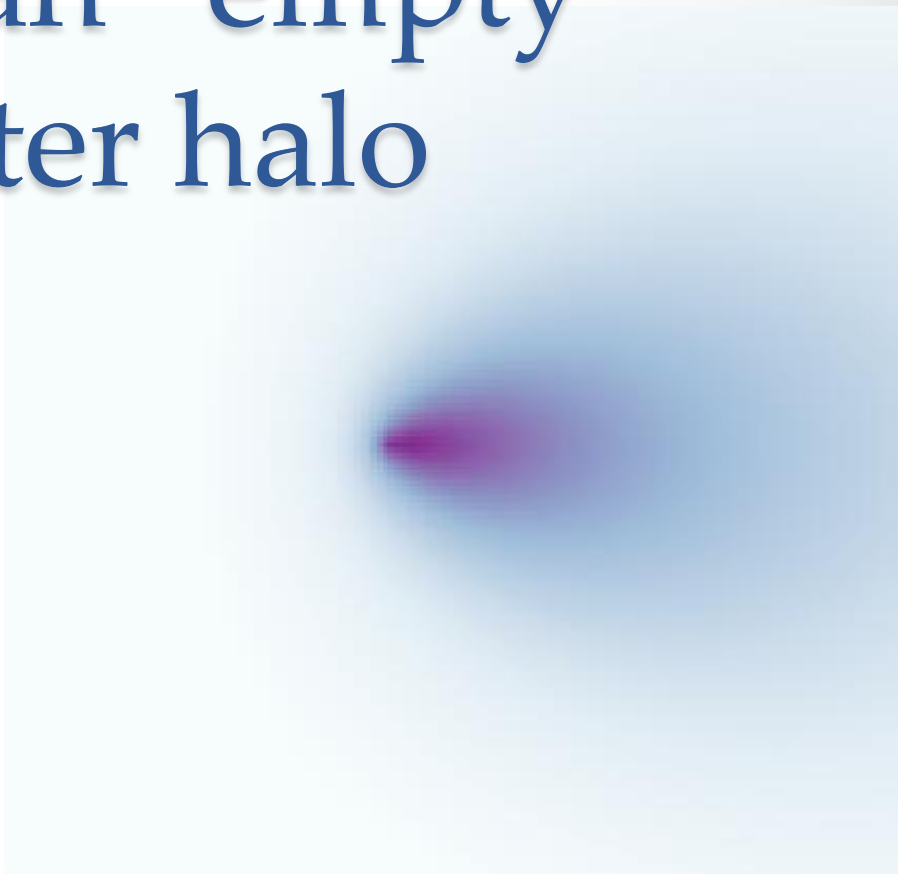
Flow of the intracluster plasma past an “empty” dark matter halo



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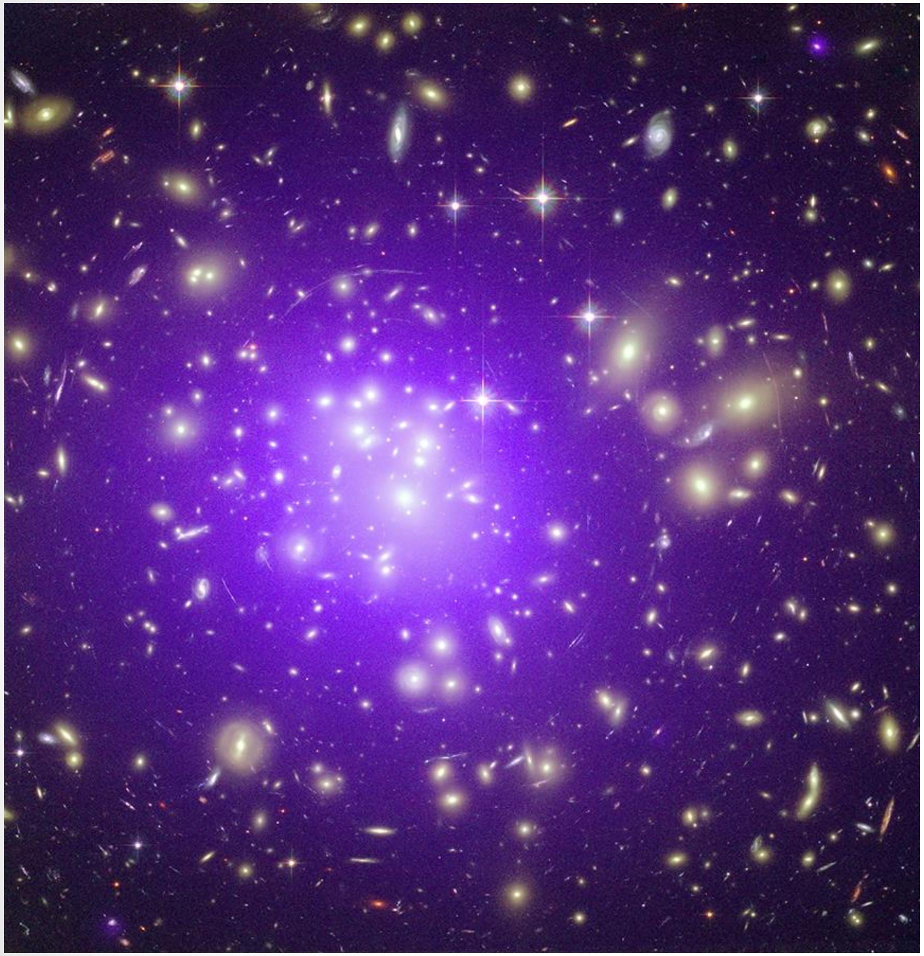
Galaxy clusters: basic properties

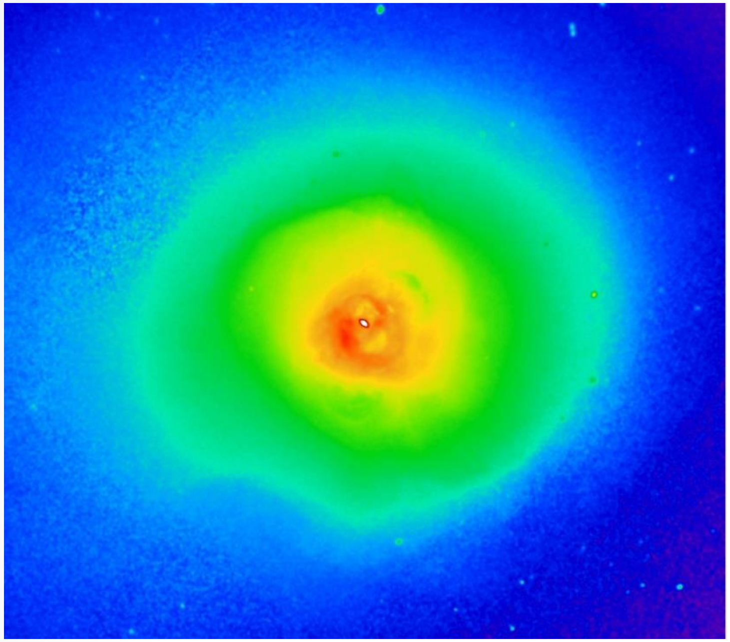


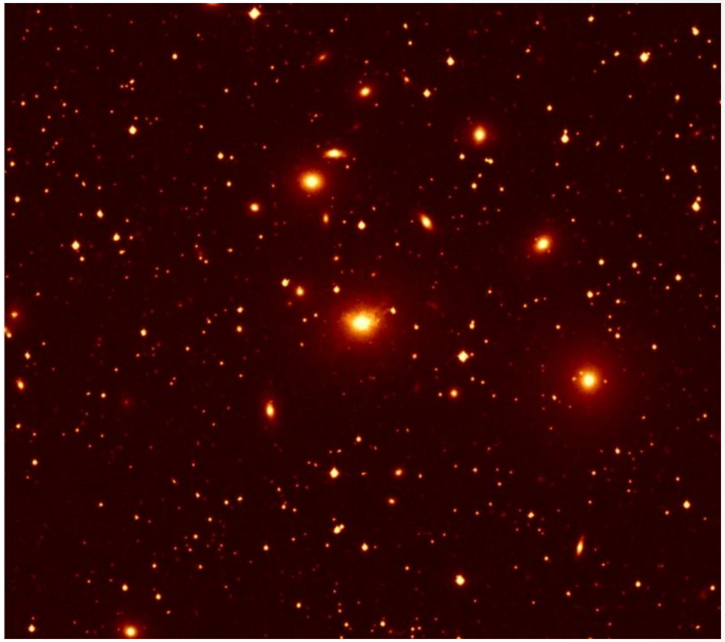
A1689
X-ray: NASA/CXC/MIT/E.-H Peng et al;
Optical: NASA/STScI

- 10^{14}-10^{15} $M_\odot$: 100-1000 galaxies
- ~85% dark matter
  ~10% hot gas
  ~5% stars
- L ~ few Mpc
- n_{gas} ~10^{-3} cm^{-3}
  T_{gas} ~1-10 KeV

bremsstrahlung
X-ray emission $\propto n_e^2$

Galaxy clusters: galaxies

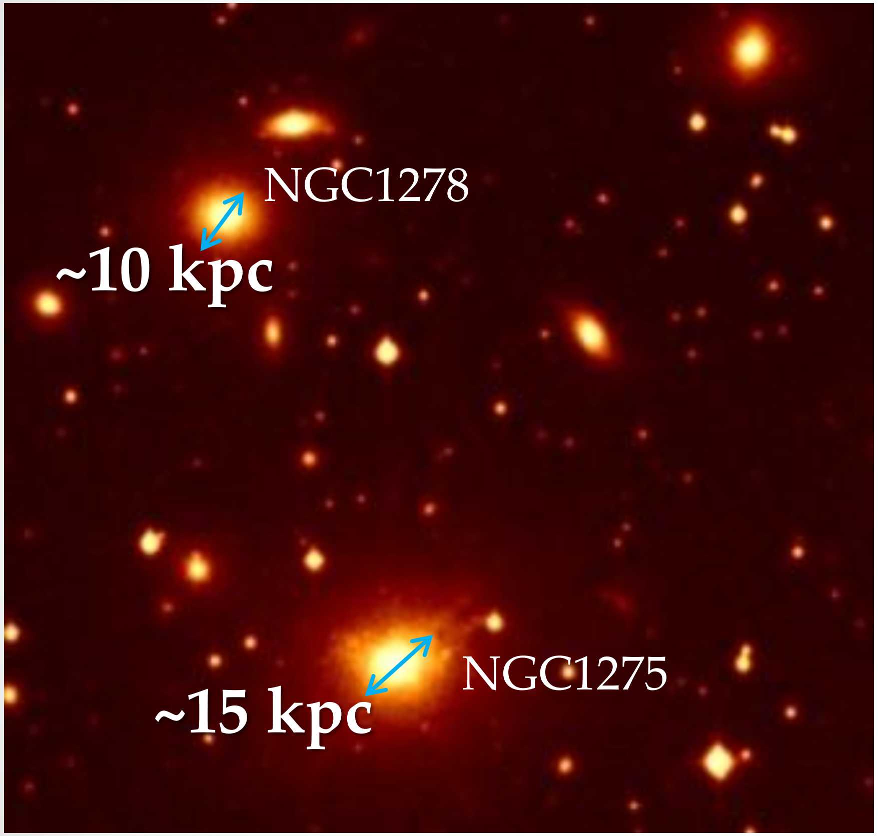




X-ray and optical images of the central 320-kpc region of the Perseus cluster

- Velocity dispersion ~1000 km/s – virial velocity of clusters
- Mostly populated by ellipticals
- Circular speed varies from 20 to 400 km/s

Size of galaxies and mean free path



optical size of the giant ellipticals NGC1275 and NGC1278 in the core of the Perseus cluster

- Dark matter halo

$$\rho(r) = \frac{\rho_0}{r/R_s(r/R_s+1)^2}$$

Navarro-Frenk-White profile

Rs – scale radius, ~1-10 kpc

- Mean free path in the ICM

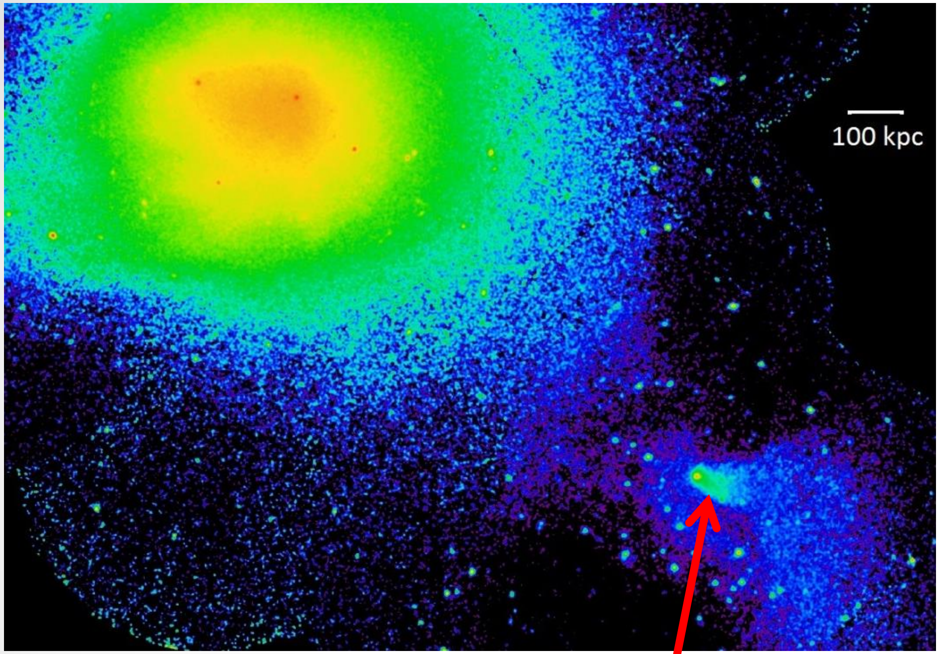
$$\lambda = \frac{3^{3/2}(kT)^2}{4\pi^{1/2} n e^4 \ln\Lambda}$$

Spitzer 1956

$$\lambda_e = 15\ \mathrm{kpc}\left(\frac{T_e}{7\ \mathrm{KeV}}\right)^2\left(\frac{n_e}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{-1}$$

- Cool dense cores: ~0.01 kpc
- Bulk: ~10-50 kpc

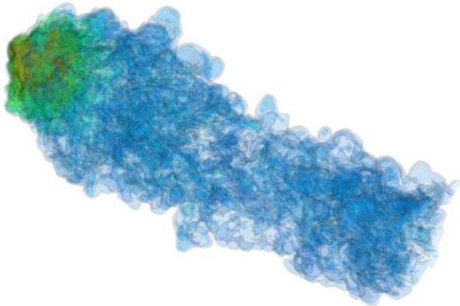
Galaxy clusters: galaxies



NGC 4839

A galaxy can lose its gas while moving through the ICM by:

1. Ram pressure stripping



e.g. Shin & Ruszkowski 2012

2. Tidal, turbulent and laminar stripping, evaporation

Many ellipticals do not have gas

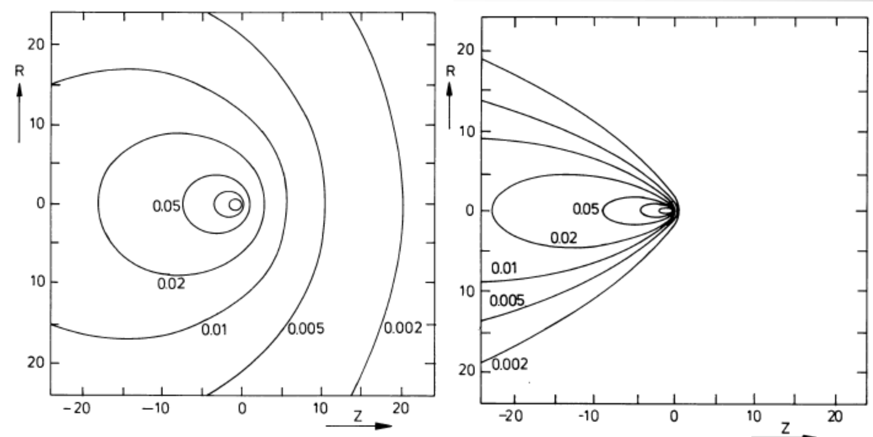
Dynamical friction

- As a galaxy deflects particles on its way through the ICM, it gets decelerated by dynamical friction.

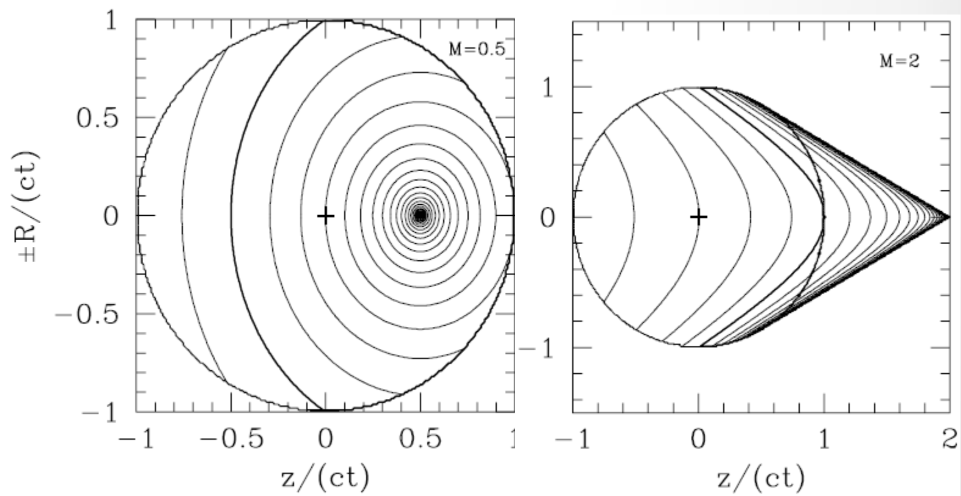
- Different types of wakes due to DF:

  1. Collisionless
     dark matter particles
     Furlanetto & Loeb 2001

  2. Hydrodynamic
     intracluster gas (if $\lambda_{mfp} < R_{halo}$)
     in the case of steady solution, small perturbations
     v < c_s: symmetrical, zero net force
     v > c_s: non-symmetrical, Mach cone



collisionless gravitational wakes (Mulder 1983)



hydrodynamic wakes (Ostriker 1999)

Motivation

- Can we distinguish between collisional and collisionless ICM plasma by estimating its perturbation created by a dark matter halo moving through the medium?
- Measuring the perpendicular (to the line of sight) velocities of galaxies.
- A chance to observe halos devoid of both gas and stars.

Regimes

Protons:

$$\frac{R_{halo}}{\lambda_{mfp}} \sim \frac{20kpc}{20\ kpc}\left(\frac{T_e}{7\ \mathrm{KeV}}\right)^{-2}\left(\frac{n_e}{10^{-3}\ \mathrm{cm}^{-3}}\right) \approx 1 \rightarrow$$

may be collisionless

Electrons:

massless, isothermal, in equilibrium → can be treated as fluid

- Pure hydro in the dense cores of clusters, where λ_{mfp} can be $\sim 10^{-1}$ kpc.
- Hybrid in the bulk and up to R_{500}, where $\lambda_{mfp} > 10$ kpc.

Hydro OR Hybrid

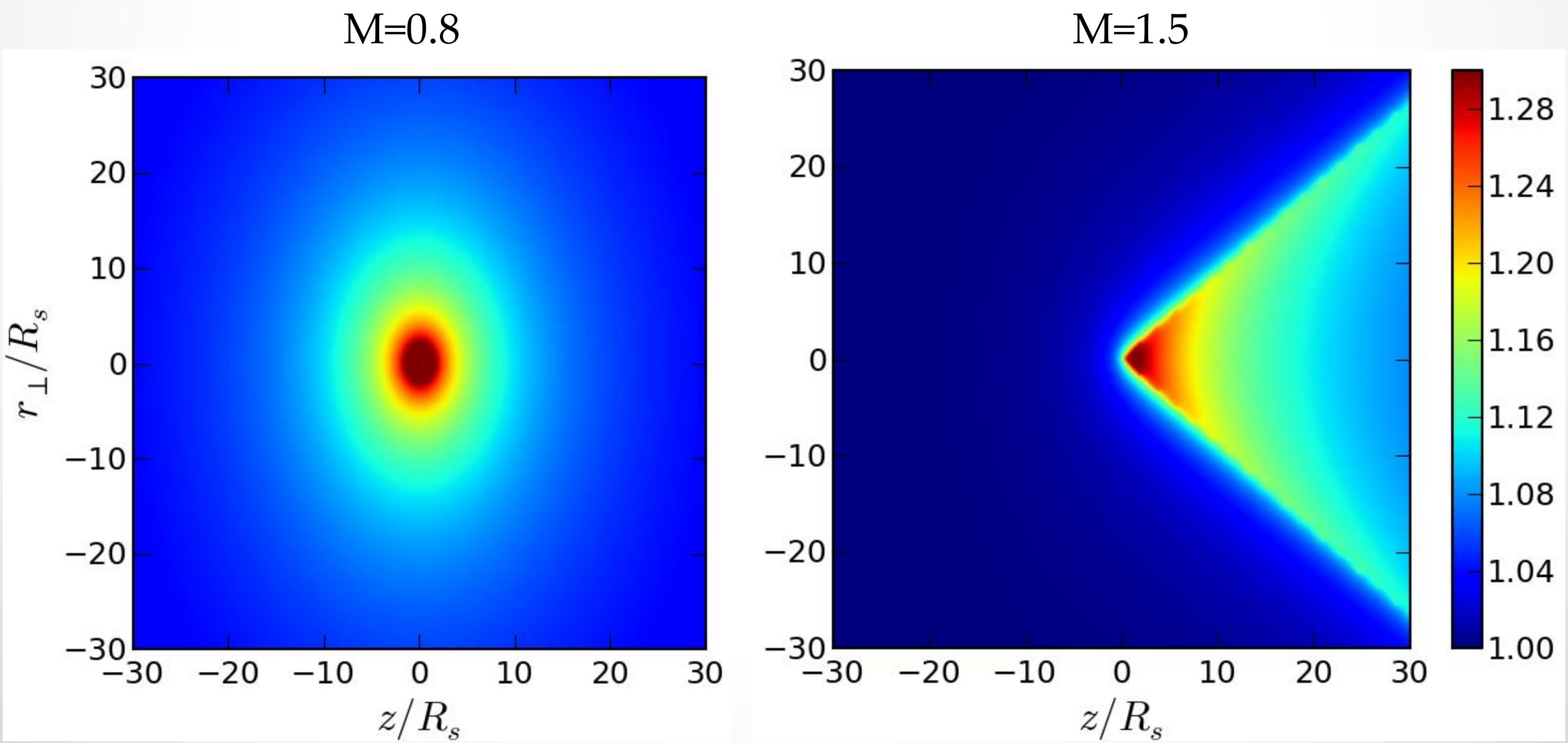
Hydrodynamics

- Small linear perturbations: $\frac{G\mathcal{M}}{R_s {c_s}^2} \ll 1$

for a point-mass perturber

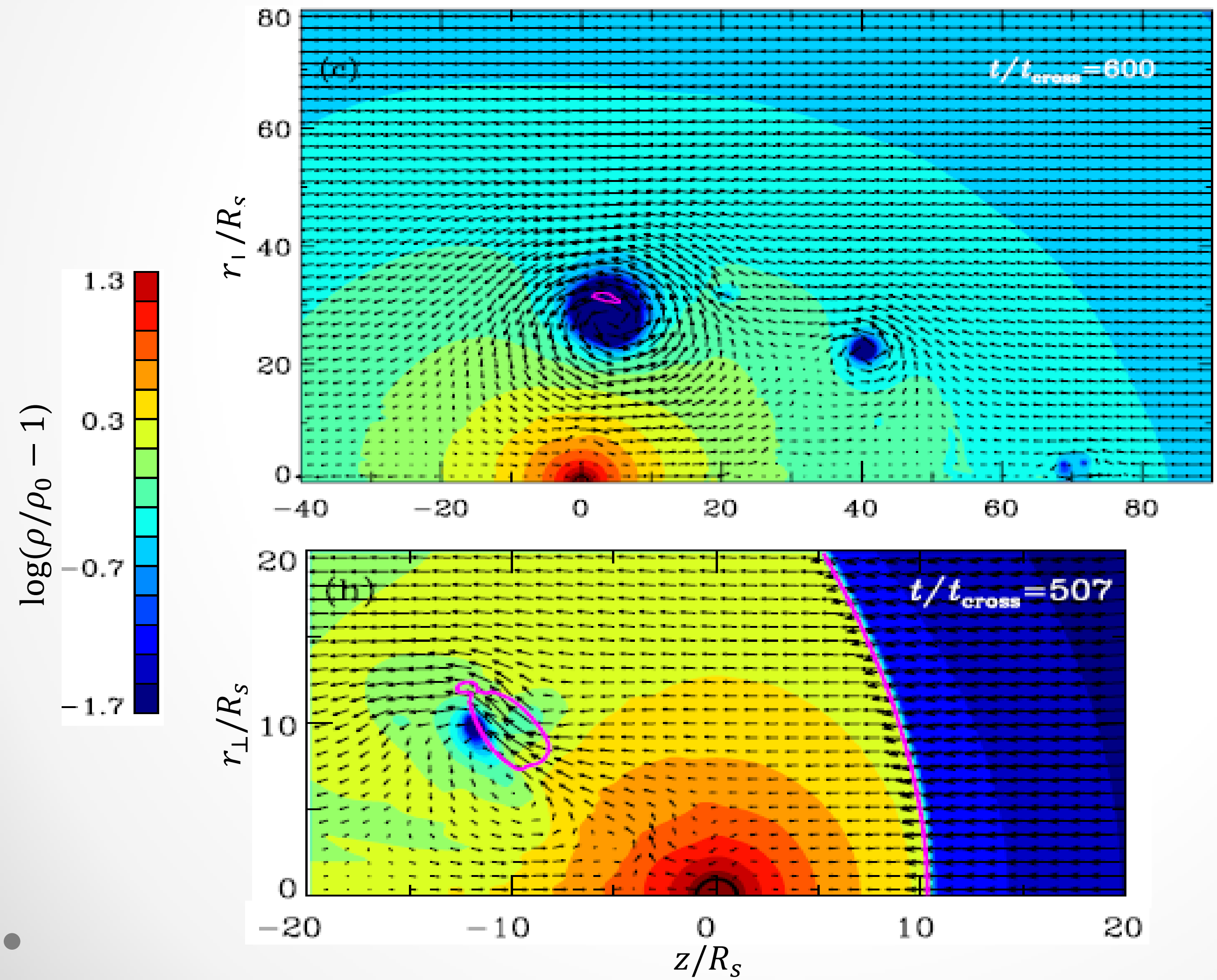
$$\boxed{\rho/\rho_0 - 1 = \frac{G\mathcal{M}/{c_s}^2}{\sqrt{z^2 + (1 - M^2){r_\perp}^2}}}$$

Ostriker 1999



Hydrodynamics

- Non-linear perturbation: $\frac{G\mathcal{M}}{R_s {c_s}^2} \gg 1$



M=0.5

M=1.5

Kim & Kim 2009

Hybrid

- Isothermal massless electrons in equilibrium:

$$-T\nabla n_e - n_e e\boldsymbol{E} = 0 \;\rightarrow\; \boxed{\boldsymbol{E} = -(T/e)\,\nabla n_e / n_e}$$

- Collisionless ions:

$$n_i = n_e$$

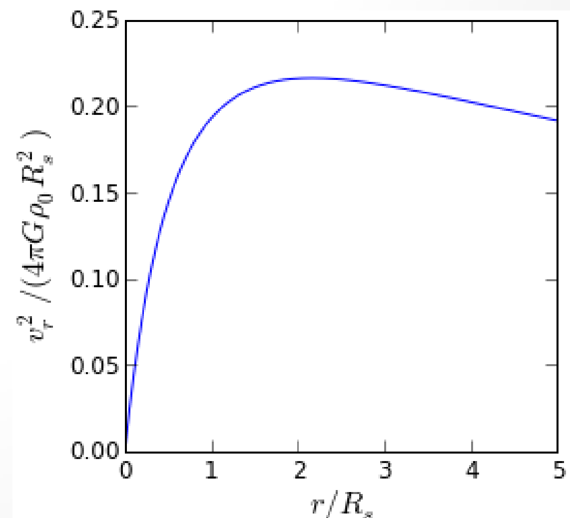
$$v\frac{\partial f_i}{\partial \boldsymbol{r}} + \left(e\boldsymbol{E}/m_i - \nabla\varphi_{gr}\right)\frac{\partial f_i}{\partial \boldsymbol{v}} = 0$$

$$\boxed{\begin{array}{l} v\dfrac{\partial f_i}{\partial \boldsymbol{r}} - \left({\sigma_{Ti}}^2\,\nabla \log n_i + \nabla\varphi_{gr}\right)\dfrac{\partial f_i}{\partial \boldsymbol{v}} = 0 \\ f_i(r=\infty, v) = (2\pi{\sigma_{Ti}}^2)^{-3/2}\exp[-v^2/(2{\sigma_{Ti}}^2)] \end{array}}$$

- Gravitational potential:

$$\varphi_{gr} = -4\pi G\rho_0 {R_s}^3\,\frac{\ln(1+r)}{r}$$

rotation curve for the NFW profile



Dependence on dimensionality

For a moment, consider the limit u = 0: isotropy

- 2D

$$n_i(r) = \int 2\pi v \mathrm{d}v f(r,v) = \int 2\pi \mathrm{d}(v_0^2/2 - \varphi_{gr} - \varphi_E) f_0(v_0) = n_0$$

- 3D

$$n_i(r) = \int 4\pi v^2 \mathrm{d}v f(r,v) =$$

$$= \int 4\pi (v_0^2/2 - \varphi_{gr} - \varphi_E)^{1/2} \mathrm{d}(v_0^2/2 - \varphi_{gr} - \varphi_E) f_0(v_0) =$$

$$= n_0 e^{-(\varphi_{gr} + \varphi_E)}$$

Density maps in hybrid case

Parameters:

1. Max rotational velocity at $r_{max} \approx 2.16R_s$

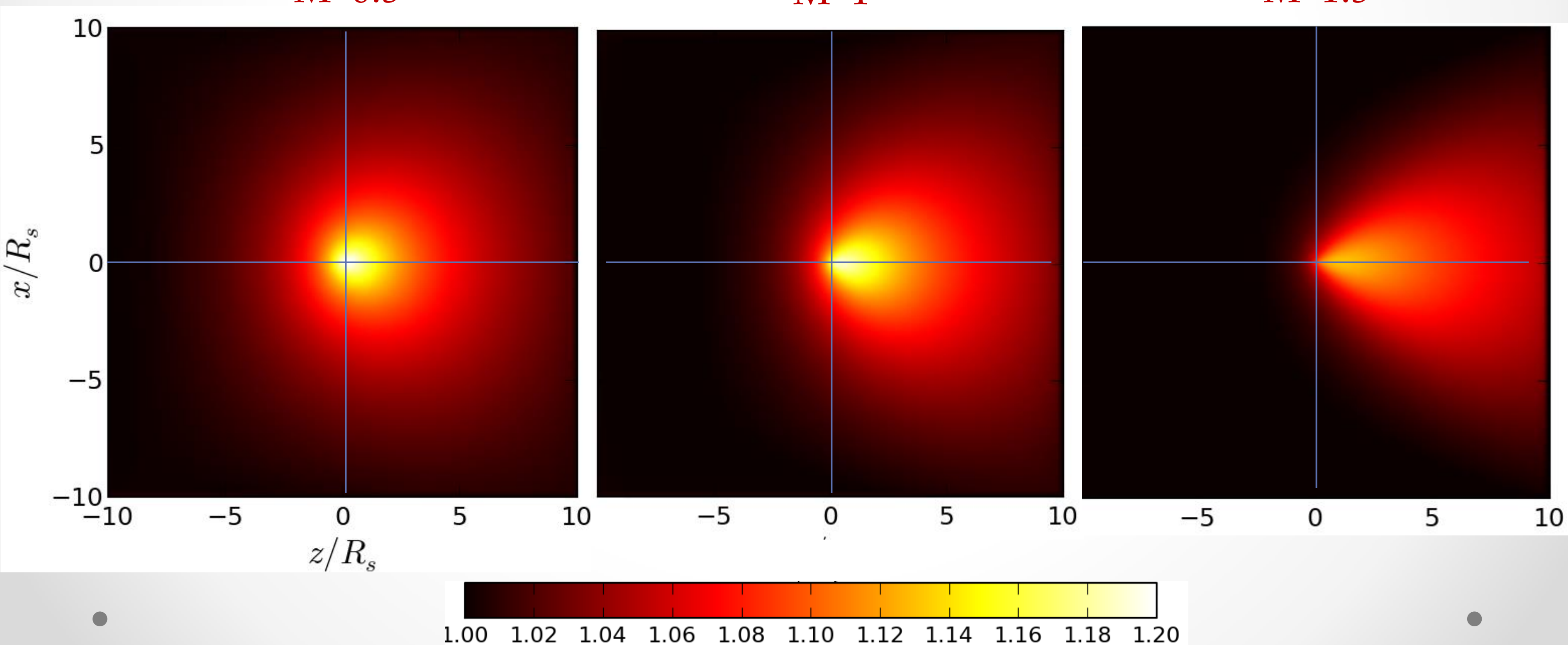
   $${v_r}^2 \approx 0.216 \times 4\pi G \rho_0 {R_s}^2$$

2. Mach number

   $M = v/c_s$, c_s=1000km/s

v_r=200 km/s

M=0.5 M=1 M=1.5



Density maps in hybrid case

Parameters:

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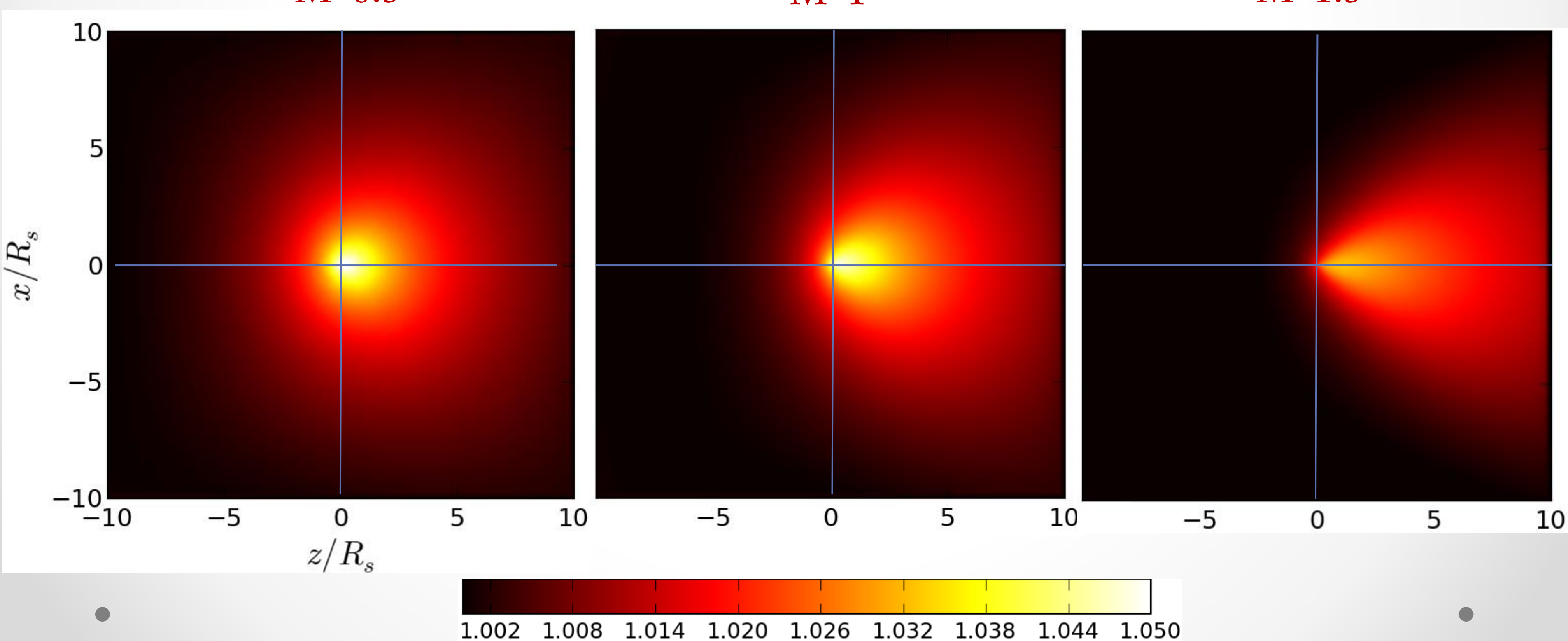
   $${v_r}^2 \approx 0.216 \times 4\pi G\rho_0 {R_s}^2$$

2. Mach number

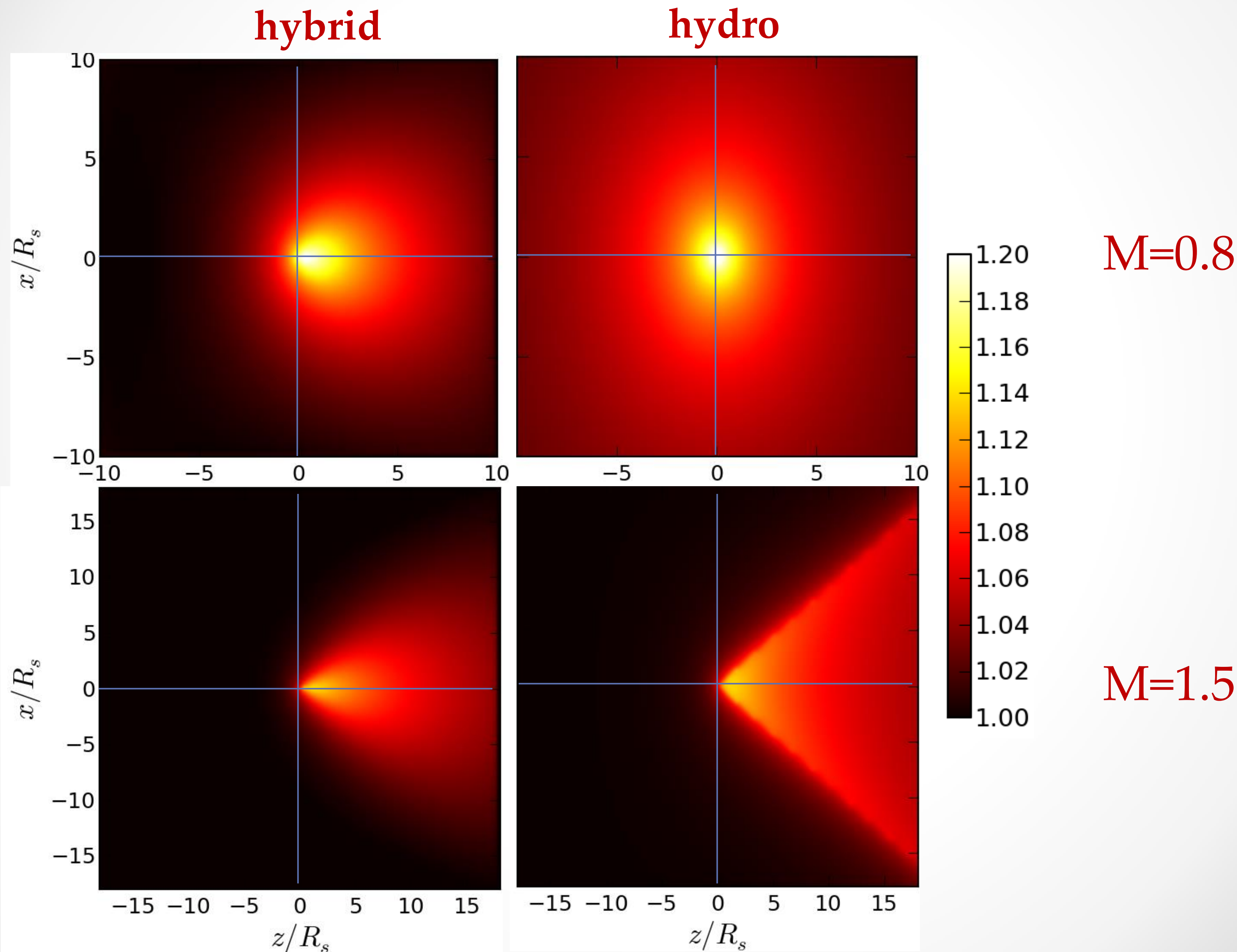
   $M = v/c_s$, c_s=1000km/s

v_r=100 km/s

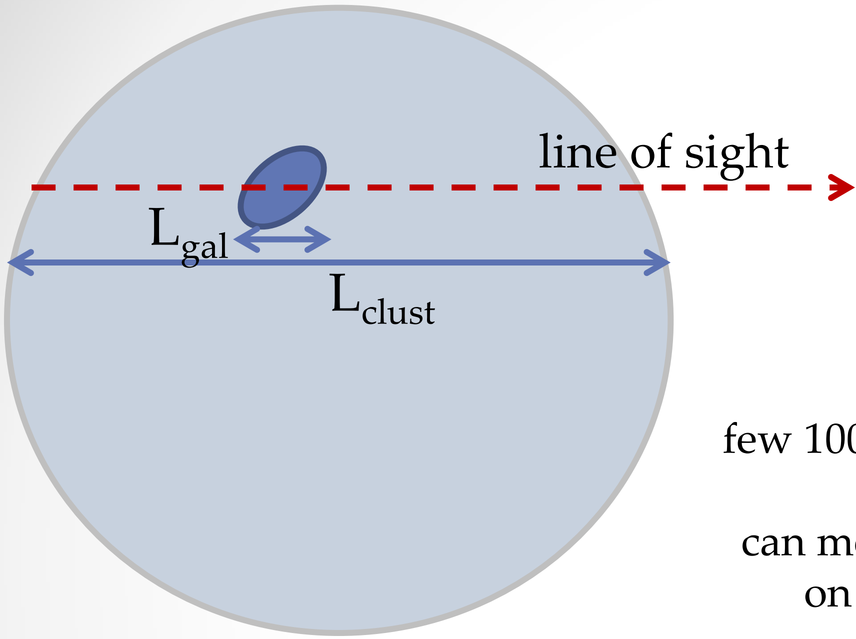
M=0.5 M=1 M=1.5

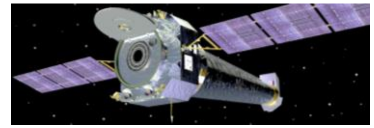


Density maps: hydro vs. hybrid



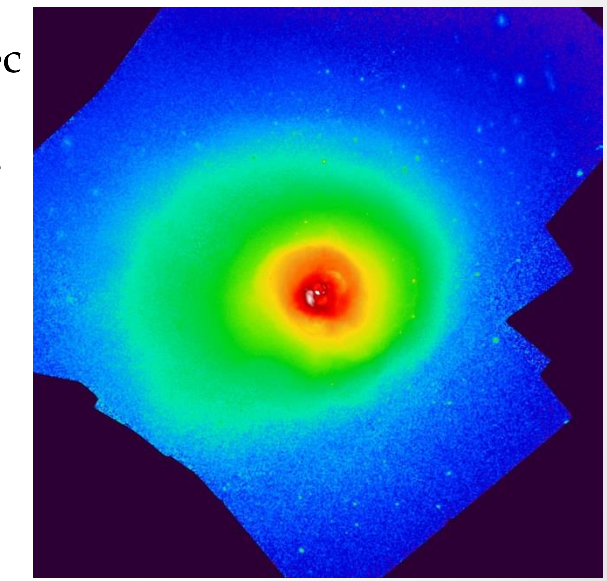
Perturbation scaling and observables





few 100 counts per sq. arcsec
-->
can measure fractions of %
on scales of ~arcmin

in the outer parts, new
instruments required
(e.g. ATHENa)



Chandra 600-kpc image of
The Perseus cluster

- δn ~ 10-20% $(v_r/200\text{km/s})^2$
- in X-rays the perturbation is

$$\frac{\int 2n_0 \delta n \mathrm{d}l}{\int n_0^2 \mathrm{d}l} \sim 2L_{gal}/L_{clust} \times \delta n/n_0 \sim$$

$$\sim 0.2 - 0.4\ \%\ (v_r/200\mathrm{km/s})^2$$

Conclusion

- In the hybrid regime, perturbations are similar in shape to the fully collisionless case
- Magnitude of perturbations scales as ${v_r}^2$ – analogously to the hydrodynamic regime.
- Fractions of % contrast expected in X-ray maps

Regimes

Electrons:

$$t_{cross}/t_{coll} = \frac{R_{halo}\,\sigma_{Te}}{\lambda_{mfp} u} \sim \frac{20kpc}{20\,kpc} M \sqrt{\frac{m_p}{m_e}} \approx 40 \text{ -> fluid}$$

Protons:

$$t_{cross}/t_{coll} = \frac{R_{halo}\,\sigma_{Ti}}{\lambda_{mfp} u} \sim \frac{20kpc}{20\,kpc} M \approx 1 \text{ -> may be collisionless}$$

- Pure hydro in the dense cores of clusters, where λ_{mfp} can be $\sim 10^{-1}$ kpc.
- Hybrid in the bulk and up to R_{500}, where $\lambda_{mfp} > 10$ kpc.

Hydro

OR

Hybrid