Centaurus A, NASA/CXC

Particle acceleration in AGN jets

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Alexander von
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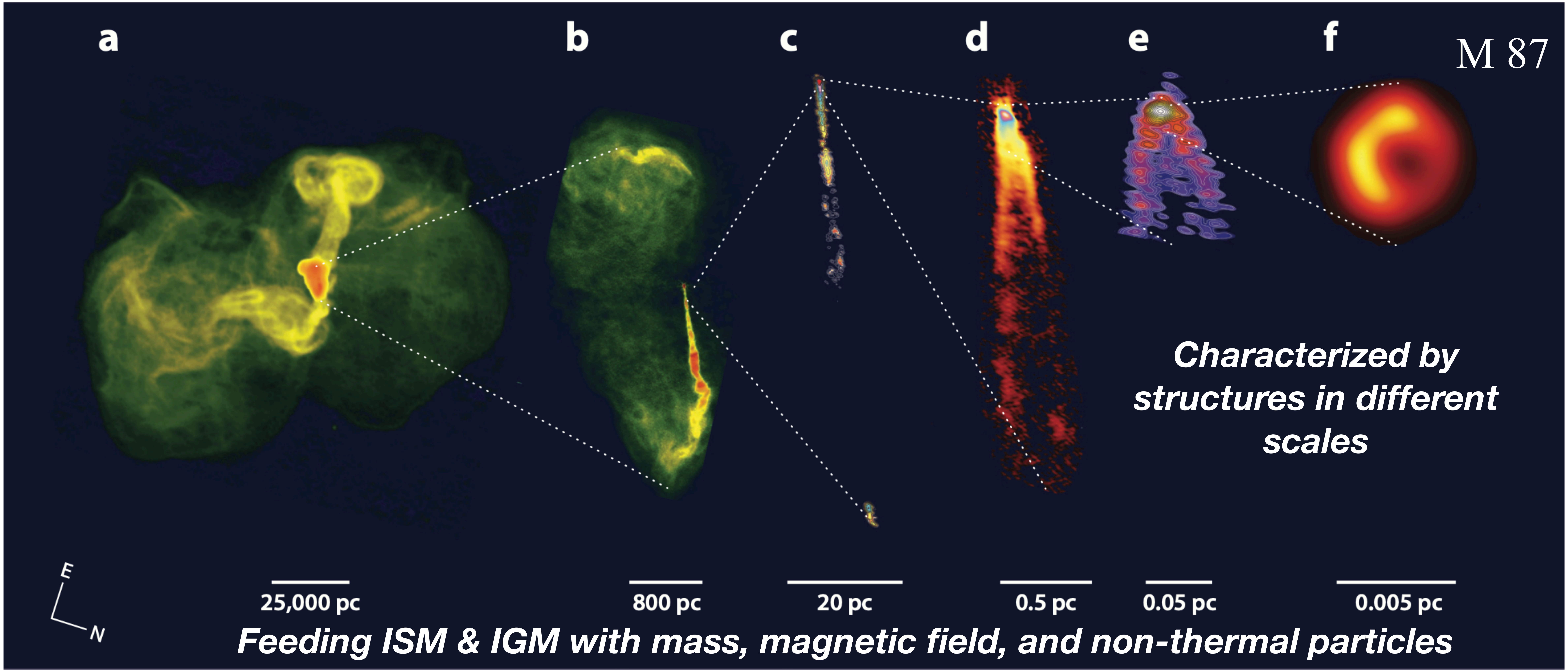
STIFTUNG

Outline

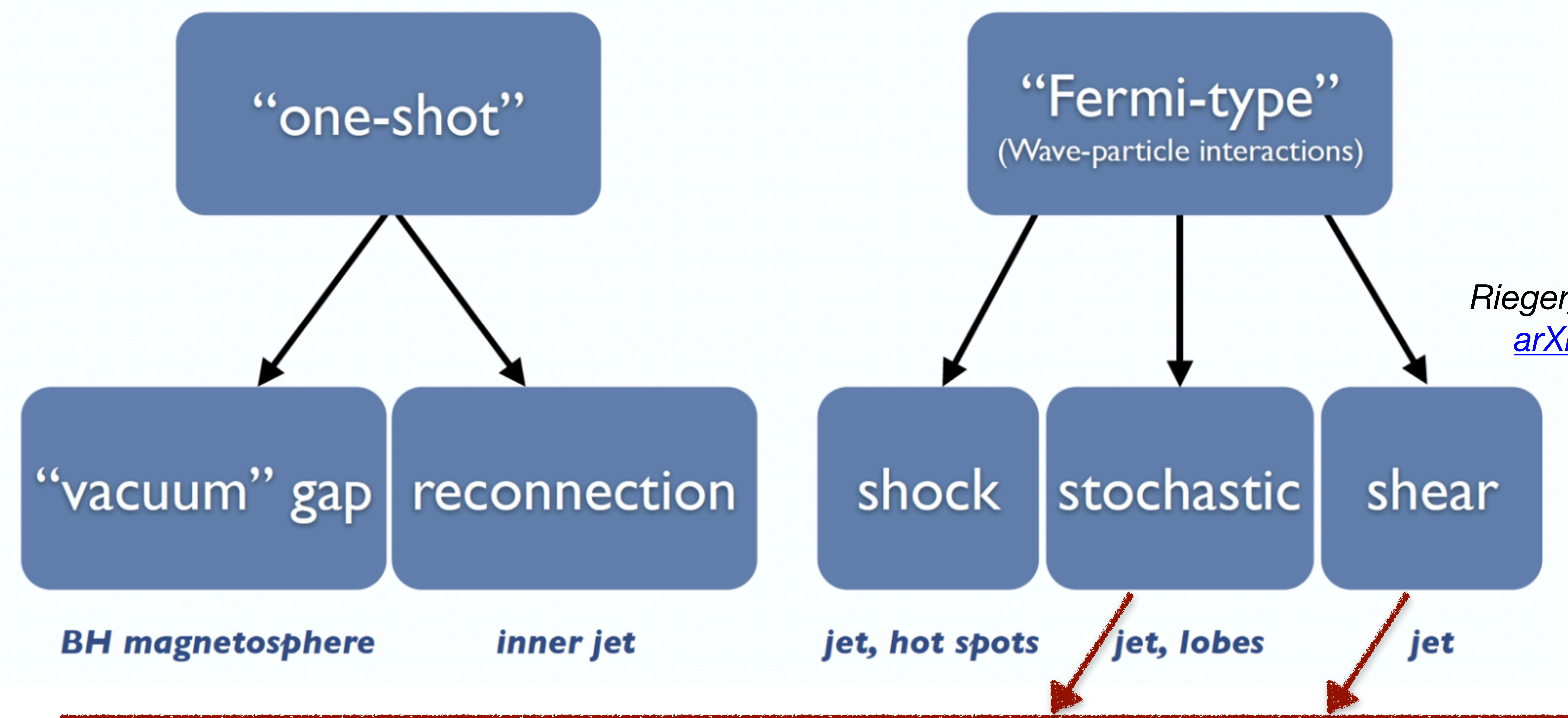
- Introduction of particle acceleration
- Analytical solutions and applications of shear and stochastic acceleration
- Numerical simulations of particle acceleration
- Summary

AGN jets in all scales



Blandford+ 2019, ARA&A, [*arXiv:1812.06025*](https://arxiv.org/abs/1812.06025)

Particle acceleration in different scales



Rieger, 2022, Universe,
arXiv:2211.12202

Stochastic and shear are distributed acceleration mechanism that will take place in all scales

Stochastic and shear acceleration

- Stochastic: standard Fermi-II mechanism
- Energy gain in each collision (Fermi, 1949, Phys. Rev. 75, 578)

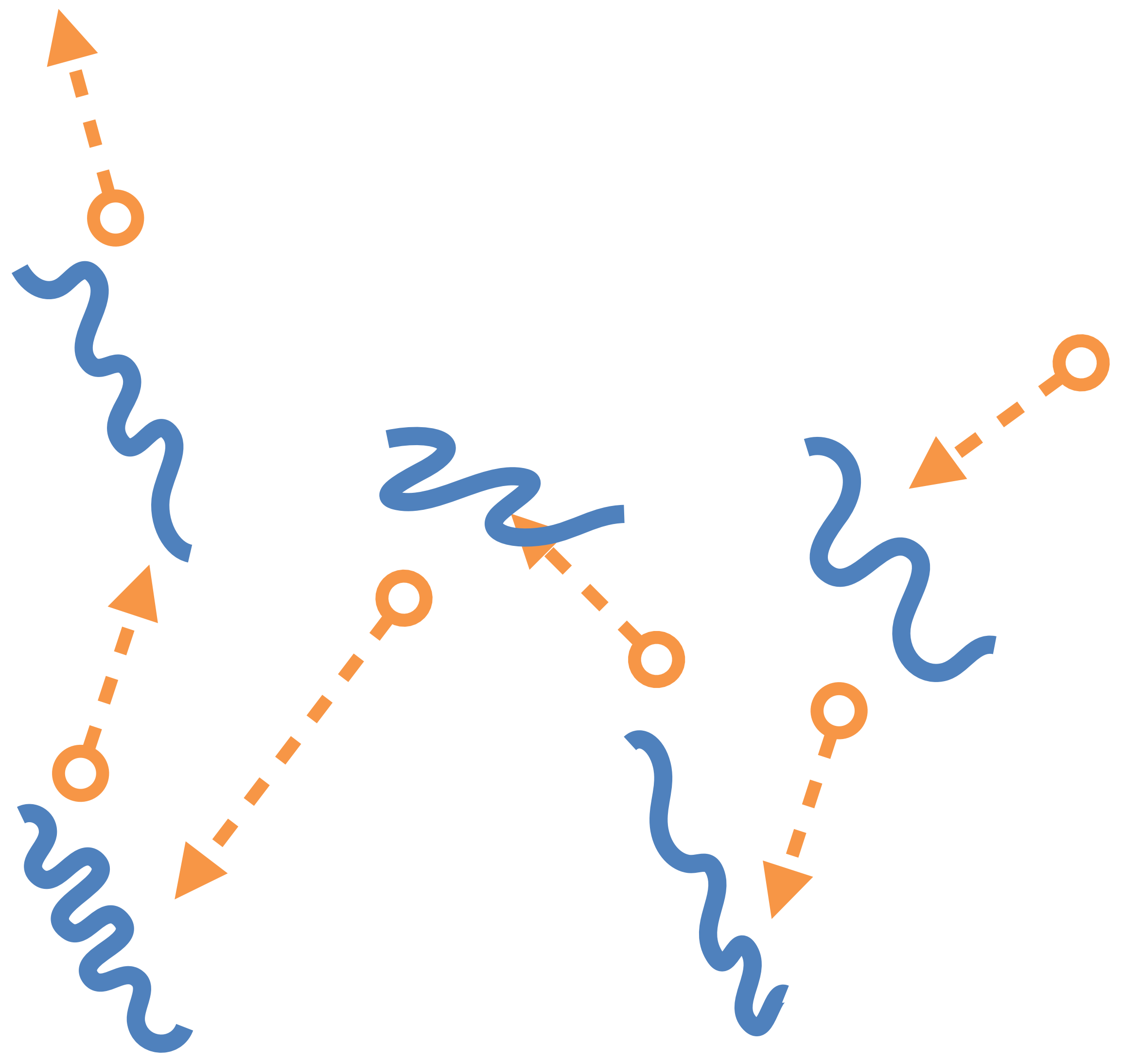
$$\frac{\langle \Delta\epsilon \rangle}{\epsilon} \propto \left(\frac{u}{c}\right)^2$$

- Scattering off MHD waves:

$$u = v_A = B/\sqrt{4\pi\rho}$$

- Scattering time: $\tau_{\rm sc} \propto \gamma^{2-q}$
- Acceleration time (Kolmogorov $q = 5/3$):

$$\tau_{\rm stoch} = \frac{\epsilon}{< \Delta\epsilon >}\tau_{sc} \propto \gamma^{1/3}$$



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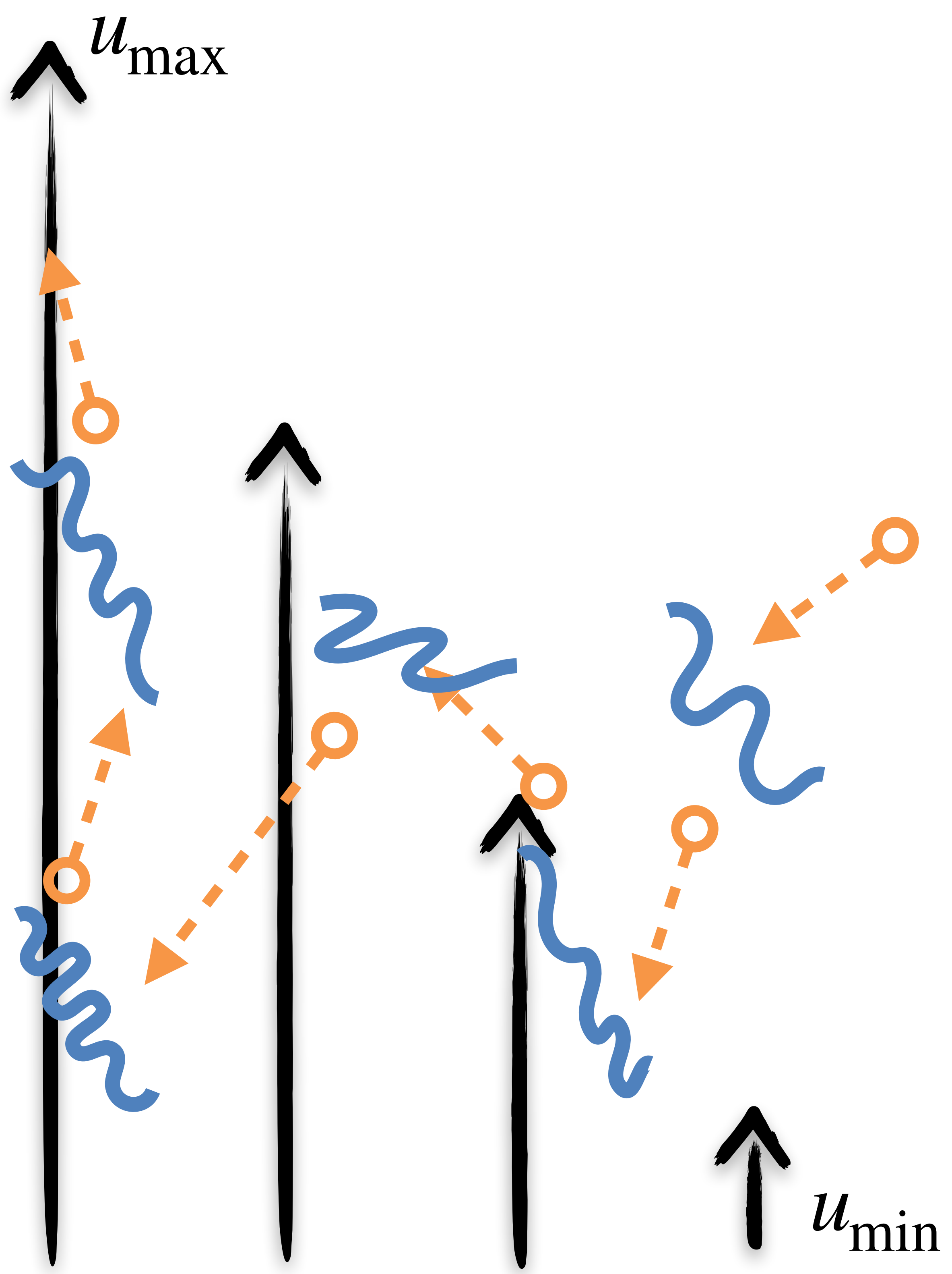


- Shear is also Fermi-II type (see Rieger, 2019, arXiv:1909.07237 for a review)
- Turbulences are embedded in velocity-shearing layers (spine-sheath)
- Particles scattering off turbulence will sample the velocity difference

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

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

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 solutions and application in kpc-scale jets

Particle spectrum from shear acceleration

- An exact solution of Fokker-Planck equation for steady-state shear acceleration:

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

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

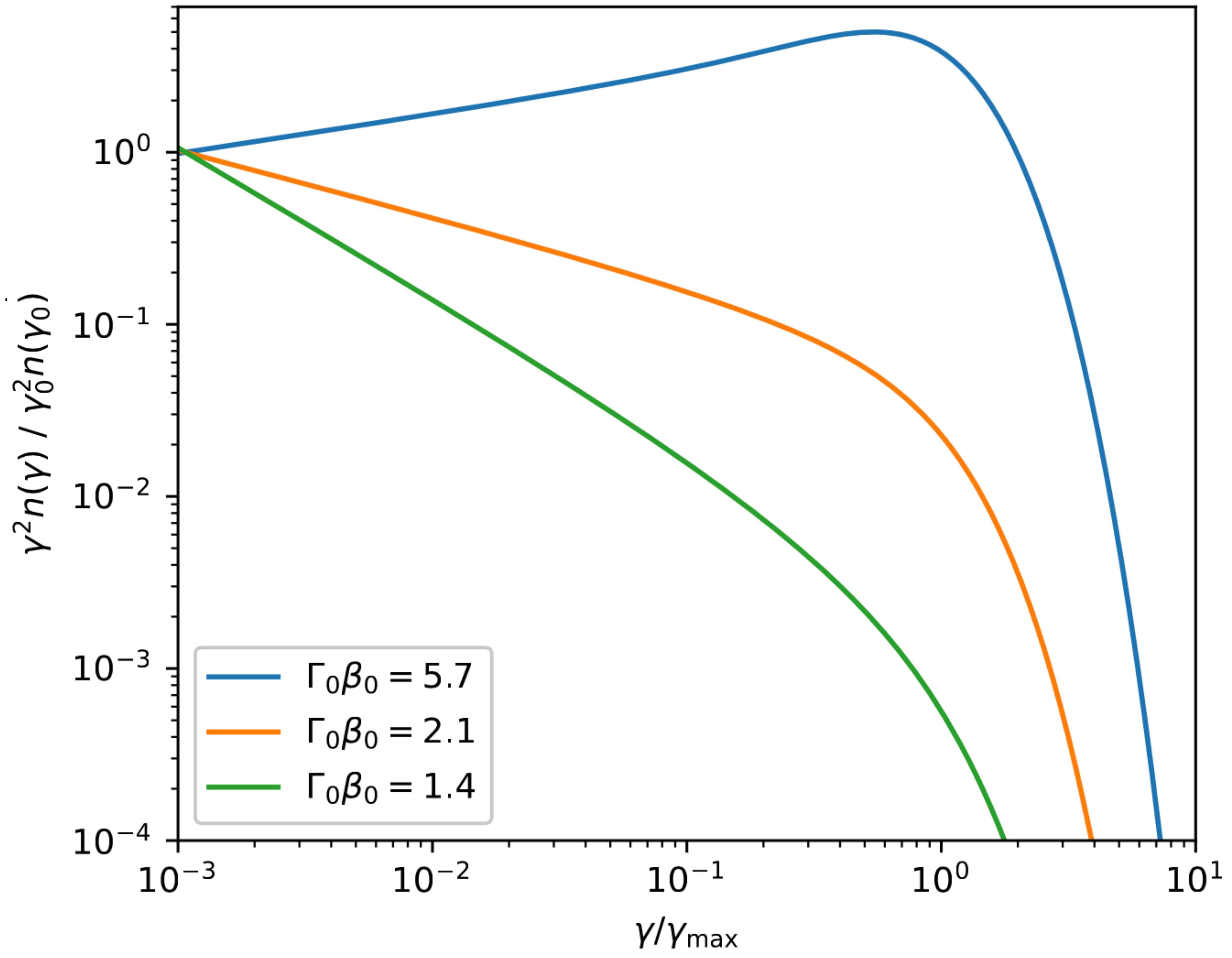
$$F_\pm(\gamma, q) = {}_1F_1\left[\frac{2+s_\pm}{q-1}, \frac{2s_\pm}{q-1}; -\frac{6-q}{q-1}\left(\frac{\gamma}{\gamma_{\max}}\right)^{q-1}\right]$$

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

- Kolmogorov turbulence: q=5/3
- Assume a linear velocity profile

Rieger & Duffy, 2019, ApJL, arXiv:1911.05348

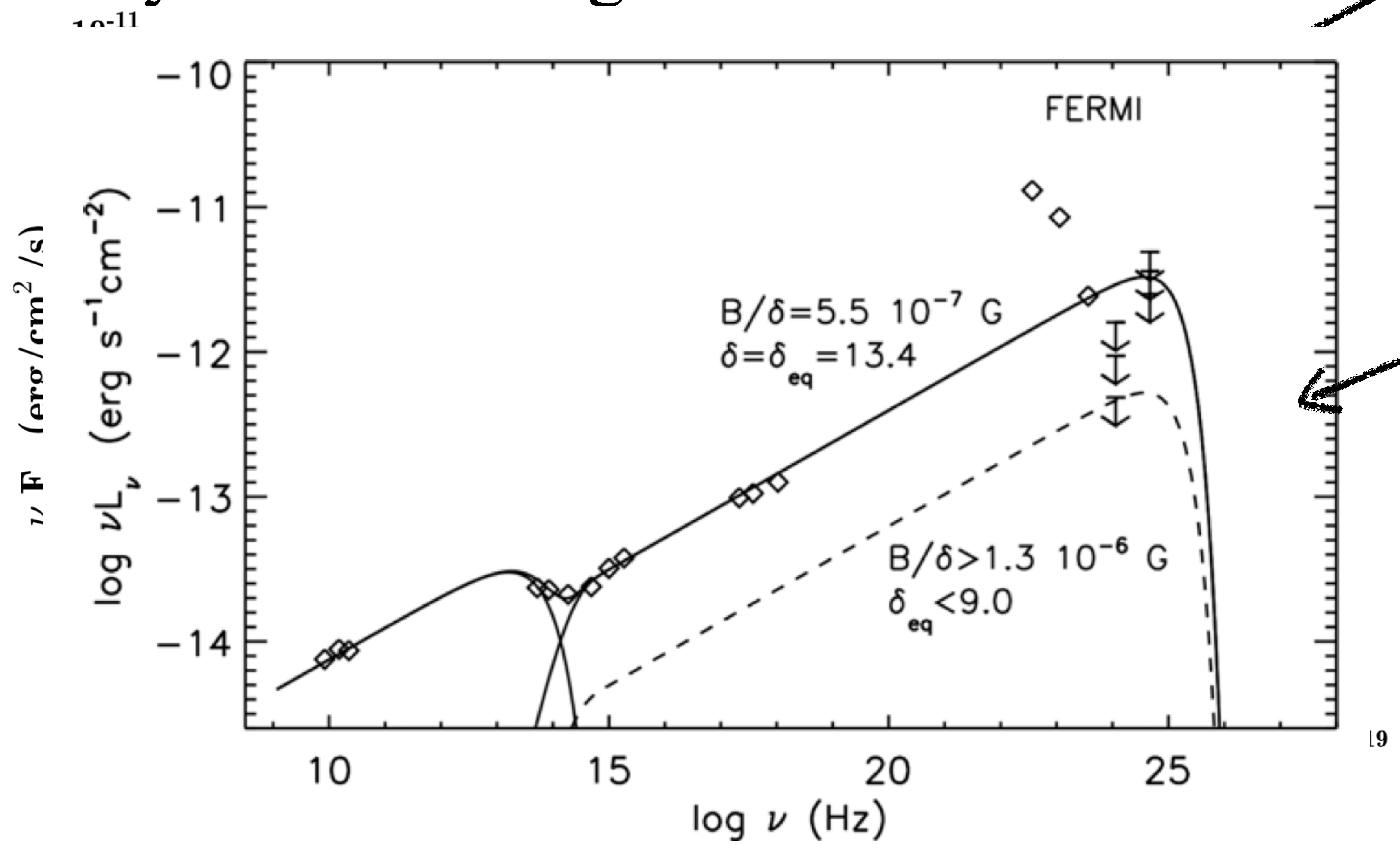
$$w = 40\ln^{-2}\frac{(1+\beta_0)}{(1-\beta_0)}$$



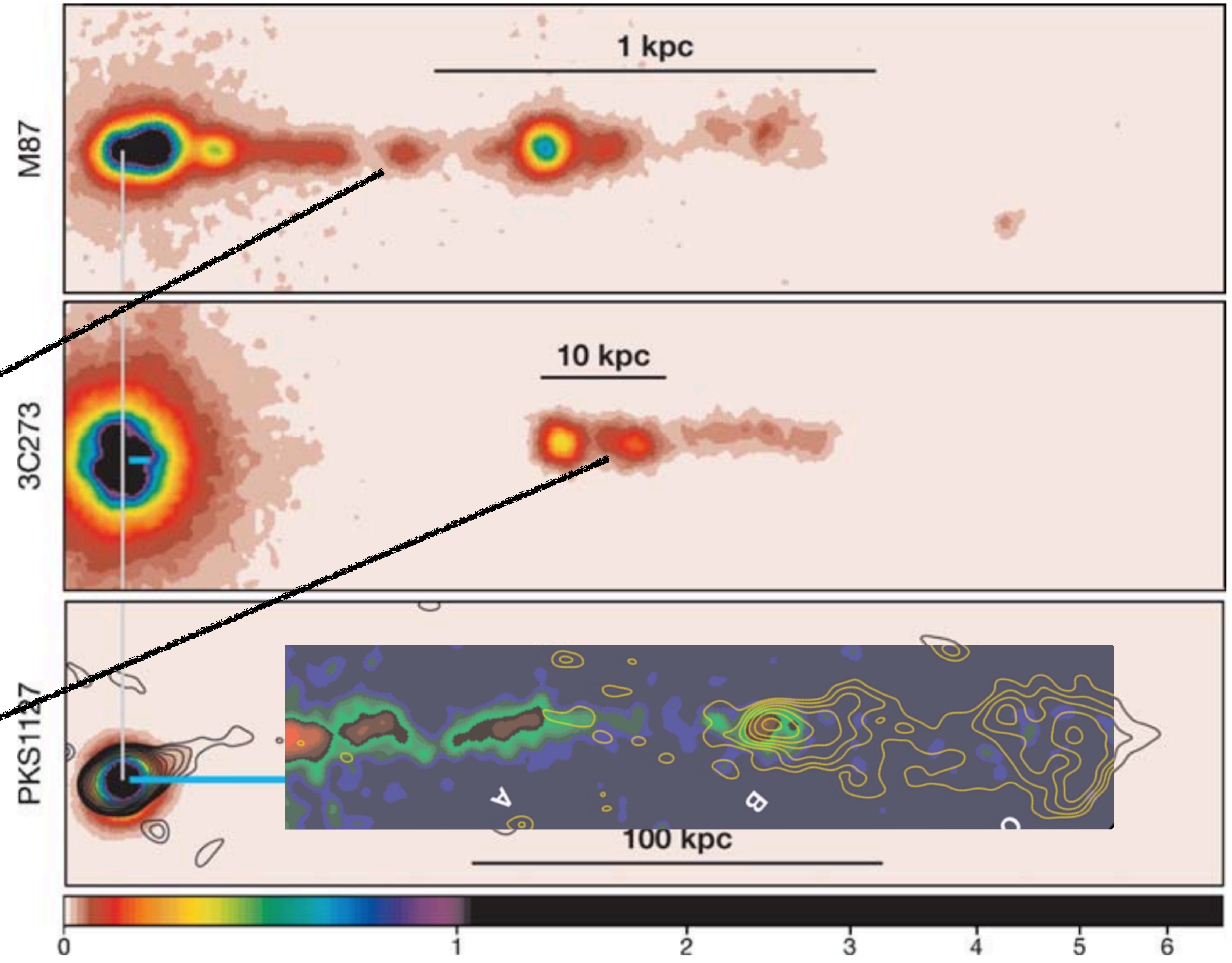
J.S.Wang+, 2021, MNRAS, arXiv:2105.08600

kpc-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



Meyer & Georganopoulos, 2014, ApJL, arXiv:1307.8421



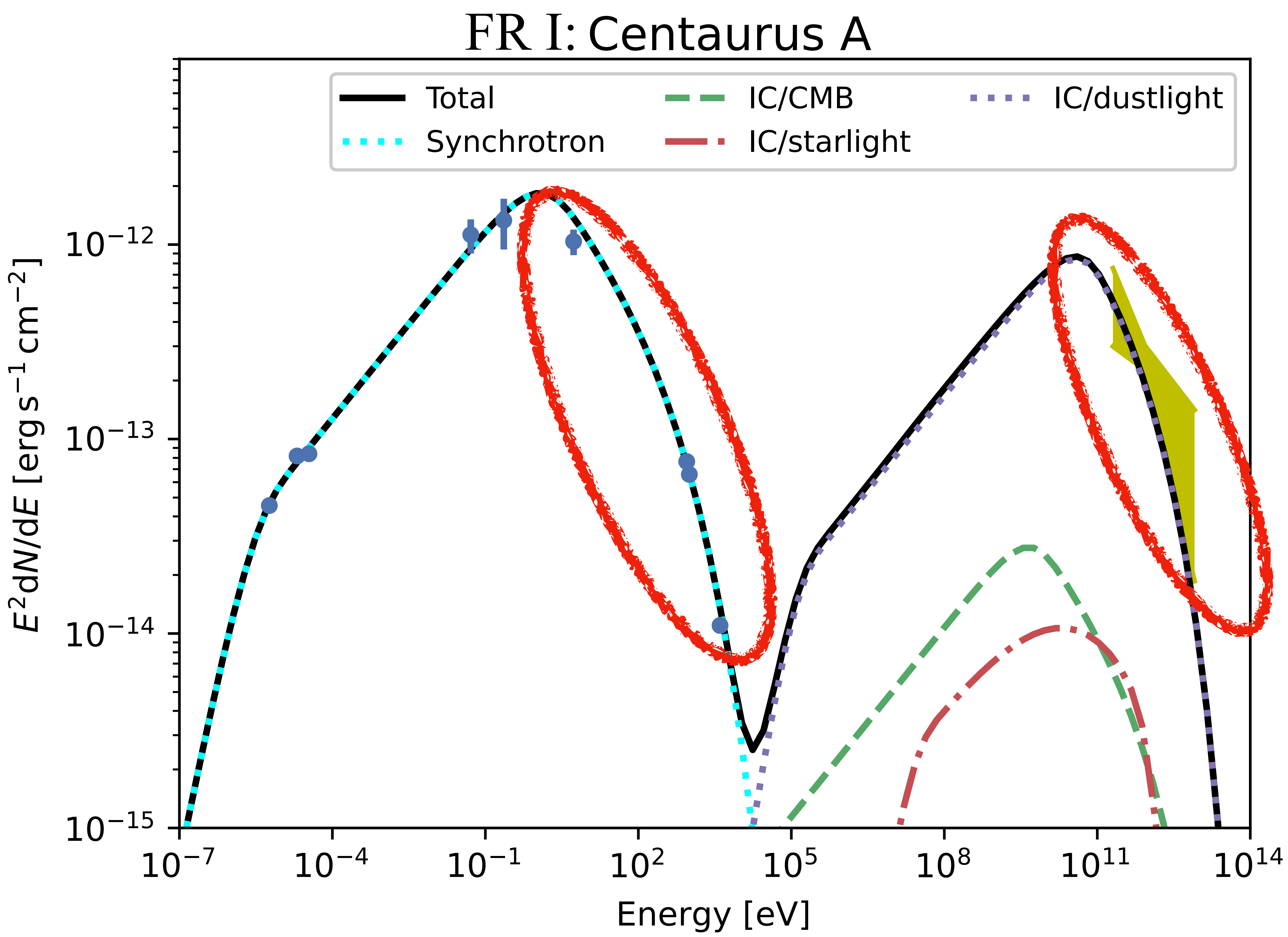
Harris & Krawczynski, 2006, ARA&A, arXiv:astro-ph/0607228

Sun+ 2018, A&A, arXiv:1712.06300

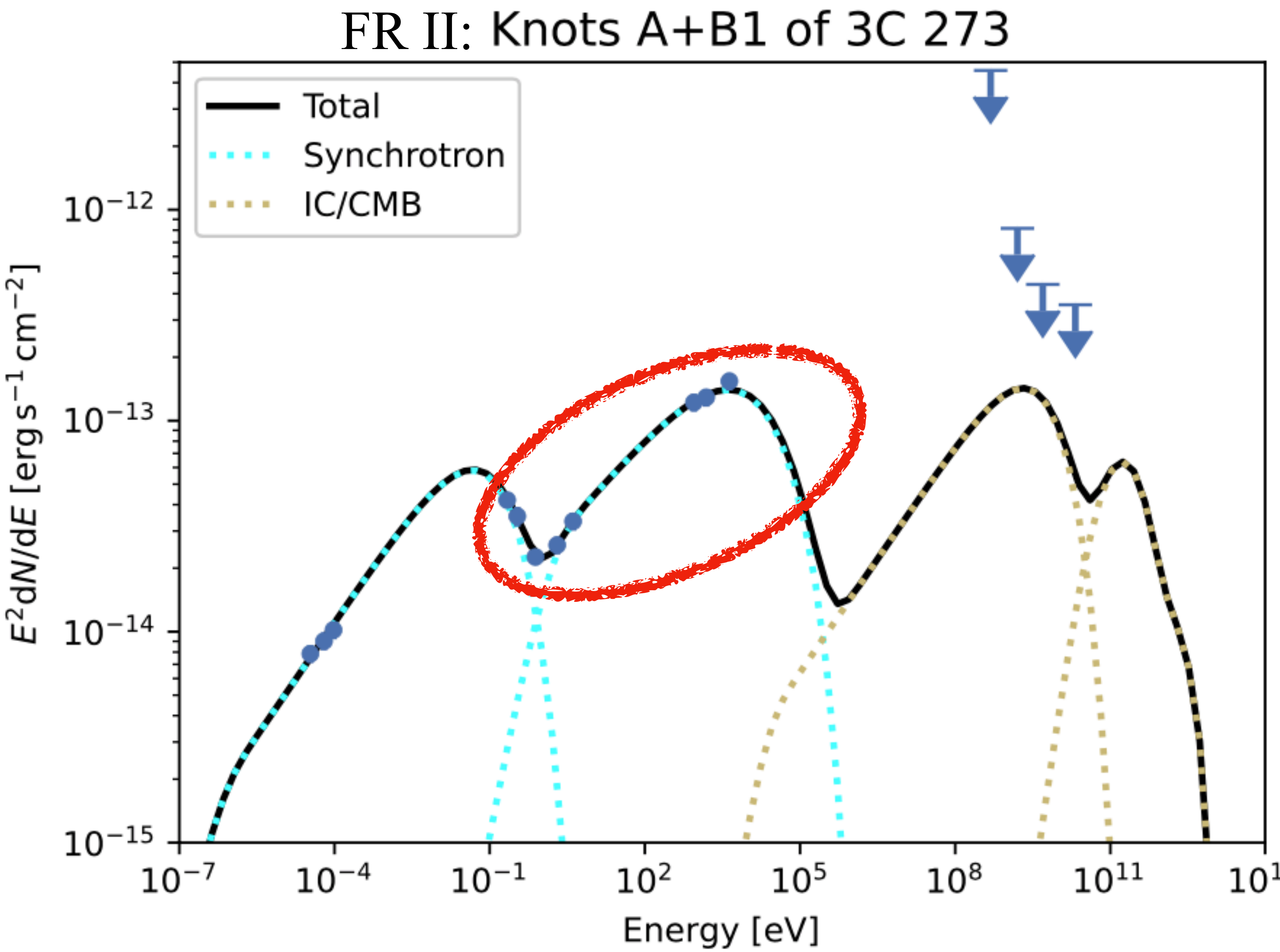
Distributed acceleration required

- 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: $\tau_{\rm syn} = 1.2 \times 10^3 (B/10\mu{\rm G})^{-2}(E_e/0.1{\rm PeV})^{-1}$ yrs $\rightarrow$ maximum travel distance $c\tau_{\rm syn} = 0.37$ 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
  - Application of analytical solution of shear acceleration

Applications of analytical solution on shear



IC and Syn from one population of electrons

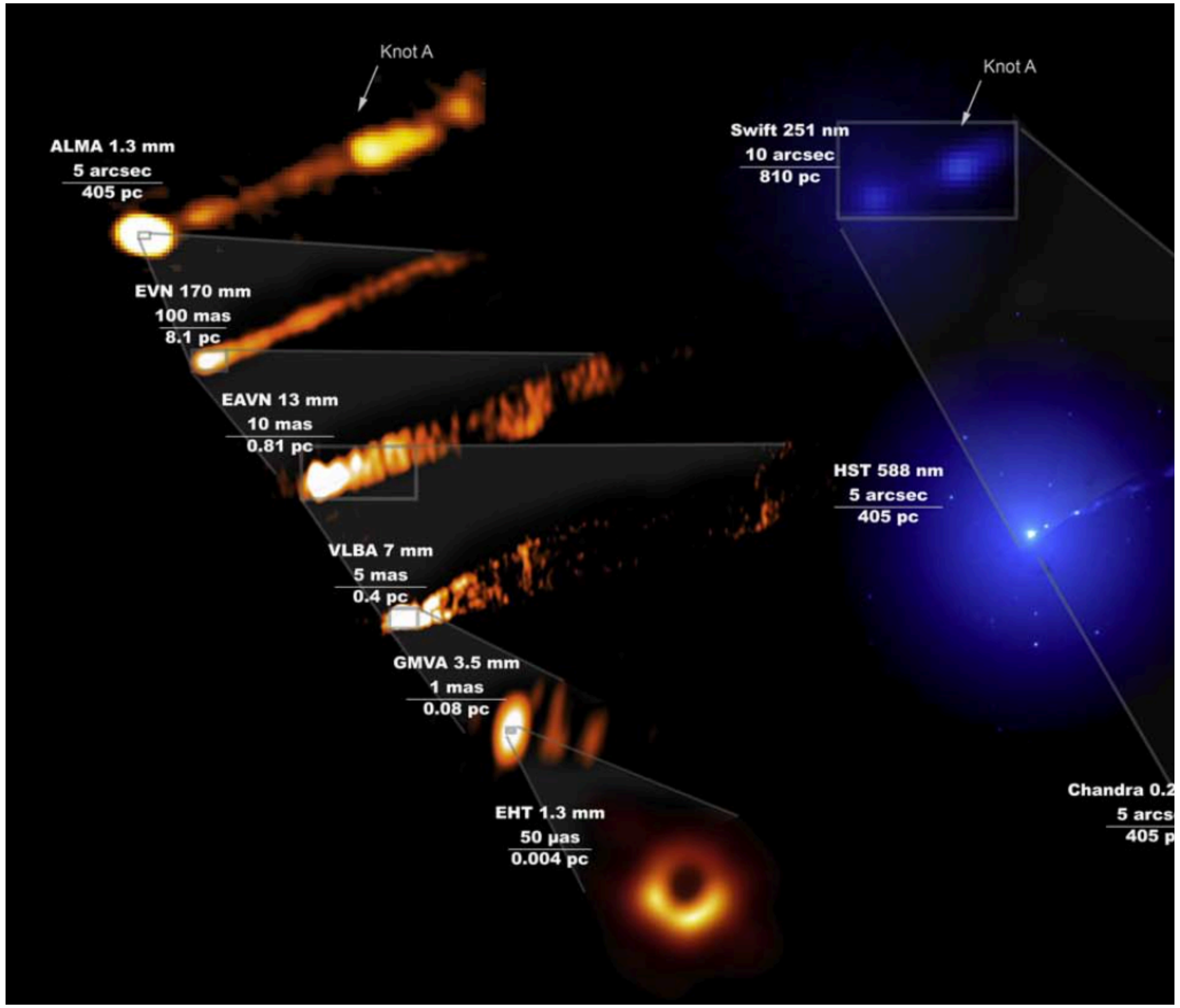


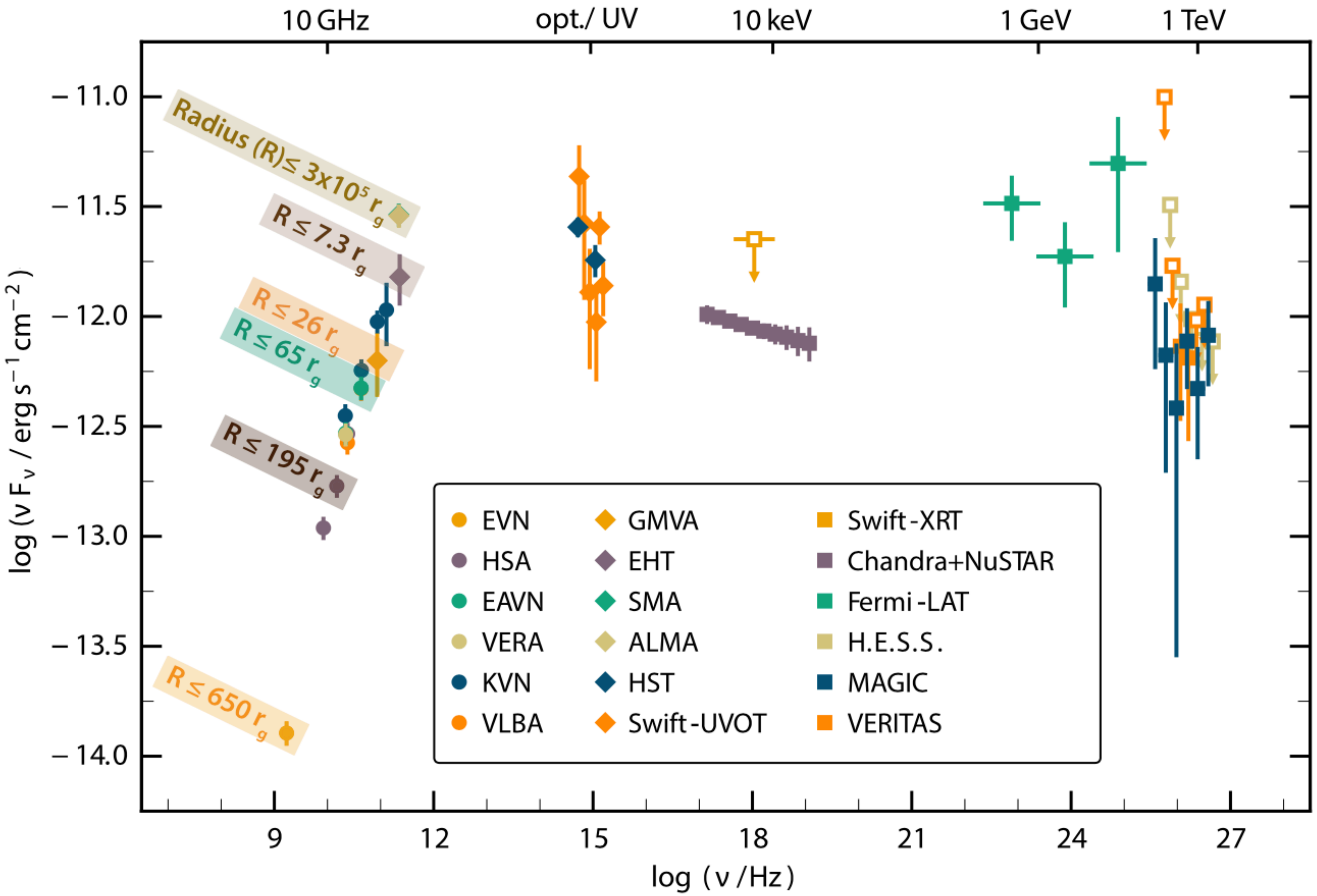
Synchrotron and IC from two populations of electrons

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

Analytical solutions and application in sub-pc-scale jets

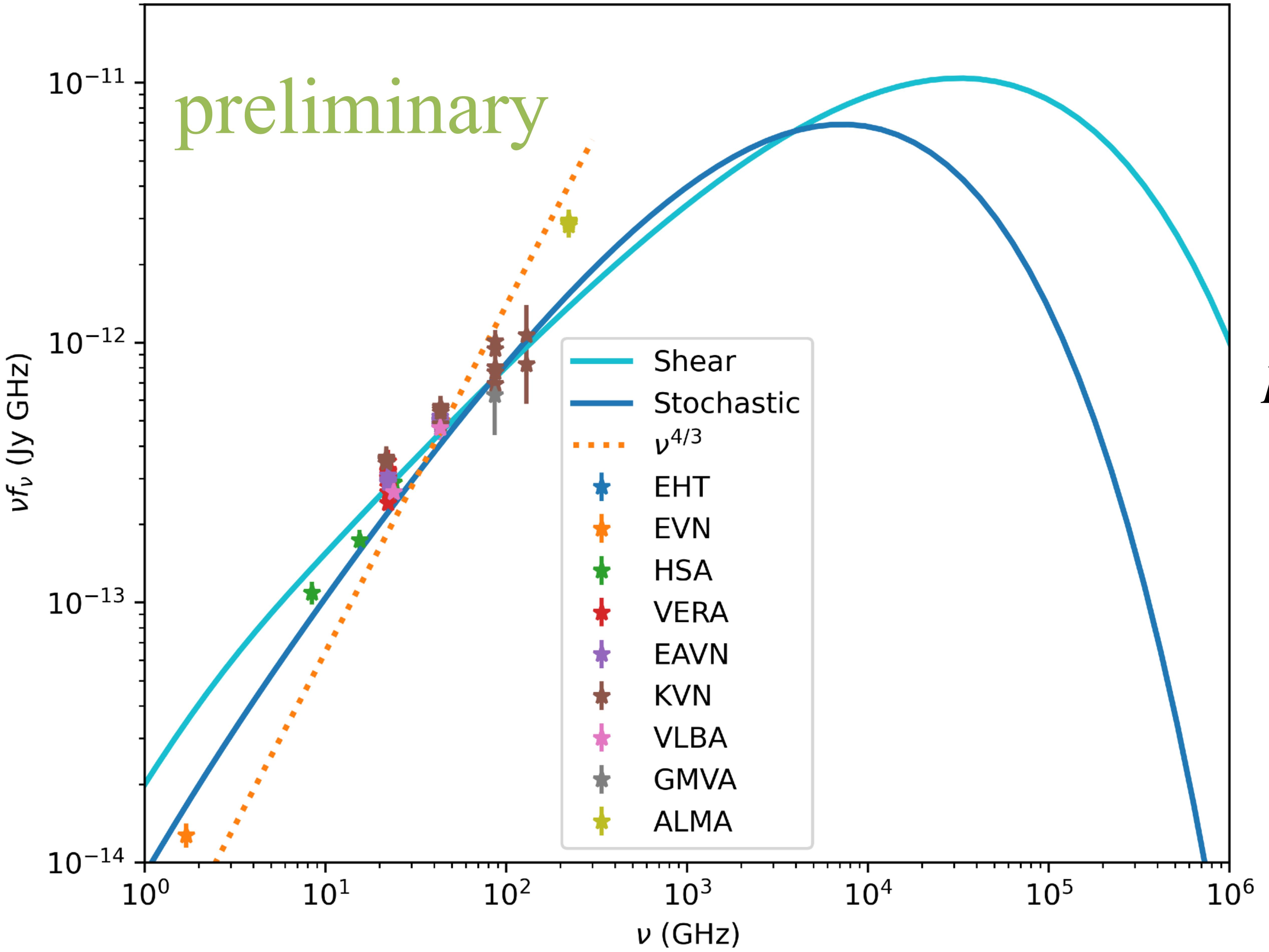
sub-pc-scale radio jet of M87



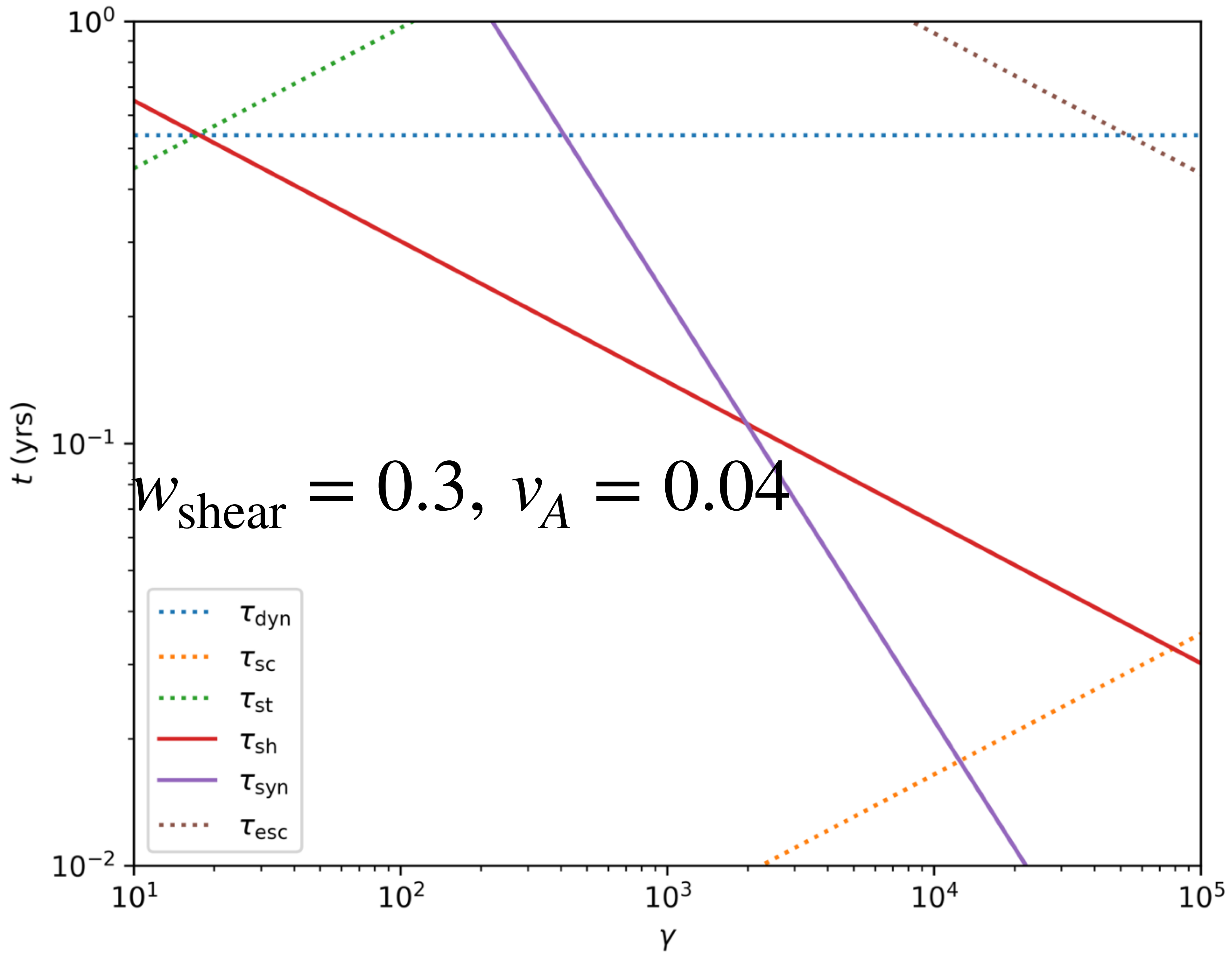


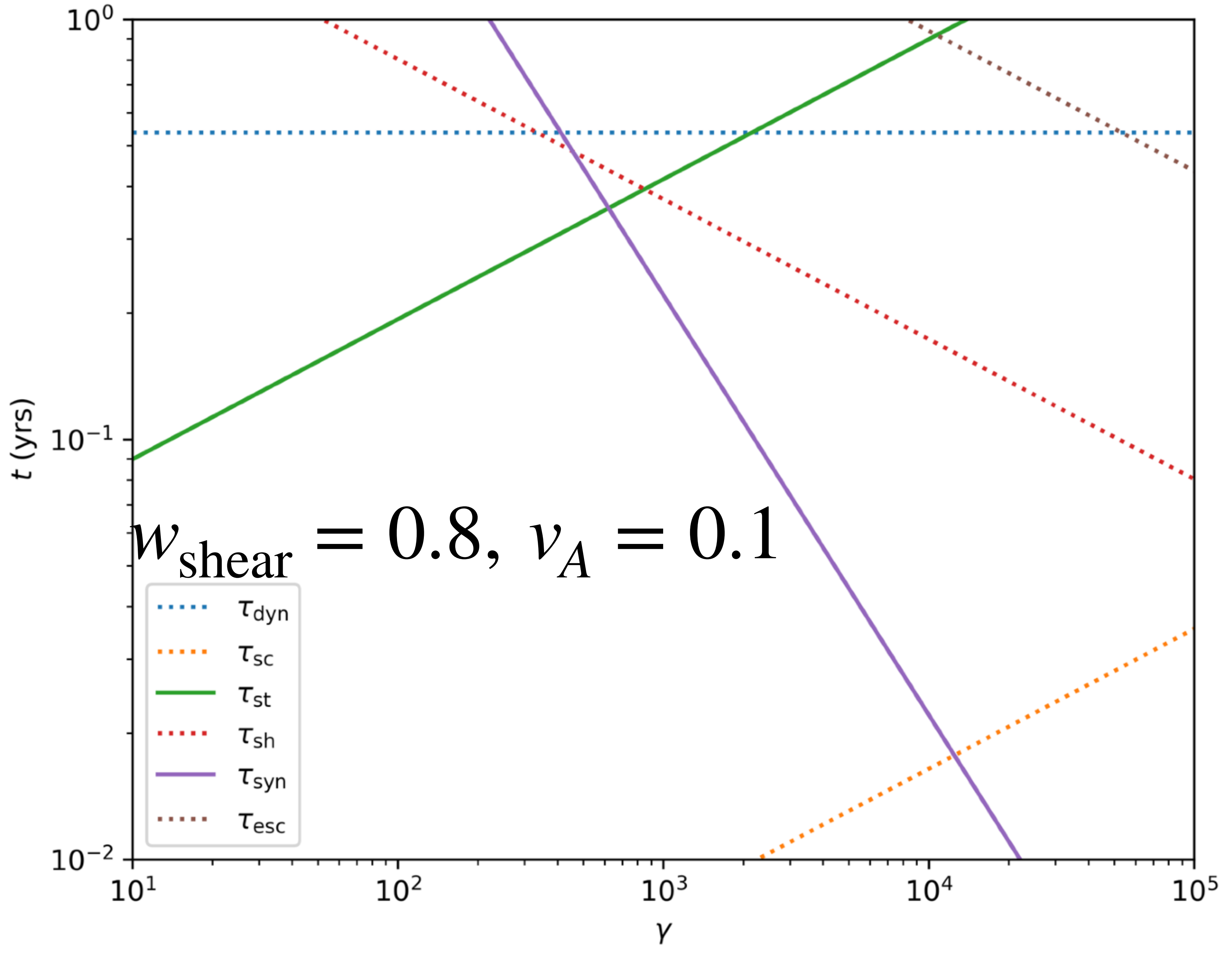
EHT MWL Science Working Group, 2021, ApJL, arXiv:2104.06855

Shear and/or stochastic



$B' = 0.3G$





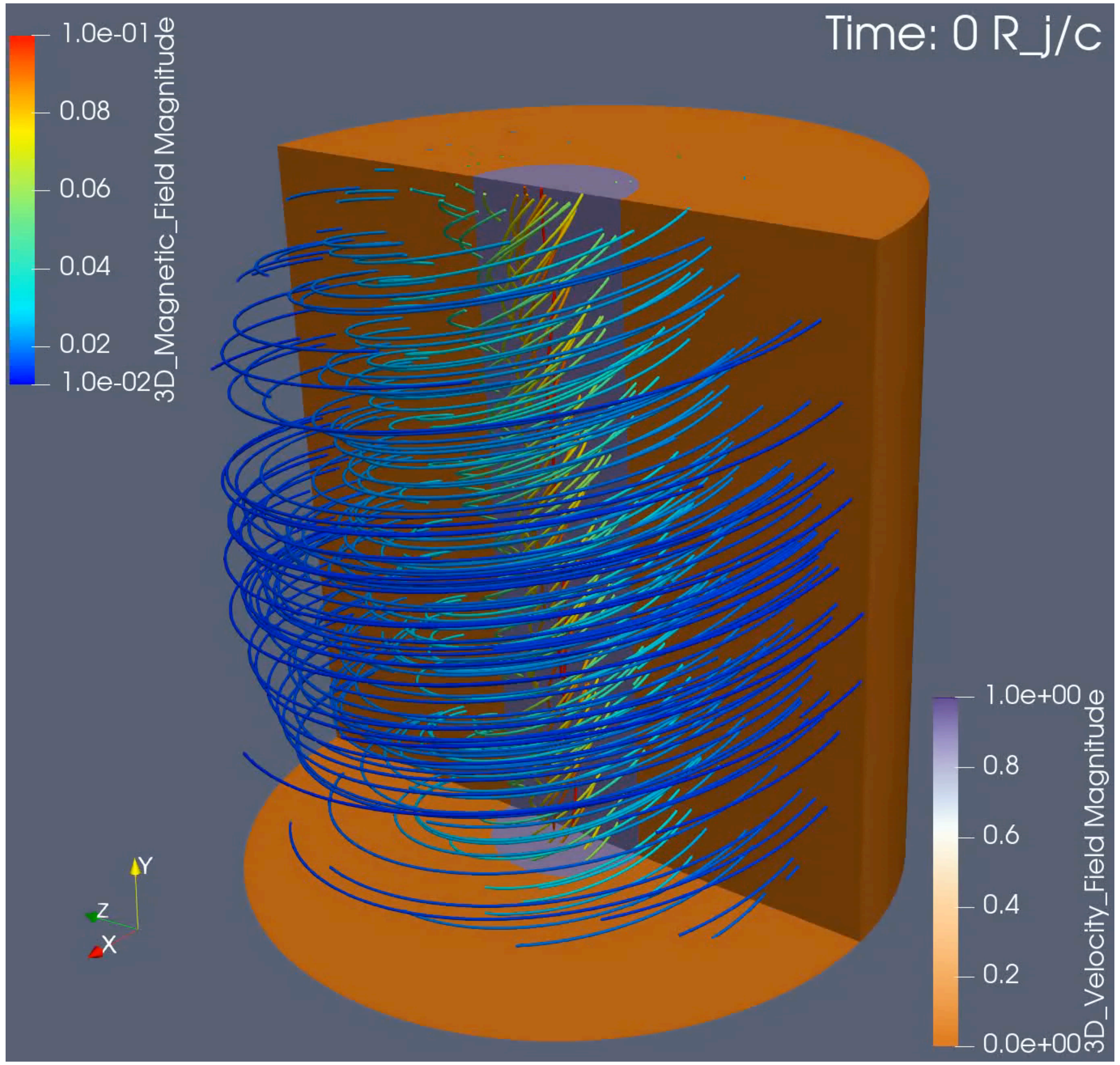
Numerical simulations

RMHD simulations with PLUTO

- Shear acceleration depends on the velocity profile, Fermi II acceleration depends on the turbulence spectrum
- Jet injected along Y axis, ambient at rest
- Periodic box along the jet axis to study the Kelvin-Helmholtz instability
- Different parameters explored with helical field $v \in [0.6c, 0.99c]$ & $\sigma \in [0.002, 0.2]$ $\quad \sigma_{y,\phi} =< B^2_{y,\phi} > /8\pi \rho_0 c^2$

Runs*	β_0	σ_y	σ_ϕ	Box size	Grid points	Θ_0	R_0	L_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}

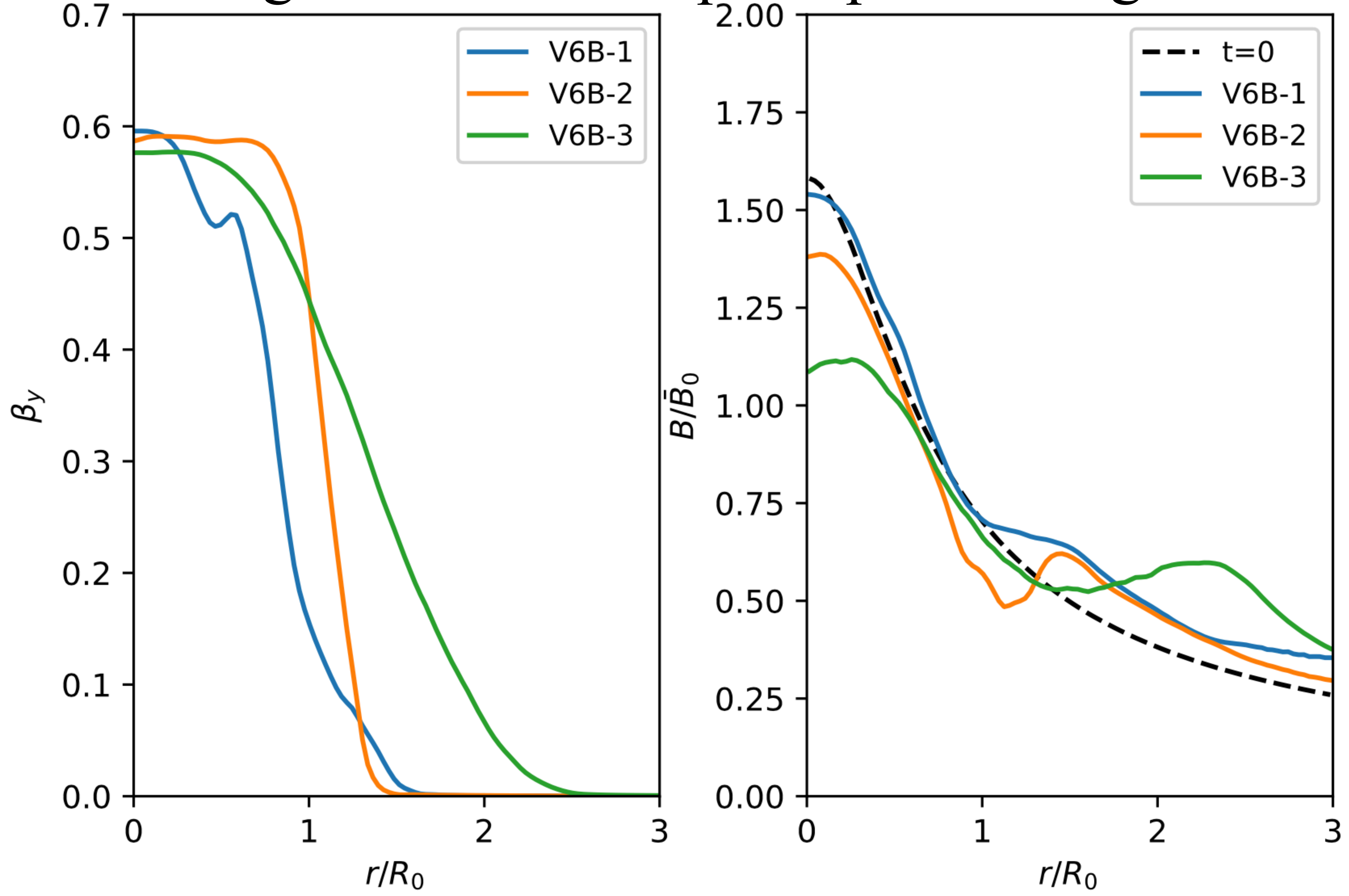
A sheath structure and turbulence can be self-generated via KH instability



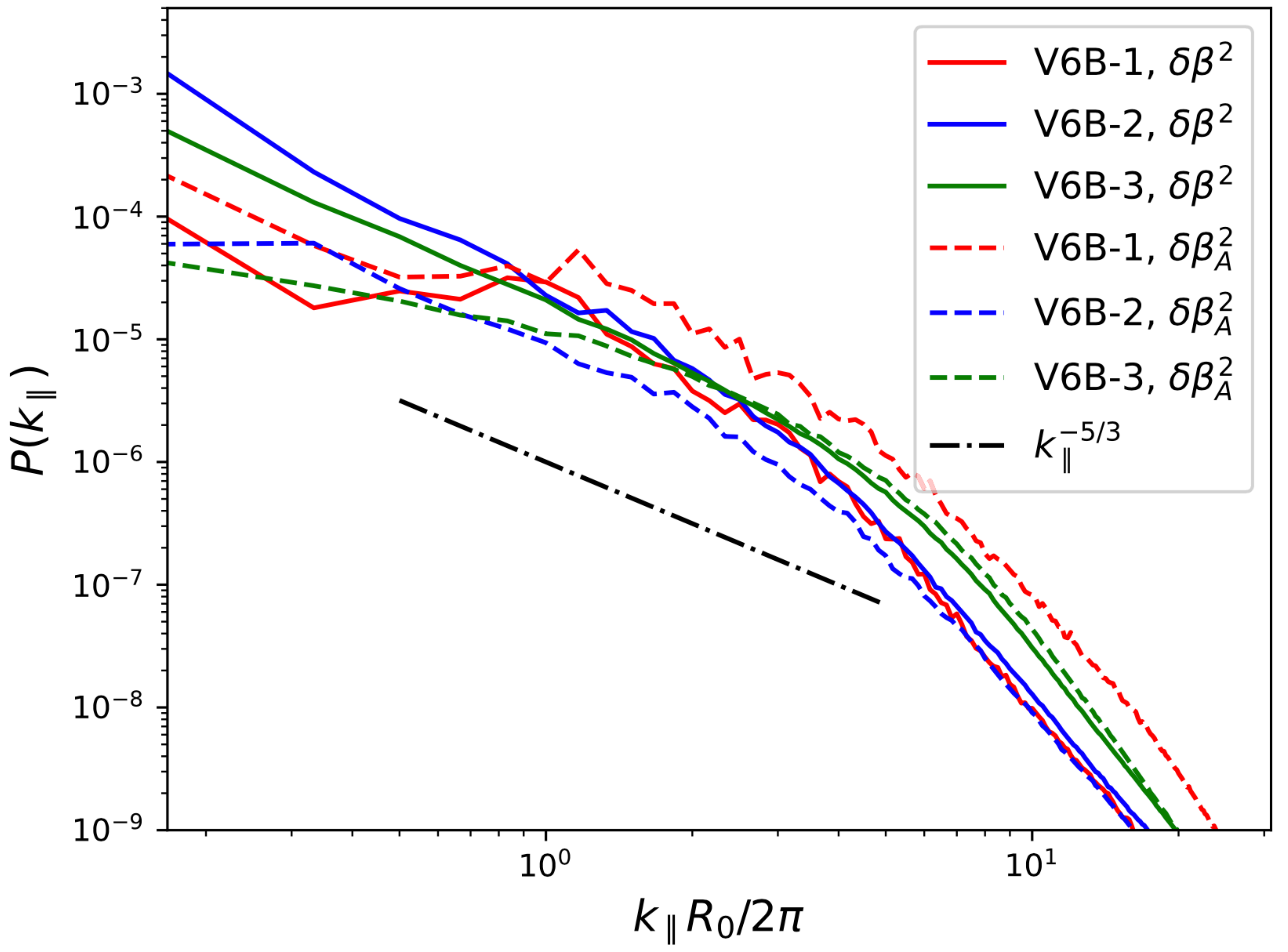
J.S.Wang+, 2023, MNRAS, arXiv:2212.03226

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

Higher velocities/lower magnetization lead to wider sheaths

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

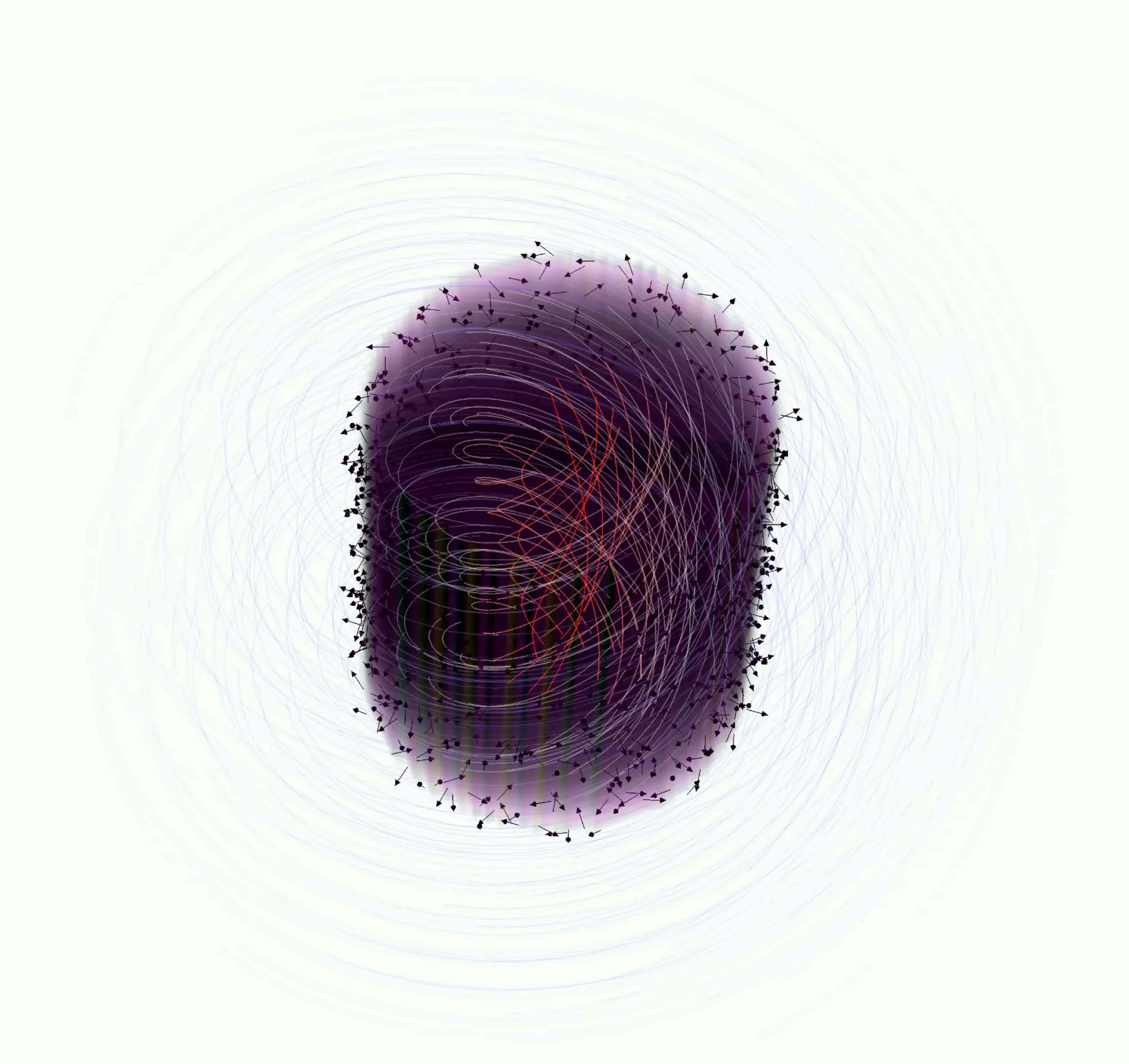
RMHD + Test-particle Simulations

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

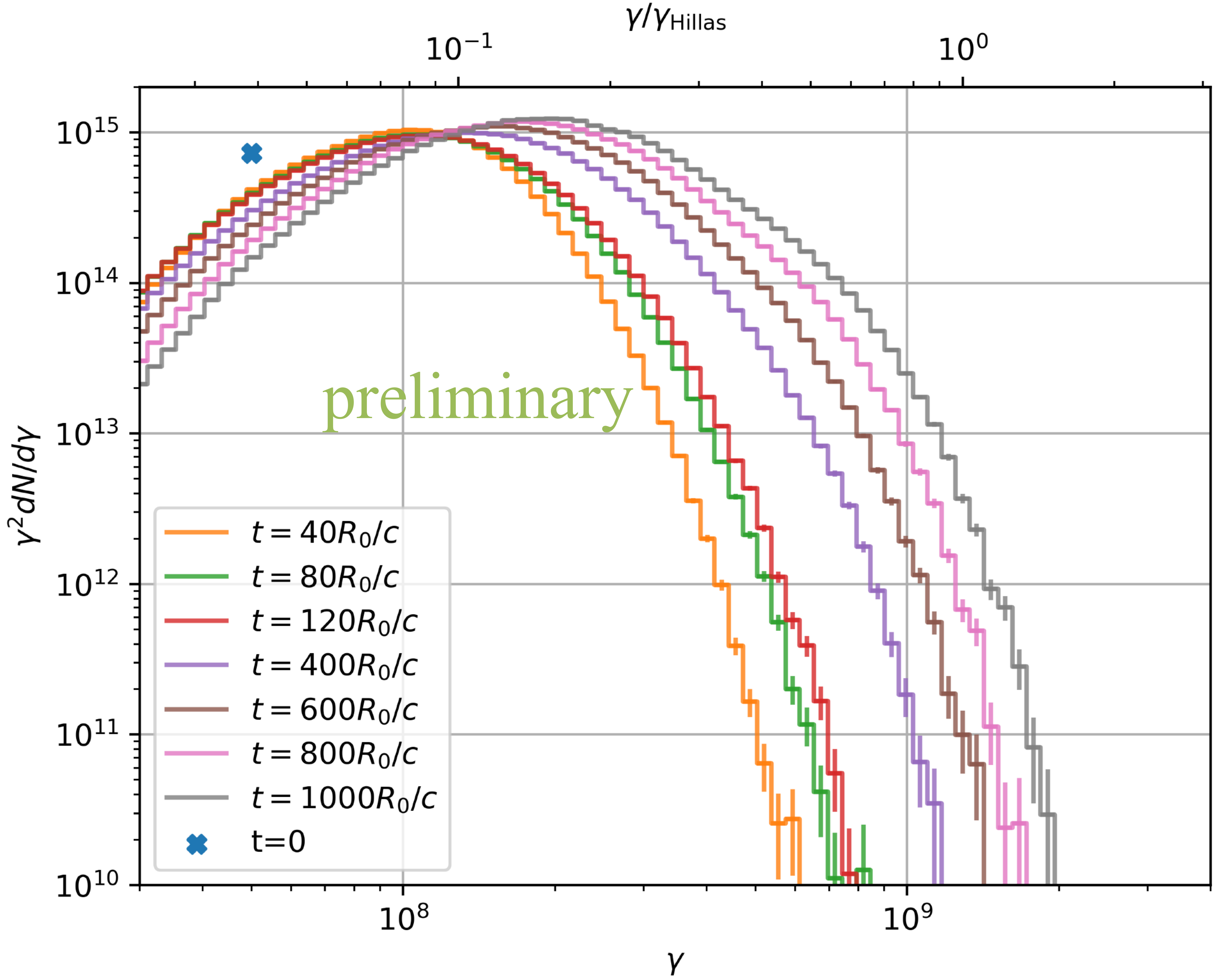
$$\frac{d\boldsymbol{x}_p}{dt} = \boldsymbol{v}_p$$

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

- To study the capability to accelerate UHECRs via shear acceleration



Numerical results



Summary

- **Shear (and stochastic)** acceleration is **unavoidable** in jets for **all scales**:
  - Self-generation of spine-sheath structure and turbulence via KH instability

- **Analytical solutions:** modeling of multi-wavelength SED
  - Shear acceleration can explain kpc-scale X-ray jet
  - Shear and stochastic acceleration can explain sub-pc-scale radio jet

- **Numerical studies** validates these mechanisms
  - Protons can achieve Hillas limit in jets via shear acceleration
  - Contribution to >EeV CRs from kpc-scale jets (Cen A)