Simulating the jet-ISM interaction in CSS-GPS galaxies

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In Collaboration with

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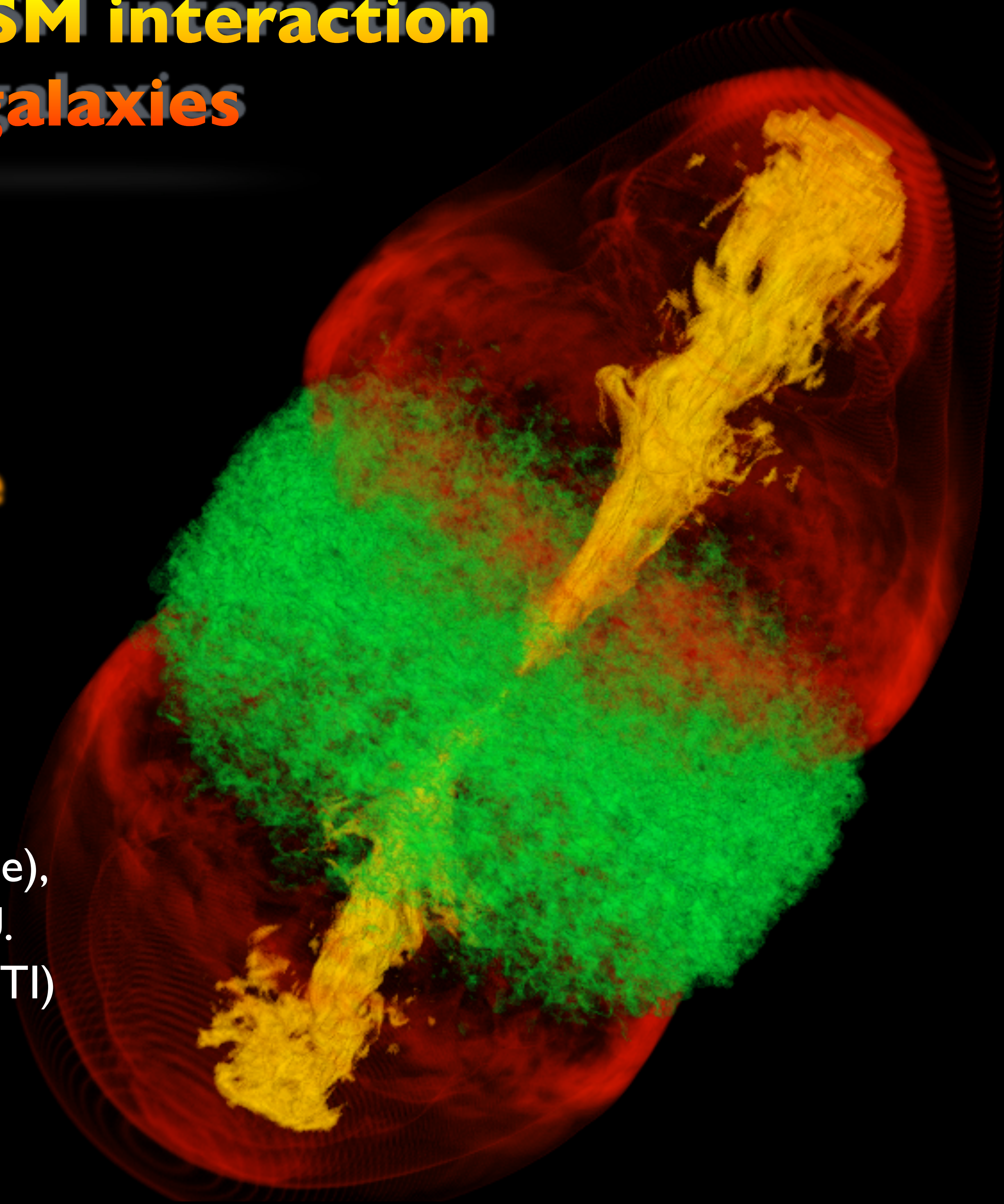
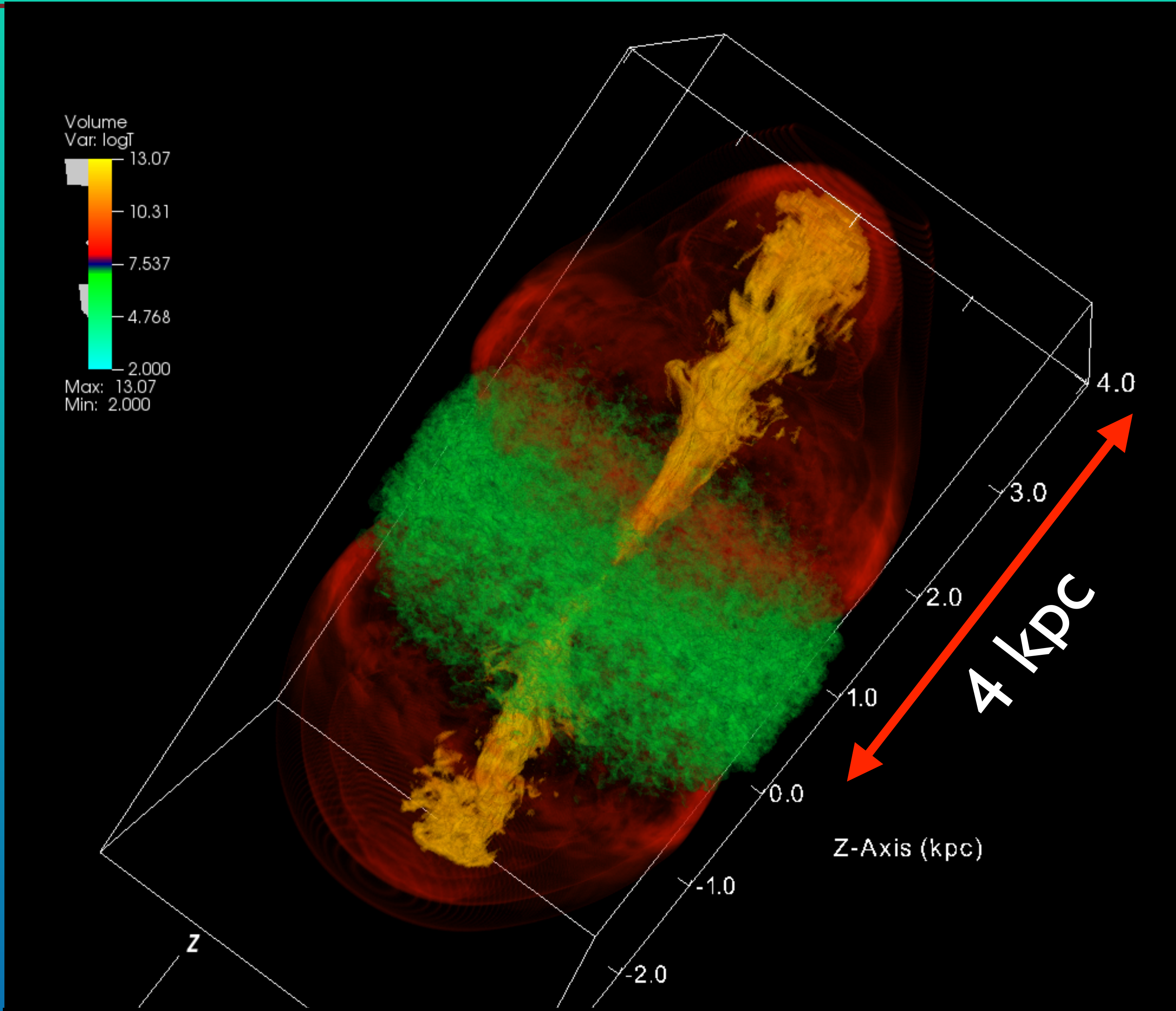


Some basic questions

- Two feedback modes in literature: Quasar vs radio. Oversimplifies impact of jets.
- Young/trapped/slow jets interact with the host's ISM. Many examples of jet-ISM interaction.
- Radio mode can have the effect of quasar mode, blending the two.
- How is star-formation rate regulated by direct interaction?
- Impact on circum-galactic gas



Relativistic jets with PLUTO RMHD code
~ 20 M CPU hrs and counting

Simulations on two scales:

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

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

Jet-ISM Simulations

Spherical gas distriution

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

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

Disks

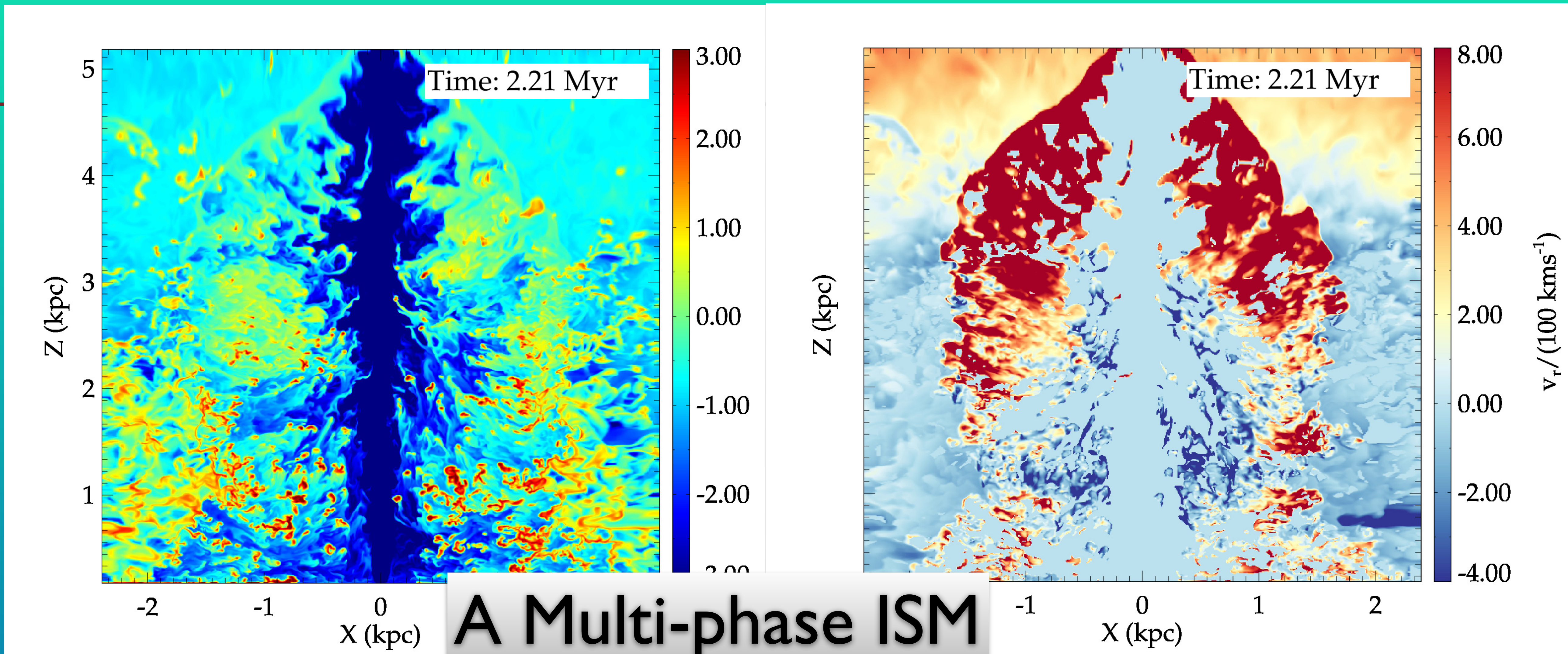
Densities: n_{w0} = 100-400 cm^{-3}

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



A Multi-phase ISM

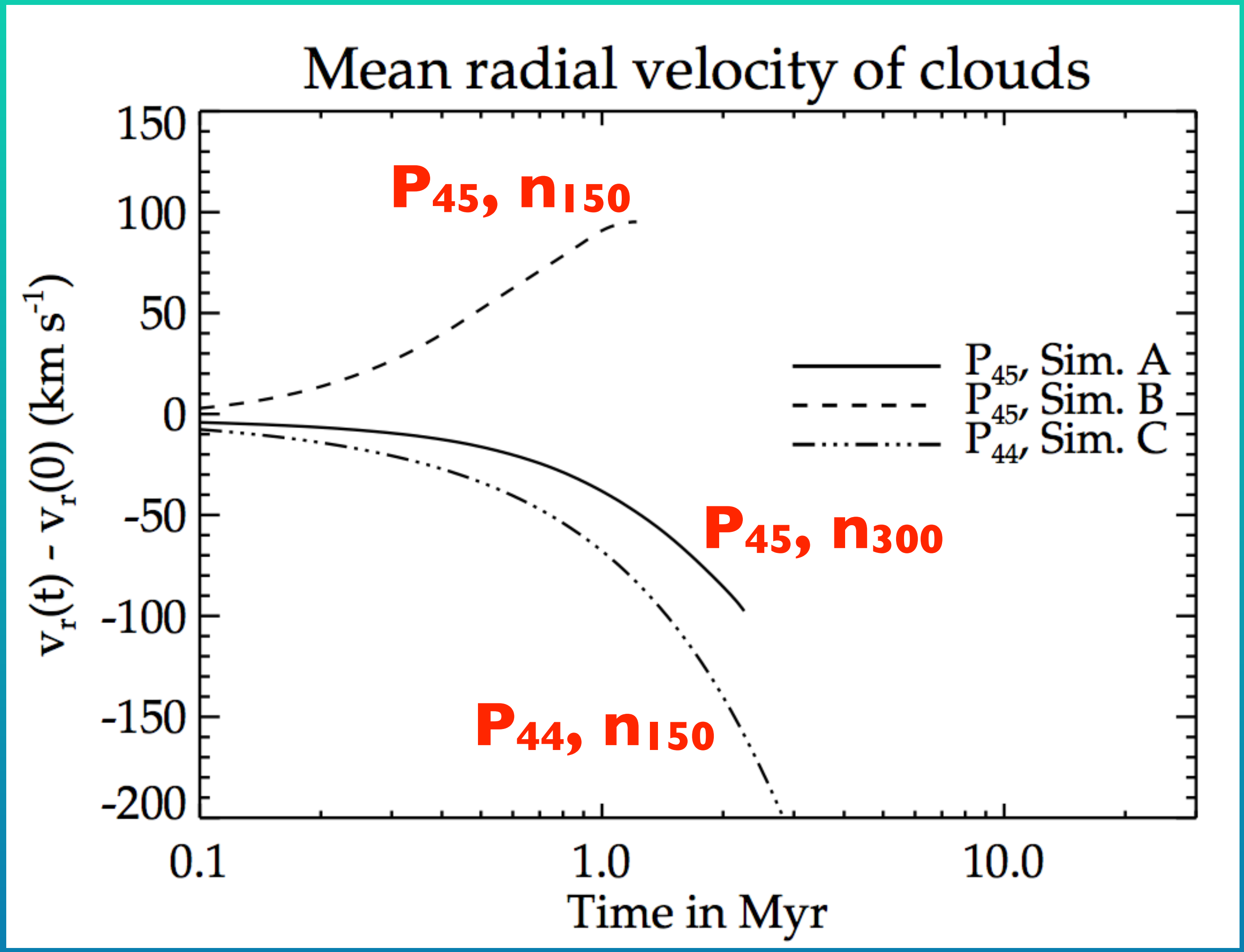
Mukherjee+2016,2017

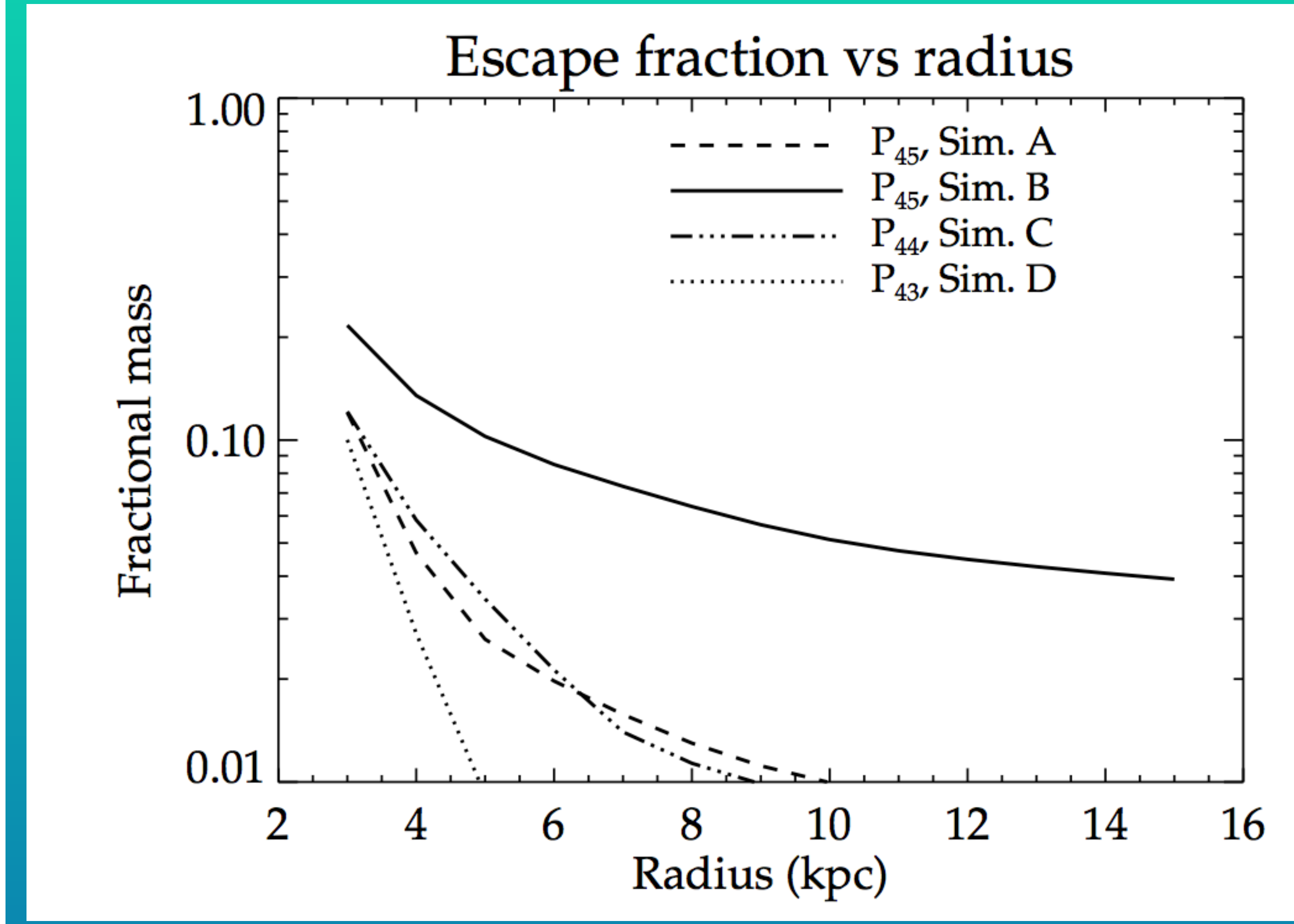
Multiphase ISM and multiphase outflows:

1. Dilute hot energy bubble
2. Shocked dense (n > 100 cm^{-3}) outflowing gas at >100 - 300 kms^{-1}
3. Less dense (n~1-10 cm^{-3}) fast flowing (>1000 kms^{-1}) from sheared cloud material
4. Low power jets remain confined. Less effective in outflow, but shock heats the ISM.

Movie: https://youtu.be/Fh5819VkQyw

Negative feedback: Mass loss



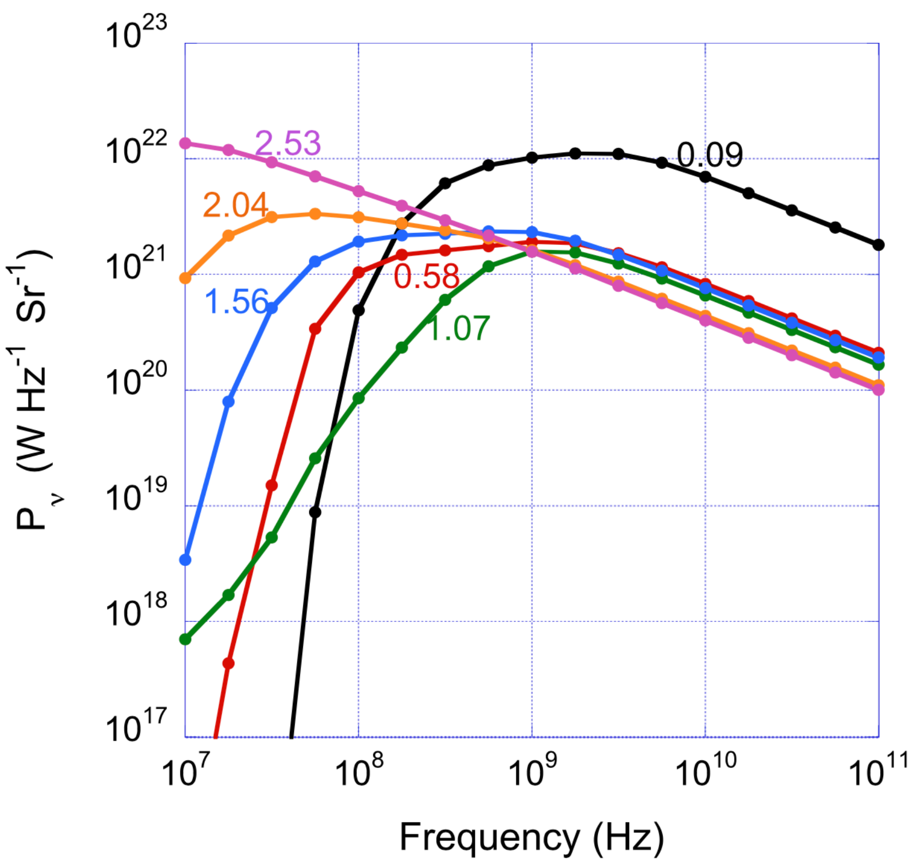


Mukherjee+2016,2017

Not enough gas 'escapes', depends on density of clouds and jet power.

Galactic Fountains!

FFA from jet induced ionisation

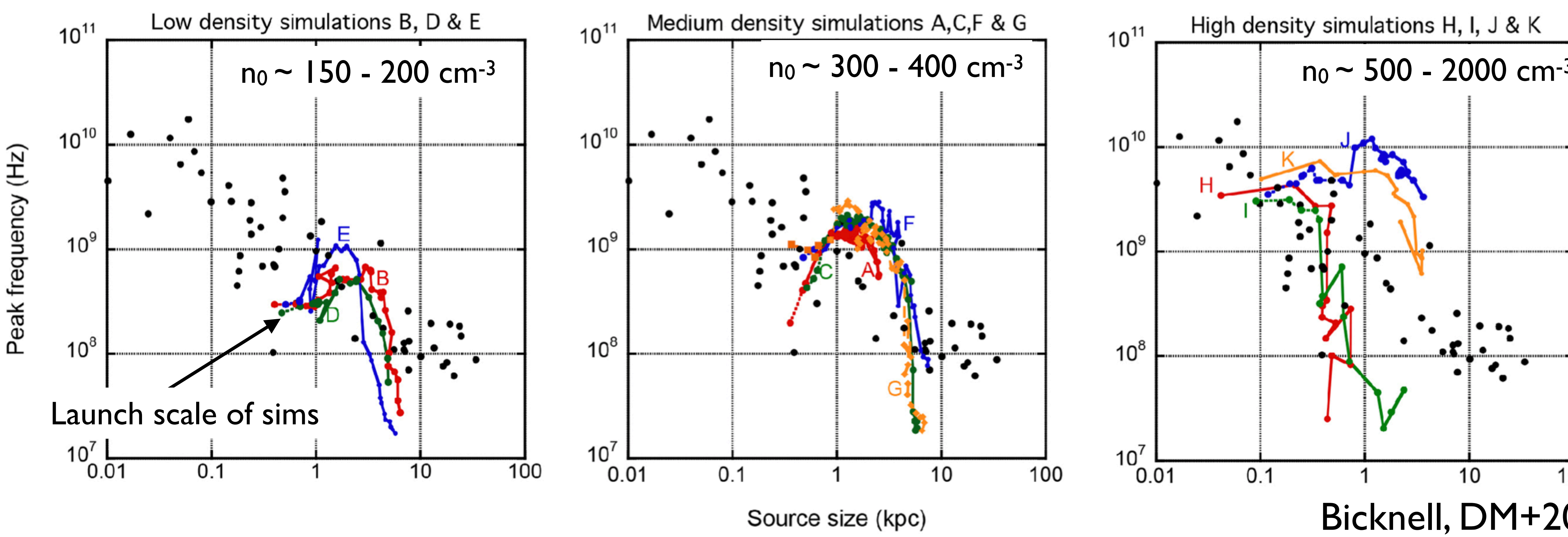


The spectra transition from a GPS to a CSS as the jet evolves to larger scales.

Pro: The sims follows the turnover-linear size correlation for some ranges of length scales and reasonable densities.

Con: Depends on the extent of the gas distribution. Our sims: have dense gas ~ 2-3 kpc. So it fails for larger sizes.

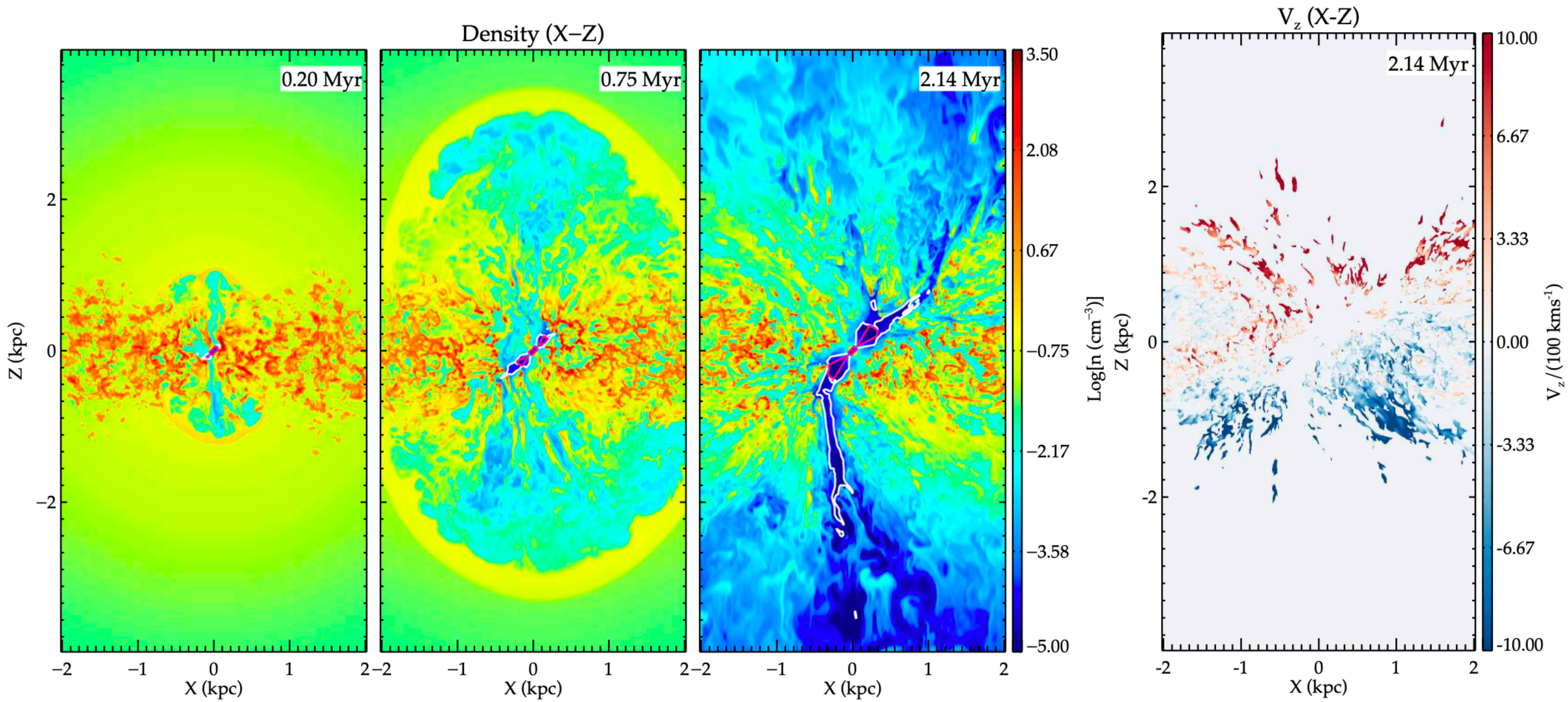
Movie: https://youtu.be/2GjKKAP_6J0



Bicknell, DM+2018

Jet-disk interaction

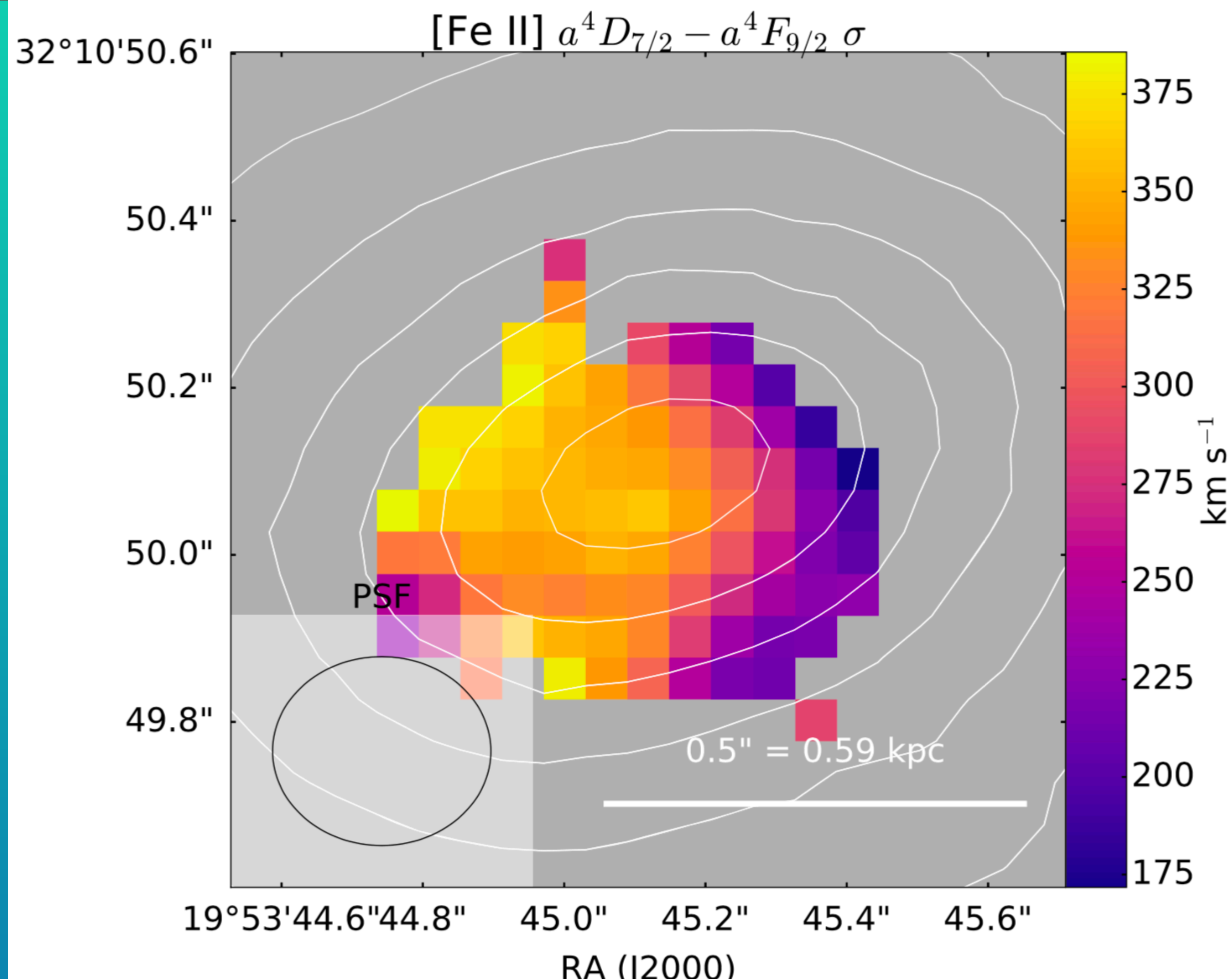
Mukherjee+2018b

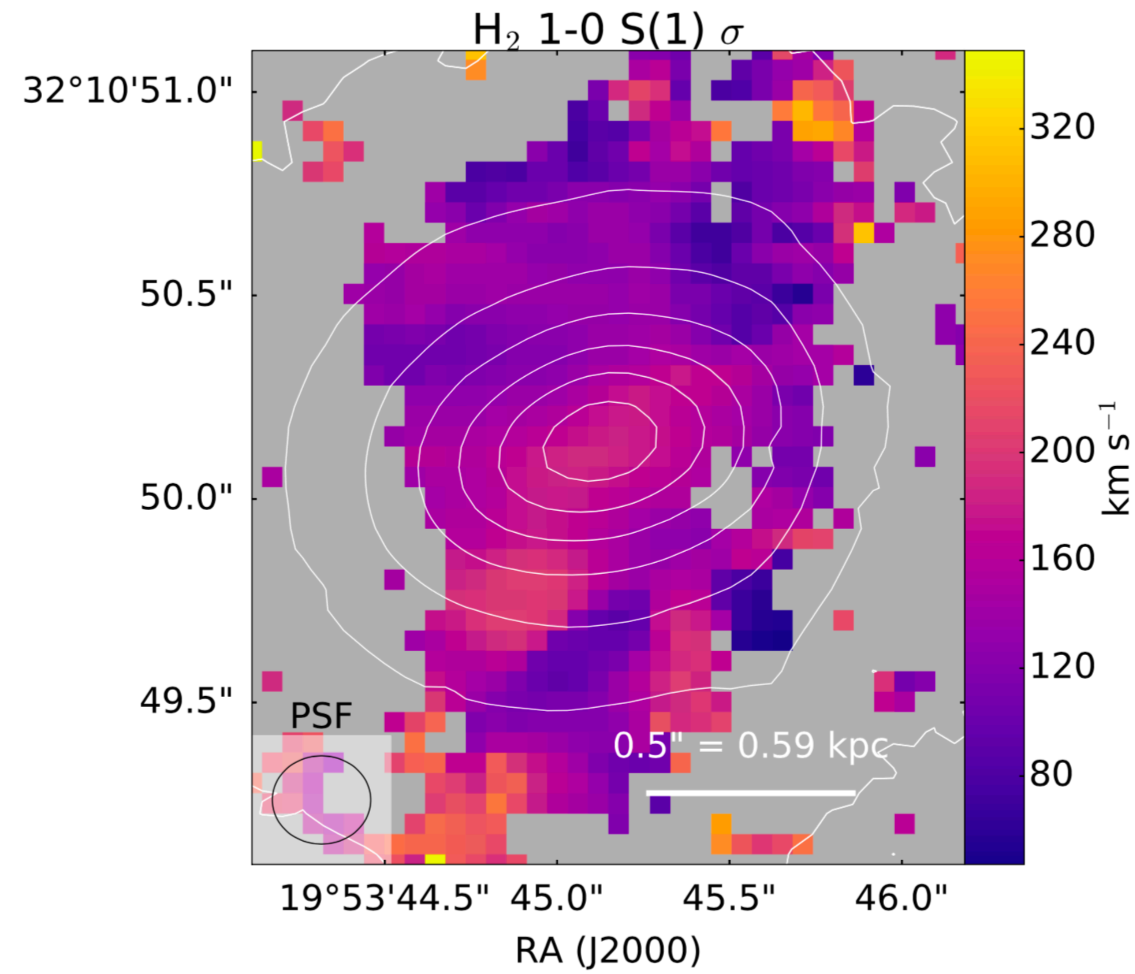


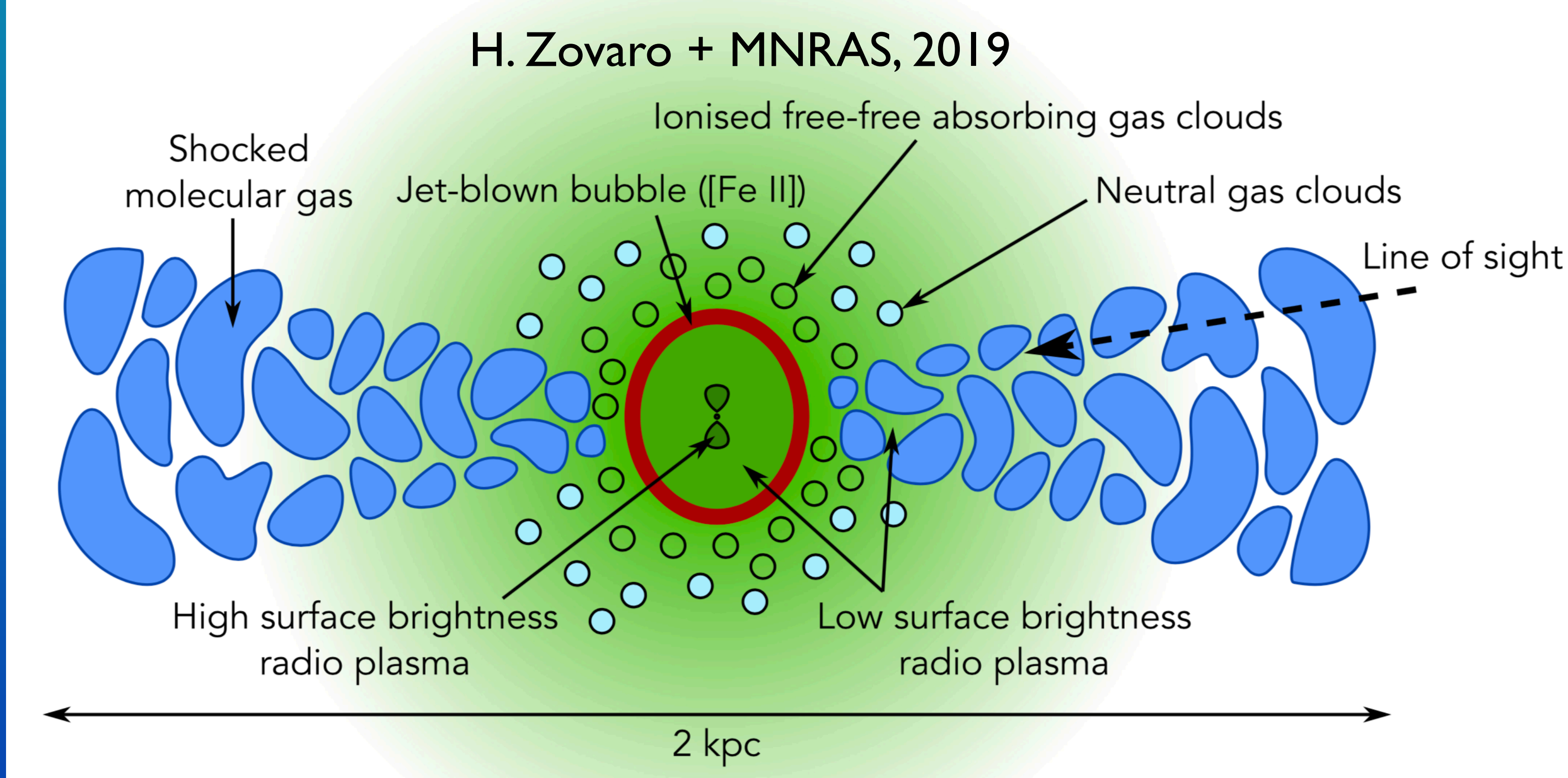
- Inclined jets couple more with turbulent disc.
- Backflow from the jet impacts a much larger part of the disc and engulfs it.
- Local outflows are launched at points of direct interaction

Movie: https://youtu.be/8eeKSc9_AJQ

Gemini observations of Jet-ISM interaction in 4C 31.04





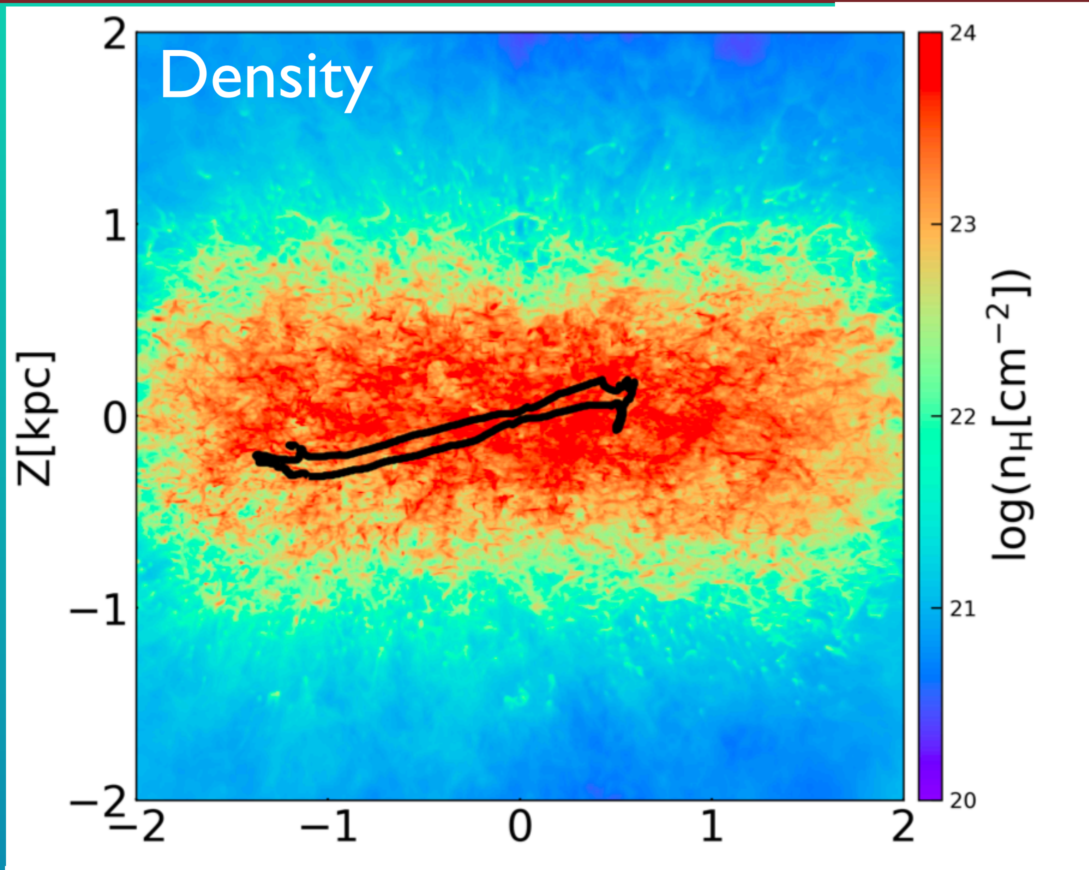


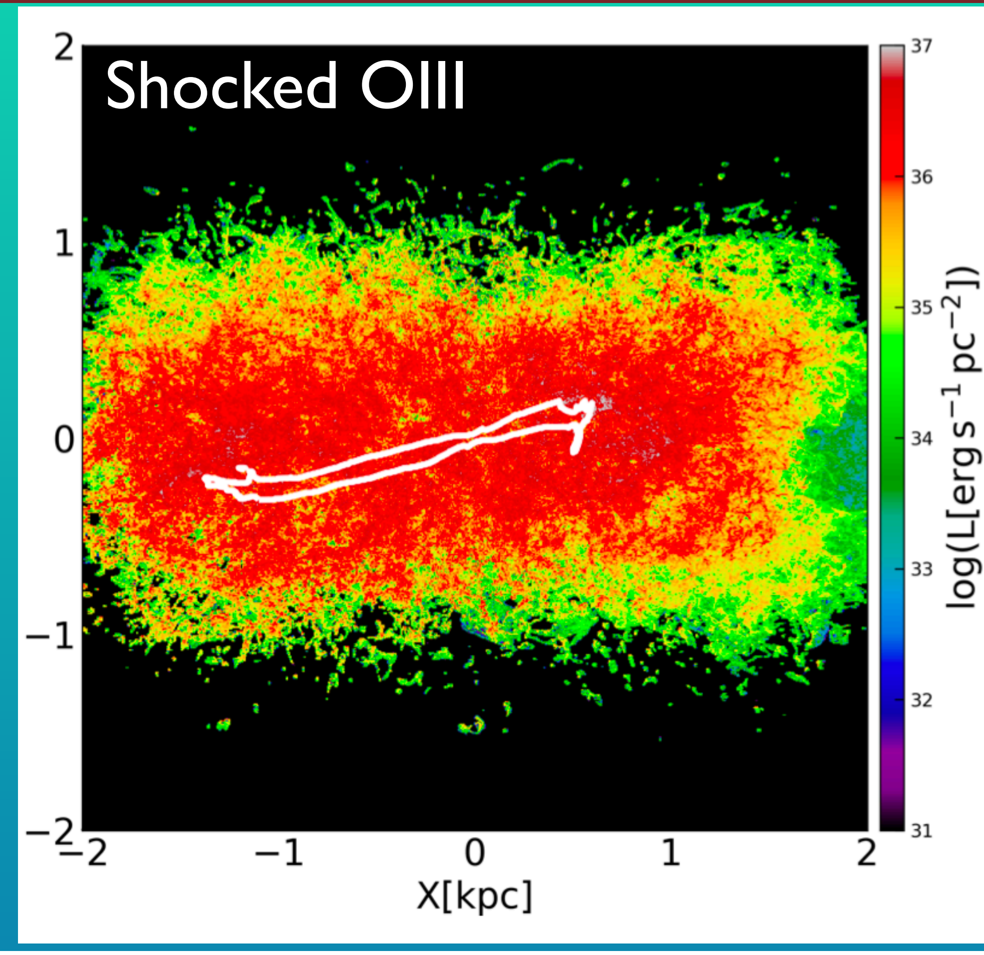
Radio jet ~ 100 pc

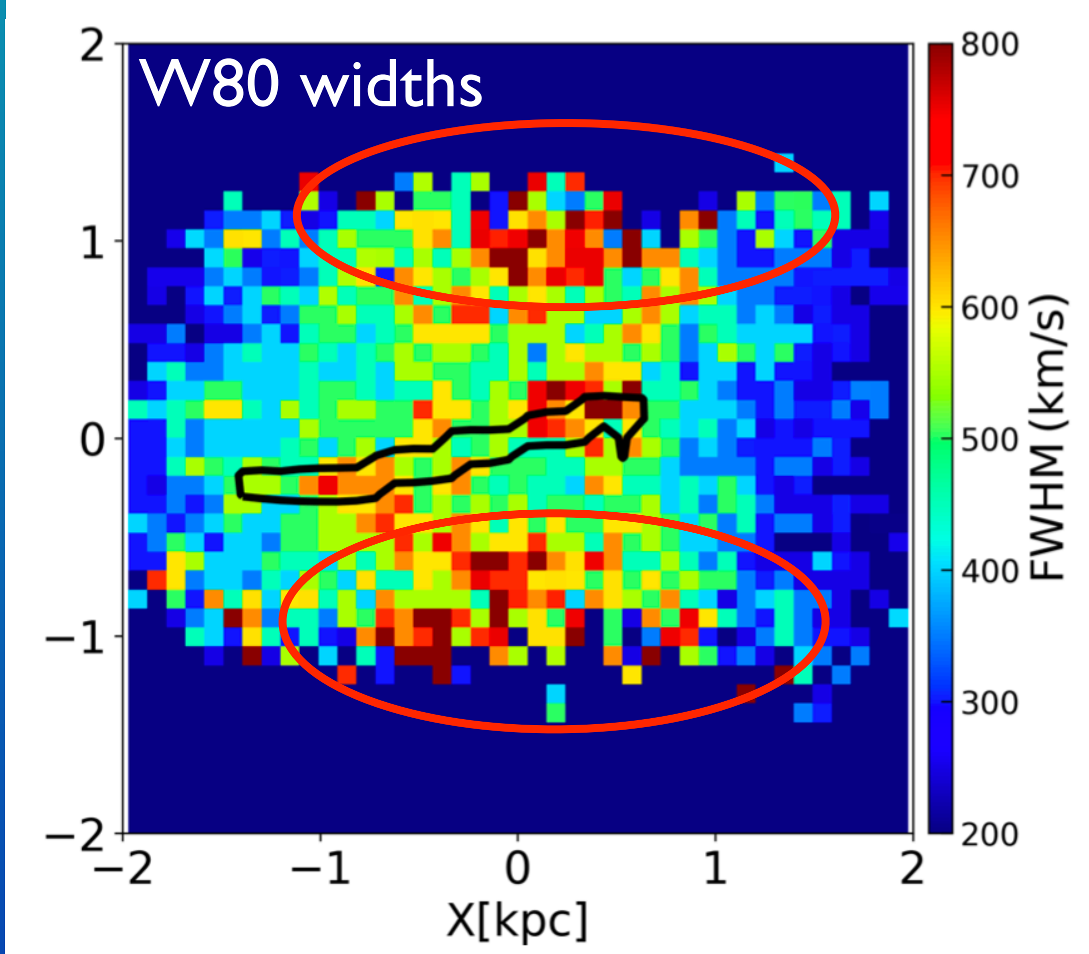
FeII ~ 300 pc

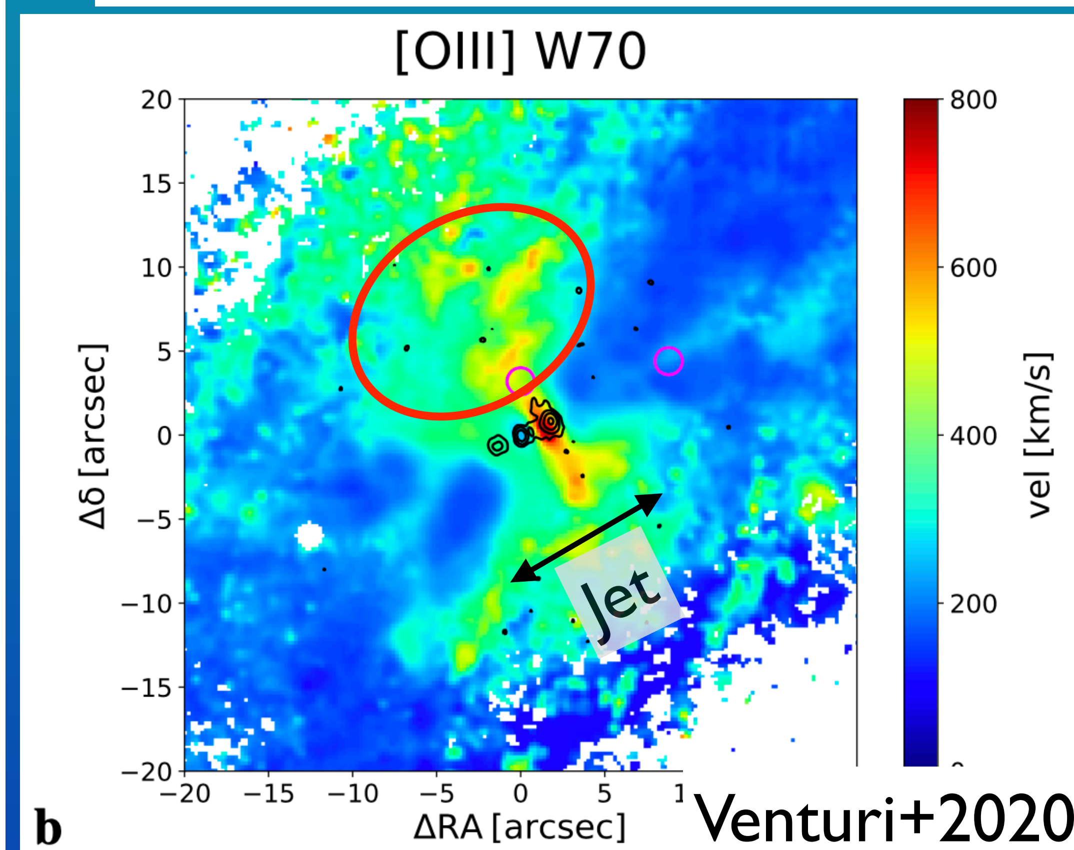
Warm H2, shocked, ~10^4 K, ~ 2 kpc;
blue shifted by 100 kms^{-1}

Observable emission features

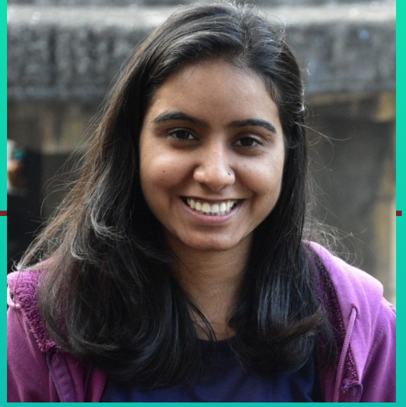








Venturi+2020



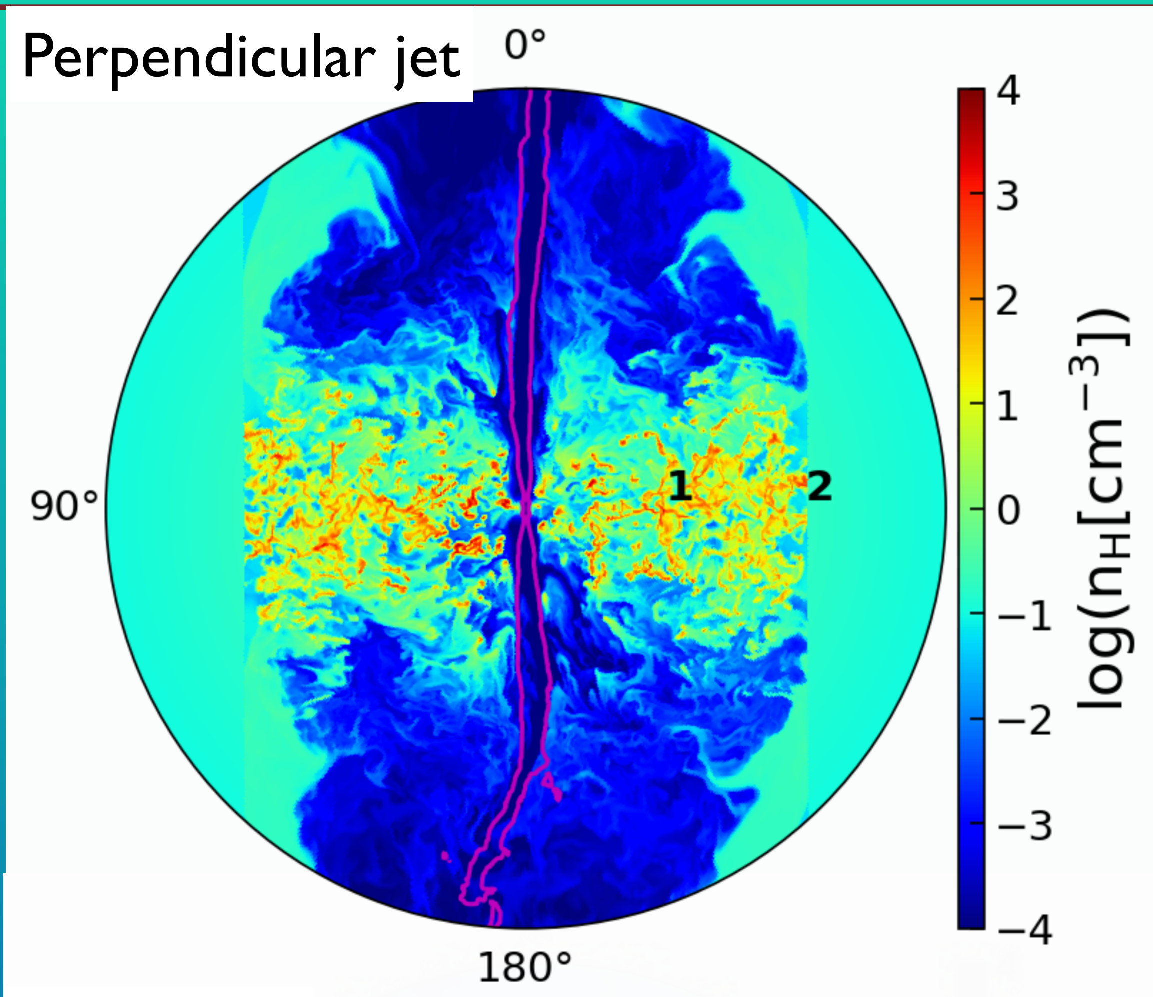
Work by Meenakshi

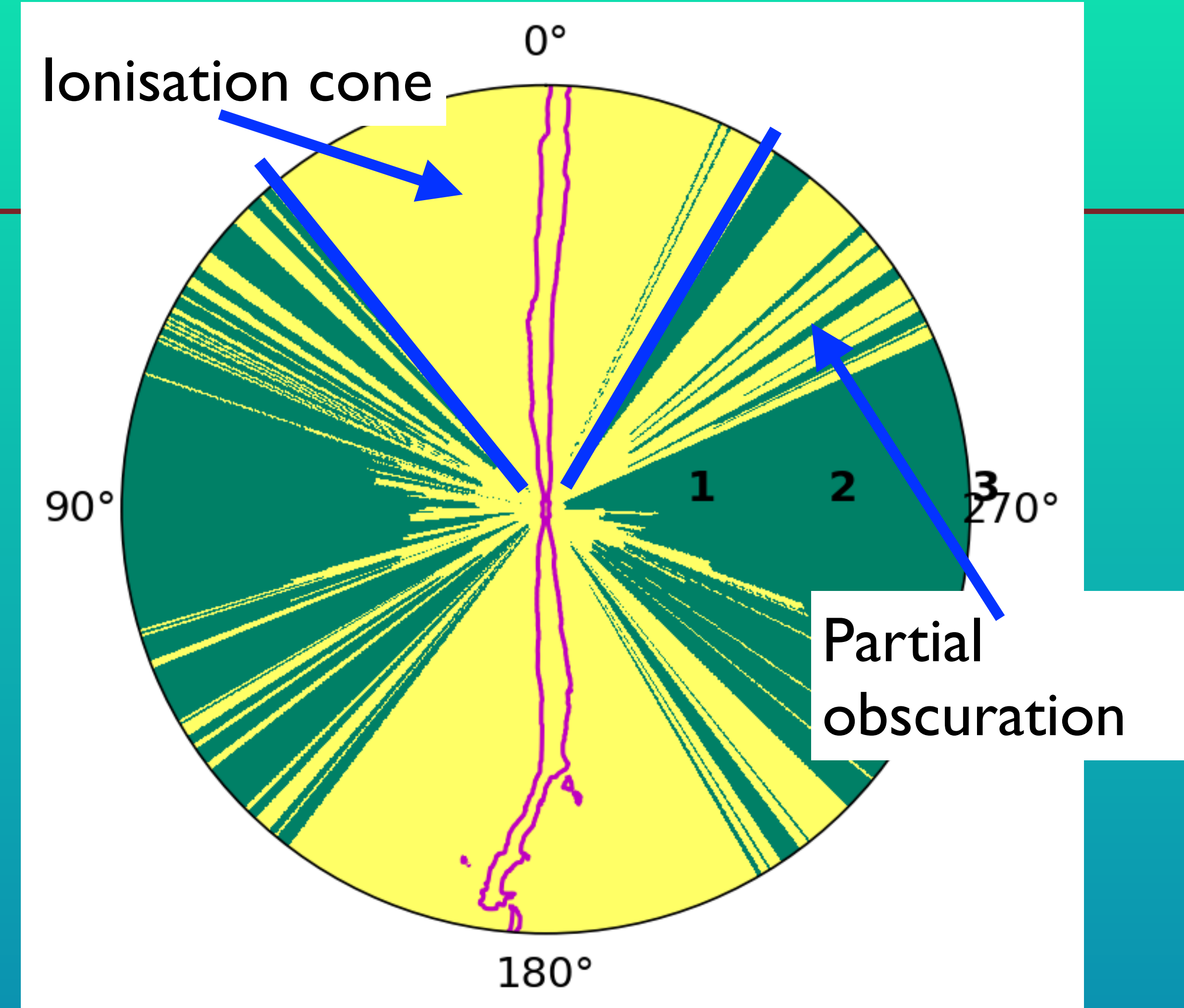
Jets induce shocks, can be observable in emission lines.

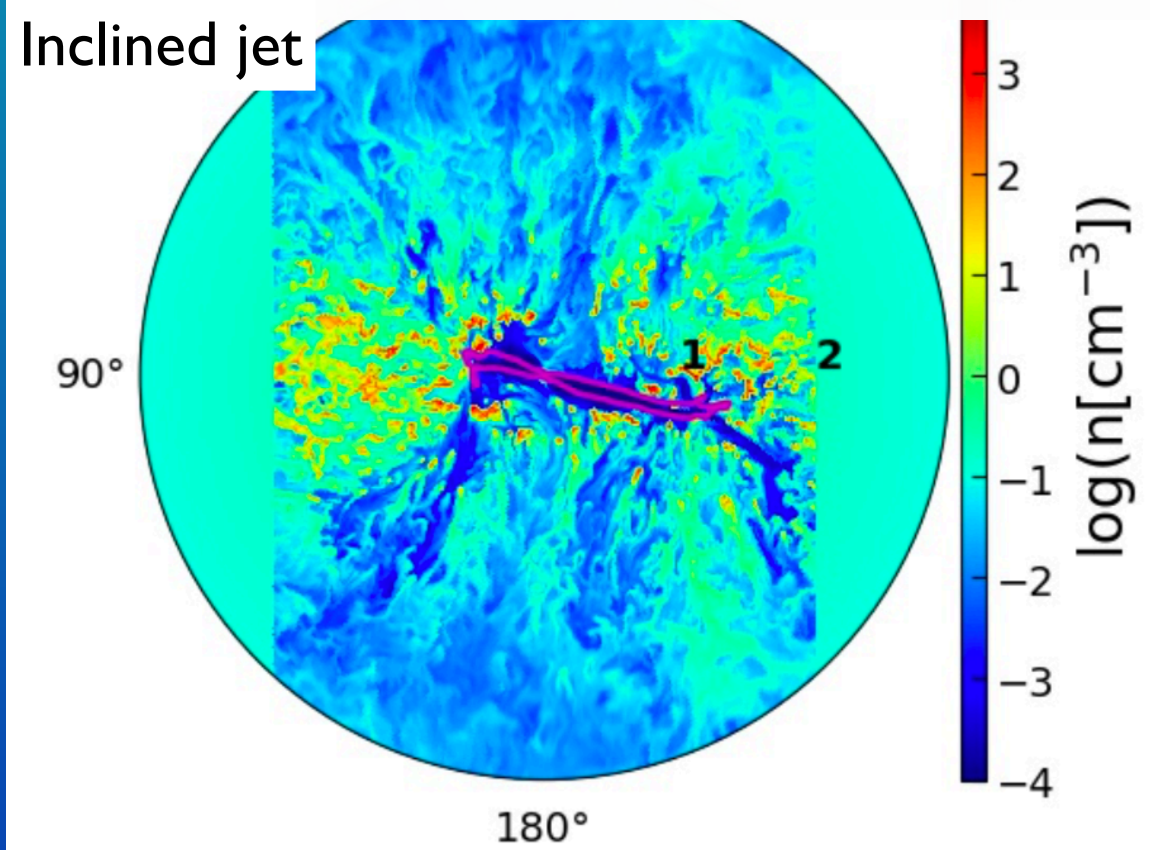
Increased dispersion perpendicular to jets.

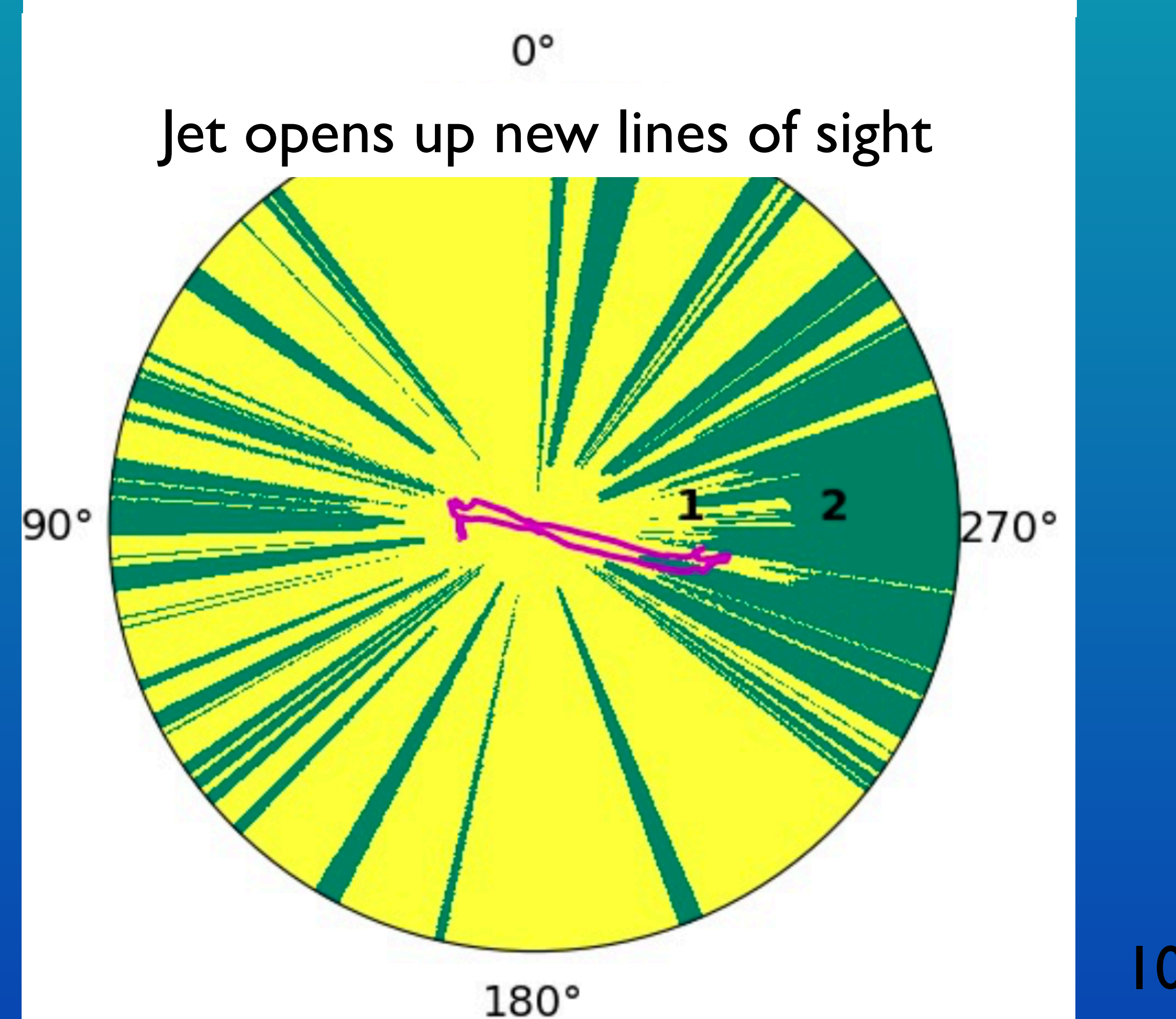
Meenakshi, DM + in prep

Photoionisation using CLOUDY



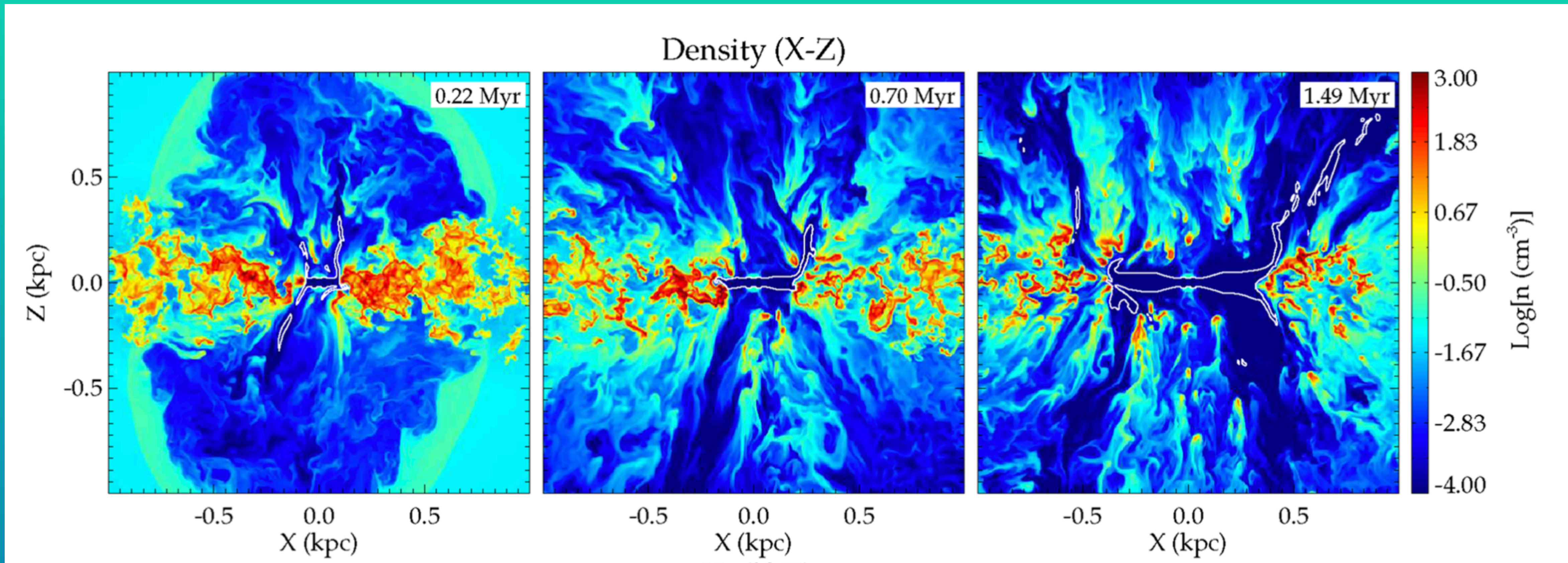


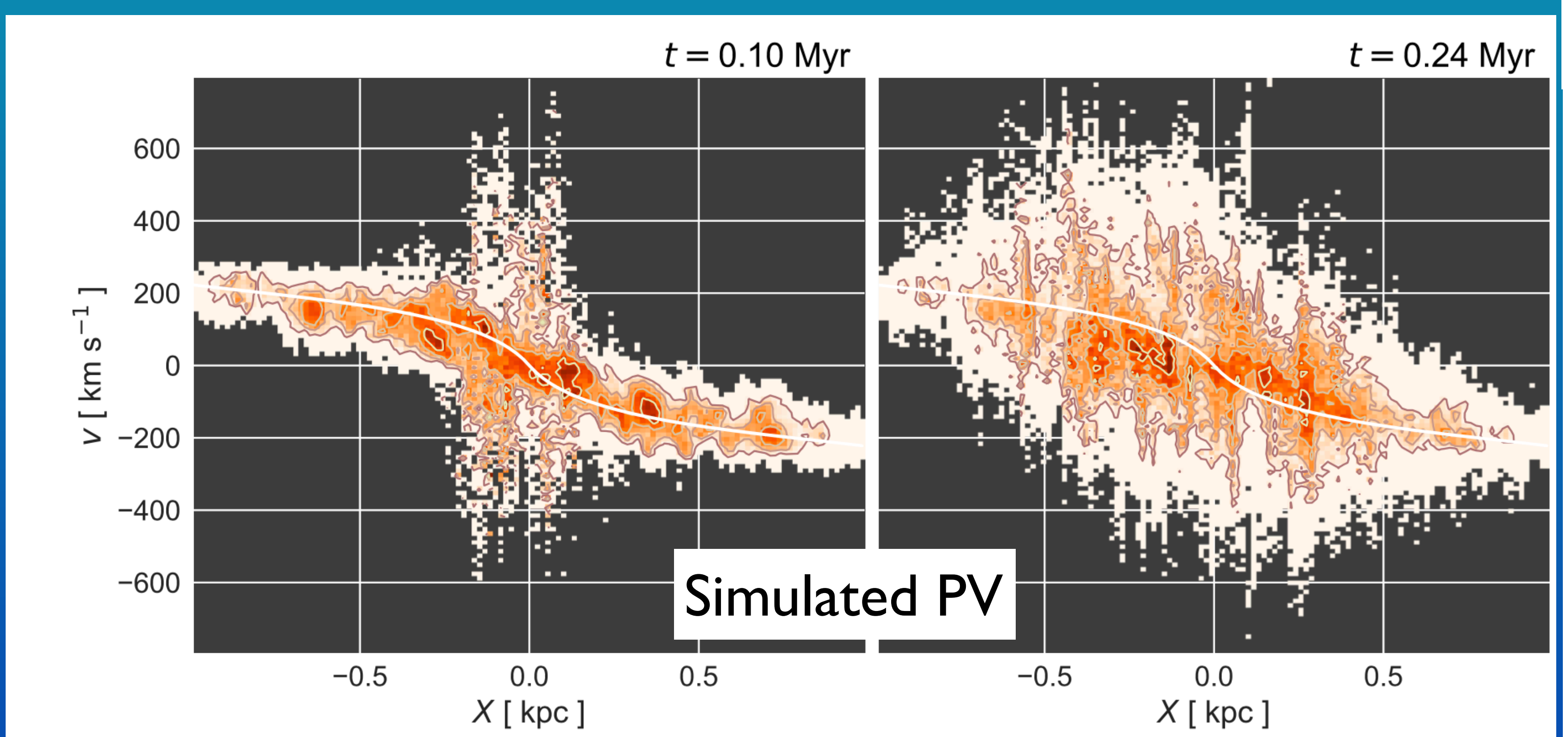




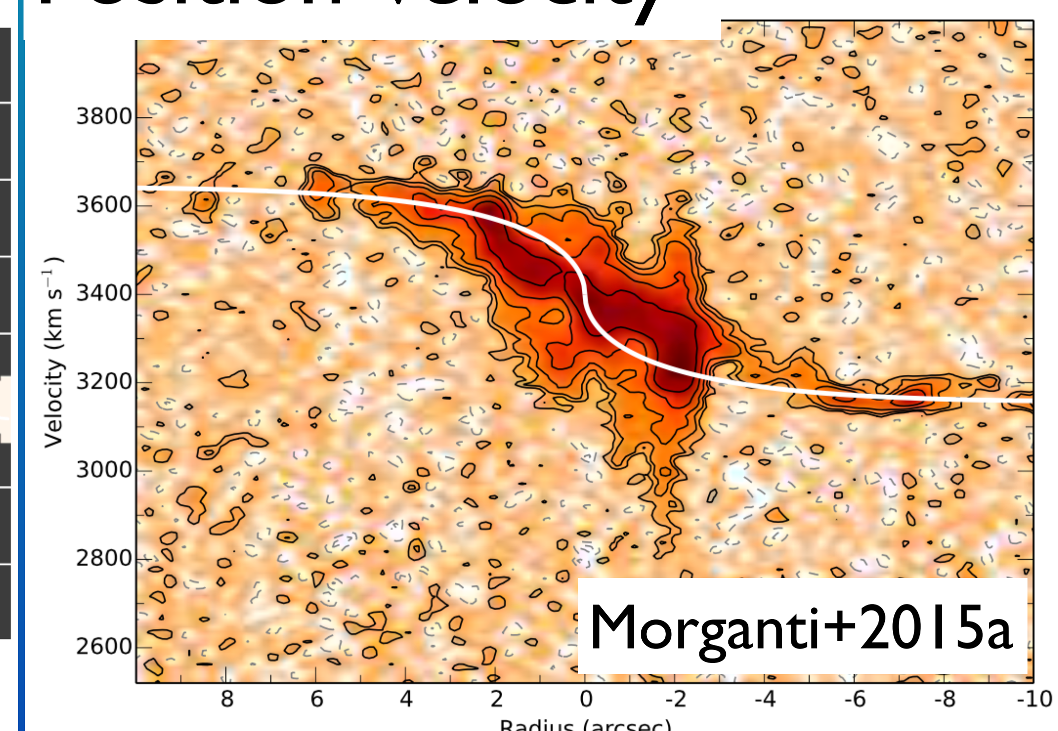
Inclined jets: IC 5063

Mukherjee+2018a

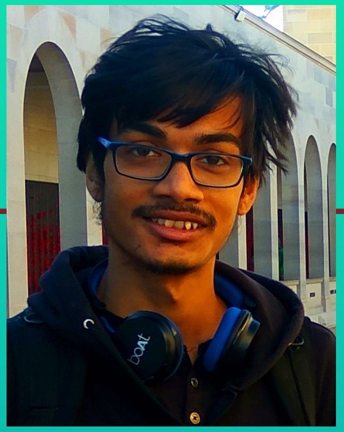




Position-velocity



Estimating SFR with improved subgrid physics

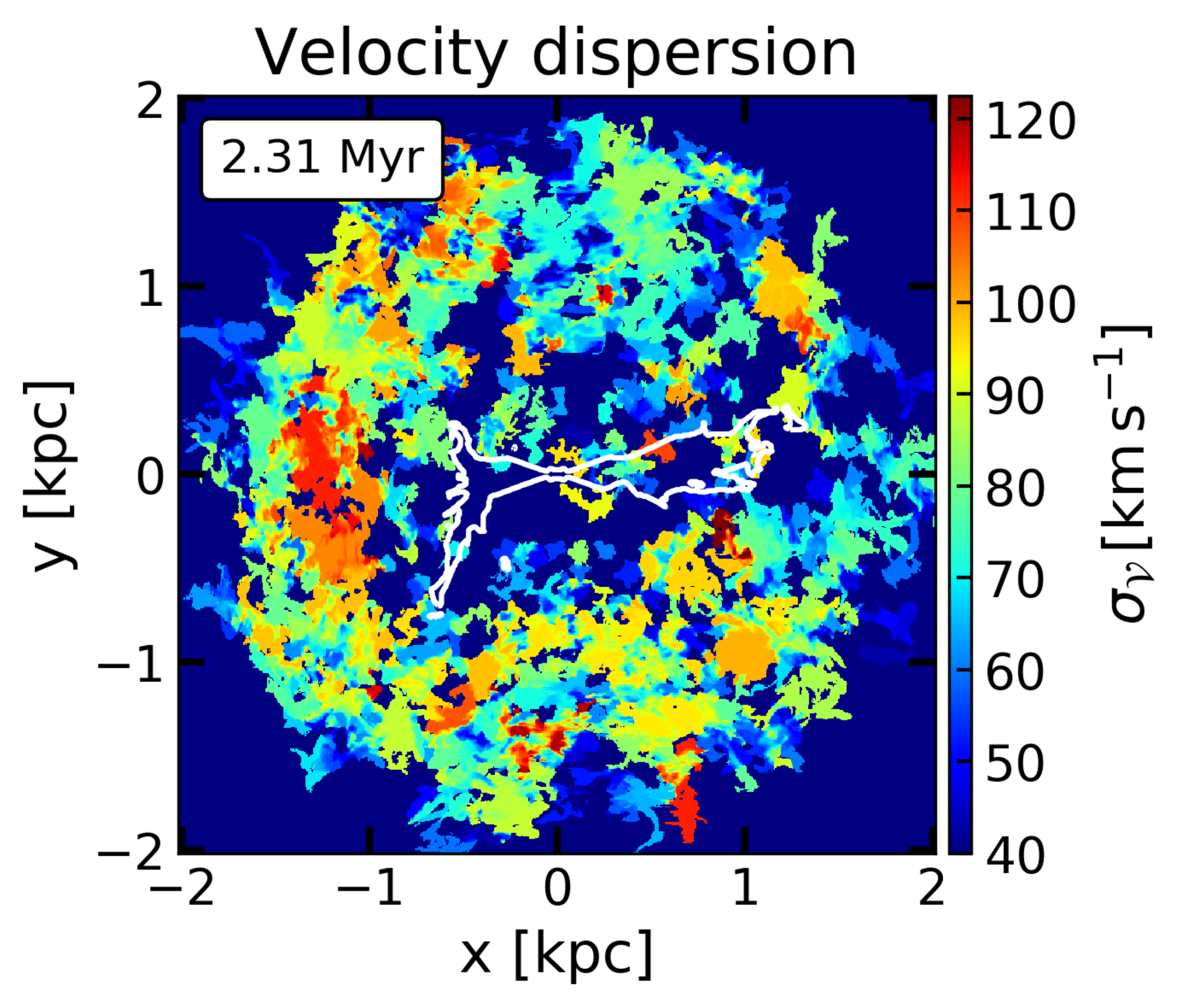


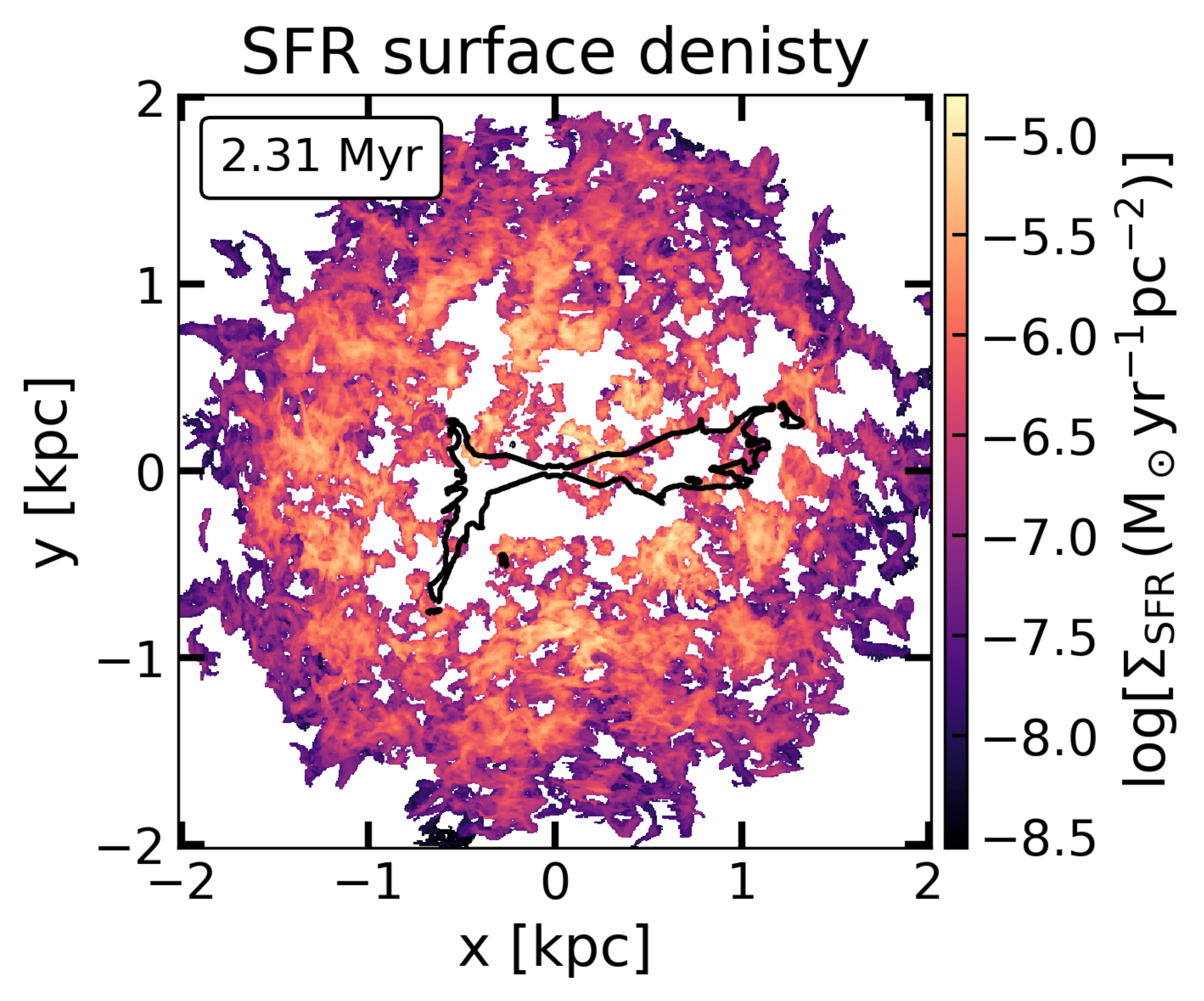
Work by Ankush Mandal

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

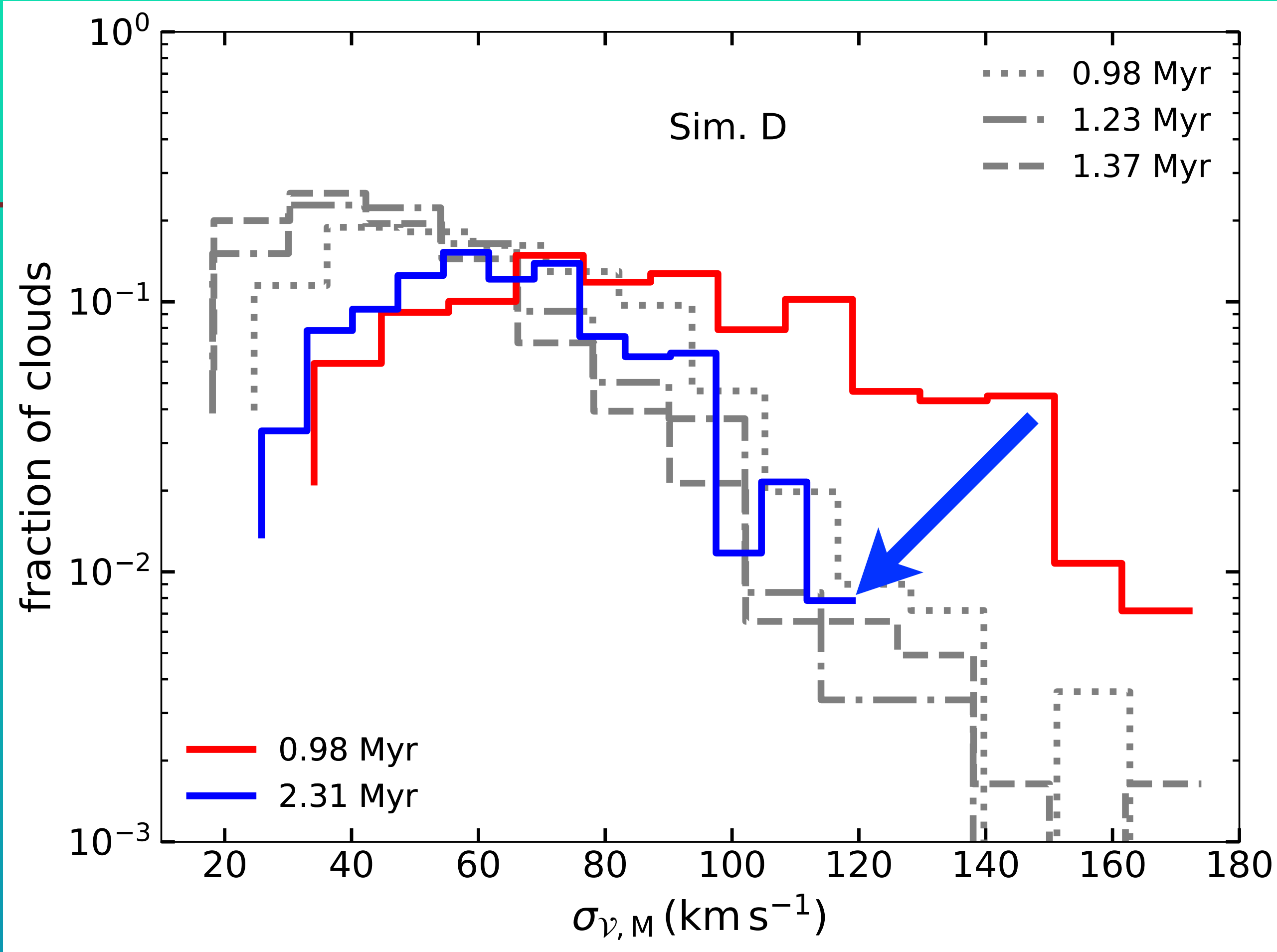
No input about turbulent velocity dispersion or Mach number.

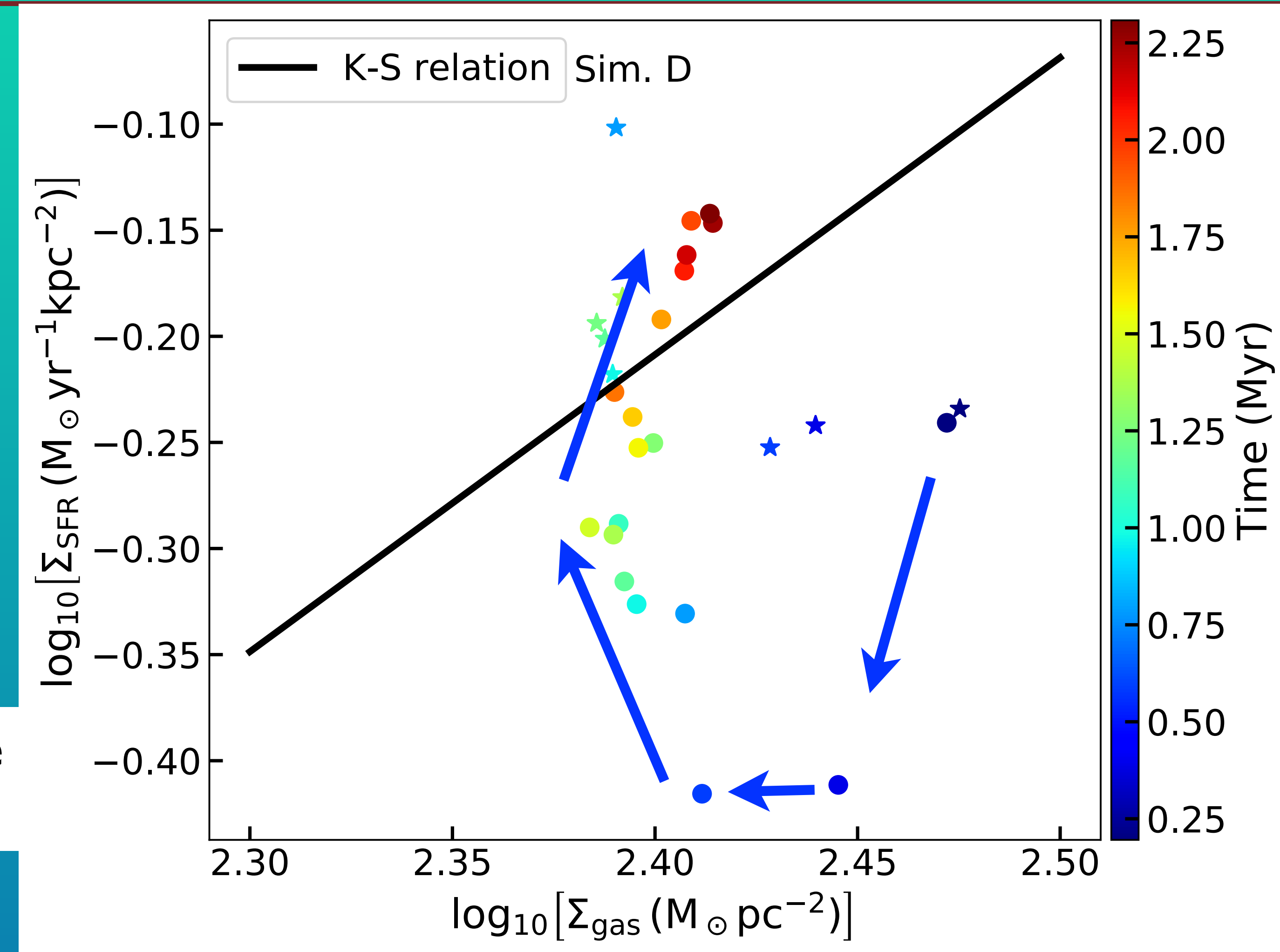
Better option: Use a turbulence based SFR prescription (Krumholz+2005, Federrath+2012).



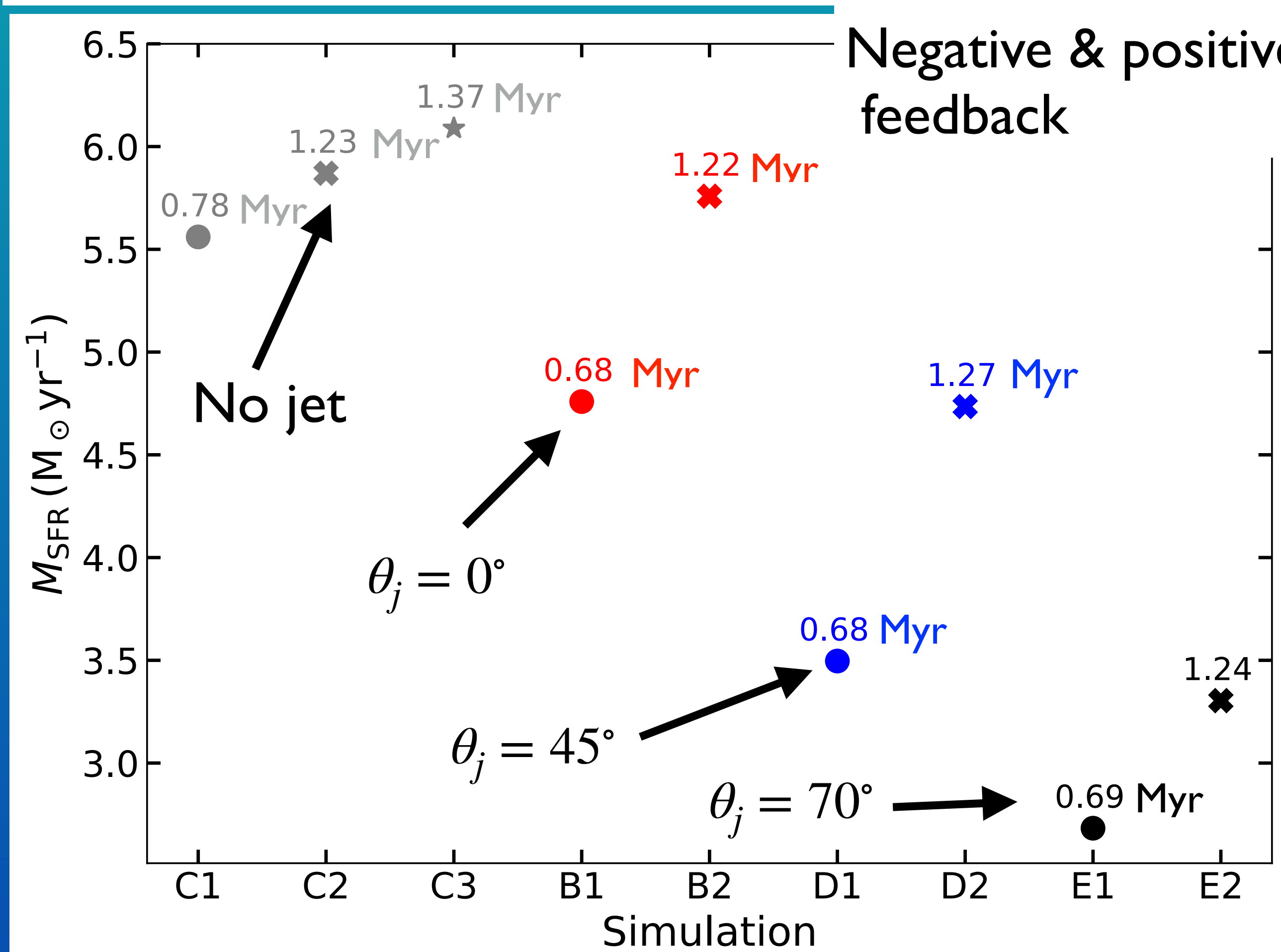


Estimating SFR





Negative & positive feedback

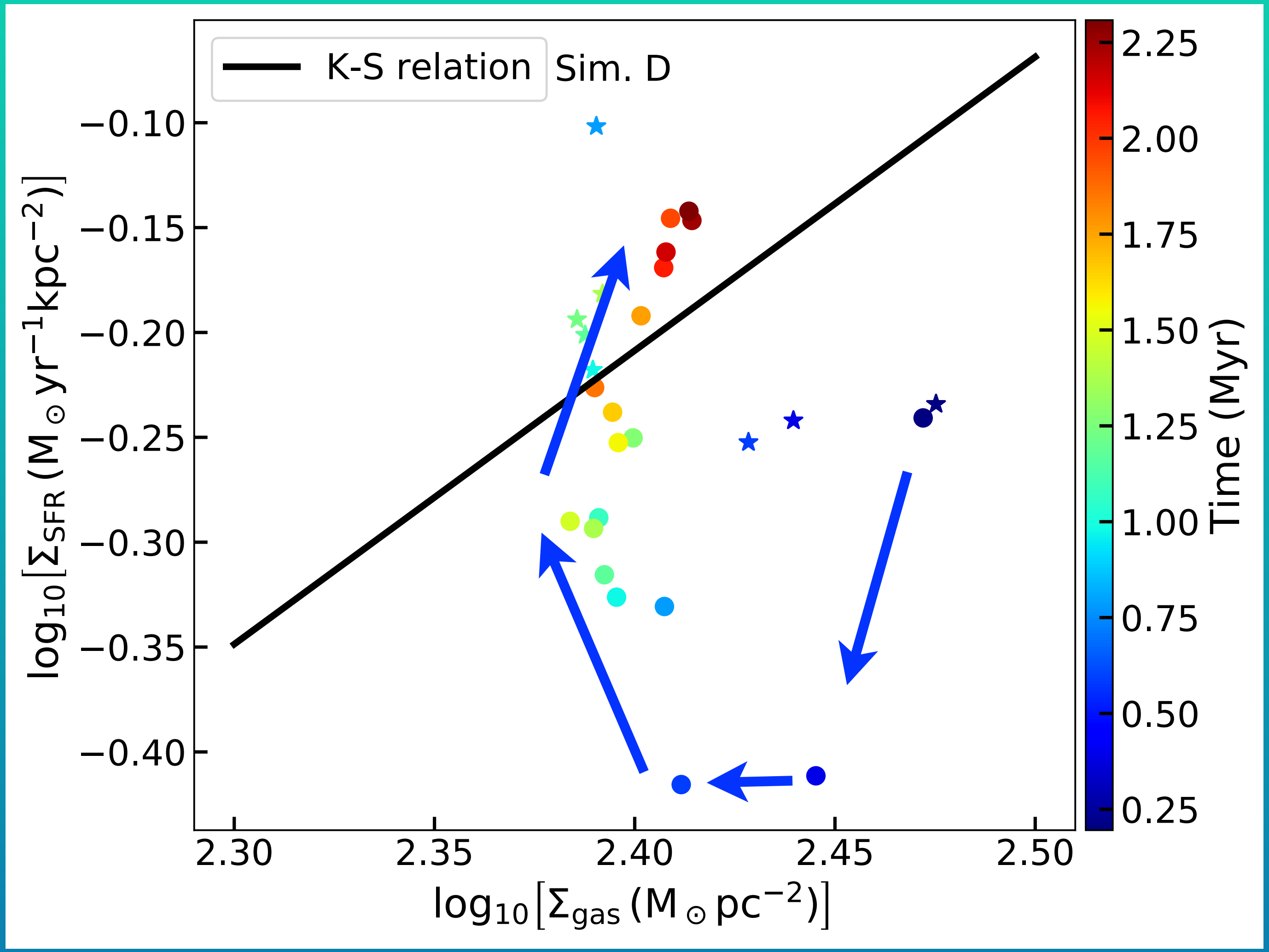


- Early times: SFR efficiency decreases, increase in turbulent dispersion (-ve feedback).
- But, shocks increase density.
- Later times: turbulence decays, enhanced density raises efficiency again (+ive feedback)

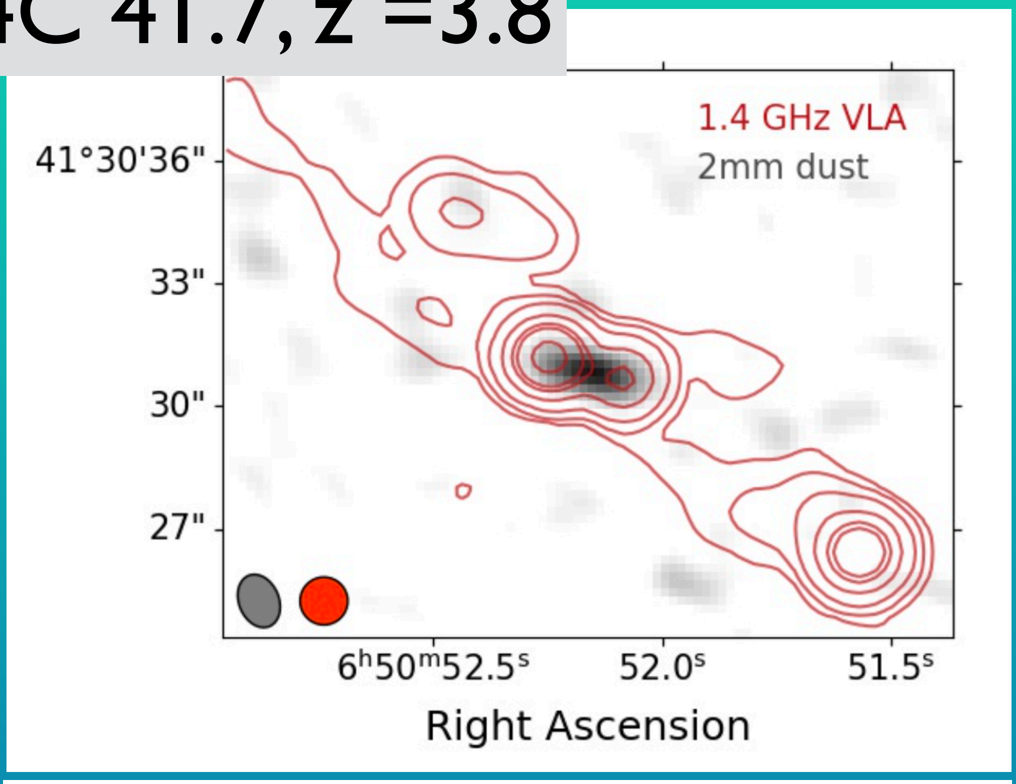
θ_j: angle between jet axis and disk-normal

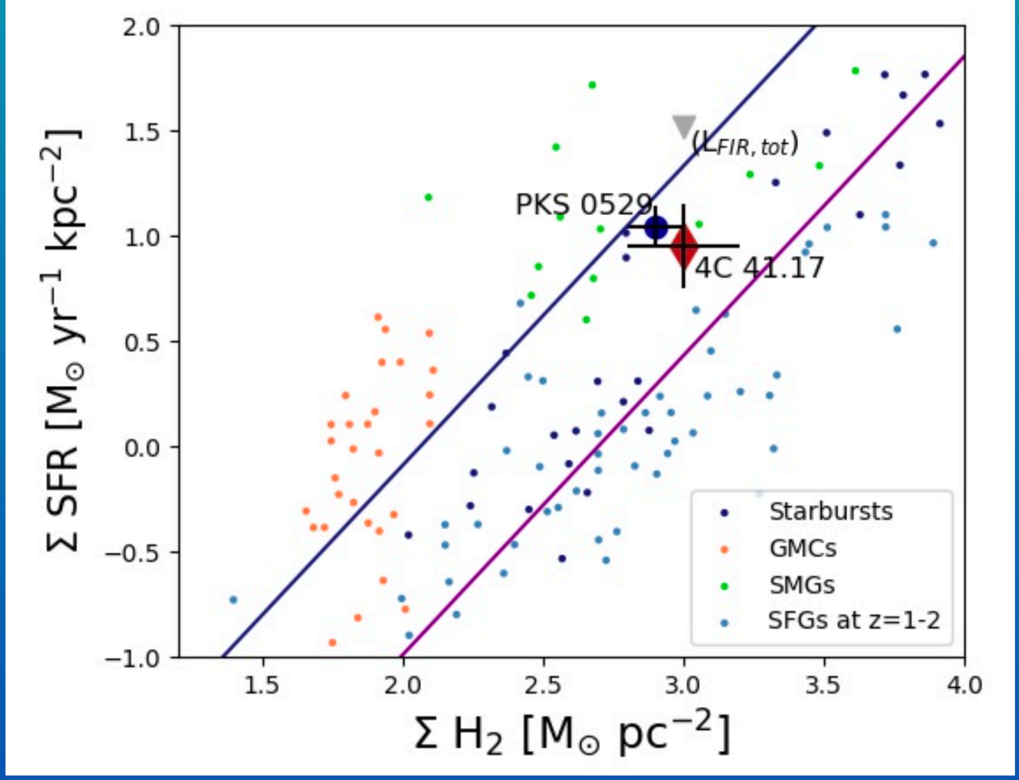
Mandal, DM + in prep

Jet feedback & SFR efficiency



4C 41.7, z =3.8





- Positive feedback may not mean strong enhanced of SFR efficiency. Ineffcient positive feedback.
- Positive & negative feedback can happen in the same system.
- Depends on many other factors: jet power, ISM density, jet-ISM coupling

Nesvadba, GVB, DM+2020

Jets with new hybrid particle + fluid scheme

Spatial evolution:

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

Spectral evolution:

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

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

Vaidya et al. 2018

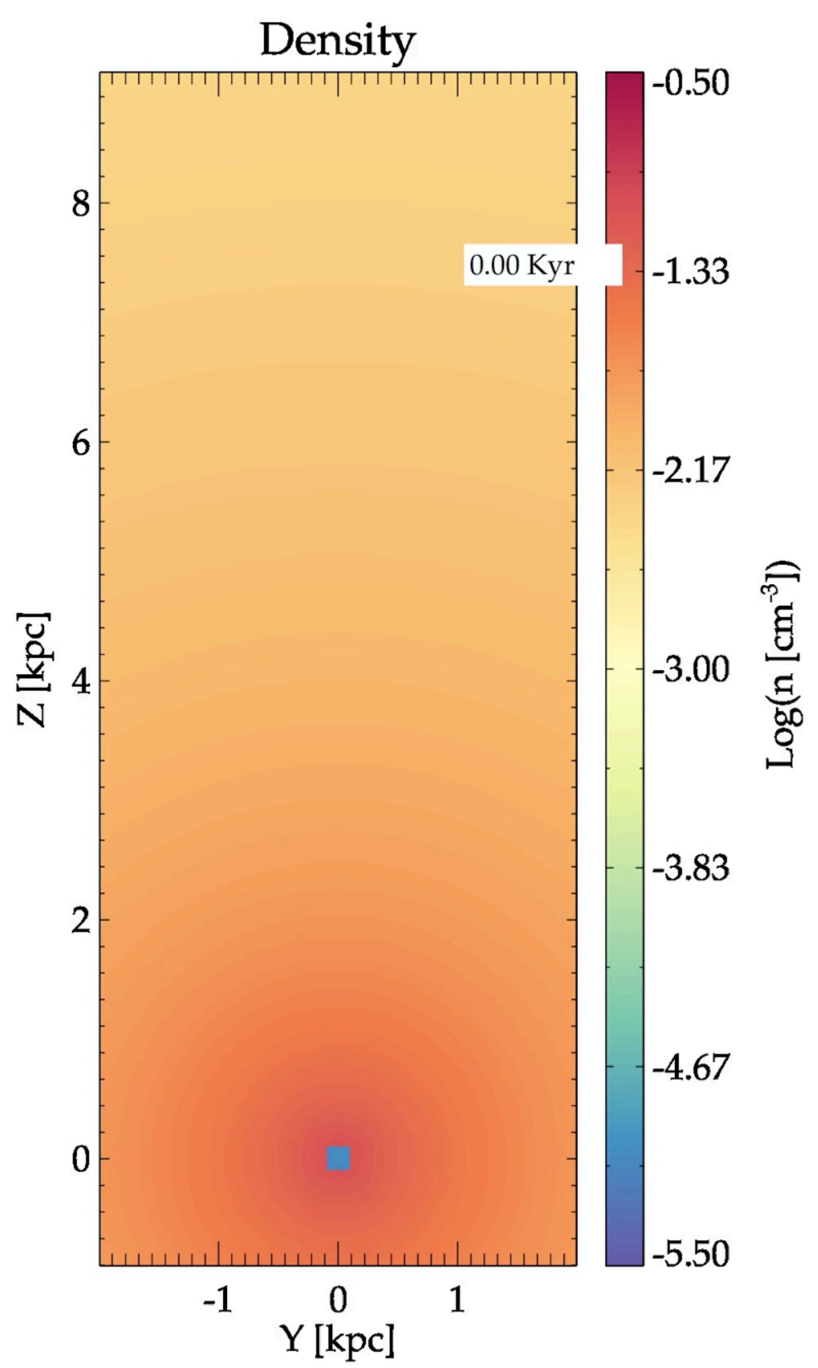
Energy losses, synchrotron, inverse compton

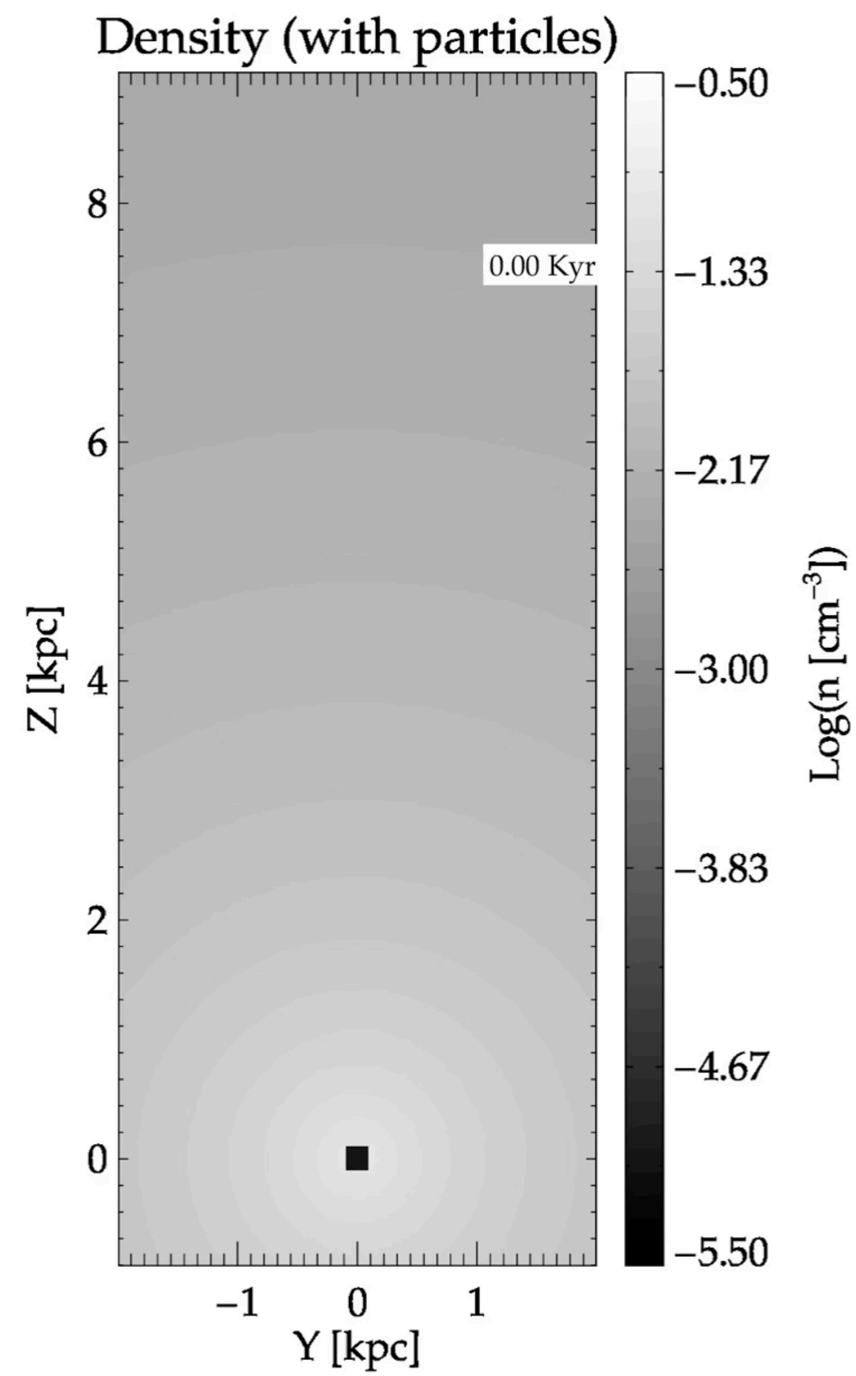
DSA model for acceleration at shocks

Finally:

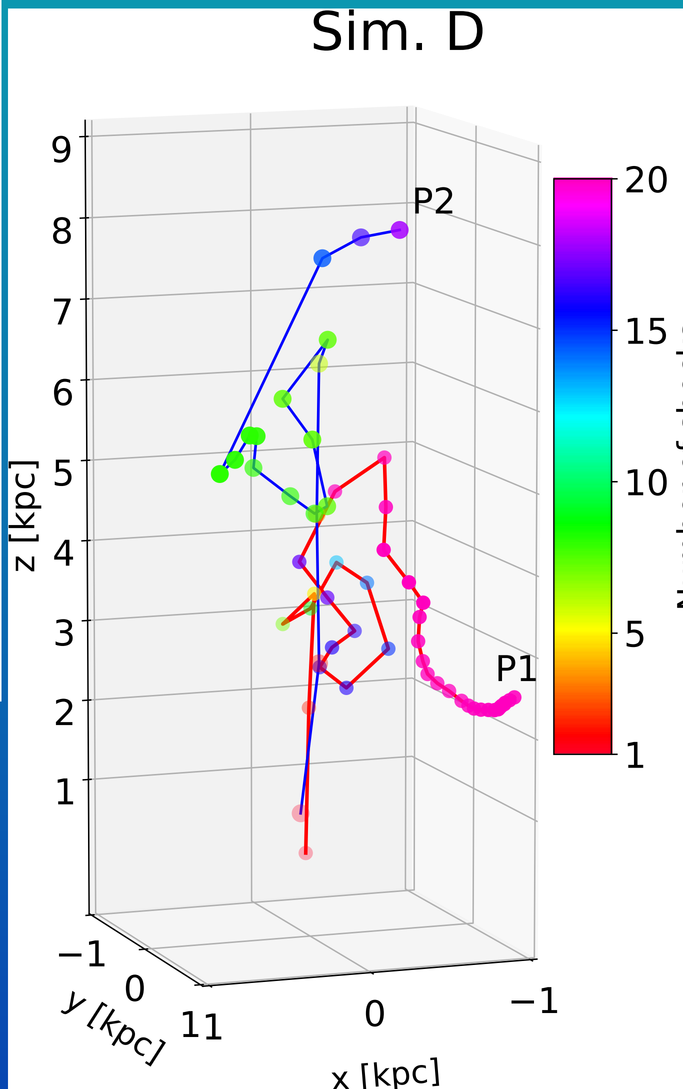
$$J'_{\rm syn}(\nu', \hat{\boldsymbol{n}}'_{los}, \boldsymbol{B}') = \frac{\sqrt{3}e^3}{4\pi m_e c^2}|\boldsymbol{B}' \times \hat{\boldsymbol{n}}'_{los}| \int_{E_i}^{E_f} \mathcal{N}'(E')F(x)dE'$$

Jets with new hybrid particle + fluid scheme





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

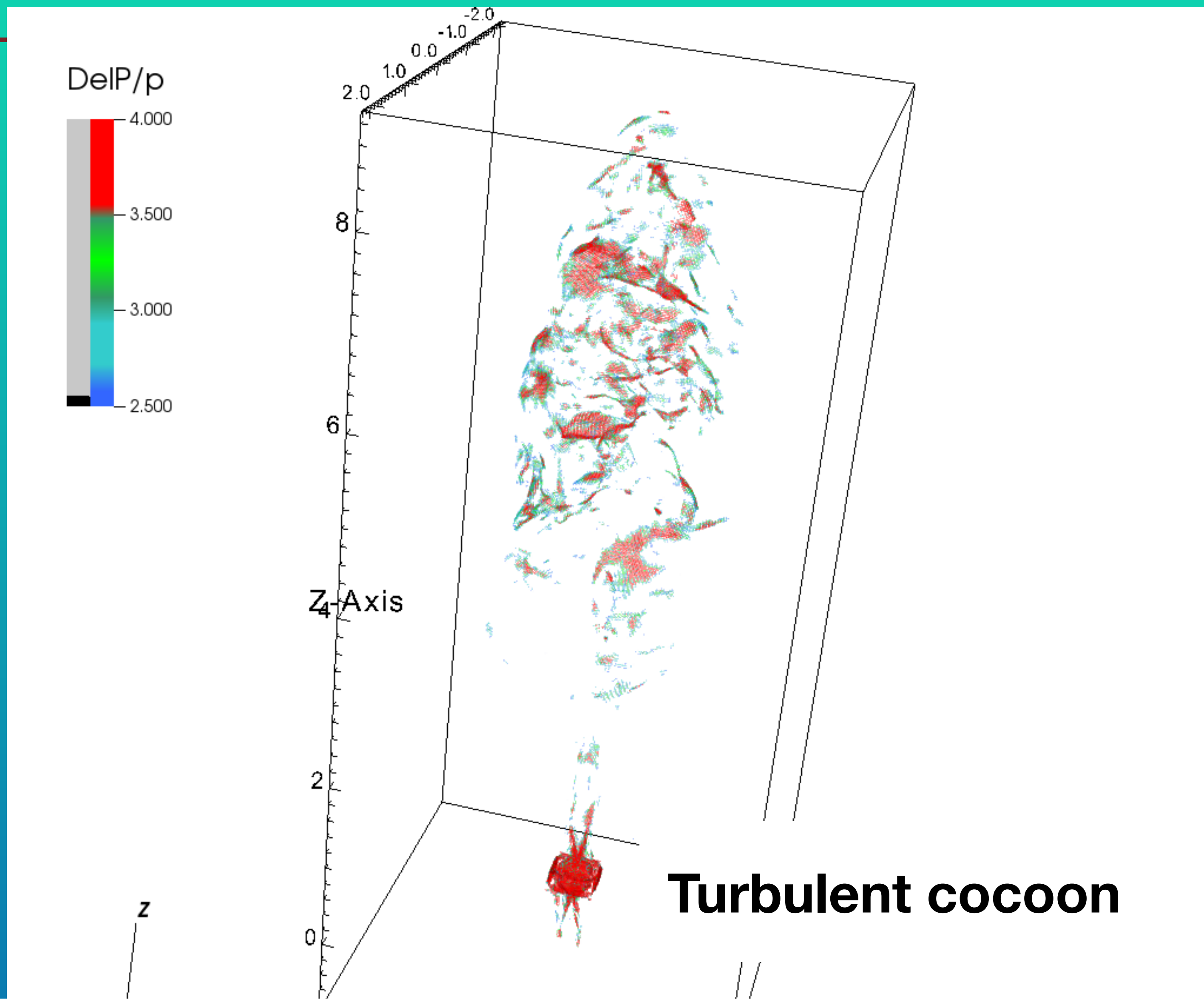


Mukherjee+2020, Mukherjee+2021

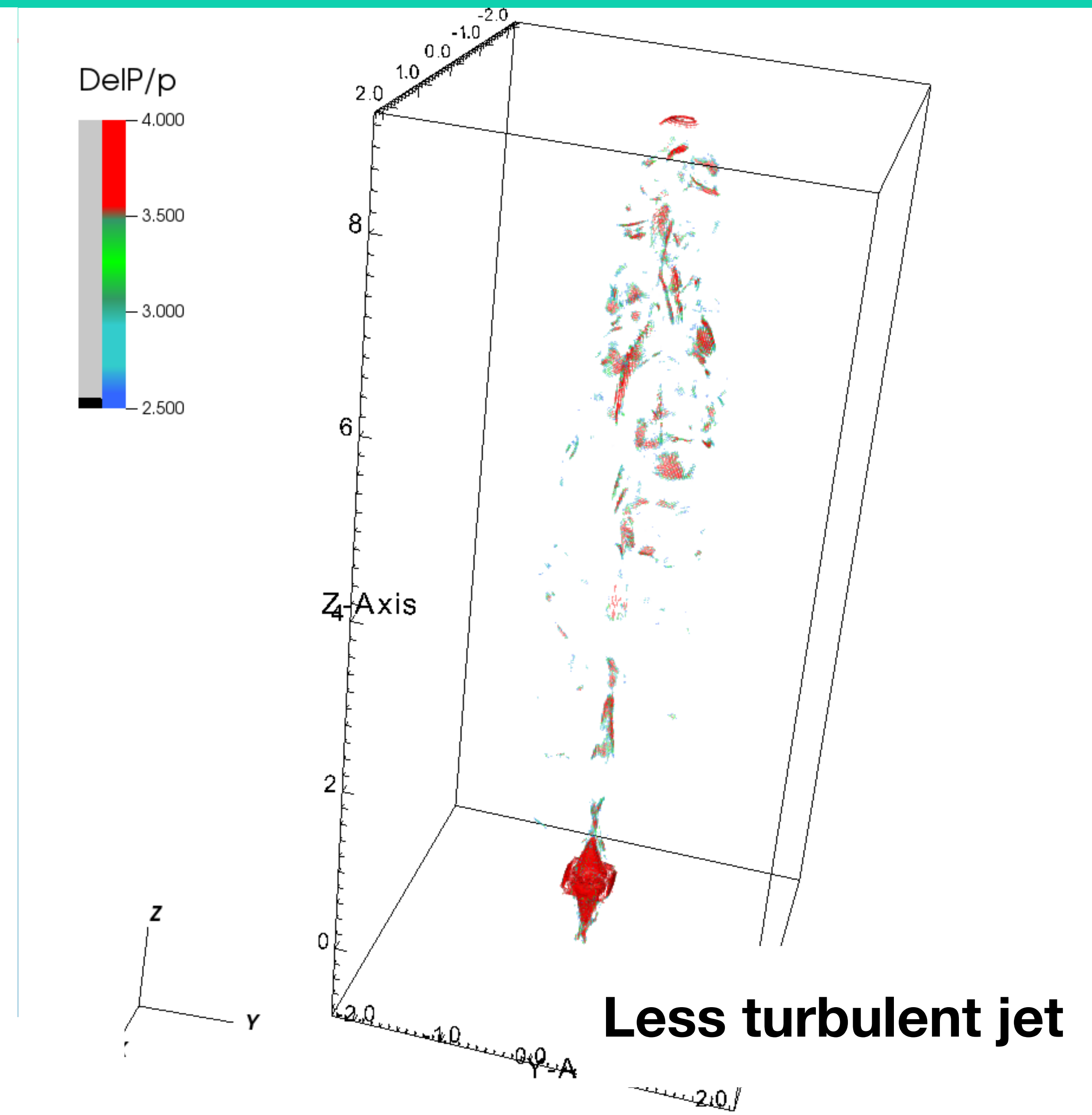
Particle color = Max energy, indicates shocks

Movie: https://youtu.be/bpFa22hjTSA

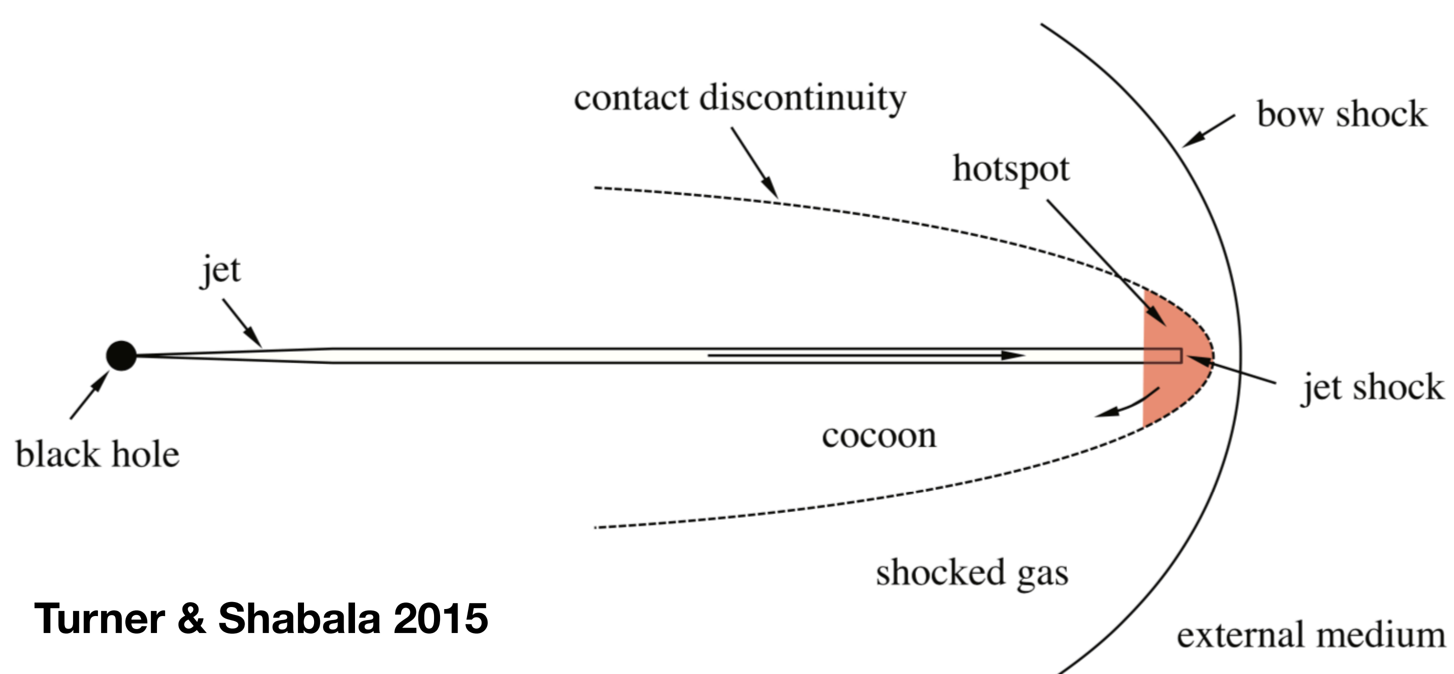
Internal shocks in turbulent cocoon



Turbulent cocoon



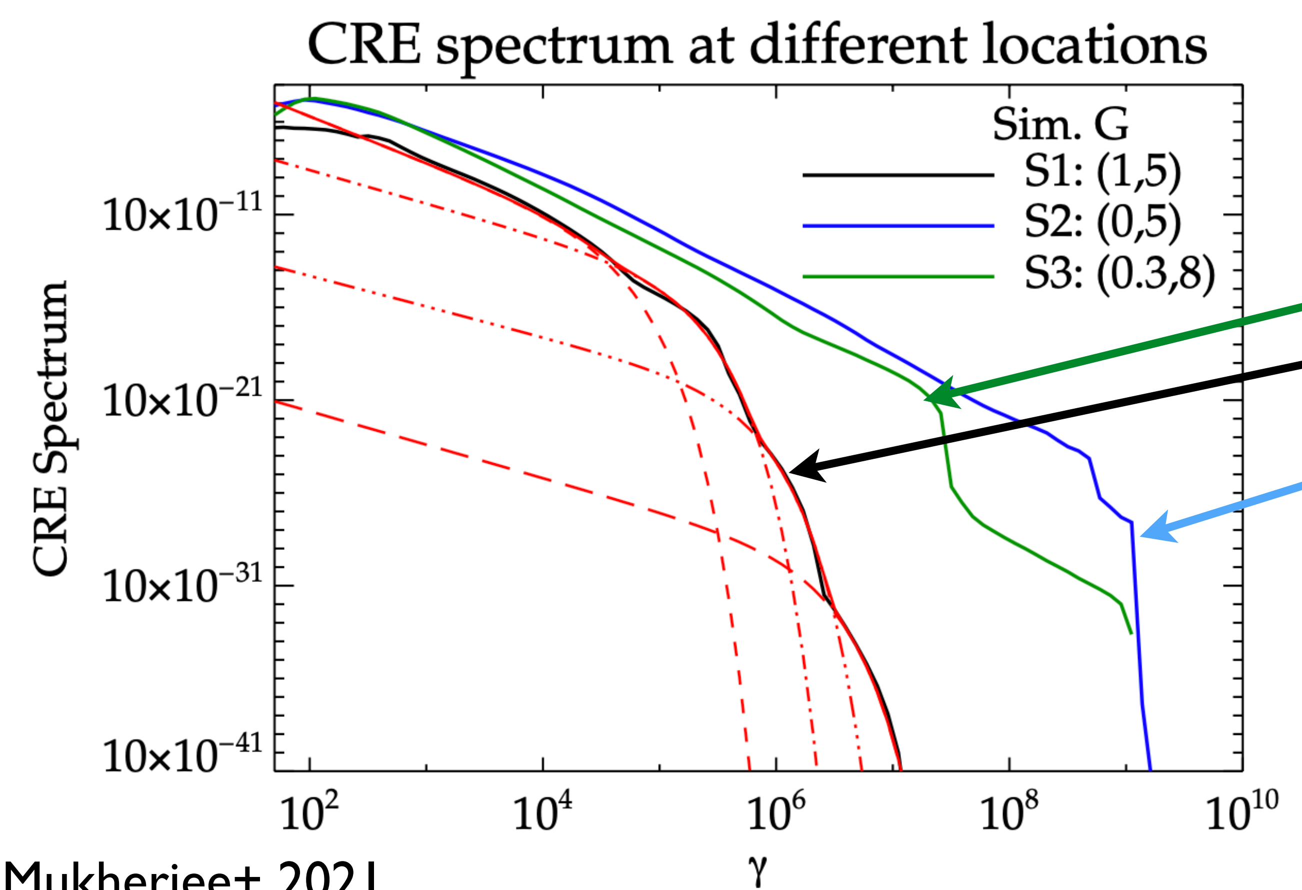
Less turbulent jet



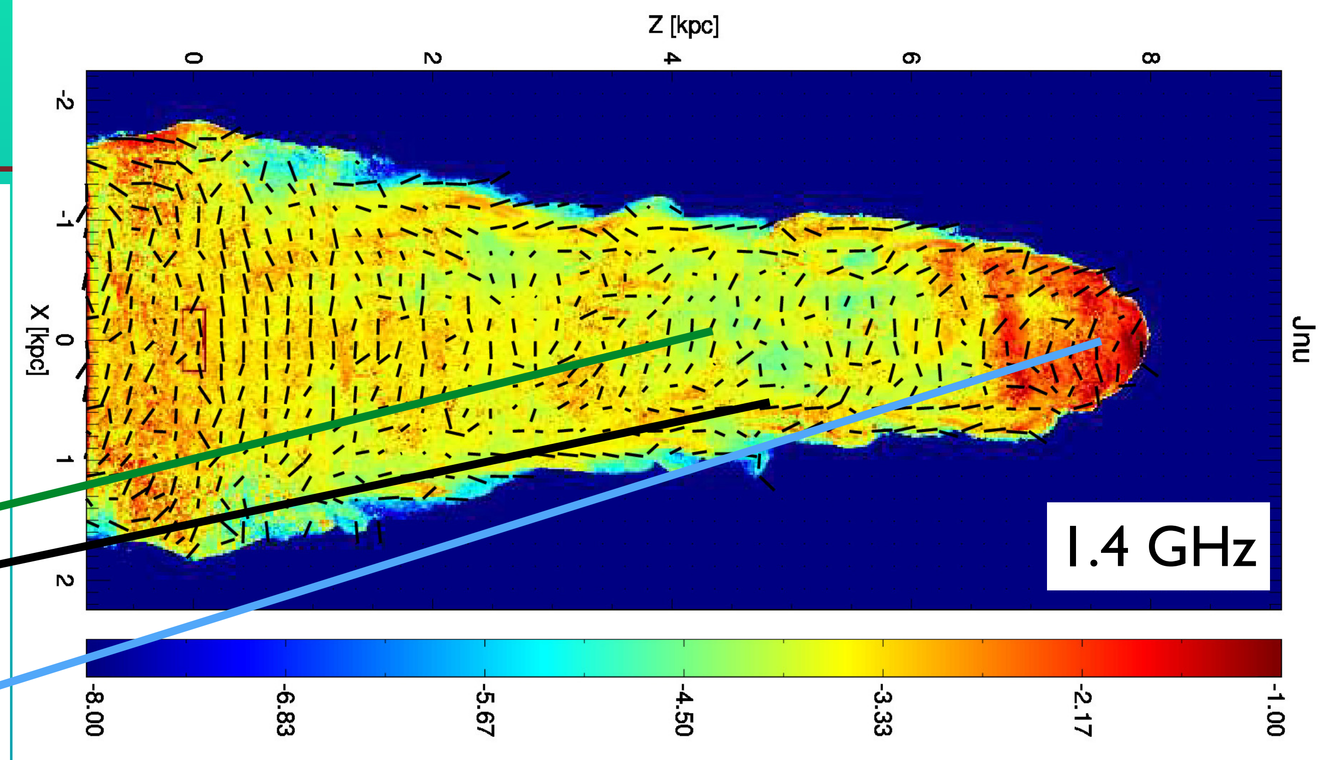
Turner & Shabala 2015

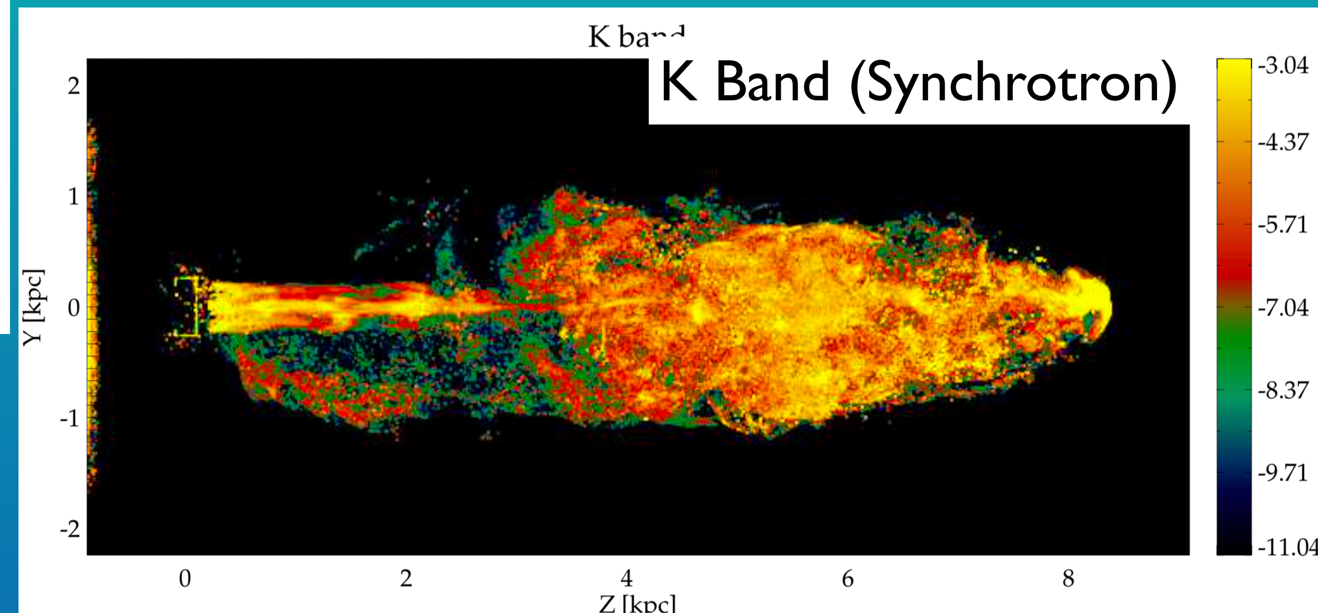
- **Multiple internal shocks** which can re-accelerate electrons in the backflow.
- Goes against the standard paradigm of a terminal hotspot and free-stream
- Turbulent cocoons have more shocks

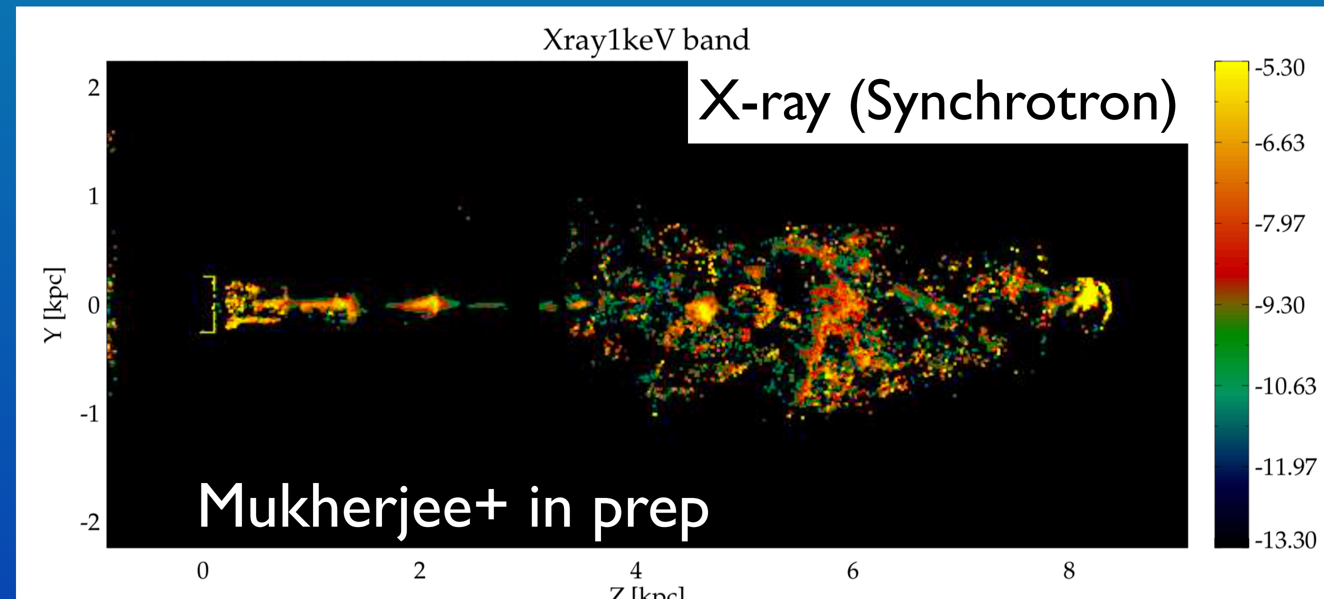
CRE Re-acceleration



Mukherjee+ 2021

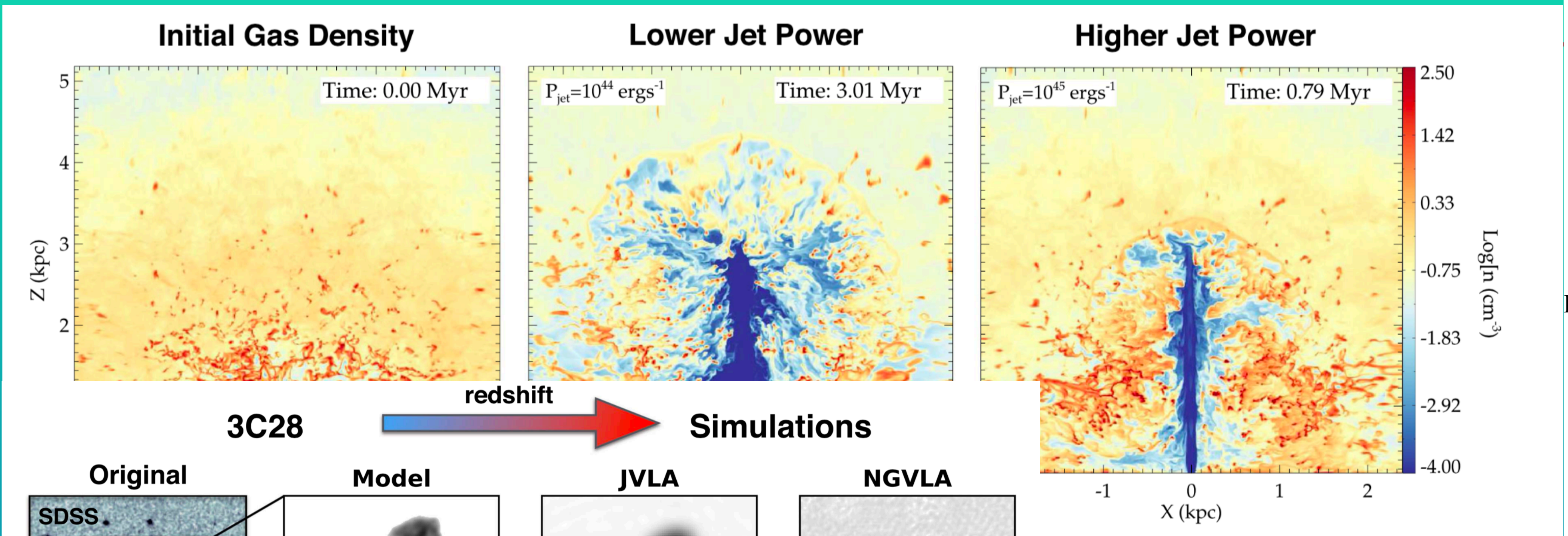


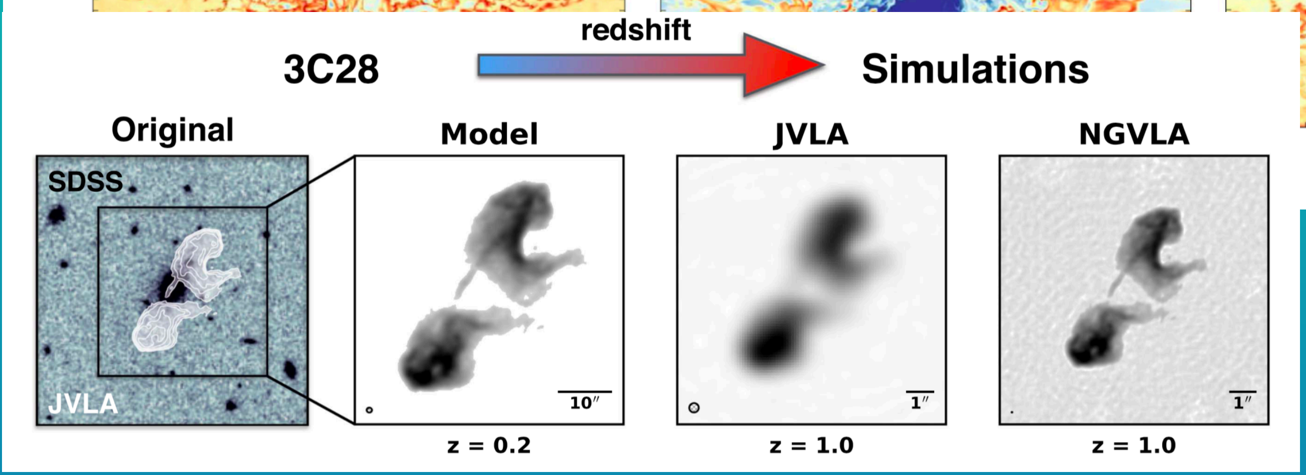




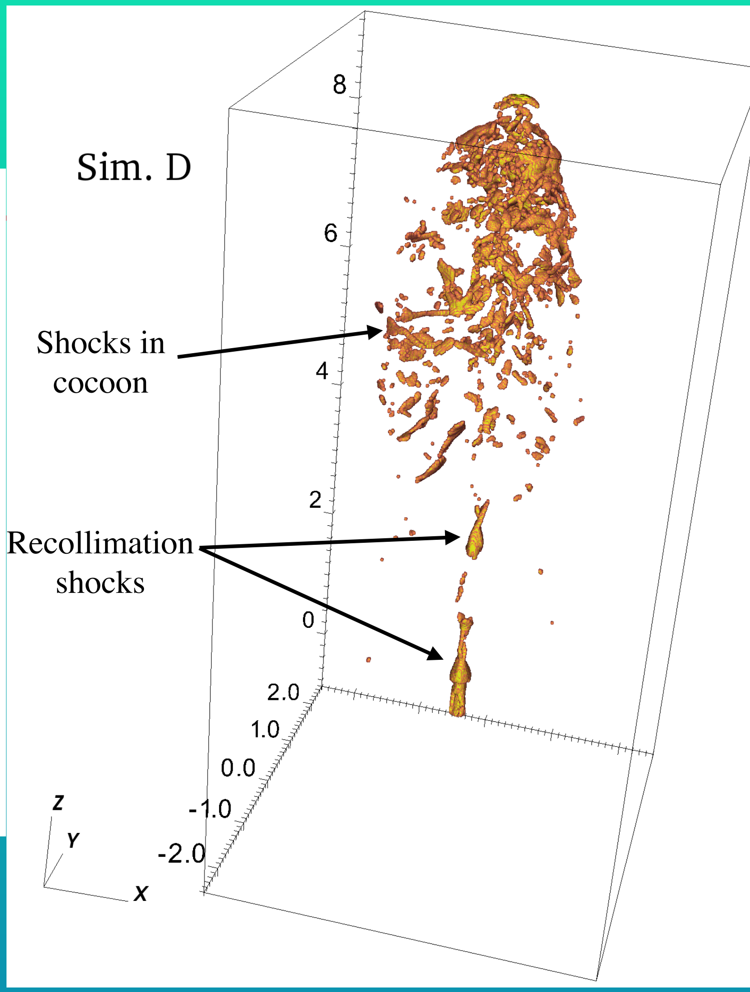
- Mixing of CREs with different shock histories in turbulent cocoon
- CRE spectrum has imprints of different pops. Not just a power-law with cut-off.
- Electron spectrum varies with region.
- Internal shocks reflected at synchrotron at higher frequencies

Summarising …



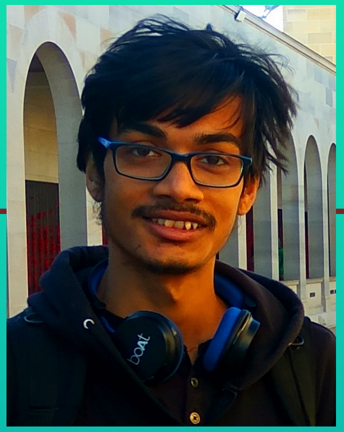


Nyland+ 2018



- 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.
- Turbulence in unstable jets can **re-accelerate non-thermal electrons** at complex shocks

Estimating SFR with improved subgrid physics

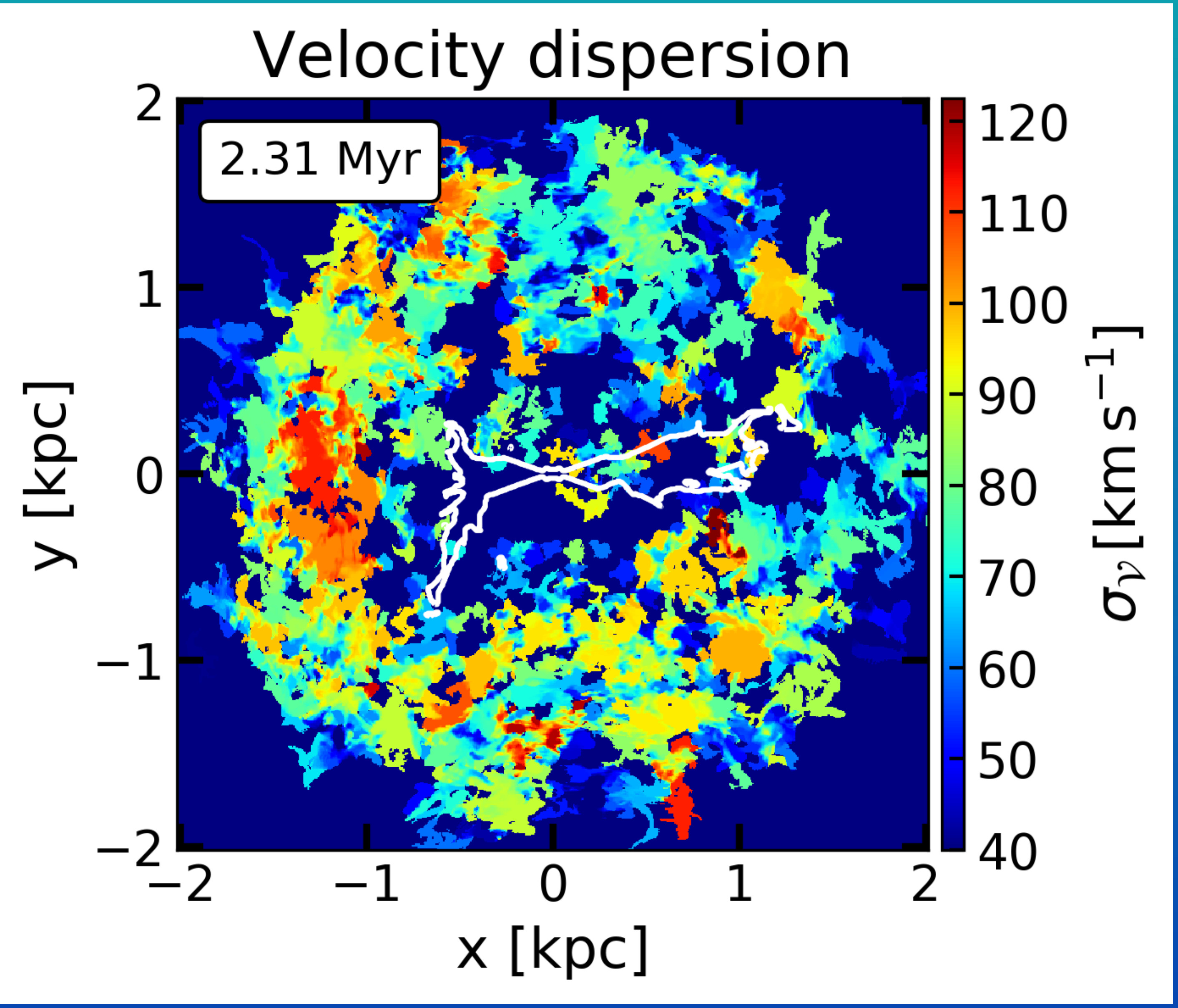


Work by
Ankush Mandal

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

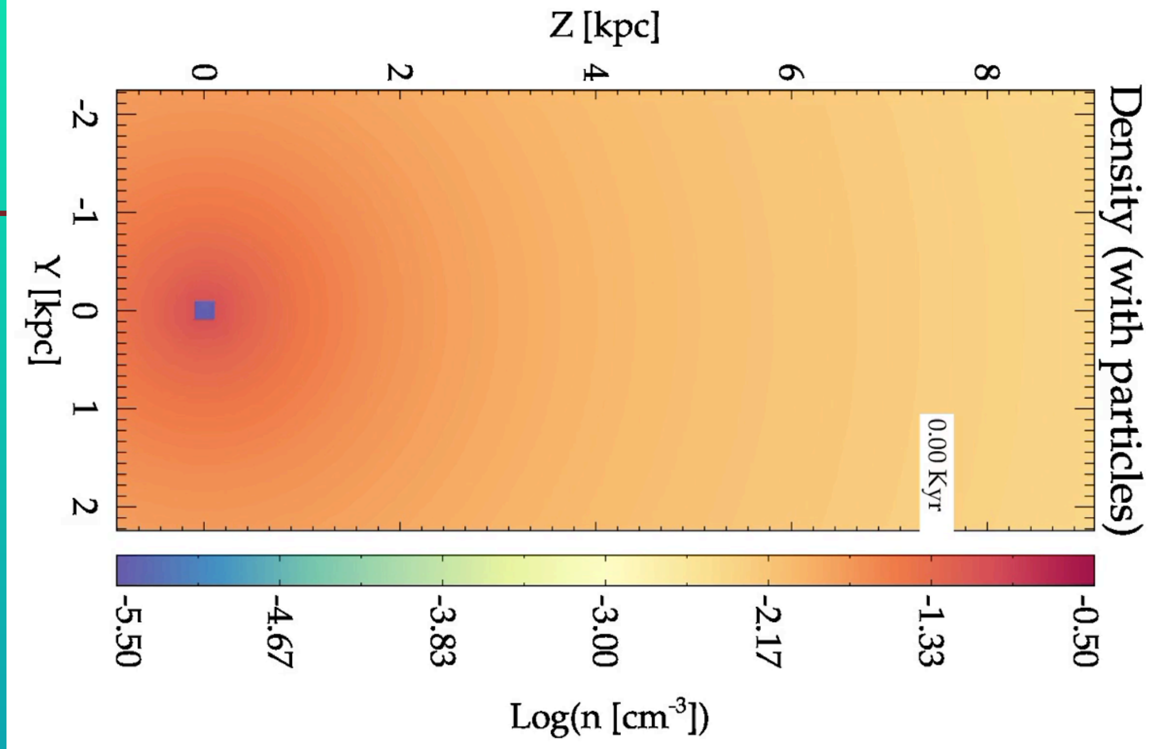
No input about turbulent velocity dispersion or Mach number.

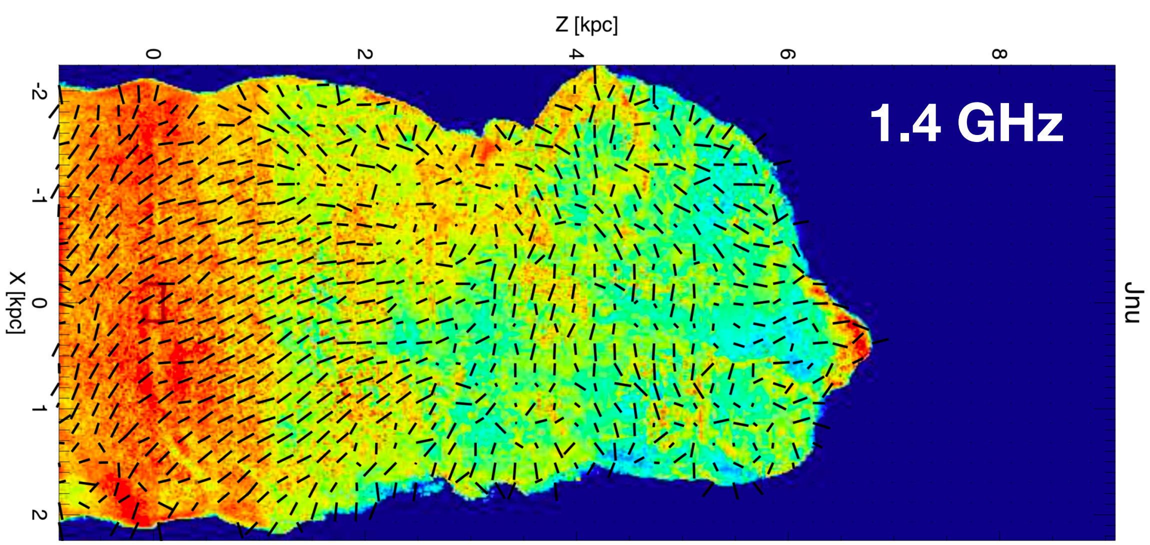
Better option: Use a turbulence based SFR prescription (Krumholz+2005, Federrath+2012).

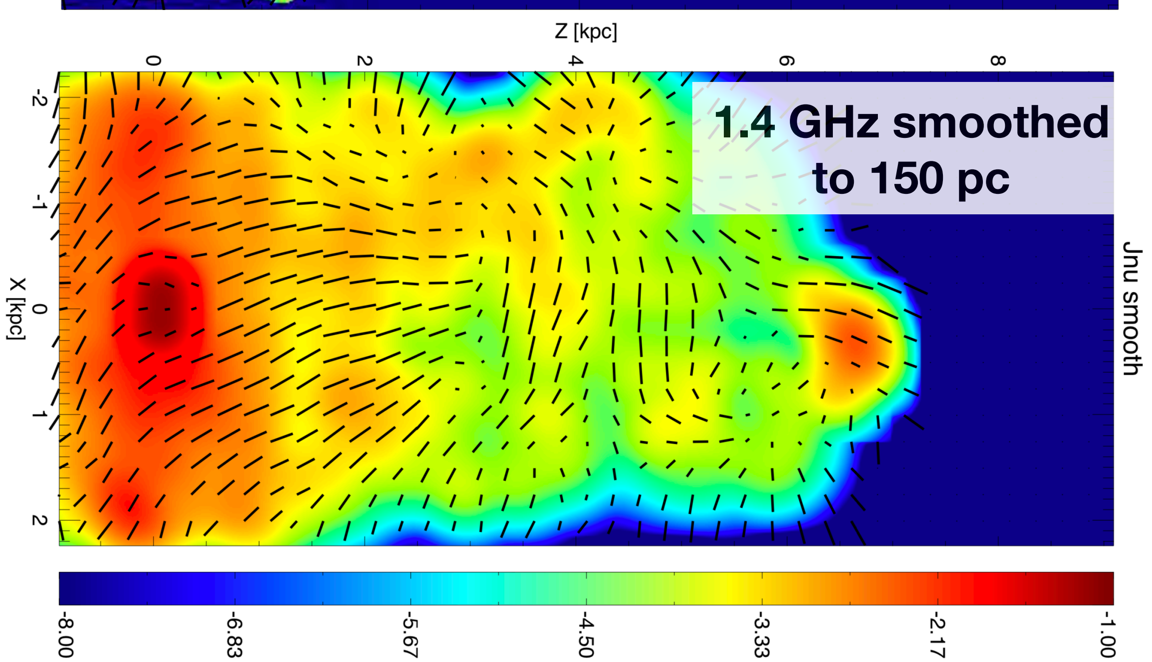


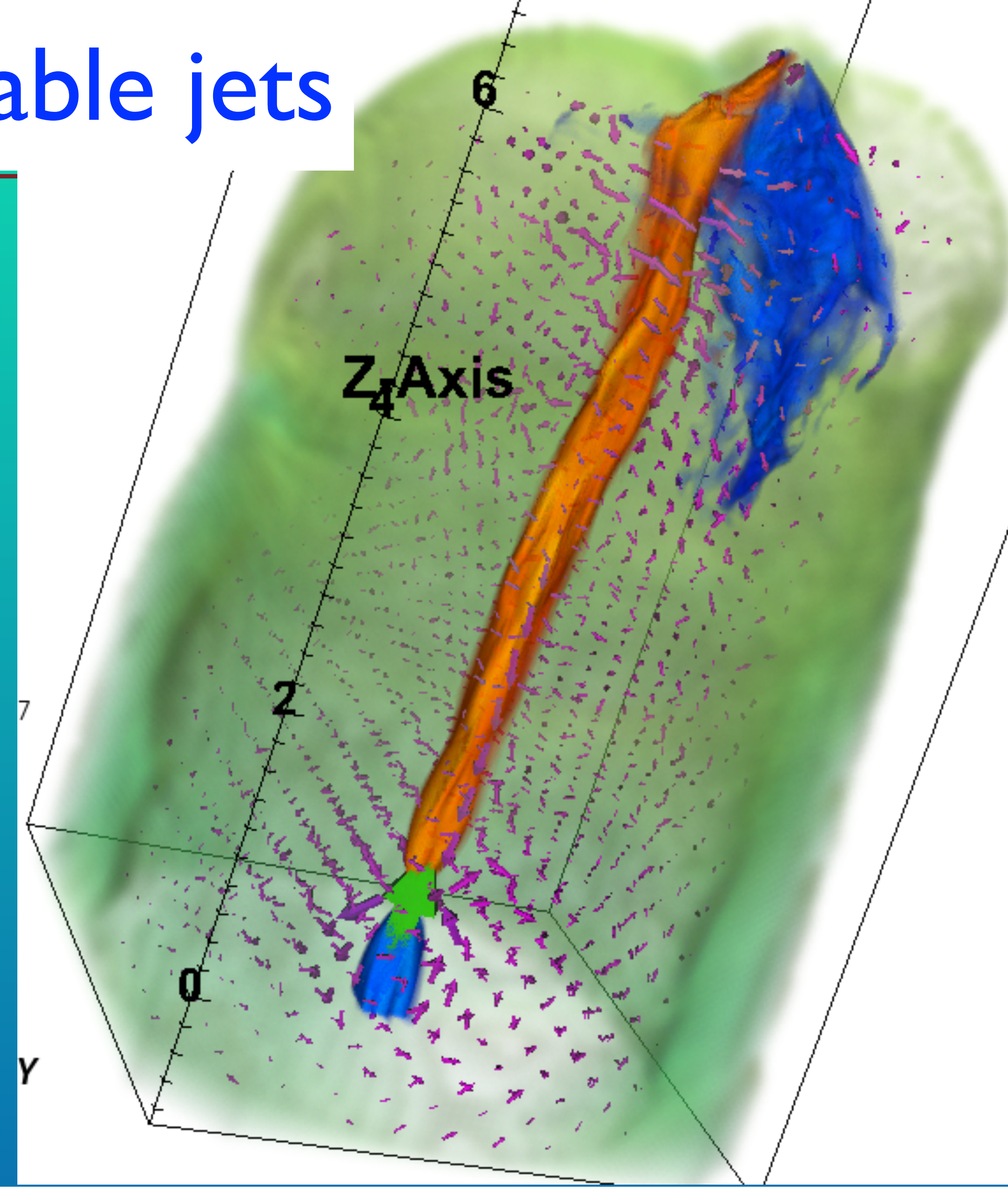
- Identify potential star forming clumps. using a clump-finder.
- Find intra-cloud statistics: velocity dispersion, Mach number.
- Compute SFR of each clump assuming a turbulence driven SFR model

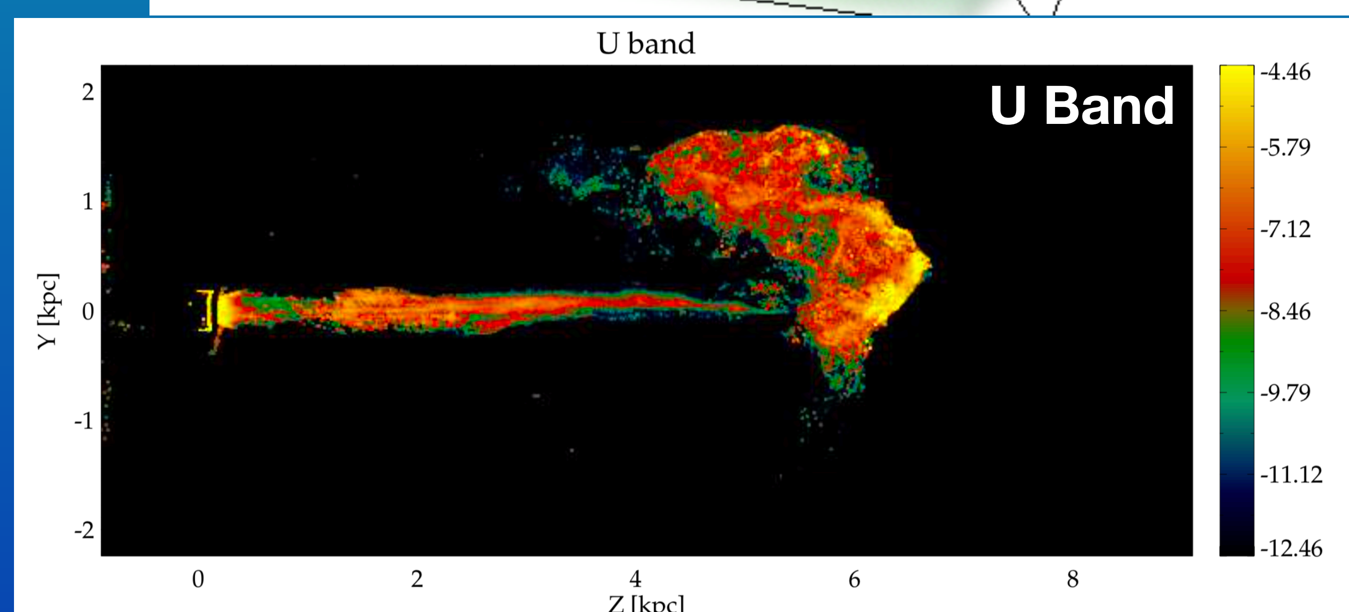
Unstable jets











Non-thermal emission from jets: Particle module in PLUTO

Webb 1989

$$\nabla_\mu (u^\mu f_0) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[-\frac{p^3}{3} f_0 \nabla_\mu u^\mu + \langle \dot{p} \rangle_l f_0\right] = 0.$$

Ignore:

- Spatial diffusion
- Shear
- Diffusion in momentum space, Fermi 2nd order

Spatial evolution: $$\frac{d\boldsymbol{x}_\mathrm{p}}{dt} = \boldsymbol{v}(\boldsymbol{x}_\mathrm{p})$$

Spectral evolution:

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

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

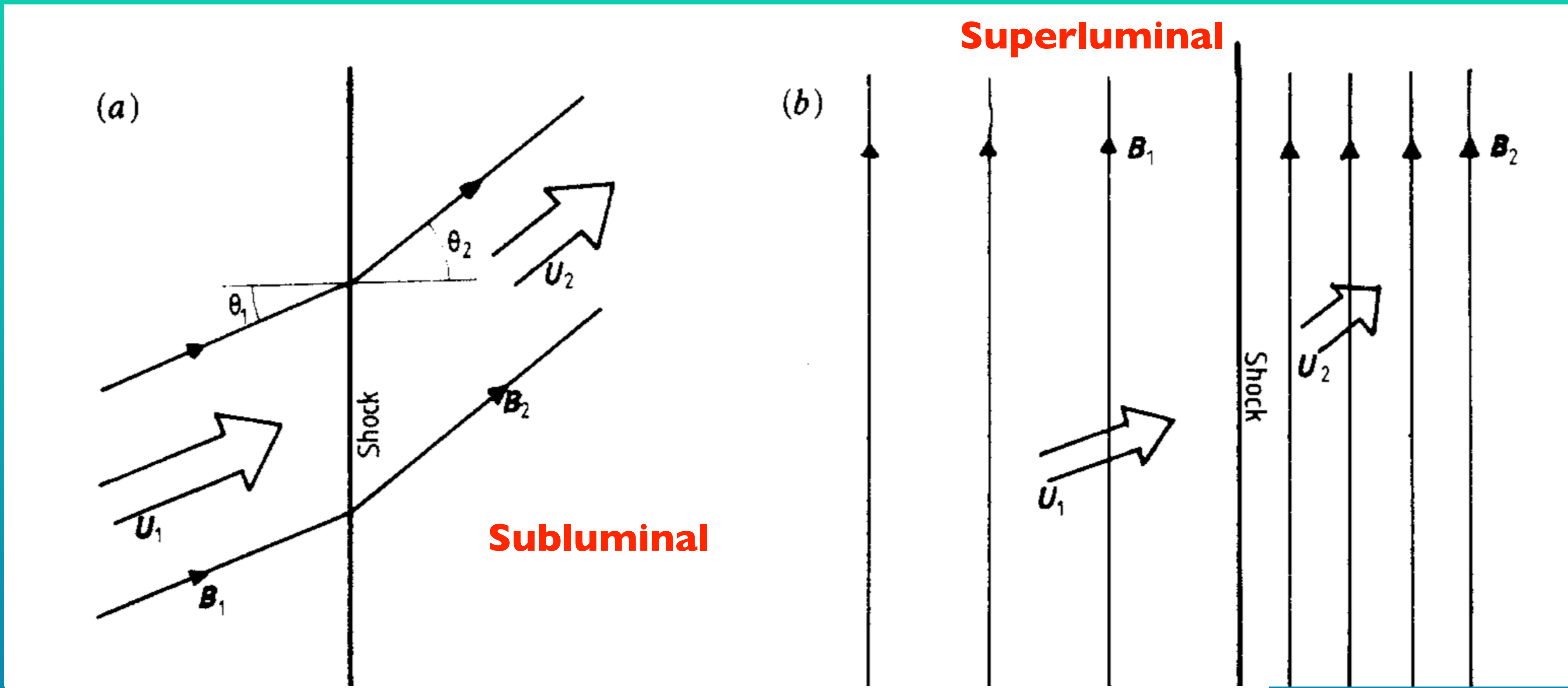
Energy losses, synchrotron, inverse compton

Vaidya et al. 2018

$$\dot{E}_l = -c_r E^2 \qquad c_r = \frac{4}{3}\frac{\sigma_T c \beta^2}{m_\mathrm{e}^2 c^4}\left[U_\mathrm{B}(t) + U_\mathrm{rad}(E_\mathrm{ph}, t)\right]$$

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

Modelling Diffusive Shock Acceleration (Fermi1)



Drury 1983

$$N_d(p) = q \int_{p_0}^{p} \left(\frac{p}{p'}\right)^{-q+2} N_u(p') \frac{dp'}{p'} + b p^{-q+2}$$

$$N_d(p) = \int_{p_0}^{p} F_{\mathrm{DSA}}(p, p') N_u(p') \frac{dp'}{p'} + b p^{-q+2}$$

Drury 1983

Subluminal

$$q = \frac{3\beta_1' - 2\beta_1'\beta_2'^2 + \beta_2'^3}{\beta_1' - \beta_2'} = q_{\mathrm{NR}} + \left(\frac{1-2r}{r-1}\right)\beta_2'^2$$

Keshet & Waxman 2005

Superluminal

$$q = q_{\mathrm{NR}} + \frac{9}{20}\frac{r+1}{r(r-1)}\eta^2\beta_1'^2$$

Takamoto & Kirk 2015

Modelling Diffusive Shock Acceleration (Fermi1)

Maximum energy of shocked electrons

$$t_{\rm sync} = \frac{\gamma m_e c^2}{P_{\rm sync}} \quad t_{\rm acc} = 2\pi a_{\rm acc}\frac{\gamma m_e c}{eB} = a_{\rm acc}\frac{2\pi}{\omega_g}$$

$$a_{\rm acc} = \frac{\eta r}{\beta_1^2(r-1)}\left[\cos^2\theta_{B1} + \frac{\sin^2\theta_{B1}}{1+\eta^2} + \frac{rB_1}{B_2}\left(cos^2\theta_{B2} + \frac{\sin^2\theta_{B2}}{1+\eta^2}\right)\right]$$

$$r_L = \frac{\gamma m_e c^2 \beta_\perp}{eB} \quad \gamma = \frac{\mathrm{MIN}(\delta x/2)eB}{m_e c^2 \beta_\perp}$$

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