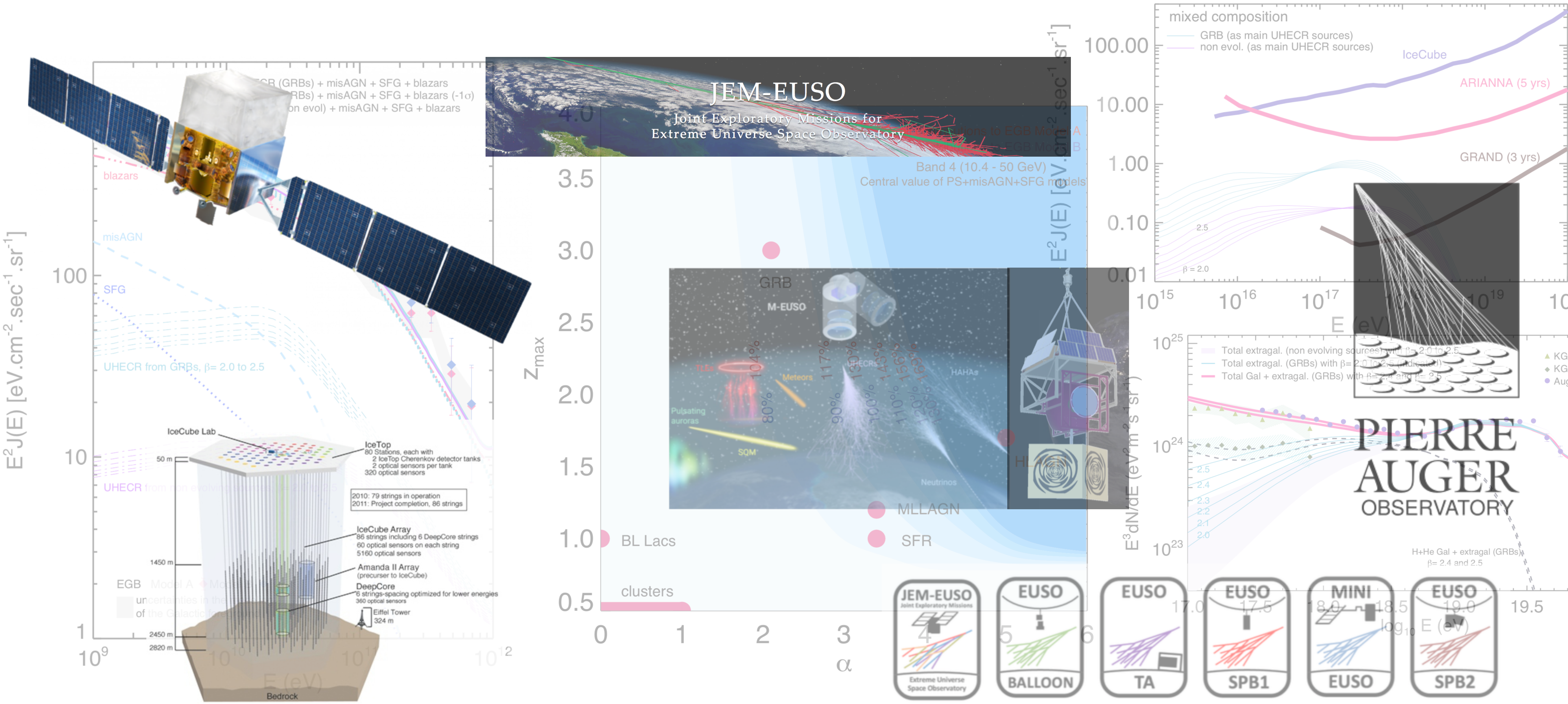
γ-ray and ν constraints on UHE cosmic rays origin… and vice versa



Denis Allard

in collaboration with N. Globus, E. Parizot, G.Decerprit, N. Busca, B. Baret et al.

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

UHECR are strongly suspected to be of extragalactic origin

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

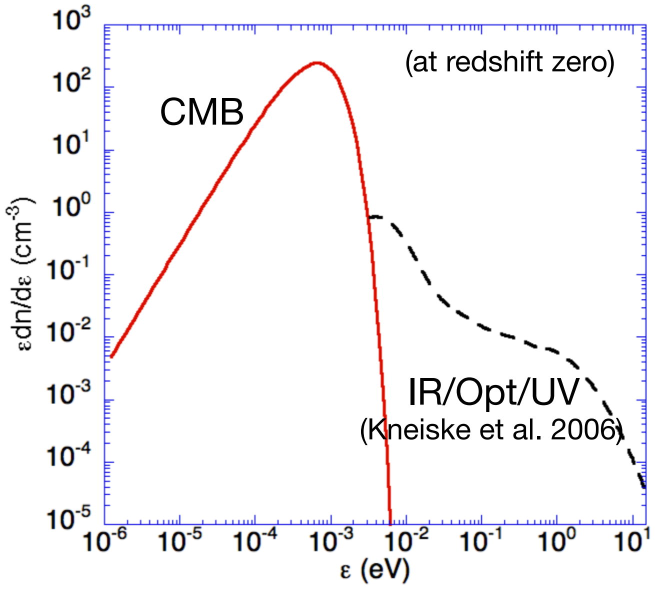
- pair production: $N+\gamma \rightarrow N+e^+/e^-$ $==> secondary\ e^{+/-}$

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

- Pion and meson production :

$$\pi^0 \rightarrow 2\gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu,\ \mu^+ \rightarrow \overline{\nu_\mu} + e^+ + \nu_e ==> secondary\ e^{+/-}, \gamma\ and\ \nu$$
$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu},\ \mu^- \rightarrow \nu_\mu + e^- + \overline{\nu_e}$$

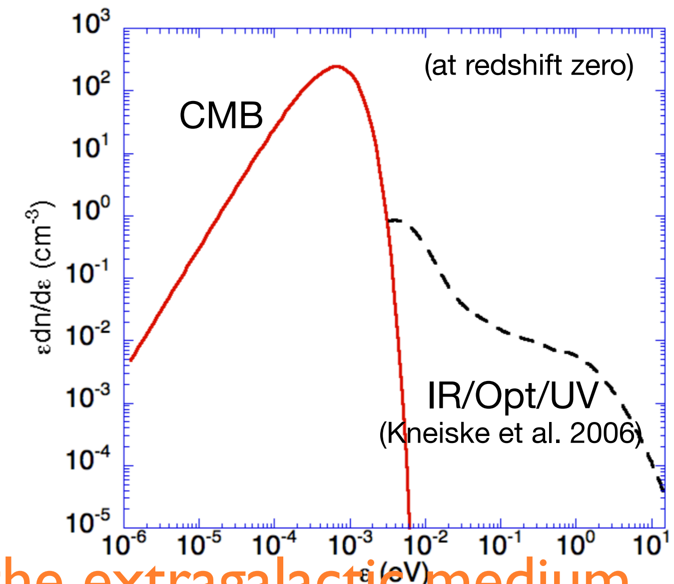
Threshold with CMB photons ~10^{20} eV per nucleon (at z=0)



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

UHECR are strongly suspected to be of extragalactic origin

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



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

$$\pi^0 \rightarrow 2\gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu,\ \mu^+ \rightarrow \overline{\nu_\mu} + e^+ + \nu_e ==> secondary\ e^{+/-}, \gamma\ and\ \nu$$
$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu},\ \mu^- \rightarrow \nu_\mu + e^- + \overline{\nu_e}$$

νs only suffer from the expansion of the universe while propagating in the extragalactic medium

e^+/e^- and γ further cascade by interacting with the photon backgrounds :

$e+\gamma_{EBL} \rightarrow e'+\gamma$ Inverse Compton

$\gamma+\gamma_{EBL} \rightarrow e^+ + e^-$ pair production

➡ the universe is opaque to high-energy γs (pile-up at sub-TeV energies)

Diffuse UHECR ($E>10^{17}$ eV) flux

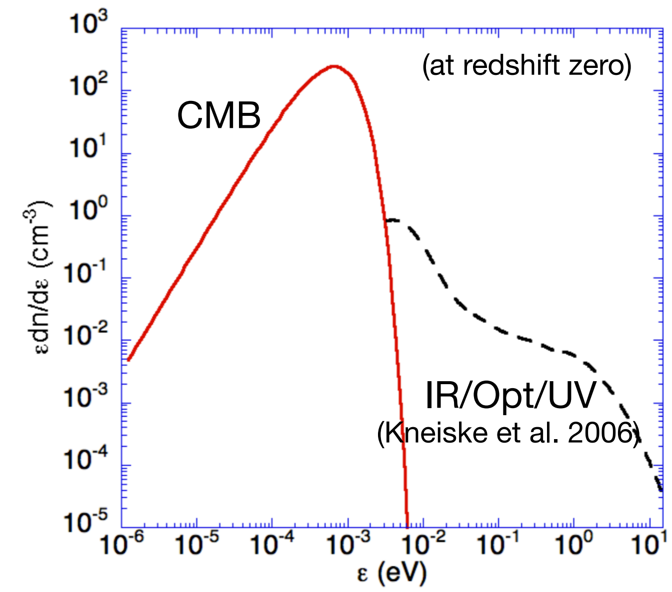
➡ diffuse ν flux in the PeV-EeV range

➡ diffuse γ-ray flux in the GeV-TeV range

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

UHECR are strongly suspected to be of extragalactic origin

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

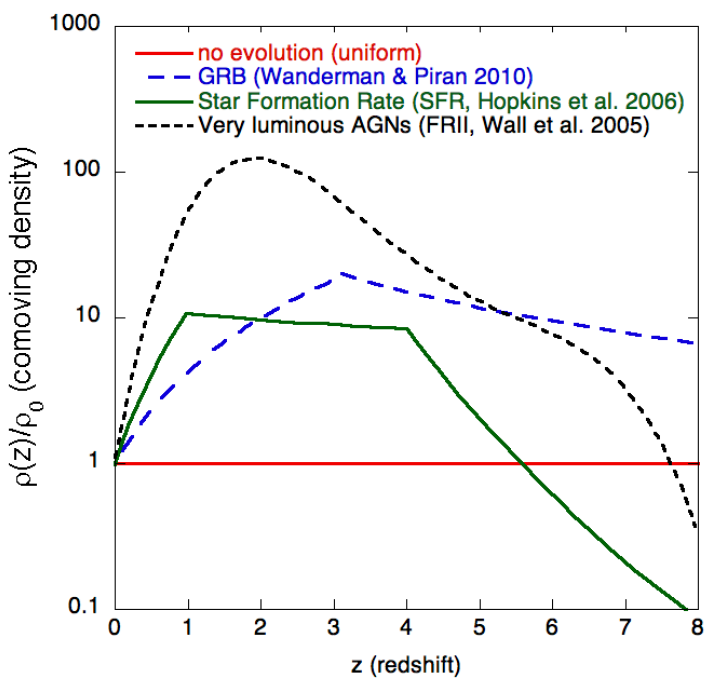


- pair production: $N+\gamma \rightarrow N+e^+/e^-$ $==>$ *secondary* $e^{+/-}$
- Pion and meson production :

$$\pi^0 \rightarrow 2\gamma$$

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

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



The extragalactic photon backgrounds evolve with time (CMB is 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

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)

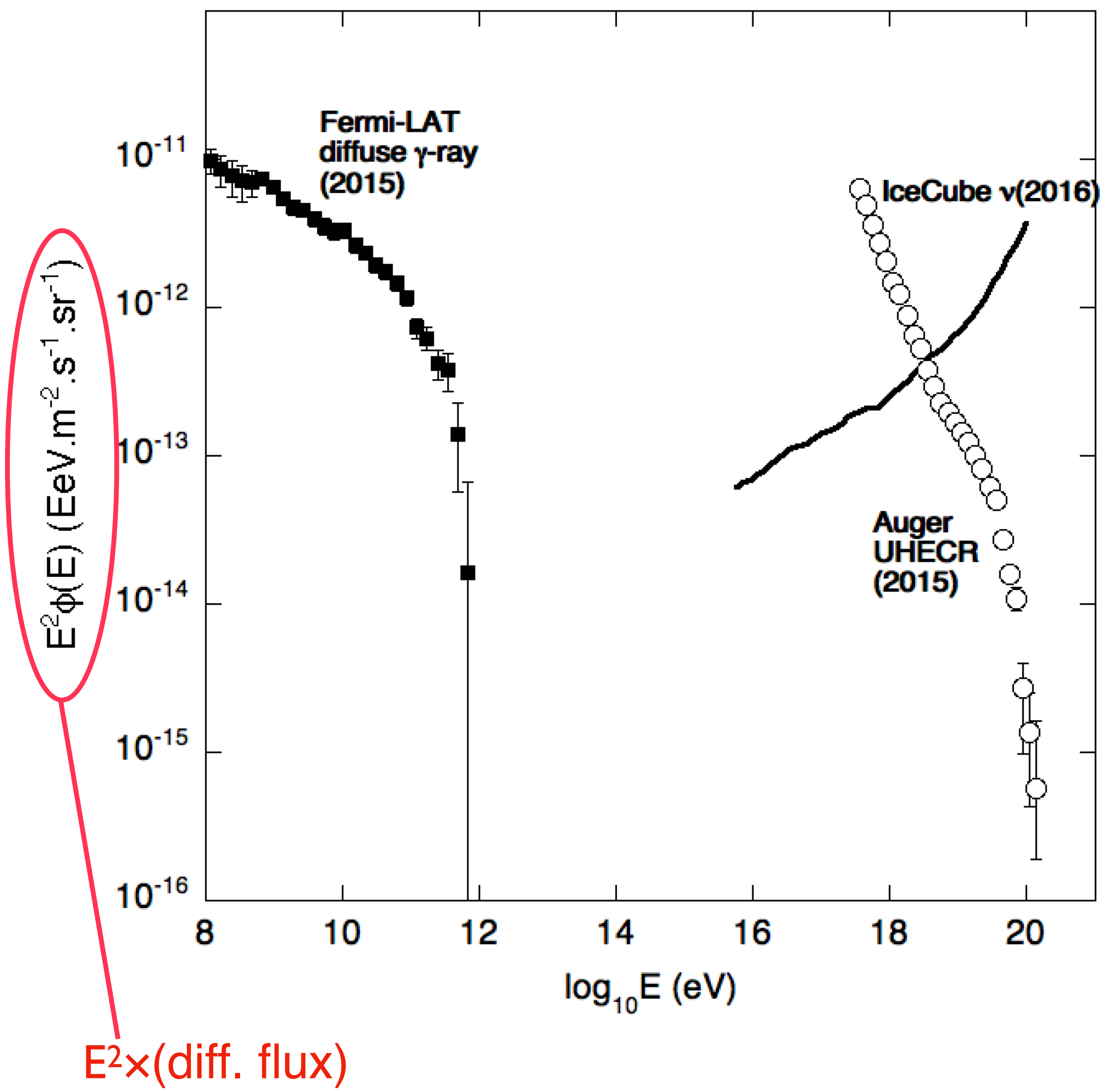
A "good" model should reproduce Auger or TA UHECR spectrum

➡ 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)

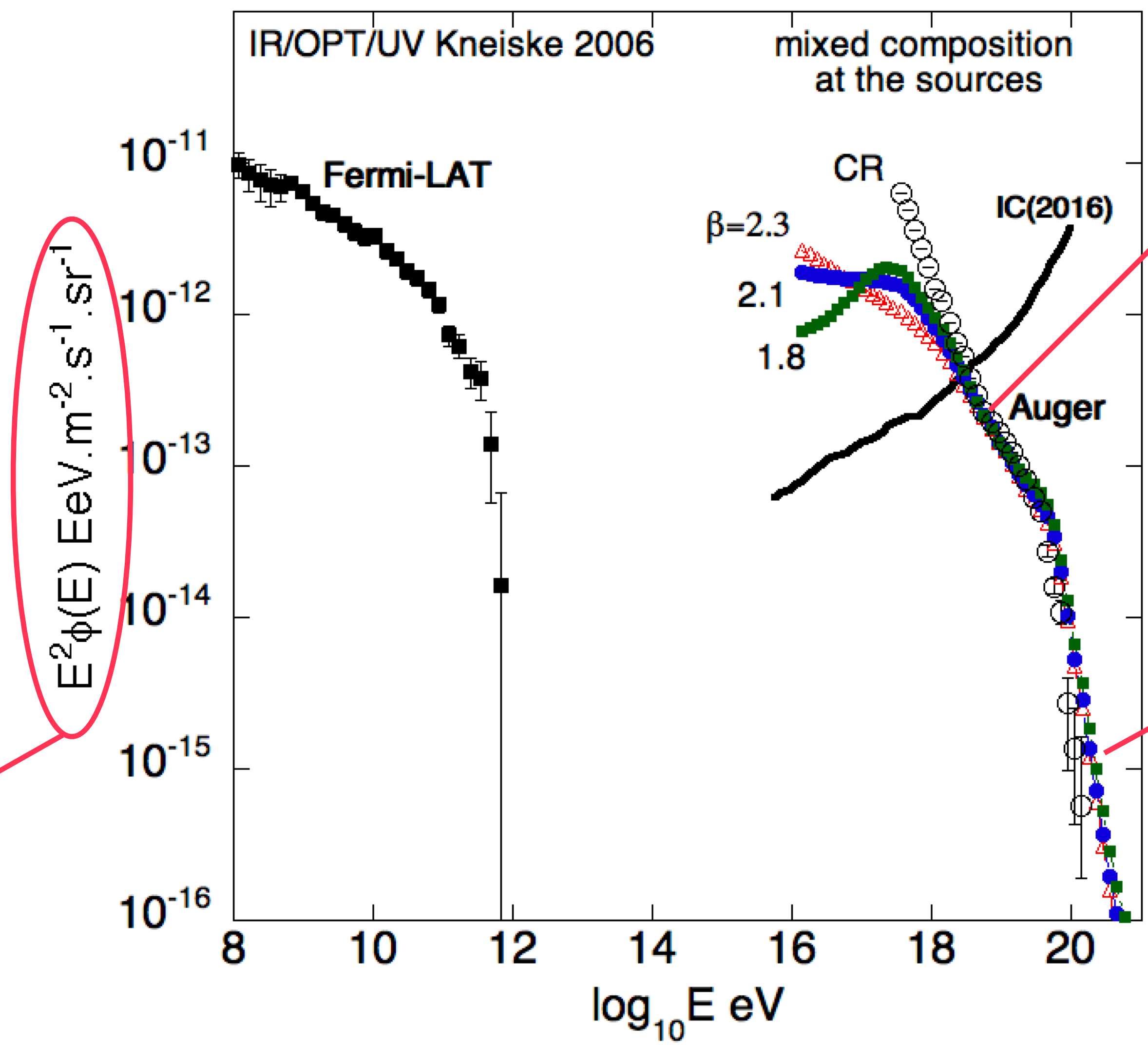


One example : mixed composition assumed at UHECR sources

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

evolutions :
uniform
SFR
FRII



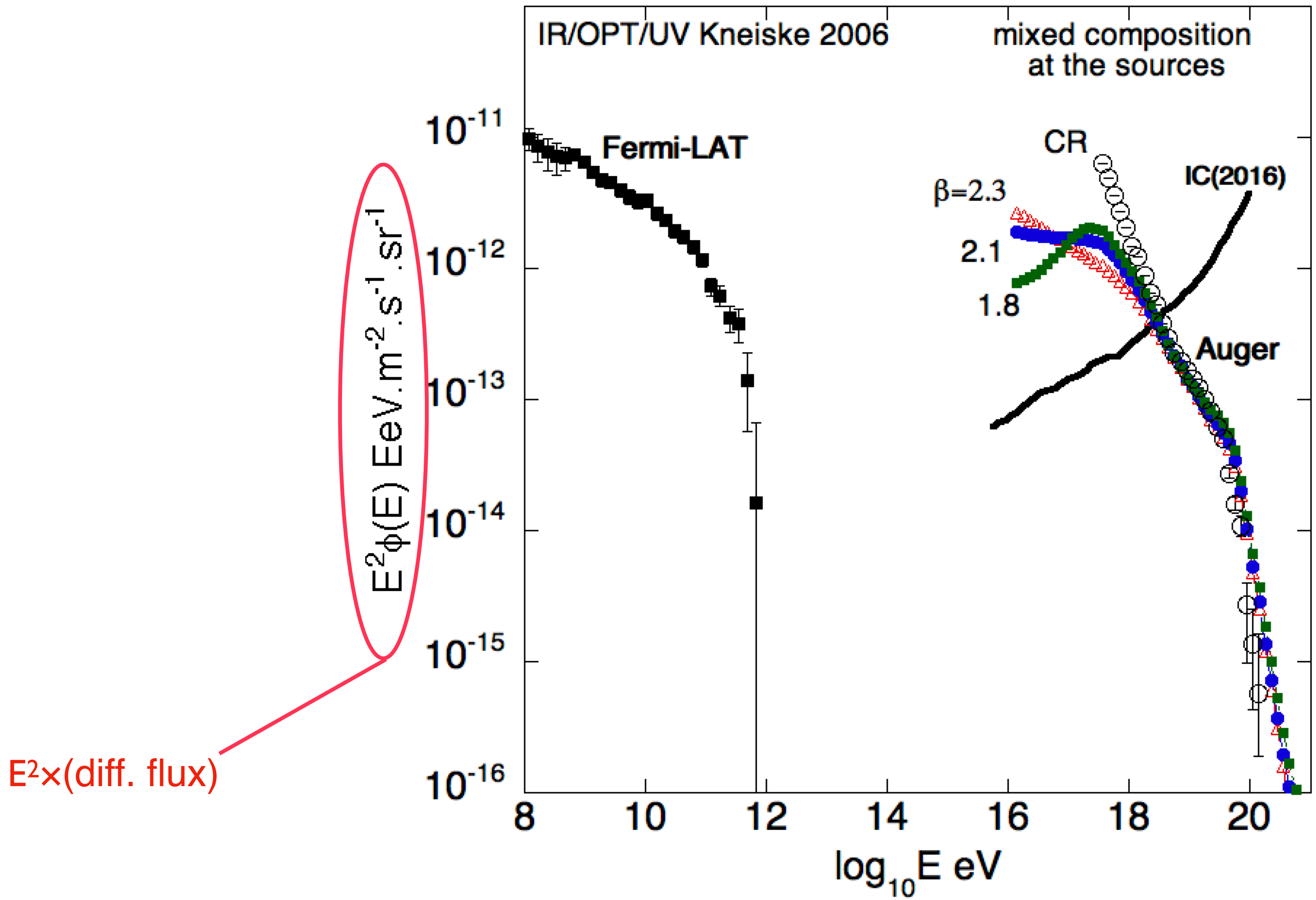
Ankle of the cosmic-ray spectrum

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

$E^2\times$(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

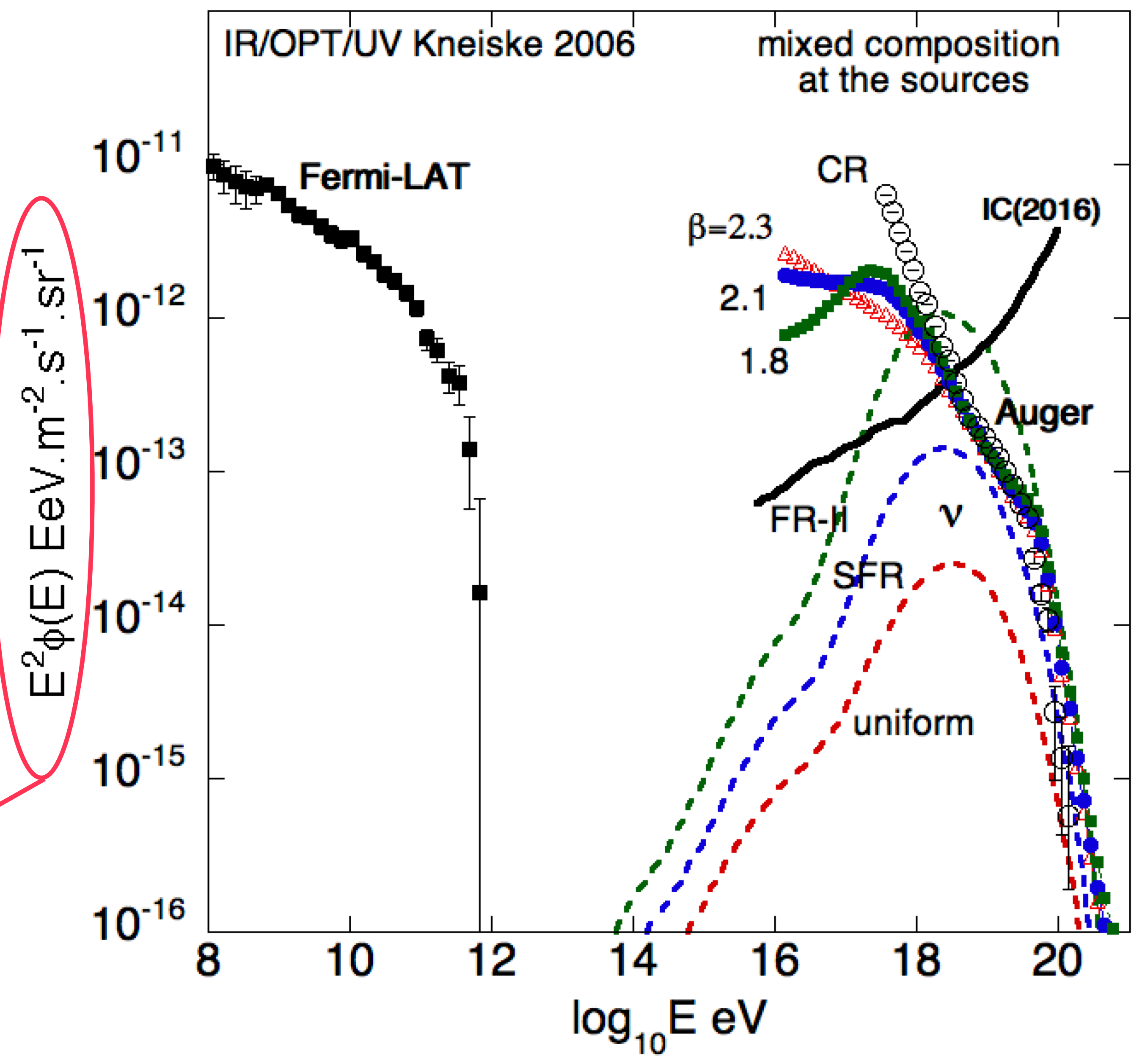
One example : mixed composition assumed at UHECR sources



One example : mixed composition assumed at UHECR sources

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

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



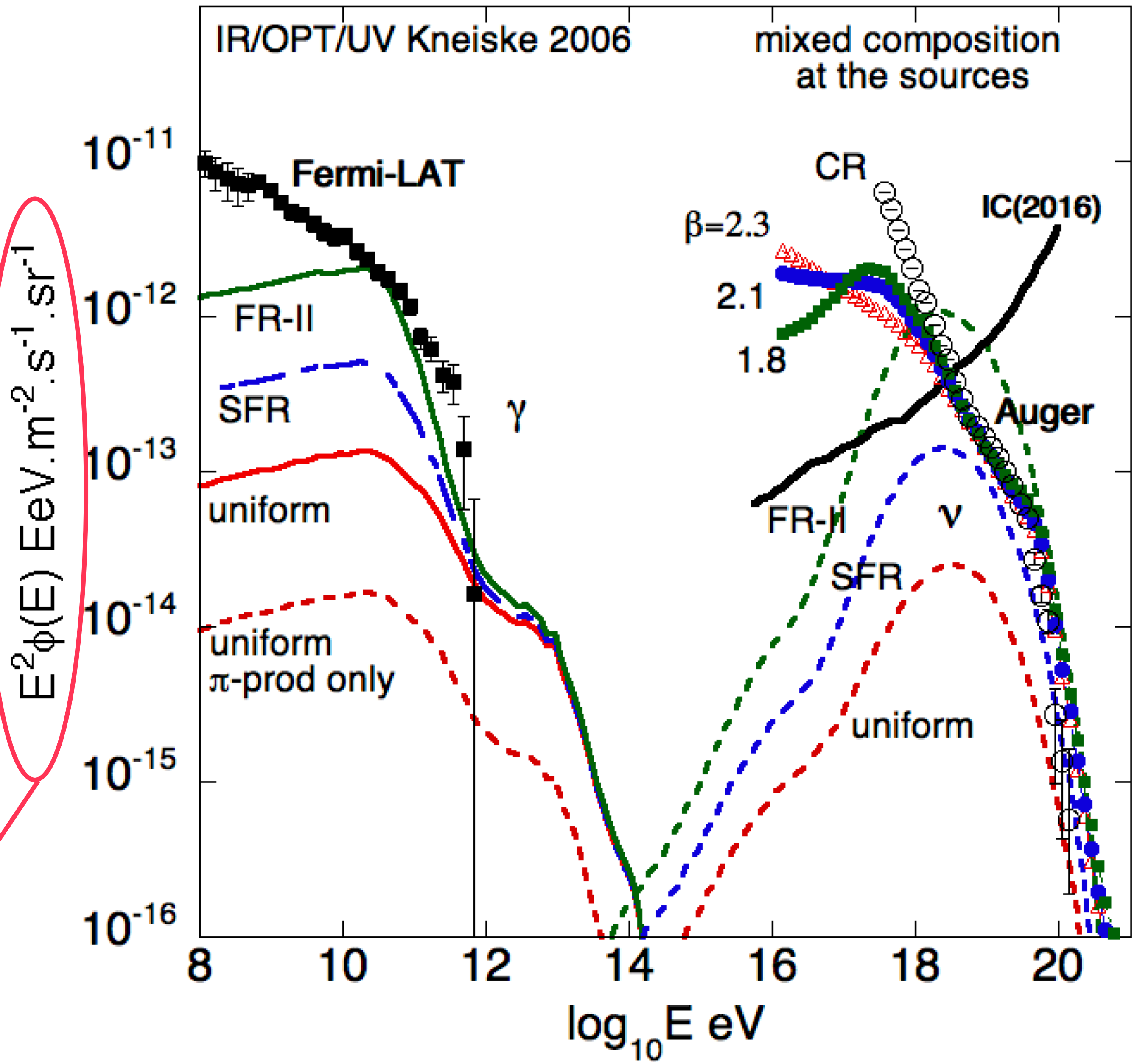
Strong impact of the cosmological evolution of the sources on the cosmogenic ν fluxes —> evolutions significantly stronger than SFR constrained by IceCube

One example : mixed composition assumed at UHECR sources

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

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

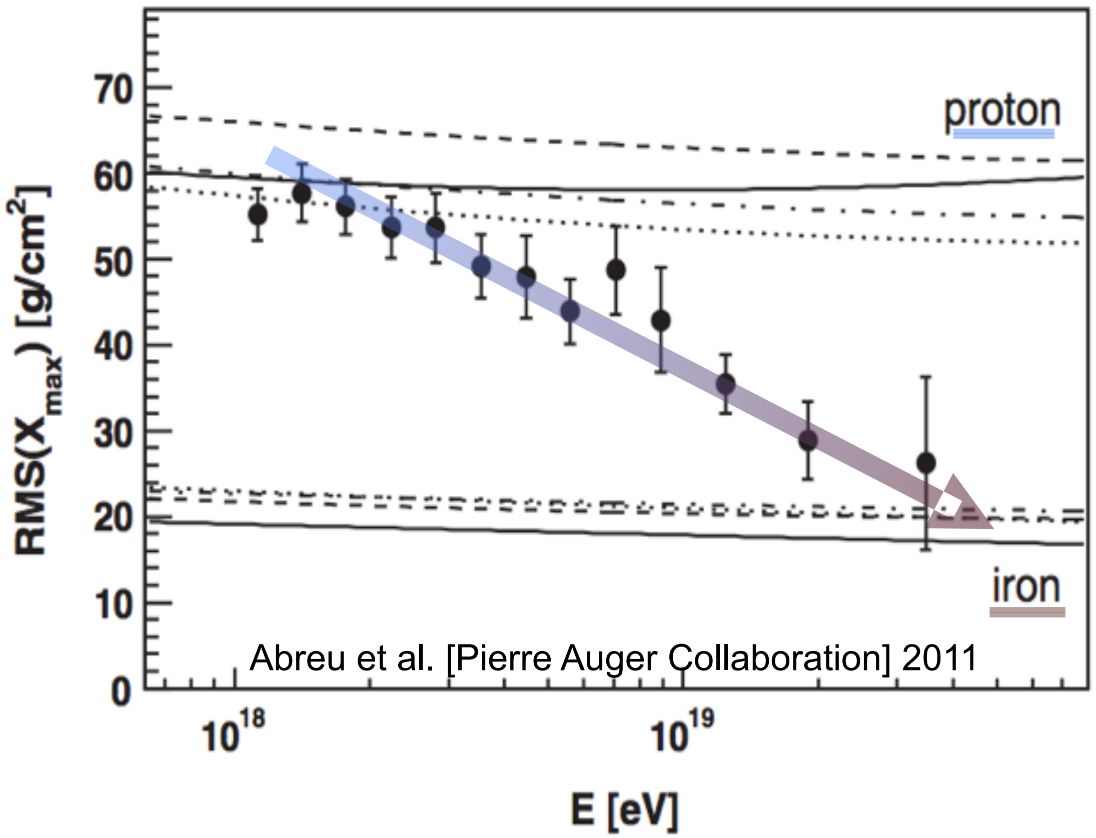
(Adapted from Decerprit and Allard, A&A, 2011)



E²×(diff. flux)

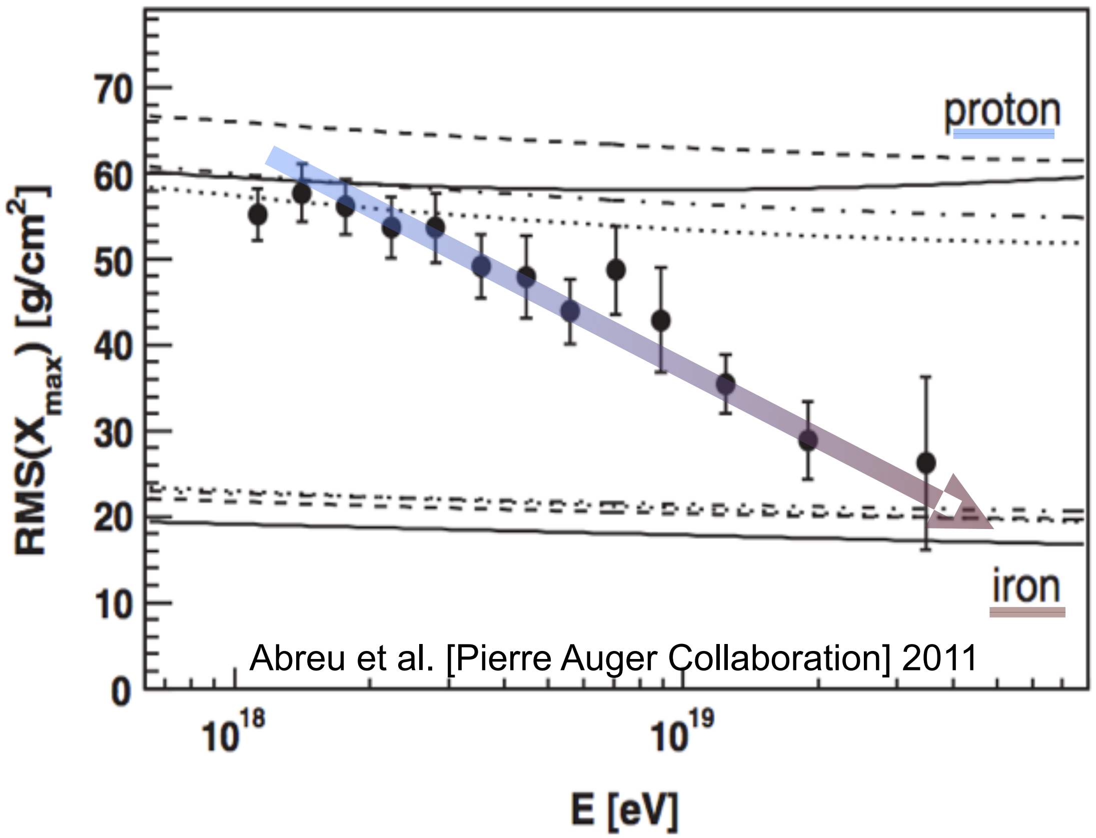
subdominant contribution of π-photoproduction to cosmogenic γs —> dominant contribution of the e⁺e⁻ pair production —> unlike cosmogenic νs, cosmogenic γs are not produced by the highest energy particles

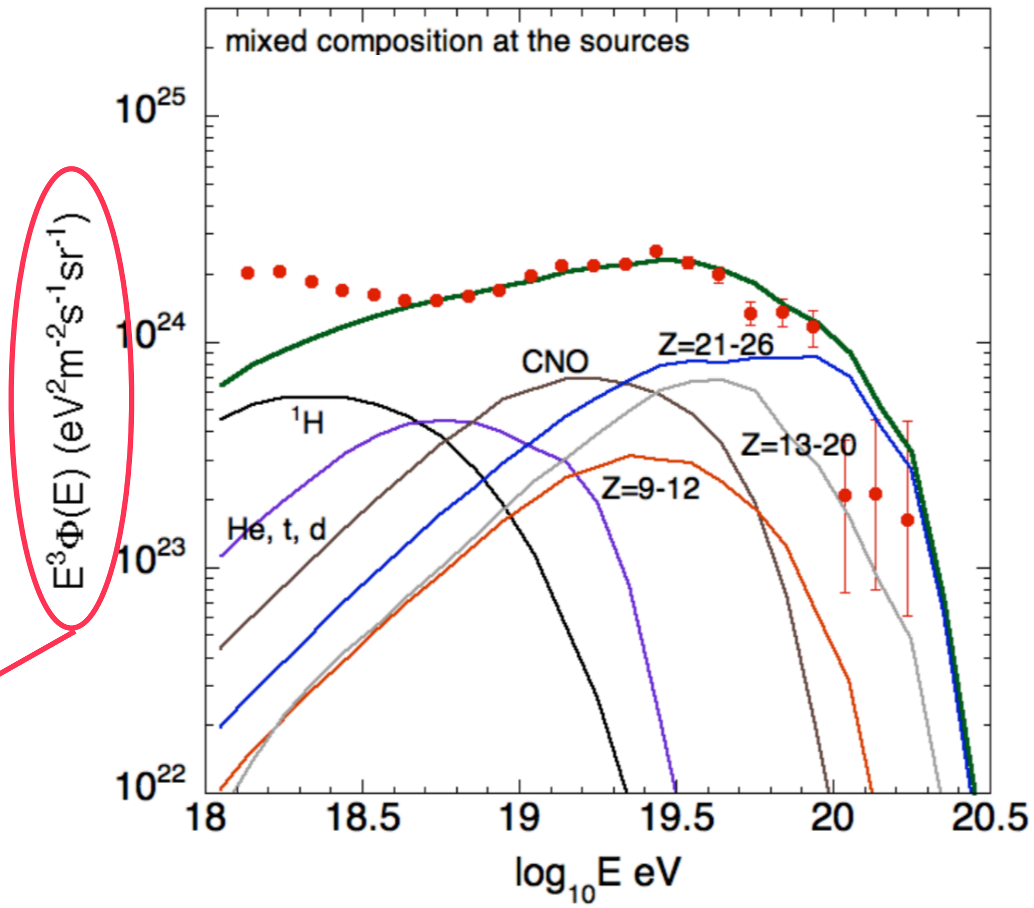
Implications of Auger composition measurements



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

Implications of Auger composition measurements





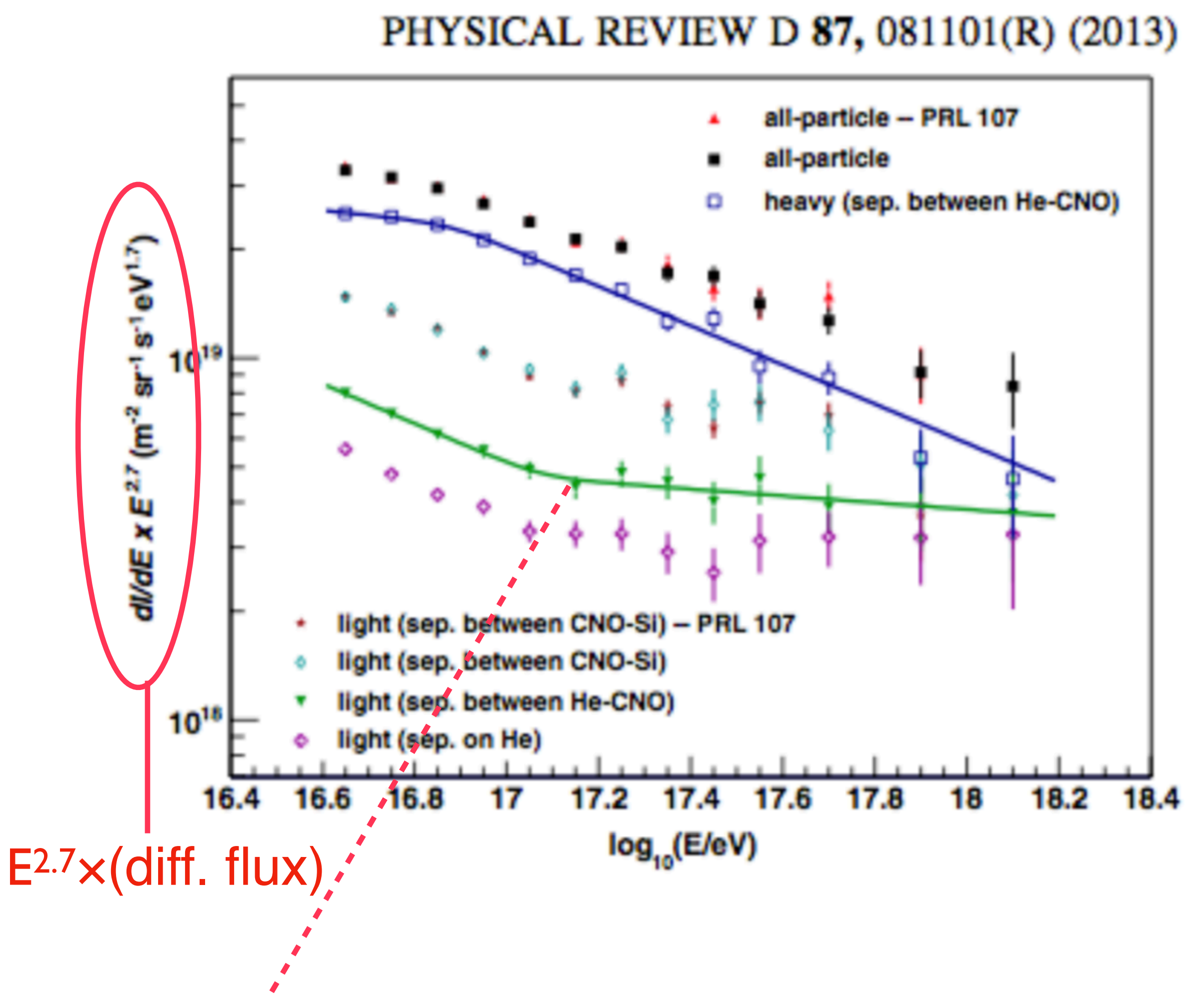
The evolution of the composition implied by Auger composition analyses strongly suggest that the composition is becoming heavier as the energy increases
—> dominant sources of UHECR do not accelerate protons to the highest energies

Low maximum energy per nucleon (a few EeV to 10^{18} eV, well below the pion production threshold with CMB photons) and hard source spectral indexes required

here $N(E) \propto E^{-\beta}$, $\beta<0$, $E_{max}(Z)=Z\times E_{max}^{proton}$, E_{max}^{proton}=a few $\times 10^{18}$ eV

obviously not a good news for UHE cosmogenic neutrinos predictions

KASCADE-Grande’s light ankle

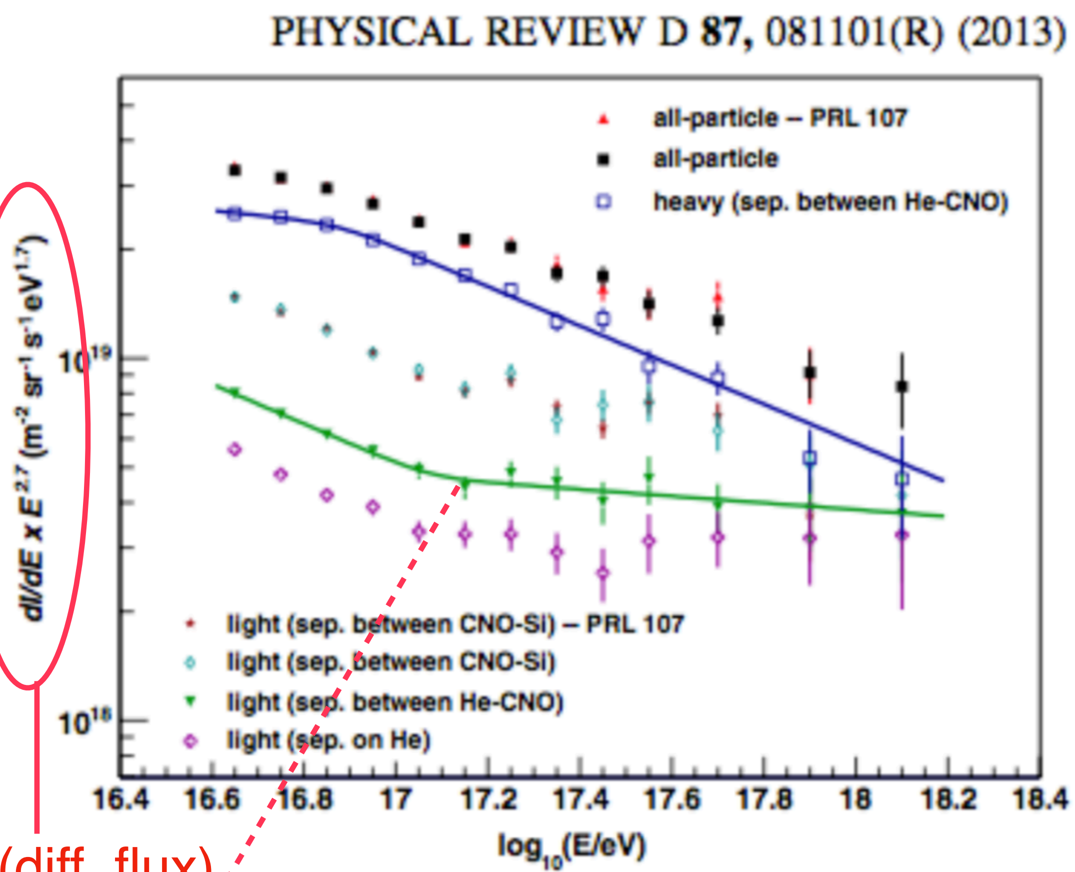


KASCADE-Grande’s light ankle, equivalent to the ankle of the cosmic-ray spectrum but for the light component (H-He), around 10^{17} eV

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

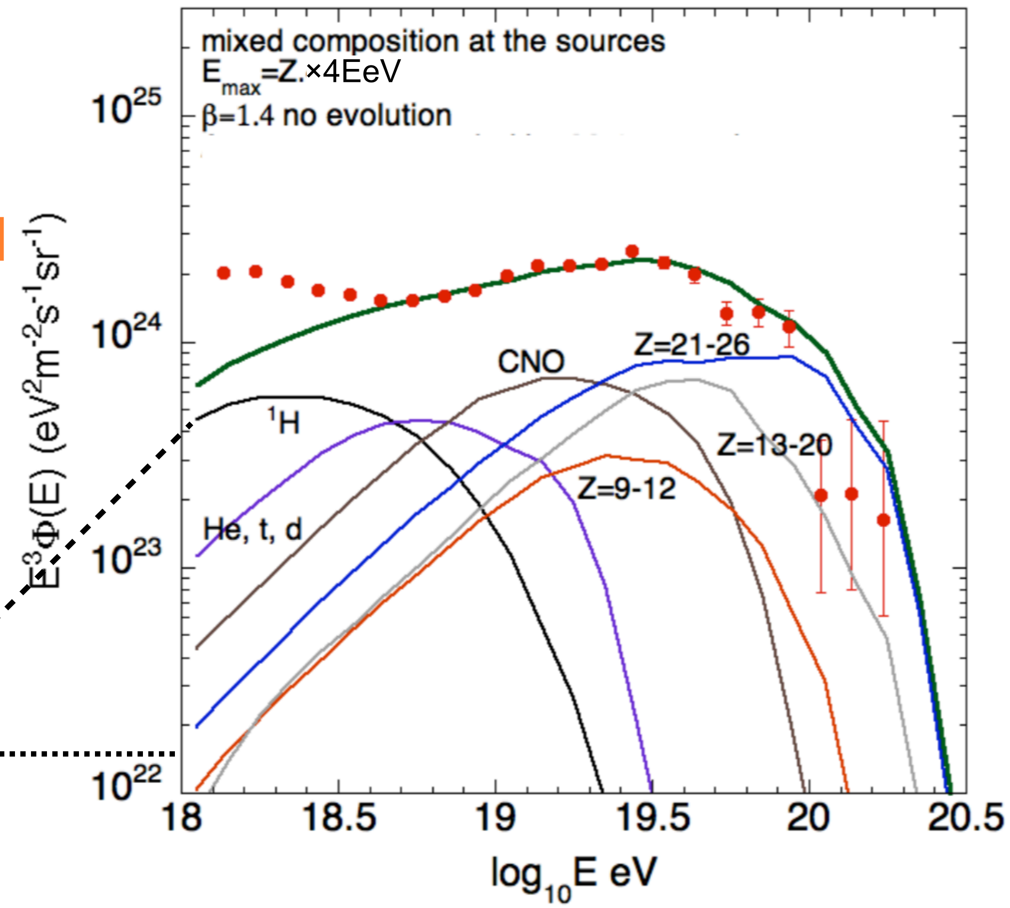
—> light component quite soft above 10^{17} eV (~2.8)

KASCADE-Grande's light ankle



$E^{2.7}$×(diff. flux)

Very hard below the 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 (~2.8)

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

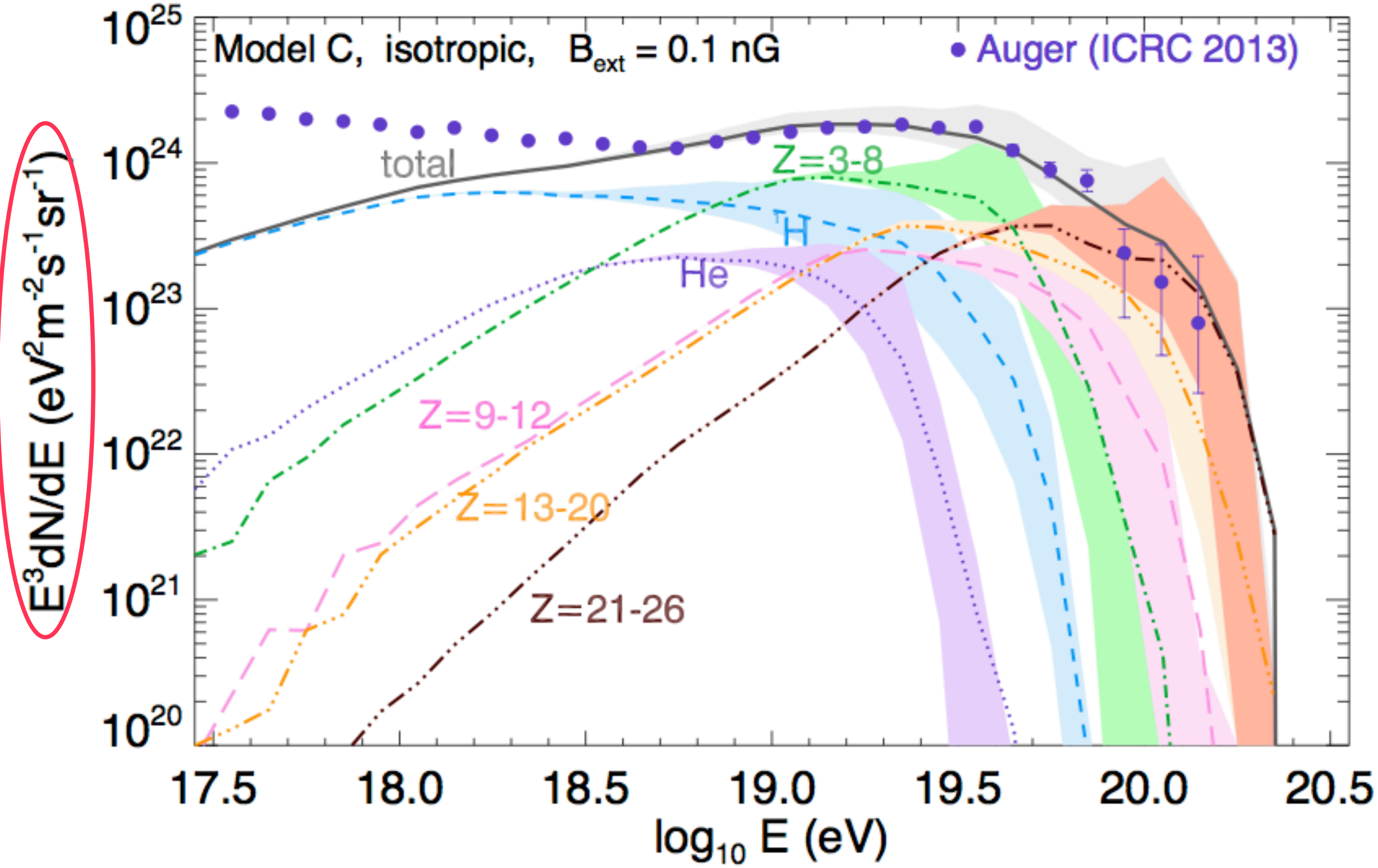
Phenomenological model of UHECR acceleration as a solution to the soft proton spectrum issue

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

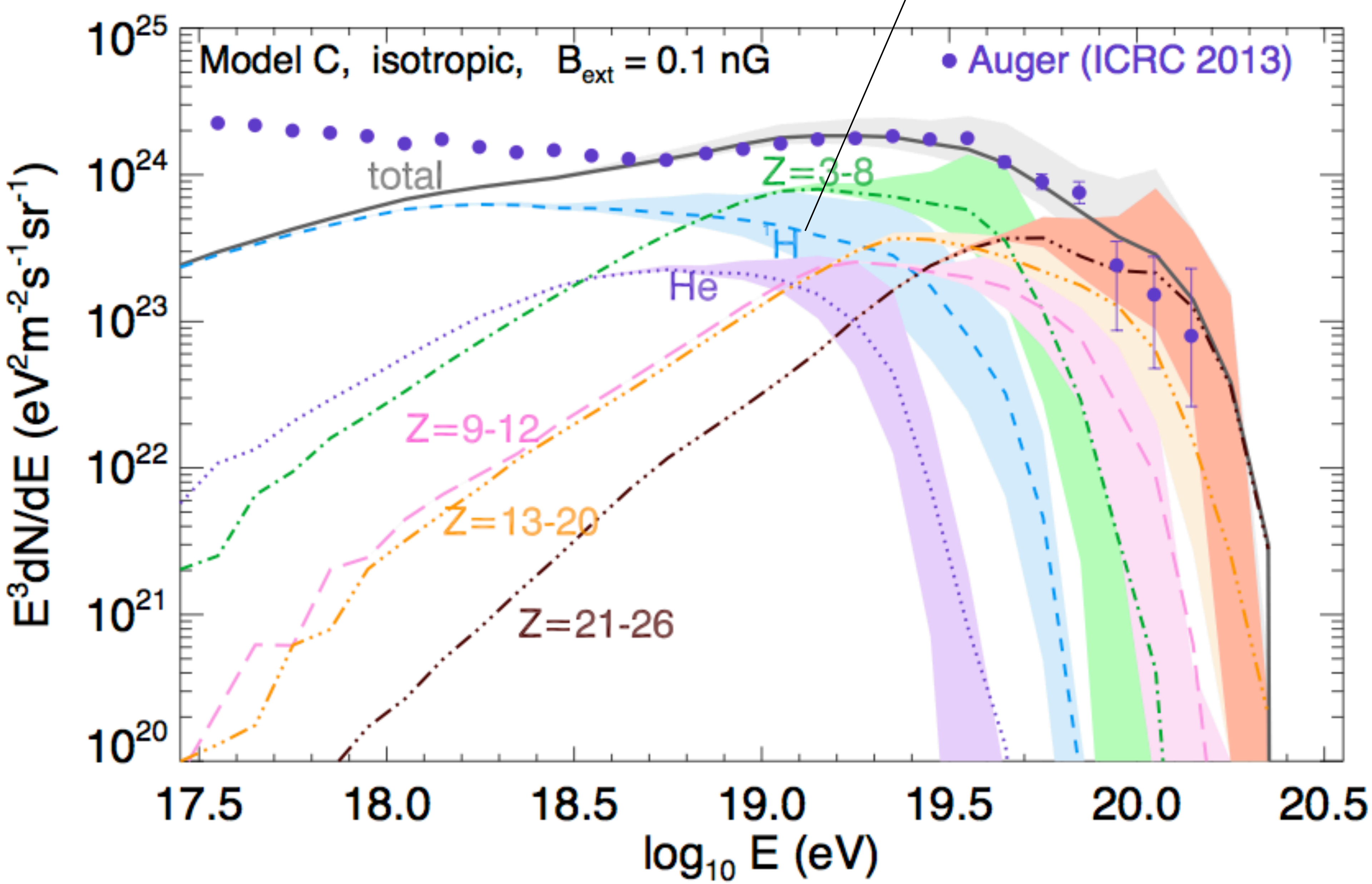
E³×(diff. flux)



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

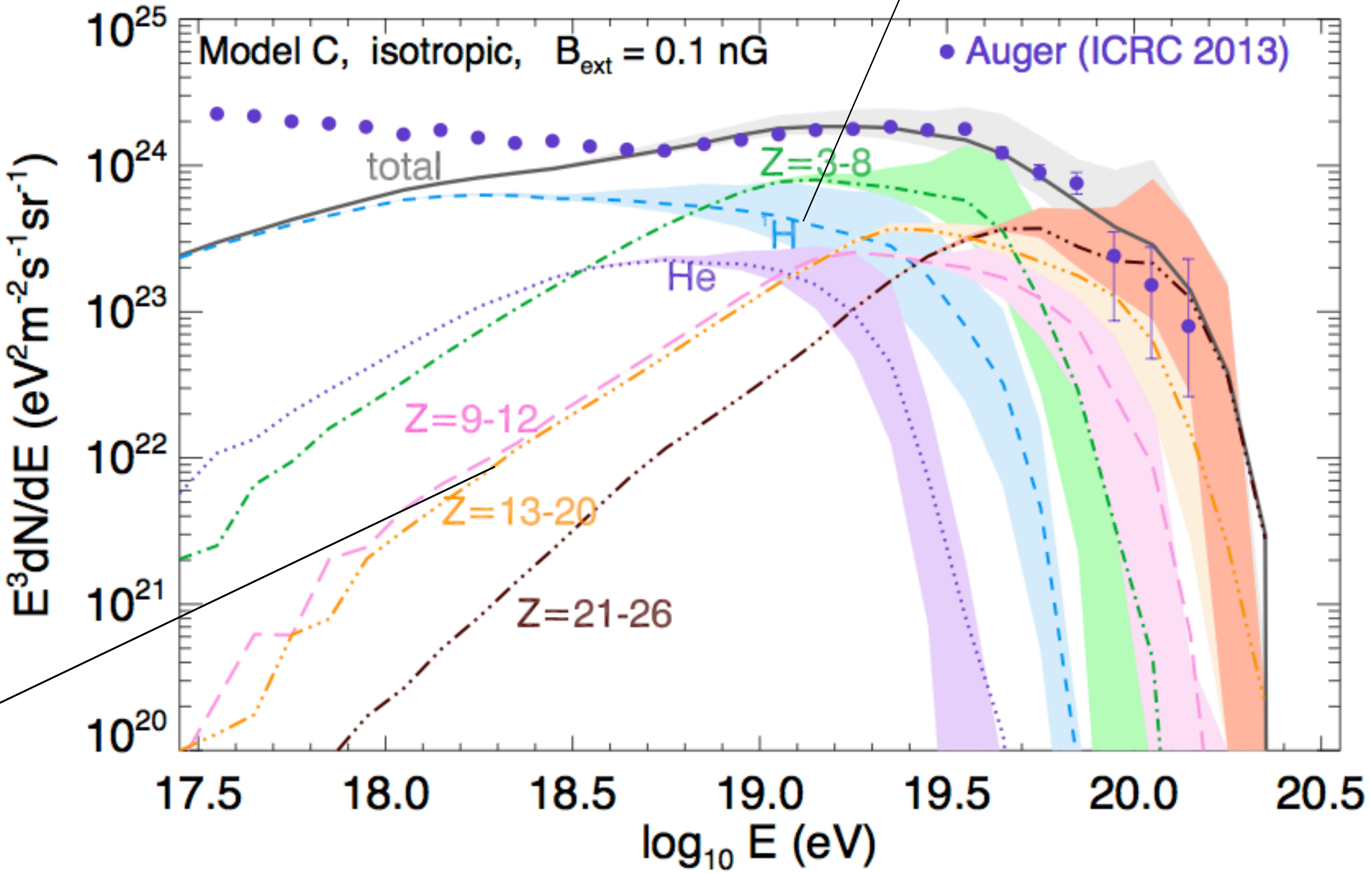
Phenomenological model : implications for the GCR to EGCR transition

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



Phenomenological model : implications for the GCR to EGCR transition

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

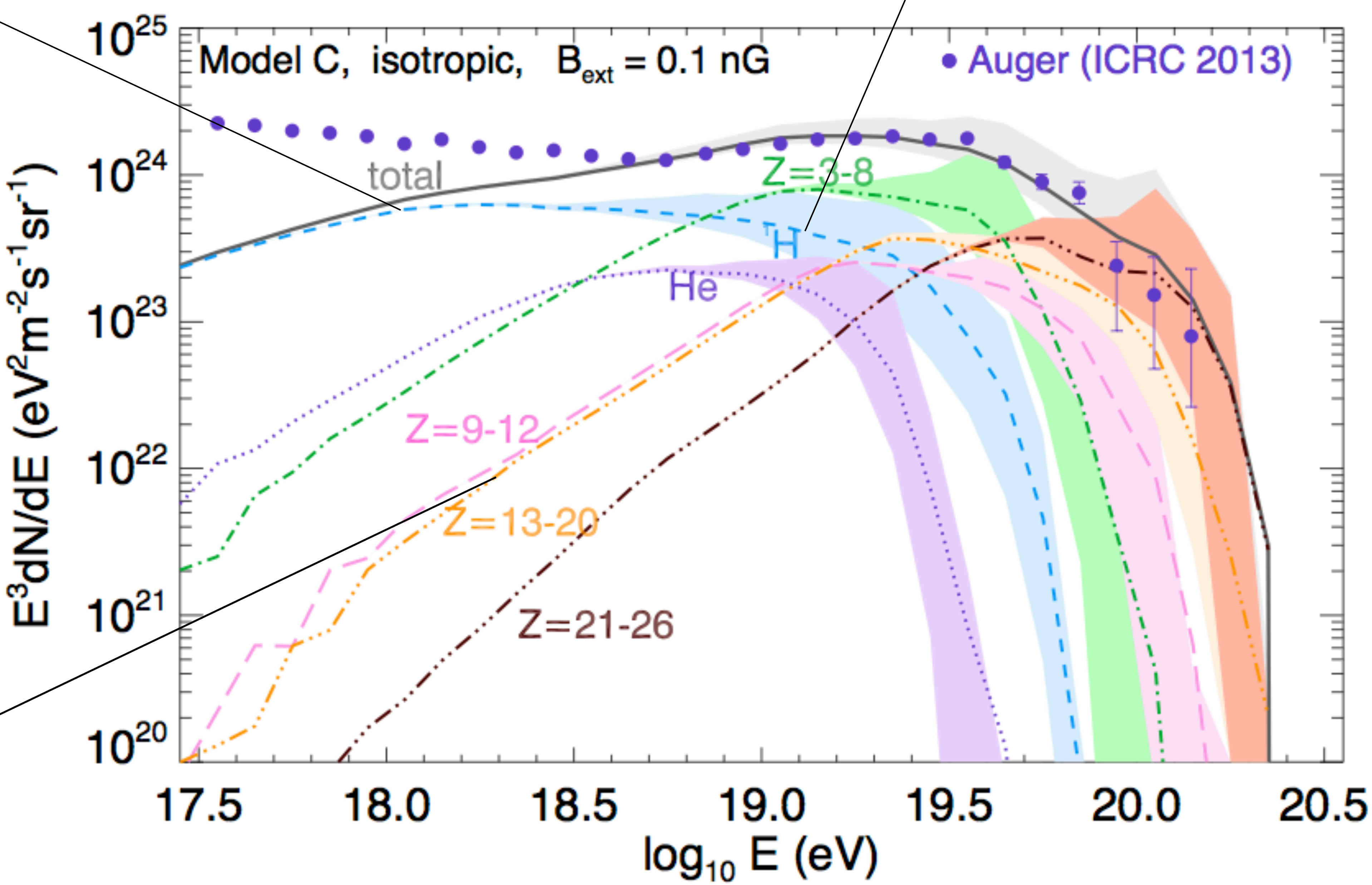


Heavier nuclei spectrum : Very hard due to the high-pass filter effect of the escape process
—> Hard nuclei spectrum required to fit Auger composition at high energy

Phenomenological model : implications for the GCR to EGCR transition

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

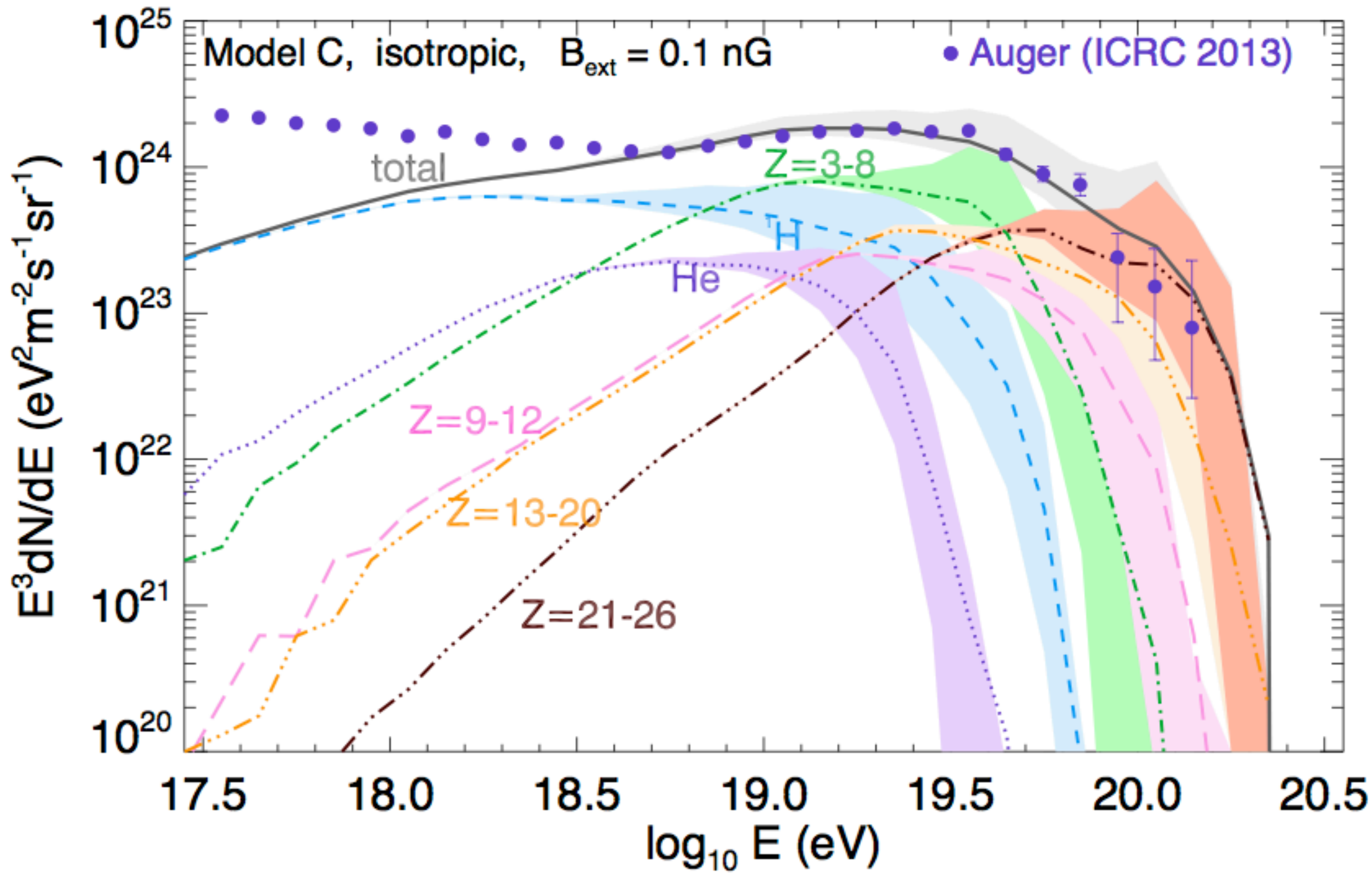


Heavier nuclei spectrum : Very hard due to the high-pass filter effect of the escape process
—> Hard nuclei spectrum required to fit Auger composition at high energy

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

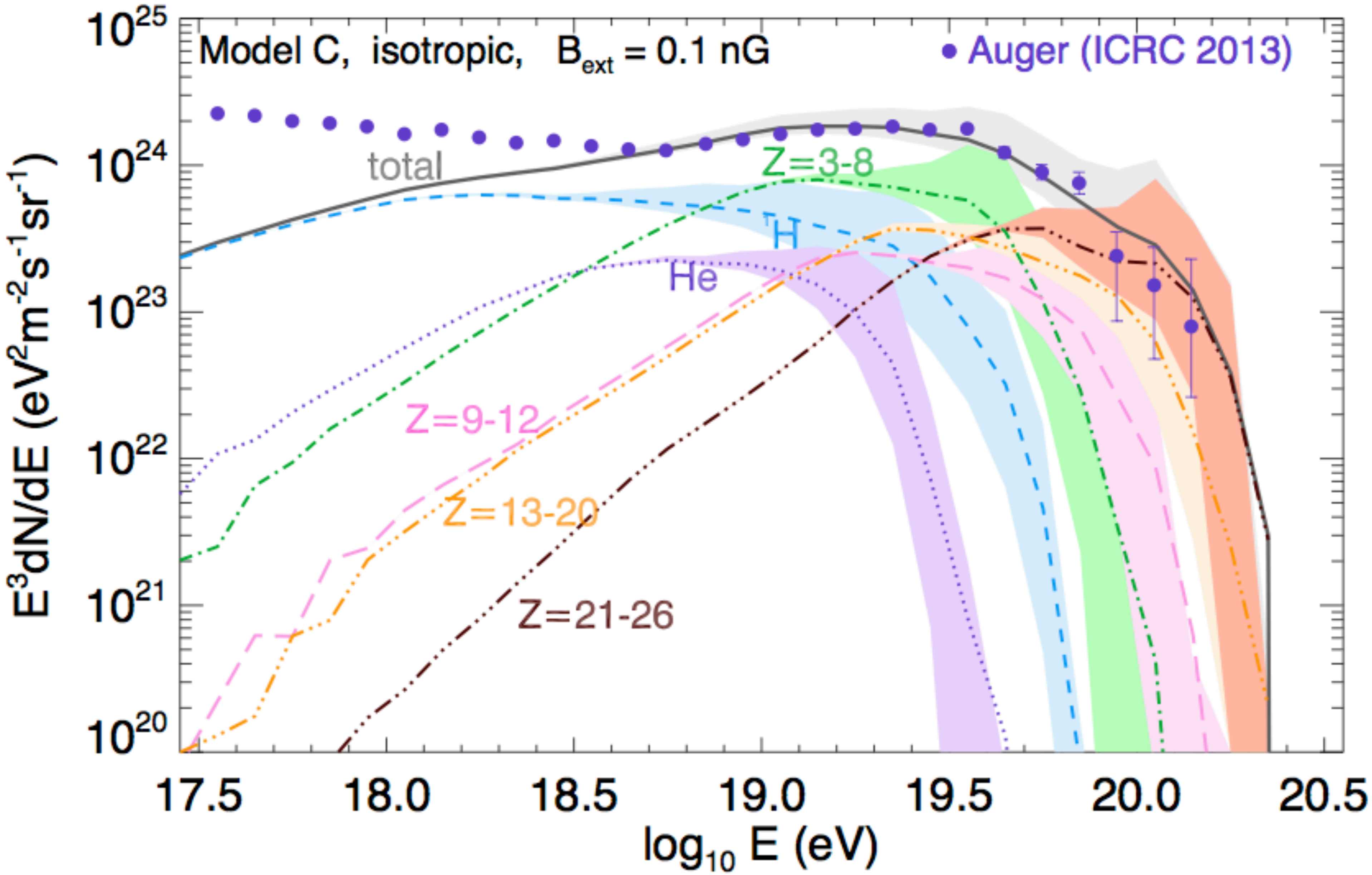
—> should not be a distinctive feature of GRB sources



Phenomenological model : implications for the GCR to EGCR transition

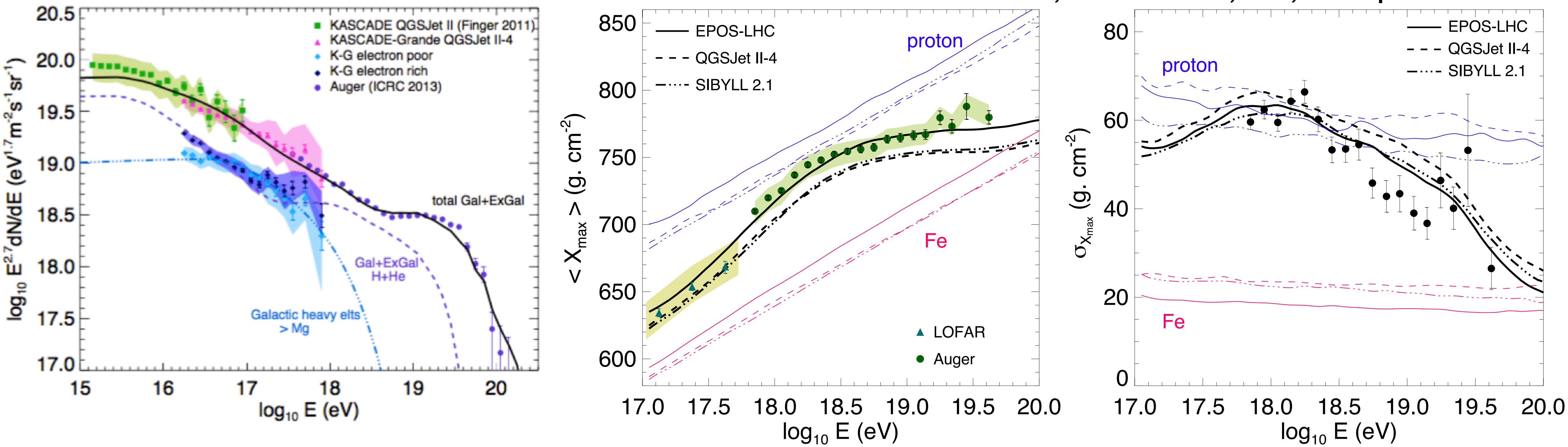
This type of model has been shown to reproduce the data from KG to Auger across the galactic to extragalactic transition region

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



Phenomenological model : implications for the GCR to EGCR transition

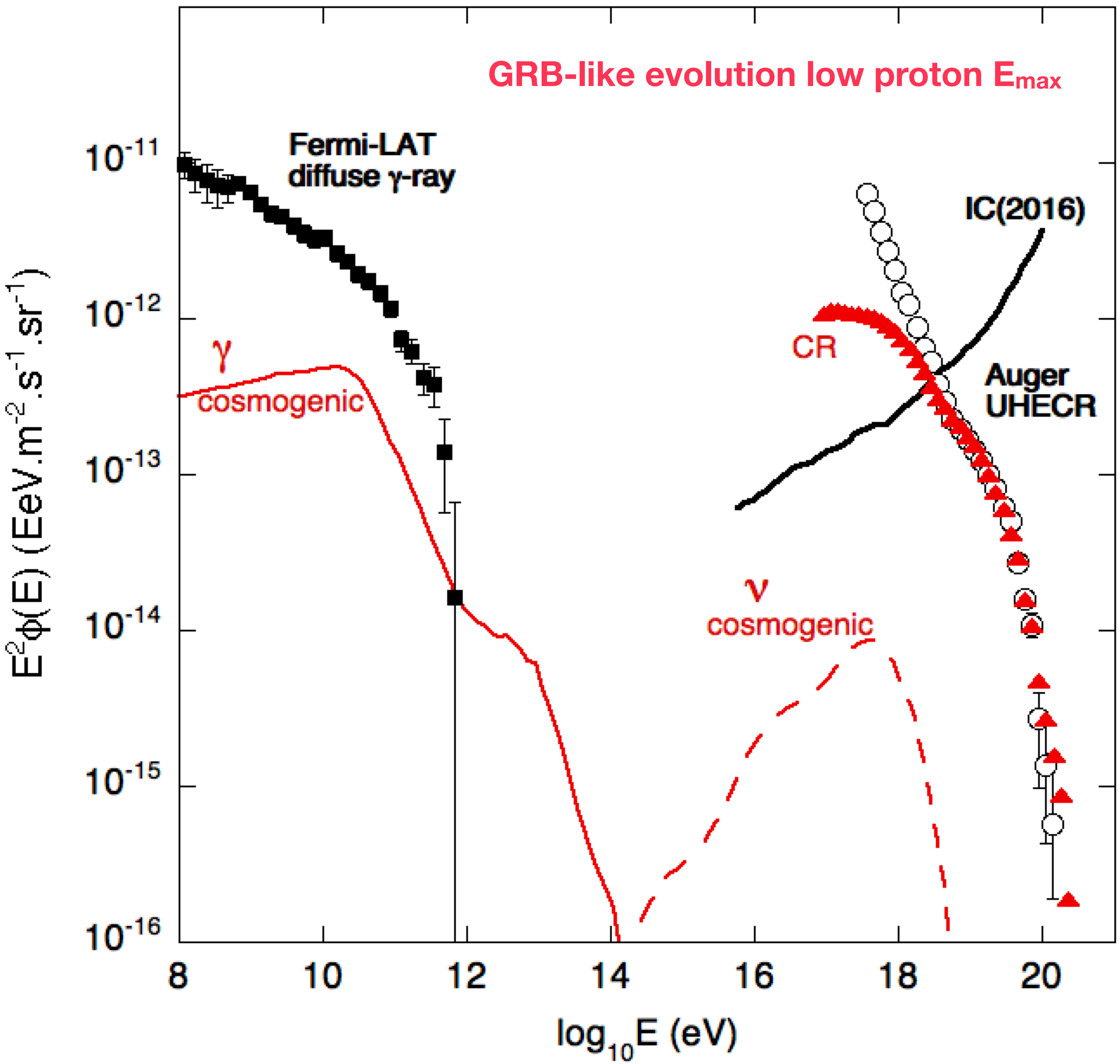
Globus, Allard & Parizot, 2015, PRD rapid com.



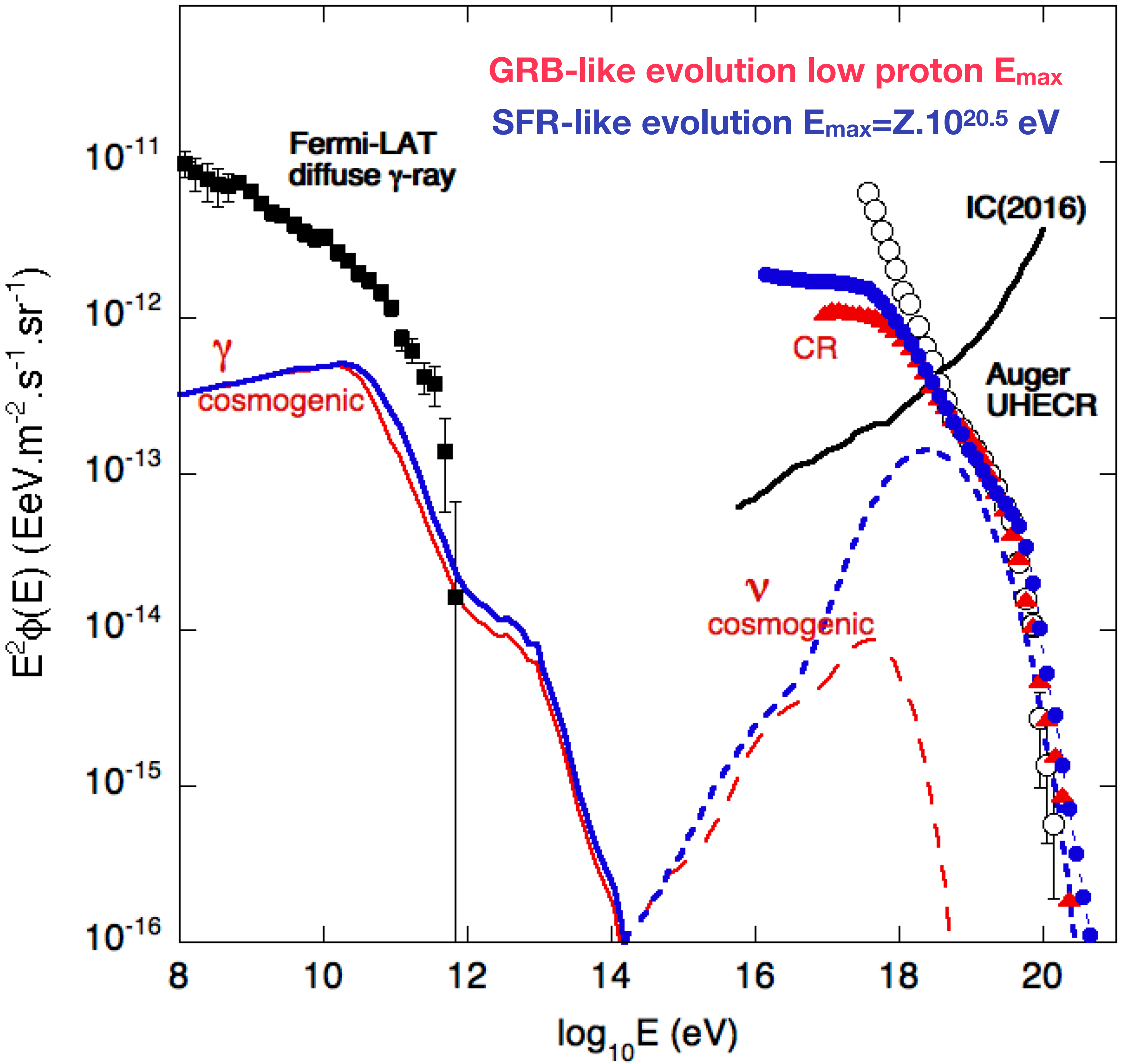
Extragalactic model coupled to a simple description of the Galactic component
(abundances obtained from balloon and satellite measurements, broken power laws assumed to reproduce the knee of the different species at energies proportional to Z)

- Fair reproduction of the light ankle and heavy galactic component
- Good description of Auger composition observables when using the latest (LHC tested) hadronic models
- Good agreement with more recent Auger analyses (down to 10^{17} eV) and recent LOFAR (radio) measurements (as well as older HiRes MIA results)

Phenomenological model : multi-messenger implications



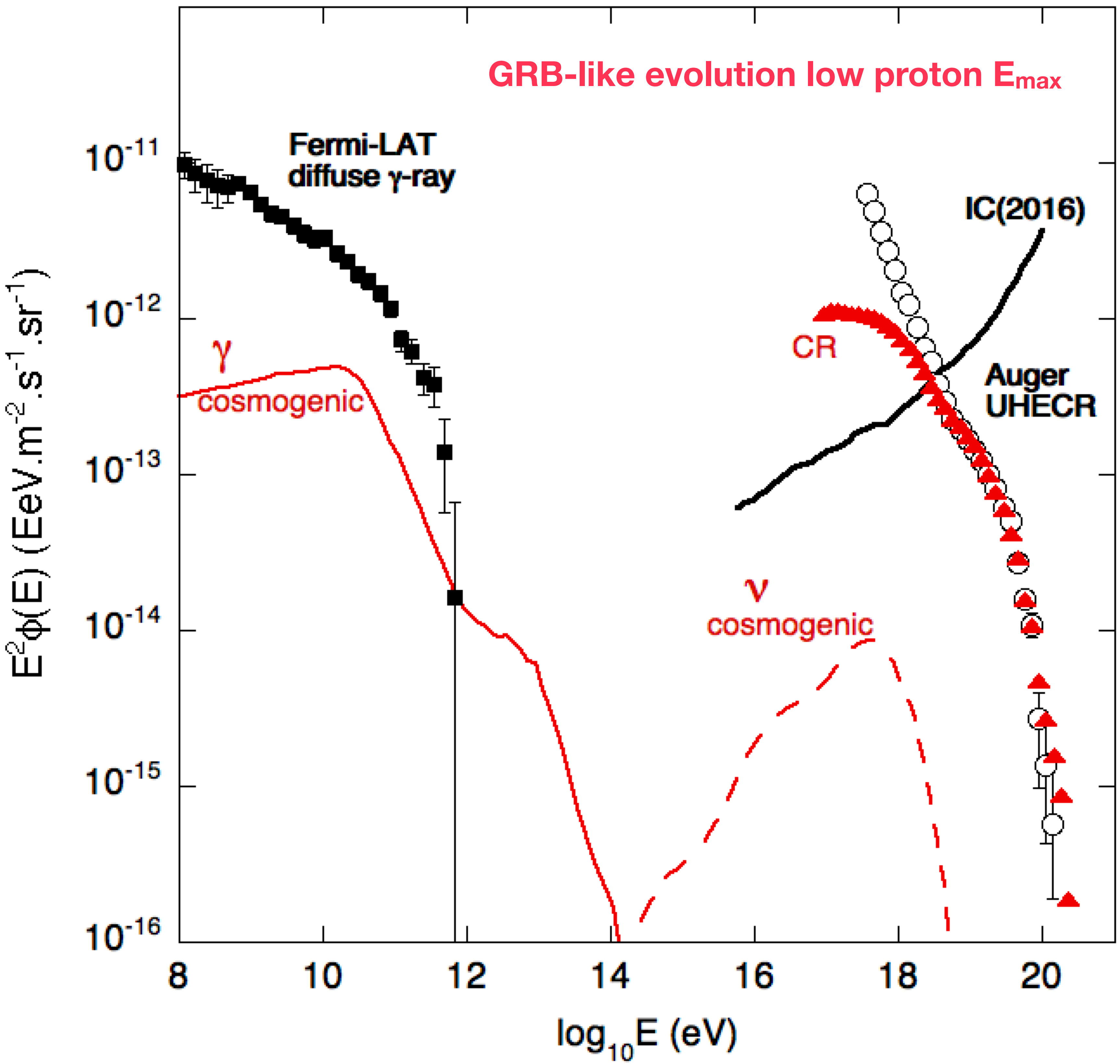
Phenomenological model : multi-messenger implications



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



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

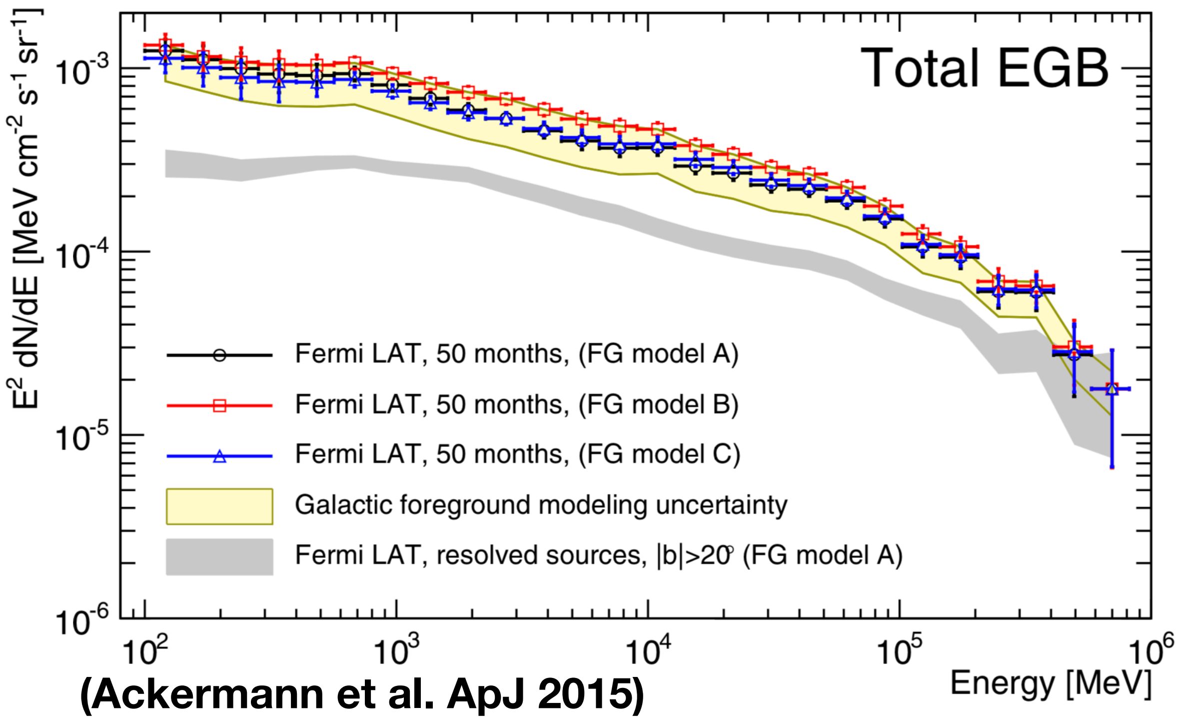
Despite the low maximum energy per nucleon, the diffuse γ-ray flux is very similar to that of previous mixed composition case

This scenario looks completely unconstrained from the point of view of cosmogenic neutrinos and photons

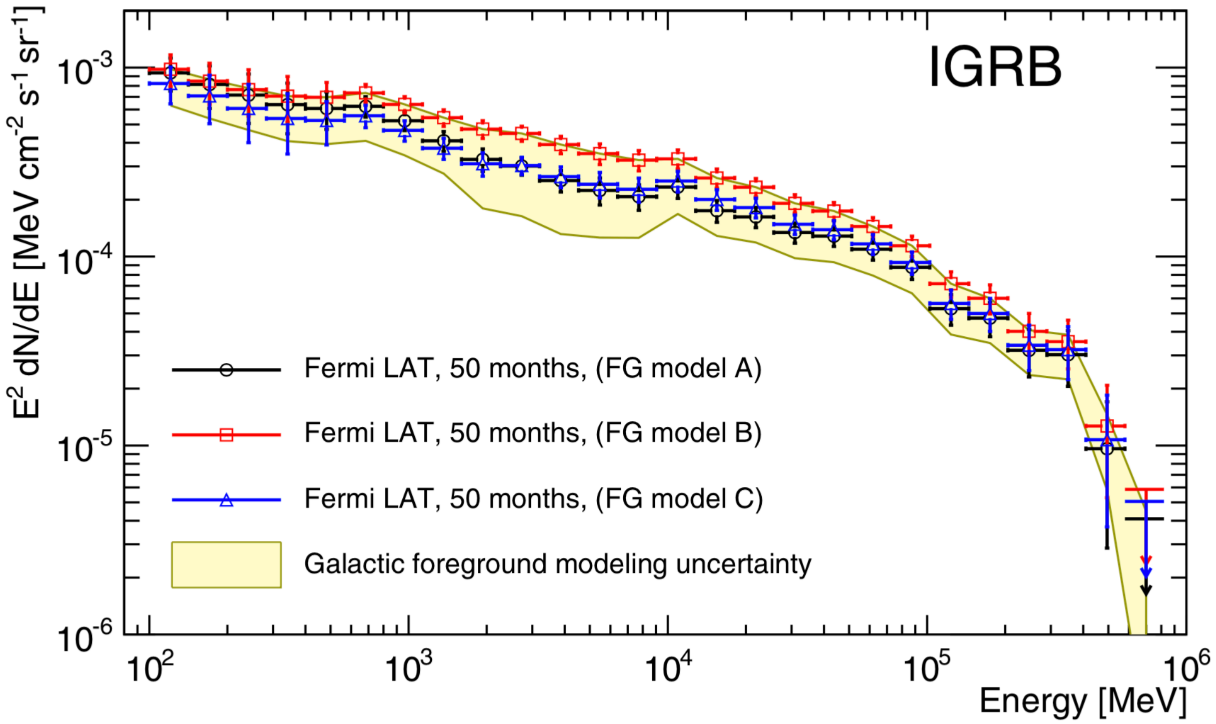
But Fermi-LAT data contain more informations than what we just discussed

Recent Fermi estimates of the extragalactic γ-ray background

Fermi recently released an updated estimate of the extragalactic γ-ray background for both the resolved and unresolved 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

NB : 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 (contribute also to the IGRB)
- truly diffuse processes (UHECR for sure, possibly DM)

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

Recent Fermi measurements : estimates of point sources contribution to the γ-ray background

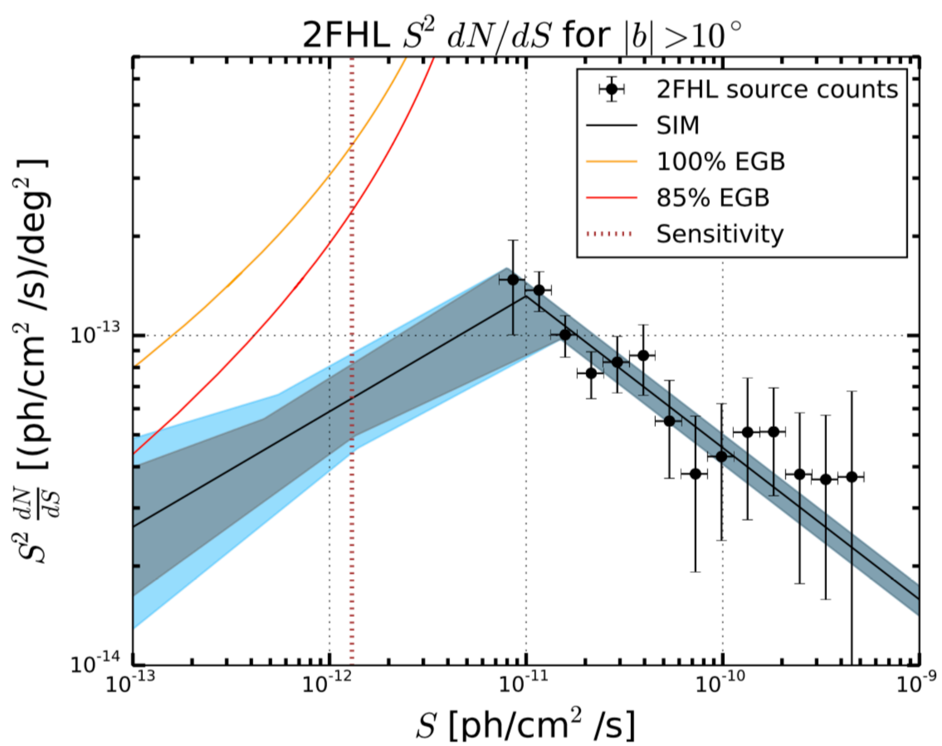
Different estimates of the contribution of point sources (resolved and unresolved) to the total γ-ray background were proposed

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} ($\times 10^{-9}\,\mathrm{cm^{-2}\cdot s^{-1}\cdot sr^{-1}}$)	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 A)	83^{+7}_{-13}	79^{+4}_{-16}	66^{+20}_{-7}	66^{+28}_{-5}	81^{+52}_{-19}	86^{+16}_{-14}
F_{PS}/F_{EGB} (% Model B)	68^{+5}_{-10}	63^{+4}_{-13}	52^{+15}_{-6}	51^{+22}_{-4}	65^{+41}_{-15}	71^{+13}_{-12}



(Ackermann et al., PRL 2016)

The contribution of the resolved point sources is estimated for fluxes well below the point source detection limits using the so-called "photon fluctuations analysis"

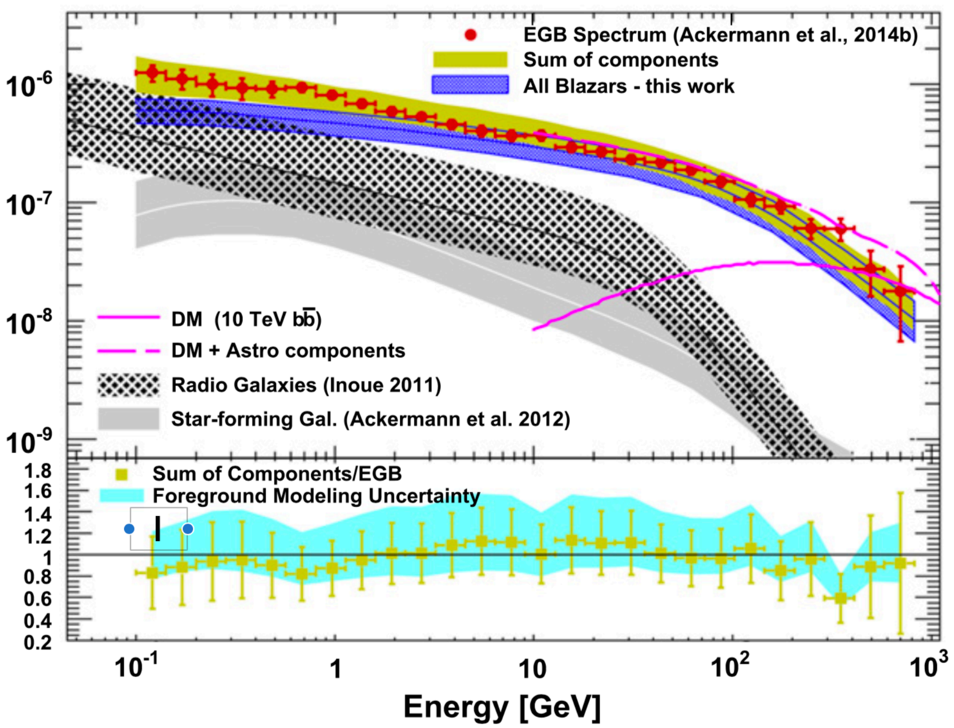
➡ fluxes due to (resolved and unresolved) point sources are estimated in each energy bands

➡ fractional contributions to the total γ-ray background are deduced in each bands

➡ **Large fractions deduced**

NB : these estimates are probably including blazar point sources and might not include the contributions of weak sources (but numerous) such as star-forming galaxies and misaligned AGNs

Recent Fermi measurements : estimates of point sources contribution to the γ-ray background



Ajello et al., ApJ, 2015

	(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
$F_{\rm PS}$ $(\times 10^{-9}\,{\rm cm^{-2}\cdot s^{-1}\cdot sr^{-1}})$	250^{+20}_{-40}	124^{+7}_{-25}	27^{+8}_{-3}	14^{+6}_{-1}	$1.7^{+1.1}_{-0.4}$	$2.07^{+0.40}_{-0.34}$
$F_{\rm PS}/F_{\rm EGB}$ (% Model B)	68^{+5}_{-10}	63^{+4}_{-13}	52^{+15}_{-6}	51^{+22}_{-4}	65^{+41}_{-15}	71^{+13}_{-12}
$F_{\rm SFG+misAGN}$ $(\times 10^{-9}\,{\rm cm^{-2}\cdot s^{-1}\cdot sr^{-1}})$	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

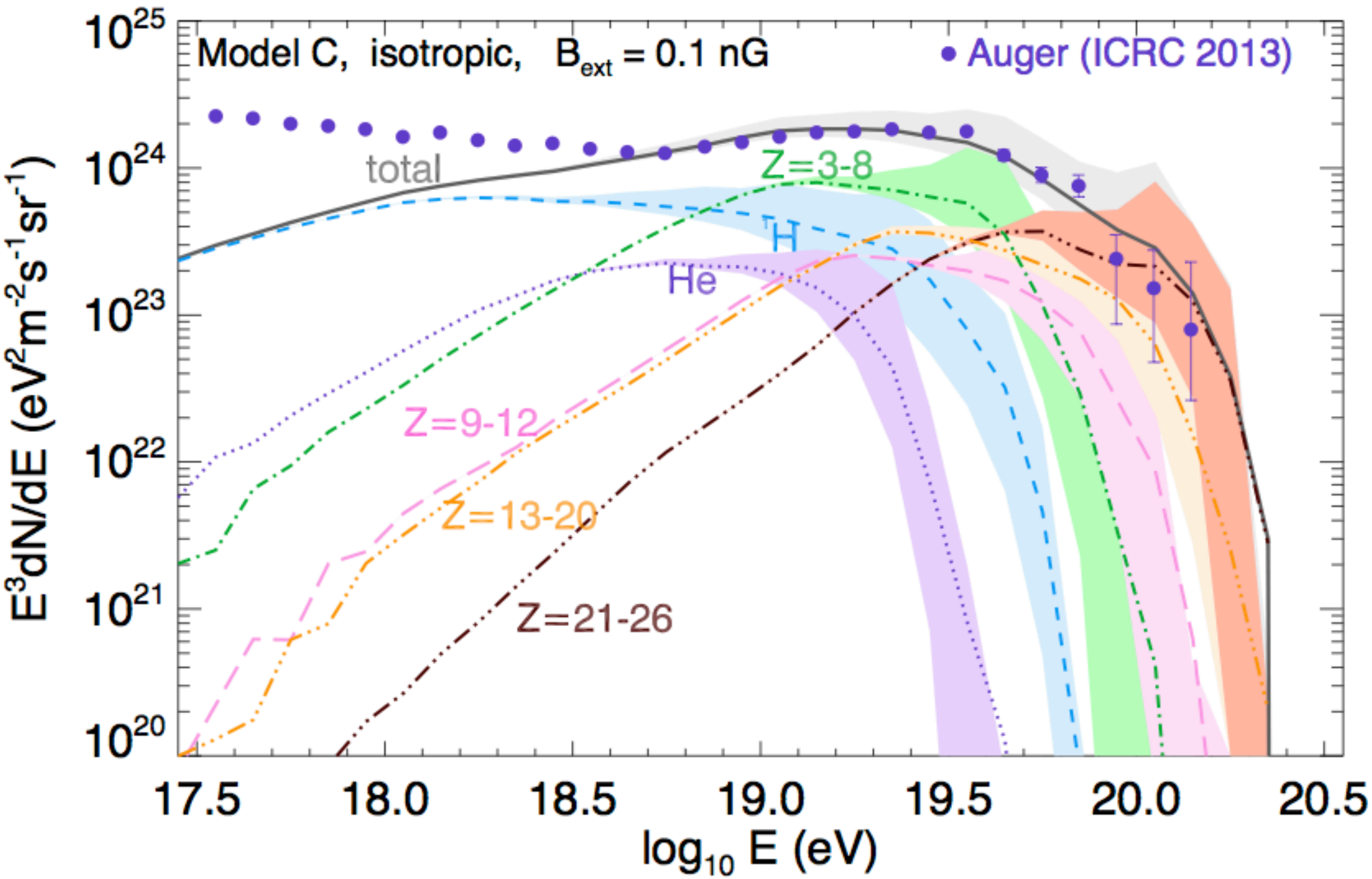
The contribution of UHECR must added to those of astrophysical sources to check whether or not a given astrophysical model is viable.

Phenomenological model : implications for the GCR to EGCR transition

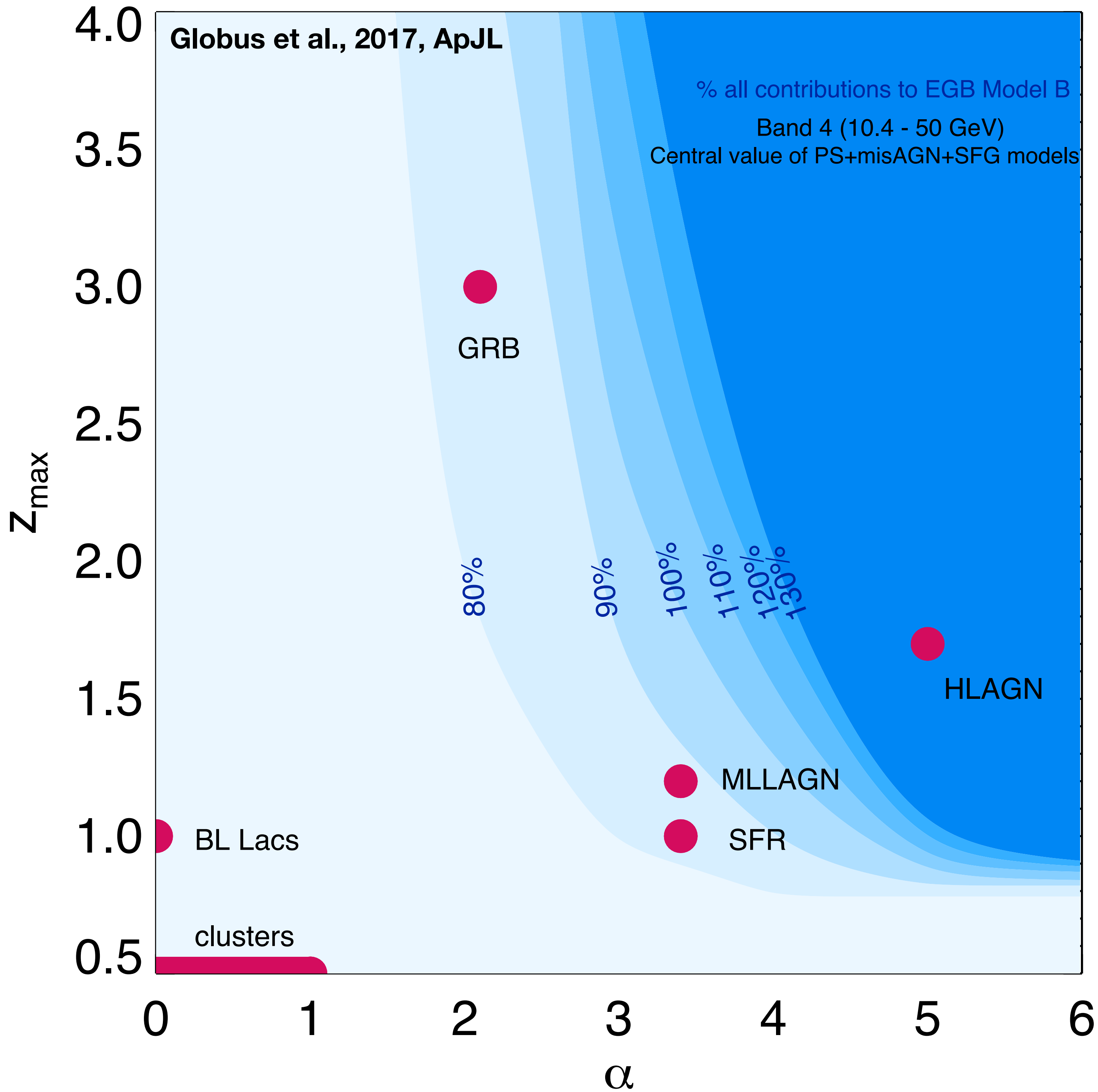
This type of model has been shown to reproduce the data from KG to Auger across the galactic to extragalactic transition region

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

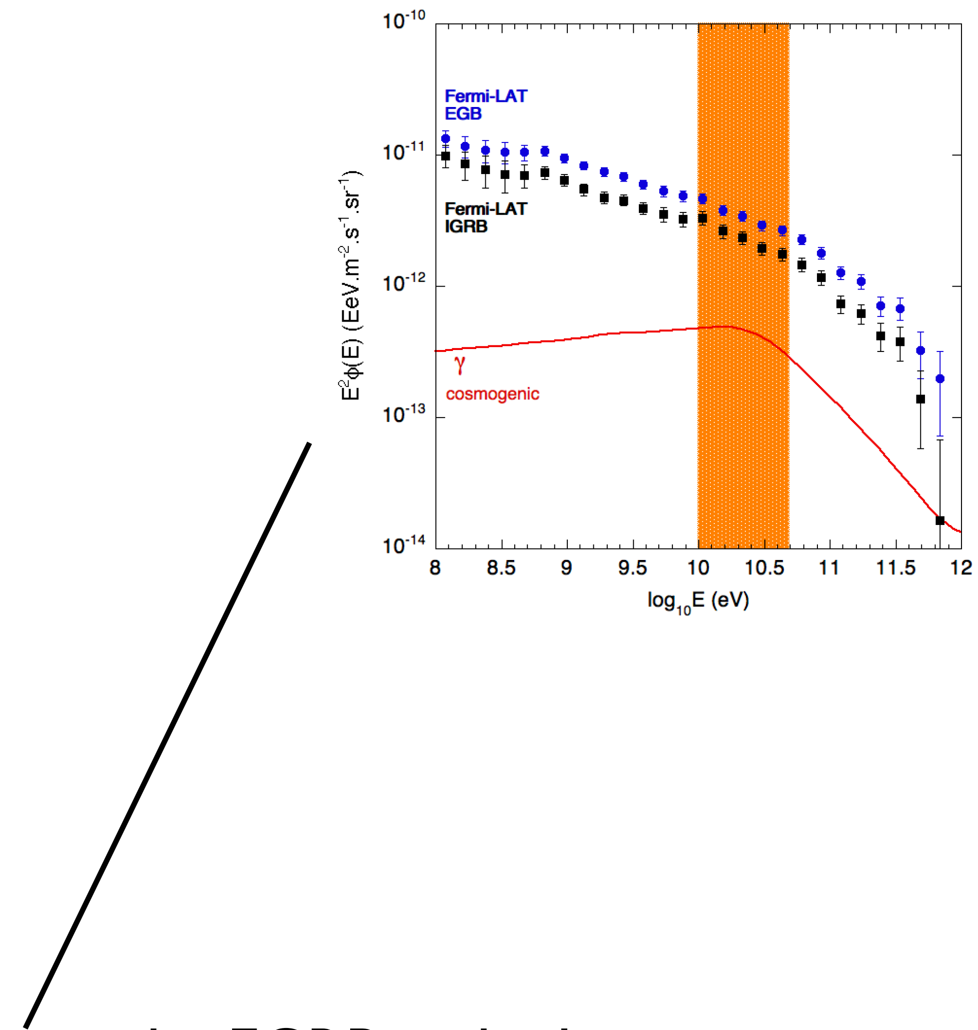
in the following we are going to use the CR output of our GRB model as a "generic source spectrum" with various cosmological evolutions —> quantitative estimate of the constraints brought by Fermi on UHECR models (source evolution)



Summary plot on the allowed cosmological evolutions



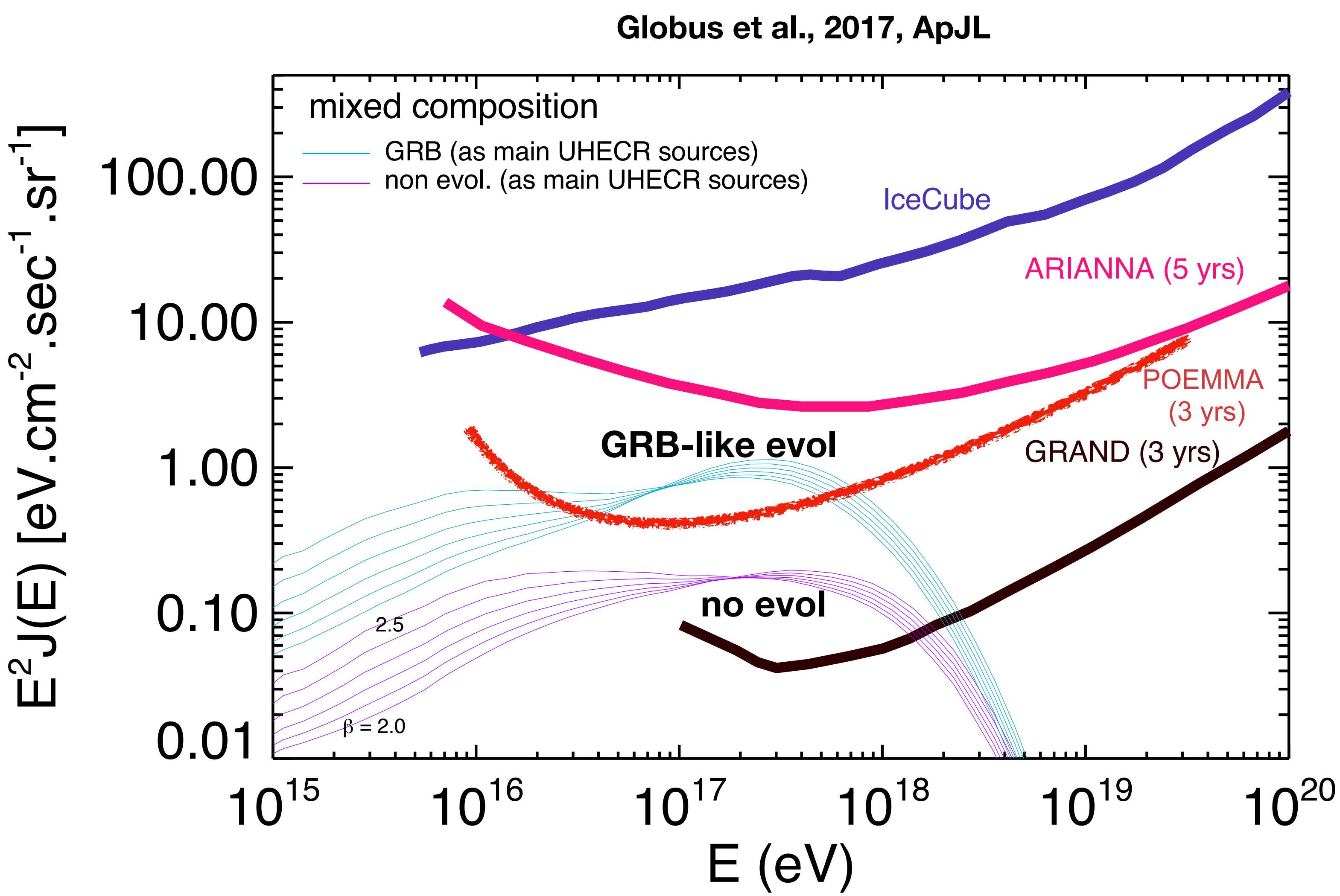
Astrophysical sources evolution usually parametrised as : $(1+z)^{\alpha}$ up to a redshift $\mathbf{z_{max}}$



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

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

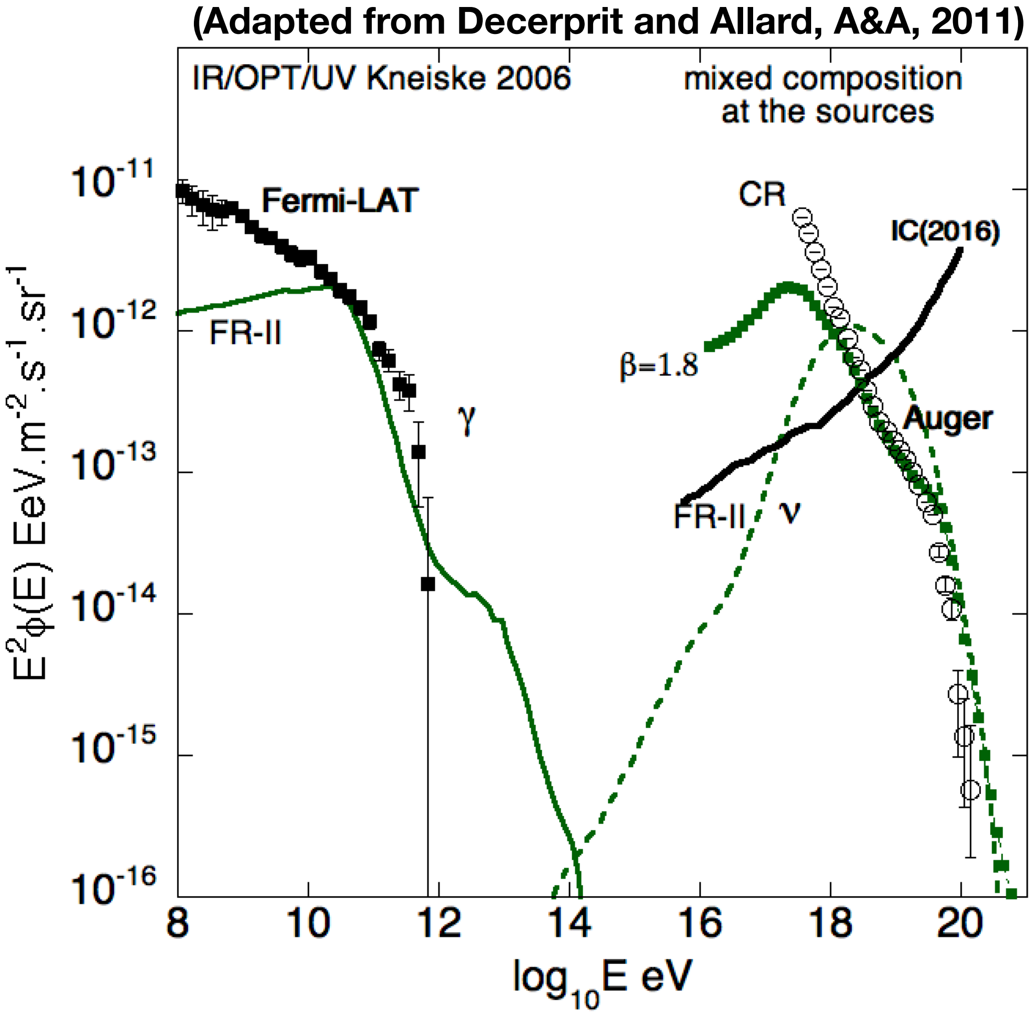
Discussion of the resulting cosmogonic neutrino fluxes



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)

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

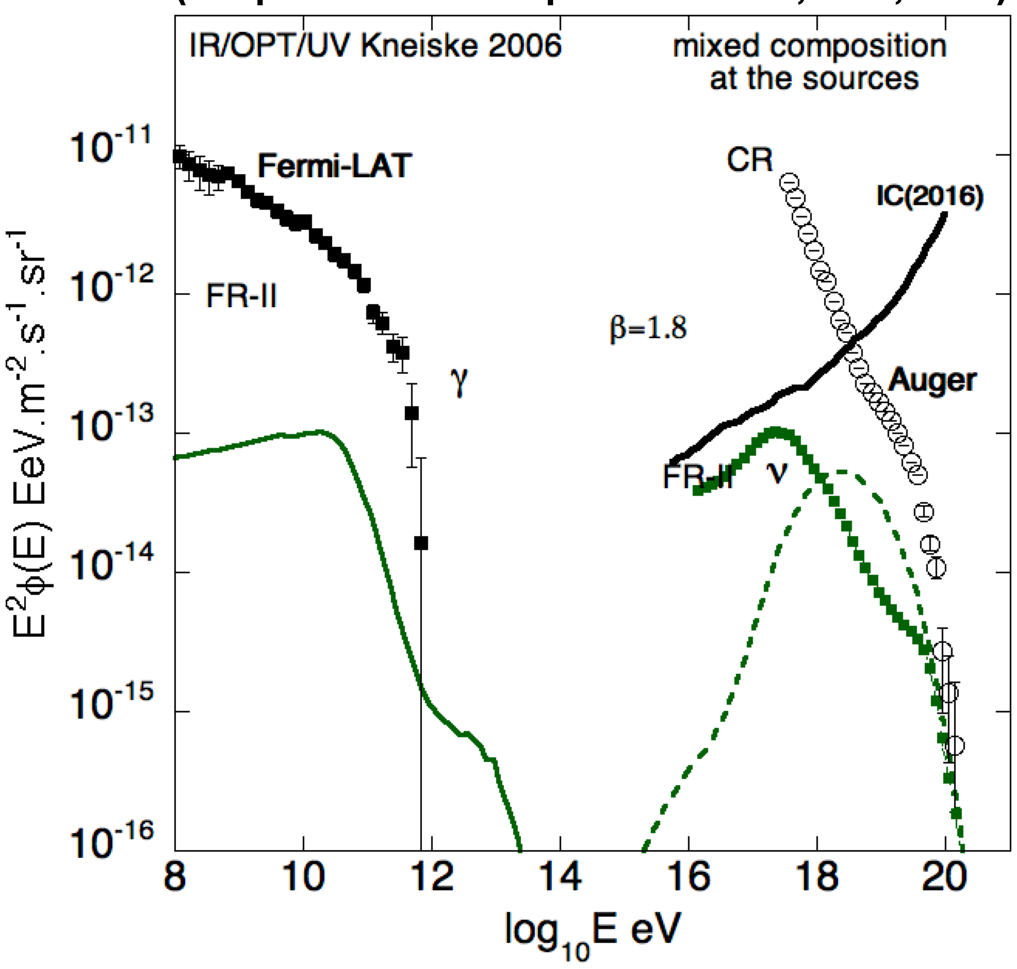


Let us consider proton accelerators (above 10^{20} eV) with a strong source evolution

- ➡ 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

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

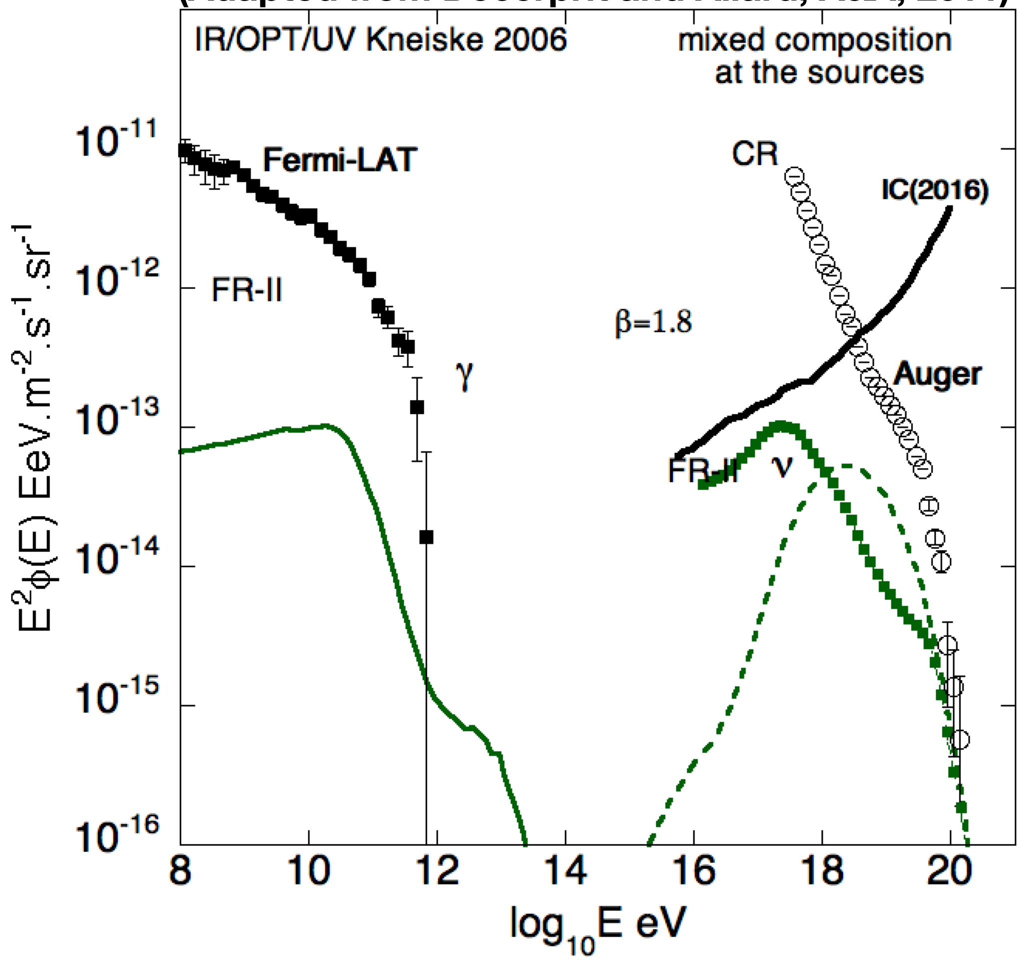


Let us consider proton accelerators (above 10^{20} eV) with a strong source evolution

- ➡ Let us instead assume it is a subdominant part of the spectrum, say 5% at 10^{19} eV
- ➡ Then it is not ruled out anymore by any experimental constraint

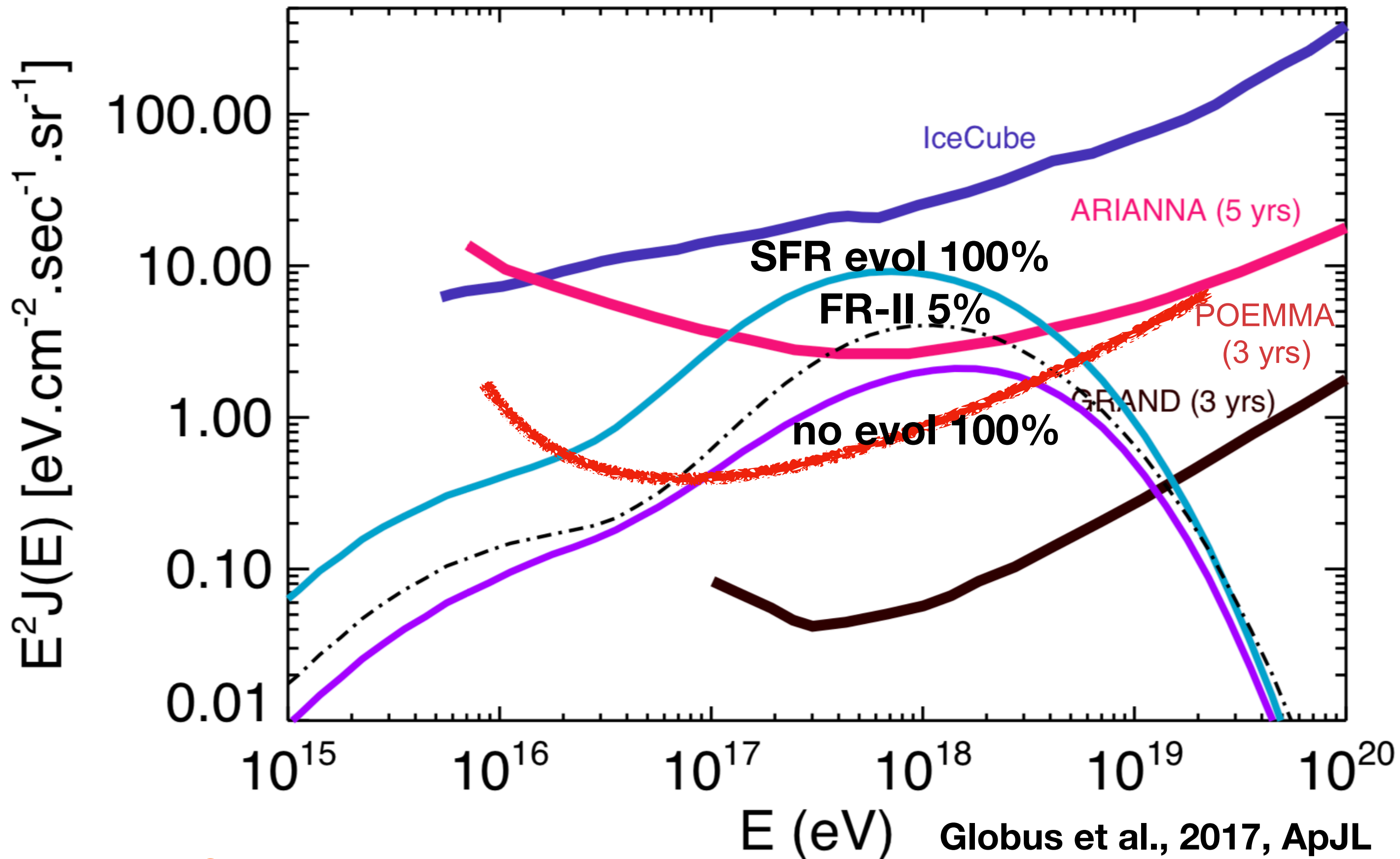
Constraining the presence of powerful protons accelerators in the universe

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



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

- ➡ Let us instead assume it is a subdominant part of the spectrum, say 5% at 10^{19} eV
- ➡ Then it is not ruled out anymore by any experimental constraint

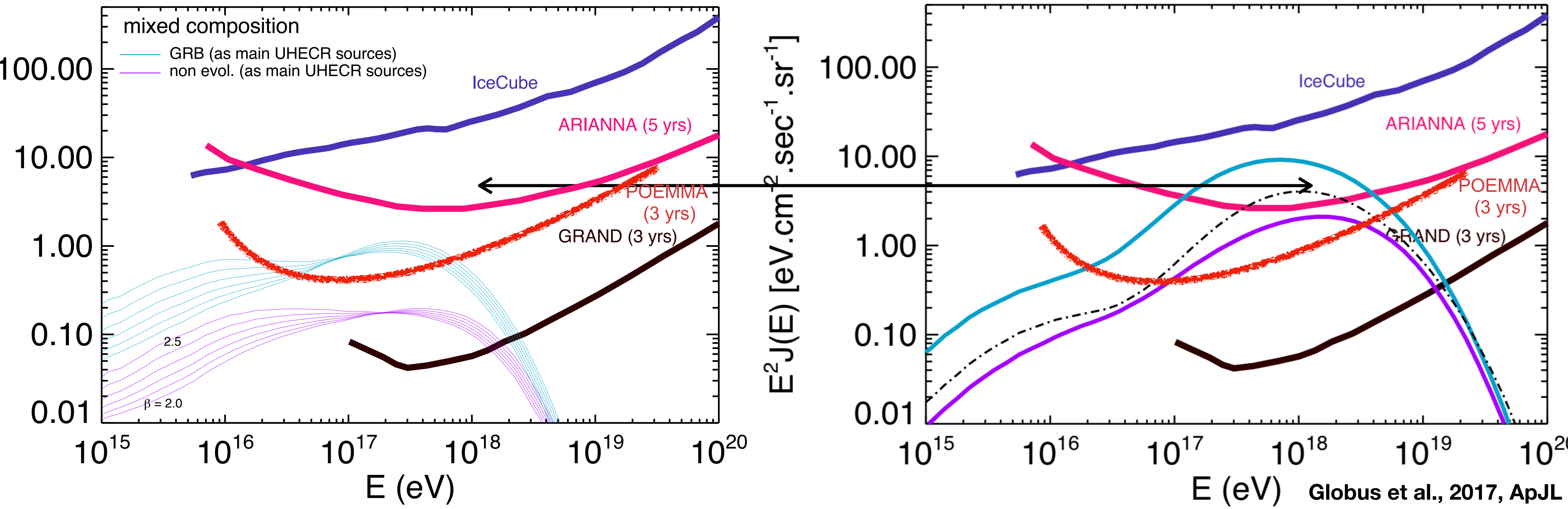


Globus et al., 2017, ApJL

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

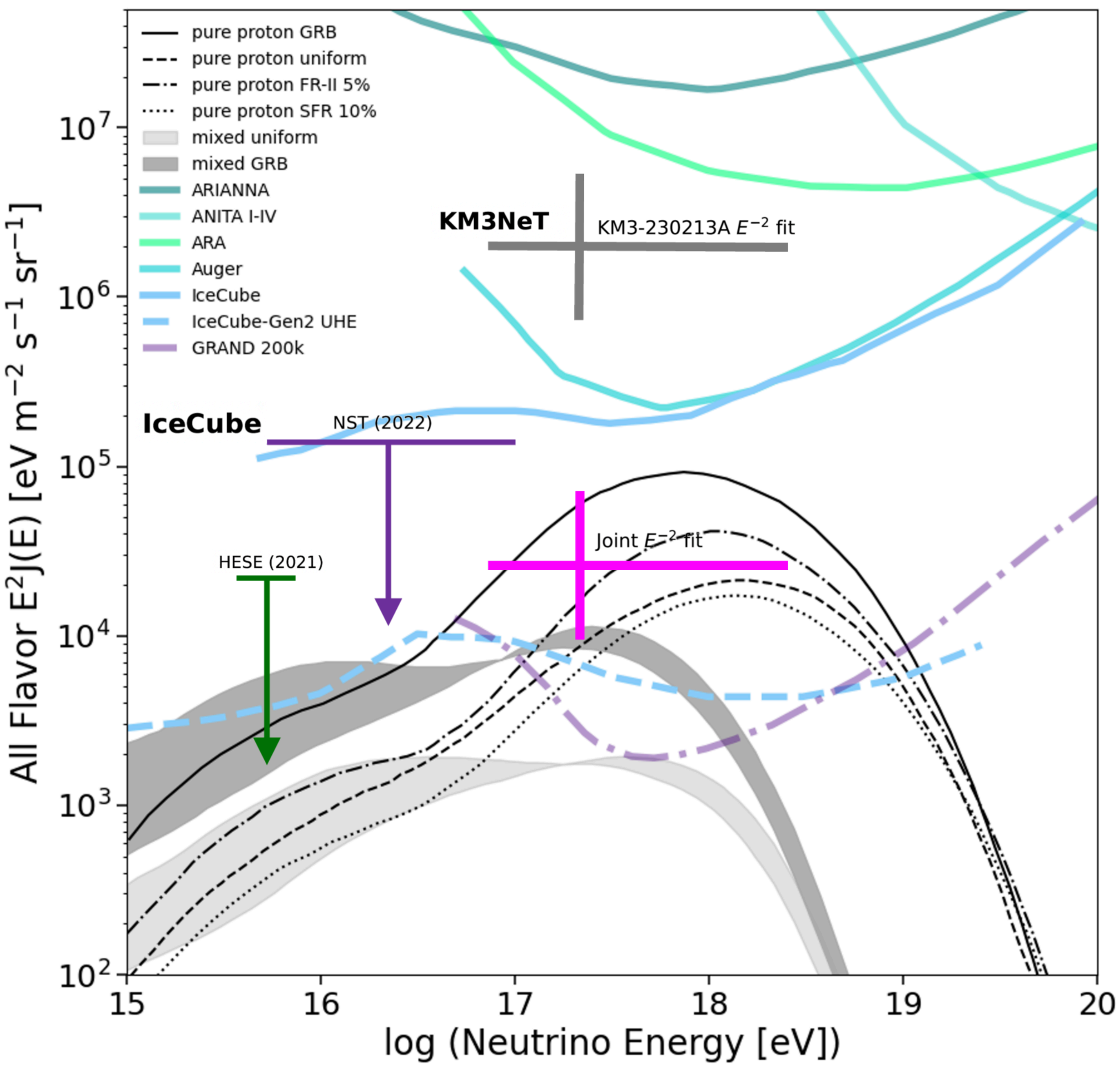
The resulting neutrino flux is significantly larger than that of the main UHECR component



Globus et al., 2017, ApJL

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

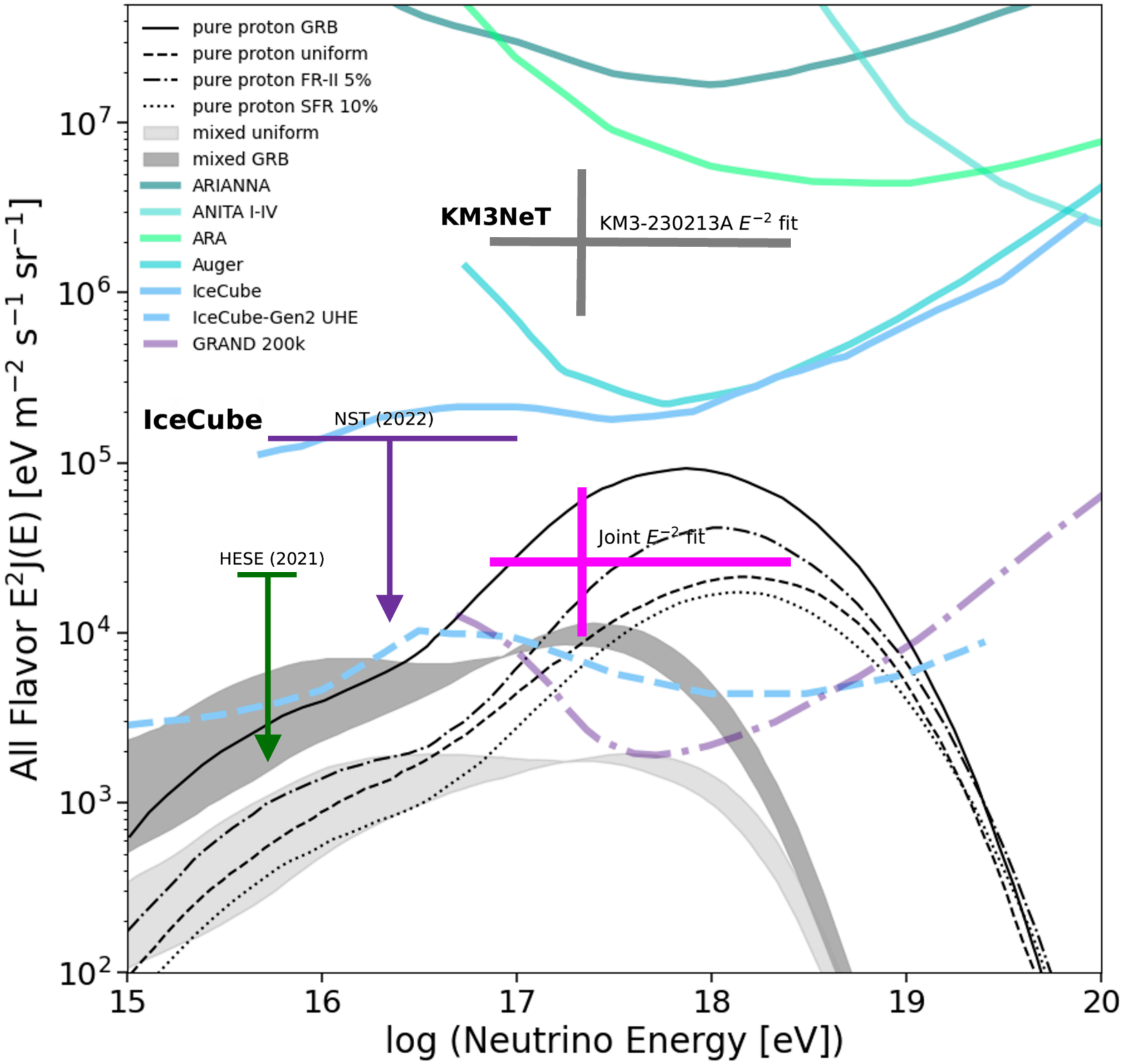
Constraining the presence of powerful protons accelerators in the universe



Courtesy of N. Globus, adapted from Globus et al., 2017, ApJL

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

Constraining the presence of powerful protons accelerators in the universe



How likely is the presence of such a subdominant component?
difficult to say
but in principle it makes sense
—> R_{max} α $L^{1/2}_{bol}$
—> sources able to accelerate 10^{20} eV proton may be rare in the nearby universe and outnumbered by weaker sources which dominate the local UHECR flux

—> rare sources with a larger individual UHECR output
—> >10^{20} eV protons produce ν after propagating a few Mpc
—> UHE neutrino quasi point sources?

Courtesy of N. Globus, adapted from Globus et al., 2017, ApJL

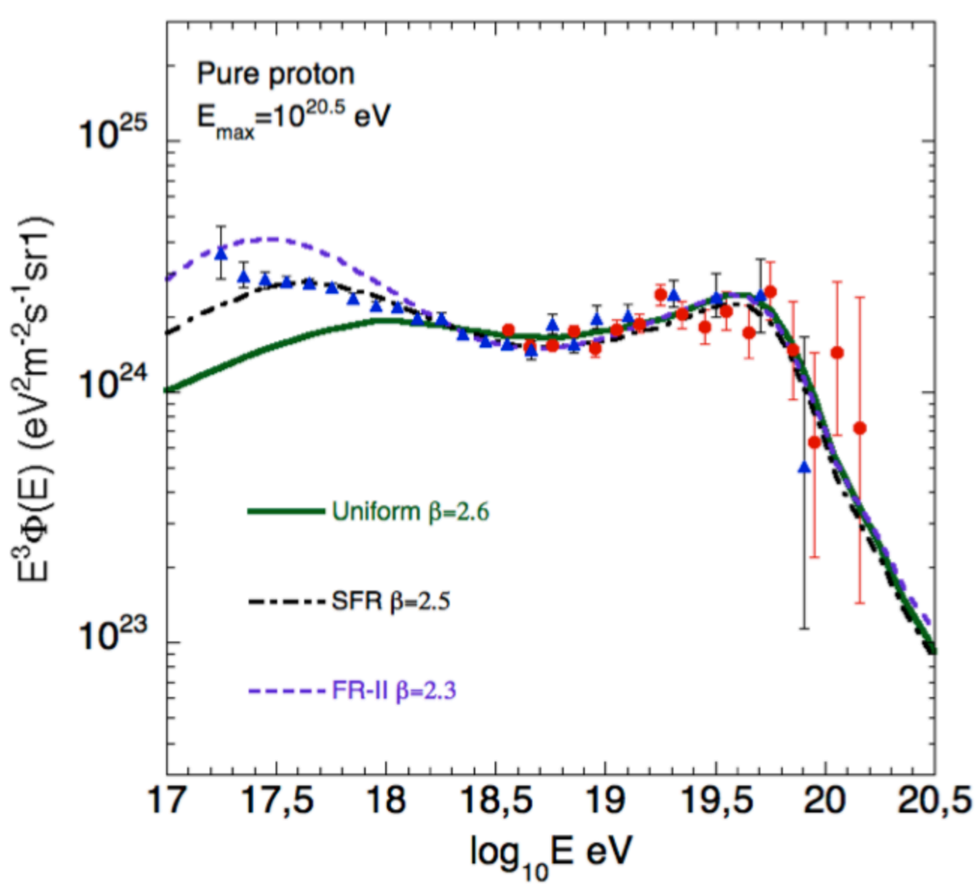
Real window to constrain the presence of proton accelerator in the universe
(and not only within the GZK horizon)

Thank you very much !!!!

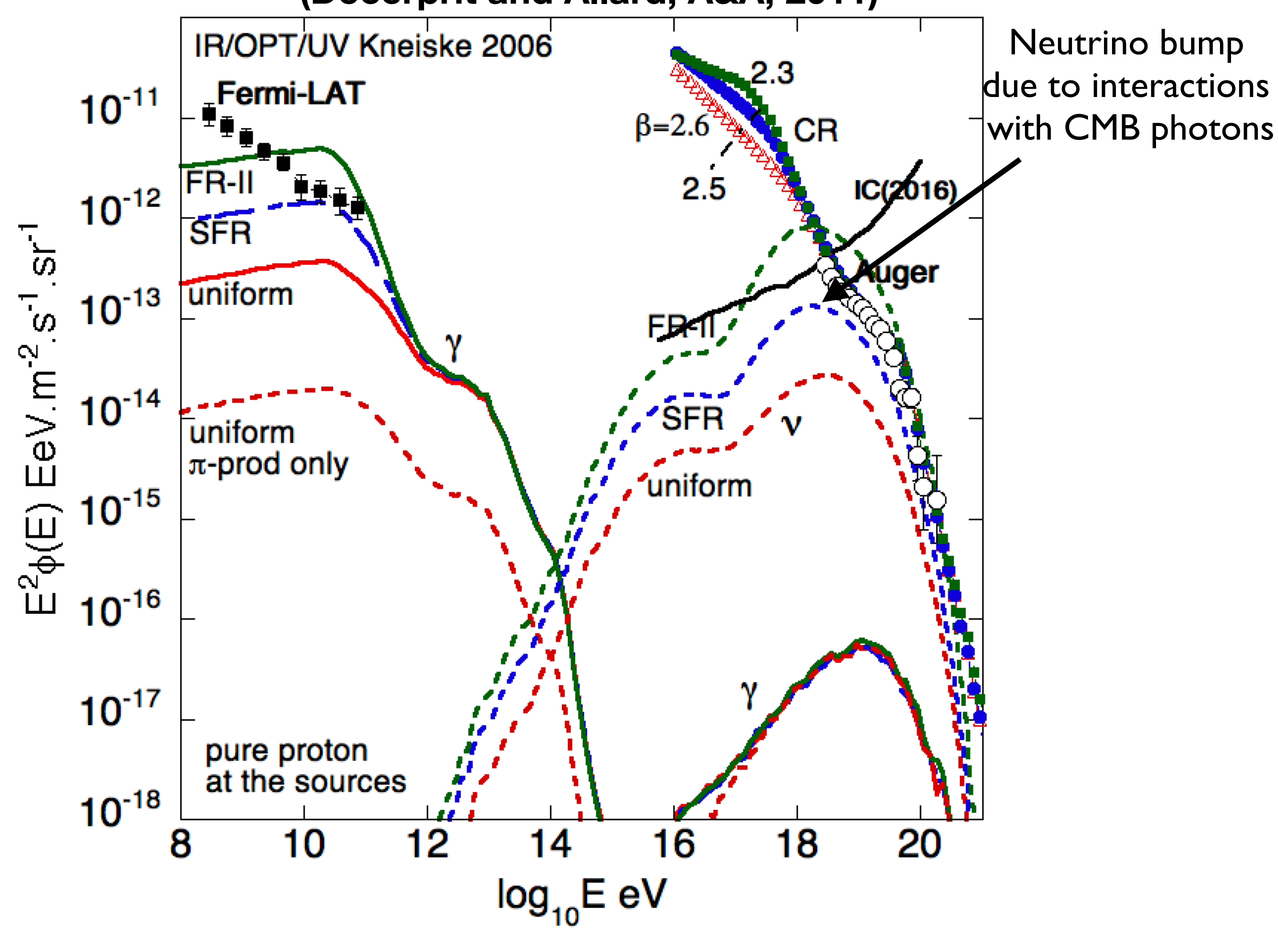
Backup

Some examples of contraints brought by cosmogenic secondaries (I)

Assuming the maximum energy per nucleon is well above 10^{20} eV (what most people thought until ~2010)
pure proton case :



(Decerprit and Allard, A&A, 2011)



Fermi diffuse background (IGRB from 2010) appears to be quite more constraining than IceCube limits. Stronger source evolutions than SFR (and their resulting neutrino flux) challenged by Fermi

==> These strong strong constraints for the γ-ray background appear to be model dependent, they are especially strong for the pure proton model due to the soft source spectral index required

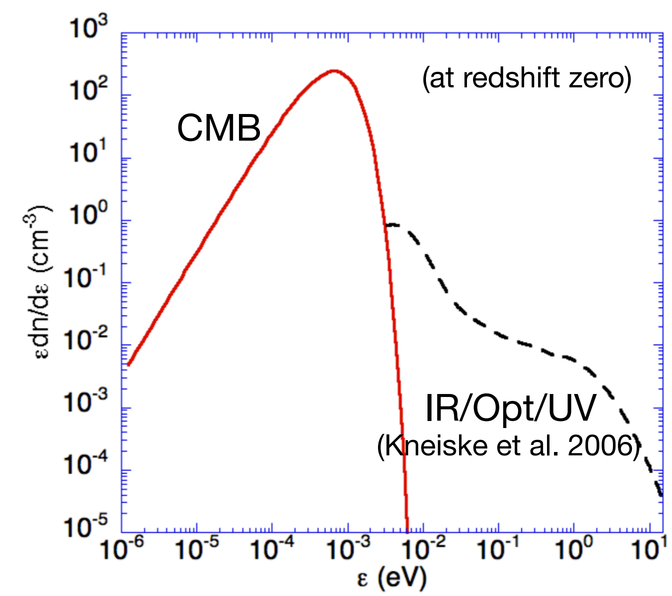
Ultra-high-energy cosmic-rays, neutrinos and photons : the multi-messenger link

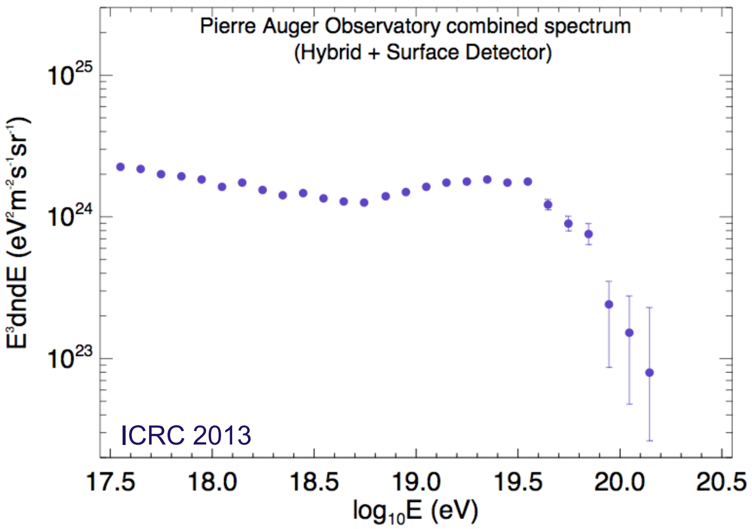
Extragalactic very-high and ultra-high-energy cosmic-rays produce secondary (cosmogenic) neutrinos and gamma-rays during their propagation interacting with the extragalactic background light (UV-optical-IR, CMB)

- pair production: $N+\gamma \rightarrow N+e^+/e^-$ ==> Threshold with CMB photons ~10^{18} eV per nucleon (at z=0)
- Pion and meson production :

$$\pi^0 \rightarrow 2\gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu,\ \mu^+ \rightarrow \overline{\nu_\mu} + e^+ + \nu_e$$
$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu},\ \mu^- \rightarrow \nu_\mu + e^- + \overline{\nu_e}$$

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



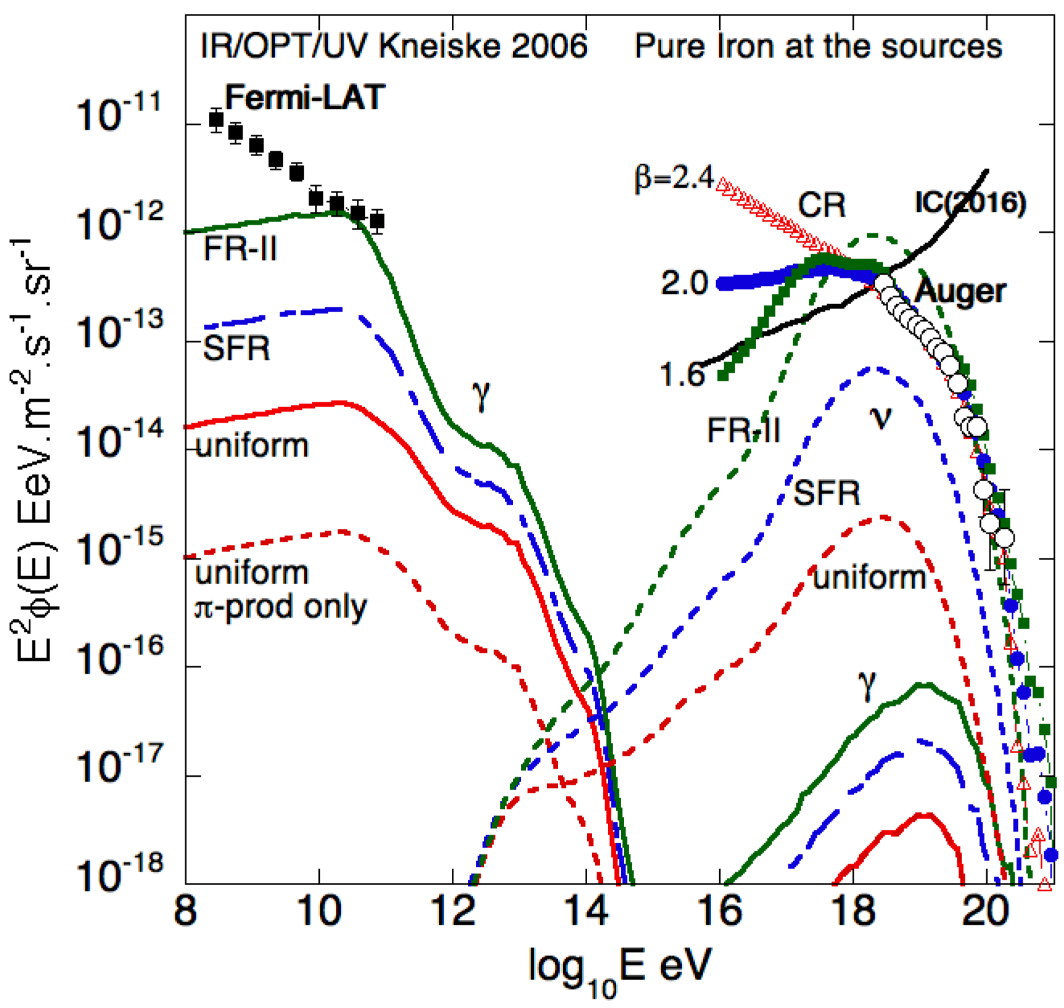


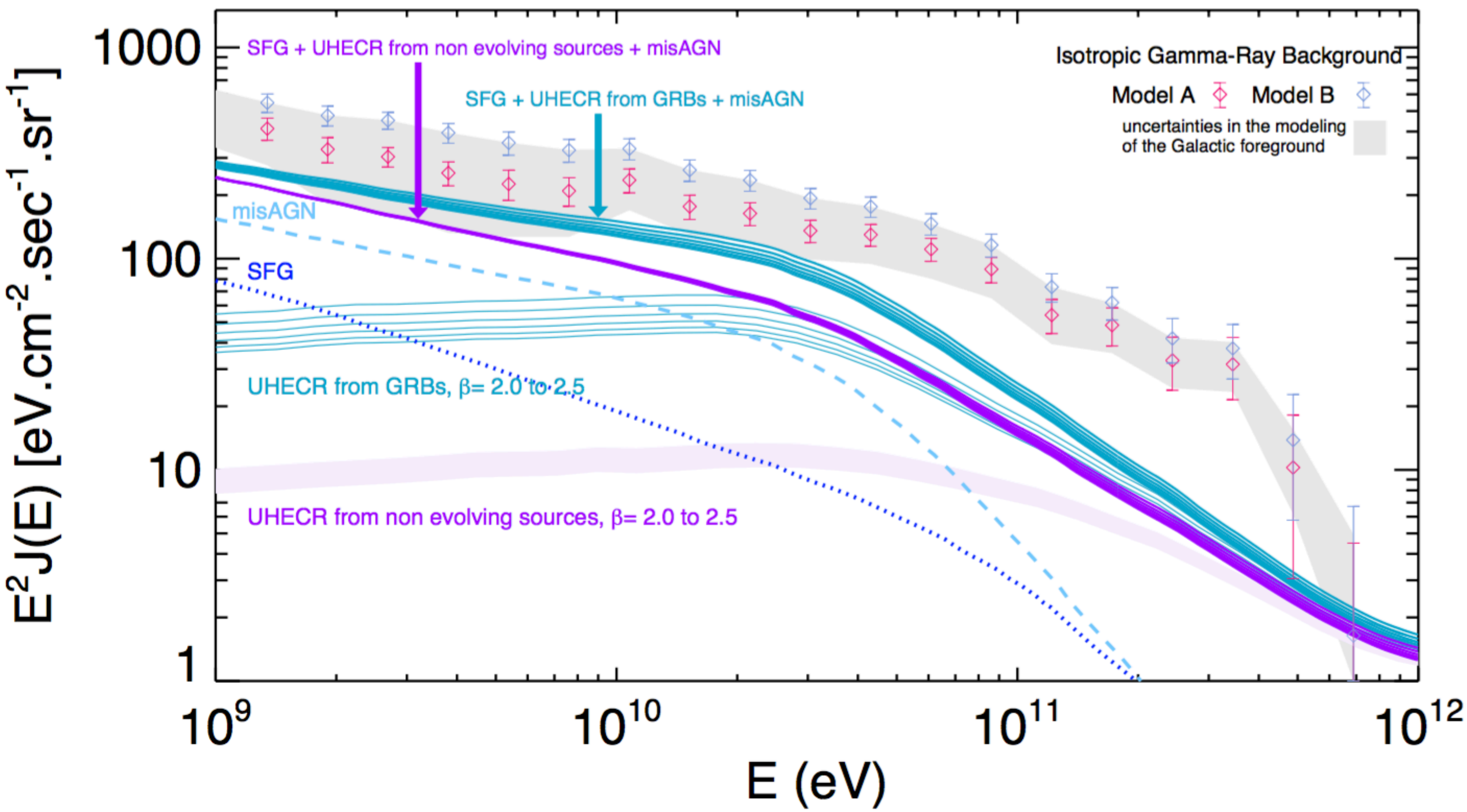
Large amount of interactions with CMB photons initiating electromagnetic cascades **guaranteed** (low energy threshold for e^+/e^-) even if the highest energy cosmic-ray are heavy

Large amount of interactions with CMB photons emitting neutrinos **not guaranteed** unless the highest energy cosmic-ray are light

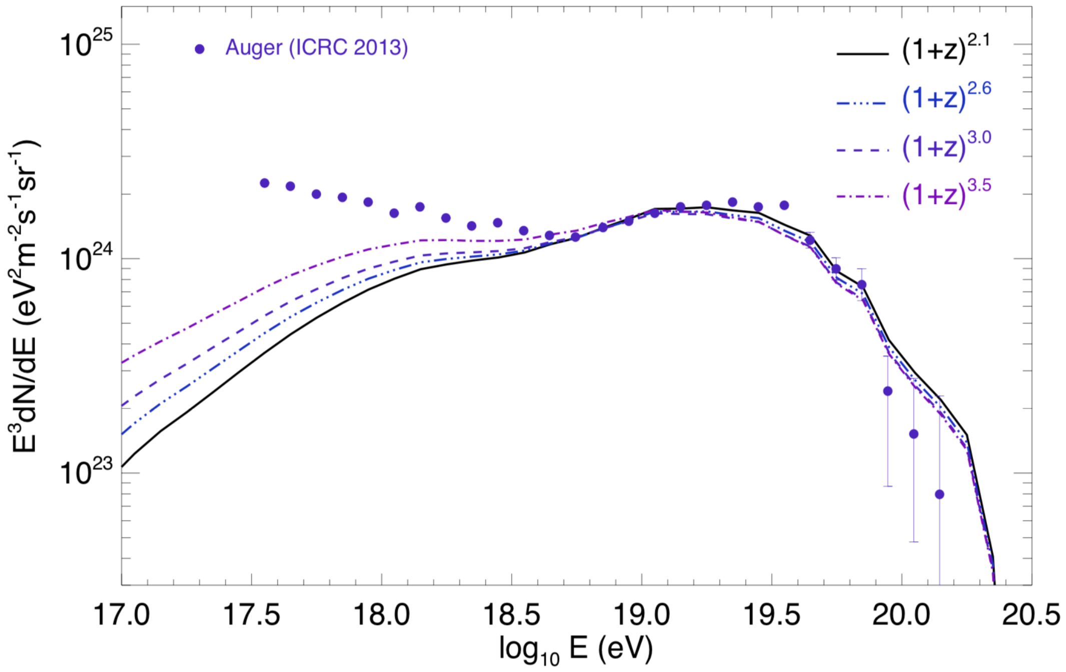
Some examples of contraints brought by cosmogenic secondaries (III)

Assuming the maximum energy per nucleon is well above 10^{20} eV (what most people thought until ~2010) pure iron at the sources :




SFG + UHECR from non evolving sources + misAGN
SFG + UHECR from GRBs + misAGN
Isotropic Gamma-Ray Background
Model A
Model B
uncertainties in the modeling
of the Galactic foreground
misAGN
SFG
UHECR from GRBs, β= 2.0 to 2.5
UHECR from non evolving sources, β= 2.0 to 2.5
1000
100
10
1
$E^2J(E)$ [eV.cm^{-2}.sec^{-1}.sr^{-1}]
10^9
10^{10}
10^{11}
10^{12}
E (eV)

Phenomenological model : implications for the GCR to EGCR transition



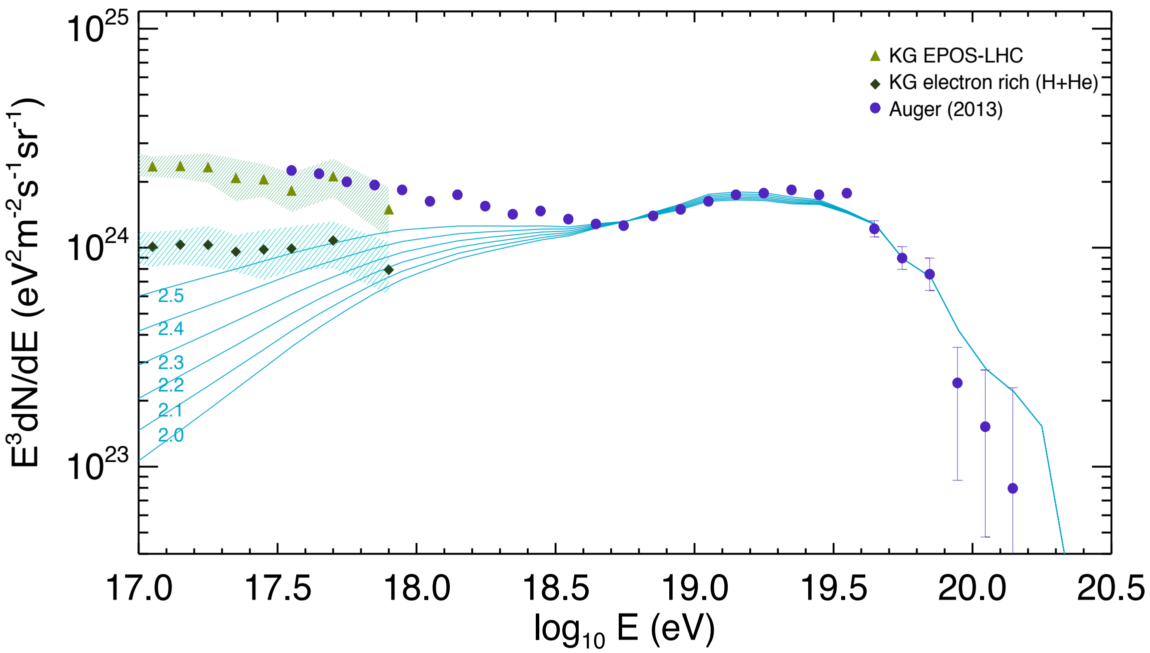
To match the KG light component estimate with post-LHC hadronic models, a boost of the predicted proton component is need

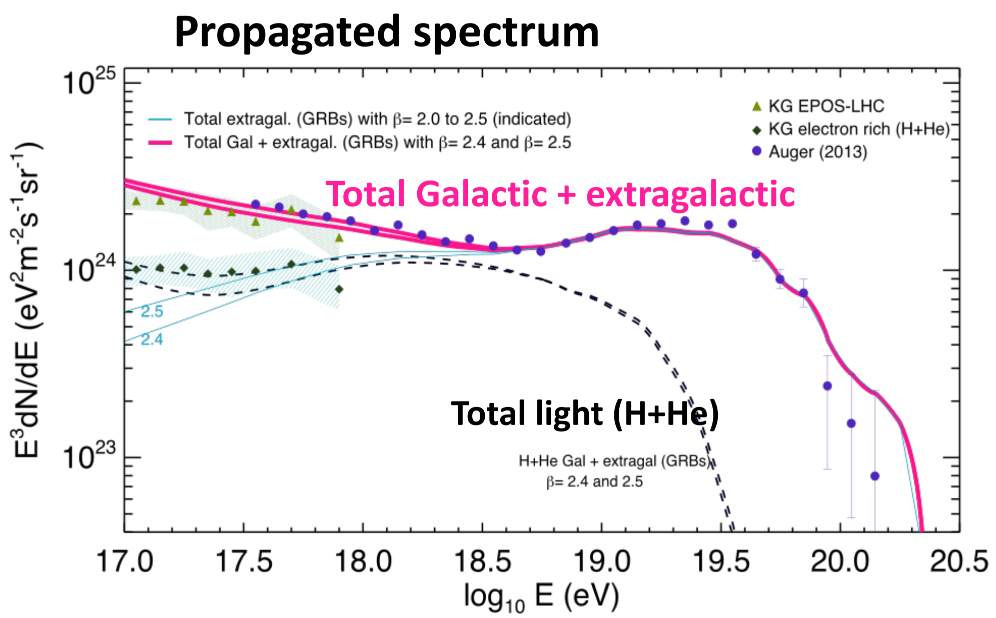
It can be done in two ways :

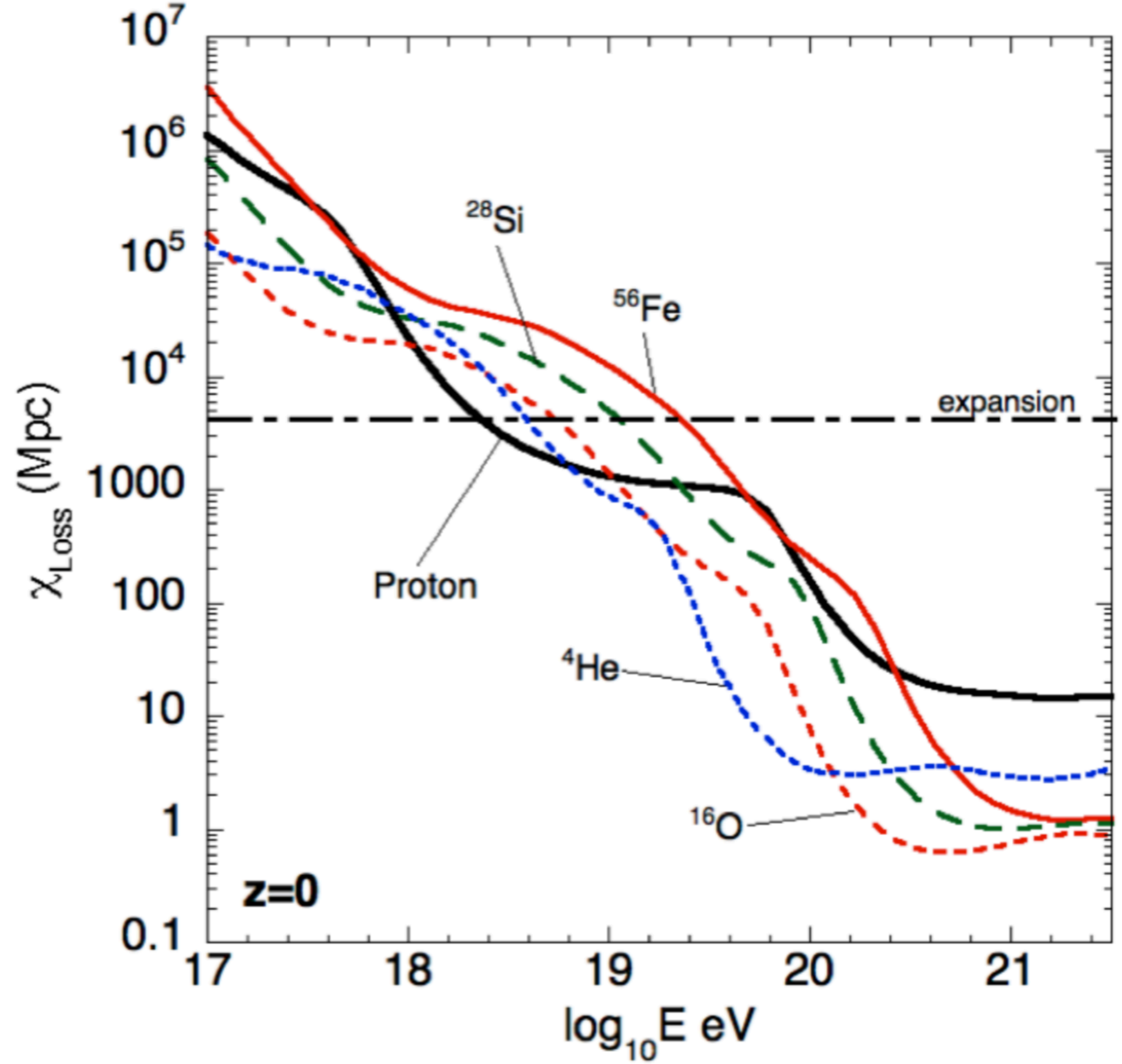
- Choose a stronger cosmological evolution
- Assume a softer spectrum for the protons

➡ in both cases these modifications result in larger predicted cosmogonic photon fluxes

These fluxes however remain compatible with Fermi 2010 IGRB



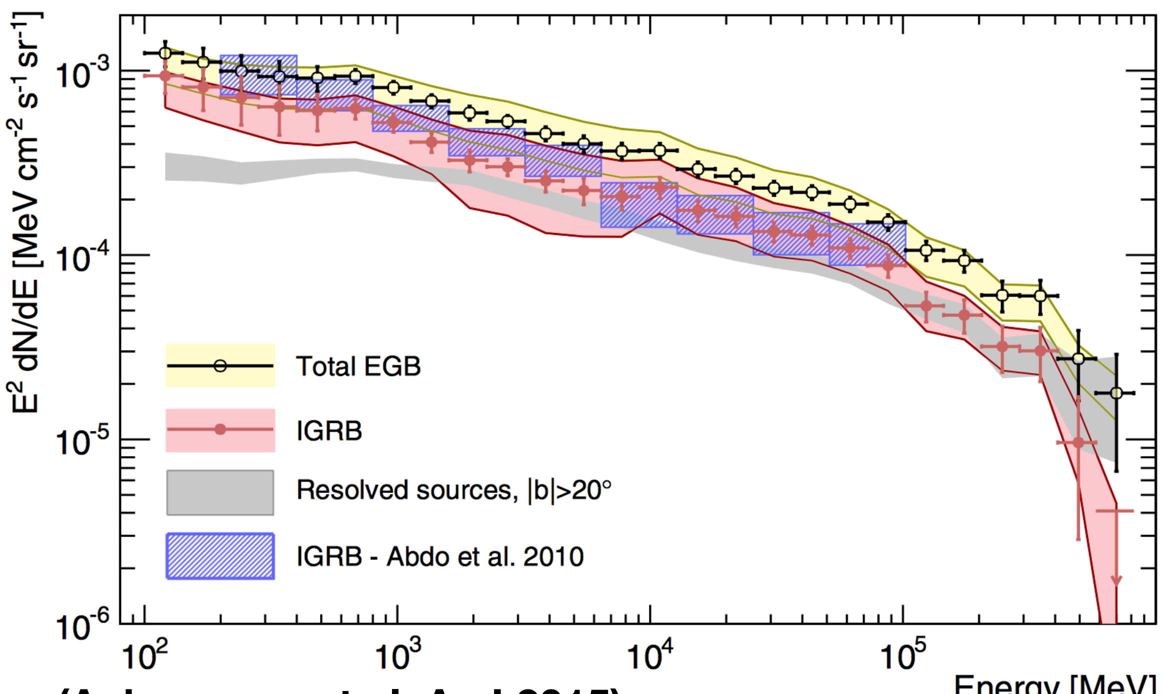




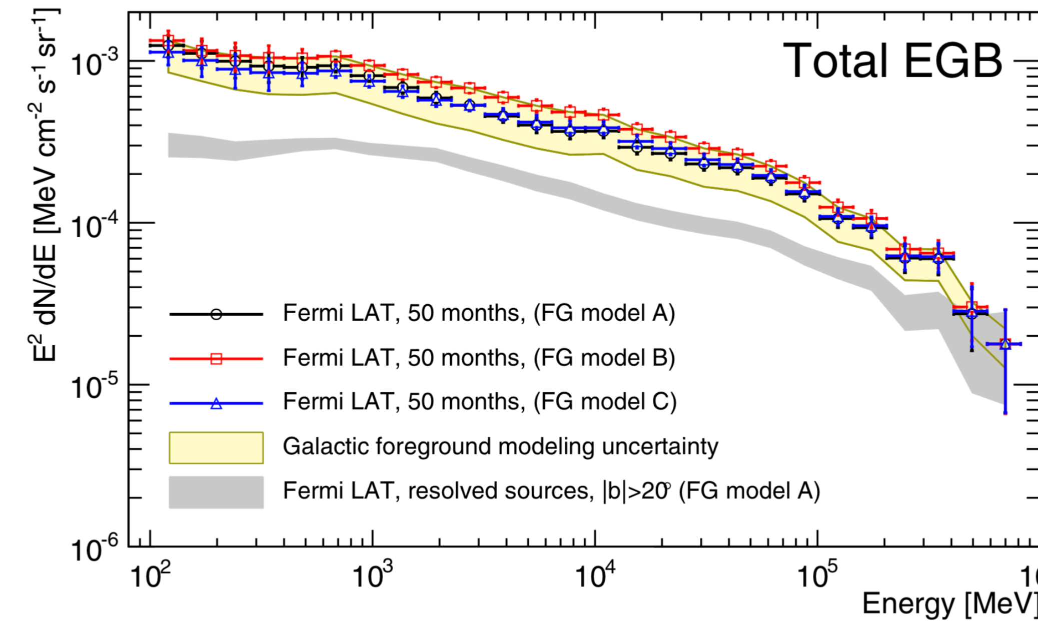
10^7
10^6
10^5
10^4
1000
100
10
1
0.1
χ_{Loss} (Mpc)
17
18
19
20
21
$\log_{10}E$ eV
^{28}Si
^{56}Fe
expansion
Proton
^{4}He
^{16}O
z=0

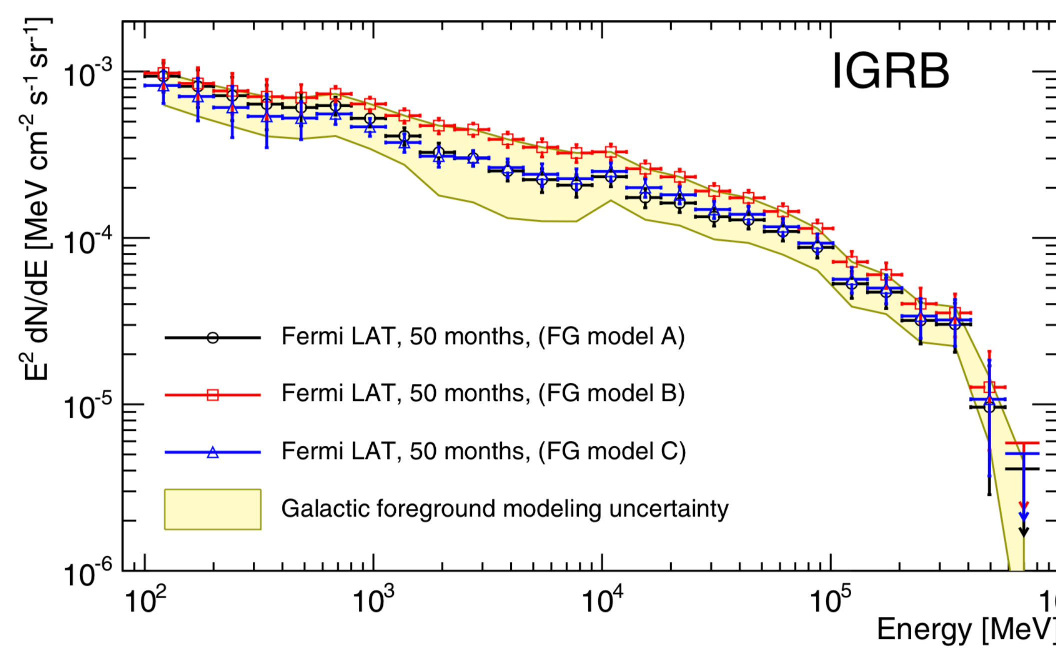
Recent Fermi measurements : extended energy range and galactic foreground intensity

Fermi recently released an updated estimate of the extragalactic γ-ray background for both the resolved and unresolved components
➡Larger statistics and extended energy range



(Ackermann et al. ApJ 2015)

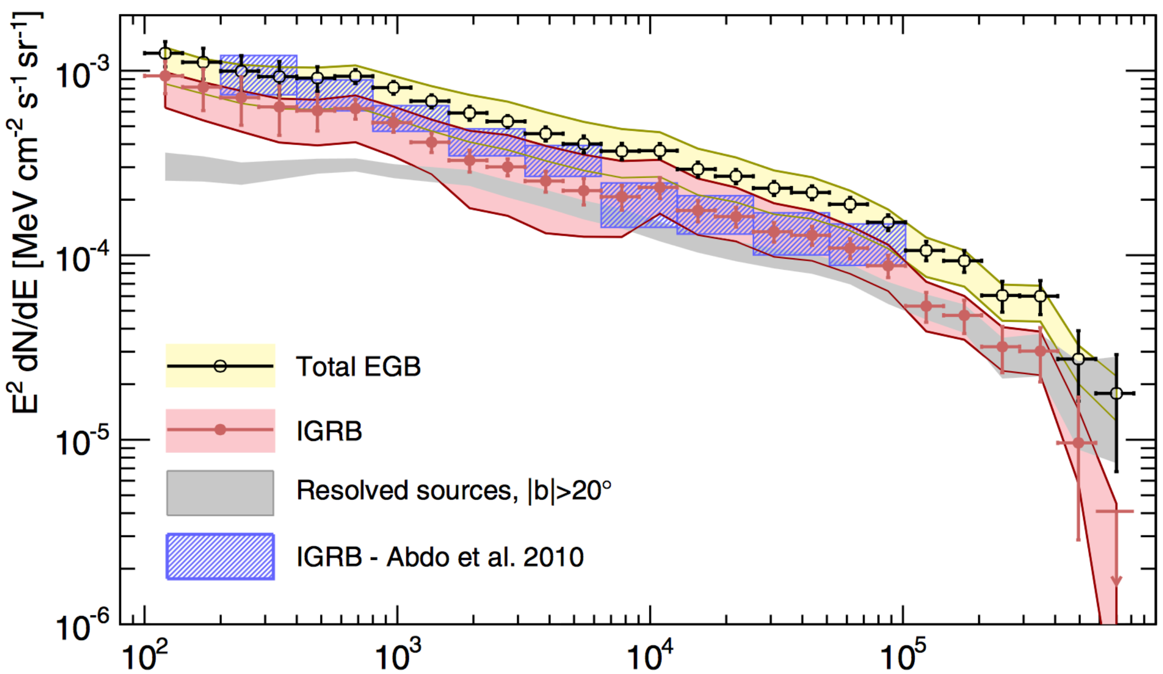




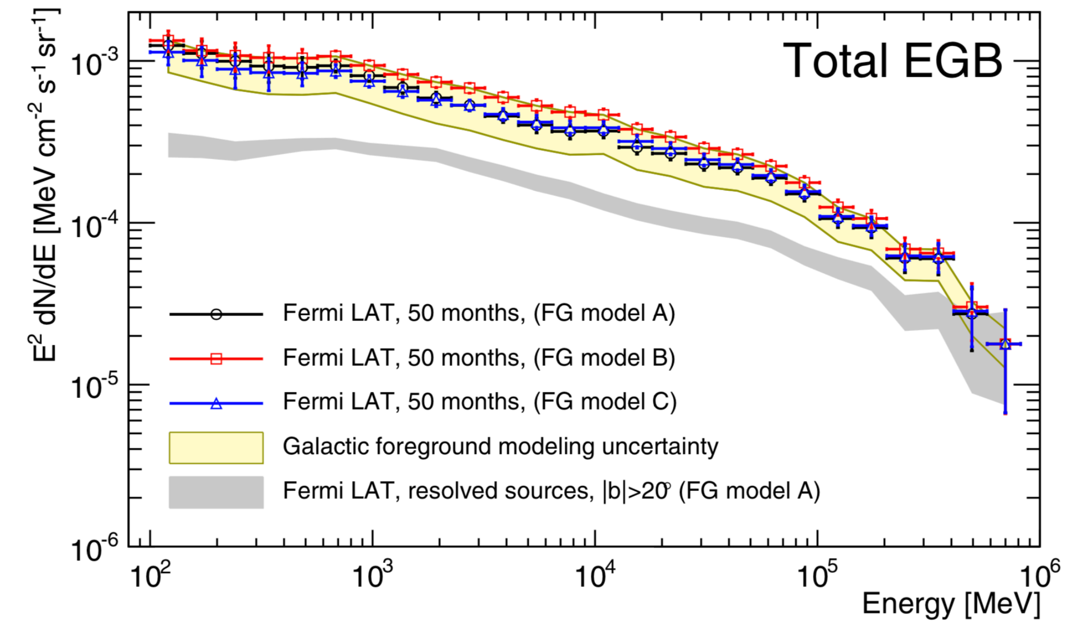
Better account of the uncertainties on the modelling of the galactic foreground
➡3 different estimates (models A, B and C) corresponding to three equally realistic theoretical modelings of the galactic foreground

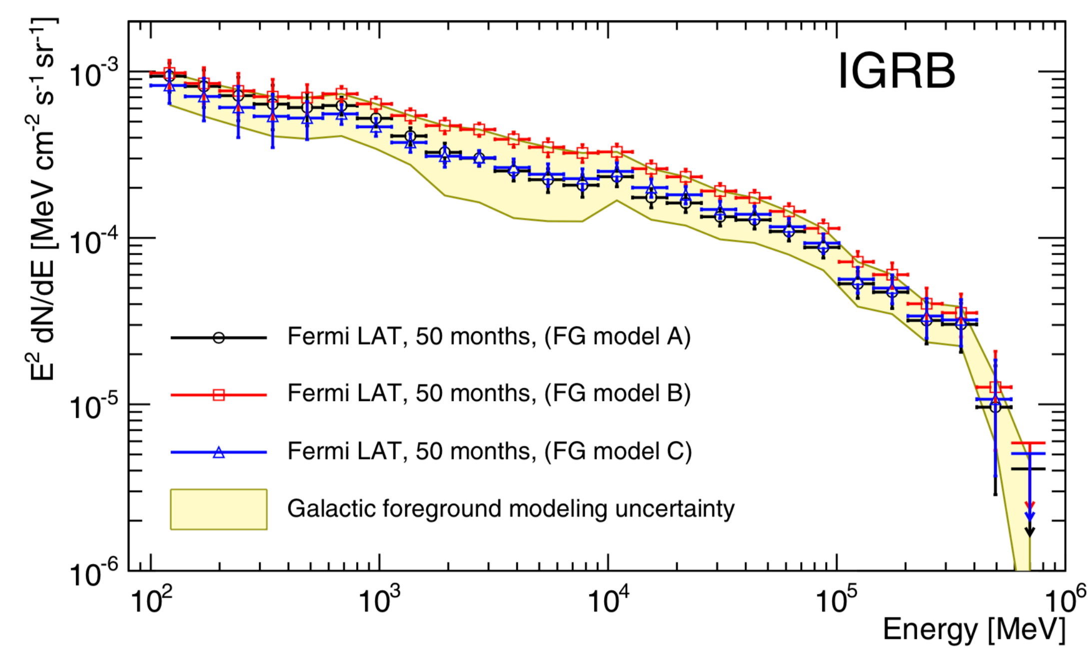
Recent Fermi measurements : extended energy range and galactic foreground intensity

Fermi recently released an updated estimate of the extragalactic γ-ray background for both the resolved and unresolved components
➡Larger statistics and extended energy range



(Ackermann et al. ApJ 2015)





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

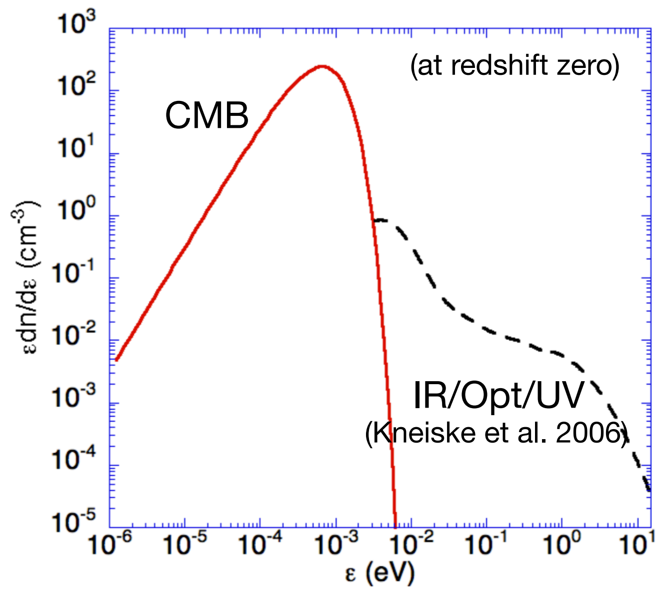
- resolved point sources (very large majority of Blazars)
- unresolved point sources (mostly blazars, misaligned AGNs and star forming galaxies (contribute also to the IGRB)
- truly diffuse processes (UHECR for sure, possibly DM)

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

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

UHECR are strongly suspected to be of extragalactic origin

Extragalactic very-high and ultra-high-energy cosmic-rays 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* $e^{+/-}$
- 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* ν

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

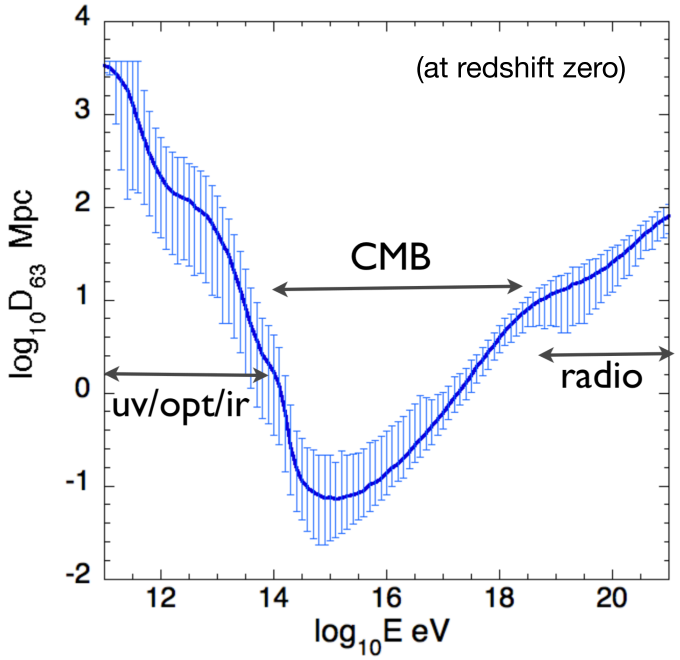
νs only suffer from adiabatic losses while propagating in the EGM

e^+/e^- and γ further cascade by interacting with the EBL :

$e+\gamma_{EBL} \rightarrow e'+\gamma$ ICS

$\gamma+\gamma_{EBL} \rightarrow e^+ + e^-$ pair production

➡ the universe is opaque to high-energy γs (pile-up at sub-TeV energies)

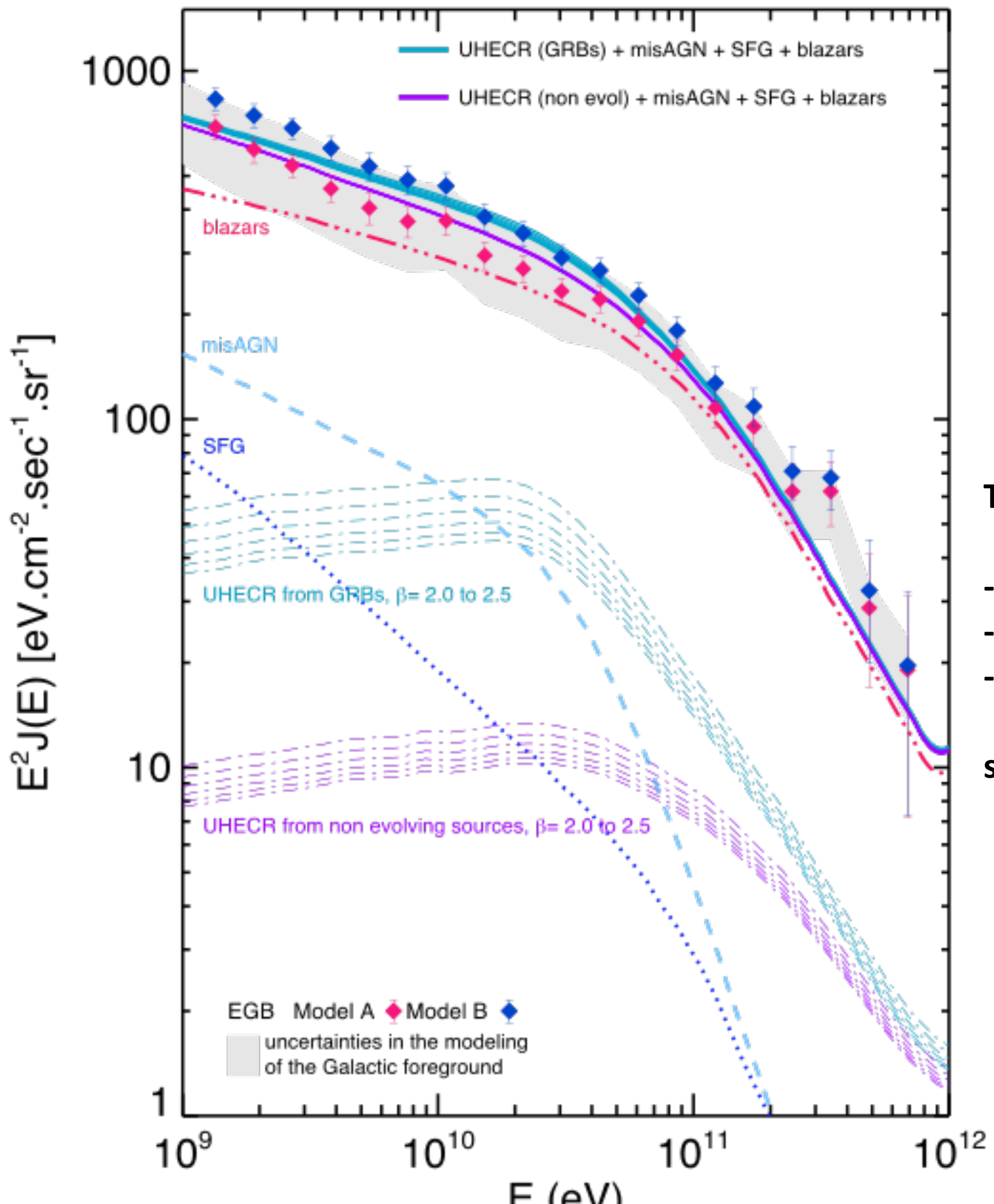


Diffuse UHECR ($E>10^{17}$ eV) flux

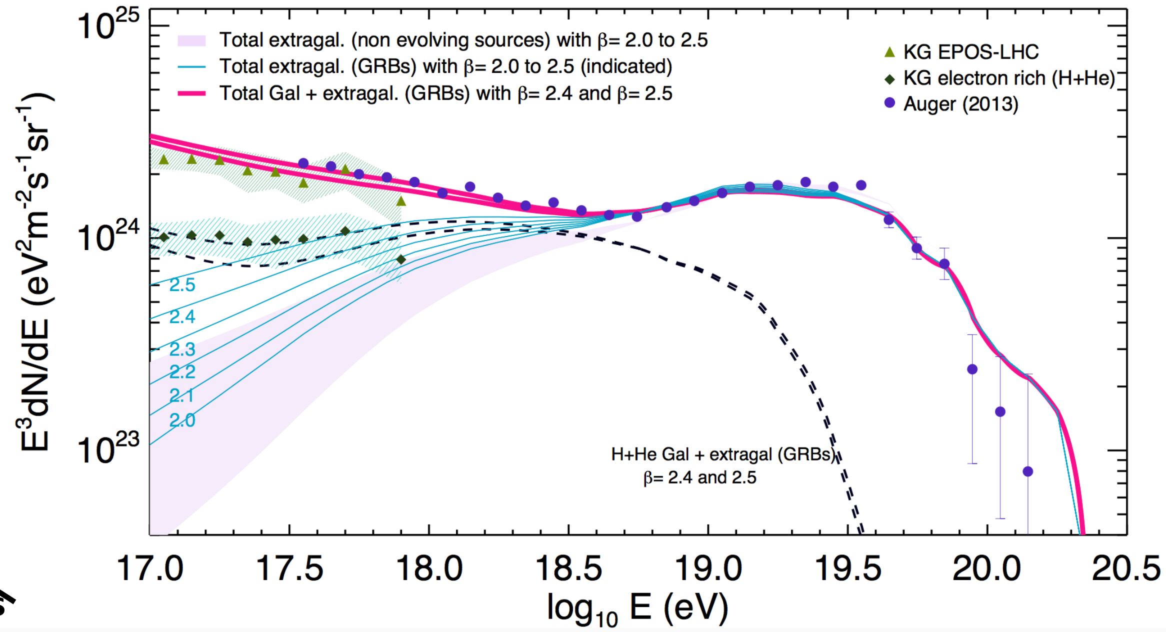
➡ diffuse ν flux in the PeV-EeV range

➡ diffuse γ-ray flux in the GeV-TeV range

Constraints on UHECR source models (I)



Globus et al., 2017, ApJL



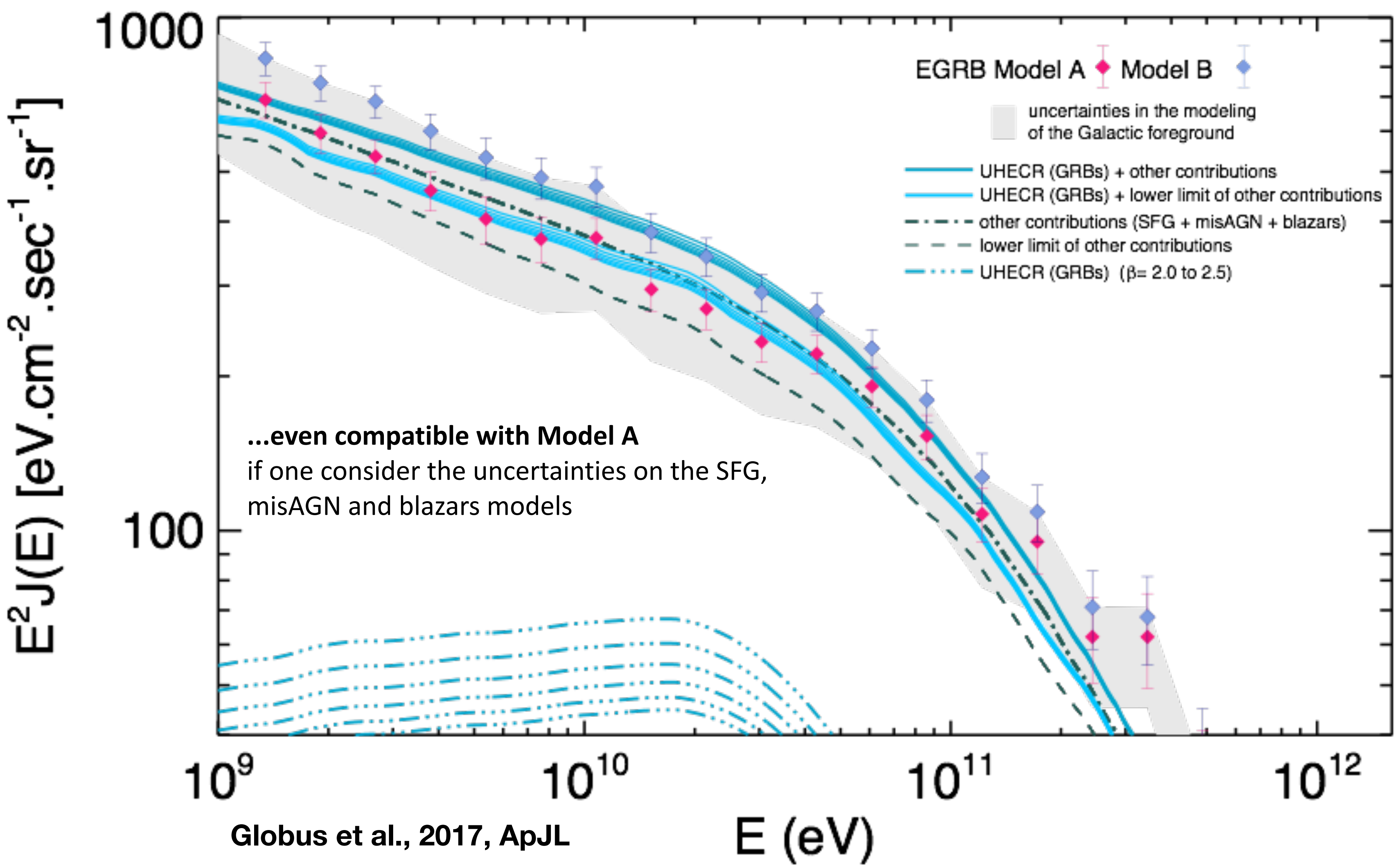
Total of all contributions

- **SFGs (**Ackermann et al. 2012, Fermi Collab.**)**
- **misaligned AGNs (**Inoue 2011**)**
- **blazars (**Ajello et al. 2015**)**

seems compatible with Model B…

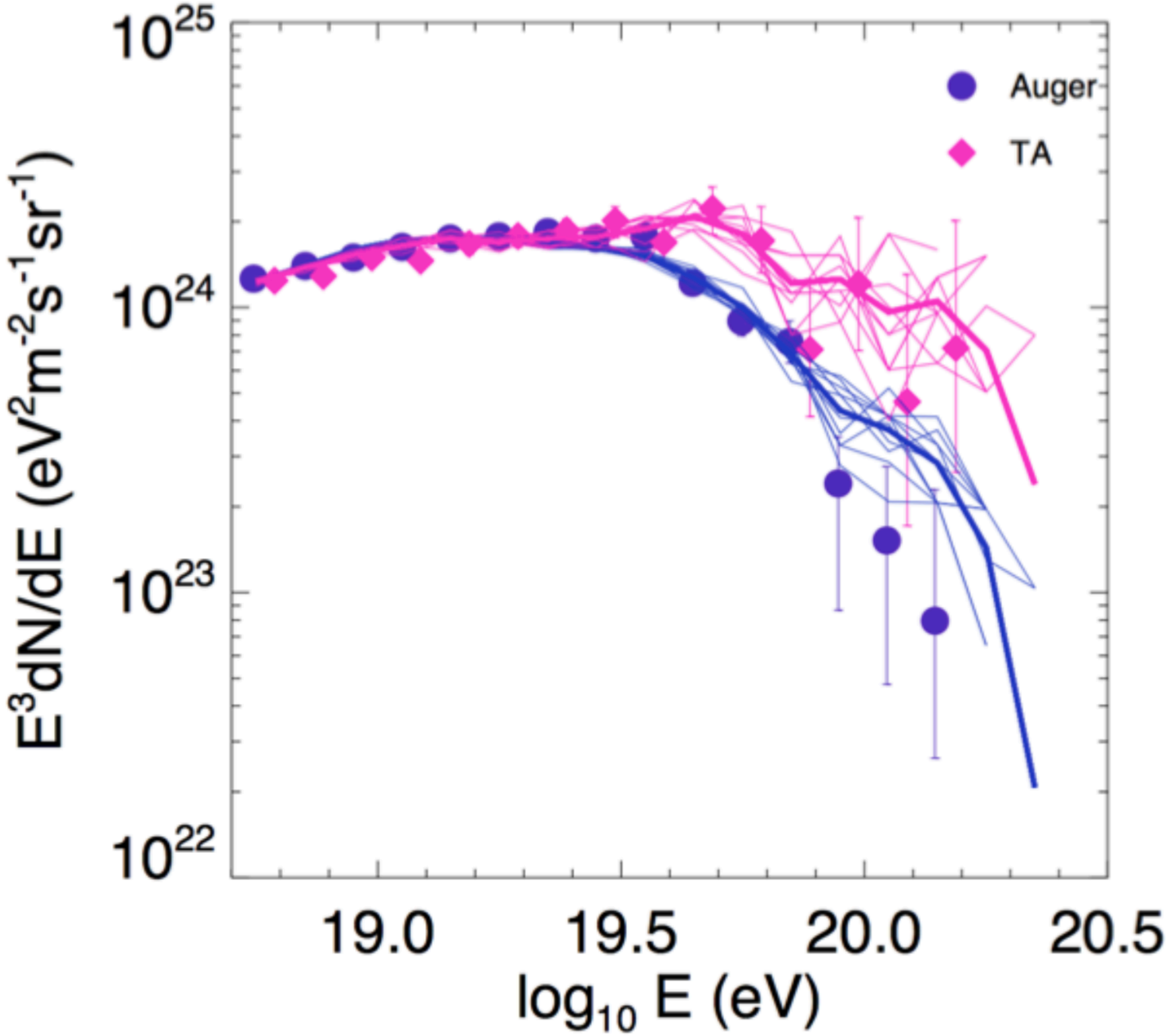
The uncertainty on the total EGRB is a major aspect of the discussion

Constraints on UHECR source models (II)



Globus et al., 2017, ApJL

The uncertainty on the amplitude of the different contributions is also a major aspect of the discussion


Auger
TA
10^{25}
10^{24}
10^{23}
10^{22}
$E^3dN/dE\ (eV^2m^{-2}s^{-1}sr^{-1})$
19.0
19.5
20.0
20.5
$\log_{10} E$ (eV)

Constraints on UHECR source models (III)

Globus et al., 2017, ApJL

Components and source evolution			Energy bands ($\beta = 2.0$) ①	②	③	④	⑤	⑥	Energy bands ($\beta = 2.5$) ①	②	③	④	⑤	⑥
	$F_{\rm UHECR}$ ($\times 10^{-10}\,{\rm cm^{-2}\,s^{-1}\,sr^{-1}}$)	GRB	170	120	44	32	2.5	2.7	260	190	67	48	3.4	3.7
		SFR	200	140	51	38	3.6	3.9	270	190	70	52	4.7	5.1
		non evol	42	30	11	8.6	1.1	1.3	58	41	15	11	1.4	1.6
% Model B	$F_{\rm UHECR}/F_{\rm EGB}$	GRB	4.6	6.2	8.5	12	9.6	9.4	7.0	9.5	13	17	13	13
		SFR	5.3	7.1	9.8	14	14	13	7.3	9.9	14	19	18	17
		non evol	1.1	1.6	2.2	3.1	4.2	4.4	1.6	2.1	2.9	4.1	5.3	5.4
	$\frac{F_{\rm (UHECR+PS+SFG+misAGN)}}{F_{\rm EGB}}$	GRB	**97**	**92**	**81**	**79**	**80**	**86**	**100**	**95**	**85**	**85**	**84**	**89**
		SFR	**98**	**93**	**82**	**81**	**85**	**90**	**100**	**96**	**86**	**86**	**89**	**94**
		non evol	**94**	**87**	**74**	**70**	**75**	**81**	**94**	**88**	**75**	**71**	**76**	**82**
% Model A	$F_{\rm UHECR}/F_{\rm EGB}$	GRB	5.7	7.7	11	15	12	11	8.7	12	16	22	16	15
		SFR	6.5	8.9	12	18	17	16	9.0	12	17	24	23	21
		non evol	1.4	1.9	2.8	4.0	5.3	5.3	1.9	2.6	3.7	5.4	6.7	6.6
	$\frac{F_{\rm (UHECR+PS+SFG+misAGN)}}{F_{\rm EGB}}$	GRB	**120**	**115**	**102**	**102**	**101**	**105**	**123**	**119**	**108**	**110**	**105**	**108**
		SFR	**121**	**116**	**104**	**105**	**107**	**110**	**123**	**120**	**108**	**112**	**112**	**114**
		non evol	**116**	**109**	**94**	**91**	**94**	**99**	**116**	**110**	**95**	**93**	**96**	**100**
% Mod A	$F_{\rm (UHECR+PS)}/F_{\rm EGB}$	GRB	89	87	77	81	93	97	92	91	82	88	97	101
		SFR	89	88	78	84	98	102	92	91	83	90	104	107
		non evol	89	87	77	81	93	97	92	91	82	88	97	101

(considering the mean values of the SFG+misAGN models)

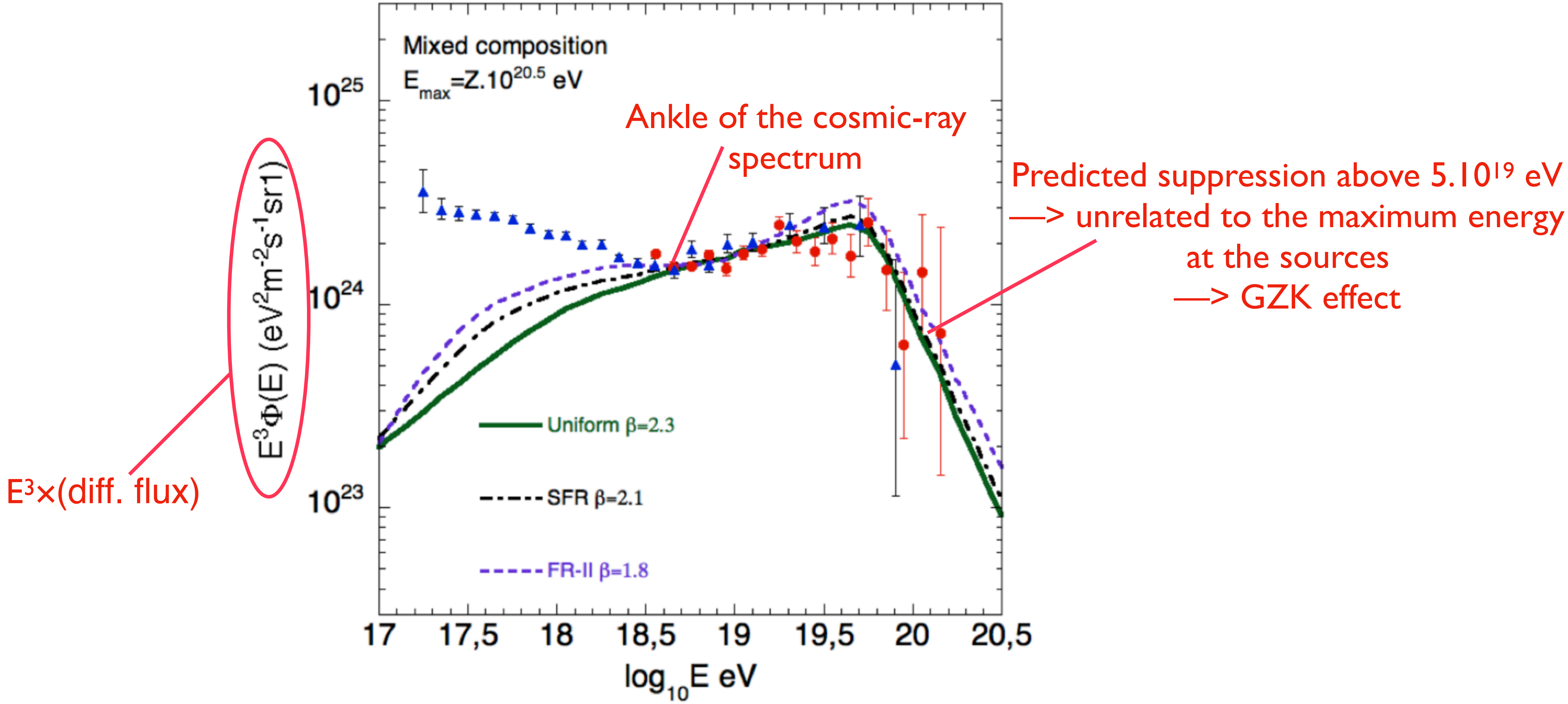
Cosmogenic γ-rays always represent a relatively small fraction of the EGRB even for GRB or SFR evolution and model A

Can be comfortably added to the other contribution in the case of model B

One example : mixed composition assumed at UHECR sources

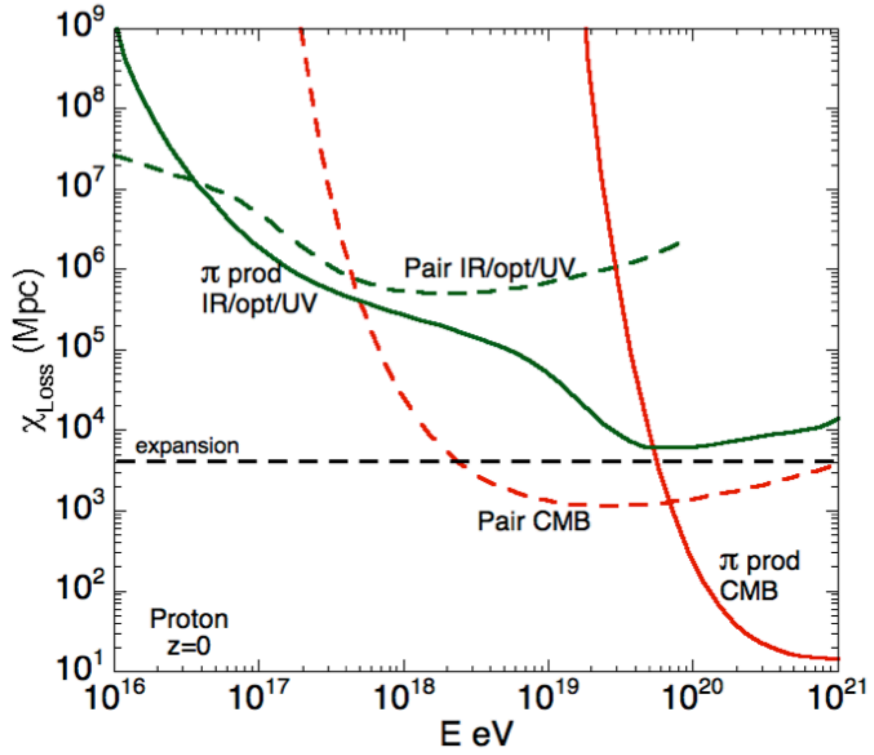
Assuming the maximum energy per nucleon is above 10^{20} eV (what most people thought until ~2010) mixed composition similar to that of low energy galactic cosmic-rays :

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



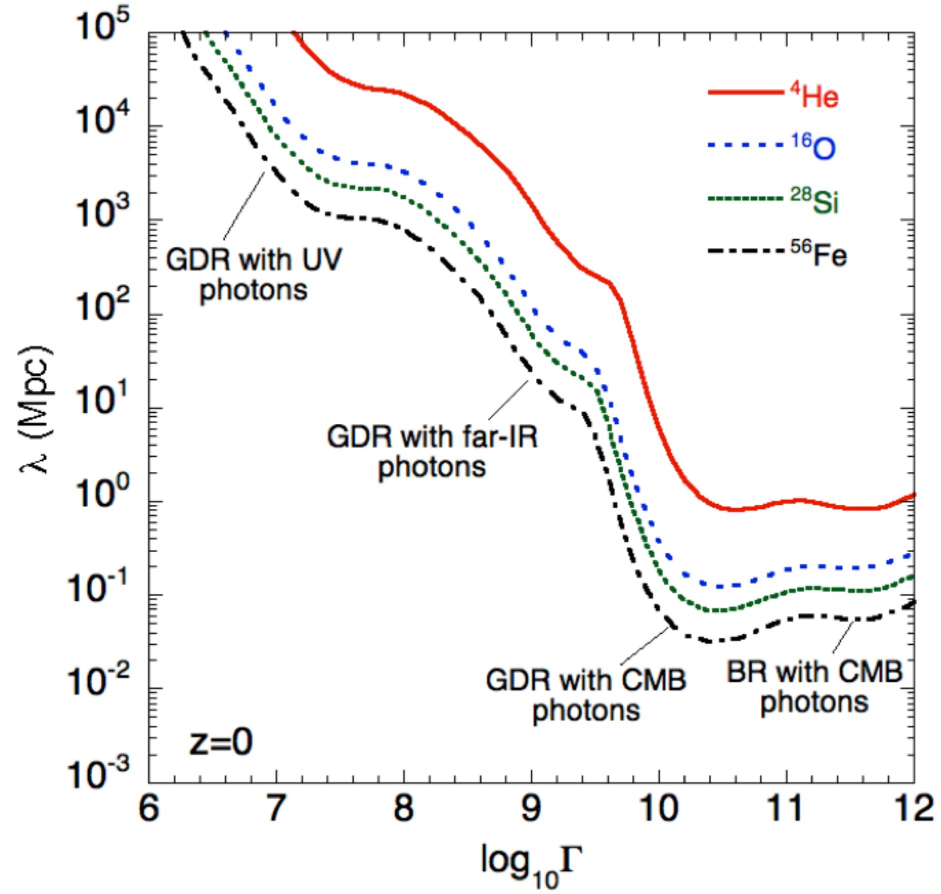
The UHECR spectrum can be well reproduced above the ankle
—> the ankle is interpreted in this case as a signature of the transition between Galactic and extragalactic cosmic-rays

The GZK effect for protons and nuclei



proton attenuation length as a function of the energy :
Strong decrease above ~5.10[19] eV due to pion production with CMB photons
—> Horizon of UHE proton gets reduced above this energy
—> GZK cut-off for protons

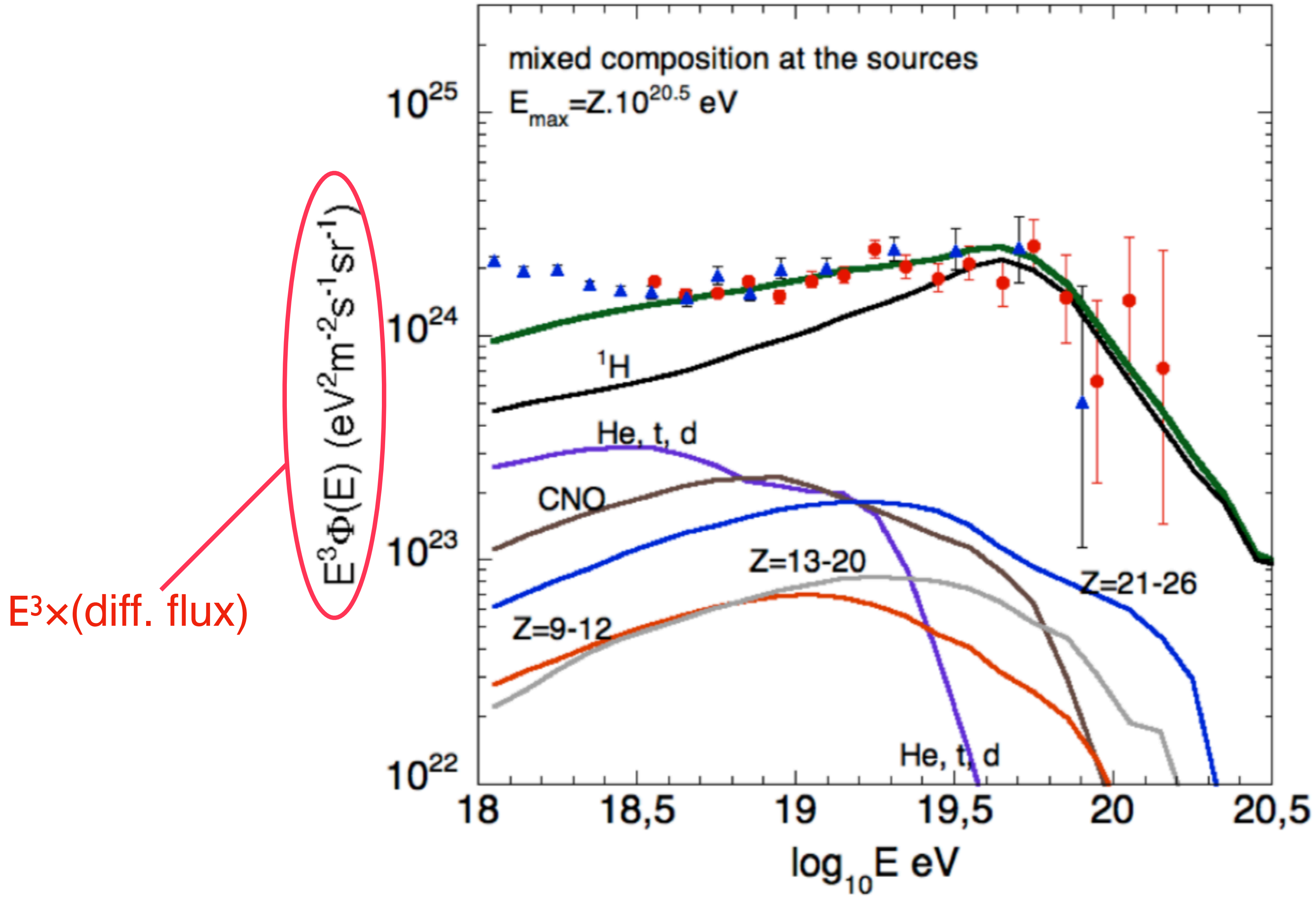
nuclei mean free path for giant dipole resonance (photodisintegration) as a function of the Lorentz factor :
Strong decrease above Γ~5.10[9] due to GDR interaction with CMB photons
—> Horizon of UHE nuclei get reduced an energy ~ A×5.10[18] eV
—> GZK cut-off for nuclei



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 :

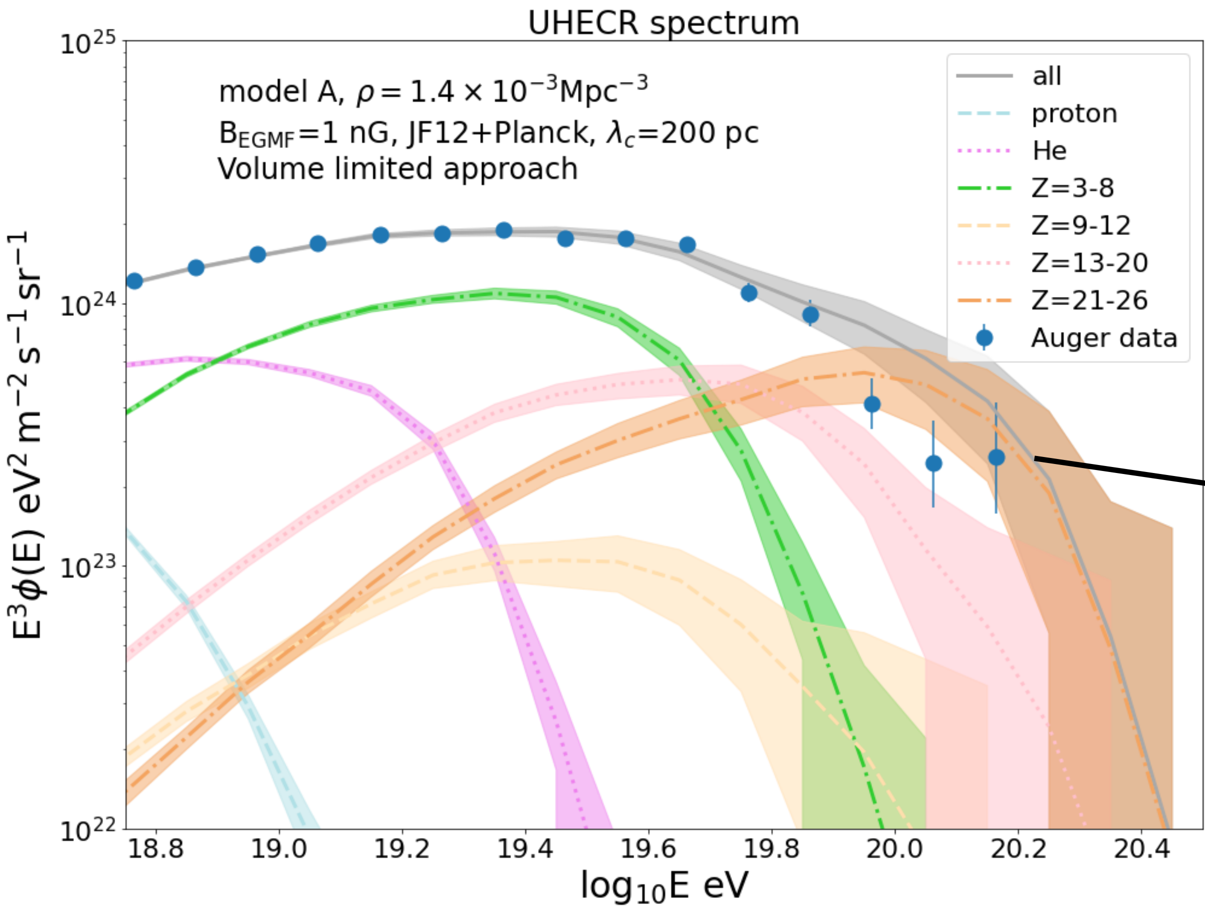
$N(E) \propto E^{-\beta}$, $E_{max}(Z)=Z\times E_{max}^{proton}$, $E_{max}^{proton}=10^{20.5}$ eV



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)

Modelling of UHECR anisotropies

source spectrum and composition



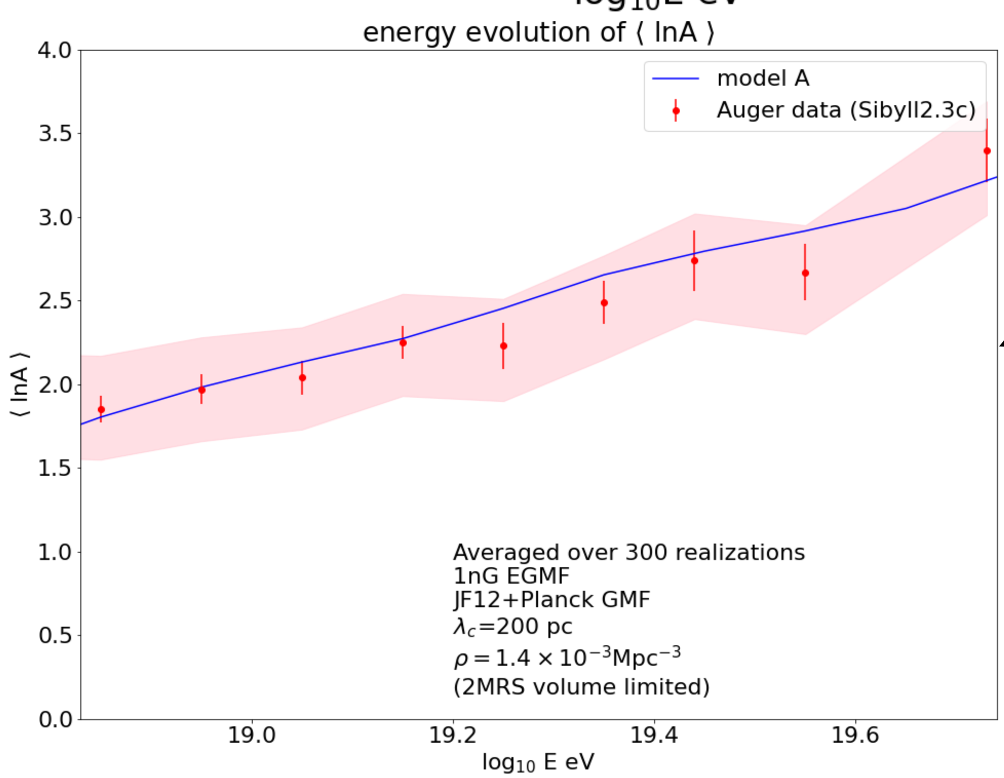
We fix the source spectrum and composition by finding a correct agreement with observed spectrum and composition

Low E_{max} scenario : $E_{max}(Z)=Z \times E_{max}^{proton}$; E_{max}^{proton} α 10^{18} eV

- hard source spectral index
- mixed composition with large contribution of He and CNO nuclei

(more details and more composition models in arXiv:2110.10761)

—> **in the framework of this class of models UHECR with rigidity larger than 10 EV are rare at all energies**



energy evolution of the mean logarithmic mass and its spread deduced from Auger Xmax measurements (adapted from Auger collab. ICRC 2019)