האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Noemie Globus

Is it possible to account for the UHECR data with a transient source model?

work in collaboration with

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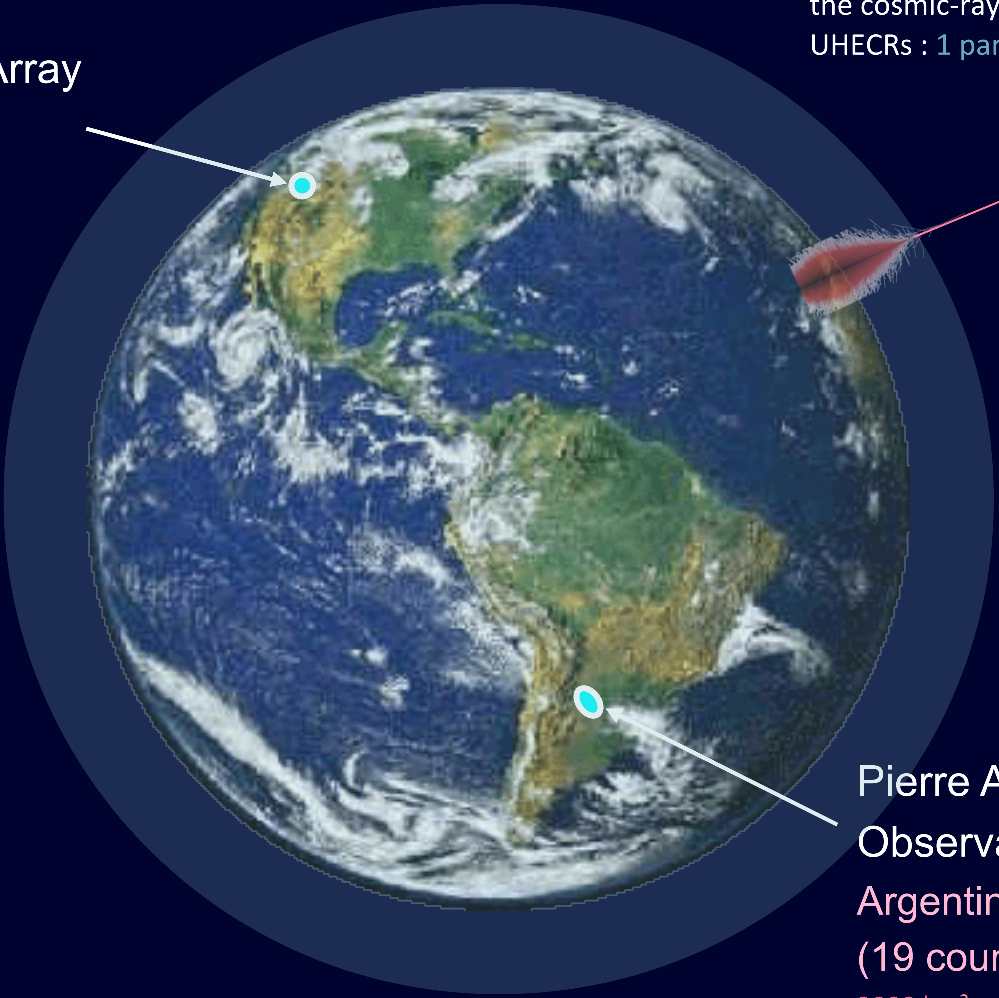
R. Mochkovitch (IAP, Paris)

Beyond a PeV, IAP, Sept.13-16, 2016

UHECR Observatories



the cosmic-rays 4 CR/cm2/s => 1 kg/year
UHECRs : 1 part/km2/century

Telescope Array
Utah, USA
(5 countries)
700 km^2 array
3 fluorescence telescopes

Pierre Auger Observatory
Argentina
(19 countries)
3000 km^2 array
4 fluorescence telescopes

Cosmic Rays primary observables

Energy spectrum

↓

Differential flux

Mass spectrum

↓

composition

Angular spectrum

↓

Arrival direction

Situation at ultra high energy : recent results of PAO and TA

Auger Anisotropy Data Set (ApJ 804 15, 2015)

SD data from period **1.01.2004 — 31.03.2014** (10 years)

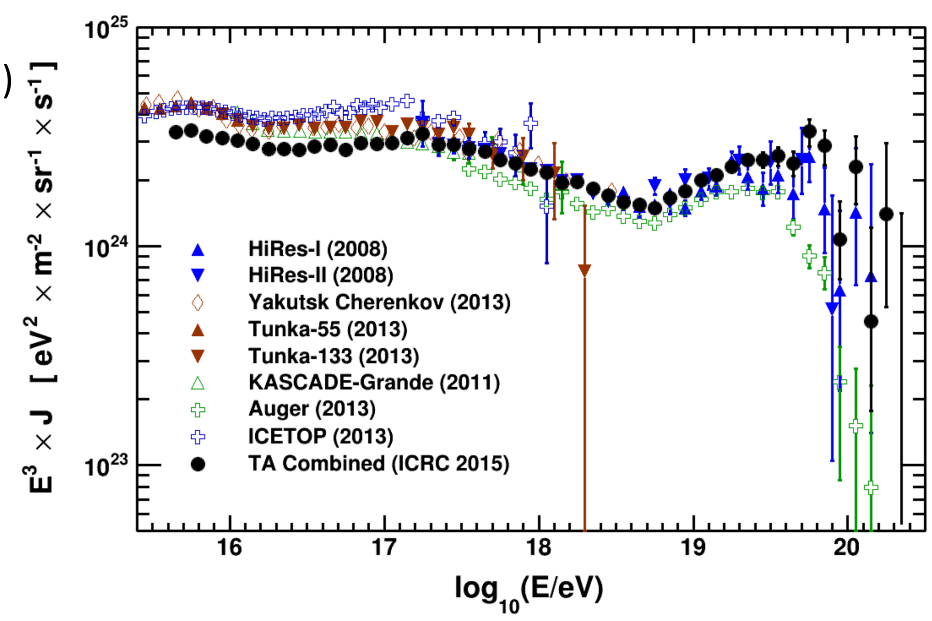
Zenith angle up to 80°

Geometrical acceptance; exposure **66,452 km² yr sr**

- 231 above 52 EeV

Angular resolution: better than 0.9°

Energy resolution: 14%



- baryonic matter density extremely low => p-p or p-N interactions are negligible

- what about photo-interactions?

Situation at ultra high energy : recent results of PAO and TA

TA Anisotropy Data Set (John Matthews' talk, ICRC 2015)

SD data from period **12.05.2008 — 11.05.2015** (7 years)

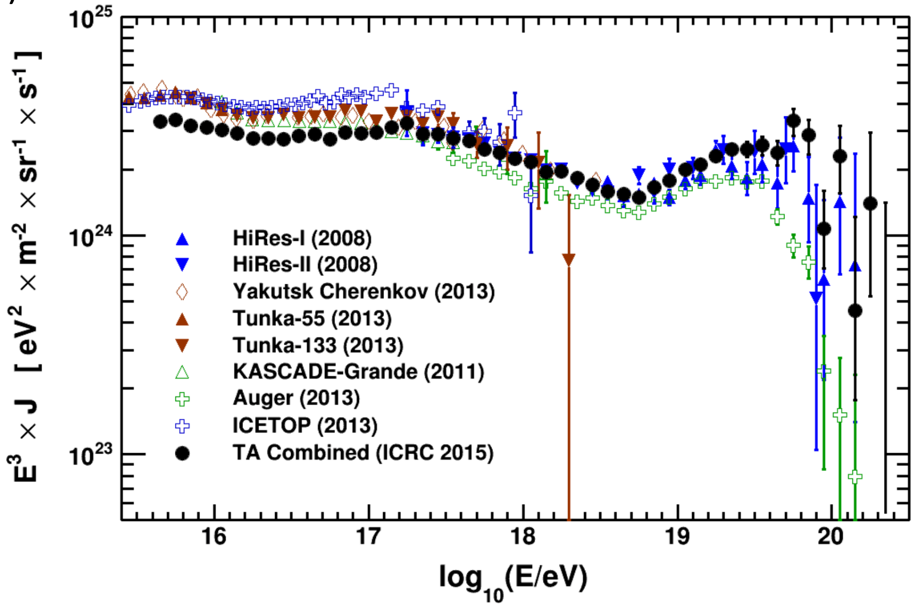
Zenith angle up to 55°, loose border cut

Geometrical acceptance; exposure **8,600 km^2 yr sr**

- 83 above 57 EeV

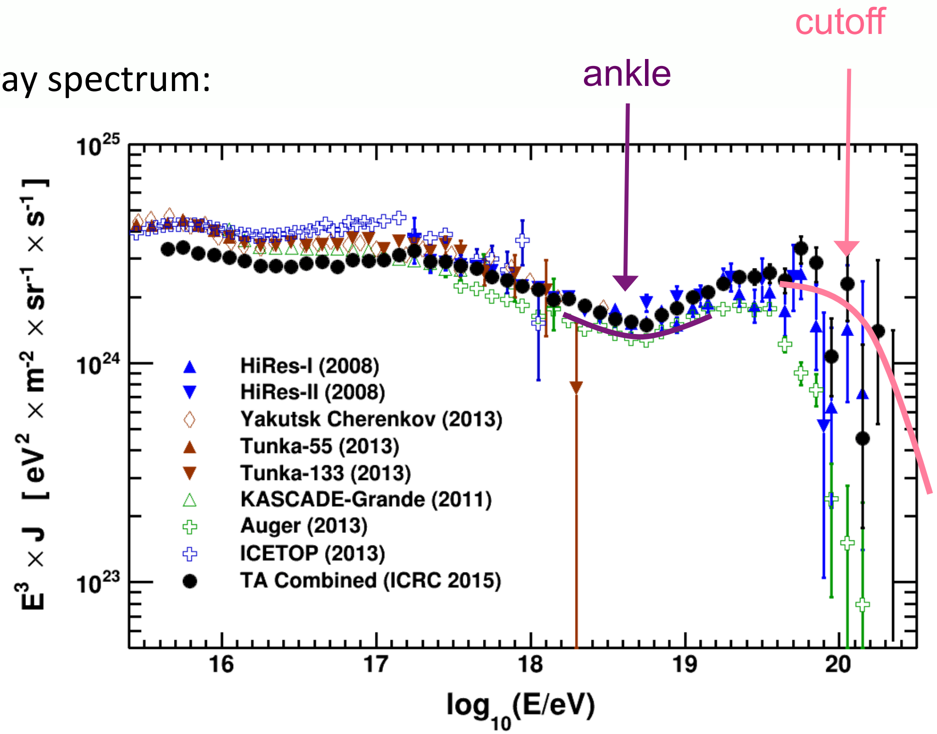
Angular resolution: better than 1.5°

Energy resolution: 20%



Situation at ultra high energy : recent results of PAO and TA

Both experiments observe two features in the cosmic-ray spectrum:



- an ankle at ~3–5 10^{18} eV
- a "cutoff" at ~3 10^{20} eV

How do we interpret them?

- UHE cosmic-rays are thought to be extragalactic

- they must travel huge distance from their source to the Earth

- they might loose energy (expansion of the Universe, interactions)

- baryonic matter density extremely low

=> p-p or p-N interactions are negligible

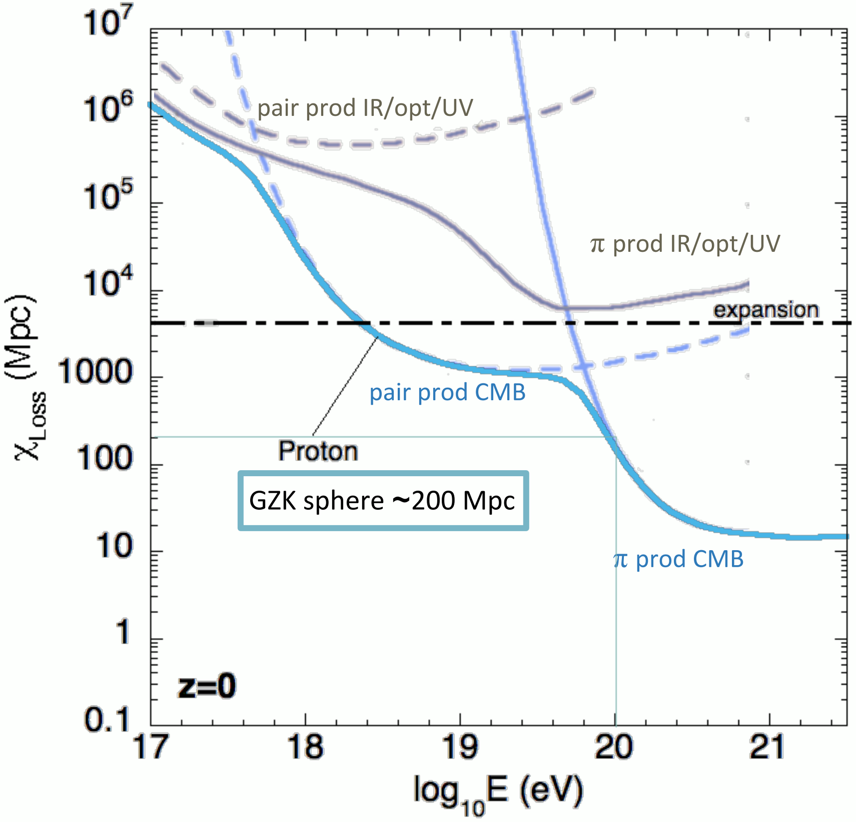
- what about photo-interactions ?

“energy horizon”

There is a upper limit on the energy of cosmic rays coming from distant sources (Greisen–Zatsepin–Kuzmin limit)

The GZK attenuation length: pure proton case

Proton attenuation length



$$\chi_{loss} = c\left(-\frac{1}{E}\frac{dE}{dt}\right)^{-1}$$

Protons suffer of:

-adiabatic losses

$$\frac{dE}{dz} = \frac{E}{(1+z)}$$

-pair production

low inelasticity process
interaction with CMB ~ 10^{18} eV

$$p + \gamma \to p + e^+ + e^-$$

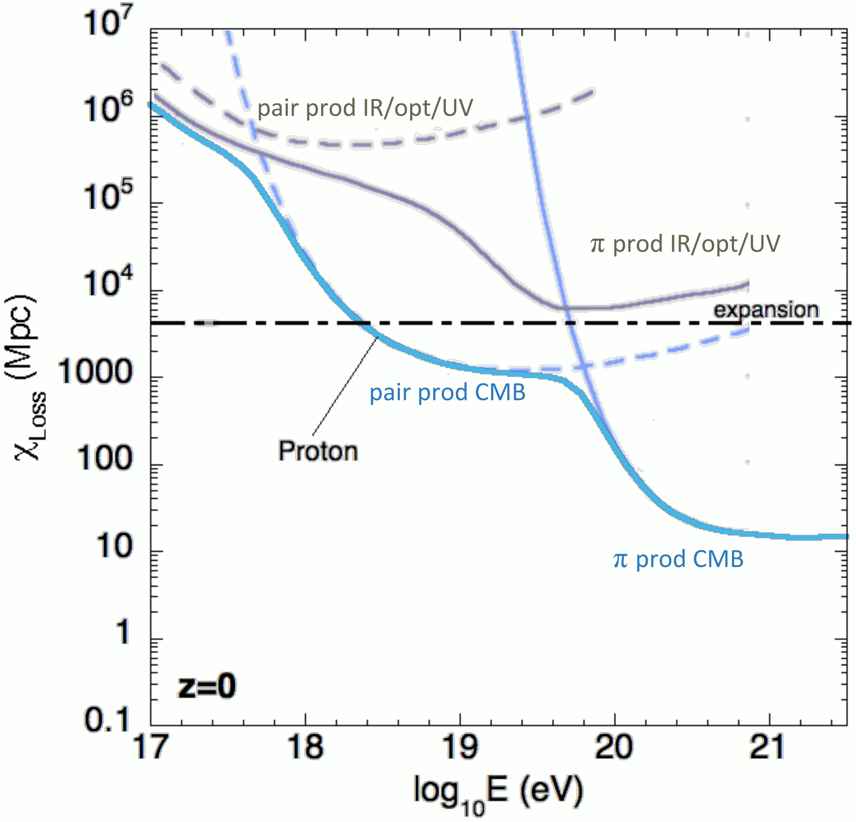
-pion production

large inelasticity process (~20%)
interaction threshold ~7.10^{19} eV

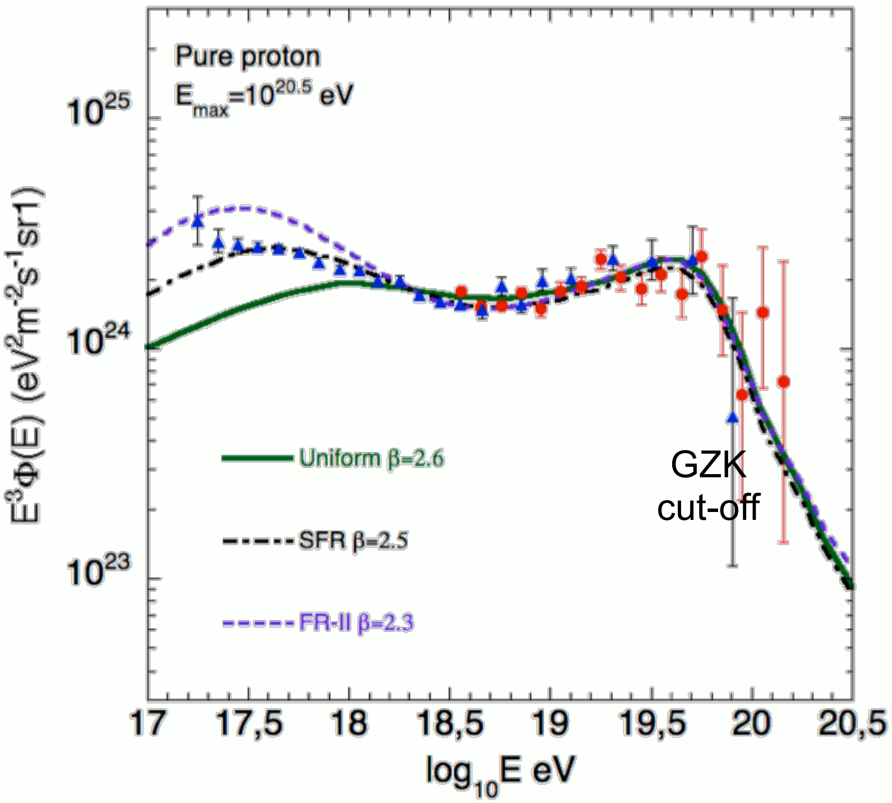
$$p + \gamma \to p|n + \Pi^0|\Pi^+|\Pi^-$$

The GZK attenuation length: pure proton case

Proton attenuation length



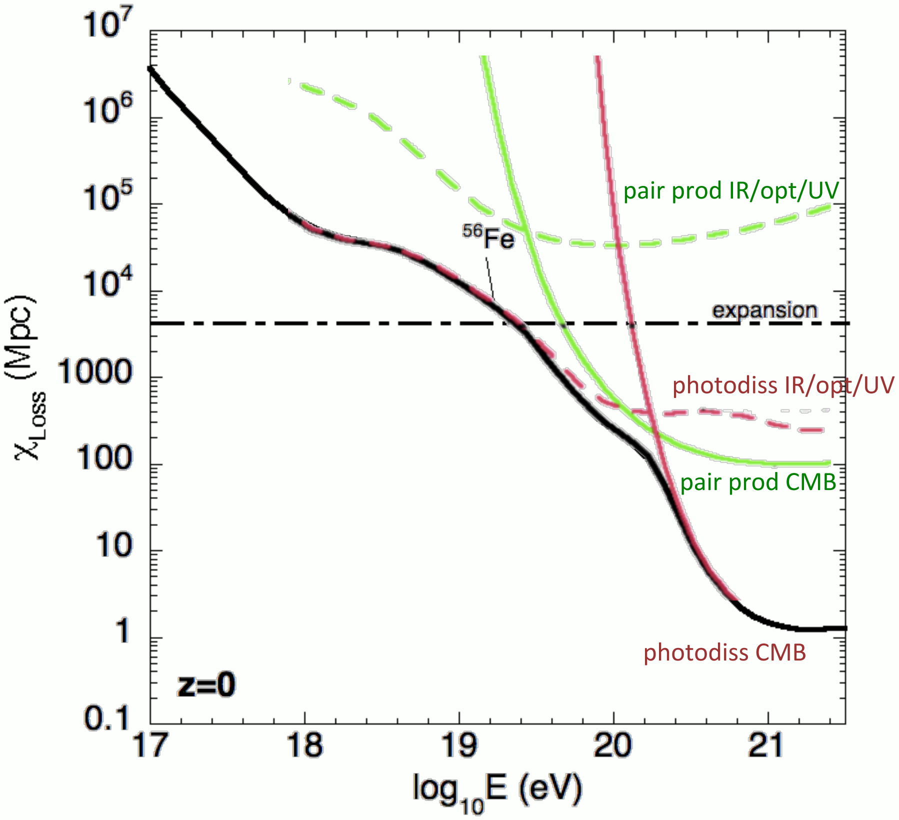
Calculation of the propagated spectrum (Allard 2005)



The ankle can be fitted by the extragalactic component itself : pair production dip->the ankle feature has nothing to do with the transition (model developed by Berezinsky et al., 2002-2007)

The GZK attenuation length for nuclei

iron attenuation length

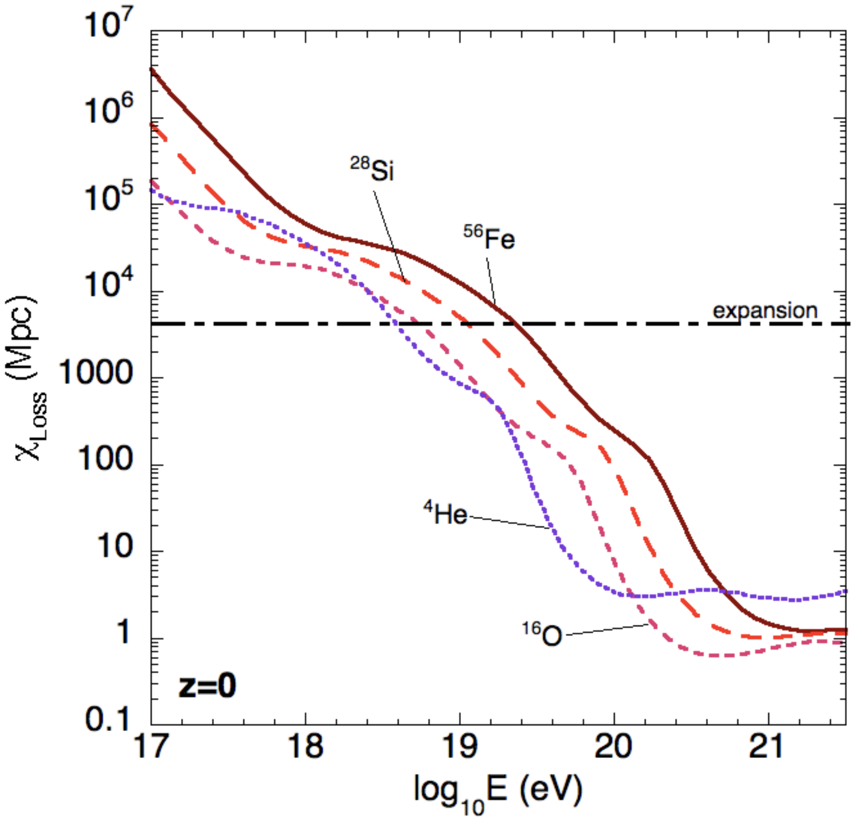


Compound nuclei suffer of:

- Processes triggering a decrease of the Lorentz Factor
  - Adiabatic losses
  - Pair production losses (energy threshold ~A·10^{18} eV)
- Photodisintegration processes
  - Giant Dipole Resonance (GDR); threshold ~ 8 - 20 MeV largest σ and lowest threshold (Khan et al., 2005)
  - Quasi-Deuteron process (QD); threshold ~ 30 MeV
  - Pion production (BR); threshold ~ 145 MeV

The GZK attenuation length for nuclei

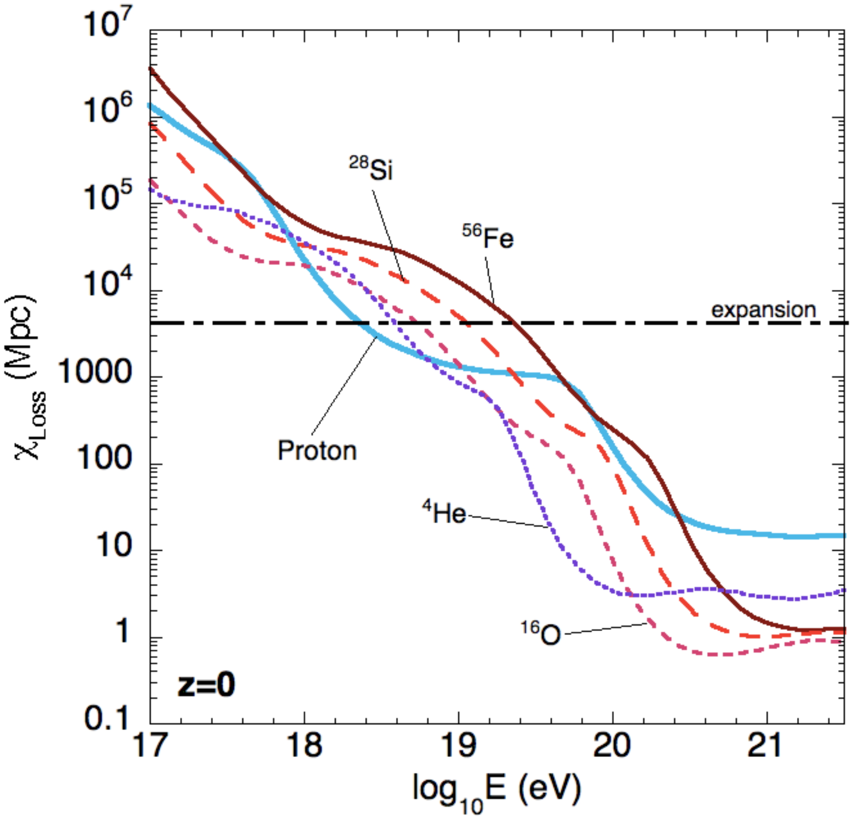
nuclei attenuation length



- similar shape of the attenuation length curve for complex nuclei (same processes at play) shifted in energy
- hard to survive above 10^{19} eV for low and intermediate mass nuclei
- different shape for protons (important implications)
- mostly protons and heavy nuclei expected at the highest energies

The GZK attenuation length for nuclei

nuclei attenuation length



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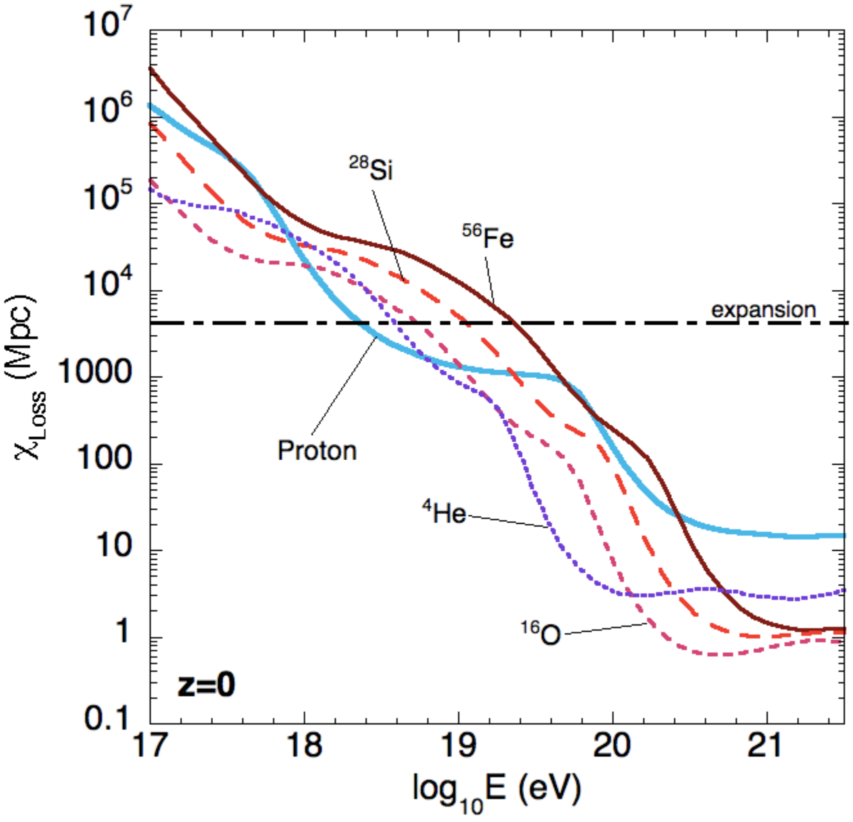
nuclei attenuation length



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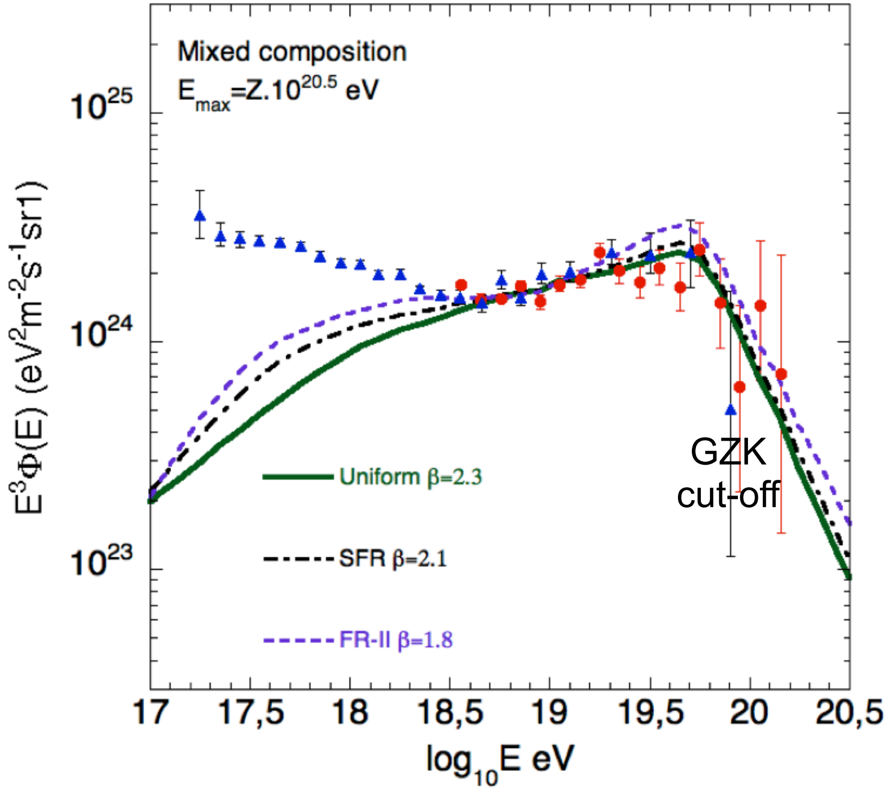
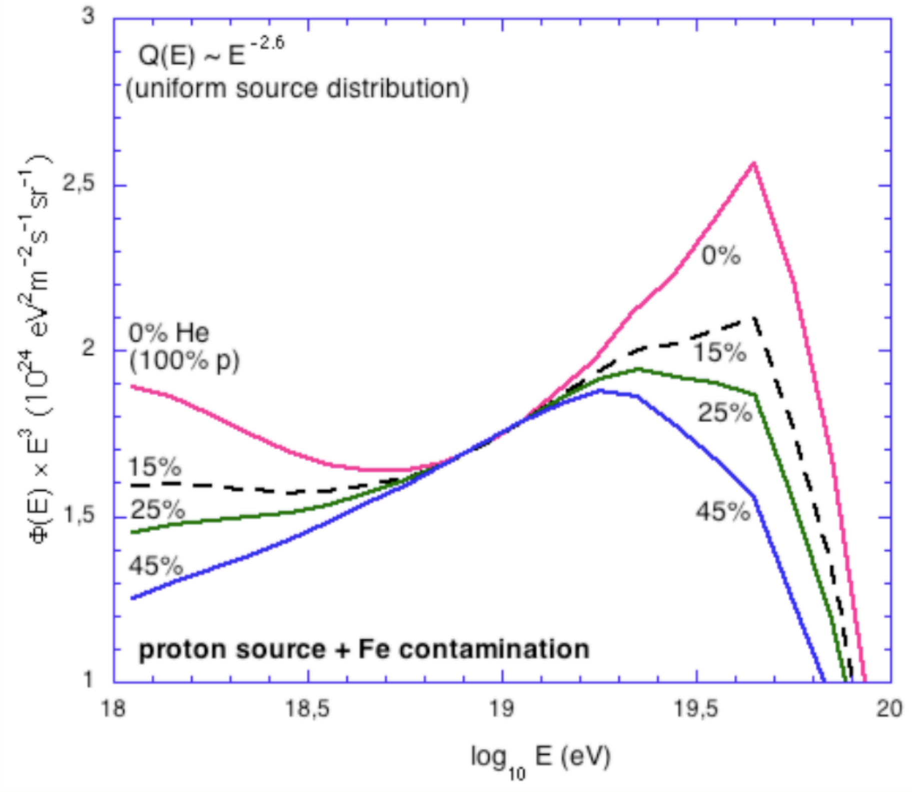


No pair production dip with a mixed composition

The GZK attenuation length for nuclei



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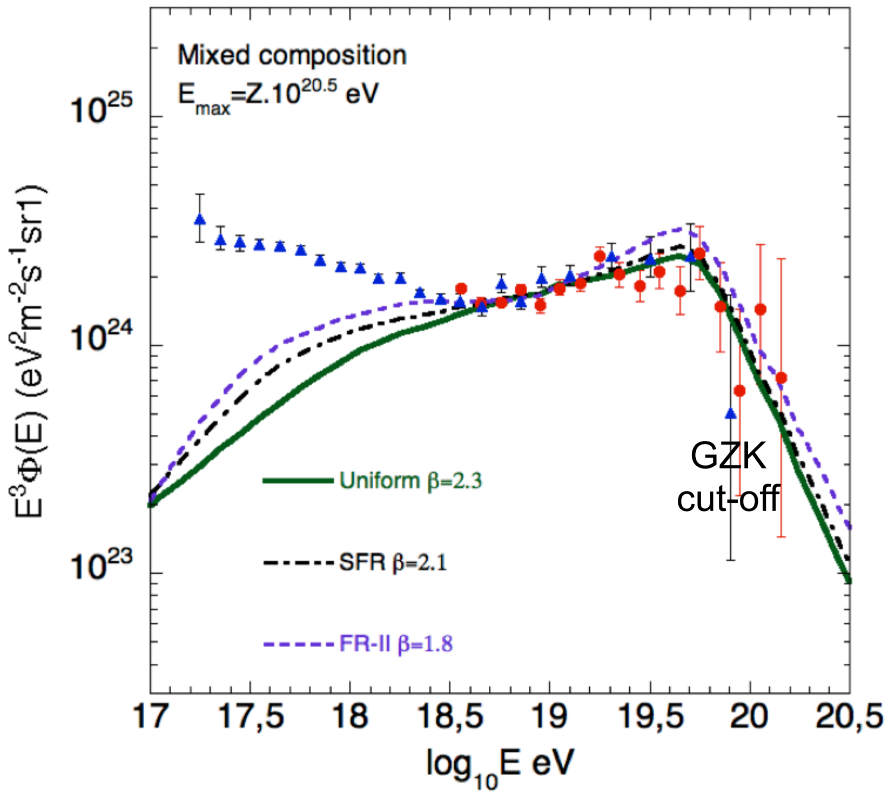
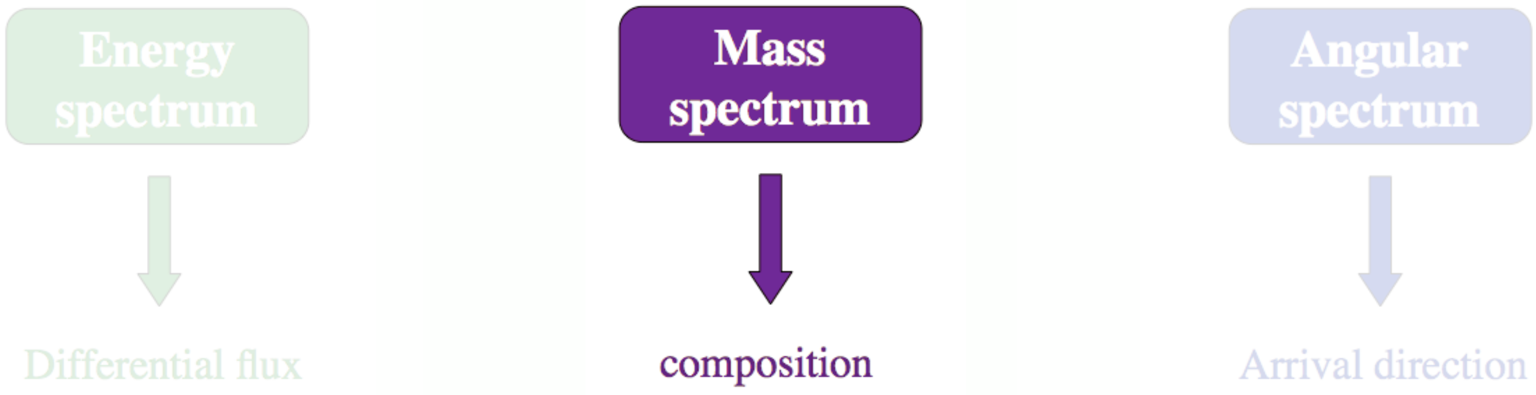


No pair production dip with a mixed composition

A small admixture of nuclei erase the dip !

The ankle is interpreted as the signature of the GCR/EGCR transition

Cosmic Rays primary observables



Energy spectrum

Differential flux

Mass spectrum

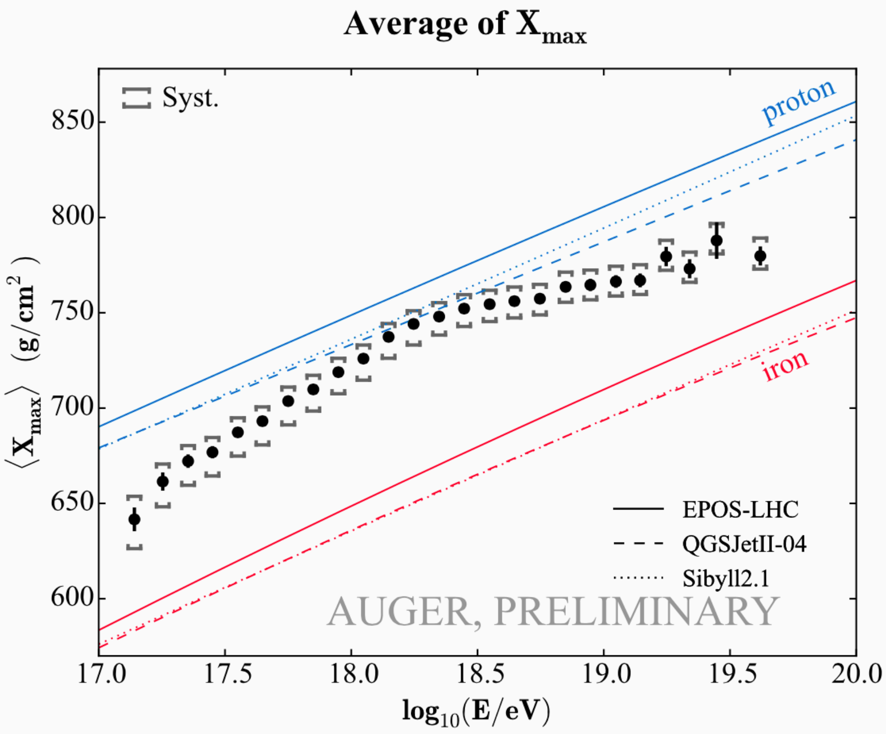
composition

Angular spectrum

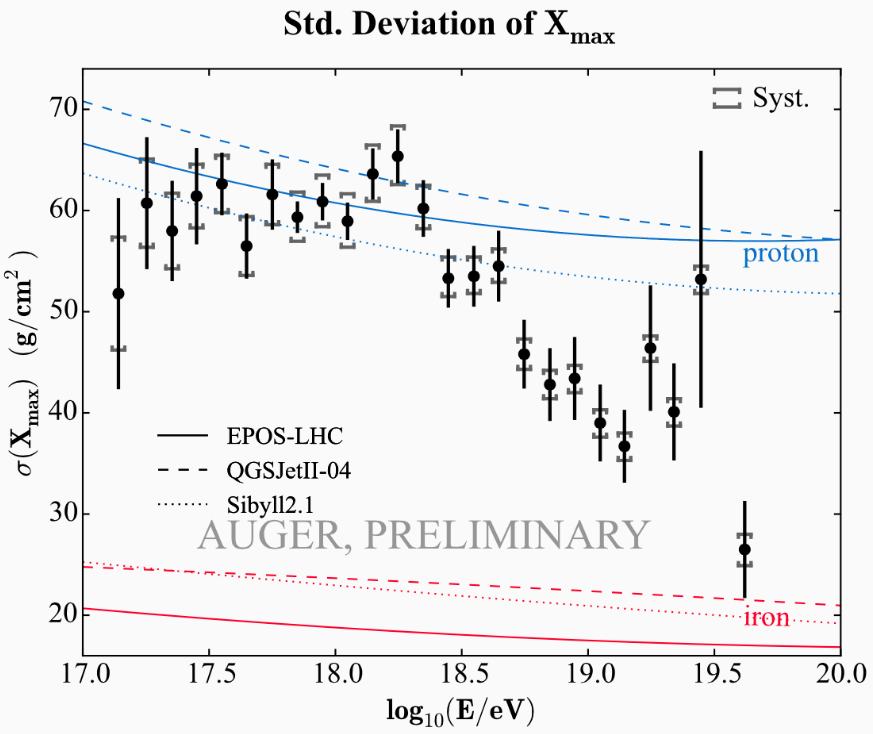
Arrival direction

Situation at ultra high energy : recent results of PAO

ICRC 2015



Average of X_{max}



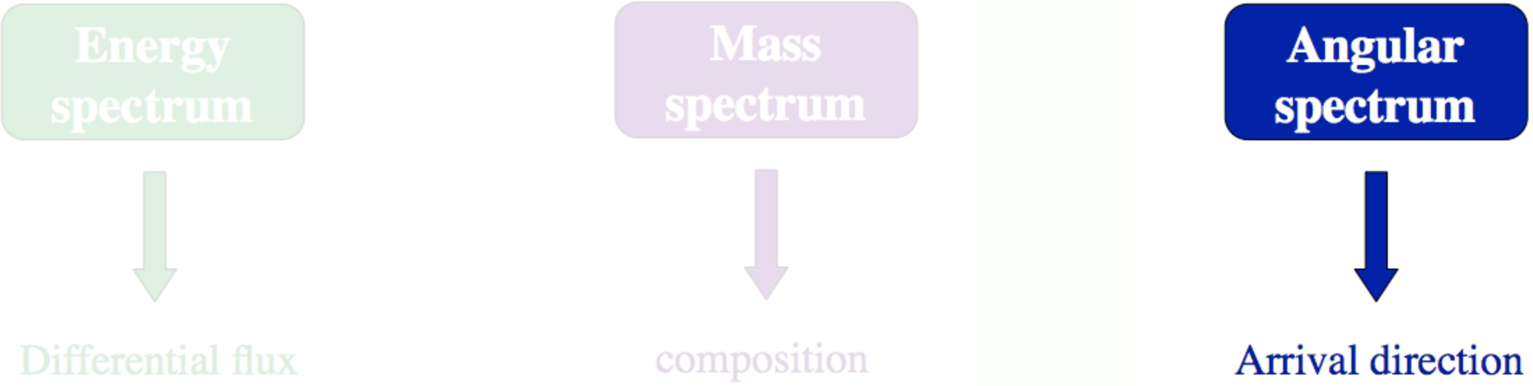
Std. Deviation of X_{max}

transition towards a heavier composition

-> some care is needed however regarding the uncertainties on the modeling of high energy hadronic interactions

-> Auger is incompatible with the pure proton scenario, TA is compatible with both scenarios

Cosmic Rays primary observables



Energy spectrum

Differential flux

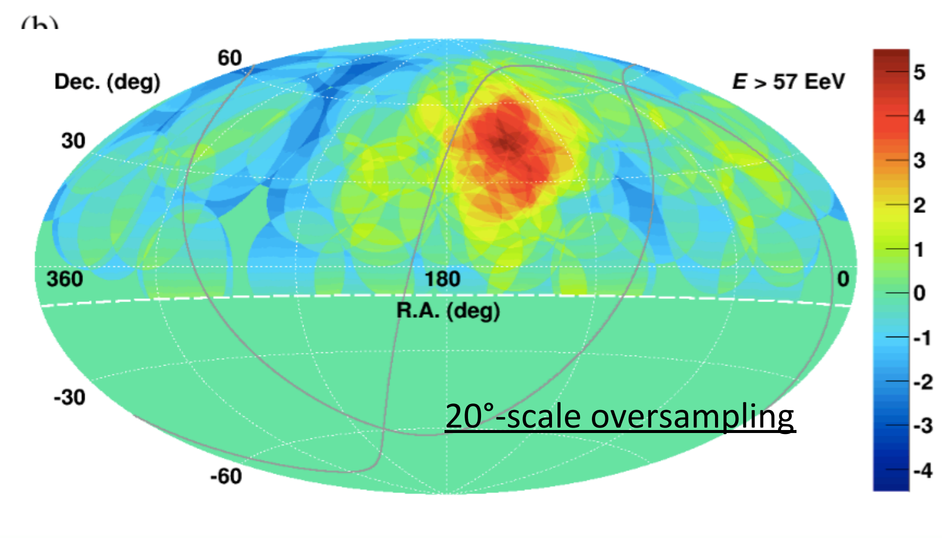
Mass spectrum

composition

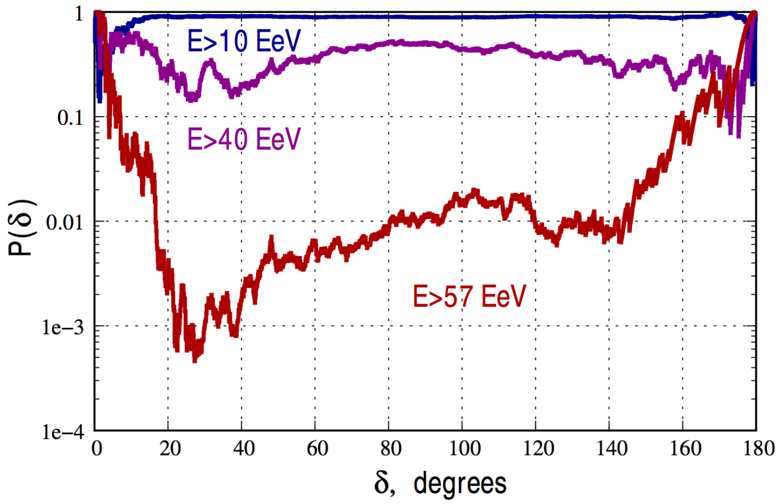
Angular spectrum

Arrival direction

At UHE, the magnetic fog seems to dissipate in the North



20°-scale oversampling



6 years of data

87 above 57 EeV (Hot Spot data set)

5.55σ (unpenalized)

7 years of data

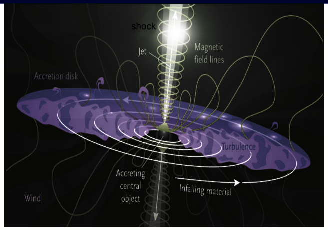
83 above 57 EeV (Anisotropy data set)

3.4σ (2pt correlation function)

"The highest-energy set with *E* > 57 EeV demonstrates moderate deviations in all the tests, which are manifestations of the "hot spot" in the distribution of the events — a concentration of the events of the radius ~ 20◦ in the direction R.A. = 148.4◦, Dec. = 44.5◦ (equatorial coordinates). The post-trial significance of the hot spot in the 7-year data set is 3.4σ, the same as in the 5-year data set".

What are the sources ?

Could UHECRs originate from GRBs?



- Gamma-ray bursts (GRBs) are among the best candidate sources for UHECRs (Levinson & Eichler 1993; Milgrom & Usov 1995; Vietri 1995; Waxman 1995...)

- Acceleration in **external shocks** : Vietri 1995, see however Gallant & Achterberg 1999 and recent other works by Niemiec et al. 2006, Niemiec & Ostrowski 2006, Lemoine, Pelletier & Revenu 2006
=> These recent studies have demonstrated the ineffectiveness of Fermi process in ultra-relativistic shocks

- Acceleration in **internal shocks**: Pioneer work by Waxman 1995, contributions by many other authors/groups : Waxman and collaborators, Dermer and collaborators, Giallis & Pelletier (2003-2005), …

- Gialis & Pelletier (2003) showed that making the assumption of an acceleration time evolving with the energy, which is different from the traditional assumption of Bohm diffusion, can jeopardize the acceleration of particles to the highest energies observed by Auger

- 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)

- Multimessenger consequences of UHECR acceleration :
    - Photons : Asano & Inoue (2007), Razzaque et al. (2010), Asano et. al (2009), Murase et. al, (2012)
    - Neutrinos : Eichler (1994), Waxman and Bahcall (1997), Guetta et al. (2004), Ahlers et al (2009-2012), Murase and collaborators (2008-2014)

Our calculation

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$\Longrightarrow$ give us an estimate of the physical quantities at the internal shocks based on a few free parameters

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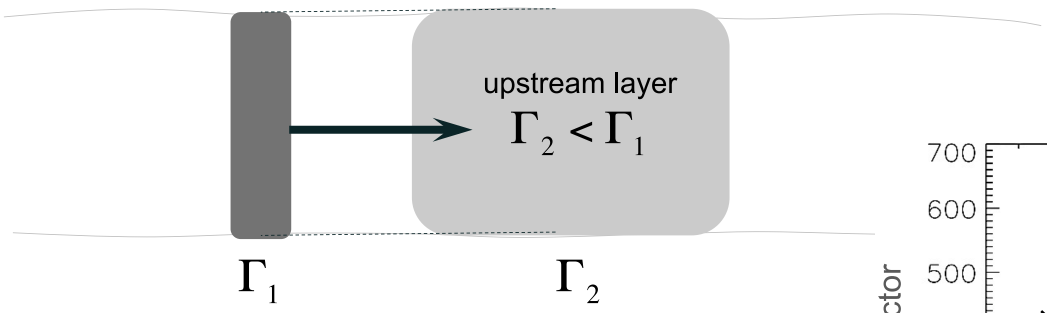
Modeling of the internal shock

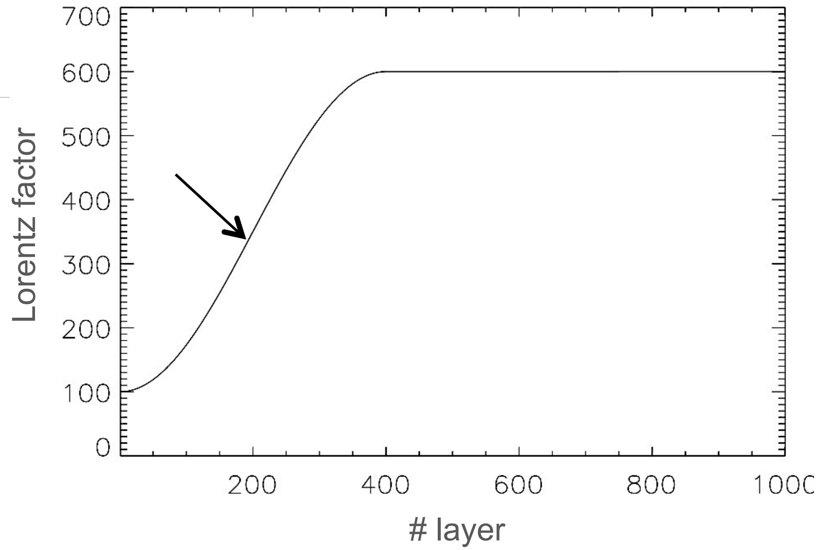
According to Daigne & Mochkovitch 1998 : a relativistic wind with a varying Lorentz factor is decomposed in discretized solid layers

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

first collision :



to model a single pulse :



Modeling of the internal shock

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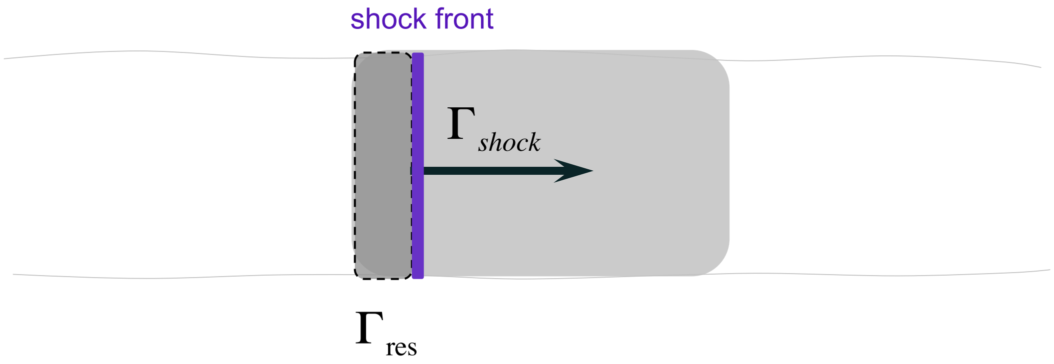

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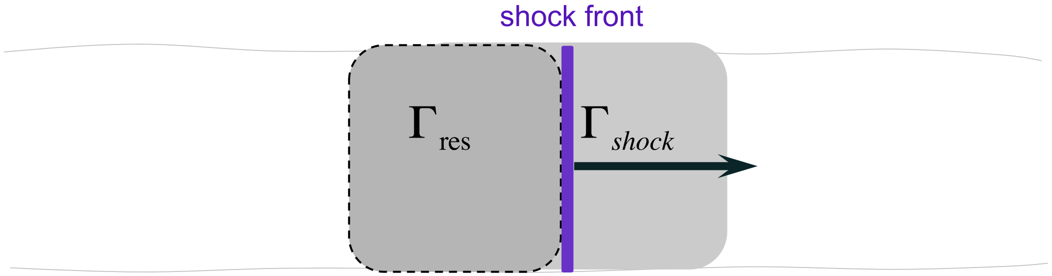

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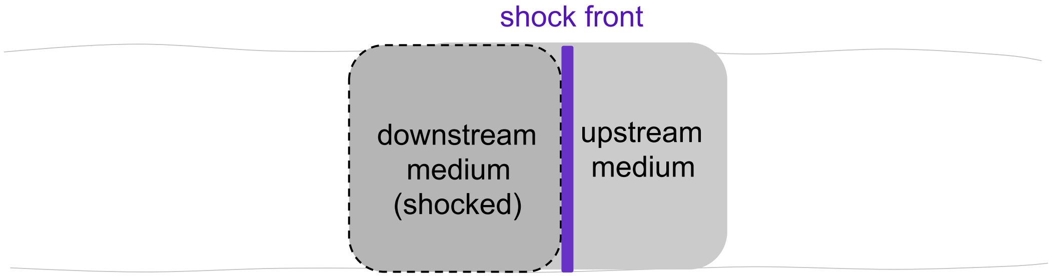

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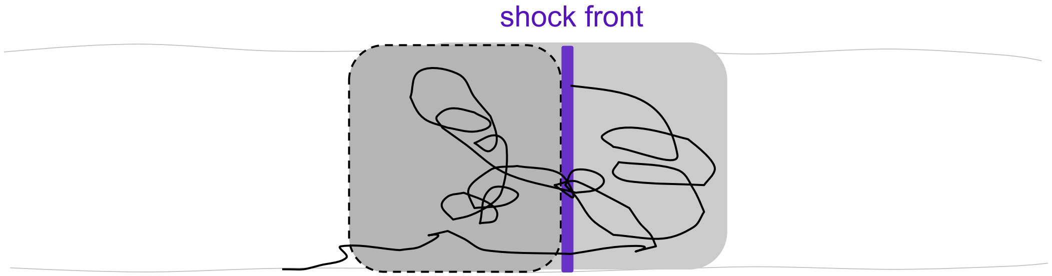


Assumptions

ε_e = 0.33

ε_B = 0.33

ε_{CR} = 0.33

ξ_e = 0.01

wind free parameters :

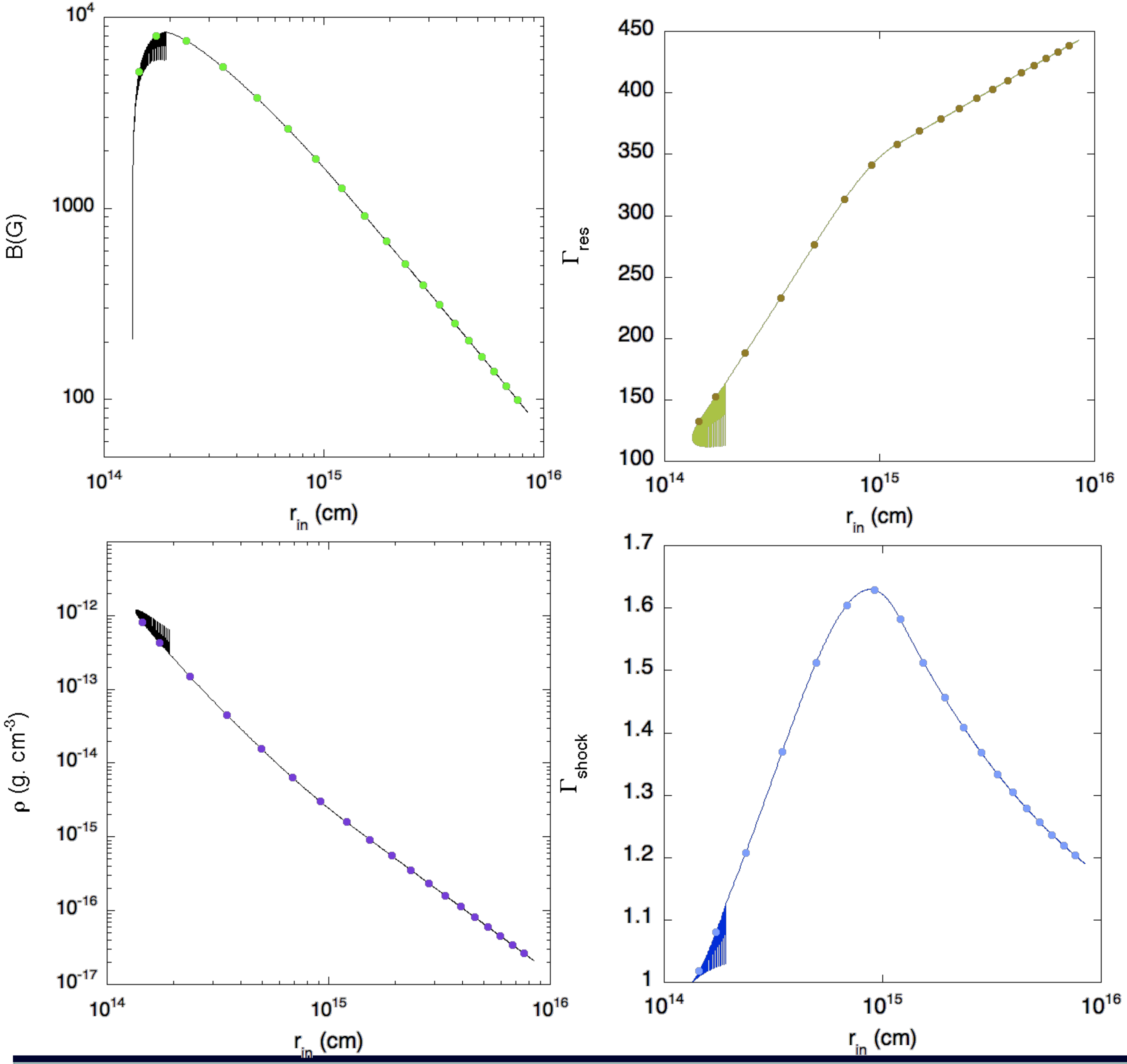
wind luminosity L_{wind}, wind duration t_{wind} (in the following we use t_{wind} = 2s and $10^{51} < L_{wind} < 10^{55}$ erg.s^{-1})

shock free parameters :

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

Γ_{shock} is given by the relative velocity between 2 colliding layers

Single synthetic pulse



output of this Toy model : physical quantities

...needed for acceleration

B_{rms} (downstream), Γ_{shock}

...needed for energy losses

Γ_{res}, r_{shock},
(needed for adiabatic losses)

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

+ density, photon background

evolution of a single pulse

$t_{wind} = 2$s
$L_{wind} = 10^{53}$ erg.s^{-1}

18 “snapshots”

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Energy losses

protons

- pair production

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

- synchrotron emission

- adiabatic losses

- pion production

$$p + \gamma \rightarrow p \mid n + \Pi^{0} \mid \Pi^{+} \mid \Pi^{-}$$

- hadronic interactions

$$p + p \rightarrow p + n \mid p + \Pi^{0} \mid \Pi^{+} \mid \Pi^{-}$$

$$p + n \rightarrow p + n + \Pi^{0}$$

$$p + n \rightarrow n + n + \Pi^{+}$$

$$p + n \rightarrow p + p + \Pi^{-}$$

Energy losses

protons

- pair production
  $p + \gamma \rightarrow p + e^{+} + e^{-}$
- synchrotron emission
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- pion production
  $p + \gamma \rightarrow p \mid n + \Pi^{0} \mid \Pi^{+} \mid \Pi^{-}$
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$$p + p \rightarrow p + n \mid p + \Pi^{0} \mid \Pi^{+} \mid \Pi^{-}$$

$$p + n \rightarrow p + n + \Pi^{0}$$

$$p + n \rightarrow n + n + \Pi^{+}$$

$$p + n \rightarrow p + p + \Pi^{-}$$

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

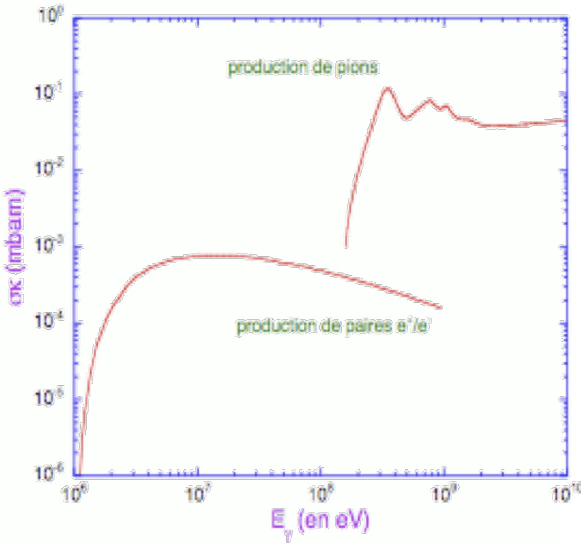
$\Gamma_N \searrow$

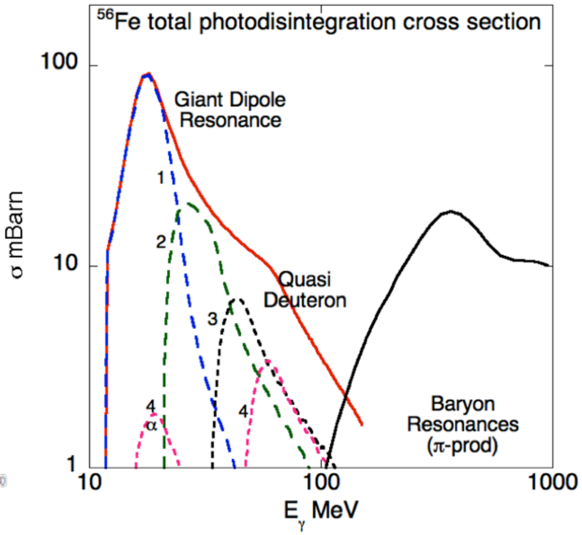
OR

$A \searrow$

- GDR (Khan 2005)
- QD
- BR

QD, BR: pion production (Rachen 1996)





output of internal shock model

Energy losses

protons

- pair production 1 MeV
  $p+\gamma \rightarrow p+e^{+}+e^{-}$
- synchrotron emission
  B
- adiabatic losses
  Γ_{res}, r_{shock}
- pion production 150 MeV
  $p+\gamma \rightarrow p\,|\,n+\Pi^{0}\,|\,\Pi^{+}\,|\,\Pi^{-}$
- hadronic interactions density

$$p+p \rightarrow p+n\,|\,p+\Pi^{0}\,|\,\Pi^{+}\,|\,\Pi^{-}$$
$$p+n \rightarrow p+n+\Pi^{0}$$
$$p+n \rightarrow n+n+\Pi^{+}$$
$$p+n \rightarrow p+p+\Pi^{-}$$

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

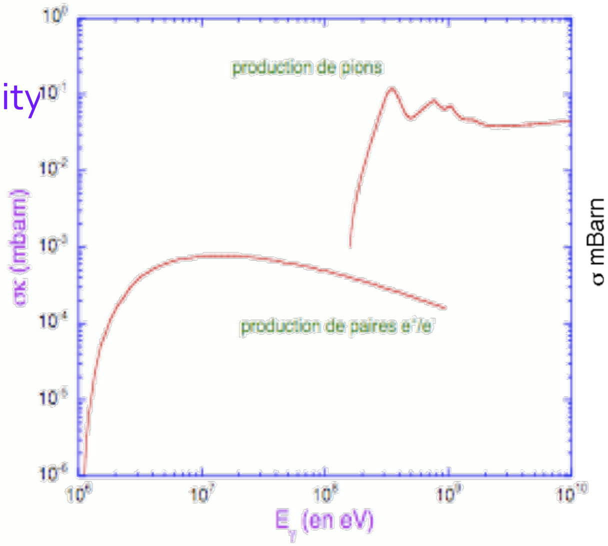
Γ_N ↘

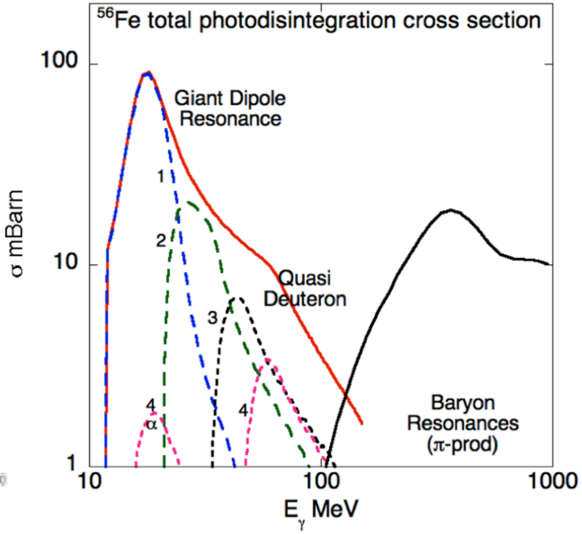
OR

A ↘

- GDR 10 MeV
- QD
- BR

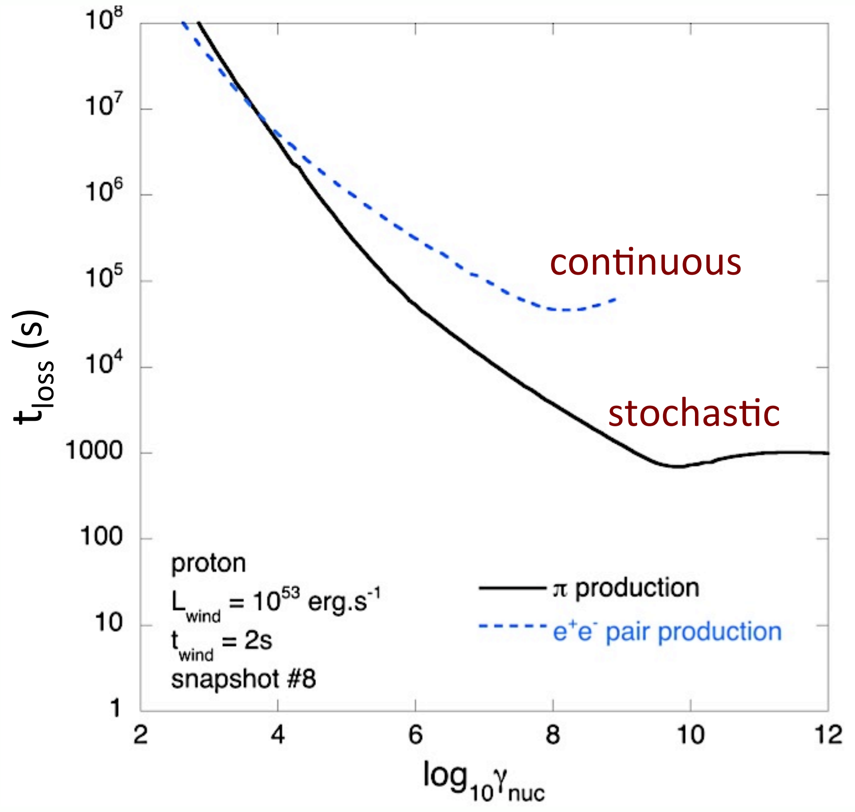
QD, BR } pion production 30 - 145 MeV





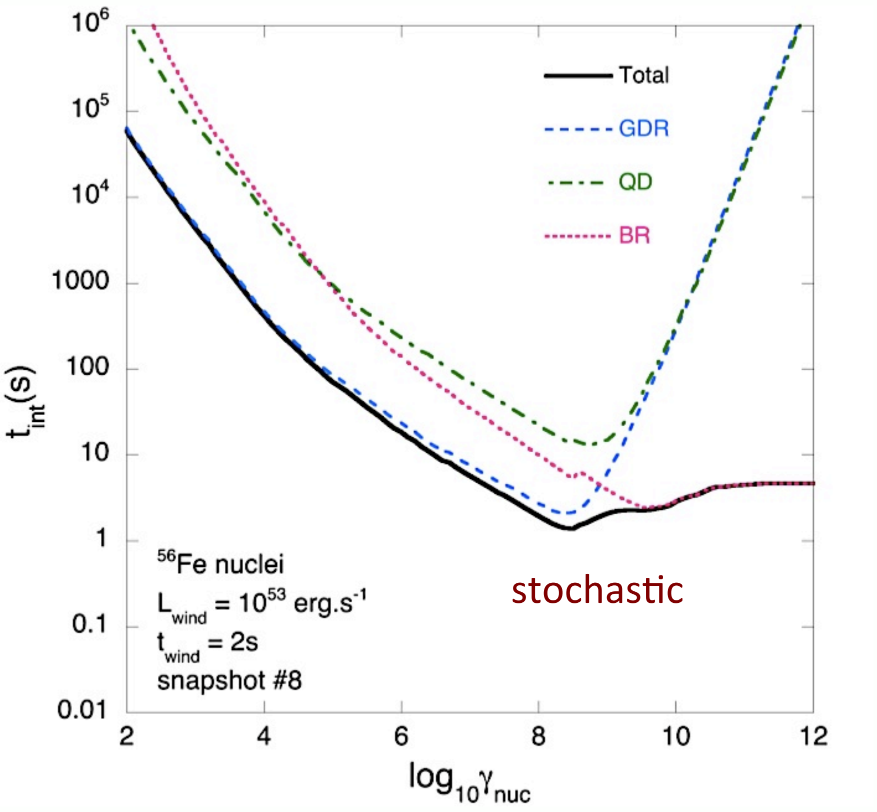
t_{loss} computed with SEDs

We apply the revised scheme of photo-nuclear interactions described in Khan et al. 2005.



continuous

stochastic



stochastic

+ adiabatic and synchrotron losses

mean free path

$$\lambda^{-1}_{Band} = \frac{1}{2\gamma^2} \int_{E'_{seuil}/2\gamma}^{E_{max}} \frac{n(E)}{E^2} \left(\int_{E'_{seuil}}^{2\gamma E} E' \sigma(E') dE' \right) dE$$

(see Allard et al., 2005 A&A, 443, 29
for details and Allard, 2012 for a review)

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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)
- Particles weight splitting

The jump conditions are given by Synge 1957 for relativistic shocks

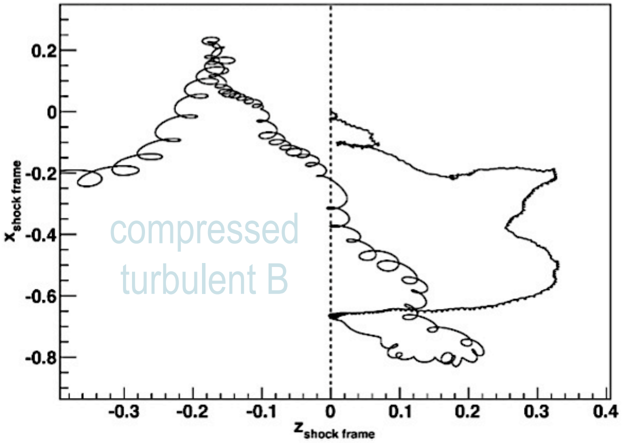
We assume a **Kolmogorov**-type turbulence uptream (see Giacalone et Jokipii 1999). The downstream magnetic field is compressed and amplified in the direction perpendicular to the shock normal.

$$\vec{B}(x,y,z) = B_0\vec{z} + \delta\vec{B}(x,y,z)$$

with $$\delta\vec{B}(x,y,z) = \sum_{n=1}^{N_m} A(k_n)\vec{\xi_n}\exp(ik_n z'_n + i\beta_n)$$

(maximum turbulence scale : $\lambda_{\max} \approx \lambda_c$)

Particle trajectory (3D) in the shock frame



9 cycles before escaping downstream. Energy gain~ 70.

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- Particles weight splitting

The jump conditions are given by Synge 1957 for relativistic shocks

We assume a **Kolmogorov**-type turbulence uptream (see Giacalone et Jokipii 1999). The downstream magnetic field is compressed and amplified in the direction perpendicular to the shock normal.

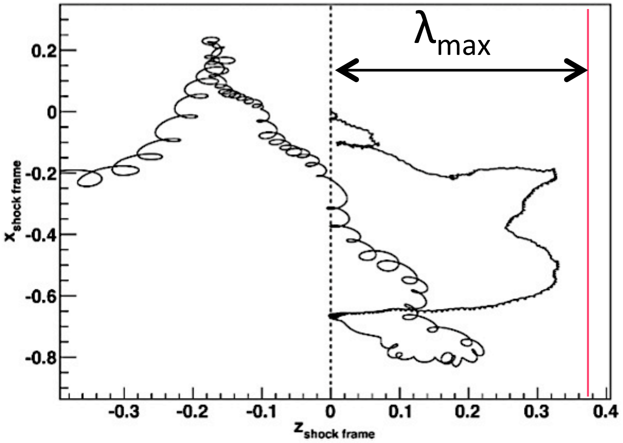
$$\vec{B}(x,y,z) = B_0\vec{z} + \delta\vec{B}(x,y,z)$$

with $\delta\vec{B}(x,y,z) = \sum_{n=1}^{N_m} A(k_n)\vec{\xi_n}\exp(ik_n z'_n + i\beta_n)$

(maximum turbulence scale : $\lambda_{\max} \approx \lambda_c$)

Maximum energy due to deconfinement (particle escape)

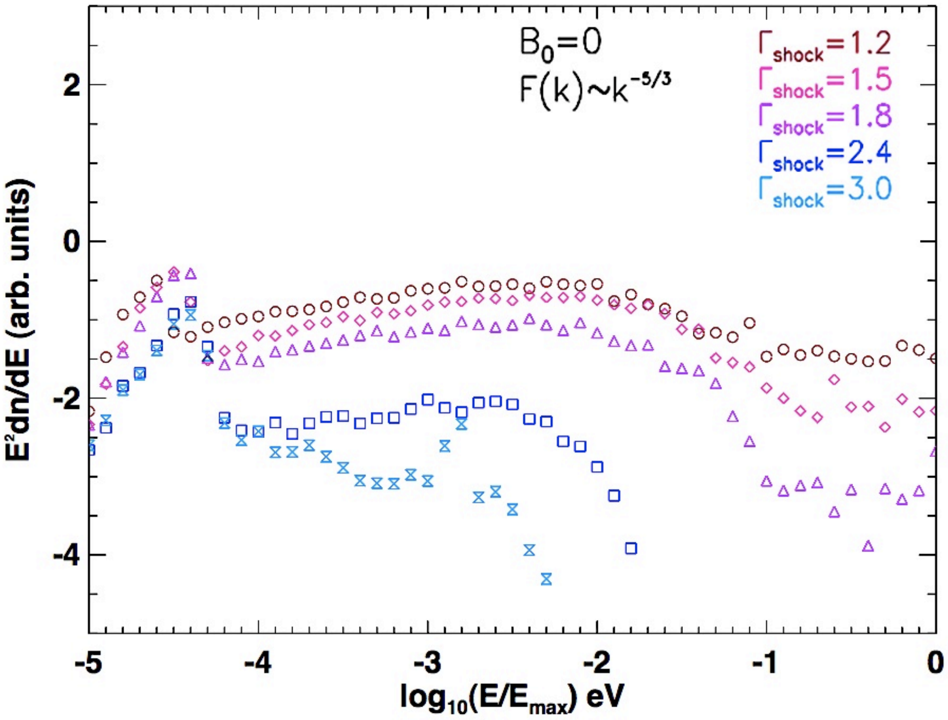
$$r_L(E_{\max}) = \frac{E_{\max}}{eZB} \equiv \lambda_{\max}$$

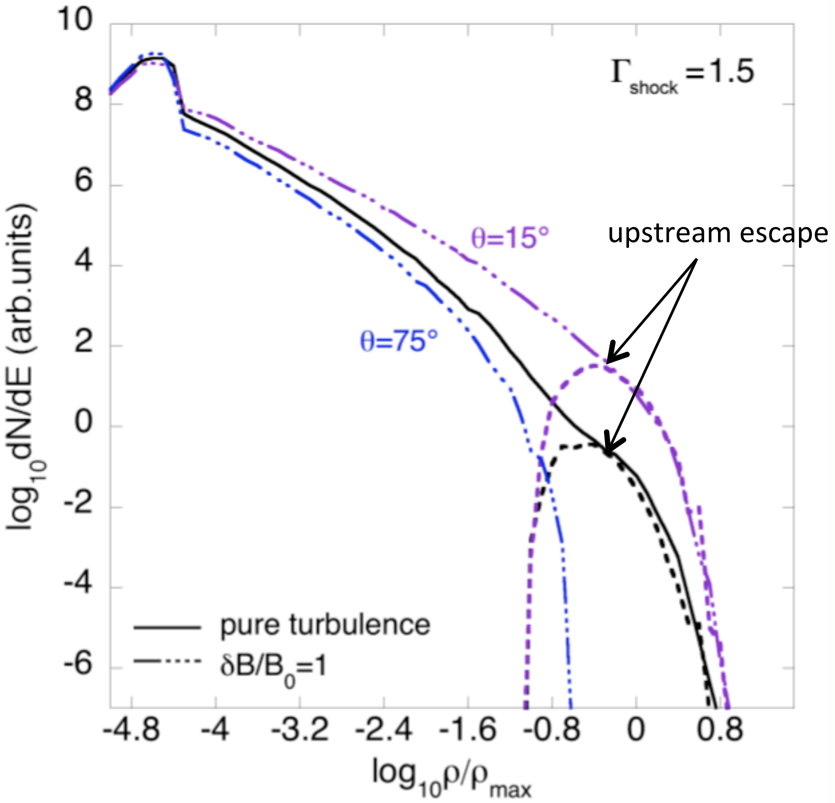


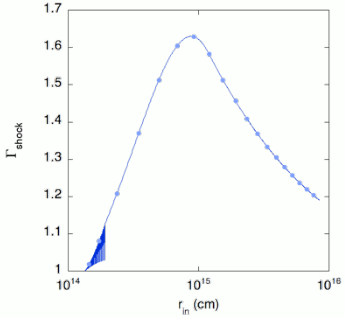
We assume a free boundary escape upstream if the particle can reach the distance $\lambda_{\max}$ from the shock

Spectra of accelerated cosmic rays

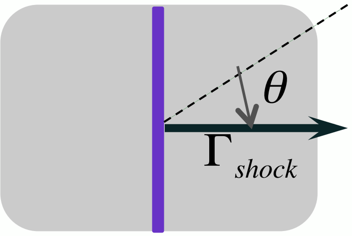
$$r_L(E_{\max}) = \frac{E_{\max}}{eZB} \equiv \lambda_{\max}$$



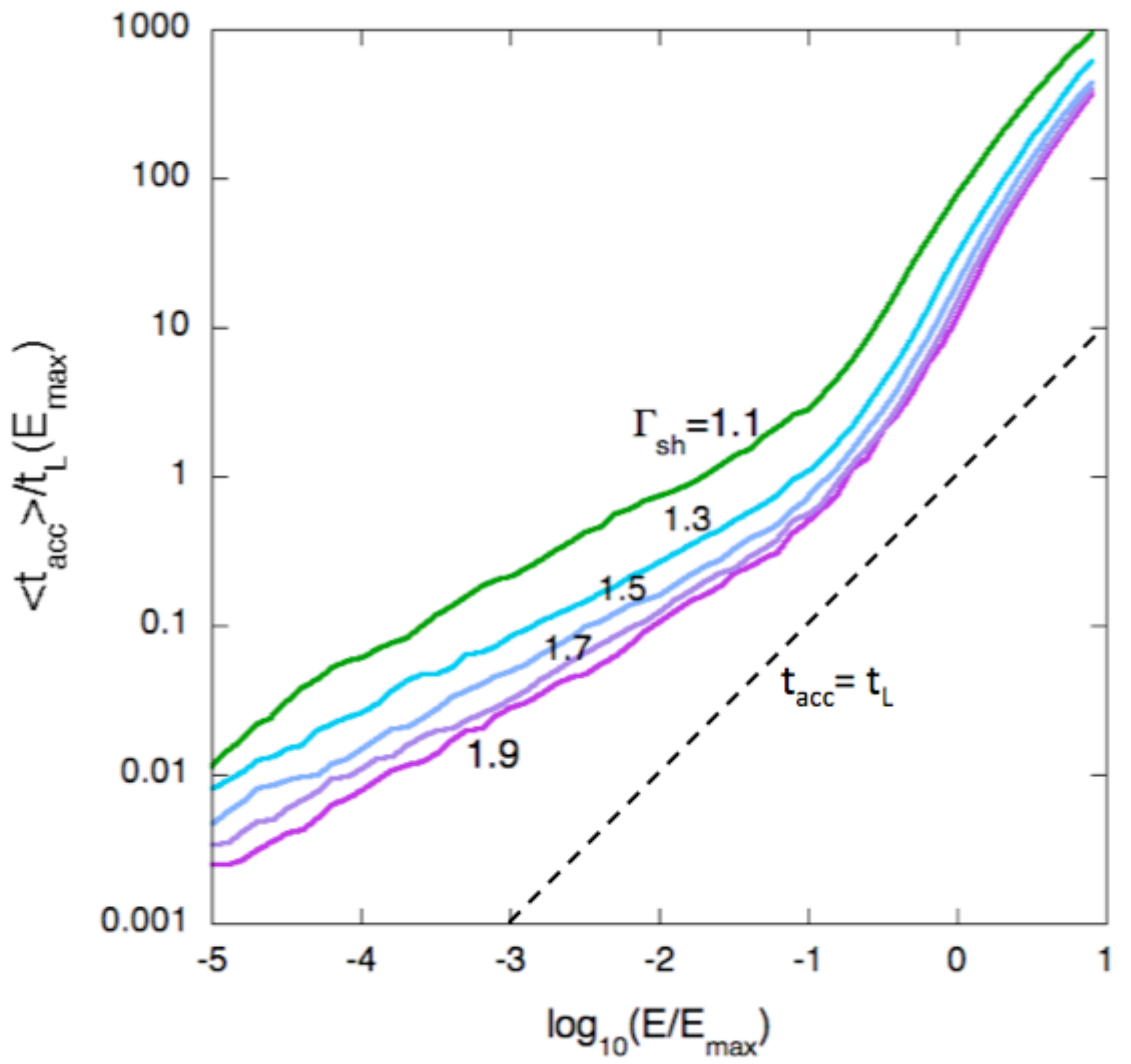




$$\vec{B}(x,y,z) = B_0\vec{z} + \delta\vec{B}(x,y,z)$$



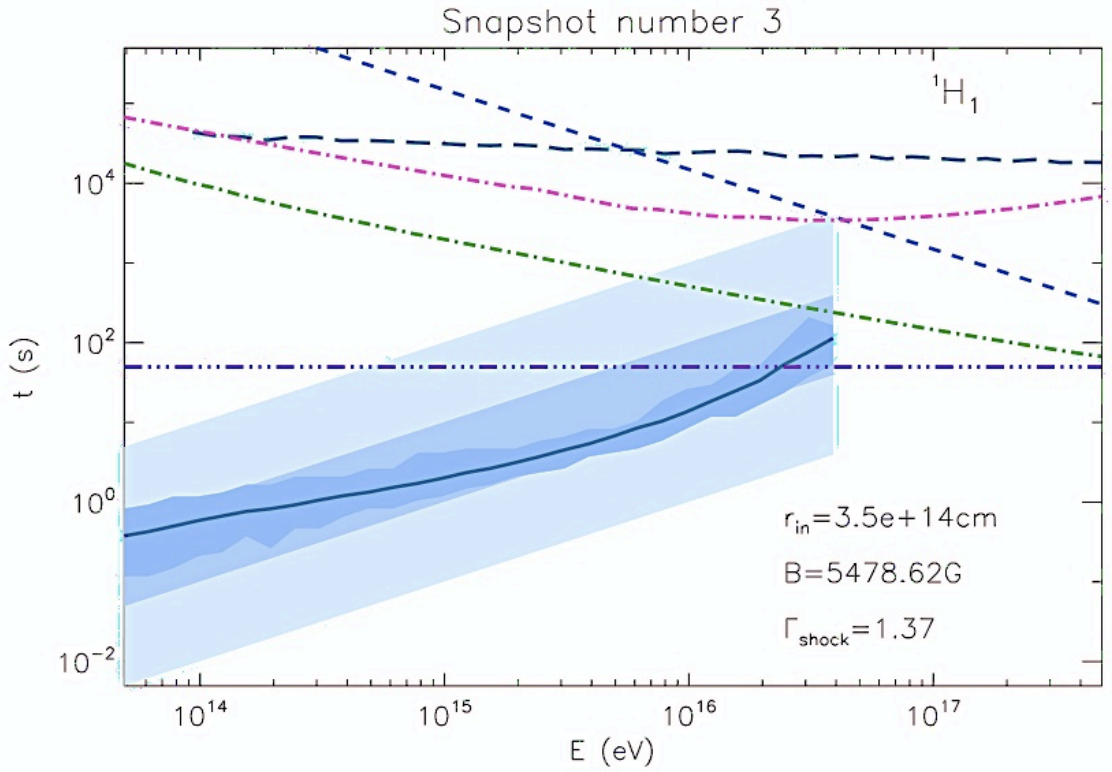
Acceleration time distribution $(\neq t_{acc} = \kappa_0 t_L\,!)$



Equating t_{acc} and t_{loss} => an estimate of the maximum energy reachable

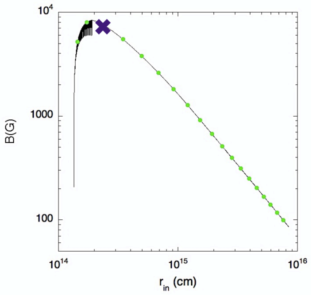
Estimate of the maximum energy reachable for protons

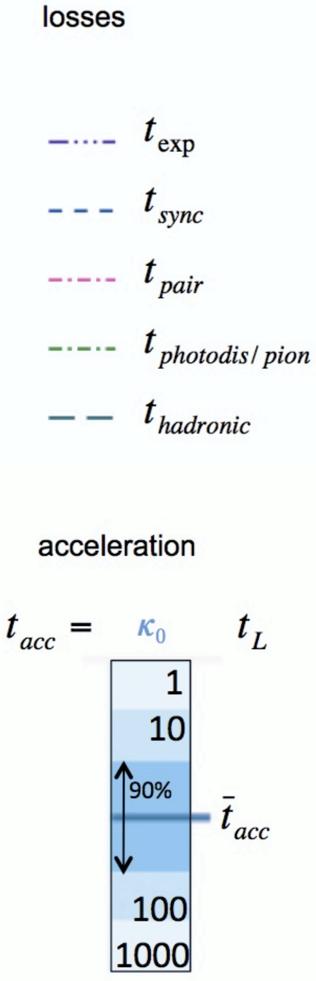
t_{wind}=2s, L_{wind}=10^{53} erg.s^{-1}, λ_{max}=r_{shock}/10Γ_{res}



$E_{max,obs}$≈ 6 10^{18} eV

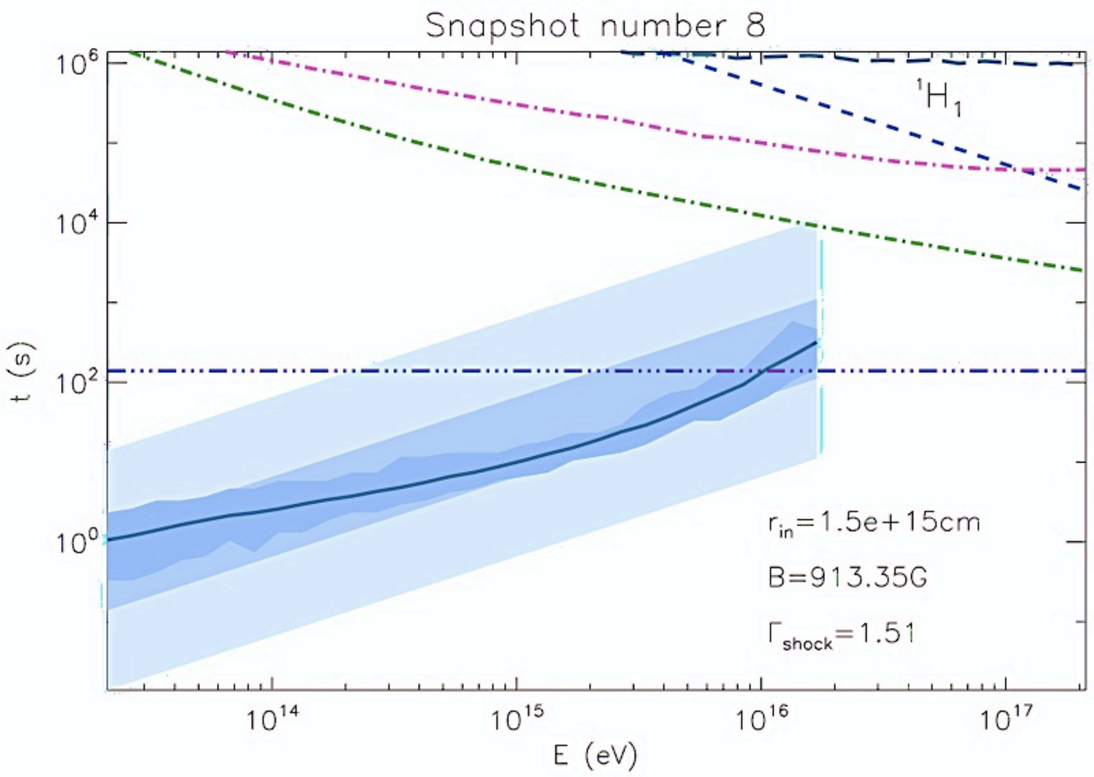
#3





Estimate of the maximum energy reachable for protons

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

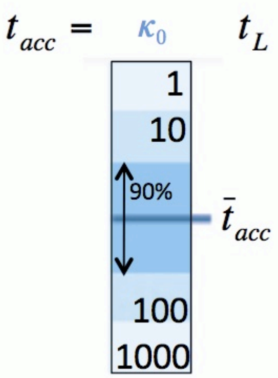


losses

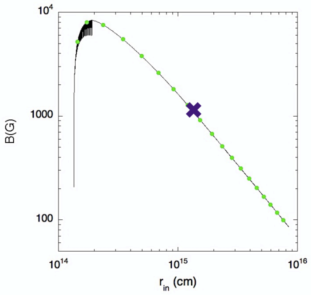
- t_{exp}
- t_{sync}
- t_{pair}
- $t_{photodis/\,pion}$
- $t_{hadronic}$

acceleration

$t_{acc} = \kappa_0 \; t_L$



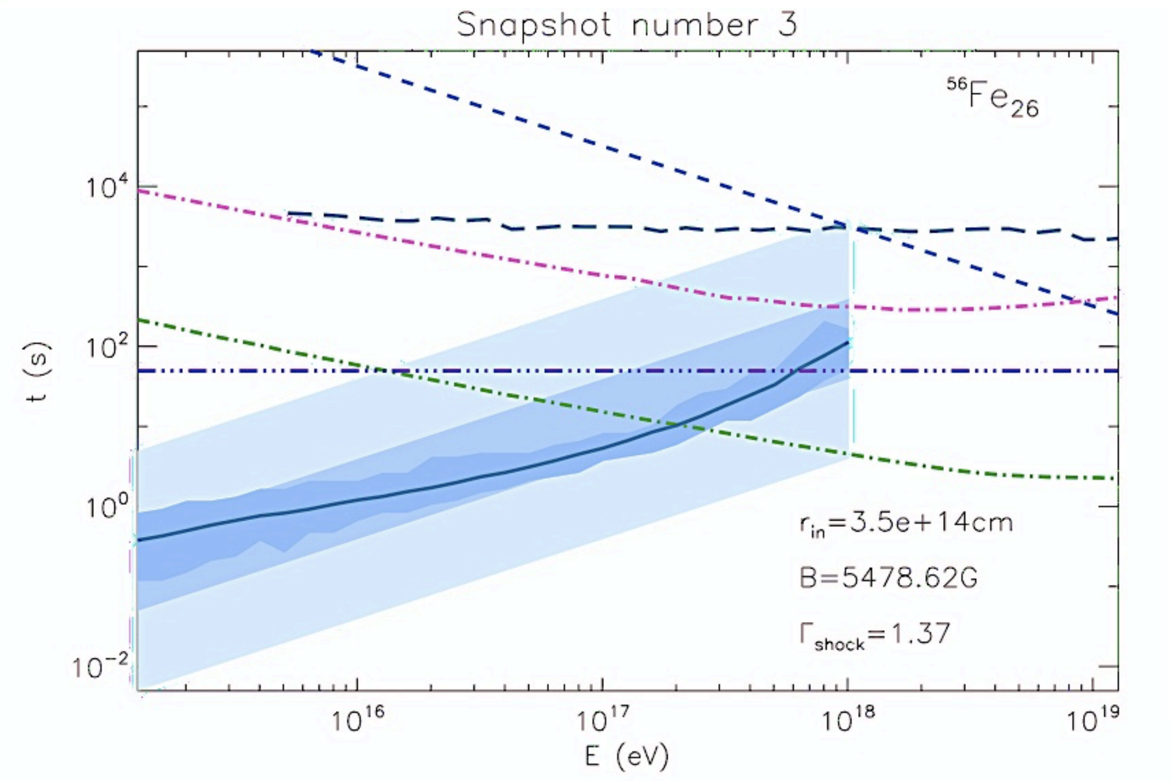
#8

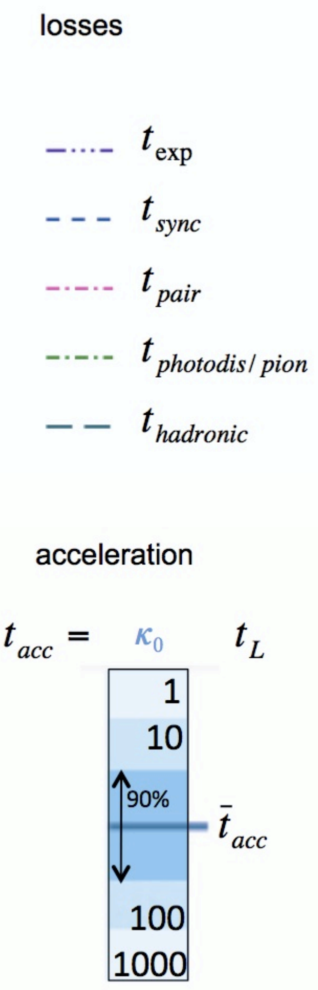


$E_{max,obs} \approx 4\ 10^{18}$ eV

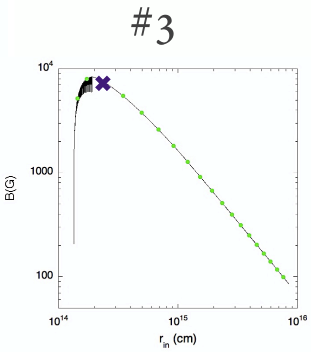
Estimate of the maximum energy reachable for iron

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



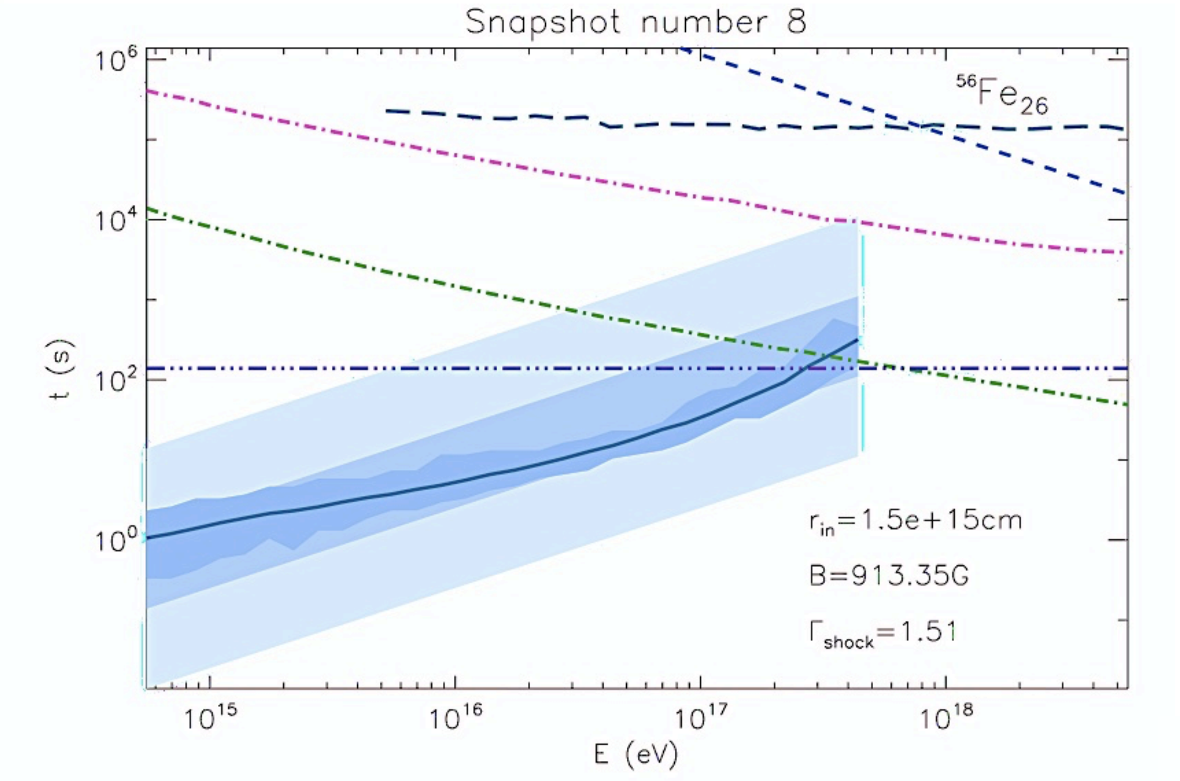


$E_{max,obs} \approx 5\ 10^{19}$ eV



Estimate of the maximum energy reachable for iron

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



losses

t_{exp}

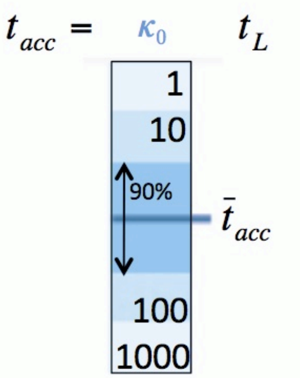
t_{sync}

t_{pair}

$t_{photodis/pion}$

$t_{hadronic}$

acceleration



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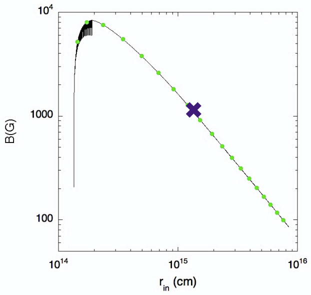
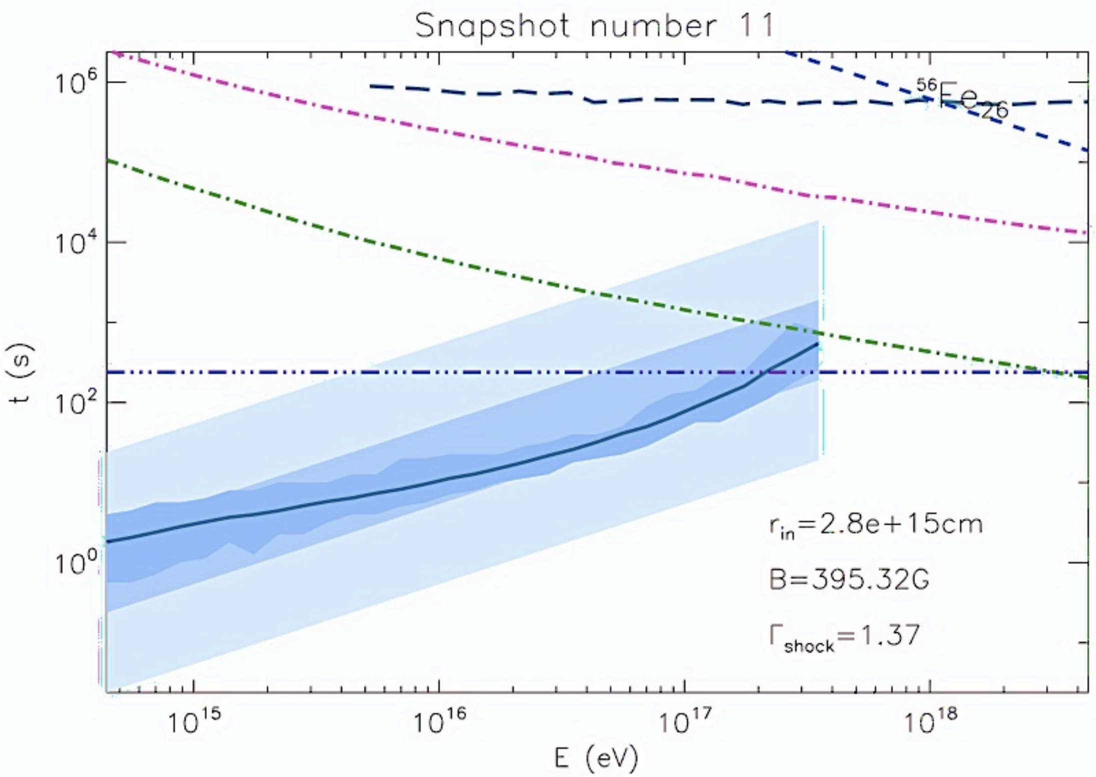


$E_{max,obs} \approx 10^{20}$ eV

Estimate of the maximum energy reachable for iron

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

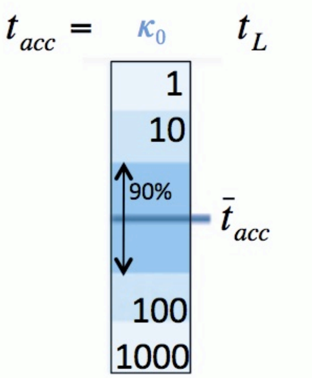


losses

- t_{exp}
- t_{sync}
- t_{pair}
- $t_{photodis/\,pion}$
- $t_{hadronic}$

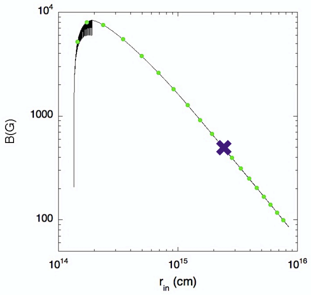
acceleration

$t_{acc} = \kappa_0 \; t_L$



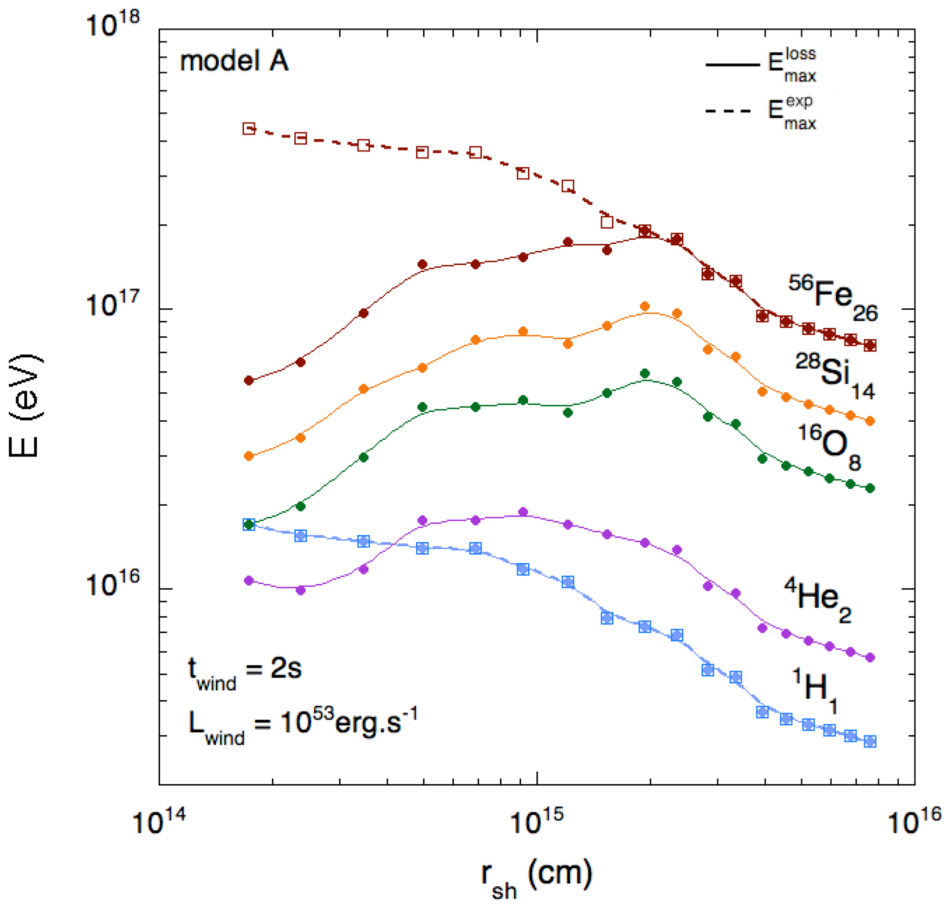
$E_{max,obs} \approx 8\ 10^{19}$ eV

#11



Estimate of the maximum energy reachable for different species

Beginning of the shock propagation :
Nuclei limited by photointeraction
➔ $E_{max}(Z) \neq Z \times E_{max}(^1H)$



Larger distances :
All species limited by adiabatic losses
➔ $E_{max}(Z) = Z \times E_{max}(^1H)$

In the following we assume the maximum turbulence scale is limited by the energy reached by cosmic-ray proton ➔ $\lambda_{max} = r_L(E_{max}\,^1H)$

Our calculation

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

- Prompt emission gamma-ray photons are used as soft photons target for the accelerated cosmic-rays => calculation of the energy losses

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

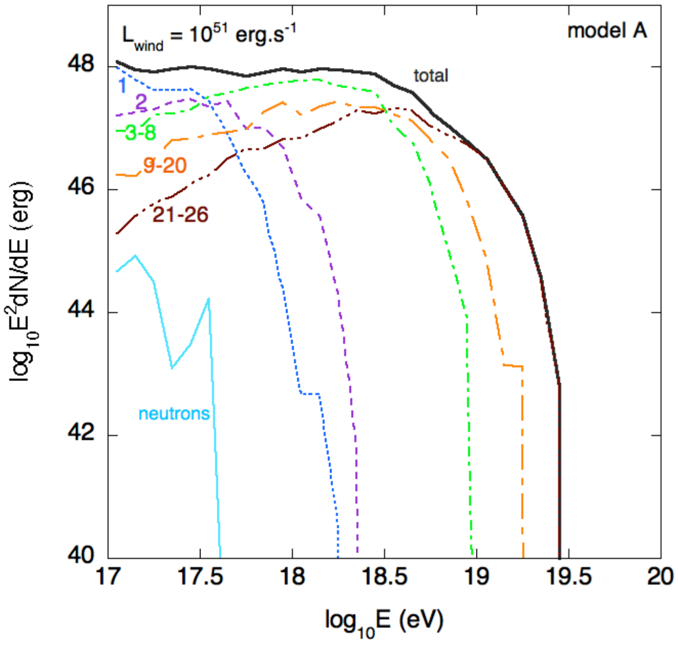
- Full calculation including energy losses (photo-hadronic and hadron-hadron)
$\Longrightarrow$ cosmic-ray and neutrino output for a GRB of a given luminosity

- Convolution by a GRB luminosity function and cosmological evolution (Wanderman & Piran 2010)
$\Longrightarrow$ calculation of the diffuse UHECR and neutrino fluxes

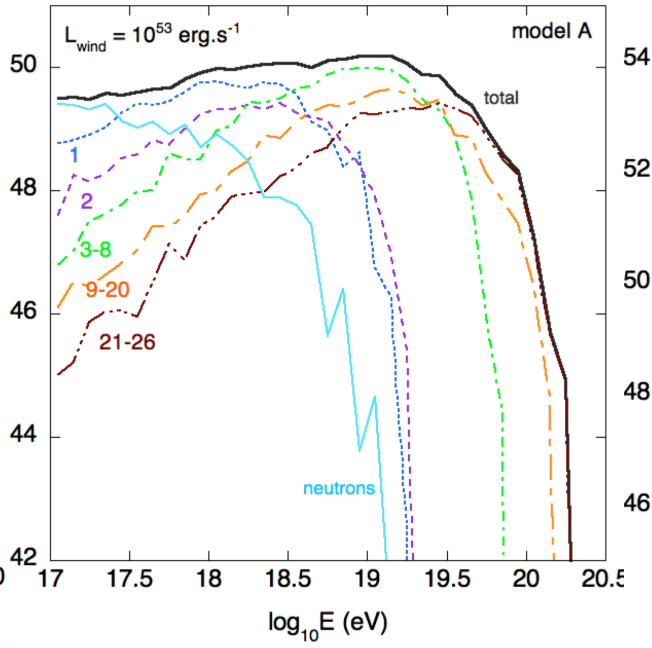
UHECR spectra (escaping from the wind)

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

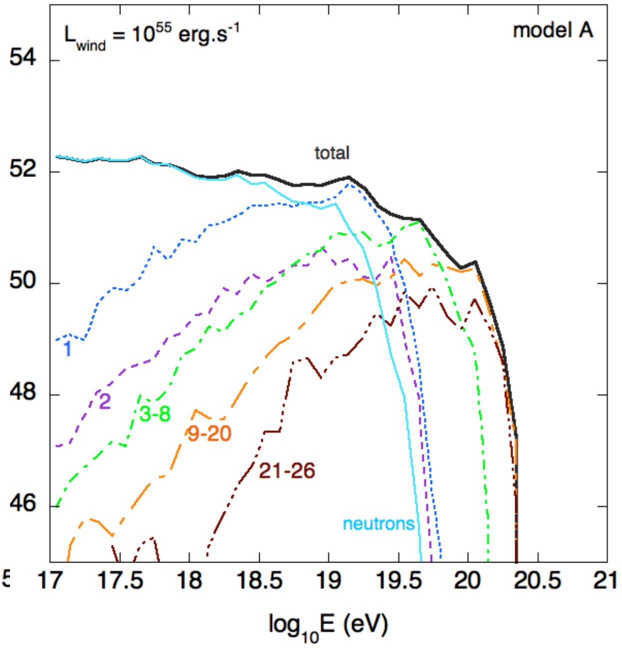
L_{wind}=**10^{51}** erg.s^{-1}



L_{wind}=**10^{53}** erg.s^{-1}



L_{wind}=**10^{55}** erg.s^{-1}



t_{wind} = 2s
metallicity :10 times the one of galactic CRs

High luminosities : Nuclei components get narrower, more neutrons emitted

Our calculation

- 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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- 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 (Wanderman & Piran 2010)
⇒ calculation of the diffuse UHECR and neutrino fluxes

Convolution by a GRB luminosity function

Assumptions

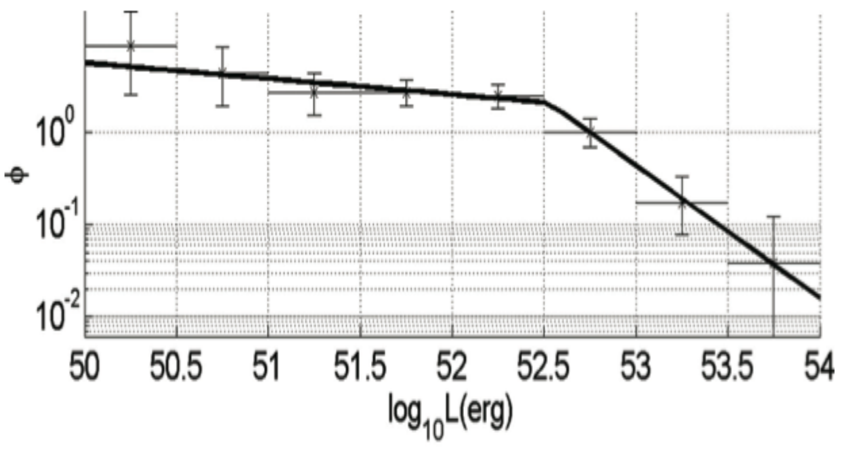
$\varepsilon_e = 0.33$

$\varepsilon_B = 0.33$

$\varepsilon_{CR} = 0.33$

$\xi_e = 0.01$

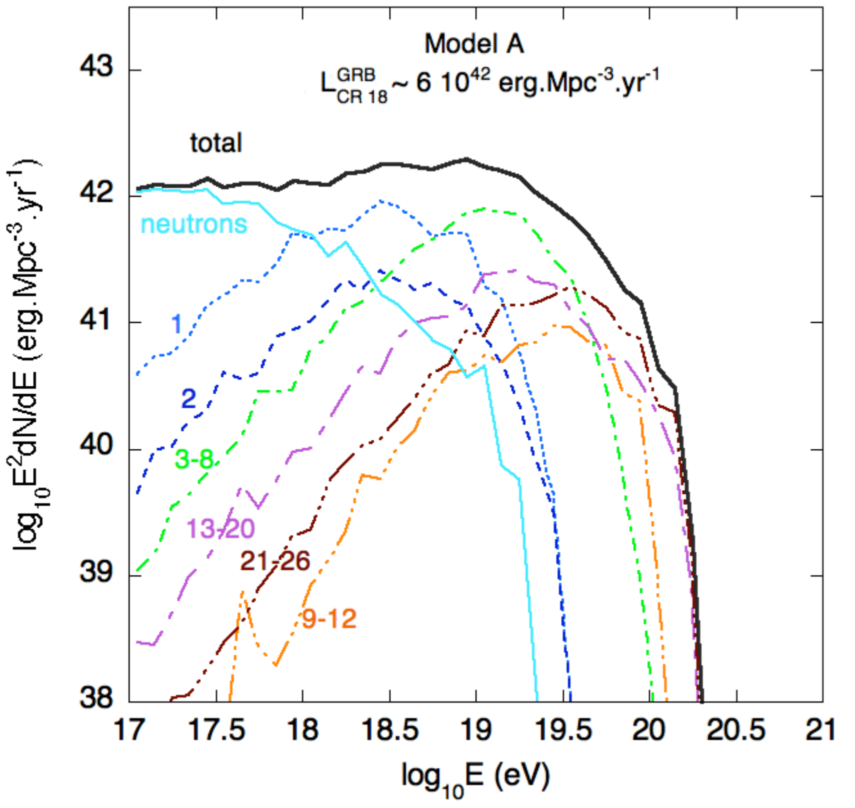
GRB rate and luminosity function from Wanderman and Piran 2010



$\alpha = 0.2^{+0.2}_{-0.1}$ and $\beta = 1.4^{+0.3}_{-0.6}$

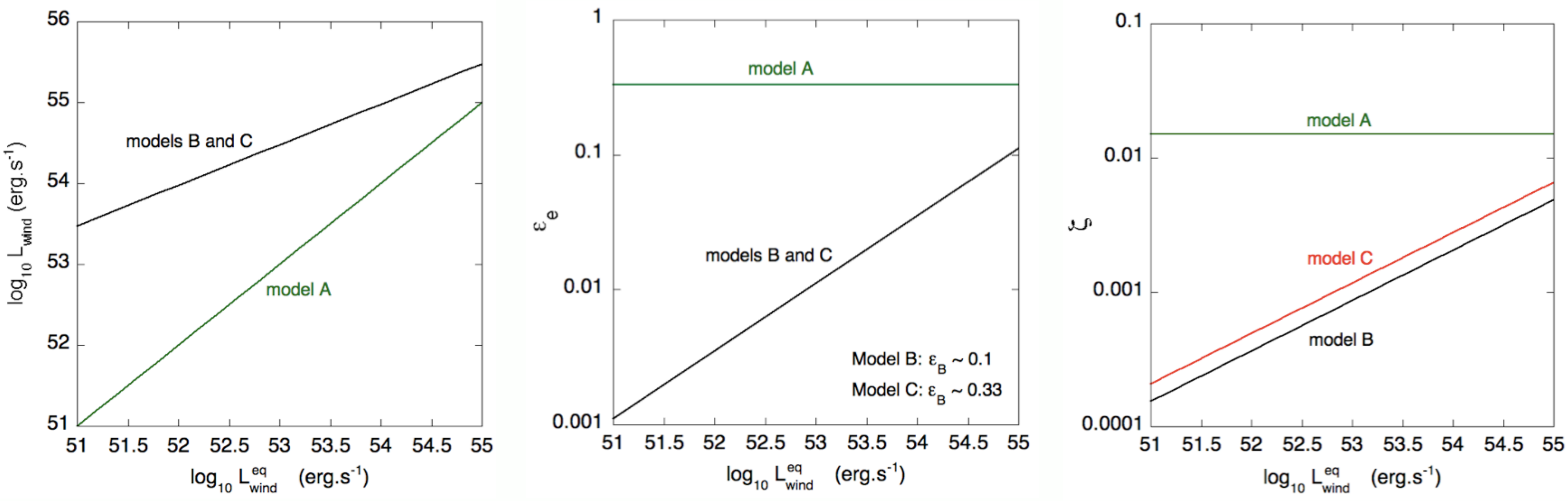
$\rho_0 \simeq 1.3^{+0.6}_{-0.7}$ (Gpc^{-3} yr^{-1})

$E_\gamma^{tot} = 1.1\ 10^{44}$ erg.Mpc^{-3}.yr^{-1}



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

Different energy partition models



New assumption: The range of L_{wind} is smaller than what suggested by the prompt emission luminosity function. Fainter GRBs are very inefficient at accelerating electrons but always efficient at accelerating cosmic-rays

- **Model A: equipartition: ε_e,= ε_B= ε_{CR}= 1/3**
  - Gamma-ray production efficiency ~5% ($L_\gamma \sim L_{wind}/20$)
  - 10^{51} erg/s ≤ L_{wind} ≤ 10^{55} erg/s => 5 10^{49} erg/s ≤ L_γ ≤ 5 10^{53} erg/s (iso)
- **Models B and C: low γ-ray efficiency: ε_e << 1**
  - 3 10^{53} erg/s ≤ L_{wind} ≤ 3 10^{55} erg/s => 5 10^{49} erg/s ≤ L_γ ≤ 5 10^{53} erg/s (iso)
  - Gamma-ray production efficiency: between 0.01% and 1%

Modeling the Cosmic Rays primary observables

Energy spectrum
↓
Differential flux

Mass spectrum
↓
composition

Angular spectrum
↓
Arrival direction

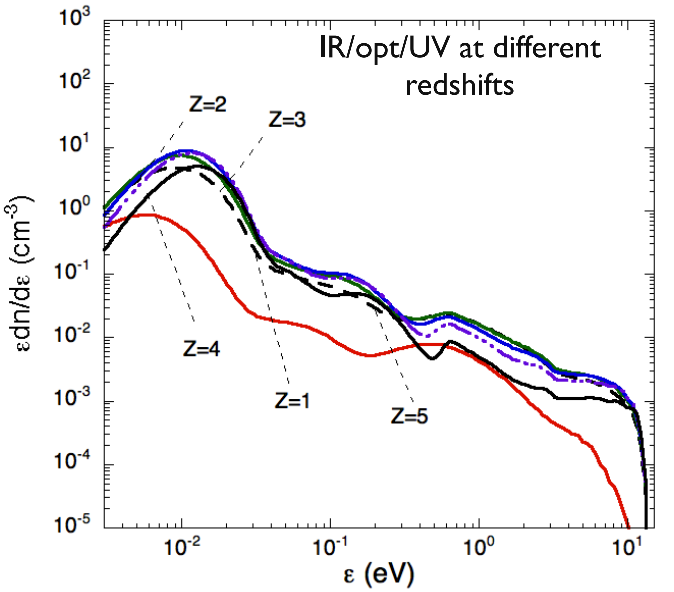
Resulting UHECR propagated spectrum

300 realisations of the history of GRB explosions in the Universe

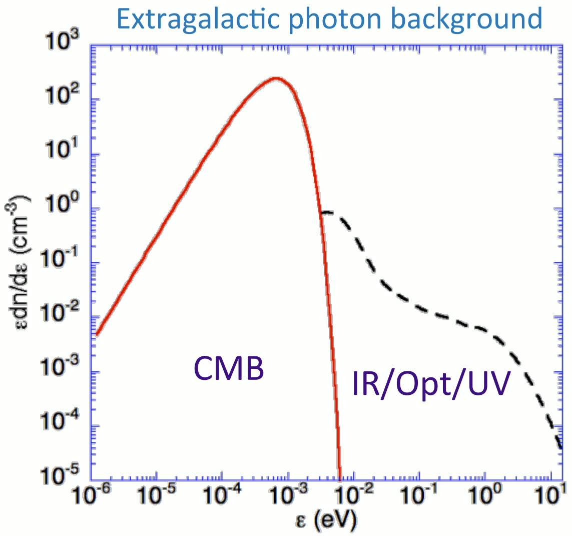
Propagation in extragalactic turbulent magnetic field, including energy losses on extragalactic photon backgrounds (see Globus, Allard & Parizot 2008 for details)

• **Cosmological Microwave Background**, very well known T=2.726K
⇒ trivial cosmological evolution $\lambda(E,z)=\lambda(E(1+z),z=0)/(1+z)^3$

• **Infra-red, optical, ultra-violet backgrounds (IR/OPT/UV)**
Time evolution dependent on the Star Formation Rate, stars aging and metalicity (especially the UV background)
⇒ non trivial but recently better constrained by astrophysical data (Spitzer telescope, etc…)



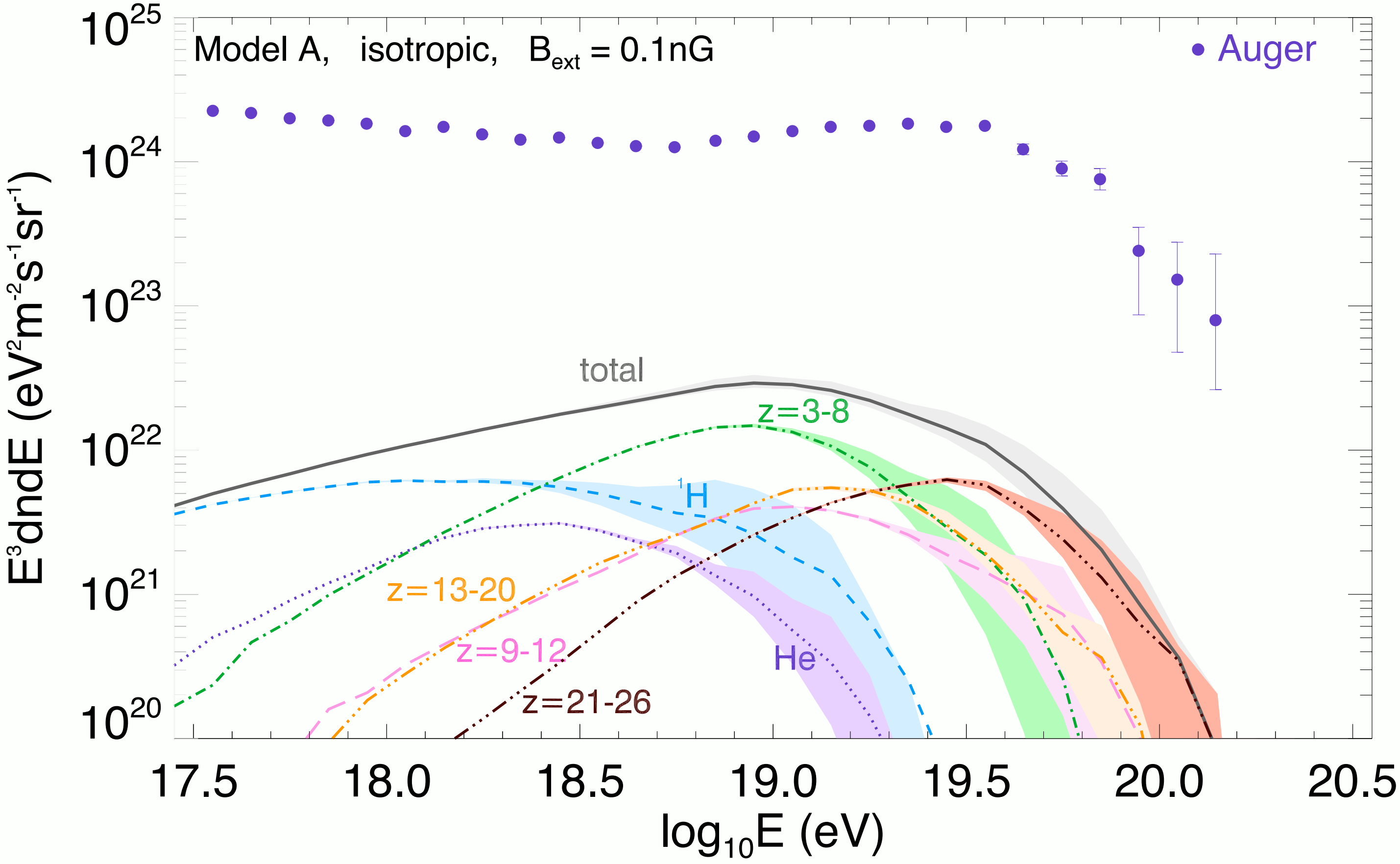
In the following calculations, we use estimate of IR/OPT/UV background density and time evolution from Kneiske et al., 2006



Resulting UHECR propagated spectrum

Assumptions
ε_e = 0.33
ε_B = 0.33
ε_{CR} = 0.33
ξ_e = 0.01

assuming equipartition:



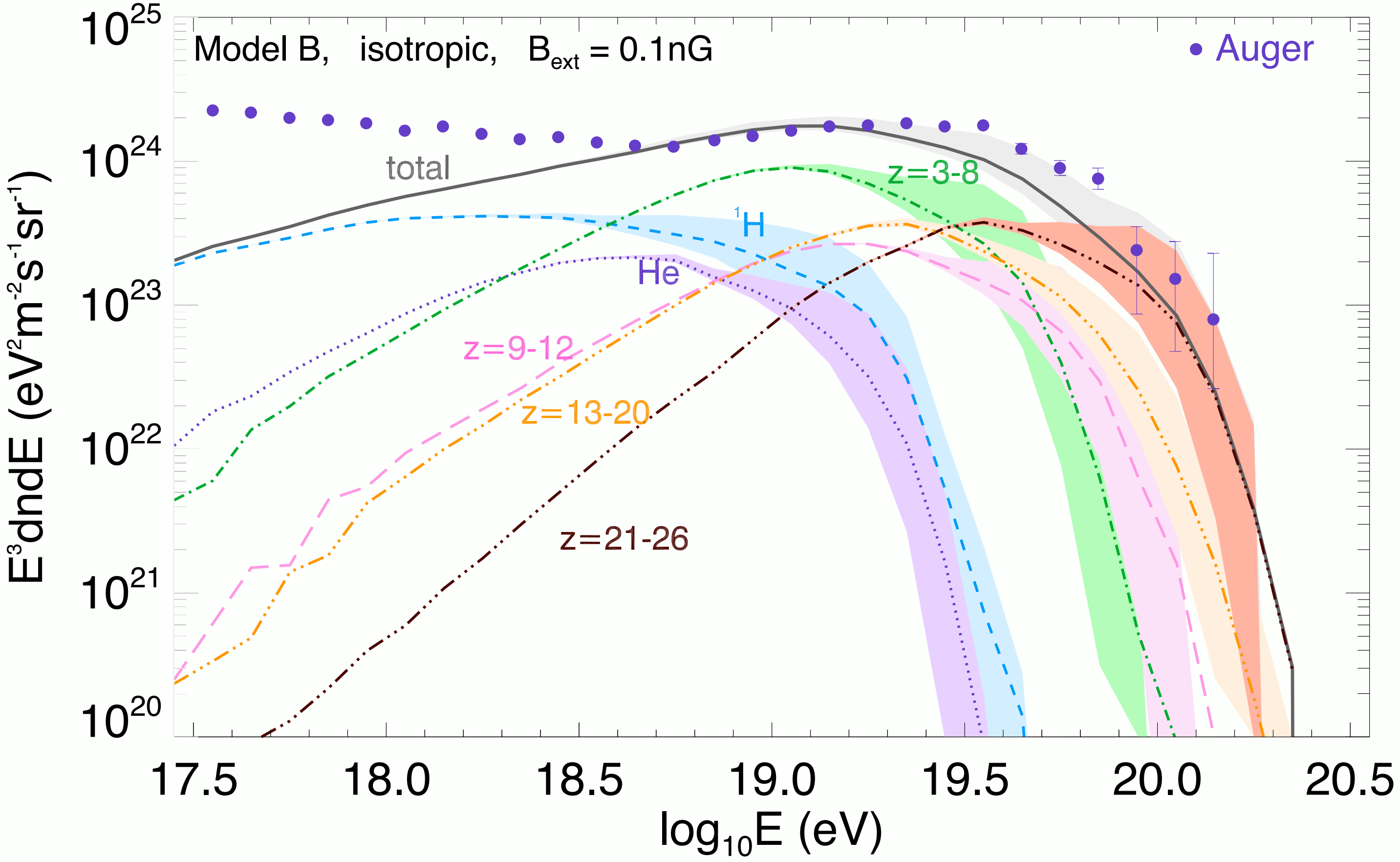
300 realisations of the history of GRB explosions in the Universe

Resulting UHECR propagated spectrum

Assumptions

ϵ_e << 1
ϵ_B ~ 0.1
ϵ_{CR} ~ 0.9
ξ_e << 1

assuming larger wind luminosities and low equipartition factor for the electrons

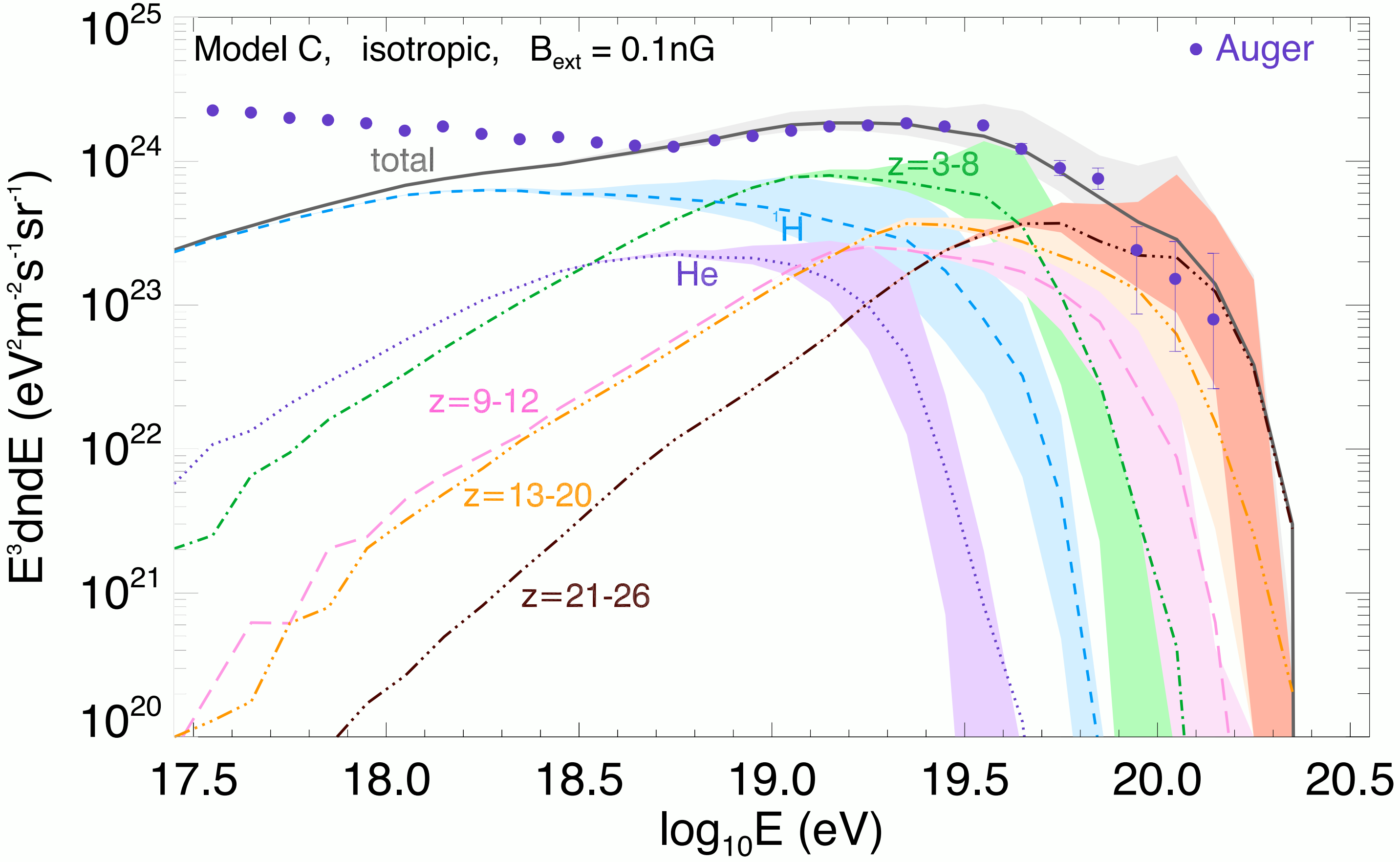


300 realisations of the history of GRB explosions in the Universe

Resulting UHECR propagated spectrum

Assumptions
ε_e << 1
ε_B ~ 0.5
ε_{CR} ~ 0.5
ξ_e << 1

assuming larger wind luminosities and low equipartition factor for the electrons



300 realisations of the history of GRB explosions in the Universe

Resulting UHECR propagated spectrum

Assumptions

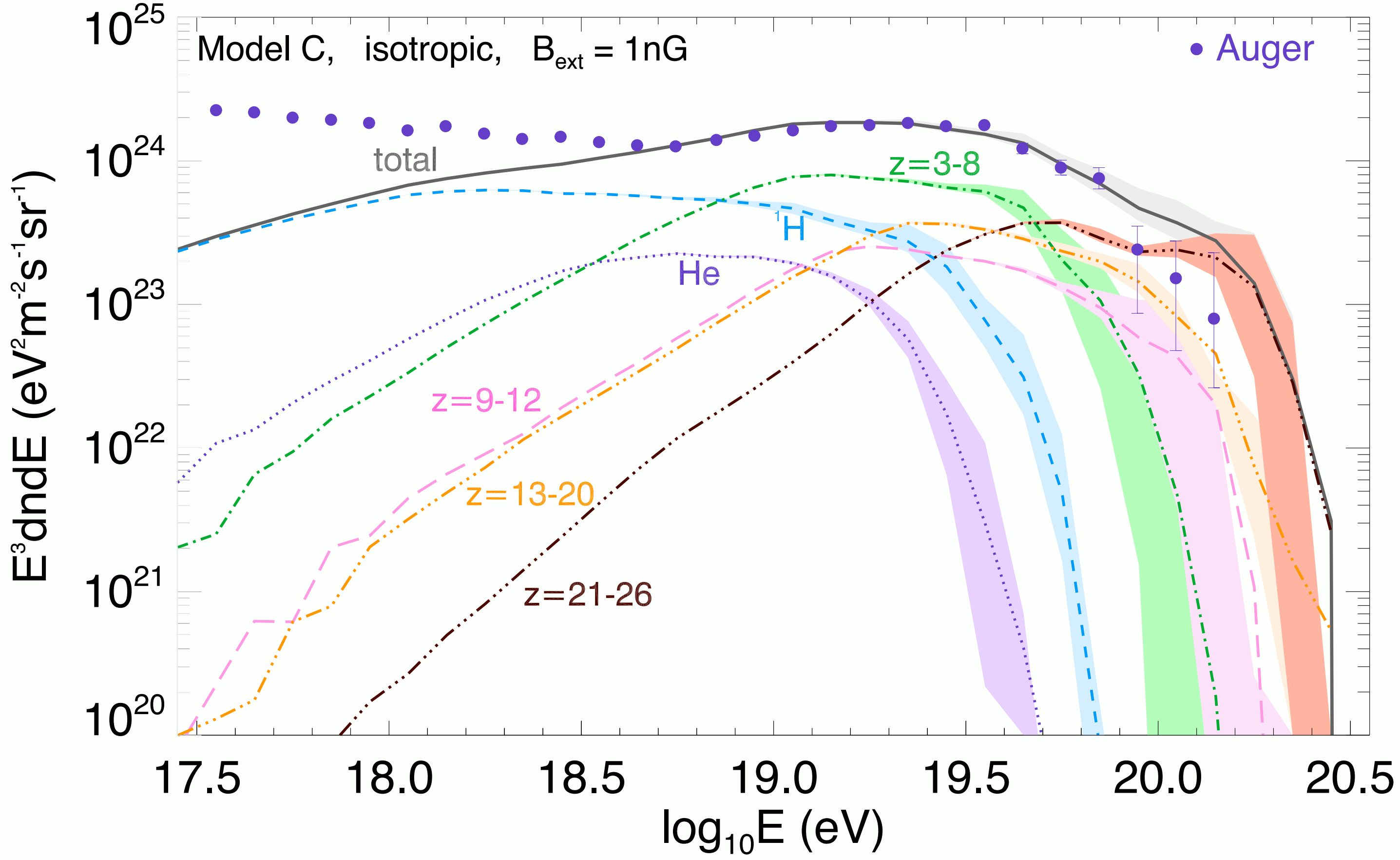
ε_e << 1

ε_B ~ 0.5

ε_{CR} ~ 0.5

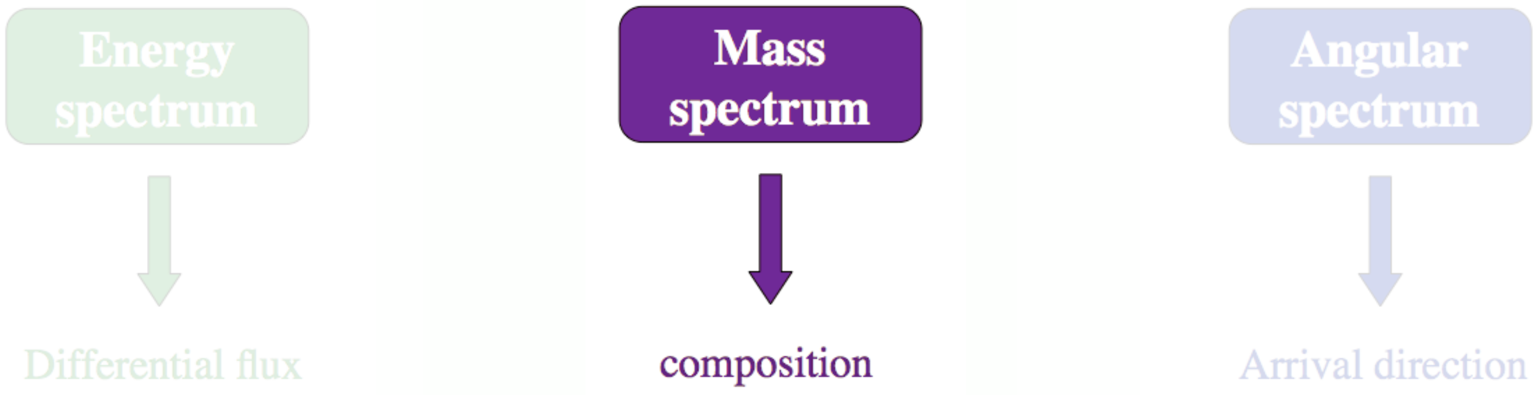
ξ_e << 1

assuming larger wind luminosities and low equipartition factor for the electrons



300 realisations of the history of GRB explosions in the Universe

Modeling the Cosmic Rays primary observables

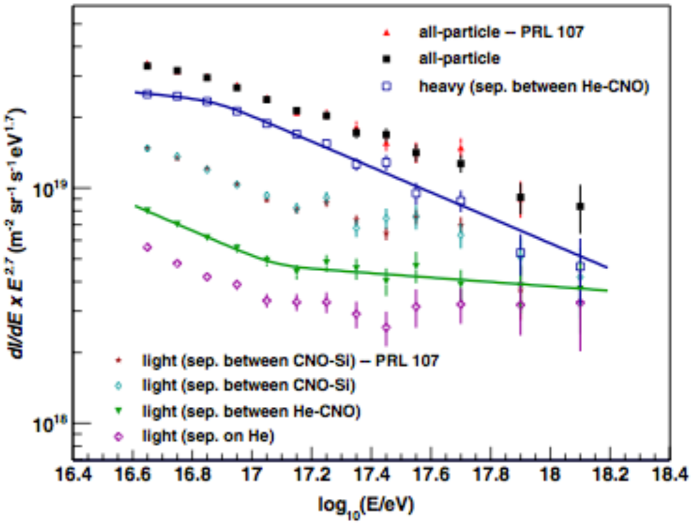


Modeling the Galactic to extragalactic transition

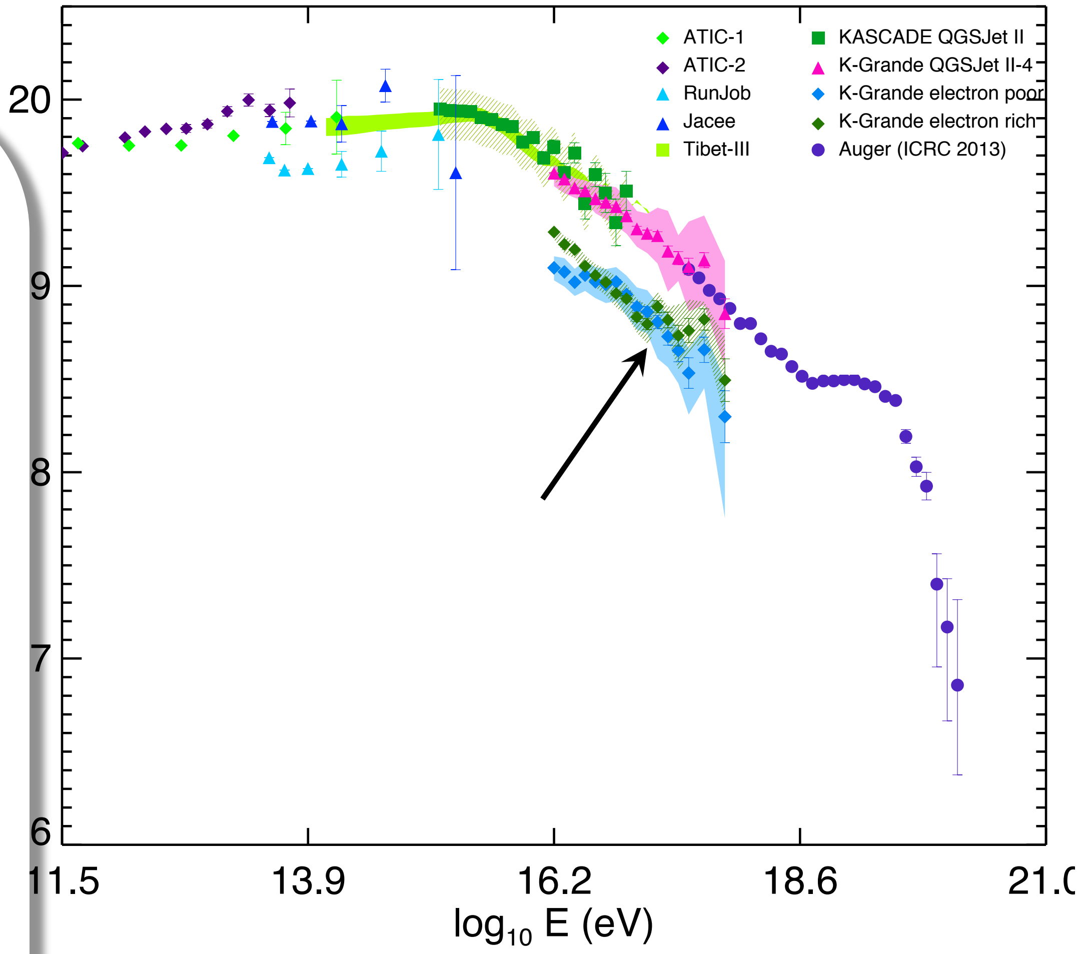
The heavy knee and the light ankle
E ~10^{17} eV

KG showed evidence for an “ankle” in the light component

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



Likely explanation : an extragalactic light component is starting to emerge on top of the light galactic component



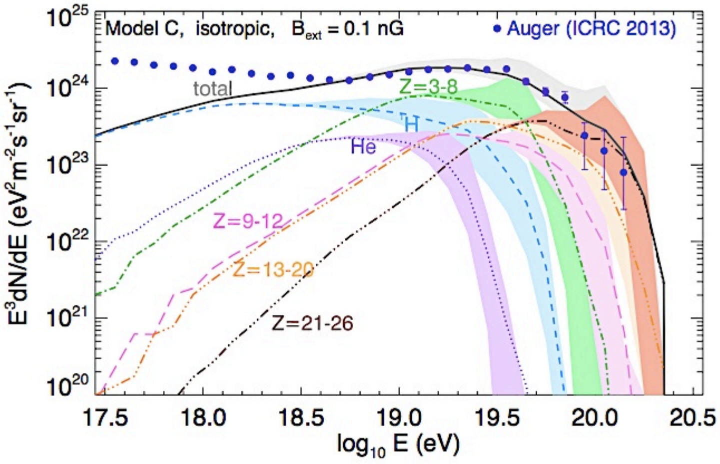
Modeling the Galactic to extragalactic transition

Two-component Model:

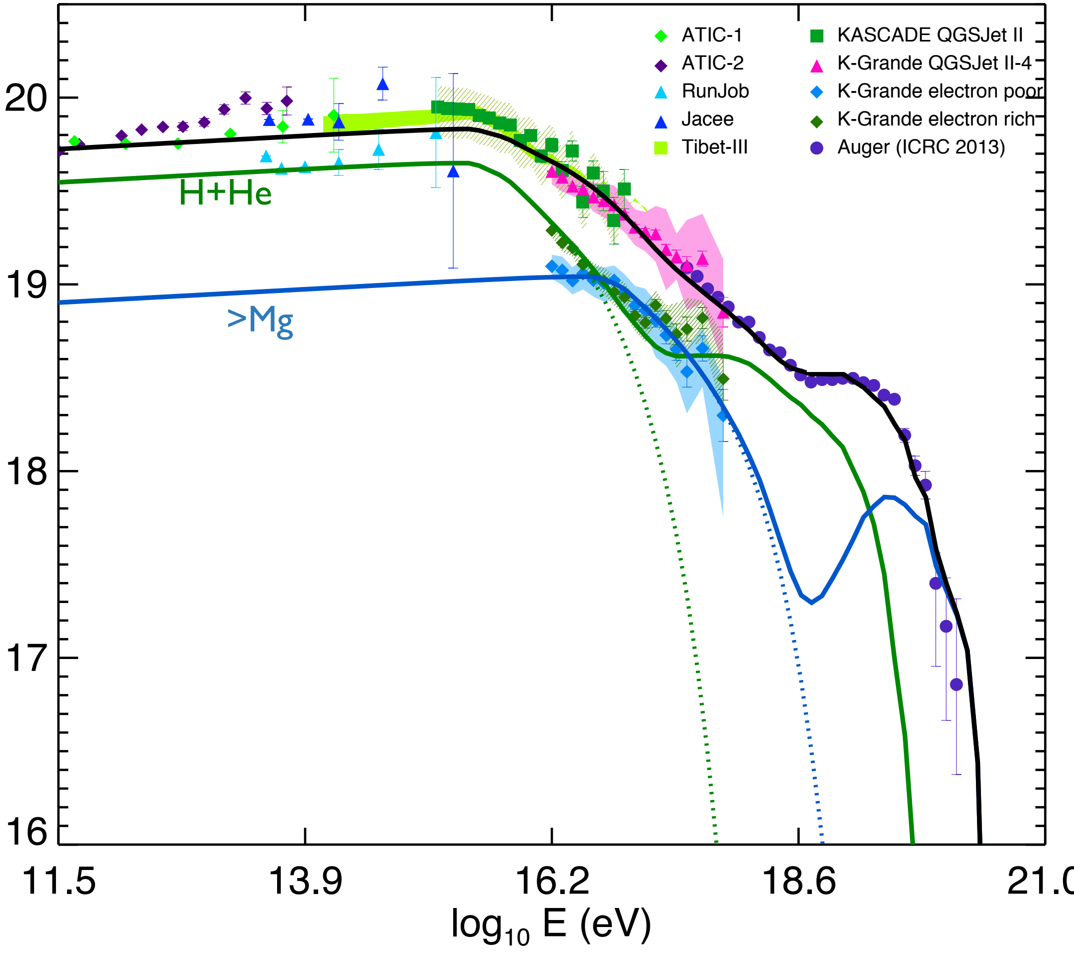
A rigidity dependent
Galactic component

+

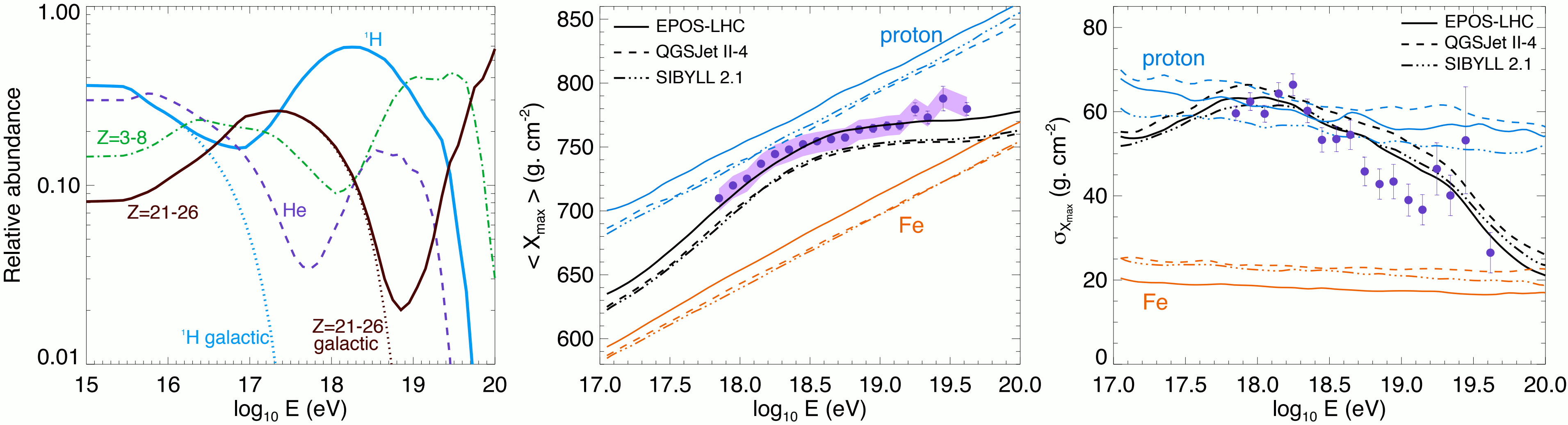
An extragalactic component
(UHECRs accelerated at
GRBs internal shocks)



please check
Globus, Allard & Parizot 2015
Phys. Rev. D 92, 021302 (Rapid Com)



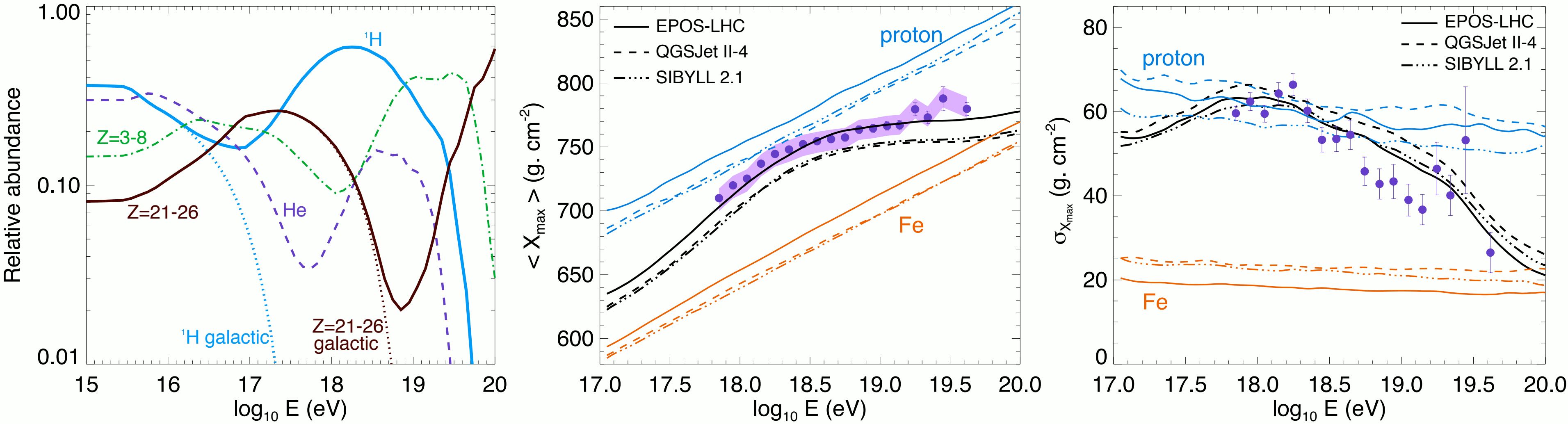
Resulting UHECR composition



⇒ **The model provides a good description of the evolution of the composition (Auger)**

Prediction: the dominant class of nuclei between ~6 10^{18} eV and ~5 10^{19} eV should be CNO

Resulting UHECR composition



⇒ **The model provides a good description of the evolution of the composition (Auger)**
Prediction: the dominant class of nuclei between ~6 10^{18} eV and ~5 10^{19} eV should be CNO

⇒ **GRB Internal shocks are good particle accelerators (protons up to few 10^{19} eV, iron to 10^{20} eV) but extragalactic GRBs as sources of UHECRs are excluded if one assumes equipartition**

⇒ **Due to neutrons escape UHE protons injected into the extragalactic medium have a much softer spectrum than UHE nuclei**
NB: this is a generic feature of acceleration models in high radiation density environment
and a key feature for the GCR/eGCR transition

Secondary messengers

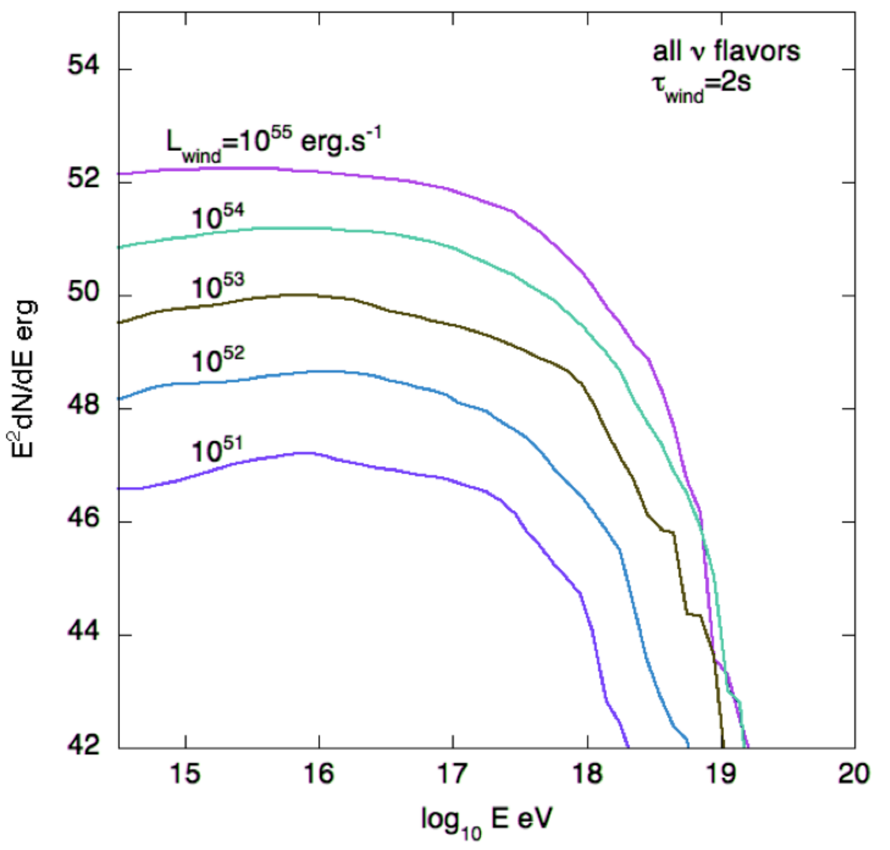
Assumptions

ε_e << 1

ε_B ~ 0.1

ε_{CR} ~ 0.9

ξ_e << 1



GRB neutrino output for a given luminosity

Neutrinos production channels :

from protons SOPHIA

$$p + \gamma \rightarrow n + \pi^+ \qquad \pi^+ \rightarrow \nu_\mu + \mu^+ \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\hookrightarrow p + e^- + \bar{\nu}_e$$

$$n + \gamma \rightarrow p + \pi^- \qquad \pi^- \rightarrow \bar{\nu}_\mu + \mu^- \qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

+ hadronic interactions
EPOS 1.99

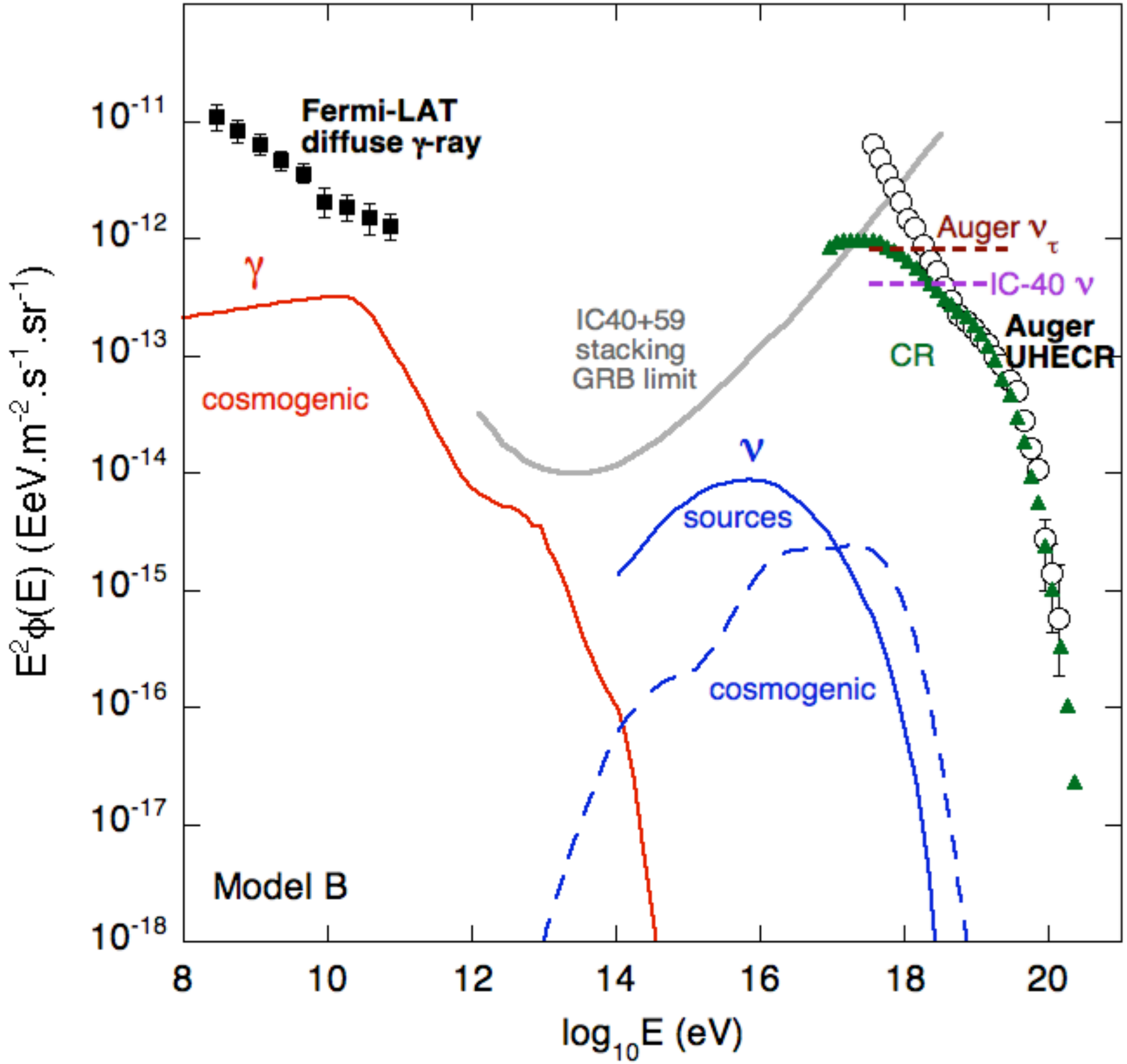
from complex nuclei

π-prod of secondary p and n; β-decay of secondary n

decay of the π produced during the BR process

we take also into account the synchrotron cooling of pions and muons

Finally



Assumptions

ε_e << 1

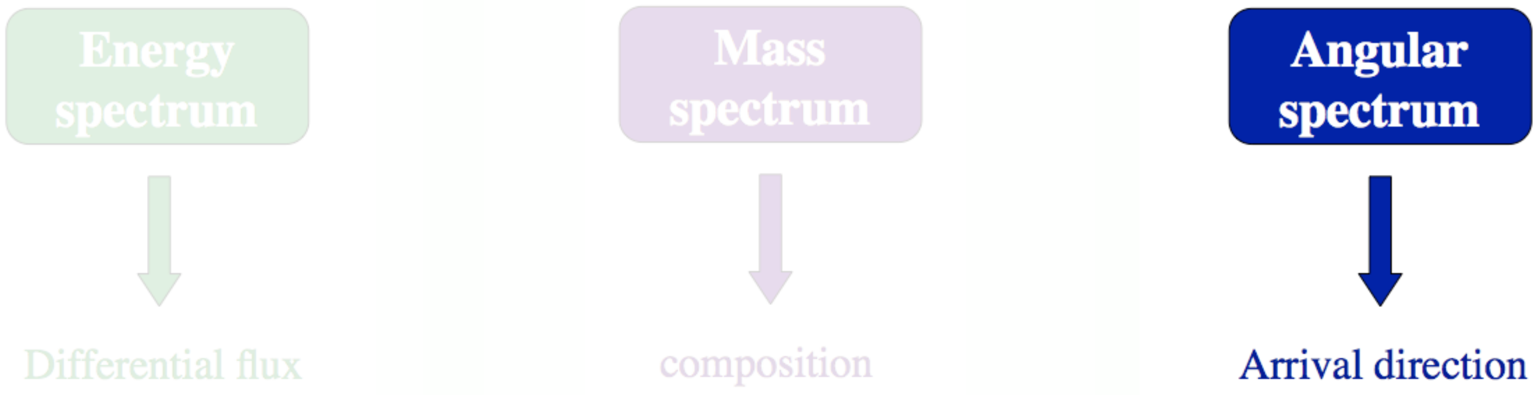
ε_B ~ 0.1

ε_{CR} ~ 0.9

ξ_e << 1

model B

Modeling the Cosmic Rays primary observables



Energy spectrum

Differential flux

Mass spectrum

composition

Angular spectrum

Arrival direction

(coming soon !
Globus, Allard, Parizot,
Lachaud and Piran –to be
submitted this week)

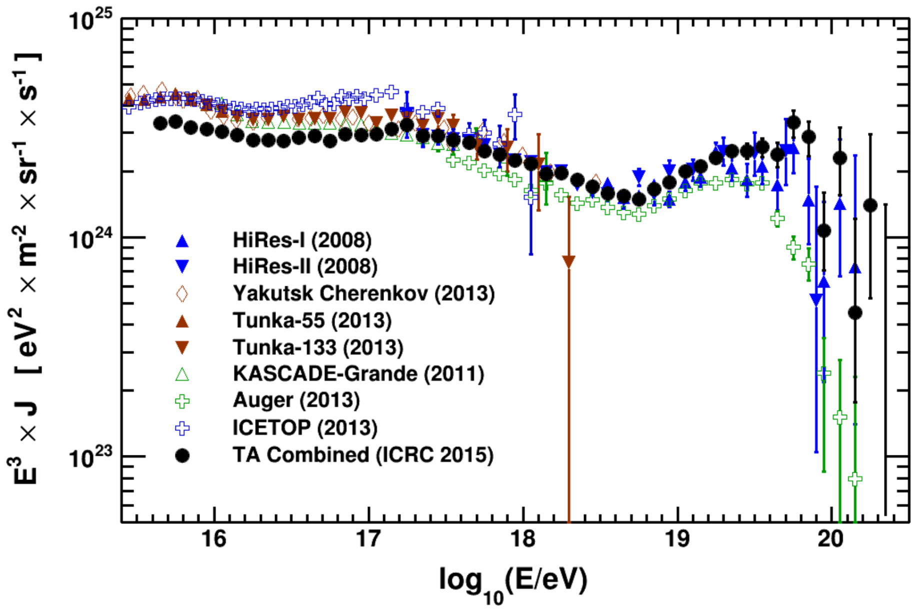
Are the UHECR northern sky and southern sky significantly different ?

Globus, Allard, Parizot, Lachaud and Piran, in final shaping

TA: 83 above 57 EeV (**TA Anisotropy Data Set)** , exposure 8,600 km^2 sr yr.
After conservatively scaling down the energy by 13%, this corresponds to **83 above 50 EeV.**

Auger: 231 above 52 EeV, exposure 66,452 km^2 sr yr.
Given the shape of the spectrum between 50 and 60 EeV, this extrapolates to ~**290 above 50 EeV**.

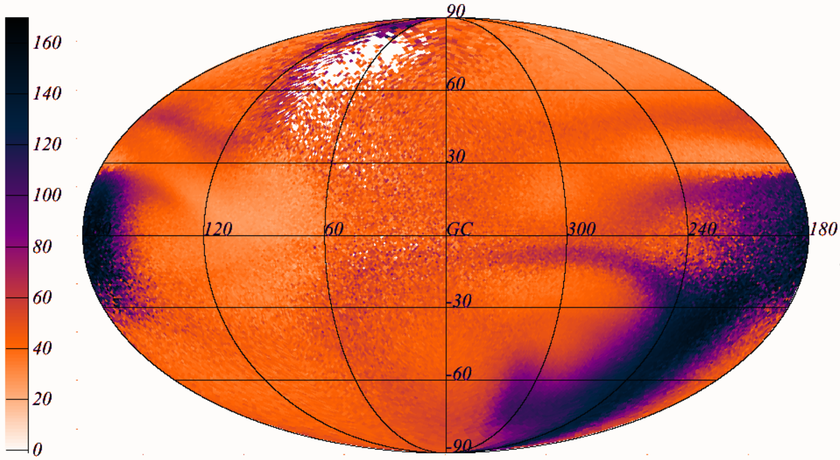
If the Auger flux is assumed to represent the average UHECR flux in the absence of anisotropy, then the expected number of events for TA is ~ 38. The actual integrated flux of TA would thus need to be a 7σ upward fluctuation.

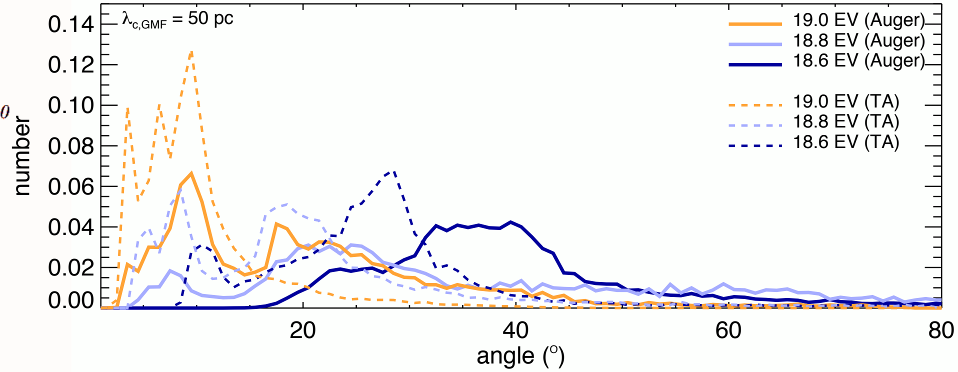


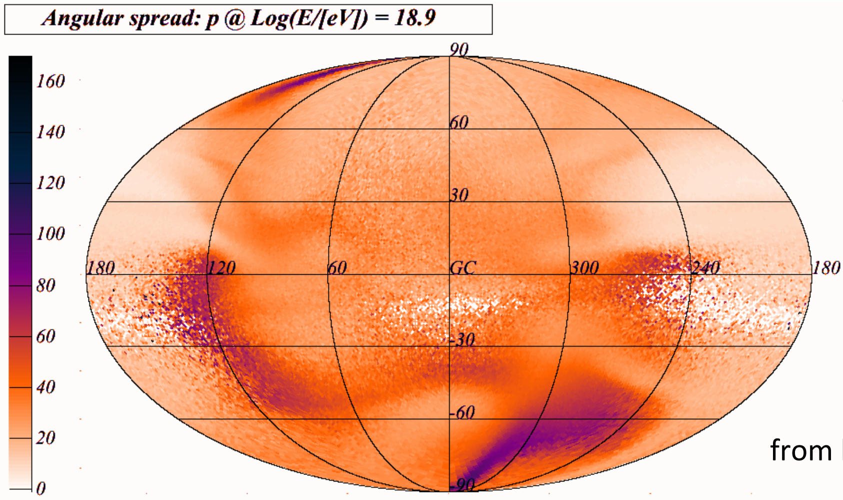
If the difference between the two spectra is taken seriously and attributed to the contribution of a dominant source, this source may represent 45%–60% of the total northern sky flux.

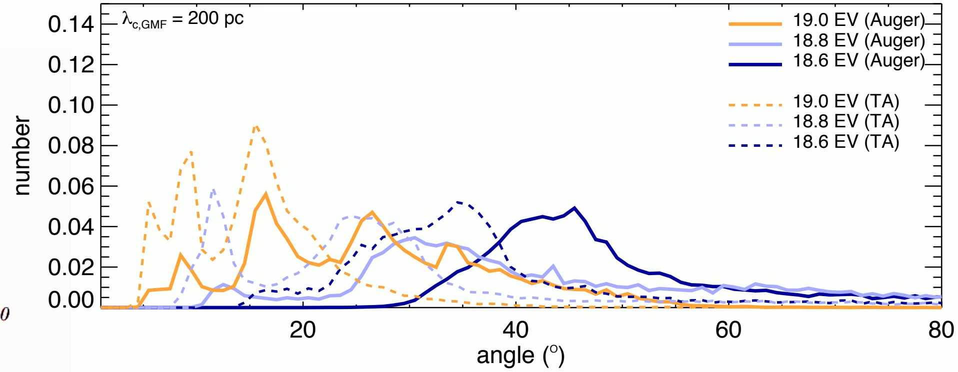
Including the GMF : Jansson & Farrar 2012

Globus, Allard, Parizot, Lachaud and Piran, in final shaping





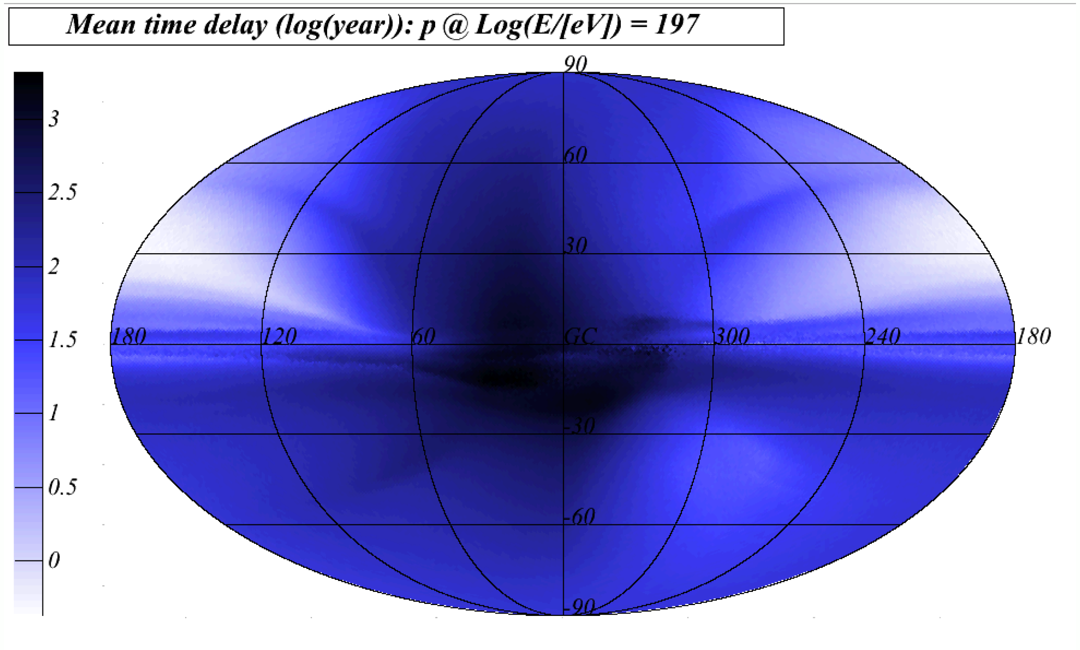


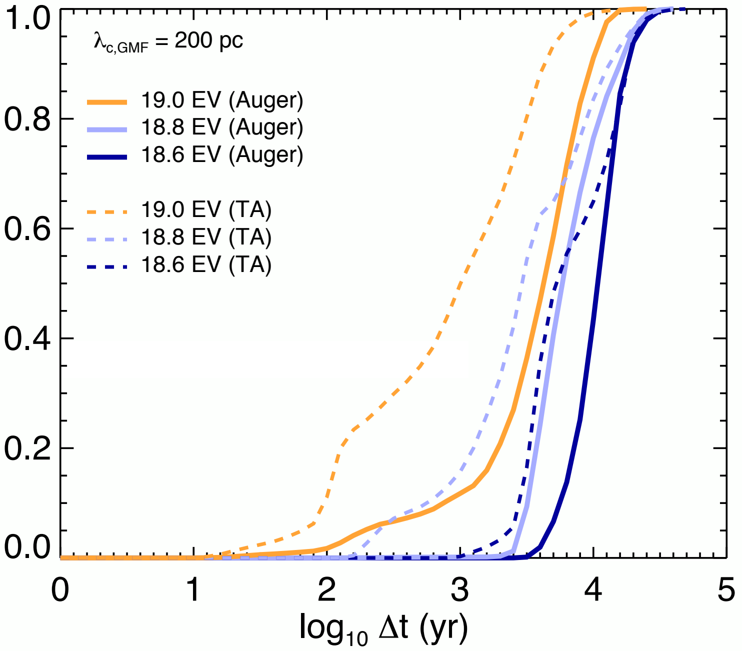


from back propagation (Rouillé d'Orfeuil et al. 2014)

Including the GMF : Jansson & Farrar 2012

Globus, Allard, Parizot, Lachaud and Piran, in final shaping


Mean time delay (log(year)): p @ Log(E/[eV]) = 197



from back propagation (Rouillé d'Orfeuil et al. 2014)

Skymap production

Globus, Allard, Parizot, Lachaud and Piran, in final shaping

1200 realizations of the history of GRB explosions in the Universe

Propagation in extragalactic turbulent magnetic field, including energy losses on extragalactic photon backgrounds and in Galactic magnetic field (back propagation)

Probability distribution of energies $P(E)$, redshifts $P(z; \underline{E})$, sources $P(S; \underline{z}, \underline{E})$, masses $P(A; \underline{z}, \underline{E}, \underline{S})$, deflection angles $P(\Delta\theta; \underline{z}, \underline{E}, \underline{S}, \underline{A})$

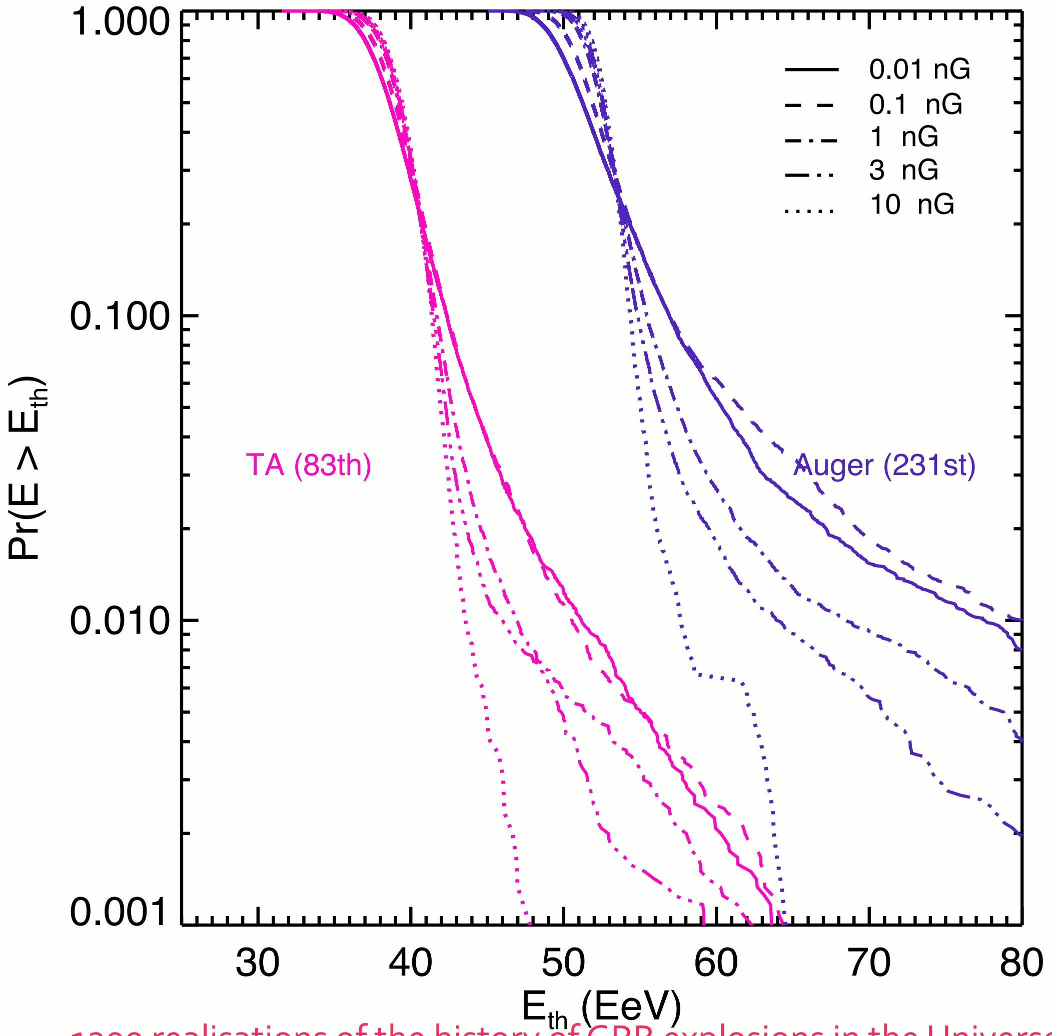
For each realization, we calculate the total spectrum, and according to this spectrum and the pre-calculated probability tables, we draw first the energy, the redshift, the source, the mass and charge of the particle, and the deflection $\Delta\theta$ which give the position of the source. Then we take into account the GMF (magnifications + deflections see Rouillé d'Orfeuil et al., 2014)

We then produce data sets (10 per realization) with Auger and TA statistics, exposure and resolution, above 5 EeV

Skymaps are built out of the 83 and 231 highest energy events for TA and Auger, respectively

E_{83} and E_{231} probability distributions

Globus, Allard, Parizot, Lachaud and Piran, in final shaping



1200 realisations of the history of GRB explosions in the Universe

A realization that fits both the excess and the anisotropy level