Revisiting angular momentum and galaxy formation

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Fundamental physical parameters of galaxies

Dimensionless spin λ:

- sets the (~scale-free) initial conditions (from tidal torques or *N*-body sims)
- not a conserved physical quantity

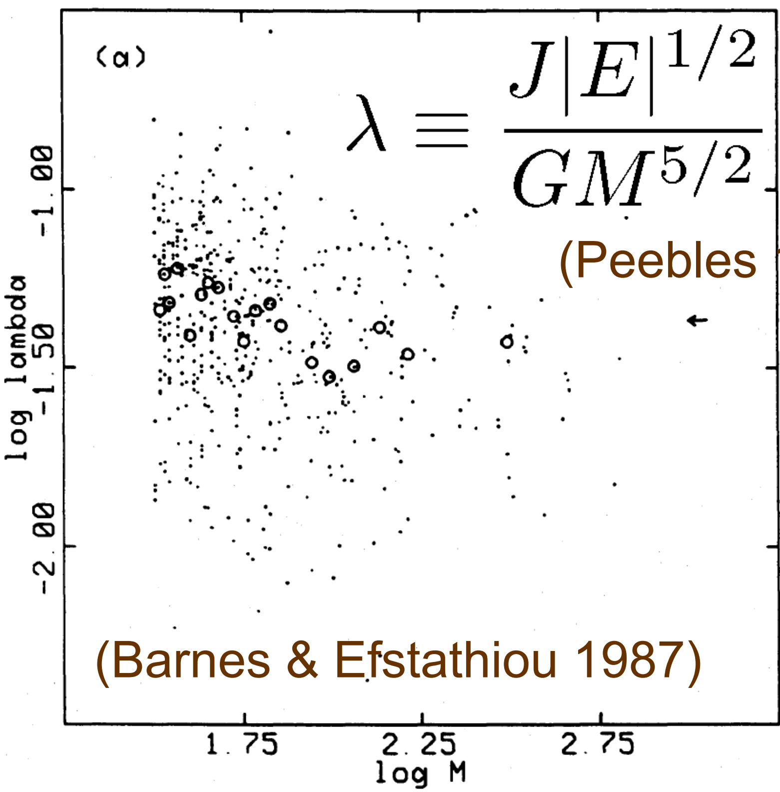
$M : \sim L$

$E : \sim L^2/R_e$

$J : \sim v_{rot} L R_e$

M, *J*

- may be conserved
- map baryons to their DM halos

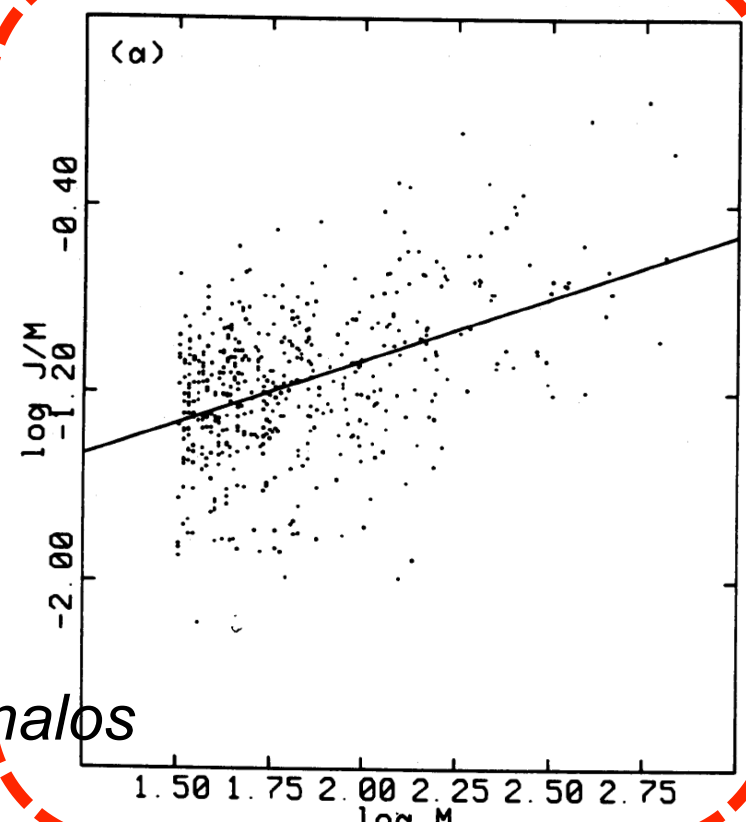


$$\lambda \equiv \frac{J|E|^{1/2}}{GM^{5/2}}$$

(Peebles 1969)

(Barnes & Efstathiou 1987)

dark matter halos



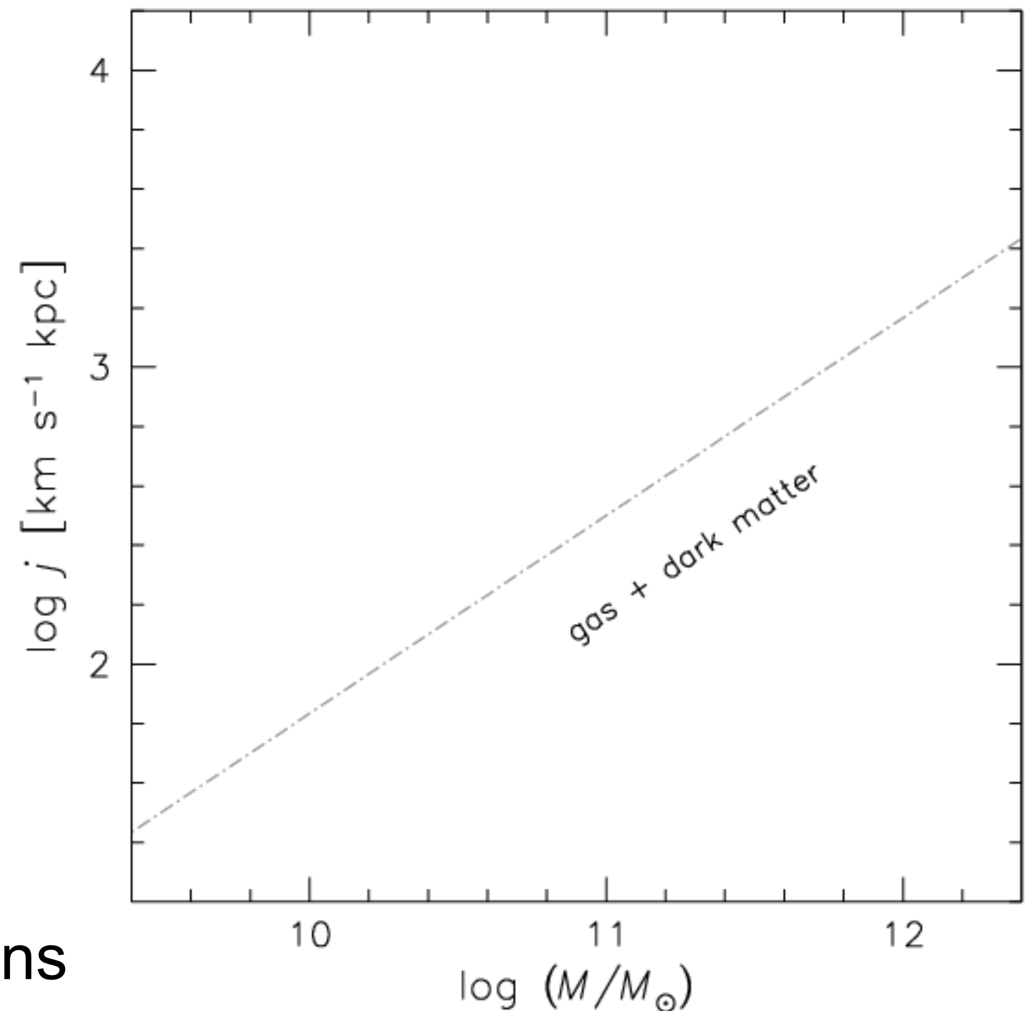
Specific angular momentum of ΛCDM halos

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

$\langle\lambda\rangle$ ~ 0.035, scatter ~ 0.23 dex
(evaluated over virial region;
Macciò+2008: WMAP5)

$$j \equiv J/M$$

→ Simple, robust *j-M* scaling relation for DM halos;
has to be linked with baryons



$$j_{\rm vir} = 4.23 \times 10^4 \ \lambda \left(\frac{M_{\rm vir}}{10^{12} M_\odot}\right)^{2/3} \ {\rm km\ s^{-1}\ kpc}$$

Evolution in the *j-M* plane: DM to baryons

1) Gas decouples from DM:
dissipative collapse

$M_{gas} = f_b\, M_{vir}$

$j_{gas} = j_{vir}$

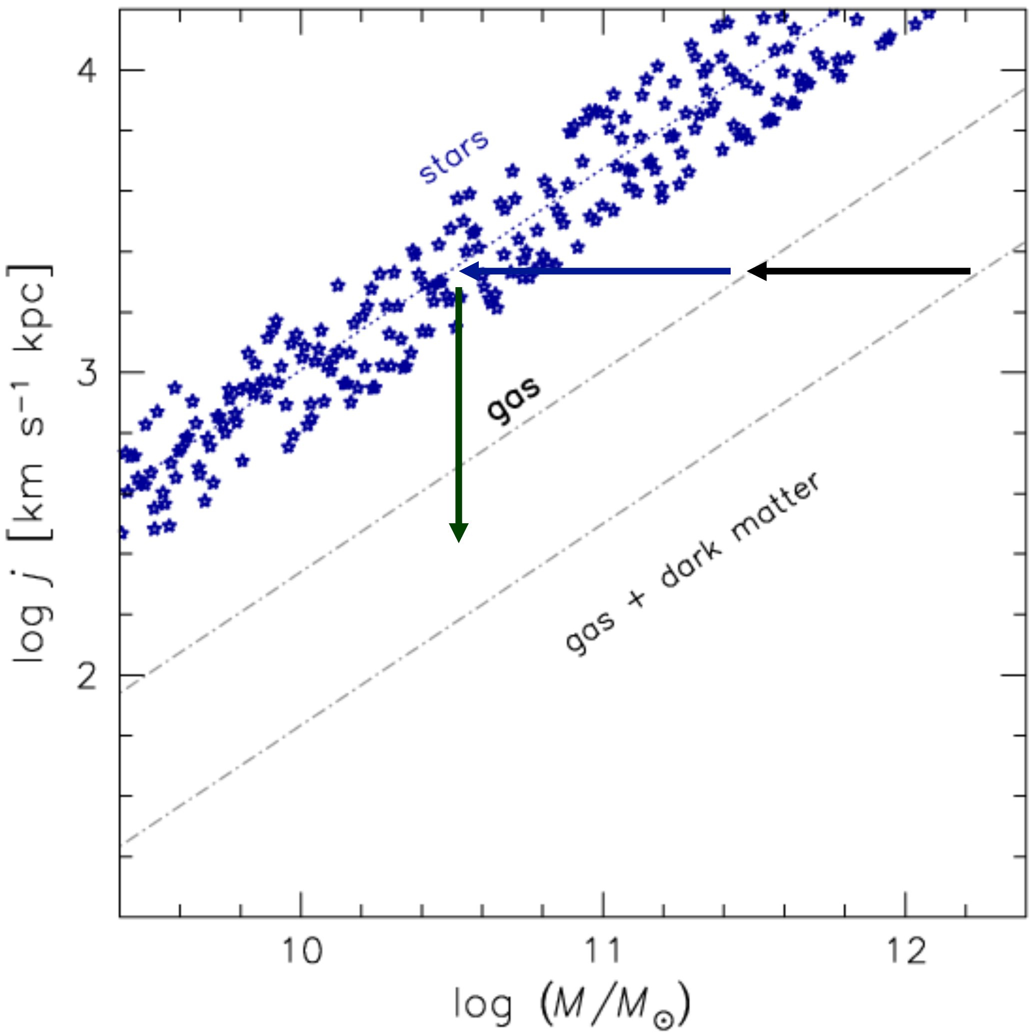
2) Stars form (in cold disks?):

$M_* = f_*\, f_b\, M_{vir}$

$j_* = j_{vir}$

3) Angular momentum loss?

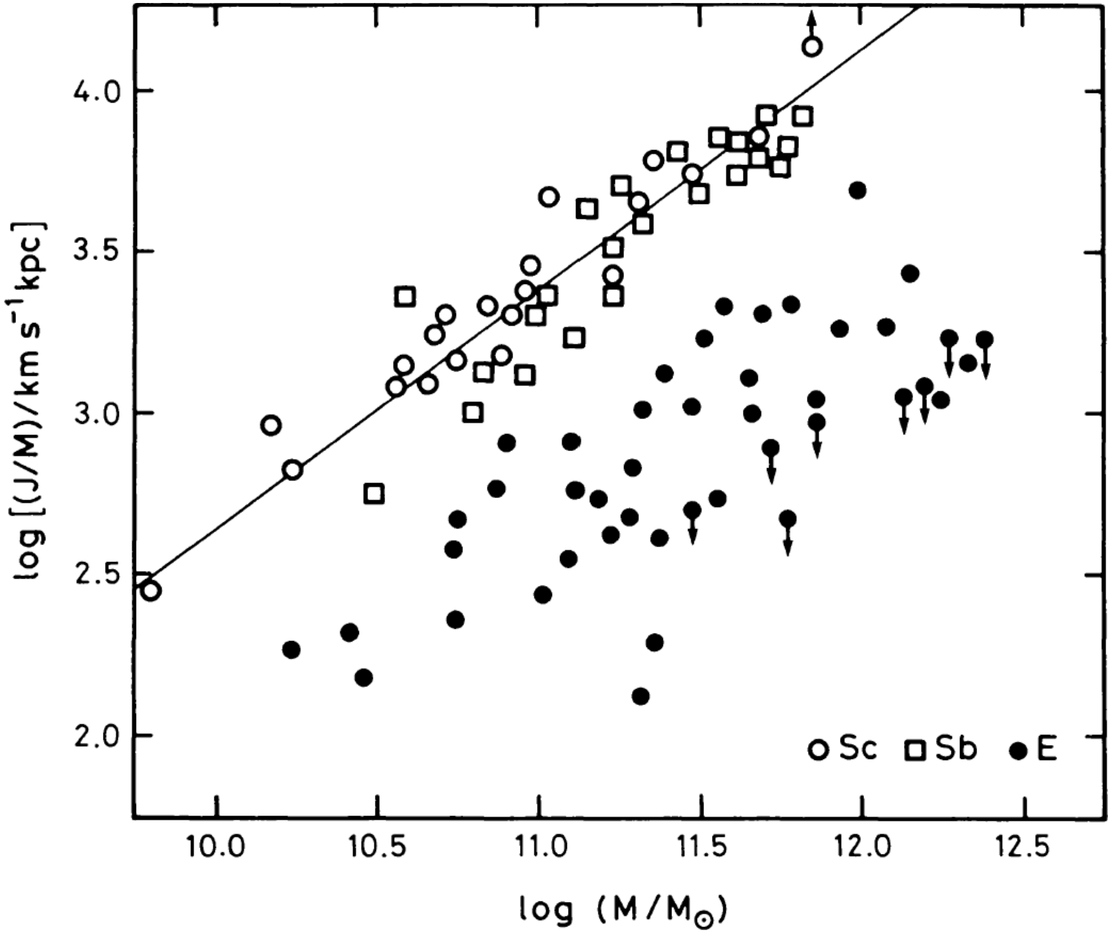
$j_* = f_j\; j_{vir}$



→ *Comparing j_*–M_* observations to ΛCDM predictions provides direct constraints on* $(f_j / f_*^{2/3})$

j_*-M_* observations: *ca. 1983*

Fall 1983
(data for Sb-Sc spirals:
Rubin+1980 etc.
for *centers* of ellipticals:
Davies+1983)



Spirals: $j_* \propto M_*^{3/4}$

→ matches slope + normalization for DM halos if: $f_* f_b \sim 0.05$, $f_j \sim 1$

→ (weak) j "conservation" !

Ellipticals: j_*-M_* ~ parallel, offset

→ $f_j \sim 0.15$

→ more scatter?

$j_d = 2\, v_{rot}\, R_d$

$j_E = 2.5\, v_{rot}\, R_e$

j_*-M_* observations: *classic constraints on theory*

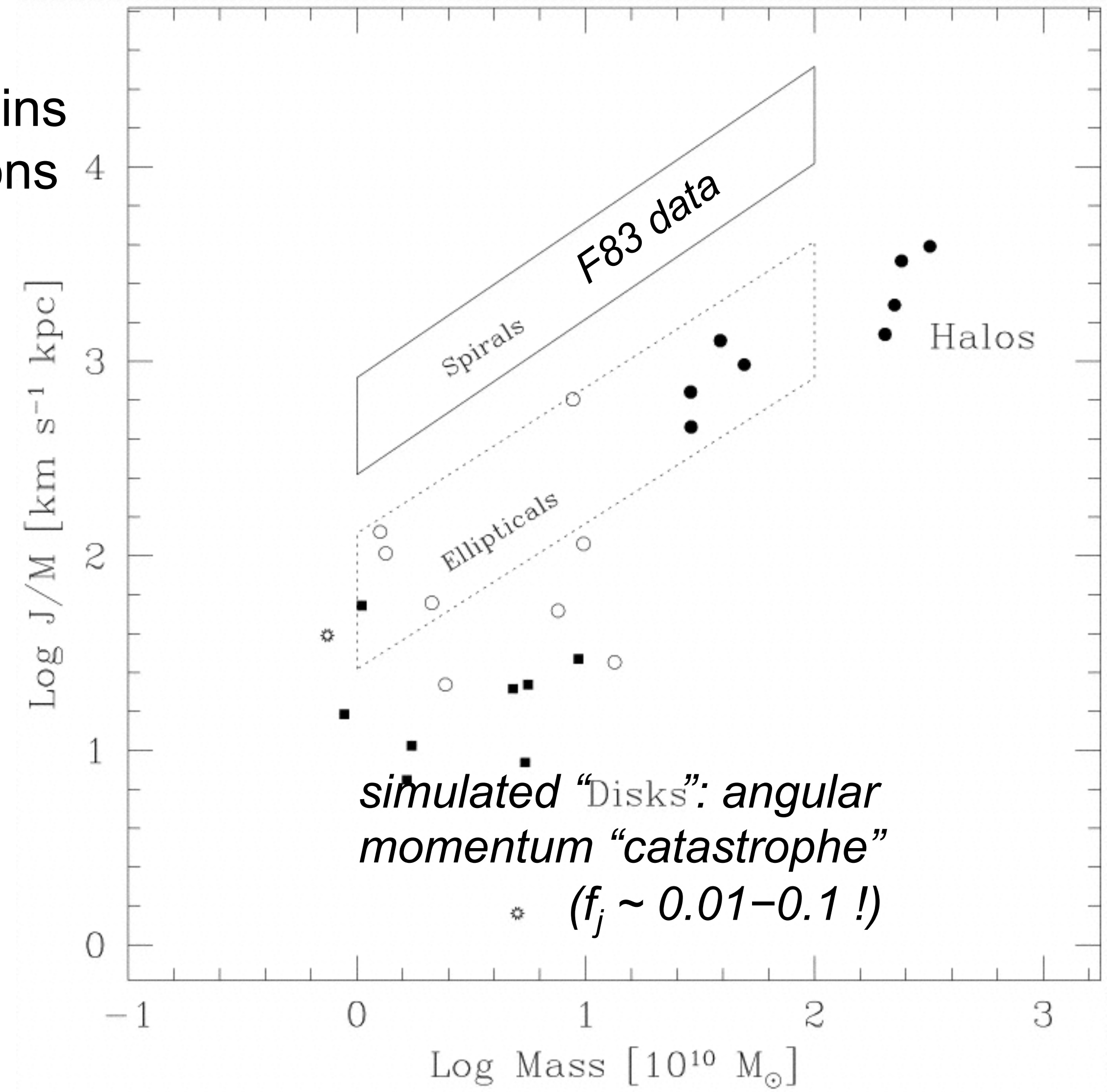
j_*-M_* diagram:

→ simple collapse model explains observed *disk* scaling relations

(Fall & Efstathiou 1980; Dalcanton+1997; Mo, Mao & White 1998)

→ benchmark for simulations

(e.g. Navarro & Steinmetz 1997; Maller & Dekel 2002; Governato+2007; Guedes+2011)



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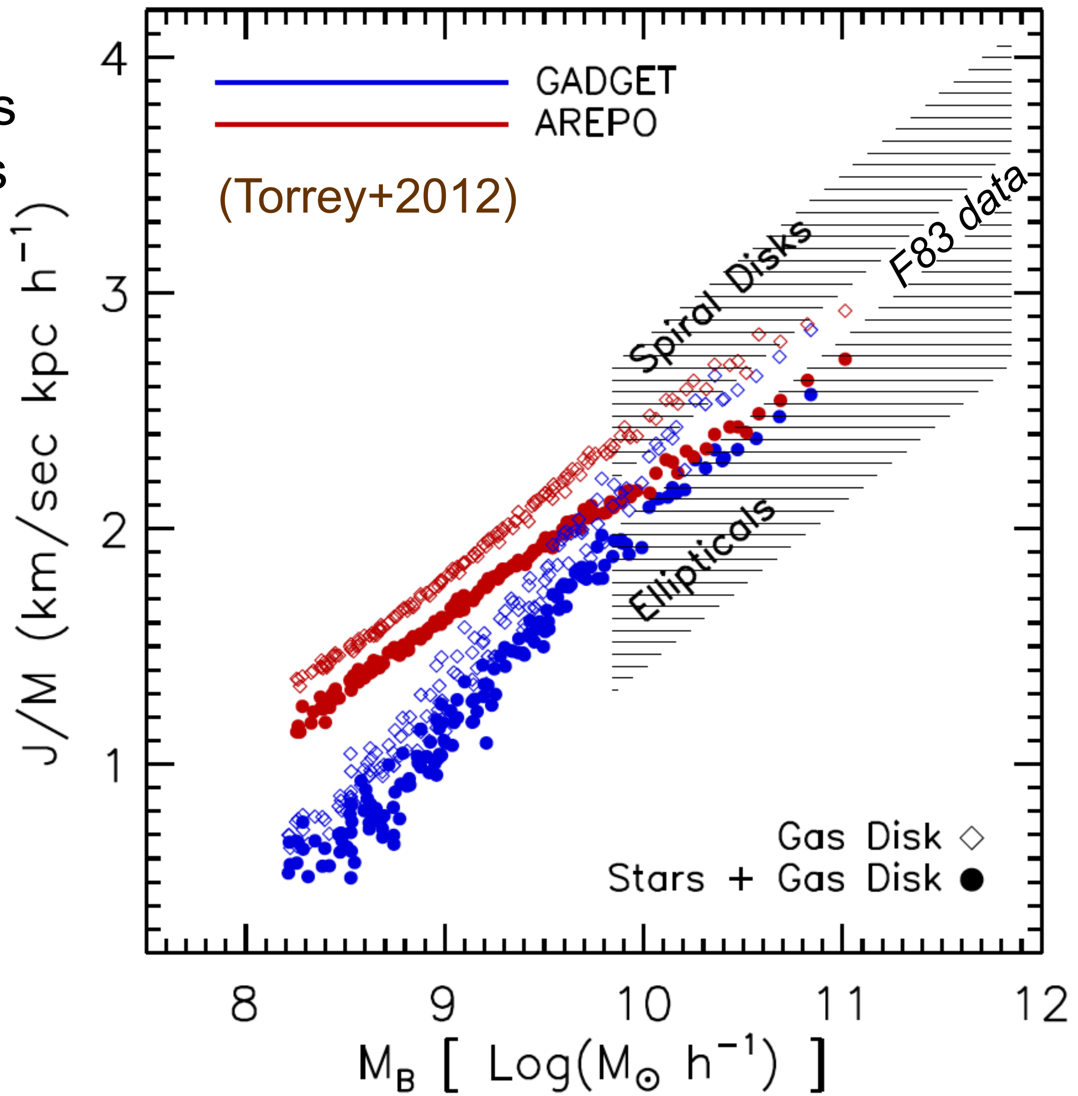


What about E/S0s?

→ are the E “data” correct?

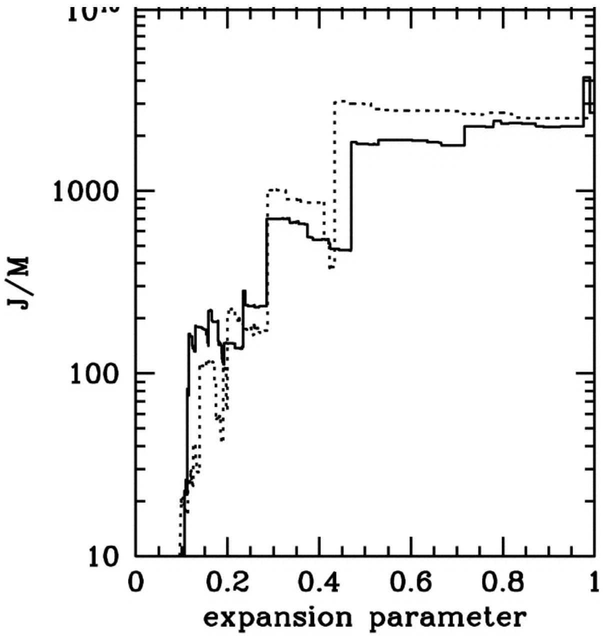
→ do Sa, S0s fill the gap?

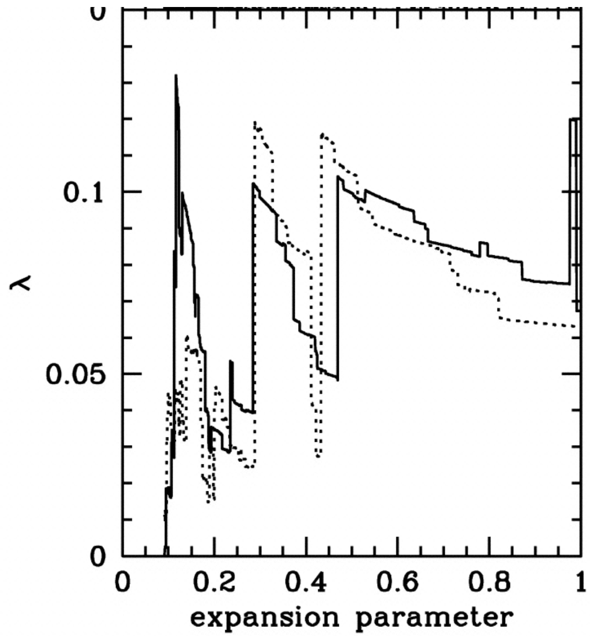
→ does spread in j_* match λ spread for ΛCDM halos?

→ do we expect Es to conserve j_{vir}?

→ *simulations not yet converged at factor of ~2 level*

j in ellipticals: theory

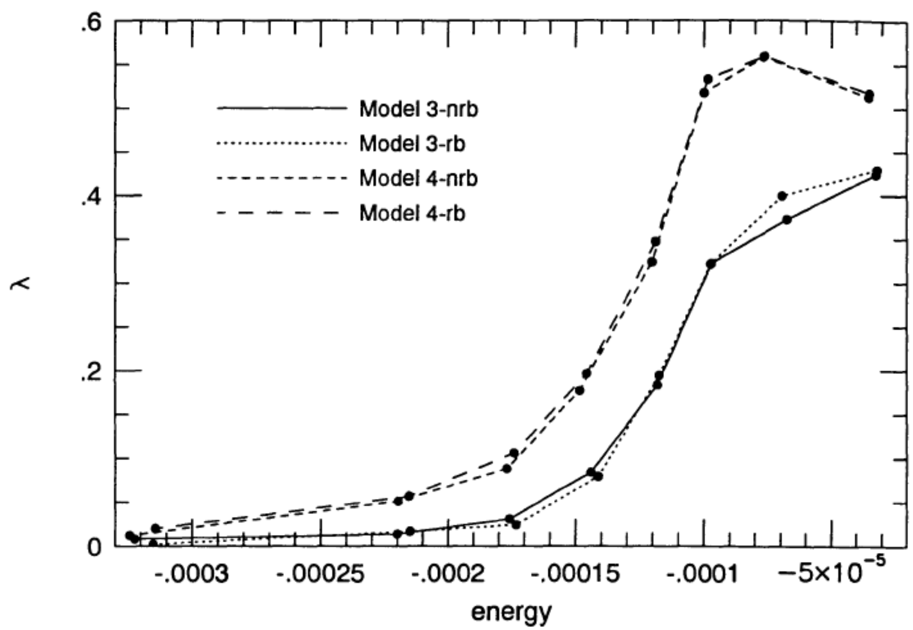




Vitvitska+2002:

Mergers of DM halos cause j , λ spikes
→ ellipticals expected to have *higher* λ_{vir} than spirals!

(but see: Hetznecker & Burkert 2006; D'Onghia & Navarro 2007)



Major mergers of disk galaxies:
internal j_* transfer:
→ stars in outer regions spun up
→ *observations…?*

(e.g., Hernquist 1992, 1993; Bendo & Barnes 2000; Cretton+2001)

"Secure" measurements of j_* in elliptical galaxies

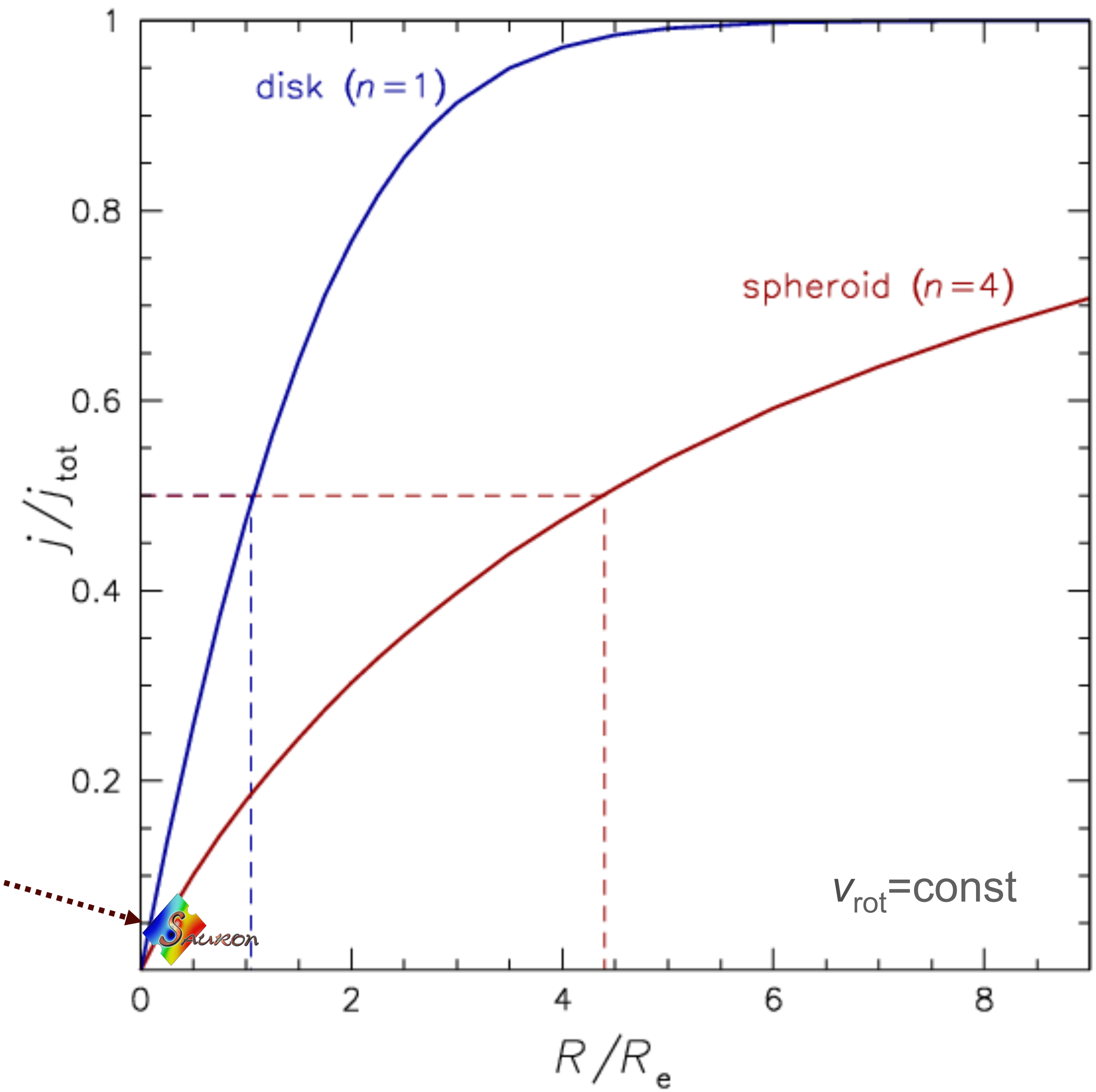
$j_*(R) = \underline{R} \times \underline{v}$,

weighted by $\Sigma_*(R)$

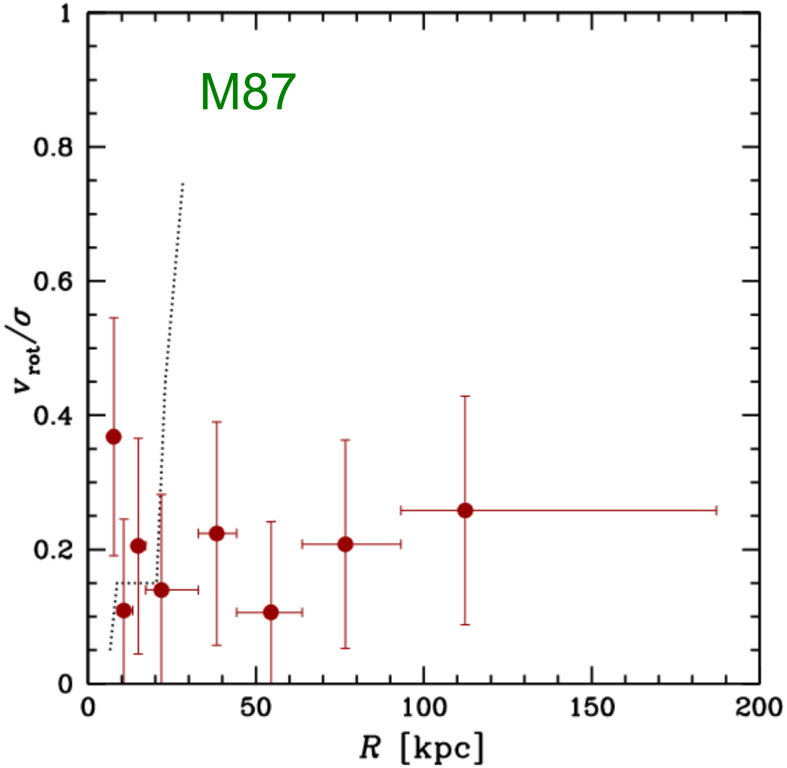
Elliptical galaxies:
need kinematical observations to ~ 4-5 R_e to be confident of j_*
(Fall 1983 extrapolated from ~ R_e)

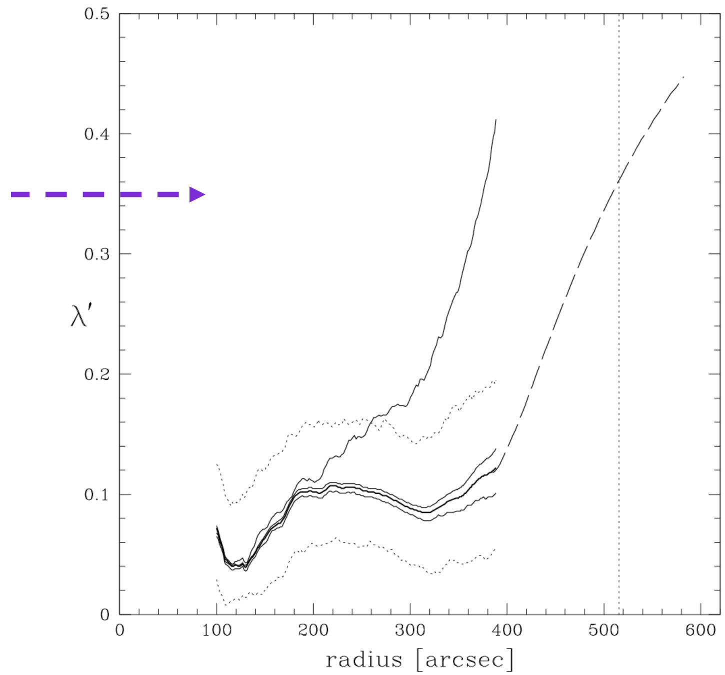
Limit of traditional integrated stellar spectroscopy

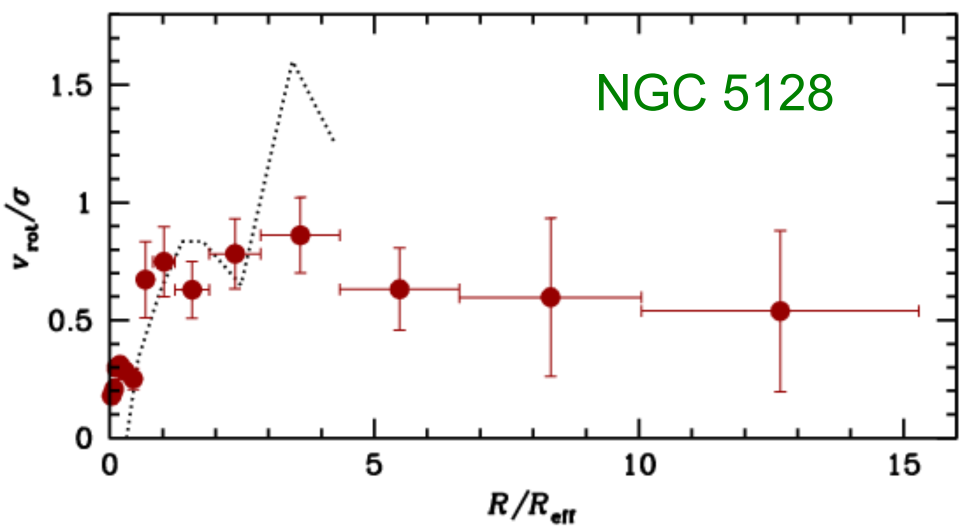
$\lambda_{Re/2} \neq j$!



Missing j_* in outer regions of ellipticals?







Observations of PNe and GCs confirmed high halo rotation

(Hui+1995; Arnaboldi+1998; Kissler-Patig & Gebhardt 1999)

… or did they?

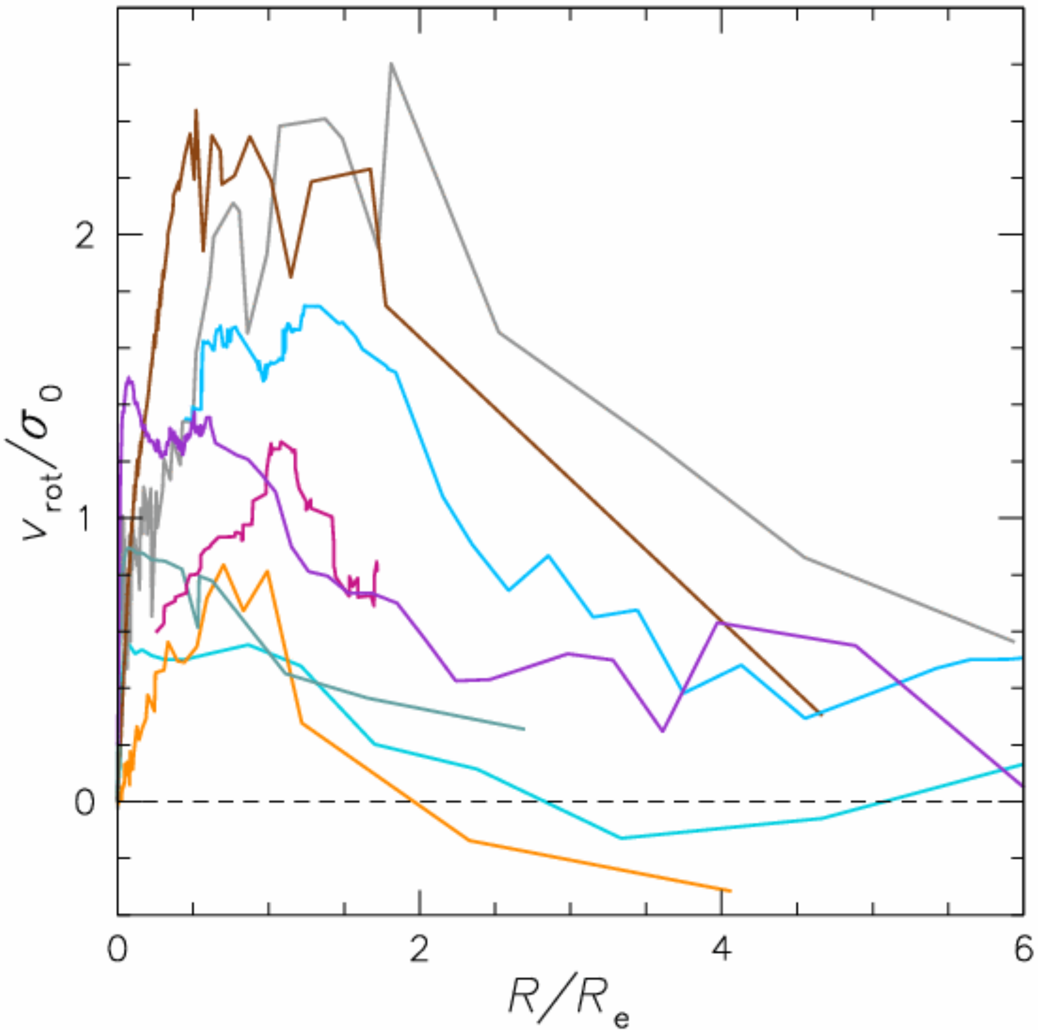
(Woodley+2010; Strader+2011)

New observational era of E/S0 halo kinematics

(e.g., Proctor+2009; Coccato+2009; Arnold+2011)

PN.S

http://sluggs.ucolick.org



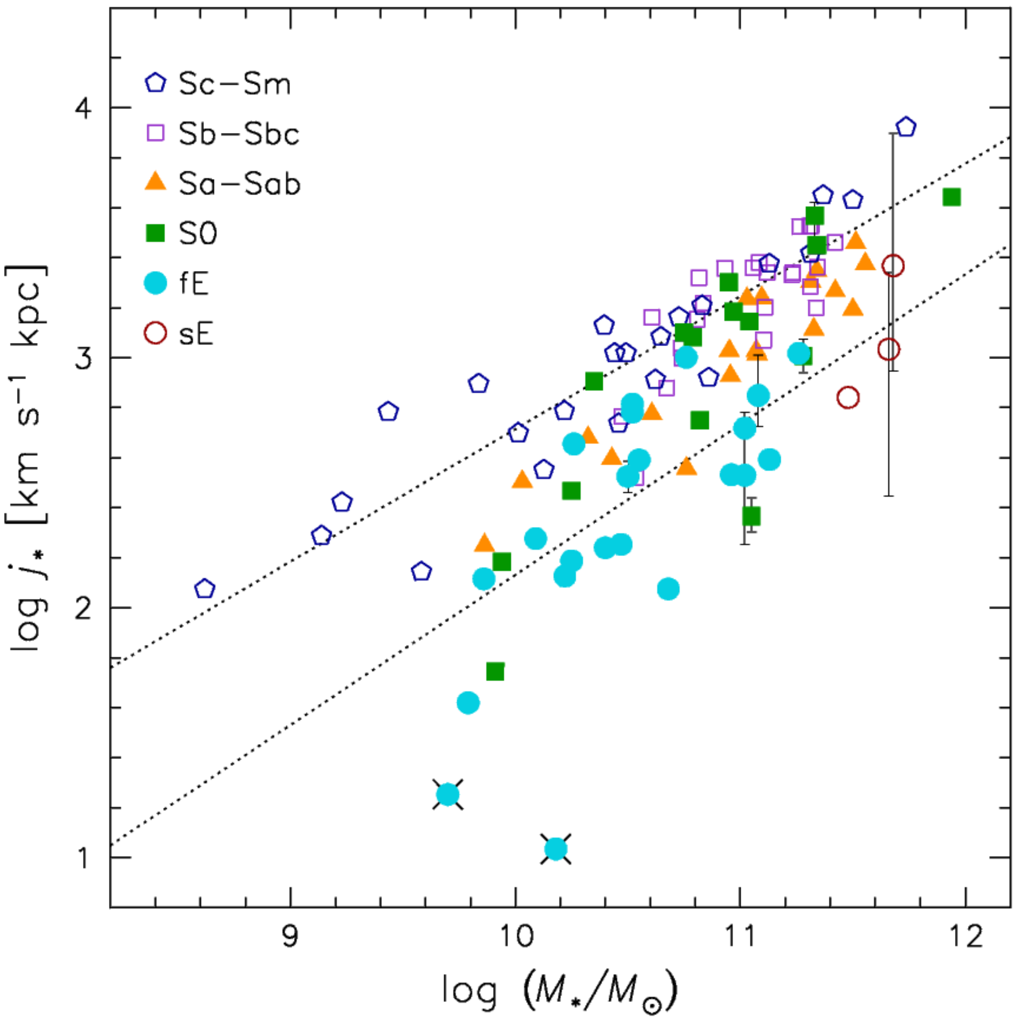
stars, planetary nebulae, globular clusters

Observed outer rotation generally const or ***declining***

→ *little indication of major-merger spin-up!*

(revised story fr Arnaboldi+1996; Kissler-Patig & Gebhardt 1999, etc.)

j_*-M_* observations: *ca. 2012*



First ever j_*-M_* plot of *all types* of bright galaxies (~100 Sm−E, drawn from literature)

Ellipticals parallel to spirals, similar scatter, factor of ~3−4 lower in j_*
(Fall 1983 generally confirmed)

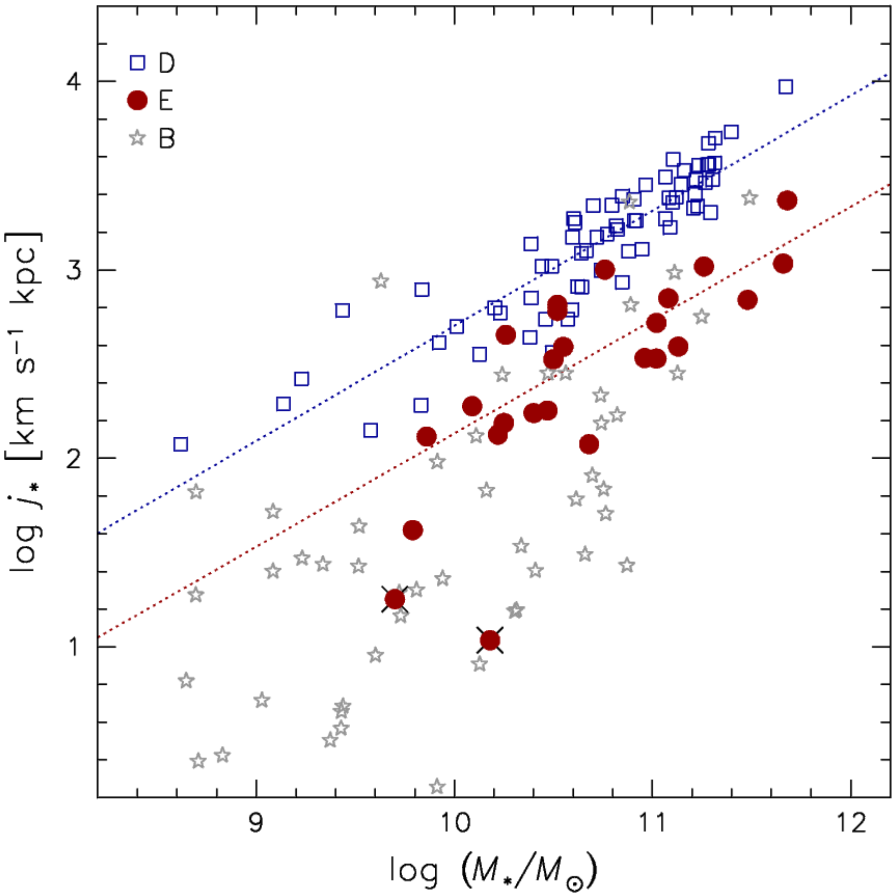
S0s intermediate in j_*

Fast- and slow-rotator Es follow similar trend

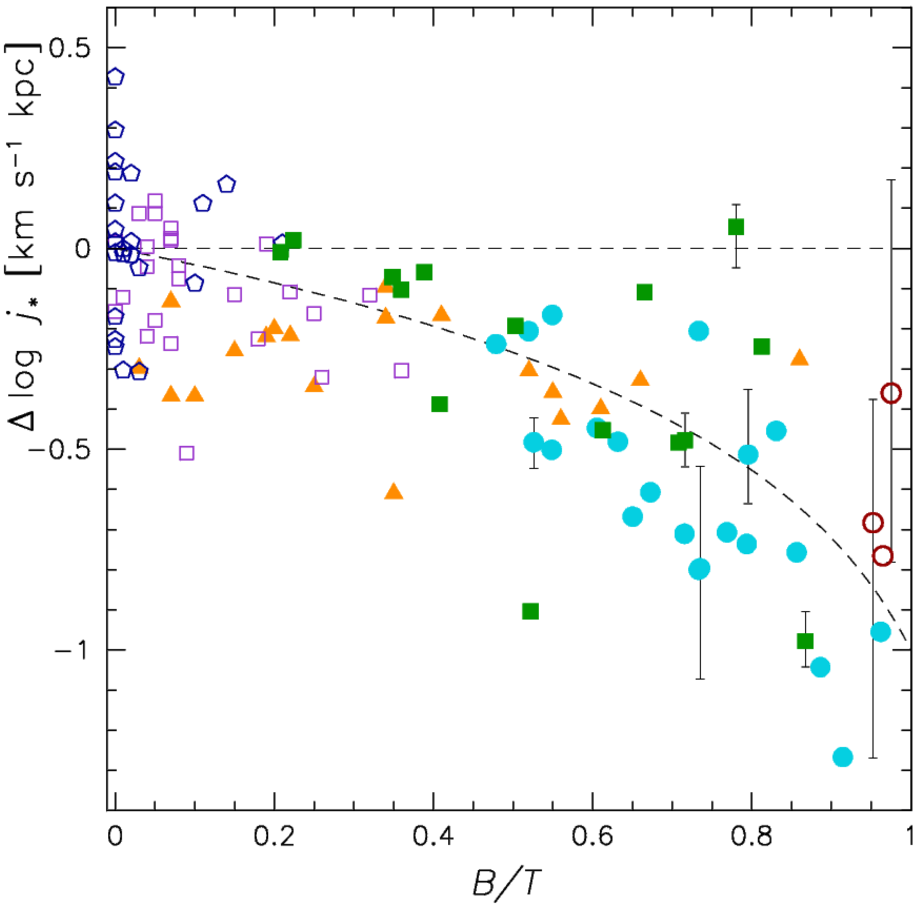
→ *Fundamental constraints for galaxy formation*

Trends in j_* driven by disks and bulges?

(classical) bulges behave like mini-ellipticals in j_*−M_*

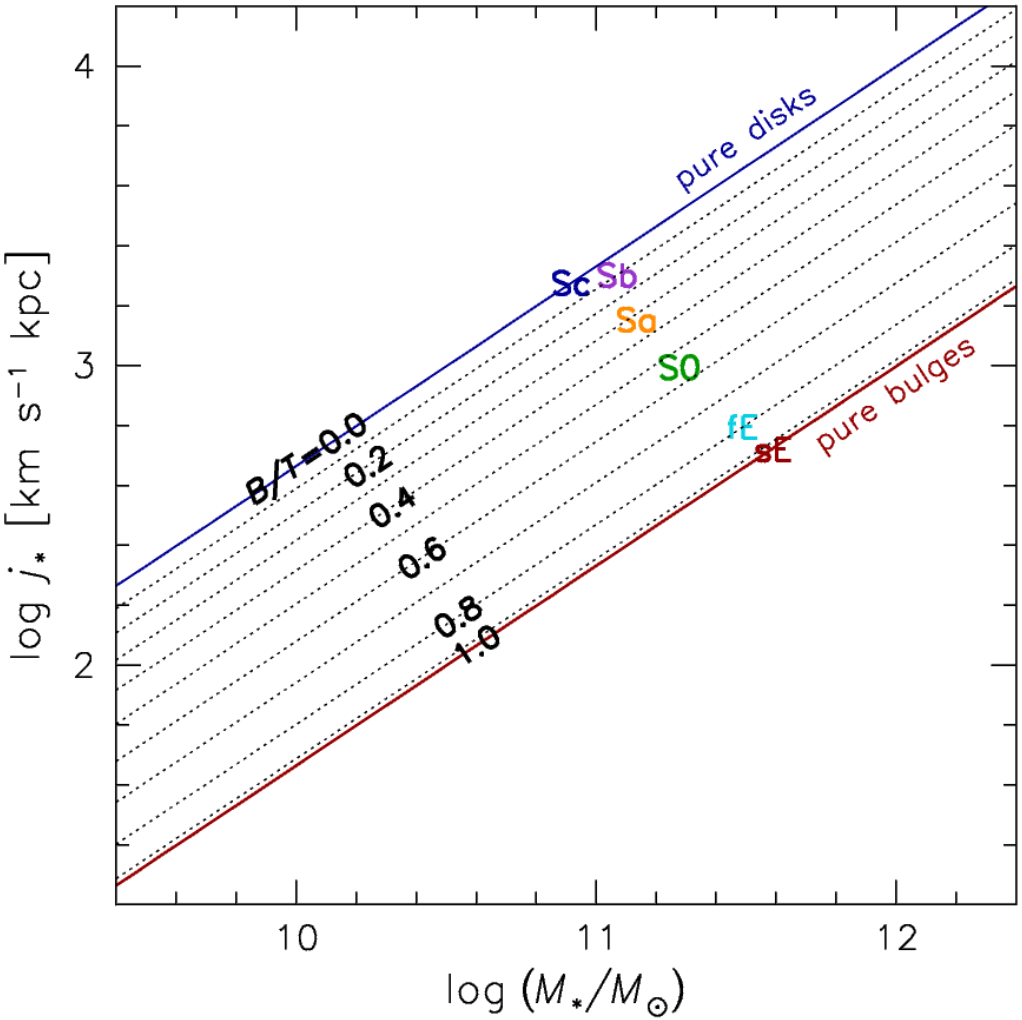


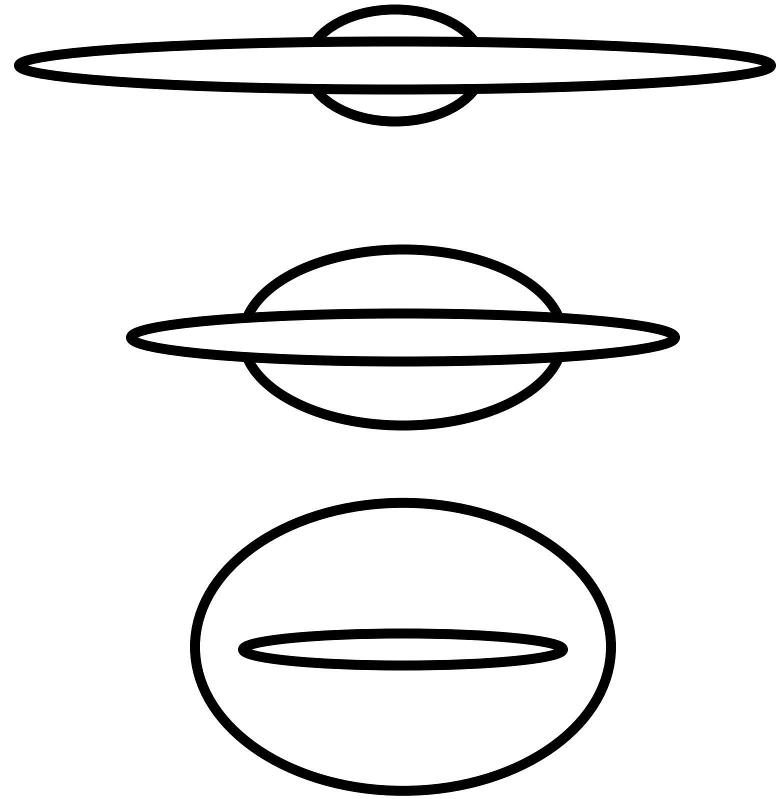
j_*−M_* residuals strongly correlated with bulge fraction



NB: trends may be partially driven by simplified bulge modeling
→ photometric+kinematic bulge−disk decompositions needed

Simple, physical framework for galaxies





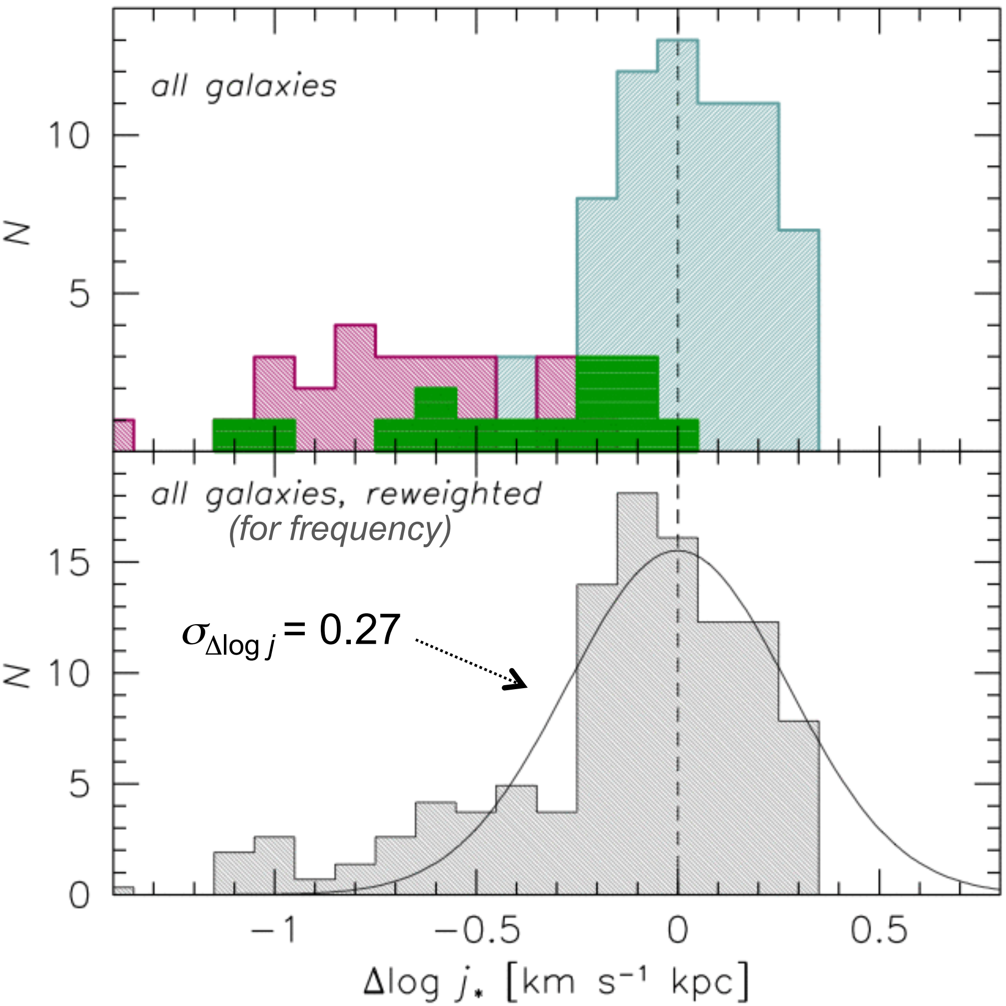
All galaxies are combination of bulge+disk w/universal scaling relations?

→ sizes of both bulges and disks set by j_*−M_* bimodality?

→ galaxy morphology as manifestation of high- and low-j_* material?

Connecting new observations to ΛCDM

$$j_\star = 2.92 \times 10^4 \, f_j \, f_\star^{-2/3} \, \lambda \left(\frac{M_\star}{10^{11} M_\odot} \right)^{2/3} \mathrm{km\ s^{-1}\ kpc}$$



Simple model with $\langle \lambda \rangle$ ~ 0.035,
$\sigma_{\log \lambda}$ = 0.23 dex (Macciò+2008)

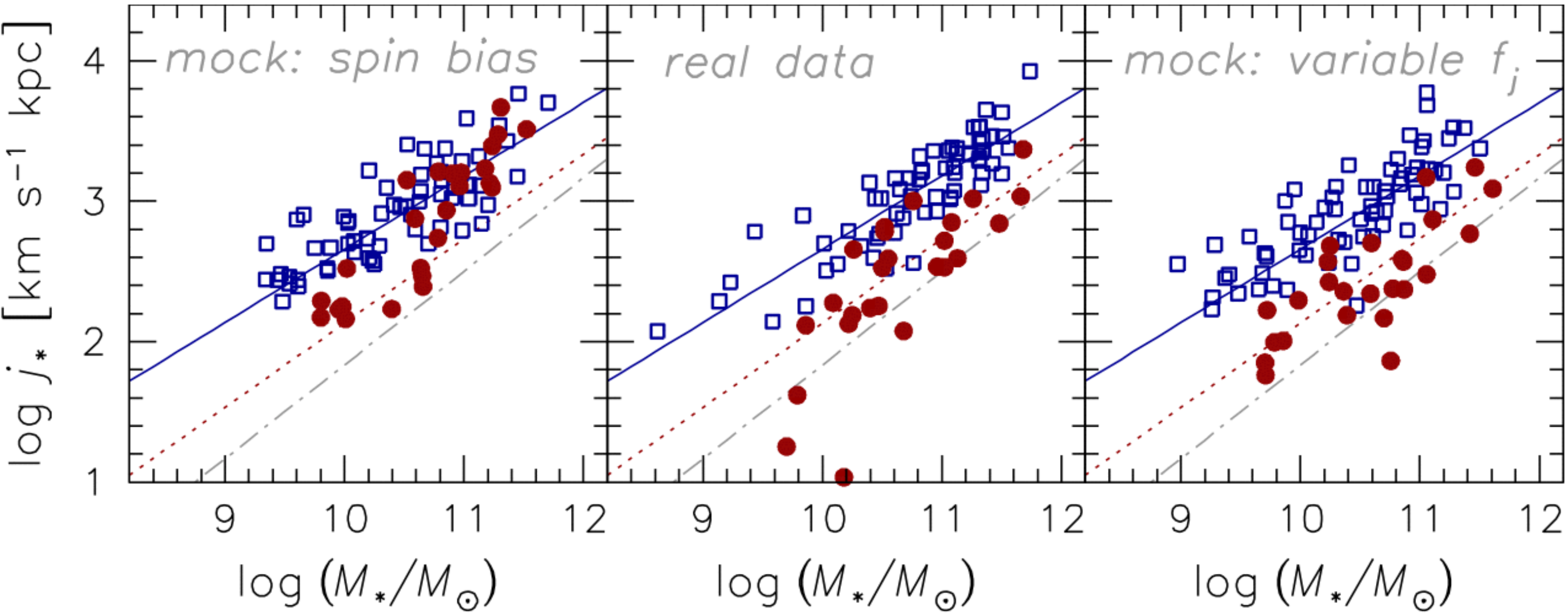
$f_*(M_*)$ from Dutton+2010:
f_* ~ 0.3, 0.1 for Sp, E

f_j = 0.55

→ *model reproduces data remarkably well to first-order*

→ *non-lognormal tails of j_* distribution observed*

Modelling the spiral-elliptical differences

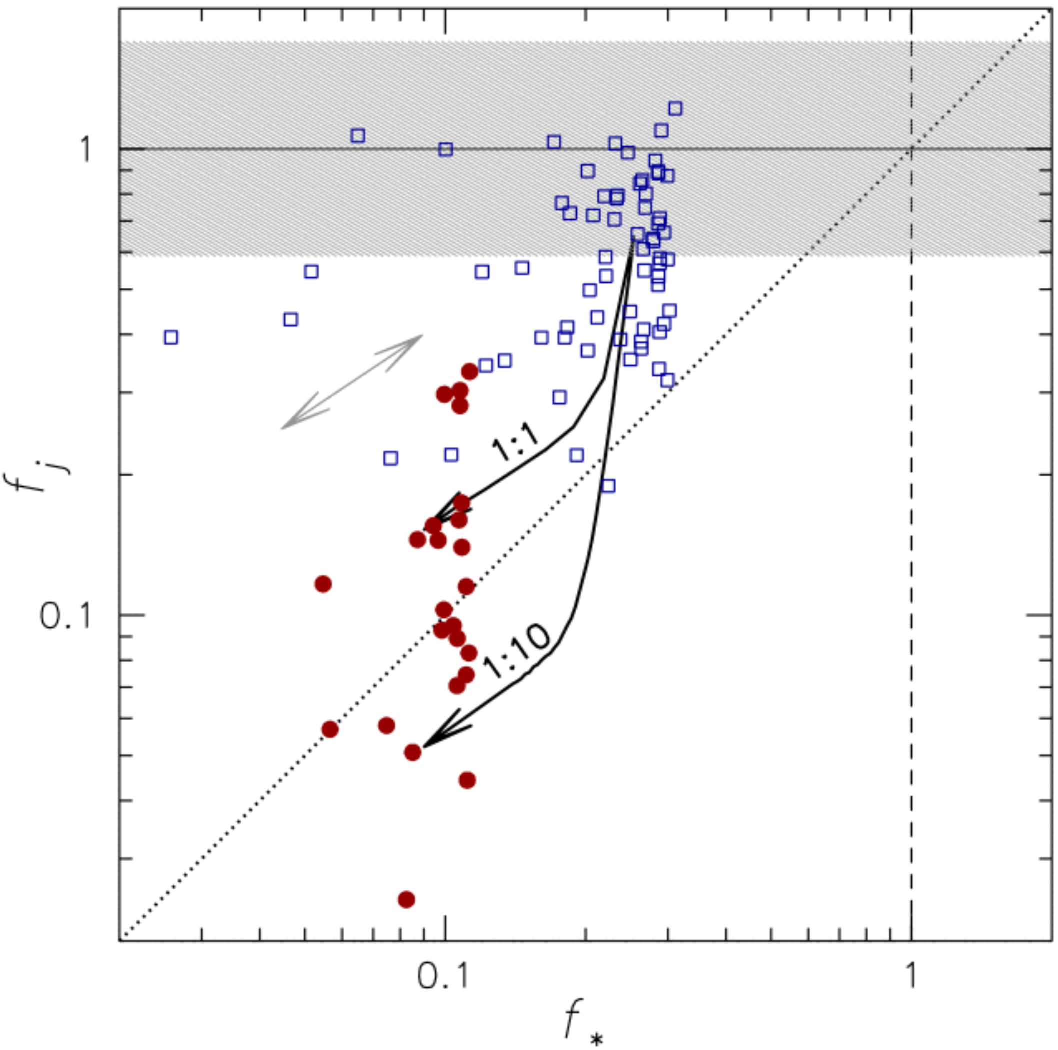


Two extreme scenarios tested with mock data sets:

→ spin bias: spirals/ellipticals formed in high/low-λ halos ✗

→ variable f_j: different angular momentum retention ✓

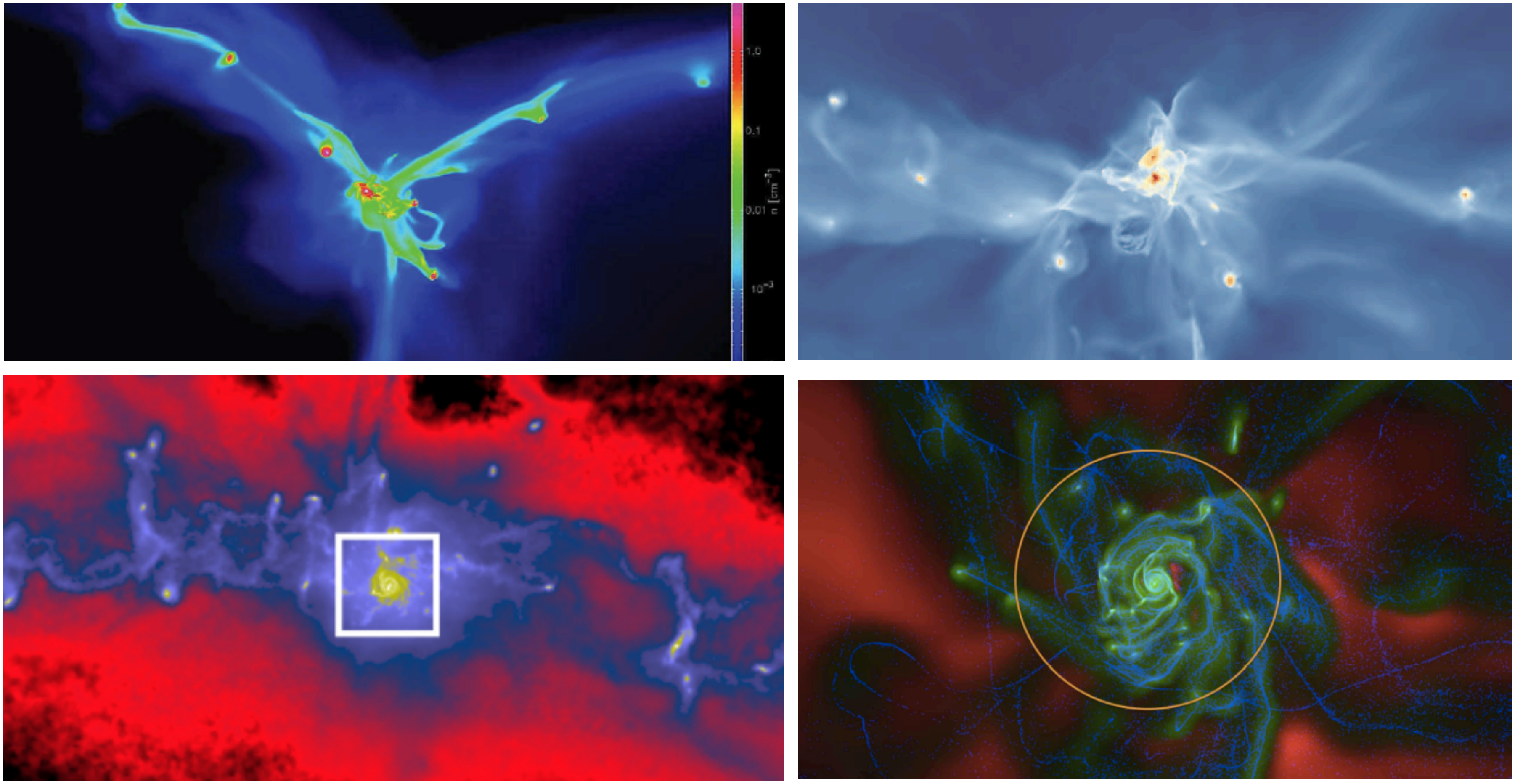
A new galaxy bimodality



Simple unbiased model implies f_j ~ 0.6, 0.1 for spirals, ellipticals

→ *Need two modes of galaxy evolution with systematically different angular momentum retention*

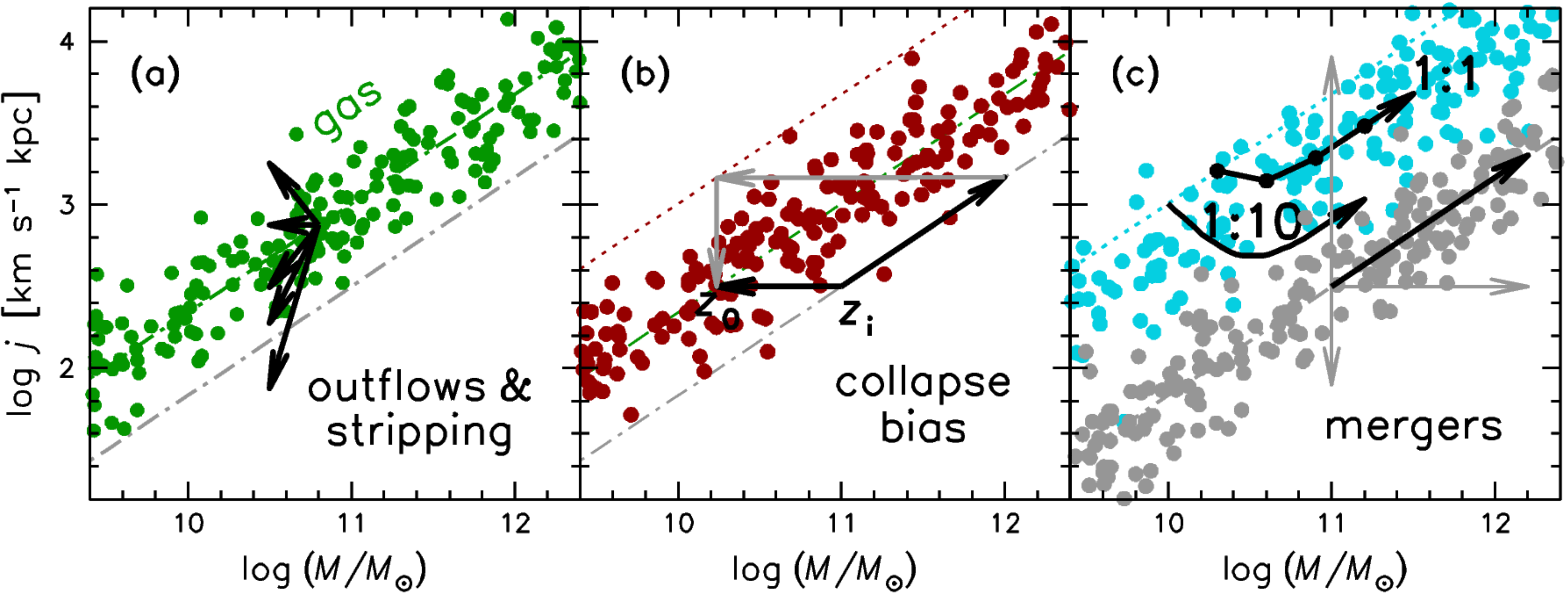
Mechanisms for angular momentum bimodality?



(Danovich+2012; Kimm+2011; Dubois+2012; Vogelsberger+2012)

→ *Need to understand why net result agrees with simple spherical collapse model, with little scatter*

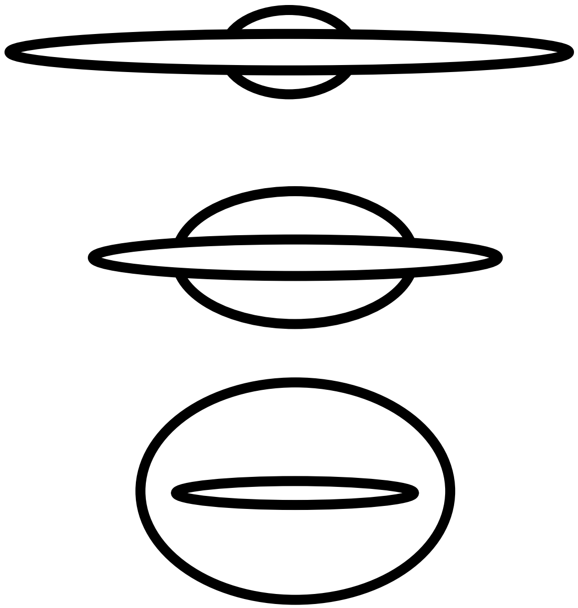
Explaining different *j* retention



(cf. Fall 2002; Kassin+2012)

Evolution in j_*−M_* plane is not arbitrary,
must involve processes respecting conservation laws

Summary: *j-M* diagram revisited



– first compilation of all galaxy types

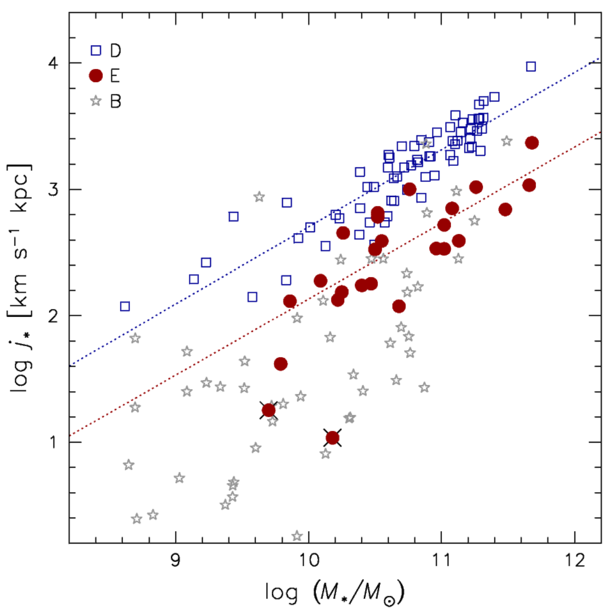
– extended kinematics data for E/S0s

– *j*-offset verified between spirals & Es

– universal trends for disks and bulges

– small scatter in j_*-M_* relations

→ ***fundamental constraints for galaxy formation***



– disks match up well to ΛCDM halo spins with *j* (weakly) conserved

– Es low *j* not drawn from tail of halo λ distribution

→ ***require bias in*** $\boldsymbol{j_{gas}}$***, or j loss***