l'Observatoire de Paris | GEPI
Galaxies Étoiles Physique et Instrumentation

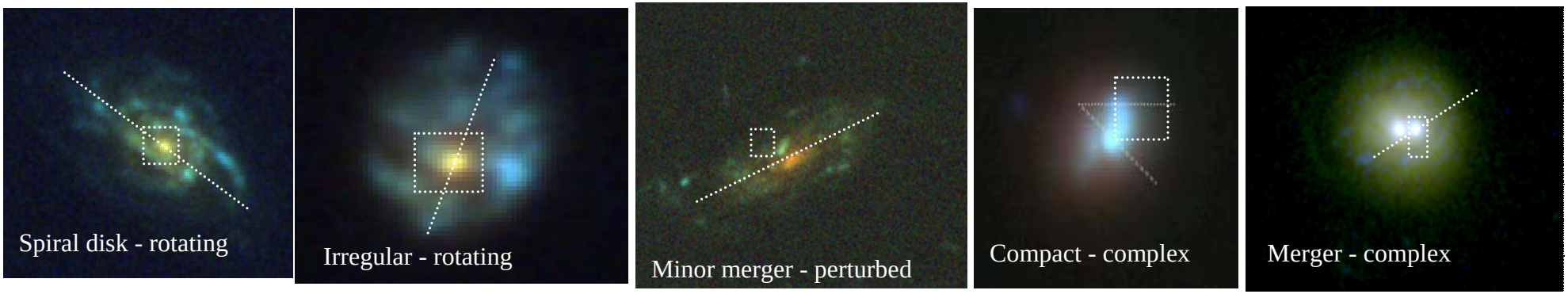
The elaboration of spiral galaxies:

morpho-kinematics analyses of their progenitors with IMAGES

by François Hammer
on behalf of the IMAGES collaboration

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



Galaxy Evolution since 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)

From evolution of:

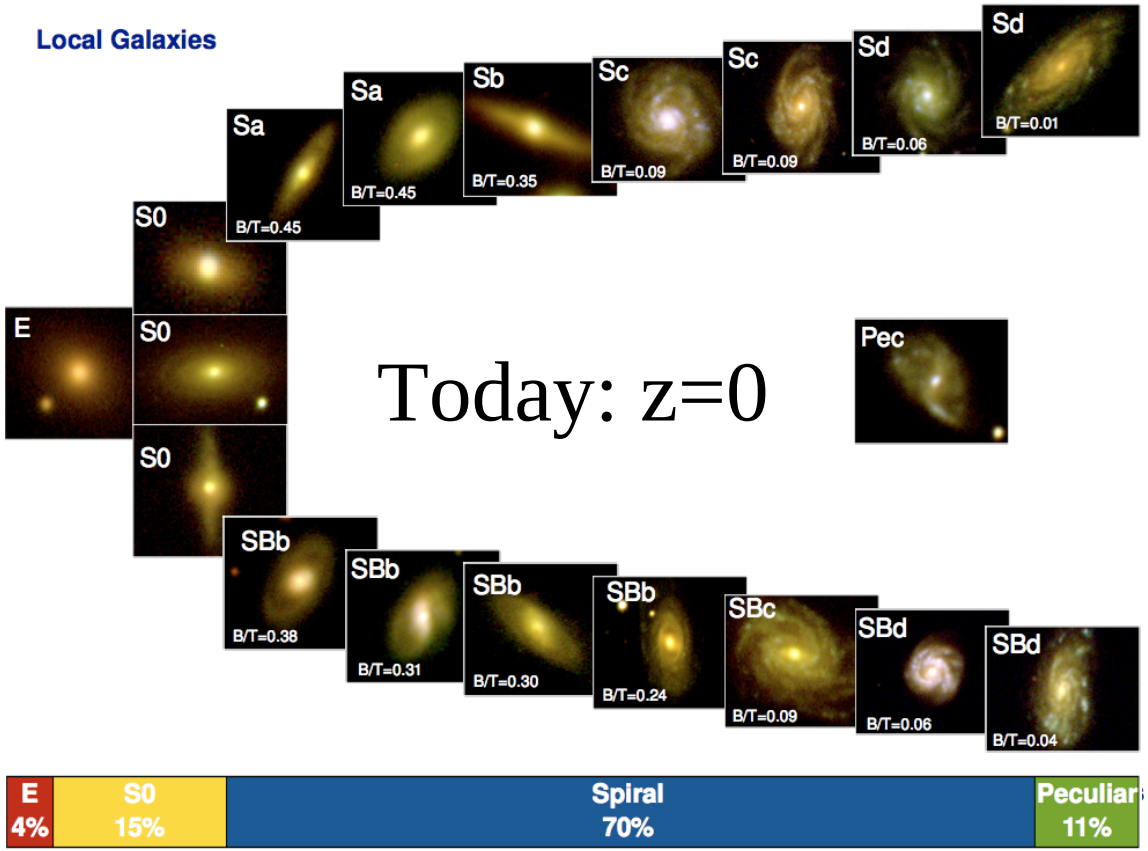
1. global stellar mass (photometry, near-IR)

2. integrated SFR (including IR light)

- Most of the stellar mass formed in LIRGs (SFR > 19 $M_\odot$/yr)
- Mostly associated to evolution of interm. mass galaxies (Hammer+05, Bell+05) :

  $2\ 10^{10} < M_{stellar} < 2\ 10^{11}\ M_\odot$, i.e. around Milky Way mass
- Today, 70% of spirals…

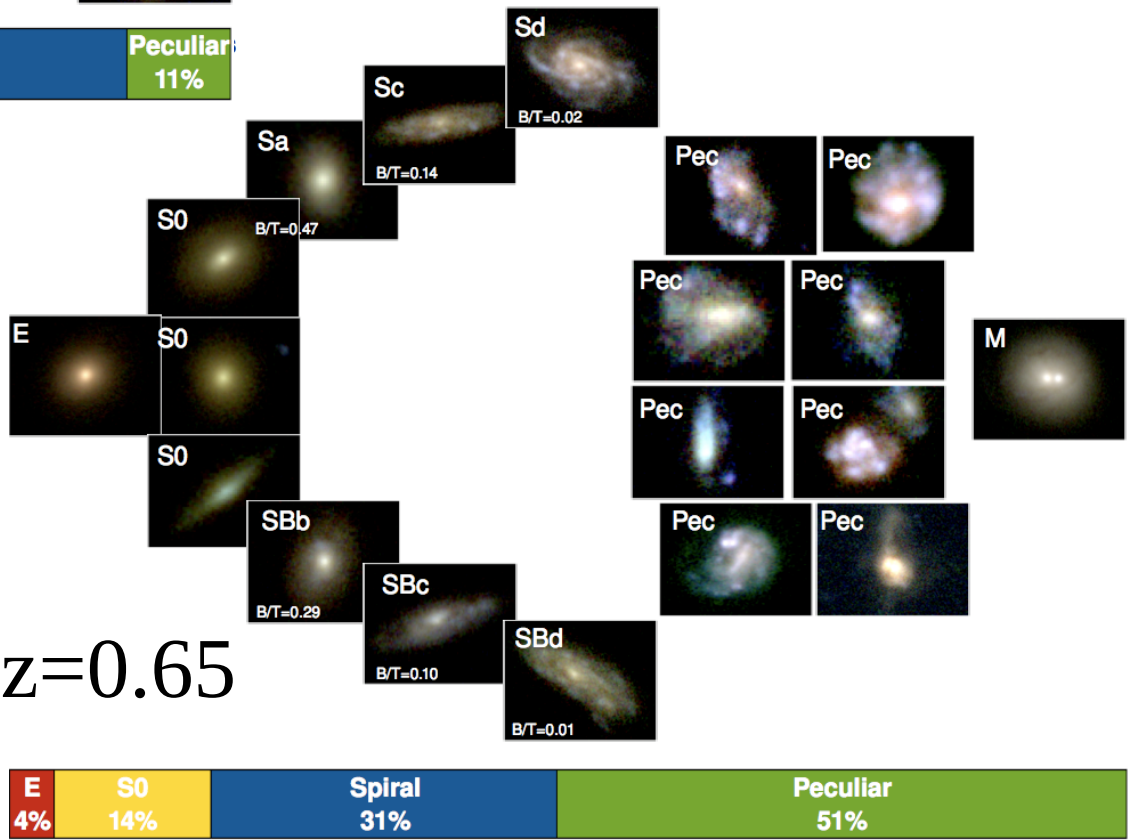
→ *requires resolved kinematics of z~0.65 intermediate-mass galaxies*



Today: z=0

$M_J < -20.2$

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



6 Gyrs ago: z=0.65

IMAGES-GTO Survey

The deepest ever made observations of distant galaxies

Sample selection

$M_J < -20.3$ & $0.4 < z < 0.9$

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

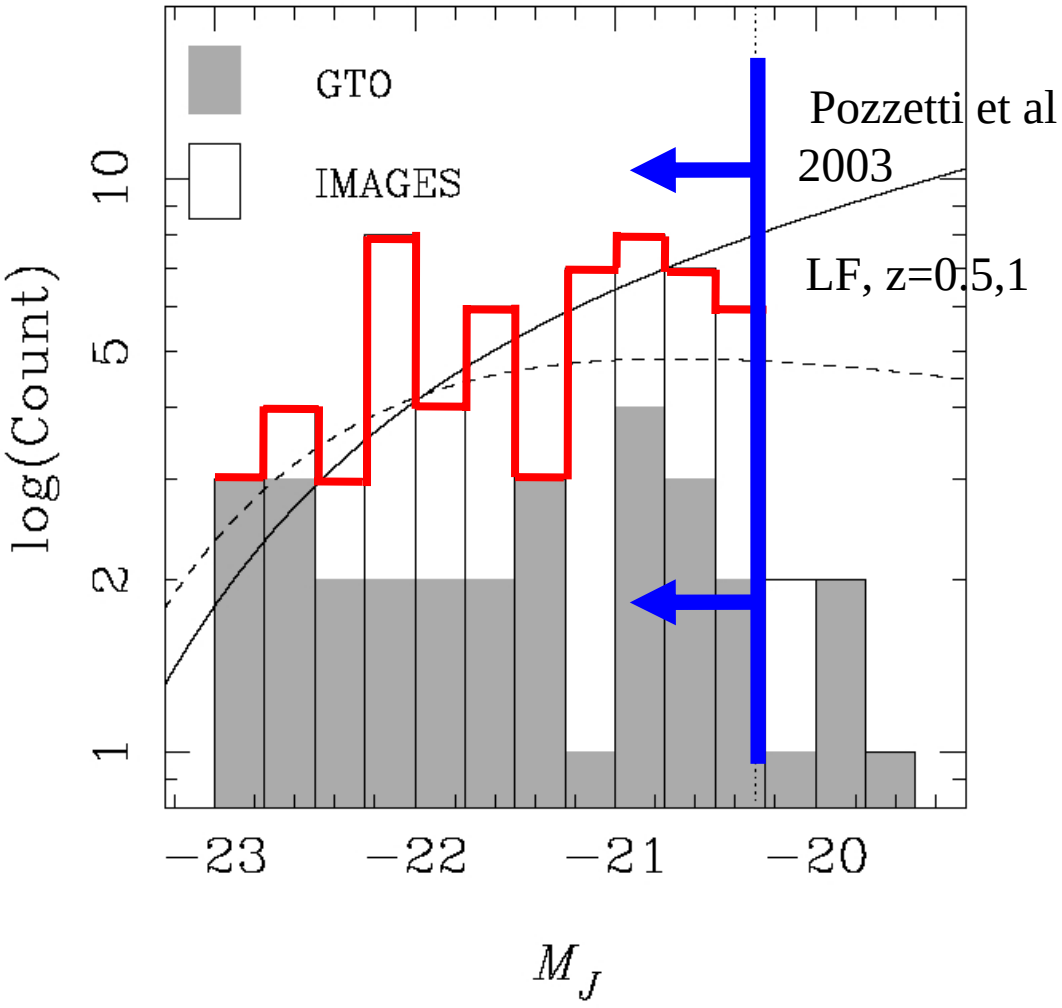
100 galaxies with spatially resolved kinematics

100 Intermediate mass galaxies :

- M_J < -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

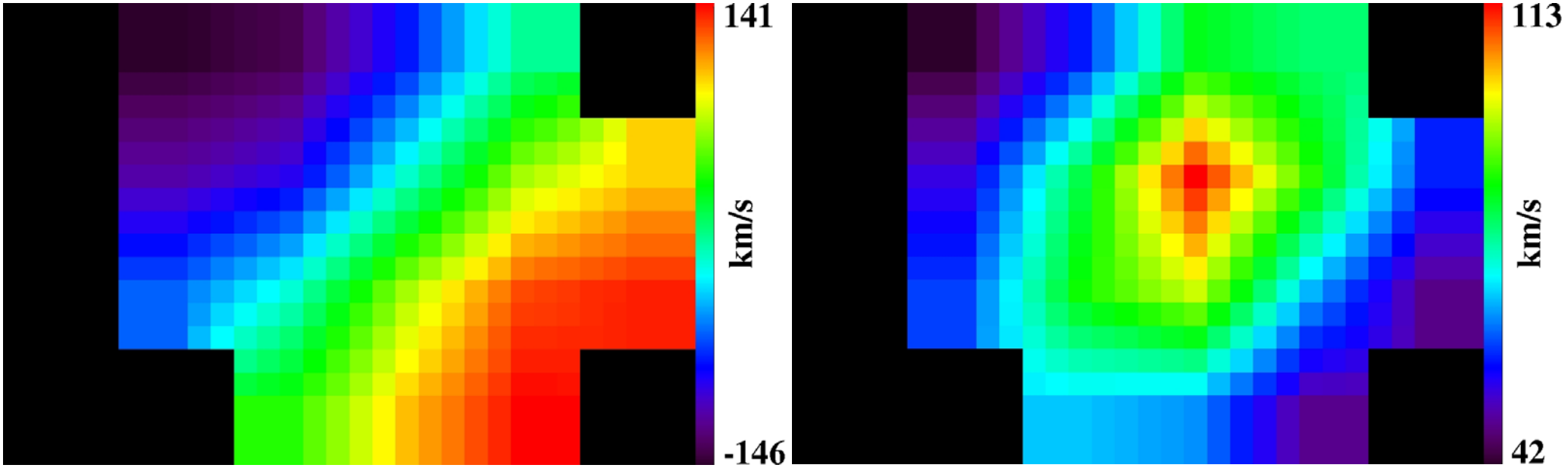


From Yang et al (2008), A&A 474, 807

Velocity fields and also σ-maps

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

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

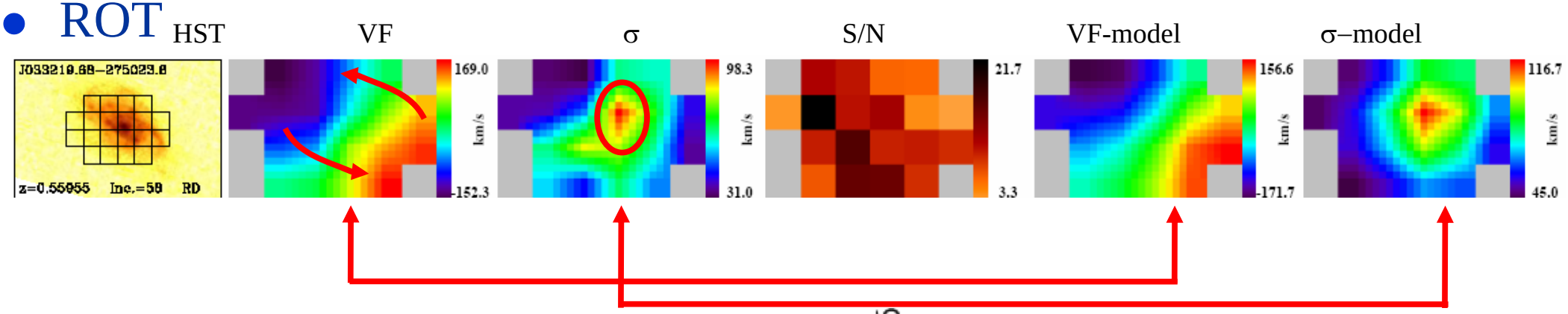


Velocity map **Dispersion or σ-map**

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

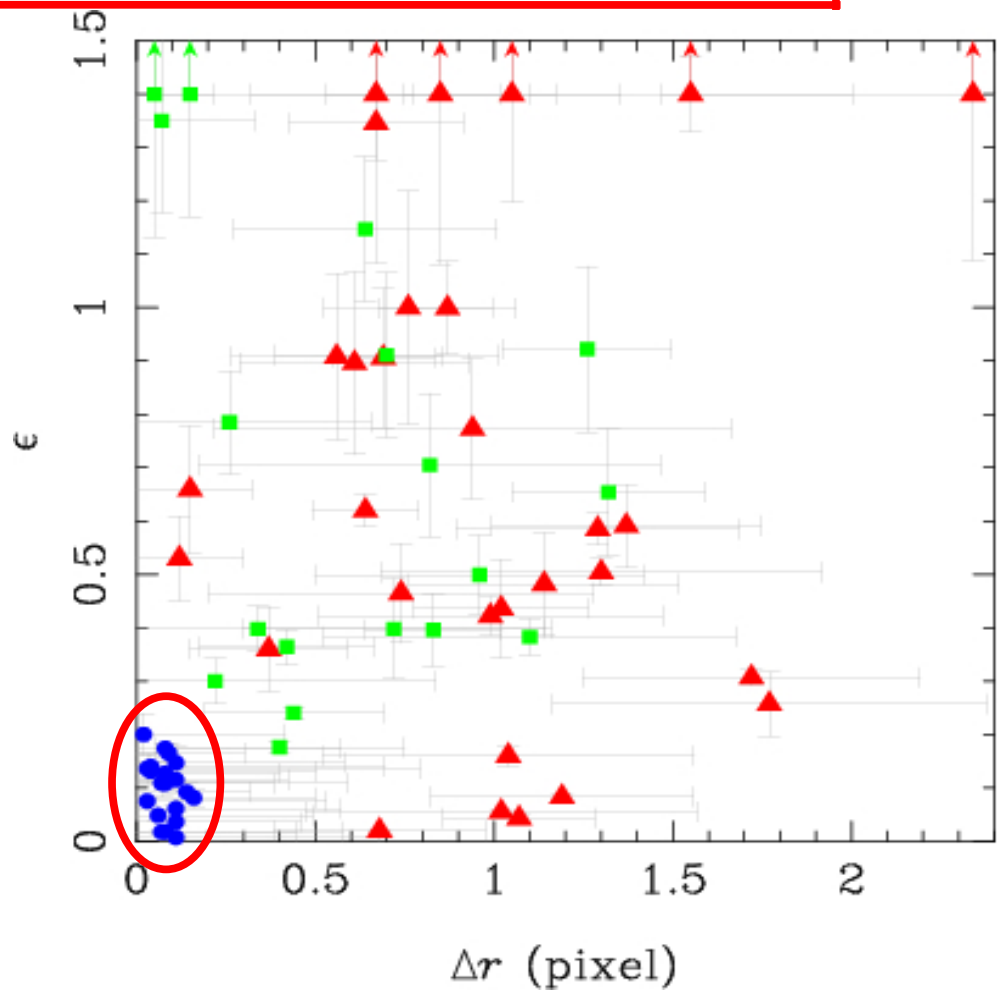
Resolved kinematics: rotating (Rot)

- ROT



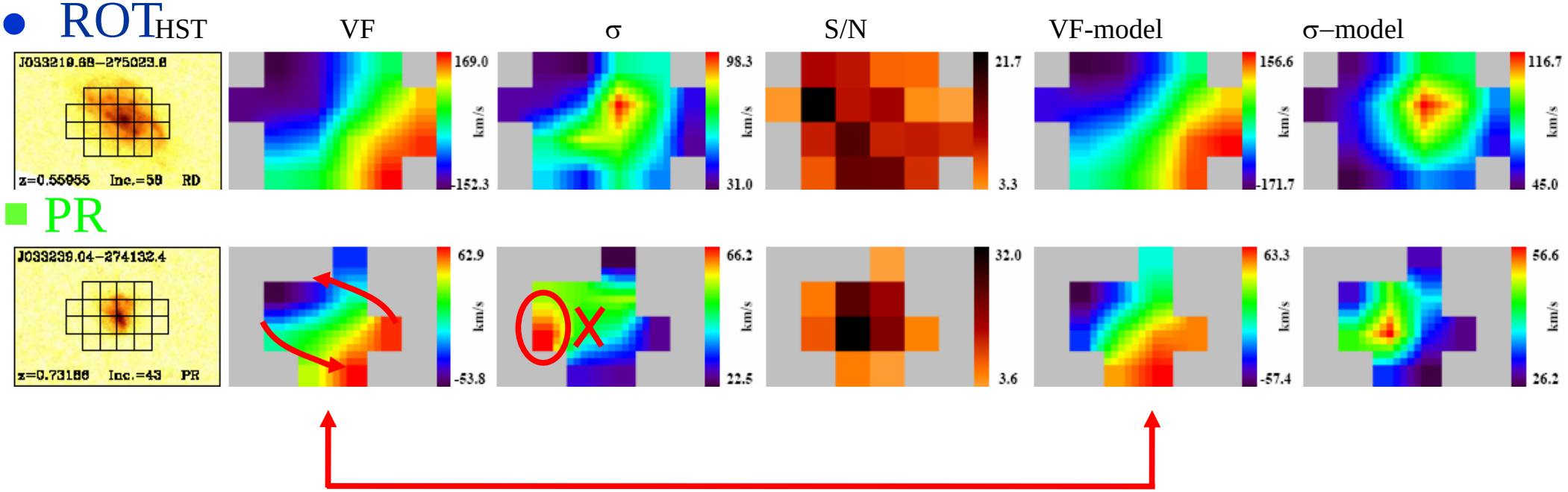
All distant galaxies are compared to local rotating disks:

- large scale motions due to rotation
- aligned with the optical axis
- simulation of corresponding VF and σ-map
- comparison of the derived σ-maps to the observed ones (relative difference of amplitude ε vs. σ peak distance Δr)

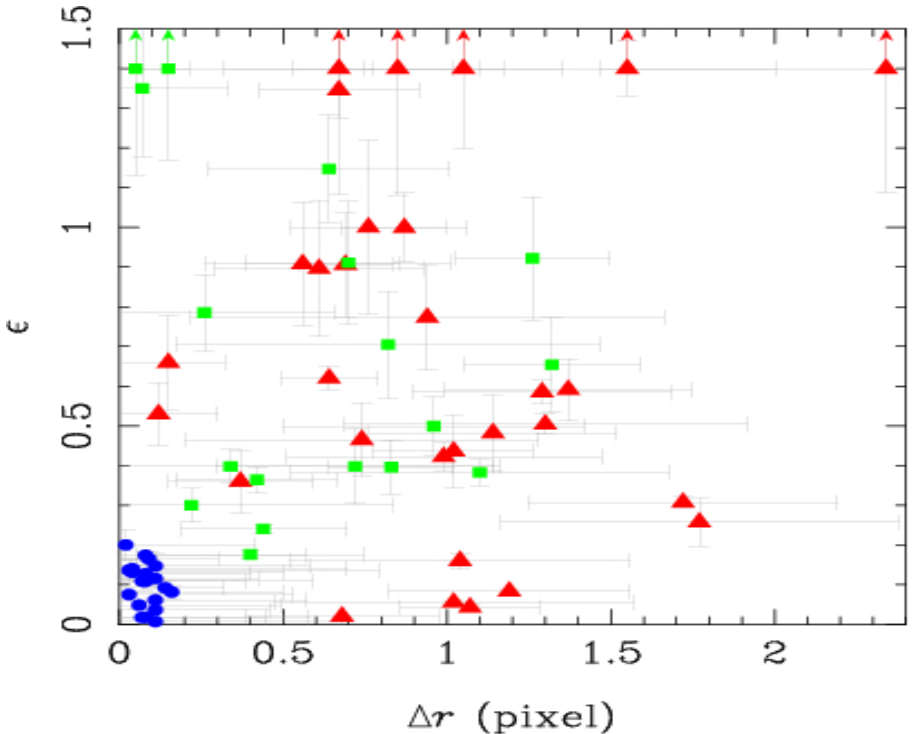


Resolved kinematics: perturbed rotation (PR)

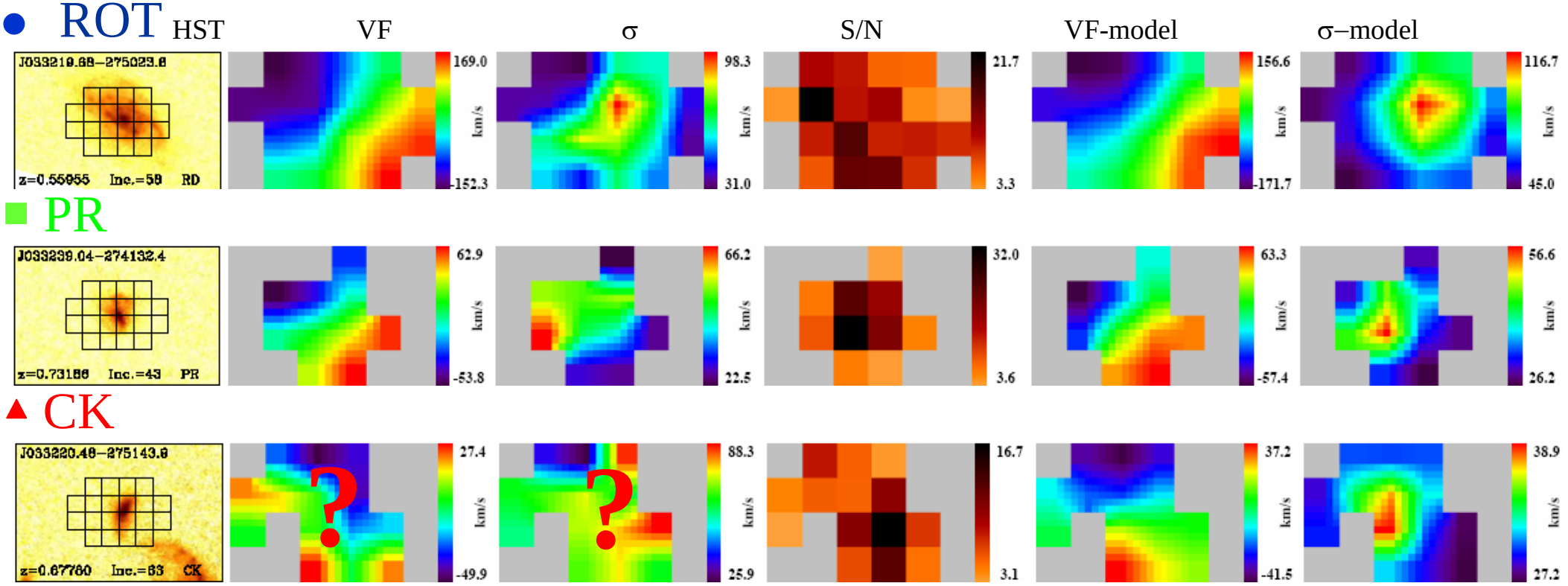
- ROT$_{HST}$
- PR



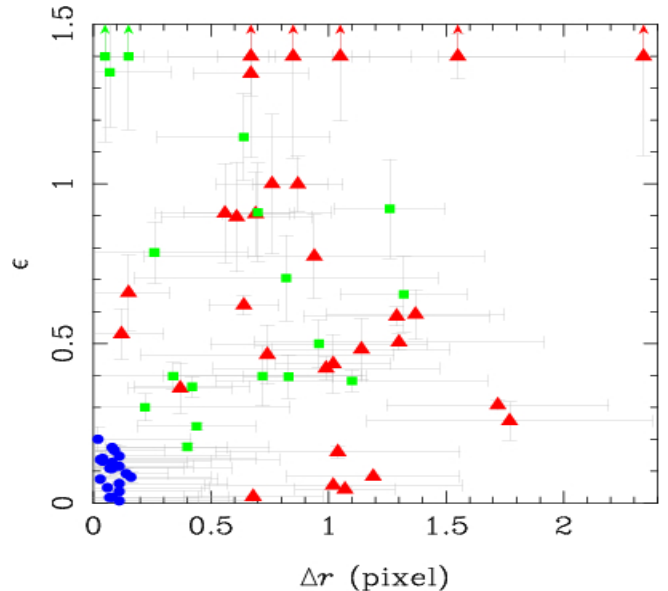
- **Rotation seen in the VF (aligned with the optical axis)**
- **Off-centred σ peak**



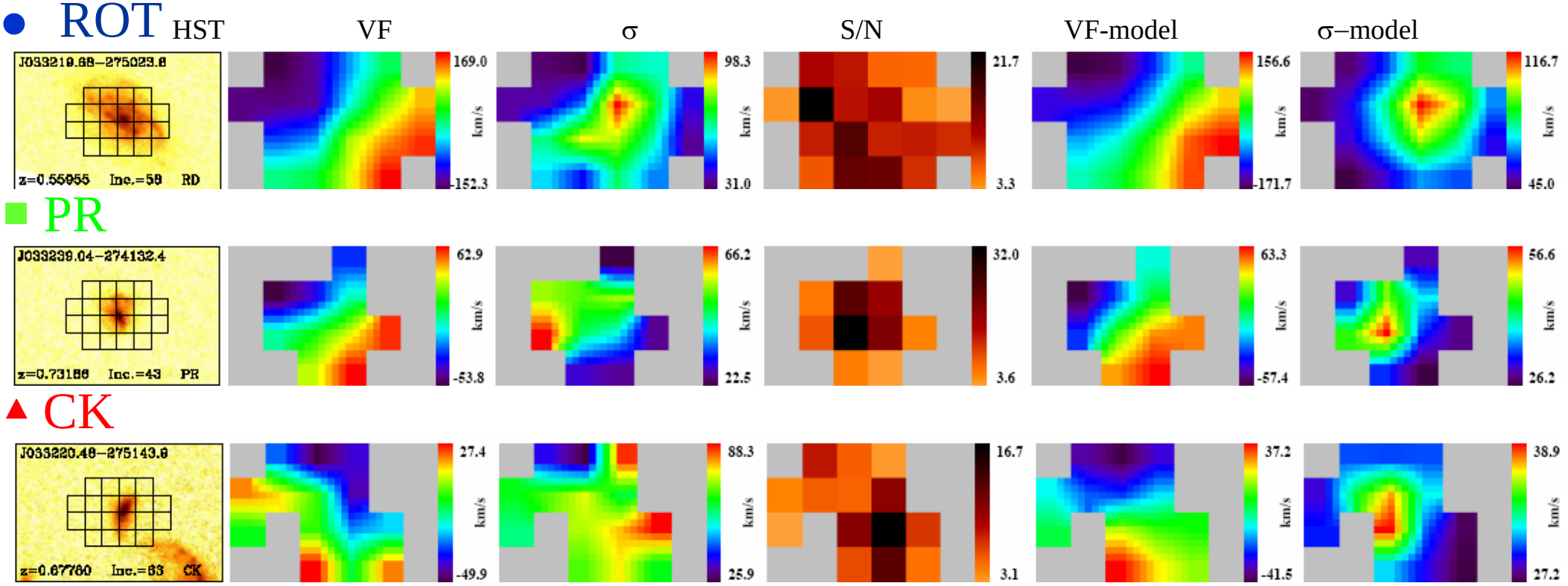
Resolved kinematics: complex kinem. (CK)



- **No obvious structure in the VF/σ-map;**
- **dynamical axis generally misaligned vs main optical axis**



Resolved Kinematics: statistics



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%)**

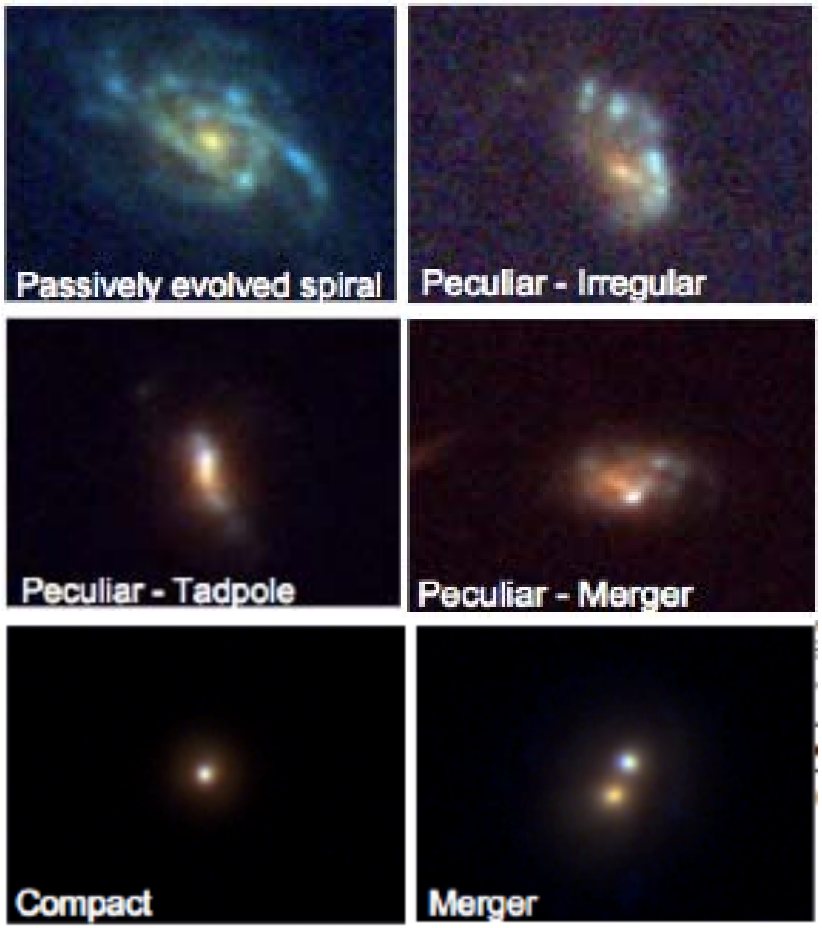
Without emission lines (E/S0/Sa..): 40%

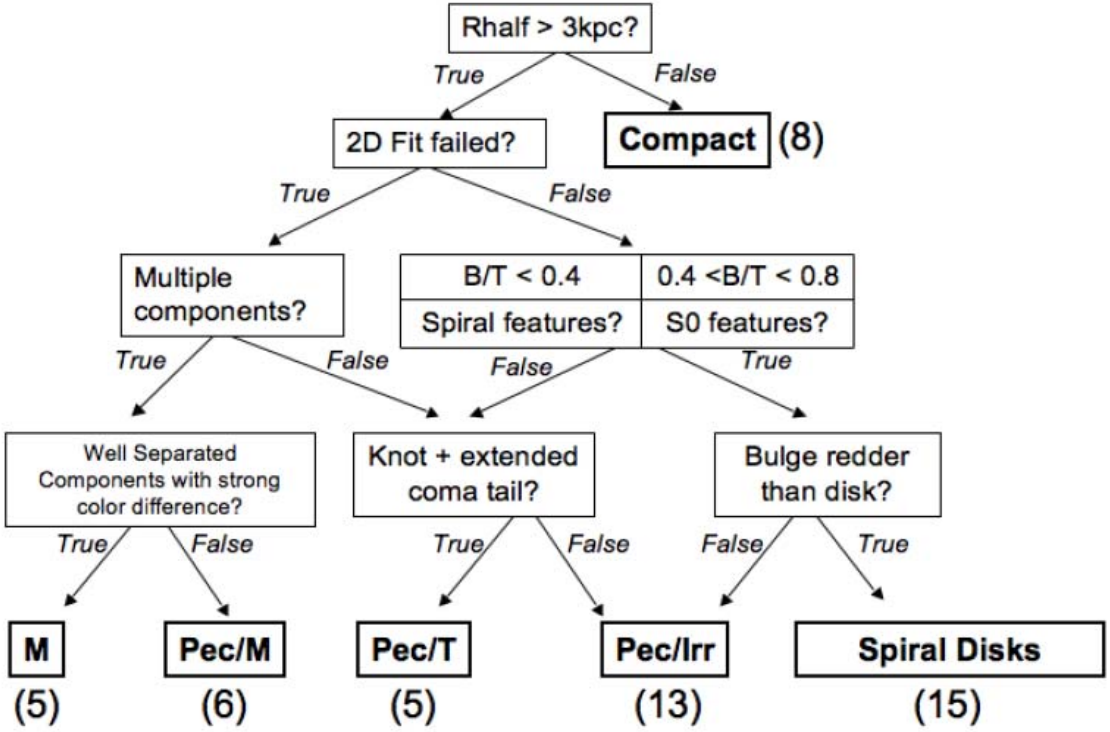
Morphology

Neichel et al. 2008, A&A, 484, 159

Classification based on similarities with local galaxies

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

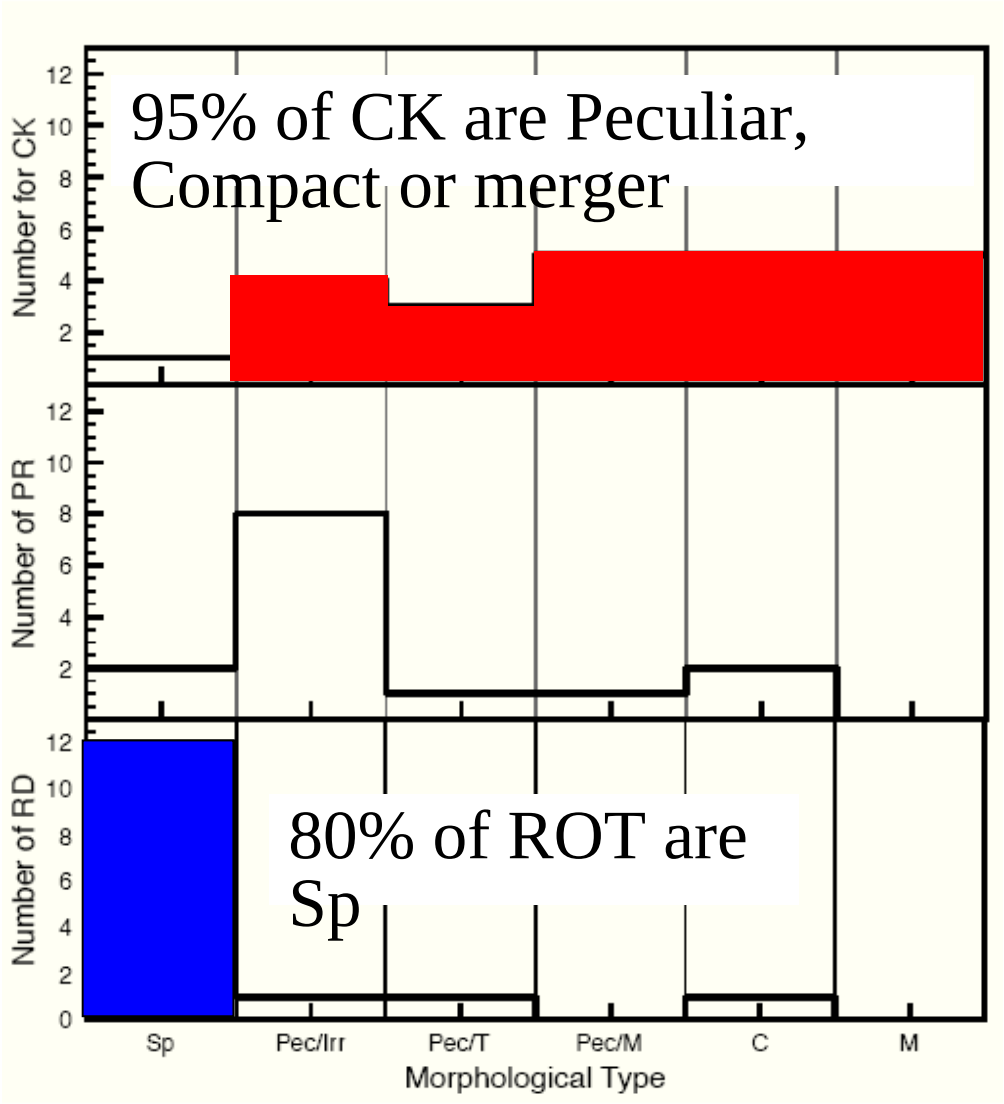




Morpho-kinematics

Neichel et al (2008)

Agreement between kinematics and morphological classifications



A small fraction of rotating spirals at z= 0.65

Neichel et al, 2008

with EW([OII])<15Å		with EW([OII])>15Å			
E/S0	RSpD	RSpD	Pec	C	M
23%	17%	16%	28%	10%	6%

33% of z=0.65 galaxies are rotating spirals against **70%** today !
it supersedes earlier results from Lilly et al (1998)

Based on:
Large scale kinematics (GIRAFFE)
+ detailed morphology HST/ACS 200pc @ z=0.65)

What evolve, what don't

Morphological Type	z ~ 0.65 Neichel et al, 2008		z=0 Nakamura et al (04, SDSS)
E/S0	23%		27%
Spiral	33%		70%
Peculiar/ compact/ merger	**44%**	**Anomalous kinematics PR & CK**	**~ 3%**
LIRGs	20%		0.5%

E/S0 mostly in place at z=0.65, half of spirals don't
Peculiar & LIRGs evolve by large factors: linked with spiral/disk formation

The origin of star formation in progenitors of spirals

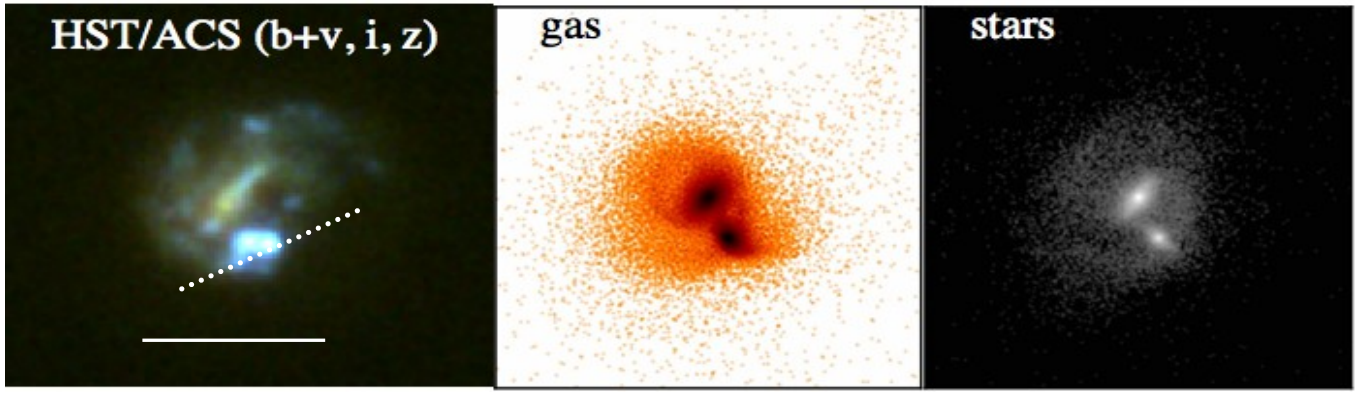
4-8 Gyrs ago

- Doubling their stellar masses
- Processes related to violent SF (LIRGs)
- At z~0.65 half of local spirals were anomalous (kinematics & peculiar morphologies)
- They are responsible of the large scatter in the M-V (TF) (see poster by M. Puech)

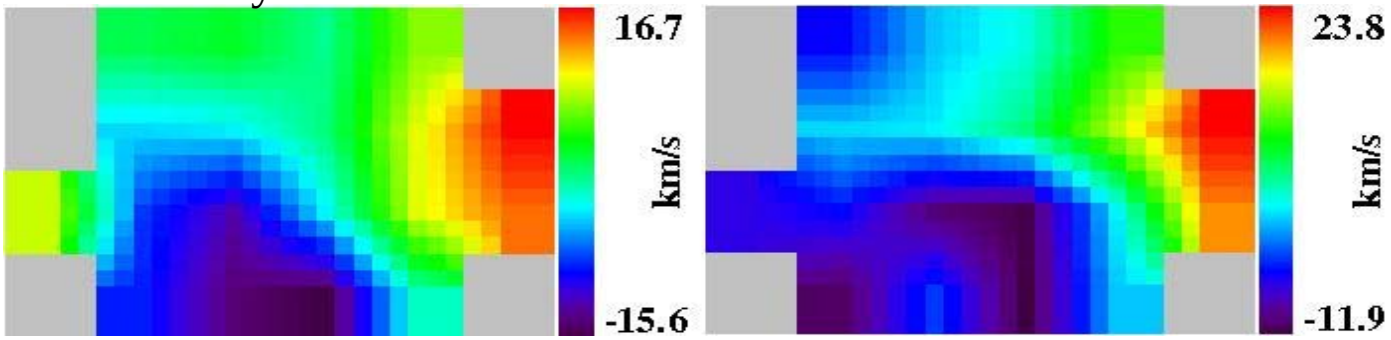
Suggests galaxy collisions or their remnants

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

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



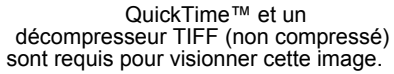
velocity: observed & simulated



QuickTime™ et un
décompresseur H.264
sont requis pour visionner cette image.

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

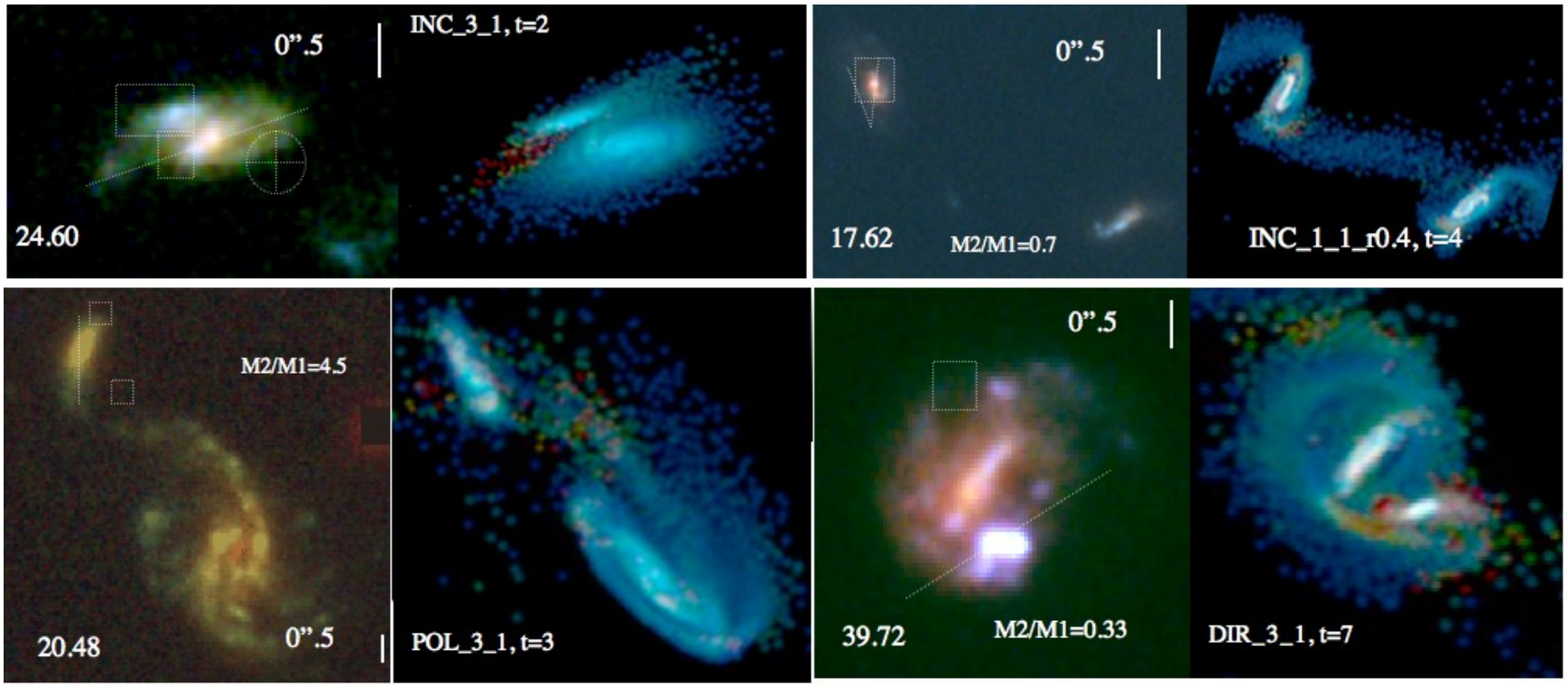
Peirani et al, 2009, A&A 496, 51



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

Half of the anomalous galaxies are obvious mergers

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



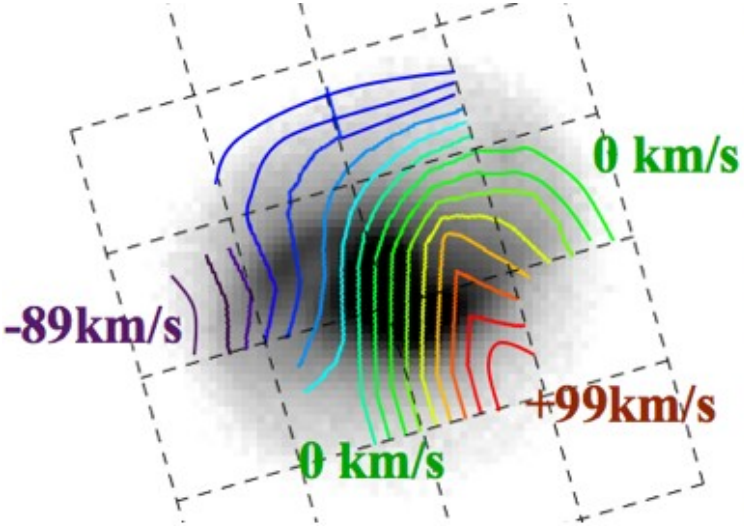
These are all before the fusion (two distinct nuclei) ==> ALL anomalous galaxies can be (and have been) reproduced by major mergers

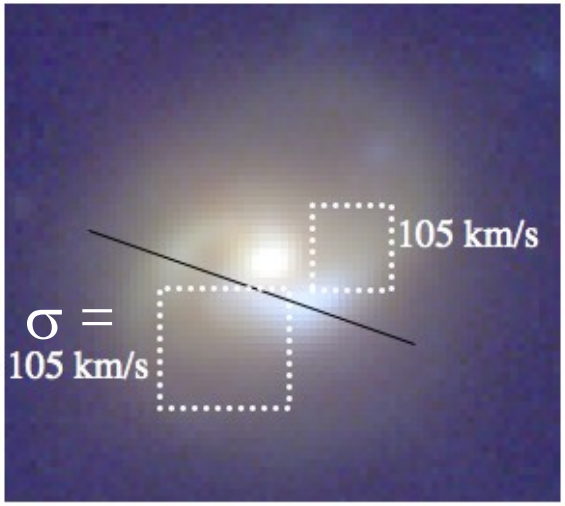
Modelling morphology AND kinematics at z~ 0.65:

==> similar accuracy than for many local galaxies

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

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





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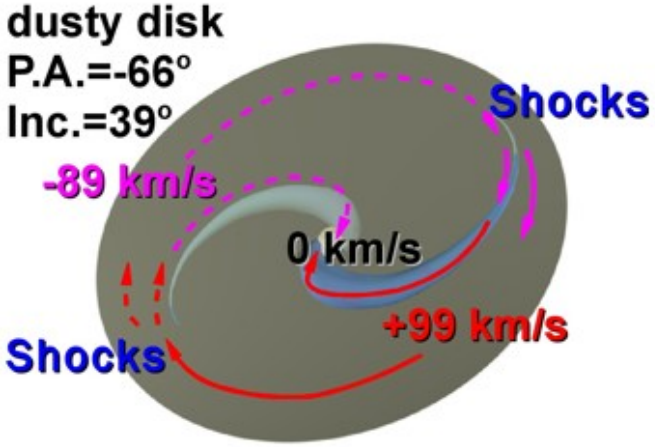
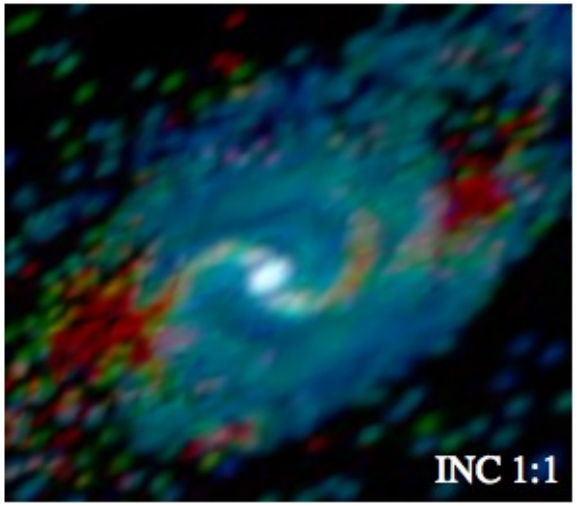




Barnes, 2002
Gas, INCLINED, 1:1

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

Hammer et al. 2009a

Observed gas fraction is 37% (from Kennicutt-Schmidt)

it was > 50% at the beginning of the interaction, 800Myrs ago

Spiral morphology & angular momentum are driven by the last major merger parameters:

here 1:1 mass ratio ==> Sc

Preliminar conclusions from IMAGES

Based on a representative sample of intermediate mass galaxies at z~0.65

Half of local spirals had anomalous kinematics at z~0.65

Detailed analyses reveal merger processes (more in progress)

Local disks rebuilt after a major merger ?

Consistent with the spiral rebuilding scenario for which 50 to 75% of local disks might have been rebuilt following a major merger since z=1

(Hammer et al. 05; see also Hopkins et al. 08)

How disks form ?

Angular momentum

tidal torque theory « *acquisition from early galaxy interactions* »
(Eggen et al, 1962; Peebles, 1976; White, 1984)

⇨ **Apply well to the Milky Way: no significant interactions since z~ 3**

However:

- **kinematics & morphology of distant galaxies**
- **angular momentum catastrophe**
- **Milky Way representativeness?**

The Milky Way versus M31 and other spirals

Hammer+07

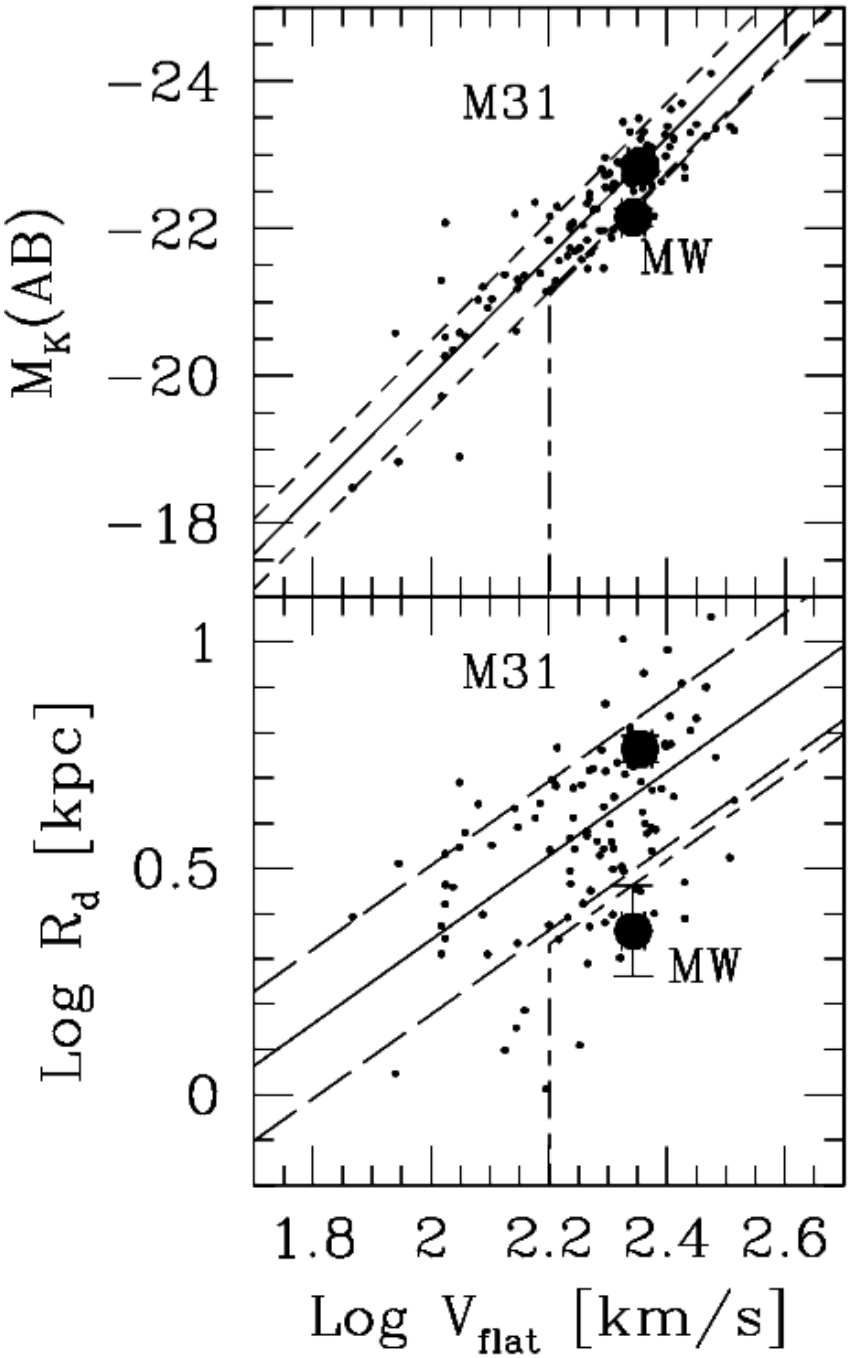
More accurate measurements of M_K, R_{disk} (COBE, Spitzer) and V_{flat} for the MW and M31

Compared to other spirals (SDSS):

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

In the (MK, Rdisk, Vflat) volume, there are only 7+/-1% of MW-like galaxies.

Star abundances in galactic outskirts (Fe/H, inner halo 5-30 kpc):
Most spirals (incl. M31) have stars in outskirts far more enriched than MW's
(see also Mouhcine et al, 2006)



Conclusion

- 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, Hopkins+08**)

Disk rebuilding scenario (Hammer+05) consistent with:

- distant galaxy properties (stellar mass assembly mainly through episodic IR phases driven by mergers);
- evolution of the gas content (31% at z ~ 0.65, Hammer+09)
- gas-rich progenitors able to rebuild significant disks (Lotz+08, Hopkins+08)

⇒ 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

Few remarks

The redshift decrease of rotating spirals (factor 2 at z~0.6) is consistent with the absence of convincing cases of massive 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?

==> a challenge for nearby galaxy studies:

- Could one find a nearby galaxy with Milky Way mass AND with either:

1. an anomalous morphology (irregular) & kinematics,
2. or anomalous star formation (doubling time $M_{stell}/SFR < 1$ Gyrs),

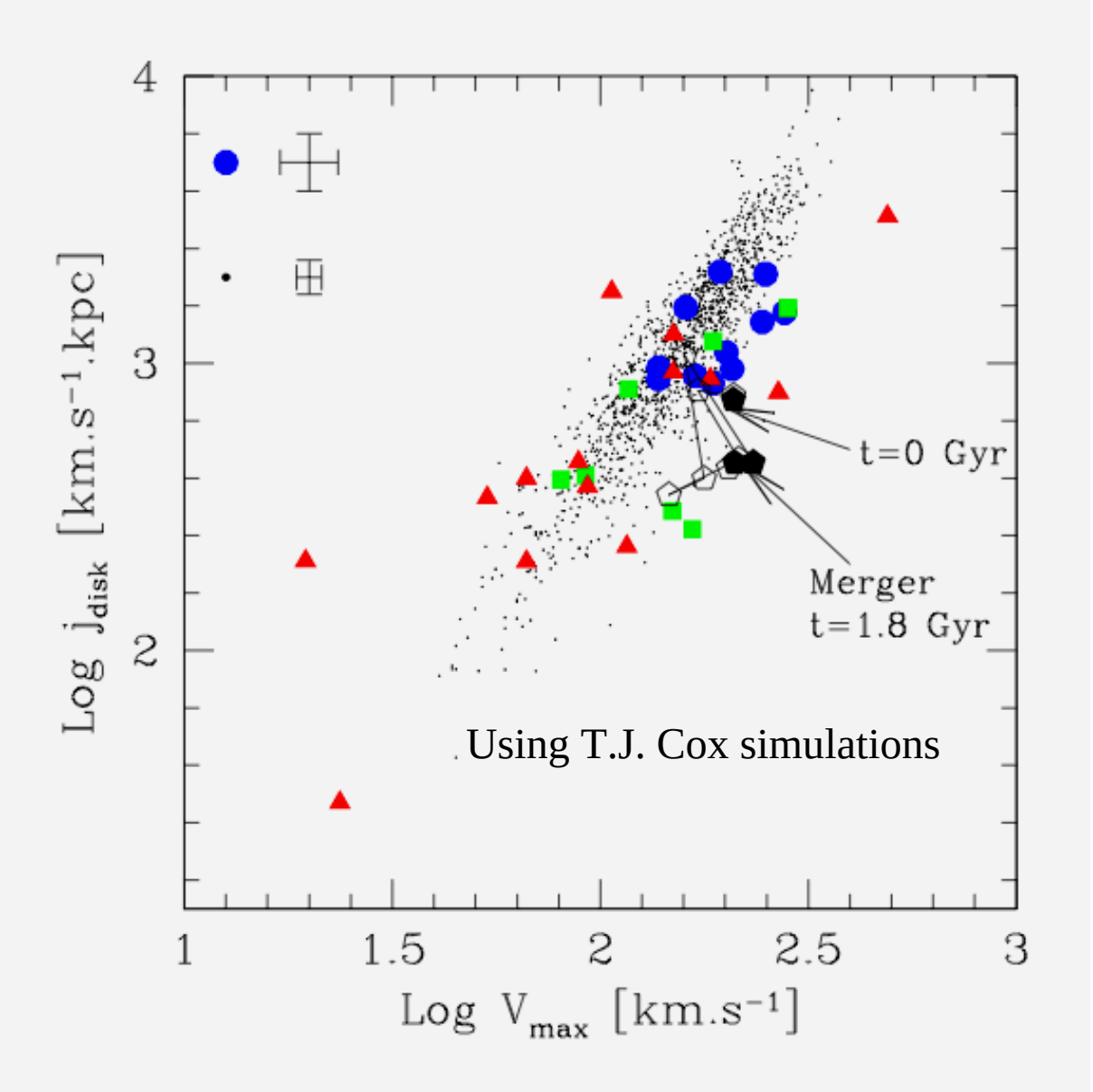
THAT is not a major merger or a remnant ?

Specific Angular Momentum

Puech et al. 2007, A&A 466, 83

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

- A random-walk evolution of j_{disk}
- Dispersion of CKs consistent with major mergers



Galaxies with complex kinematics (CK): mostly major merger remnants?

Pair fraction at z~0.6 : *remarkable agreement* on **5 ± 1 %**

(Le Fevre+00; Conselice+03; Bell+06; Lotz+08; Rawat+08, Jogee+08)

$\oplus$

Fraction of CKs at z~0.6: **26%**

(Yang+08; see also Kutdemir+08)

If CKs are major merger remnants, then: $\frac{\tau_{remnant}}{\tau_{pair}} = \frac{f_{remnants}}{f_{pairs}} \sim 5$

Assuming τ_{pair} = 0.3-0.5 Gyr ⇨ $\tau_{remnant}$ = 1.5-2.5 Gyr

➡ Predicted by simulations of major mergers

(e.g., Robertson+06; Cox+07, Governato+07)

Galaxies are not isolated systems

close-box model

Rodrigues et al. 2008
arXiv:0810.0272
See Rodrigues poster

QuickTime™ et un
décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

Comparison with TF evolution:

It needs that ~30% of the stellar mass must be formed from external gas supply

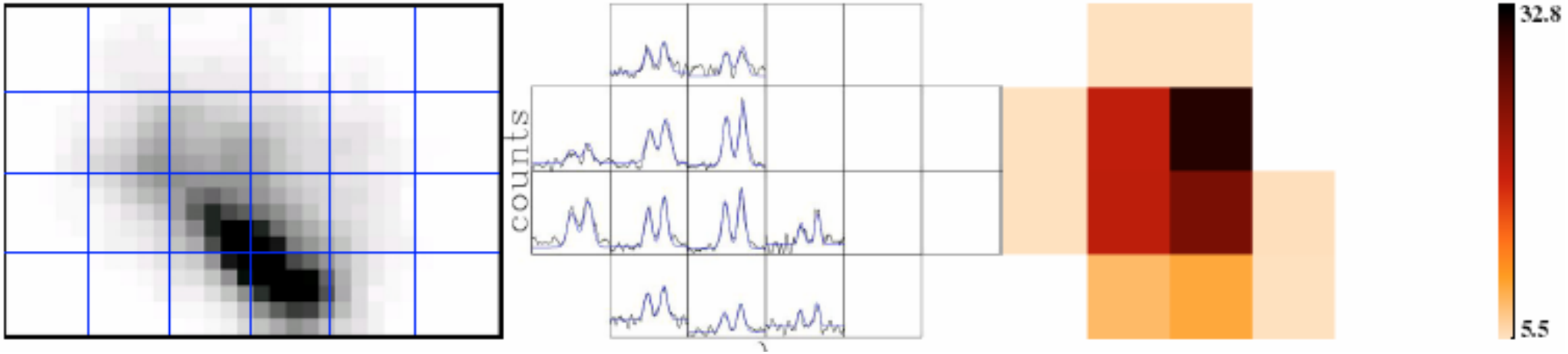
⇩

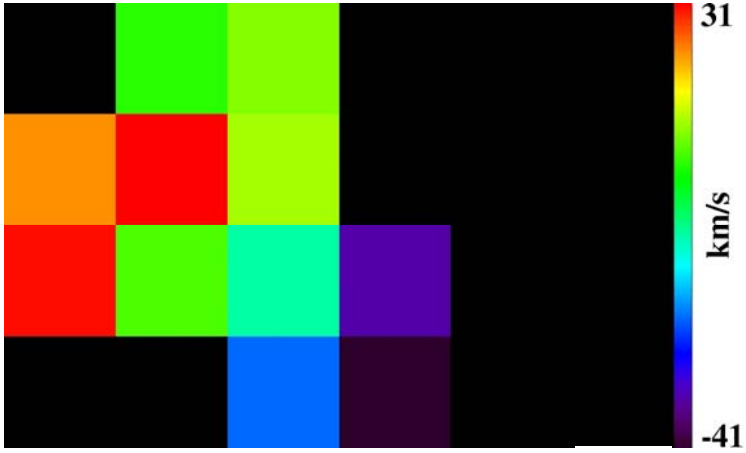
The closed-box model is ruled out

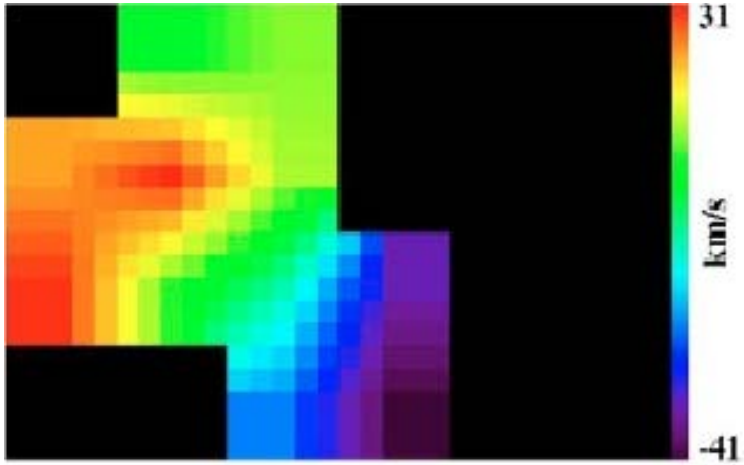
FLAMES/GIRAFFE on the VLT

8 to 24 hrs exposure on an 8 m

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

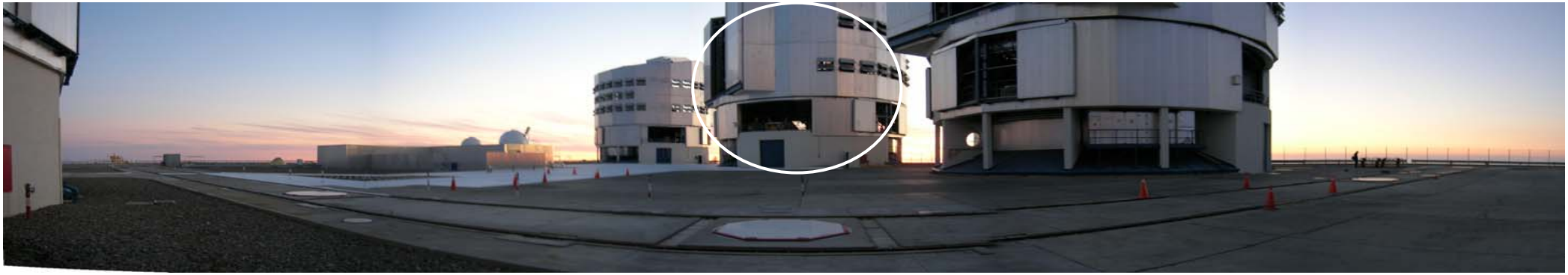




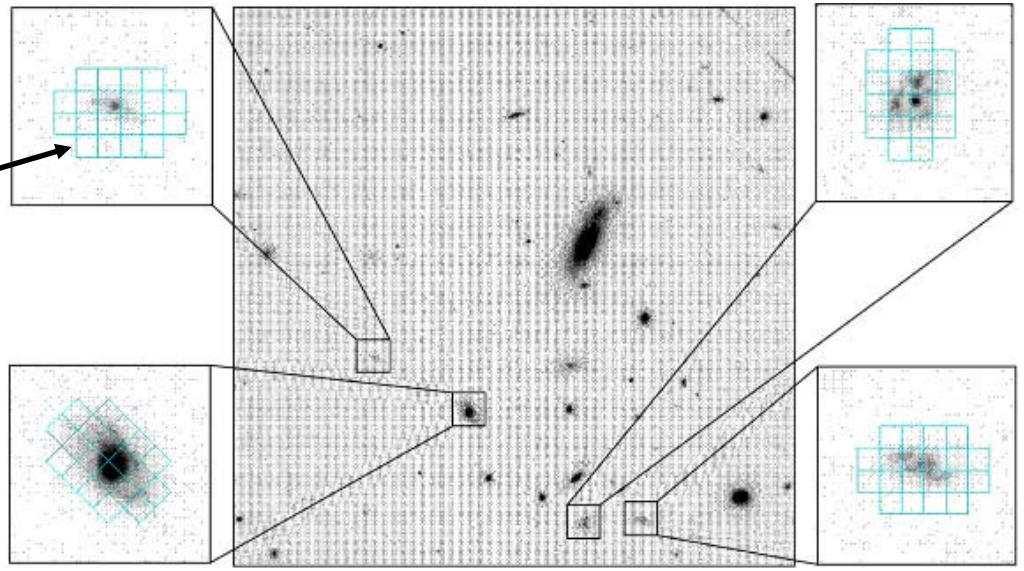


5x5 linear interpolation

FLAMES/GIRAFFE on VLT



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



15 deployable IFUs over a 20 arcmin FoV with $R_{effective}$= 13000

➔ the [OII] doublet is well resolved

A surviving disk from a 6:1 mass ratio central collision

Yang et al, 2008b, A&A submitted

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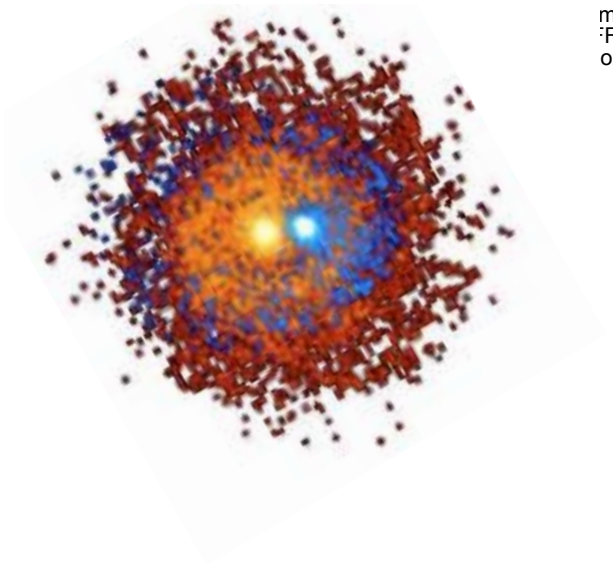
décompresseur TIFF (non compressé)
sont requis pour visionner cette image.



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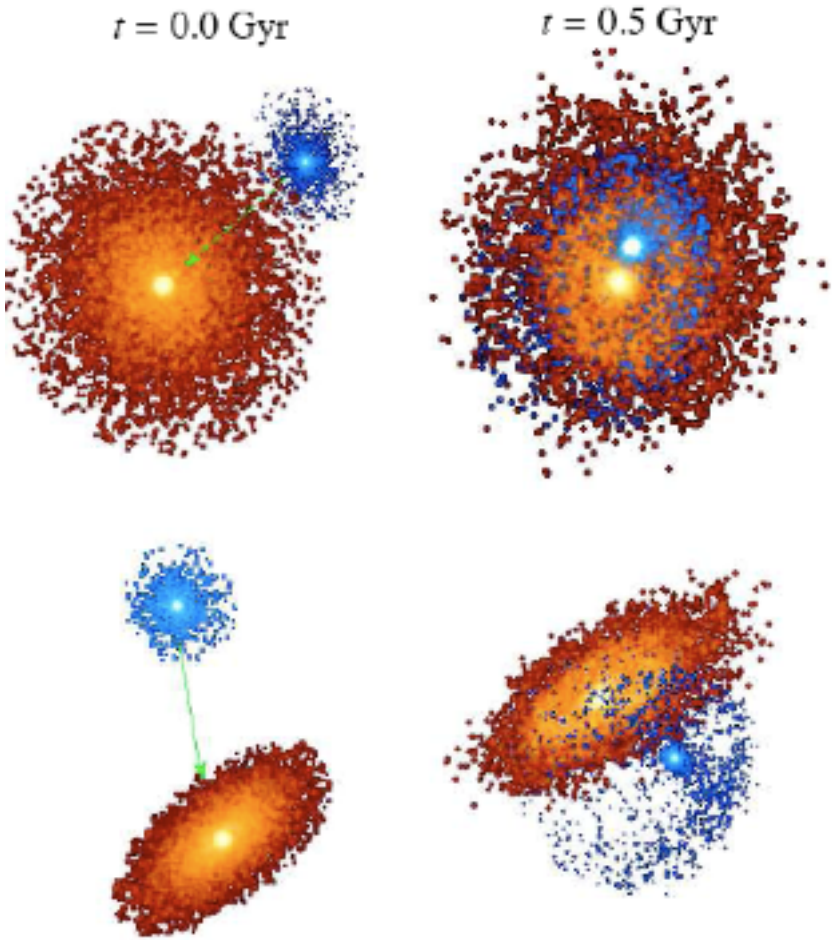


Spiral morphology & angular momentum are driven by the last major merger parameters (here 1:6 mass ratio, Sa)

Learning from local spirals (including MW & M31)

Intermediate mass galaxies at z=0.6 are their progenitors, and many show anomalous kinematics due to merging

- MW past history **without** major interaction since z=3
- M31 **with** much more interactions

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

Is MW a typical spiral or alternatively M31 ?

THE MILKY WAY, AN EXCEPTIONALLY QUIET GALAXY: IMPLICATIONS FOR THE FORMATION OF SPIRAL GALAXIES

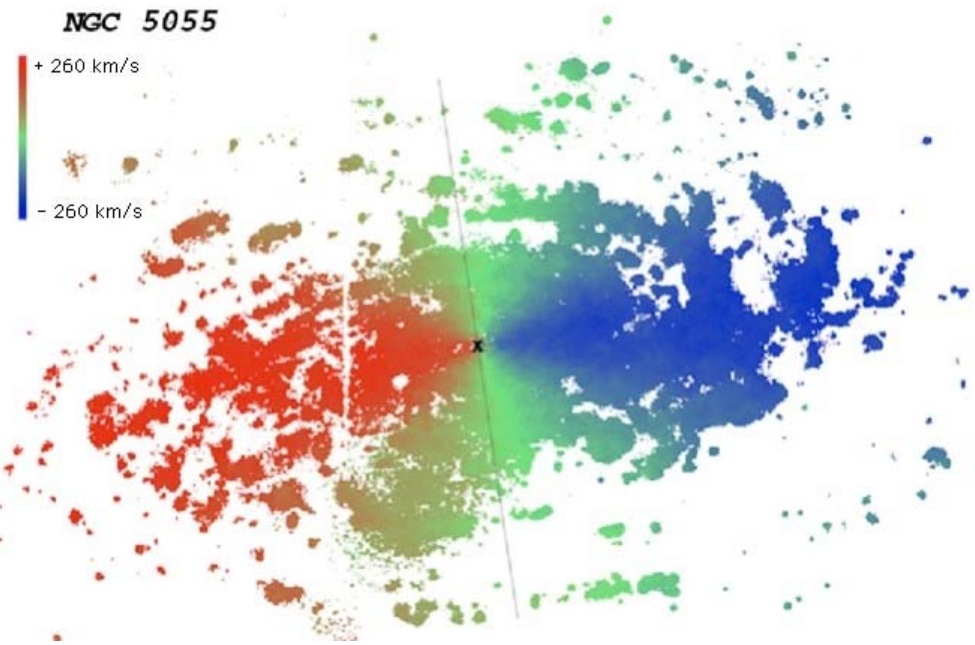
F. HAMMER, M. PUECH, L. CHEMIN, H. FLORES, AND M. D. LEHNERT

décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

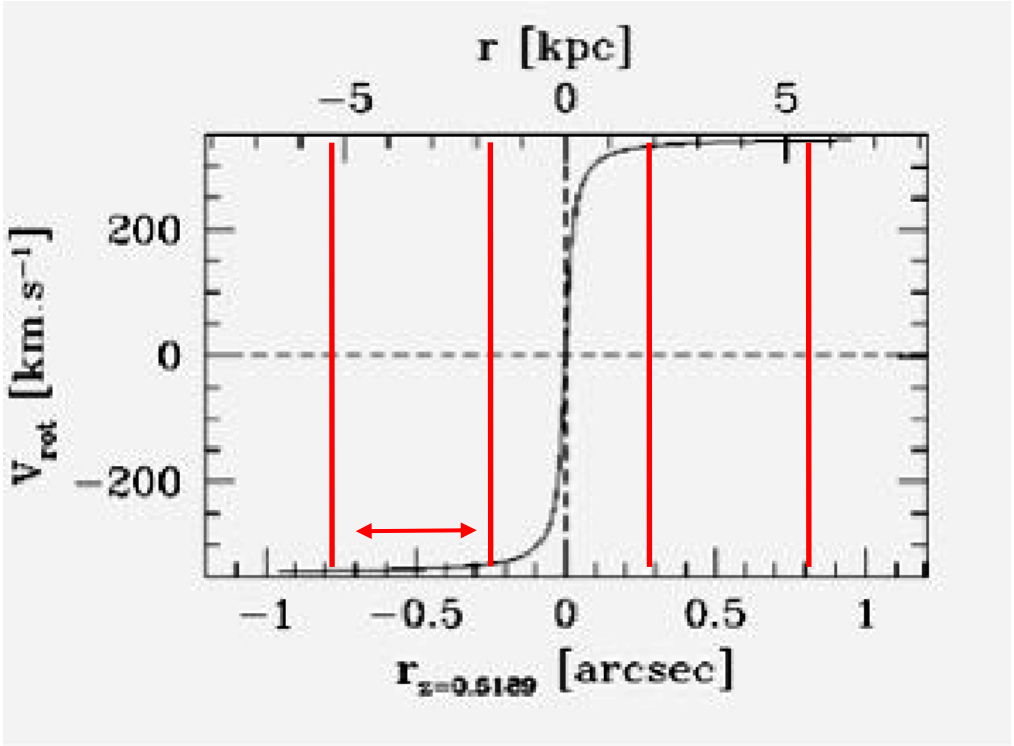
Velocity fields and also σ-maps

<u>Provided by</u>: the absence of cross-talk between individual spectra.

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



Blais-Ouellete, Amram et al, 2002
(Fabry-Perot/Halpha)



GIRAFFE pixel @ z=0.6

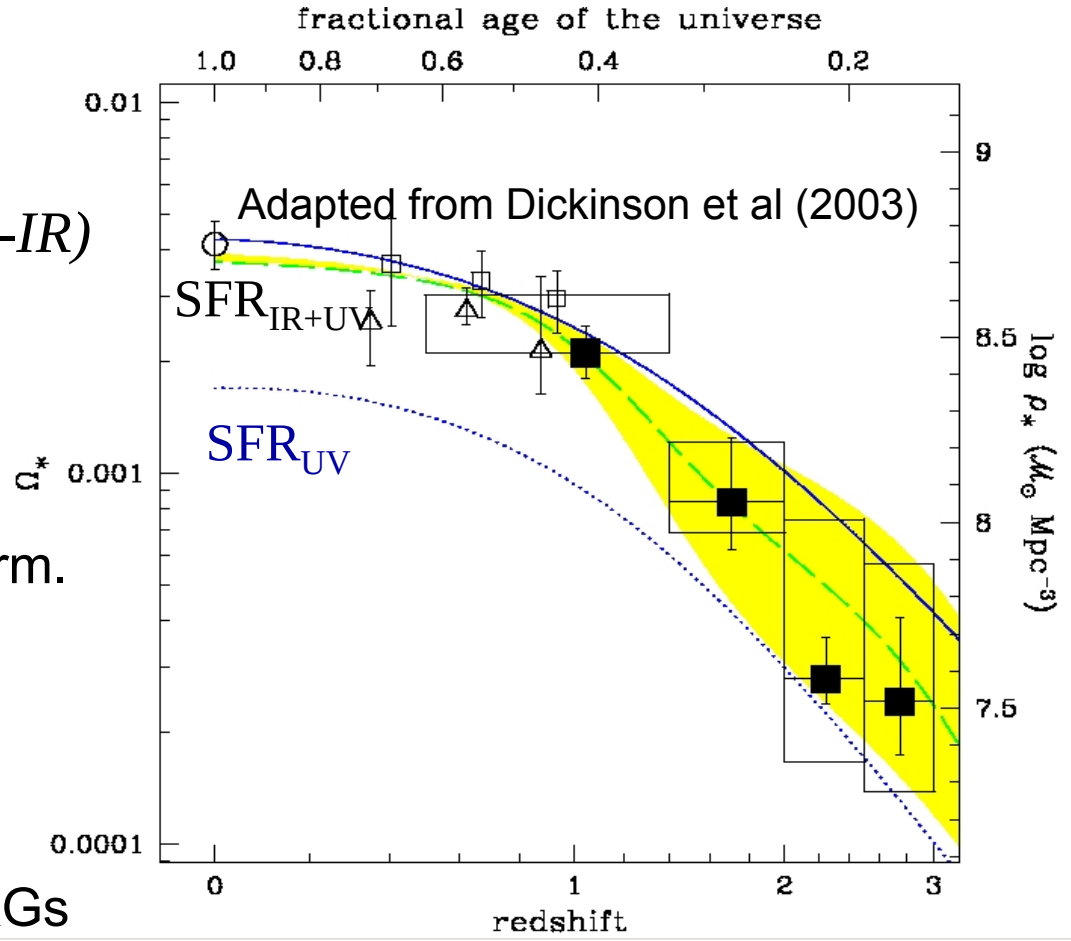
Galaxy Evolution since z=1

- 50% of the local stellar mass was formed during the last 8 Gyr, i.e., since z=1 (e.g., Dickinson+03 ; Drory+04)

From evolution of:

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

2. integrated SFR (including IR light)



- Mostly associated to evolution of interm. mass galaxies (Hammer+05, Bell+05) :
- $2\ 10^{10} < M_{stellar} < 2\ 10^{11}\ M_\odot$;
- Today, 70% of spirals;
- Most of the stellar mass formed in LIRGs (SFR > 19 $M_\odot$/yr)

➡ *requires resolved kinematics of z~0.6 intermediate-mass galaxies*

Morpho-kinematics

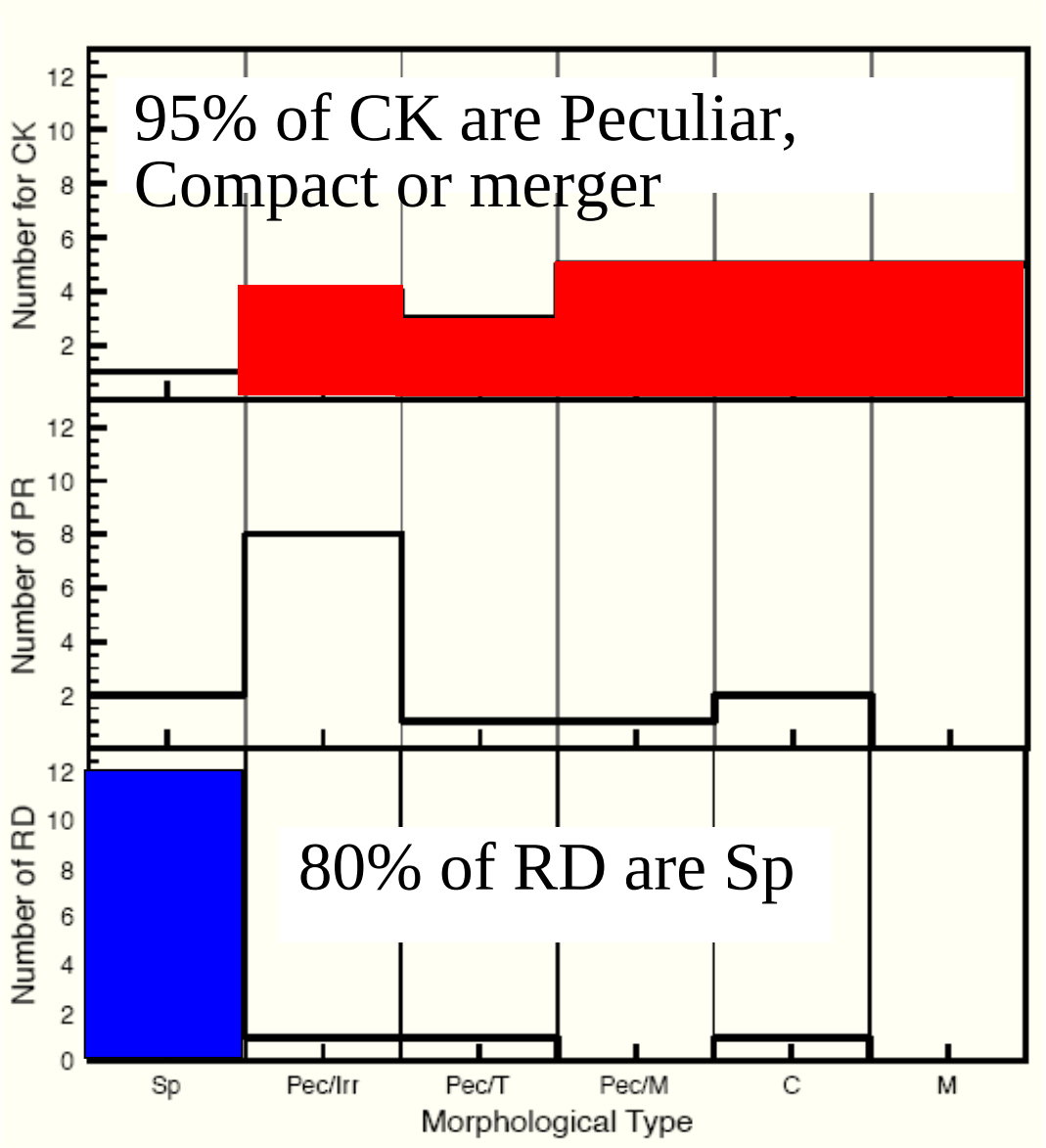
Neichel et al (2008)

Agreement between kinematics and morphological classifications

Automatic classification methods (C-A or Gini-M20):

- not predictive
- overestimate the number of spirals

only 16% of the sample is classified as Sp+RD



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

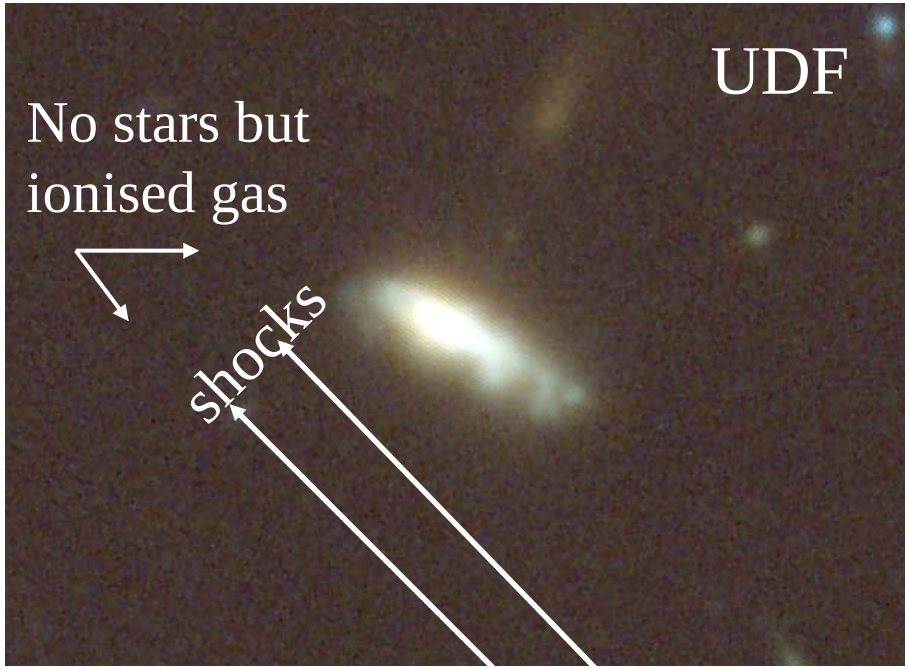
Hammer et al. 2009a

- The kinematical axis is misaligned by 45° from the optical axis
- No outflows from spectroscopy (z_{abs}~ z_{emi} & NaD dominated by stars)
- The velocity dispersion peaks coincide with the end of the « two arms » system
- Half of stars have ages lower than 800Myrs
- Gas fraction is 37% (from Kennicutt-Schmidt) and was 67% 800Myrs ago
- All properties favour a merging scenario rather than a perturbed disk

Spiral morphology & angular momentum are driven by the last major merger parameters (here 1:1 mass ratio, Sc)

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

Puech et al. 2008, A&A 493, 899



f_gas=73-82%

(SED fitting+TF & Kennicutt-Schmidt)

Barnes 02, DIR 1:1

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décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

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