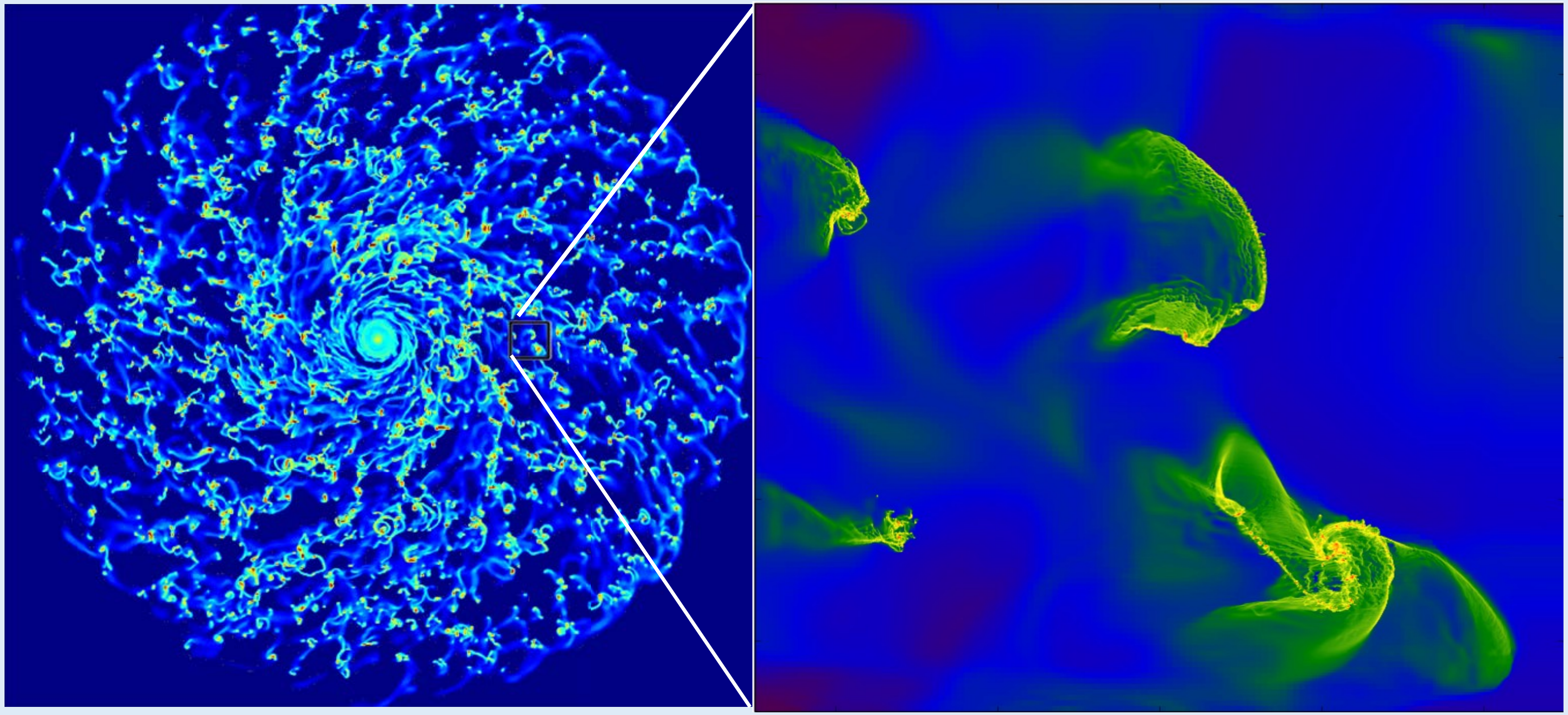
The Structure and Dynamics of Filaments and Clumps in Giant Molecular Clouds



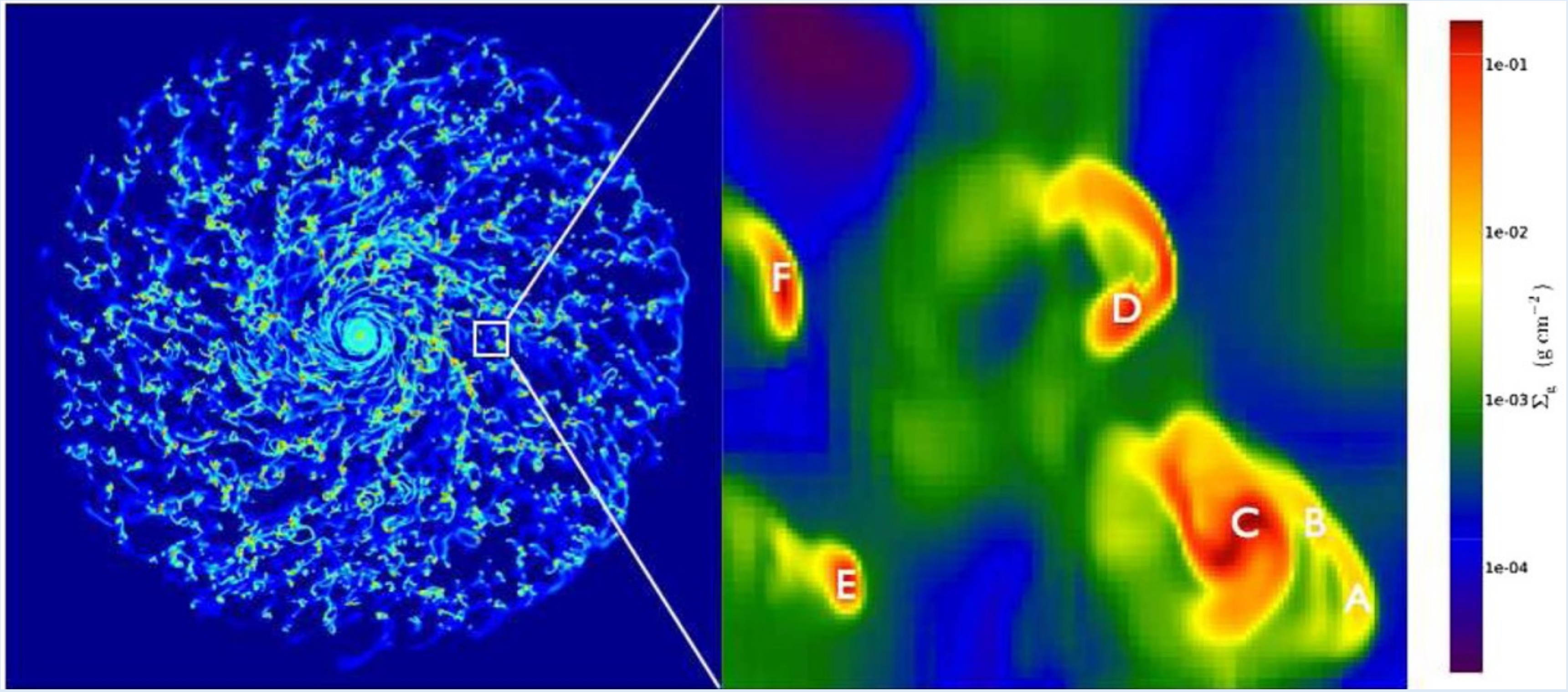
Michael Butler (University of Zurich)
Jonathan Tan (University of Florida)
Sven Van Loo (University of Leeds)
Romain Teyssier (University of Zurich)
Elizabeth Tasker (Hokkaido University)

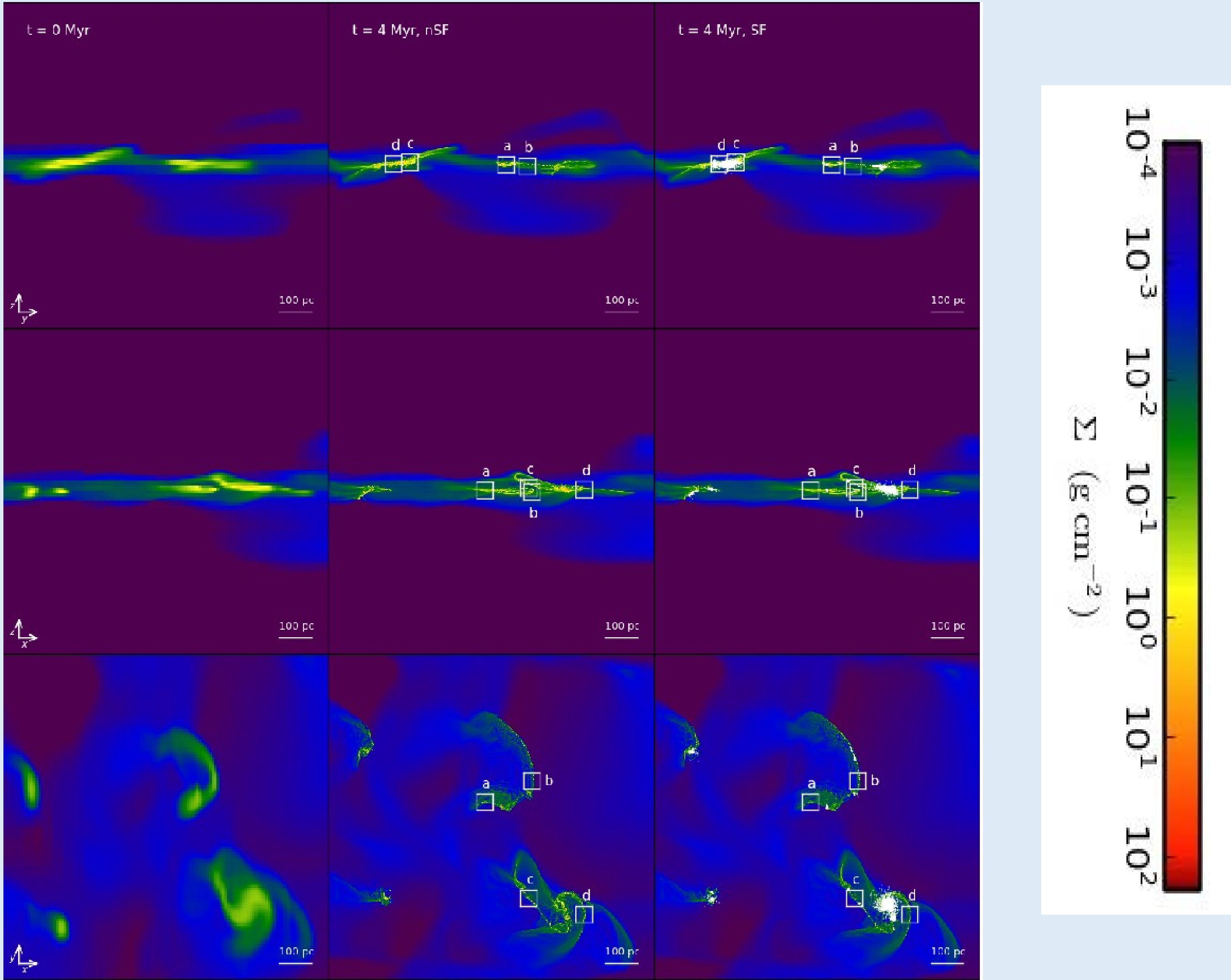
Outline

- Simulation set-up: from global galaxy simulation to kiloparsec-scale
  - Pseudo-shearing box initial conditions
  - Molecular cooling down to T ~ 5K – Cloudy
  - Resolve down to ~0.5 pc (Van Loo et al. 2013) – 0.12 pc (Butler et al. 2014 to be submitted)
- Filament Structure
  - Σ PDF – comparison to IRDCs
  - Longitudinal – Mass per unit length, core separation
  - Lateral – Filament width
- Filament Kinematics & Dynamics
  - P-v diagrams, velocity spectra, velocity gradient along filaments
  - Filamentary virial analysis
- Magnetic fields + radiative feedback

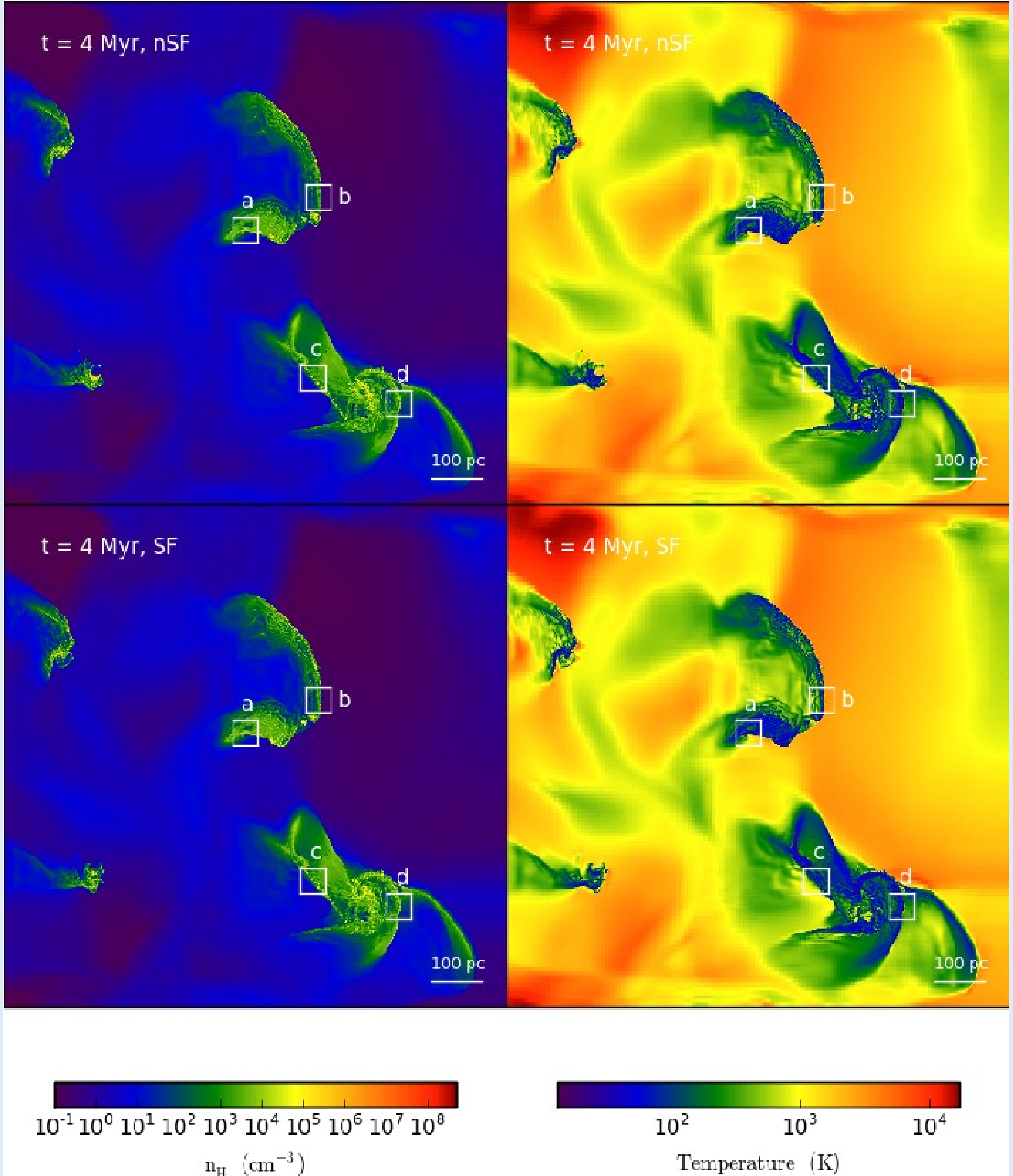
Simulation setup

- Global galaxy simulation from Tasker & Tan (2009) using Enzo
  - Extract 1 x 1 x 2 kpc region from the t = 250 Myr output
  - Subtract circular velocity, add shear velocity appropriate for the region's location in the disk to initial conditions
- Use molecular cooling function calculated using Cloudy (Van Loo et al. 2013)
- Star formation included at a fixed rate per freefall time ($\circ_{ff}$ = 1%)





t = 0 Myr
t = 4 Myr, nSF
t = 4 Myr, SF
a
b
c
d
100 pc
Σ (g cm⁻²)
10-4
10-3
10-2
10-1
10^0
10^1
10^2

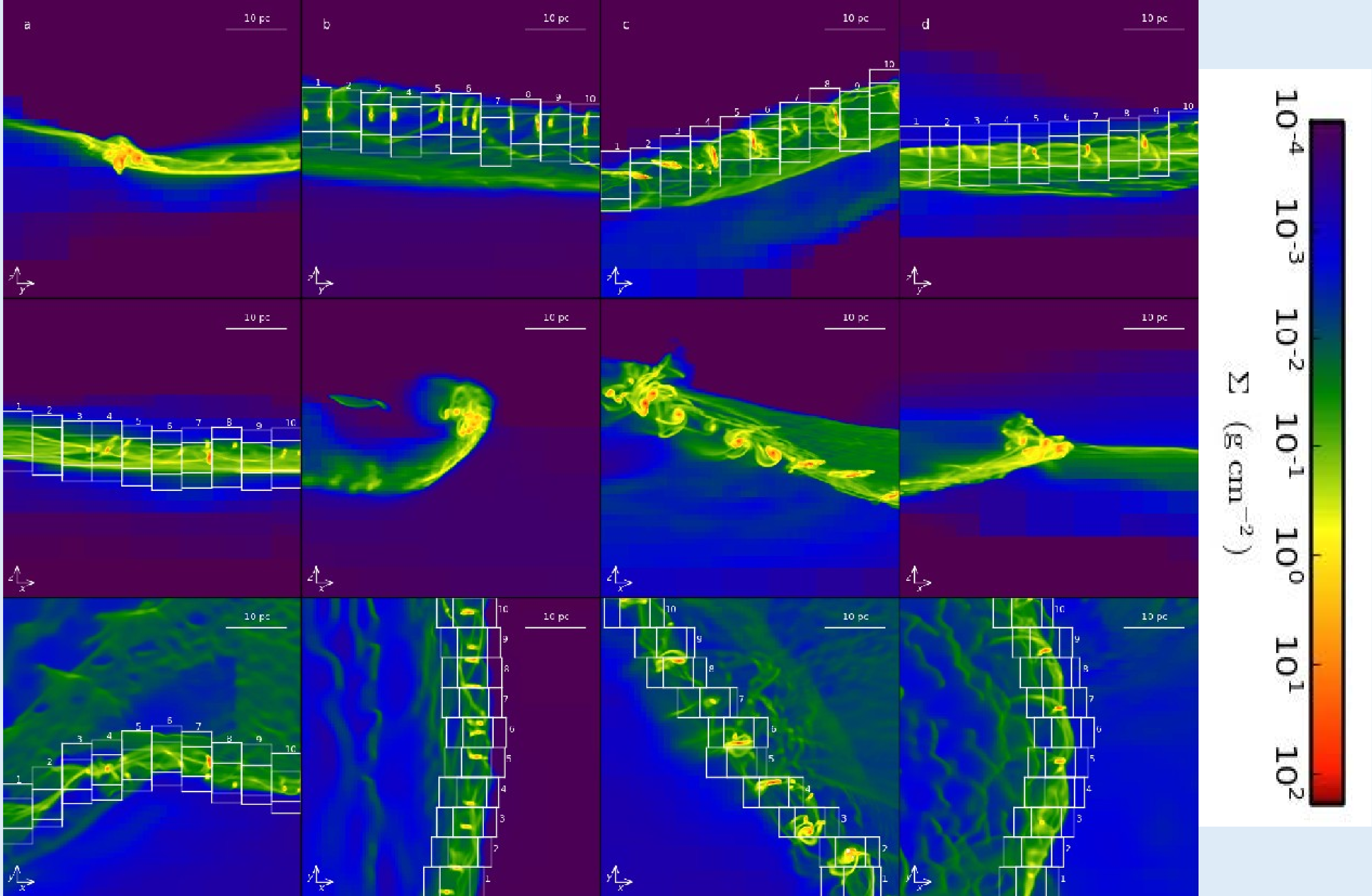

t = 4 Myr, nSF
t = 4 Myr, nSF
t = 4 Myr, SF
t = 4 Myr, SF
a
b
c
d
100 pc
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8}
n_H (cm^{-3})
10^{2} 10^{3} 10^{4}
Temperature (K)

Filament Sample

- Select four 50 pc regions centered on filaments for detailed structure and kinematics/dynamics analysis
- Explore three methods of defining filament and envelope regions
  - Inner filament – 5x5x5 pc strips iteratively centered on the filament's COM
    - Envelope – 2.5x5x5 pc regions on each end of filament region
  - Outer filament – 5x10x10 pc strips
    - Envelope – 5x5x10 pc regions on each end of filament region
  - Dense inner filament – Same as inner, but filament is gas with $n_H > 10^3$ cm^{-3}
    - Envelope – gas in filament region with $n_H < 10^3$ cm^{-3}

Table 1: Filament 50-pc Region Properties

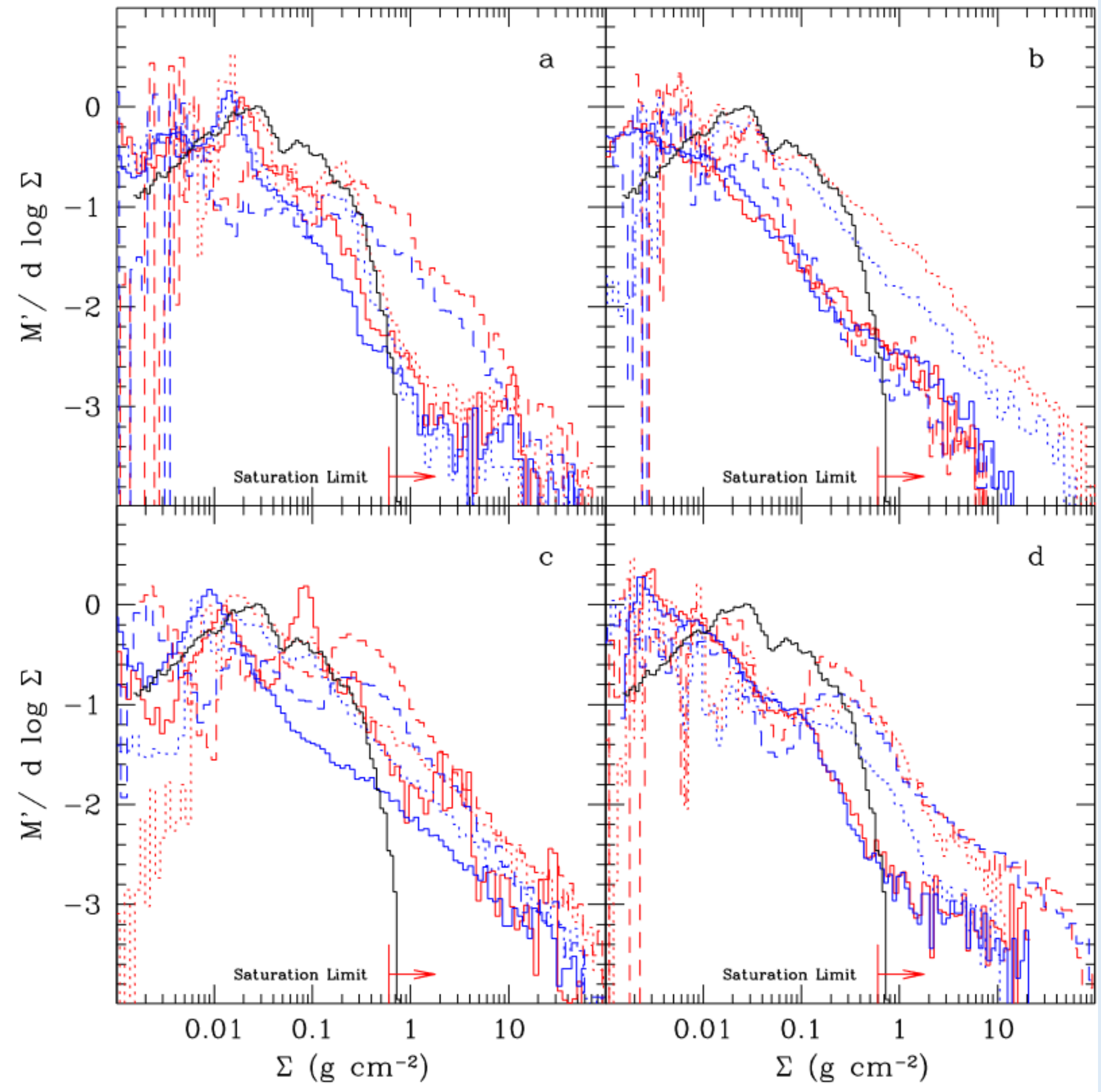
Filament	x_c (pc)	y_c (pc)	z_c (pc)	Mass (10^4 $M_\odot$)	$\bar{n}_H$ (10^4 cm^{-3})	$\bar{v}_x$ (km s^{-1})	$\bar{v}_y$ (km s^{-1})	$\bar{v}_z$ (km s^{-1})	σ_{vx} (km s^{-1})	σ_{vy} (km s^{-1})	σ_{vz} (km s^{-1})
a	480[482]	545[546]	3.00[1.38]	22.3	145	−20.7	7.62	−1.87	5.37	6.54	3.18
b	625[626]	610[612]	−3.50[−1.05]	14.2	42.7	−7.44	−9.97	−0.561	5.93	3.85	2.58
c	614[618]	251[248]	20.3[19.1]	38.6	326	−13.9	−7.69	−1.17	7.35	6.21	4.37
d	785[783]	200[202]	10.0[5.98]	2.00	44.9	−18.3	11.7	1.41	7.50	8.87	2.85



a
b
c
d
10 pc
Σ (g cm⁻²)
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2

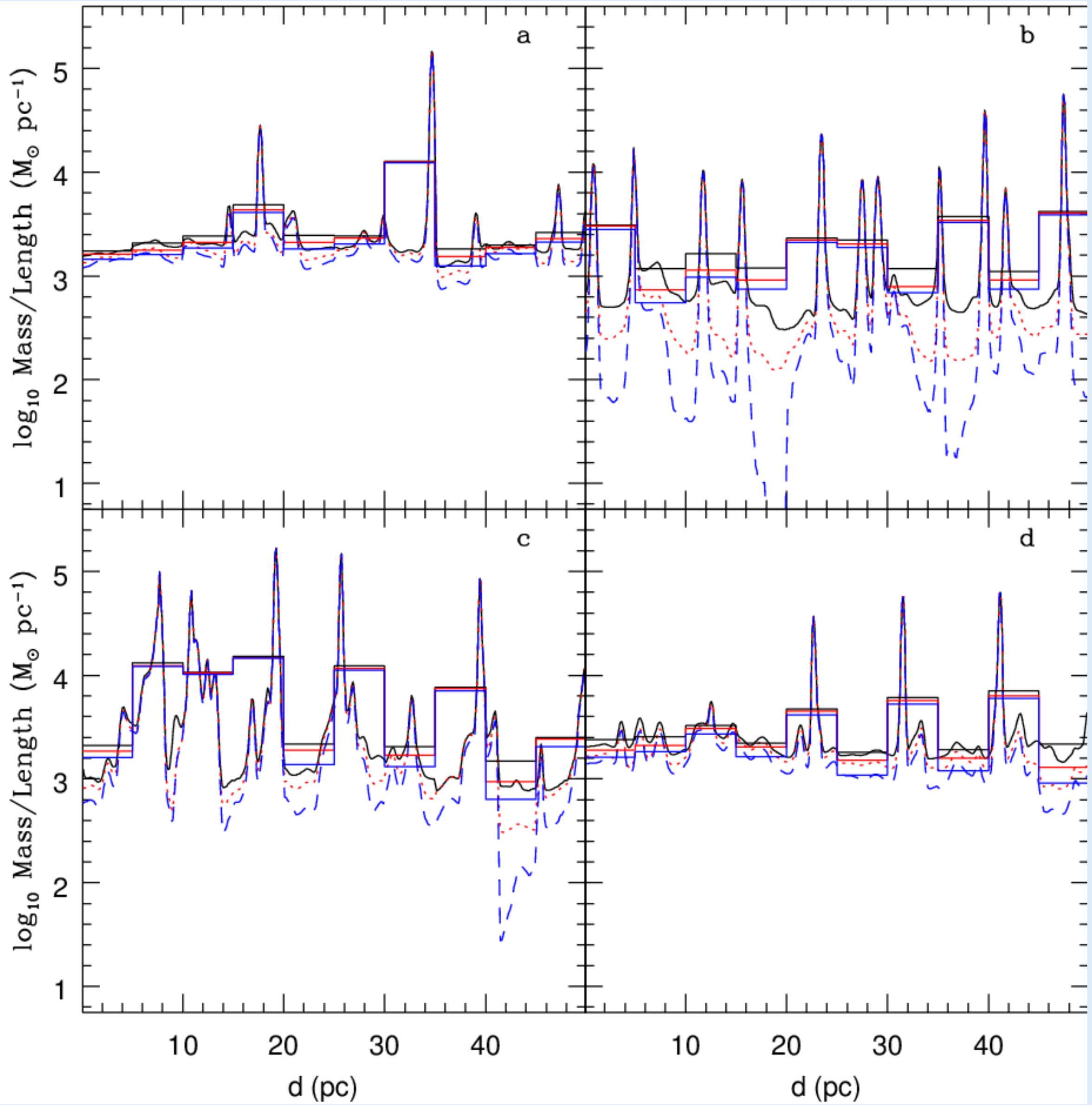
Filament Regions

- Σ PDFs can provide insight into processes governing a cloud’s structure
- Kainulainen et al. (2009) showed that clouds undergoing star formation have wider column density PDFs, including a power law tail of high column densities, while non-star-forming clouds have narrower distributions, better fit by a single log-normal function
- We construct mass-weighted PDFs of each 50 pc filament region (blue), and a smaller 25 pc region (red) centered on the region’s center of mass, and compare to observed IRDC profile (Butler et al. 2014, black)
- Observe power law tails at high Σ
- Boundary can have significant effects on PDF



Filament Structure - Longitudinal

- Measure mass per unit length along each filament in each of the three regions (outer, inner, dense)
- Observe typical values of $m_l \sim 10^{3.5}$ M_{sun}/pc, with large fluctuations due to the formation of clumps
- Observed values of ~100 (Ragan et al. 2014) - 300 M_{sun}/pc in IRDCs (Hernandez et al. 2012), ~500 M_{sun}/pc in longer filaments ("Nessie", Jackson et al. 2010)

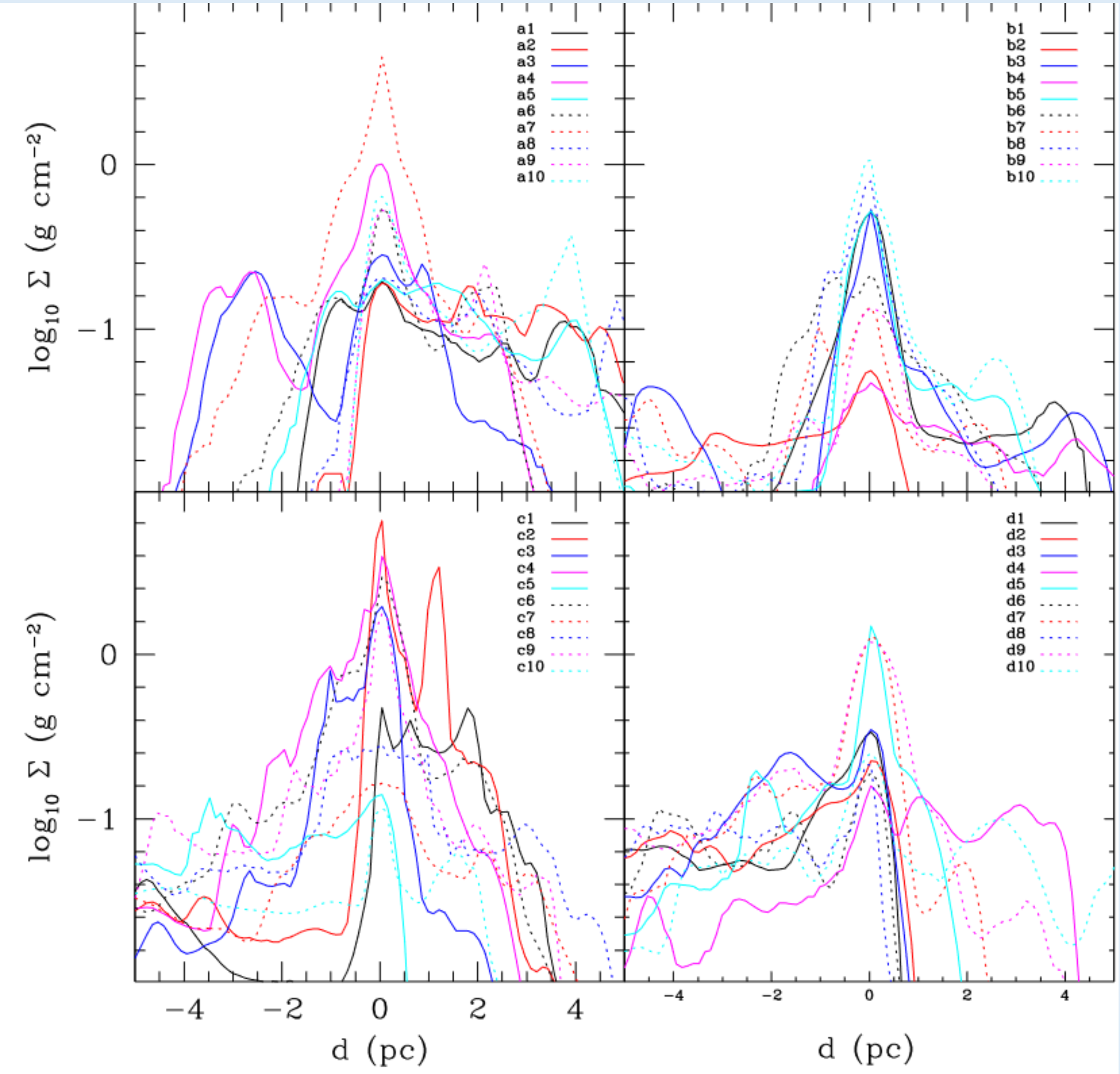


Filament Fragmentation

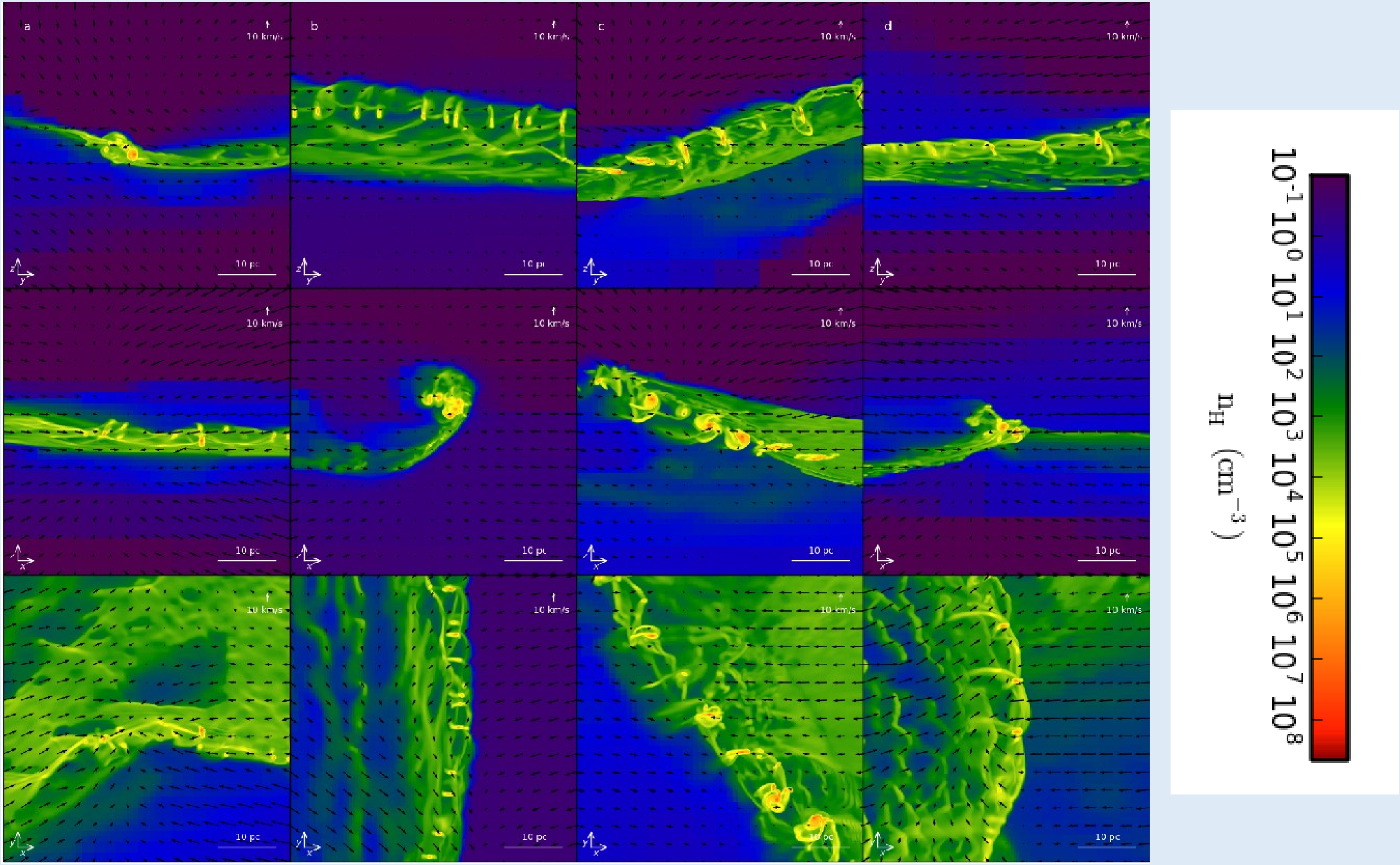
- The peaks in m_l correspond to dense clumps that appear to have formed by fragmentation of the filament.
- In gravitationally bound filaments, clumps are predicted to form by fragmentation at roughly regular intervals, caused by the so-called “sausage” or “varicose” fluid instability (e.g., Chandrasekhar & Fermi 1953; Nakamura et al. 1993)
- Use clump finding routine (Smith et al. 2008) in yt (Turk et al. 2011)
- Find 7, 11, 11, and 5 clumps in filaments a-d, respectively, with a density threshold of $n_H = 10^5$ cm^{-3}
- Find mean separation of 6.01 pc, comparable to the range of 4-6 pc typically observed (e.g. Jackson et al. 2010)

Lateral Structure – Filament Width

- The width of filaments in the ISM can provide insight into the conditions from which they formed. Arzoumanian et al. (2011) found a characteristic width of ~0.1 pc for a sample of 27 filaments in the Herschel Gould Belt Survey toward the IC 5146 molecular cloud, suggesting that the dissipation of large-scale turbulence may have played an important role in the filaments' formation.
- We find mean widths of ~ 1 pc, but we note that we cannot resolve structure to the same scale as the Arzoumanian sample. The presence of clumps also makes these widths more difficult to accurately measure



Filament kinematics



Filament regions – outer (black), inner (red)

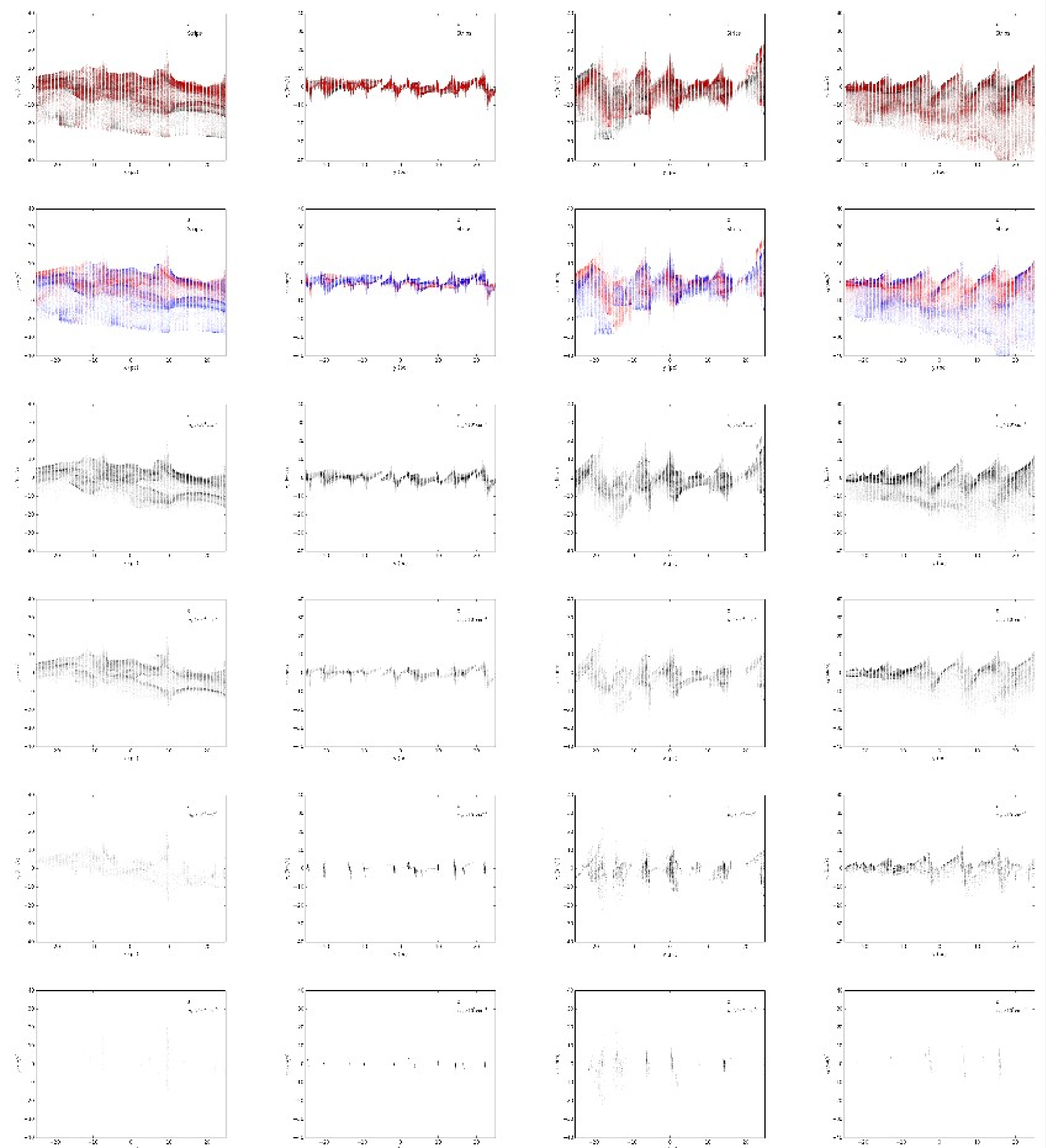
Filament regions – near (red), far (blue)

Filament regions – $n_H > 10^2$ cm^{-3}

Filament regions – $n_H > 10^3$ cm^{-3}

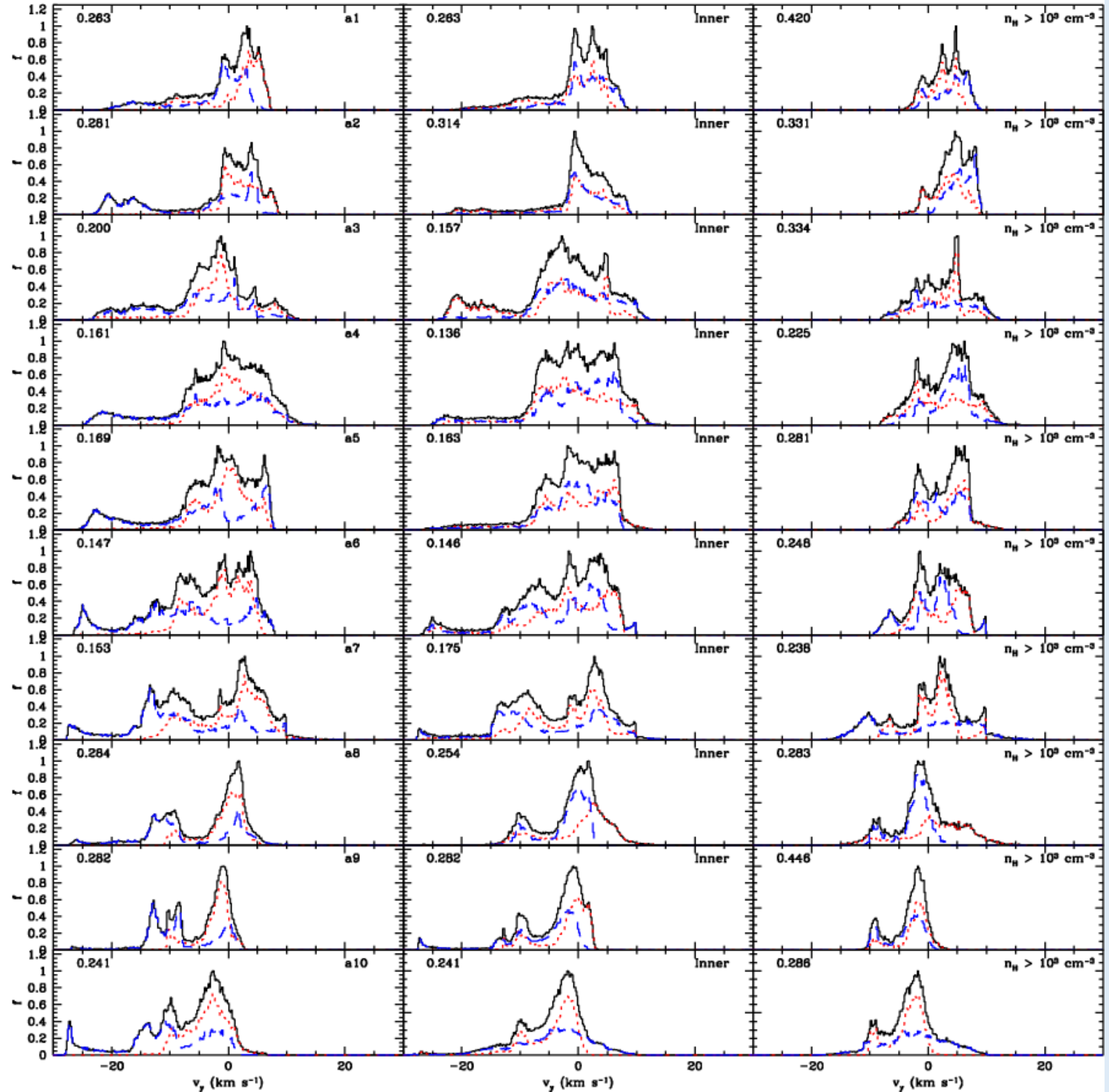
Filament regions – $n_H > 10^4$ cm^{-3}

Filament regions – $n_H > 10^5$ cm^{-3}



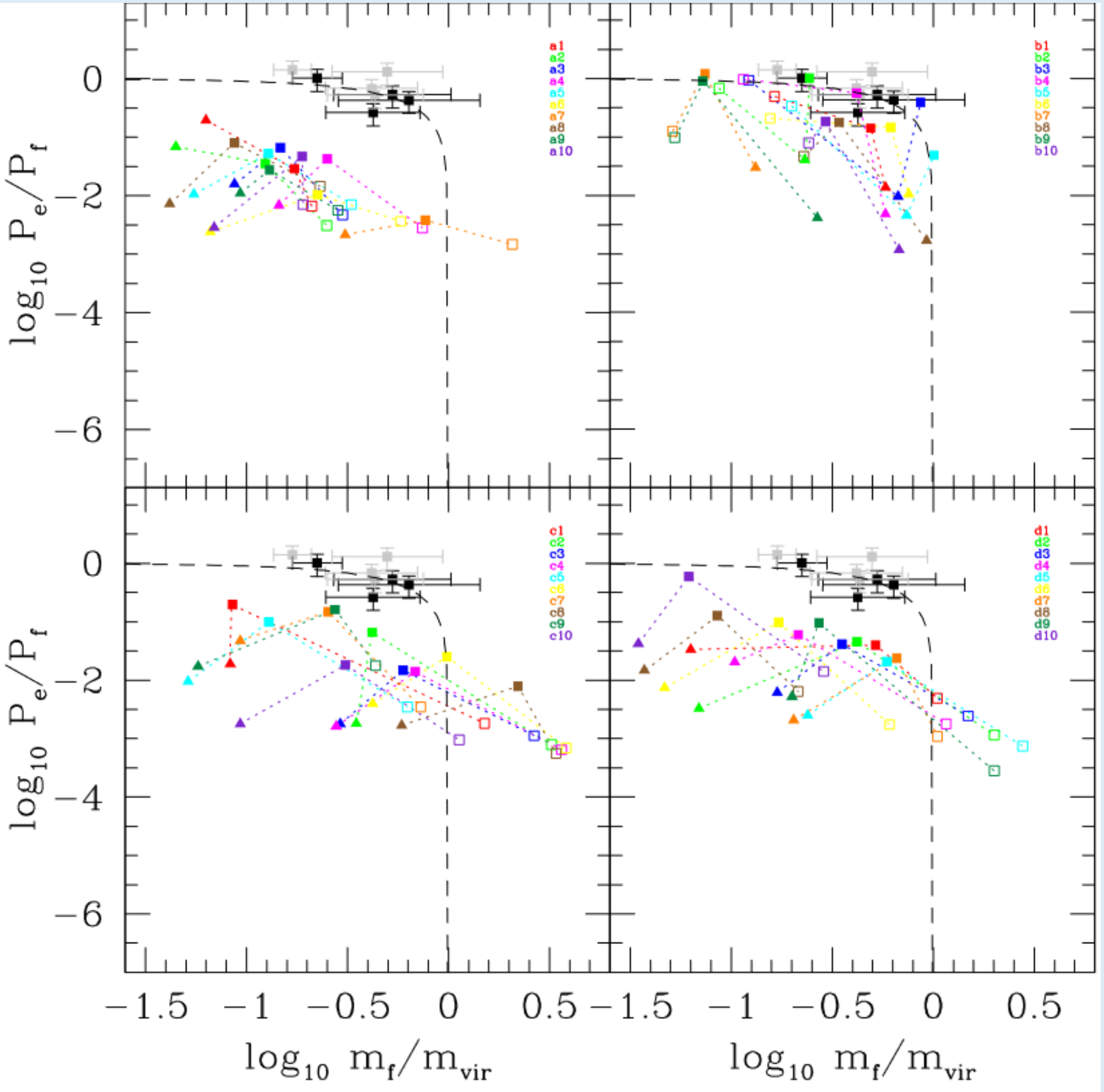
Filament Kinematics

- P-v diagrams show a large range in velocity (up to ~60 km/s) with large dispersions in the dense gas
- Velocity spectra show some complex structures, with some evidence of infall
- Comparison between near and far side shows that the filament kinematics are highly disordered
- Velocity gradients are also measured – we find gradients of ~ 0.2 km/s/pc on the 50 pc scale, with gradients of ~0.5 km/s/pc at the 5 pc strip scale.
- Observed gradients are typically ~ 0.1 km/s/pc (Jackson et al. 2010) or lower, e.g. ~0.05 km/s/pc (Ragan et al. 2014)



Filament Dynamics

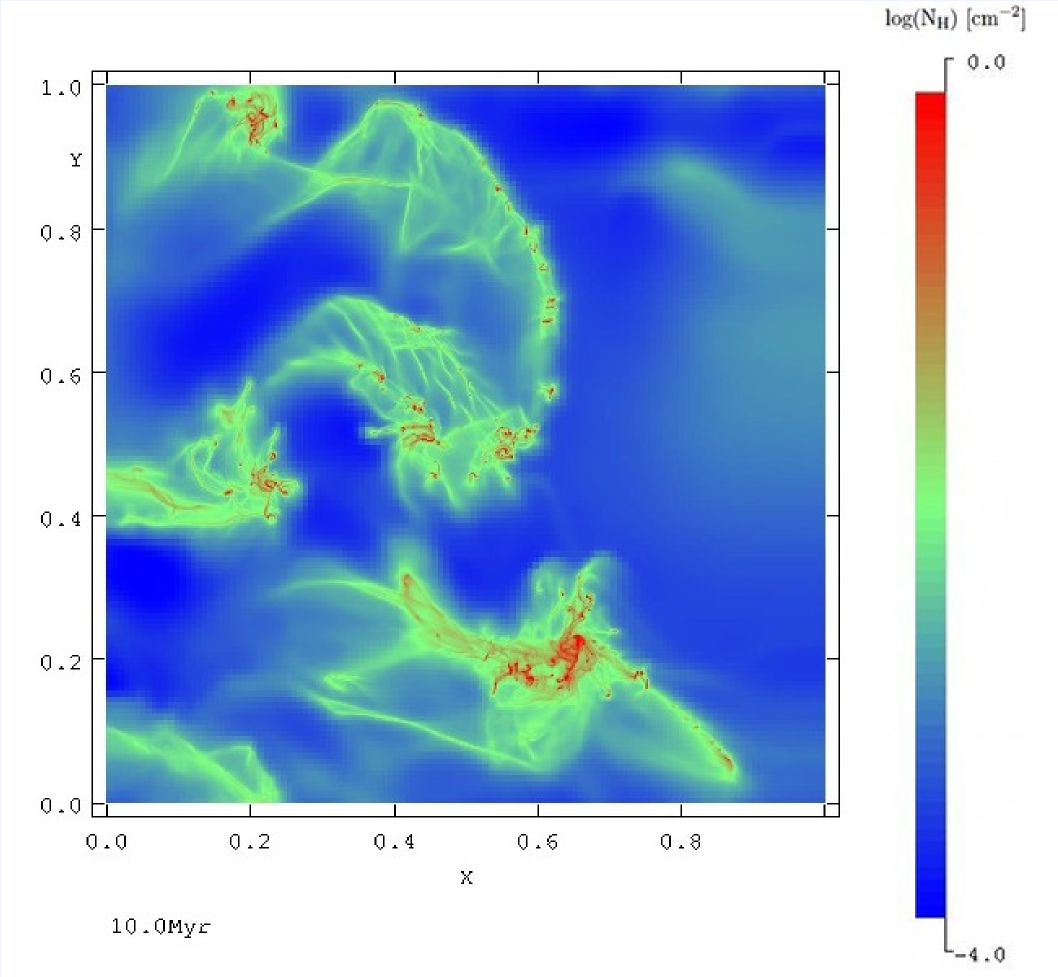
- We assess the filamentary virial state in each strip for each filament
- $\frac{P_0}{P} = 1 - \frac{m_l}{m_{\rm vir}}\left(1 - \frac{\mathcal{M}_l}{|W_l|}\right)$
- $m_{\rm l,vir} \equiv 2\sigma^2/G$ $P = \rho\sigma^2$
- $P_e/P_f = n_{\rm H,e}\,\sigma_e^2/n_{\rm H,f}\,\sigma_f^2$
- We find that most strips have m_l < m_vir, with larger envelope pressures than typically observed in filaments

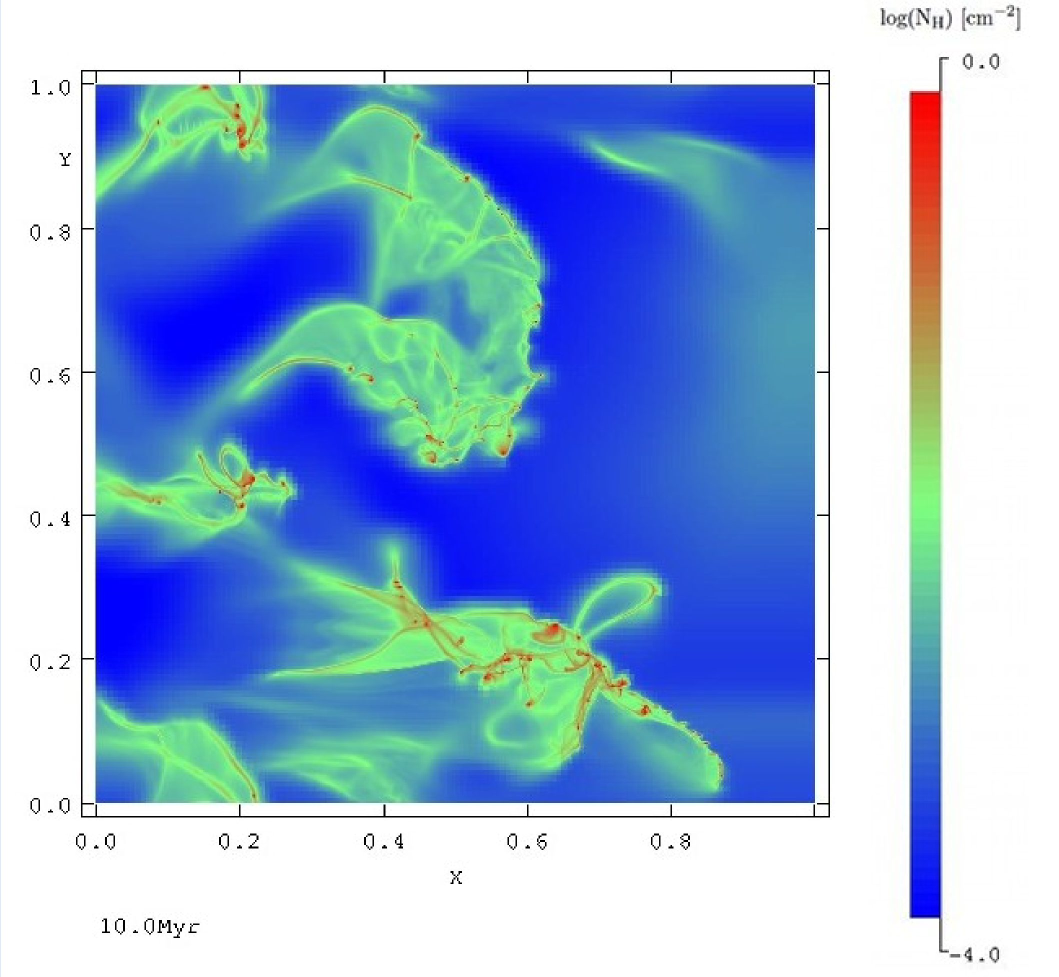


Summary

- Follow 1 kpc patch of a disk galaxy simulation to high ~0.1 pc resolution
- Selected four 50 pc filament regions, finding:
  - Mass ~ 2×10^5 M_{sun}
  - Mass per unit length ~ $10^{3.5}$ M_{sun}/pc
  - Filament width ~ 1.0 pc
  - Core separation of ~ 6 pc
  - Line of sight velocity dispersion of ~ 5 km/s
- Filaments collapse to unrealistically high column densities with highly disordered kinematics – need processes to inhibit fragmentation, soften kinematic interactions
  - Magnetic fields (Van Loo et al. 2014 in prep)
  - Feedback (Butler, Teyssier et al. in prep)

Future Directions – Magnetic Fields, Feedback





Van Loo et al. (2014, in prep)