Constraining and understanding particle acceleration

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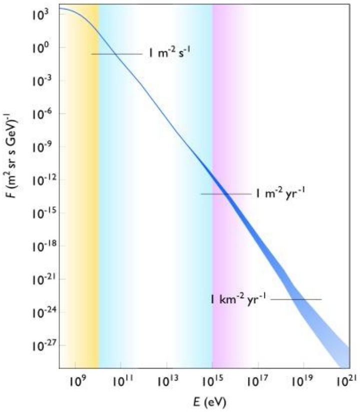
Cosmic rays

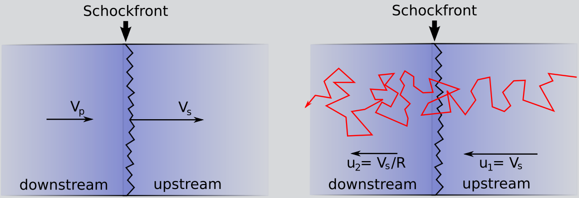
The paradigm for understanding the cosmic ray spectrum:
Diffusive shock acceleration at SNR shock waves followed by energy-dependent propagation through the turbulent ISM
Active Galactic Nuclei are prime candidates
Nonthermal particle distributions are associated with nonthermal radiation signatures
How can we decipher UHE cosmic rays from their nonthermal emission spectra?
Can we reproduce the accelerated particles in numerical simulations?



Diffusive shock acceleration

Fermi-I

Multiple shock crossings
Compression ratio $r = u_u/u_d$ defines spectral index
($1 \leq r \leq 4$ non-relativistic, $1 \leq r \leq 3$ relativistic)
Spectral index $s = \frac{r+2}{r-1}$ for non-relativistic-shock
Relativistic shock: Anisotropic particle distribution ($s \approx 2.2$)



Diffusive shock acceleration

Fermi-I beyond $s = 2$

Alfvén waves may increase the effective compression ratio (Vainio& Schlickeiser 1998)
Works well when the fluctuating amplitude is large compared to the background field (low Mach number)
Shock modification (Berezhko & Ellison 1999)

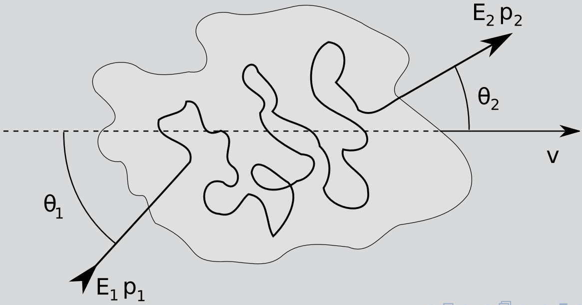
Diffusive shock acceleration

Fermi-II

Energy diffusion by stochastic scattering off Alfvén waves

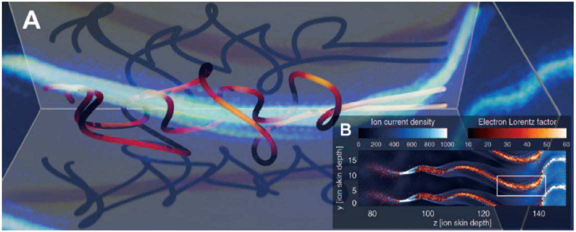
$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial}{\partial p}f\right)$$

Energy gain $\propto u^2/c^2$
Acceleration time $\propto c^2/v_A^2 p^\alpha$
Possibly flatter spectra to $s \to 1$ (Virtanen & Vainio, 2005)



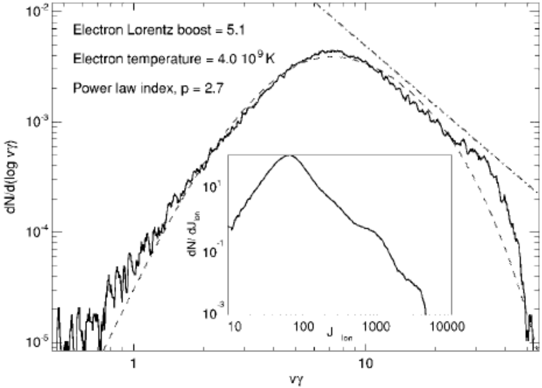
Novel mechanisms

Since Hededal et al. (2004) filamentation / Weibel instability is discussed
Non-magnetized counterstreaming plasmas generate filaments



(From Hededal et al. 2004)

Novel mechanisms

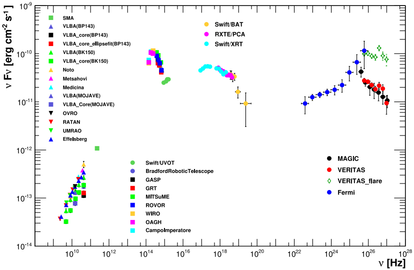


(From Hededal et al. 2004)

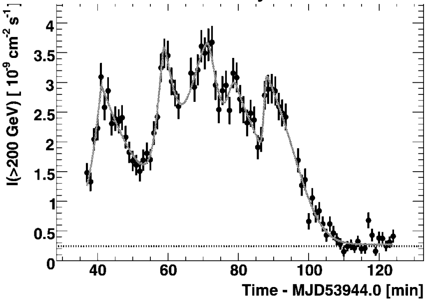
In situ observations

How to determine in situ particle spectra?
Using high energy emission of Active Galactic Nuclei, in situ particle spectra can be deduced

Multiwavelength Spectrum



Variability



AGN are a candidate source for hadronic CR
The proton content of the source is yet to be determined.

Radiation modeling

Kinetic equations: acceleration zone

Fermi-I and Fermi-II process in acceleration zone

$$\partial_t n_{e^-} = \partial_\gamma \left[(\beta_e \gamma^2 - t_{\mathrm{a,e}}^{-1} \gamma) \cdot n_{e^-} \right] + \partial_\gamma \left[[(a+2) t_{\mathrm{a,e}}]^{-1} \gamma^2 \partial_\gamma n_{e^-} \right] + Q_{0,e} - t_{\mathrm{esc,e}}^{-1} n_{e^-}$$

$$\partial_t n_{p^+} = \partial_\gamma \left[(\beta_p \gamma^2 - t_{\mathrm{a,p}}^{-1} \gamma) \cdot n_{p^+} \right] + \partial_\gamma \left[[(a+2) t_{\mathrm{a,p}}]^{-1} \gamma^2 \partial_\gamma n_{p^+} \right] + Q_{0,p} - t_{\mathrm{esc,p}}^{-1} n_{p^+}$$

Kinetic equations: radiation zone

Fully-consistent radiation modeling including

- Synchrotron radiation
- Invers-Compton scattering
- Photohadronic production
- Pair processes

See poster by M. Weidinger

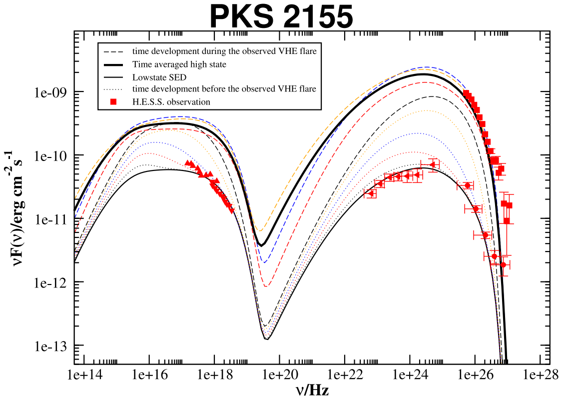
Radiation modeling

Parameters relevant to acceleration

t_{acc}	energy independent acceleration time
t_{esc}	energy independent acceleration time
a	Ratio of shock and Alfvén speed
B	Magnetic field, determines synchrotron losses

Is this sufficient to understand AGN spectra?

AGN results

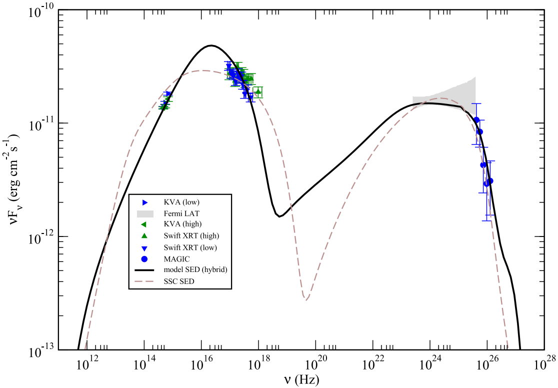


$Q_e(\mathrm{cm}^{-3})$	$Q_p(\mathrm{cm}^{-3})$	$B(\mathrm{G})$	$R_{\mathrm{acc}}(\mathrm{cm})$	$R_{\mathrm{rad}}(\mathrm{cm})$
$8.0 \cdot 10^5$	0	1.4	$1.0 \cdot 10^{13}$	$5.0 \cdot 10^{14}$

$t_{\mathrm{acc}}/t_{\mathrm{esc}}$	a	δ	$\gamma_{0,e}$	$\gamma_{0,p}$
1.13	20	49	3300	—

AGN results

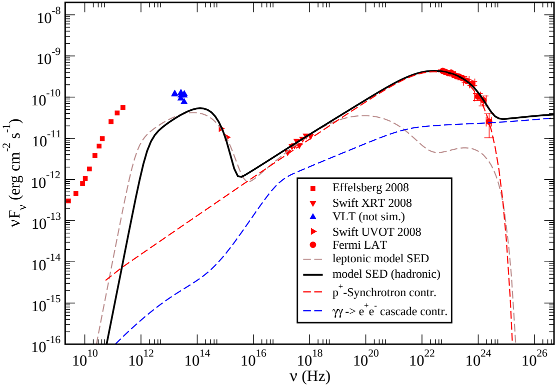
1ES1011



$Q_e(\mathrm{cm}^{-3})$	$Q_p(\mathrm{cm}^{-3})$	$B(\mathrm{G})$	$R_{\mathrm{acc}}(\mathrm{cm})$	$R_{\mathrm{rad}}(\mathrm{cm})$
$3.78 \cdot 10^7$	$1.55 \cdot 10^8$	8	$2.2 \cdot 10^{12}$	$1.75 \cdot 10^{15}$

$t_{\mathrm{acc}}/t_{\mathrm{esc}}$	a	δ	$\gamma_{0,e}$	$\gamma_{0,p}$
1.3	20	36	3400	$7.50 \cdot 10^4$

3C454.3



$Q_e(\mathrm{cm}^{-3})$	$Q_p(\mathrm{cm}^{-3})$	$B(\mathrm{G})$	$R_{\mathrm{acc}}(\mathrm{cm})$	$R_{\mathrm{rad}}(\mathrm{cm})$
$3.8 \cdot 10^7$	$4.20 \cdot 10^8$	10.2	$5.0 \cdot 10^{13}$	$5.0 \cdot 10^{15}$

$t_{\mathrm{acc}}/t_{\mathrm{esc}}$	a	δ	$\gamma_{0,e}$	$\gamma_{0,p}$
1.10	5000	43	580	300

AGN parameterspace

Source	Magnetic field [G]	Spectral index	Mach number
PKS 2155	1,40	2,13	4,47
1ES1218	0,12	2,11	3,16
Mkn501	0,09	2,20	7,07
1ES2344	0,10	2,05	7,07
Mkn180	0,21	2,34	16,58
B3 2247	0,07	2,09	∞
1ES1011	8,00	2,30	4,47
PKS 0521	17,00	2,48	7,07
3C279	30,30	2,15	7,07
3C454	10,20	2,10	70,71

AGN parameterspace

Source	Magnetic field [G]	Spectral index	Mach number
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
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3C454	10,20	2,10	70,71

Spectral index is not a problem!
Fermi-I/-II are able to explain most
Acceleration time scales?

AGN parameterspace

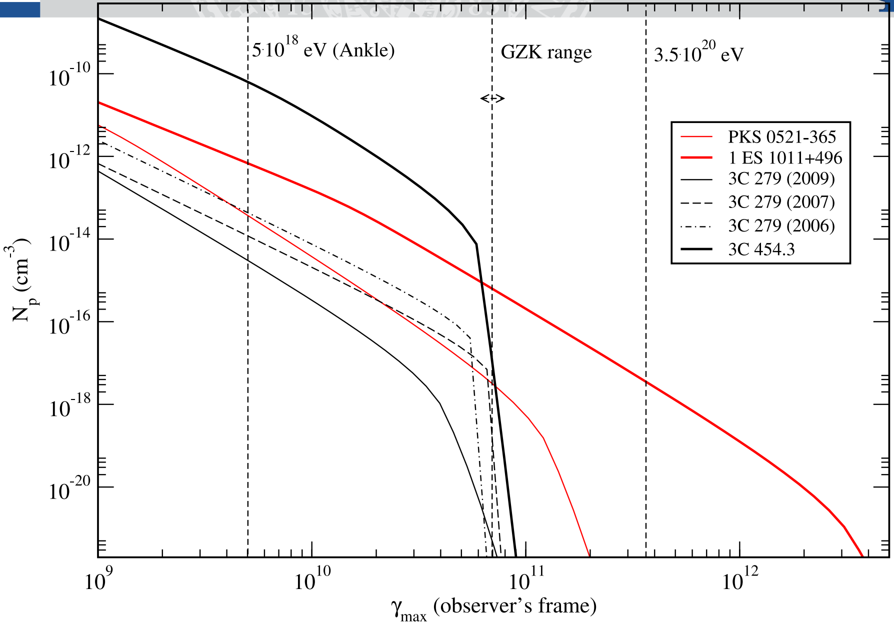
Source	$\gamma_{p,0}$	$\gamma_{e,0}$
PKS 2155	-	3300
1ES1218	-	3
Mkn501	-	12
1ES2344	-	3
Mkn180	-	7
B3 2247	-	4
1ES1011	600	3400
PKS0521	10	100
3C279	$4.25 \cdot 10^6$	155
3C454	300	580

AGN parameterspace

Injected luminosity is well in the Eddington Limit
Minimum Lorentz factor is a bigger problem

Source		
Mkn180	-	7
B3 2247	-	4
1ES1011	600	3400
PKS0521	10	100
3C279	$4.25 \cdot 10^6$	155
3C454	300	580

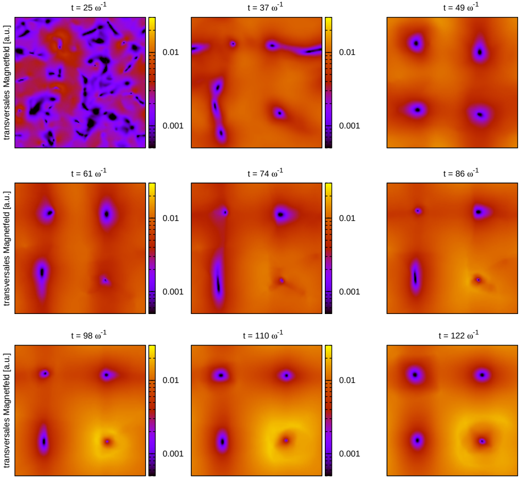
AGN CR contribution



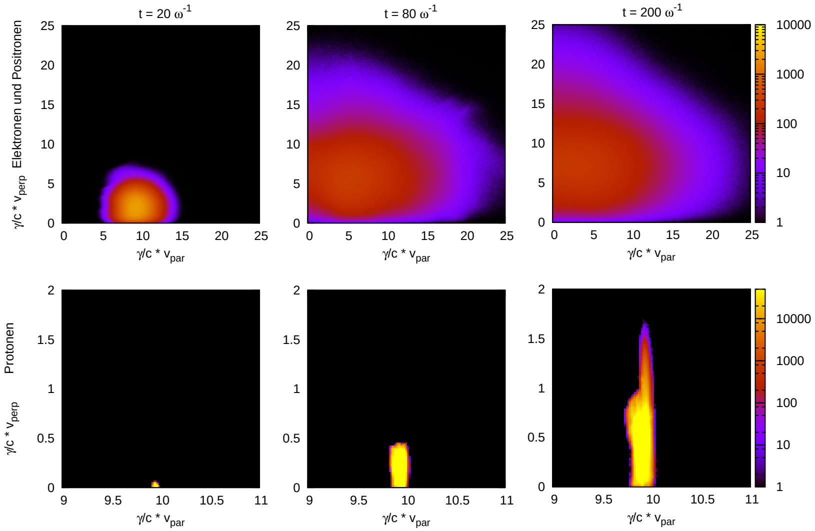
Particle-in-Cell

Particle-in-Cell simulations are pretty popular
Can Particle-in-Cell solve the question of acceleration?
Yes and No!

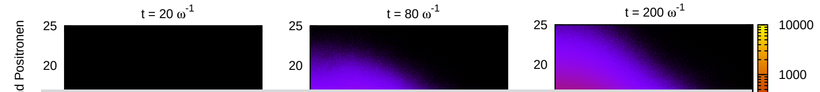
Filamentation stability



Filamentation stability



Filamentation stability

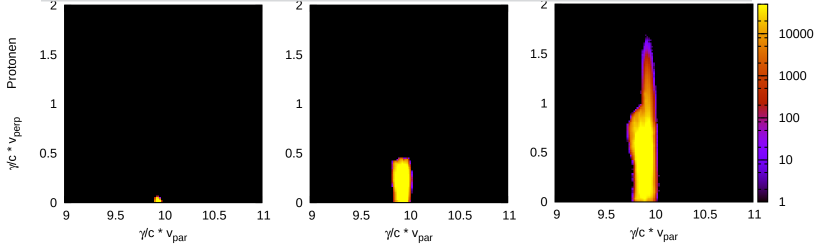


Filamentation instability yields $< 3\%$ nonthermal particles

$\gamma \approx 25$

BUT:

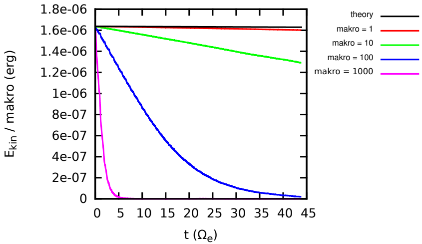
Simulation depends strongly on geometry and mass ratio!



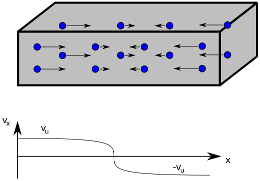
PiC and synchrotron

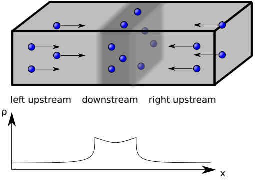
Determining acceleration time scales from PiC is complicated

- Synchrotron losses not accounted for correctly
- Correct simulations require the resolution of gyroradii in all 3 (!) dimensions

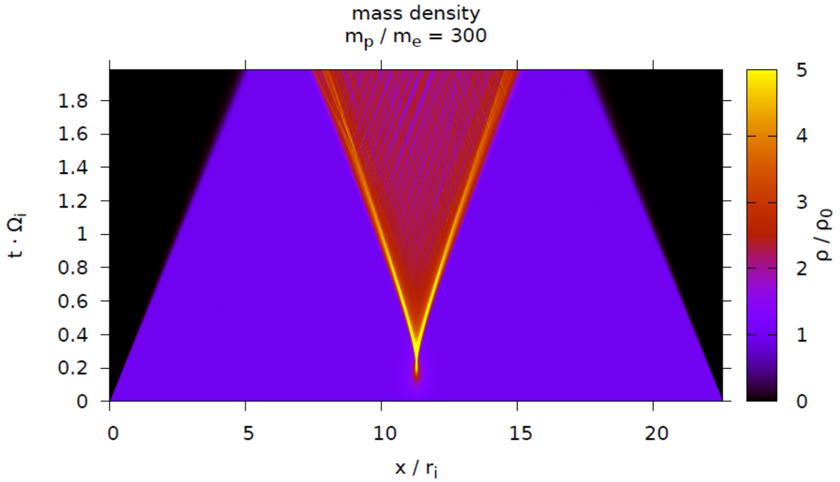


Shock acceleration

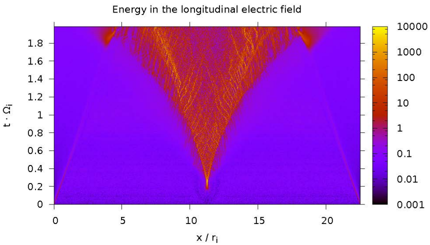


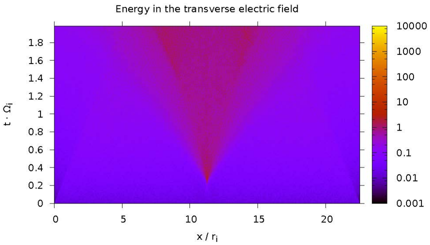


Shock acceleration



Shock acceleration



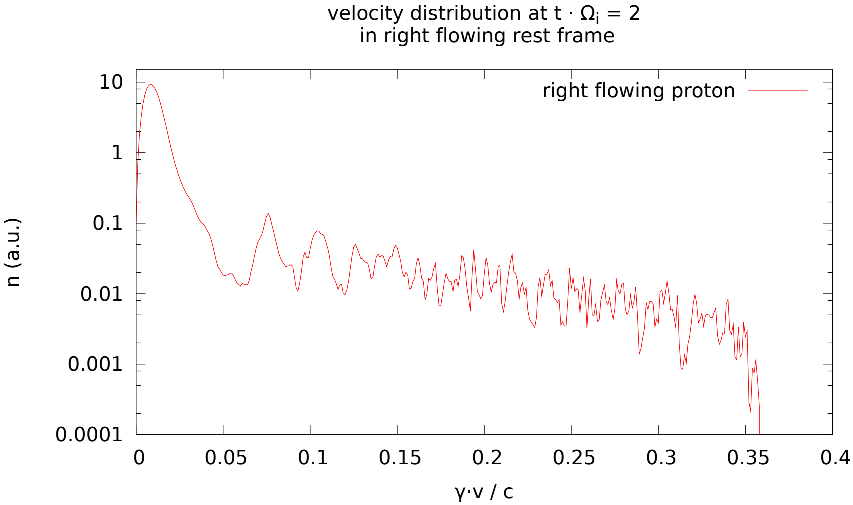


Shock shows structure in the longitudinal field

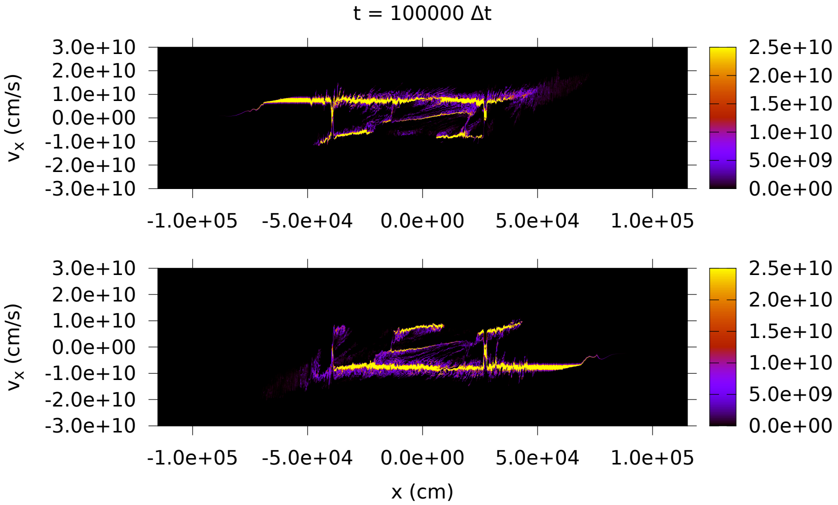
Mass density is not a uniform jump

$\Rightarrow$ Acceleration not only by pure Fermi-I!

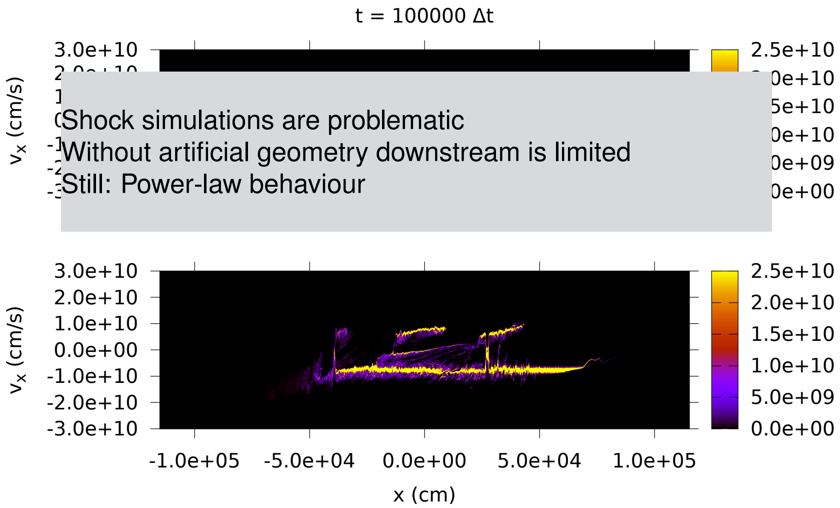
Shock acceleration



Shock acceleration



Shock acceleration



Shock simulations are problematic

Without artificial geometry downstream is limited

Still: Power-law behaviour

Summary

- AGN are still a prime candidate for UHECR
- Fermi-I/II are a probable acceleration mechanism
- Injection problem is still a problem