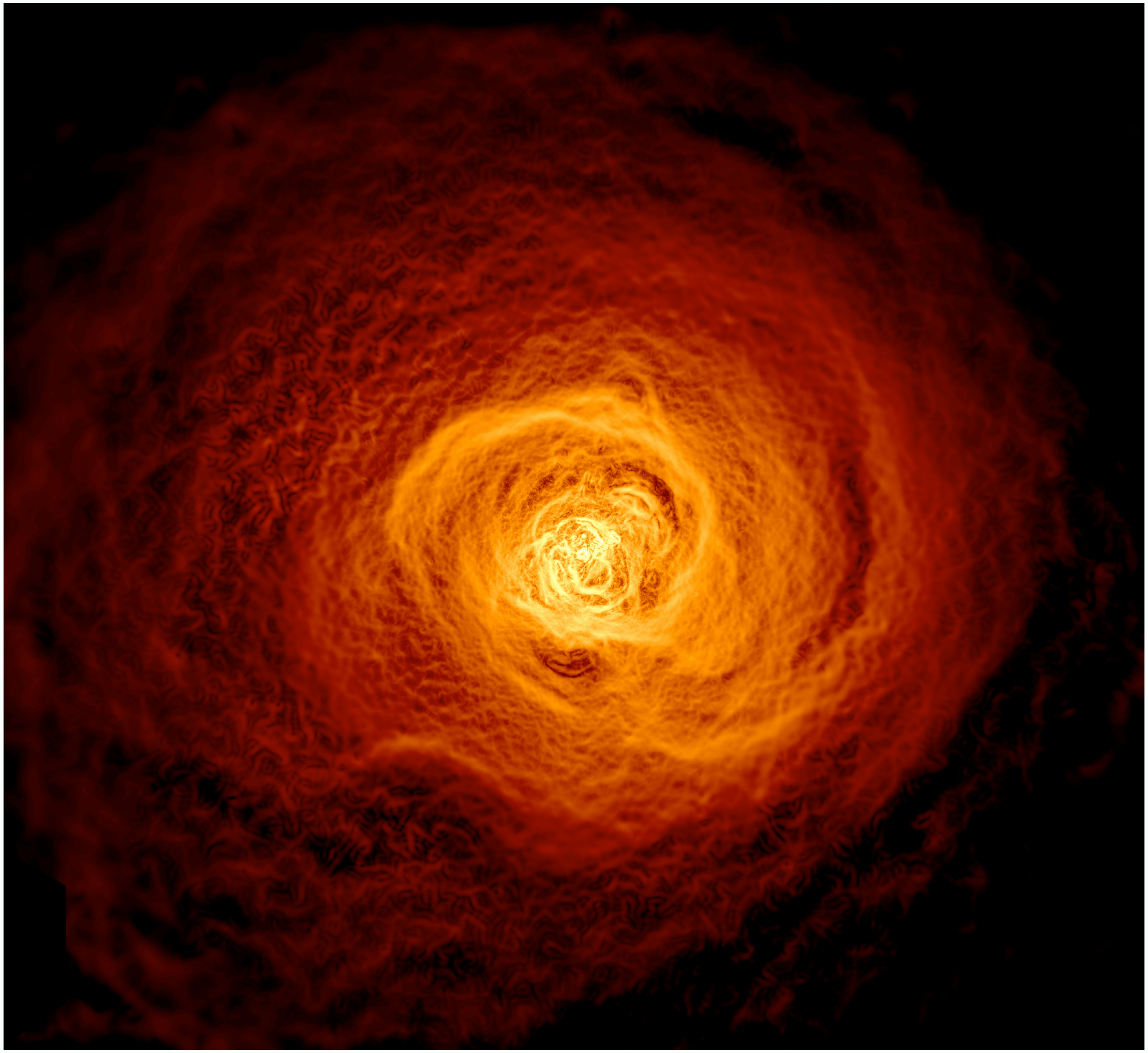
Measuring Dark Matter In Galaxies: The Mass Fraction Within 5 Effective Radii

Bill Harris, McMaster University

April 2020

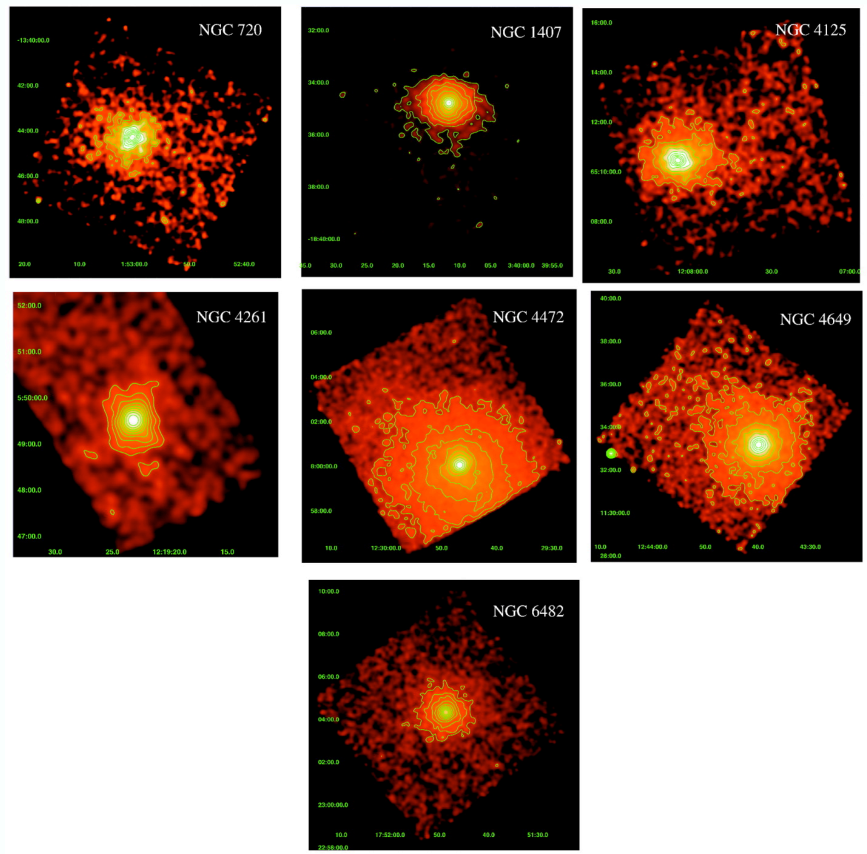
Collaborators:
Rhea-Silvia Remus (Munich)
Gretchen Harris (Waterloo)
Iurii Babyk (Waterloo /UC Irvine)
Brian McNamara (Waterloo)

Chandra (X-ray) image of the Perseus cluster of galaxies

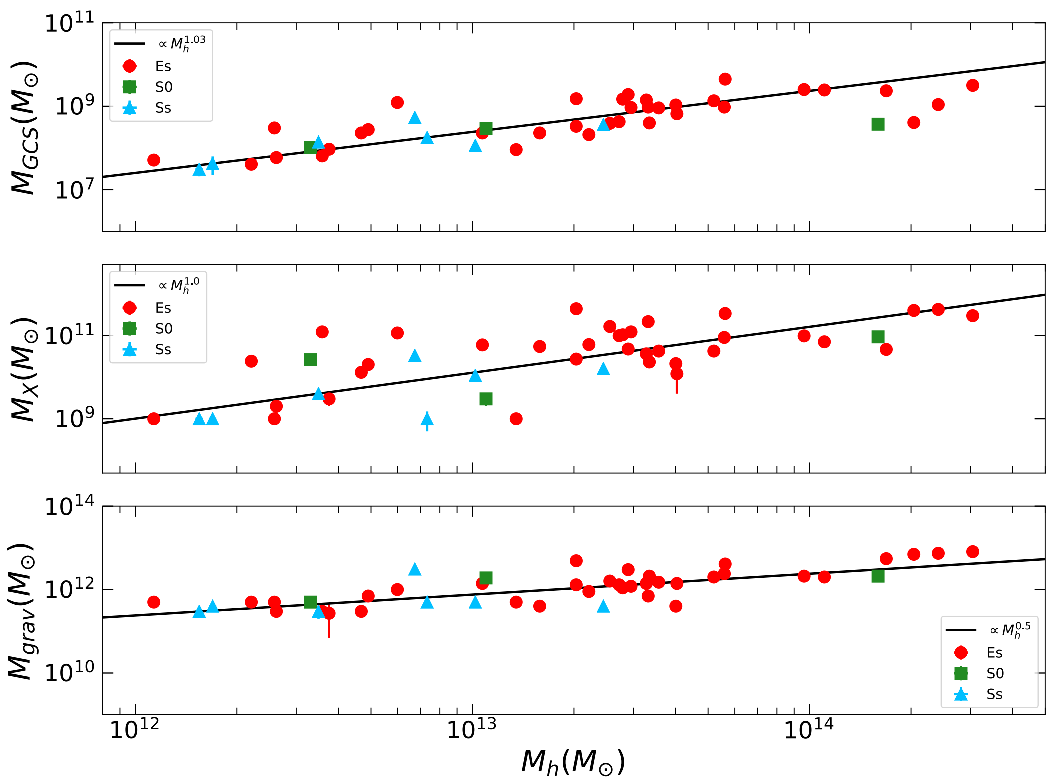


Chandra image of the X-ray gas in NGC 4649, a Virgo giant ETG

Some other Chandra galaxies (Humphrey+2006)



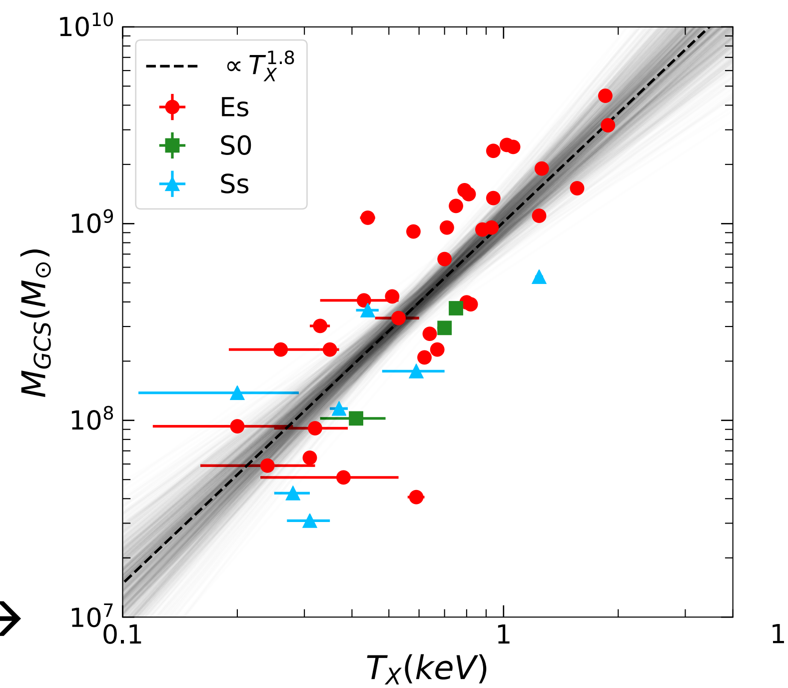
Global properties of the ISM X-ray gas correlate with total DM potential and other proxies (like globular cluster populations!)
G.Harris, I.Babyk, W.Harris, B.McNamara 2019, ApJ 887, 259



T_X is a decent indicator of the total potential well (thus, cooler for individual galaxies than for entire clusters)

M_h ("halo mass") ~ M_{200}
Total mass of galaxy, dominated by DM

(1 keV ~ 12 x 10^6 K) →

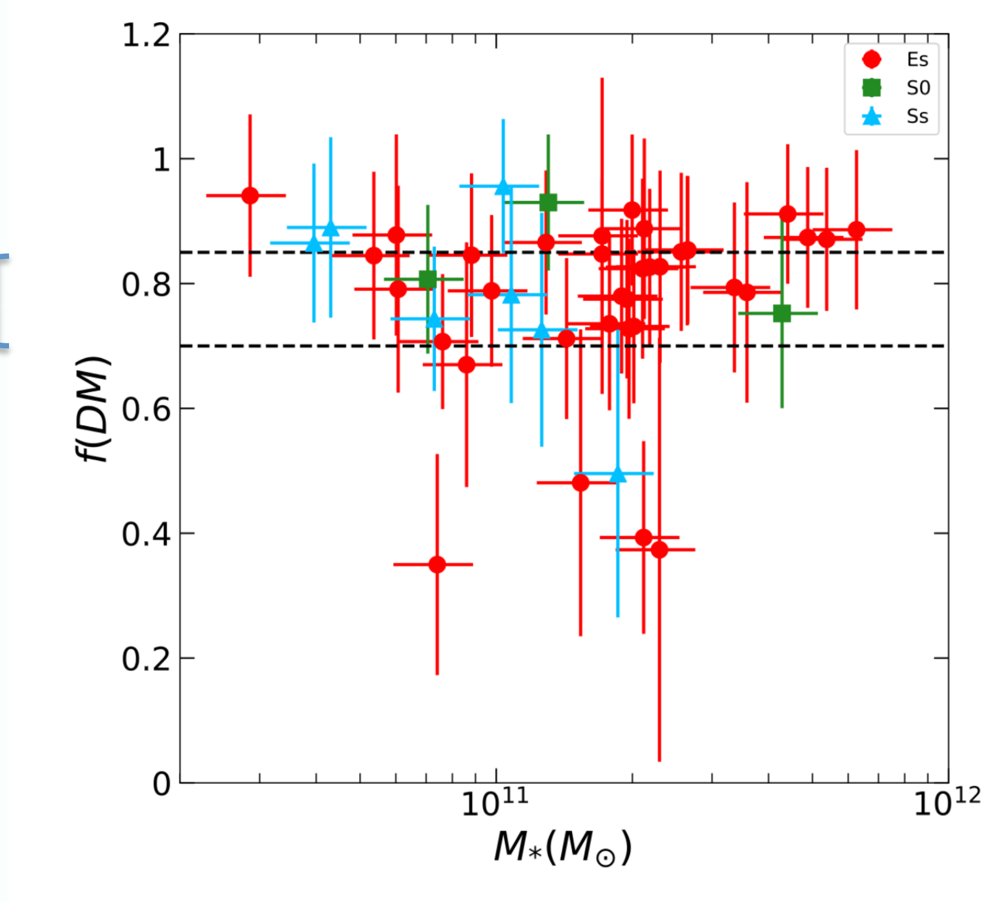


The DM mass fraction within a radius r is important:

$$f_{DM}(r) = 1 - \frac{M_{bary}(r)}{M_{tot}(r)}$$

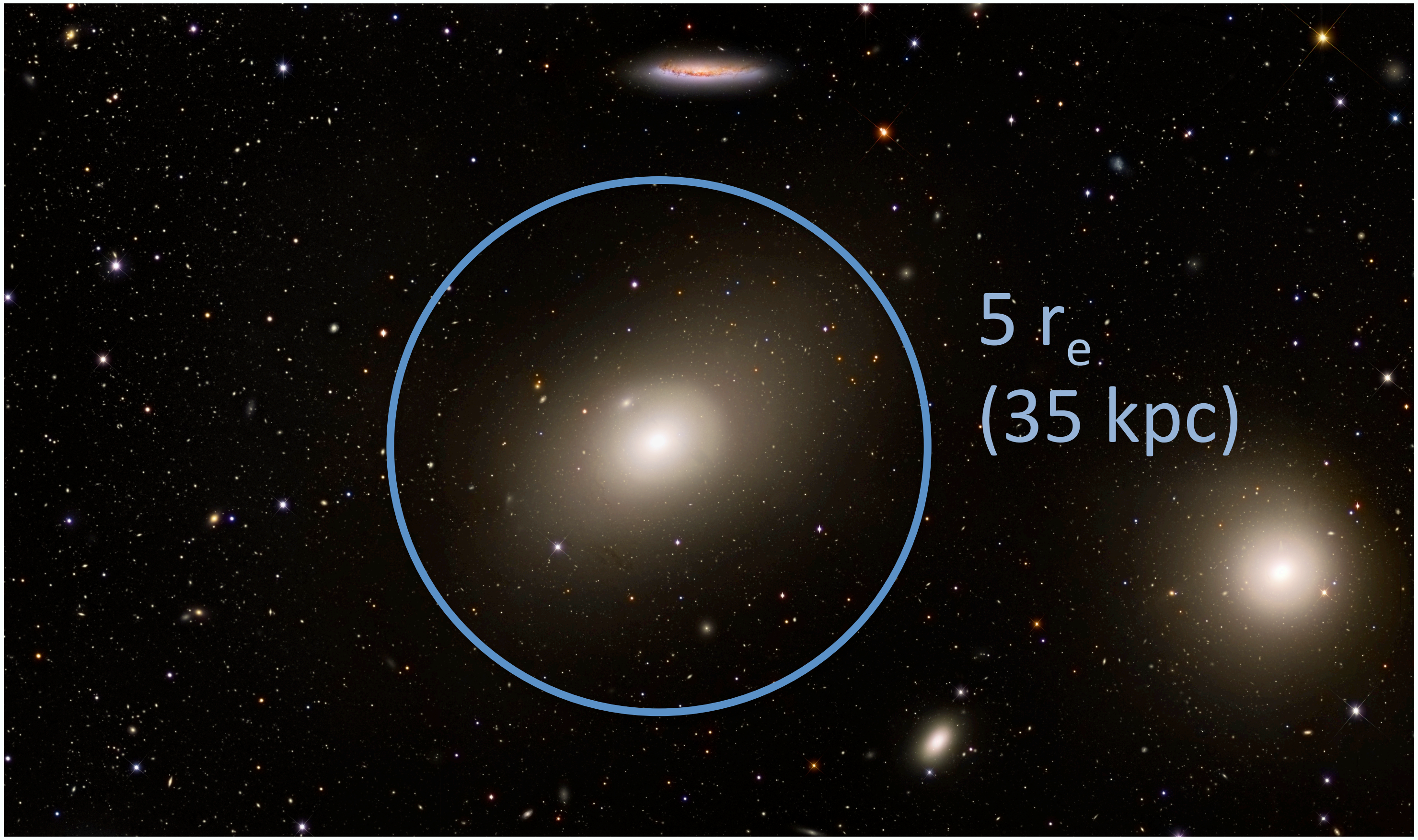
- A function of radius
- Tracer of halo history (big mergers, halo contraction or expansion, feedback)

Range of Magneticum Pathfinder simulations (Remus et al. 2017)



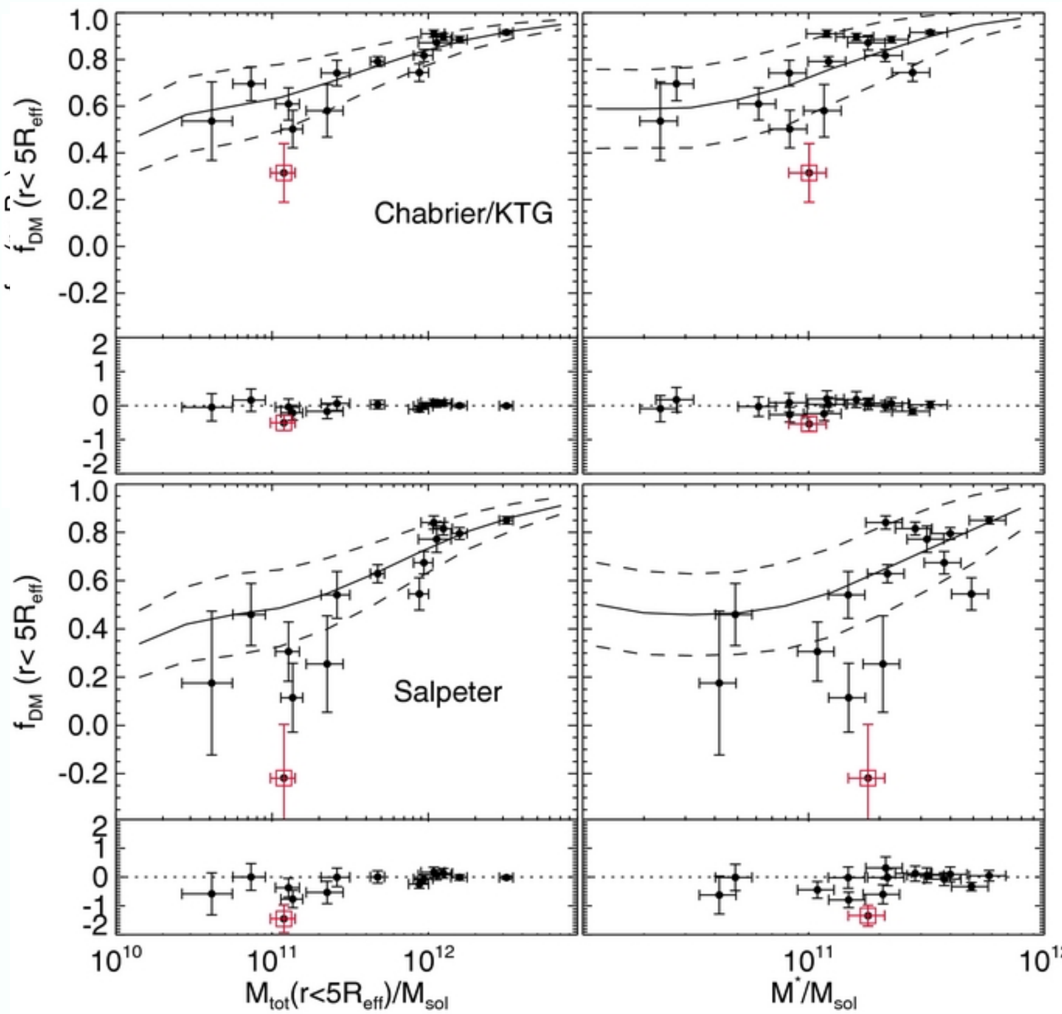
f_{DM} within *5 effective radii* is now a popular choice and can be predicted from simulations of galaxy formation and growth

NGC 4406 (M86) in Virgo cluster



$5\ r_e$ typically encloses 90% of the total stellar light (Sersic profiles)

Some analytical predictions
(Deason+2012)



Hernquist profile for galaxy + NFW profile for DM halo

Data points: globular cluster kinematics

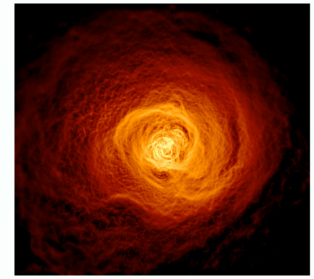
X-ray gas density profile model (the "β-model"): Originated from analysis of intergalactic X-ray gas in clusters of galaxies (1970's)

??

$$\rho_g(r) = \rho_0\left(1+\left(r/r_0\right)^2\right)^{-3\beta/2}$$

??

(Power law with core radius)



Hydrostatic equilibrium: $$\frac{dP}{dr} = -\frac{GM(r)\rho}{r^2}$$

(3D)

Gas: $$P_{gas} = \frac{k}{\mu H}\rho_{gas}T$$

Galaxies: $$P_{gal} = \frac{1}{3}\rho_{gal}\sigma_V^2$$

Both are *isothermal* $$\Rightarrow \quad \frac{1}{3}\sigma_V^2\frac{1}{\rho_{gal}}\frac{d\rho_{gal}}{dr} = \frac{kT}{\mu H}\frac{1}{\rho_{gas}}\frac{d\rho_{gas}}{dr}$$

so then $\rho_{gas} \propto \rho_{gal}^{\beta}$ where $\beta = \dfrac{\sigma_V^2}{\left(3kT/\mu H\right)}$

β is the ratio of ***specific energies*** of galaxies to gas:

Galaxies: mean KE per particle = $\sigma_V^2/2$

Gas: mean KE per particle = $3kT/2\mu H$

$$\beta = \frac{\sigma_V^2}{\left(3kT/\mu H\right)}$$

The galaxies are observed to follow a cored power-law density profile ***within their cluster*** with an empirical fit of:

$$\rho_{gal} = \rho_0 (1+(r/r_0)^2)^{-3/2}$$

So the gas density profile is: $\rho_{gas} \propto \rho_{gal}^{\beta}$

$$\rho_{gal} = \rho_0 (1+(r/r_0)^2)^{-3\beta/2}$$

(see Gorenstein+1978 for a nice derivation.)

For clusters of galaxies, $\beta \sim 1$ (both gas and galaxies follow the DM potential well of the entire cluster)

Borrow the same formalism for the diffuse X-ray gas inside individual galaxies. There, β differs widely from one case to another but is often near $\beta \sim 0.5$

The enclosed mass, M(r), comes directly from the hydrostatic equilibrium equation:

$$M_{tot}(r) = -\frac{kT}{G\mu H}\frac{d\ln\rho_{gas}}{d\ln r} \quad \rightarrow \quad \frac{3k}{G\mu H}\beta T_X r \quad \text{(large r)}$$

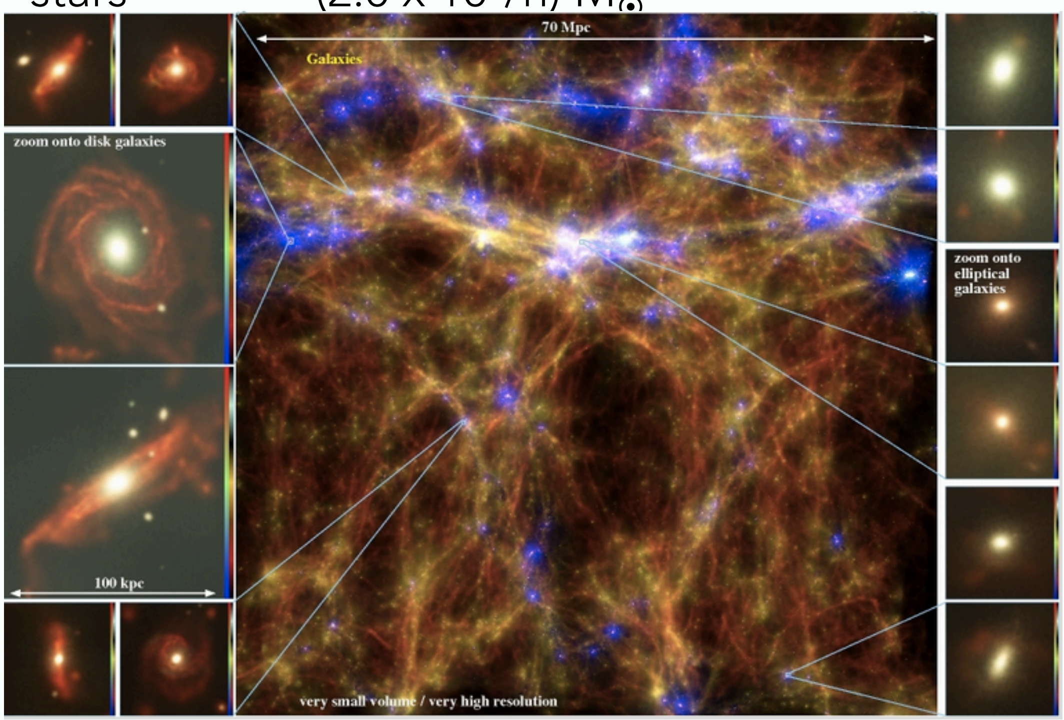
This gives us a way to determine the mass profiles of galaxies that is nearly independent of the more well known satellite-velocity technique (globular clusters, planetary nebulae, halo stars, dwarf satellites)

Features of the Magneticum Pathfinder simulations

Cosmological hydrodynamic runs with range of box sizes and resolutions
Standard ΛCDM parameters

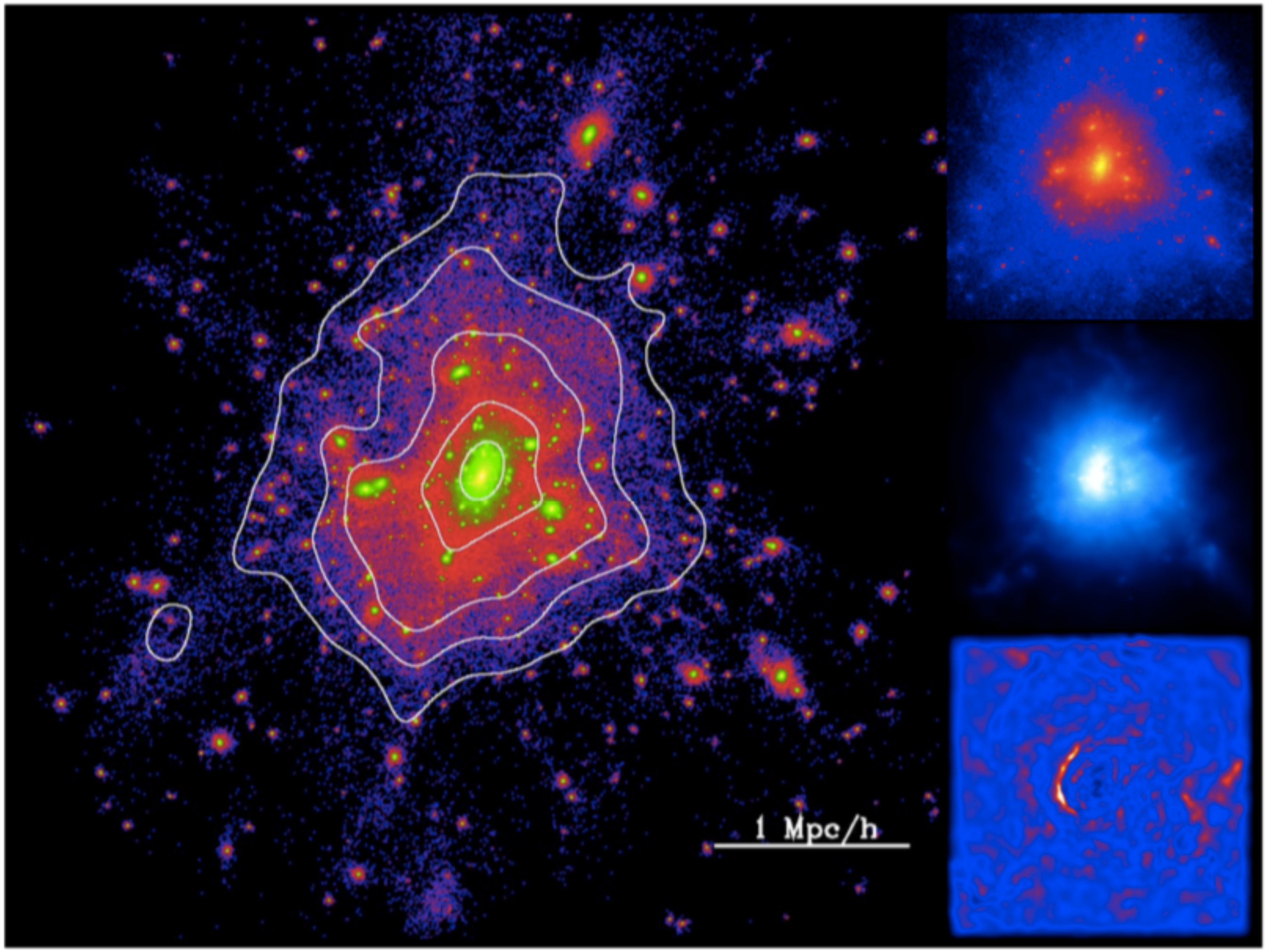
"centrals" from box width (640/h) Mpc
- dark matter: $(6.9 \times 10^8/h)\ M_\odot$
- gas $(1.4 \times 10^8/h)\ M_\odot$
- stars $(3.5 \times 10^7/h)\ M_\odot$

"normals" from box width (48/h) Mpc
- dark matter: $(3.6 \times 10^7/h)\ M_\odot$
- gas $(7.3 \times 10^6/h)\ M_\odot$
- stars $(2.0 \times 10^6/h)\ M_\odot$



www.magneticum.org

Example run with large cluster and BCG



Mass density

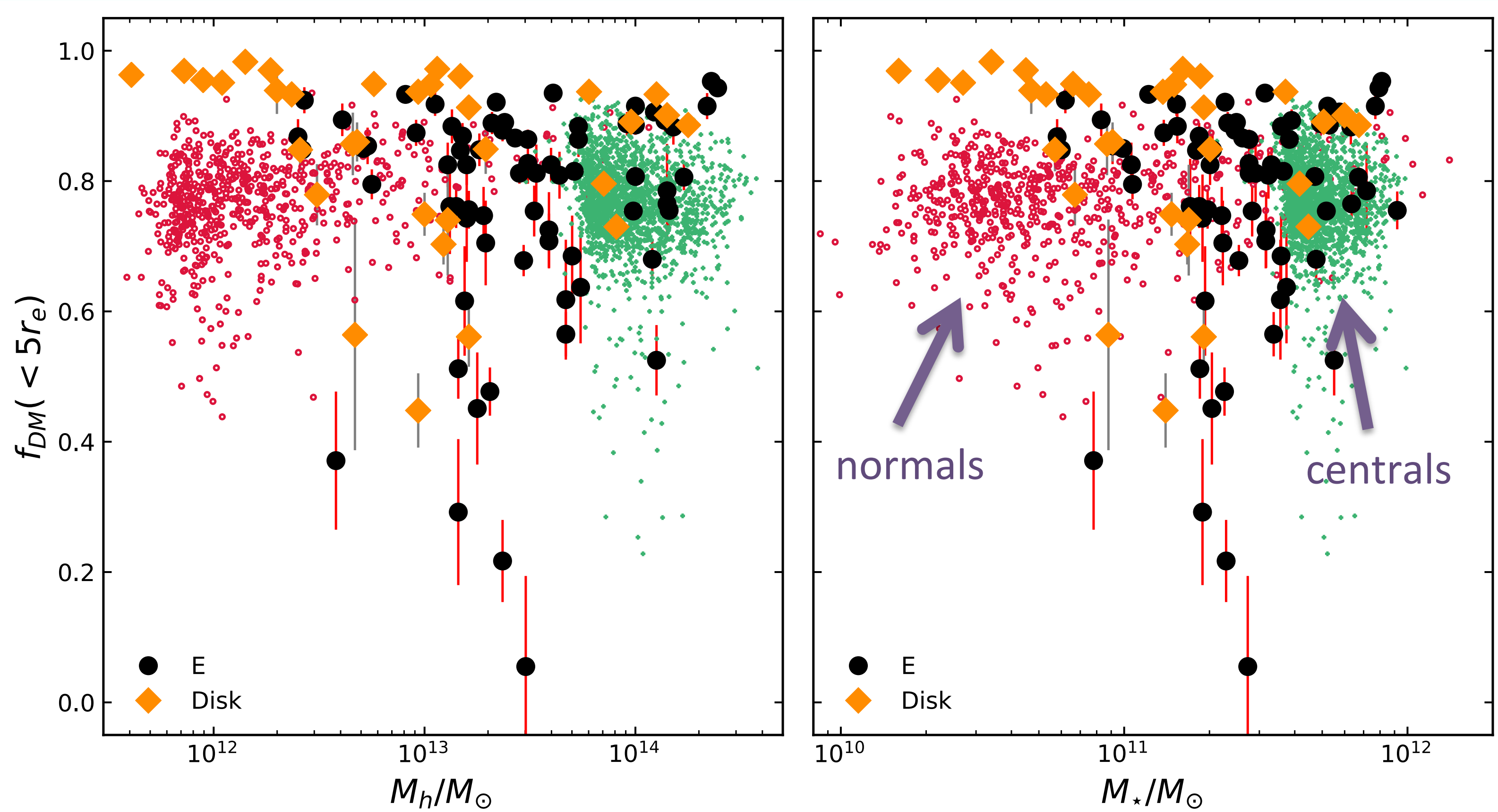
X-ray gas

Gas pressure map (shocks)

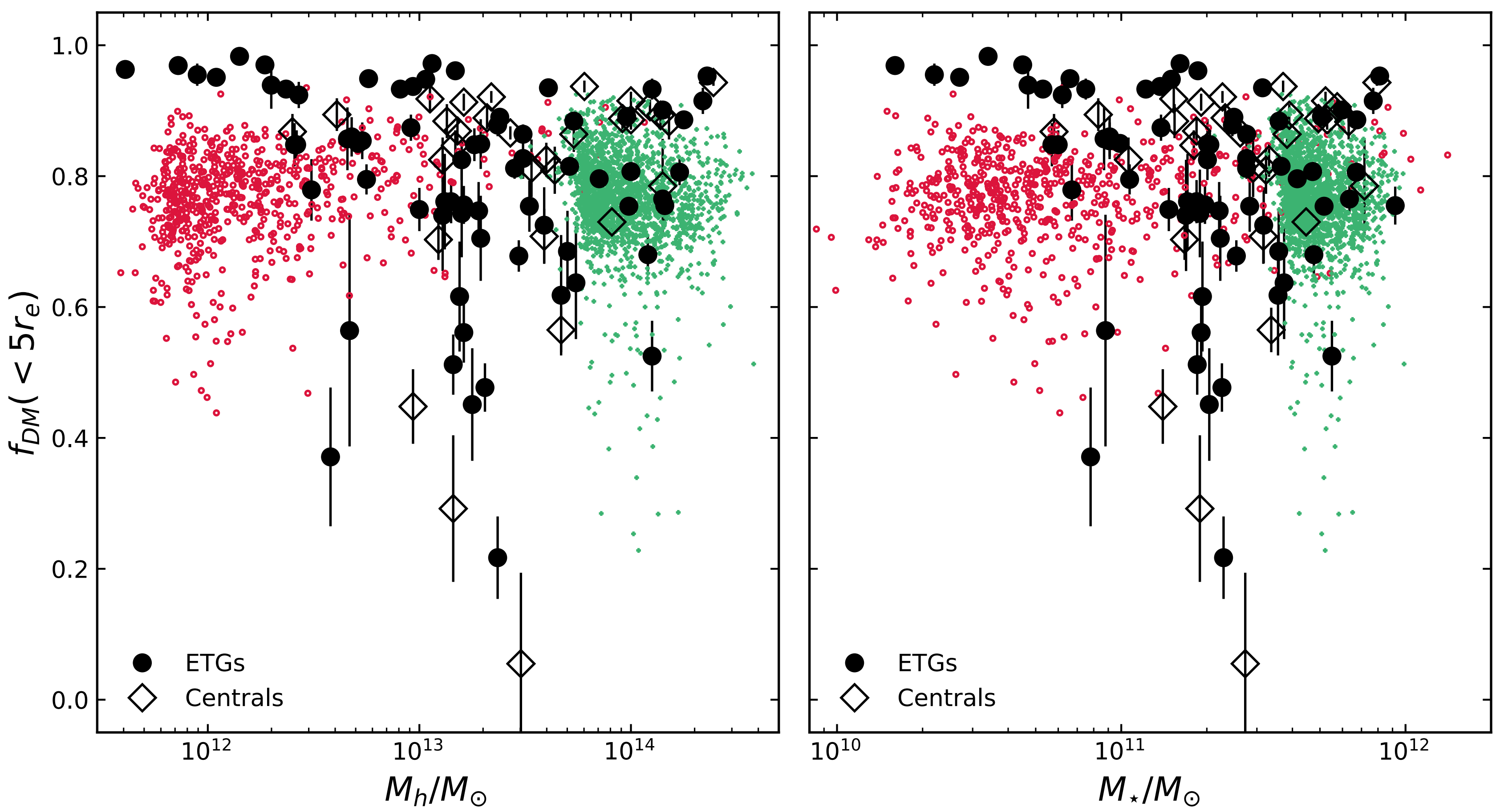
Remus+2017 (1709.02393)

W.Harris, Remus, G.Harris, Babyk 2020 (ApJ, submitted):
102 galaxies with *Chandra* X-ray profiles used to measure
M_X , M_{tot} and thus f_5

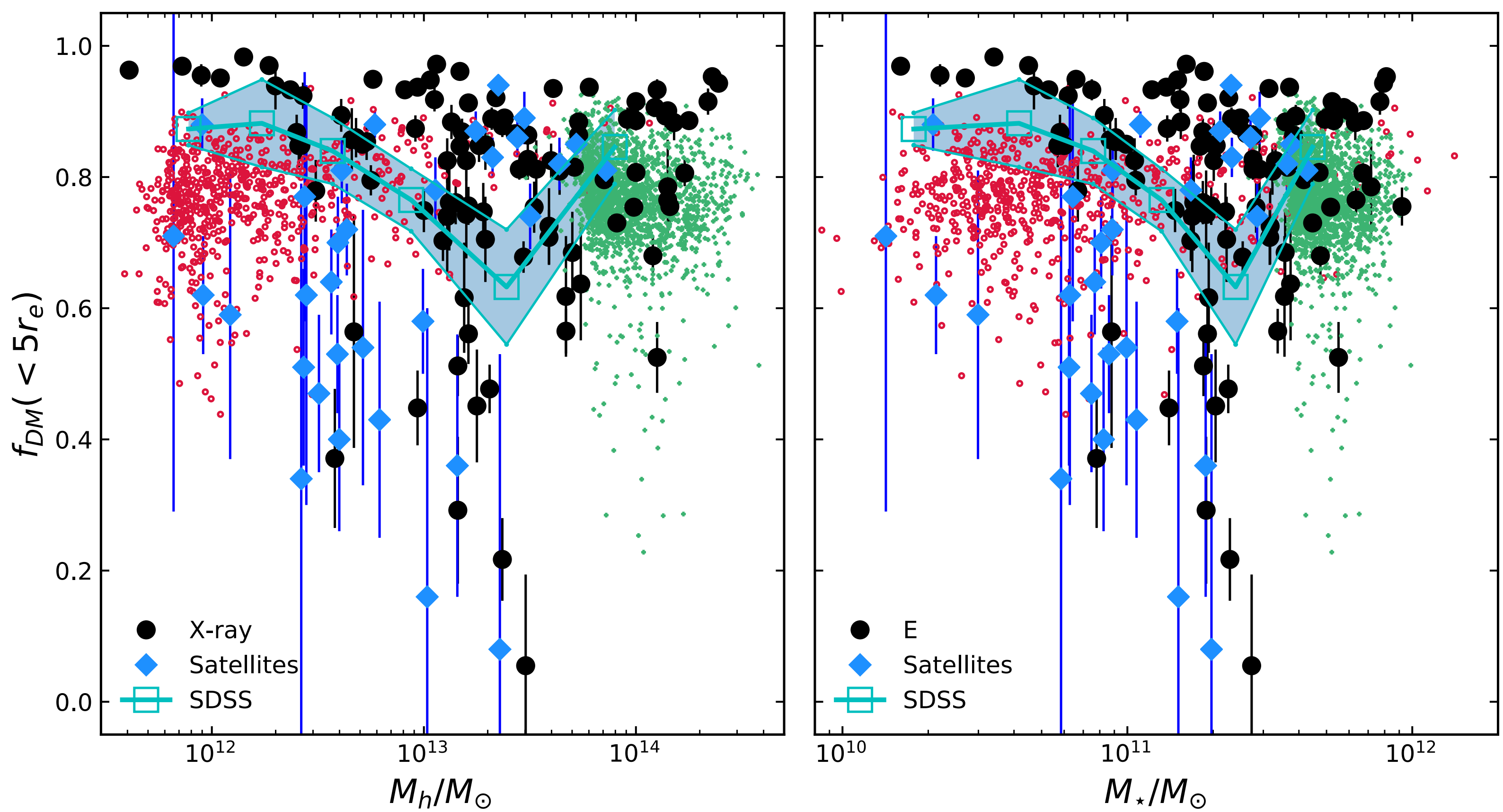
$$f_5 = 1 - \frac{(qM_* + M_X)}{M_{tot}}$$



‘Normals’ vs. ‘Centrals’ (BCGs or BGGs)



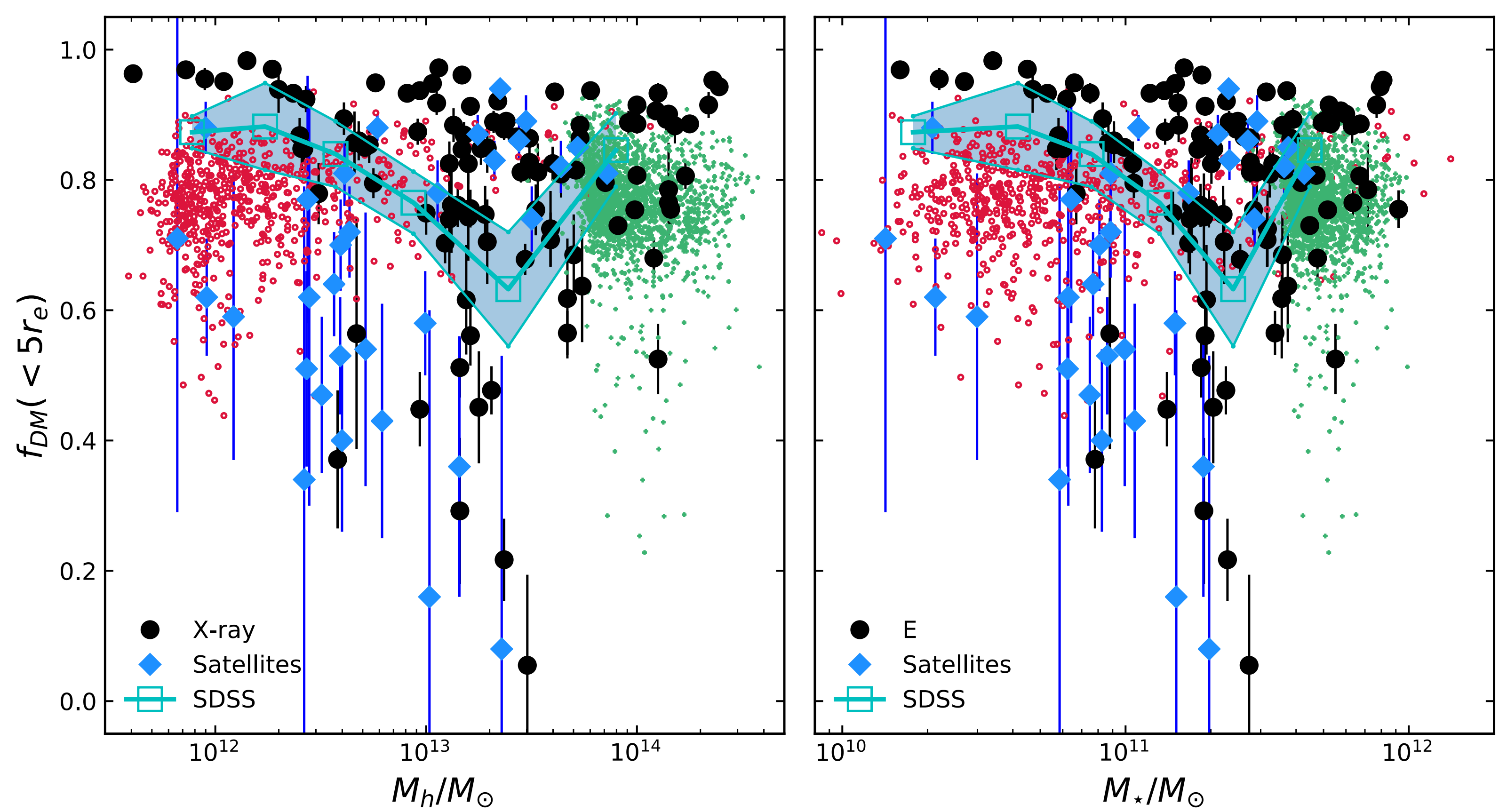
To first order we have good agreement between the data and the simulations.
How about a comparison with the satellite dynamics method?



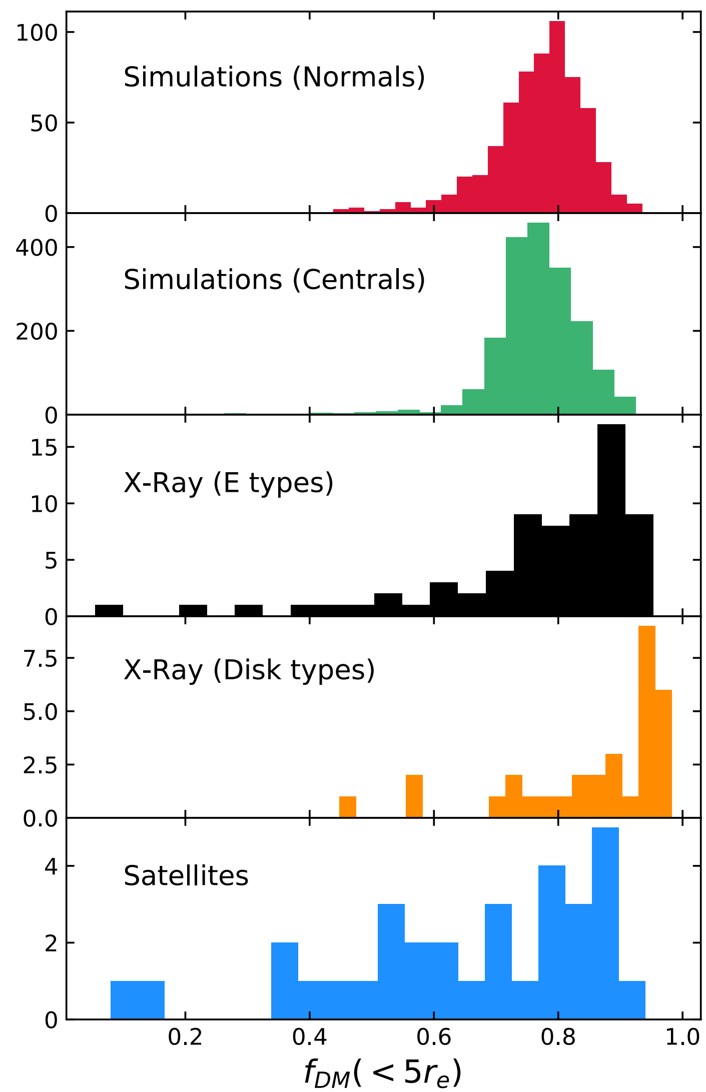
Data for the satellite analyses: Alabi et al. 2017, Wojtak & Mamon 2014

Both methods have potential biasses and problems

- Satellites: unknown orbit anisotropy; sample size issues
- X-ray profiles: assumptions of symmetry, equilibrium, gas physics



But these biasses and problems are ***<u>different</u>*** between the two →
we have something close to genuinely independent methods



Physically, how do we get very large or very small f_5 ?

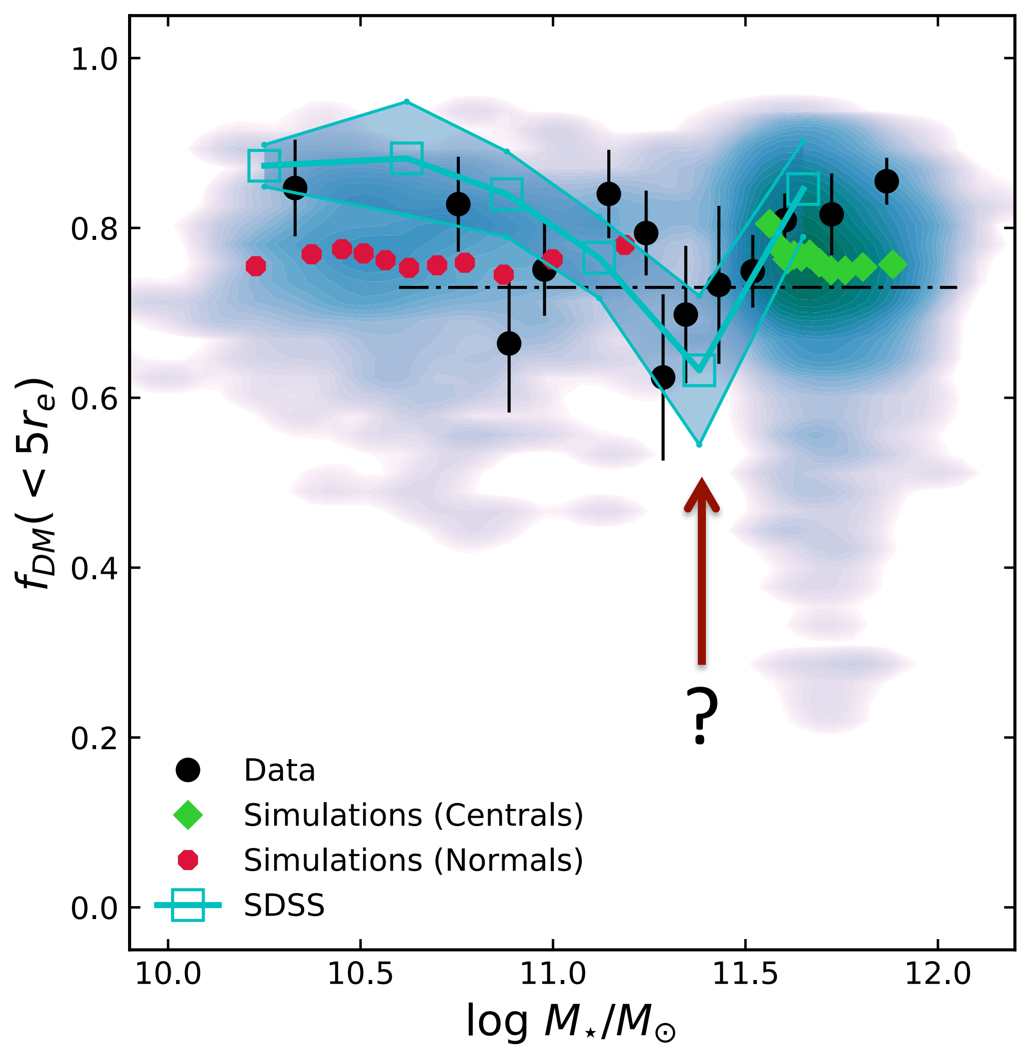
- Adiabatic contraction of halo (plus, not much big merging or violent activity) at early stages will increase f(DM)
- Major feedback (such as AGN activity; big mergers) can decrease f by surprising amounts (but note $f_5 < 0.5$ is pretty rare in the simulations)

$$f_5 = 1 - \frac{(qM_* + M_X)}{M_{tot}}$$

Observational uncertainty: mostly due to M_{tot} , but asymmetrically

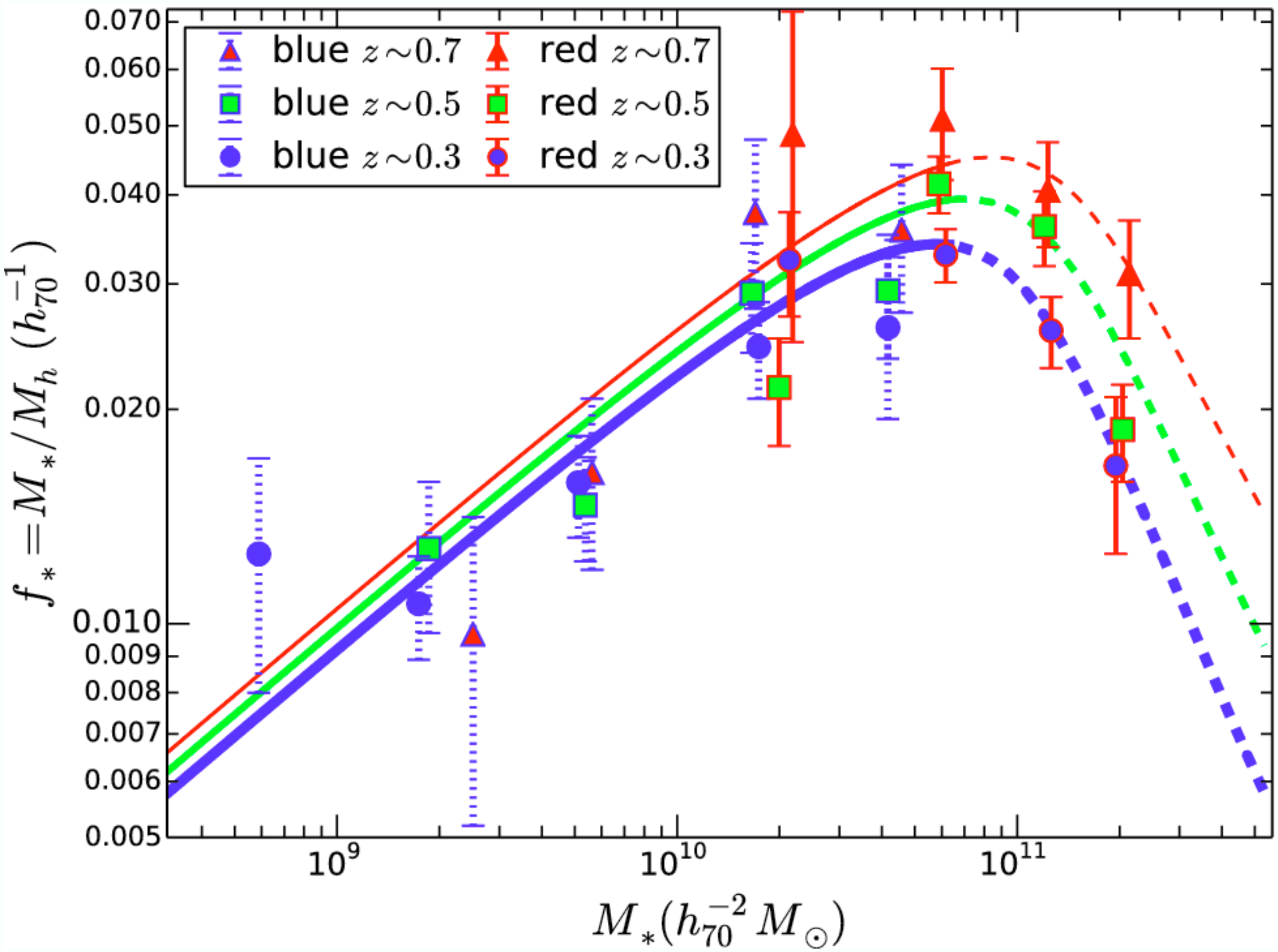
- Overestimate → slight increase in f_5
- Underestimate → can lower f_5 a lot
- Big overestimate of M_X can also decrease f_5

Average up the X-ray and satellite data (N= 117 galaxies total)
Divide into 13 bins by stellar mass



161 galaxies measured
via strong lensing!
(Oguri+2014)
<f_5> = 0.73 +- 0.05

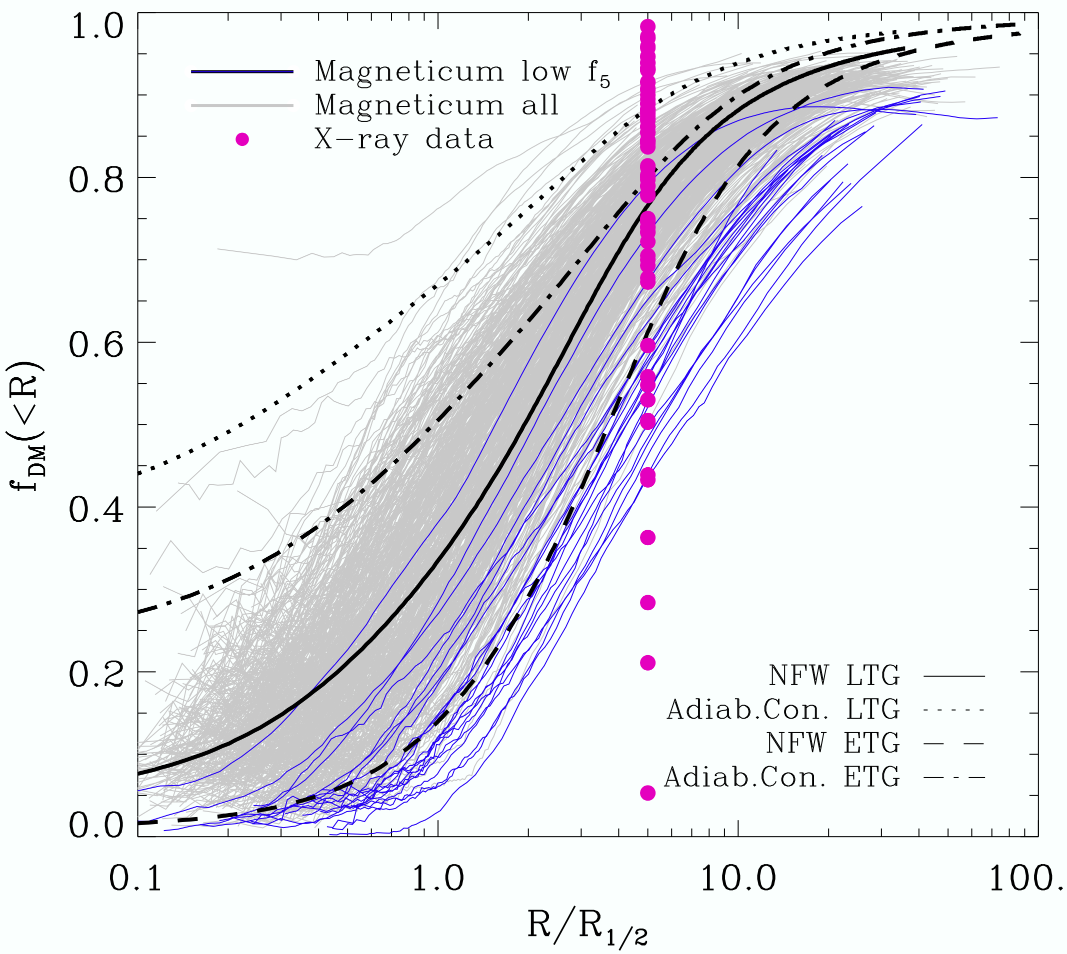
SHMR calibration from Hudson+2015



Maximum star formation efficiency near 10^{11} M(sun)

Future prospects?

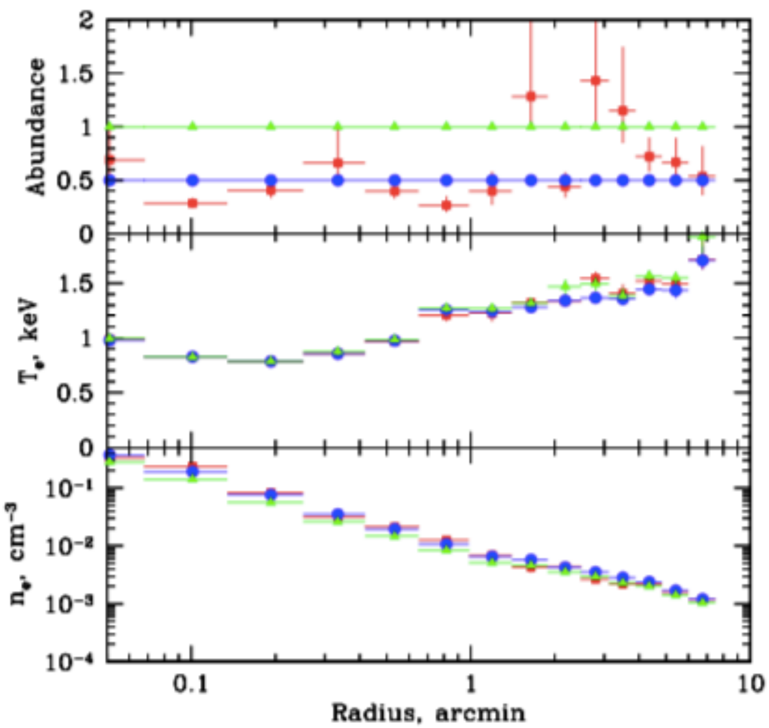
What about radial profiles of f(DM)? Don't restrict to 5 r(eff)



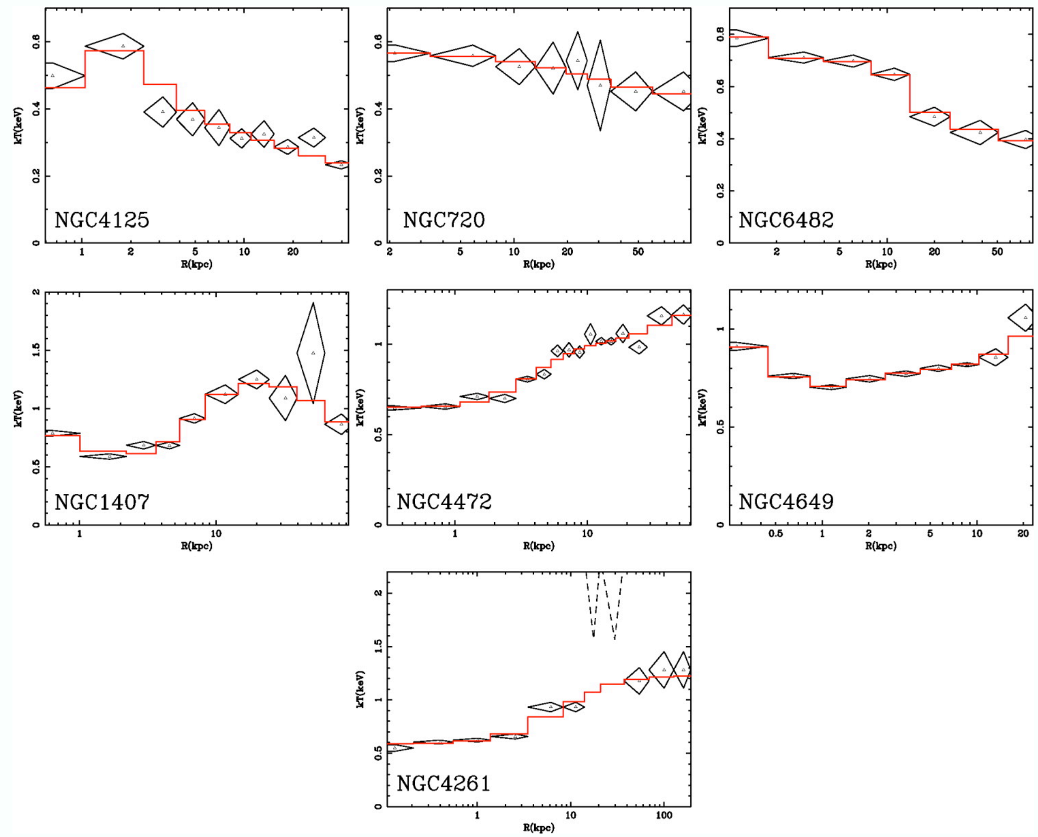
For particularly good cases, could allow us to read major episodes in galaxy history

Currently underway!

Evidence regarding isothermality: some results from Chandra spectral mapping



NGC 1399 (Fornax BCG)
(Churazov+2019)



7 luminous ETGs (Humphrey+2006)