Ultra-High energy cosmic rays acceleration at GRBs internal shocks

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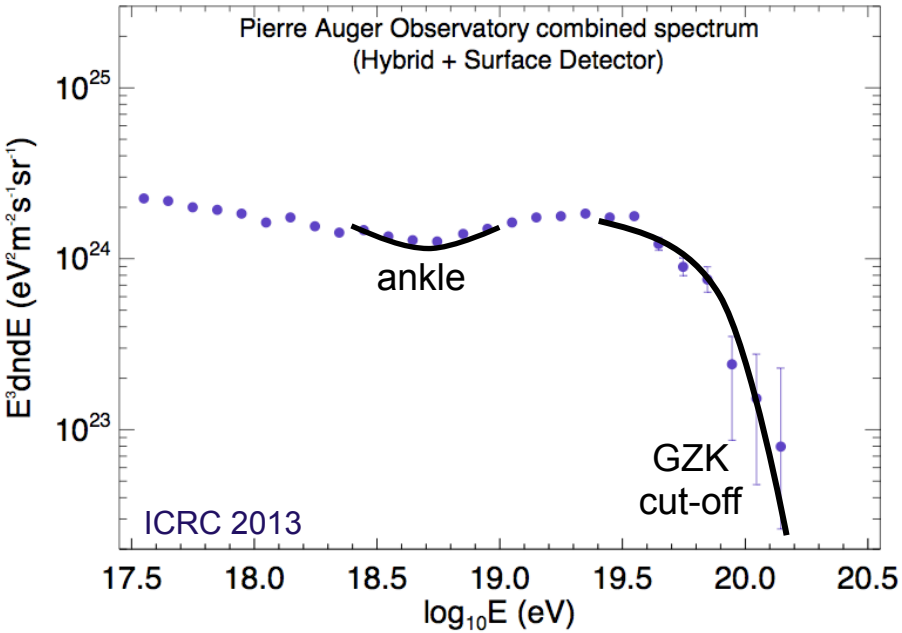
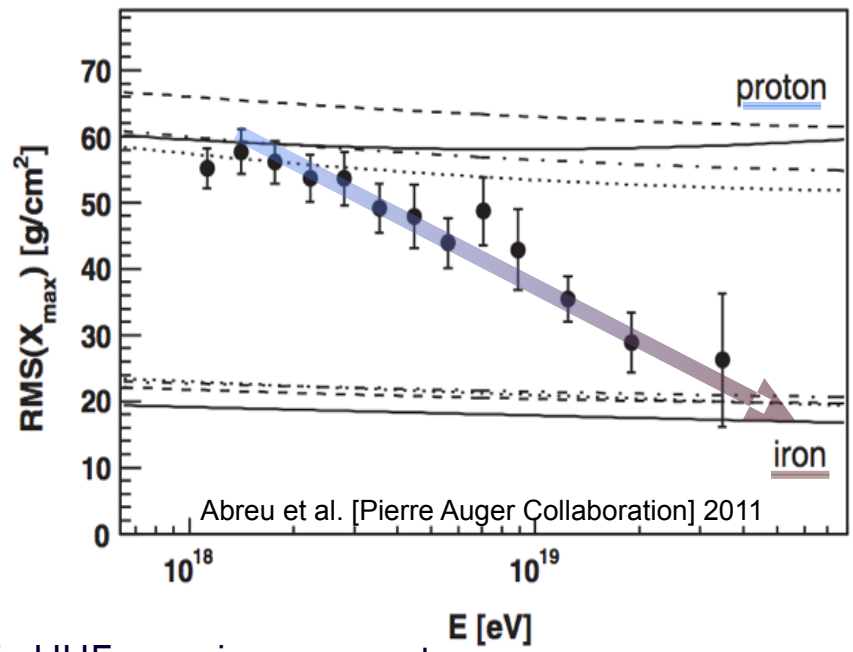
GRB in the multimessenger era, june 17th 2014, Paris France

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 ?

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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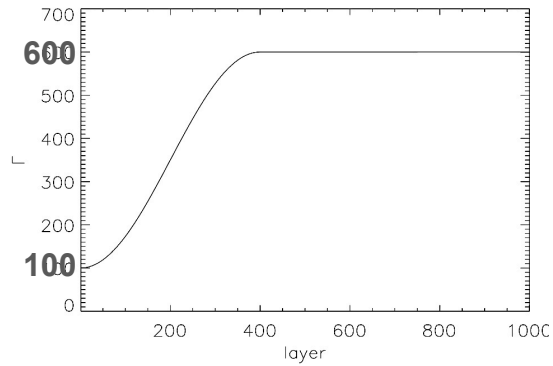
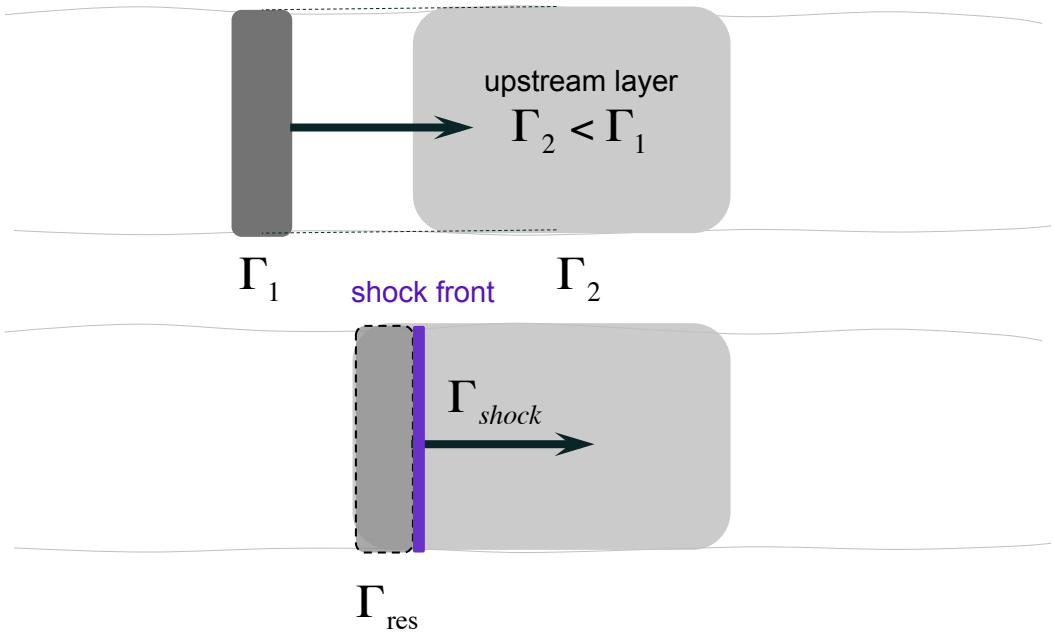
Modeling of the internal shock

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

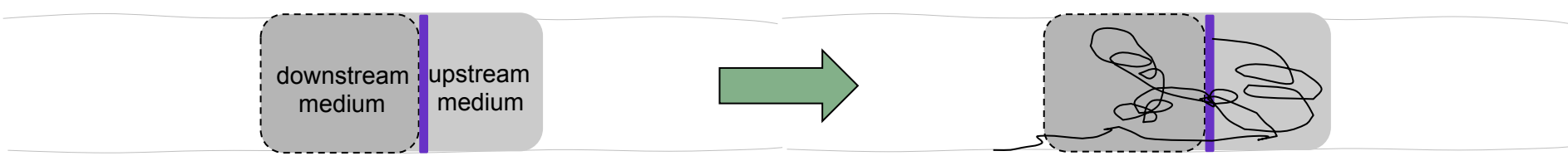
⇒ Layers collisions mimic the propagation of a shock in the wind



Lorentz factor profile



Fermi acceleration



Modeling of the internal shock

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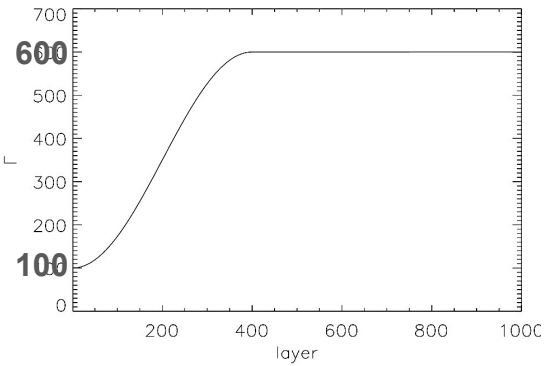

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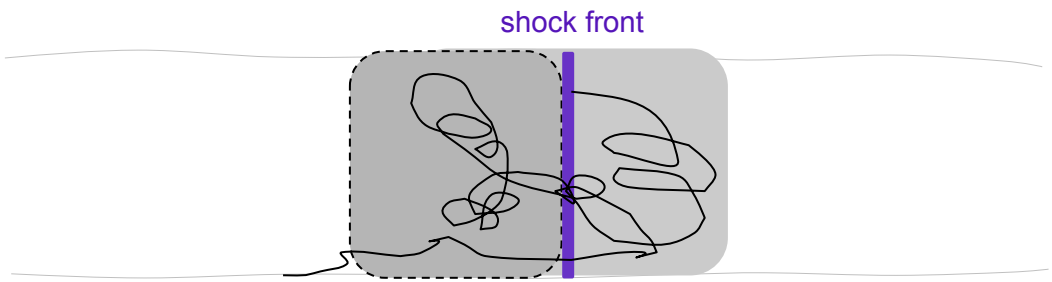


...needed for acceleration

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)

shock free parameters :

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

...needed for energy losses

r_{shock},

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

density,

photon background...

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

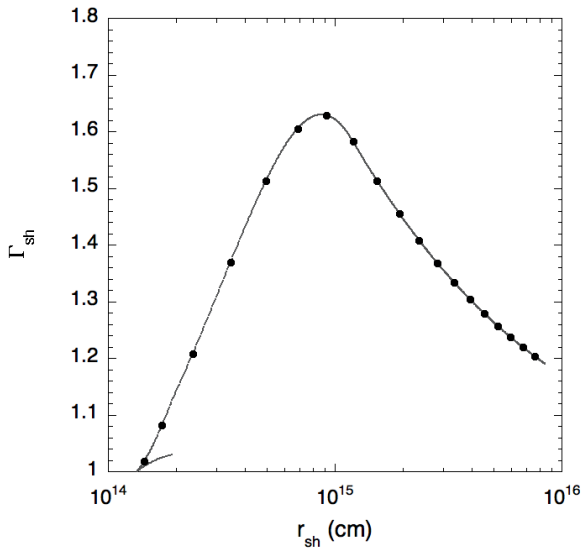
Assumptions
ε_e << 1
ε_B ~ 0.1
ε_{CR} ~ 0.9

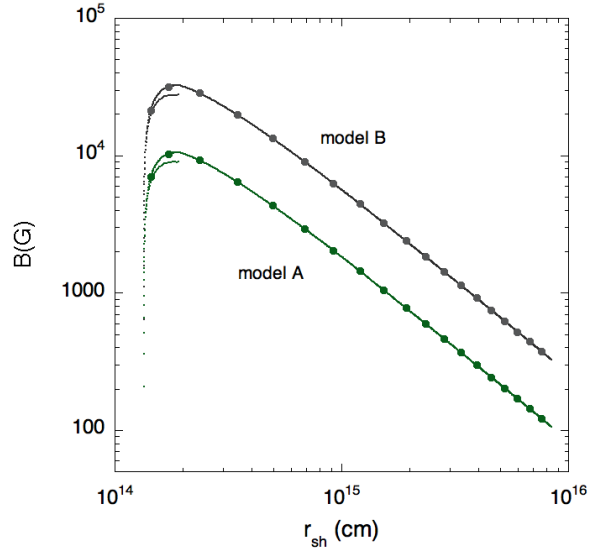
model C

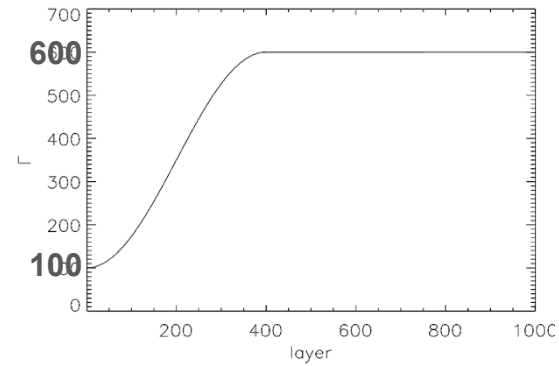
Assumptions
ε_e << 1
ε_B ~ 0.33
ε_{CR} ~ 0.66

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}

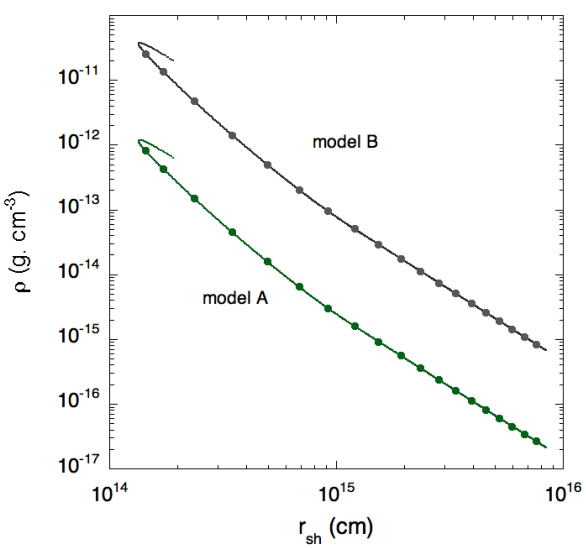
Single synthetic pulse

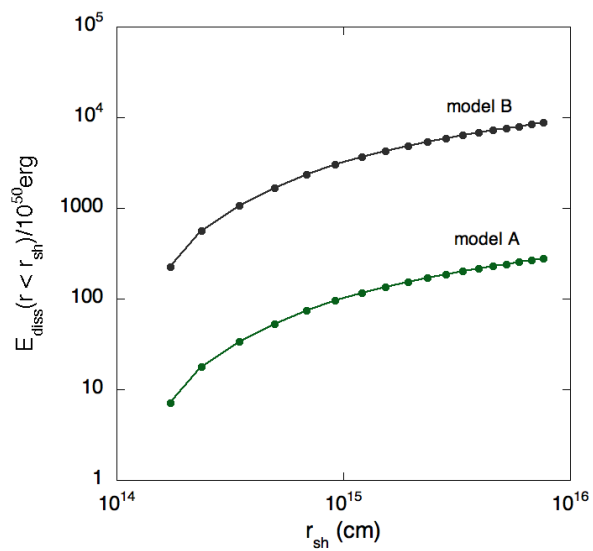






Lorentz factor profile





Example:

t_{wind}=2s

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

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

18 “snapshots”

Our calculation

• Modeling of the internal shock according to Daigne & Mochkovitch 1998 ("solid layers" collision model)
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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

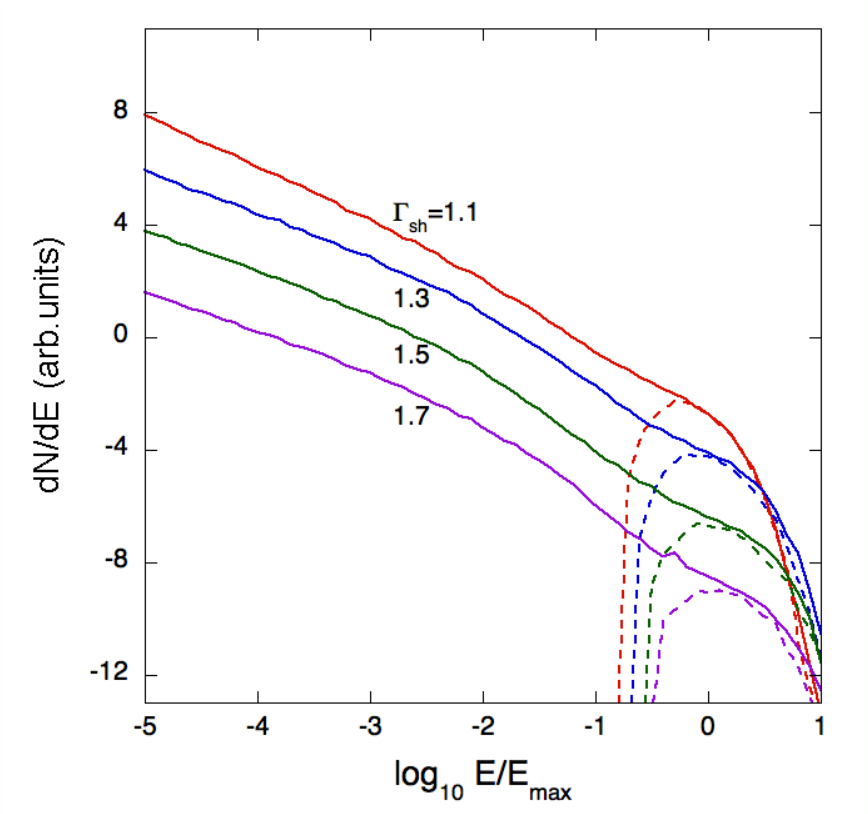
- Needs assumption on free boundaries :

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

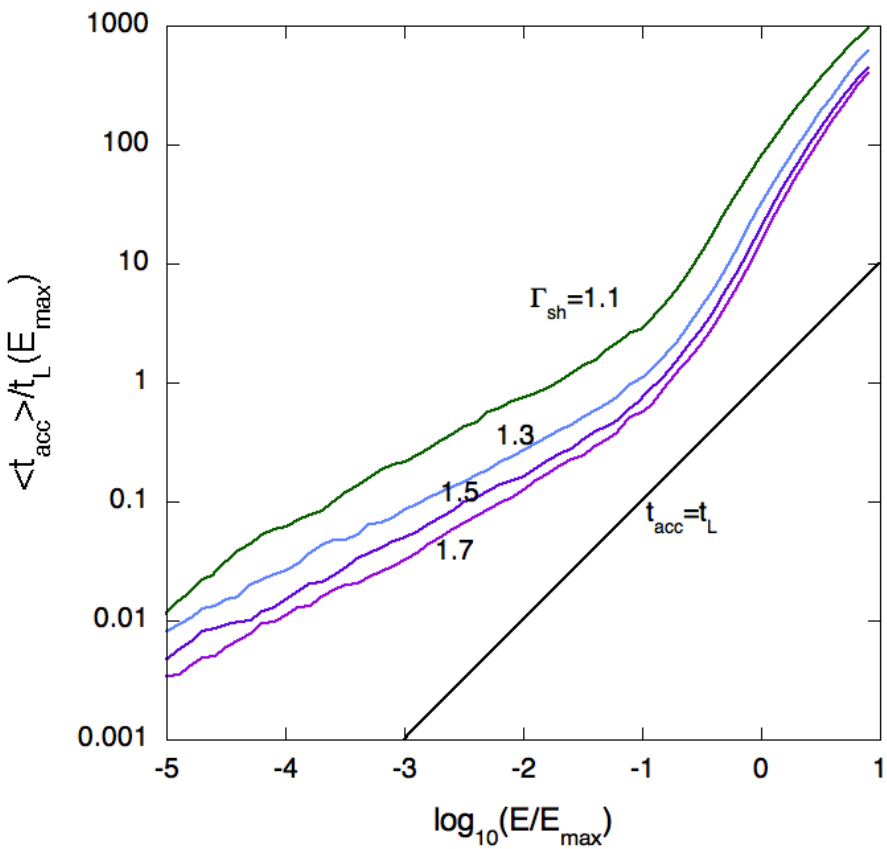
E_{max} definition : $r_L(E_{max}) = \frac{E_{max}}{eZB} \equiv \lambda_{max}$



- 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)

cosmic rays acceleration time

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



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

$t_{acc}=t_L$ 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 in energy losses

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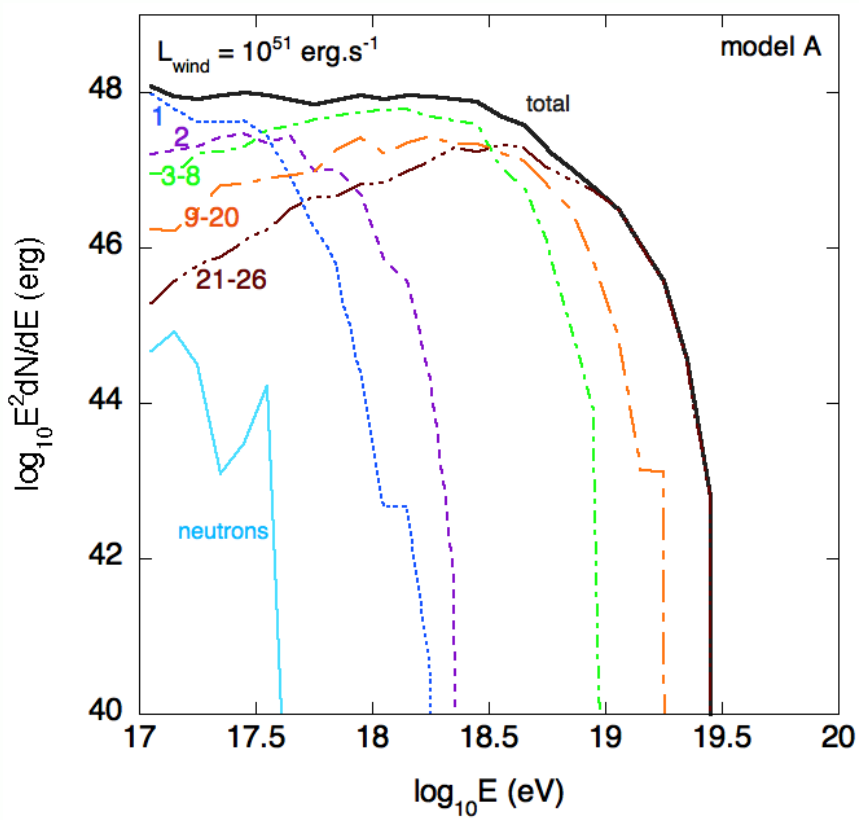
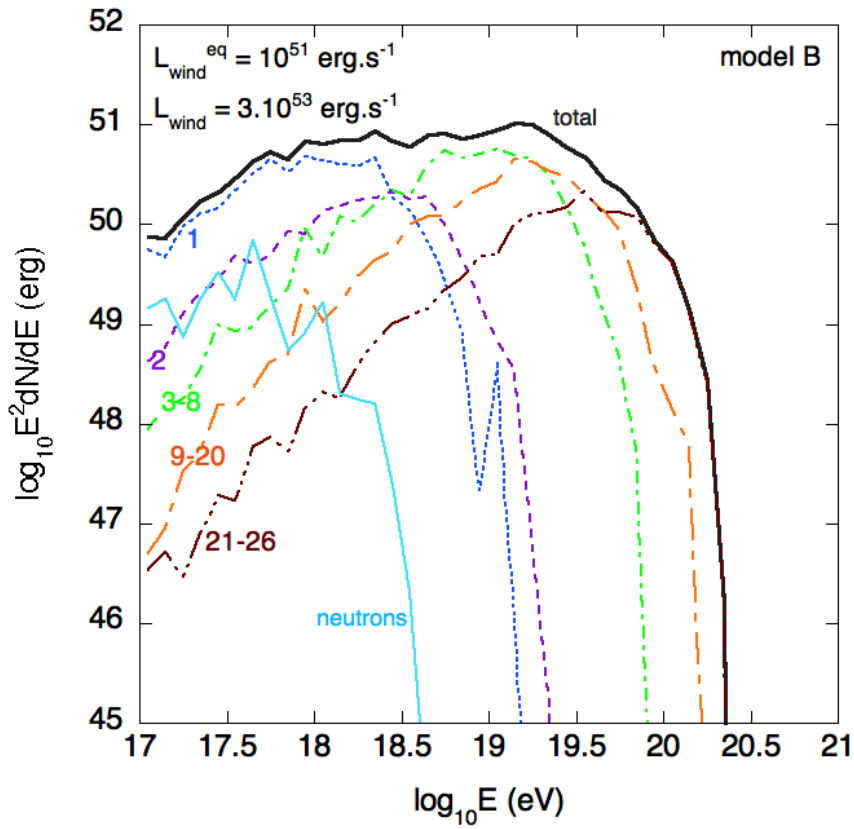
UHECR spectra (escaping from the wind)

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

⇒ **GRB output for :** L_{wind}^{eq}=**10^{51}** erg.s^{-1} t_{wind} = 2s
metallicity : 10 X galactic CRs





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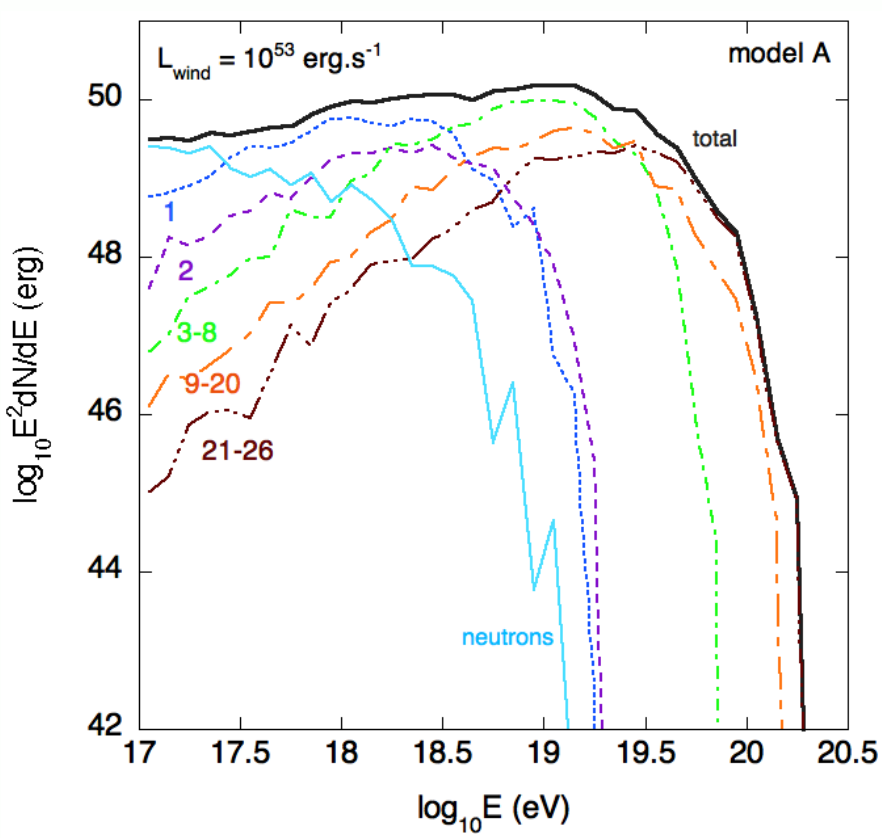

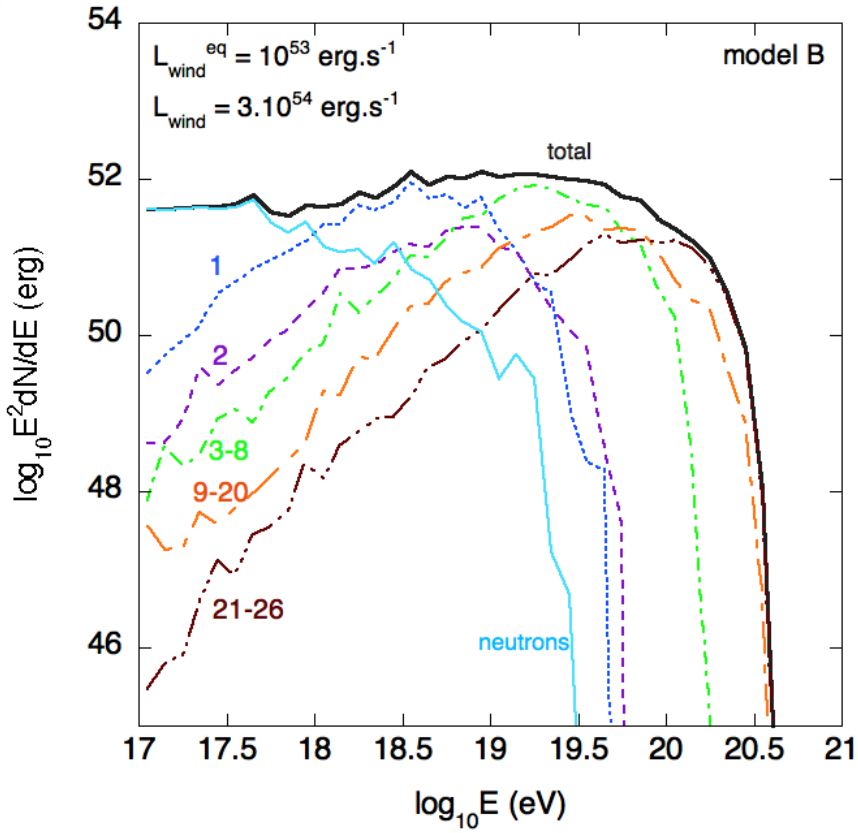

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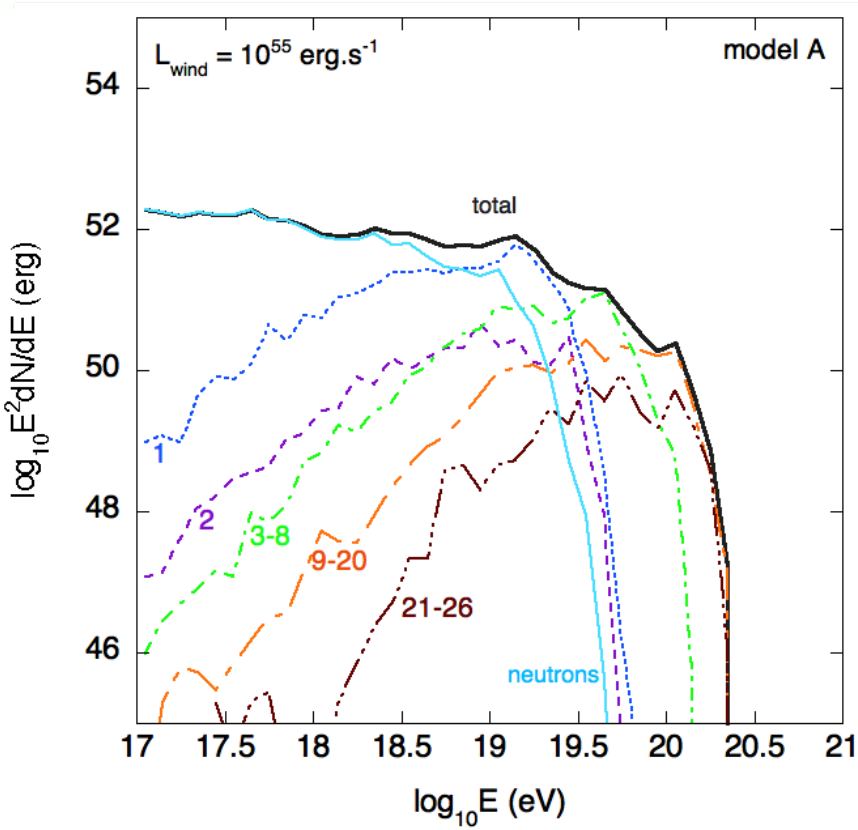

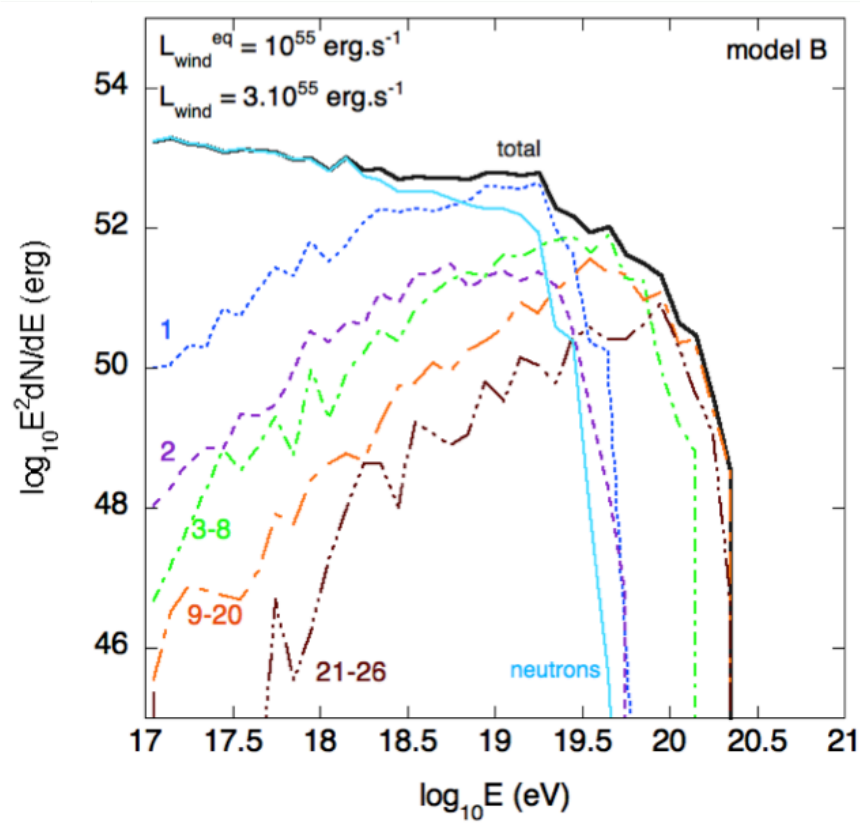

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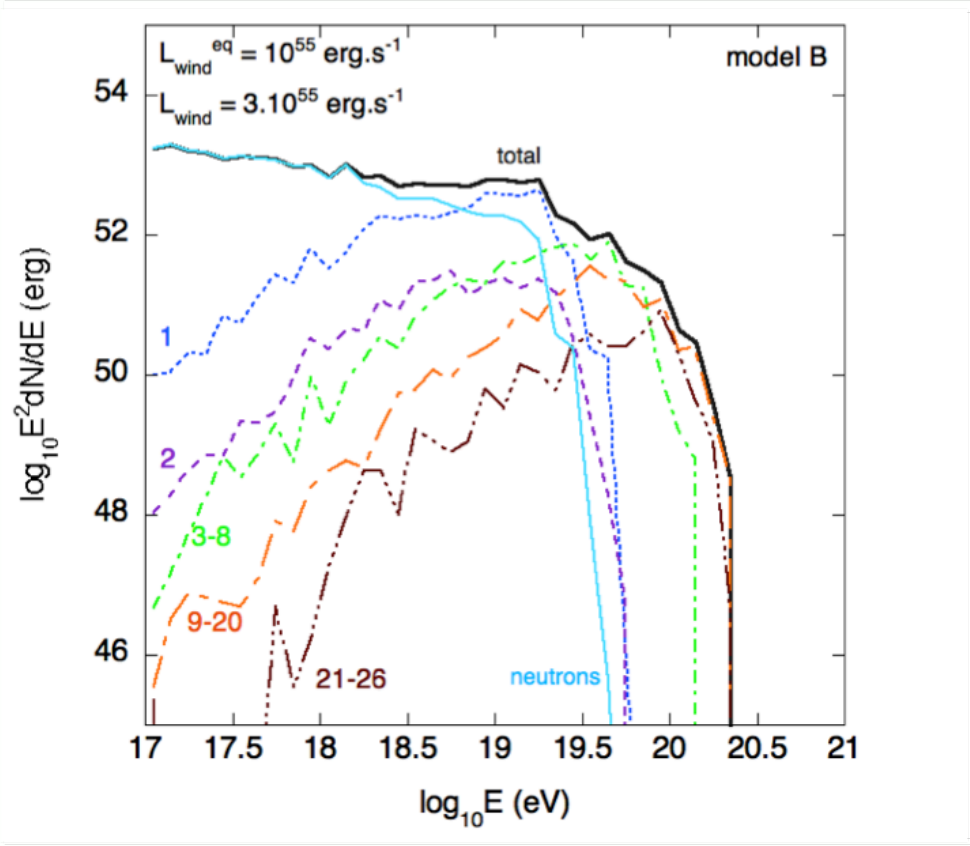

High luminosities : Nuclei components get narrower, more neutrons emitted
➔ photointeractions

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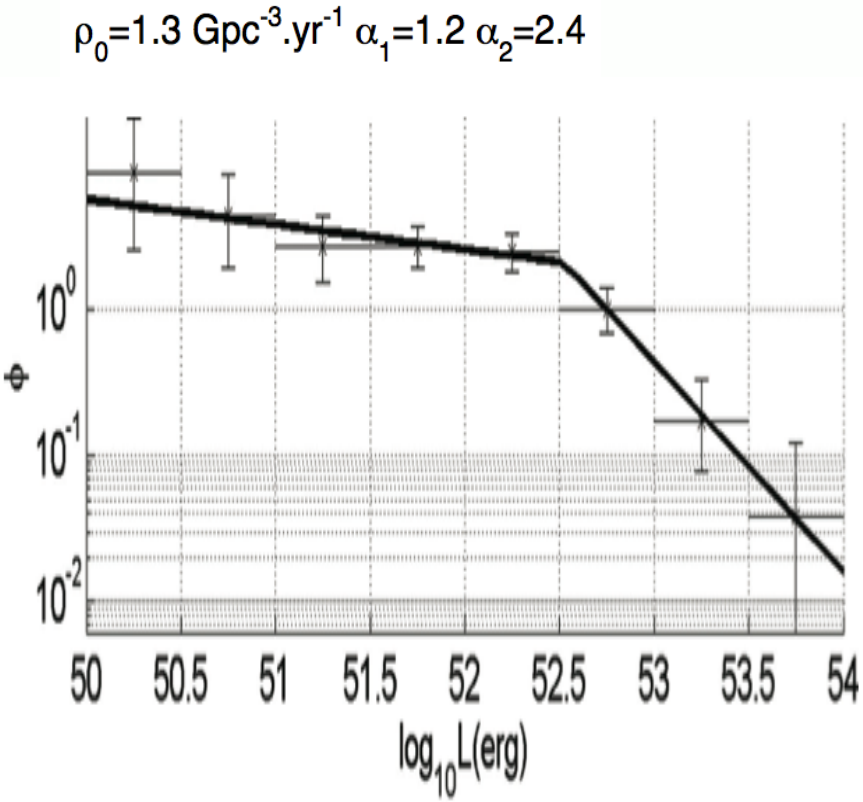
Convolution by a GRB luminosity function

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



Assuming the central source activity lasts 20 s

UHECR emissivity above 10^{18} eV :

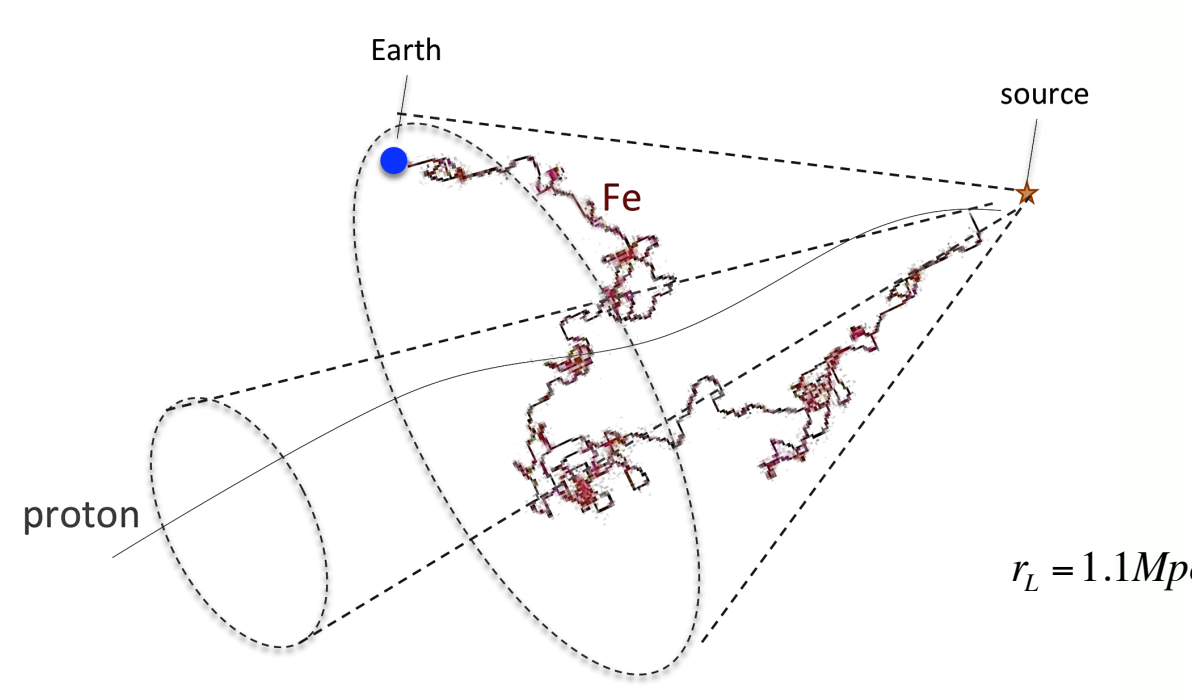
Model A : ~6.10^{42} erg.Mpc^{-3}.yr^{-1}

Model B and C : ~5-6.10^{42} 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)

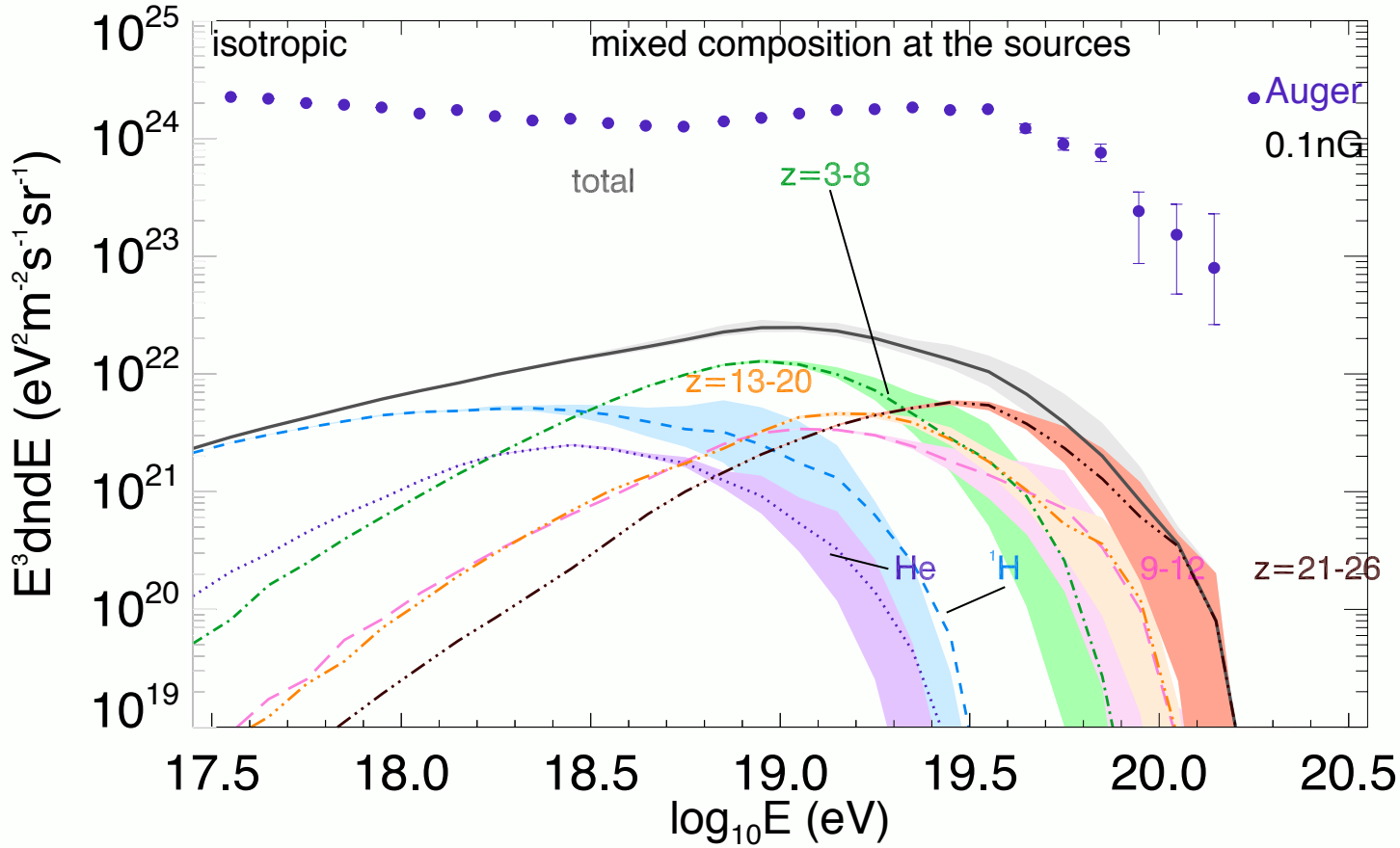


$$r_L = 1.1 Mpc \times \frac{E_{EeV}}{ZB_{nG}}$$

Propagated spectrum

Assumptions
$\varepsilon_e = 0.33$
$\varepsilon_B = 0.33$
$\varepsilon_{CR} = 0.33$

model A

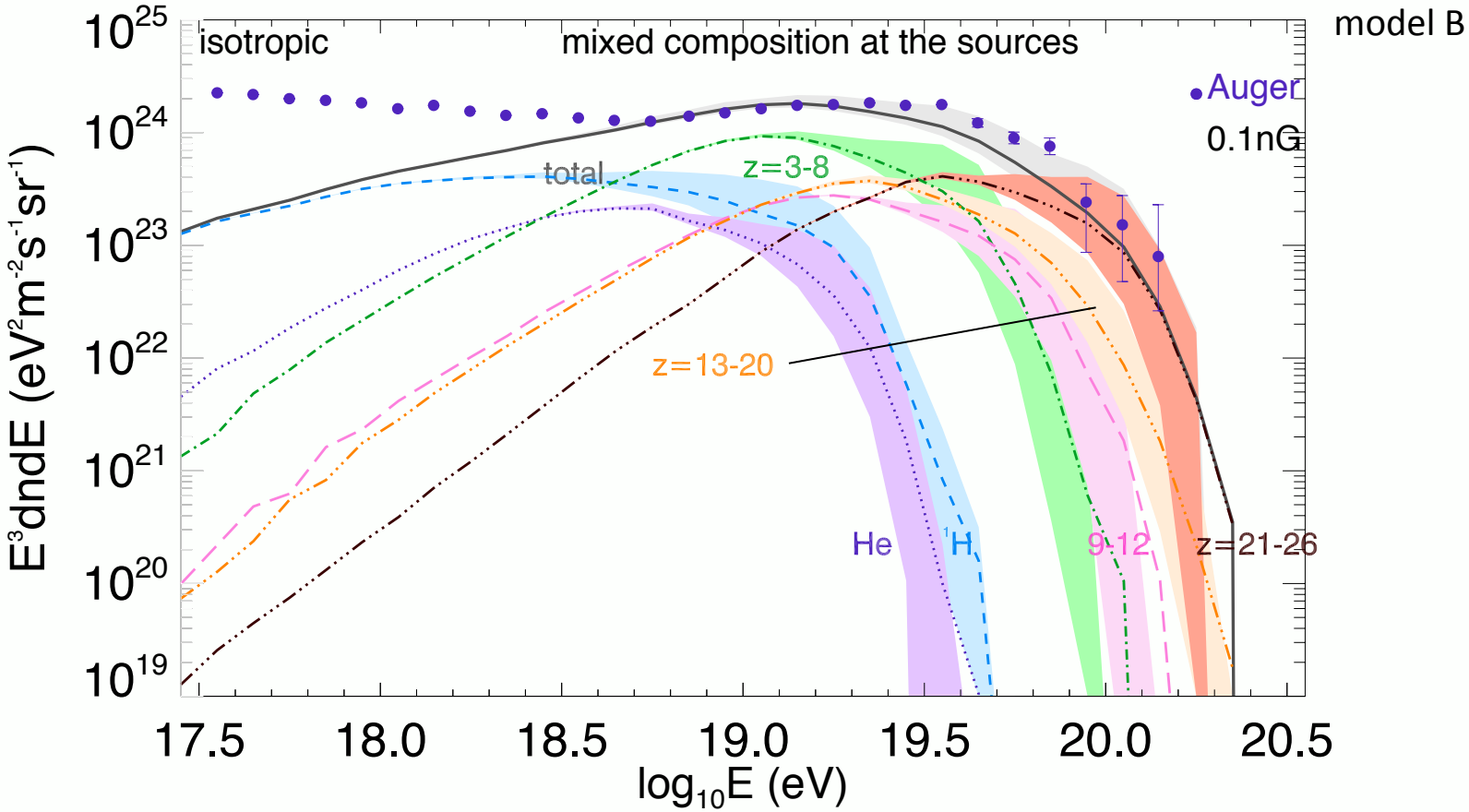


300 realisations of the history of GRB explosions in the Universe

Propagated spectrum

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

assuming larger wind luminosities and low equipartition factor for the electrons



300 realisations of the history of GRB explosions in the Universe

Propagated spectrum

assuming larger wind luminosities and low equipartition factor for the electrons

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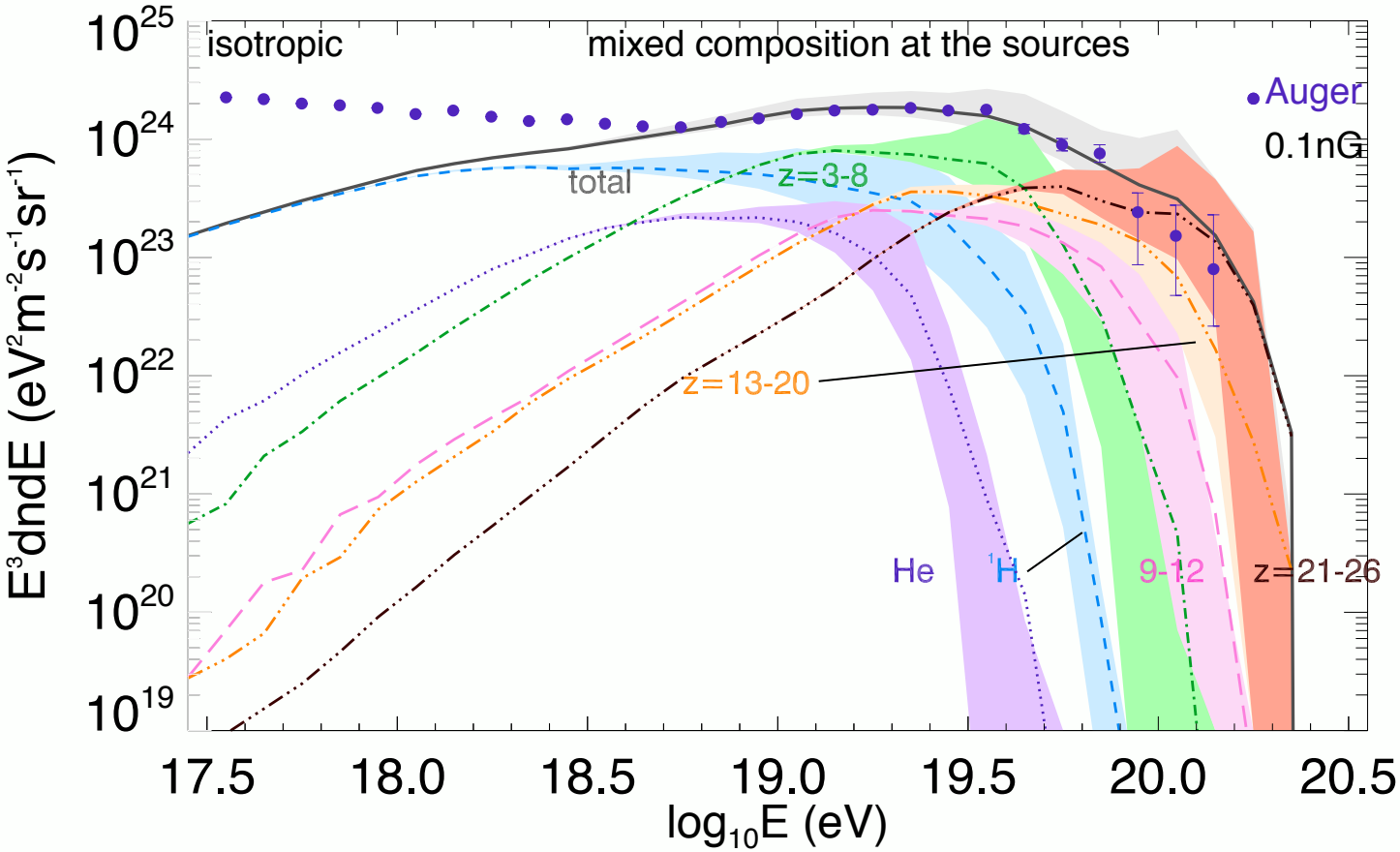
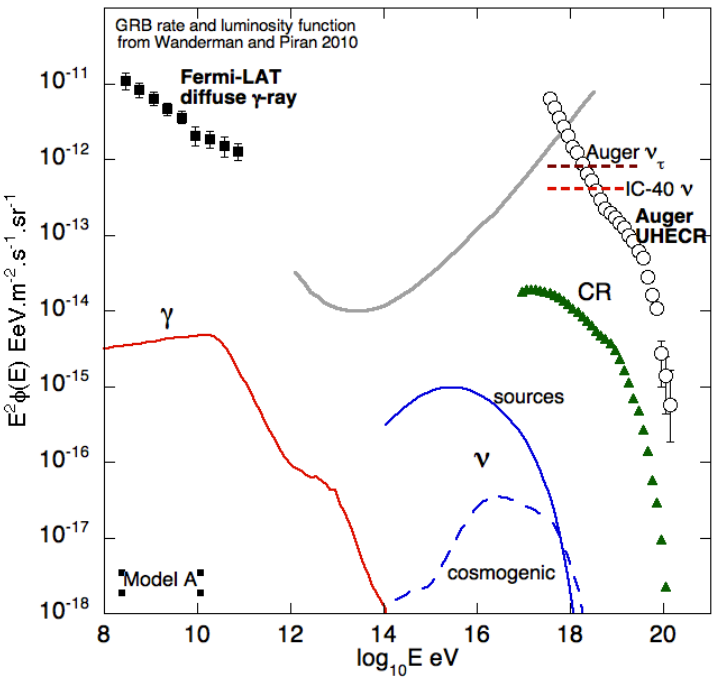
ε_{CR} ~ 0.66

Model C



300 realisations of the history of GRB explosions in the Universe

Finally


GRB rate and luminosity function
from Wanderman and Piran 2010
Fermi-LAT
diffuse γ-ray
Auger ν_τ
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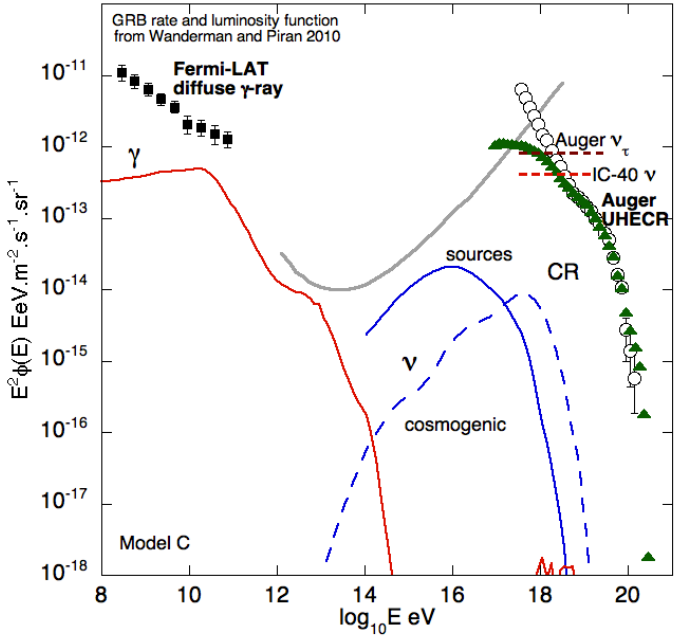
Model A
E²φ(E) EeV.m⁻².s⁻¹.sr⁻¹
log₁₀E eV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ν
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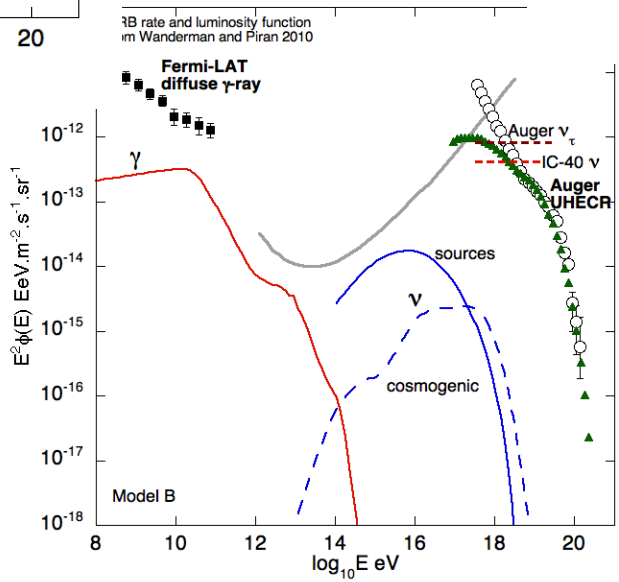
Model C
E²φ(E) EeV.m⁻².s⁻¹.sr⁻¹
log₁₀E eV


Fermi-LAT
diffuse γ-ray
Auger ν_τ
IC-40 ν
Auger
UHECR
γ
sources
ν
cosmogenic
Model B
E²φ(E) EeV.m⁻².s⁻¹.sr⁻¹
log₁₀E eV

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 ➔"dark" GRBs required with energy of the shocks dissipated mostly in cosmic rays and larger wind luminosities➔ realistic? Compatible with other GRB observation? With theory?

• Not challenged by Ice-Cube current non observation of VHE neutrinos from GRBs

Propagated spectrum

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

In the extragalactic medium (very low density), ultra-high energy nuclei mainly interact with photon backgrounds:

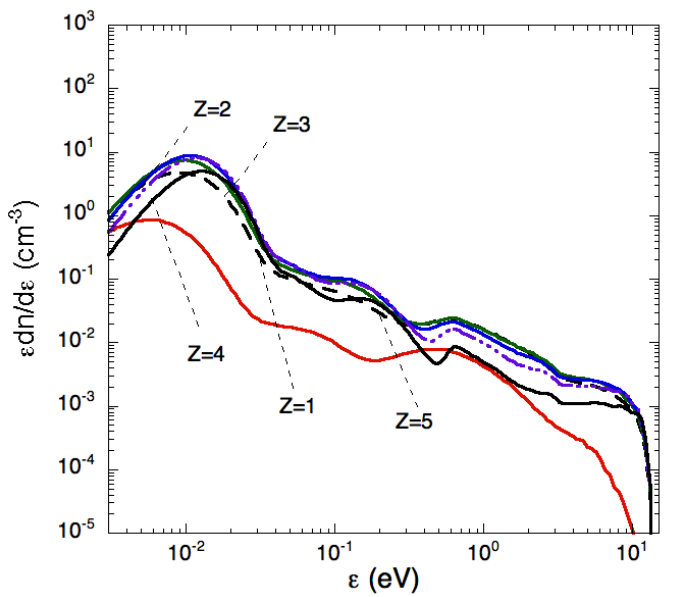
- **Cosmological Microwave Background**, very well known T=2.726K

⇒ trivial cosmological evolution $\lambda(E,z)=\lambda(E(1+z),z=0)/(1+z)^3$ Dominant photon background

- **Infra-red, optical, ultra-violet backgrounds (IR/OPT/UV)**

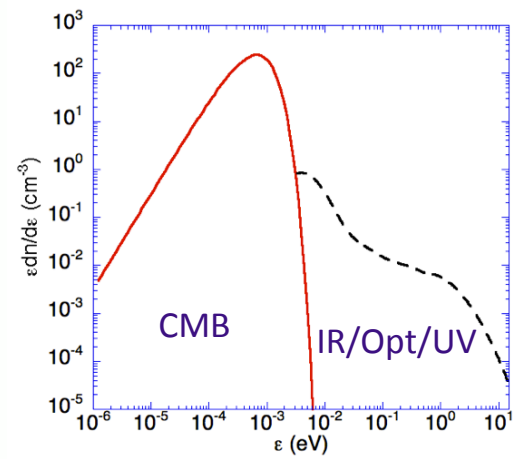
Time evolution dependent on the Star Formation Rate, stars aging and metalicity (especially the UV background)

⇒ non trivial but recently better constrained by astrophysical data (Spitzer telescope, etc…)

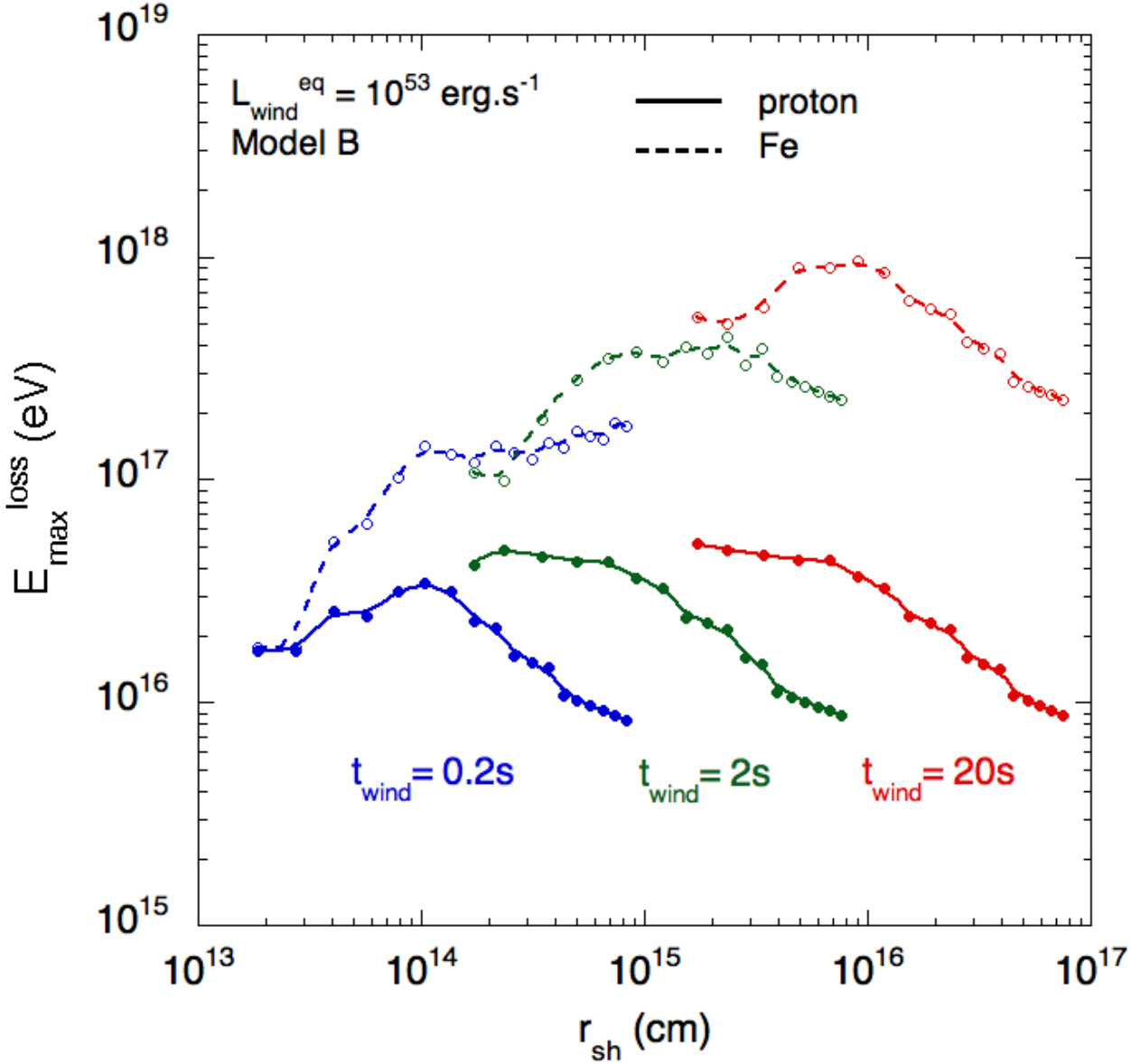


In the following calculations, we use estimate of IR/OPT/UV background density and time evolution from Kneiske et al., 2006

Photon background



Estimate of the maximum energy reachable for iron



Shock optical depth

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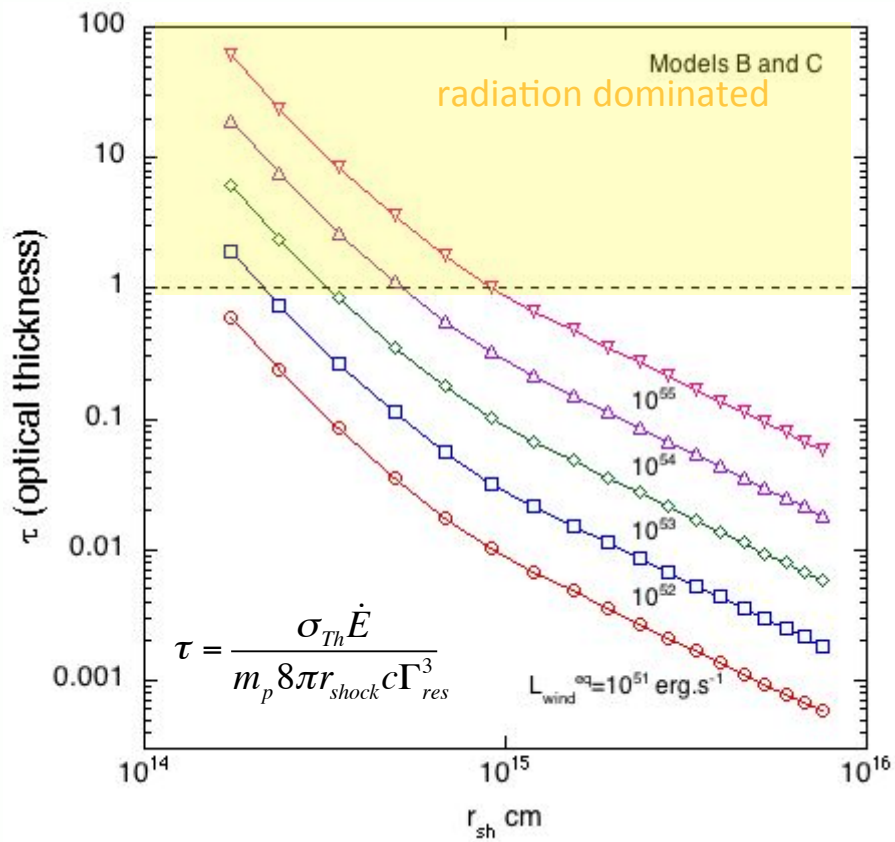
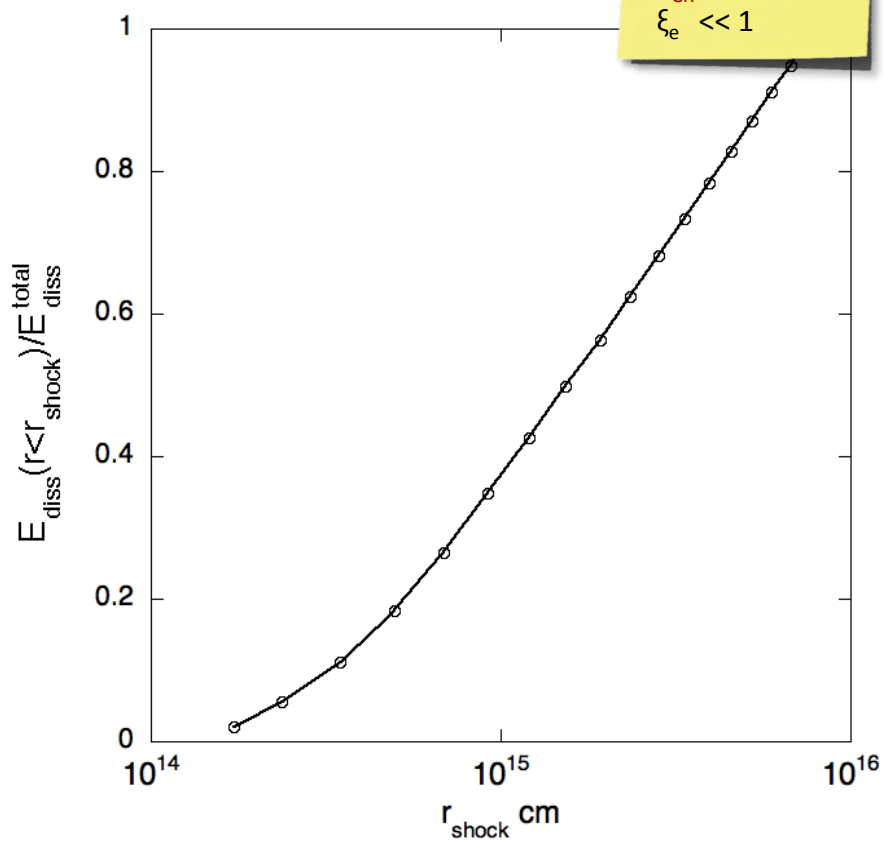
ε_B ~ 0.1
ε_{CR} ~ 0.9
ξ_e << 1



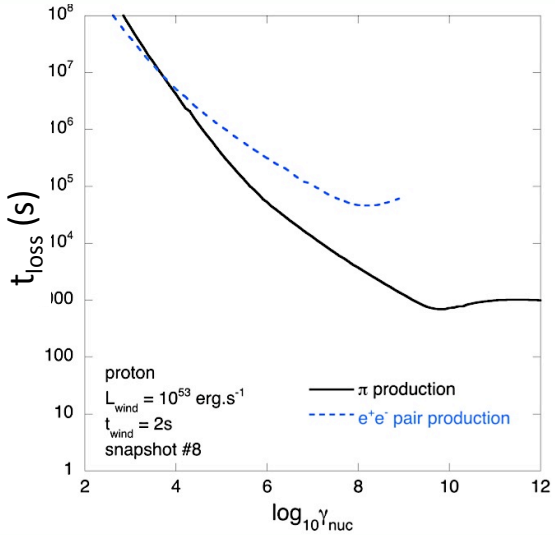


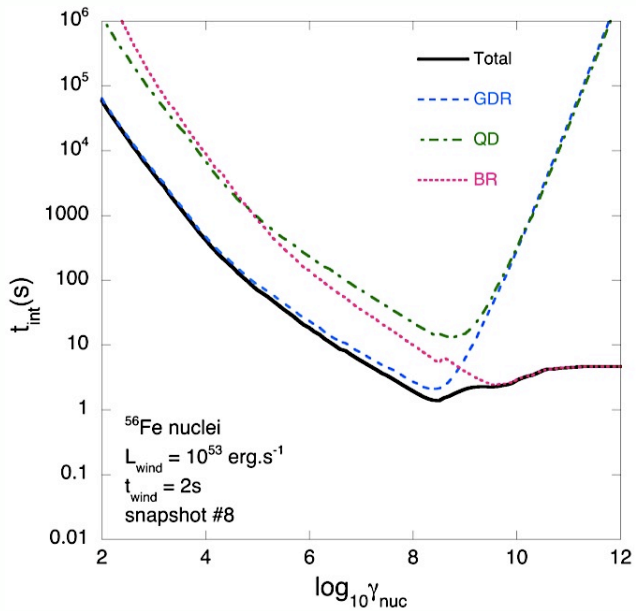
In our calculation, before collisionless internal shocks occurs, there is a phase where the Thomson depth exceeds unity

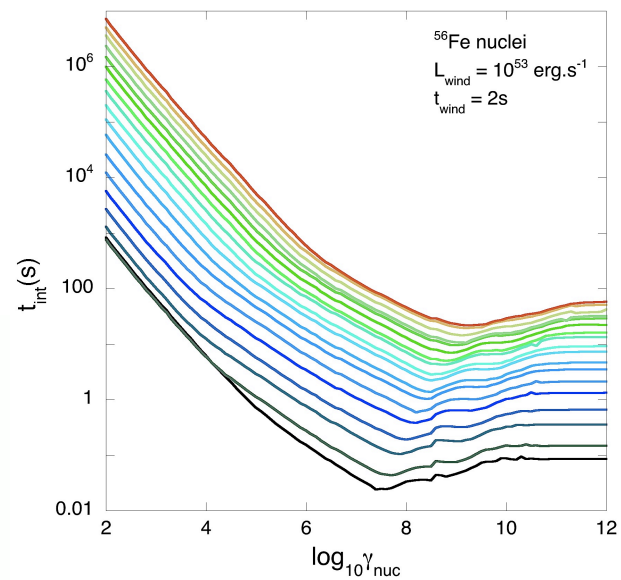
⇒ radiation dominated shock phase, only significant for high luminosities

⇒ **if this phase was dominant we could not accelerate particles** (see Bromberg & Levinson 2008, Levinson 2012 for structure and SEDs of relativistic, radiation dominated shocks)

t_{loss} computed with SEDs



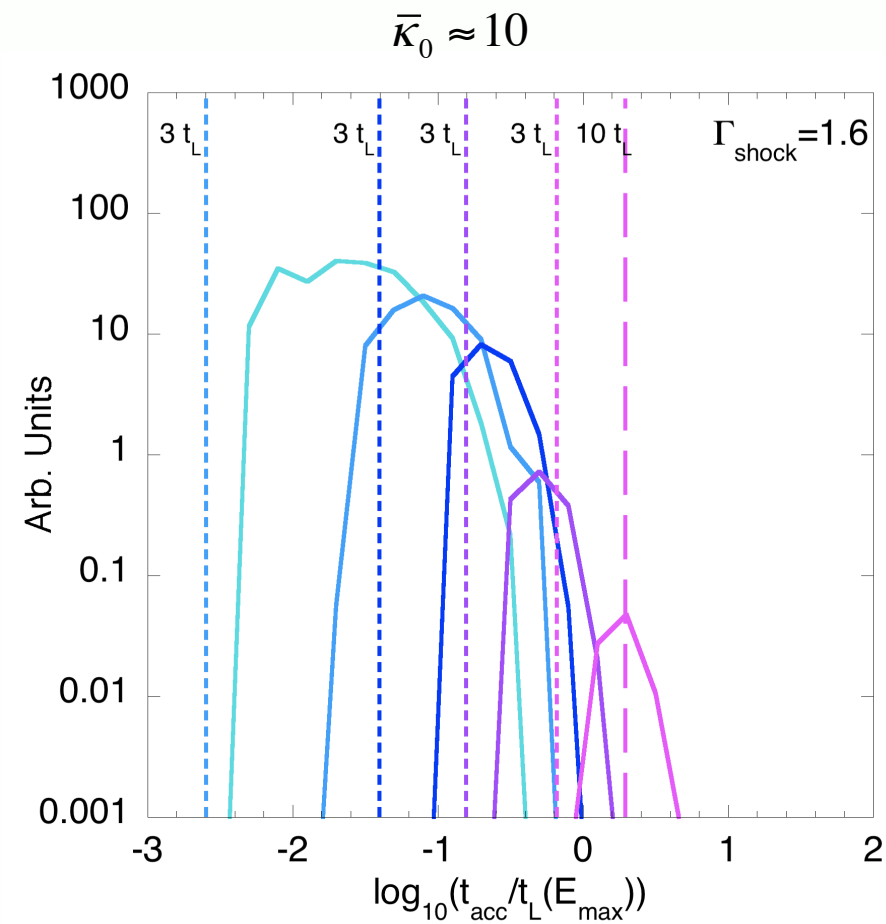


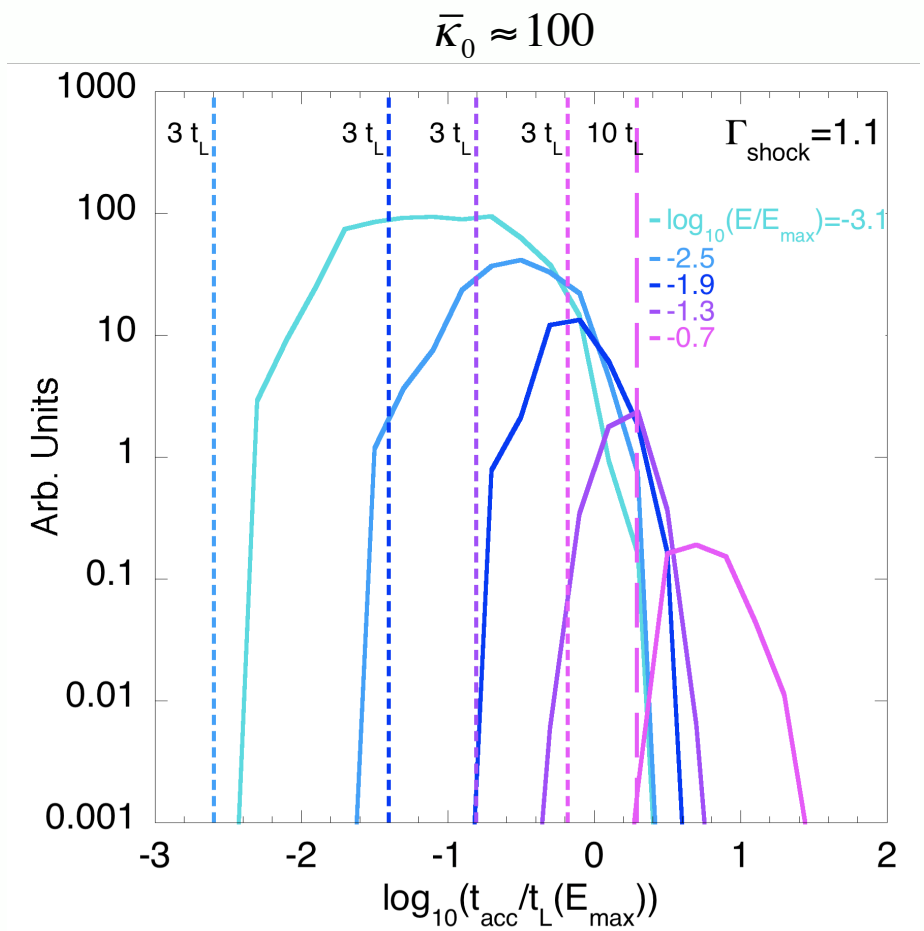


mean free path

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

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

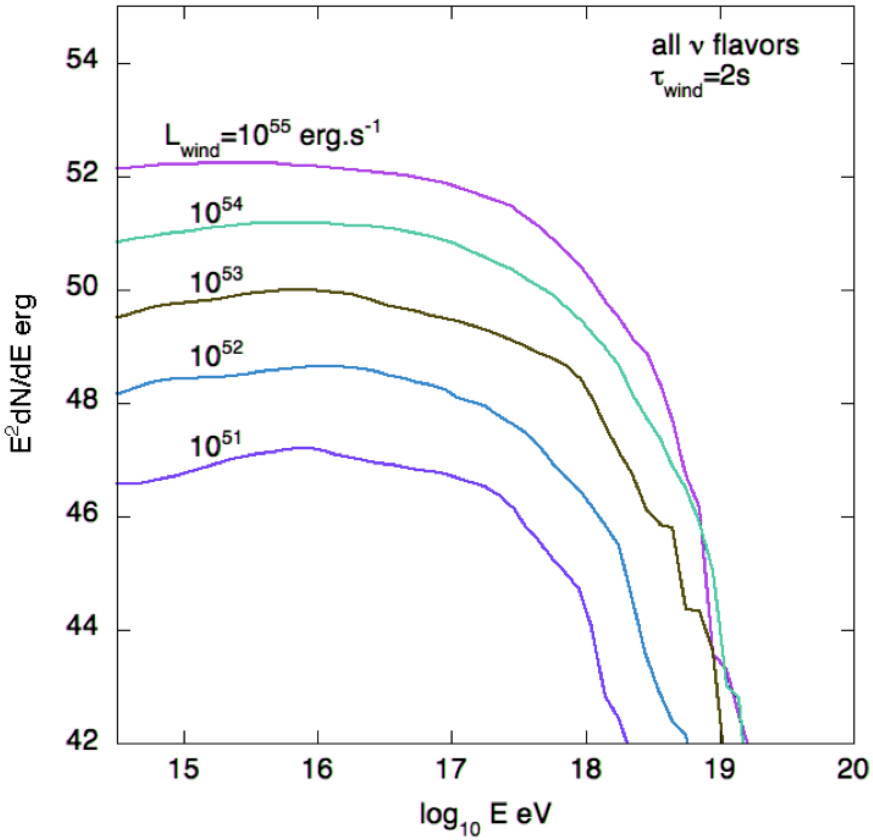




Equating t_{acc} and t_{loss} gives an estimate of the maximum energy reachable

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

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

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

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

+ 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

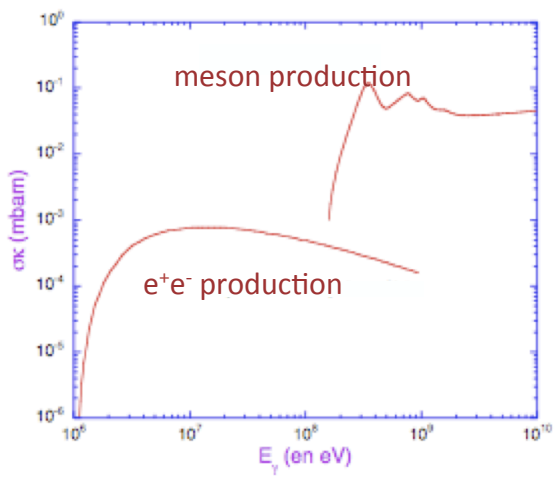
Energy losses

Protons and nuclei :

- synchrotron emission
- adiabatic losses
- Pair production
- Hadronic interactions (EPOS 1.99)

Protons :

- Photomeson production (SOPHIA)

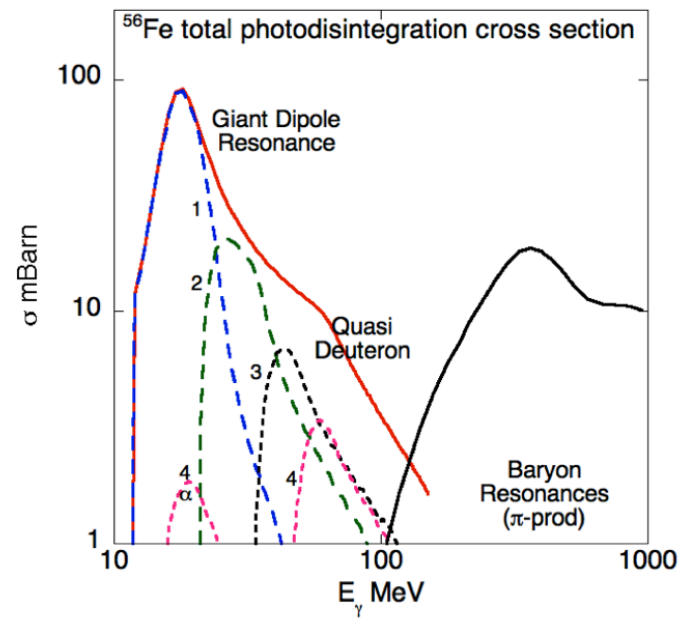


nuclei $^{A}N_{Z}$

photodisintegration

- GDR (Khan 2005)
- QD
- BR (π-prod)

(Rachen 1996)



Energy losses

protons

- pair production

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

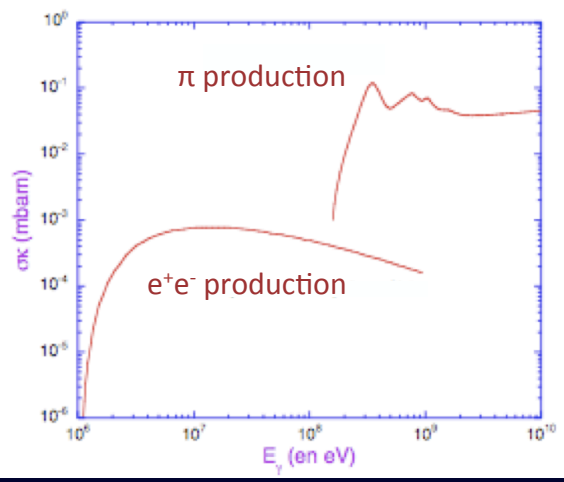
- synchrotron emission
- adiabatic losses

- pion production

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

- hadronic interactions

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



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

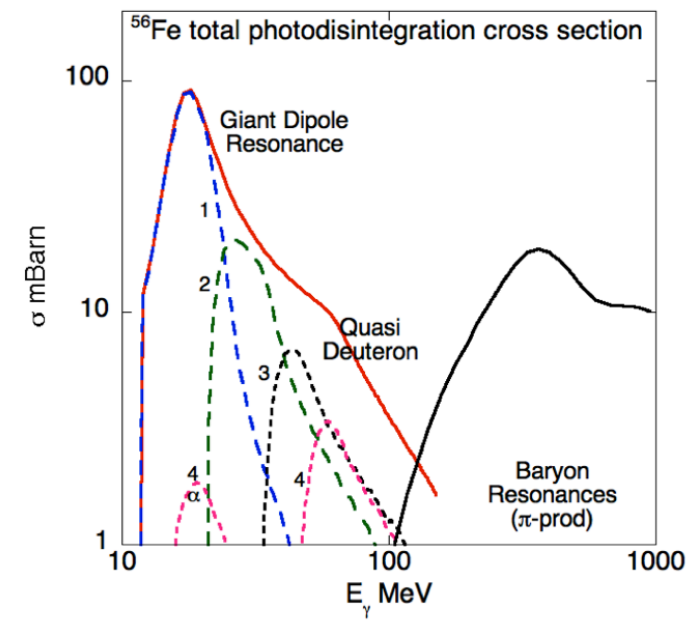
$\Gamma_N \searrow$

OR

$A \searrow$

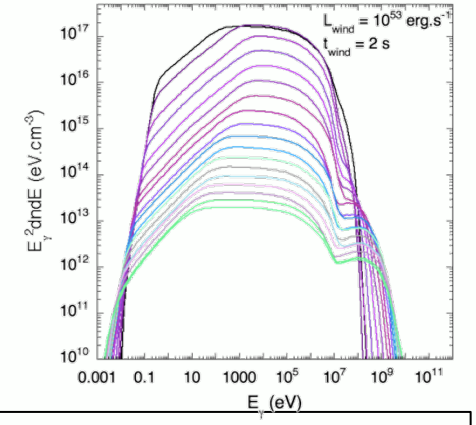
- GDR (Khan 2005)
- QD
- BR (π-prod)

(Rachen 1996)



output of internal shock model

Energy losses



protons

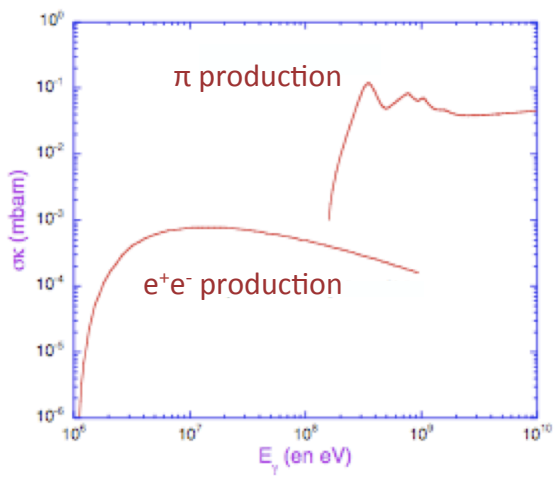
- pair production
  $p+\gamma \rightarrow p+e^{+}+e^{-}$ ~ 1 MeV
- synchrotron emission B
- adiabatic losses Γ_{res}, r_{shock}

$\Gamma_N \searrow$

OR

- pion production
  $p+\gamma \rightarrow p\,|\,n+\Pi^{0}\,|\,\Pi^{+}\,|\,\Pi^{-}$ ~ 150 MeV

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

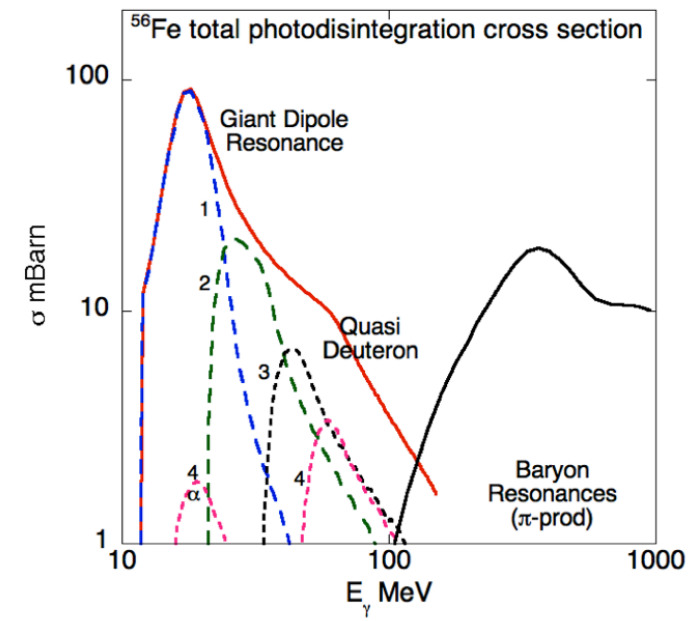


complex nuclei $^{A}N_{Z}$

$A \searrow$

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

(Rachen 1996) ~ 30 - 145 MeV

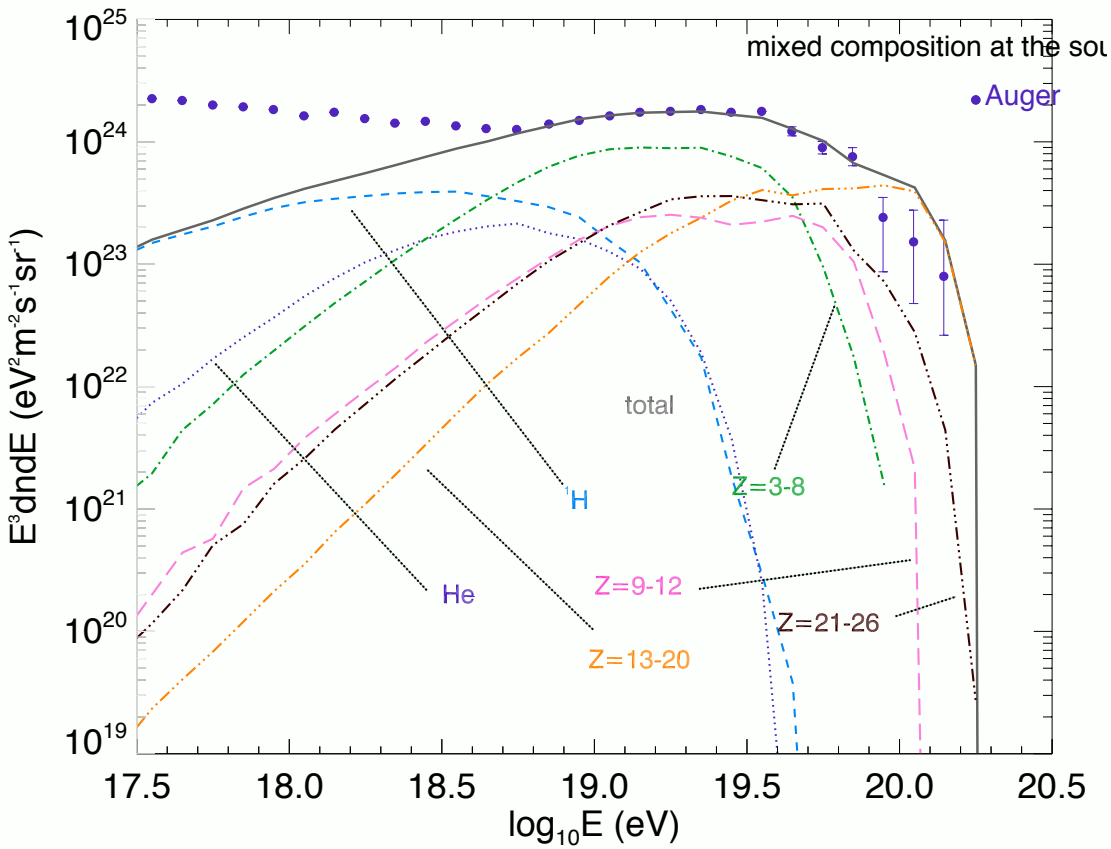


Propagated spectrum

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

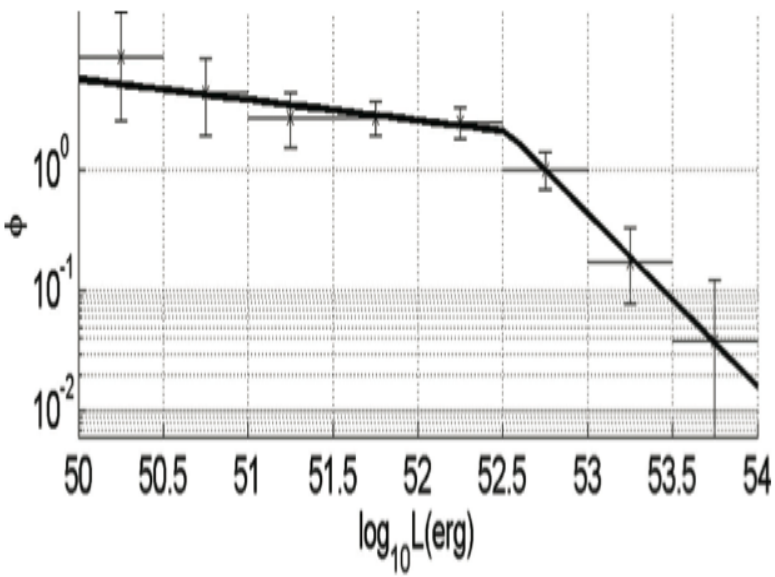
model B



300 realisations of the history of GRB explosions in the Universe

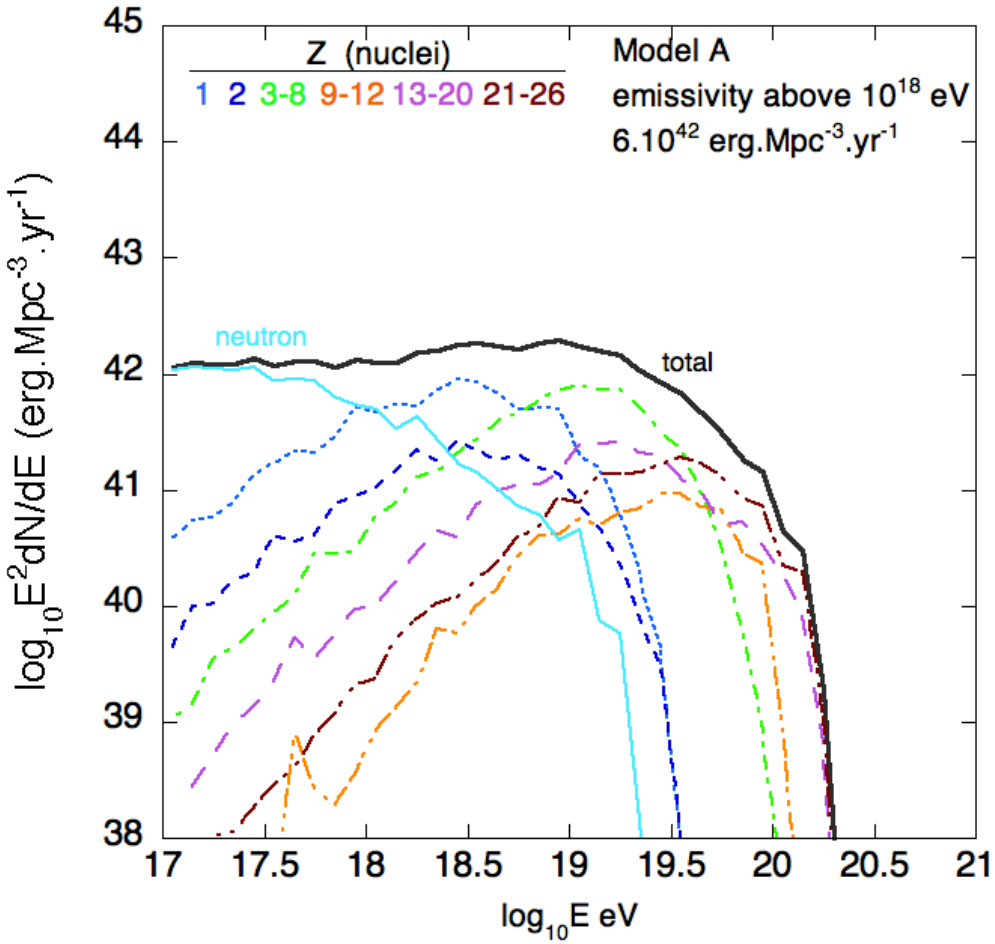
Convolution by a GRB luminosity function

GRB rate and luminosity function 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}



Convolution by a GRB luminosity function

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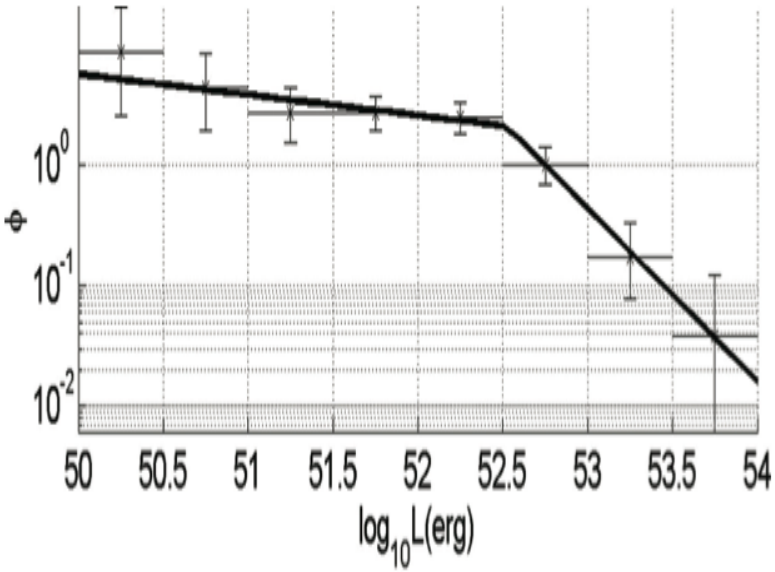

ρ_0=1.3 Gpc^{-3}.yr^{-1} α_1=1.2 α_2=2.4

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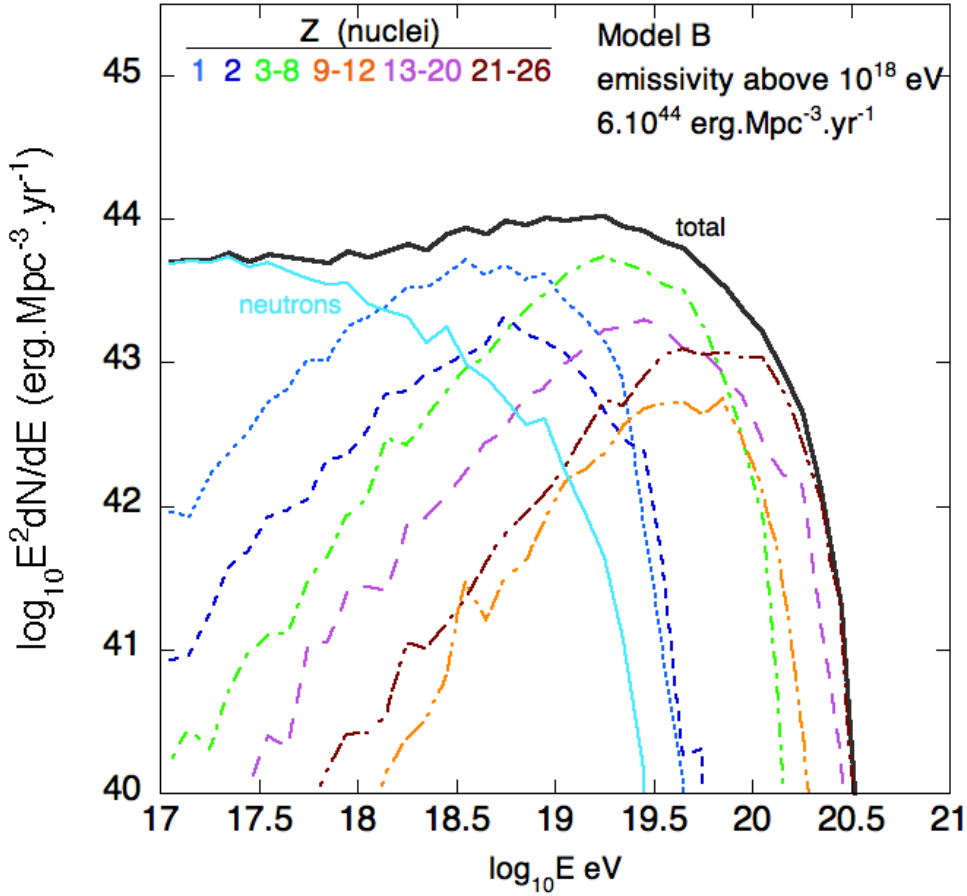


Acceleration of UHECR at GRBs internal shocks

- 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), Baerwald et al. (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

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

- jump conditions given by Synge 1957 for relativistic shocks

- We assume a Kolmogorov-type turbulence uptream ➔ **B** compressed and amplified in the direction perpendicular to the shock normal

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

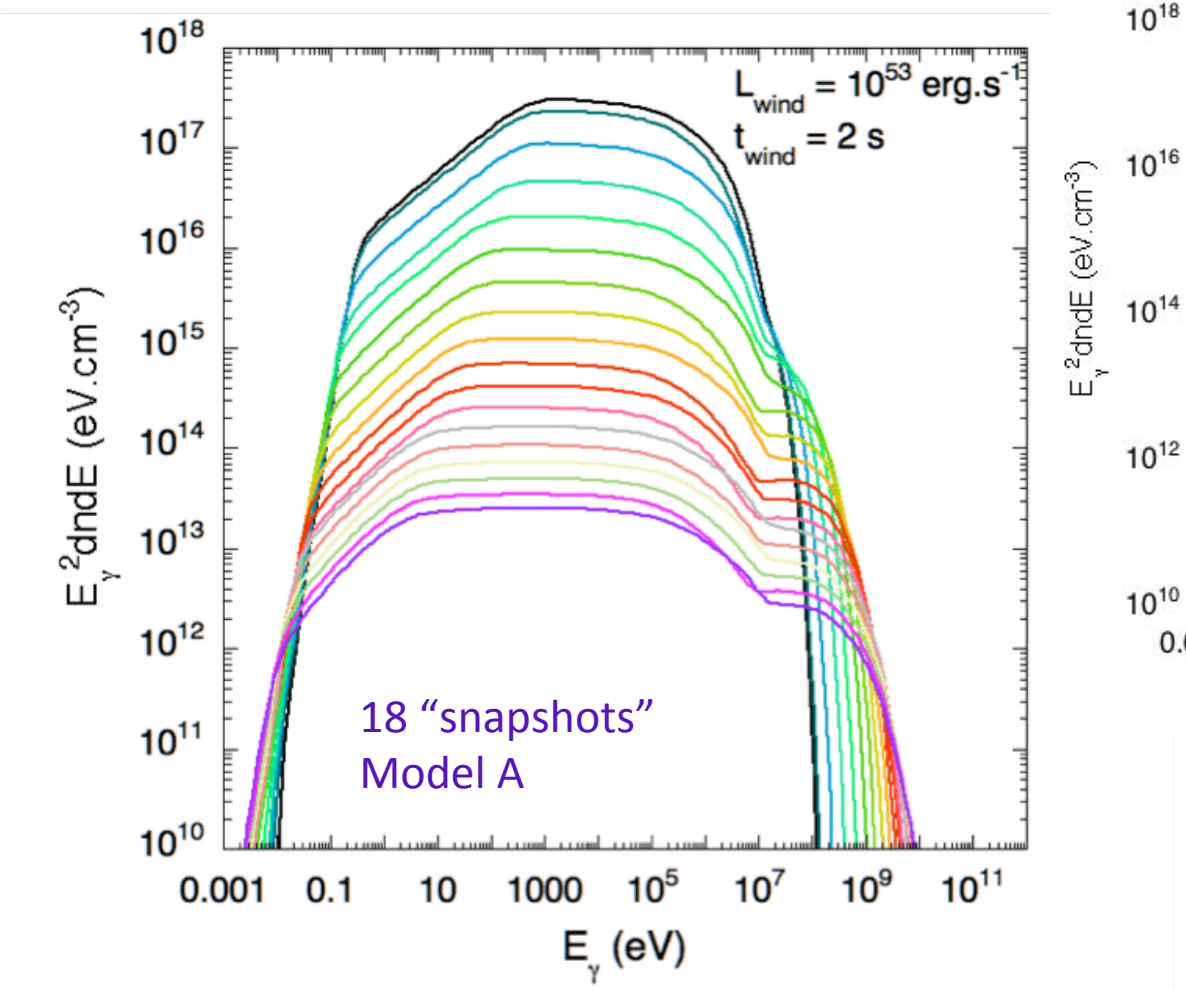
$$\delta\vec{B}(x,y,z) = \sum_{n=1}^{N_m} A(k_n)\vec{\xi_n}\exp(ik_n z'_n + i\beta_n)$$

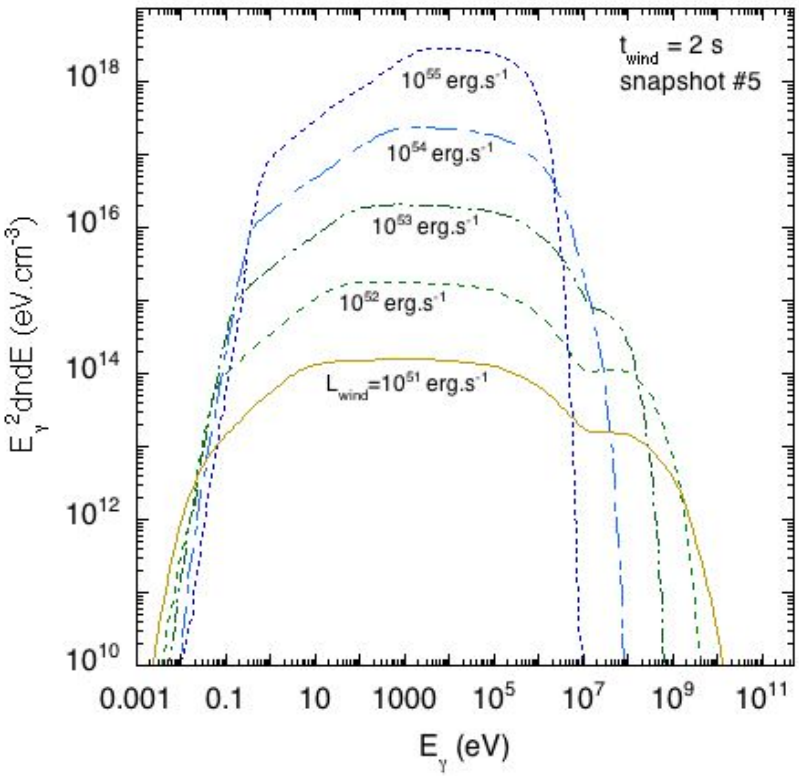
Giacalone et Jokipii 1999

- Time consuming but well tested method ➔ it was used to show the problems of Fermi-like acceleration at ultrarelativistic shock

Prompt emission SEDs

see Daigne, Bosnjak & Dubus 2009 for details

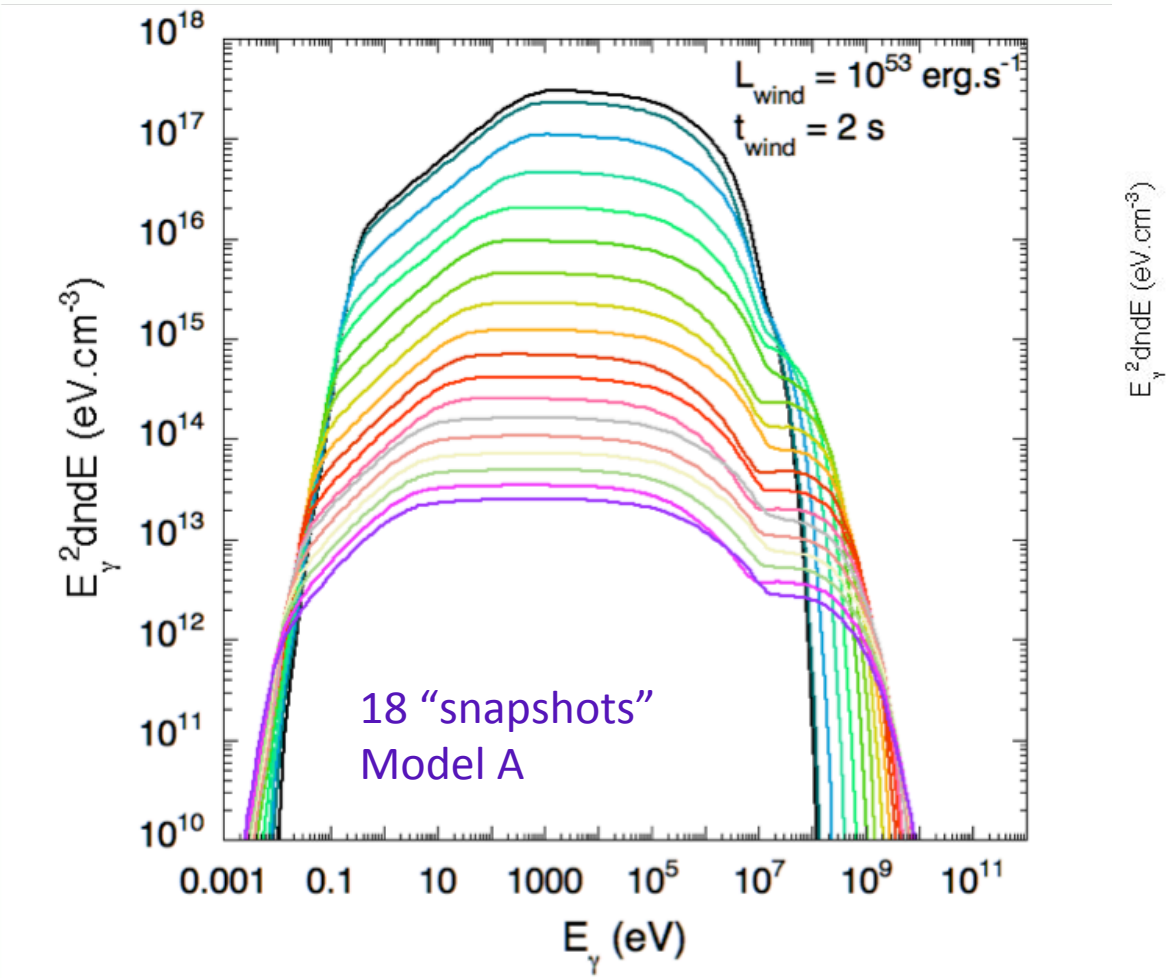


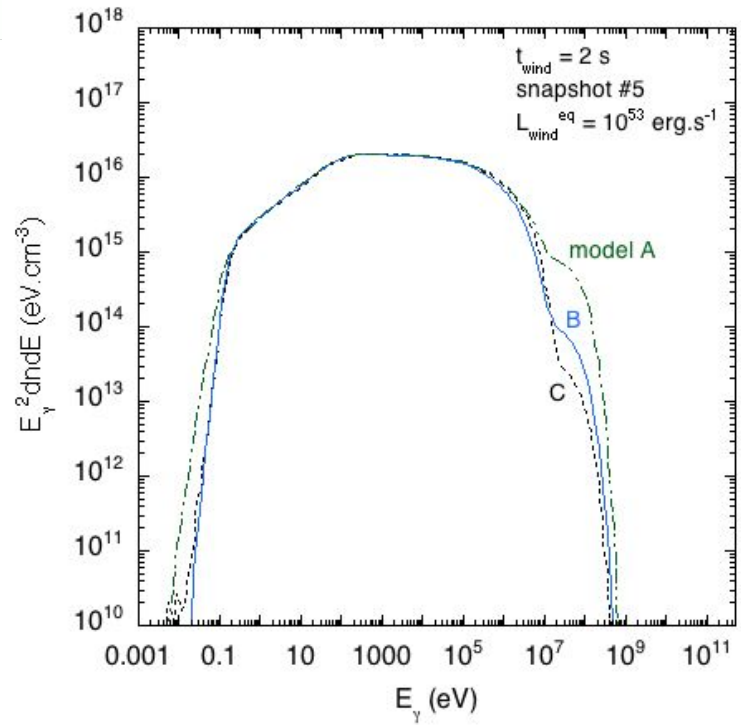


Efficiency ~ 5% ➔ $L\gamma \sim L_{wind}/20$

Prompt emission SEDs

see Daigne, Bosnjak & Dubus 2009 for details





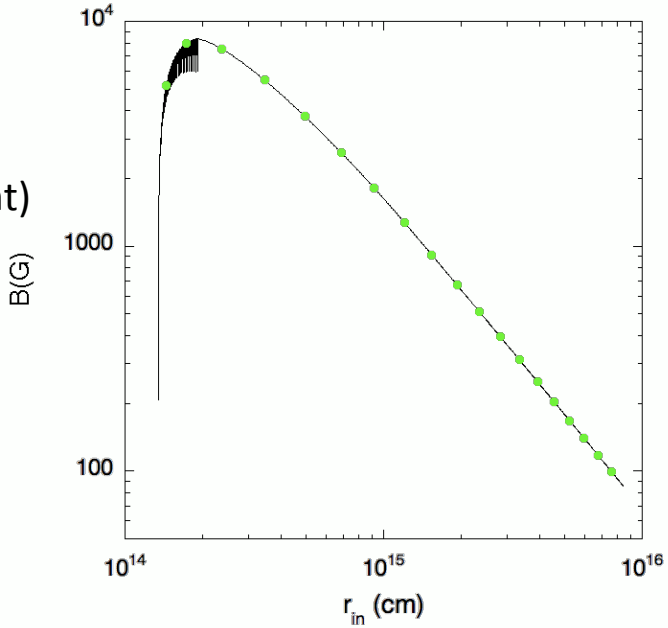
Efficiency ~ 5% ➔ $L\gamma \sim L_{wind}/20$

Prompt emission SEDs

Calculation based on the work by Daigne, Bosnjak & Dubus 2009 :

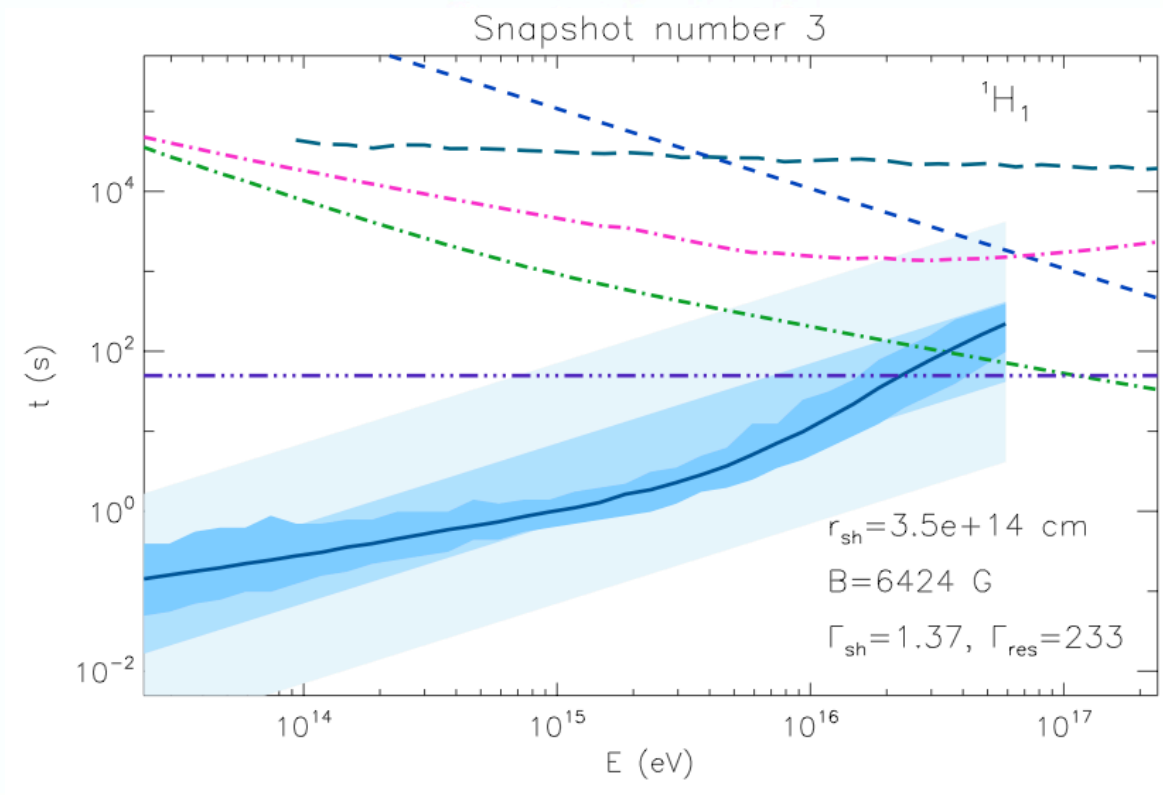
includes :

- synchrotron emission by accelerated electrons
- synchrotron self-Compton
- synchrotron self-absorption
- $\gamma\gamma$ pair production (pairs created taken into account)



Estimate of the maximum energy reachable for protons

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



losses

t_{exp}

t_{sync}

t_{pair}

$t_{photodis/pion}$

$t_{hadronic}$

acceleration

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

1

10

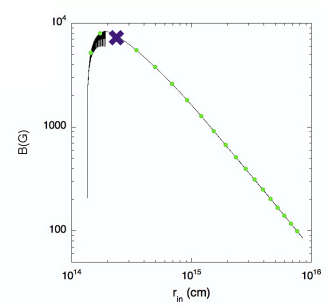
90%

$\bar{t}_{acc}$

100

1000

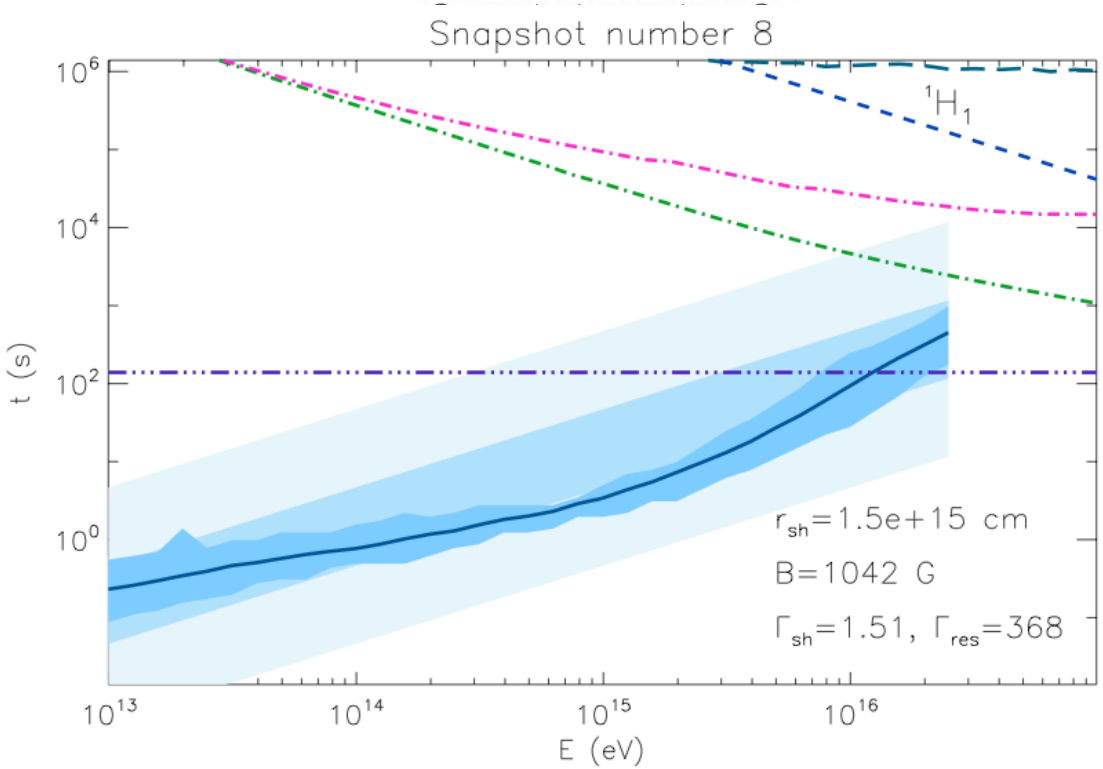
#3



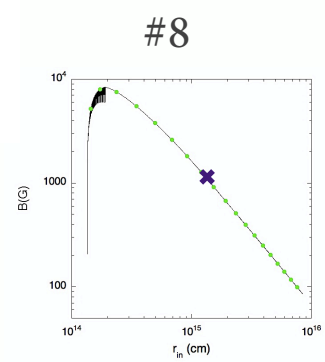
$E_{max,obs} \approx 5.10^{18}$ eV

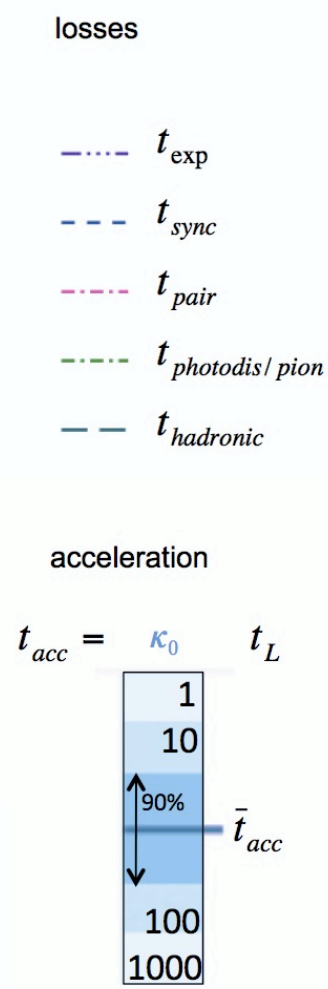
Estimate of the maximum energy reachable for protons

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



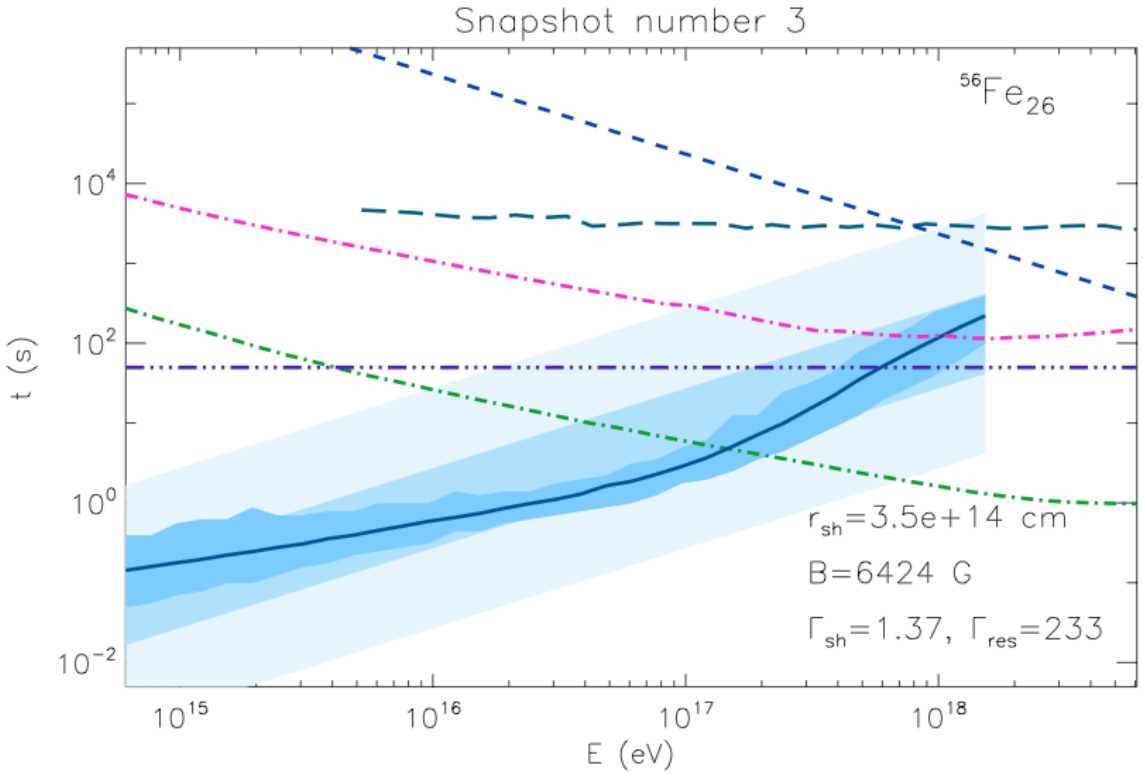
$E_{max,obs} \approx 4\ 10^{18}$ eV

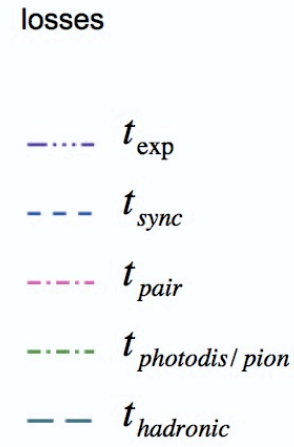


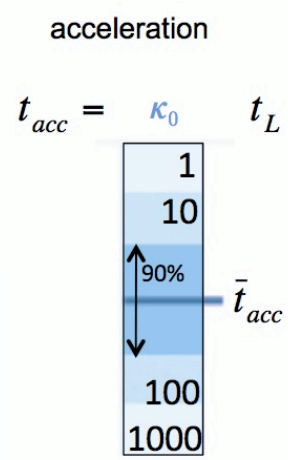


Estimate of the maximum energy reachable for iron

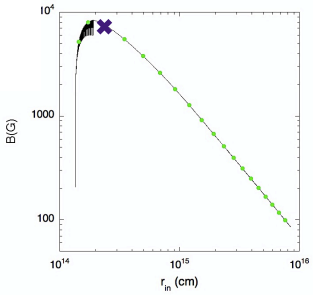
t_{wind}=2s L_{wind}=10^{53} erg.s^{-1} $\lambda_{max}=r_{shock}/30\Gamma_{res}$







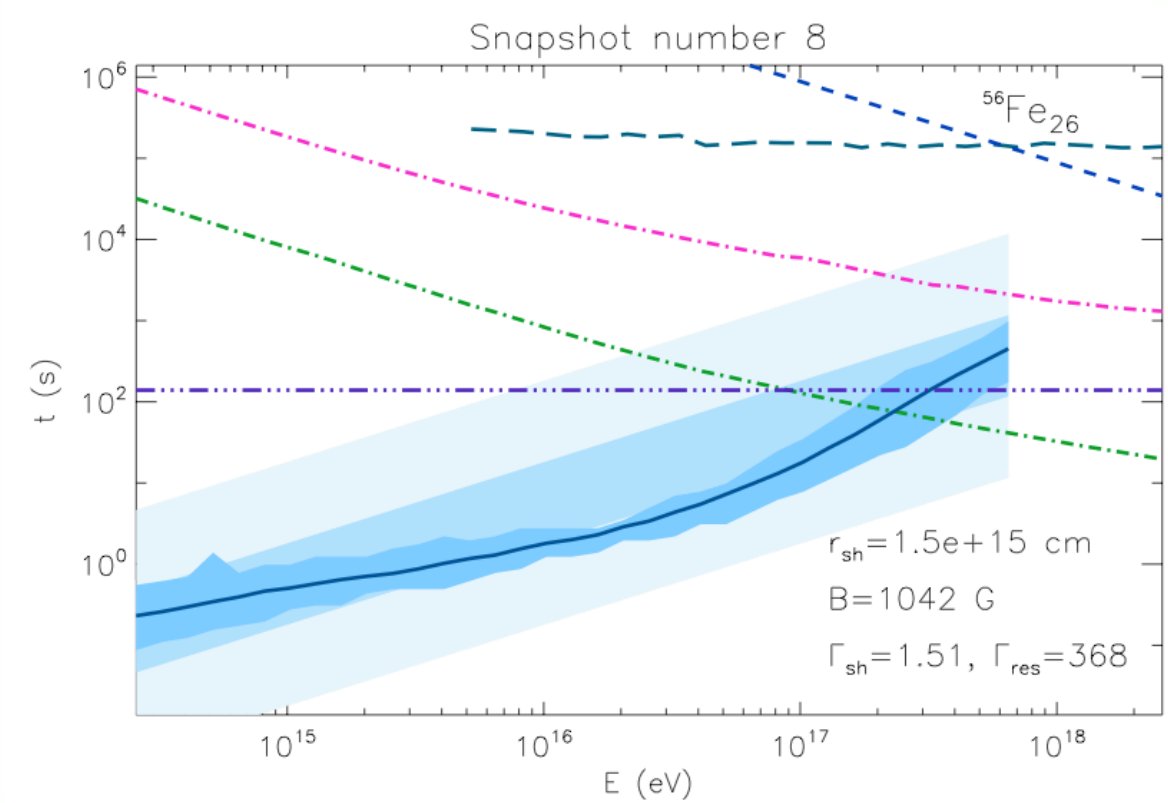
#3



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

Estimate of the maximum energy reachable for iron

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



losses

t_{exp}

t_{sync}

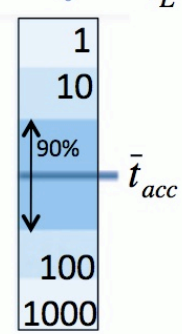
t_{pair}

$t_{photodis/pion}$

$t_{hadronic}$

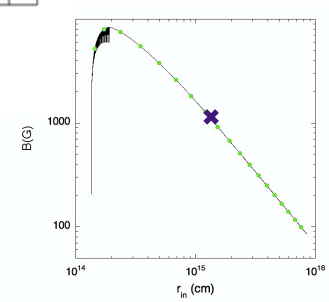
acceleration

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



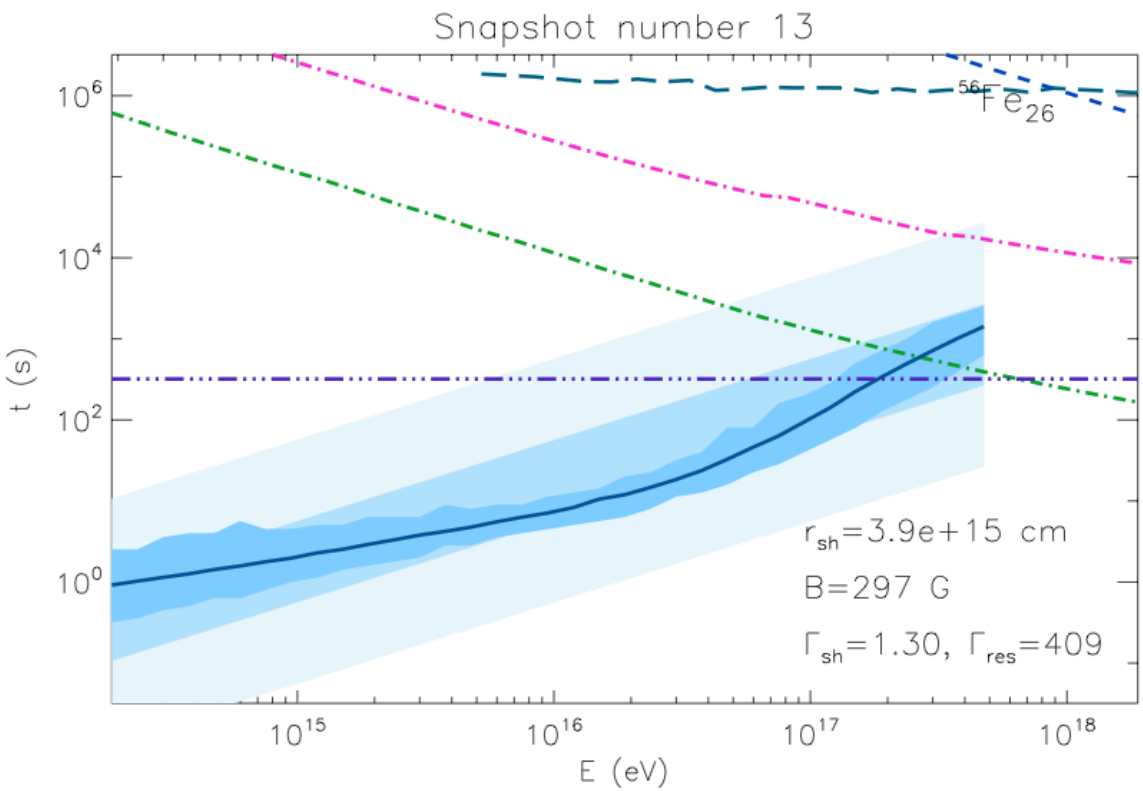
$E_{max,obs} \approx 10^{20}$ eV

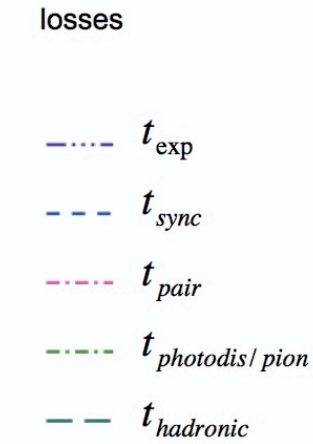
#8

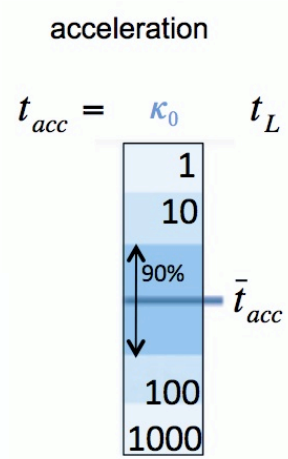


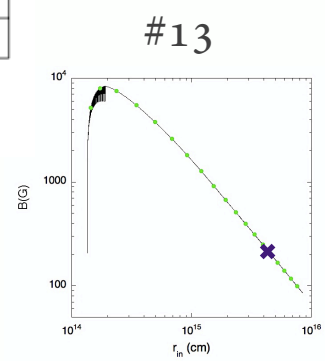
Estimate of the maximum energy reachable for iron

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

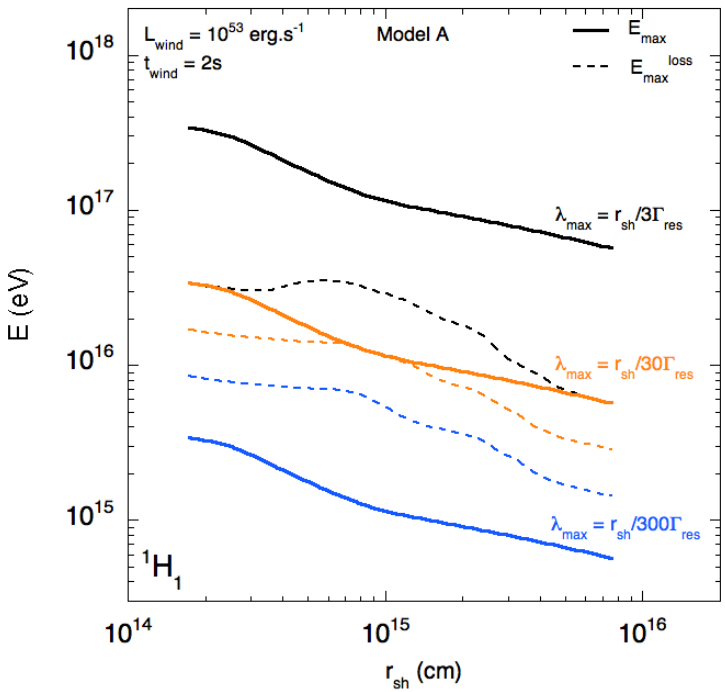








$E_{max,obs} \approx 8\ 10^{19}$ eV


$L_{wind} = 10^{53}$ erg.s^{-1}
t_{wind} = 2s
Model A
E_{max}
E_{max}^{loss}
$\lambda_{max} = r_{sh}/3\Gamma_{res}$
$\lambda_{max} = r_{sh}/30\Gamma_{res}$
$\lambda_{max} = r_{sh}/300\Gamma_{res}$
$^1H_1$
E (eV)
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{15}
10^{16}
r_{sh} (cm)

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

$$L_{wind} = 3\times L_{wind}^{eq} \times (L_{wind}^{eq} / 10^{55})^{-1/2} \text{ erg.s}^{-1}$$

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}

model B

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

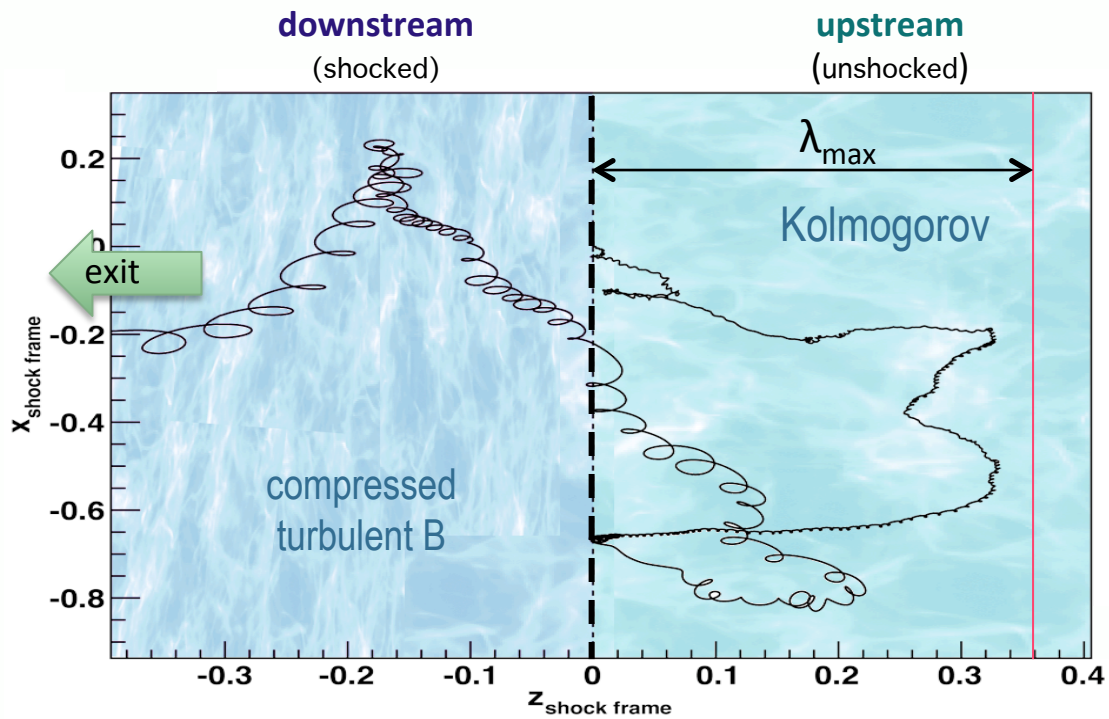
model C

Assumptions
ε_e << 1
ε_B ~ 0.33
ε_{CR} ~ 0.66

L_{wind}	$L_{wind, eq}$
3.10^{53}	10^{51}
10^{54}	10^{52}
3.10^{54}	10^{53}
10^{55}	10^{54}
3.10^{55}	10^{55}

Numerical method for CR acceleration at relativistic shock

We follow Niemiec & Ostrowski 2004-2006 method to simulate Fermi cycles at relativistic shocks.



Particle trajectory (3D) in the shock frame

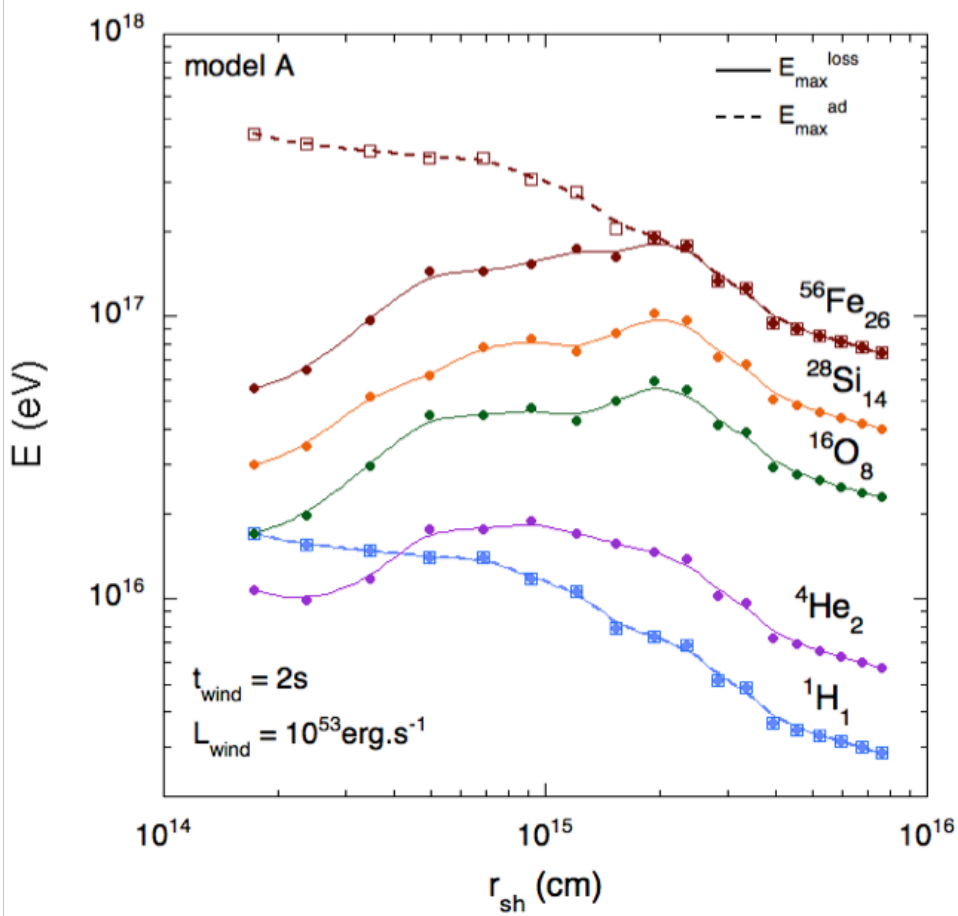
9 cycles before escaping downstream. Energy gain~ 70.

We assume a free boundary escape upstream if the particle can reach the distance $10\lambda_{max}$ from the shock

Downstream escape if the particle passes a boundary far away downstream

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 ➔ $\lambda_{max} = r_L(E_{max}{}^1H)$