F. Hammer

Disk formation in massive spirals: merger or secularly induced star formation?

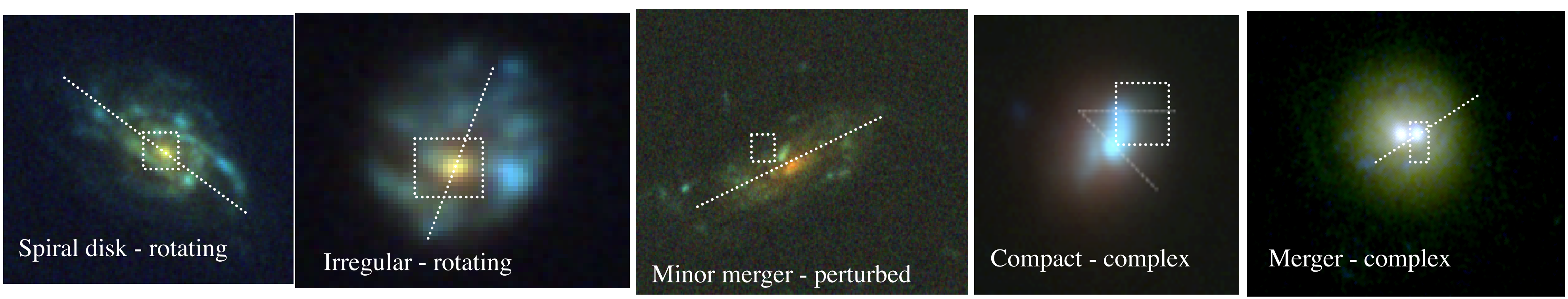
Using the deepest and most complete observations of distant galaxies, we investigate how large disks could have been formed. Observations include spatially-resolved kinematics, detailed morphologies and photometry from UV to mid-IR. Six billions years ago, half of the present-day spirals were experiencing major mergers, evidenced by their anomalous kinematics and morphologies as well as their relatively high gas fractions. They are consequently modelled using the state of the art hydrodynamics models. This provides a new channel of disk formation, e.g. disks reformed after gas-rich mergers. Then one may estimate which fraction of the stellar mass density has been formed during mergers. This will be compared to expectations from nearby galaxies, including the Milky Way and M31.

The formation of disks in massive spirals

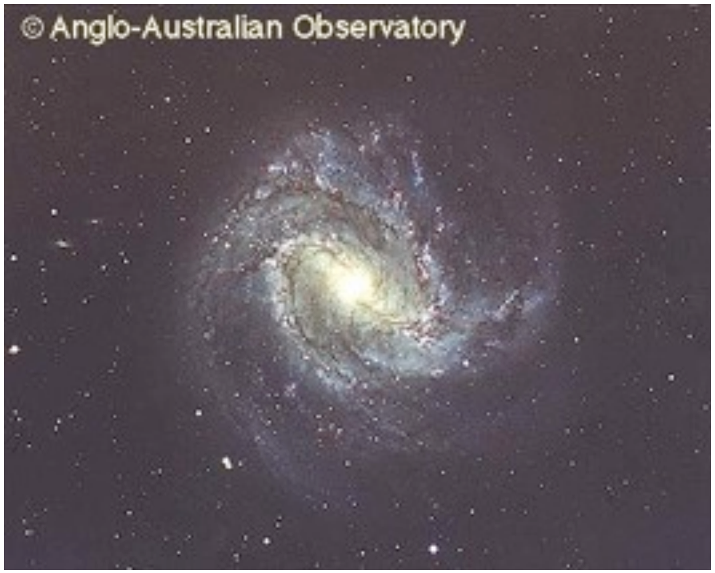
by François Hammer

H. Flores, M. Puech, R. Delgado-Serrano, B. Neichel, S. Peirani, M. Rodrigues, Y. Yang, P. Amram, E. Athanassoula, C. Balkowski, L. Chemin, B. Epinat, I. Fuentes-Carrera, Y. Liang

Intermediate Mass Galaxy Evolution Sequence



Most -72%- large galaxies have spiral structures



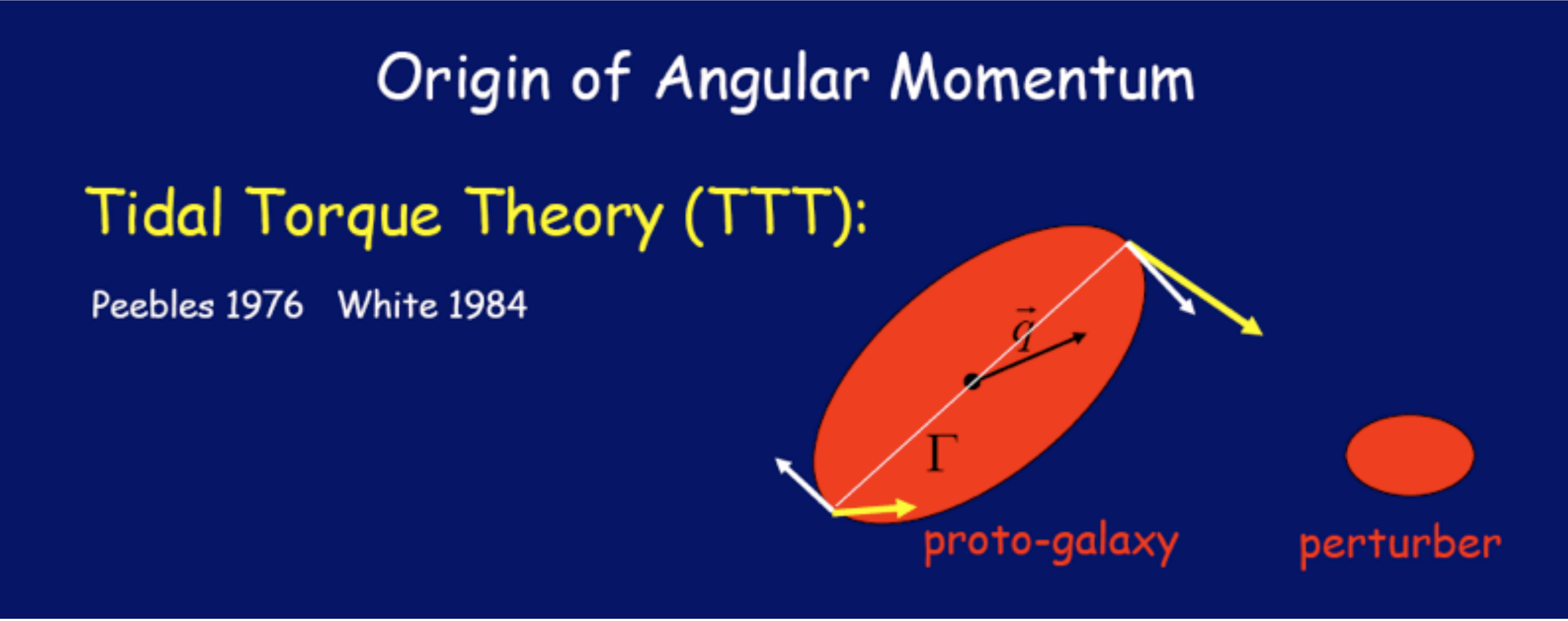
M83

NGC 1365

M100 SABbc

Thin disks are fragile to collisions

Mergers with other galaxies can easily destroy thin disks (e.g. Toth & Ostriker, 1992)

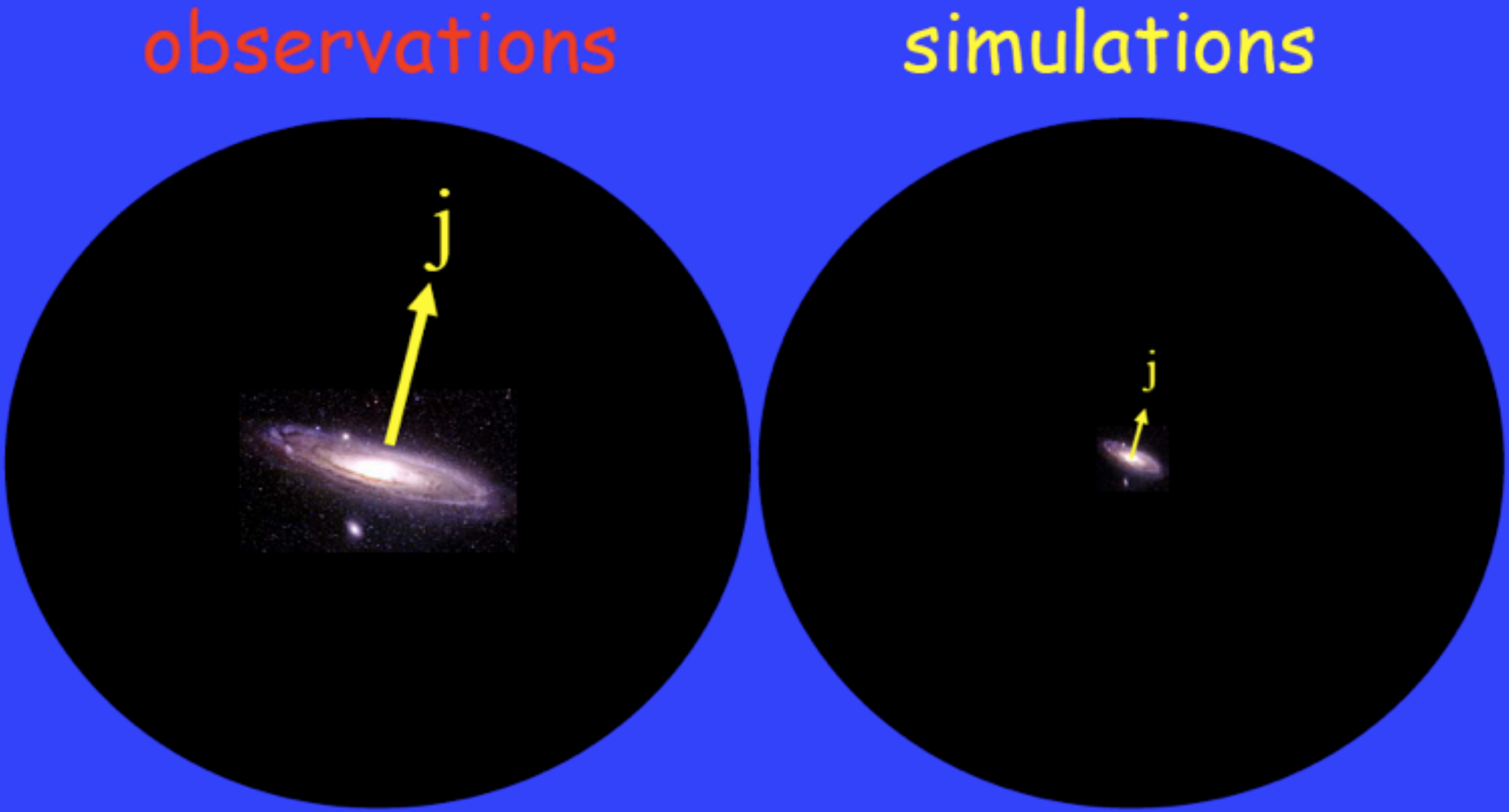


Angular momentum acquired from galaxy interactions at earliest epochs:

Galactic disks are then assumed to evolve without subsequent major mergers ➔ so called “secular” scenario

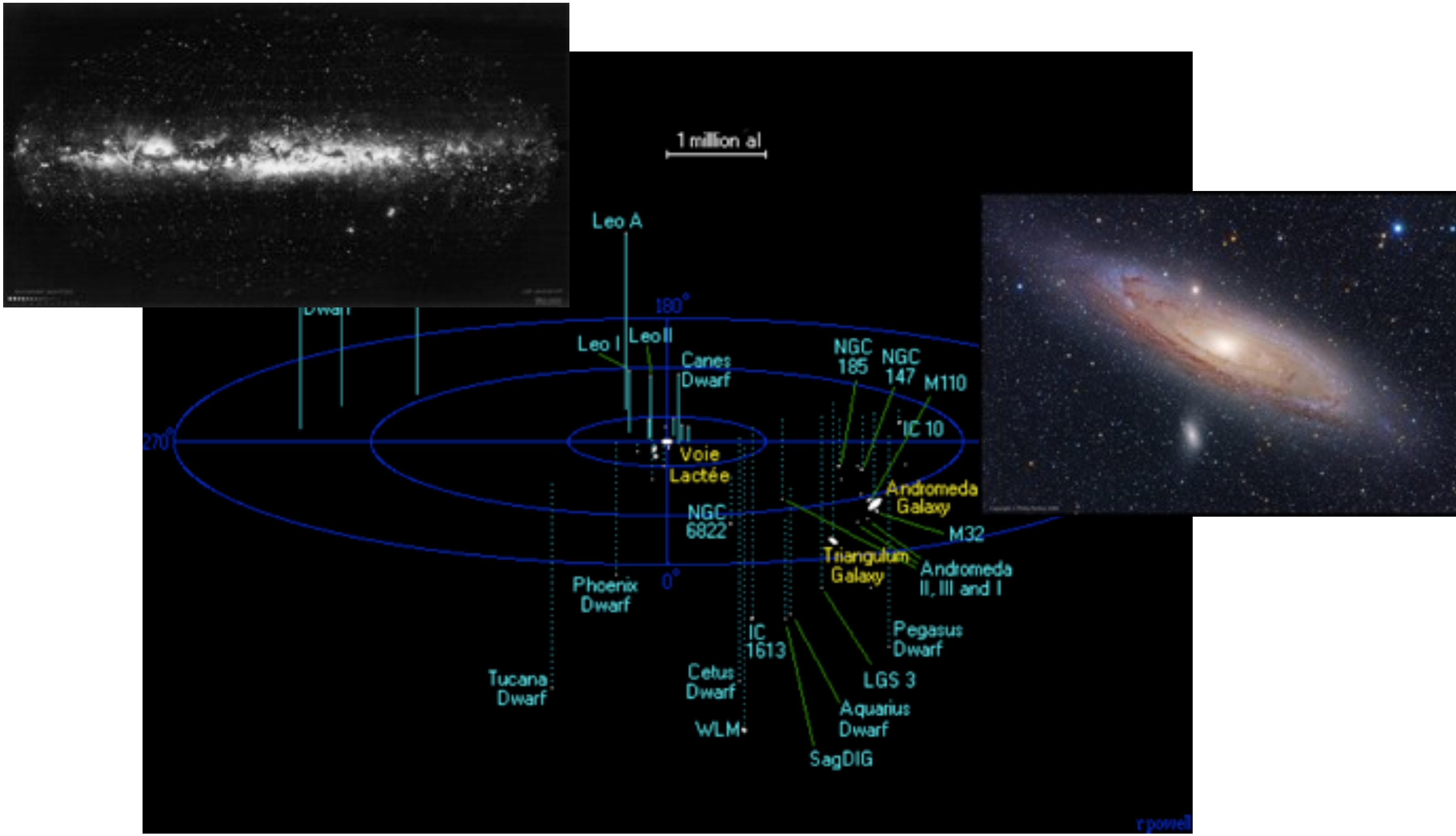
The Spin Catastrophe

Navarro & Steinmetz et al.

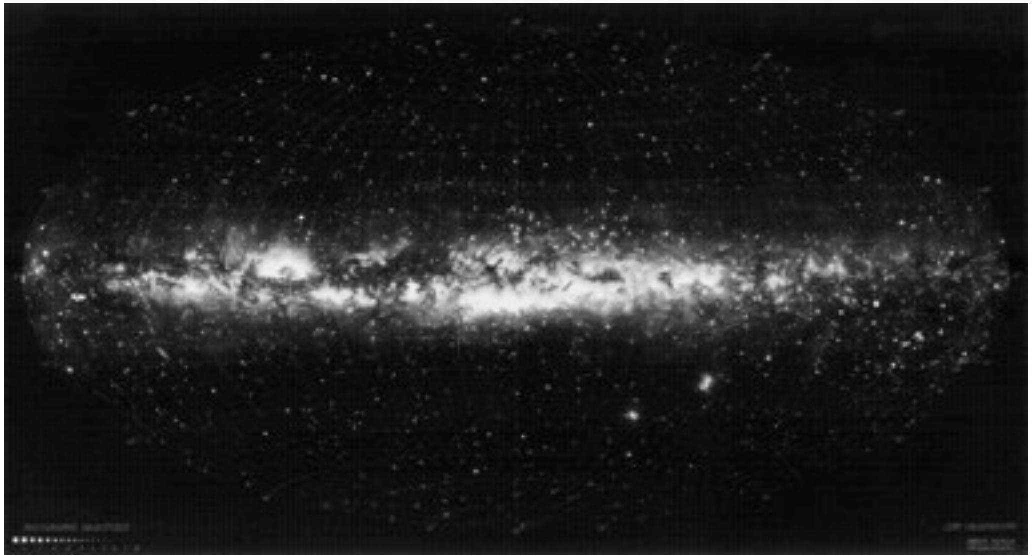


Excerpt from Dekel, Paris courses, 2006

Milky Way and M31



The Milky Way: a quiescent history



Today: absorbing a very dwarf galaxy, Sagittarius

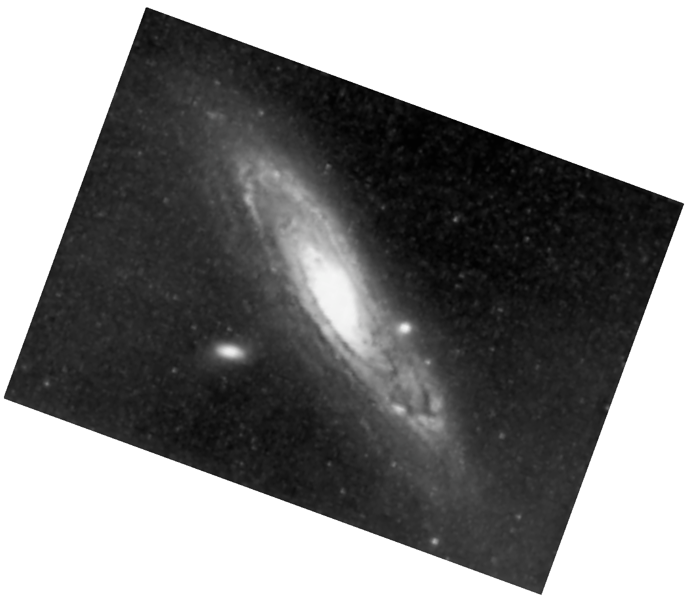
Past history of the Milky Way:

- Halo shows almost no evolved stars
- No major merger since the last 10-11 billions years

The tumultuous history of M31 (Andromeda)

(Ibata et al, 2001; 2004; Beasley et al, 2004; Brown et al, 2006, 2008)

see also Block et al. 2006 & Mc Connachie, 2009



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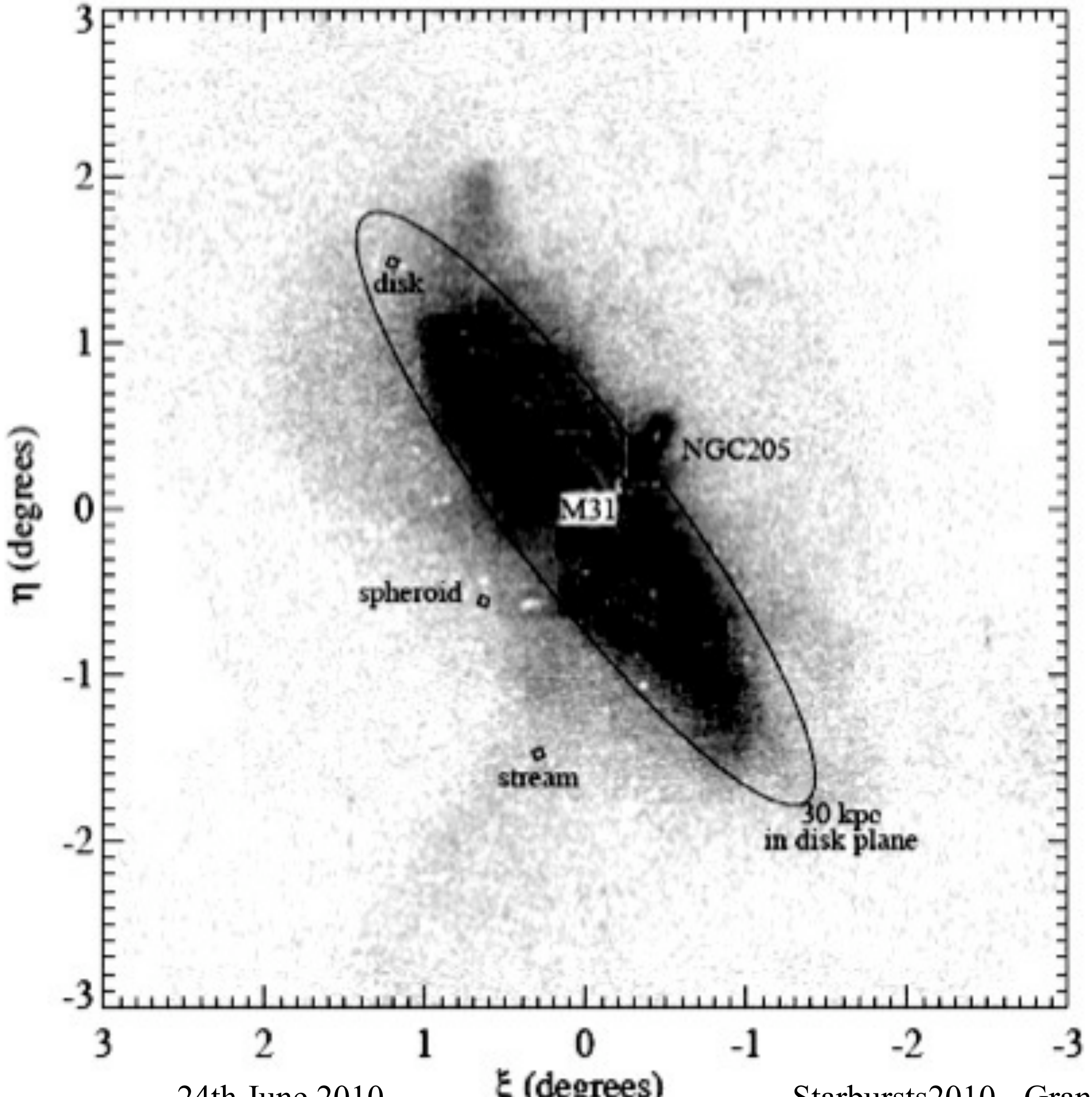
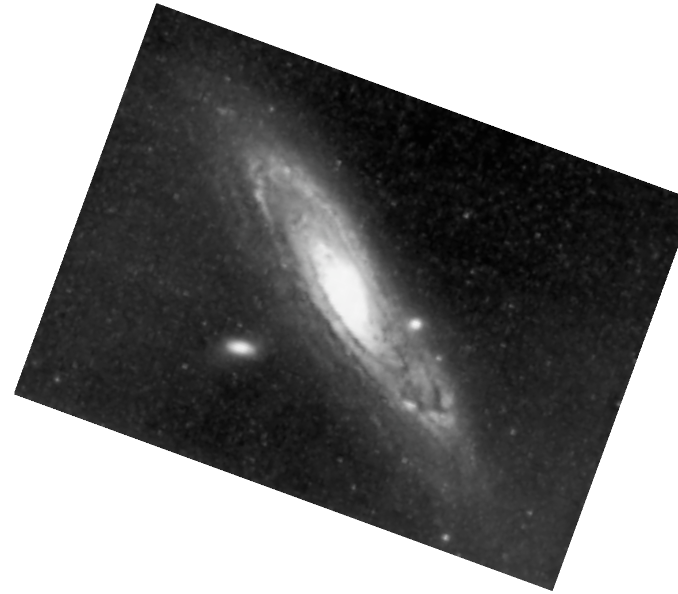




Low surface brigthness features:

Giant stream, clumpy disk &

outer ring, made of evolved stars

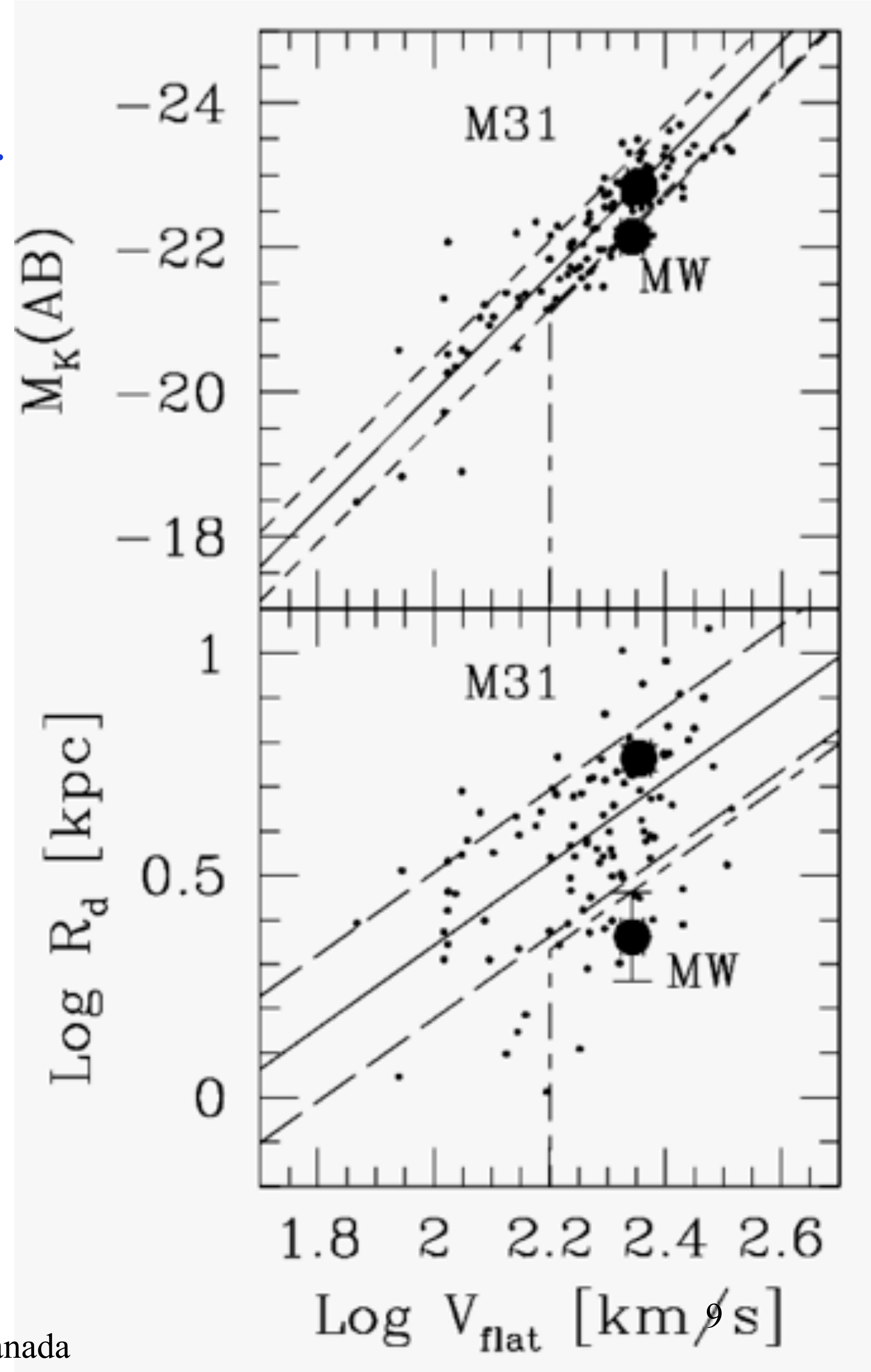
➔ **Either several minor and/or**

a major merger, 7-8 Gyrs ago?

The Milky Way versus M31 and other spirals

Hammer et al. 2007, ApJ, 662, 322

Accurate measurements for the MW and M31:
M_K & R_{disk} (COBE/DIRBE, Hipparcos…)
and V_{flat}



<u>Compared to other spirals (SDSS)</u>:
- the MW has a too small stellar mass, radius & angular momentum;
- **M31 is rather typical.**

The Milky Way versus M31 and other spirals

Hammer et al. 2007, ApJ, 662, 322

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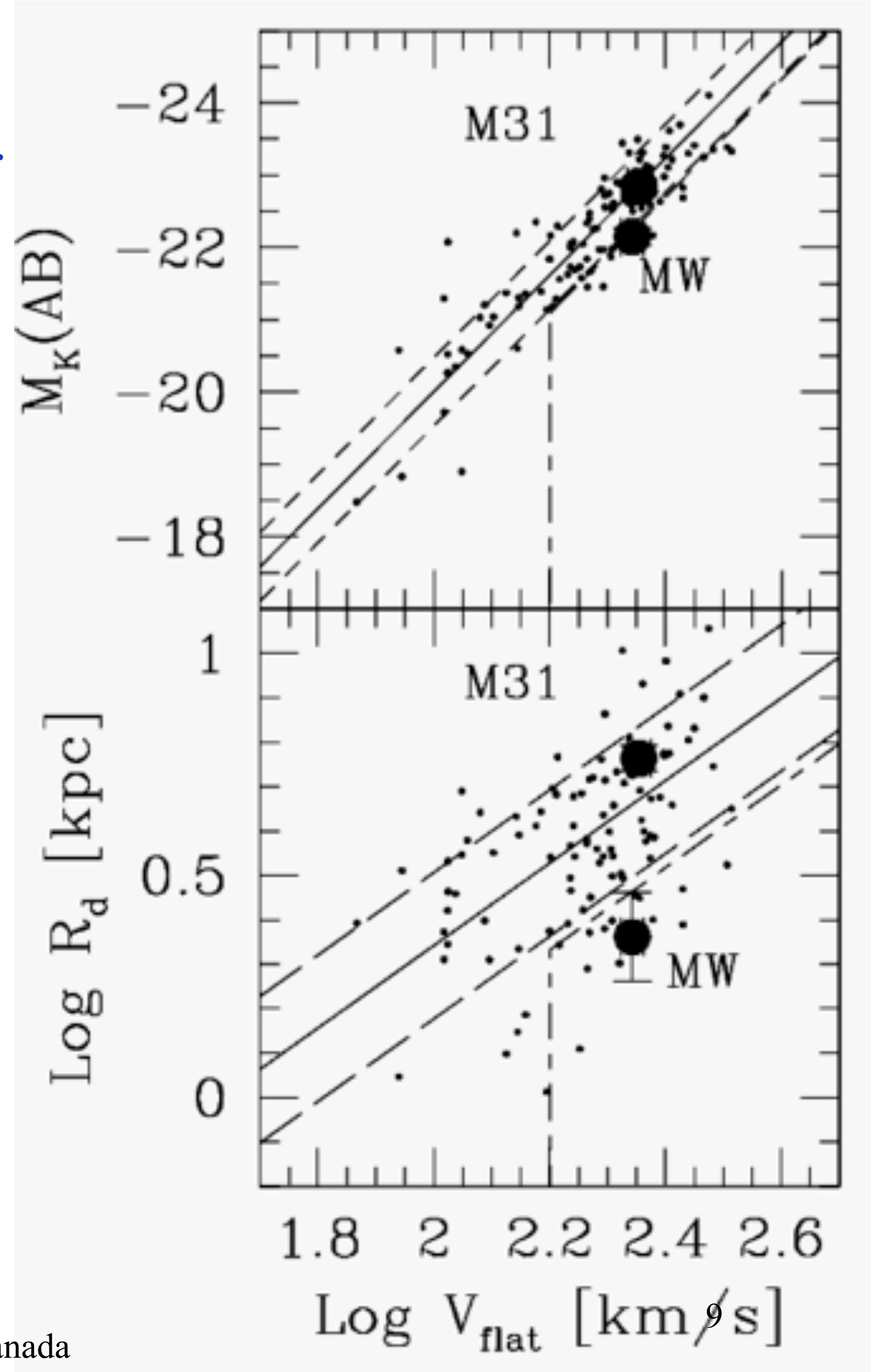
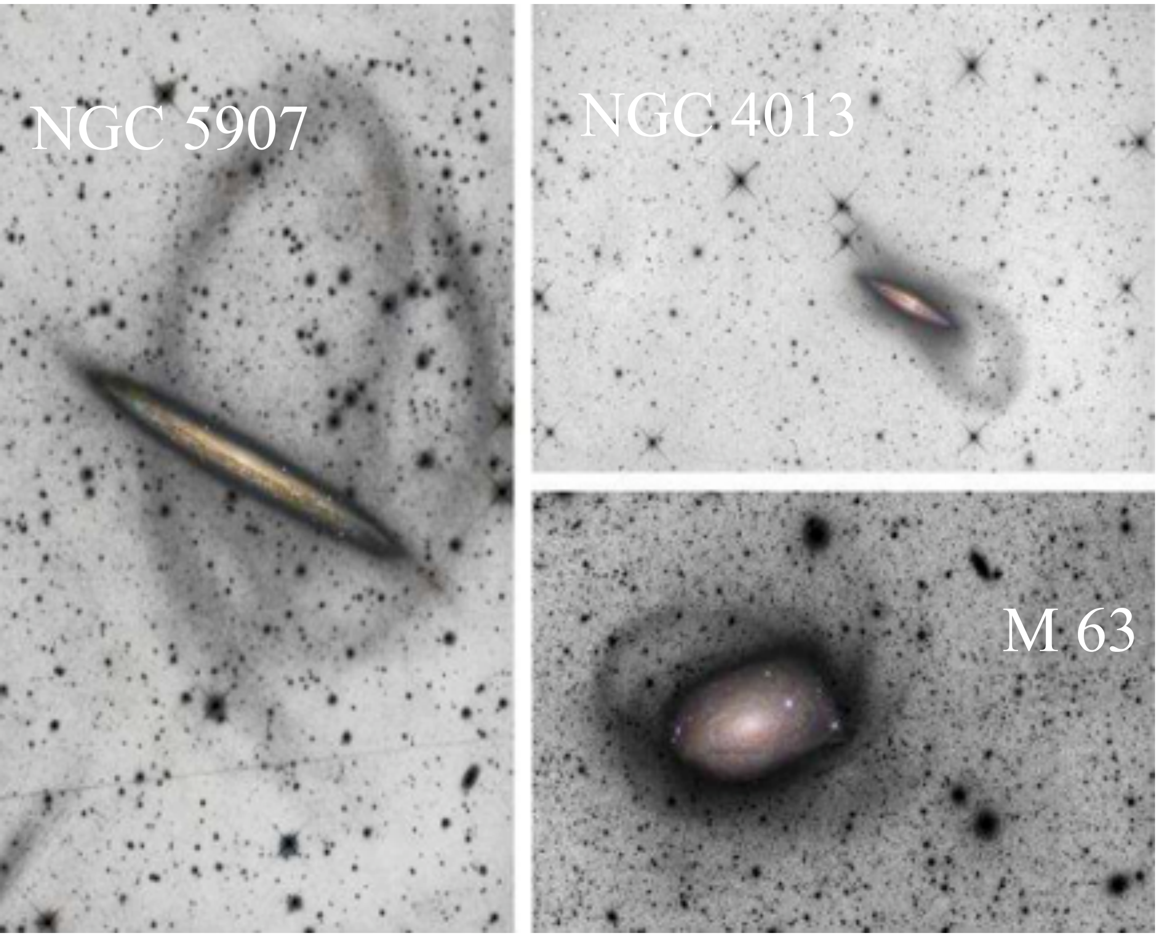
• the MW has a too small stellar mass, radius & angular momentum;
• **M31 is rather typical.**

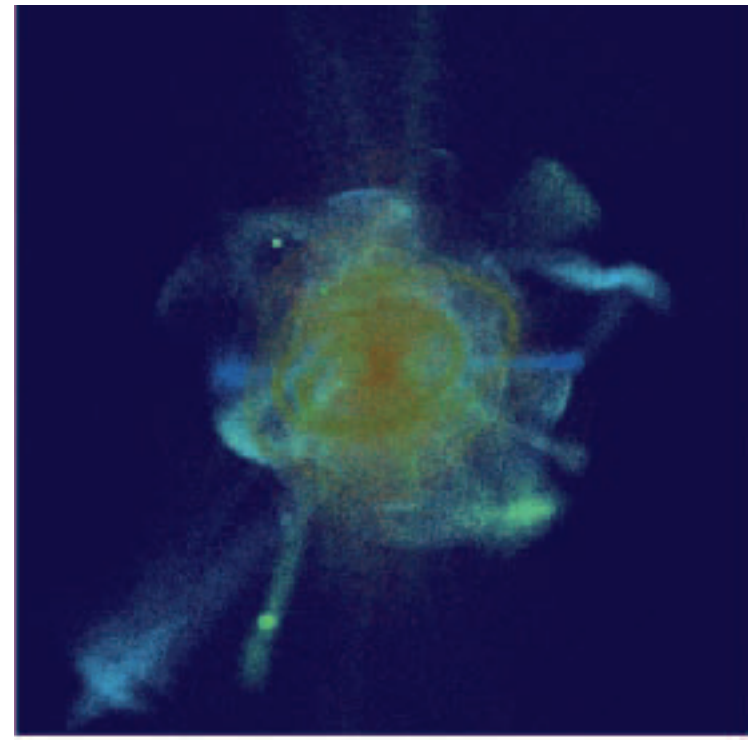
In the (M_K, R_{disk}, V_{flat}) volume, there are only <u>7+/-1%</u> of Milky Way-like galaxies.



The tumultuous history of other spirals

(Martinez-Delgado et al. 2008, 2009)





Simulations from Font et al. 2006

Minor or major mergers?

What is the past history of giant spiral

Galaxy Evolution since the last 8 Gyrs (z=1)

- CFRS, 1995-1997: strong decrease of star-formation density since z=1
- ~ half of present-day stellar mass density formed since z=1 *(e.g., Dickinson+03; Drory+04)*

<u>From evolution of</u>:

1. global stellar mass (photometry, near-IR)

2. integrated Star Formation Rates (SFR, including IR light)

- Most of the stellar mass formed in Luminous IR Galaxies (SFR = 19-190 $M_{\odot}$/yr)
- Galaxies with Milky Way or M31 masses form half of their stars

$2\ 10^{10} < M_{stellar} < 2\ 10^{11}\ M_{\odot}$ *(Hammer+05, Bell+05)*

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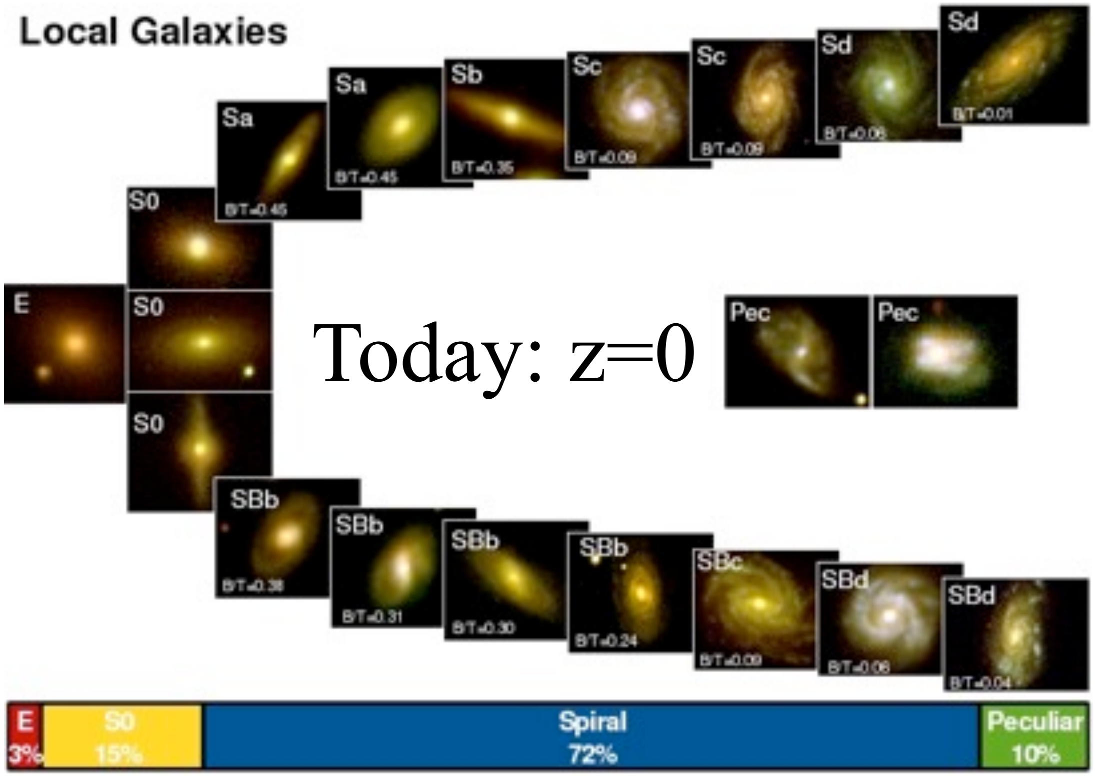
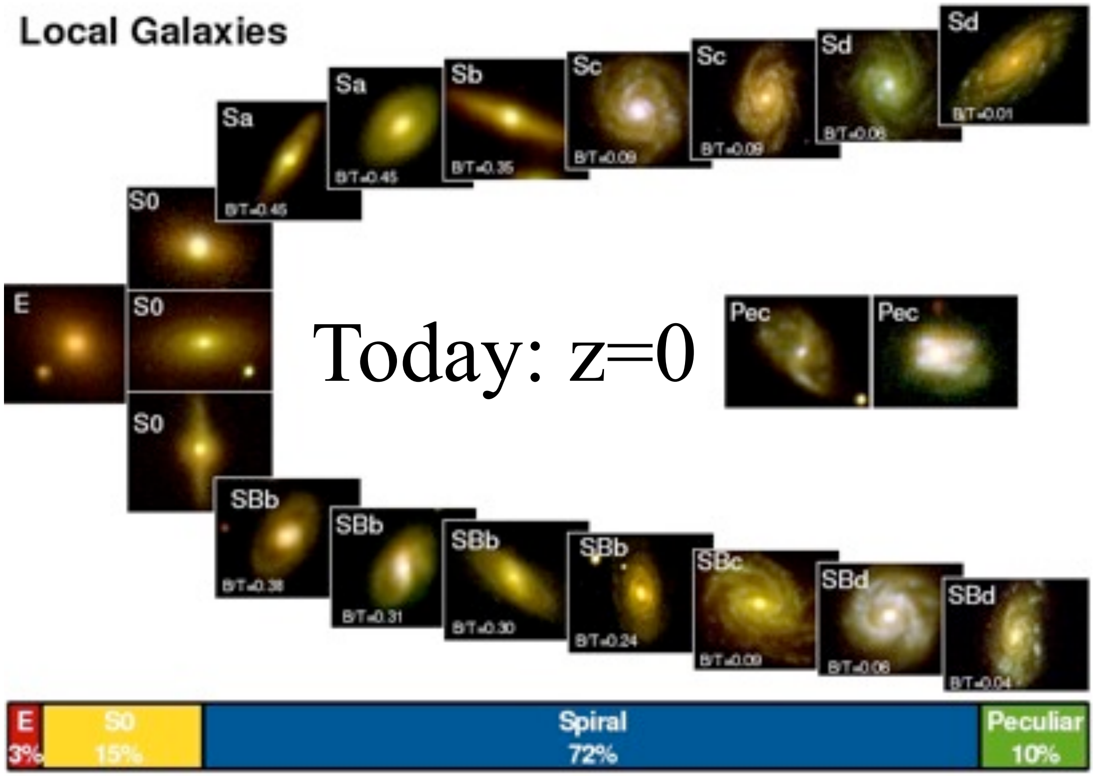
→ **Mostly spiral galaxies**



$M_{J(AB)} < -20.3$

$\sim M_{stellar} > 1.5\ 10^{10} M_{\odot}$

Delgado et al. 2010, A&A, 509, 78



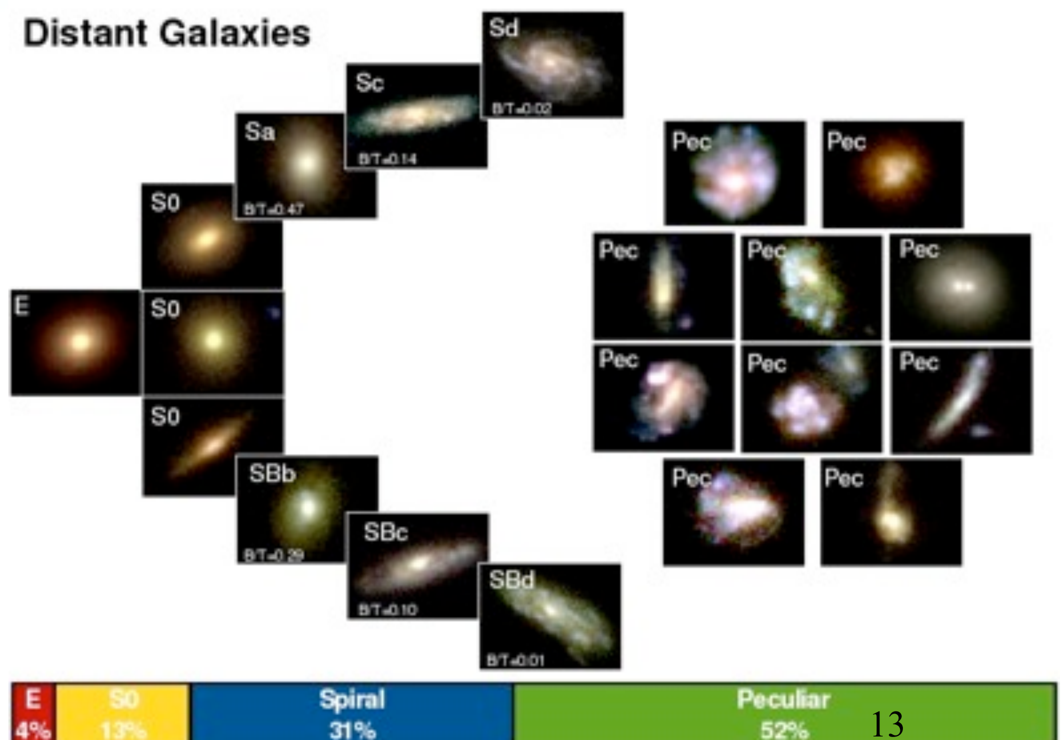
Today: z=0

$M_{J(AB)} < -20.3$

$\sim\ M_{stellar} > 1.5\ 10^{10} M_{\odot}$

Delgado et al. 2010,A&A, 509, 78

6 Gyrs ago: z=0.65



Morphological fractions in agreement

with van den Bergh (2002)

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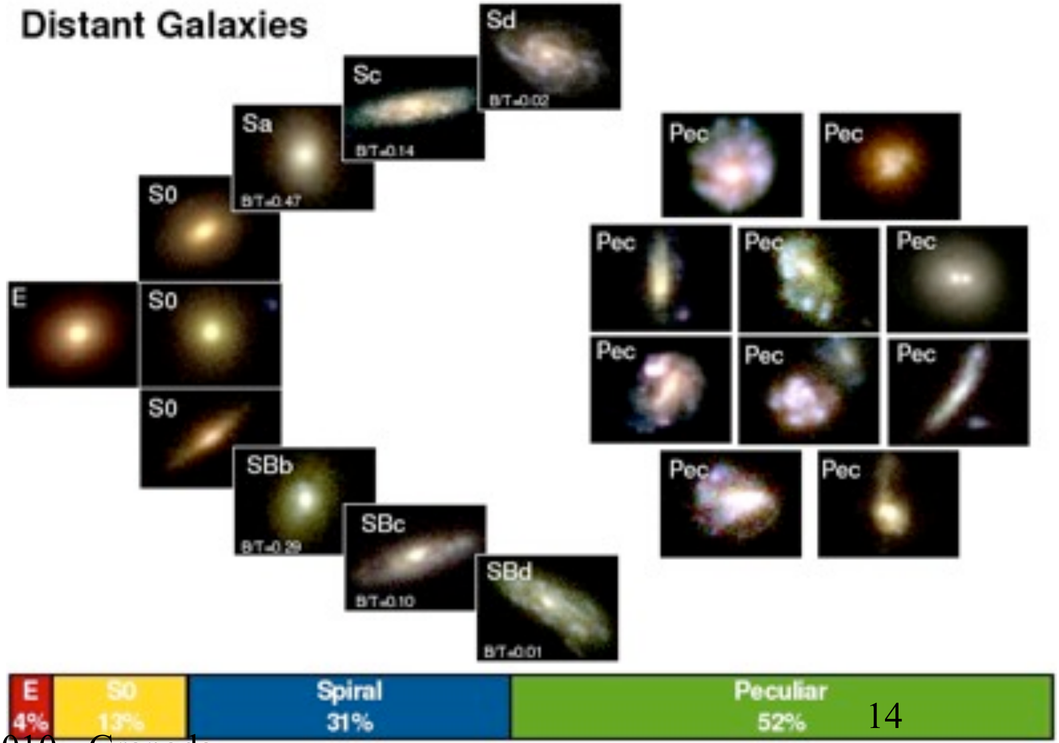
6 Gyrs ago: z=0.65

requires to spatially resolve kinematics of z~0.65 intermediate-mass galaxies



Methodology of the IMAGES Survey

The deepest & most complete observations of distant galaxies

Sample selection
$M_{J(AB)} < -20.3$ & $0.4 < z < 0.9$
4 fields including CDFS

→ **Intermediate-mass galaxies**
$M_{stellar} > 1.5\ 10^{10} M_{\odot}$
(average ~M*, e.g. MW)

↓

Integrated properties

Spitzer
VLT/FORS2 (600RI+600z)

→ SFR
Metallicity of the gas (O/H)

Imaging
ACS imagery

→ Color-morphology
S.E.D.

3D Spectroscopy
VLT/FLAMES-GIRAFFE

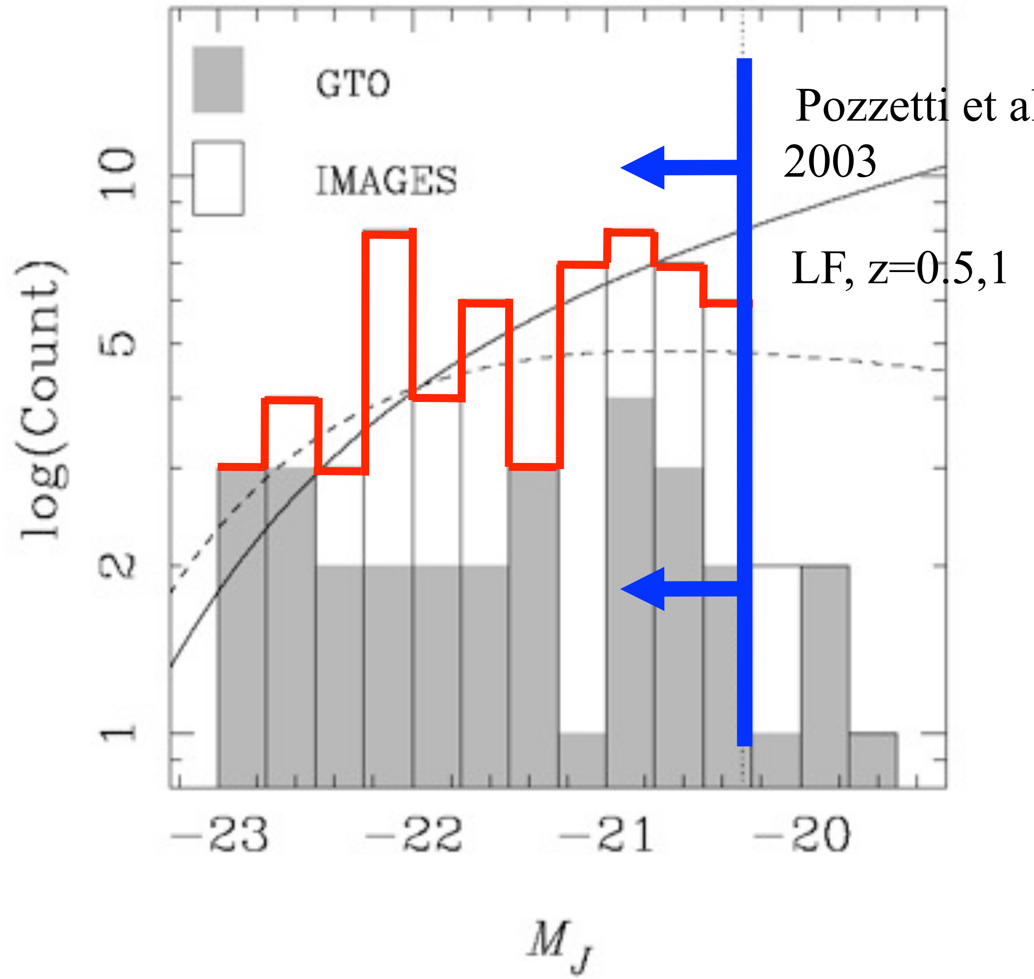
→ Kinematics (R=9000, 8-24hrs exposure)
Dynamics

100 Intermediate mass galaxies :

- $M_{J(AB)} < -20.3$
- $0.4 < z < 0.9$

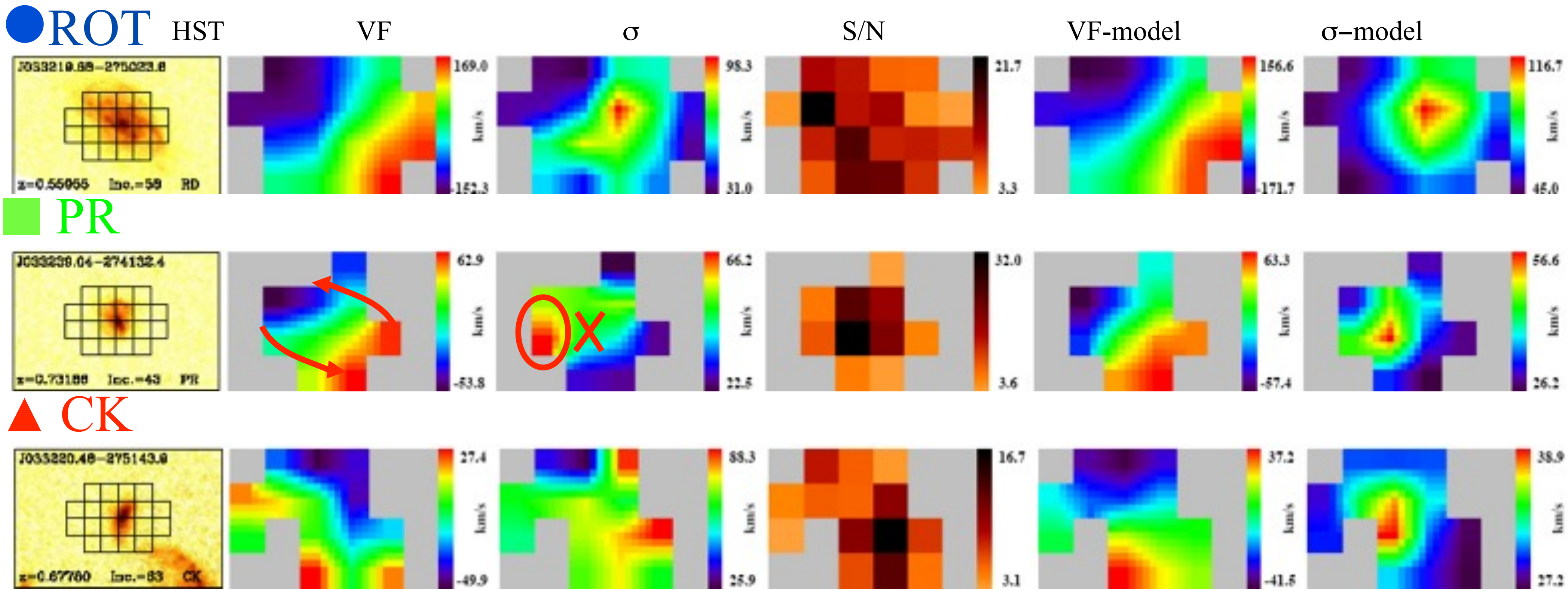
In this talk:

Representative sample of 63 Milky Way mass galaxies selected in 4 different fields of view, with $0.4 < z < 0.75$



From Yang et al (2008), A&A 474, 807

Spatially resolved kinematics of distant galaxies



Flores et al (2006)
Puech et al (2006a)
Yang et al (2008)

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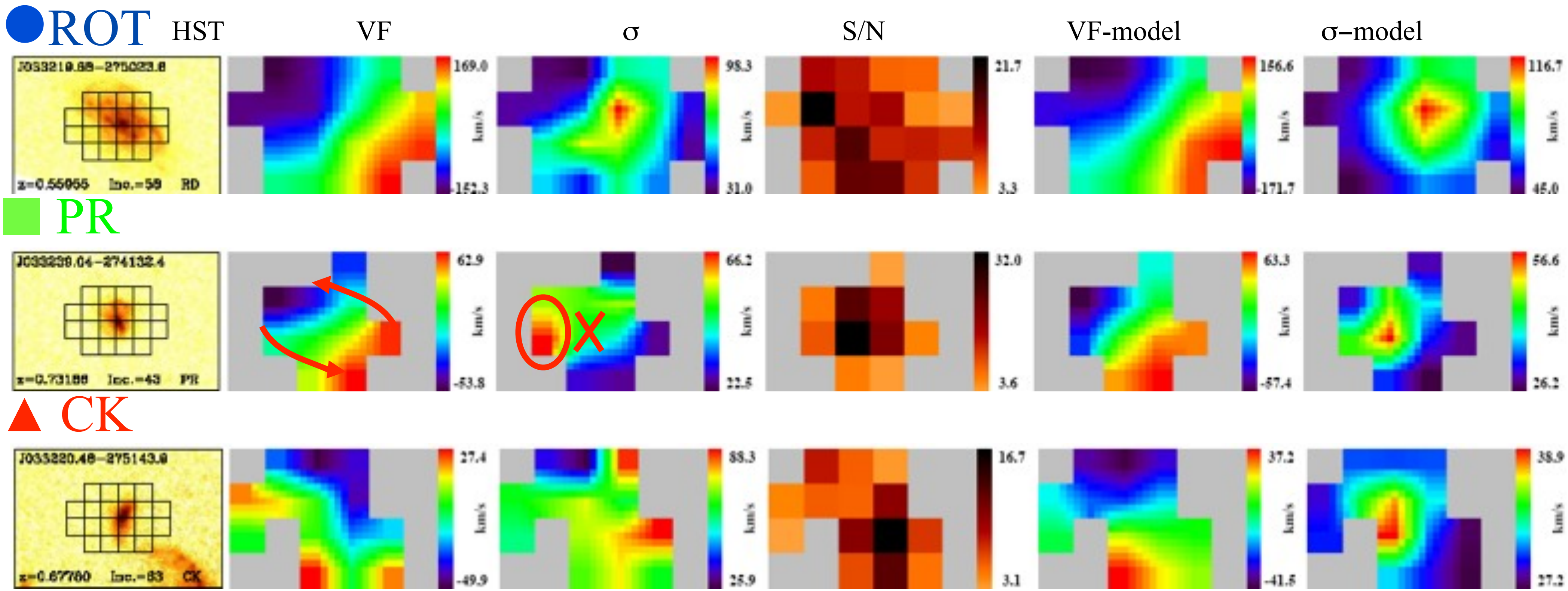

Flores et al (2006)
Puech et al (2006a)
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<u>Fraction of z~0.65 intermediate-mass galaxies</u>:

Normal rotation, ROT : 19%

Anomalous kinematics: 41% (incl. PR: 15%, CK: 26%)

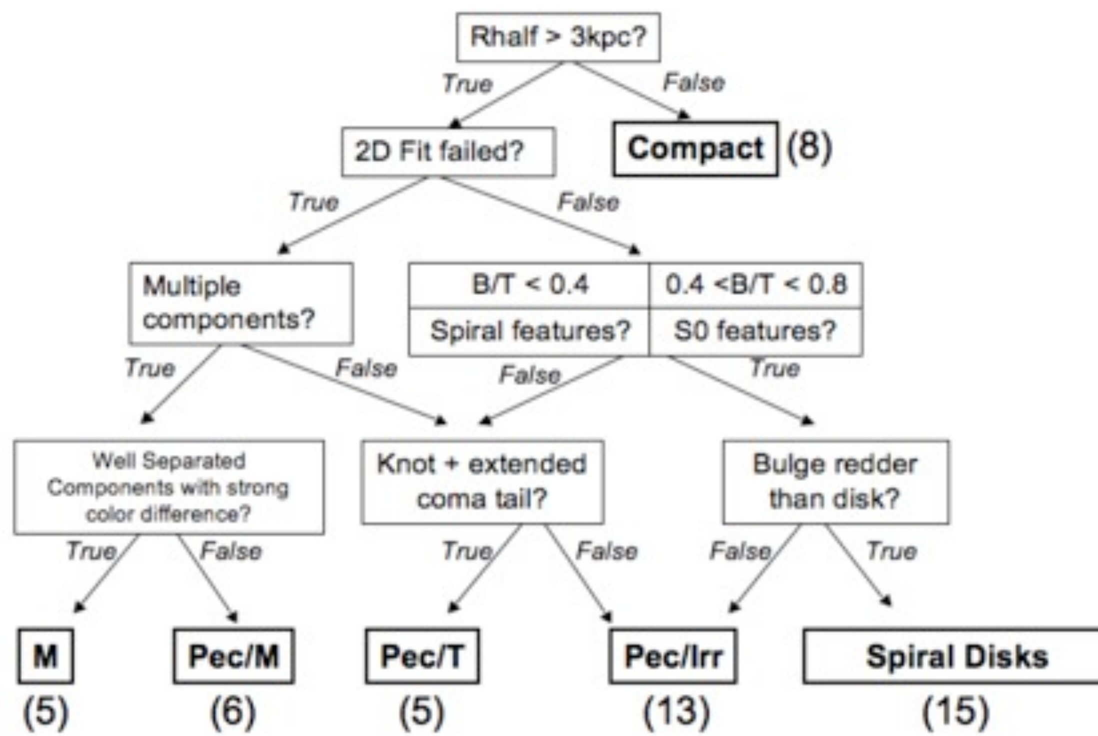
Without emission lines (E/S0/Sa..): 40%

Morphology

Neichel et al. 2008, A&A, 484, 159; see also Zheng et al. 2005, 2006

<u>Classification based on similarities with local galaxies</u>

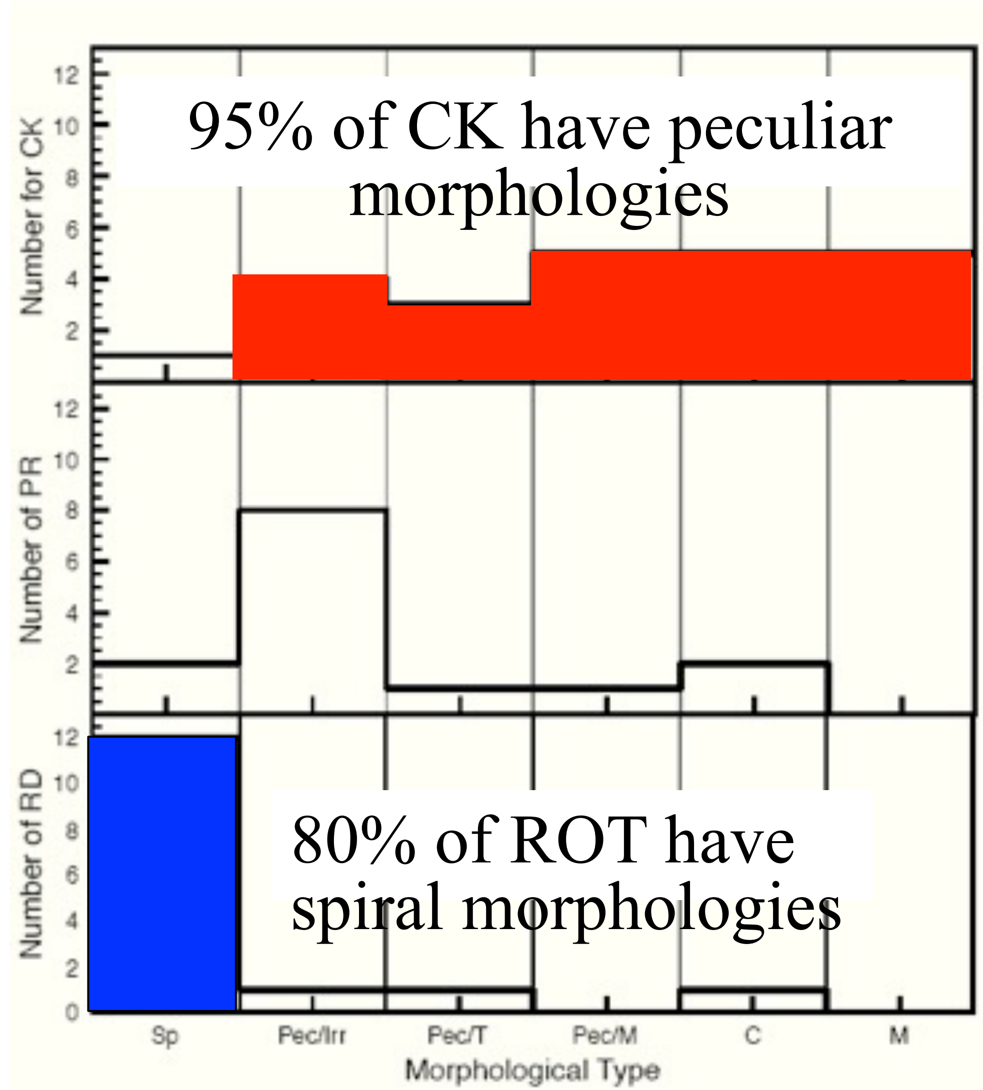
Semi-automatic decision tree: GALFIT + Colour maps + Visual inspection



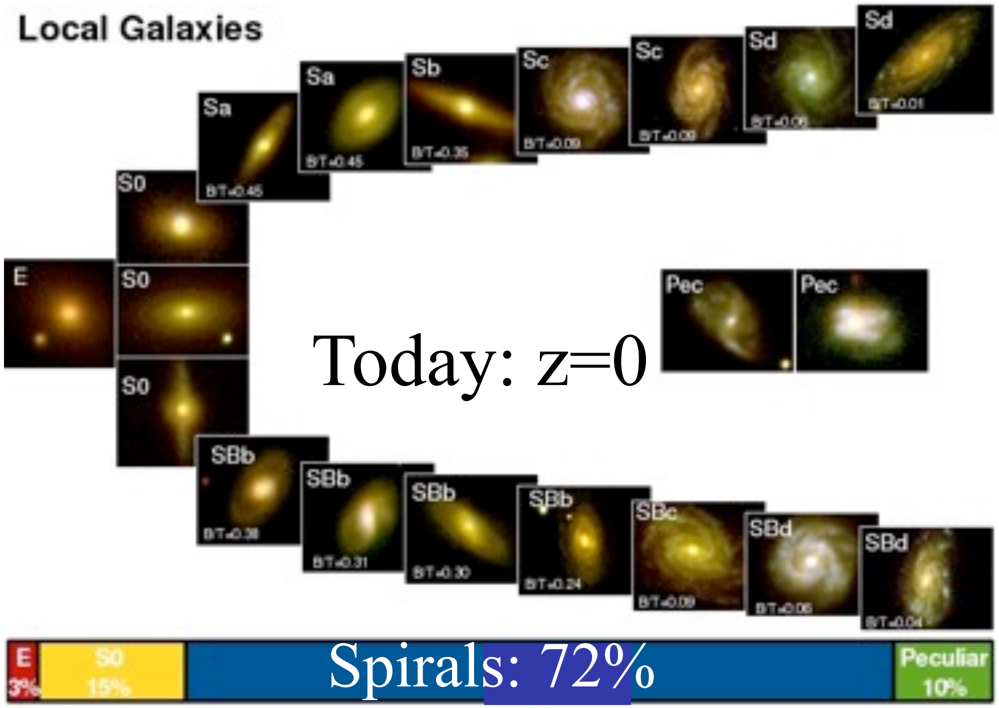
Morphology versus kinematics

Neichel et al (2008, A&A 484, 159)

Agreement between kinematics and morphological classifications



Anomalous kinematics of the gaseous component is almost always linked to anomalous morphological distribution of the stars



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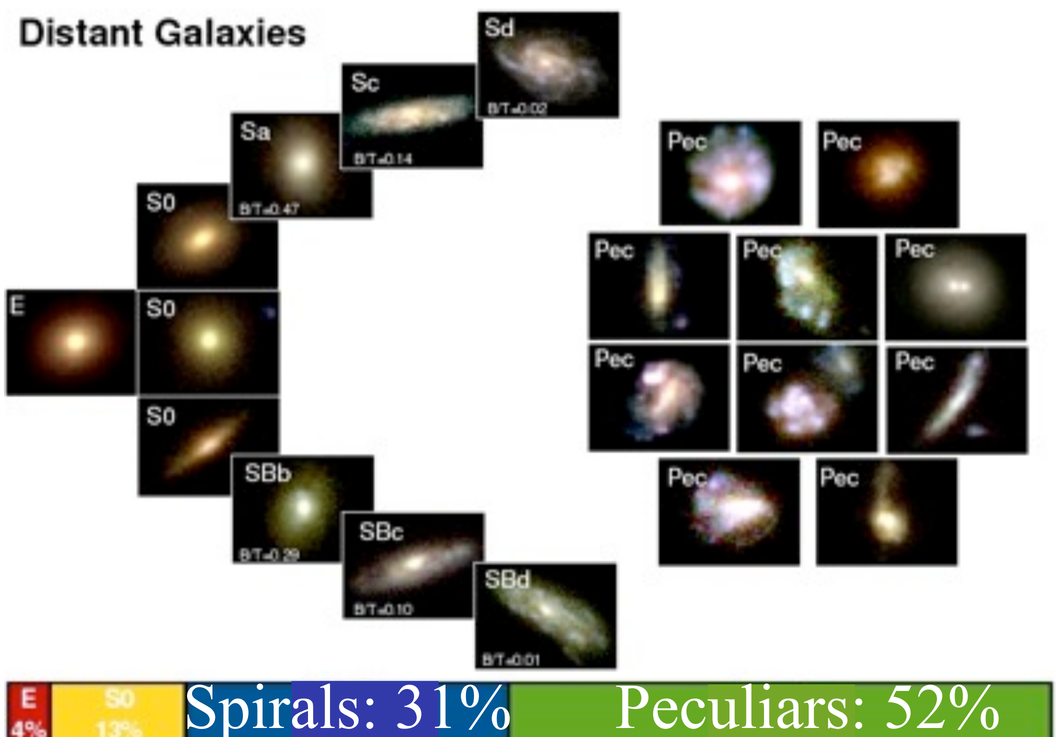
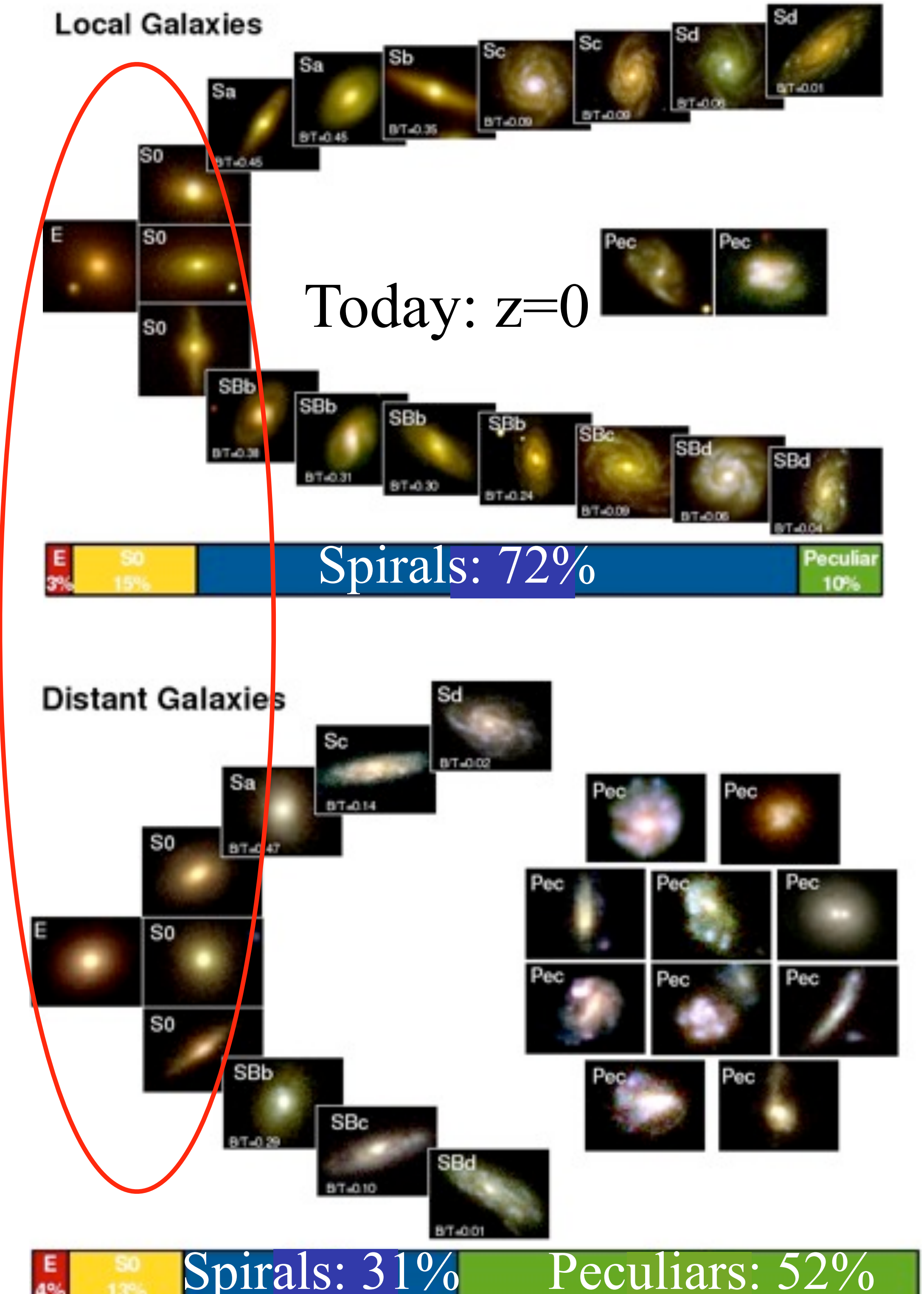
6 Gyrs ago, z=0.65:





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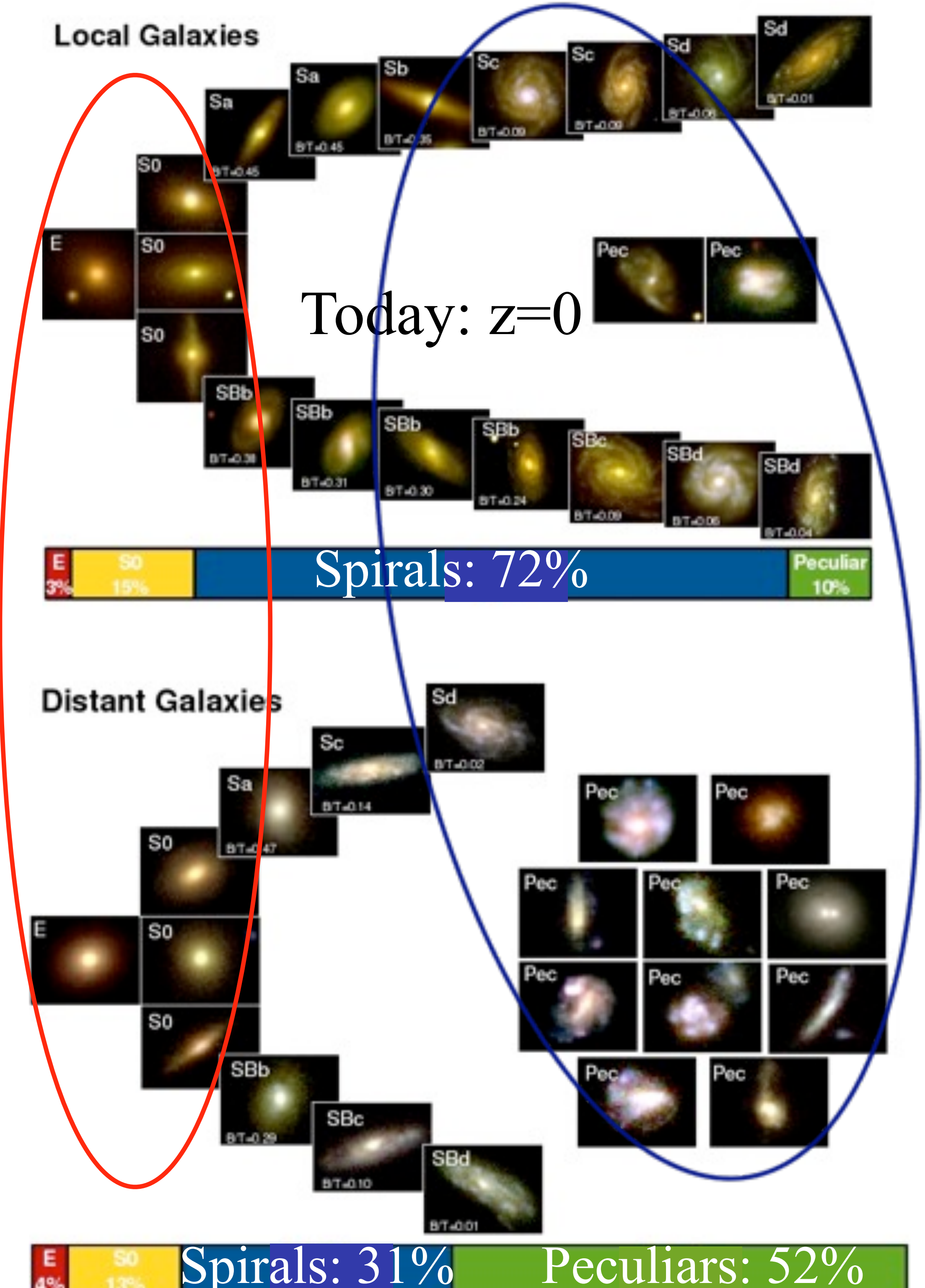
6 Gyrs ago, z=0.65:

- E/S0 were mostly in place



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Delgado et al. 2010,A&A, 509, 78

6 Gyrs ago, z=0.65:

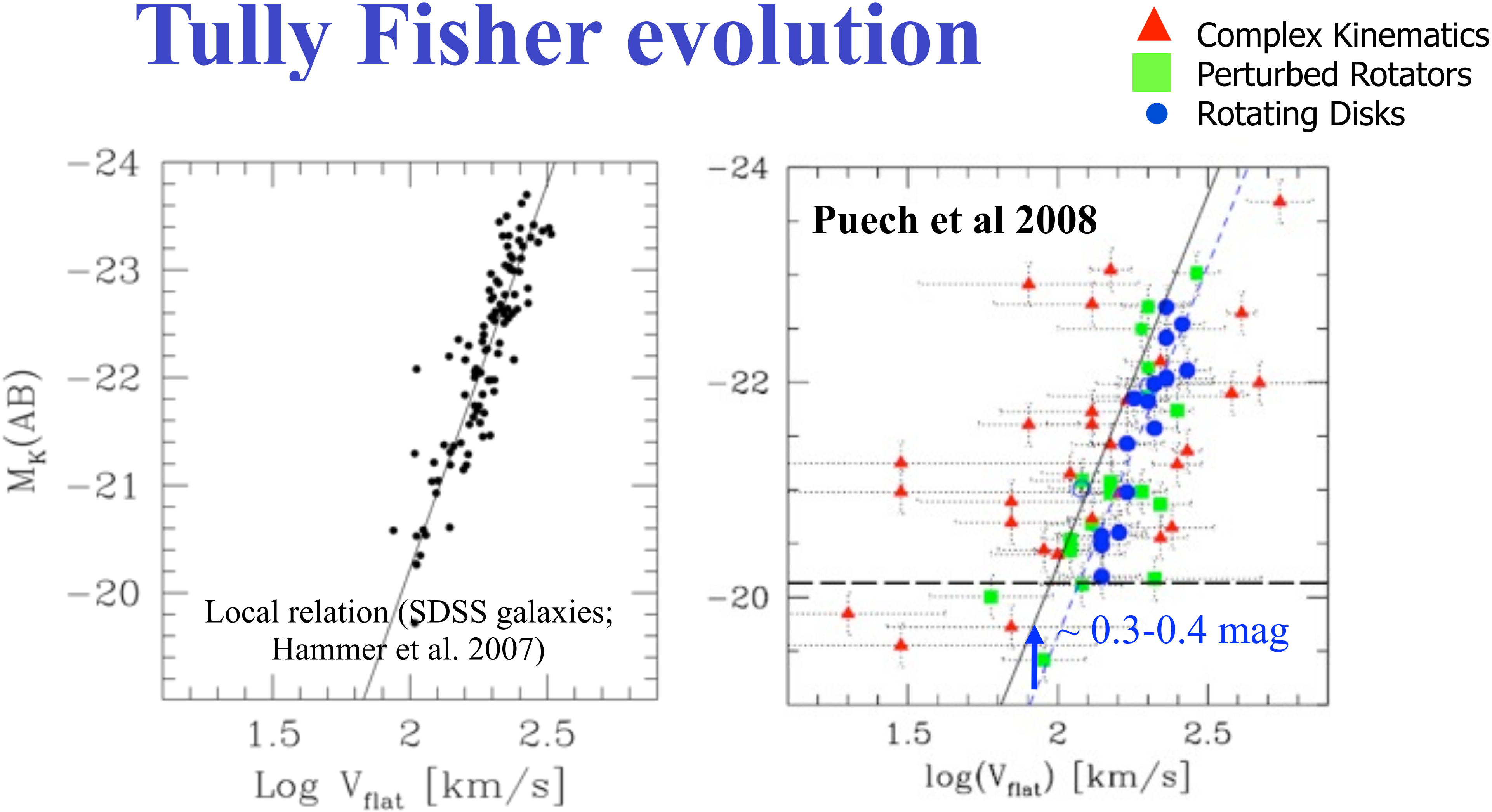
- E/S0 were mostly in place

- half of spirals did not

➔ they had peculiar morphologies

and anomalous kinematics

Tully Fisher evolution



- Large scatter at z ~ 0.65 is only due to the non-relaxed/anomalous galaxies;
- Covington+09: simulations of major mergers ➔ shocks in the gaseous phase

➔ energy transfered from bulk to random motions

Spiral galaxies and their progenitors, 4-8 Gyrs ago

- Doubling their stellar masses
- Half of local spirals **had anomalous kinematics & peculiar morphologies**

➔ *responsible of the large scatter in the M-V (TF)*

⬇

All explained by galaxy collisions and/or their remnants?

Expectations from theory

Excerpt from Lia Athanassoula, in Granada, 2009

Disc + Disc = Elliptical

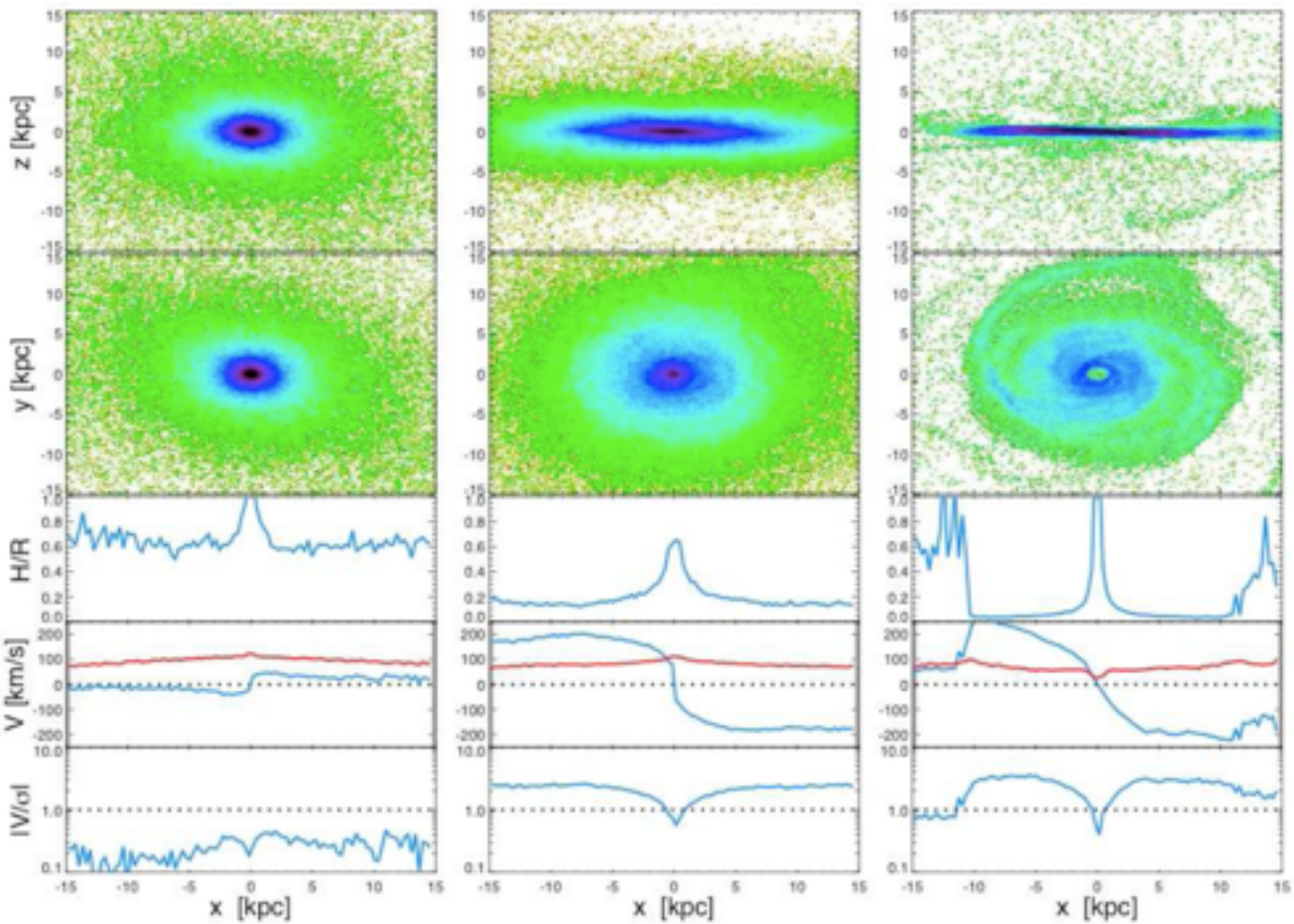
Toomre & Toomre 72; Barnes & Hernquist 92; Barnes 98; Naab & Burkhart 03; Naab, Khochfar, Bukhart 06 etc

but also

Disc + Disc = Disc

Observational starting point: Hammer et al 05, 09

Simulations: Dominguez-Tenreira et al. 98; Barnes 02; Scannapieco, Tissera 03; Brook et al 04, 07; Springel & Hernquist 05; Robertson et al 06,08, Hopkins et 08; Governato et al 07, 08; Stewart et al 09



1:2 merger, 20% of gas

Hopkins et al. (2009)

High gas fractions ➔ production of disk dominated galaxies

if sufficient gas before fusion ➔ thin disk reform (*Abadi et al. 2003)*

Gas content at z ~0.65

Puech et al, 2010, A&A 510, 68

Inversion of Kennicutt law:

(SFR from IR & UV; gas radii from ionised emissions)

- Median f_{gas} = **31±1%**
- 2.5 times median f_{gas} at z=0

A project:

the elaboration of the Hubble sequence

Analyses of distant galaxies

Kinematics

Large scale motions
(GIRAFFE 3kpc @ z=0.65)

+

Morphology

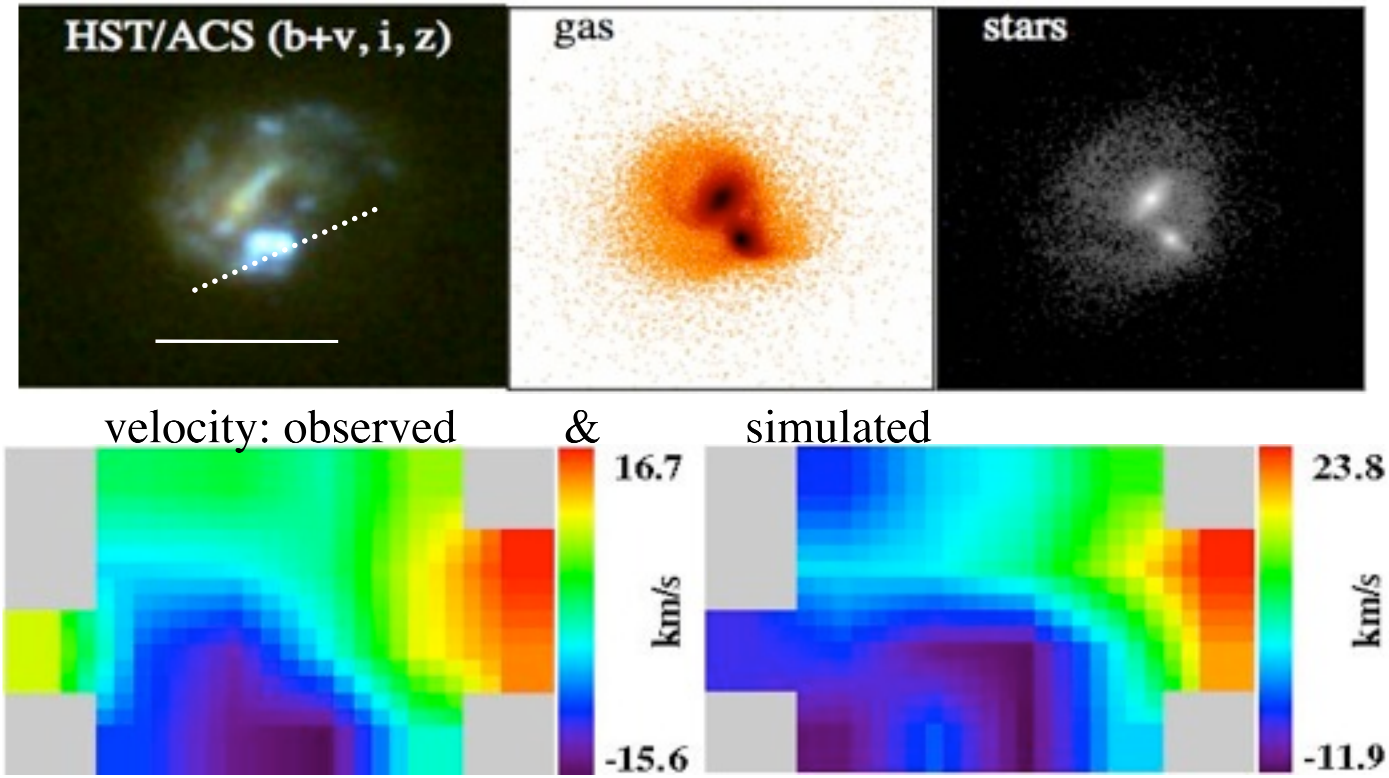
Multi band imagery
(HST/ACS 200pc @ z=0.65)

Numerical models

(GADGET2 & ZENO)

A giant, starburst, bar induced by a 3:1 merger

Peirani et al, 2009, A&A 496, 51



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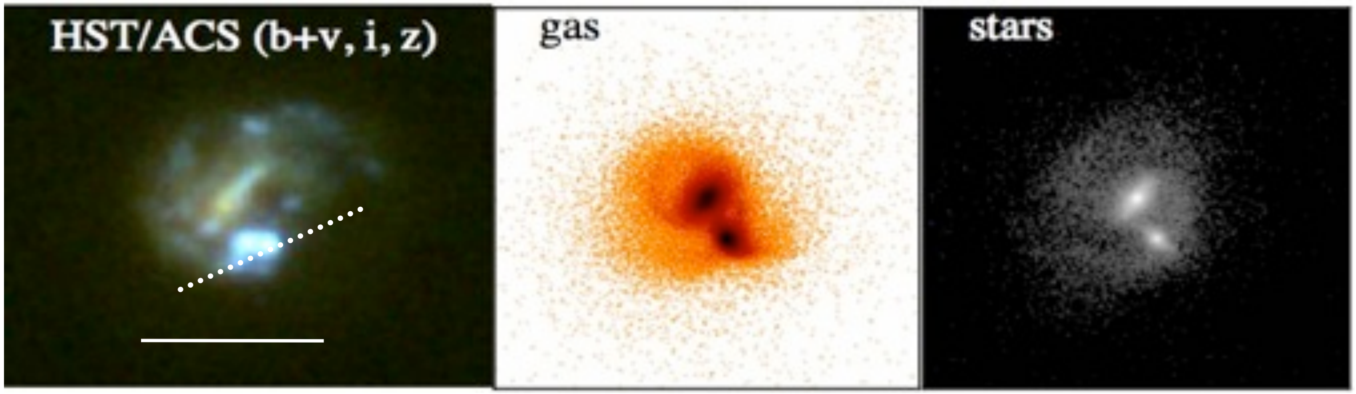
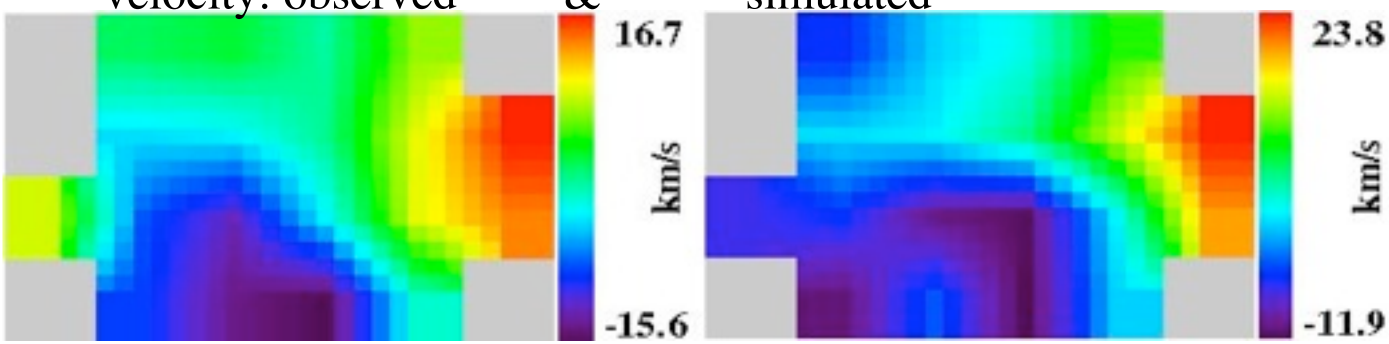
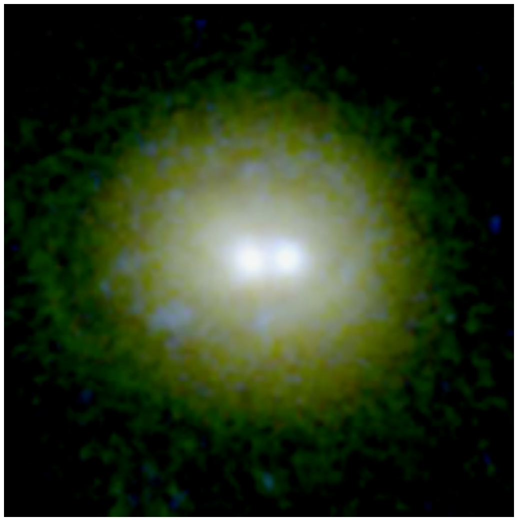


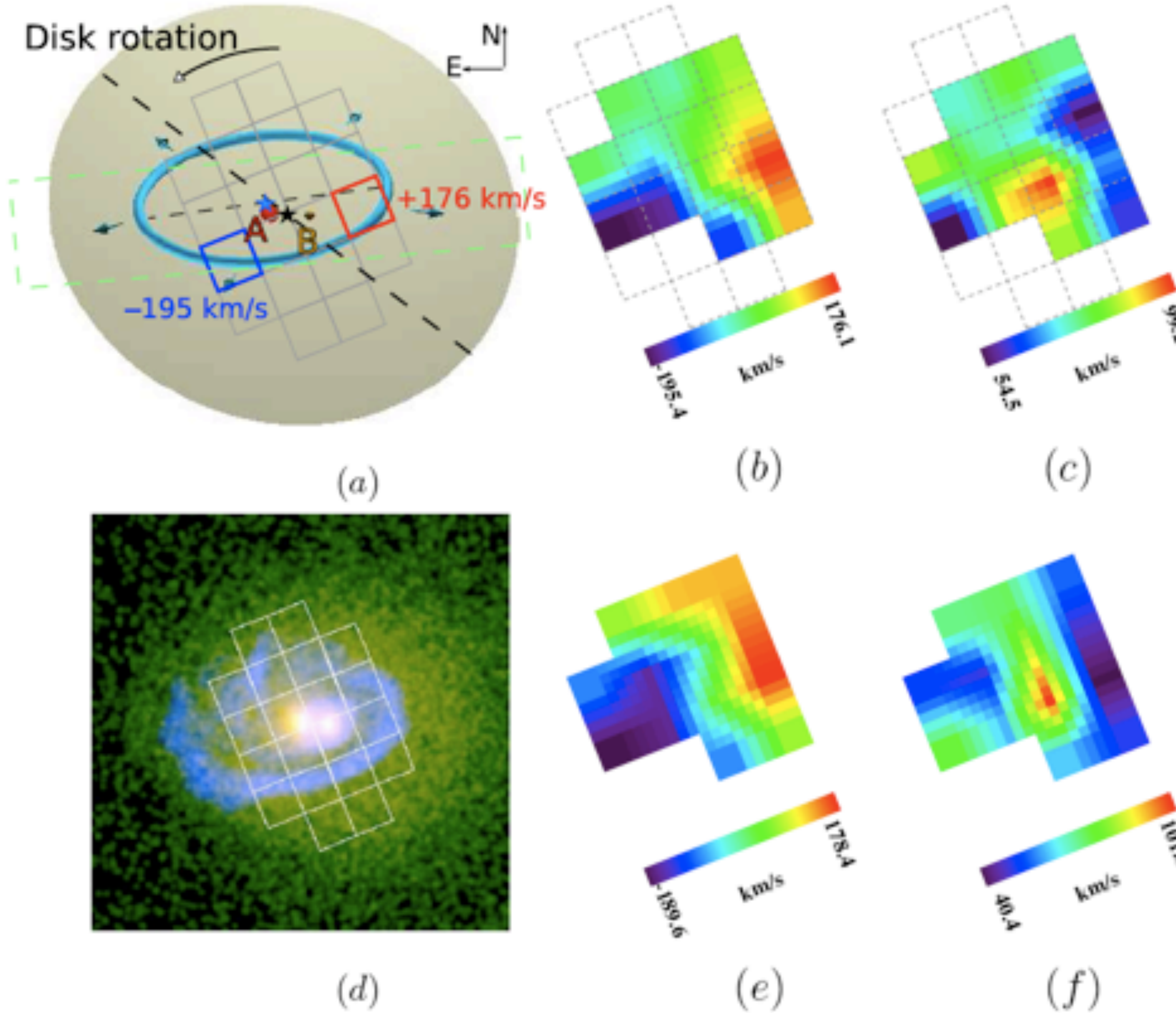
velocity: observed & simulated



50% of anomalous galaxies show two components or are in pairs & could be reproduced by major mergers, before the fusion

Yang et al, 2008b, A&A 501 437)





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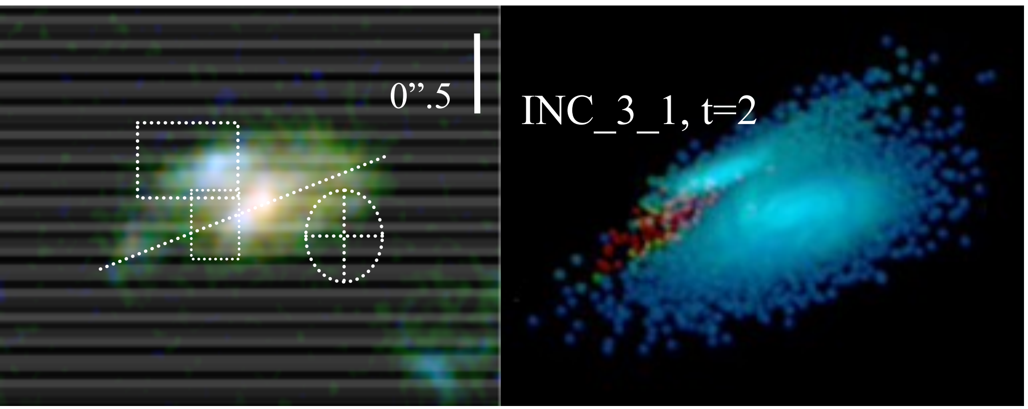
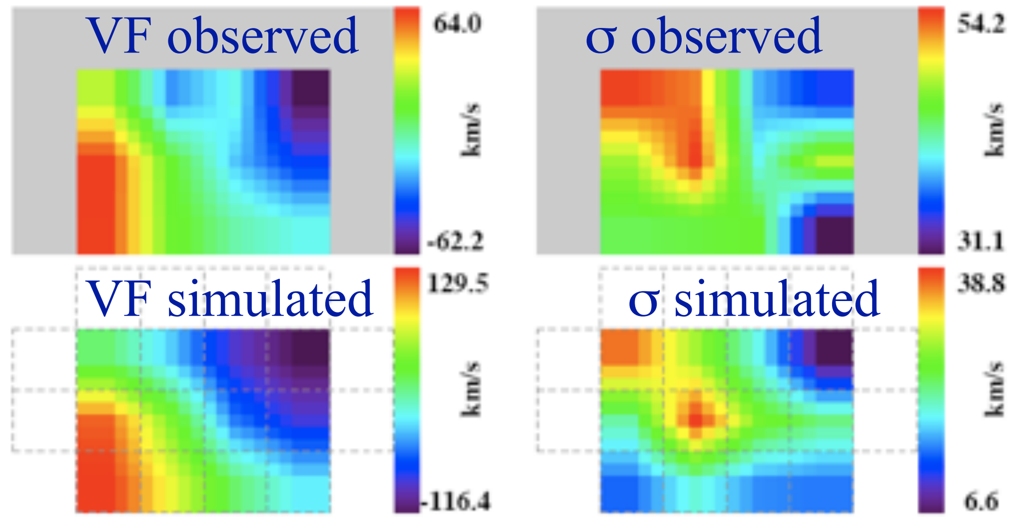
Hammer et al. 2009, A&A, 507, 1313

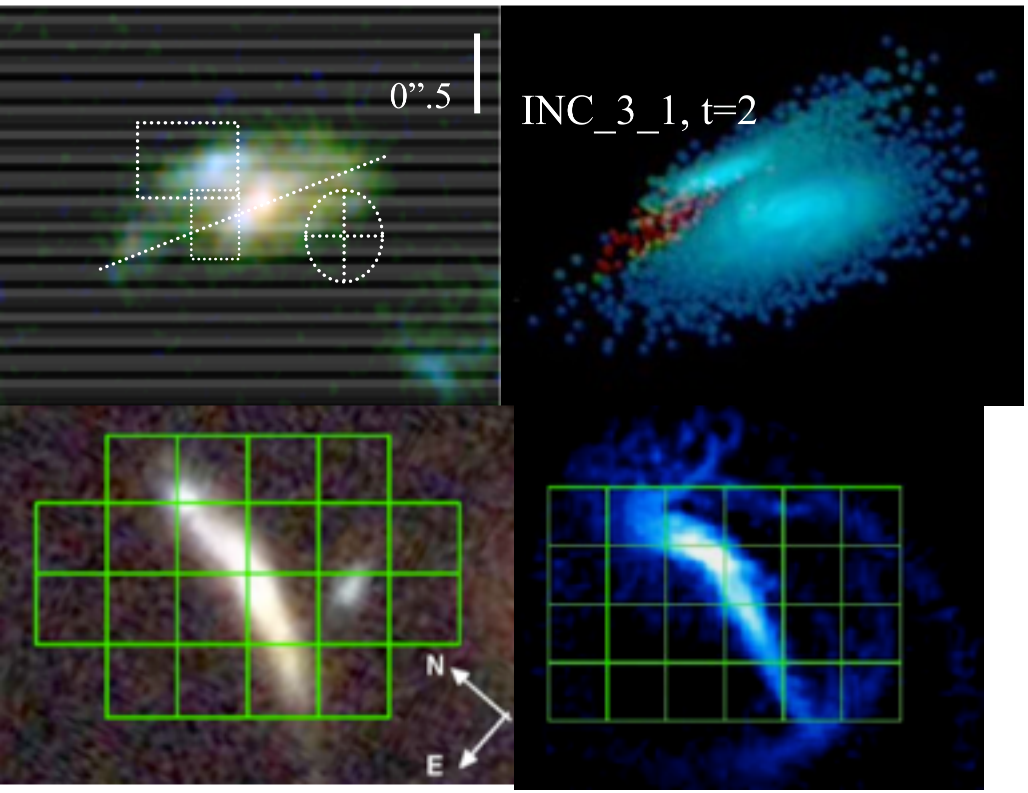


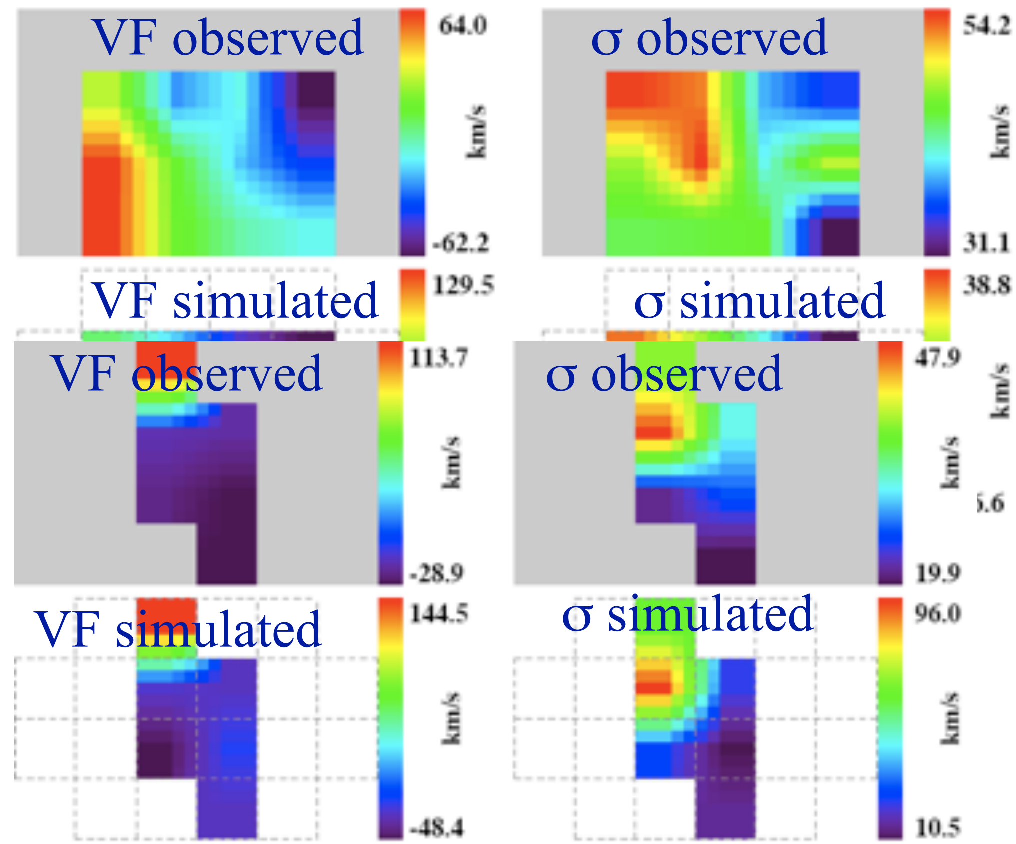


➔ **Are other anomalous galaxies merger remnants?**

50% of anomalous galaxies show two components or are in pairs & could be reproduced by major mergers, before the fusion

Hammer et al. 2009, A&A, 507, 1313



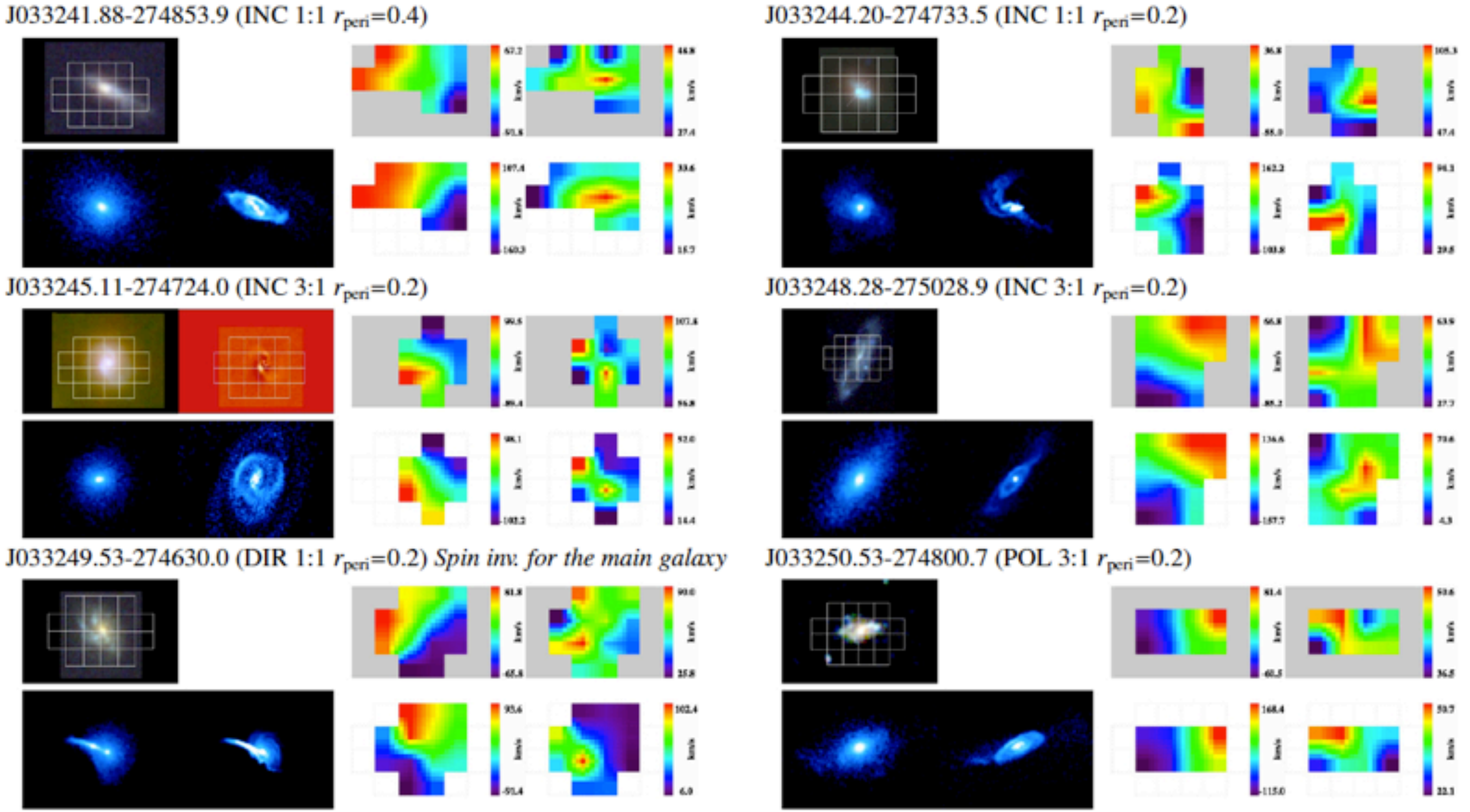


see also Fuentes-Carrera et al. 2010, A&A, 513, 43

➔ **Are other anomalous galaxies merger remnants?**

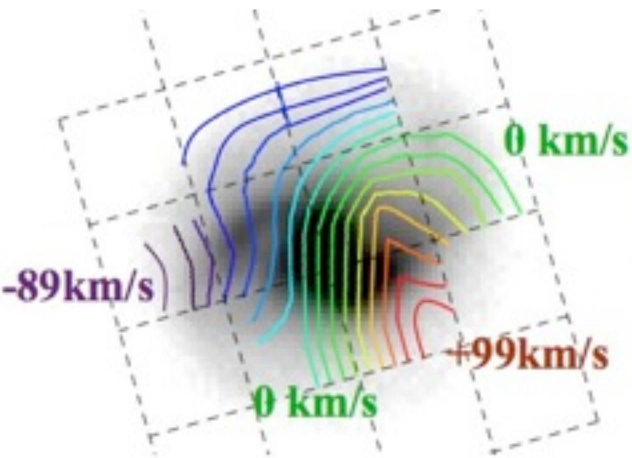
Most other anomalous galaxies could be reproduced by major mergers, after fusion

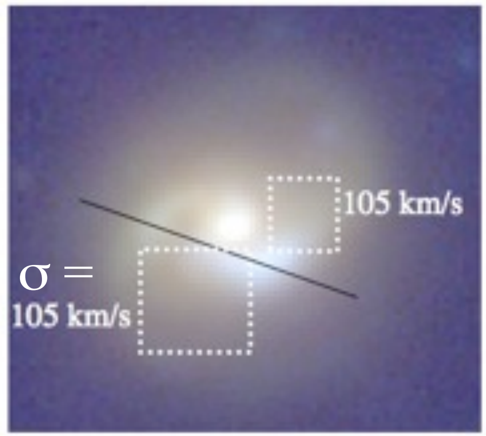
Excerpt of Fig. 2 from Hammer et al. 2009, A&A, 507, 1313

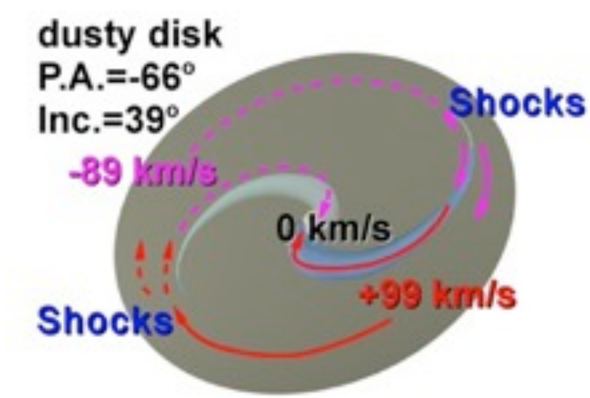


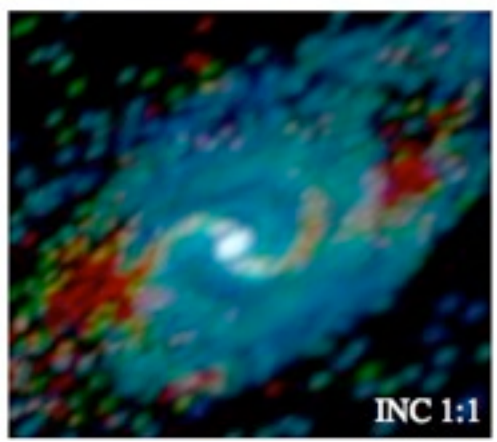
A disk rebuilt 500 Myrs after a gas rich merger at z~0.4?

Hammer et al. 2009, A&A 496, 381







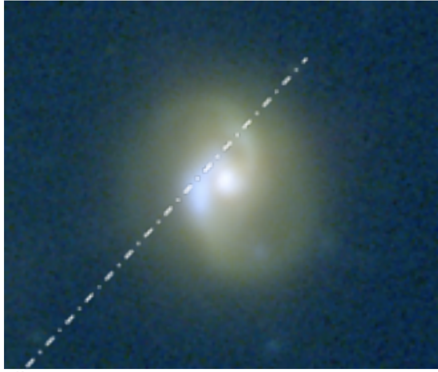


Using Barnes, 2002
Gas, INCLINED, 3:1

Explain well:

- the 45° misalignement of dynamical & optical axes
- the offset σ peaks
- the dusty disk and central features

A disk rebuilt 500 Myrs after a gas rich merger at z~0.4?

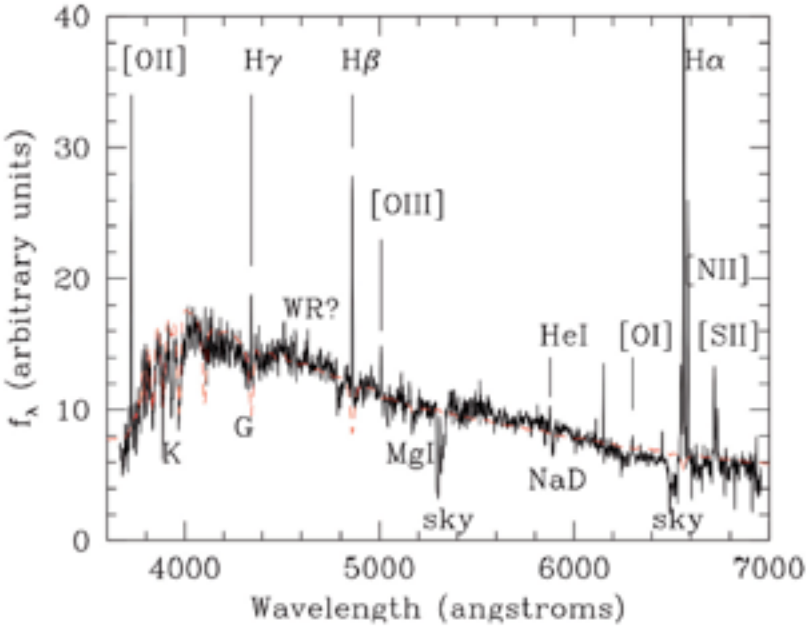


- Observed gas fraction is 37% (from Kennicutt)
- it was > 50% at the beginning of the interaction, 1 Gyr earlier

➔ The red dusty disk is being rebuilt…(e.g. Robertson+06; Lotz+09)

Strong Balmer continuum

& absorptions



Spiral morphology & angular momentum are driven by the last major merger (1:1 mass ratio) ➔ *Sc*

How large disks form their angular momentum?

<u>Tidal Torque Theory</u>

Acquisition from early galaxy interactions:

• too small disks & angular momentum catastrophe

(Steinmetz & Navarro 99)

• reproduce well the Milky Way?

➔ *But is MW representative?*

• how to explain kinematics & morphologies of spirals progenitors, 6 Gyrs ago?

• not necessarily consistent with observed merger rates

How large disks form their angular momentum?

Tidal Torque Theory

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➔ *But is MW representative?*

• how to explain kinematics & morphologies of spirals progenitors, 6 Gyrs ago?

• not necessarily consistent with observed merger rates

Disk rebuilding scenario *(Hammer+05)*

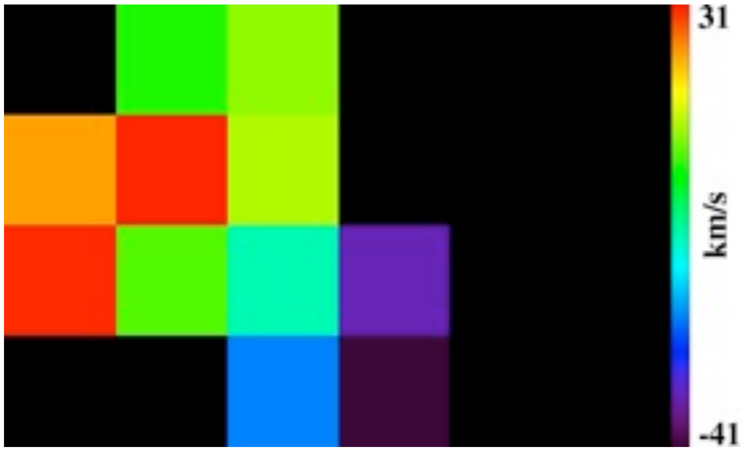
Inherited from the orbital momentum of major mergers: *(Robertson+06, Hopkins+08)*

• requires large gas fraction in the progenitors: we find 30% in remnants
➔ *for "M31-mass" galaxies:*
$f_{gas} \sim 50\%$ *for* $M_{stell} \sim 2.5\ 10^{10}\ M_{\odot}$

• kinematics & morphologies of anomalous distant galaxies reproduced *(Hammer+09; Yang+09; Peirani+09, Puech +09,Fuentes-Carrera+10)*

• presence of large disks at higher redshift?

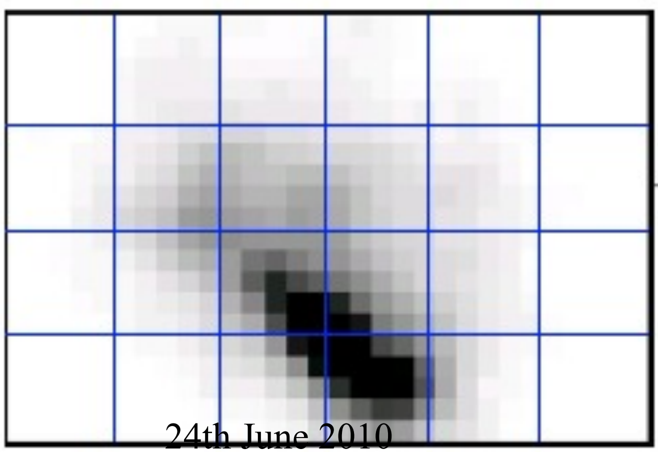
FLAMES/GIRAFFE on the VLT

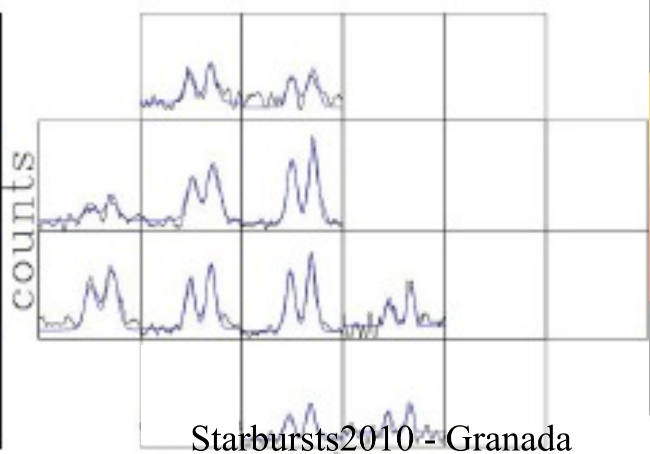


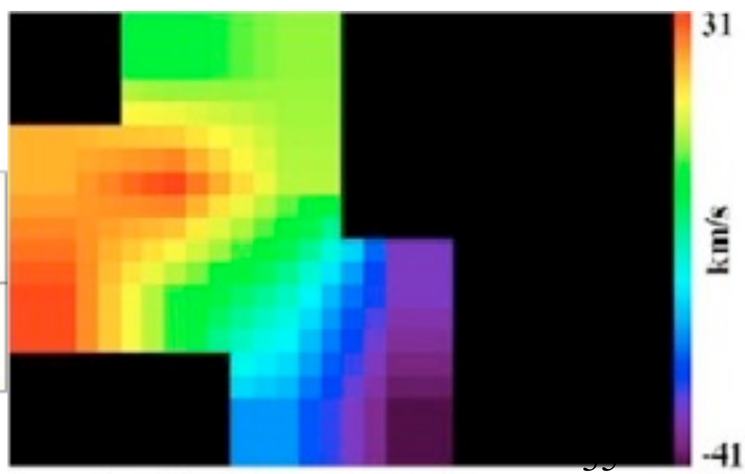
IFU Mode: 15 x 3”x2”arrays (20 sq. μlenses, 0”.52)

15 IFUs deployable over a 20 arcmin FoV with $R_{effective}$>13000 ➔ the [OII] doublet can be resolved

CFRS03.0488, z=0.46, (3”x2”)







5x5 linear interpolation