# Angular momentum of dwarf galaxies


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# Angular momentum (AM)

- Mass and AM are fundamental parameters.
- AM in galaxies is originated from tidal torques between neighbouring halos. (Peebles 1969)
- Models predict specific angular momentum (j) of halo $j_H \propto M_H^{2/3}$
- Baryons and dark matter acquire identical AM initially. (van den Bosch et al. 2002)

# Observations

- Stellar $j_*$ & $M_*$ follow $j_*=kM_*^{2/3}$, with ellipticals have 5x lower than spirals. (Fall 1983; Romanowsky & Fall 2012)
- Baryonic $j_b$ and mass $M_b$ correlate with bulge fraction ($\beta$), $j_b \propto M_b$ for a fixed $\beta$. (Obreschkow & Glazebrook 2014)
- Dwarfs lie above $j_b$-$M_b$ relation for bulge-less spirals.

(Butler et al. 2017, Chowdhury & Chengalur 2017)

# Environmental dependence?

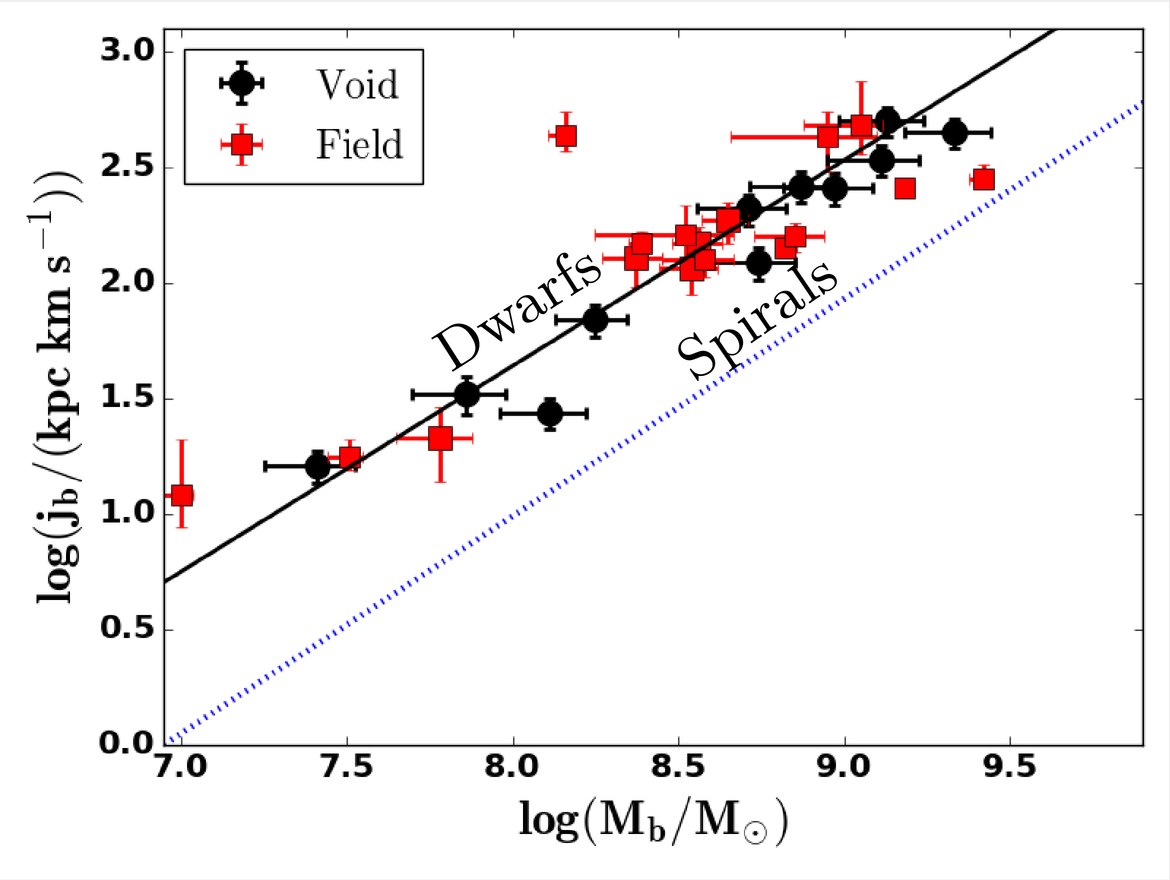
- What are the physical processes that determine AM?
  - e.g. tidal torques, feedback, accretion, and stripping
- Different processes dominate in different environments $\rightarrow$ Investigate environmental dependence of $j_b$-$M_b$ relation.

# Environmental dependence?

- What are the physical processes that determine AM?
  - e.g. tidal torques, feedback, accretion, and stripping
- Different processes dominate in different environments → Investigate environmental dependence of $j_b$-$M_b$ relation.
- Sample: 11 galaxies from Lynx-Cancer void.
- AM is calculated using the HI kinematics (GMRT, VLA) and SDSS images.

# Results: $j_b$-$M_b$ relation for dwarfs

*Kurapati et al. 2018*




Field dwarfs -> Butler et al. 2017, CC 2017

$j_b$ of dwarfs in void is similar to dwarfs in field.

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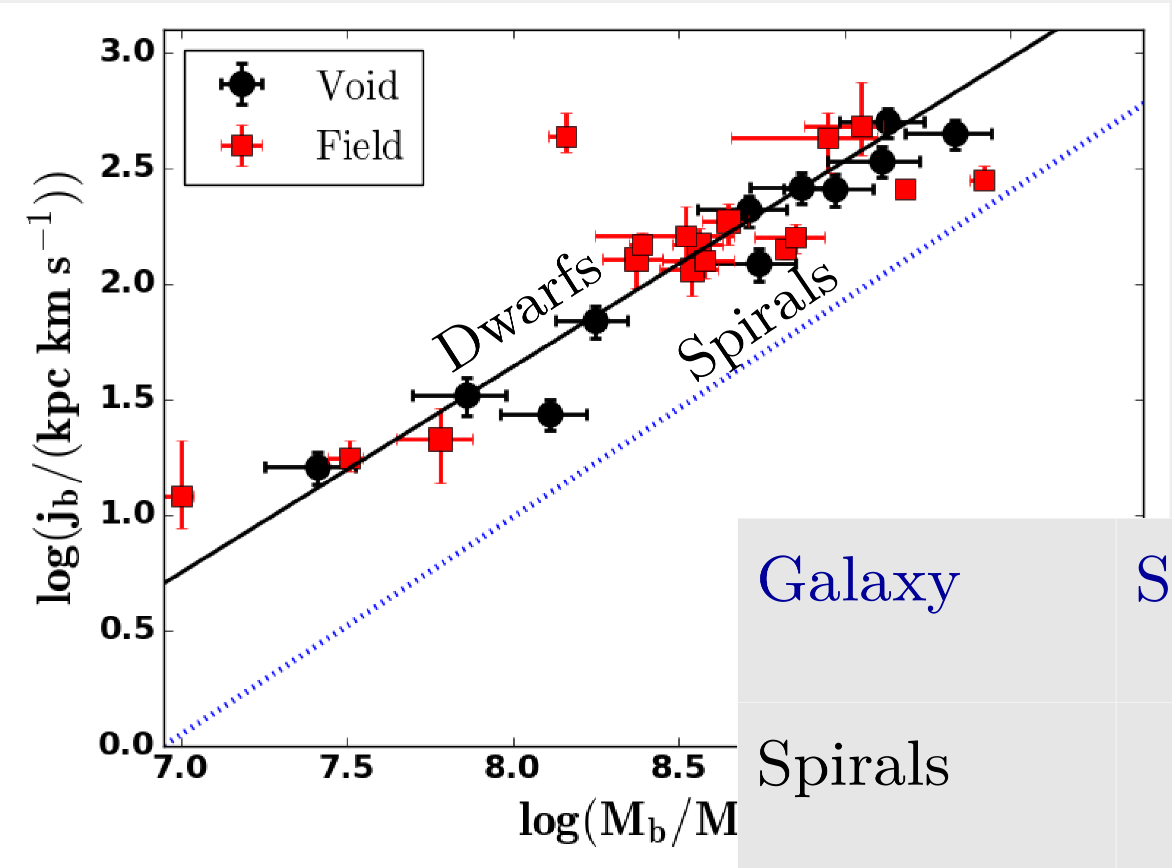



$j_b$ of dwarfs in void is similar to dwarfs in field.

| Galaxy | Slope | Intercept |
|---|---|---|
| Spirals | 0.94± 0.05 | -0.13± 0.04 |
| Dwarfs | 0.89± 0.05 | 0.40± 0.08 |

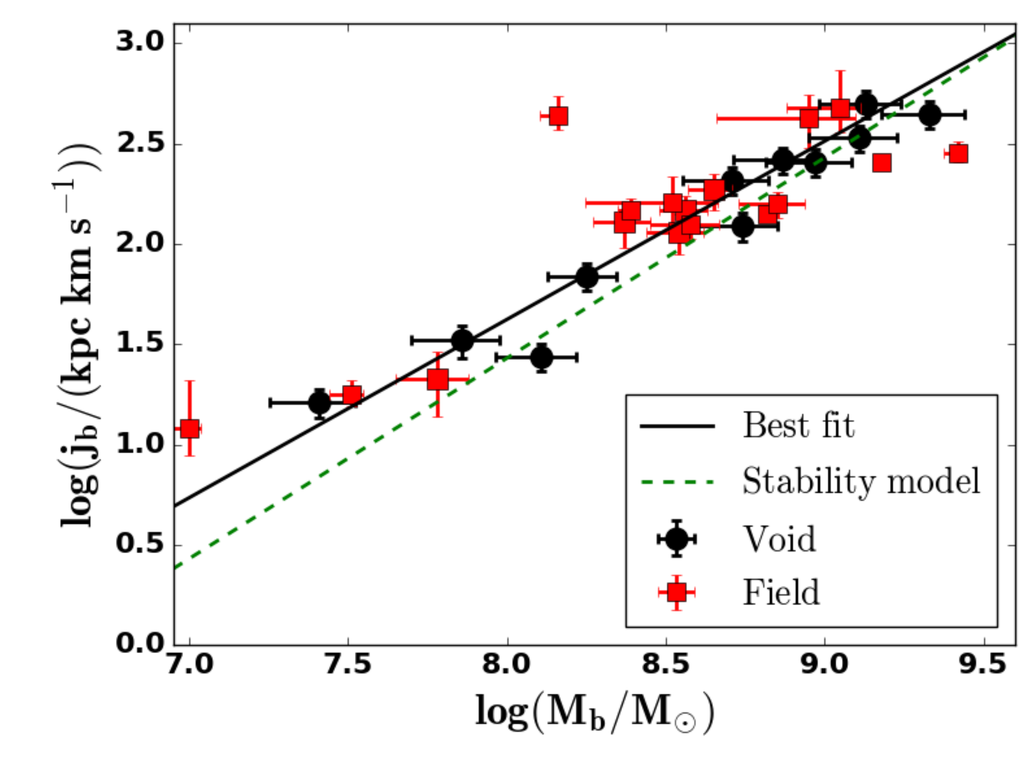
*Dwarfs have higher $j_b$ compared to bulge-less spirals.*

# Stability model

*Kurapati et al. 2018*

- If j is regulated by stability criterion, $j \propto M \times (\sigma/Q)^{-1}$, where $\sigma$ is velocity dispersion.

  (Zasov & Zaitseva 2017)

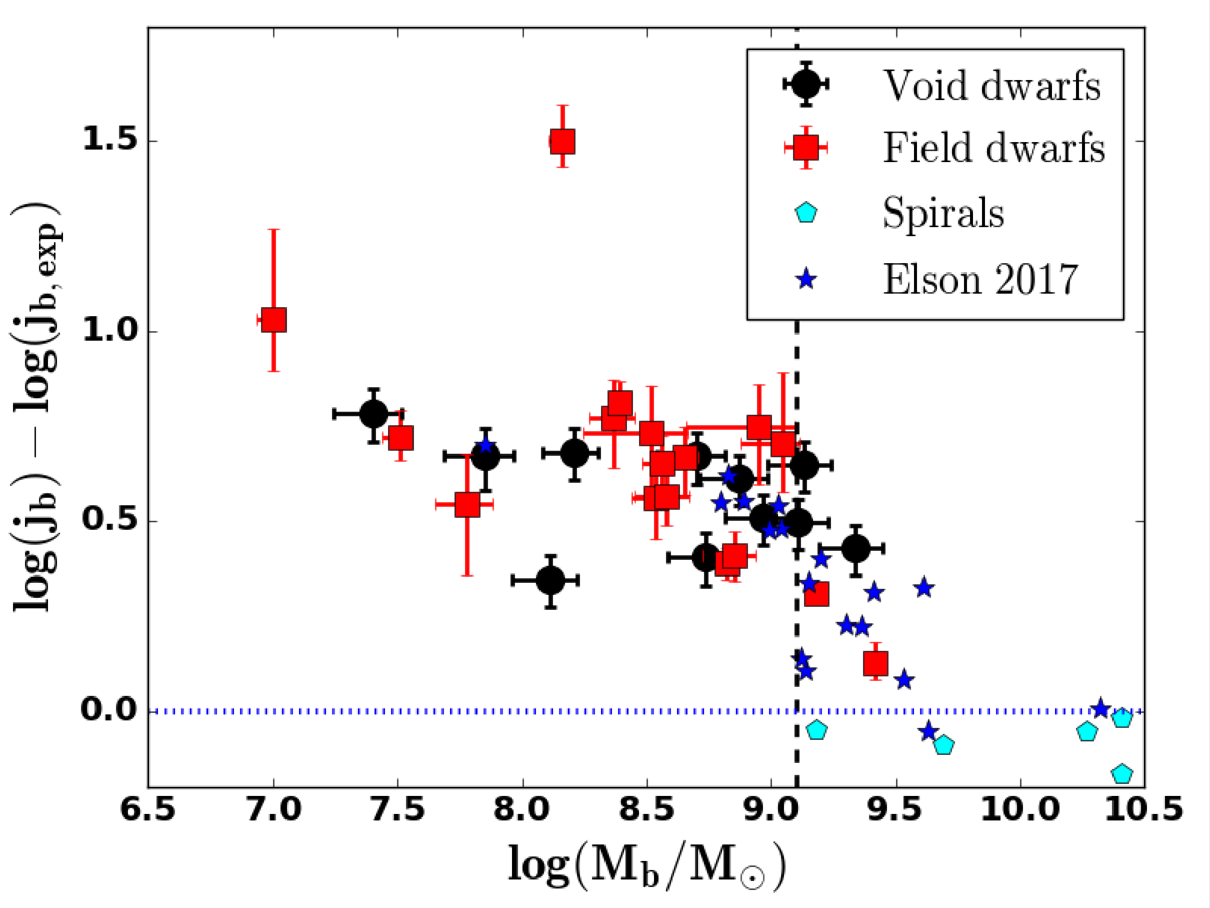



Best fit value of $\sigma/Q$ is 2.8 km/s;

matches to canonical values of $\sigma$ (6-10 km/s) and Q (2-4)

# Dwarfs versus spirals

*Kurapati et al. 2018*




*Break at $M_b \sim 10^{9.1}\ M_\odot$, similar to thickening of gas discs.*

# Stellar feedback

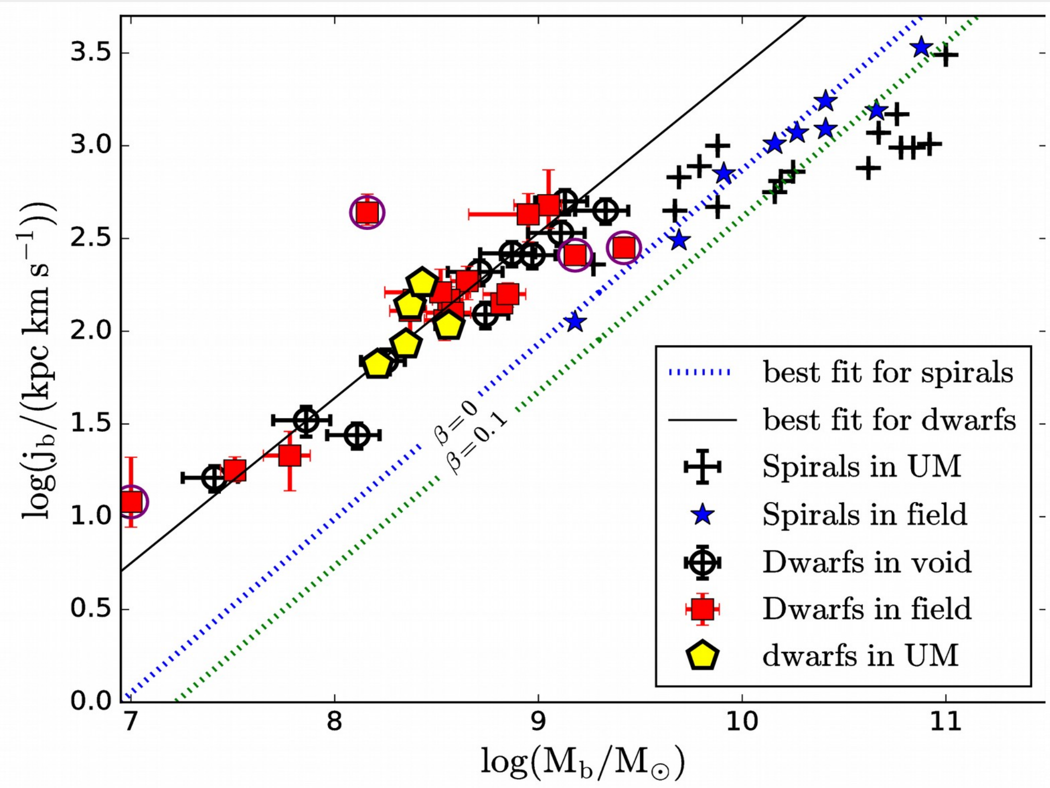
- Increase in $j_b$ sets at $M_b \sim 10^{9.1}\,M_\odot$, which is similar to thickening of gas discs.
- Stellar feedback might be responsible for both increase $j_b$ and thickness of discs.
- Quantitatively, star formation in dwarfs is insufficient to increase in $j_b$ for a marginally stable disc.

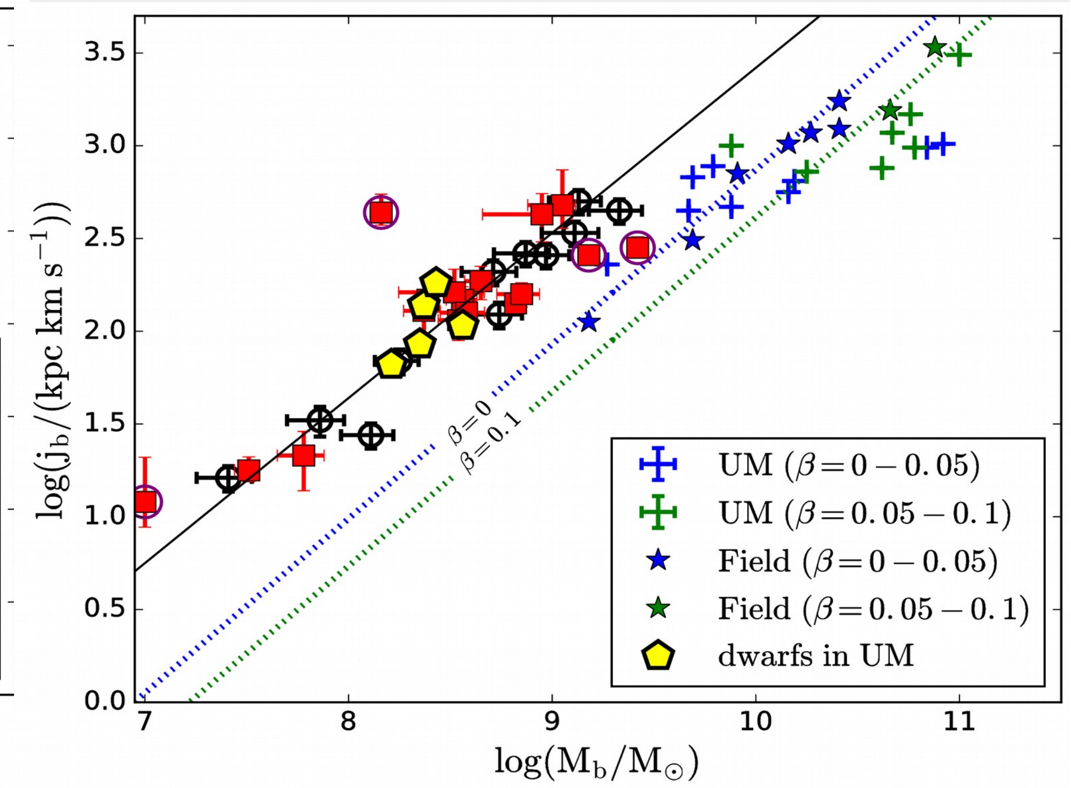
# Summary

- Dwarfs in voids and field have similar $j_b$ values.
- $j_b$-$M_b$ slope is consistent with marginally stable disk.
- Dwarfs have higher $j_b$ values than bulge-less spirals.
- Increase in $j_b$ sets at $M_b \sim 10^{9.1} M_\odot$, which is similar to thickening of gas disks.
- Stellar feedback processes are probably responsible; SF may not be sufficient to produce the observed increase in j.

# Additional slides

# j-M relation: UM cluster




*Dwarfs in UM have similar j as dwarfs in other densities.*

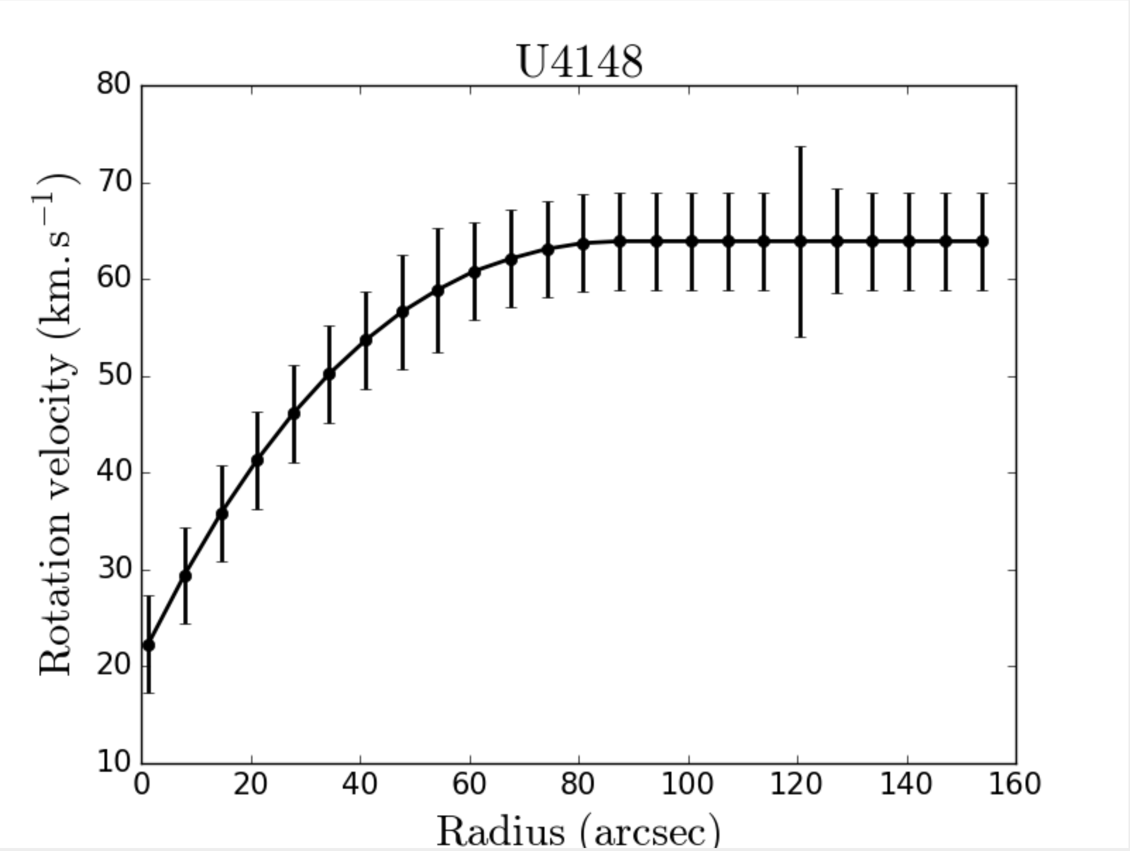
*Spirals in UM have lower j compared to spirals in other densities.*

# Stability model

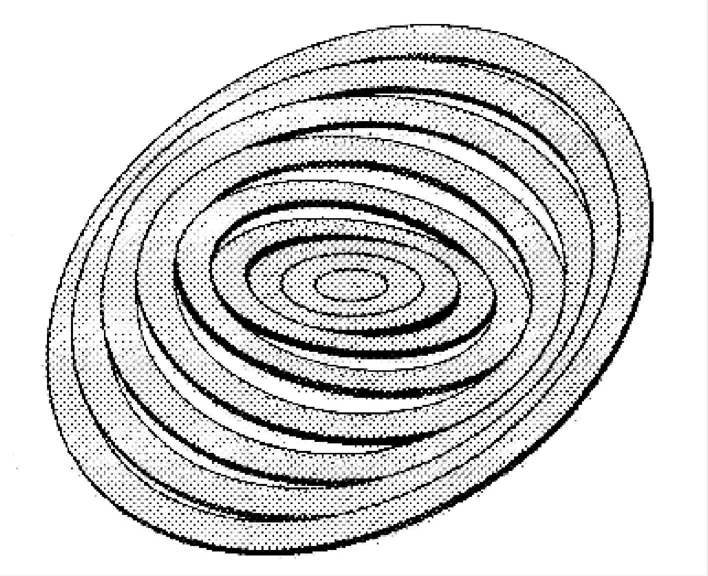
- Local instabilities could lead to star formation, which may lead to outflows. The remaining material adjusts itself so that the disk is marginally stable.
- The stability condition against gravitational perturbations is characterized by Toomre Q.
- In case of a thin disc, critical value is $Q = 1$. Non-zero thickness of a disc makes the disc more stable.
- If the j is regulated by stability criterion, $j = M \times (QG/4\sigma)$. Where, $\sigma$ is the velocity dispersion.

# Rotation curves

Tilted ring model was fit to HI data cube using FAT (3D)




(Rogstad et al. 1974)



# Sample

- Lynx-Cancer void (D ~ 18 Mpc), consists of 103 faint galaxies.

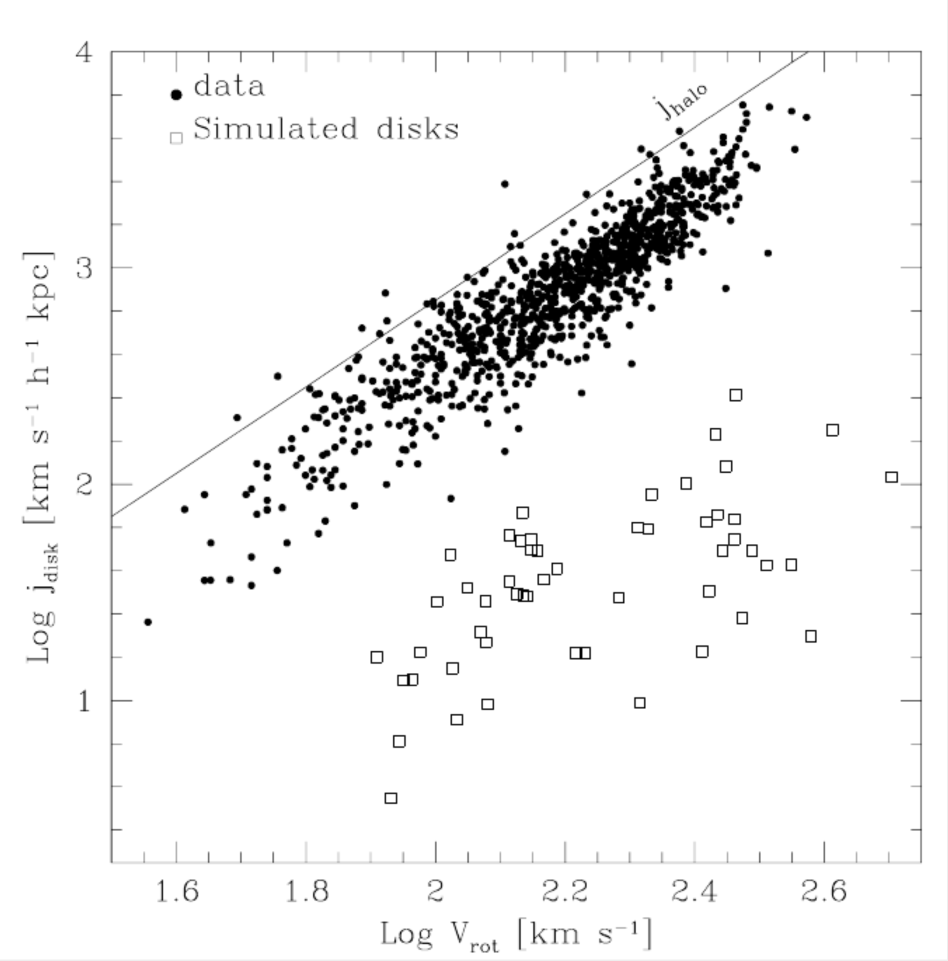
  (Pustilnik et al. 2011)

- 25 gas-rich galaxies ( $M_{HI}/L_B$ >1.9, $M_B$ >-16) were selected.
- To get good rotation curves, galaxies with
  - well behaved velocity fields
  - at least 6 beams across the major axis
  - inclinations greater than $35^0$ were selected.
- The galaxy KK246 from Tully void is also included

$\rightarrow$11 galaxies

# Angular momentum Catastrophe

- Disks in simulations show are an order of magnitude smaller.
- Gas loses significant angular momentum to dark matter due to “over-cooling”.



# Angular momentum catastrophe-solution

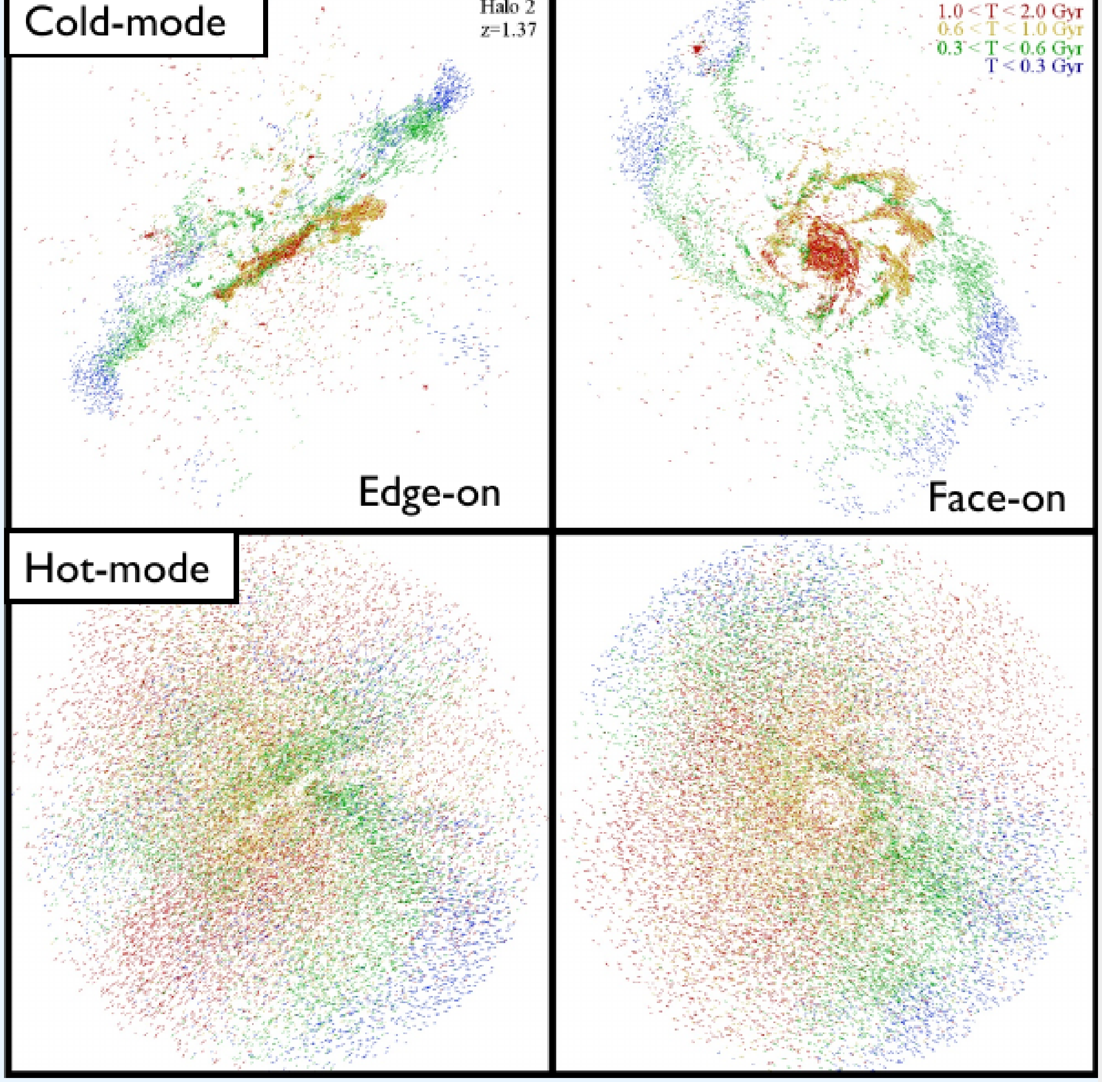
- The problem diminished in the models which include baryonic feedback such as
  - Stellar winds
  - Supernovae feedback
- Outflows can preferentially remove low angular momentum gas.

E.g. Gas outflows from M 82

Image credits: J. Gallagher, M. Mountain and P. Puxley

# Cold-mode accretion

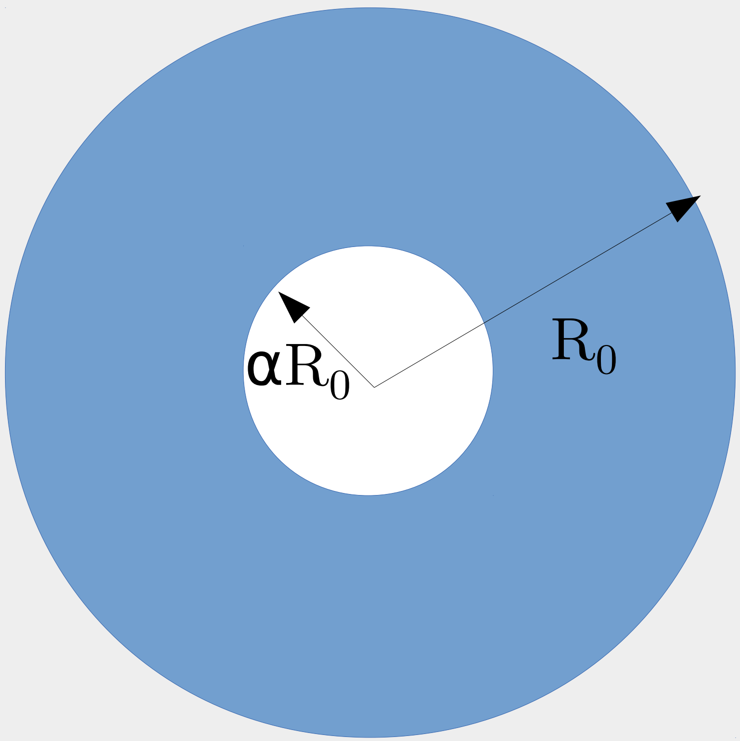
- Cold-mode accretion
  - Flows along filaments
  - Carries more AM
  - Dominant in low-mass haloes.




Stewart et al. 2013

# Is feedback sufficient?

- Assuming
- If we assume all material within a fractional radius $\alpha$ is lost,
  - Mass will decrease by a factor of $(1-\alpha)$
  - Offset in $j_b$-$M_b$ plane will increase by $\log((1+\alpha)/(1-\alpha))$



# Angular momentum

- Tidal torquing in early universe: $j_H = k M_H^{2/3}$
- At early epochs, $j_b^0 = j_H$
- Baryon to dark matter fraction: $f_b = M_H \,/\, M_b$
- Angular momentum retention fraction $f_j = j_b^0 \,/\, j_b$
- Then, $j_b \propto f_j f_b^{-2/3} M_b^{2/3}$

$j_H$ , $j_b$ are sAM of dark matter halo, baryons.

$M_H$ , $M_b$ are mass of dark matter halo, stars and baryons.

# Sample

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- The galaxy

$\rightarrow$11 galaxies

# Tilted Ring Model

- Rotation curves can be derived by fitting a tilted ring model; assumes gas is confined to a thin disk and is in circular motion **(Warner et al.1973)**
- A set of concentric rings is used to describe the motion of gas; each ring has a constant rotation velocity $V_{rot}$ , depends only on mean radius
- Each ring is characterized by an inclination i, a position angle(PA) of major axis projected onto sky $\Phi$ . If $V_{sys}$ is systematic velocity, $\theta$ is PA in plane of galaxy, then line of sight velocity at any point (x,y) is

$$V(x,y) = V_{sys} + V_{rot} sin(i) cos(\theta)$$

$$cos(\theta) = \frac{-(x-x_0)sin(\phi) + (y-y_0)cos(\phi)}{R}$$

$$sin(\theta) = \frac{-(x-x_0)cos(\phi) + (y-y_0)sin(\phi)}{Rcos(i)}$$