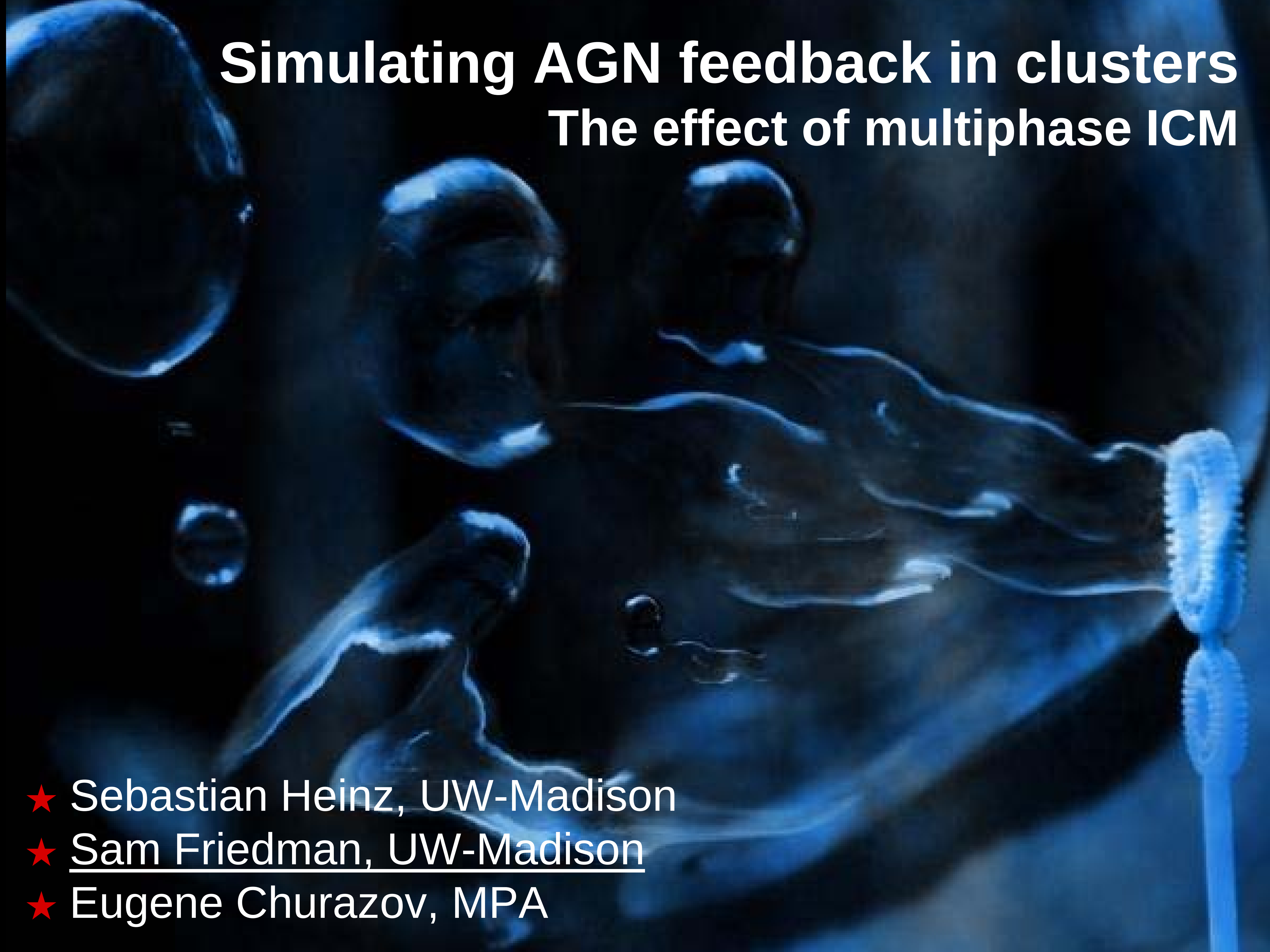


Simulating AGN feedback in clusters

The effect of multiphase ICM

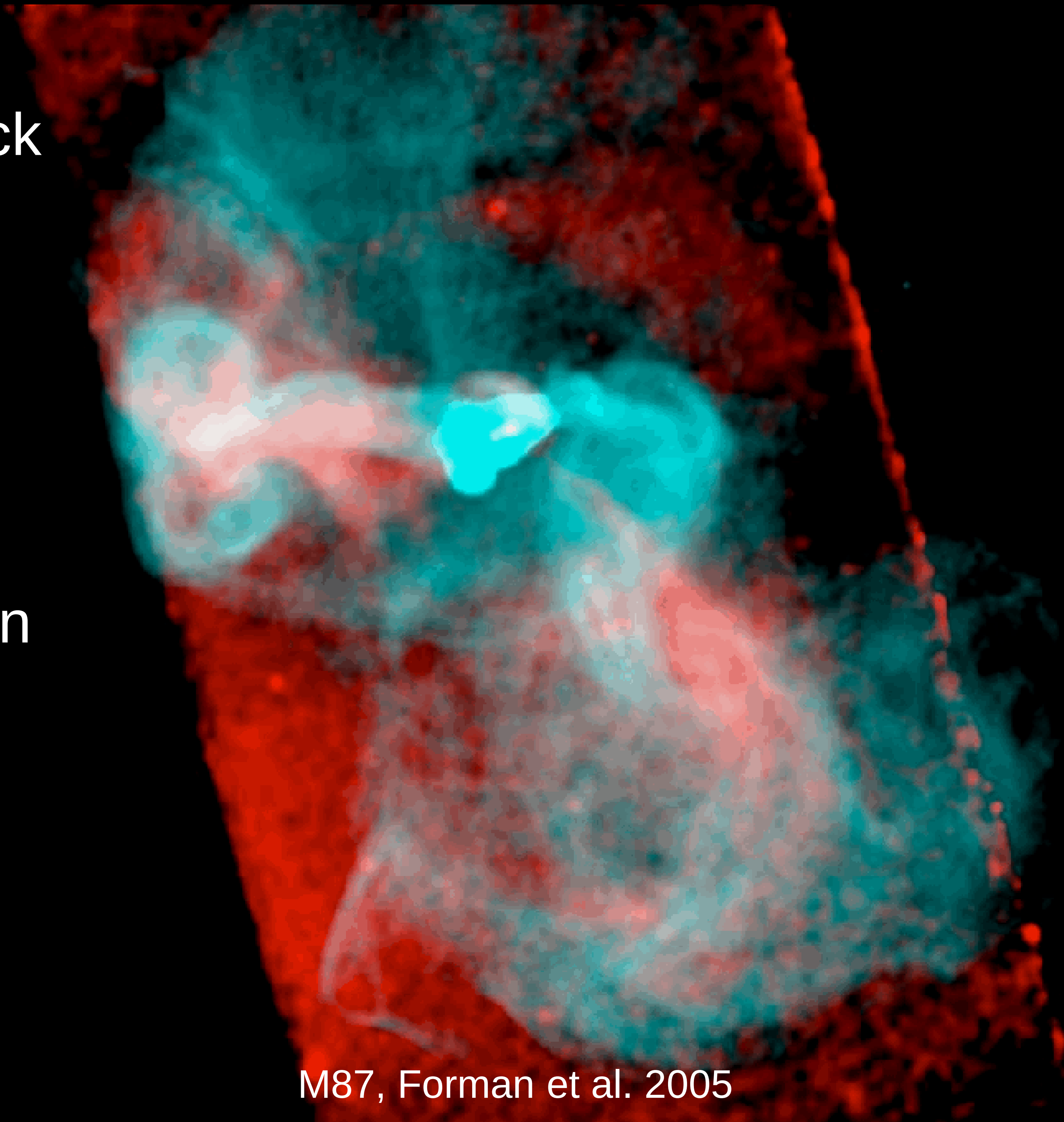
- Sebastian Heinz, UW-Madison
- <u>Sam Friedman, UW-Madison</u>
- Eugene Churazov, MPA

Multi-phase?

- “Effervescent heating by lots of small bubbles”?
- Shredding of plasma?
- Mixing by turbulence?

Radio plasma in galaxy clusters

- Central supermassive black holes:
  - 10^9 solar masses
  - Every big galaxy has one
- Copious plasma production
- Manifestation:
  - "Radio lobes"
  - buoyant bubbles
  - "NATs, WATs"



M87, Forman et al. 2005

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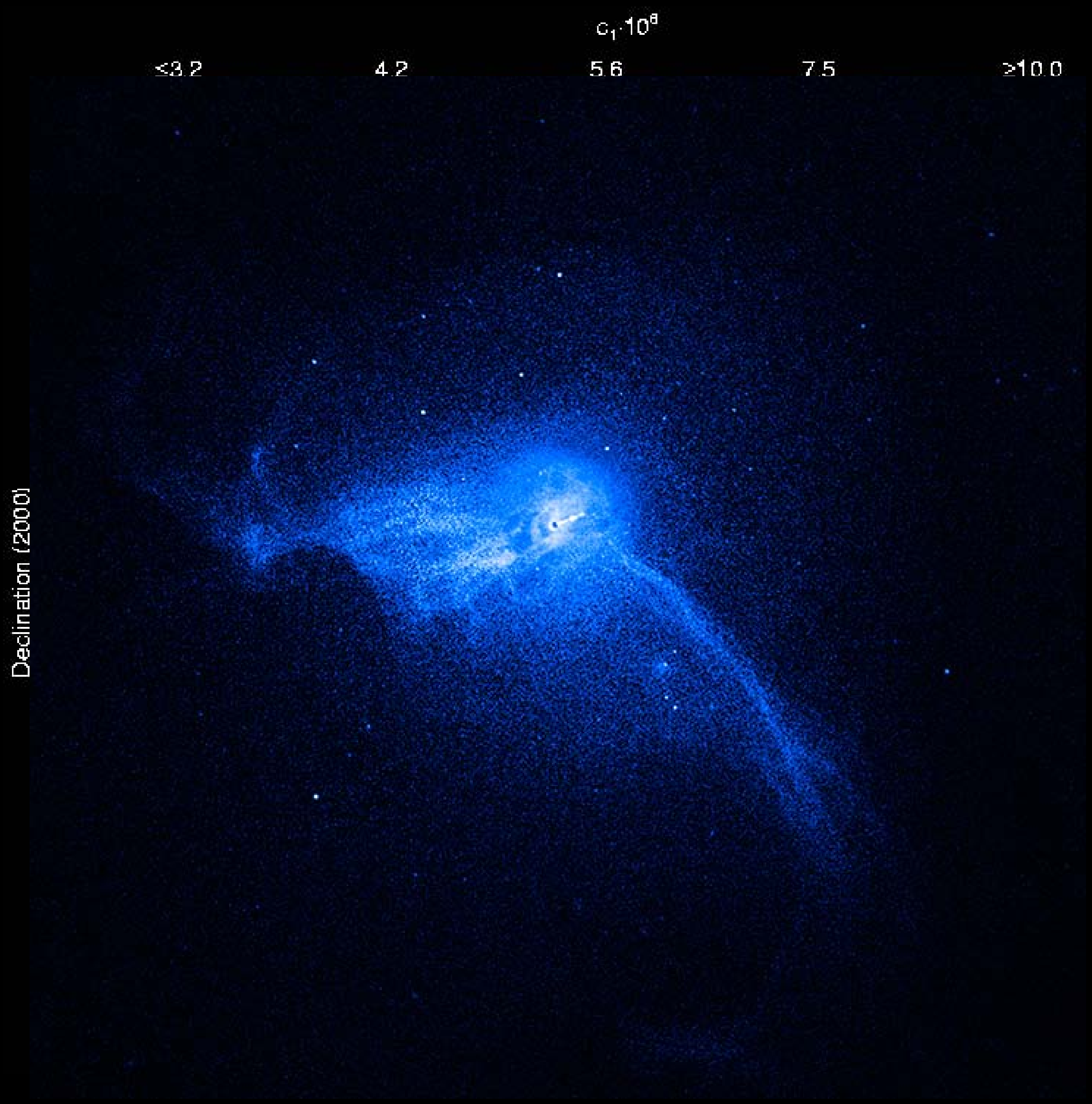

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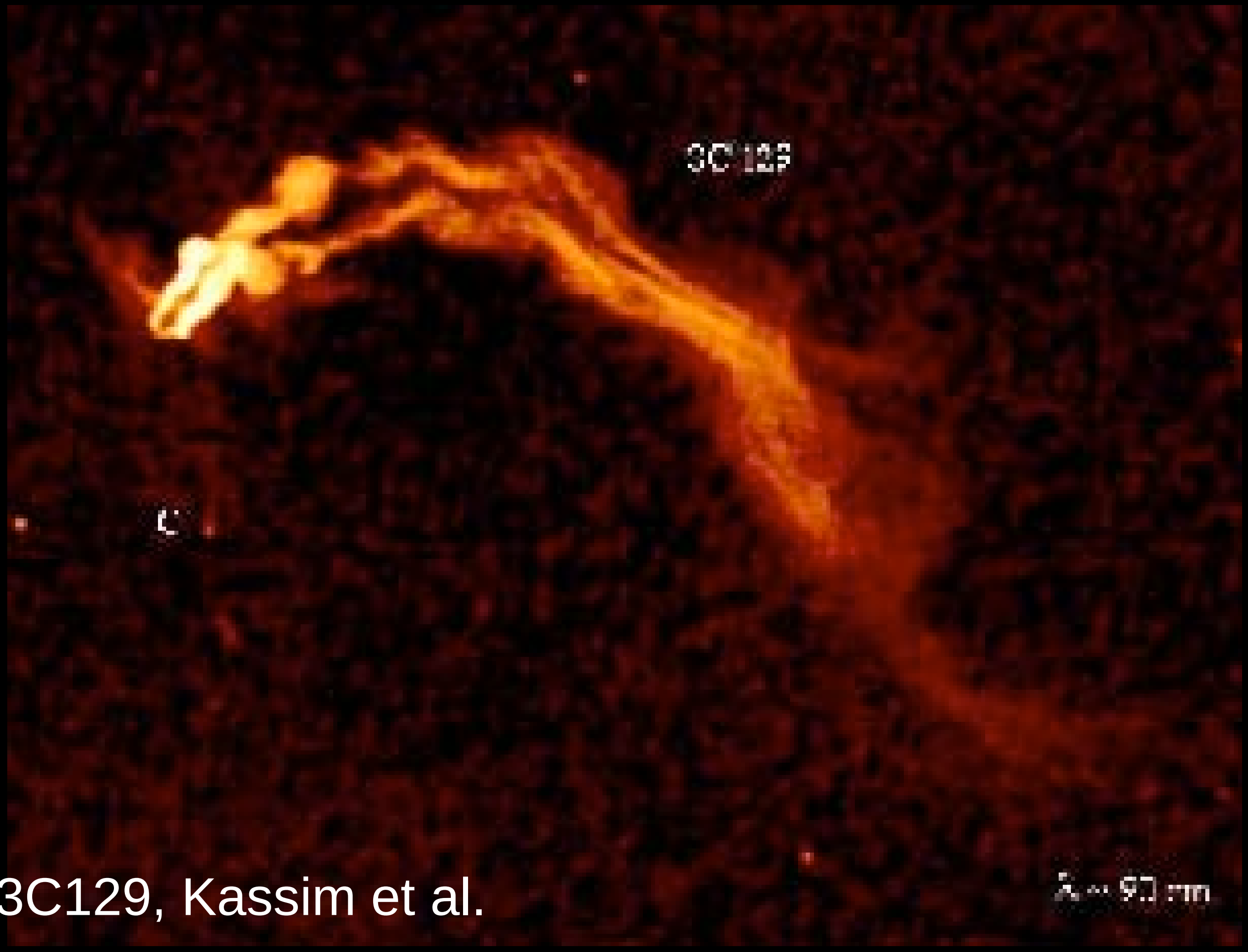
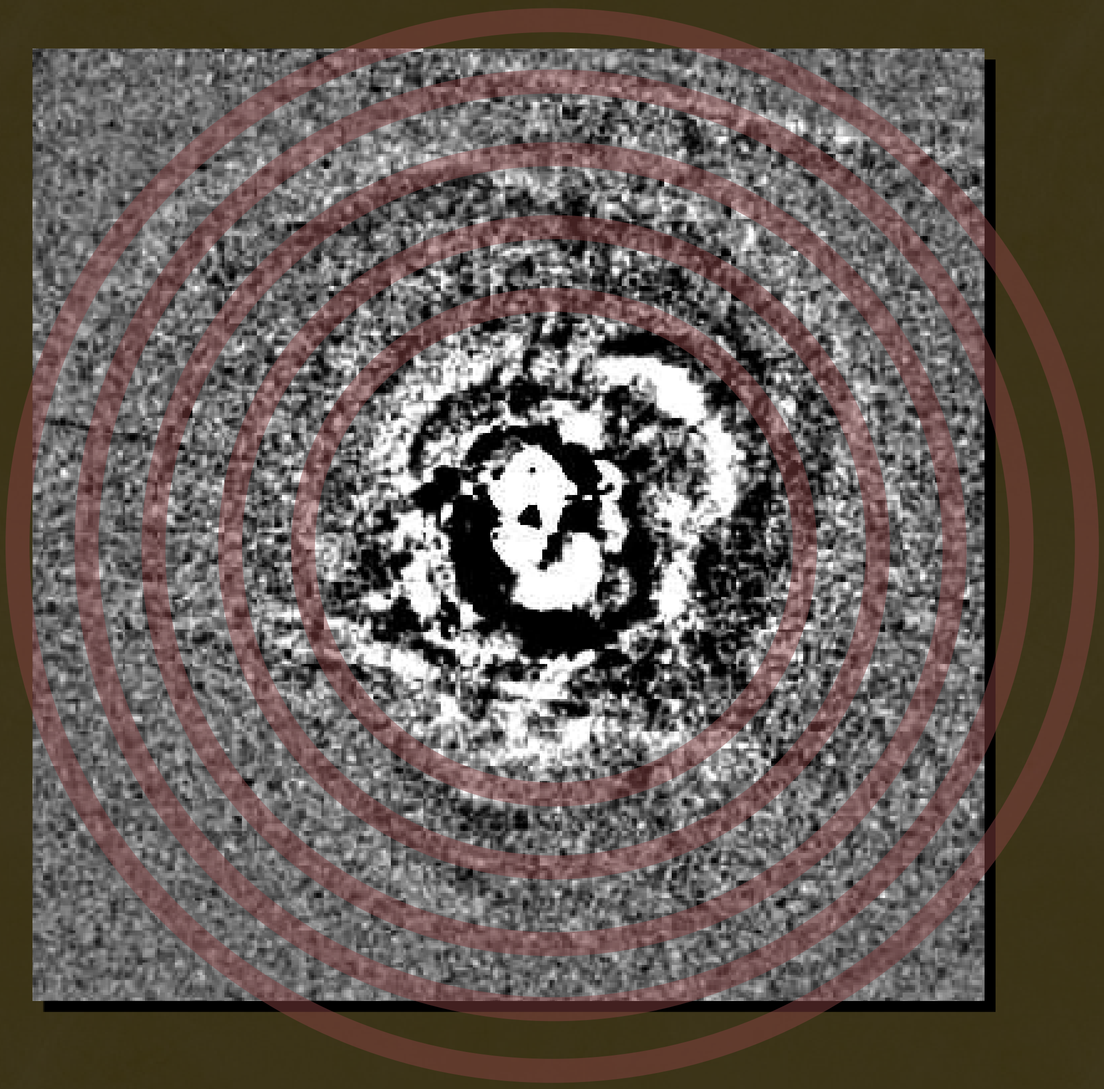


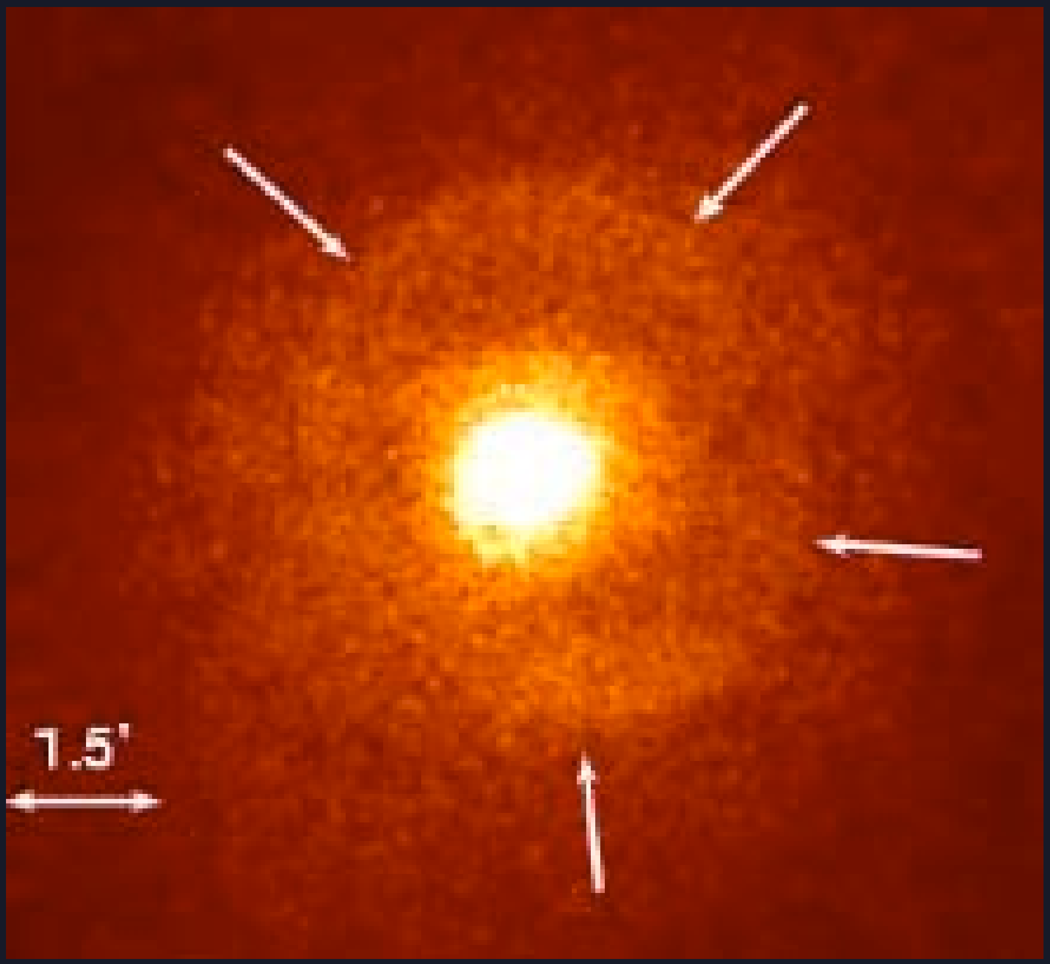
3C129, Kassim et al.

waves in clusters



Perseus cluster, Fabian et al. 2003

Sound waves: W > 10^{45} ergs s^{-1}

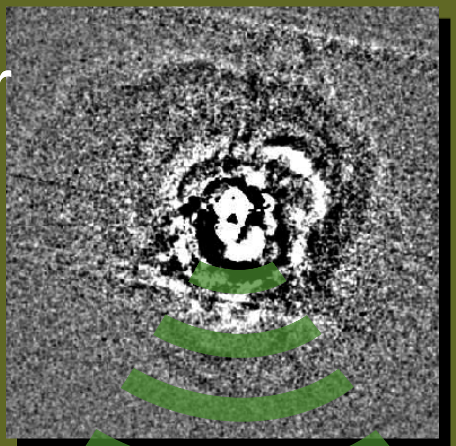


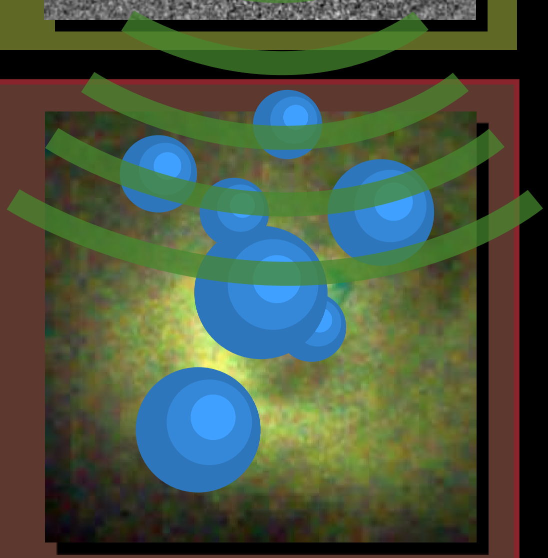
Forman et al. 2007

Shock waves: Mach 1.2

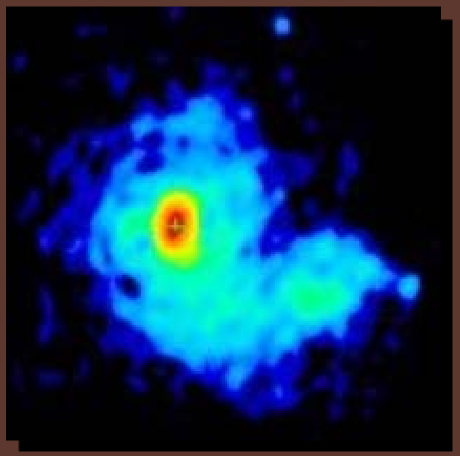
Waves + bubbles

- Wave Energy: ~ 25% of BH power
  - Where does it go?
  - Viscosity?

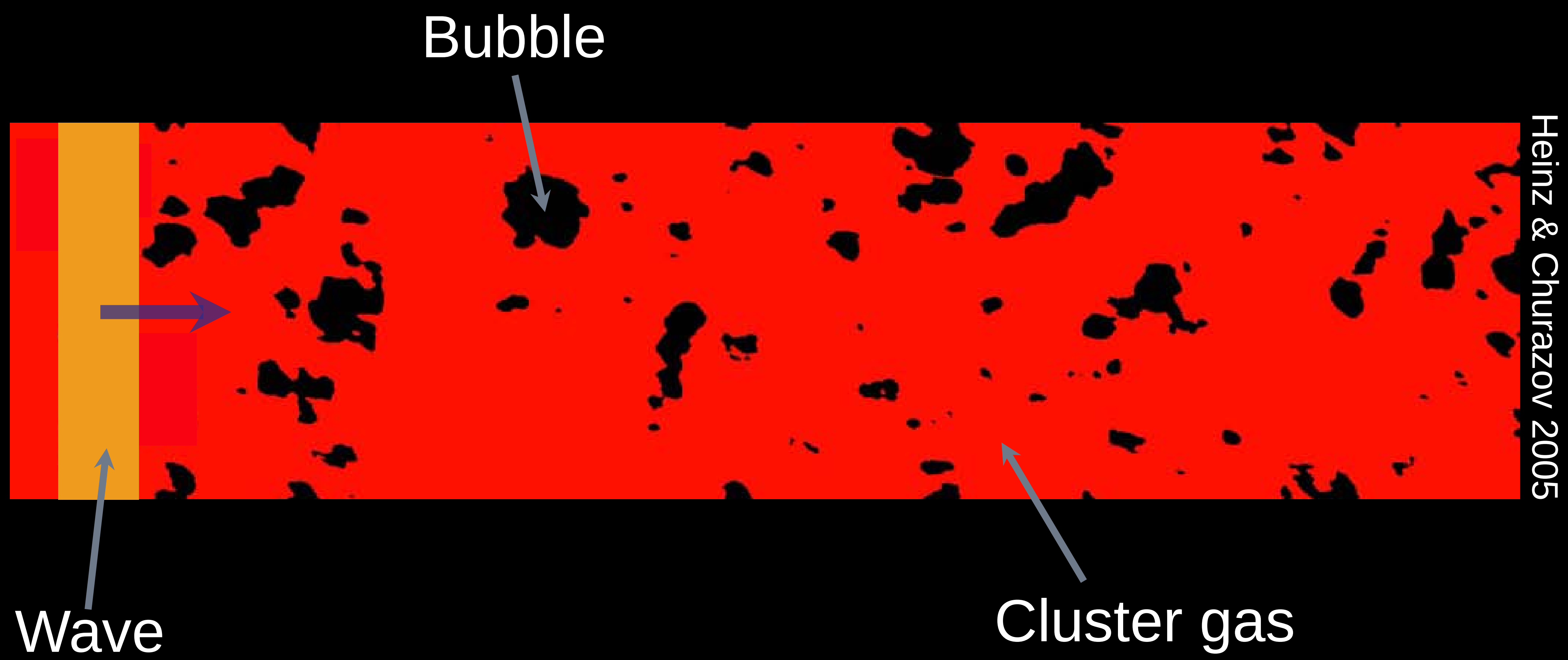




- X-ray cavities / radio bubbles
  - Relativistic gas
  - $c_s \approx 60\% \ c$
  - Low density
  - Appreciable filling factor
  - Filamentary

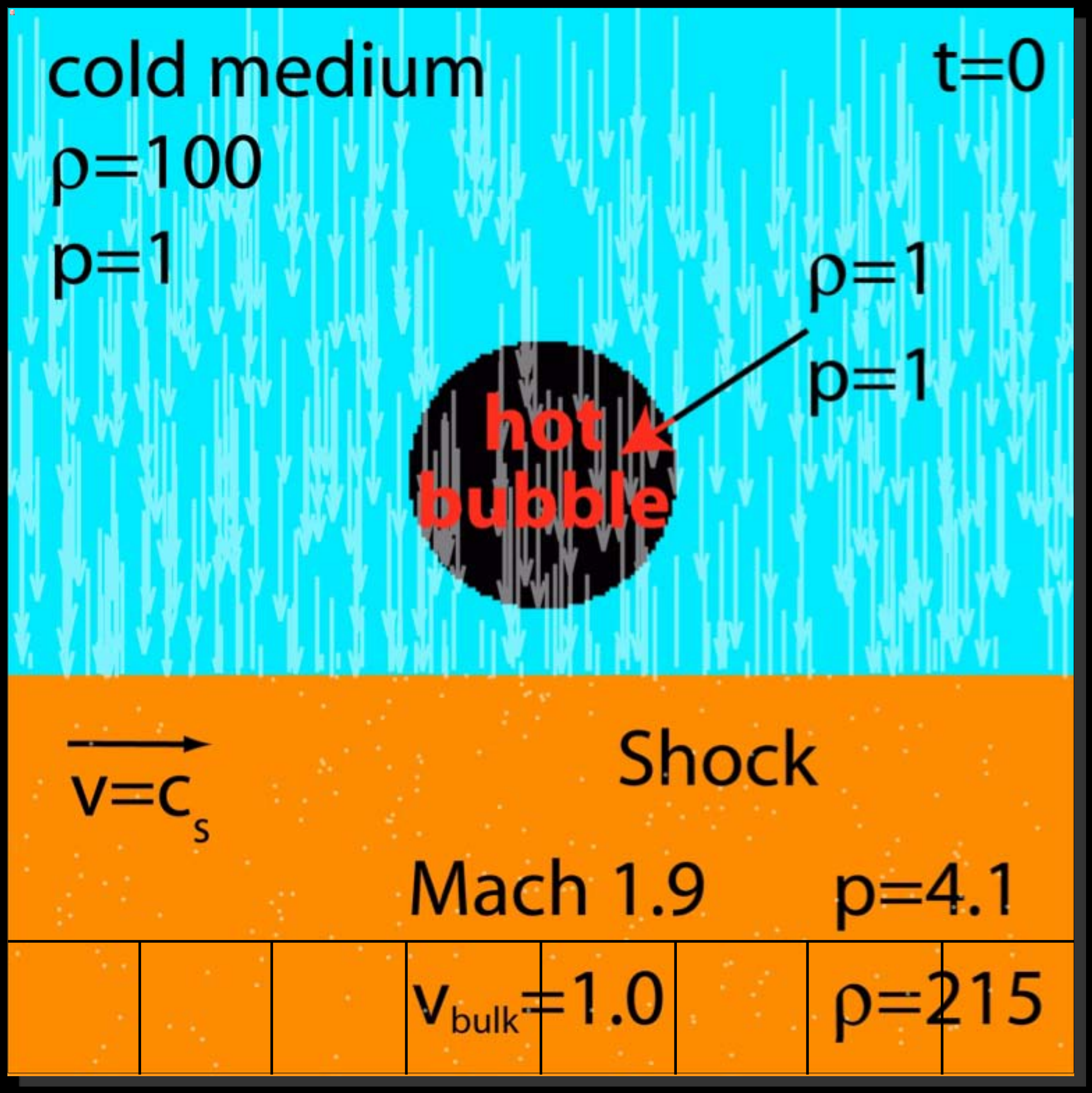


THE INTERACTION OF WAVES AND BUBBLES



Toy cluster

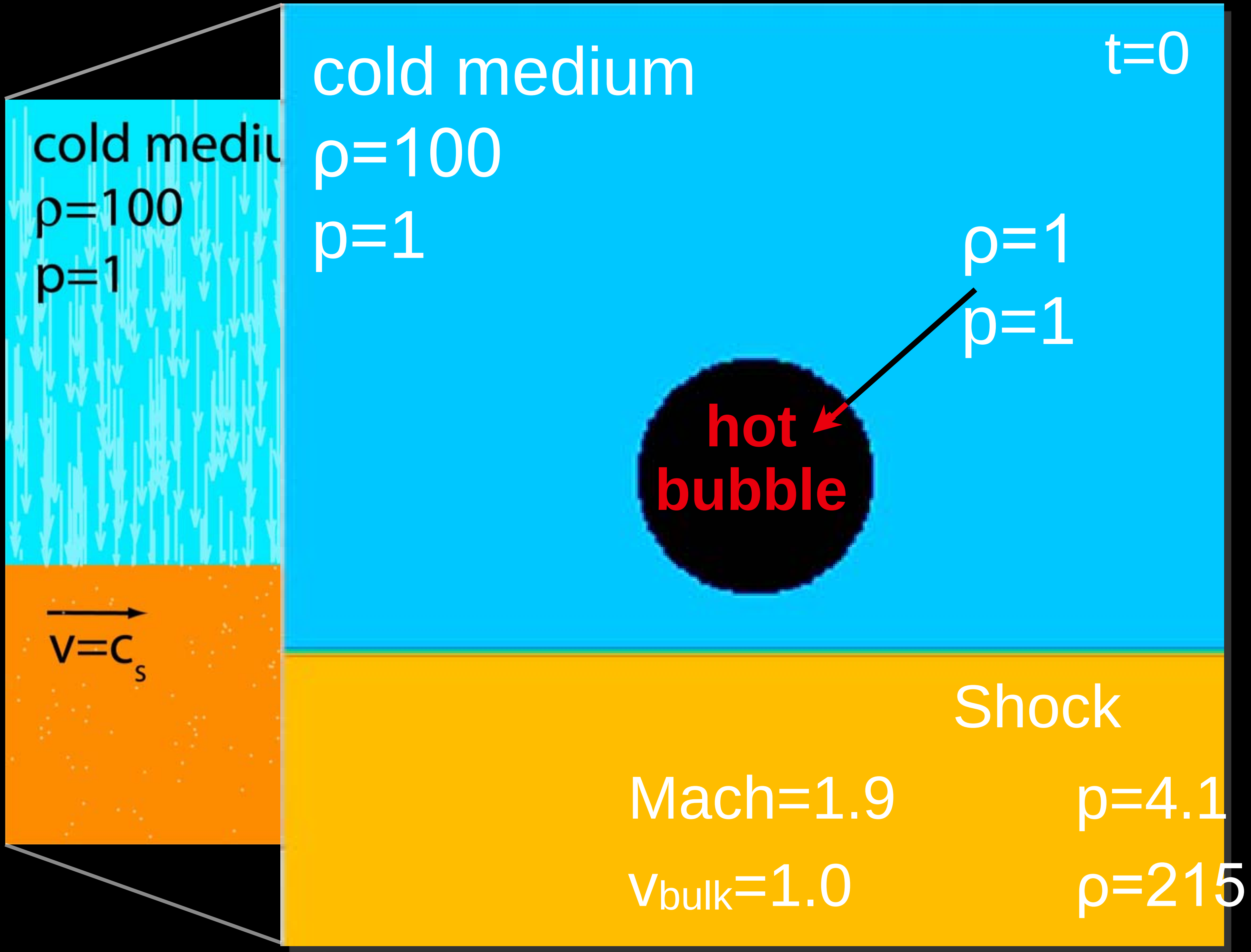
THE INTERACTION OF WAVES AND BUBBLES



Heinz & Churazov 2005

- 2D & 3D hydro simulations
- 2D & 3D MHD
- FLASH3 code:
  - Adaptive Mesh Refinement
  - 2nd order accurate
  - Public (ASCI center @ UChicago)
  - Fryxell et al. 2000

THE INTERACTION OF WAVES AND BUBBLES



Heinz & Churazov 2005

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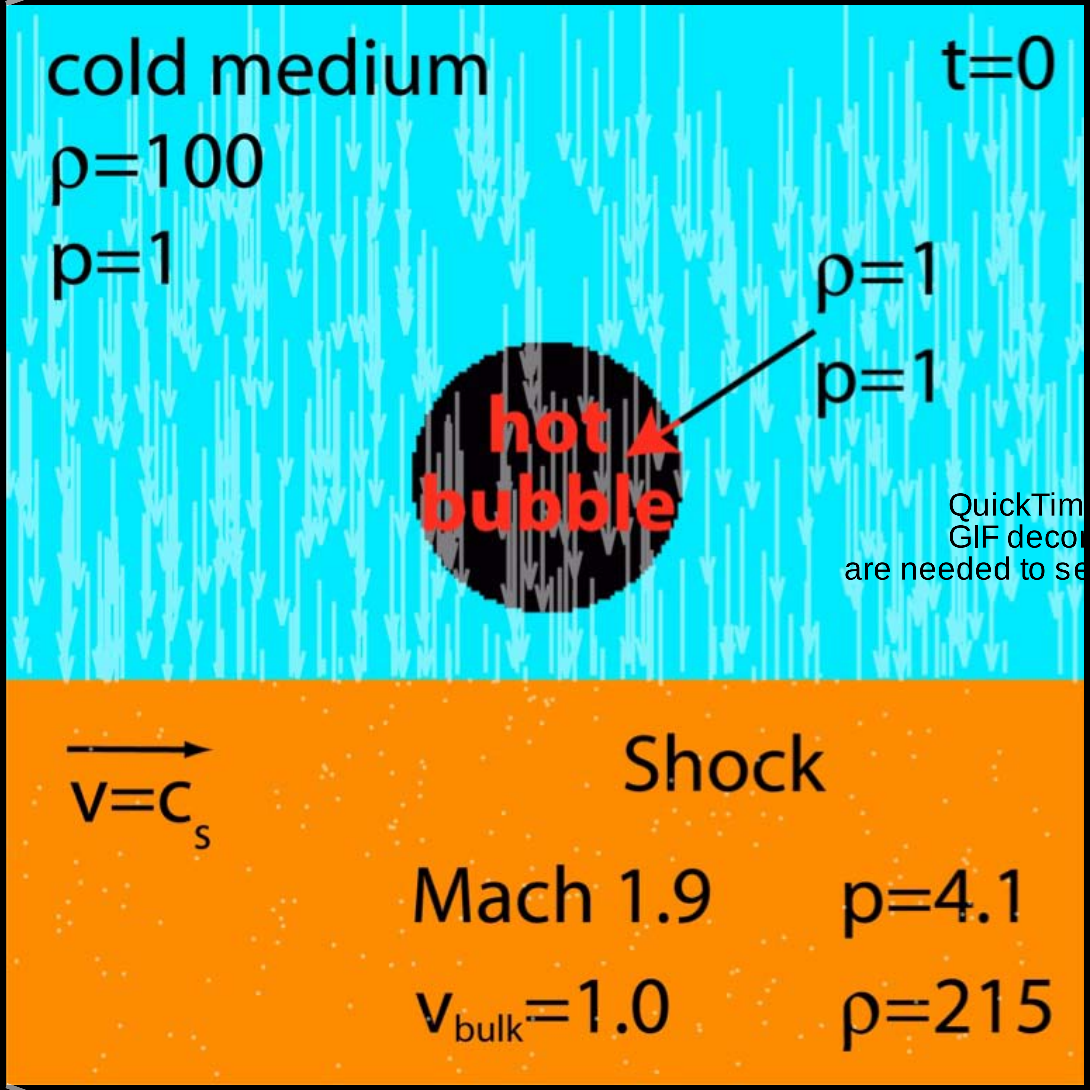

Heinz & Churazov 2005

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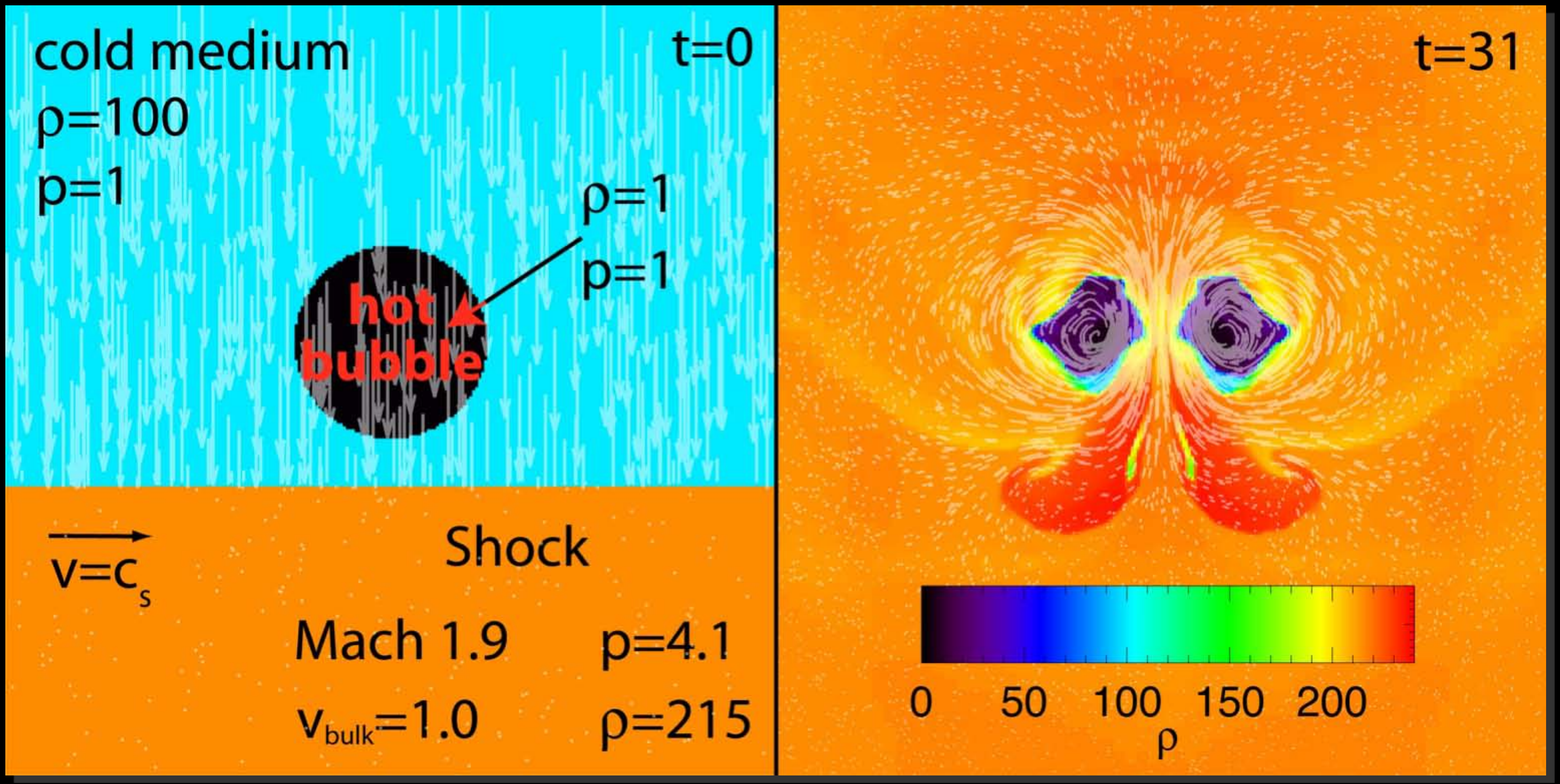
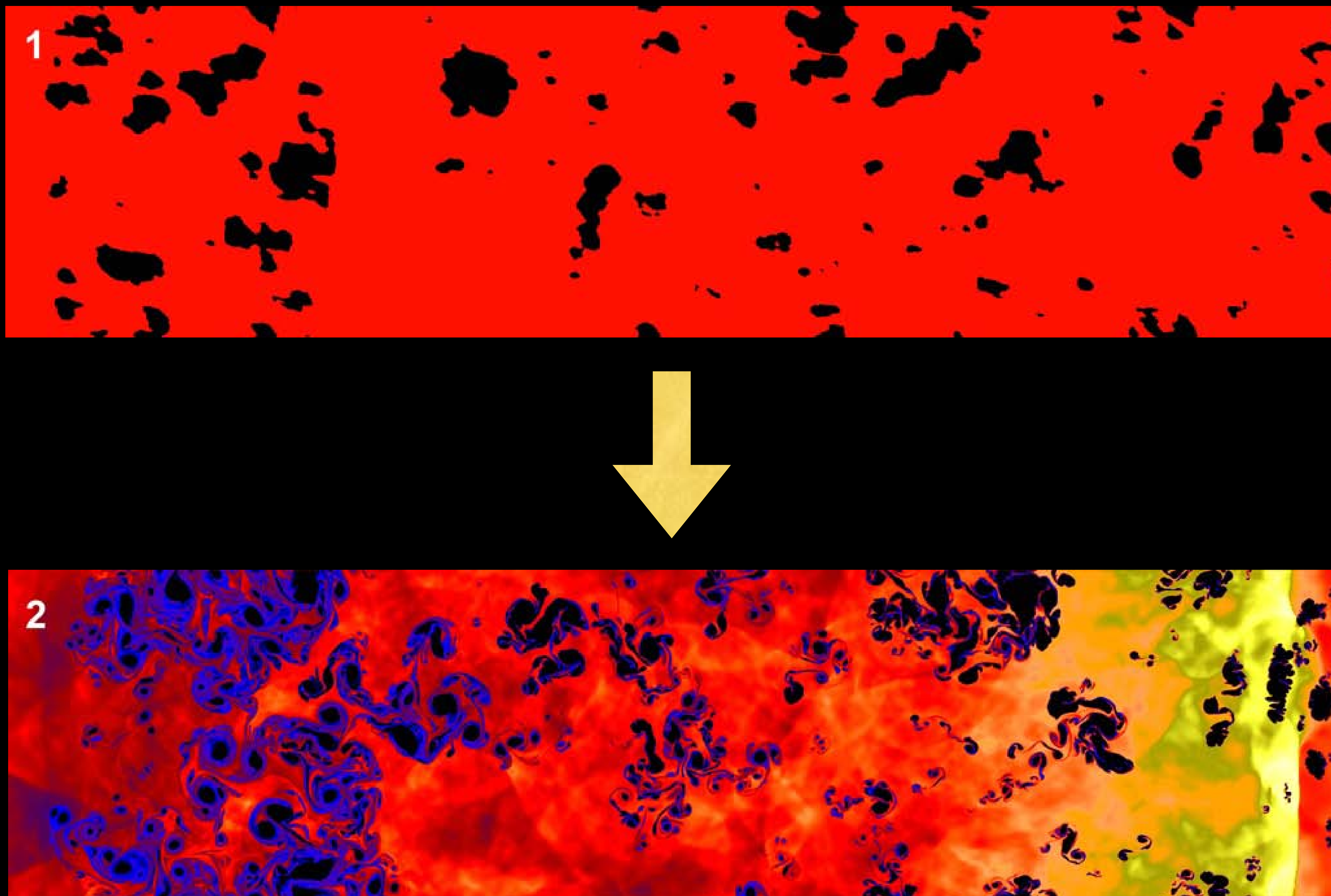


Heinz & Churazov 2005

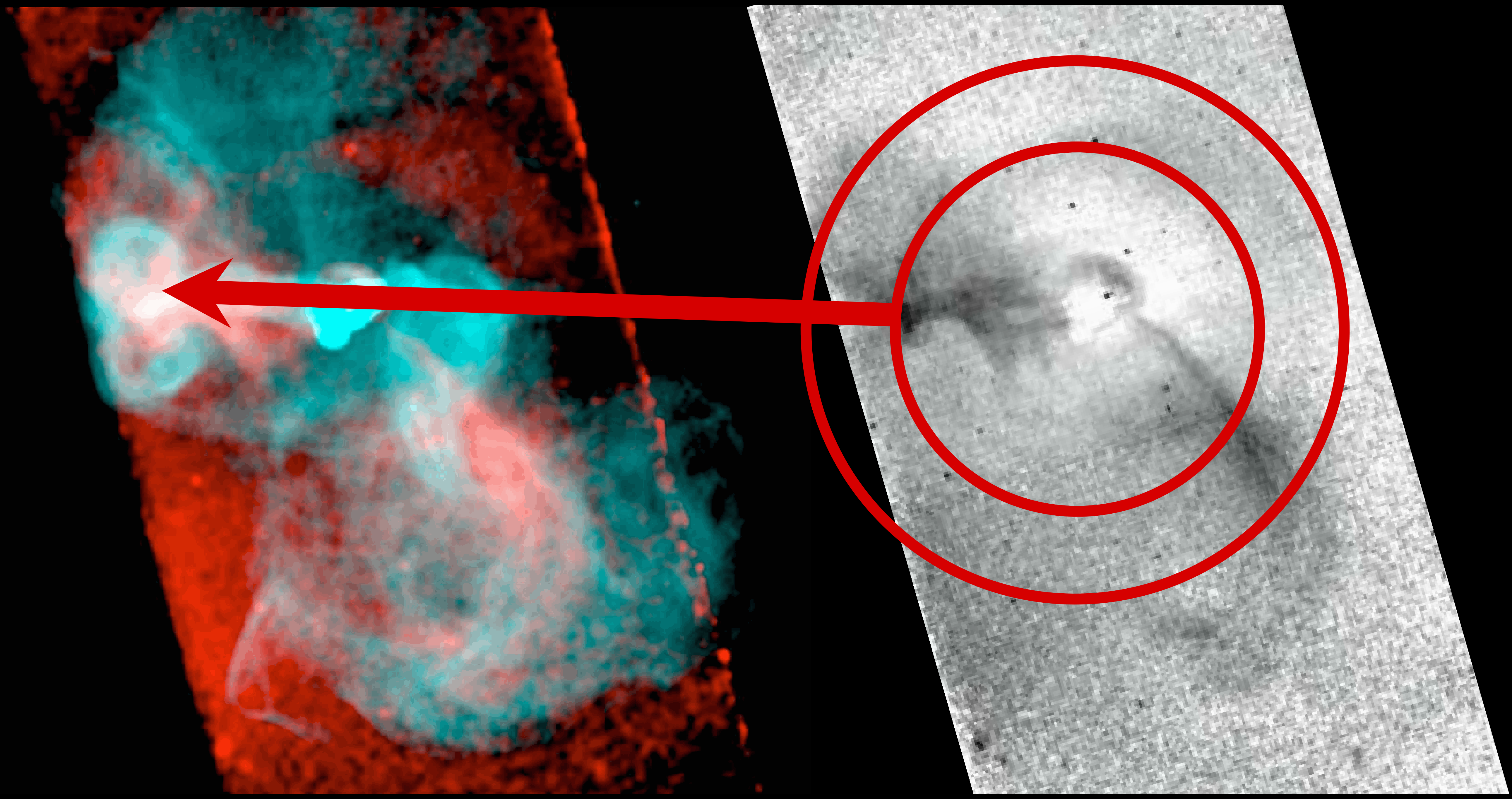
"*Richtmyer-Meshkov*" instability

THE INTERACTION OF WAVES AND BUBBLES



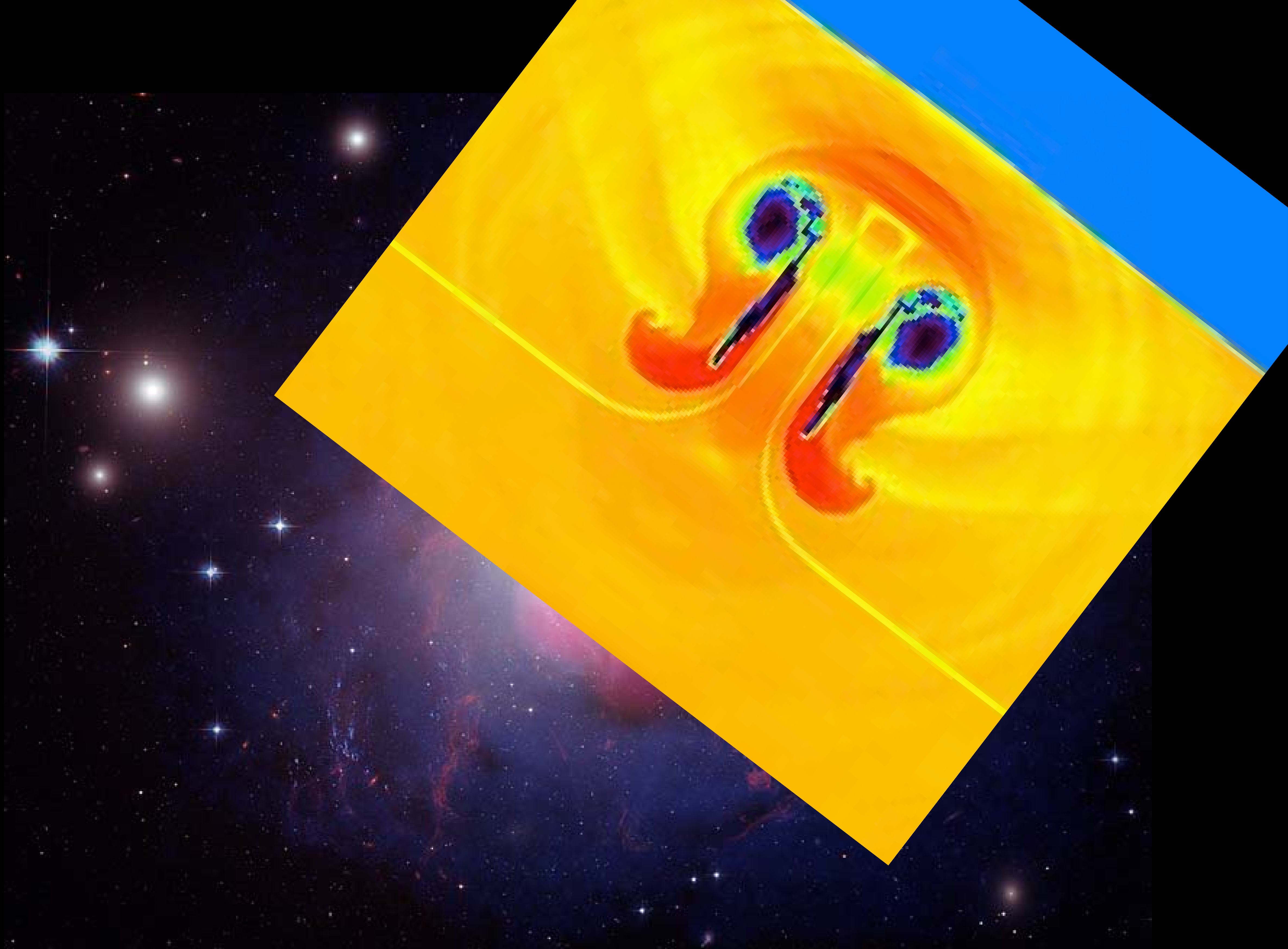
Heinz & Churazov 2005

Evidence For RMI?

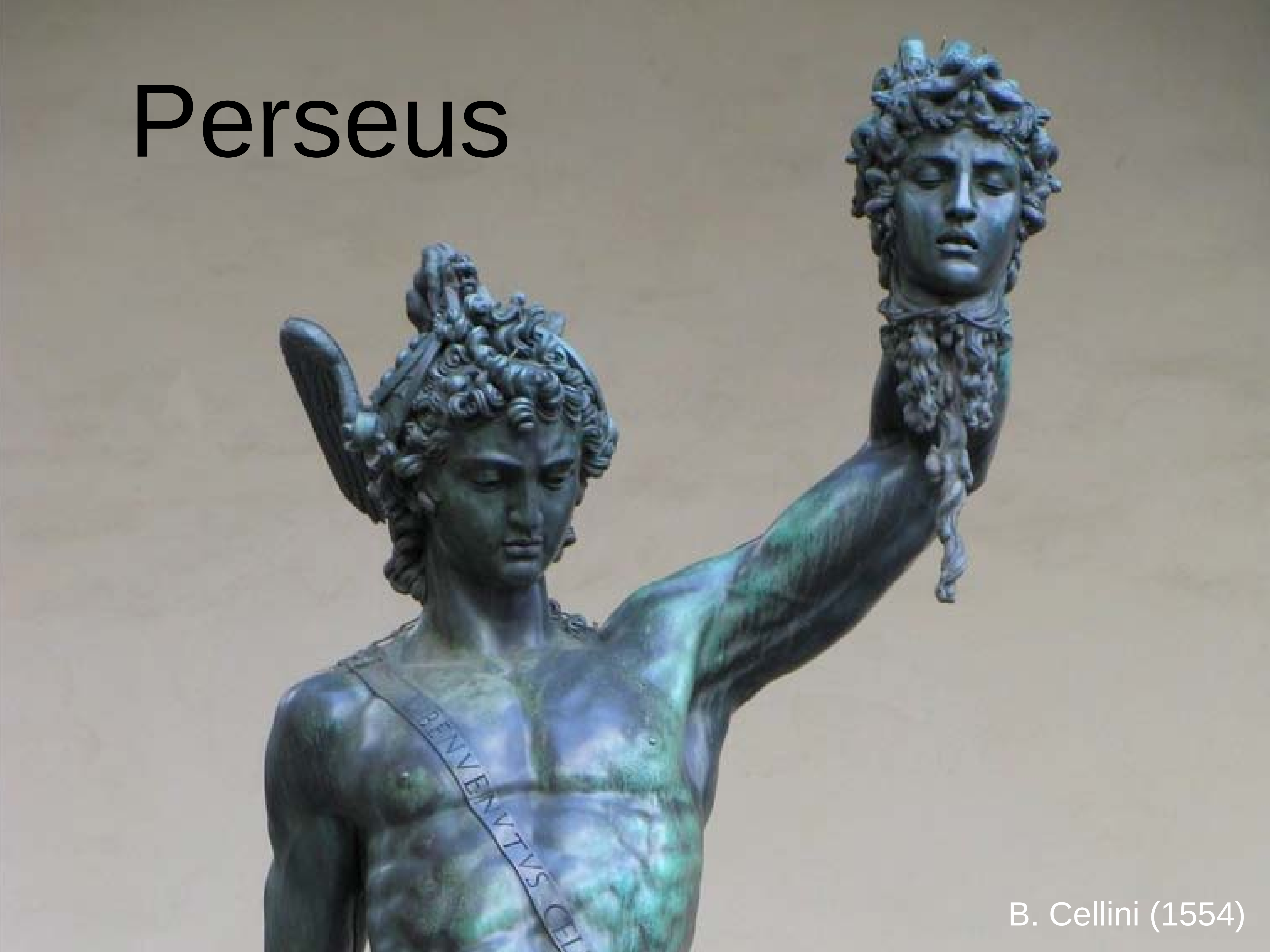


Forman, Nulsen, Heinz, et al. 2005

Filaments?



Perseus



B. Cellini (1554)

Vorticity Generation

- We reconstruct the solenoidal component of the velocity $v_{\rm r}$ using a spectral Helmholtz decomposition

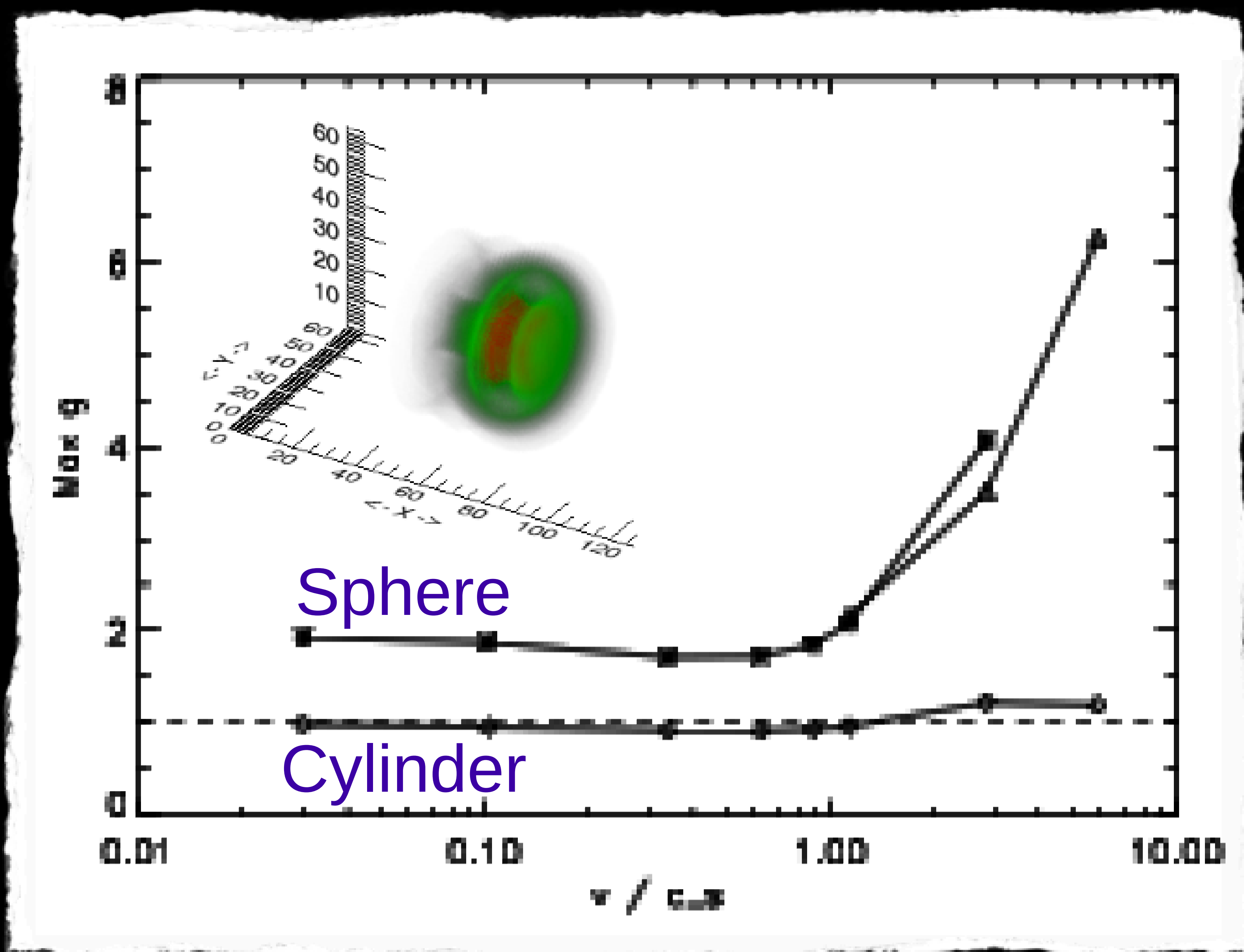
- We define the vortex energy associated with V_r as

$$E_{\rm rot} \equiv \int dV \left(\frac{v_{\rm rot}^2}{2} \rho \right) \approx V_{\rm bubble} \cdot \left(\frac{v_{\rm wave}^2}{2} \rho_{\rm IGM} \right) \cdot g$$

- We define g as the efficiency (similar to an oscillator strength)

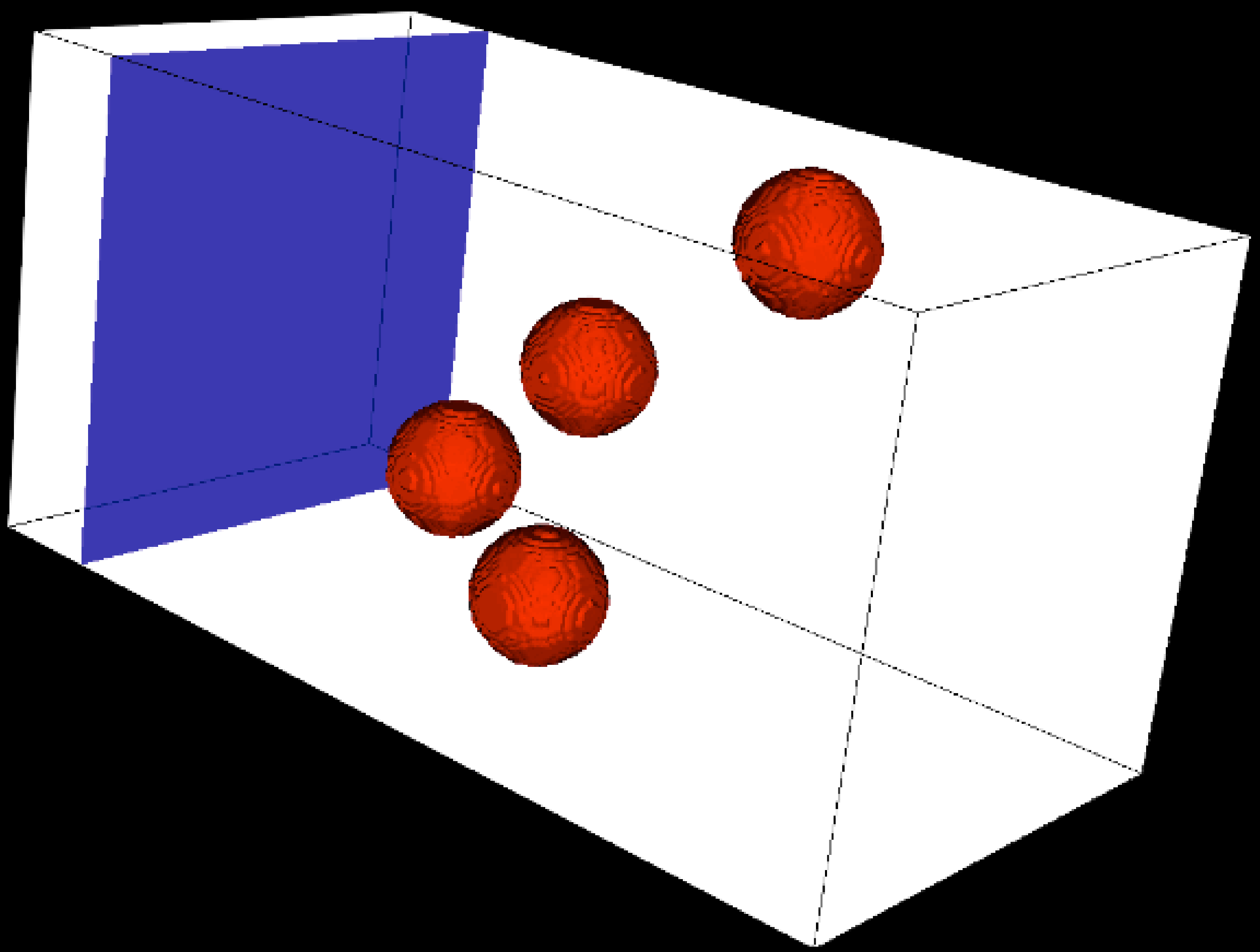
- Fiducial back-of-the envelope estimate: g=1.

3D : 2x more efficient



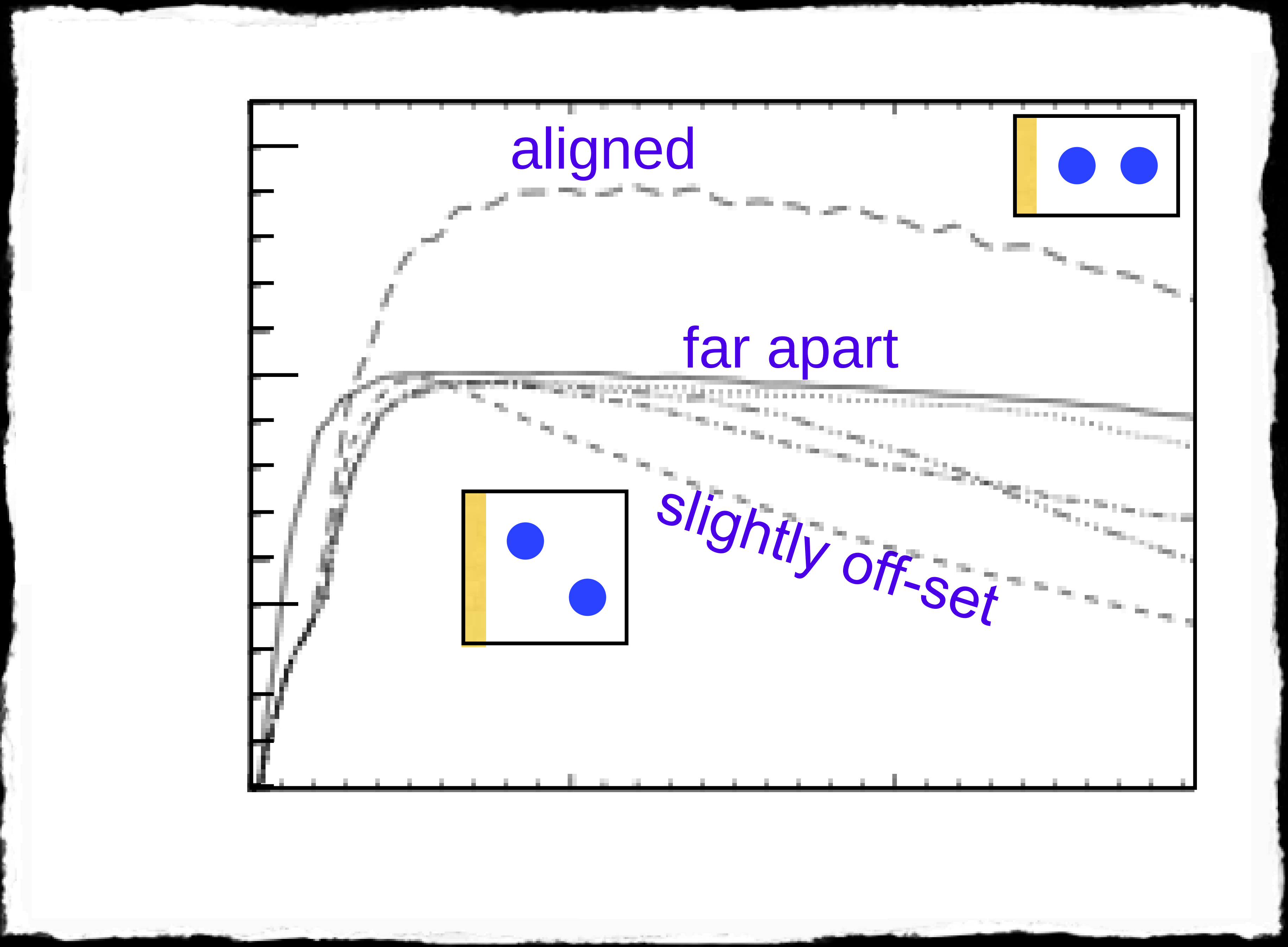
Friedman et al. 2010

Non-linear Interaction



2010, in prep

Non-linear evolution



Viscous dissipation

- Bubble size requirement to heat typical cooling flow:

$$R < \mathrm{kpc}\sqrt{\frac{\epsilon}{10\%}\,\frac{\nu}{\nu_{\mathrm{Spitzer}}}}$$

- Assumption:
  - ★ Sufficient amount of energy in wave field
  - ★ AGN can provide the energy & plasma for this

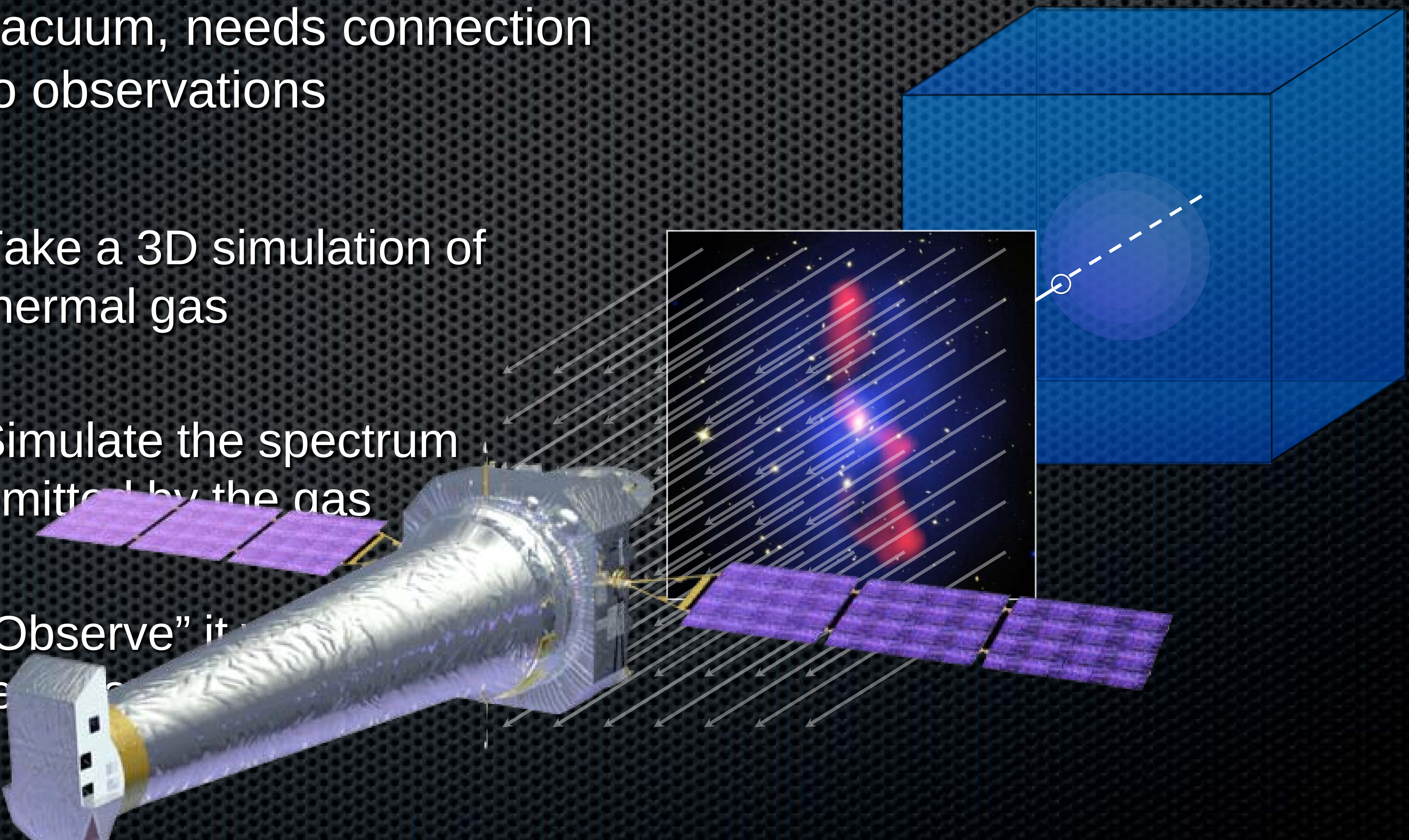
Interface: simulations/observations

- A simulation is useless in vacuum, needs connection to observations

1. Take a 3D simulation of thermal gas

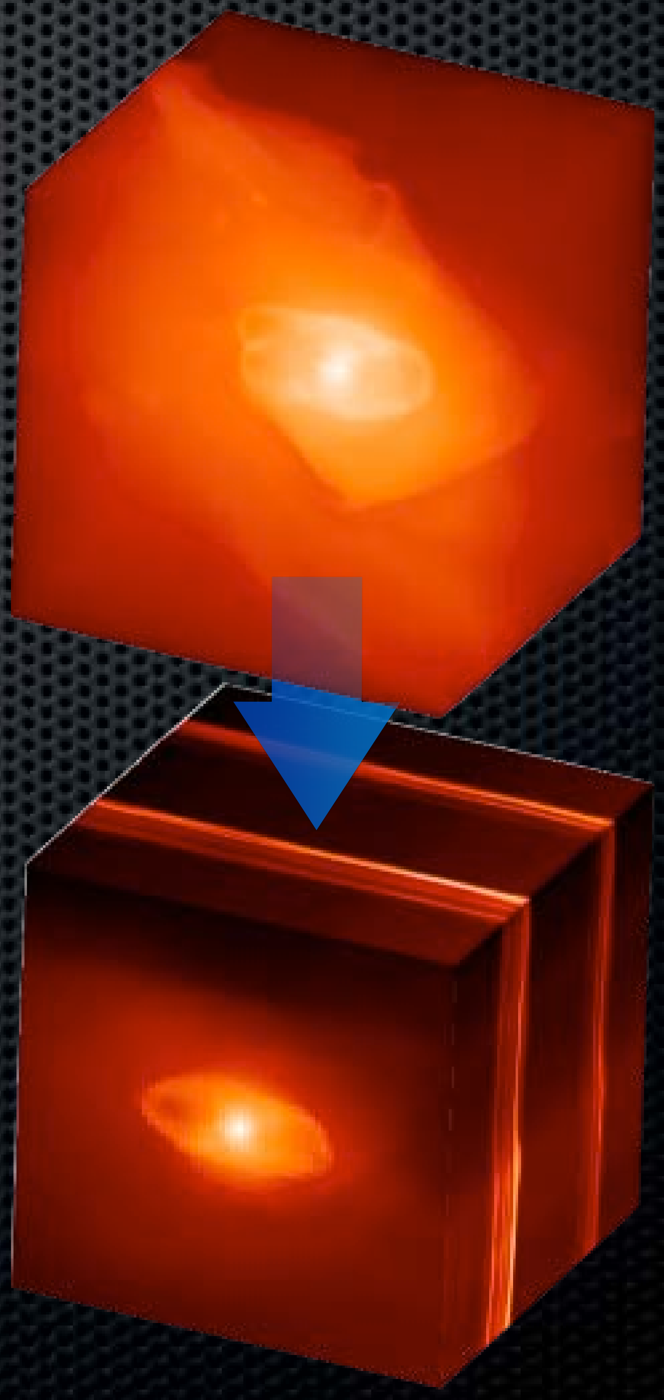
2. Simulate the spectrum emitt… by the gas

3. “Observe” it … te…



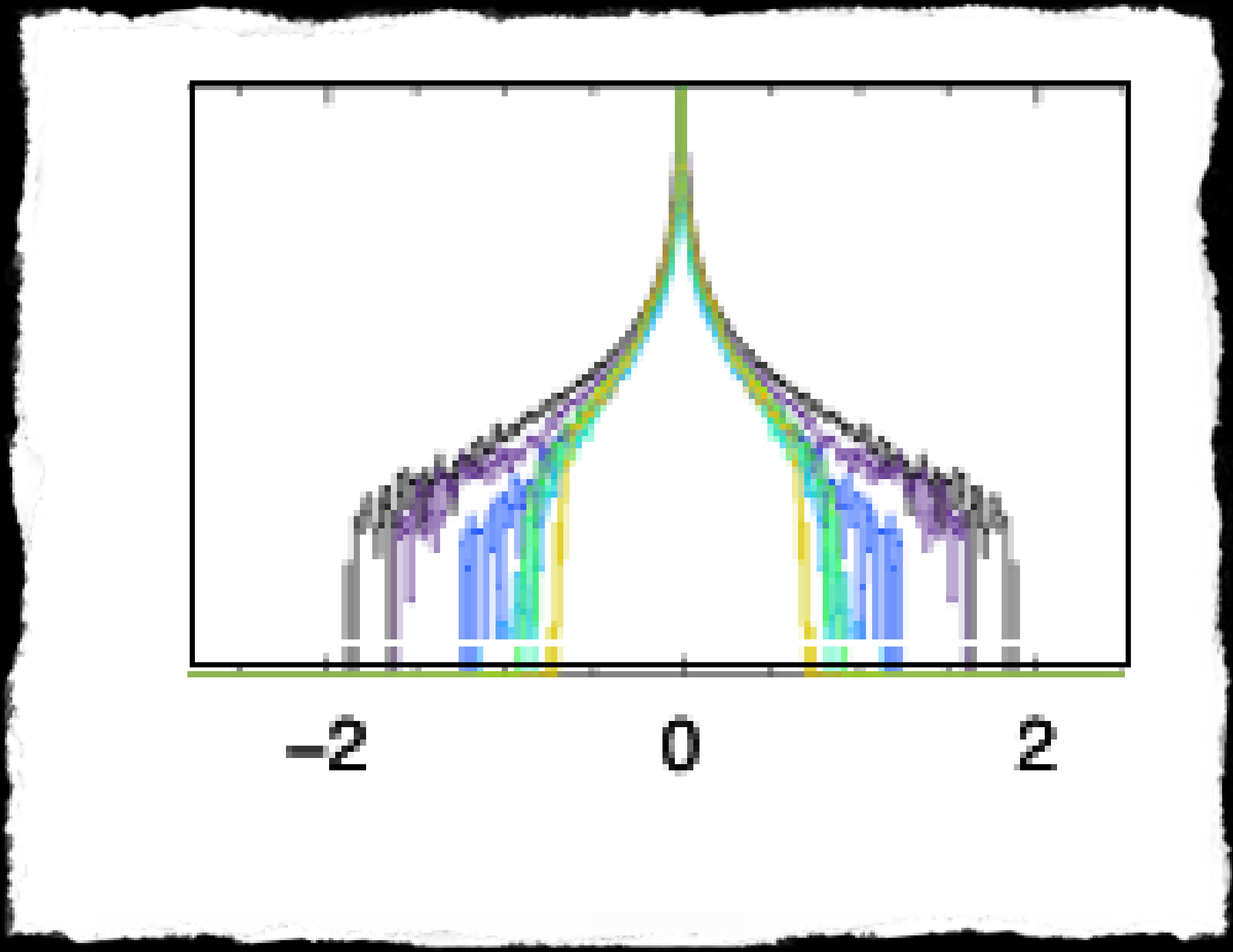
XIM: A virtual X-ray observatory for numerical simulations

1. 3D Input: $n_e n_H$, T, velocity, metallicity, filling factor
2. Thermal emission (APEC + thermal broadening)
3. Line-of-sight integration along arbitrary vector
4. Telescope PSF convolution
5. Convolution with instrument response
6. Add blank sky & instrument background
7. Add Poisson noise
8. *Optional*: Interface with MARX (Chandra only)
9. Output FITS events file, pha file



The vortex profile

- Test dynamics observationally
- Prediction:
  - ★ Lorentzian @ 90°



Summary

- Multi-phase gas subject to RM instability
  - Can greatly increase level of turbulence
  - In simplest case, efficiency of energy extraction from steepened waves up to 200% of fiducial efficiency
  - Non-linear interaction reduces efficiency
- In clusters:
  - Small bubbles are more efficient at dissipation
  - Line profile: Modified Lorentzian

Summary

- Multi-phase gas subject to RM instability
  - Can greatly increase level of turbulence
  - In simplest case, efficiency of energy extraction from steepened waves up to 200% of fiducial efficiency
  - Non-linear interaction reduces efficiency
- In clusters:
  - Small bubbles are more efficient at dissipation
  - For effective dissipation, need bubbles smaller than ~ kpc