Ultra-High energy cosmic rays source models and the transition from Galactic to extragalactic cosmic-rays

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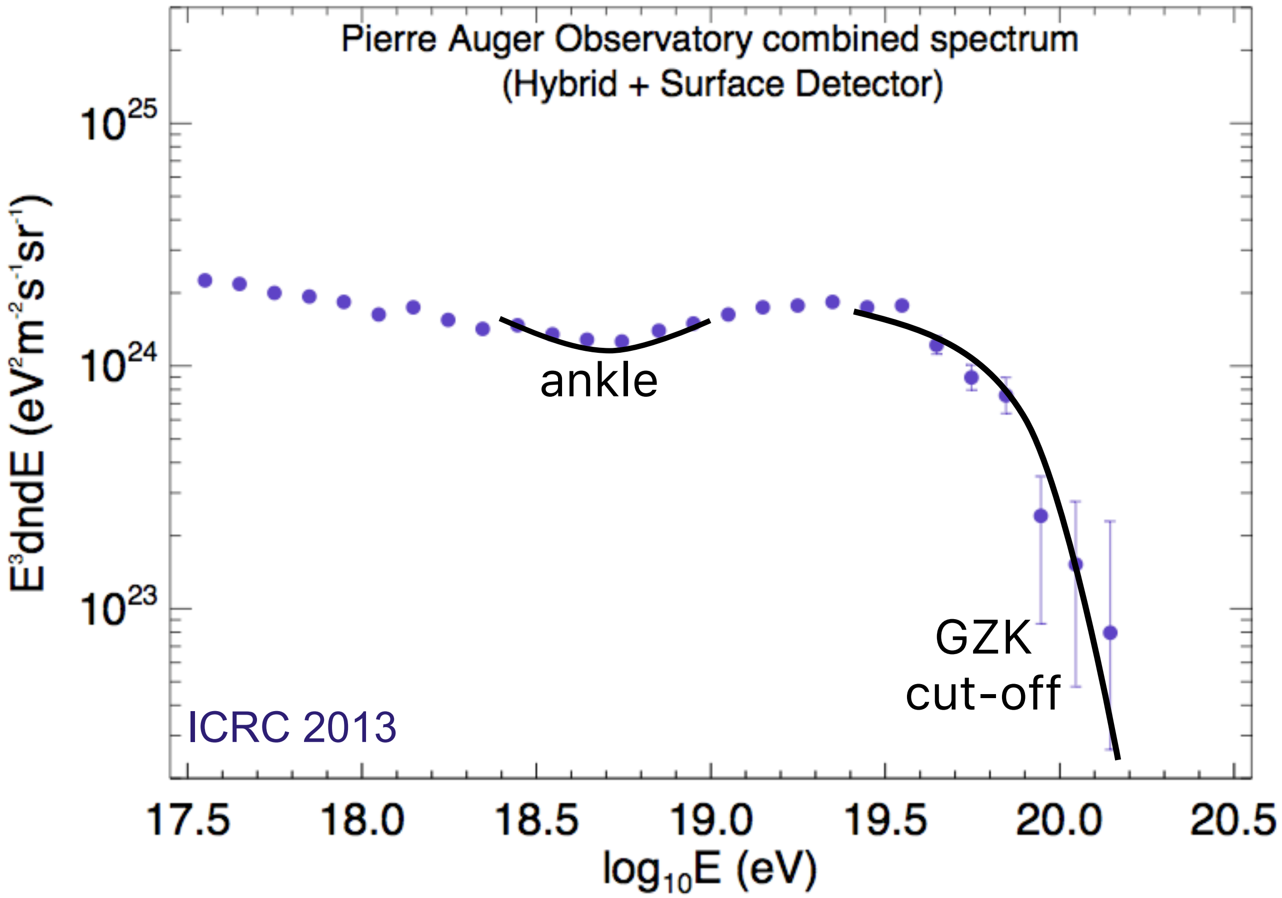
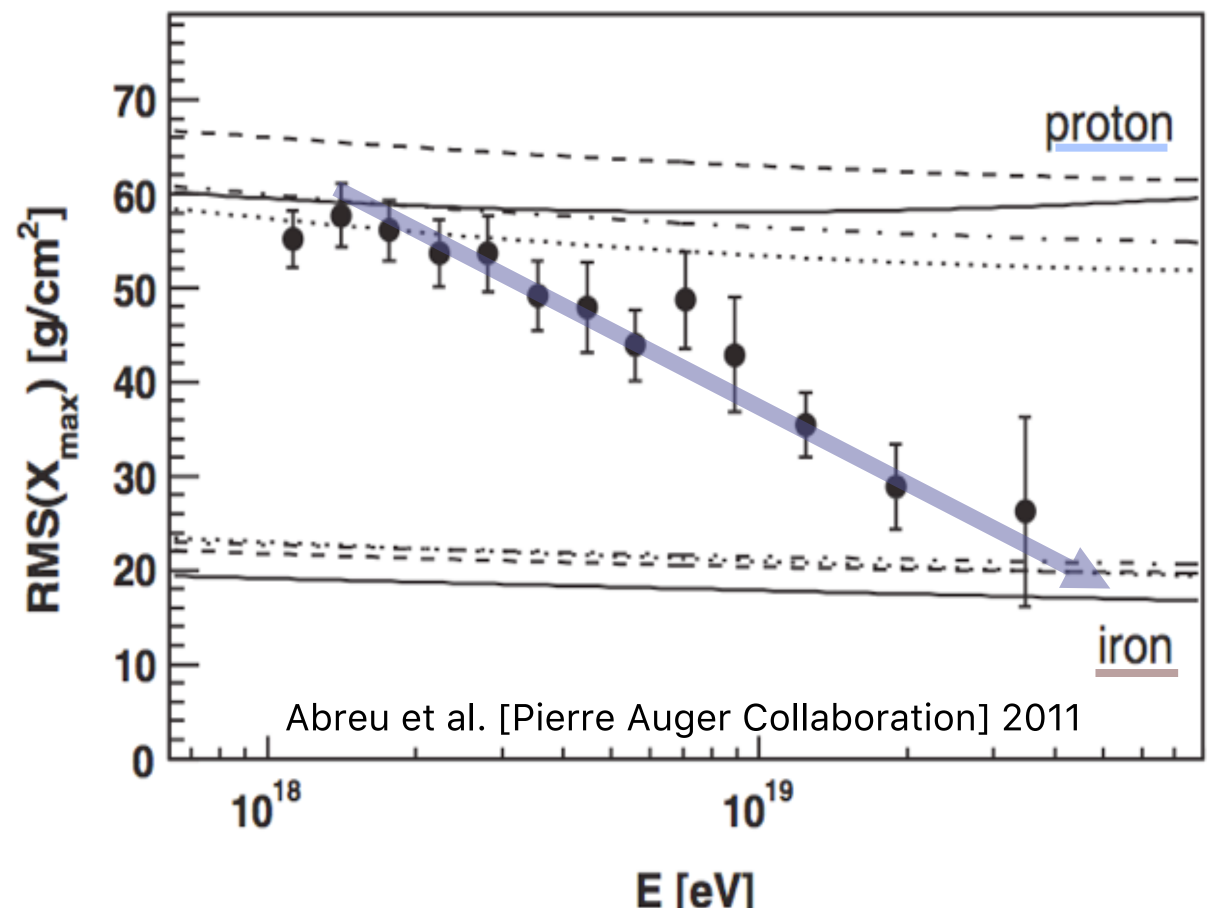
QCD at cosmic energies workshop, Chilkida (Greece), May 16th 2016

Situation at ultra-high energy : Recent results from the Pierre Auger Observatory

Energy spectrum



Mass spectrum



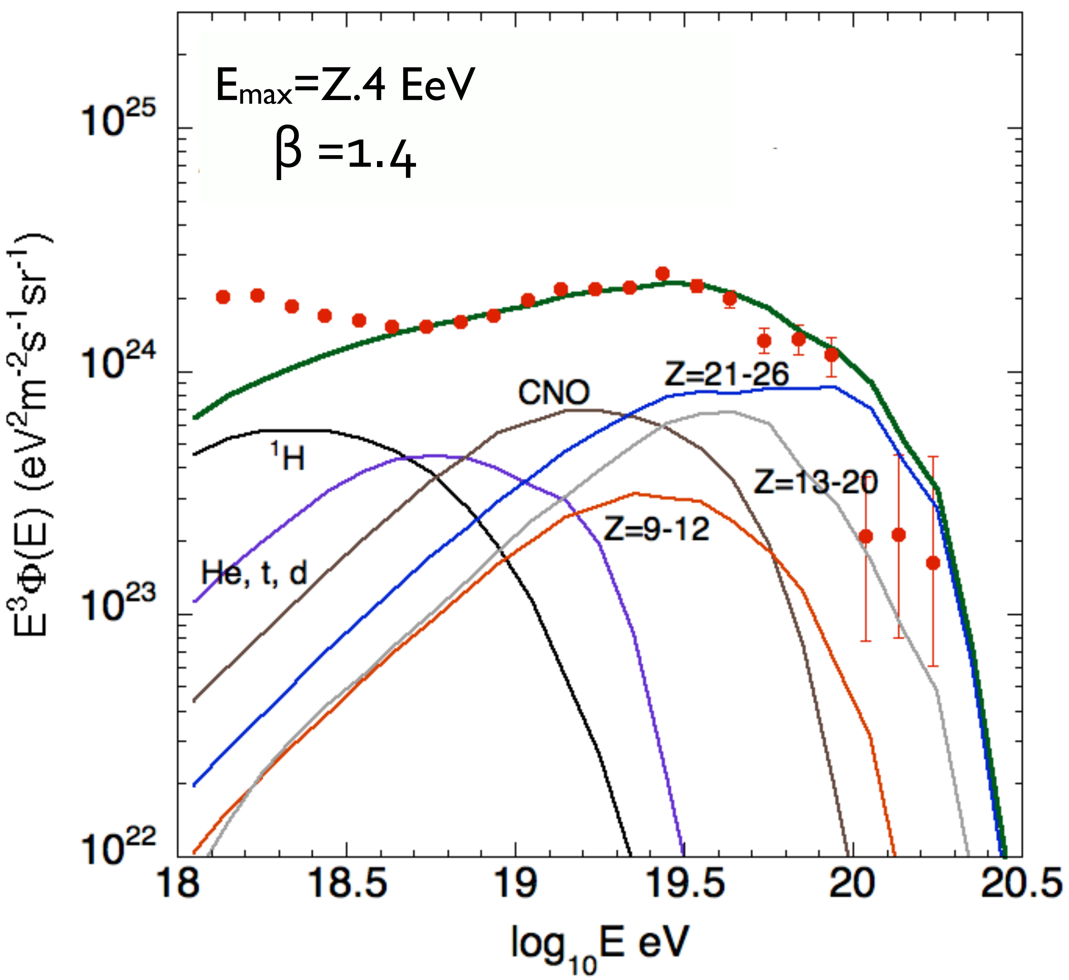
Evidence for two important features in UHE cosmic-rays spectrum :

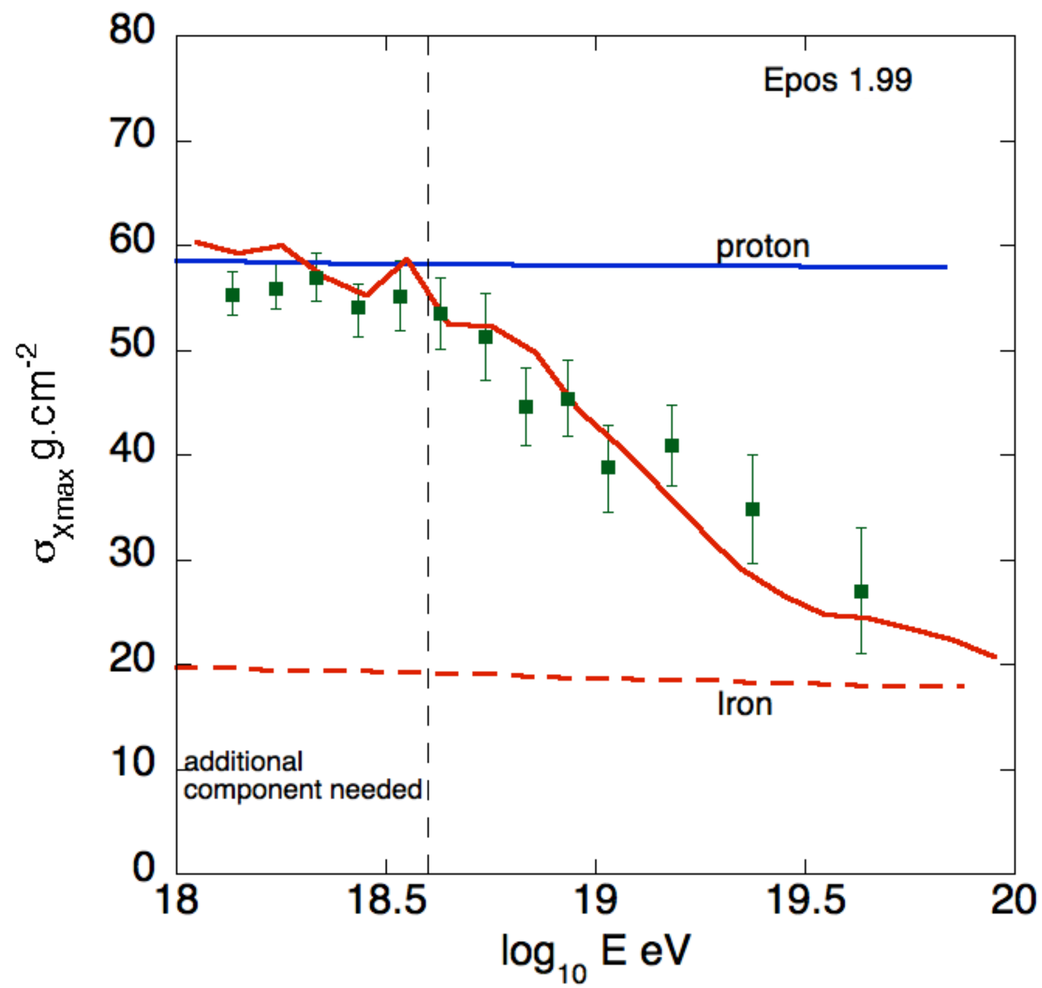
- The ankle
- Suppression of the flux above **3-4×10^{19}** eV

Transition from a light composition at the ankle to a heavier composition above 10^{19} eV

What sources for those extragalactic high energy nuclei ?

Situation at ultra-high energy : Recent results from the Pierre Auger Observatory





The spectrum and composition can be fitted with (over-)simple astrophysical models (same source spectrum for all the species, maximum energy proportional to Z, standard candle sources), good fits require

- A low value of the maximum energy of protons E_{max} ≈ 3-10 EeV
- A hard source spectral index (β ≈ 1-1.5)

Interesting but limited exercise :

With all the simplifying hypotheses used in these calculation the fit parameters are only "effective parameters" and their interpretation remain unclear (for instance how should we understand the required value of β ?) ==> more elaborated source models might provide better clues about what is going on

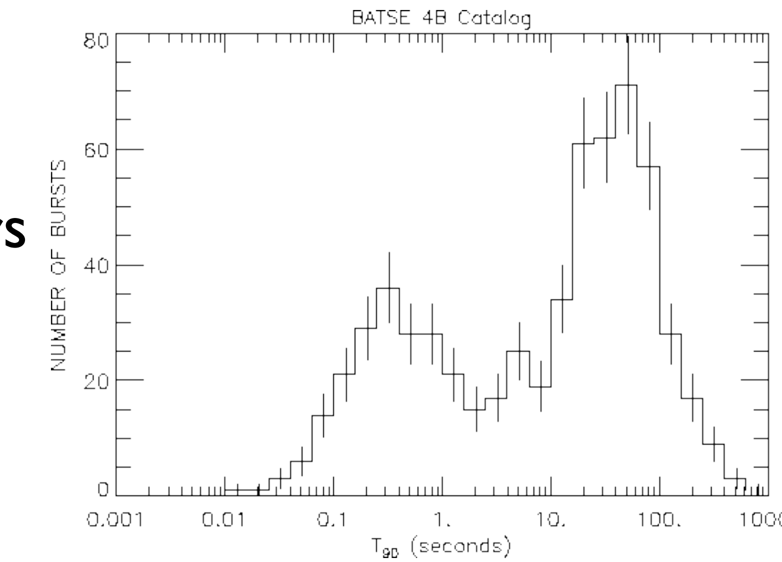
GRBs : among the most luminous high energy sources in the universe

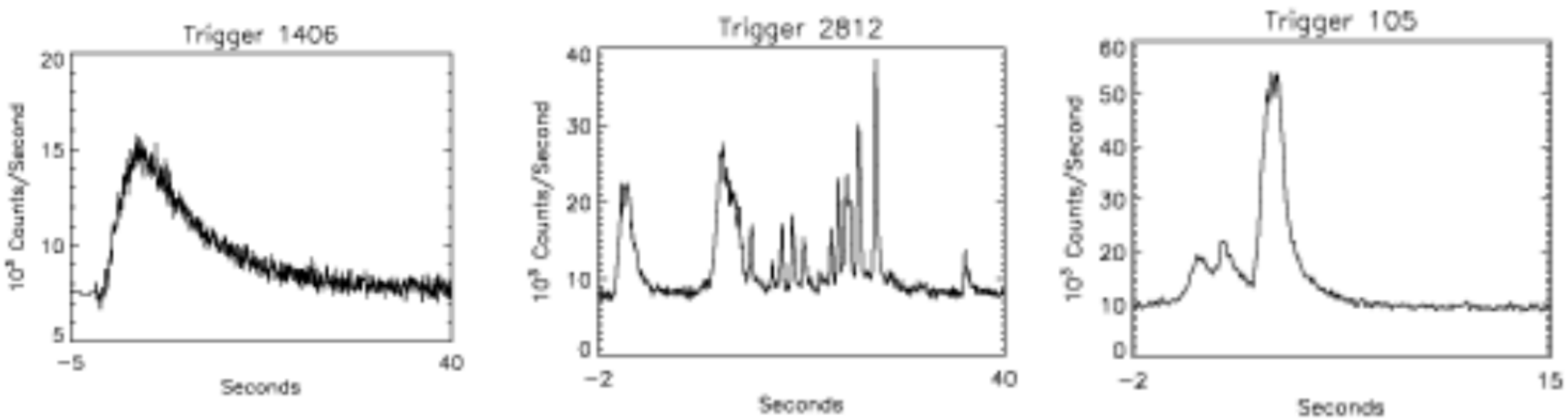
Gamma-ray bursts are very brief and very intense gamma-ray emission, reaching extraordinary luminosities/total radiated energies

★ discovered in the late sixties, first reported in the seventies

★ two separate populations : short bursts (<2s) and long bursts

★ long bursts thought to be related to collapse of very massive stars





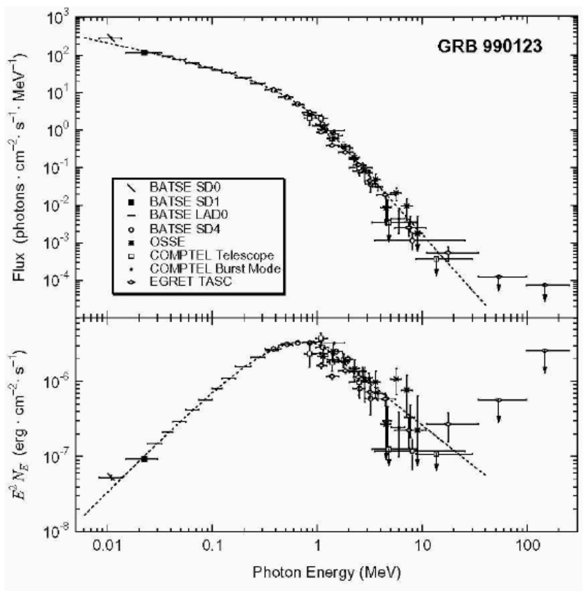
★ large variety of profiles (or light curves) but usually composed of one or several pulse (often fast rise and exponential decay shapes) with typical duration of the order of a few seconds

★ Typical spectral shape, broken power law (band function)

★ Peak energy typically varies from bursts to bursts (or even during a given burst) from ~10 keV to several MeV

★ Luminosities between ~10^{50} erg.s^{-1} and ~10^{54} erg.s if the emission is isotropic --> GRBs are though to have a beamed emission(more modest energy budget)

★ Rare events (~1 Gpc^{-3}.yr^{-1})

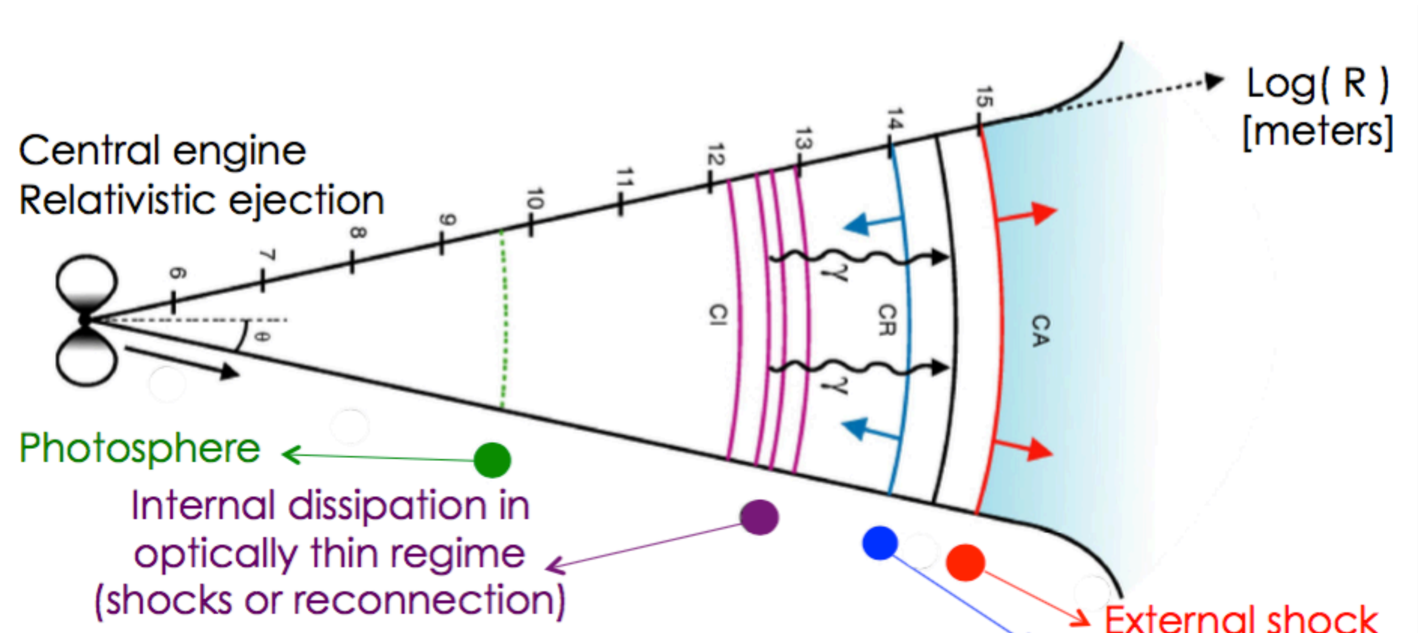


Internal shocks : a model for GRBs prompt emission

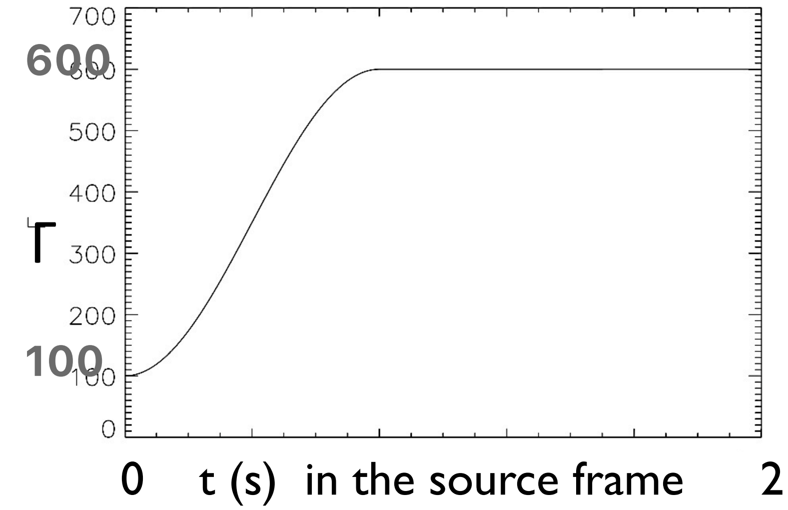
Considering the huge luminosity of GRBs, the emission region must be moving ultra-relativistically (Γ>100) to justify the observation of photons above a few 100 keV

Basic principle of the internal shock model :

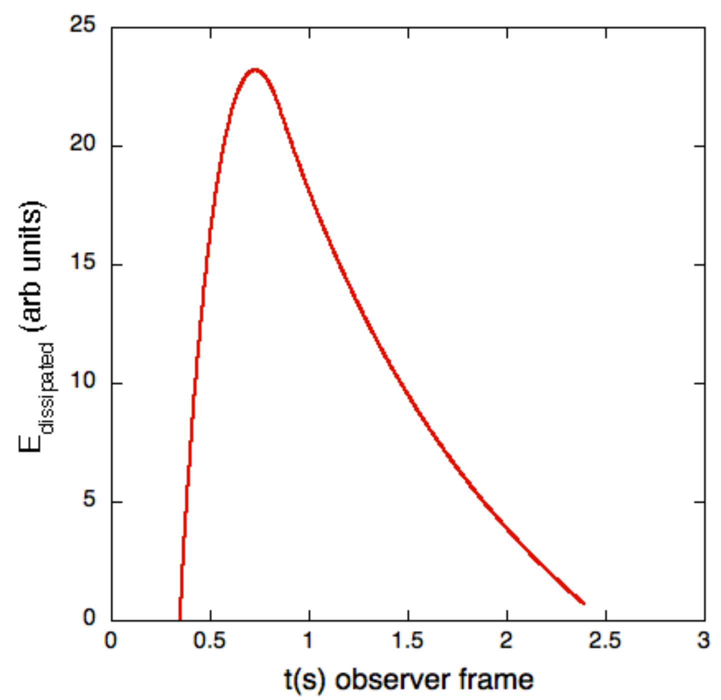
★ The central source (compact stellar remnant) ejects a ultra-relativistic wind
★ Variability of velocity within the ejected wind
★ Fastest parts of the wind will eventually catch the slower ones emitted before
 ---> a (or several) shock(s) forms ---> internal shock(s)



Courtesy of Frederic Daigne



Lorentz factor profile



★Energy dissipated throughout the shock propagation
---> particle acceleration (e^-, cosmic-rays), magnetic field amplification
★ Cooling of accelerated particles ---> emission of radiation
---> intense light pulse (duration in the observer frame related to the variability time scale in the source frame)

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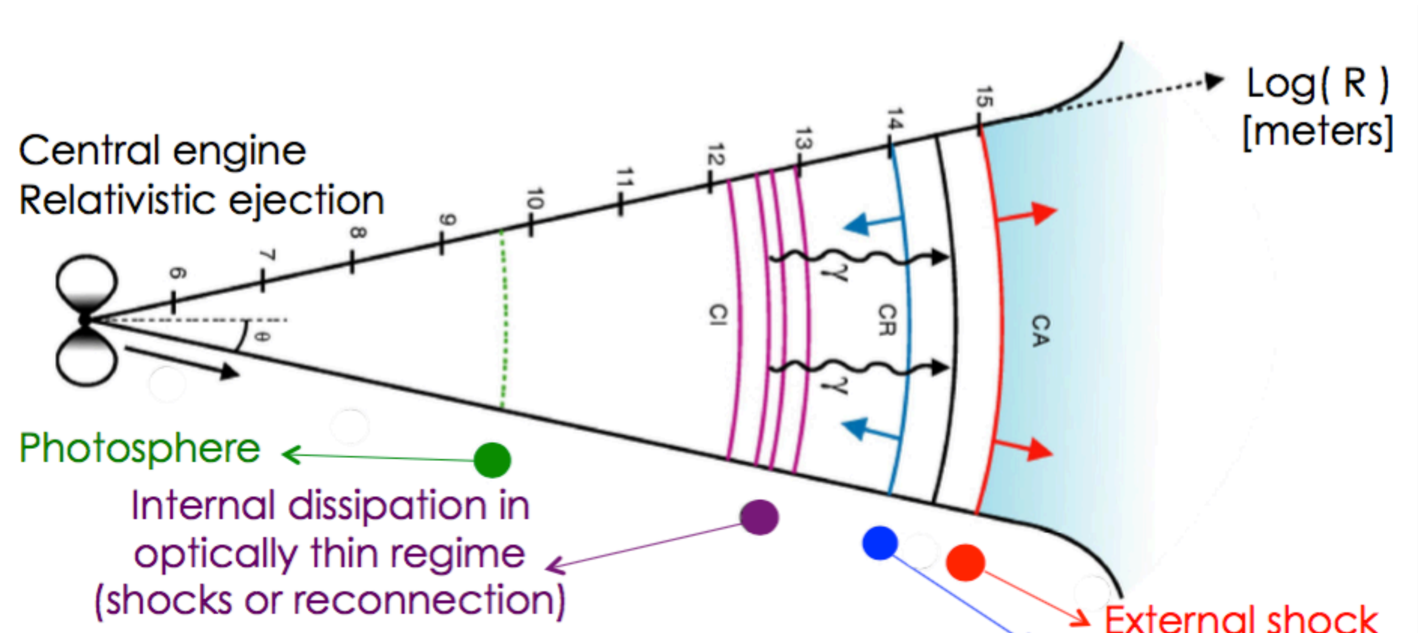

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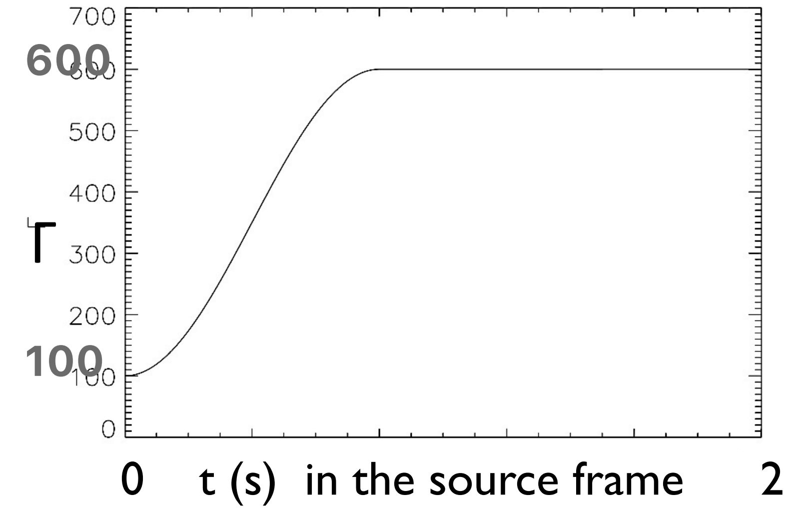

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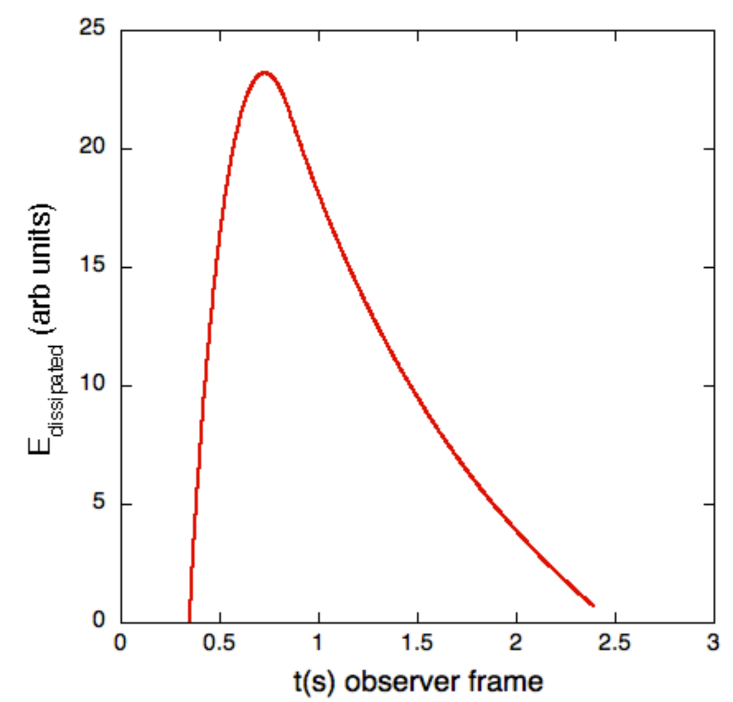


★The internal shock model is among the most popular models to explain GRBs prompt emission but is not established
★ Strength : light curve profiles, spectral evolution, transition between the prompt emission and the afterglow
★ Weakness : low energy spectral shape, efficiency (?)

Acceleration of UHECR at GRBs internal shocks

- Pioneer work by Waxman (1995) ➔ Internal shocks fulfill Hillas conditions & gamma-rays luminosity ≈ CR luminosity above 10^{18} eV

- Contributions by many other authors/groups : Waxman and collaborators, Dermer and collaborators, Giallis & Pelletier (2003-2005), …

- Acceleration of nuclei : Wang et. al (2008), Murase et. al (2008), Metzger et. al (2011) (➔ nucleosynthesis)

- Survival of nuclei in jets : Horiuchi et. al (2012)

- Galactic GRBs and cosmic-rays : Atoyan & Dermer (2006) (➔ GCR), Calvez et al. (2010) (➔ UHECR)

- Multimessenger consequences of UHECR acceleration :
  - Photons : Asano & Inoue (2007), Razzaque et al. (2010), Asano et. al (2009), Murase et. al, (2012)
  - Neutrinos : Waxman and Bahcall (1997), Guetta et al. (2004), Ahlers et al (2009-2012), Murase and collaborators (2008-2014)

- Other possible contribution of GRBs to UHECRs :
  - external shocks : Vietri (1995), see however Gallant and Achterberg (1999)
  - canonball model : series of papers by Dar, De Rujula and Plaga

Our calculation : modeling of UHECR acceleration at GRBs internal shocks

• Modeling of the internal shock according to Daigne & Mochkovitch 1998 ("solid layers" collision model)
⇒give us an estimate of the physical quantities at the internal shocks based on a few free Parameters

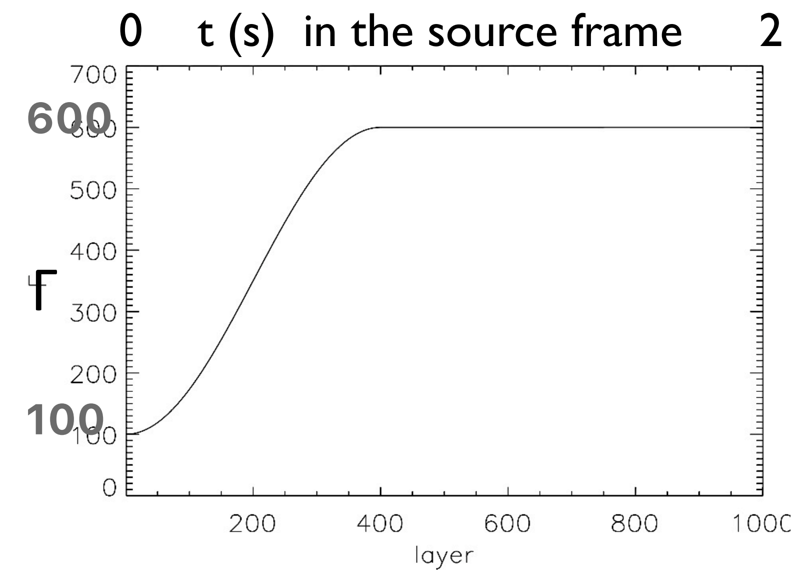
• Calculation of the prompt emission SED according to Daigne, Bosnjak & Dubus 2009
⇒SED are are used as soft photons target for the accelerated cosmic-rays

• Midly relativistic acceleration of cosmic-rays using the numerical approach of Niemiec & Ostrowski 2004-2006
⇒shock parameters are given by the internal shock model

• Full calculation including energy losses (photo-hadronic and hadron-hadron)
⇒cosmic-ray and neutrino output for a GRB of a given luminosity

• Convolution by a GRB luminosity function and cosmological evolution (Piran & Wanderman 2010)
⇒diffuse UHECR and neutrino fluxes

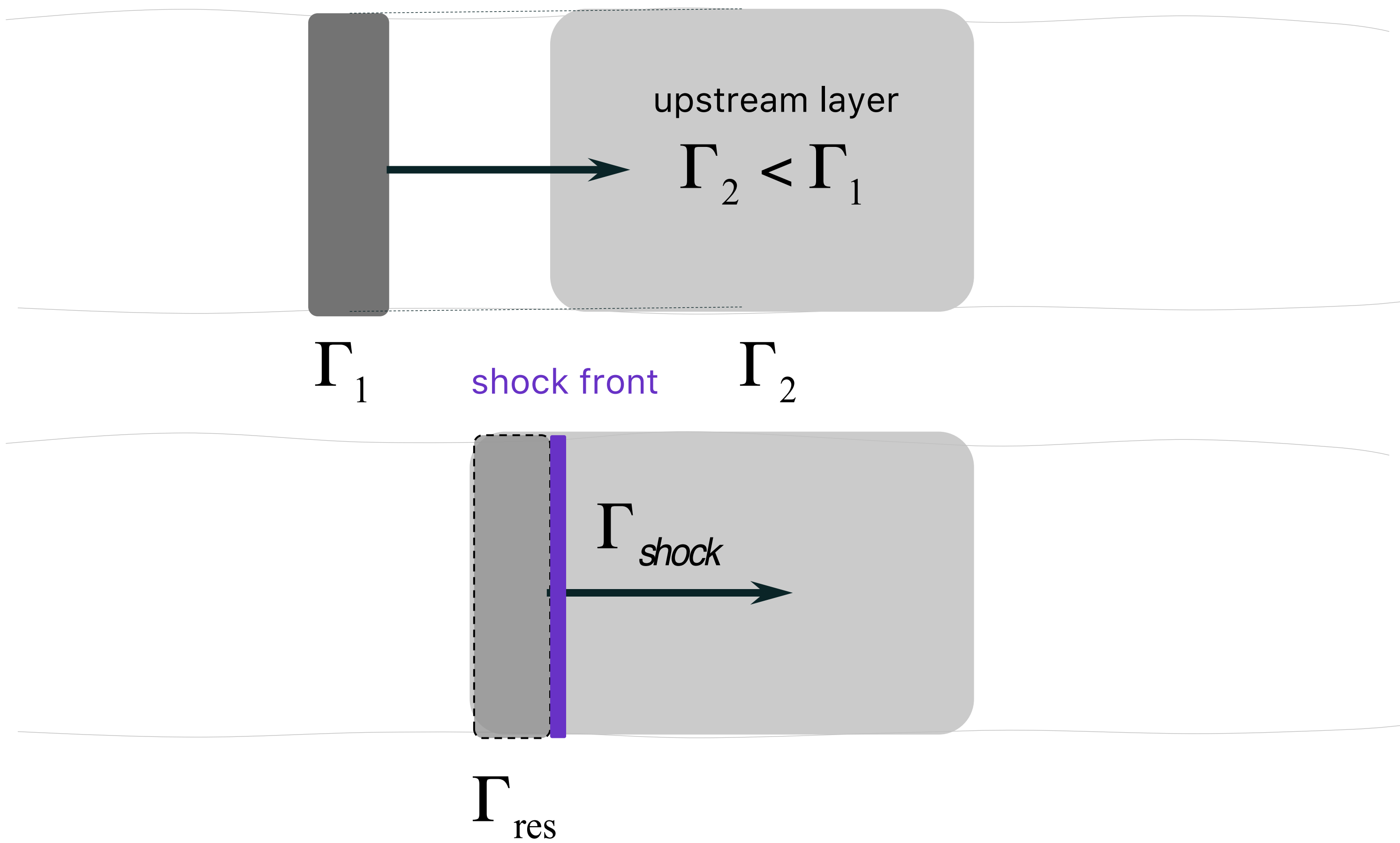
Modeling of an internal shock



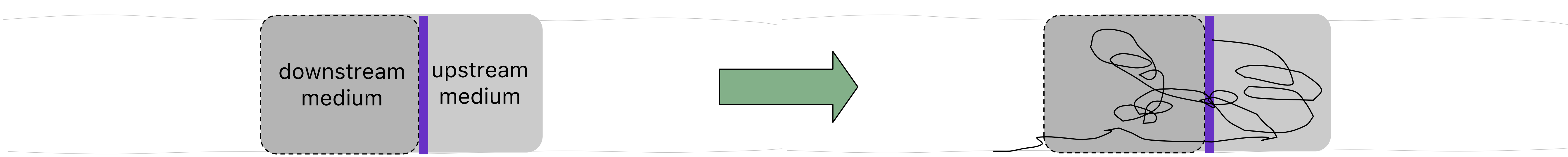
Lorentz factor profile

We follow Daigne & Mochkovitch 1998 : a relativistic wind with a varying Lorentz factor is decomposed in discretized solid layers

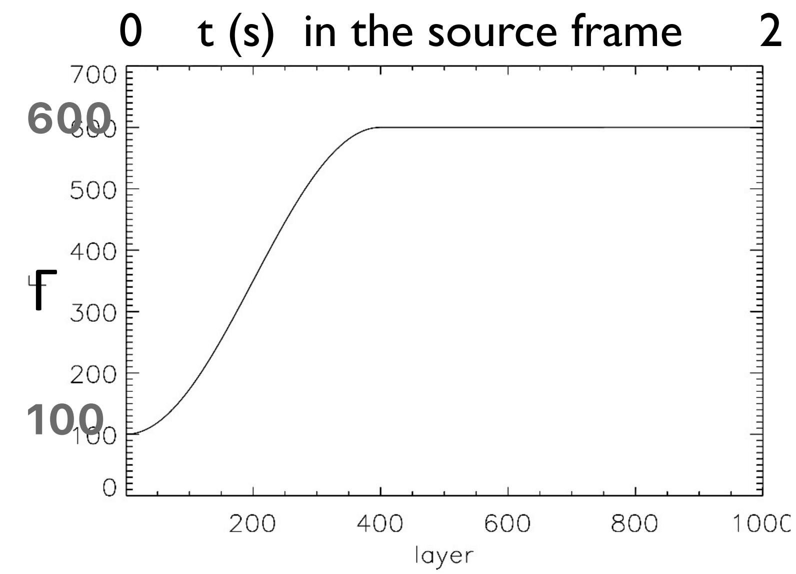
$\Rightarrow$ Layers collisions mimic the propagation of a shock in the wind



Fermi acceleration



Modeling of the internal shock



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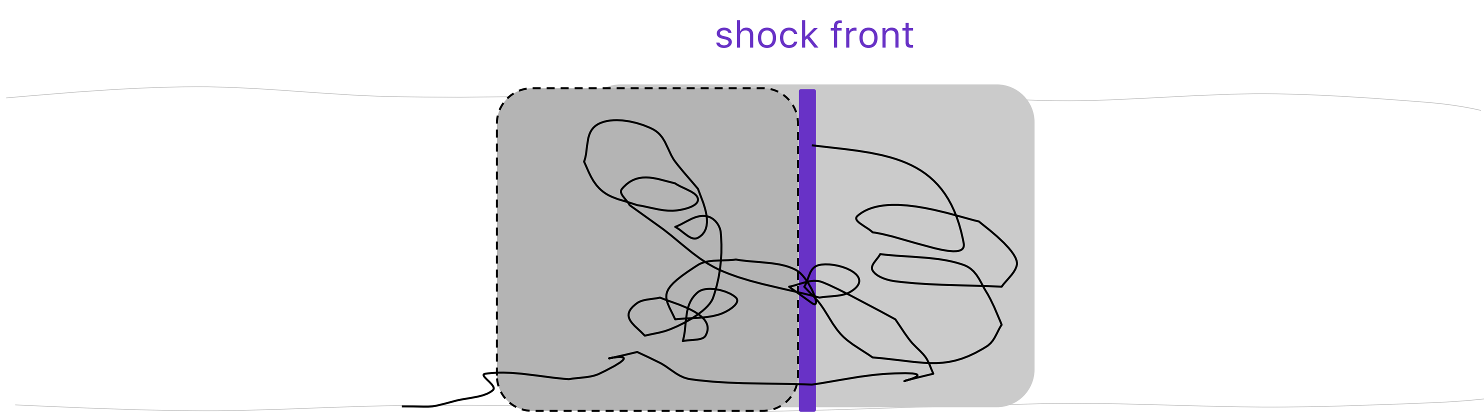


...needed for acceleration

B_{rms} (downstream), Γ_{shock}, Γ_{res}

wind free parameters :

wind luminosity L_{wind}, wind duration t_{wind} (in the following we use t_{wind}=2s and $L_{wind}=10^{51}$-10^{55} erg.s^{-1} isotropic)

...needed for energy losses

$r_{shock}(t)$

$$\frac{1}{E}\frac{dE}{dt} = t_{\rm exp}^{-1} = \frac{\Gamma_{res} c}{r_{shock}}$$

matter density, photon background...

shock free parameters :

ε_e, ε_B, ε_{CR} equipartition factors for the released energy

Three energy partition models

- Model A : equipartition, ε_e,= ε_B= ε_{CR}=0.3333 ➔ **gamma efficiency ~ 5% ➔ $L\gamma \sim L_{wind}/20$**

We use L_{wind} between 10^{51} and 10^{55} erg.s^{-1} ➔ $L\gamma$ between 5.10^{49} and 5.10^{53} erg.s^{-1}

- Models B and C : much lower fraction of the energy goes to electrons ➔ lower efficiency in gamma-ray ➔ larger wind luminosity required to produce the same gamma-ray emission as Model A

L_{wind} between 3.10^{53} and 3.10^{55} erg.s^{-1} ➔ $L\gamma$ between 5.10^{49} and 5.10^{53} erg.s^{-1}➔ gamma efficiency between ~0.01% and 1%

model B

Assumptions

ε_e << 1

ε_B ~ 0.1

ε_{CR} ~ 0.9

model C

Assumptions

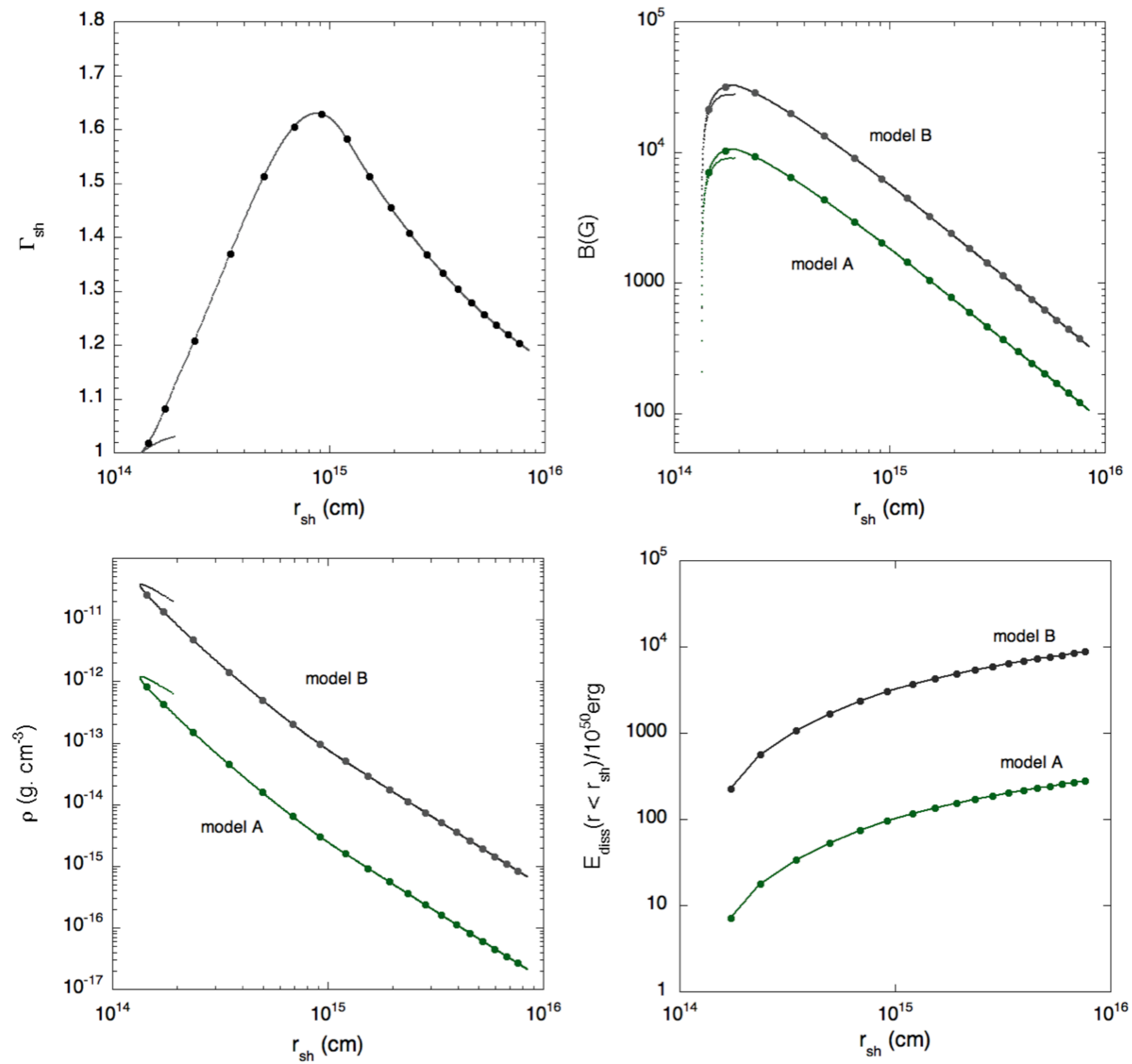
ε_e << 1

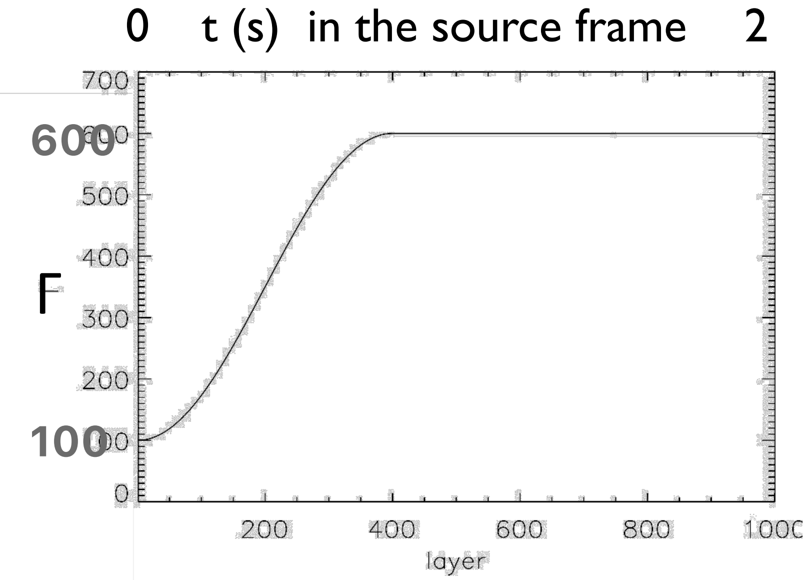
ε_B ~ 0.33

ε_{CR} ~ 0.66

L_{wind}	$L_{wind, eq}$	L_{gamma}
3.10^{53}	10^{51}	5.10^{49}
10^{54}	10^{52}	5.10^{50}
3.10^{54}	10^{53}	5.10^{51}
10^{55}	10^{54}	5.10^{52}
3.10^{55}	10^{55}	5.10^{53}

Single synthetic pulse





Lorentz factor profile

Example:

t_{wind}=2s

Lγ=5.10^{51} erg.s^{-1}

L_{wind}^{eq}=10^{53} erg.s^{-1} for model A

L_{wind}=3.10^{54} erg.s^{-1} for model B

18 “snapshots”

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Numerical method for CR acceleration at relativistic shock

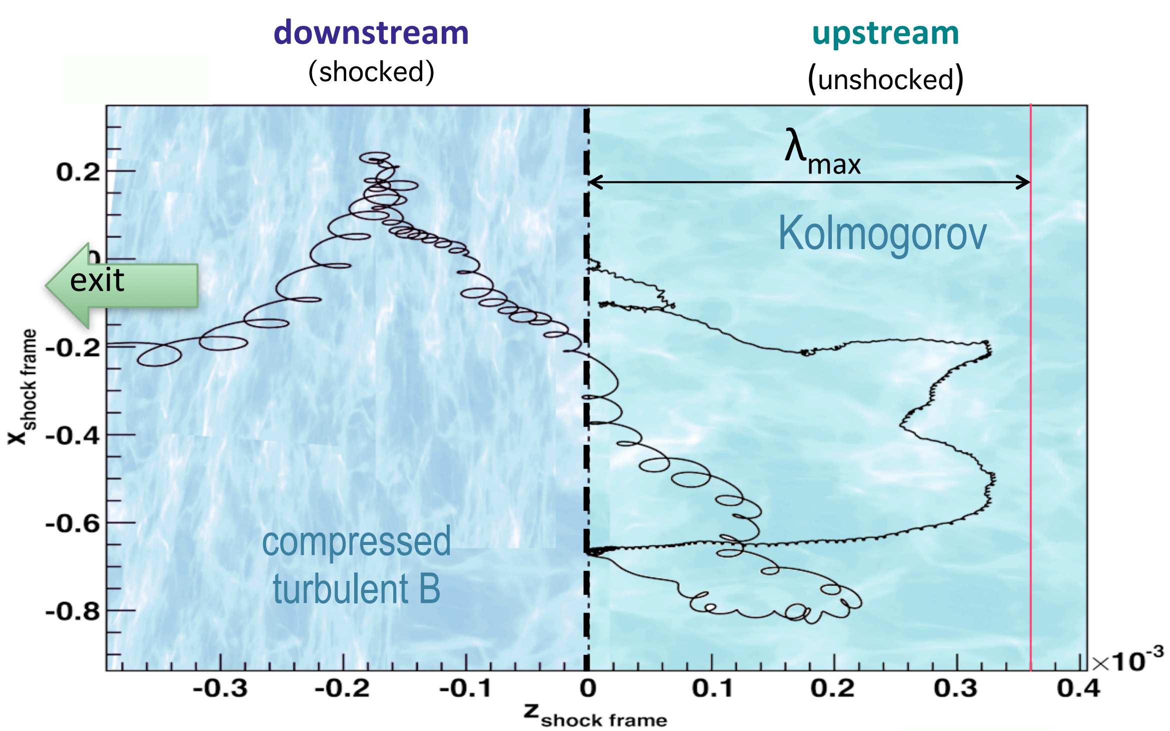
We follow Niemiec & Ostrowski 2004-2006 method to simulate Fermi cycles at relativistic shocks :
Full calculation of particles trajectories and shock crossing ➔ Fermi cycles

- Needs assumption on the magnetic field configuration upstream
- jump conditions given by Synge 1957 for relativistic shocks

➔ **B** compressed and amplified in the direction perpendicular to the shock normal

- We assume a Kolmogorov-type turbulence uptream in what follows

- Needs assumptions on free boundaries :



Particle trajectory (3D) in the shock frame
9 cycles before escaping downstream. Energy gain~ 70.

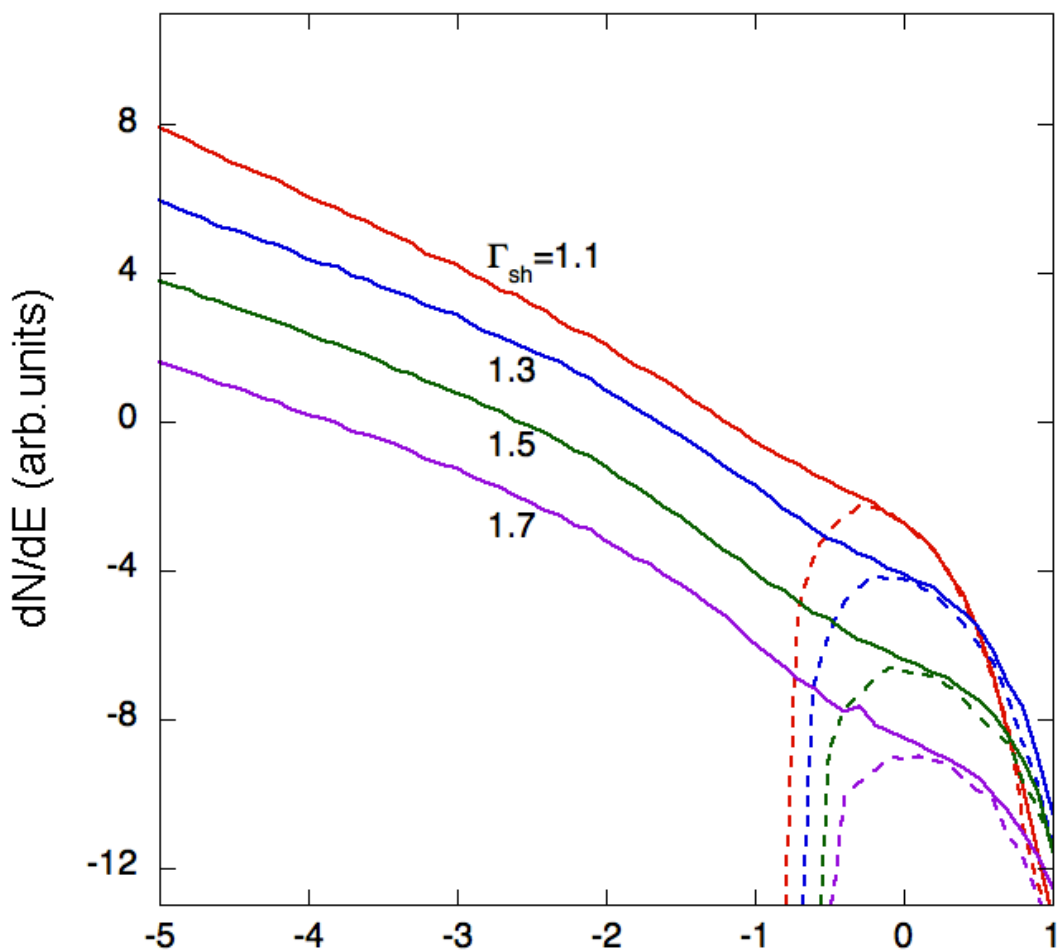
Downstream boundary is set by the comoving width of the shocked medium at a given stage of the shock propagation ➔ Input from F. Daigne hydrodynamical code

Upstream we assume that the turbulence does not extend further than a distance $10\lambda_{max}$ from the shock (λ_{max} is the maximum turbulence scale)

Spectra of accelerated cosmic rays

rigidity $R = \frac{pc}{Ze} \approx \frac{E(eV)}{Z}$

R_{max} definition : $r_L(R_{max}) = \frac{R_{max}}{Bc} = \lambda_{max}$



$\log_{10} \frac{R}{R_{max}}$

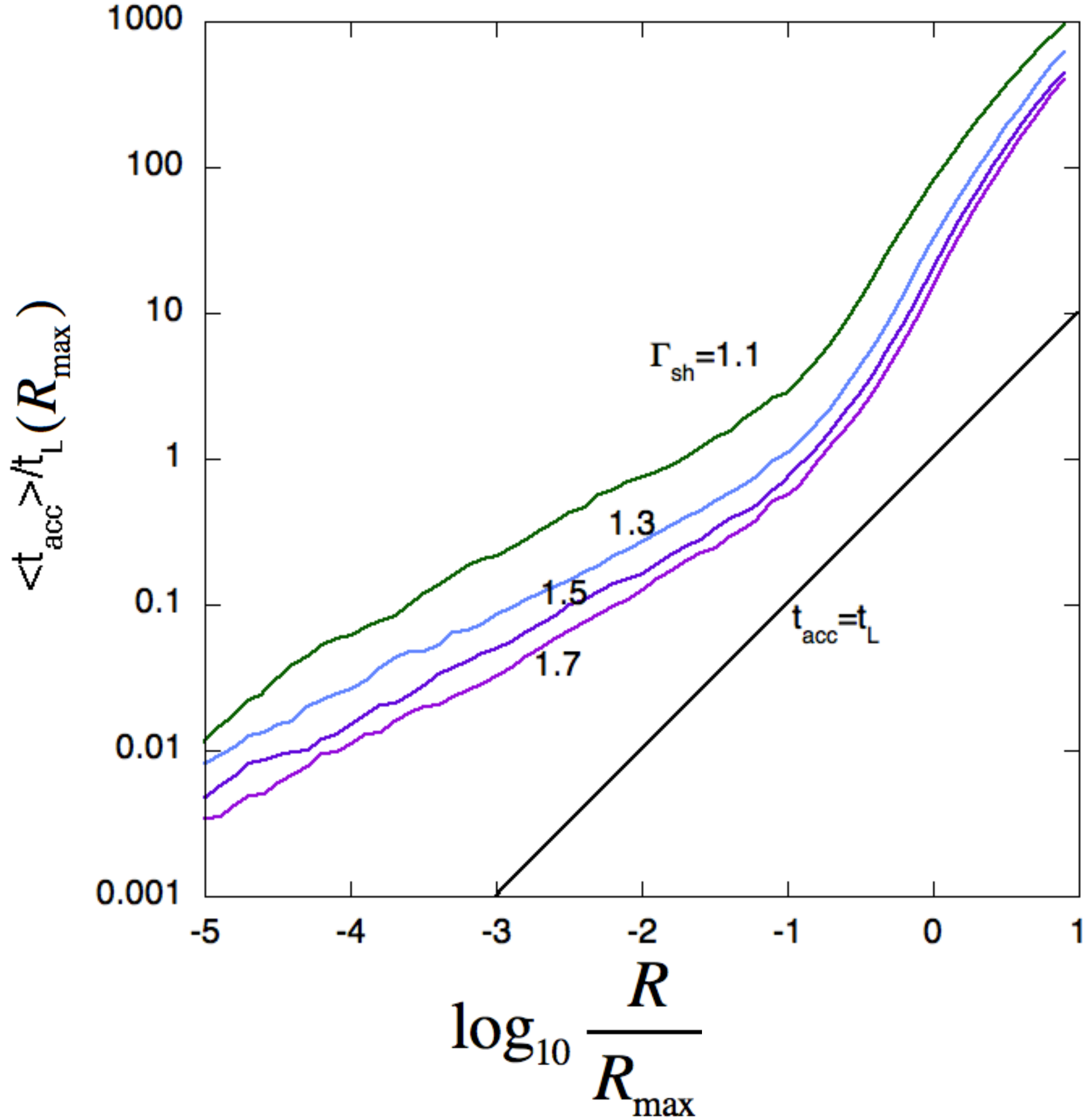
- Escape upstream : high pass filter (select particles in the weak scattering regime)

- Escape downstream : should become a high pass filter in presence of energy losses (particles must leave fast enough before being cooled by energy losses)

Spectrum of accelerated cosmic-rays are never really perfect power law
The shape depends strongly on the magnetic field configuration
Parallel shocks can lead to very hard spectral indexes
Perpendicular shocks can lead to soft spectra with early cut-offs
(results qualitatively identical to those obtained by Niemiec & Ostrowsky)

cosmic rays acceleration time

R_{max} definition : $r_L(R_{max}) = \frac{R_{max}}{Bc} = \lambda_{max}$



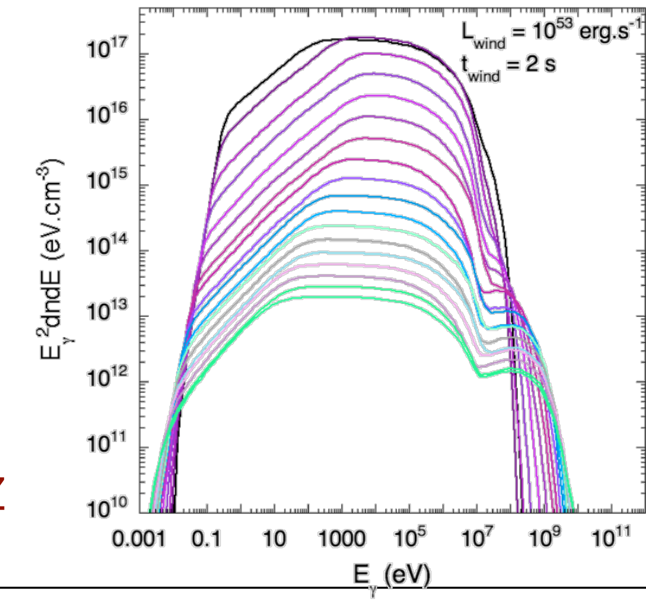
The acceleration time increases faster in the weak scattering regime ($E \sim E_{max}$)

$t_{acc}=t_L=r_L/c$ leads to much more optimistic expectations than our calculations
At $E=E_{max}$ ➔ t_{acc} between ~20 and 80 times t_L

For a complete picture one needs to plug energy losses in

output of internal shock model :
- matter and radiation densities
- dynamics
- magnetic fields

Energy losses

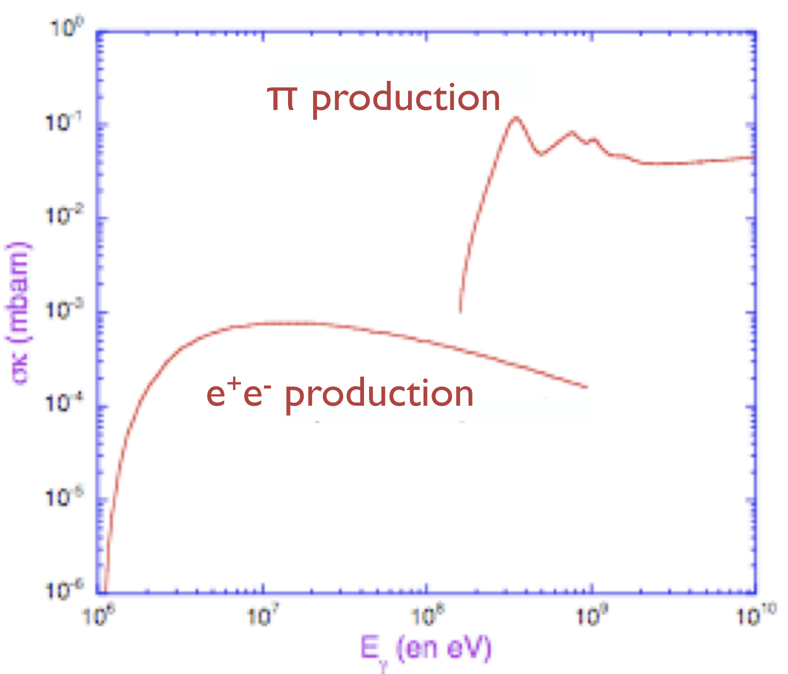


protons

- pair production
  $p+\gamma$ ® $p+e^{+}+e^{-}$ ~ 1 MeV
- synchrotron emission B
- adiabatic losses Γ_{res}, r_{shock}

- pion production
  $p+\gamma$ ® $p \mid n+\Pi^0 \mid \Pi^+ \mid \Pi^-$ ~ 150 MeV

- hadronic interactions
  $p+p$ ® $p+n \mid p+\Pi^0 \mid \Pi^+ \mid \Pi^-$ density



Γ_N

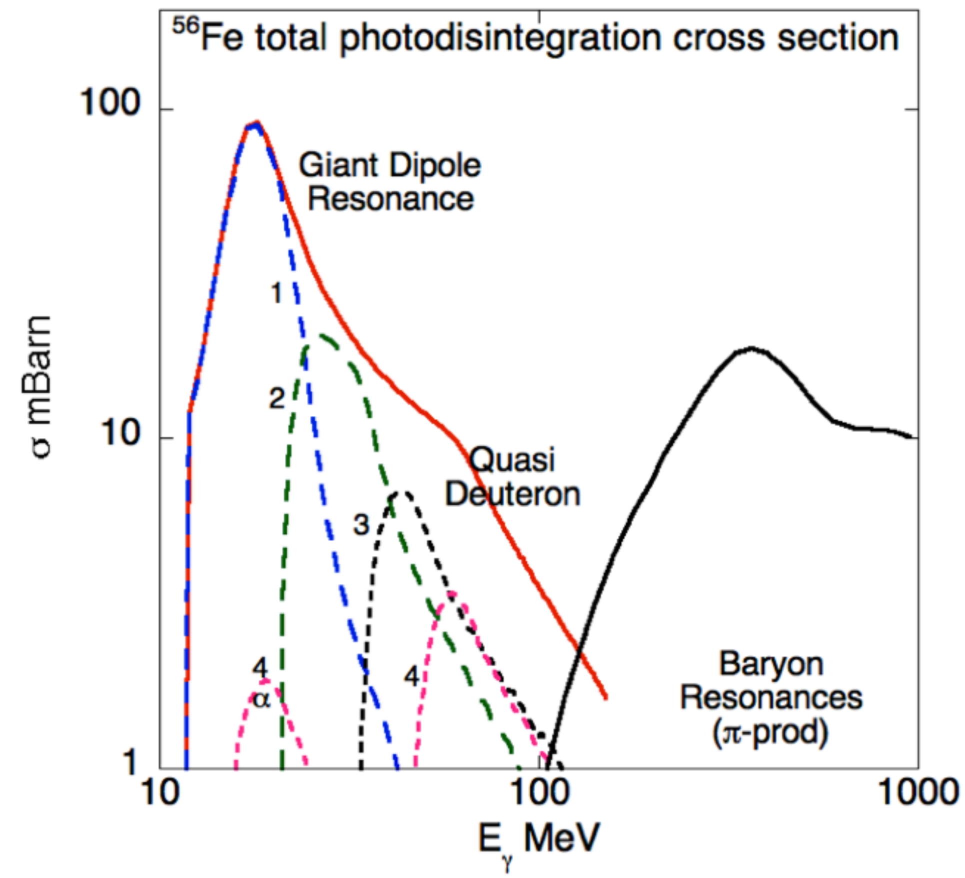
OR

A

complex nuclei $^{A}N_{Z}$

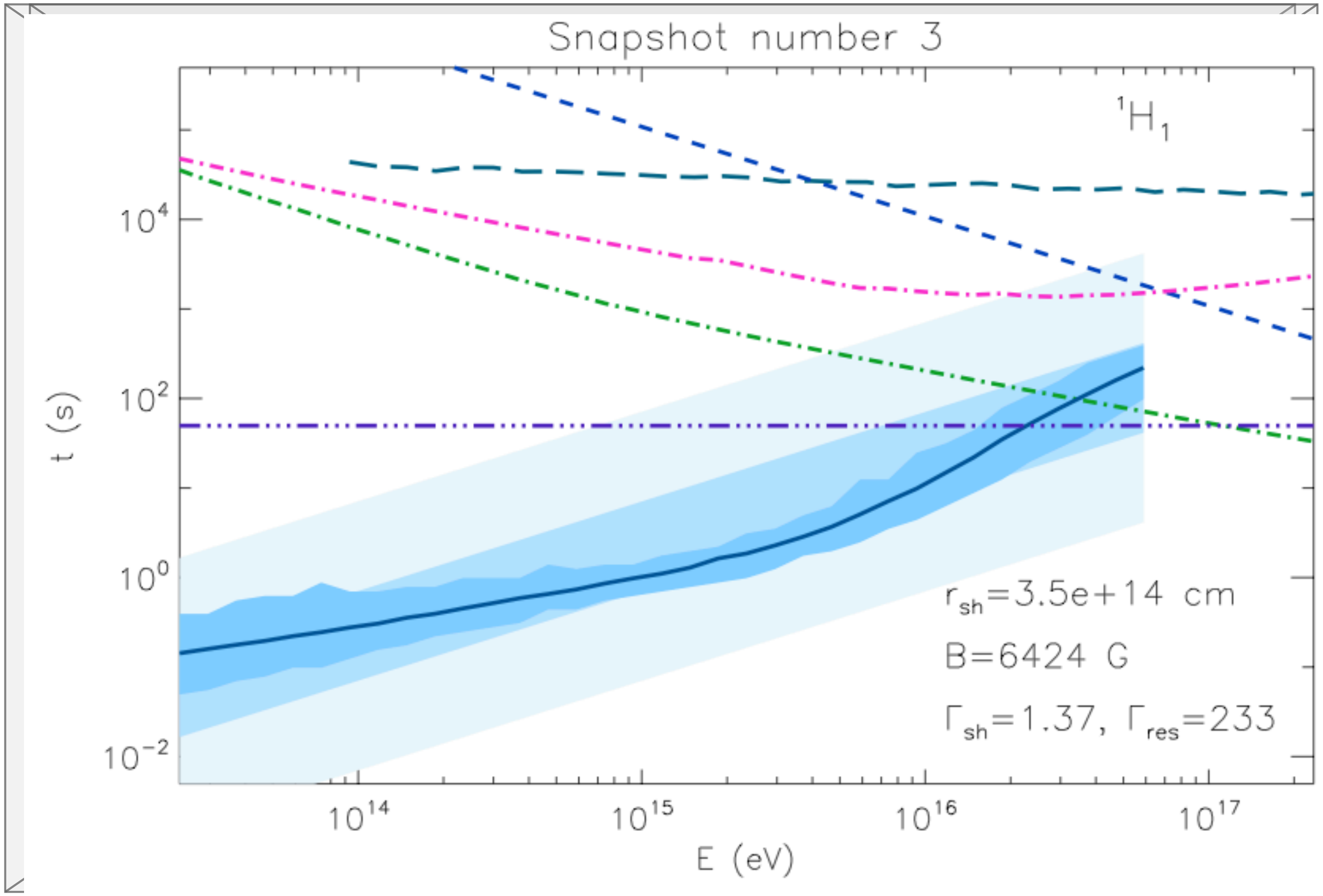
- GDR (Khan 2005) ~ 10 MeV
- QD
- BR (π-prod)

(Rachen 1996) ~ 30 - 145 MeV



Estimate of the maximum energy reachable for protons

t_{wind}=2s L_{wind}=10^{53} erg.s^{-1} λ_{max}=$r_{shock}/30\Gamma_{res}$



losses

t_{exp}

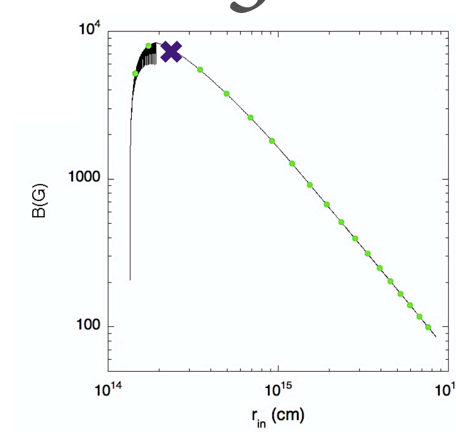
t_{sync}

t_{pair}

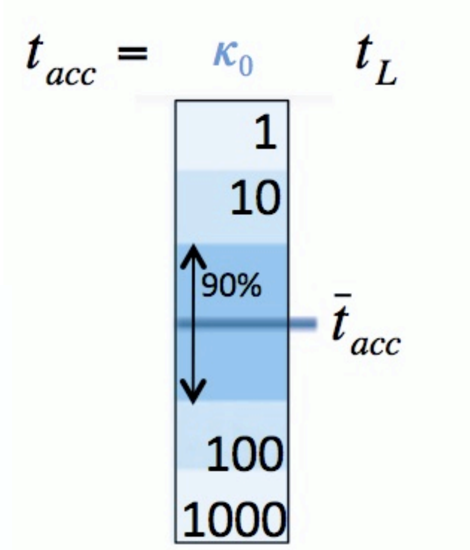
$t_{photodis/pion}$

$t_{hadronic}$

#3



acceleration



$E_{max,obs} \approx 5.10^{18}$ eV

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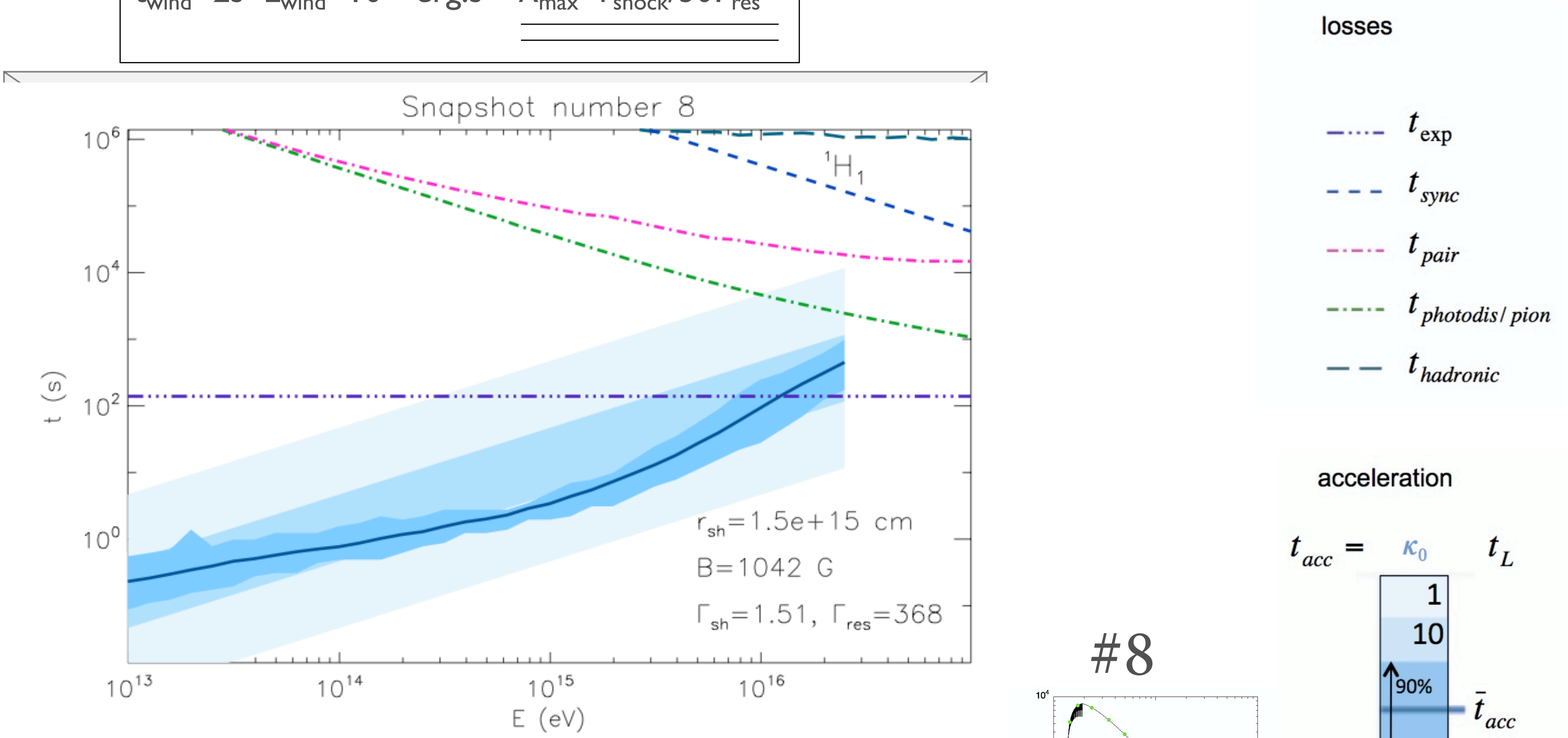
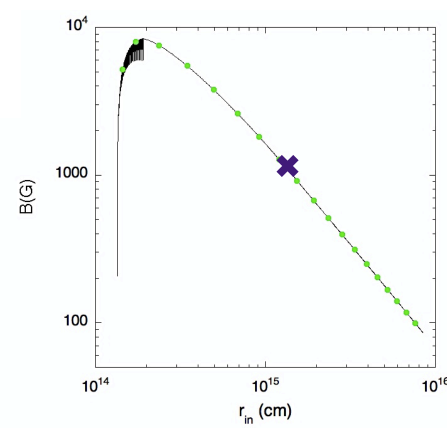


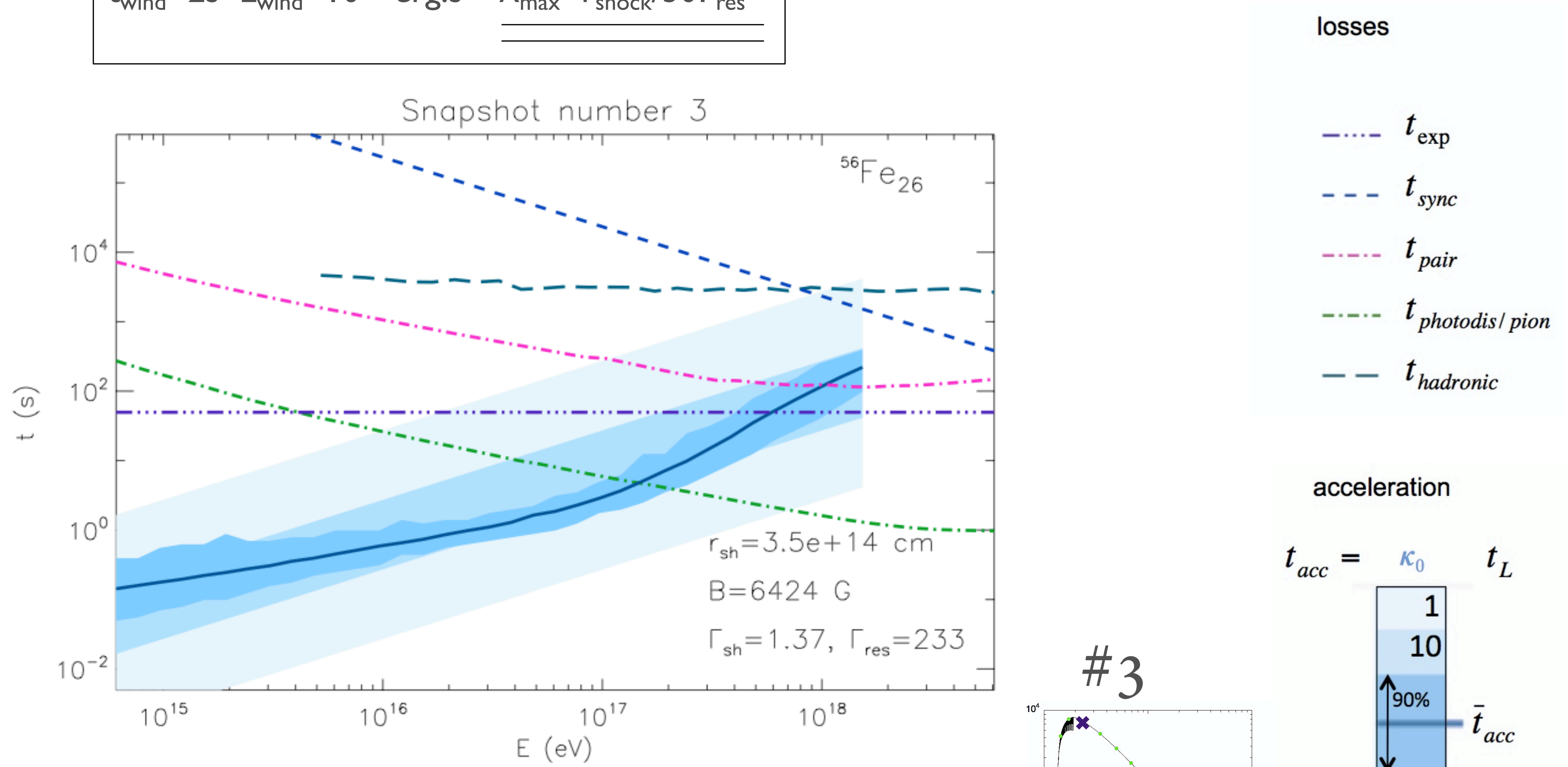
$E_{max,obs} \approx 4\ 10^{18}$ eV

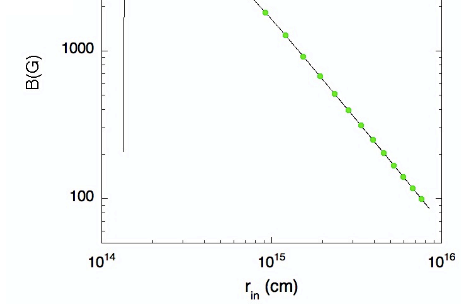
#8

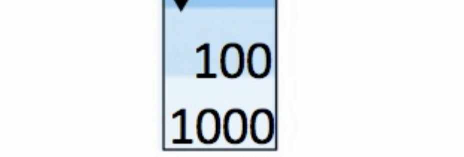


Estimate of the maximum energy reachable for iron

t_{wind}=2s L_{wind}=10^{53} erg.s^{-1} λ_{max}=$r_{shock}/30\Gamma_{res}$



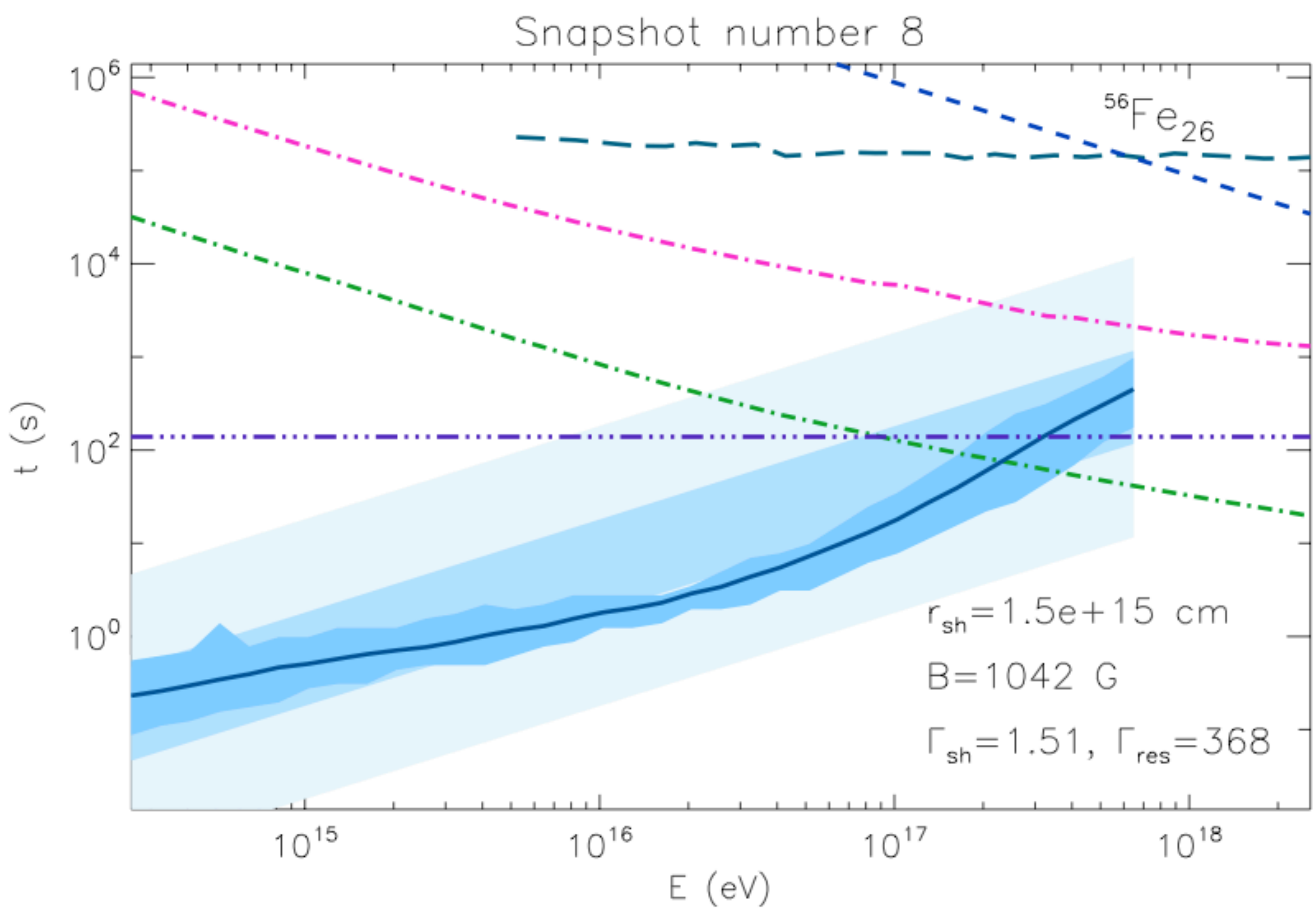


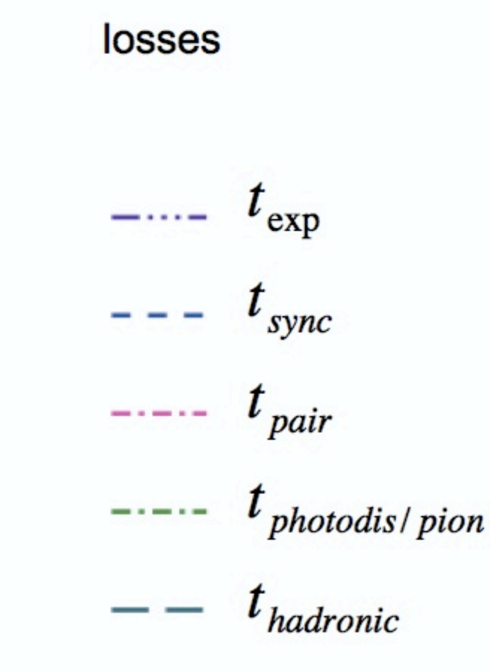


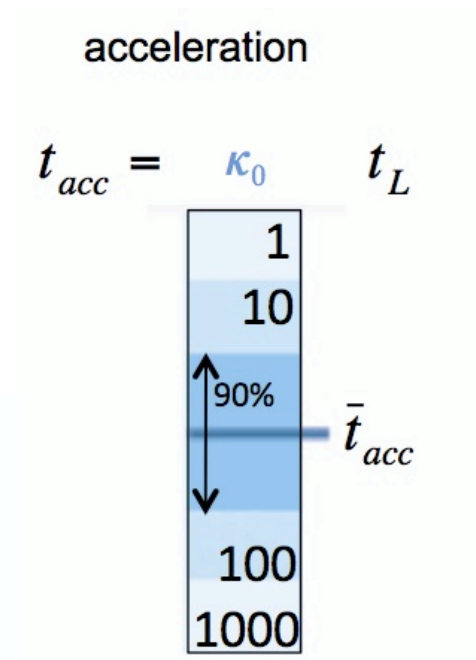
$E_{max,obs} \approx 4.10^{19}$ eV

Estimate of the maximum energy reachable for iron

t_{wind}=2s $L_{wind}=10^{53}$ erg.s^{-1} $\lambda_{max}=r_{shock}/30\Gamma_{res}$

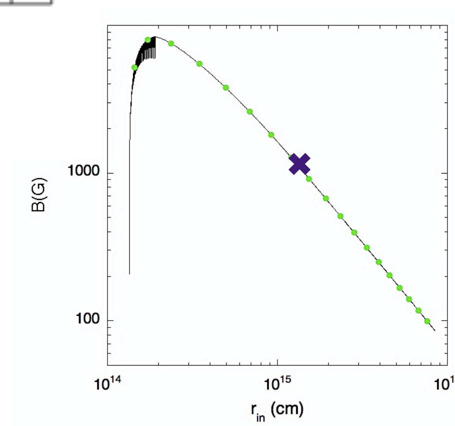






$E_{max,obs} \approx 10^{20}$ eV

#8



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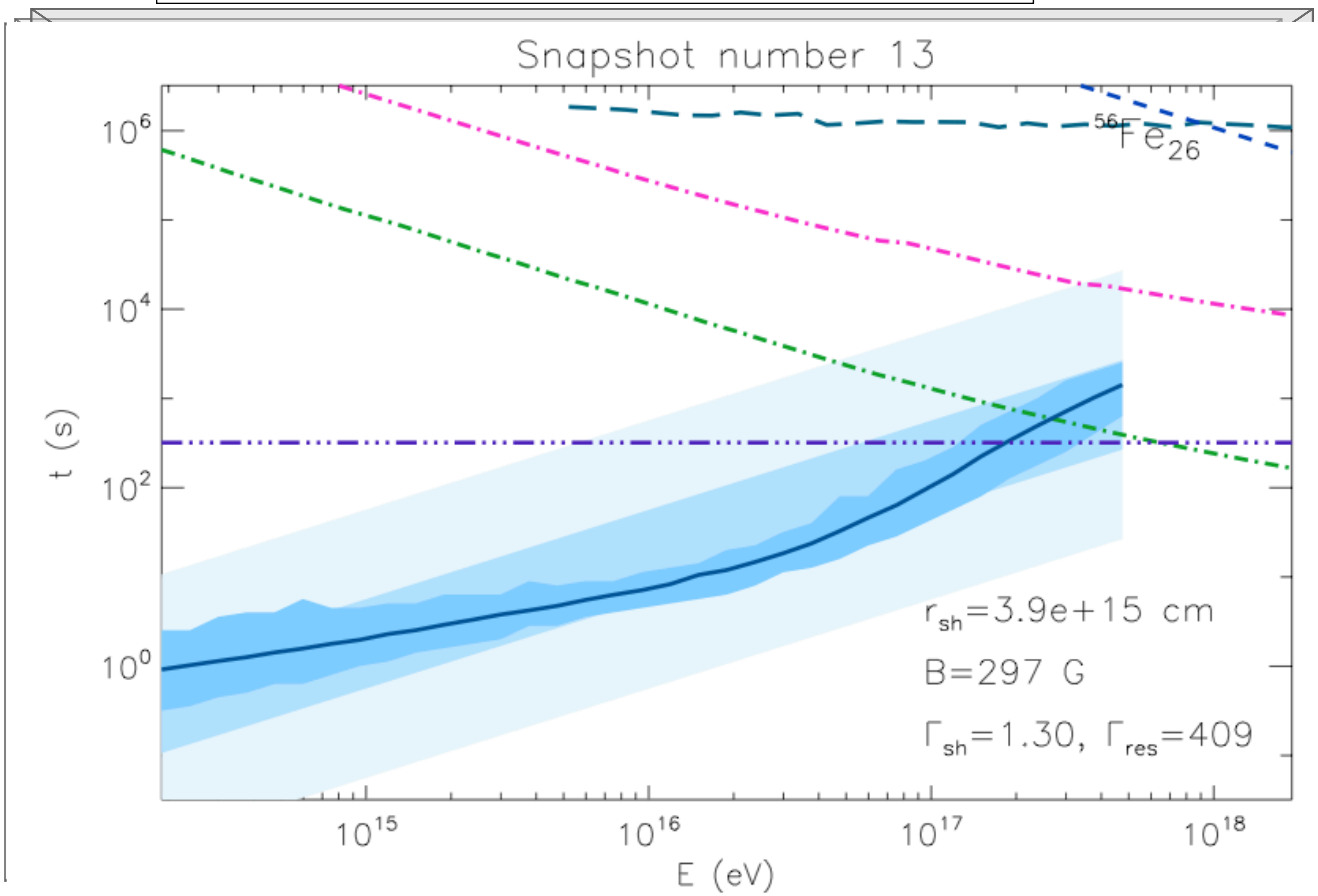
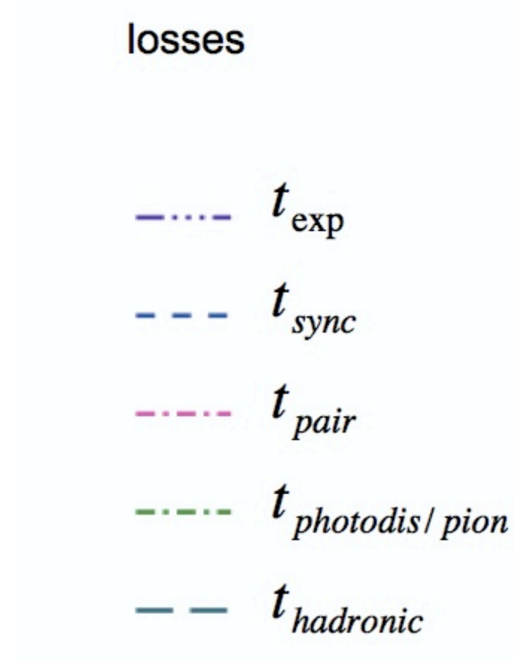
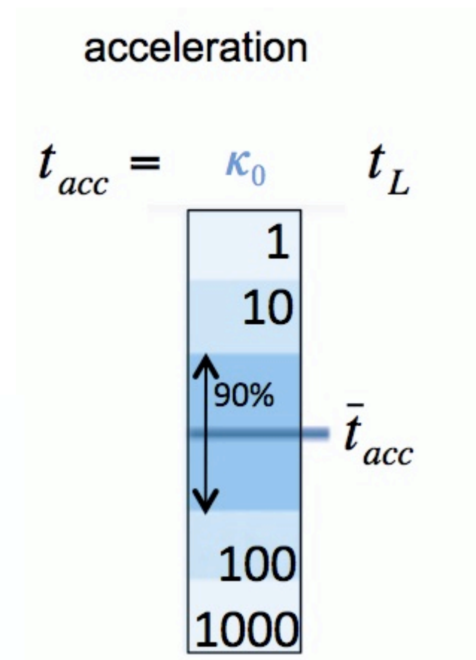
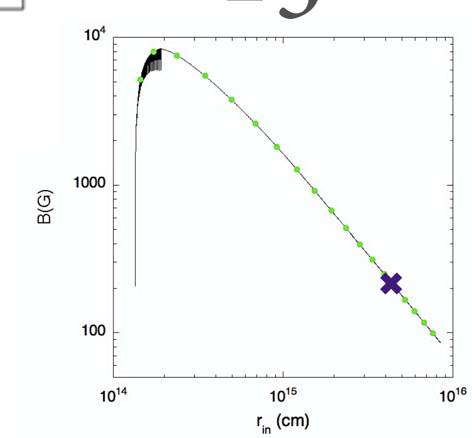






#13



$E_{max,obs} \approx 8\ 10^{19}$ eV

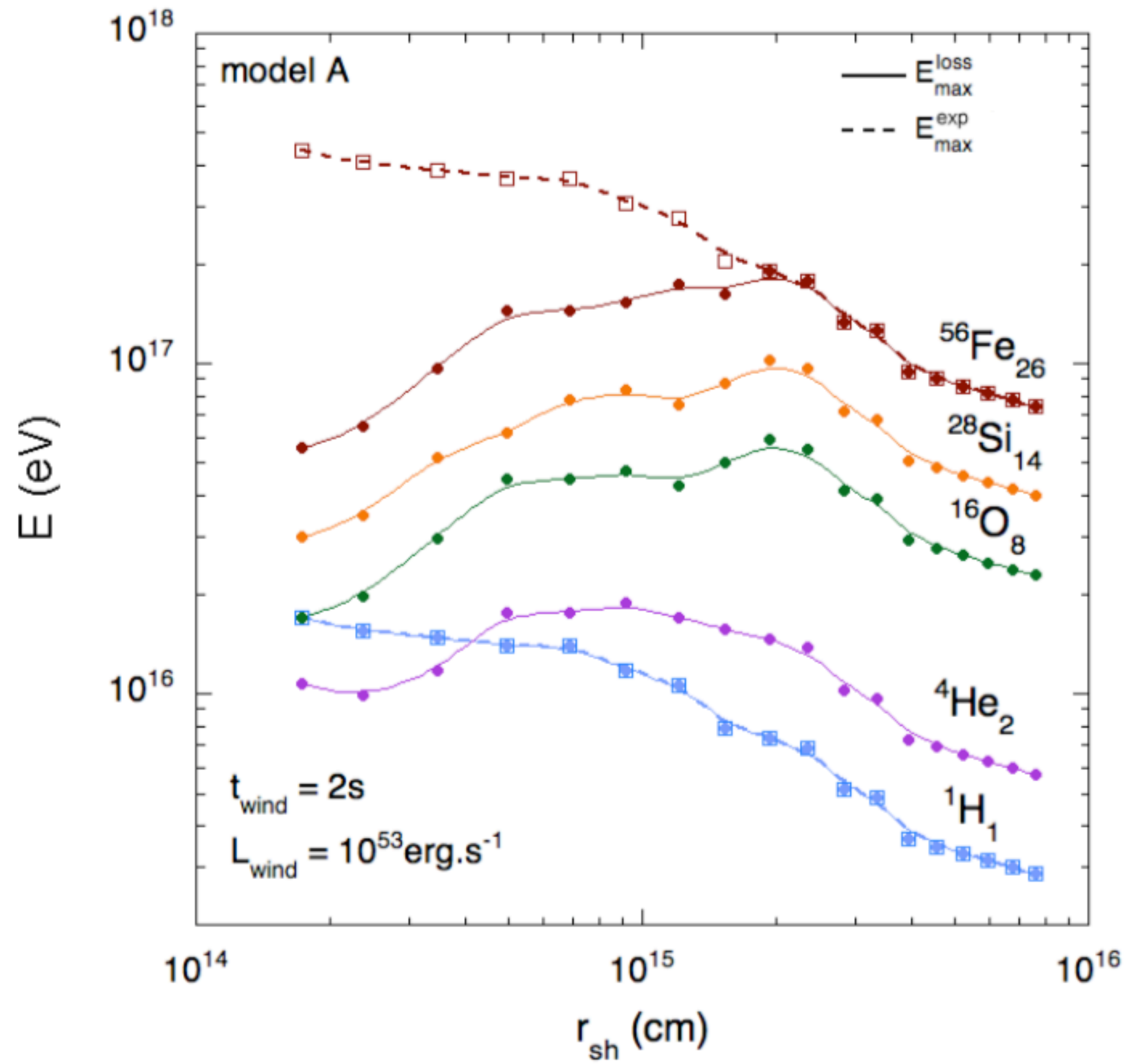
Estimate of the maximum energy reachable

example of an intermediate luminosity burst :

- Proton maximum energy limited by adiabatic losses during the whole shock propagation

- Nuclei maximum energy limited by photodisintegration during the early stage of the shock propagation and by adiabatic losses at later times

=> Scaling of the maximum energy with Z not necessarily trivial for intermediate and high luminosity bursts



Our calculation : modeling of UHECR acceleration at GRBs internal shocks

- Modeling of the internal shock according to Daigne & Mochkovitch 1998 ("solid layers" collision model)
==> give us an estimate of the physical quantities at the internal shocks based on a few free Parameters

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==> cosmic-ray and neutrino output for a GRB of a given luminosity

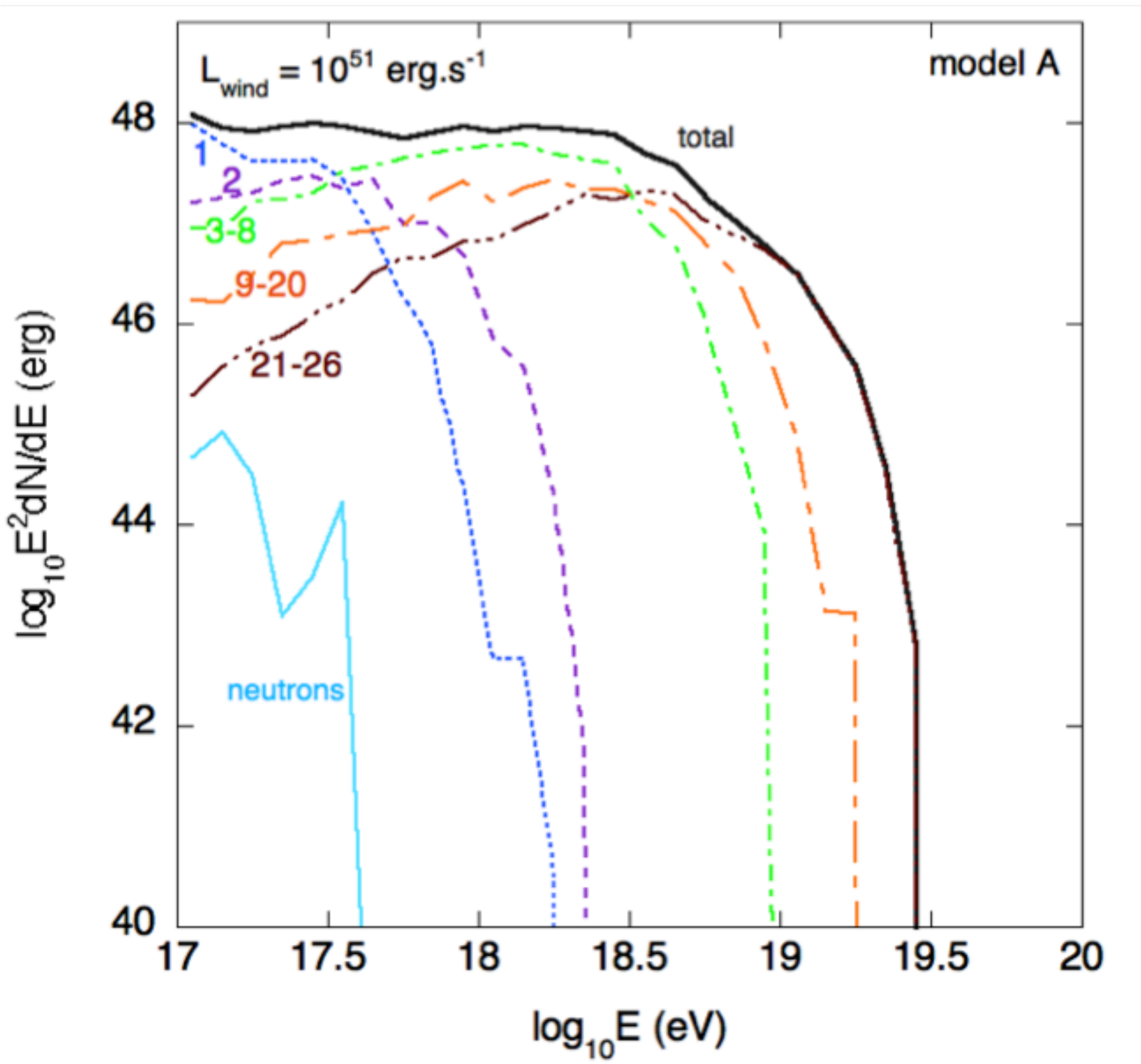
- Convolution by a GRB luminosity function and cosmological evolution (Piran & Wanderman 2010)
==> diffuse UHECR and neutrino fluxes

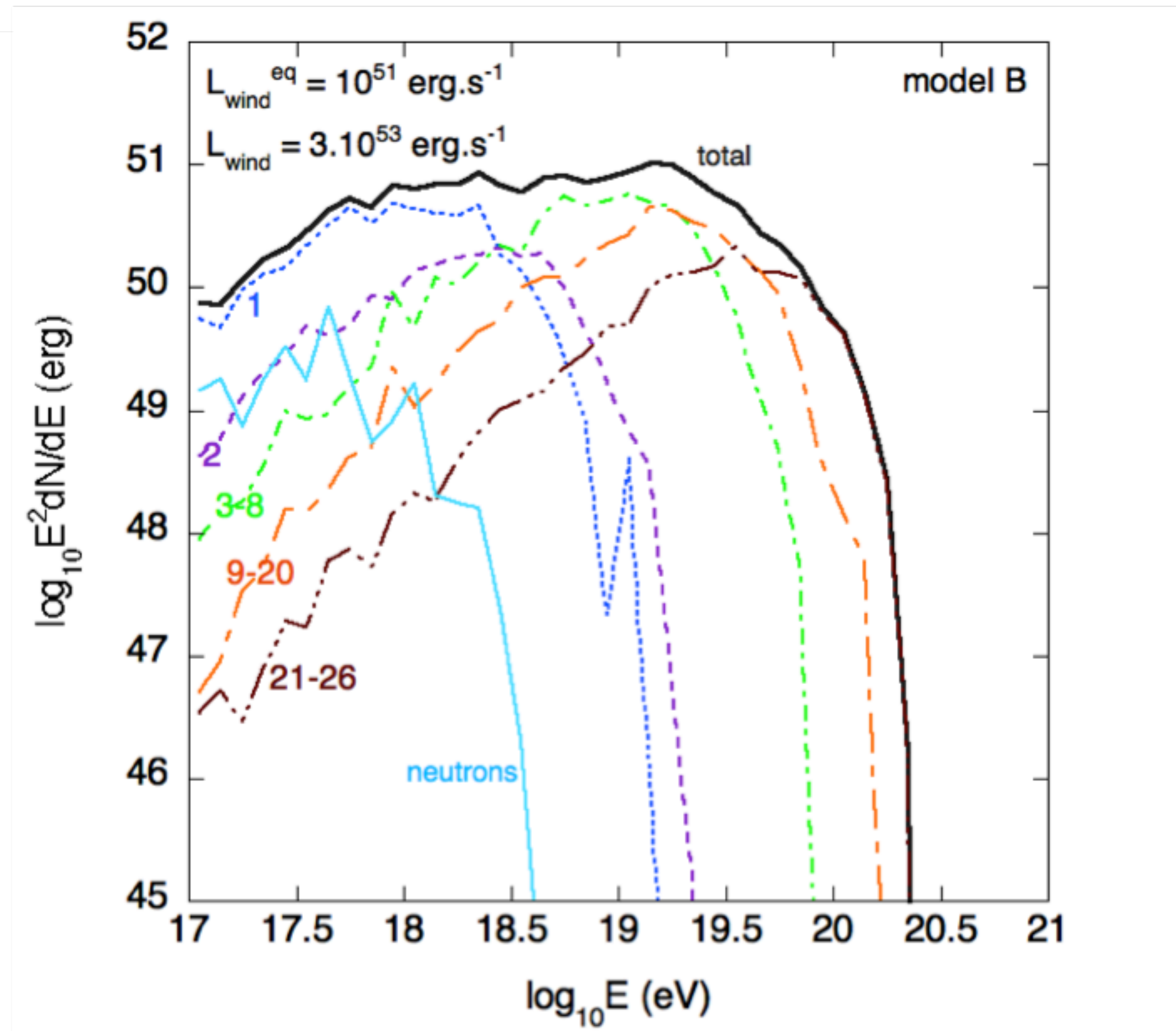
UHECR spectra (escaping from the wind)

We calculate spectra of escaping cosmic-rays for wind luminosities between 10^{51} and 10^{55} erg.s^{-1}

⇒**GRB output for :** **$L\gamma$=5.10^{49}** erg.s^{-1} t_{wind} = 2s

metallicity : 10 X galactic CRs





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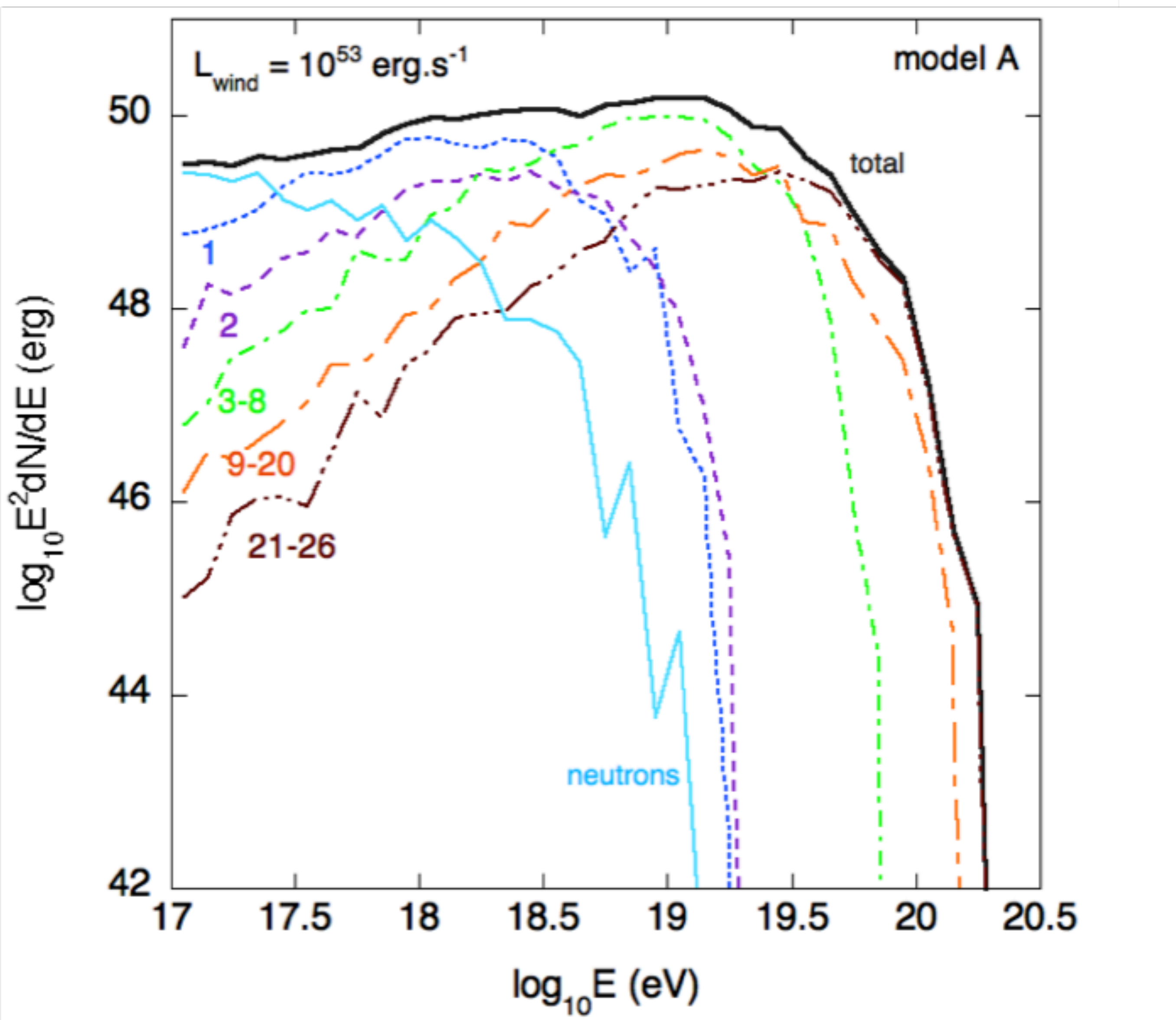

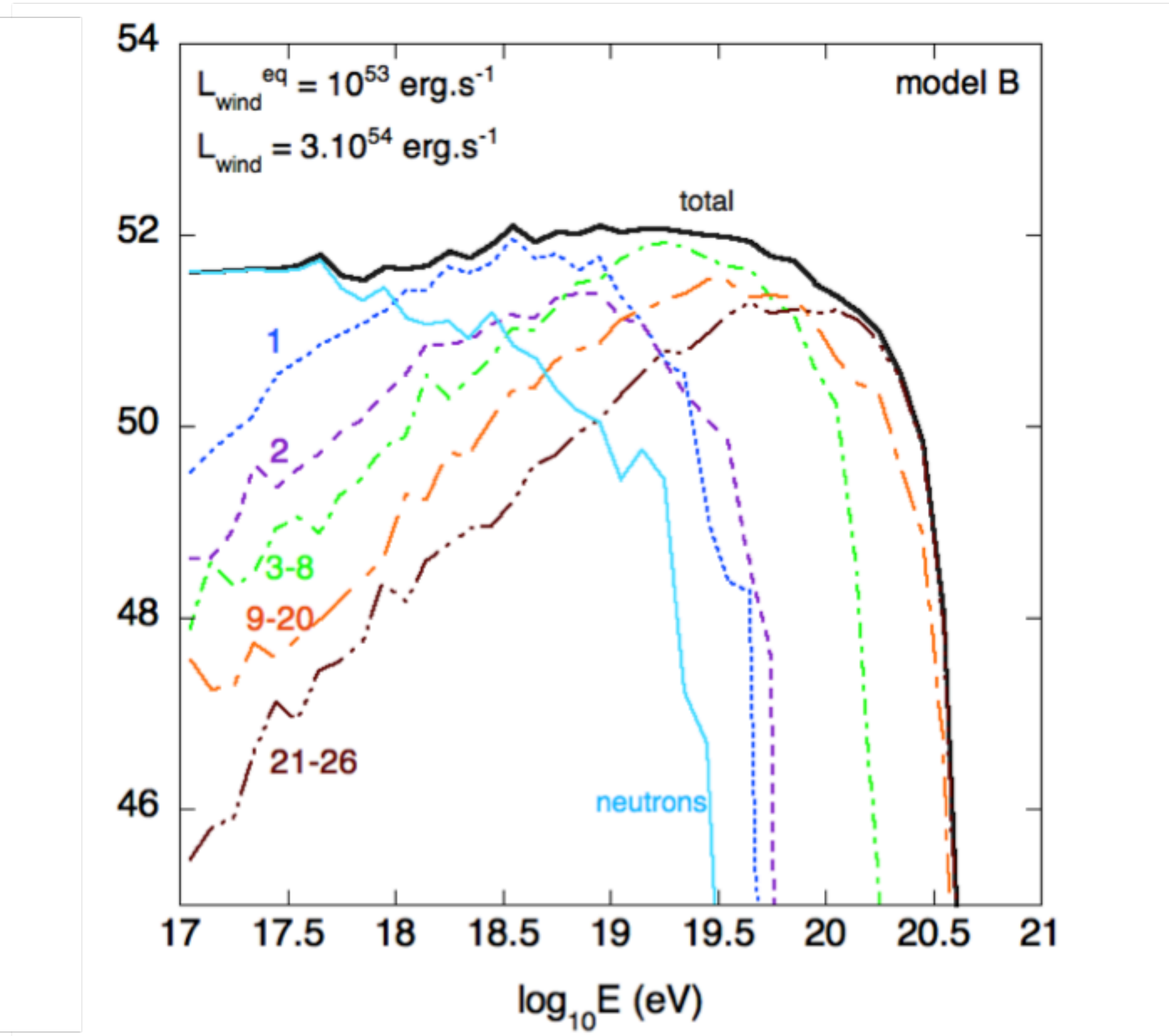

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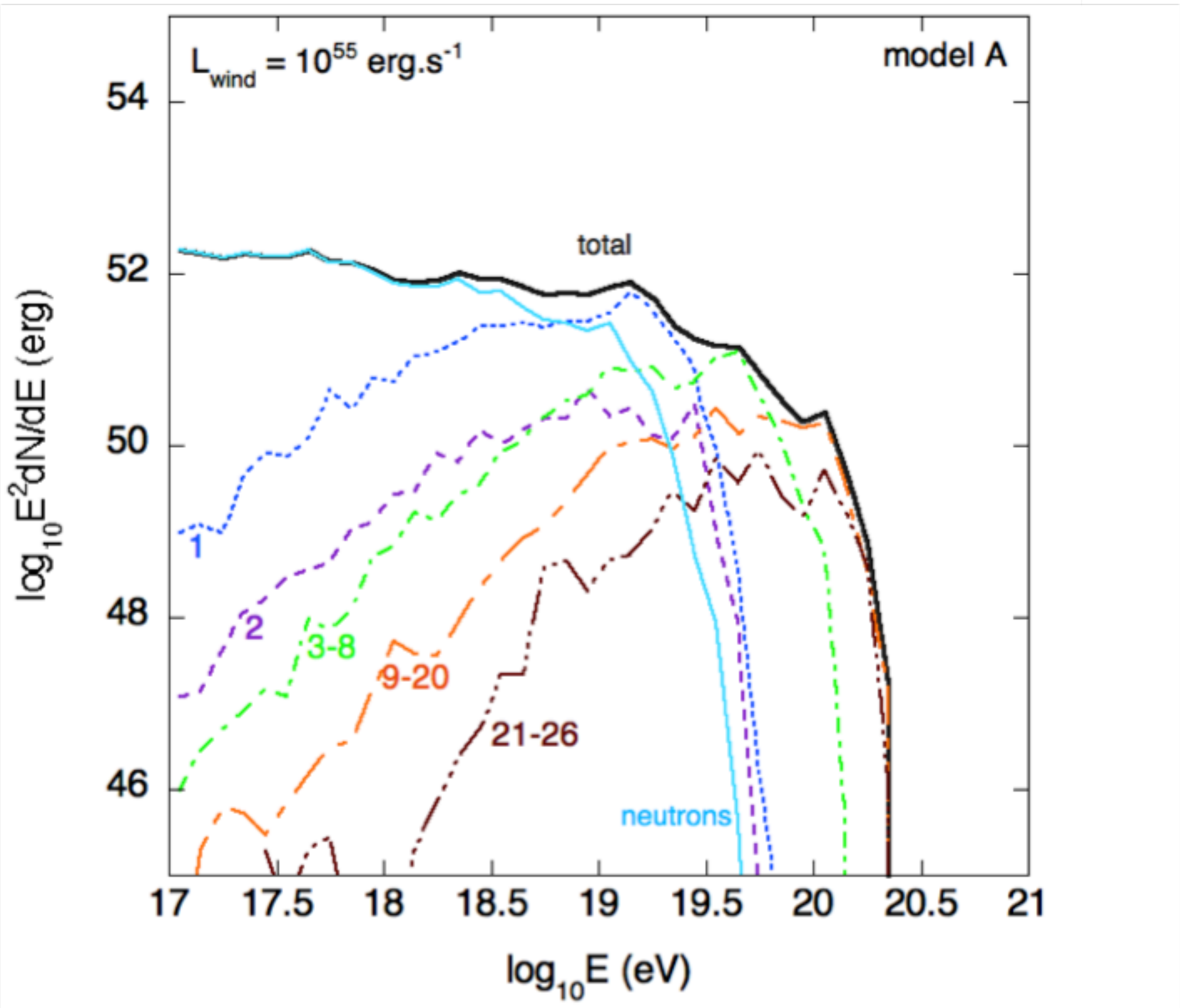

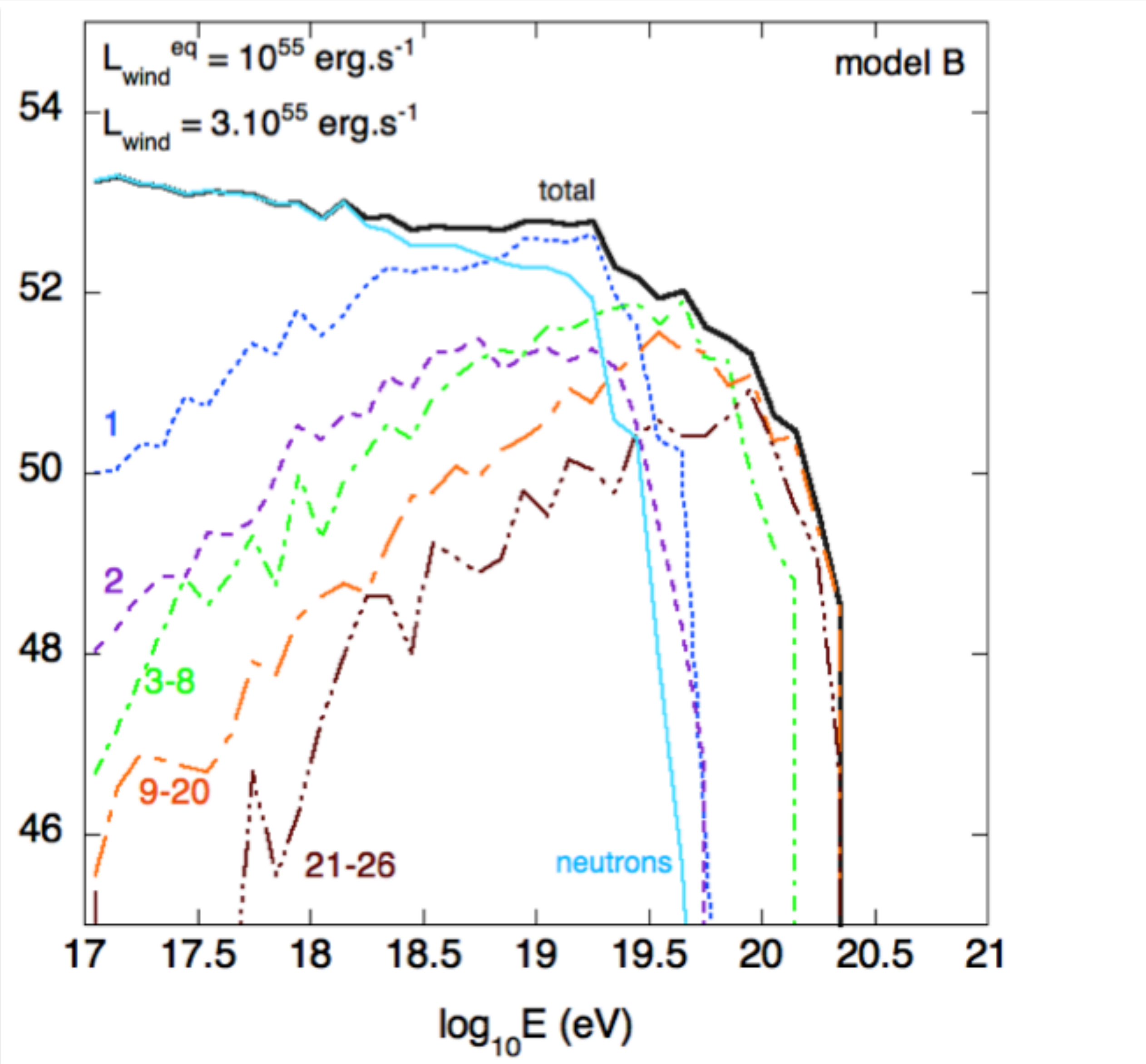

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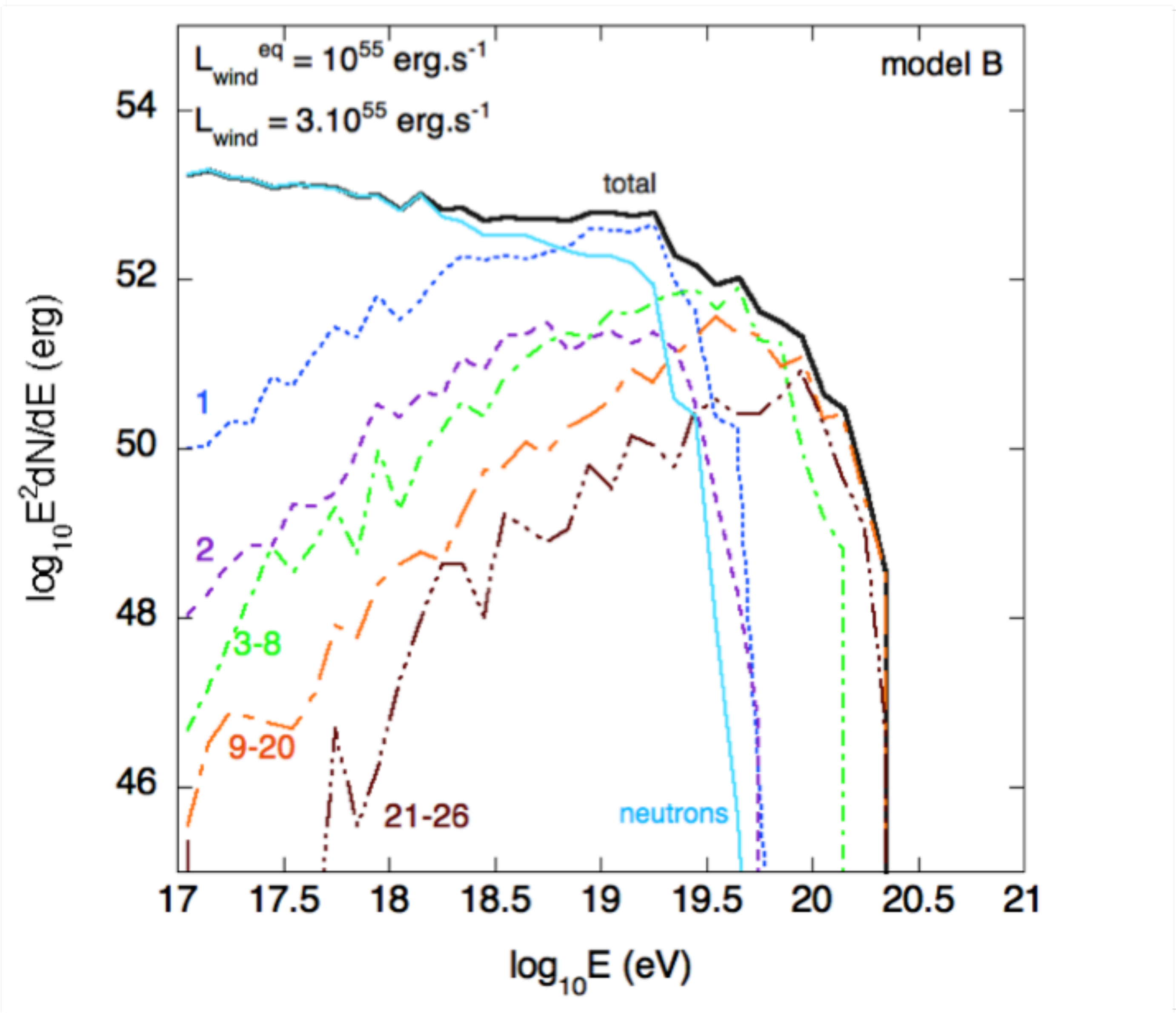

High luminosities : Nuclei components get narrower, more neutrons emitted
➔ photointeractions of nuclei

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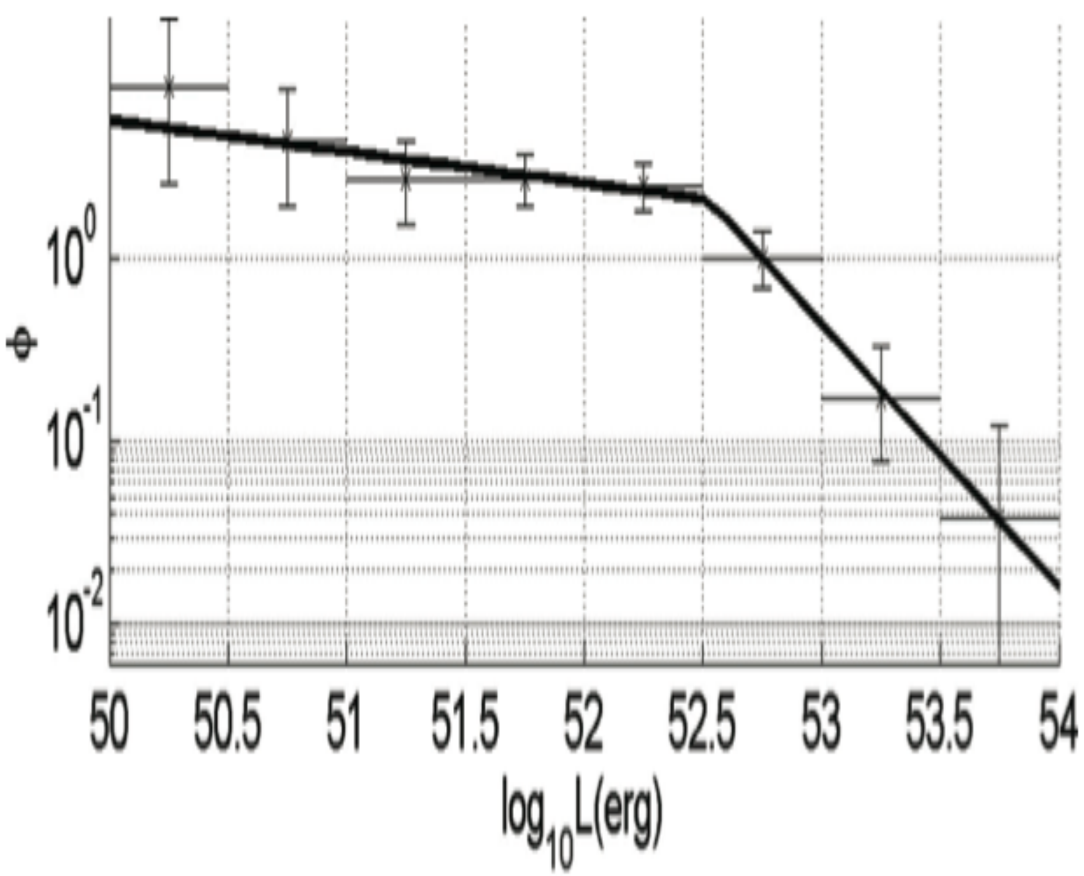
Convolution by a GRB luminosity function

GRB rate and luminosity function, and the corresponding cosmological evolution from Wanderman and Piran 2010

ρ_0=1.3 Gpc^{-3}.yr^{-1} α_1=1.2 α_2=2.4

E_γ^{tot}=1.1 10^{44} erg.Mpc^{-3}.yr^{-1}



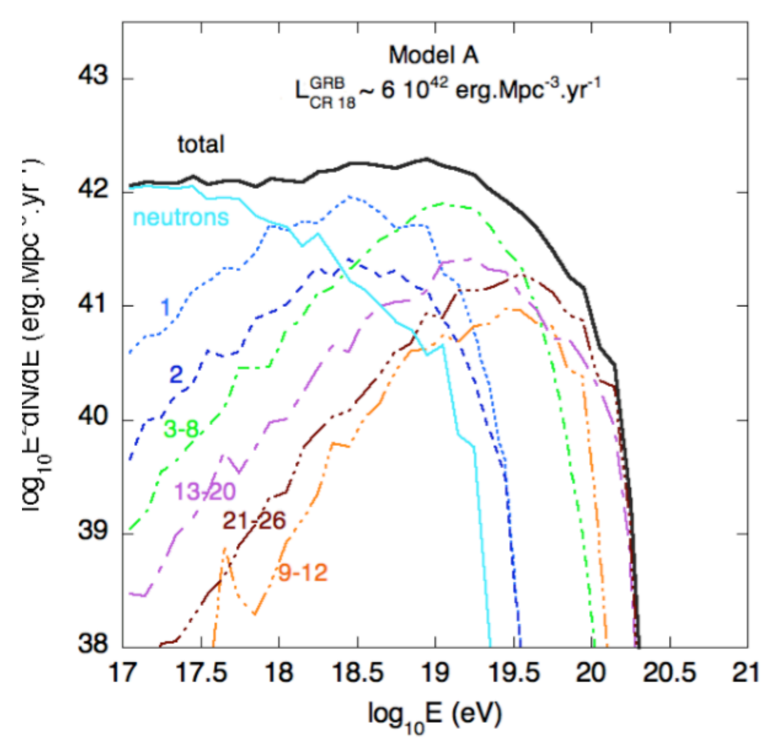
Assuming the central source activity lasts 20 s

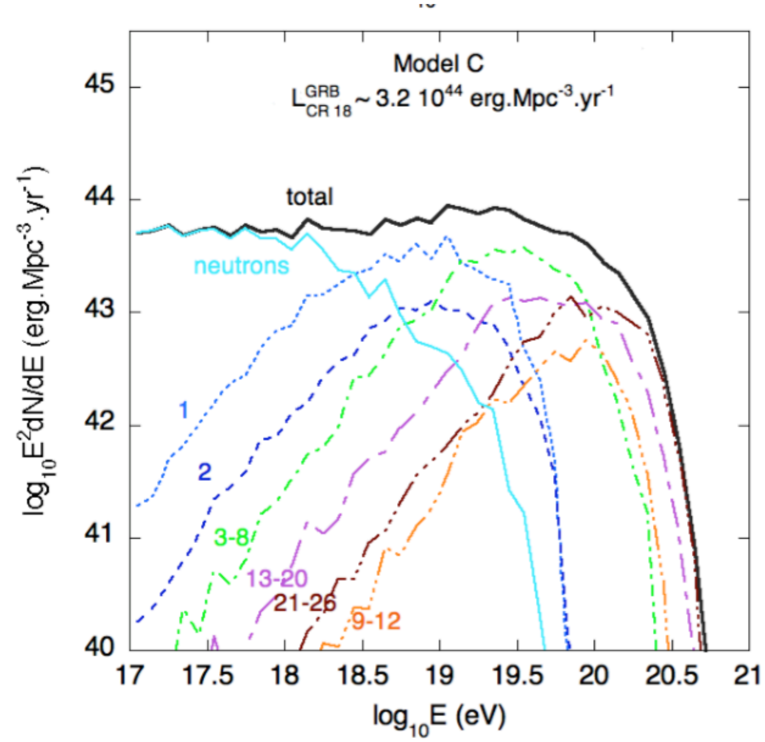
UHECR emissivity above 10^{18} eV :

Model A : ~6.10^{42} erg.Mpc^{-3}.yr^{-1}

Model B and C : ~3-4.10^{44} erg.Mpc^{-3}.yr^{-1}

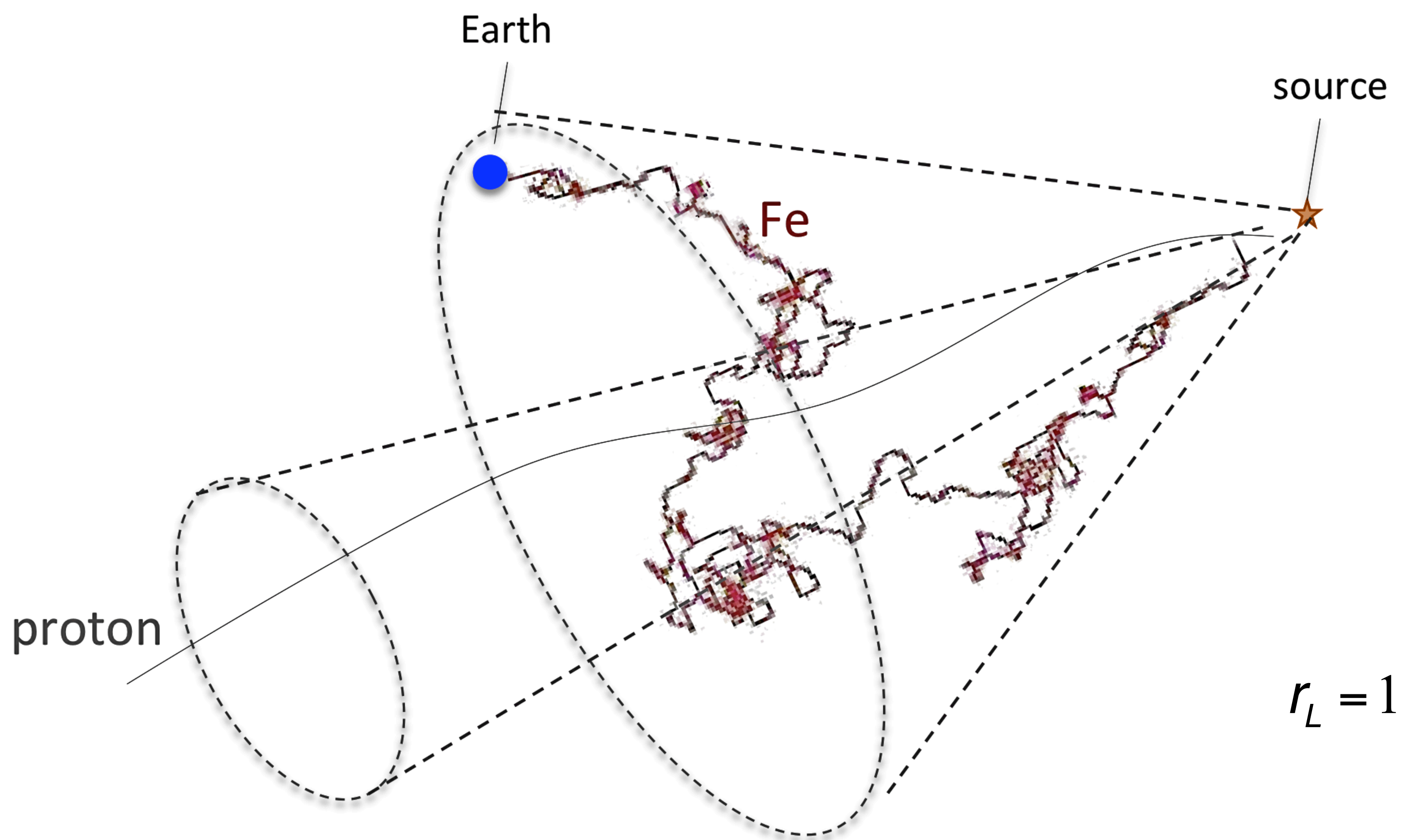
One would need a few 10^{44} erg.Mpc^{-3}.yr^{-1}
Above 10^{18} eV to reproduce the UHECR data





Propagated spectrum

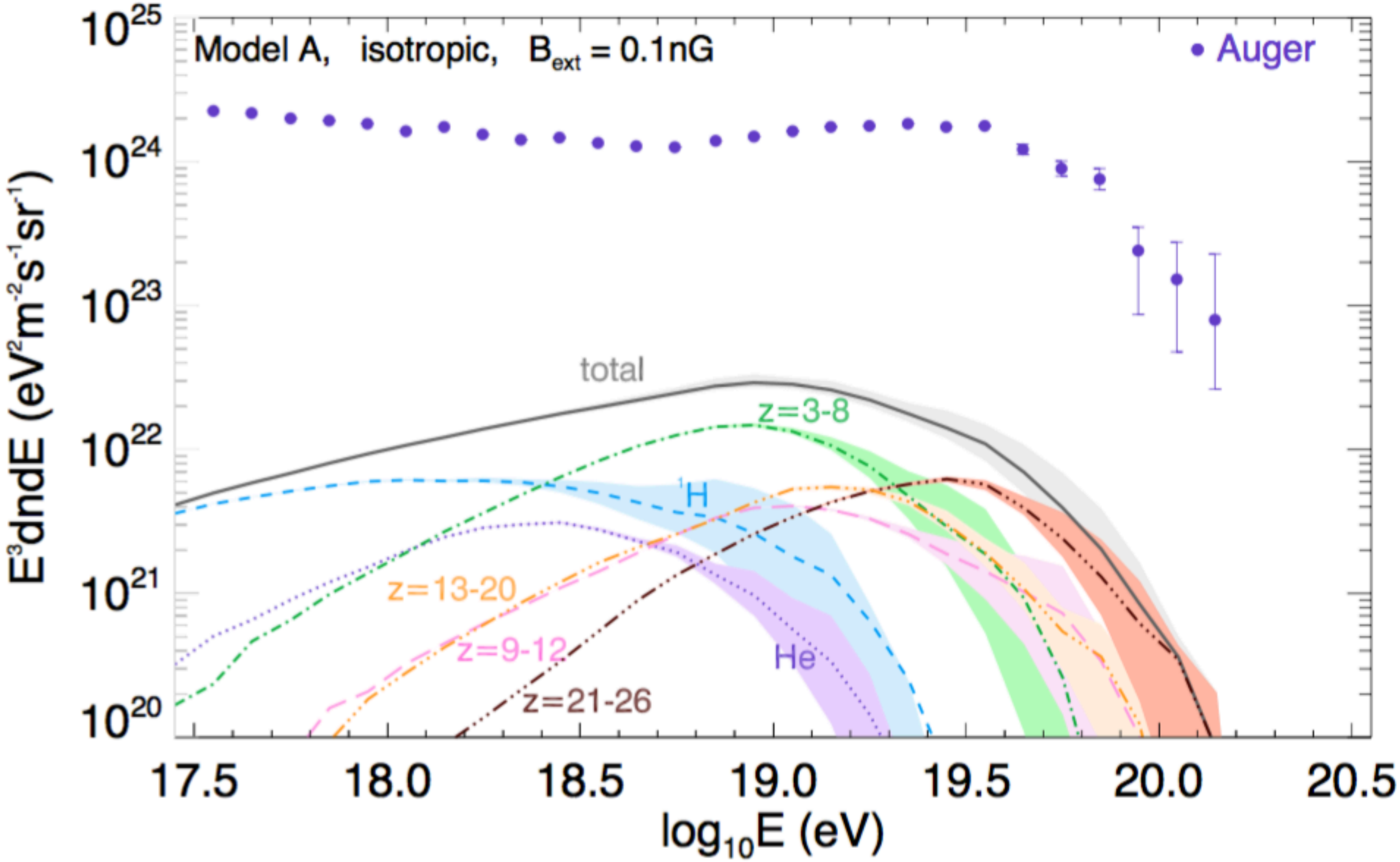
Propagation in extragalactic turbulent magnetic field, including energy losses on extragalactic photon backgrounds (see Globus, Allard & Parizot 2008 for details)



$$r_L = 1.1 Mpc \times \frac{E_{EeV}}{ZB_{nG}}$$

Propagated spectrum

Assumptions
ε_e = 0.33
ε_B = 0.33
ε_{CR} = 0.33



model A

300 realisations of the history of GRB explosions in the Universe

Propagated spectrum

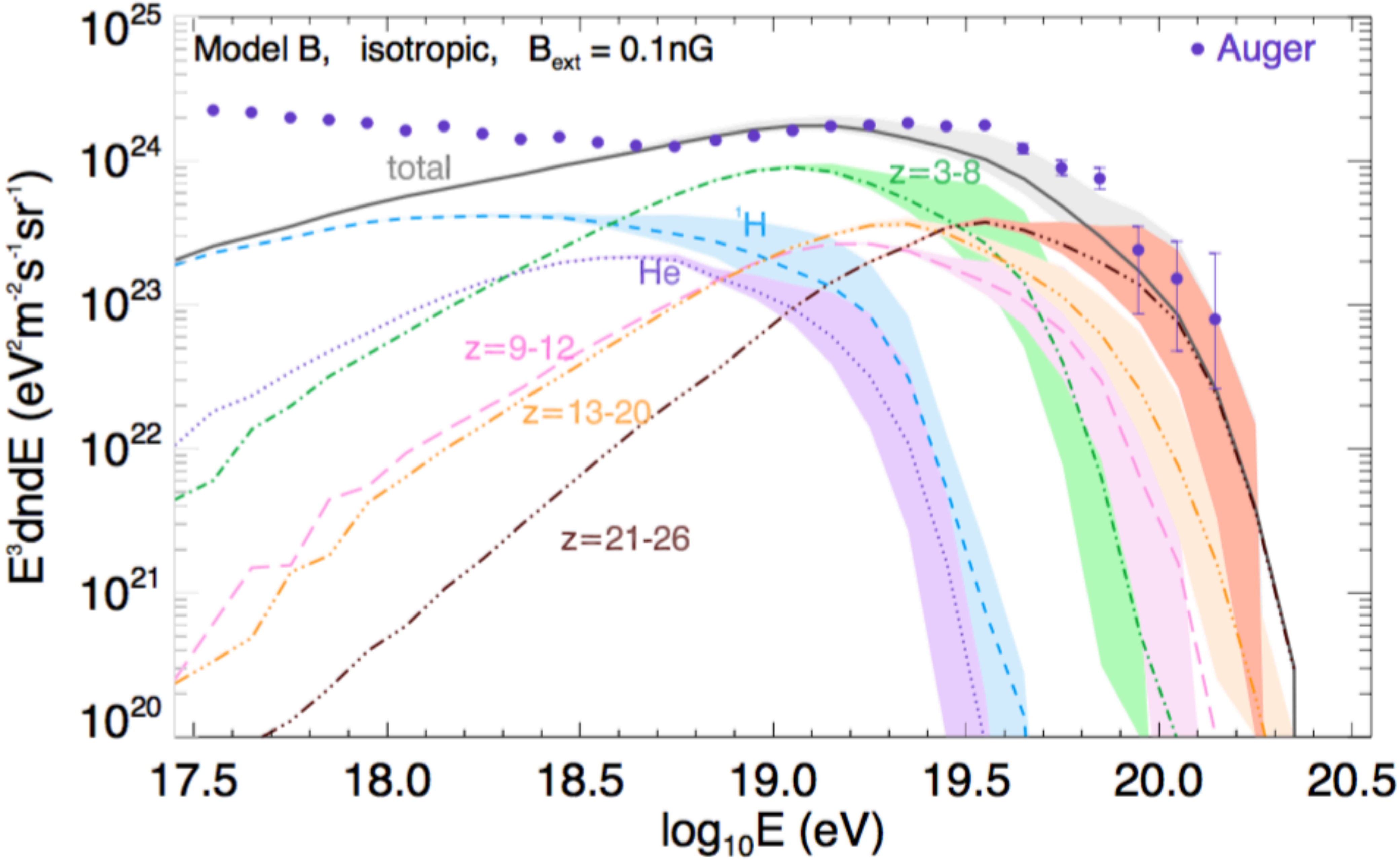
Assumptions

ε_e << 1

ε_B ~ 0.1

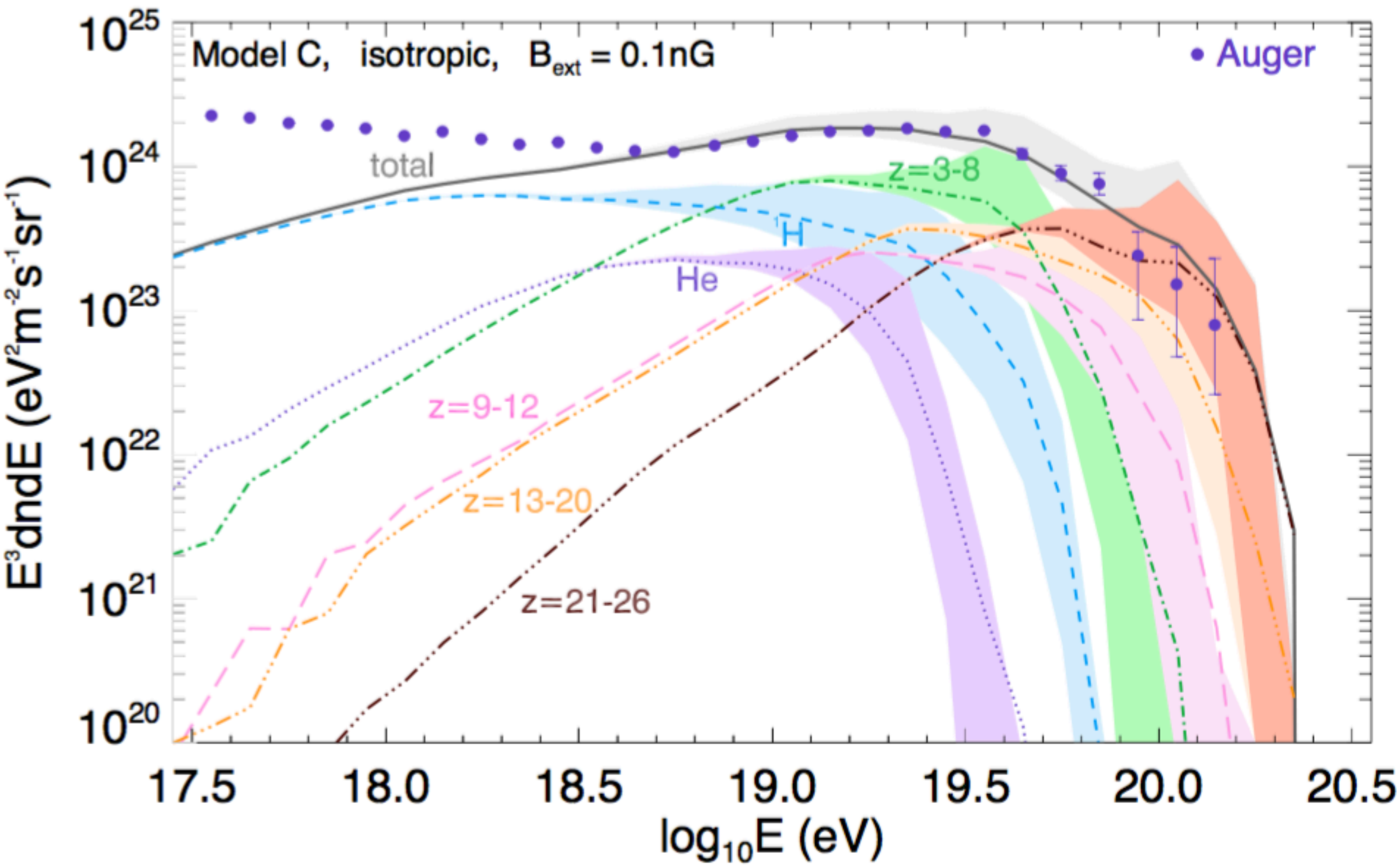
ε_{CR} ~ 0.9

model B



300 realisations of the history of GRB explosions in the Universe

Propagated spectrum



Assumptions

ε_e << 1

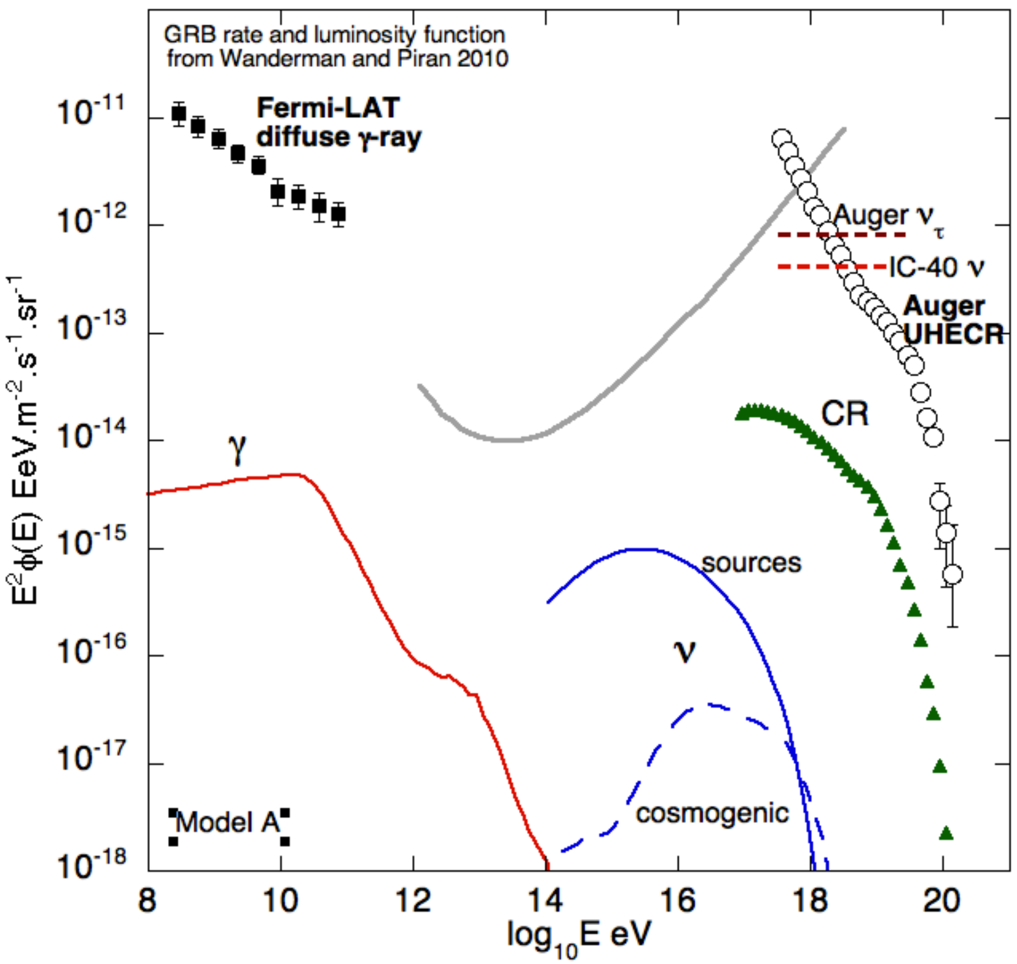
ε_B ~ 0.33

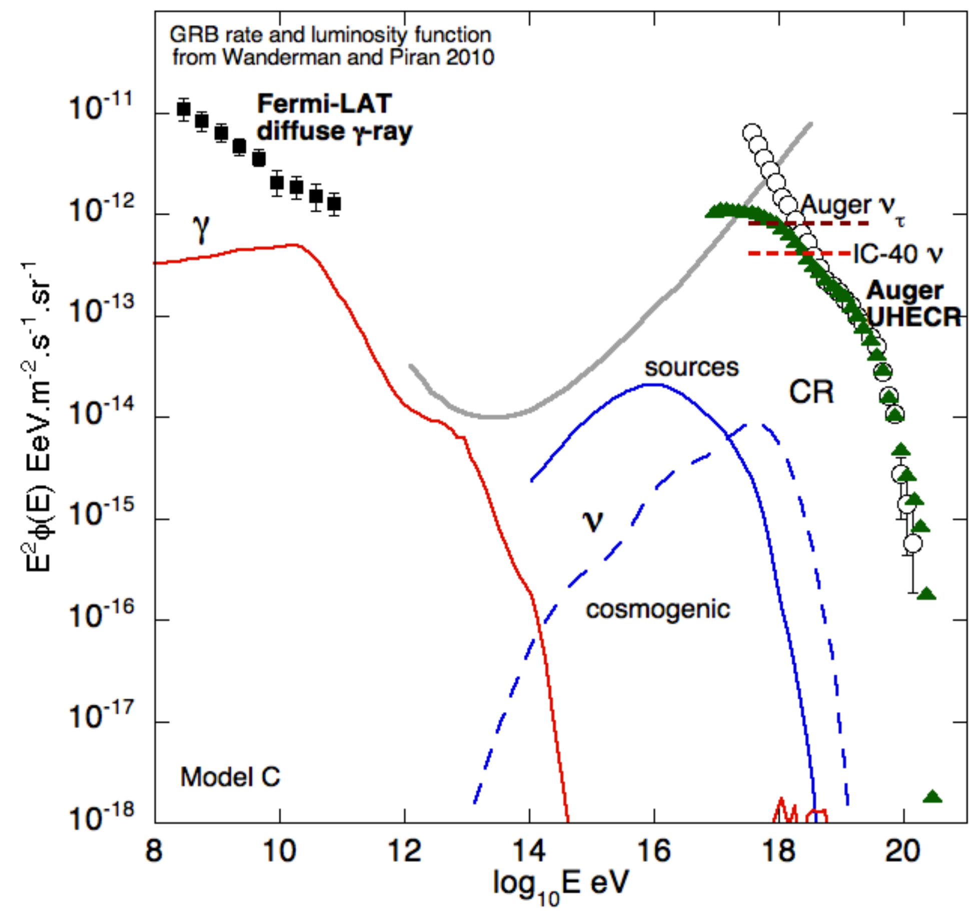
ε_{CR} ~ 0.66

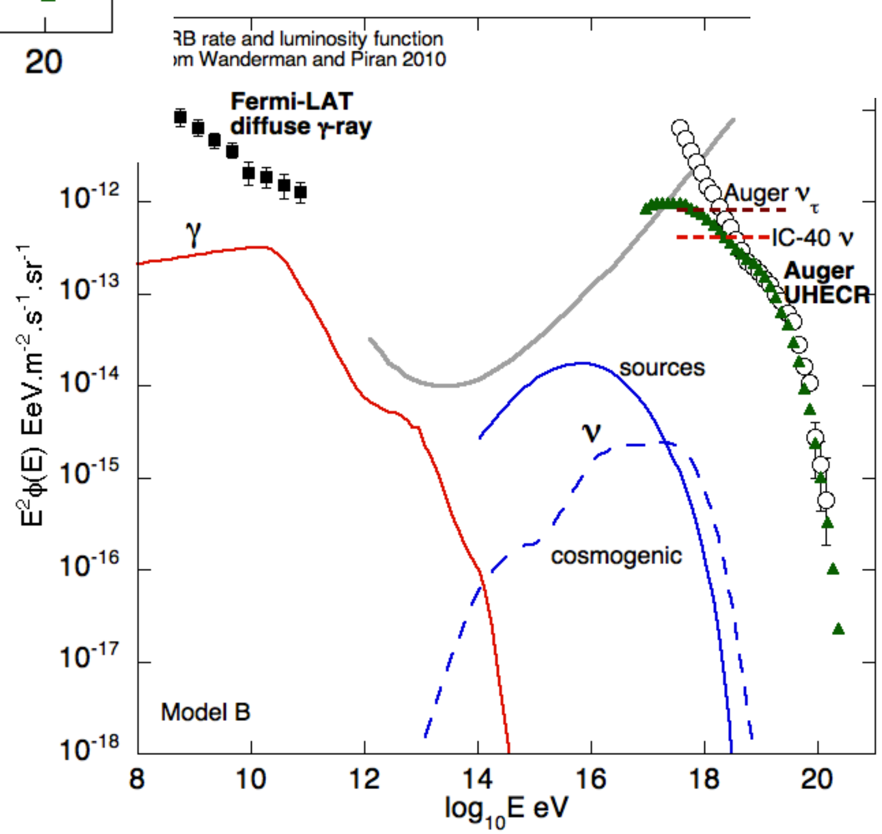
model C

300 realisations of the history of GRB explosions in the Universe

Secondary neutrinos and photons







Rough estimate extrapolating from the latest IceCube publication : between ~0.6 and 0.9 events should have been seen by IceCube in the case of model C
--> a flux of this magnitude should be detected within IceCube lifetime

At most ~20% of the Fermi diffuse gamma-ray flux
--> probably acceptable taking into account the uncertainties on the contribution of known astrophysical (Blazars, radio galaxies, etc...)

conclusions

• gamma-ray bursts internal shocks are able to accelerate nuclei up to 10^{20} eV in in most cases

• Protons acceleration only approach 10^{20} eV for the most extreme luminosities

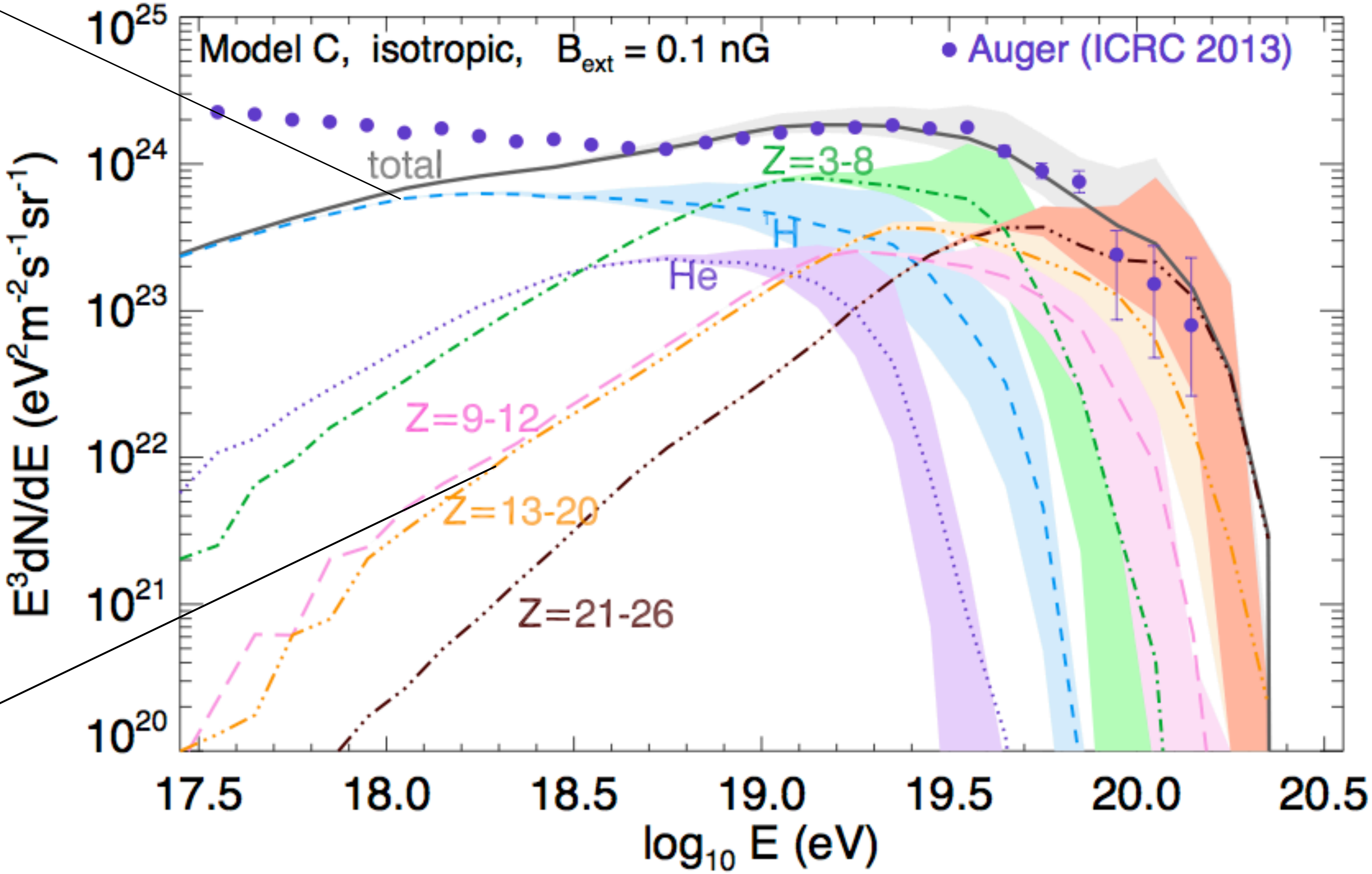
• UHECR acceleration at GRBs internal could fit nicely Auger composition trend providing nuclei are significantly present at internal shocks

• internal shocks as the sources of UHECR are excluded if one assumes equipartition ➔energy dissipated at the shocks mostly goes to cosmic rays ➔ larger wind luminosities required ➔realistic? Compatible with other GRB observation? With theory?

- Not challenged by Ice-Cube current non observation of VHE neutrinos from GRBs
- Potentially interesting feature : proton spectrum expected to be much softer than that of nuclei ==> probably not a specific prediction of GRBs

Propagated spectrum

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



Heavier nuclei spectrum : Much harder due to the high-pass filter effect of the escape process

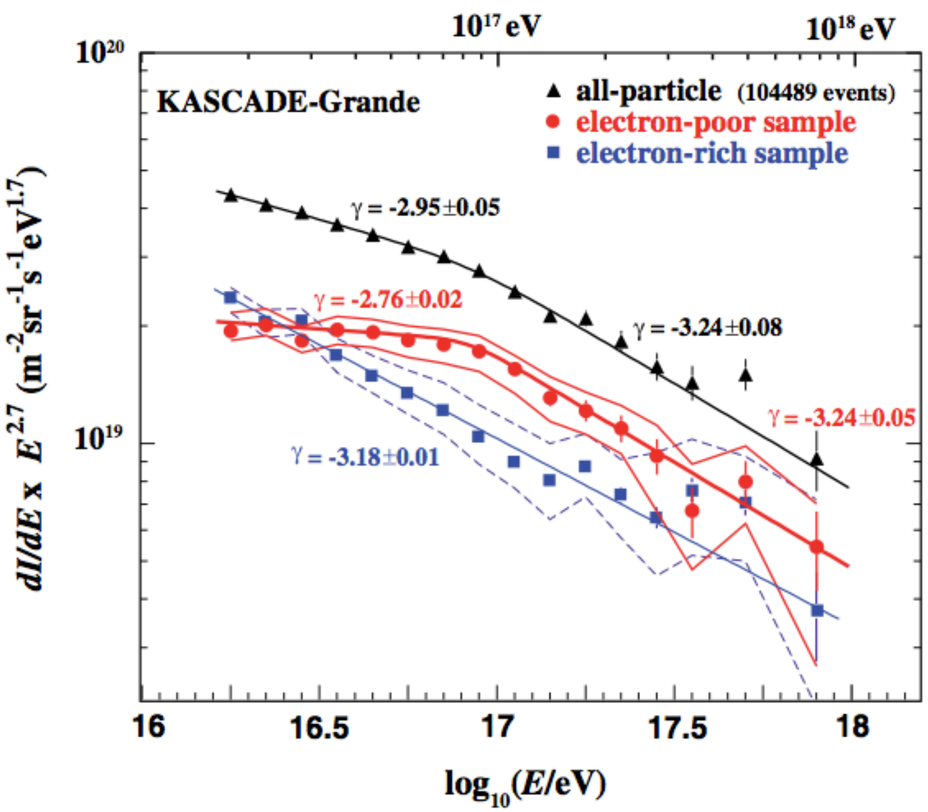
N. Globus, D. Allard, R. Mochkovitch, E. Parizot, MNRAS, 2015

Recent Kascade-Grande analyses

• The Kascade-Grande collaboration recently released composition analyses claimed to be robust (i.e the main conclusions do not depend strongly of hadronic models)

• Based on the separation between electron rich (light CRs) and electron poor (heavy CRs) showers at a given energy

Evidence for a "heavy knee"



KG collab, Phys. Rev. Lett., 2011

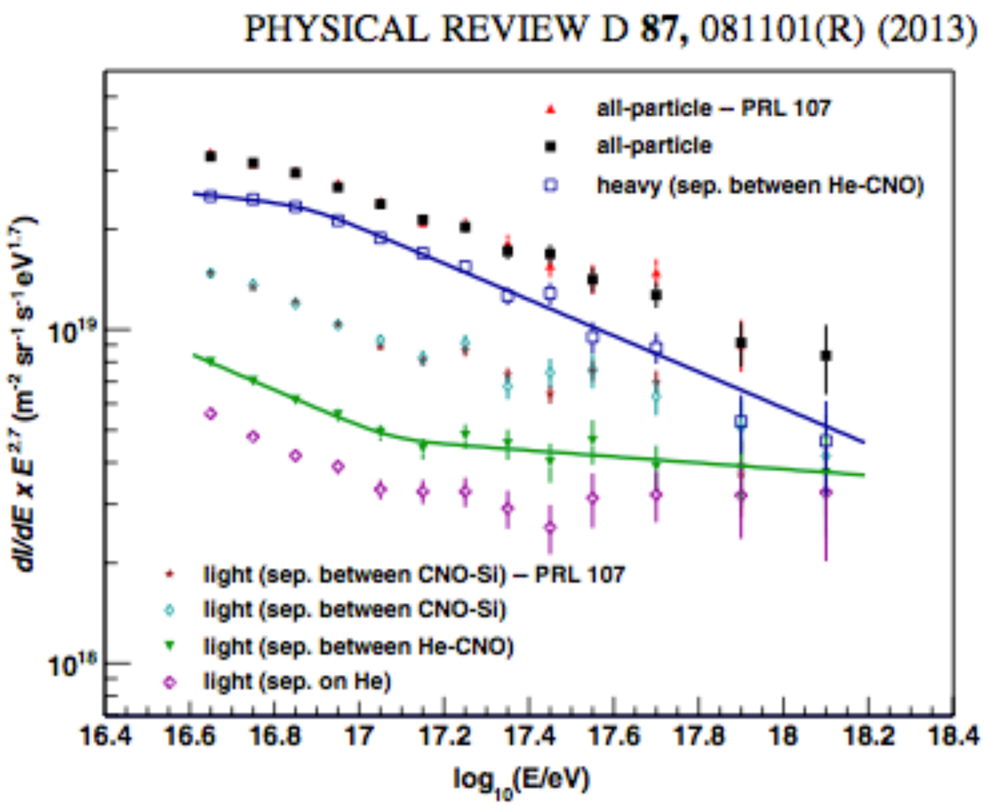
Table 3
Slope of the different spectra and break positions obtained with the three different hadronic interaction models, by applying the k parameter analysis in order to separate the spectra into different mass groups. QGSjet results are from Apel et al. (2011).

Model	EPOS	QGSjet	SIBYLL
All-particle			
γ_1	-3.00 ± 0.03	-2.95 ± 0.05	-2.98 ± 0.05
γ_2	-3.19 ± 0.04	-3.24 ± 0.08	-3.17 ± 0.05
$\log_{10}(E/eV)$	16.82 ± 0.09	16.92 ± 0.10	16.90 ± 0.12
significance (σ)	2.8	2.1	2.7
Heavy component			
γ_1	-2.98 ± 0.05	-2.76 ± 0.02	-2.79 ± 0.03
γ_2	-3.54 ± 0.10	-3.24 ± 0.05	-3.28 ± 0.07
$\log_{10}(E/eV)$	16.82 ± 0.07	16.92 ± 0.04	16.96 ± 0.04
significance (σ)	4.0	3.5	7.4
Light component			
γ	-3.05 ± 0.01	-3.18 ± 0.01	-3.21 ± 0.02

KG collab, PASR, 2014

- Significant break of the heavy component (supposed to be Si+Fe) spectrum seen for all hadronic models
- Moderate change of spectral index ~0.5 in all cases
- The heavy component does not seem to disappear immediately after its knee (smooth knee rather than sharp)
- The heavy component still seems to be significantly there at 10^{18} eV in all cases
- The hadronic model dependence is mostly found in the relative abundance of the heavy component (not in the existence or the sharpness of the break)

Evidence for a “light ankle”

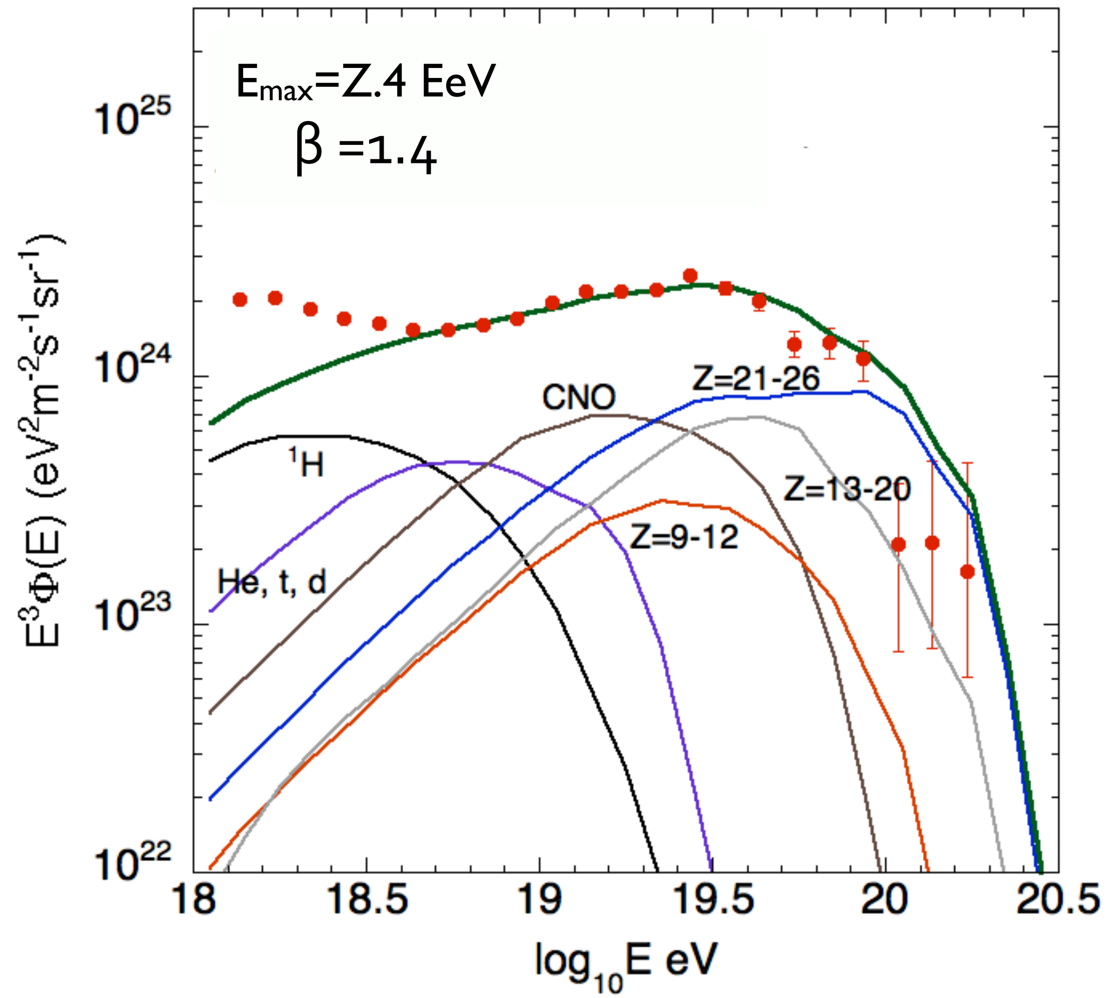


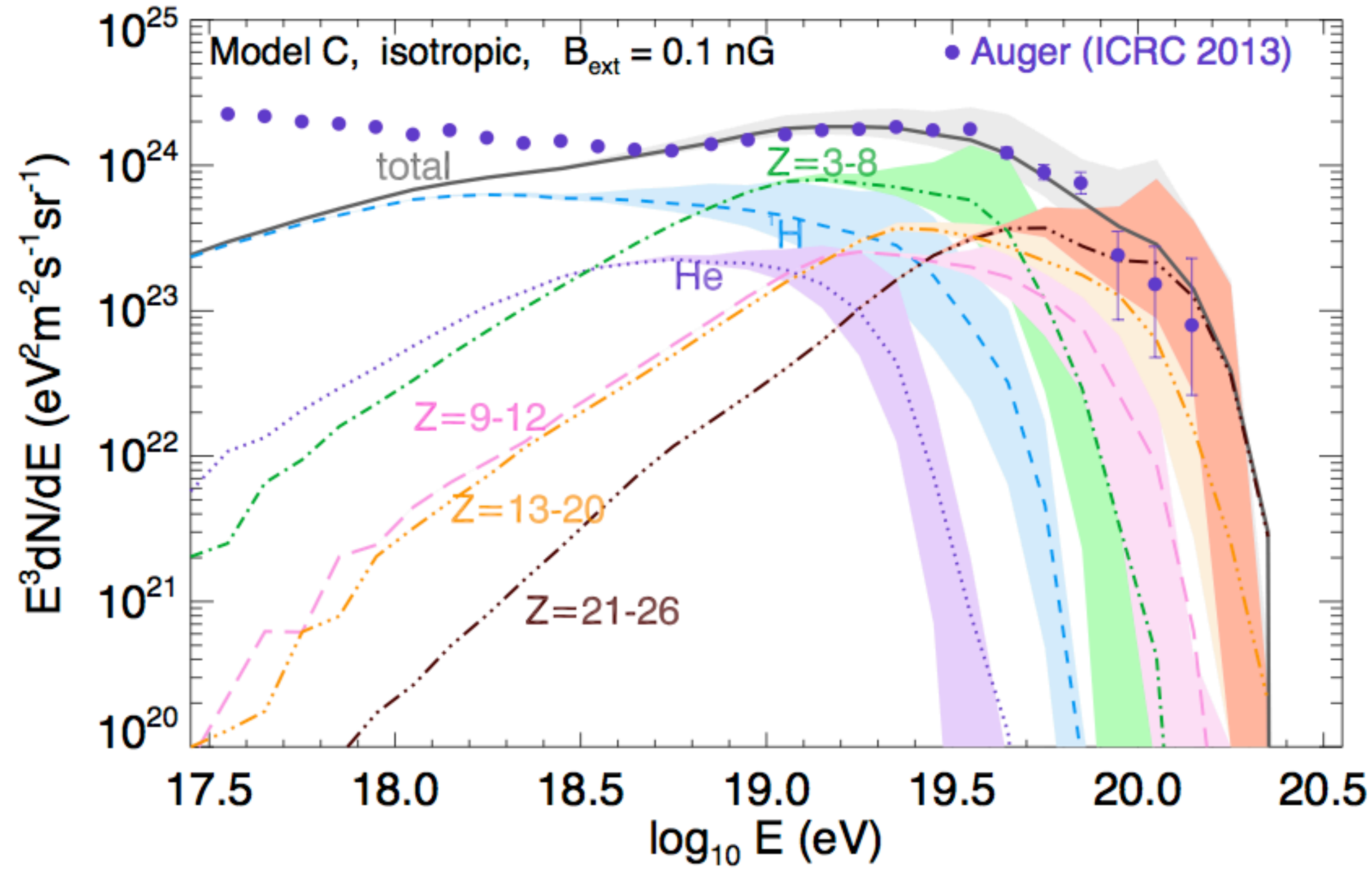
- A similar analysis showed evidence for an “ankle” in the light component
- The spectral index before the “light ankle” is compatible with the post knee spectral index of the heavy component
- Likely explanation : an extragalactic light component is starting to emerge on top of the light galactic component

==> smooth knee for the light component too ==> post knee protons at ~10^{17} eV (?)

- Cross check with other hadronic models ==> the result seems to be confirmed

Consequences for UHECRs phenomenology





In the context of a simple model with all the species having the same spectral no way to explain the emergence of the proton component at 10^{17} eV due to the hard source spectral index required to fit the UHECR spectrum

==> some have proposed a second extragalactic component to account for the KG observations

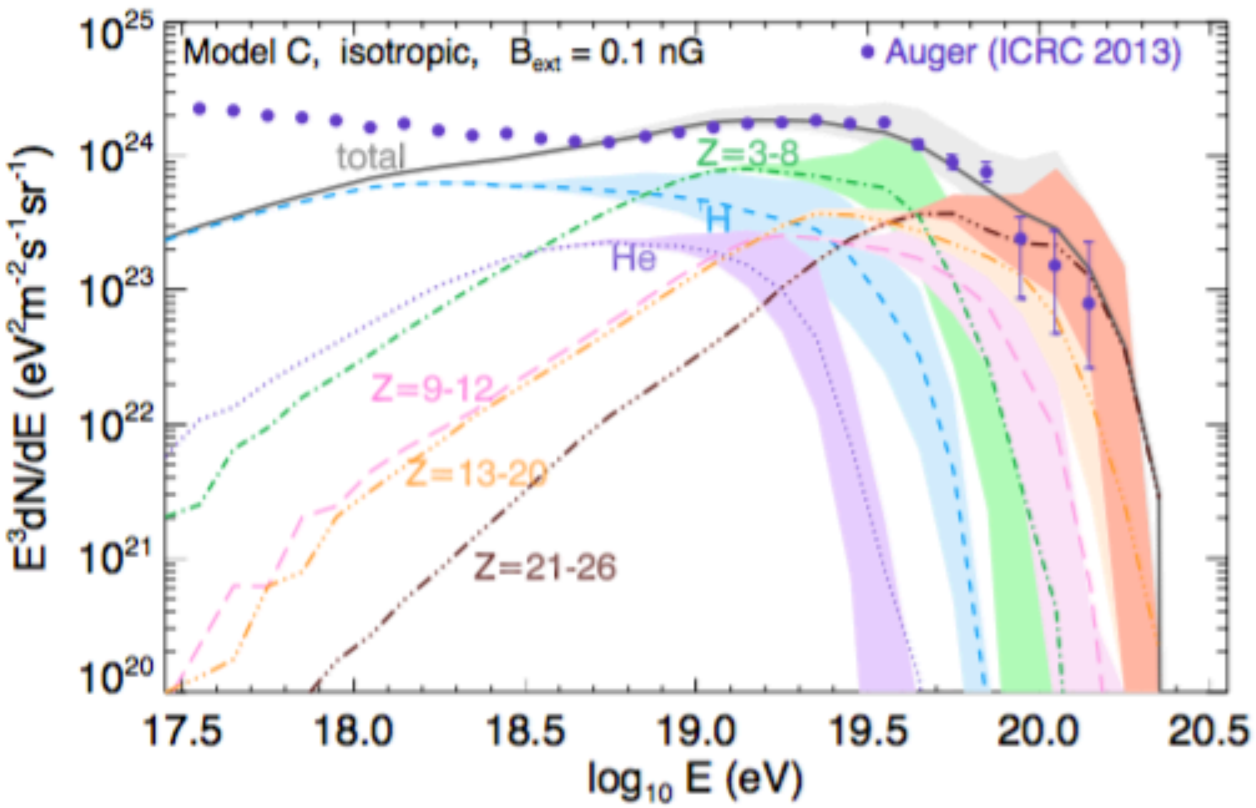
In our modeling :

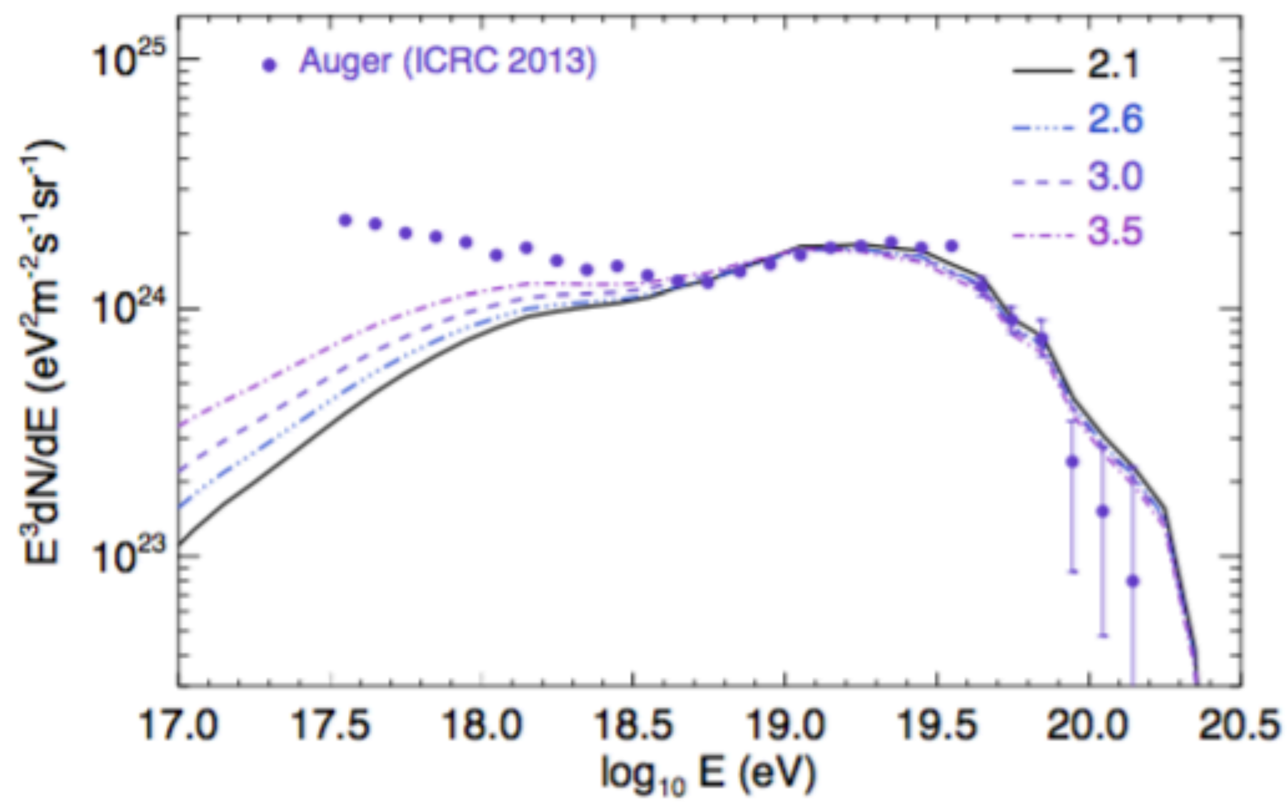
- the proton component is soft due the escape of neutron (close to the spectrum of accelerated cosmic-rays) from the source environment
- heavier nuclei have a much harder spectrum (the escape from the source acts as an high pass filter)

==> provides in a quite natural way the hard source spectrum for nuclei required to fit Auger and the softer proton component required to explain KG observations

Extragalactic component

We stick to what was obtained after the study of GRB internal shock only allowing for a change of the assumed cosmological evolution of the source





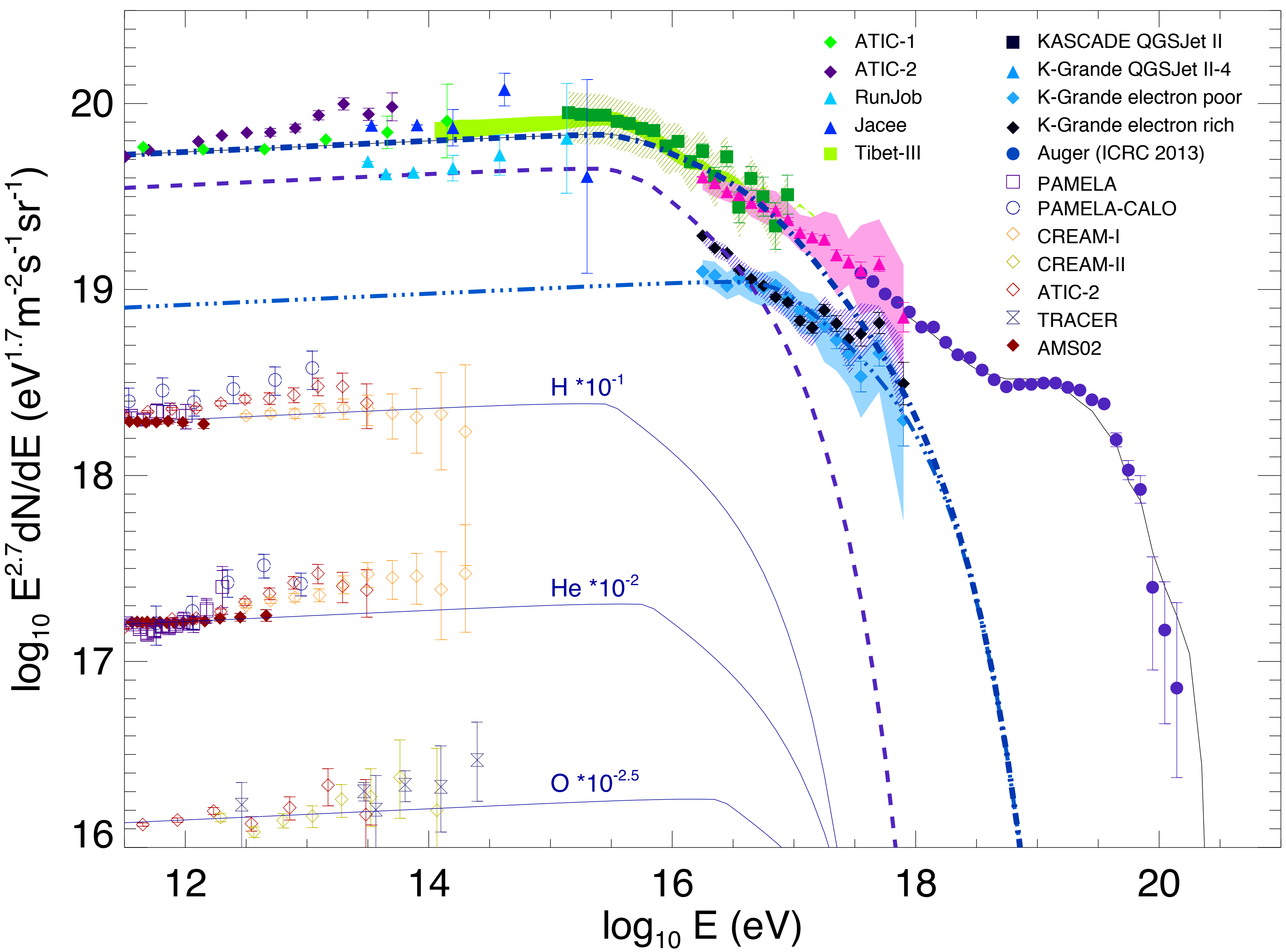
N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

Galactic component

- KG does not suggest any strong asymmetry between the different components
- the knees of the different components are probably smooth

==> we use the same broken power law for the different species (break at the respective knees)

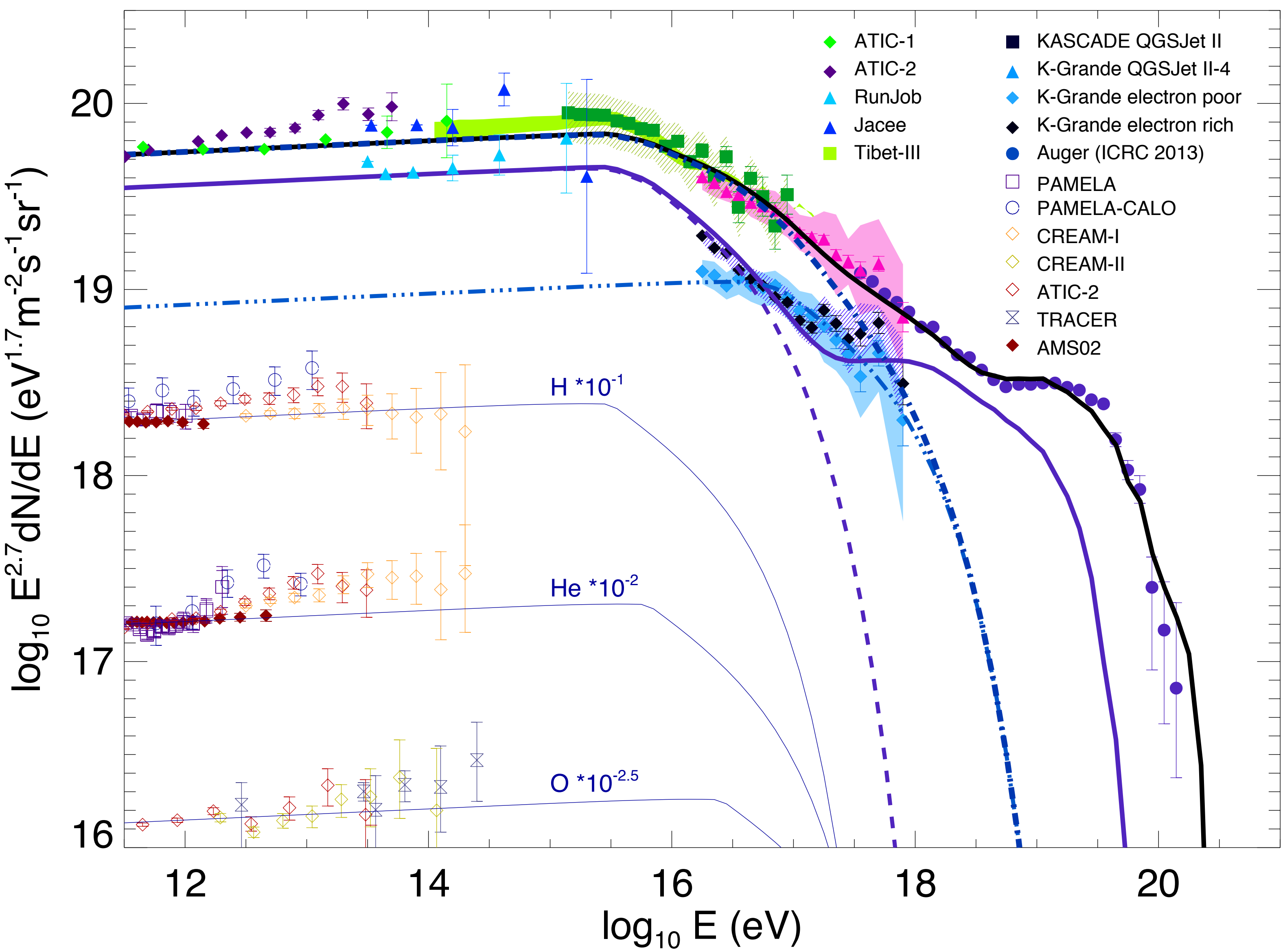
We normalize the different component with satellites measurements



$E_{break(p)} = 10^{15.5}$ eV,
$x = 2.67$, $\Delta x = 0.45$
$E_{max(p)} = 6\,10^{16}$ eV
(exponential cutoff above E_{max})

N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

Galactic + extragalactic component



N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

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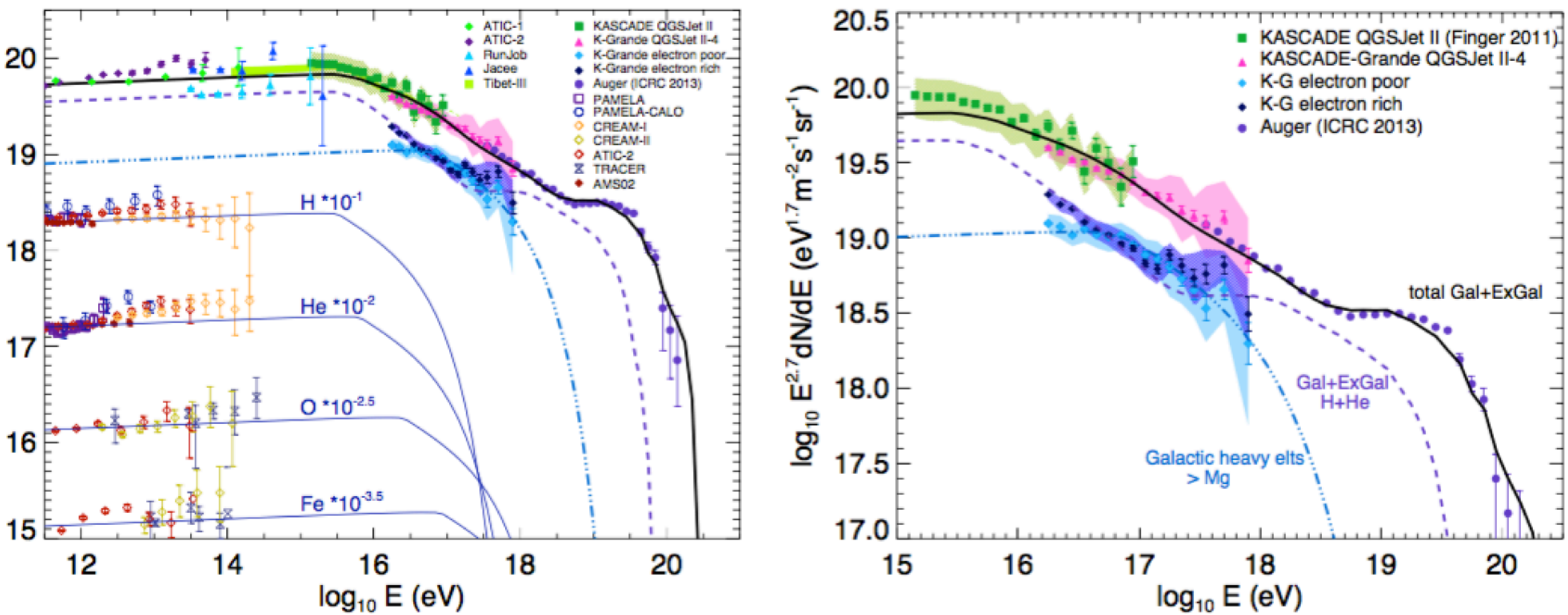
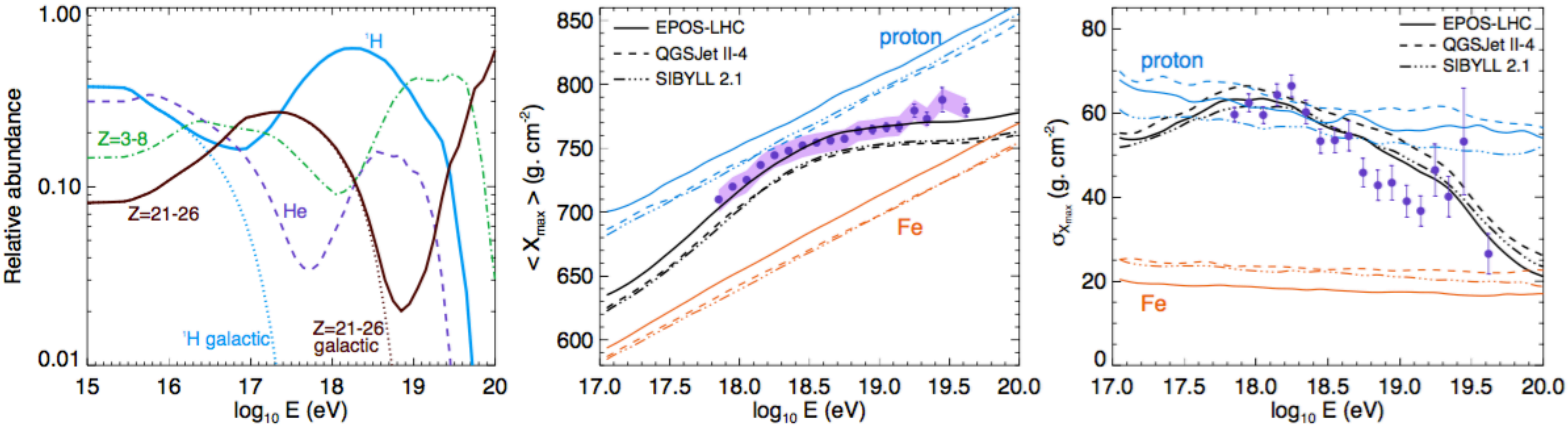


N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

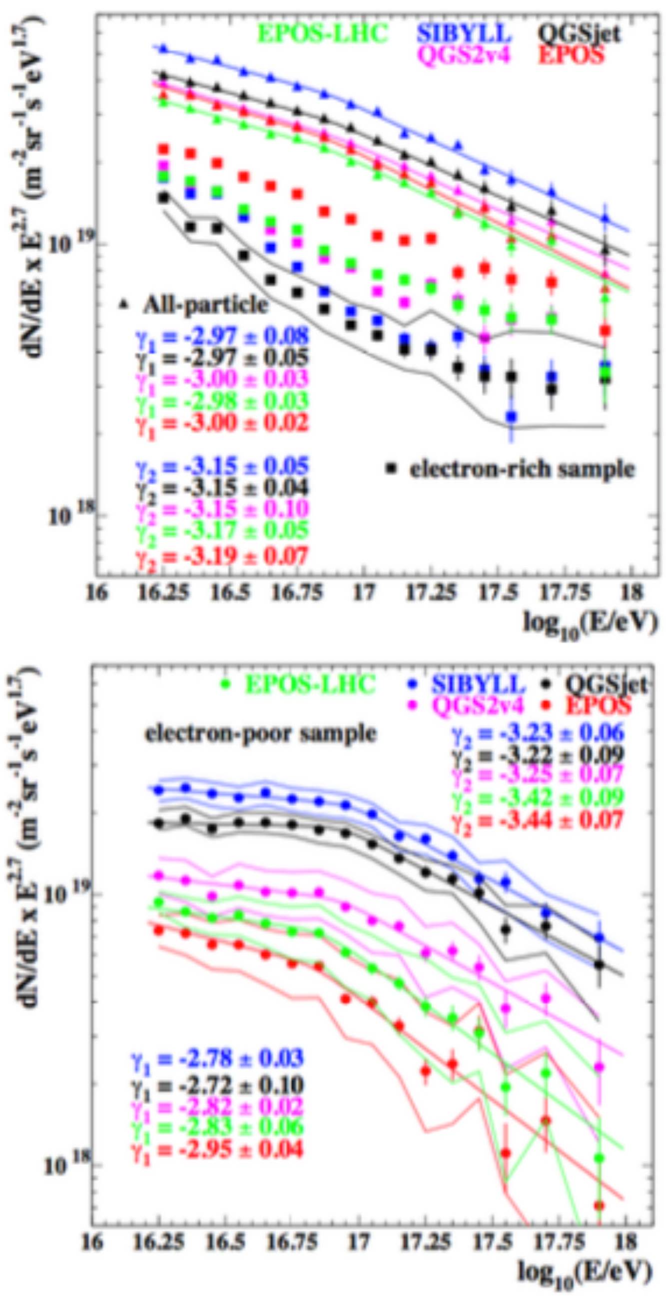
Evolution of the composition



N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

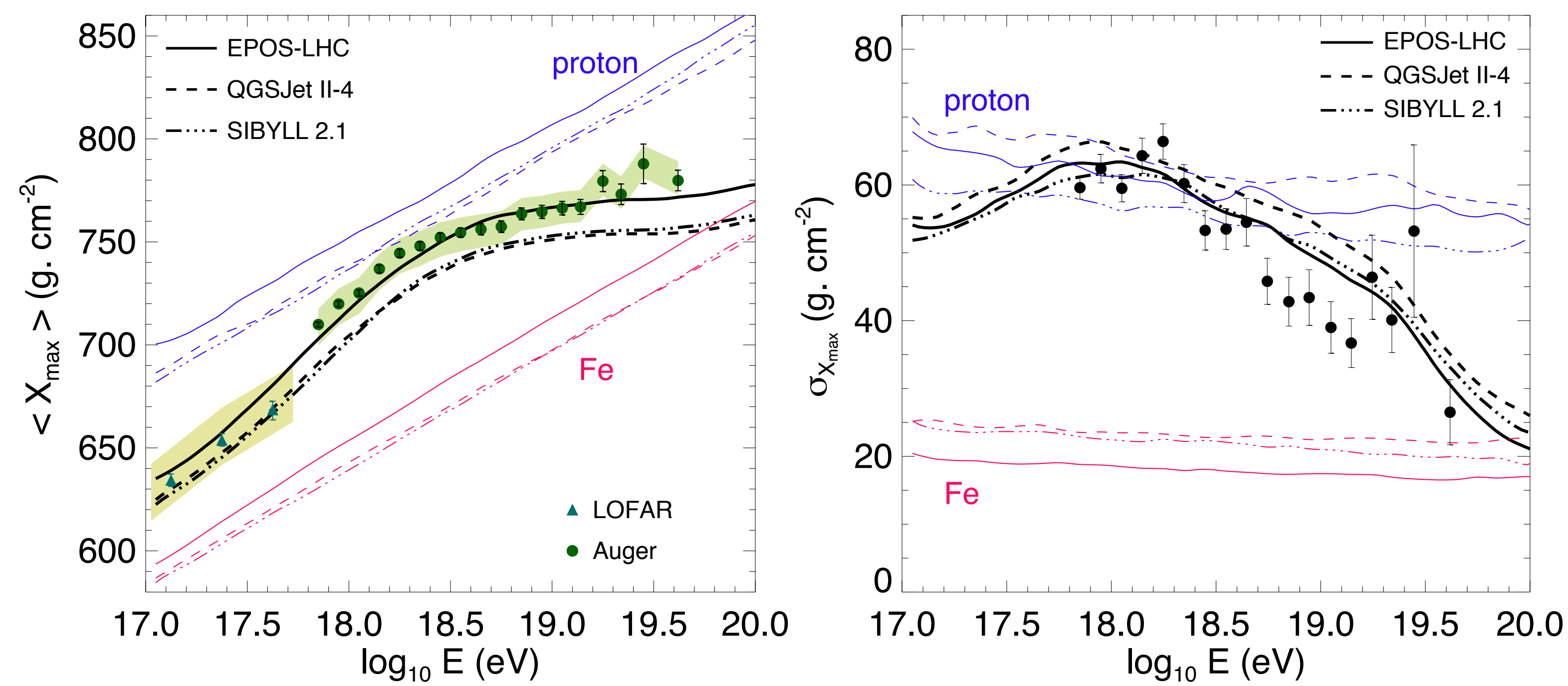
- Good description of Auger composition observables when using the latest (LHC tested) hadronic models
- Good agreement with more recent Auger analyses (down to 10^{17} eV) and recent LOFAR (radio) measurements
  - NB : Auger and KG composition results are quite coherent when analyzed with the most recent hadronic models

New data



M. Bertaina ICRC 2015

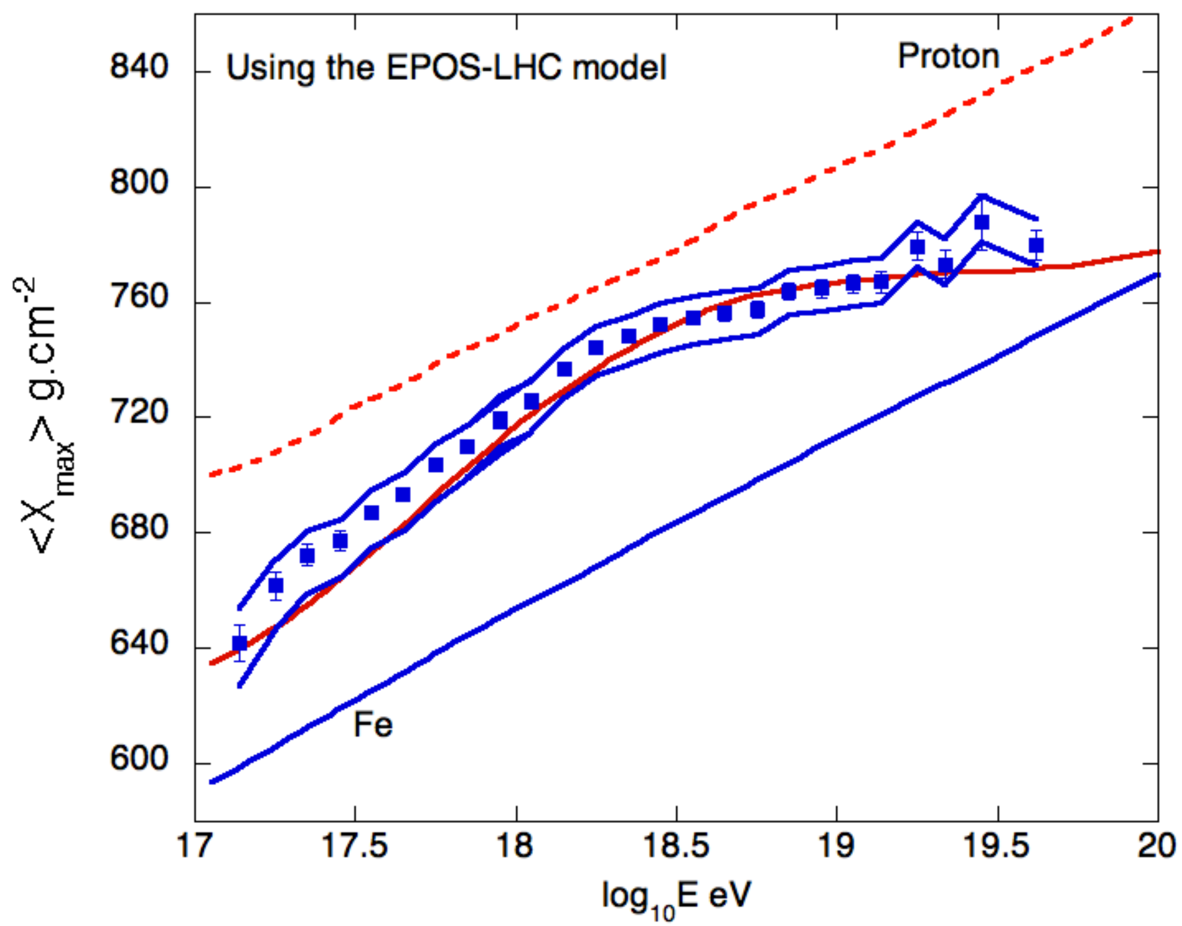
KG data analyses using EPOS-LHC shown at ICRC 2015
- light component quasi identical to that of QGSJet-II4
- heavy component a bit lower
---> relatively small differences between the two models

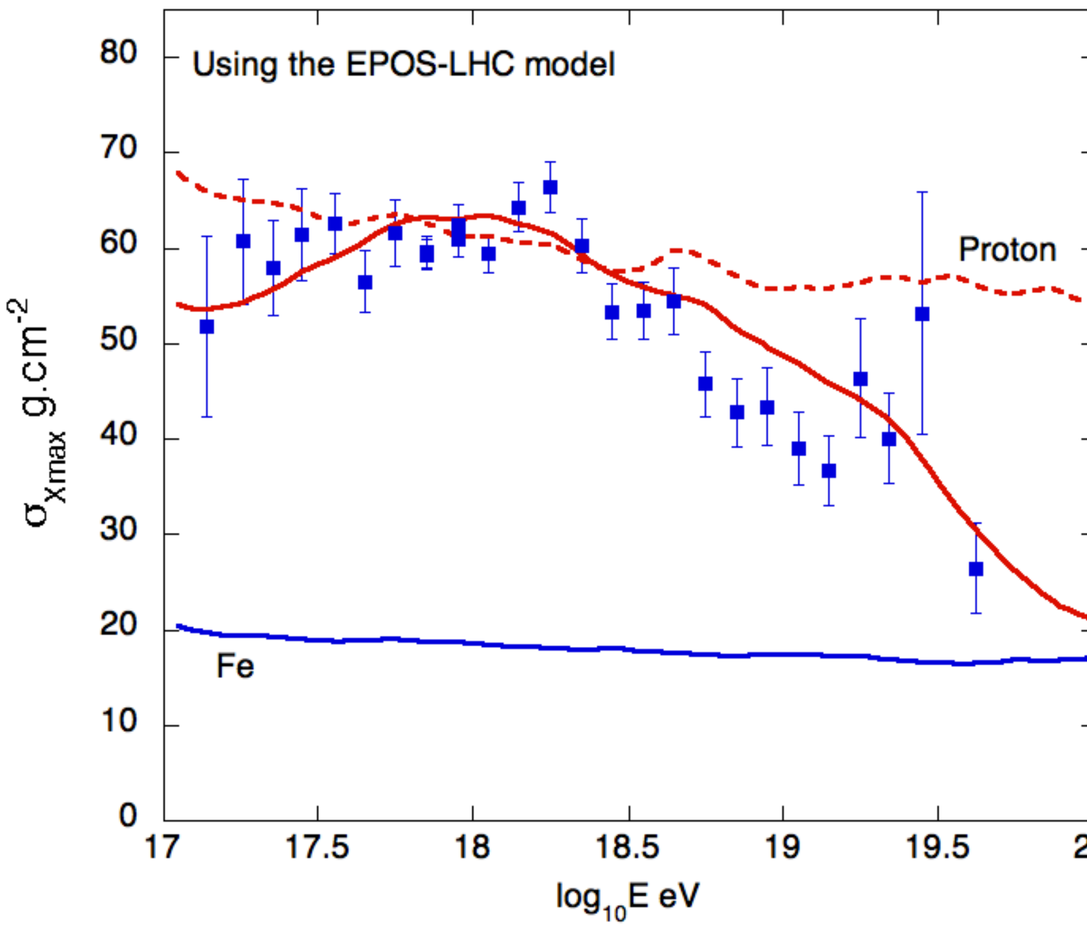


LOFAR (2016) : data analyzed with QGSJet-II4, relatively good agreement

Data points expected to slightly move up (a few g.cm^{-2}) when using EPOS-LHC ---> the agreement should be very good with this model

New data





Auger released the first data from the high elevation fluorescence telescope (HEAT)
--> mean and spread of X_{max} now available down to 10^{17} eV
--> very good qualitative agreement between the model with two component (one Galactic - one extragalactic) and the features seen in the data
--> very correct quantitative agreement with the most recent versions of hadronic models
--> hadronic models are key to get a coherent global understanding of data coming from different experiments on a wide energy range
--> The situation seems to have improved with the recent version of the hadronic models
--> Future developments along with future data will be key to solve the puzzle of cosmic-ray origin