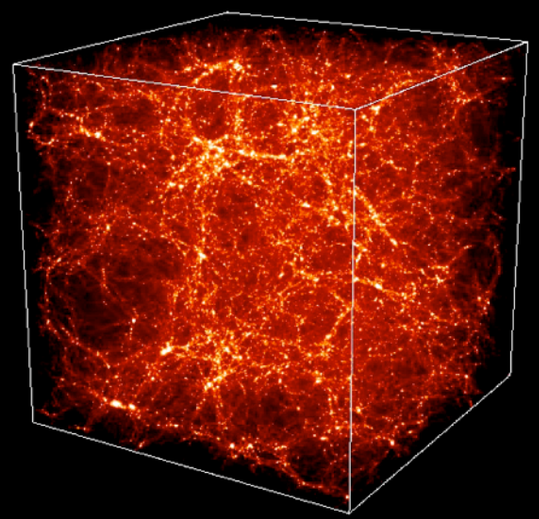
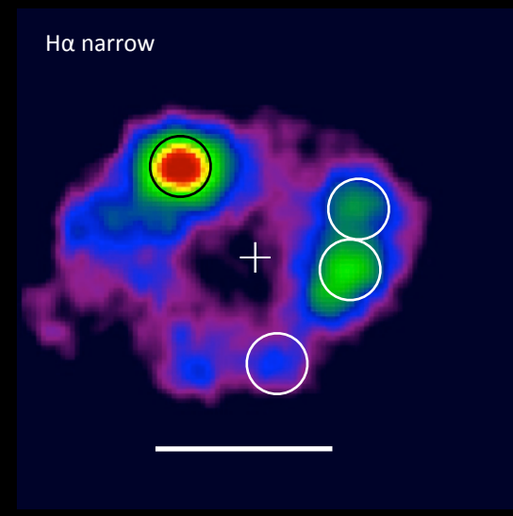
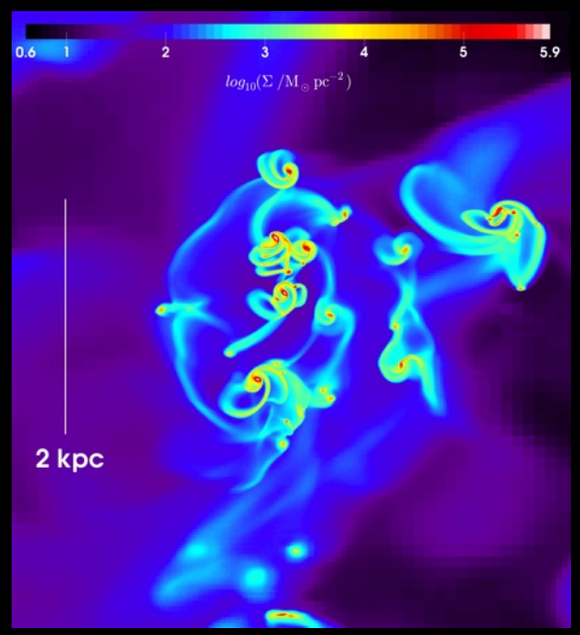
Angular momentum and rotation of high-z disk galaxies

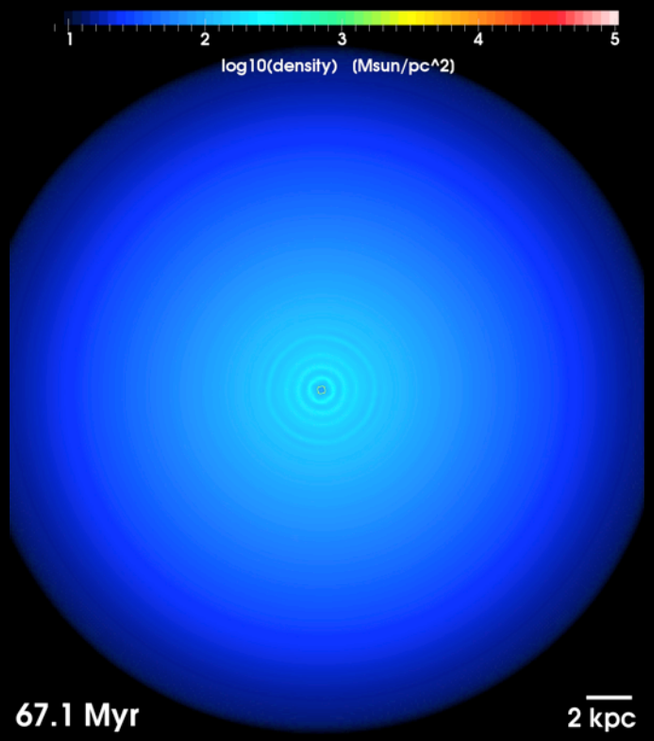
Andreas Burkert
USM & MPE

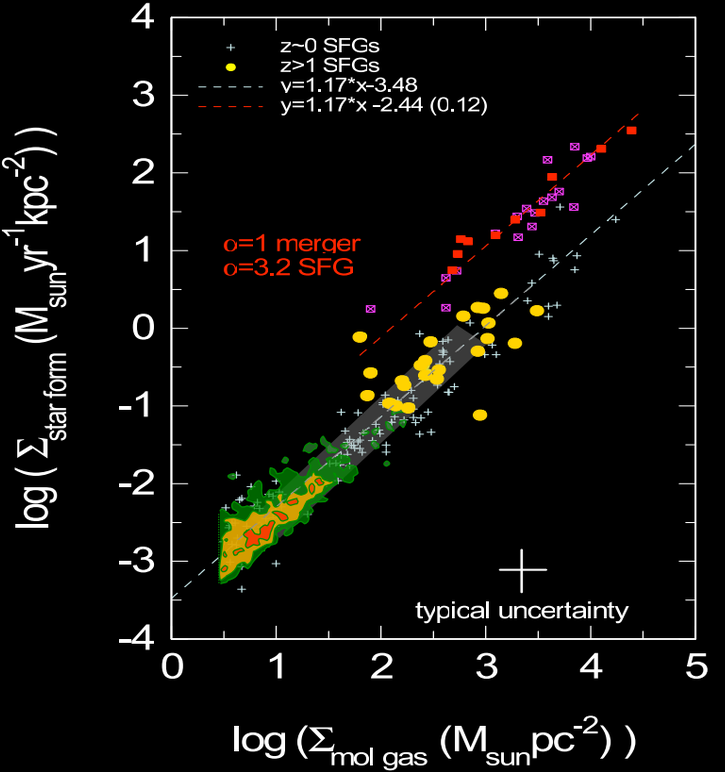
M. Behrendt, M. Schartmann,
R.Genzel, L. Tacconi, N. Förster-Schreiber
+ SINS











Angular momentum + energy dissipation = disk

Angular momentum + energy dissipation = disk

Lowest energy state for given angular momentum

Angular momentum + energy dissipation = disk

High angular momentum → *disk*

Angular momentum + energy dissipation = disk

Disk ⟶ *high angular momentum* $j = v_{rot} \cdot r$

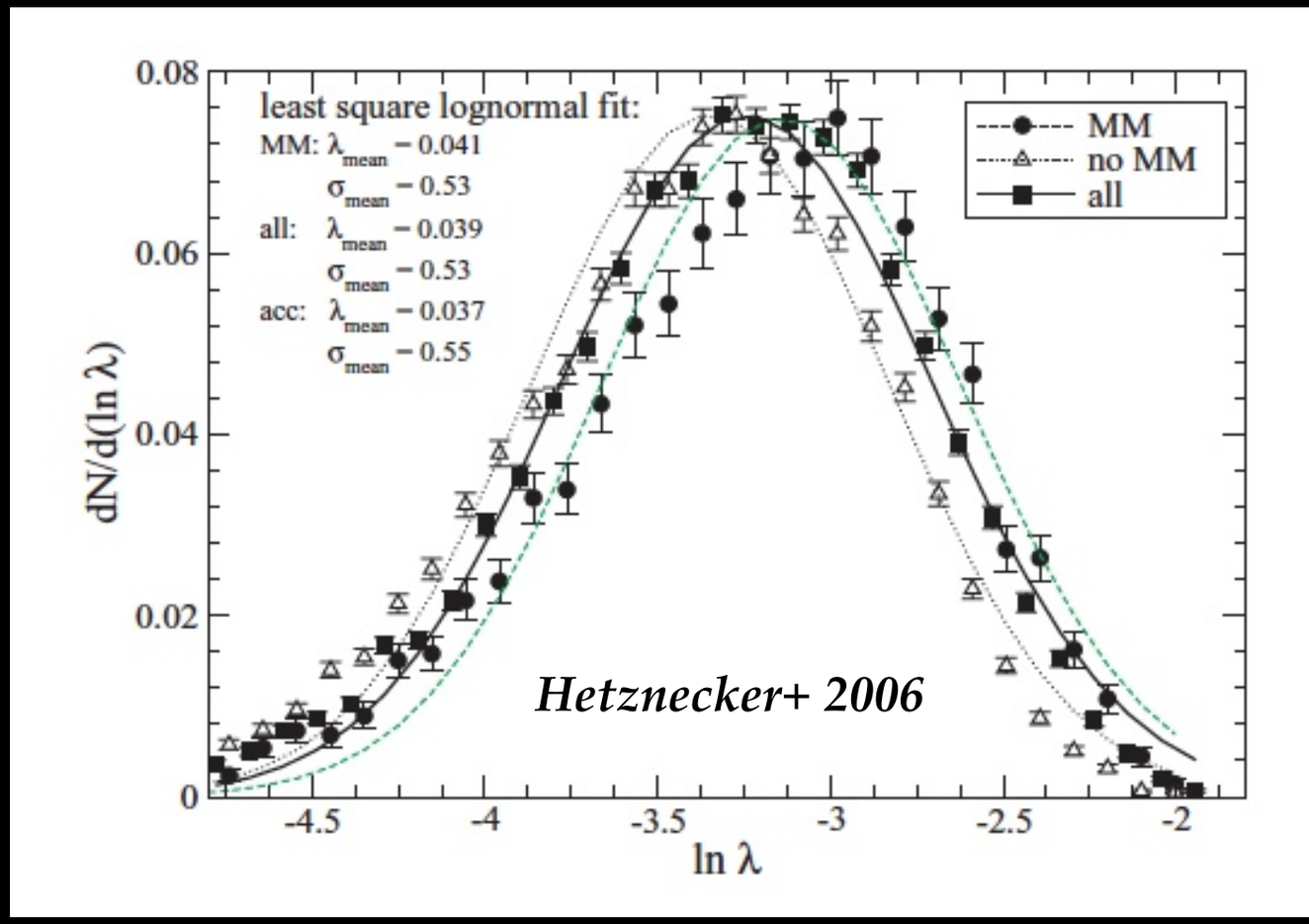
The dimensionless spin parameter of dark matter halos

Peebles+ (1969)

$$\lambda = \frac{J|E|^{1/2}}{GM^{5/2}}$$

Bullock+ (2001)

$$\lambda = \frac{J}{\sqrt{2}M_{vir}V_{vir}R_{vir}}$$



$$\lambda_0 = 0.035 \pm 0.005$$
$$\sigma_{\ln\lambda} = 0.5 \pm 0.03$$

$$P(\lambda) = \frac{1}{\lambda\sqrt{2\pi\sigma}}\exp\left(-\frac{\ln^2\left(\lambda/\lambda_0\right)}{2\sigma^2}\right)$$

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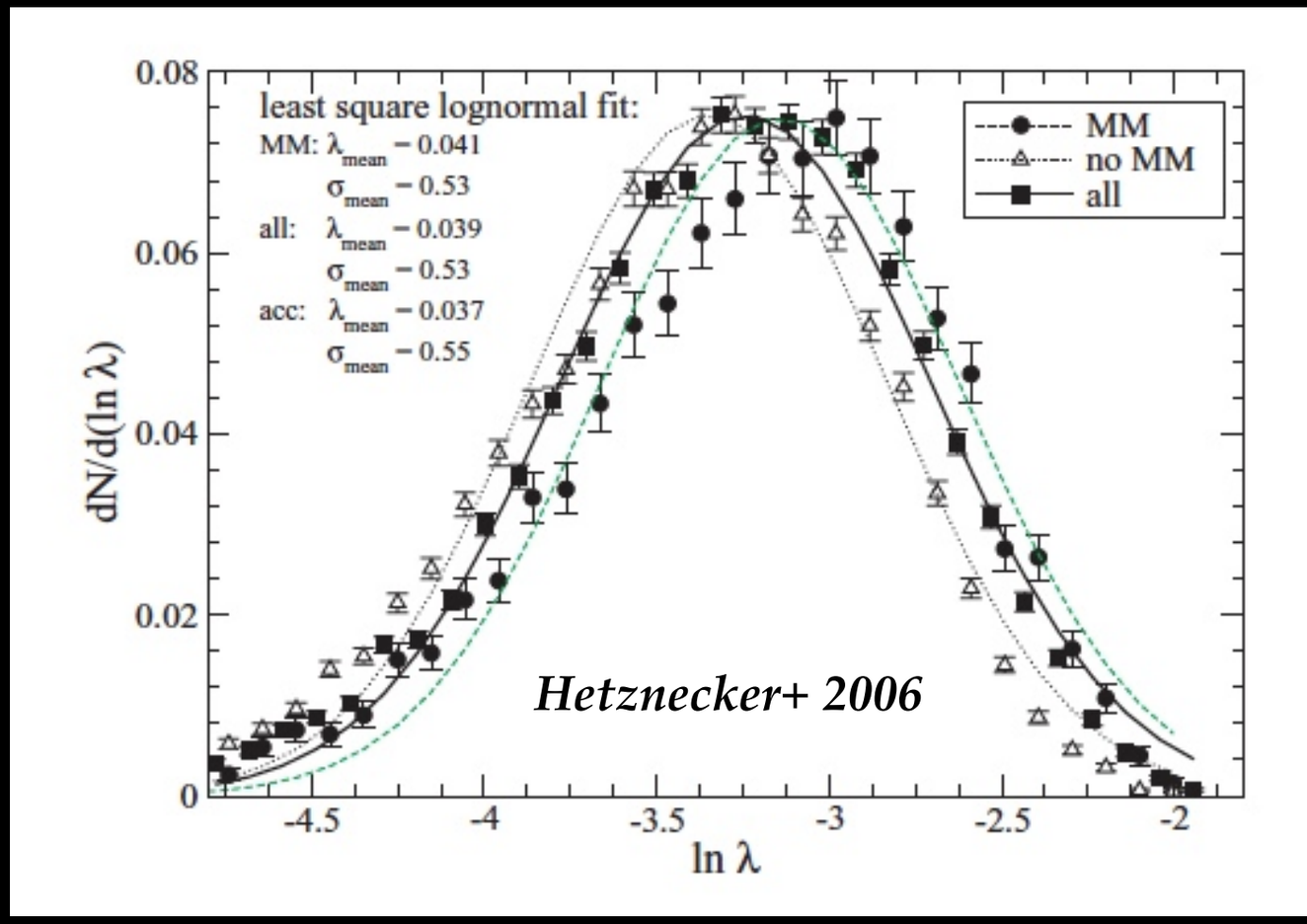


$$\lambda_0 = 0.035 \pm 0.005$$
$$\sigma_{\ln\lambda} = 0.5 \pm 0.03$$

Independent of redshift and halo mass

→ $\lambda_{\rm infall} = \frac{5}{3}\lambda_{halo}$ →

Inside-out growth of disks
(e.g. Lilly&Carollo 16)

And the baryons?

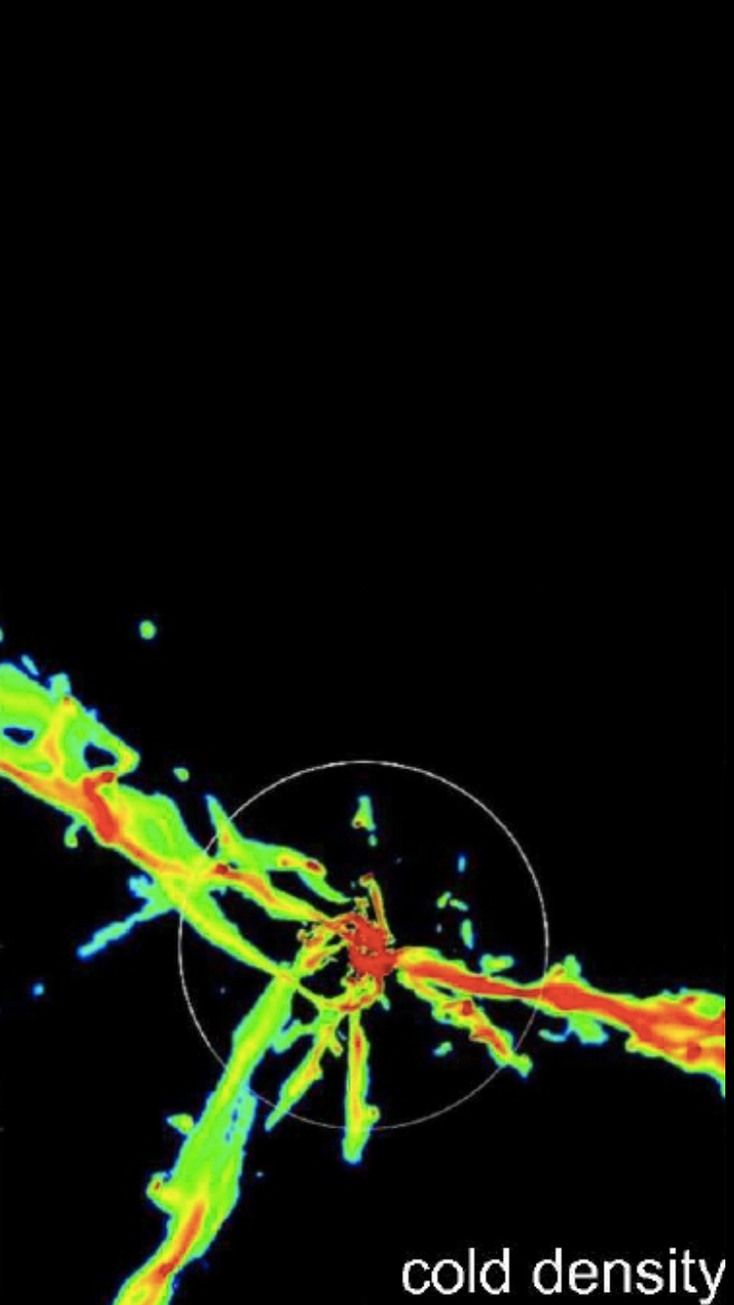
$$\lambda_{disk} = \lambda_{halo} \; ?$$

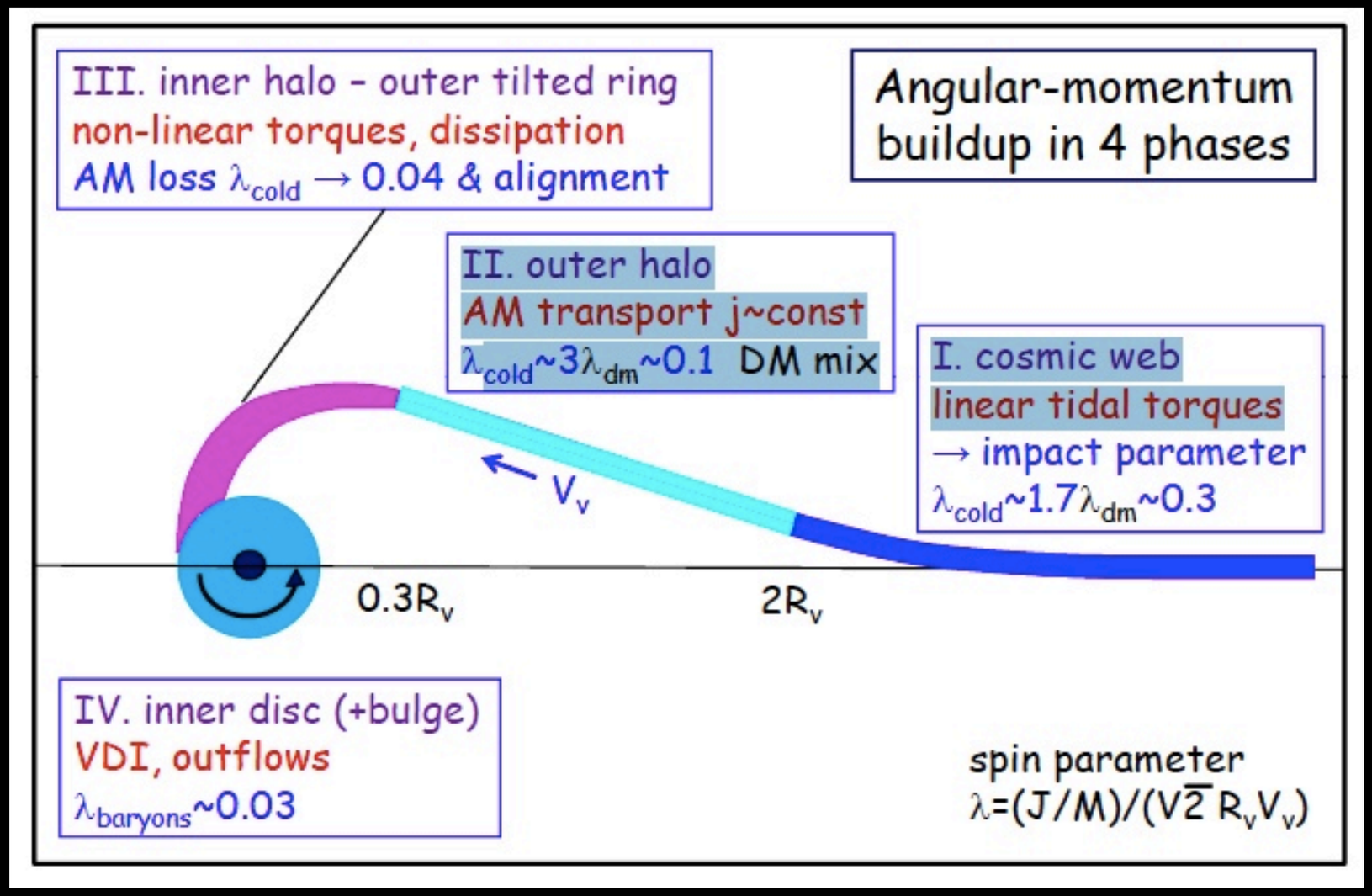
$$\lambda_{disk} = \frac{(J/M)_{disk}}{\sqrt{2} V_{vir} R_{vir}}$$

$$\lambda_{halo} = \frac{(J/M)_{vir}}{\sqrt{2} V_{vir} R_{vir}}$$

The complexity of gas infall

(Birnboim&Dekel 03; Keres+ 05, 09; Ceverino+10; Pinoch+11; Danovich+12; Codes+12; Steward+13; Mandelker+14, 16; Genel+15; Teklu+15)

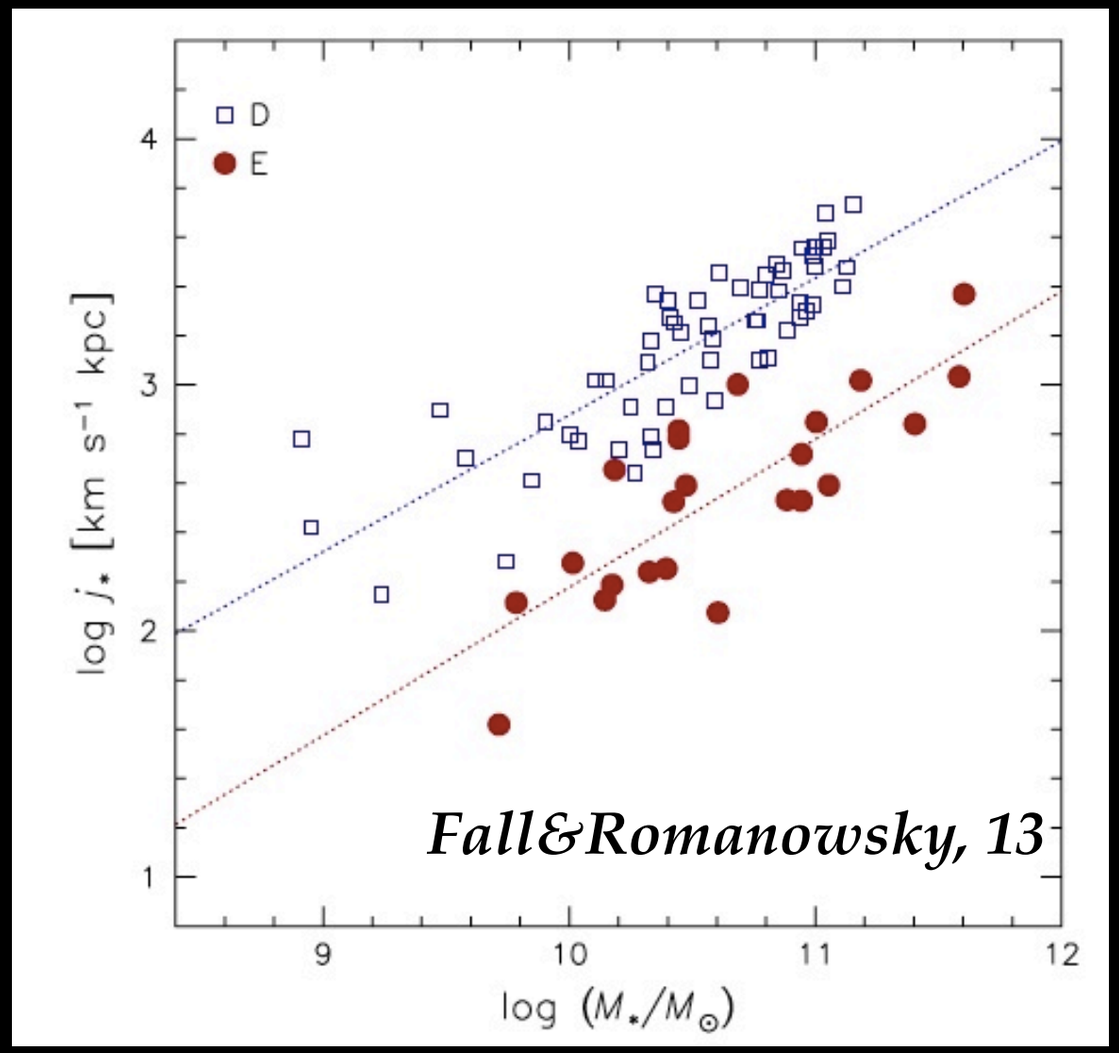




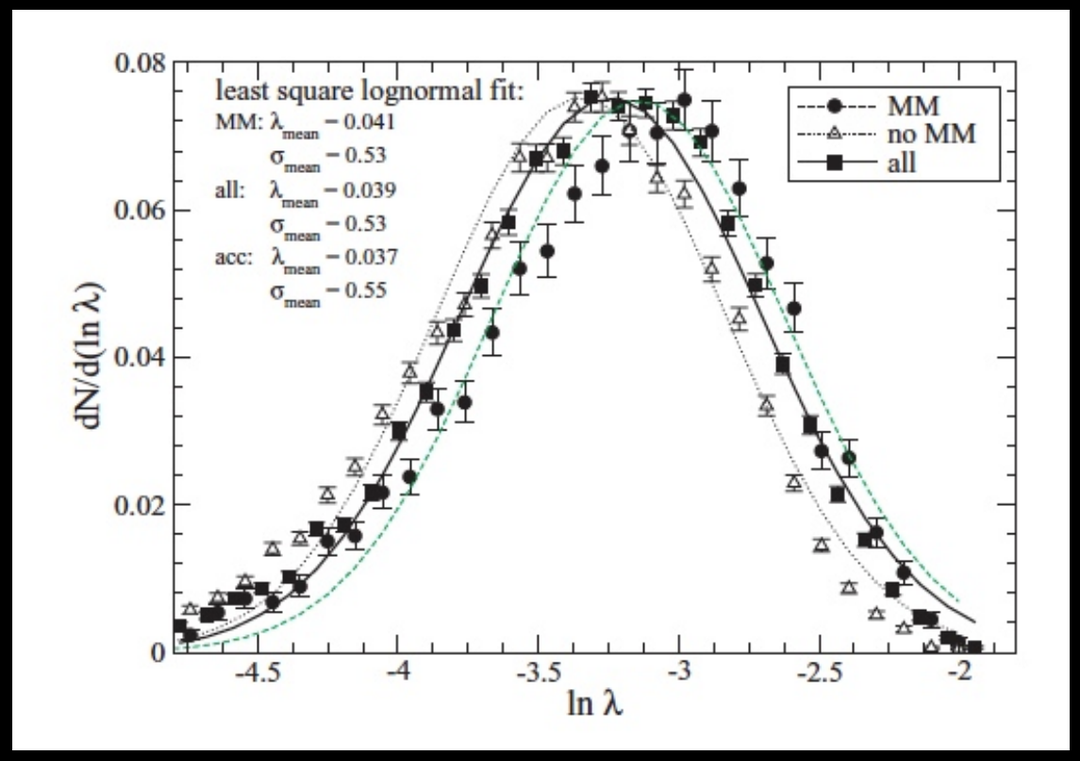
Danovich+(15)

Galaxy morphology: Boundary/initial condition versus internal evolution

(Hernandez+07; Scannapieco+09; Sales+12)



Fall&Romanowsky, 13



Galaxy morphology: Boundary/initial condition versus internal evolution

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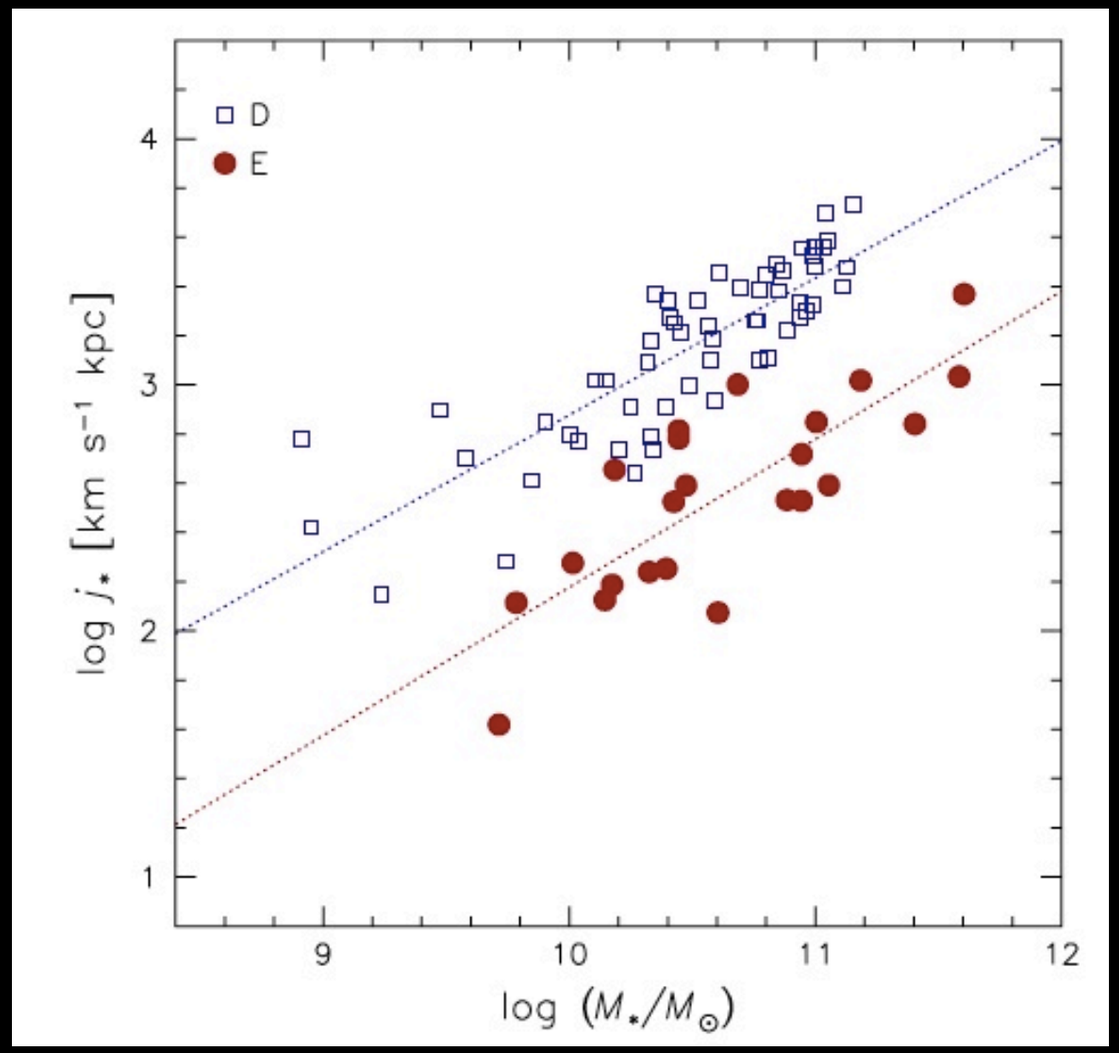
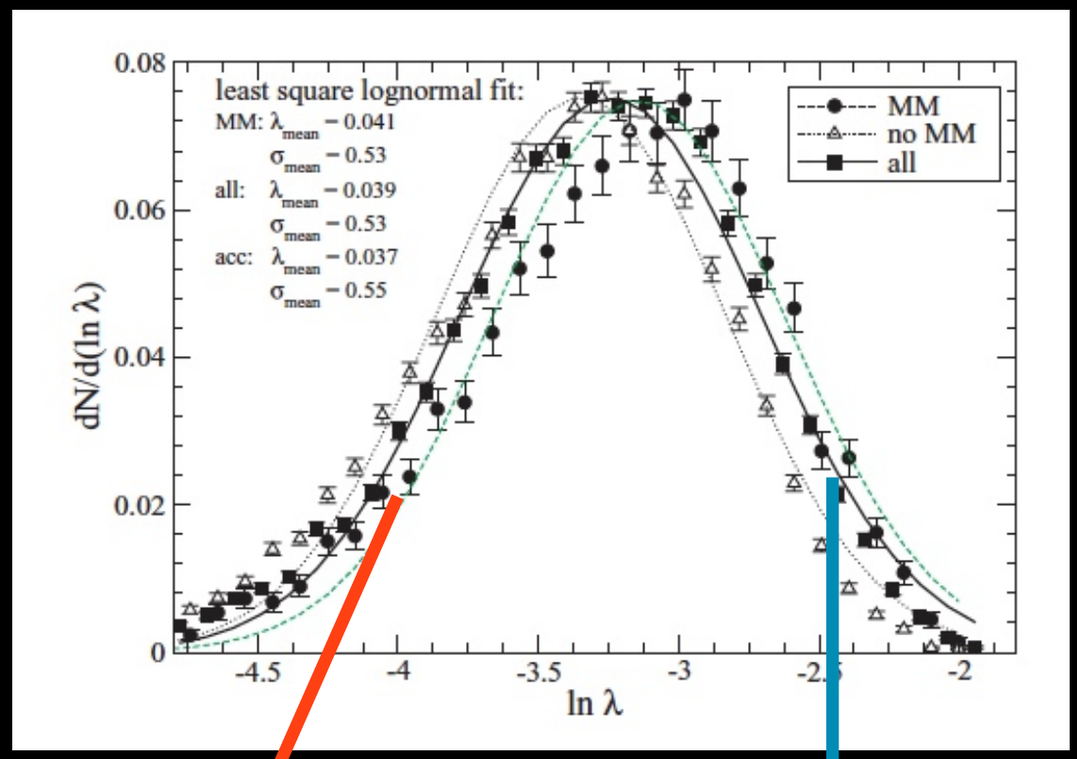




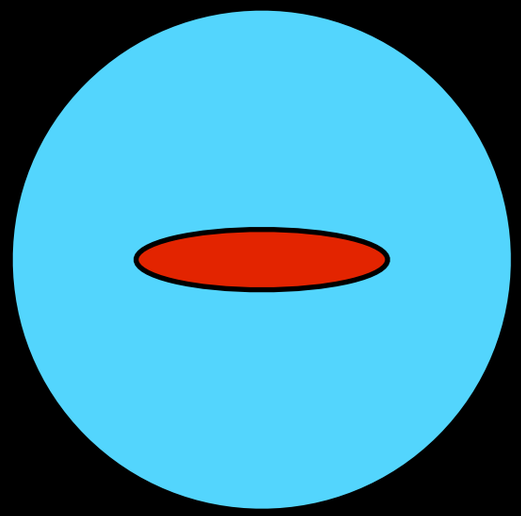
Red cloud ellipticals

Main sequence spirals

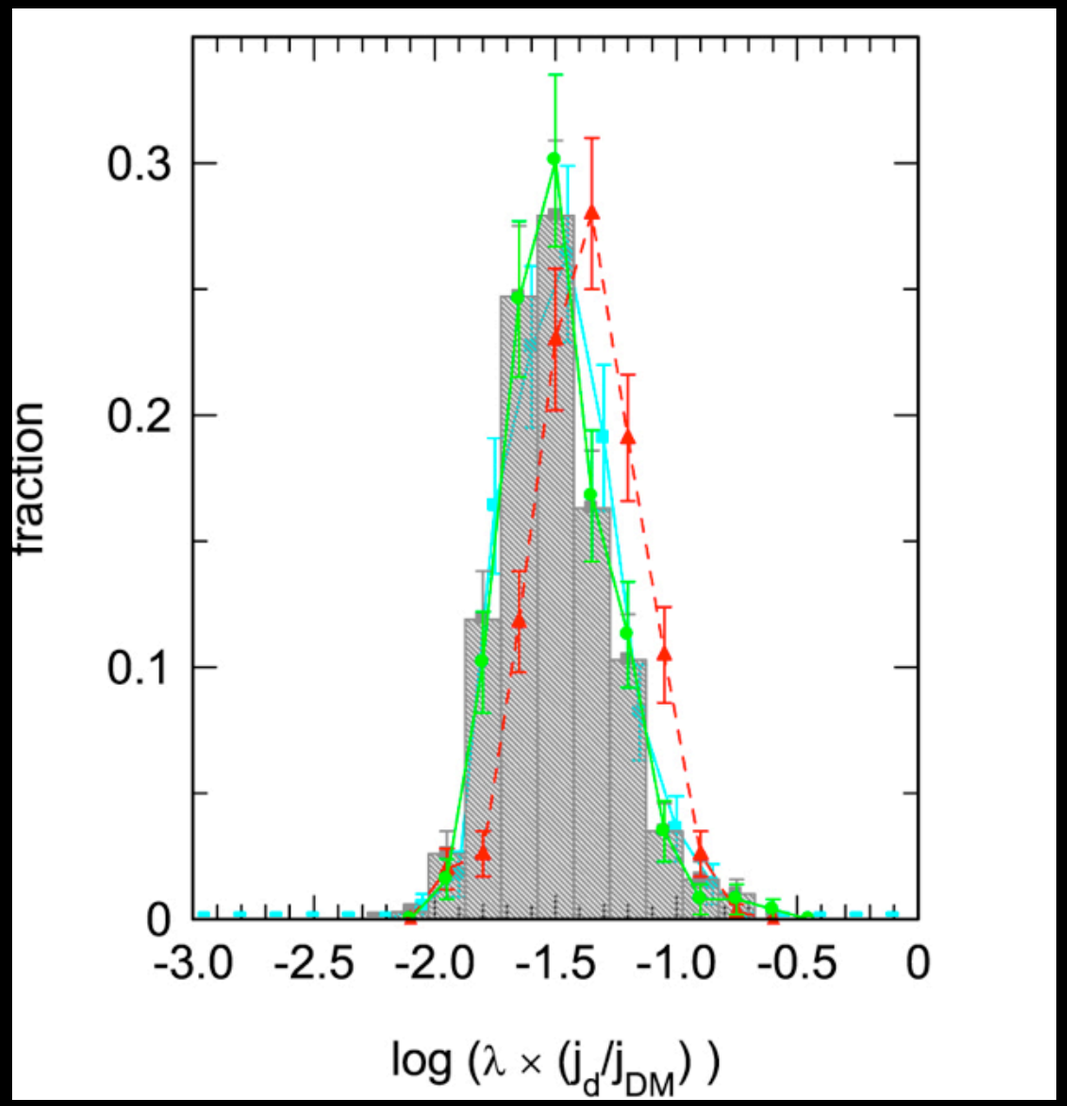
Spin parameter of ~360 star forming galaxies from z = 0.8 - 2.4

(Burkert+16)

disk+halo



$$v_{rot}^2 = v_{disk}^2 + v_{DM}^2 - 2\sigma^2 \left(\frac{R}{R_{disk}} \right)$$



$$\lambda_{disk} = \frac{j_{disk}}{\sqrt{2} R_{vir} \cdot V_{vir}}$$

$$m_{disk} = M_{disk} / M_{vir}$$

CDM

$$\lambda_0 = 0.035 \pm 0.005$$

$$\sigma_{\ln\lambda} = 0.5 \pm 0.03$$

$$\langle \lambda_{disk} \rangle = 0.037$$

$$\sigma_{\ln\lambda} = 0.6$$

Spin parameter of ~360 star forming galaxies from z = 0.8 - 2.4

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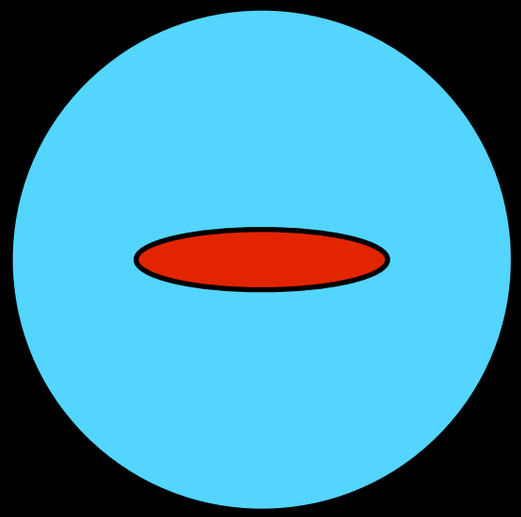
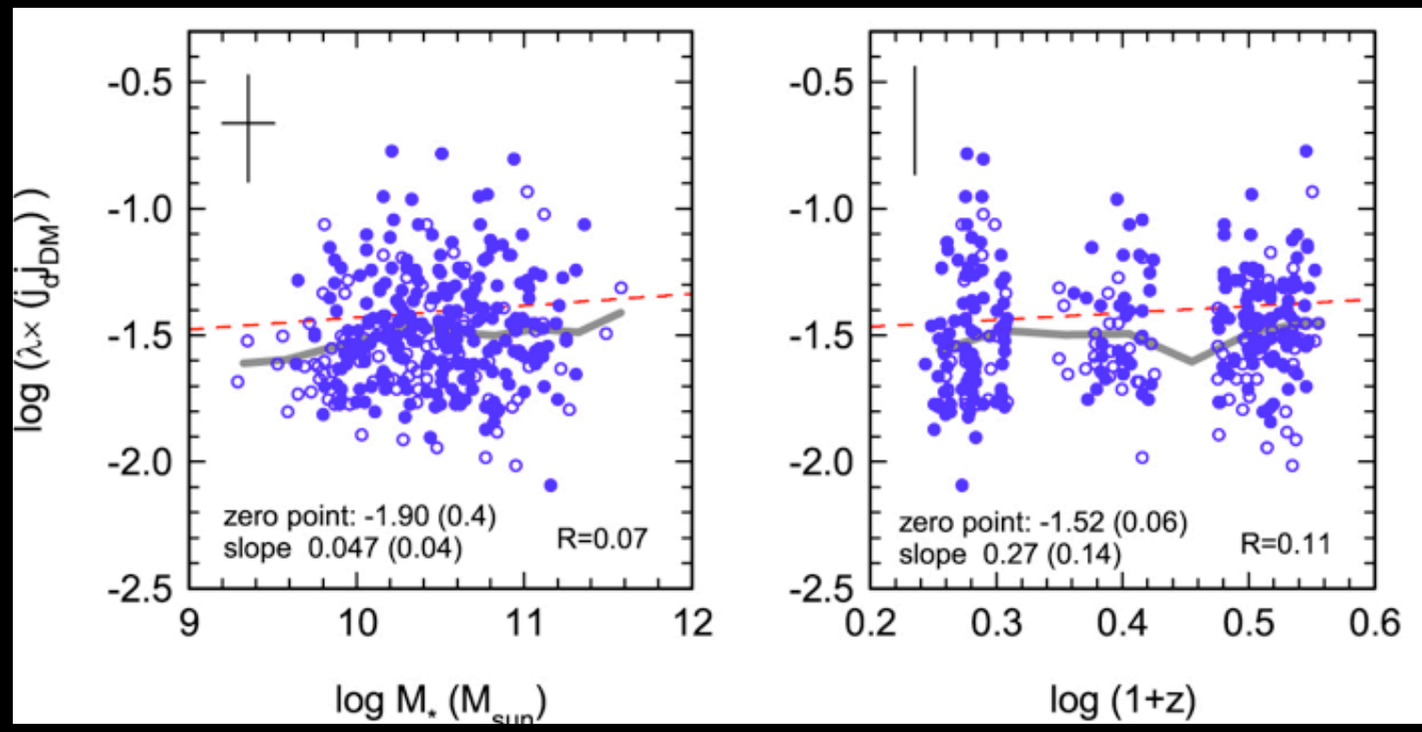


$$v_{rot}^2 = v_{disk}^2 + v_{DM}^2 - 2\sigma^2\left(\frac{R}{R_{disk}}\right)$$

$$\lambda_{disk} = \frac{j_{disk}}{\sqrt{2}R_{vir}\cdot V_{vir}}$$

$$m_{disk} = M_{disk} / M_{vir}$$



No dependence on mass and redshift

$$\langle \lambda_{disk} \rangle = 0.037$$

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Spin parameter of ~360 star forming galaxies from z = 0.8 - 2.4

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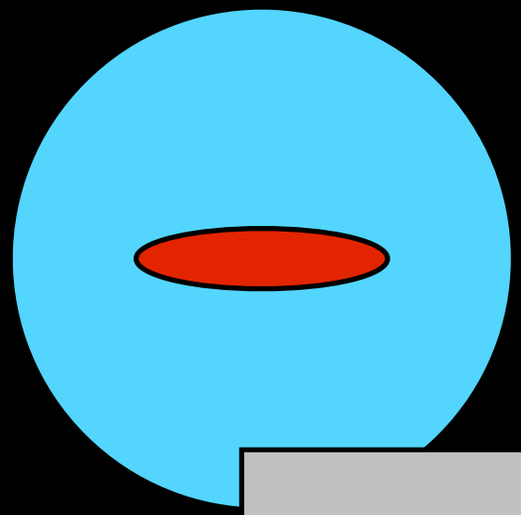

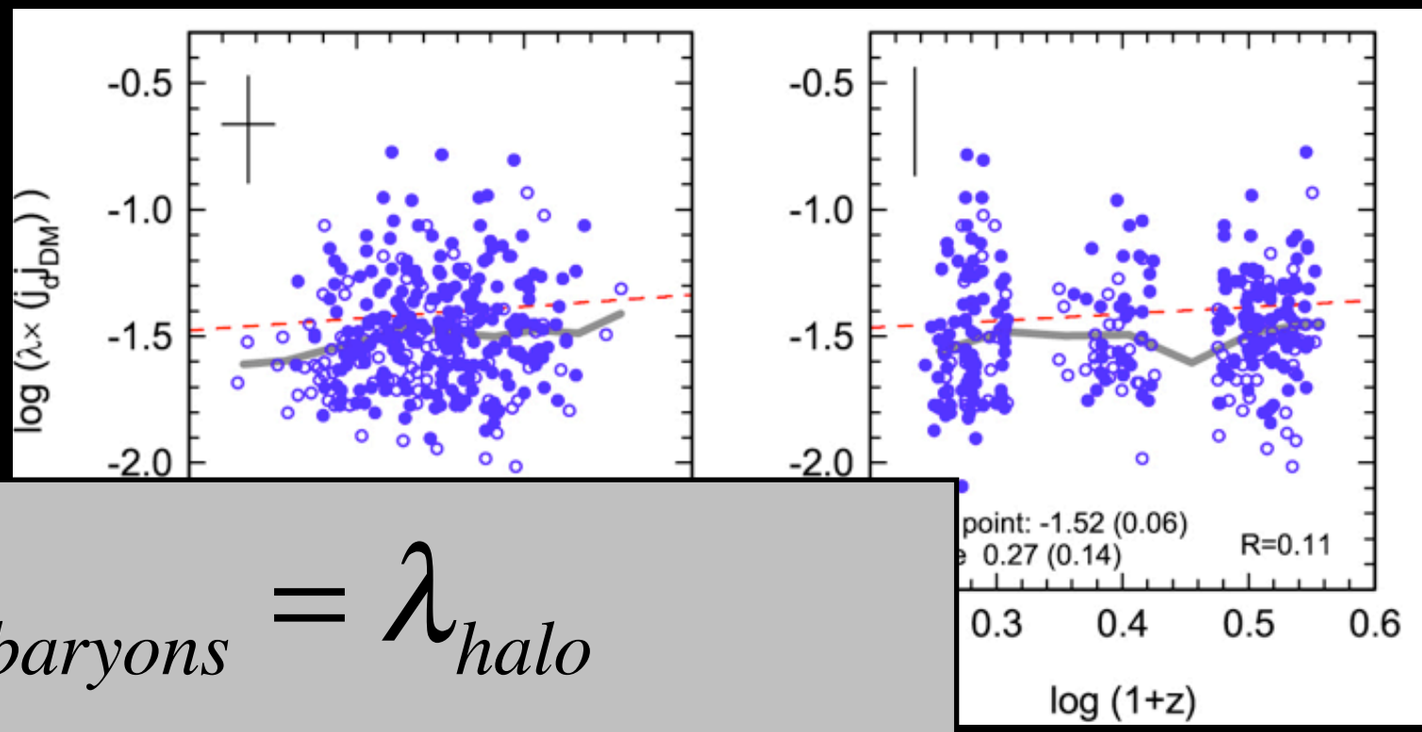

$$\lambda_{baryons} = \lambda_{halo}$$

$$v_{rot}^2 = v_{disk}^2 + v_{DM}^2 -$$

$$\left(\quad disk \right)$$

$$\lambda_{disk} = \frac{j_{disk}}{\sqrt{2} R_{vir} \cdot V_{vir}}$$

$$m_{disk} = M_{disk} / M_{vir}$$

No dependence on mass and redshift

$$\langle \lambda_{disk} \rangle = 0.037$$

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Spin parameter of ~360 star forming galaxies from z = 0.8 - 2.4

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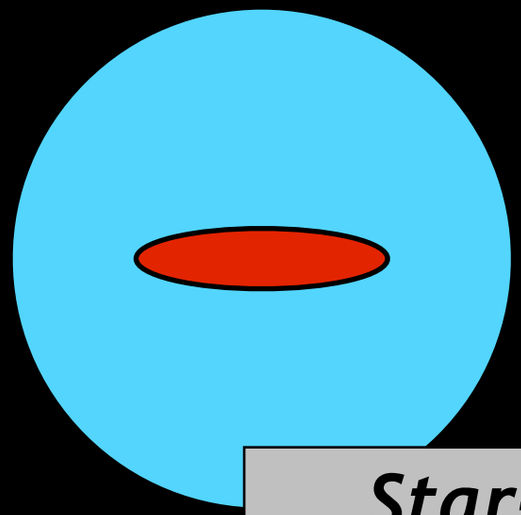
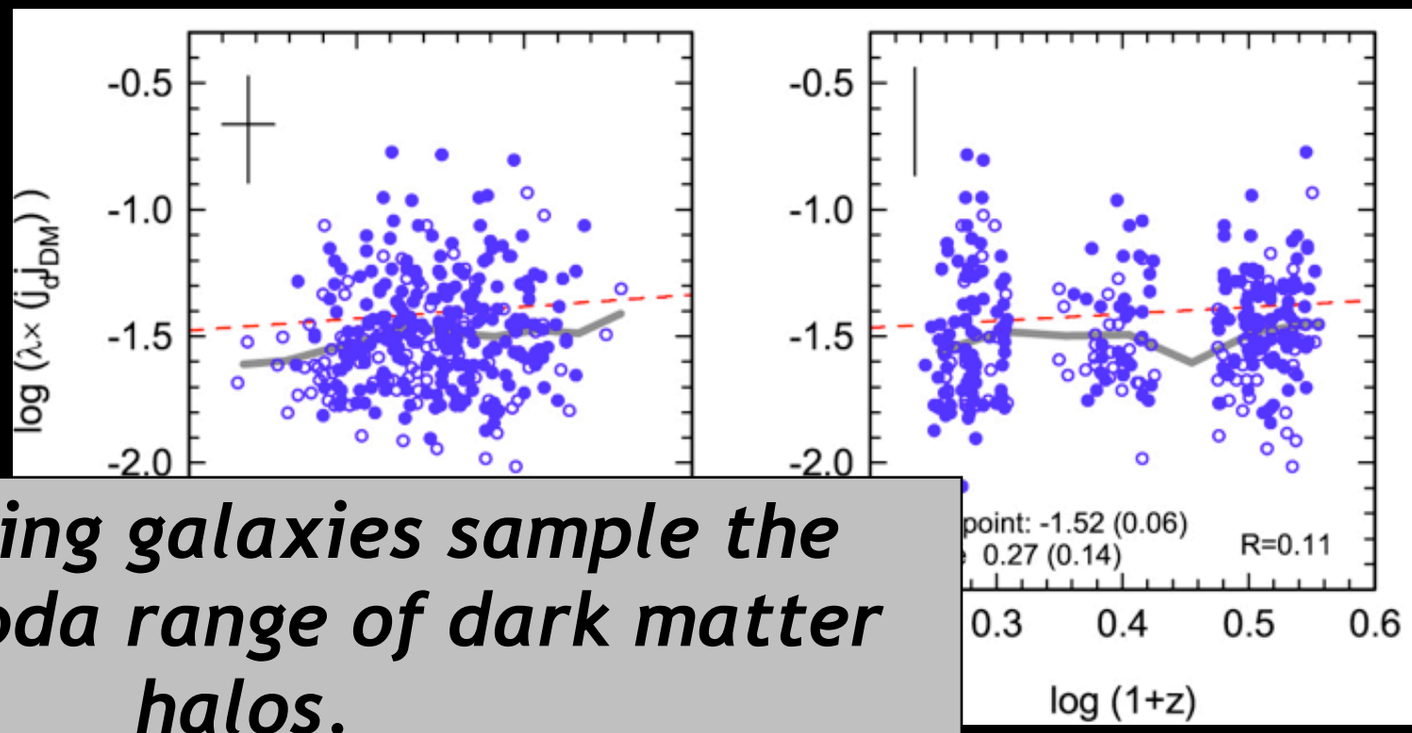
disk+halo





Star-forming galaxies sample the whole lambda range of dark matter halos.

$$v_{rot}^2 = v_{disk}^2 + v_{DM}^2 -$$

$$\left(v_{disk} \right)$$

$$\lambda_{disk} = \frac{j_{disk}}{\sqrt{2} R_{vir} \cdot V_{vir}}$$

$$m_{disk} = M_{disk} / M_{vir}$$

No dependence on mass and redshift

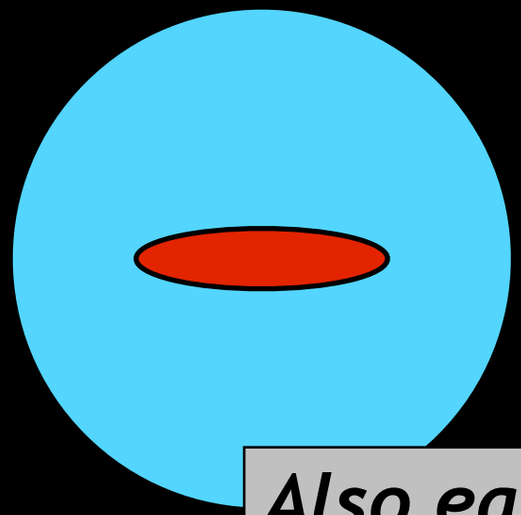
$$\langle \lambda_{disk} \rangle = 0.037$$

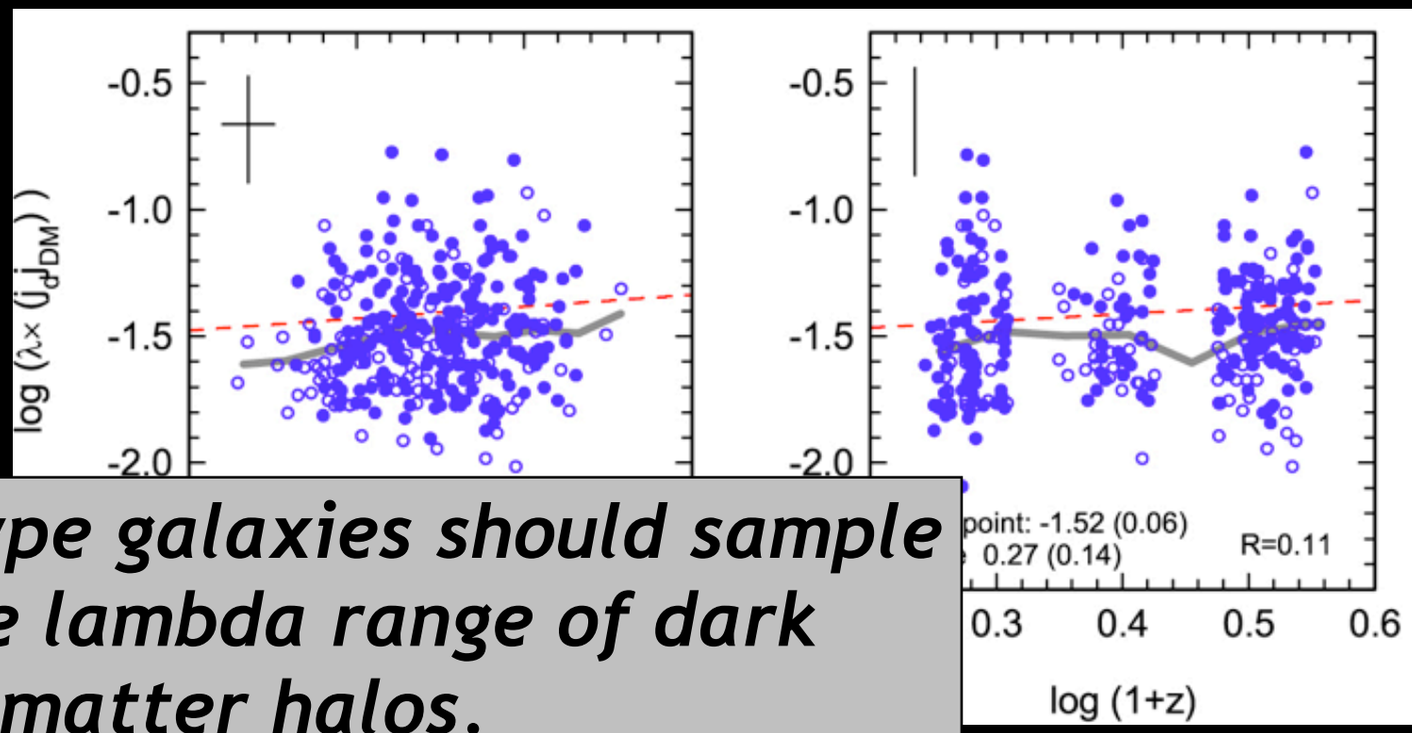
$$\sigma_{\ln \lambda} = 0.6$$

Spin parameter of ~360 star forming galaxies from z = 0.8 - 2.4

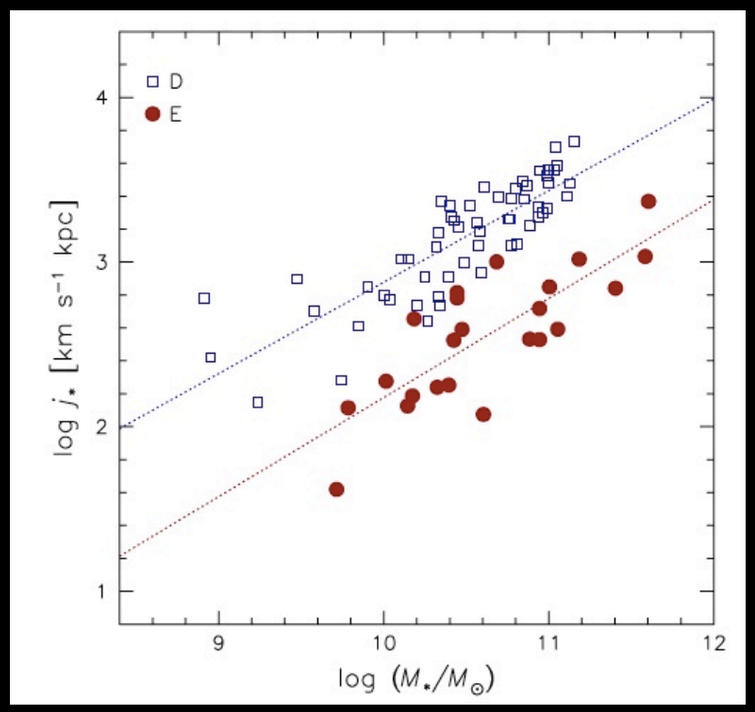
(Burkert+16)

disk+halo





Also early-type galaxies should sample the whole lambda range of dark matter halos.



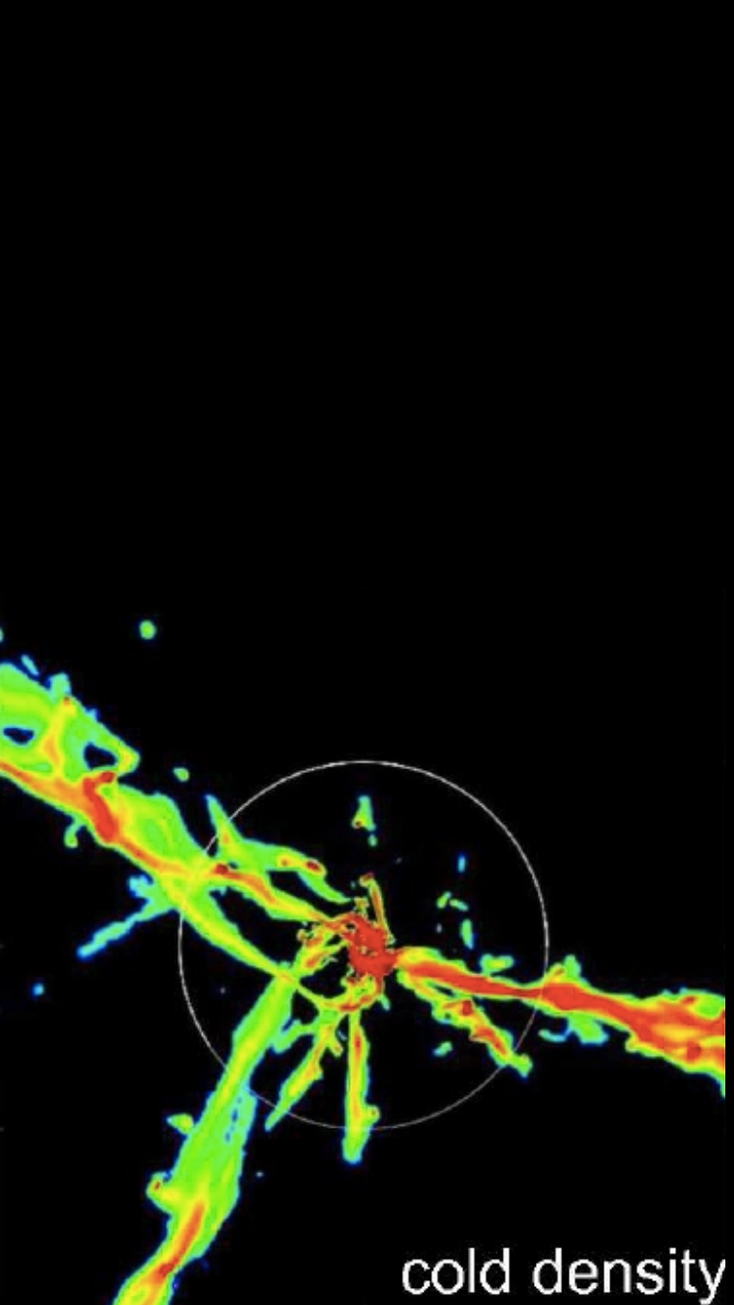
No dependence on mass and redshift

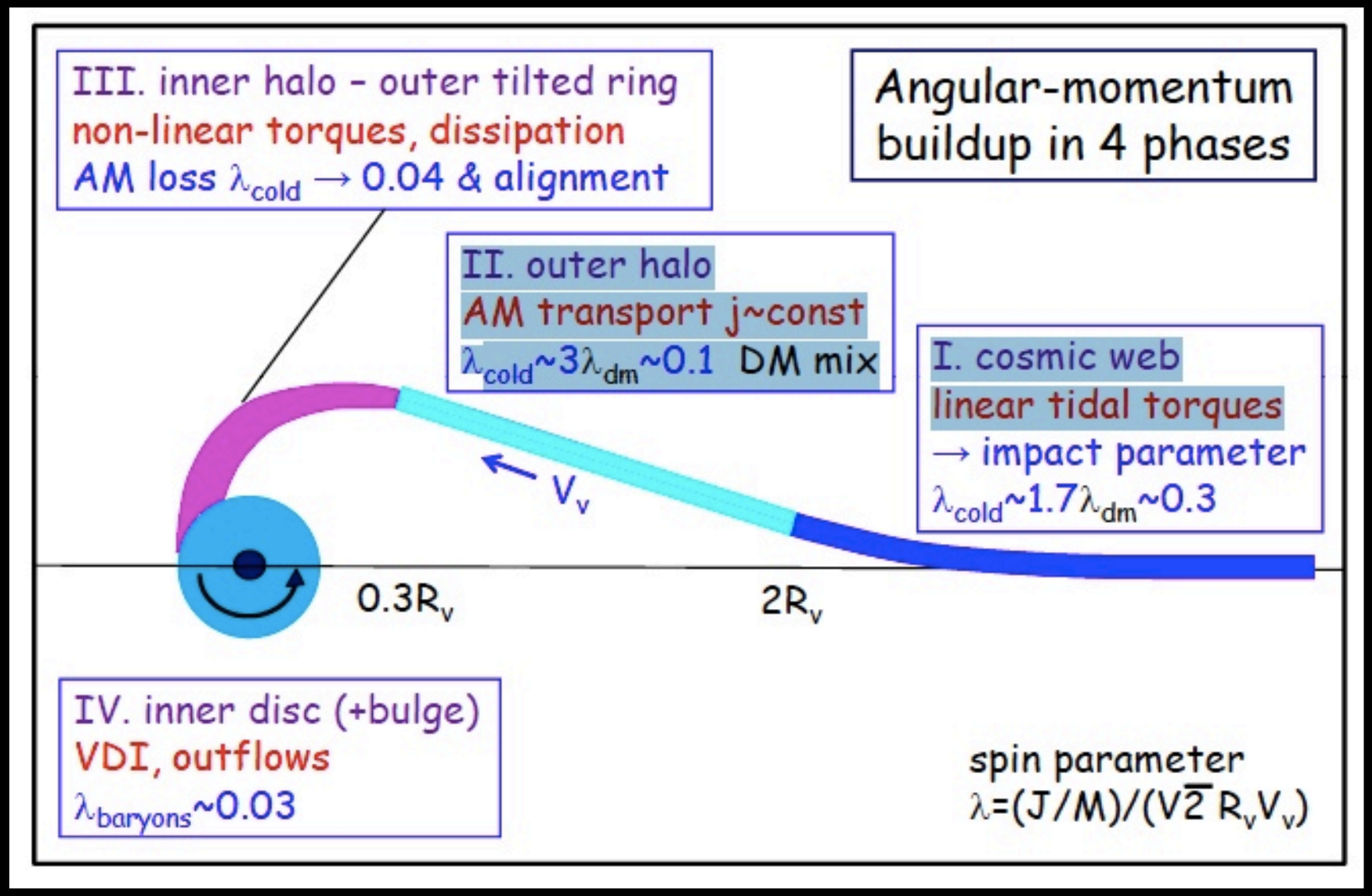
$$\langle \lambda_{disk} \rangle = 0.037$$

$$\sigma_{\ln \lambda} = 0.6$$

The complexity of gas infall

(Birnboim&Dekel 03; Keres+ 05, 09; Ceverino+10; Pinoch+11; Danovich+12; Codes+12; Steward+13; Mandelker+14, 16; Genel+15; Teklu+15)

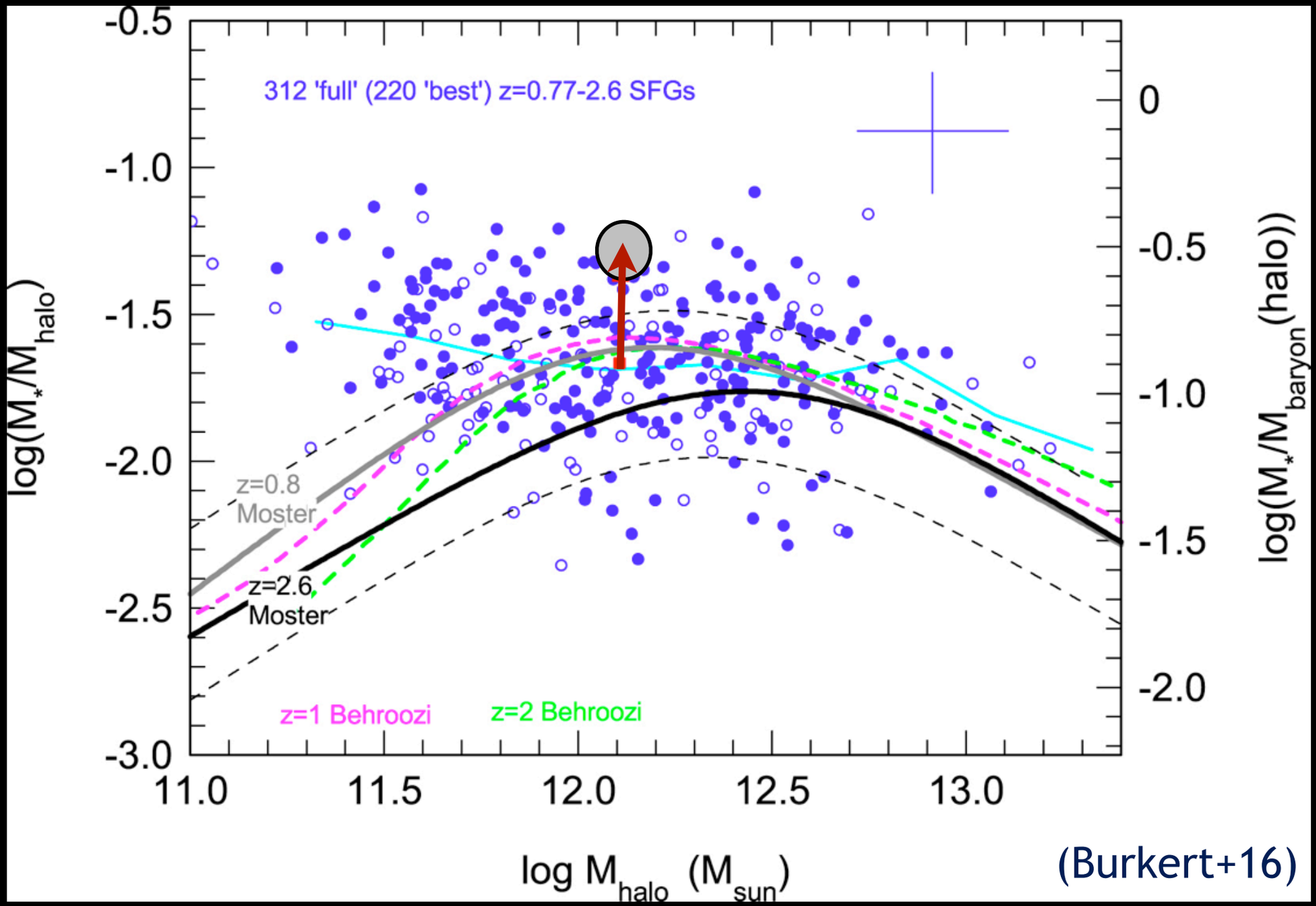




Danovich+(15)

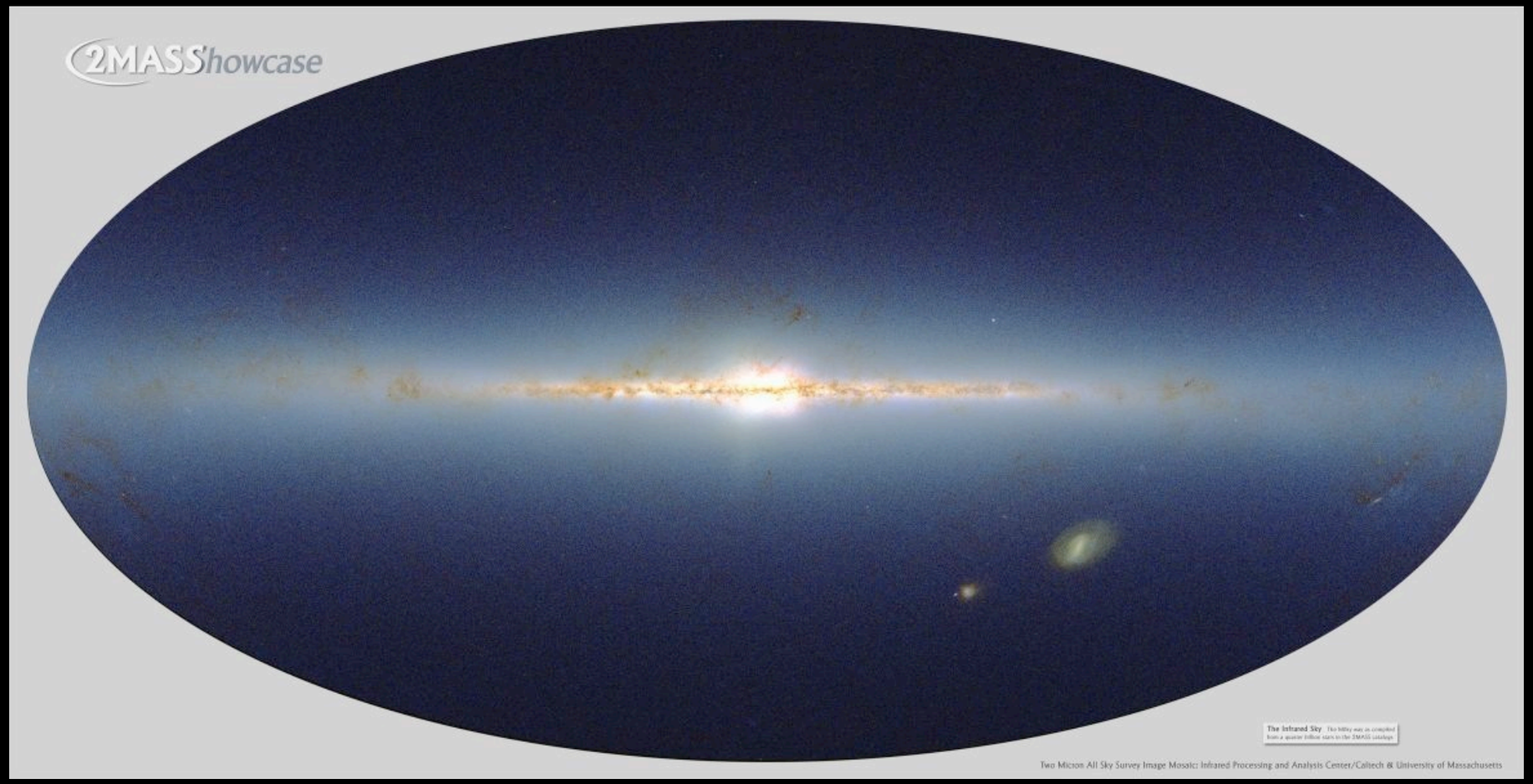
Baryon fraction of star forming galaxies from z = 0.8 - 2.4

$$\log\left(\frac{M_*}{M_{vir}}\right)$$



(Burkert+16)

- Average stellar-to-dark matter mass ratio: 2%
- **Including the gas component** the average is 5% which corresponds to **31% of the cosmic baryon fraction**

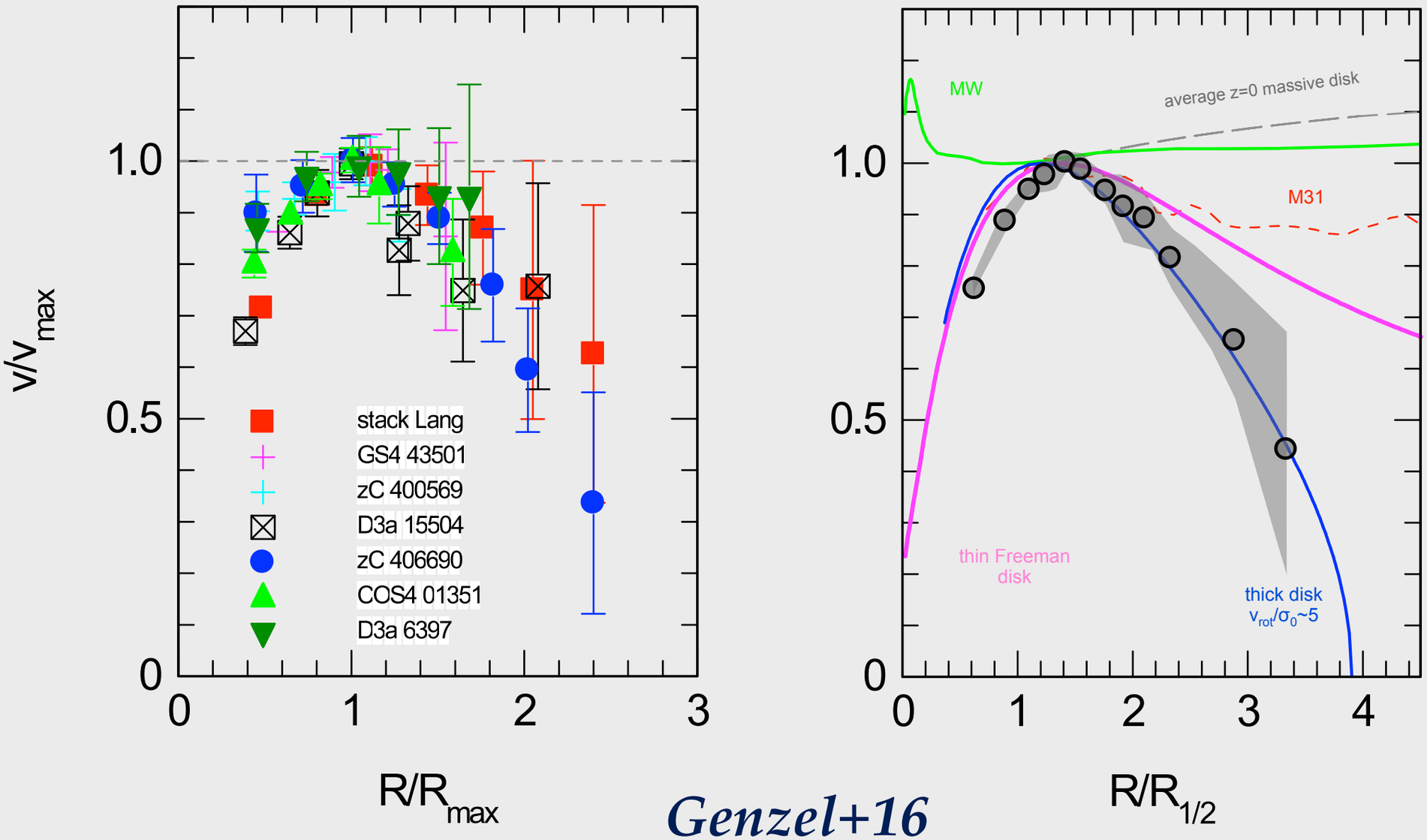


$$M_{DM} \approx 10^{12} M_{\odot}$$

$$M_{disk} \approx 6 \cdot 10^{10} M_{\odot}$$

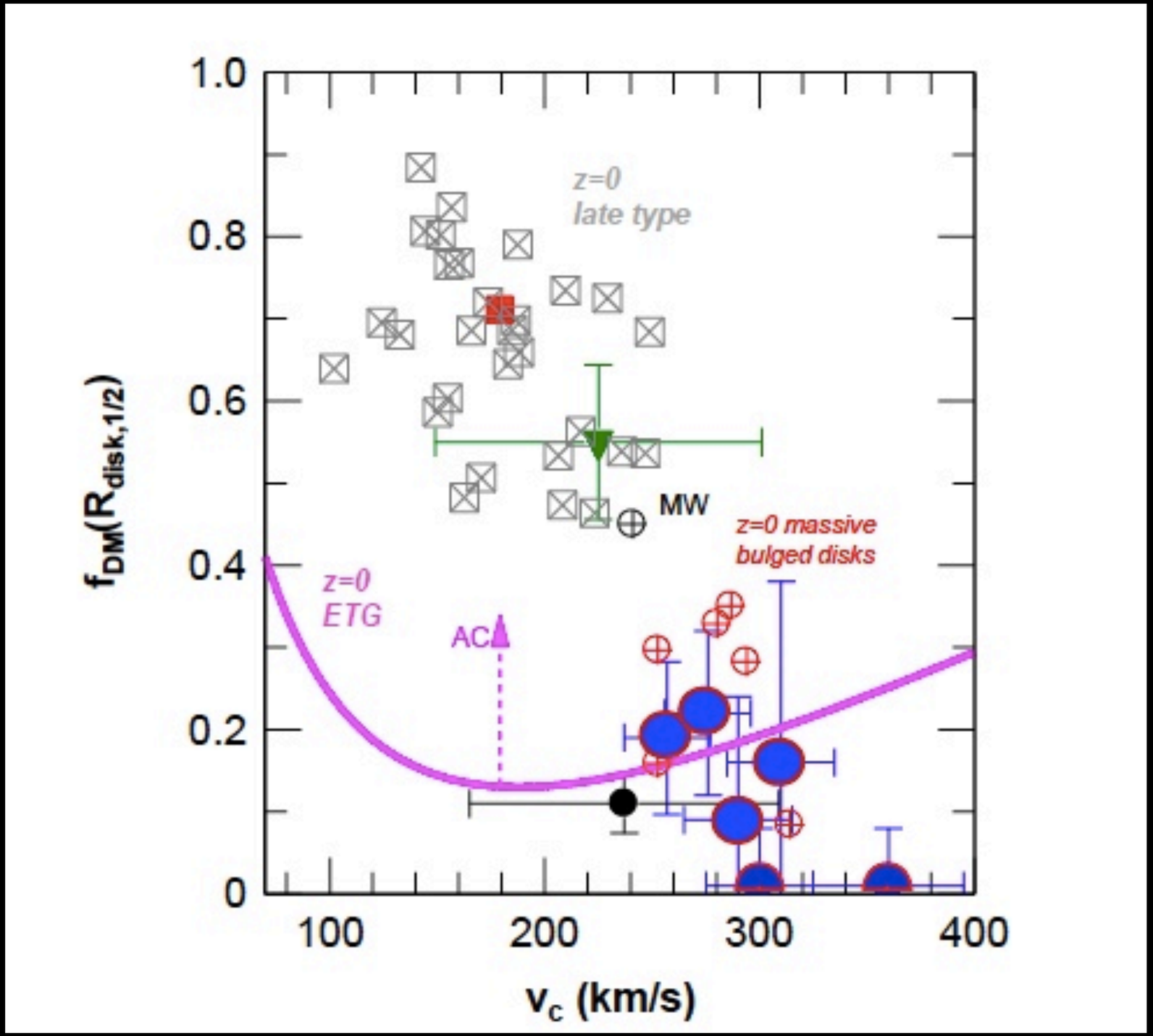
Declining outer rotation curves in high-z galaxies

6 individual SFGs with 10-33h t_{int}, +stack of 105 SFGs



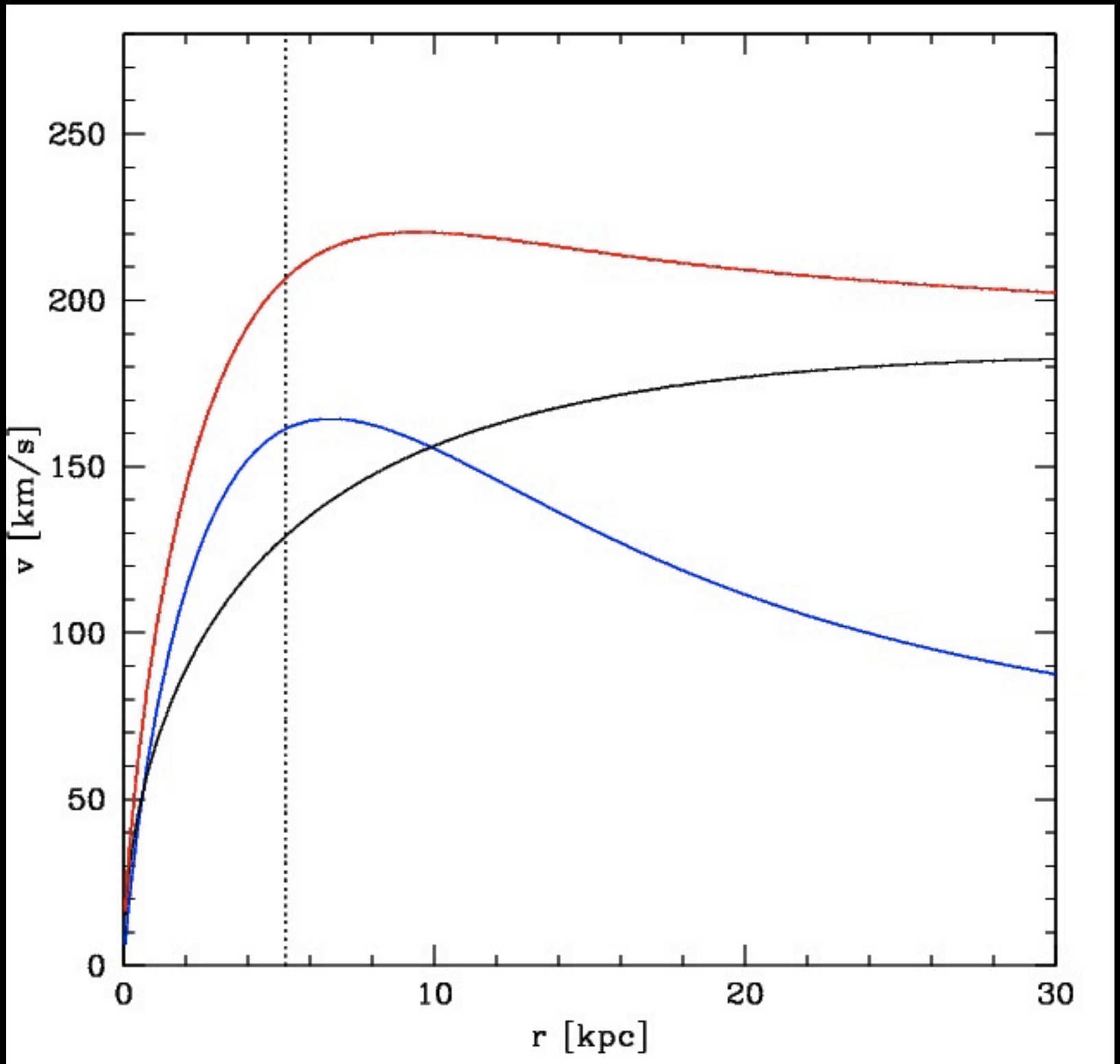
Lang +16, Genzel +16, Burkert +16, Tiley +16

Declining outer rotation curves in high-z galaxies



Lang +16, Genzel +16, Burkert +16, Tiley +16

$$M = 10^{12} M_{\odot} \quad \lambda \approx 0.035$$



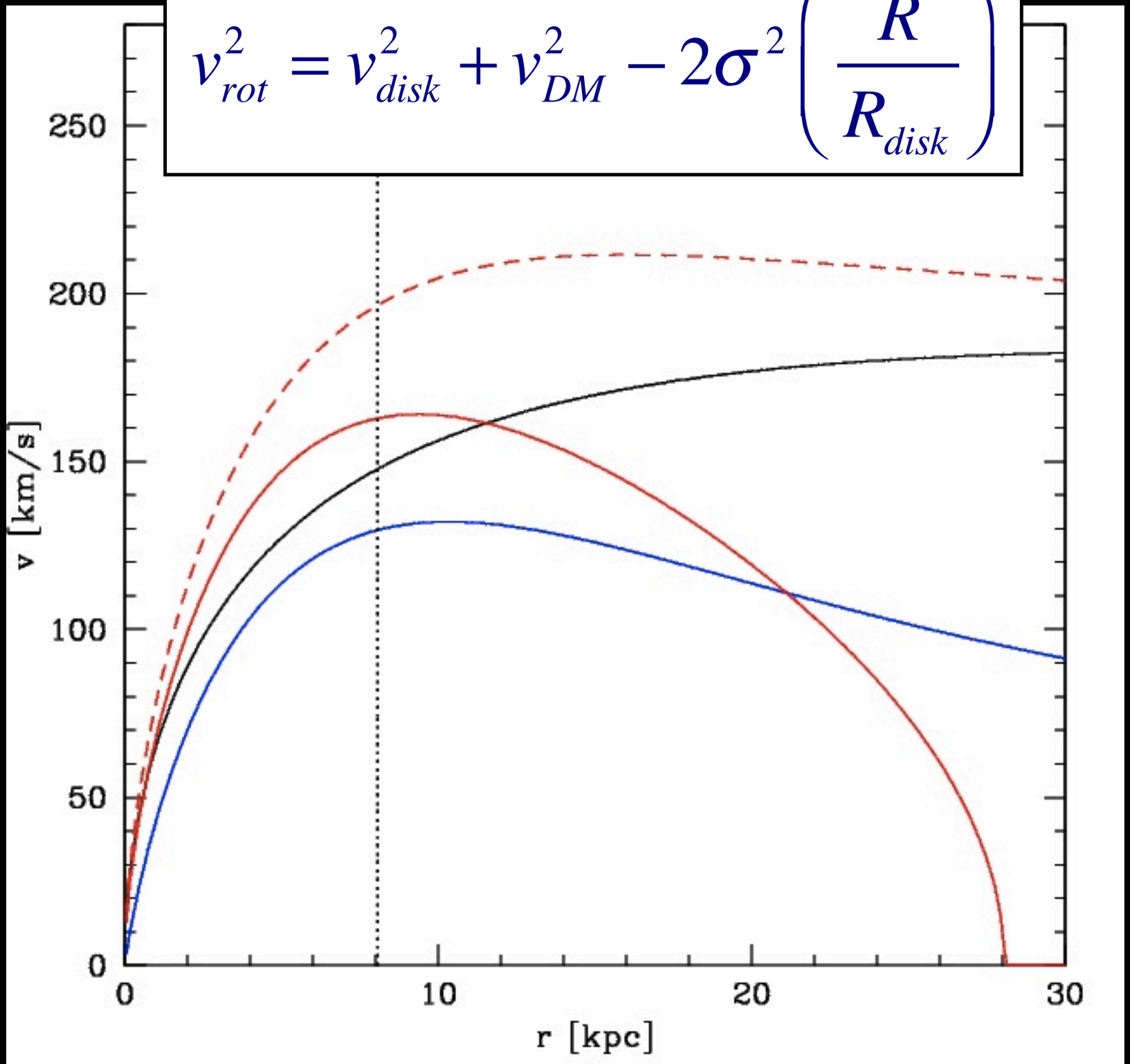
$$z = 0$$

$$\sigma = 0 \ km/s$$

$$r_{disk} = 3.1 kpc$$

$$M = 10^{12} M_{\odot} \quad \lambda \approx 0.035$$

$$v_{rot}^2 = v_{disk}^2 + v_{DM}^2 - 2\sigma^2 \left(\frac{R}{R_{disk}} \right)$$

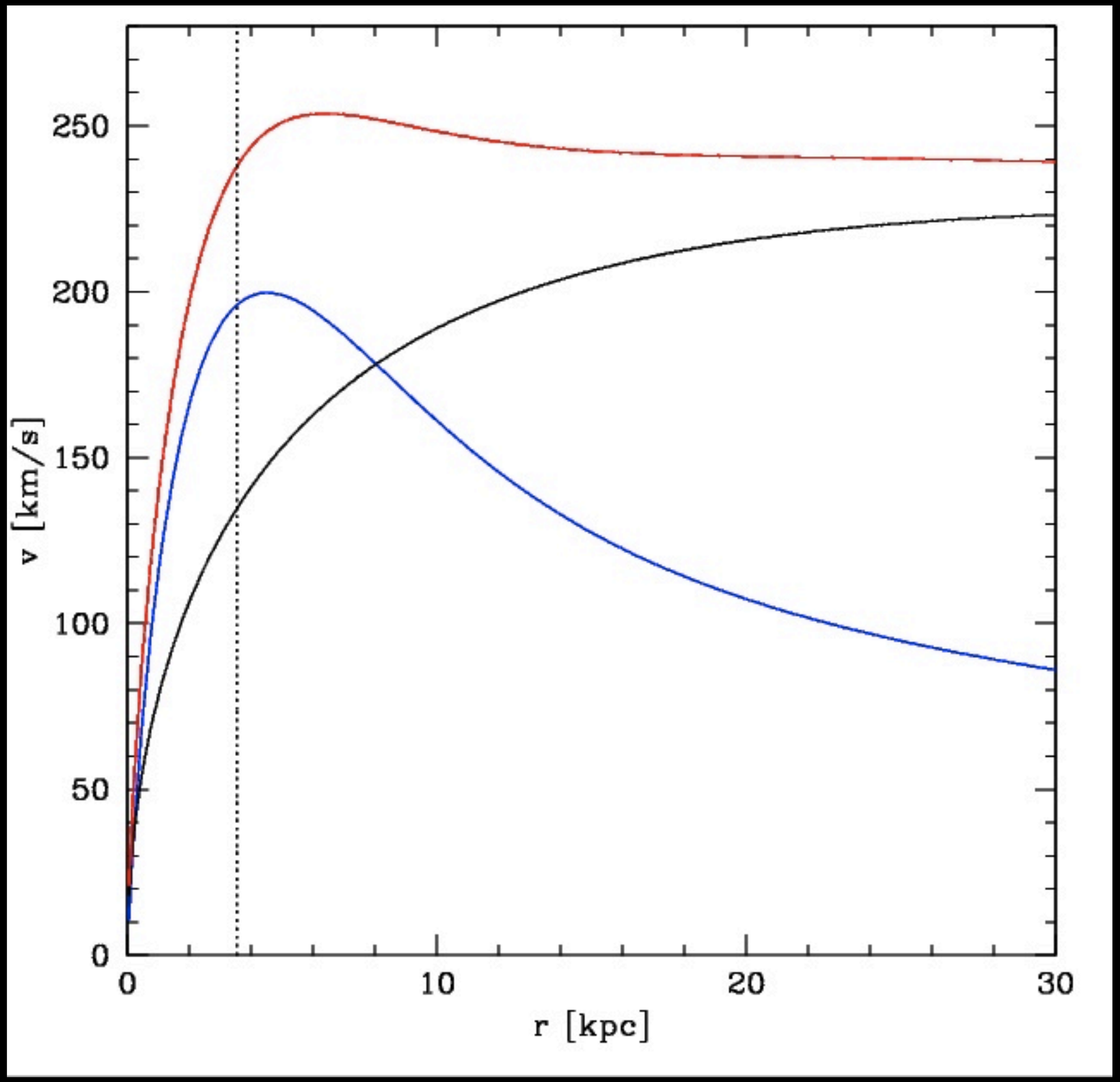


$$z = 0$$

$$\sigma = 60 \ km/s$$

$$r_{disk} = 4.8 kpc$$

$$M = 10^{12} M_{\odot} \quad \lambda \approx 0.035$$

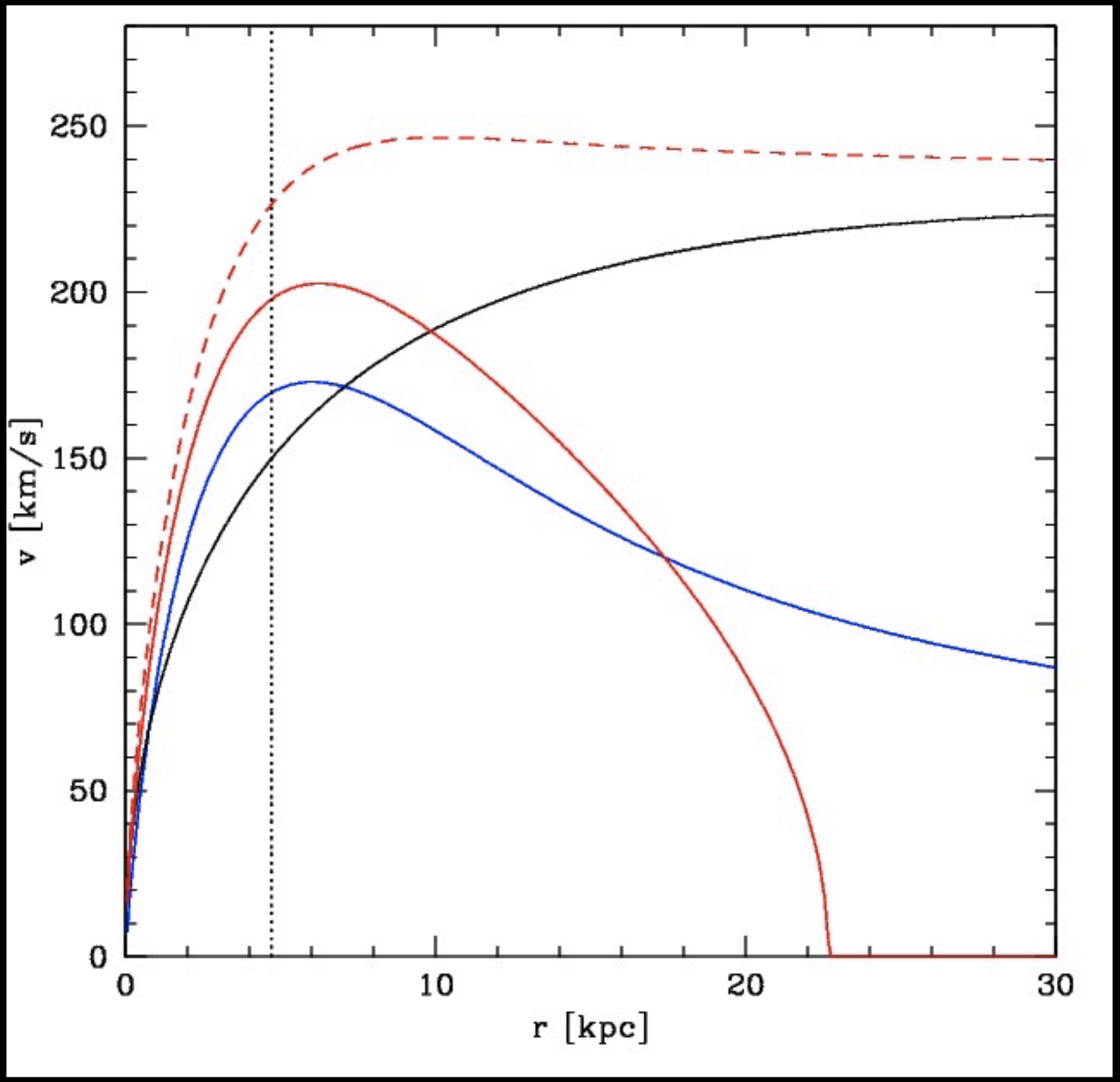


$$z = 2$$

$$\sigma = 0 \ km/s$$

$$r_{disk} = 2.1 kpc$$

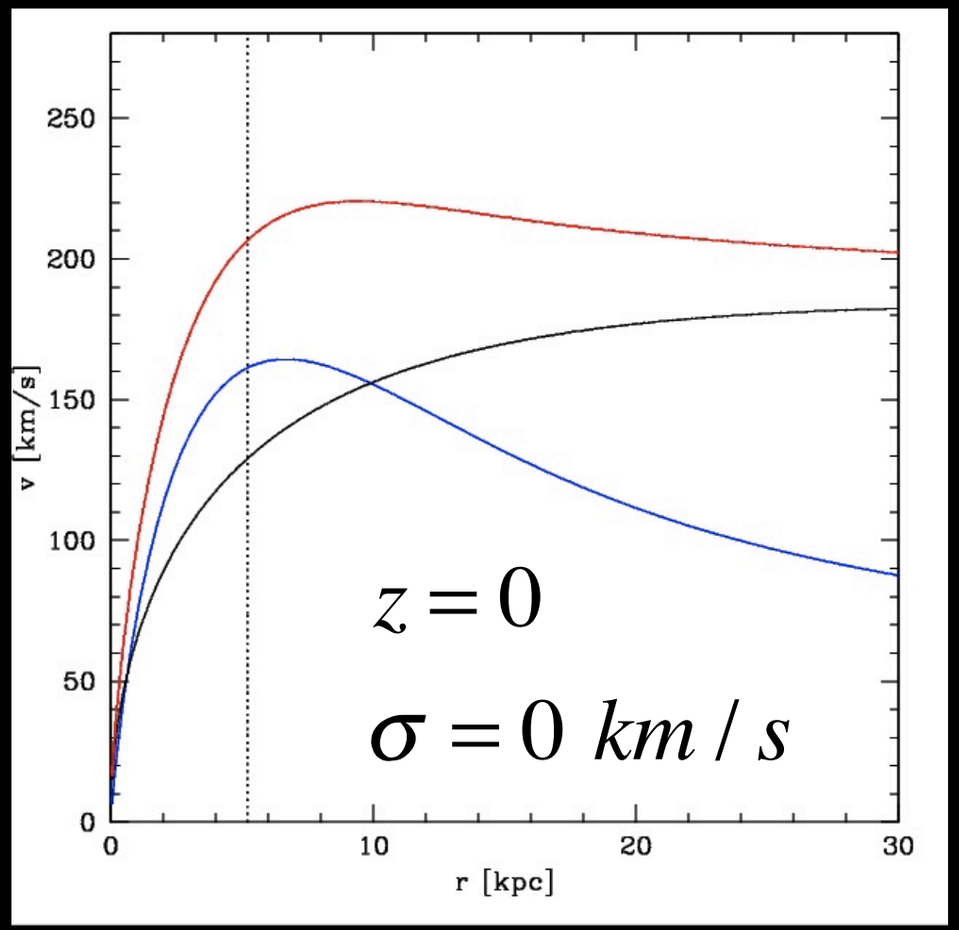
$$M = 10^{12} M_{\odot} \quad \lambda \approx 0.035$$



$$z = 2$$

$$\sigma = 60 \ km / s$$

$$r_{disk} = 2.8 kpc$$


250
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$z = 0$
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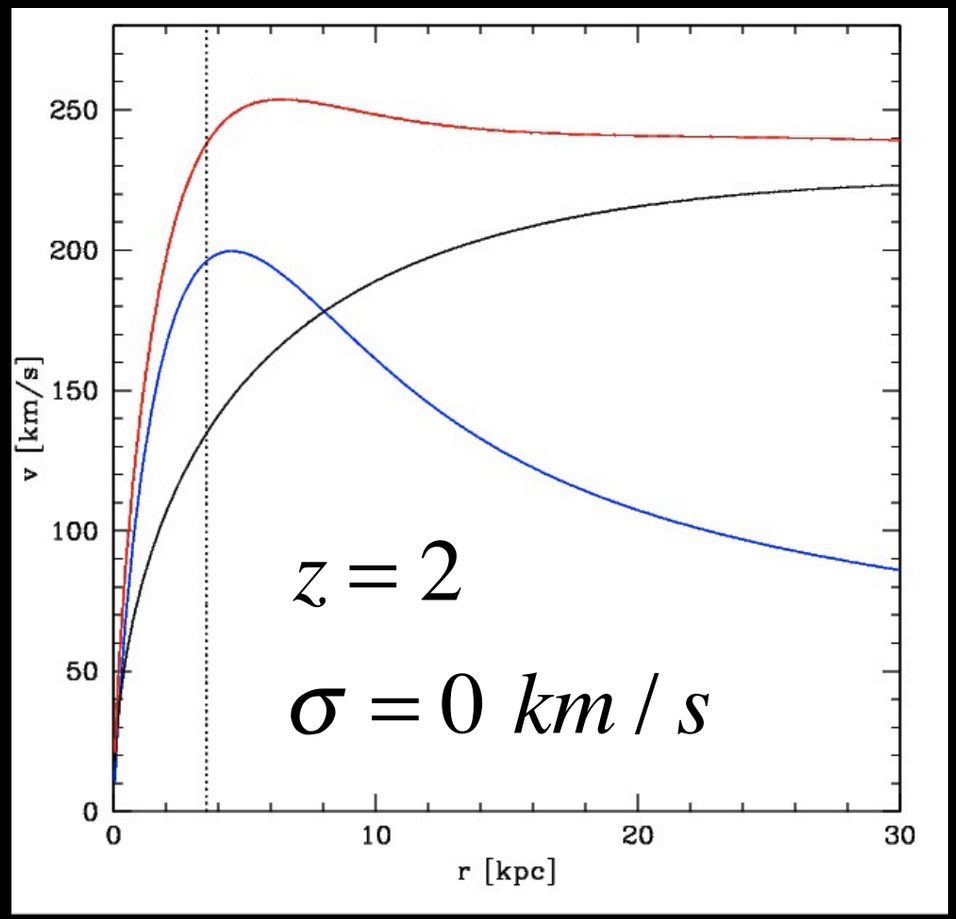
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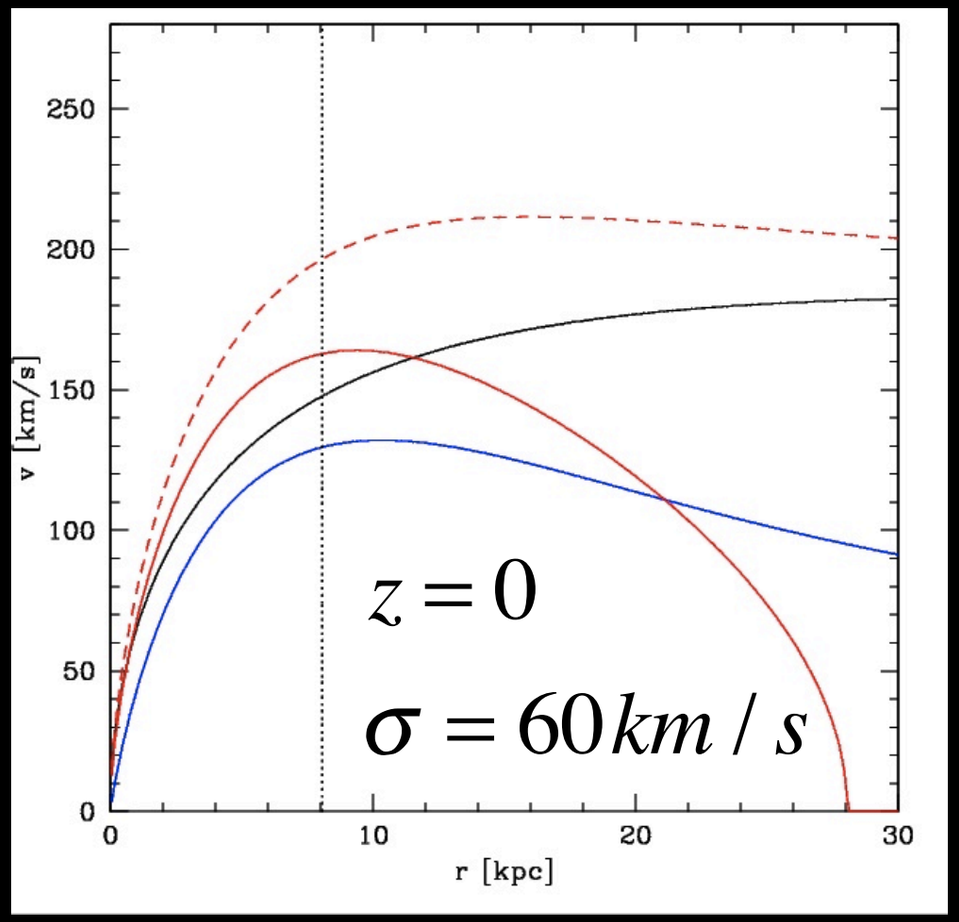
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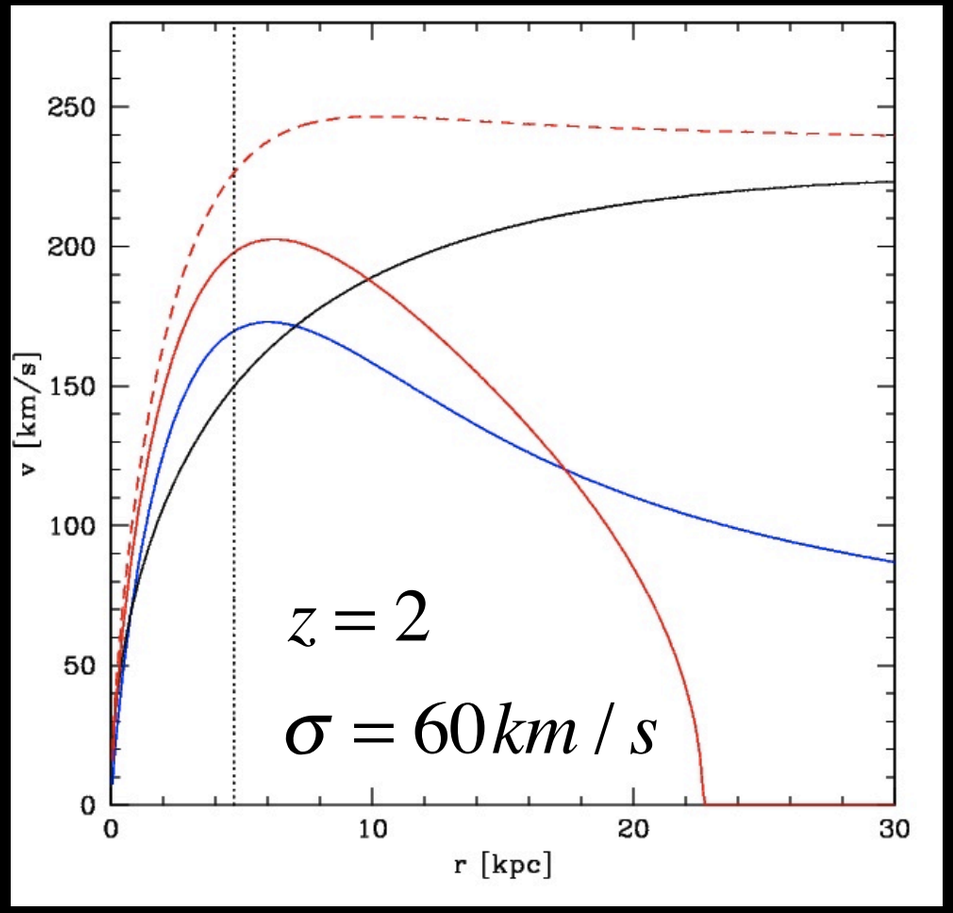
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