Simulating the impact of kpc scale jets on multiphase ISM in galaxies

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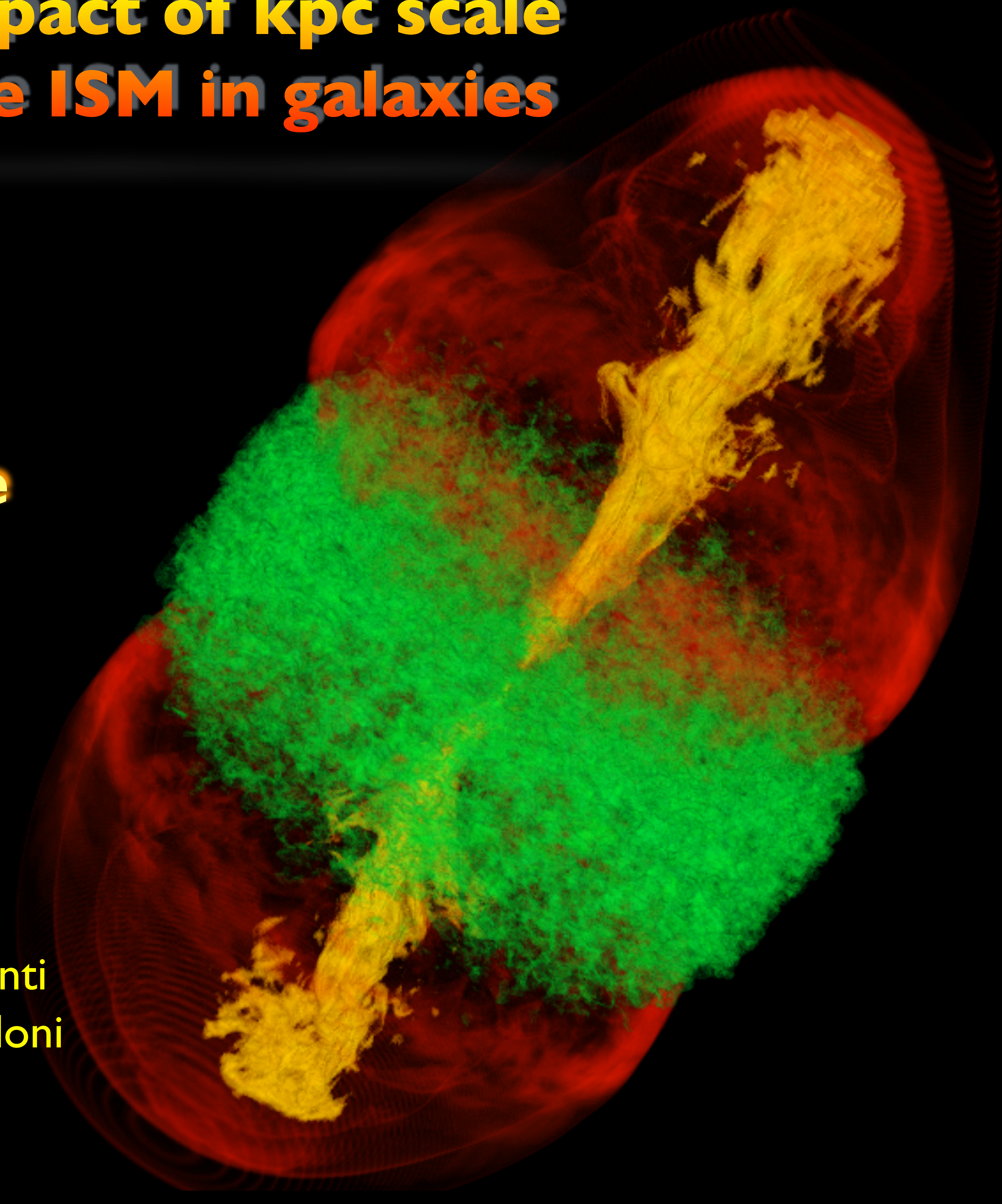
IUCAA, India.

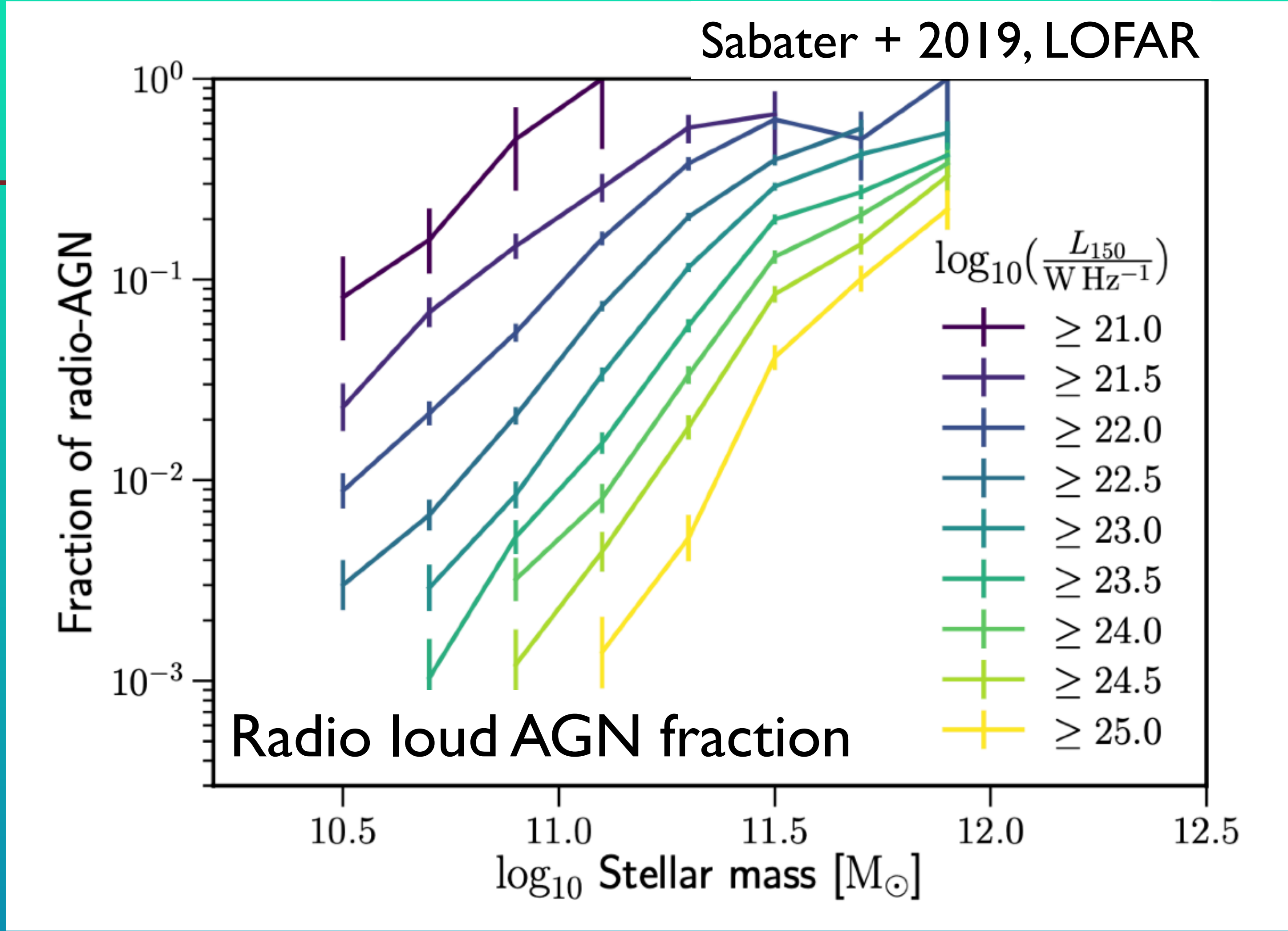


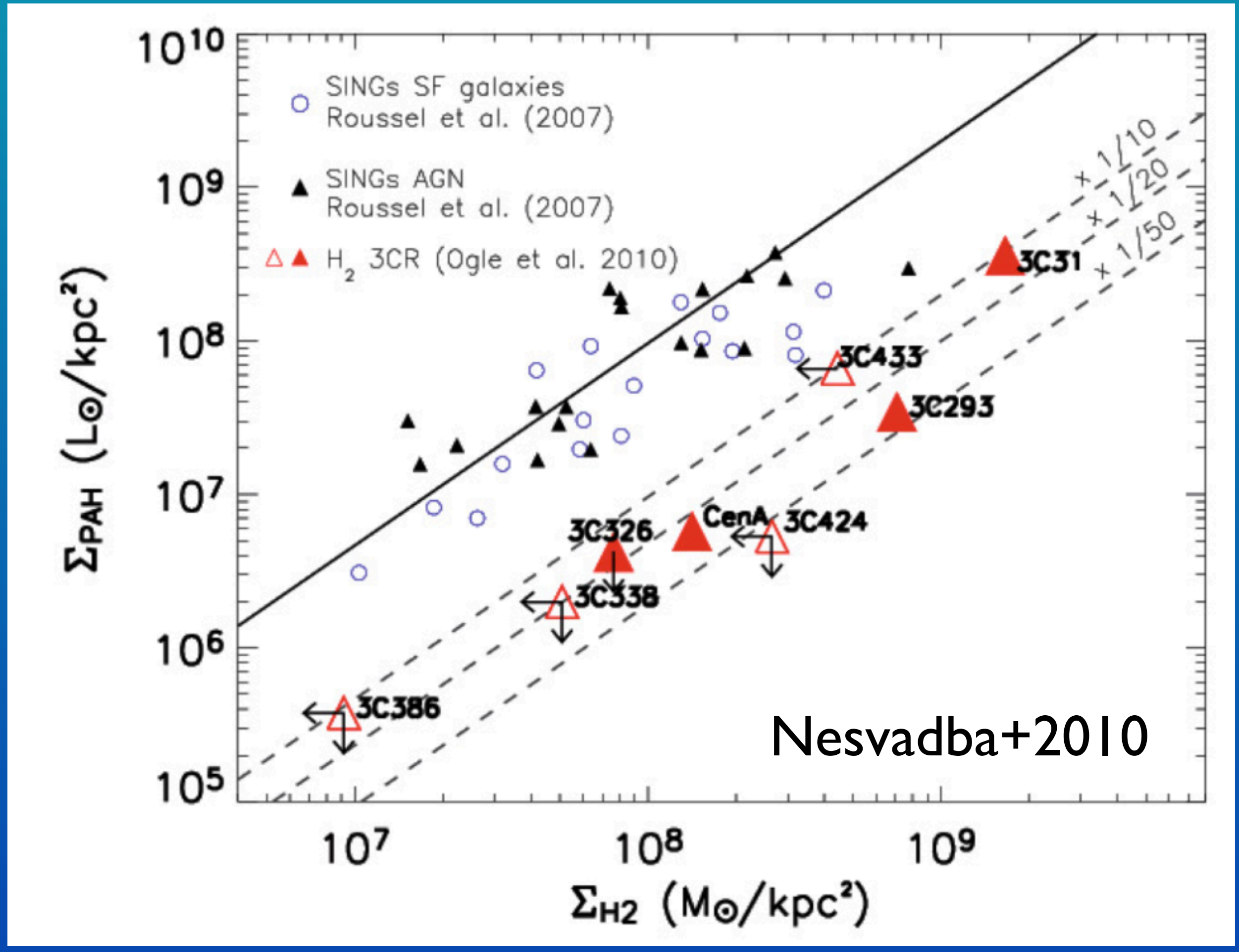
In Collaboration with

G. Bicknell (ANU), A. Wagner (U. Tsukuba), A. Mignone (U. Torino), G. Bodo (INAF), B. Vaidya (IITI), N. Nesvadba (OCA, France), R. Morganti (Astron), P. Fabbiano (CFA), I. Prandoni (IRA) and others

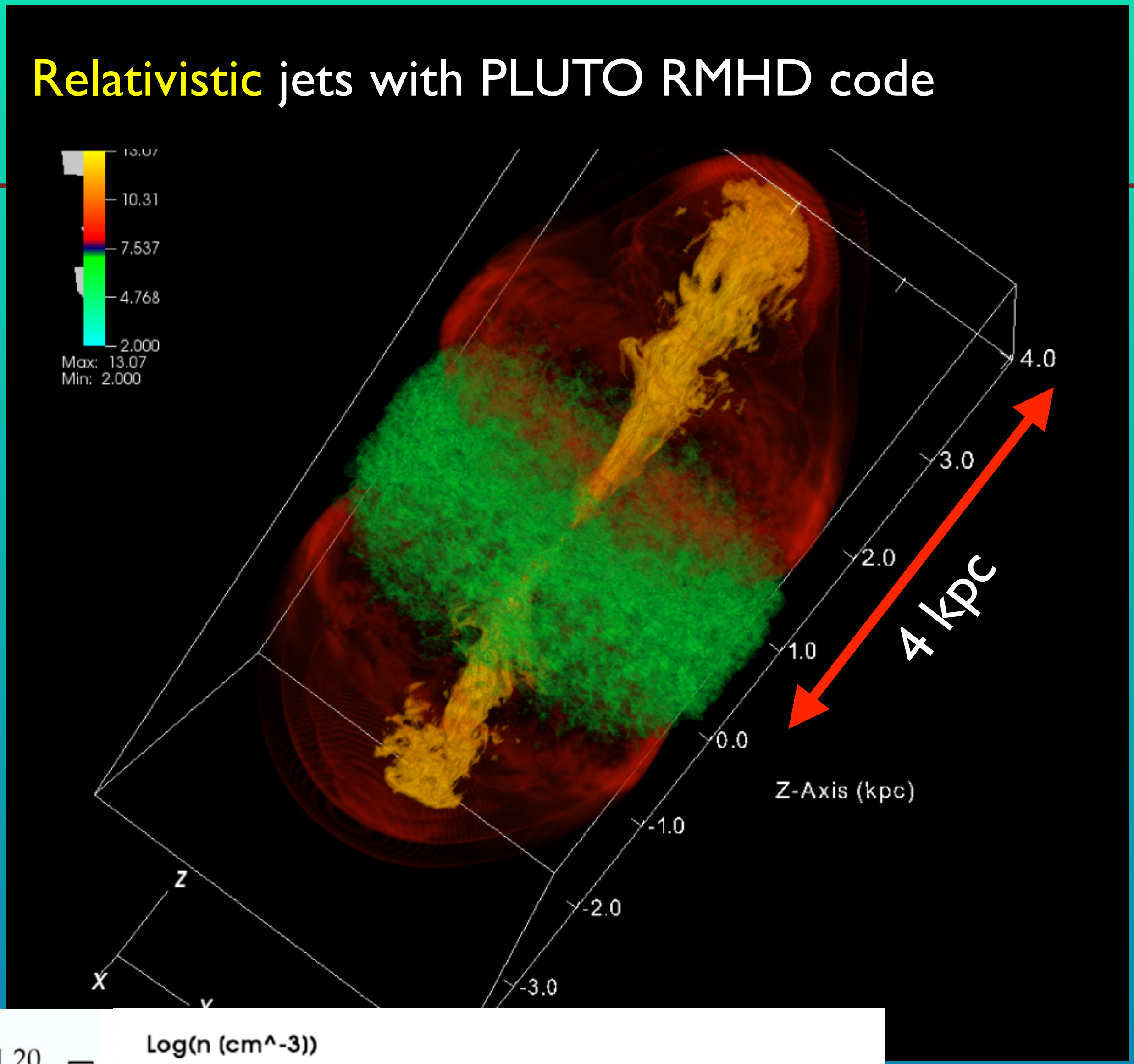
Some topics of interest

- Do radio jets affect the host or just the extra-galactic gas?
  - Young/trapped/slow jets interact with the host's ISM. Many examples of jet-ISM interaction.
  - RLAGN more frequent at low powers.
  - RLAGNs can be gas rich
- How is star-formation rate ***actually*** regulated in the host?
- Observational implications? Multi-phase observations from radio - high energies.





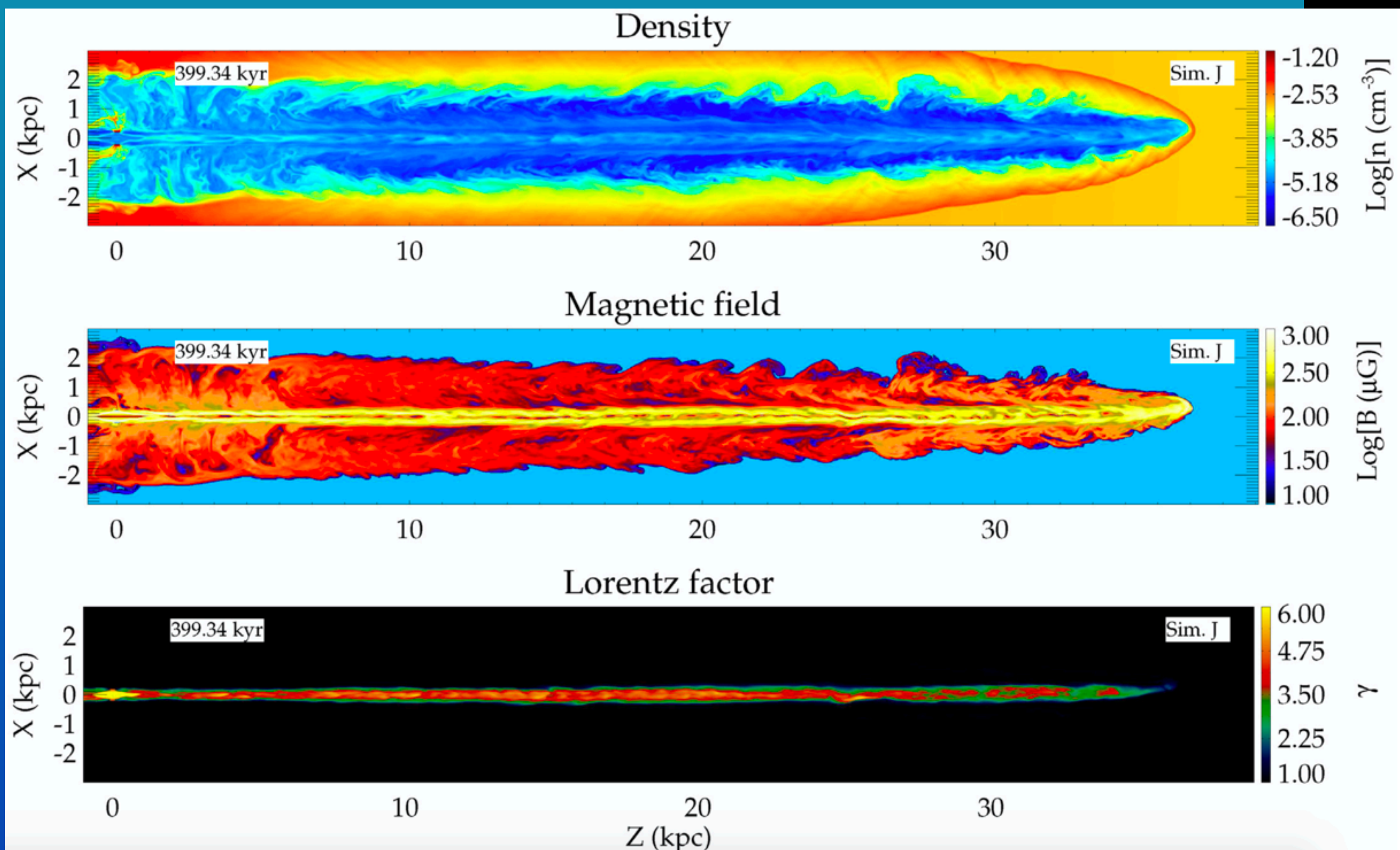
Some basic questions

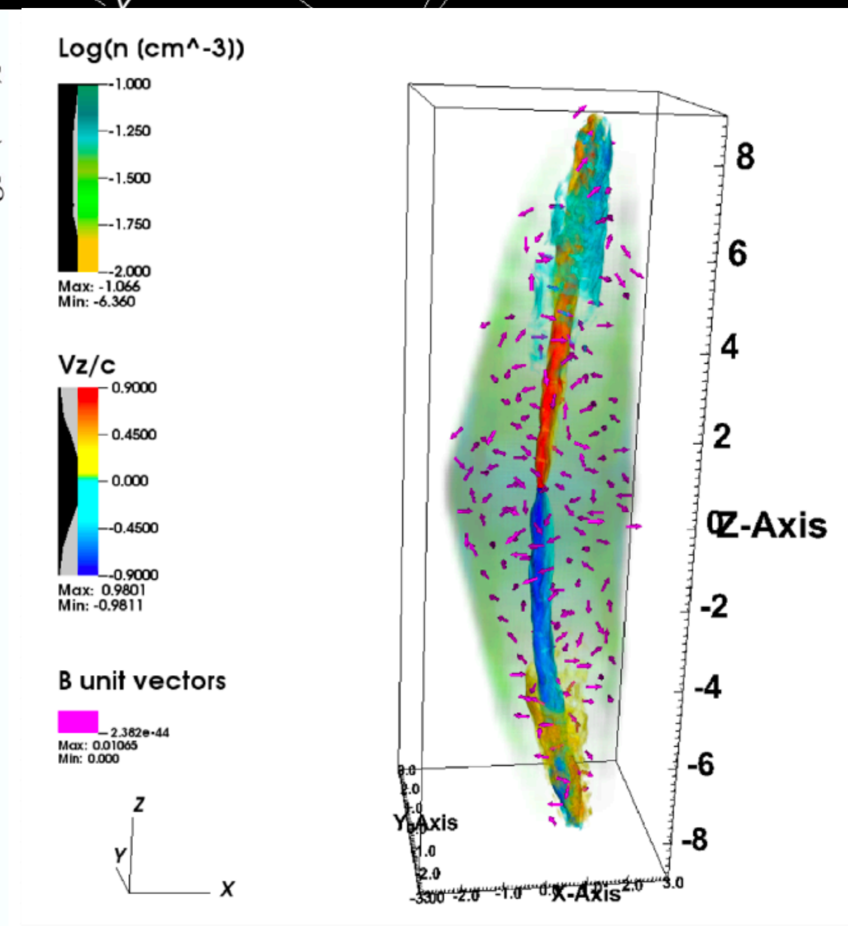


Simulations on two scales:

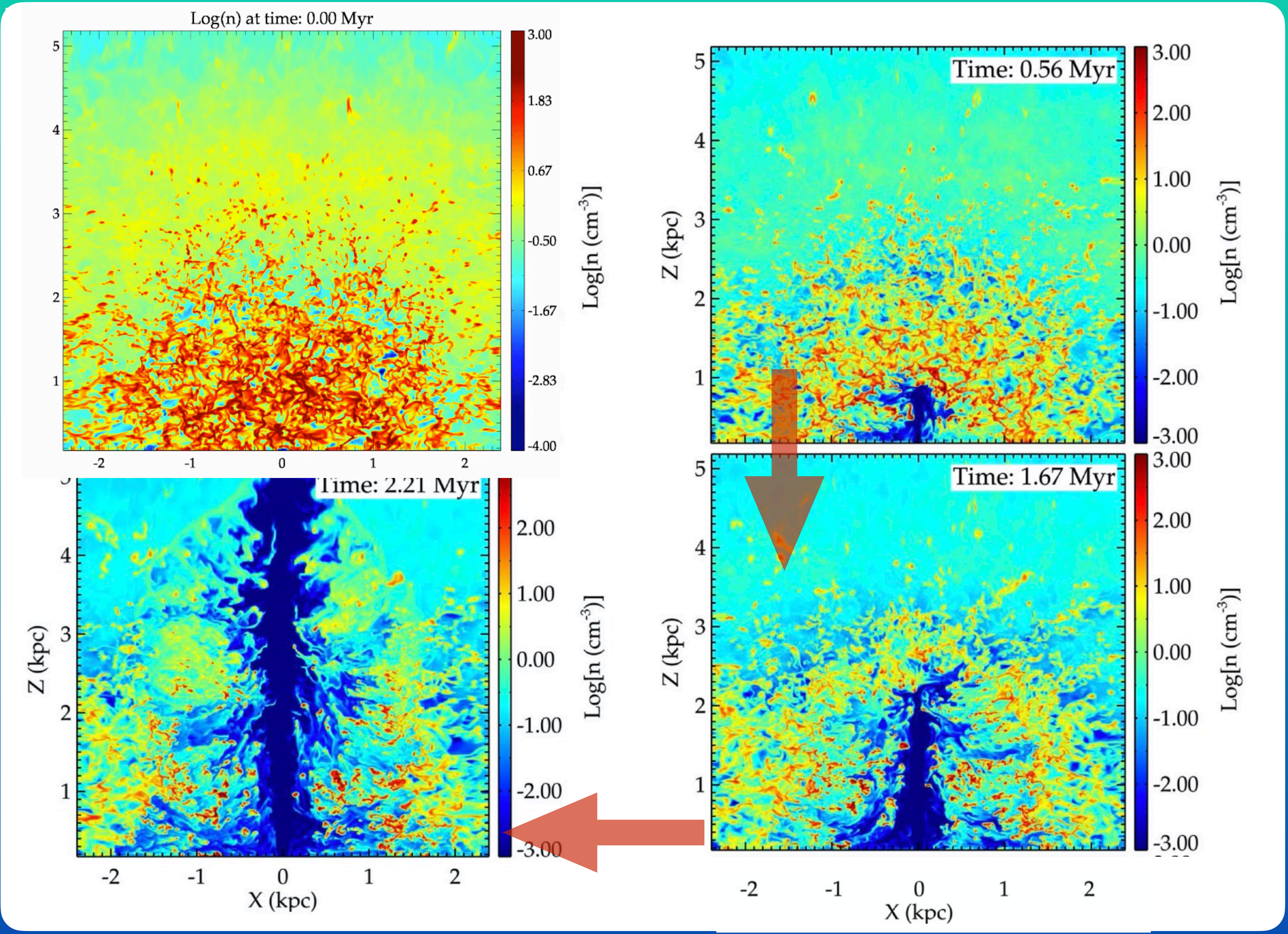
Jets inside the galaxy's potential ~ 5 kpc -> focus on jet-ISM interaction, feedback.

Intermediate length scales 10-20 kpc -> Focus on jet dynamics & non-thermal emission

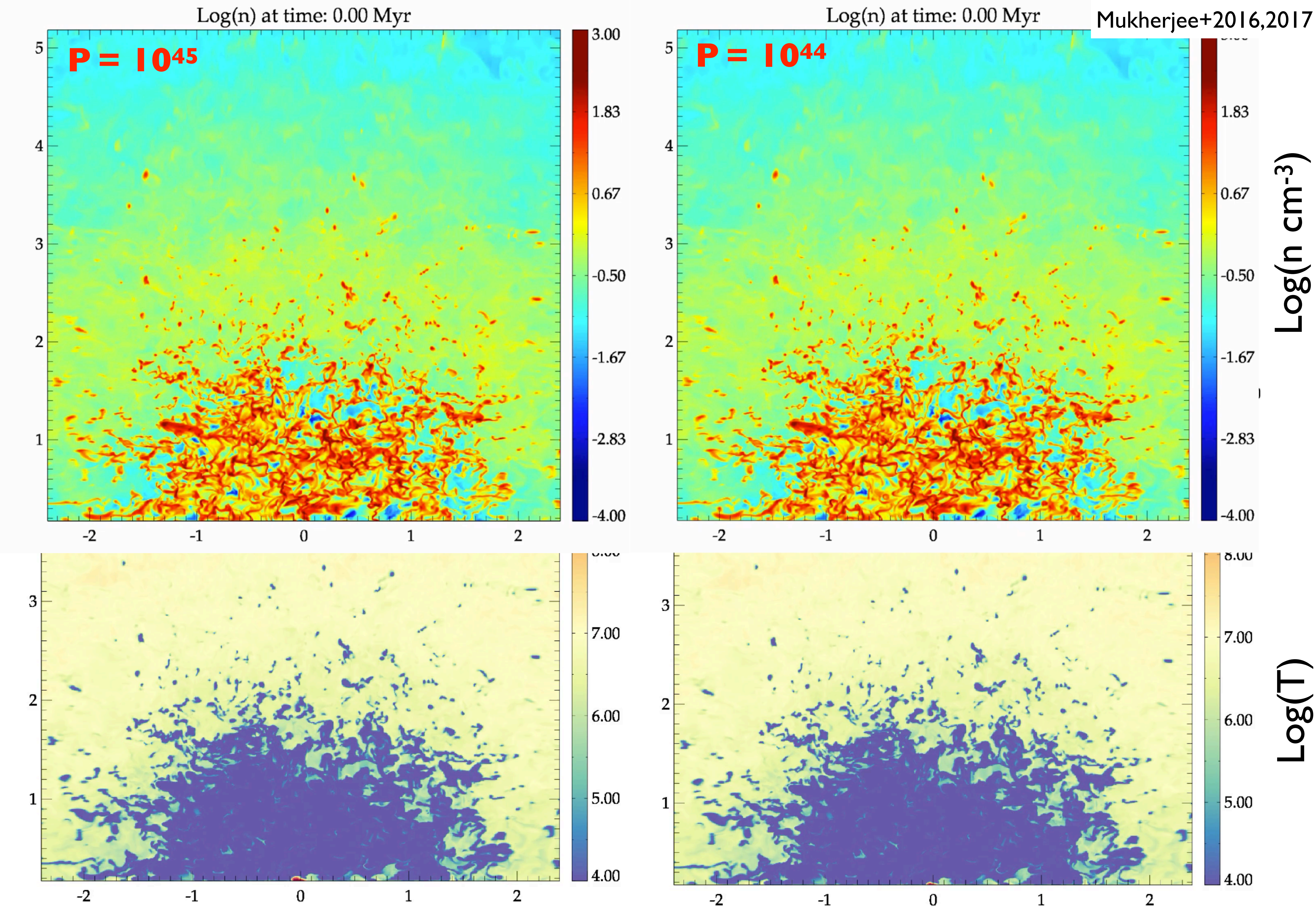




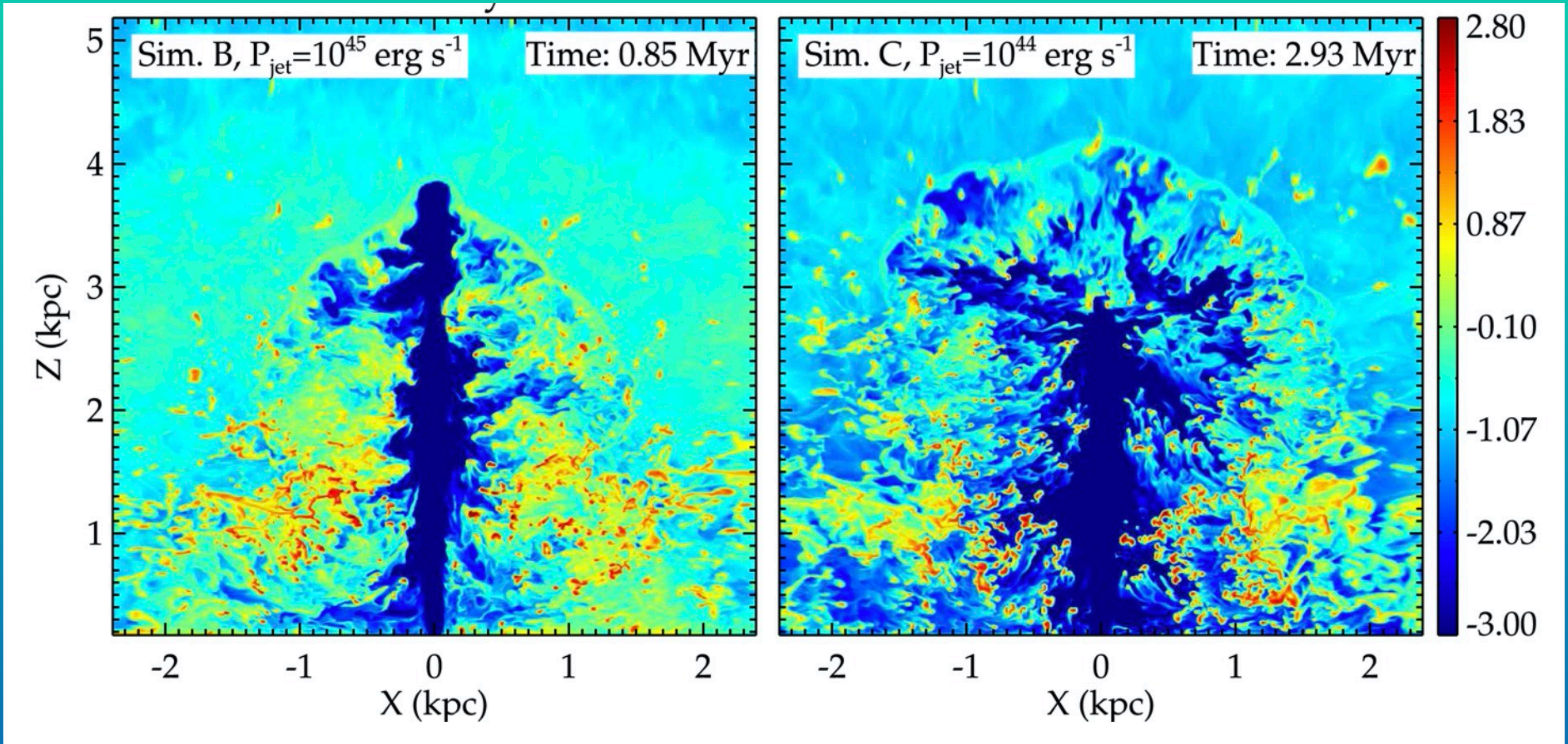
Jets through turbulent spherical ISM



Feedback from lower power confined jet

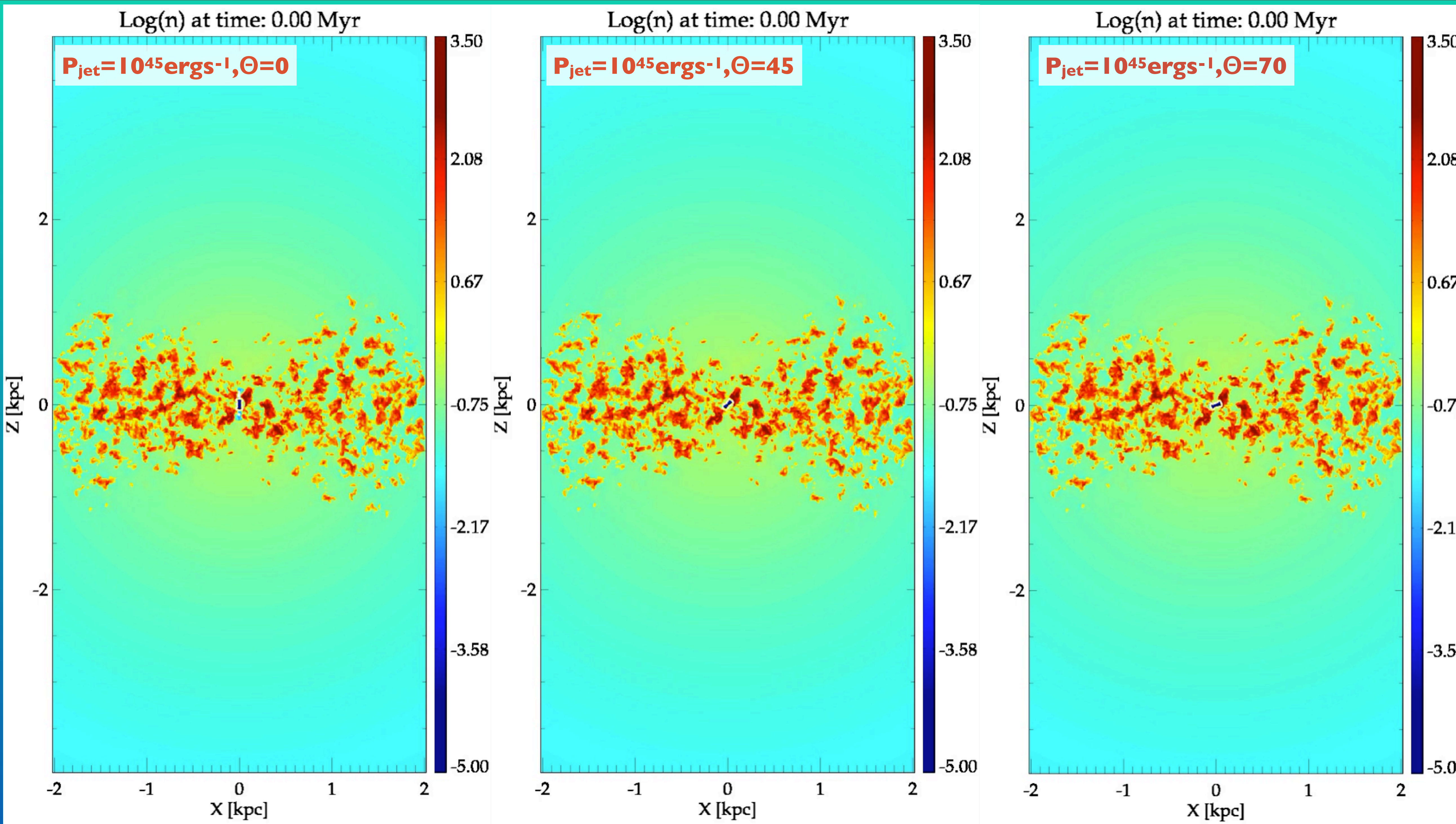


Feedback from lower power confined jet



- Jets of different power through identical ISM.
- Lower power jet confined longer.
- However, efficient in spreading shocks and shearing clouds over kpc scale.

Jet-disk interaction

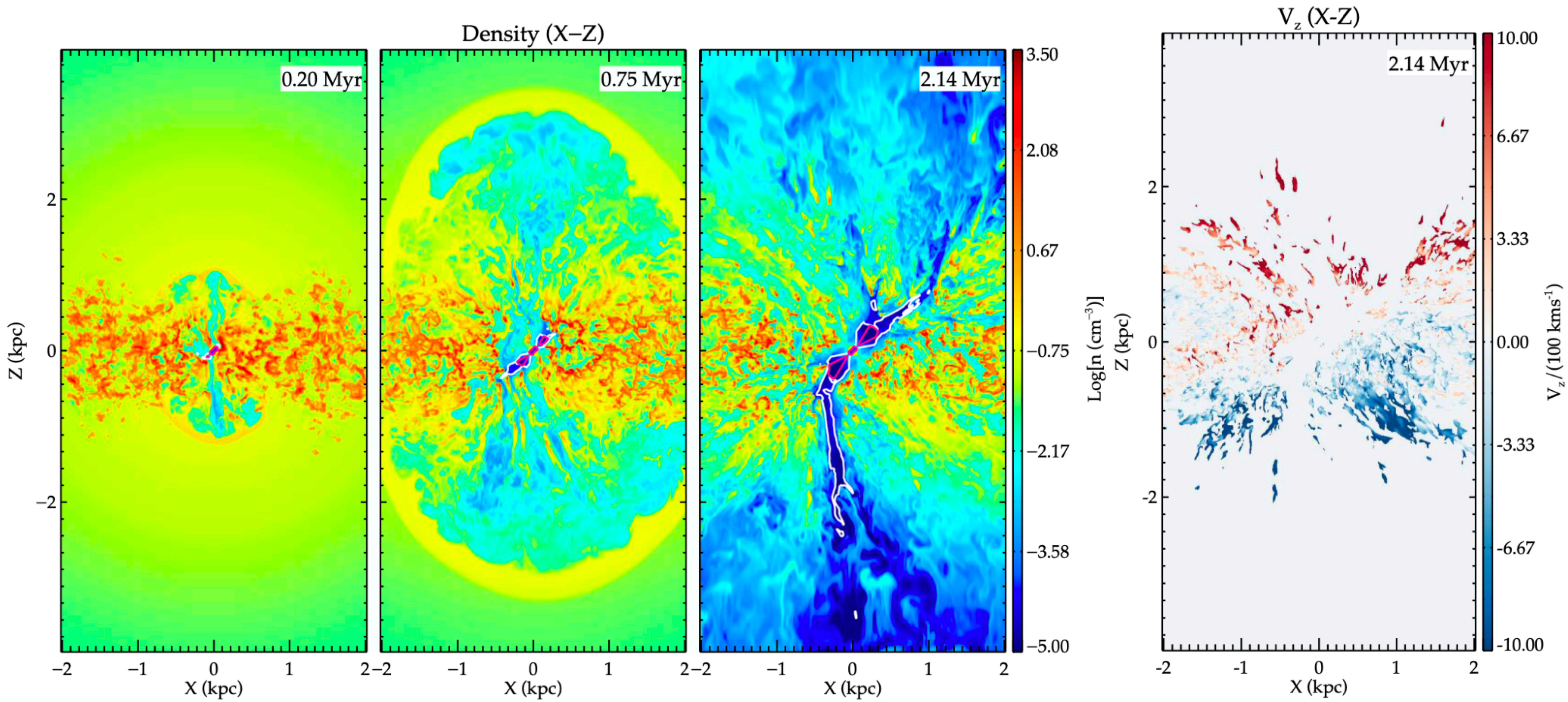


- Inclined jets couple more with turbulent disc
- More clouds are lifted off the disc
- The cavity is filled with ablated thermal gas + non-thermal plasma

Mukherjee+2018b

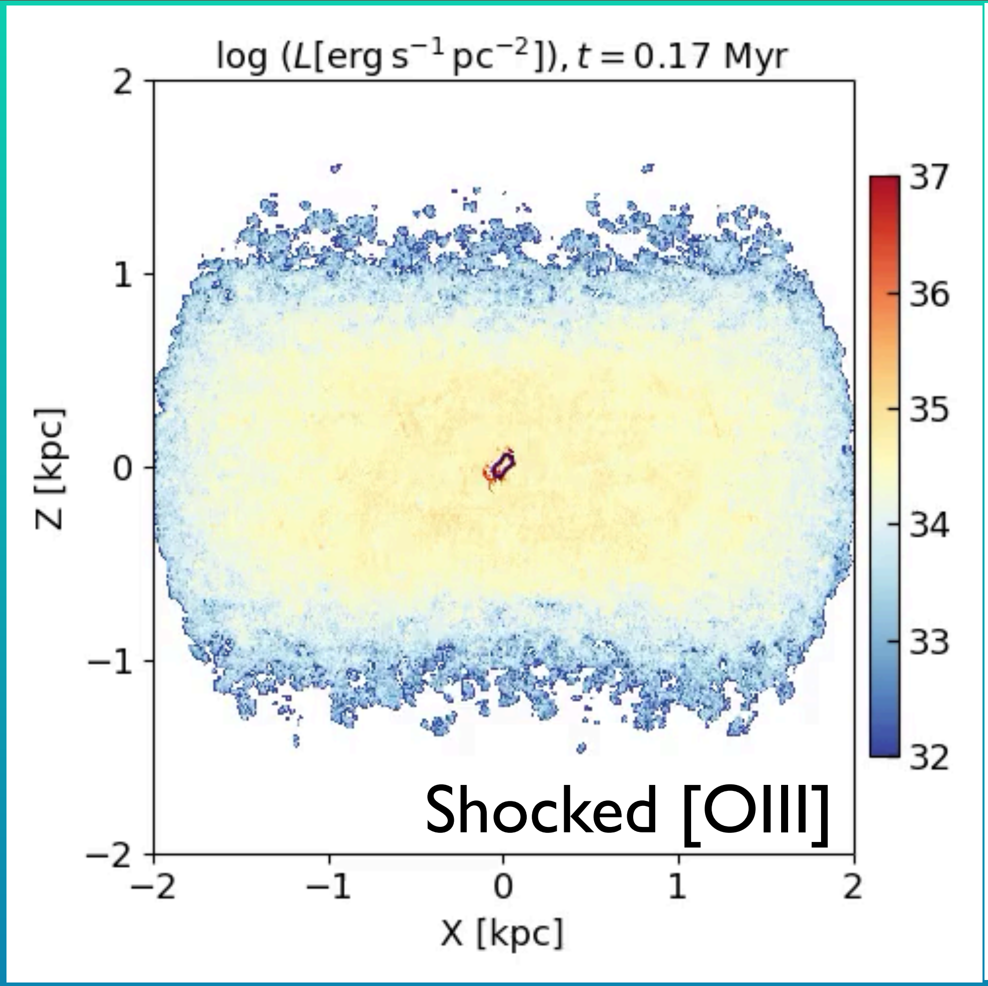
Jet-disk interaction

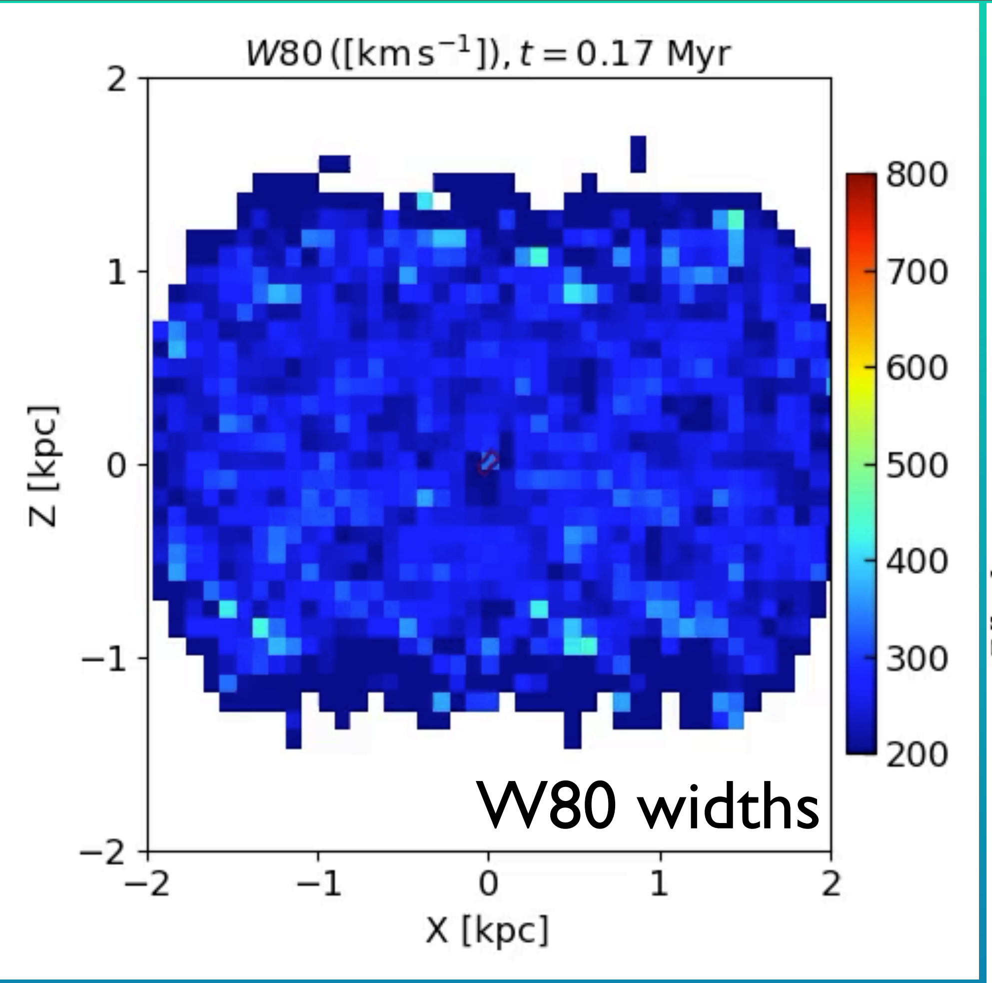
Mukherjee+2018b

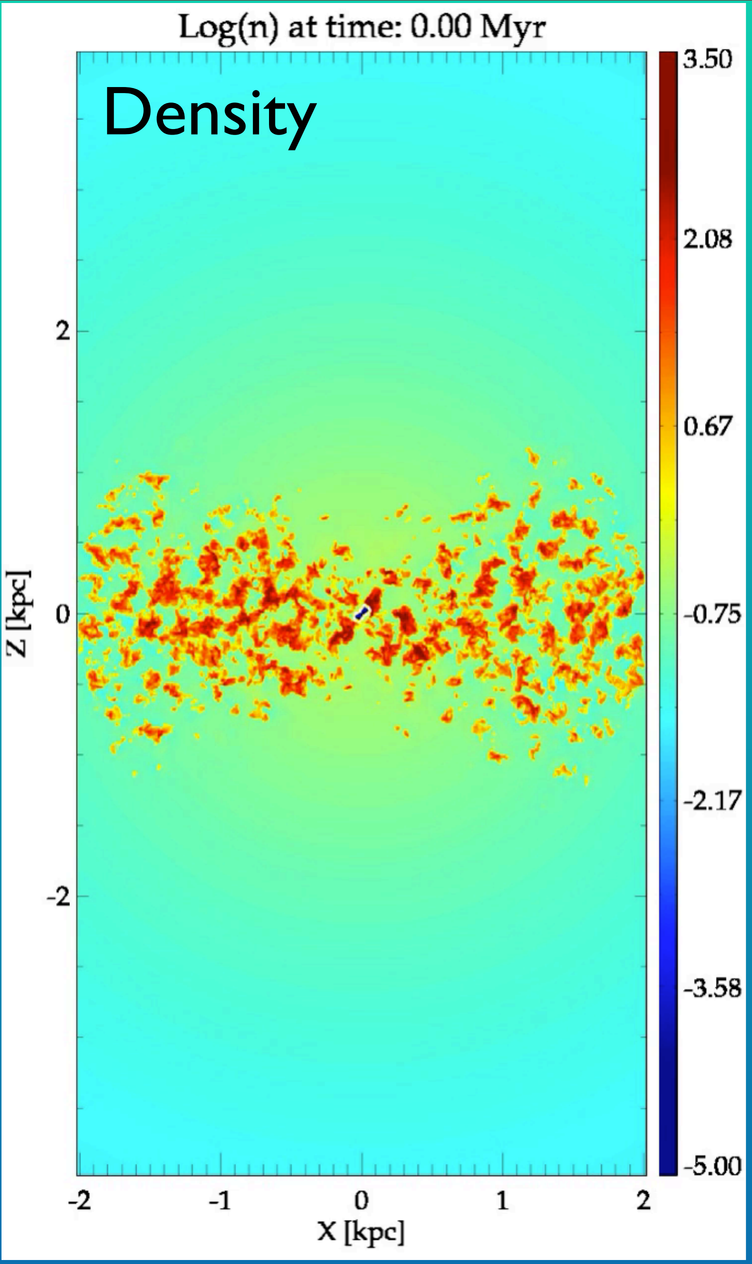


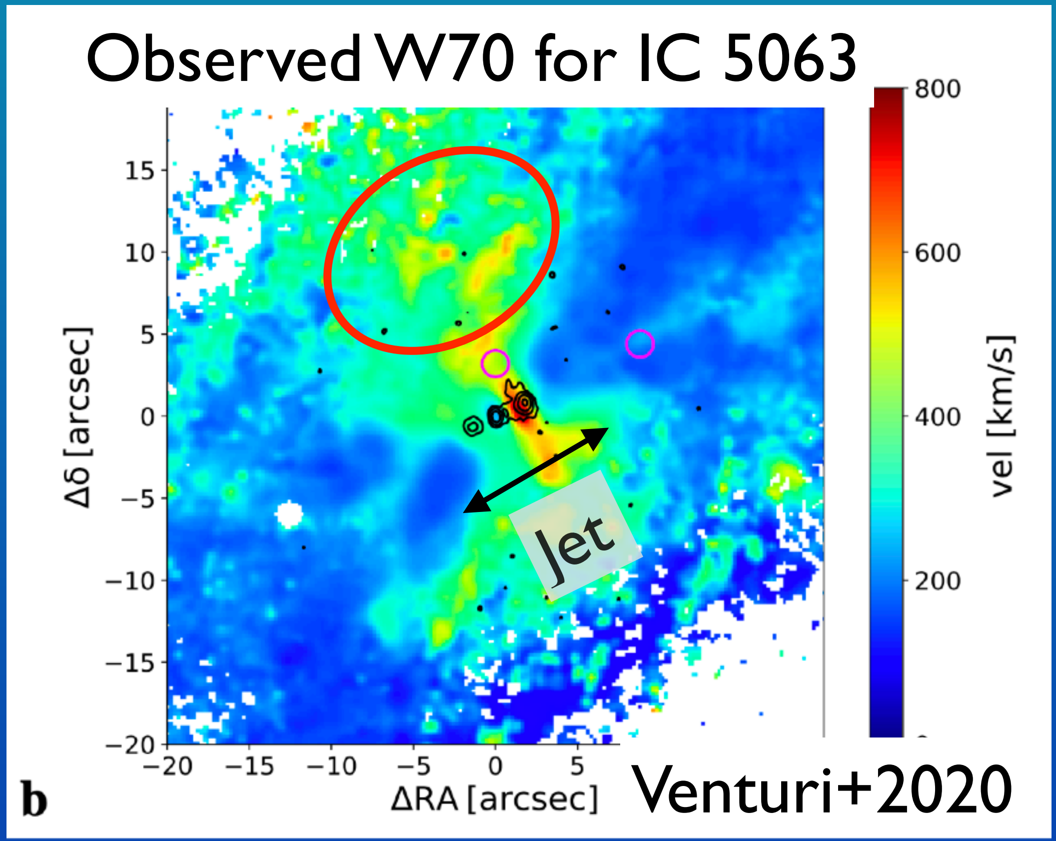
- Inclined jets couple more with turbulent disc.
- Backflow from the jet impacts a much larger part of the disc and engulfs it.
- Local outflows are launched at points of direct interaction

Observable emission features









Jets induce shocks, can be observable in emission lines.

Increased dispersion perpendicular to jets due to outflows leaking along minor axis from inclined jets.

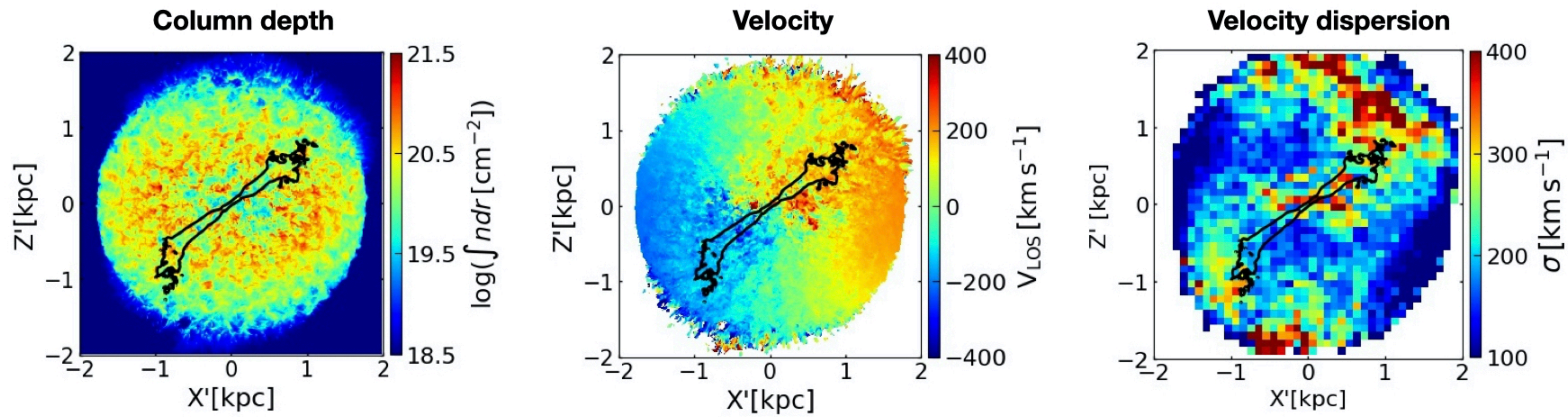
Tentatively observed in several systems: IC 5063 (Venturi+2020), J1316+1753 (Girdhar+2022).

Meenakshi, DM + MNRAS in press (arXiv: 2203.10251)

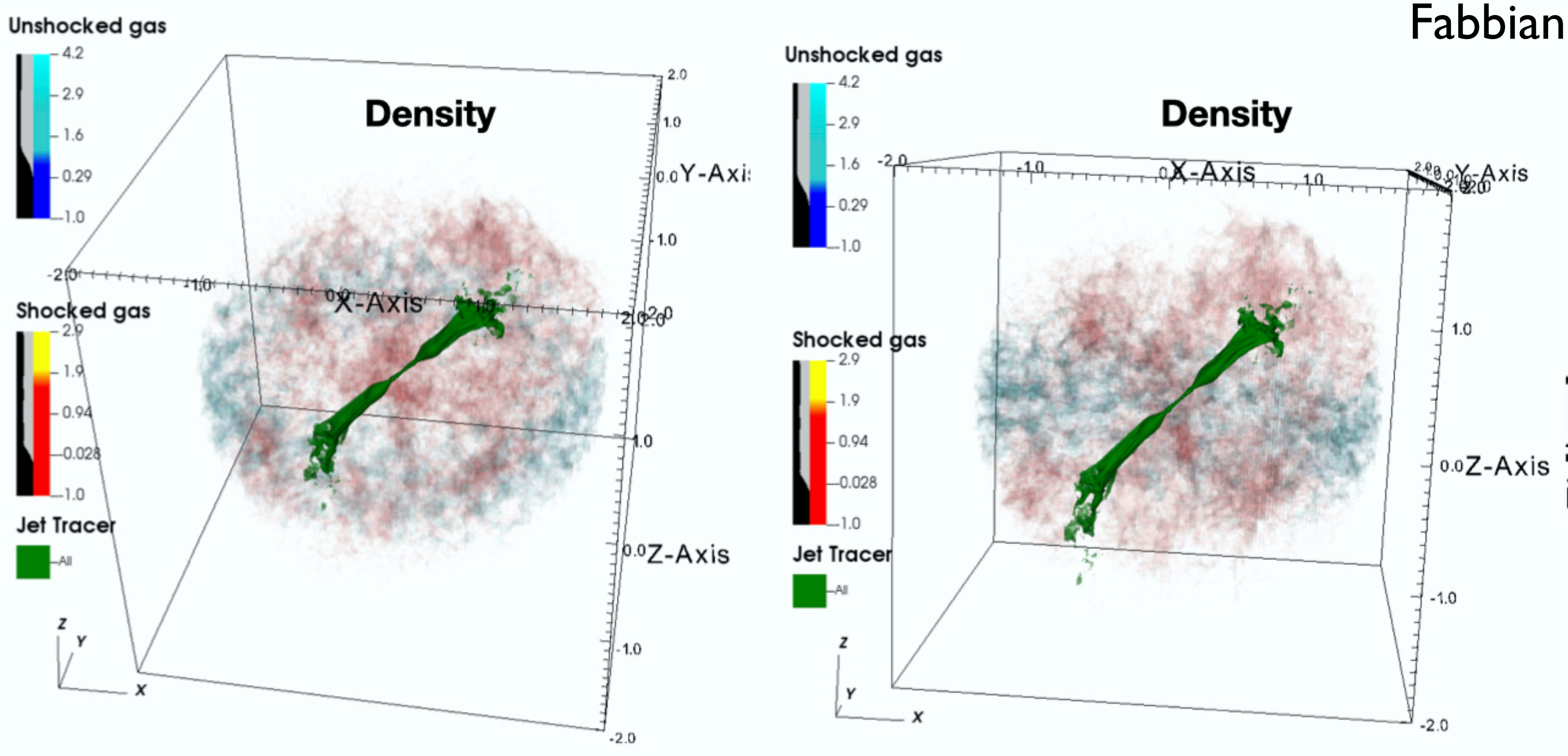
Observations of jet-ISM interactions

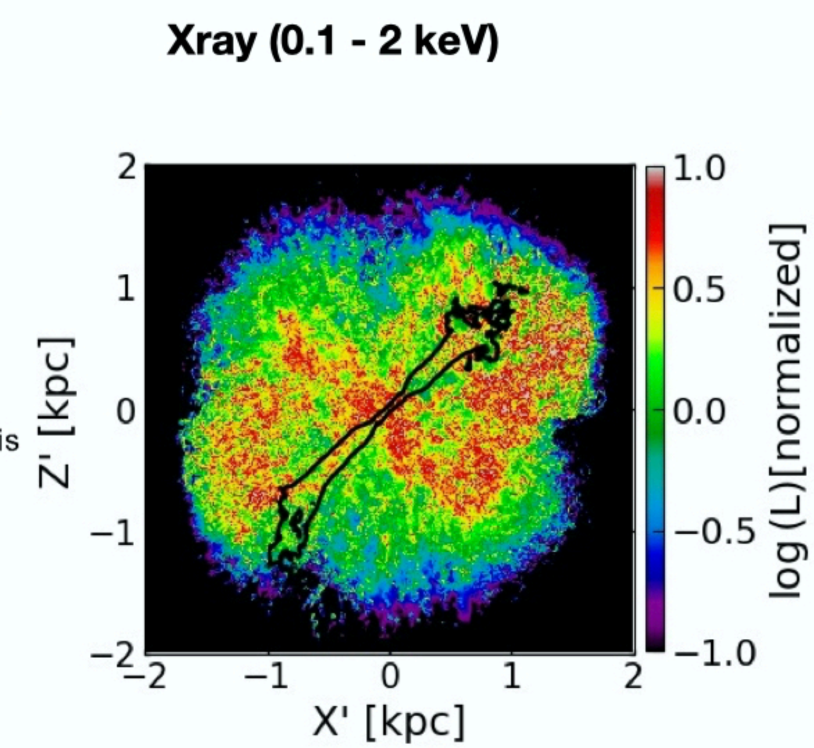
Jet – ISM Interaction in NGC 1167/B2 0258+35, a LINER with an AGN Past

ApJ, submitted



Fabbiano, DM + 2022, submitted





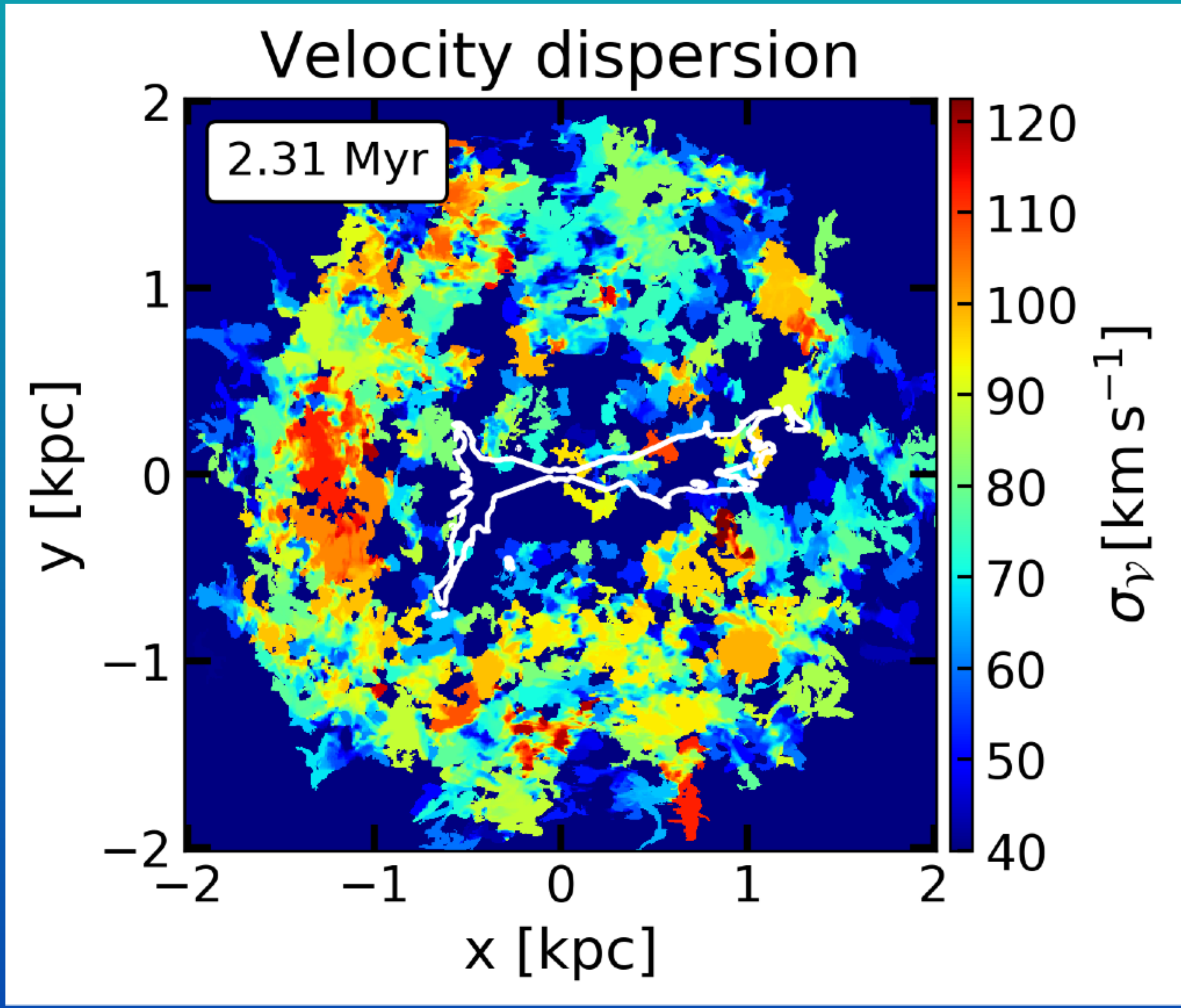
Estimating SFR with improved subgrid physics

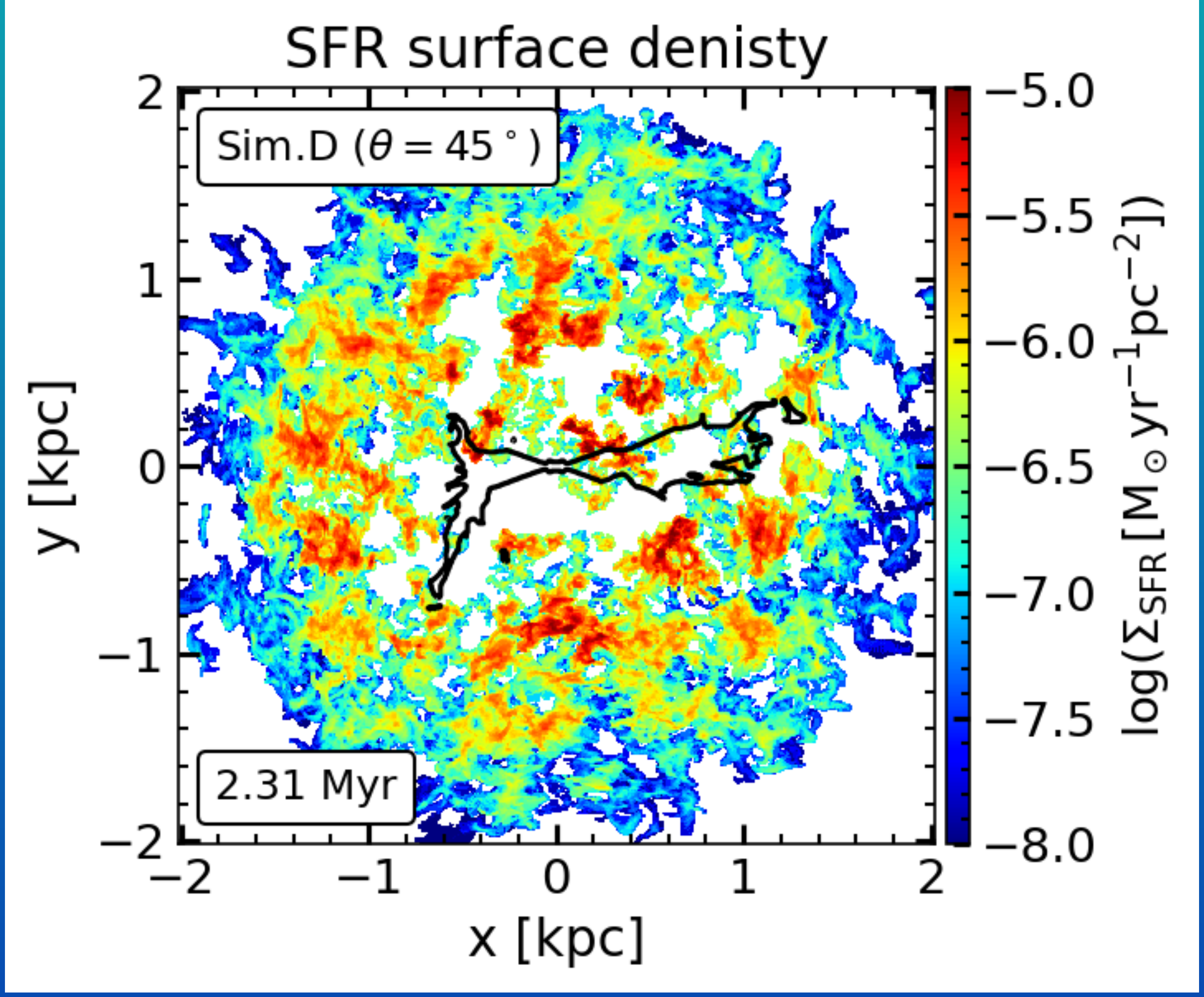
Work by Ankush Mandal

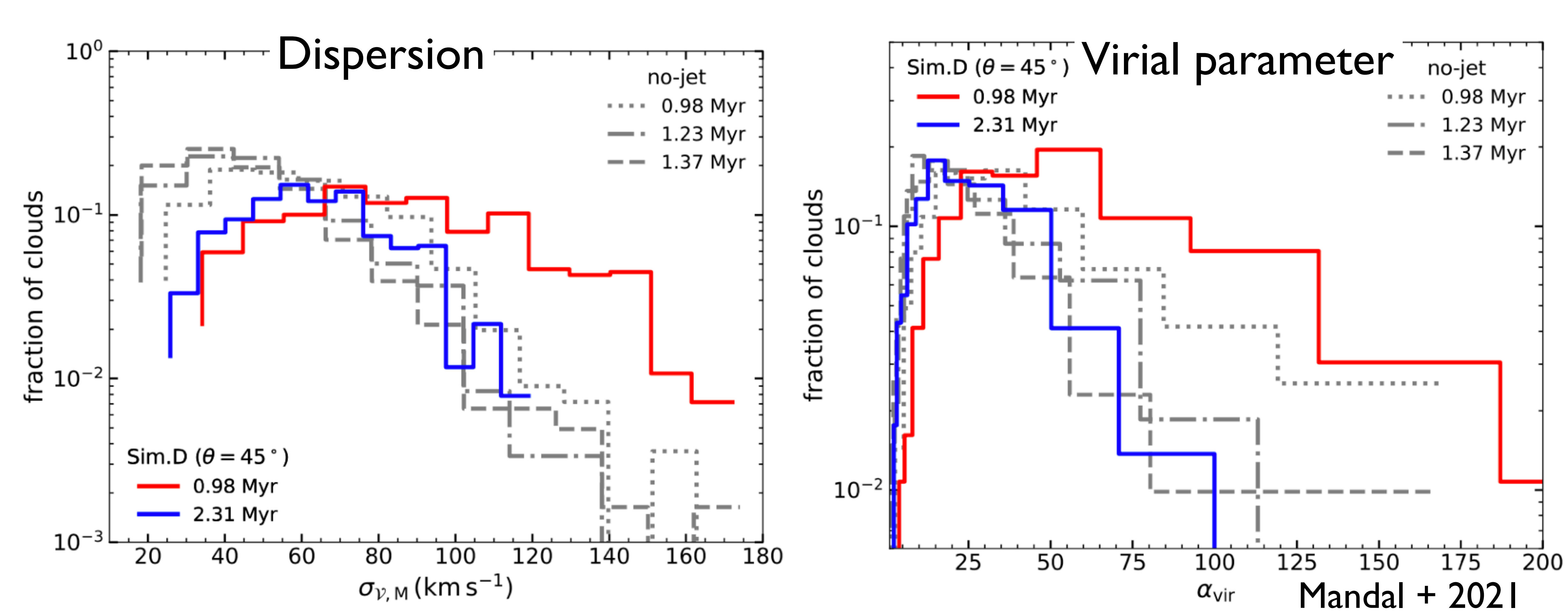
Standard approaches: $\mathrm{SFR} = \dfrac{M}{t_{\mathrm{ff}}}$ for $\rho > \rho_{\mathrm{threshold}}$, $t_{\mathrm{ff}} \propto \rho^{-1/2}$

No input about turbulent velocity dispersion or Mach number.

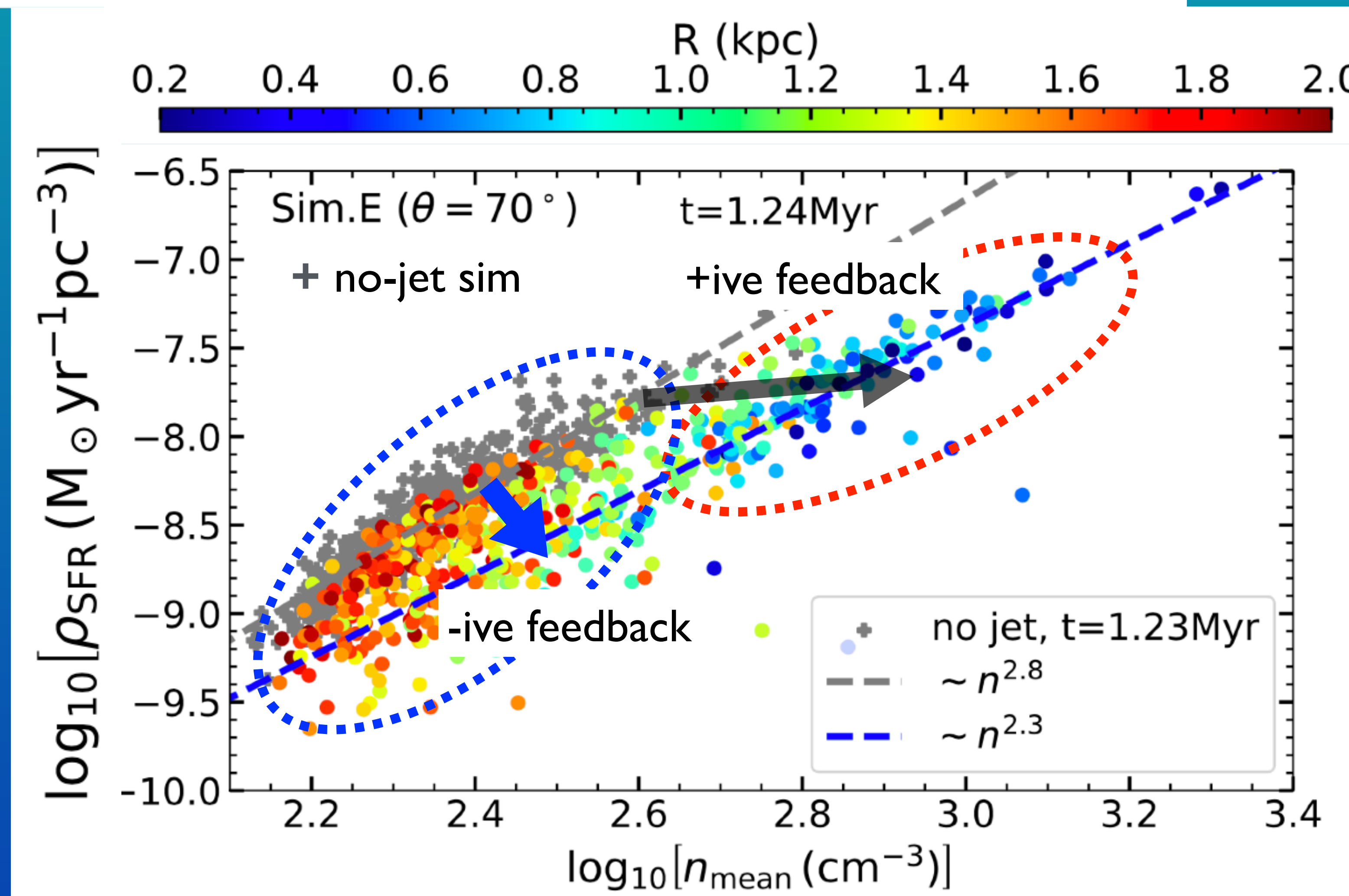
Better option: Use a turbulence based SFR prescription (Krumholz+2005, Federrath+2012).







- Positive & negative feedback can happen in the same system.
- Inefficient positive feedback: +ive due to density enhancement at sites of direct impact. But efficiency lowered due to simultaneous increase in turbulence.



Jets with new hybrid particle + fluid scheme

Spatial evolution:

$$\frac{d\boldsymbol{x}_{\rm p}}{dt} = \boldsymbol{v}(\boldsymbol{x}_{\rm p})$$

Energy losses, synchrotron, inverse compton

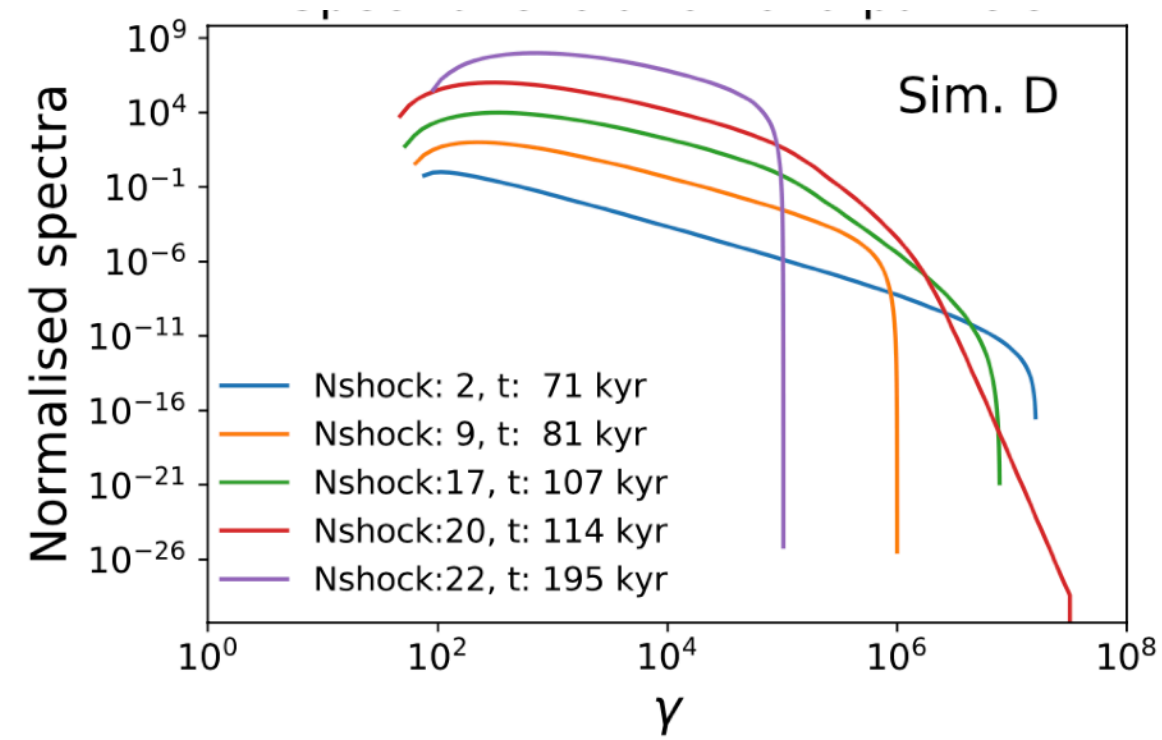
Vaidya et al. 2018

Spectral evolution:

$$\mathcal{N}(p,\tau) = \int d\Omega p^2 f_0 \approx 4\pi p^2 f_0.$$

$$\frac{d\mathcal{N}}{d\tau} + \frac{\partial}{\partial E}\left[\left(-\frac{E}{3}\nabla_\mu u^\mu + \dot{E}_l\right)\mathcal{N}\right] = -\mathcal{N}\nabla_\mu u^\mu$$

Evolution of spectrum of one particle, with Shock acceleration + cooling losses

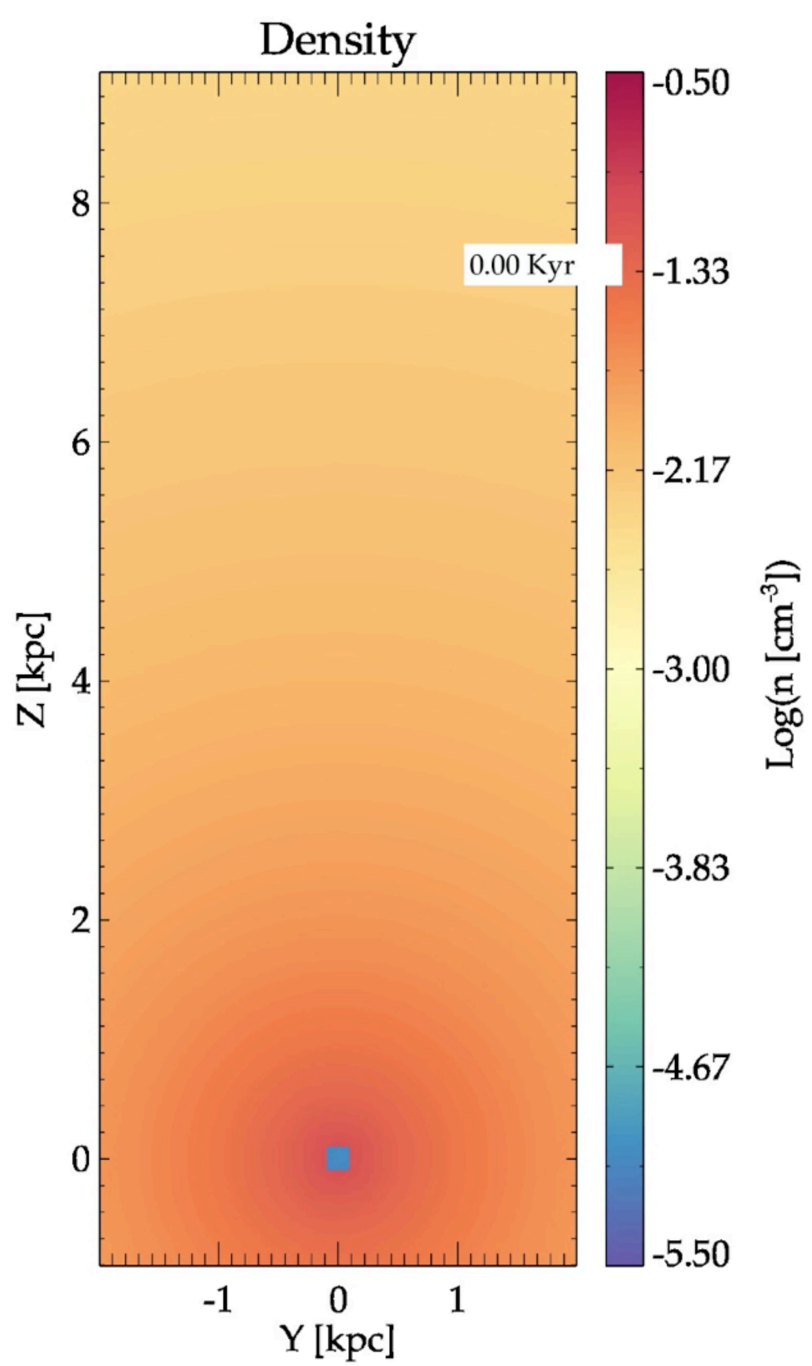


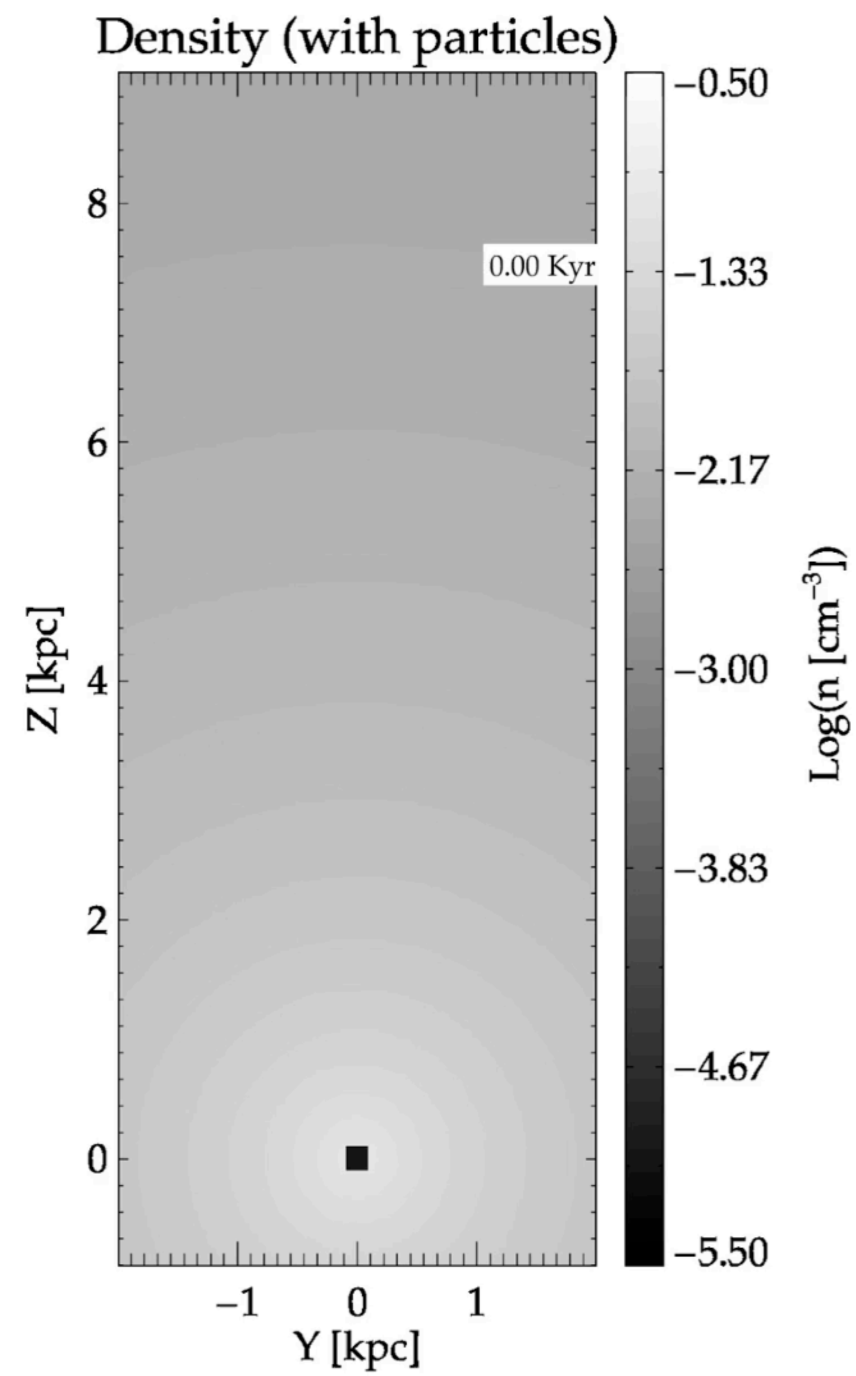
DSA model for acceleration at shocks

Finally:

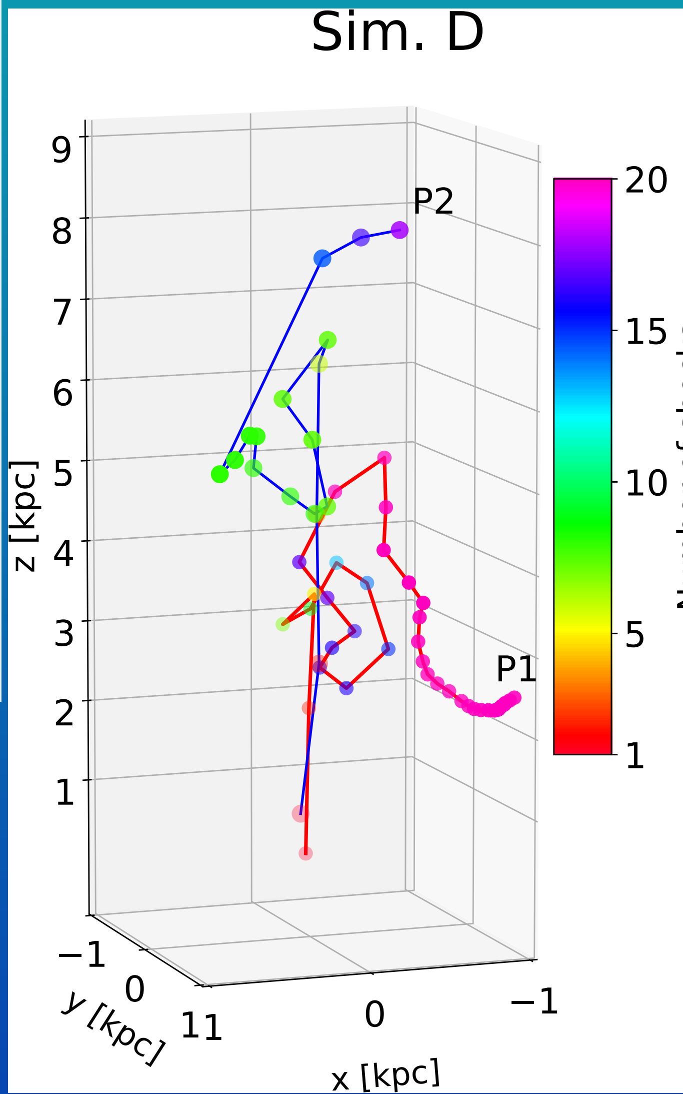
$$J'_{\rm syn}(\nu', \hat{\boldsymbol{n}}'_{los}, \boldsymbol{B}') = \frac{\sqrt{3}e^3}{4\pi m_e c^2}|\boldsymbol{B}'\times\hat{\boldsymbol{n}}'_{los}| \int_{E_i}^{E_f} \mathcal{N}'(E')F(x)dE'$$

Jets with new hybrid particle + fluid scheme





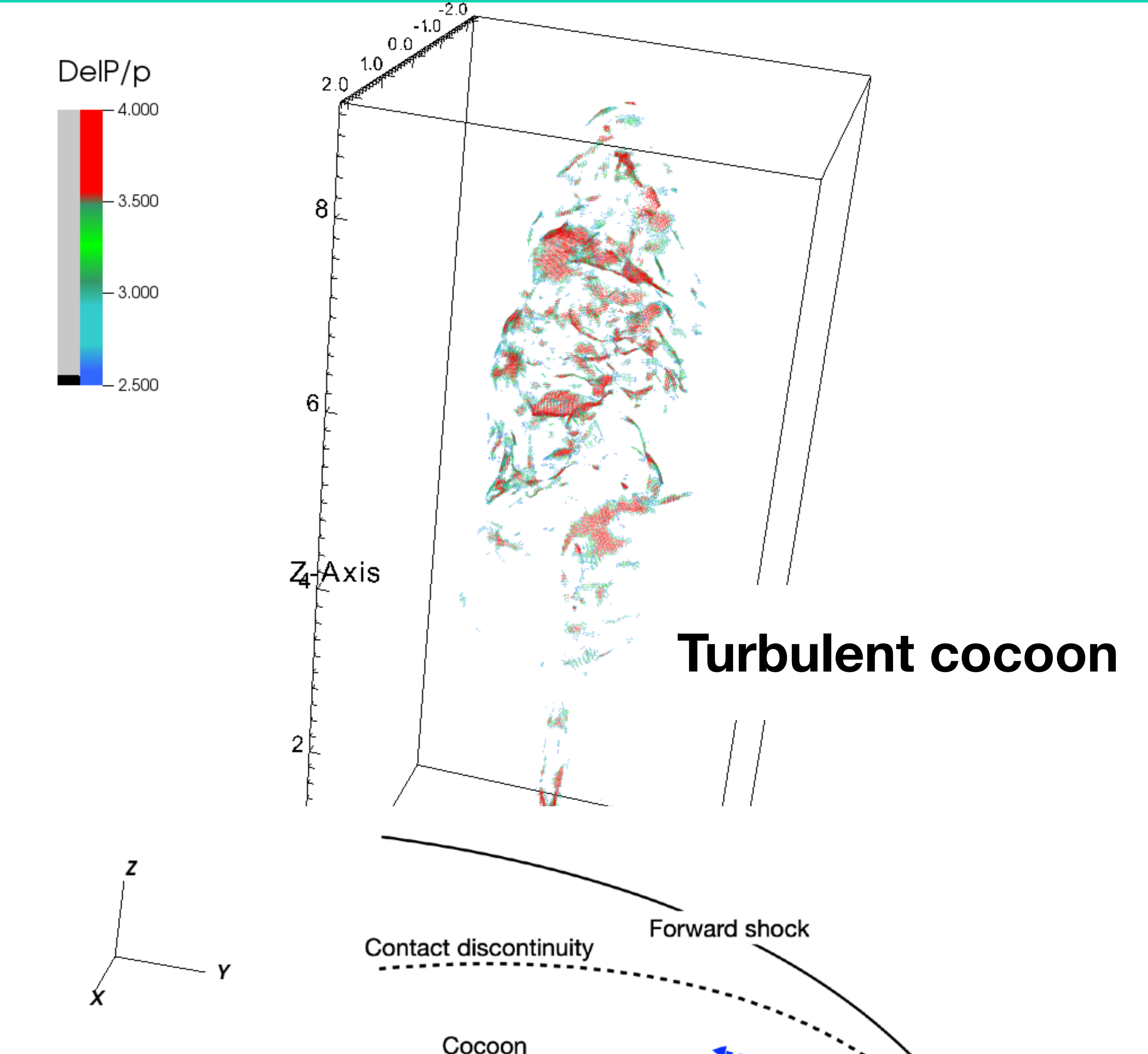
- Particles get energized at shocks.
- Shocks inside the jet spine, jet-head and cocoon
- Complex trajectories

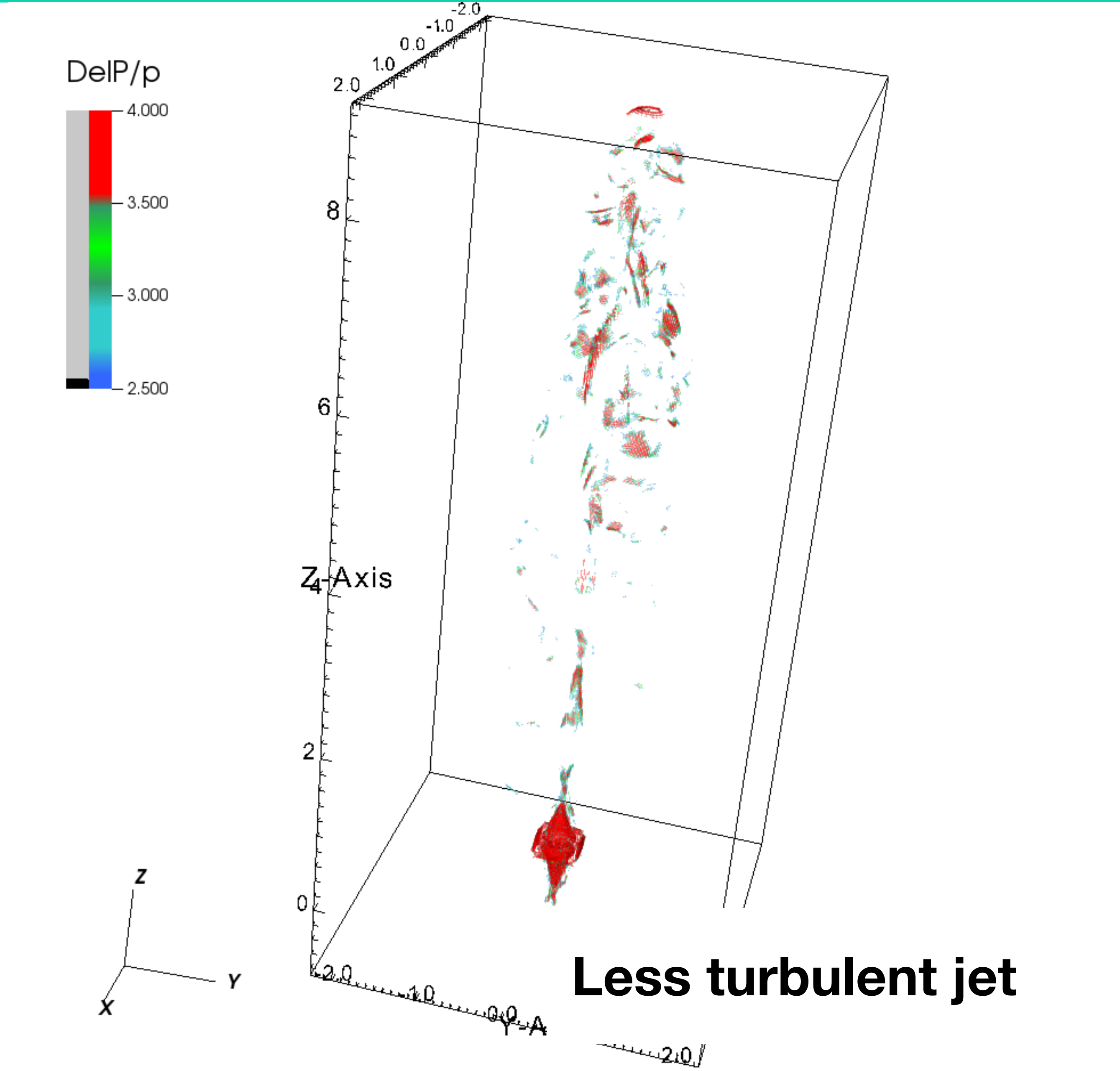


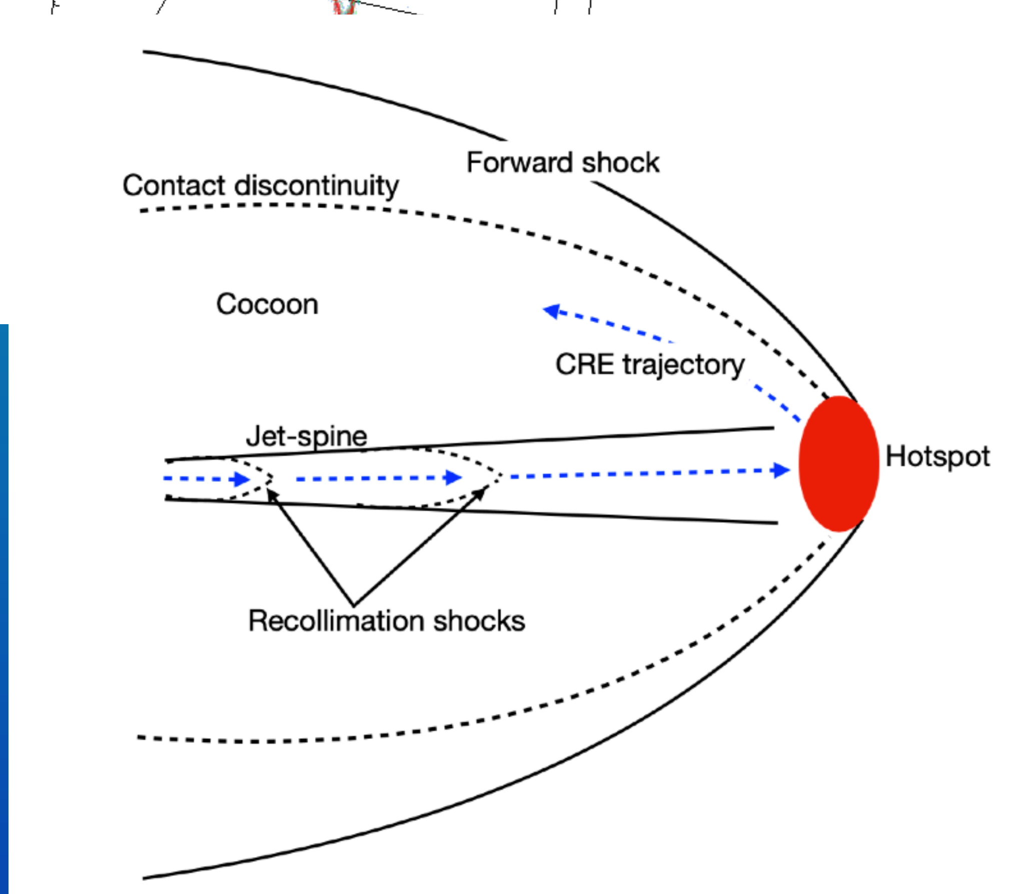
Mukherjee+2020, Mukherjee+2021

Particle color = Max energy, indicates shocks

Internal shocks in turbulent cocoon



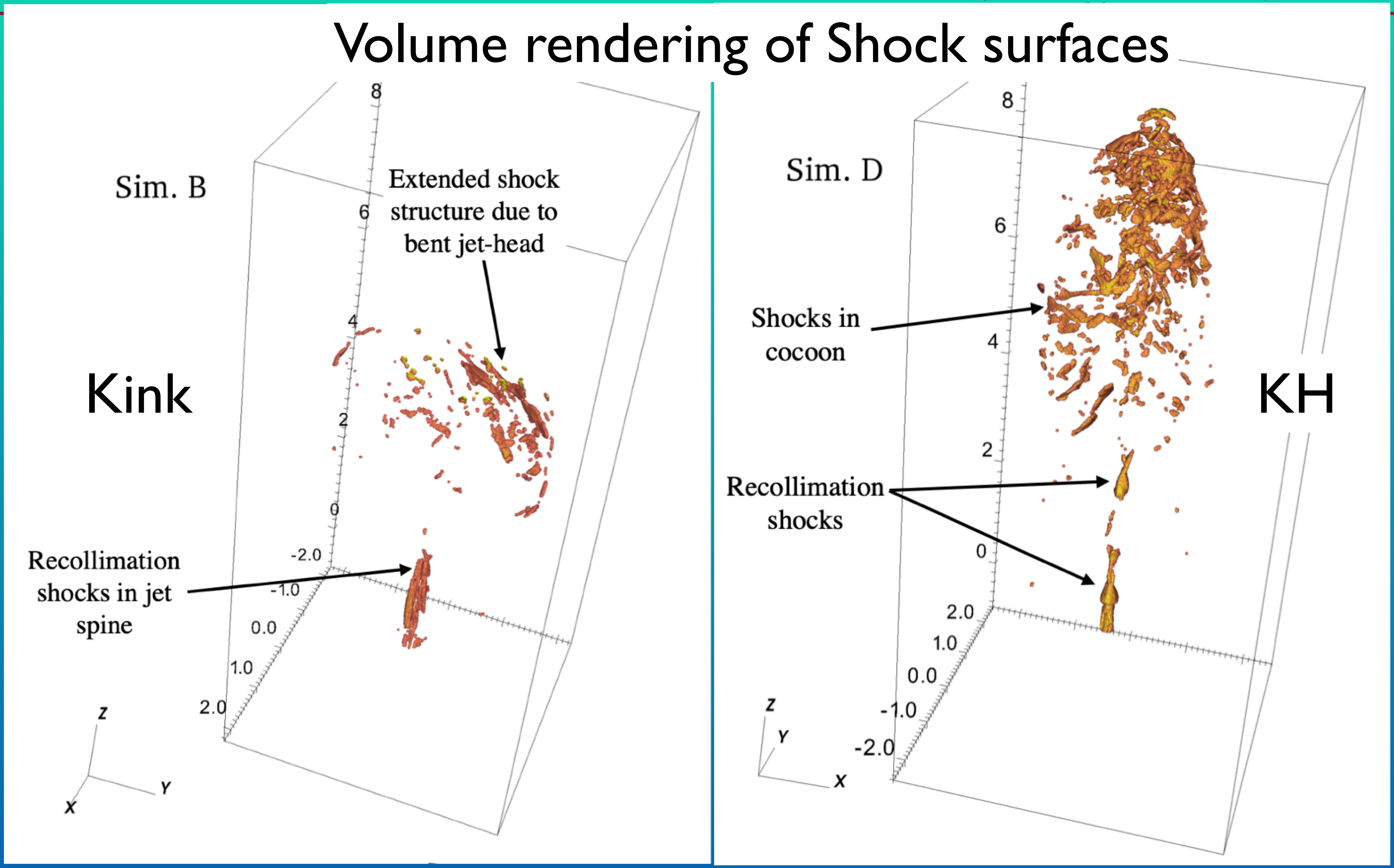




- **Multiple internal shocks** which can re-accelerate electrons in the backflow.
- Goes against the standard paradigm of a terminal hotspot and free-stream
- Turbulent cocoons have more shocks

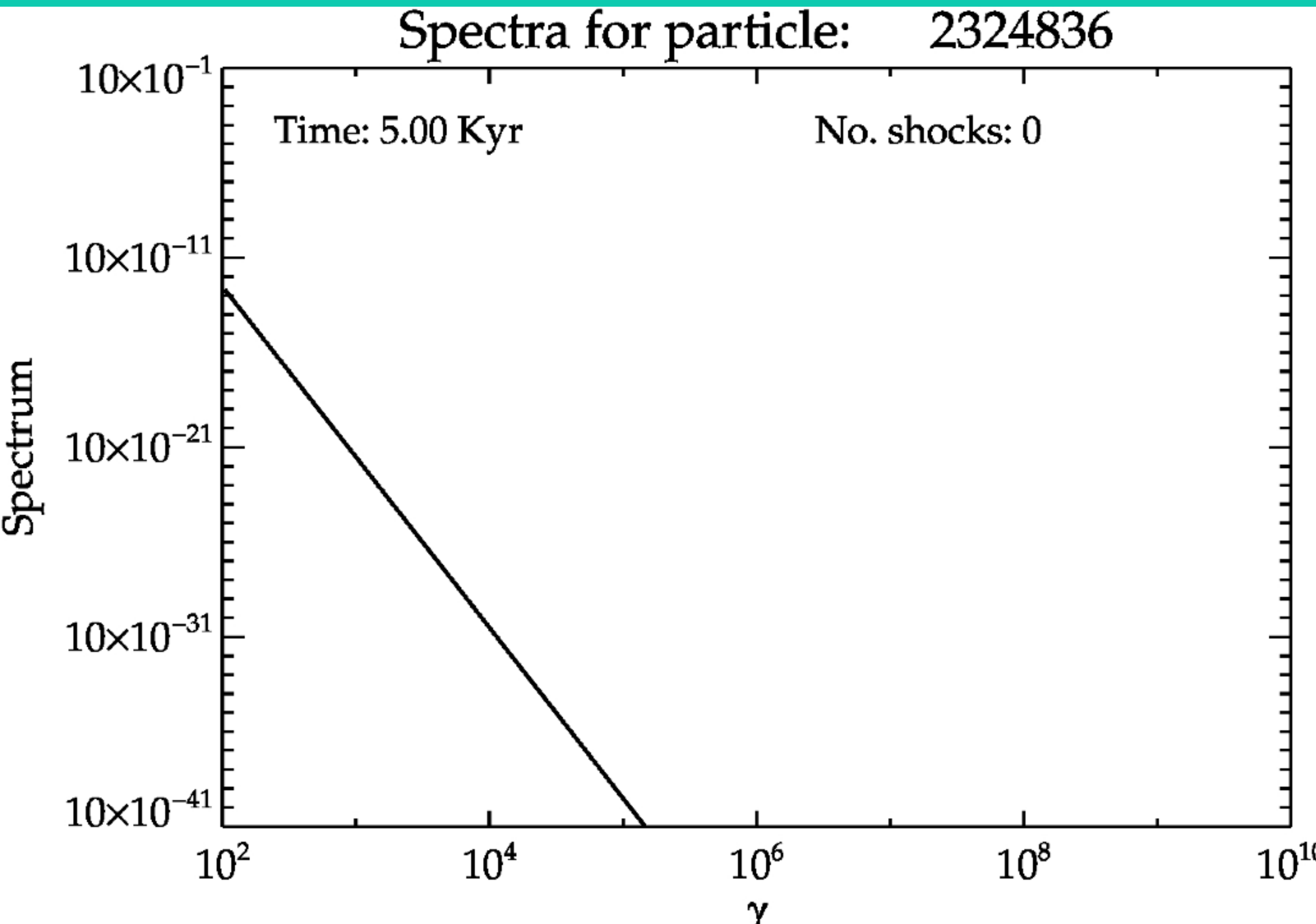
Kink vs KH

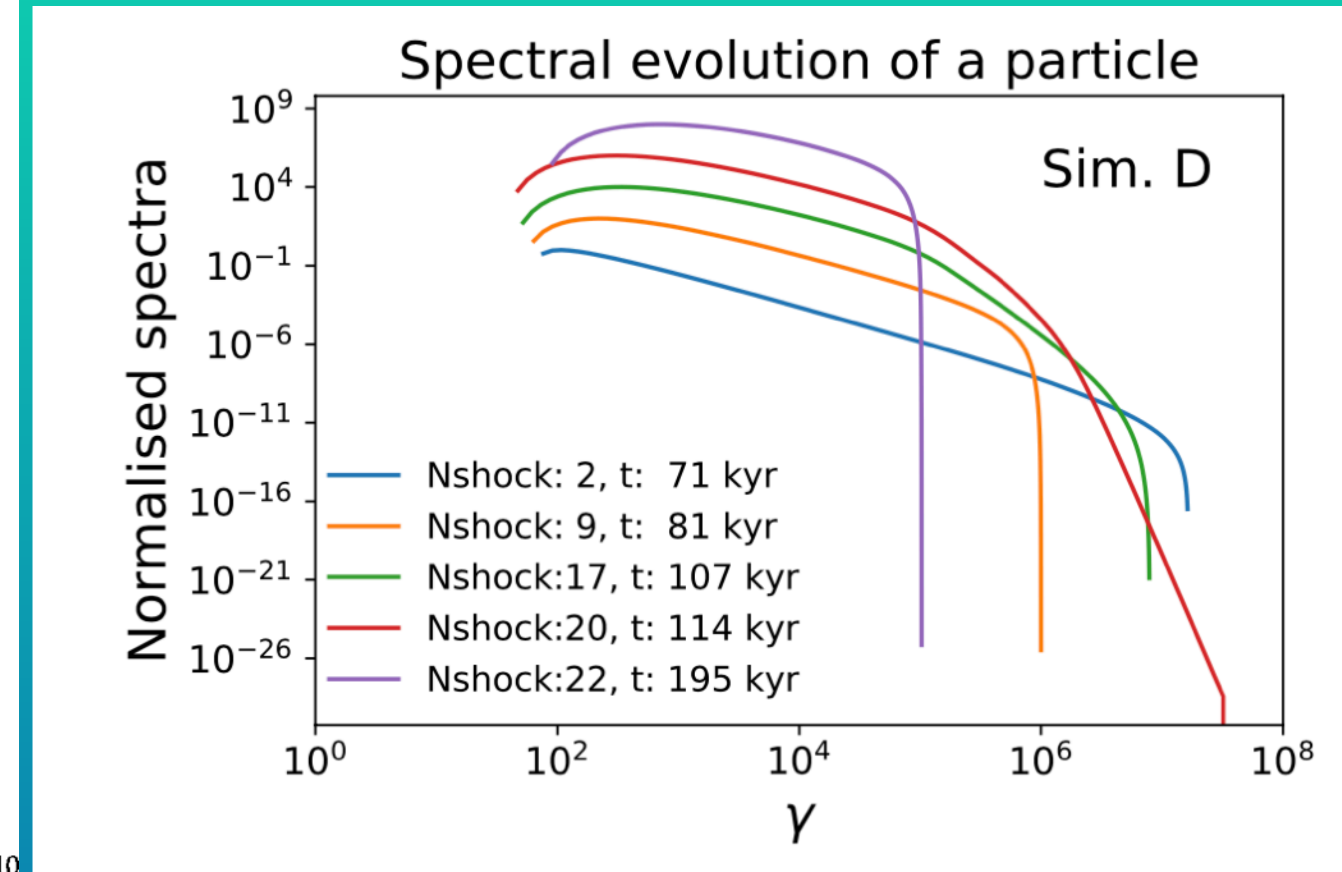
Mukherjee+2020, Mukherjee+2021

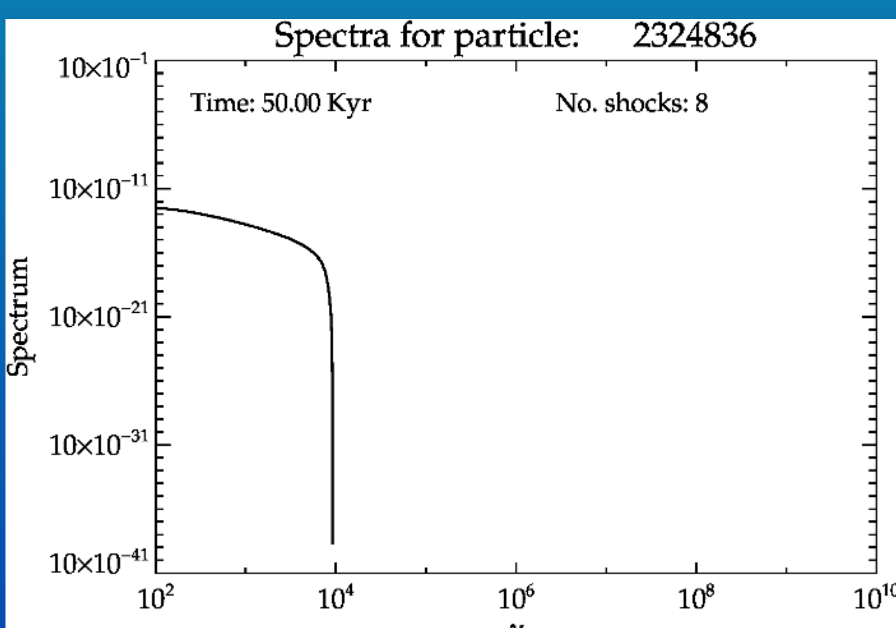


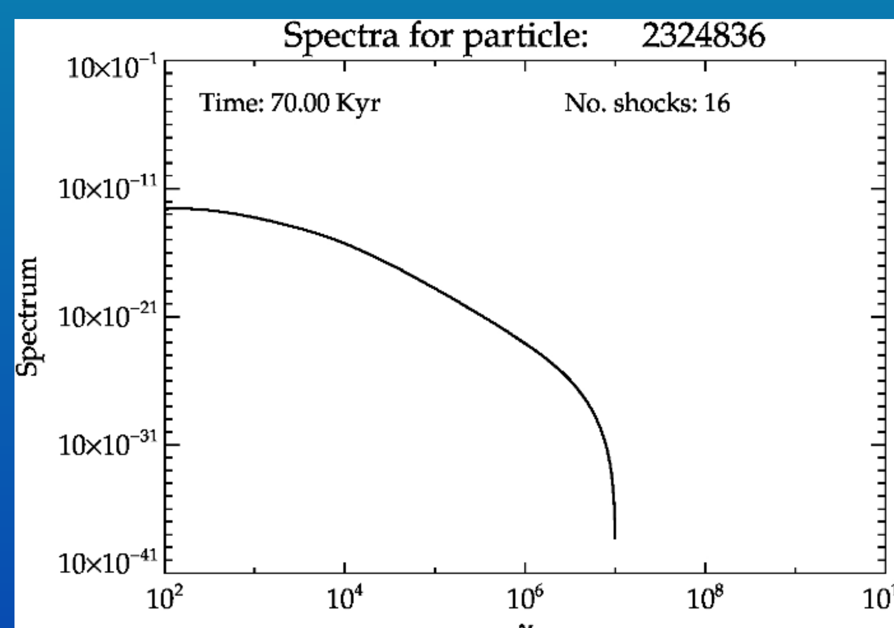
- The nature of the shock acceleration is fundamentally different between the kink and KH modes.
- Kink modes have extended terminal shock which accelerates CREs
- KH modes have weaker internal shocks all through the cocoon.

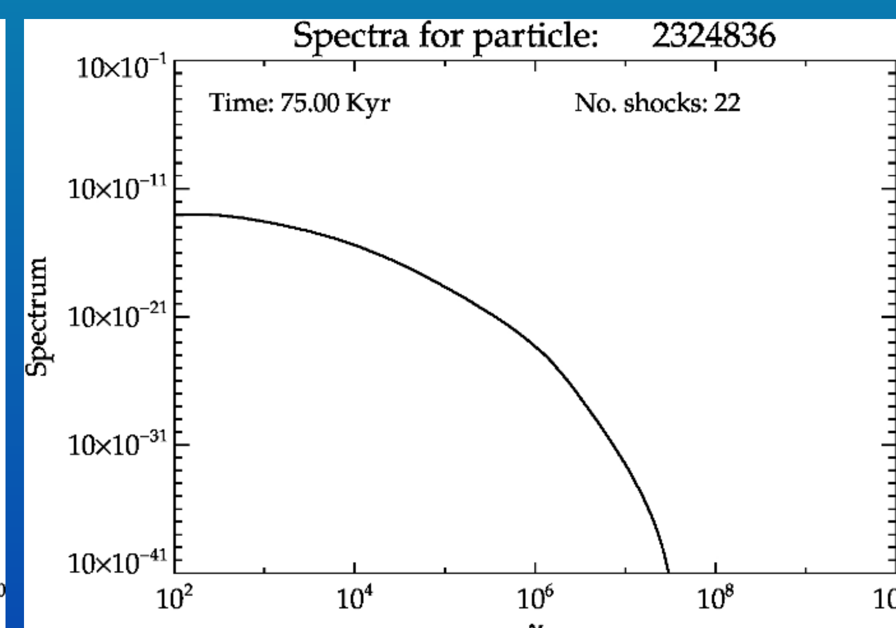
Multiple shock crossings



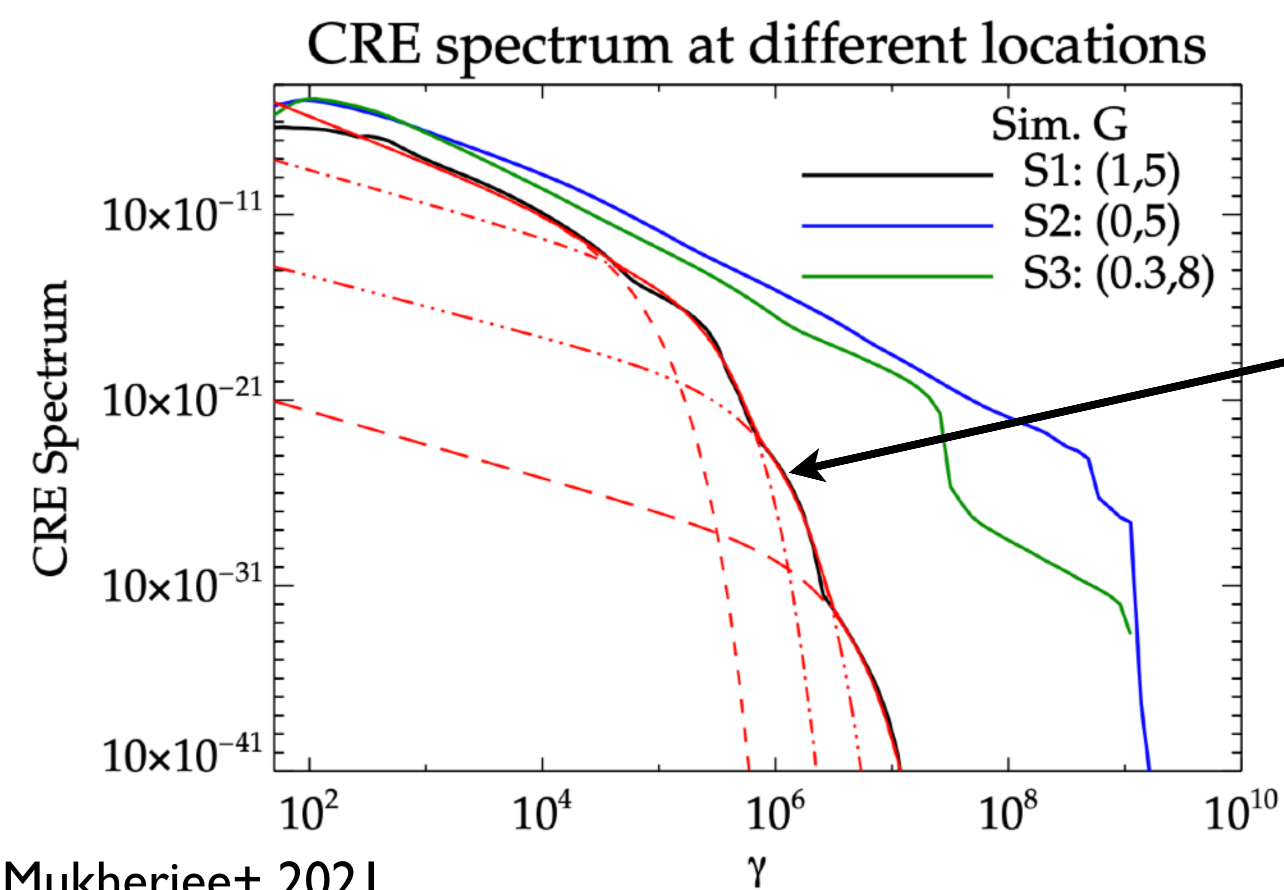




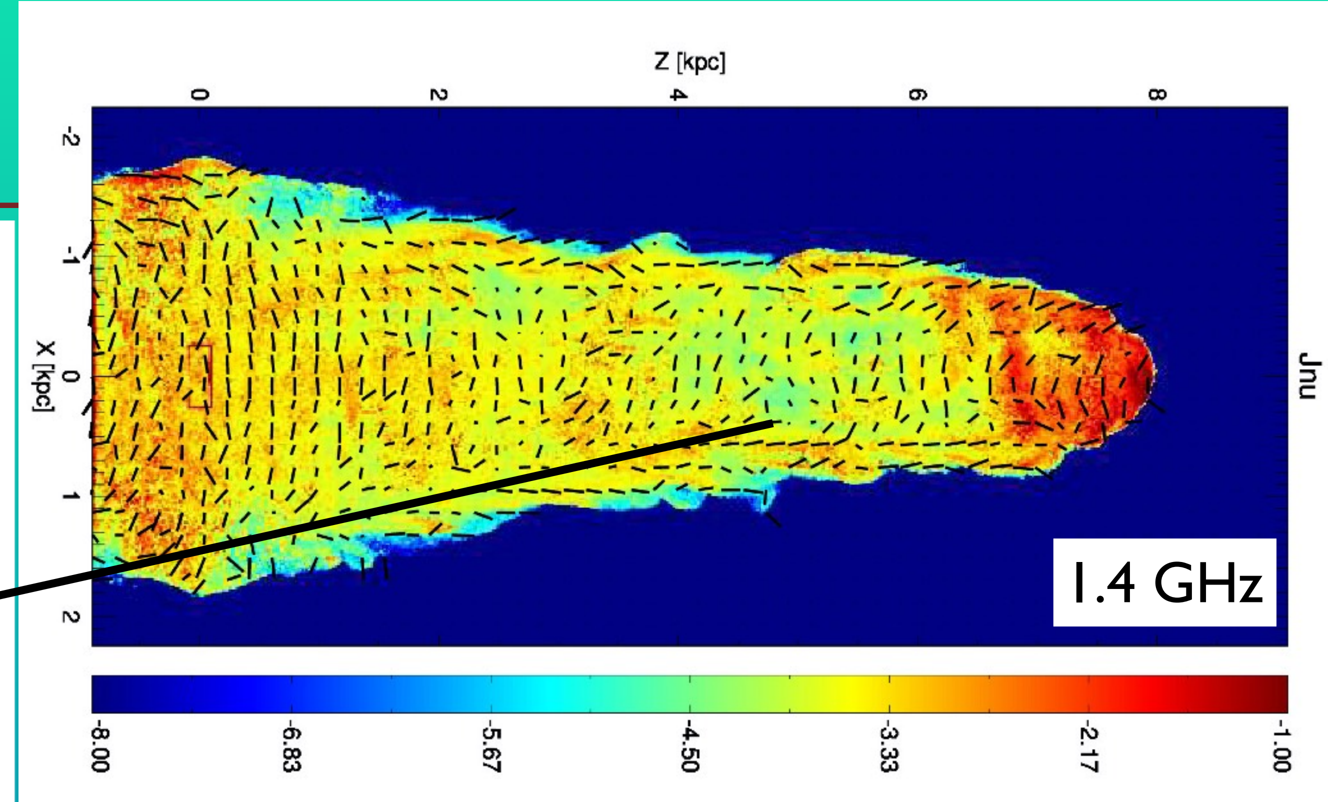


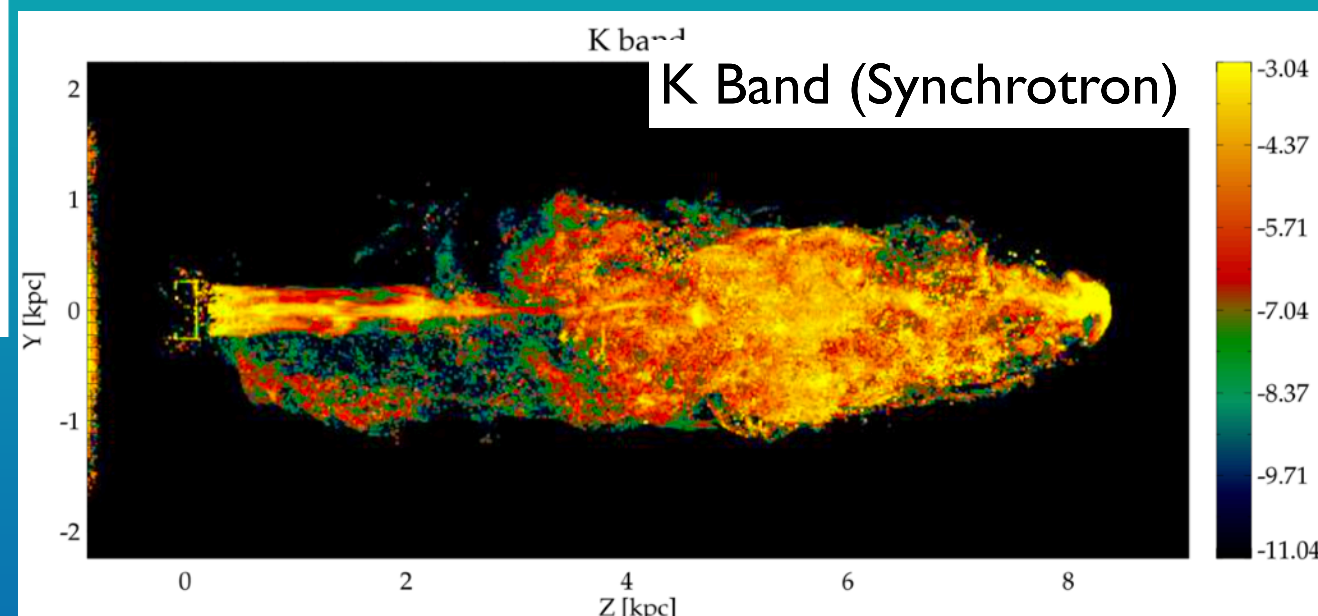


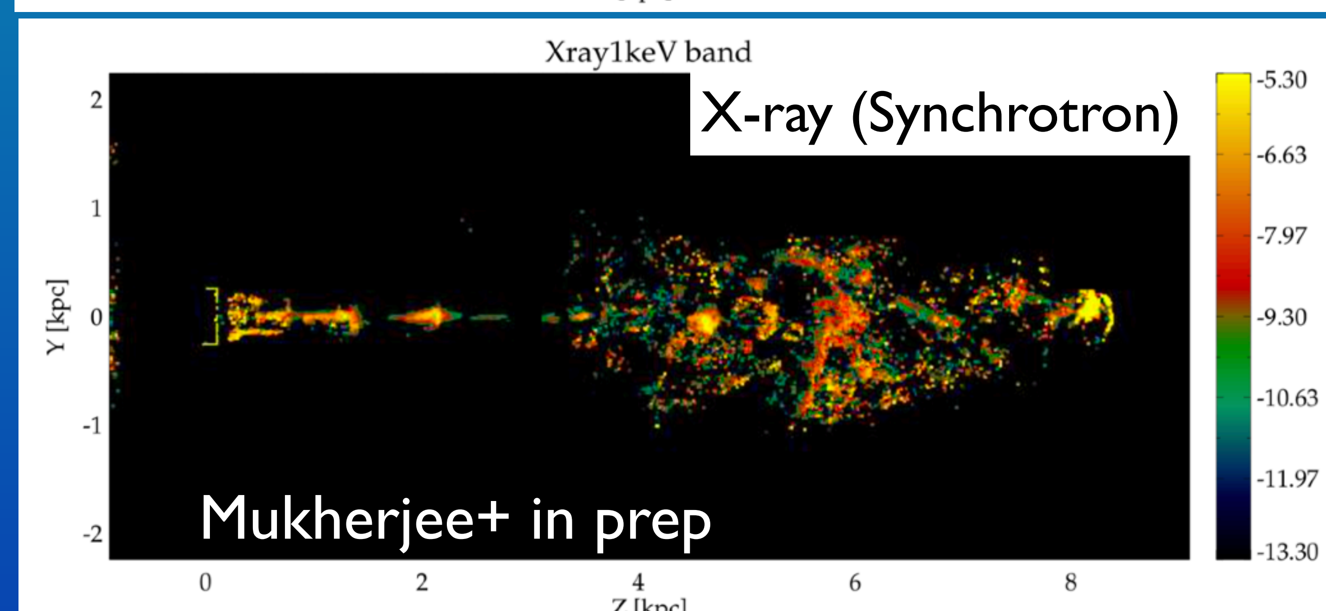
CRE Re-acceleration



Mukherjee+ 2021

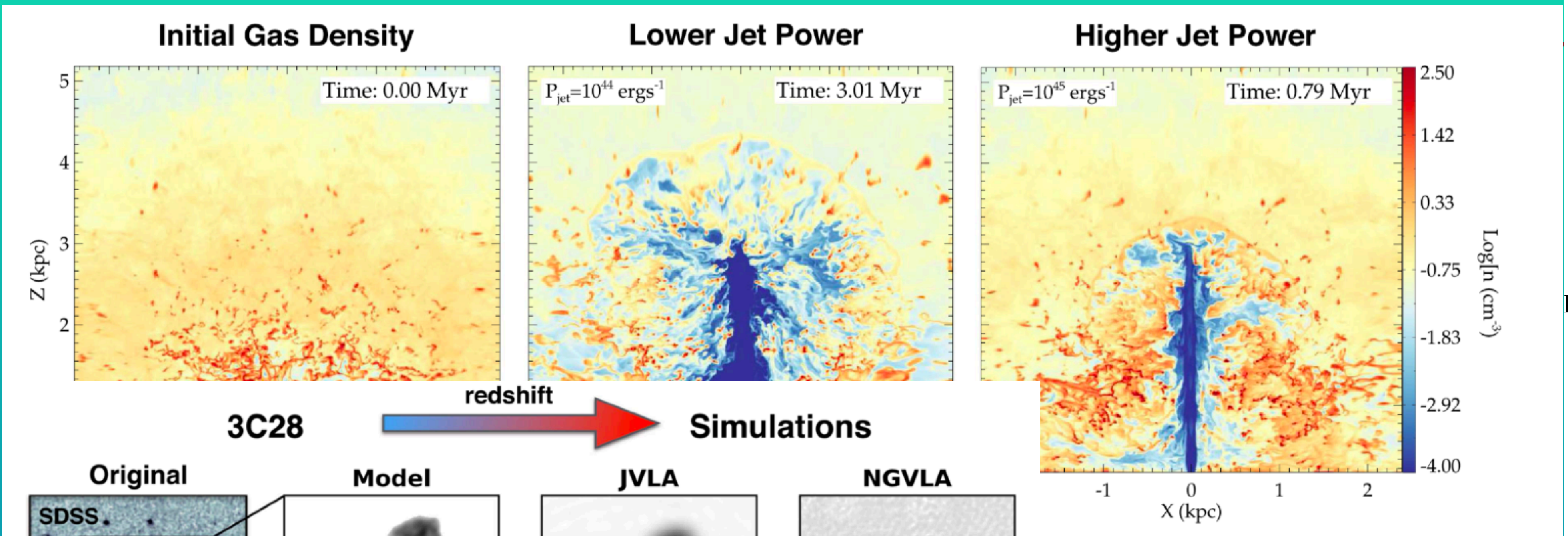


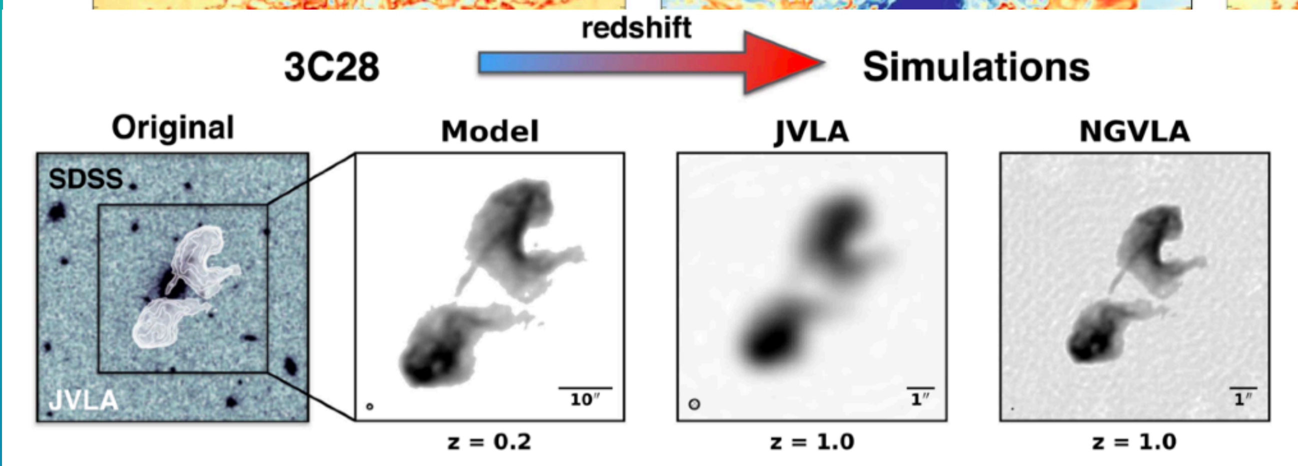




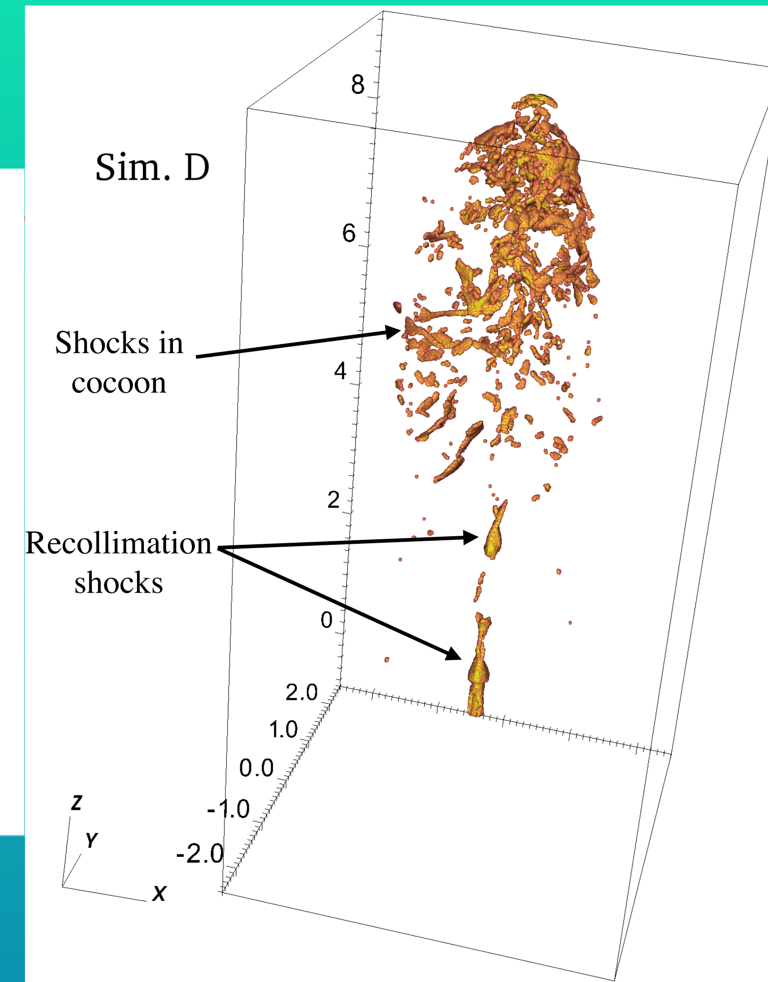
- Mixing of CREs with different shock histories in turbulent cocoon
- CRE spectrum has imprints of different pops. Not just a power-law with cut-off.
- Electron spectrum varies with region.
- Internal shocks reflected at synchrotron at higher frequencies

Summarising …





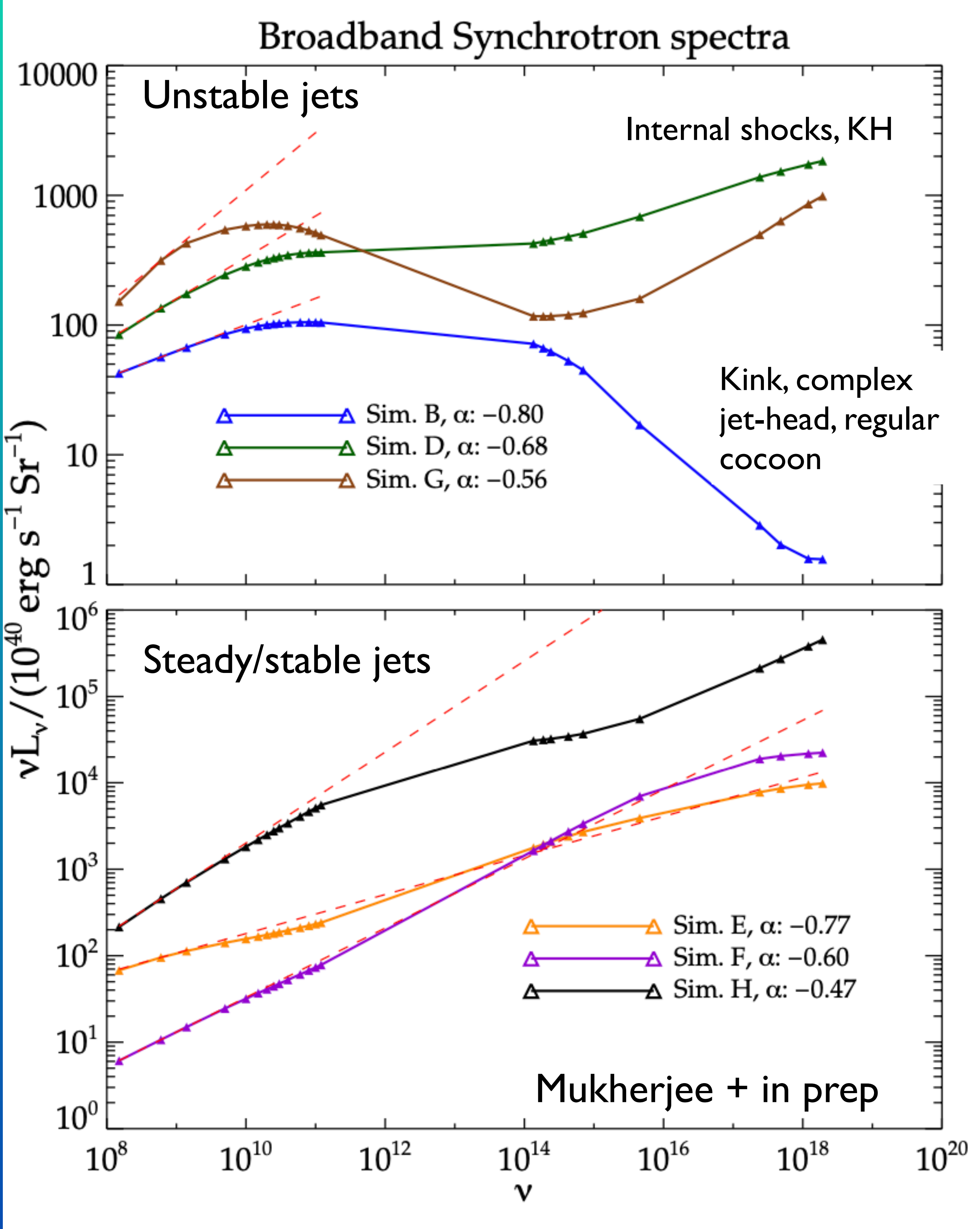
Nyland, DM+ 2018, an AGN feedback case for NgVLA

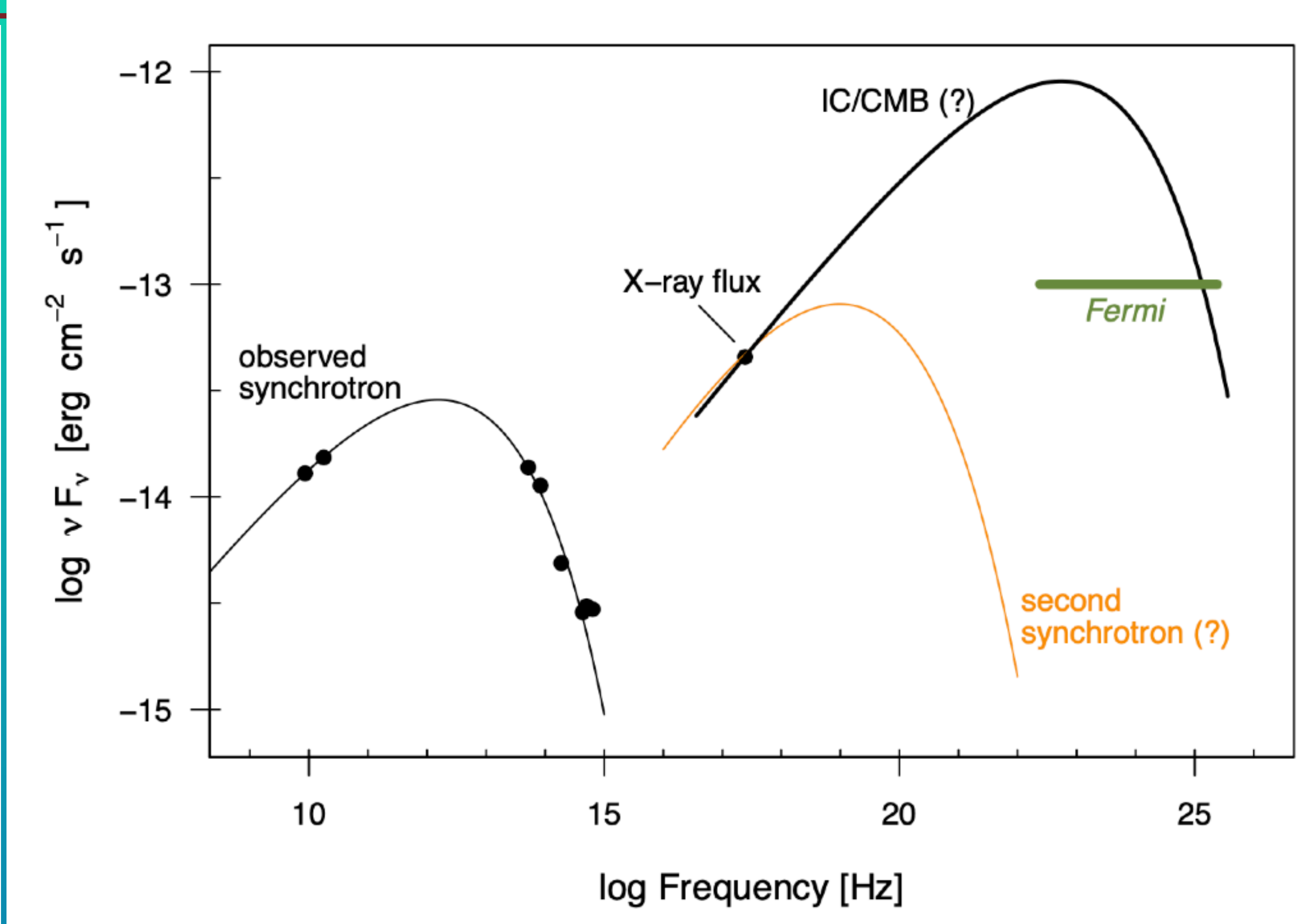


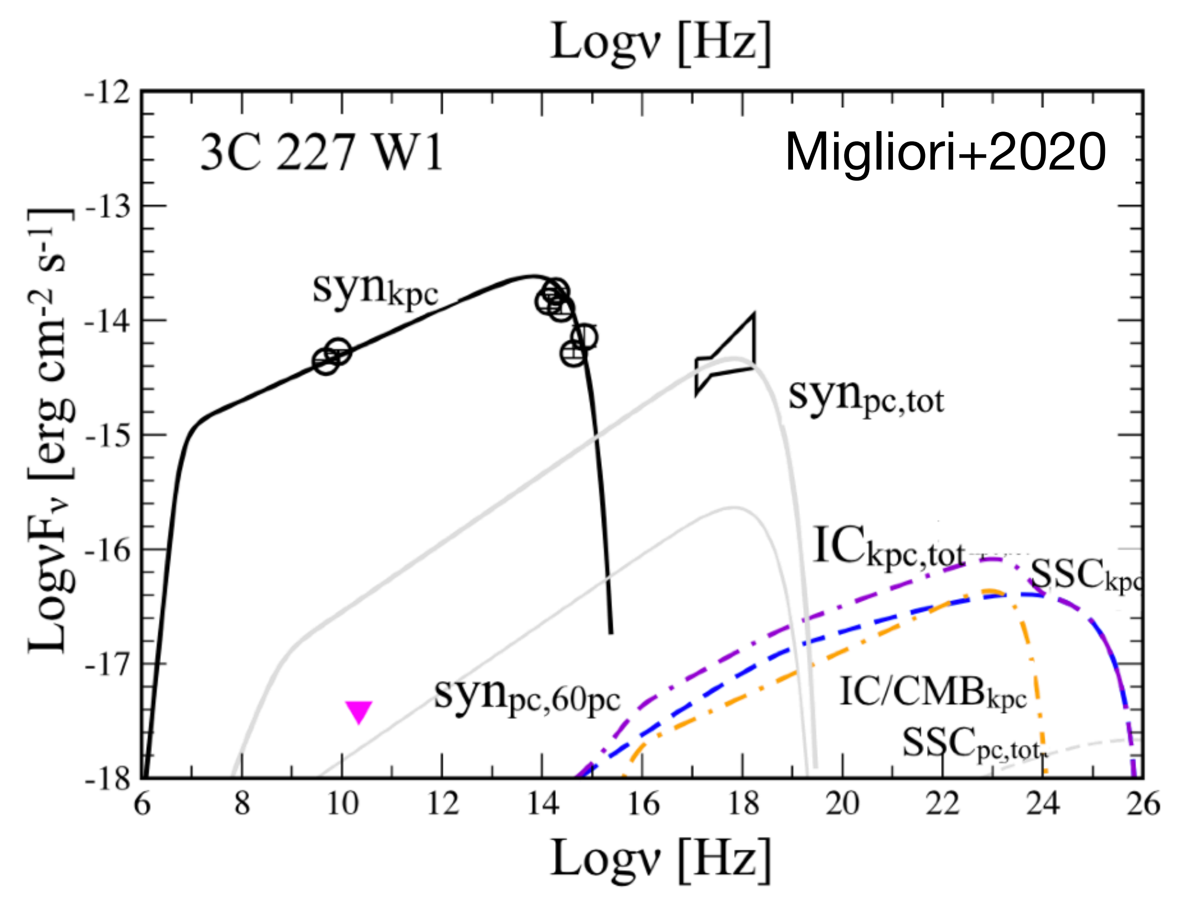
- Within the galactic potential jets couple strongly with host's ISM
- **Low power jets are important!** Couple more with the ISM, will induce more turbulence and more numerous!
- Both **turbulence (-ive)** and **compression (+ive)** may affect SFR. Net **mass-loss/ ejection** difficult.
- Hybrid particle+RMHD simulations give new insights. Turbulence in unstable jets can **re-accelerate non-thermal electrons** at complex shocks

A shocked secondary population of CREs

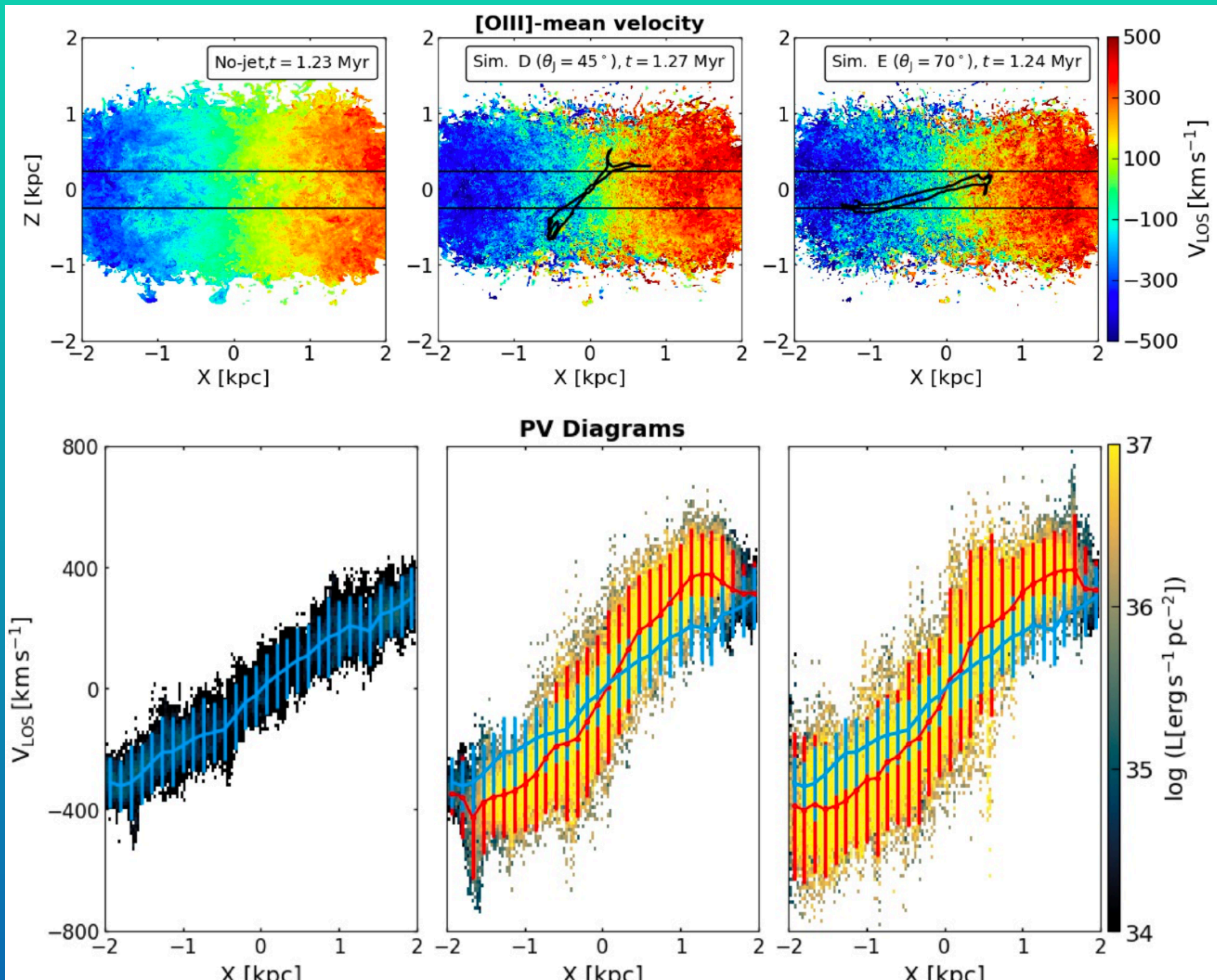
Meyer et al. 2015, on the lack of IC-CMB in PKS 0637-752

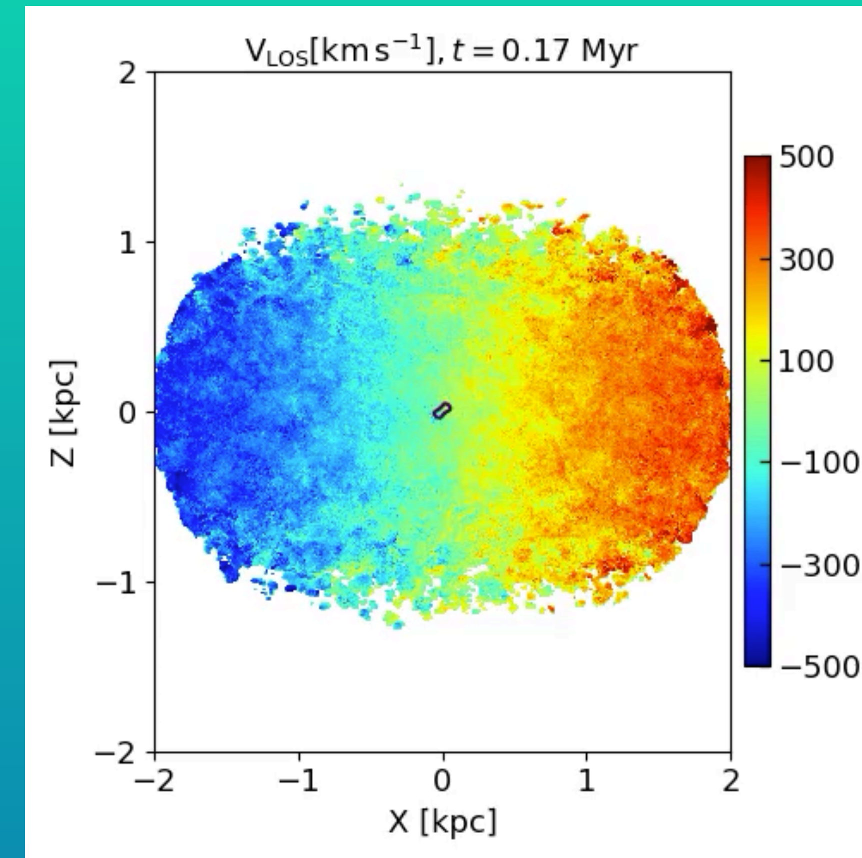


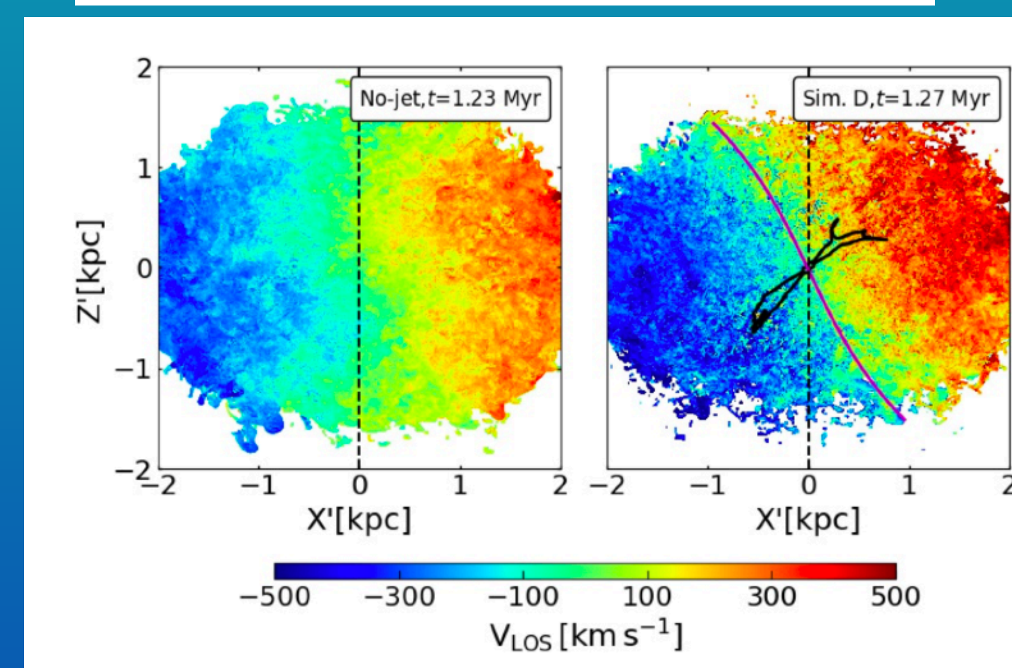




Distortions in the rotation profile





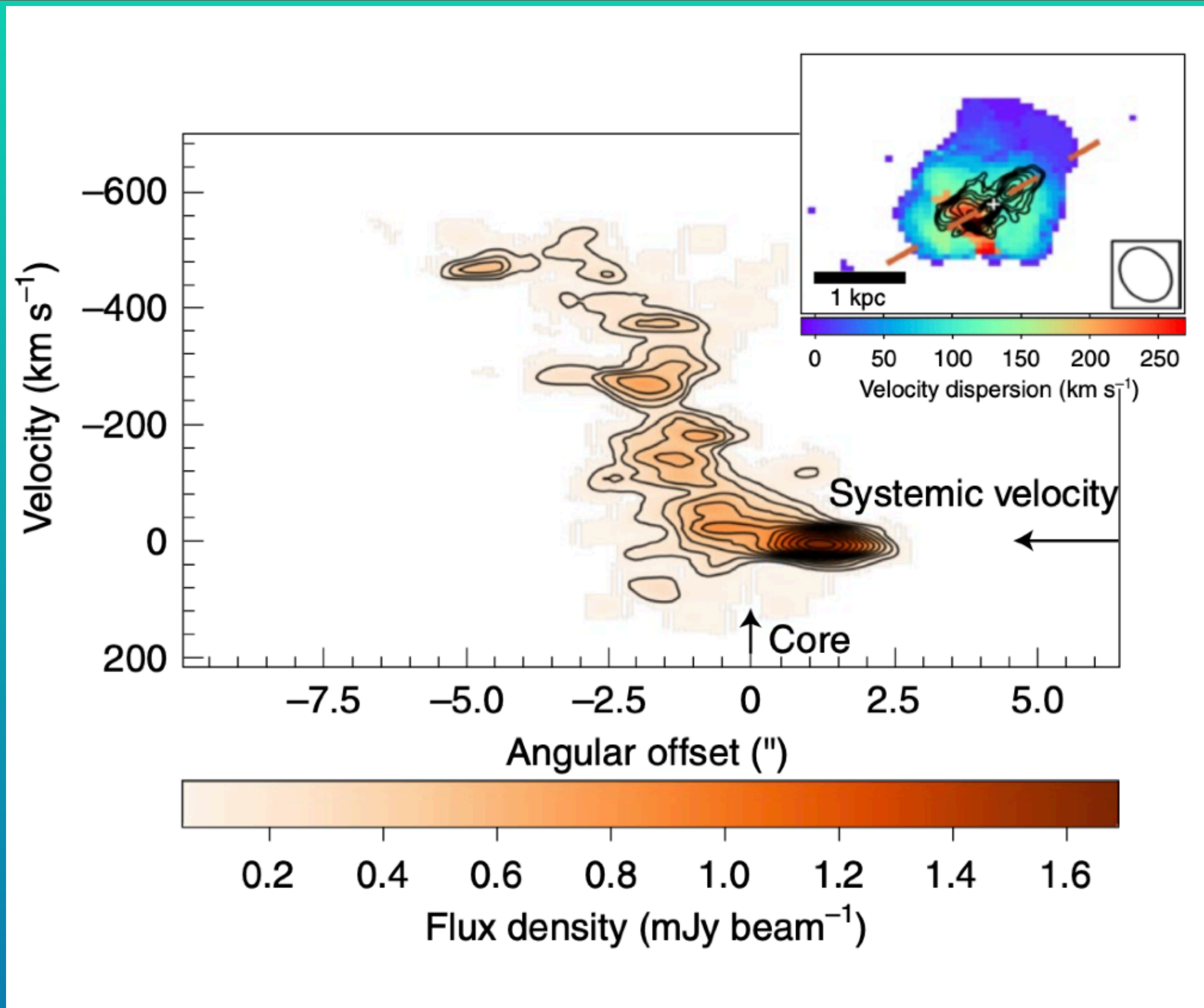


Outflows can change the rotation profile, making steeper PV slopes as well as distortions in apparent gas rotation axis.

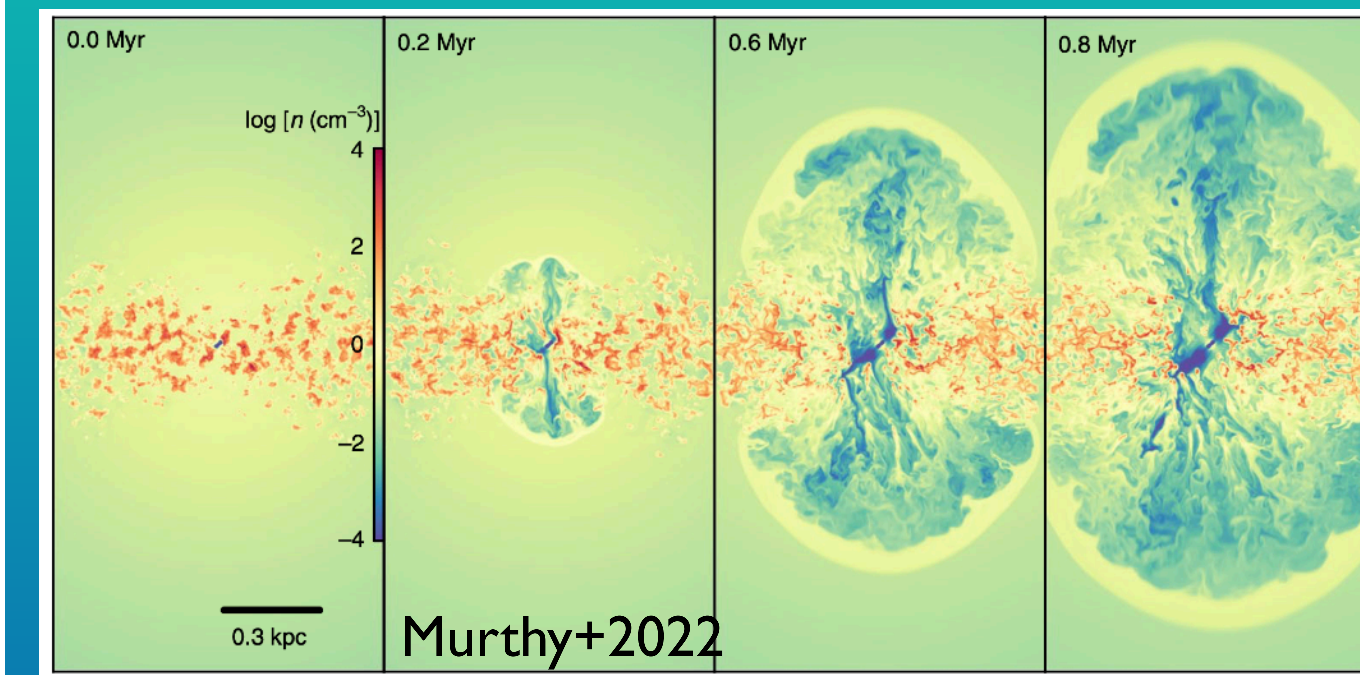
Meenakshi, DM + in press (arXiv: 2203.10251)

A weak radio-jet clearing gas in a galaxy

Murthy, Morganti..DM+2022, Nature A



A position velocity plot of outflowing CO. The outlow is offset from the core, indicating impact of jet hostpot.

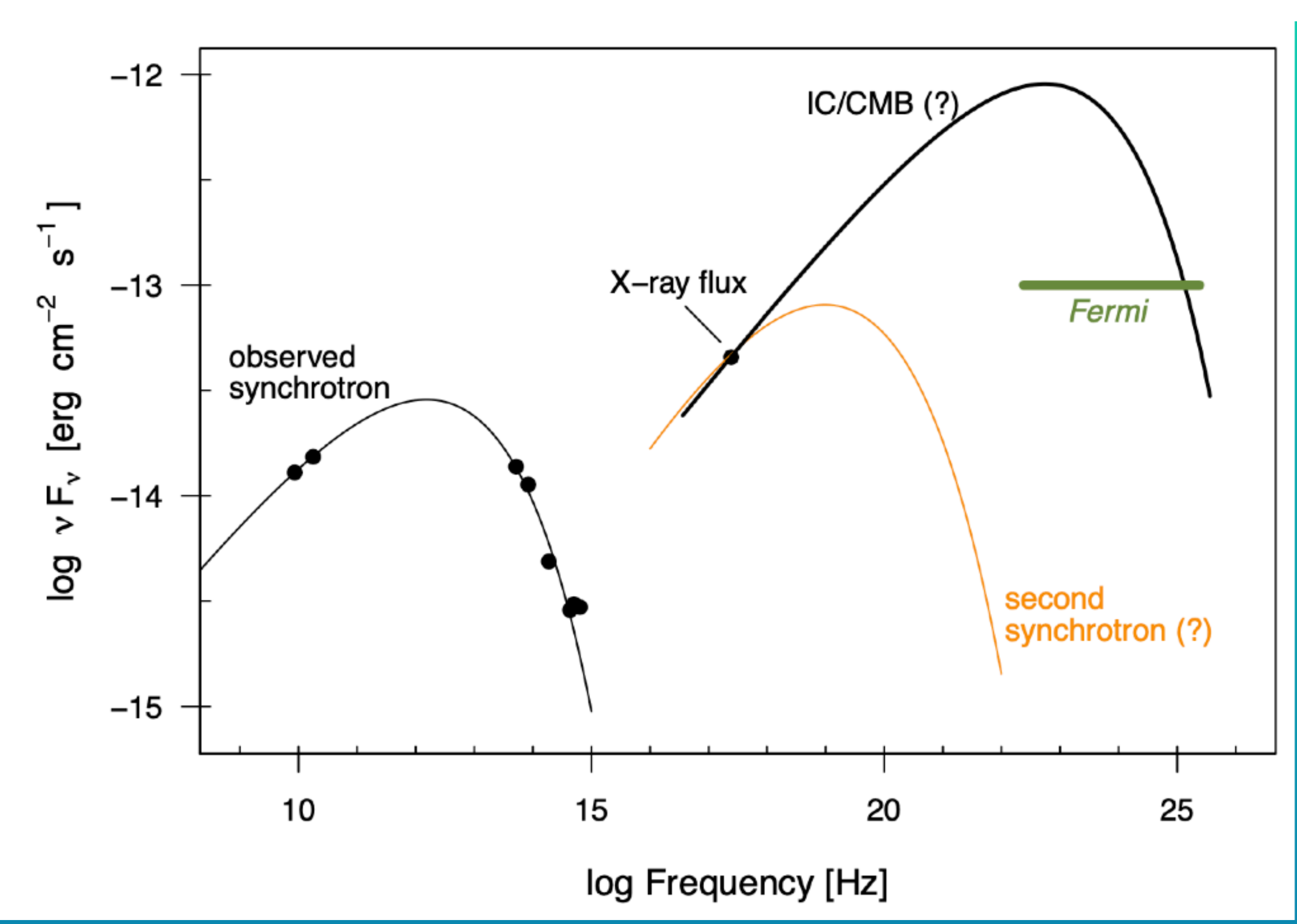


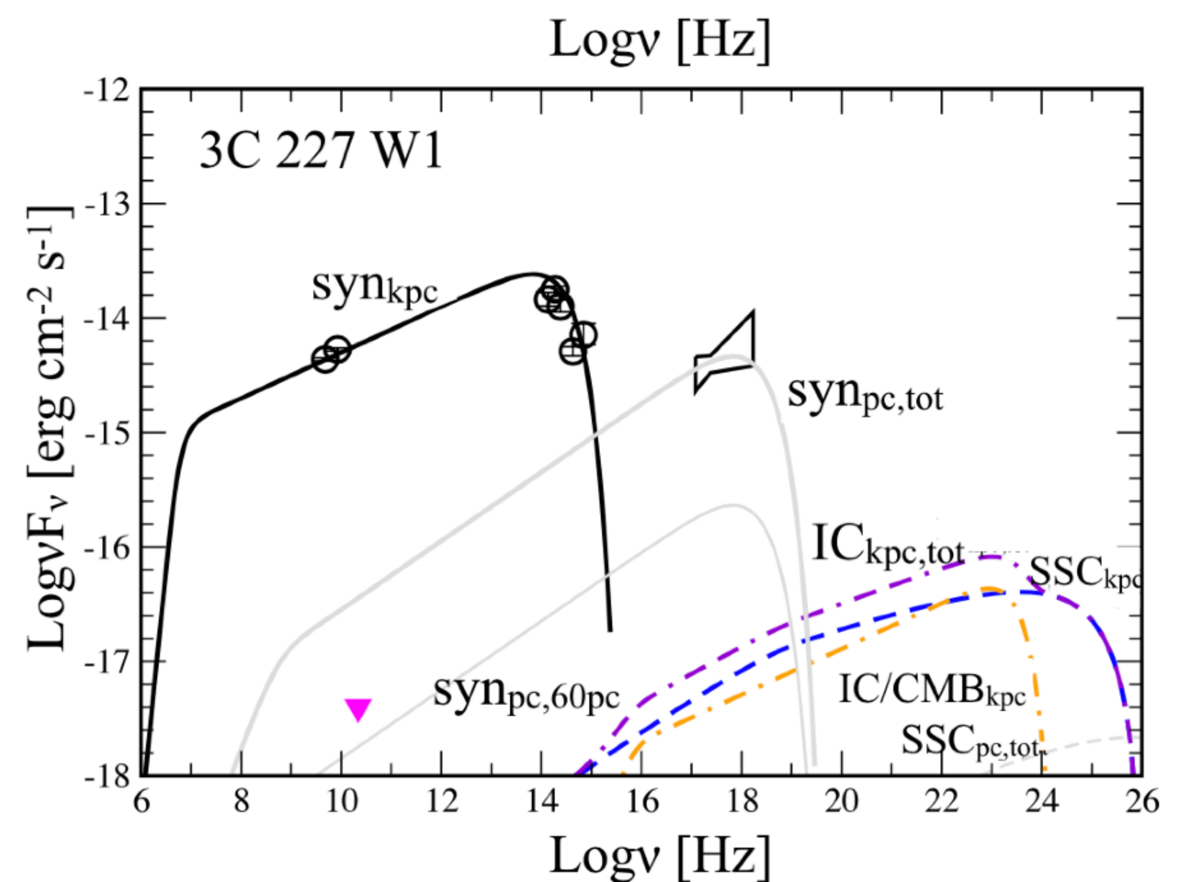
First unambiguous detection of a moderately powered radio jet driving an outflow that is clearing 75% of the central gas reservoir. Molecular gas (CO 1-0) was observed with NOEMA by colleagues at ASTRON. This was cross-matched with simulations performed by DM in Mukherjee et al. 2018. Confirms strong effect of local jet-feedback, as predicted by the sims.

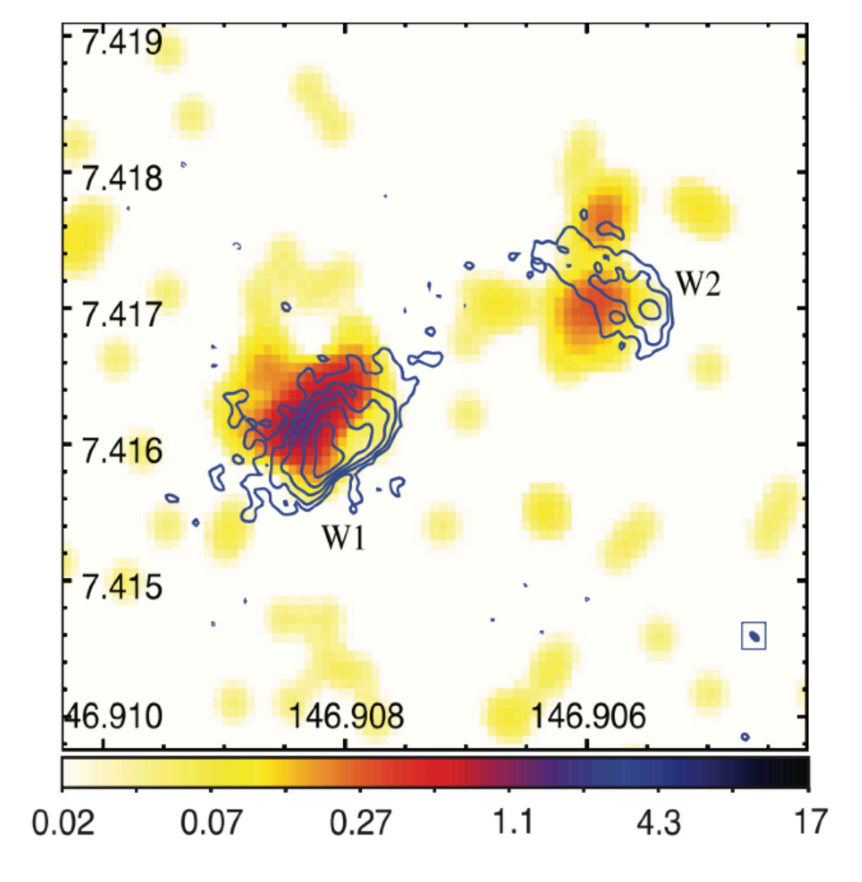
A shocked population of CREs

- The sites of strong shocks (both terminal and internal cocoon shocks) can host highly energetic electrons.
- These can be described as a distinct secondary population of energised electrons, separate from the other cooling pop.
- This has been hinted in some recent observations of Xrays from jets.

Meyer et al. 2015, on the lack of IC-CMB in PKS 0637-752

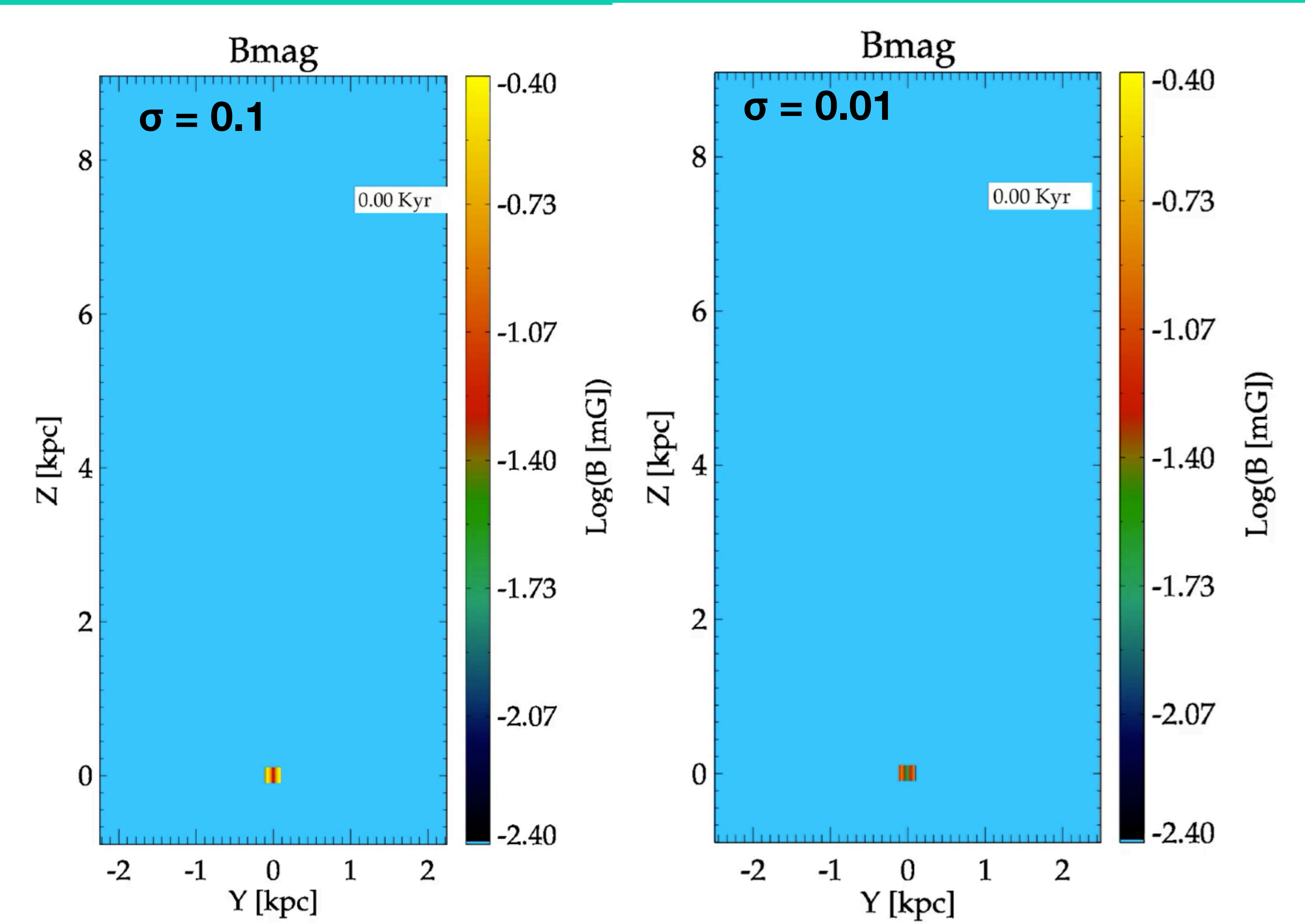


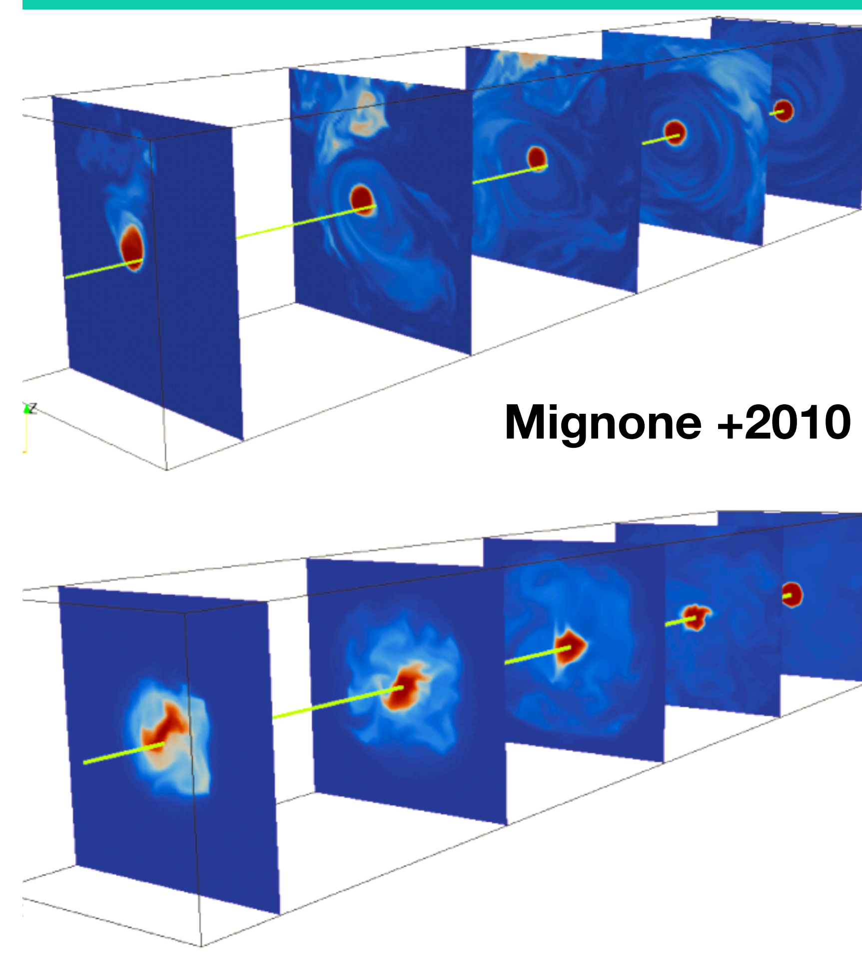




Co-incident Xray and radio in 3C-227 by Migliori et al. 2020

KH modes, turbulence & magnetic collimation

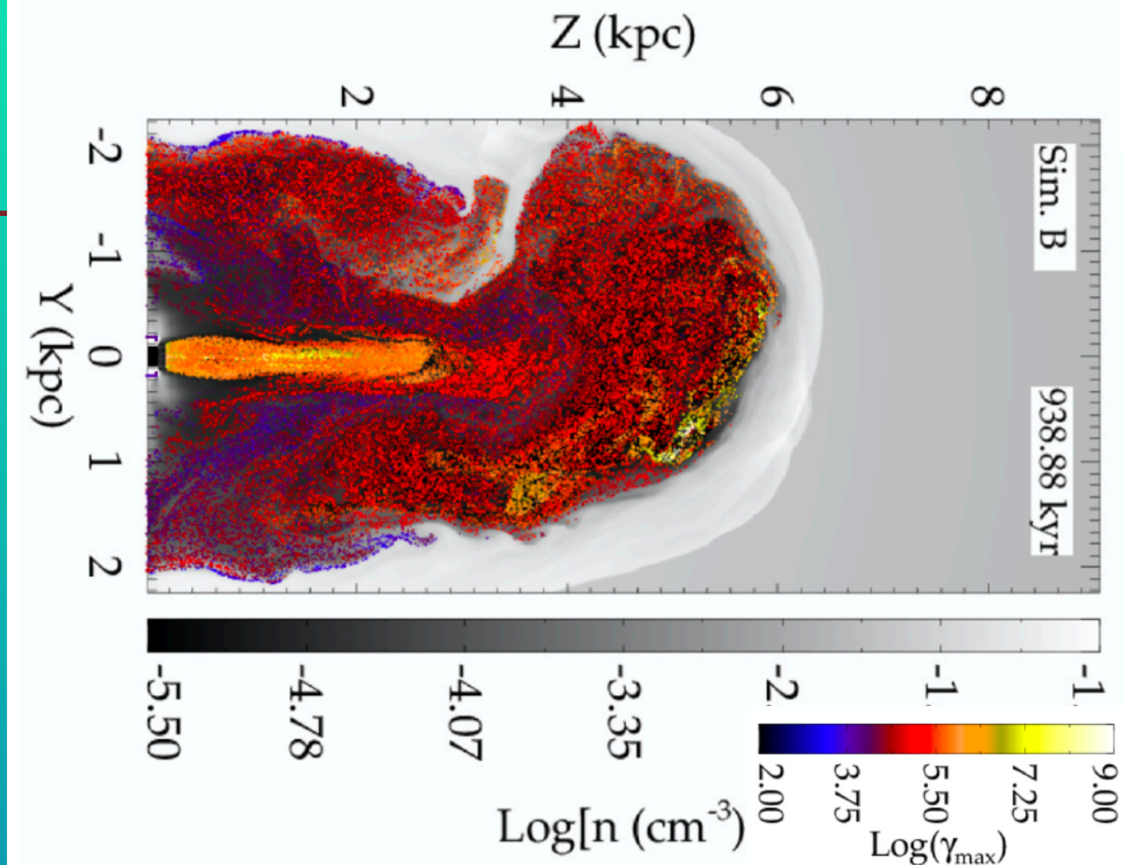




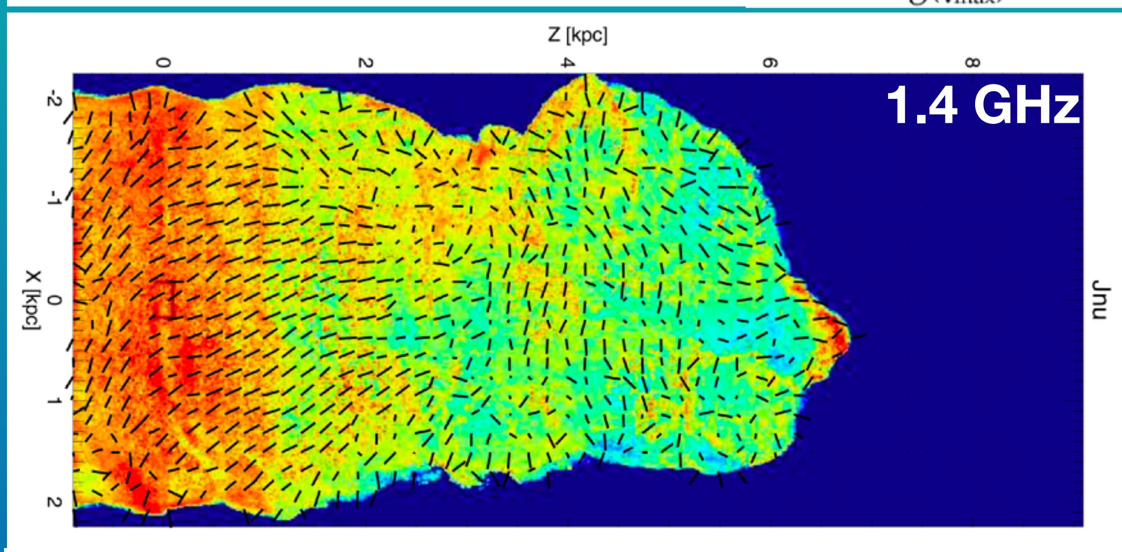
Stronger magnetic field: shields the inner flow from shear, suppresses higher order kink modes

Weaker fields: stronger shear and mixing; turbulence

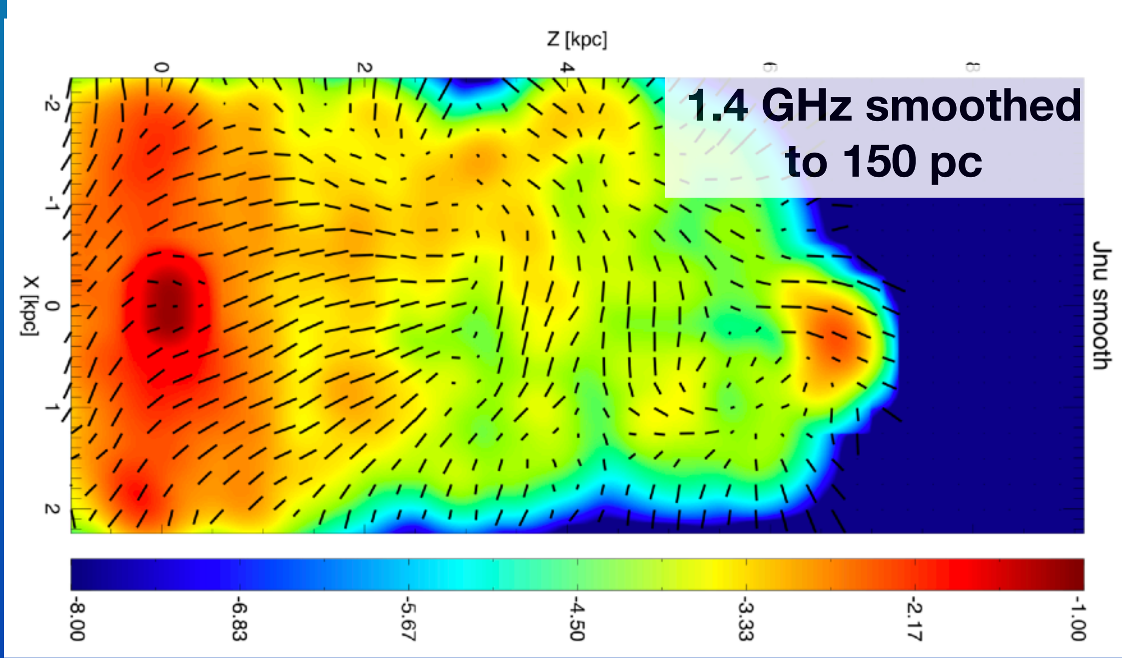
Kink modes



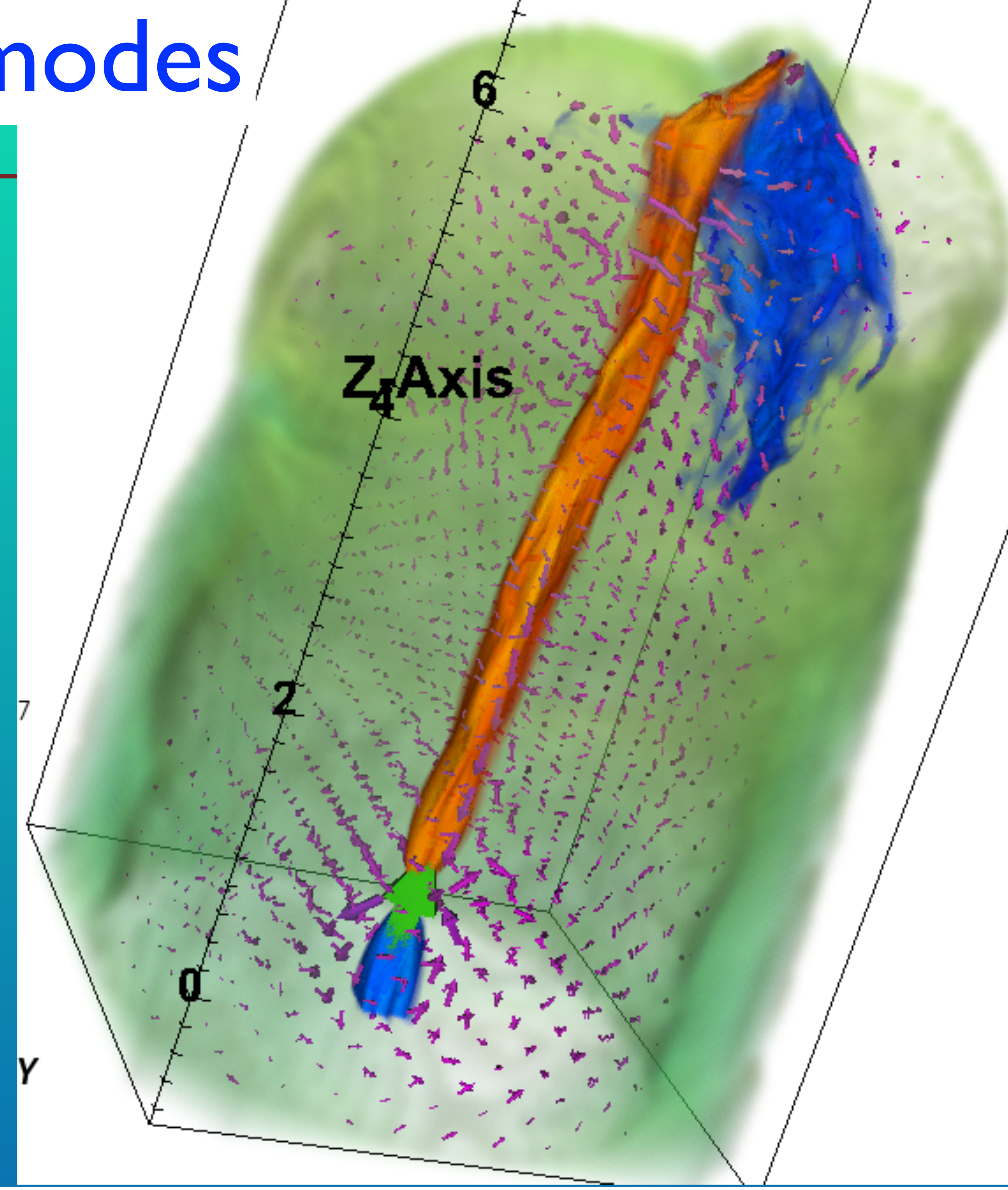
Z (kpc)
Y (kpc)
Sim. B
938.88 kyr
Log[n (cm^{-3})]
Log(γ_{max})



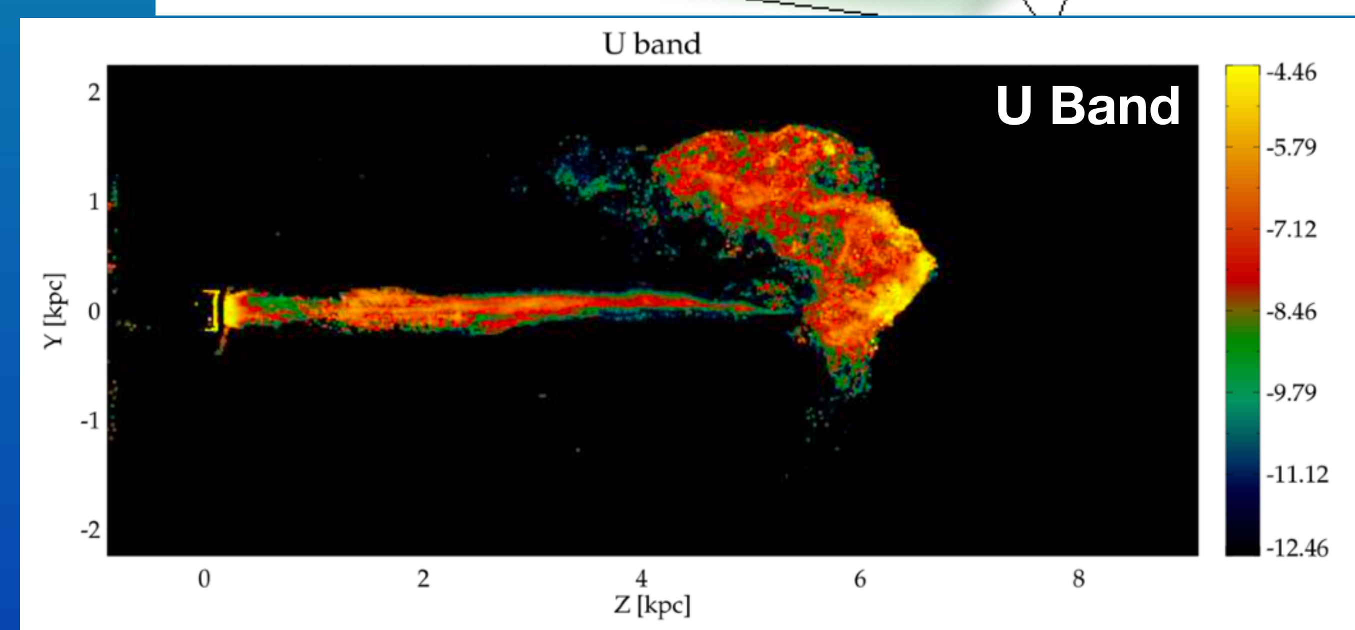
1.4 GHz
Z [kpc]
X [kpc]
Jnu



1.4 GHz smoothed to 150 pc
Z [kpc]
X [kpc]
Jnu smooth



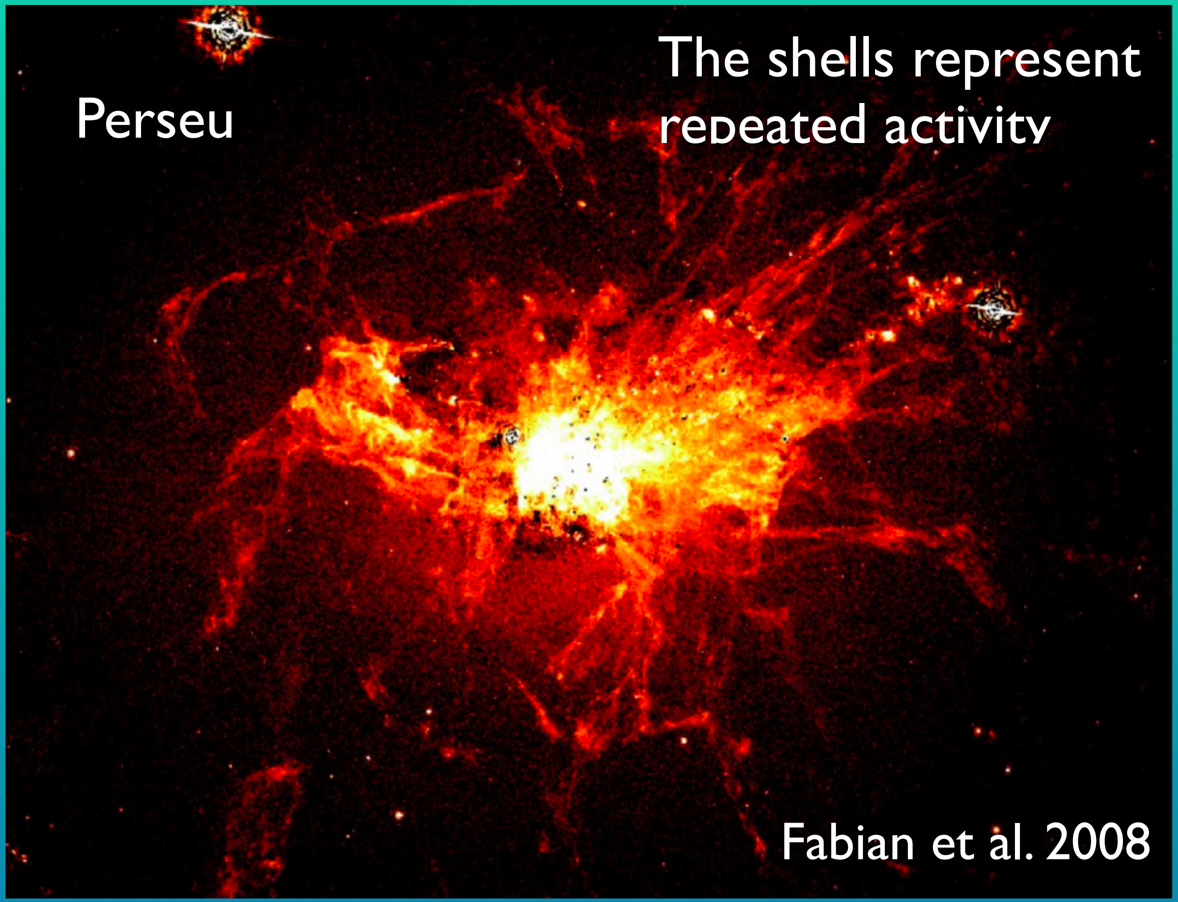
Z Axis
Y

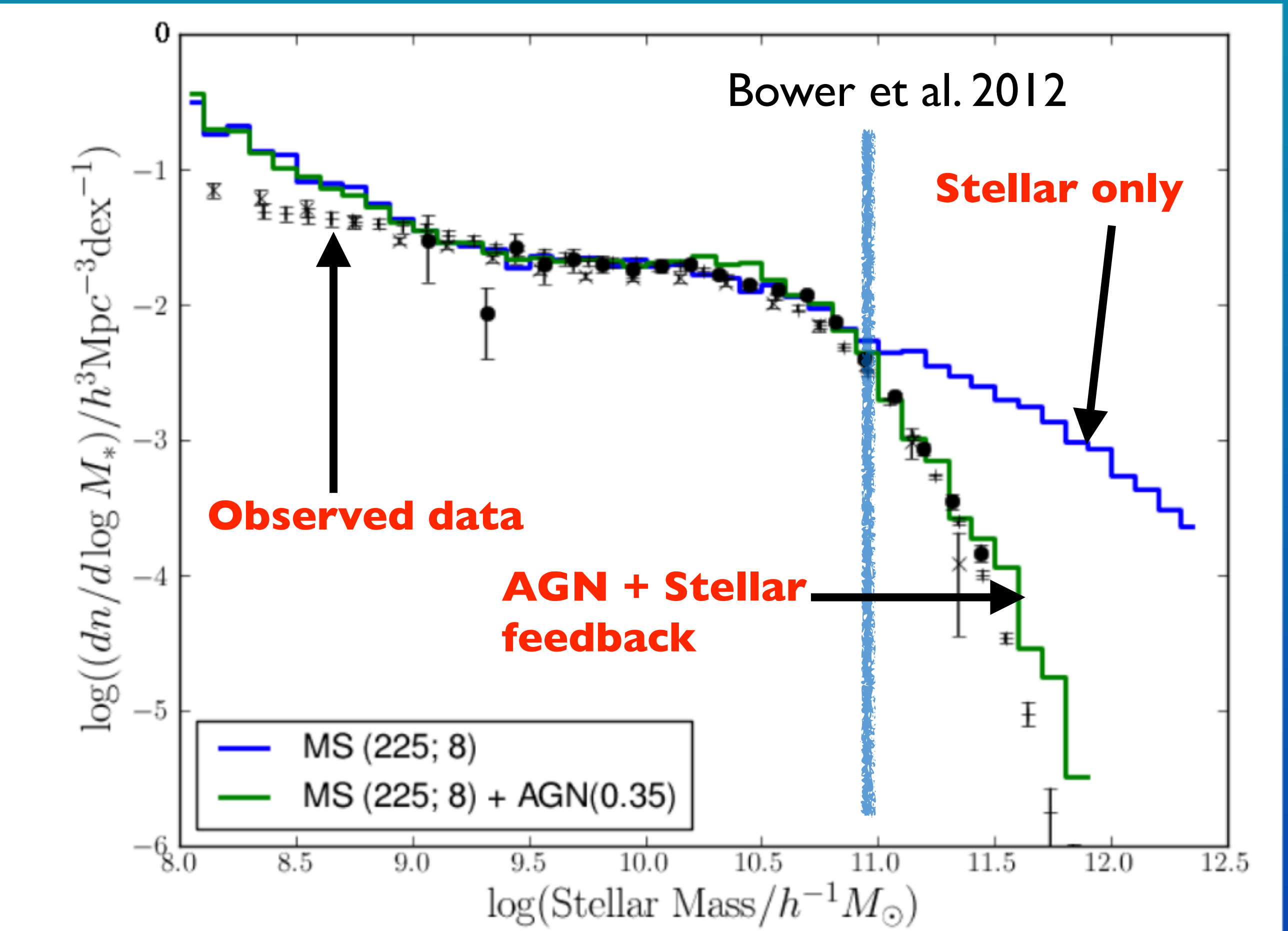


U band
U Band
Y [kpc]
Z [kpc]

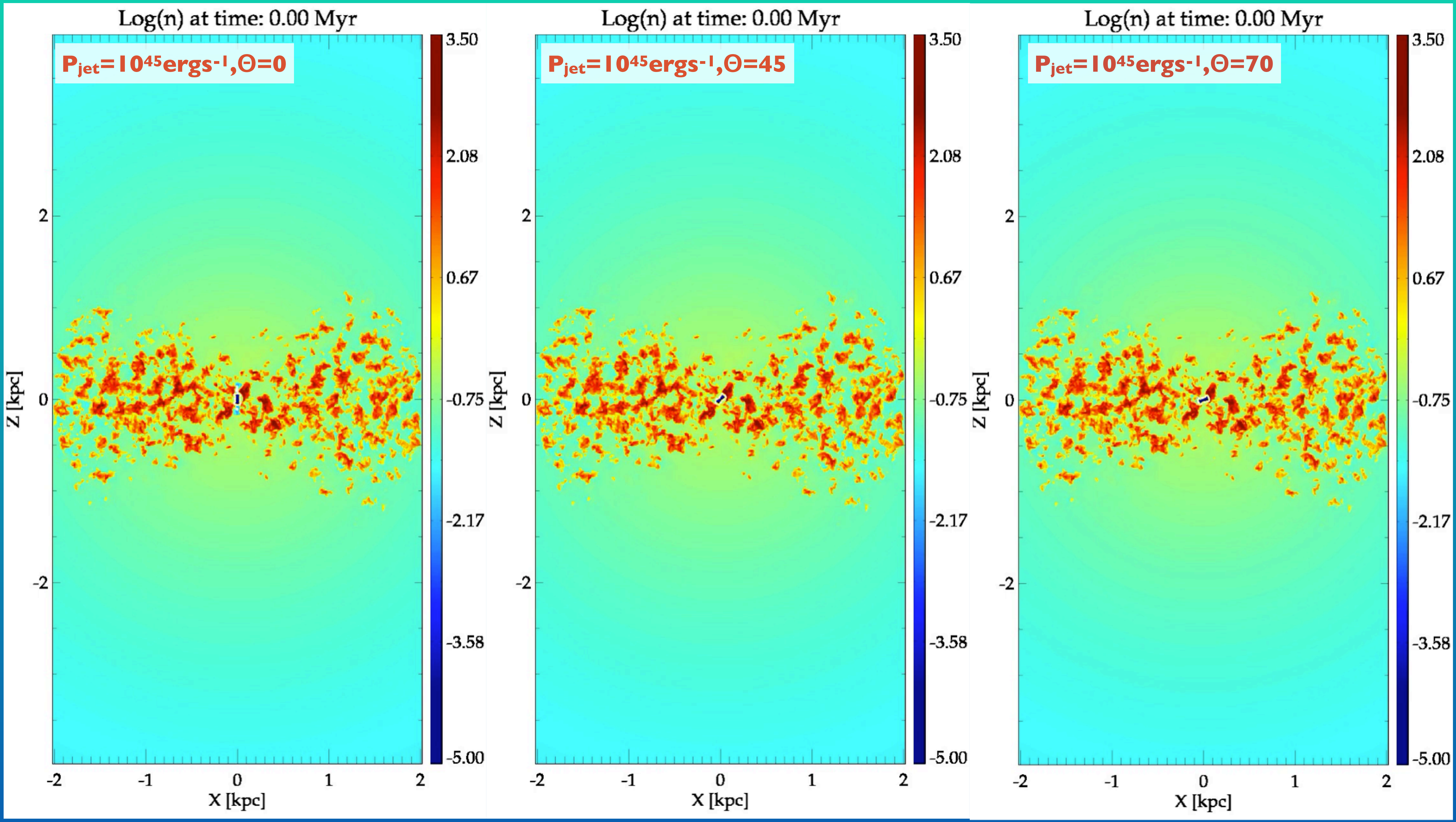
Jets as a source of feedback: from kpc to IGM scales

- The good: powerful, very large & extended, more efficient in momentum transfer
- Can potentially transfer energy to large extra-galactic scales.
- The bad: collimated, thin. Efficiency and volume coverage?
- Energy from AGNs are a key ingredient in galaxy evolution.
- What is the role of jets? The two feedback modes in literature: Quasar vs radio *oversimplifies* impact of jets.





Jet-disk interaction



- Inclined jets couple more with turbulent disc
- More clouds are lifted off the disc
- The cavity is filled with ablated thermal gas + non-thermal plasma

Mukherjee+2018b

Feedback from lower power confined jet