Filament Formation by Collision-induced Magnetic Reconnection (CMR)

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The CARMA-NRO Orion Survey: Filament Formation via Collision-induced Magnetic Reconnection—the Stick in Orion A

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CMR exploration I – filament structure with synthetic observations

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CMR exploration II – filament identification with machine learning

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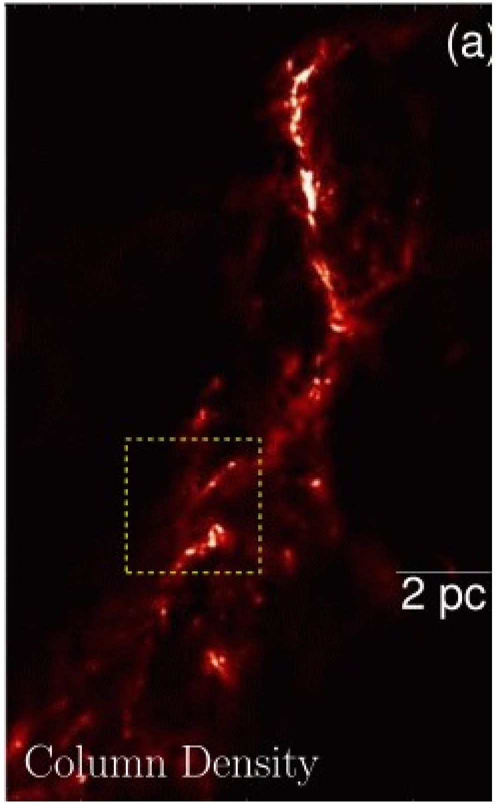
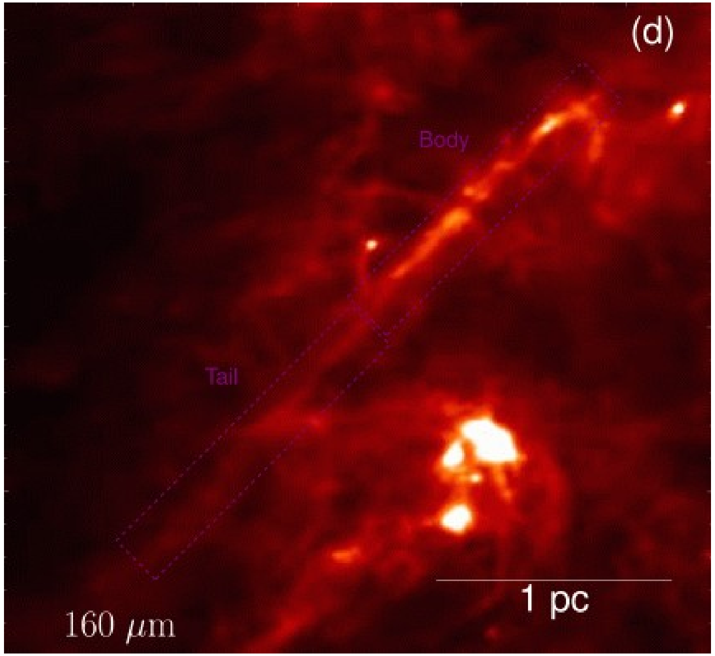
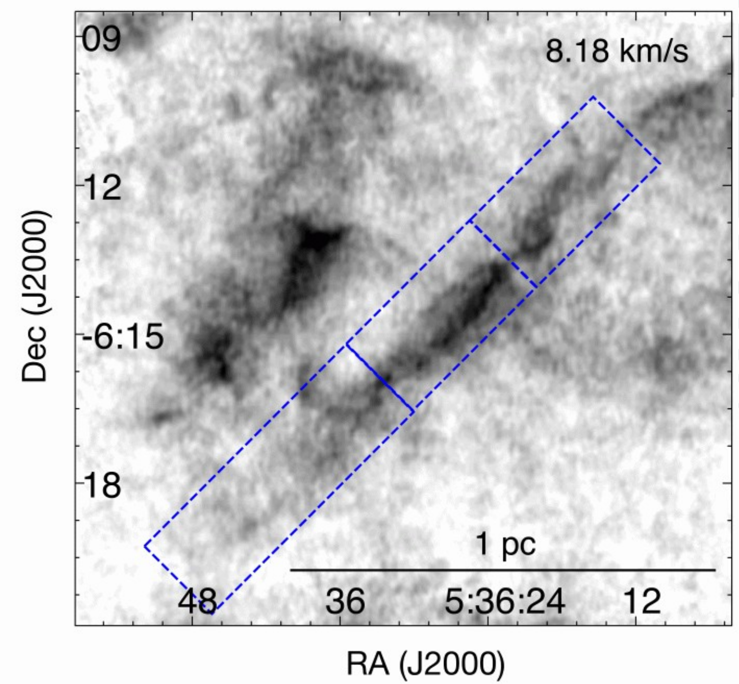
Observational motivation

- Large-scale Orion mapping
  - prominent very straight filament close to L1630



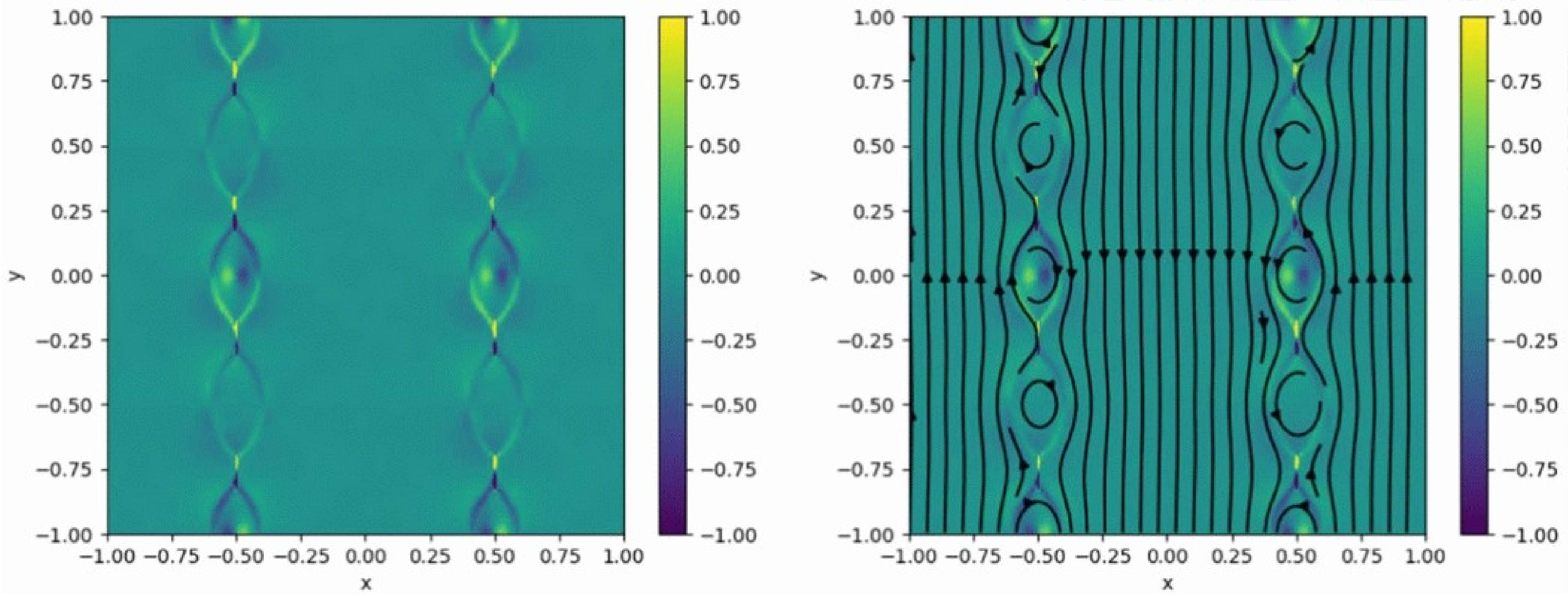




- Breaks up into rings and forks, in particular in velocity slices

Association

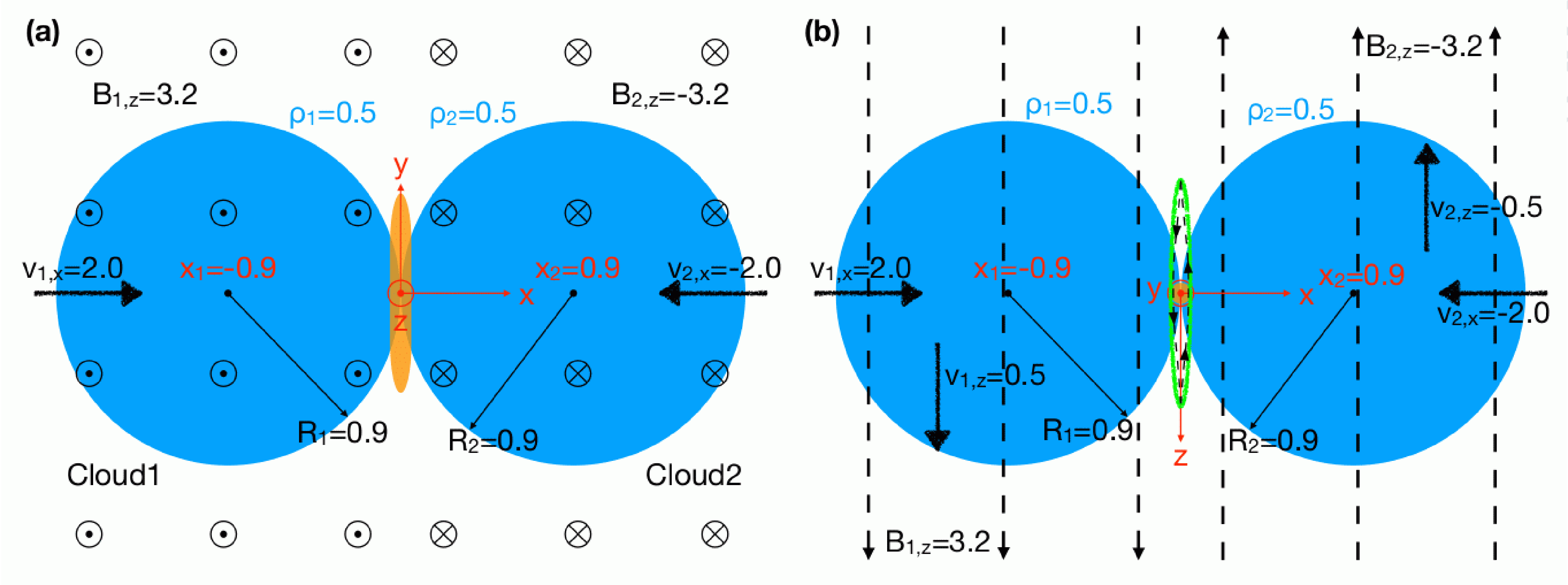
- Magnetic reconnection
  - Structure formation at the boundary of opposite magnetic fields



- Velocity pattern in MR

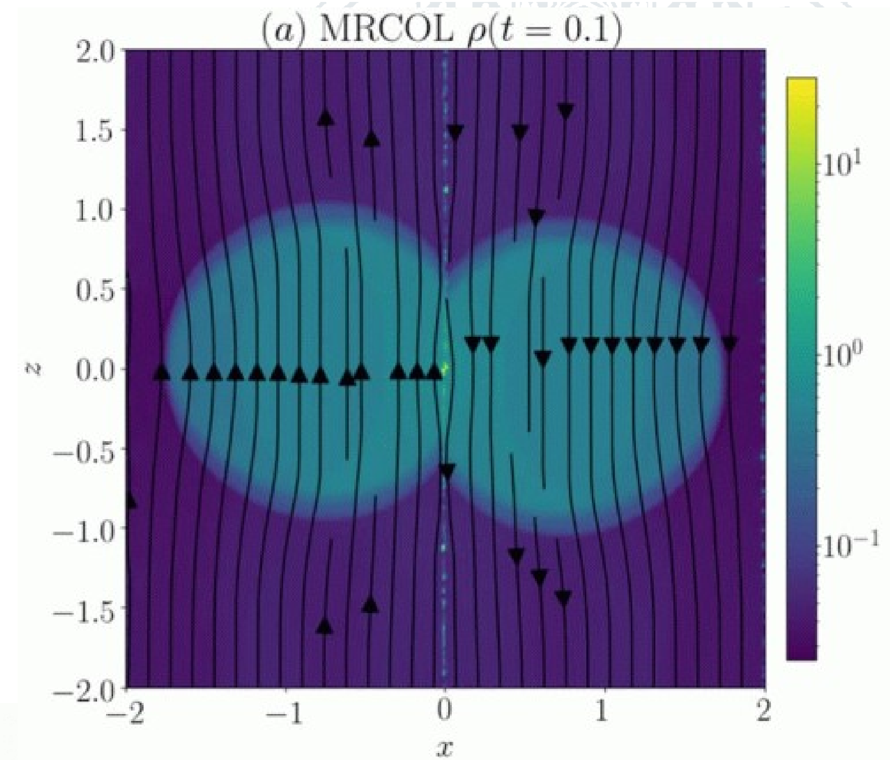
Fundamental model

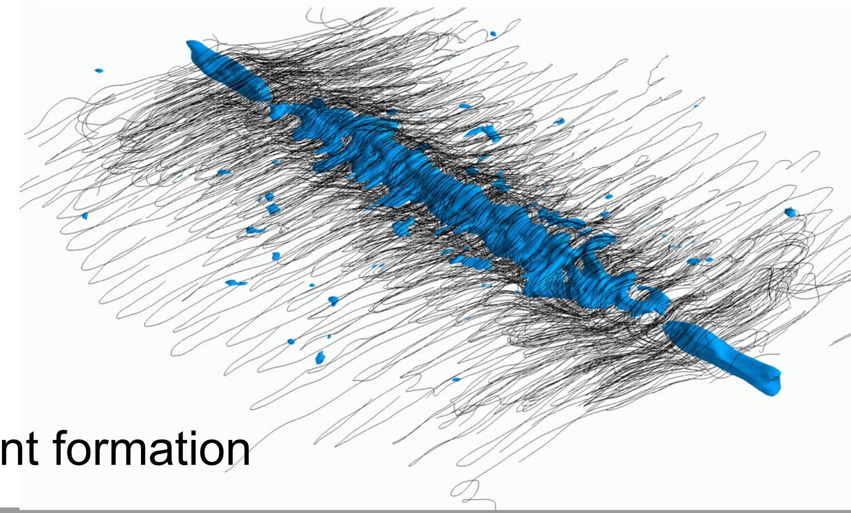
- Collision-indiced Magnetic Reconnection (CMR)
  - Filament forms perpendicular to velocity and *B* field



Simulation

- ATHENA++ (Stone et al. 2020)
  - Resistive MHD
  - isothermal
  - uniform Cartesian grid
    - 512^3 voxels: 0.0078pc = 1600AU → 4pc box
    - Default parameters: n_H=840 cm-2, T=15K, v=0.51 km/s, B=10µG
  - Radiative transfer with RADMC-3D and Simline3D



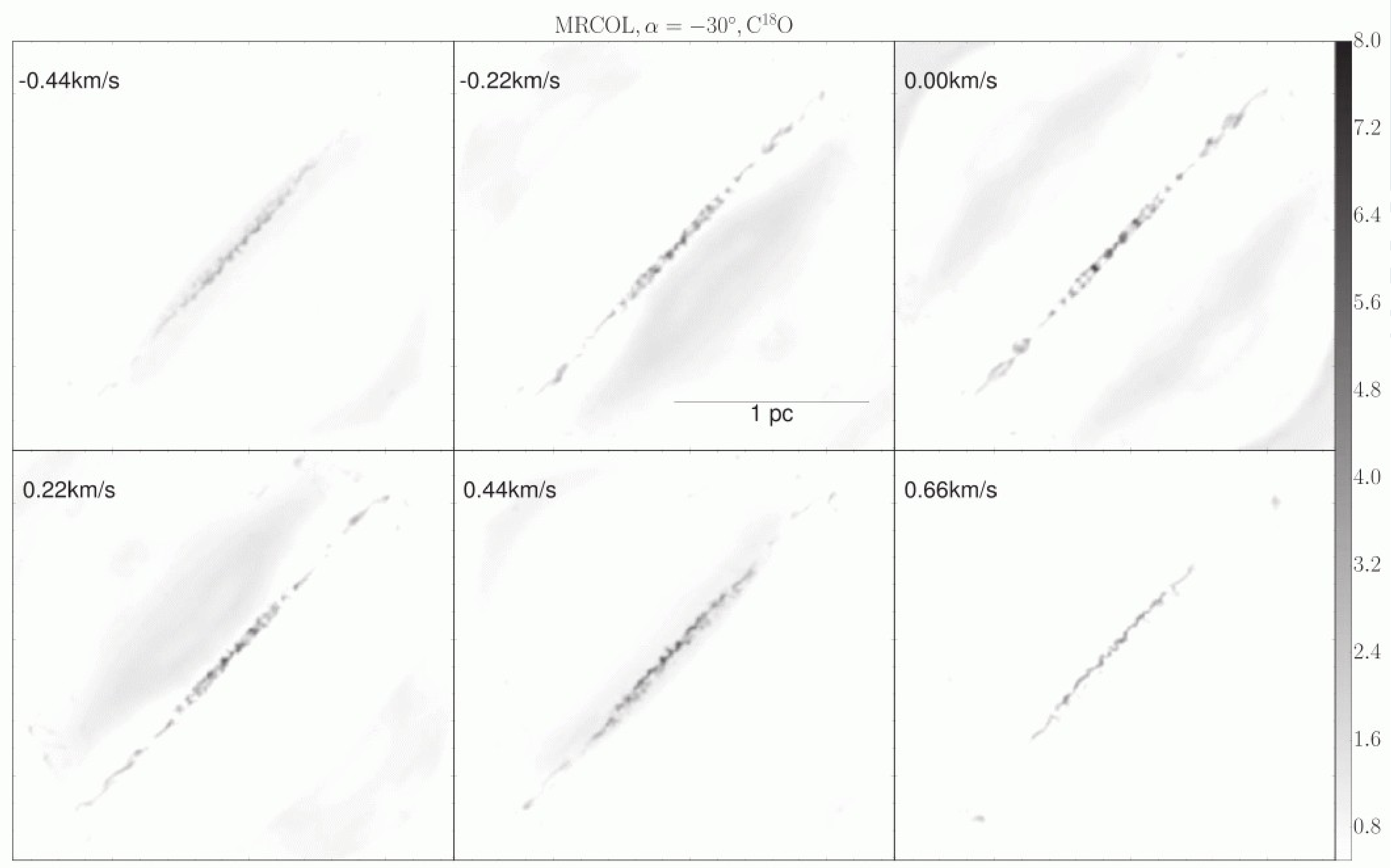


- Early step in filament formation

Features reproduced

- Rings and forks in particular in velocity channels

- Process in Orion supported by Zeeman measure-ments



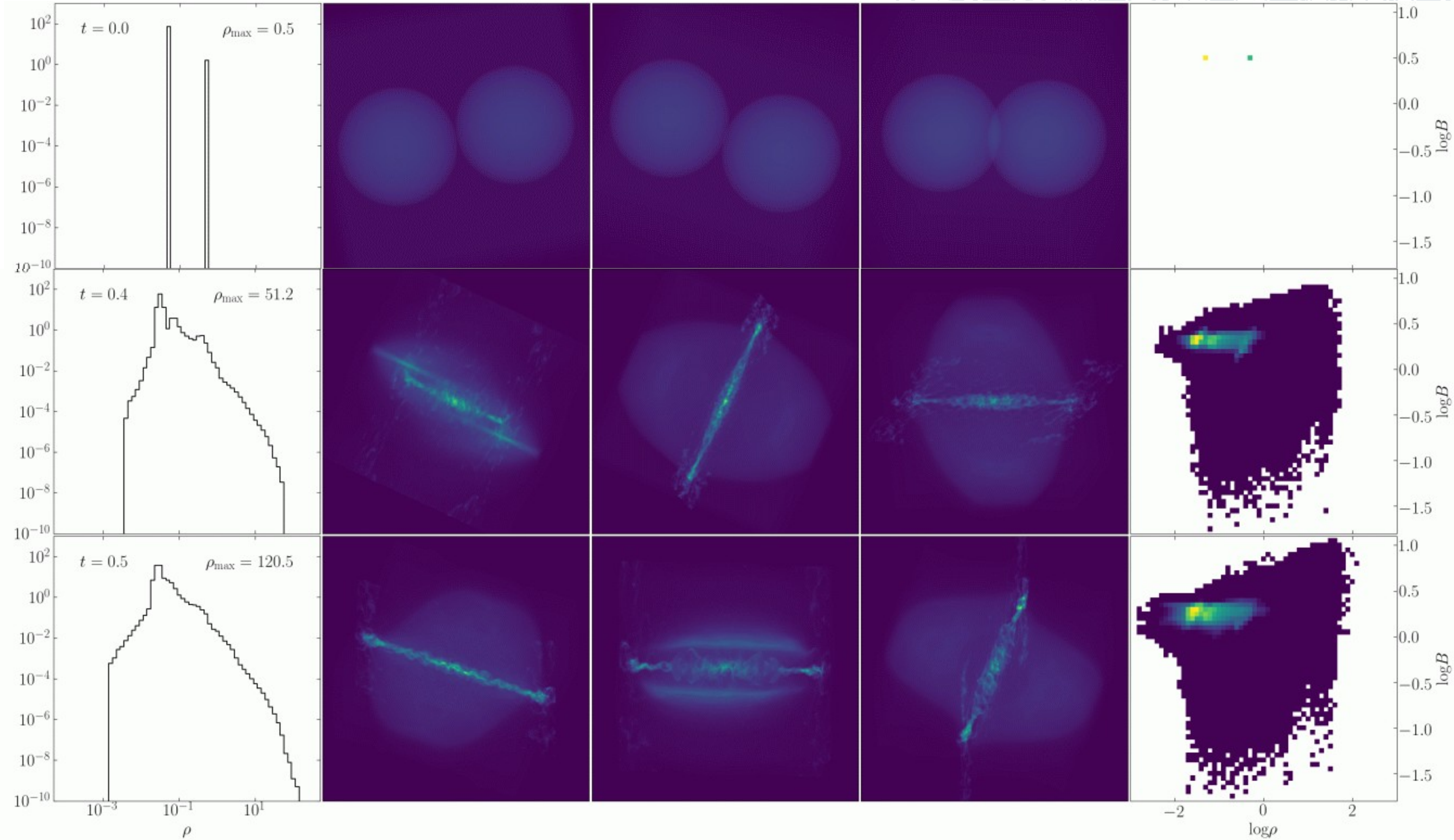
Systematics

- Variation of parameters, like collision angle – study 400 different viewing angles

Model	#	T	η	Cloud1					Cloud2				
				ρ_1	R_1	$v_{1,x}$	$v_{1,z}$	$B_{1,z}$	ρ_2	R_2	$v_{2,x}$	$v_{2,z}$	$B_{2,z}$
MRCOL (§1)	(0)	15	0.001	0.5	0.9	2.0	0.5	3.2	0.5	0.9	-2.0	-0.5	-3.2
η_L (§4.1)	(1)	15	<u>0.0001</u>	0.5	0.9	2.0	0.5	3.2	0.5	0.9	-2.0	-0.5	-3.2
η_H (§4.1)	(2)	15	<u>0.01</u>	0.5	0.9	2.0	0.5	3.2	0.5	0.9	-2.0	-0.5	-3.2
B_L (§4.2)	(3)	15	0.001	0.5	0.9	2.0	0.5	<u>1.6</u>	0.5	0.9	-2.0	-0.5	<u>-1.6</u>
B_H (§4.2)	(4)	15	0.001	0.5	0.9	2.0	0.5	<u>6.4</u>	0.5	0.9	-2.0	-0.5	<u>-6.4</u>
ρ_2_L (§4.3)	(5)	15	0.001	0.5	0.9	2.0	0.5	3.2	<u>0.25</u>	0.9	-2.0	-0.5	-3.2
ρ_2_H (§4.3)	(6)	15	0.001	0.5	0.9	2.0	0.5	3.2	<u>1.0</u>	0.9	-2.0	-0.5	-3.2
R_2_L (§4.4)	(7)	15	0.001	0.5	0.9	2.0	0.5	3.2	0.5	<u>0.45</u>	-2.0	-0.5	-3.2
R_2_H (§4.4)	(8)	15	0.001	0.5	0.9	2.0	0.5	3.2	0.5	<u>1.8</u>	-2.0	-0.5	-3.2
T_L (§4.5)	(9)	<u>10</u>	0.001	0.5	0.9	2.0	0.5	3.2	0.5	0.9	-2.0	-0.5	-3.2
T_H (§4.5)	(10)	<u>30</u>	0.001	0.5	0.9	2.0	0.5	3.2	0.5	0.9	-2.0	-0.5	-3.2
v_x_L (§4.6)	(11)	15	0.001	0.5	0.9	<u>1.0</u>	0.5	3.2	0.5	0.9	<u>-1.0</u>	-0.5	-3.2
v_x_H (§4.6)	(12)	15	0.001	0.5	0.9	<u>4.0</u>	0.5	3.2	0.5	0.9	<u>-4.0</u>	-0.5	-3.2
v_z_L (§4.7)	(13)	15	0.001	0.5	0.9	2.0	<u>0.25</u>	3.2	0.5	0.9	-2.0	<u>-0.25</u>	-3.2
v_z_H (§4.7)	(14)	15	0.001	0.5	0.9	2.0	<u>1.0</u>	3.2	0.5	0.9	-2.0	<u>-1.0</u>	-3.2

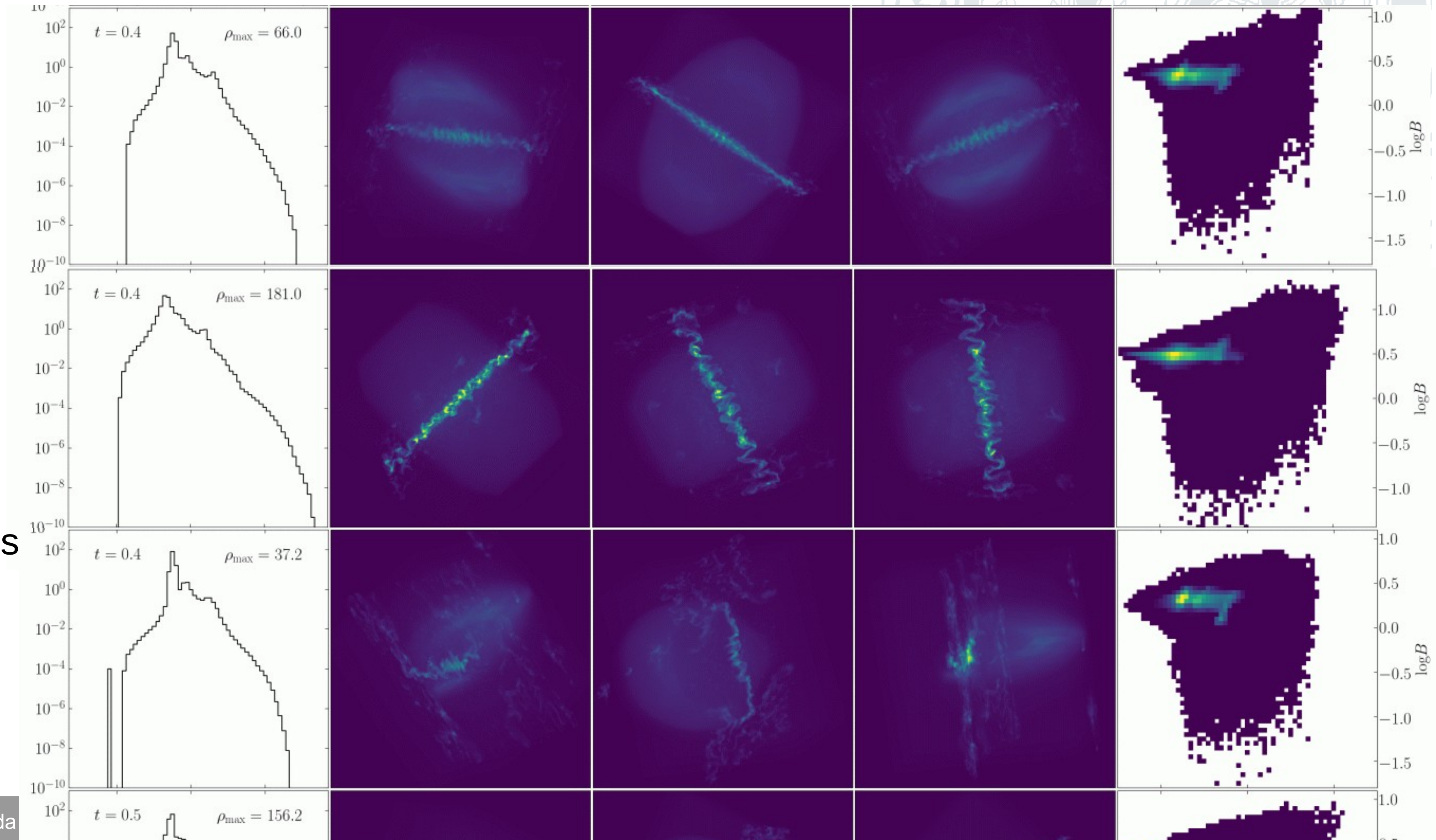
Examples

- Fiducial case (#0)



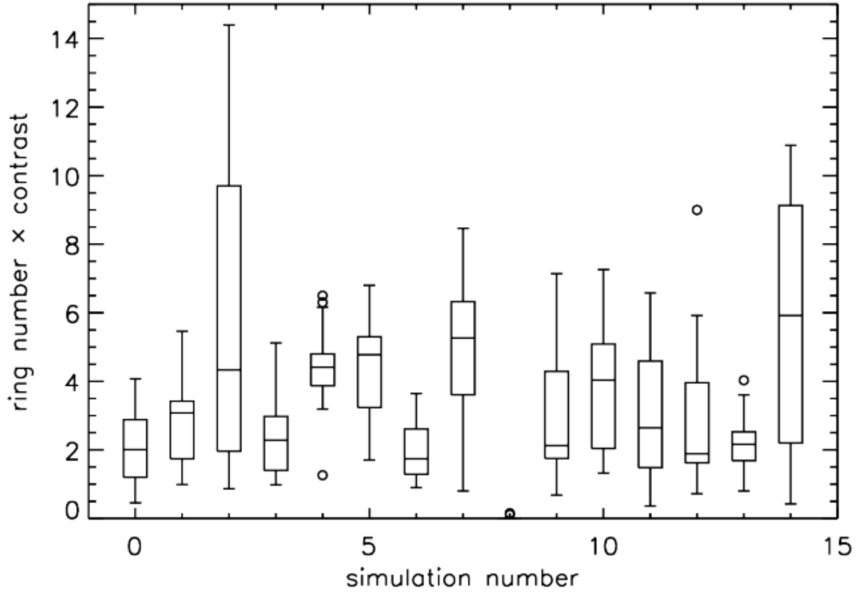
Examples

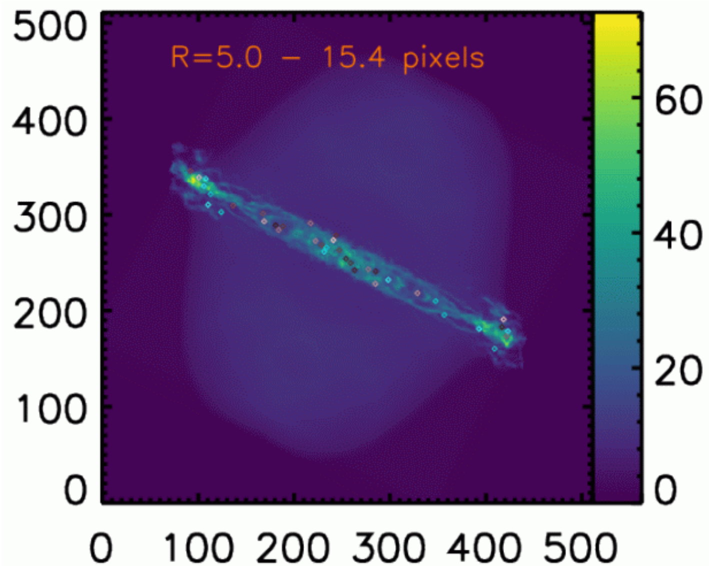
- Low Ohmic resistance (#1)
- High B field (#4)
- 1/8 mass ratio (#7)

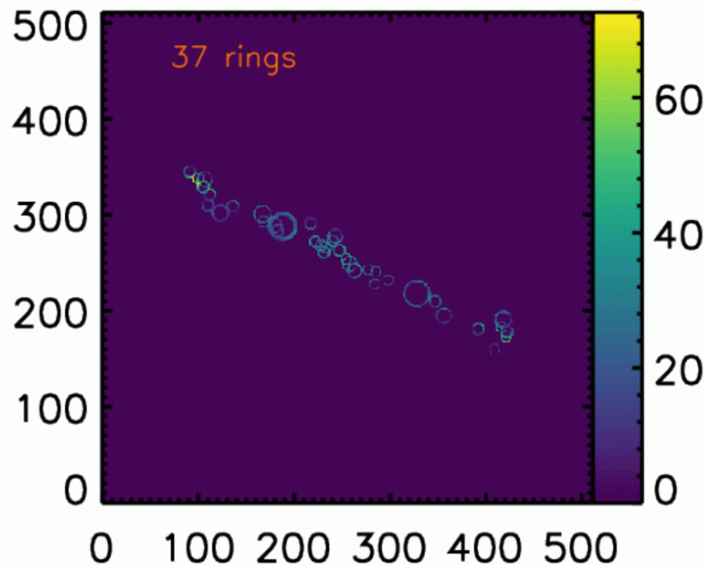


Systematics

- Analysis of “ringiness”
  - Wavelet-based ring-finder

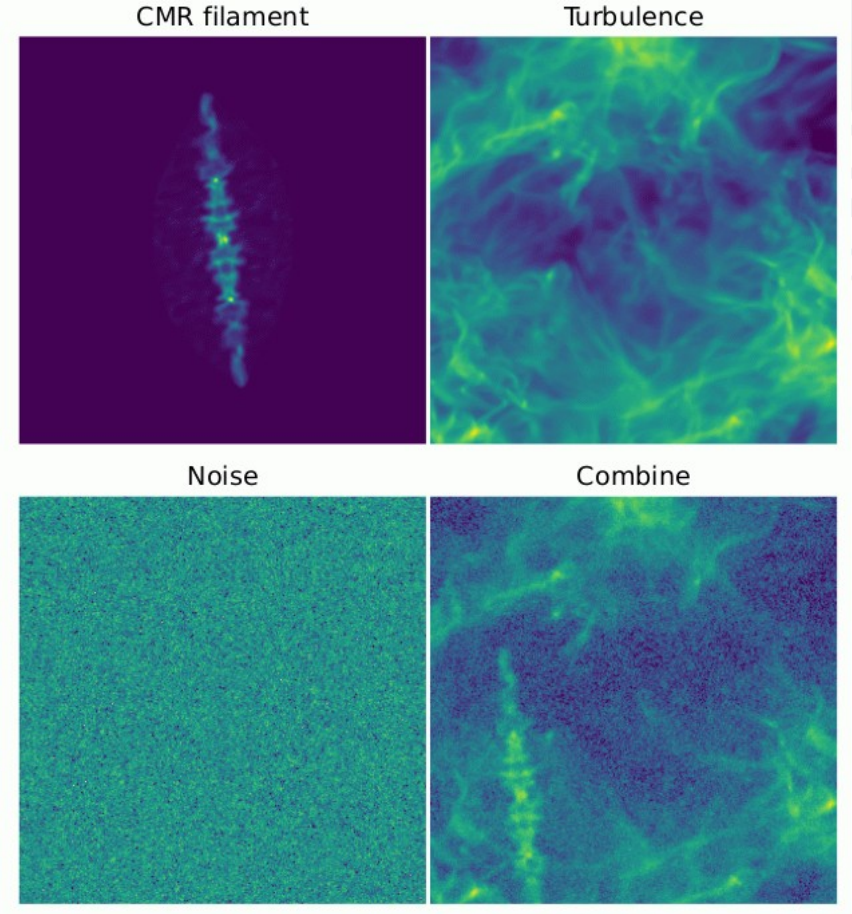






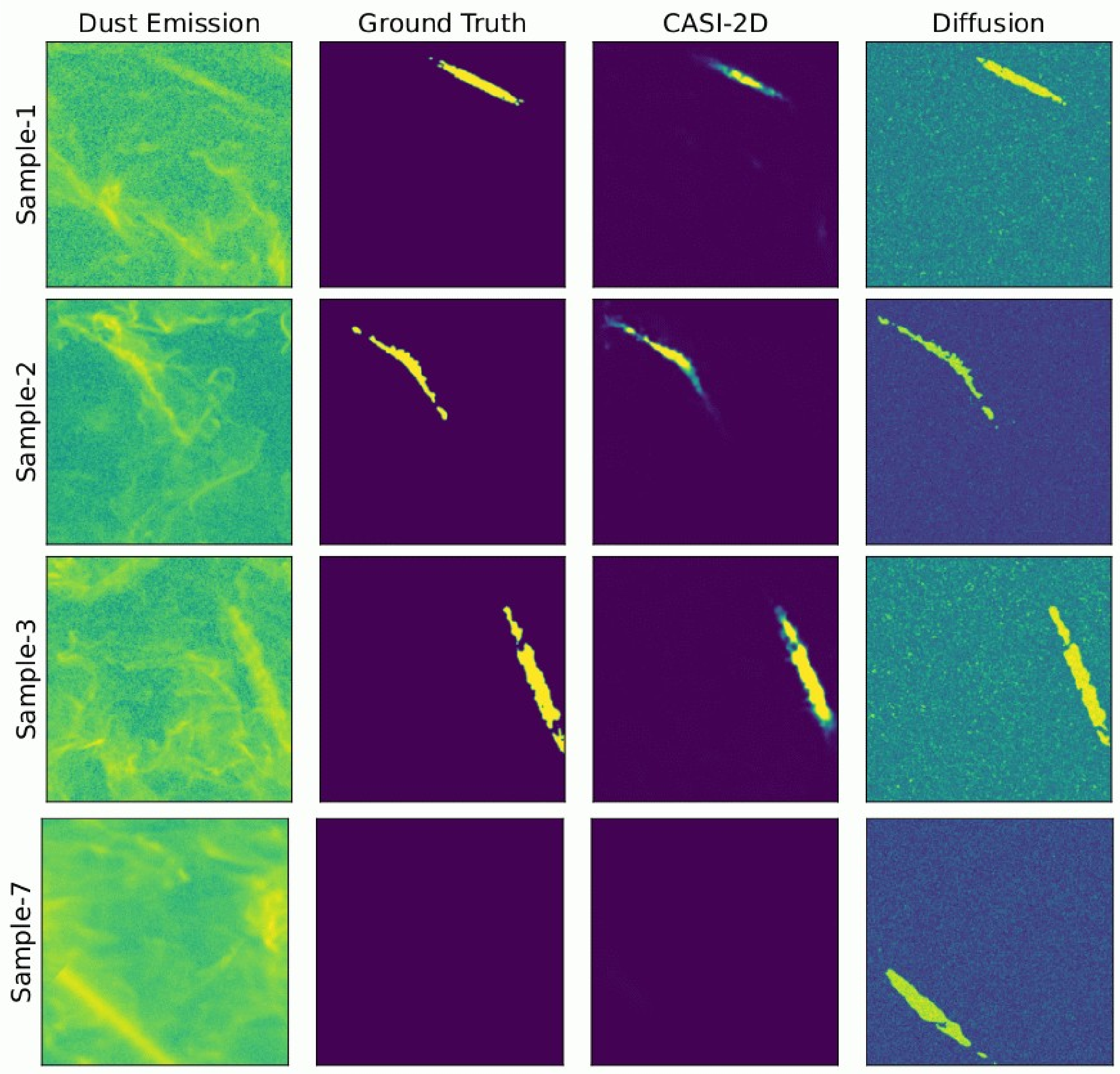
Better systematics

- Look for CMR filaments in observational data
  - Train CNN to find the filaments
  - 2 approaches
    - CASI-2D
    - Denoising Diffusion Probabilistic Model (DDPM)
  - Training data:
    - 14 simulations with 400 viewing angles
    - Negative set: MHD simulations of random turbulent boxes



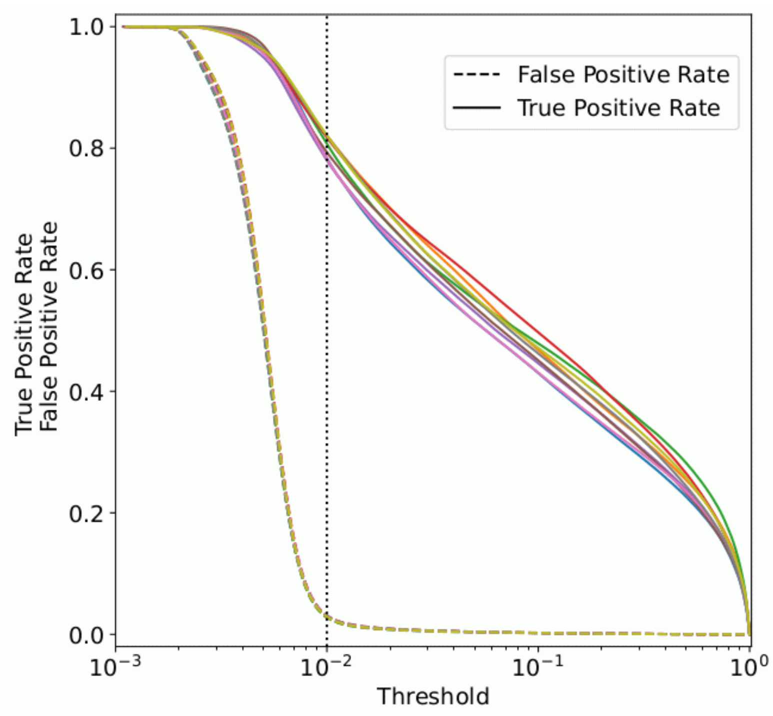
Results

- Network output giving the detection level for CMR filament membership of individual pixels
  - false detections in individual network output
    - often at map edges
  - Combining both networks eliminates most false detections

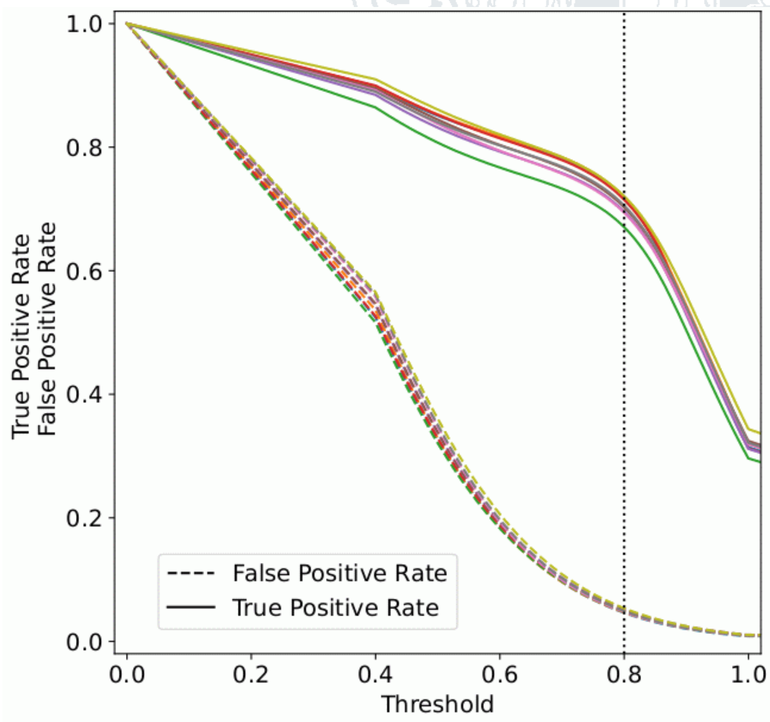


Optimum threshold

- Receiver Optimum Characteristics (ROC) curves
  - Different thresholds for the two networks: force false detections < 6%



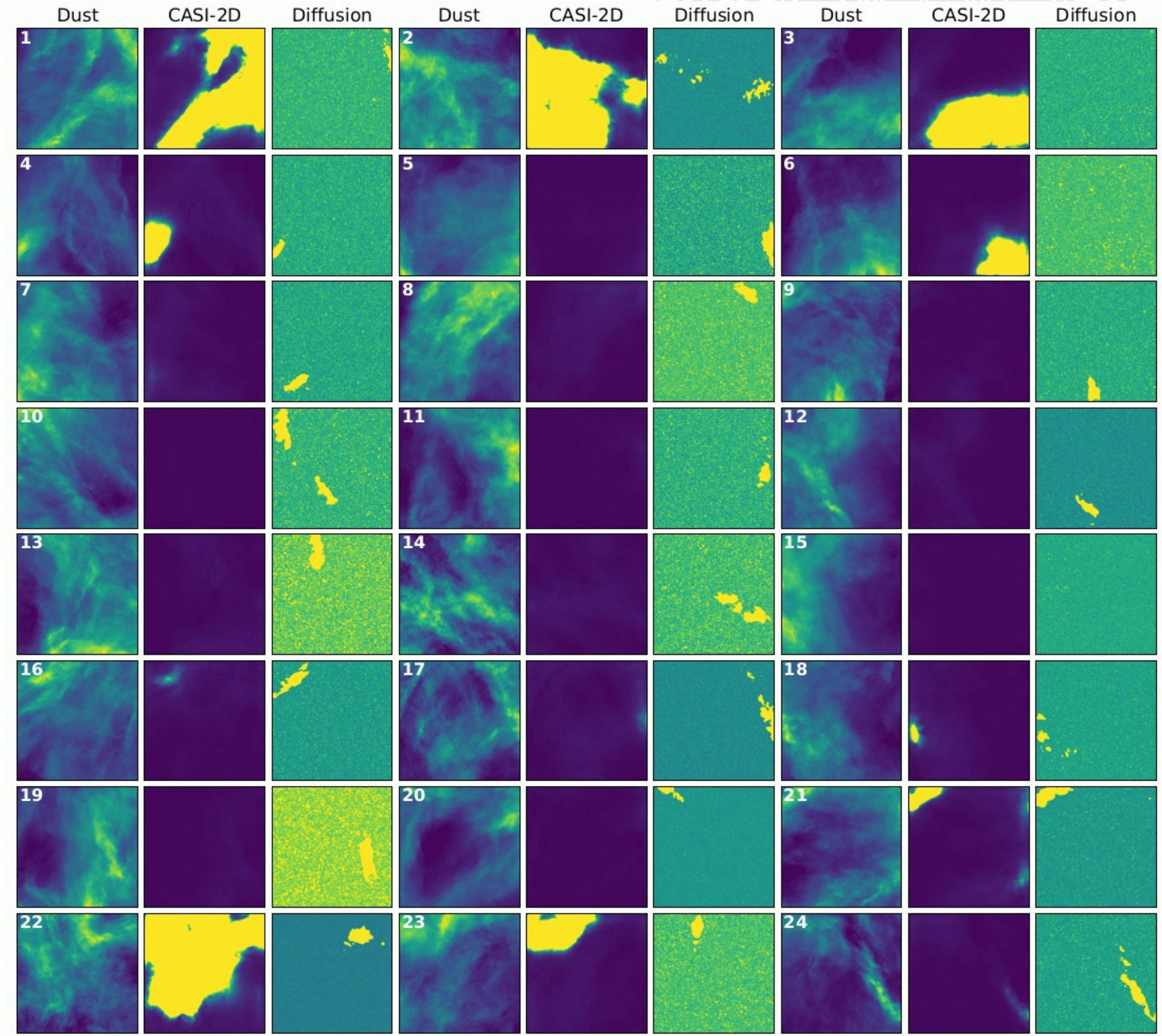
CASI-2D



diffusion model

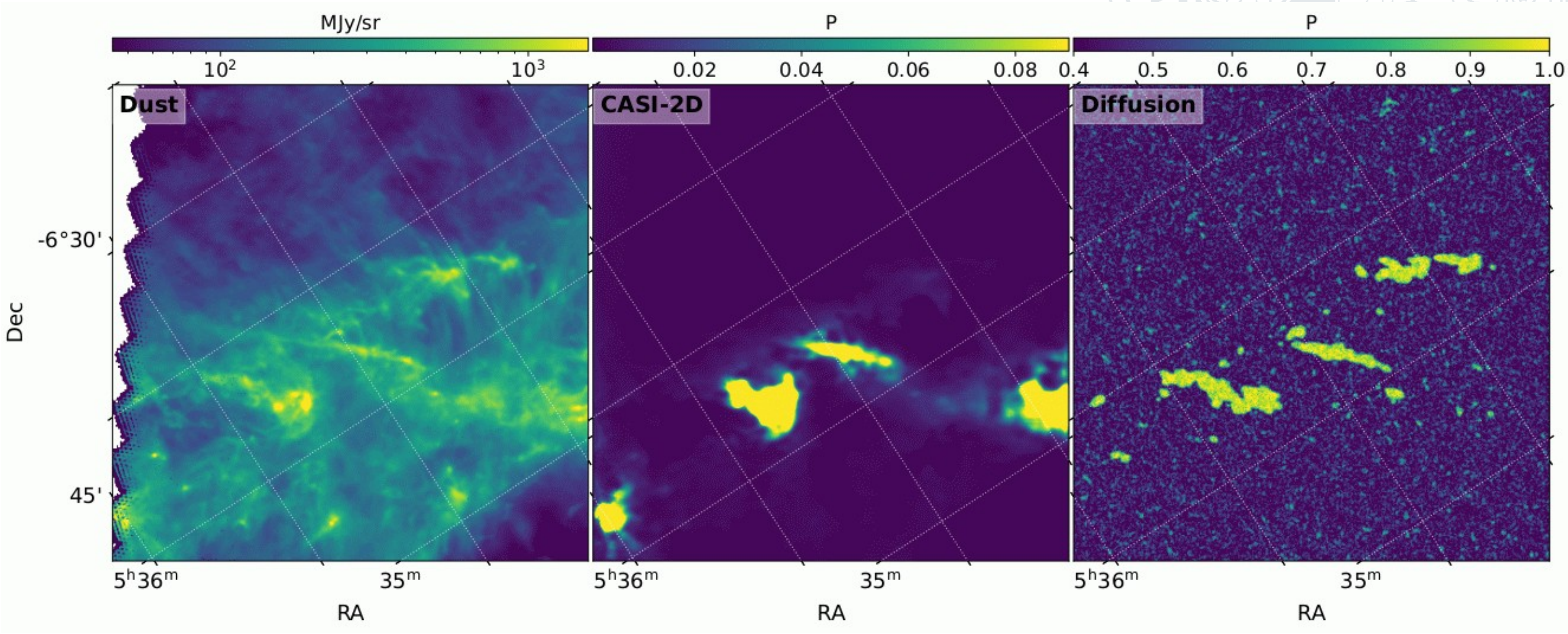
Fake identifications

- Test with HD simulations (Federrath 2021)
  - No CMR
  - Combining both networks eliminates most false detections
  - Problems at edges



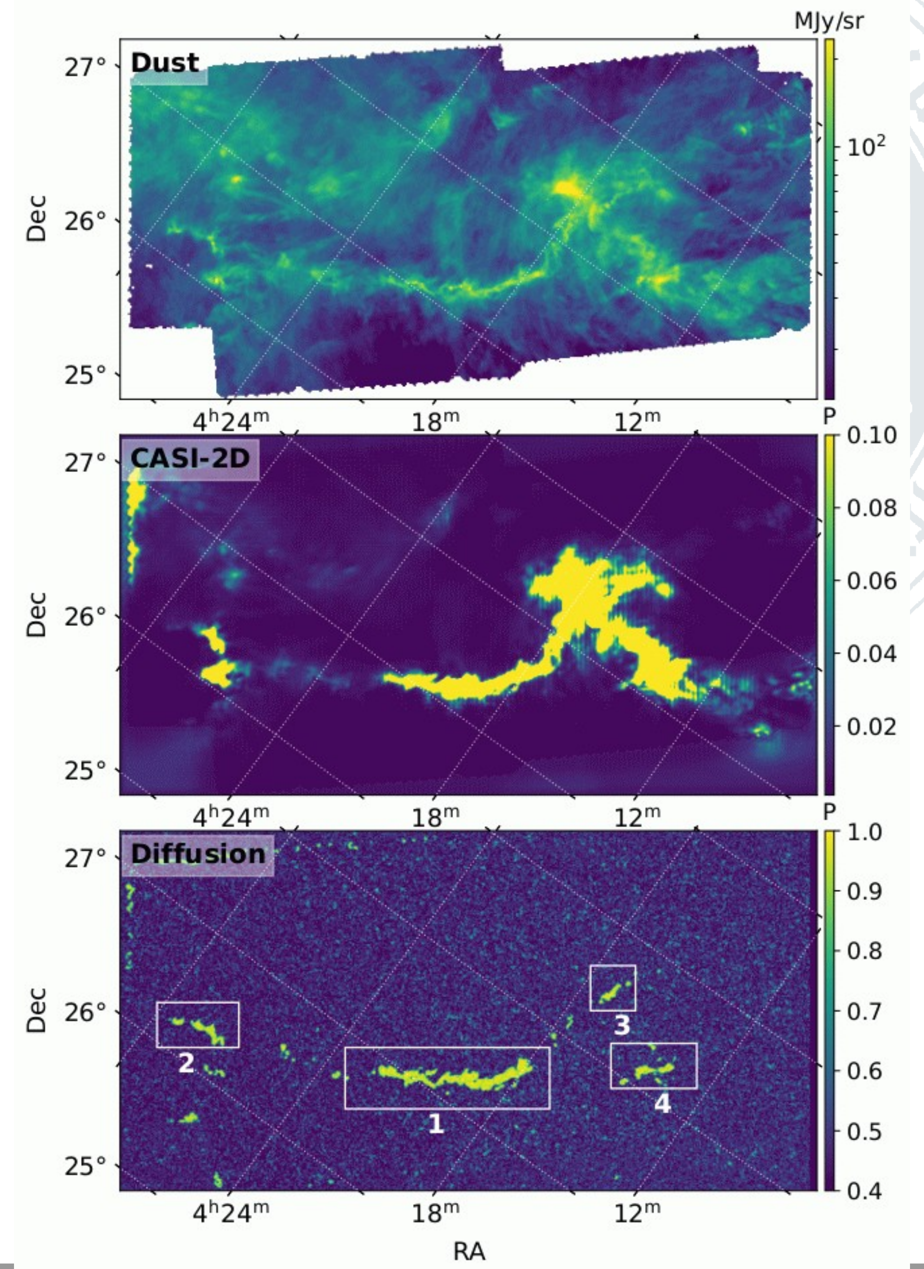
Known case

- Stick well detected
  - Other peaks can be excluded based on morphology



Application: Taurus

- B213 as candidate for high probability CMR filament
  - Others easily excluded based on morphology



Conclusions

- Two approaches (CASI-2D and diffusion model) need to be combined to obtain reasonable reliability

- Identification of candidates for CMR filaments
  - Confirmation needs measurement of magnetic field direction