The motion of stars in galaxies (Part I)

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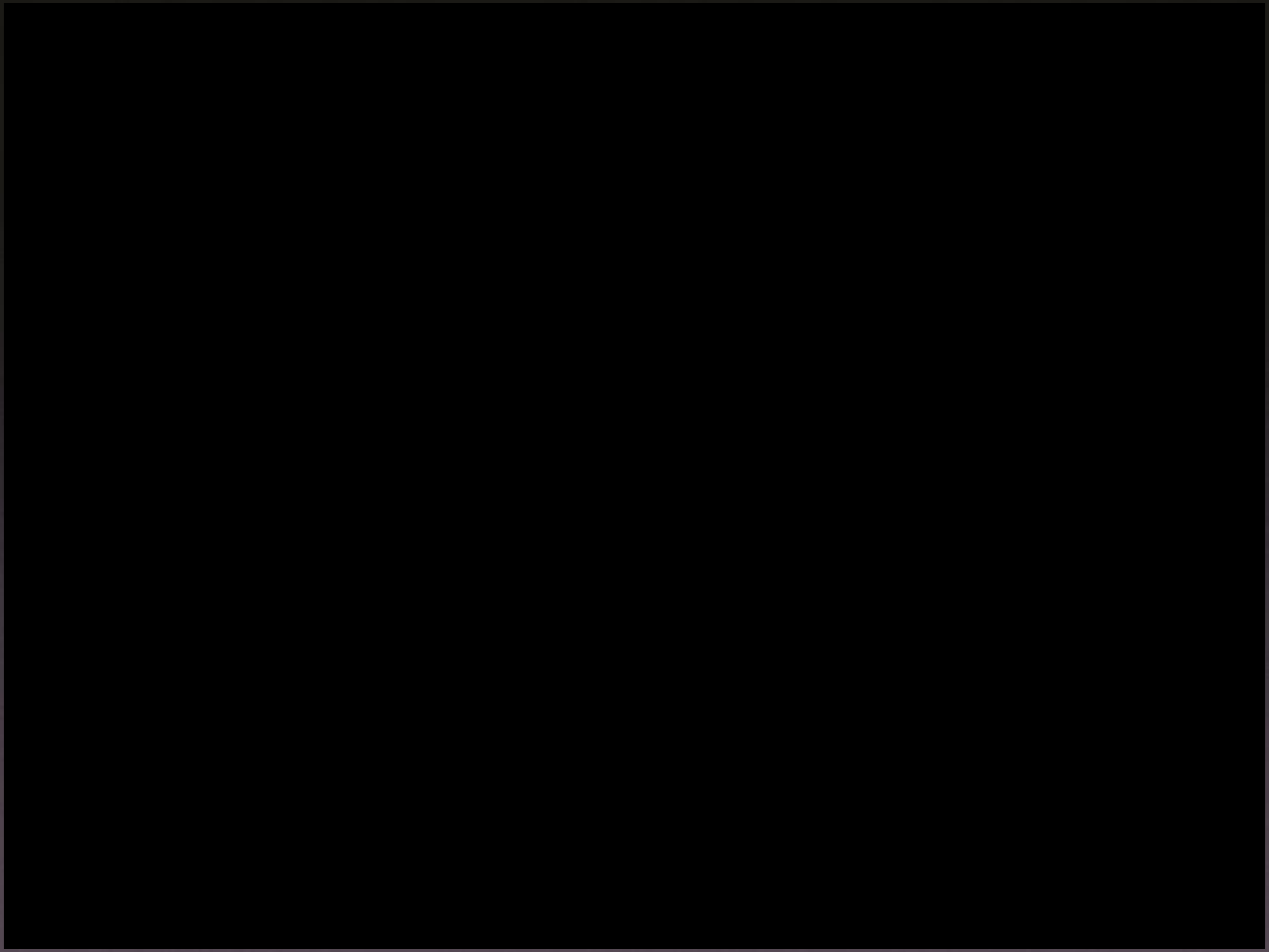
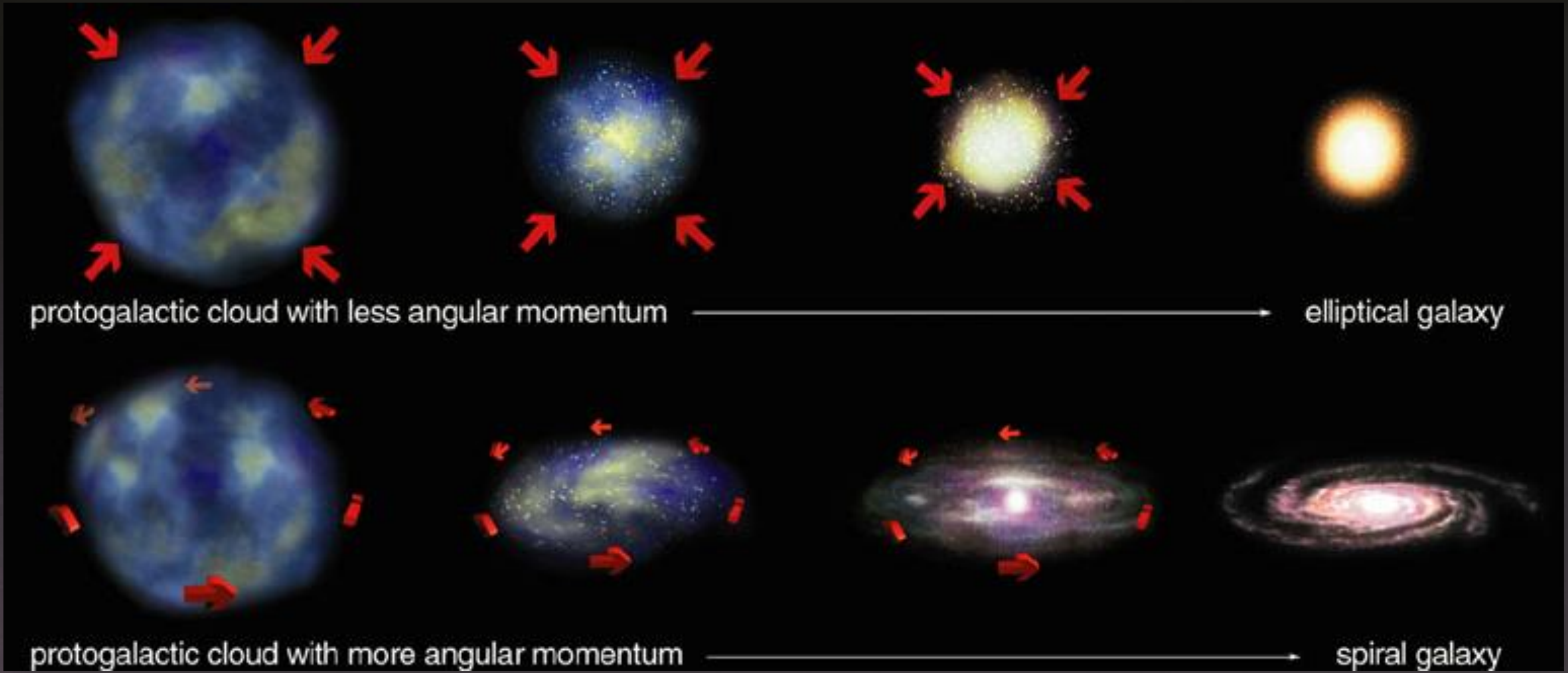
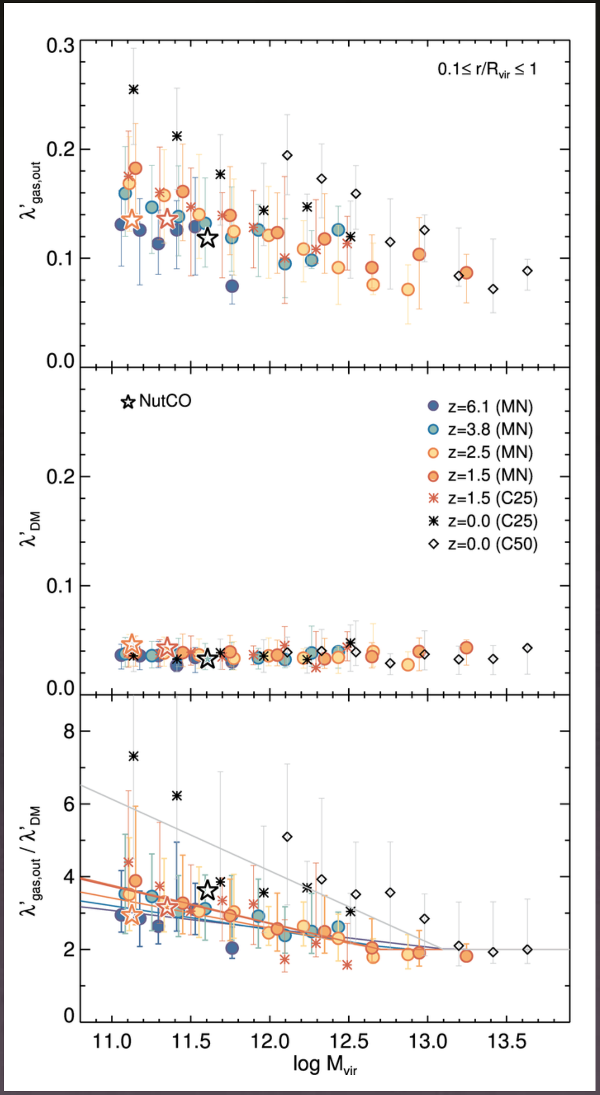
The Universe in motion



THE UNIVERSE IN MOTION



The importance of Angular Mom.

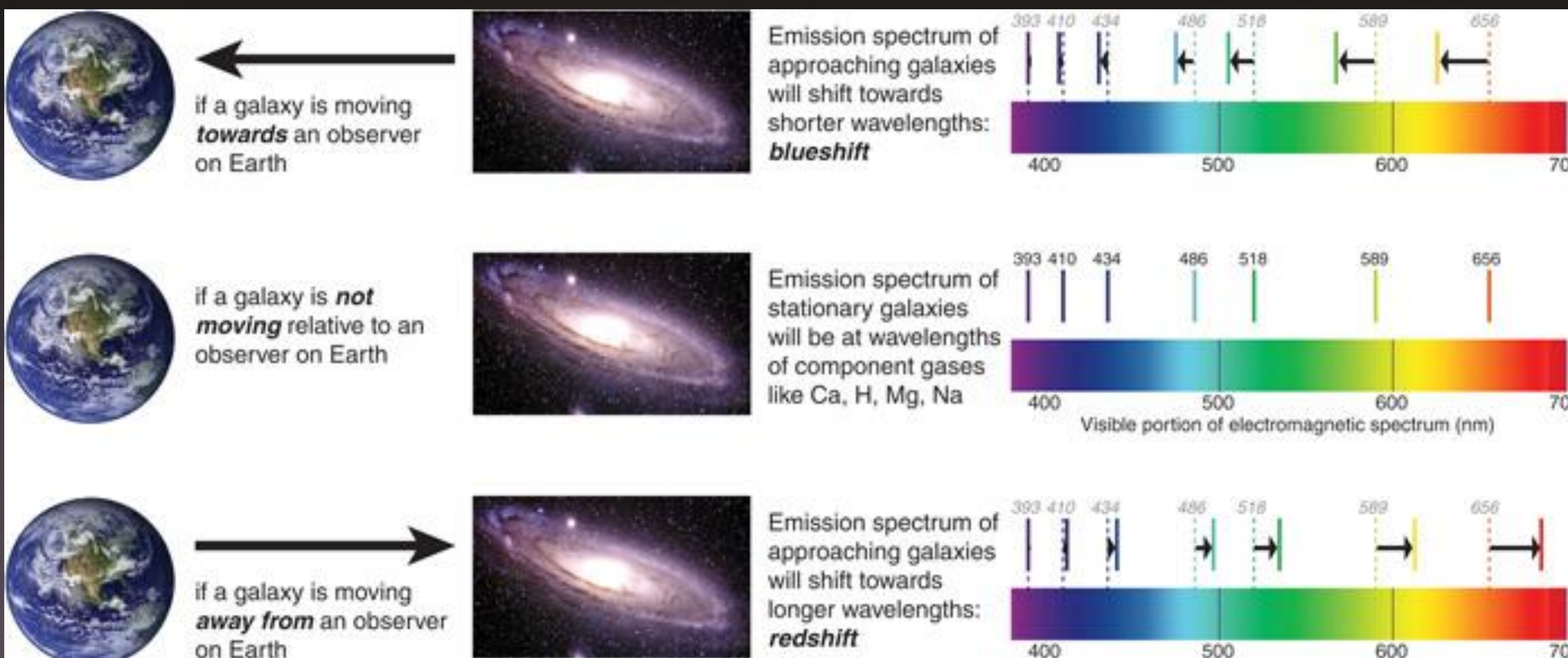


Kimm et al. (arxiv: 1106.0538)

- Angular momentum is set early on in the life of galaxies
- Importance for discriminating formation and evolution scenarios
- Angular momentum in DM halos shows a narrow distribution with hardly any evolution in redshift or mass
- Evolution in baryons much more complex
  - Star formation
  - Feedback
  - Dynamical instabilities
  - …..

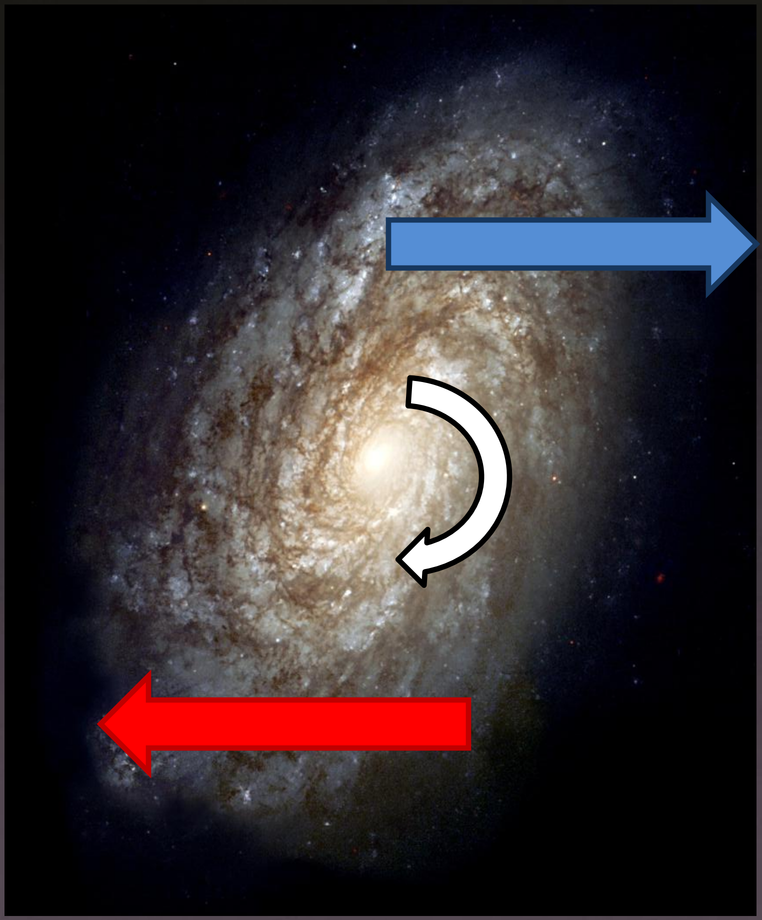
How do we measure AM?

- We need to trace the movement of the stars
- This is done via the Doppler effect



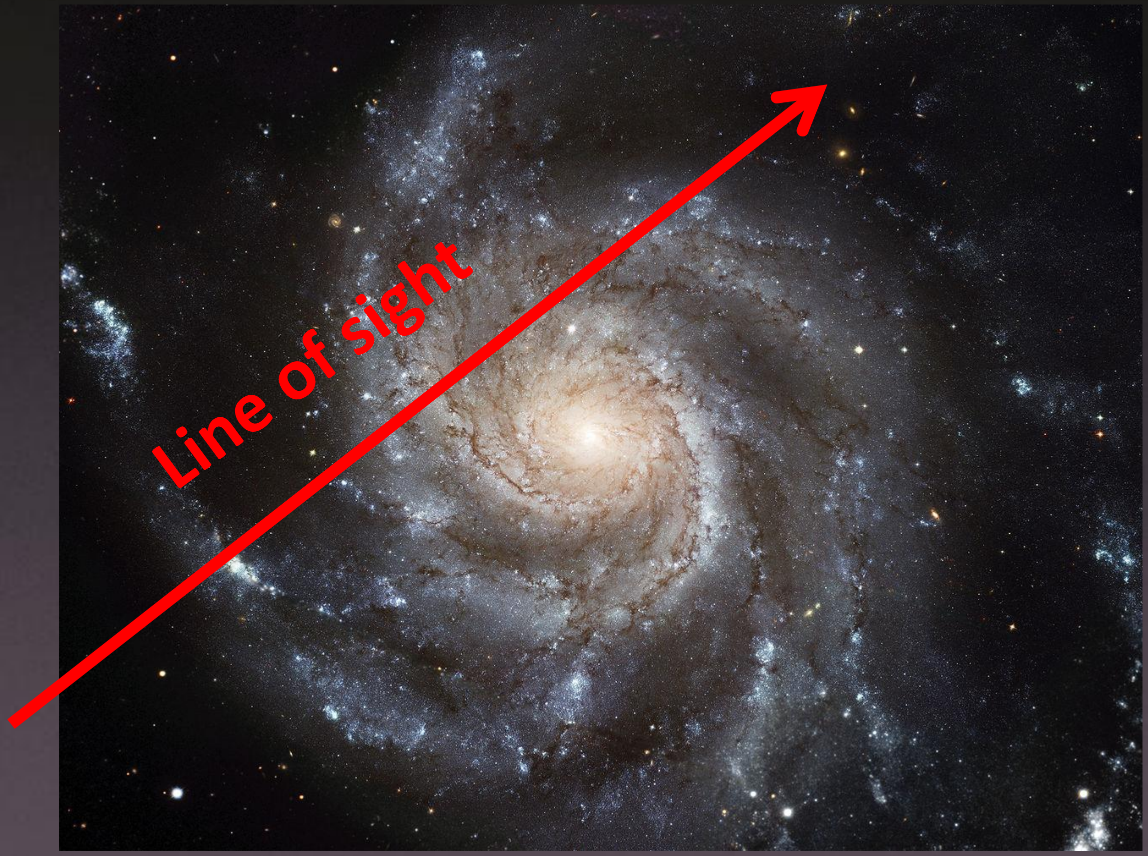
HOW DO WE MEASURE AM?

- Star motions can be traced also within galaxies



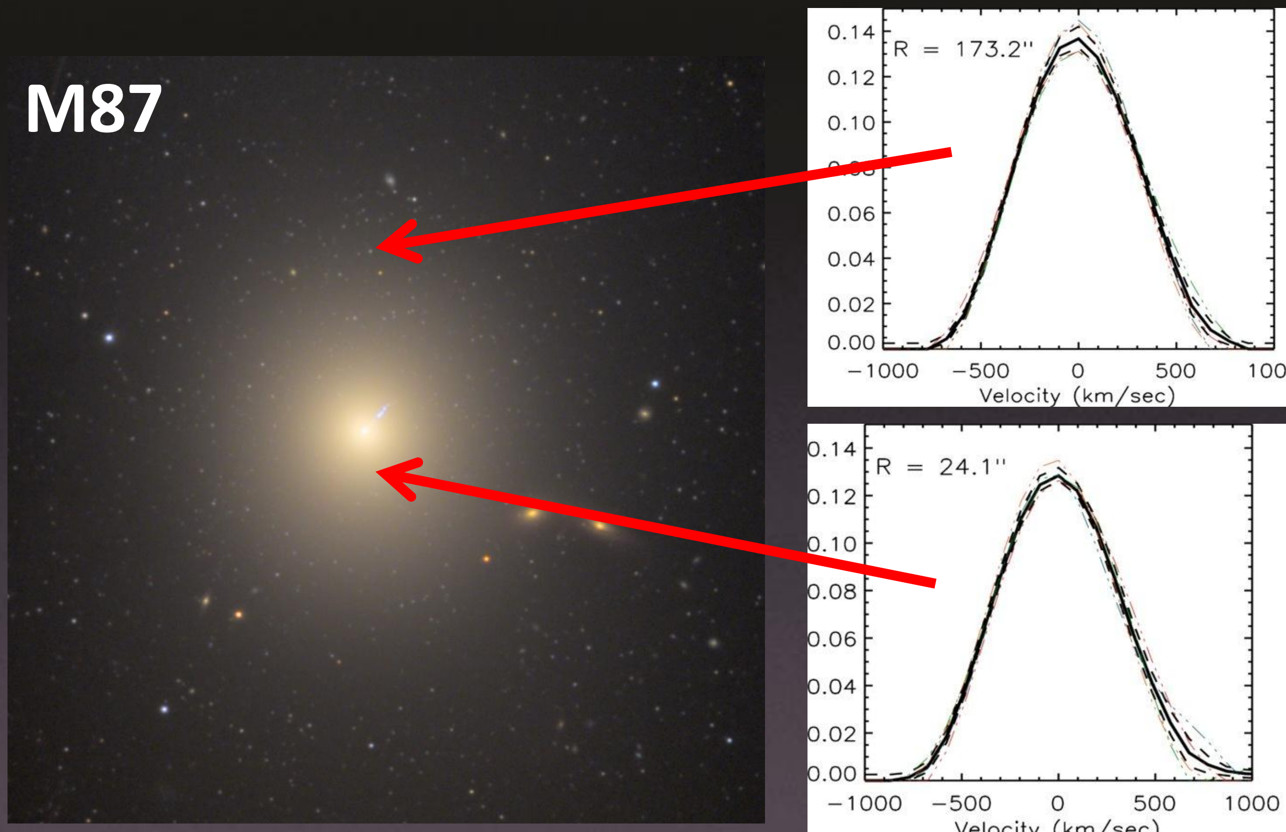
What do we really measure?

- Remember that all we measure is the *Line-of-sight Velocity Distribution* (LOSVD) of stars



Line-of-sight Velocity Distribution

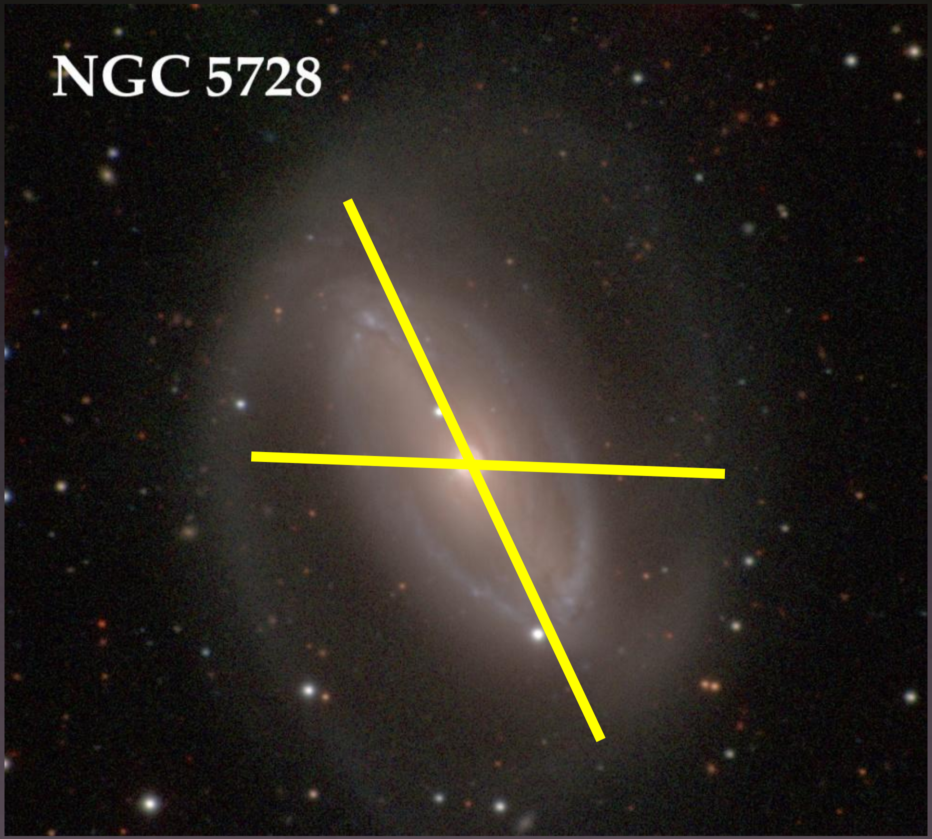
- For simple galaxies LOSVD are close to Gaussian

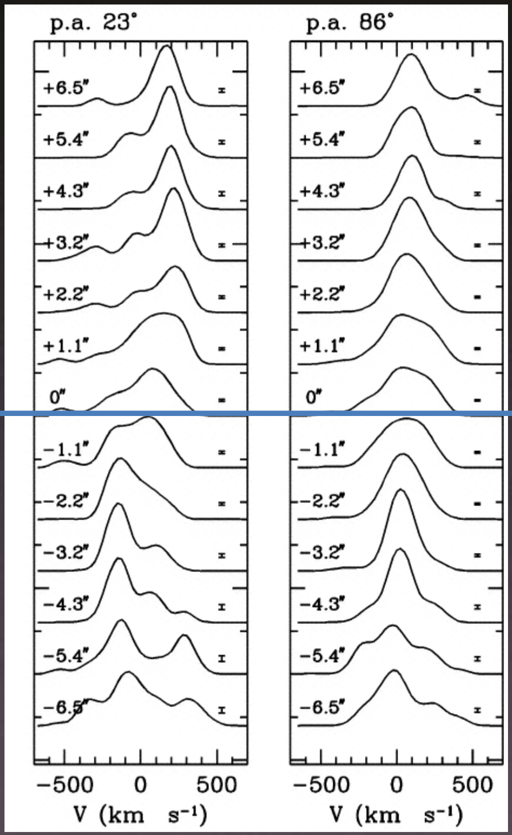


Murphy et al. (2011)

LINE-OF-SIGHT VELOCITY DISTRIBUTION

- LOSVD can be very complex depending on the number of substructures/components present in galaxies

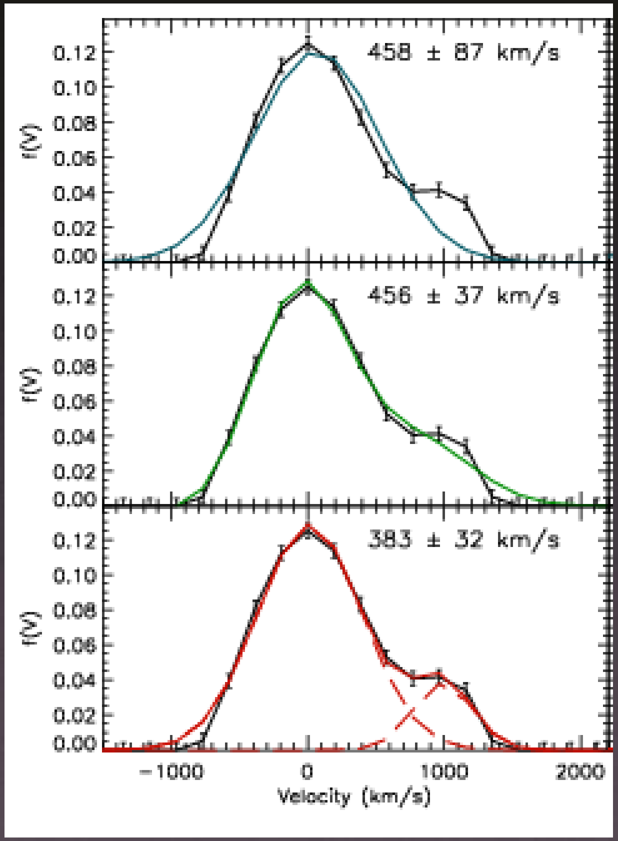




Prada & Gutierrez (1999)

Line-of-sight Velocity Distribution

- LOSVD recovered by fitting templates to spectra
- Most methods today assume a parametric form

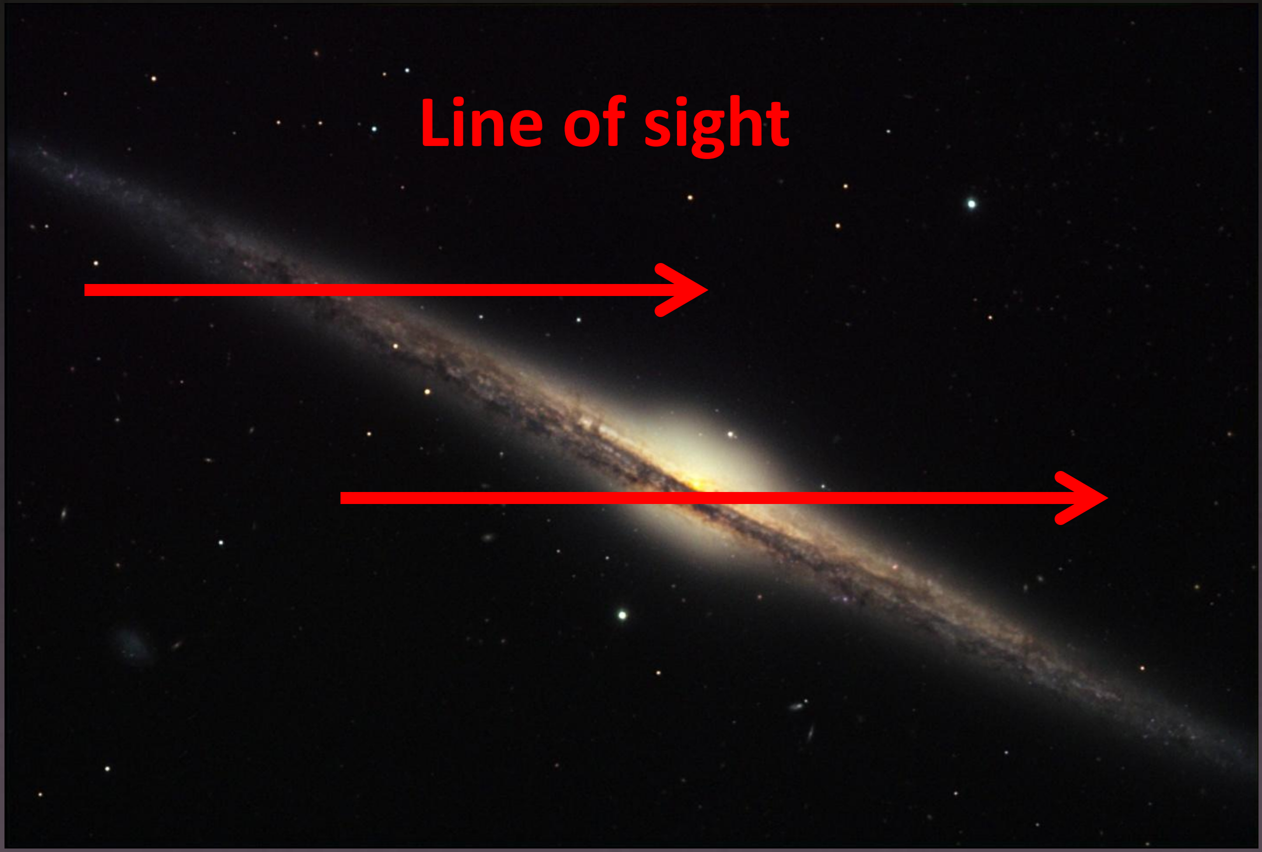


Murphy et al. (2014)

- **Single Gaussian**
  - Velocity (V), Dispersion (σ)
- **Gauss-Hermite**
  - Velocity (V), Dispersion (σ), h3, h4
- **Multiple Gaussians**
  - Velocity (V_i), Dispersion (σ_i)

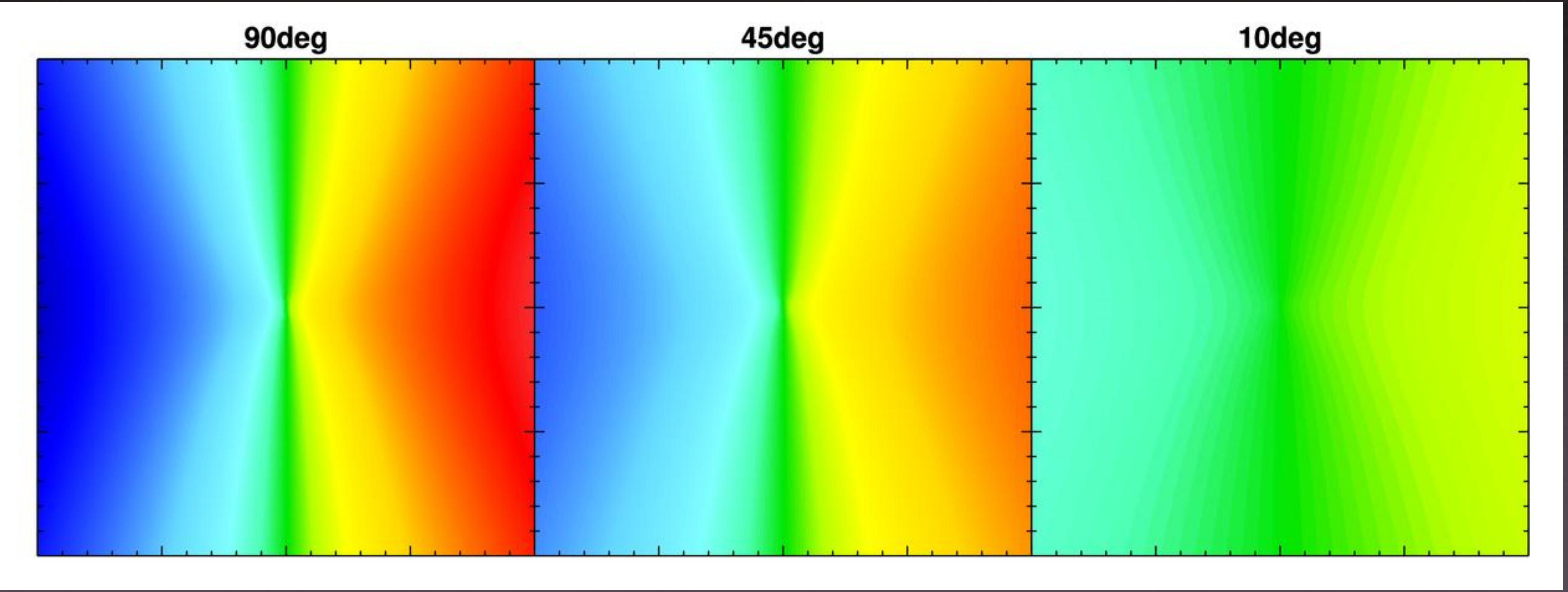
LOSVD AND INCLINATION

- Inclination makes LOSVD integration substantially different from one the next in galaxies



LOSVD and Inclination

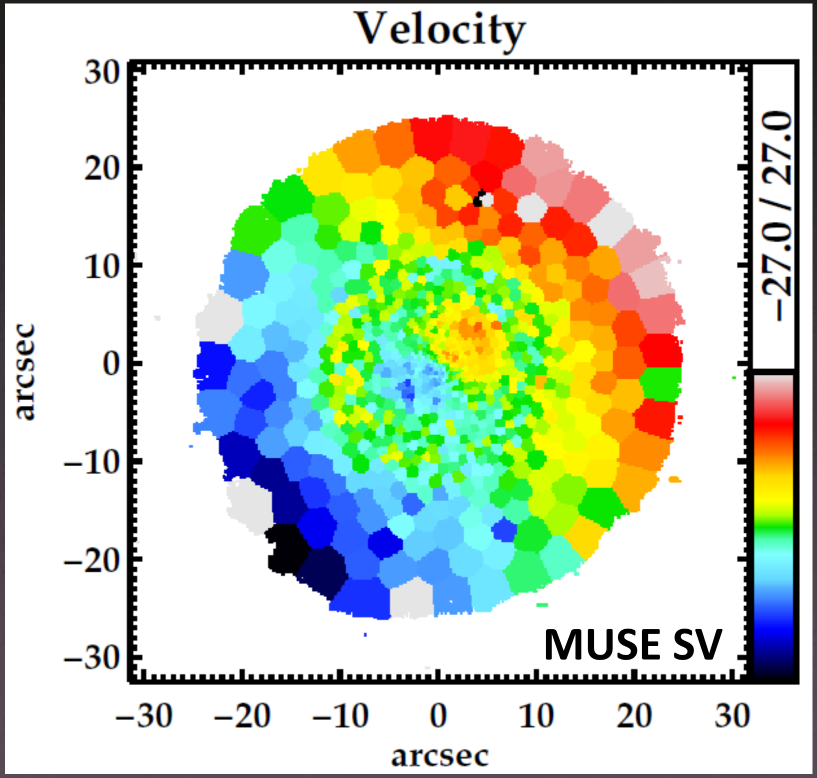
- Rotation amplitude is maximum towards edge-on orientations and minimum when face-on
- Dependence scales to sin(inclination)



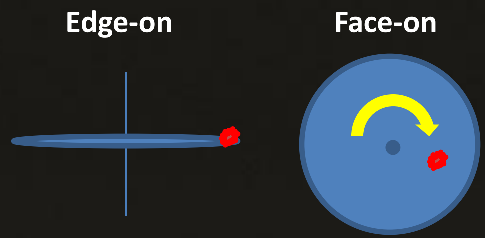
LOSVD and Inclination

- Galaxies are not infinitely thin
- Vertical motions can be measured even in face-on conf.

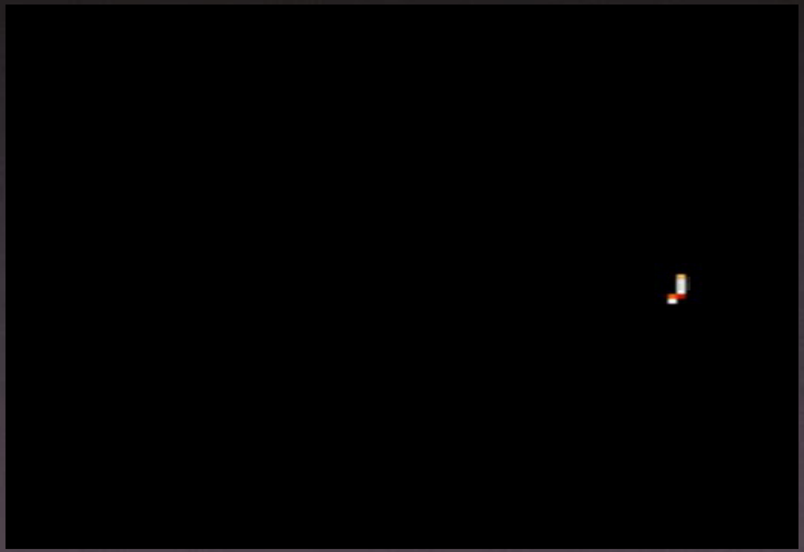
WPFC2/F336W/F555W/F675W



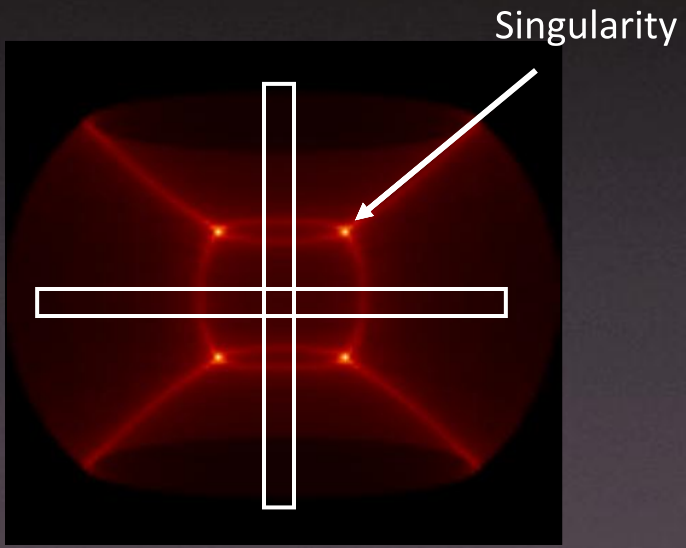
Galaxies are 3D structures



- Stars move on orbits in 3D
- Most of the action happens near singularities
- Orbits are weakly constrained by major/minor axis obs.

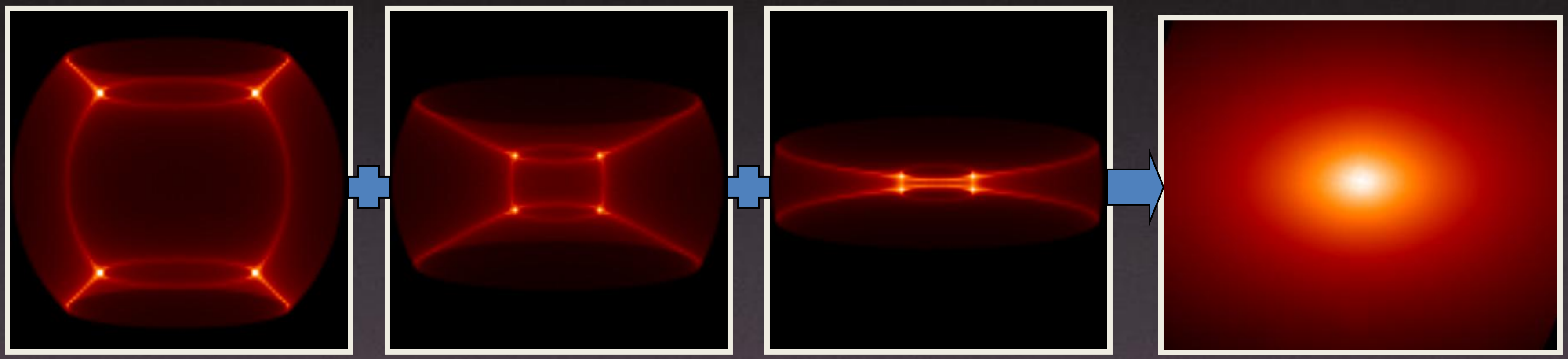


movie by R. van den Bosch



Galaxies are 3D structures

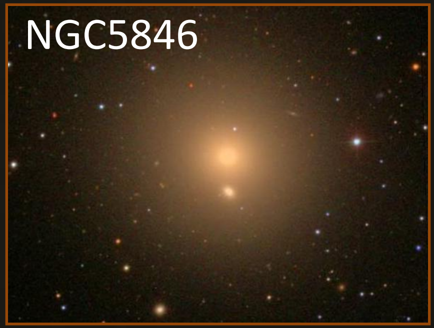
- Galaxies are a collection of stellar orbits
- The particular combination of orbit families present determine the shape and overall motions of a galaxy



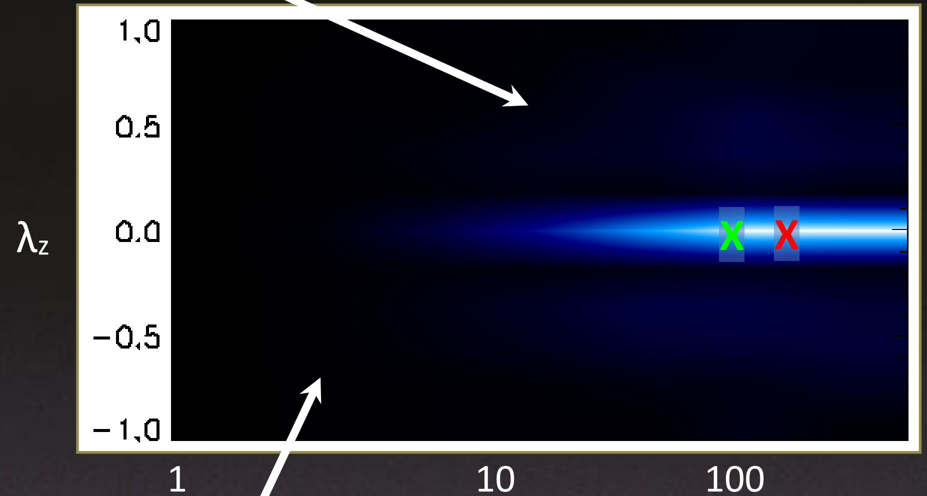
images of model orbits

Observed galaxy image

GIANT ELLIPTICAL GALAXY

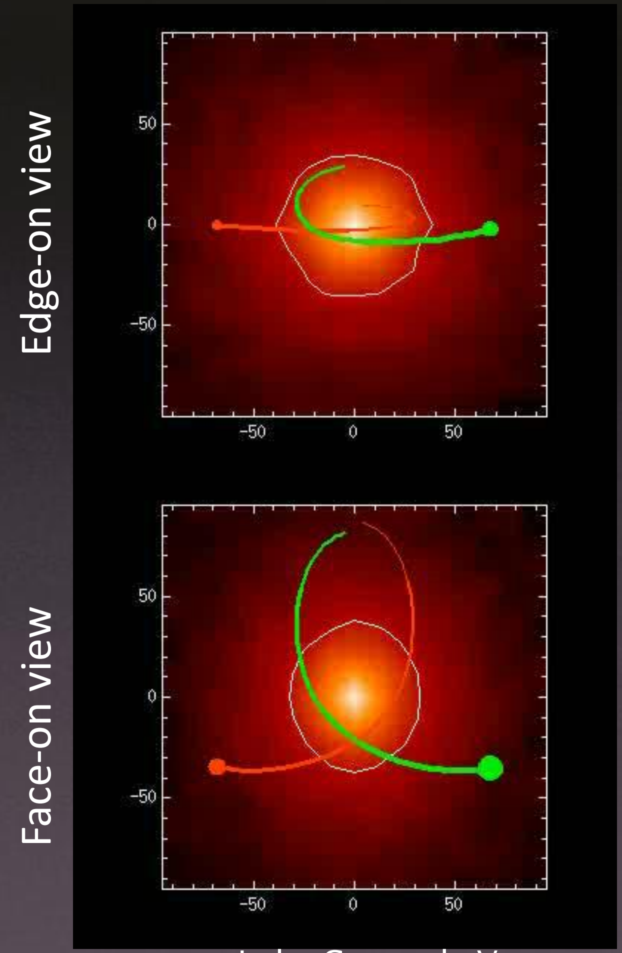


prograde circular orbits



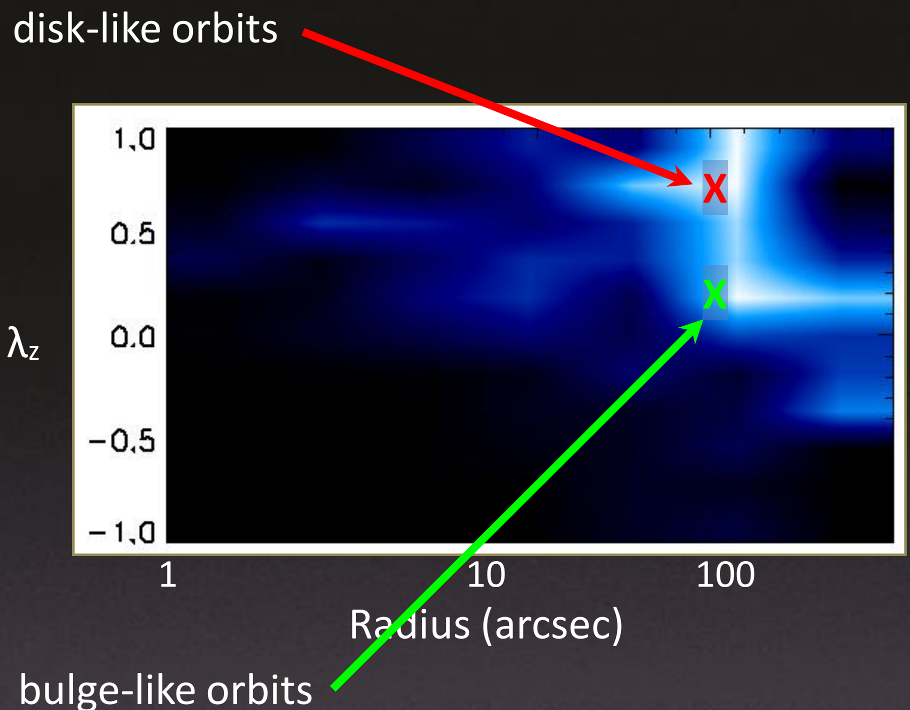
retrograde circular orbits

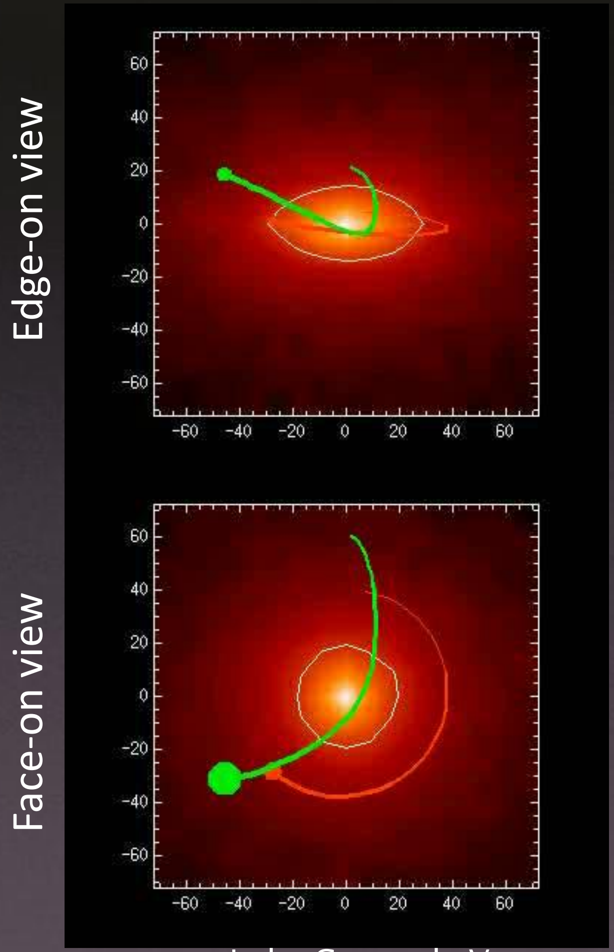
λ_z = normalized angular momentum around short *z*-axis



movie by G. van de Ven

BULGE-DOMINATED ETG





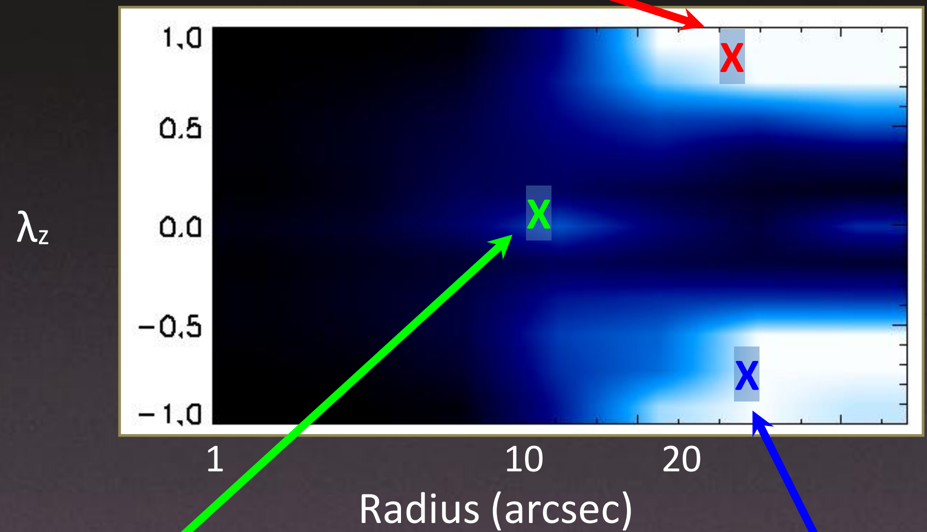
movie by G. van de Ven

λ_z = normalized angular momentum around short *z*-axis

DISK-DOMINATED ETG

NGC4550 known to host two counter-rotating disks with different scale-heights (Rix et al. 1995)

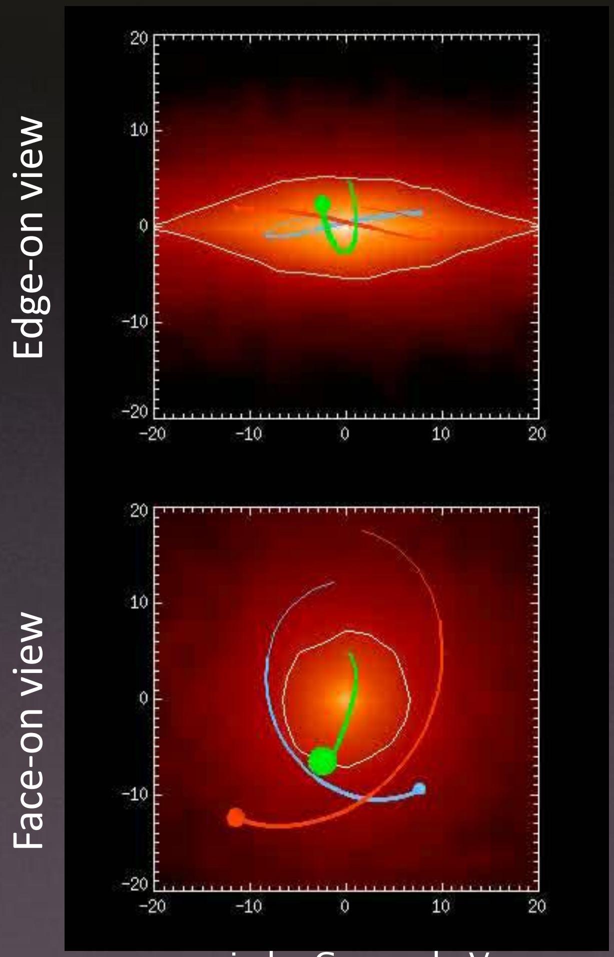
prograde disk-like orbits



bulge-like orbits

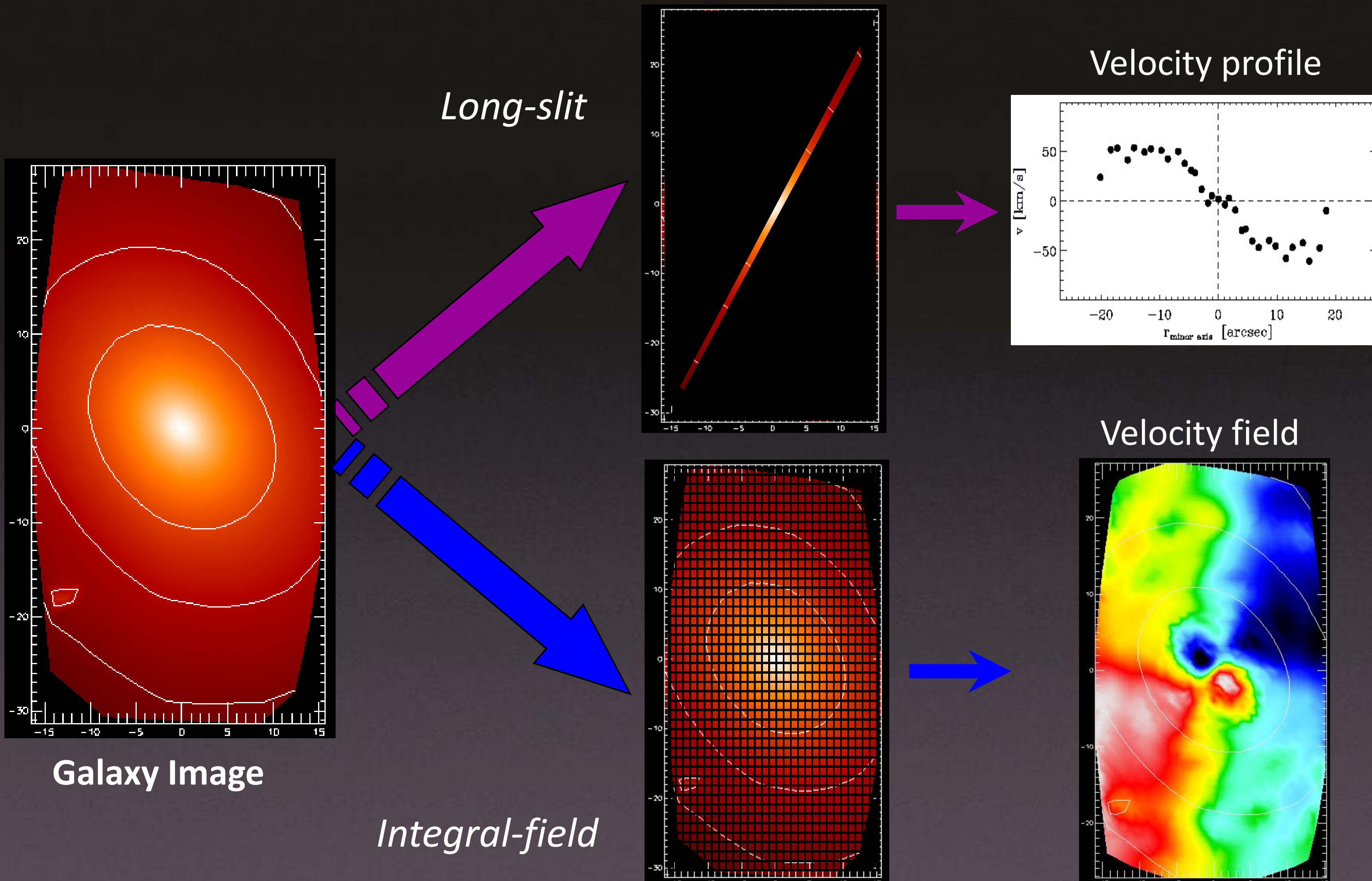
retrograde disk-like orbits

λ_z = normalized angular momentum around short *z*-axis

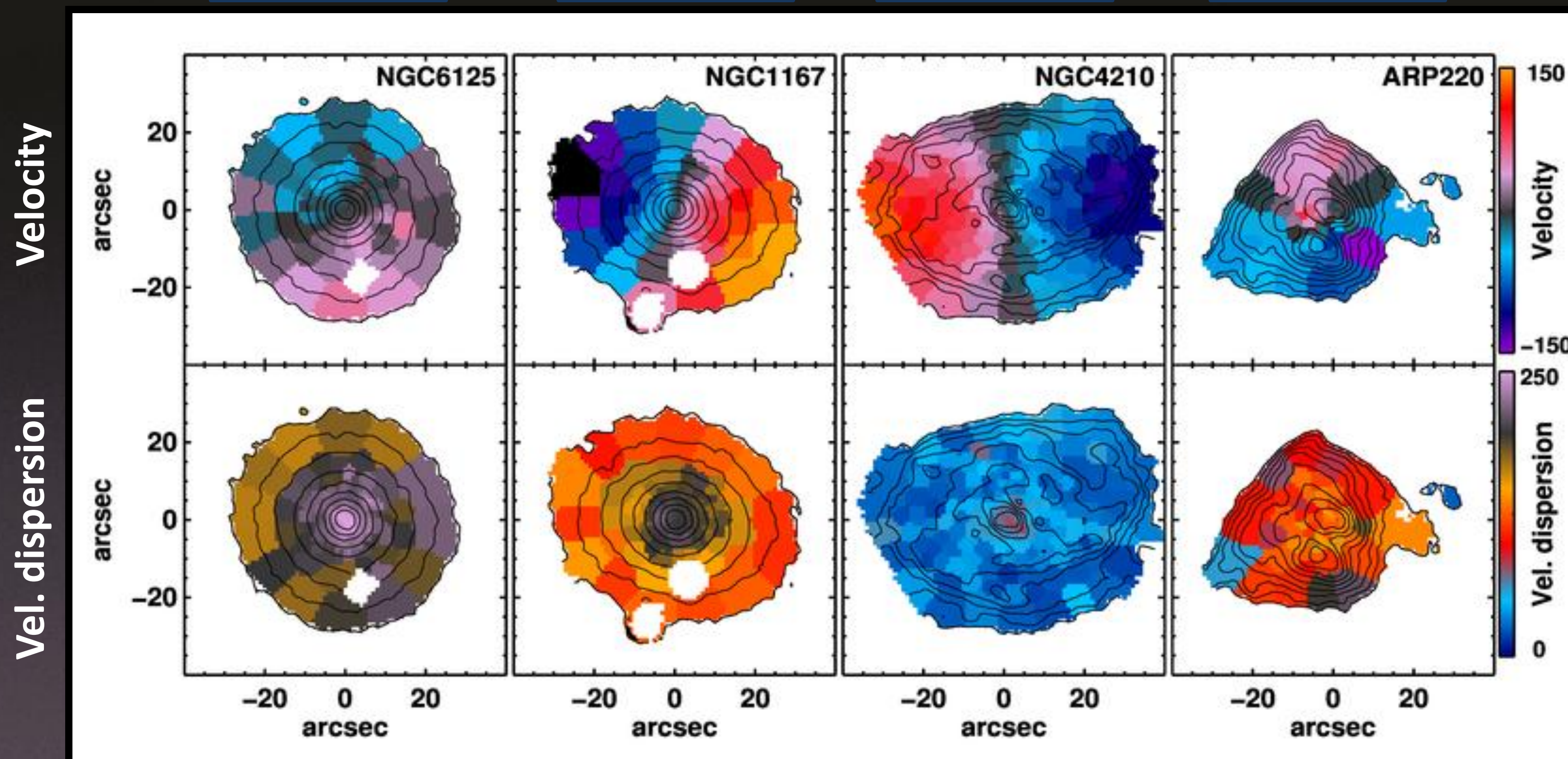


movie by G. van de Ven

THE NEED FOR IFS



GALAXIES ARE COMPLEX



Slow Rotator
(low V, high σ)

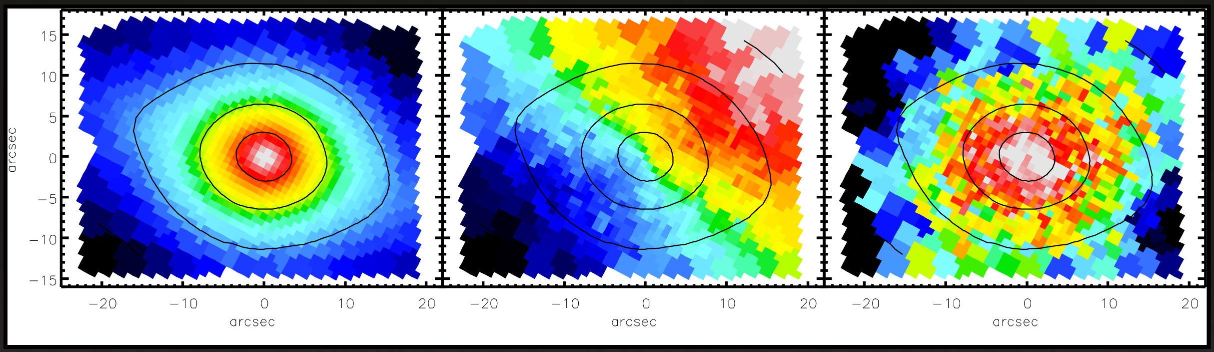
Bulge + Disk
(high V, high σ)

Pure disk
(high V, low σ)

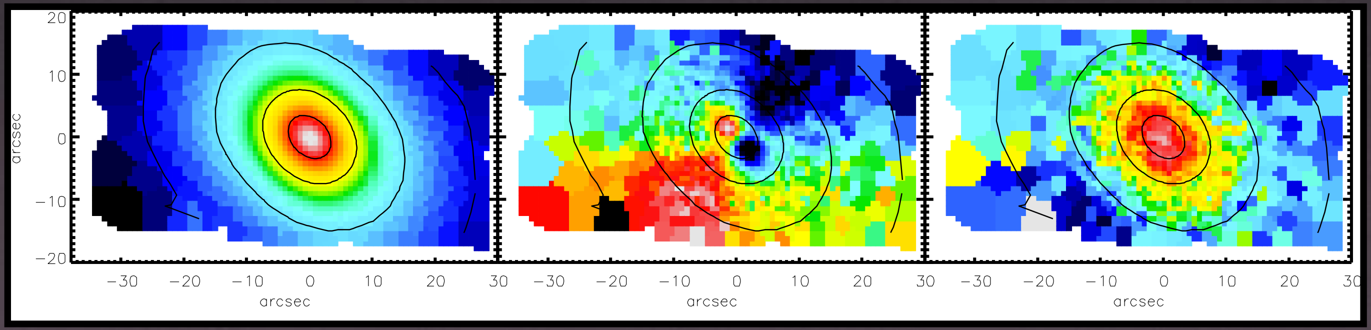
Interacting
(e.g. ARP220)

Galaxies are complex

- Kinematic twists

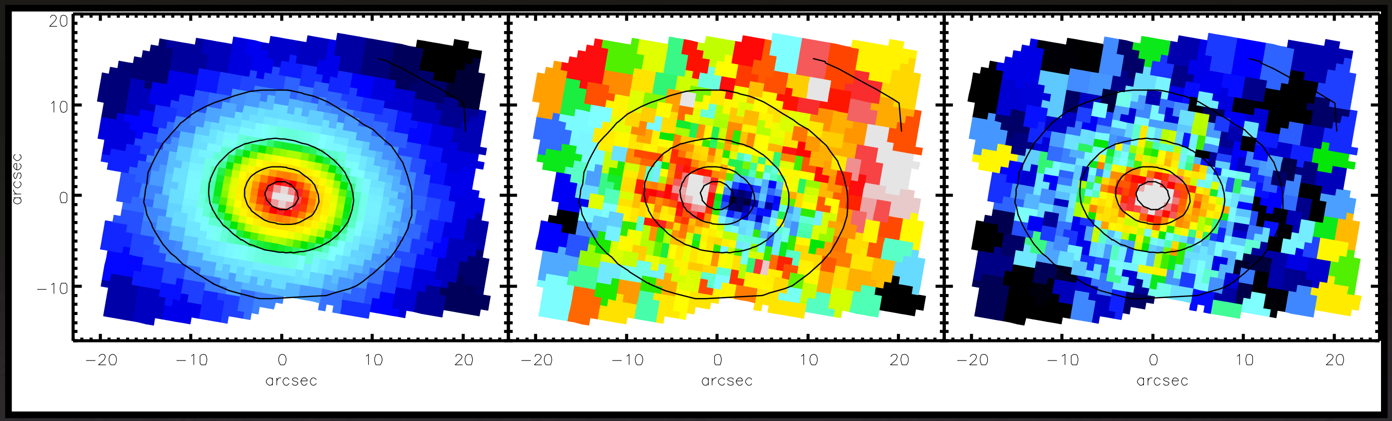


- Kinematically Decoupled Cores

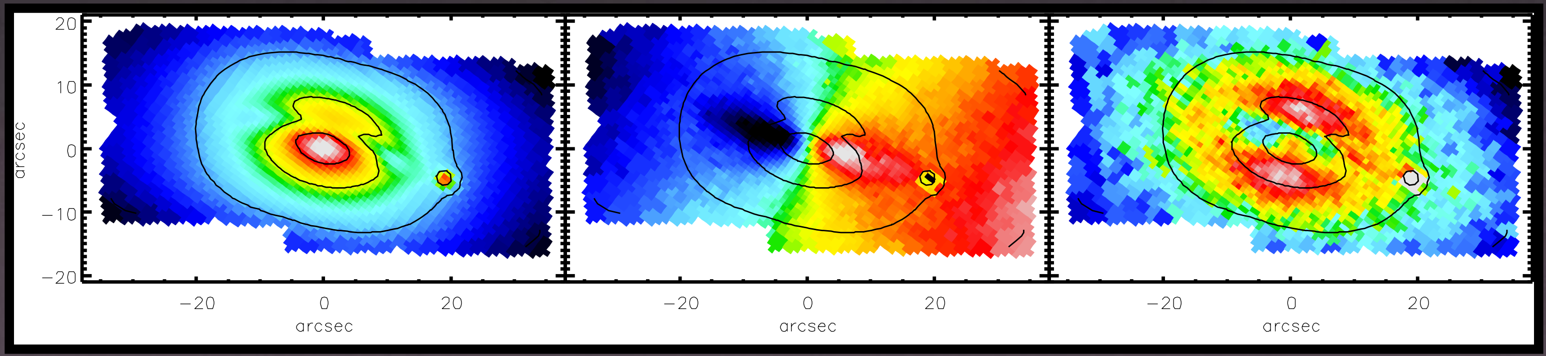


Galaxies are complex

- Counter-rotating inner components

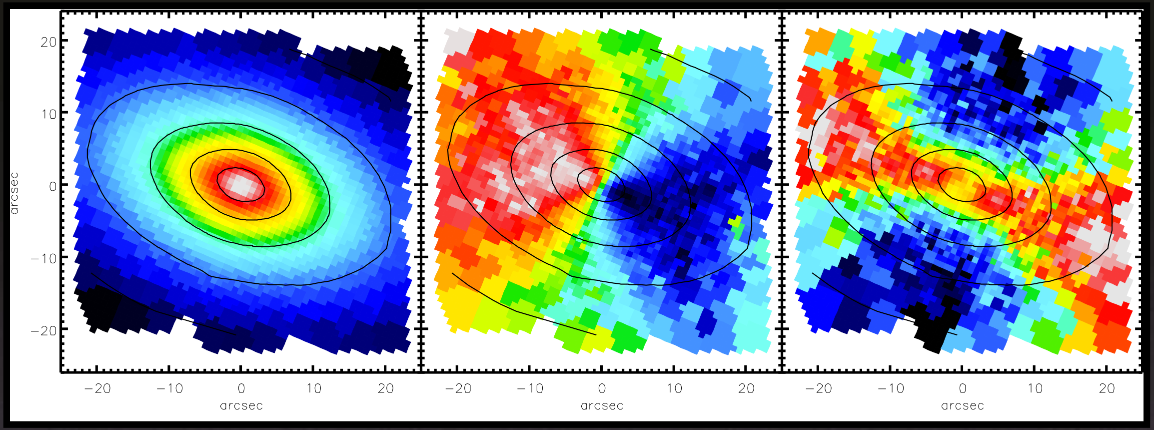


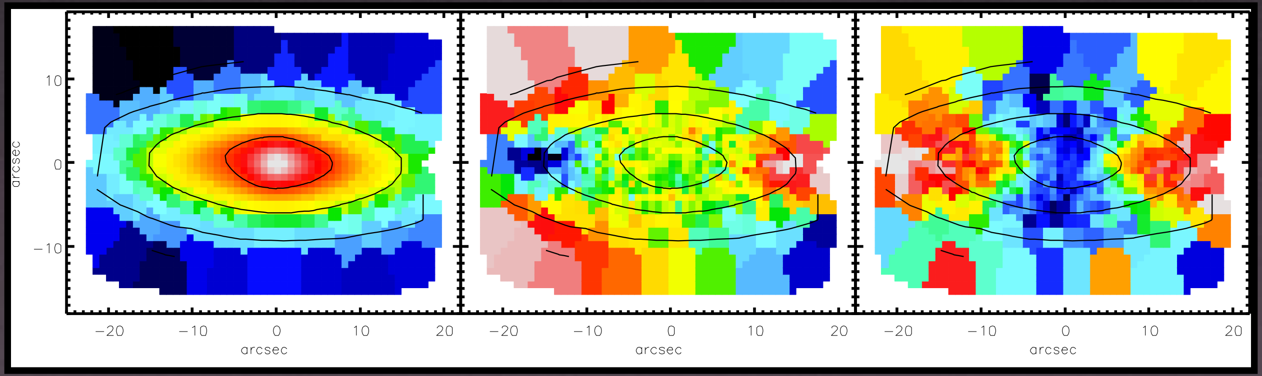
- Inner disks



Galaxies are complex

- Multiple large-scale disk components





End of Part I

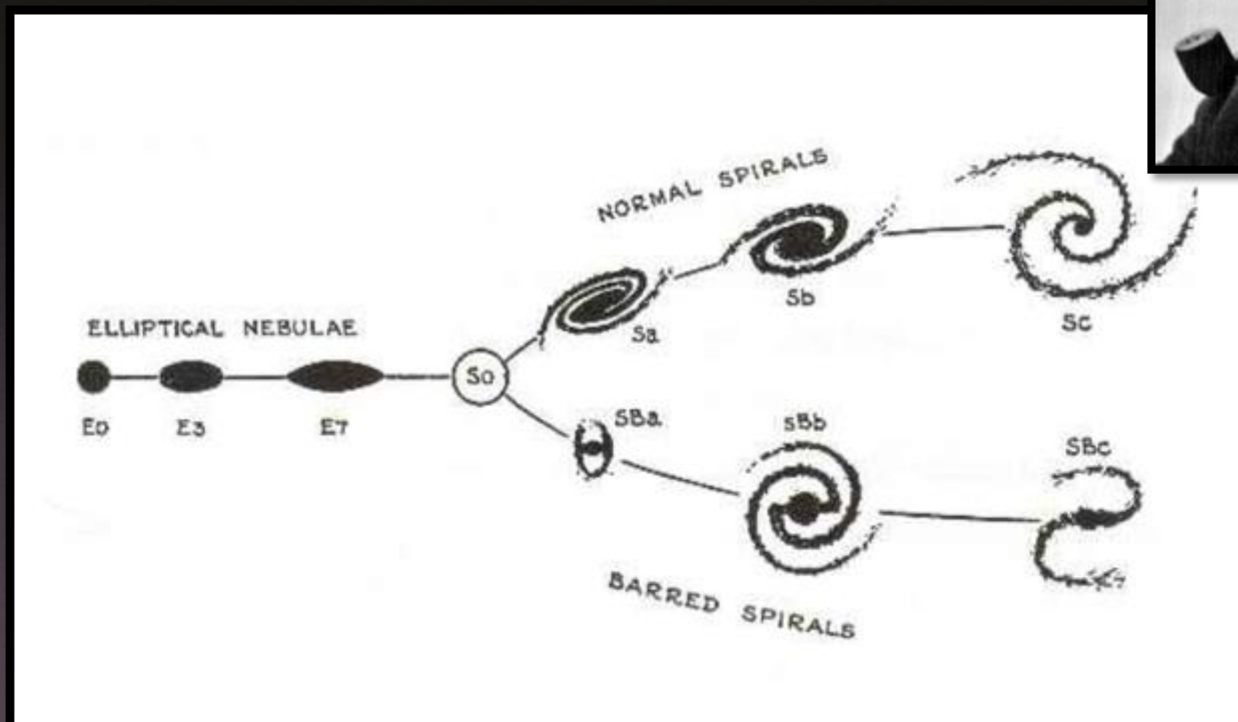
Angular Momentum in galaxies Across the Hubble Sequence (Part II)

Jesús Falcón-Barroso

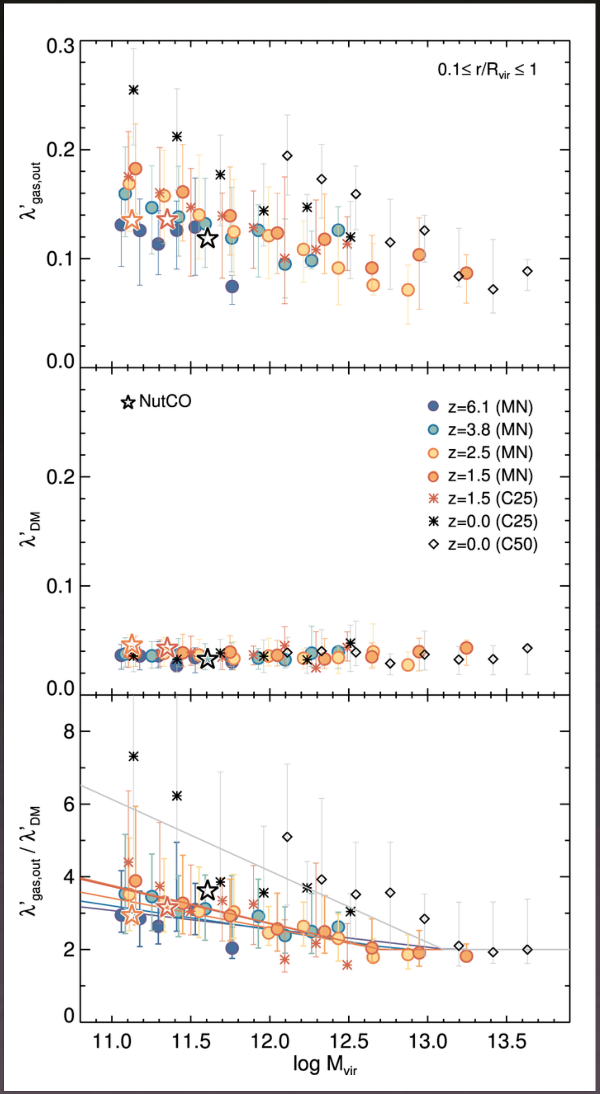
Guillermo Haro School 2014 – INAOE, Puebla

THE STARTING POINT

The Hubble ``tuning fork'' (Hubble 1936)



THEORETICAL CONTEXT



Kimm et al. (arxiv: 1106.0538)

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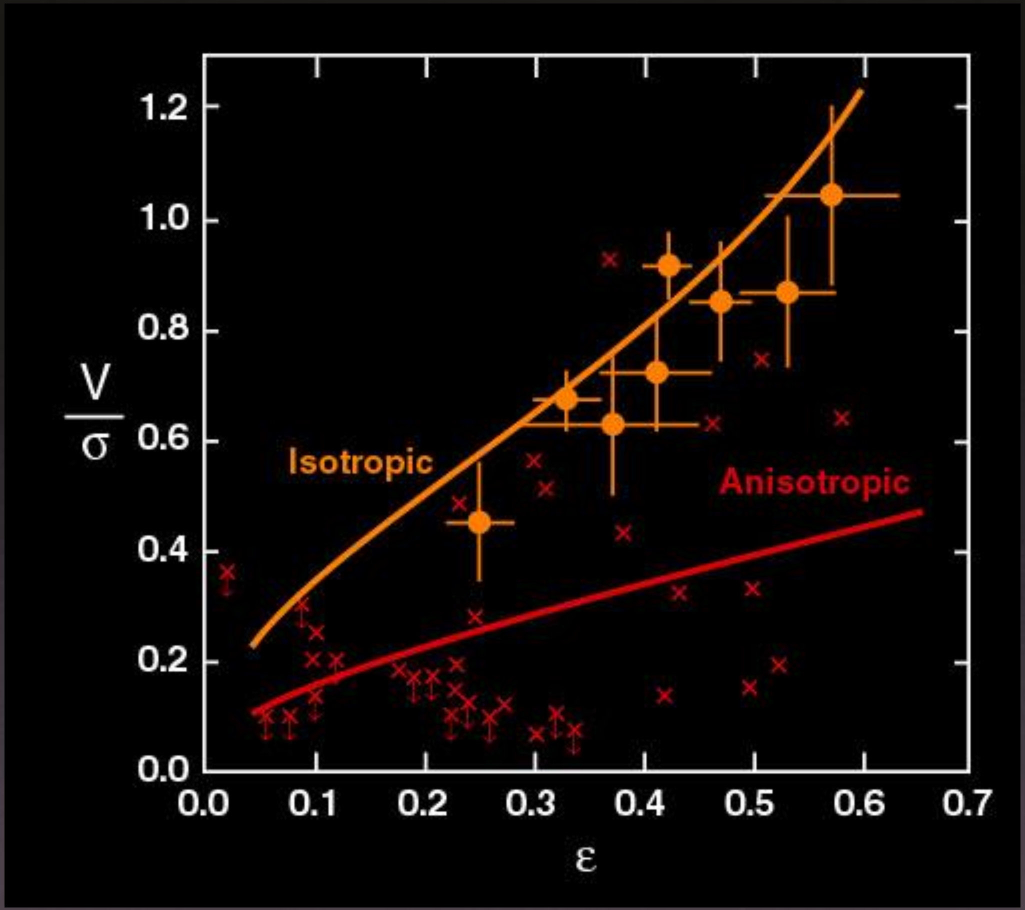
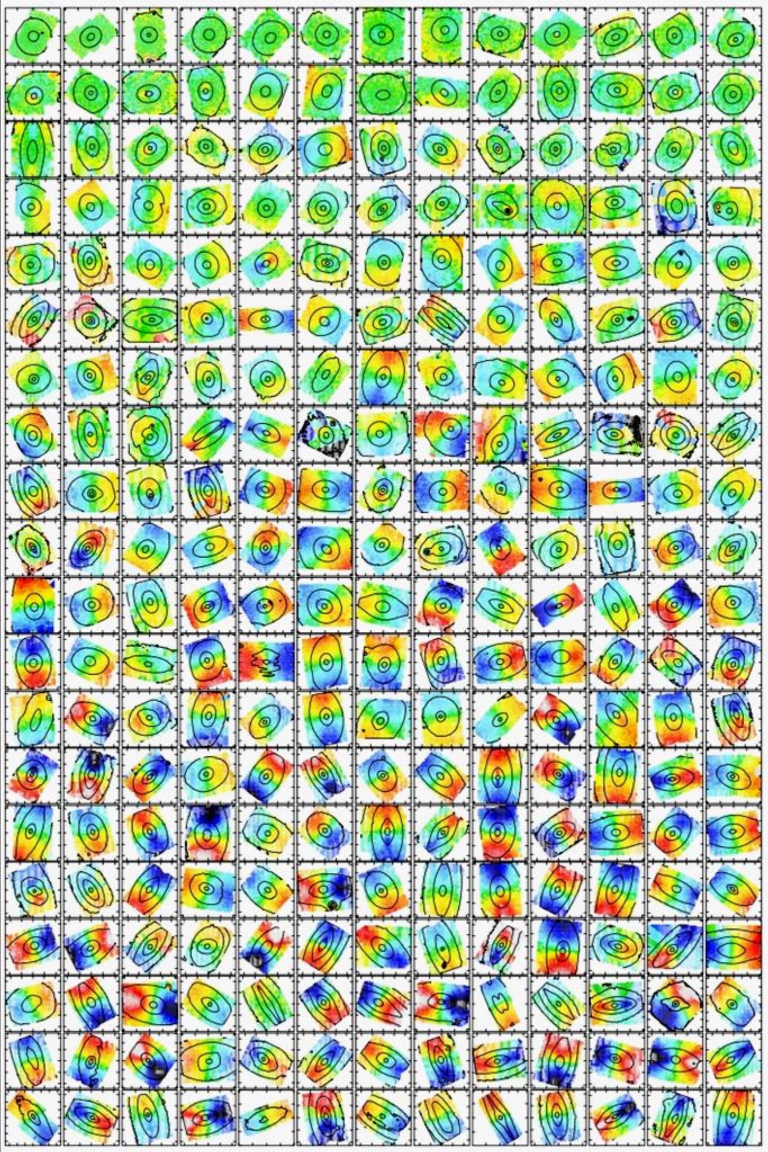
AM of Early-type galaxies

- Originally ellipticals thought to be axisymmetric flattened by rotation
- Giant ellipticals rotate slowly and are likely triaxial (Bertola & Capaccioli 1975; Binney 1978)
- Faint ellipticals rotate more rapidly
- Consistent with isotropic rotators (Davies et al. 1983)
- Tend to have disky isophotes (Bender et al. 1989)
- Do they actually contain disks? (Rix & White 1990)



Kormendy & Illingworth (1982)

OBSERVATIONAL CONSTRAINTS

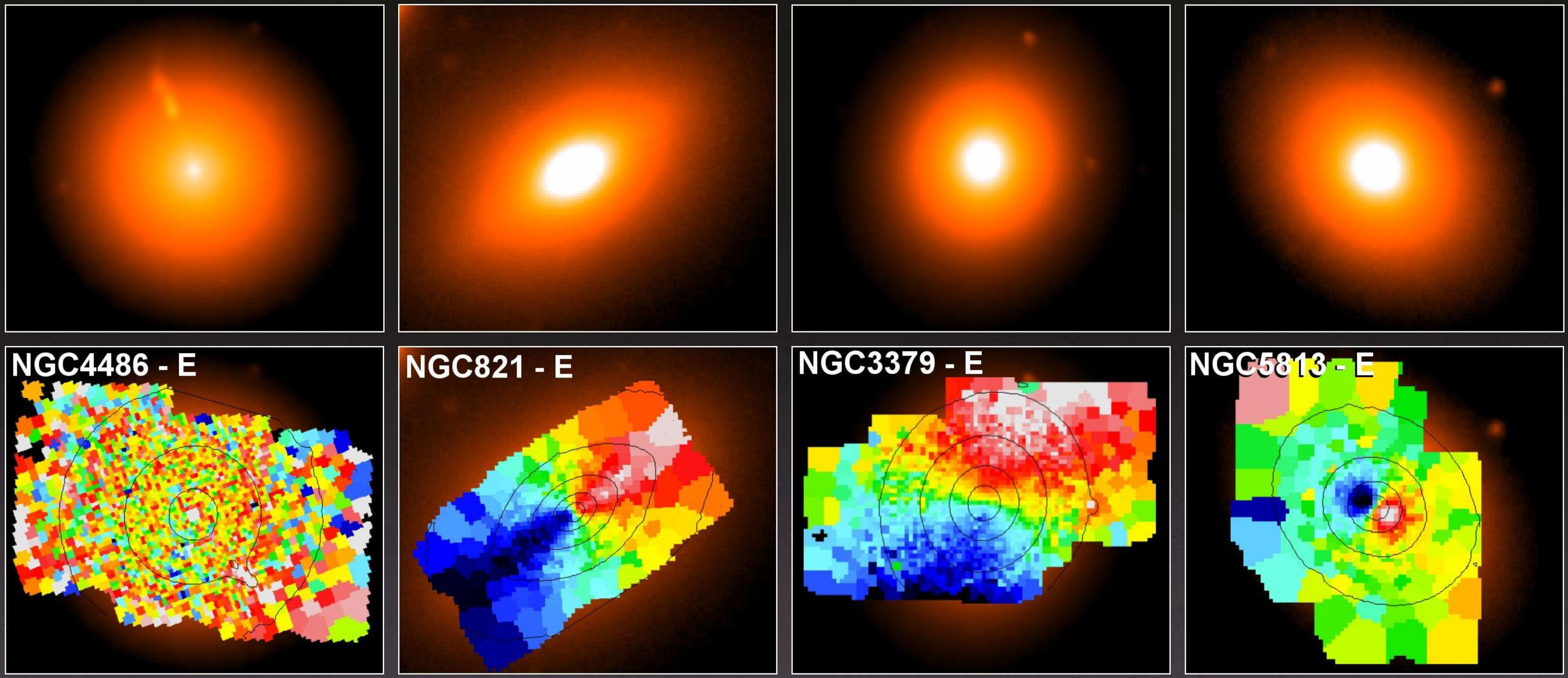


Krajnović et al. (2011)

- Early studies on this issue (e.g. Bertola & Capaccioli 1978; Binney 1978; Davies et al. 1983; Franx et al. 1989)
- Difficult to gather large samples to homogeneously study this aspect
- ***SAURON*** and ***ATLAS3D***
  - Slow/Fast rotators
  - Defined AM parameter (λ_R)

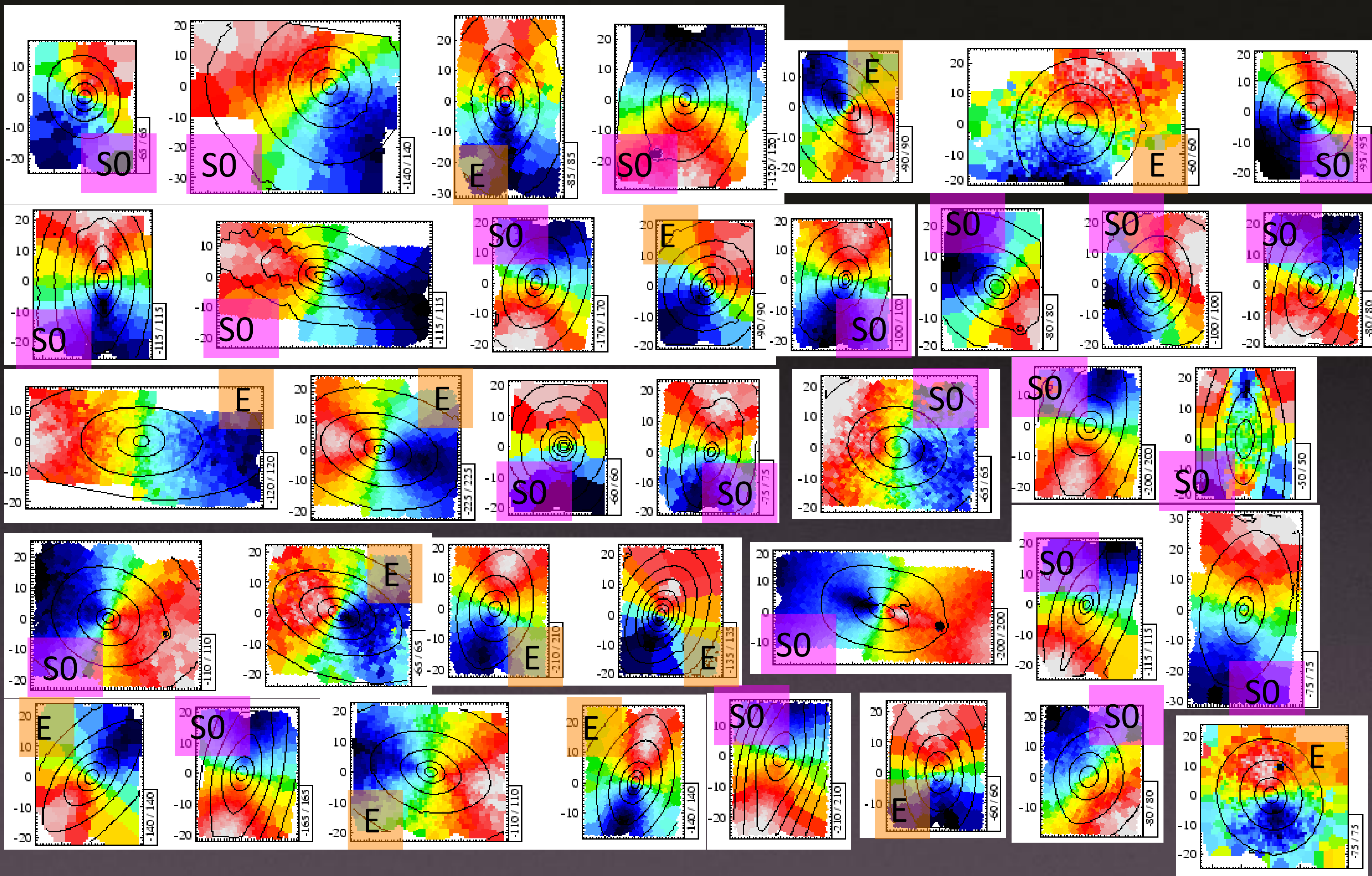
Looks can be deceiving

The case of Early-type Galaxies



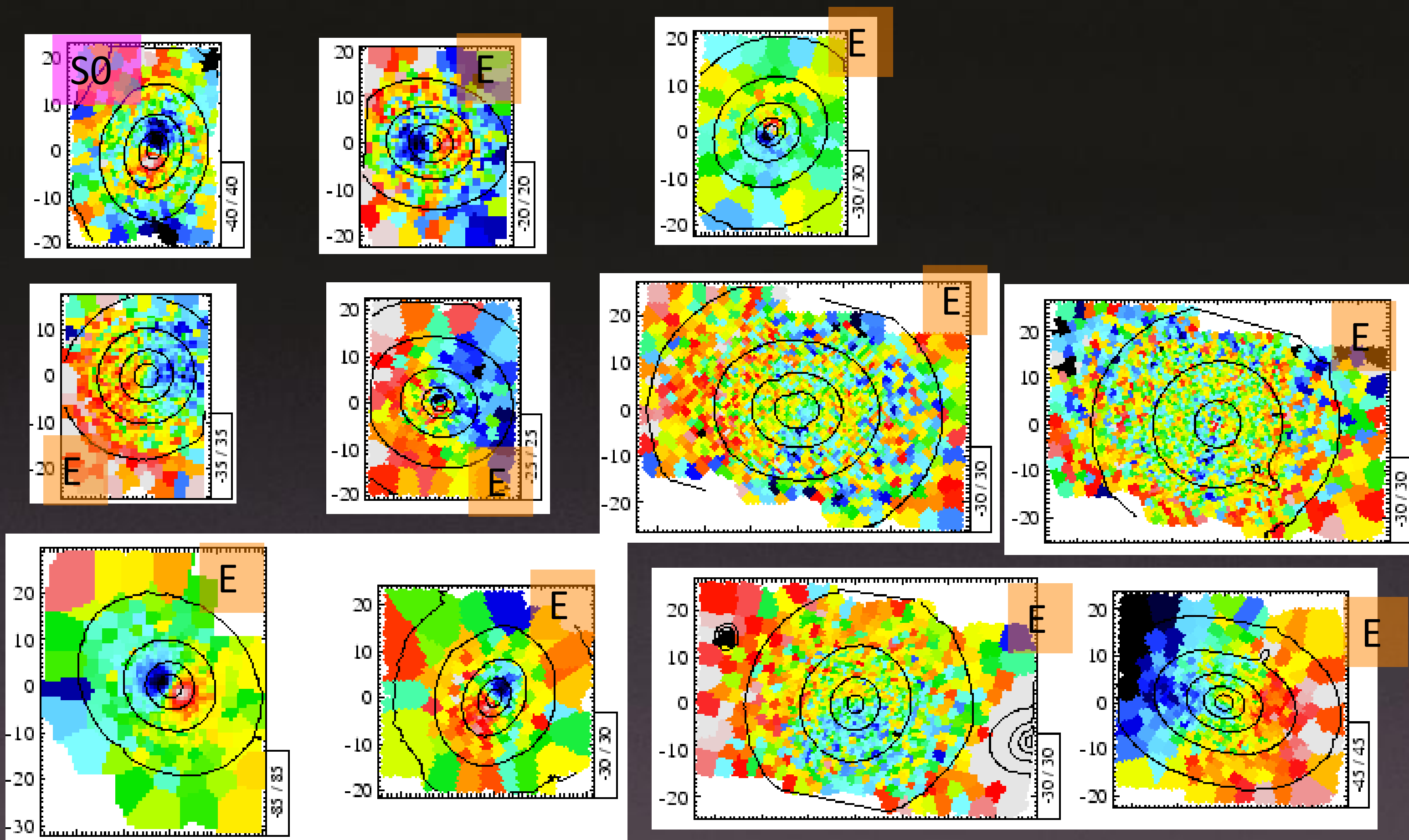
- Elliptical galaxies are spheroidal – look similar from all directions
- S0 galaxies (disk+bulge) look like E if near face-on
- Some “E” galaxies show kinematics similar to S0

Large-scale rotation – Fast Rotators



40% classified by RC3 as ellipticals

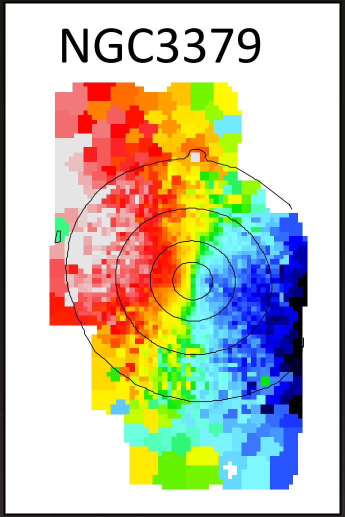
Slowly rotating SAURON galaxies



General agreement with RC3

New Kinematic Quantifier: λ_R

- SAURON galaxies show either ordered rotation, or no rotation except for decoupled component
- How to quantify the spatial difference in velocity maps?

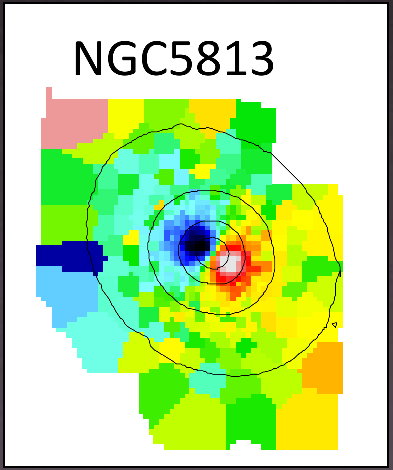


Weighted with Radius

$$\lambda_R = \frac{\langle R \times |V| \rangle}{\langle R \times \sqrt{V^2 + \sigma^2} \rangle}$$

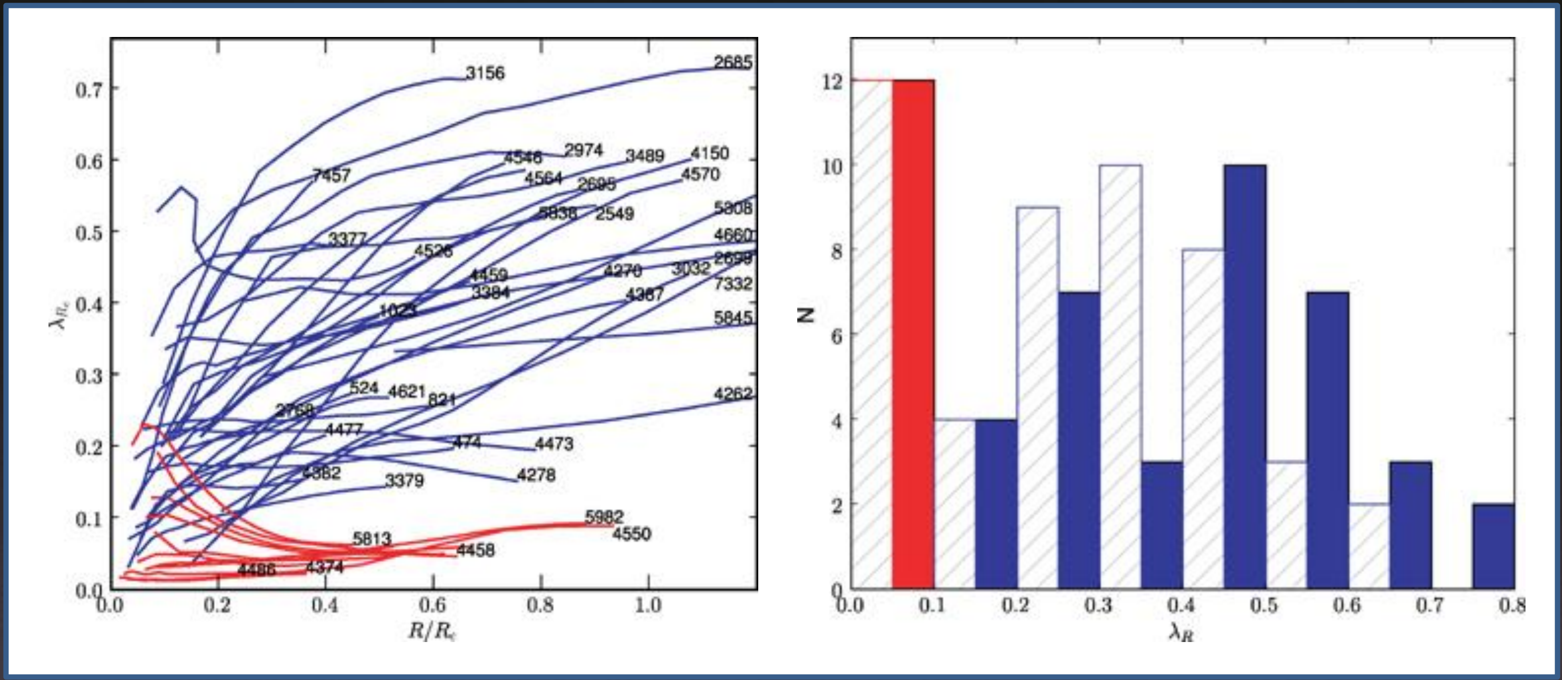
Sky-averaged
- Need IFU

Normalized by Mass



(Emsellem et al. 2007)

Angular Momentum in ETGs

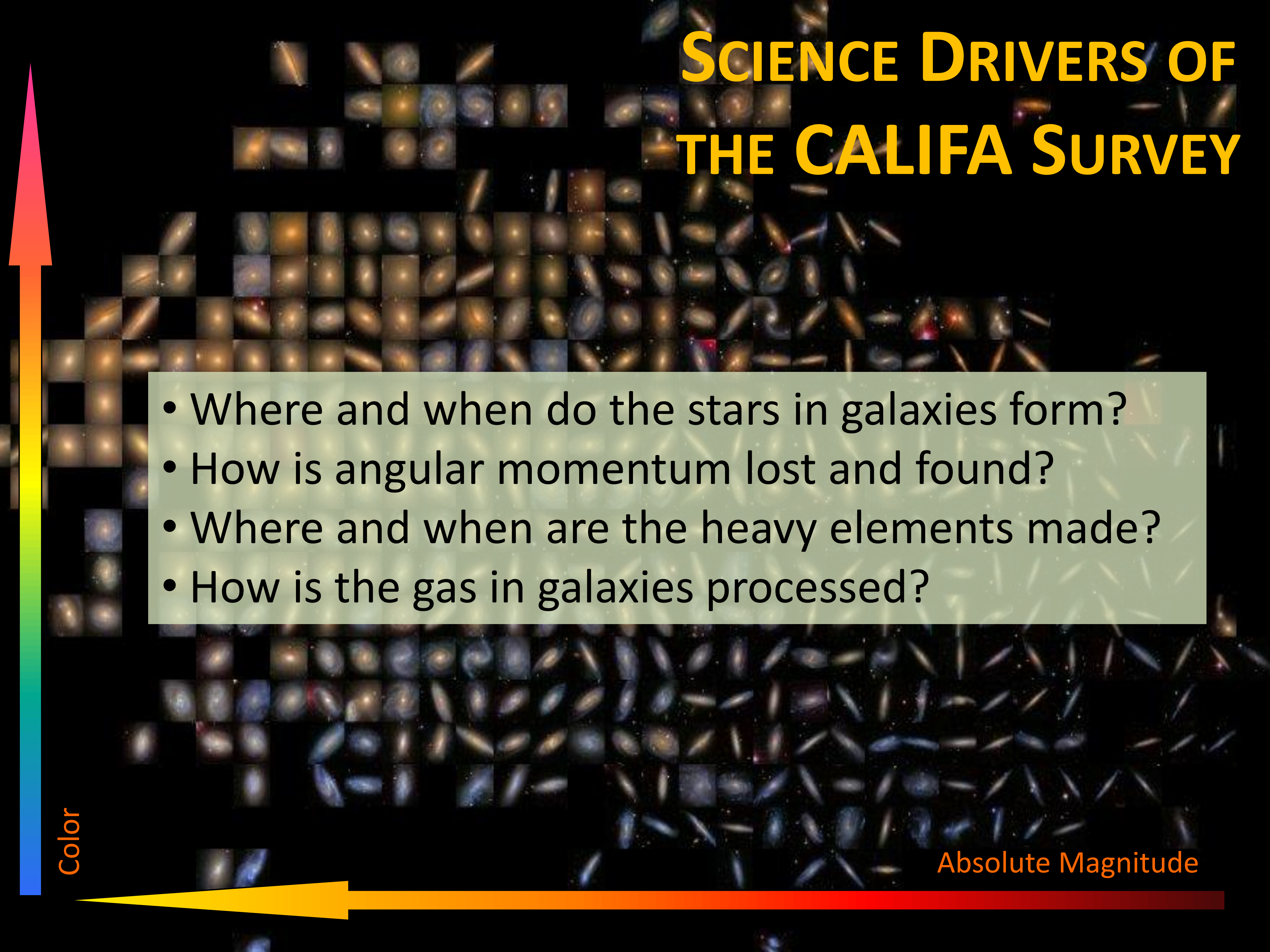


(Emsellem et al. 2007)

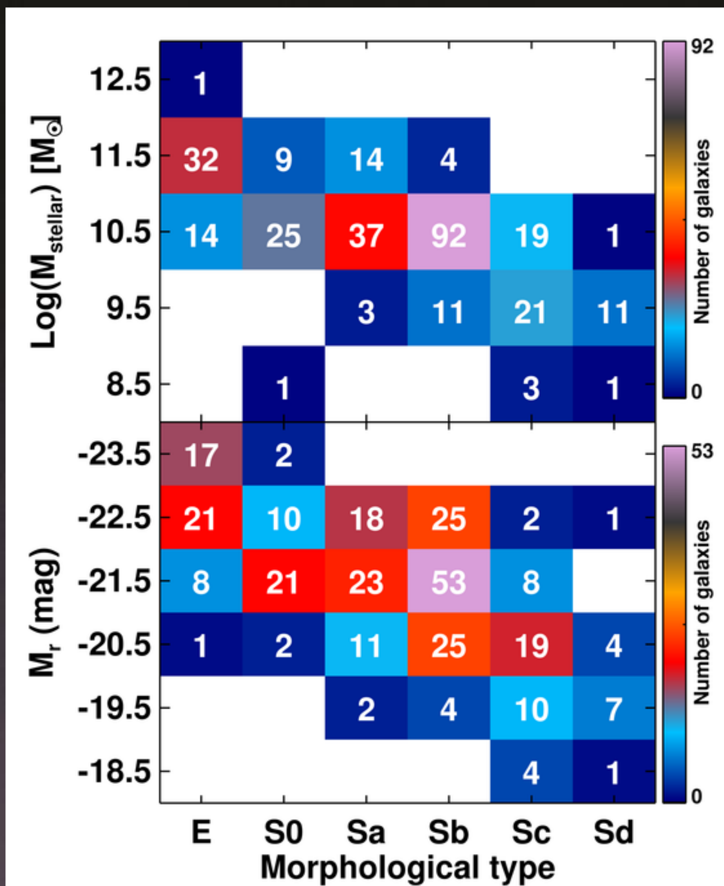
- AM profiles (with radius) were different
- Marked difference in integrated (1Re) values

Science Drivers of the CALIFA Survey

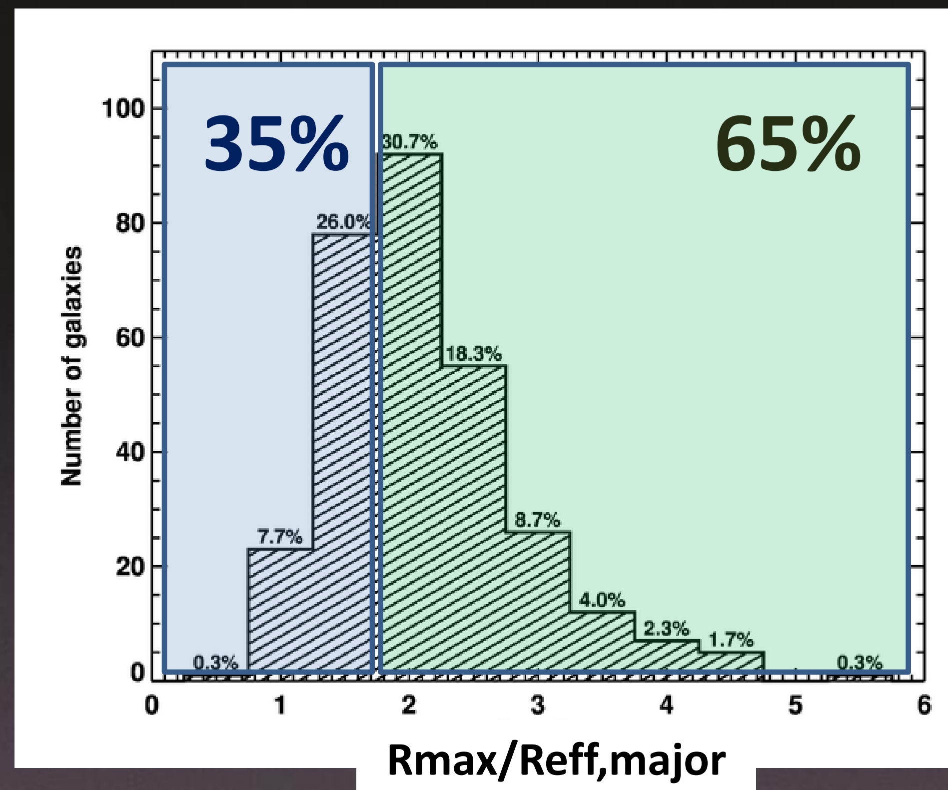
- Where and when do the stars in galaxies form?
- How is angular momentum lost and found?
- Where and when are the heavy elements made?
- How is the gas in galaxies processed?



SAMPLE PROPERTIES
(300 galaxies)

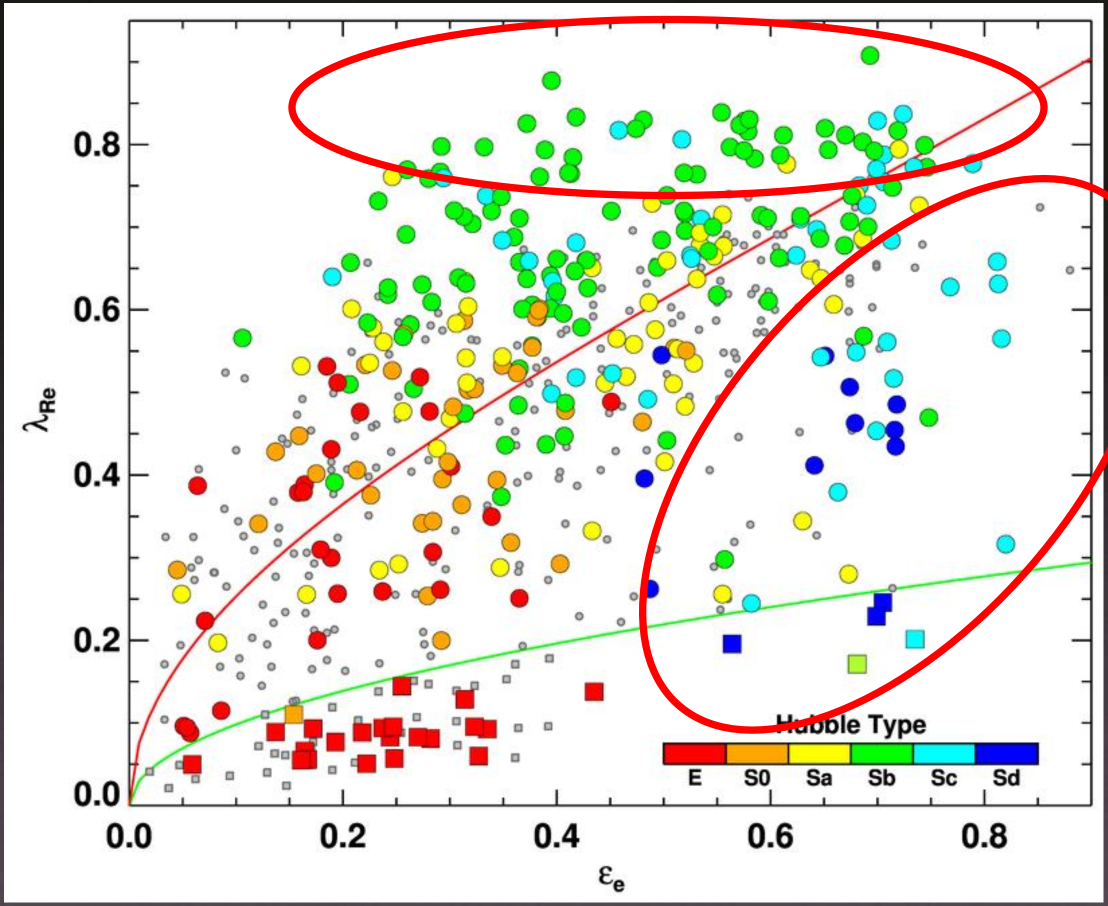


Selection allows for volume corrections



- Good coverage across Hubble sequence
- Most galaxies reaching up to 2 Reff

Angular Momentum across Hubble Sequence

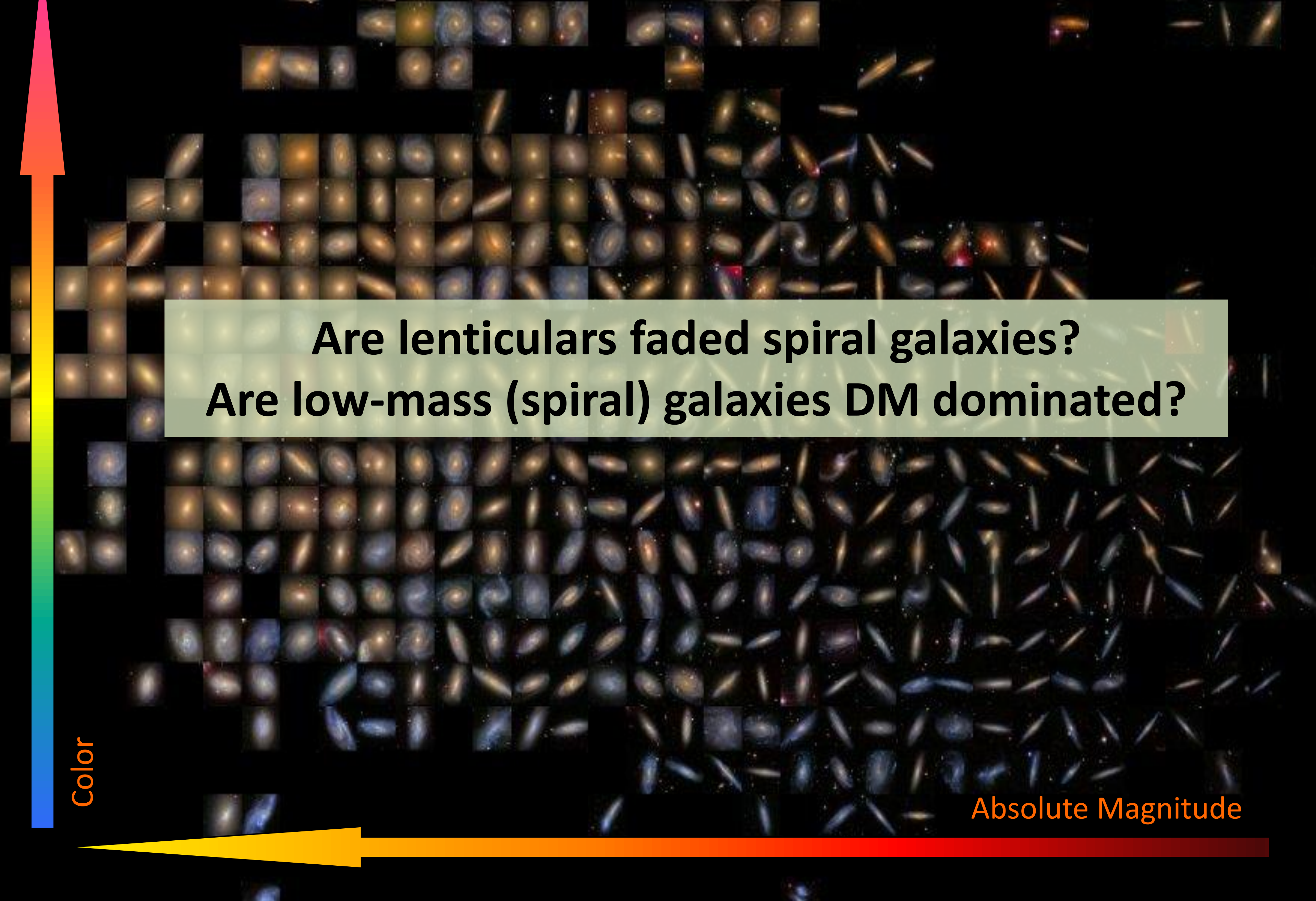


- Alternative to the classical (V/σ) vs ellipticity diagram developed by SAURON & A3D
- Distribution of CALIFA ETGs galaxies similar to A3D
- Target selection favours edge-on over face-on galaxies
- This samples two areas:
  - Very Fast rotators
  - Low-λ_{Re} spiral galaxies

THE CALIFA SURVEY

Are lenticulars faded spiral galaxies?

Are low-mass (spiral) galaxies DM dominated?

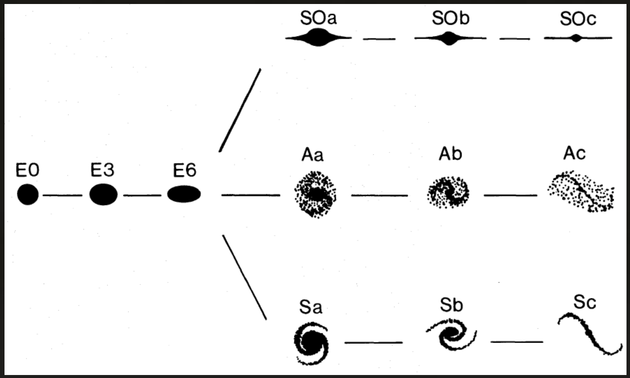


ARE LENTICULARS FADED SPIRALS?

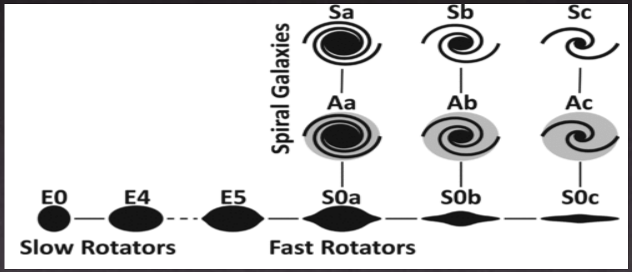
- What processes dominate this Morphological (kinematic) transition?
  - Minor/Major mergers
  - Secular evolution
  - Environmental processes (e.g. harrasment)

- The idea has been around for some time (e.g. van den Berg 1976)

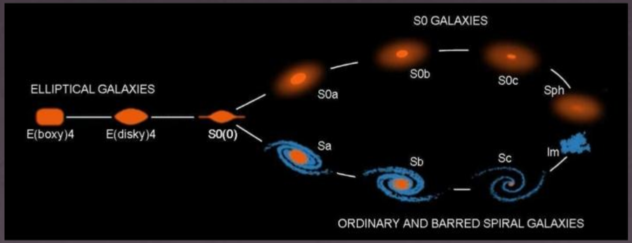
- Revived again recently (e.g. Laurikainen et al. 2010, A3D team, Kormendy & Bender 2012)



van den Berg (1976)



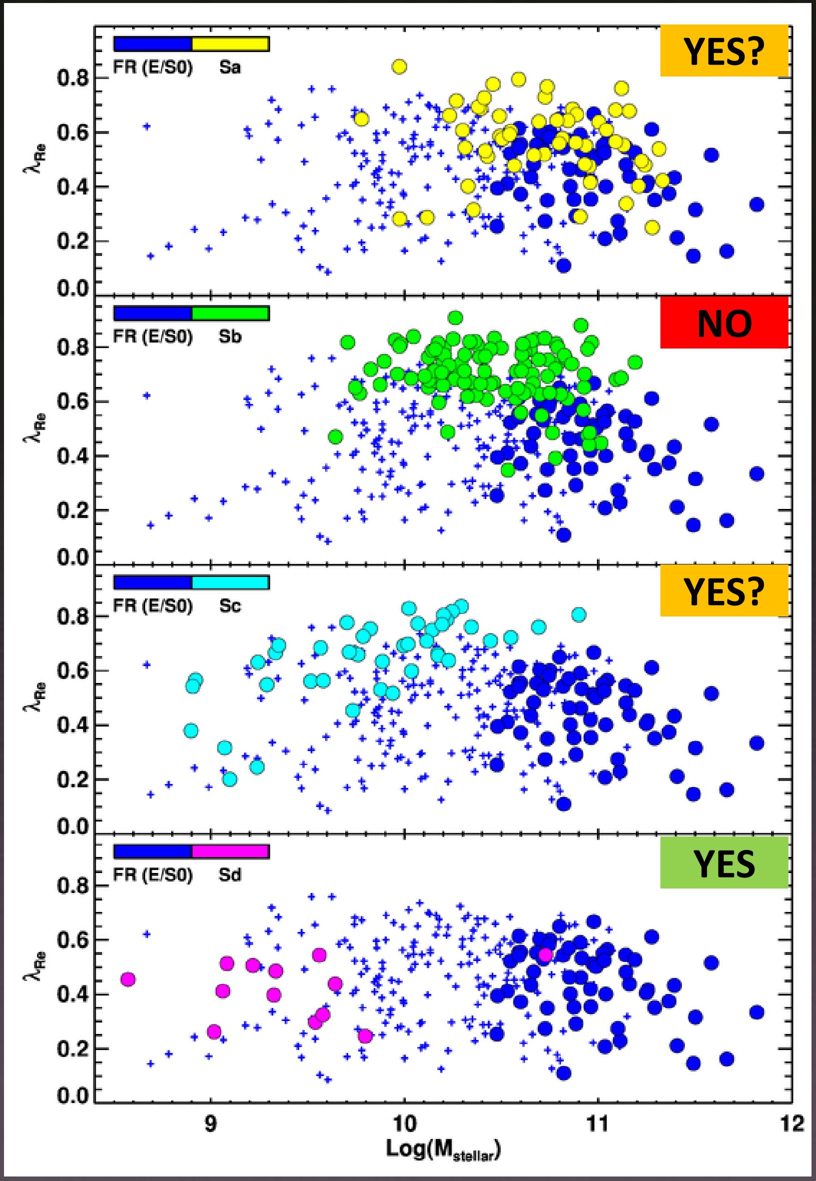
Cappellari et al. (2011)



Kormendy & Bender (2012)

ARE LENTICULARS FADED SPIRALS?

(ANGULAR MOMEMTUM CONSISTENCY)

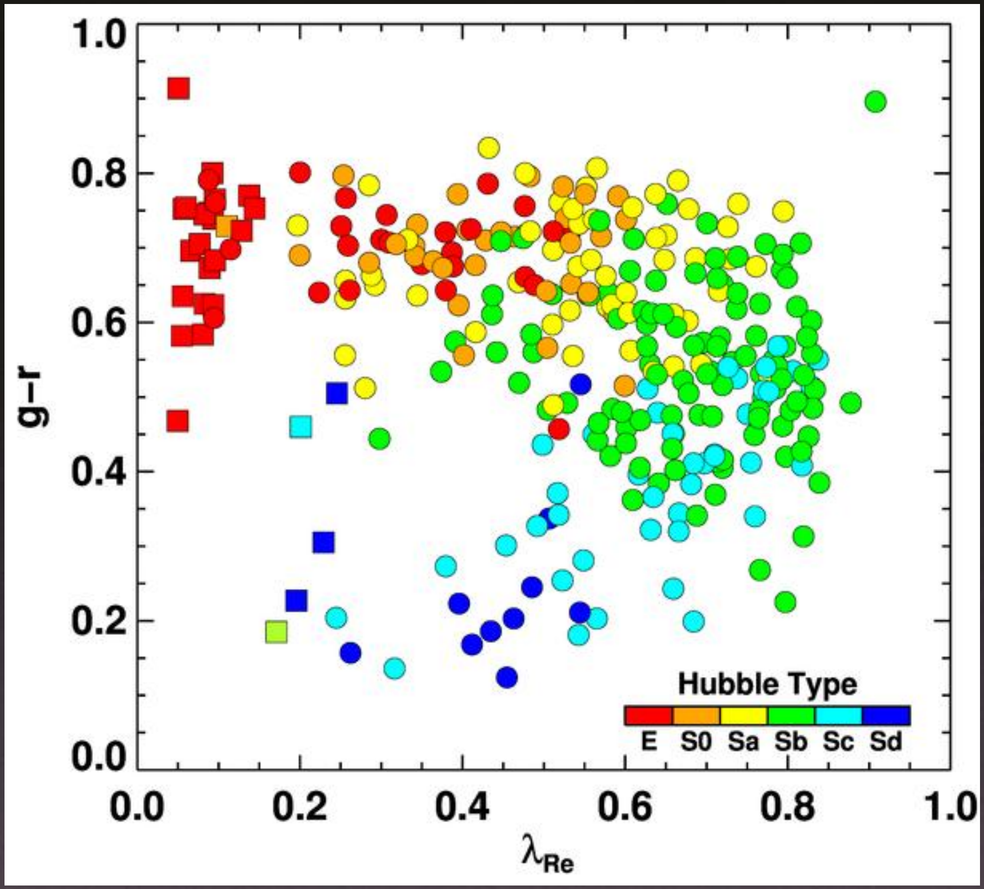


- Sa galaxies in general compatible with FRs
- Many Sb galaxies cannot turn into FRs by *fading*
- Sc galaxies mostly compatible as well
- Sd galaxies compatible

But this is not the whole story….

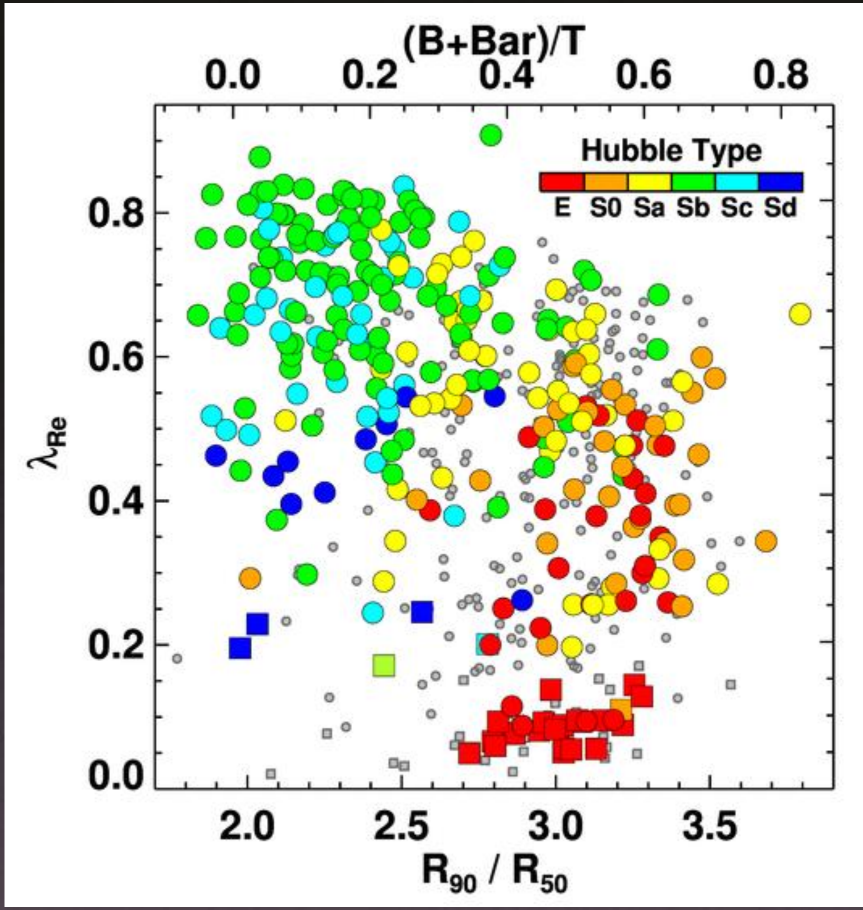
Are Lenticulars faded Spirals?

(Gas supply)



Sc/Sd galaxies cannot make it to the Red sequence by *fading* alone

NOT FADING (ALONE)



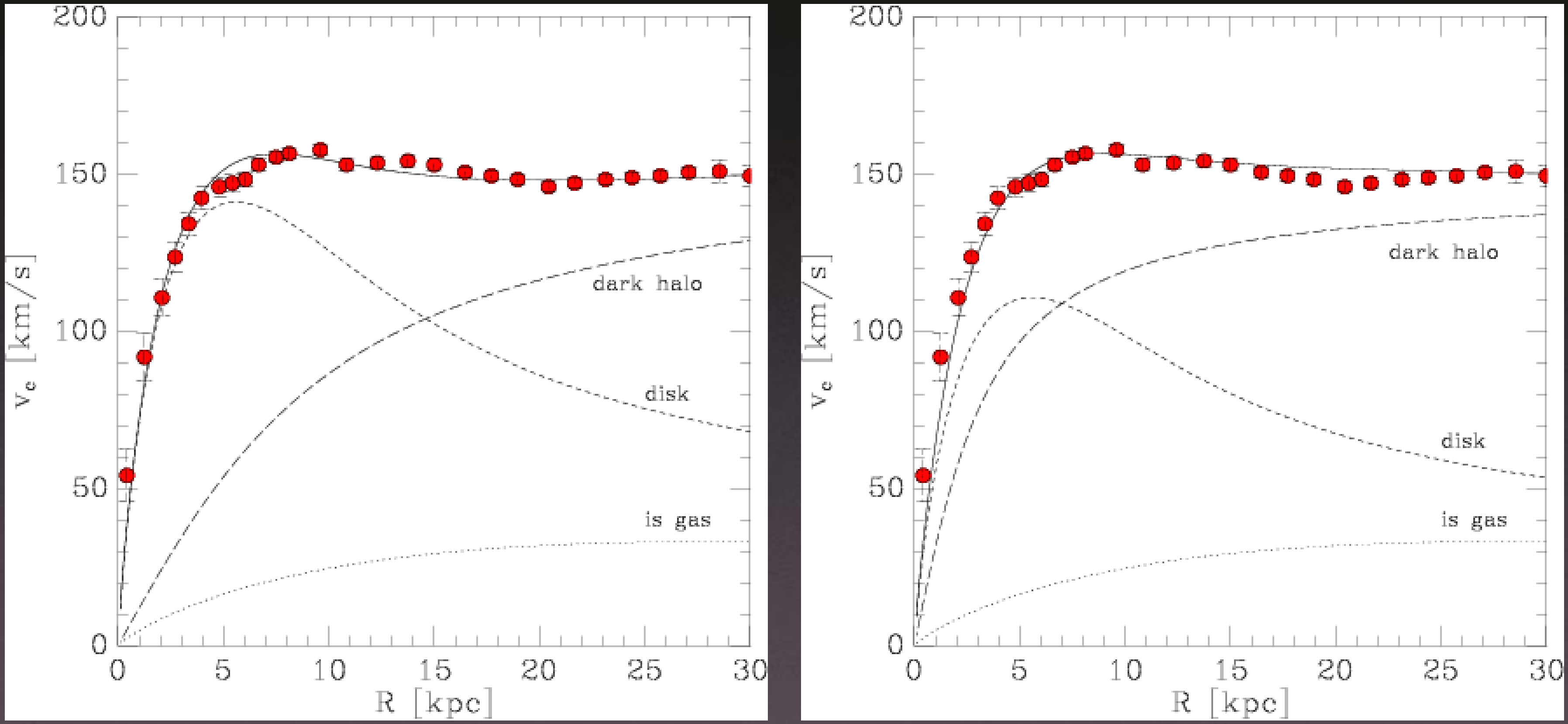
- Fastest rotators ($\lambda_R > 0.8$) contain very small bulges

- Mergers:
  - major/minor?
  - wet/dry?
- Environment:
  - tidal harassment?
  - ram pressure stripping?
- Internal:
  - feedback?
  - fading?

Are low-mass spirals DM dominated?

Motivation

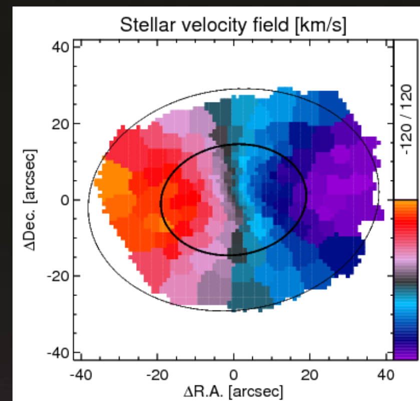
- Study of DM content is a direct way to relate to cosmological simulations

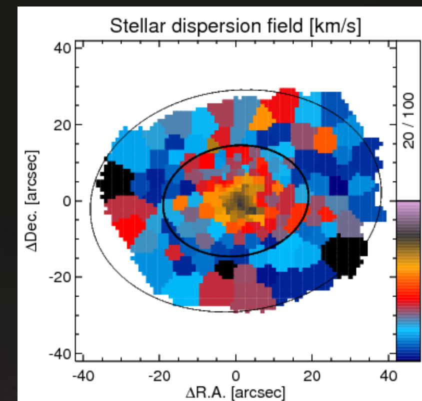


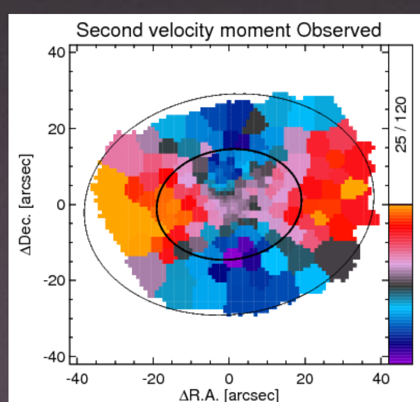
Fuchs (2008)

TOTAL MASS FROM DYNAMICAL MODELLING

NGC4210



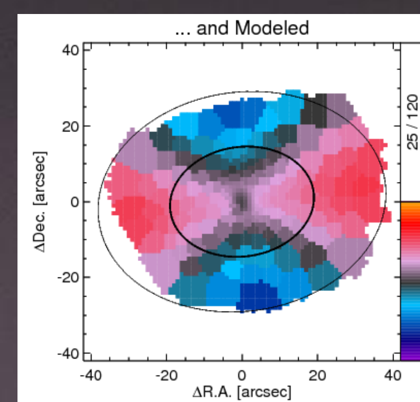




Jeans dynamical models

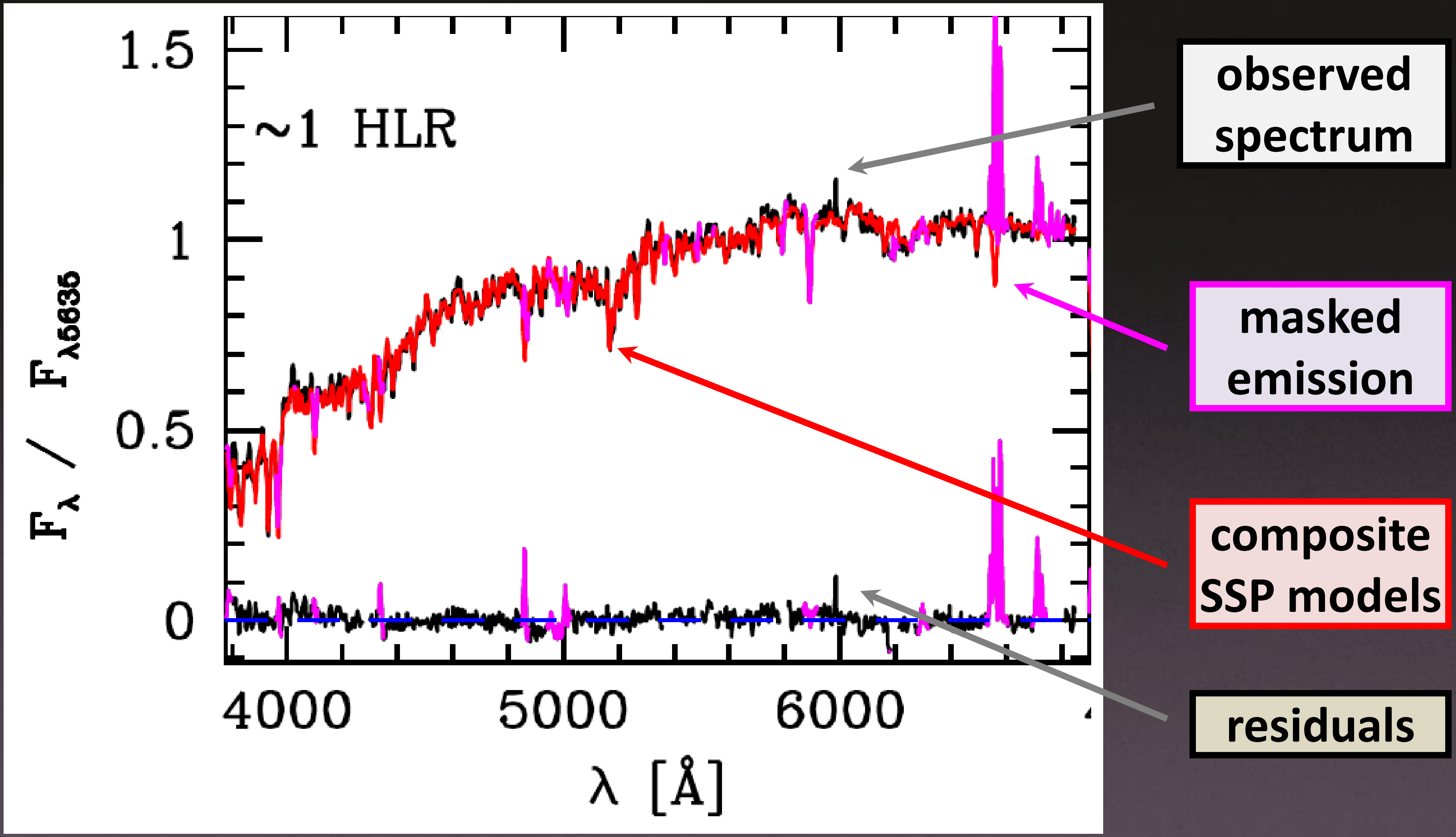
&

Schwarzschild



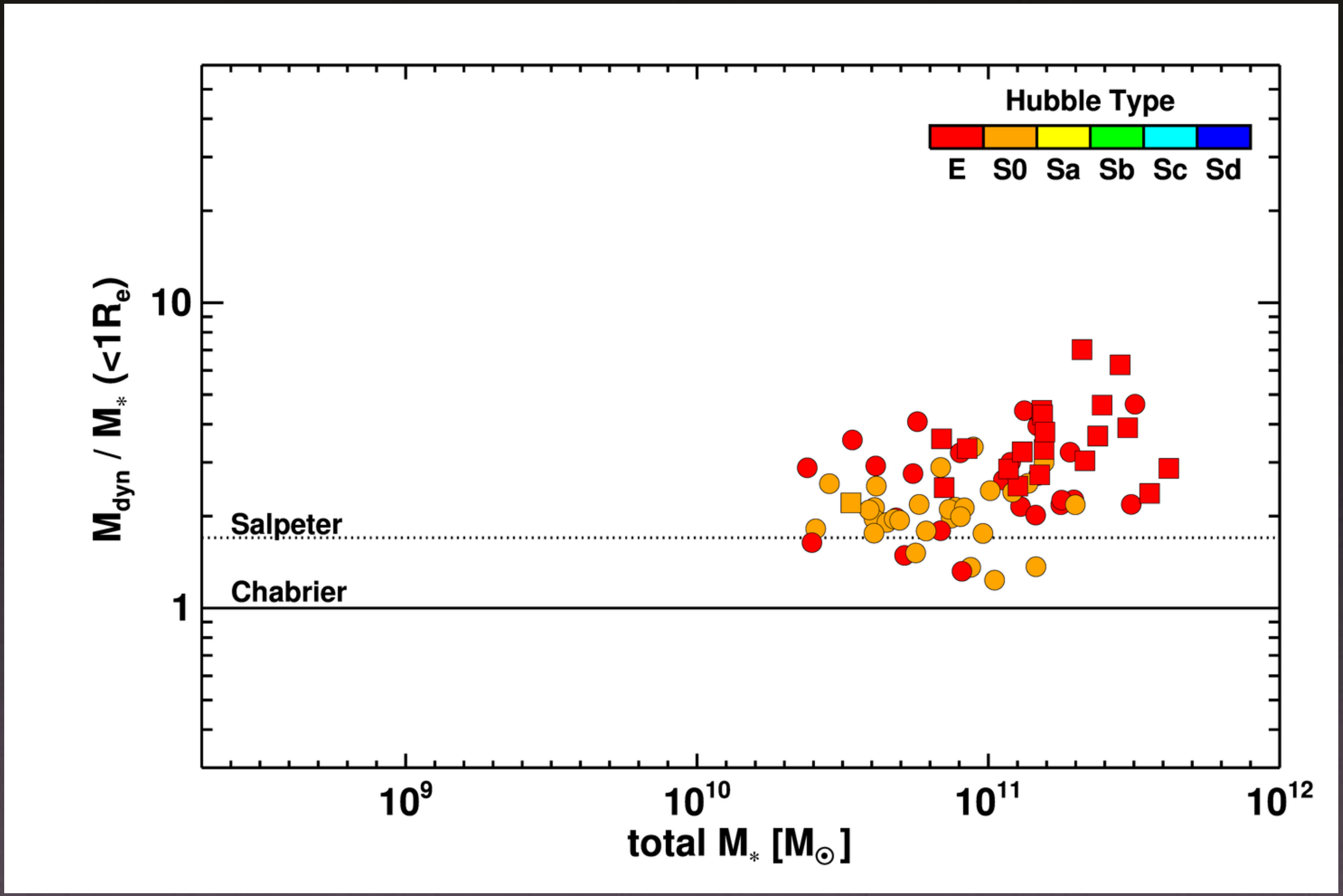
STELLAR MASSES FROM SPECTRAL FITTING

STARLIGHT code applied to CALIFA (Cid Fernandes et al. 2013)



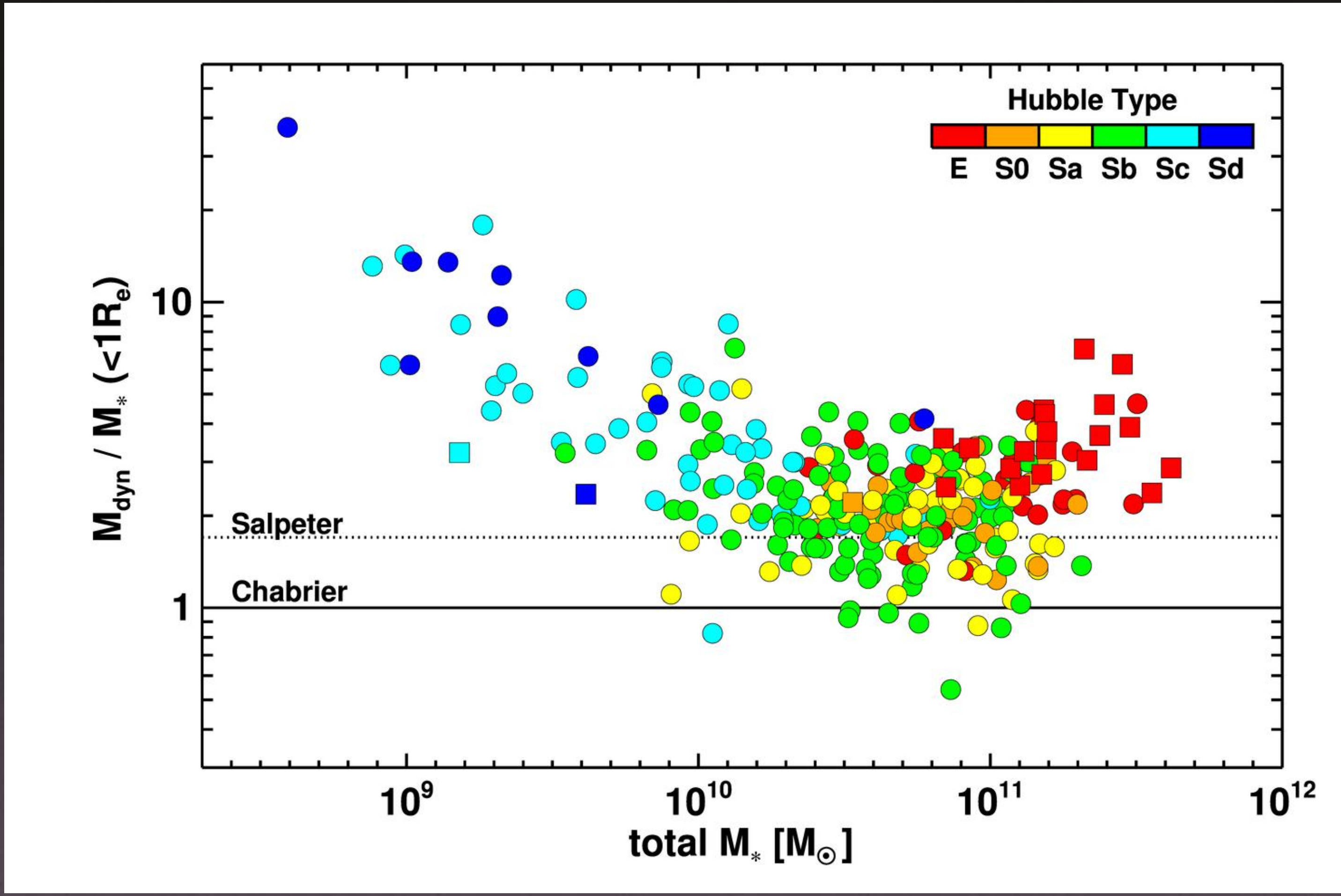
González-Delgado et al. (2014)

ARE LOW-MASS SPIRALS DM DOMINATED?



If bottom-heavy IMF, DM content of most massive galaxies will decrease

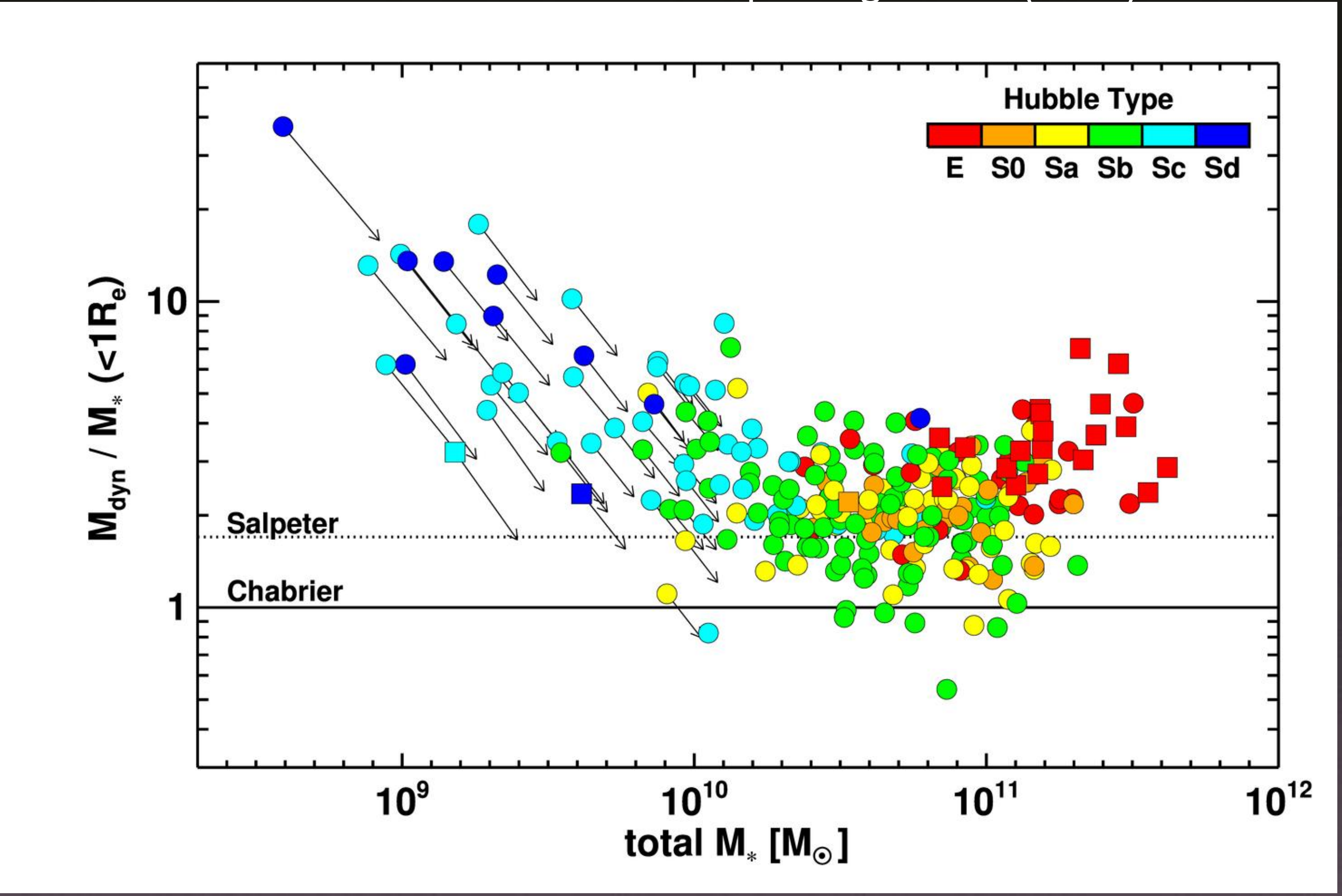
Are low-mass spirals DM dominated?



Most galaxies have similar DM content except low-mass spirals

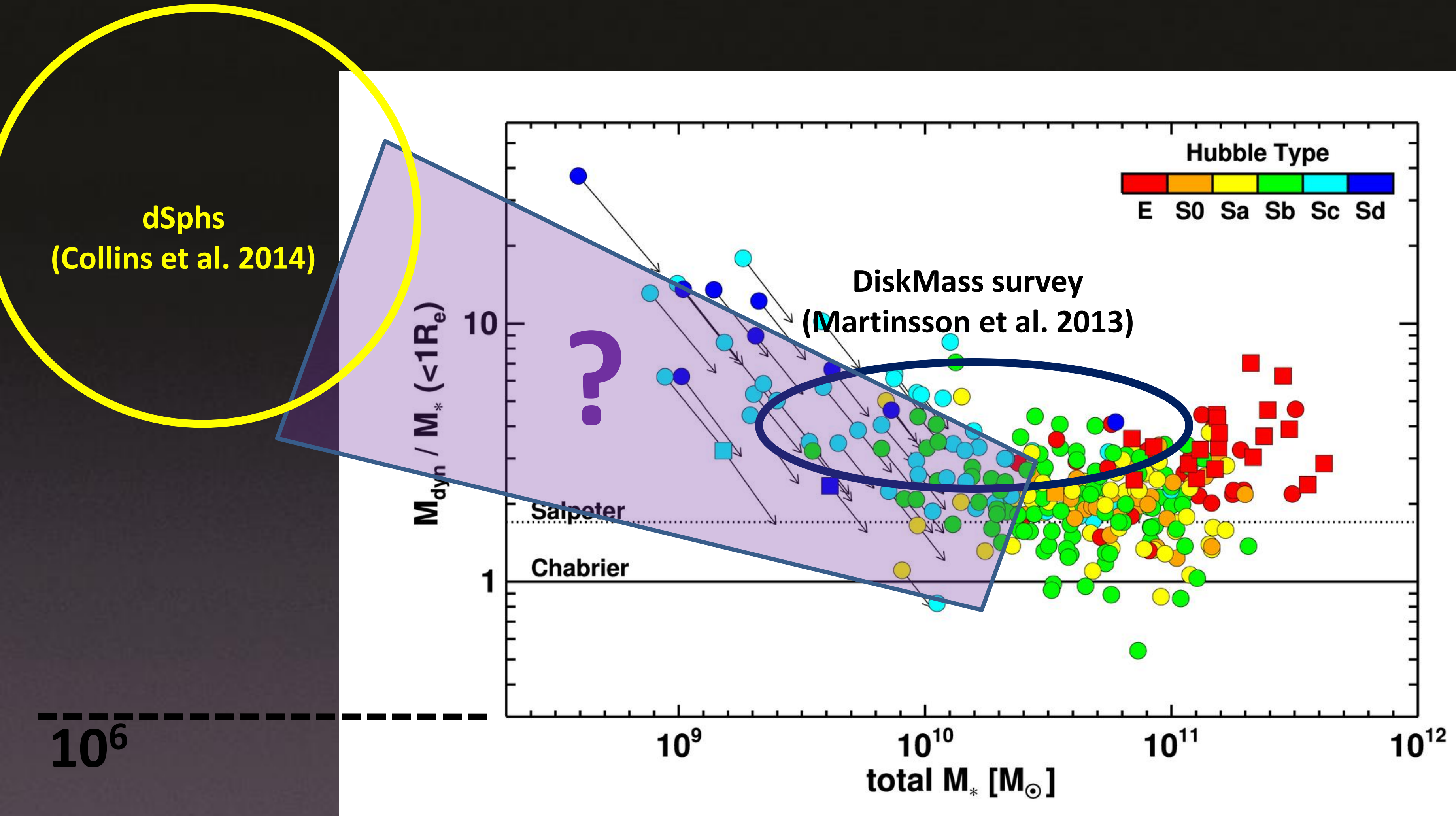
Are low-mass spirals DM dominated?

Gas mass estimates from Papastergis et al. (2012)



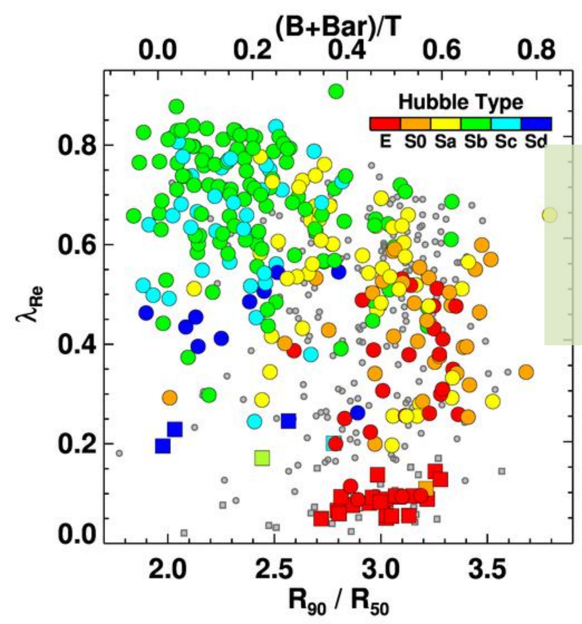
Situation remains even if gas content considered

ARE LOW-MASS SPIRALS DM DOMINATED?

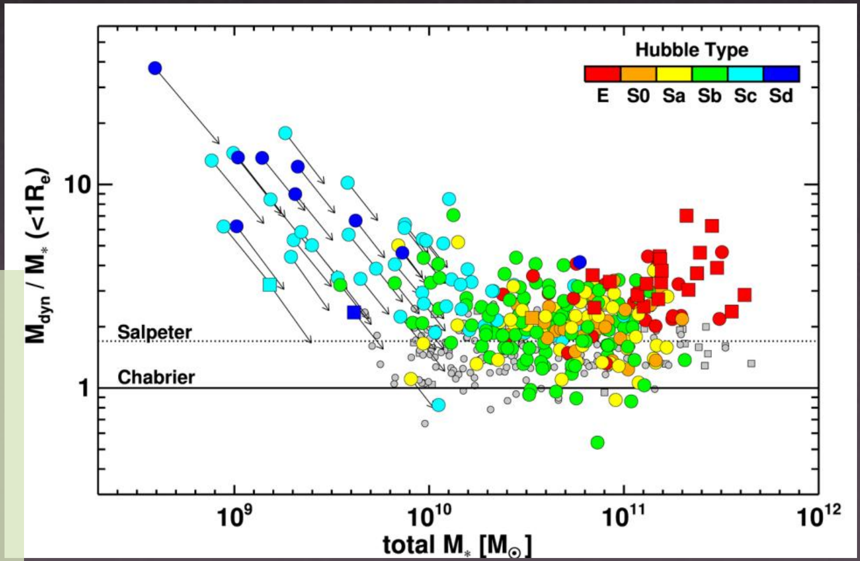


CONCLUSIONS

AM is a powerful parameter to unravel the evolution of galaxies



Are lenticulars faded spiral galaxies? NO



Are low-mass (spiral) galaxies DM dominated? YES

The End