Shear Acceleration in Large-scale Jets

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

Brian Reville (MPIK), Yosuke Mizuno (TDLI, SJTU), Frank Rieger (Uni-Heidelberg), Felix Aharonian (DIAS,MPIK), Ruoyu Liu (NJU)

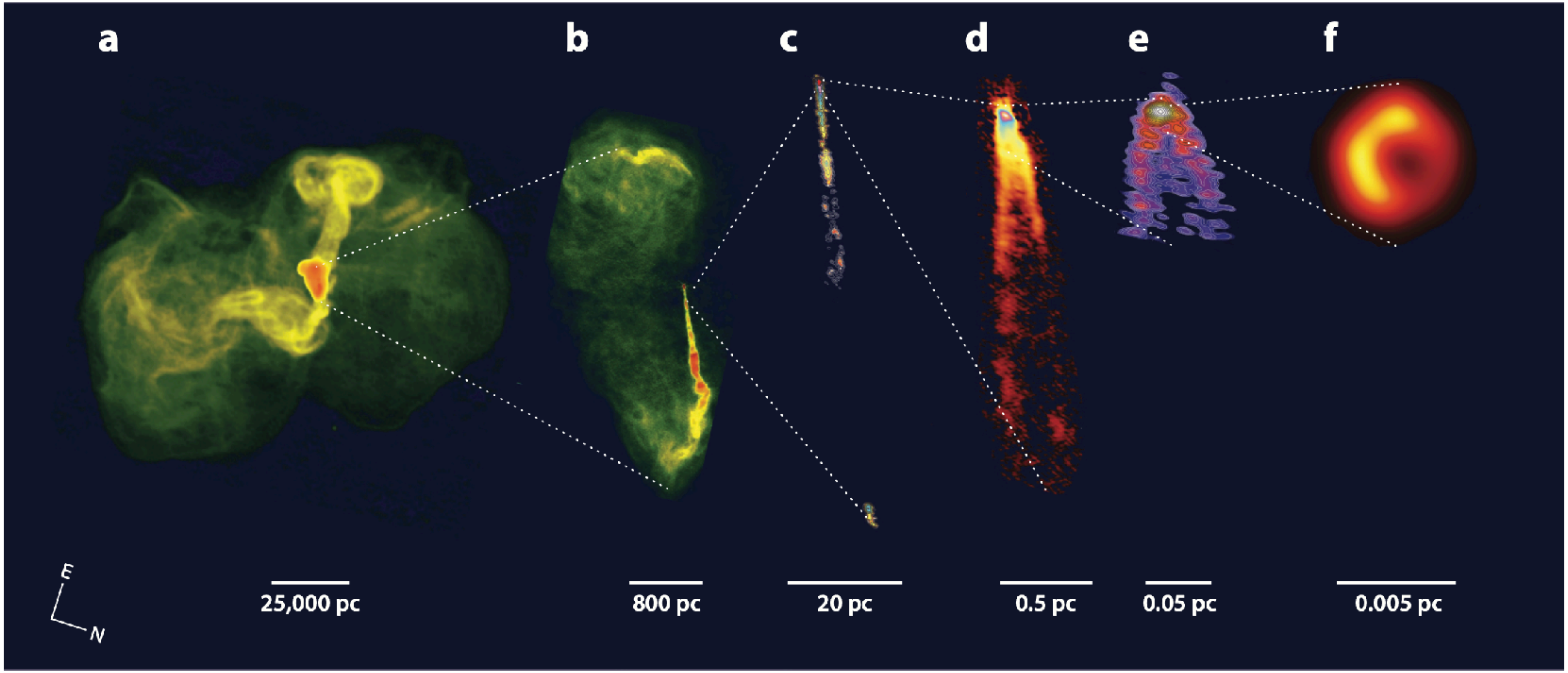
4 July @ Gamma 2022 - Universitat de Barcelona

Unterstützt von / Supported by
Alexander von Humboldt Stiftung/Foundation

Outline

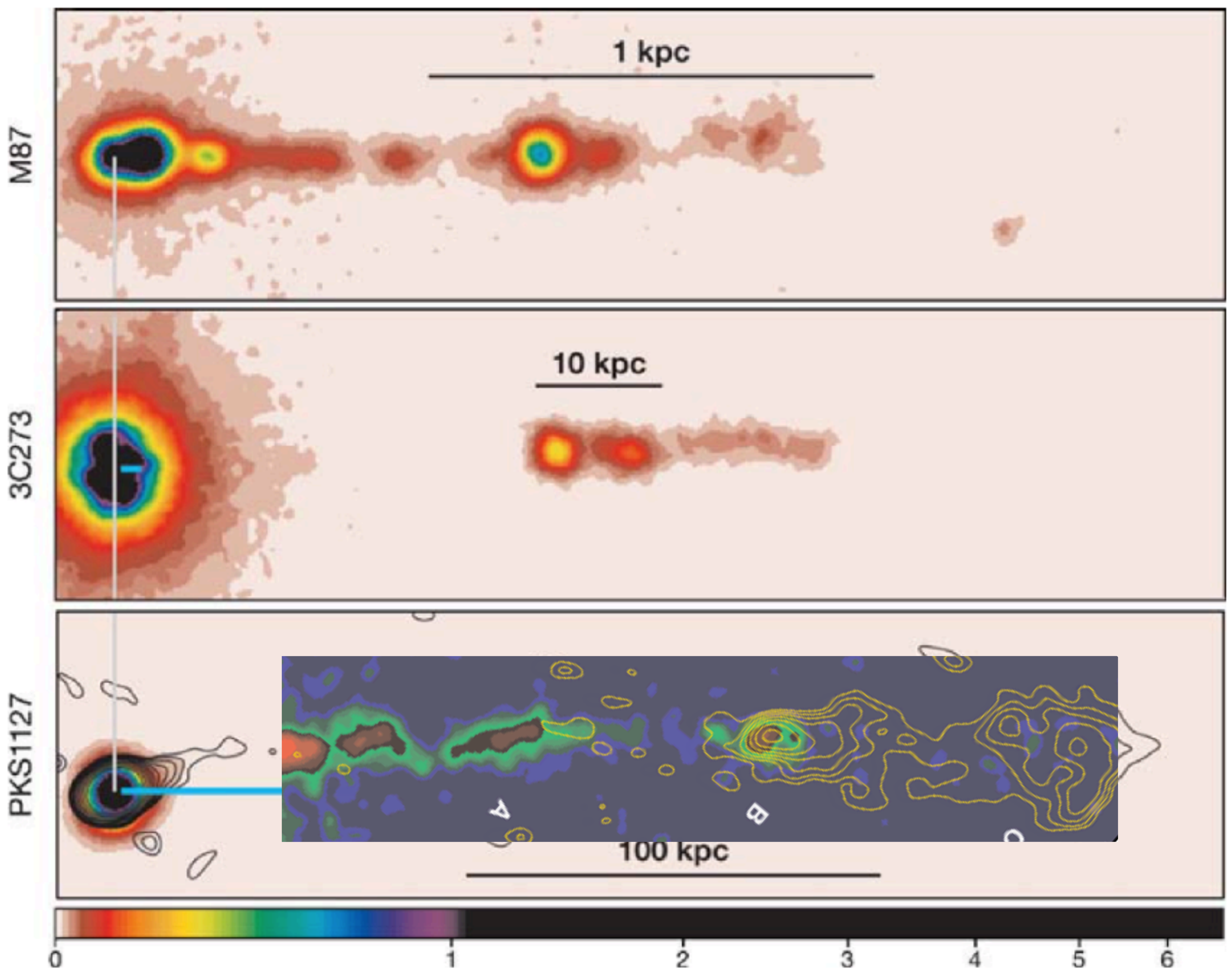
AGN jets in all scales

Mass and Energy transfer from < sub-pc scale to ~Mpc scale



Blandford R., Meier D., Readhead A., 2019, ARA&A, 57, 467

X-ray jet: accelerators



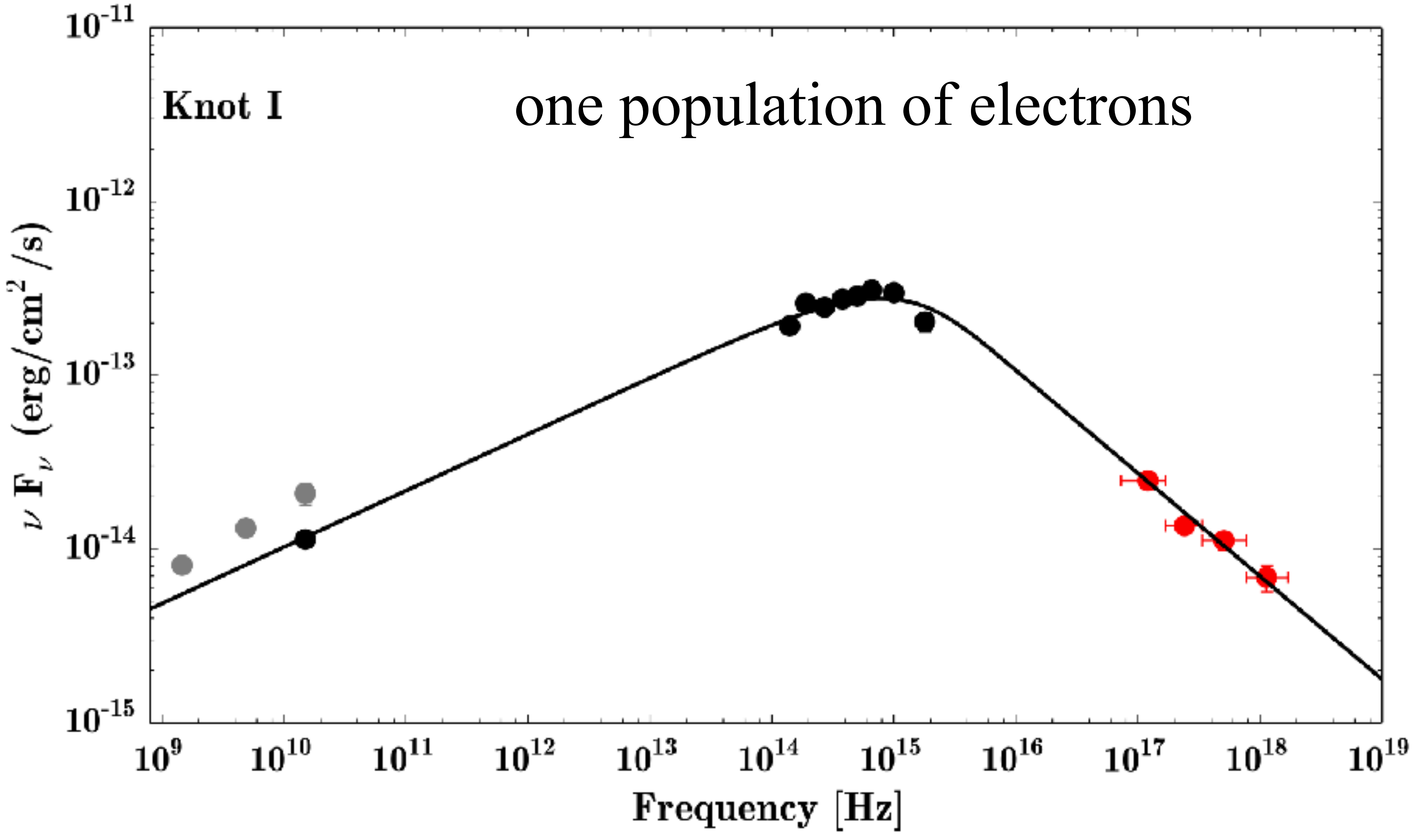
Harris D. E., Krawczynski H., 2006, ARA&A, 44, 463

Generic Name	R.A. (J2000) hh:mm:ss.s	Dec. (J2000) dd:mm:ss.s	z	Class	X-ray Features	Assoc. optical	Assoc. radio
3C6.1	00:16:31.1	+79:16:49.9	0.8404	FRII RG	both HS	?	yes
3C9	00:20:25.2	+15:40:54.7	2.012	LDQ	jet, CL	?	yes
3C15	00:37:04.1	-01:09:08.5	0.0730	FRI RG	knot, lobes	yes	yes
3C17	00:38:20.5	-02:07:40.7	0.22	FR2 RG	knot	yes	yes
NGC315	00:57:48.9	+30:21:08.8	0.0165	FRI RG	inner jet knots	?	same as X-ray
3C31	01:07:24.9	+32:25:45.0	0.0167	FRI RG	inner 8" jet	yes	jet
0106+013	01:08:38.8	+01:35:0.317	2.099	CDQ	knot	?	same as X-ray
3C33	01:08:52.9	+13:20:13.8	0.0597	FRII RG	both hotspots	yes	yes
3C47	01:36:24.4	+20:57:27.4	0.425	LDQ	hsS	no	yes
4C+35.03	02:09:38.6	+35:47:50.9	0.0369	FRI RG	inner jet	no	yes
PKS0208-512	02:10:46.3	-51:01:02.9	0.999	CDQ	jet/knot	no	yes
3C66B	02:23:11.4	+43:00:31.2	0.0215	FRI RG	inner 8" jet	jet	jet
0234+285	02:37:52.4	+28:48:08.9	1.213	CDQ	jet	?	similar as X-ra
0313-192	03:15:52.1	-19:06:44.3	0.067	FRI RG	inner jet	?	same as X-ray
3C83.1	03:18:15.7	+41:51:27.9	0.0251	FRI RG	E and W knots	??	similar
PKS0405-12	04:07:48.4	-12:11:36.6	0.574	CDQ	hs	same as X-ray	yes
3C109	04:13:40.4	+11:12:13.8	0.3056	FRII RG	hsS	no	yes
PKS0413-21	04:16:04.4	-20:56:27.5	0.808	CDQ	jet/knot	no	yes
3C111	04:18:21.3	+38:01:35.8	0.0491	FRII RG	knots	?	similar as X-ra
3C120	04:33:11.1	+05:21:15.6	0.0330	Sy I	inner jet; 4"knot; 25"knot; 80"knot	some	same as X-ray
3C123	04:37:04.4	+29:40:13.7	0.2177	FRII RG	hsE, hsW	no	same as X-ray
3C129	04:49:09.1	+45:00:39.3	0.0208	FRI RG	two inner knots	no	jet
0454-463	04:55:50.8	-46:15:58.7	0.858	CDQ	knot	?	similar as X-ra
PictorA	05:19:49.7	-45:46:44.5	0.0350	FRII RG	linear jet, W hs, CL	W hs	W hs, CL

>100 sources @ https://hea-www.harvard.edu/XJET/#morph

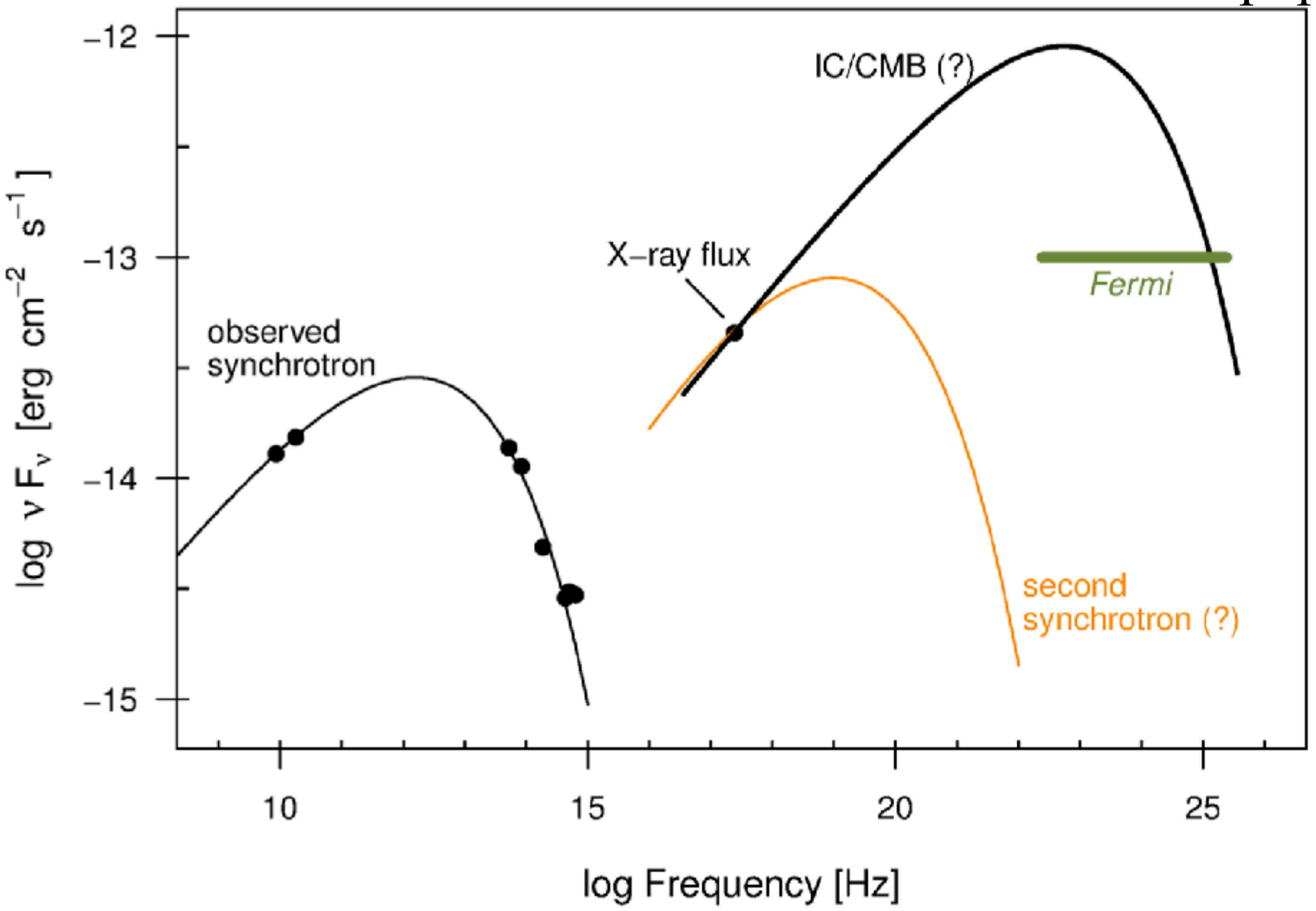
Fanaroff–Riley (FR) classification of jets

- Radio morphology:
  - FR I: low power & the brightest emission near the radio cores
  - FR II: high power & the brightest emission at outer extremities (hotspots)
- SED for FR I jets: X-rays can be explained by synchrotron radiation

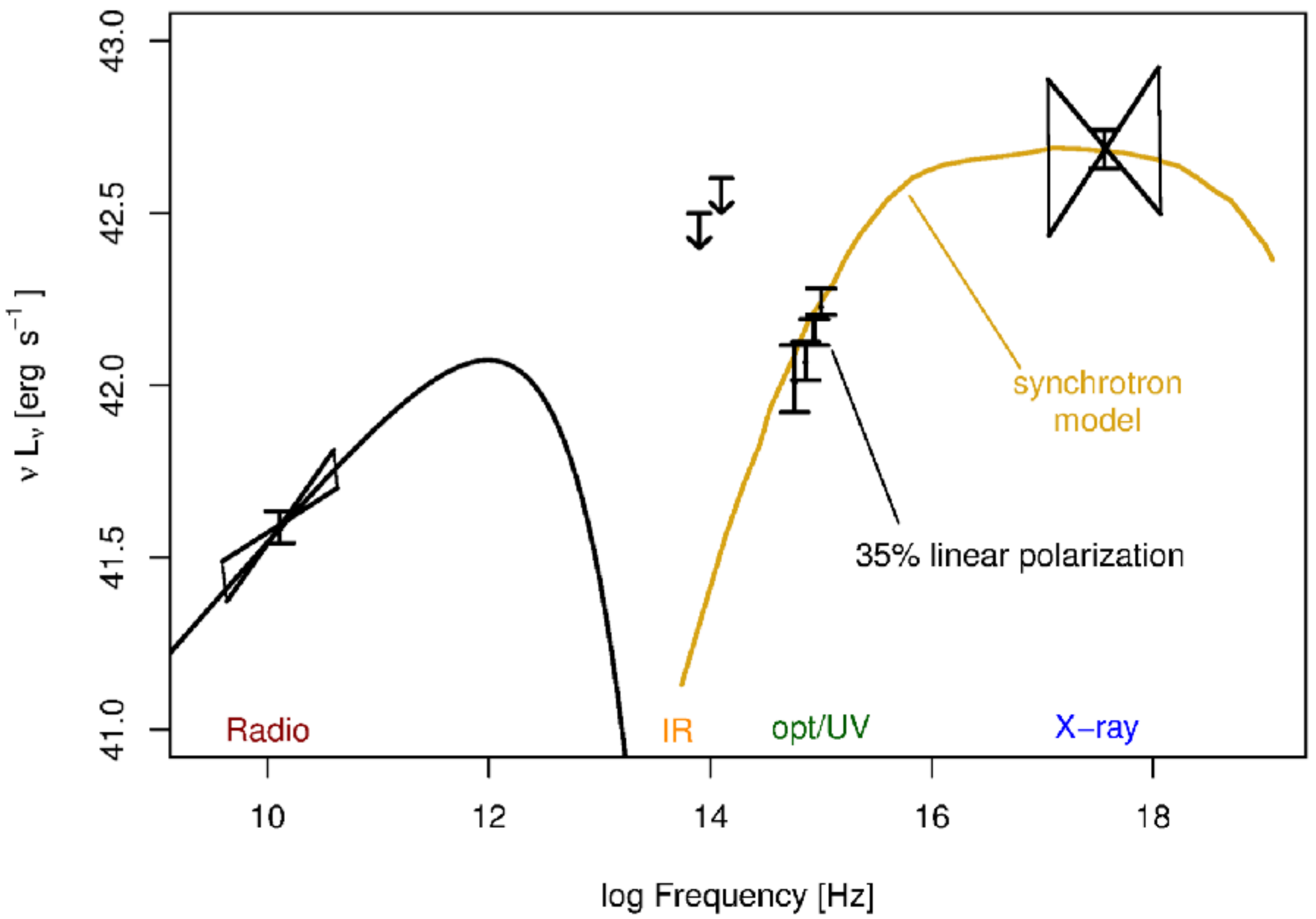


FR II jets: synchrotron for X-rays

two populations of electrons



Fermi observation rules out IC/CMB for PKS 0637-752



Polarimetry Rules out IC/CMB for PKS 1136-135

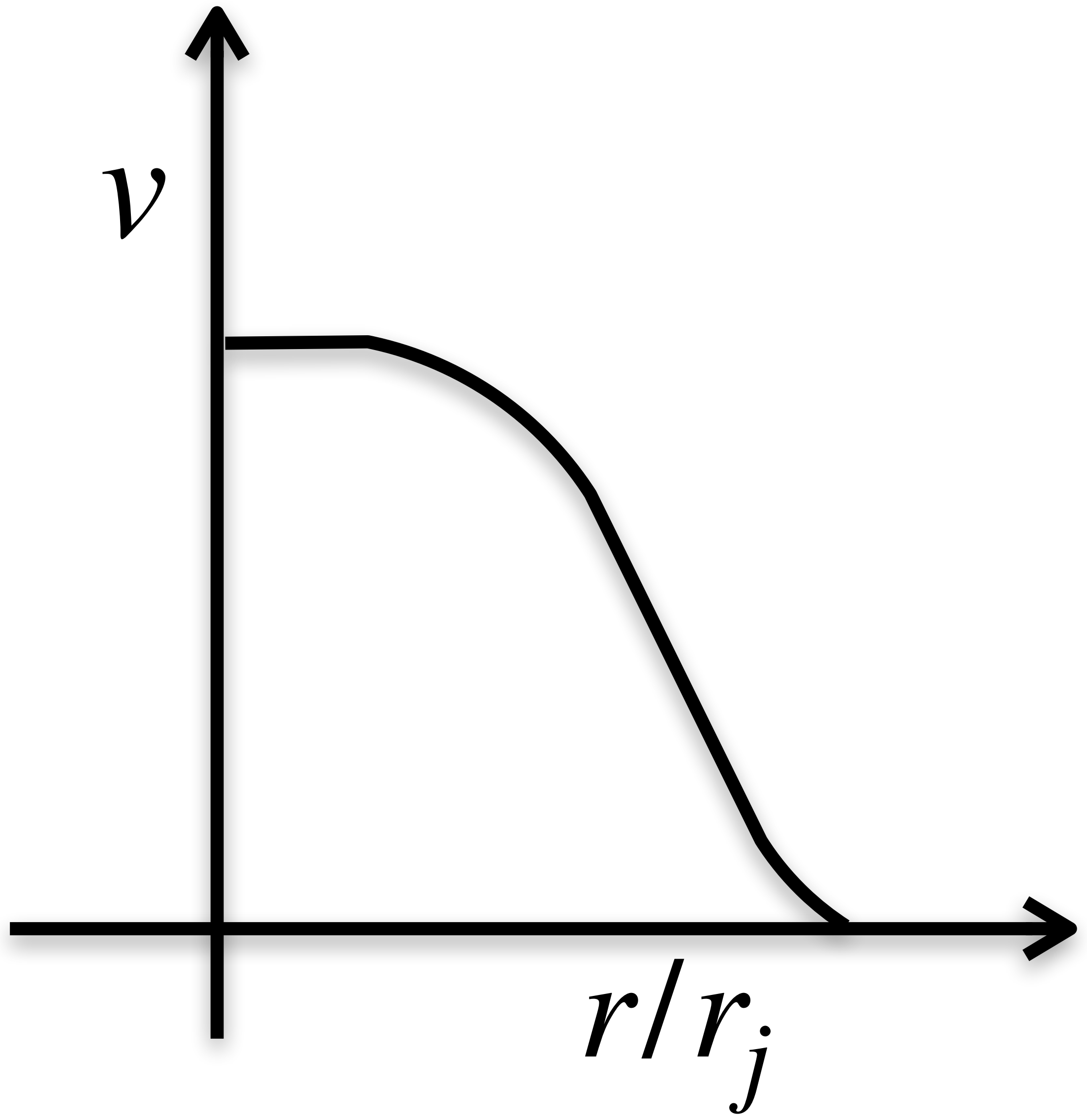
Georganopoulos M., Meyer E., Perlman E., 2016, Galaxies, 4, 65

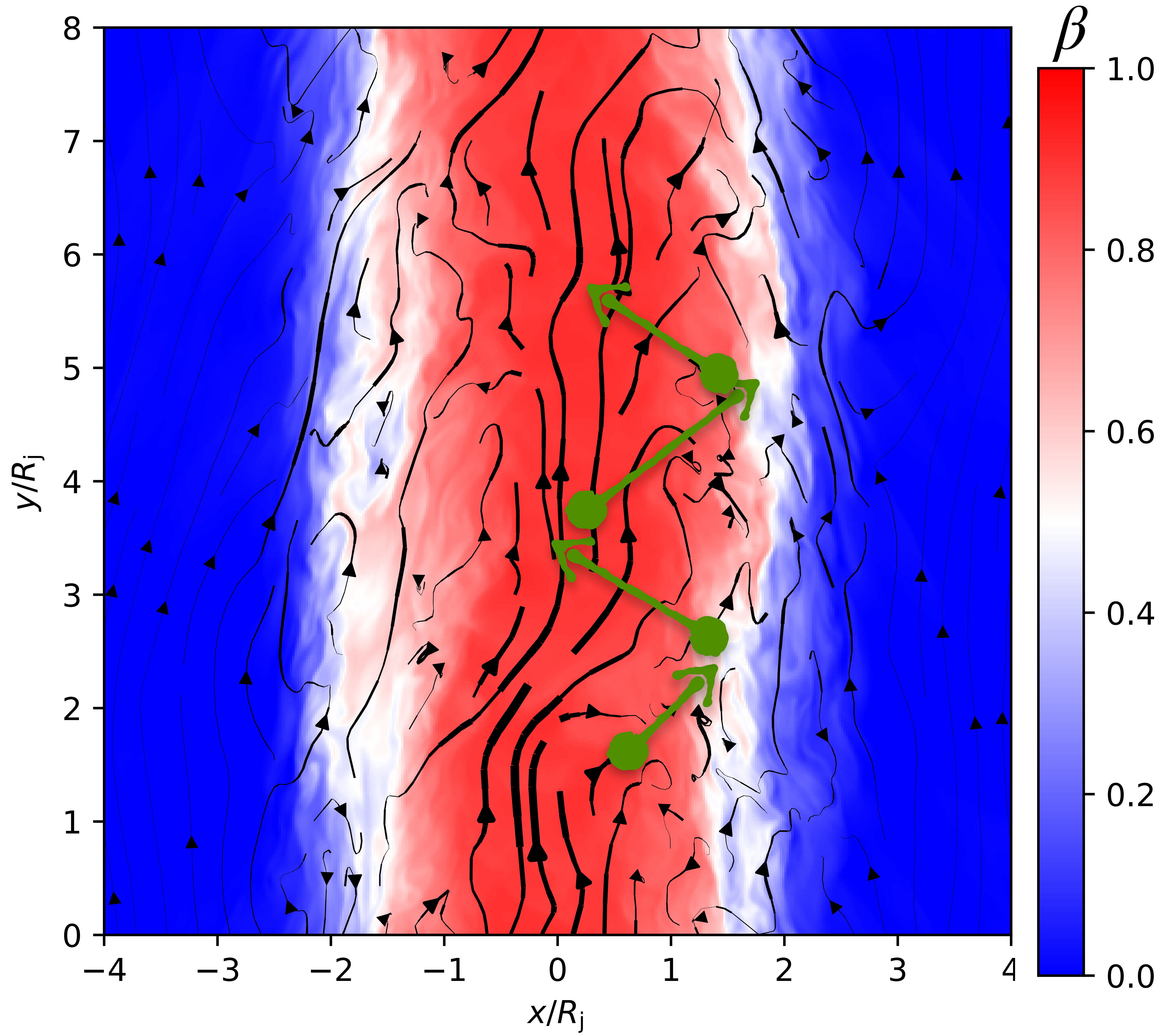
Particle (re-)acceleration

- Synchrotron origin of X-rays requires sub-PeV electrons:
  $E_{\rm syn} = 2(E_e/0.1{\rm PeV})^2(B/10\mu{\rm G})$ 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 —> $c\tau_{\rm c} = 0.37{\rm kpc}$
- For jet length >> kpc, particles accelerated by the jet head shock will cool down immediately after the shock passes (standing shocks may exist in specific locations)
- *In-situ* (re-)acceleration mechanisms required for large-scale X-ray jet
  - Shear acceleration

Shear acceleration

- Shear acceleration is Fermi II like
- Velocity profiles in jets (spine-sheath)
- Turbulences are embedded in shearing layers
- Particles scatter off turbulence and sample the velocity difference





Formulation of shear acceleration

- Fokker–Planck description for energy-space diffusion equation

Cooling

$$\langle \dot{\gamma}_c \rangle = \frac{\sigma_T \gamma^2 B^2}{6\pi m_e c}(1+f) \equiv A_2 \gamma^2$$

$$f = U_{rad}/U_B$$

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

Acceleration

$$\left\langle \frac{\Delta\gamma^2}{\Delta t}\right\rangle_{sh} \simeq D_{sh}\gamma^2 \tau_{sc} \equiv A_1 \gamma^{4-q}$$

$$D_{sh} = \frac{1}{15}\Gamma_j^4(r) c^2 \left(\frac{\partial \beta_j(r)}{\partial r}\right)^2$$

$$\tau_{sc} = \xi_1^{-1}\left(\frac{r_L}{\Lambda_{max}}\right)^{1-q}\frac{r_L}{c} \equiv A_0 \gamma^{2-q}$$

$$\xi_1 = \delta B^2 / B_0^2$$

Injection at $\gamma < \gamma_{cr}$

$$Q(\gamma, t) = 0 \text{ for } \gamma > \gamma_{cr}$$

Escape $\tau_{esc} = \frac{\Delta r_j^2}{2\kappa} = \frac{3\Delta r_j^2}{2c^2}\tau_{sc}^{-1} \equiv A_3 \gamma^{q-2}$

Liu R.-Y., Rieger F. M., Aharonian F. A., 2017, ApJ, 842, 39

Steady-state solution

- Steady state: can be solved analytically and exactly $\partial n(\gamma, t)/\partial t = 0$

$$n(\gamma) \propto \gamma^s j \qquad z = -\frac{6-q}{q-1}(\gamma/\gamma_{\max})^{q-1}$$

$$z\frac{d^2 j_\pm}{dz^2} + (b_\pm - z)\frac{dj_\pm}{dz} - a_\pm j_\pm = 0$$

$$b_\pm = 2s_\pm/(q-1) \qquad a_\pm = (2+s_\pm)/(q-1)$$

- The exact solution:

$$\gamma_{\max} = \left(\frac{6-q}{2}\frac{A_1}{A_2}\right)^{1/(q-1)}$$

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

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

$$\gamma \ll \gamma_{\max}, \; F_\pm \approx 1$$

Wang et al., 2021, MNRAS, 505, 1334

Particle spectra

- Exact solutions for shear acceleration:

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

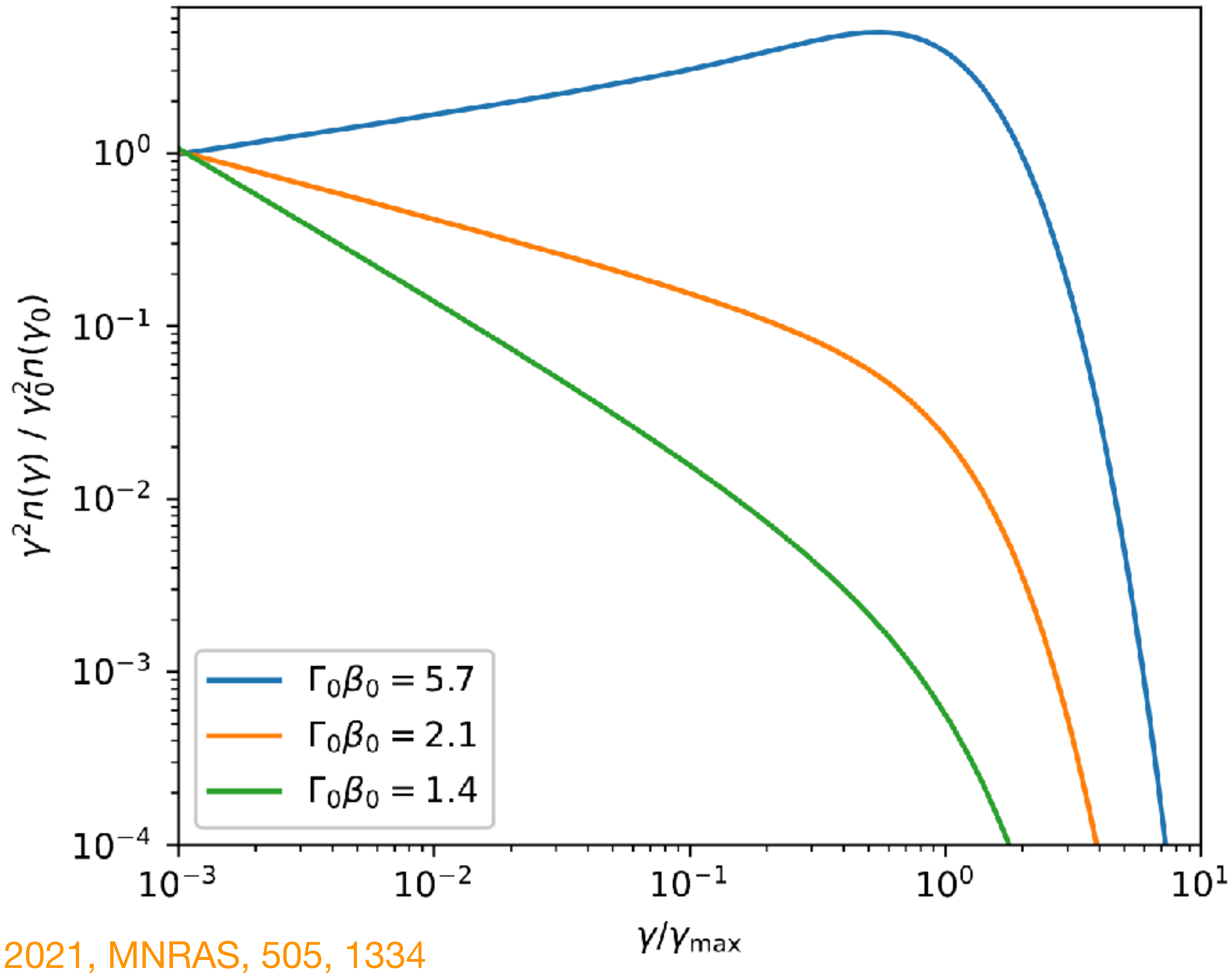
$$s_\pm = \frac{q-1}{2} \pm \sqrt{\frac{(5-q)^2}{4} + w}$$

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

- Kolmogorov turbulence: q=5/3

- Assume a linear decreasing profile

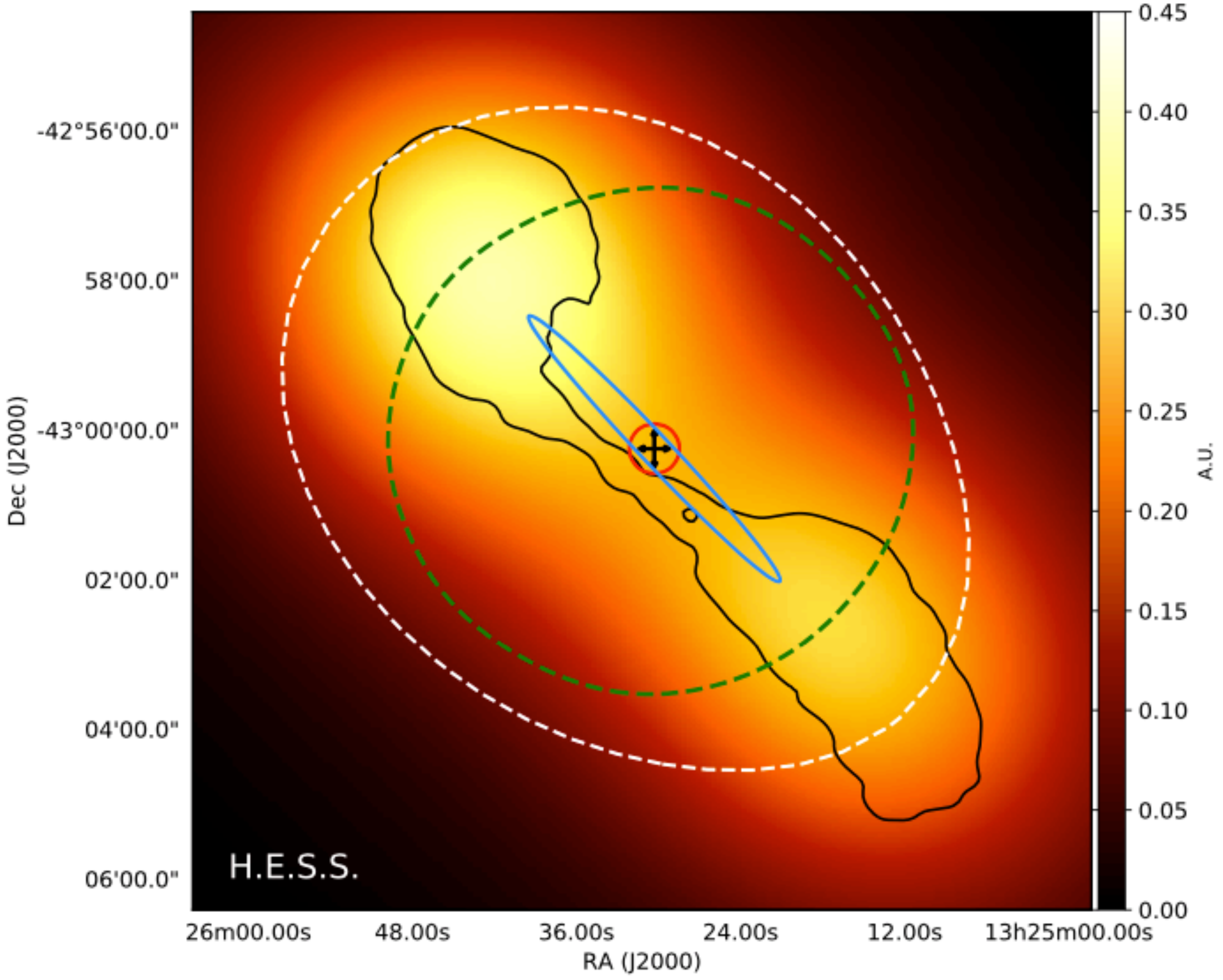
$$w = 40 \ln^{-2} \frac{(1+\beta_0)}{(1-\beta_0)}$$



Wang et al., 2021, MNRAS, 505, 1334

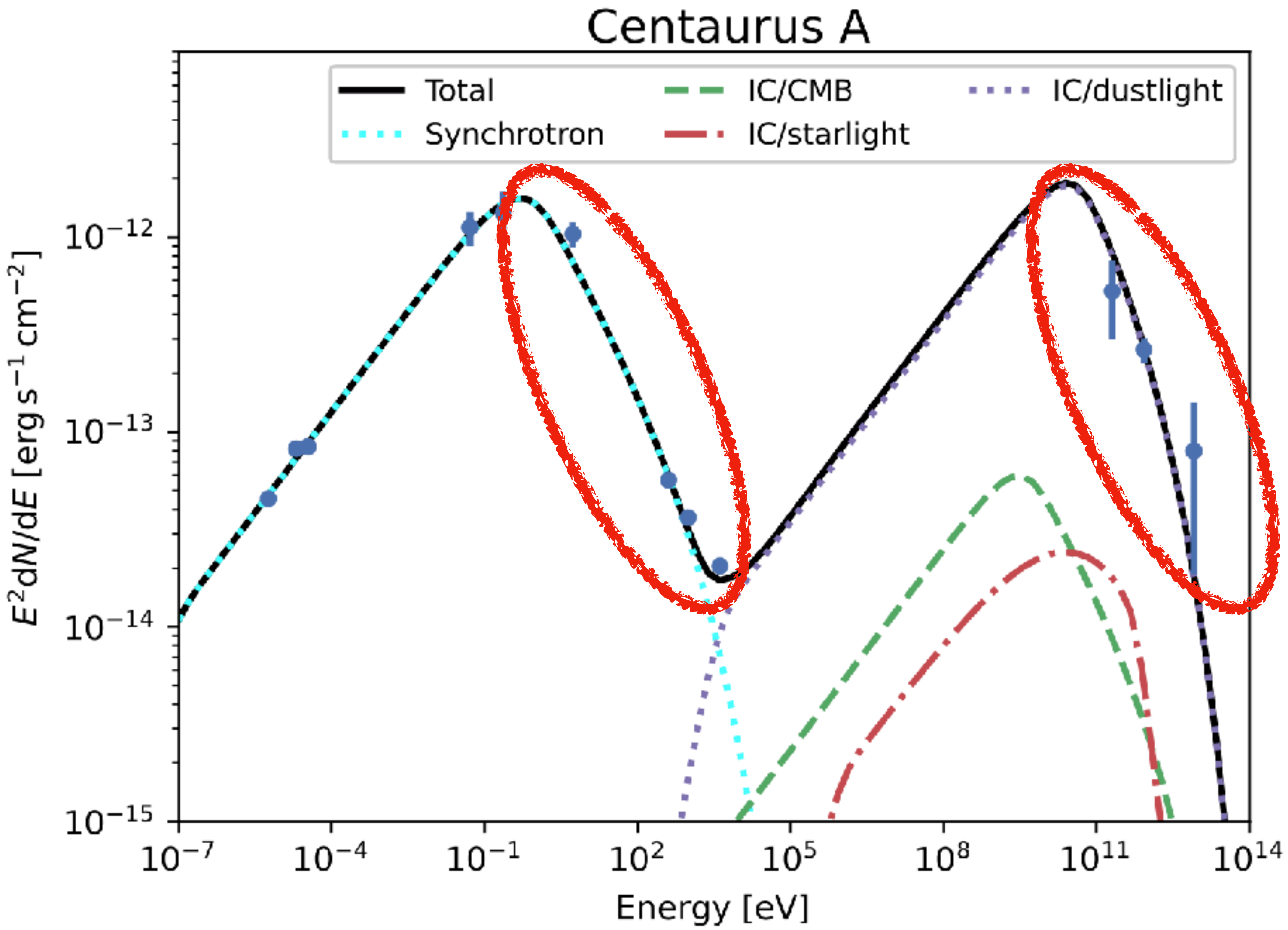
Application to Centaurus A (FR I)

Radio and TeV gamma-ray



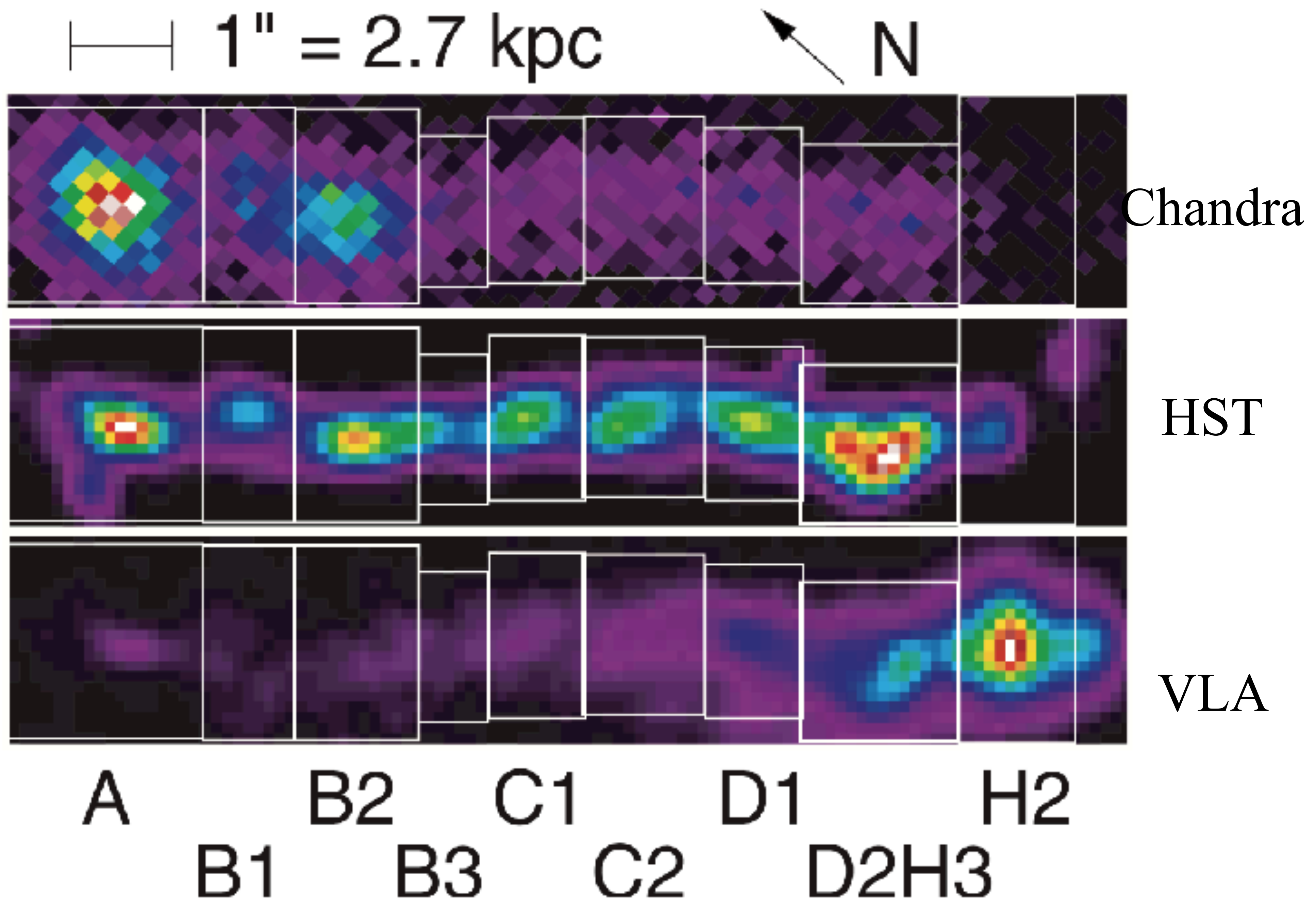
H. E. S. S. Collaboration et al., 2020, Nature, 582, 356

IC and Syn from one population of electrons
An examplary fitting with code NAIMA

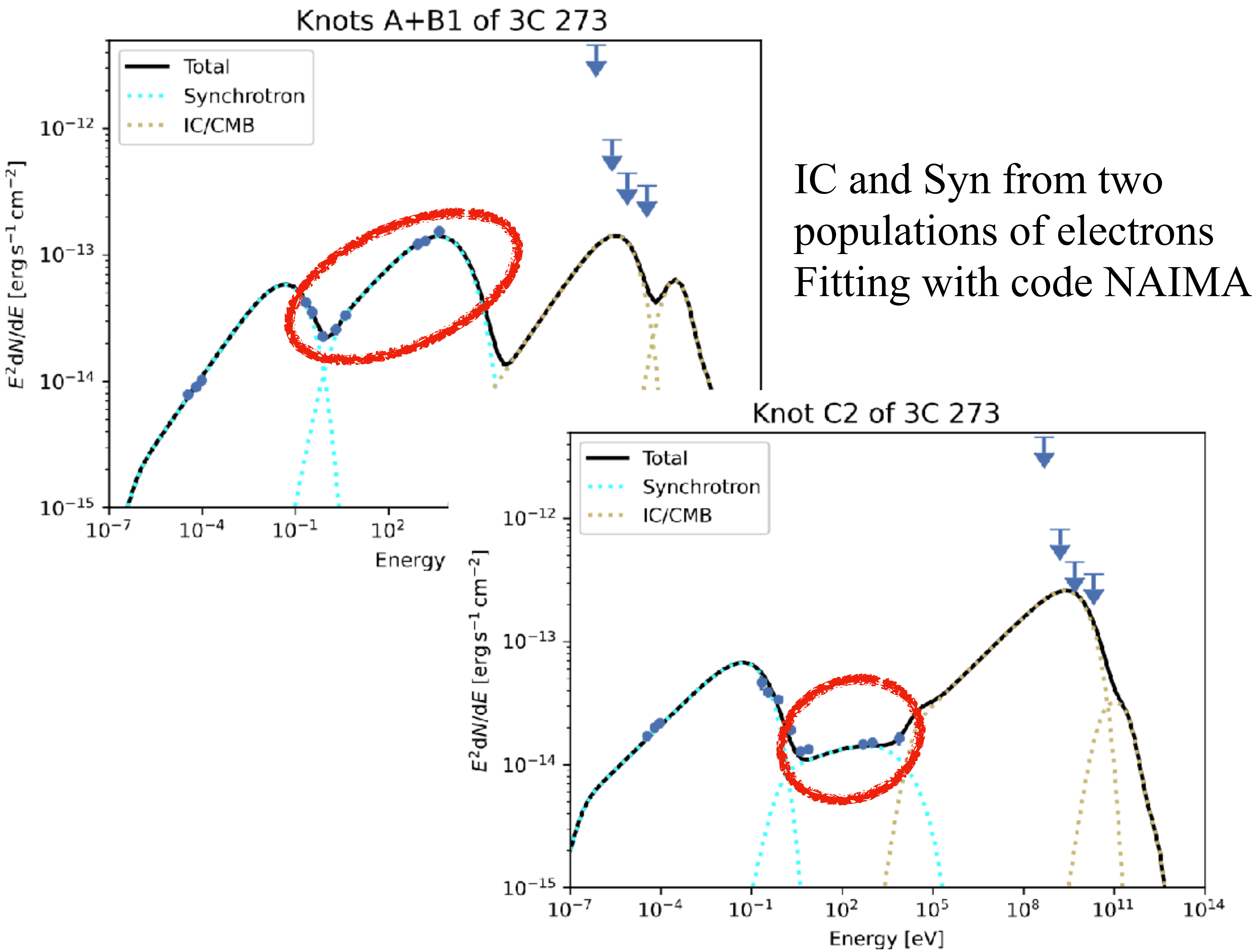


Wang et al., 2021, MNRAS, 505, 1334

Application to 3C 273 (FR II)



Jester et al., 2006, ApJ, 648, 900



IC and Syn from two populations of electrons

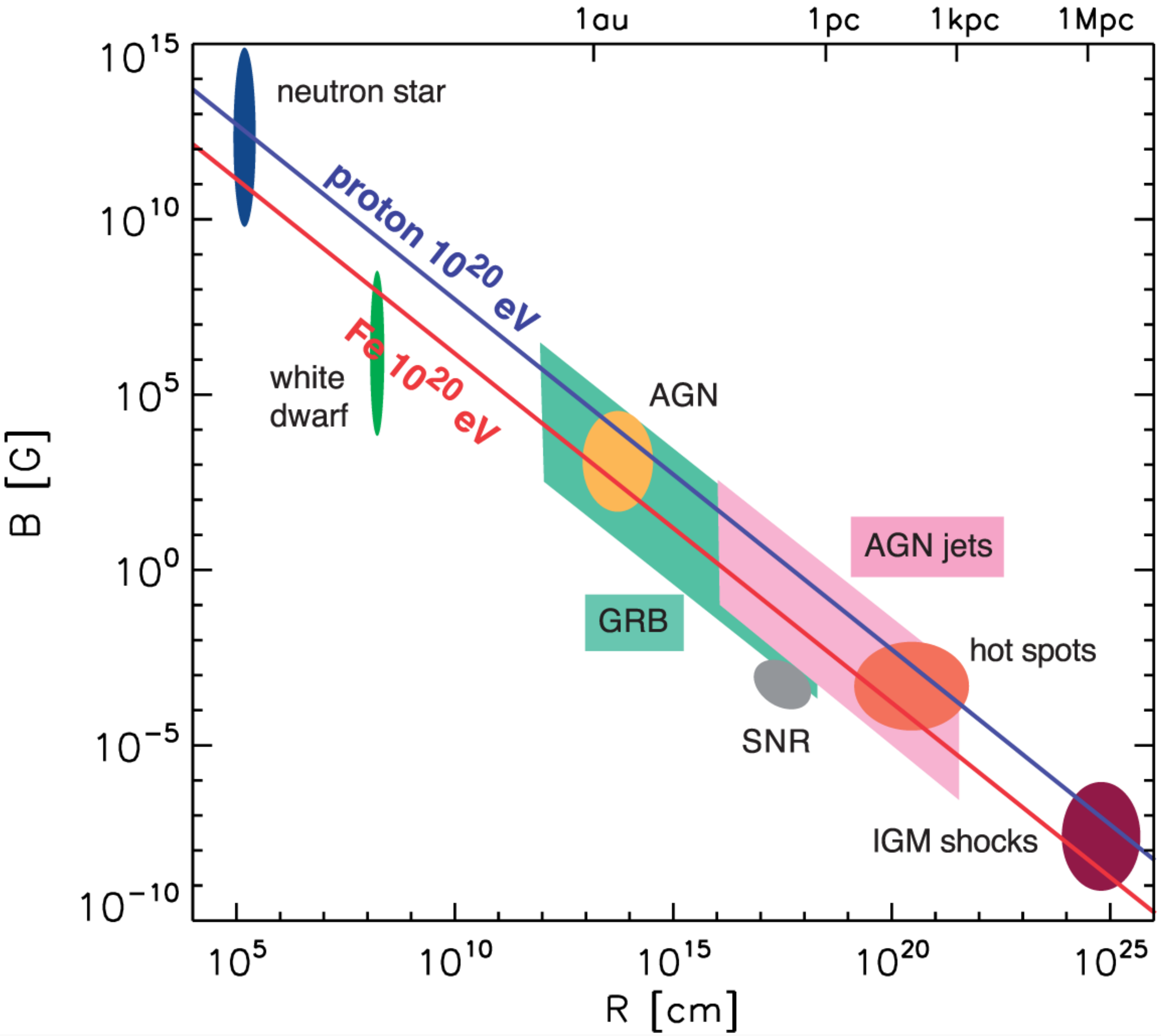
Fitting with code NAIMA

	uncooled component	**Shear acceleration**		
Source name	Low-energy component ($E_{\mathrm{min},1}$, E_{b}, α_1)	High-energy component ($E_{\mathrm{min},2}$, w, B, $\Delta r_{\mathrm{j},2}$)	Jet power in units of erg/s and L_{Edd}	Jet speed
Centaurus A	0.2 GeV, 0.75 TeV, −2.31	-, 15.0, 17.1 μG, 1	3.7×10^{42} erg/s, $5.4\times10^{-4} L_{\mathrm{Edd,CenA}}$	$0.67c$
3C 273 - Knots A+B1	1.5 GeV, 1.1 TeV, −2.28	2.5 TeV, 4.7, 2.8 μG, 10	2.7×10^{45} erg/s, $3.2\times10^{-3} L_{\mathrm{Edd,3C273}}$	$0.90c$
3C 273 - Knot C2	1.5 GeV, 1.6 TeV, −2.52	1.9 TeV, 6.8, 2.2 μG, 10	1.3×10^{46} erg/s, $1.5\times10^{-2} L_{\mathrm{Edd,3C273}}$	$0.84c$

- Shear acceleration accounts for the population of high-energy electrons
- Consistent with General picture: FR I low-power jets / FR II high-power jets

Wang et al., 2021, MNRAS, 505, 1334

Shear acceleration of UHECRs



$$\tau_{\rm sc} \lesssim \tau_{\rm sh} \quad r_{{\rm L},p} \lesssim \Delta r_{\rm j} \quad \tau_{\rm sh} \lesssim \tau_{\rm syn}$$

$$E_{\rm seed\ nuclei} > 38 Z B_{-5} \Delta r_{{\rm j},2}^4 w^3 \beta_0^3 \chi_1^{-3} \eta^{-3} r_{{\rm j},2}^{-3}\ {\rm TeV}$$

$$E_{\rm max} = \min[9,\ 2w^{3/2}\eta^{-3}]\ Z\ B/(10\mu{\rm G})\ \Delta r/(1\ {\rm kpc})\ {\rm EeV}$$

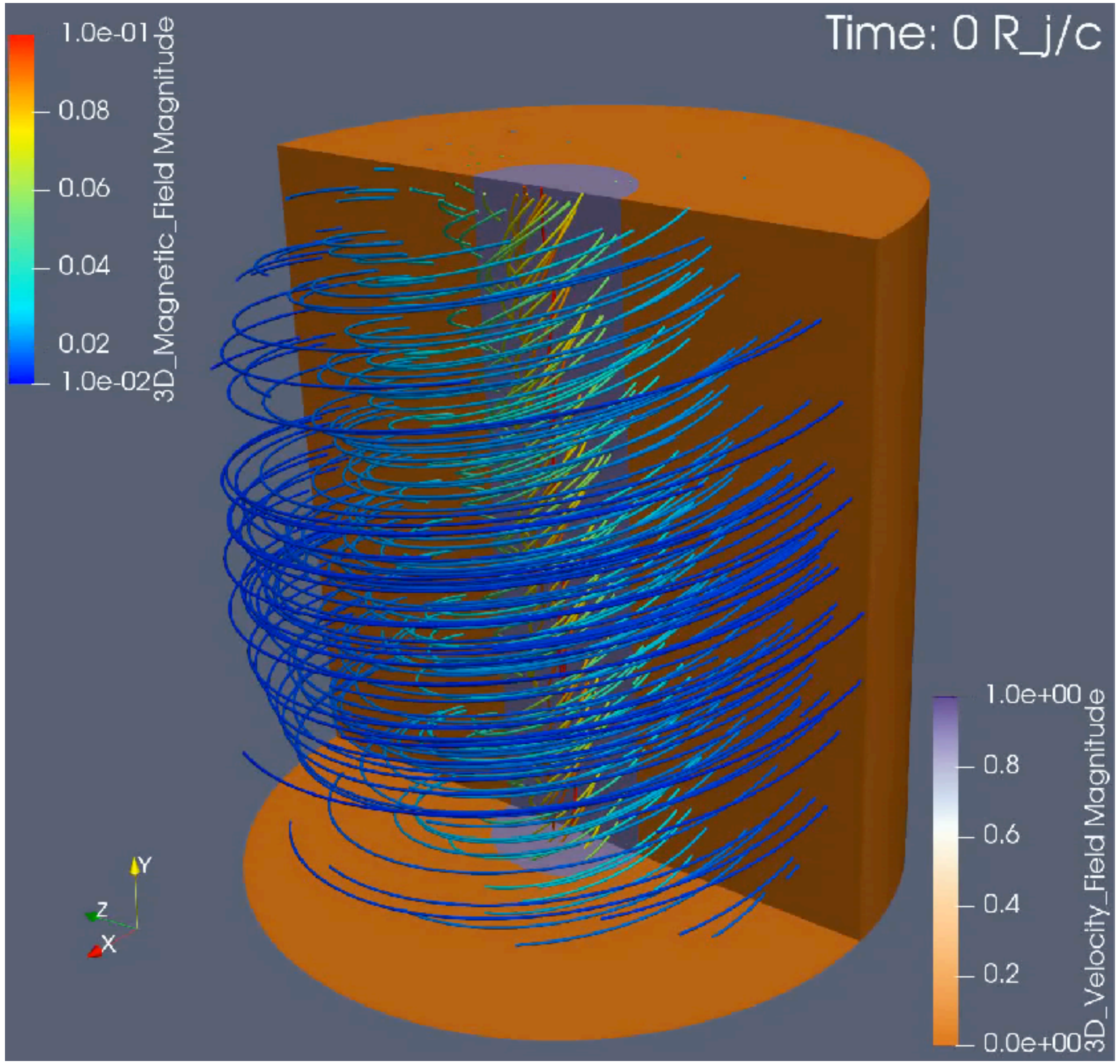
Escape spectrum:

$$\dot{n}_{\rm esc} \propto \gamma^{s_-}/\tau_{\rm esc} = \gamma^{2-q+s_-}$$

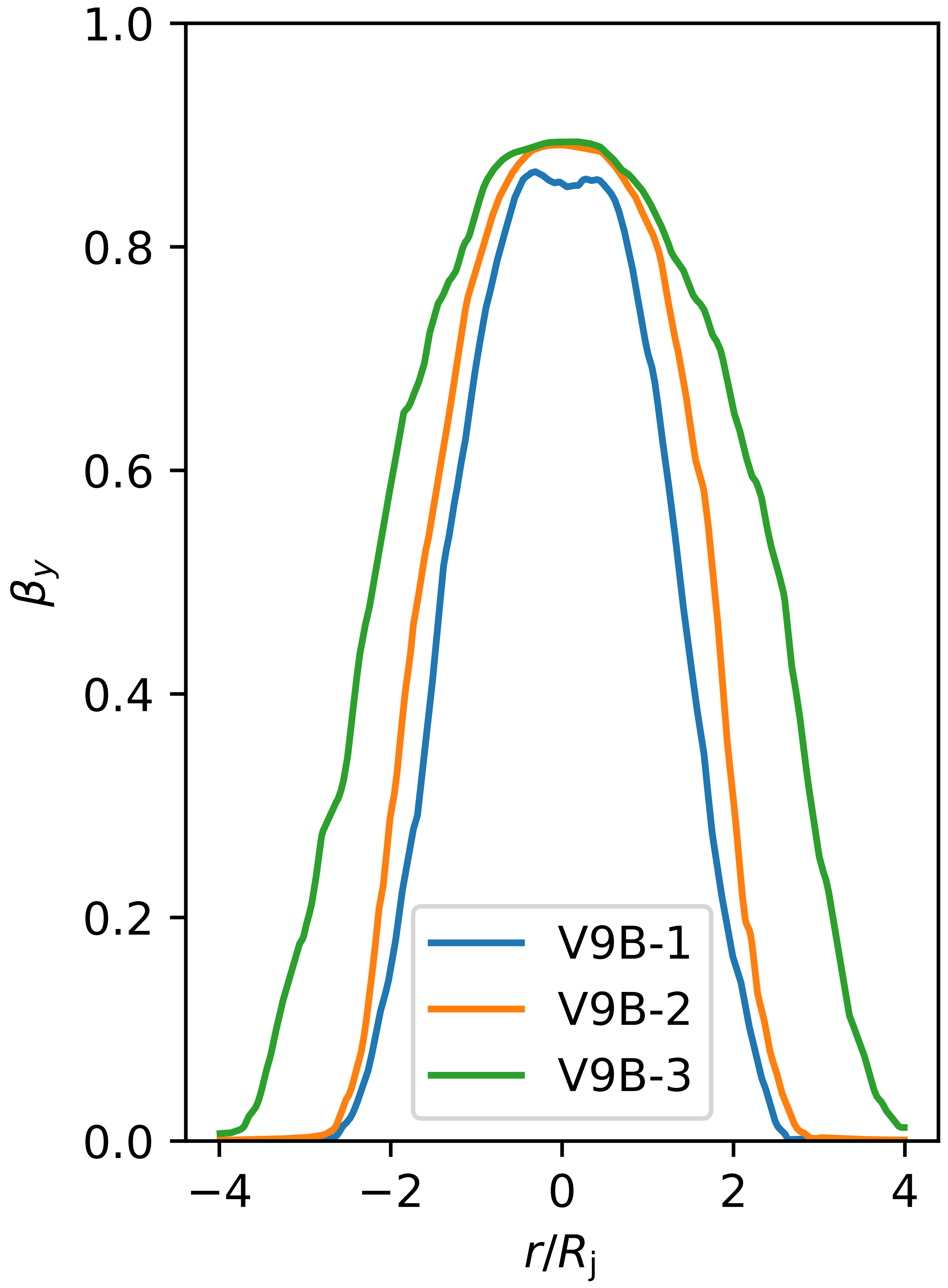
Wang et al., 2021, MNRAS, 505, 1334

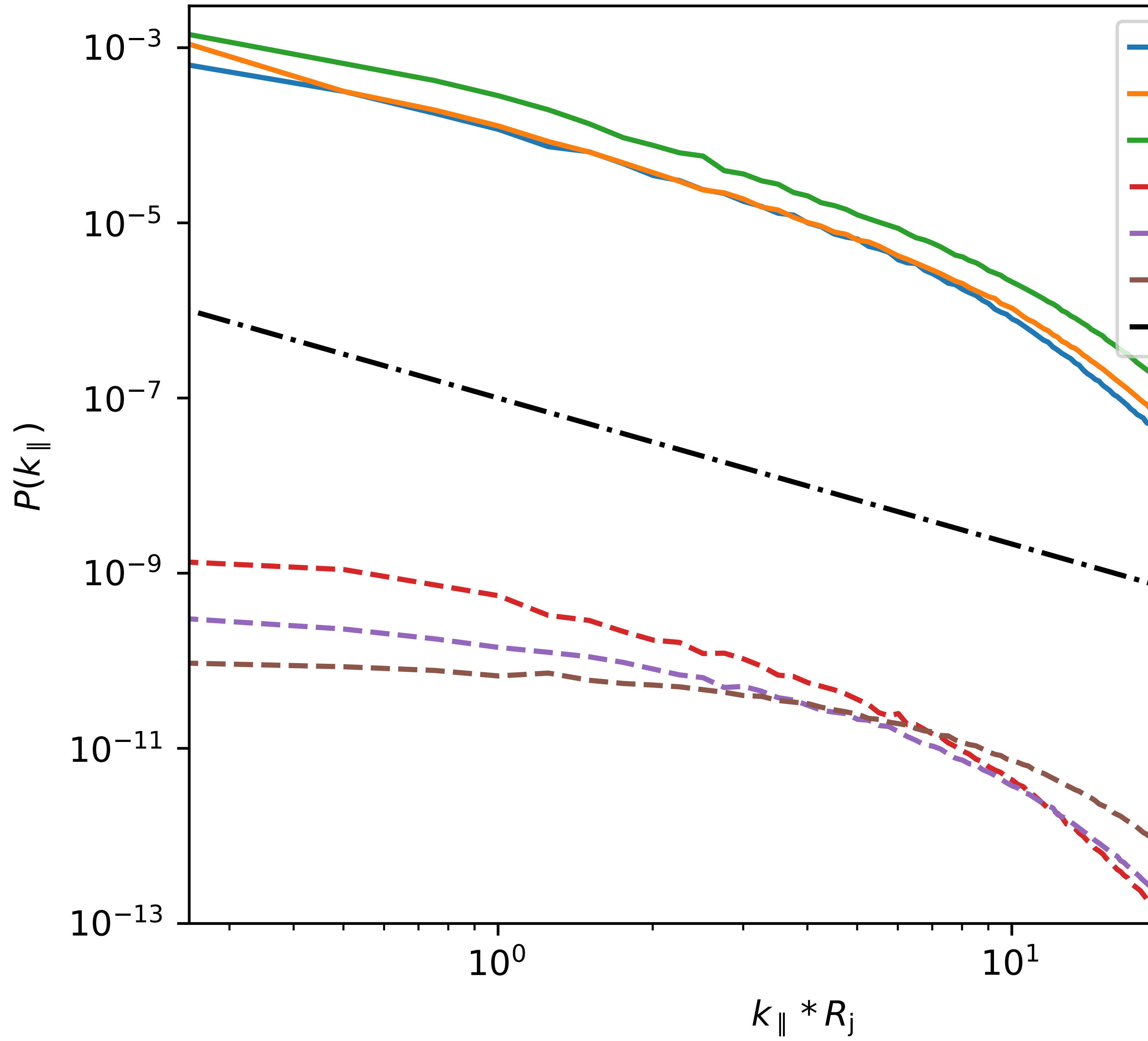
Hillas, 1984, ARAA, 22, 425; Kotera & Olinto, 2011, ARAA, 49, 119

RMHD simulations with PLUTO



Preliminary





Short Summary

- Shear acceleration can produce cut-off power-law spectra
- Multi-wavelength SED of FR I/II jets can be explained
- >10 Z EeV CRs can be achieved
- More to come: RMHD simulations + test particle simulations
- The SED difference between FR I and II jets remains to be answered