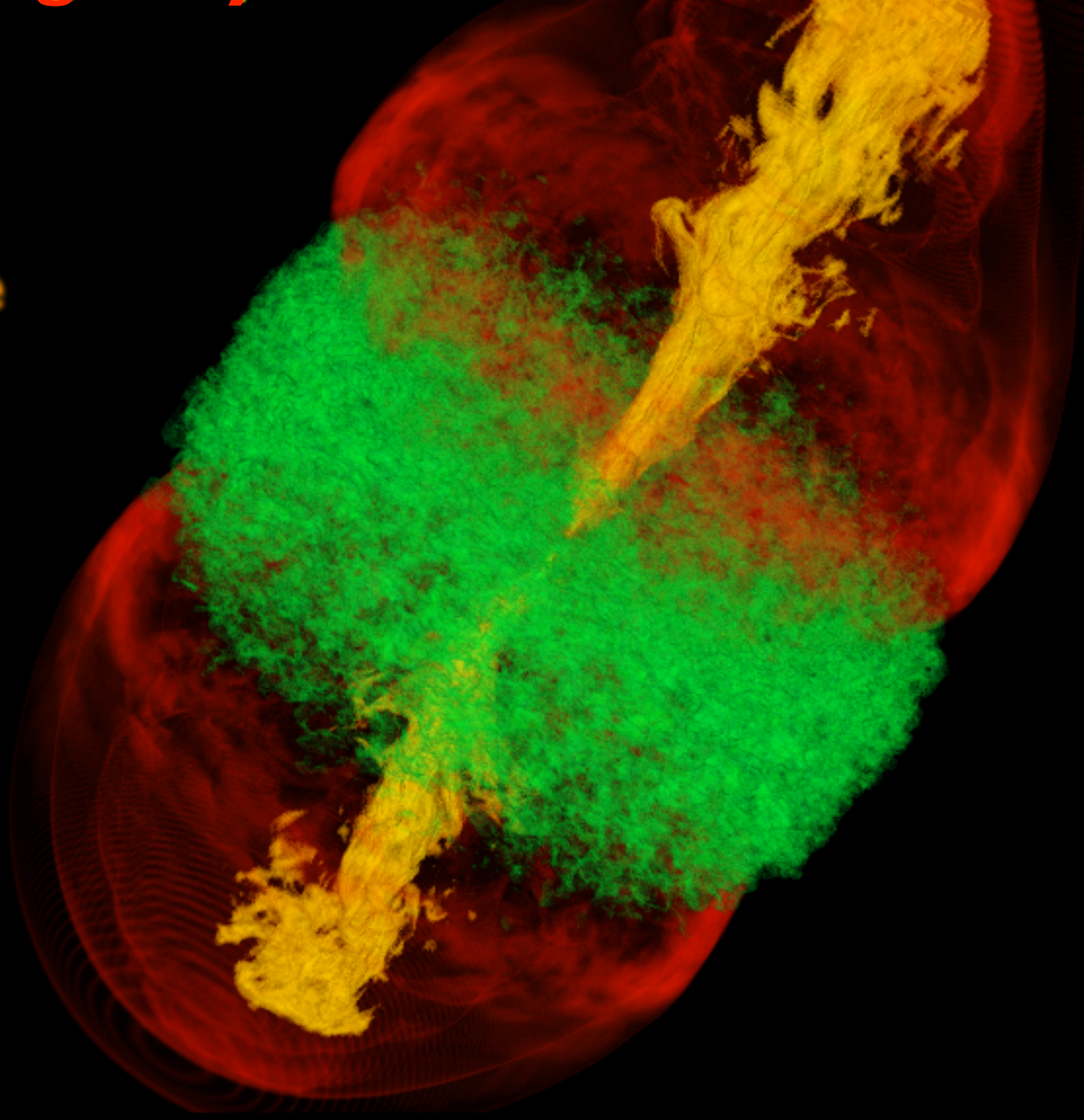
Impact of relativistic jets on the ISM of their host galaxy

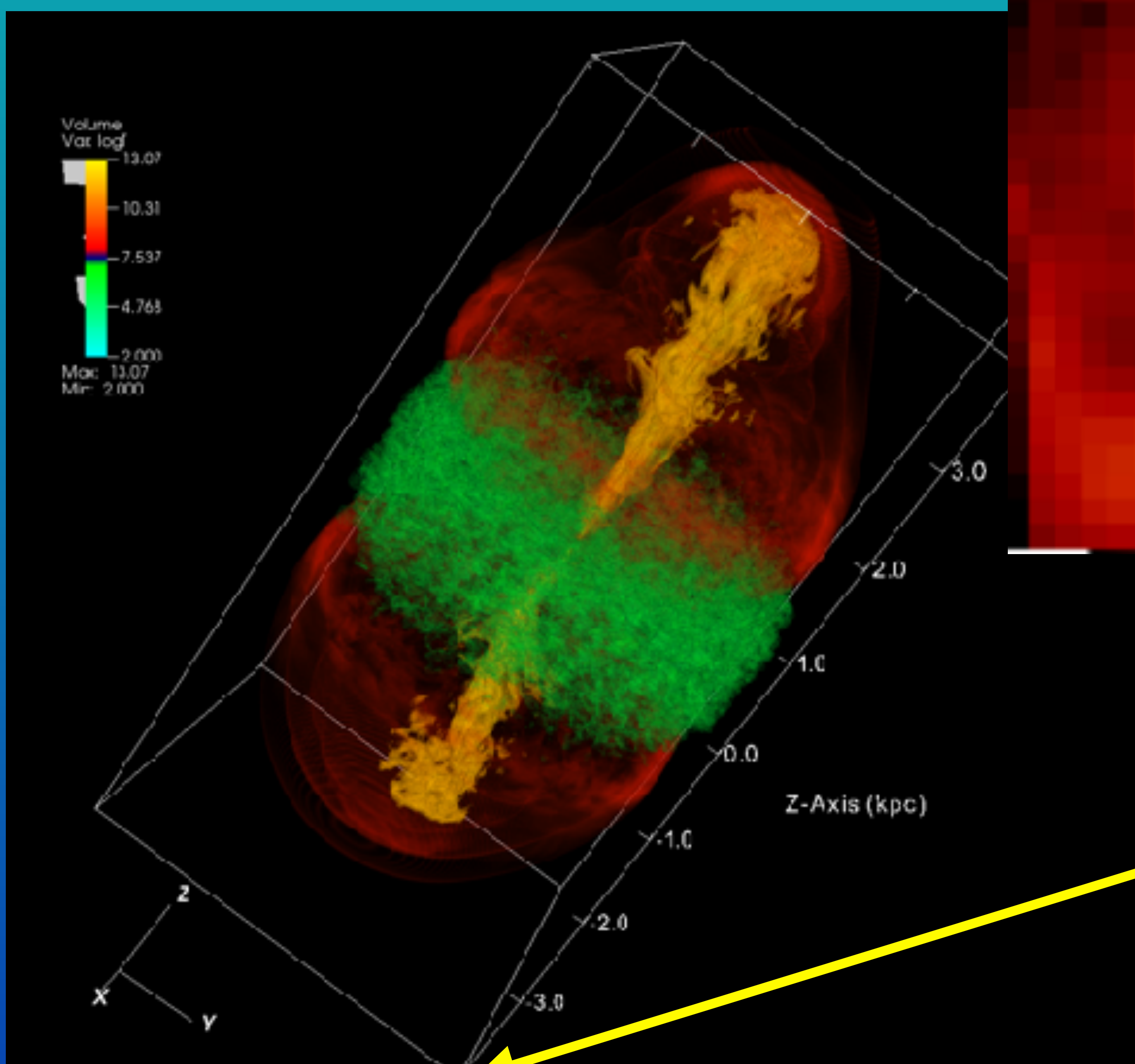


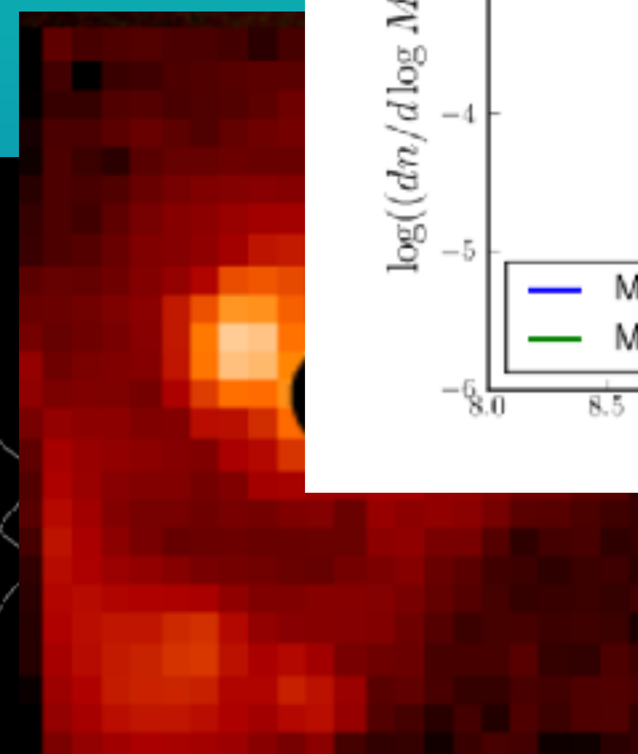
Dipanjan Mukherjee
Universita di Torino

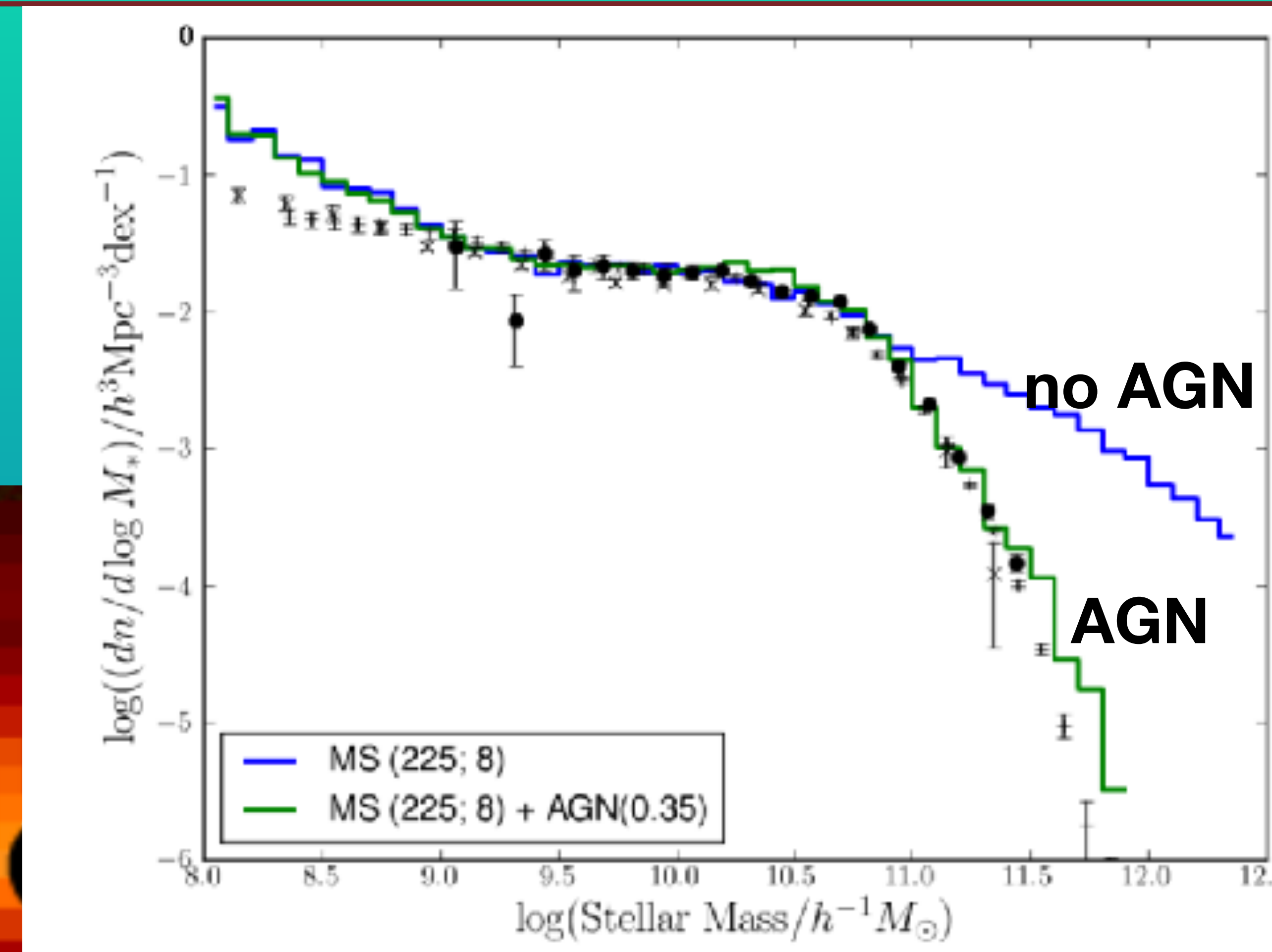
with
Geoff Bicknell
Alex Wagner
Ralph Sutherland

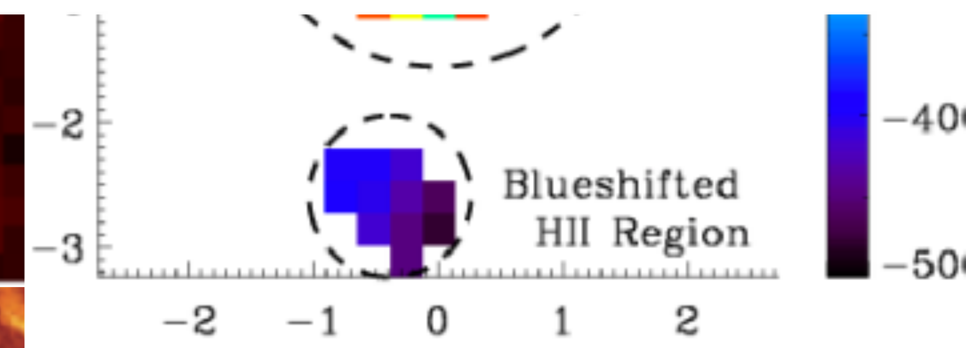
AGN feedback and galaxy

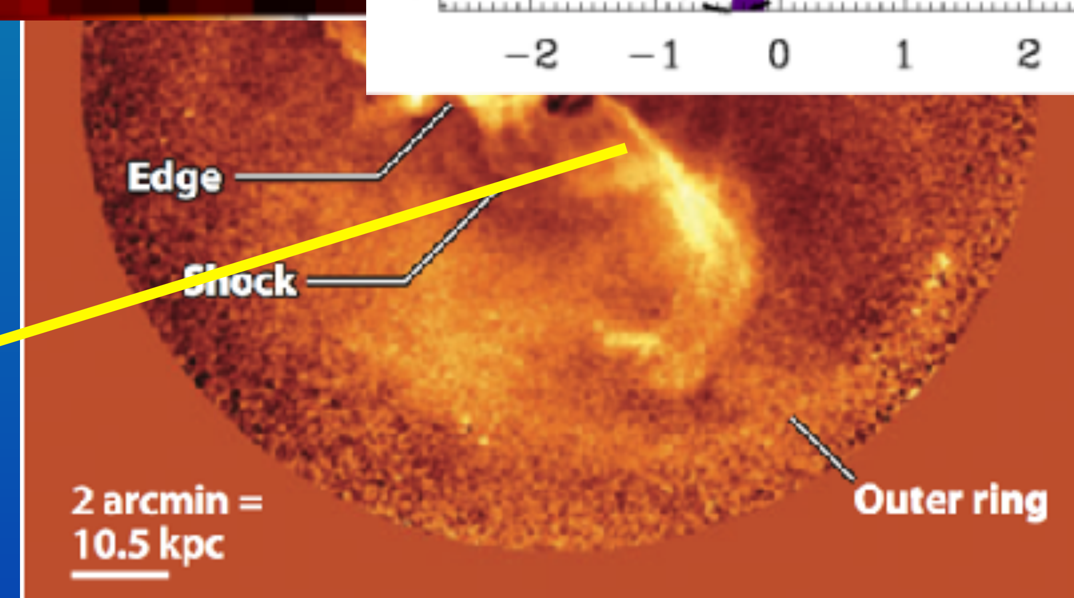
- AGN feedback crucial to match galaxy mass function
- Can be in the form of winds (Quasar mode/Establishment mode)











Some basic questions

- What is the effect of relativistic jets at galactic scales?
- Over what scales? Do the jets affect just a narrow channel or a wider region?
- Outflow? or turbulence? (both)
- How is SFR regulated? Is it ejective (outflows)? Preventive (turbulence)? Passive evolution (strangulation?)? (all?)
- What are the observational signatures of jet-ISM interaction?

The set up

We perform simulations (with PLUTO) of 3D relativistic jets from AGNs interacting with a turbulent ISM

- **Turbulent ISM:** fractal log normal density distribution with Gaussian velocity dispersion (values similar to forster-schreiber et al 2009).
- Different **ISM densities**, **morphology** (disk + spherical), **jet power**.
- Domain size ~ **5kpc**, resolution ~ **6pc**. External gravity (DM+Baryons). Atomic cooling via MAPPINGS V.

Simulation list

Spherical gas distriution

Densities: n_{w0} = 150-2000 cm^{-3}

Power = 10^{44} - 10^{46} $ergs^{-1}$

Disks

Densities: n_{w0} = 100-400 cm^{-3}

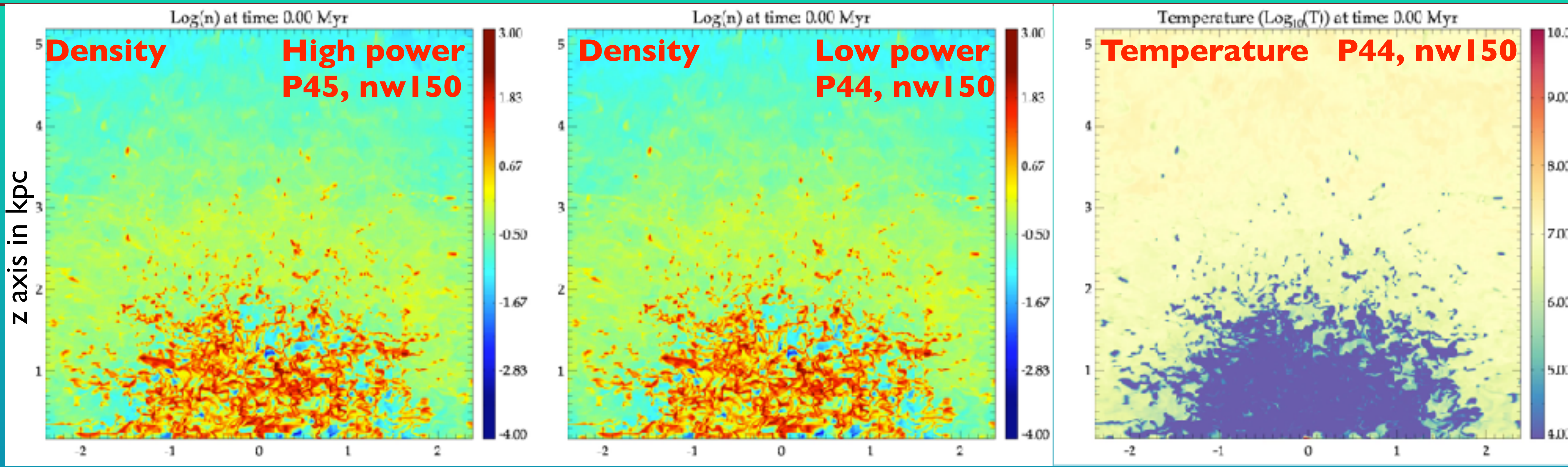
Power = 10^{45} - 10^{46} $ergs^{-1}$

Θ = 0, 20, 45, 70

Gas mass ~ 10^9-10^{10} $M_\odot$

No	Geometry	Power Log (P)	Density (n_{w0}, in cc)	Inclination
1	Spherical	44	400	
2		44	400	
3		45	400	
4		45	150	
5		45	200	
6		45	400	
7		45	1000	
8		46	2000	
9	Disk	45	100	0
10		45	200	0
11		45	200	20
12		45	200	45
13		45	200	70
14		46	100	0
15		46	200	0
16		46	400	0
17	IC 5063	45	200	90
18		44	200	90

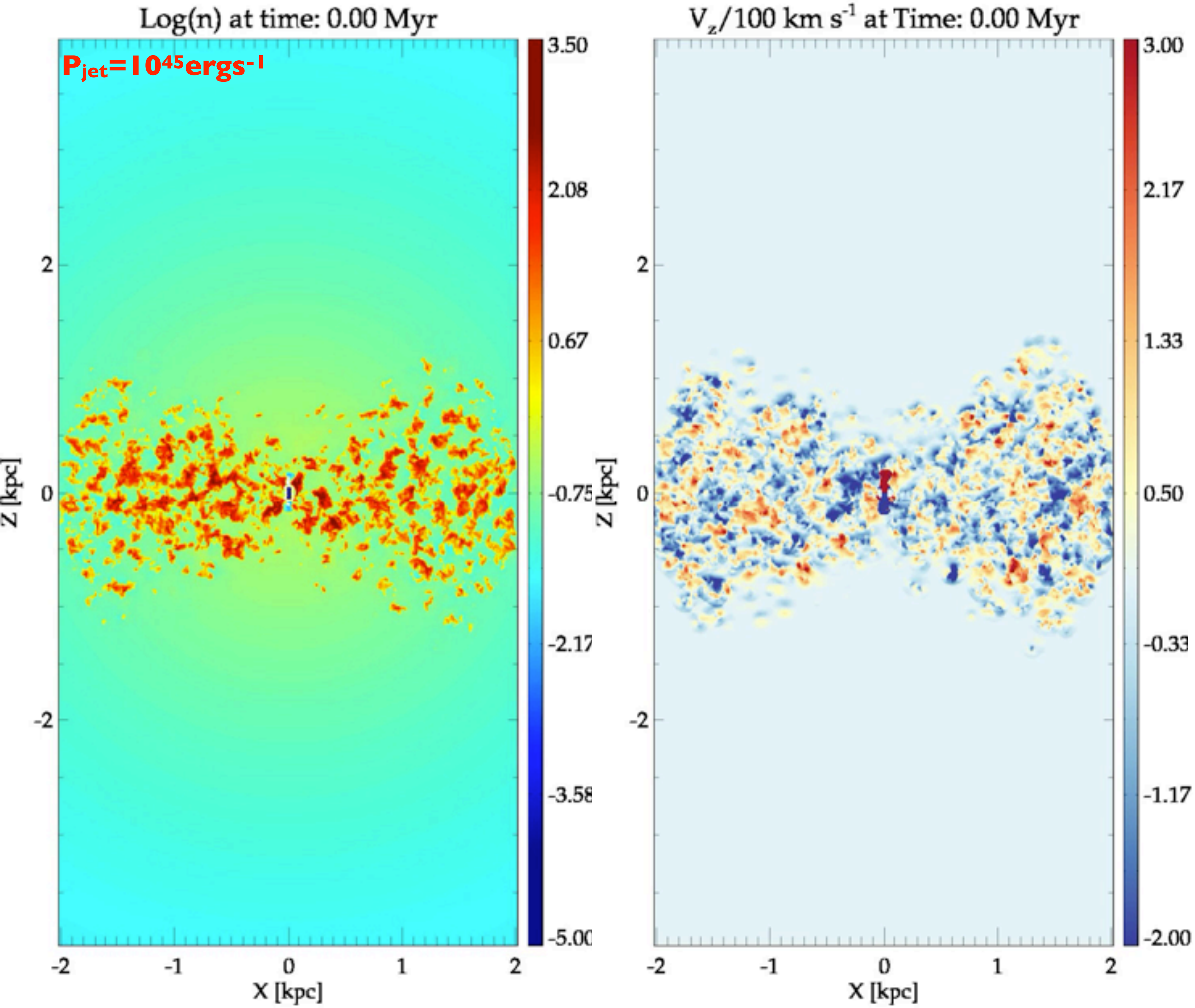
The dentist drill in spherical gas distribution

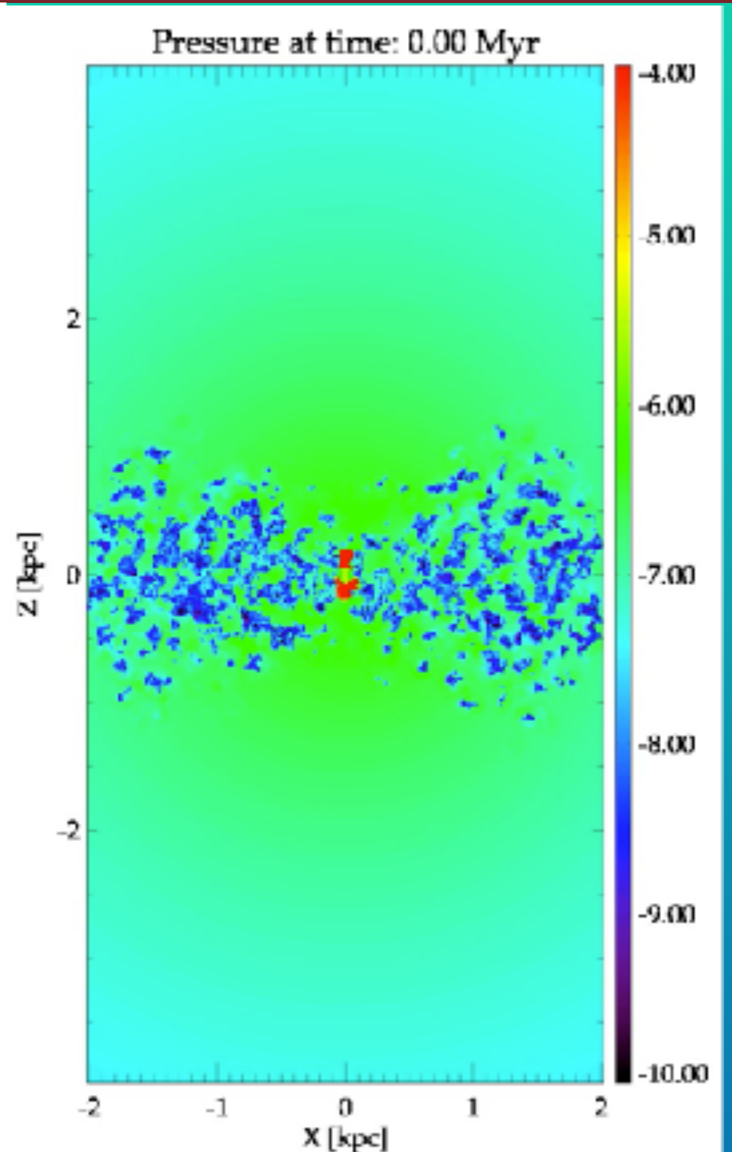


- Jets couple strongly with host's ISM.
- Launch **fast multiphase outflows** but not enough to escape.
- **Low power jets are important!** Couple more with the ISM, will induce more turbulence and more numerous!
- Gas distribution spherical. Easier to couple. **Disks?**

Mukherjee et al. 2016, 2017

Feedback in disk galaxies



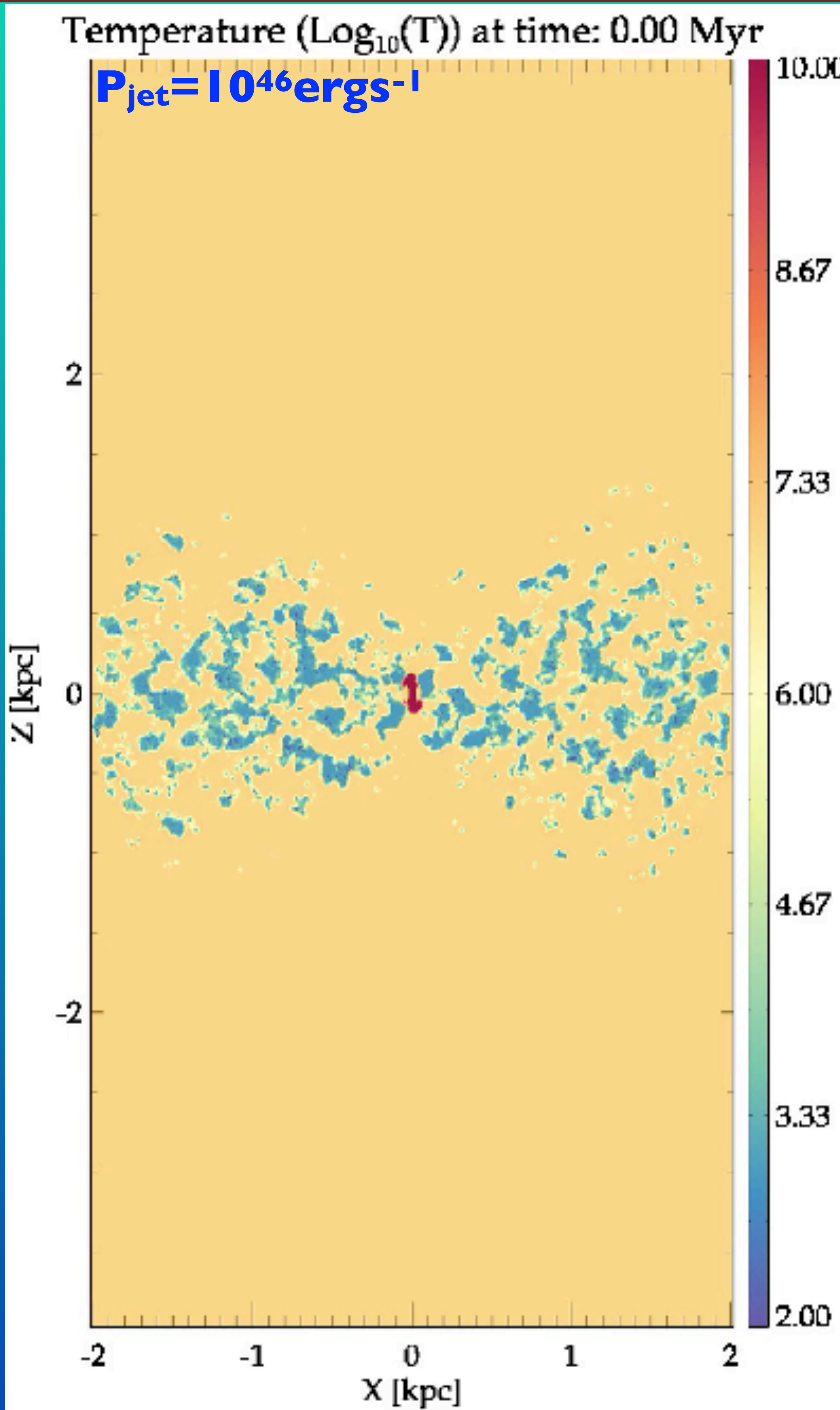


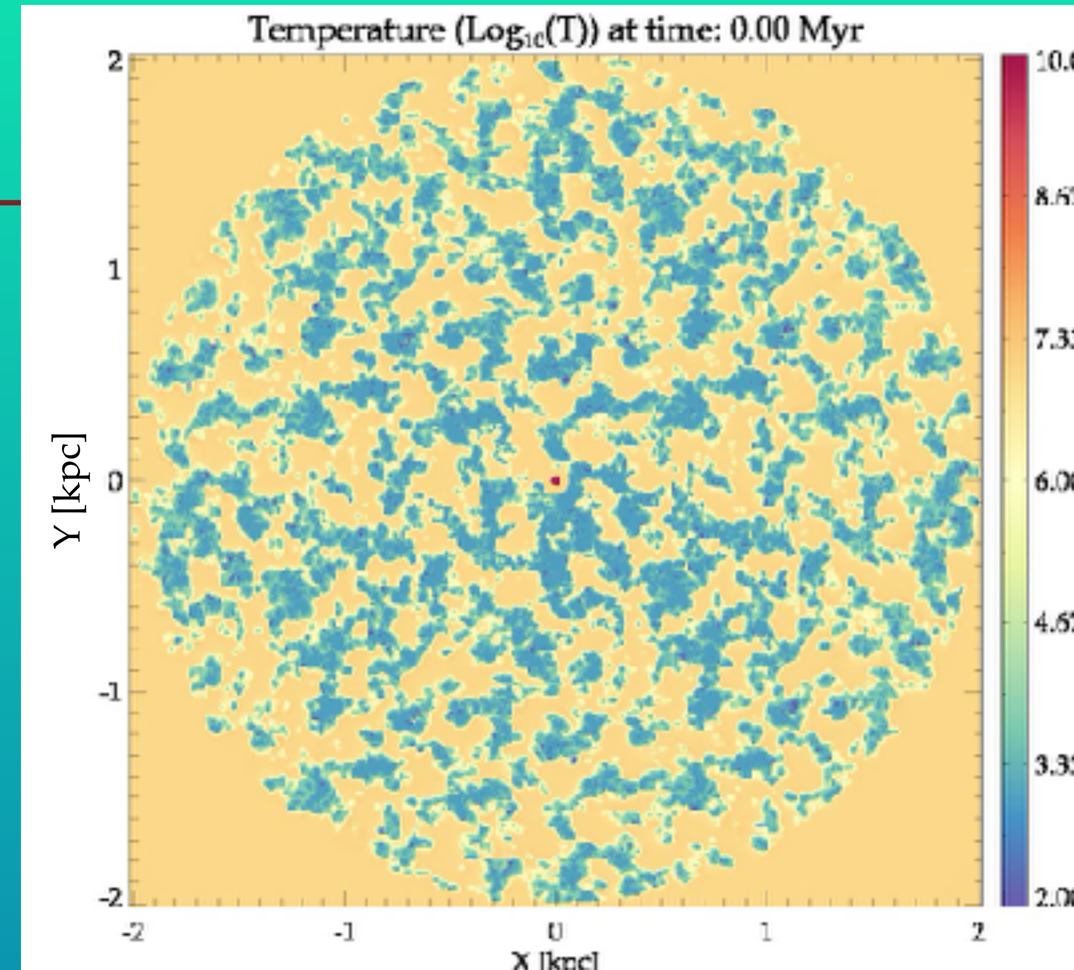
- Central outflow < 1kpc
- Compression & shocks on outer edges

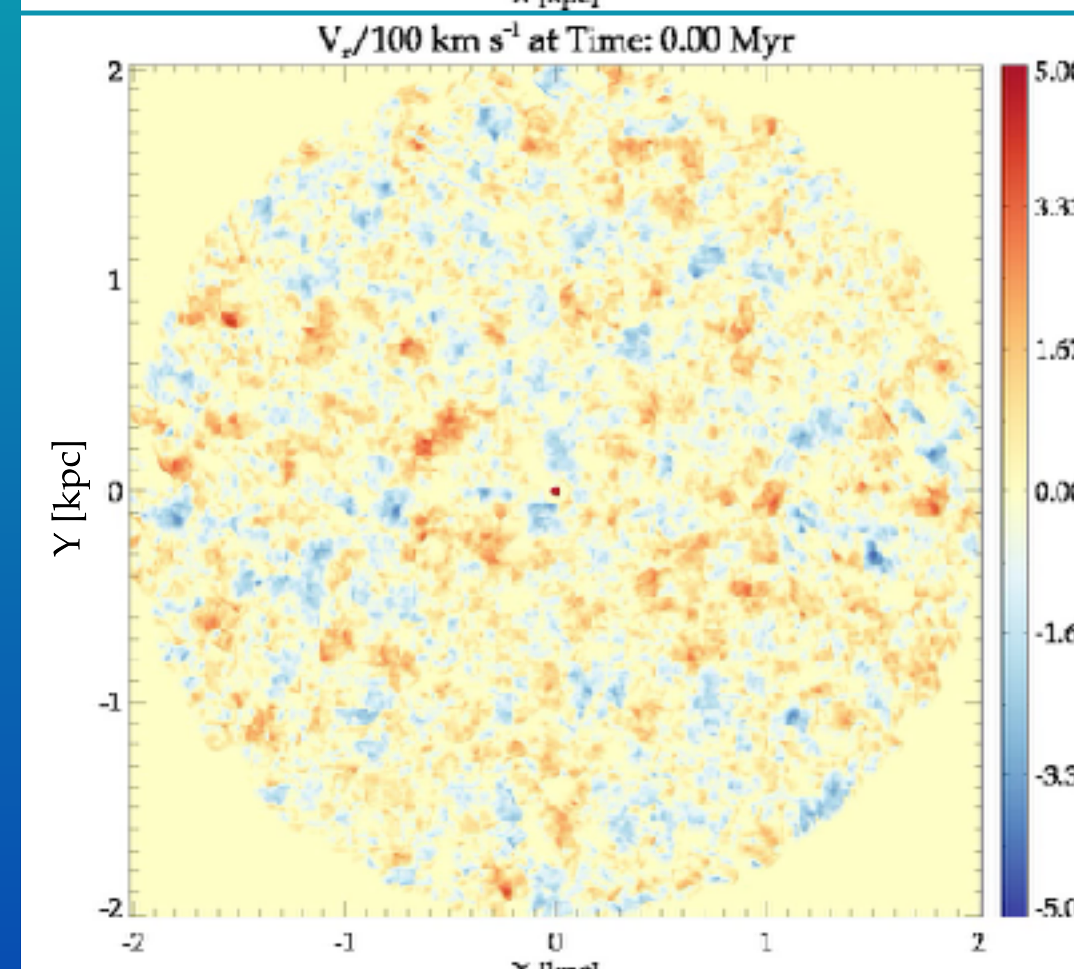
$P_{jet}=10^{45} erg s^{-1}$ Contours: β=0.4c,0.9c

arXiv:1803.08305

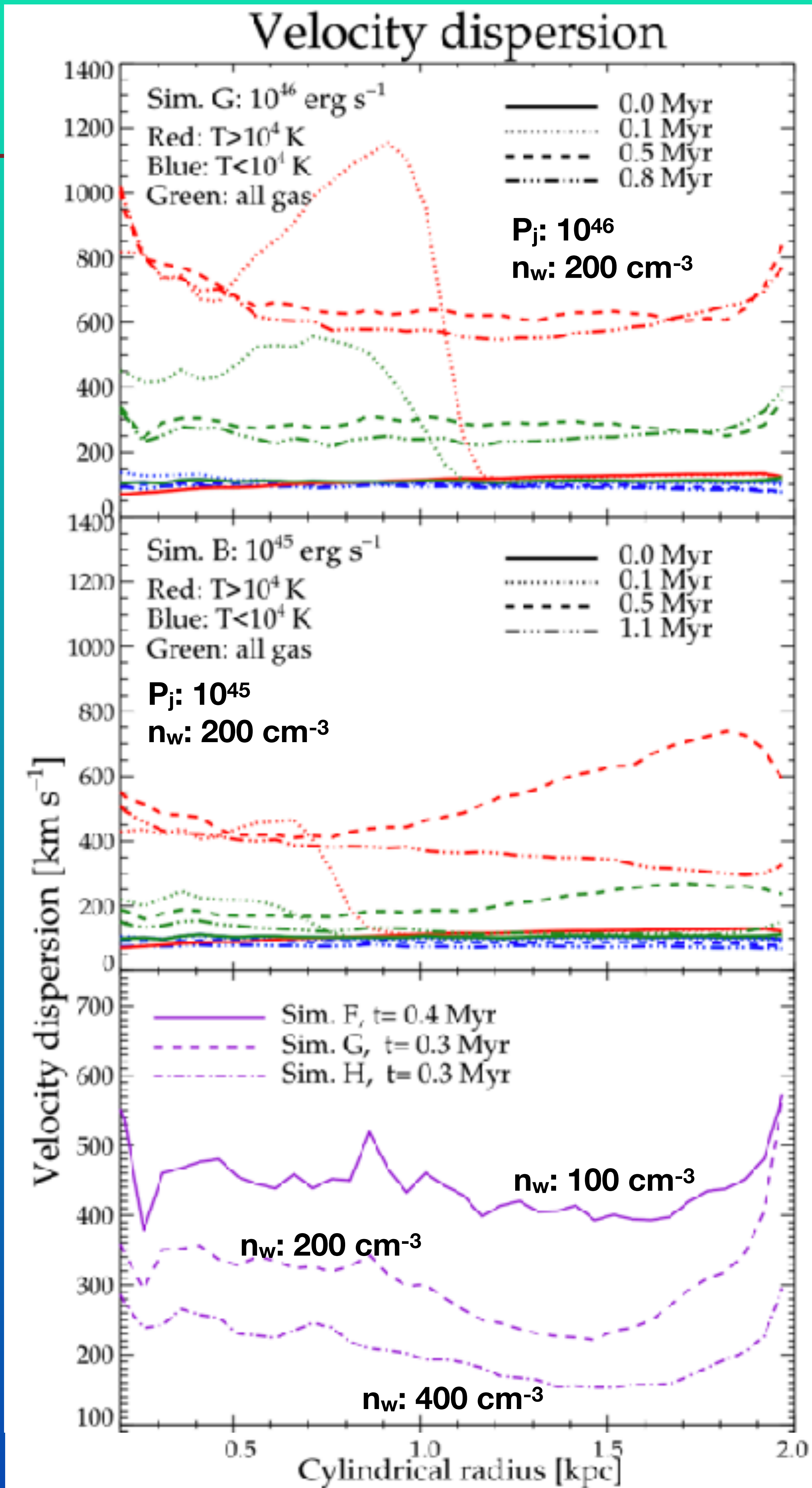
Feedback in disk galaxies

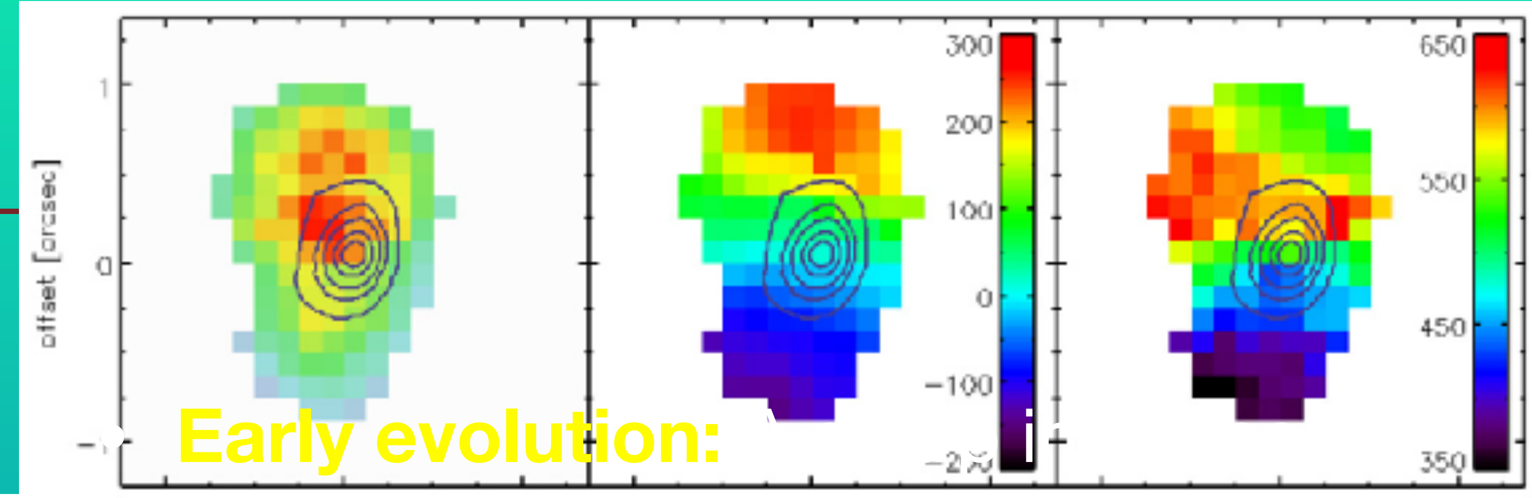






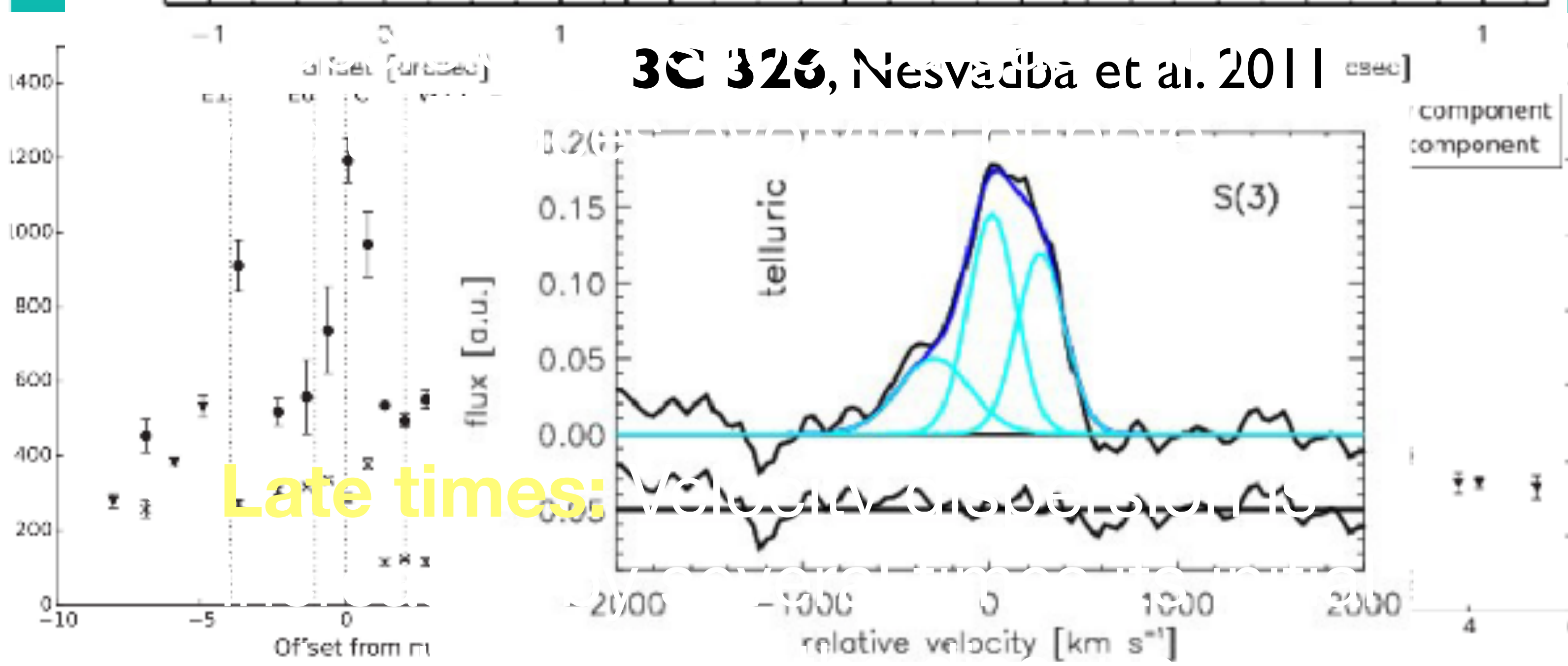
arXiv:1803.08305



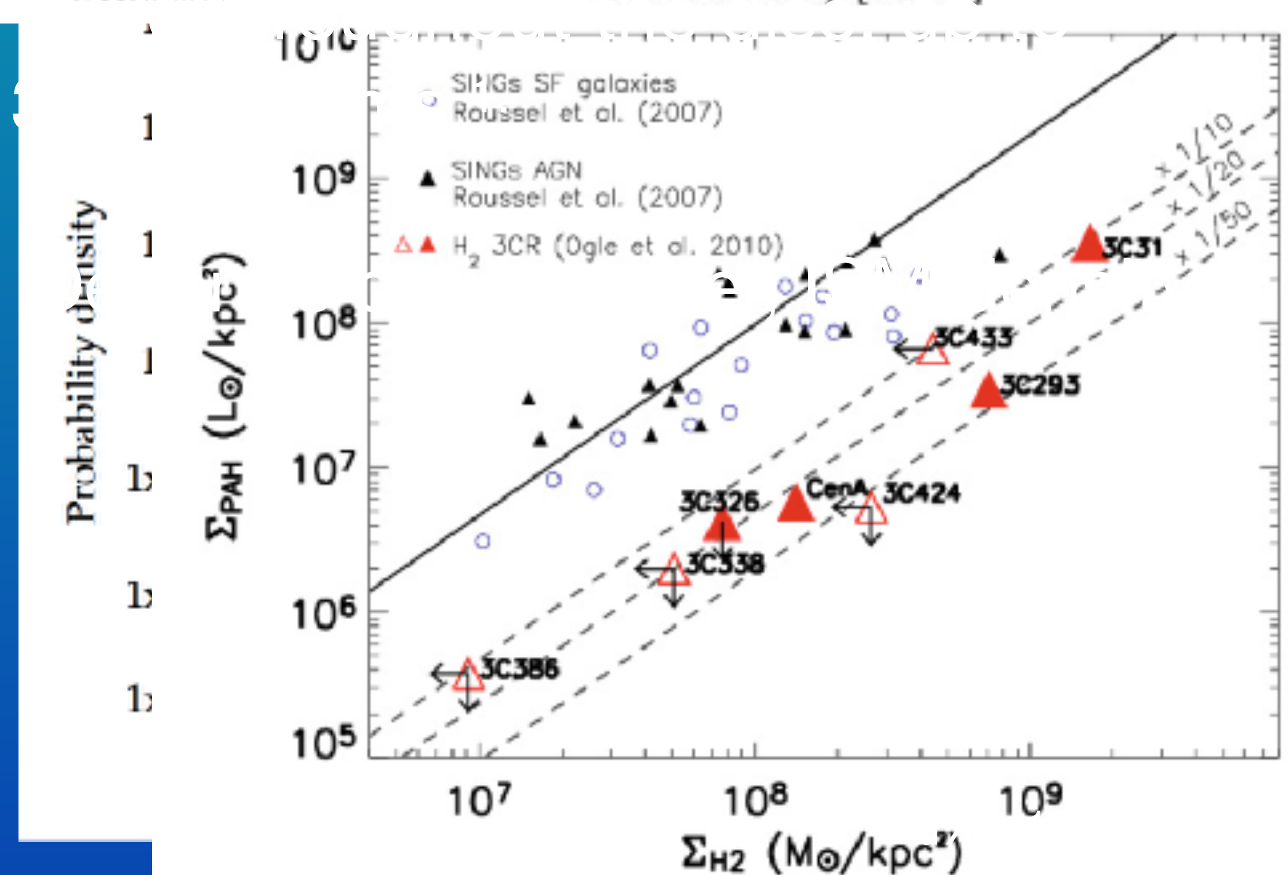


Early evolution:

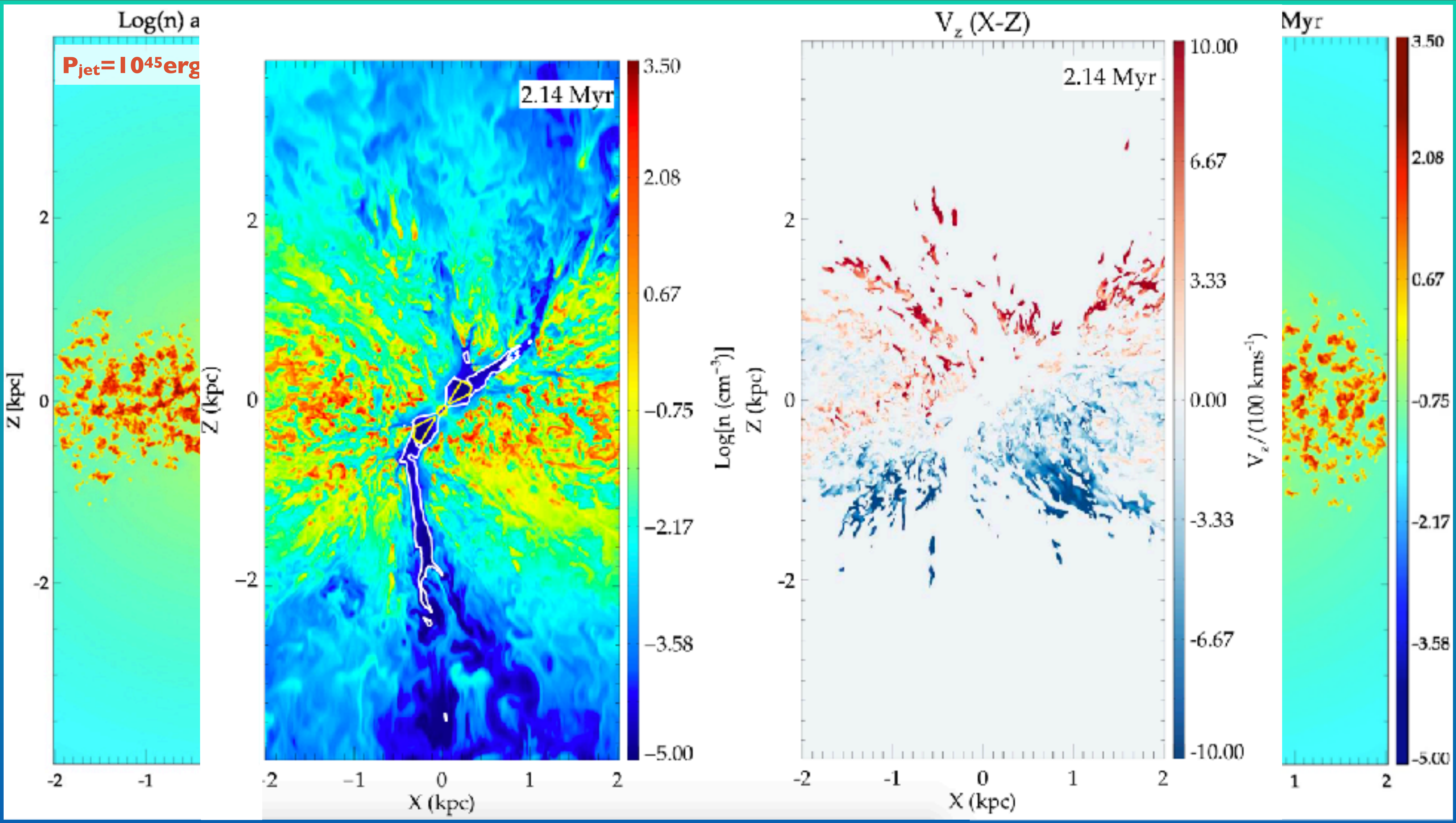
3C 326, Nesvadba et al. 2011



Late times:

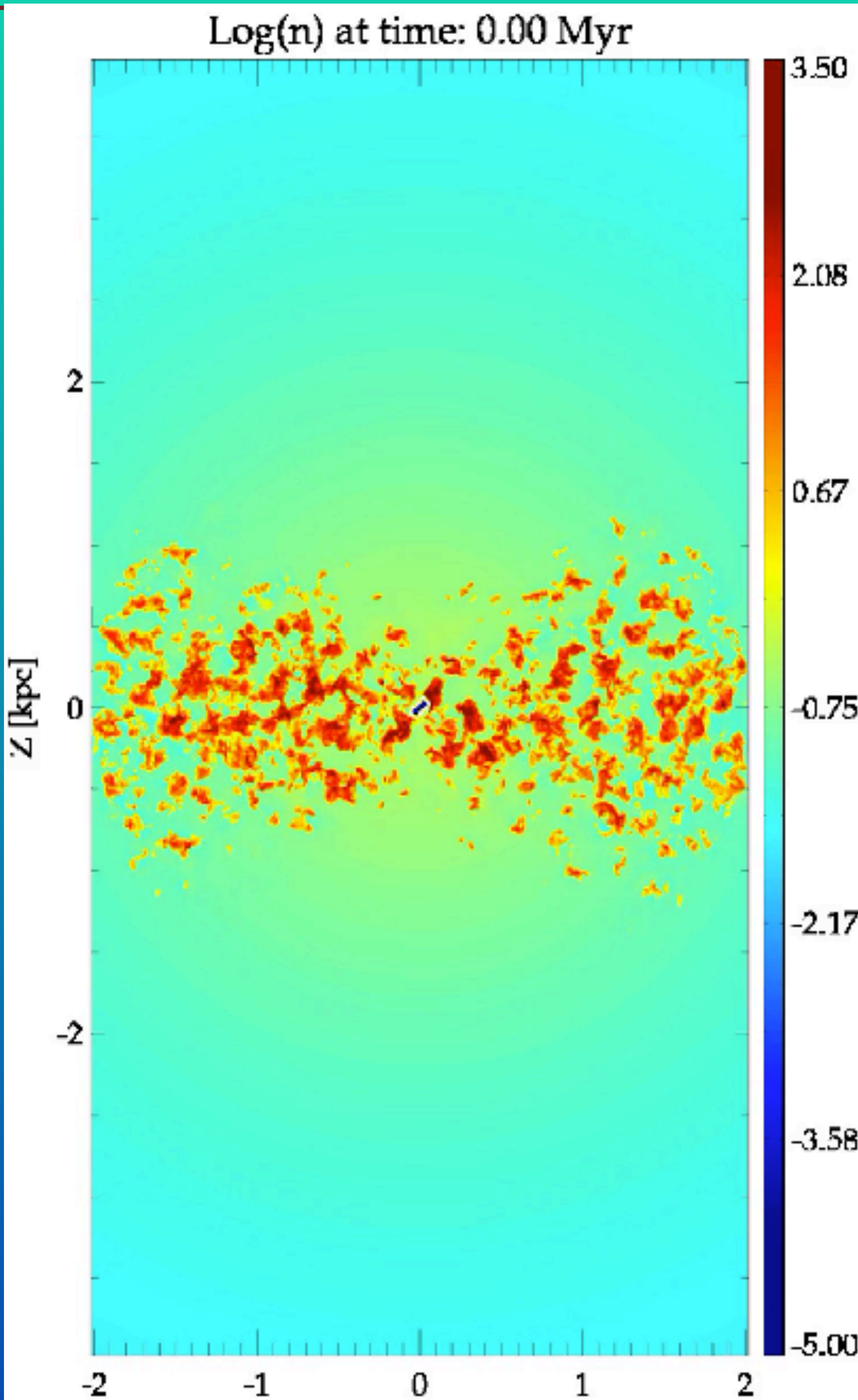


Inclined jets

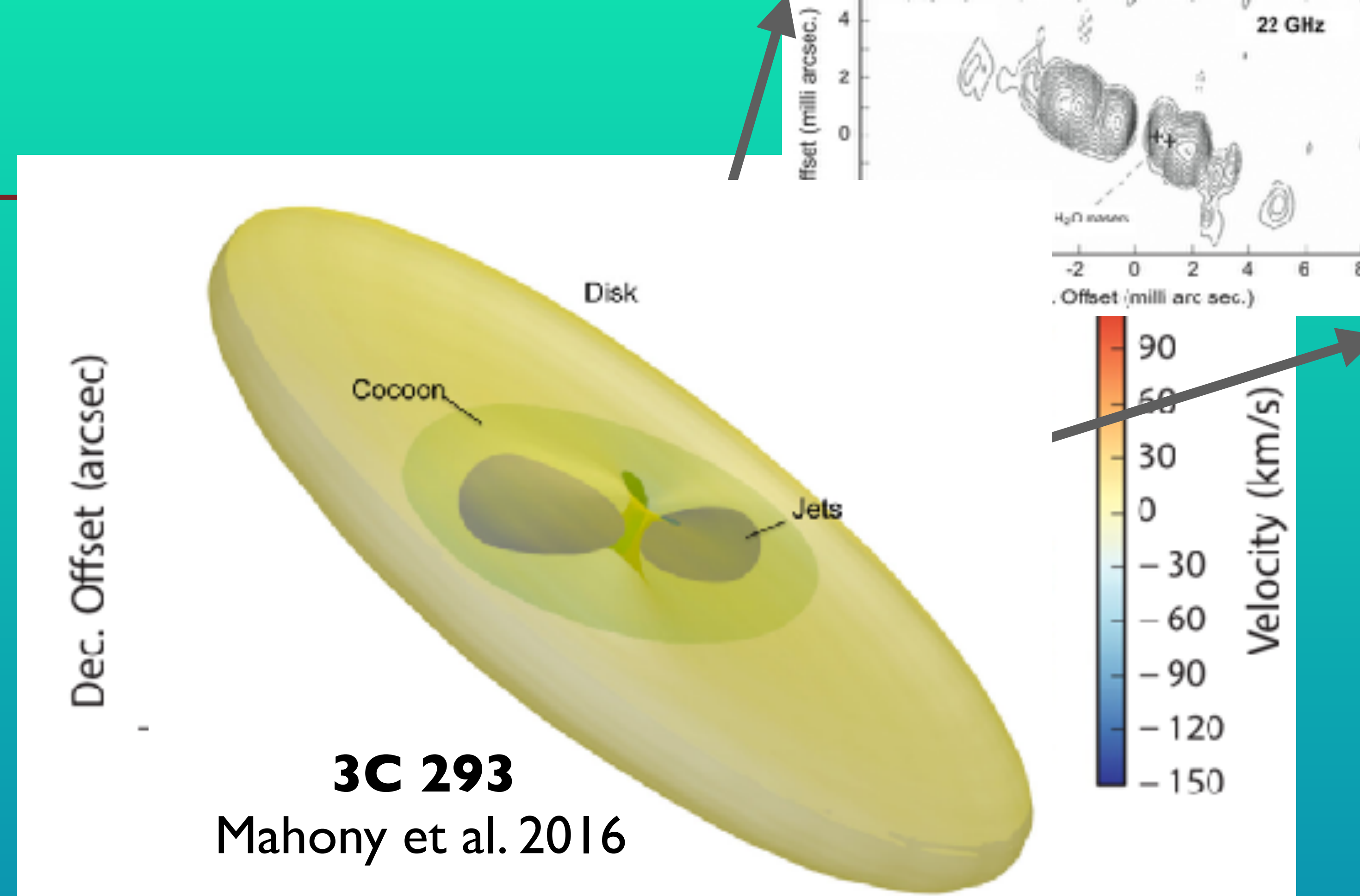


- Inclined jets couple more with turbulent disc
- More clouds are lifted off the disc
- The cavity is filled with ablated thermal gas + non-thermal plasma

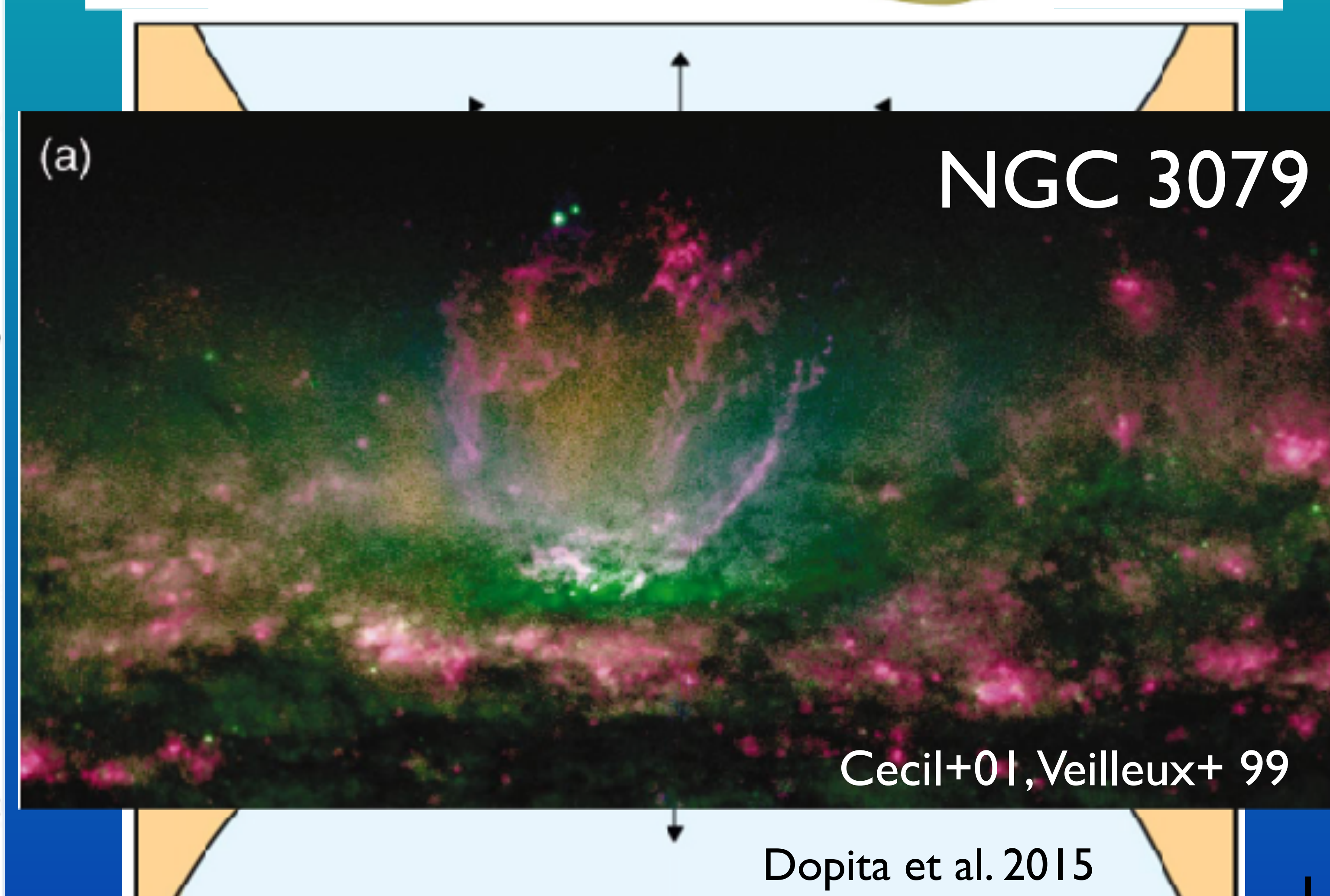
Inclined jets



Inclined at 45⁰



3C 293
Mahony et al. 2016

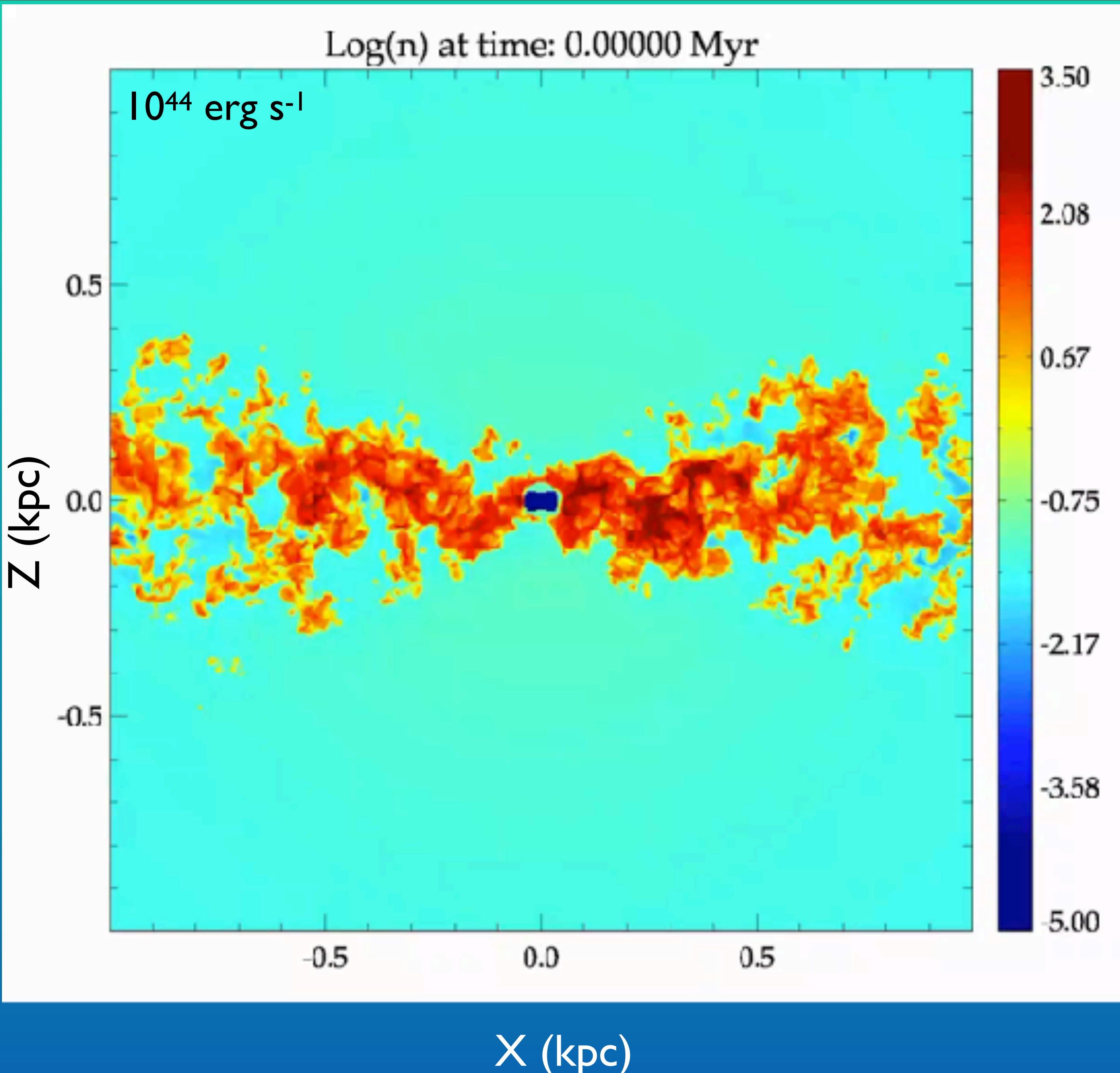


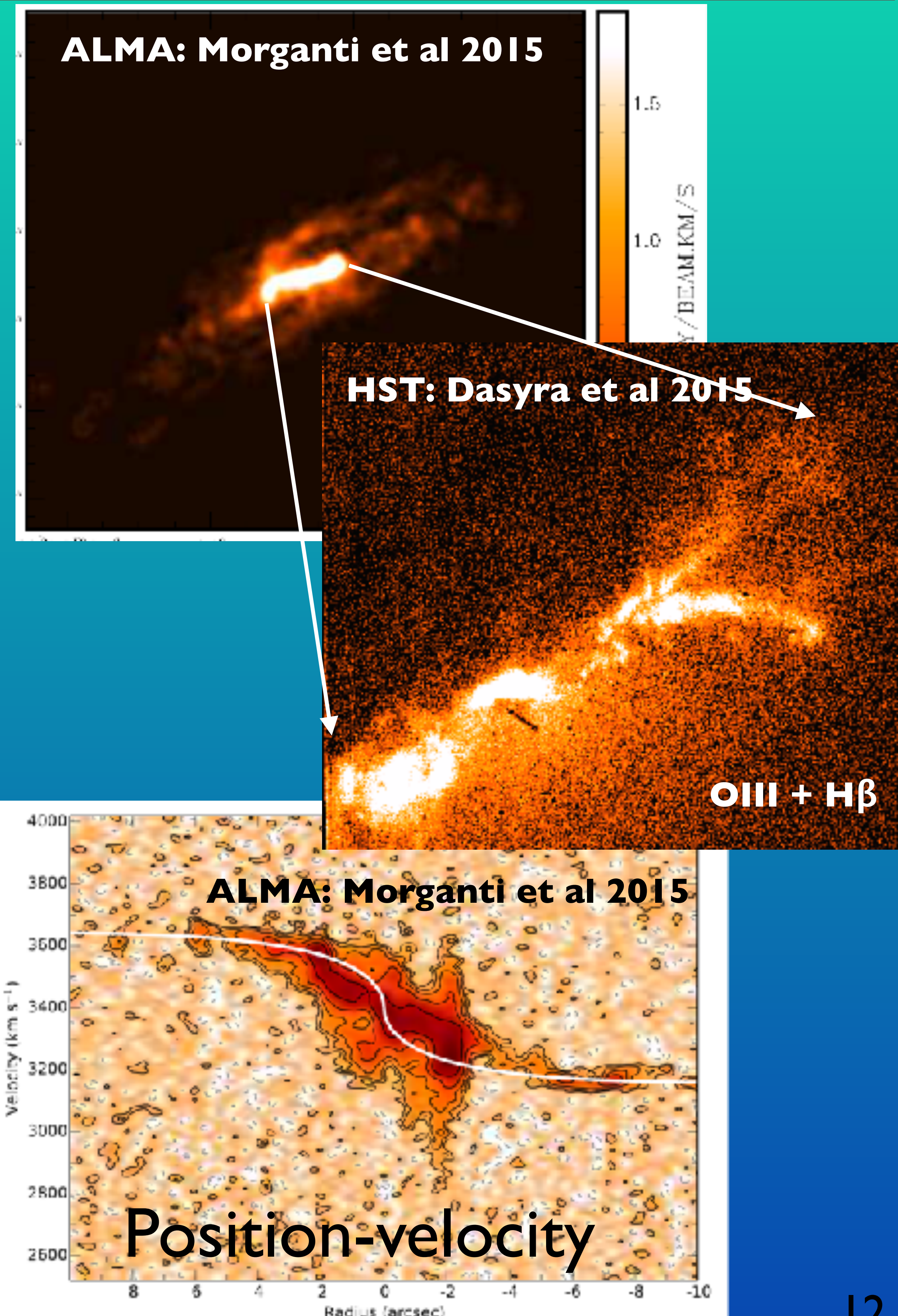
NGC 3079

Cecil+01, Veilleux+ 99

Dopita et al. 2015

Inclined jets: IC 5063

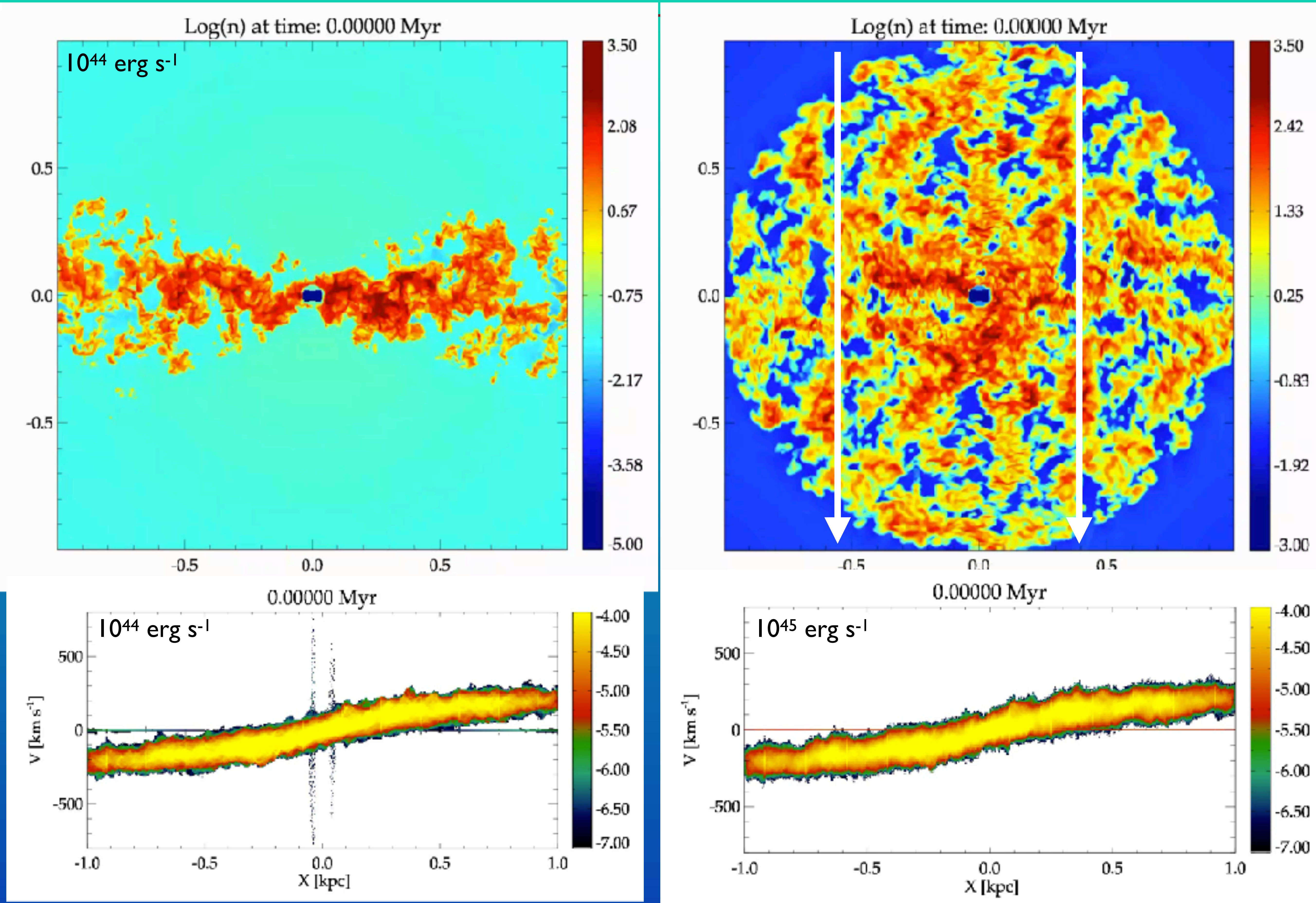




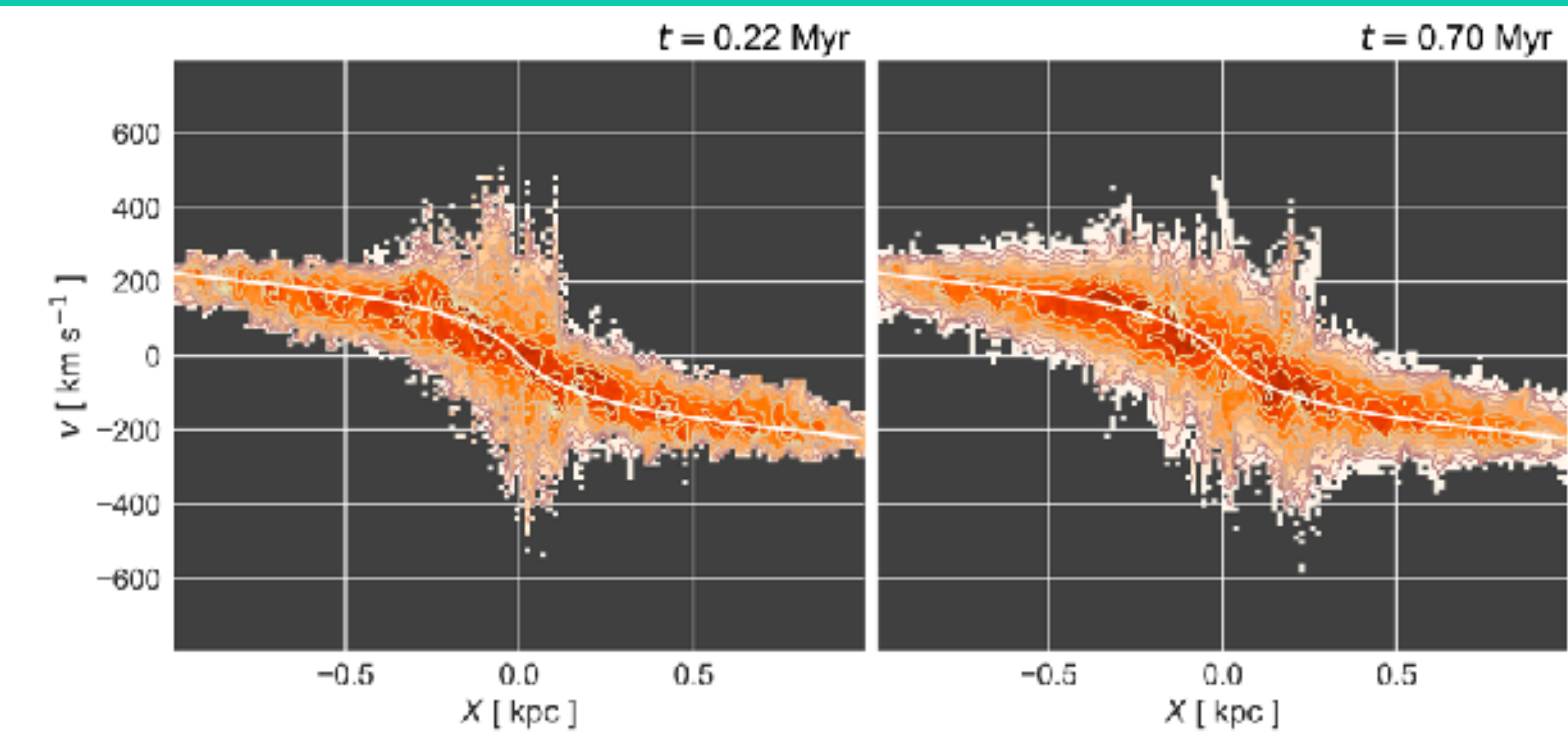
IC 5063 has a jet going through its disk. Multiwavelength observations (ALMA, HST, VLT) show shock excited outflowing gas

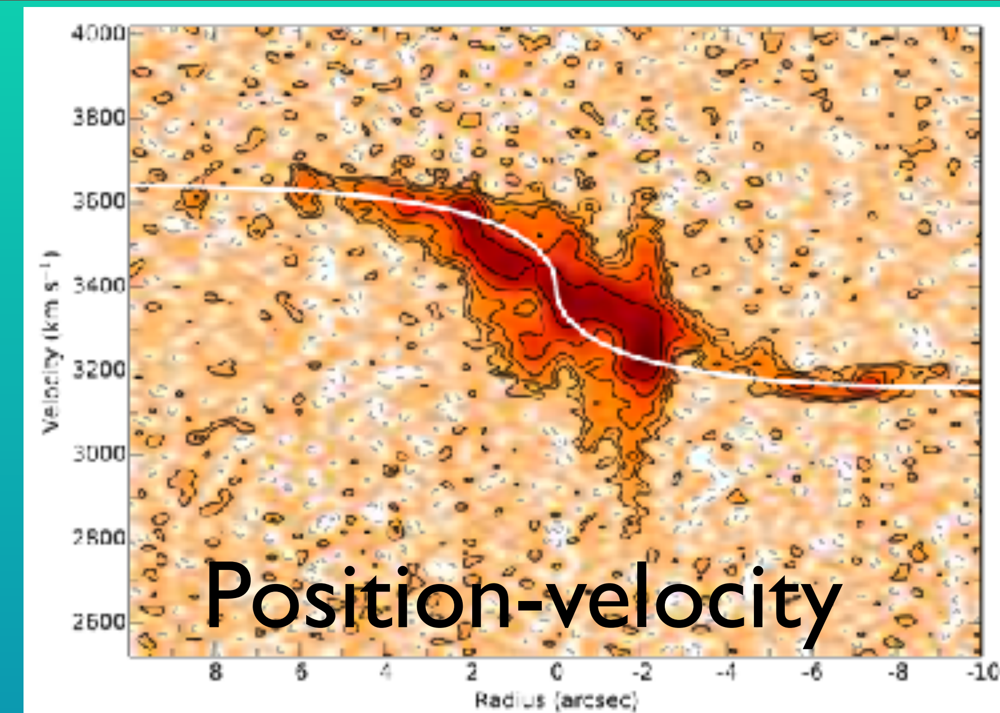
Inclined jets: IC 5063

Mukherjee et al. 2018, arXiv:1801.06875

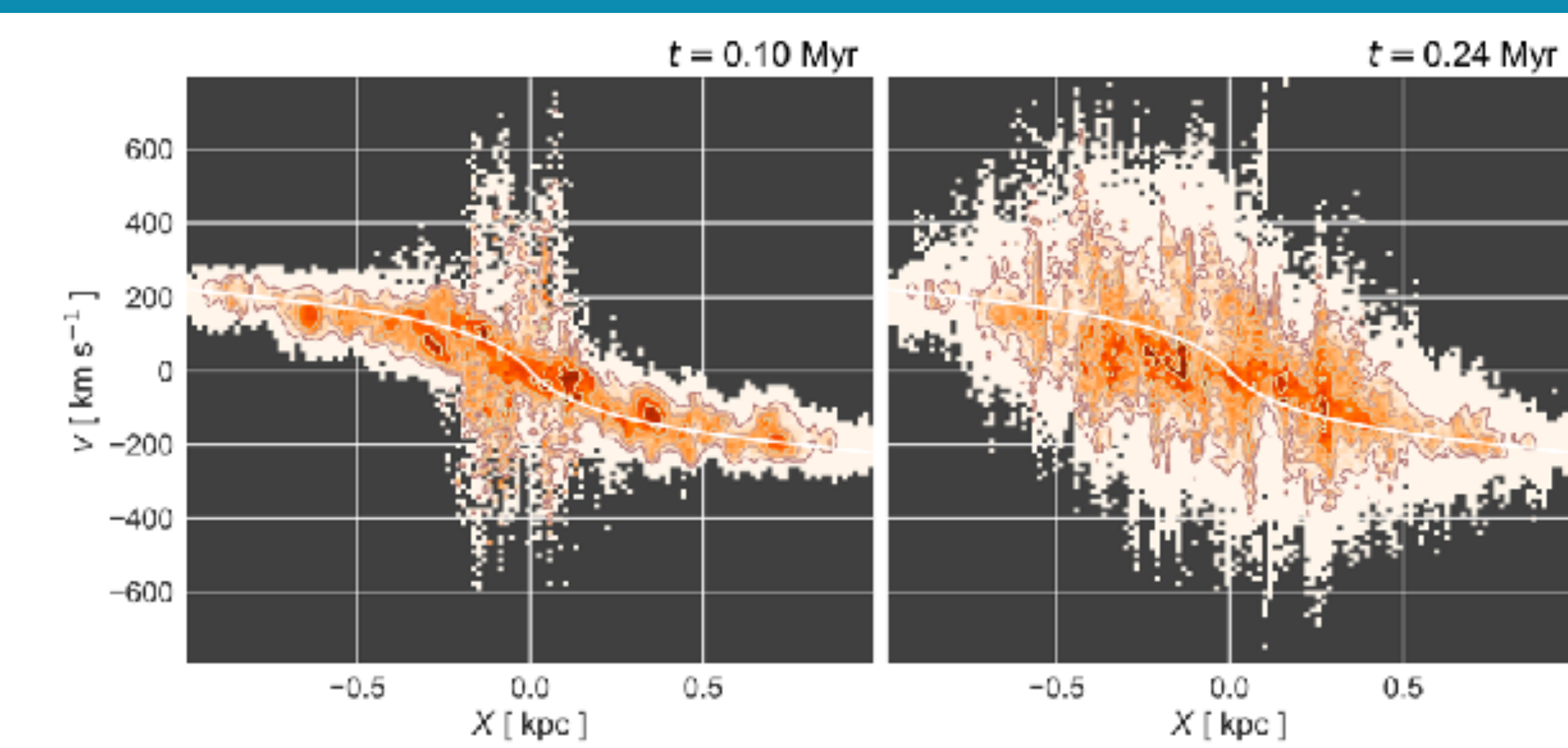


Inclined jets: IC 5063





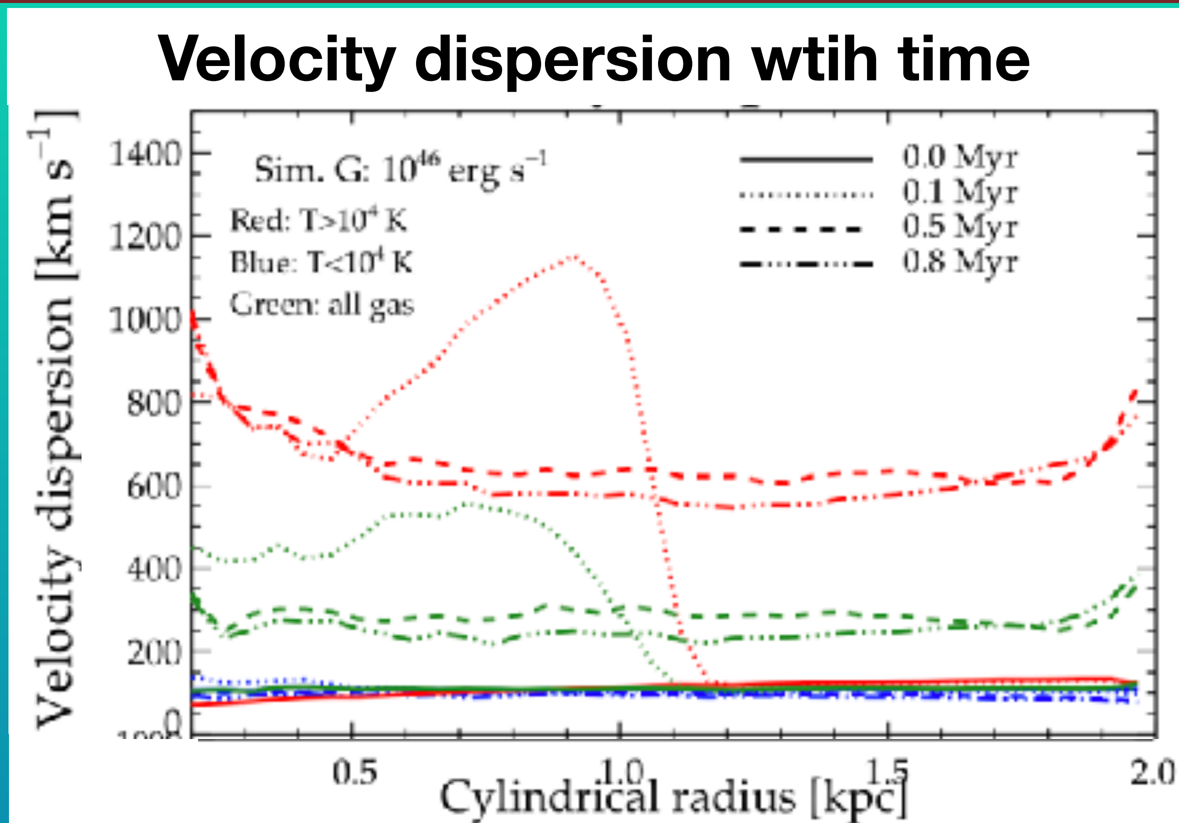
- The overall increased dispersion matches ALMA obs, indicates clearing due to expanding bubble.

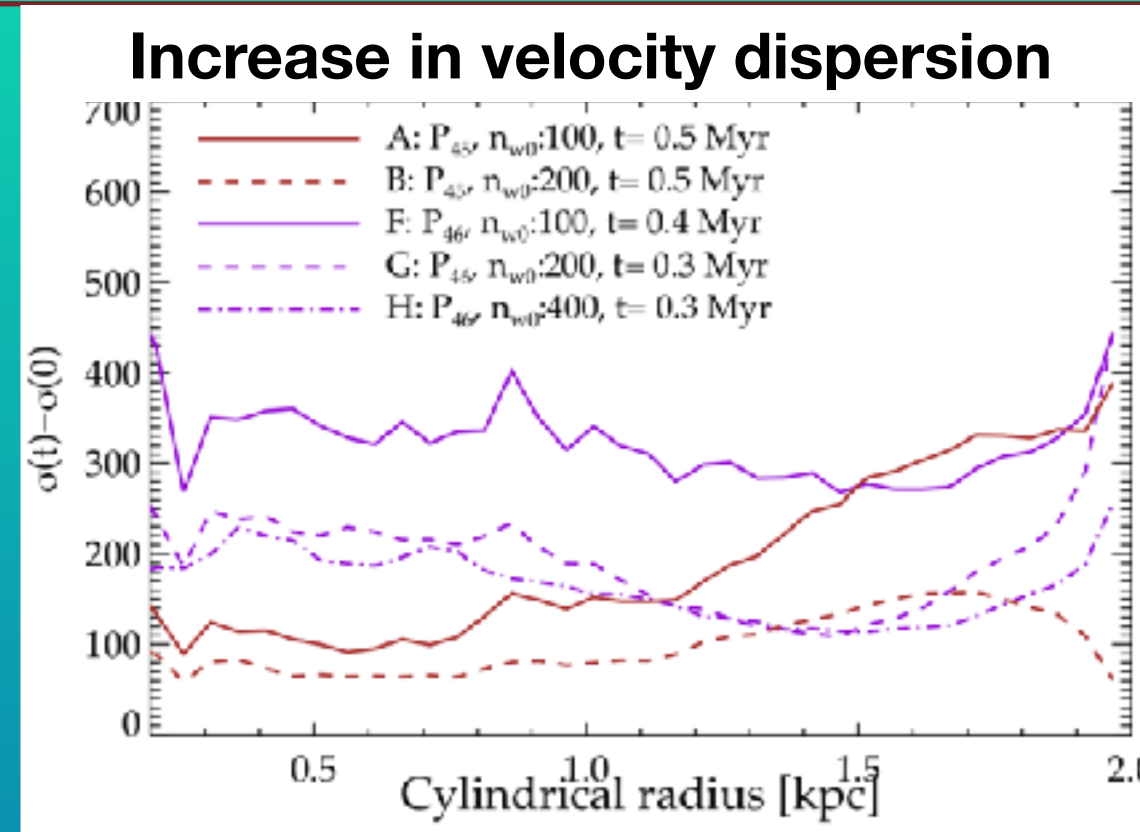


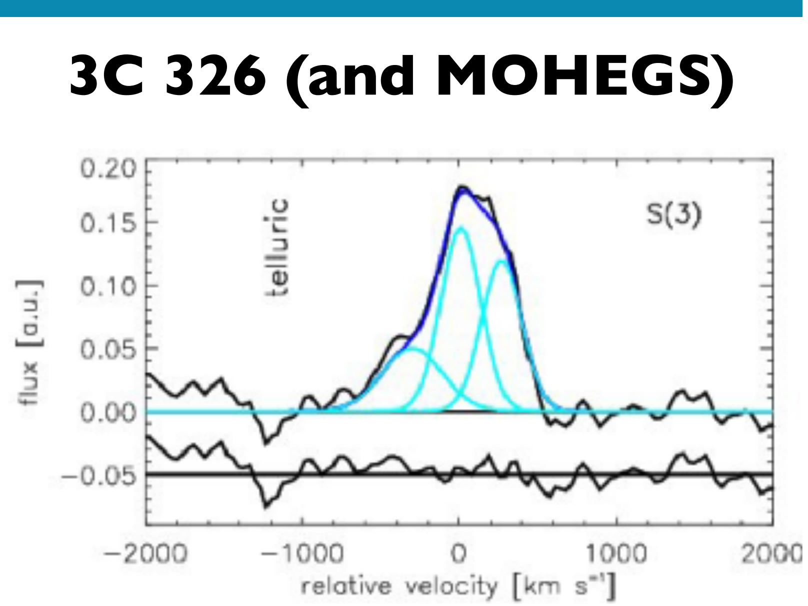
- Spiky features in the PV is reproduced, indicates jet interaction with clumpy ISM
- P=10^{45} erg s^{-1} jet has increased dispersion, and non-uniform PV

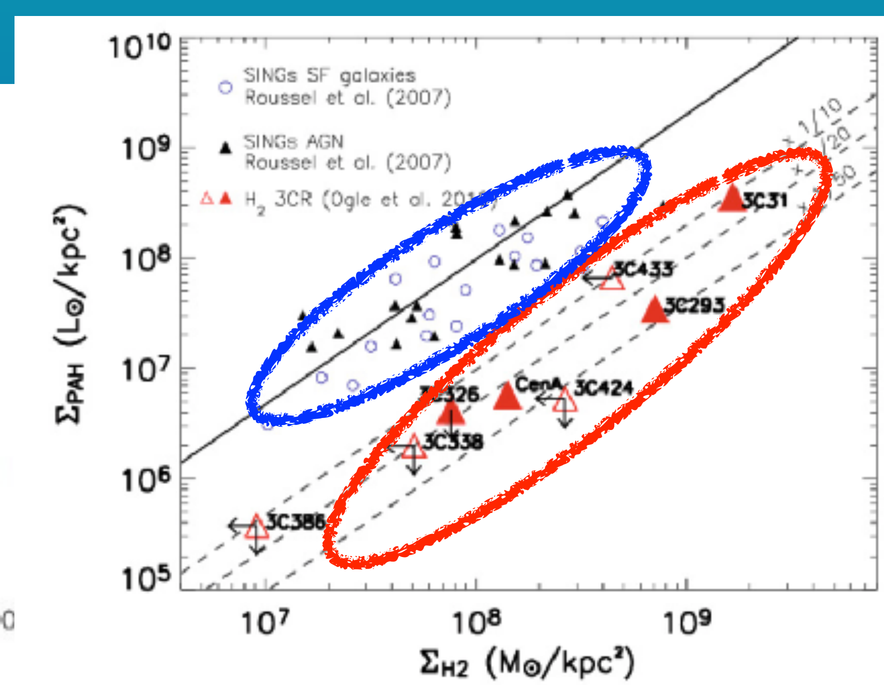
Mukherjee et al. 2018, arXiv:1801.06875

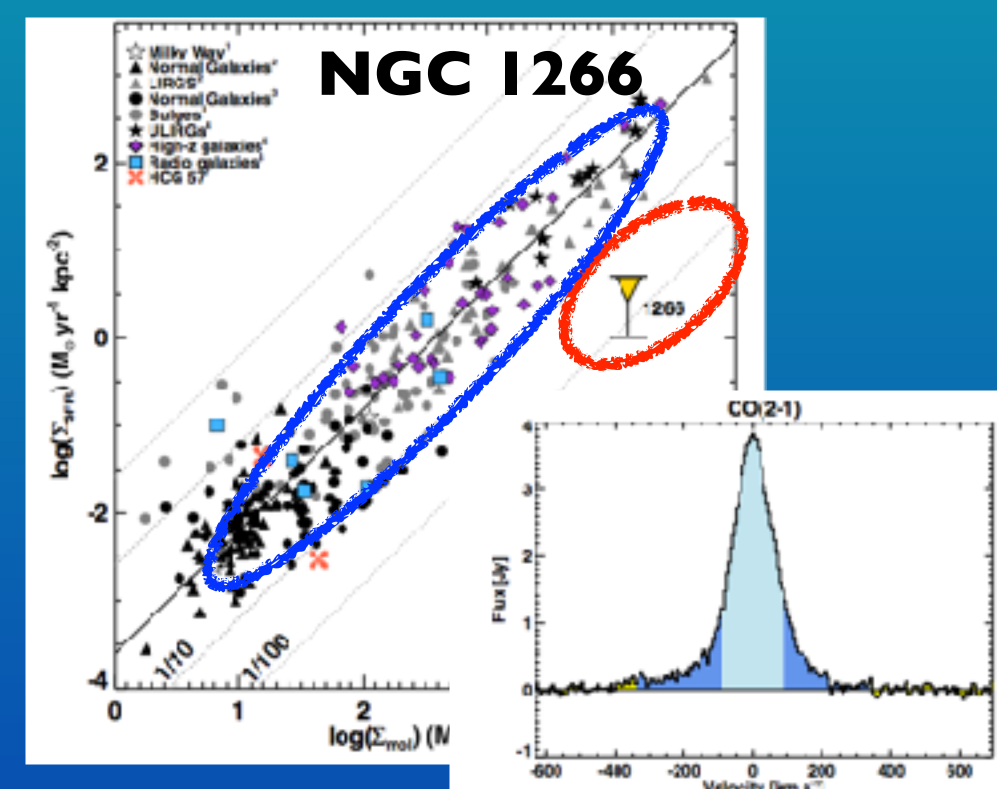
Quenching via turbulence?







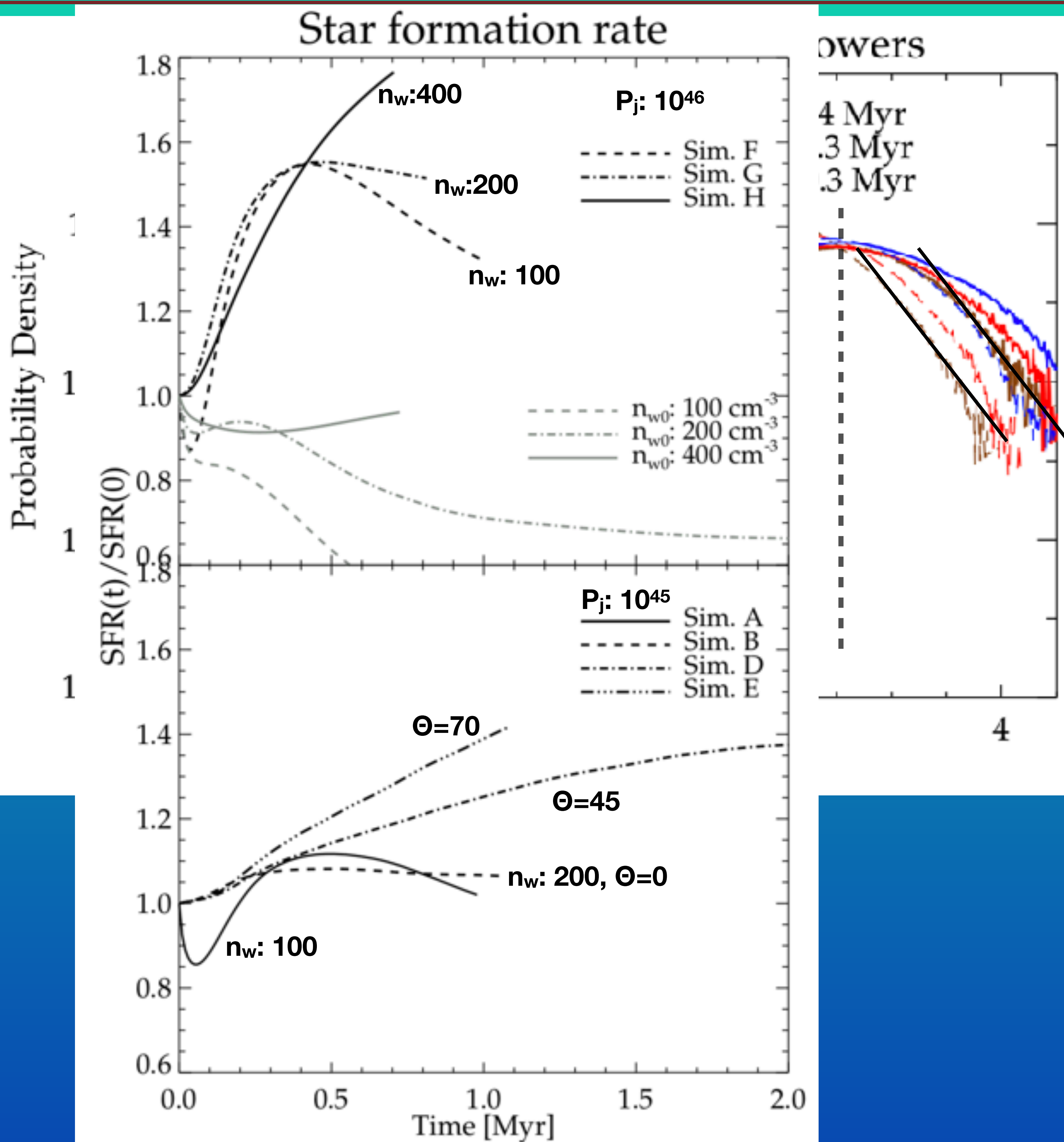




Nesvadba et al. 2010, 11

Alatalo et al. 2011, 15

Positive feedback?

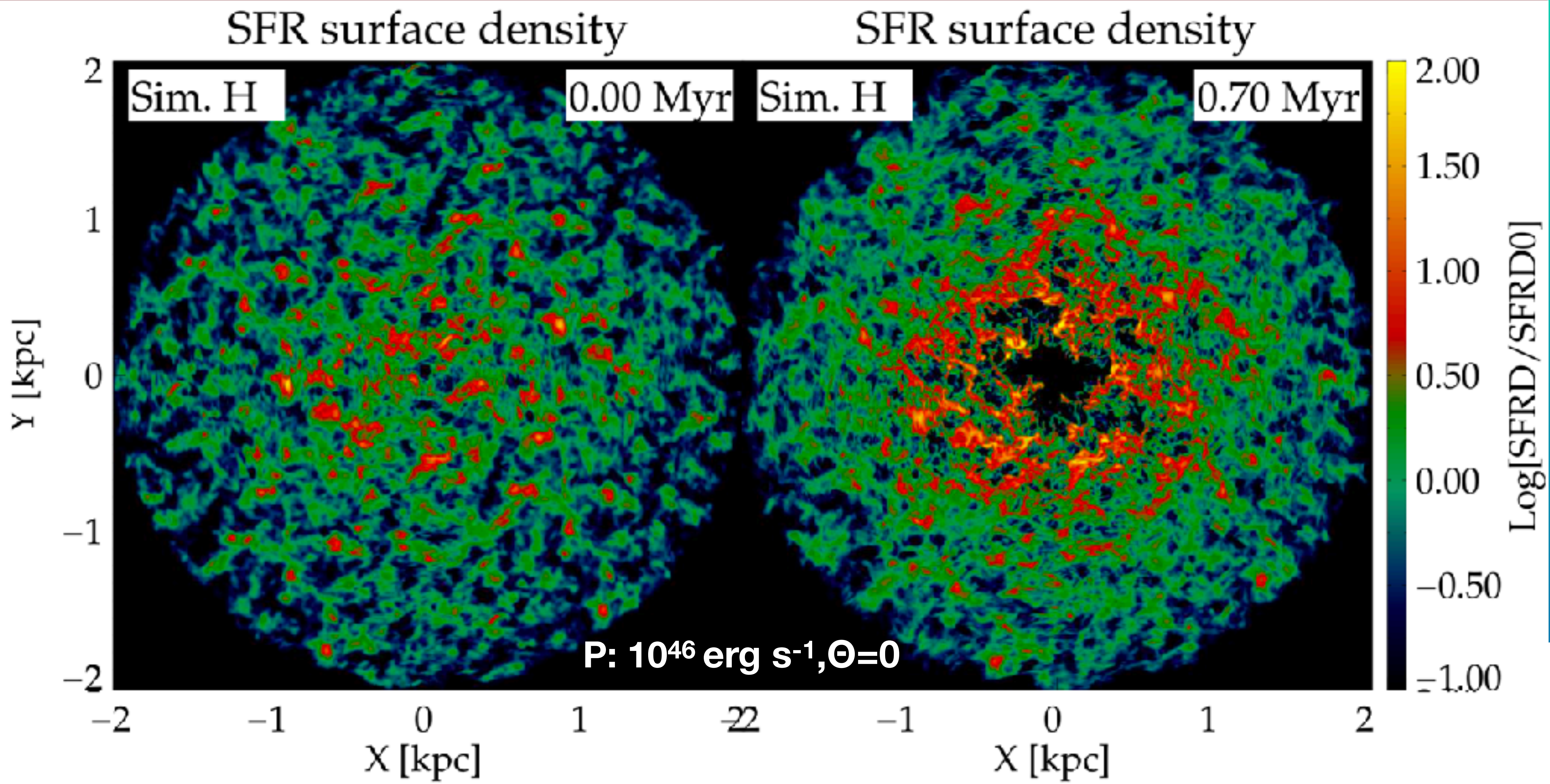


Density enhancement due to radiative shocks

$$\mathrm{SFR} = \epsilon_{\mathrm{SFR}}(\rho d^3 x)/t_{\mathrm{ff}}$$
$$t_{\mathrm{ff}} = (3\pi/(32G\rho))^{1/2}$$

- Jets with $P=10^{46}$ erg/s show a significant enhancement.
- Inclined jets couple more, higher enhancement.
- Low density ISM show a decline after an initial increase

Star formation surface density?



$$\mathrm{SFR} = \epsilon_{\mathrm{SFR}}(\rho d^3 x)/t_{\mathrm{ff}}$$
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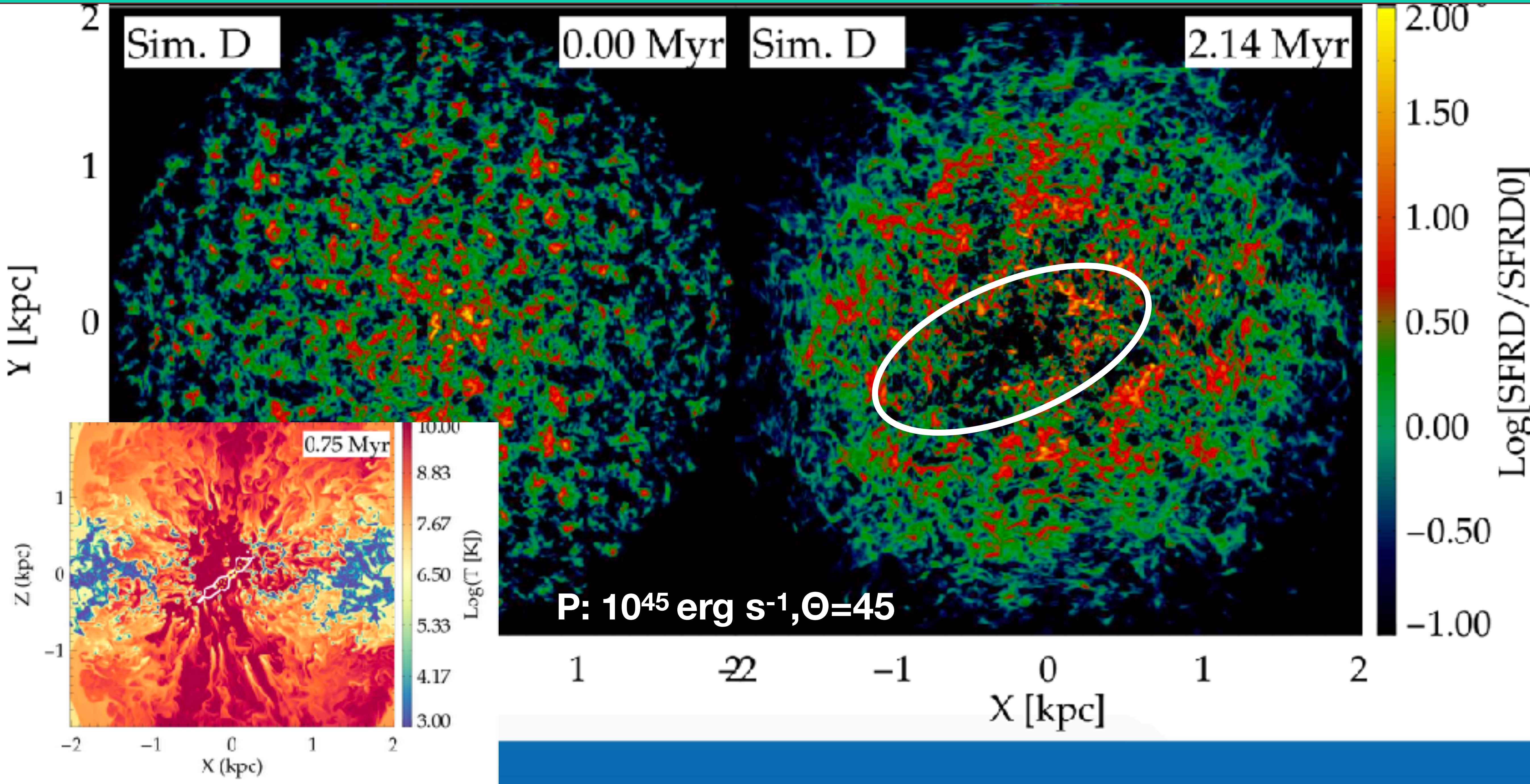
$$\mathrm{SFRD} = \int (\rho/t_{\mathrm{ff}}) dz$$

arXiv:1803.08305

Star formation surface density?



$$\mathrm{SFR} = \epsilon_{\mathrm{SFR}}(\rho d^3 x)/t_{\mathrm{ff}}$$
$$t_{\mathrm{ff}} = (3\pi/(32G\rho))^{1/2}$$

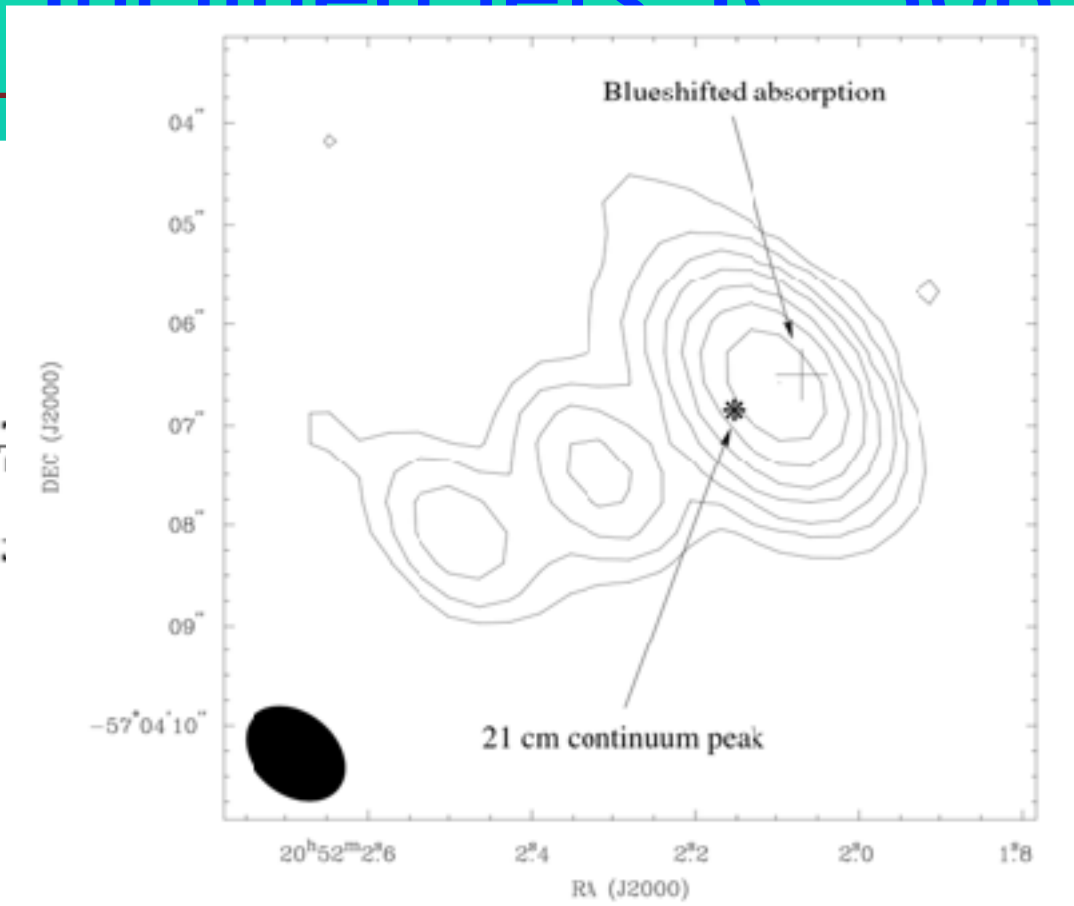
$$\mathrm{SFRD} = \int(\rho/t_{\mathrm{ff}})dz.$$

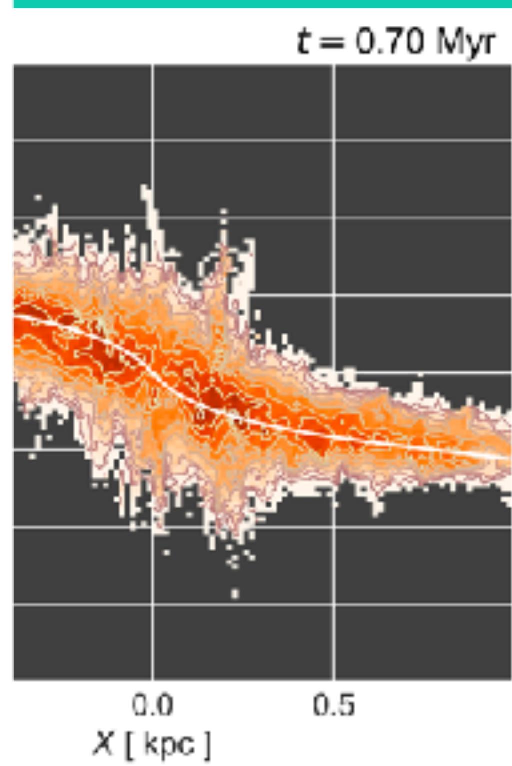
Concluding...

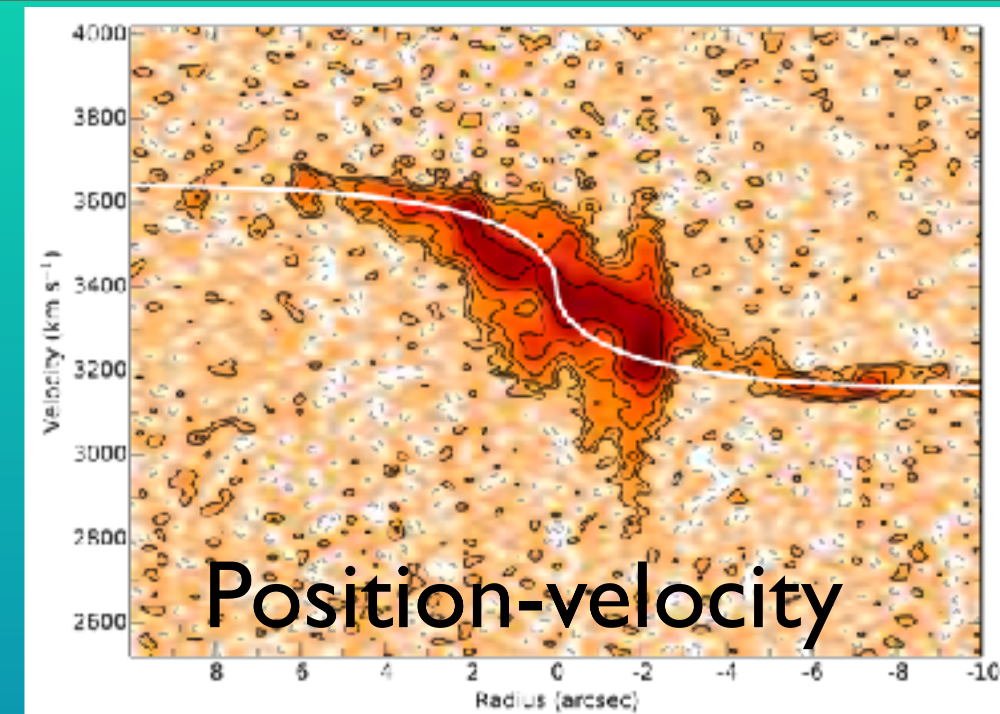
- Jets launch **fast multiphase outflows** over **several kpc** but not enough to escape.
- **Low power jets are important!** Couple more with the ISM, will induce more turbulence and more numerous!
- Jets make **disks turbulent**. **Inclined** jets more.
- SFR will be regulated by shocks from the energy bubble and turbulence, rather than mass ejection. **Initial SFR burst** possible.

Thank you!

Inclined jets: IC 5063







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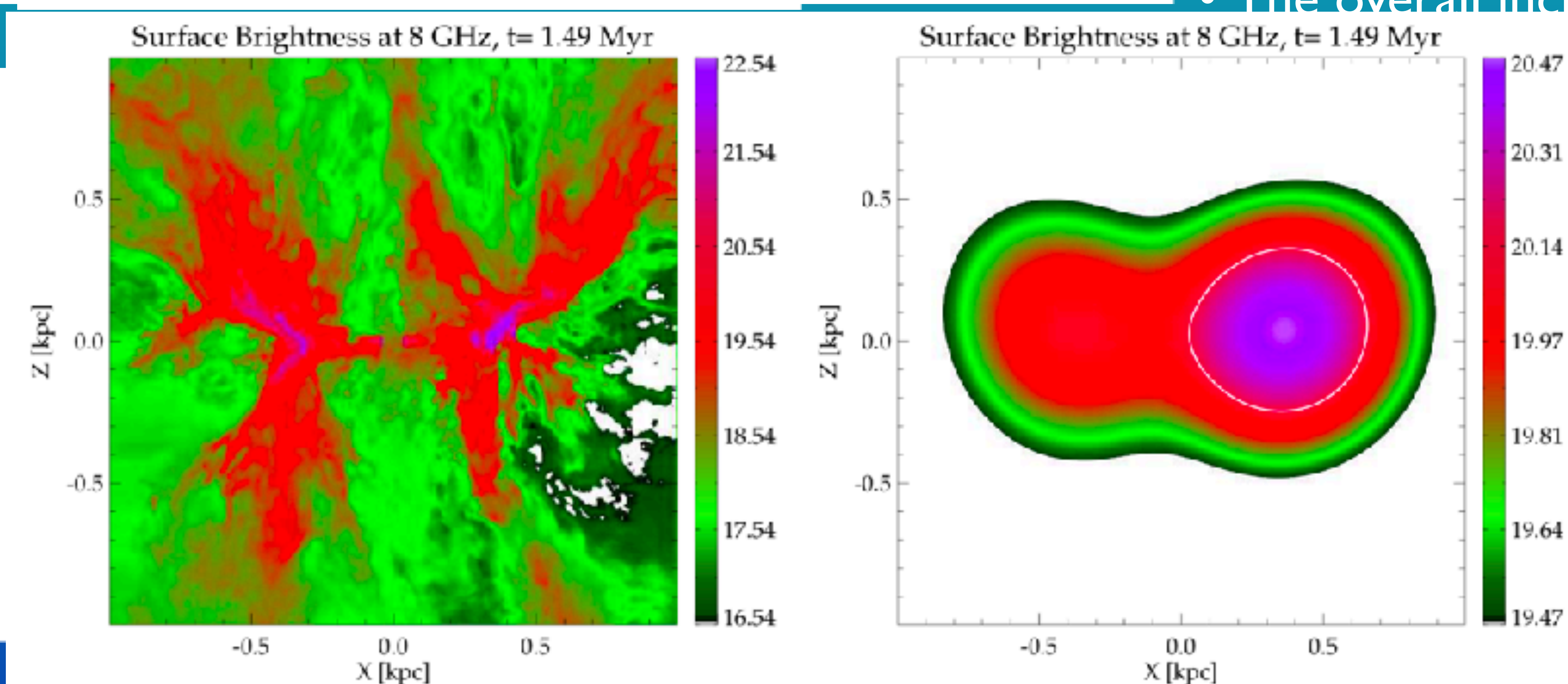


Mukherjee et al. 2018, arXiv:1801.06875

Simulation list

Spherical gas distriution

Densities: nw_0 = 150-2000 cm^{-3}

Power = 10^{44} - 10^{46} $ergs^{-1}$

Gas mass ~ 10^9-10^{10} $M_\odot$

Model	log $P_{\rm jet}$ ergs s^{-1}	Warm clouds σ_c km s^{-1}	n_0 cm^{-3}	Mass $M_\odot$	$T_{\rm floor}$ K	r_B kpc
A	44	50	400	6.46×10^9	10^2	1.0
B	44	100	150	2.89×10^9	10^4	1.0
C	45	50	400	6.46×10^9	10^2	1.0
D	45	100	150	2.89×10^9	10^4	1.0
E	45	100	200	2.44×10^9	10^2	1.0
F	45	100	300	9.24×10^9	10^4	1.0
G	45	250	400	6.61×10^9	10^2	1.0
H	45	250	1000	3.47×10^9	10^2	0.4
I	46	250	1000	3.47×10^9	10^2	0.4
J	46	250	2000	4.76×10^{10}	10^2	1.0
K	46	300	1000	1.20×10^{10}	10^2	0.4

Disks

Densities: nw_0 = 100-400 cm^{-3}

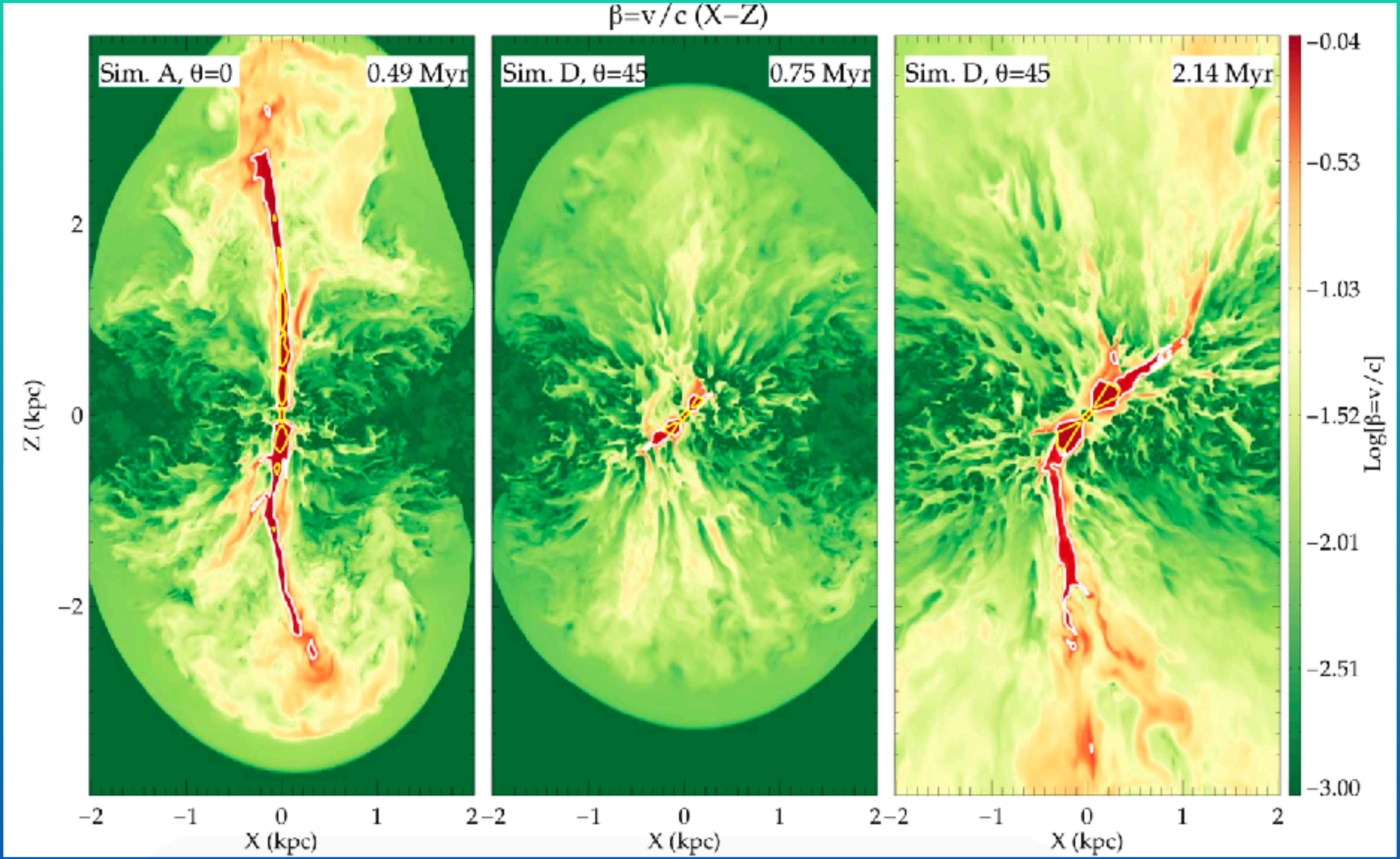
Power = 10^{45} - 10^{46} $ergs^{-1}$

Θ = 0, 20, 45, 70

Gas mass ~ 10^9-10^{10} $M_\odot$

Simulation Label	Power ($ergs^{-1}$)	n_{w0} (cm^{-3})[a]	$\theta_{\rm inc}$[b]	χ[c]	Γ[d]	Gas Mass ($10^9 M_\odot$)
A	10^{45}	100	0	10	5	2.05
B	10^{45}	200	0	10	5	5.71
C	10^{45}	200	20	10	5	5.71
D	10^{45}	200	45	10	5	5.71
E	10^{45}	200	70	10	5	5.71
F	10^{46}	100	0	80	10	2.05
G	10^{46}	200	0	80	10	5.71
H	10^{46}	400	0	80	10	20.68

Wide-angled sub-relativistic outflow



- Launch vertical sub-relativistic wide-angles outflow along the minor axis (chimney effect)