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Galaxies Étoiles Physique et Instrumentation

IMAGES

The formation of galaxies

by François Hammer

Intermediate Mass Galaxy Evolution Sequence

Challenges in Astrophysics, Sofia, 2009, October 13rd l'Observatoire de Paris | GEPI

Galaxies Étoiles Physique et Instrumentation

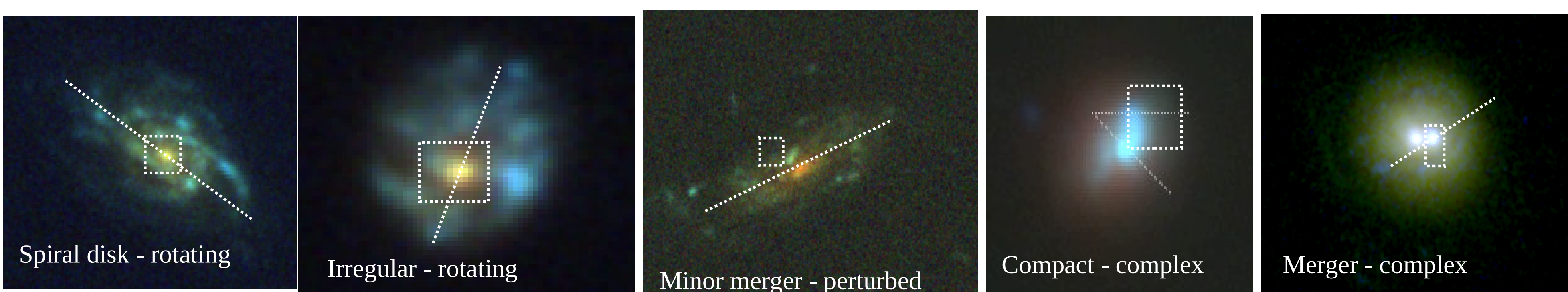
IMAGES

The formation of disks in massive spirals

by François Hammer

H. Flores, M. Puech, R. Delgado, 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



Challenges in Astrophysics, Sofia, 2009, October 13rd

Most -72%- large galaxies have spiral structures

An evidence for dark matter: stars are rotating too fast!
(e.g. Zwicky, 1933)

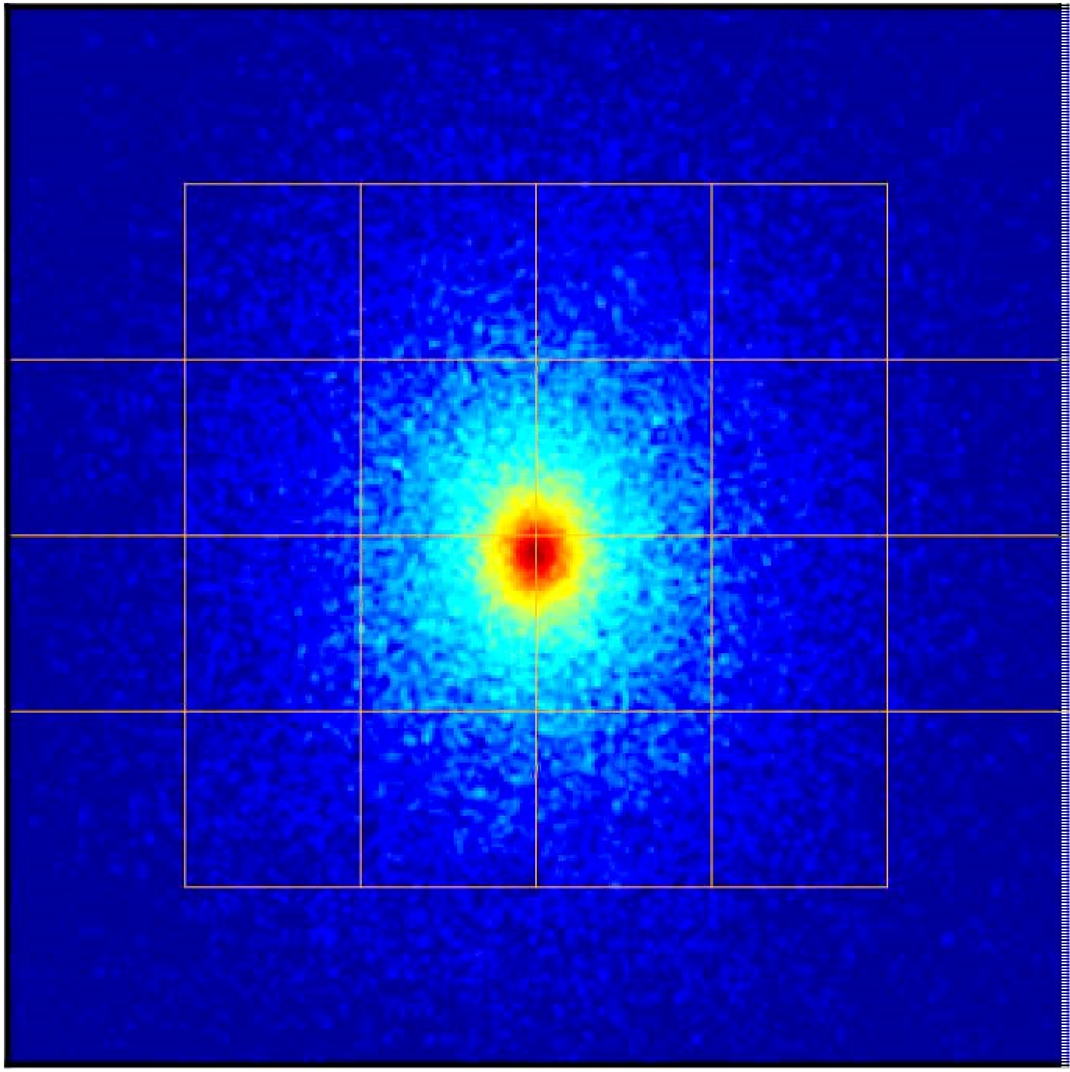
M83

NGC 1365

M100 SABbc

How to form disks: they are fragile to collisions

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

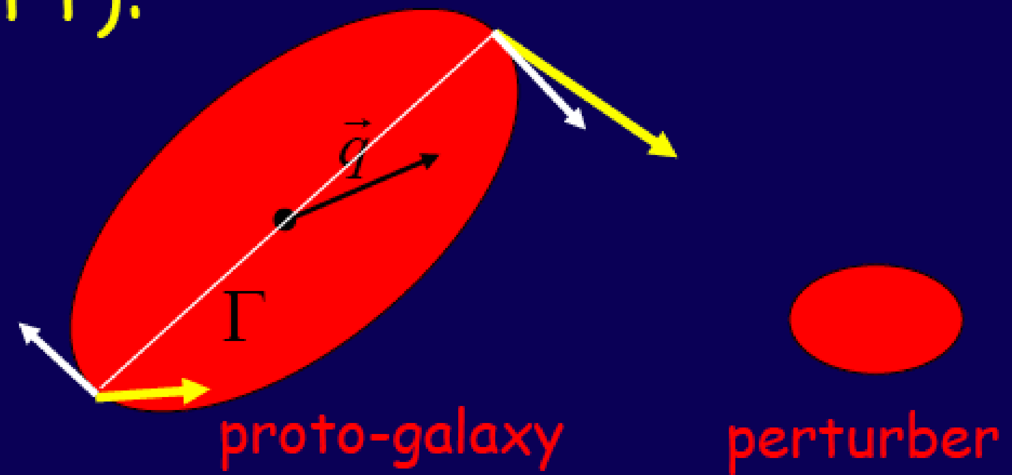


Simulation: GADGET2, Peirani, private communication

Origin of Angular Momentum

Tidal Torque Theory (TTT):

Peebles 1976   White 1984



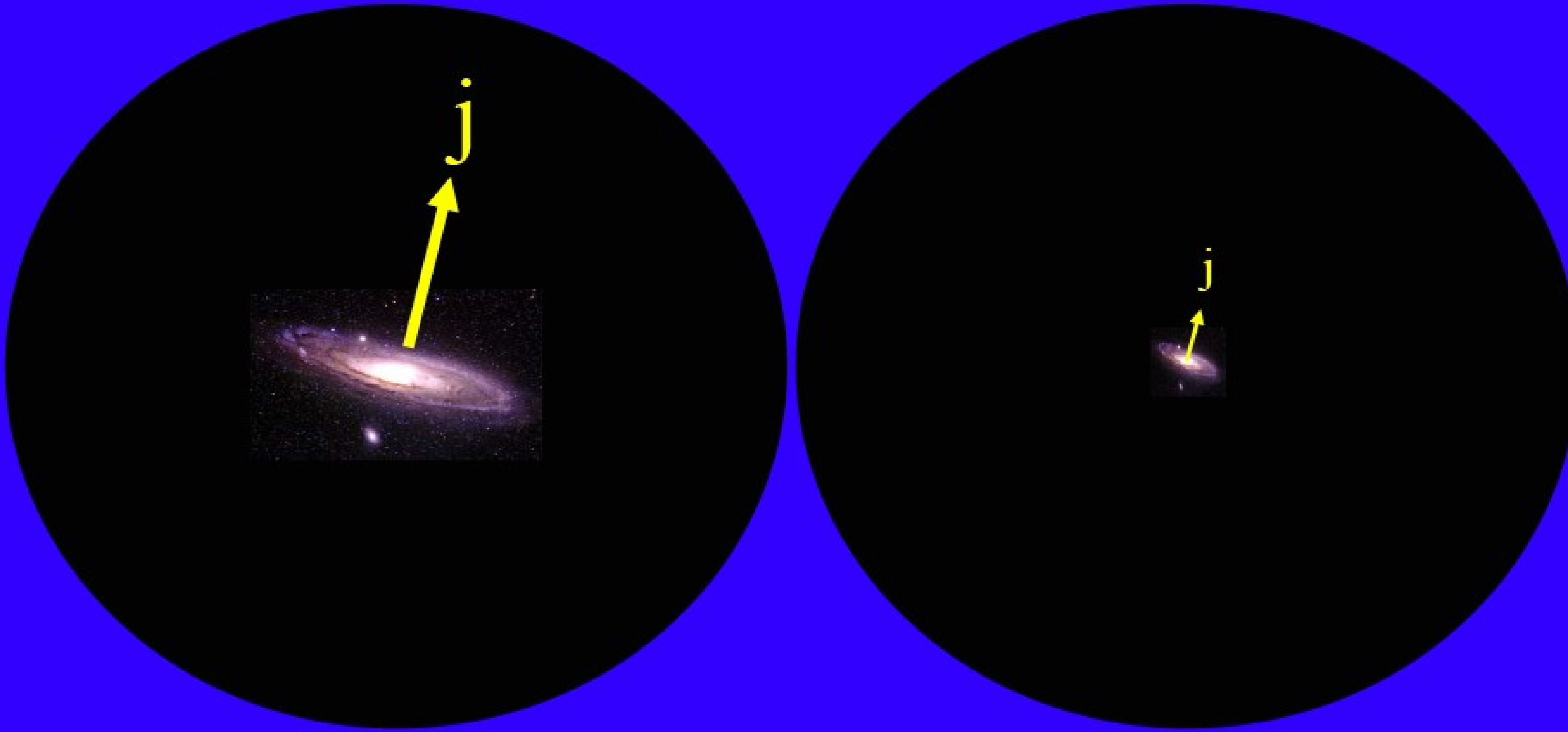
Angular momentum acquired from galaxy interactions at earliest epochs:

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

The Spin Catastrophe

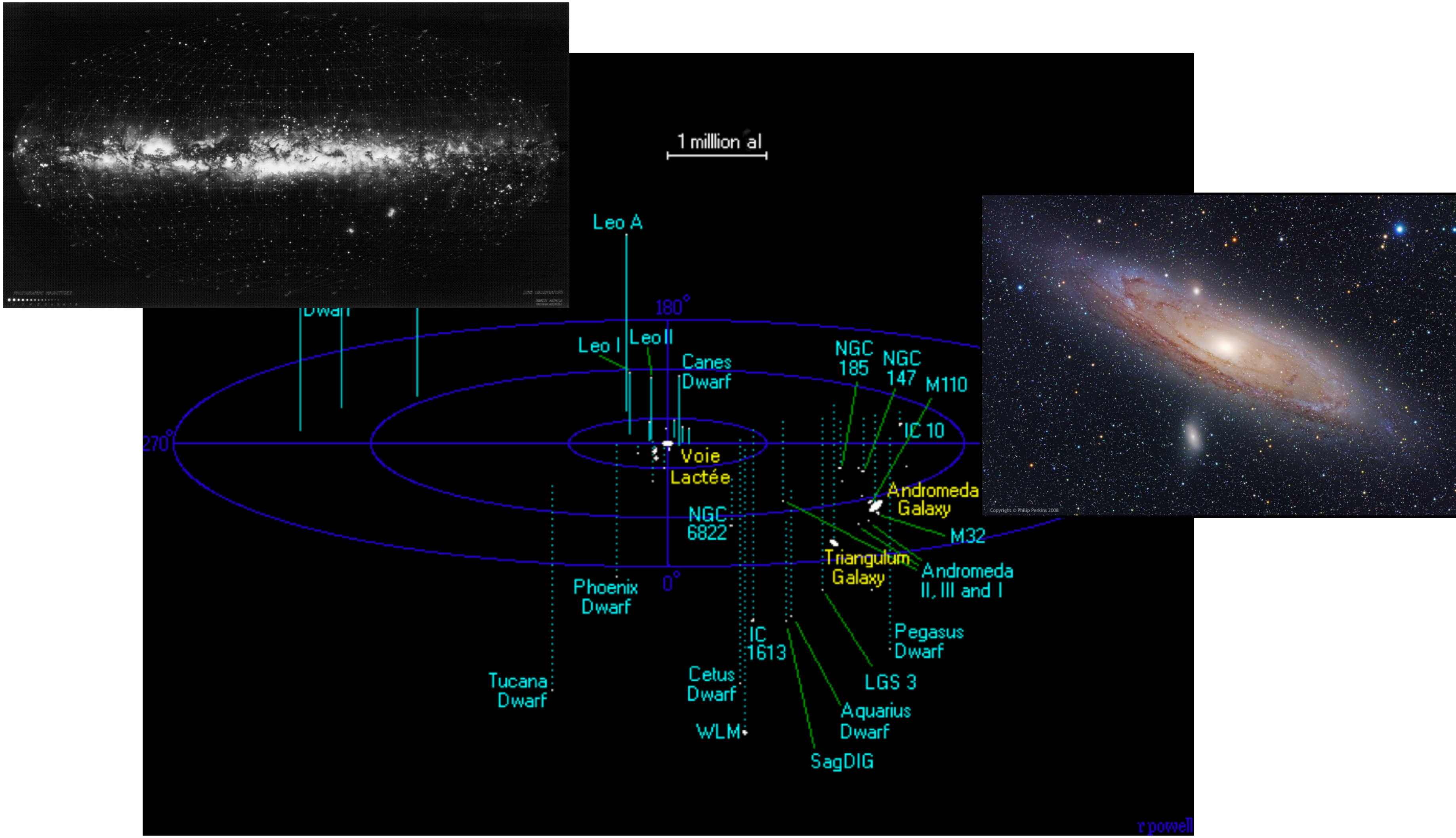
Navarro & Steinmetz et al.

observations | simulations

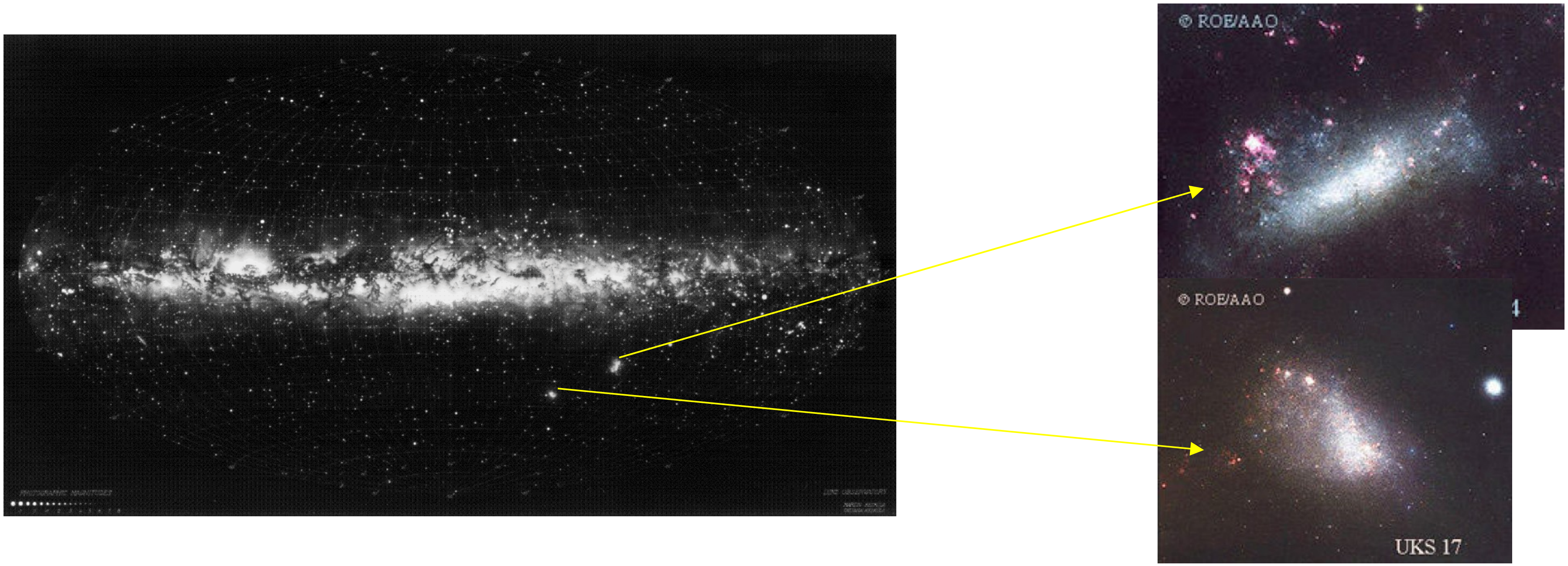


Excerpt from Dekel, Paris courses, 2006

Milky Way and M31



The Milky Way: a quiescent history



Today: absorbing a dwarf galaxy, Sagittarius

Within 500 millions years: Magellanic clouds;

Within few billions years: major collision with Andromeda (M31)

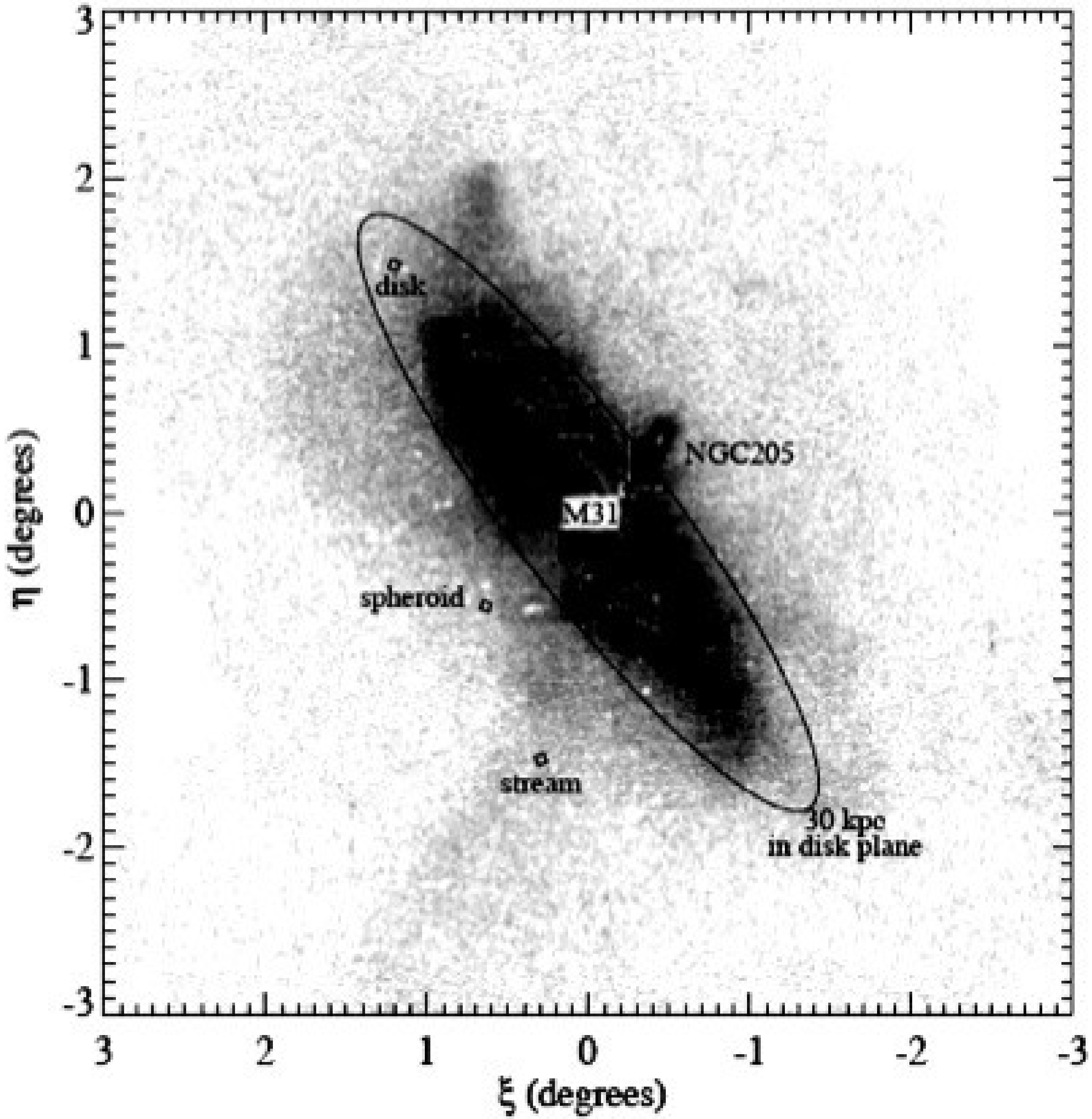
Past history of the Milky Way:

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



Low surface brigthness features:

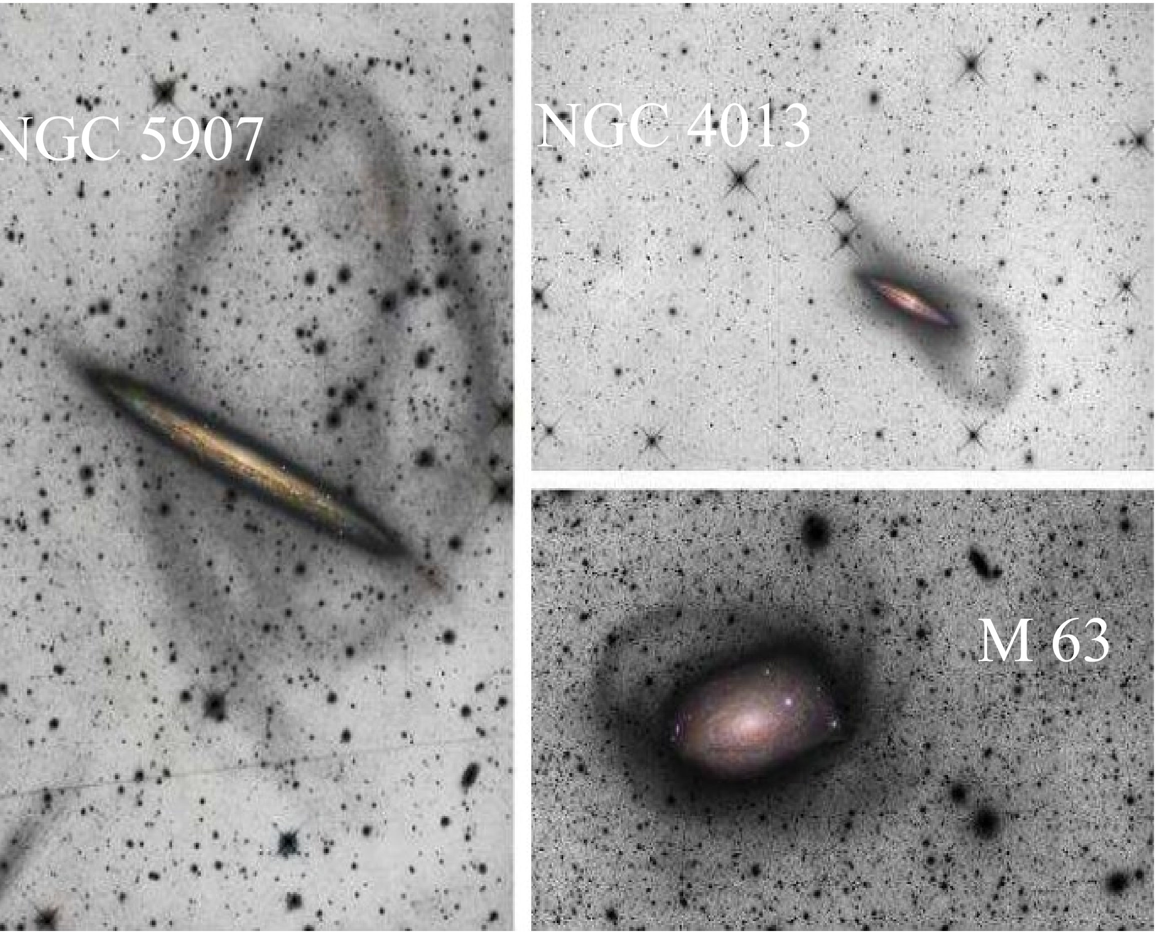
Giant stream, clumpy disk &

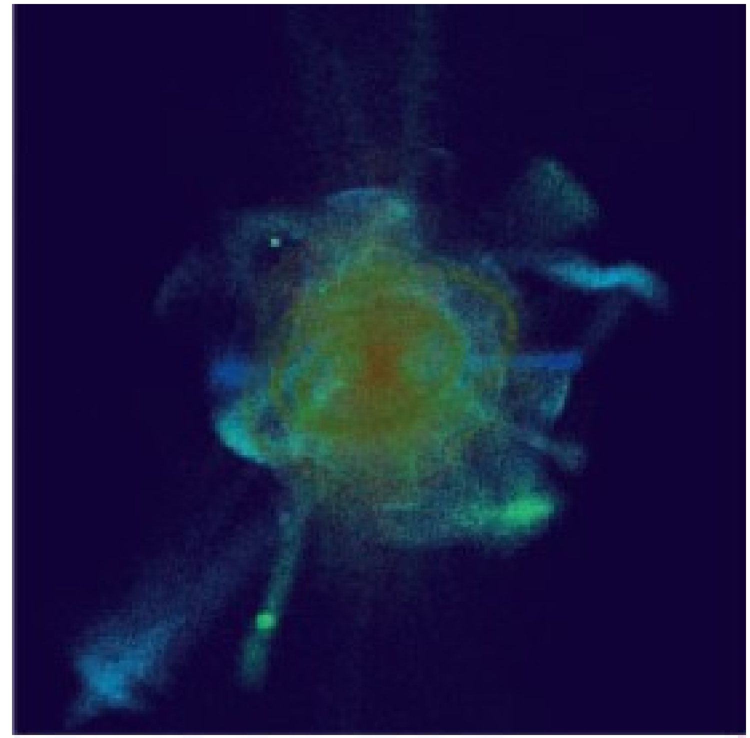
outer ring, made of evolved stars

➔ **Either several minor and/or a major merger, 7-8 Gyrs ago?**

The tumultuous history of some other spirals

(Martinez-Delgado et al. 2008, 2009)

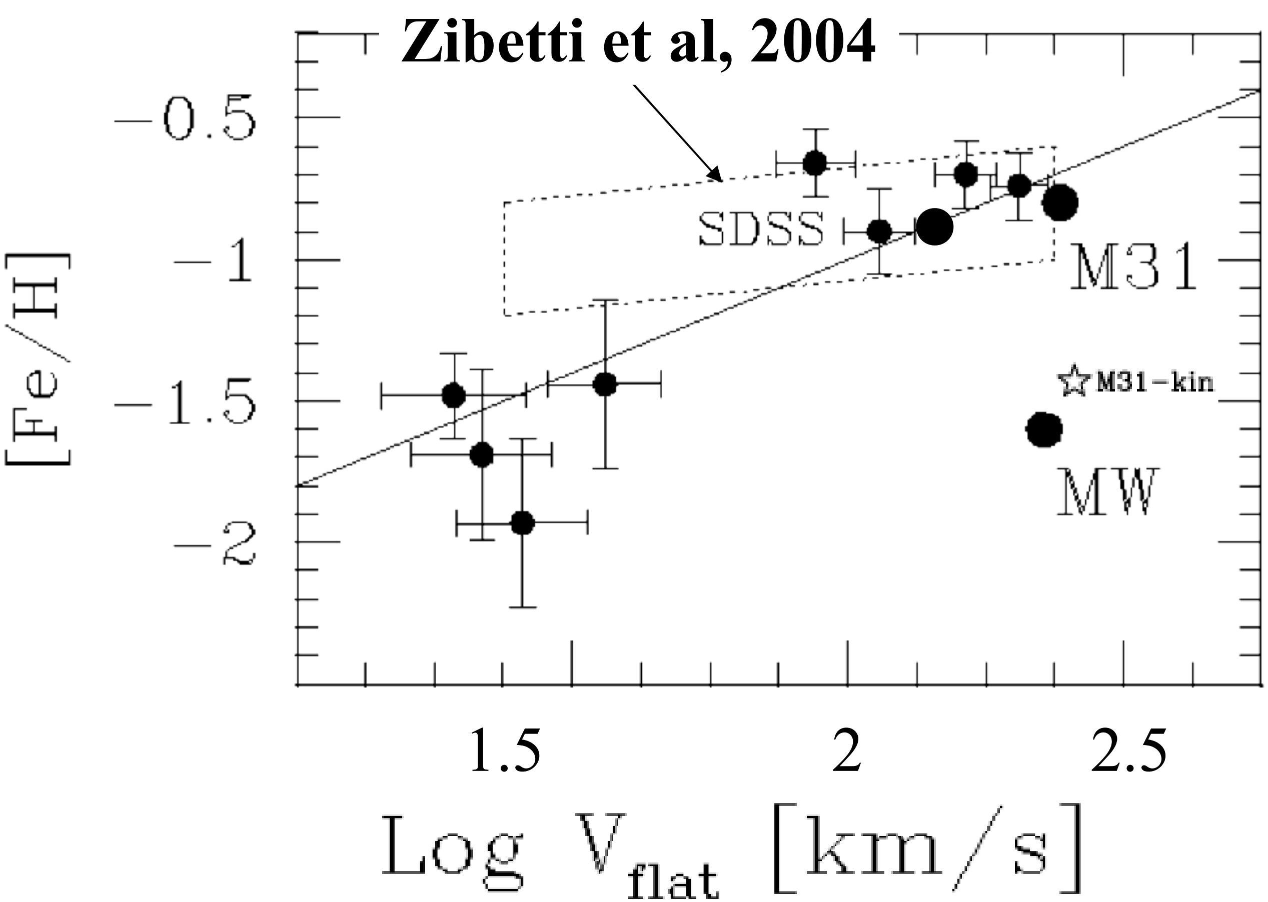




Simulations from Font et al. 2006

The Milky Way versus M31 and other spirals

Star abundances in galactic outskirts (Fe/H, inner halo 5-30 kpc): most spirals (including M31 & SDSS galaxies) have stars in outskirts far more enriched than MW's *(e.g. Mouhcine et al, 2006 & 2007)*



At 60-150 kpc, the "pristine" halo of M31 is retrieved *(Chapman et al. 2006)*:

M31 halo ⇔ MW halo + merger residuals

(see Ibata et al. 2007)

The Milky Way versus M31 and other spirals

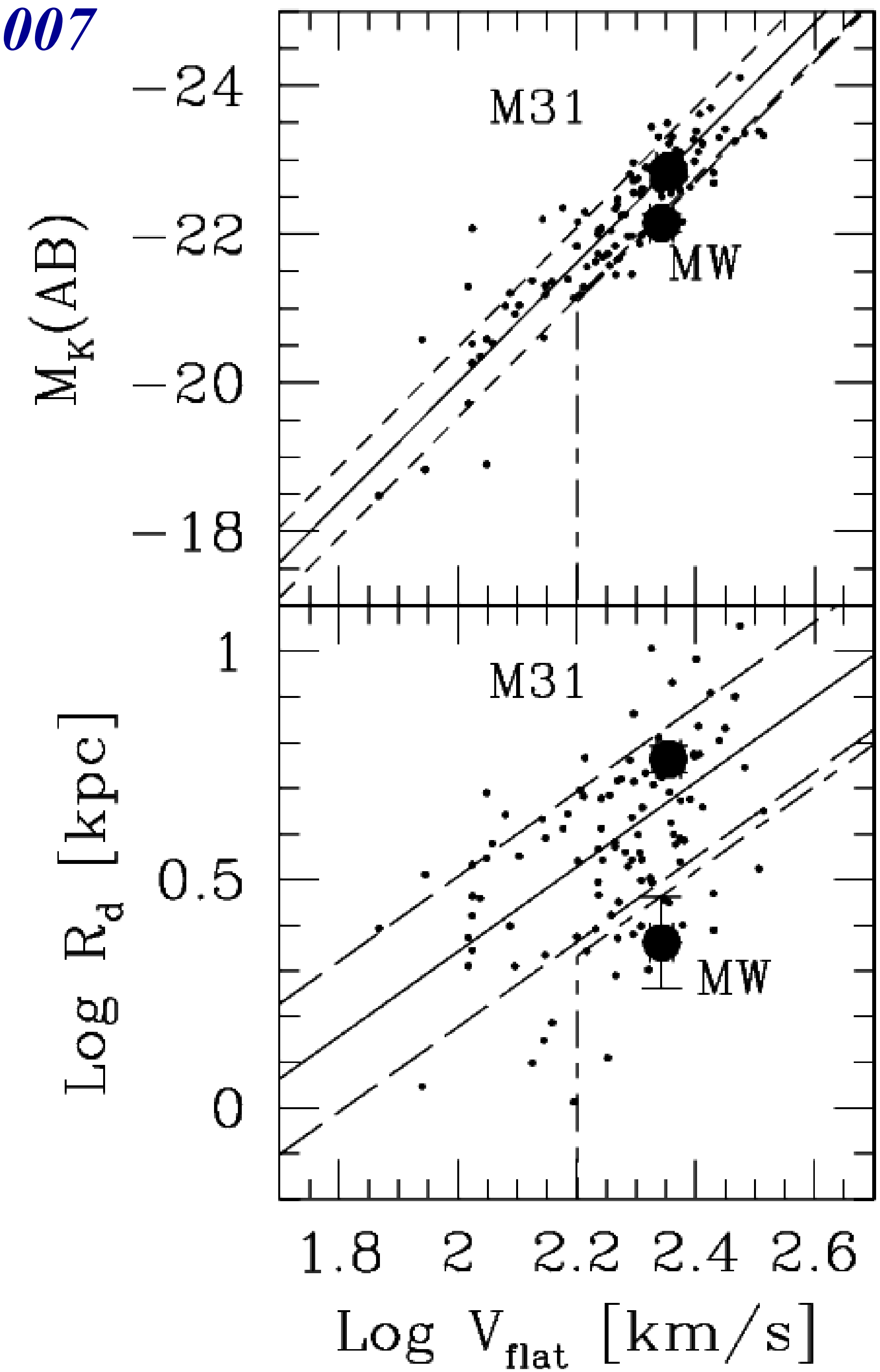
Hammer et al. 2007

More accurate measurements of M_K, R_{disk} (COBE, Spitzer) and V_{flat} for the MW and M31

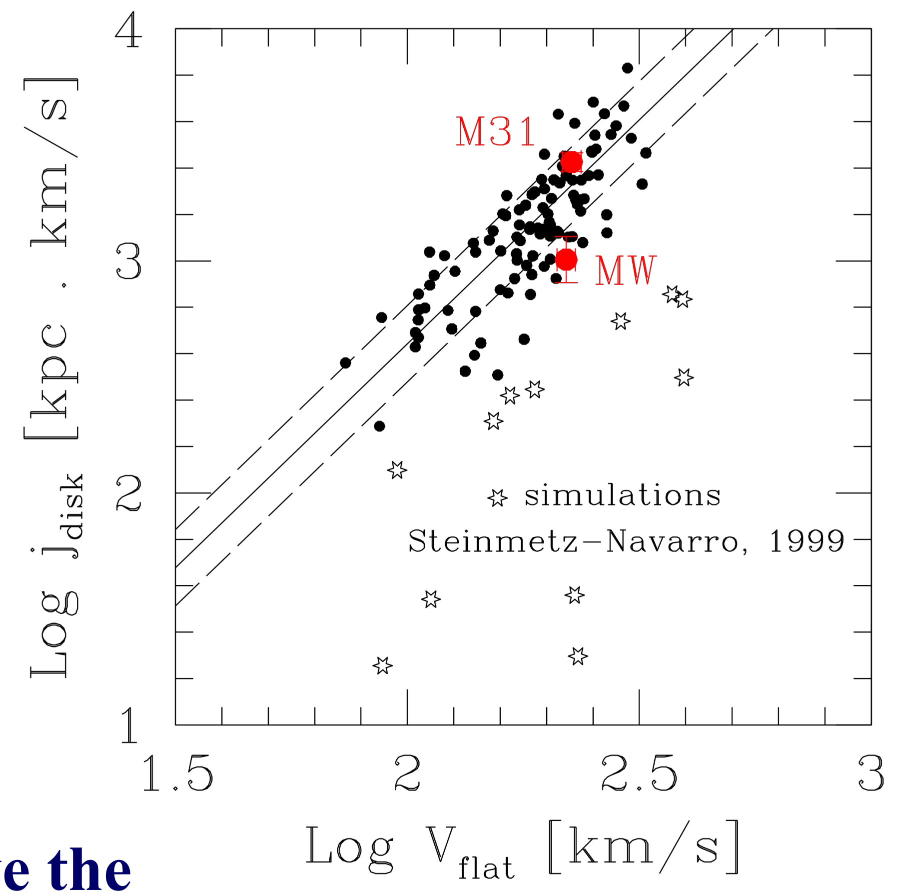
Compared to other spirals (SDSS):

- 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 ***7+/-1%*** *of Milky Way-like galaxies.*



Local galaxies: angular momentum



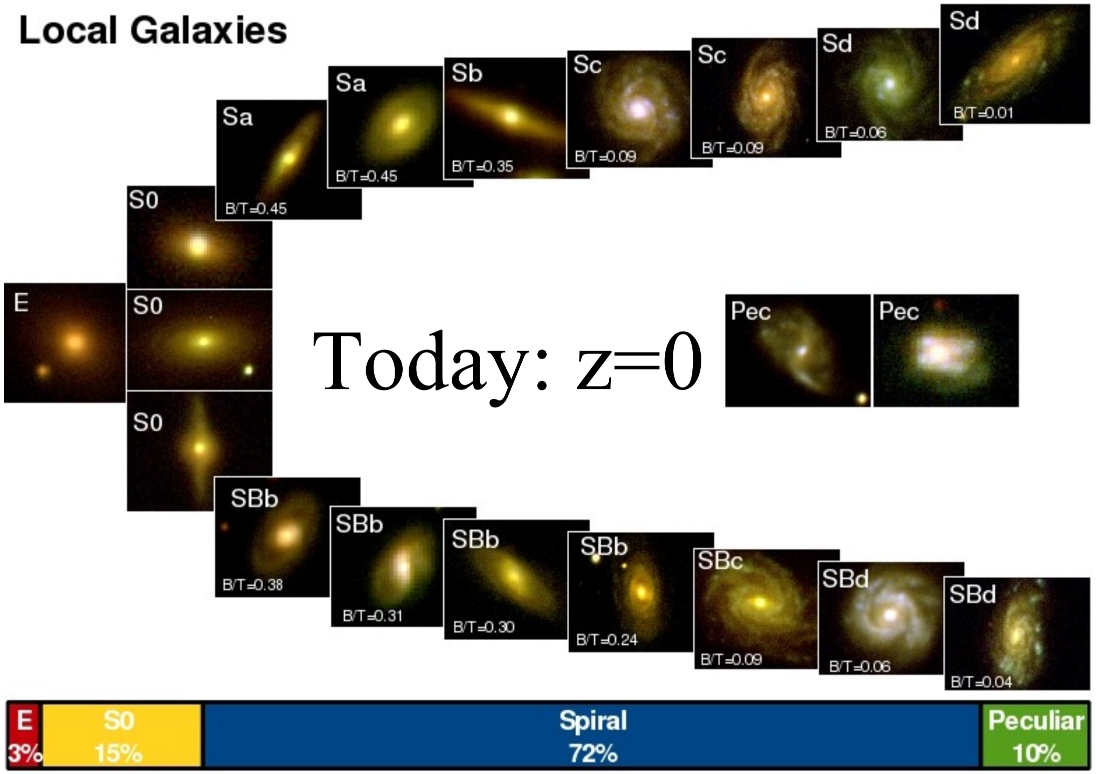
- Milky Way had an exceptionally calm past history; its angular momentum is twice smaller than that of median spirals

- M31 had a tumultuous merger history and appears to be more representative of median spirals
- **The orbital angular momentum may solve the spin "catastrophe"** *(Maller, Dekel & Somerville, 2002)*:

➔ Does it explain the lack of angular momentum of the Milky Way when compared to M31 and SDSS galaxies?

What is the past history of giant spiral galaxies?

Their progenitors are within distant galaxies



Today: z=0

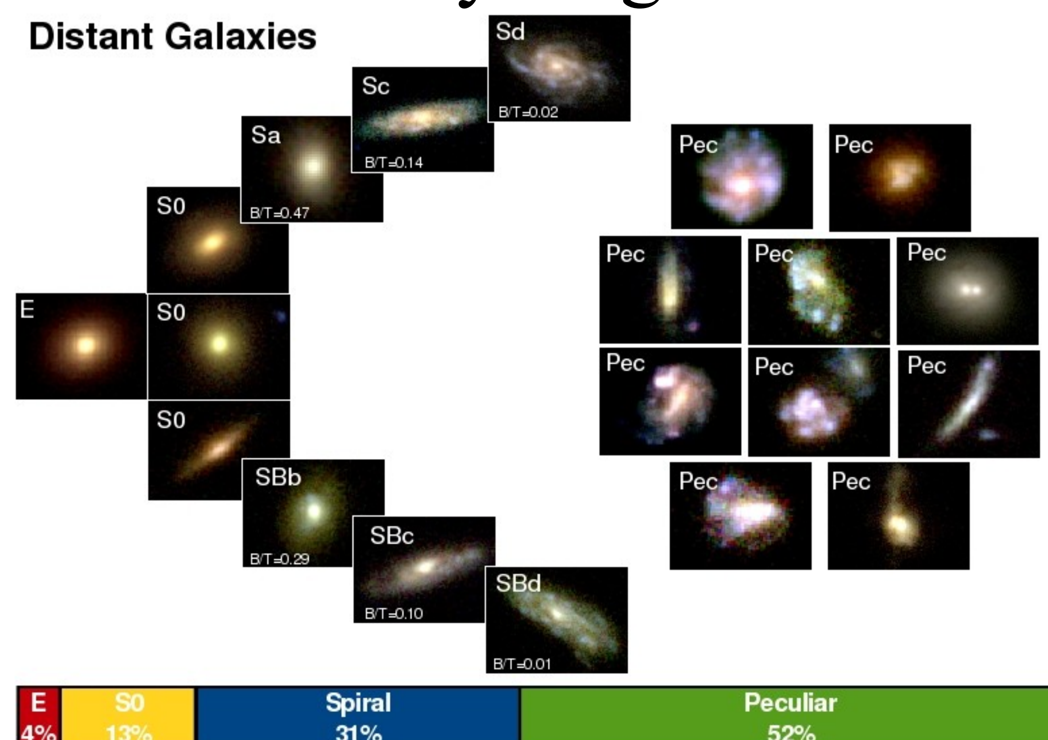
$M_{J(AB)} < -20.3$

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

Delgado et al. 2009

A&A, in press, arXiv0906.2805

6 Gyrs ago: z=0.65



Morphological fractions in agreement with van den Bergh (2002)

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)*

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

Methodology: 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

Dynamics

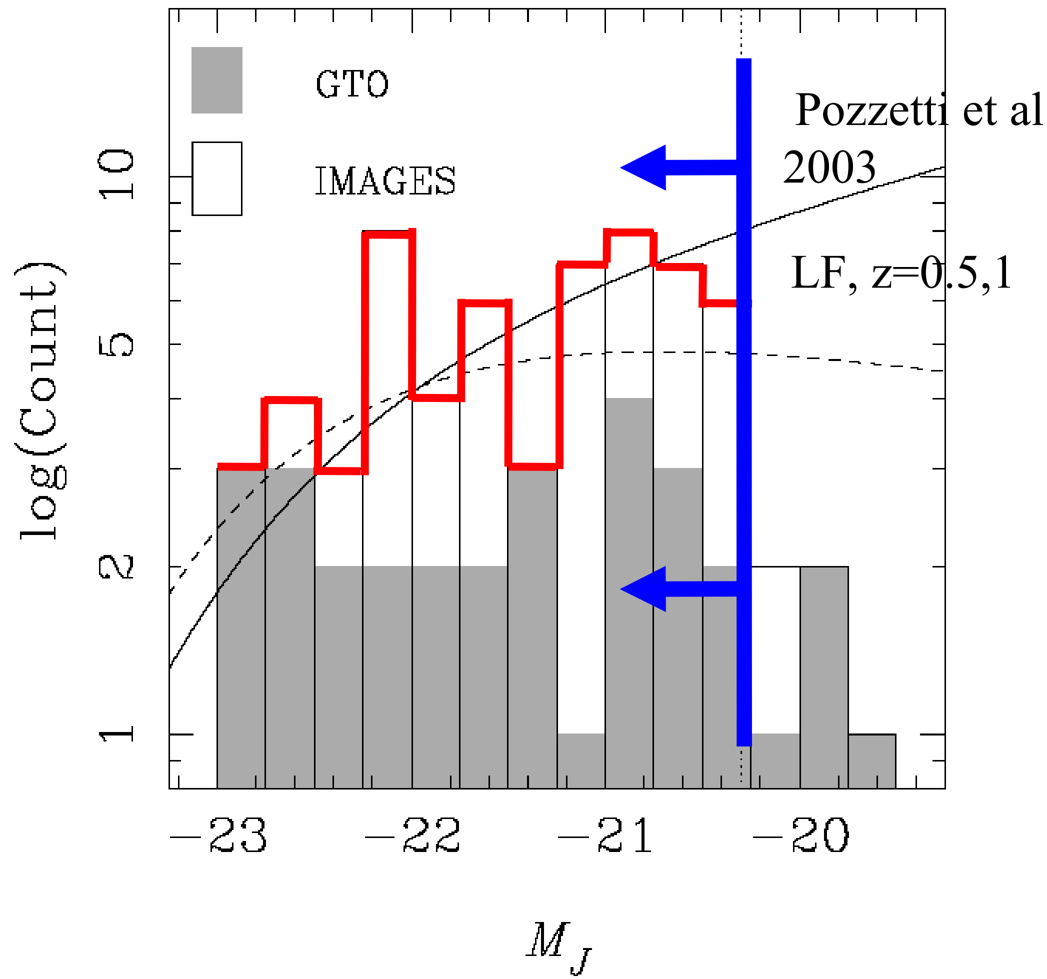
100 galaxies with spatially resolved kinematics

100 Intermediate mass galaxies :

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

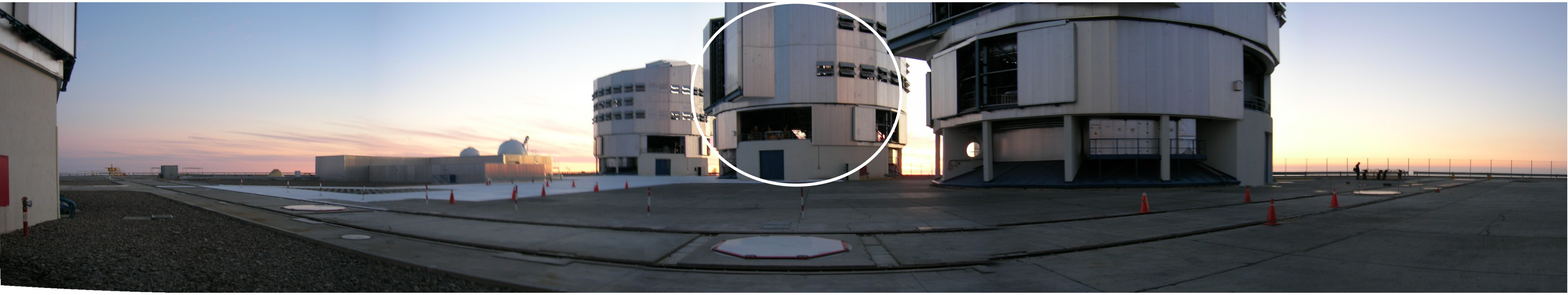
In this talk:

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

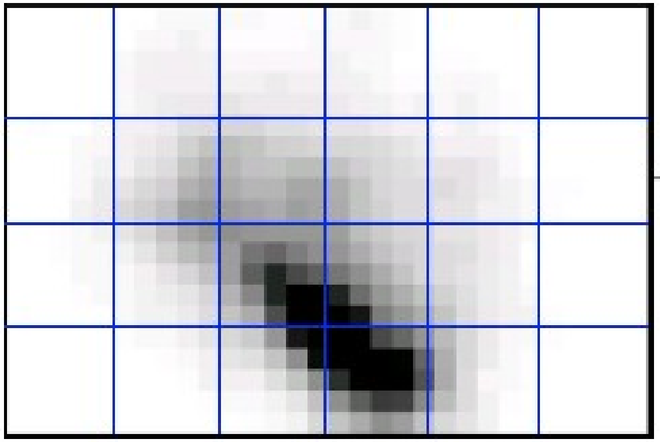
FLAMES/GIRAFFE on the VLT

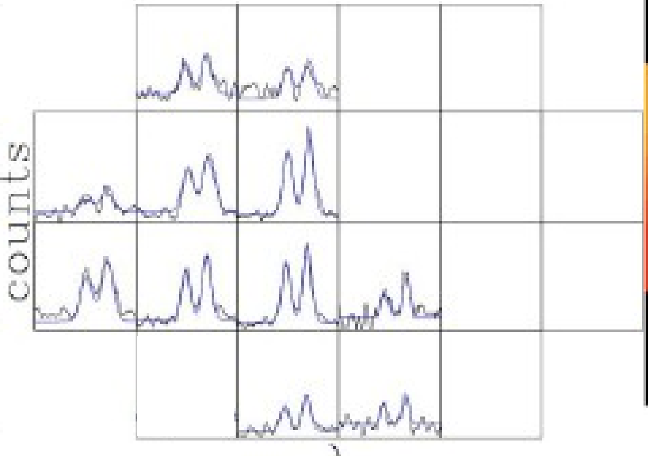


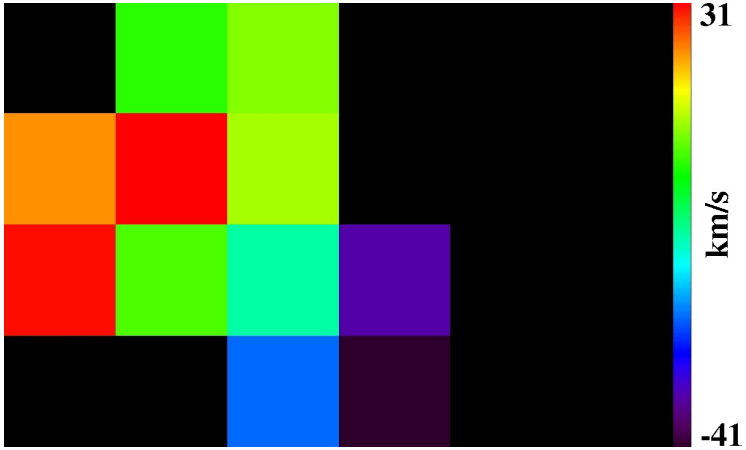
IFU Mode: 15 x 3''x2''arrays (20 sq. μlenses, 0''.52)

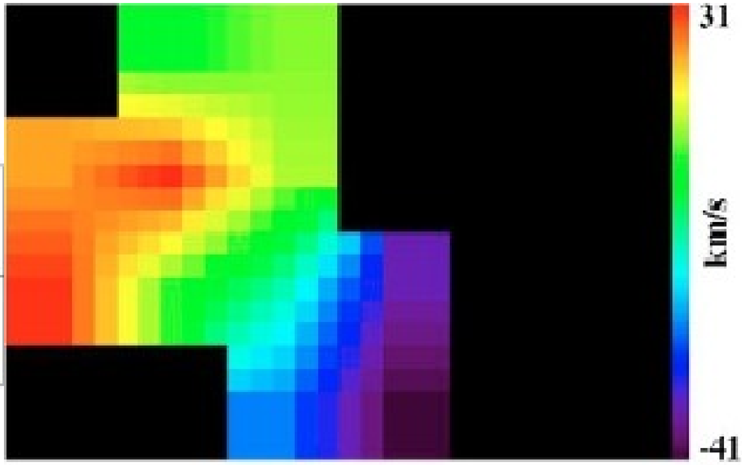
15 IFUs deployable over a 20 arcmin FoV with $R_{effective}$>13000 ➔ the [OII] doublet can be resolved

CFRS03.0488, z=0.46, (3''x2'')



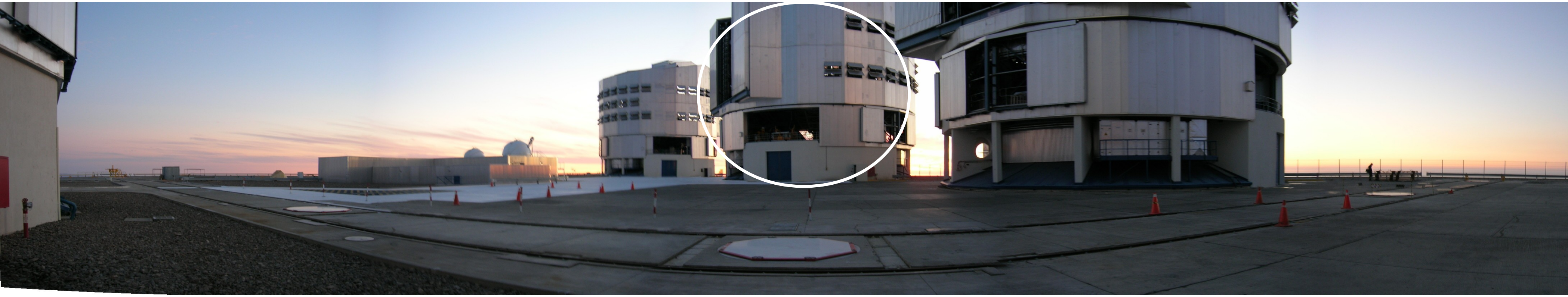






5x5 linear interpolation

FLAMES/GIRAFFE on the VLT



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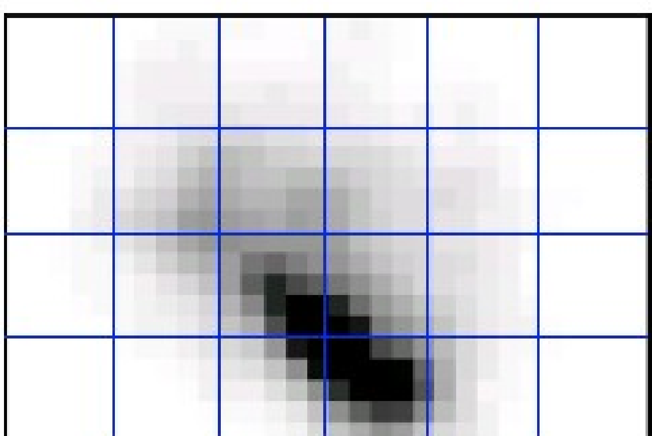
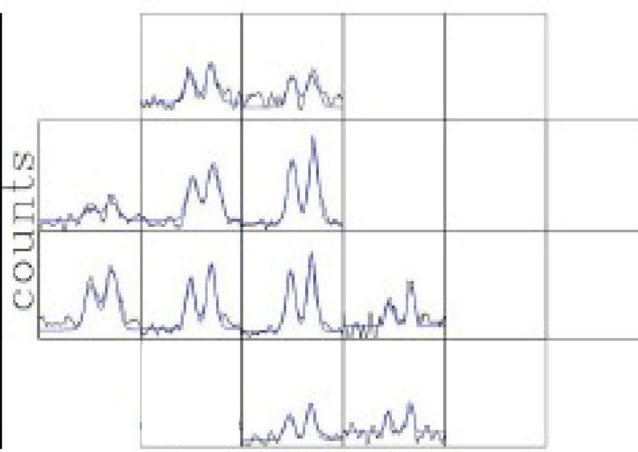
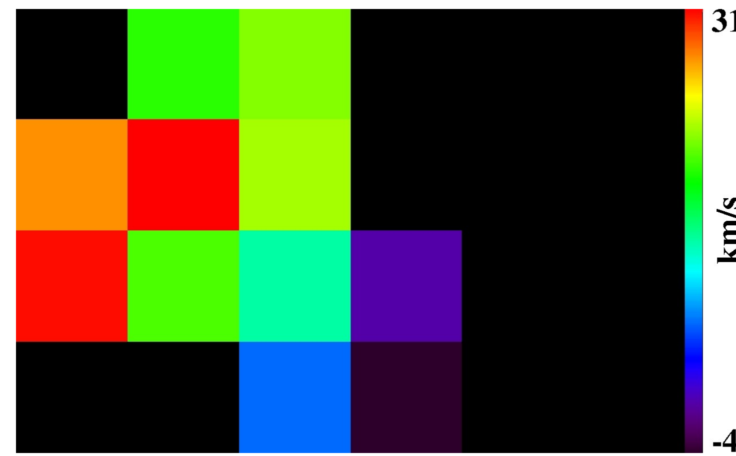
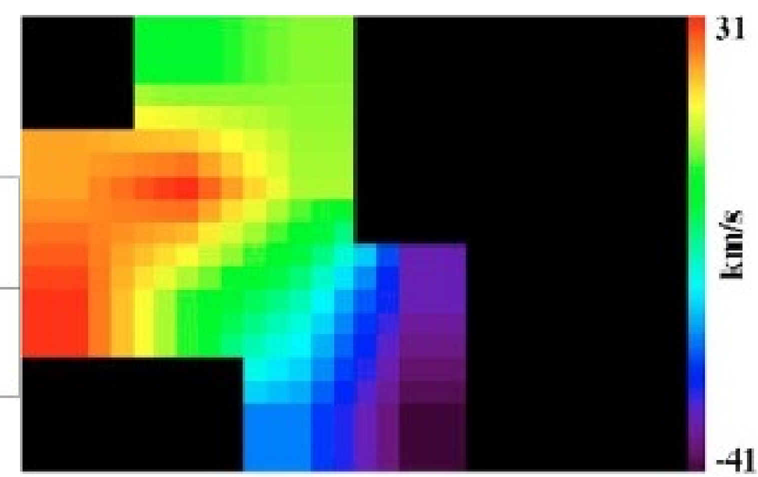


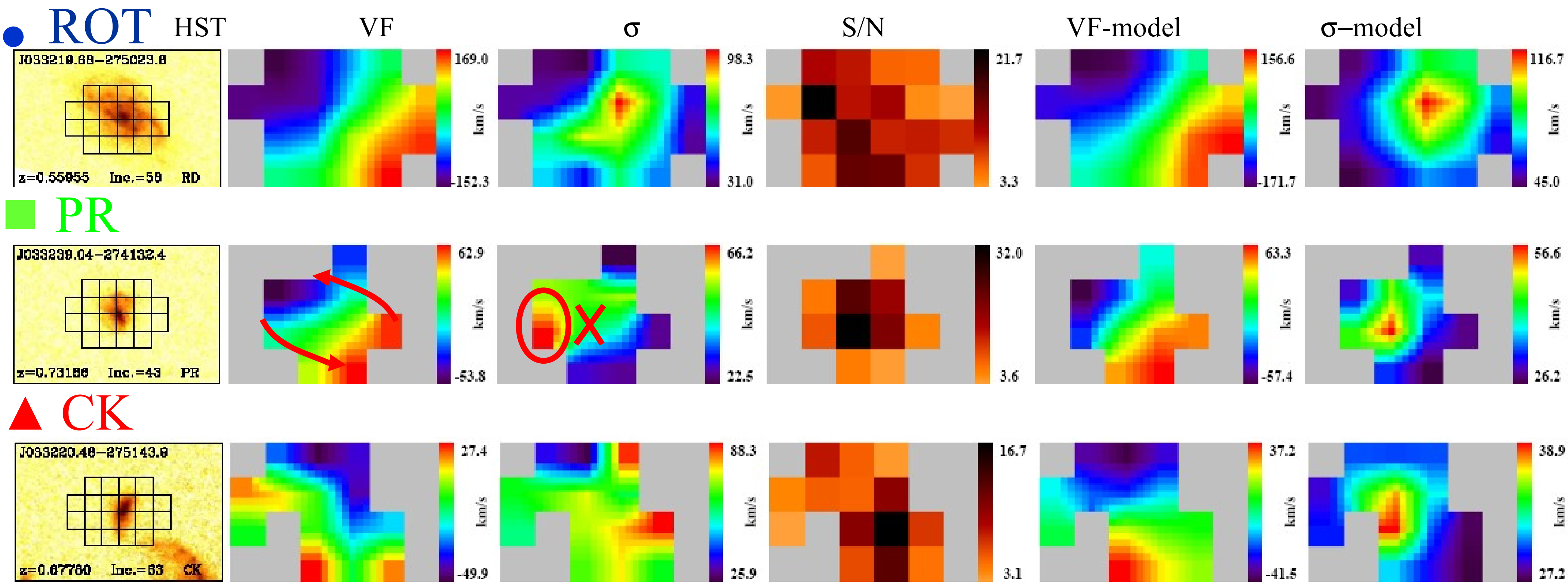






5x5 linear interpolation

Spatially resolved kinematics of distant galaxies



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

Fraction of z~0.65 intermediate-mass galaxies:

Normal rotation, ROT : 19%

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

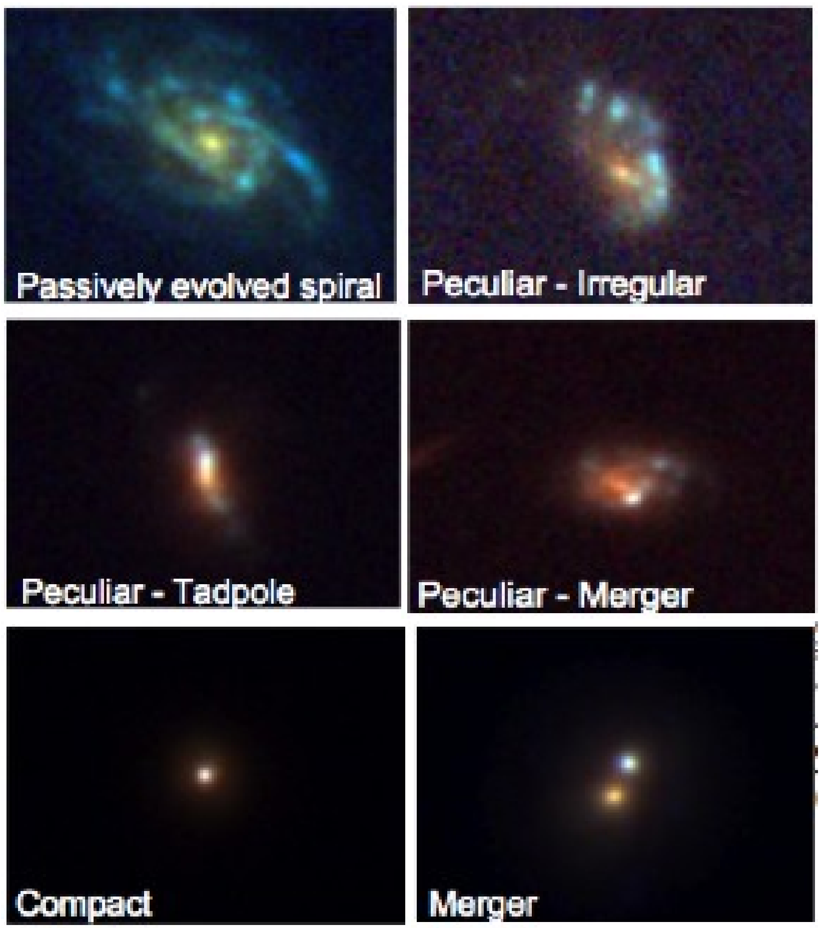
Without emission lines (E/S0/Sa..): 40%

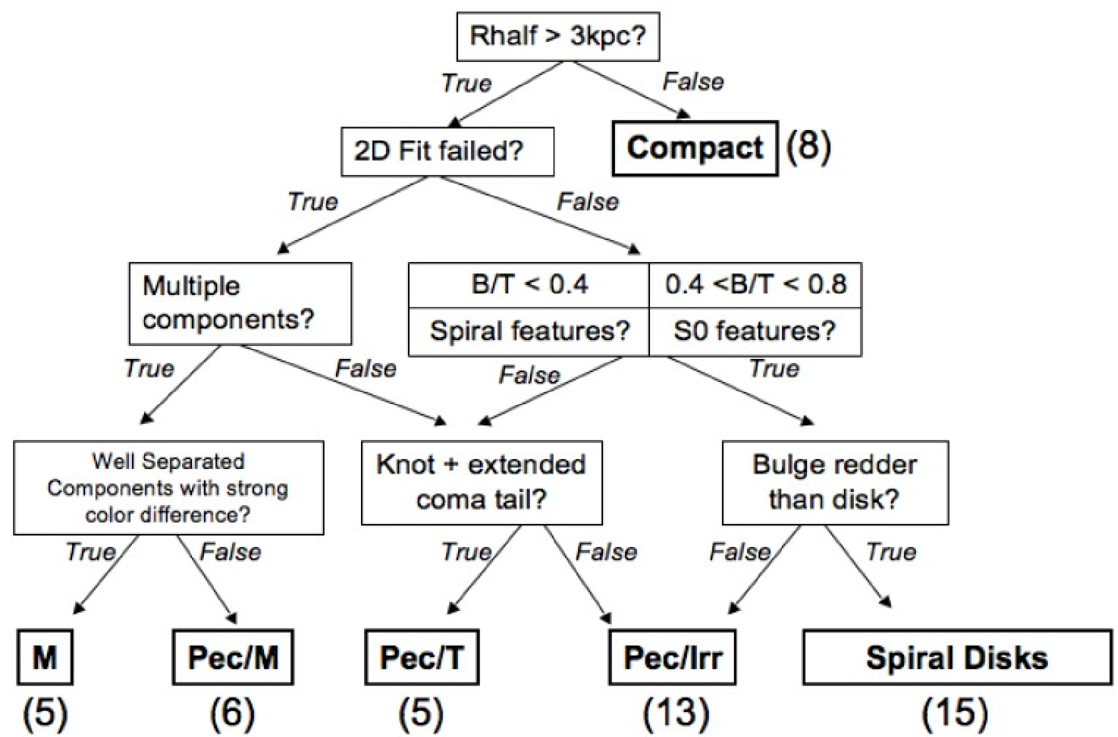
Morphology

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

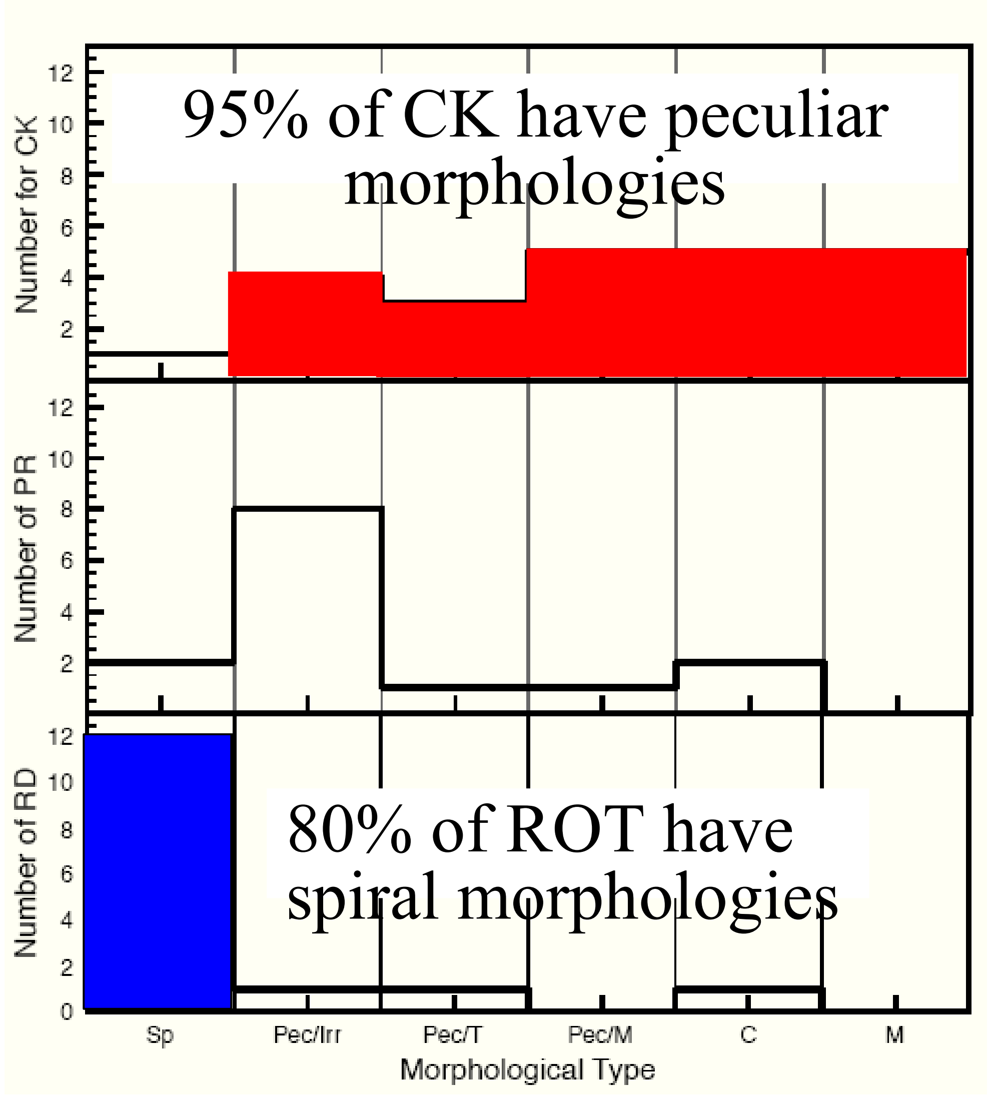




Morphology versus kinematics

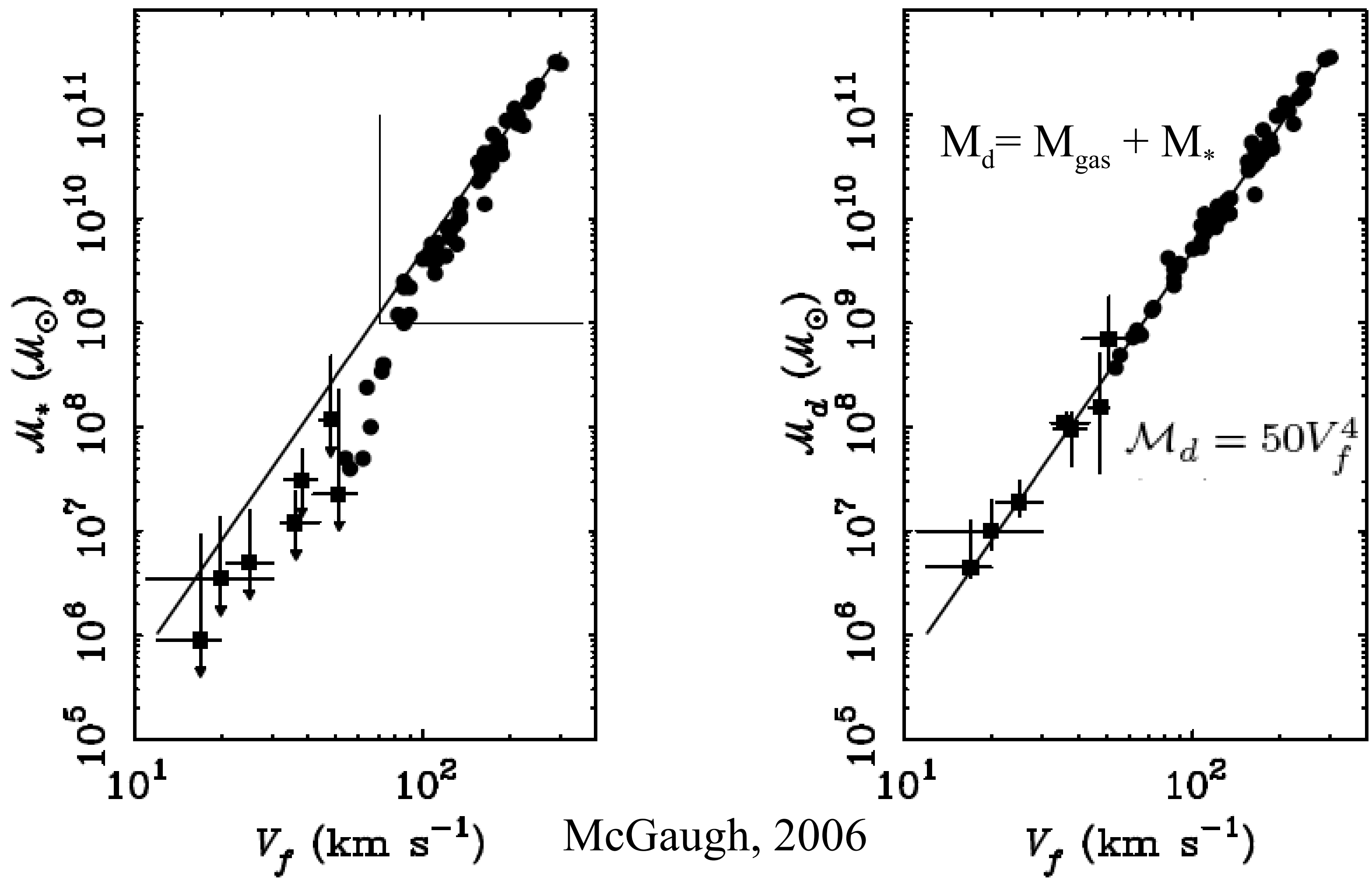
Neichel et al (2008)

Agreement between kinematics and morphological classifications



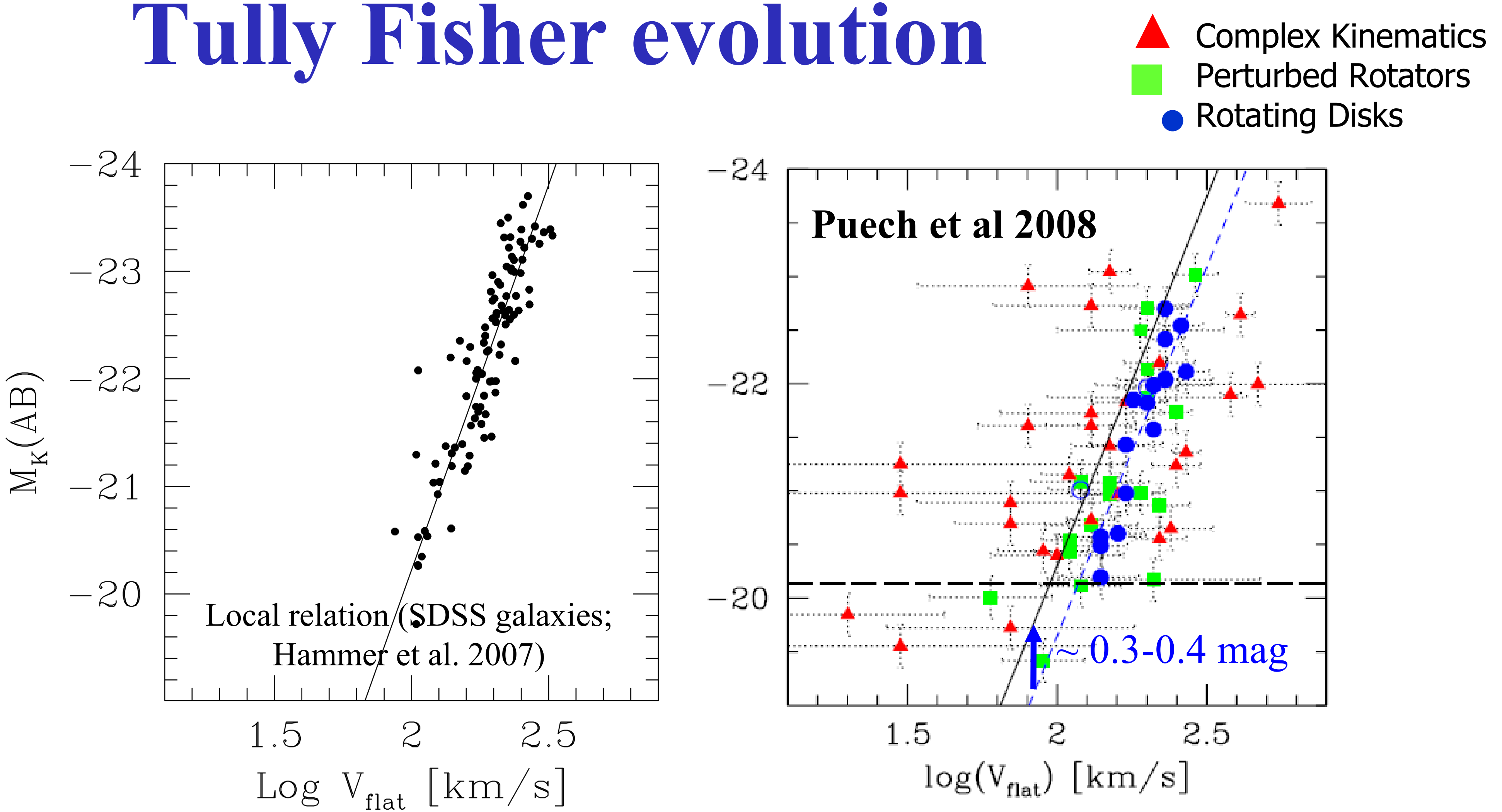
Anomalous kinematics of the gaseous component is almost always linked to anomalous morphological distribution of the stars

Luminosity/mass versus circular velocity: the local Tully-Fisher relation



To reproduce slope and zero points requires specific assumptions on halo (no contraction) and on stellar physics (feedback, IMF): see Dutton, 2007, 2009

Tully Fisher evolution



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

➔ energy transfered from bulk to random motions

Gas content at z ~0.65

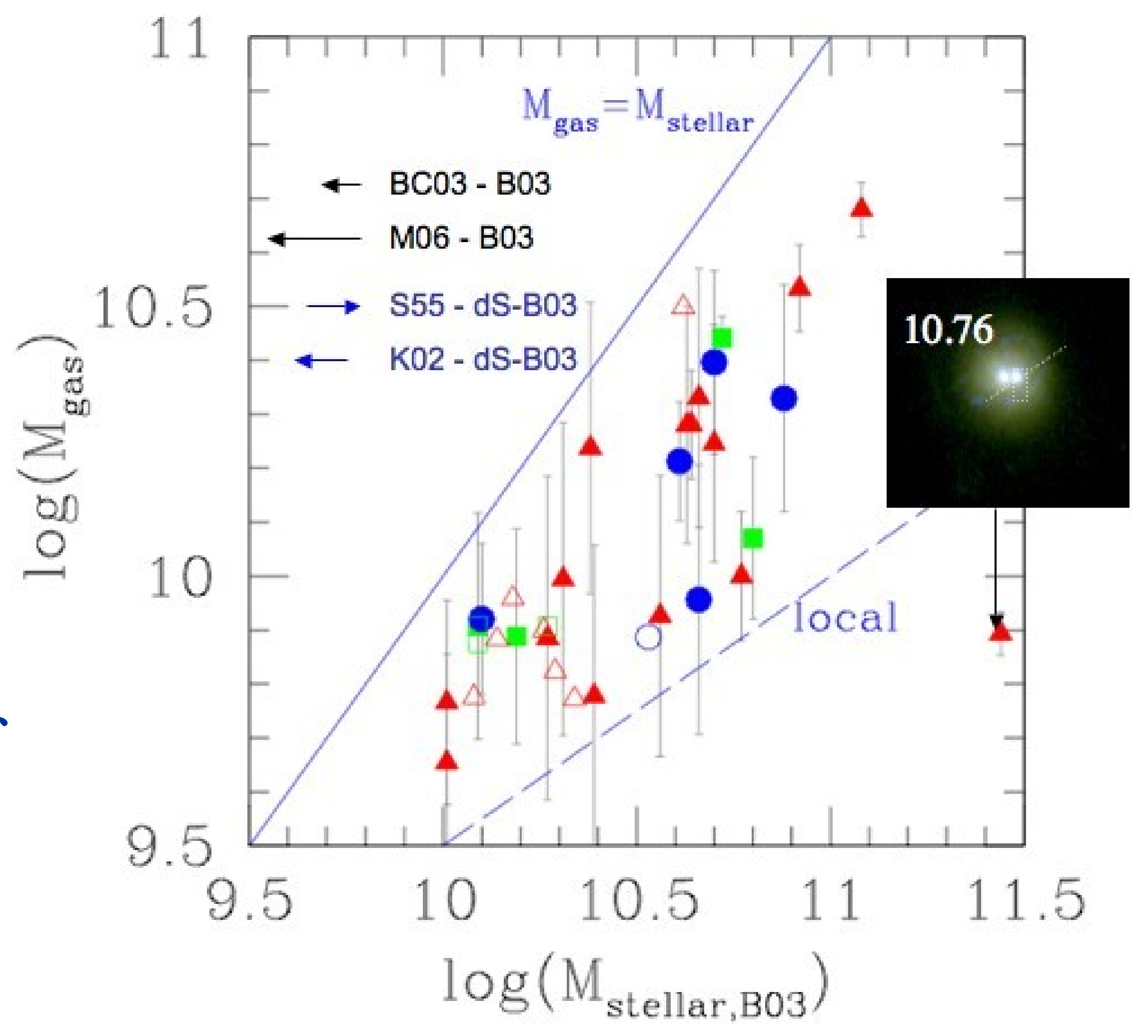
Inversion of Kennicutt law:

Median f_{gas} = **31±1%**

3 times median f_{gas} at z=0

Consistent with the evolution of the M_{stell}-O/H relation

(Liang+06; Rodrigues+08)



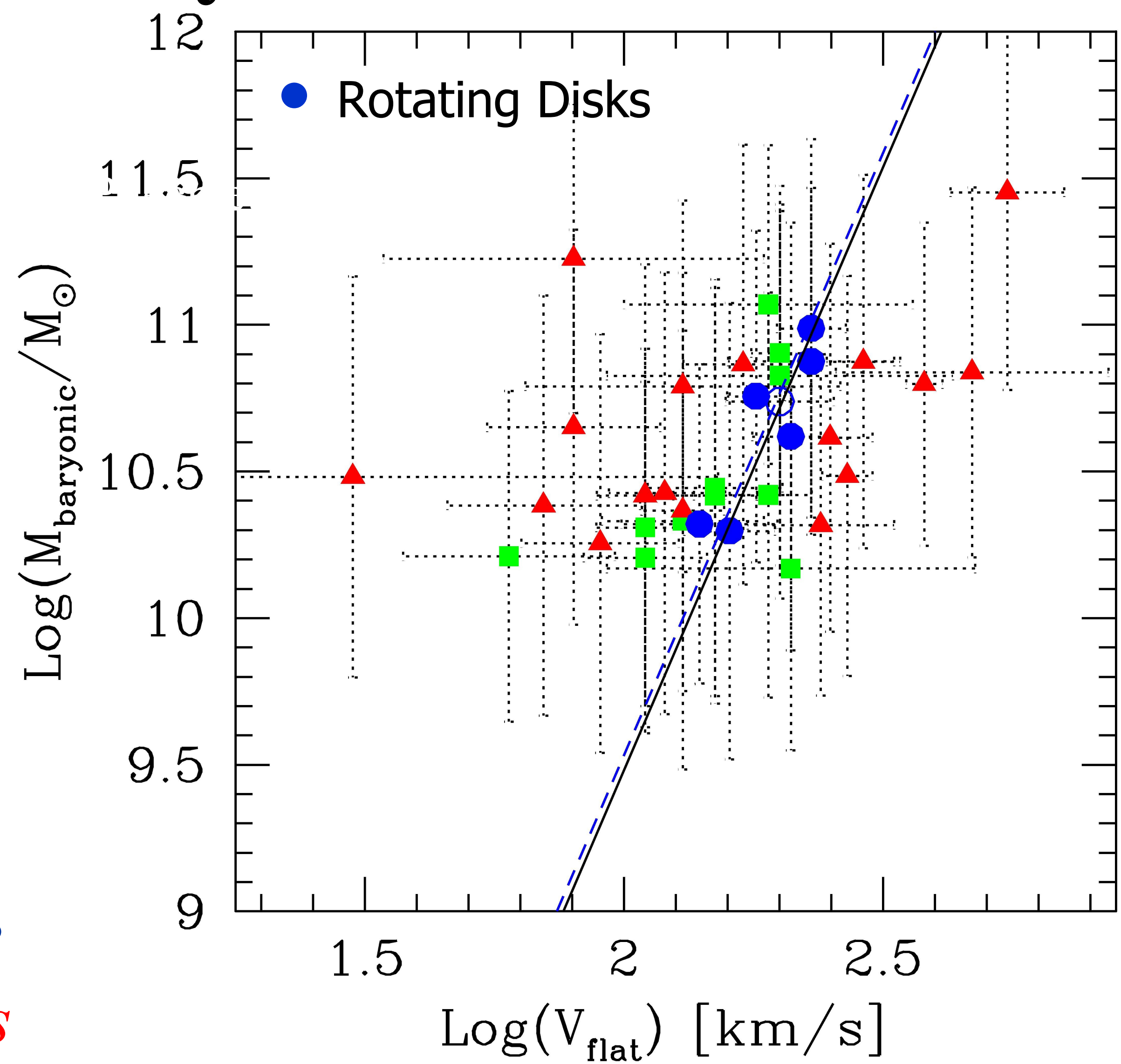
Baryonic Tully Fisher at z~0.65

Rotating disks:

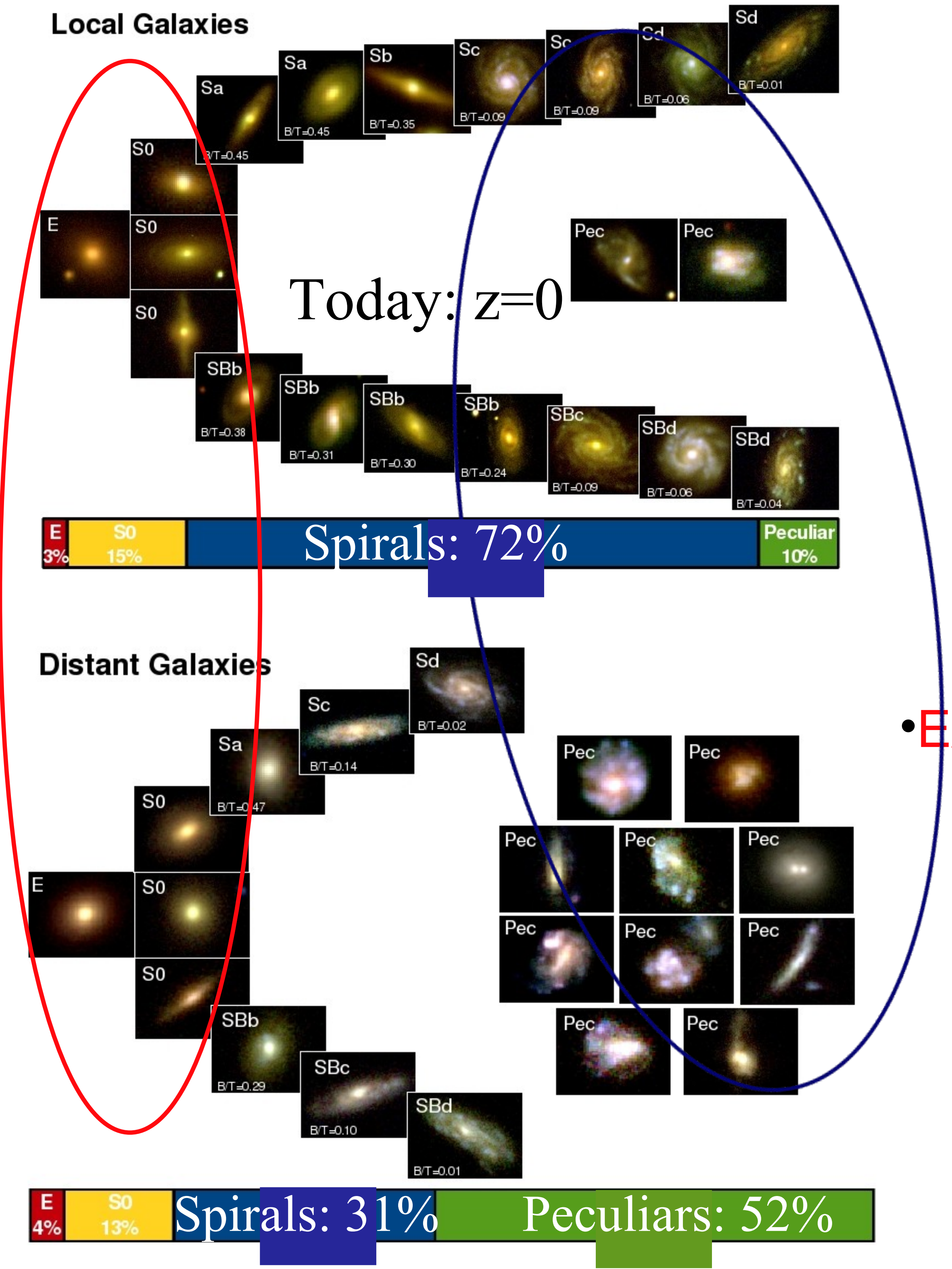
no significant evolution in slope or zero point within random and systematic uncertainties

Reservoir of gas already gravitationally bound to rotating spirals

No need for external gas accretion?



Puech et al, 2009



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

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

Delgado et al. 2009

arXiv0906.2805

6 Gyrs ago, z=0.65:

- E/S0 were mostly in place
- half of spirals did not

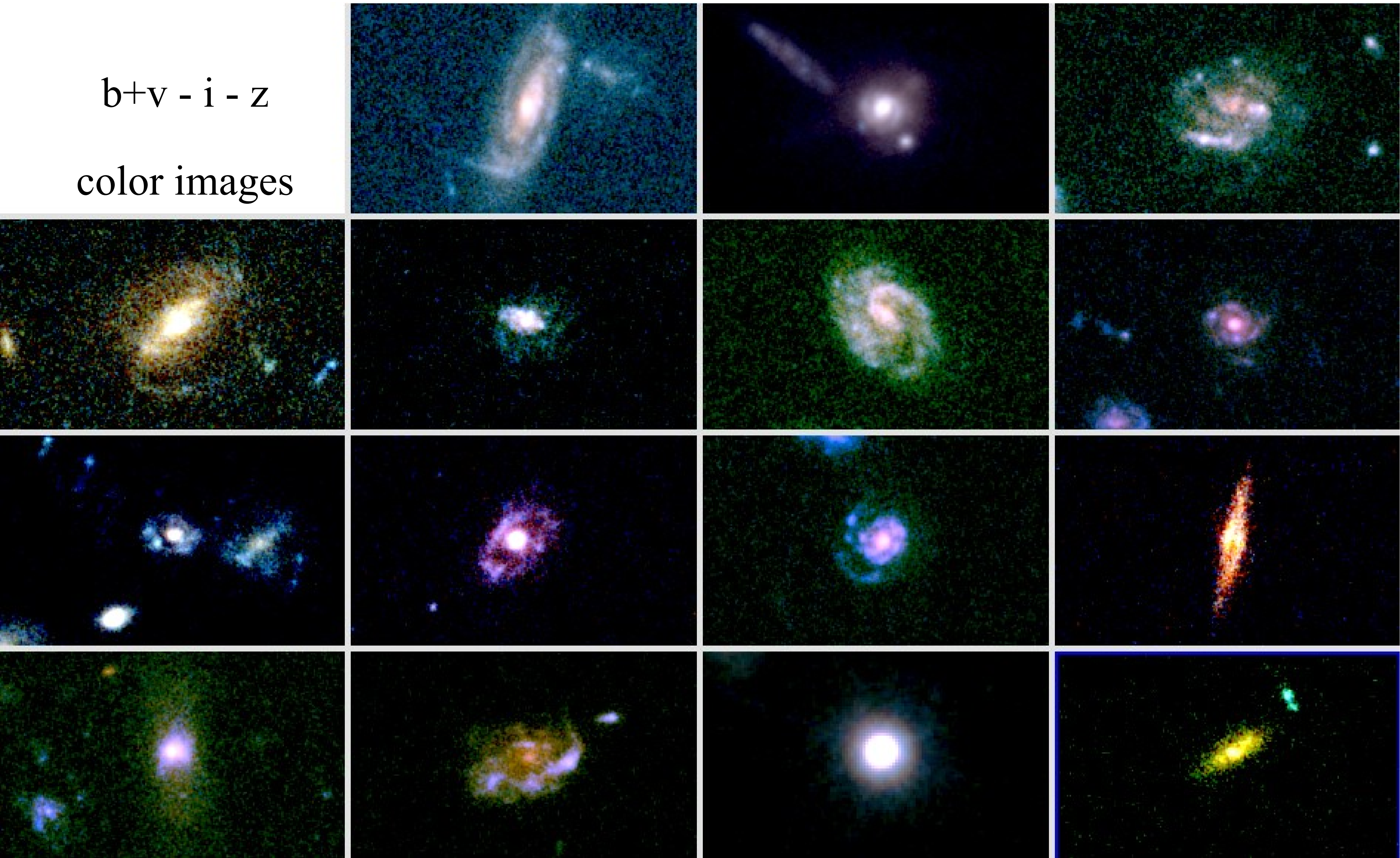
➔ they had peculiar morphologies and anomalous kinematics

The origin of star formation in progenitors of spirals, 4-8 Gyrs ago

- Processes related to **violent star formation** (LIRGs)

➔ *doubling their stellar masses*

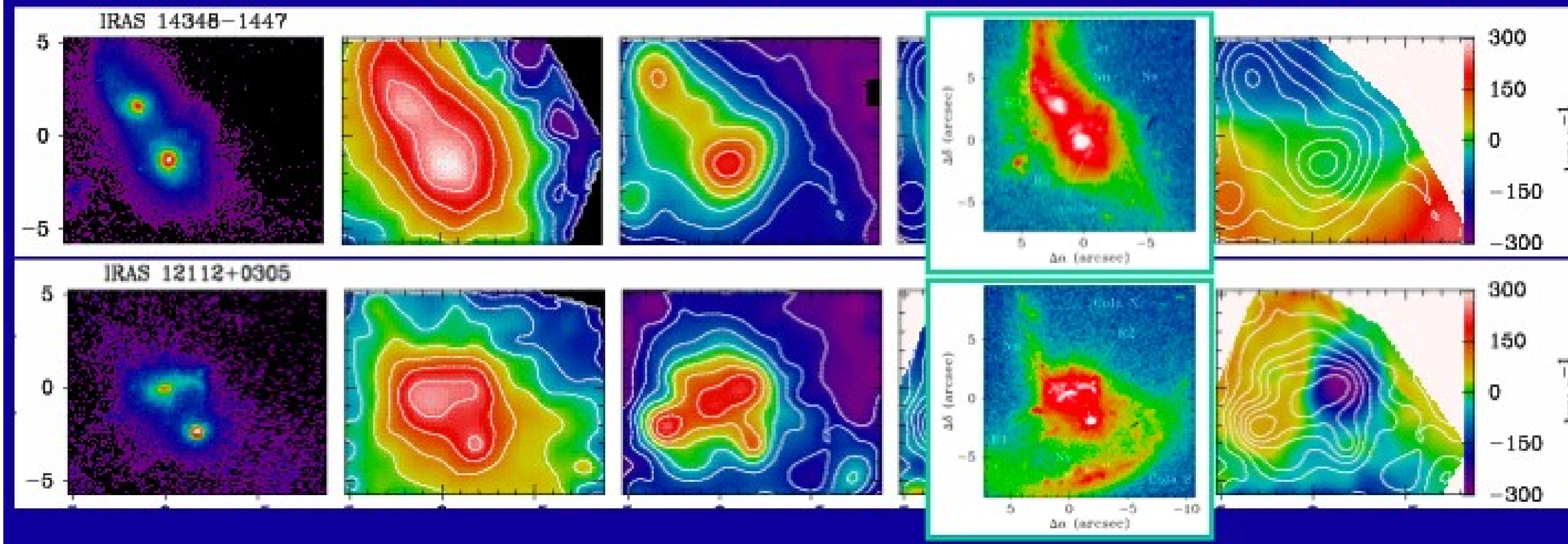
Morphologies of z~0.6 LIRGs in GOODS: mostly linked with spirals, although with many strong peculiarities (rings, tidal tails, irregularities, mergers).
(sample from Melbourne+07, images from Flores et al.)



HIGH-Z GALAXIES: ROTATION AND DYNAMICAL MASS?

Excerpt from Luis Colina, Garching, 2005

HST F160W | CONT. | Hα | VELOCITY DISP. | VELOCITY FIELD



RELATIVE VELOCITY OF TIDAL TAILS AND/OR GALAXIES IN PAIRS MIMIC ROTATION

ROTATION IN HIGH-Z GALAXIES? CAUTION!
DYNAMICAL MASS FROM VELOCITY GRADIENTS? CAUTION!

The origin of star formation in progenitors of spirals, 4-8 Gyrs ago

- Processes related to **violent star formation** (LIRGs)

➔ *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

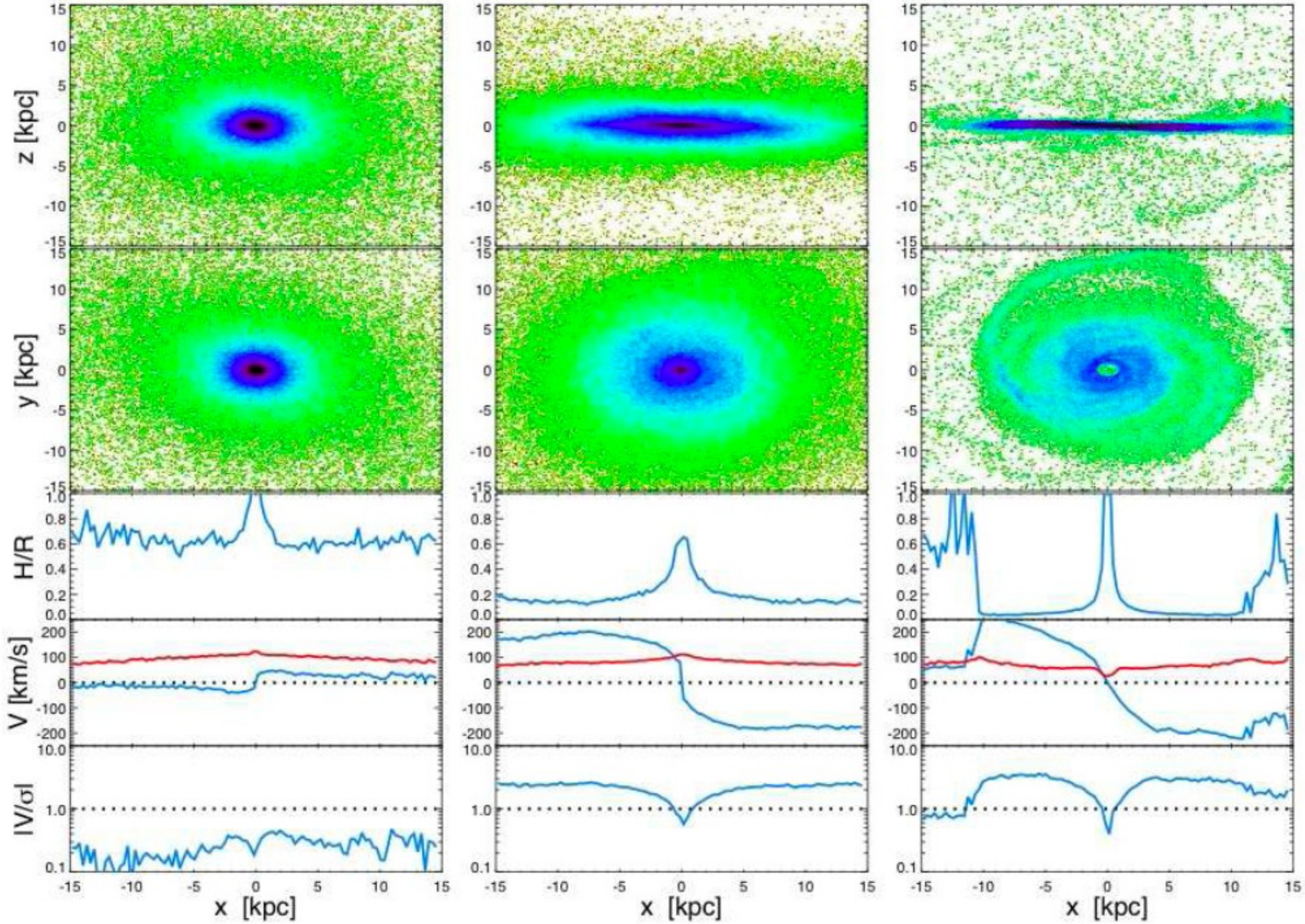
but also

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

Expectations from simulations



1:2 merger, 20% of gas

Hopkins et al. (2009)

Higher gas fractions: 40% and more

➔ production of disk dominated galaxies

Project: the elaboration of the Hubble sequence

(see hubble.obspm.fr)

- Can we model all anomalous distant galaxies as merger or their remnants?

  Method: reproduce both morphology & kinematics

- Are spiral's progenitors enough gas rich to produce disk dominated galaxies?

  Method: verify the gas content of distant galaxies

- Could one reproduce the present-day Hubble sequence mostly through their last major merger?

  Method: detailed modelling and conservation of mass & angular momentum

First detailed 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)

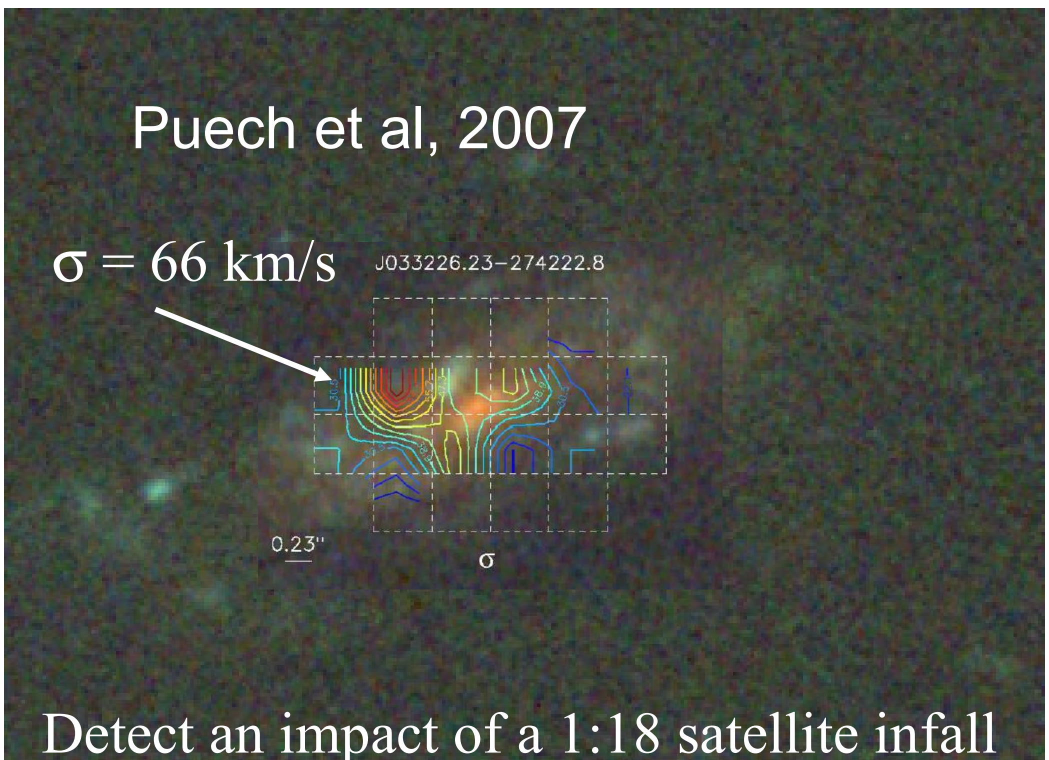
similar accuracy than for many local galaxies

7 cases already done … among 100 !

Detailed studies

" Examine the objects as they are and you will see their true nature; look at them from your own ego and you will see only your feelings; because nature is neutral, while your feelings are only prejudice and obscurity."

邵雍 , *Shao Yong,* 1011–1077



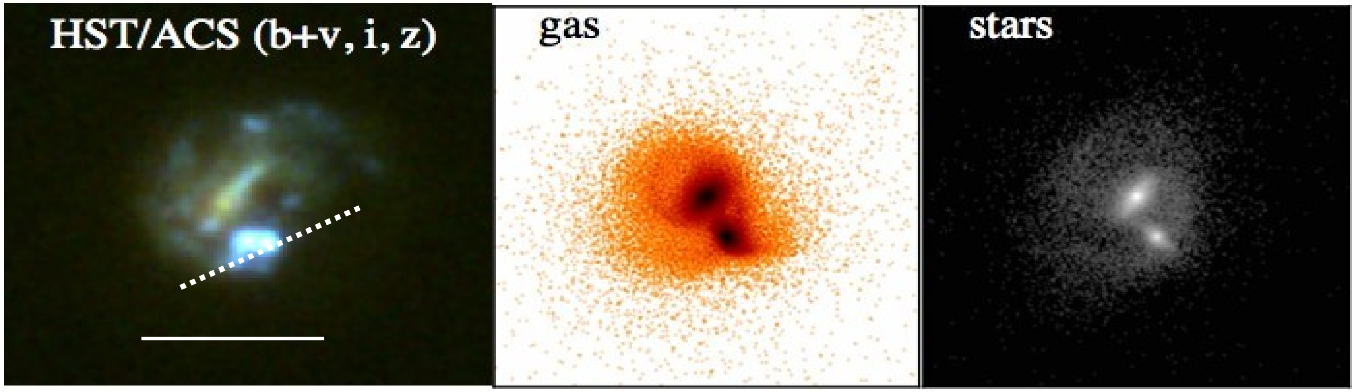
modelling z~ 0.6 galaxies

with a similar accuracy than

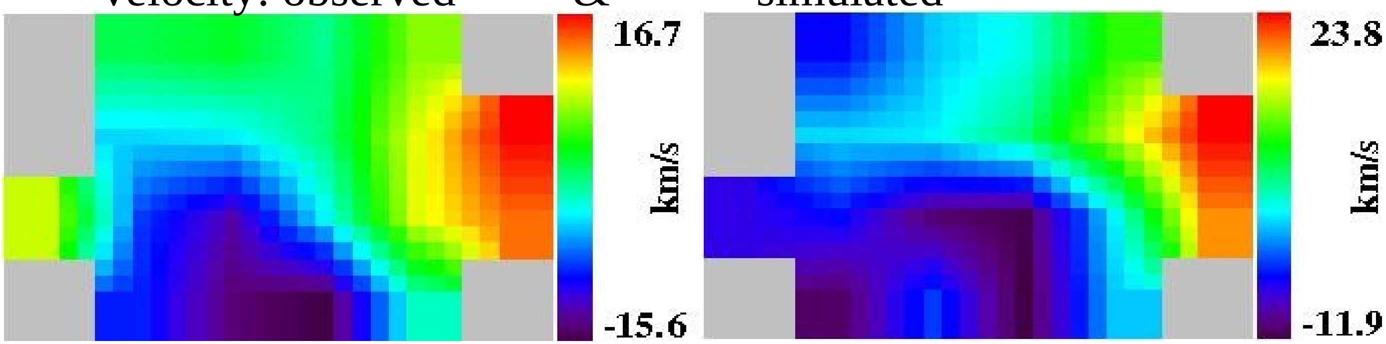
for local galaxies

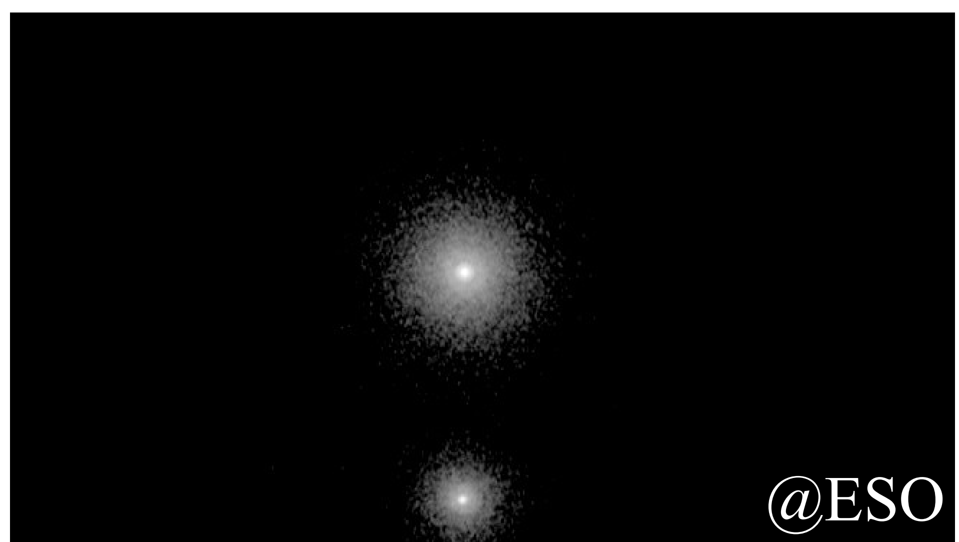
A giant, starburst, bar induced by a merger at z=0.4

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



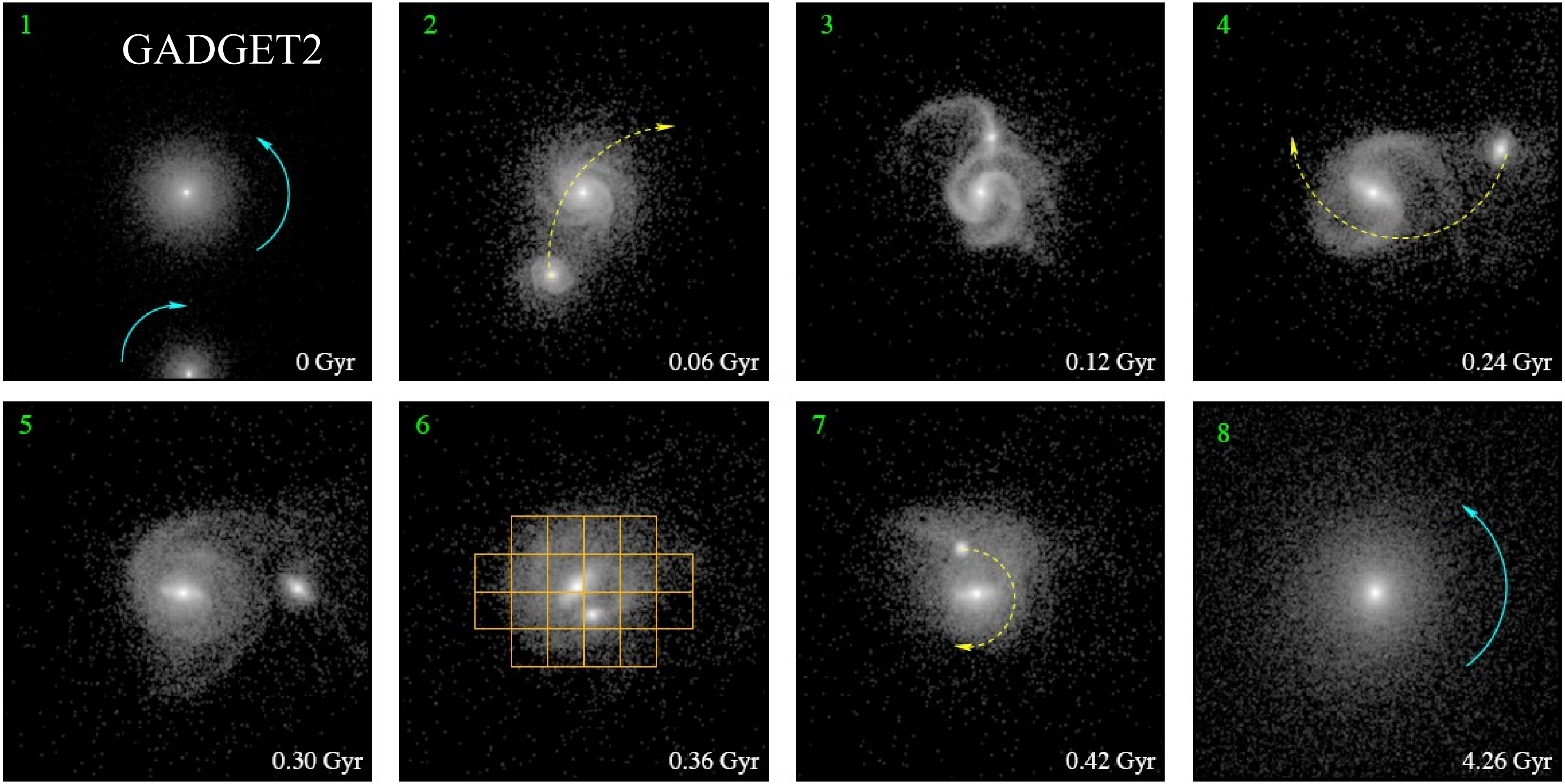
velocity: observed & simulated





A giant, starbust, bar induced by a merger at z=0.4

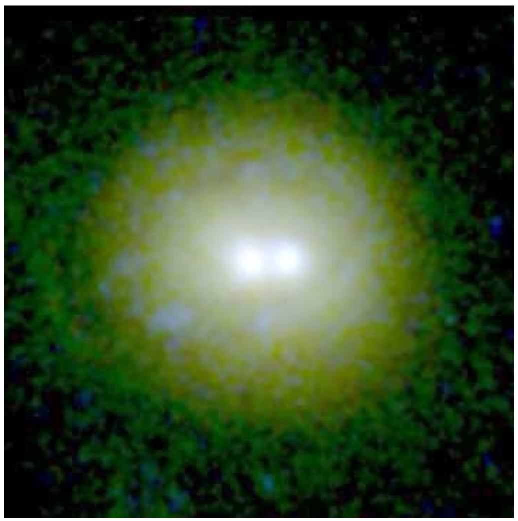
Peirani et al, 2009, A&A 496, 51

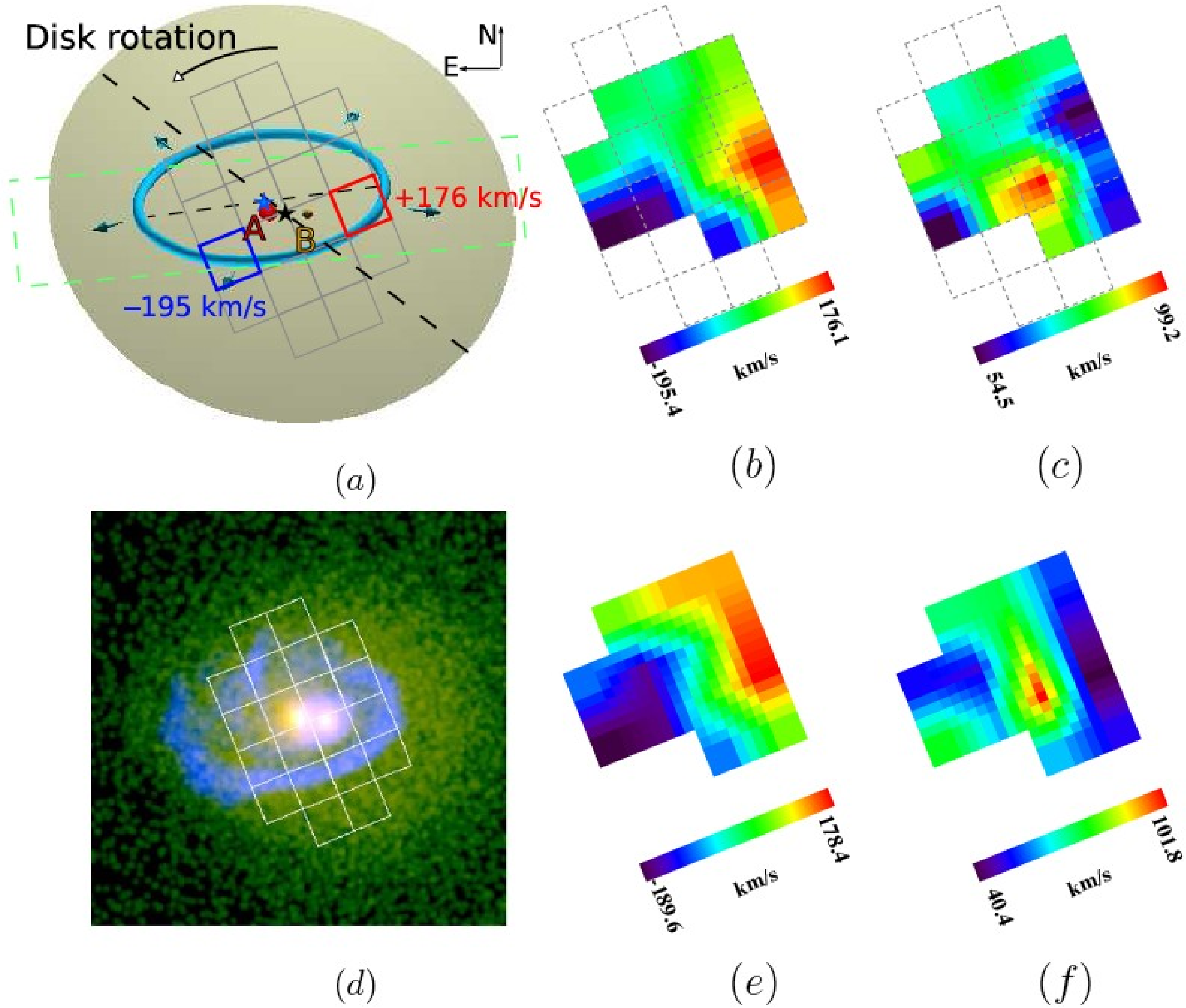


Galaxy morphology & angular momentum are driven by the last major merger (here 1:3 mass ratio, S0_a)

A surviving disk from a 4:1 mass ratio, central collision: a single shot?

Yang et al, 2008b, A&A in press (arXiv0904.1621)





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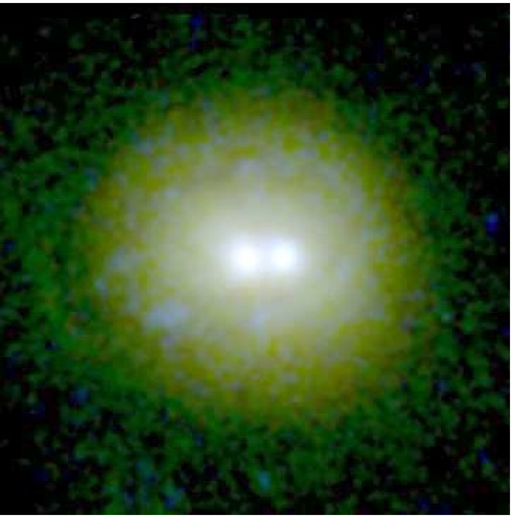
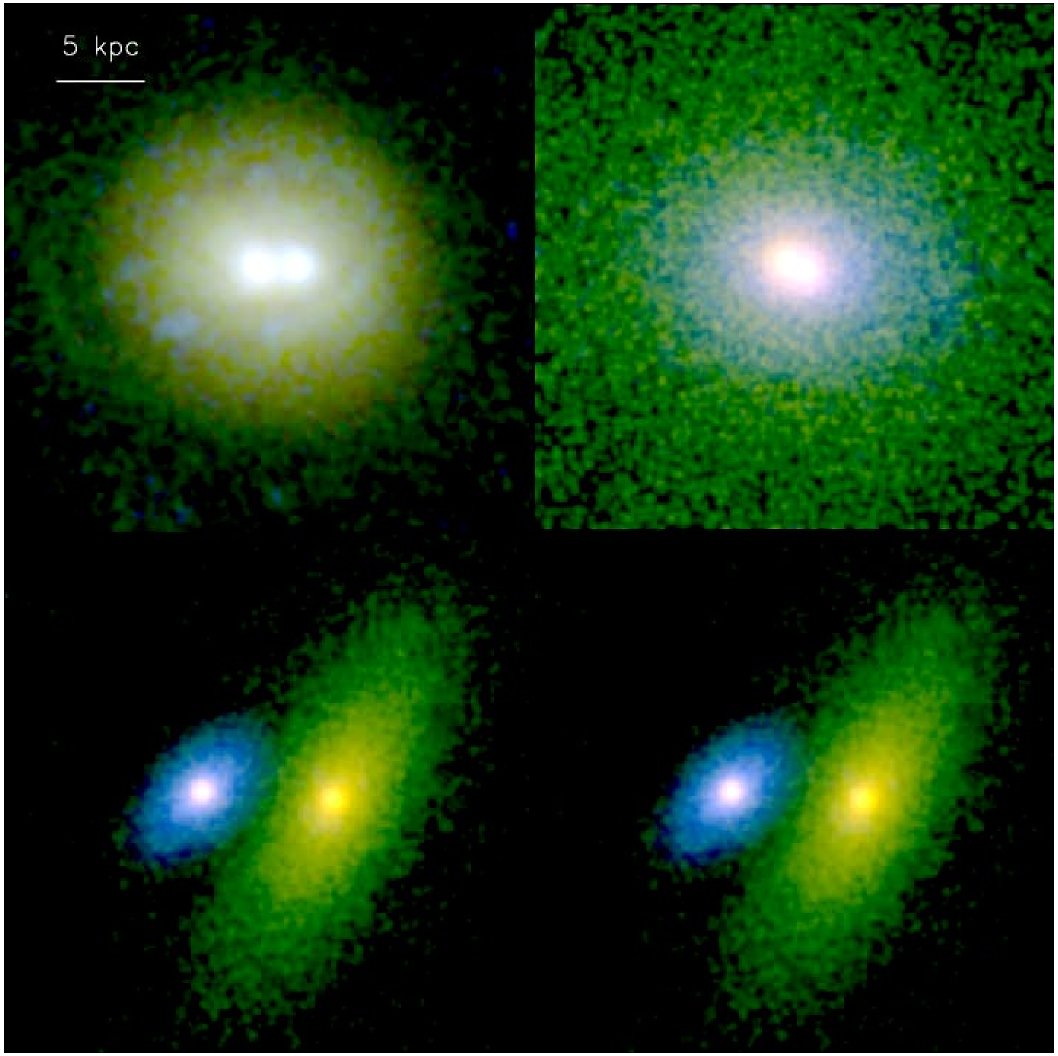
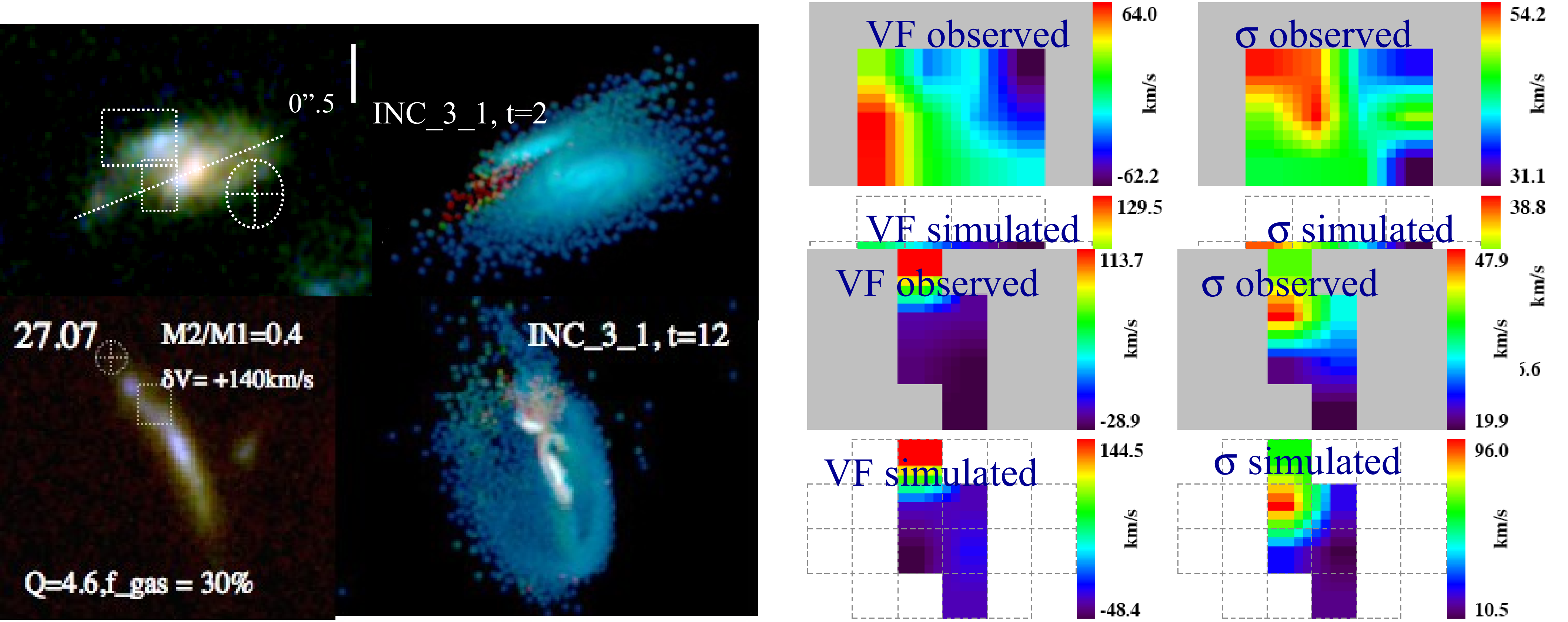
Yang et al, 2008b, A&A in press (arXiv0904.1621)





Half of the anomalous galaxies show two nuclei
& could be reproduced by major mergers, before the fusion

Hammer et al. 2009, A&A, in press, arXiv0903.3962H



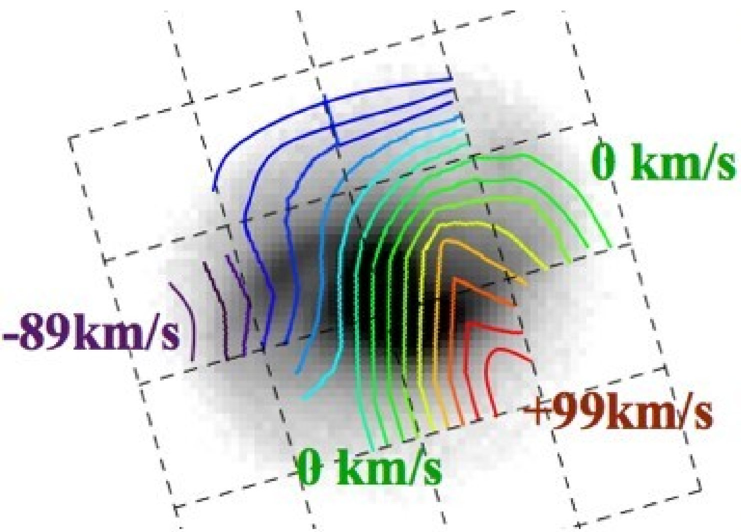
➔ Are all anomalous galaxies merger or their remnants?

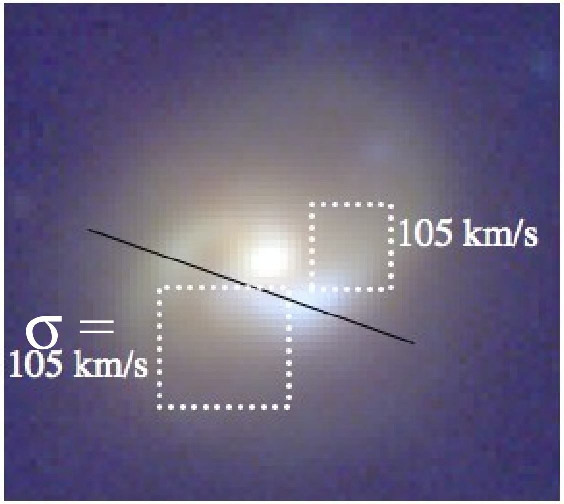
Progenitors of M31 mass galaxies would be with:

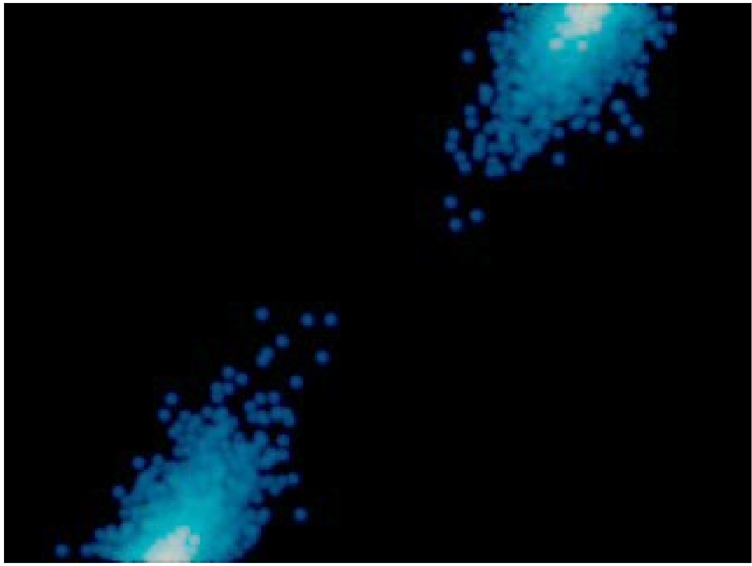
$M_{stell} \sim 1.5\ 10^{10}\ M_\odot$ and $f_{gas} \sim 50\%$

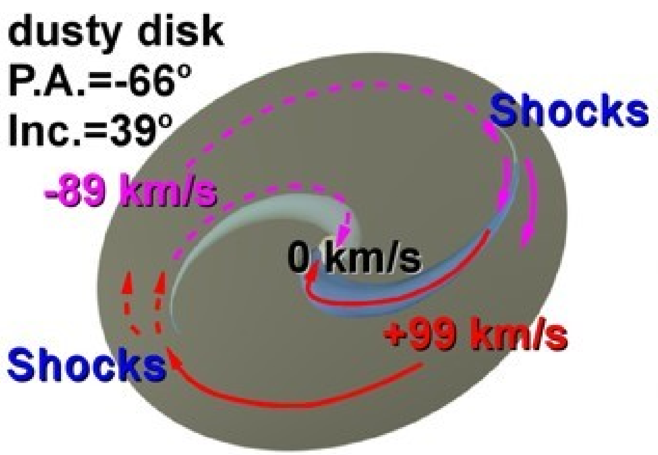
A disk rebuilt 500 Myrs after a gas rich merger at z~0.4?

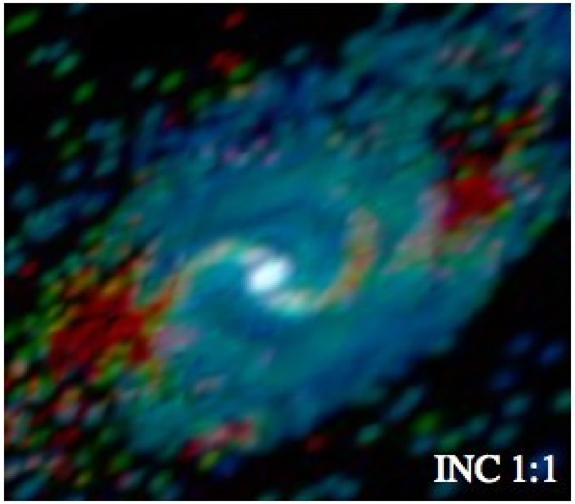
Hammer et al. 2009,
A&A 496, 381











Barnes, 2002
Gas, INCLINED, 1:1

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

- Explain well the 45° misalignement between dynamical & optical axes
- Observed gas fraction is 37% (from Kennicutt-Schmidt)
- it was > 50% at the beginning of the interaction, 800Myrs ago

➔ disk rebuilding…(e.g. Robertson+06; Hopkins+09; Lotz+09)

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?*

• could it explain kinematics & morphologies of spirals progenitors, 6 Gyrs ago?

• not necessarily consistent with observed merger rates

<u>Disk rebuilding scenario</u> *(Hammer+05)*

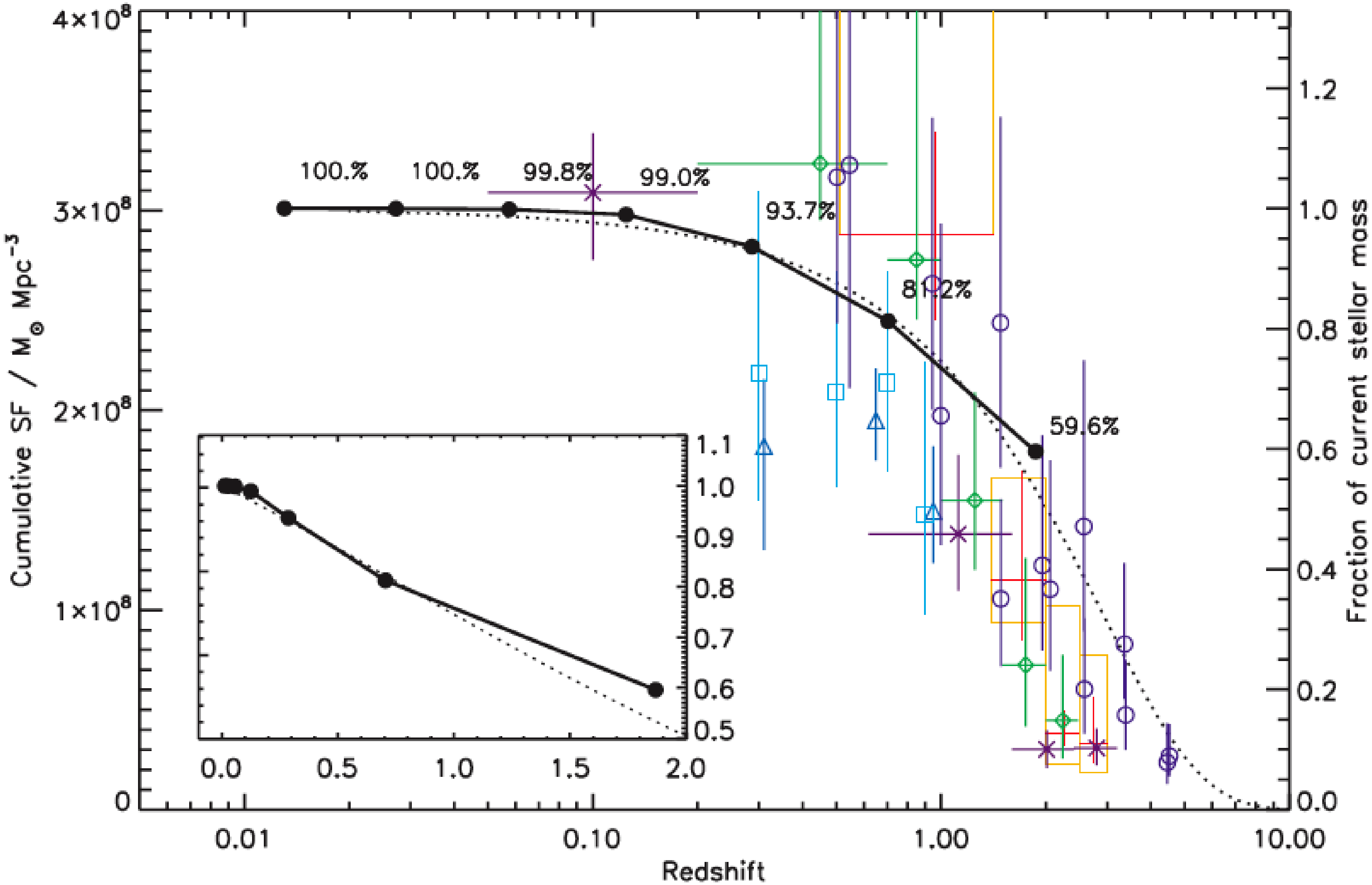
Inherited from the orbital momentum of the merger: *(Robertson+06, Hopkins+08)*

• requires large gas fraction in the progenitors: 40-50% to produce Sab-Sbc
➔ *Small & gaseous-rich (e.g. past merging of galaxies twice M33 could produce M31)*

• need to test age and fraction of oldest stars in large disks (M31: 5-7 Gyrs)
➔ *Still strong uncertainties in derivation the SFH from SDSS galaxies*

• presence of disks at higher redshift?

Star formation histories



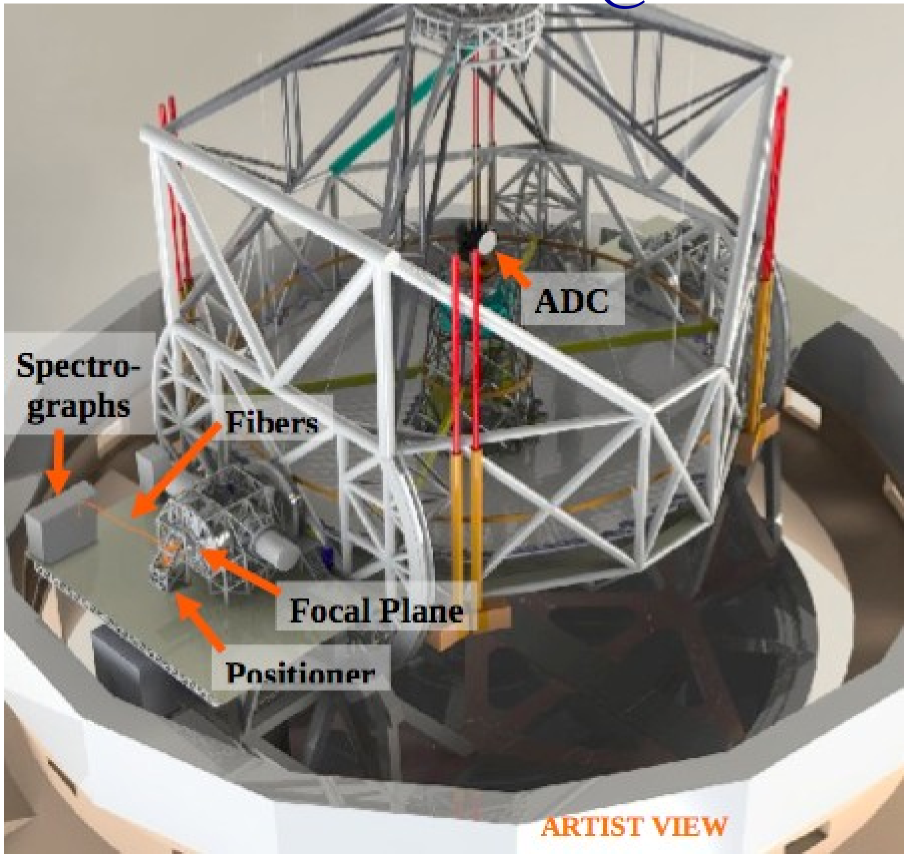
From Panter et al. 2007

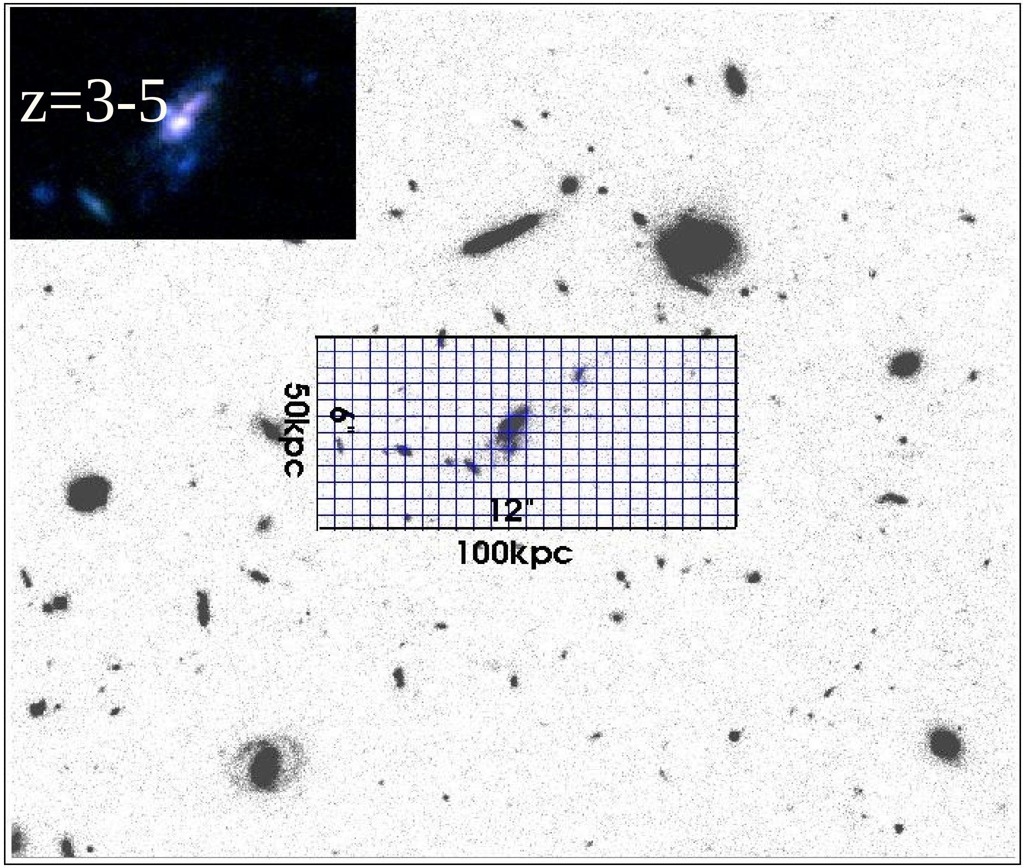
- still large uncertainties related to methodology, IMF choices;
- smaller fraction of stars formed since z=1: 30% *(Panter et al. 2007)*

➔ *but a large star fraction (> 50%) have to be formed in disks!*

Near future:
Halo kinematics in distant galaxies

OPTIMOS-EVE @ELT



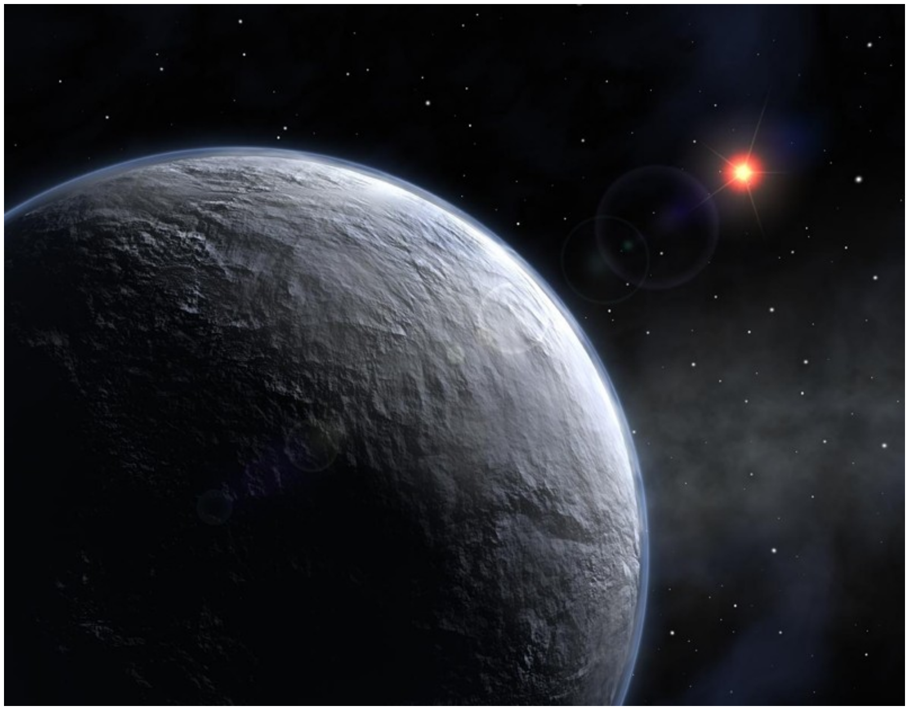


Resolved stars in galaxies

-With R=5000 down to I=25 we shall be able to measure kinematics and chemical composition of the stellar populations in the giant elliptical Cen A and of other galaxies of that group;

- R=15000 for detailed chemistry (Lithium…)

Extra-solar planets and their environments

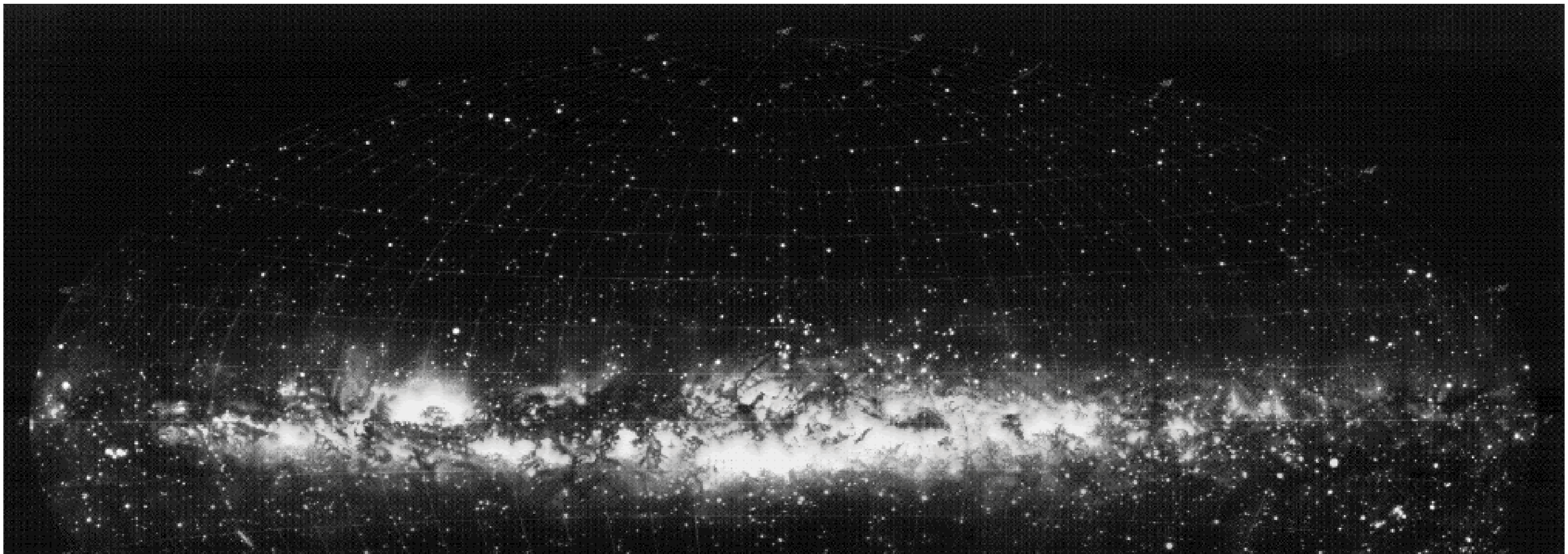


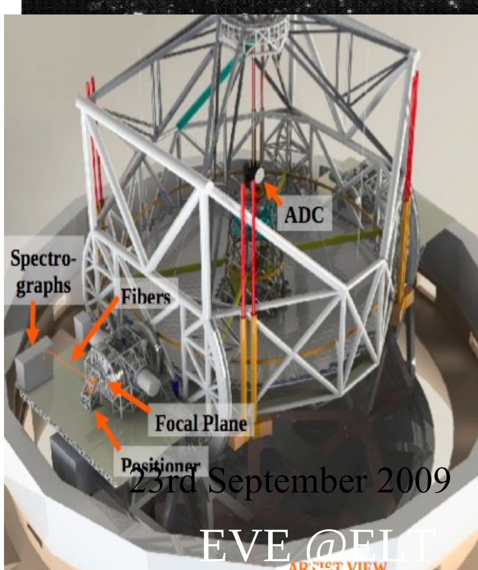
With a radial velocity precision of 10 m/s we may search for exo-planets in all ther Milky Way to … external galaxies

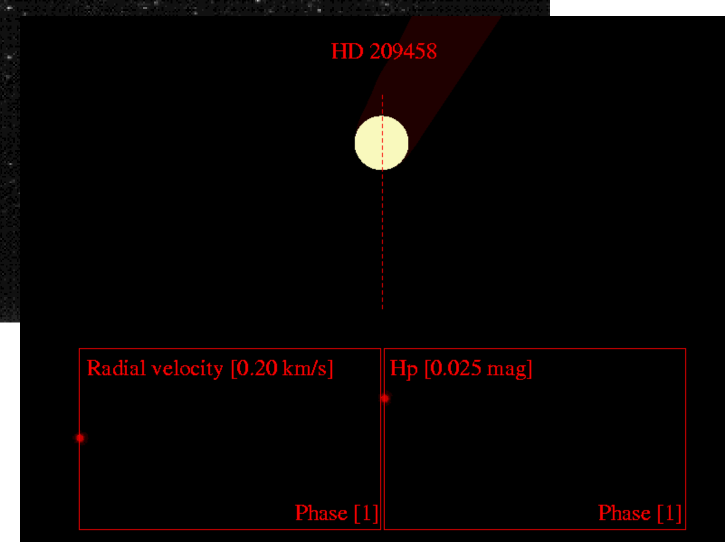
What	m_V [mag]
Galactic Bulge, giant	≈ 16
GC NGC 6397, turn-off	16.5
47 Tuc, turn-off	17.6
ω Cen, turn-off	18.1
Sagittarius, red clump	18.2
Sagittarius, turn-off	(21.5)
LMC, giant	≈ 18.5
SMC, giant	≈ 19.0

Numbers based on experience with FLAMES/GIRAFFE;
Better with focus-injection on fibres, under study at ESO
EVE consortium.

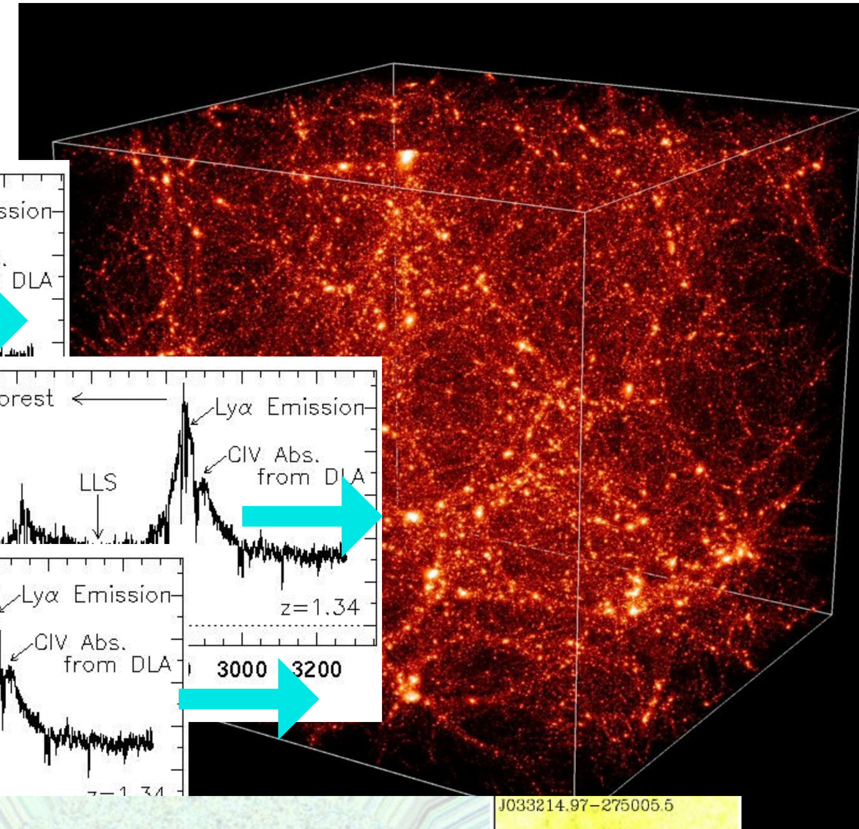
Search for planets in most of the Milky Way to the Magellanic Clouds

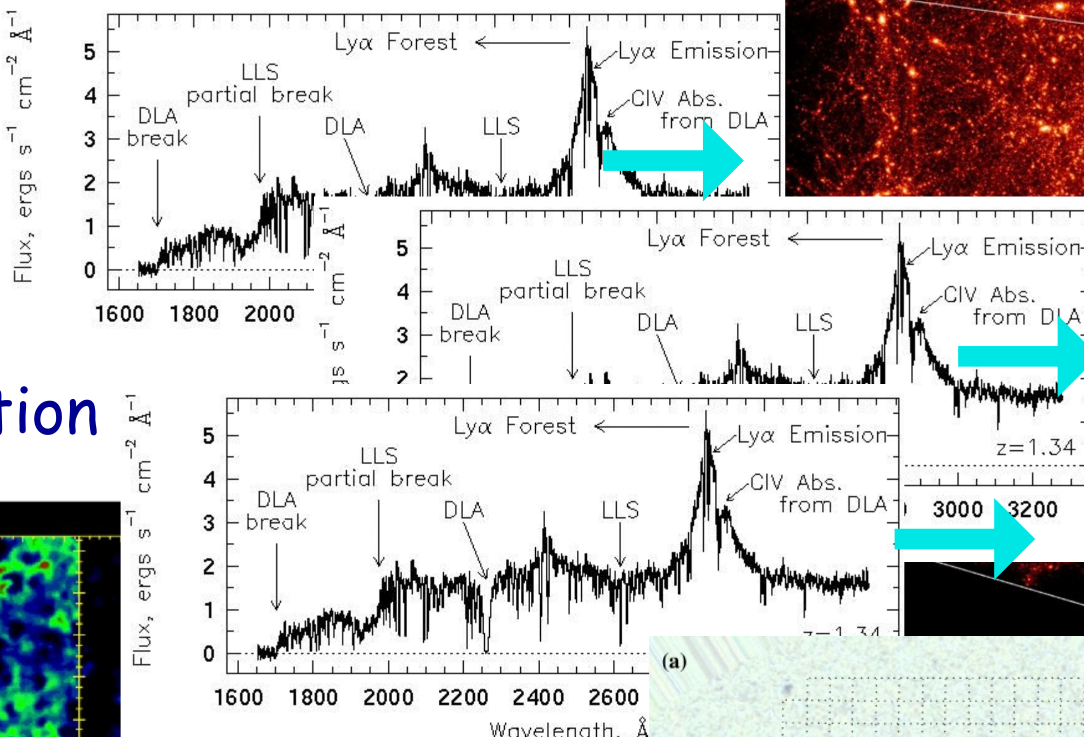




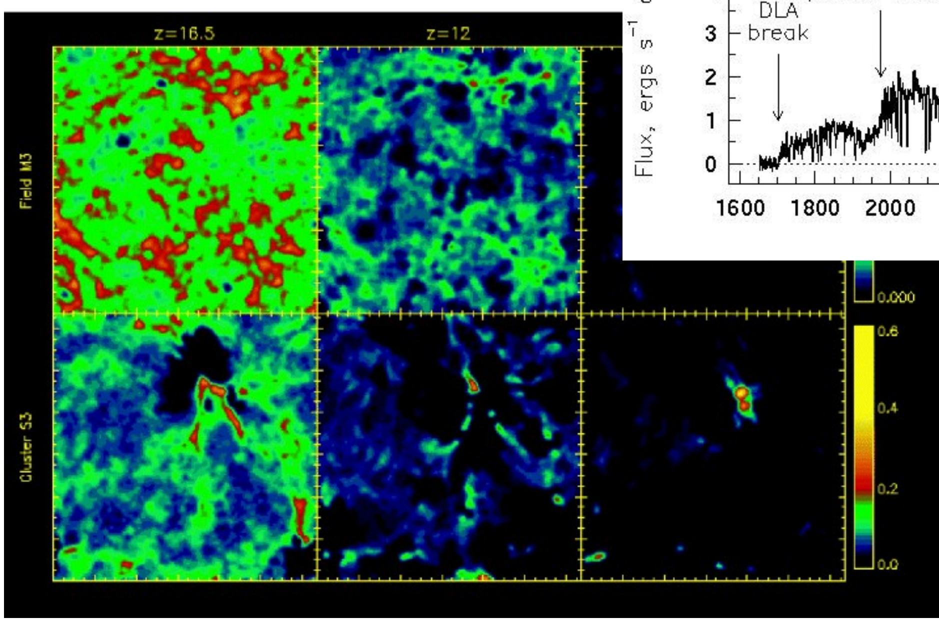


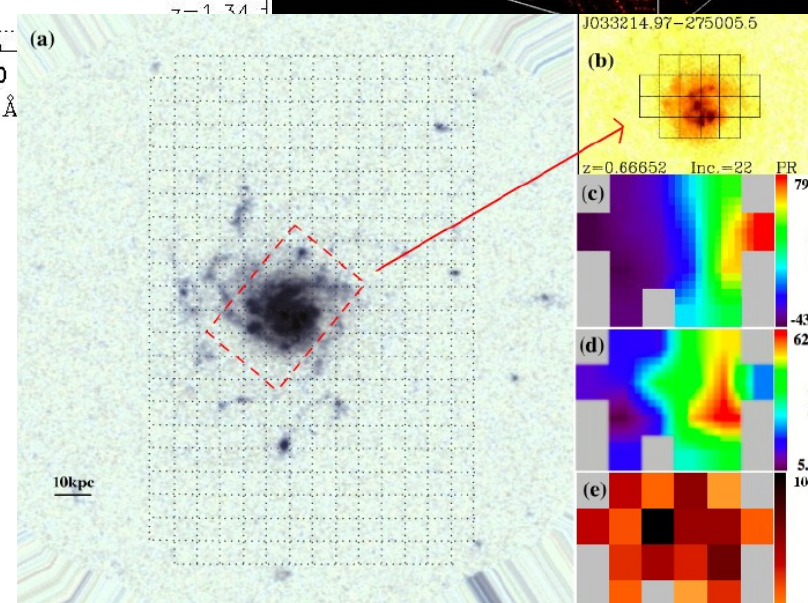
Tomography of the IGM





Tracing reionization





Kinematics of galactic haloes

Few remarks

The redshift decrease of rotating spirals (factor 2 at z~0.6) is consistent with the absence of convincing cases of rotating spirals at z= 1.5-3 (see e.g. Robertson & Bullock08)

The physics of disk building has to be fully revisited, possibly including:

- bar formation (see e.g. Hopkins+08);
- re-accreted gas & stars material (IMAGES project);
- ring formation;
- evolution of globular clusters & tidal dwarves (z~0.6: VLT/GIRAFFE;
  z~ 2 ELT/OPTIMOS-EVE)
- etc…

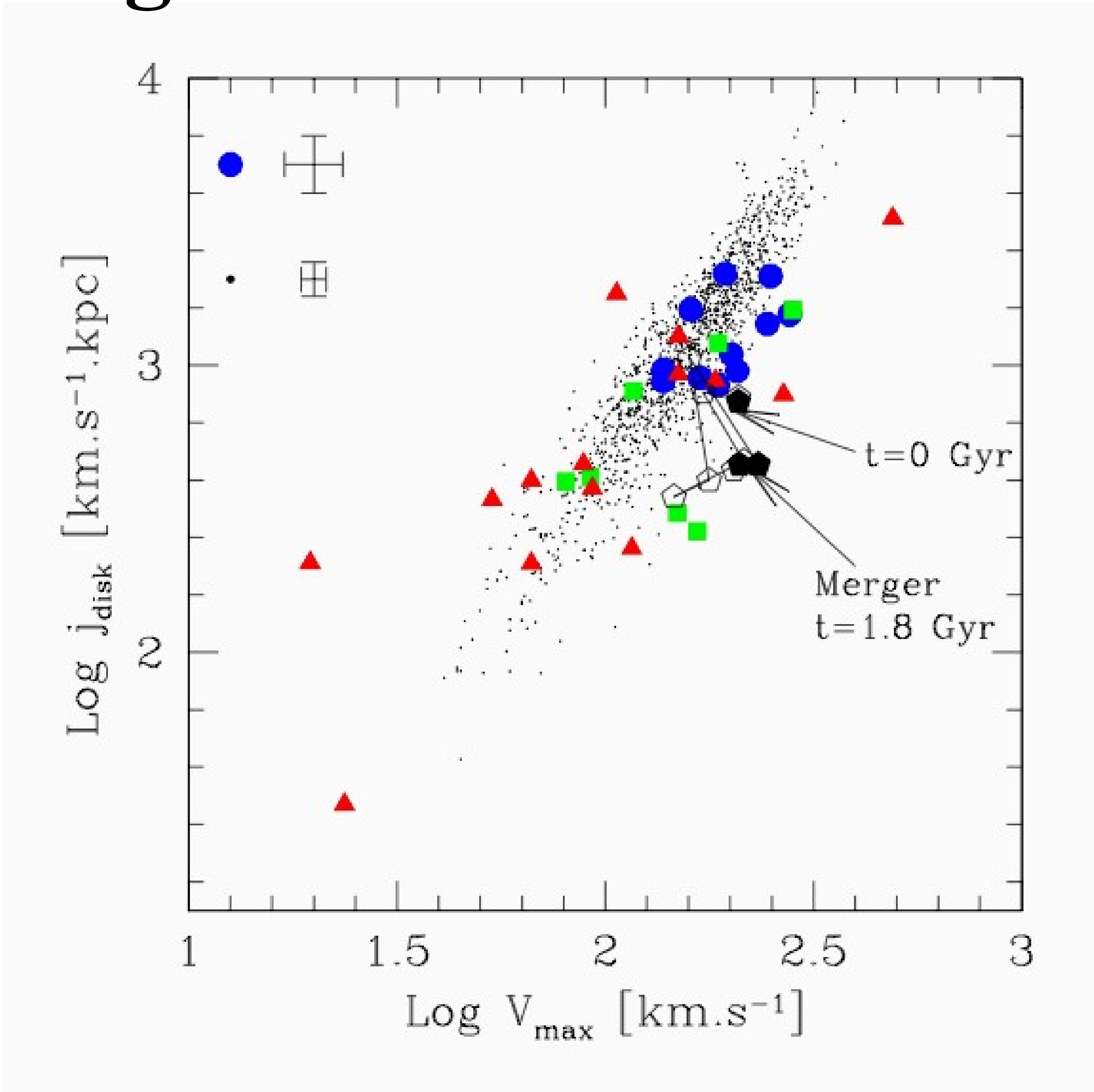
==> systematic comparison of models with a fair representation of nearby galaxies (SDSS+3D spectroscopy) combined with distant galaxies (IMAGES)

Specific Angular Momentum

$j_{disk}=2R_dV_{max}$

➢A random-walk evolution of j_{disk}

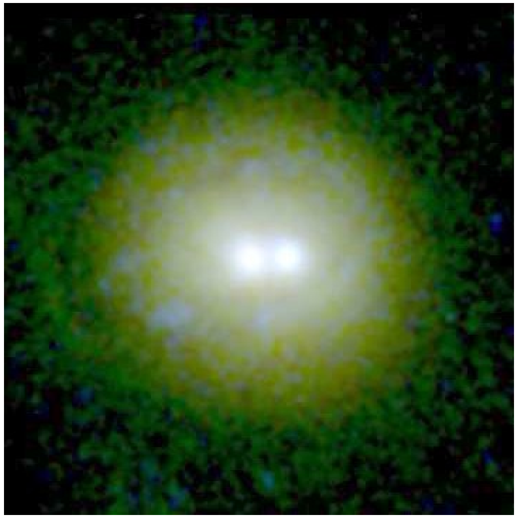
➢Dispersion of CKs consistent with major mergers



Complex Kinematics
Perturbed Rotators
Rotating Disks

Puech et al. 2007

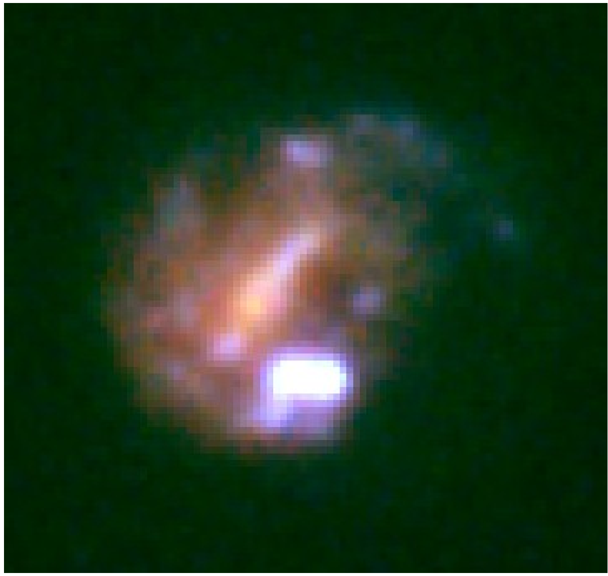
Feedback or not feedback?



Feedback has not been considered *a priori* in simulations:

• Deep spectroscopy show no differences between z_gas & z_stars, except for 4 robust mergers (Hammer+09);

•SFR are not extreme (<< 100 M/yrs) in these massive galaxies;



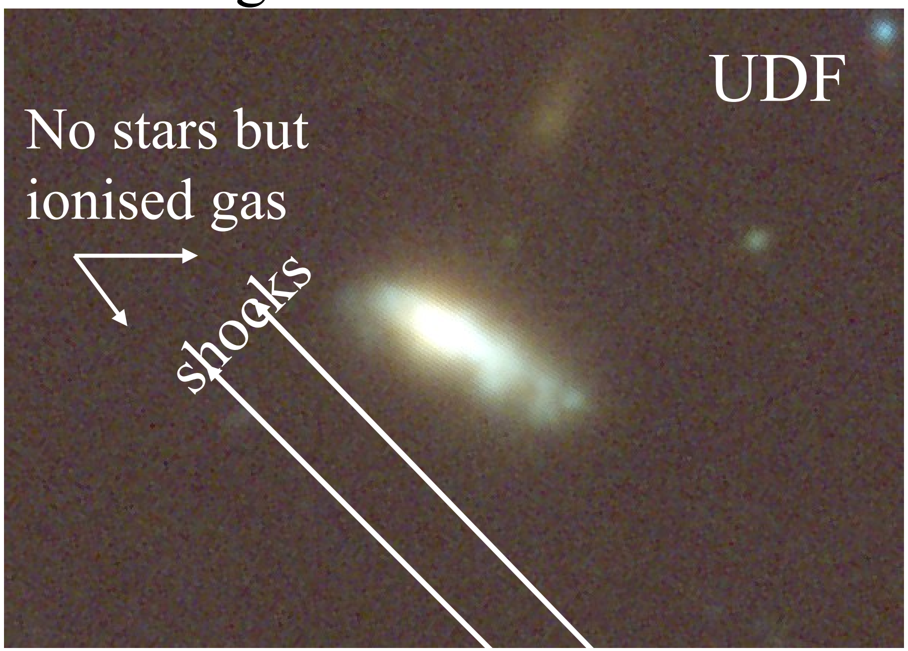
• gravitational physics in gaseous-rich mergers dominates feedback in rebuilding disks (Hopkins+09)

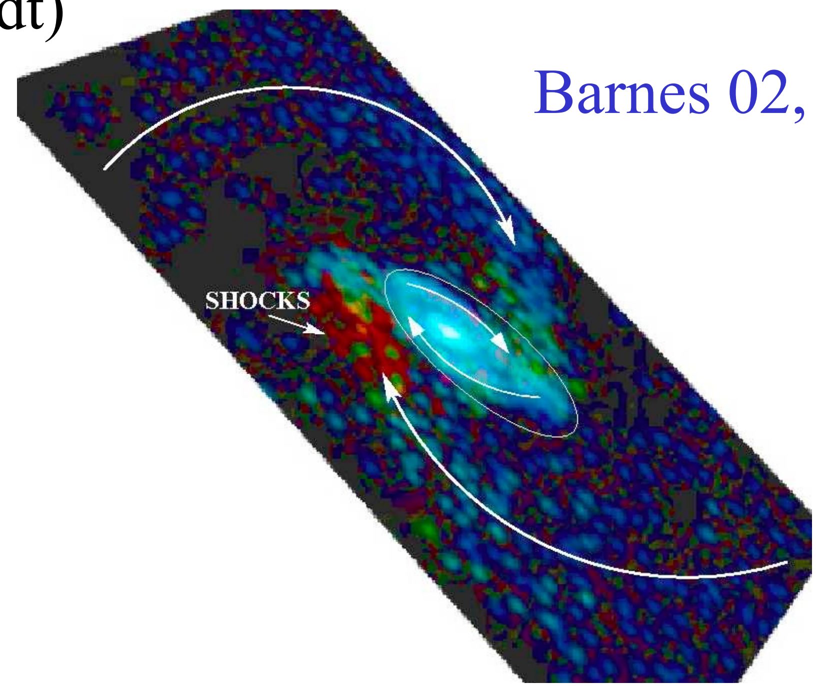
• we do see feedback at smaller scales in few galaxies

Gas ionisation induced by shocks in a z~0.6 forming galaxy

Puech et al. 2008, A&A submitted

f_gas=73-82%
(SED fitting+TF & Kennicutt-Schmidt)





Barnes 02, DIR 1:1

Property	Starbursting Rotating Disk	Major Merger Remnant
Extention of the peak of dispersion in the Southern part	Cause unknown	Heating due to shocks between the gas in tidal tails and the central regions
Decoupling between the distribution of the ionized gas & stars	Photo-ionization can account for only 10% of $EW_0([OII])$	Shocks can ionize the gas and account for 100% of $EW_0([OII])$, while preventing star formation

Conclusions

- the MW has an exceptionally quiet history since z=3: most other spirals (e.g. M31) may have had a much richer merger history;
- 6 Gyr ago half of the spiral progenitors were out of equilibrium, mostly showing merger remnant properties;

==> disk survival is a key issue ! (Hammer+07; Stewart+08; Purcell+08)

Disk rebuilding scenario consistent with:

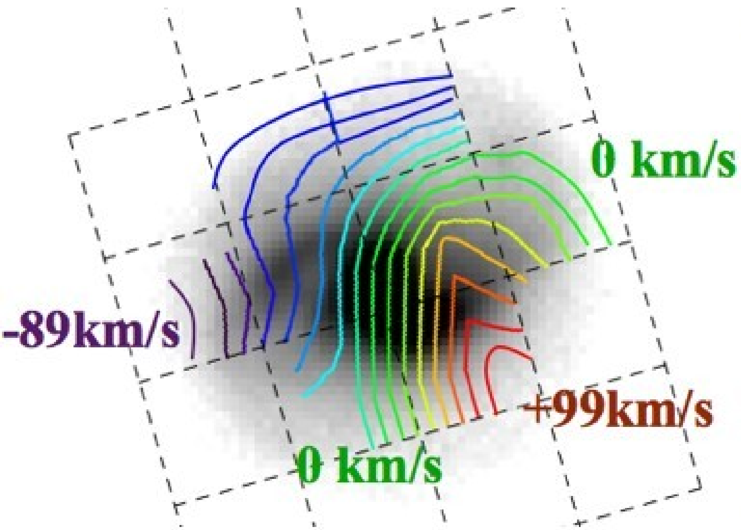
- **distant galaxy properties (stellar mass assembly mainly through episodic IR phases driven by mergers);**
- **evolution of the gas content;**
- **the relics in haloes of local spirals.**

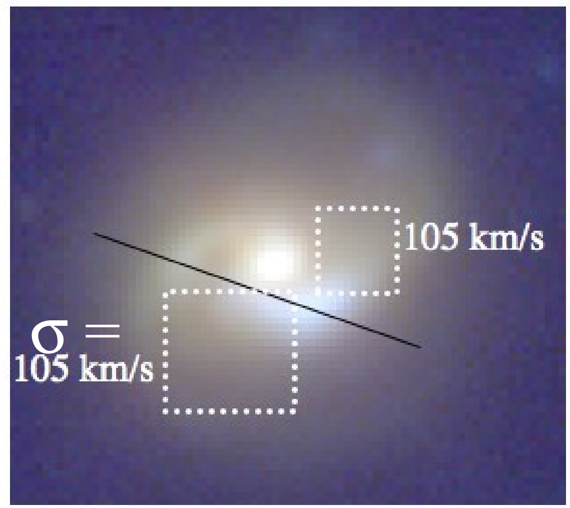
==> in excellent agreement with hierarchical prediction (both E & Sp are hierarchically formed)

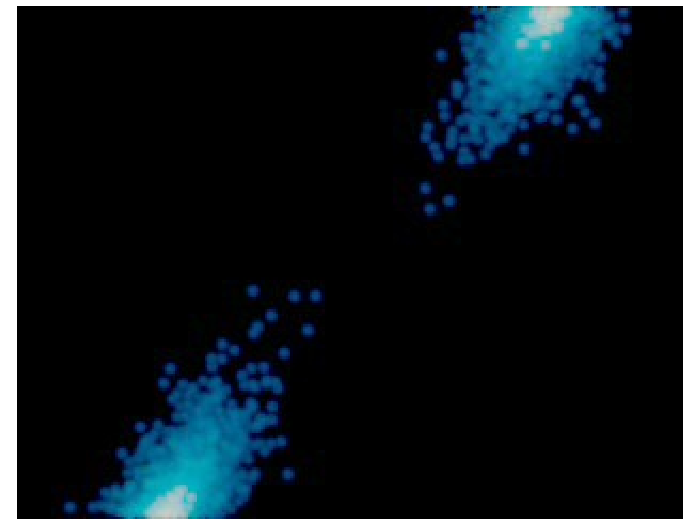
Potentially could solve the angular momentum catastrophe and explain the elaboration of the Hubble sequence

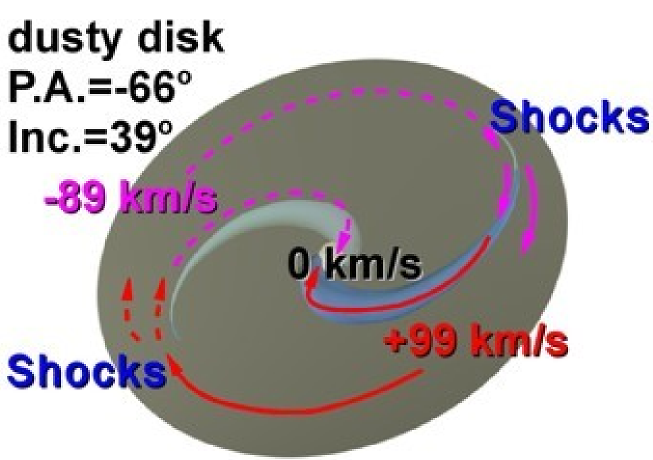
A disk rebuilt 500 Myrs after a gas rich merger at z~0.4?

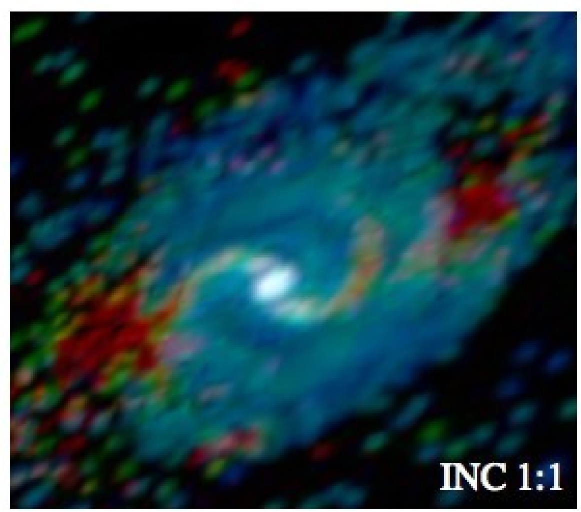
Hammer et al. 2009,
A&A 496, 381







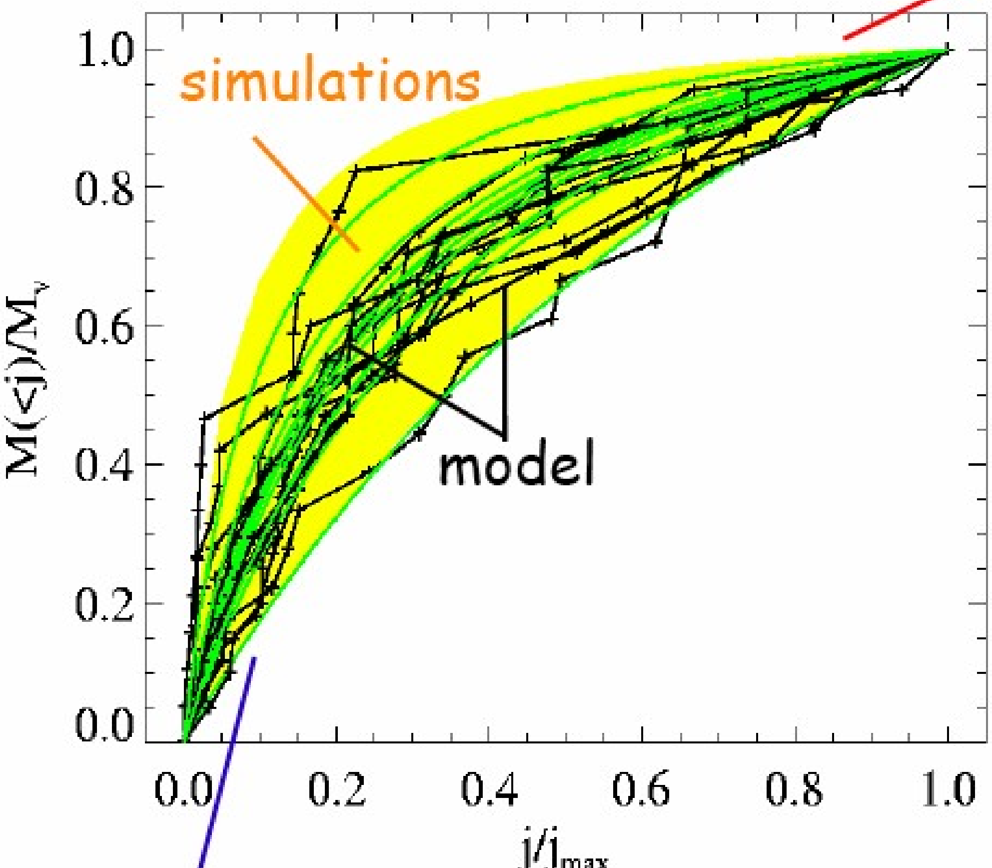


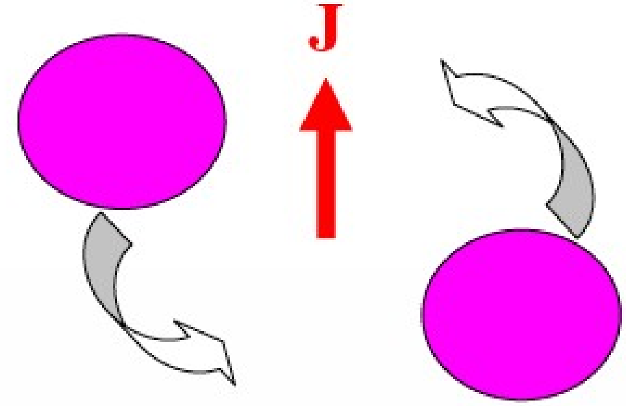


Barnes, 2002
Gas, INCLINED, 1:1

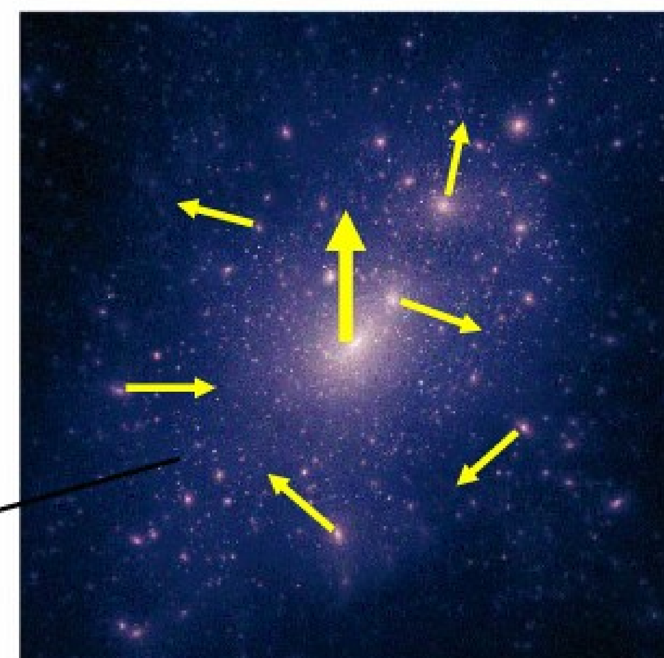
Low/high-j from minor/major mergers

High-j from major mergers





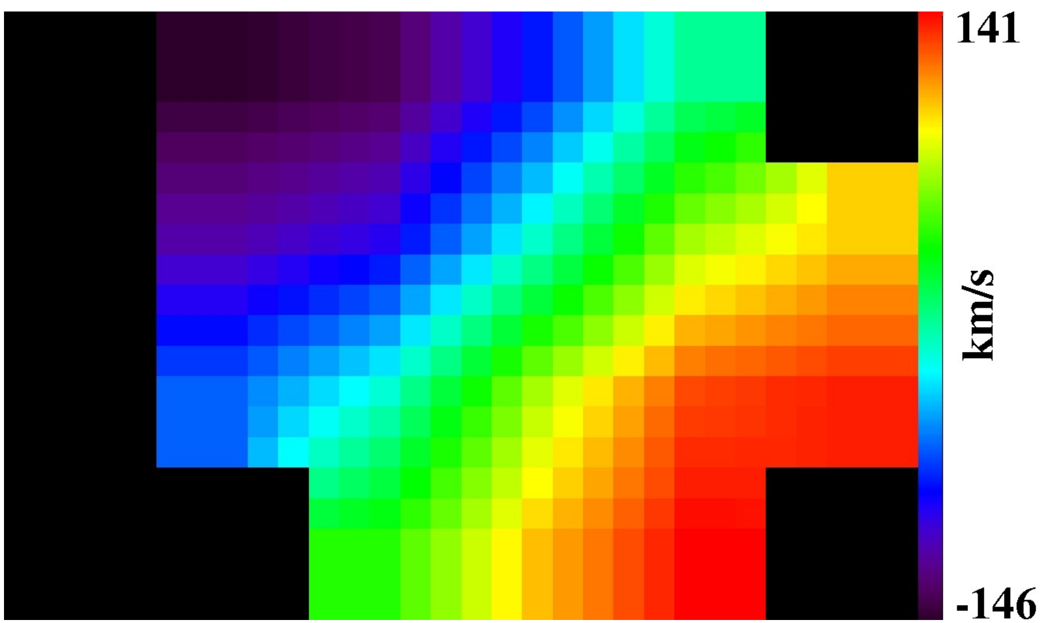
Low-j from minor mergers



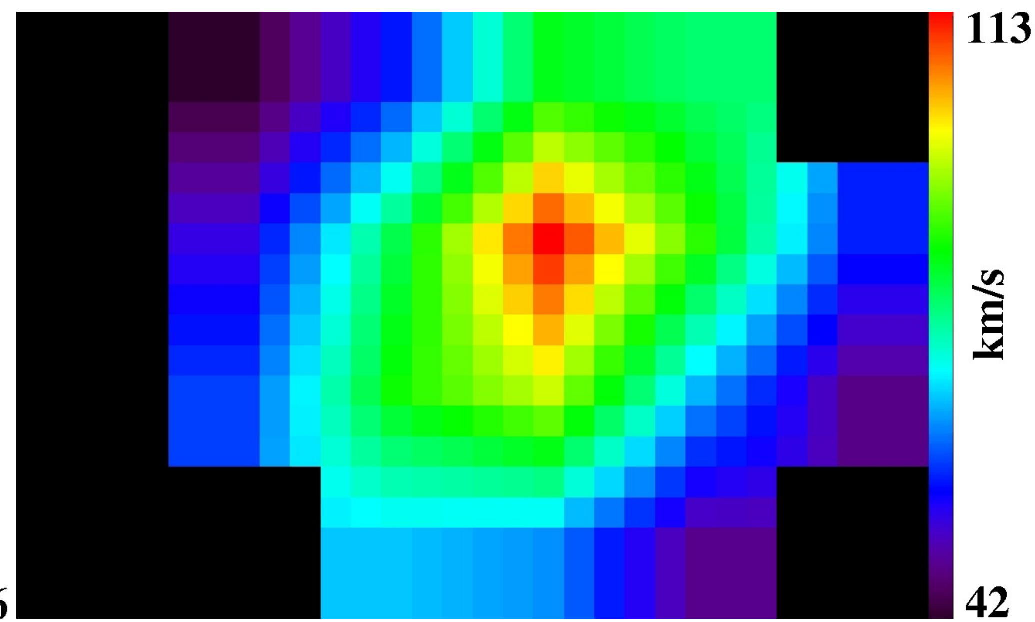
Velocity fields and also σ-maps

At low spatial resolution, dispersion maps of rotating disks do show a peak in their dynamical center

$$\sigma_{pixel} = \sigma_{random\_motions} \otimes \Delta V_{large\_scale\_motions}$$



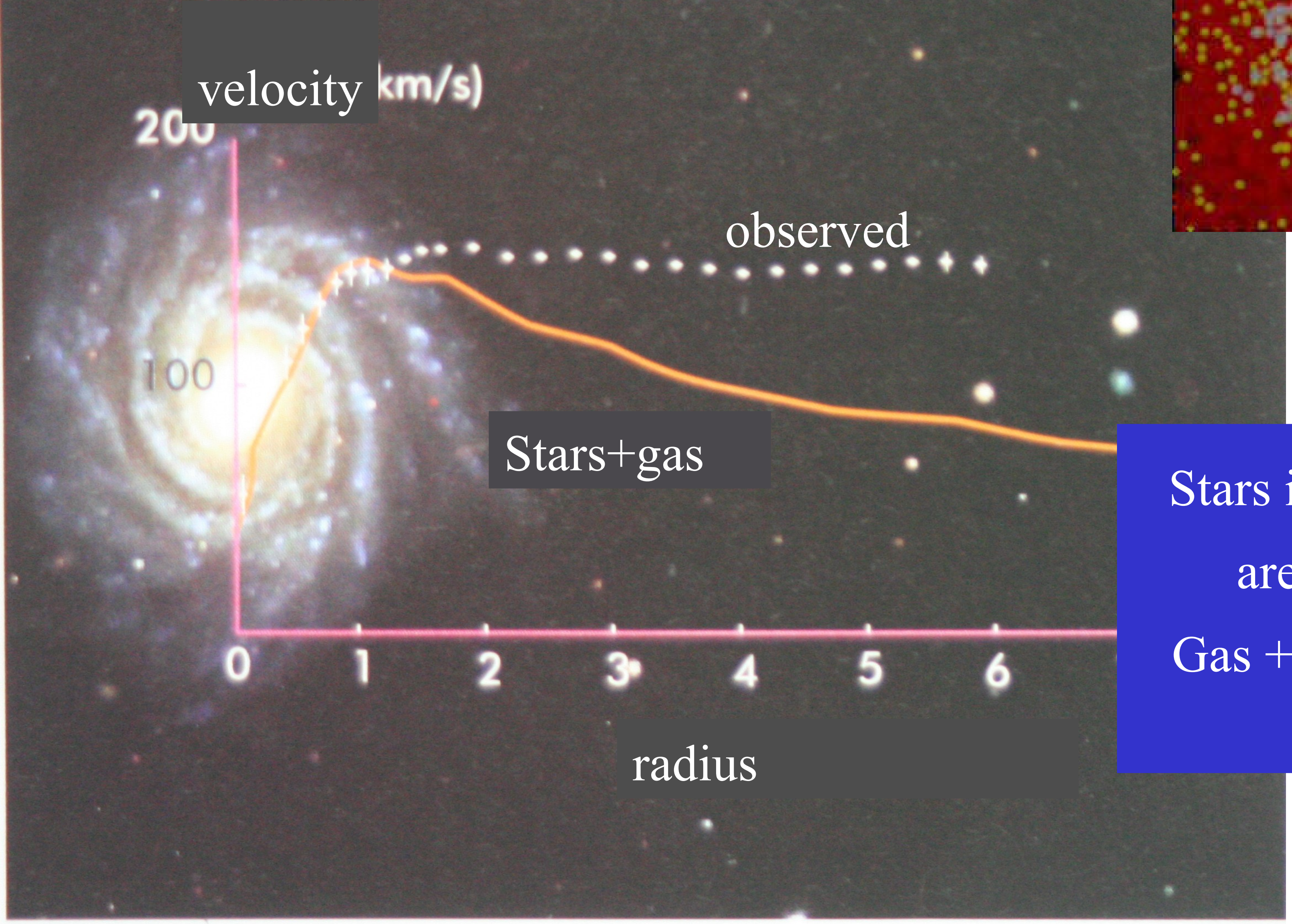
Velocity map

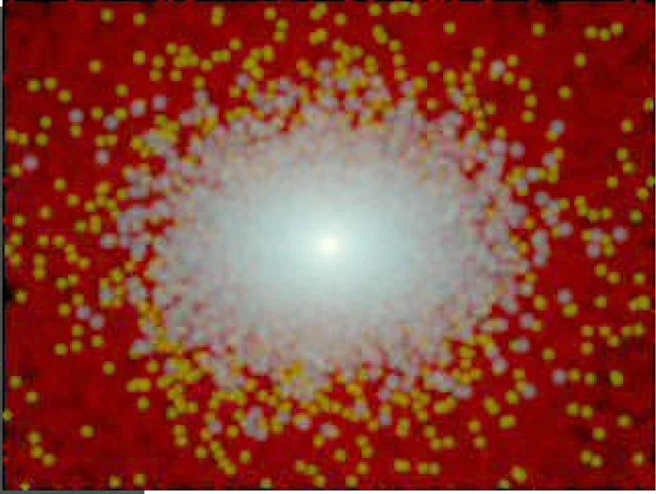


Dispersion or σ-map

see e.g. Flores+06, Yang+08, Epinat+09

An evidence for dark matter



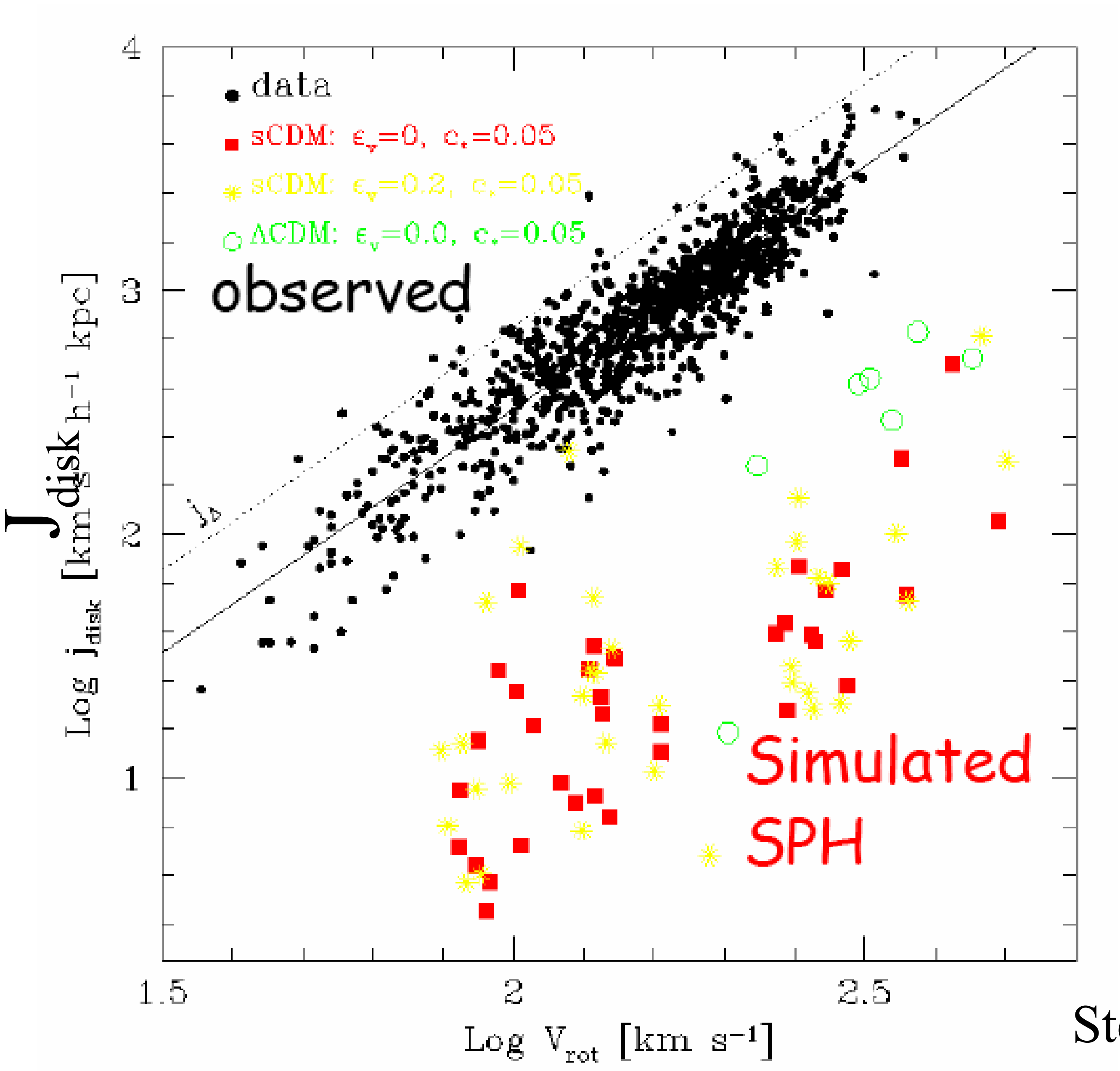


Stars in rotating spirals are rotating fast!

Gas + stellar mass: not sufficient

e.g. Zwicky, 1933

The angular momentum catastrophe



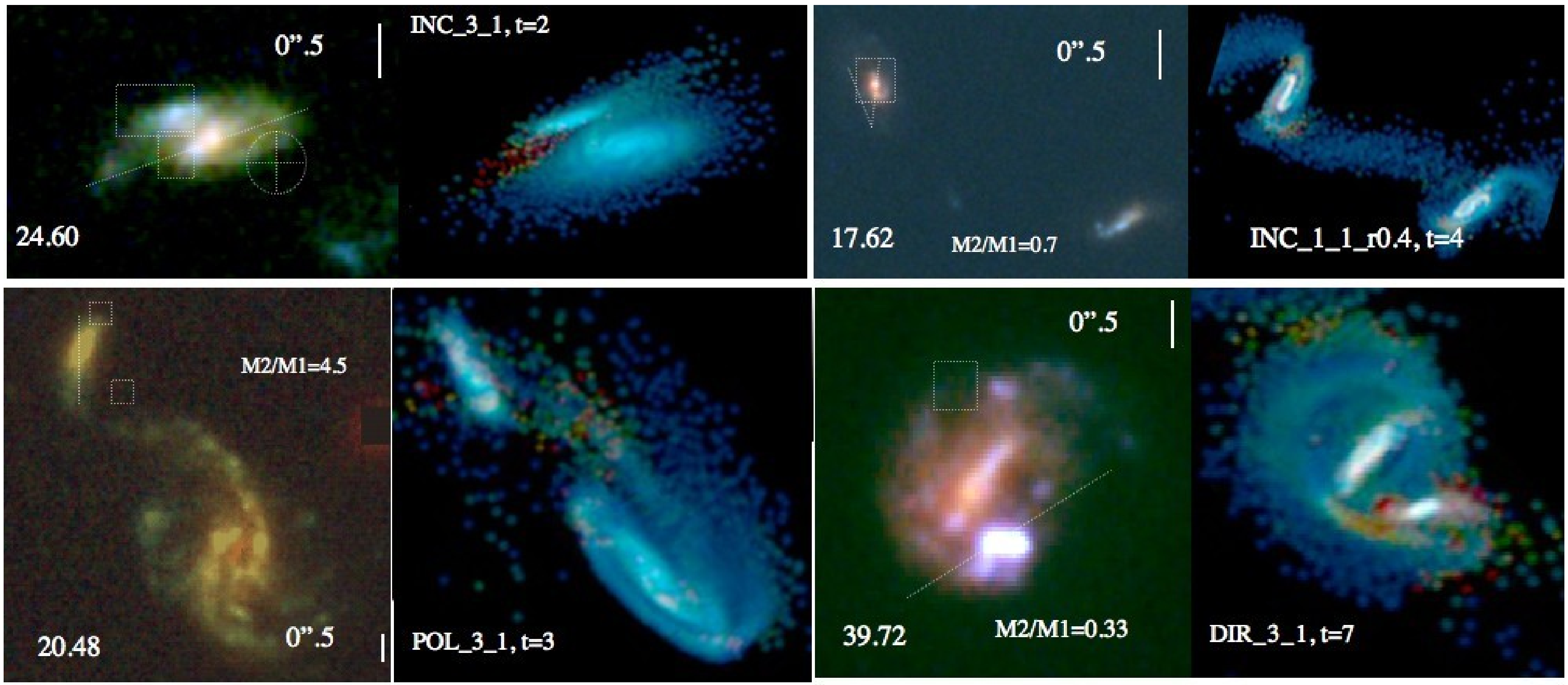
~ R-V relation

Steinmetz & Navarro, 1999

V

Half of the anomalous galaxies could be reproduced by major mergers, before the fusion, i.e. they show two nuclei …

Hammer et al. 2009, A&A, submitted, arXiv0903.3962H



➔ **Are all anomalous galaxies merger or their remnants?**

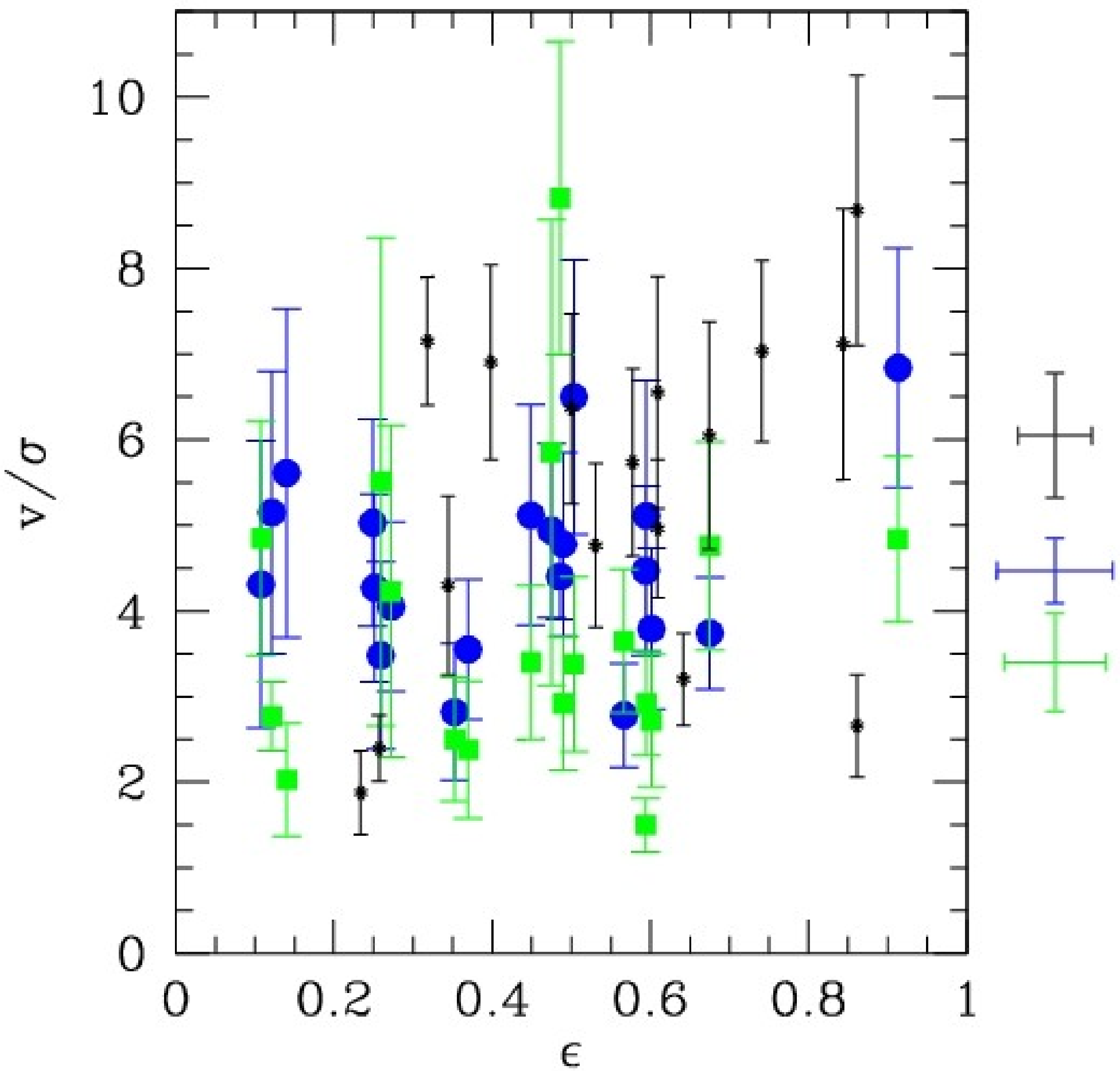
Progenitors of Milky Way mass (M_{stell}=5 10^{10} $M_{\odot}$) galaxies would be with M_{stell}~ 1.5 10^{10} $M_{\odot}$ and f_{gas} ~ 50%

Dynamical support of the gaseous disks

- Gaseous disks are heated compared to local disks

- Suggest gas accretion and/or minor mergers according to simulations

Dynamical imprint of the accretion of the external gas supply ?



Updated from Puech et al. 2007