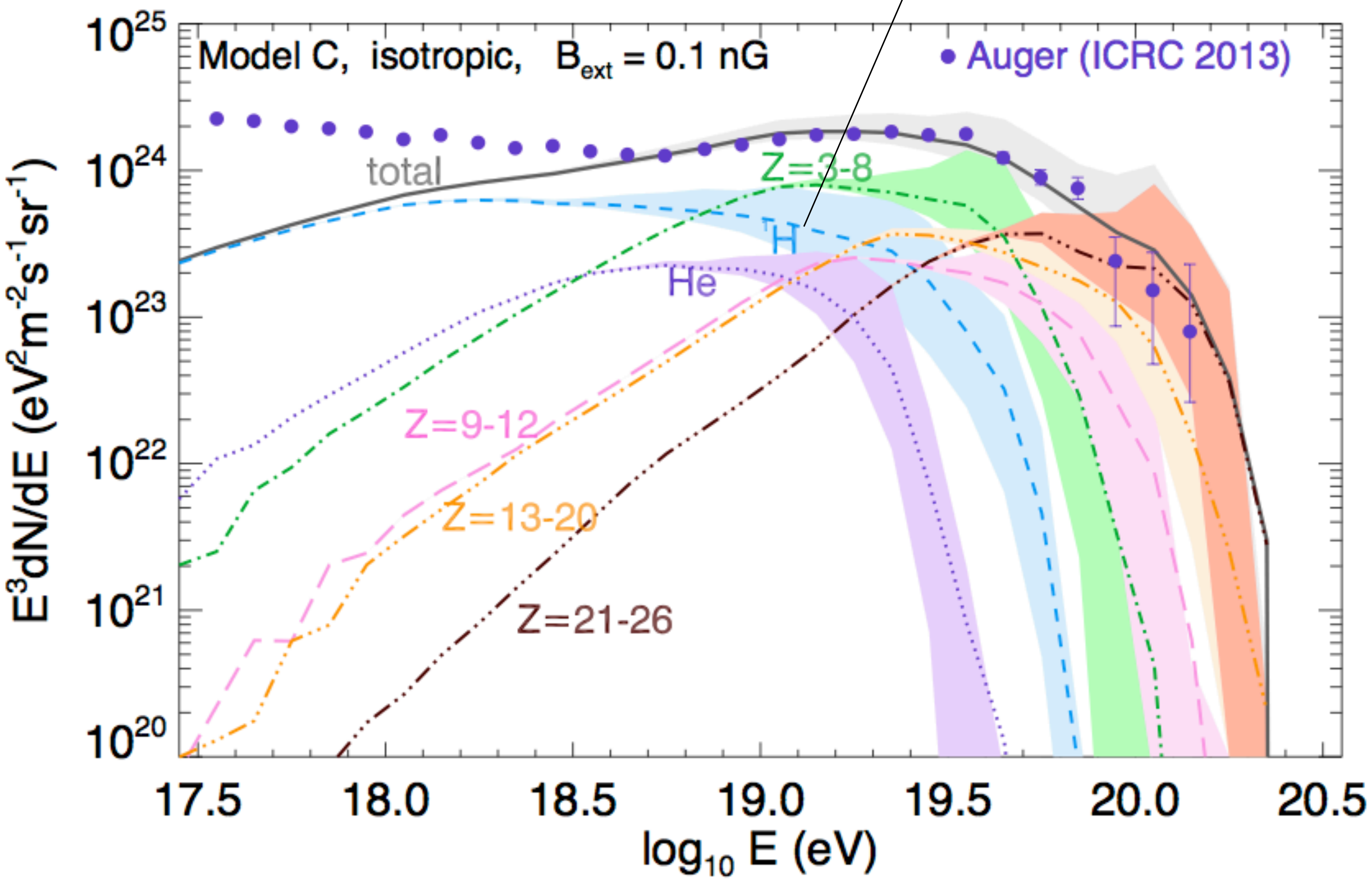
$E^3\times$(diff. flux)

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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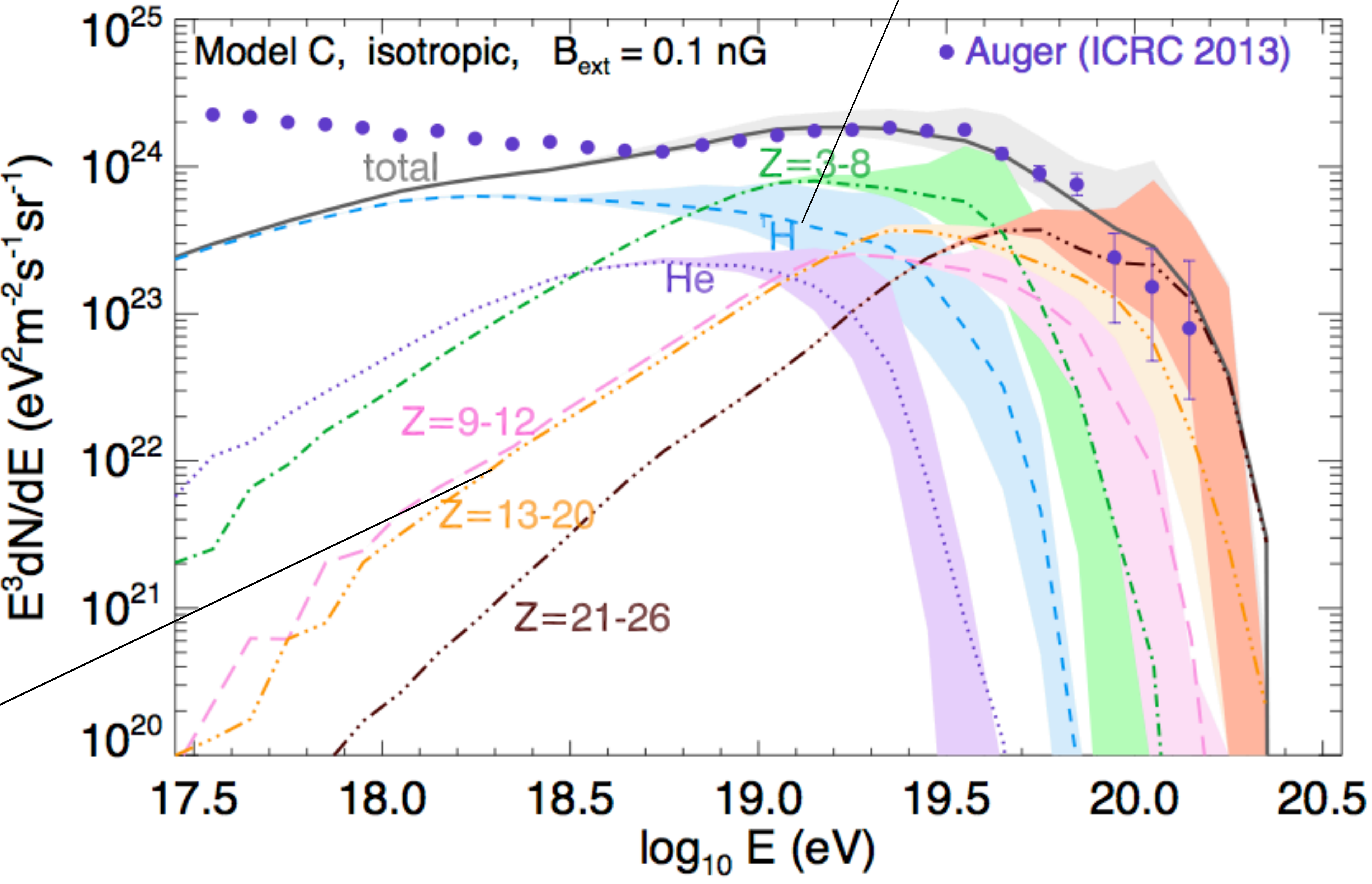


Heavier nuclei spectrum : Very hard due to the high-pass filter effect of the escape process
—> Hard nuclei spectrum required to fit Auger composition at high energy

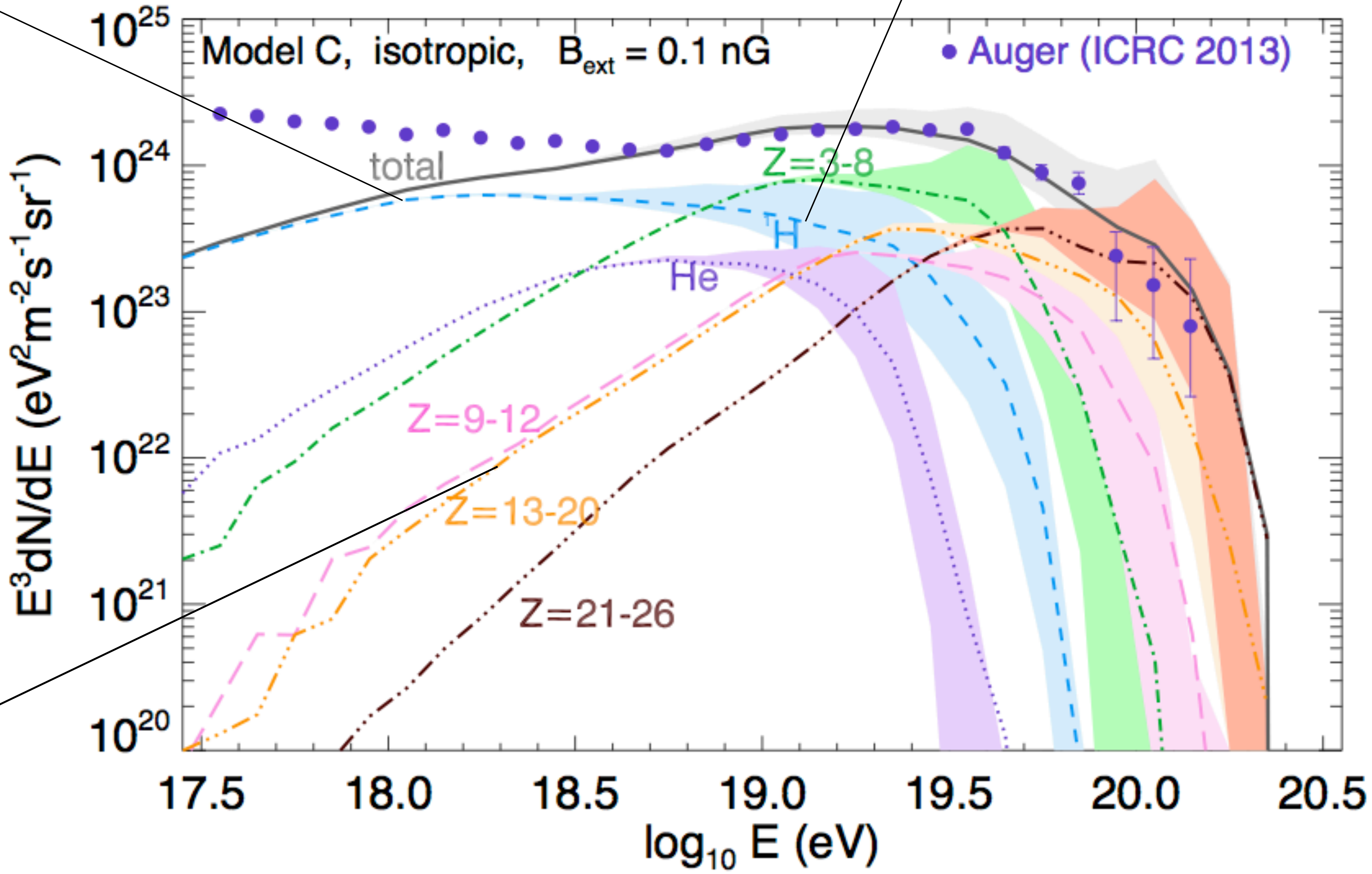
Phenomenological model : implications for the GCR to EGCR transition

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

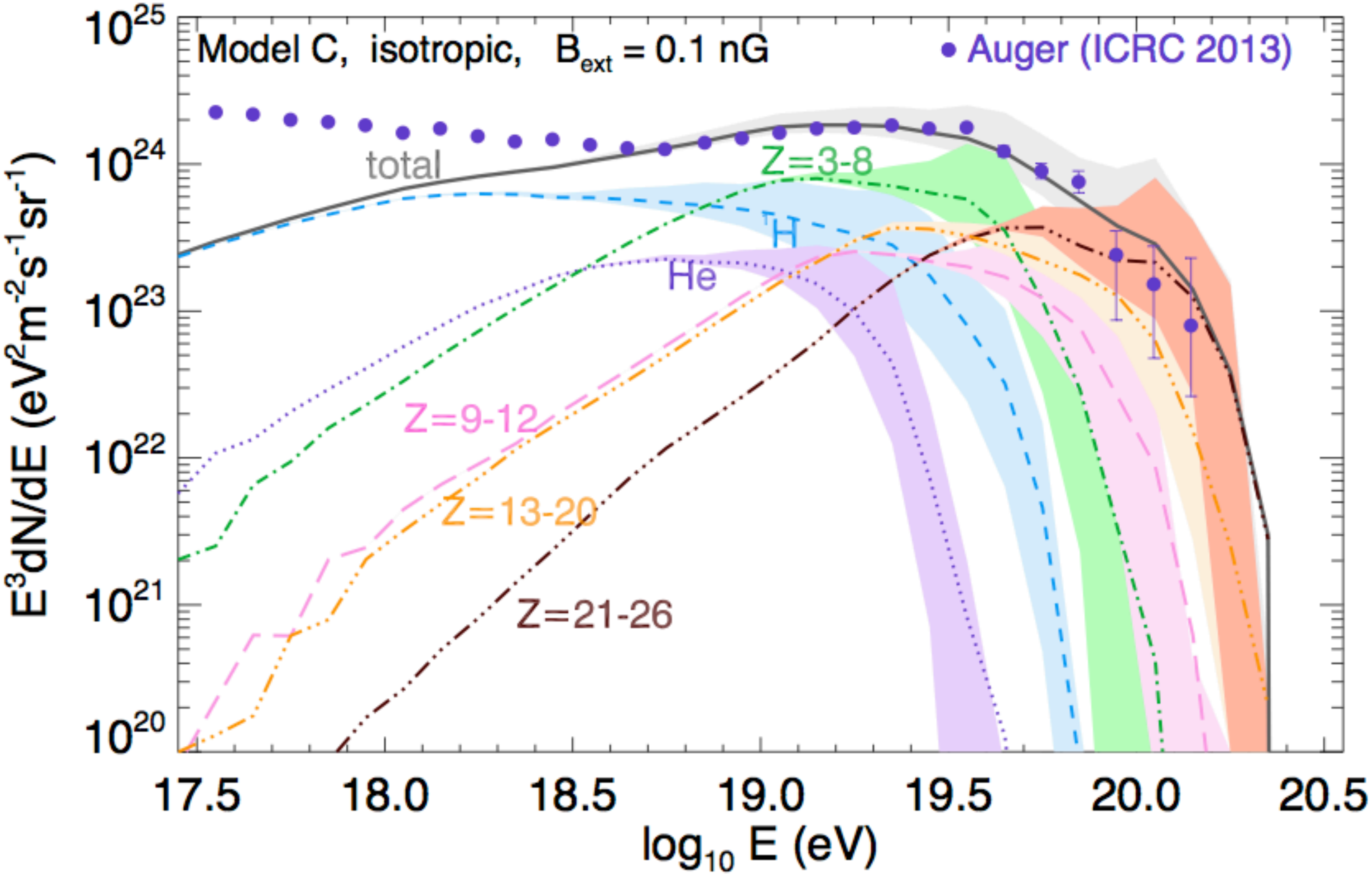
Phenomenological model : implications for the GCR to EGCR transition

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

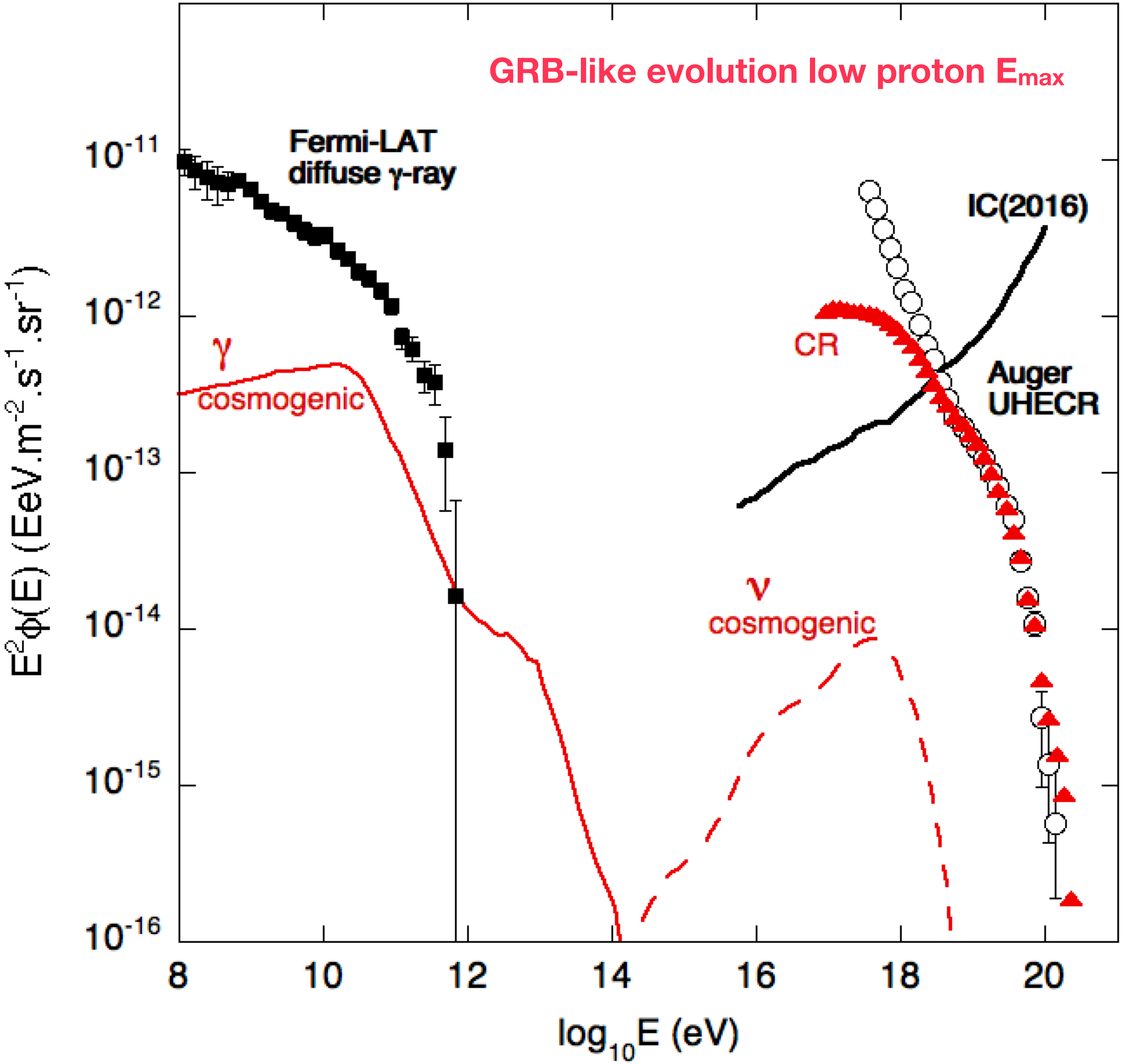
—> should not be a distinctive feature of GRB sources

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.



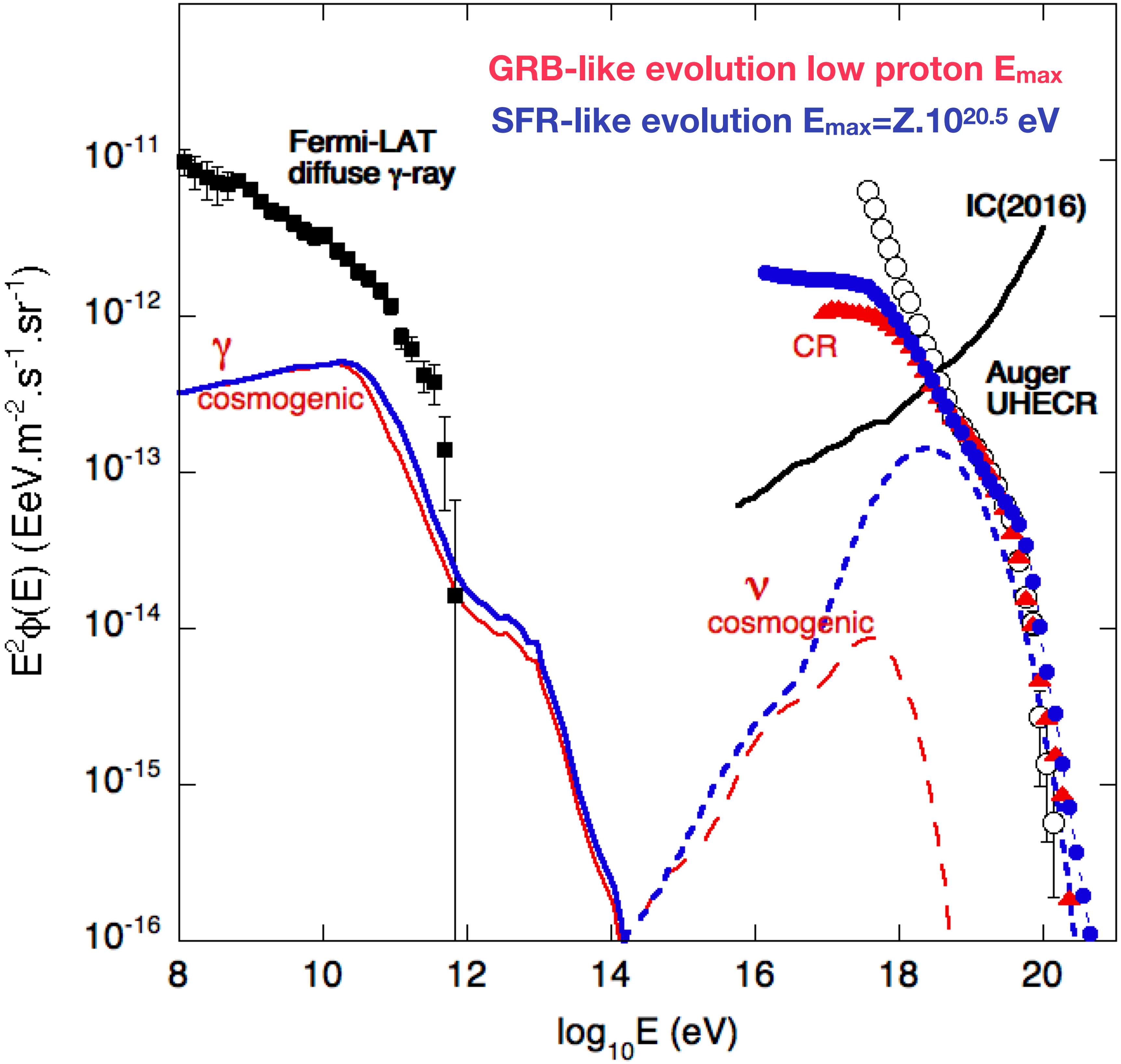
Phenomenological model : multi-messenger implications



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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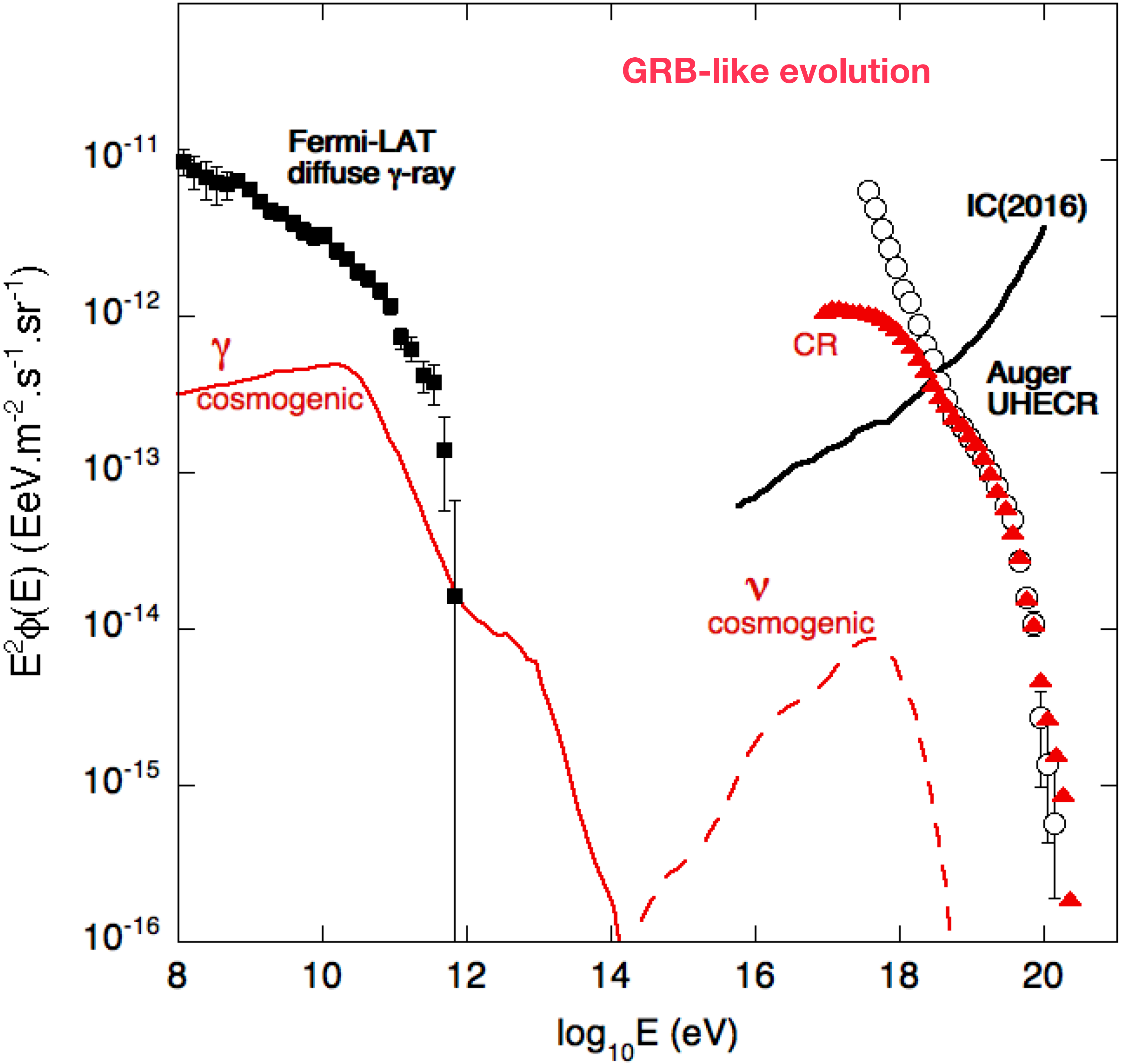


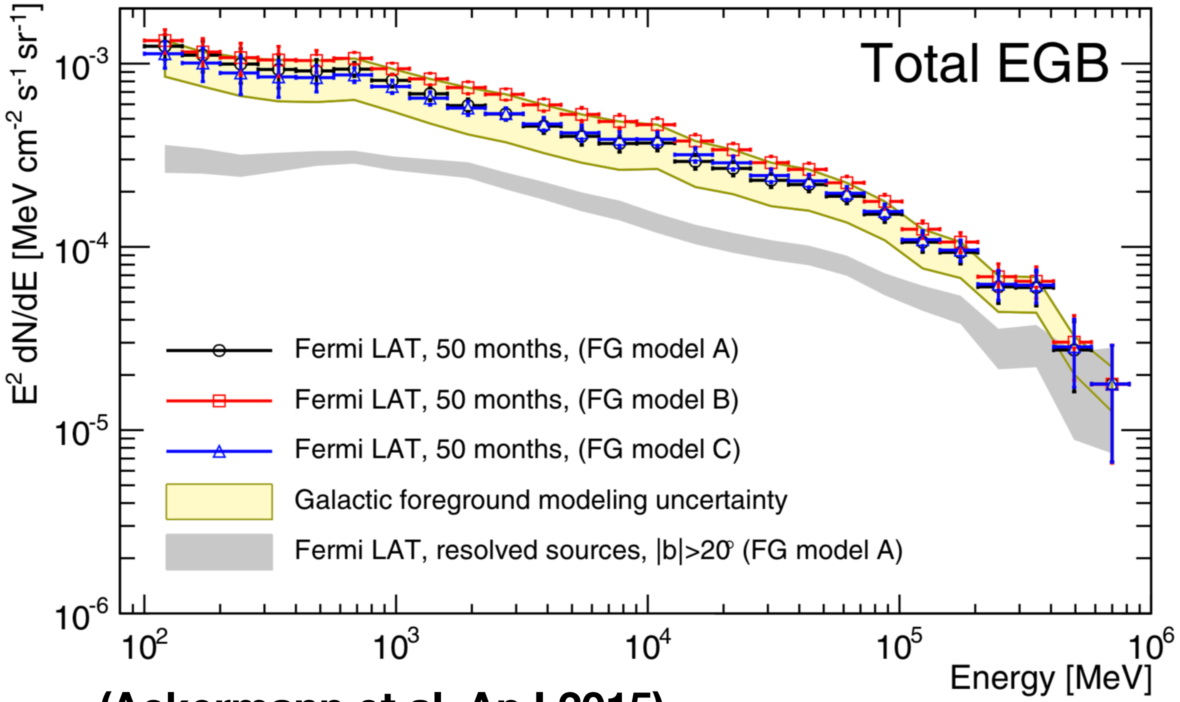
The impact is, as expected, very strong on the predicted cosmogenic neutrino fluxes

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

Fermi estimate of the total extragalactic γ-ray background (unresolved + resolved components)



(Ackermann et al. ApJ 2015)

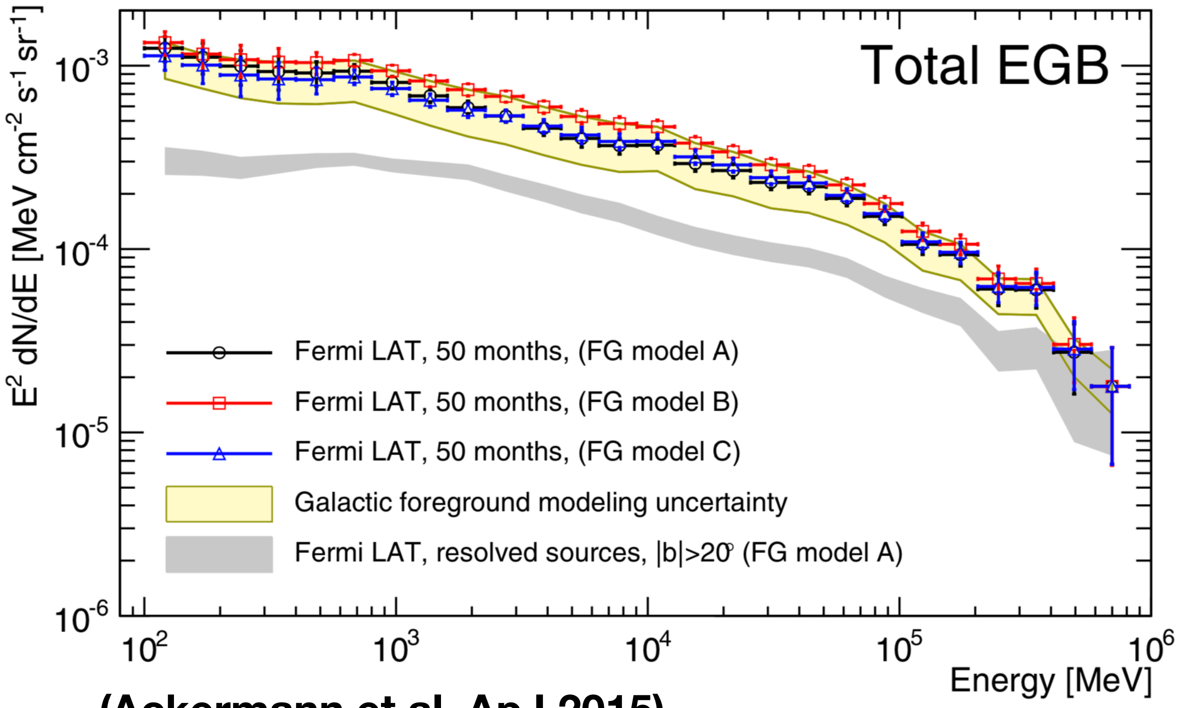
Account of the uncertainties on the modelling of the galactic foreground

➡3 different estimates (models A, B and C) corresponding to three equally realistic theoretical modelings of the galactic foreground

➡ In the following we consider only the largest estimated background (namely model B) to discuss the constrains brought by the EGB composition on UHECR origin

Composition of the extragalactic γ-ray background

Fermi estimate of the total extragalactic γ-ray background (resolved + unresolved components)



(Ackermann et al. ApJ 2015)

The total extragalactic γ-ray background is made of several contributions :

- resolved point sources (very large majority of Blazars)
- unresolved point sources (mostly blazars, misaligned AGNs and star forming galaxies)
- truly diffuse processes (UHECR for sure, possibly DM)

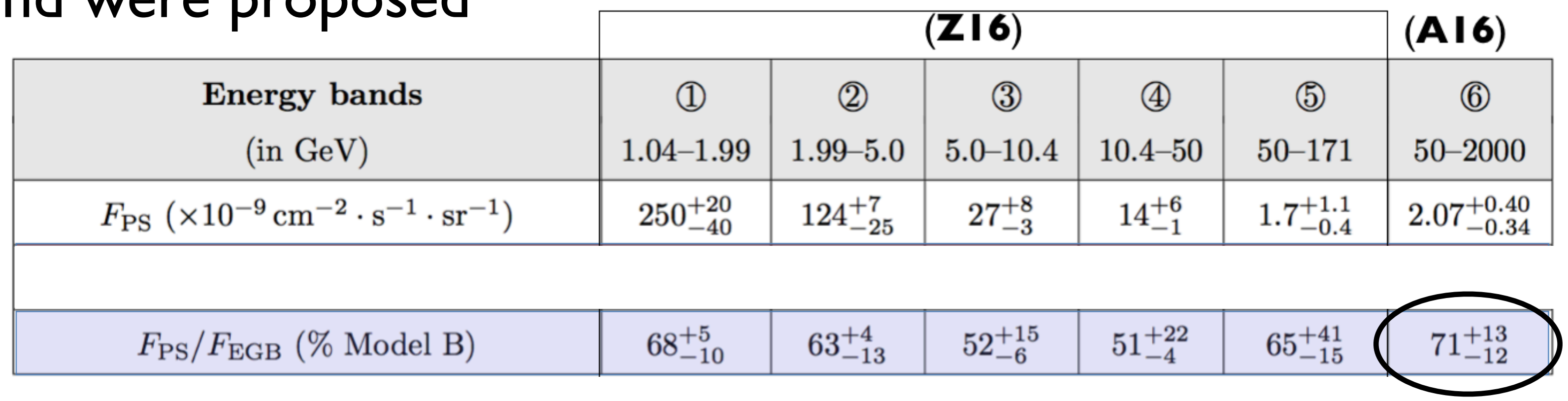
➡ **estimating the different contributions would help constraining that of UHECRs**

Different estimates from Fermi data of the contribution of blazar point sources (resolved and unresolved) to the total γ-ray background were proposed

2 recent studies:

- Ackermann et al. , PRL, 2016 (**A16**)
- Zechlin et al., ApJ, 2016 (**Z16**)

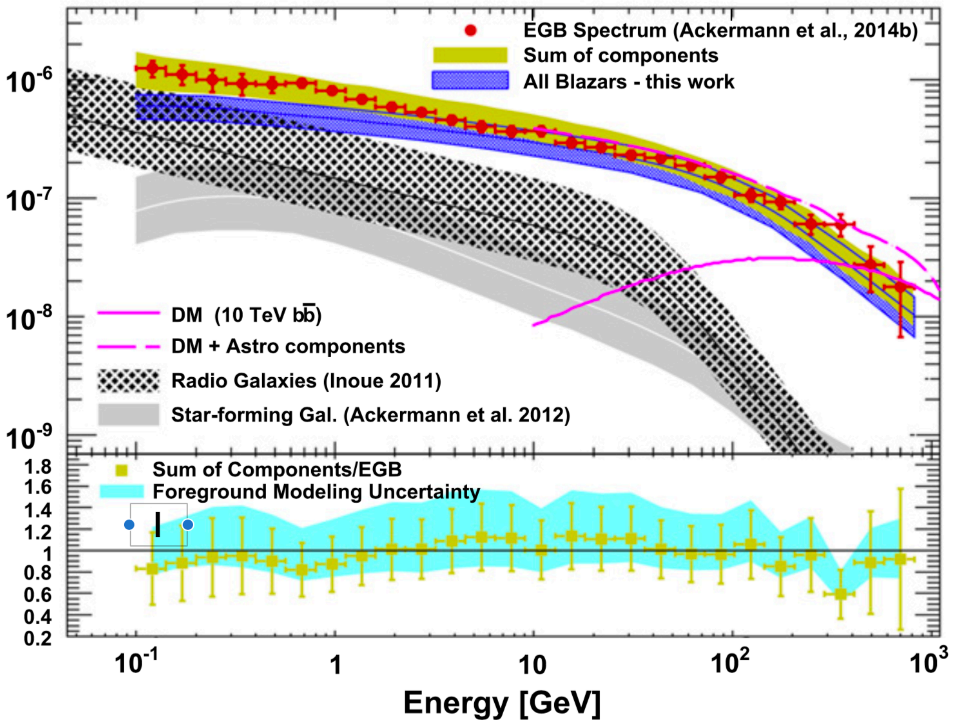
(based on a method proposed in Malyshev & Hogg 2011)



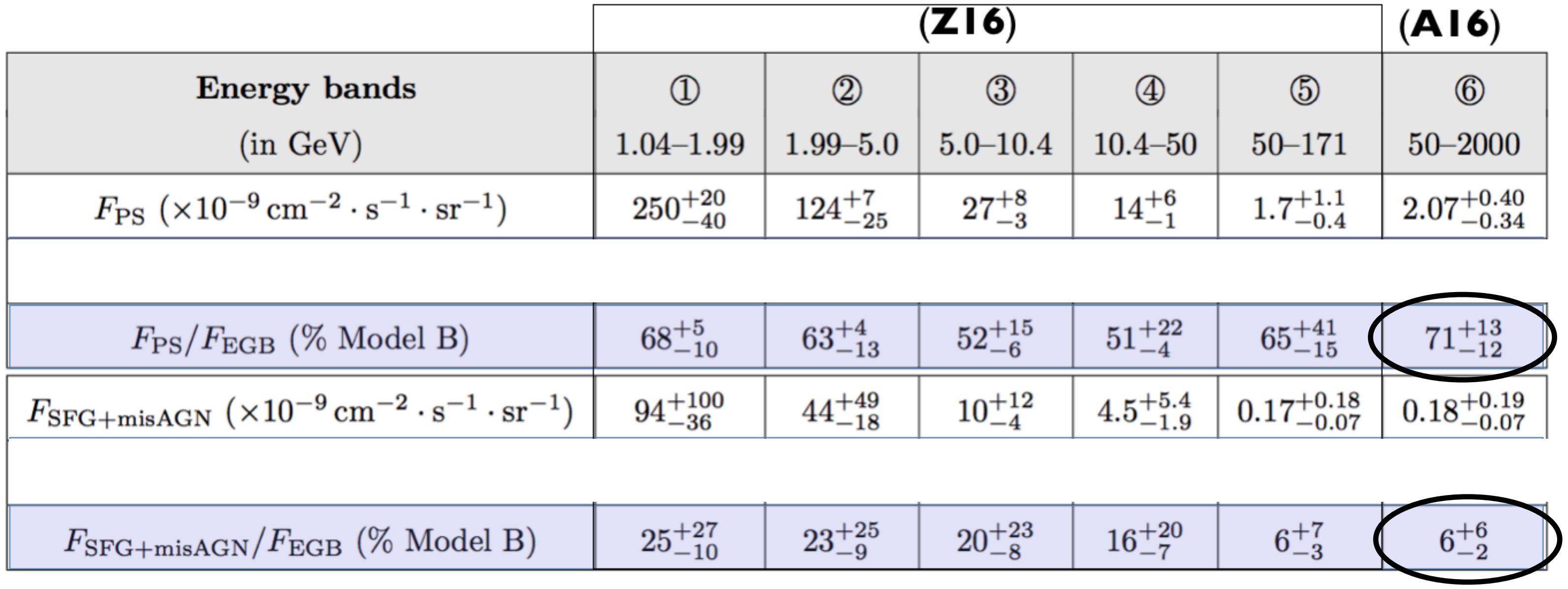
	(Z16)					(A16)
Energy bands (in GeV)	① 1.04–1.99	② 1.99–5.0	③ 5.0–10.4	④ 10.4–50	⑤ 50–171	⑥ 50–2000
F_{PS} ($\times 10^{-9}\,cm^{-2} \cdot s^{-1} \cdot sr^{-1}$)	250^{+20}_{-40}	124^{+7}_{-25}	27^{+8}_{-3}	14^{+6}_{-1}	$1.7^{+1.1}_{-0.4}$	$2.07^{+0.40}_{-0.34}$
F_{PS}/F_{EGB} (% Model B)	68^{+5}_{-10}	63^{+4}_{-13}	52^{+15}_{-6}	51^{+22}_{-4}	65^{+41}_{-15}	71^{+13}_{-12}

Besides blazars, SFGs and misaligned AGNs should contribute significantly to the EGB but these contributions were not constrained by **A16 and Z16**

Composition of the extragalactic γ-ray background



Ajello et al., ApJ, 2015



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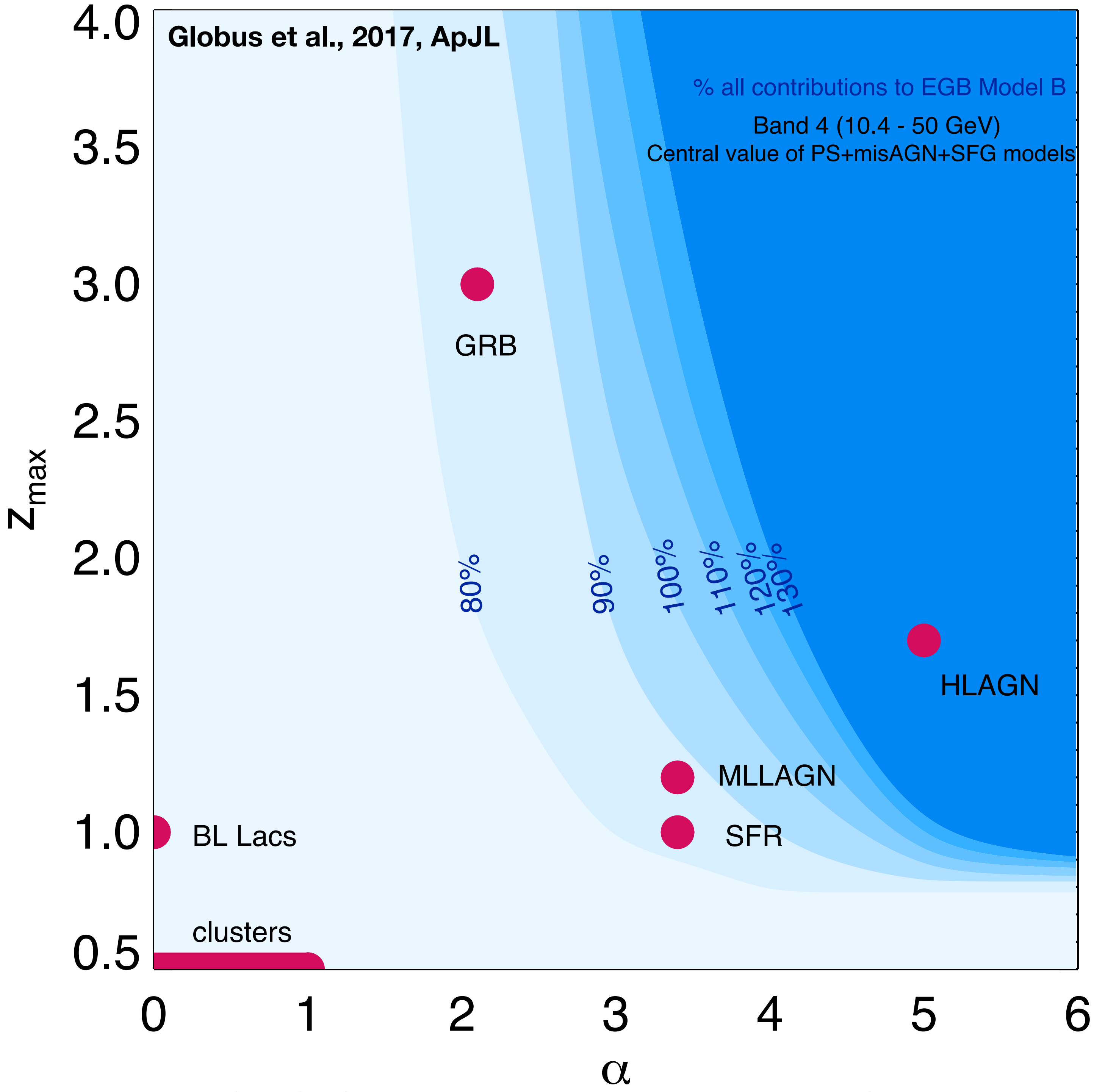
$F_{\rm SFG+misAGN}$ $(\times 10^{-9}\,{\rm cm^{-2}\cdot s^{-1}\cdot sr^{-1}})$	94^{+100}_{-36}	44^{+49}_{-18}	10^{+12}_{-4}	$4.5^{+5.4}_{-1.9}$	$0.17^{+0.18}_{-0.07}$	$0.18^{+0.19}_{-0.07}$
$F_{\rm SFG+misAGN}/F_{\rm EGB}$ (% Model B)	25^{+27}_{-10}	23^{+25}_{-9}	20^{+23}_{-8}	16^{+20}_{-7}	6^{+7}_{-3}	6^{+6}_{-2}

Using theoretical estimates of the contribution (almost exclusively unresolved) of SFG and misaligned AGNs one can add their contributions to that attributed to blazars in Z16 and A16

The contribution of UHECR must added to those of astrophysical sources to check whether or not a given 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

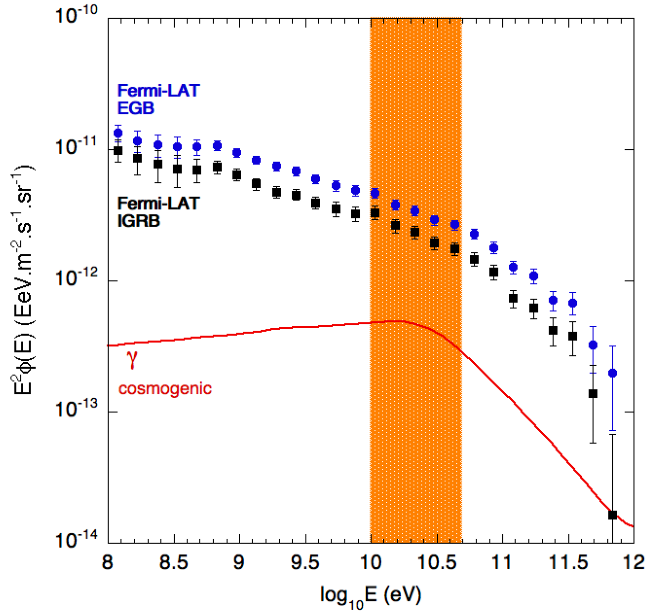
Summary plot on the allowed cosmological evolutions



Astrophysical sources evolution usually parametrised as :

$(1+z)^{\alpha}$

up to a redshift $\mathbf{z_{max}}$

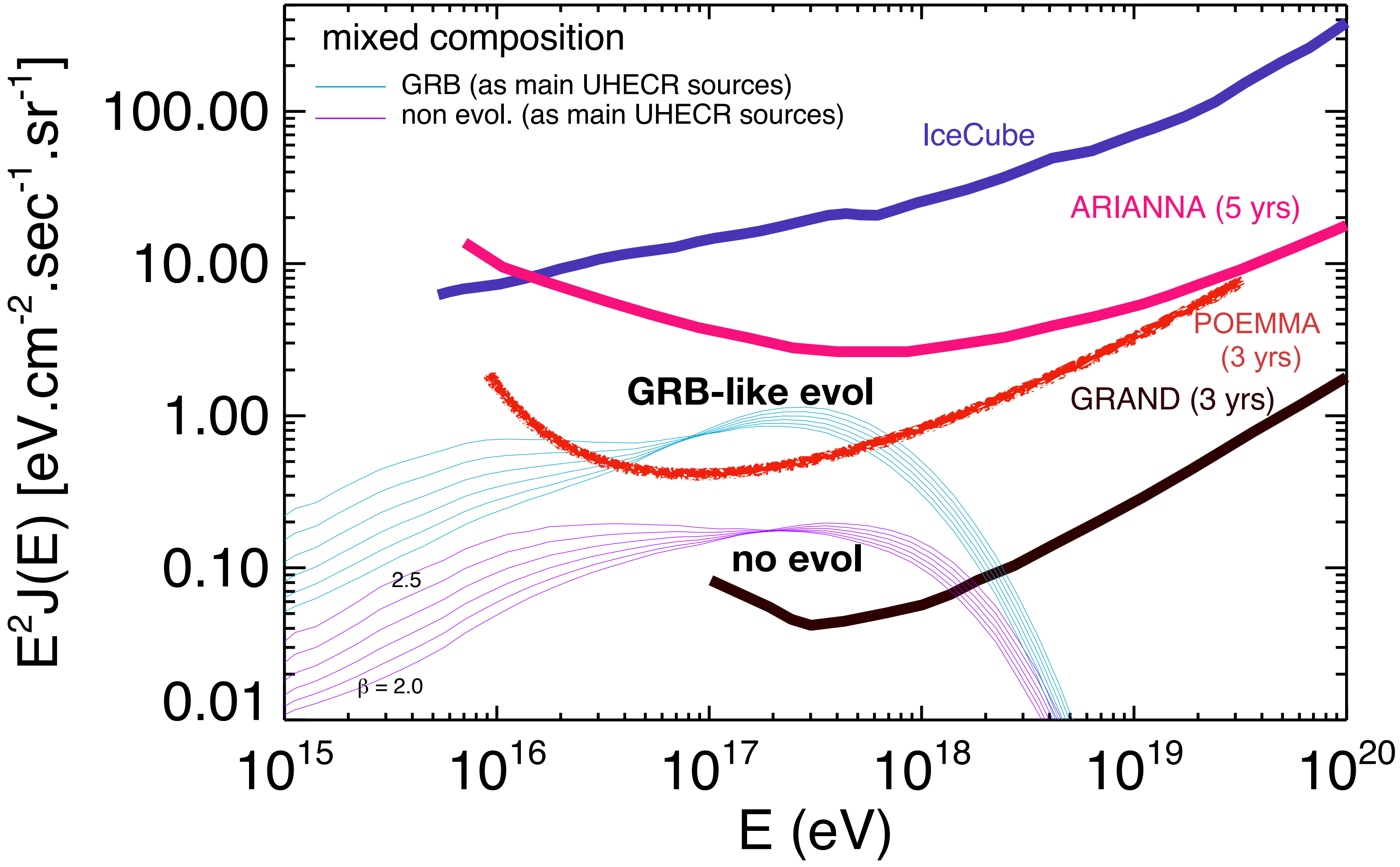


In the 10-50 GeV band, where the UHECR contribution to the EGRB is the largest

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

Globus et al., 2017, ApJL

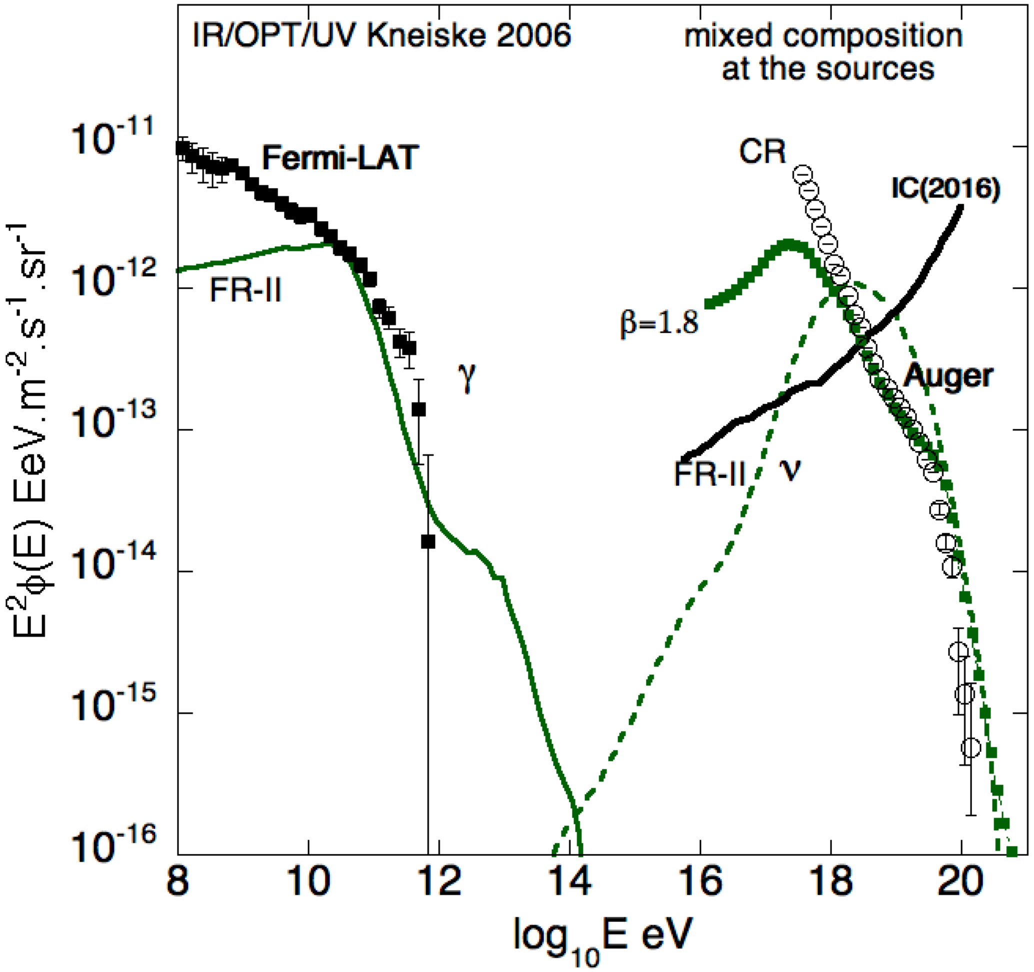


The range of cosmogenic neutrino fluxes predicted in the framework of our model are low (mostly due to the low value of the maximum energy per nucleon)

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

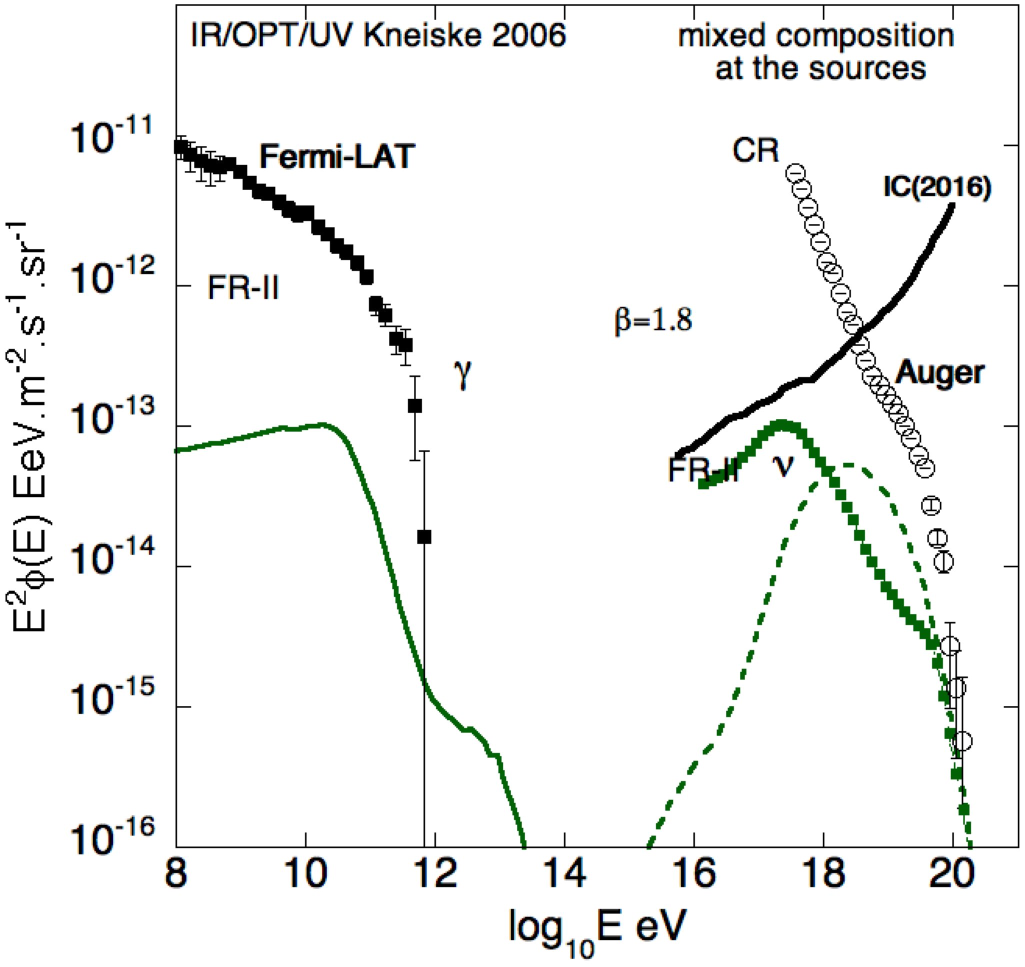
Constraining the presence of powerful protons accelerators in the universe



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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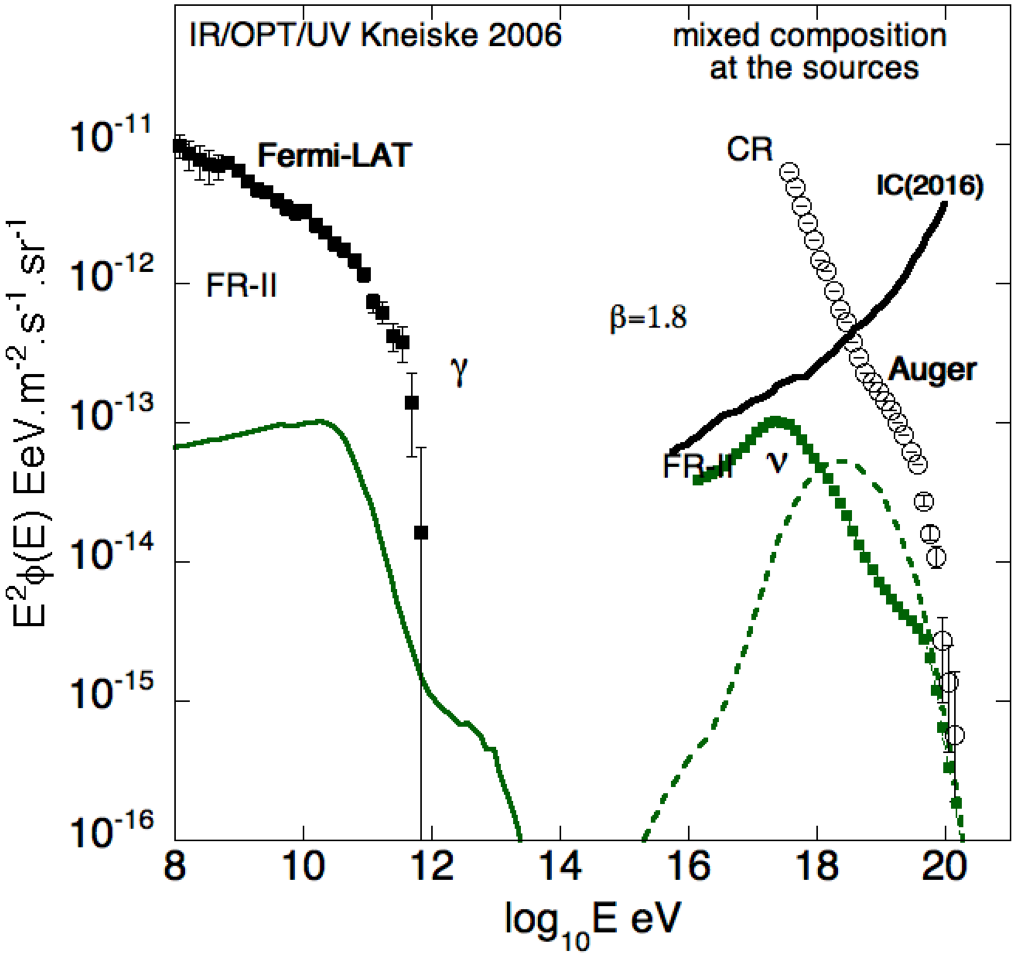

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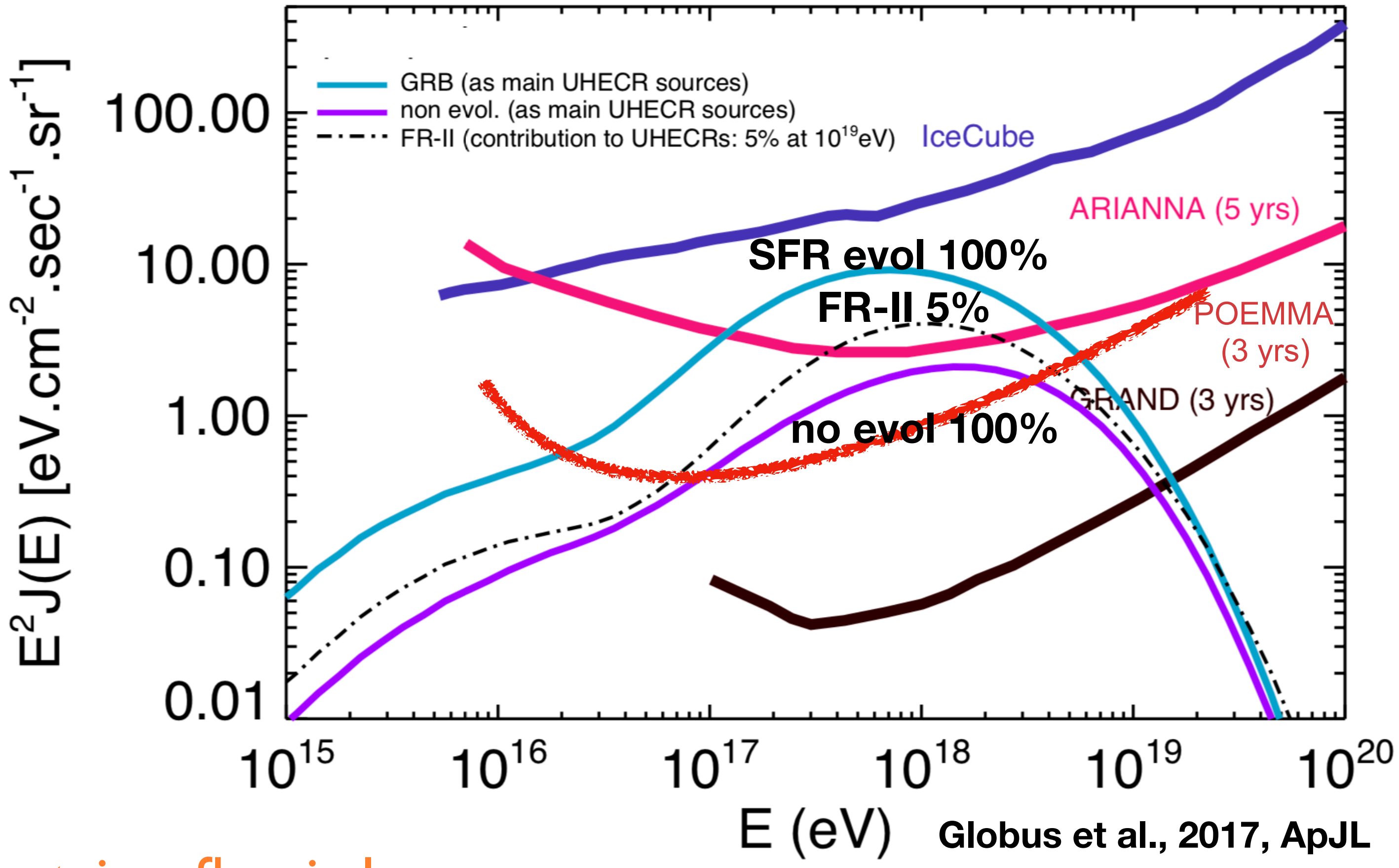
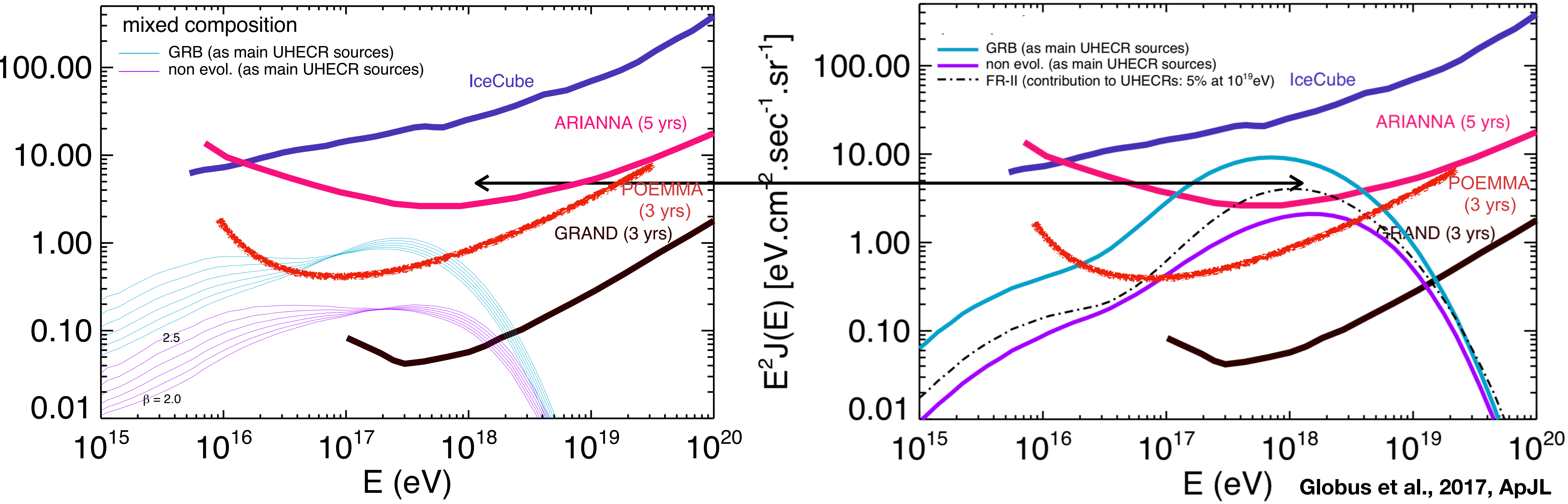


Globus et al., 2017, ApJL

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)

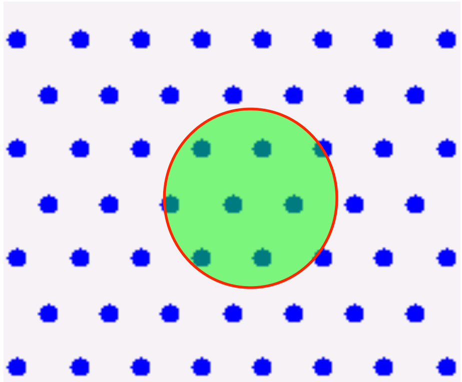
THE END

THANK YOU FOR YOUR ATTENTION!!!

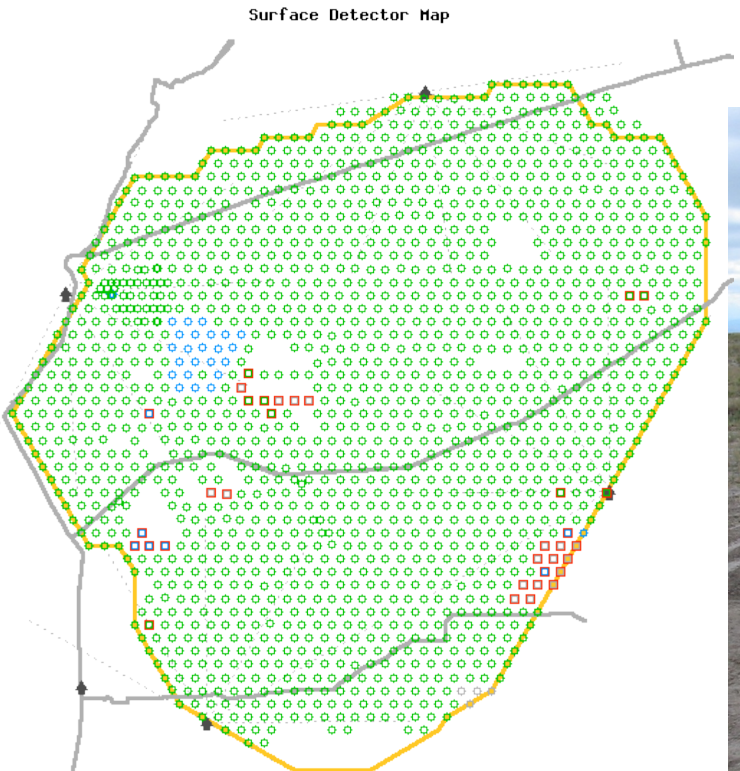
Ground array detectors

- 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