Particle Acceleration in Large Scale Jets of AGN

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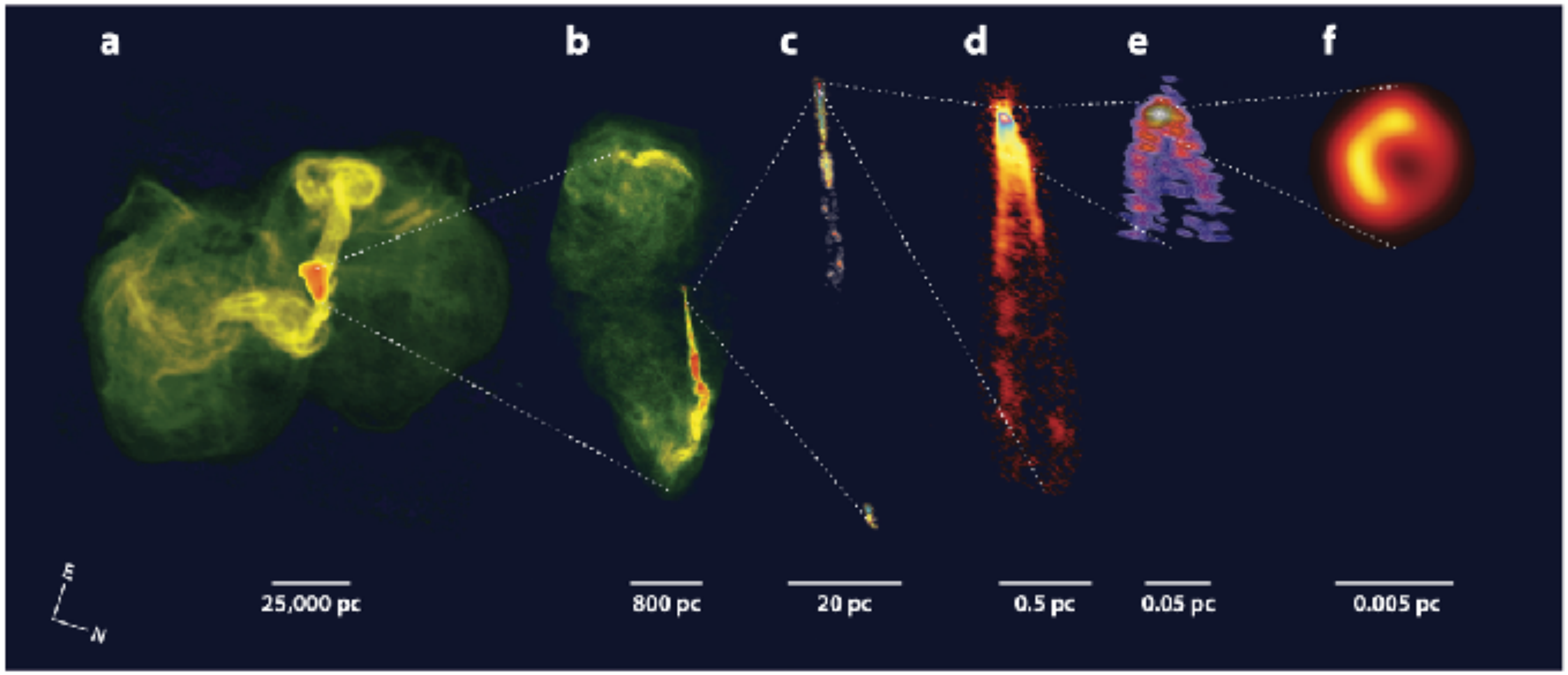
Max-Planck-Insitut für Kernphysik

CDY lecture series on the extreme non-thermal universe
Feb 21, 2024

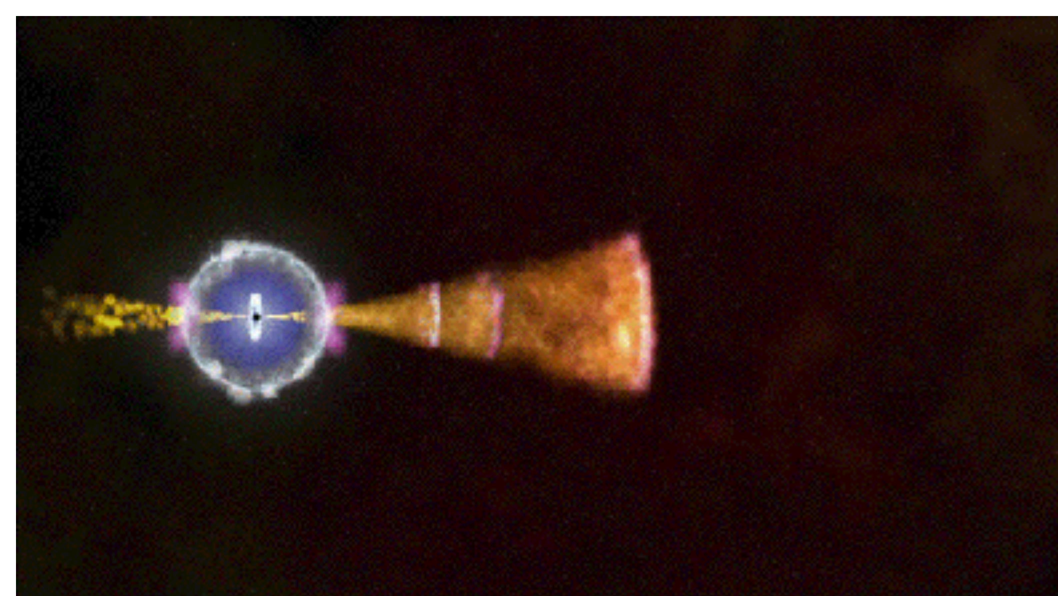
With many thanks to J Wang, F. Rieger, F. Aharonian, ZQ Huang, J Kirk, G Giacinti, L. Olivera Nieto, A. Taylor, S. O'Sullivan and many many others

Pervasive Nature of Jets

BH in M87 - impact observable over 6 decades in length scale



Blandford R., Meier D., Readhead A., 2019



Cartoon of GRB jet
Credit NASA

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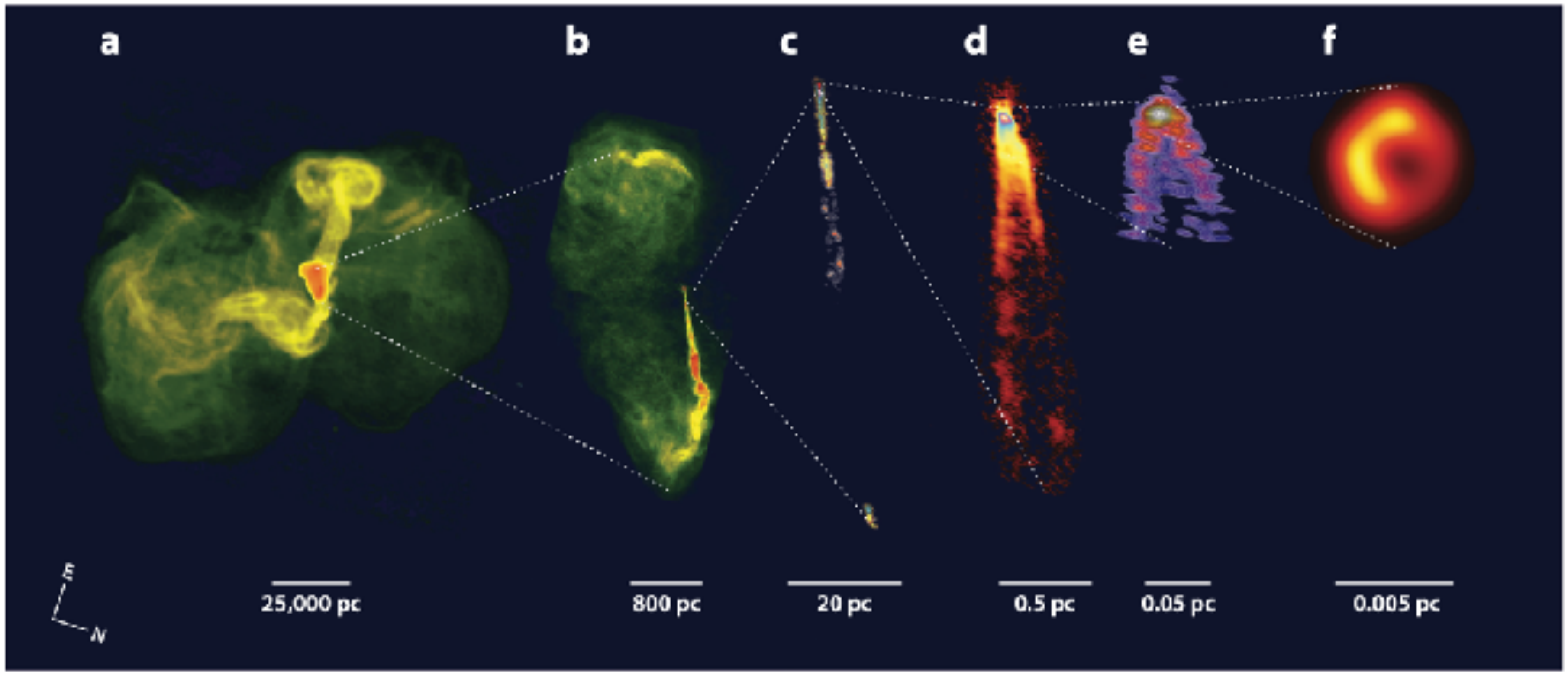

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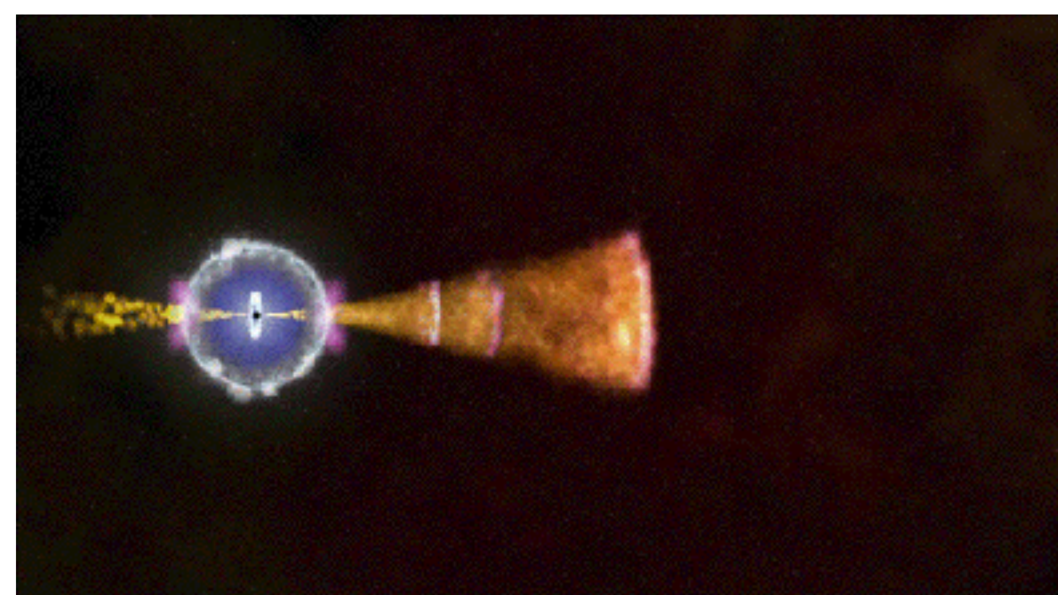

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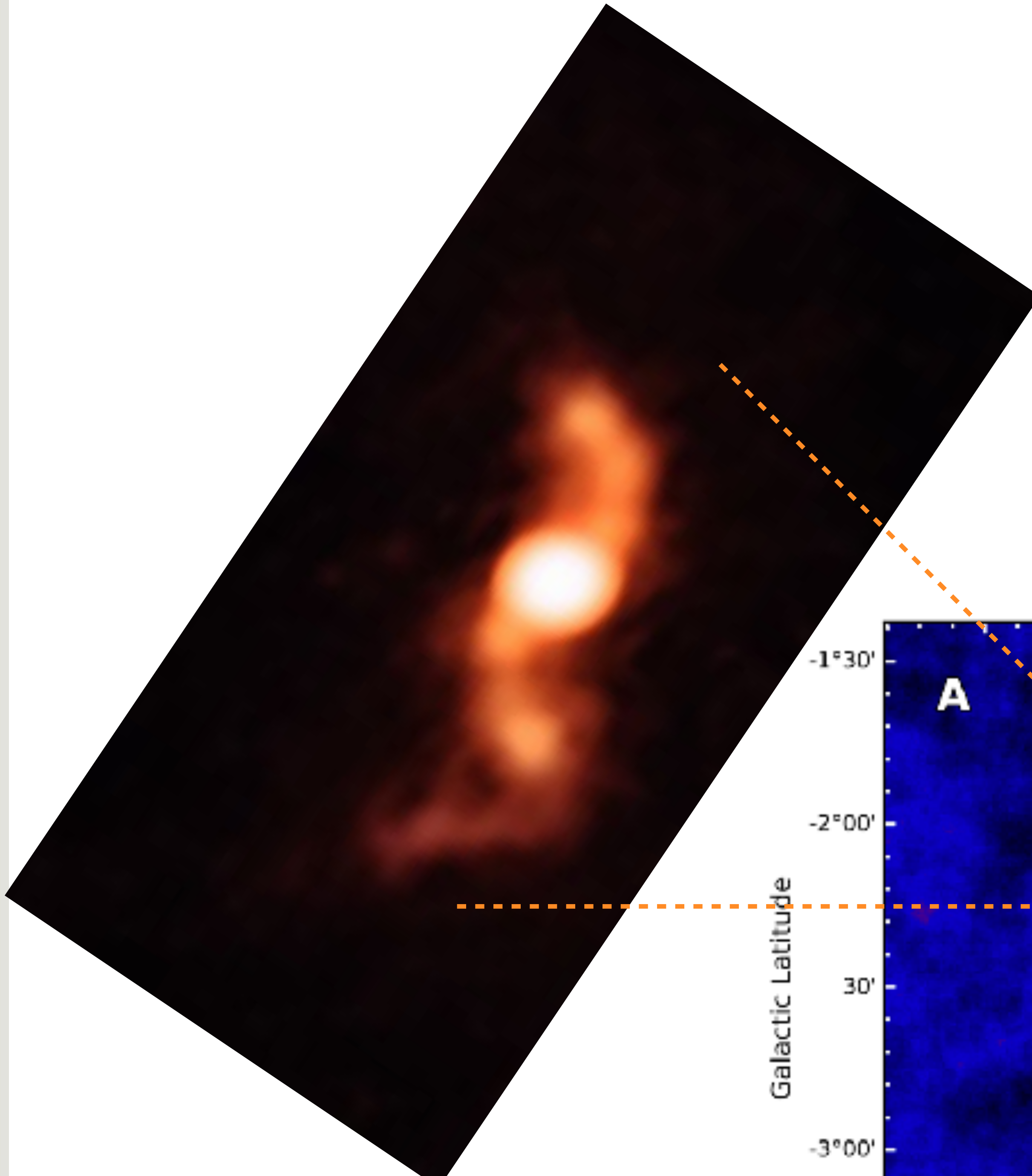
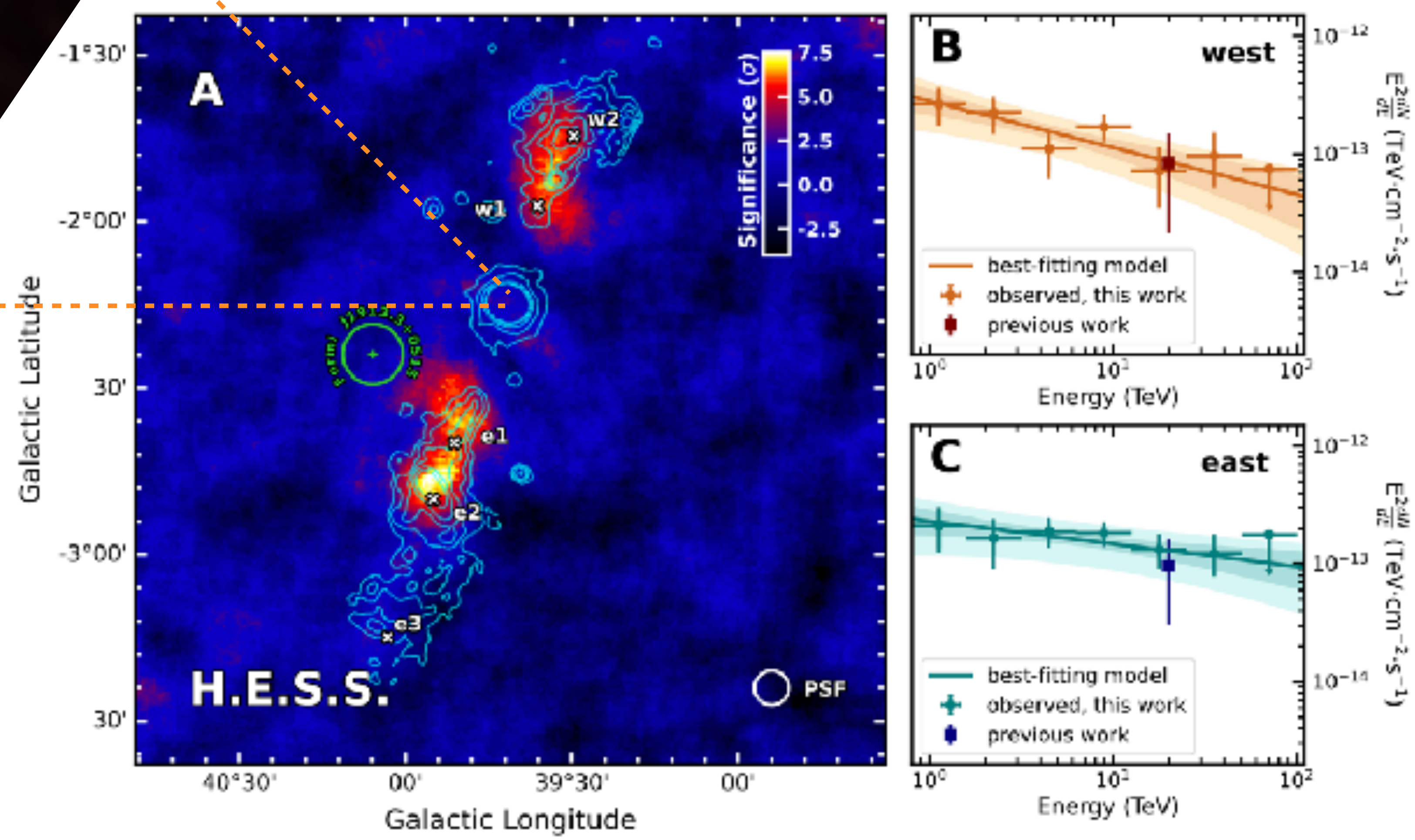
Pervasive Nature of Jets

Galactic microquasar SS 433



Credit: ALMA (ESO/NAOJ/ NRAO) Blundell et al. '18



HESS Collab., Science 2024

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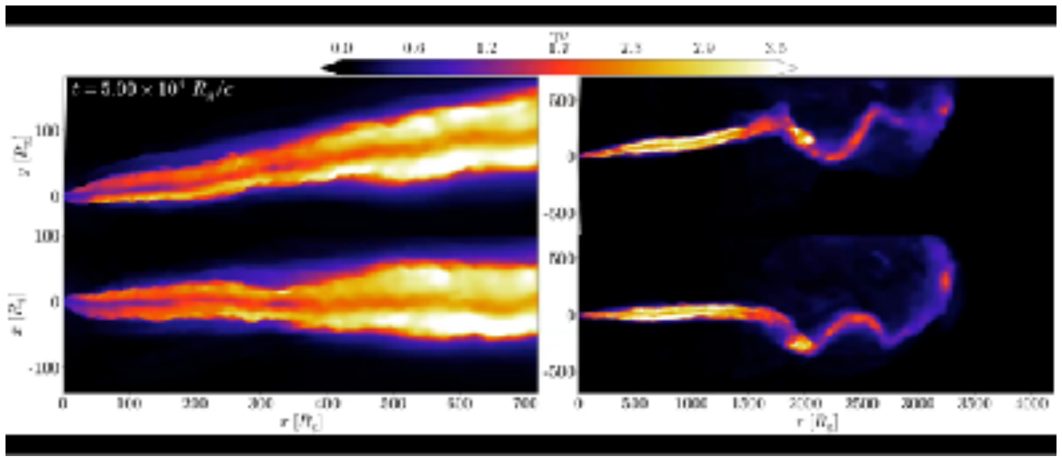
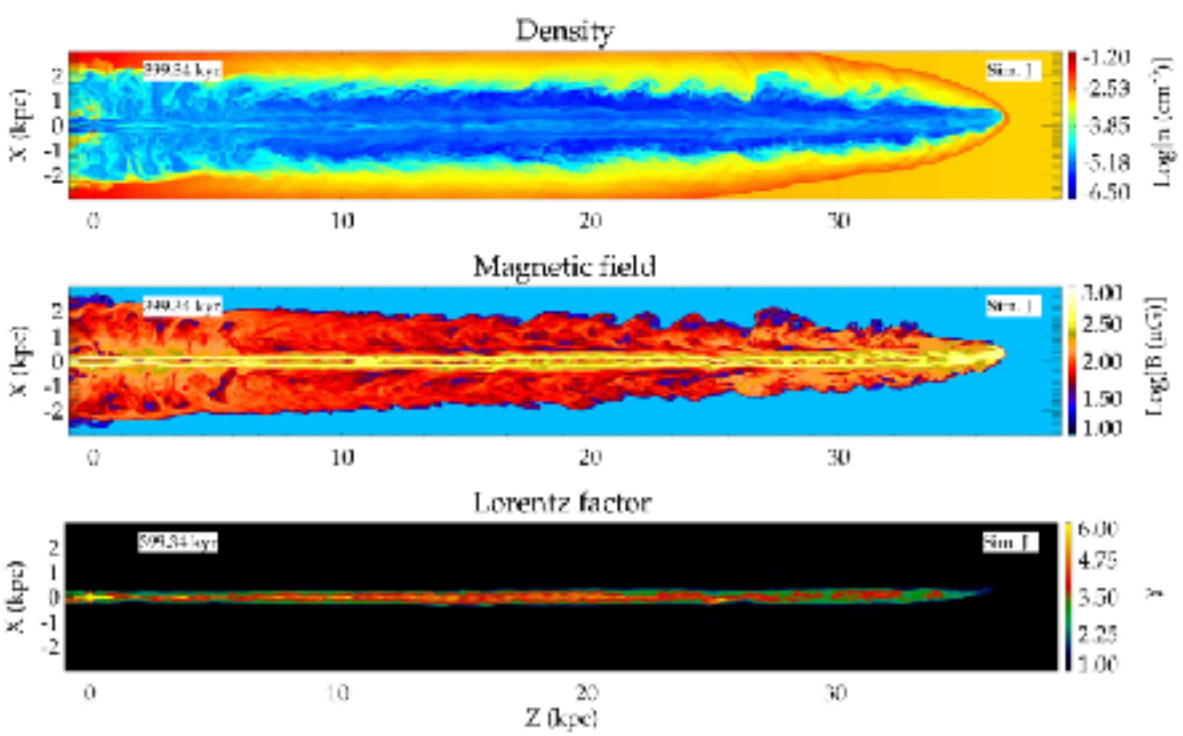
Jet Structure - insight from simulations



GRMHD sims of Jet launching - Lalakos et al, arXiv



3D RMHD jet sims - Jet power 10^{46}erg s^{-1} Mukherjee et al. (2020)

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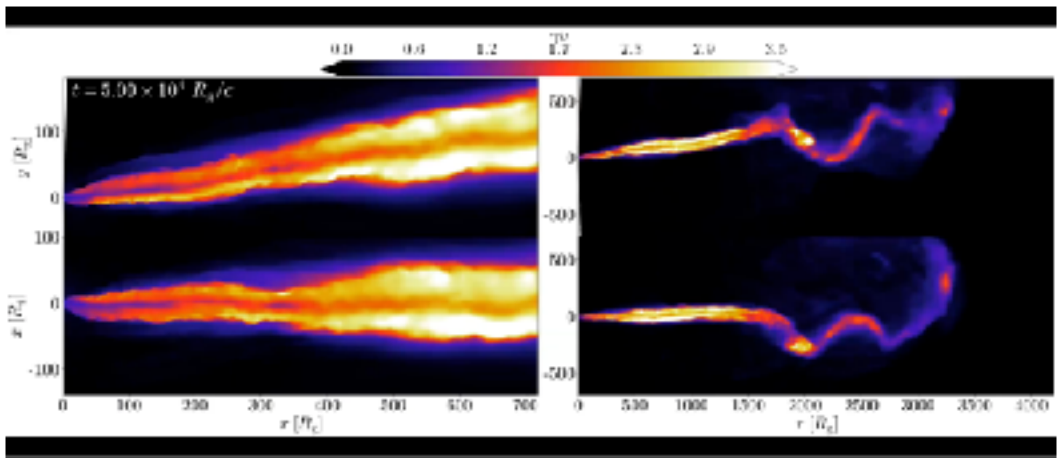

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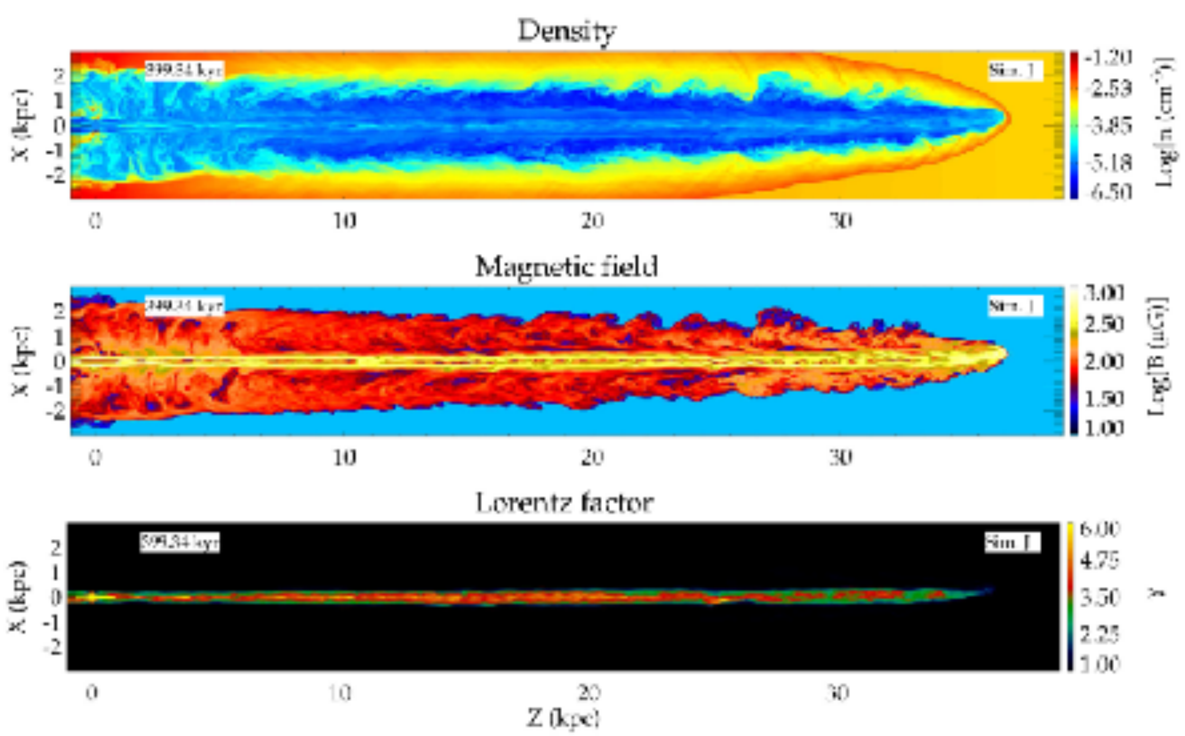

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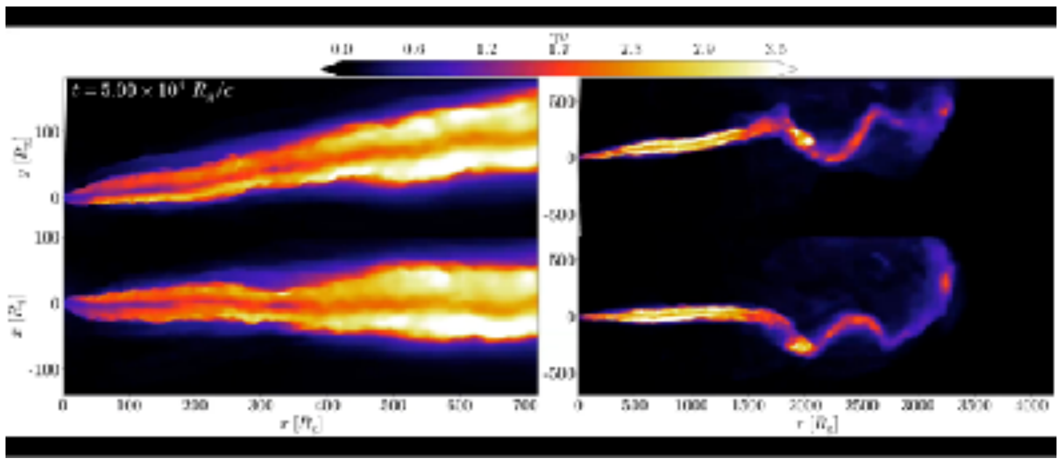

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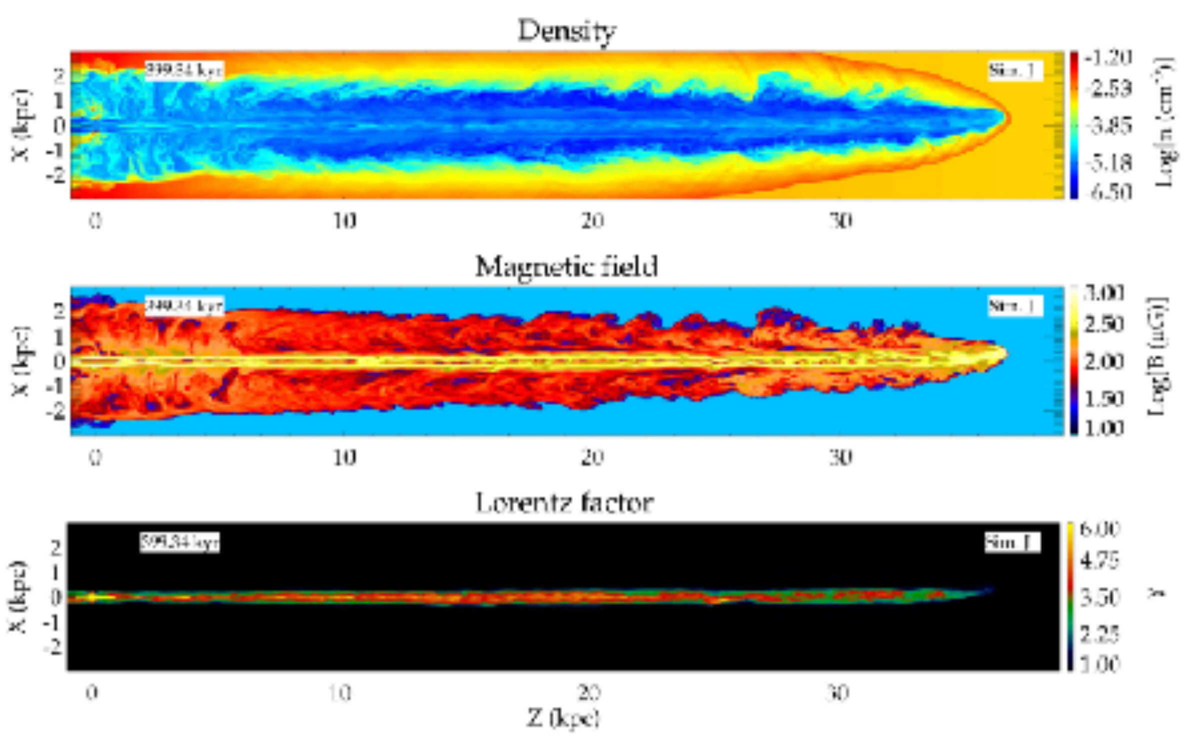

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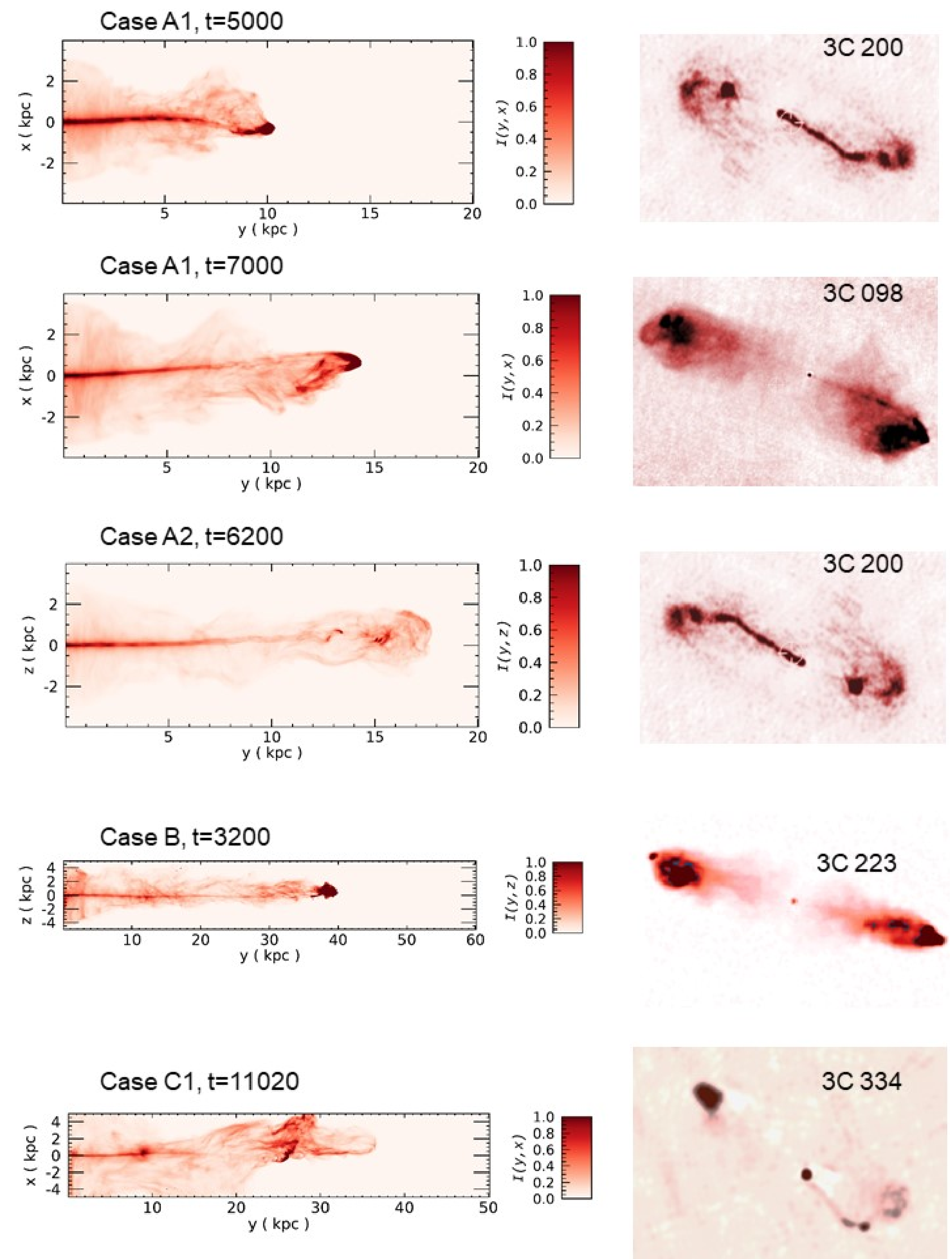

Massaglia et al. 2022

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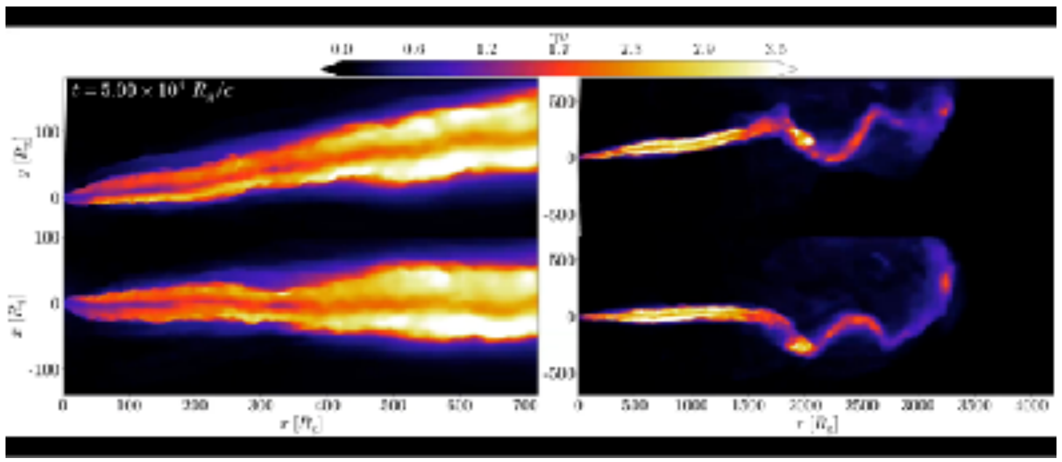

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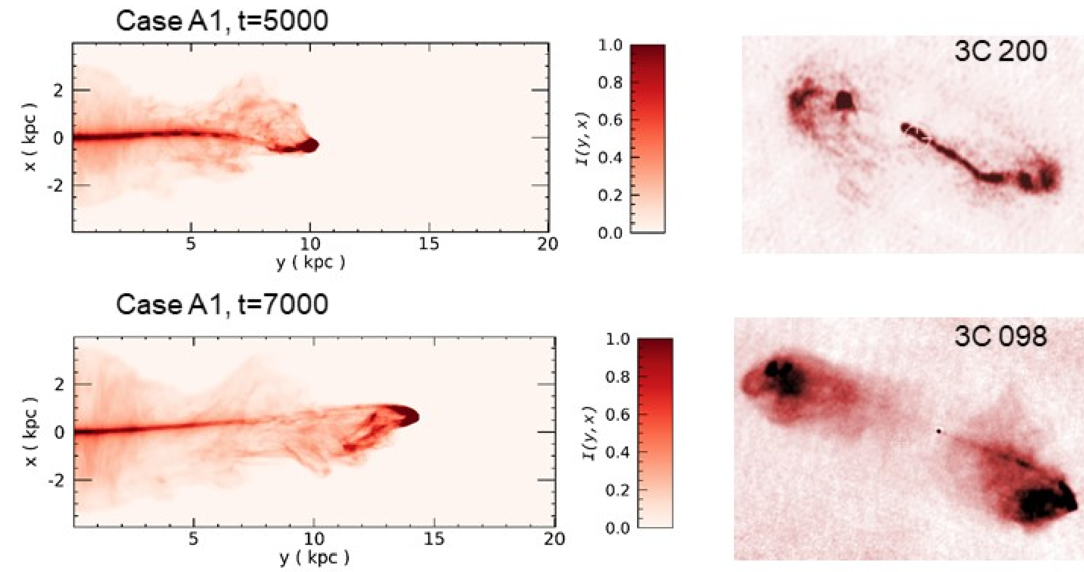

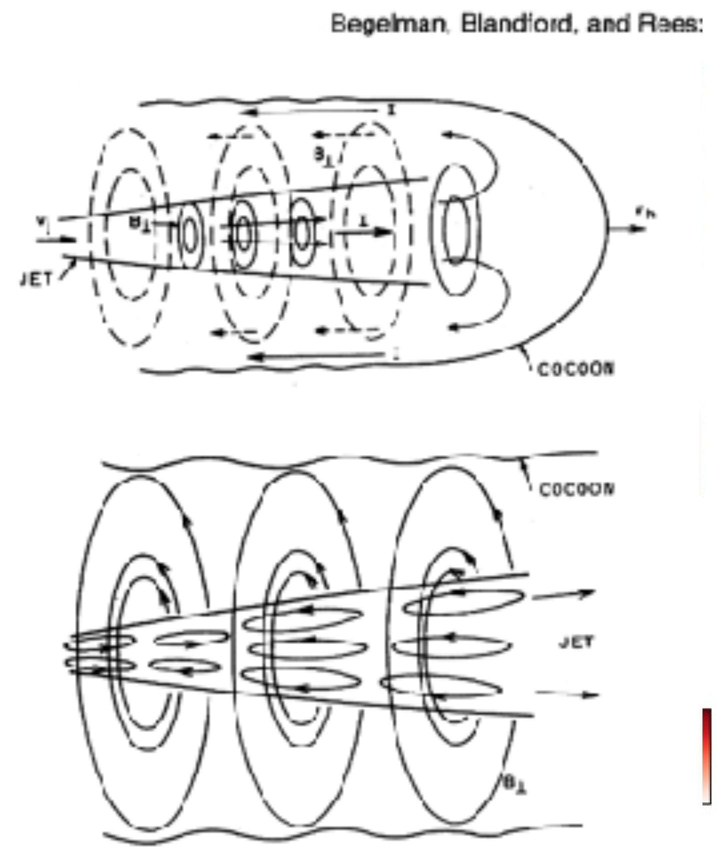

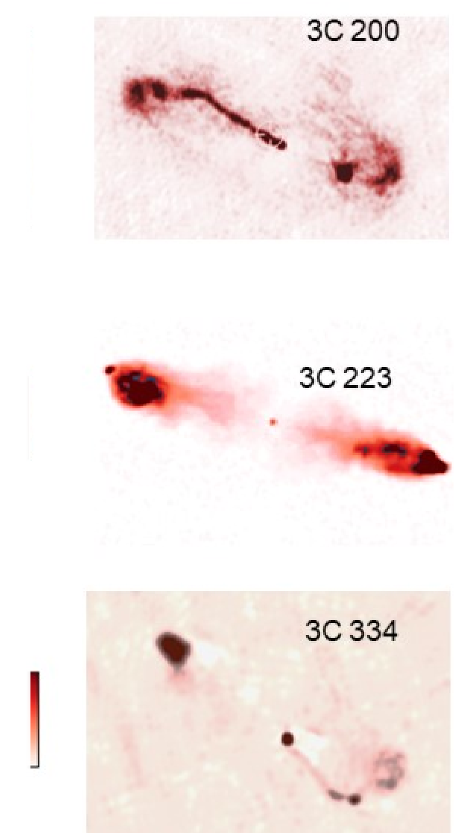

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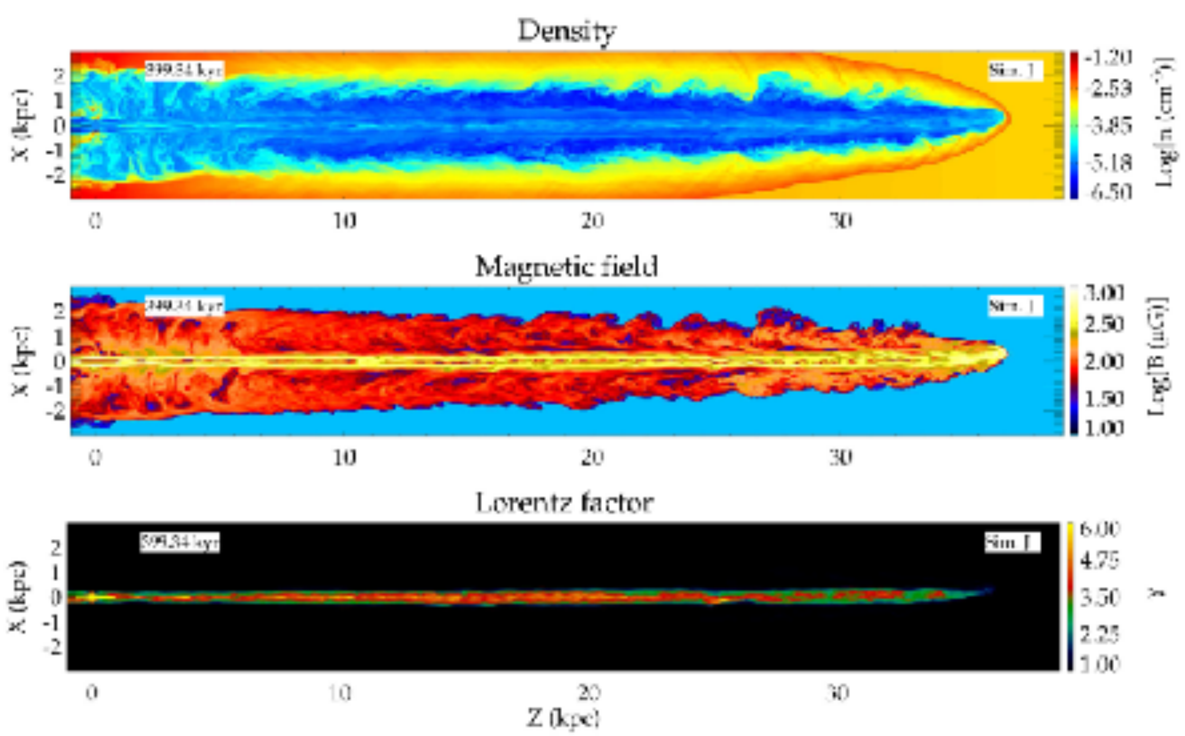

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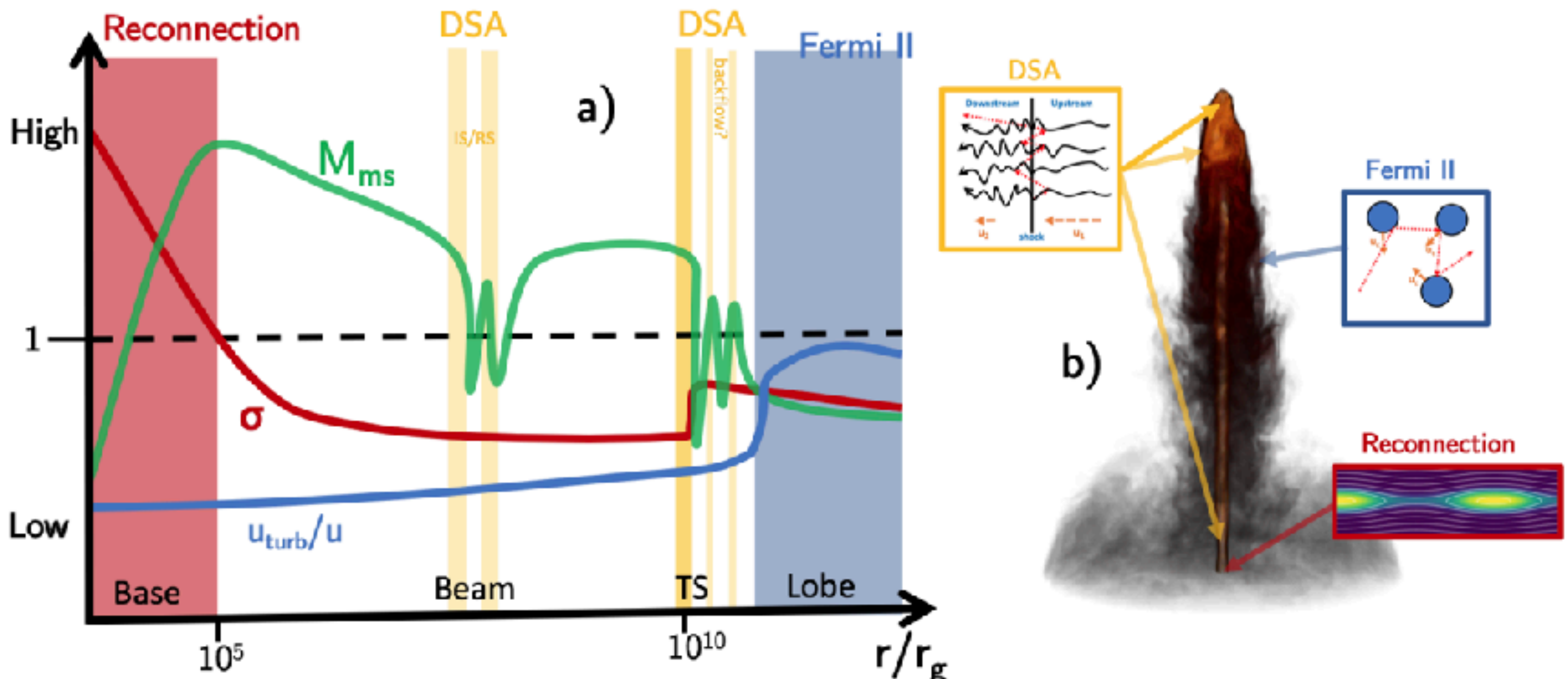
Particle Acceleration Sites

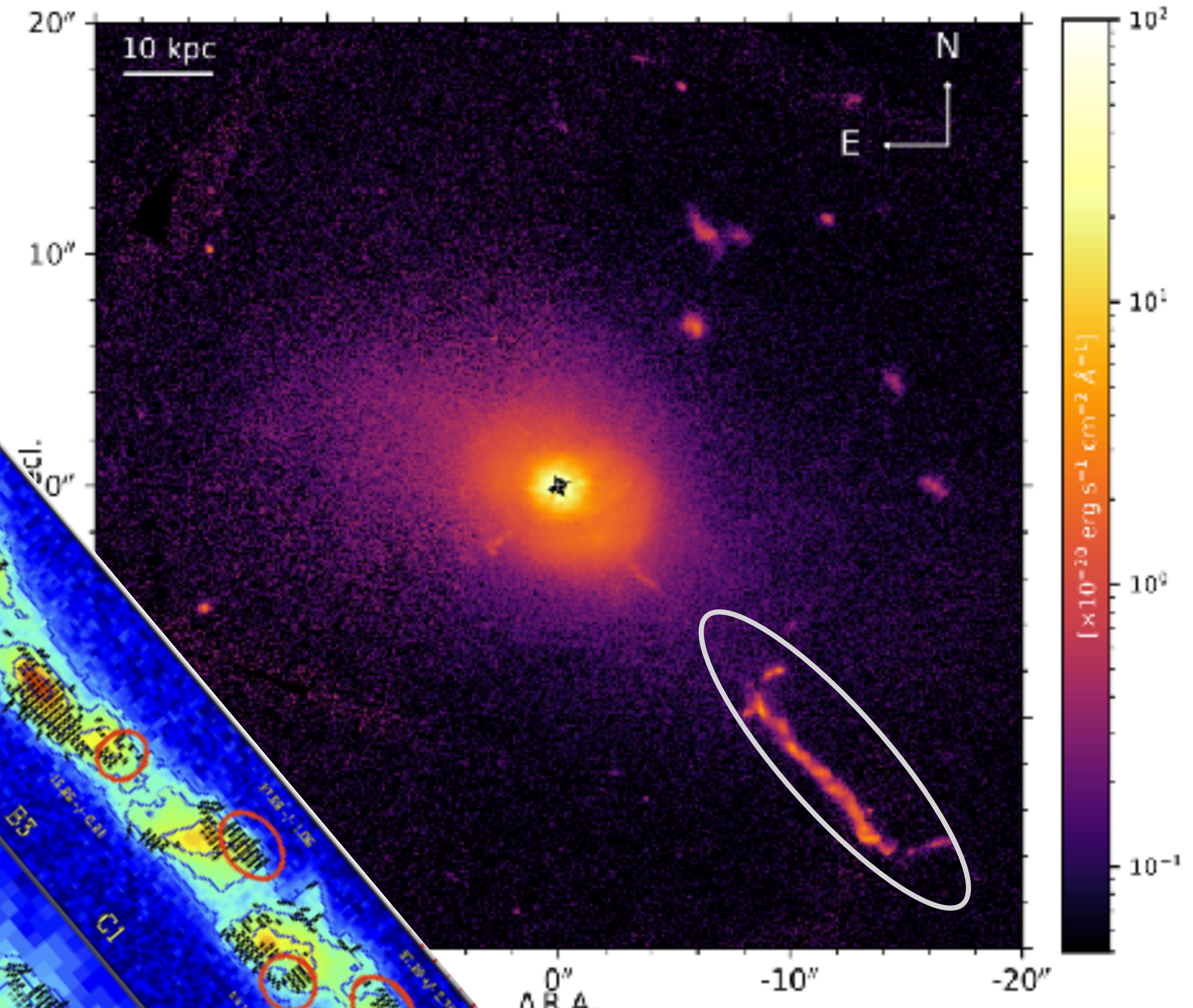


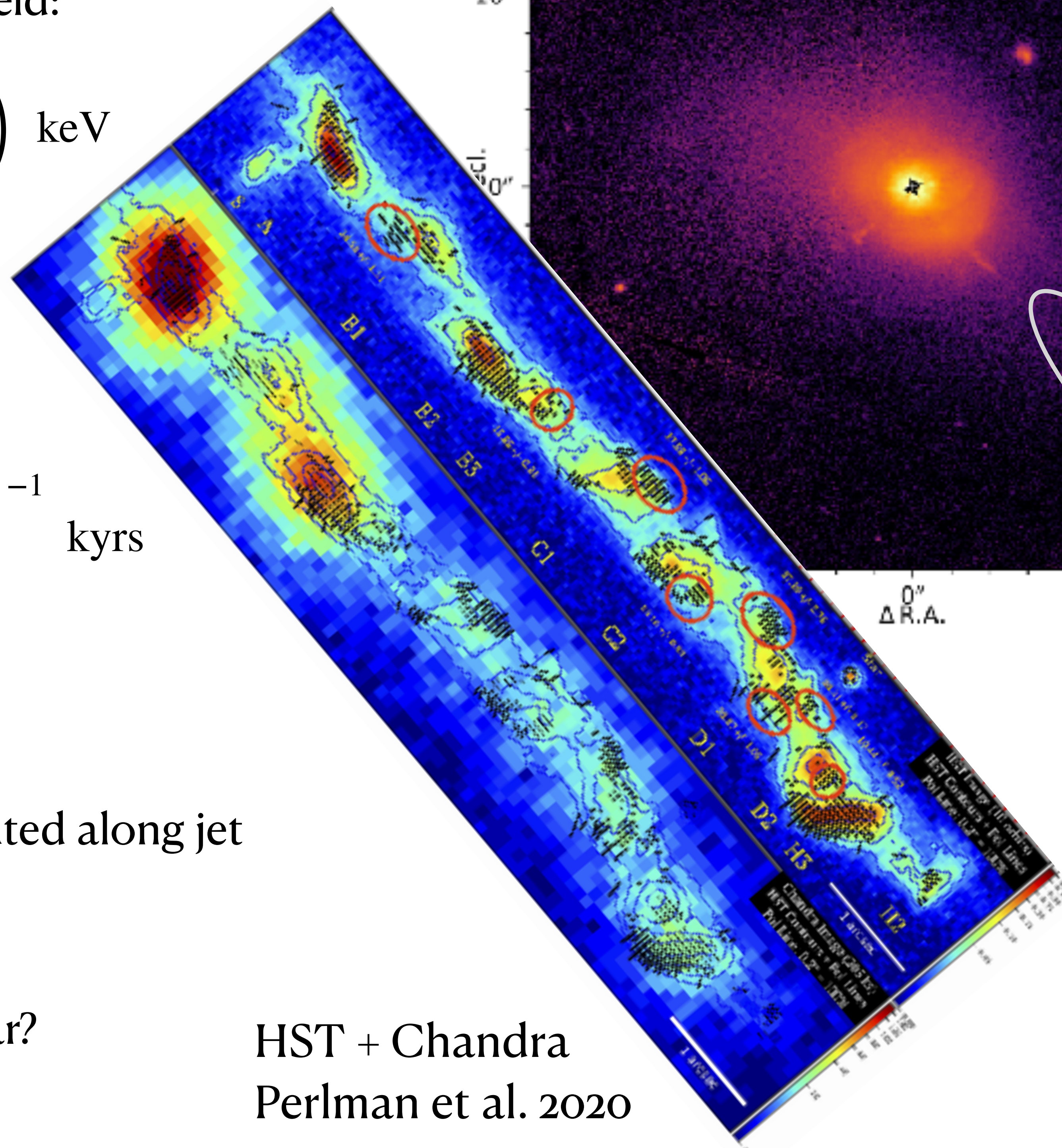
Matthews, Bell & Blundell, 2020

In-situ acceleration

- Synchrotron origin of X-rays requires energetic electrons & large field:
- $$h\nu_{\rm syn} \approx \left(\frac{E_e}{0.1{\rm PeV}}\right)^2 \left(\frac{B}{10\mu{\rm G}}\right)\ {\rm keV}$$
- Cooling time of electrons:
$$t_{\rm cool} \approx \left(\frac{B}{10\mu{\rm G}}\right)^{-2} \left(\frac{E_e}{0.1{\rm PeV}}\right)^{-1}\ {\rm kyrs}$$
i.e. $ct_{\rm cool} \lesssim {\rm kpc}$
- Acceleration process distributed along jet
- Reconnection? Fermi II? Shear?

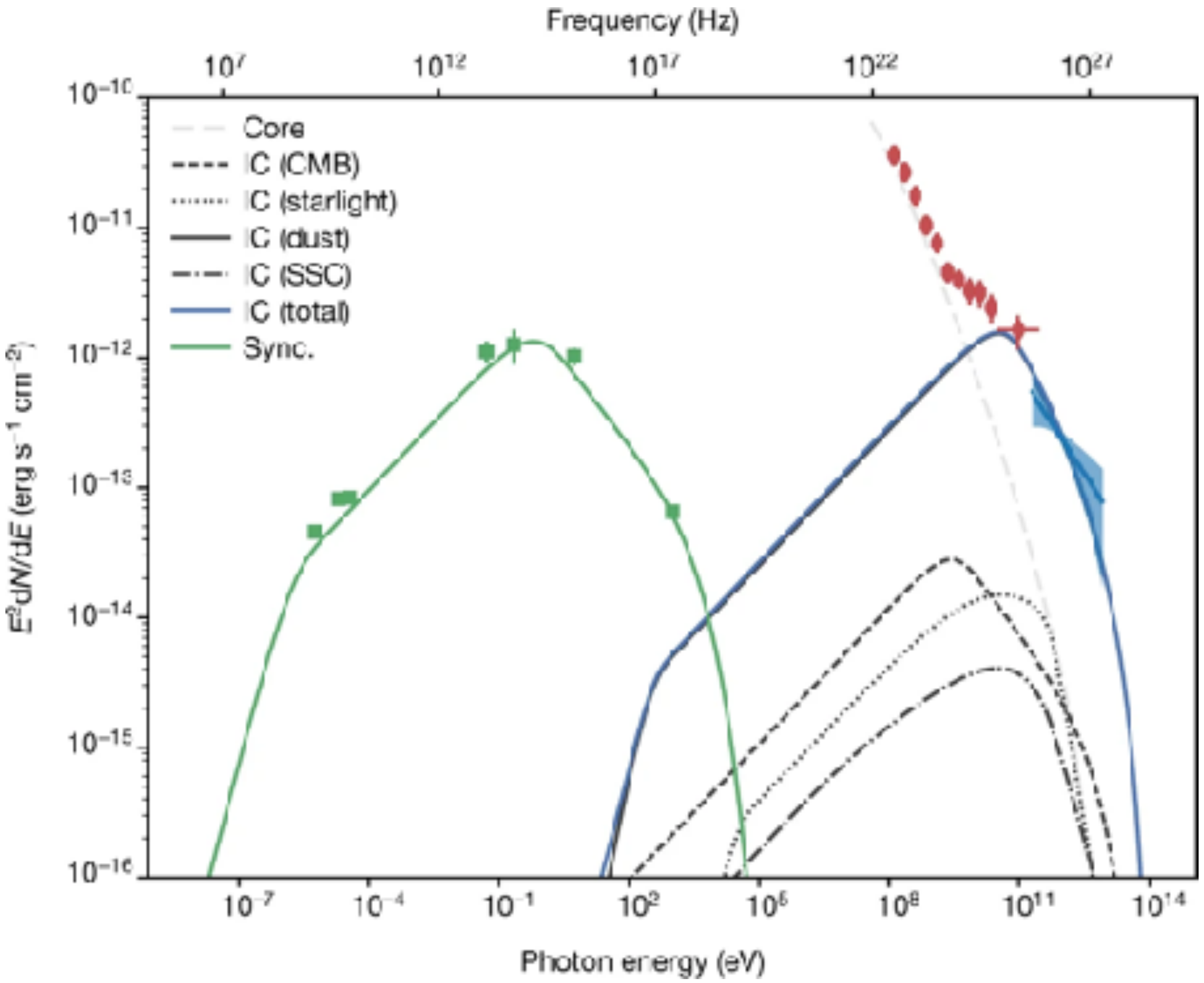
HST/STIS coronagraph 3C 273 (Ren et al. 2024)

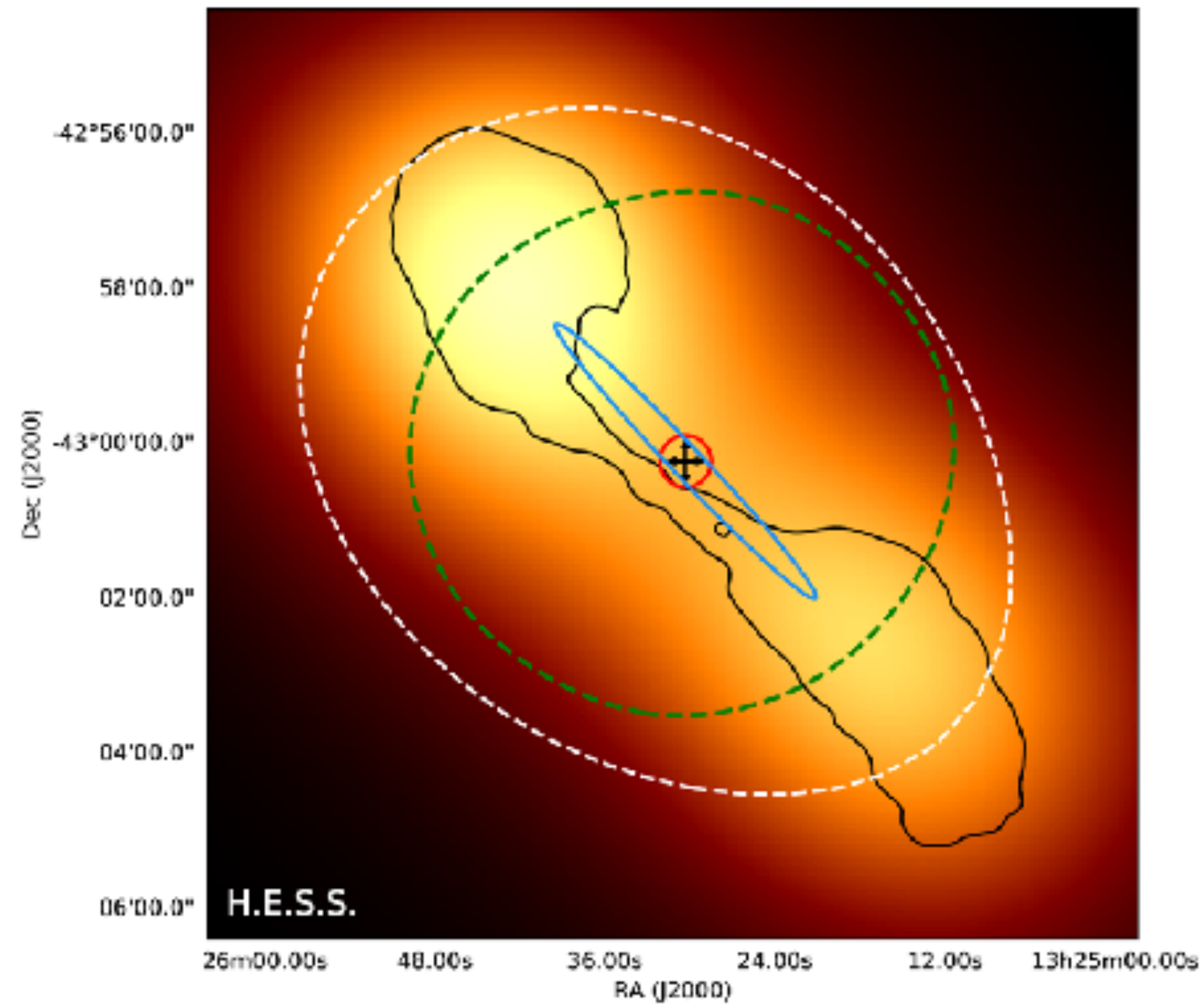




HST + Chandra
Perlman et al. 2020

Emission on large scales





TeV emission from Cen A
HESS Collab., Nature 2020

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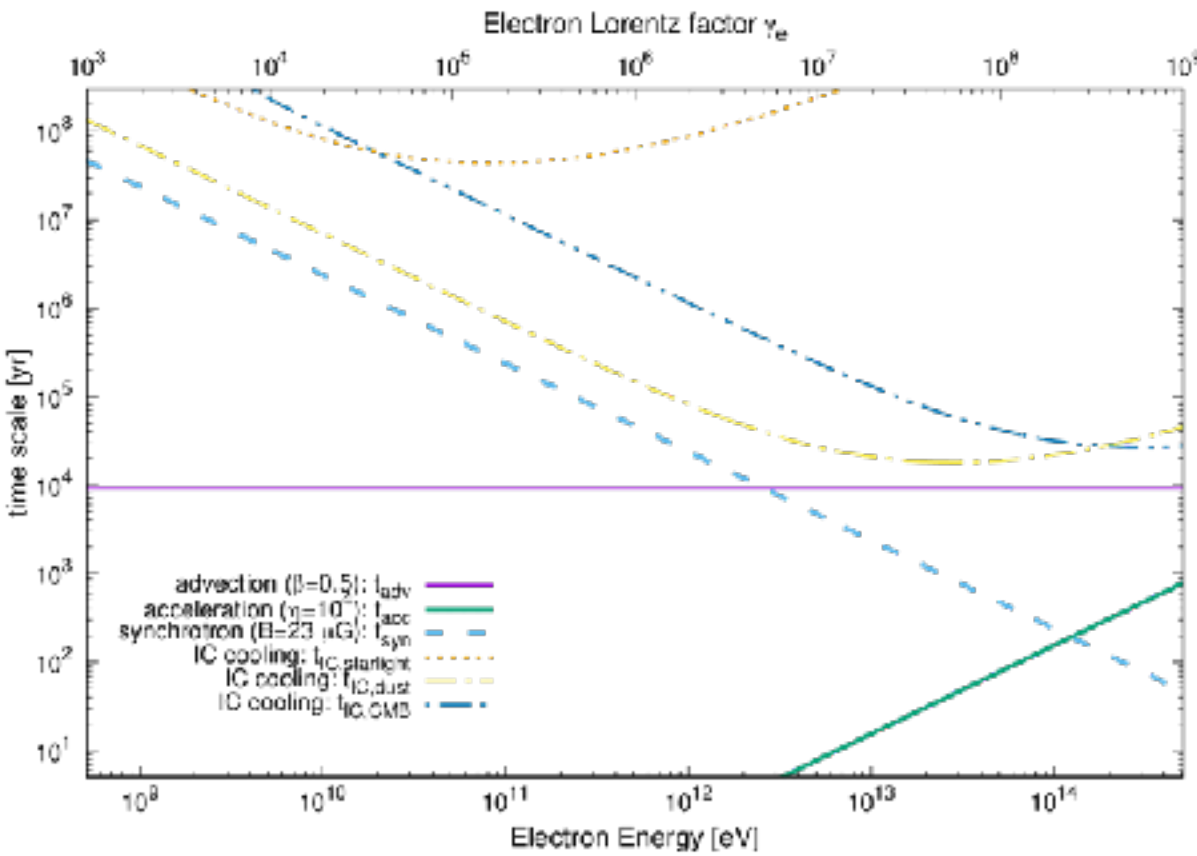

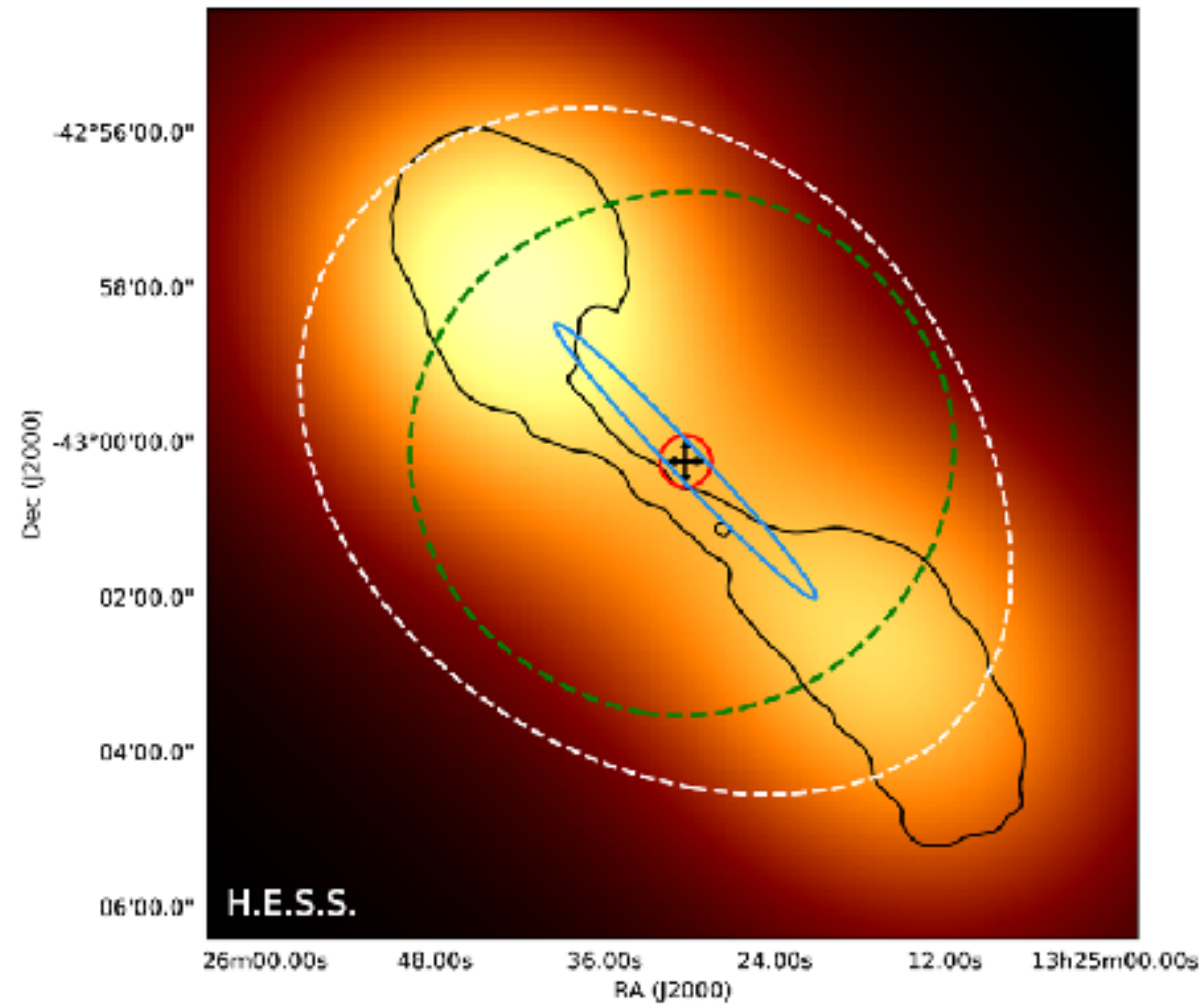

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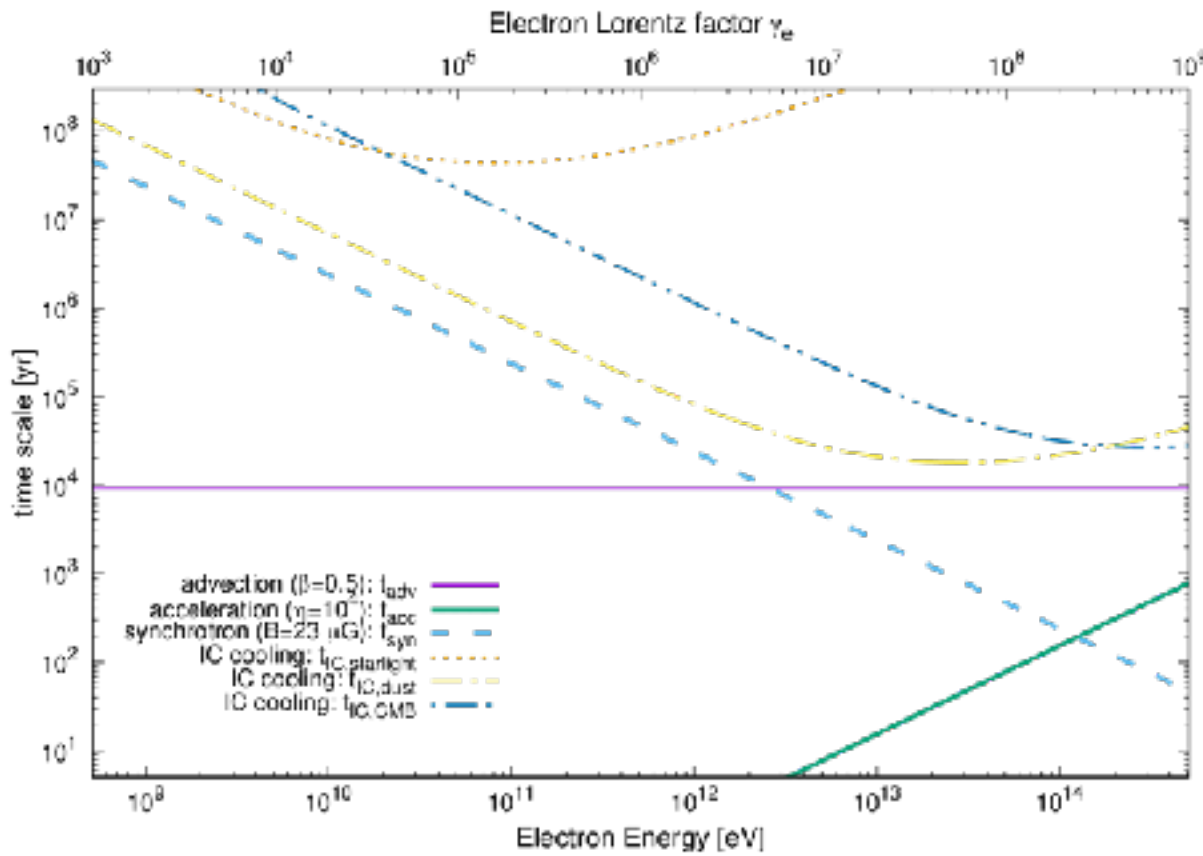

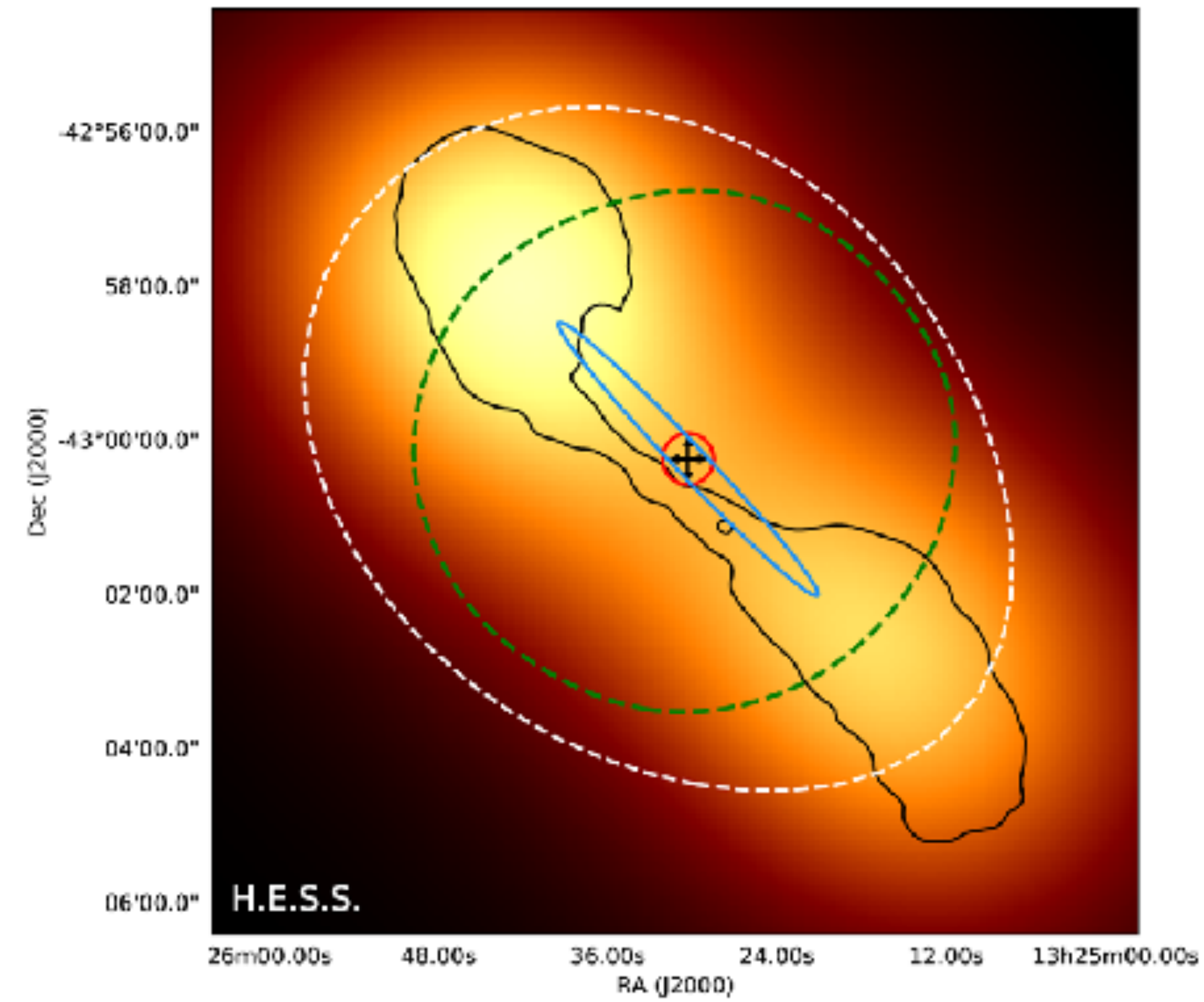

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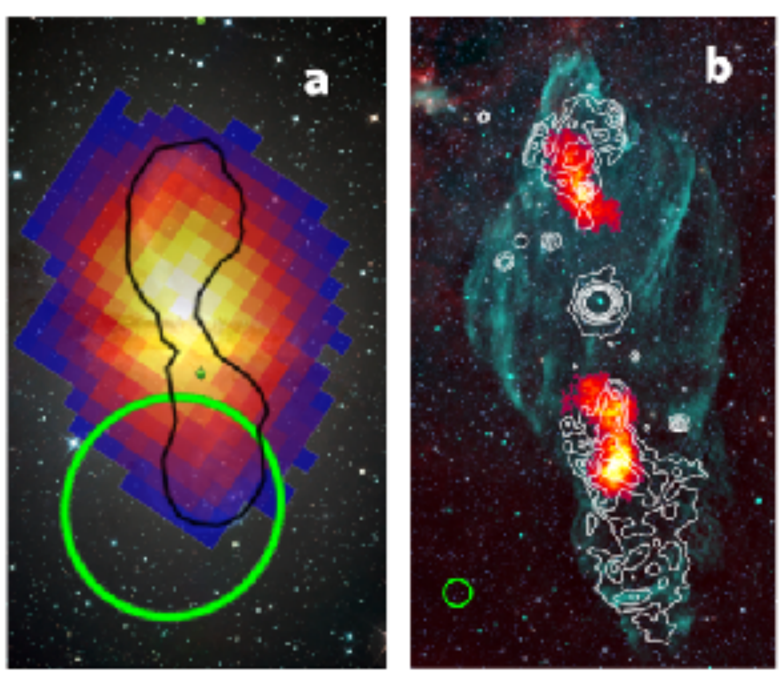

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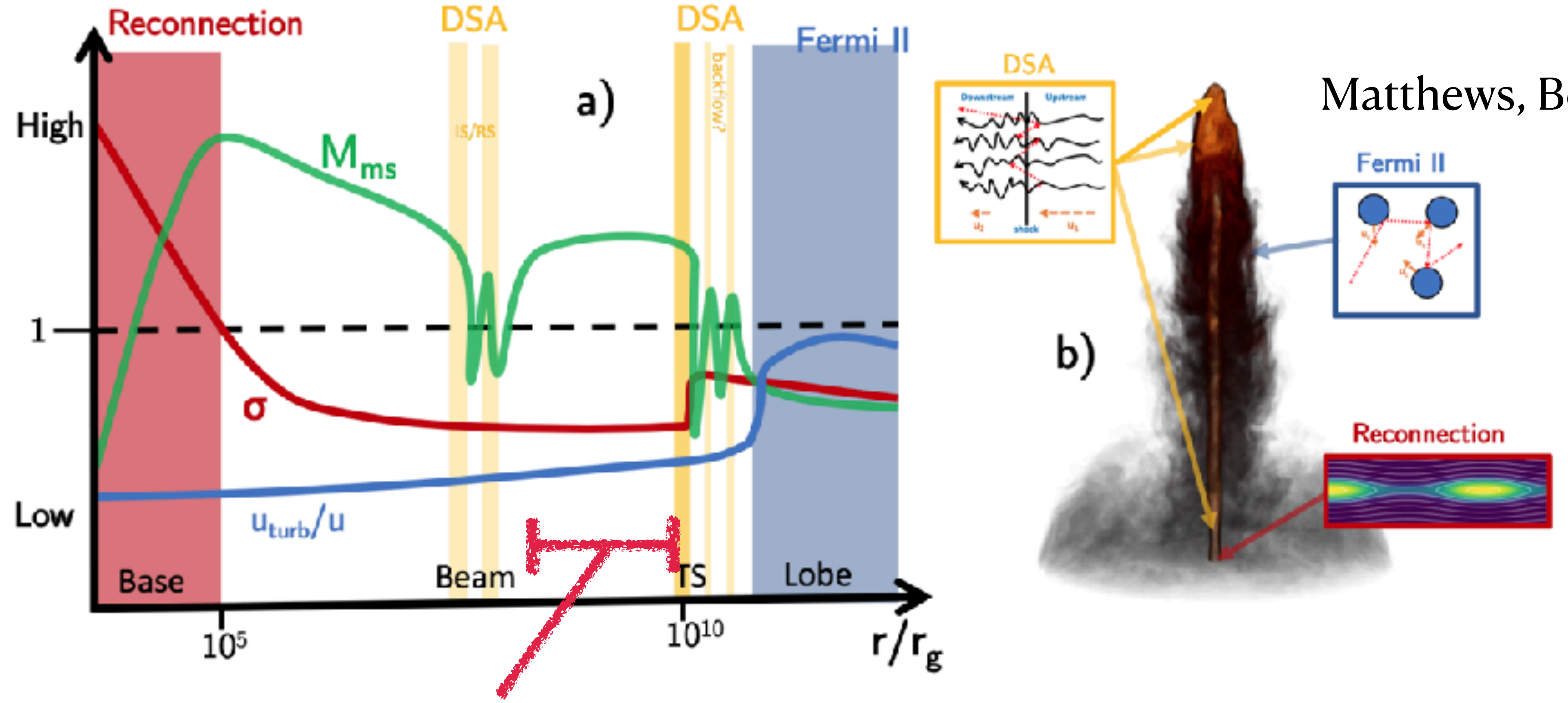
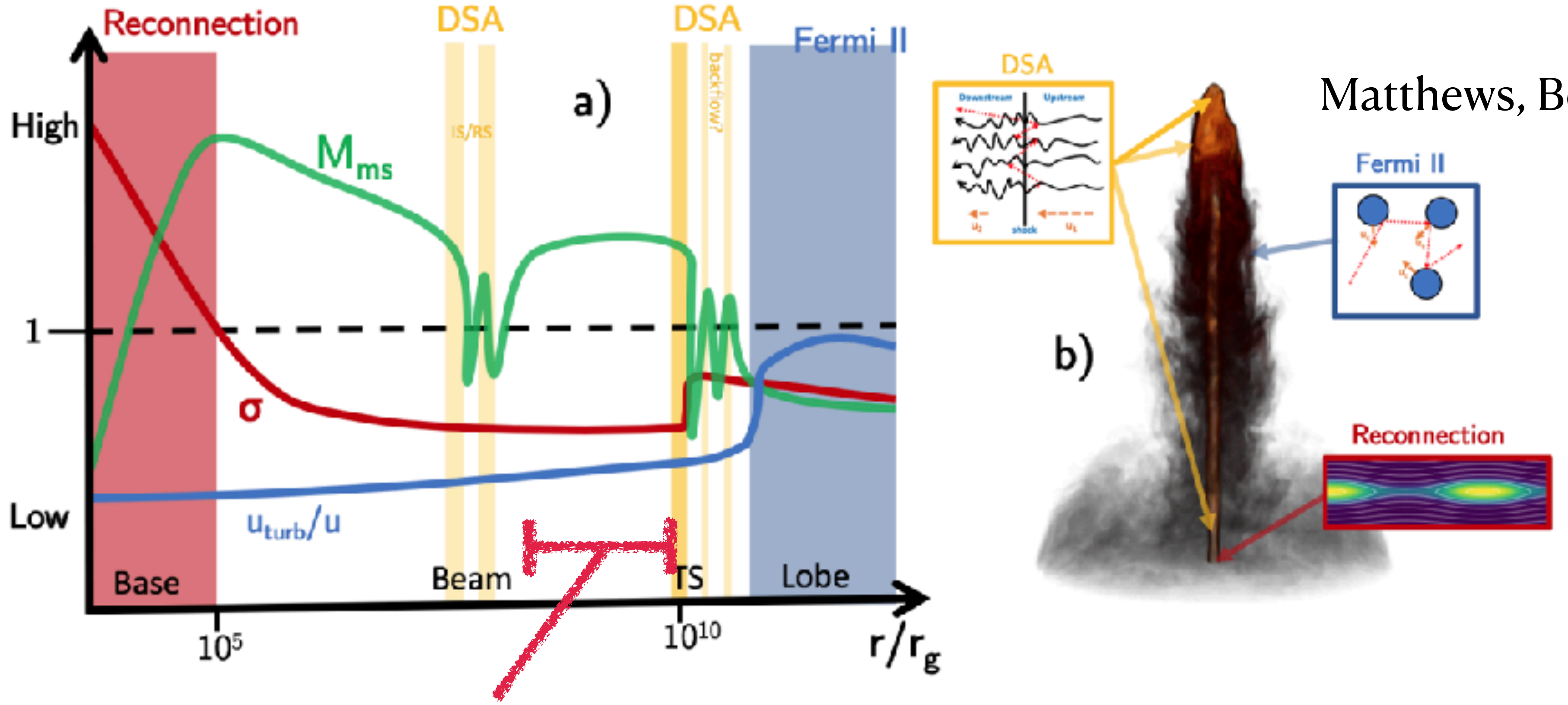


Matthews, Bell & Blundell, 2020

Which processes operate here?

Particle Acceleration Sites



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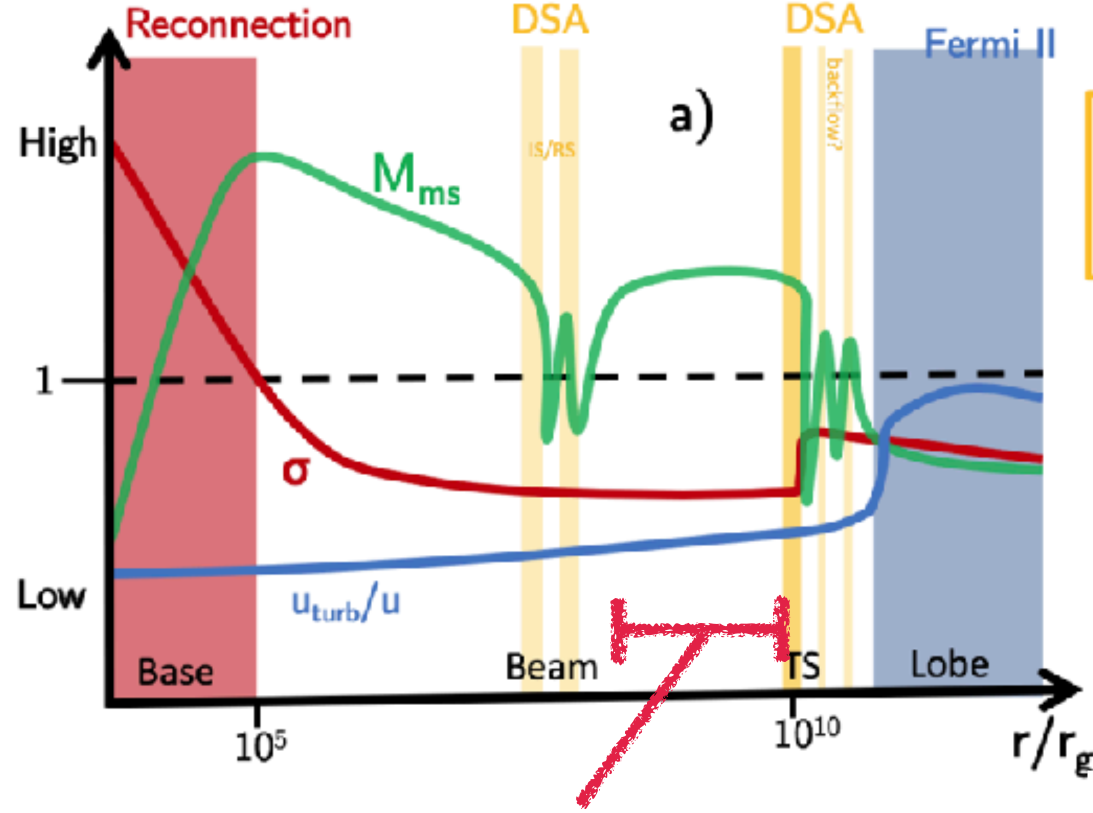
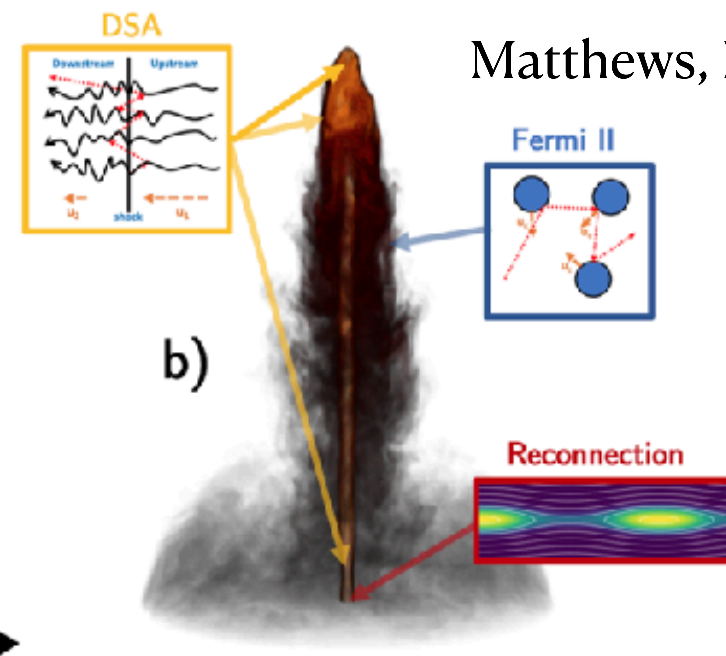
Which processes operate here?

Fermi-II type acceleration occurs in the jet sheath

e.g. Stawarz & Ostrowski ’02, Rieger et al. ’07, Webb et al. 18, 19, 20 ….

Particle Acceleration Sites

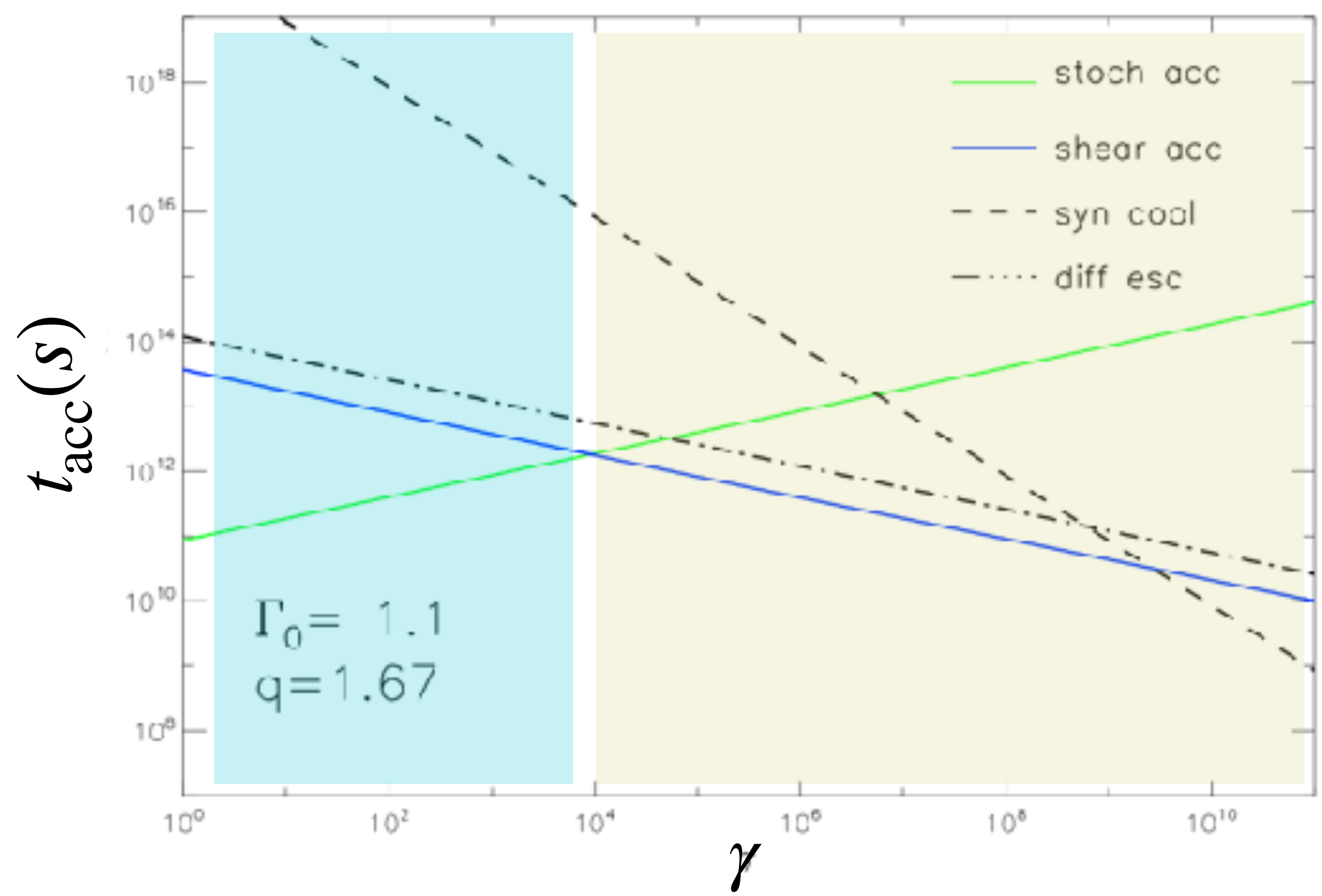




Matthews, Bell & Blundell, 2020

Which processes operate here?

Liu et al. '17



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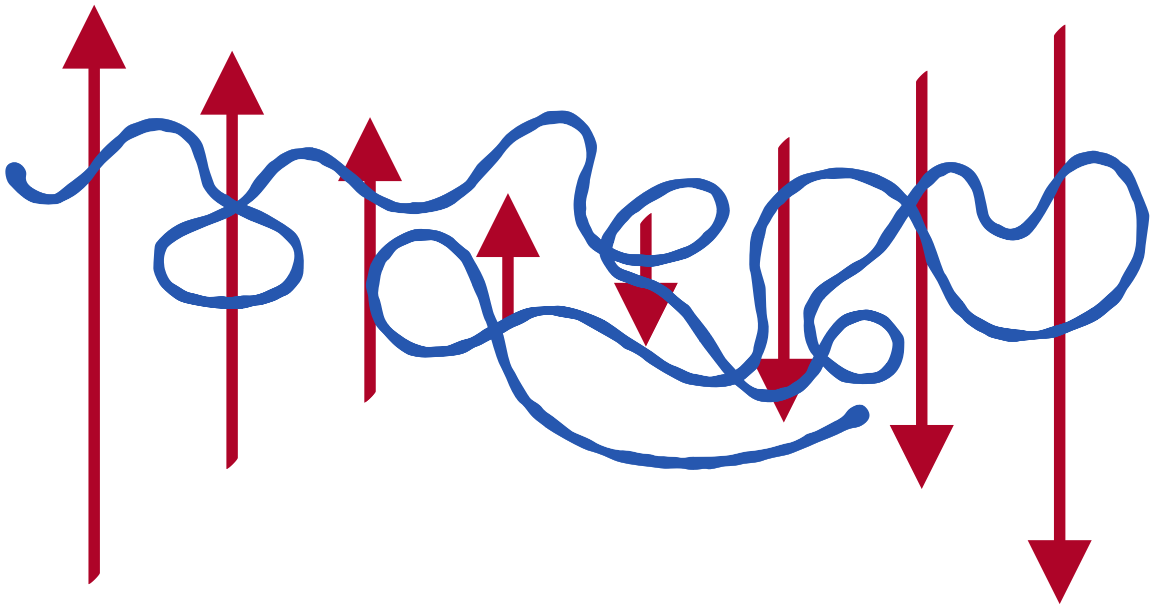
Particle Acceleration in sheared flows

First explored by Berezhko & Krymskii (1981)

Particles gain energy by scattering against direction of flow (viscous momentum transfer) Note dependence of $t_{\rm acc}$ on D_{xx}



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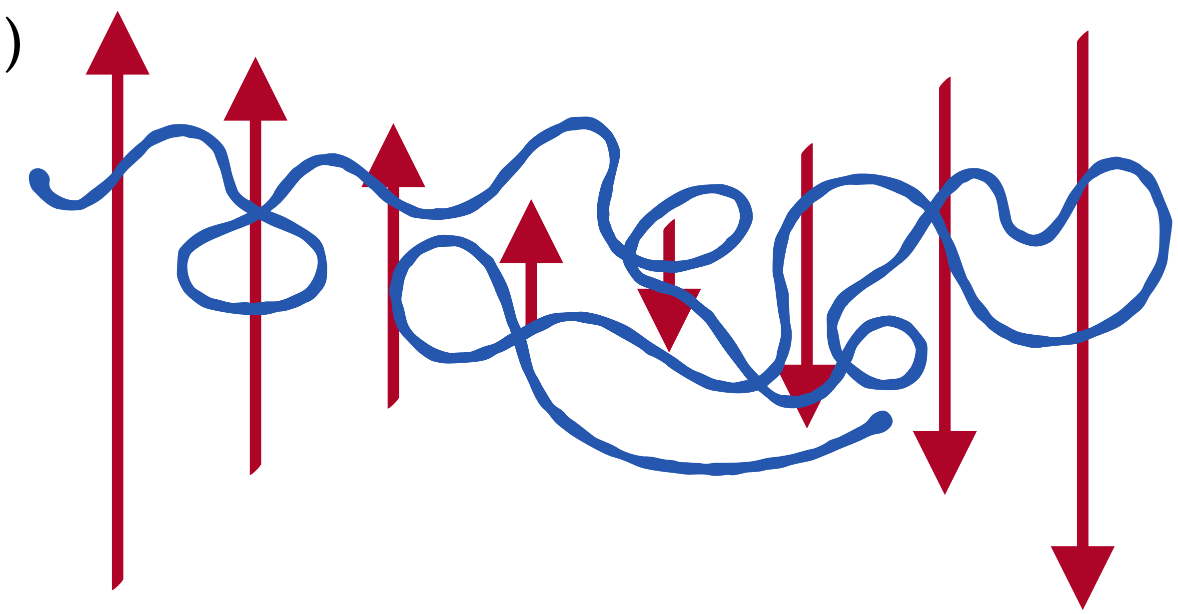
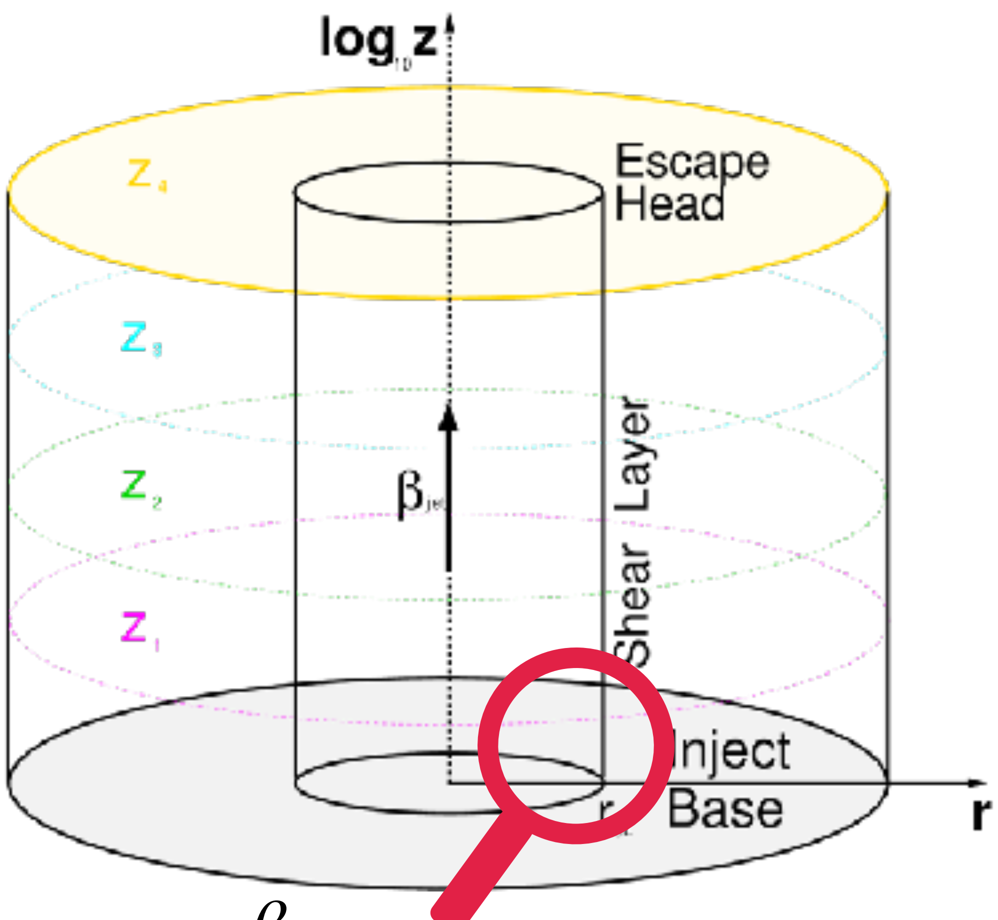
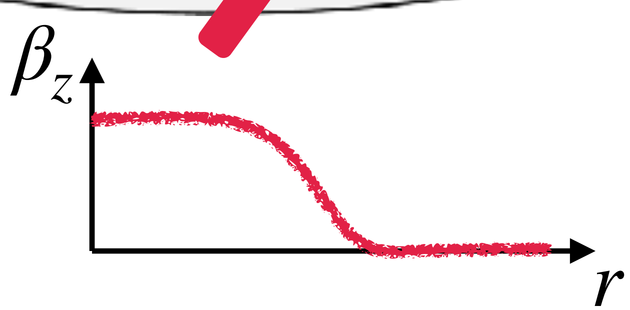




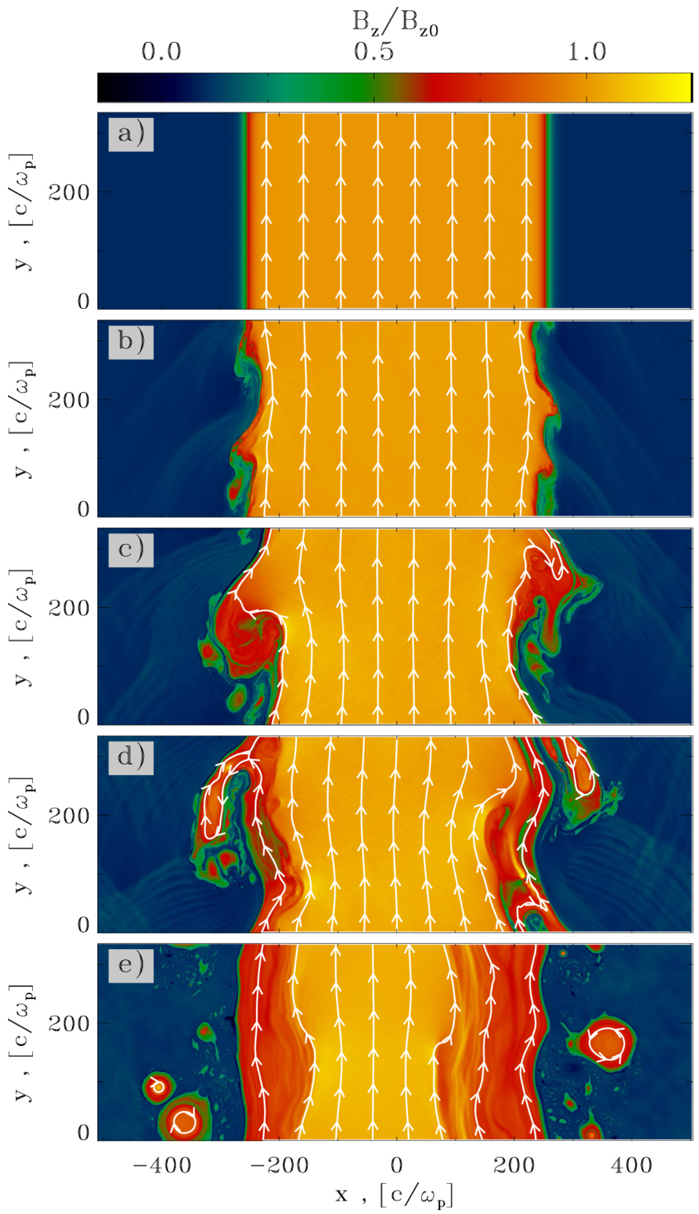


First consider a toy model of *non-gradual shear in a jet* (e.g. Ostrowski '90, Rieger Duffy '04, Caprioli '15, Webb ety al 18, O'Sullivan et al '21, etc.):

We run some simple Monte Carlo simulations

- Random isotropic scattering in local frame $\lambda(E) \propto E^{\alpha}$
- Note, particles injection process needed

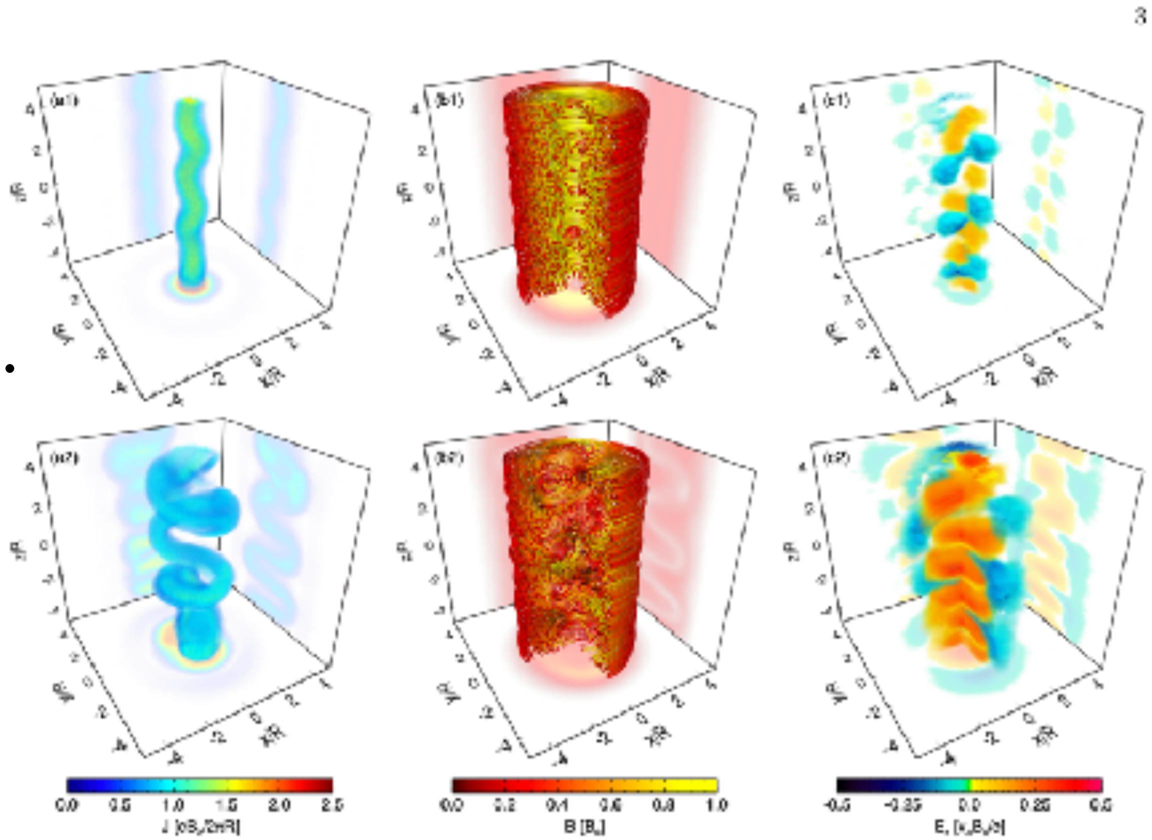
Kinetic simulations

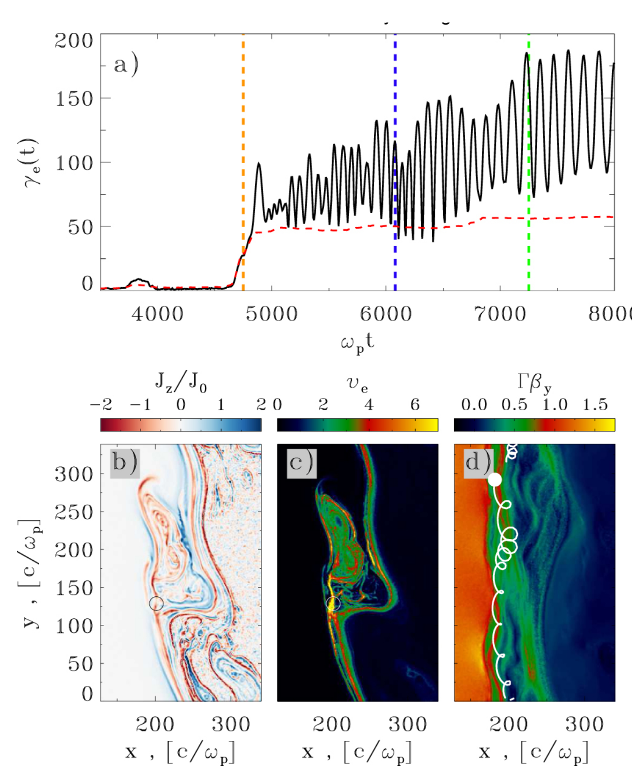


2D PIC sims by Sironi et al. '21

Increasing time

3D PIC sims by Alves et al.





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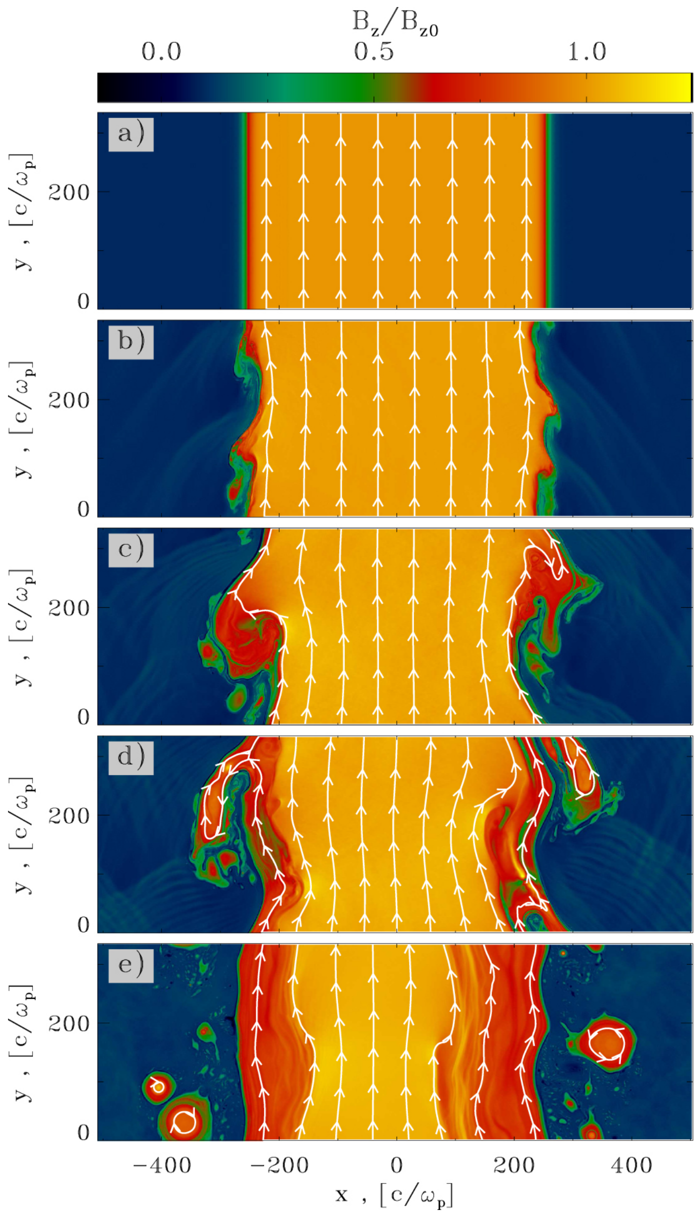

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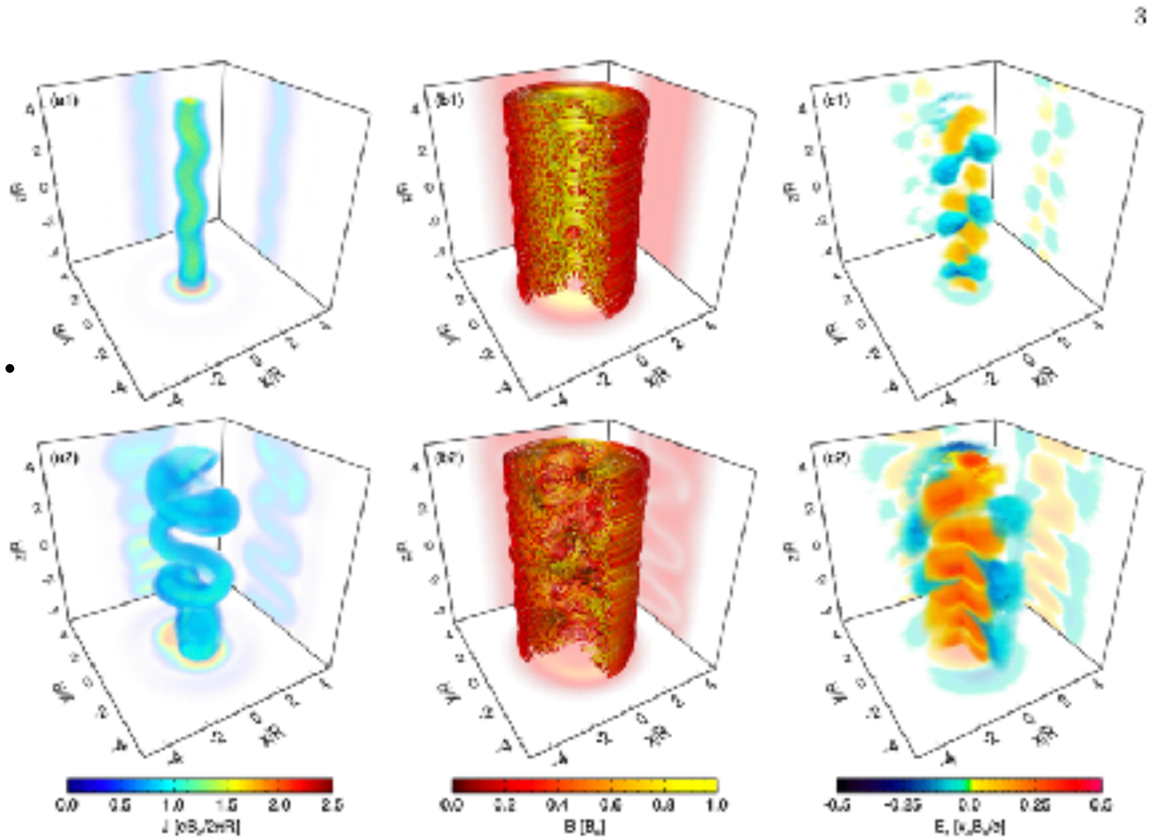

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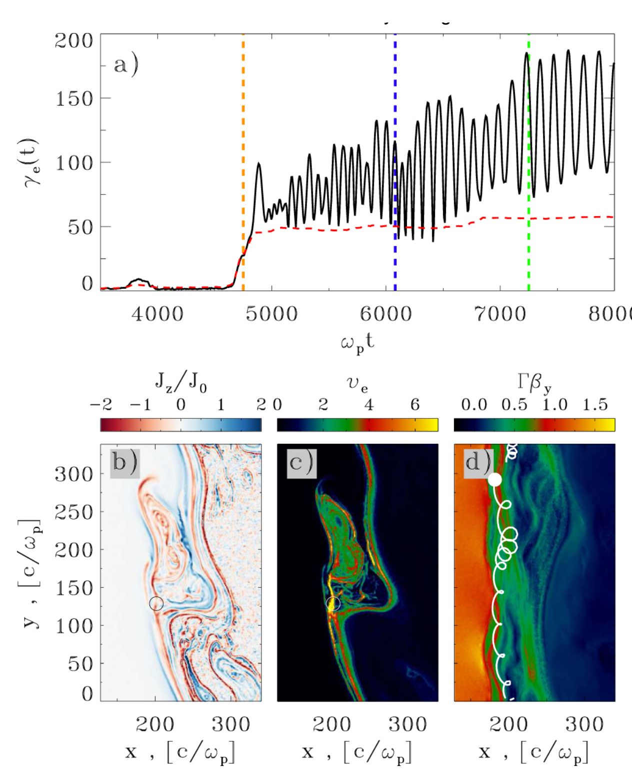
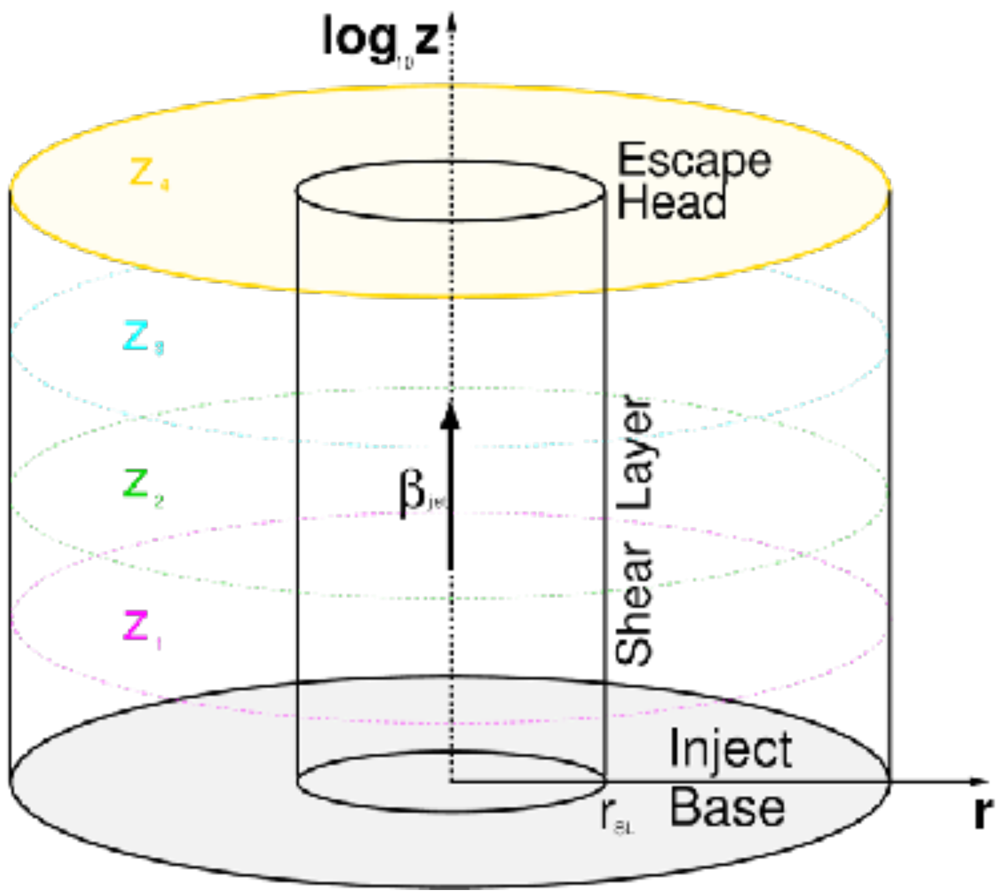


Kinetic effects can generate non-thermal seed particles both internally and on jet interface

Particle Acceleration in top-hat jet

Toy model of *non-gradual shear in relativistic jets*

- Top-hat jet profile (Here we adopt $\Gamma_j = 10$)
- Random isotropic scattering in local frame (Here Kolmogorov)
- Particles injected at jet base



O'Sullivan, Taylor, BR, ICRC '21

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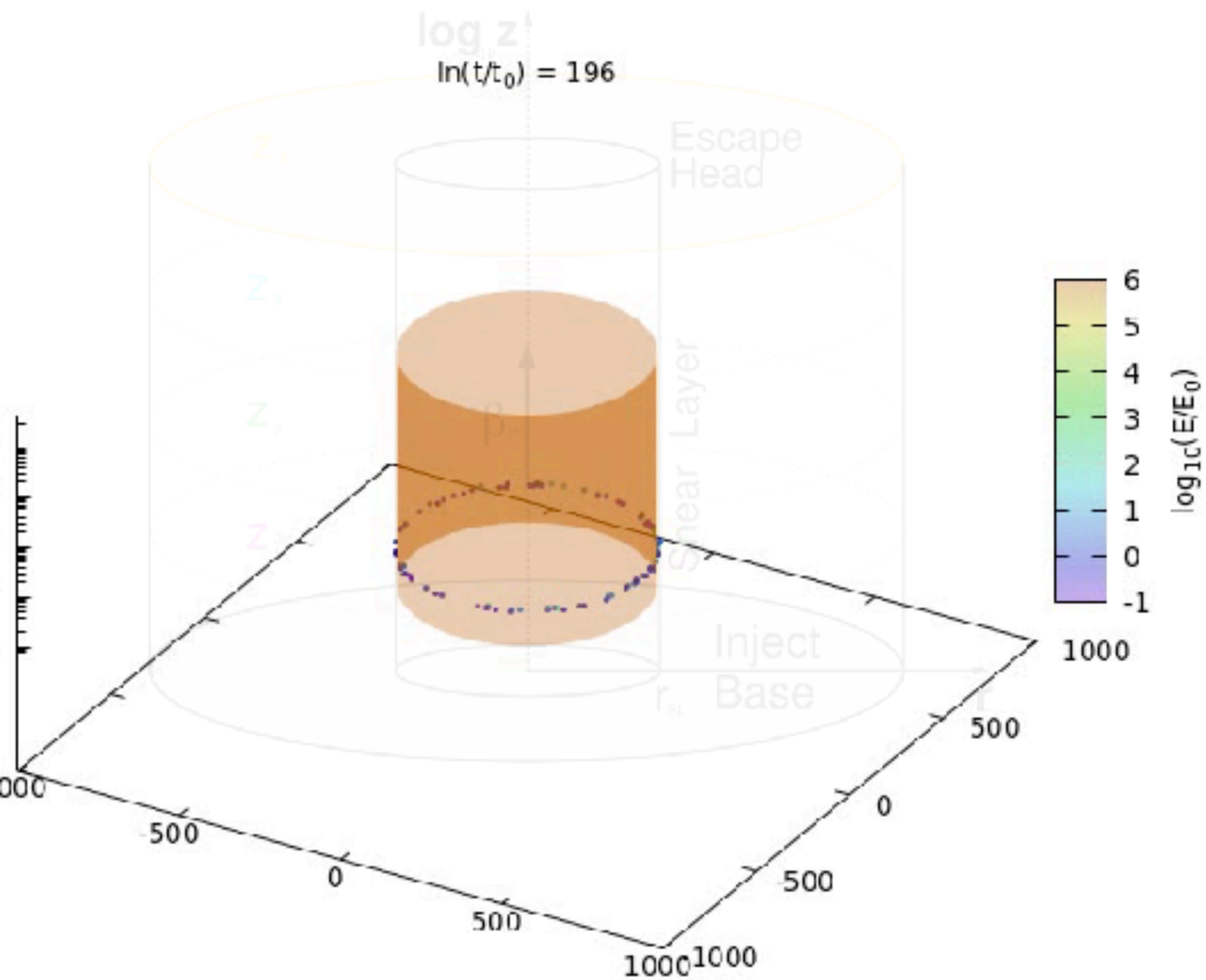

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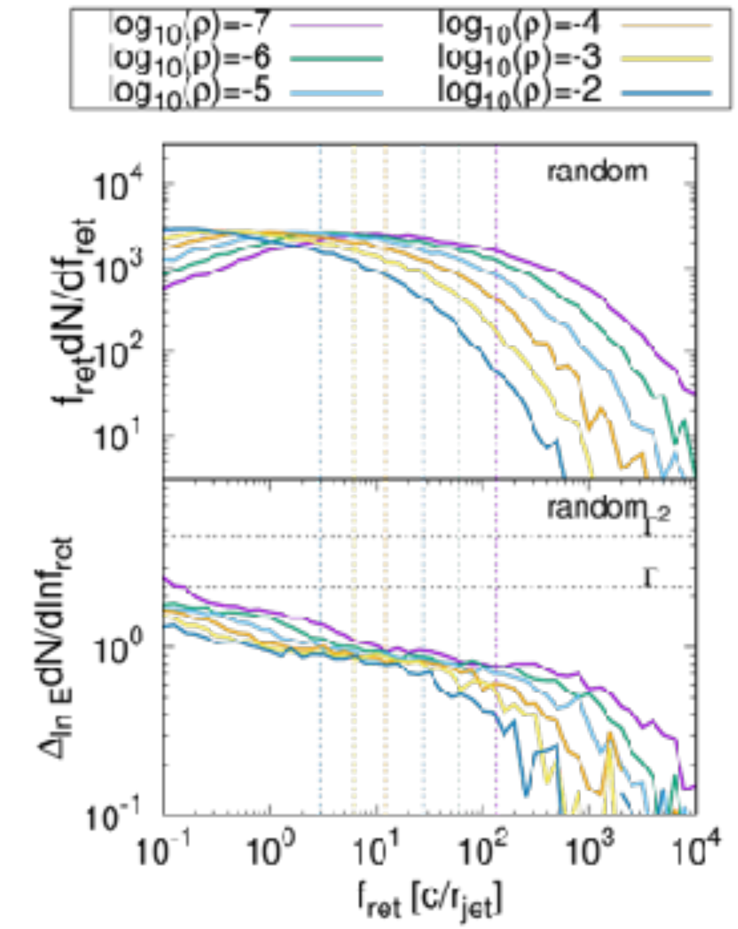
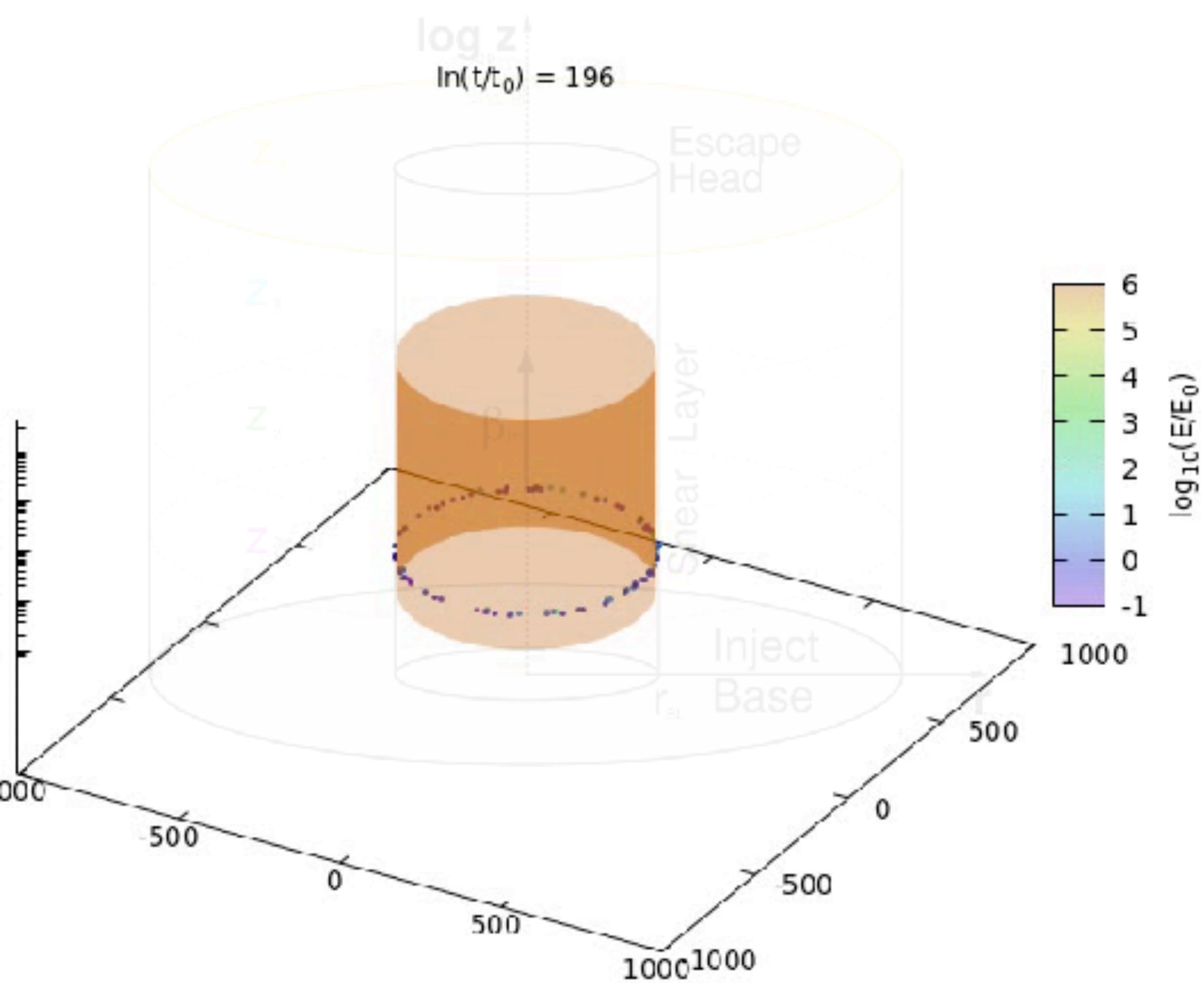
Return time distribution

Energy boost distribution





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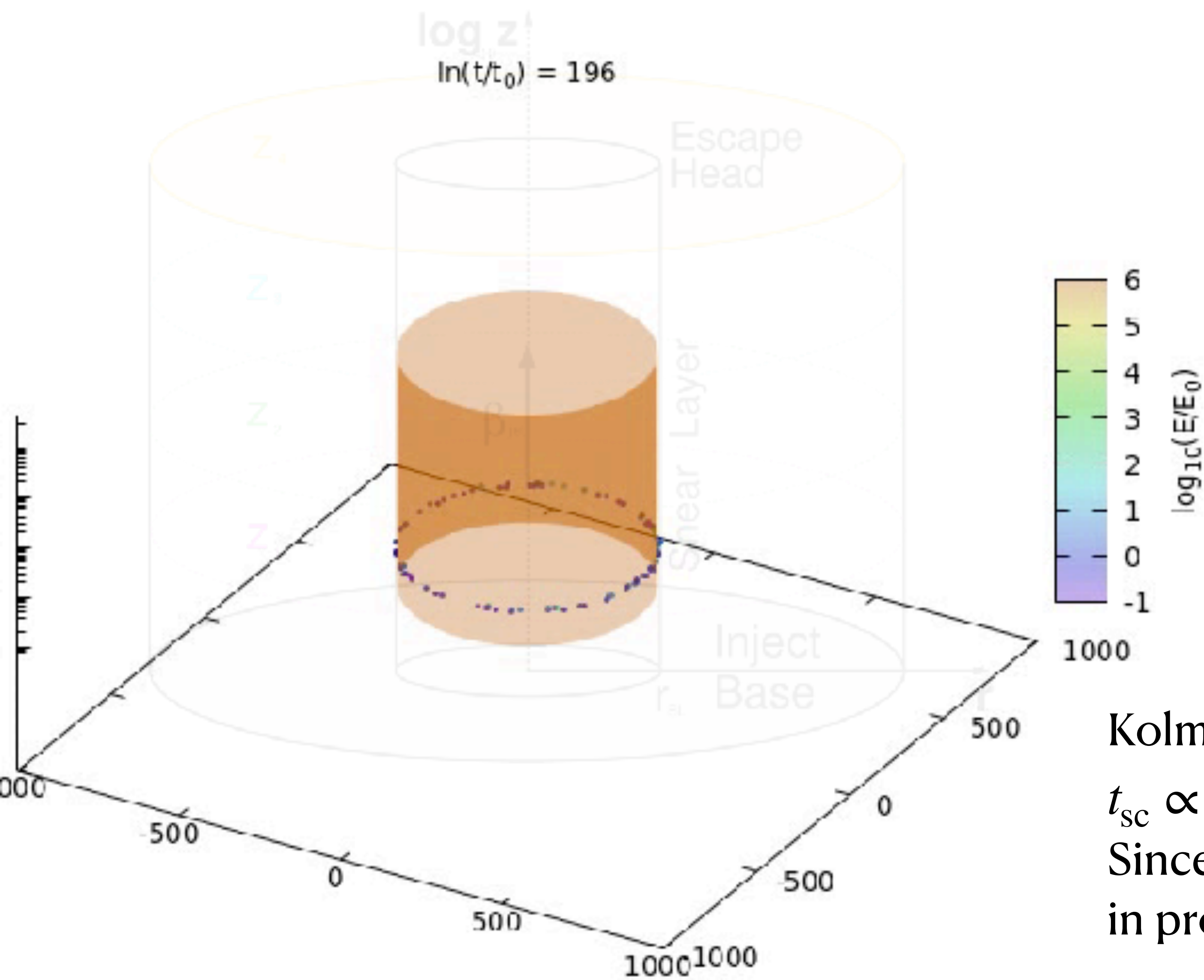
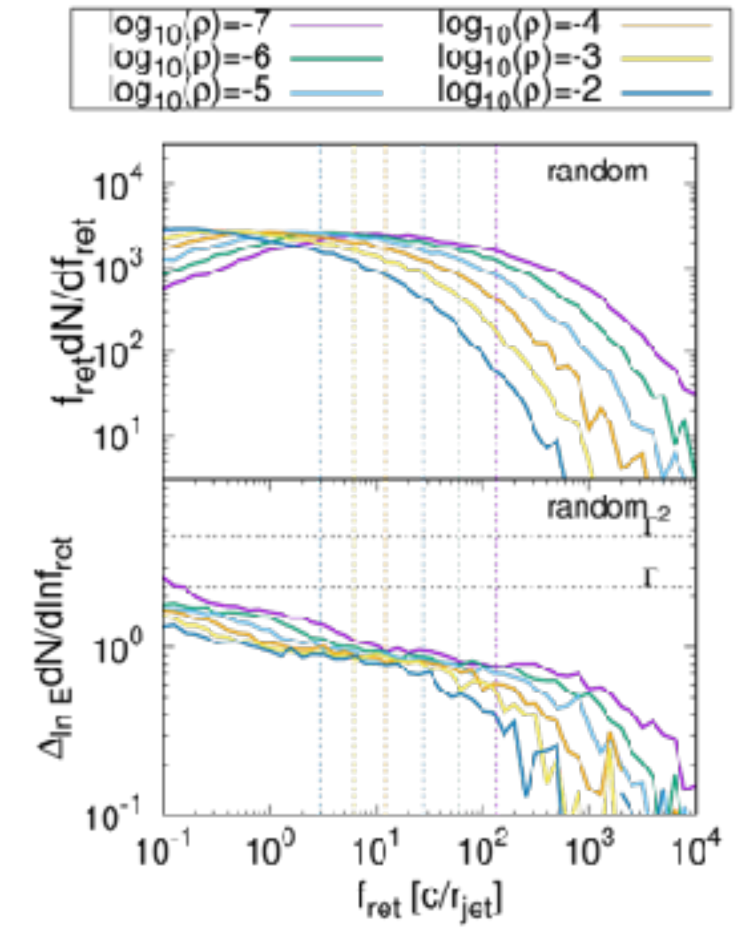


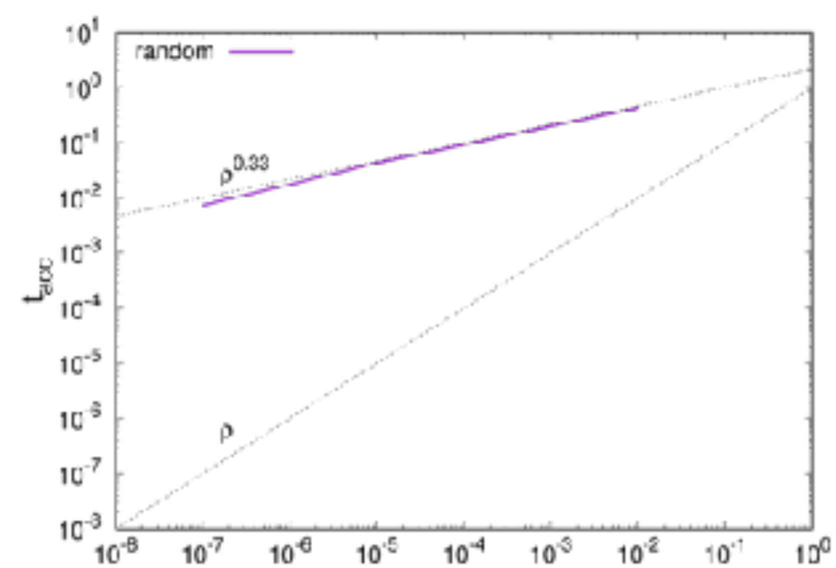


Kolmogorov scattering

$t_{sc} \propto E^{1/3}$

Since only one timescale in problem,

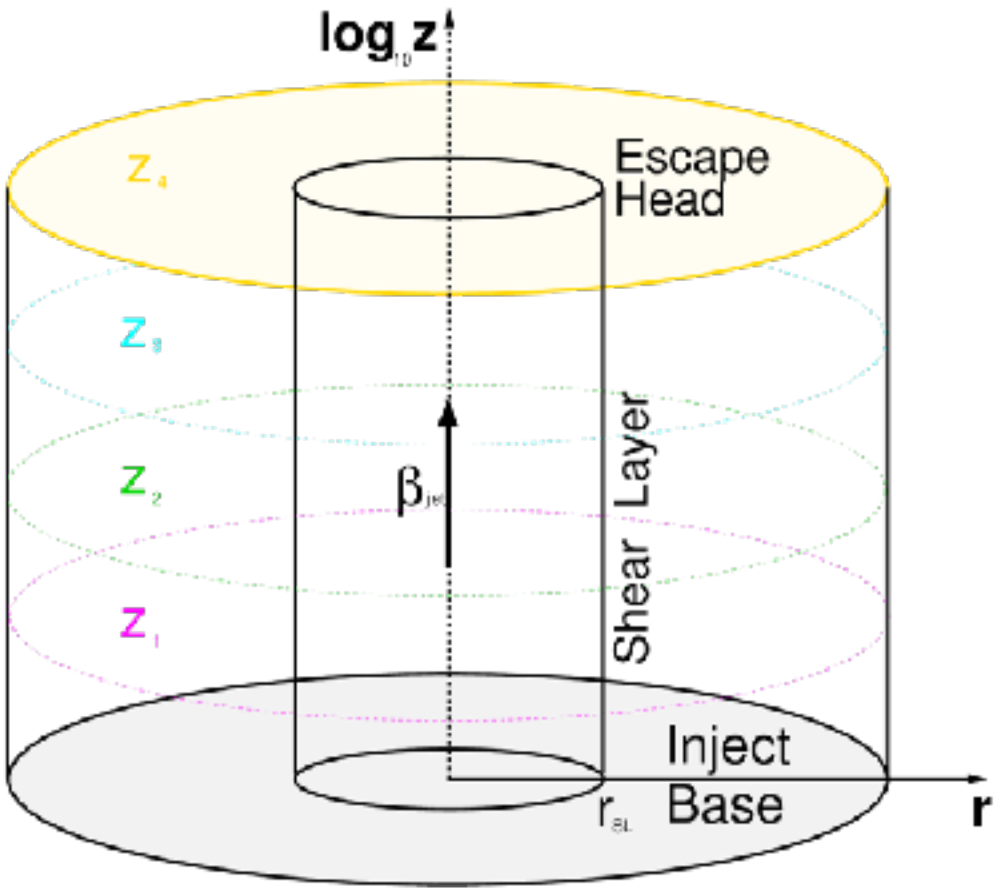
unsurprisingly $t_{acc} \propto E^{1/3}$



$\rho = r_g / r_{jet}$

O'Sullivan, Taylor, BR, ICRC '21

Beyond simple scattering



Trying to move beyond the simple toy model instantly reveals an issue

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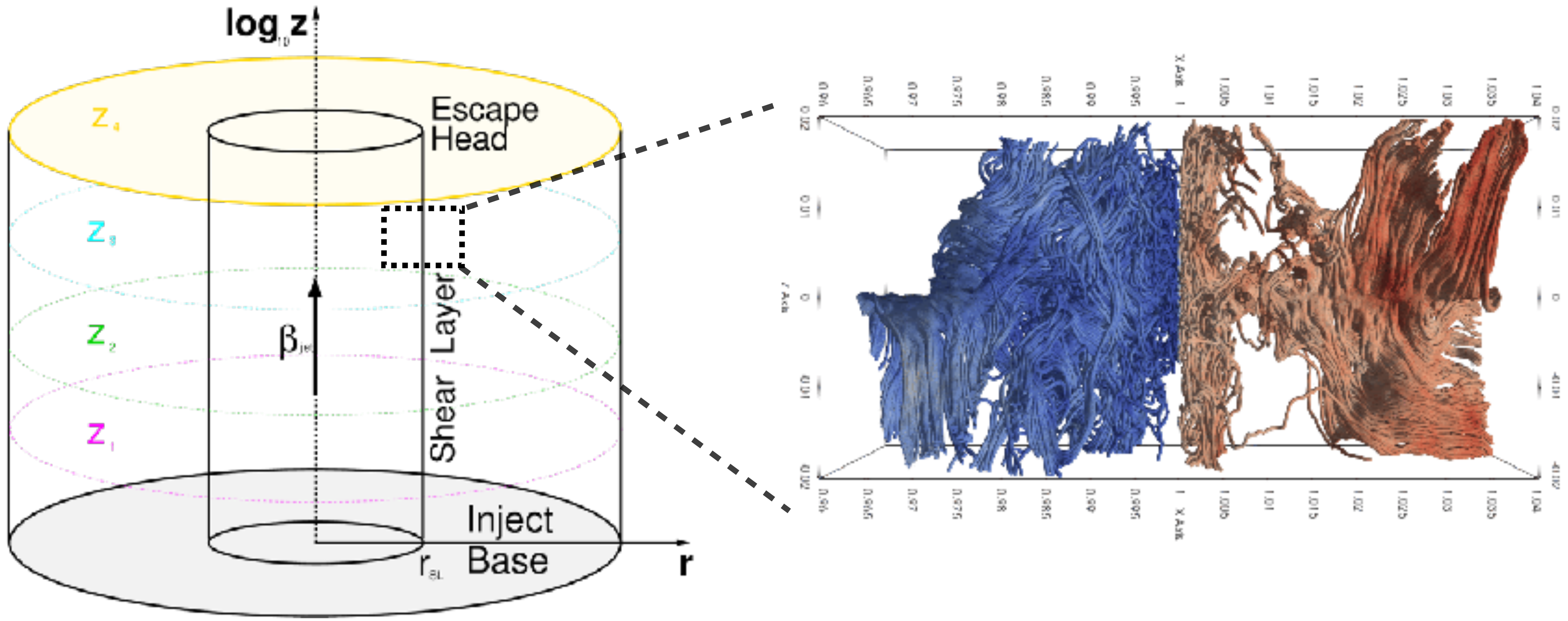

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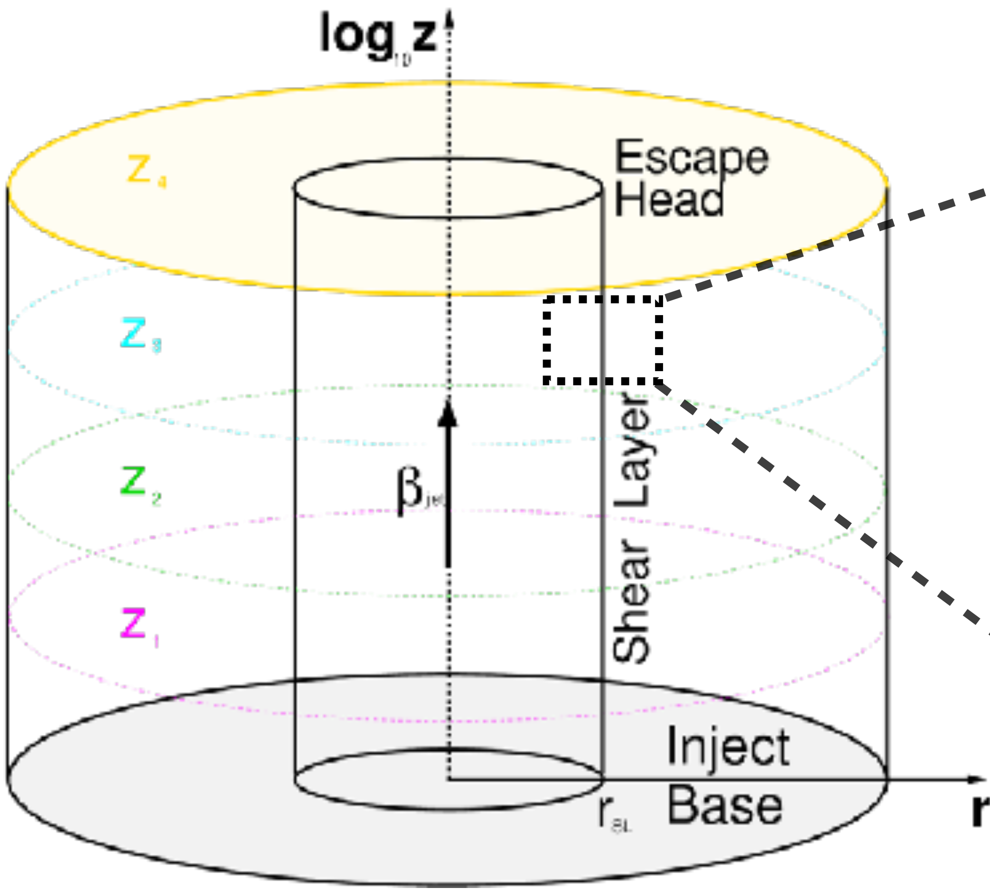

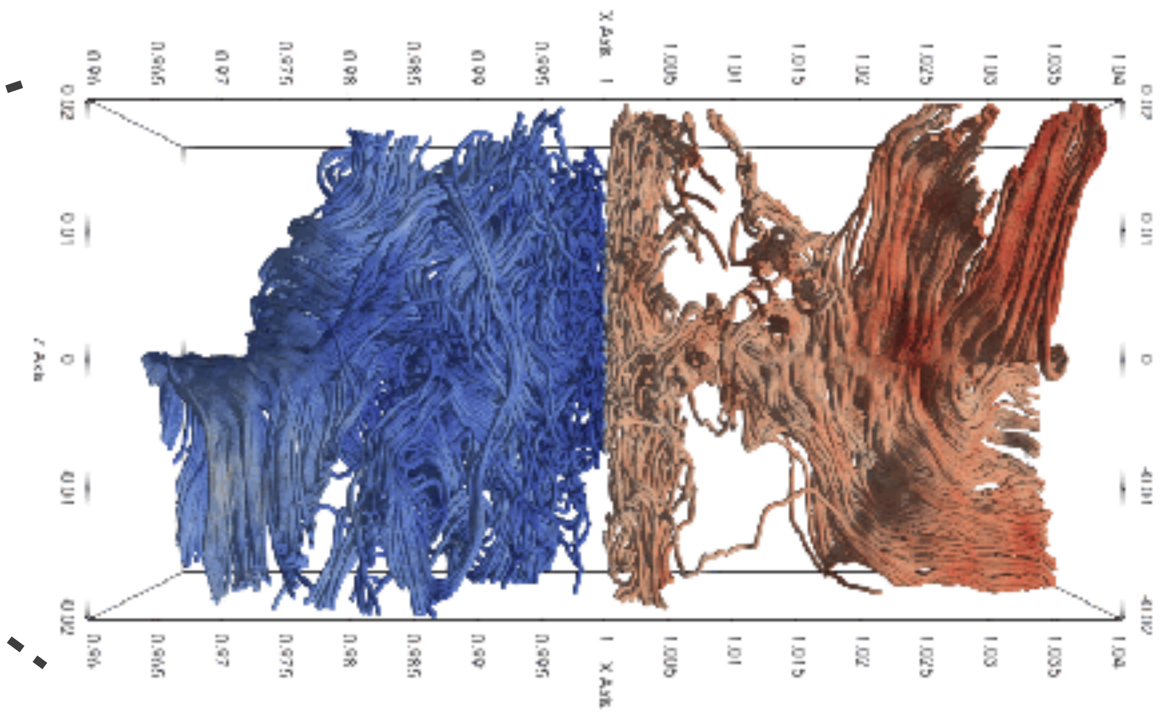

Field lines should **not** thread the boundary.
Numerically, fields are uncorrelated.

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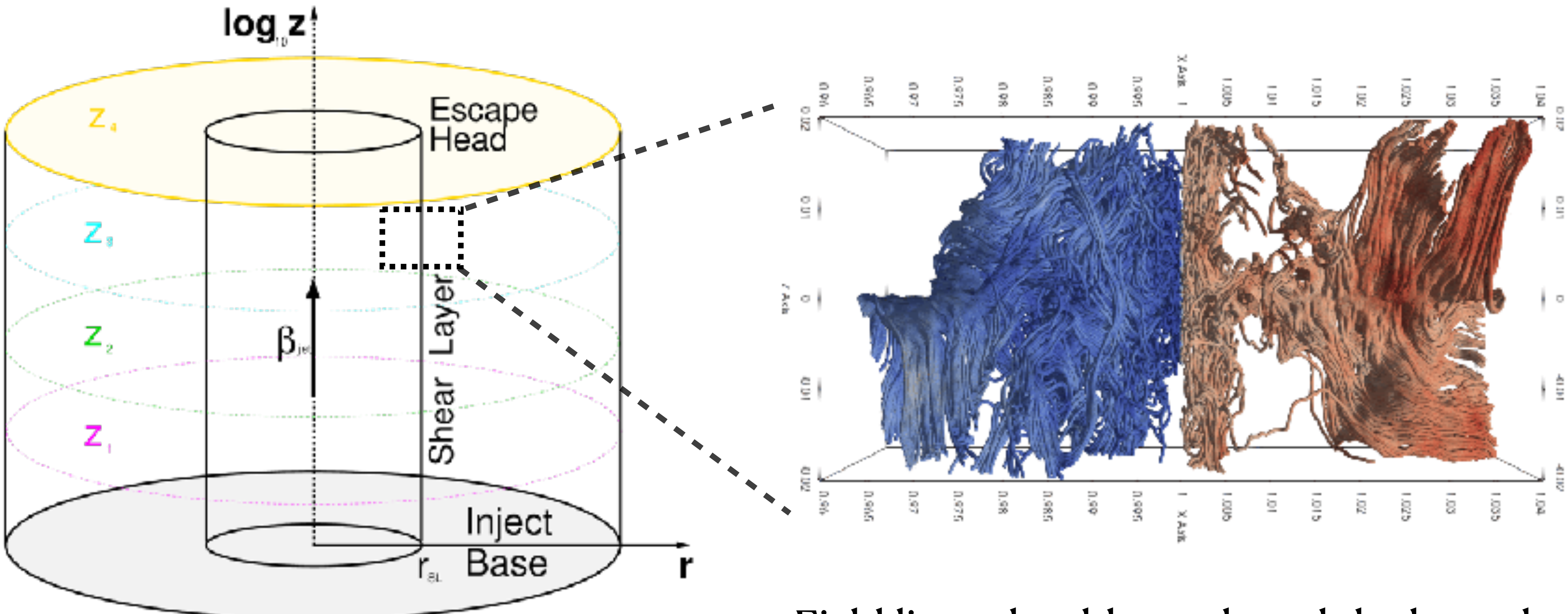

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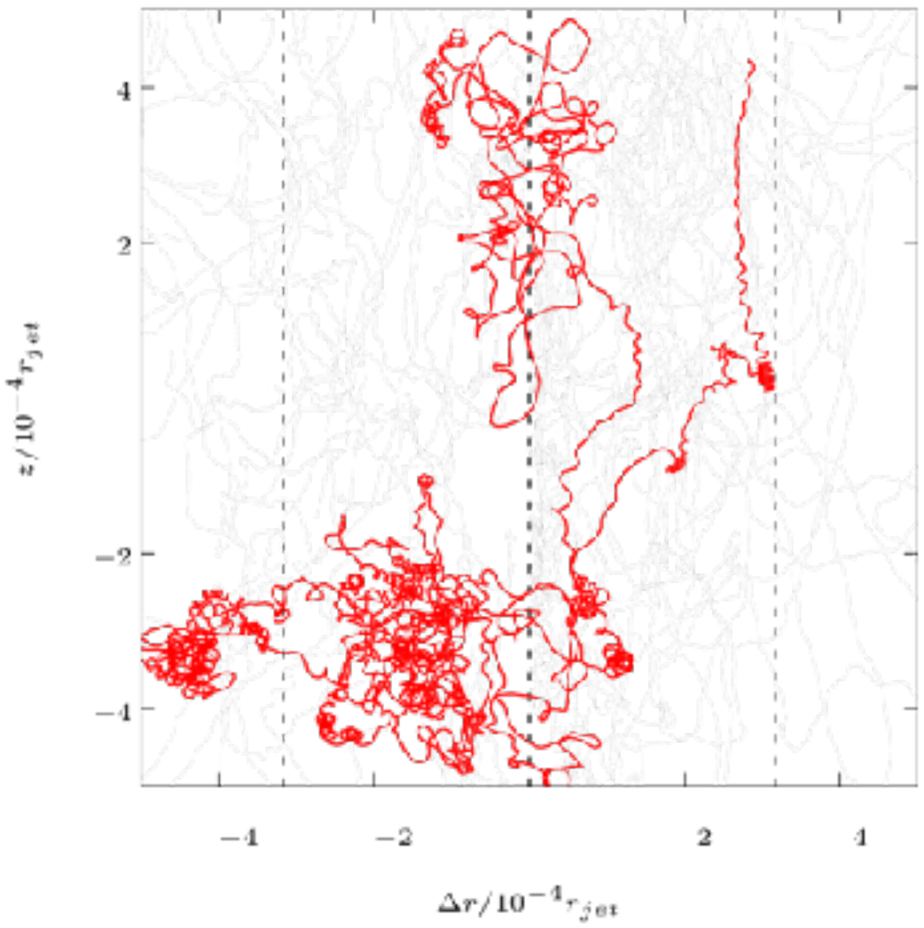
Numerically, fields are uncorrelated.

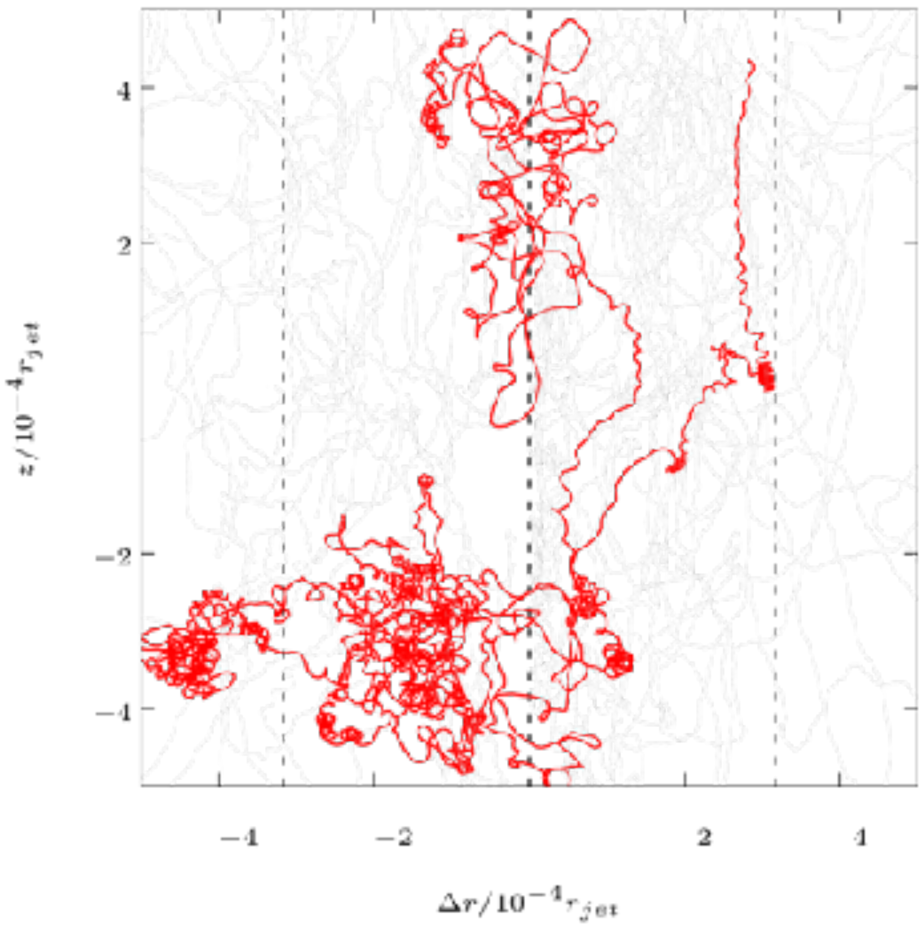
Constructing fields with this property is not easy, and might overlook important physics!!

Non-diffusive behaviour I



Non-diffusive behaviour I

Swarm Plots 1 - sample trajectories in reduced field model - region with **larger** field patches



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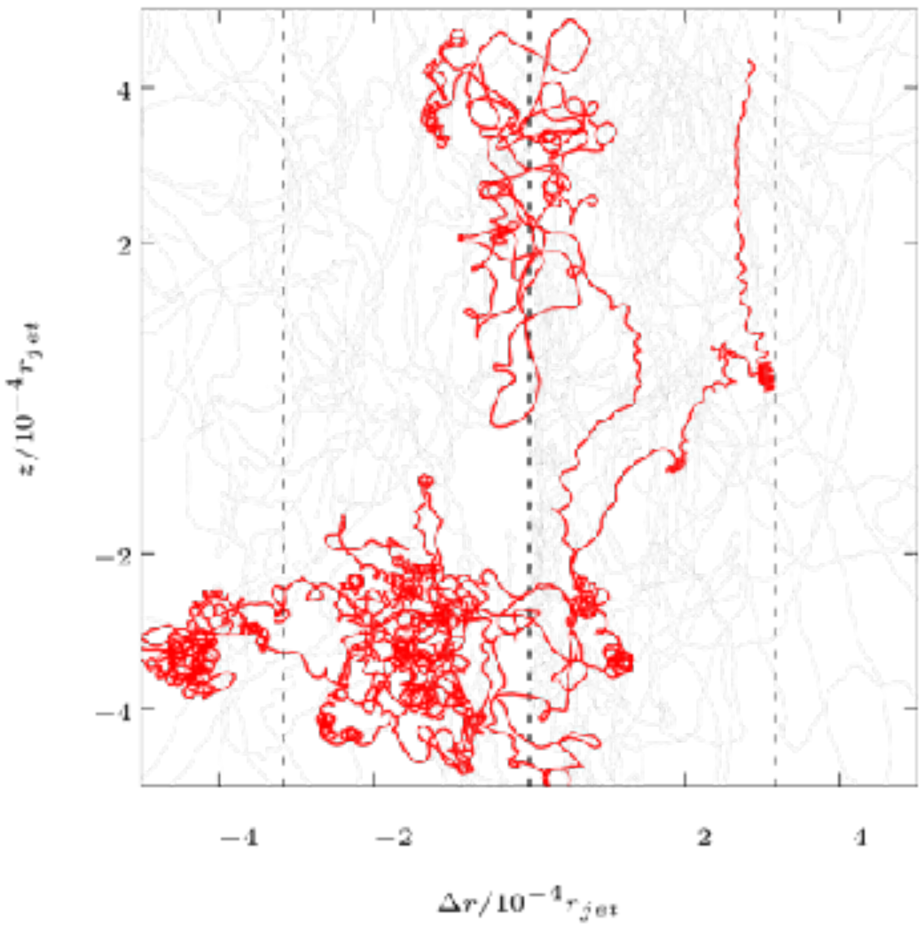
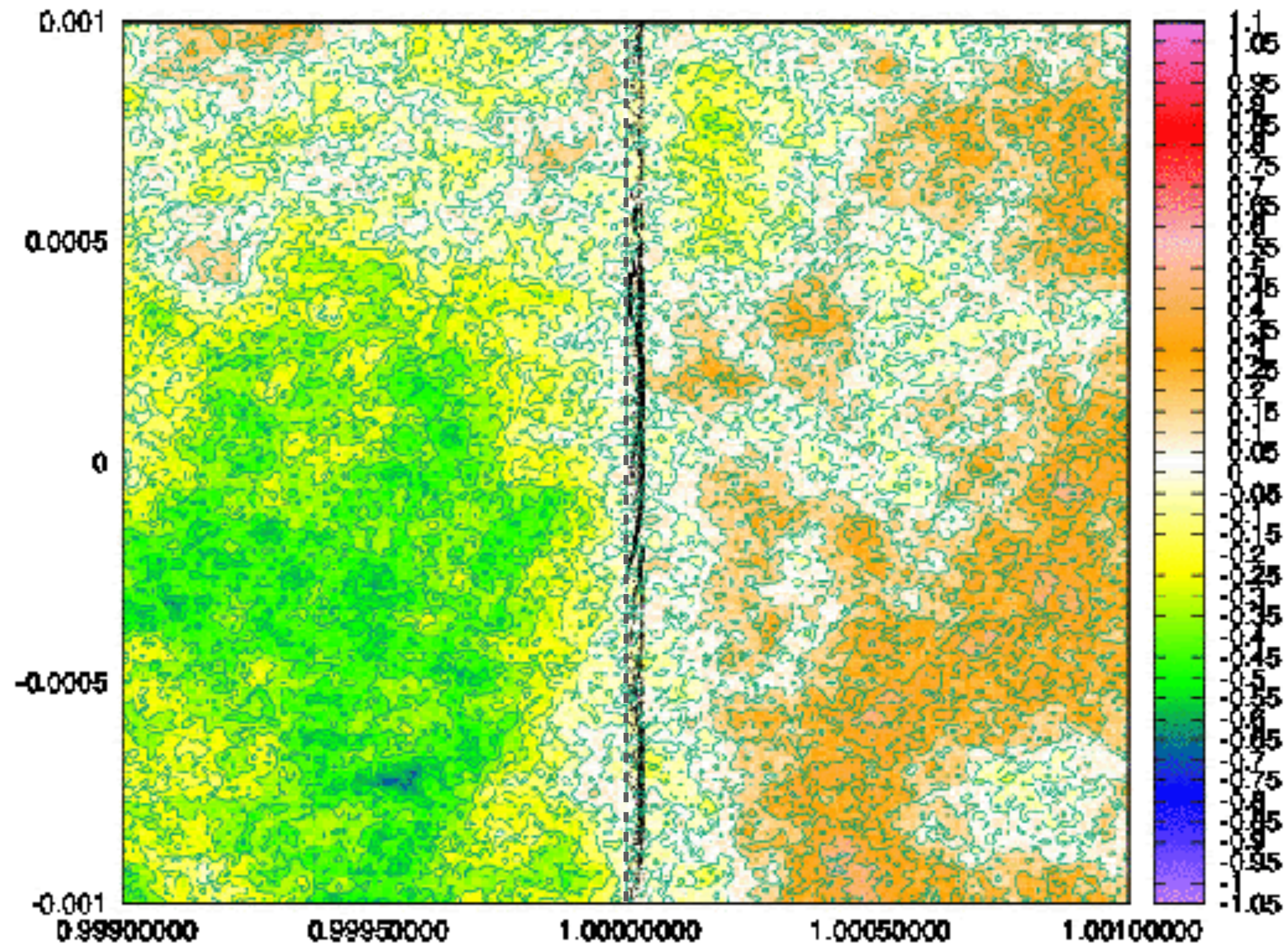
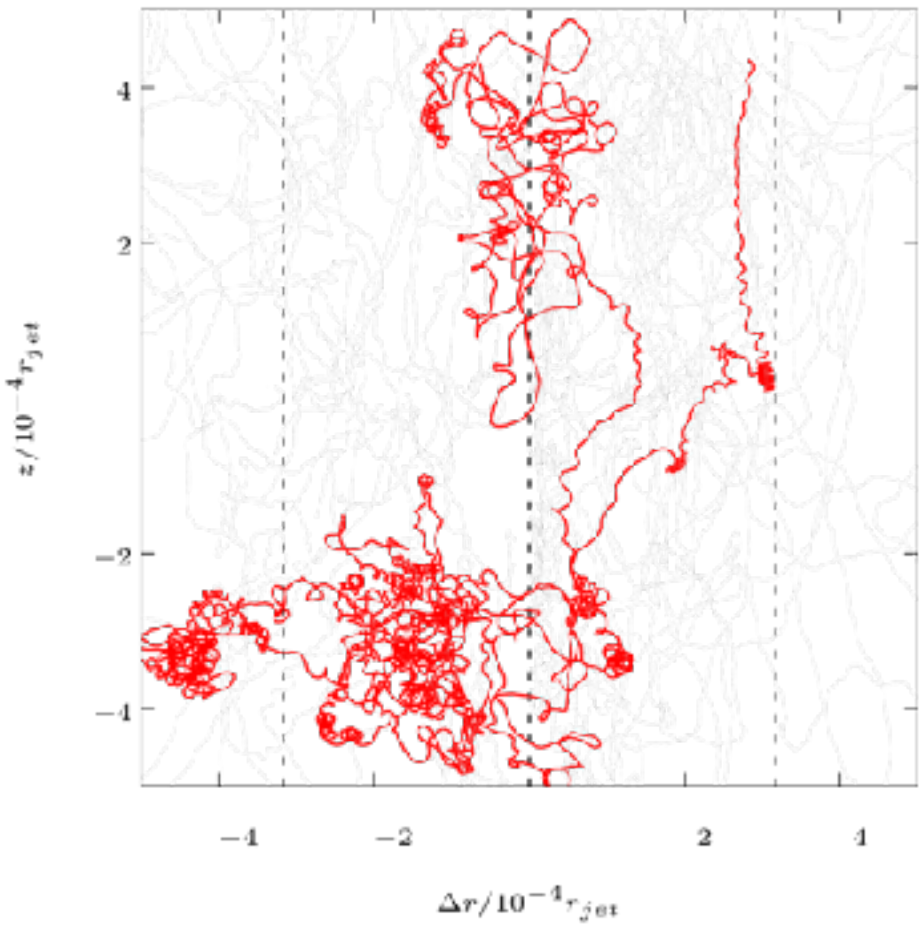
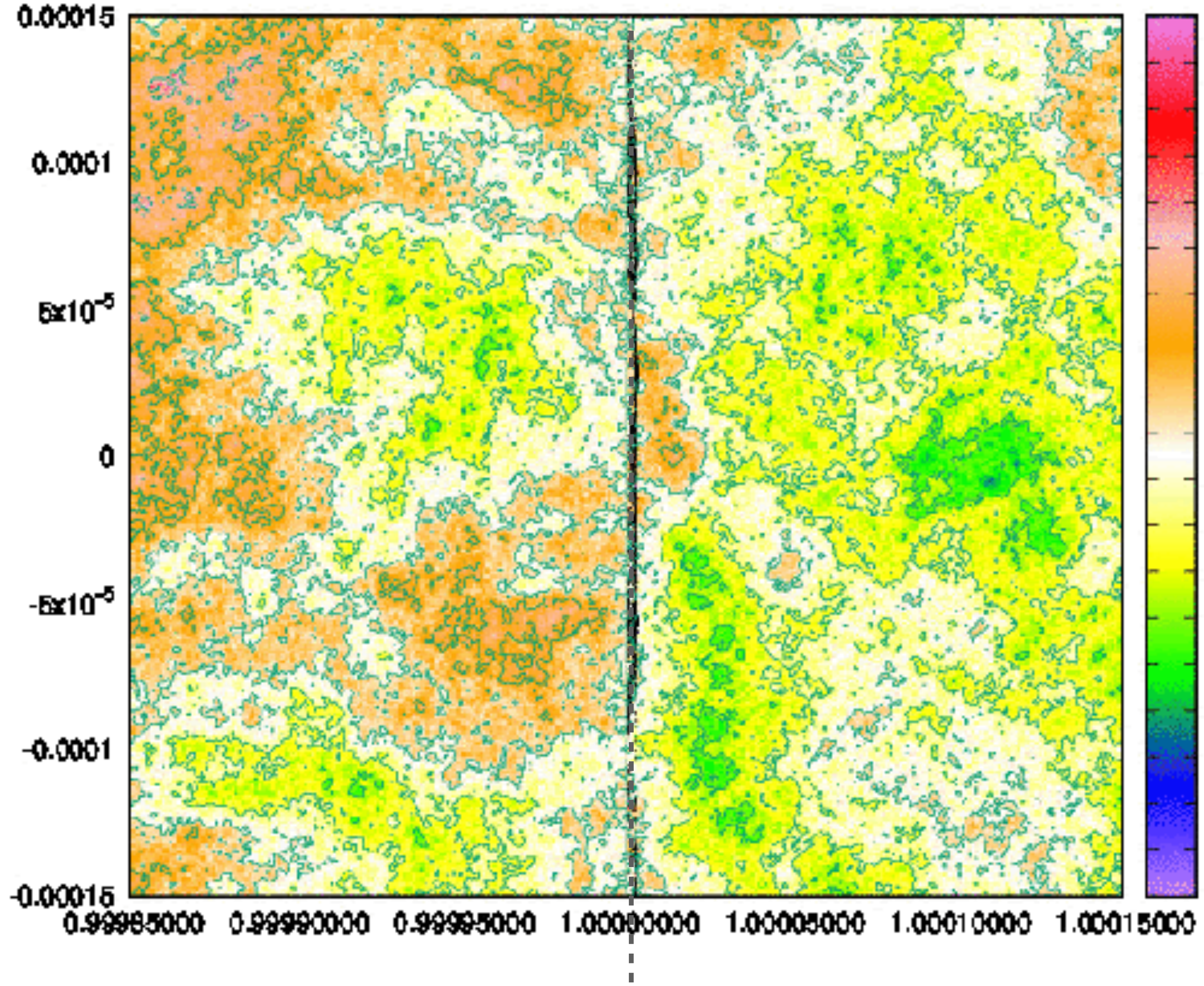




Non-diffusive behaviour II

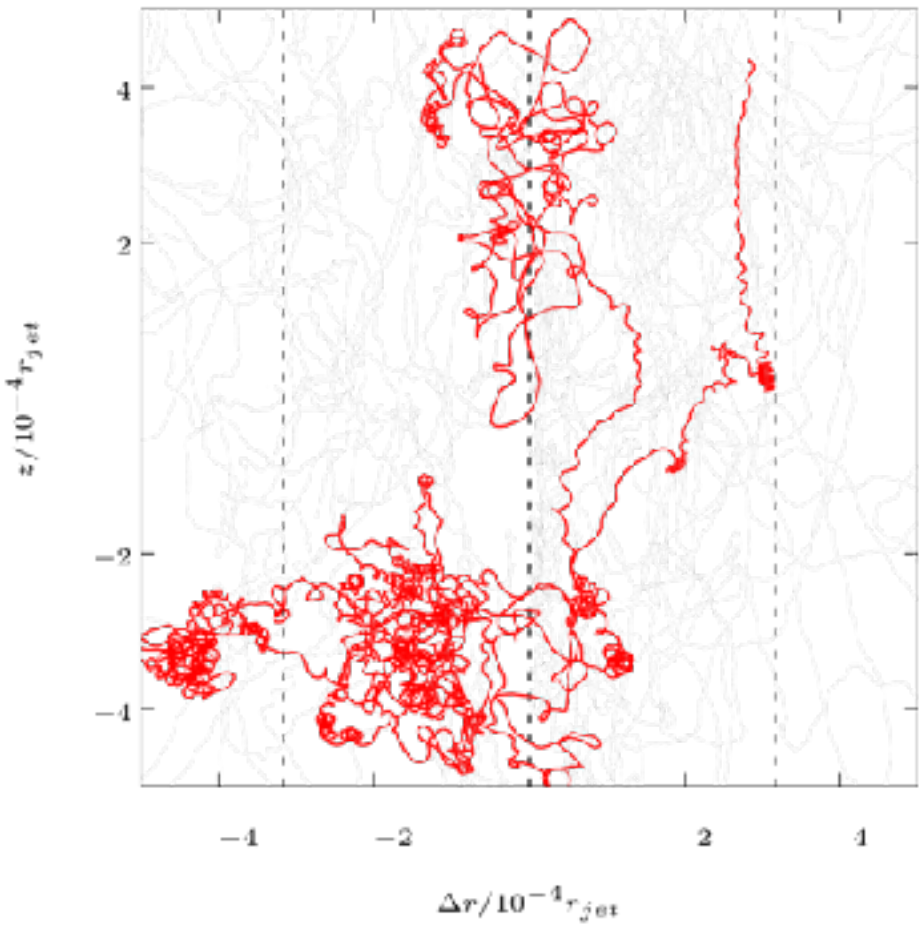
Swarm Plots 2 - sample trajectories in reduced field model - region with **smaller** field patches

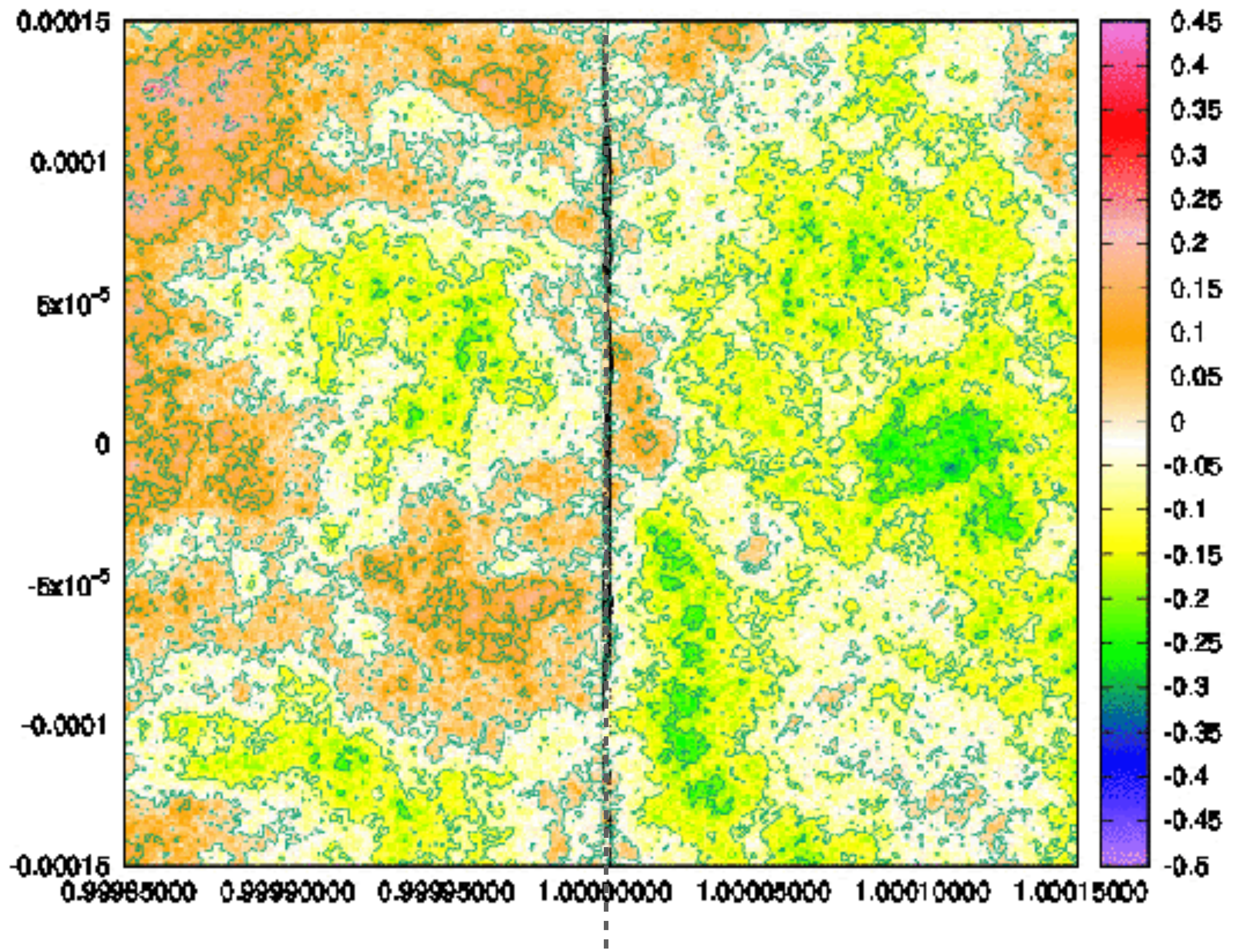




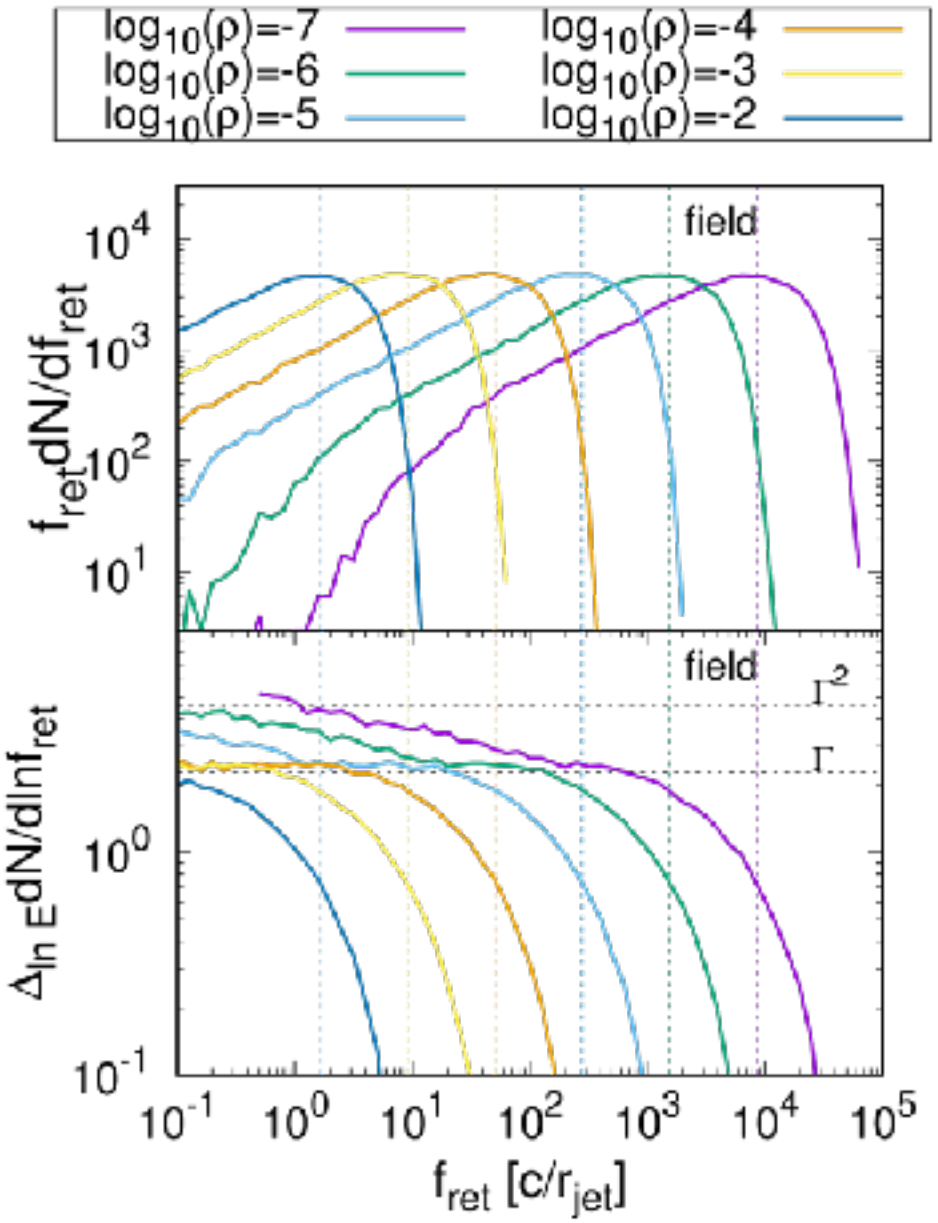
Non-diffusive behaviour II

Swarm Plots 2 - sample trajectories in reduced field model - region with **smaller** field patches





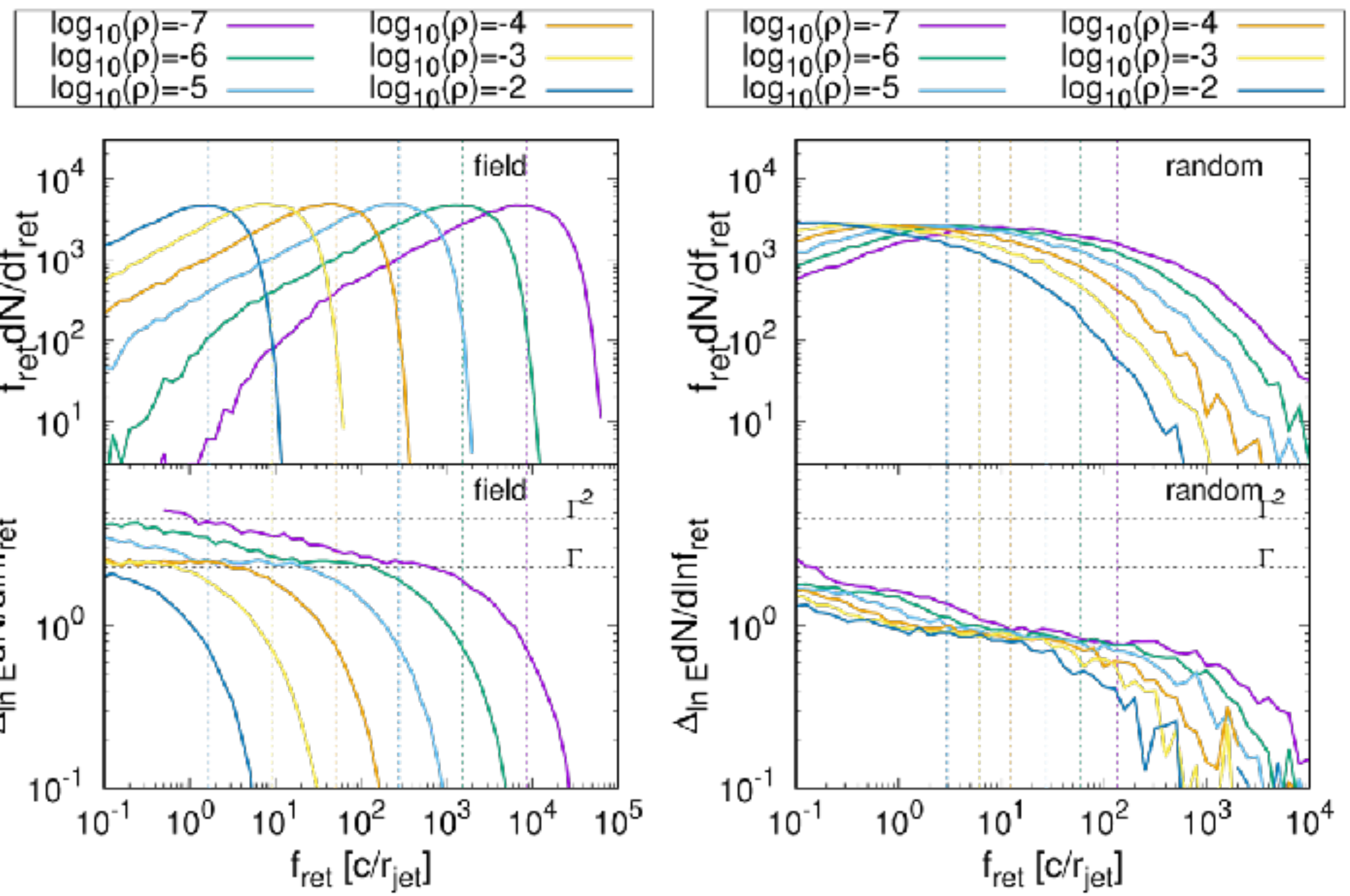
Does it matter?



Return time distribution

Energy boost distribution

Does it matter?



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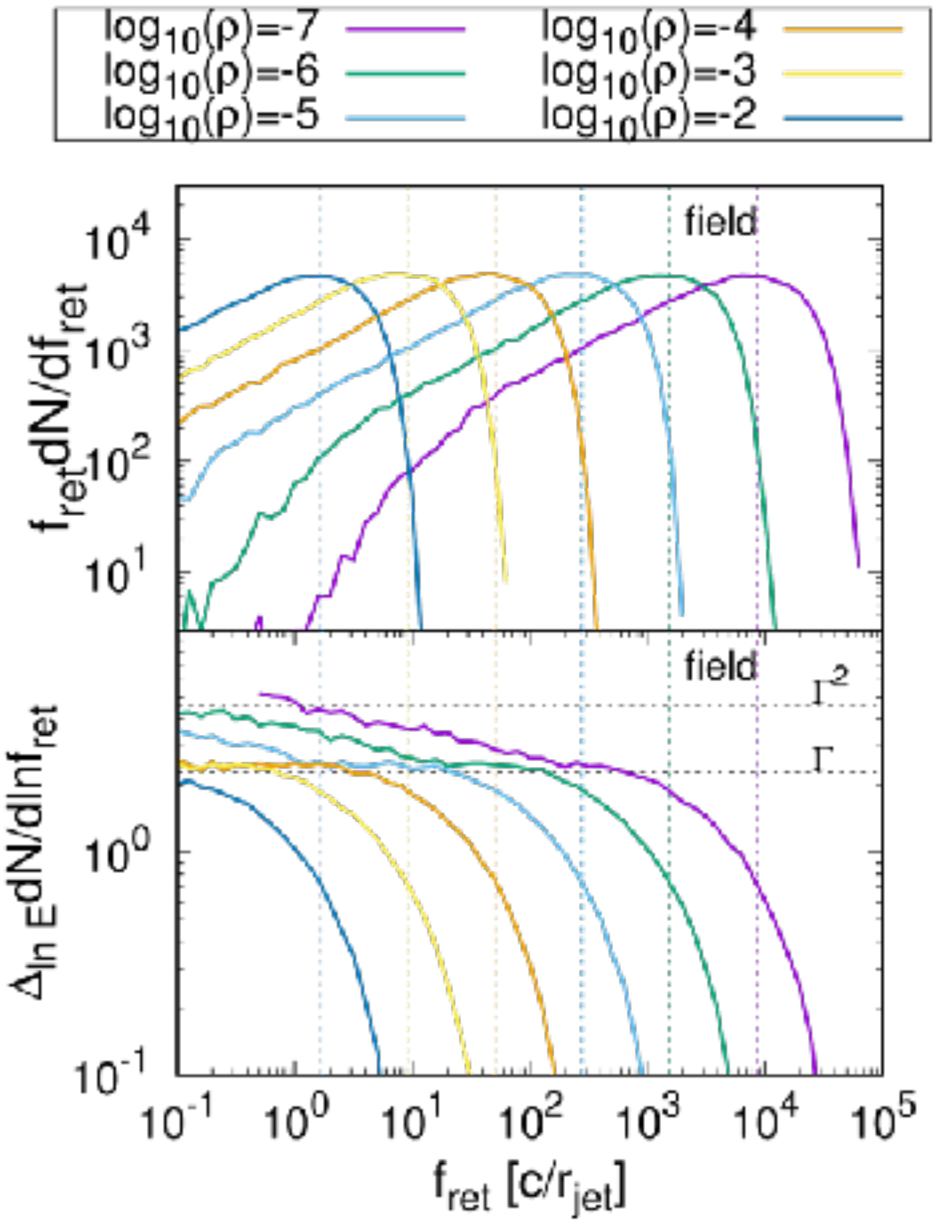
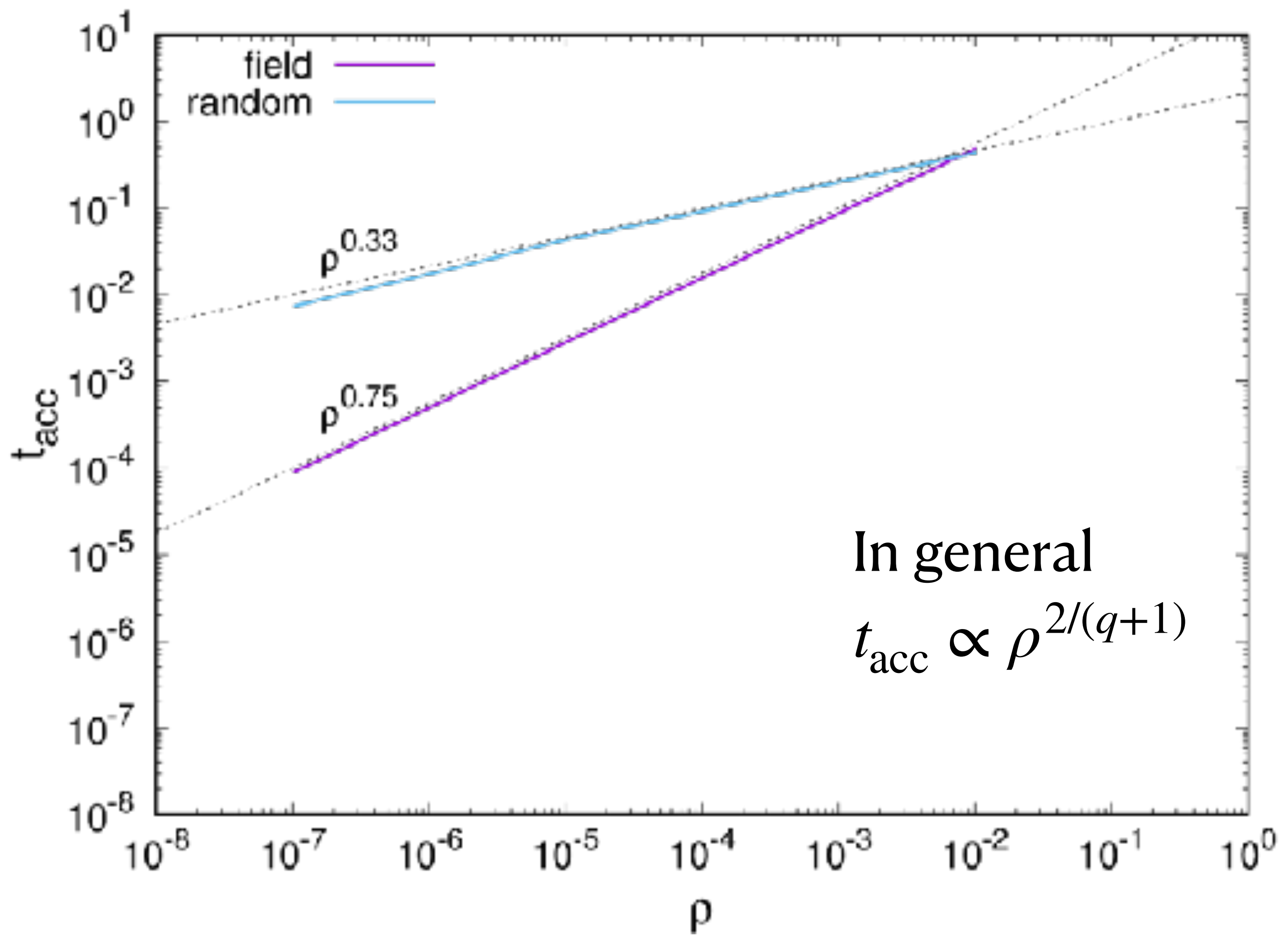
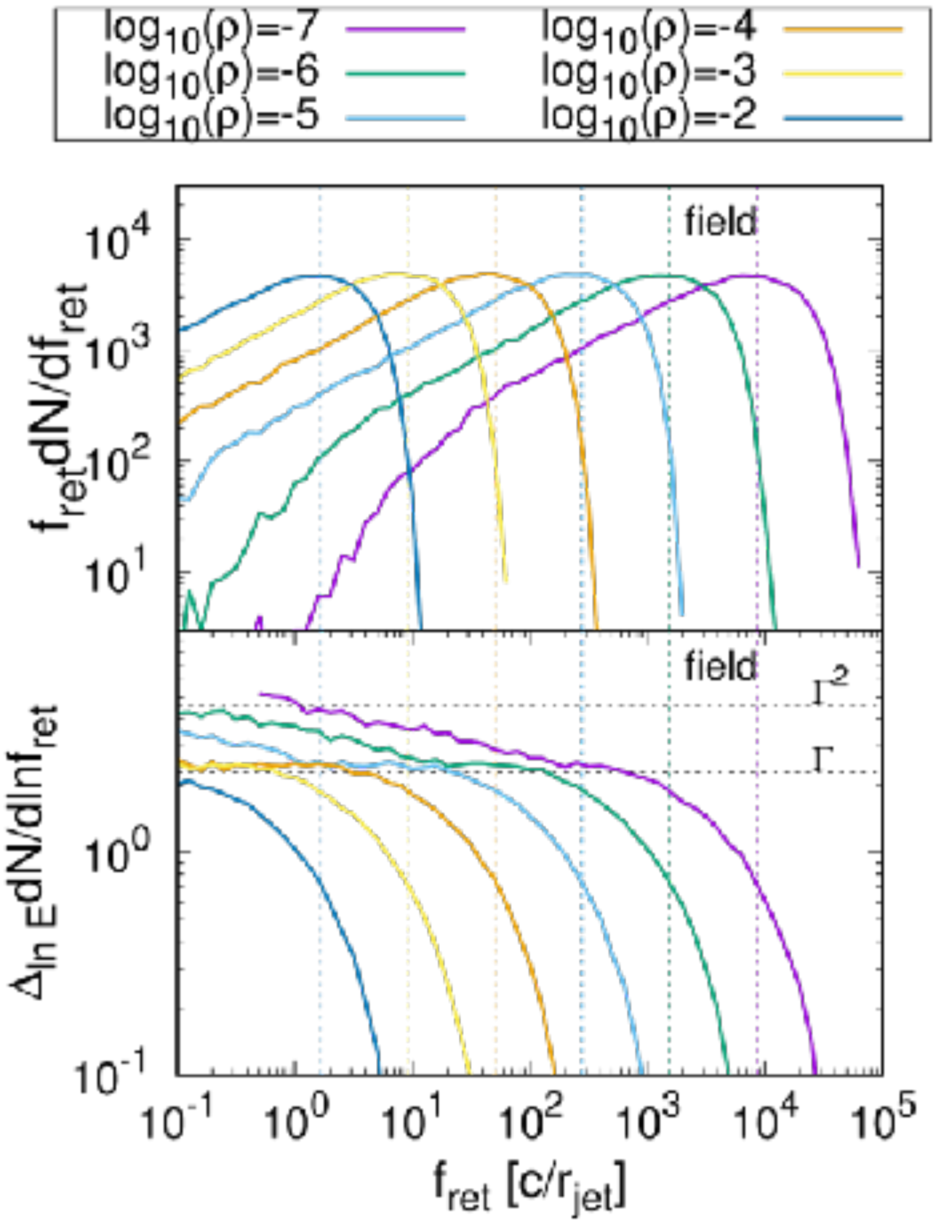


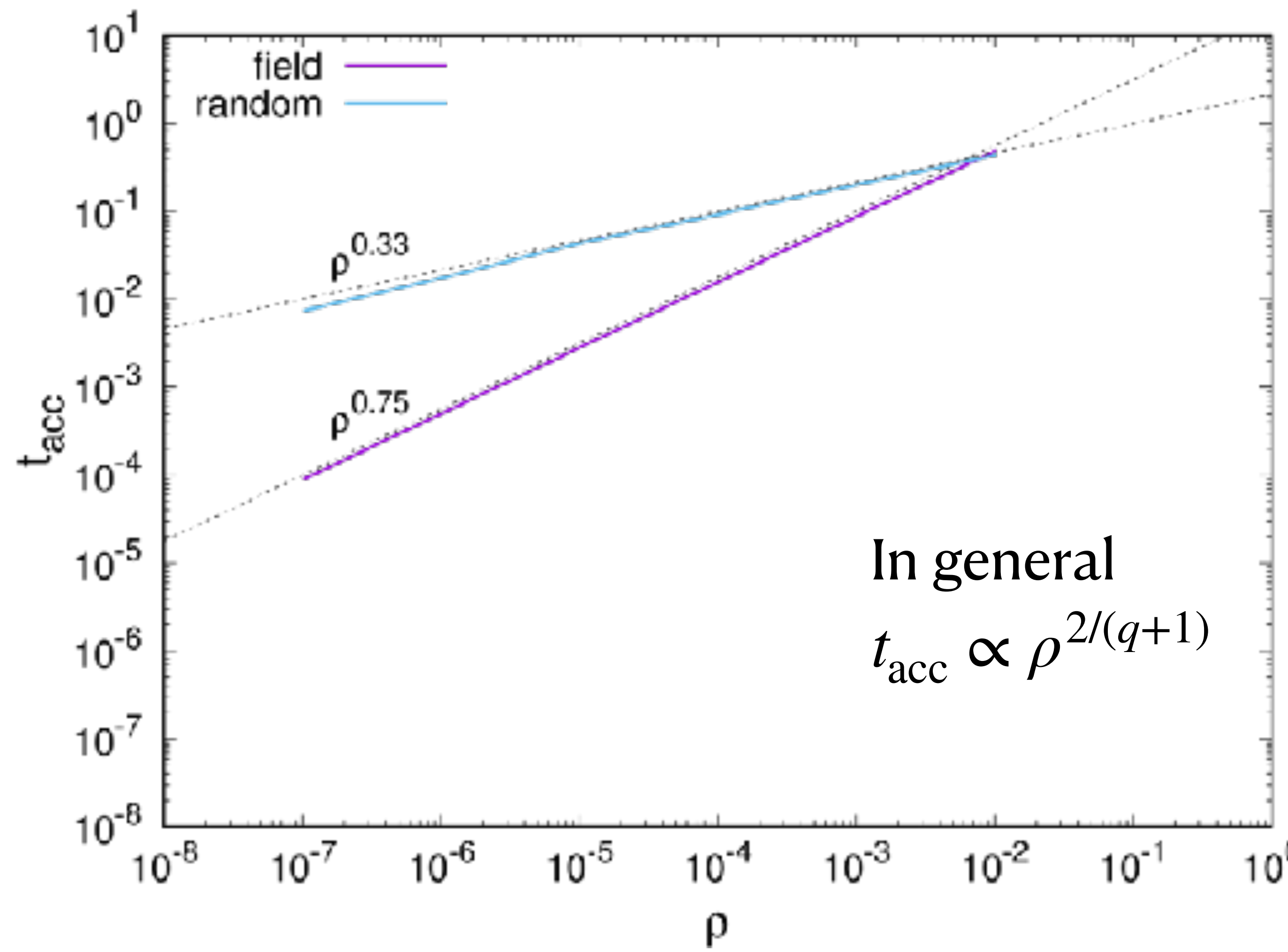


In general

$t_{\rm acc} \propto \rho^{2/(q+1)}$

Does it matter?

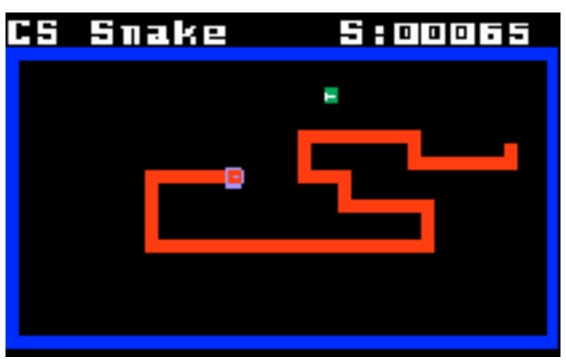




Acceleration rate enhanced relative to simple random scattering model

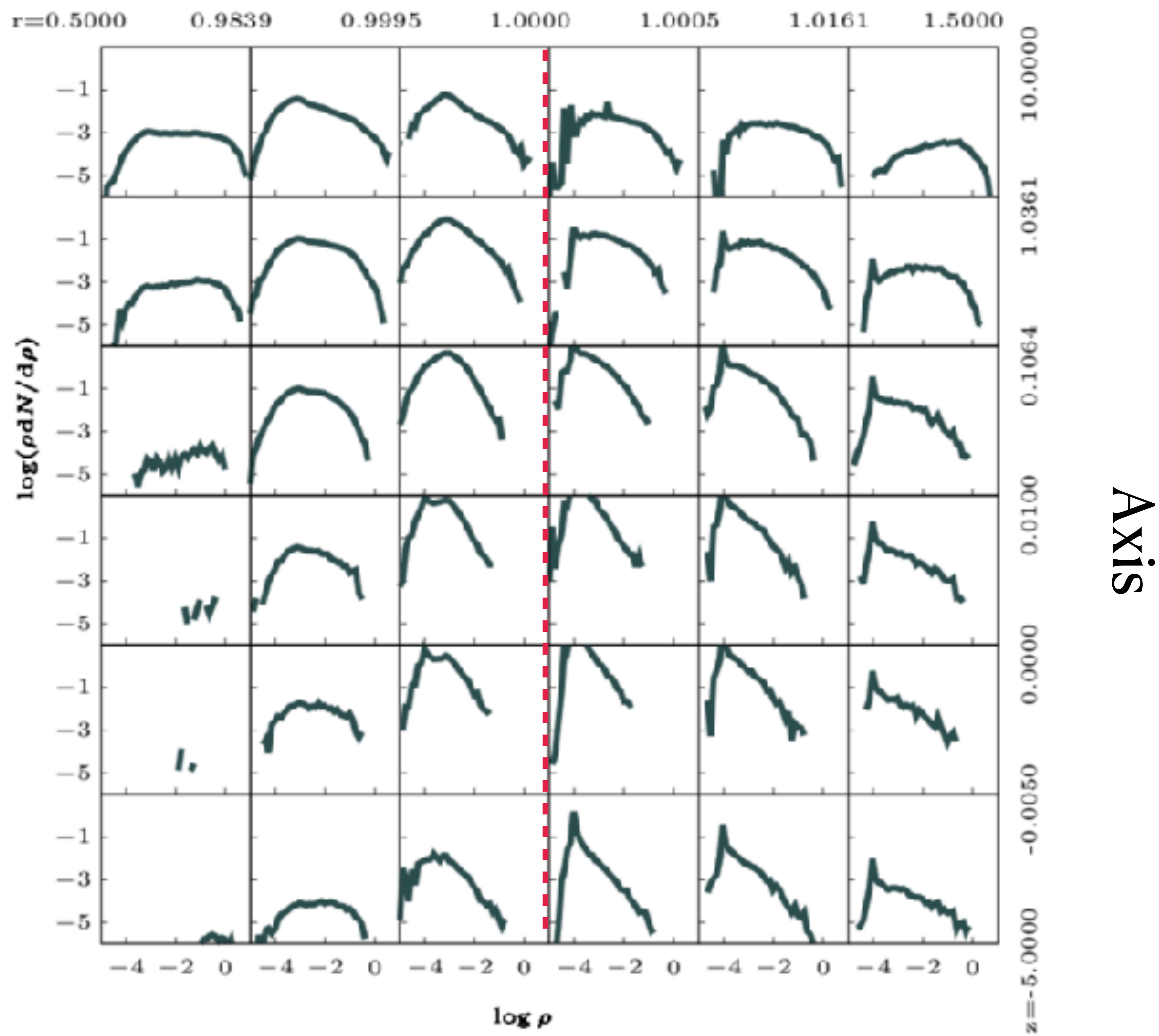
Spectrum and Maximum Energy

Steady-state spectrum for continuous injection at base of jet



Spectrum is **hard.** Highest energy particles accumulate at head of jet

Radius



Spectrum and Maximum Energy

Steady-state spectrum
for continuous injection
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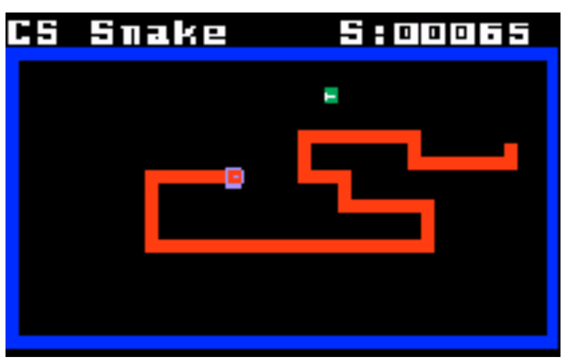

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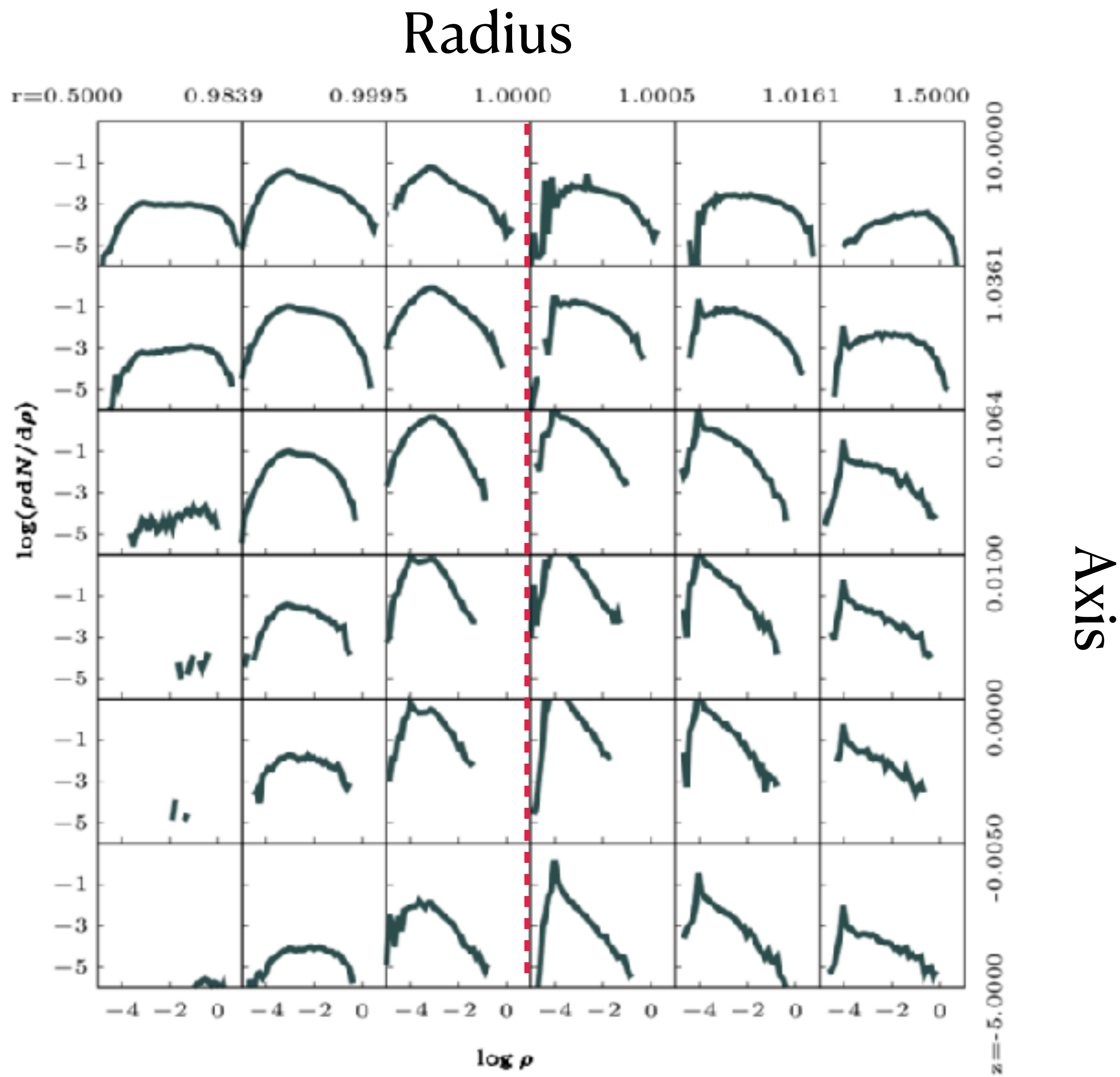

Spectrum and Maximum Energy

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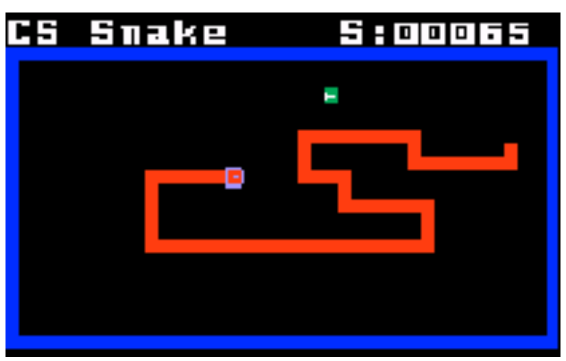

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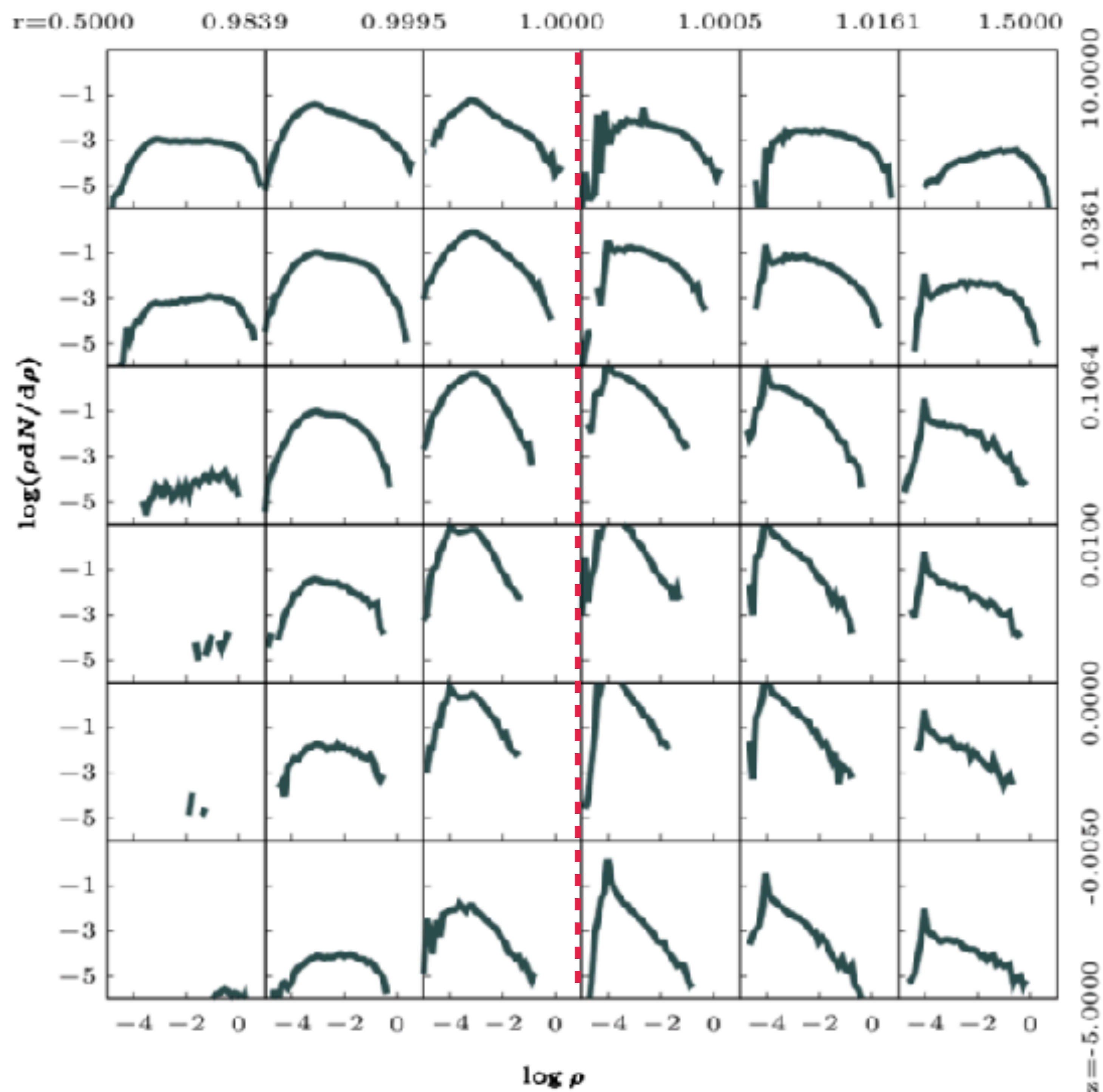
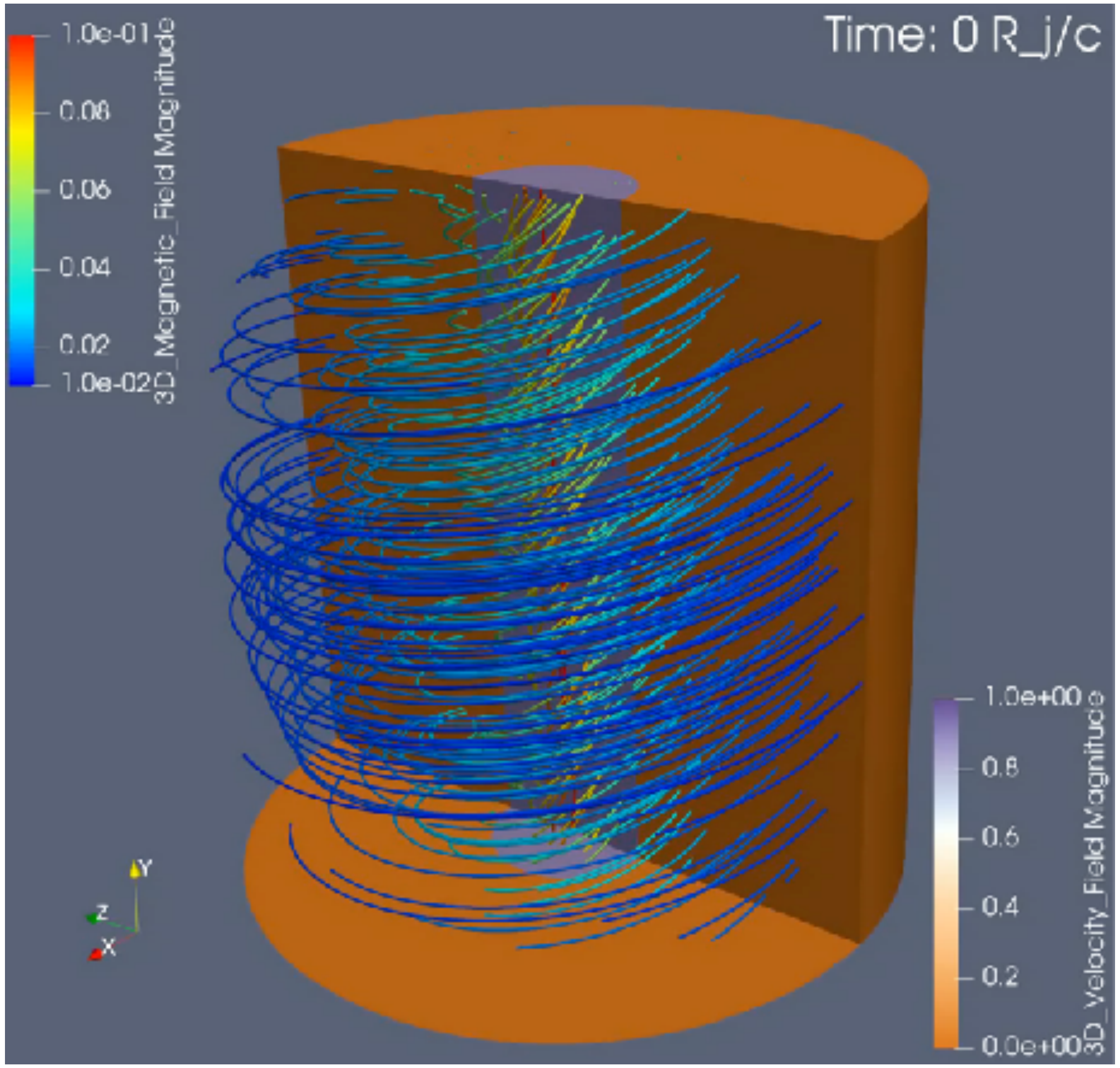


Axis

Can we go beyond simple toy models with synthetic fields?

Relativistic MHD simulations

- Evolve turbulent sheath structure on jet edge via KHI



From Wang et al '23

Relativistic MHD simulations

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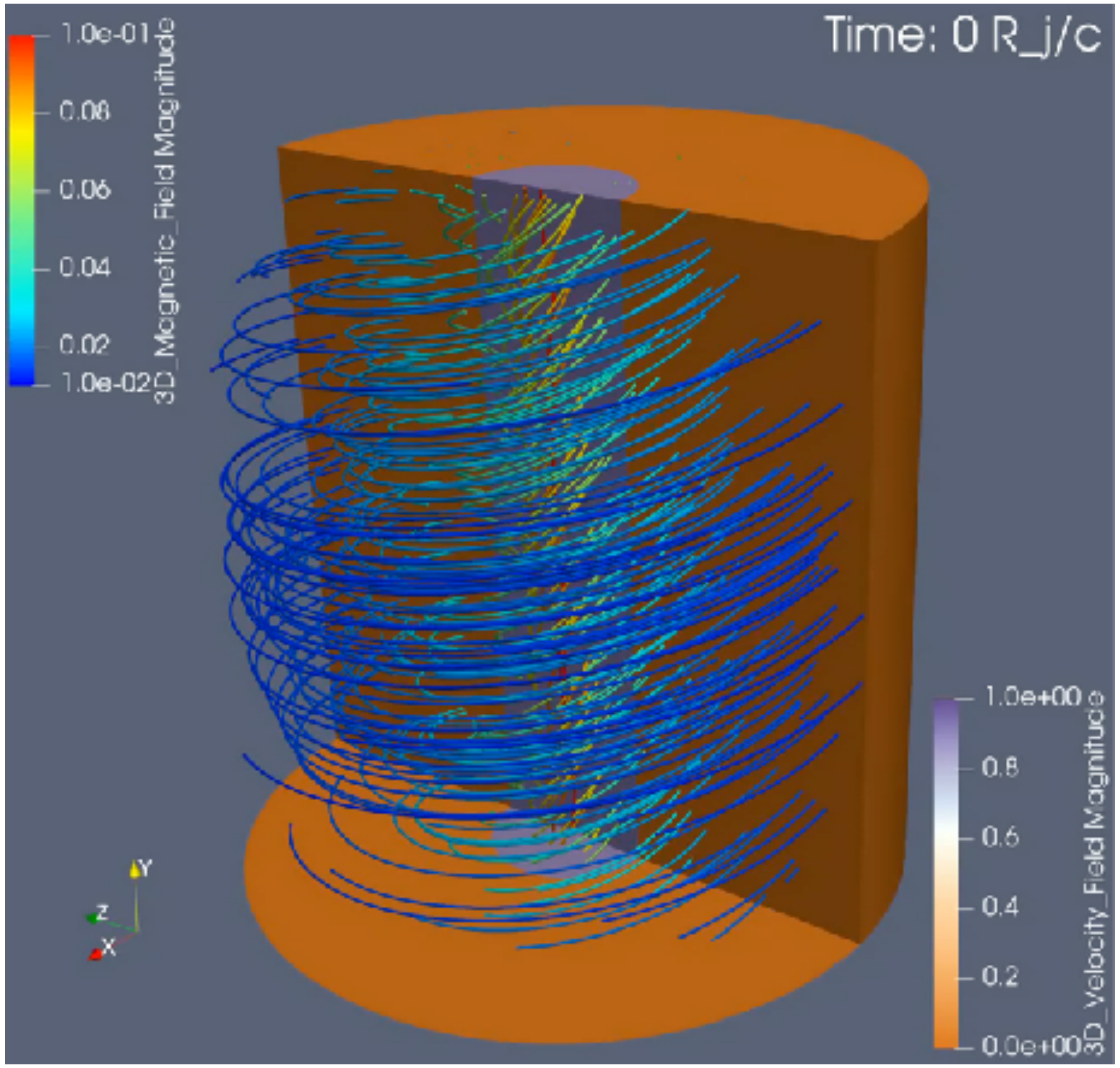

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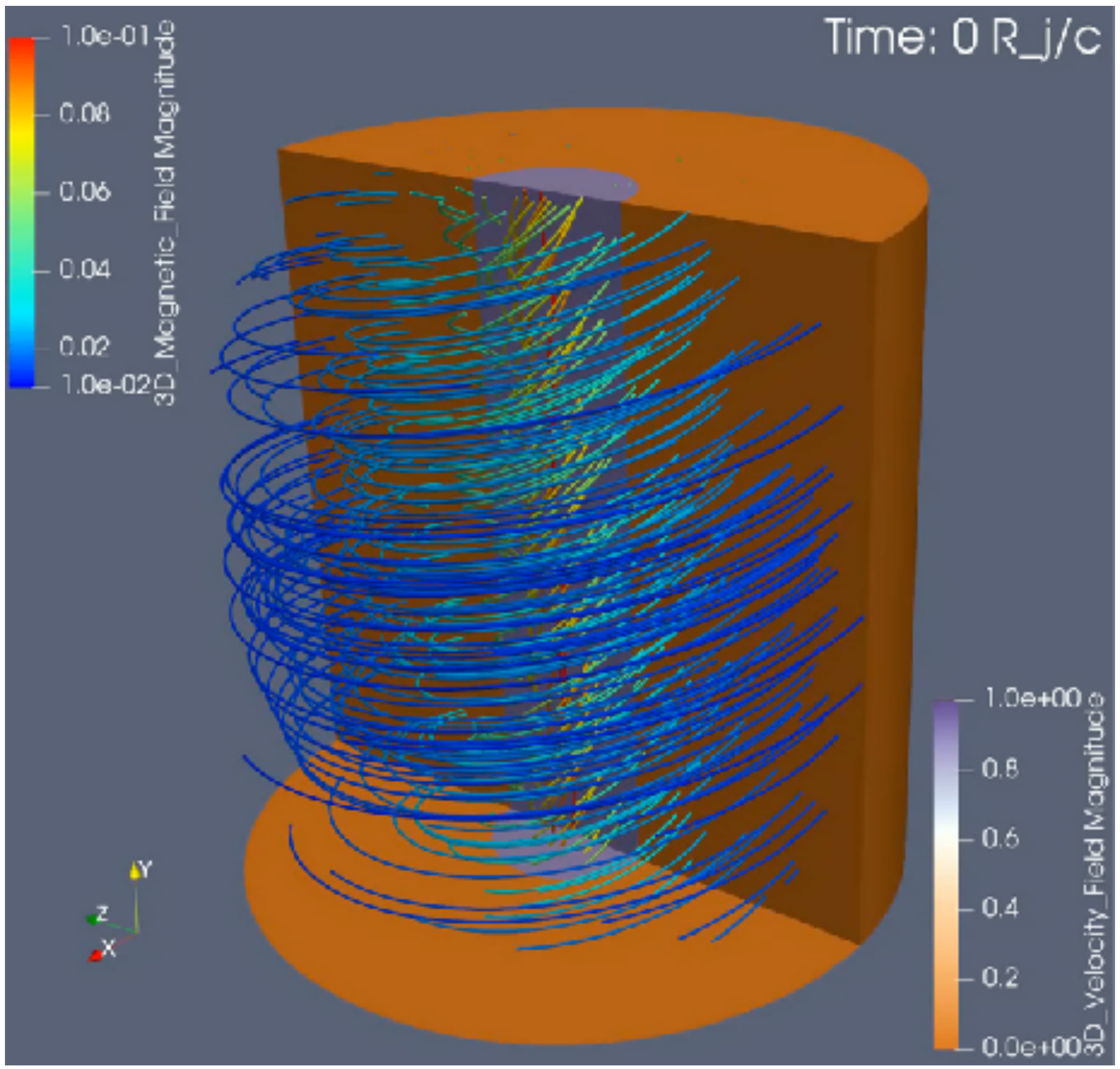
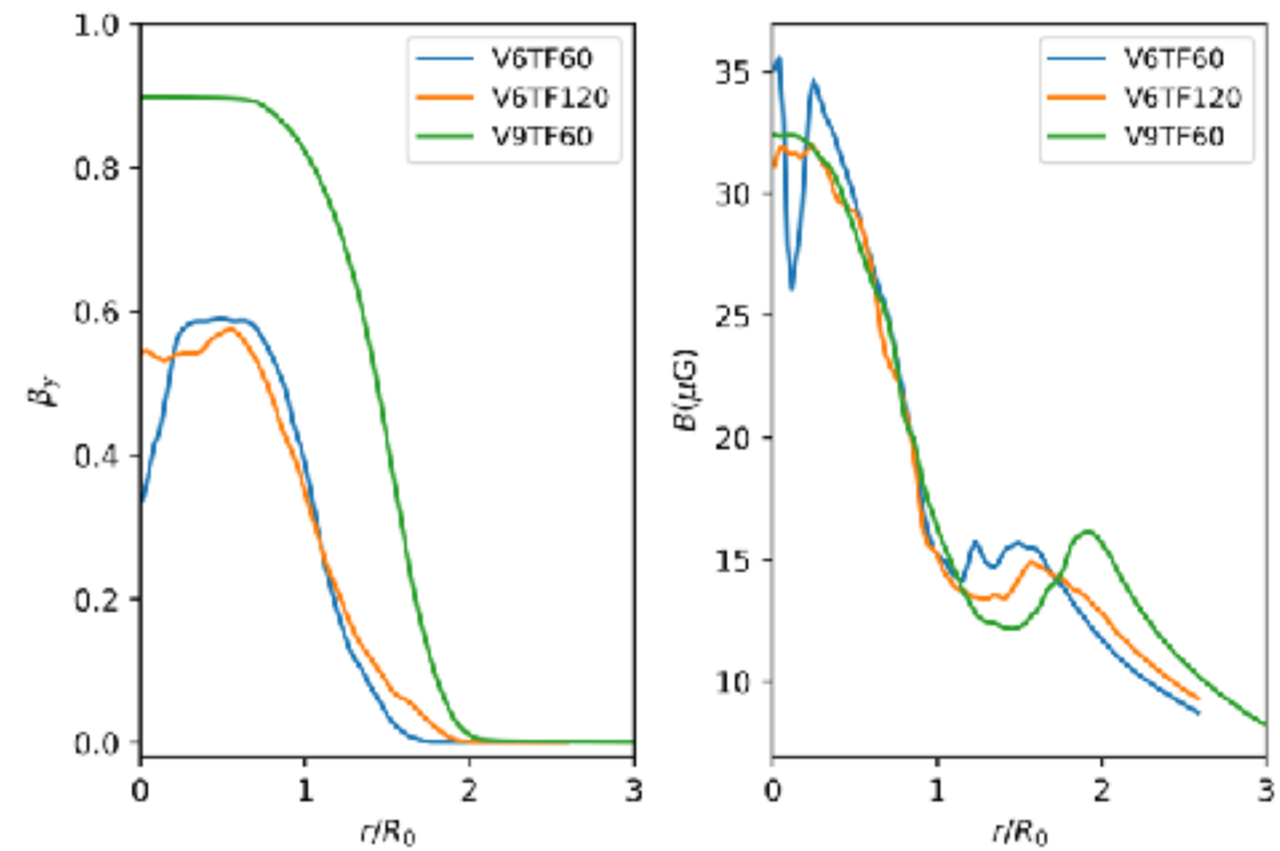


- Cen A represented by V6 (v=0.6c) case
- Powerful FR II radio galaxies represented by V9 (v=0.9c)



From Wang et al '23

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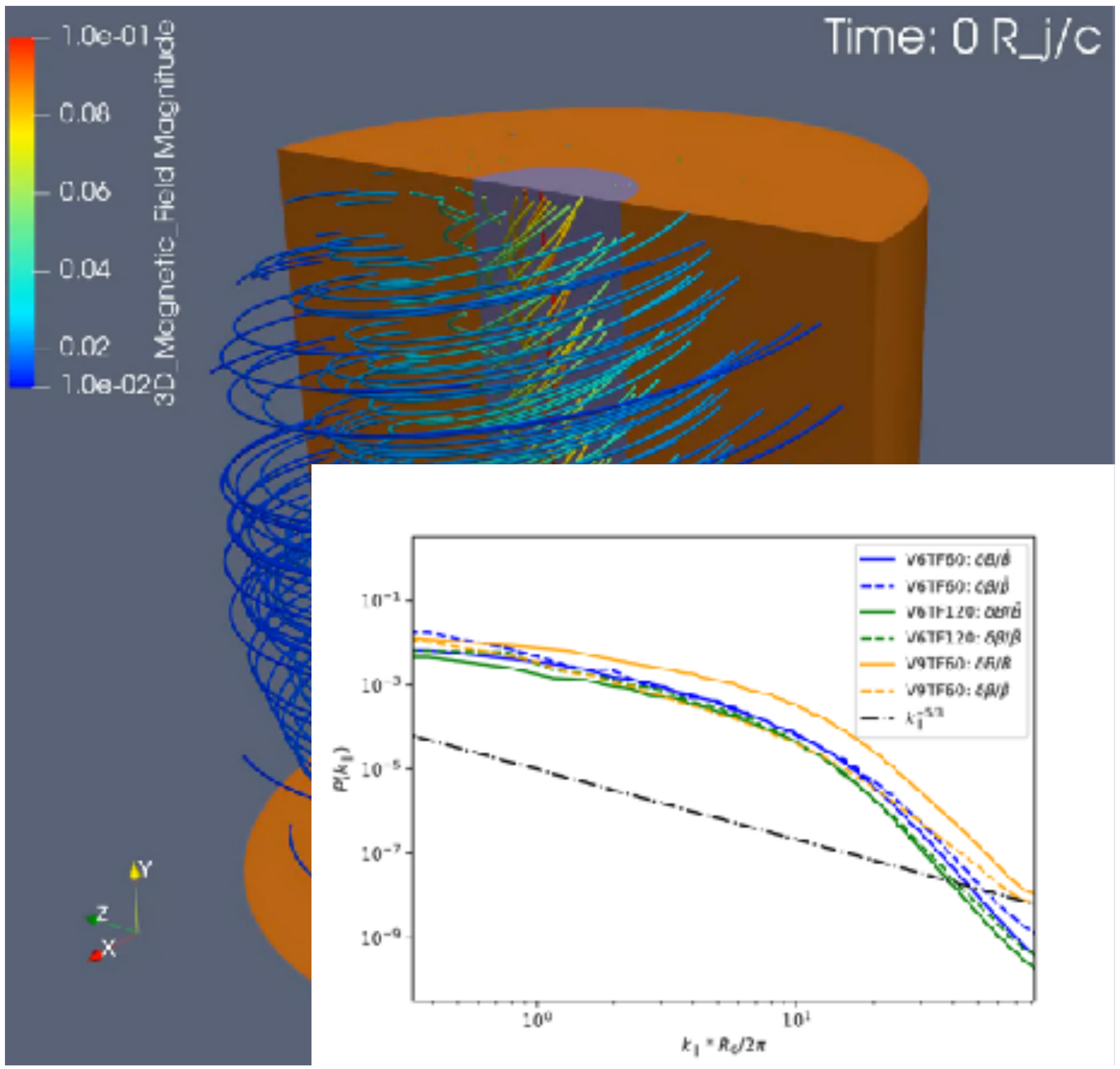

From Wang et al '23

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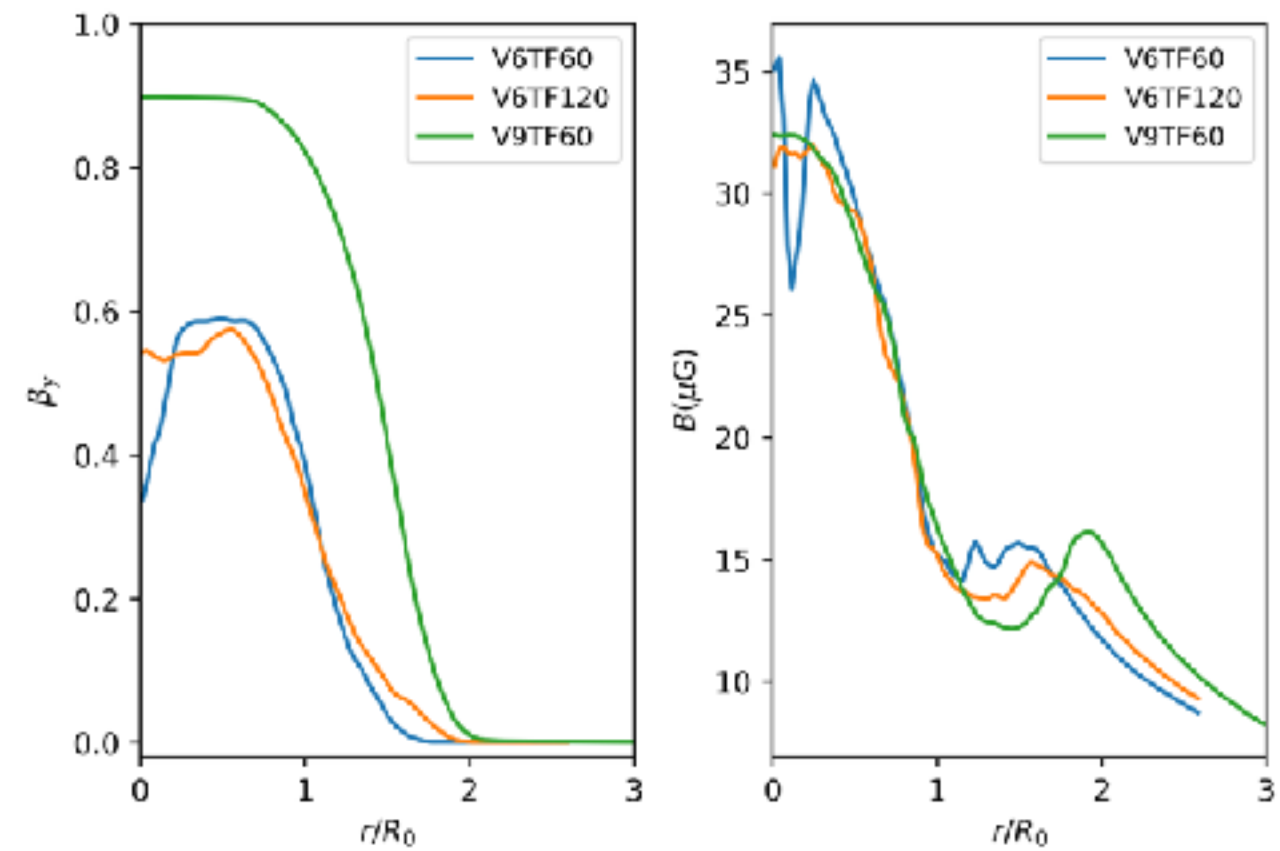
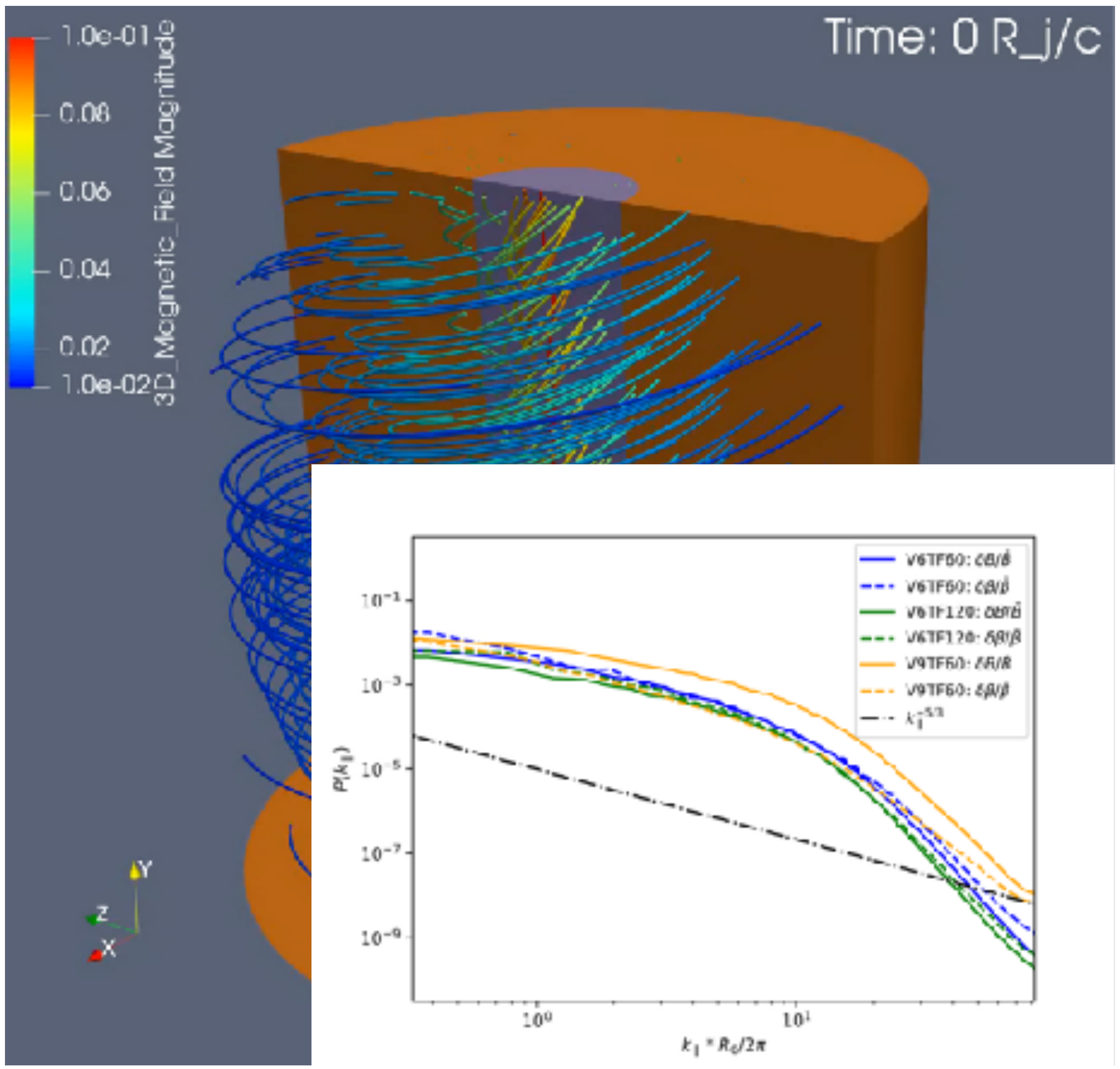


Kolmogorov turbulent spectrum established in jet sheath.

Relativistic MHD simulations

- Evolve turbulent sheath structure on jet edge via KHI



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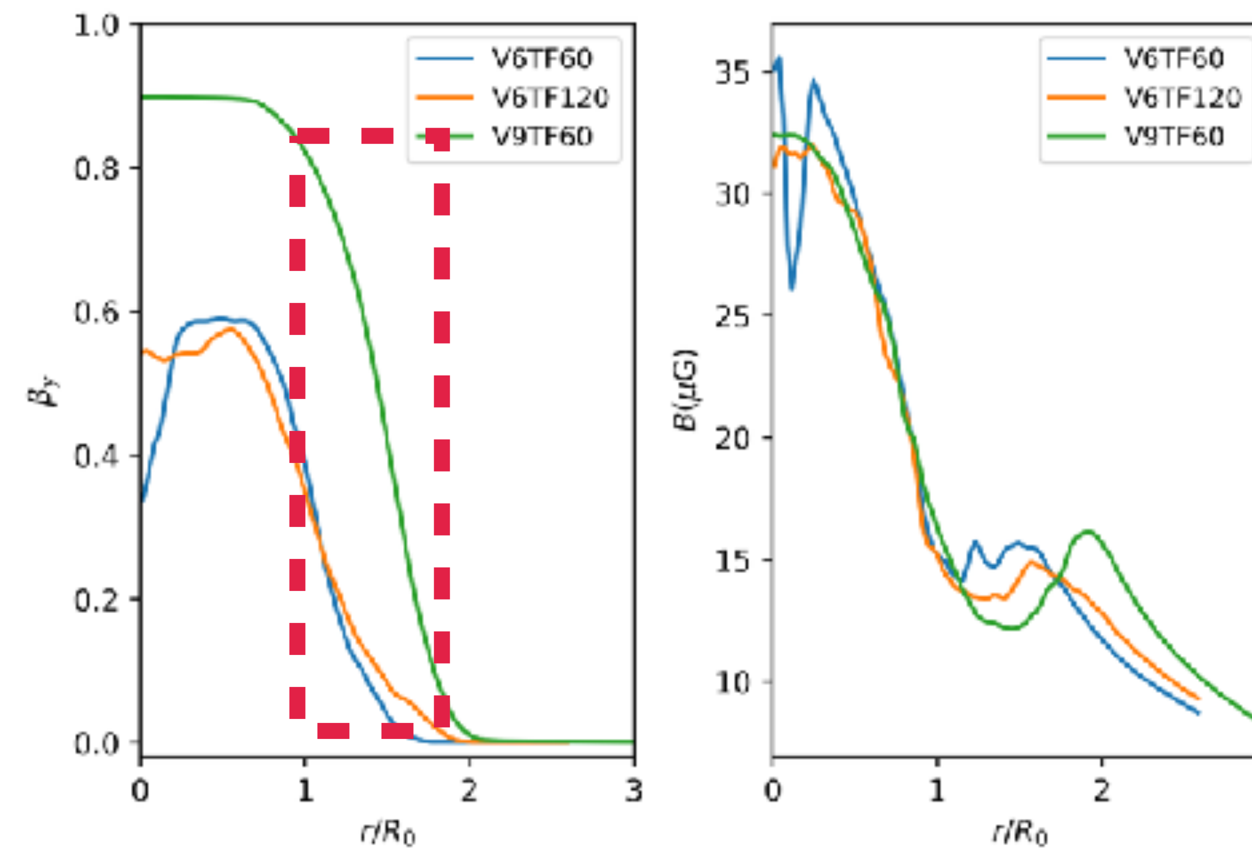


Kolmogorov turbulent spectrum established in jet sheath.

From Wang et al '23

Particle spectrum in gradual shear flow

$$\frac{\partial n(\gamma,t)}{\partial t} = \frac{1}{2}\frac{\partial}{\partial \gamma}\left[\left\langle \frac{\Delta\gamma^2}{\Delta t}\right\rangle \frac{\partial n(\gamma,t)}{\partial \gamma}\right] - \frac{\partial}{\partial\gamma}\left[\left(\left\langle\frac{\Delta\gamma}{\Delta t}\right\rangle - \frac{1}{2}\frac{\partial}{\partial\gamma}\left\langle\frac{\Delta\gamma^2}{\Delta t}\right\rangle + \langle\dot{\gamma}_c\rangle\right) \times n(\gamma,t)\right] - \frac{n}{t_{\rm esc}} + Q(\gamma,t),$$

- Kolmogorov turbulence: q=5/3
- Linear velocity profile motivated from simulations

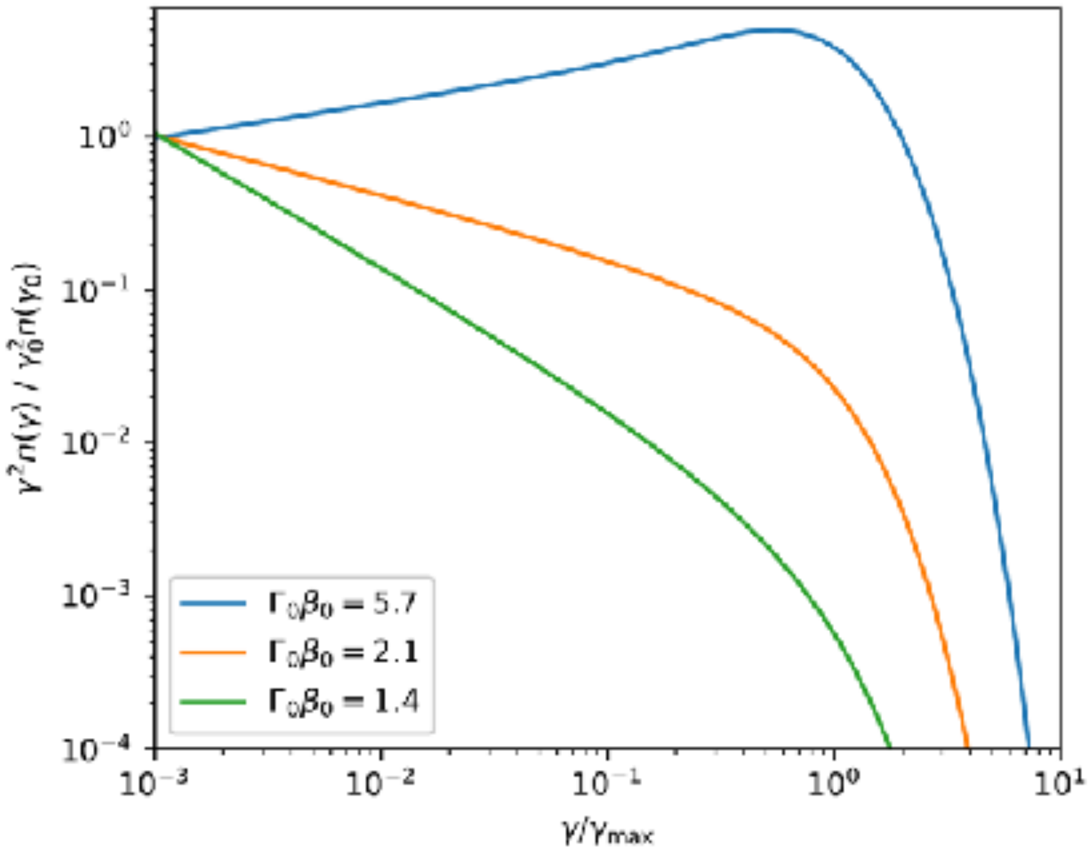
<u>Steady-state</u> solution of Fokker-Planck equation with synch. losses

$$n(\gamma) = C_+\gamma^{s_+}F_+(\gamma,q) + C_-\gamma^{s_-}F_-(\gamma,q)$$

$$s_\pm = \frac{q-1}{2} \pm \sqrt{\frac{(5-q)^2}{4} + w}$$

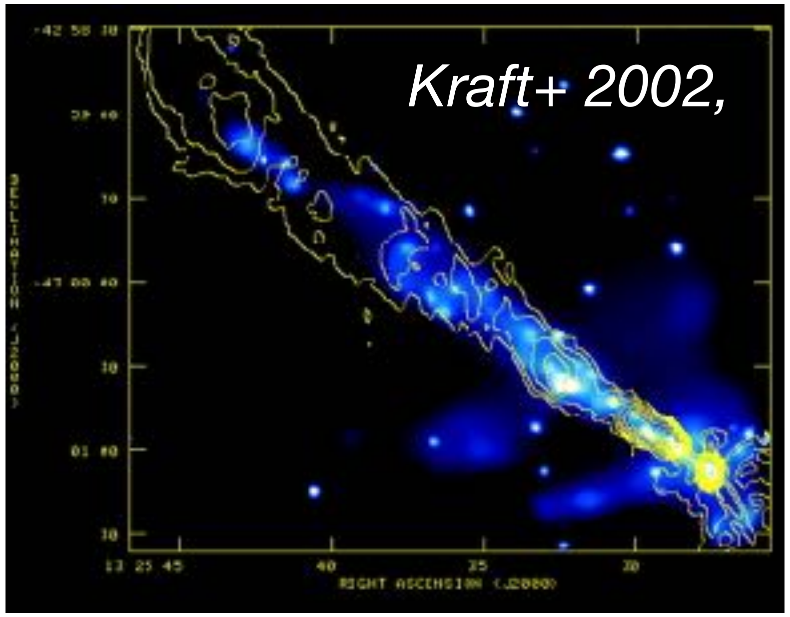
$$F_\pm(\gamma,q) = {}_1F_1\left[\frac{2+s_\pm}{q-1}, \frac{2s_\pm}{q-1}; -\frac{6-q}{q-1}\left(\frac{\gamma}{\gamma_{\rm max}}\right)^{q-1}\right]$$

$$n \rightarrow 0 \text{ for } \gamma \rightarrow \infty$$



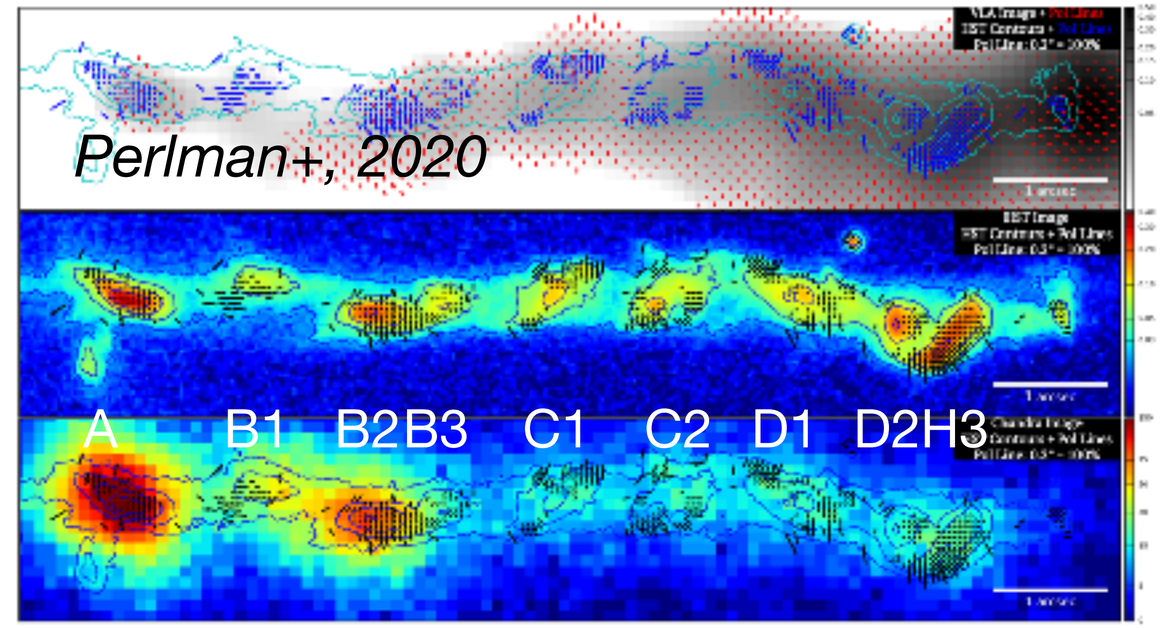
J.S.Wang+, 2021, MNRAS, arXiv:2105.08600

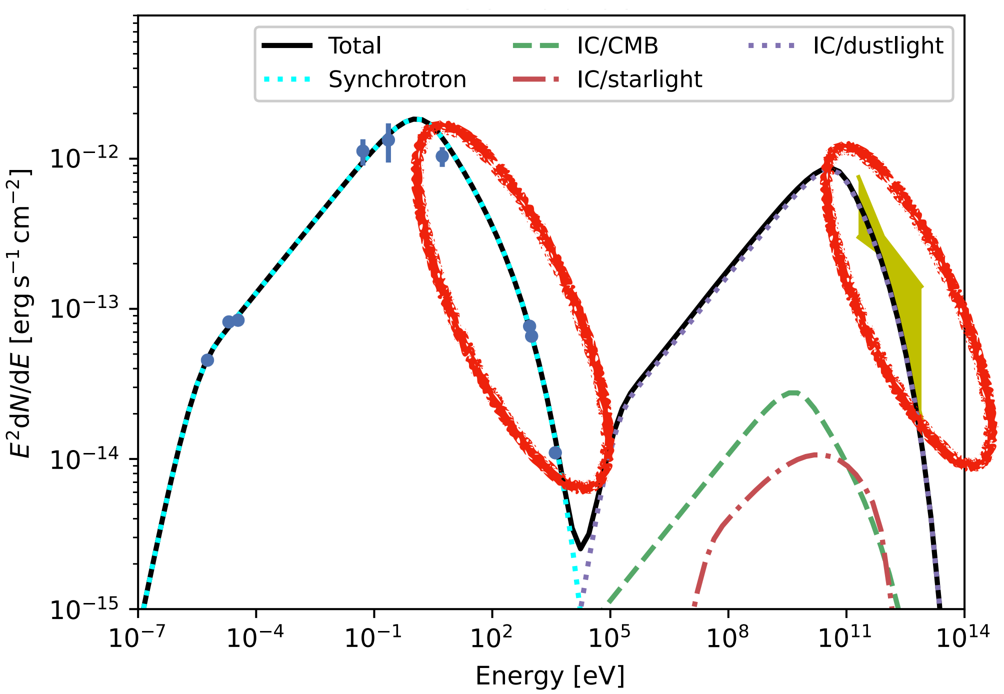
Explaining kpc-scale X-ray jets

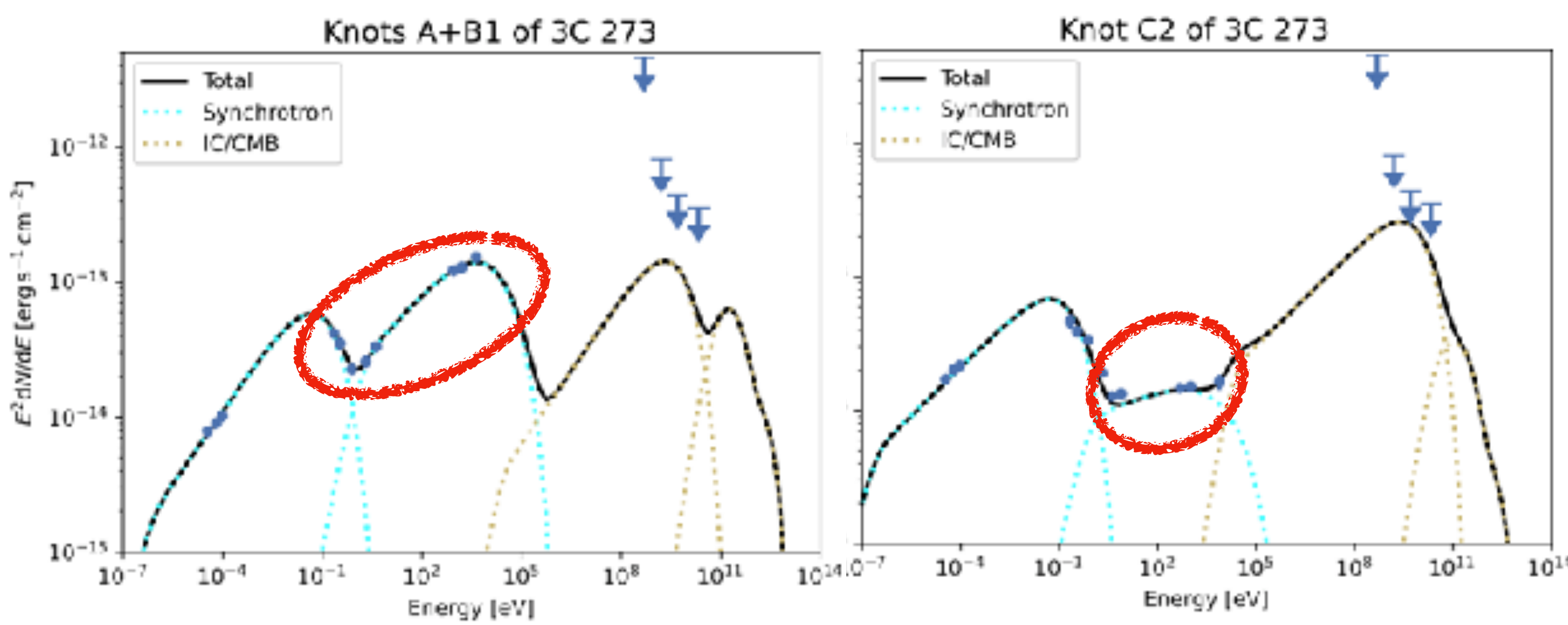


Centaurus A
4Mpc

3C 273
z =0.158







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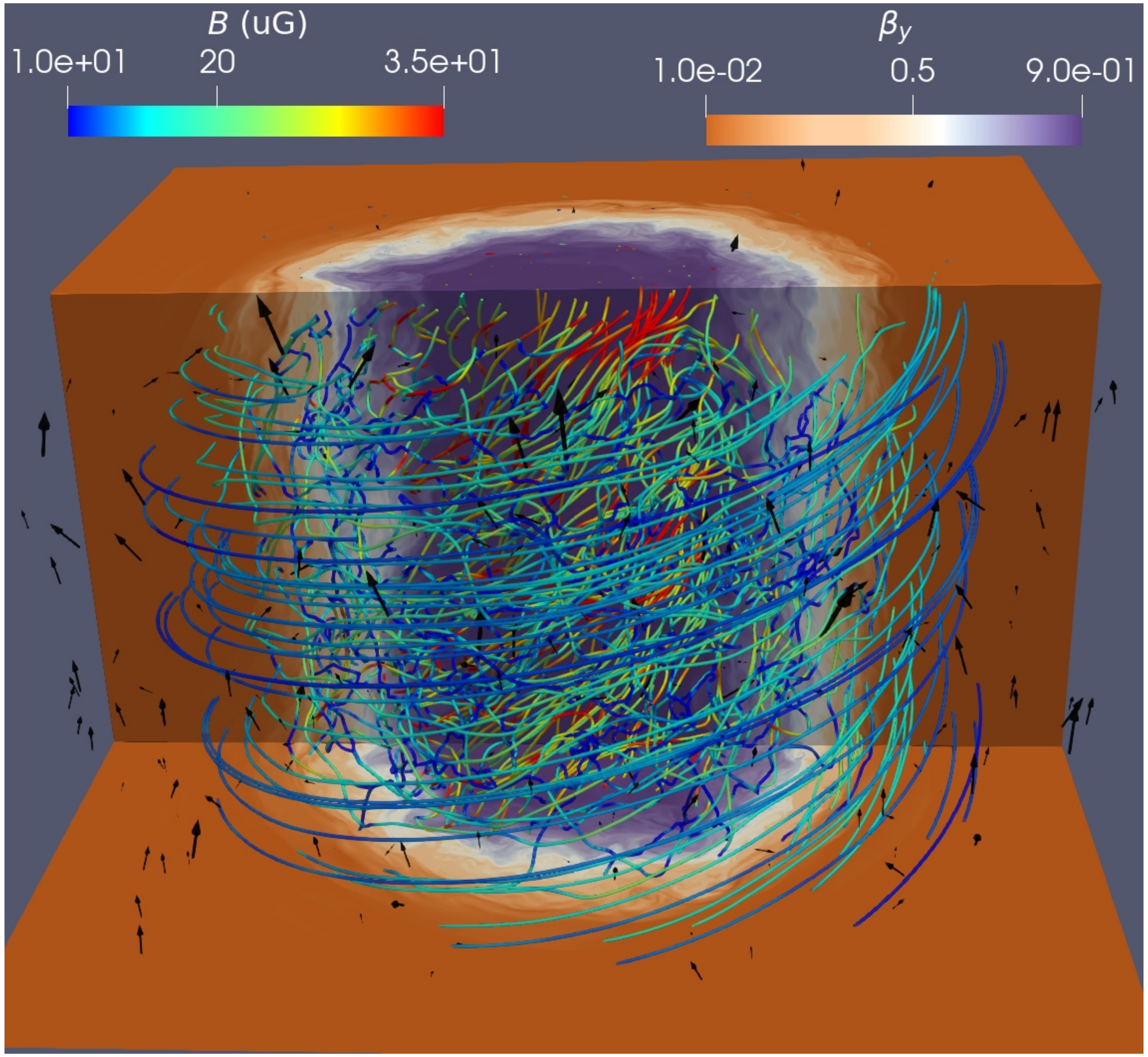
Relativistic MHD simulations



Using Pluto MHD-PIC routine, we integrate test particles in the self-generated fields

$$\frac{d\boldsymbol{x}_p}{dt} = \boldsymbol{v}_p$$

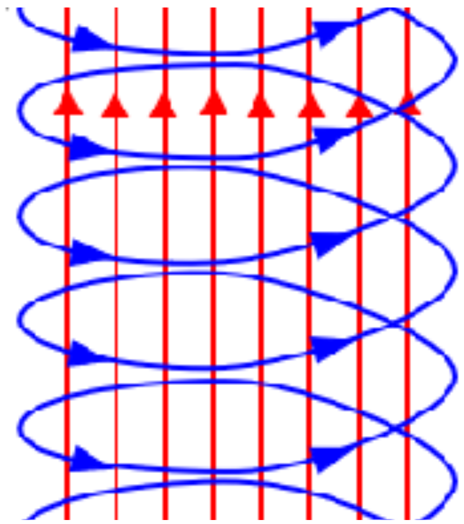
$$\frac{d(\gamma \boldsymbol{v})_p}{dt} = \alpha_p(c\boldsymbol{E} + \boldsymbol{v}_p \times \boldsymbol{B})$$

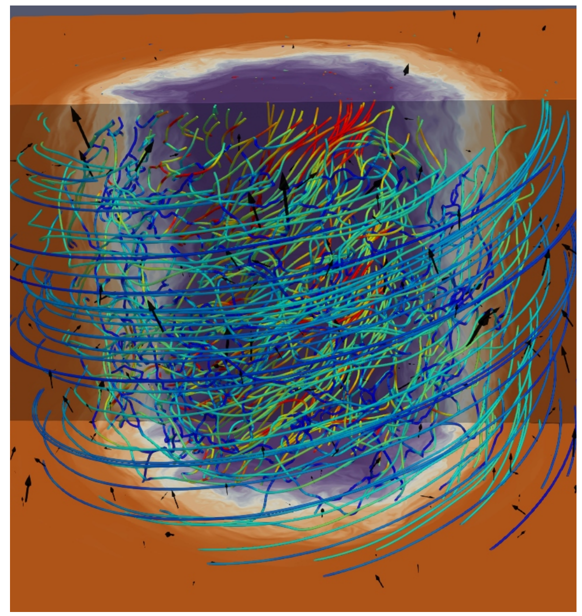
Only relevant for particles with gyro radius > cell size

Limits dynamic range

From Wang et al., under review

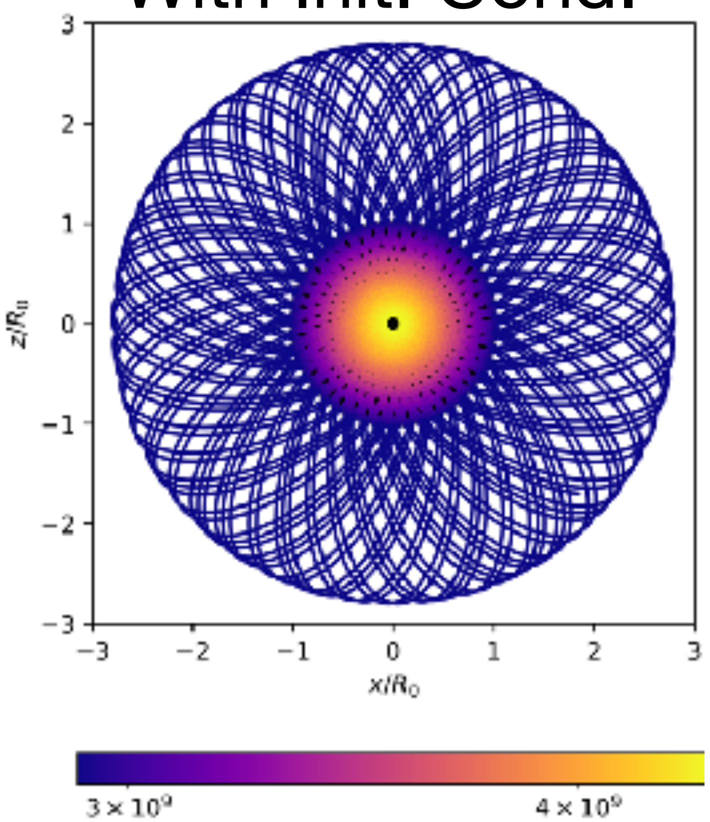
Particle trajectories

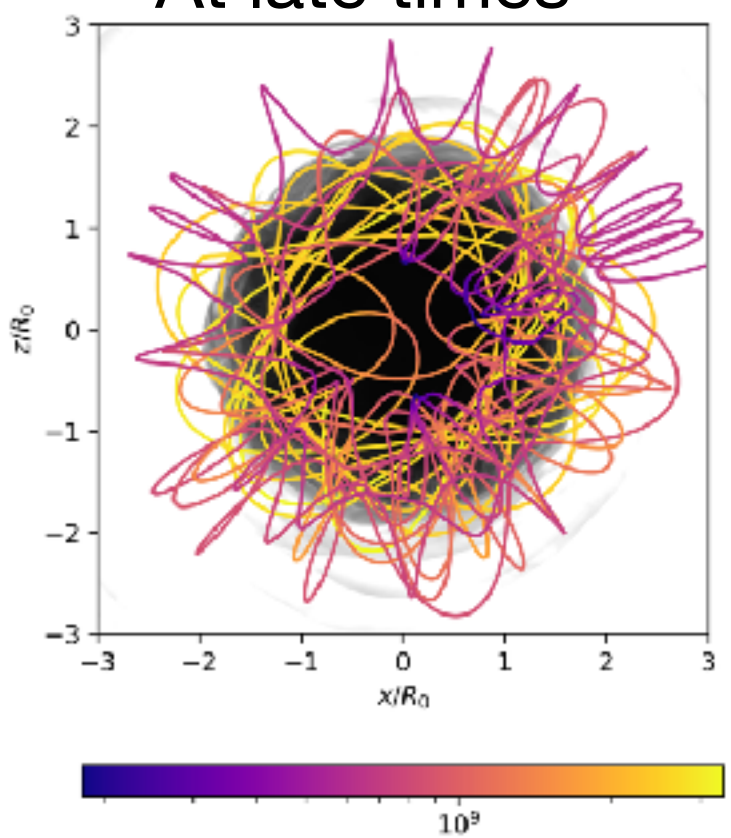




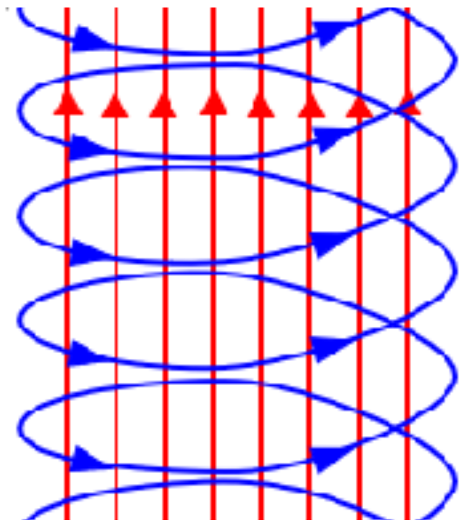
With Init. Cond.

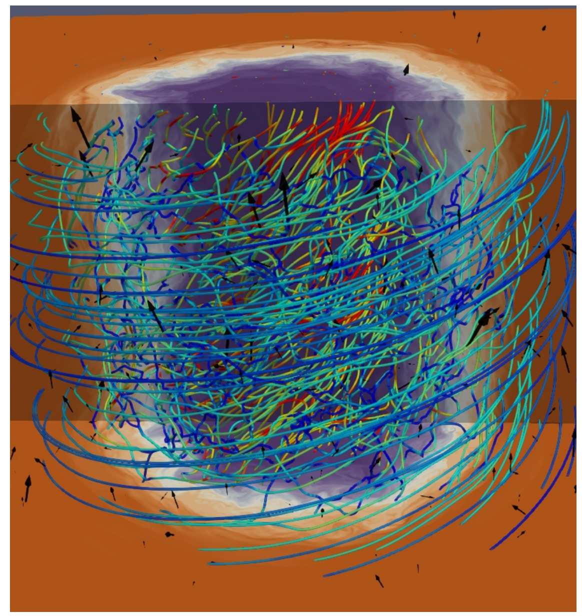
At late times

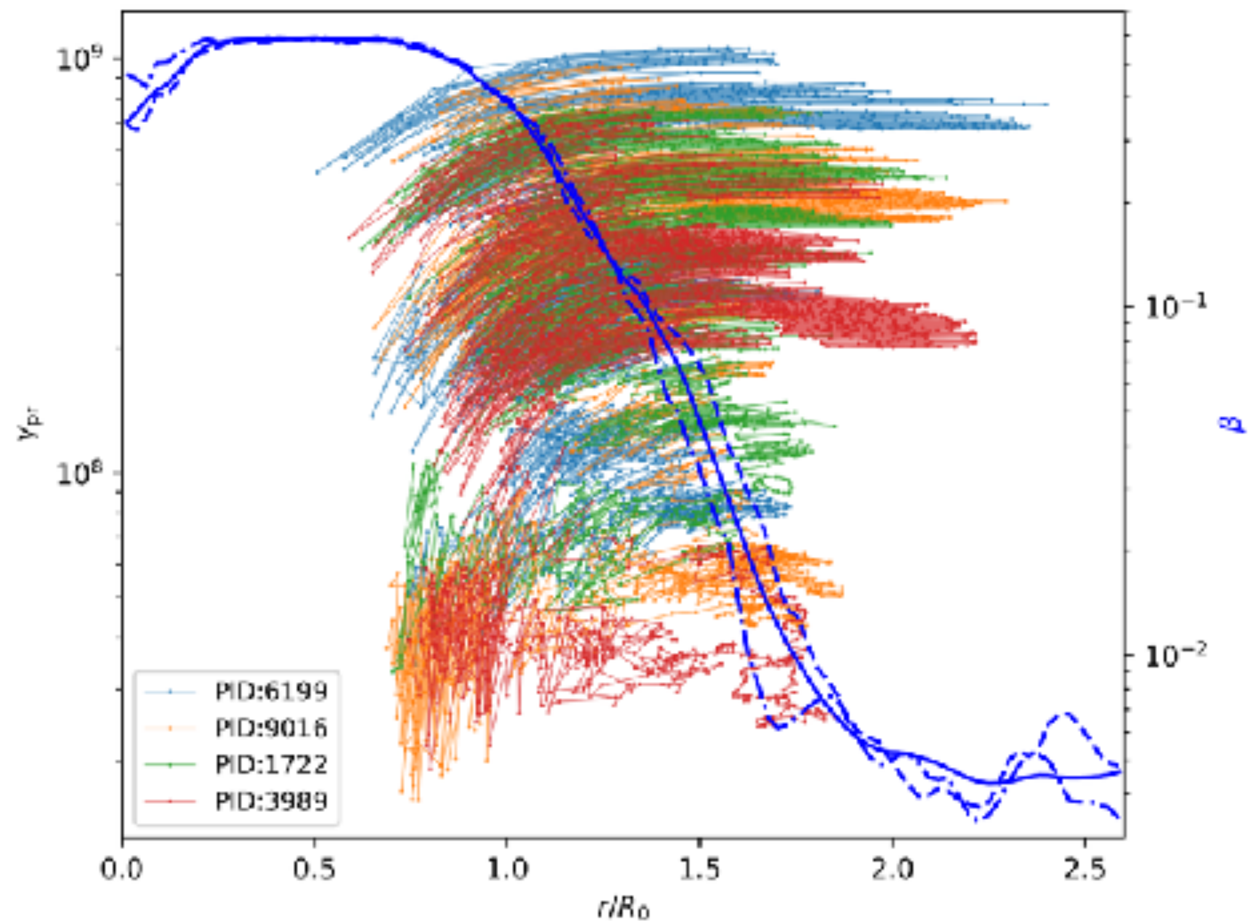




Particle trajectories







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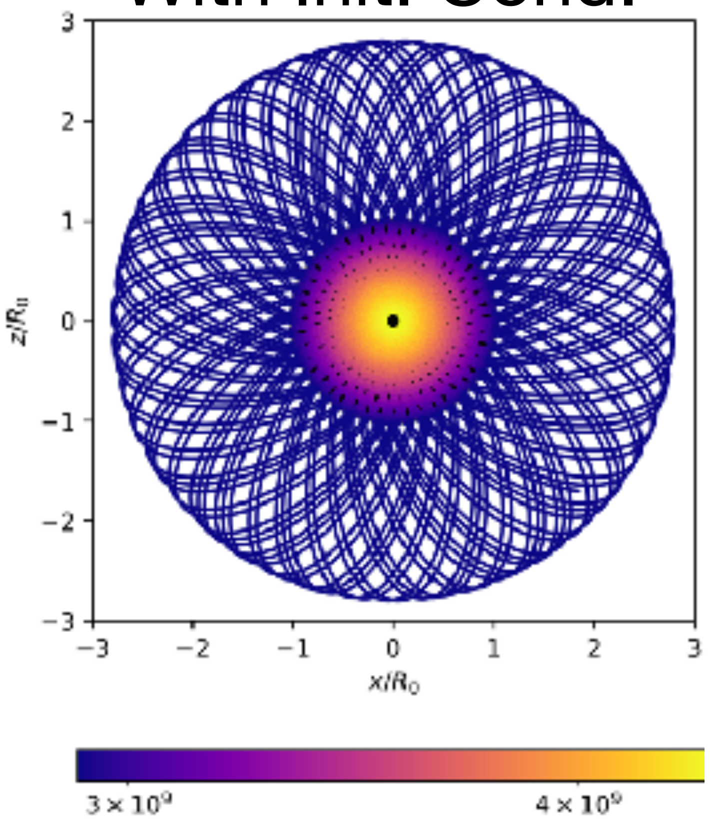

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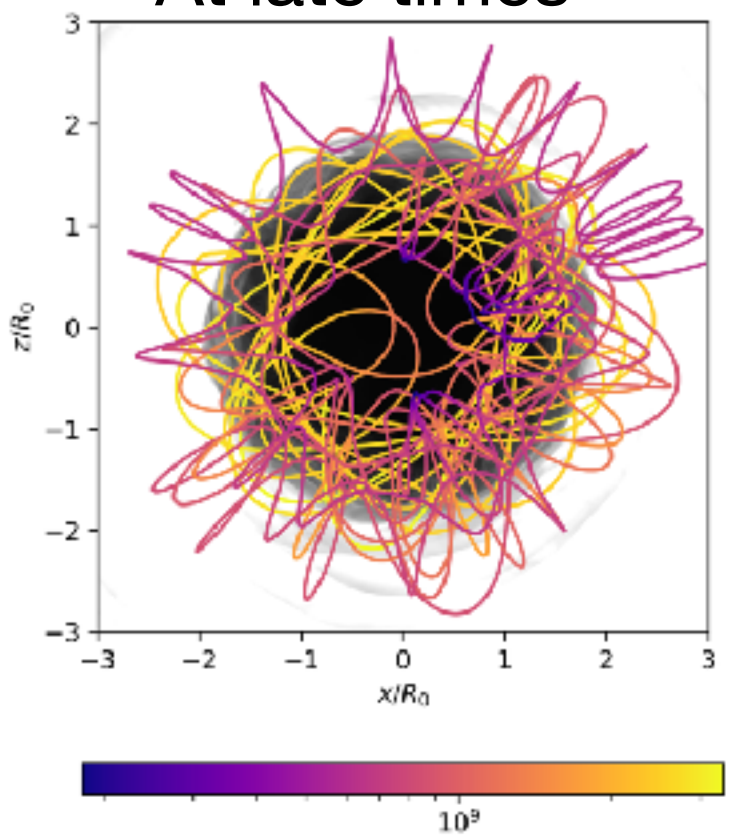


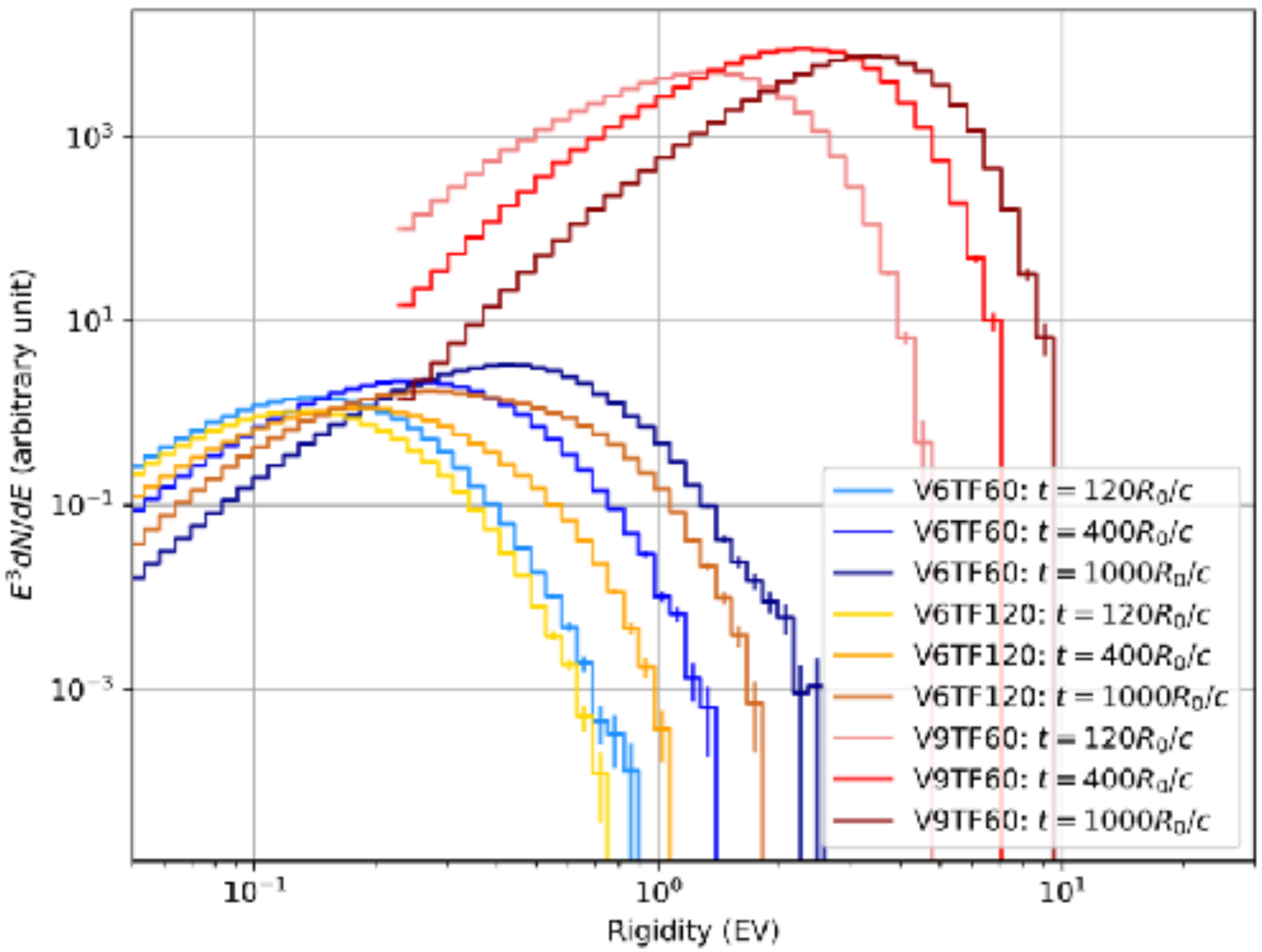
Particles accelerated until they reach the scale of the sheath layer.

Remain magnetised.

Escape hindered by weakly perturbed external field

Evolution of particle spectrum over time

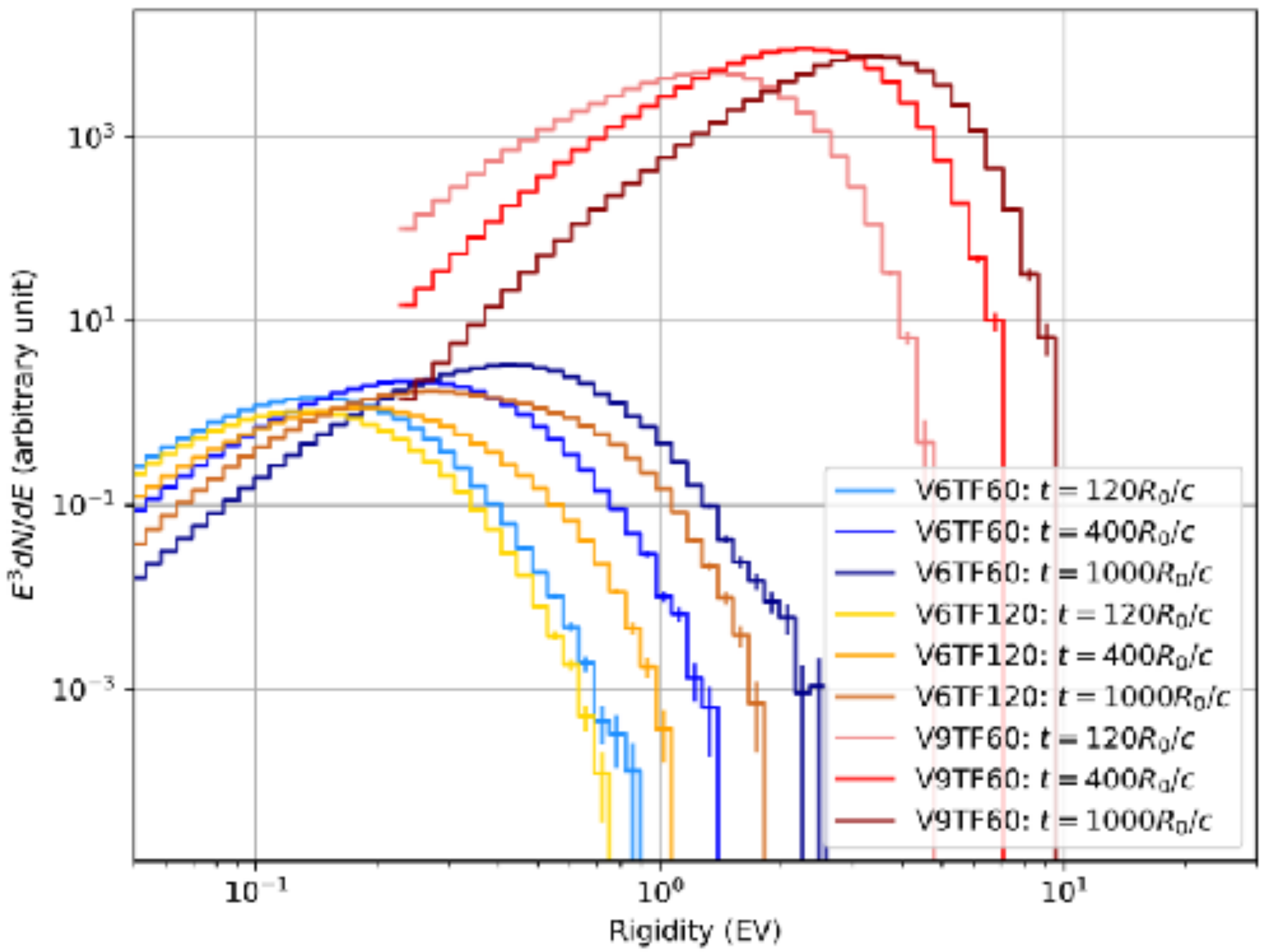
Snap shots



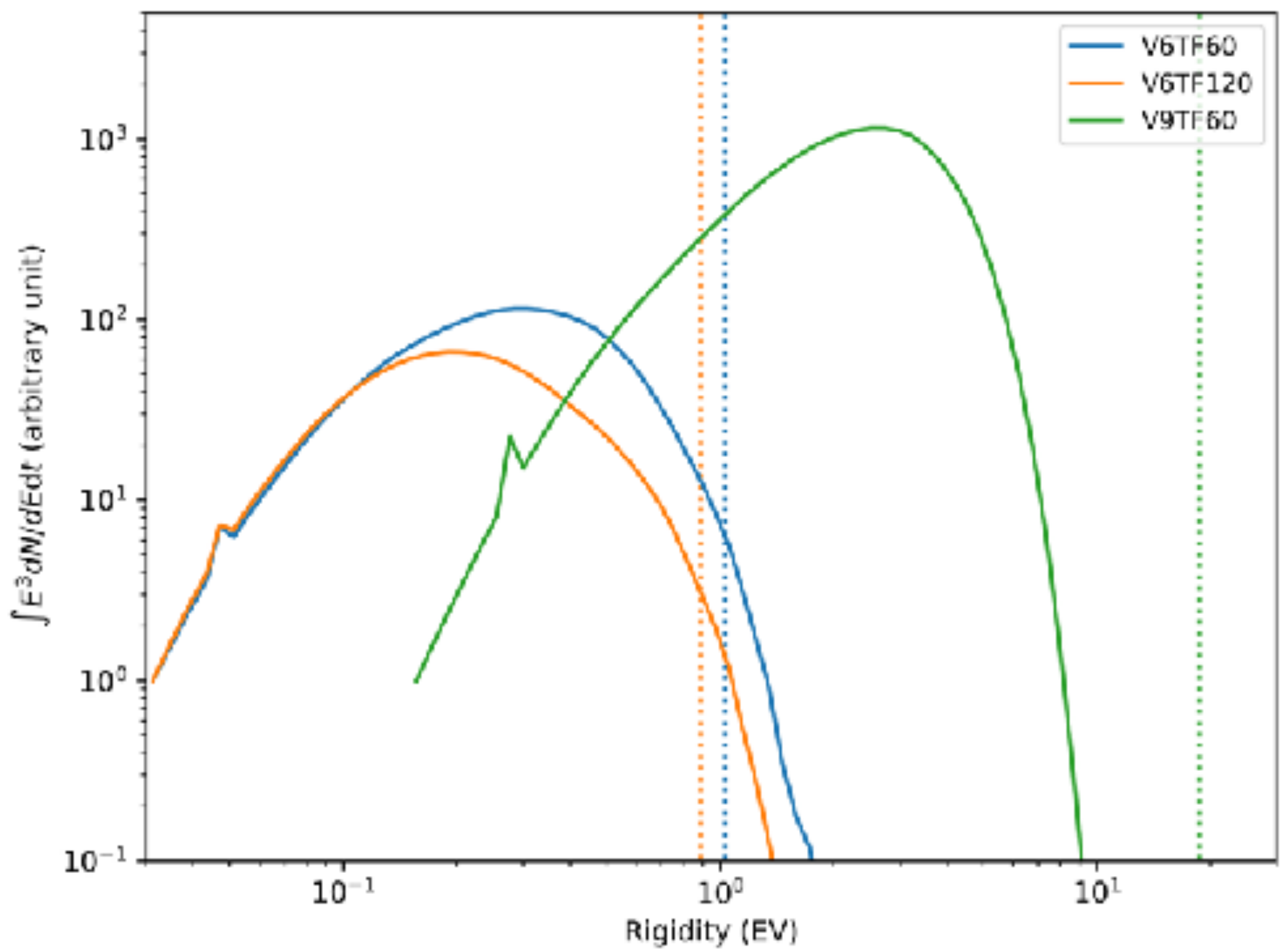
Spectral broadening, peak shift to higher energies, hard spectrum

Evolution of particle spectrum over time

Snap shots



Time integrated



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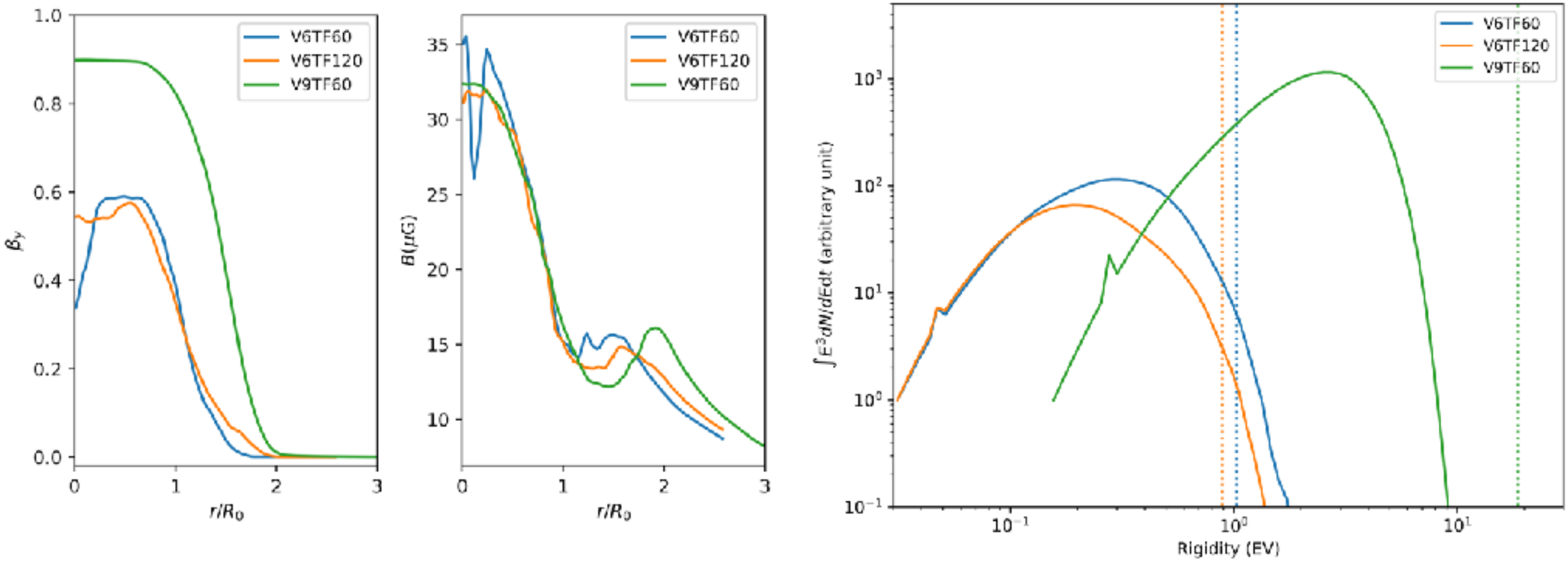
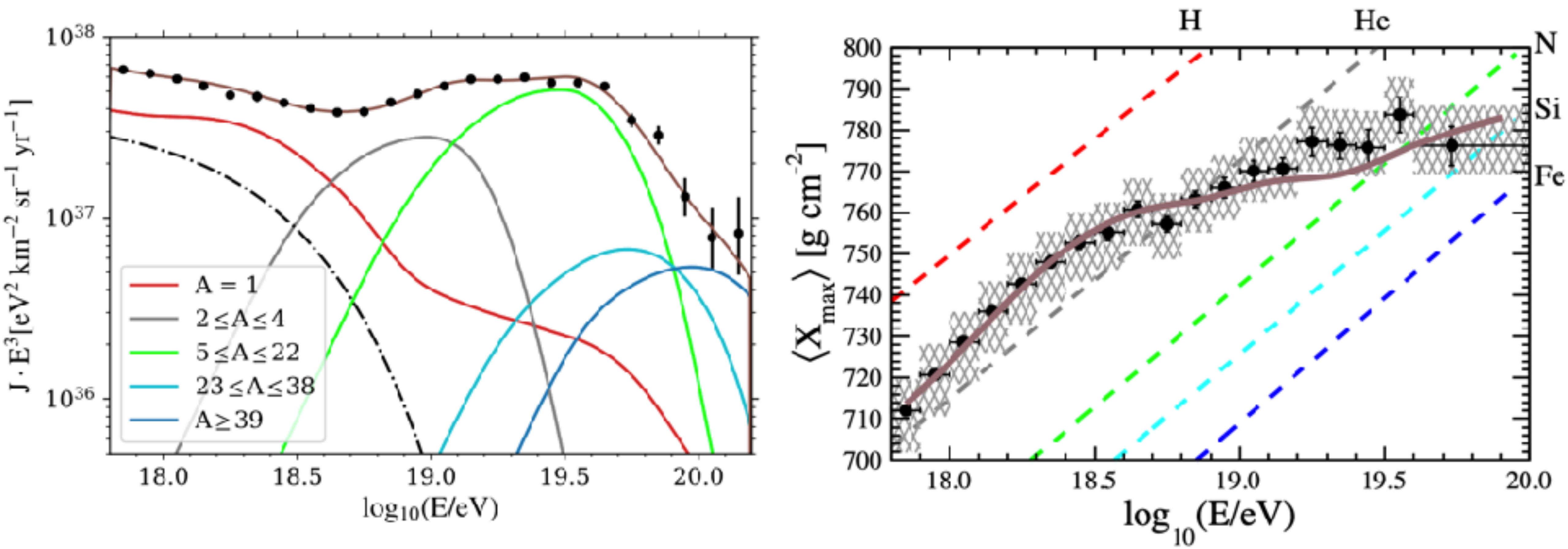


Spectral broadening, peak shift to higher energies, hard spectrum

A steeper velocity profile leads to higher acceleration efficiency

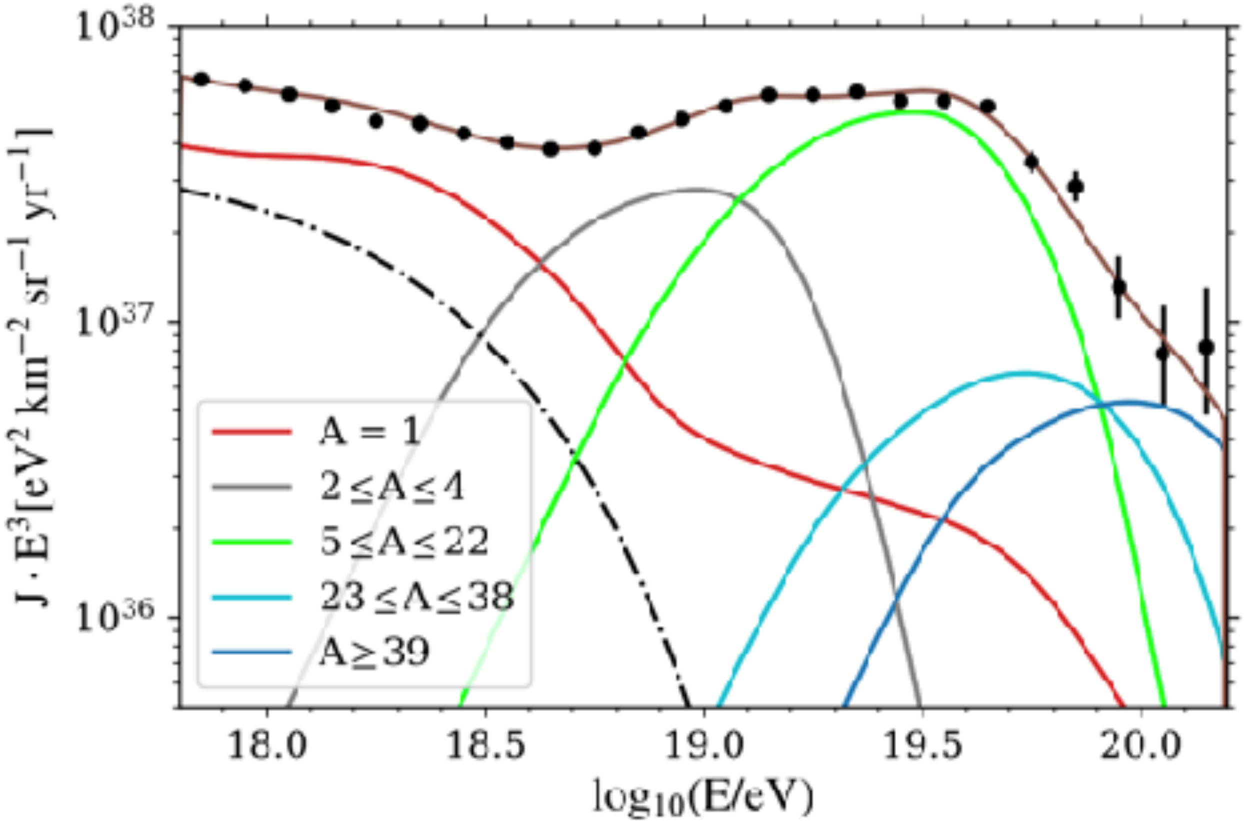
Particles approach Hillas limit, here defined: $E_{\text{Hillas}} = q\bar{\beta}_j\bar{B}_jR_j$

Ultra-high-energy Cosmic Rays

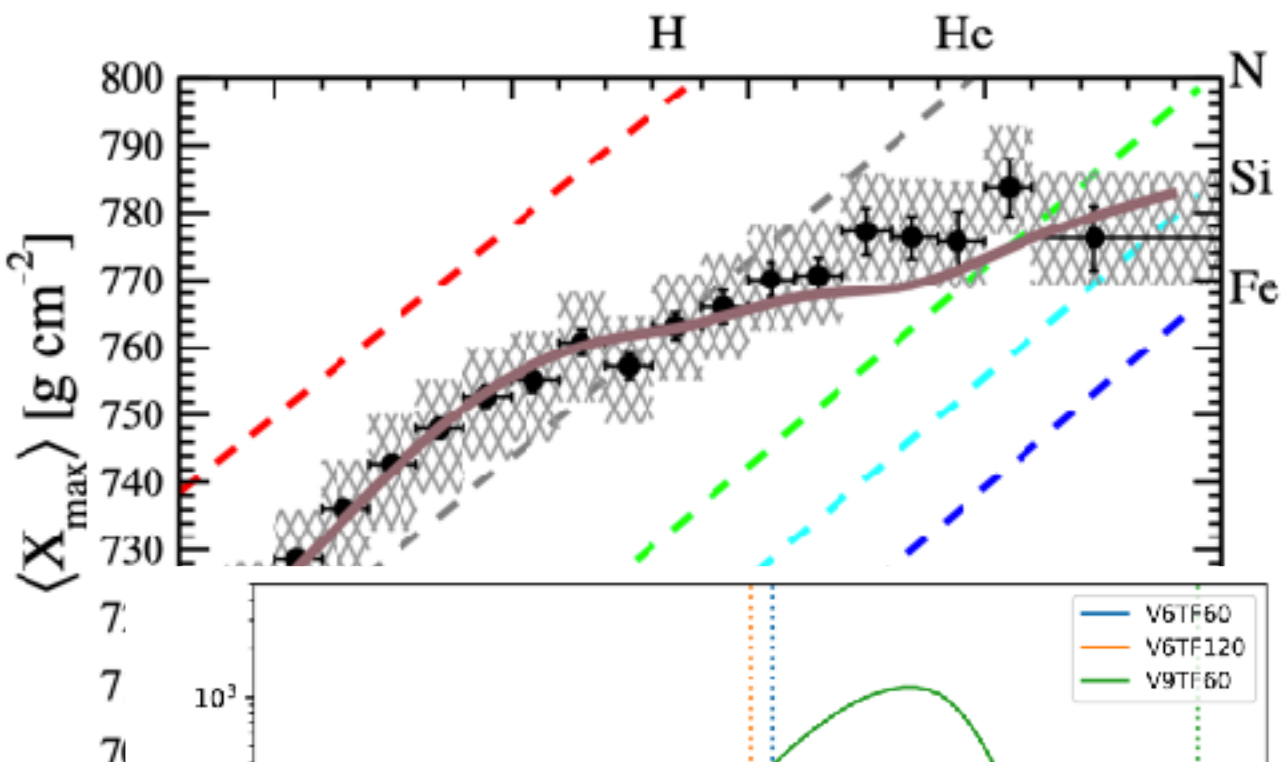


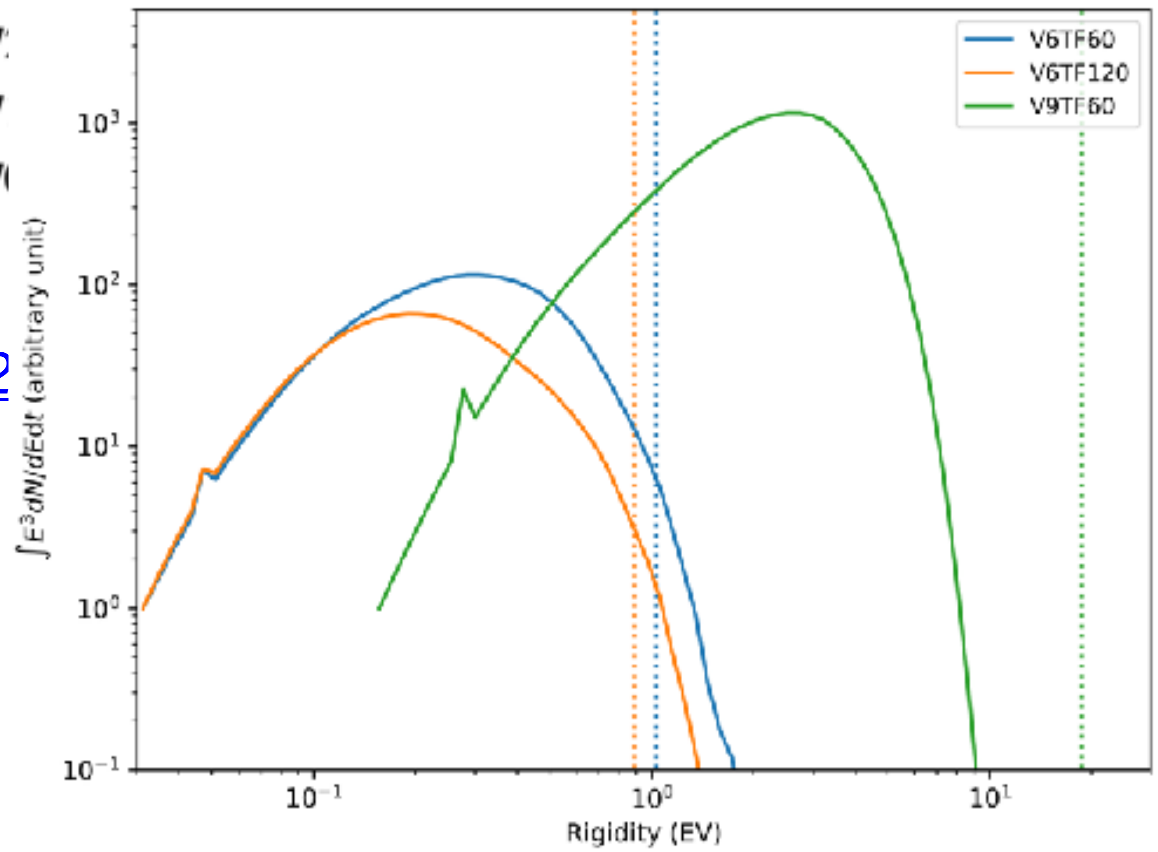
Pierre Auger Collaboration, 2023, JCAP, [*arXiv:2211.02857*]

Ultra-high-energy Cosmic Rays



Pierre Auger Collaboration, 2023, JCAP, [arXiv:2](#)





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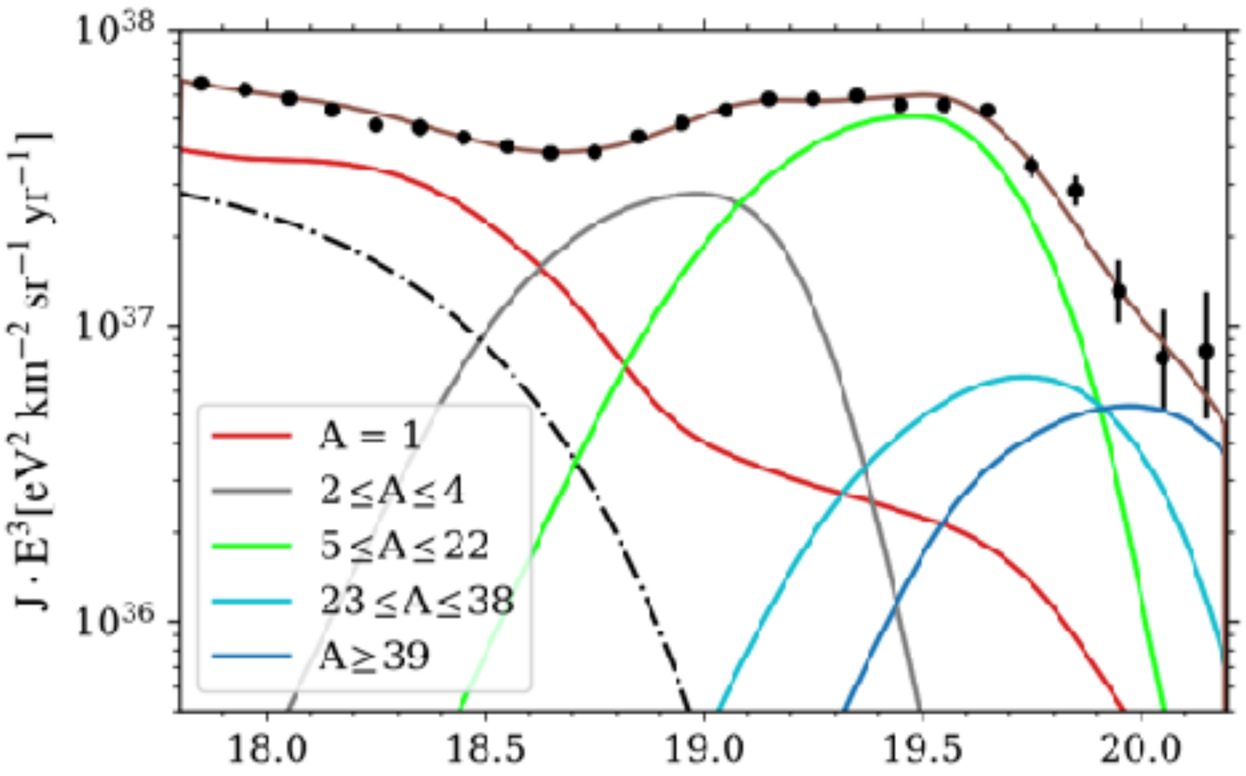
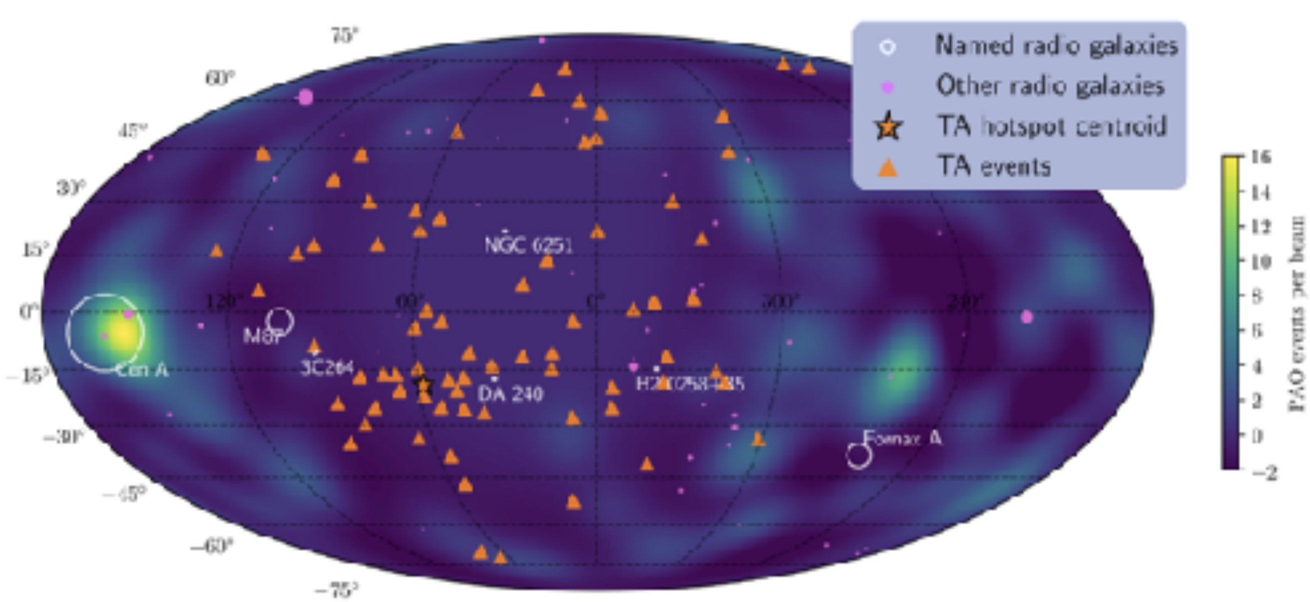
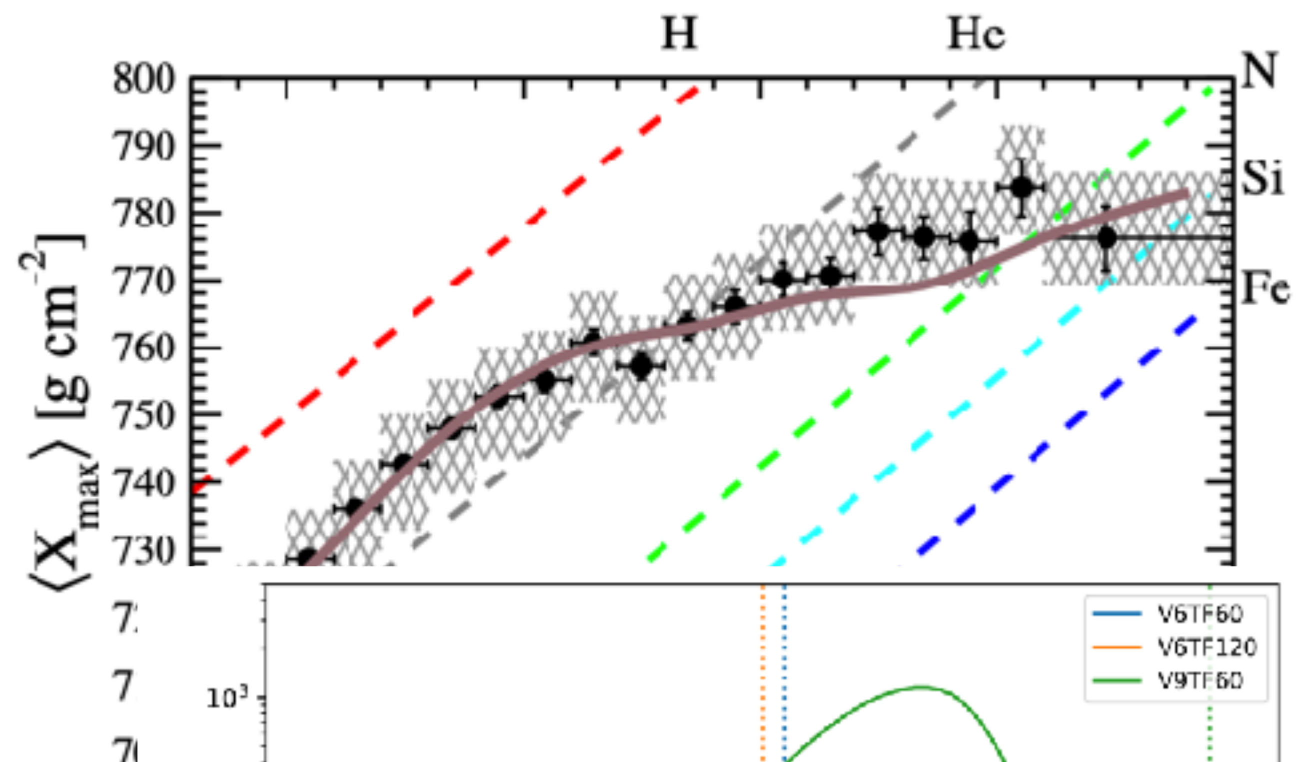
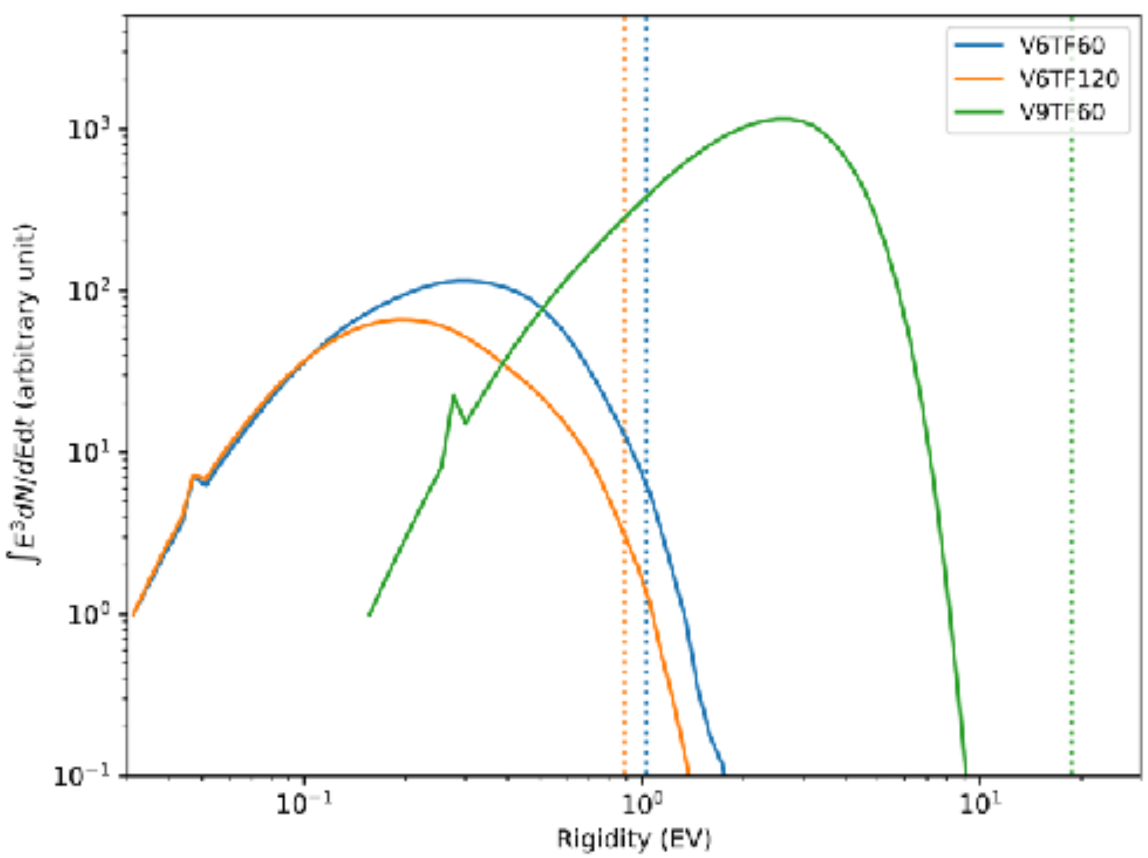


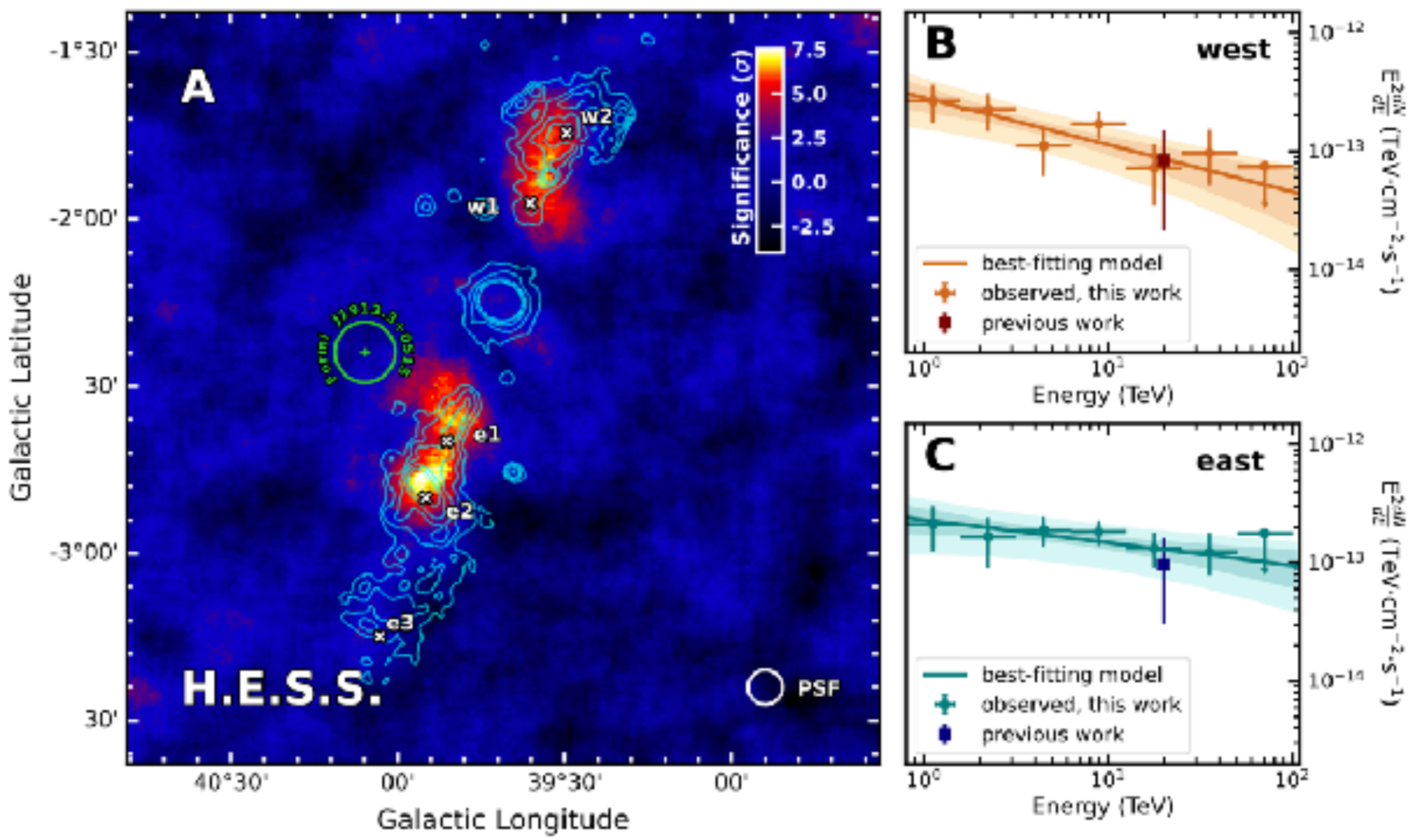






Back to Shocks

Galactic microquasar SS 433

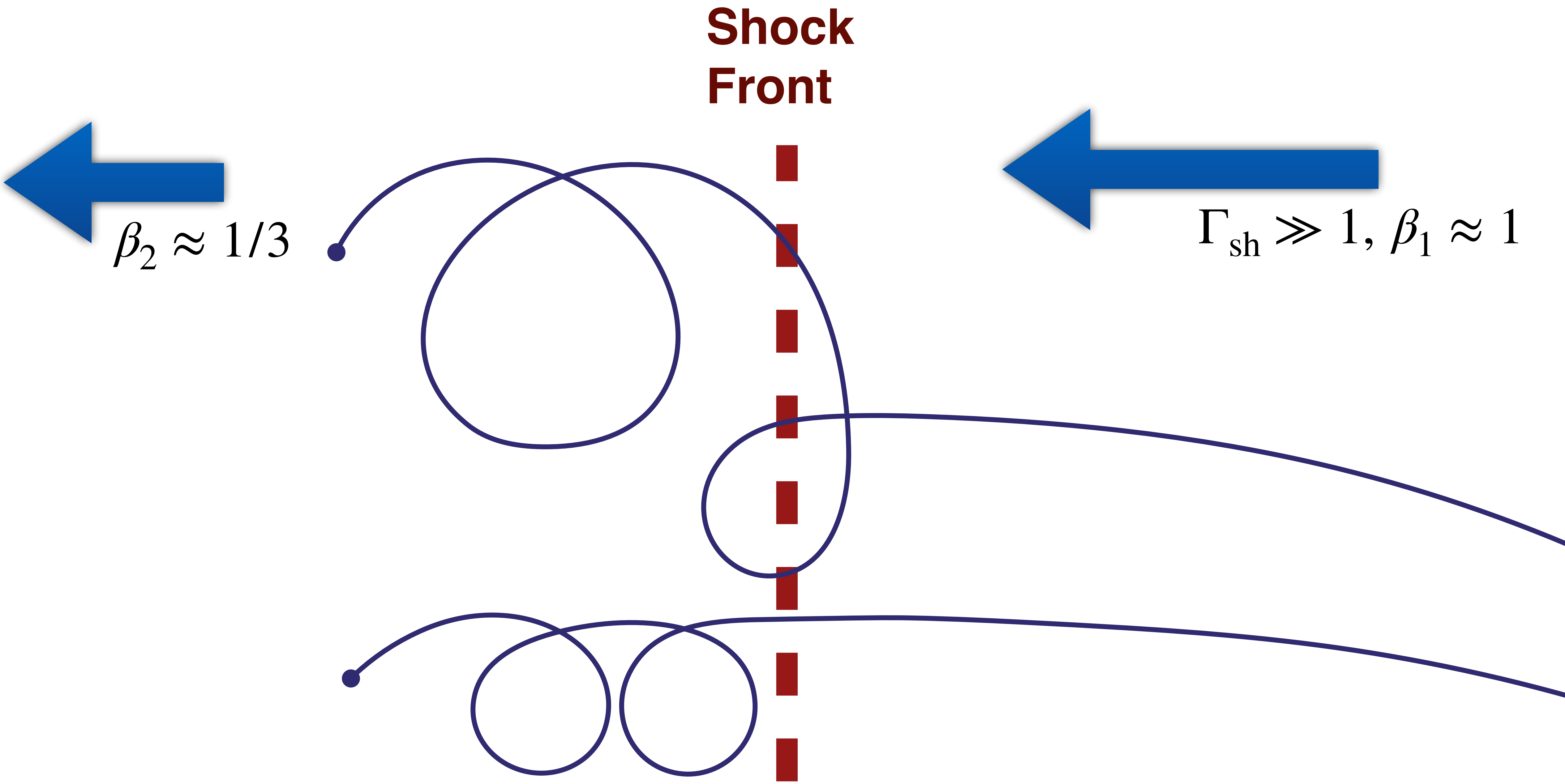


HESS Collab. 2024

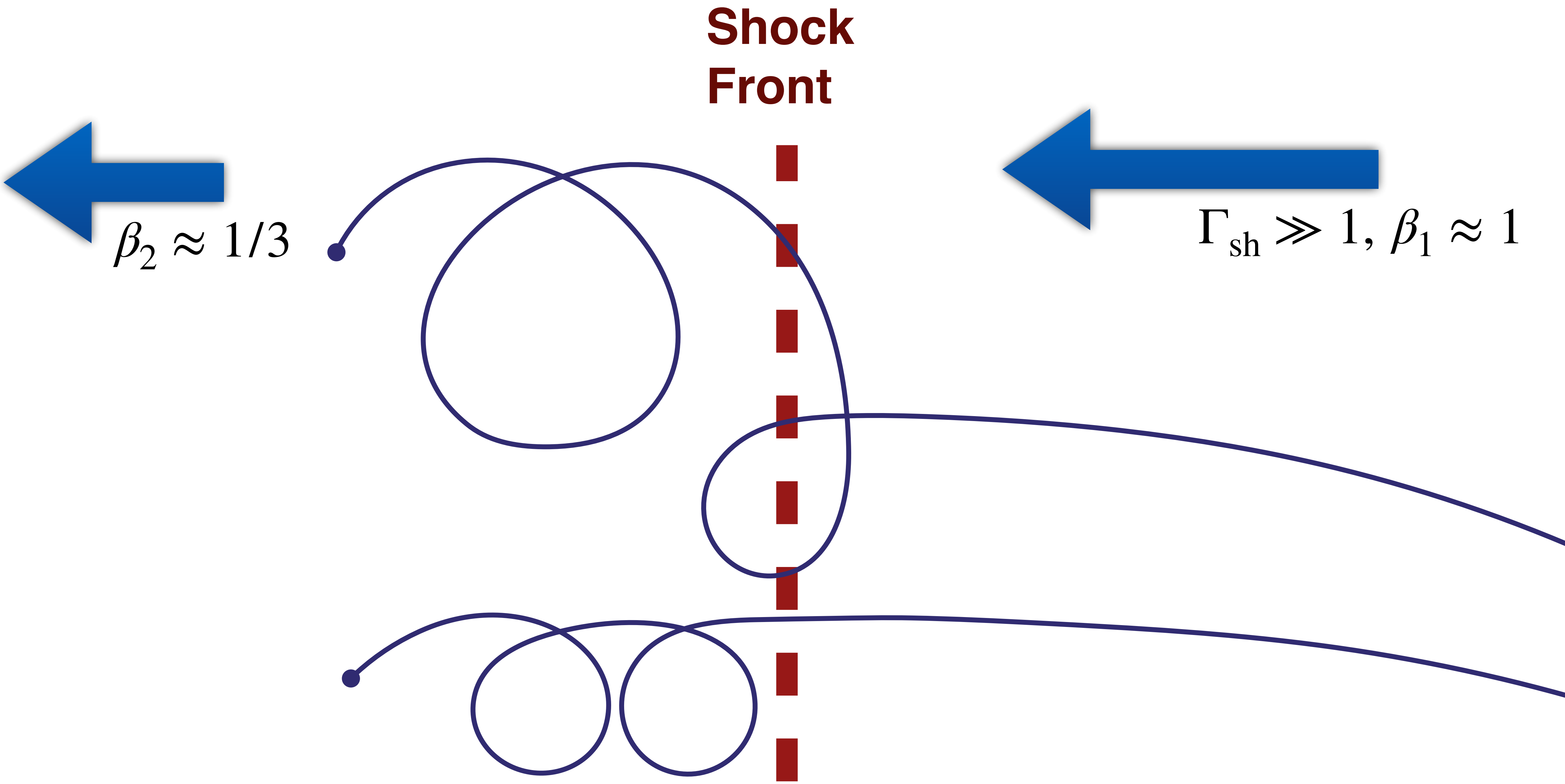
Mildly to very relativistic shocks can occur at various positions along large-scale jets.

Are such shock effective particle accelerators?

The trouble with relativistic shocks

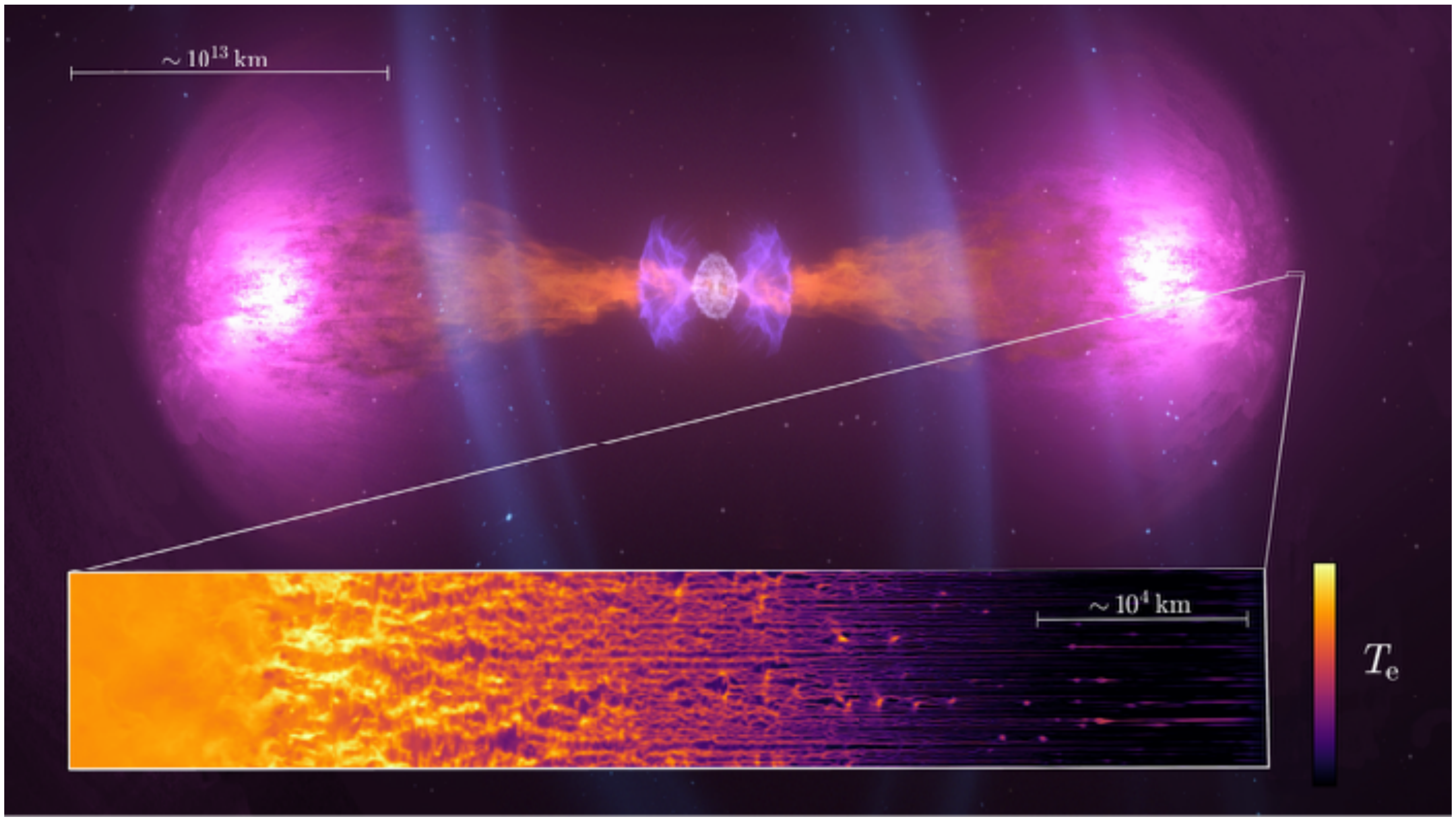


The trouble with relativistic shocks



Particle is limited to ≤ 3 crossings (Begelman & Kirk '90)
Strong scattering needed to overcome the $\mathbf{E} \times \mathbf{B}$ drift which acts to transport particles downstream at $\approx c/3$

Lessons from kinetic simulations

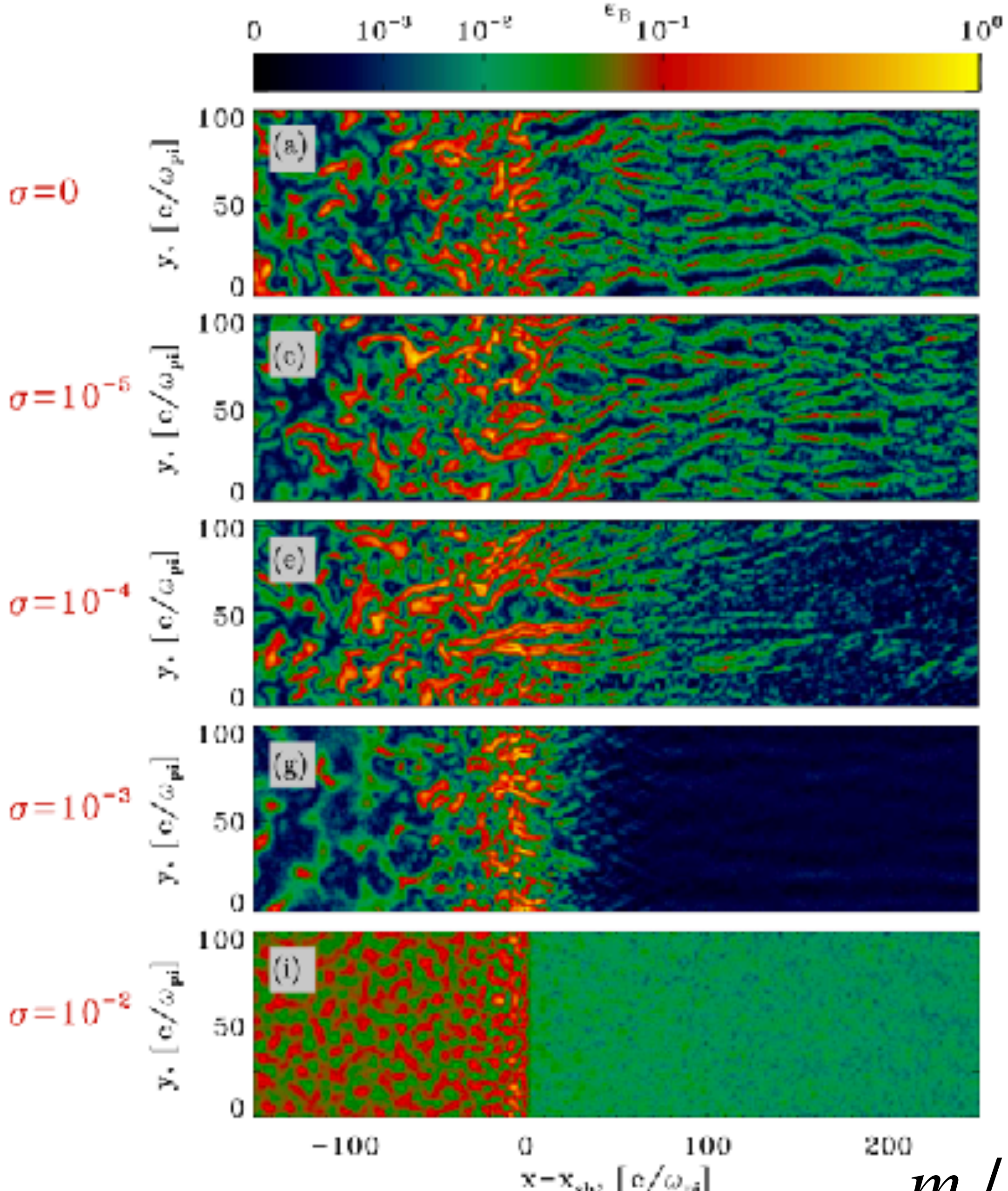


Credit: Arno Vanthieghem

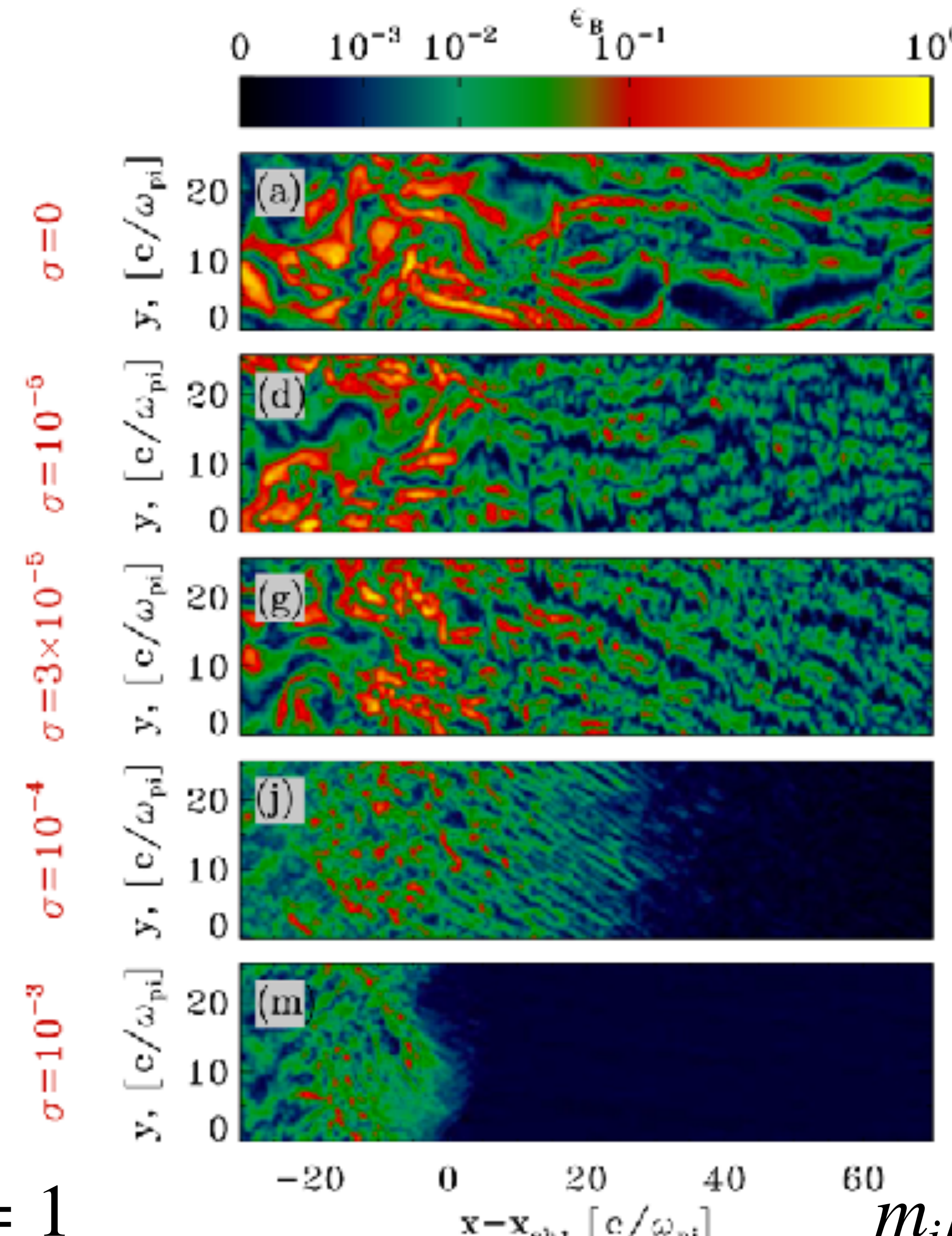
Particle in Cell simulations allow us to probe the shock micro-physics
Confirm that relativistic shocks are efficient accelerators **in certain regimes**

Insights from PIC simulations

2D simulations by Sironi, Spitkovsky & Arons 13



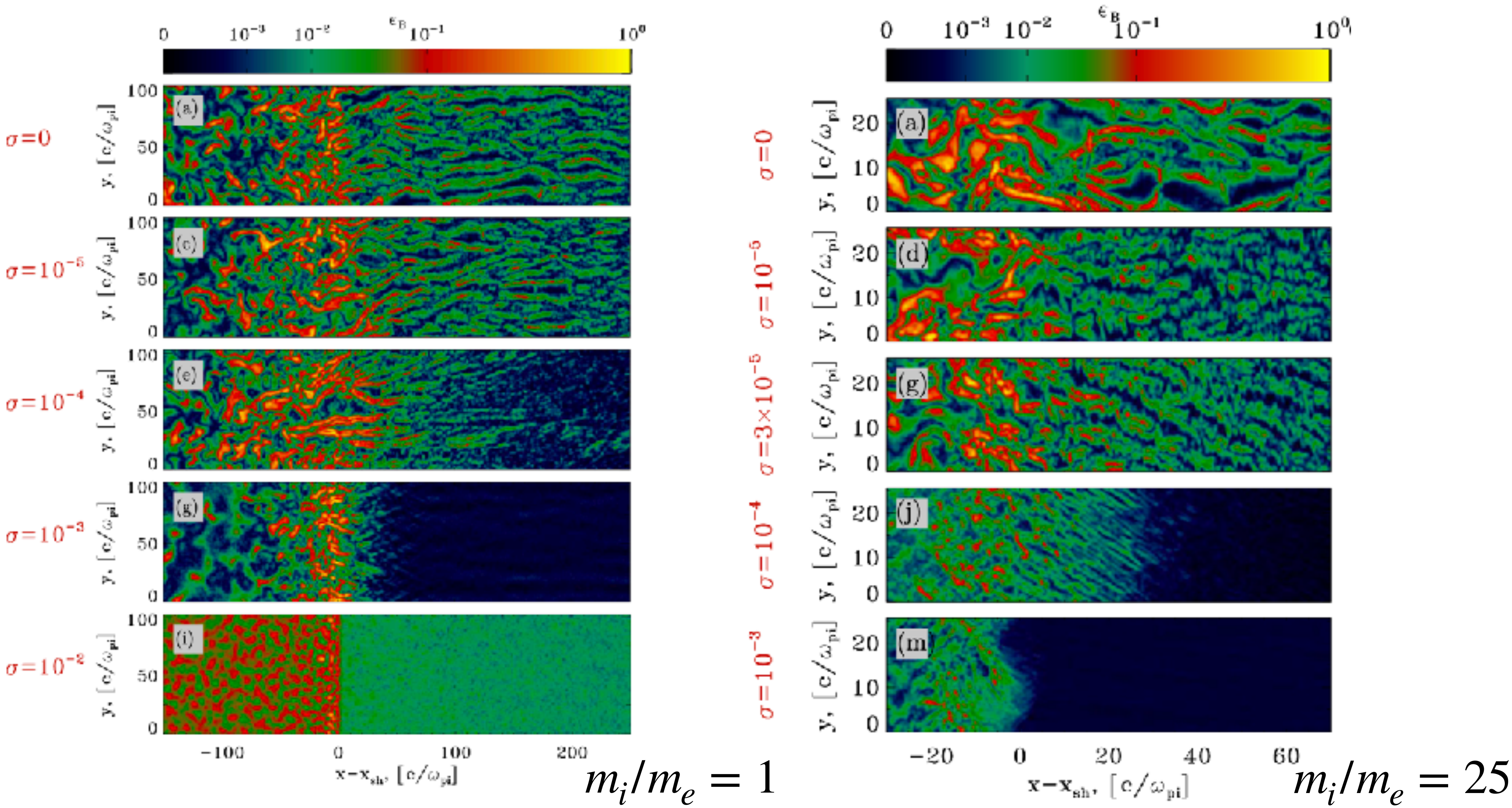
$m_i/m_e = 1$



$m_i/m_e = 25$

Insights from PIC simulations

2D simulations by Sironi, Spitkovsky & Arons 13

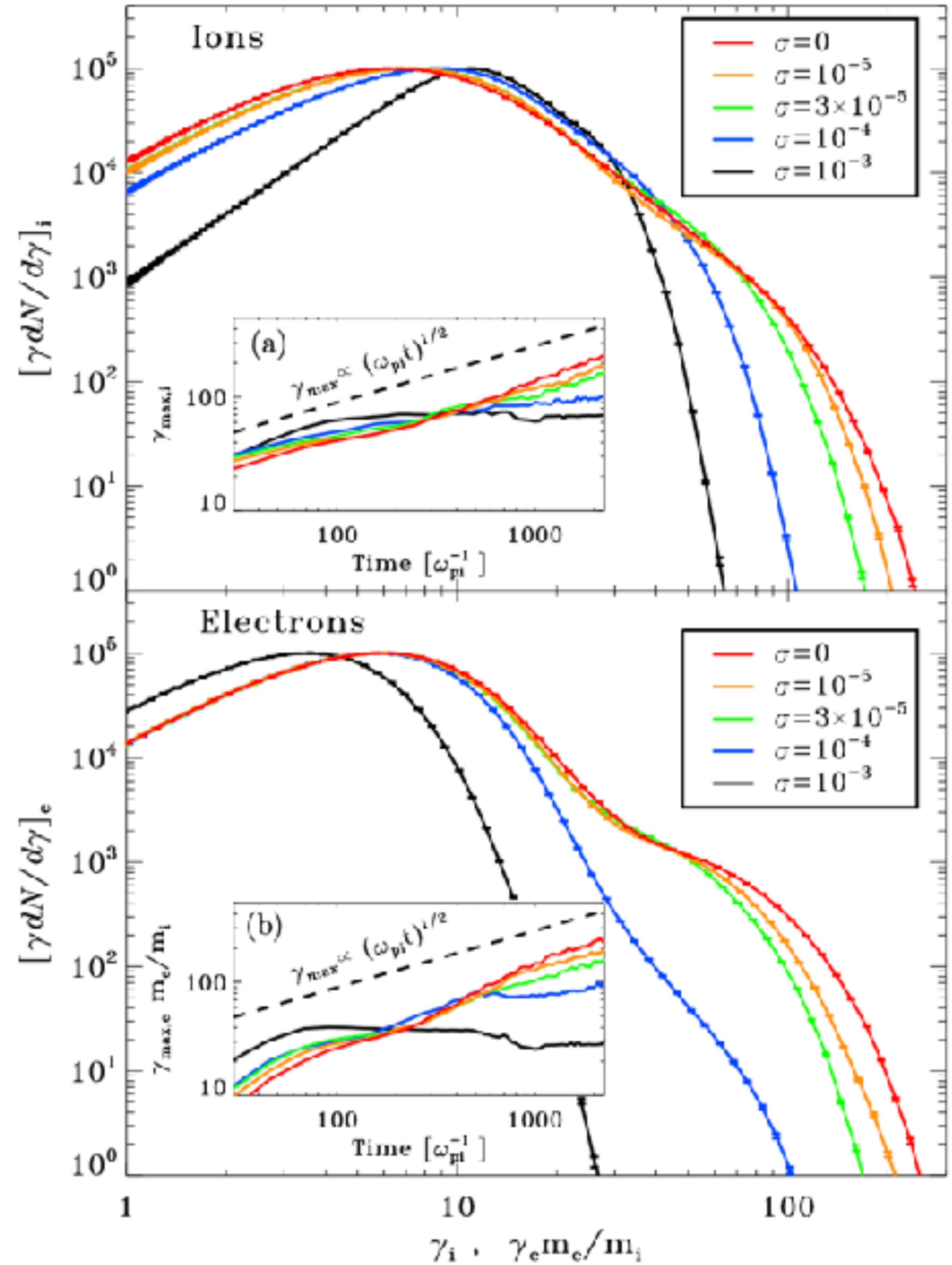


Weakly magnetised shocks appear “turbulent” enough to enable multiple shock crossings - particles can be **unmagnetised** - Fermi accel. proceeds

Non-thermal spectra

Sironi, Spitkovsky & Arons 13

Bulk of particles are thermalised, but for $\sigma < 10^{-3.5}$ (approx) non-thermal spectra appear to be an inevitable outcome.



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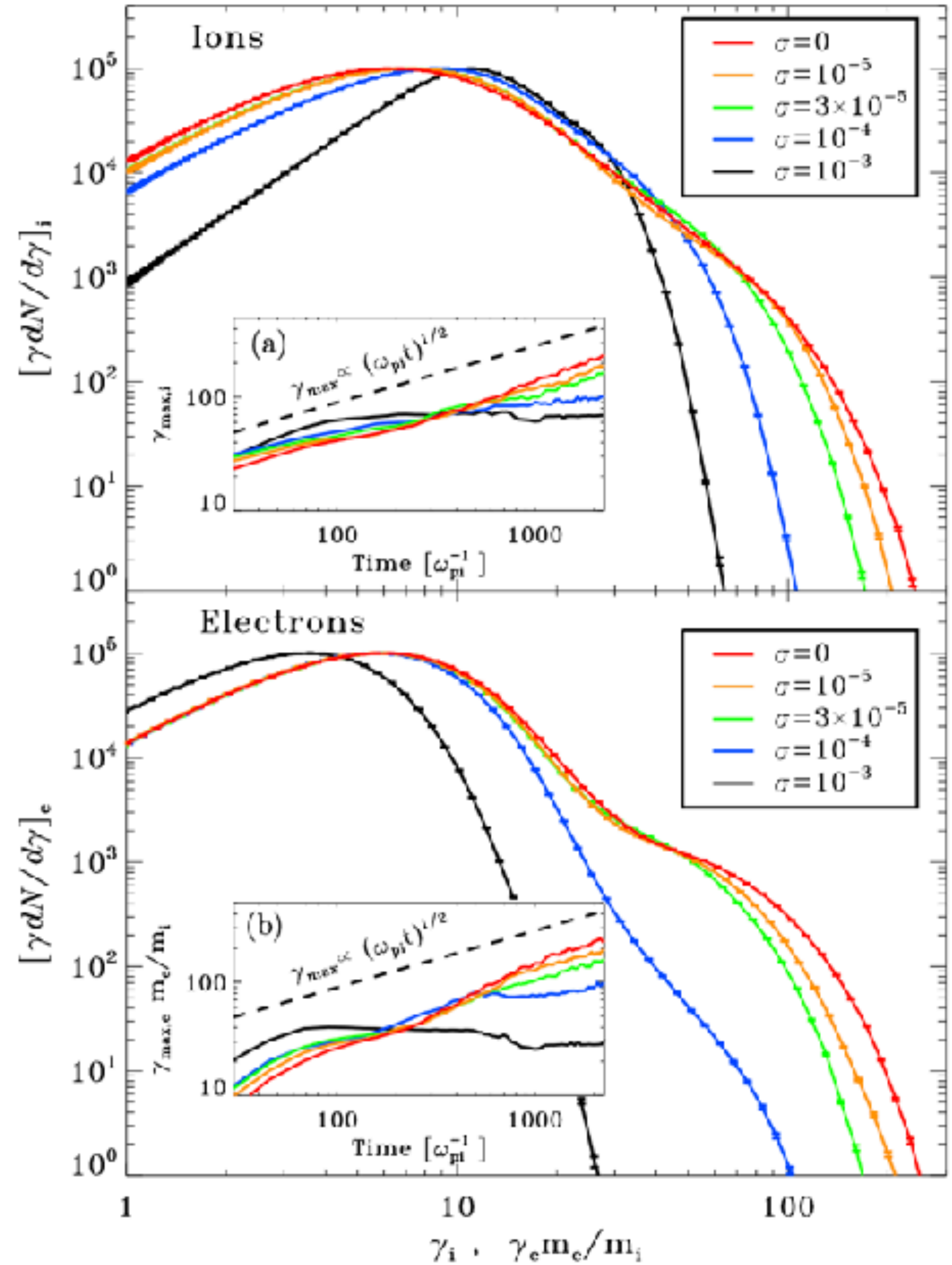
Non-thermal spectra

Sironi, Spitkovsky & Arons 13

Bulk of particles are thermalised, but for $\sigma < 10^{-3.5}$ (approx) non-thermal spectra appear to be an inevitable outcome.

Tails are reasonably consistent with predictions from analytic theory which predict $dN/d\gamma \propto \gamma^{-2.2}$ (Kirk et al. 2000)



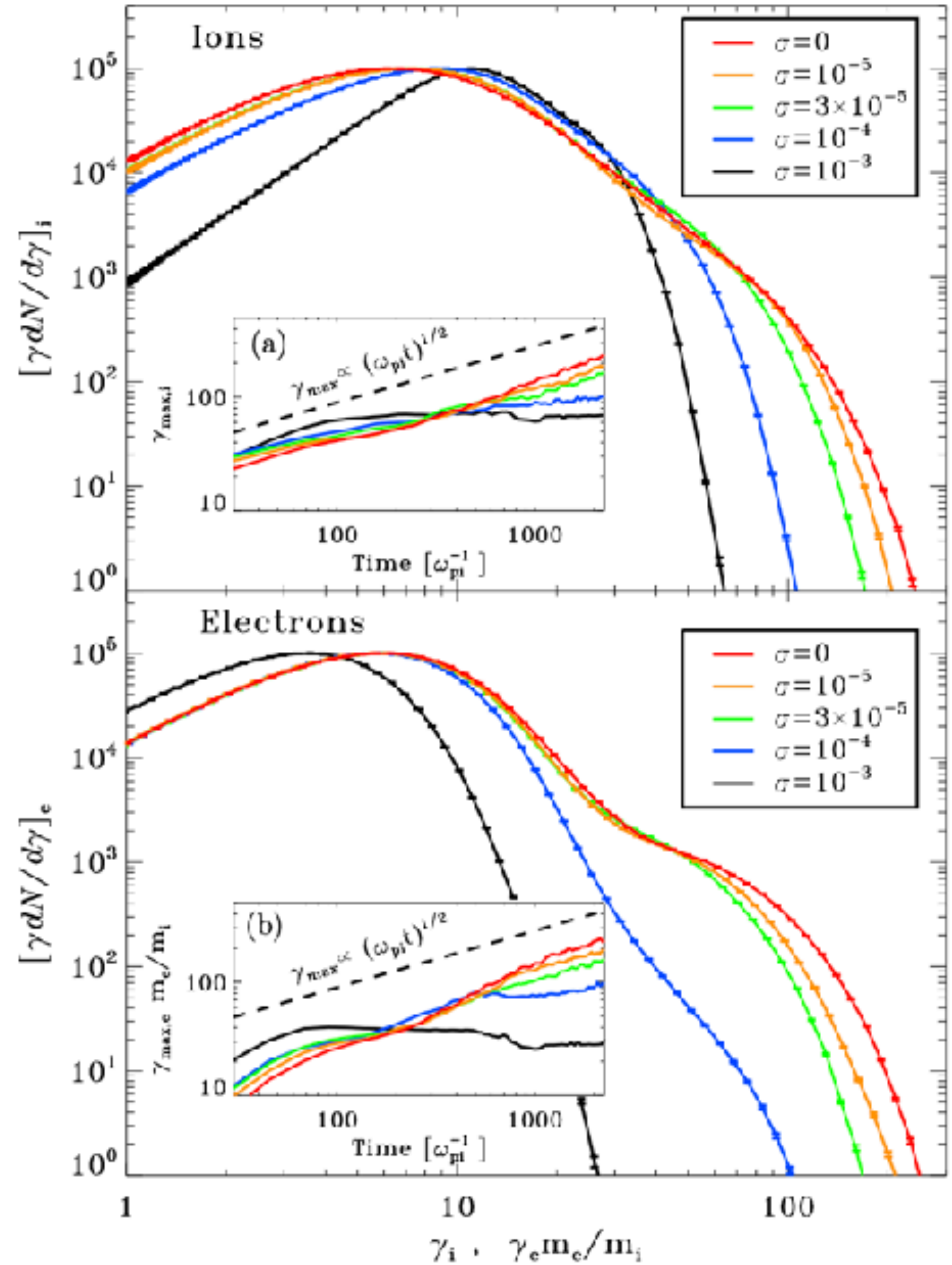
Non-thermal spectra

Bulk of particles are thermalised, but for $\sigma < 10^{-3.5}$ (approx) non-thermal spectra appear to be an inevitable outcome.

Tails are reasonably consistent with predictions from analytic theory which predict $dN/d\gamma \propto \gamma^{-2.2}$ (Kirk et al. 2000)

Acceleration consistent with expectations for small-angle scattering (non-resonant scattering).

Sironi, Spitkovsky & Arons 13



Predicted particle spectrum

Kirk et al. 2000: parallel shock - scattering dominated up & downstream

$$dN/d\gamma \propto \gamma^{-2.2}$$

Achterberg et al 2001: scattering downstream, regular deflection upstream

$$dN/d\gamma \propto \gamma^{-2.2\pm 0.1}$$

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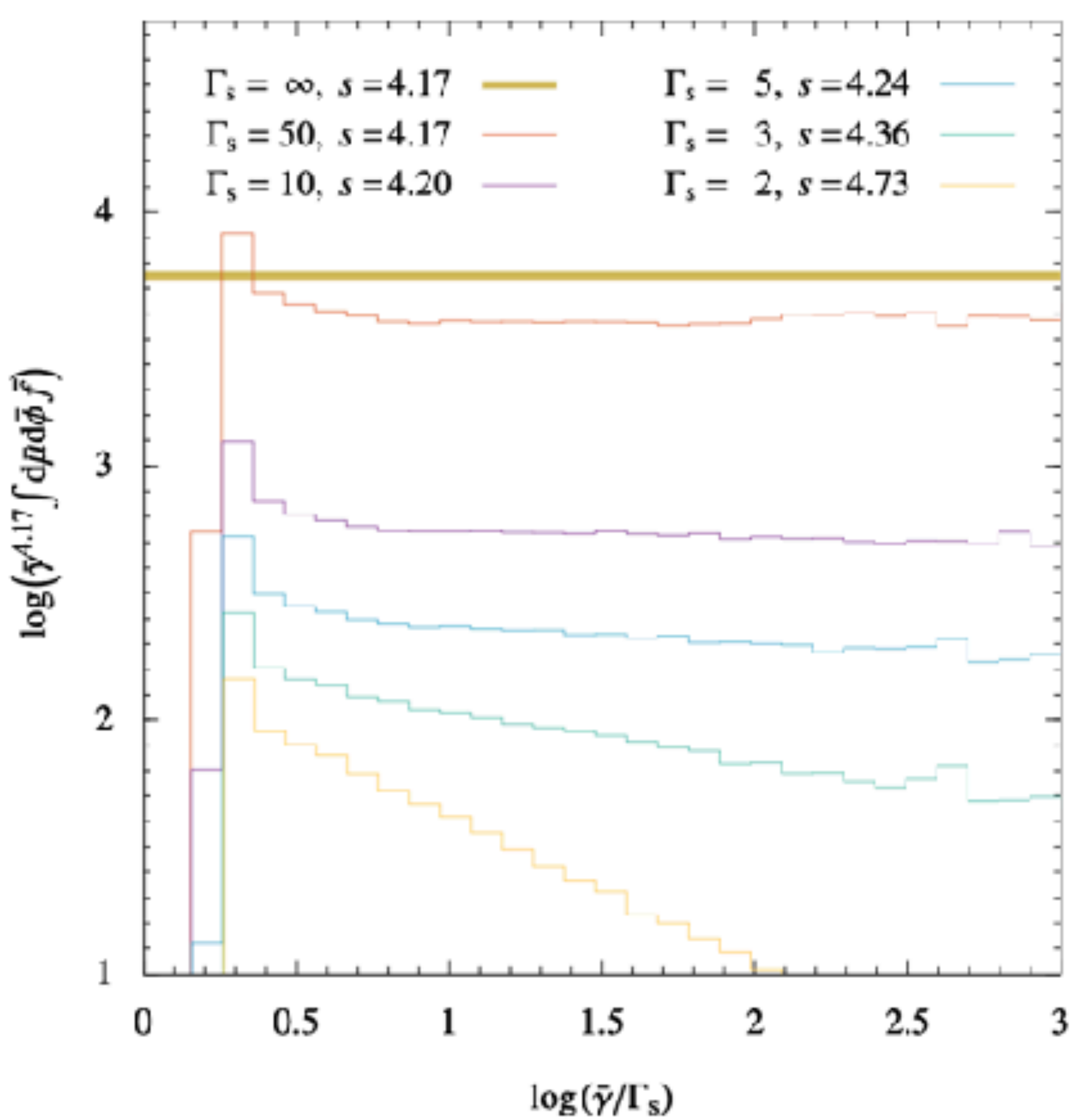

Kirk et al. 2023: Scattering upstream, regular deflection downstream

$$dN/d\gamma \propto \gamma^{-2.17}$$

(Only slightly harder then parallel case)

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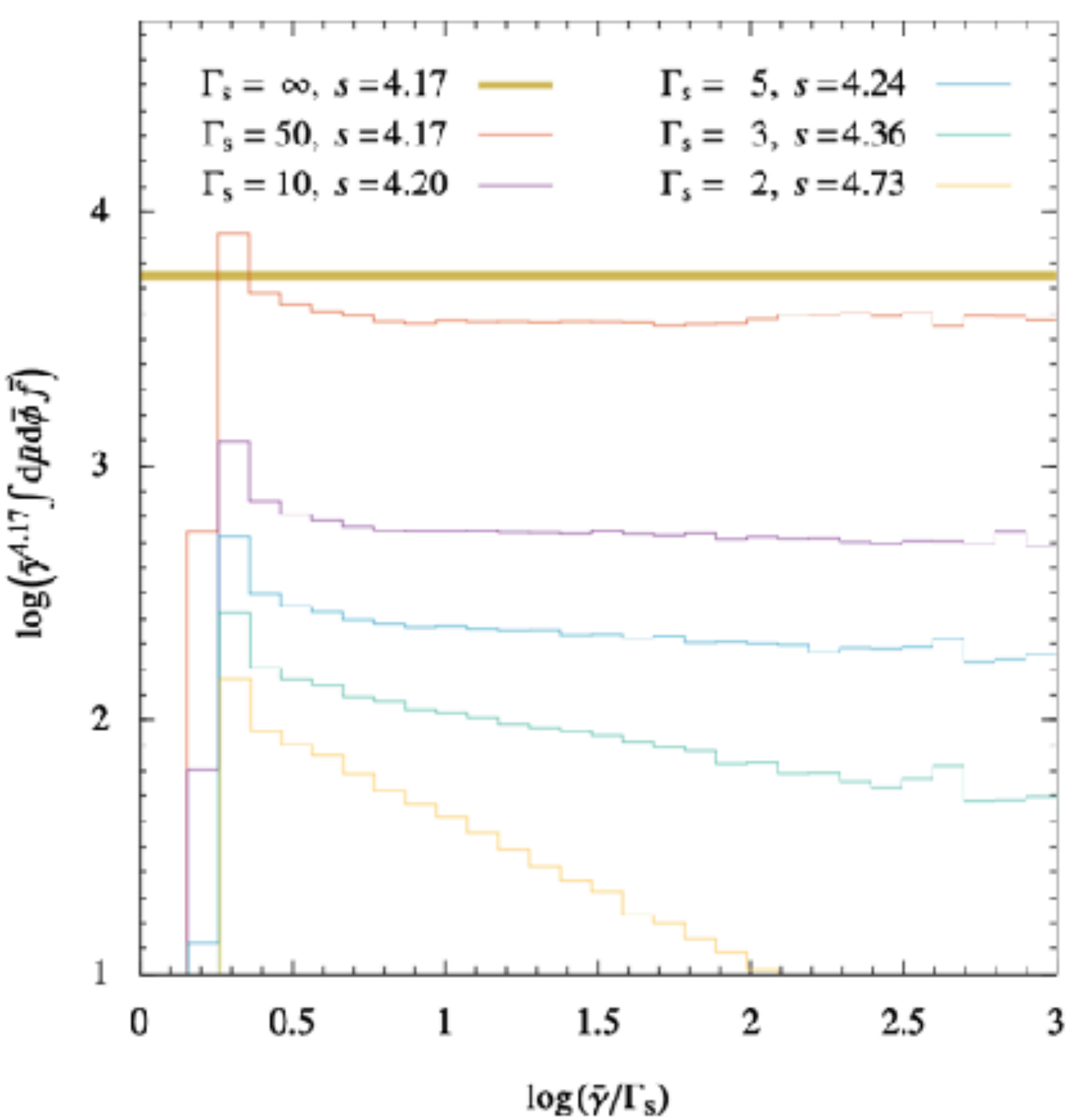

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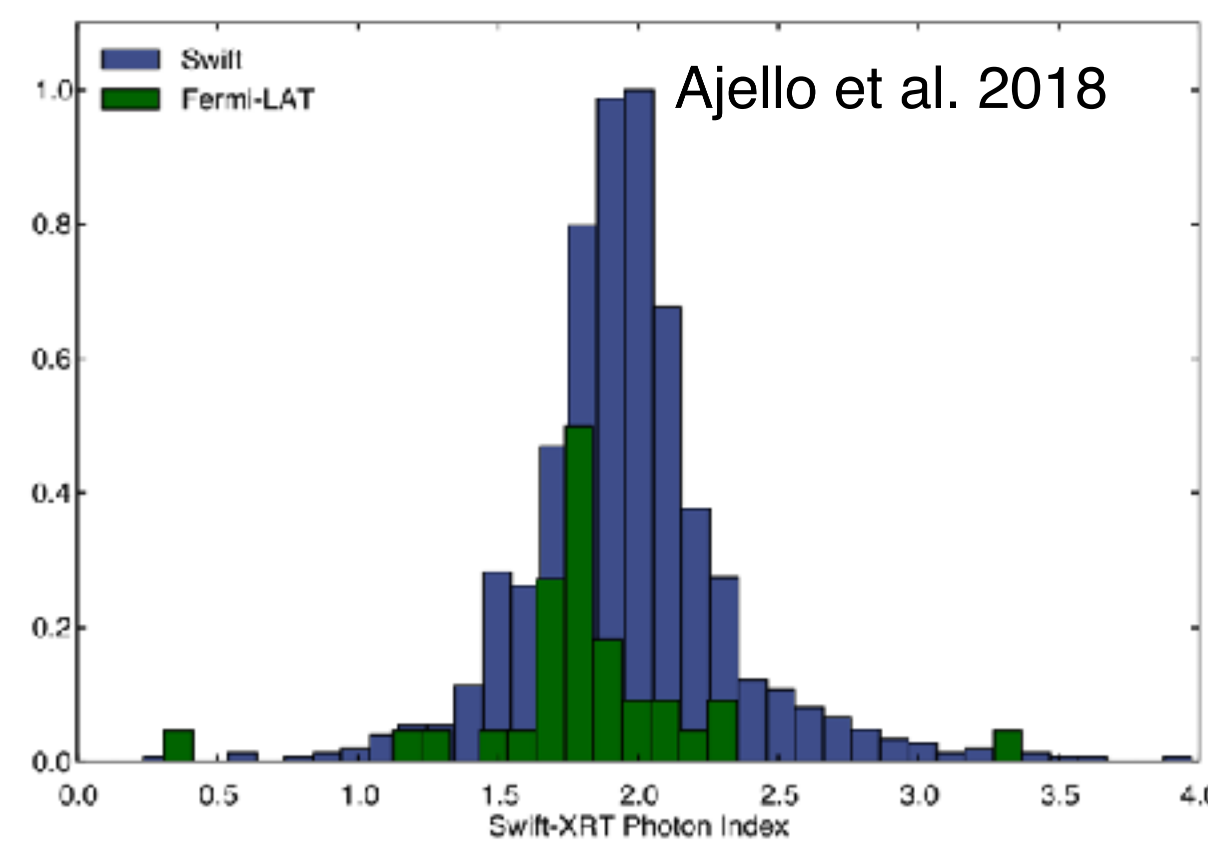
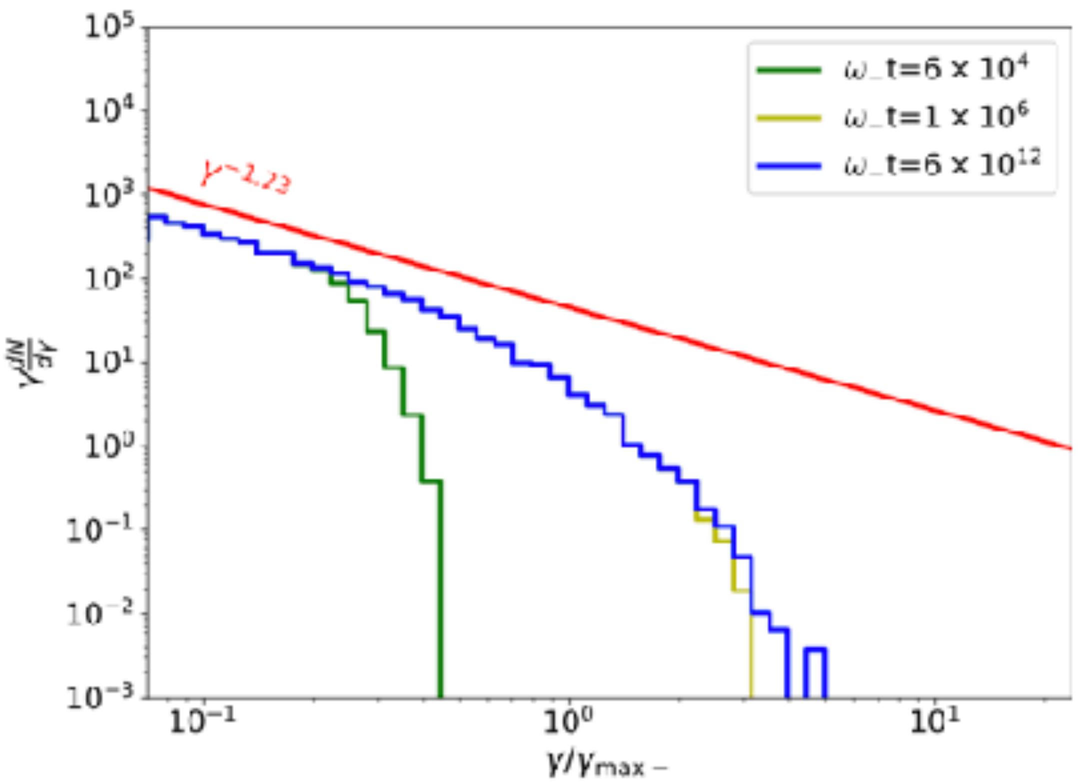


Predicted maximum energy for shocks propagating in large scale uniform fields

Downstream scattering dominated



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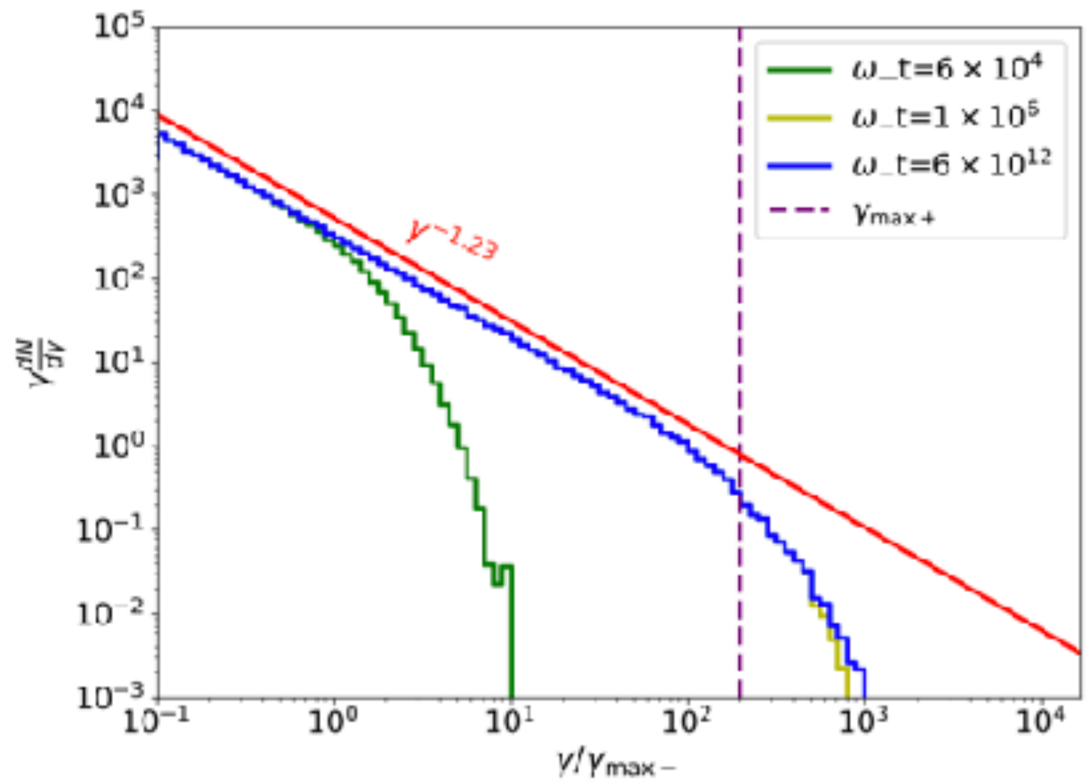

Monte-Carlo simulations from Huang et al 23

In absence of cooling losses, maximum energy is established when particles are magnetised on **both** sides of the shock

Let $\nu_{\rm sc} = \nu_{\pm}\gamma^{-2}$, then $\gamma_{\rm max,\pm}$ found when scatter rate = gyro-rate in mean field

$\gamma_{\rm max,-} = \nu_{-}/\omega_{g,-}$ while. $\gamma_{\rm max,+} = \sqrt{8}\Gamma_{\rm sh}\nu_{+}/\omega_{g,-}$

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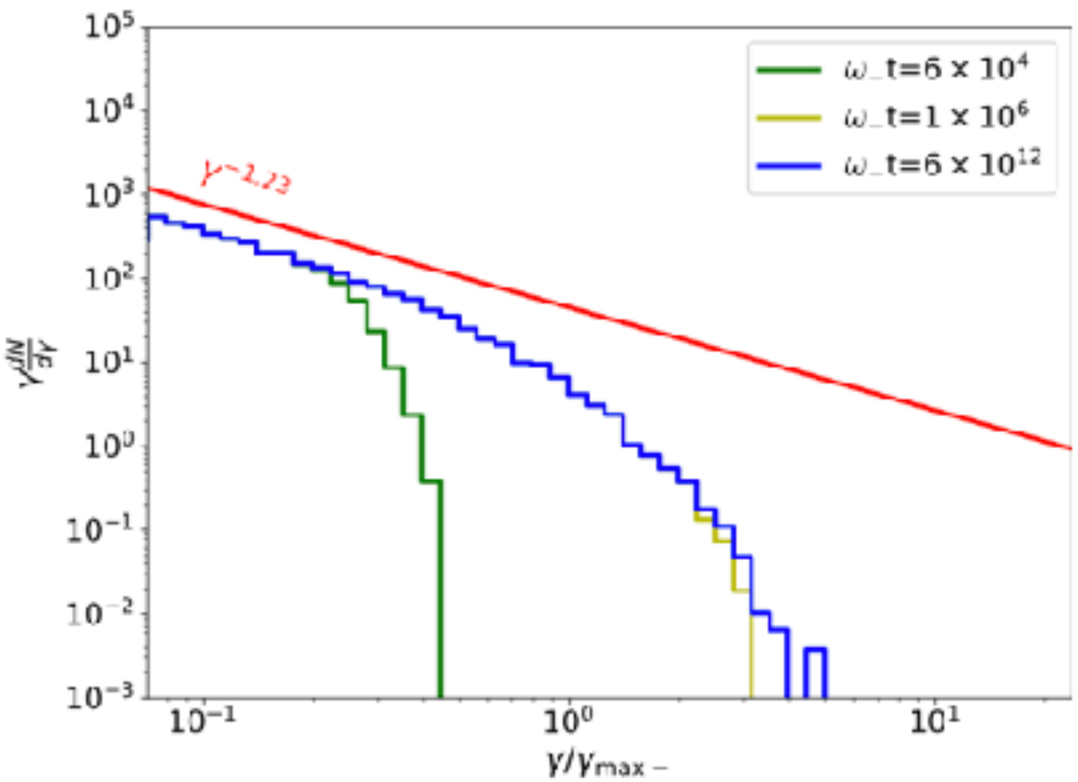

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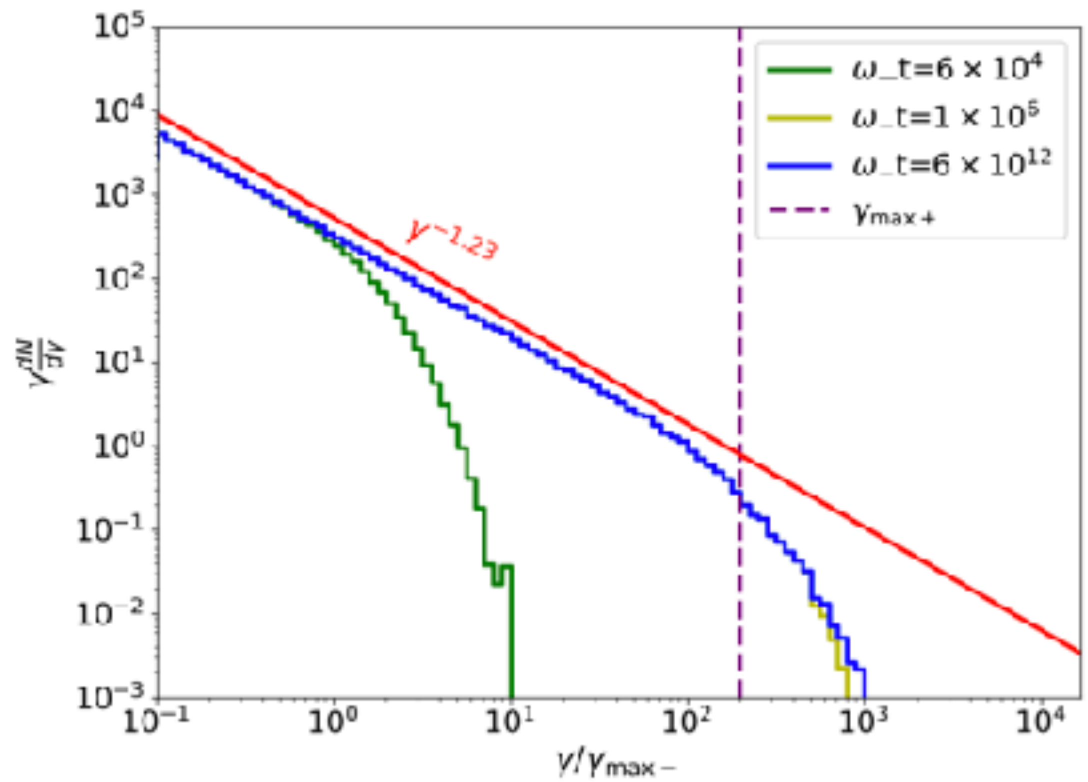

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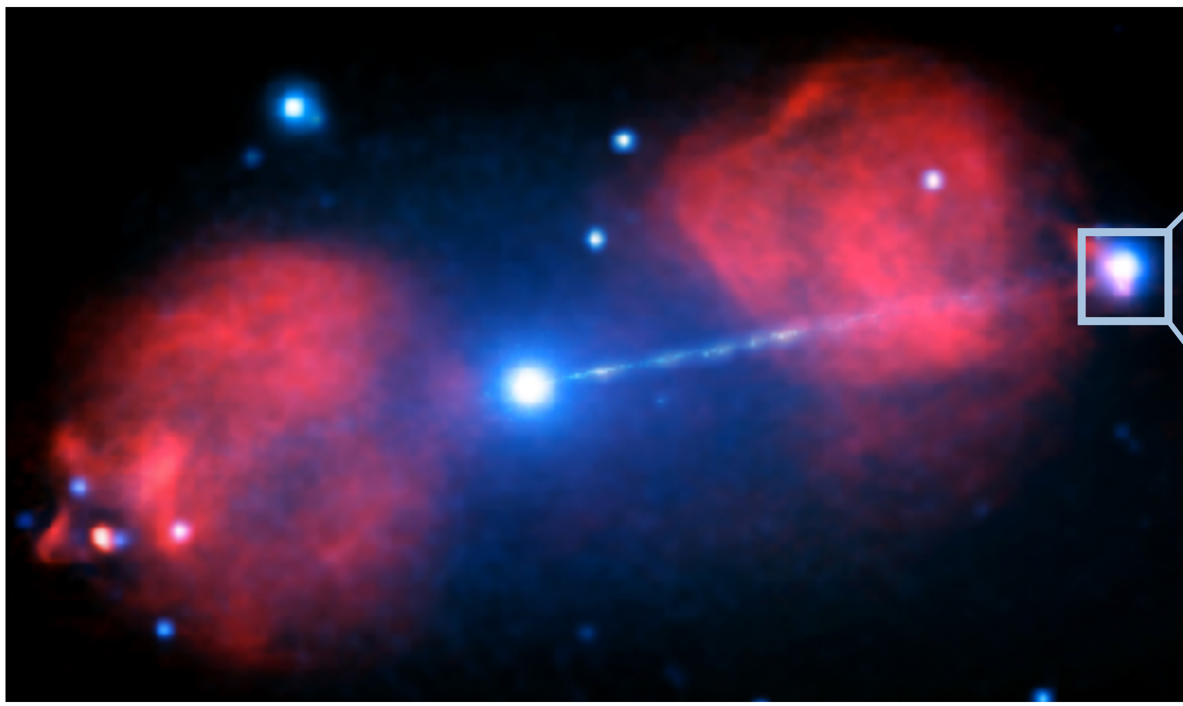
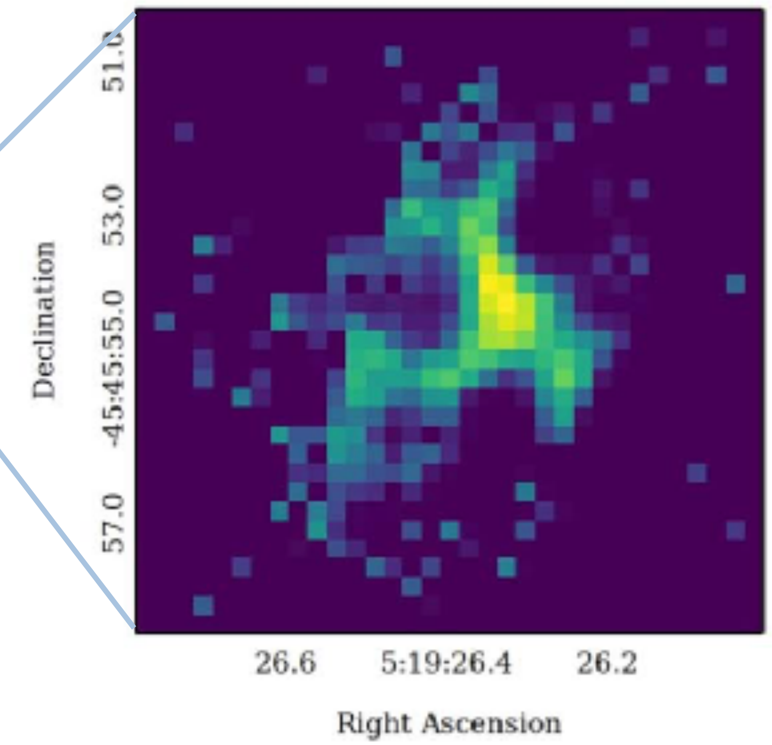
For GRB external shock, synch cut-off in X-rays, for AGN, << keV

X-ray hotspots in Pictor A

Thimmappa et al. ‘22





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X-ray synchrotron - electron energies of ~ 100 TeV

What are we missing?

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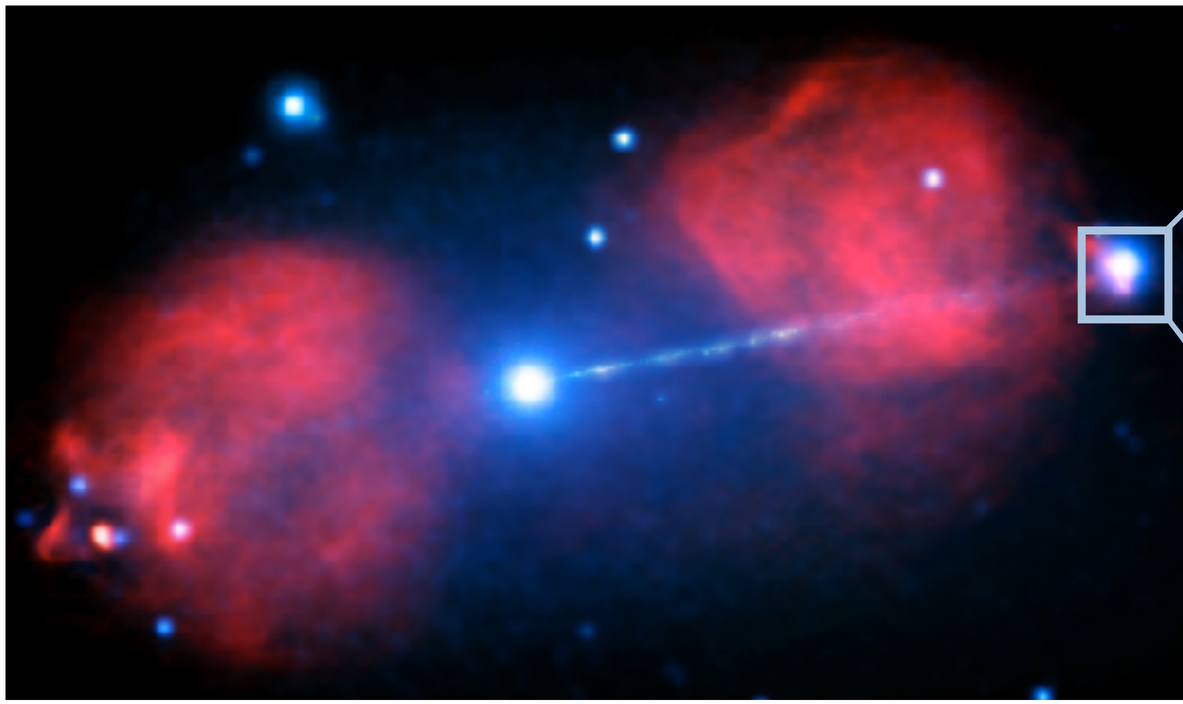

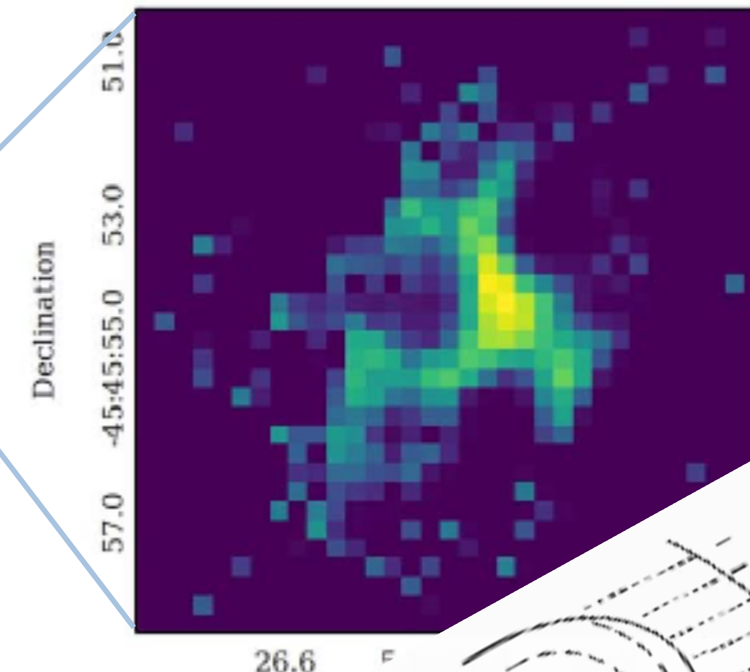

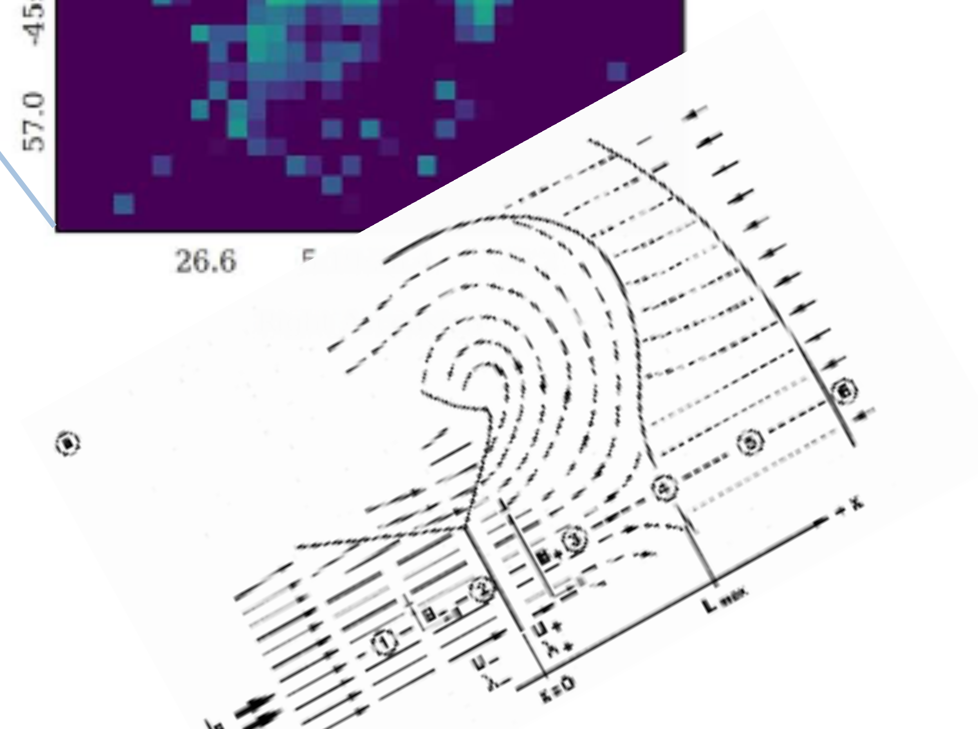

Meisenheimer et al ‘96

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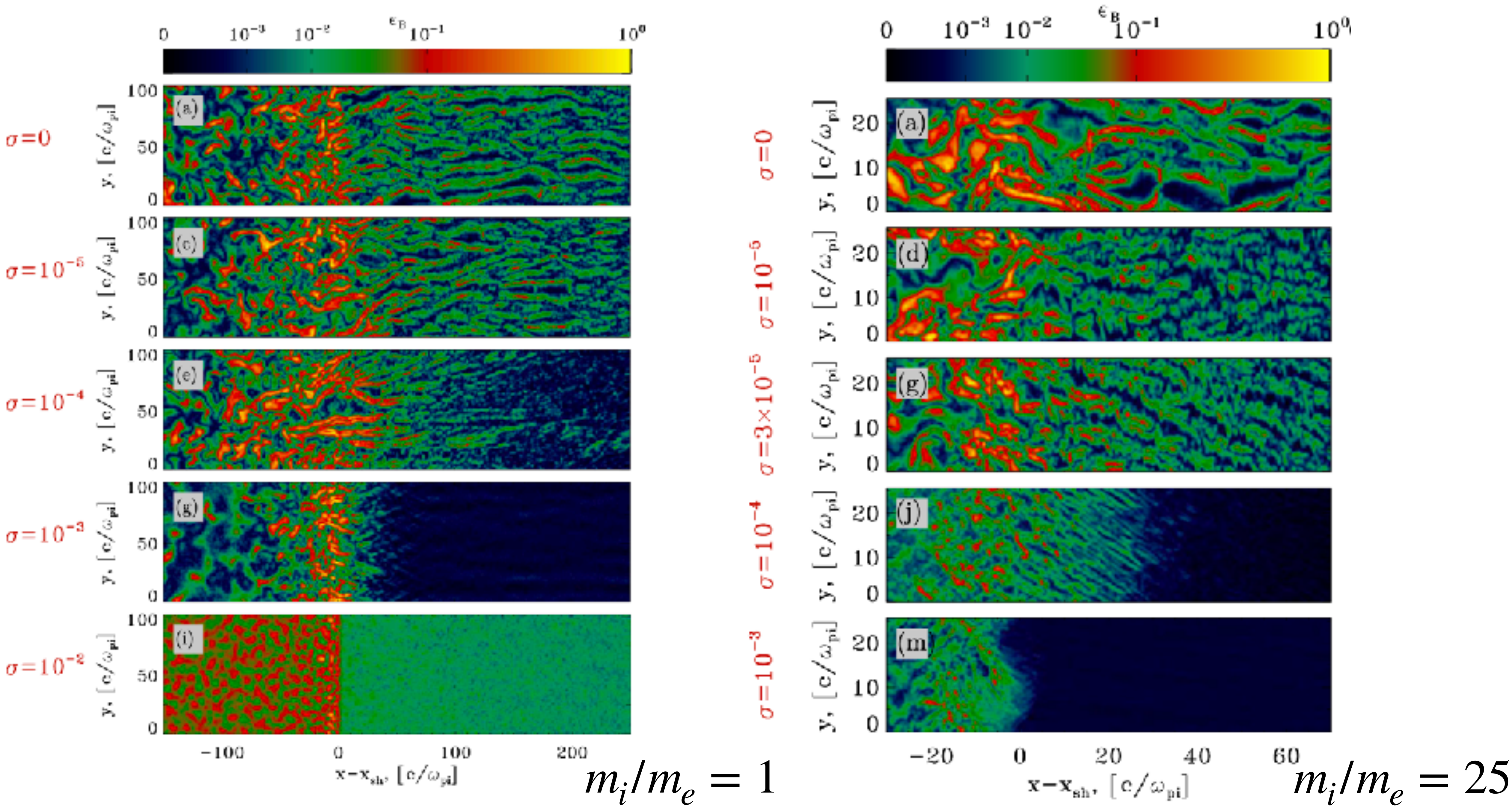

2D simulations by Sironi, Spitkovsky & Arons 13

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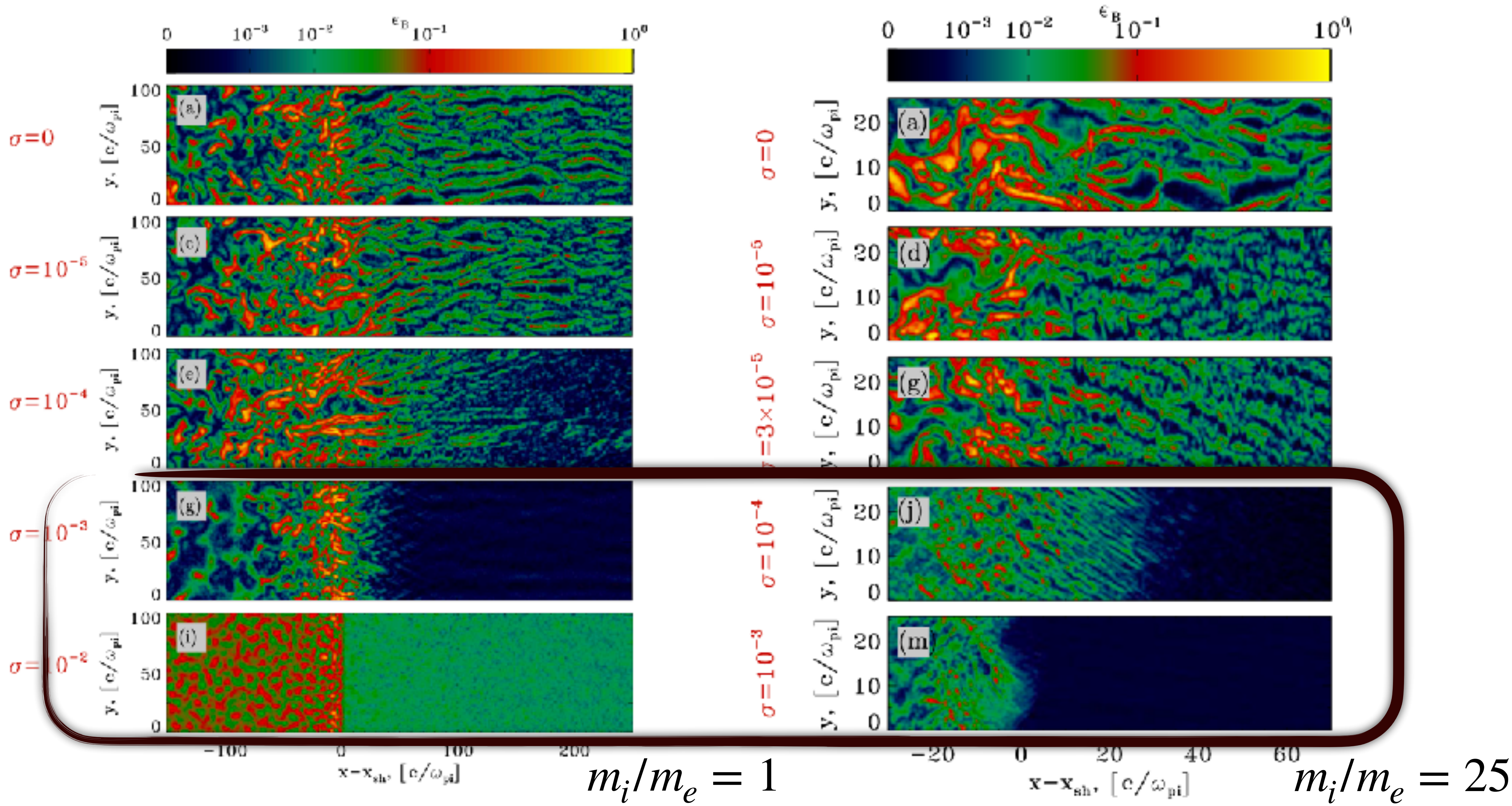

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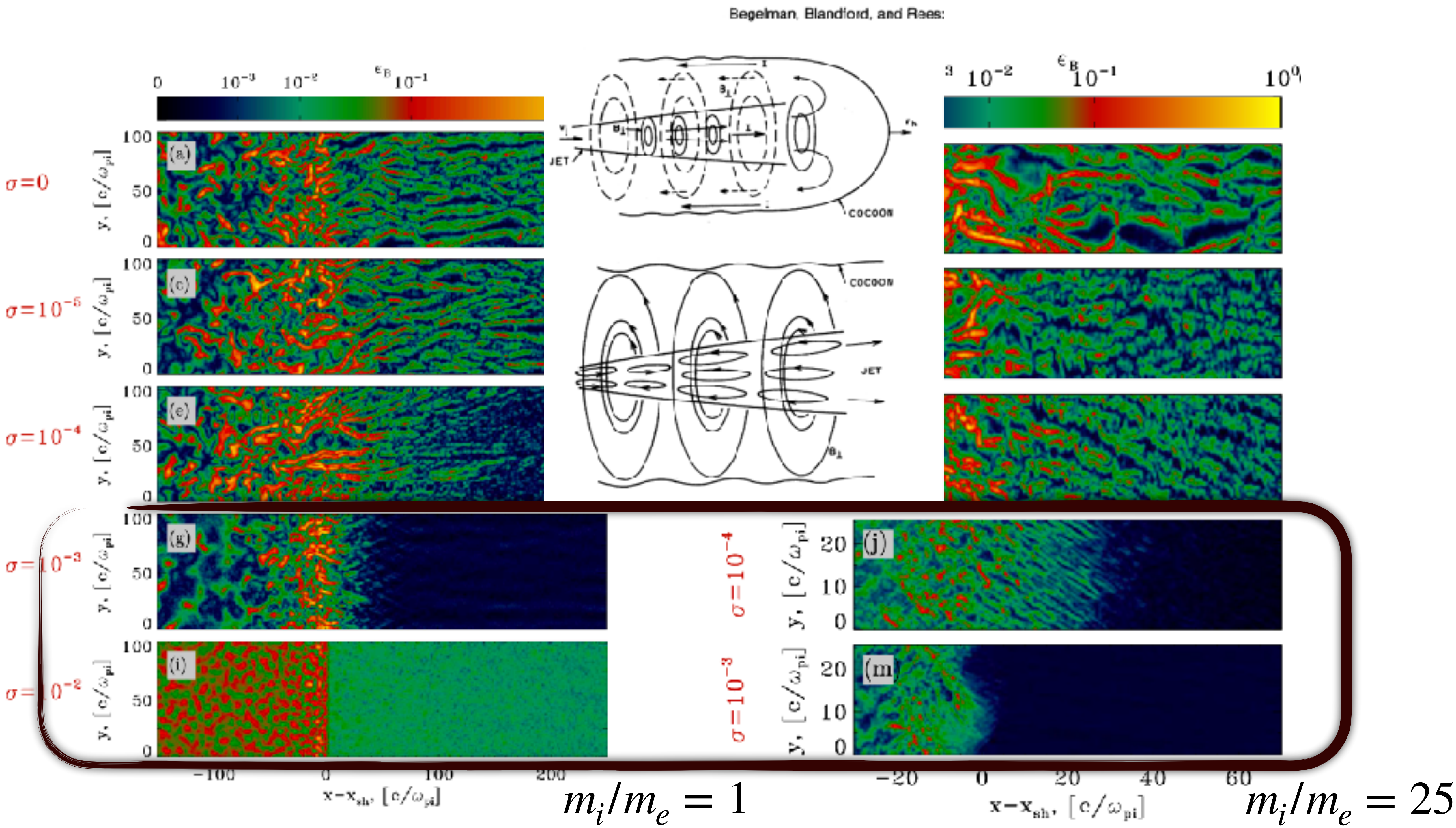

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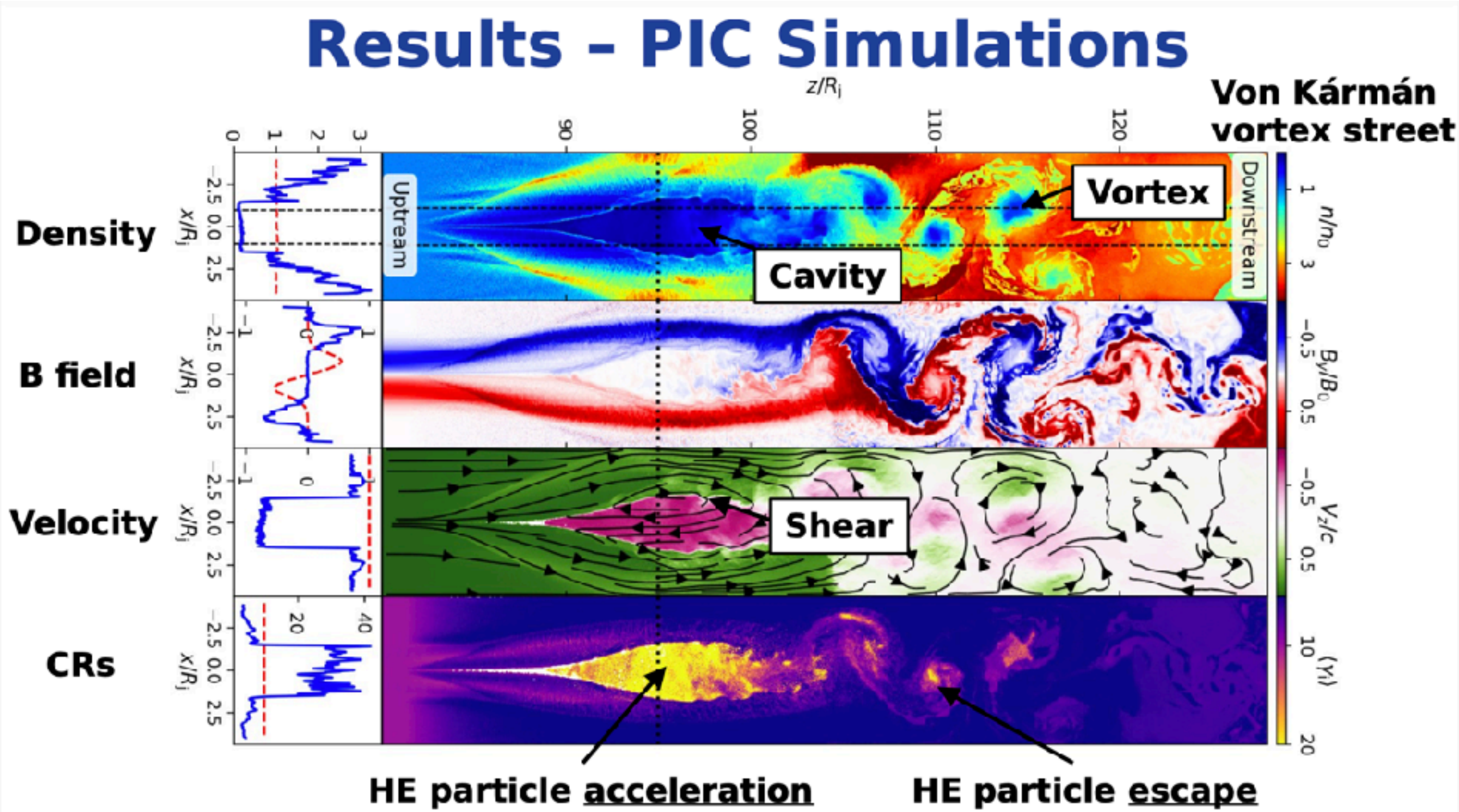
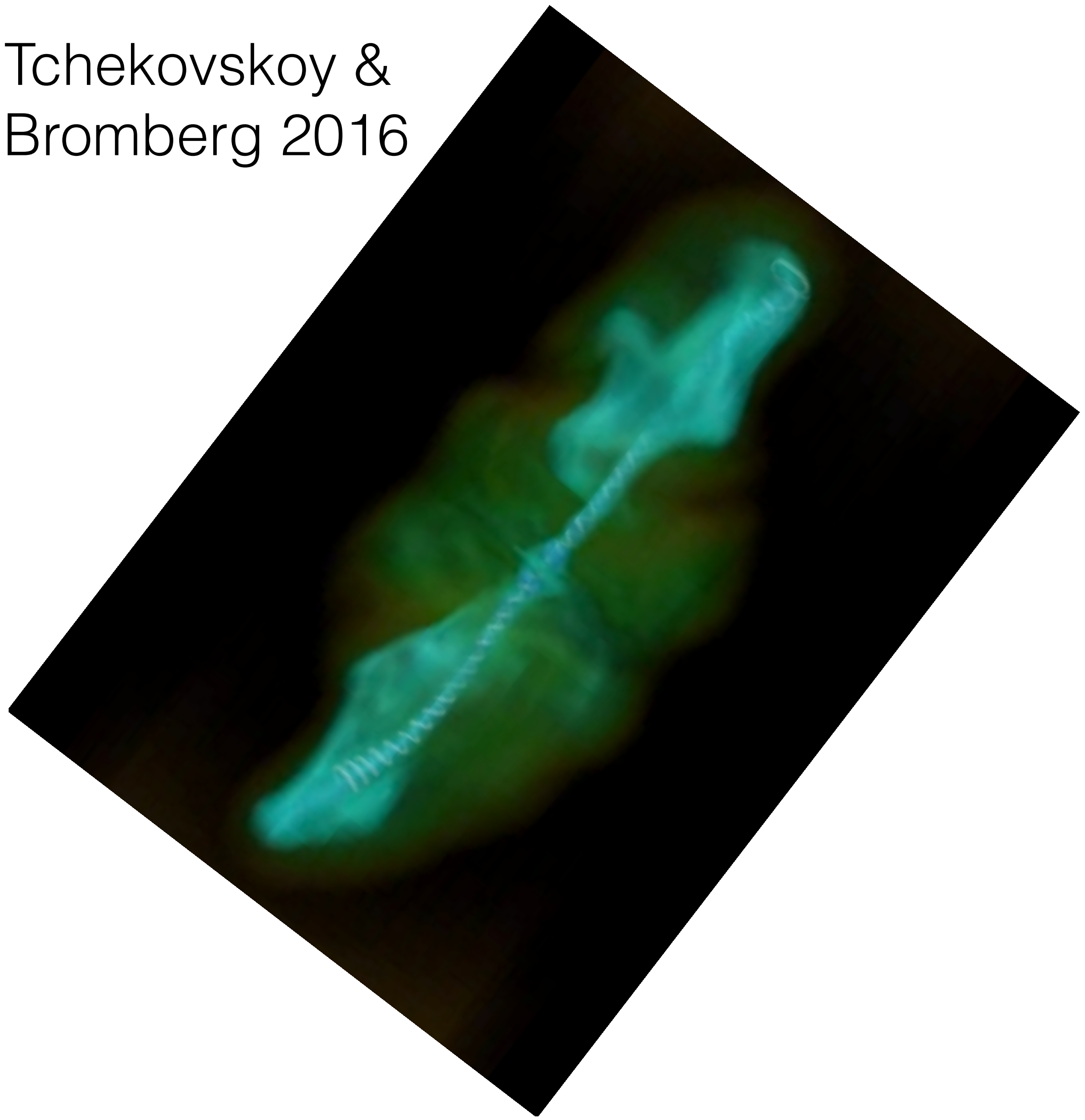


Slide from G. Giacinti's CDY talk, Feb 7

Figure from Cerutti & Giacinti '23

Shocks in current carrying jets

Tchekovskoy &
Bromberg 2016



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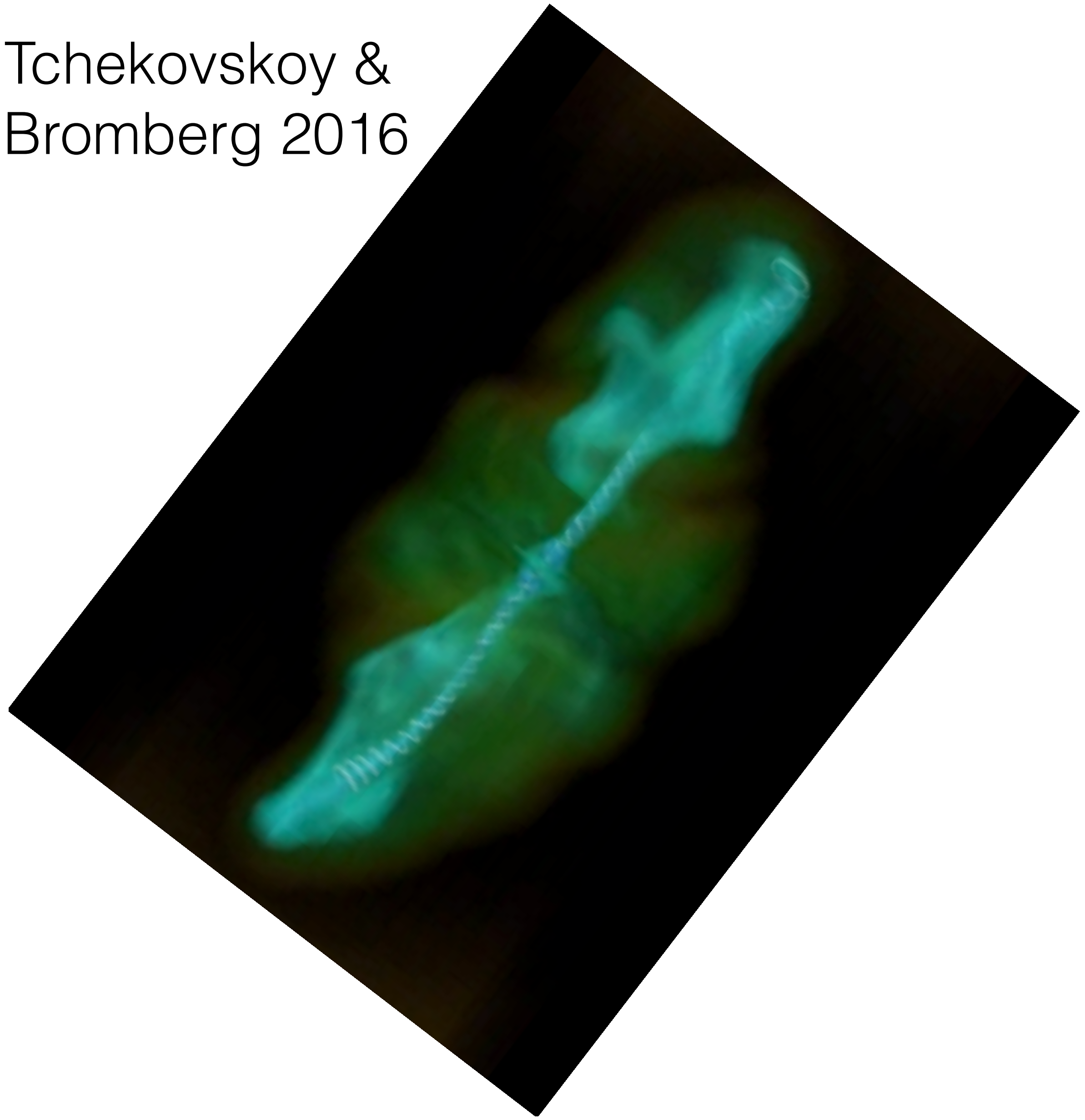
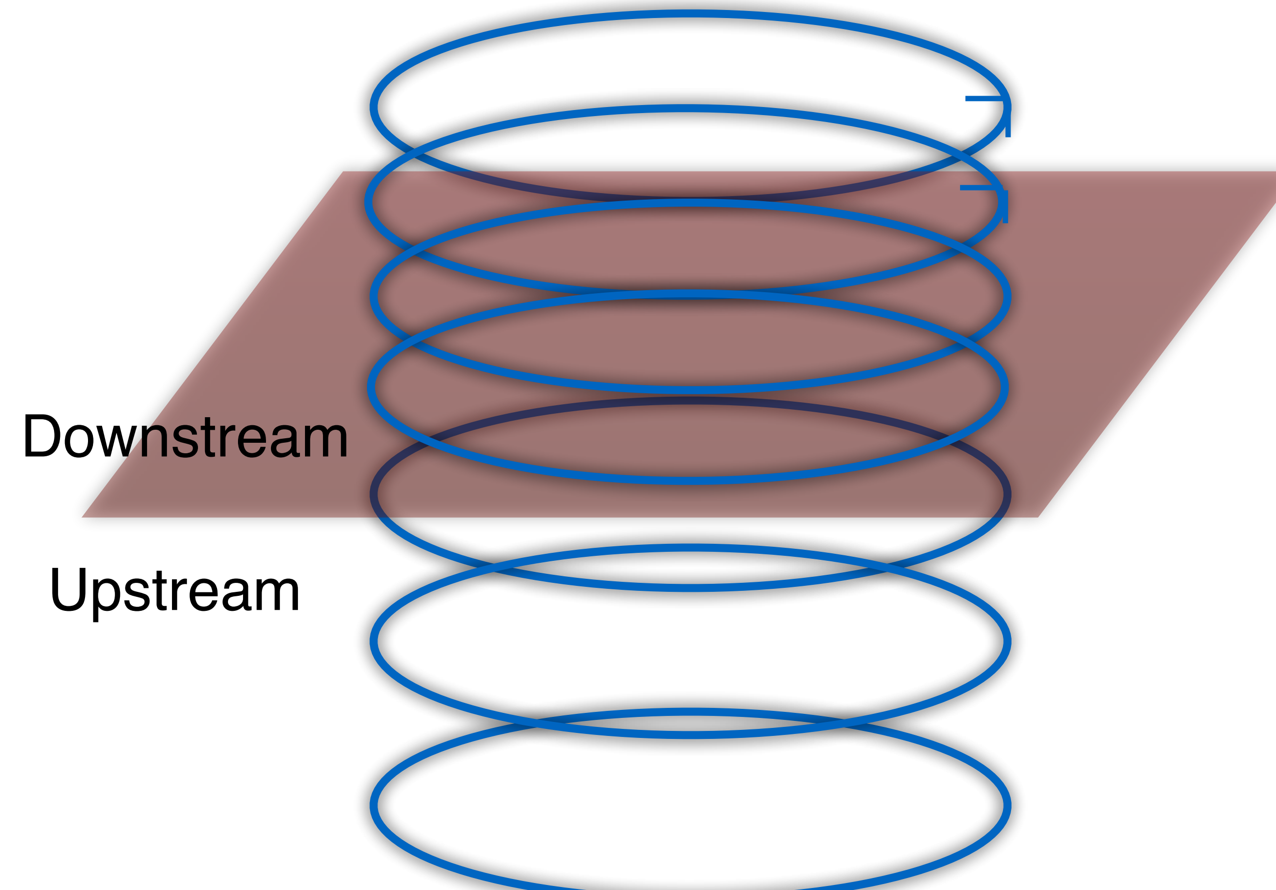


Consider a scatter free trajectory

Far from axis, we approximate
$$\mathbf{A} = -B_0\rho\ \hat{\mathbf{z}} \Rightarrow \mathbf{B} = B_0\hat{\phi}$$

γ, P_z and P_ϕ are constants of motion



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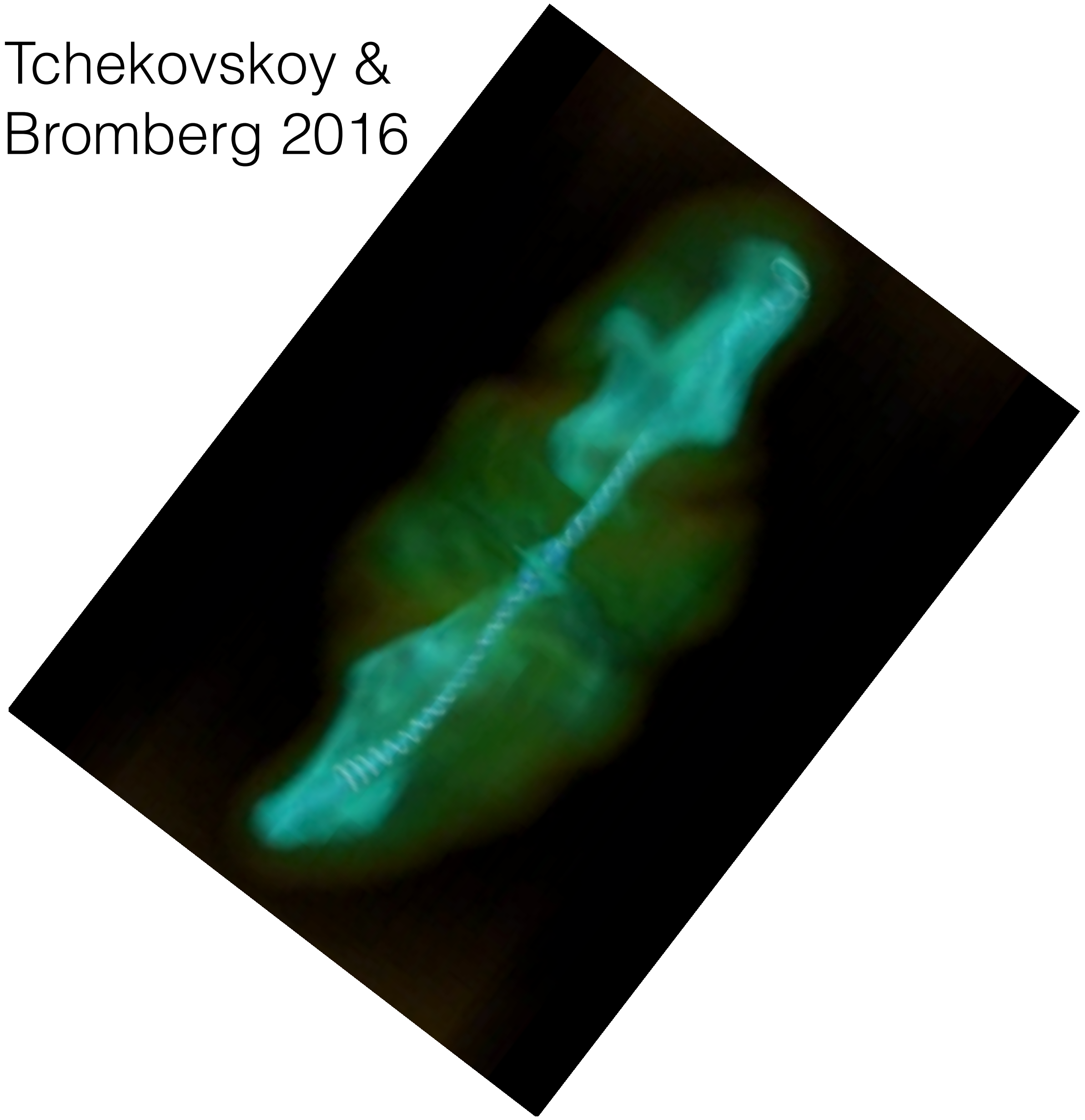

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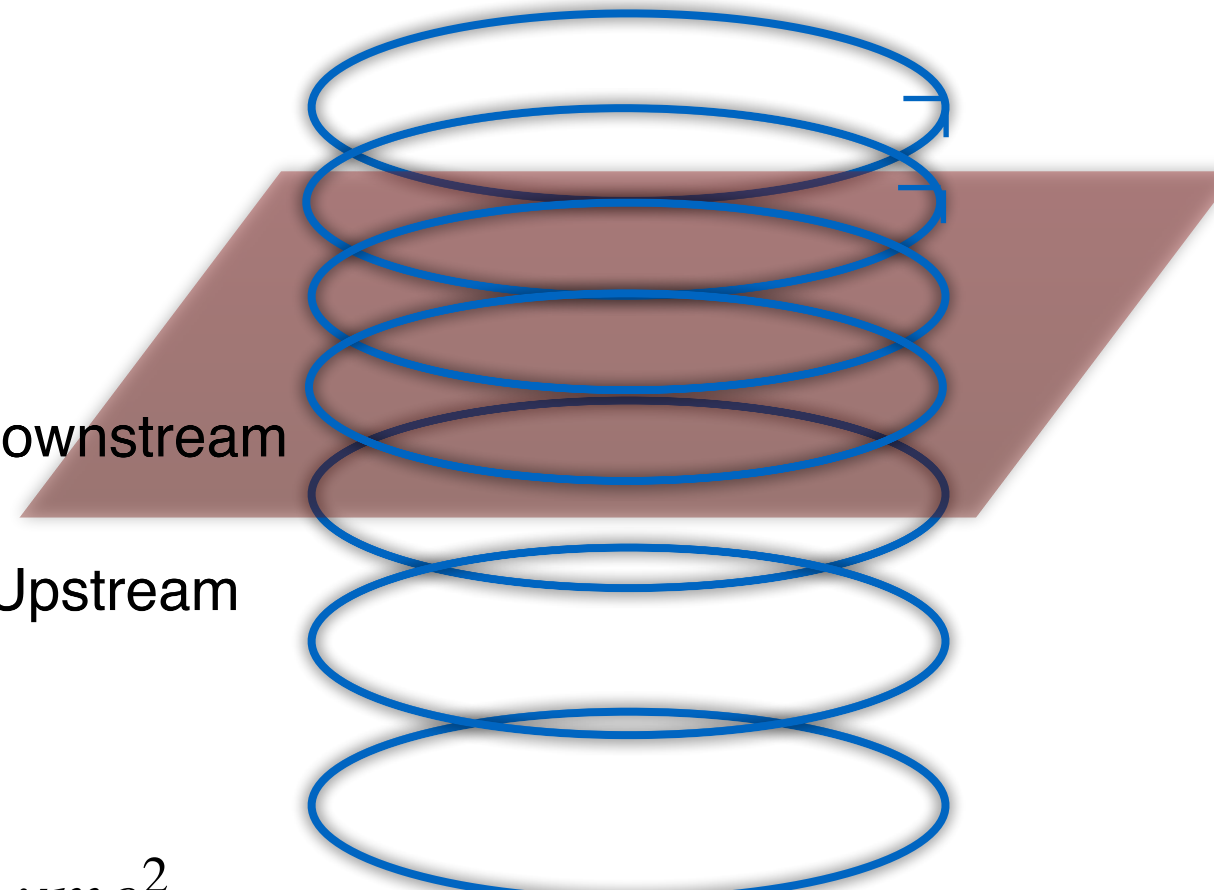

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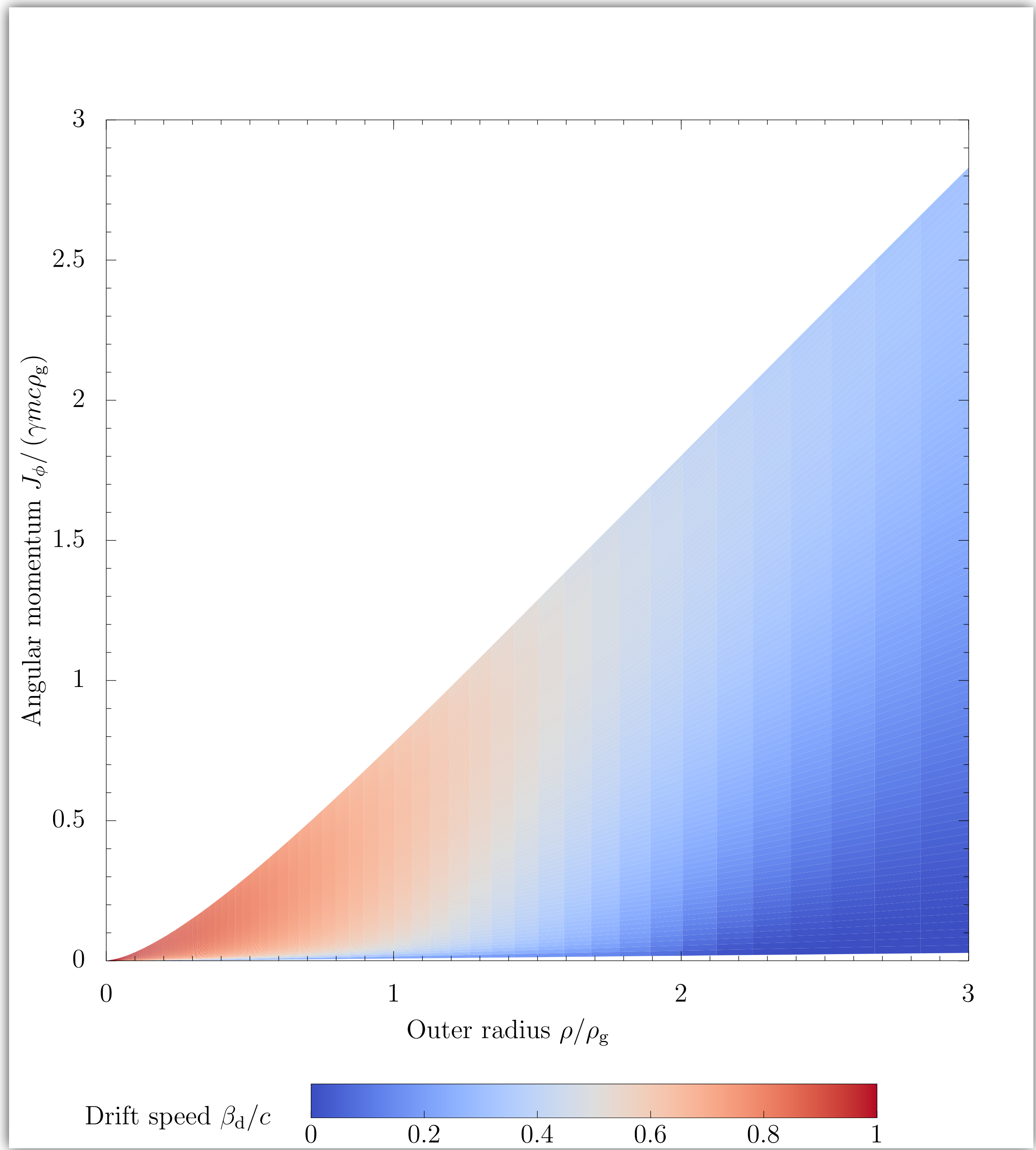

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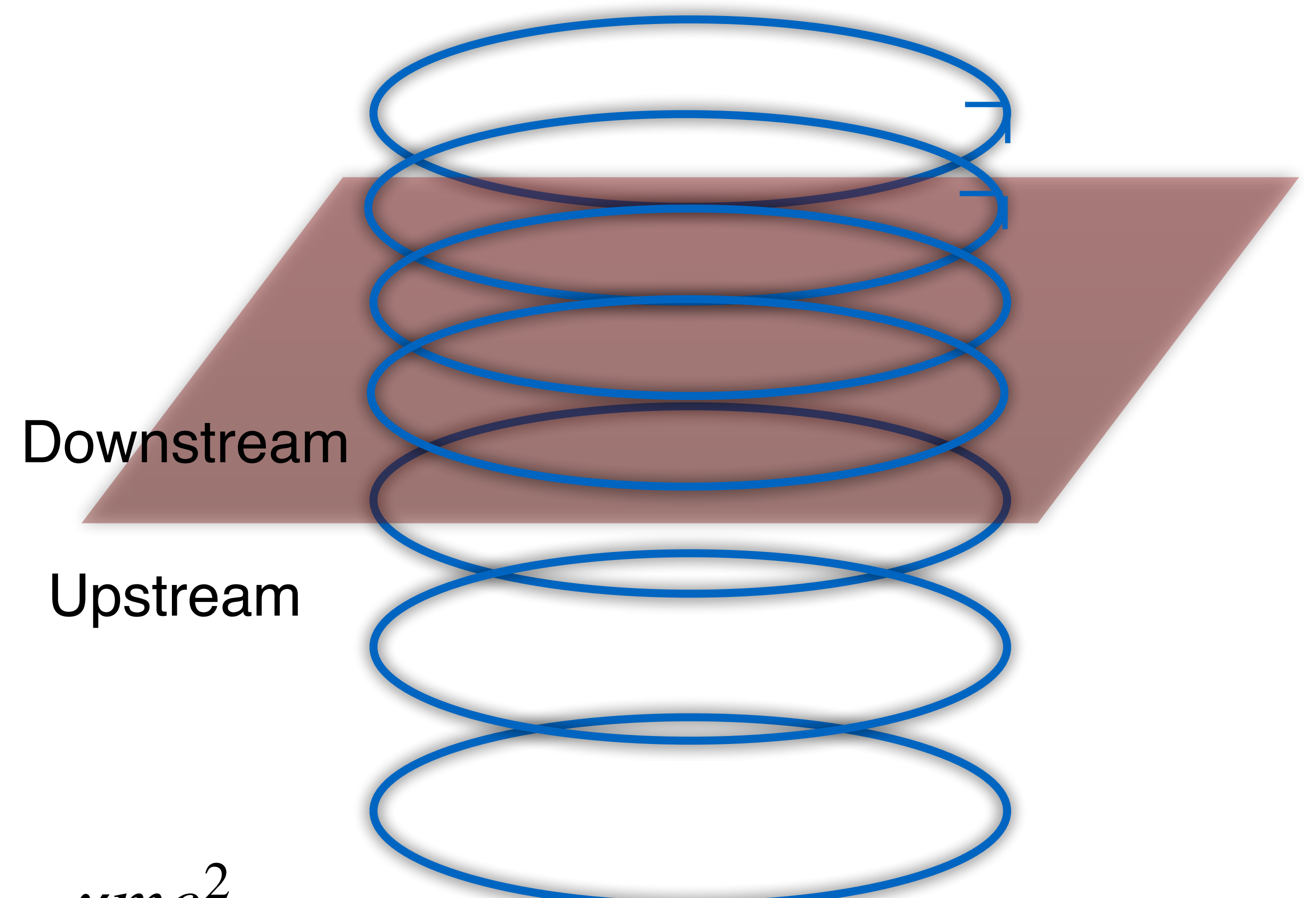

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Shocks in cylindrical field jets

Monte Carlo simulations of particle accelerated at ultra-relativistic shock. Assumes:

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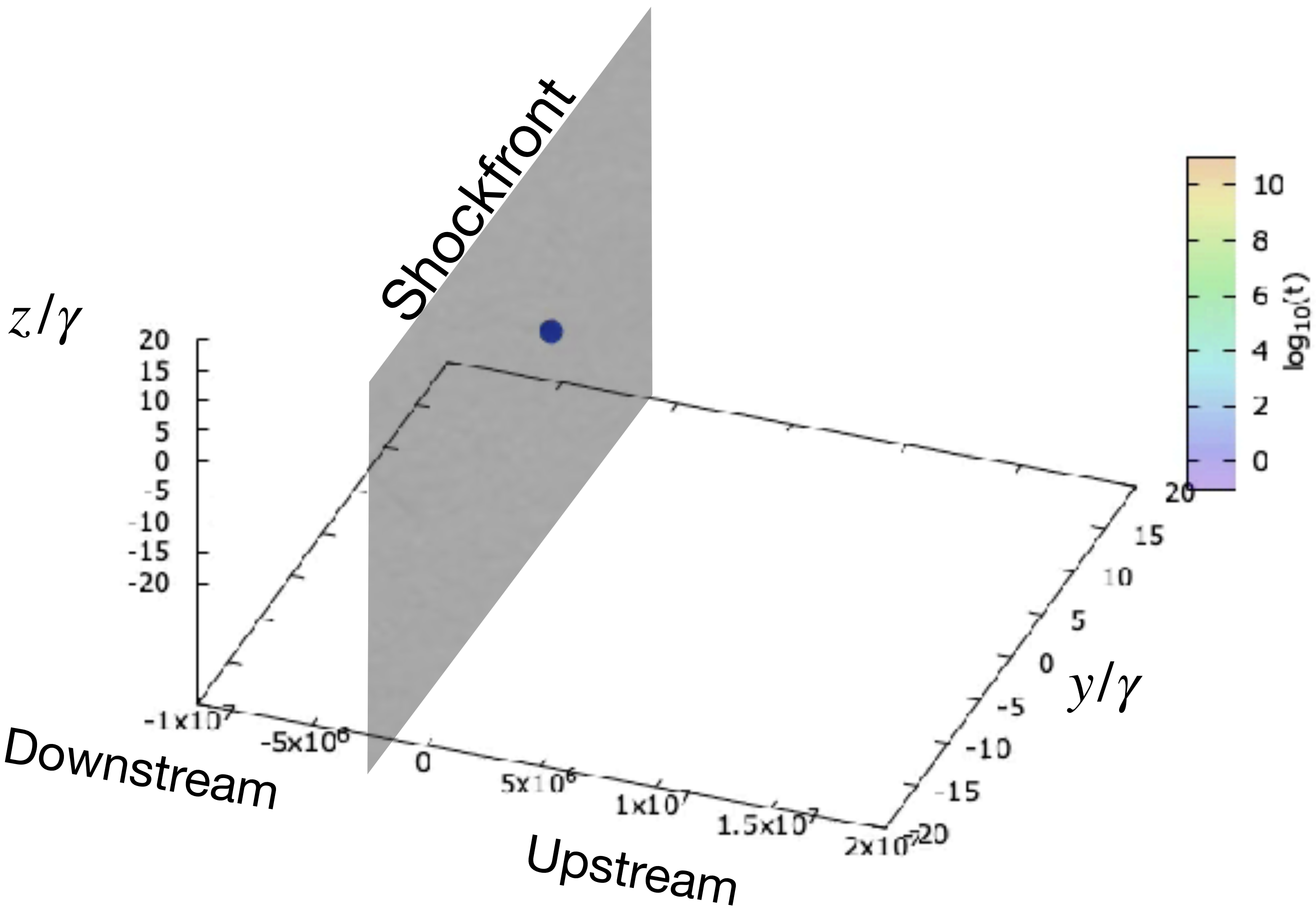

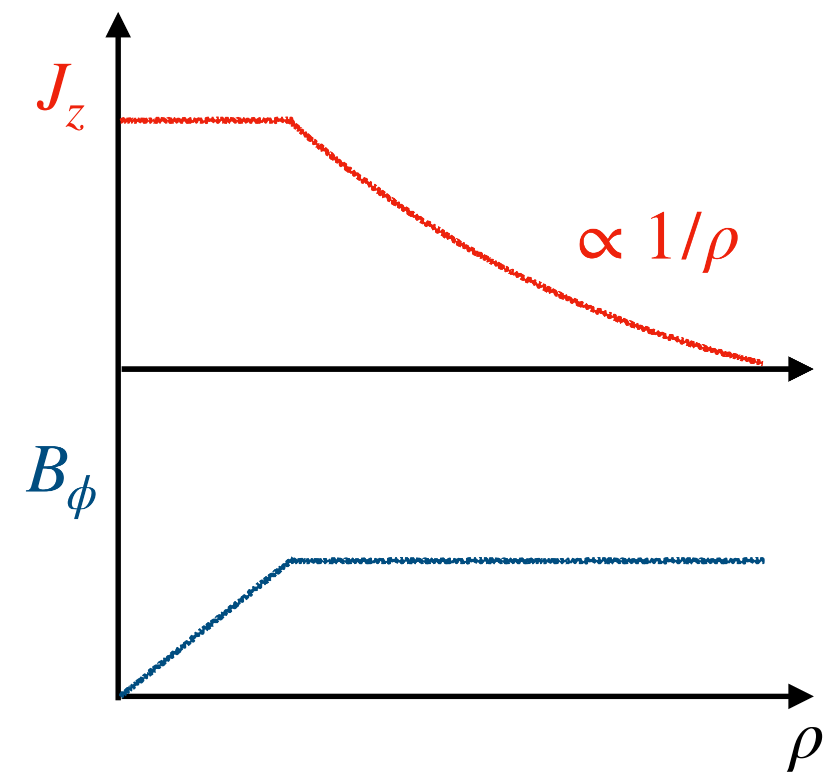

Huang et al., MNRAS 2023

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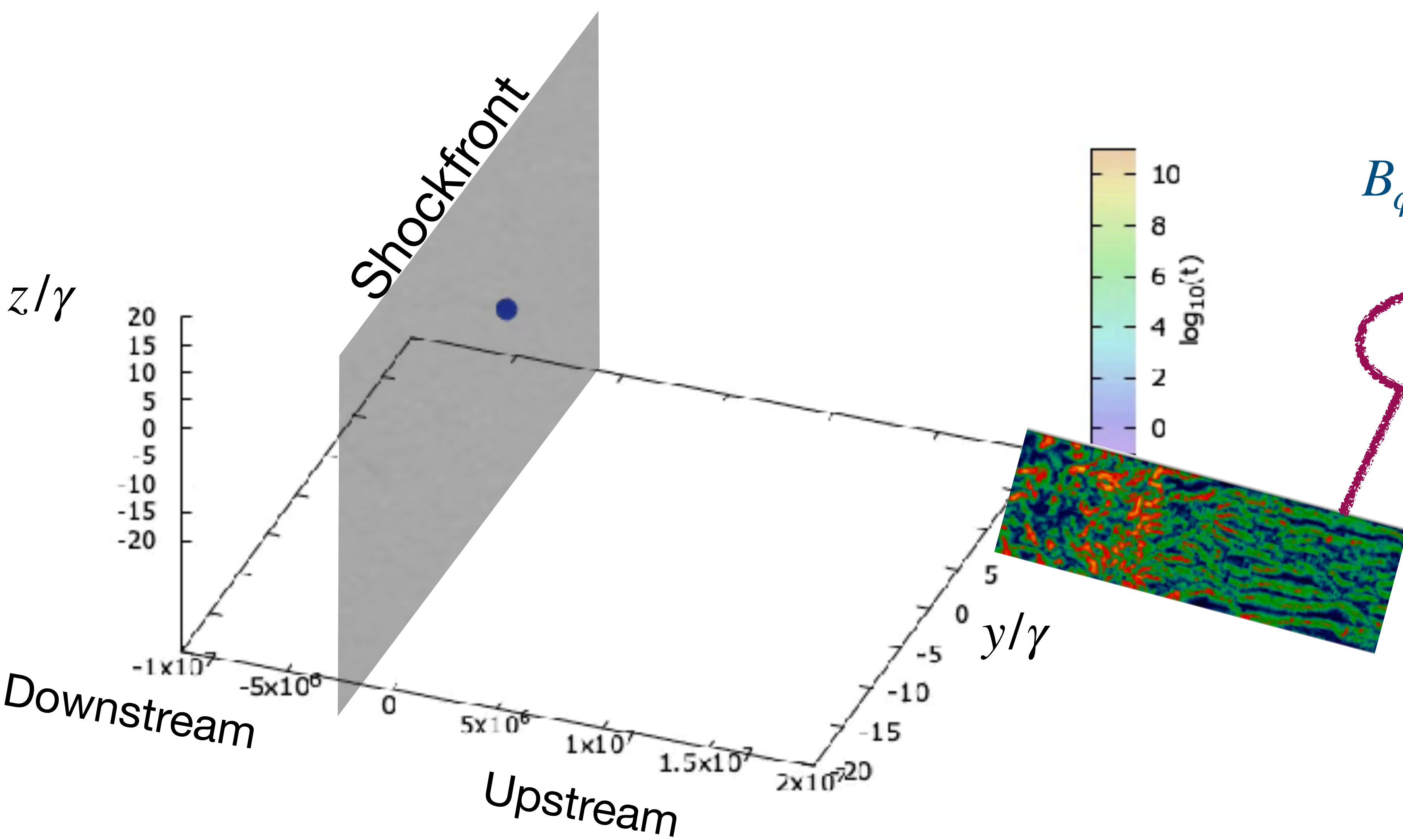

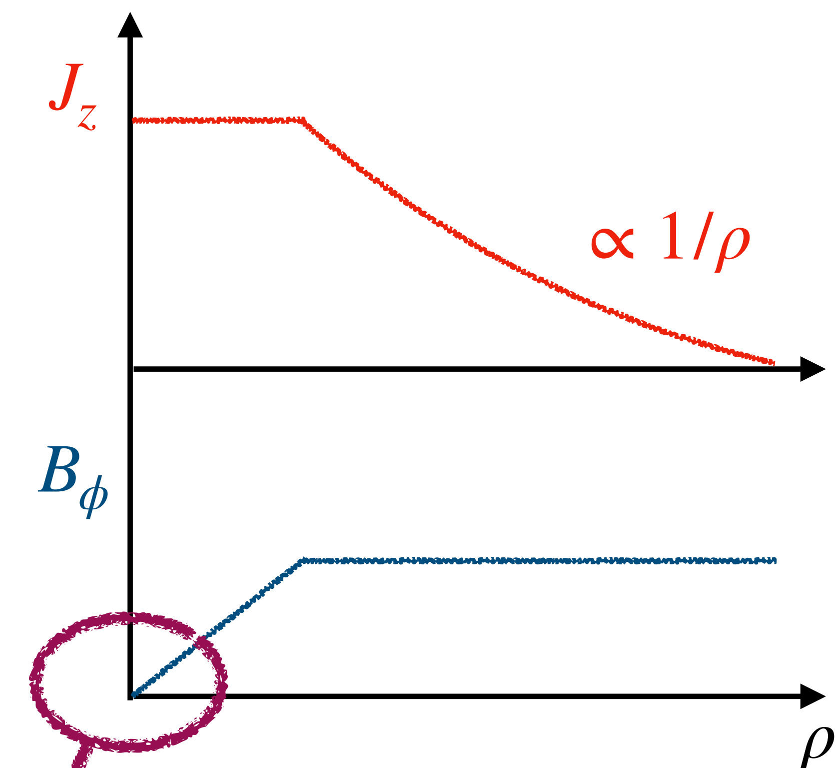

Field near axis is weak or quasi-parallel

PIC simulations show such shocks are (in principle) efficient accelerators

(See G. Giacinti's previous CDY seminar)

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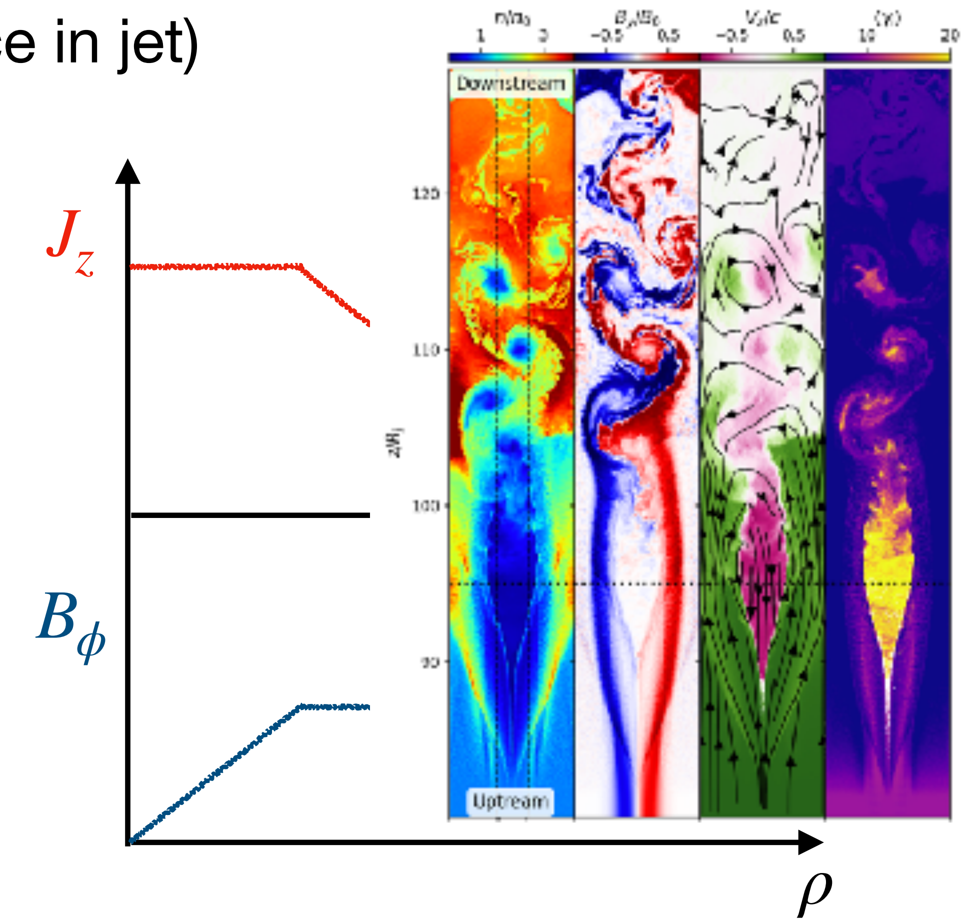
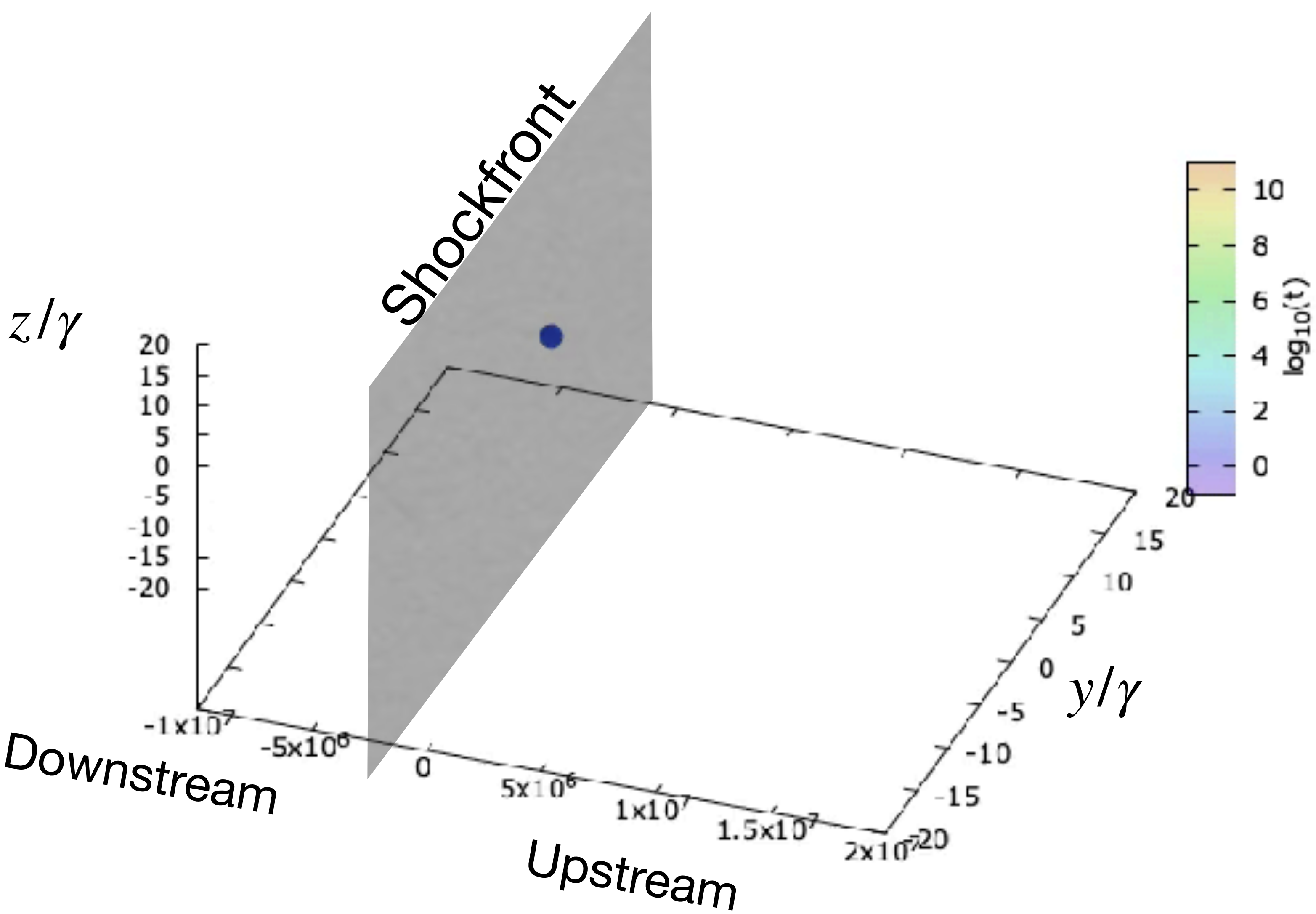
Cerruti & Giacinti '23





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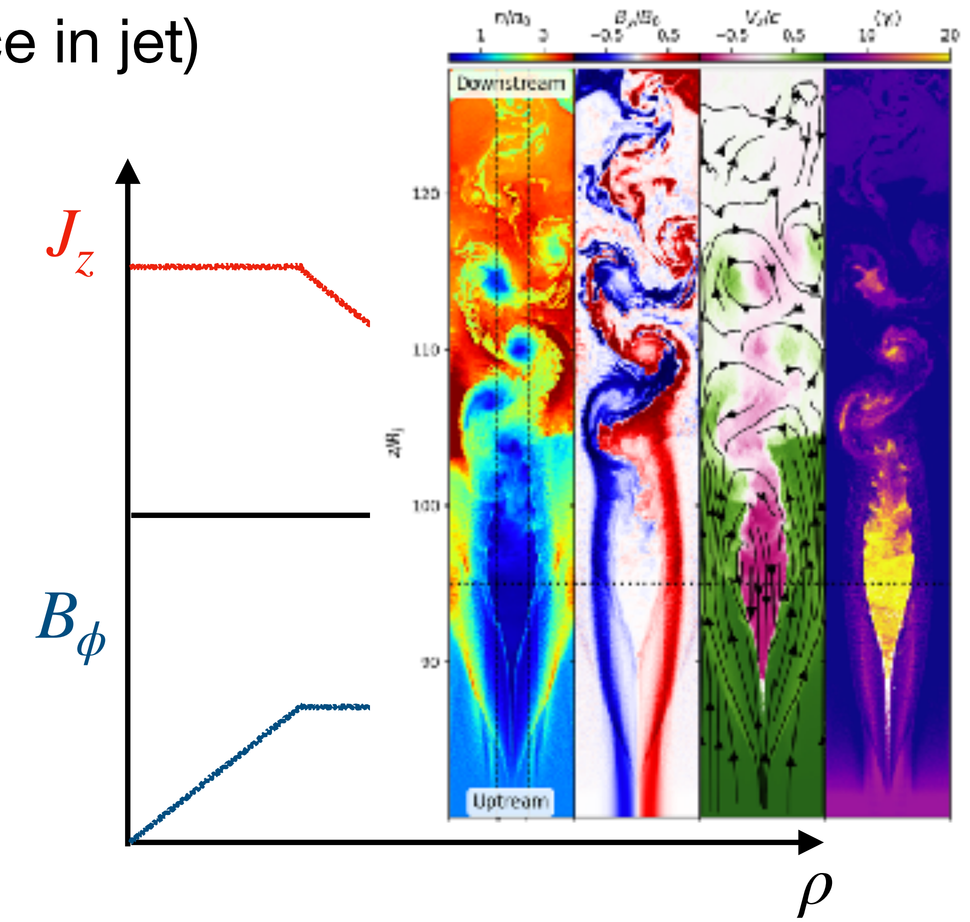

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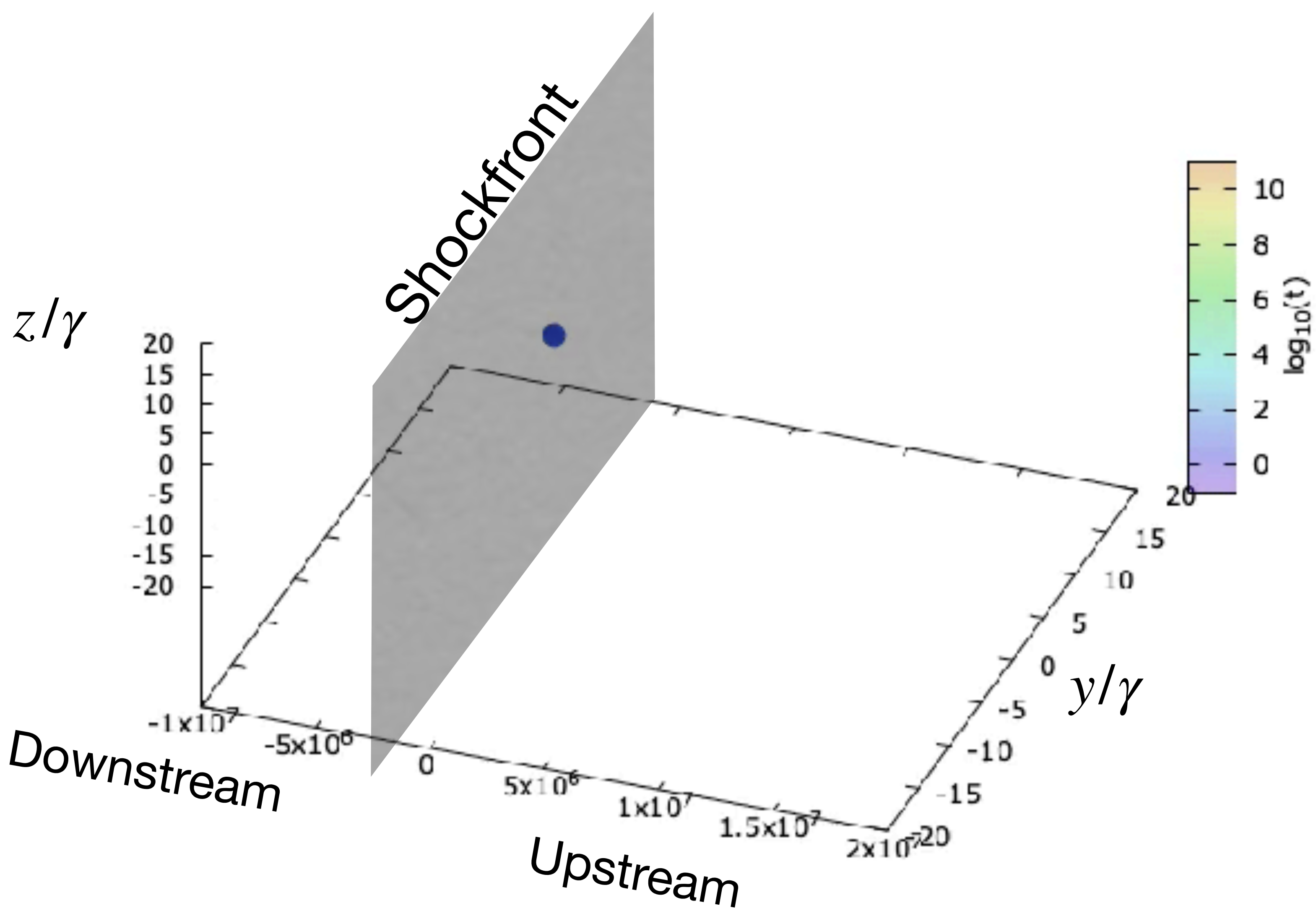

Huang et al., MNRAS 2023

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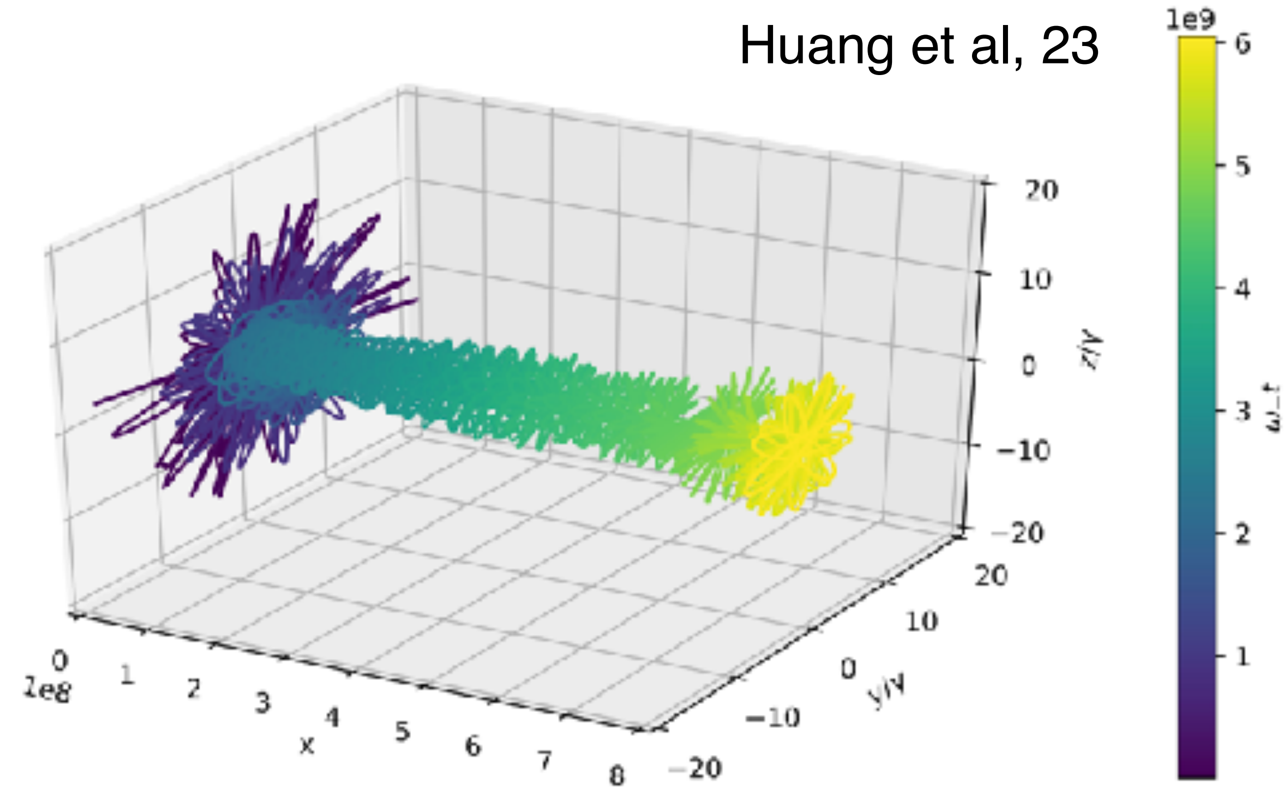
Because scattering is weak (an assumption), particles close to axis stay there.

Huang et al, 23



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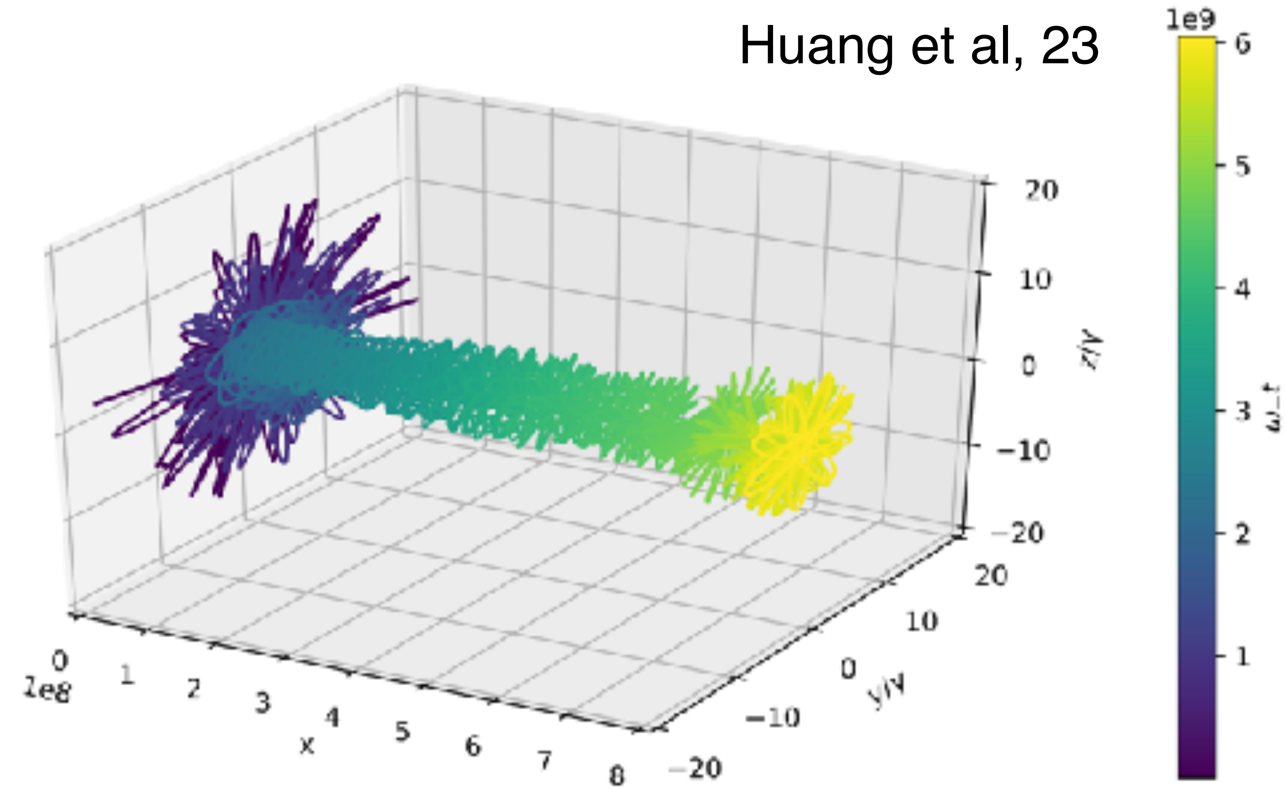

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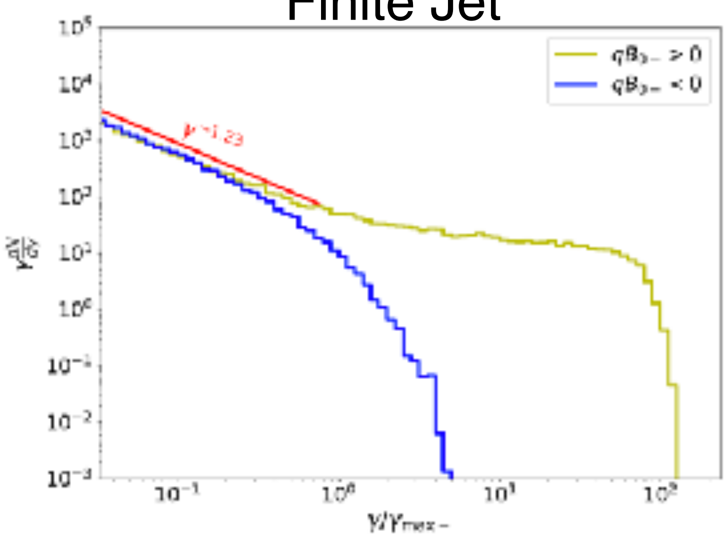

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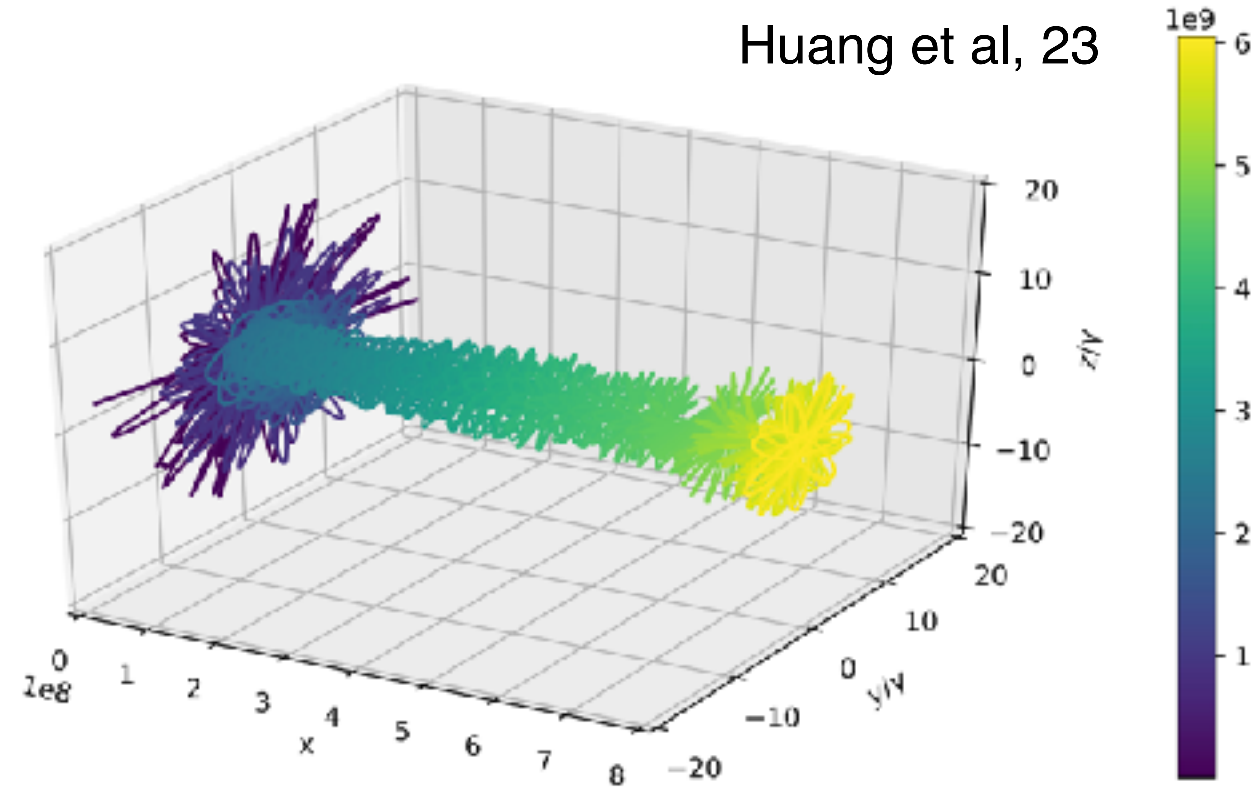

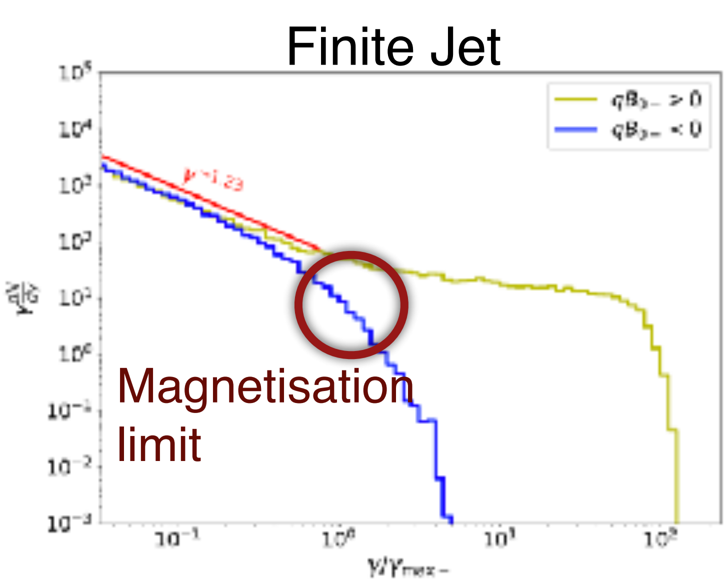

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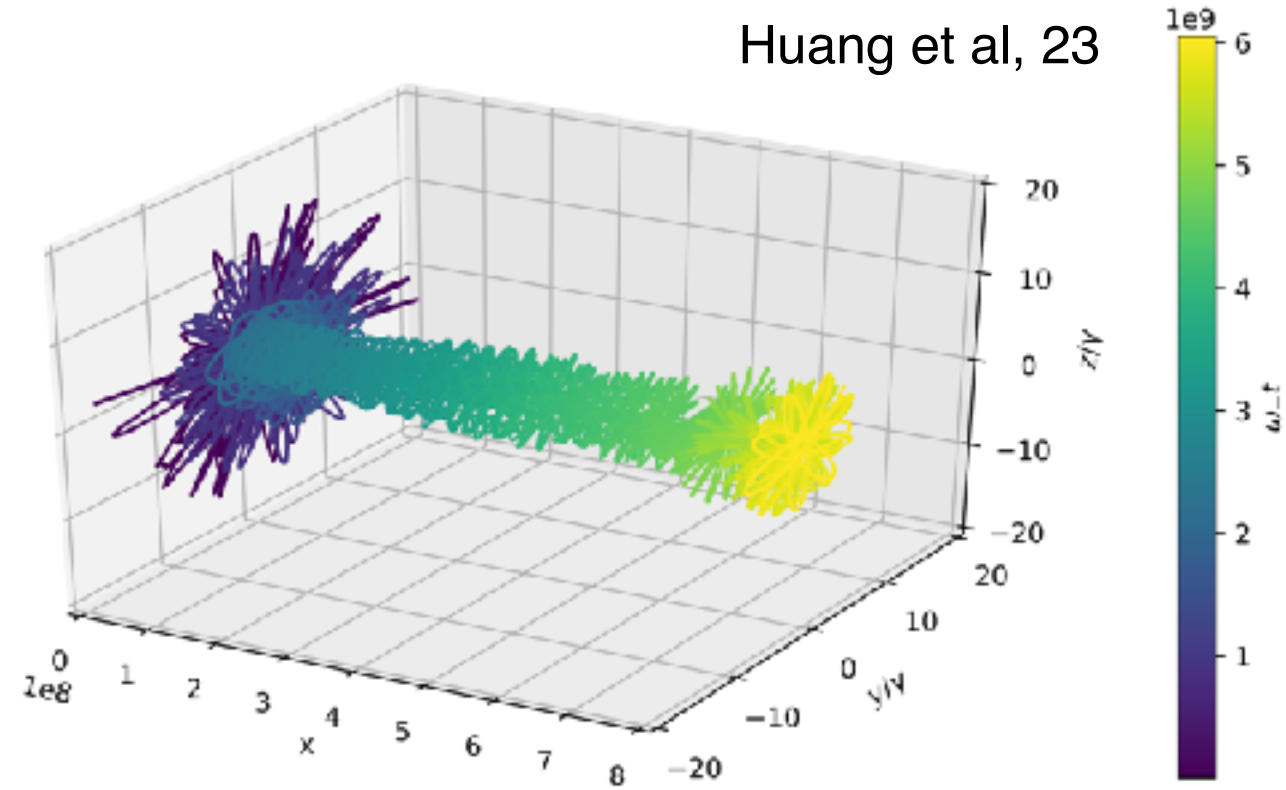

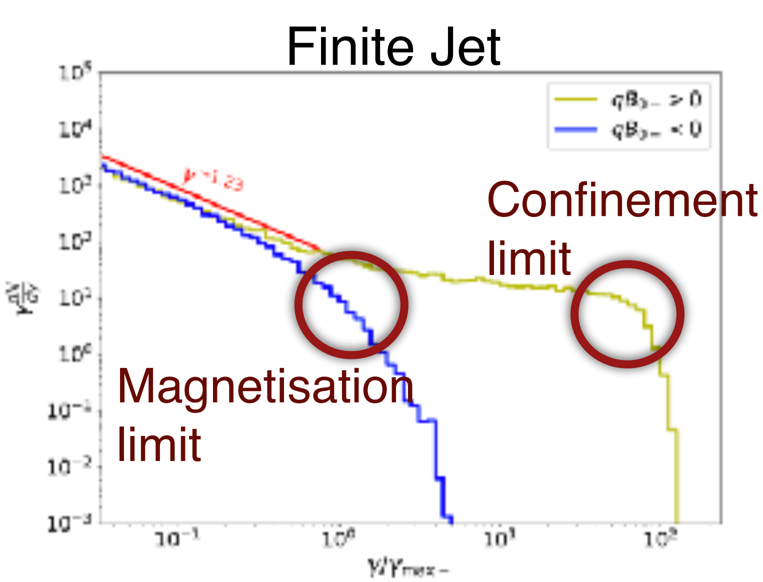

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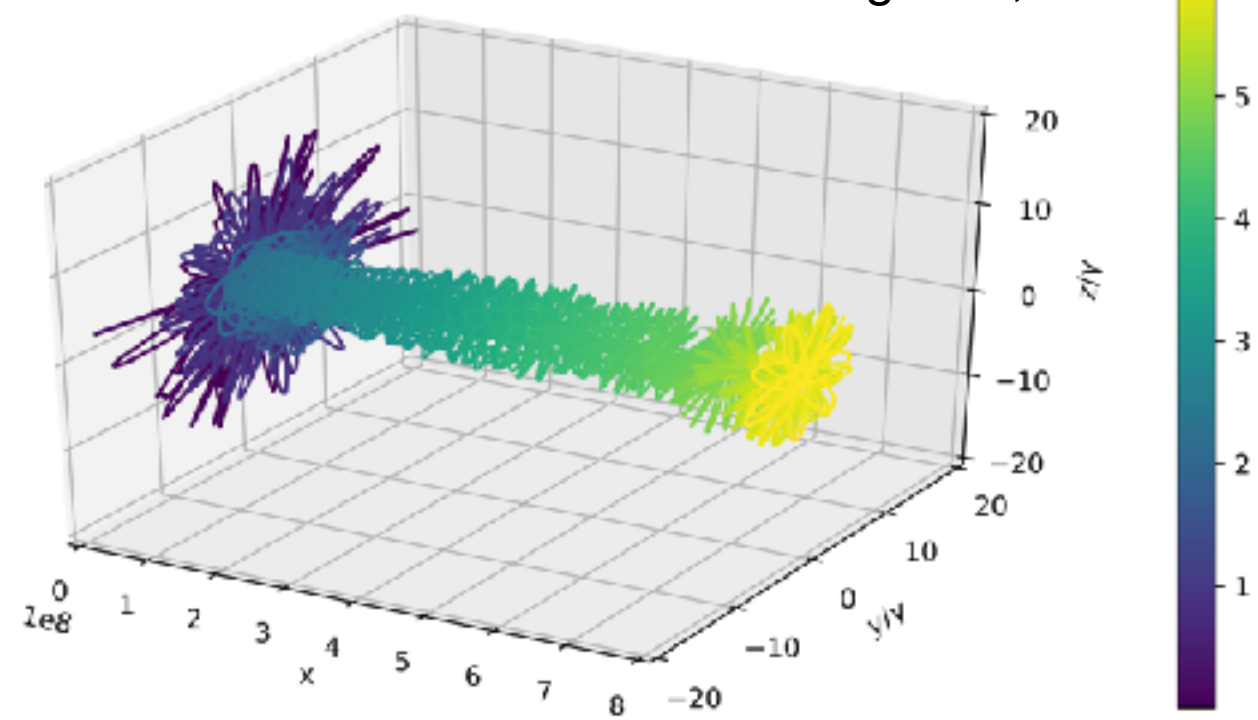

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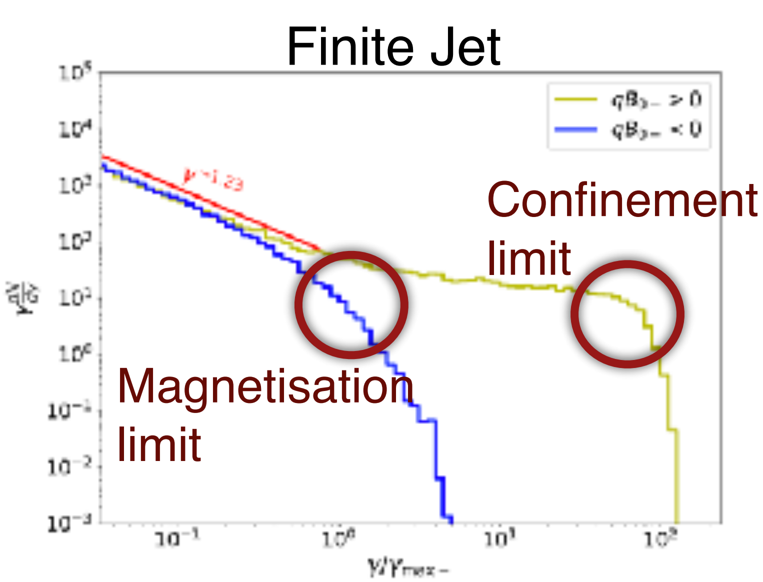

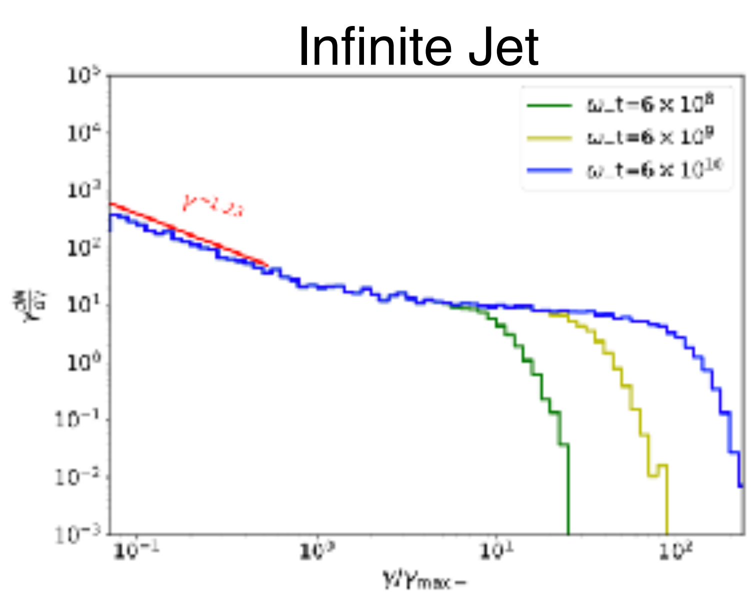

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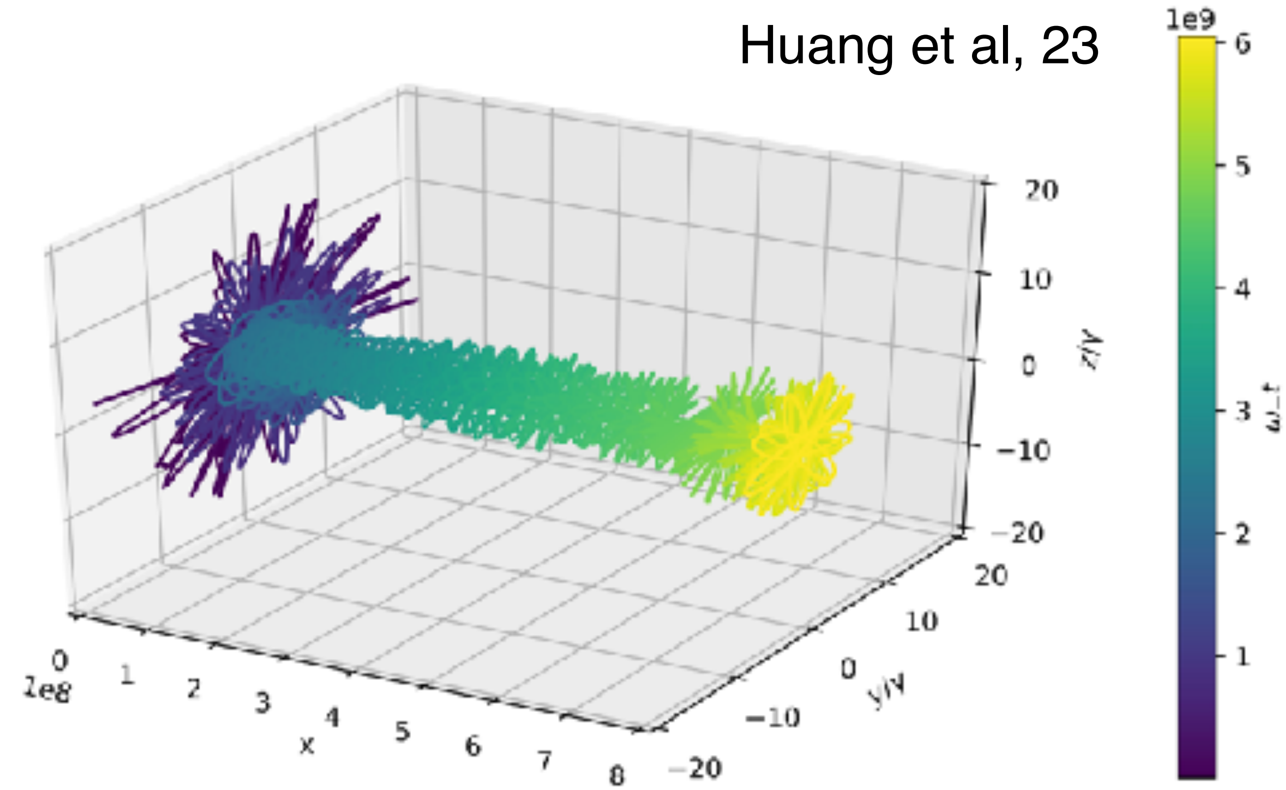

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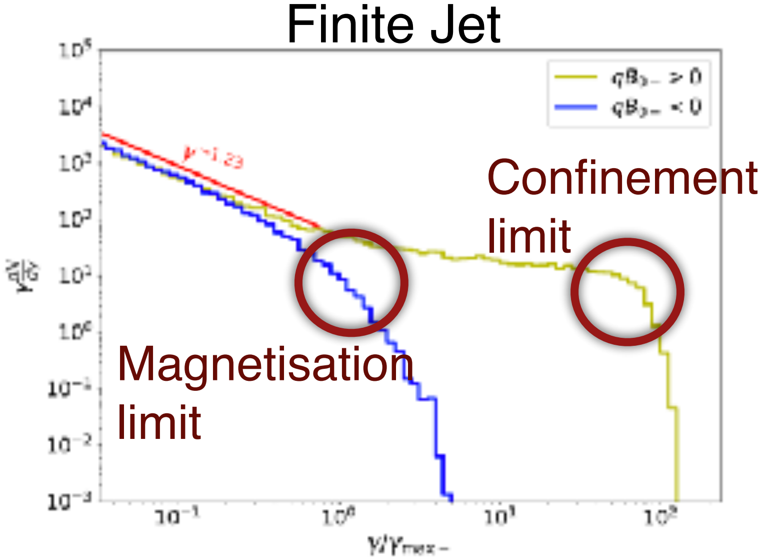

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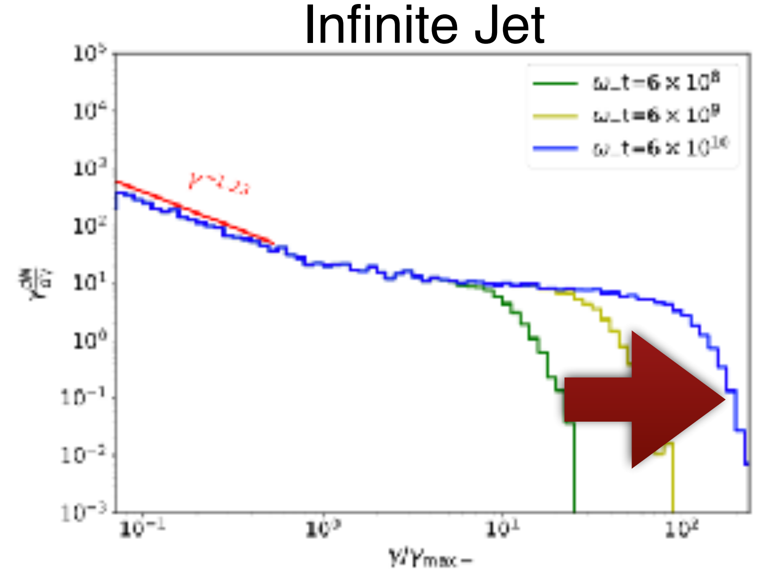

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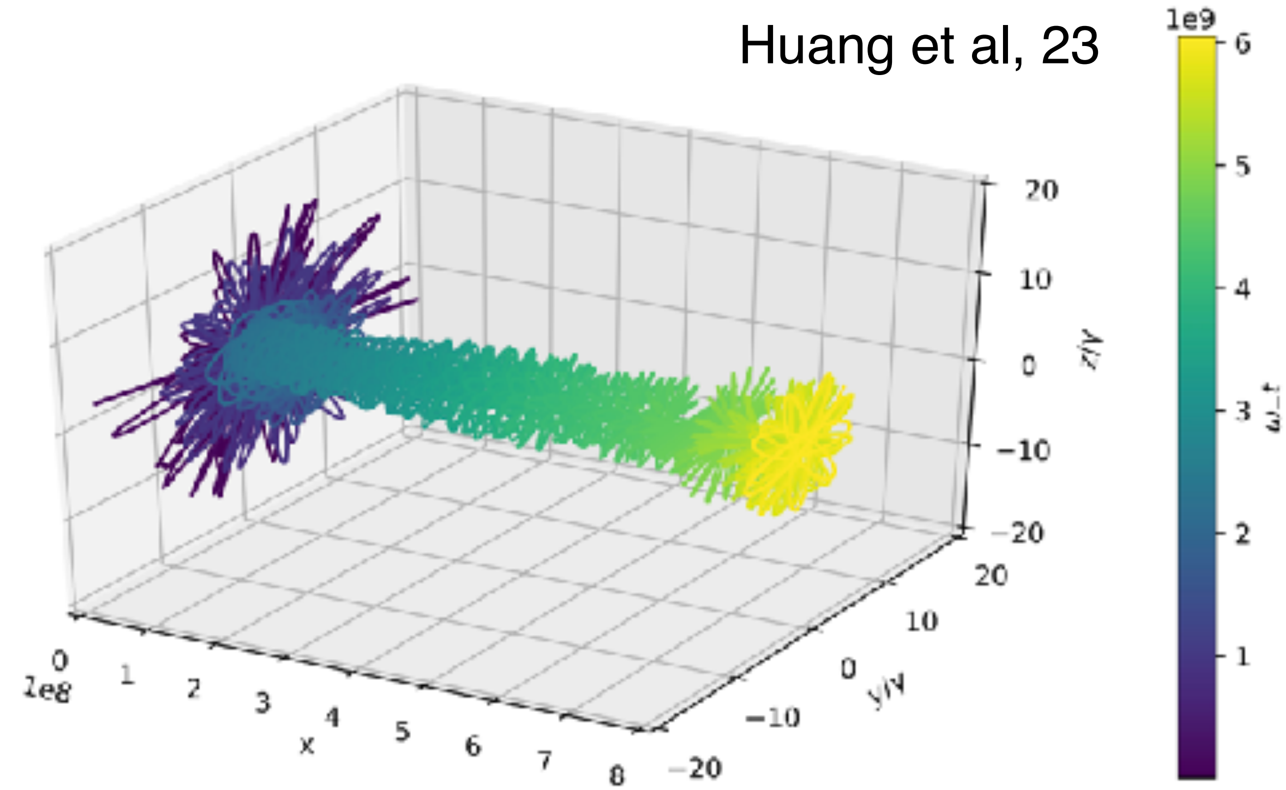

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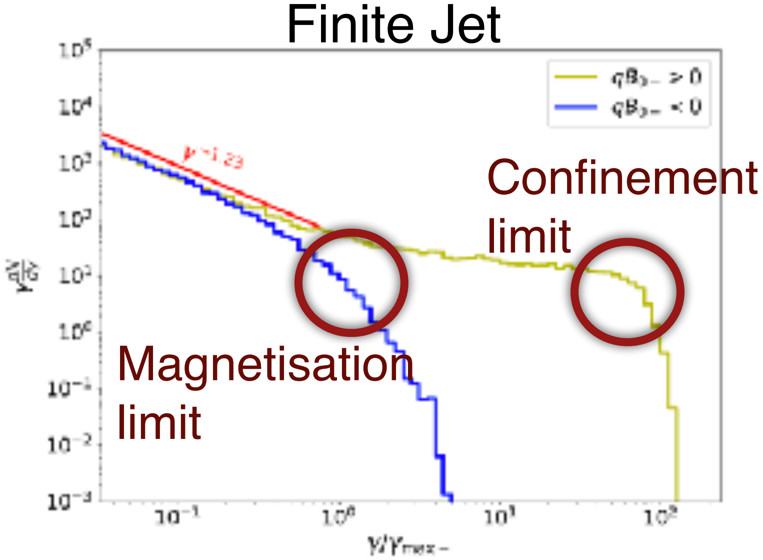

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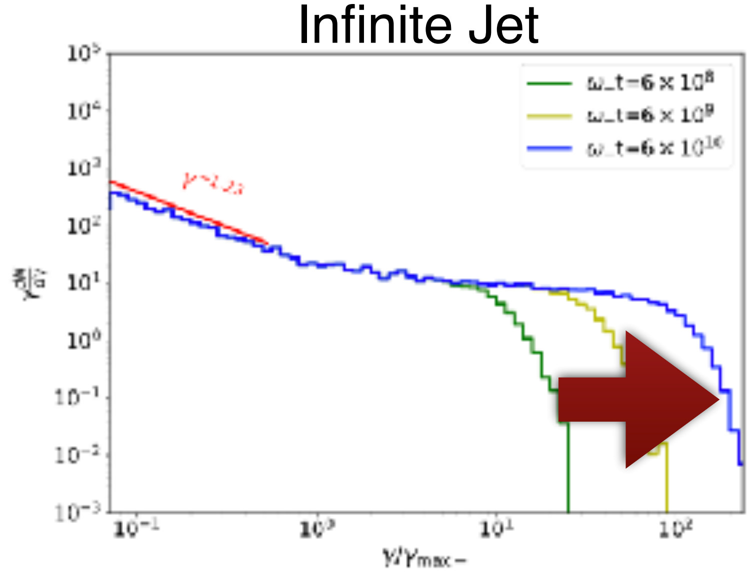
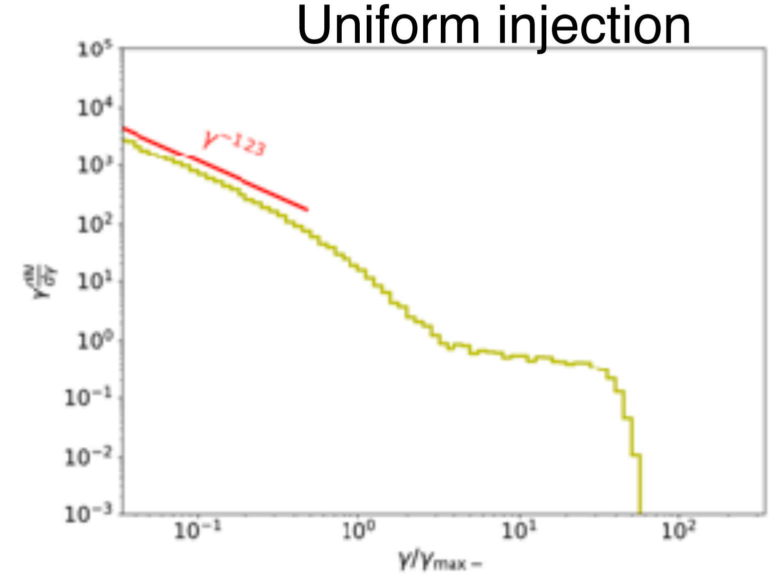


Uniform injection



Summary

- Case presented for shear acceleration in AGN jets
  - Discontinuous shear with random scattering
  - Discontinuous shear with synthetic turbulence
  - Gradual shear Fokker-Planck modelling
  - Gradual shear, with test-particles integration

- Shear acceleration offers a possible route to explain X-rays in large scale jets (and UHECR acceleration ?)

- Relativistic shocks still on the menu

- Powerful jets (launched by BZ for example), can carry current, and hence large scale helical fields. Can enhance acceleration at shocks.

(Still) Open Questions

- What is the EM structure of jets on all scales?
- What process sustains X-ray emission on large scales?
- Doe proton synchrotron contribute to X-ray emission?
- Are relativistic shocks good particle accelerators?
- What role do converter mechanisms play?
- What determines the maximum particle/photon energy?
- Are UHECRs produced primarily in AGN jets?