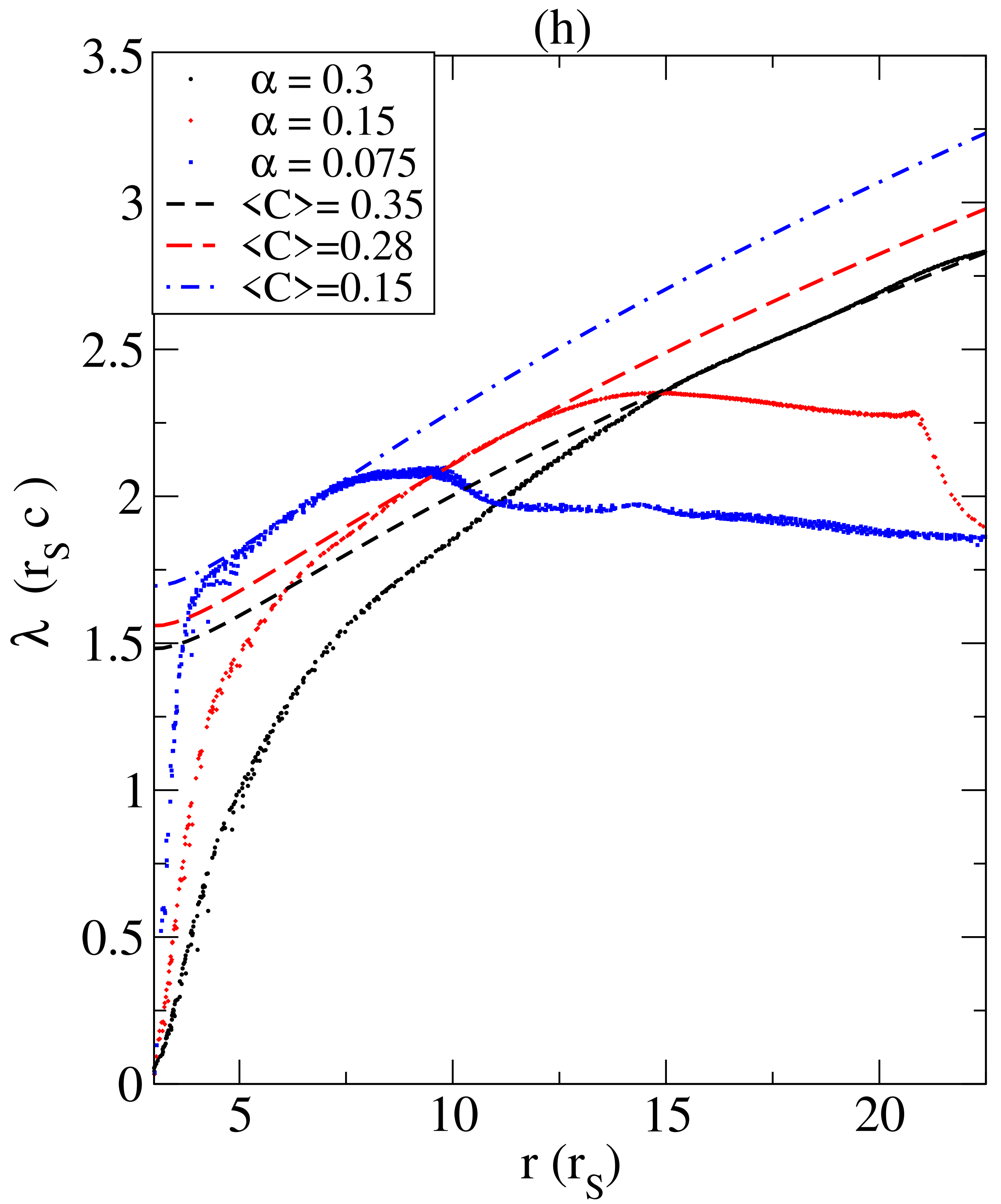
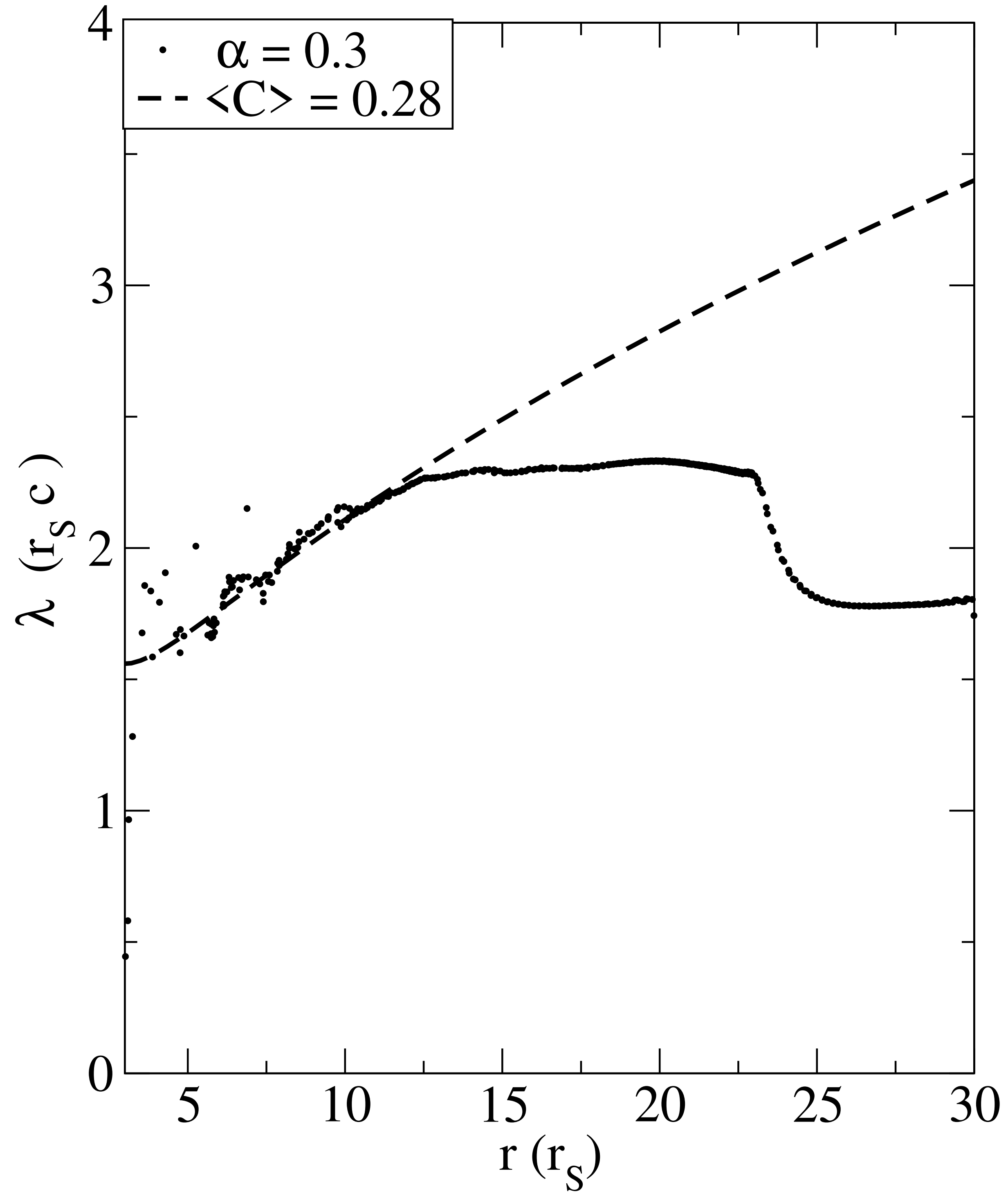
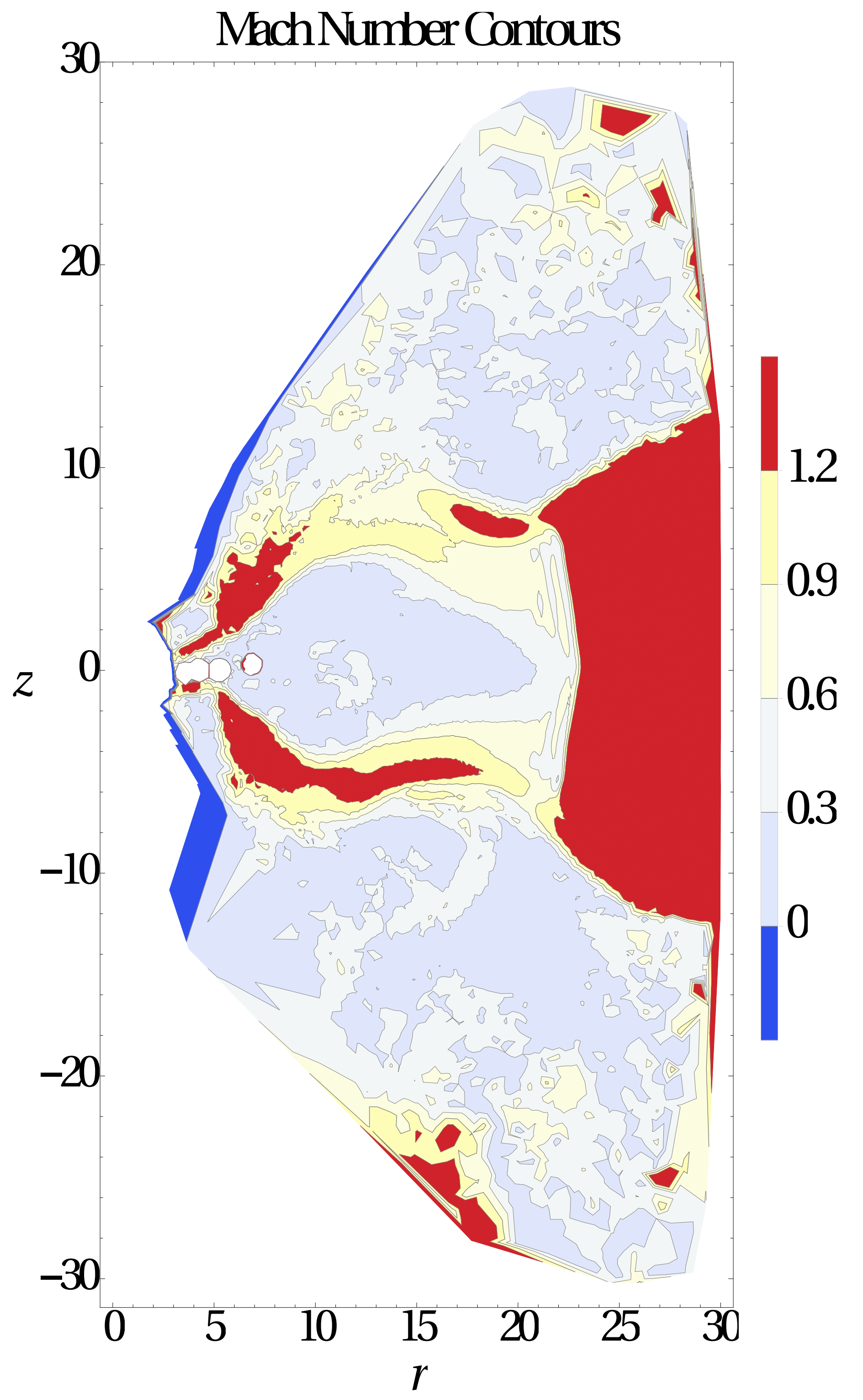
Results: Timing Properties

Viscous Flows



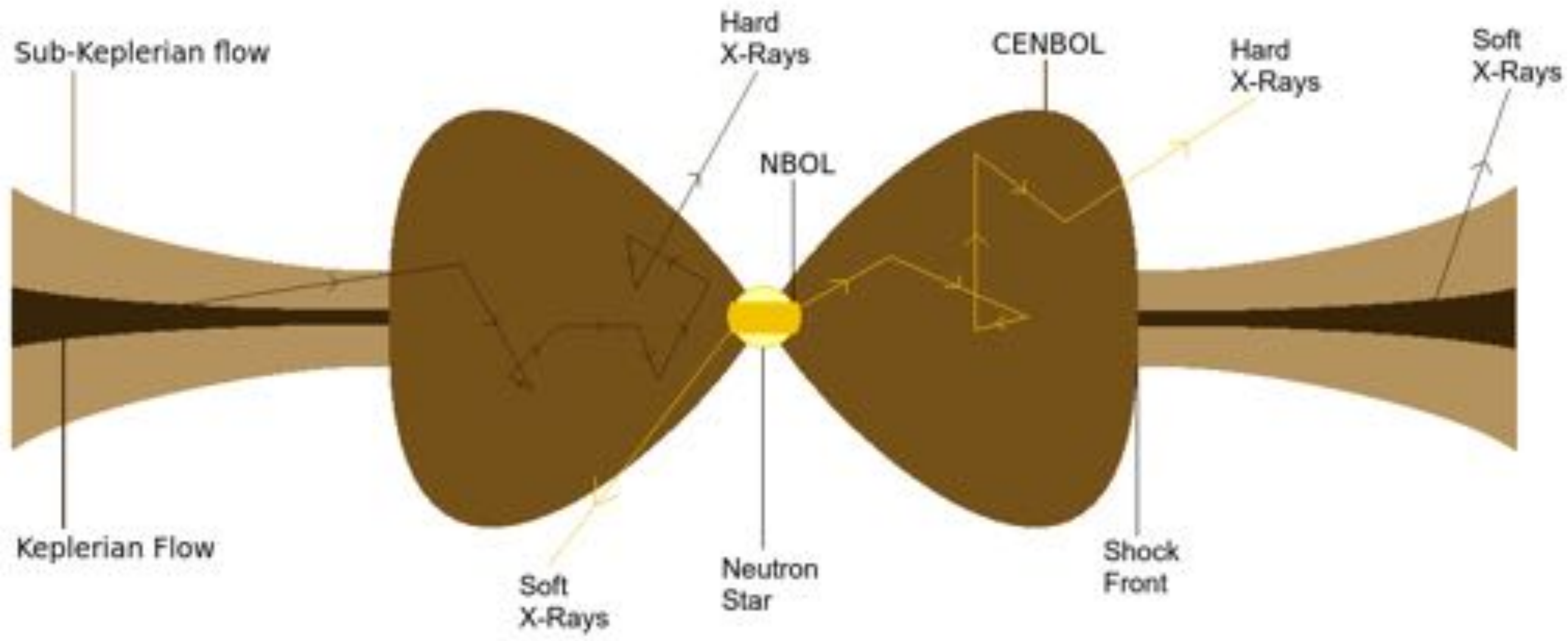




1. A transition layer is seen to be forming to accommodate the change in angular momentum at the NS surface.
2. When viscosity is raised, this transition layer grows radially.
3. A Keplerial disk forms between the transition layer and the sub-Keplerian flow.

Results: Spectral Properties

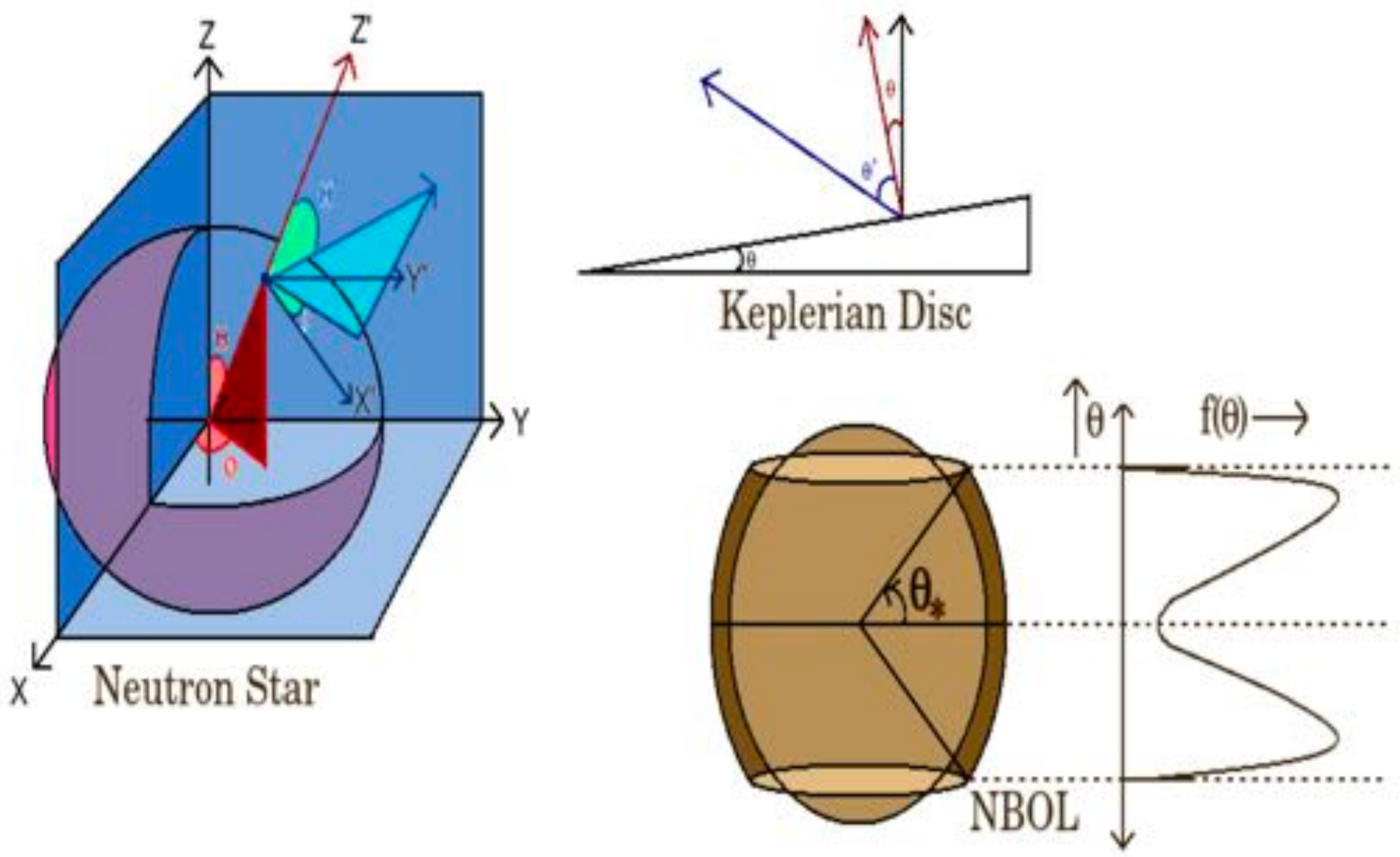
TCAF around Neutron Stars



Bhattacharjee A., Chakrabarti S. K., MNRAS **472**, 1361-1371 (2017)

Results: Spectral Properties

TCAF around Neutron Stars



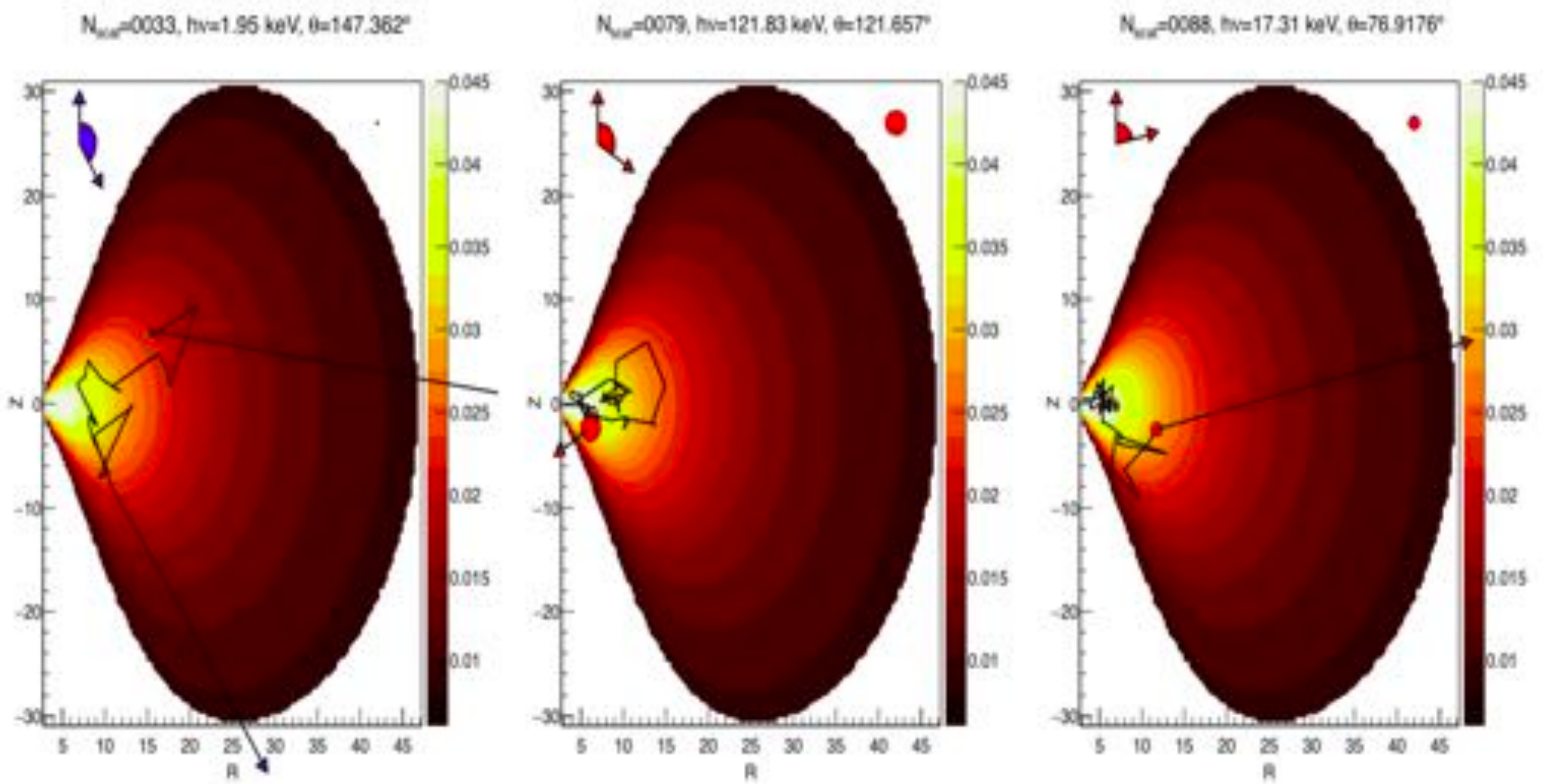


Table 2

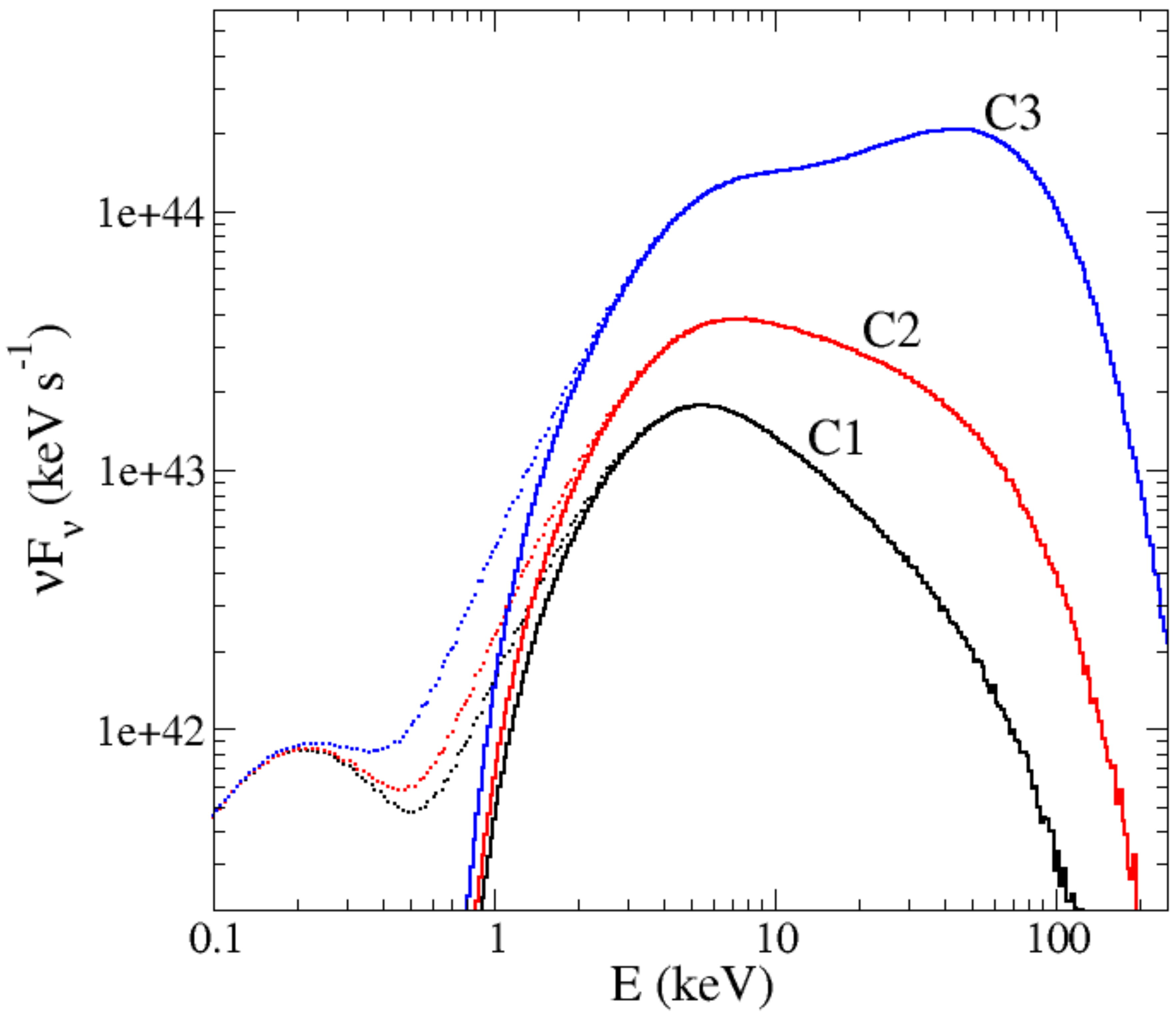
List of parameters for the system used in simulation

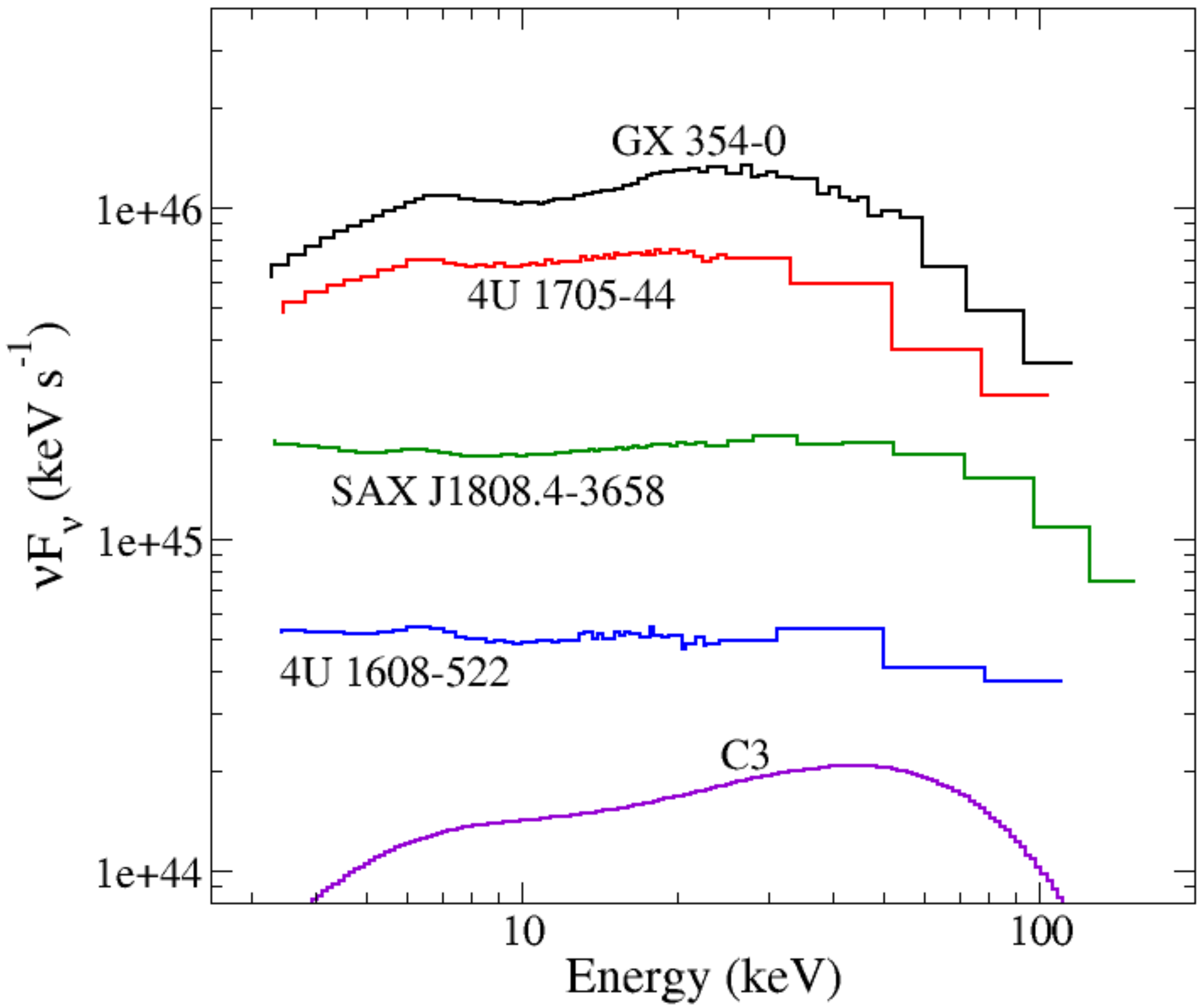
ID	$\dot{m}_d$ ($\dot{M}_{EDD}$)	$\dot{m}_h$ ($\dot{M}_{EDD}$)	X_s (r_S)	T_{CE} (keV)	n_{ce} ($\times 10^{18}$)	T_{NS} (keV)	θ_* (degrees)	$T_e(\tau_0)$ (keV)
C1	0.1	0.1	46.8	25.0	1.772	0.802	11.52	22.062
C2	0.1	0.2	46.8	25.0	2.658	0.888	17.48	22.062
C3	0.1	0.5	46.8	25.0	5.317	1.056	36.90	22.062
C4	0.2	0.1	30.0	10.0	1.515	0.888	17.48	8.909
C5	0.2	0.2	30.0	10.0	2.020	0.954	23.61	8.909
C6	0.2	0.5	30.0	10.0	3.535	1.098	44.40	8.909
C7	0.5	0.1	21.8	3.0	2.100	1.056	36.90	2.705
C8	0.5	0.2	21.8	3.0	2.450	1.098	44.40	2.705
C9	0.5	0.5	21.8	3.0	3.500	1.200	90.00	2.705

Bhattacharjee A., Chakrabarti S. K., MNRAS **472**, 1361-1371 (2017)

Results: Spectral Properties

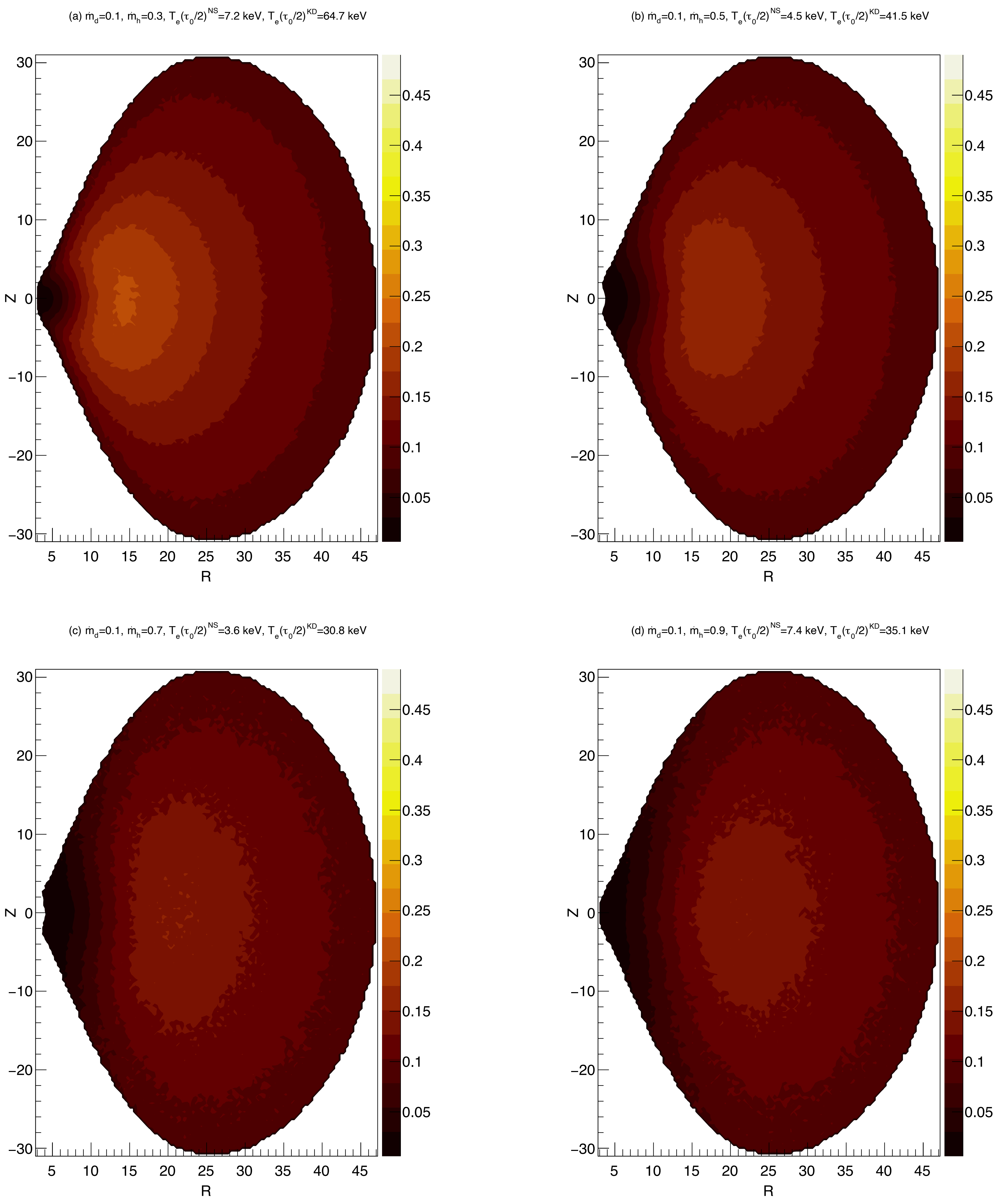
TCAF around Neutron Stars





1. Both the disk and halo accretion rate control the spectral shape.
2. Increase in halo accretion increases the hardness of the spectra.
3. The simulated spectra matches well with multiple neutron stars X-ray binaries.

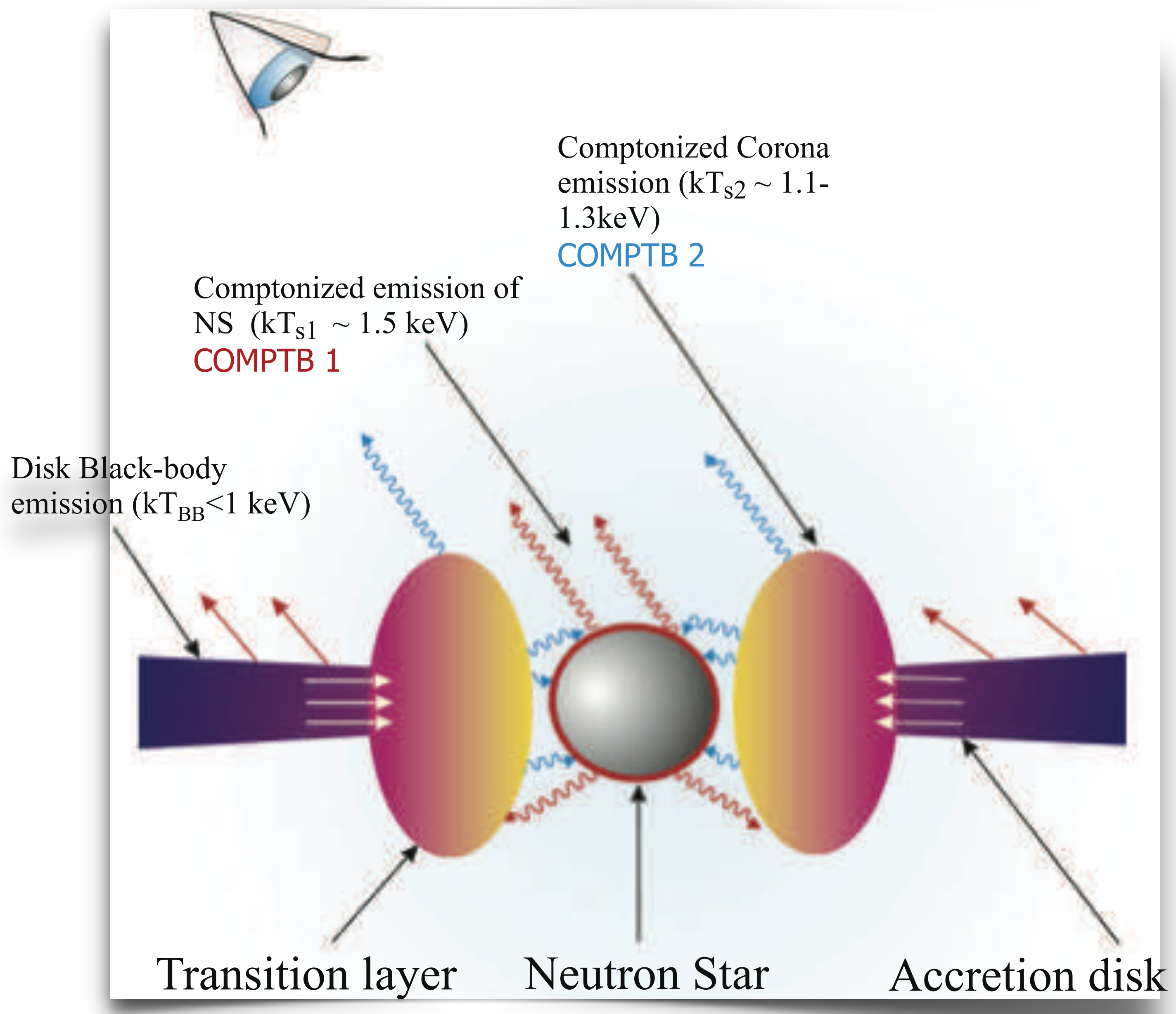
Results: Spectral Properties



Bhattacharjee A., Chakrabarti S. K., MNRAS **472**, 1361-1371 (2017)

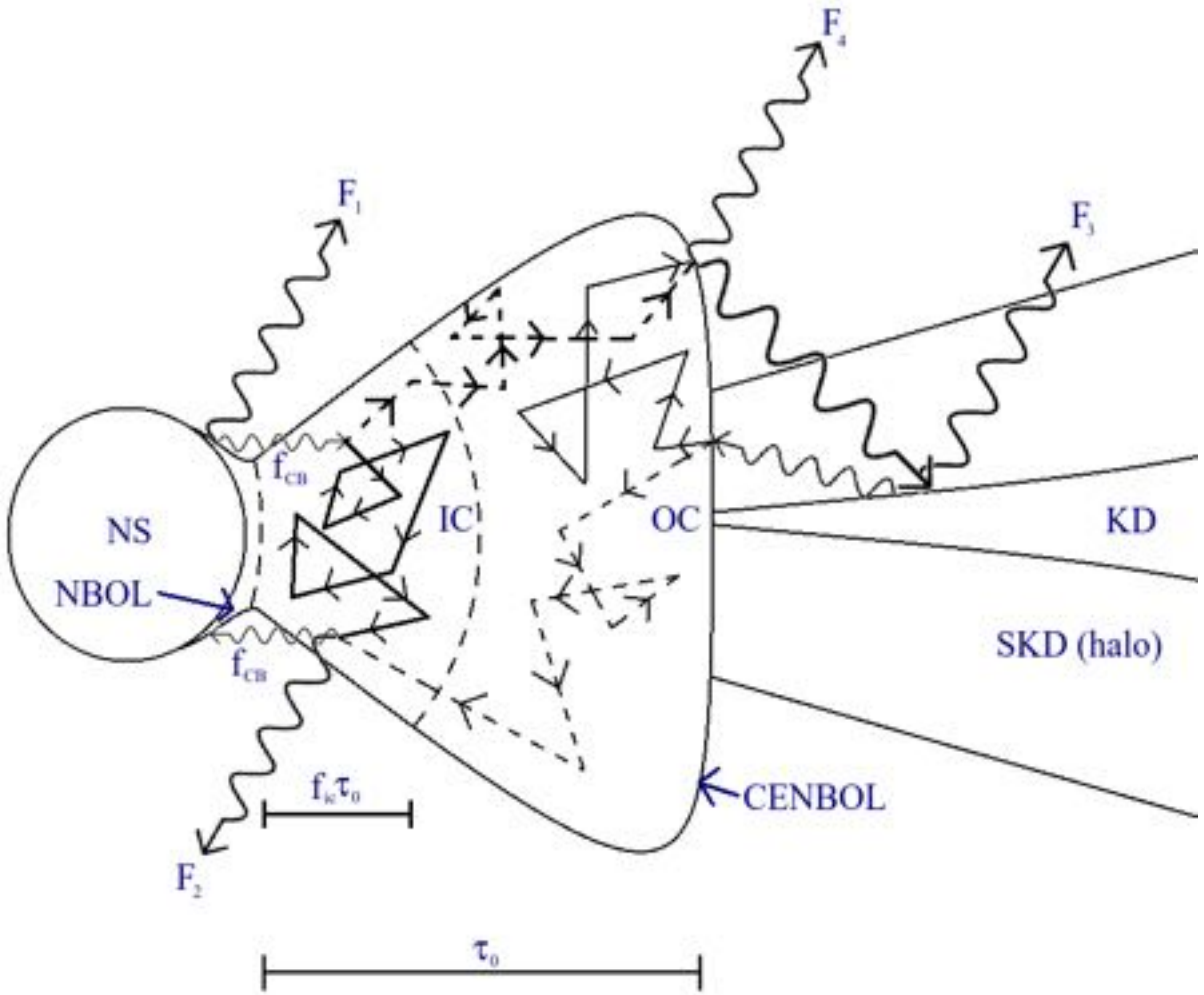
TCAF around Neutron Stars

1. Cooling of CENBOL.
2. Shift of peak temperature location.
3. Matches with models used for spectral analysis.



Tcaf **A**round **C**ompact **O**bjects or… ***TACO***??

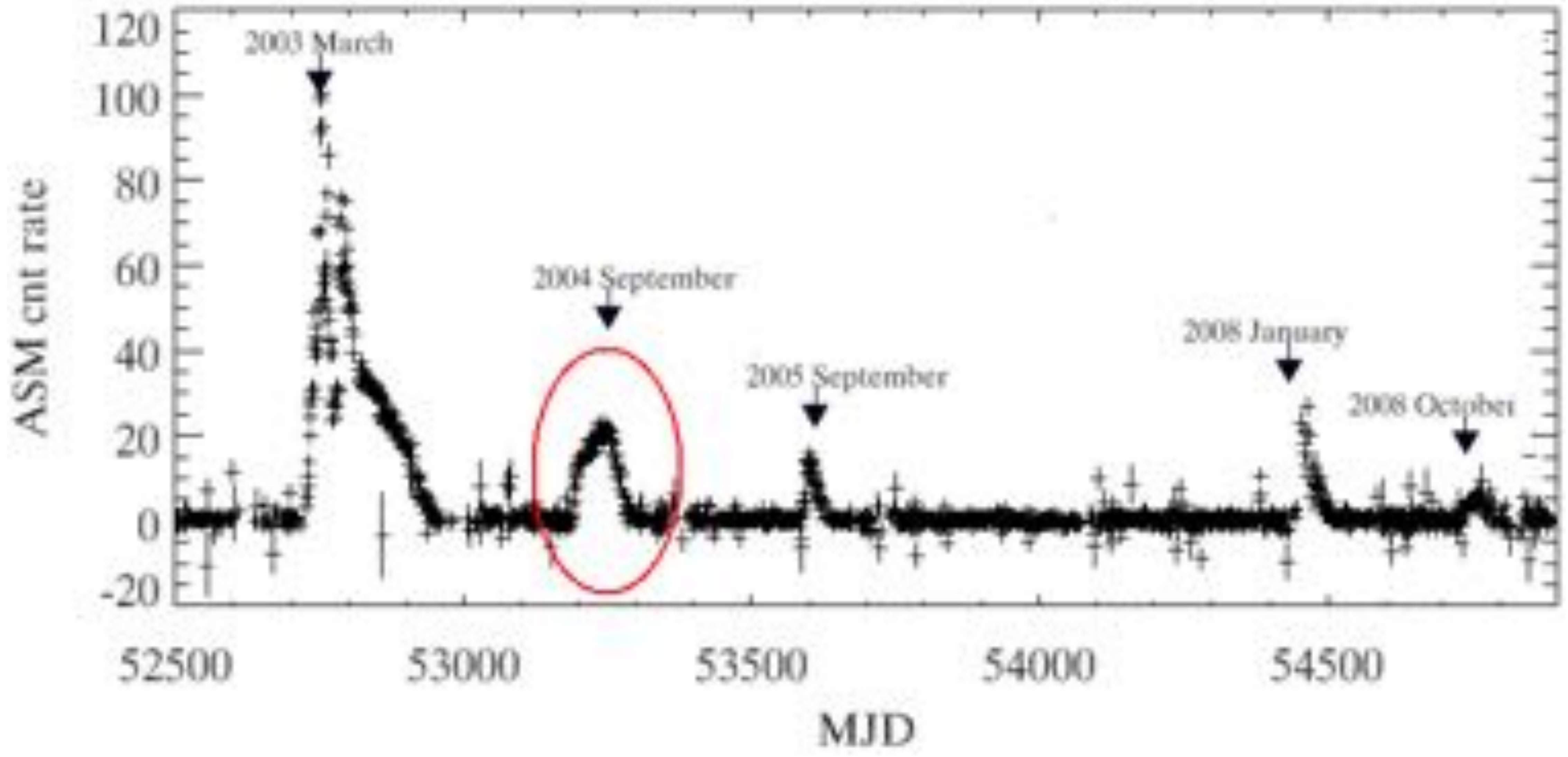
Schematic of the Model



For BH:
$T_{CO} = 0.0,$
$f_{IC} = 0.0,$
$f_{CB} = 0.0$

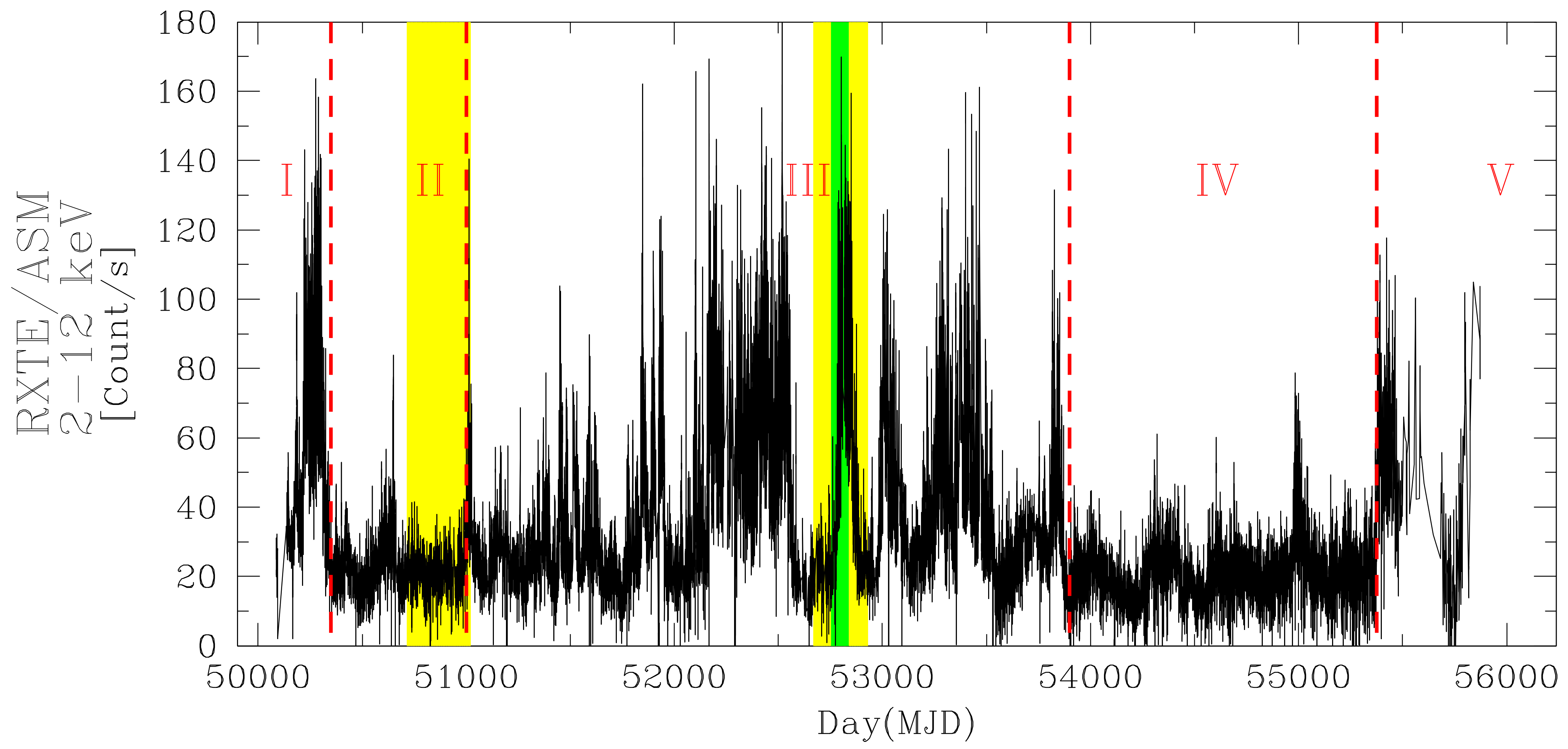
Use of TCAF: Case Studies

Transient: H1743-322



Bhattacharjee et al. 2017, MNRAS, 466, 1372

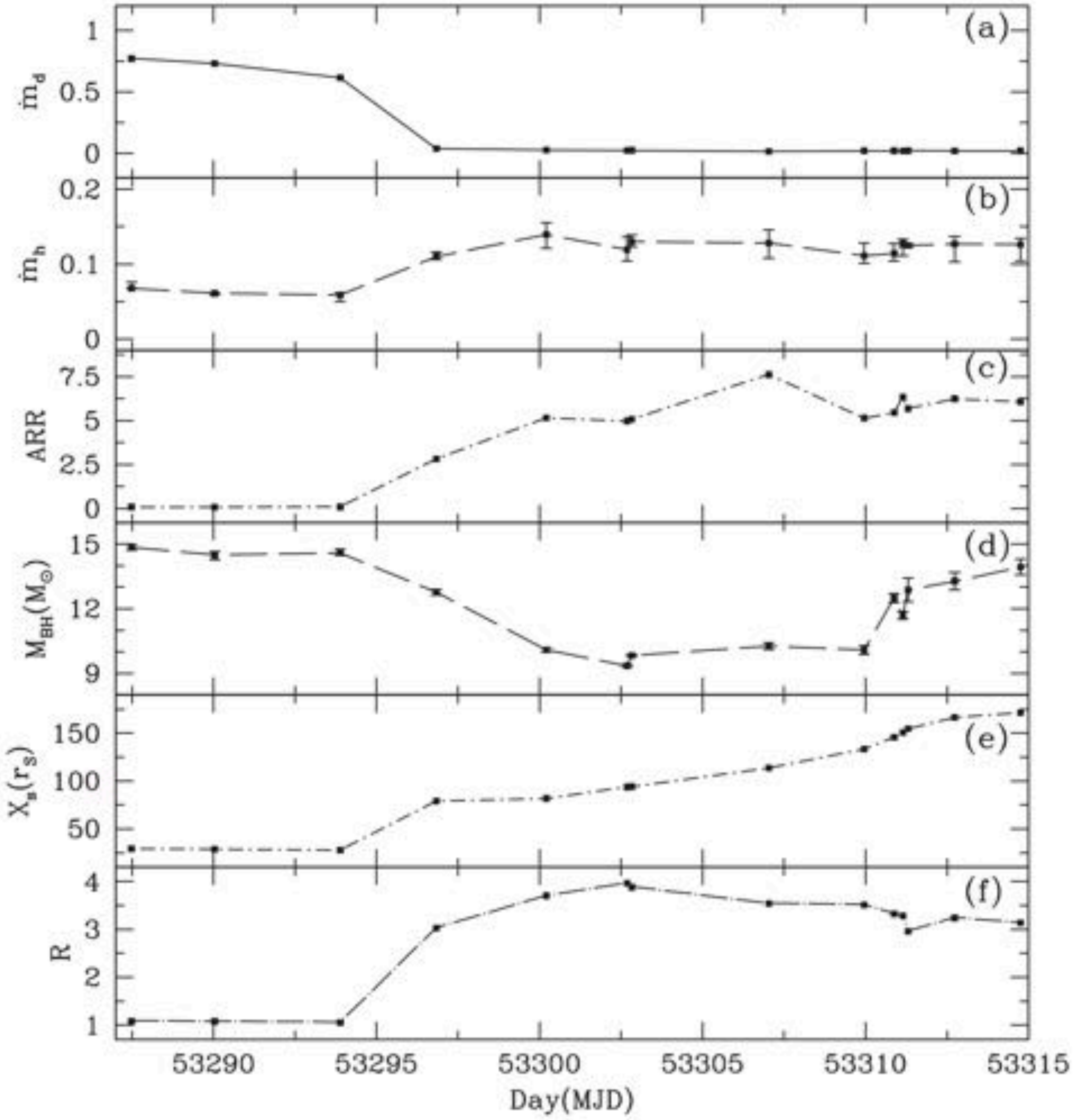
Persistent: Cygnus X-1



Banerjee et al. 2019, arXiv, 1904.11644

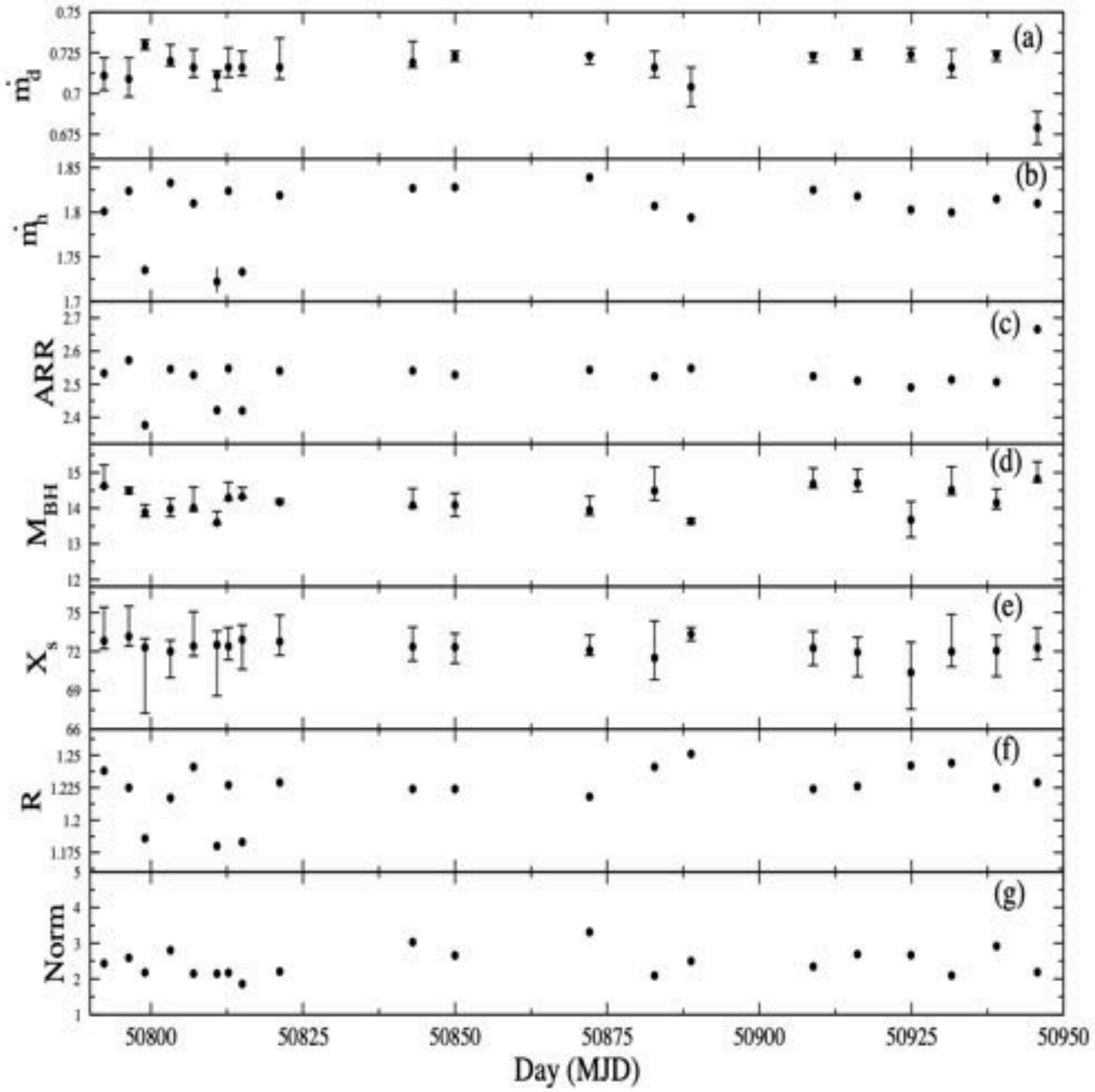
TCAF Modelling of BH Sources

H1743-322



Bhattacharjee et al. 2017, MNRAS, 466, 1372

Cygnus X-1

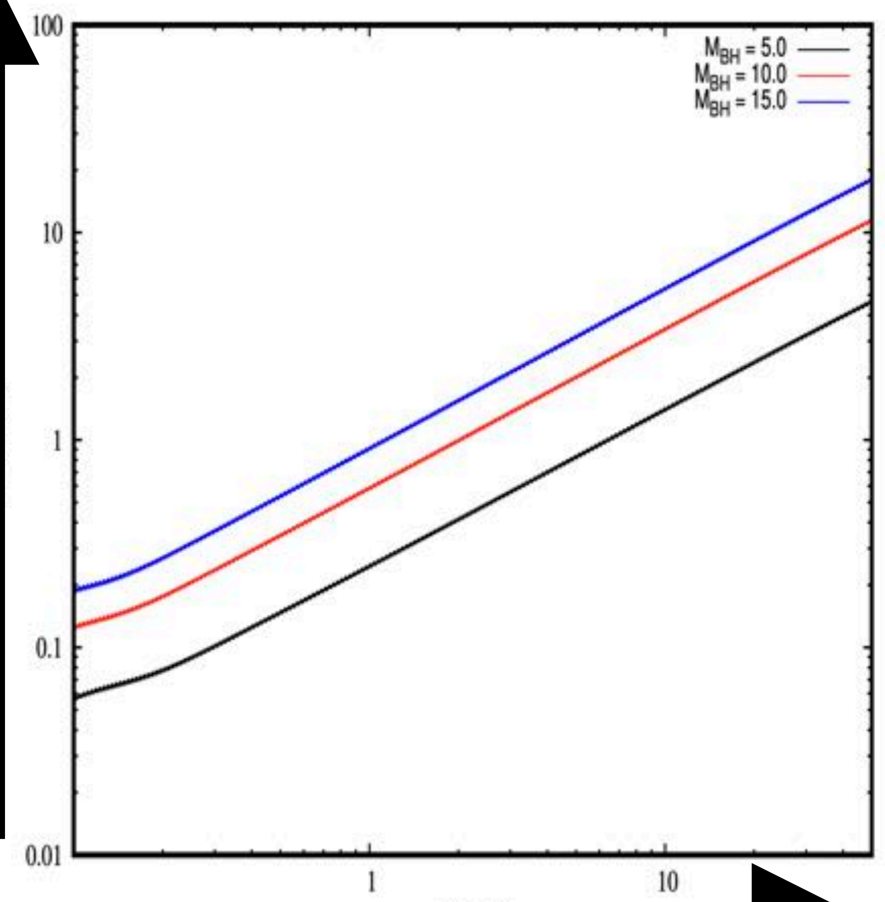


Banerjee et al. 2019, arXiv, 1904.11644

TACO: Simulated Spectra of BH

Variation with M_{BH}

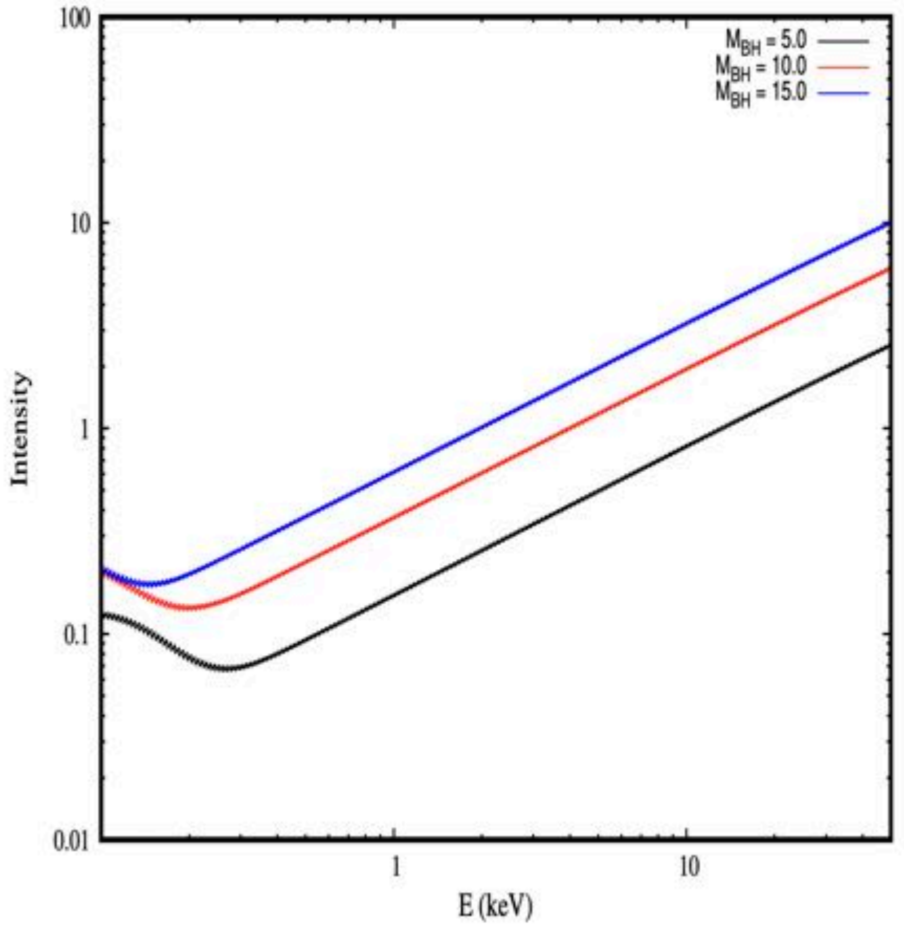
Hard State



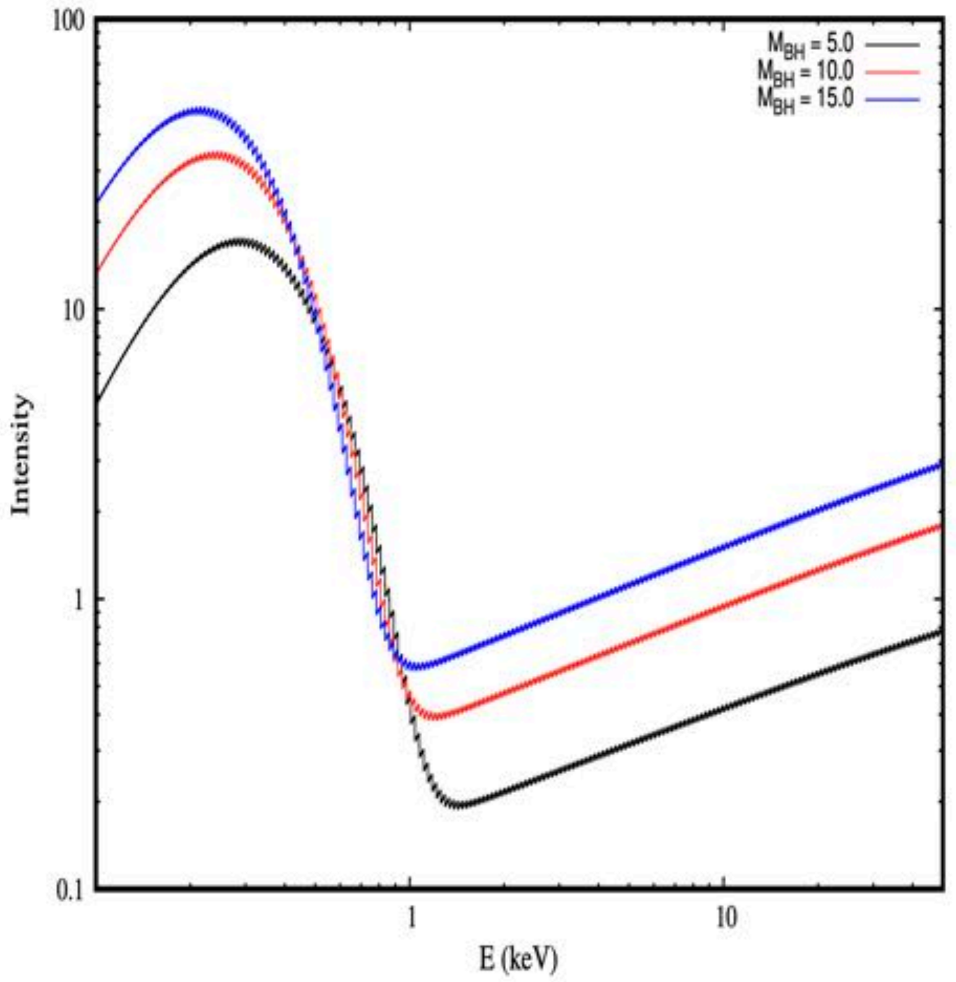
Intensity

E (keV)

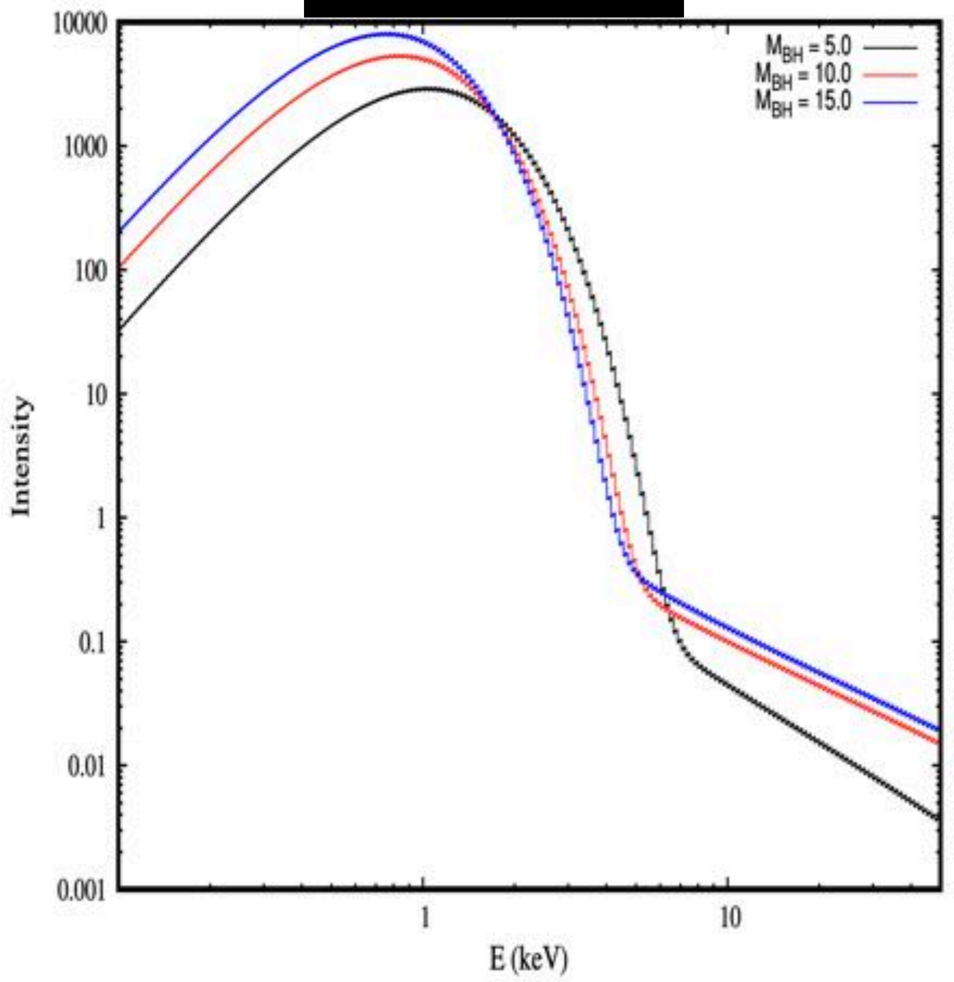
Hard-Intermediate State



Soft-Intermediate State



Soft State



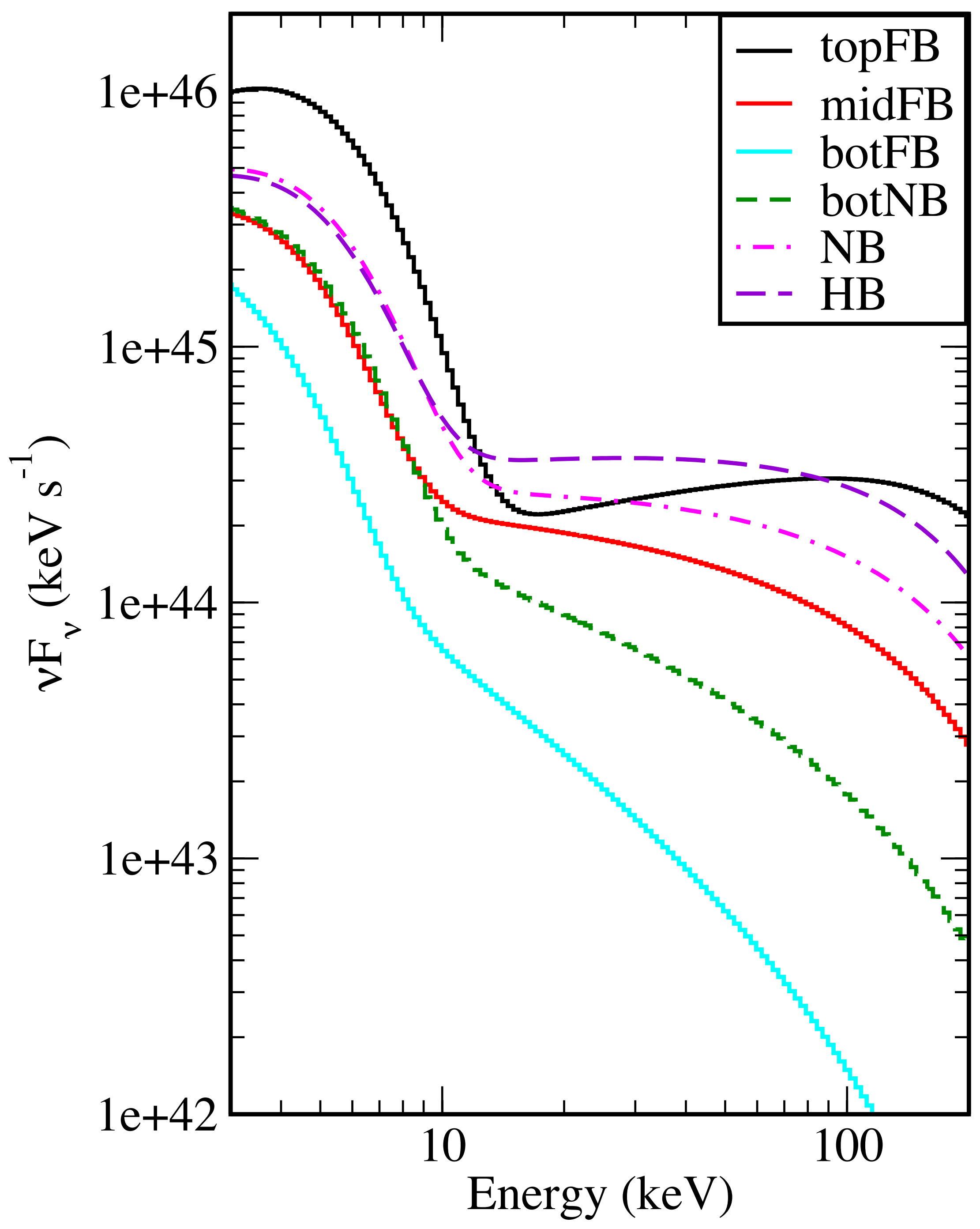
$M_{BH} = 5.0,$

$M_{BH} = 10.0,$

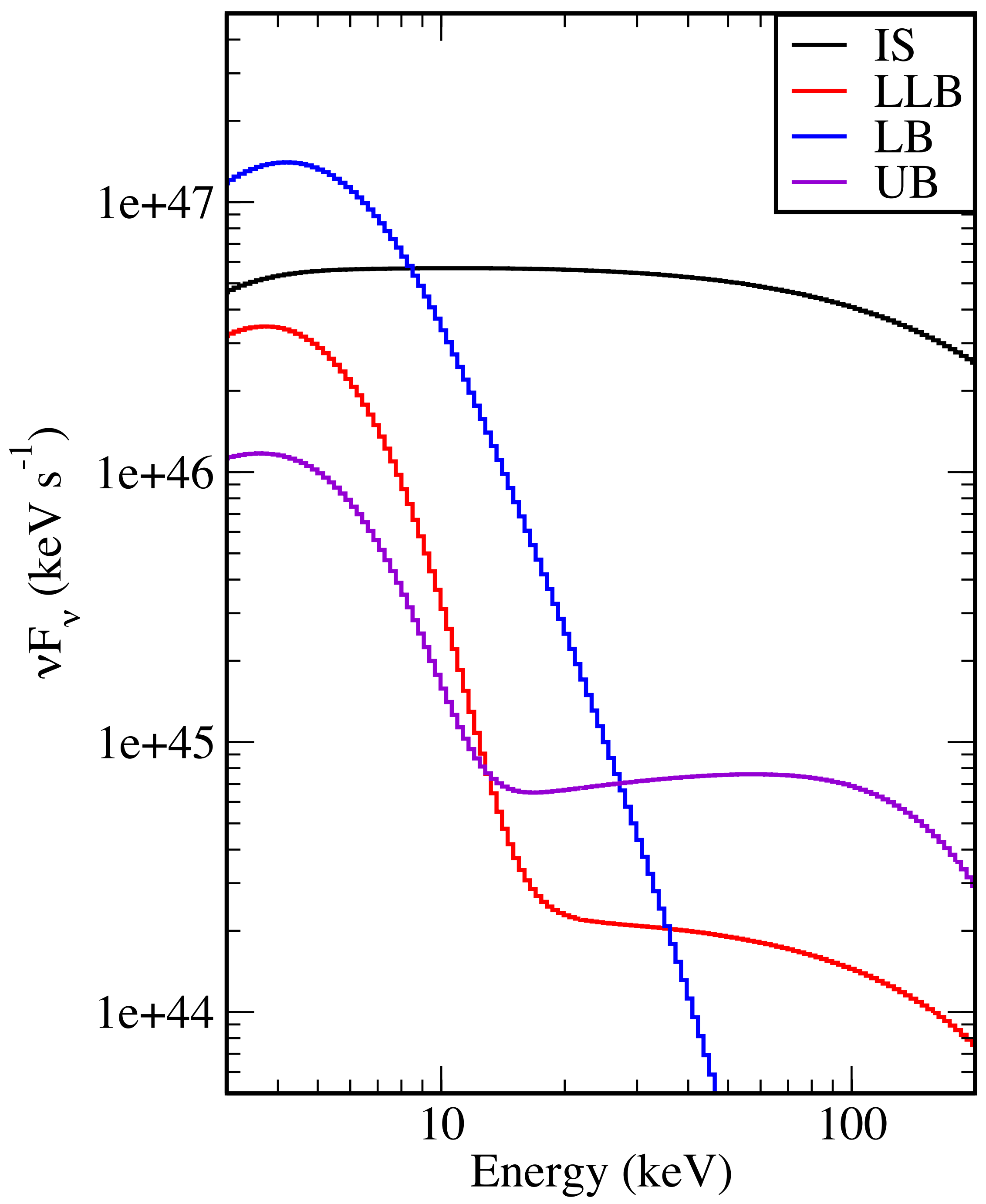
$M_{BH} = 15.0$

TACO: Simulated Spectra of NS

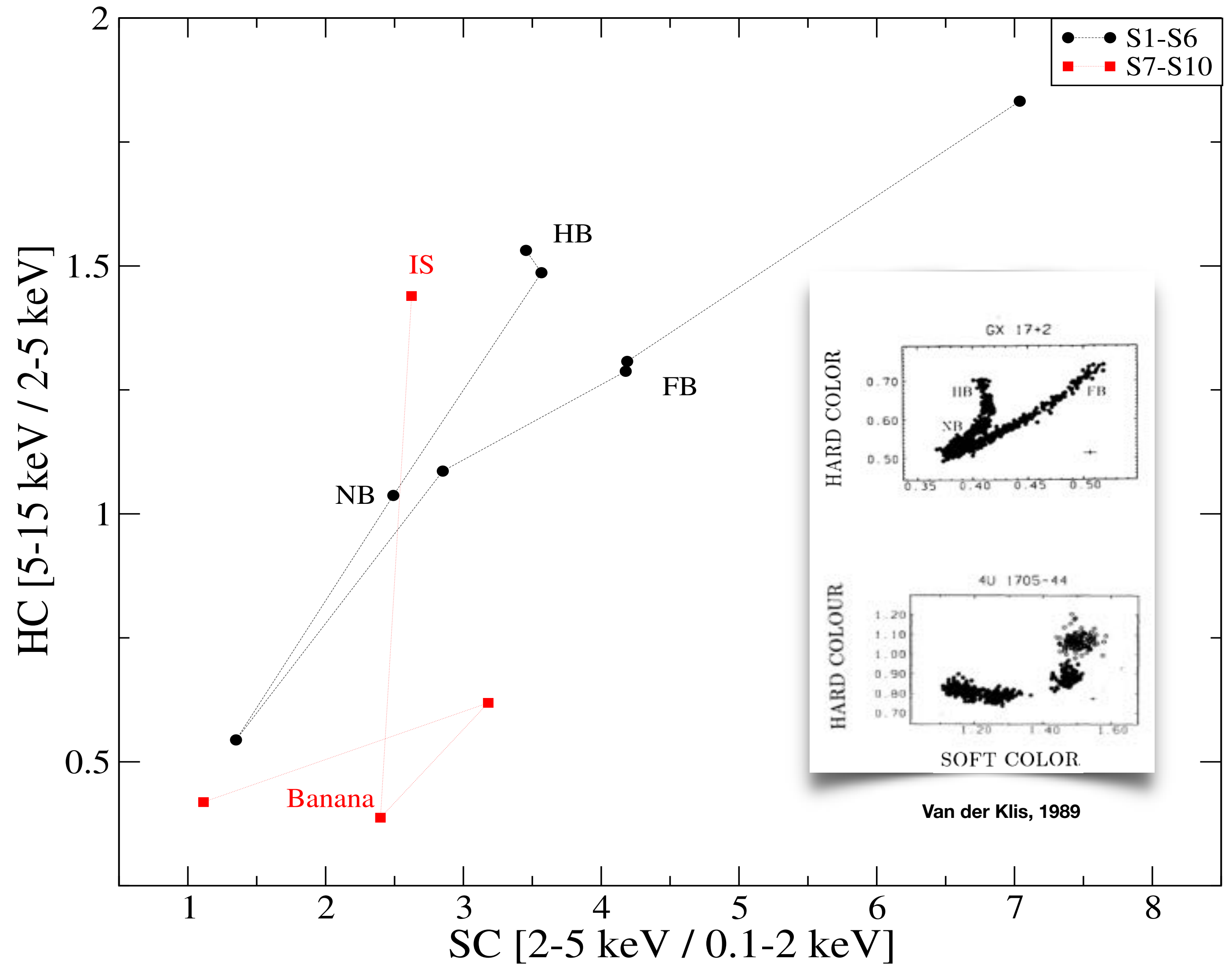
Z-type



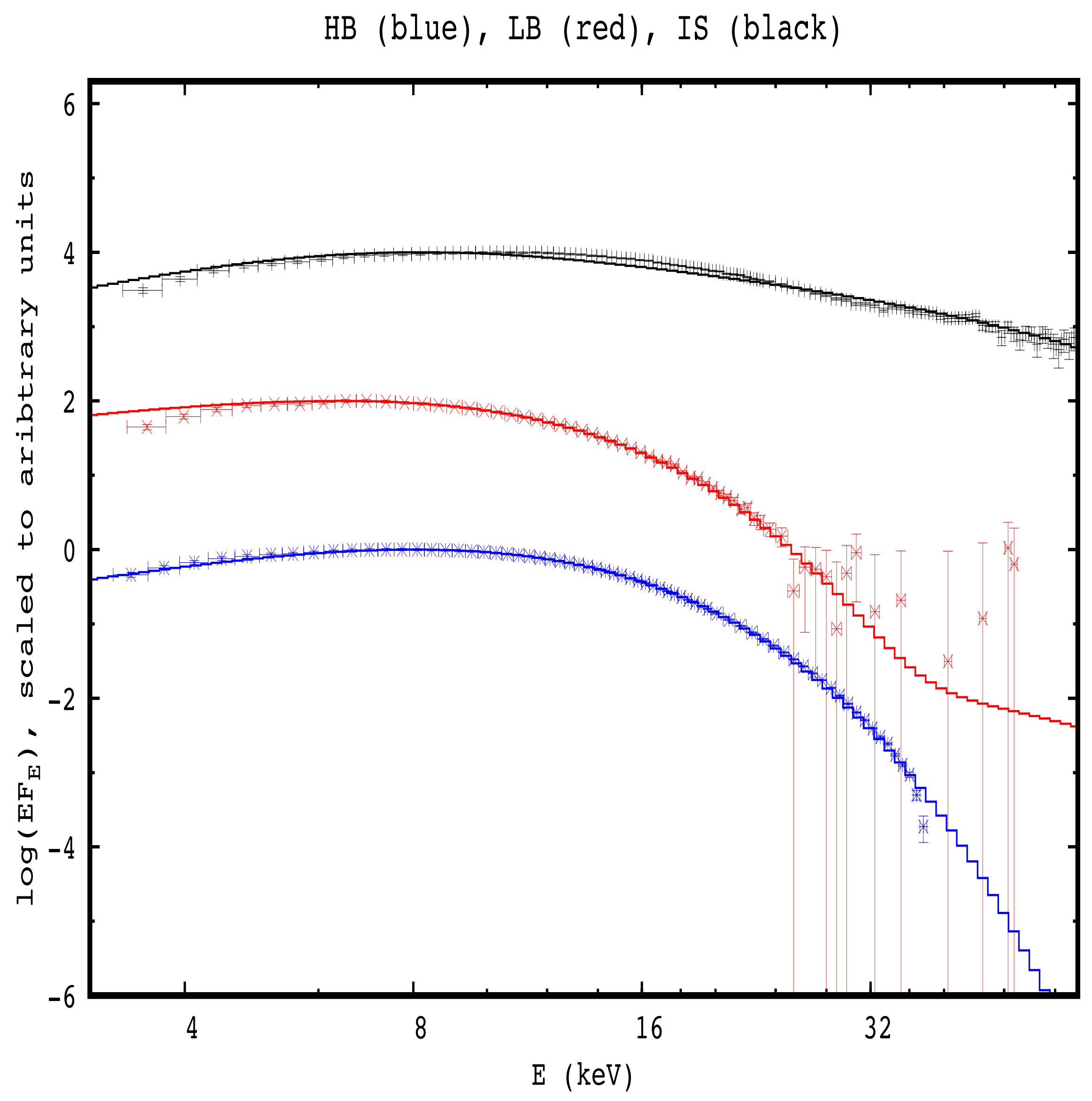
Atoll-type



Color-Color Diagram



Spectral fits of NS sources using TACO



Bhattacharjee and Chakrabarti, 2020 (arXiv: 2012.14502)

Conclusions: P1

Accretion around Compact Objects

- The accretion process around compact objects can be explained with two components of accretion: a Keplrian disk and a sub-Keplerian disk (Chkarabarti and Titarchuk 1995). This framework seems to provide a reasonable insight into the spectral and temporal variation of black holes and neutron stars, especially in the X-ray (Bhattacharjee 2018).

- Simulating accretion around such objects can be done with a combination of radiation loss within a hydrodynamic code (Bhattacharjee and Chakrabarti 2019).

- Formation of Keplerian disk requires a treatment for viscosity and more realistic treatment of radiative loss (Bhattacharjee and Chakrabarti 2020, 2021).

- Jets and outflows are produced due to the formation of shocks in the accretion (Bhattacharjee and Chakrabarti 2019).

Thank You!

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Numerical Simulations of Accretion-Ejection around Compact Objects: What to include (and what not to)?

P2. Study of Jets

Ayan Bhattacharjee

UNIST

The 68th Workshop on Gravitational Waves and Numerical Relativity
2023.03.16, APCTP

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What are Radio Galaxy Jets?

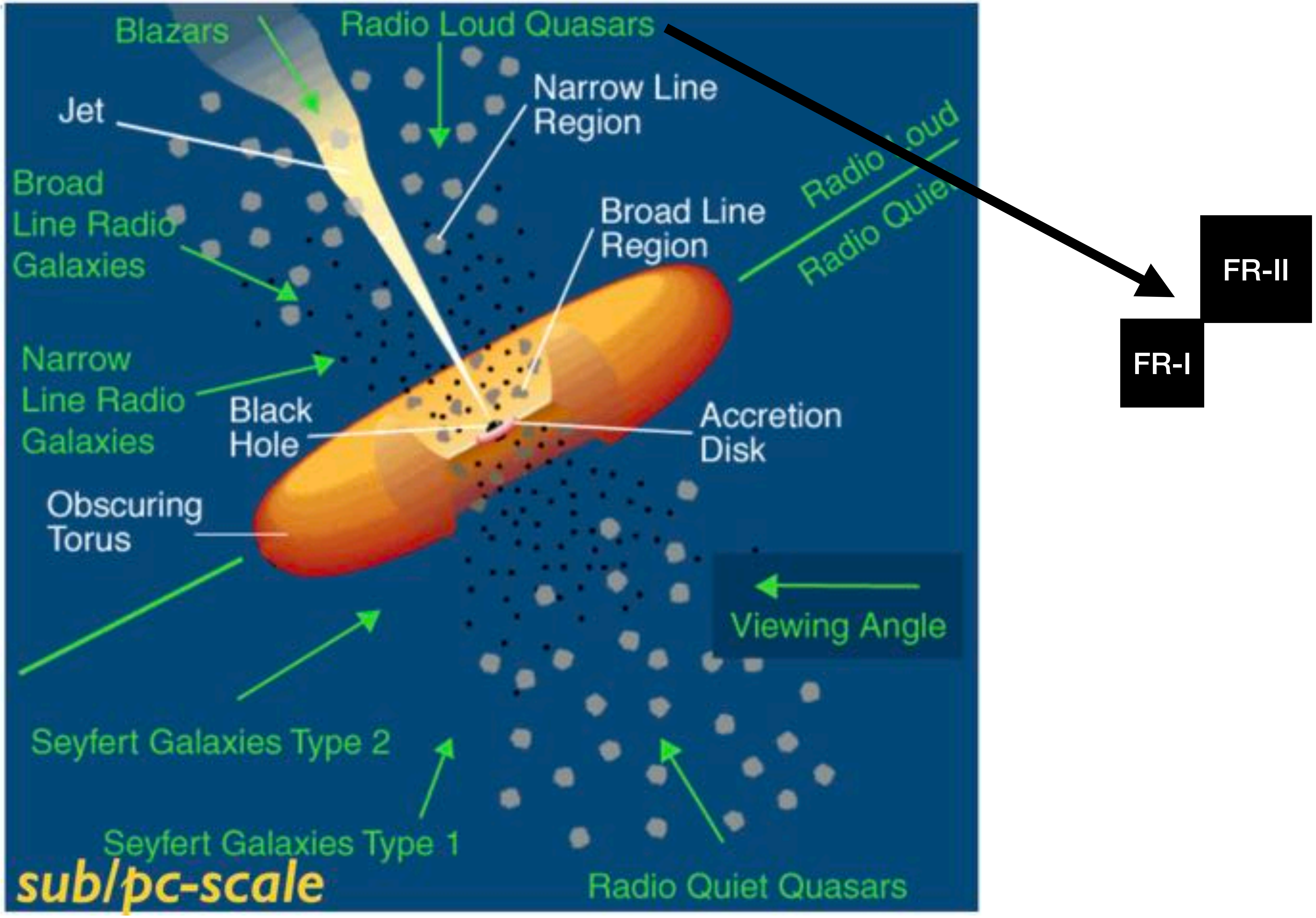
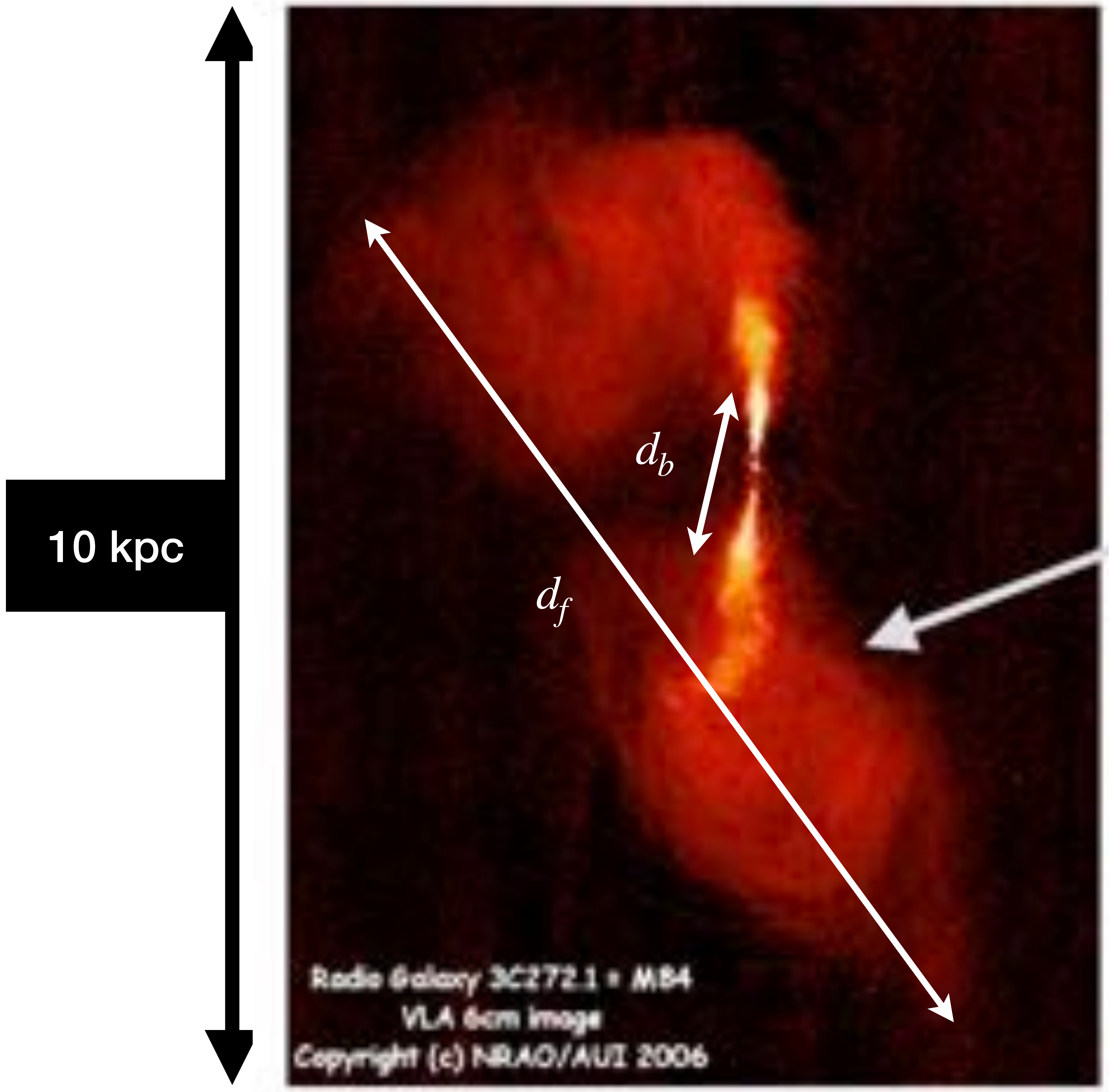
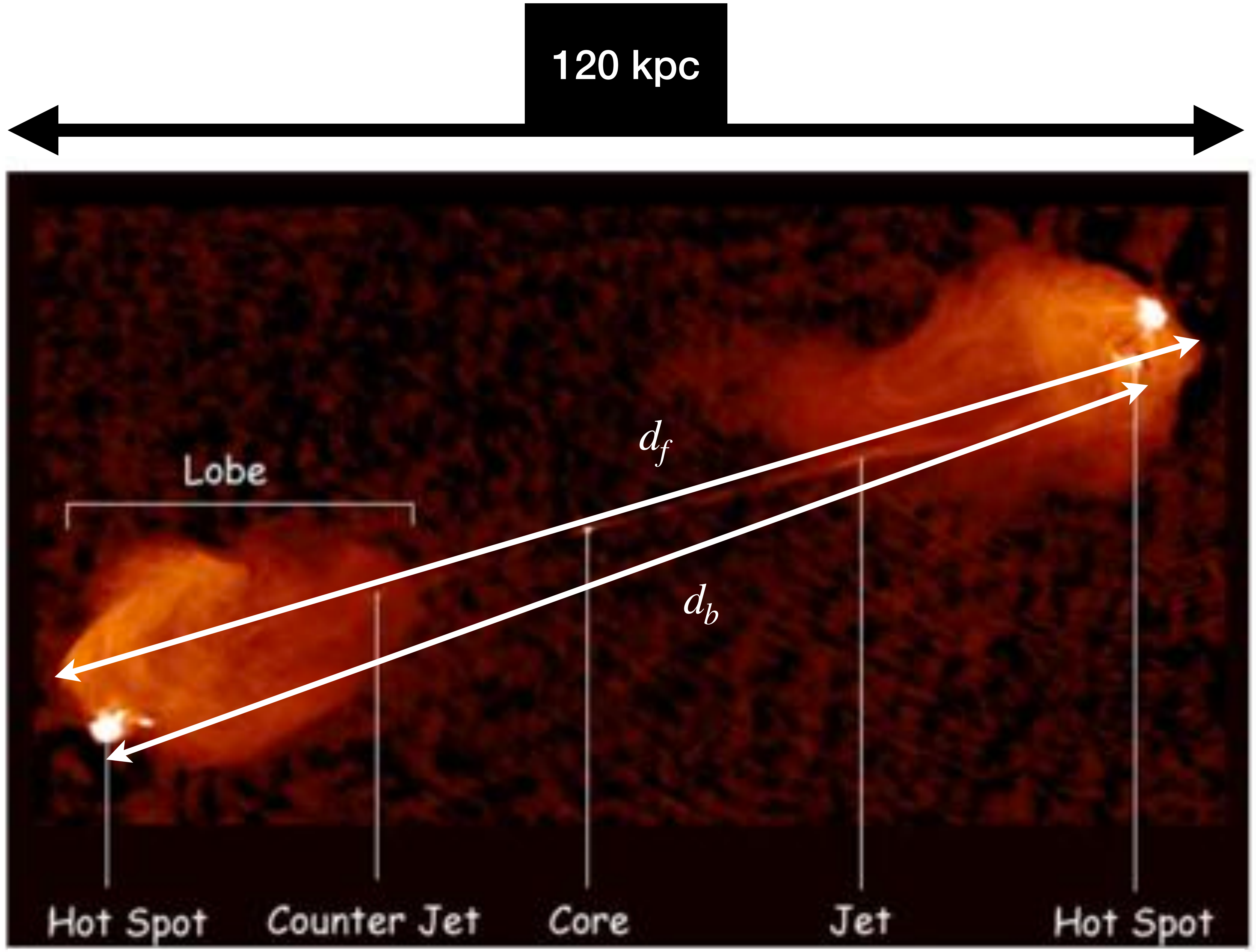


Image Credits: Frank M. Reiger

Morphological Dichotomy of Jets: Fanaroff-Riley Classification



$\frac{d_b}{d_f} < 0.5$, FR-I

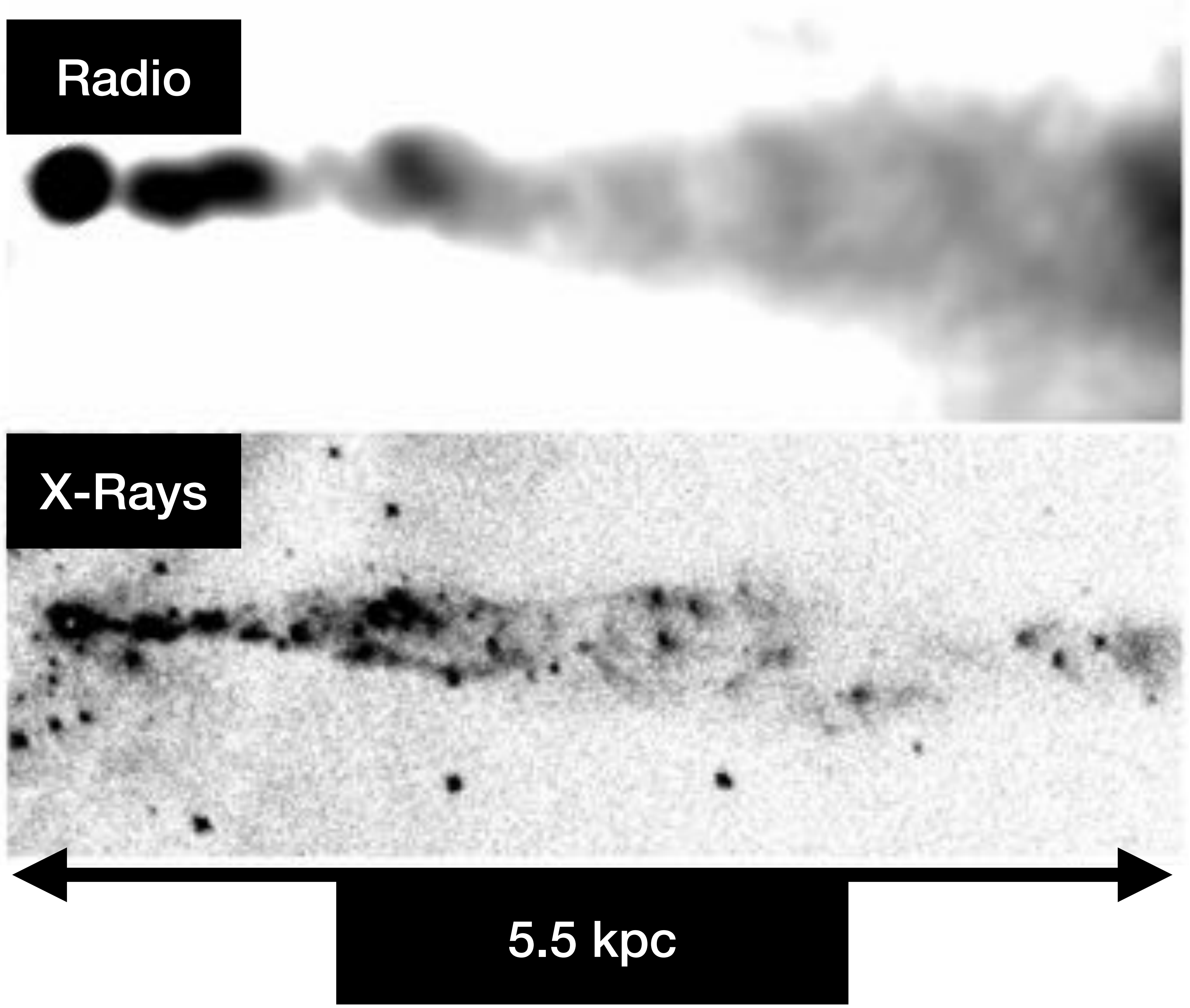


Radio galaxy **Cygnus A** at 5 GHz , d ~ 220 Mpc, (z=0.056), extension ~120 kpc (credits: NRAO/AUI, A. Bridle)

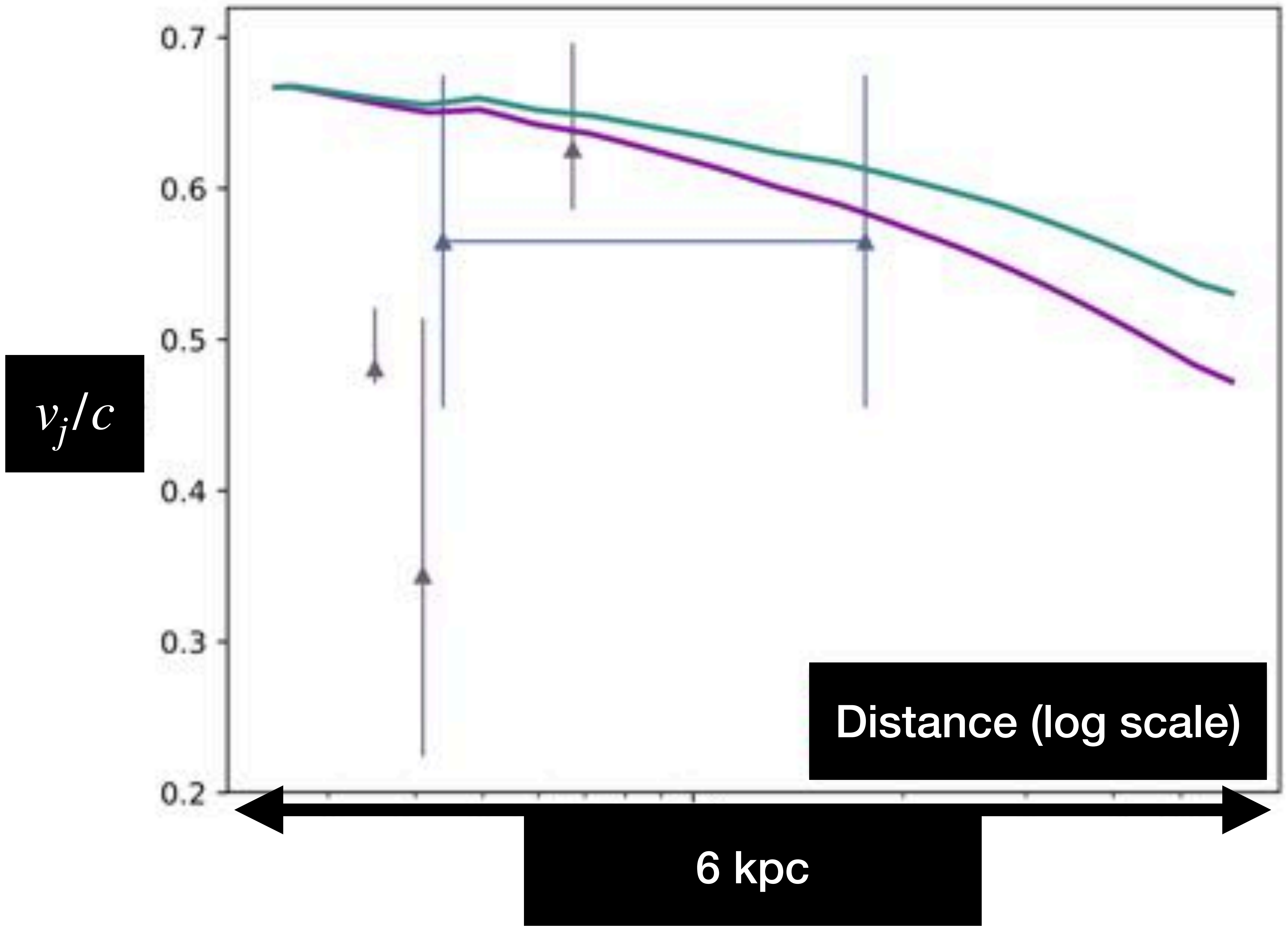
$\frac{d_b}{d_f} > 0.5$, FR-II

Image Credits: Frank M. Reiger

What are the key characteristics of FR-I?



Hardcastle and Croston, 2011, MNRAS, 415, 133

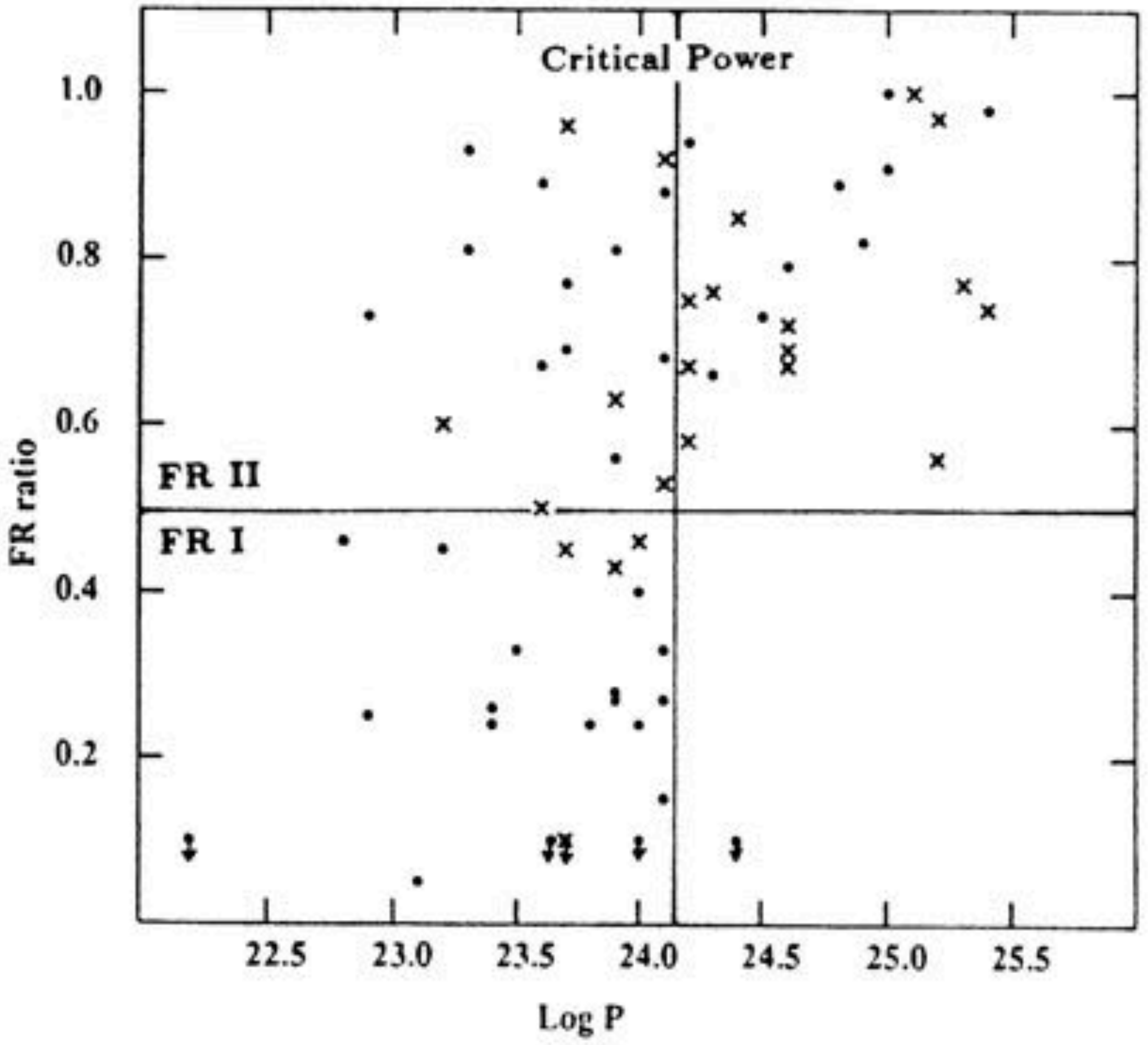


Wykes et al. 2019, MNRAS, 485, 872

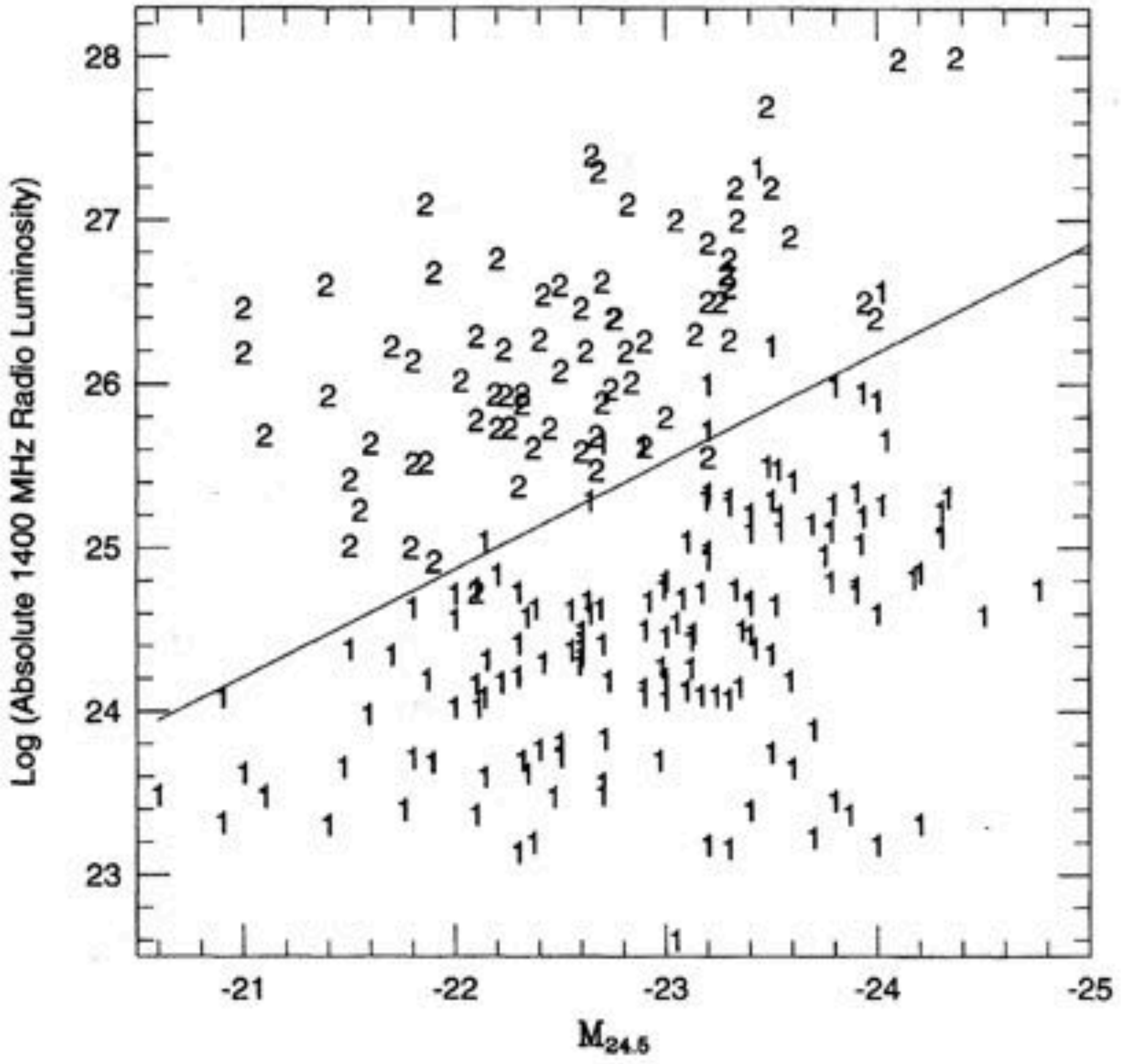
- **Diffused emission in radio**
- **Deceleration of jet**

Observational Outlook: Evolving Dichotomy

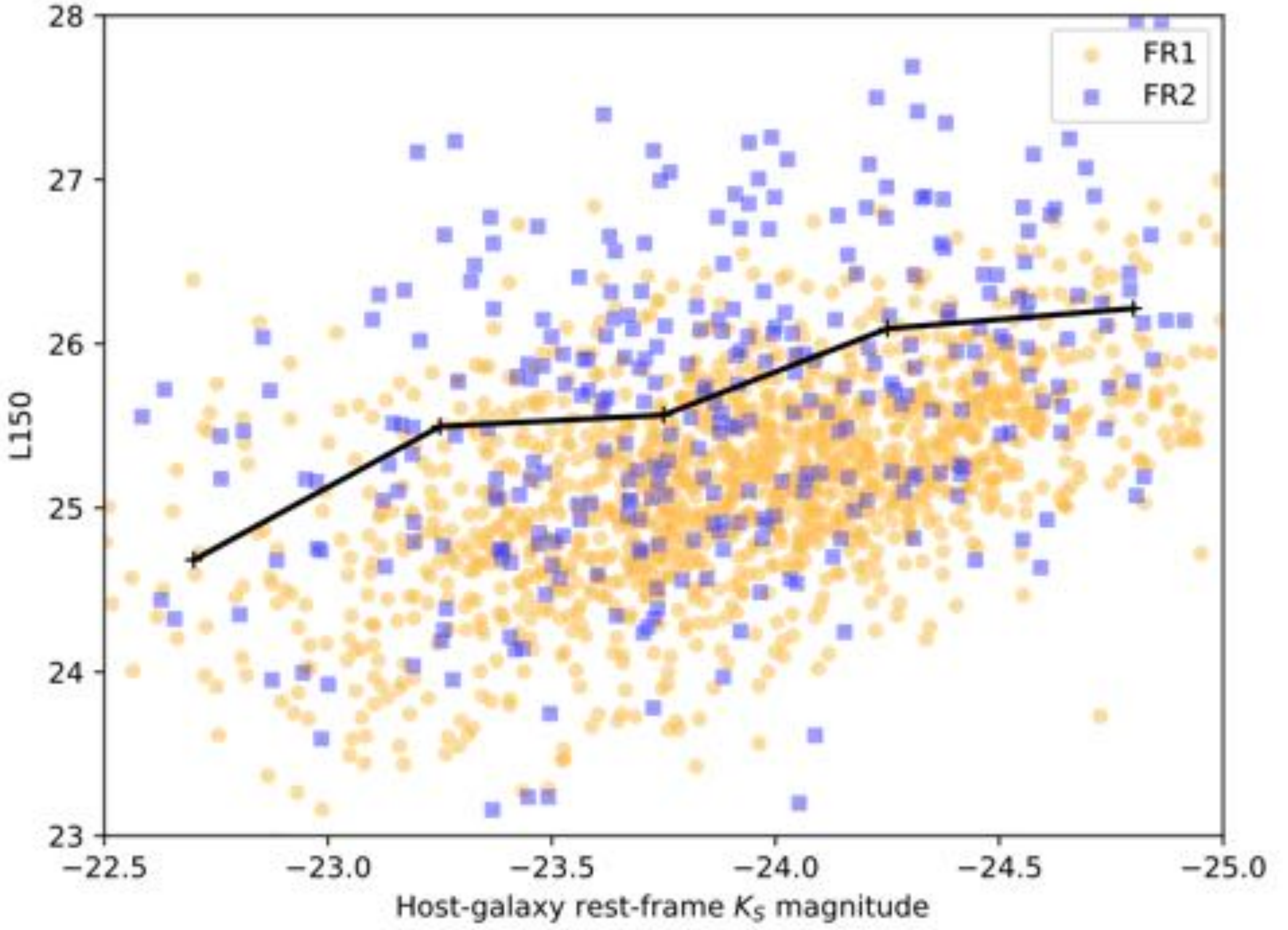
Fanaroff and Riley 1974



Ledlow and Owen 1996

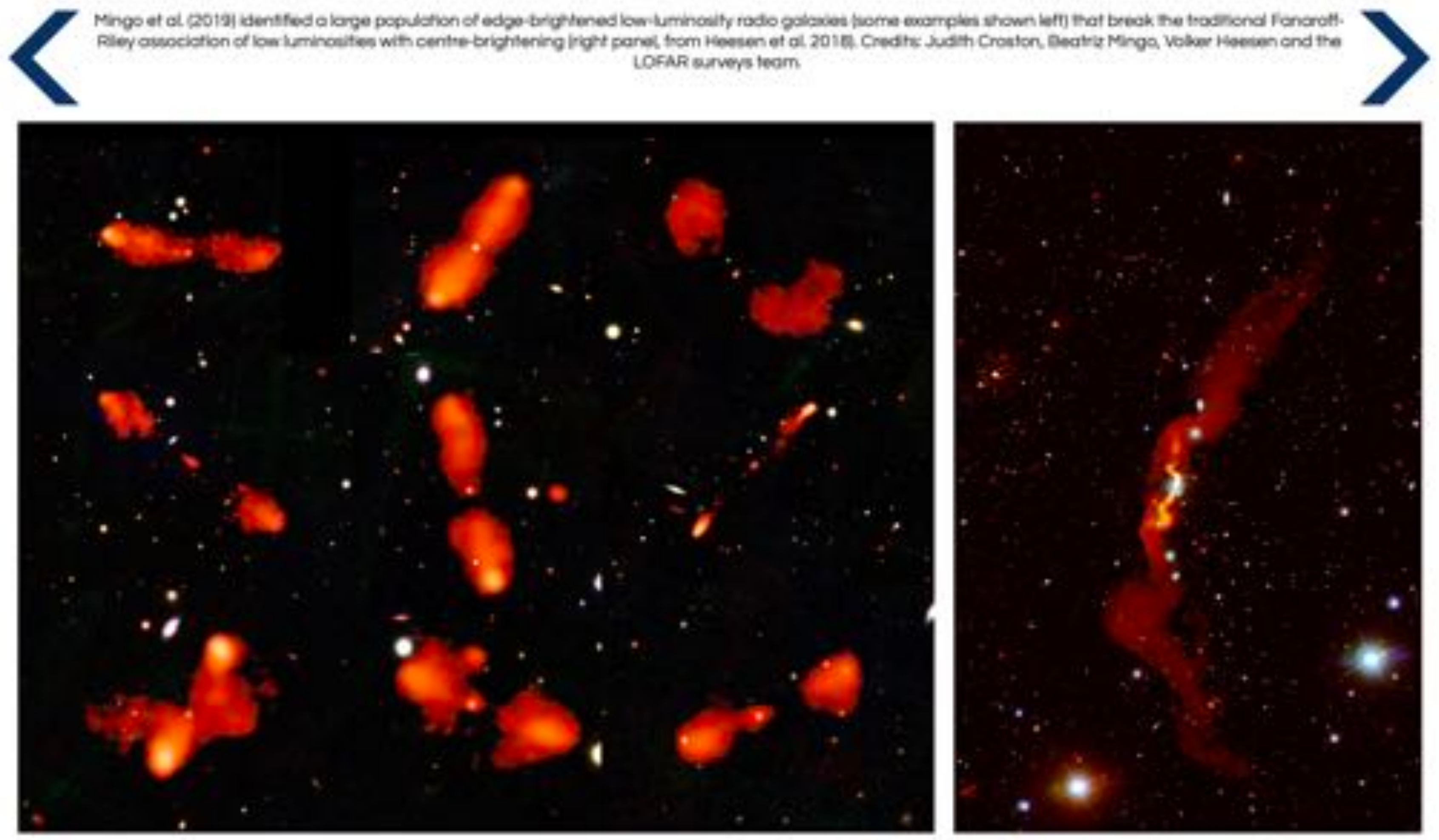


Mingo et al. 2019

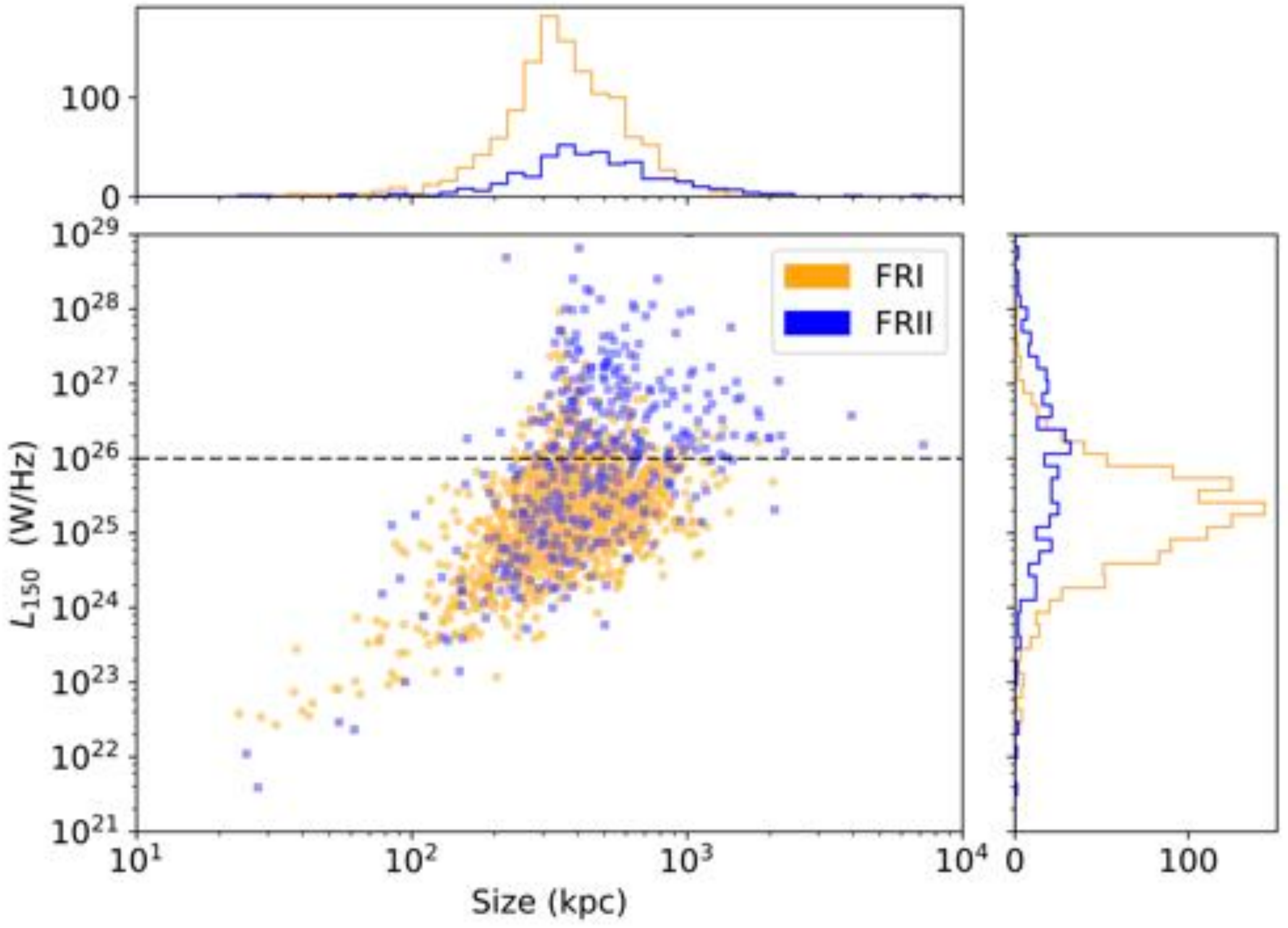


Observational Outlook: Present View

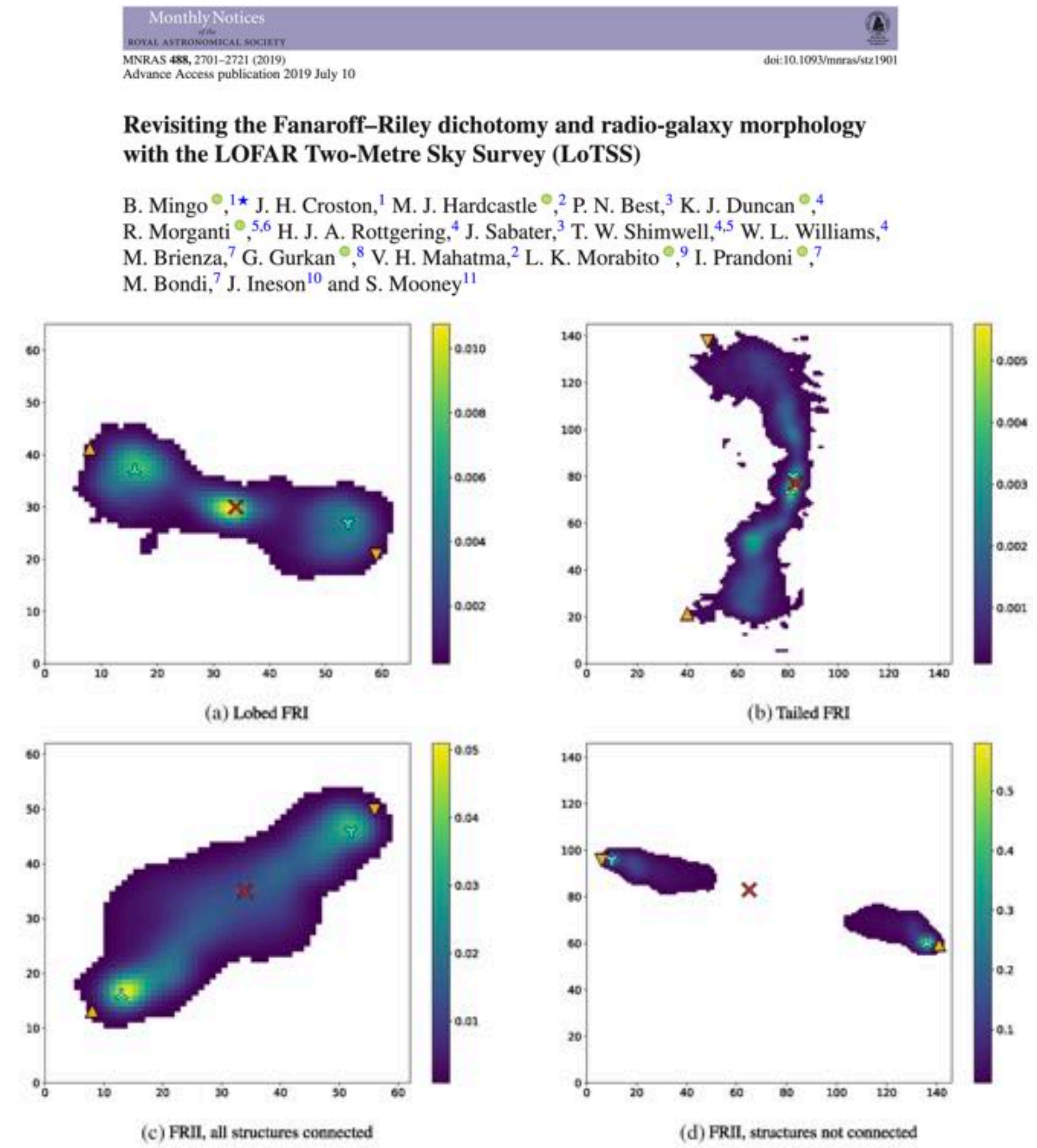
Low-Powered FR-II



Overlap of FR-I/II



Subclasses of FR-I/II



Monthly Notices of the Royal Astronomical Society

MNRAS 488, 2701–2721 (2019)
Advance Access publication 2019 July 10

doi:10.1093/mnras/stz1901

Revisiting the Fanaroff–Riley dichotomy and radio-galaxy morphology with the LOFAR Two-Metre Sky Survey (LoTSS)

B. Mingo,[1★] J. H. Croston,[1] M. J. Hardcastle,[2] P. N. Best,[3] K. J. Duncan,[4] R. Morganti,[5,6] H. J. A. Rottgering,[4] J. Sabater,[3] T. W. Shimwell,[4,5] W. L. Williams,[4] M. Brienza,[7] G. Gurkan,[8] V. H. Mahatma,[2] L. K. Morabito,[9] I. Prandoni,[7] M. Bondi,[7] J. Ineson[10] and S. Mooney[11]

(a) Lobed FRI

(b) Tailed FRI

(c) FRII, all structures connected

(d) FRII, structures not connected

FR-I

FR-II

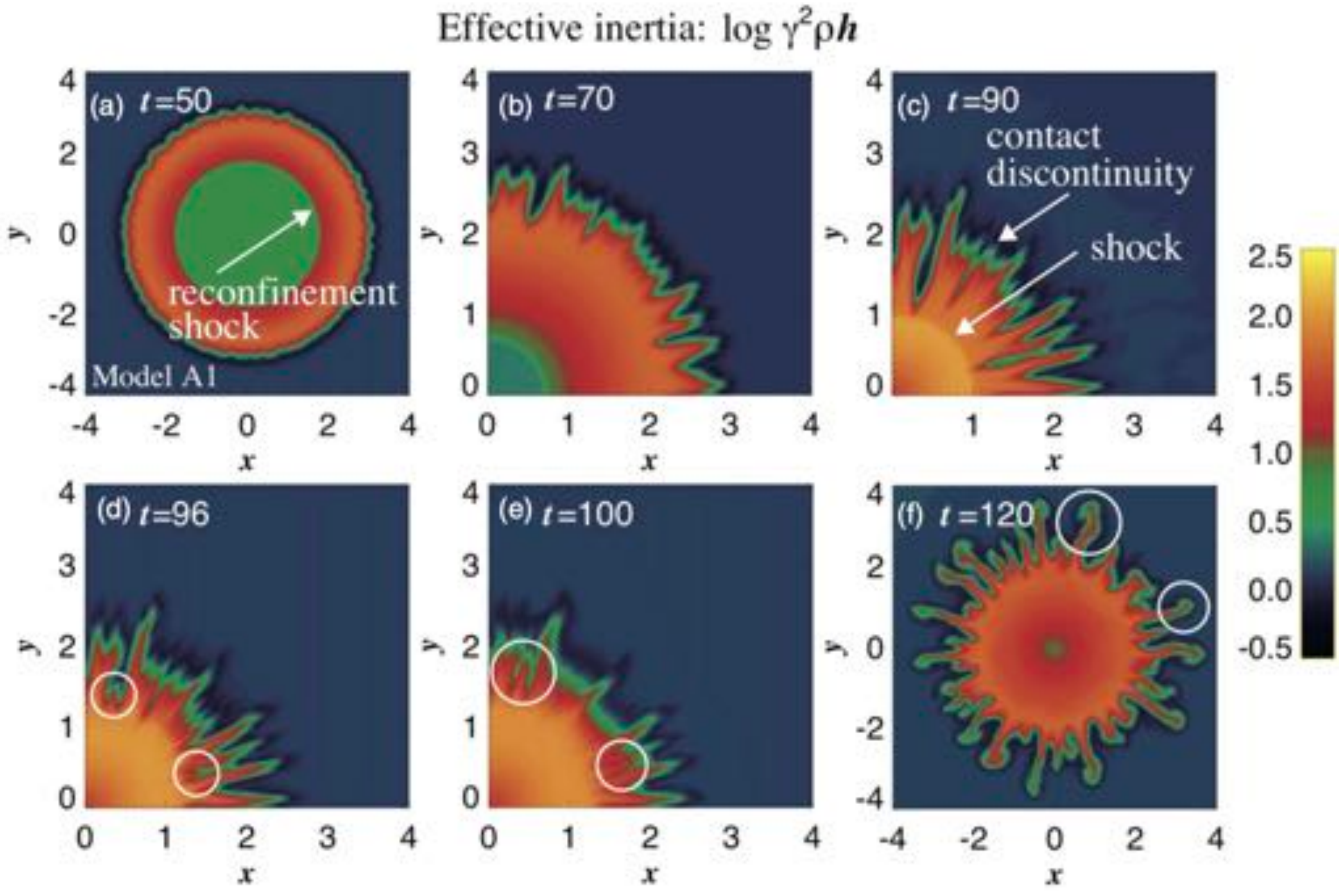
Mingo et al. 2019

Theoretical Outlook: Present View

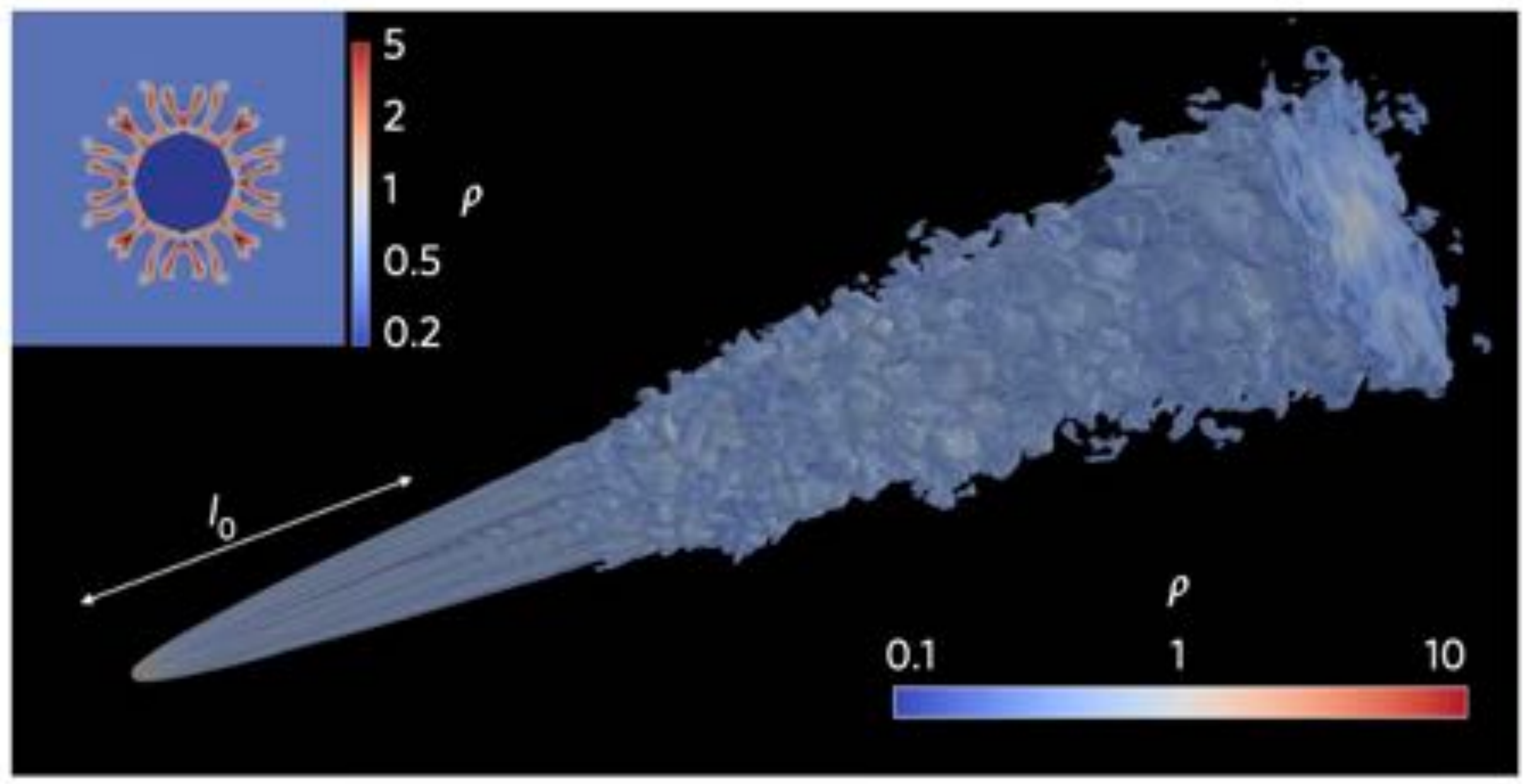
RTI

CFI

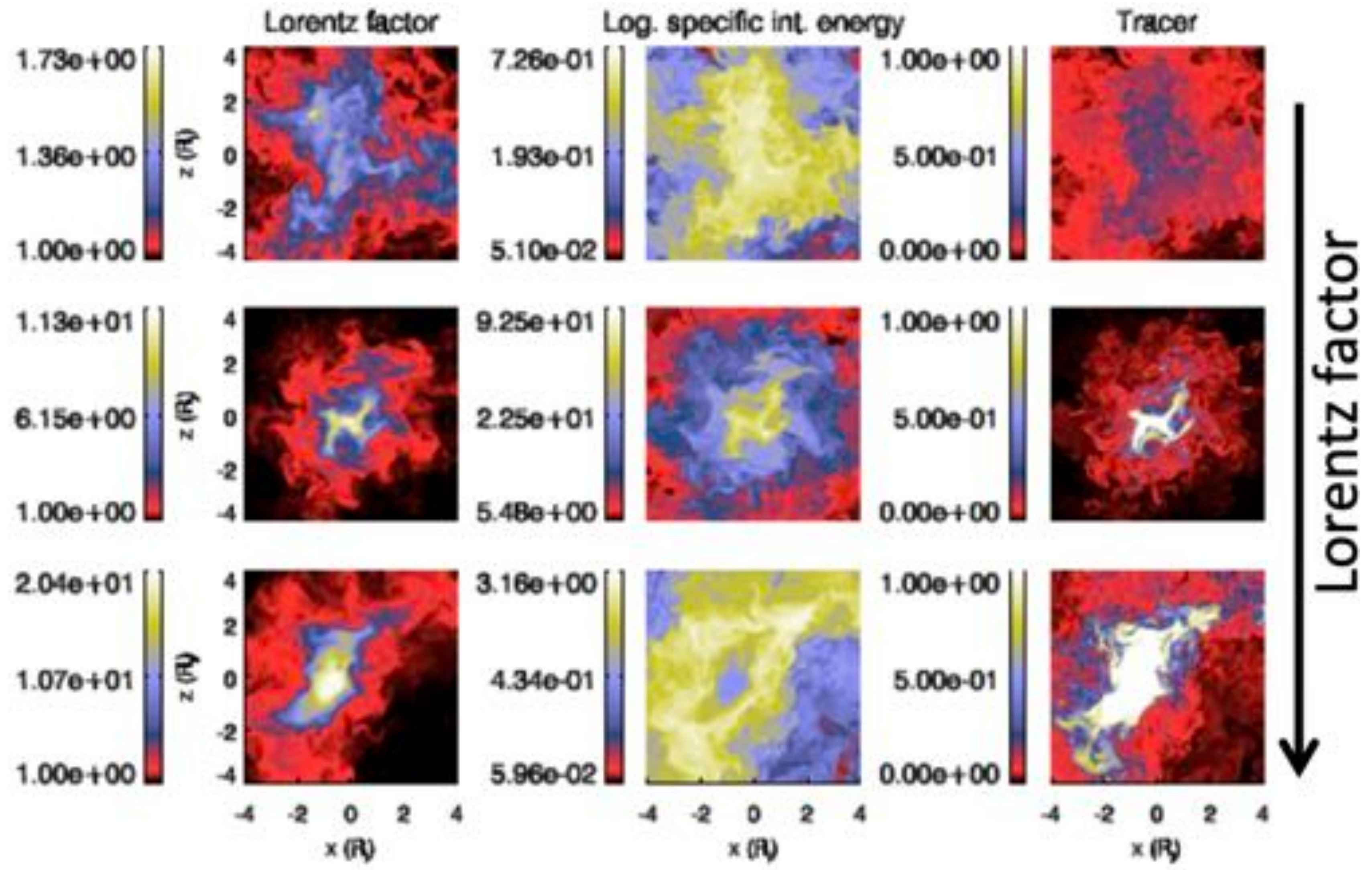
KHI



Matsumoto+ 2017

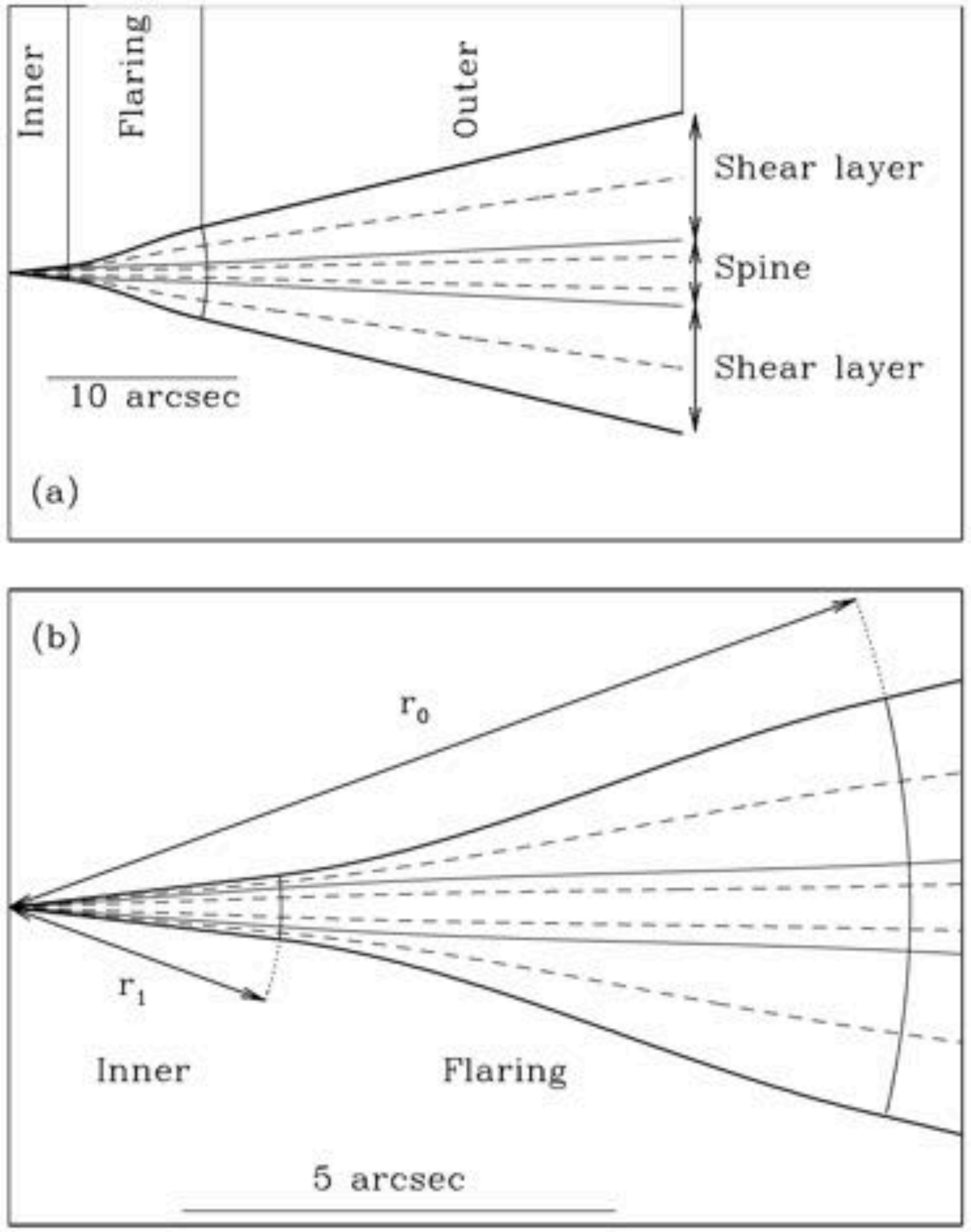


Gourgouliatos, Komissarov 2018

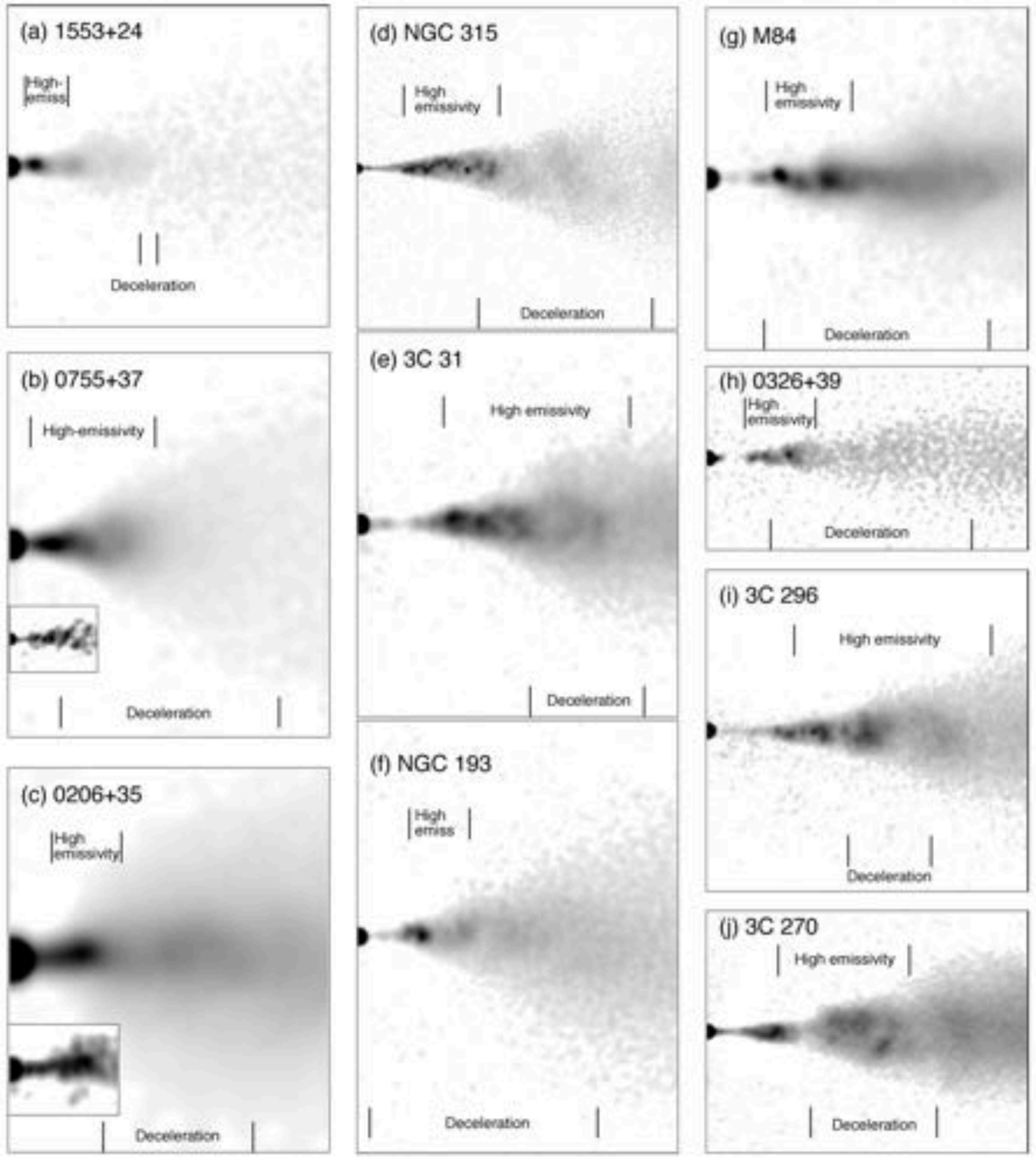


Perucho+ 2010

Observation vs Theory



Laing and Bridle 2002



Laing and Bridle 2014, many more

Simulation Setup

King Profile

$$P_{ext} = \frac{k_B T_{ext}}{\mu X} n_{ext} = \frac{k_B T_{ext}}{\mu X} n_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta_{atm}/2};$$

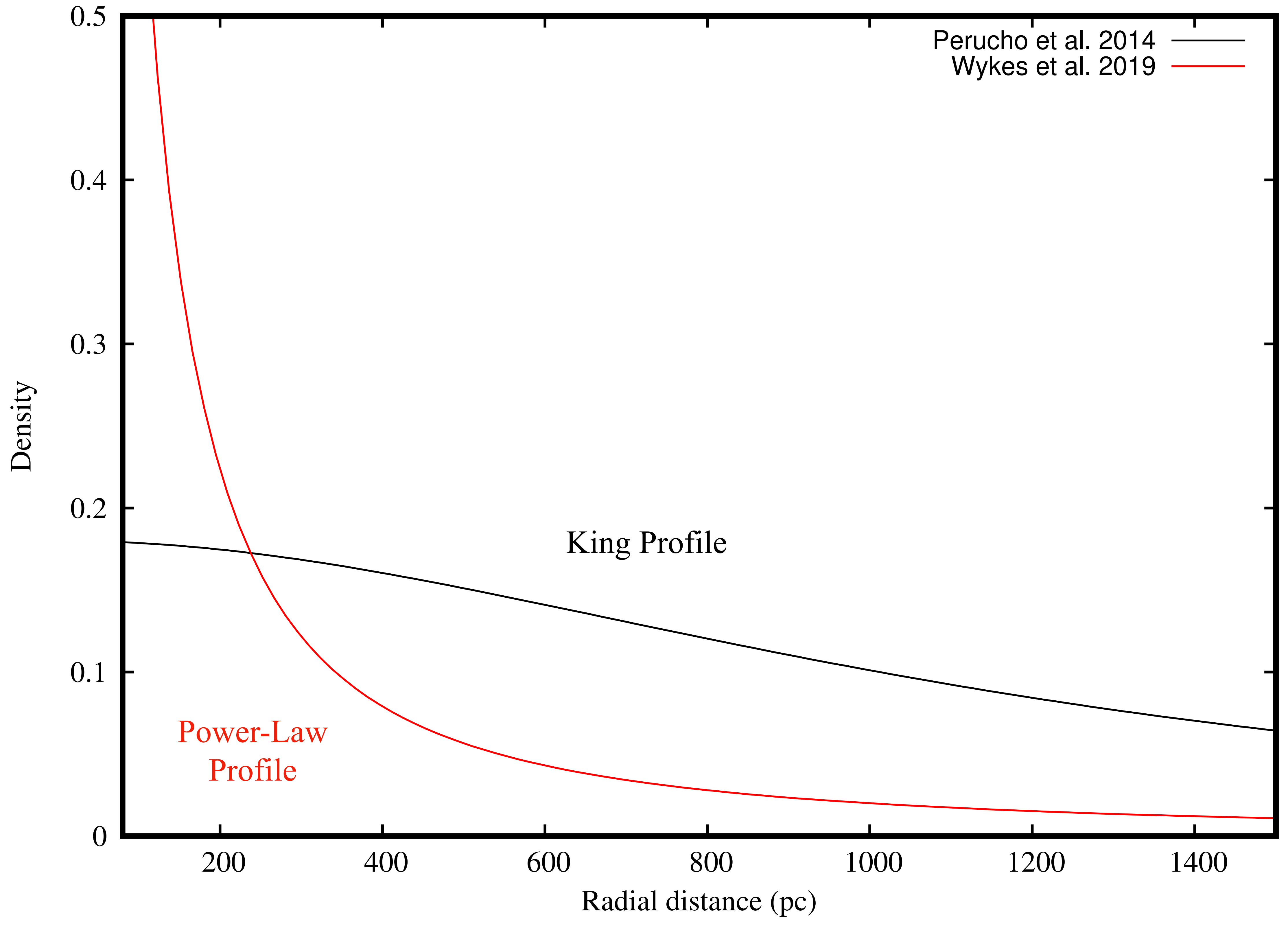
$$\mu = 0.5,\ X = 1,\ n_0 = 0.18 cm^{-3},\ r_c = 1.2\ kpc,\ \beta_{atm} = 0.73.$$

Perucho et al. 2014, MNRAS, 441, 1488

Power-Law Profile

$$P_{ext} = (5.7 \pm 0.9) \times 10^{-11} (r/r_0)^{-1.5 \pm 0.2}\ dyn\ cm^{-2};$$
$$r_0 = 1.0\ kpc\,.$$

Wykes et al. 2019, MNRAS, 485, 872

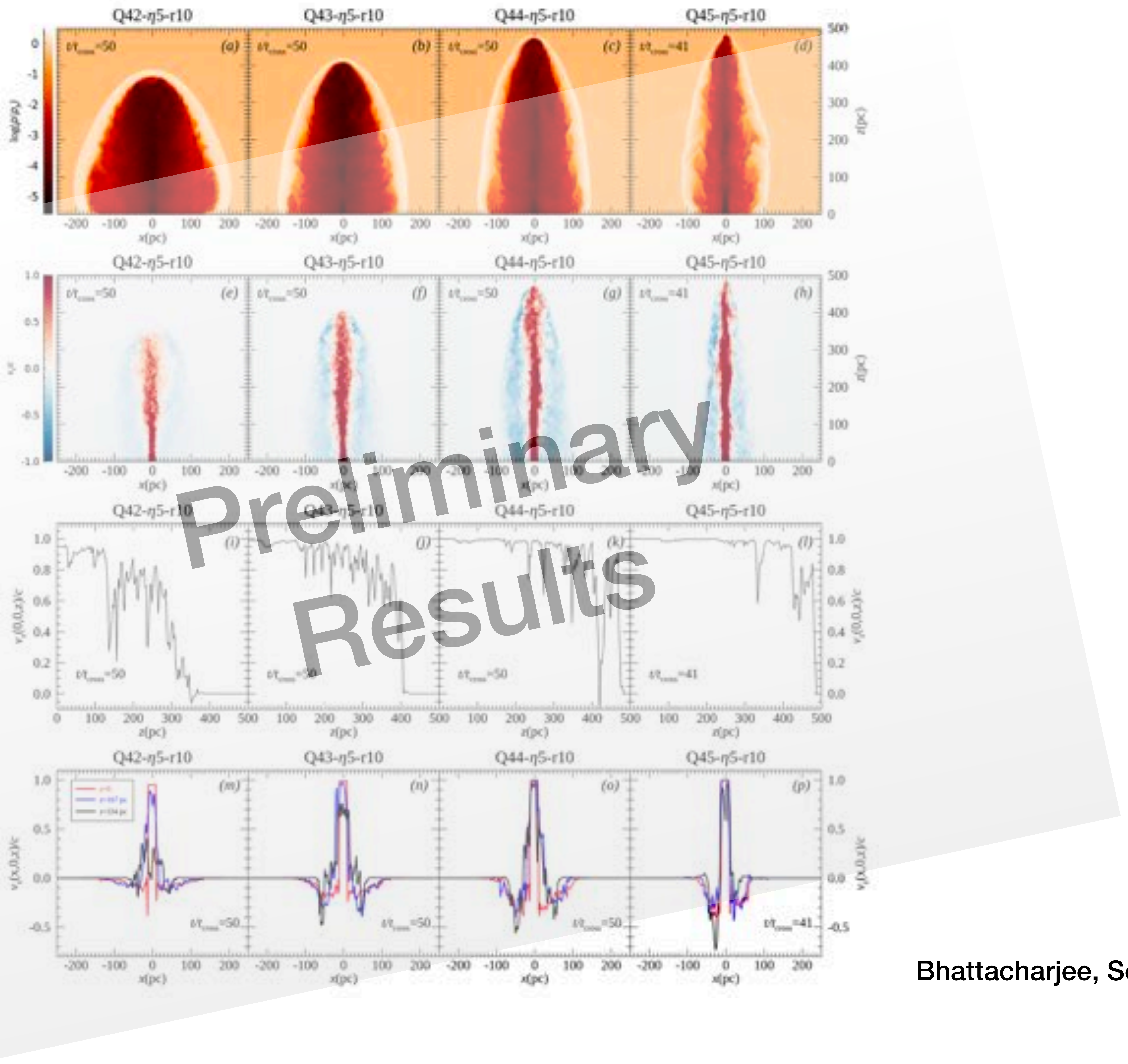


Stellar Mass-Loading Profile

$$\text{Stellar Mass-Loading Rate: } Q = Q_0 \left(\frac{r_b}{r}\right)^{\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha},\ \alpha = 2.0,\ \beta = 0.46,\ \gamma = 0,\ r_b = 265 pc\,.$$

Perucho et al. 2014, MNRAS, 441, 1488

Fiducial Set: Variation of Flow Structure with Jet Power



Bhattacharjee, Seo, Ryu, Kang, 2023a (in prep)

Simulating Radio Maps

$$D_{\rm L} = 1/(\Gamma[1-\beta\cos\theta_{\rm obs}])$$

Estimating B_{comov}

- $\frac{B_p^2}{8\pi} = \frac{p}{\beta}; \beta = 100.$
- $\frac{B_{turb}^2}{8\pi} \approx E_{K,turb}.$
- $\frac{B_{Bell}^2}{8\pi} \approx \frac{3v_s}{2c}(0.1\rho_1 v_s^2).$

$B_{comov} = \max(B_p, B_{turb}, B_{Bell})$

$$j'_{\nu'} = \frac{4}{9}\left(\frac{q^2}{mc^2}\right)^2 u'_B \nu'^{\frac{1}{2}} \nu_0'^{-\frac{3}{2}} \beta_e'^2 c \mathcal{N}'_e\left(\sqrt{\frac{\nu'}{\nu'_0}}\right),$$

$$\alpha'_{\nu'} = -\frac{2}{9}\frac{\mathcal{P}+2}{m\nu'^2}\left(\frac{q^2}{mc^2}\right)^2 u'_B \nu_0'^{-1} \beta_e'^2 c \mathcal{N}'_e\left(\sqrt{\frac{\nu'}{\nu'_0}}\right).$$

$$j_\nu = D_{\rm L}^2 j'_{\nu'}(\nu_{\rm obs}/D_{\rm L}),$$

$$\alpha_\nu = D_{\rm L}^{-1}\alpha'_{\nu'}(\nu_{\rm obs}/D_{\rm L}).$$

$$\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu.$$

$\nu_{obs} = 1.5$ GHz

Estimating $\mathcal{N}'_e$

$$\mathcal{N}'_e(\gamma') = \mathcal{N}'_0 \gamma'^{-\mathcal{P}}.$$

$$\mathcal{N}'_0 = \left(\frac{e'(\mathcal{P}-2)}{1-C_E'^{2-\mathcal{P}}}\right)^{\mathcal{P}-1}\left(\frac{1-C_E'^{1-\mathcal{P}}}{\frac{\rho'}{m_p}(\mathcal{P}-1)}\right)^{\mathcal{P}-2}$$

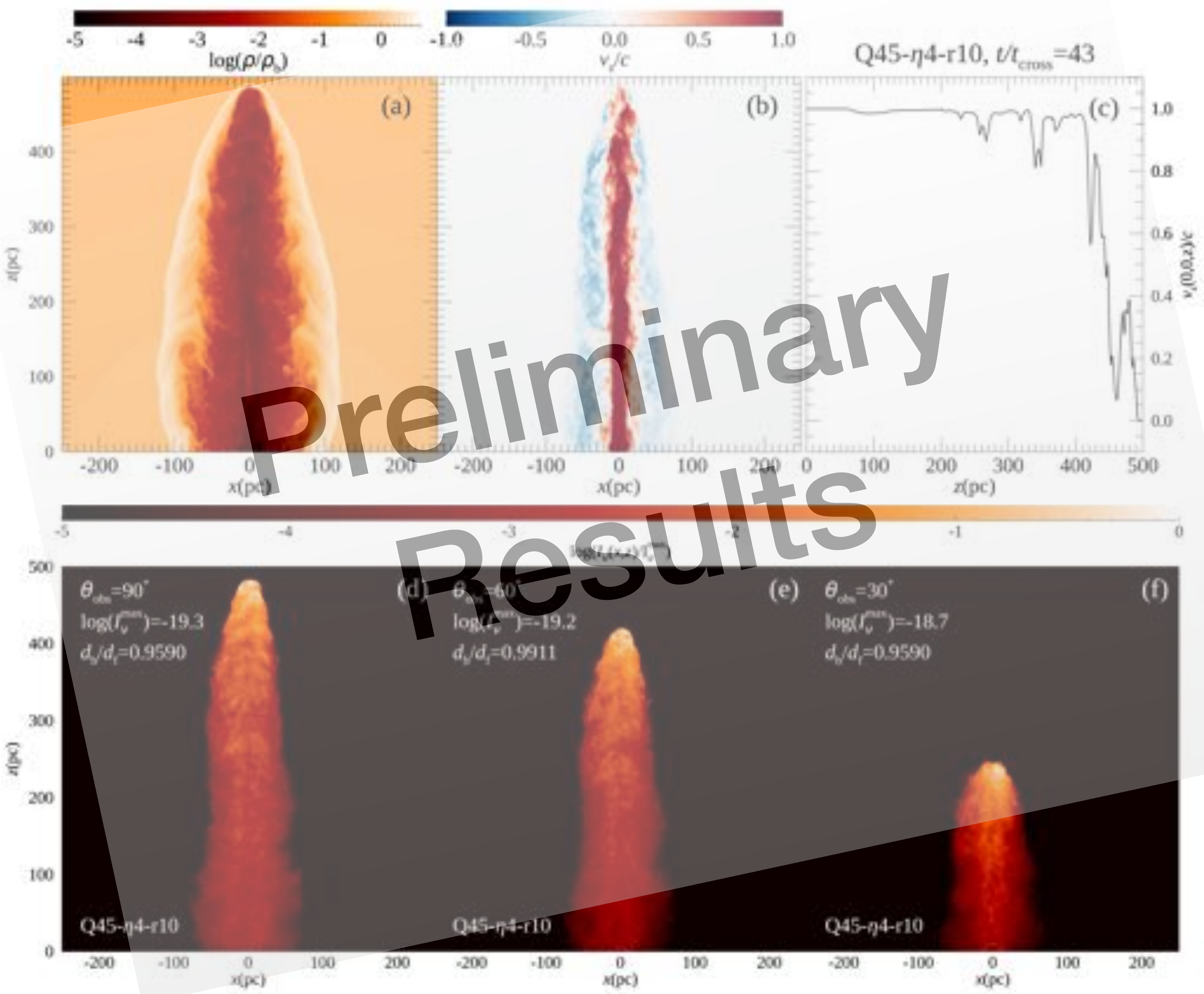
$p = 3.0,\ C'_E = 10^3.$

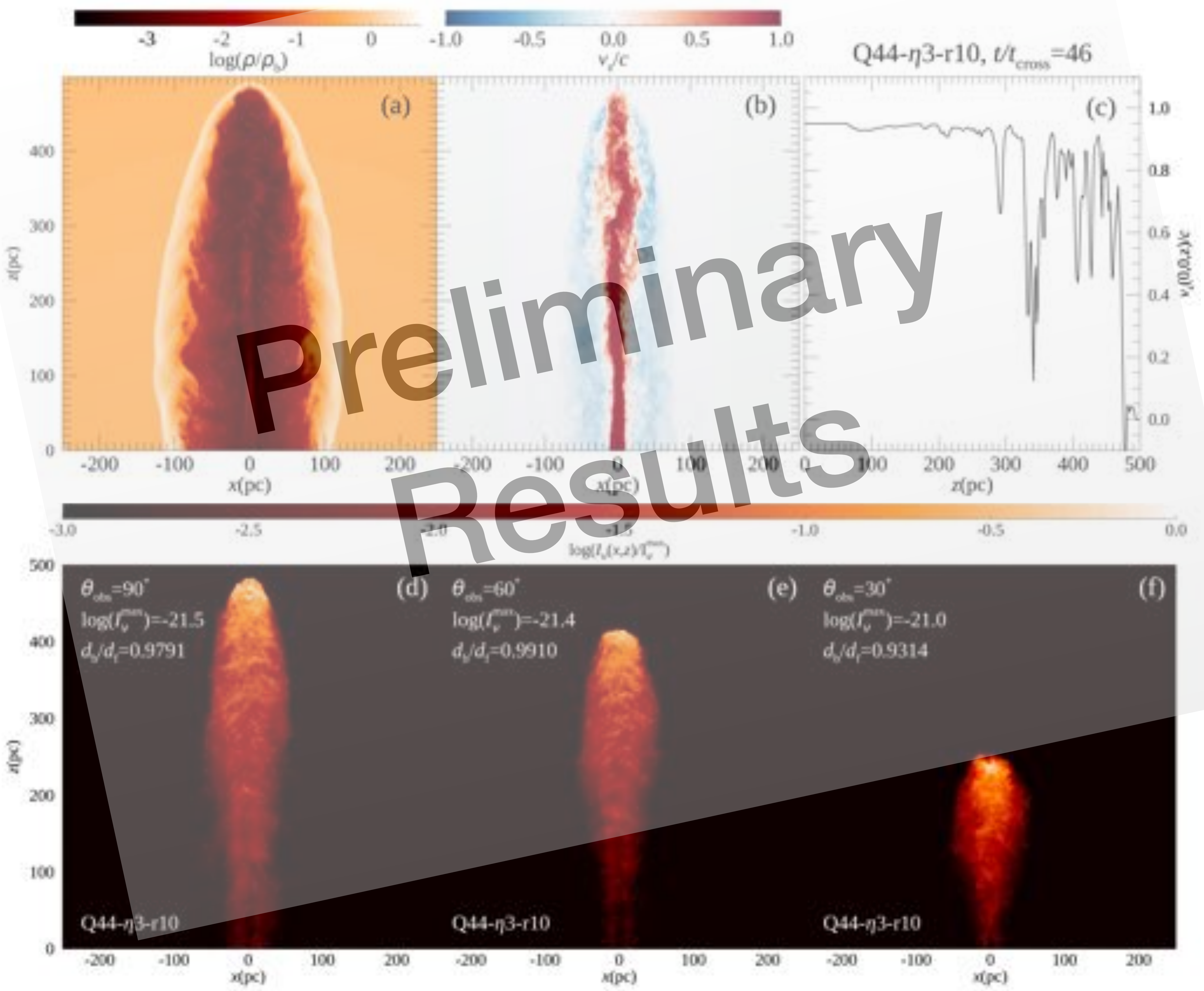
Bhattacharjee, Seo, Ryu, Kang, 2023a (in prep)

Fiducial Set: Variation of Radio Image with Jet Power

Bhattacharjee, Seo, Ryu, Kang, 2023a (in prep)

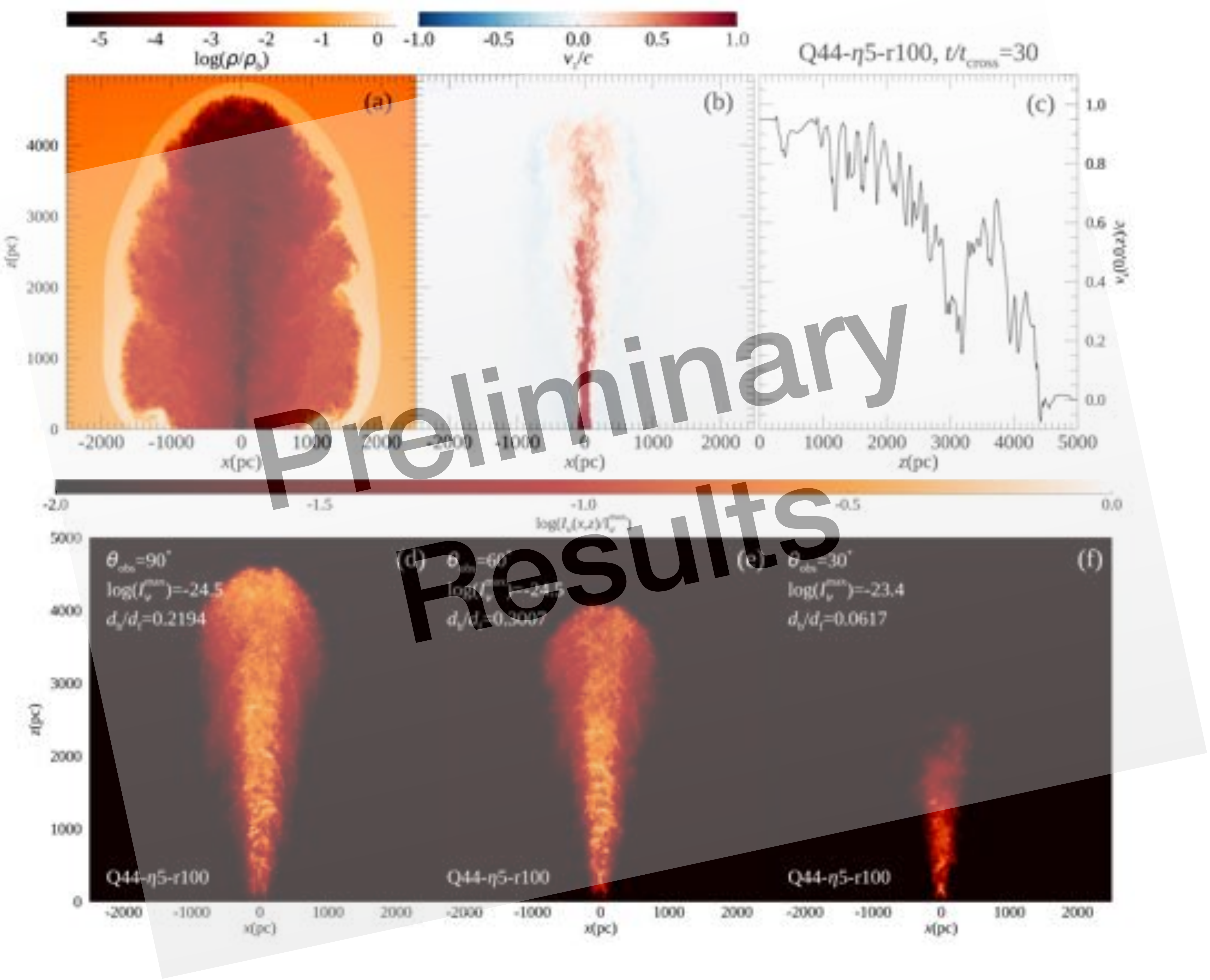
Effects of Jet Density

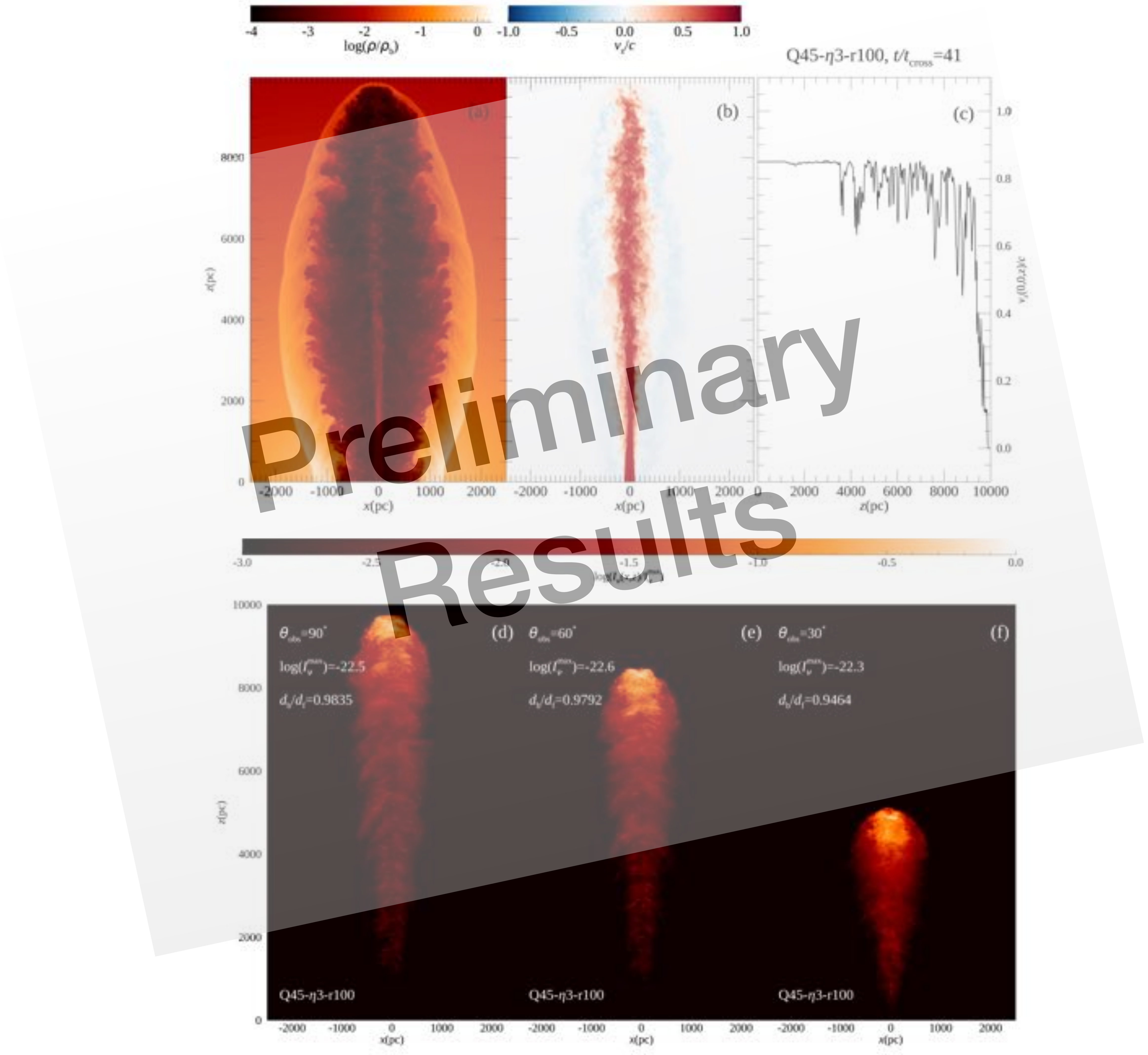




Bhattacharjee, Seo, Ryu, Kang, 2023a (in prep)

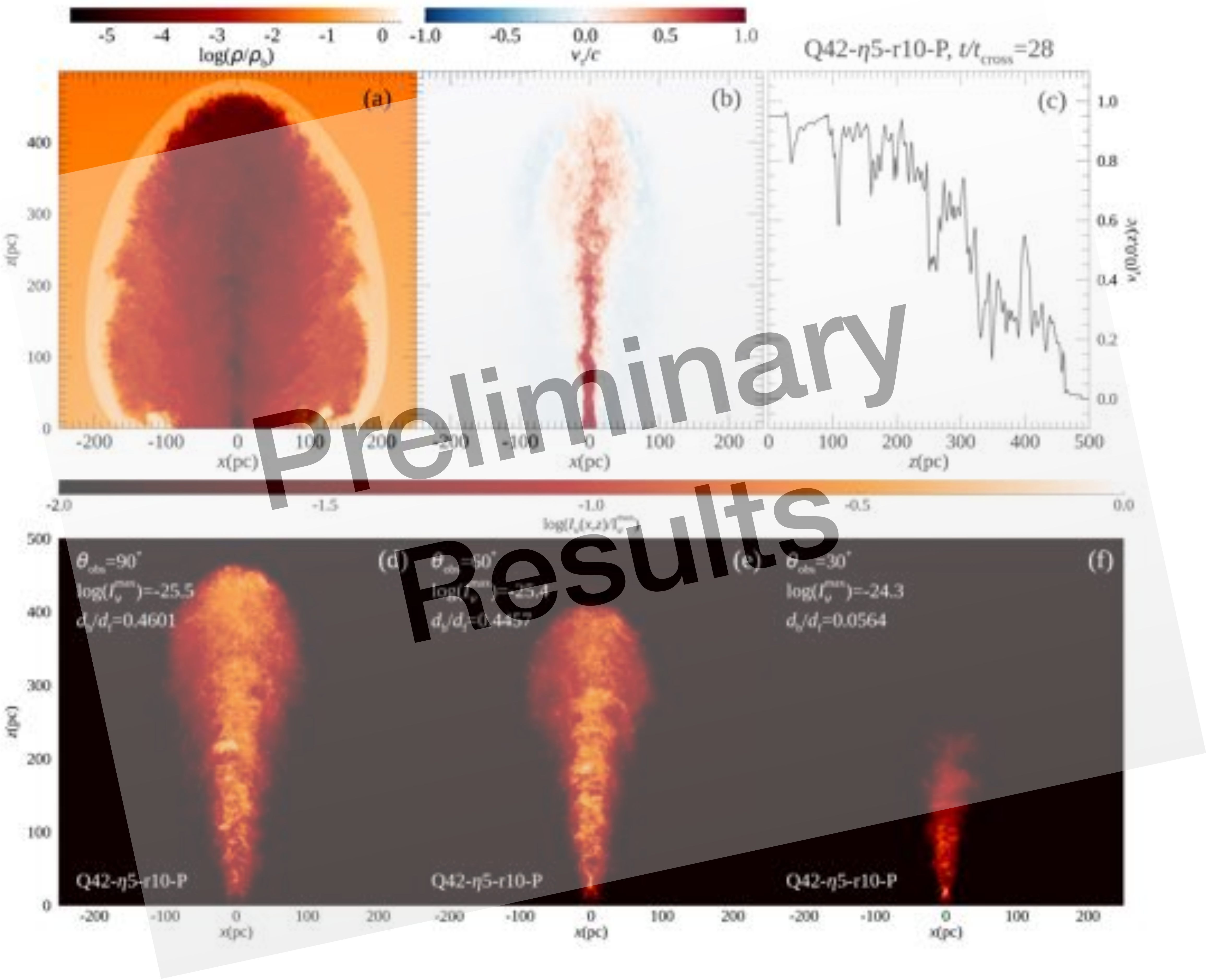
Effects of Scales of Propagation and Jet Radius

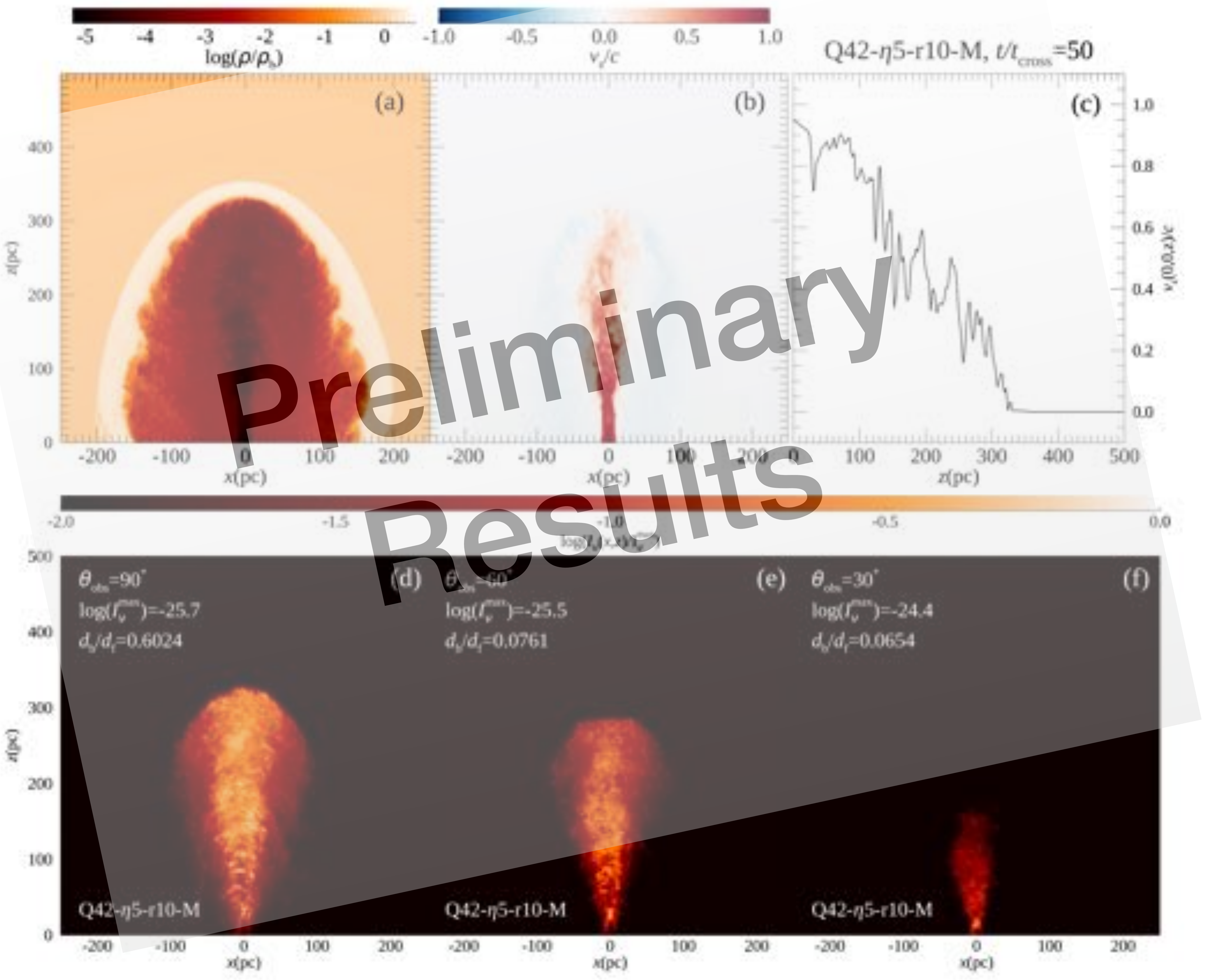




Bhattacharjee, Seo, Ryu, Kang, 2023a (in prep)

Effects of Ambient Media: Steeper Background vs Background with Mass-Loading





Bhattacharjee, Seo, Ryu, Kang, 2023a (in prep)

Effects of Ambient Media: King vs Power-Law

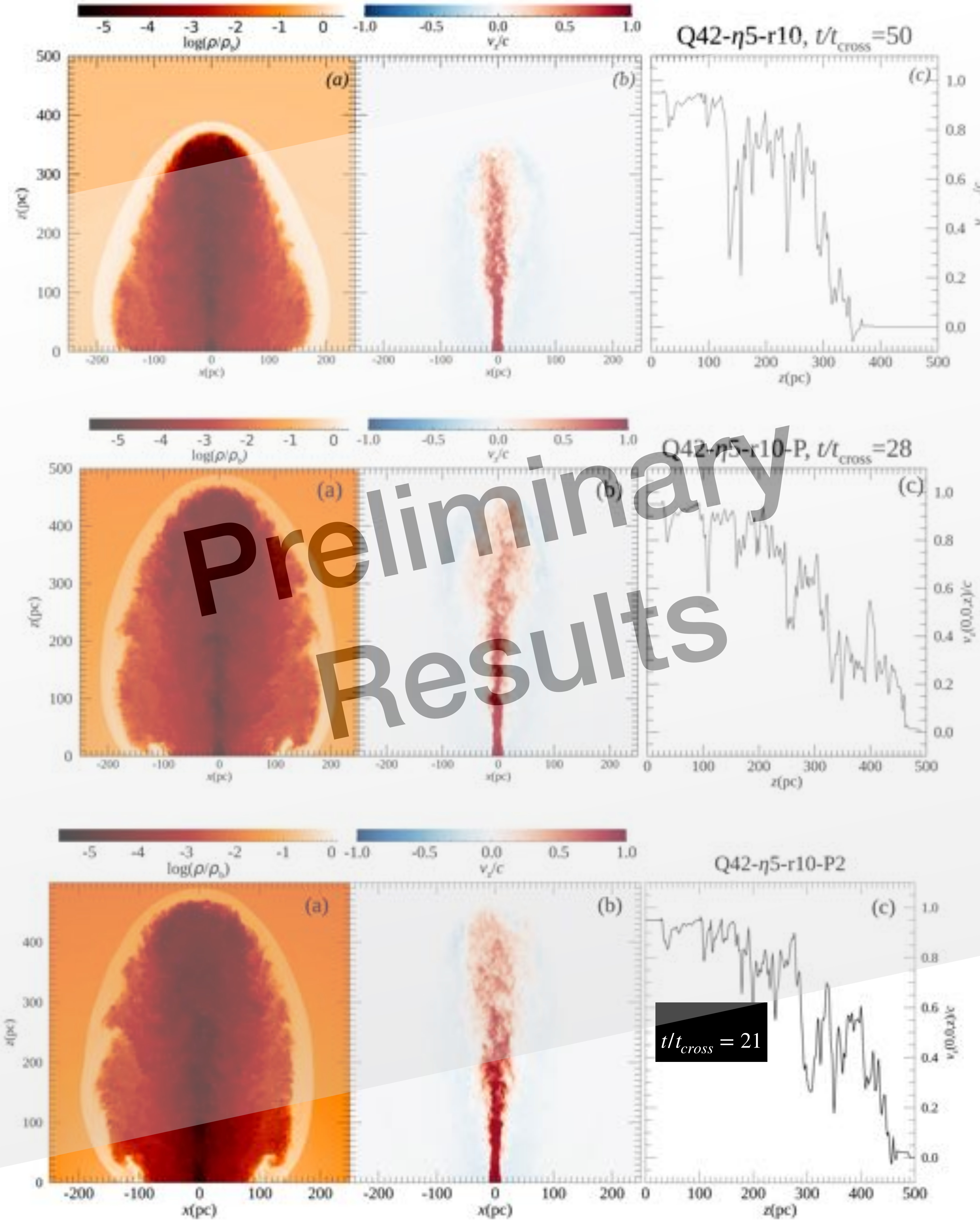
$Q42 - \eta 5 - r10$

$\rho_b \sim d^{-3/2}$

$Q42 - \eta 5 - r10 - P$

$\rho_b \sim d^{-2}$

$Q42 - \eta 5 - r10 - P - 2.0$



500 pc

500 pc

500 pc

Bhattacharjee, Seo, Ryu, Kang, 2023b (in prep)

Effects of Ambient Media: Mass-Loading

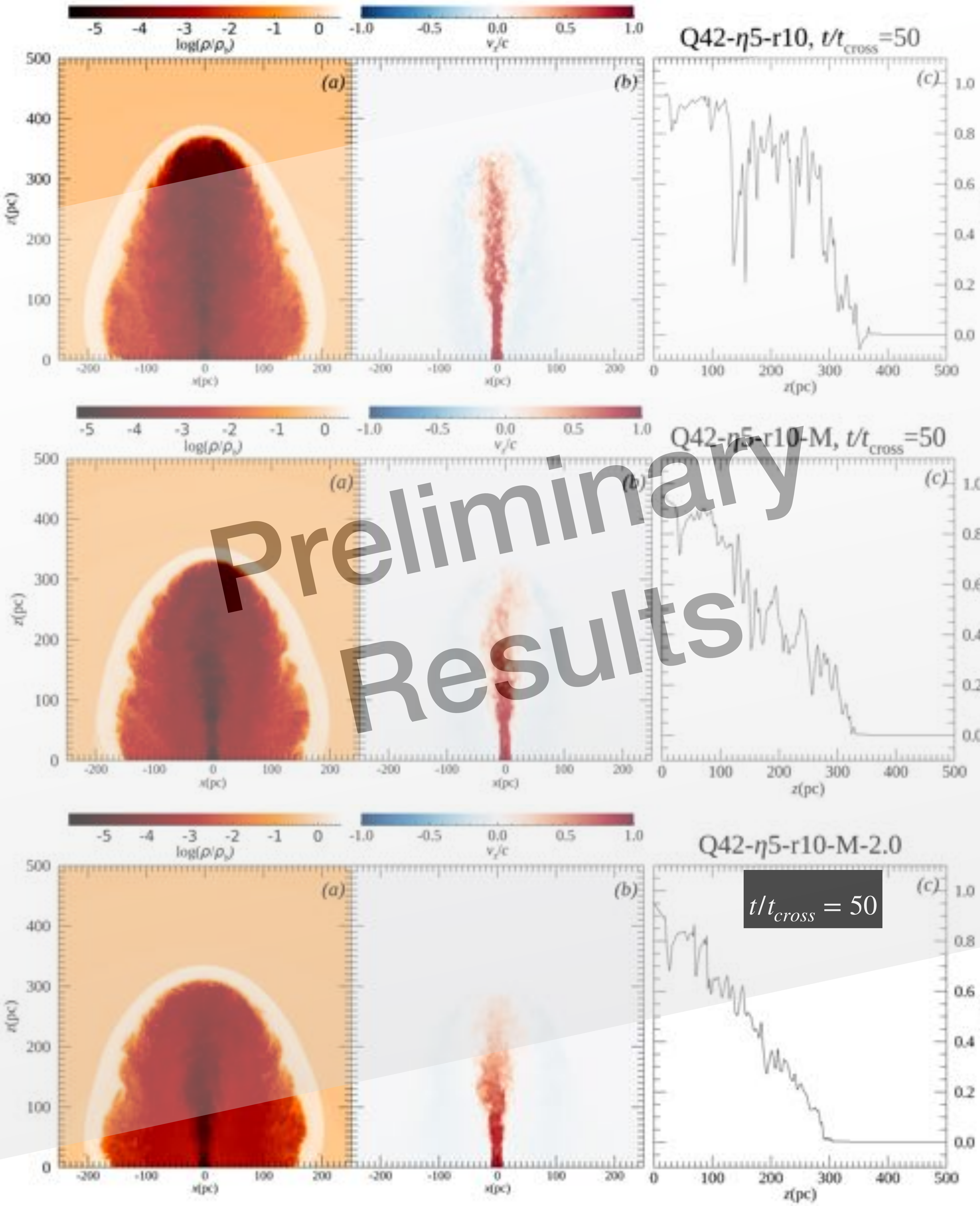
$Q42 - \eta5 - r10$

$Q_0^{'} = Q_0$

$Q42 - \eta5 - r10 - M$

$Q_0^{'} = 2Q_0$

$Q42 - \eta5 - r10 - M - 2.0$



Preliminary Results

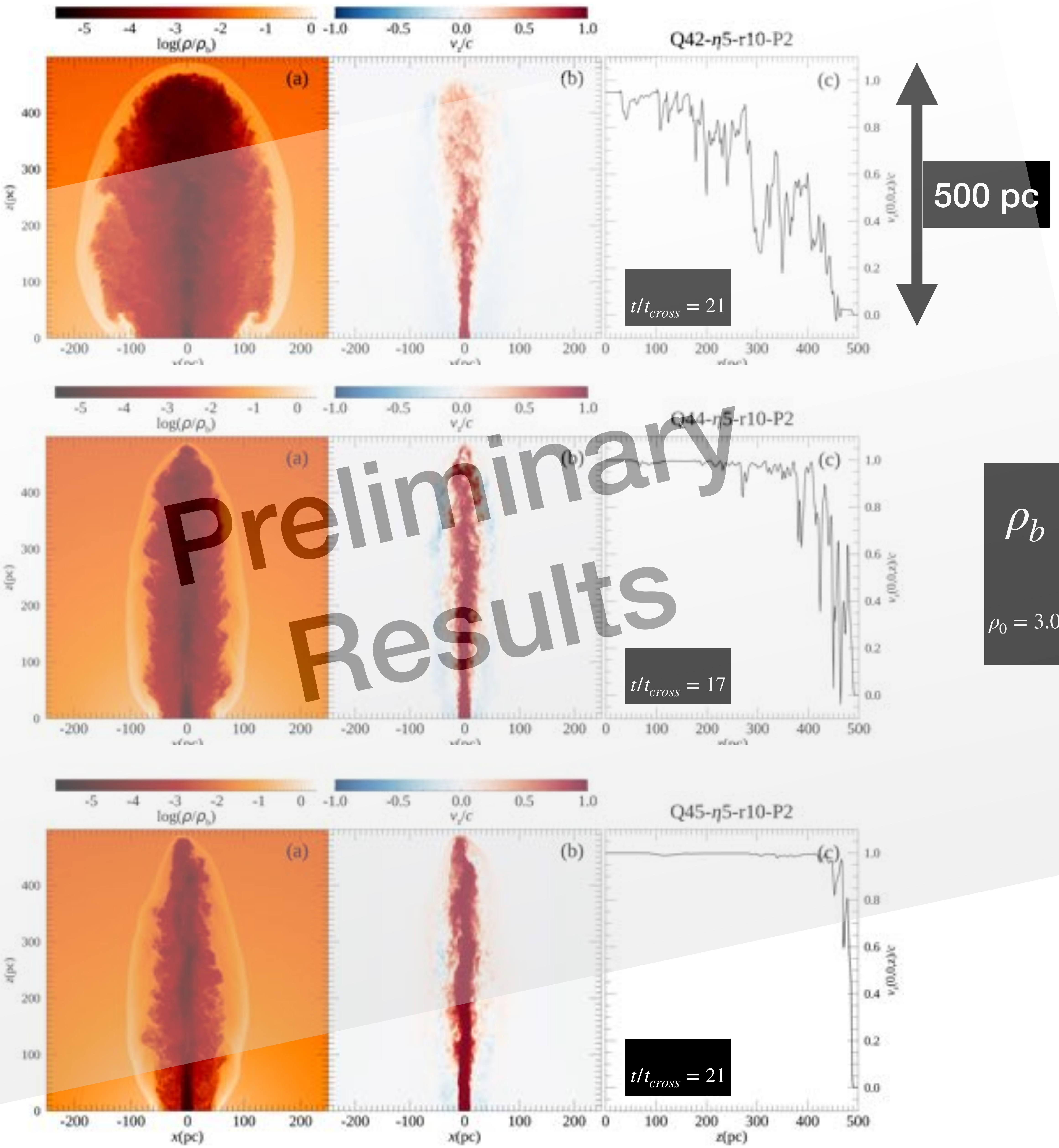
500 pc

500 pc

500 pc

Bhattacharjee, Seo, Ryu, Kang, 2023b (in prep)

Effects of Ambient Media: $Q_j \sim 10^{42} - 10^{45}$ erg/s

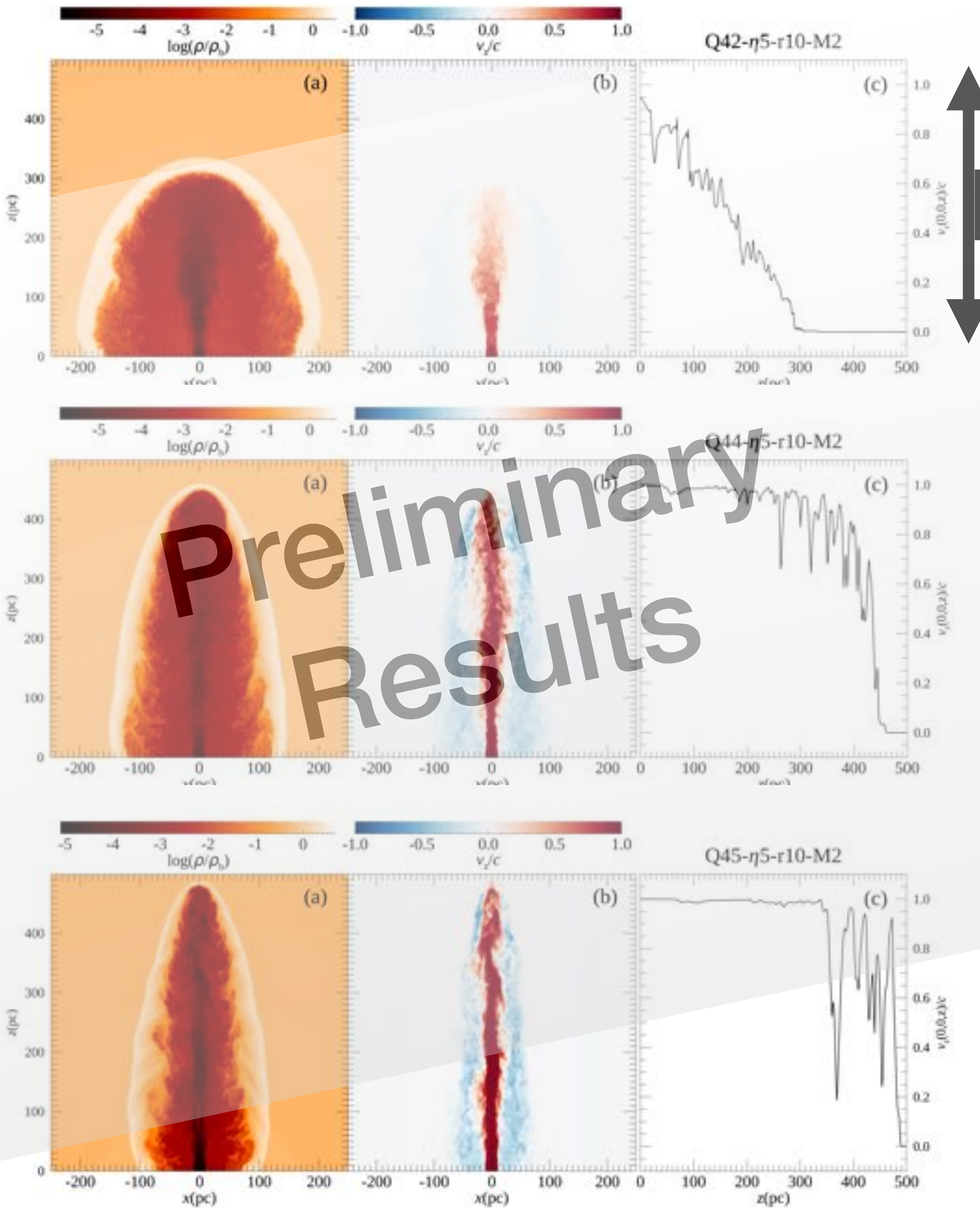


$\rho_b \sim d^{-2}$

$\rho_0 = 3.0 \times 10^{-25} gcm^{-3}$

Bhattacharjee, Seo, Ryu, Kang, 2023b (in prep)

Effects of Mass-Loading: $Q_j \sim 10^{42} - 10^{45}$ erg/s



500 pc

$Q_0 = 9.49 \times 10^{23}\ gyr^{-1} pc^{-3}$

$Q_0 \sim 19 \times Q_{Perucho}$

$Q_0' = 2Q_0$

Bhattacharjee, Seo, Ryu, Kang, 2023b (in prep)

Conclusions: P2

Jets around AGN

- The jets ejected from AGN requires different treatment at different stages of their lifetime.

- Expanded jets, which have reached ICM and have reached mildly relativistic speeds can be treated well within a purely hydrodynamic setup (Massaglia et el. 2016).

- Jets that transition from ultra-relativistic to mildly relativistic or non-relativistic speeds requires Relativistic Hydrodynamic simulations for correctly capturing their dynamics [Rossi et al. 2008; Perucho et al. 2014; Bhattacharjee et al. 2023 (in prep)].

- Launching of jets do not require strong magnetic fields and is most likely can have hydrodynamic origin.

- Magnetic fields can be important in the acceleration phase of jets, however, radiative acceleration can also be important and this treatment requires further comparative studies.

Thank You!

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