Particle acceleration in shearing flows:

numerical simulation of jets and colliding winds

Jieshuang Wang
jswang@mpi-hd.mpg.de
Max-Planck-Institut für Kernphysik,
Heidelberg

Apr. 13 @ VGGRS, University of Innsbruck

In collaboration with
Brian Reville (MPIK)
Frank Rieger (Uni-Heidelberg)
Yosuke Mizuno (TDLI, SJTU)
Felix Aharonian (DIAS,MPIK)
Valenti Bosch-Ramon (ICCUB)

Max-Planck-Institut
für Kernphysik

Centaurus A, credit: NASA/CXC

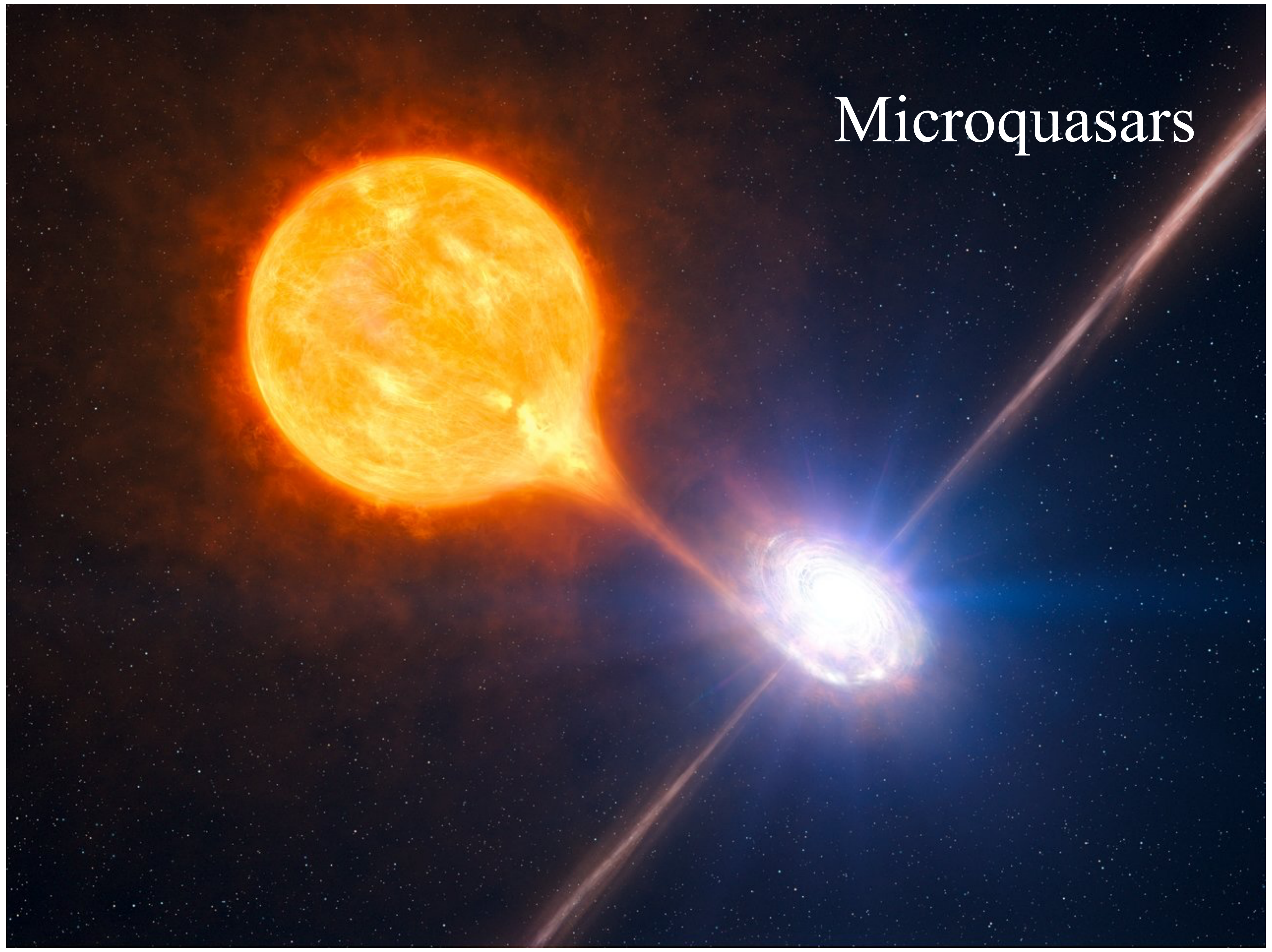
UNTERSTÜTZT VON / SUPPORTED BY
Alexander von
HUMBOLDT
STIFTUNG

Outline

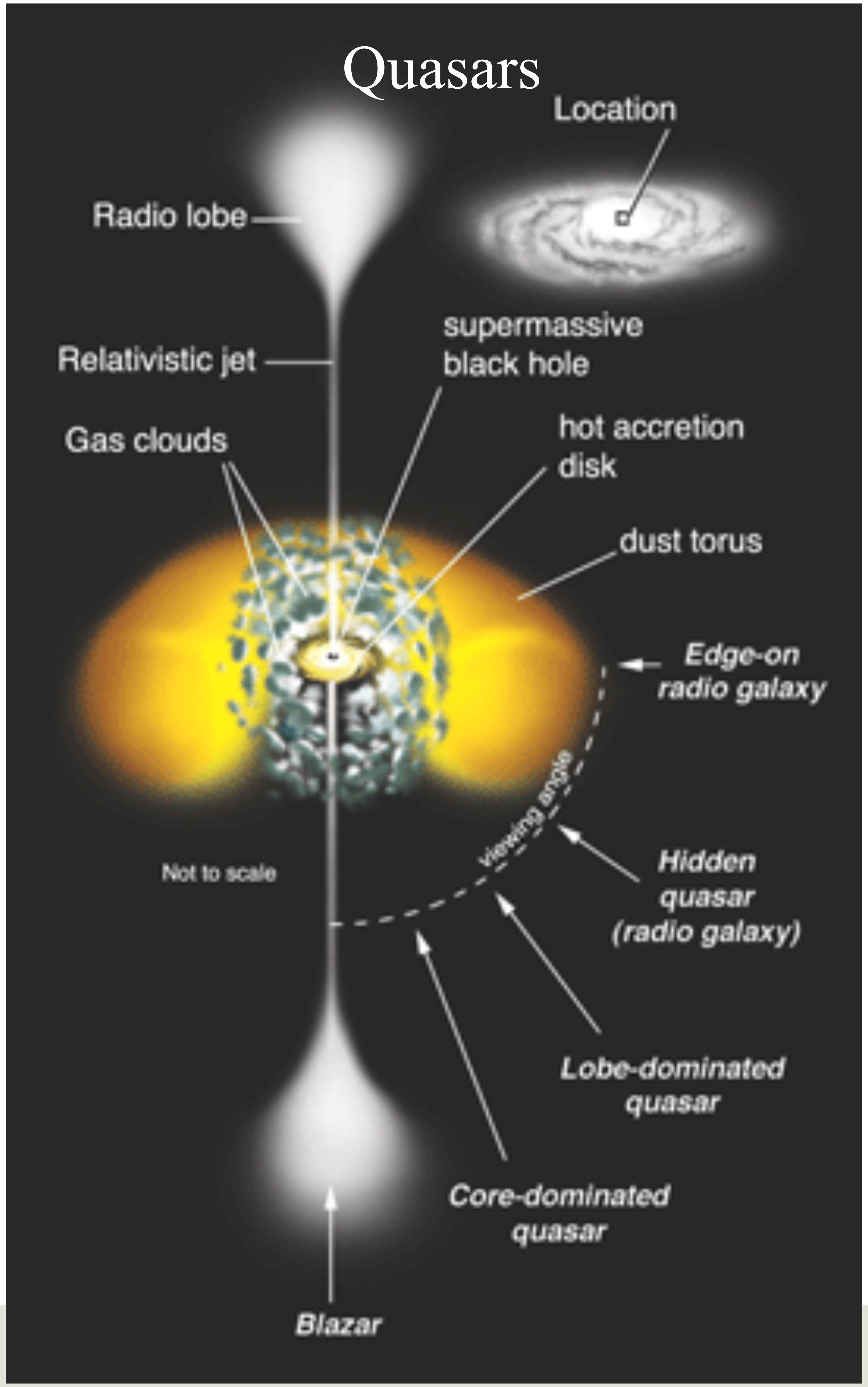
- Backgrounds and motivation
- Analytical theory of shear acceleration and its application
- RMHD and test-particle simulations of jets
- RHD simulation of colliding wind binary
- Summary

Astrophysical Jets

- Jets are ubiquitous in accreting systems

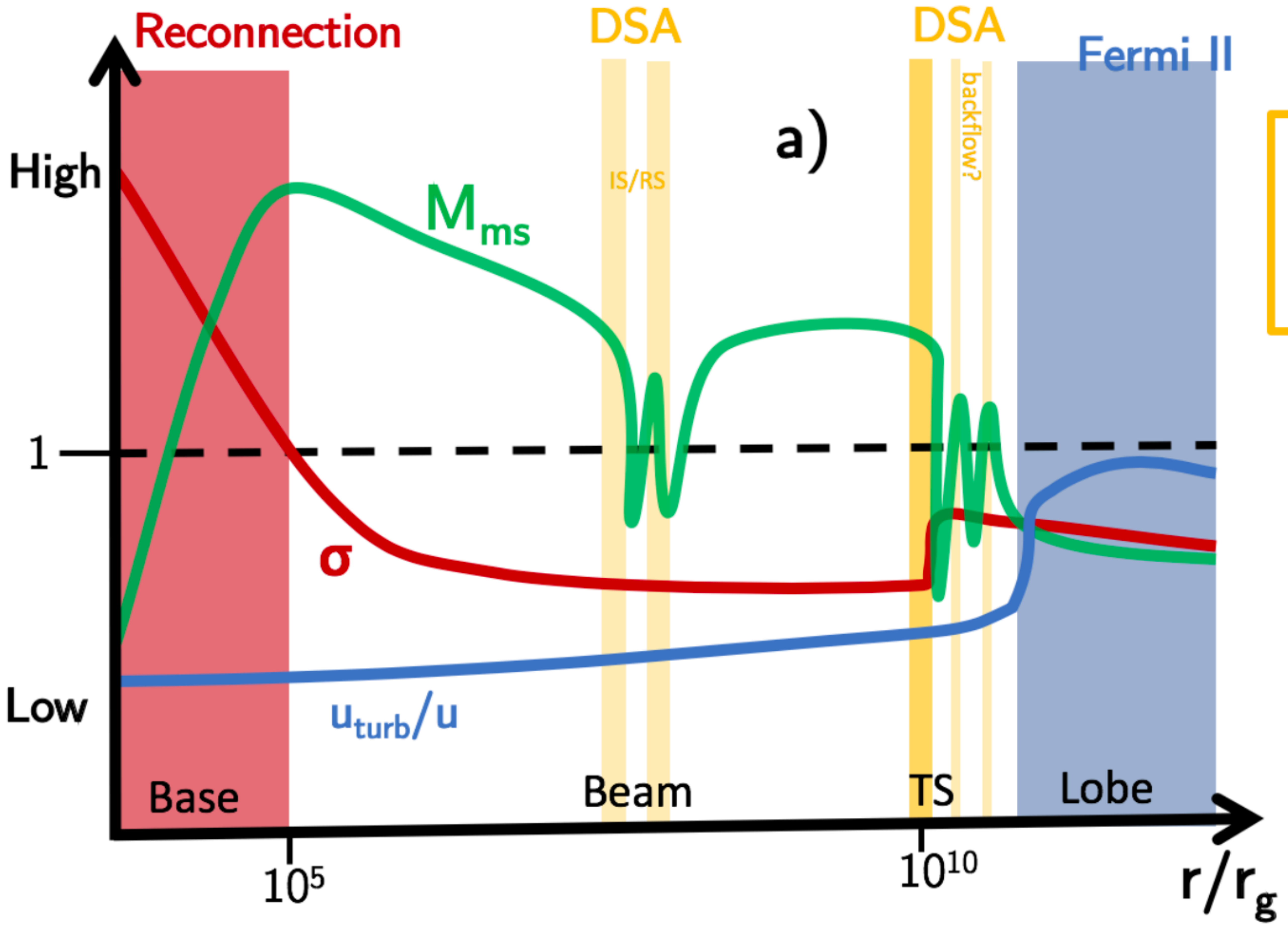


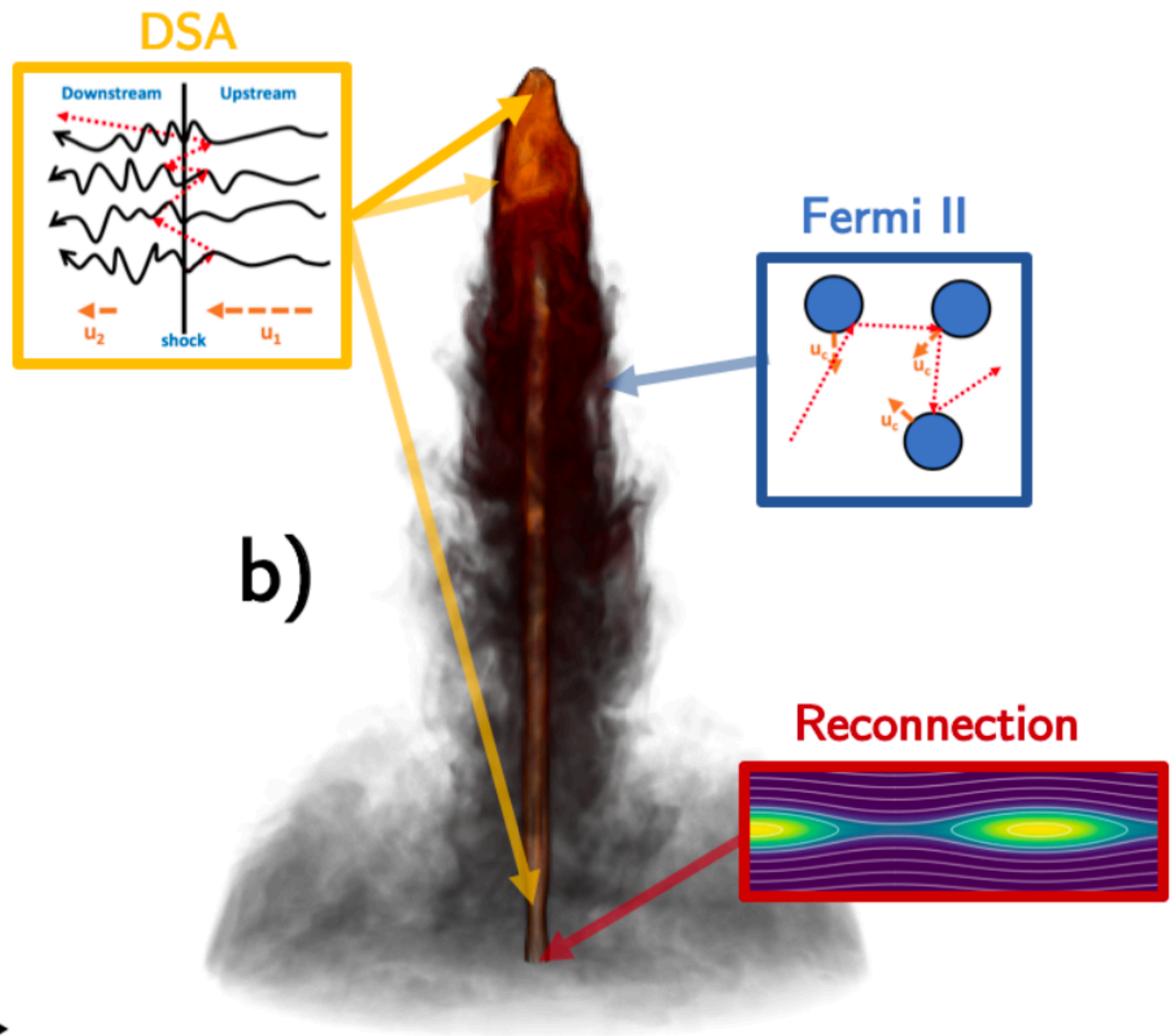
Credit: ESO/L. Calçada/M.Kornmesser



Credit: Science/ M.Kornmesser

Particle acceleration in jets



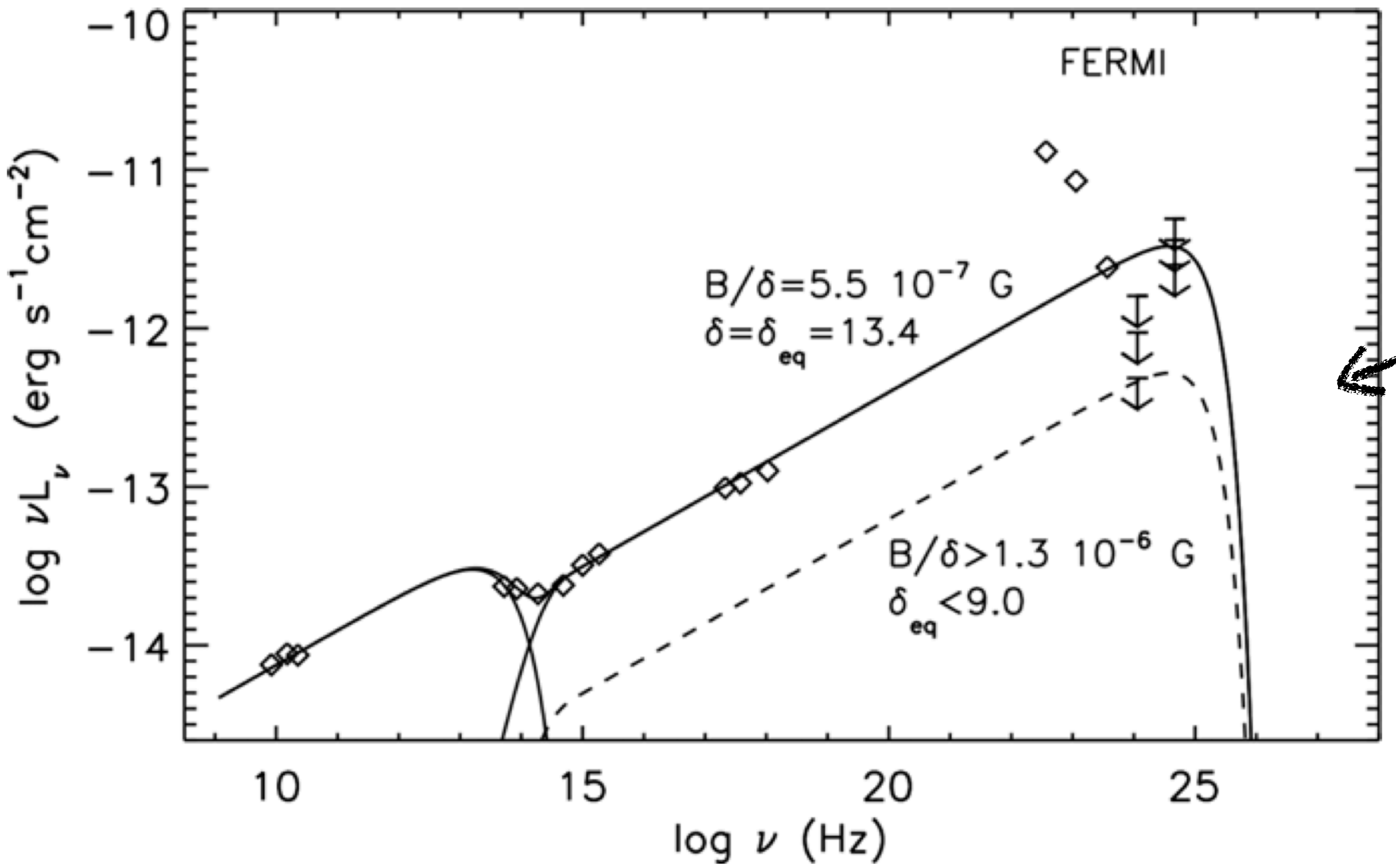


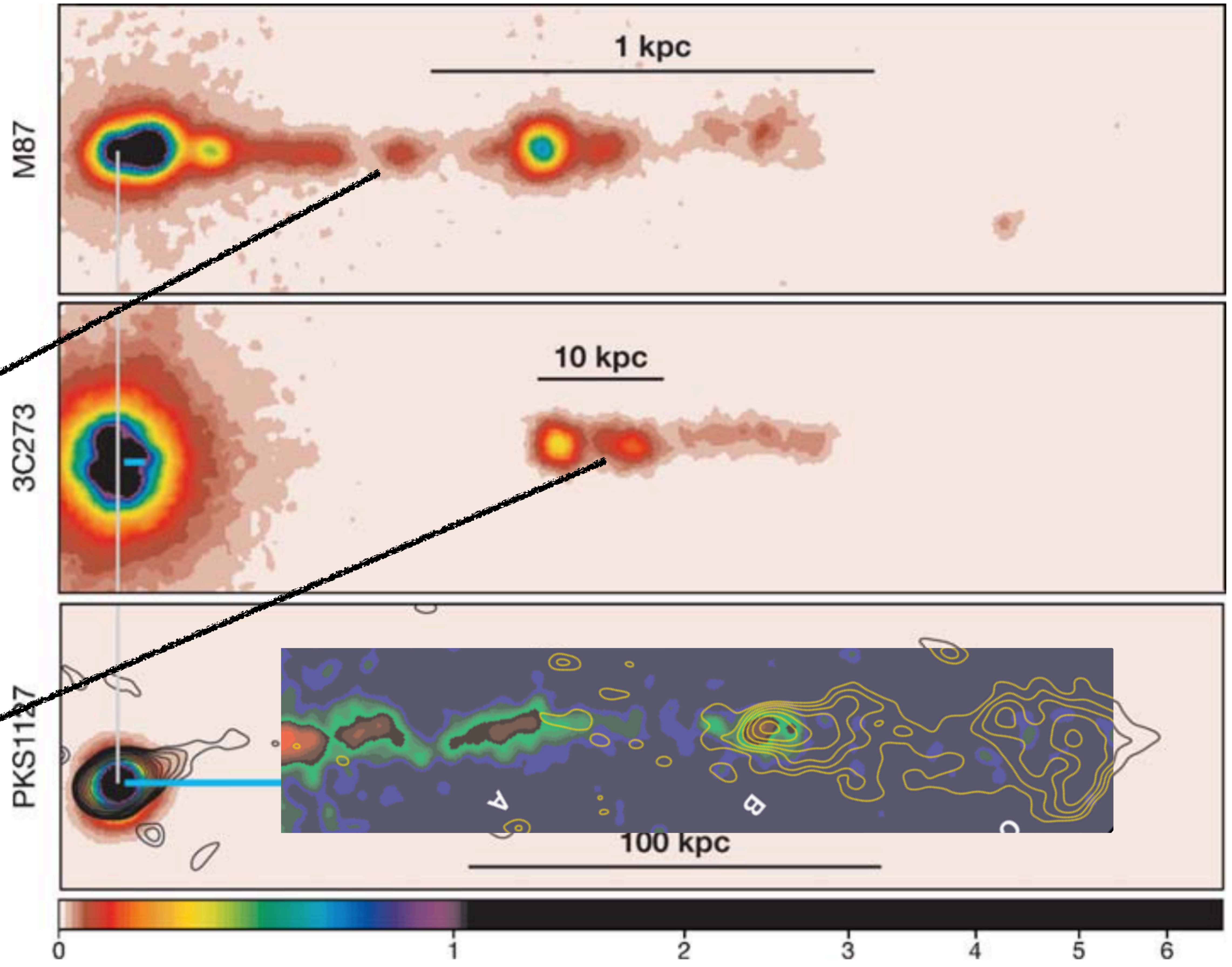
Matthews+ 2020, arXiv:2003.06587

No efficient distributed acceleration mechanism along the jet

Large-scale X-ray jets

- Quasi continuous X-rays are observed from kpc - 100kpc
- More than 100 sources @ https://hea-www.harvard.edu/XJET/#morph
- Synchrotron origin is favored





Harris & Krawczynski, 2006, ARA&A, [arXiv:astro-ph/0607228](https://arxiv.org/abs/astro-ph/0607228)

Meyer & Georganopoulos 2014, ApJL, [arXiv:1307.8421](https://arxiv.org/abs/1307.8421)

Sun+ 2018, A&A, [arXiv:1712.06300](https://arxiv.org/abs/1712.06300)

Distributed acceleration required

- Synchrotron origin of X-rays requires sub-PeV electrons (PeV = 10^{15}eV): $E_{\rm syn} = 2(E_e/0.1{\rm PeV})^2(B/10\mu{\rm G})$ keV
- Cooling time of sub-PeV electrons: $\tau_{\rm c} = 1.2 \times 10^3(B/10\mu{\rm G})^{-2}(E_e/0.1{\rm PeV})^{-1}$ yrs → maximum $c\tau_{\rm c} = 0.37$ kpc
- For jet length > kpc, particles accelerated by the jet head shock will cool down immediately after the shock passes (standing shocks may only exist in specific locations)
- *In-situ* (re-)acceleration mechanisms are required along the jet
  - $\boxed{\text{Shear acceleration}}$

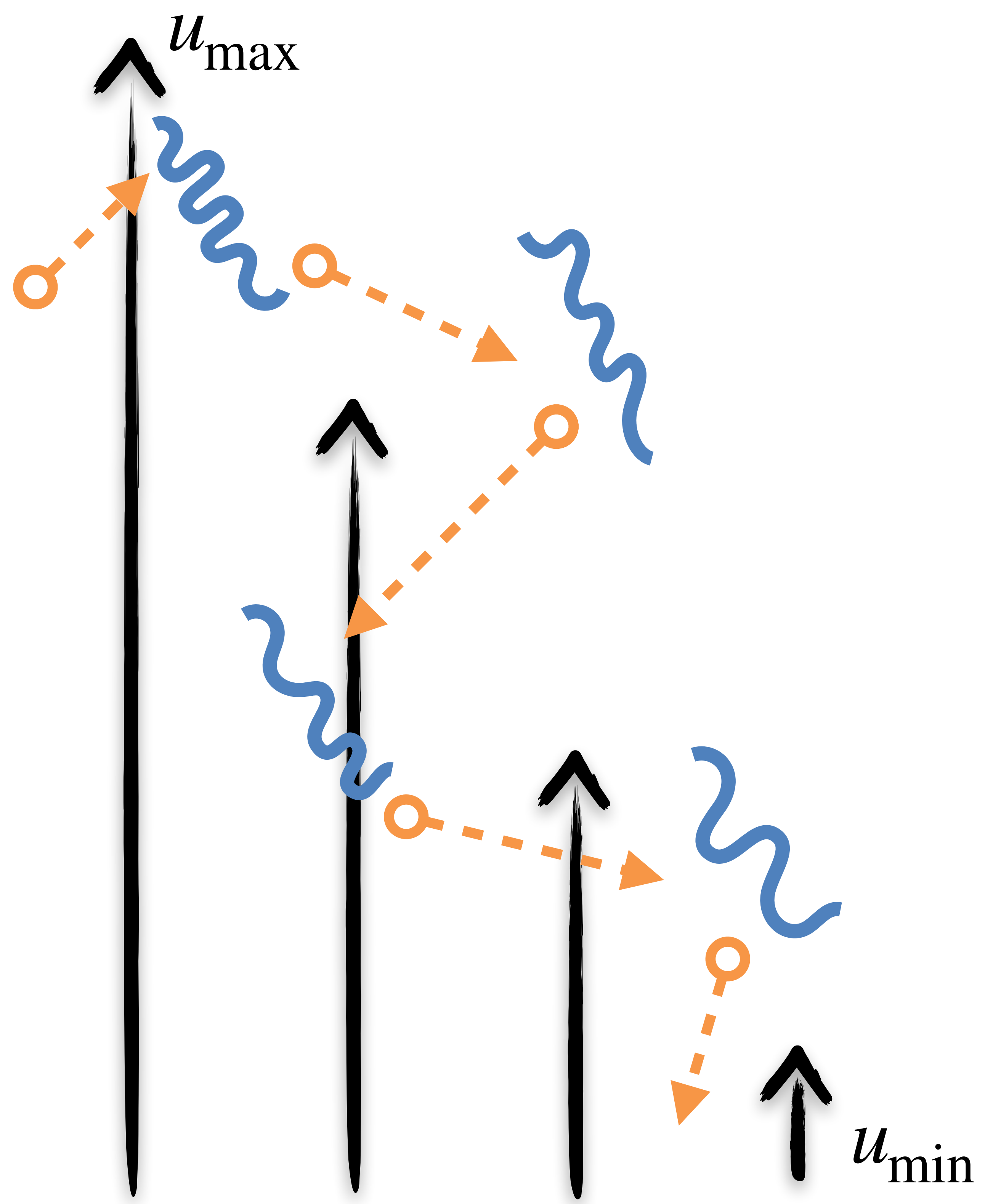
Shear acceleration

- Shear acceleration is Fermi-II type (see Rieger, 2019, arXiv:1909.07237 for a review)
- Velocity profiles in jets (spine-sheath)
- Turbulences are embedded in shearing layers
- Particles scatter off turbulence (timescale: $\tau_{\mathrm{sc}} \propto \gamma^{2-q}$, $q = 5/3$ for Kolmogorov) and sample the velocity difference

$$\frac{\langle \Delta\epsilon \rangle}{\epsilon} \propto \left(\frac{\bar{u}}{c}\right)^2 \propto \left(\frac{\partial u_z}{\partial x}\right)^2 \tau_{\mathrm{sc}}^2$$

$$t_{\mathrm{shear}} = \frac{\epsilon}{\Delta\epsilon}\tau_{\mathrm{sc}} \propto \tau_{\mathrm{sc}}^{-1} \propto \gamma^{-1/3}$$

For comparison: $t_{\mathrm{classical}} \propto \tau_{\mathrm{sc}} \propto \gamma^{1/3}$



Berezhko & Krymsky 1981; Berezhko 1982; Earl+ 1988; Webb 1989; Jokipii & Morfill 1990; Webb+ 1994; Rieger & Duffy 2004, 2006, 2016; Liu+ 2017; Webb+ 2018, 2019; Lemoine 2019; Rieger & Duffy 2019, 2021,2022

Analytical theory: particle spectrum

- An exact solution in the steady state:

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

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

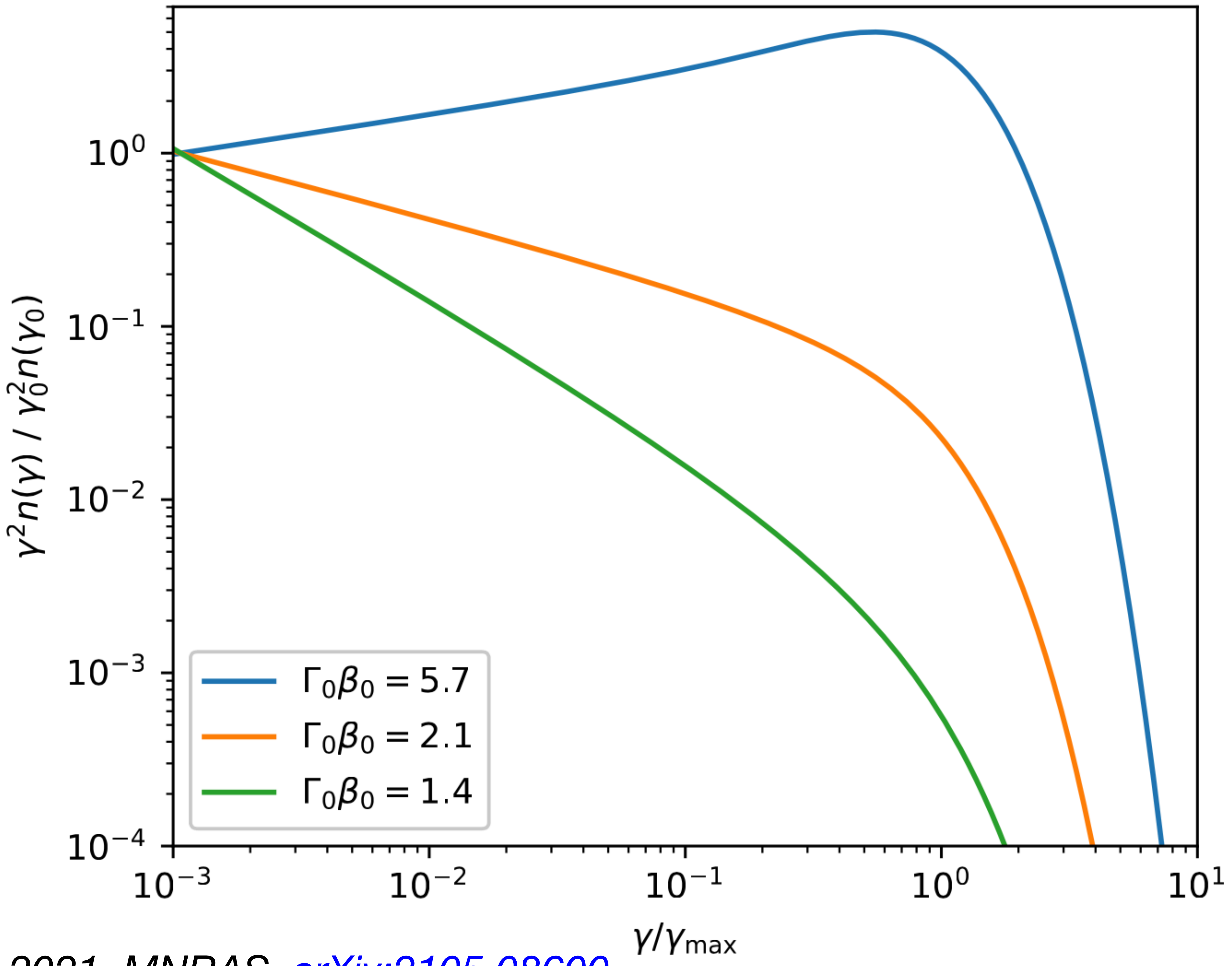
$$n \ \rightarrow \ 0 \ \text{ for } \gamma \ \rightarrow \ \infty$$

- Kolmogorov turbulence: q=5/3

- Assume a linear velocity profile

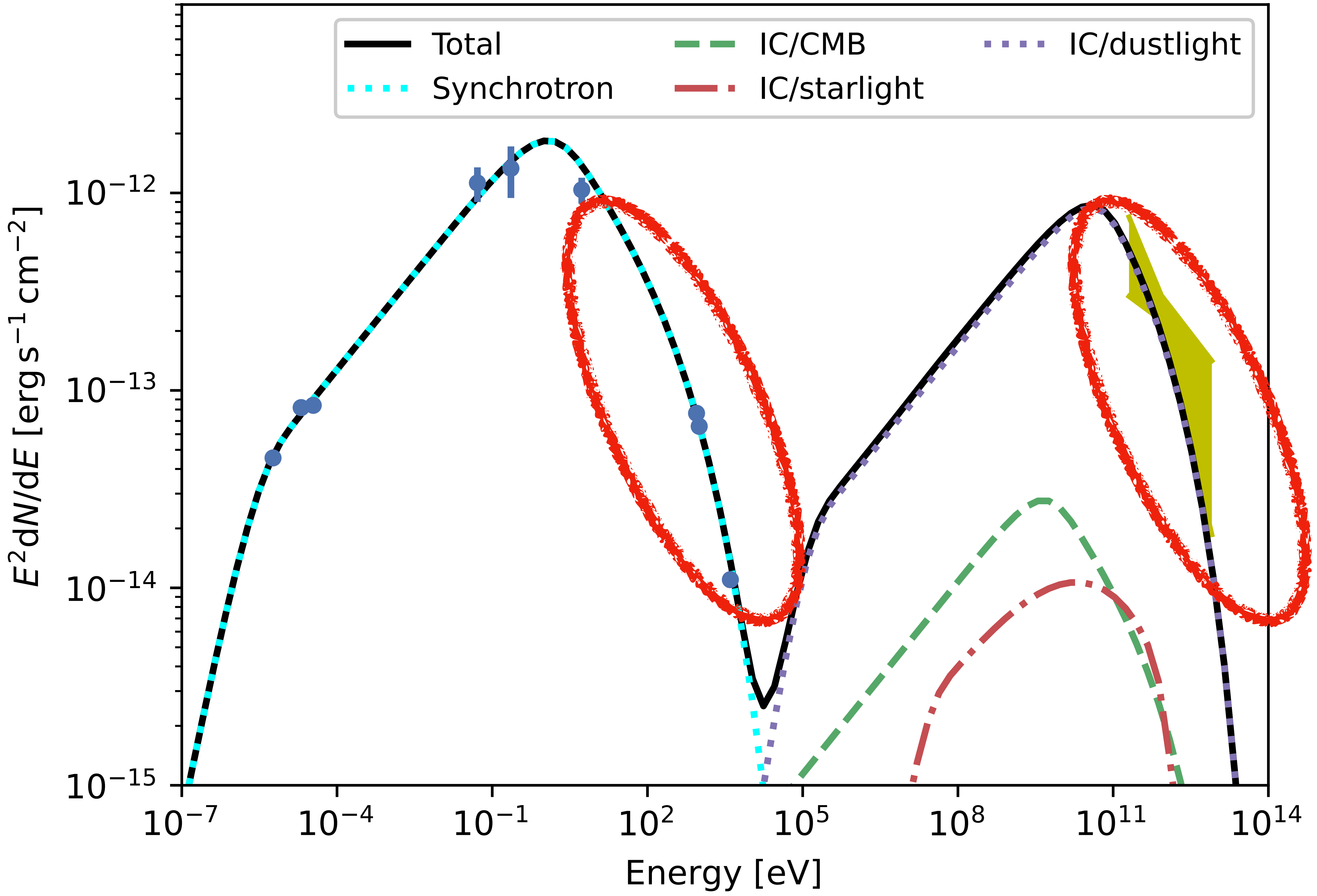
Rieger & Duffy, 2019, ApJL, [arXiv:1911.05348](https://arxiv.org/abs/1911.05348)

$$w = 40\ln^{-2}\frac{(1+\beta_0)}{(1-\beta_0)}$$

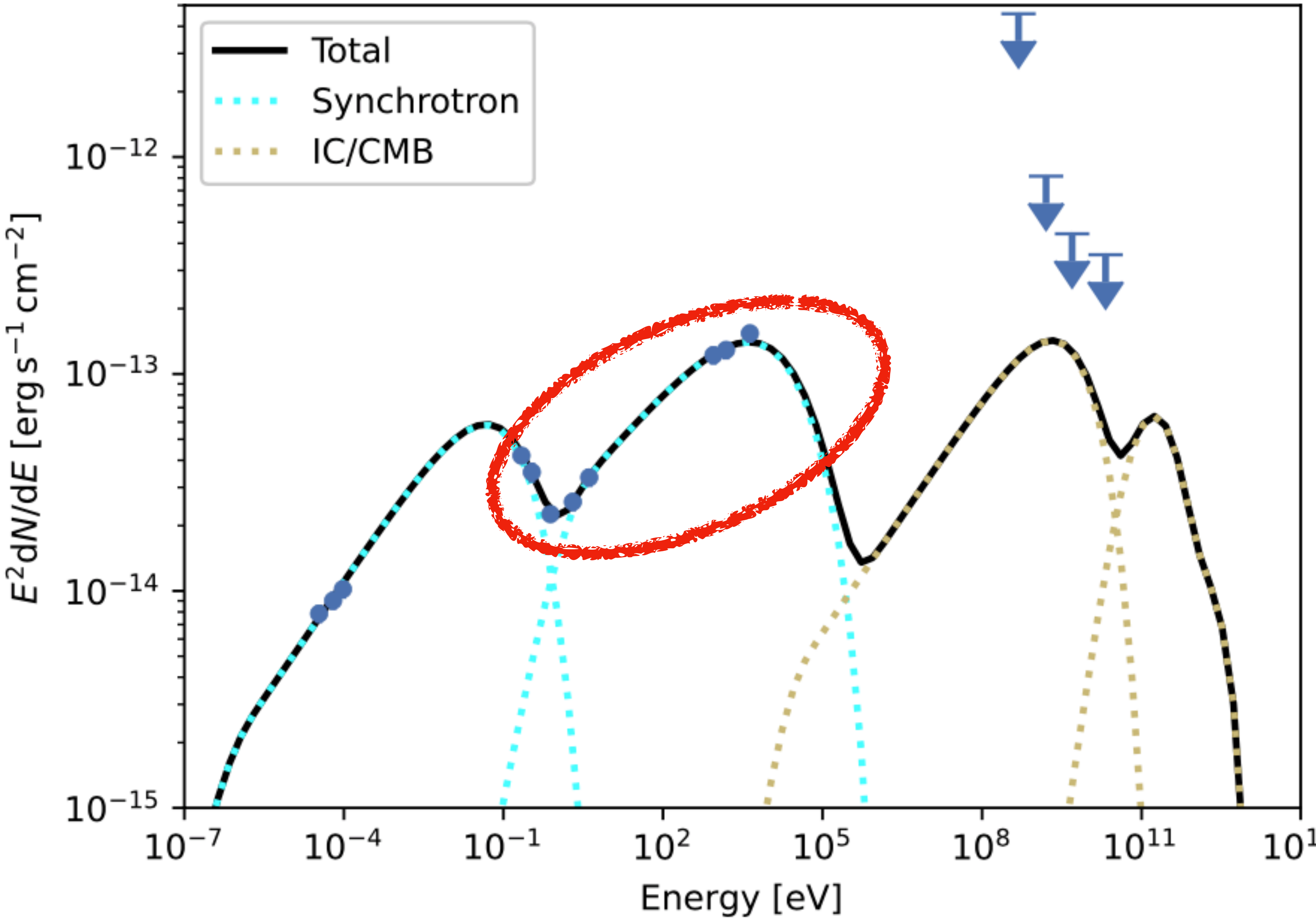


J.S.Wang+, 2021, MNRAS, [arXiv:2105.08600](https://arxiv.org/abs/2105.08600)

Applications


FR I: Centaurus A

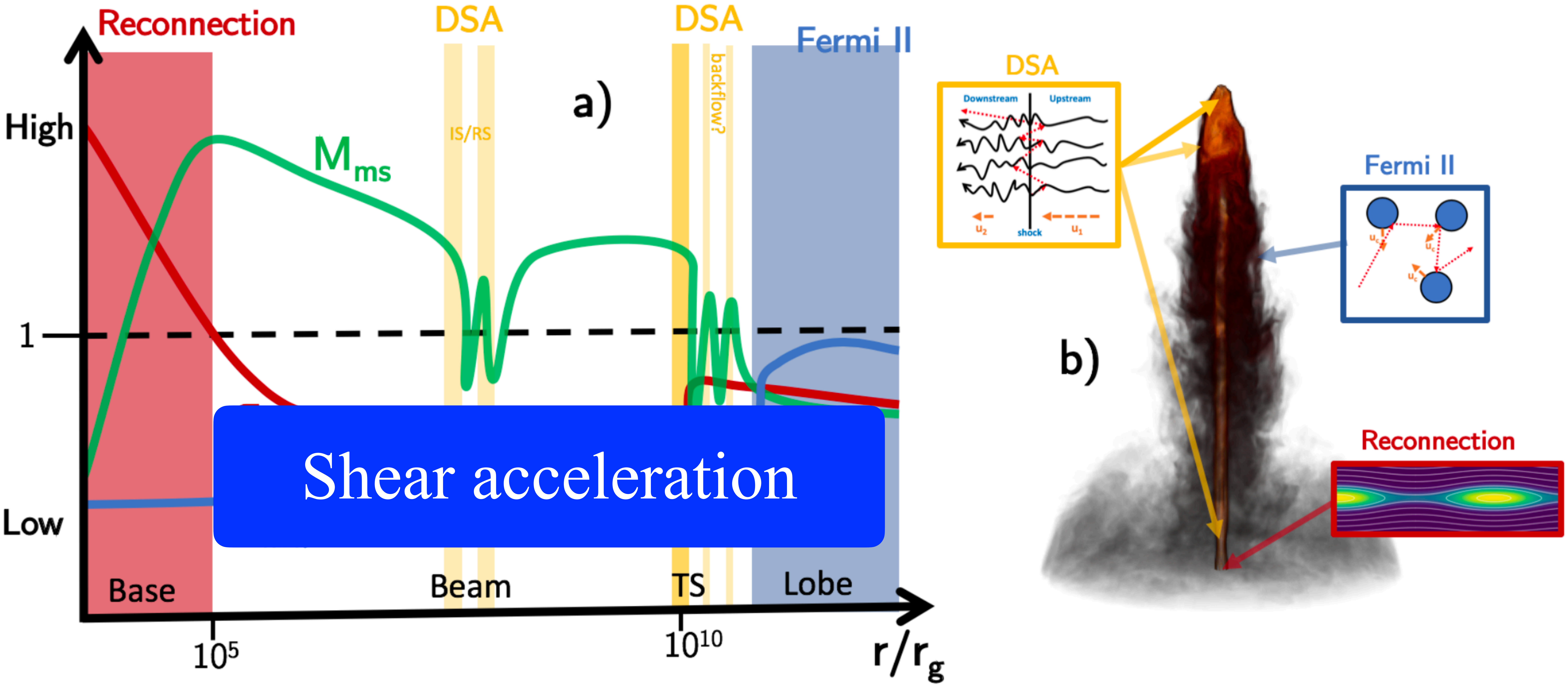
IC and Syn from one population of electrons


FR II: Knots A+B1 of 3C 273

Synchrotron and IC from two populations of electrons

J.S.Wang+, 2021, MNRAS, [arXiv:2105.08600](https://arxiv.org/abs/2105.08600)

Particle acceleration in jets



Shear acceleration

Shear acceleration provides a good explanation to the SEDs of X-ray jets, which depends on turbulence and velocity profile

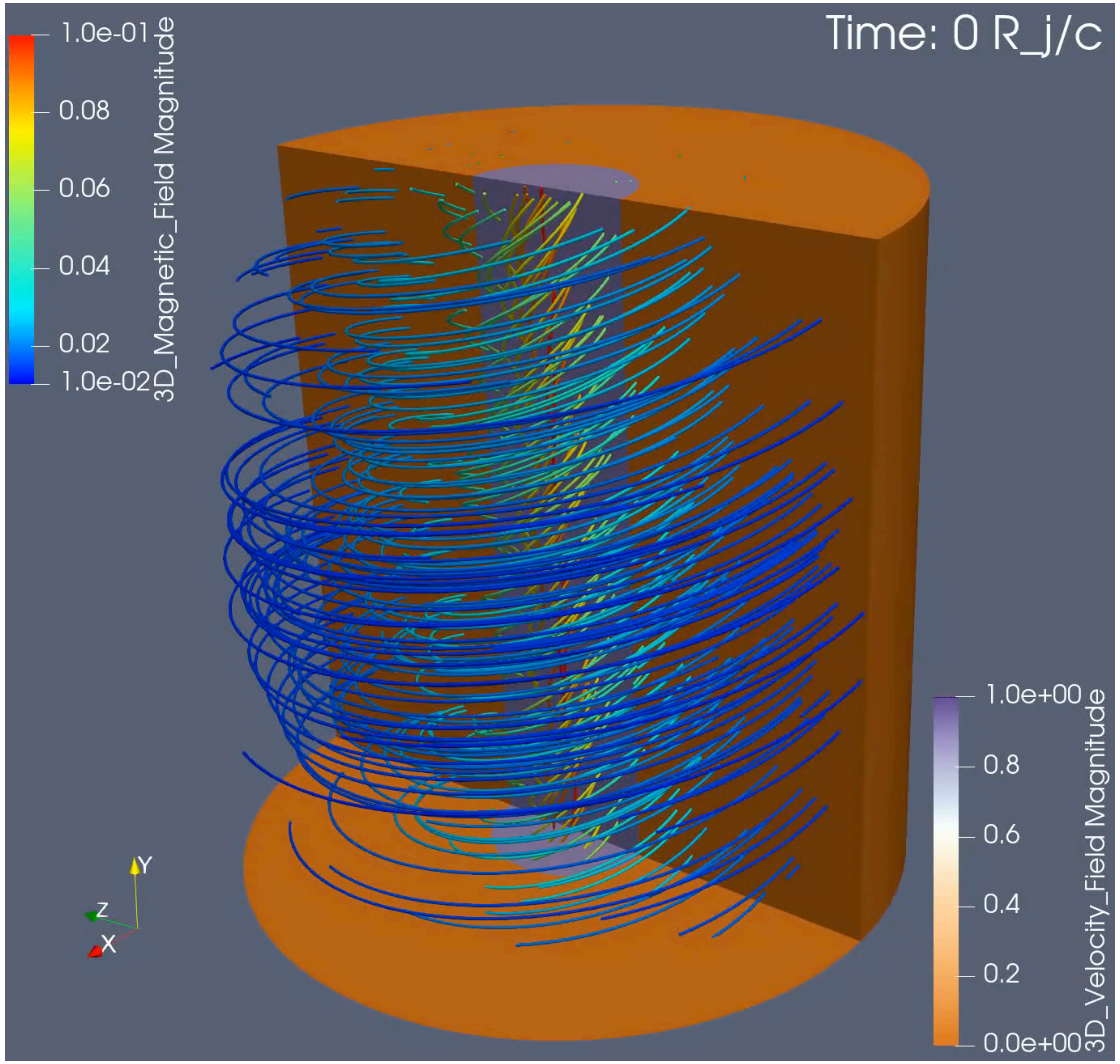
→ Validating shear acceleration via numeric simulations: RMHD+Test particles

RMHD simulations with PLUTO

- Jet injected along Y axis, ambient at rest
- Periodic box along the jet axis to study the Kelvin-Helmholtz instability
- Different parameters explored
  $v \in [0.6, 0.99]$ & $\sigma \in [0.002, 0.2]$

$$\sigma_{y,\phi} =< B^2_{y,\phi} > /8\pi\rho_0 c^2$$

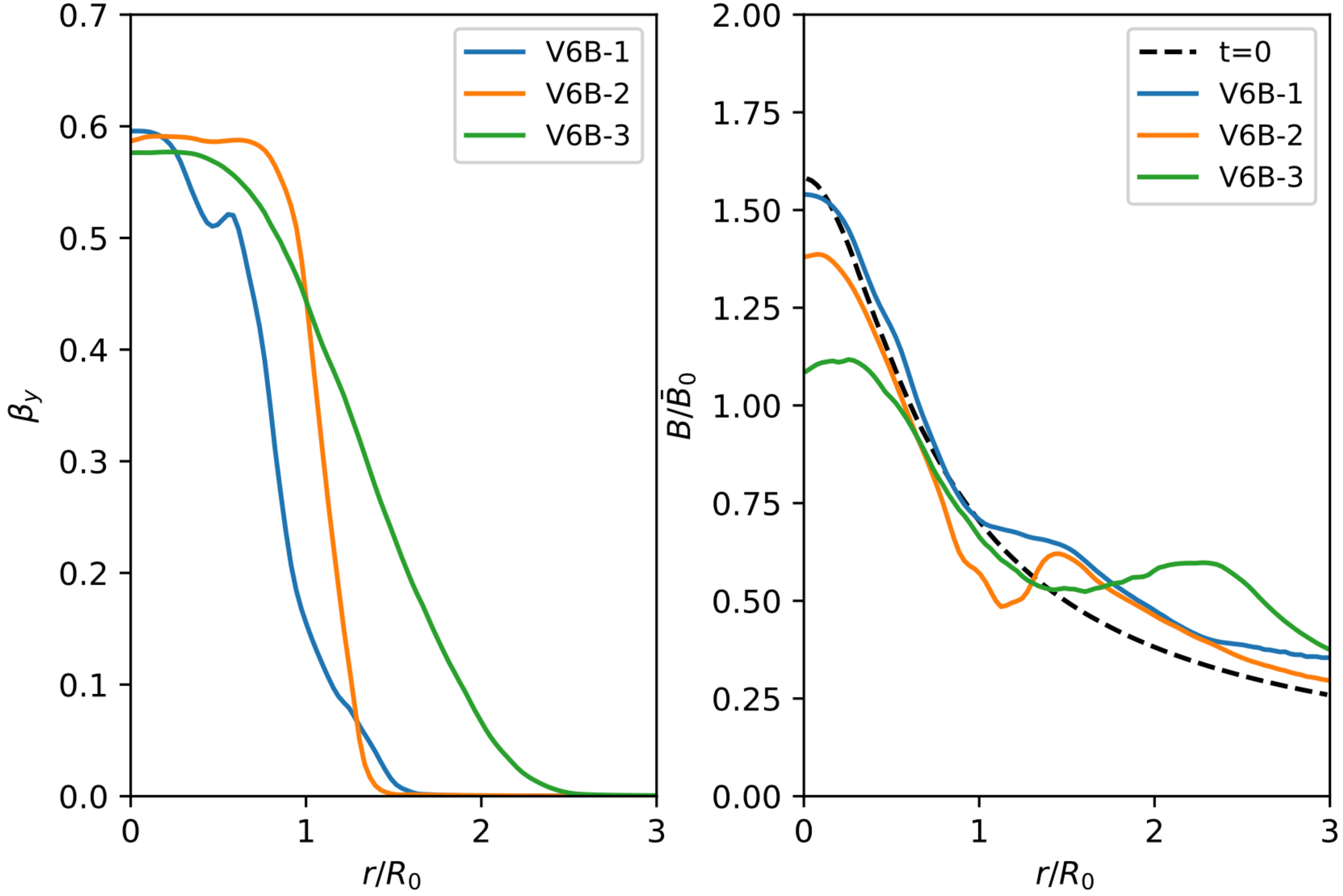
Runs*	β_0	σ_y	σ_ϕ	Box size	Grid points	Θ_0	R_0	$L_{\rm K}$(erg s^{-1})
V6B-1	0.6	10^{-1}	10^{-1}	$6.0R_0$	375^3	0.01	0.1kpc	1.3×10^{43}
V6B-1-SB	0.6	10^{-1}	10^{-1}	$4.8R_0$	300^3	0.01	0.1kpc	1.3×10^{43}
V6B-1-LR	0.6	10^{-1}	10^{-1}	$6.0R_0$	200^3	0.01	0.1kpc	1.3×10^{43}
V6B-2	0.6	10^{-2}	10^{-2}	$6.0R_0$	375^3	0.01	0.1kpc	1.3×10^{43}
V6BA-2	0.6	0.016	0.004	$6.0R_0$	375^3	0.01	0.1kpc	1.3×10^{43}
V6BT-2	0.6	0.004	0.016	$6.0R_0$	375^3	0.09	0.1kpc	1.6×10^{43}
V6B-3	0.6	10^{-3}	10^{-3}	$6.0R_0$	375^3	0.01	0.1kpc	1.3×10^{43}
V9B-1	0.9	10^{-1}	10^{-1}	$8.0R_0$	500^3	0.09	1 kpc	6.7×10^{45}
V9B-2	0.9	10^{-2}	10^{-2}	$8.0R_0$	500^3	0.04	1 kpc	7.0×10^{45}
V9B-3	0.9	10^{-3}	10^{-3}	$8.0R_0$	500^3	0.02	1 kpc	6.7×10^{45}
V99B-2	0.99	10^{-2}	10^{-2}	$8.0R_0$	500^3	0.07	1 kpc	7.9×10^{46}



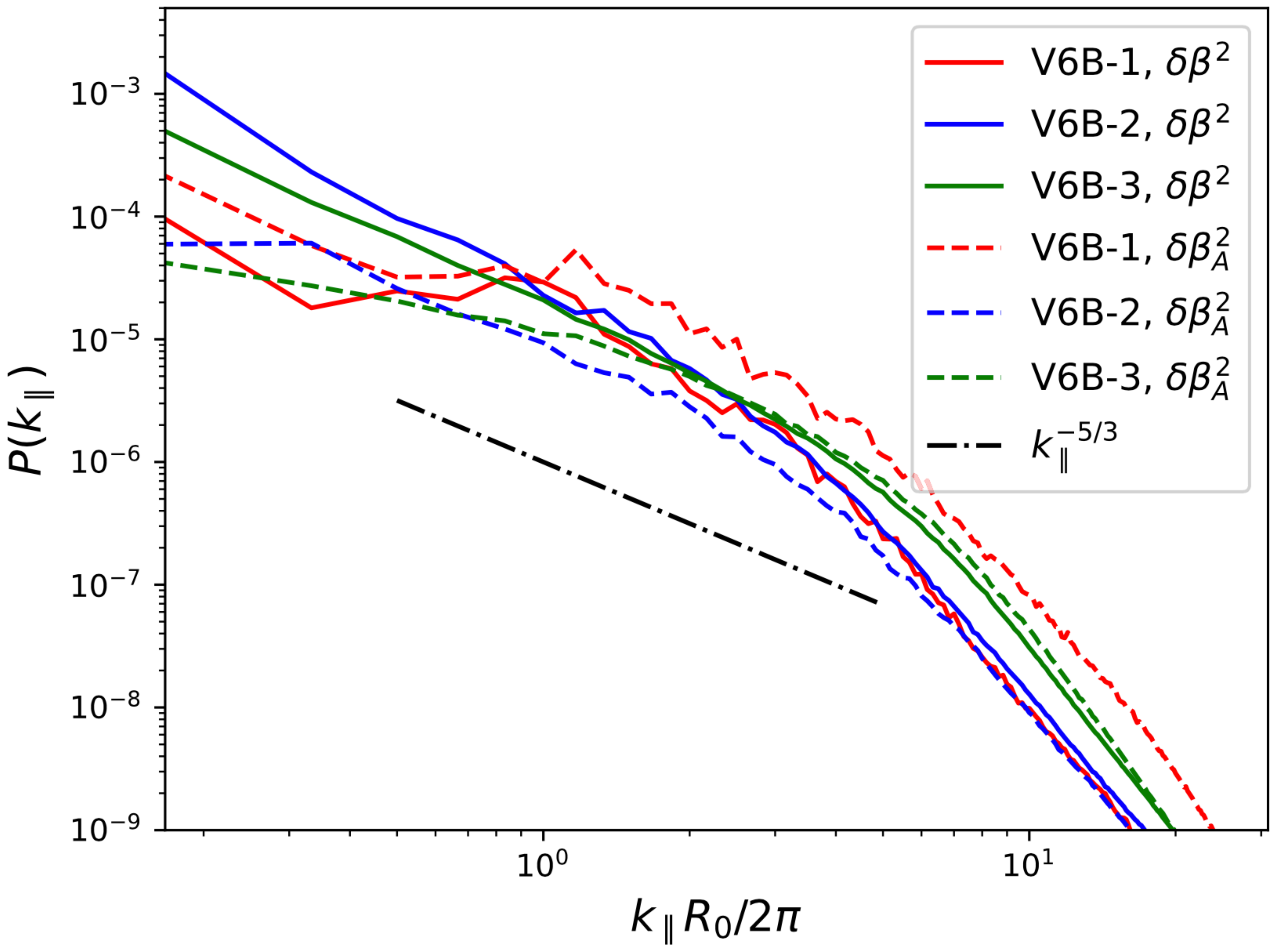
J.S.Wang+, 2023, MNRAS, arXiv:2212.03226

v=0.6c cases in saturated KHI stage

lower magnetization case: wider sheaths
& significant B filed pile-up at the edge



Velocity turbulence :Kolmogorov theory



J.S.Wang+, 2023, MNRAS, arXiv:2212.03226

v=0.9c cases in saturated KHI stage

J.S.Wang+, 2023, MNRAS, arXiv:2212.03226

- A sheath structure and turbulence can be self-generated via KH instability
- Higher velocities/lower magnetization lead to wider sheaths in saturated KHI stage
- Turbulence mostly consistent with Kolmogorov theory

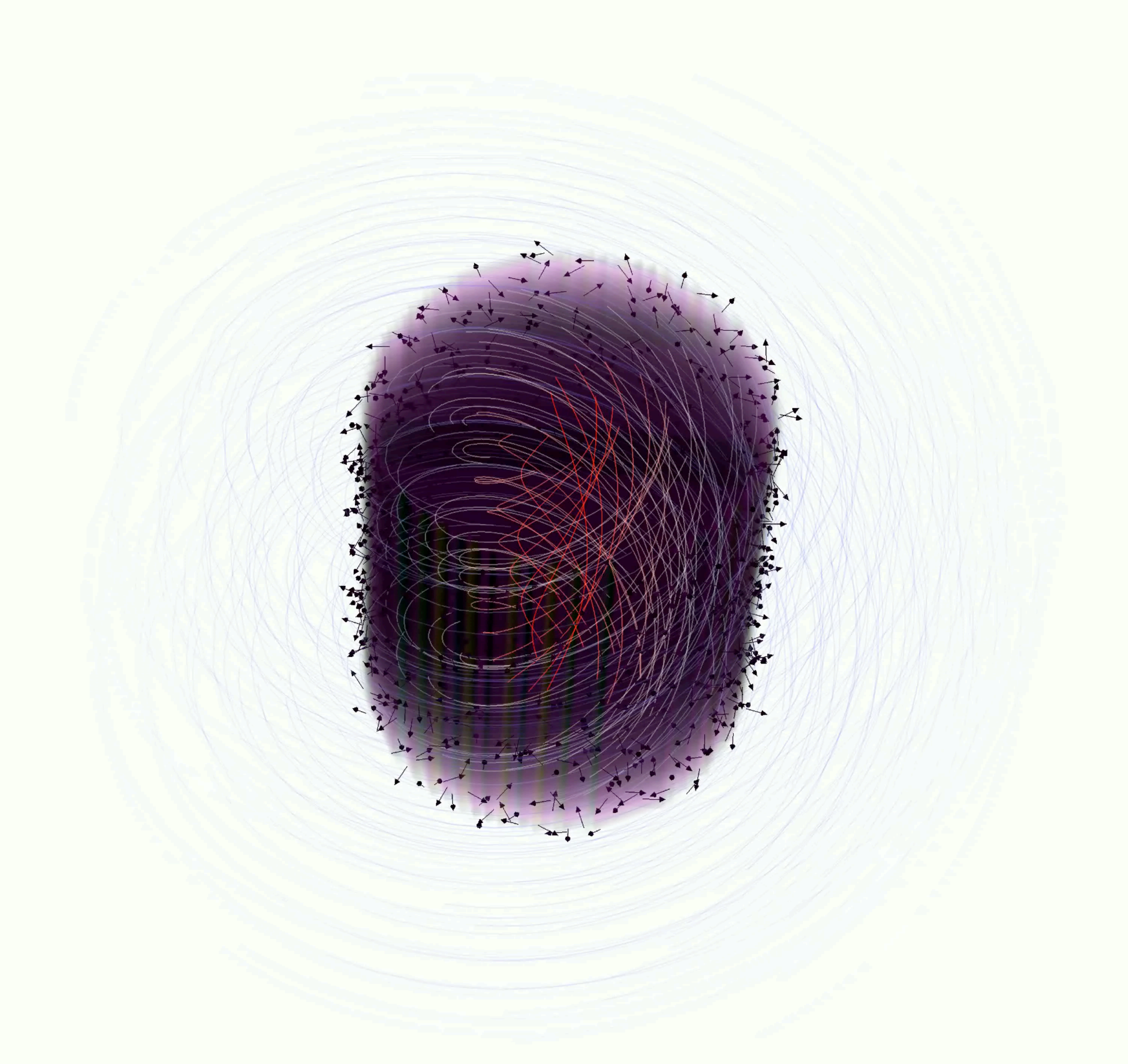
RMHD + Test-particle Simulations with PLUTO

- More self-consistent particle acceleration
- Higher-resolution runs
- Inject protons with Larmor radii at a few grid scales to avoid sub-grid physics

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

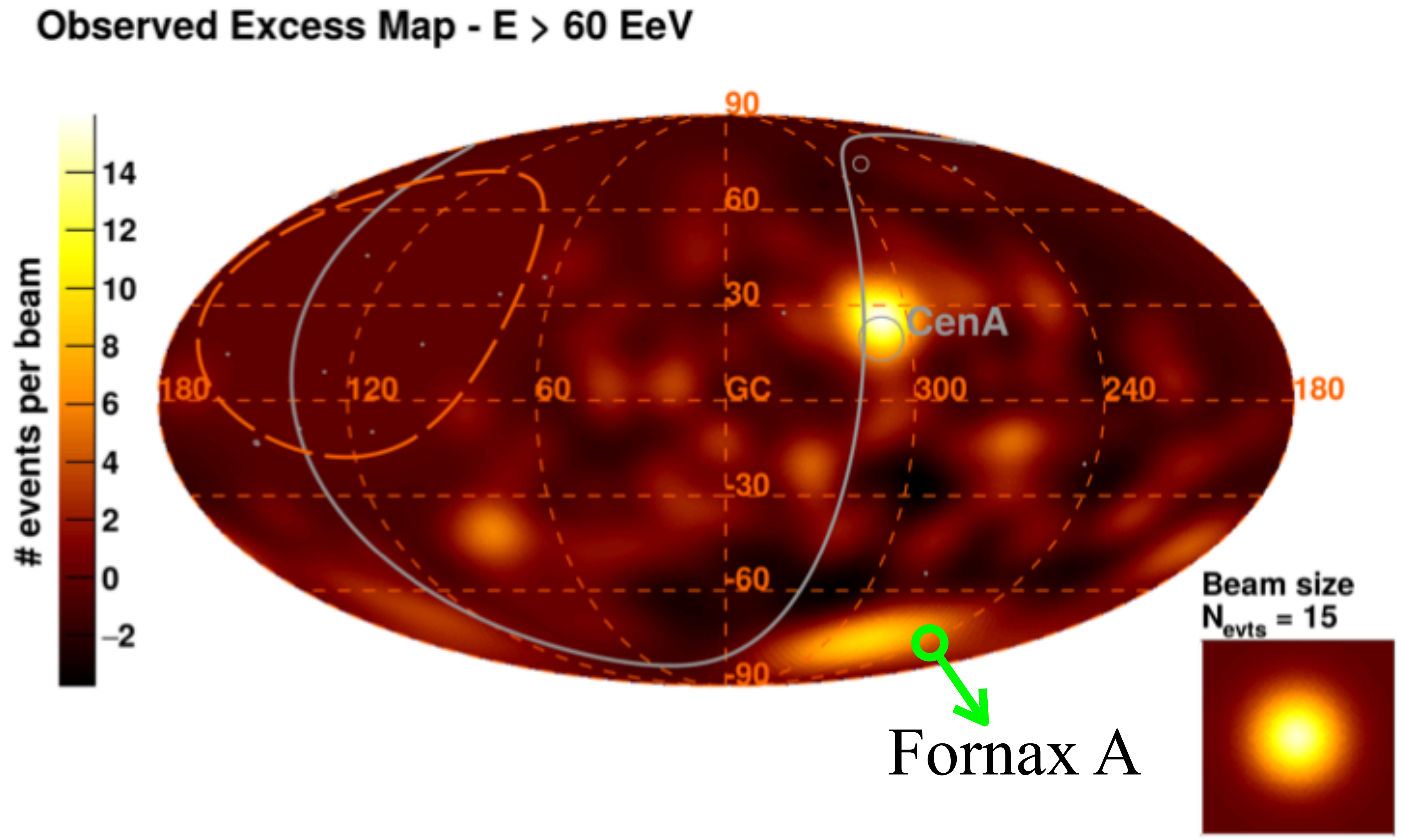
$$\frac{d\,(\gamma\boldsymbol{v})_p}{dt} = \alpha_p(c\boldsymbol{E} + \boldsymbol{v}_p \times \boldsymbol{B})$$

- To study the capability to accelerate UHECRs via shear acceleration



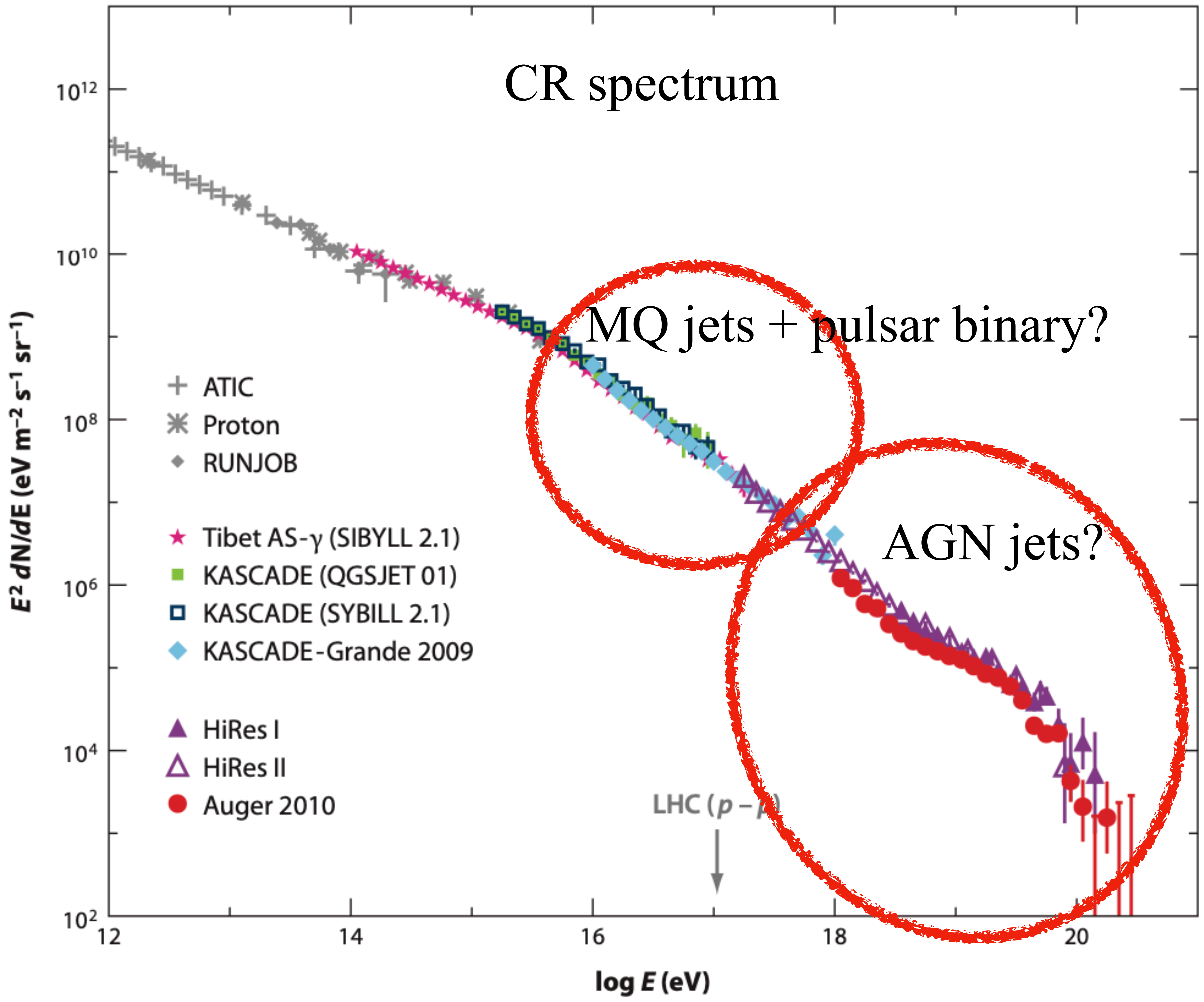
Cosmic Rays

Radio galaxies (Cen A) as UHECR sources



Fornax A

Pierre Auger Collaboration, 2018, ApJ, [arXiv:1801.06160](https://arxiv.org/abs/1801.06160)



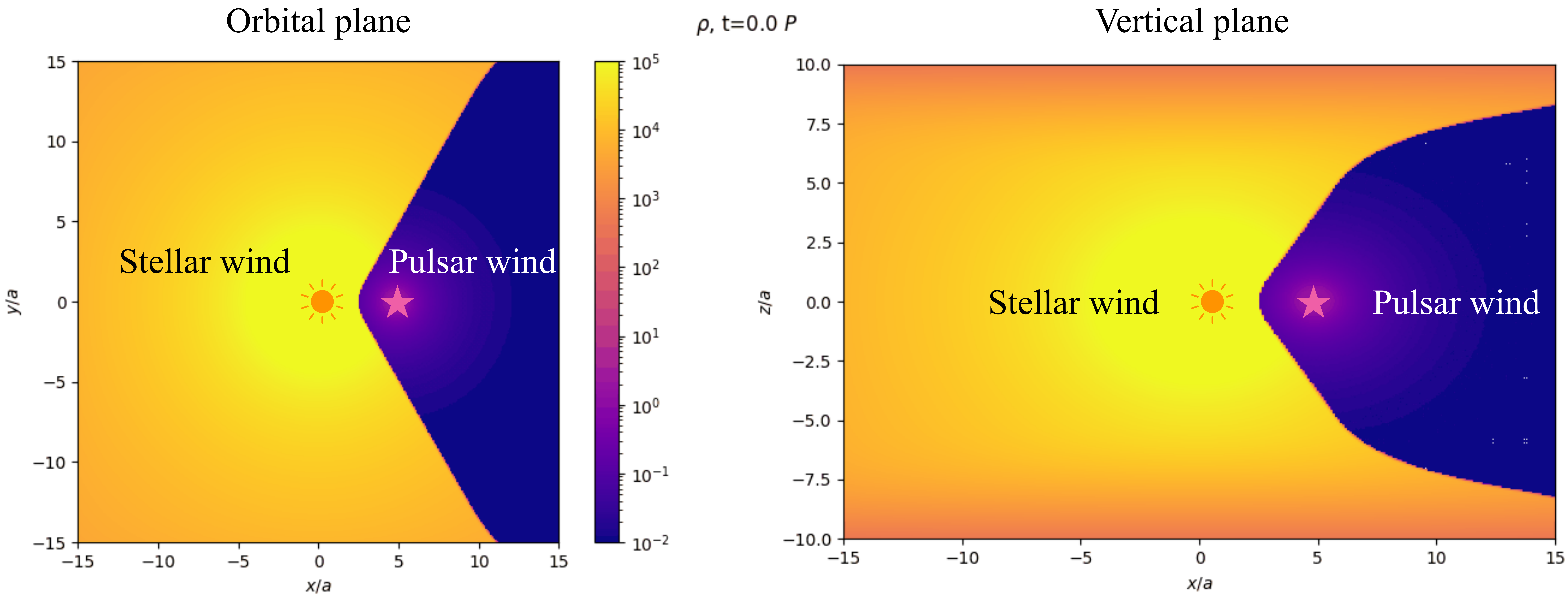
CR spectrum

MQ jets + pulsar binary?

AGN jets?

Particle acceleration in pulsar binary?

Colliding wind binary: RHD simulation



Summary

- Shear acceleration is unavoidable in jets:
  - Self-generation of spine-sheath structure and turbulence via KH instability
  - Distributed particle acceleration along the jet
- Protons can achieve Hillas limit in jets via shear acceleration
  - Contribution to >EeV CRs from AGN jets and >10 PeV CRs microquasar jets
- Analytical solution for shear acceleration: cut-off power-law spectra
  - Bridging theory and observations: modeling SED to get the jet parameters
- Particle acceleration in colliding pulsar wind binary to be explored (need to simplify/ decouple)