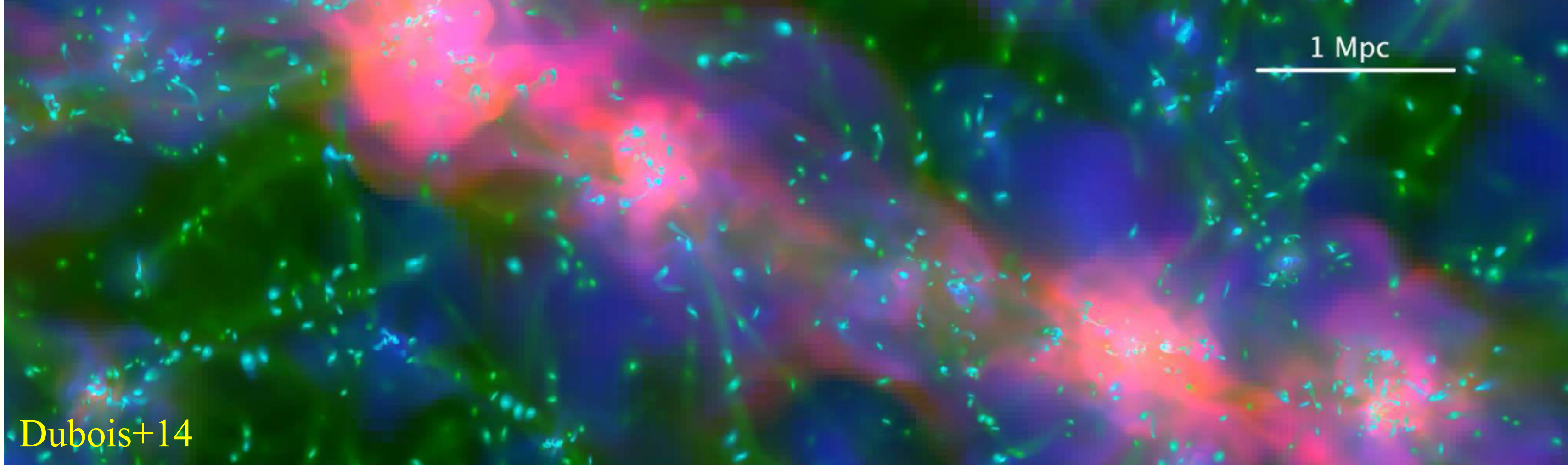

Fate of galaxies and their angular momentum

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22 June 201

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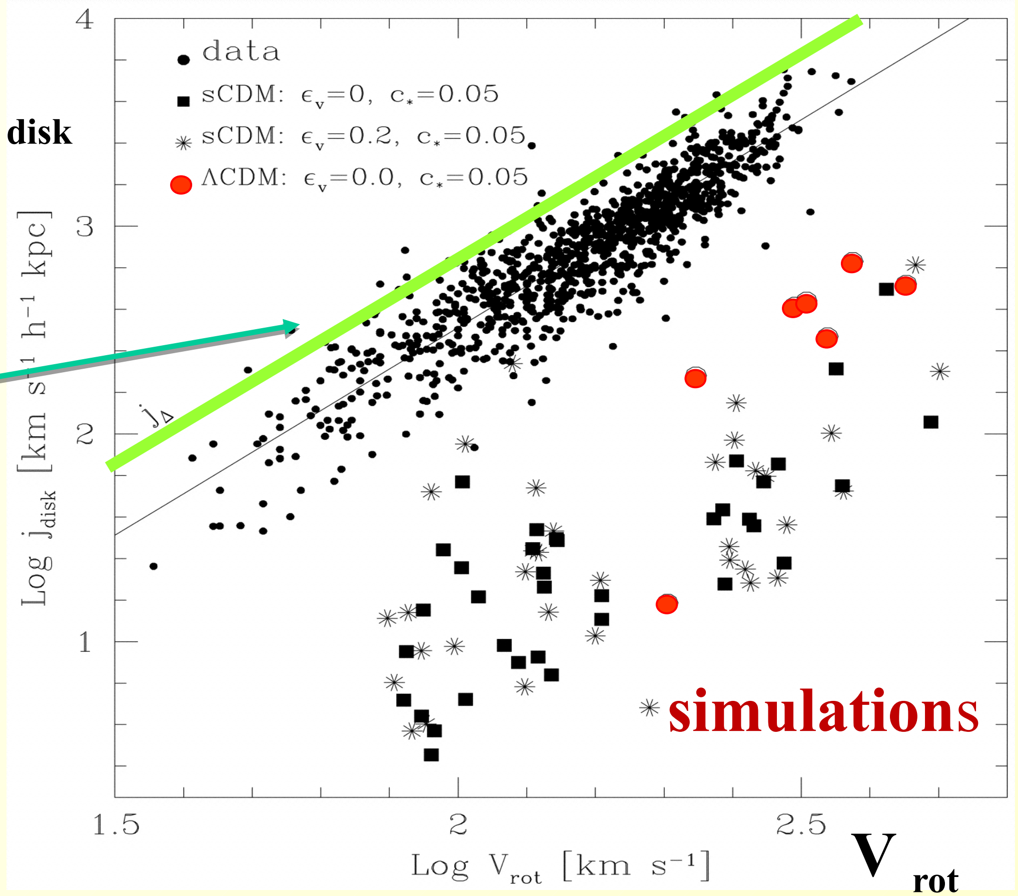
The angular momentum problem

Angular Momentum

J = r V

Prediction of the simple model



(Navarro et al. 2000)

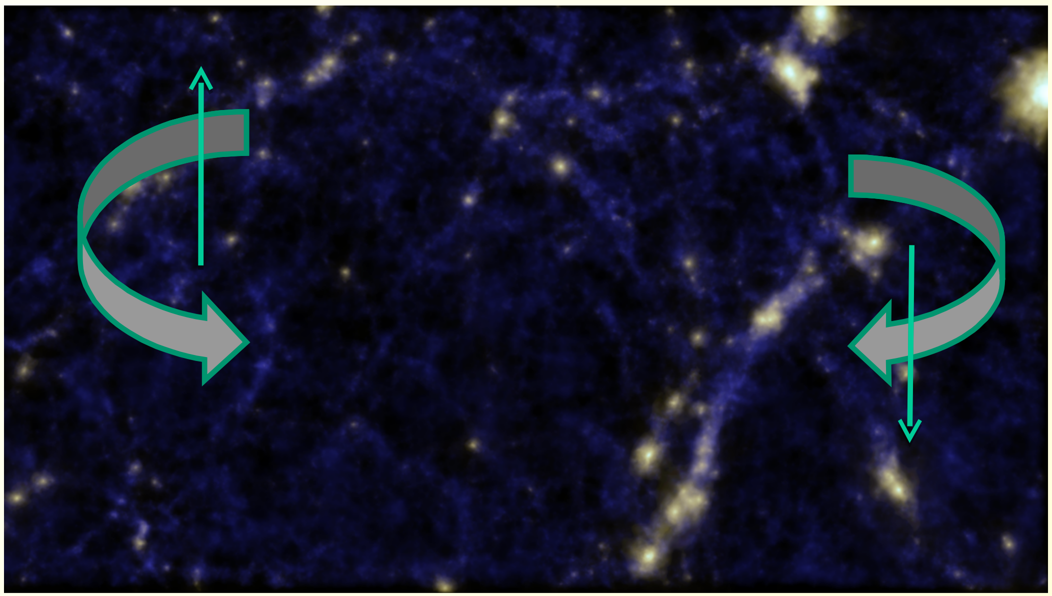
➔Disks keep only half of the initial angular momentum

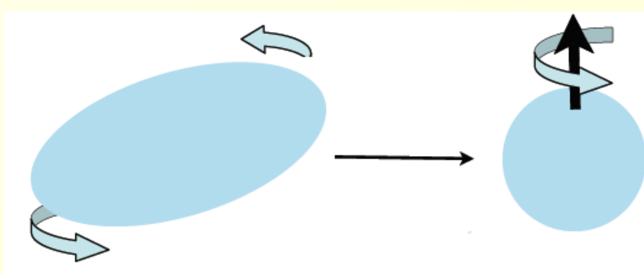
Link with over-cooling pb

Simulated disk galaxies have sizes **10 times lower** than what is observed ➔ look like bulges

Origin of the angular momentum

At the collapse epoch, before decoupling from expansion, tidal torques create angular momentum





➔ Spin Parameter

$$\lambda \equiv J|E|^{1/2}G^{-1}M^{-5/2}$$

Average value

$\langle\lambda\rangle$ = **0.05**

Fall & Efsthatiou 1980

Evolution of angular momentum

Model for disk formation

Initially baryons have the same momentum as DM **<--> ~0.05**

-- Conservation of angular momentum
when baryons fall into dark matter potentials (Mo et al 1998)

-- Adiabatic contraction (Barnes and White 1984, Bluementhal et al 1986)

-- Formation of bulges/spheroids by mergers or disk instability
(Toomre & Toomre 1972, Combes et al 1990, Dalcanton et al 1996)

-- Feedback from Supernovae (Dekel & Silk 1986, van der Bosch et al 2002)

Problems of standard model

Angular momentum catastrophy

Cosmological simulations show that the angular momentum of baryons is not conserved during collapse

(Navarro and Benz 1991, Steinmetz and Navarro 1998, 2000; Sommer-Larson et al 2000)

The momentum distribution

The distribution of specific J in simulations does not correspond to observations (Bullock et al 1999, van der Bosch et al 2000)

Other problems:

Size of disks determined not only by λ

(Lacey and de Jong 2000)

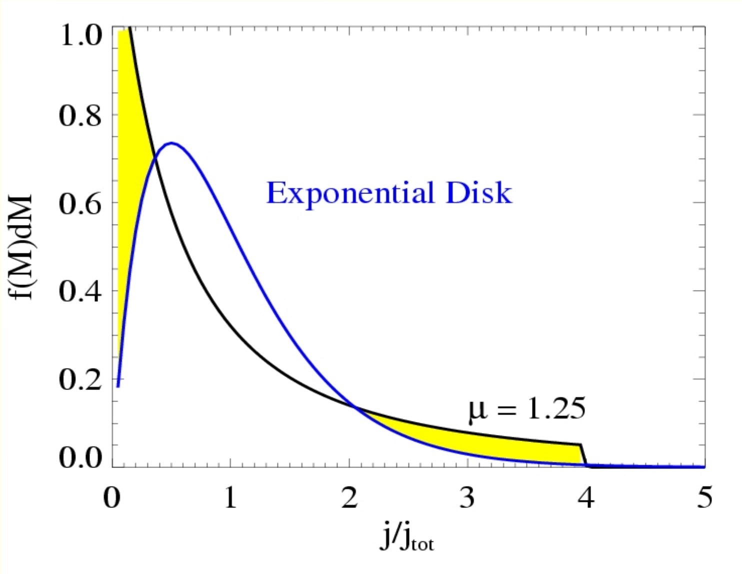
Major mergers ➔ ∼≅ too large (spheroids)

(D'Onghia et al 2006)

Distribution of momentum J

The problem might be linked with too frequent galaxy mergers which cancel angular momentum

$$\frac{M(<j)}{M_{\rm vir}} = \frac{\mu\, j/j_{\rm max}}{\mu - 1 + j/j_{\rm max}}, \quad \mu > 1$$



log-normal distribution

But the distribution of momentum J is not correct either

Excess of matter with low and high momentum, in comparison with an exponential disk

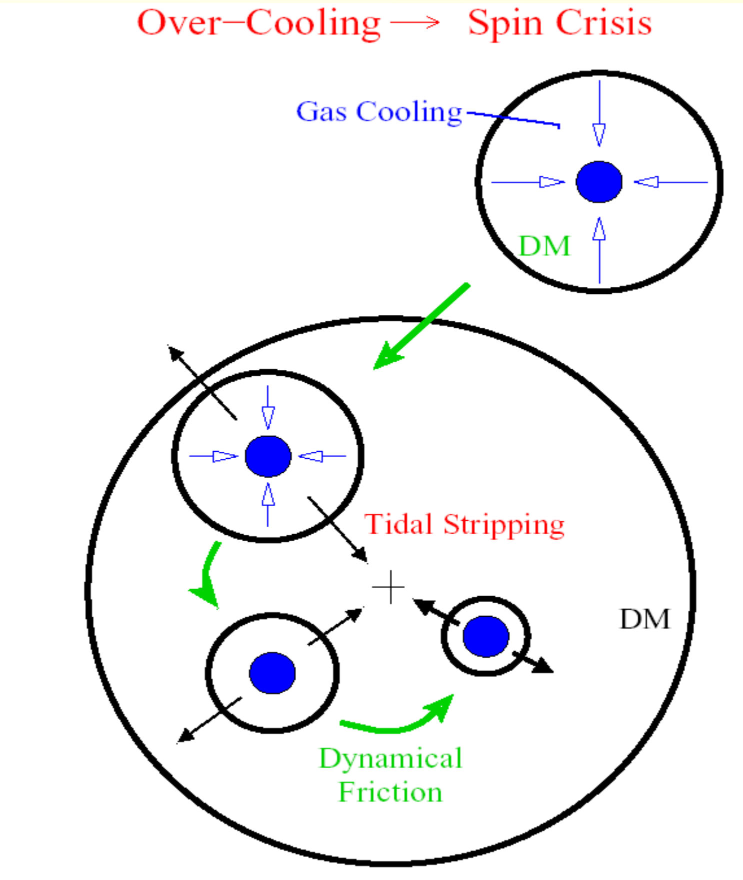
Major mergers have the highest -

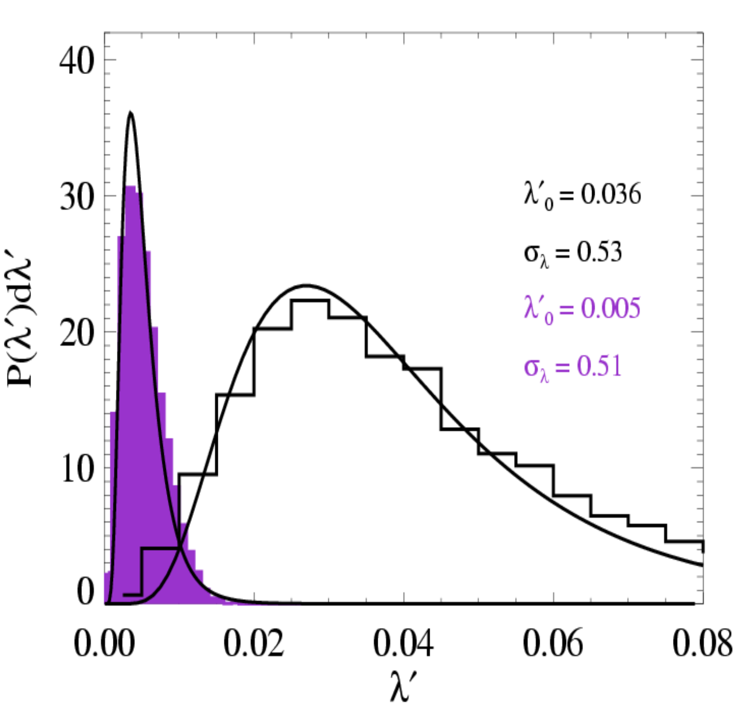
D'Onghia & Burkert (2004)

The angular momentum problem comes from baryon contraction

The center is shielded from tidal forces while the outer parts (DM) are diluted

➔Diluted regions do not suffer dynamical friction

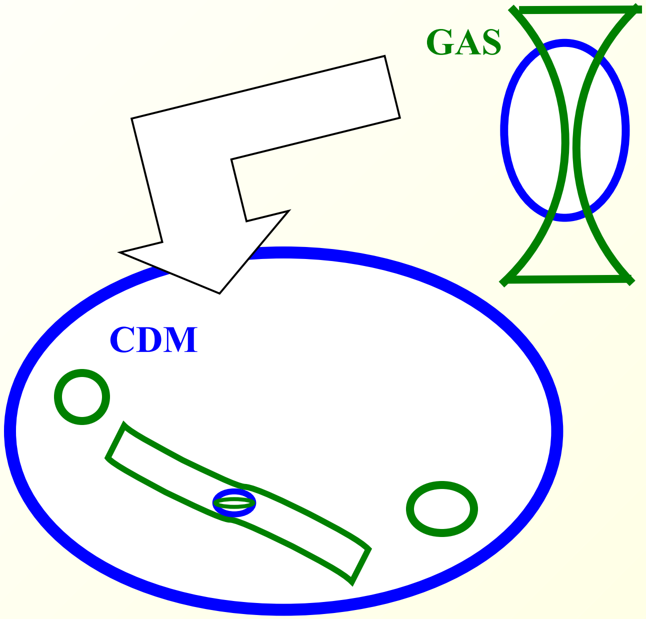




Solution: prevent baryons to infall
Or supernovae, AGN to eject them

Maller & Dekel 2002

Avoid dynamical friction



If the gas is accreted slowly
as a cold phase in galaxies,
Less loss of angular mometum
through hierarchical mergers
and dynamical friction

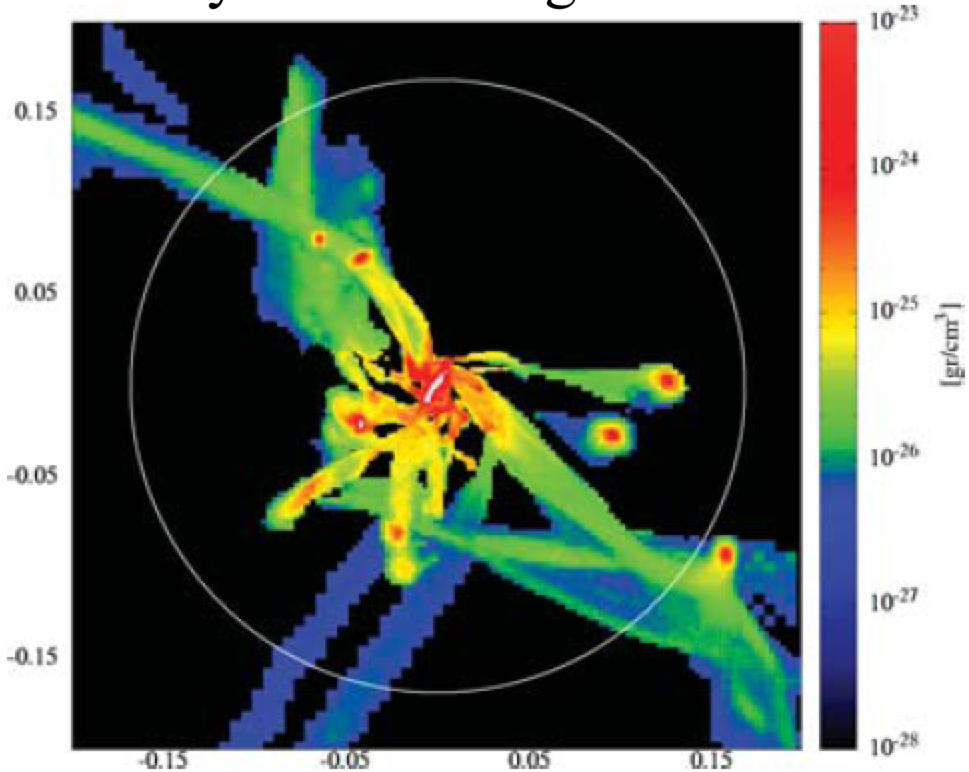
Late accretion in the universe

Same process as feedback,
but more efficient
(Gnedin & Zhao 2002)

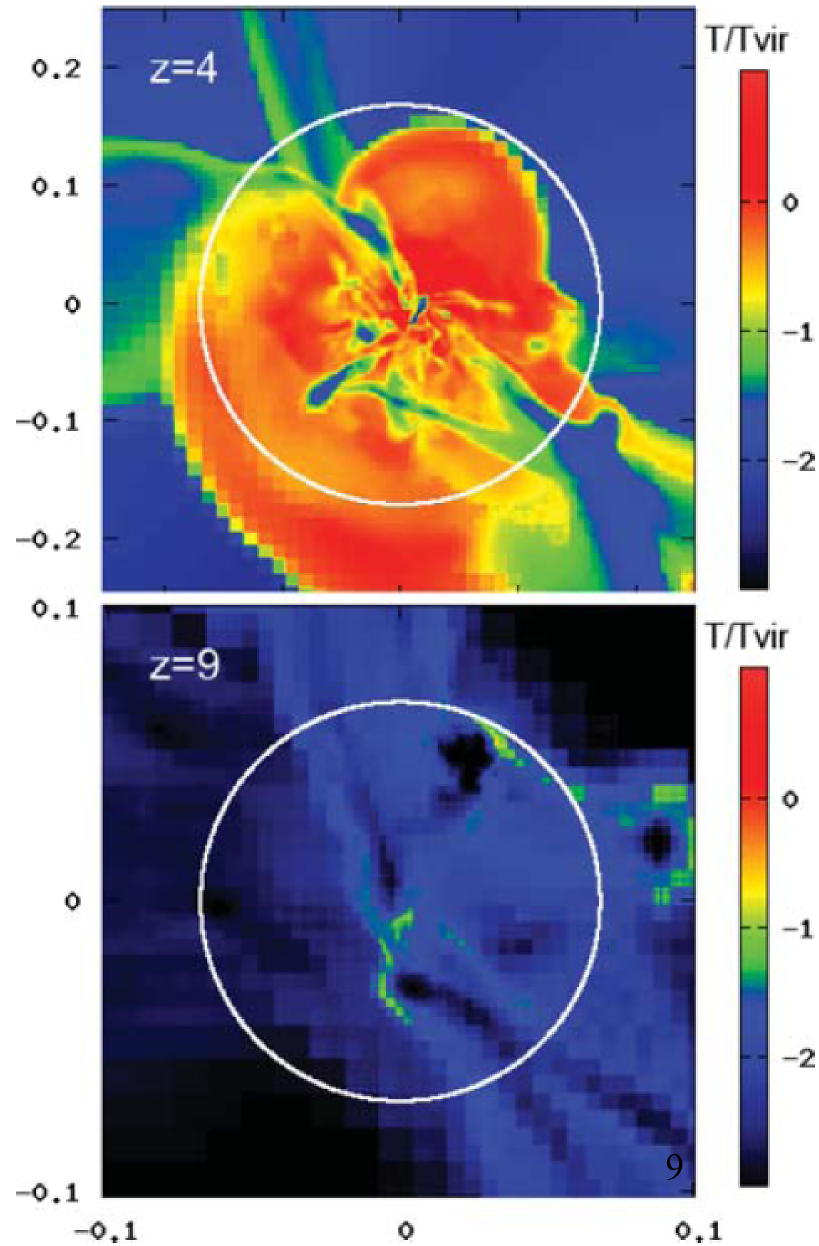
The gas, stripped and diluted, does not suffer dynamical friction

Cold gas inflow in filaments

Density of the cold gas



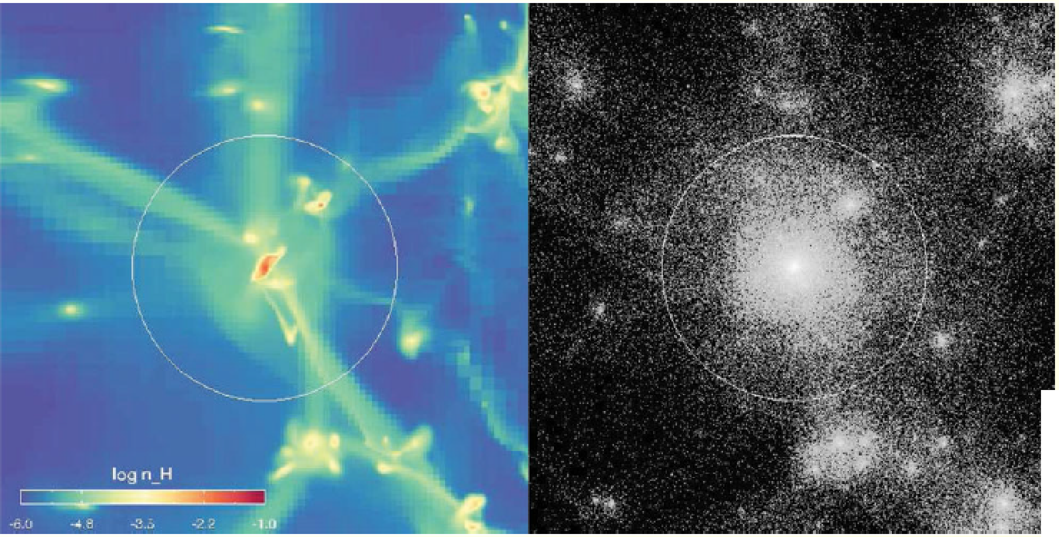
Temperature



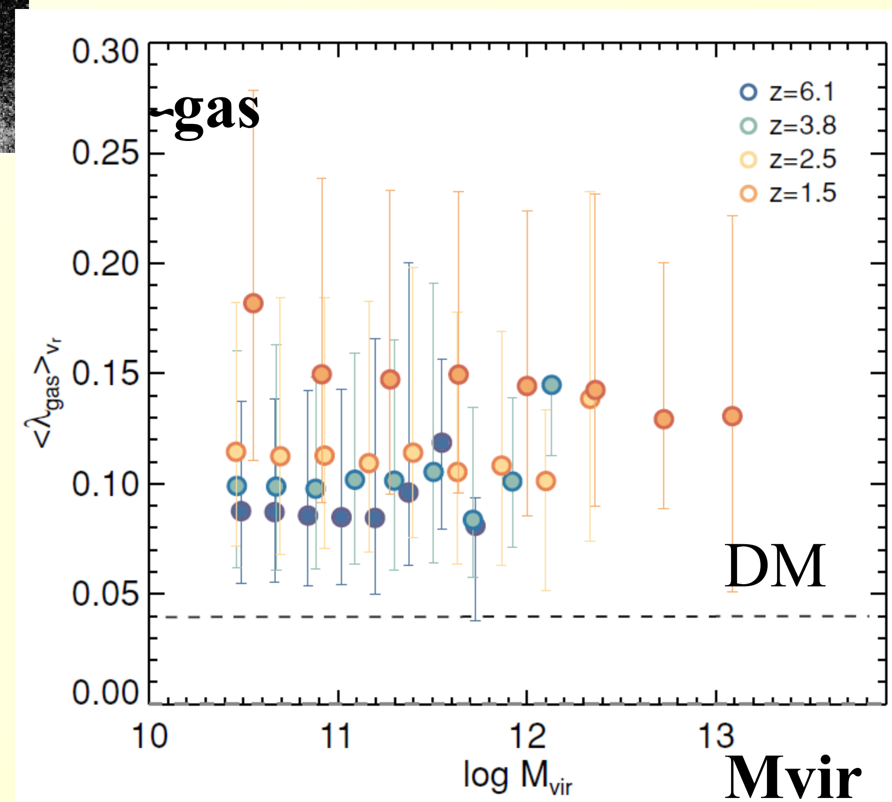
Quenching of star formation
Depending on redshift and mass

Dekel & Birnboim (2006))

Angular momentum from filaments



Gas filaments thinner
Concentrate J
~ larger than the
average ~=**0.04 for DM**



Gas AM keeps high, until R~0.1 Rvir, where it falls drastically, through vector cancellation(Kimm et al 2011)

Stars have lower ~ than gas

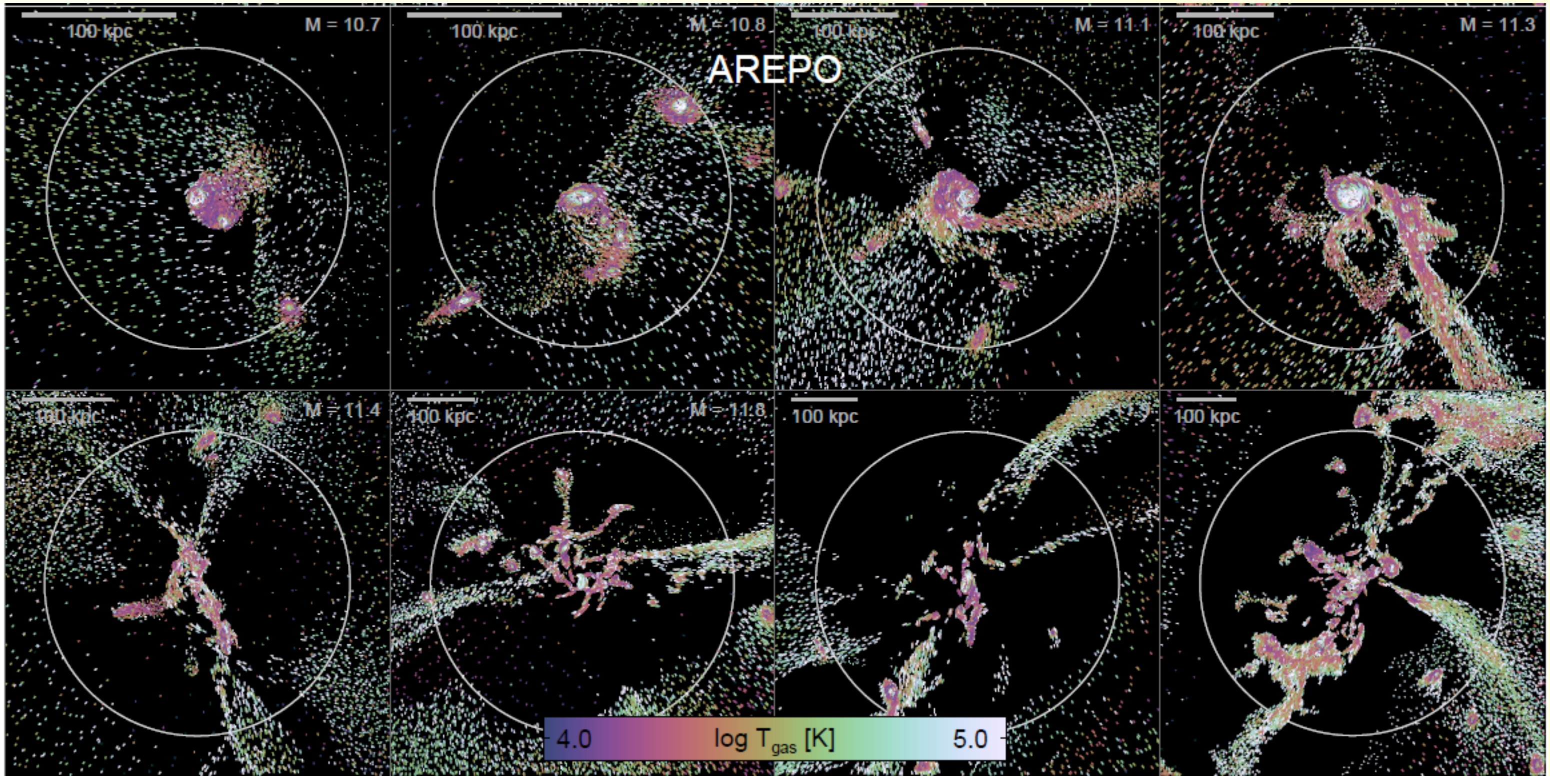
Pichon et al 2011

AM depends on detailed gas physics

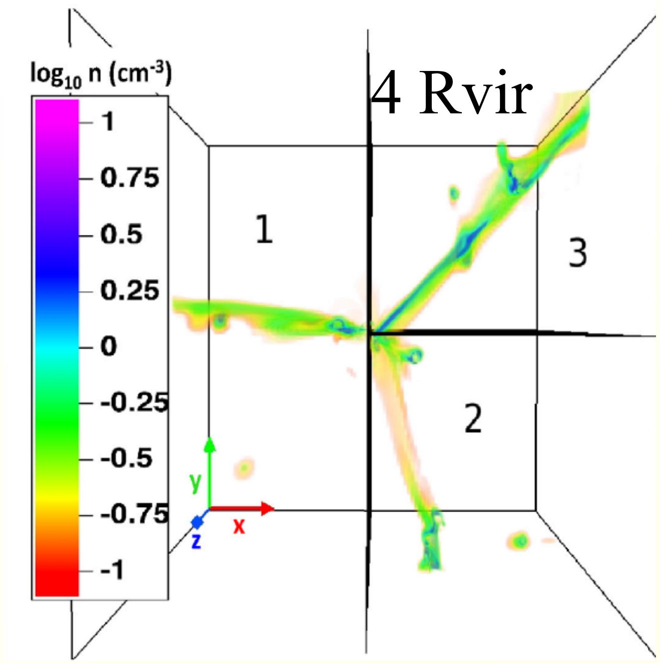
Nelson et al (2013) AREPO, formation of gas clumps,
➔heating, and hot gas accretion

Multiphase gas?

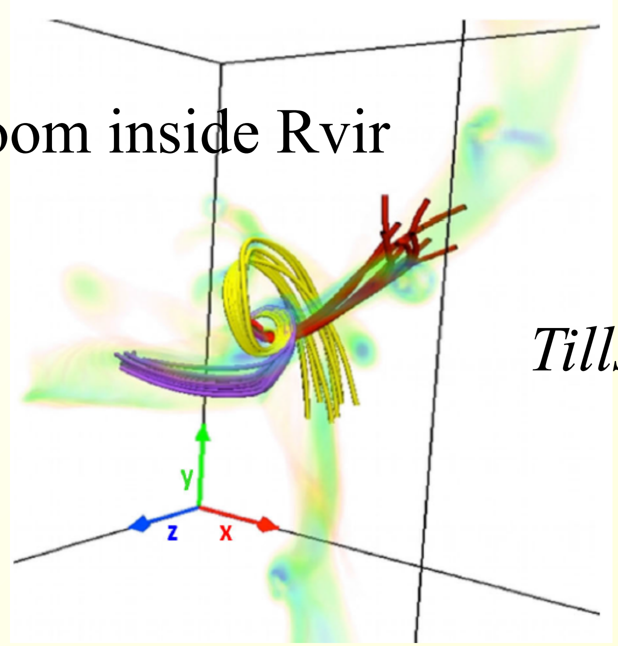
Tillson et al (2015) AMR: fluid eulerian gas, smoother
➔Cold accretion maintains longer, in mass and redshift
however, AM cancellation



4 Rvir

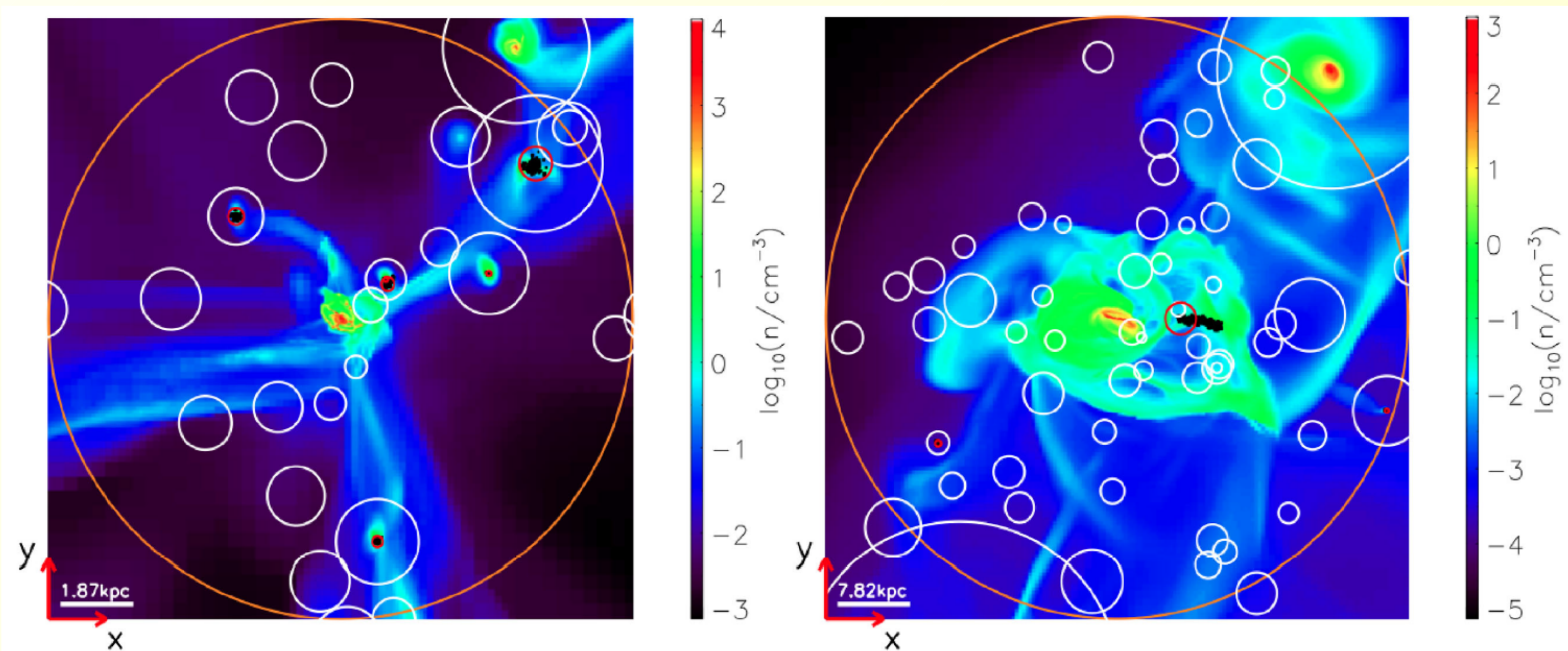


Zoom inside Rvir



Tillson et al 2015

Minor mergers with satellites are a negligible contribution



Spin swings, filament alignments

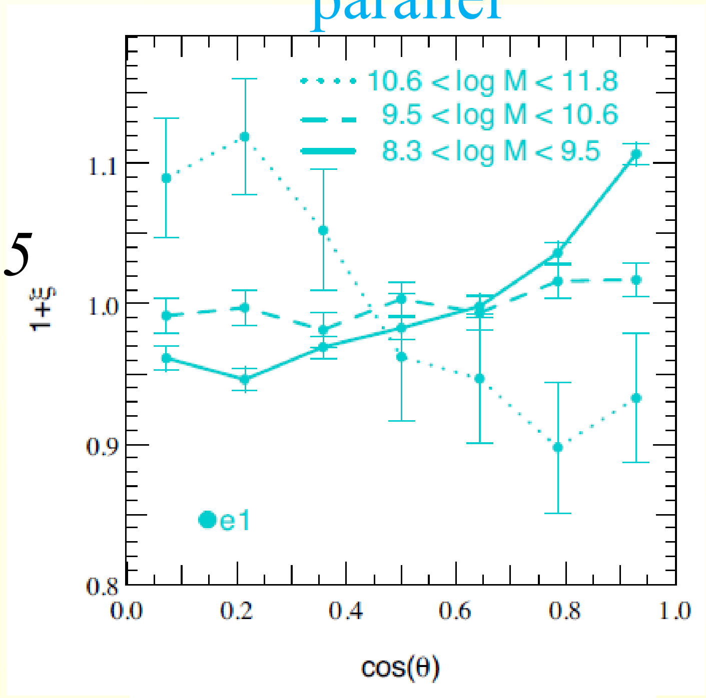
Galaxy spin is **parallel to the filament for low-mass, blue galaxies**, and **perpendicular to it for high-mass, red galaxies**

➔massive galaxies have been re-oriented by mergers

Dubois et al 2014

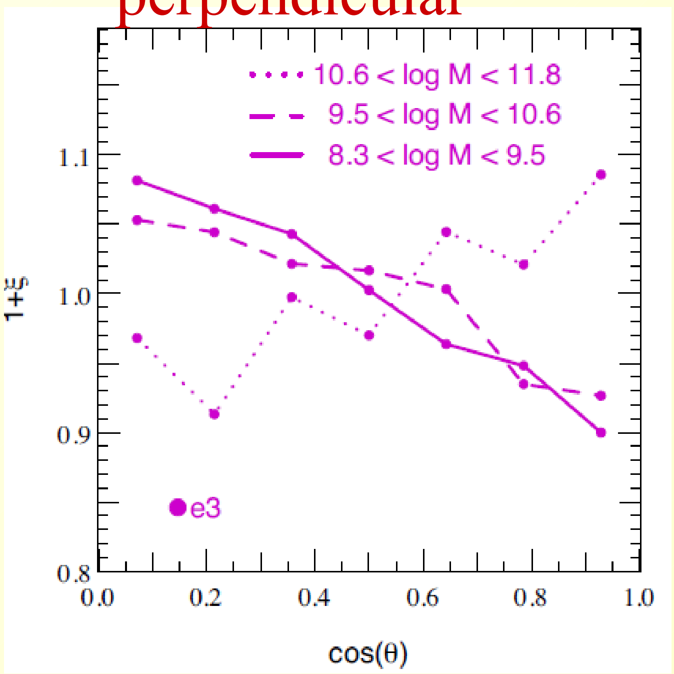
Codis et al 2015

parallel



$$\cos\theta = \mathbf{L}\cdot\mathbf{e}_i/|\mathbf{L}|$$

perpendicular



Bailin & Steinmetz 2005, Welker et al 2014

Evidence for gas accretion

Most of the gas from cosmic filaments is accreted at large scales, and settles down to the disk
➔Warps and Polar rings are the best tracers
Lopsidedness (Jog & Combes 2009)

➔Some gas is projected in the halo, either by stellar feedback, or through tidal disruption of satellites
HVC and Magellanic stream as examples

Gas in the halo is accreted progressively, with an interface of multiphase gas
But at a rate lower than the star formation rate (< 1 Mo/yr)
(0.4 Mo/yr in the Galaxy, Putman etal 2012)

Polar Ring Galaxies (PRG)

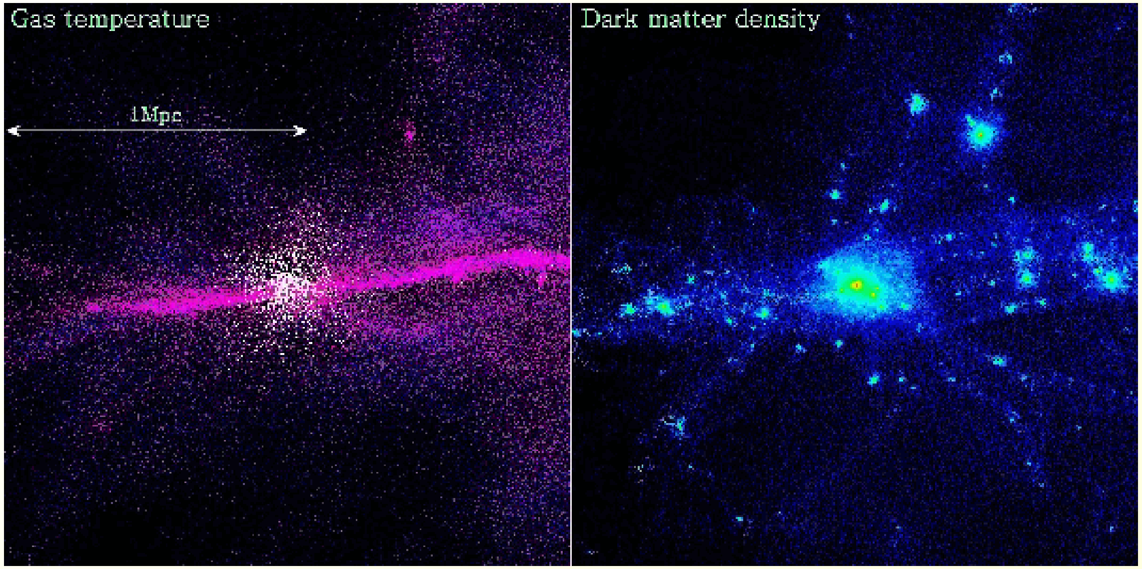
The polar ring is akin to late-type galaxies
large amount of HI, young stars, blue colors
Probability to have a PRG ~5%
(Whitmore et al 90)

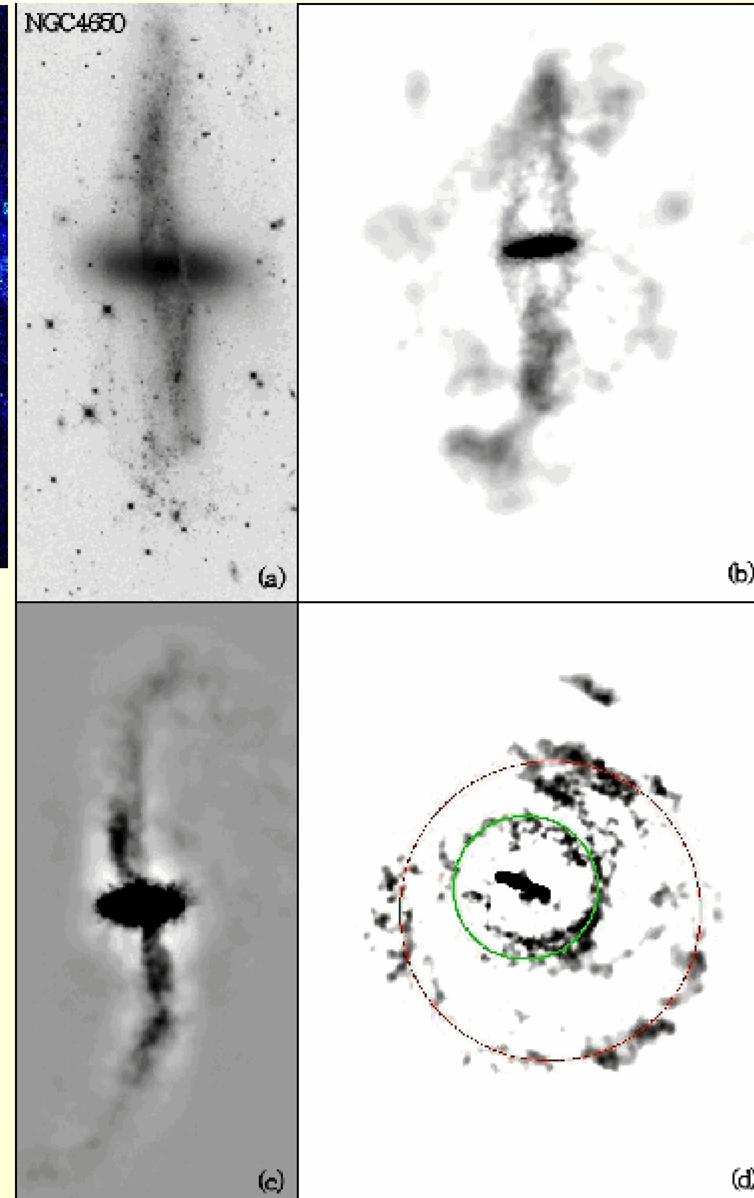
Galaxy Zoo (Finkelman et al 2012)
16 candidates at slightly higher-z
Even higher z (HST) Reshetnikov 1997
Moiseev et al 2011: 275 candidates

Unique opportunity to check the shape of
dark matter halo

But several **formation scenarios**
Galaxy interactions or..

Cold accretion from cosmic filaments

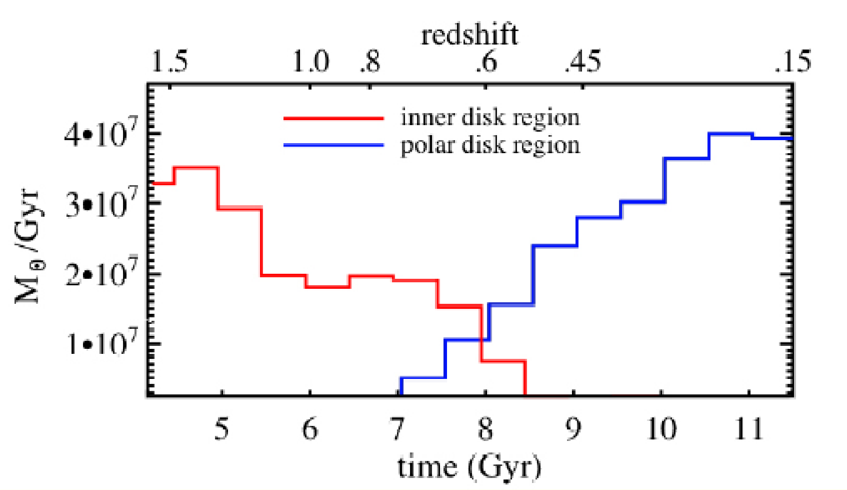




Maccio et al 2006

- Gas in the PR and stars in the host
- Several small companions also in the filament
- Dark matter quite round in the visible part after the infall of gas

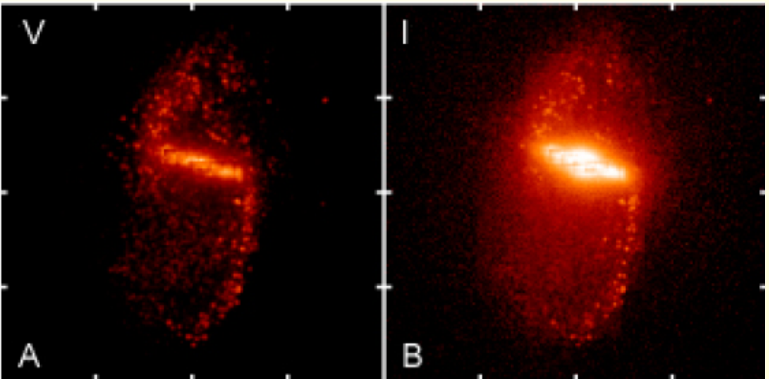
Polar rings from cosmic gas accretion



Brook et al 2008

➔After 1.5 Gyr, interaction between the two disks destroys the PRG

➔Velocity curve about the same in both equatorial and polar planes



Misaligned cosmic infall

The fact that some PRGs are polar disks more than polar rings supports the formation through cosmic accretion
Spavone et al. (2010)

While the presence of **a true ring** supports the tidal accretion

Snaith et al. (2012) develop cosmic accretion as in Brook et al. (2008):
The polar disk is progressively formed **out of gas and dark matter** infalling from a cosmic filament

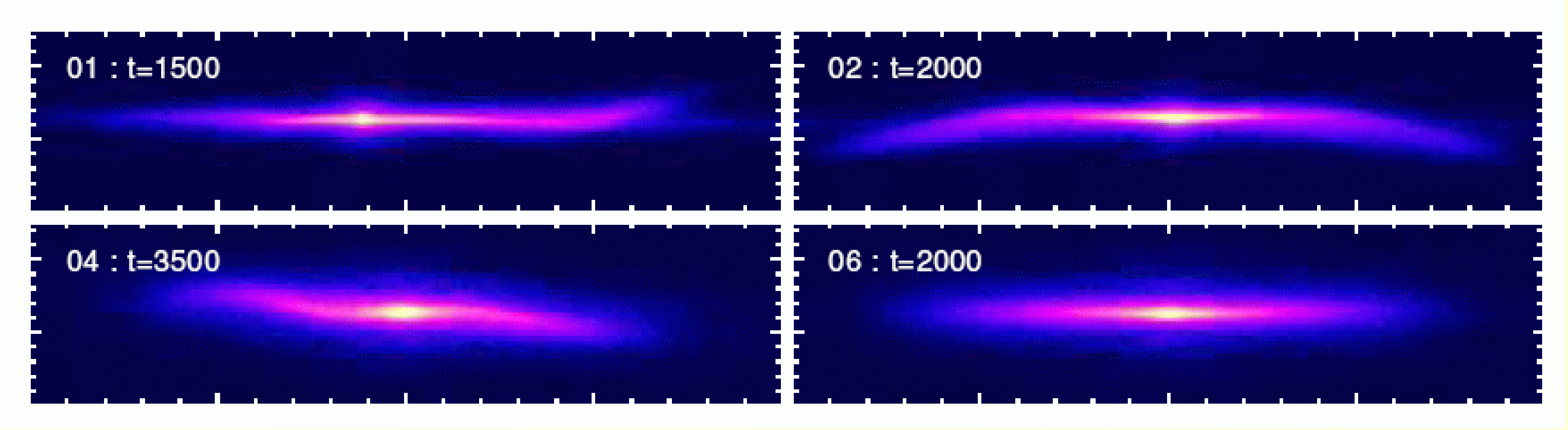
➔This implies that the dark matter is aligned with the polar system

Warps: constraints on dark matter

If the disk is self-gravitating, spontaneous bending instabilities
Can explain warps (Revaz & Pfenniger 2004)
If below Araki limit ≅ z/≅ r = 0.293
Optical warps (weak), not the HI warps

≅ z/≅ r = 0.18

≅ z/≅ r = 0.22



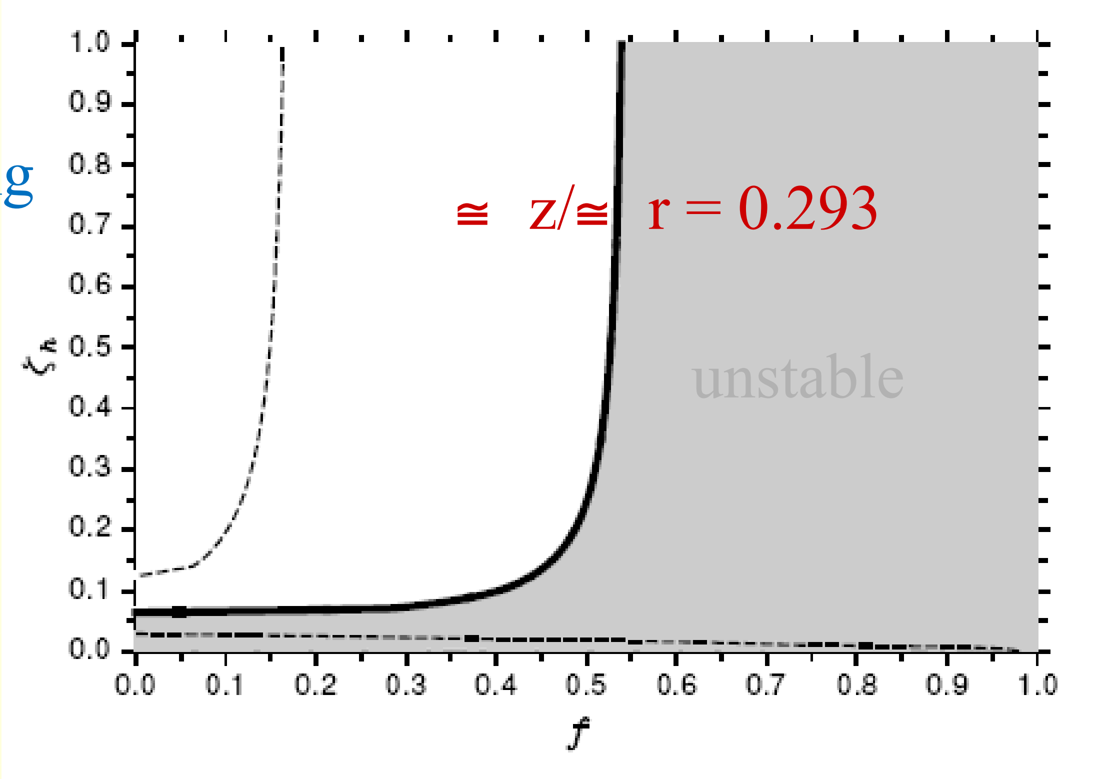
≅ z/≅ r = 0.28

≅ z/≅ r = 0.32

Fraction of dark matter in the disk

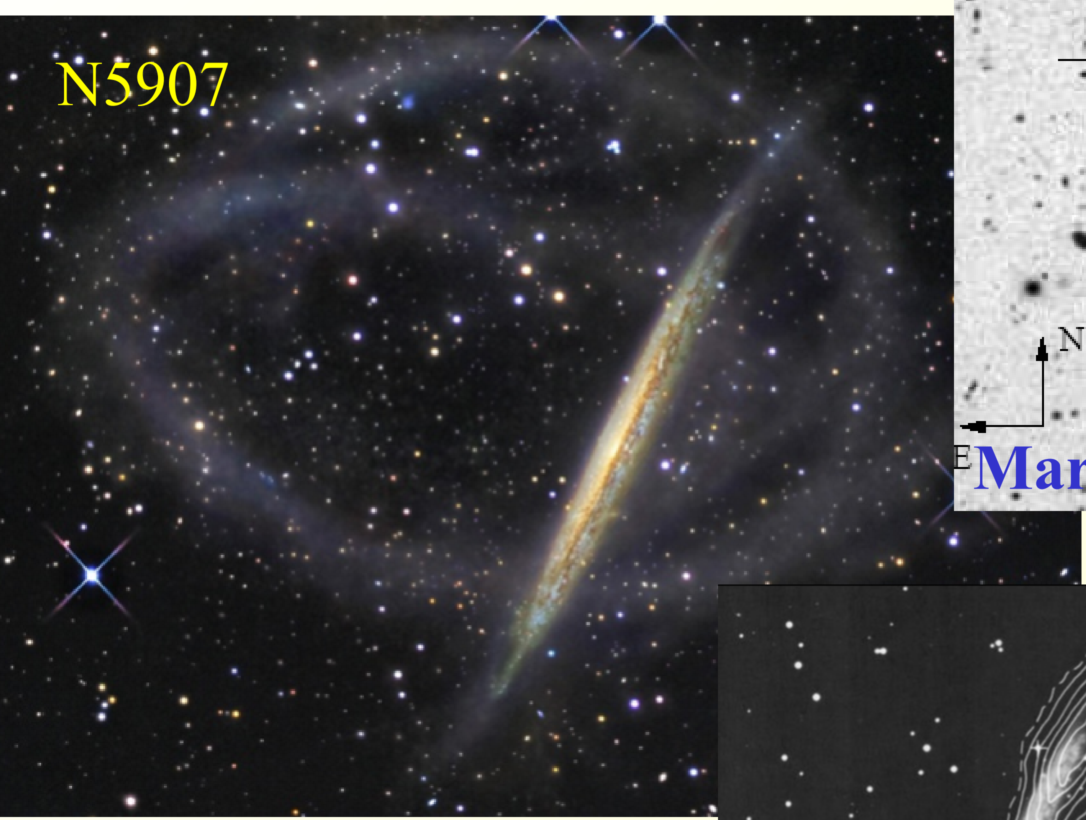
Above a certain fraction f=0.5, the disk is always unstable

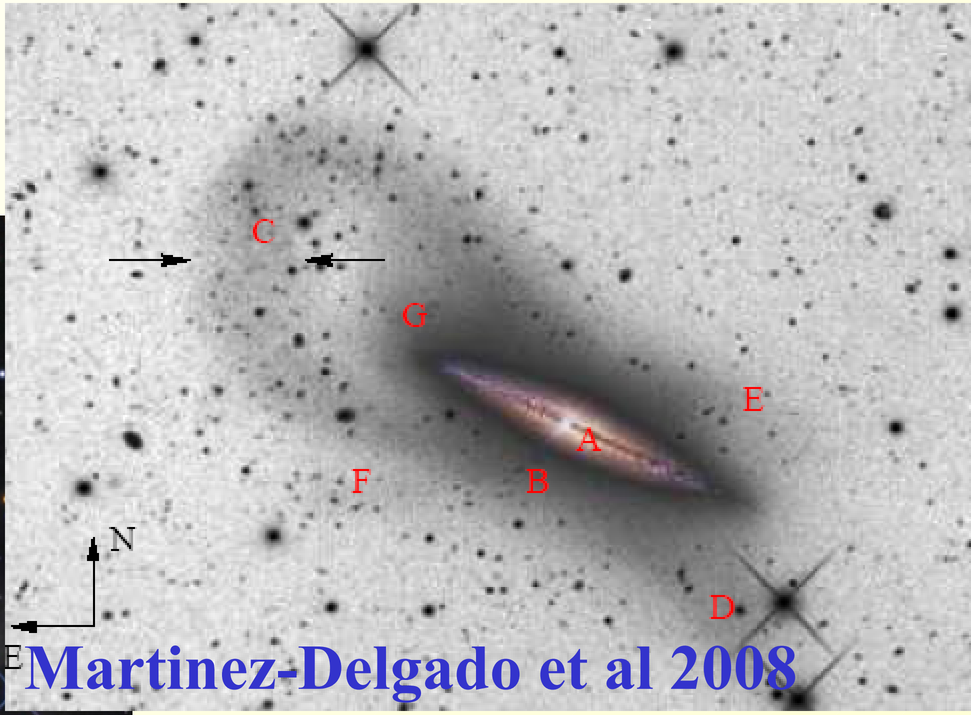
Halo flattening



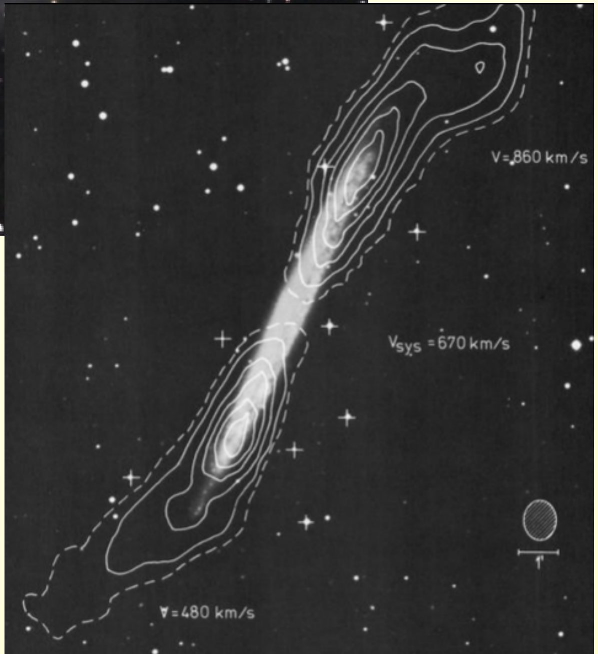
Revaz & Pfenniger 2004

Warped disks

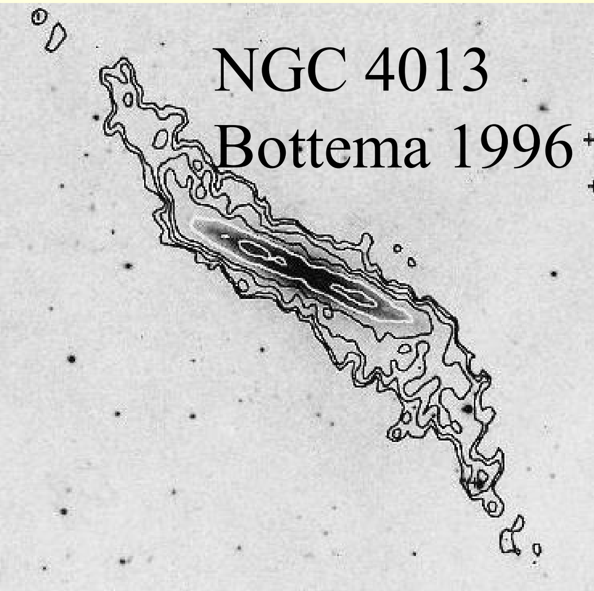




Martinez-Delgado et al 2008



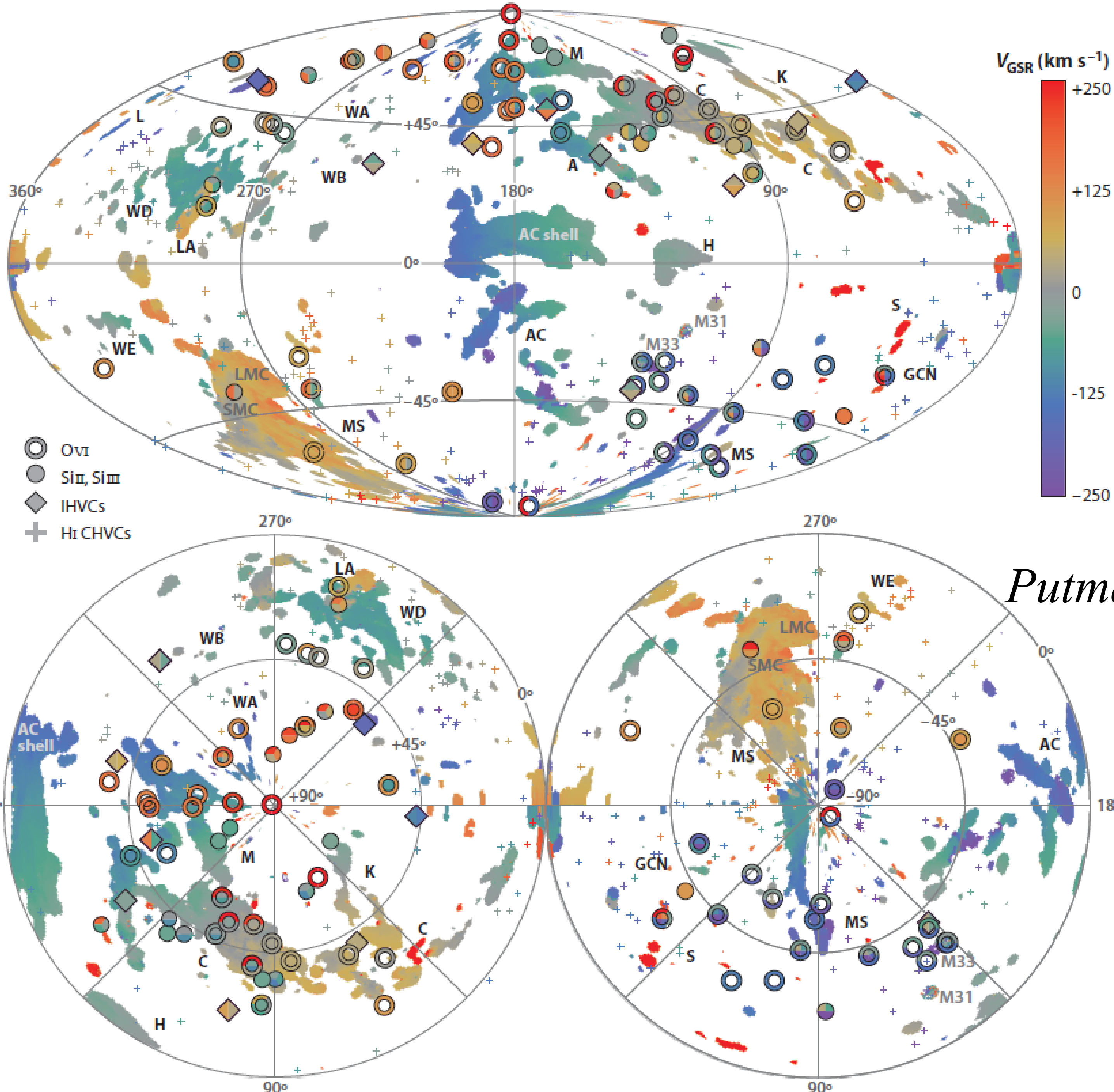
Sancisi 1976



NGC 4013
Bottema 1996

Companions?

HVC in the Milky Way

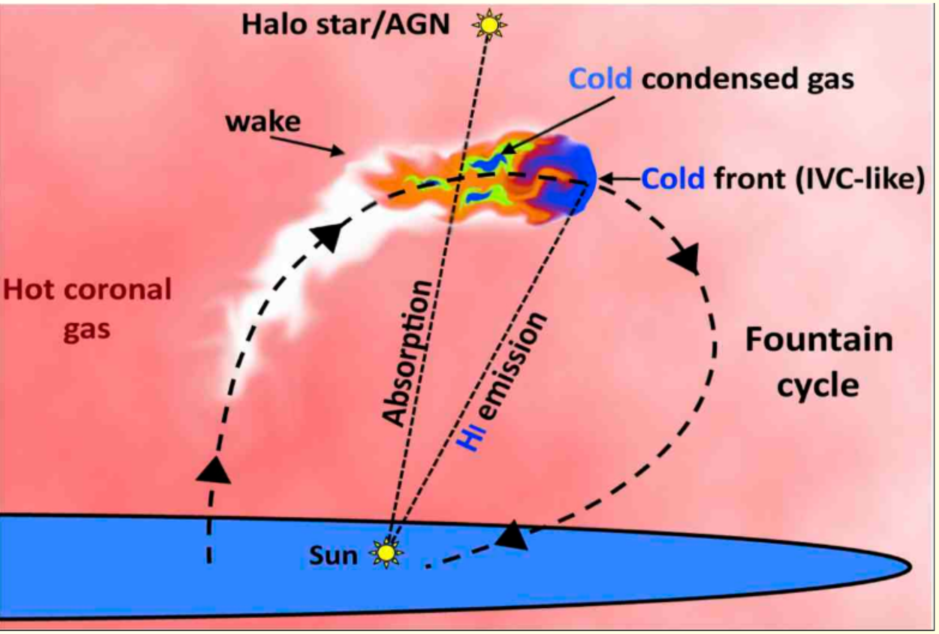


Putman et al 2012

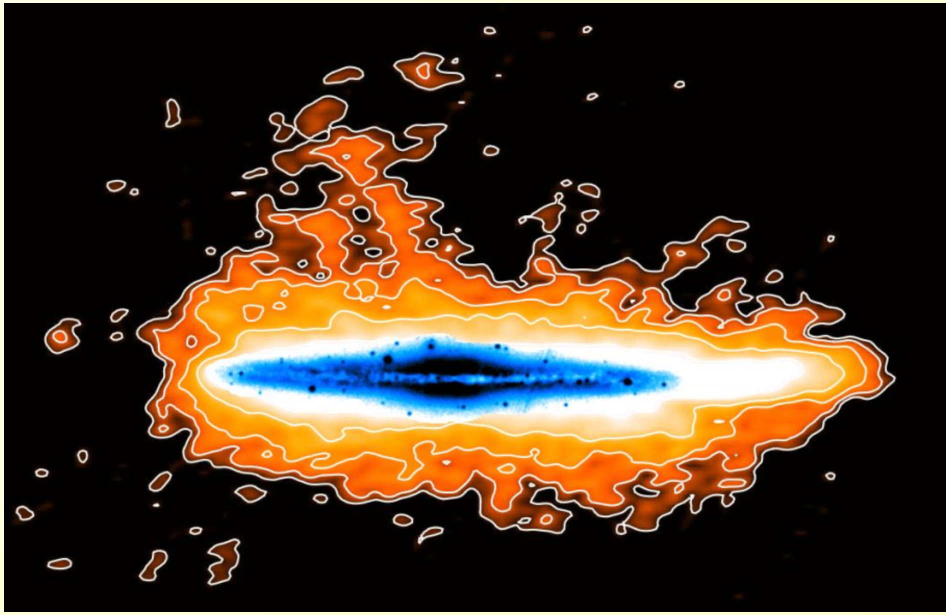
Fountain effect triggers cooling

NGC 891, Oosterloo et al 2007, Lelli et al 2013

Not all the gas is of external origin

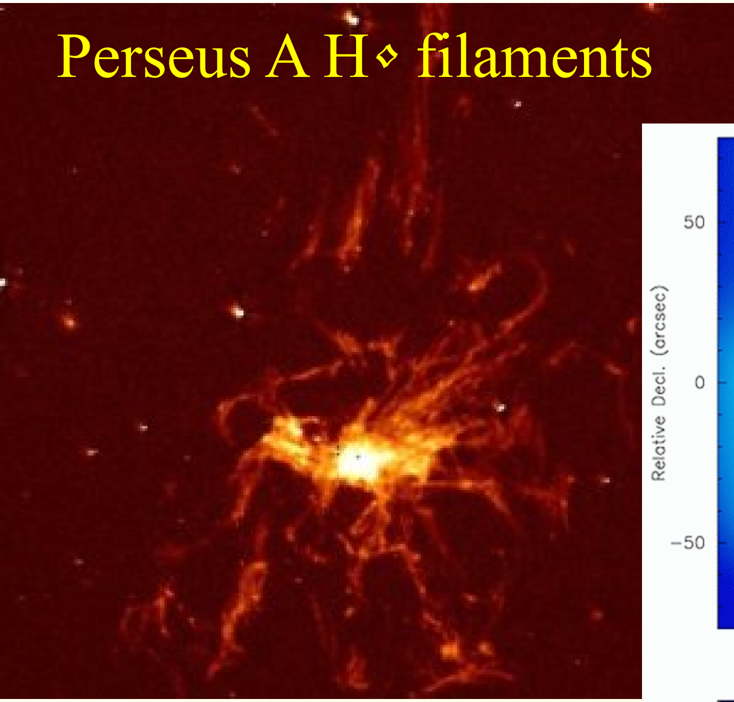


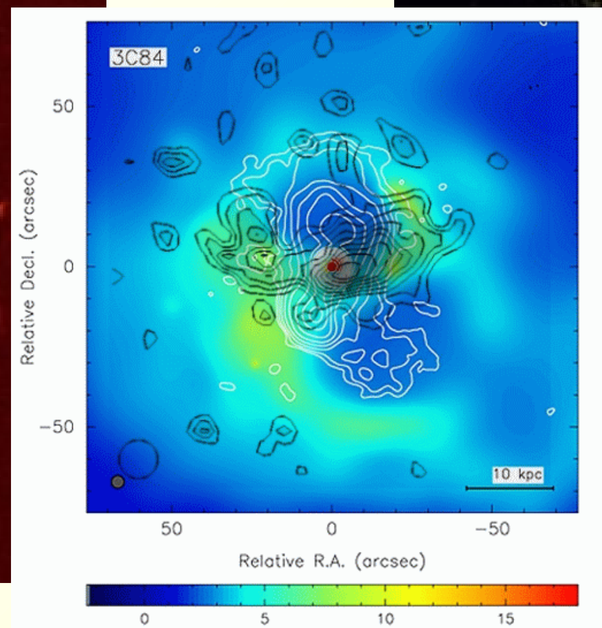
Fraternali & Binney 2008

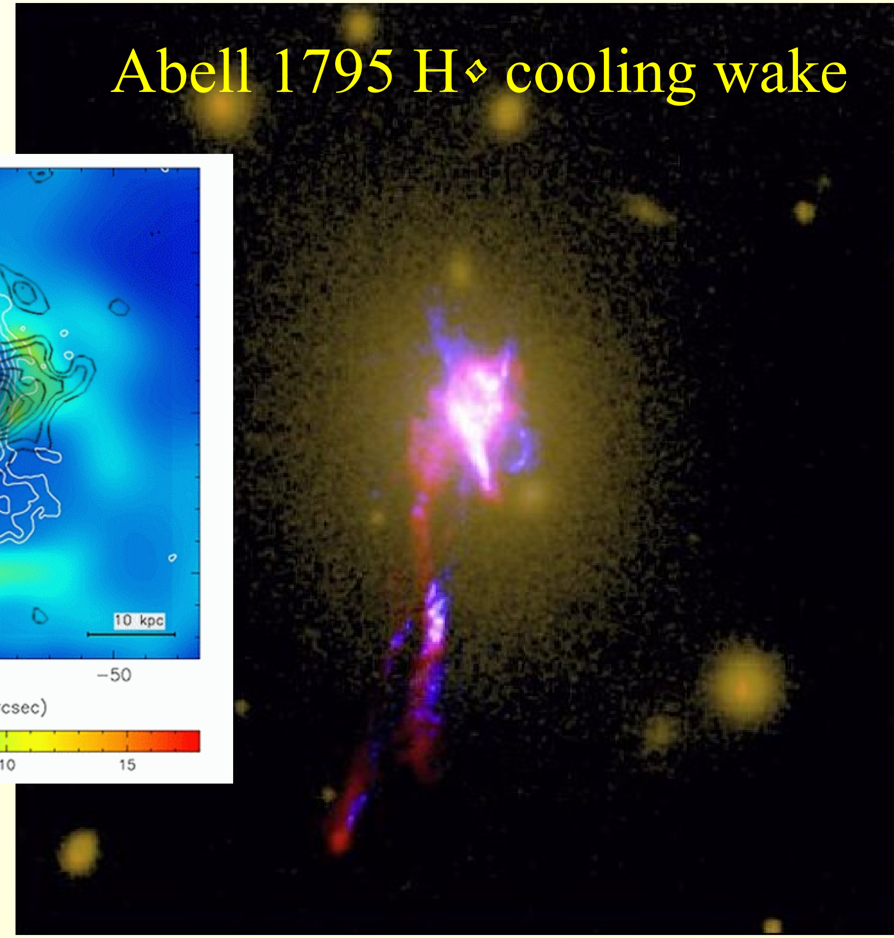


A way to operate hot gas accretion

Cooling flows in galaxy clusters







In rich environments, cold gas accretion is quenched

But **hot gas cools in the center**,

As witnessed by large **cold molecular gas** detections

(Salome et al 2006, McDonald et al 2012)

Conclusions

- Specific angular momentum of DM and gas ~ ~0.05
- Baryons in filaments: more AM than dark matter
- Filaments dominate the mass, and the angular momentum

- Close to galaxies, loss of AM, highly dependent on the gas physics, clumps, temperature, cooling
- Evidence of accretion ➔ polar rings, warps, HVC
- As for polar rings, warps might be explained by interactions and mergers