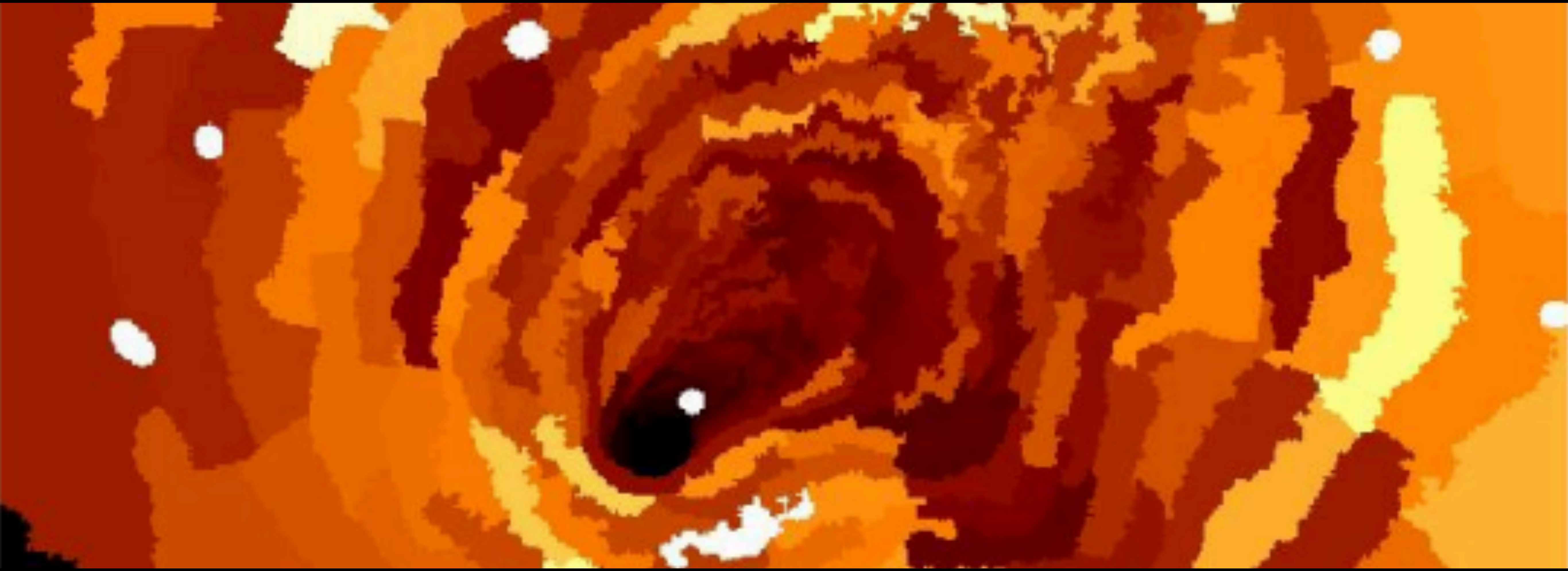
Reconstructing galaxy cluster mergers
with multi-wavelength observations and hydrodynamical simulations

The case of Abell 2146



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with
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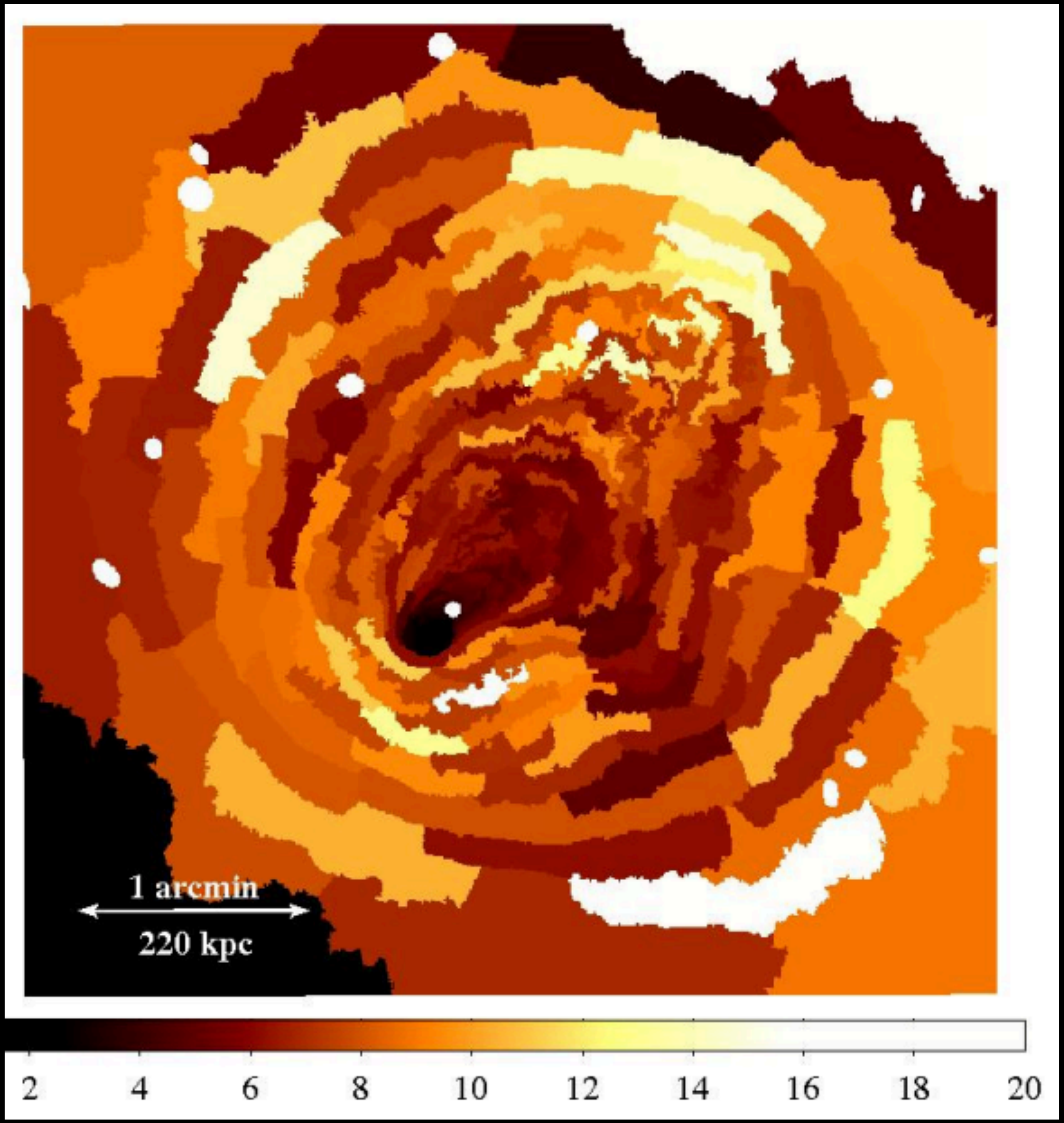
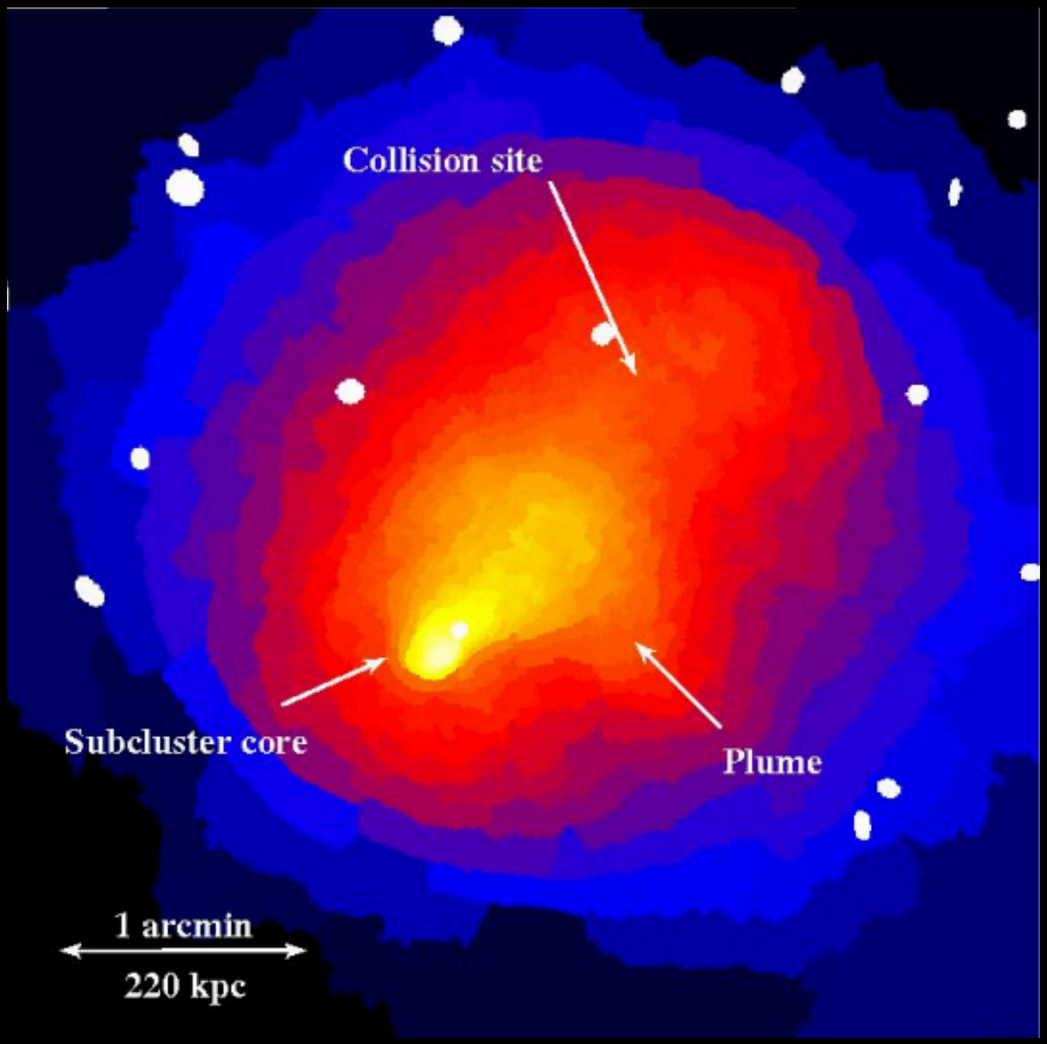
Abell 2146

- Detected as a merging cluster in the X-ray by Russell+ 2010
- Recently completed 2Ms XVP observations (PI Russell, in prep.)
  - deepest yet of merging galaxy cluster



Long-Term Questions

- **What is the nature of microphysics of the ICM?**
  - electron-ion equilibration, thermal conduction and viscosity
- Why is extended radio emission suppressed?
  - Lack of “fossil electrons” from previous mergers/AGN events that could be re-accelerated?



Immediate Challenge

Rapidly narrow down space of **cluster merger parameters** using **hydrodynamical simulations** and constraints from **multiple observations**

GAMER-2

- **<u>G</u>**PU-accelerated **<u>A</u>**daptive **<u>ME</u>**sh **<u>R</u>**efinement code
- 100x faster than FLASH, 10x than Enzo
- Available modules:

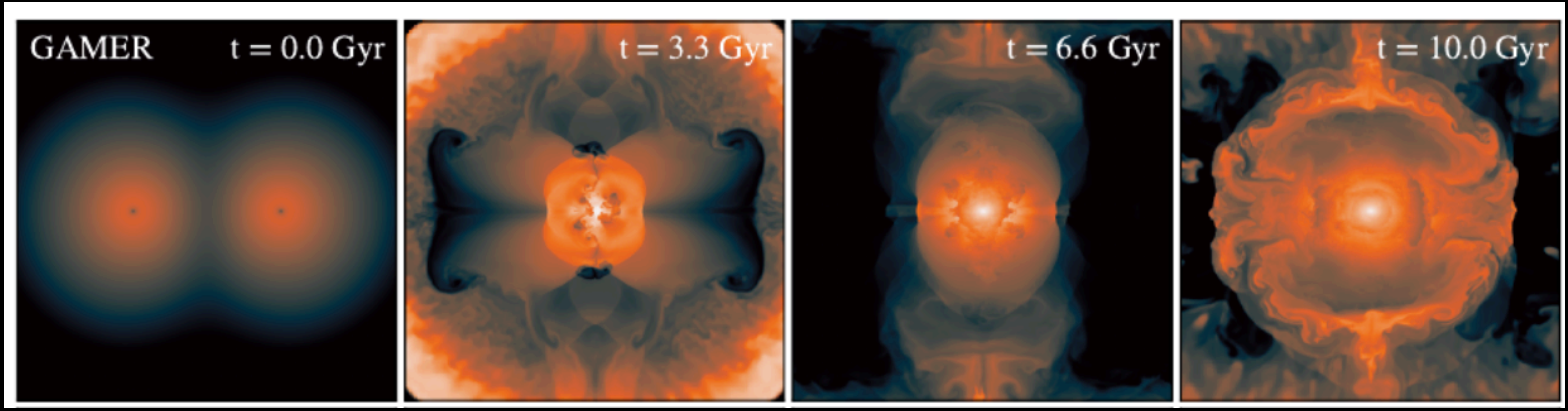
✓ non-radiative gas with self-gravity

✓ star formation and feedback

✓ radiative cooling

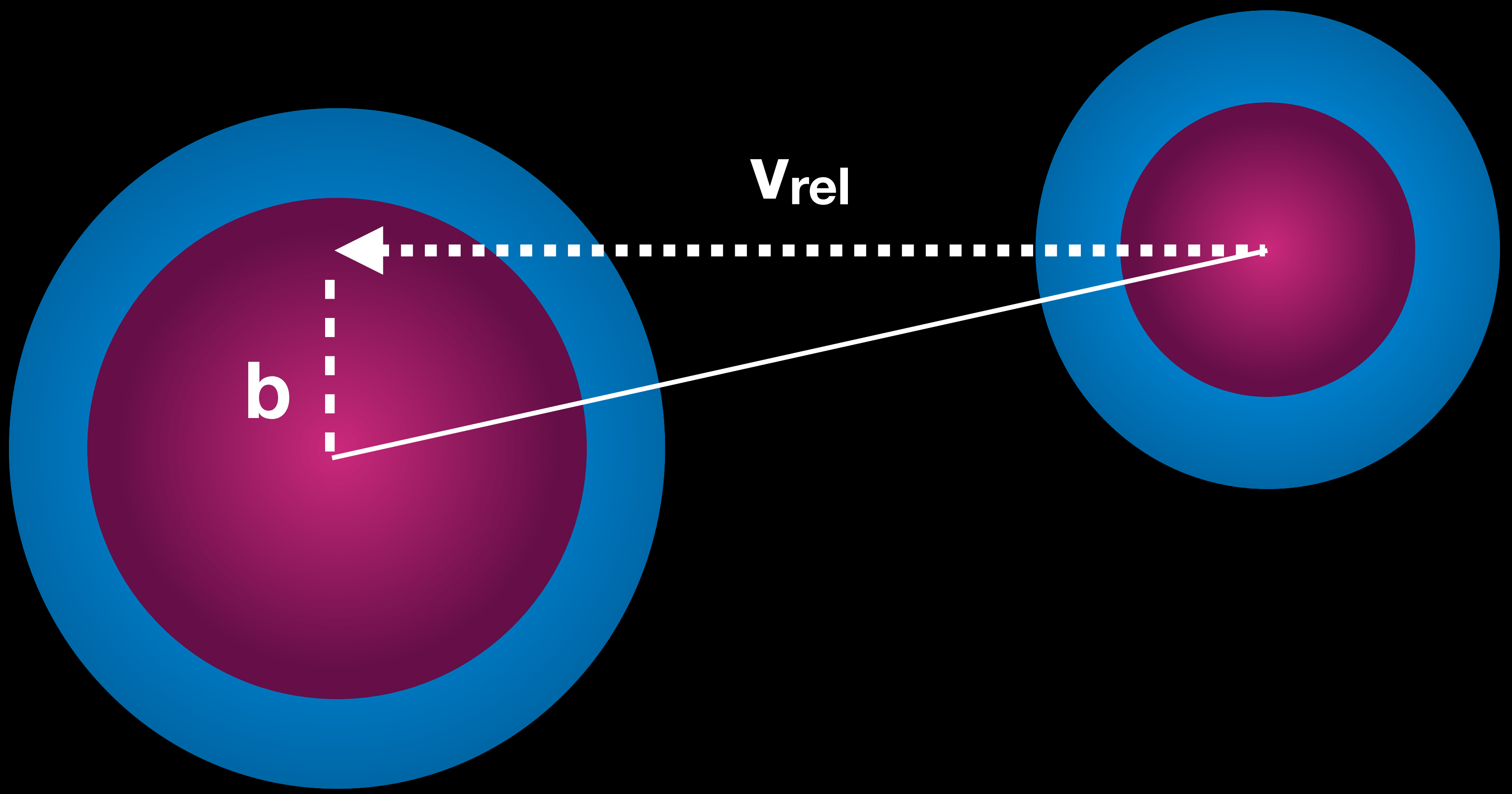
☐ MHD

Schive+ 2017



Step 1: Initial Conditions

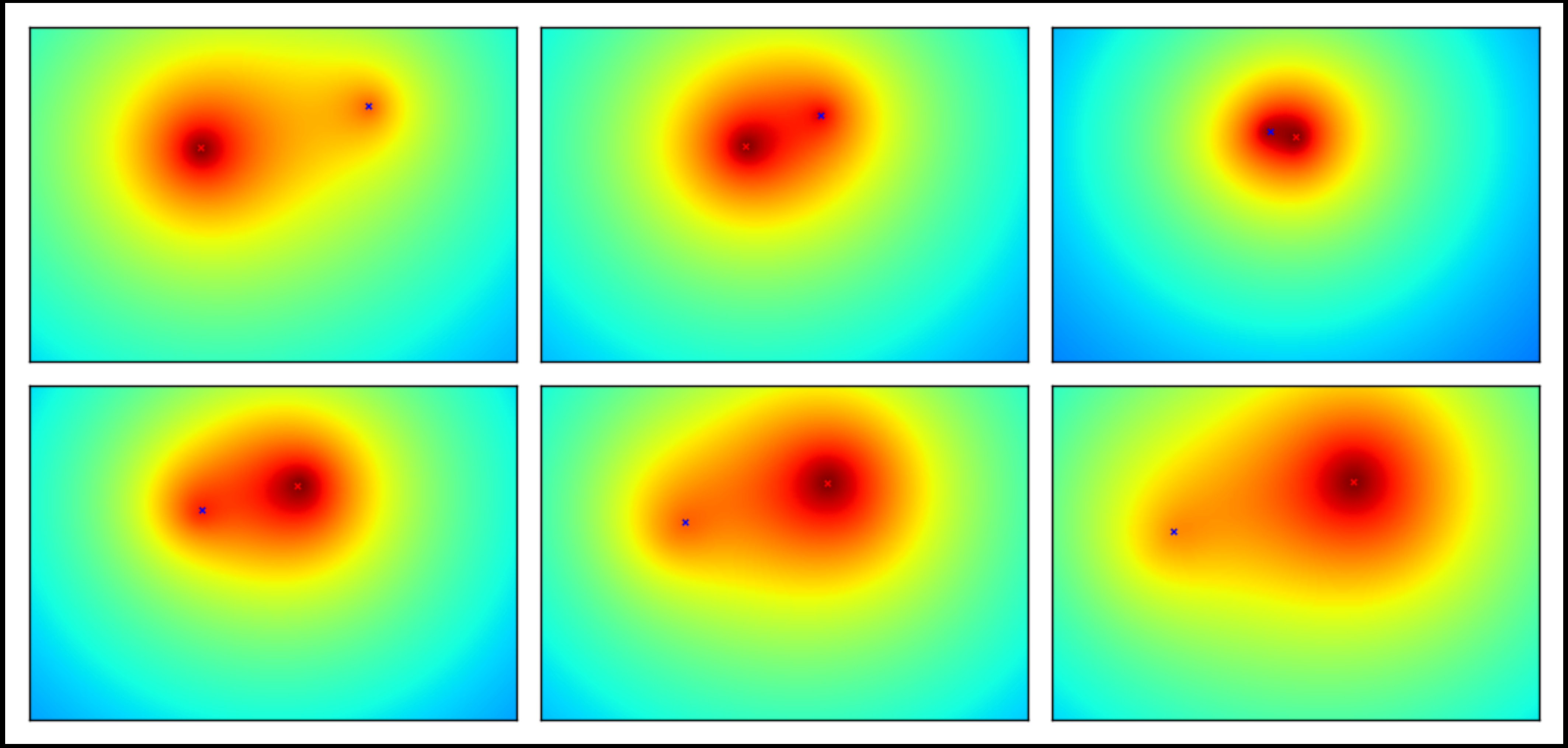
- **Halo masses** M_1, M_2 from **lensing and dynamical analyses**
  - truncated NFW profile for the dark matter - c_{DM}
  - Vikhlinin modified beta profile for the gas - α_{gas}
- Initial velocity v_{rel}
- Impact parameter b



8 free parameters

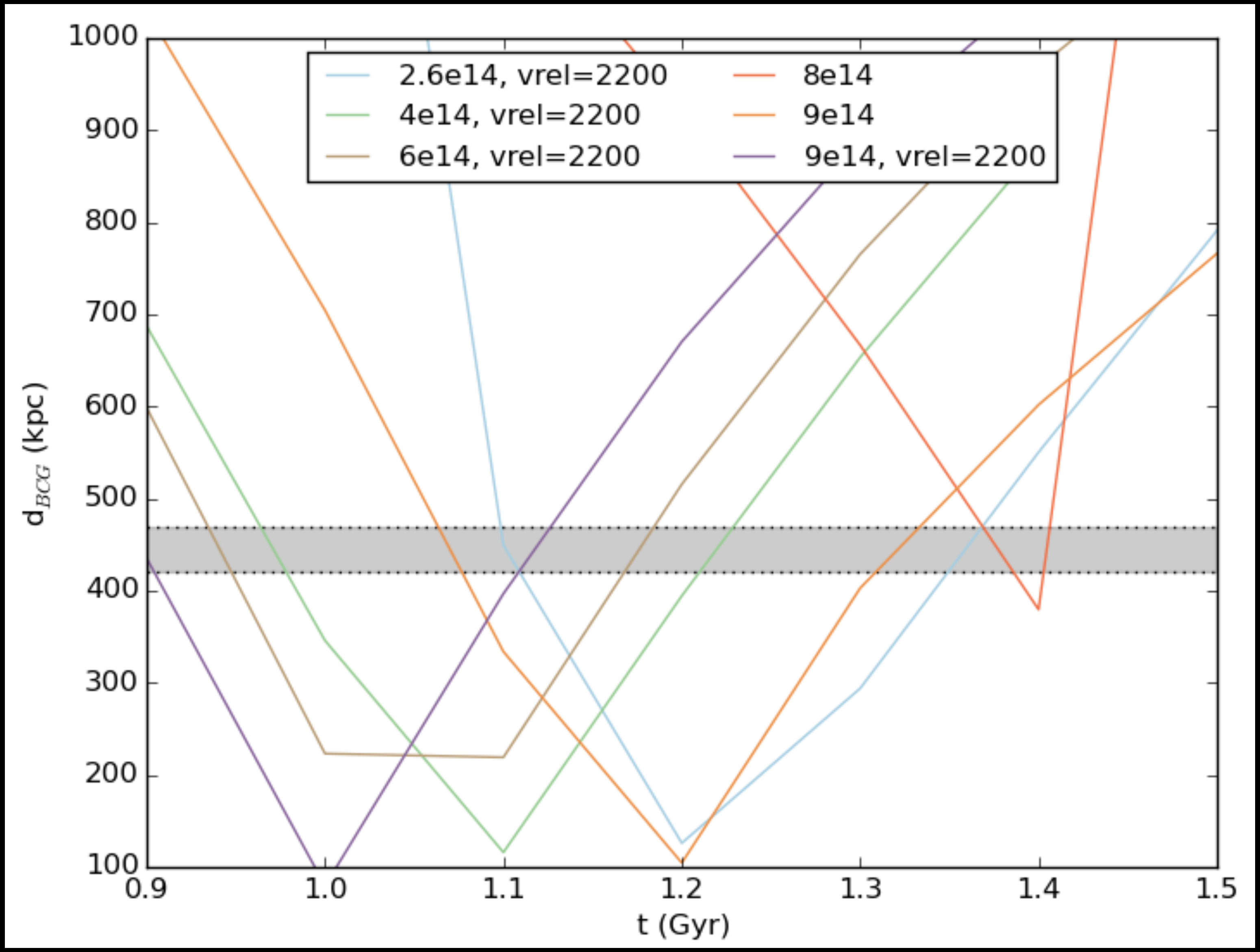
Step 2: Separation of BCGs

- **BCG positions limited only by astrometry, trace** ϕ_{grav}
- Slice of gravitational potential in plane of the merger
  - identify local minima



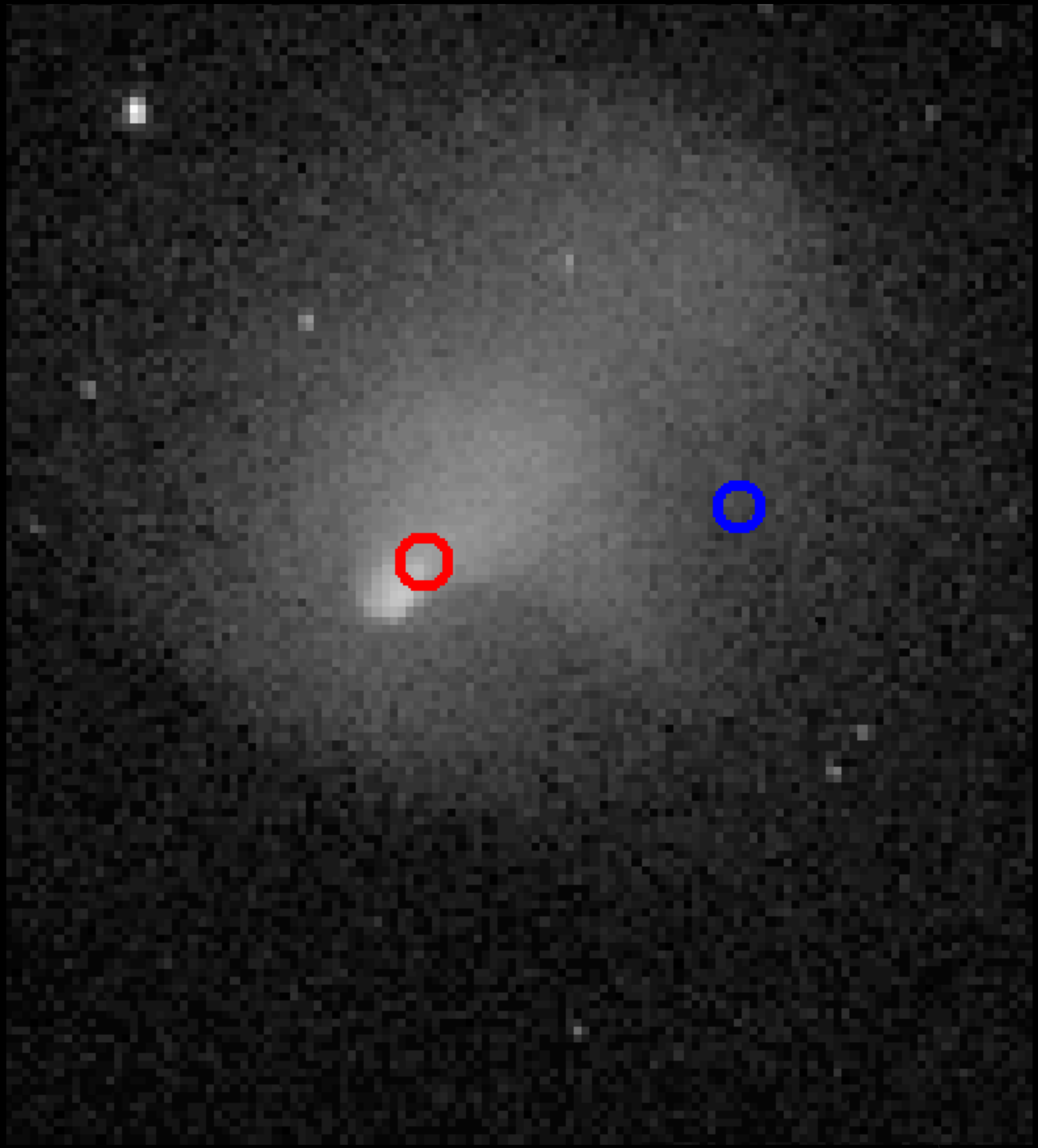
Result: 1-3 snapshots

- Lucky because visibility of shock fronts + dynamics tightly constrains projection angle. If θ_{proj} less certain, more snapshots.
- But strong selection because BCGs move very fast close to merger!

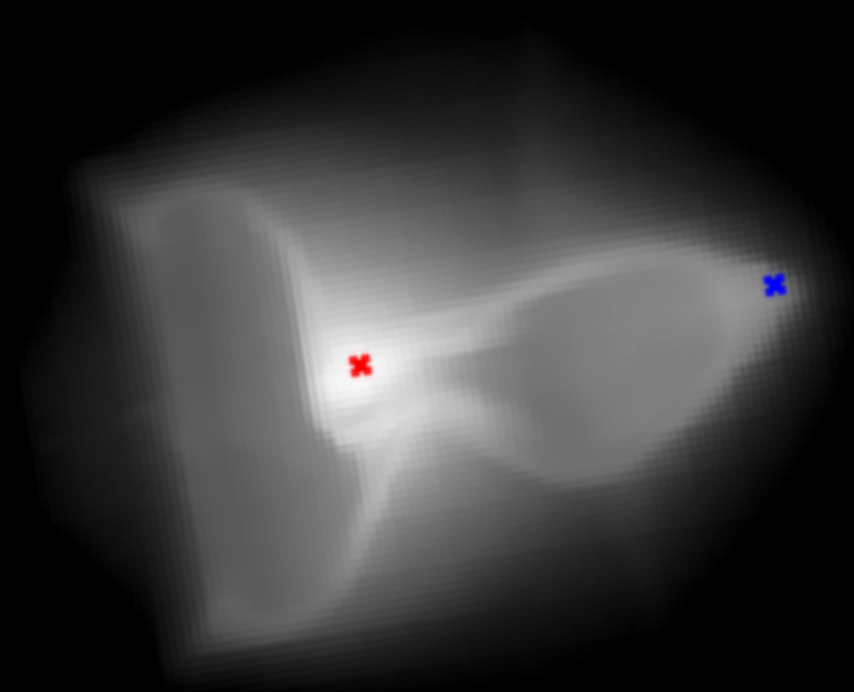


Step 3: Rotate and project

- Sets rotation in plane of sky
- Then vary projection angle ± 20°



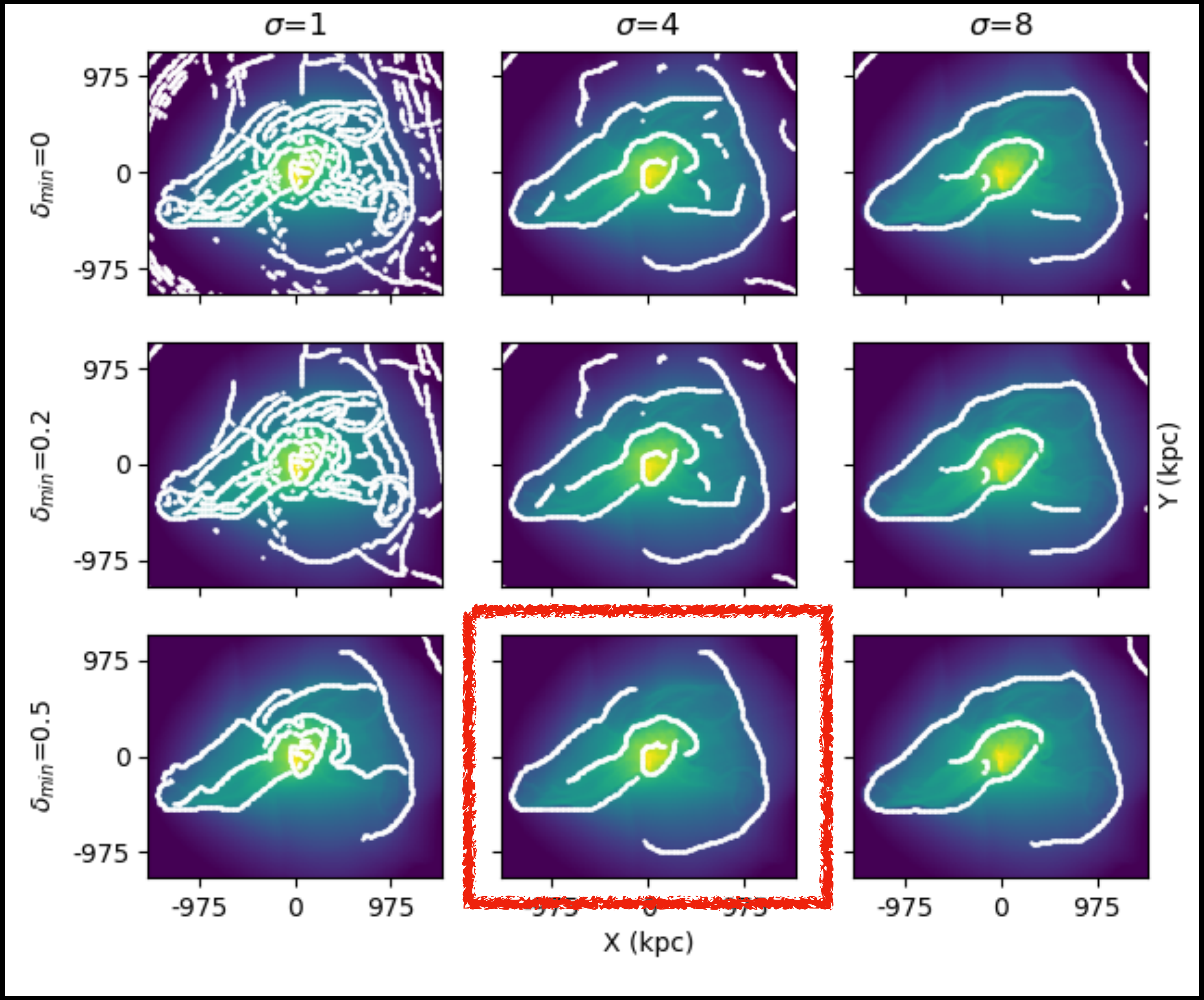
$$M_1 = 9 \times 10^{14} M_\odot, M_2 = 2.4 \times 10^{14} M_\odot$$



b = 50 kpc, t = 0.3 Gyr post periapsis

Step 4: Feature recognition

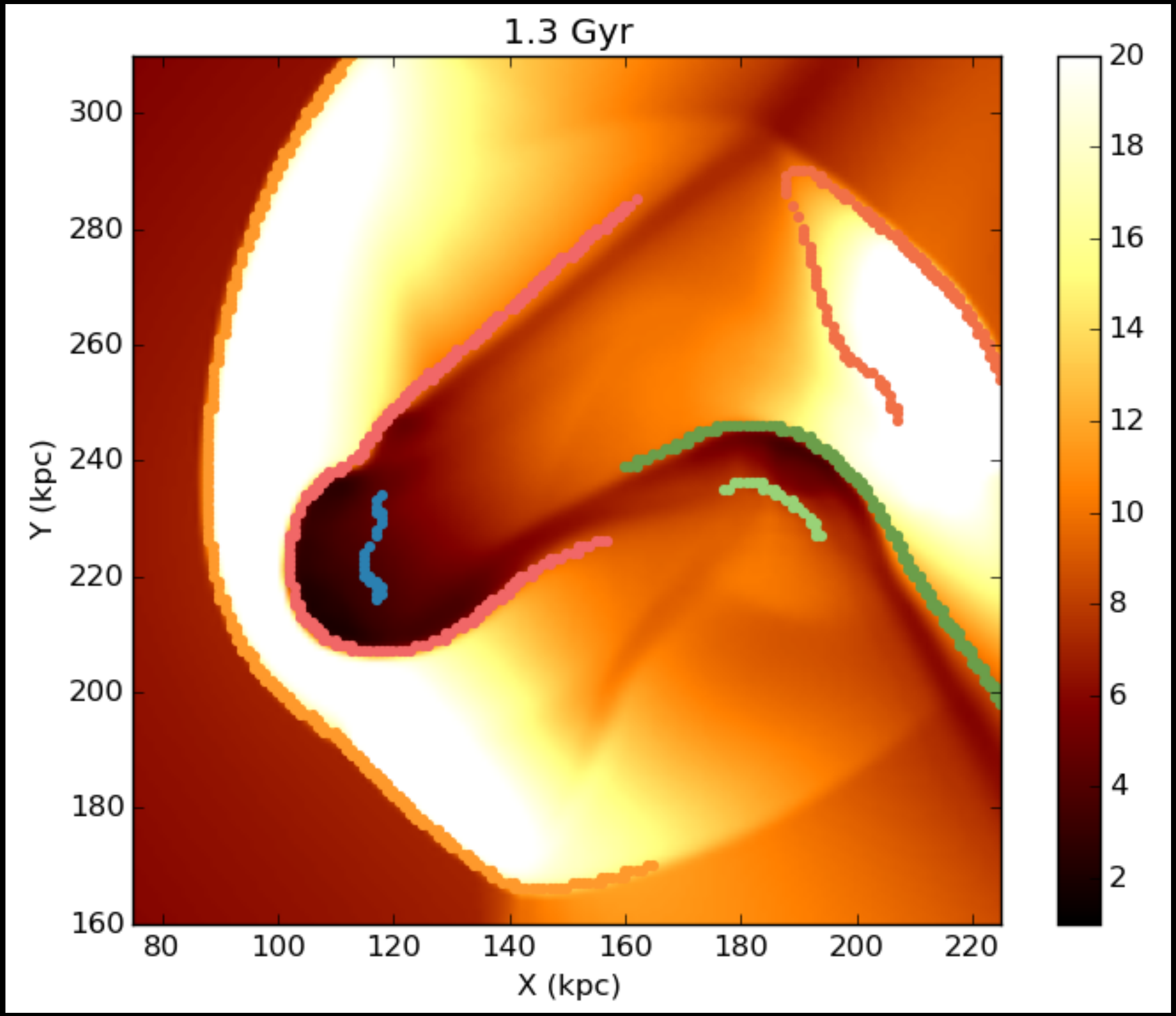
- Identify bright, high contrast regions
  - **Canny algorithm** - vary smoothing length, minimum contrast



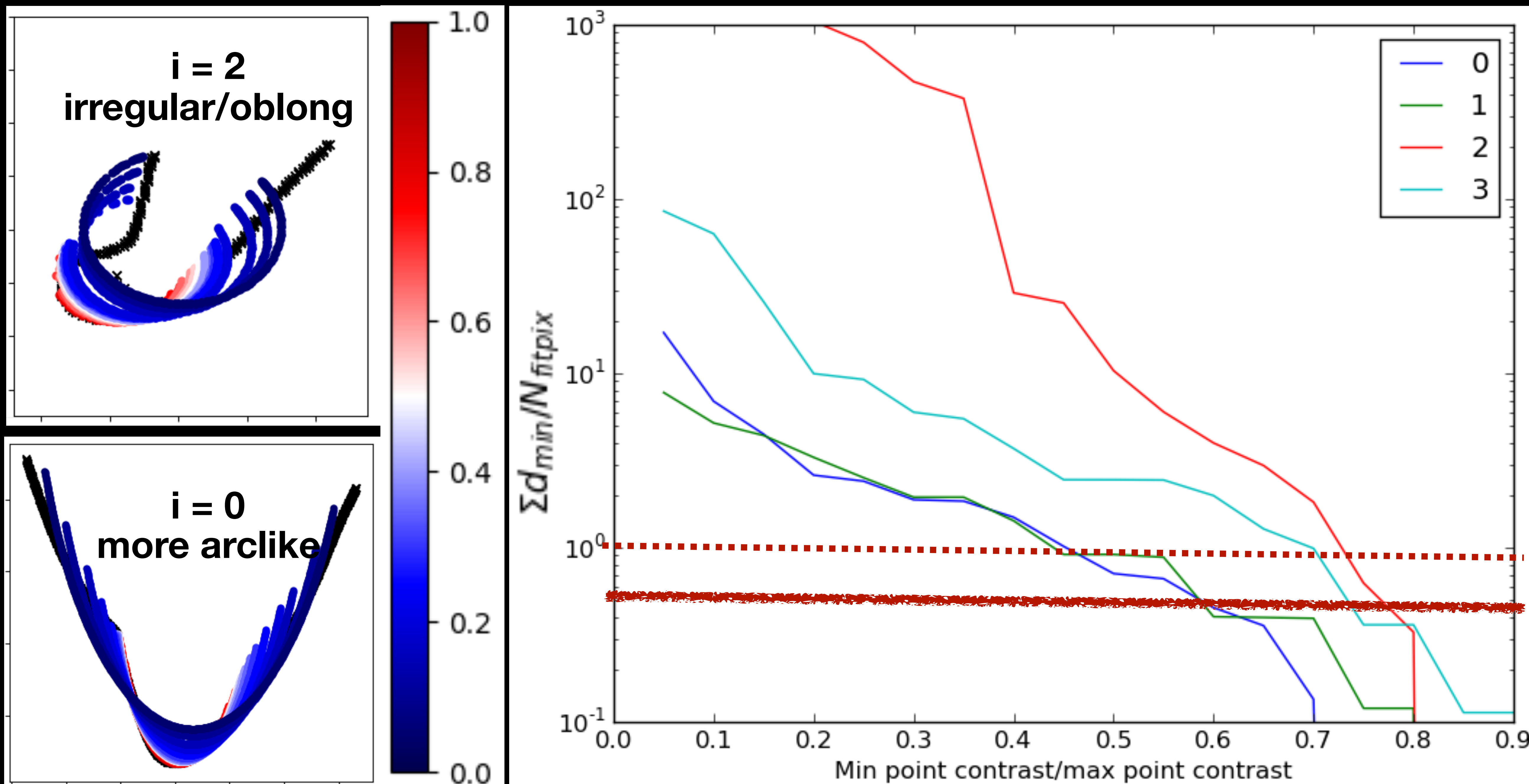
Step 5: Feature sorting

- **Sort adjacent points into separate features**
- **Apply surface brightness/contrast cuts from X-ray maps**
  - feature lengths, relative separations
  - T, profiles across them

Features from T map

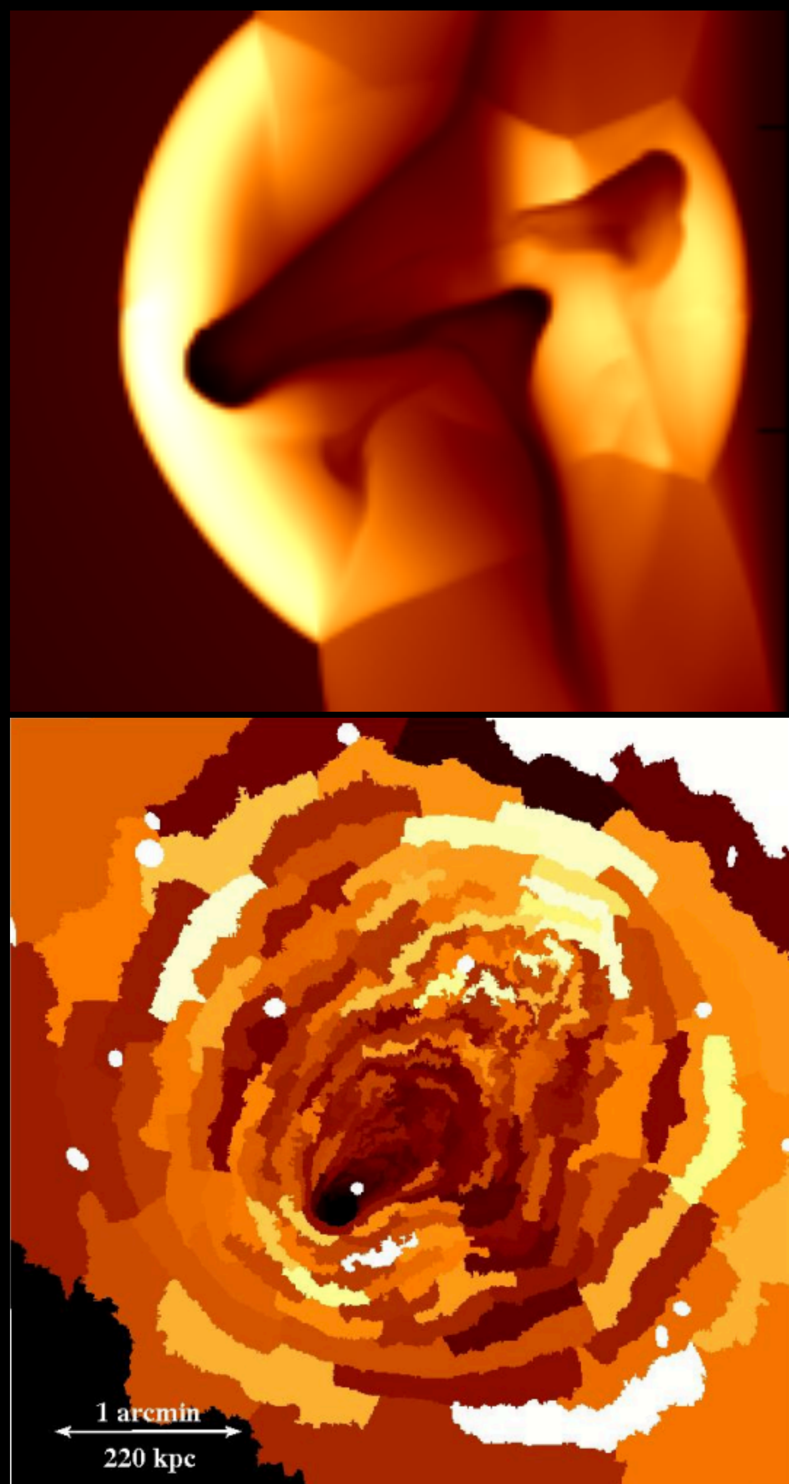


Step 6: Fit arcs



- **For mergers, the shock fronts are more circular, whereas disrupted cool cores are more irregular**

Key feature observables



- Radius of curvature + standoff distance
  - Highly sensitive to **halo masses, initial velocities, impact parameter**
- Gas parameter effects much smaller scale - useless to fine-tune without better physics

To be continued

- MHD
- viscosity (isotropic + Braginskii)
- thermal conduction
- electron-ion equilibration through Coulomb collisions

Conclusions

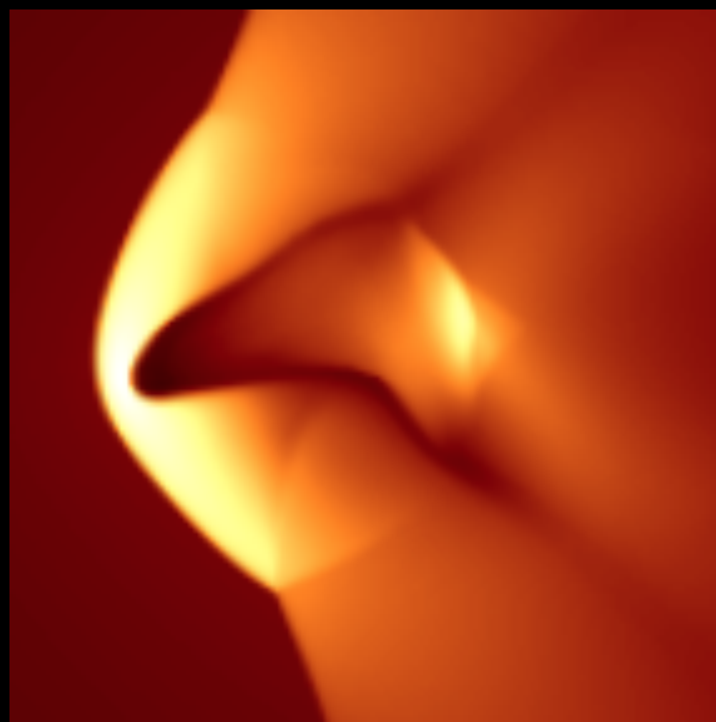
- **We present a pipeline to compare simulations to multi-wavelength observations to constrain cluster merger parameters**
    - Current case: Abell 2146

1. Initial conditions from **lensing + dynamical analyses**
2. **Positions of BCGs**/potential minima strongly constrain time in simulation
3. Fix rotation angle in plane of sky
4. **X-ray emissivity, temperature maps** then relatively rank images
    - edge-finding algorithms allow **shock/cold front detection**
    - Then compare radius of curvature, standoff distance
5. Iteratively explore parameter space with fast simulation codes like GAMER

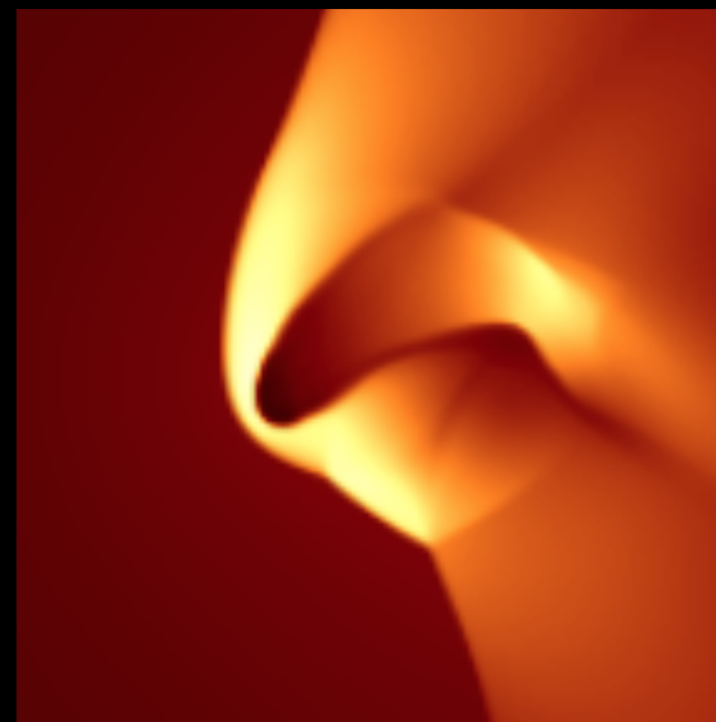
Backups

Parameter tests: Impact parameter

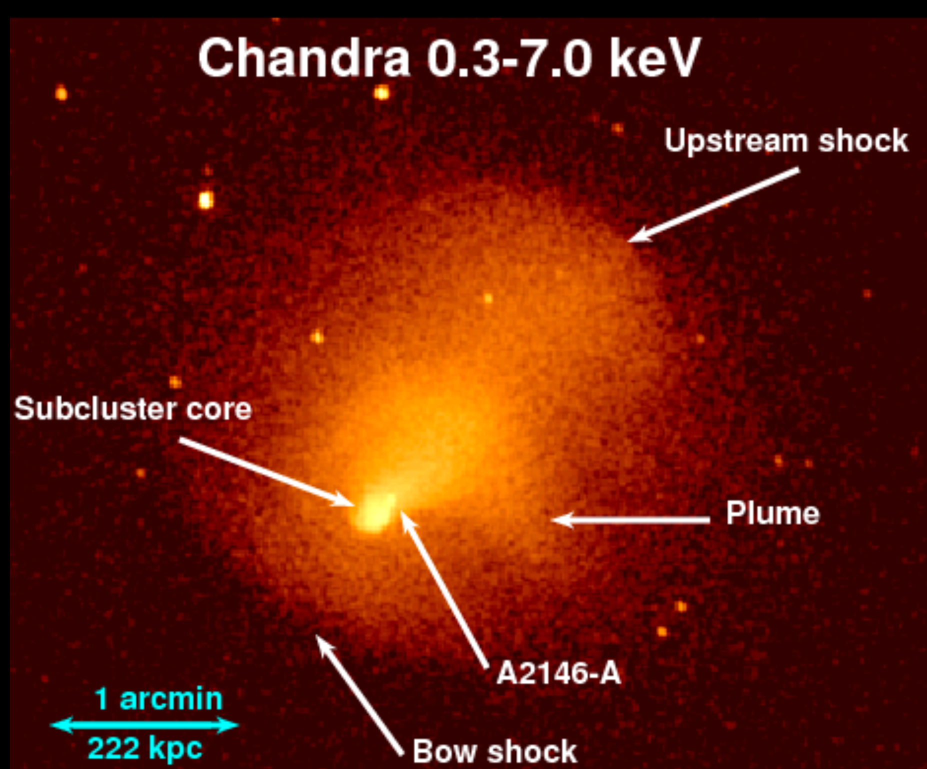
b = 100

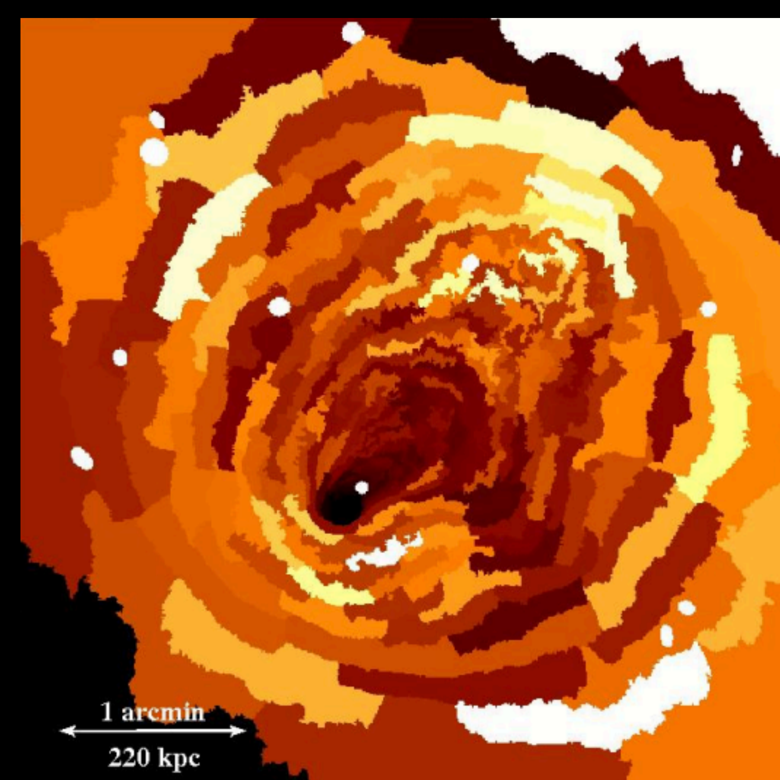


b = 250



b=375



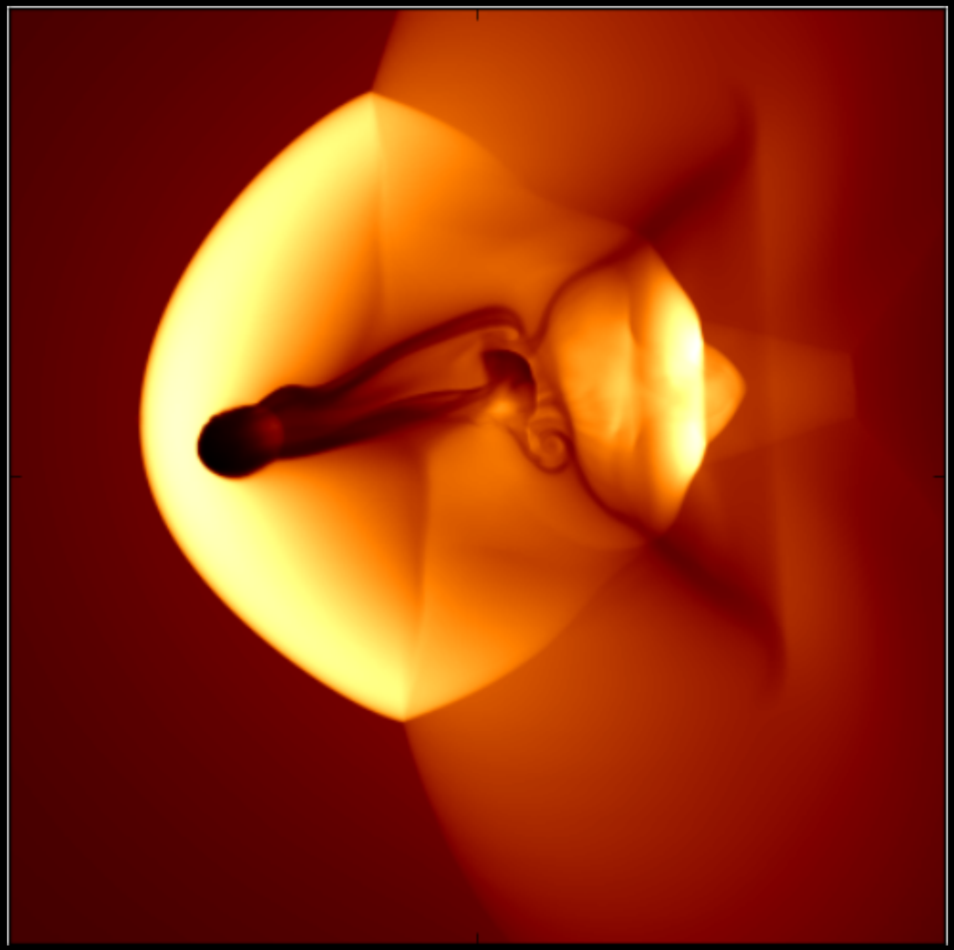


Parameter tests: Halo mass

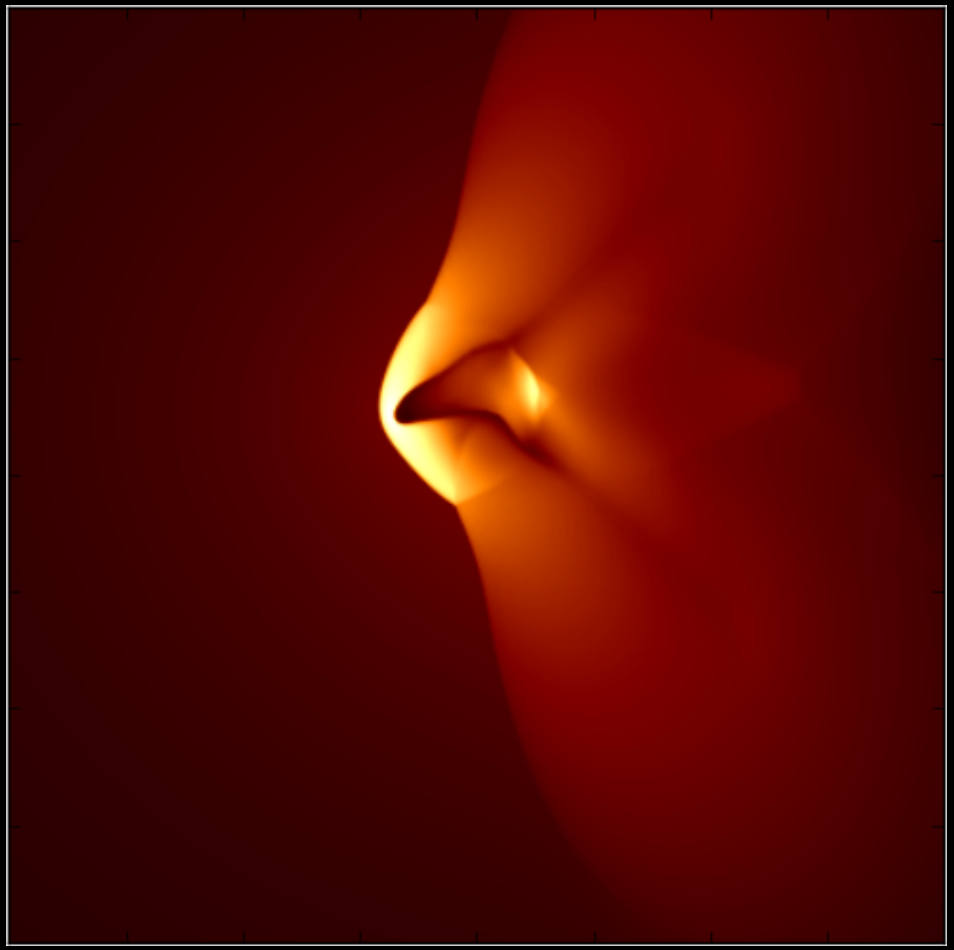
Lensing models degenerate between concentration and total mass

Greater halo mass —> larger features, greater separation between bow shock and cold front

$M_1 = 1.1 \times 10^{15}\ M_{sun}$



$M_1 = 8.1 \times 10^{14}\ M_{sun}$



Parameter tests: halo concentrations

c_{DM} of main halo

α of main halo

c_{DM} of secondary halo