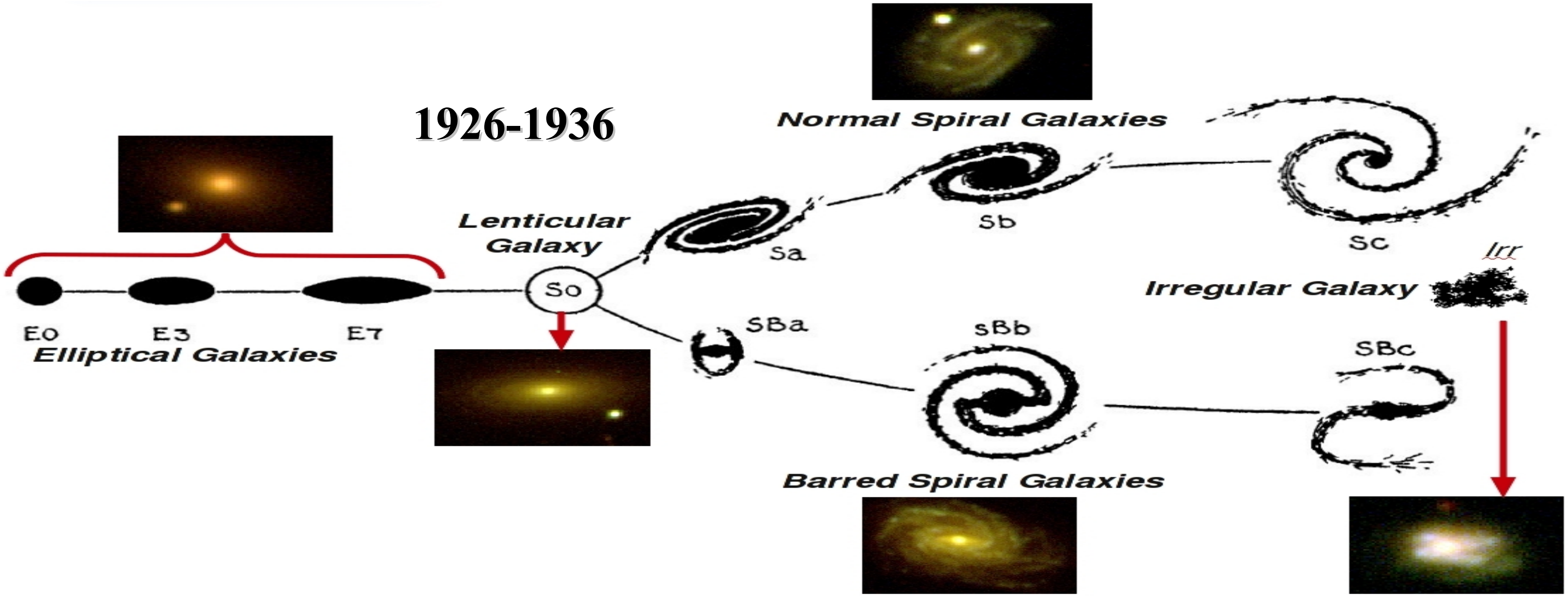
The observed Hubble sequence 6 Gyr ago: implications in galaxy evolution and mergers simulations.


1926-1936

R. Delgado-Serrano

Technological University of Panama
Observatory of Panama

Team : F. Hammer, Y. Yang, M. Puech,
H. Flores, M. Rodrigues
Observatory of Paris-Meudon

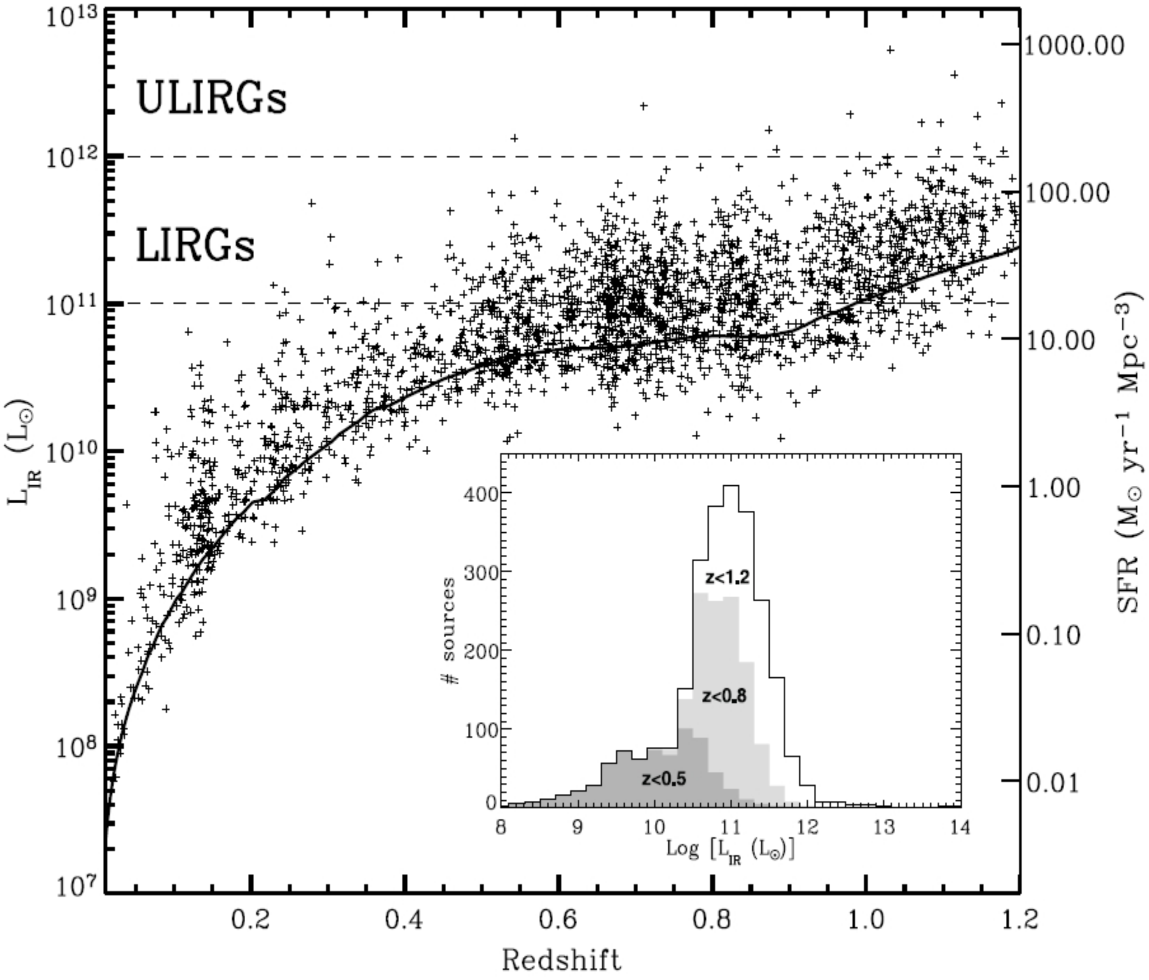
27th Texas Symposium, Dallas-TX
December 8-13, 2013

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)

<u>From evolution of</u>:
1. global stellar mass
(photometry, near-IR)
2. integrated SFR
(including IR light)

- Most of it was formed in LIRGs (SFR > 20 $M_\odot$/yr; Hammer+05; Bell+05), which are intermediate-mass galaxies



Le Floc'h et al. (2005)

Intermediate-mass galaxies

$3.10^{10} < M_{\rm stellar} < 3.10^{11}\,M_{\odot}$, i.e., $\sim M_{*}$ galaxies

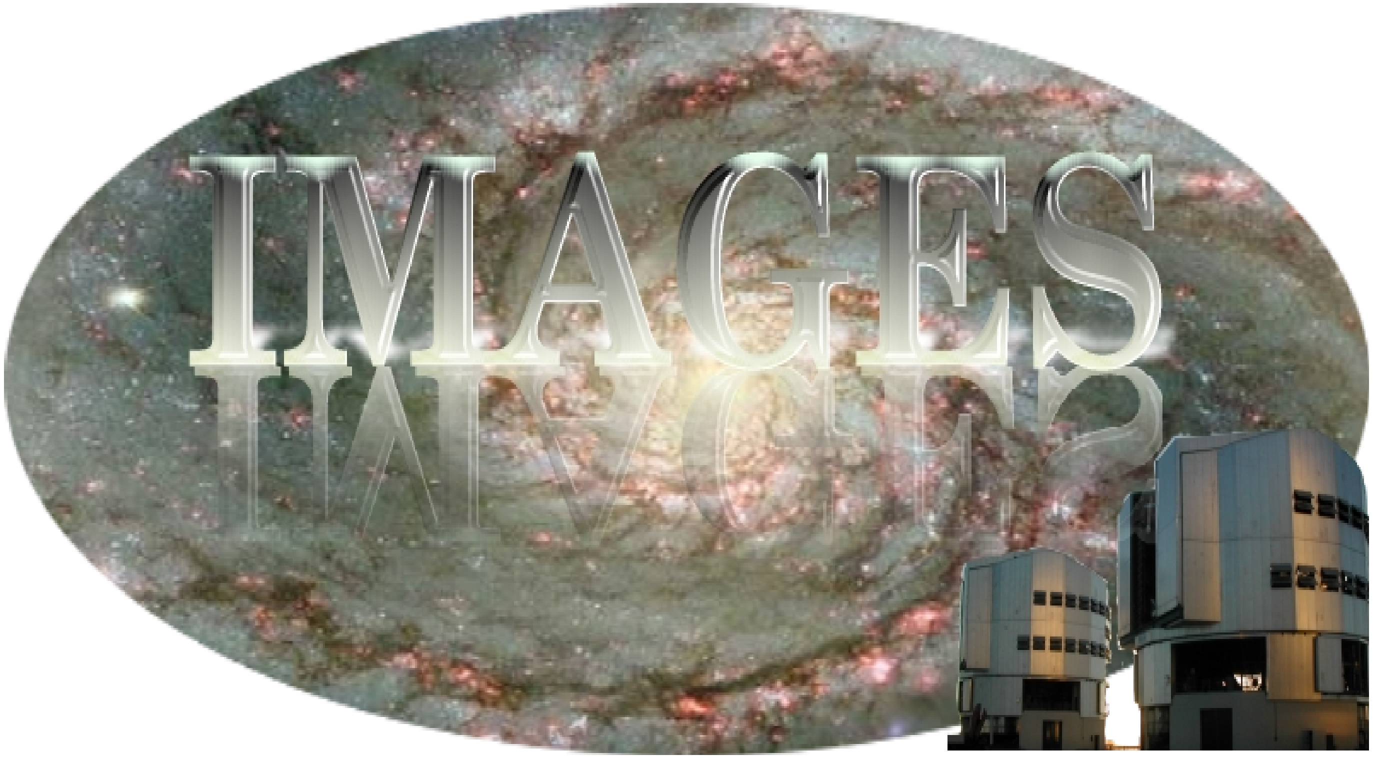
- LIRGs are intermediate-mass systems, probably associated with episodic luminous phases (Hammer+05; Marcillac+06)

- The high fraction of z~0.6 LIRGs can be explained if each galaxy experiences 3-4 IR luminous phases since z=1, producing local intermediate-mass galaxies (Hammer+05)

- Local intermediate-mass galaxies are mostly spirals (70% of them)

- According to Hammer et al. (2005), 50 to 75% of local spirals have had a LIRG episode

How can we link the distant galaxies to local ones? … and to the Hubble sequence?



Intermediate
Mass
Galaxy
Evolution
Sequence

The IMAGES collaboration:

M. Puech[1,2], H. Flores[2], F. Hammer[2], Y. Yang[2], B. Neichel[2], M. Lehnert[2], L. Chemin[2], N. Nesvadba[2], B. Epinat[5], P. Amram[5], C. Balkowski[2], C. Cesarsky[1], H. Dannerbauer[6], S. di Serego Alighieri[7], I. Fuentes-Carrera[2], B. Guiderdoni[8], A. Kembhavi[3], Y. C. Liang[9], G. Östlin[10], L. Pozzetti[4], C. D. Ravikumar[11], A. Rawat[2,3], D. Vergani[12], J. Vernet[1], and H. Wozniak[8], **R. Delgado-Serrano**, M. Rodrigues

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.

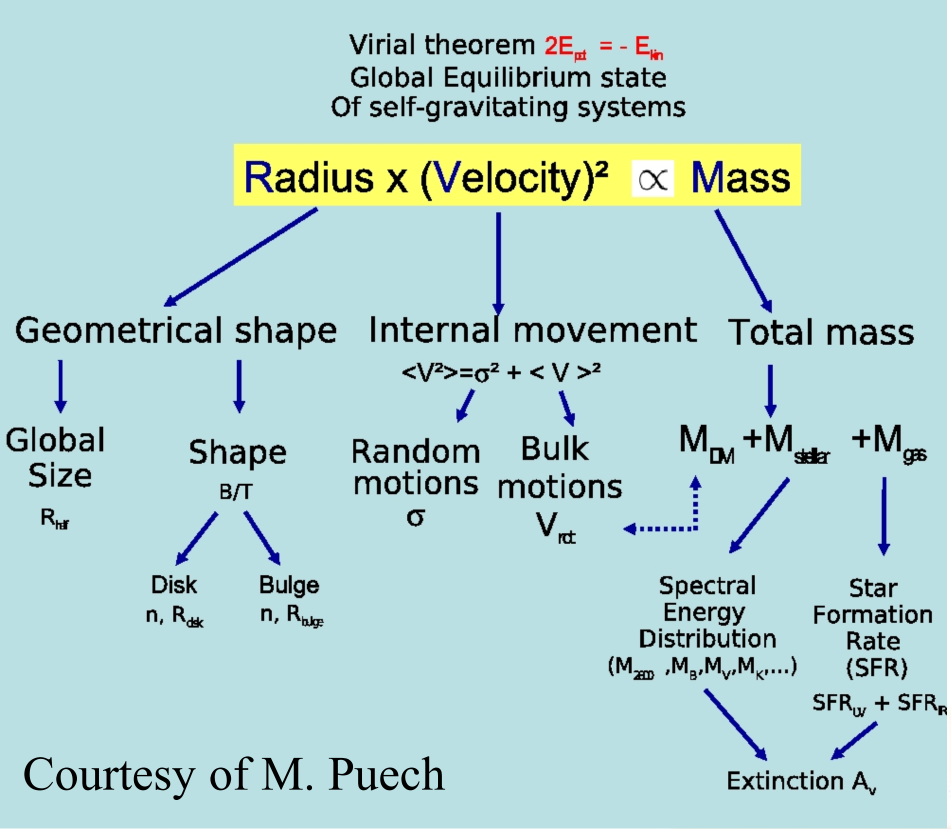
3D Spectroscopy

VLT/FLAMES-GIRAFFE

Kinematics

Dynamics

IMAGES has given us a complete description of the galaxies properties, 6 Gyr ago



Virial theorem $2E_{pot} = - E_{kin}$
Global Equilibrium state
Of self-gravitating systems

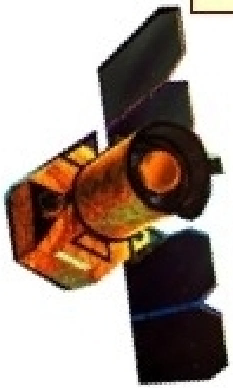
Radius x (Velocity)² ∝ Mass

Geometrical shape
- Global Size R_{half}
- Shape B/T
  - Disk n, R_{disk}
  - Bulge n, R_{bulge}

Internal movement
$<V^2> = \sigma^2 + <V>^2$
- Random motions σ
- Bulk motions V_{rot}

Total mass
$M_{DM} + M_{stellar} + M_{gas}$
- Spectral Energy Distribution (M_{2800}, M_B, M_V, M_K, ...)
- Star Formation Rate (SFR) $SFR_{UV} + SFR_{IR}$
- Extinction A_V

Courtesy of M. Puech



GALEX → UV light

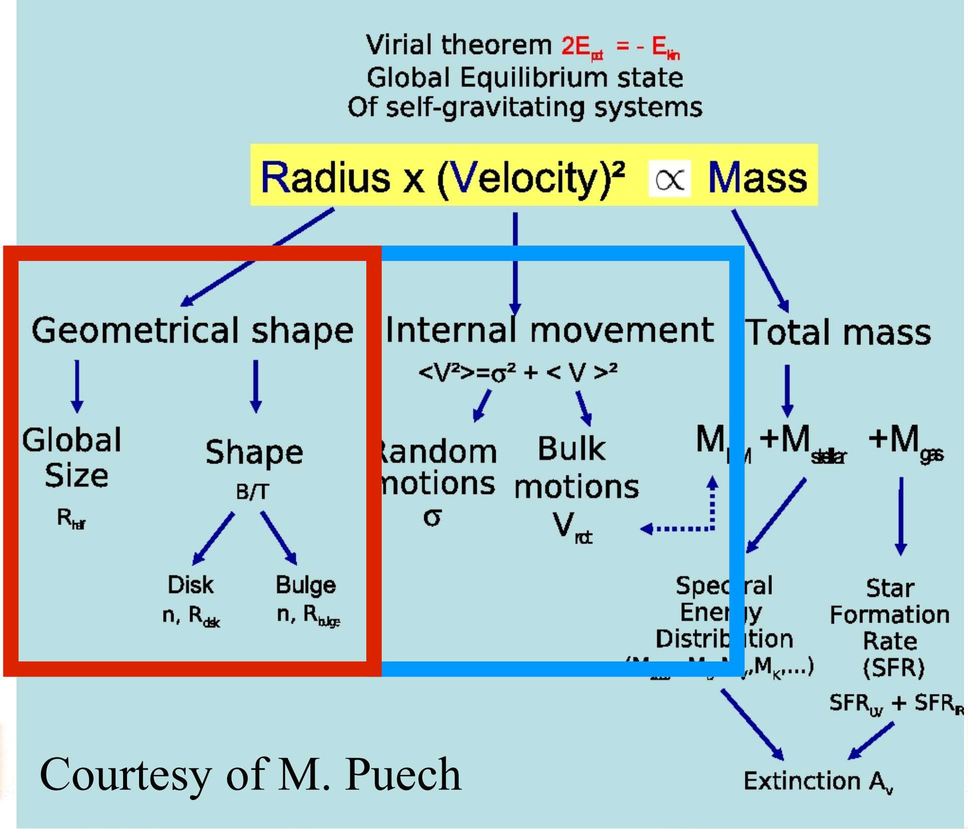
HST/ACS → Morphology

VLT/FORS2 → Metallicity – stellar population

VLT/GIRAFFE → Kinematics

Spitzer → Dust – Star formation

IMAGES has given us a complete description of the galaxies properties, 6 Gyr ago



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Random motions σ

Bulk motions V_{rot}

Total mass

M_{M} $+M_{stellar}$ $+M_{gas}$

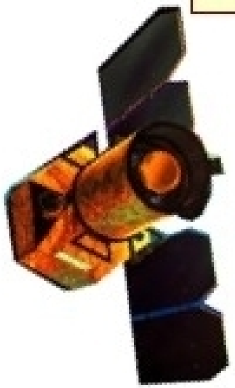
Spec ral Ener y Distrib tion $(M \; M \; ,M_K,\ldots)$

Star Formation Rate (SFR)

$SFR_{UV} + SFR_{IR}$

Extinction A_v

Courtesy of M. Puech



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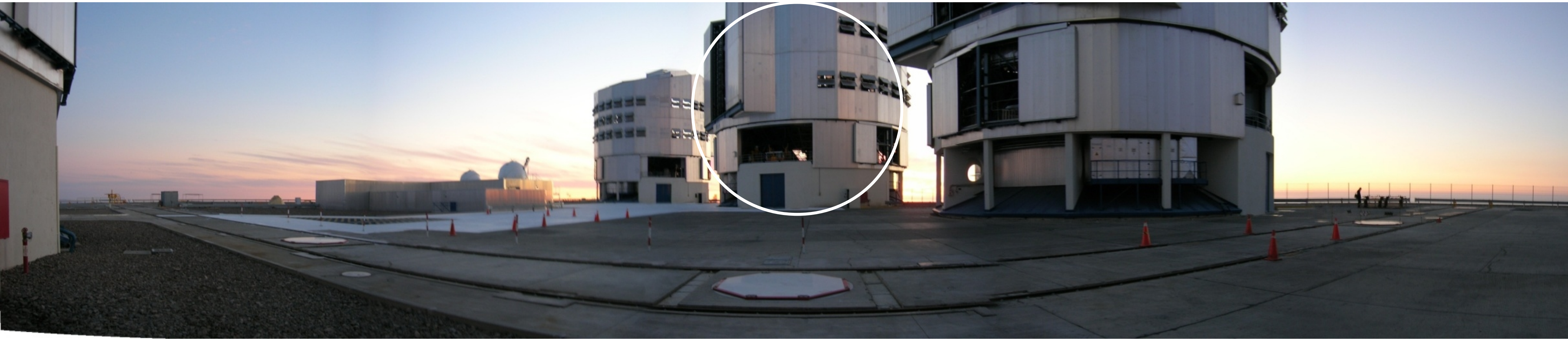
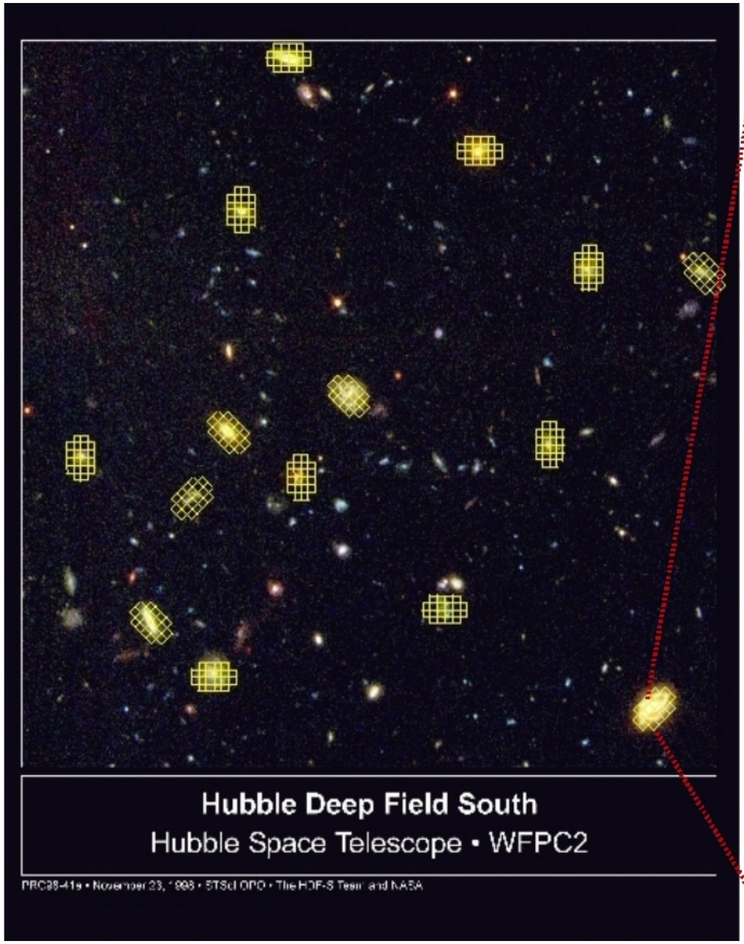
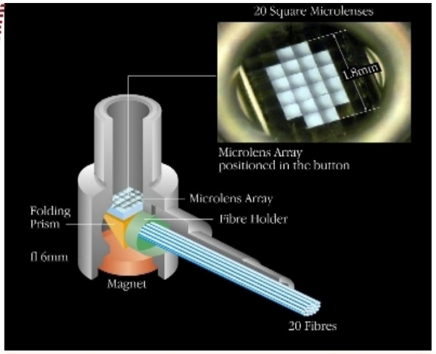
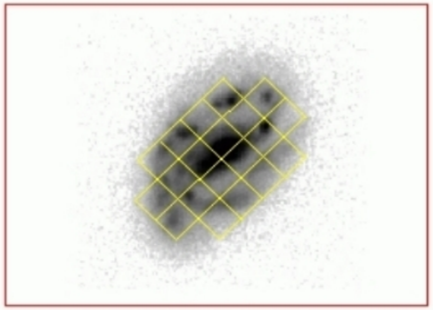
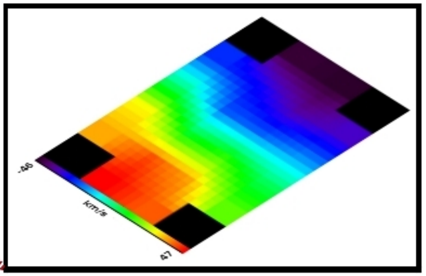
Kinematics











FLAMES/GIRAFFE on the VLT

The need of 3D spectroscopy at high z

IFU mode:

15 IFUs deployable over a 20 arcmin FoV

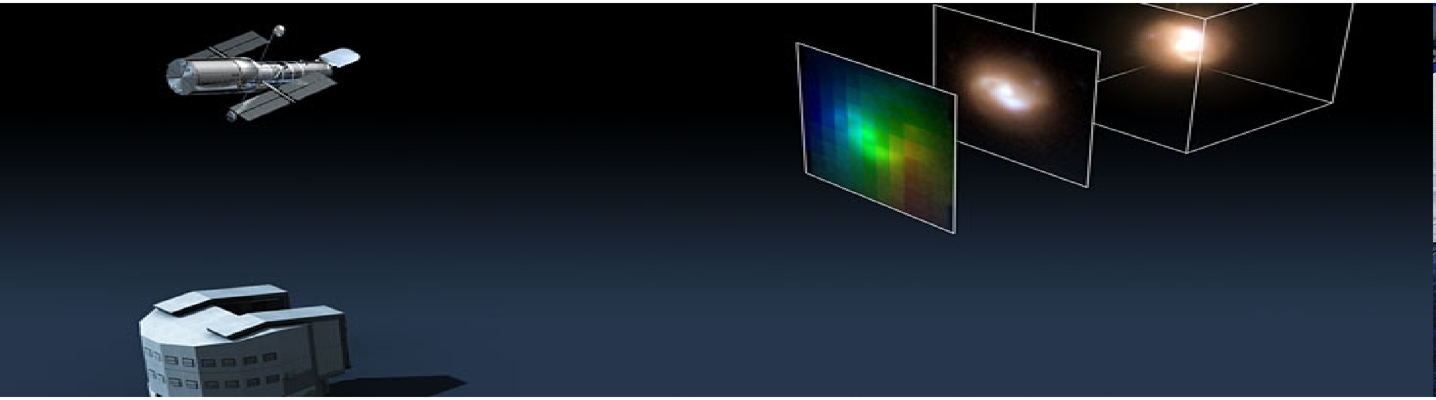
Each IFU has a 3''x2'' FoV with:

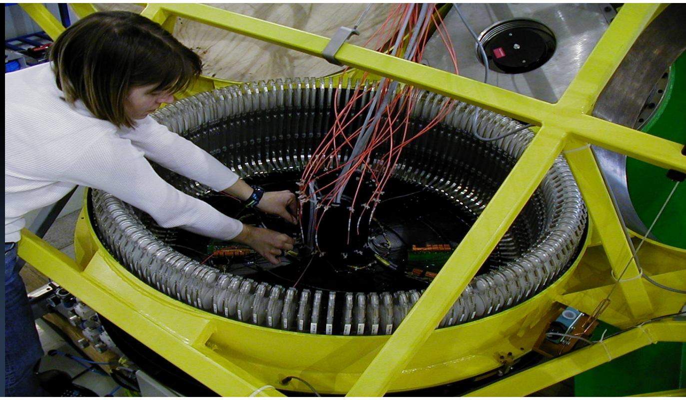
20 sq. μLenses, each one with a 0,52"x 0.52" FoV, cutting the integral light of the galaxy

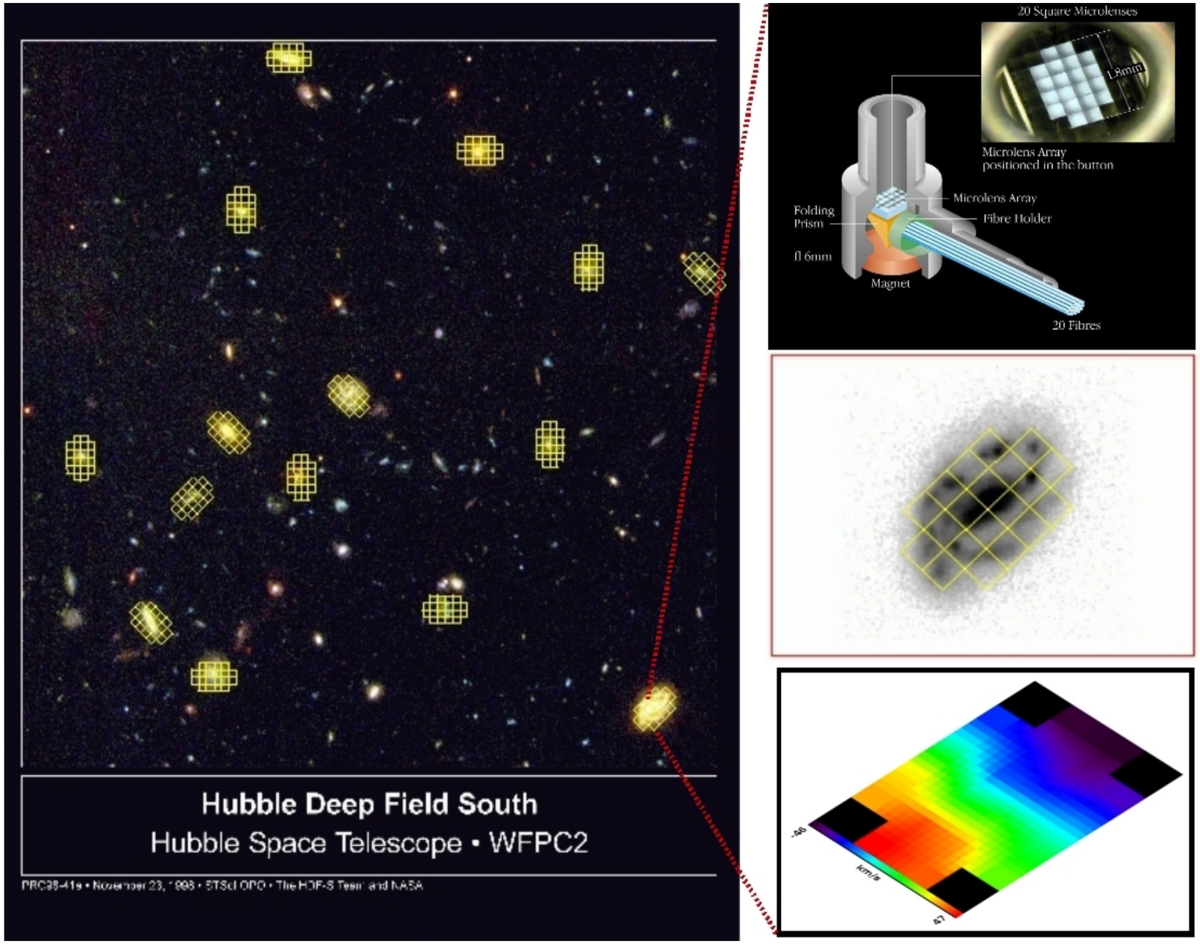
⬇

20 spectrum with a resolution of ~10 000

Kinematics







FLAMES/GIRAFFE on the VLT

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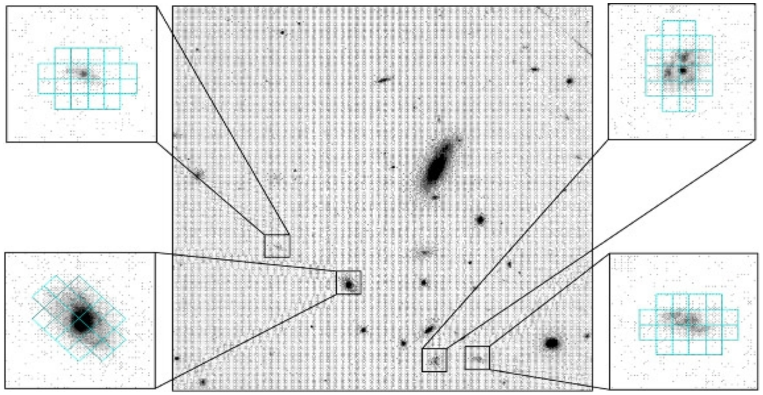
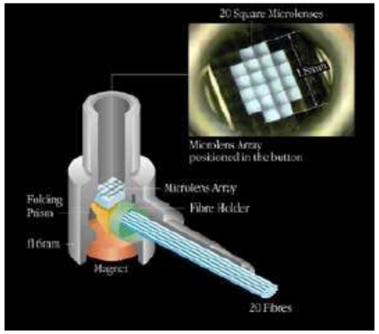
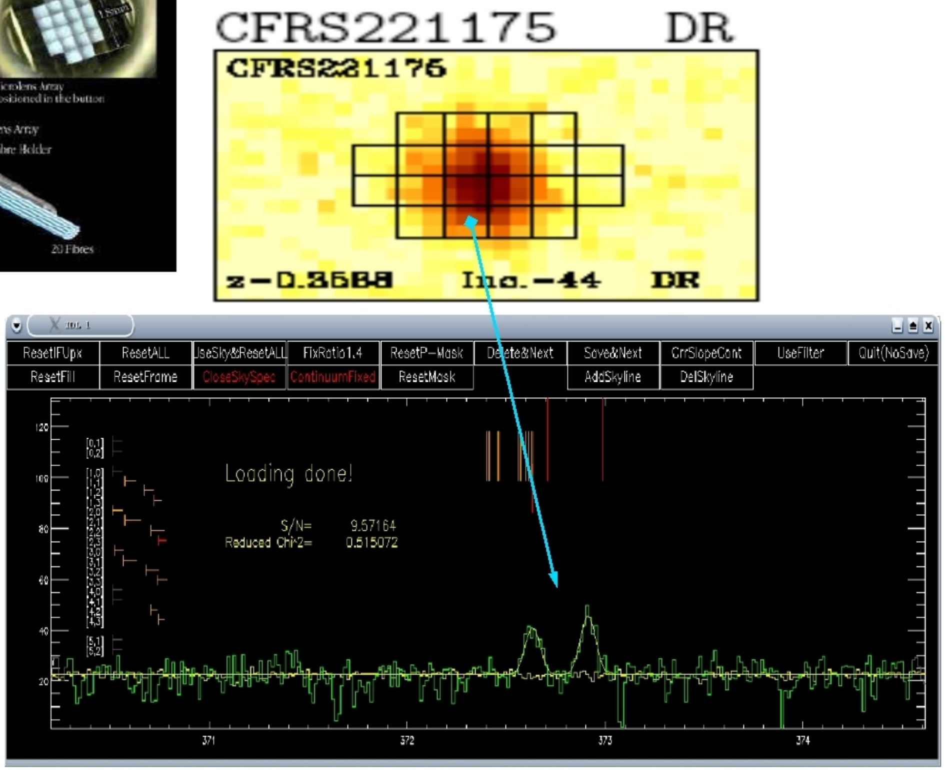




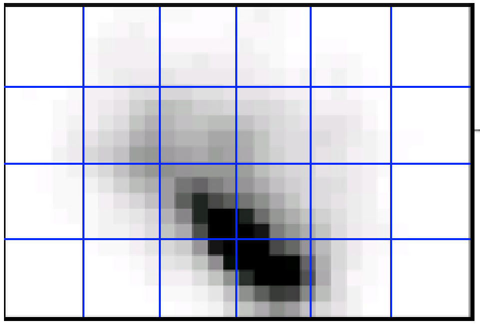


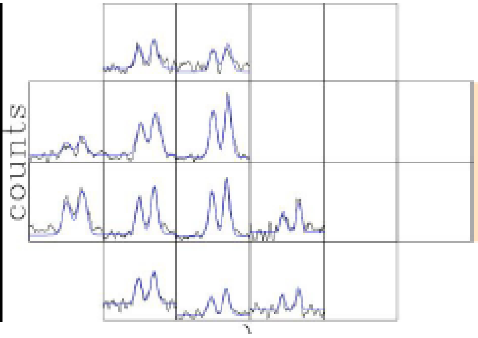
```
Loading done!

          S/N=      9.57164
Reduced Chi^2=      0.515072
```

Mode IFU:

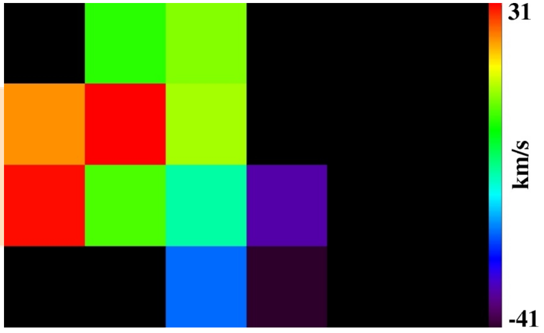
R ~ 10000 ➔ le [OII] doublet can be resolved

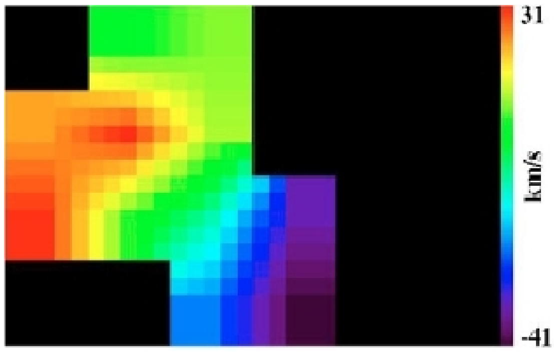
CFRS03.0488, z=0.46, (3''x2'')





VF using pixels with S/N > 3





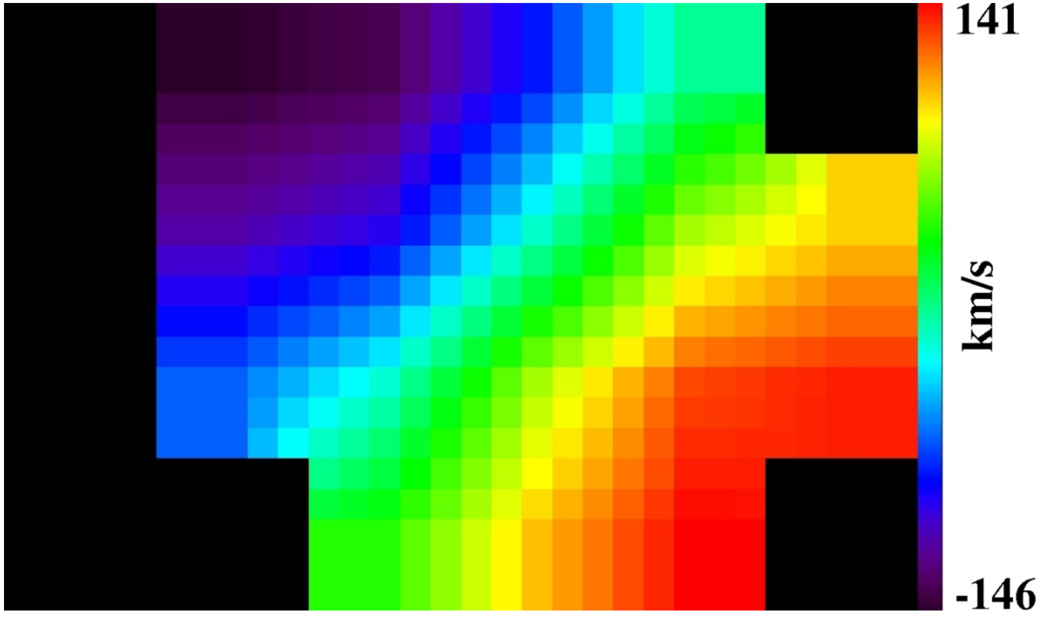
5x5 linear interpolation

Velocity field and dispersion map

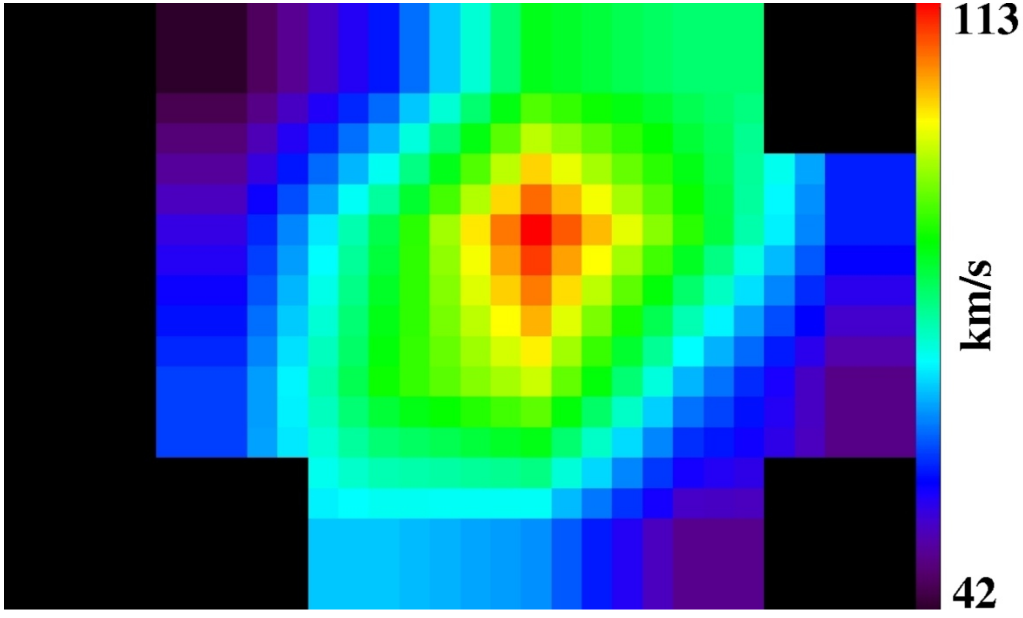
Provided by: the absence of cross-talk between individual spectra.

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

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



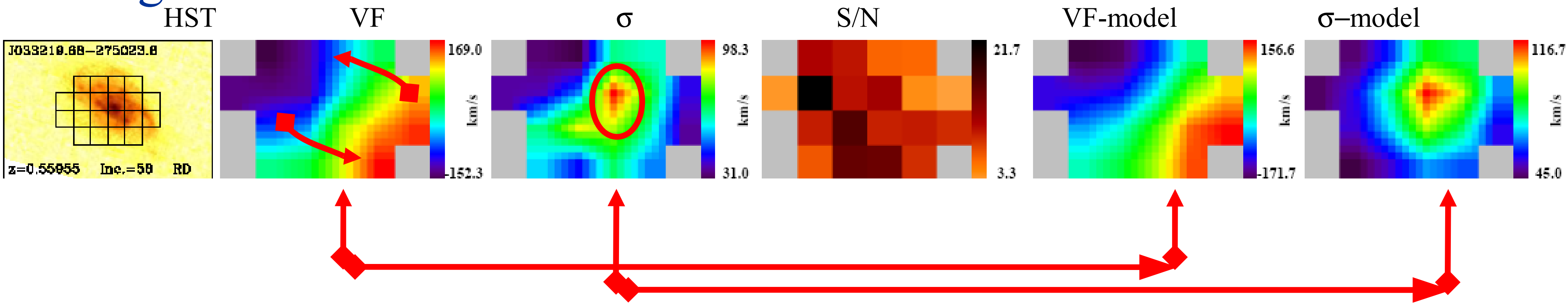
Velocity map



Dispersion or σ map

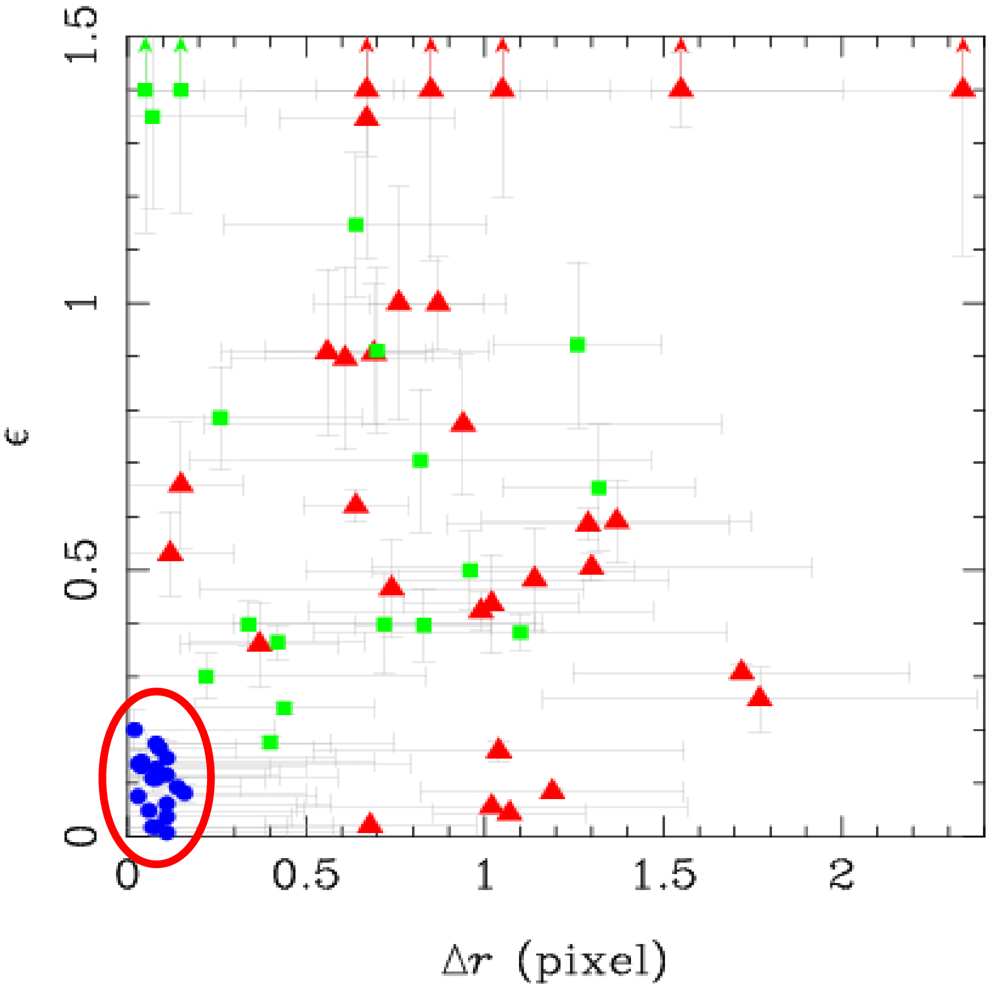
Resolved Kinematics

Rotating Disk

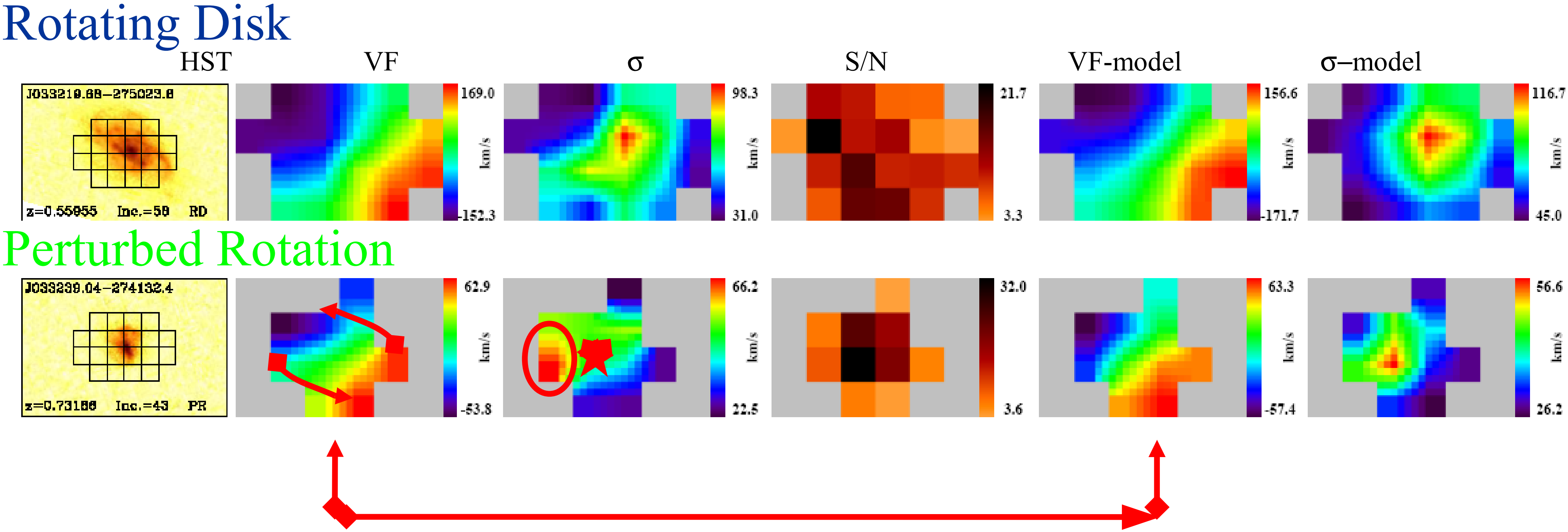


All galaxies are assumed to be rotating disks:

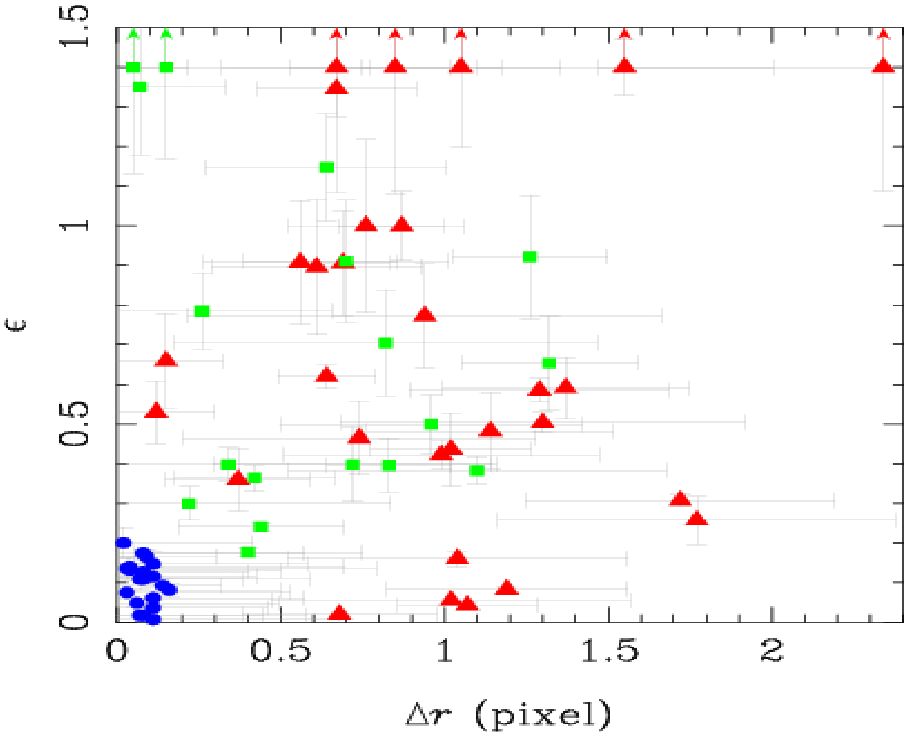
- **their large scale motions are due to rotation**
- **simulation of corresponding VF and σ-map**
- **comparison of the derived σ-maps to the observed ones (relative difference of amplitude ε vs. σ peak distance Δr)**



Resolved Kinematics

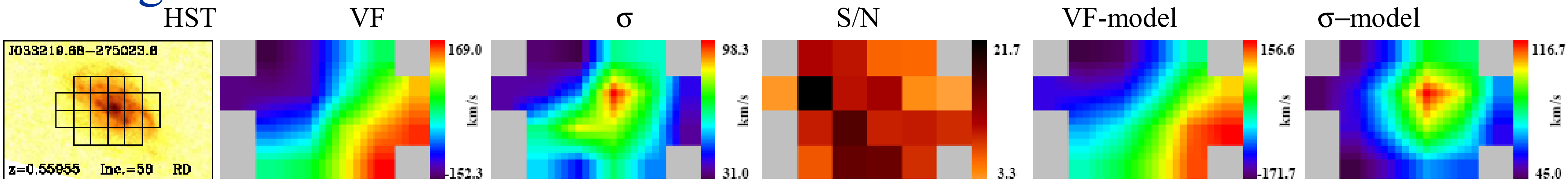


- **Rotation seen in the VF**
- **Off-centred σ peak**

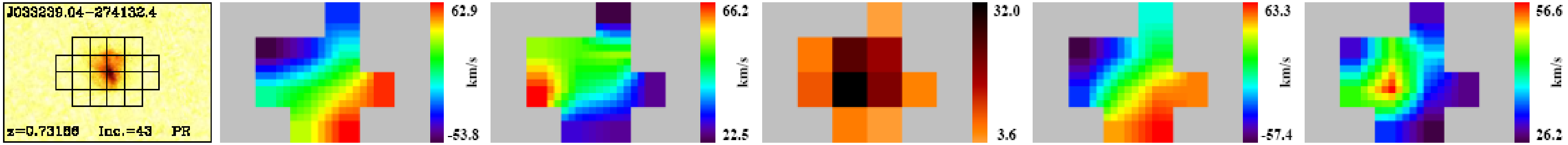


Resolved Kinematics

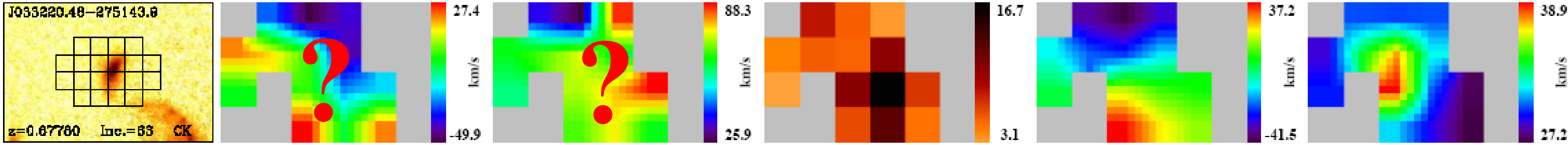
Rotating Disk



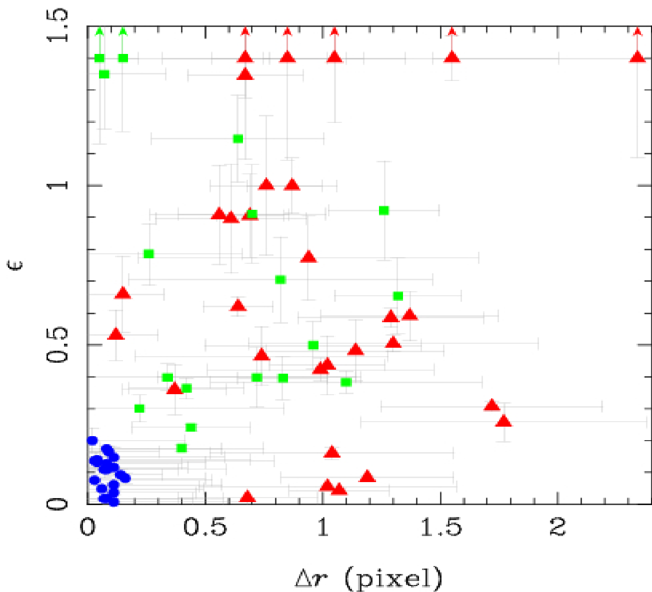
Perturbed Rotation



Complex Kinematics

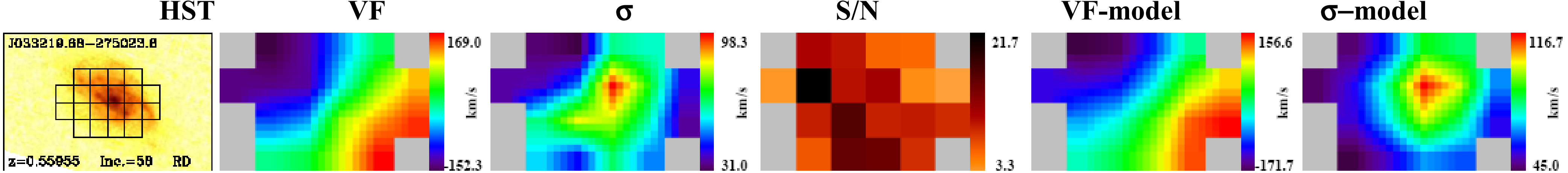


- **No obvious structure in the VF/σ-map**

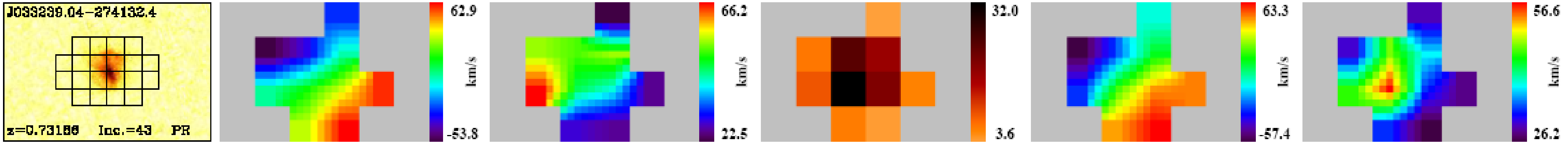


Resolved Kinematics

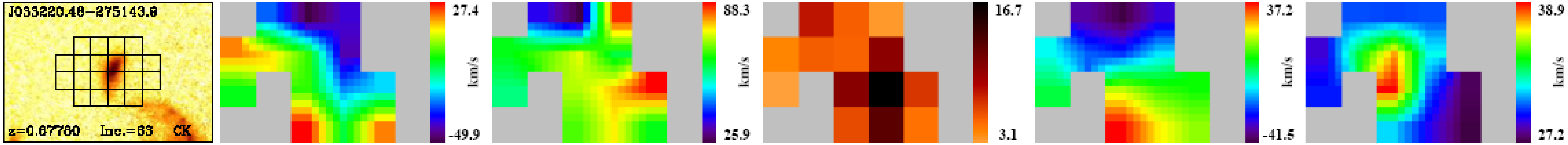
Rotating Disk



Perturbed Rotation



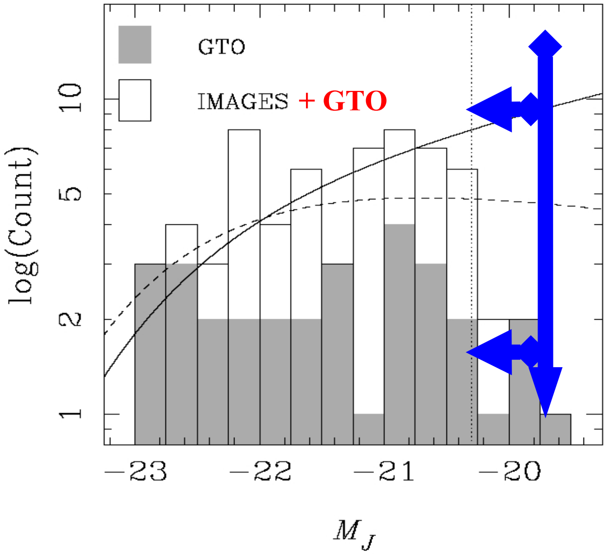
Complex Kinematics



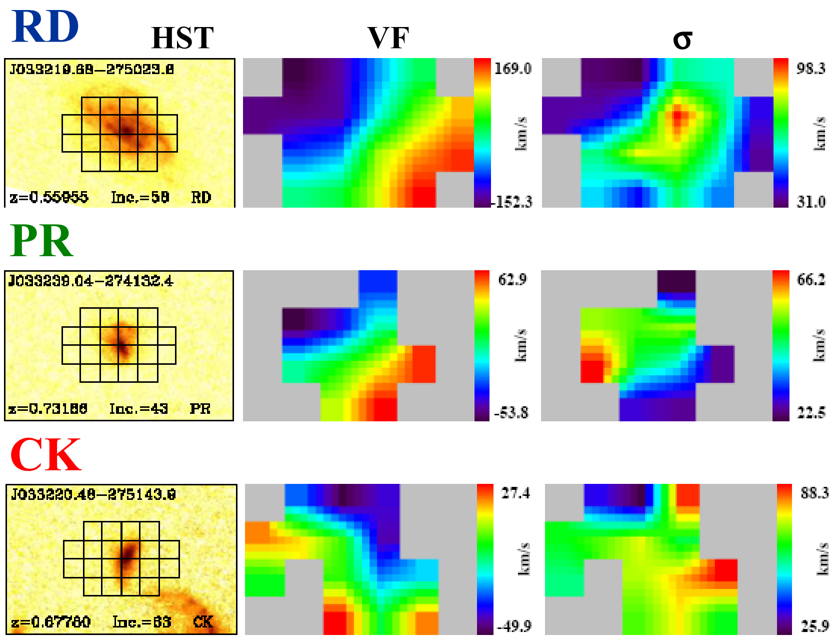
Flores et al (2006)
Puech et al (2006a)
Yang et al (2007)

Statistics in the sample

	HDFS	CFRS22h	CFRS03h	CDFS	Total (fraction)
RD	4	2	5	9	20 (32%±12%)
PR	2	2	2	10	16 (25%±12%)
CK	3	2	6	16	27 (43%±12%)
UC	3 in total			3	6 (9%)



Resolved Kinematics



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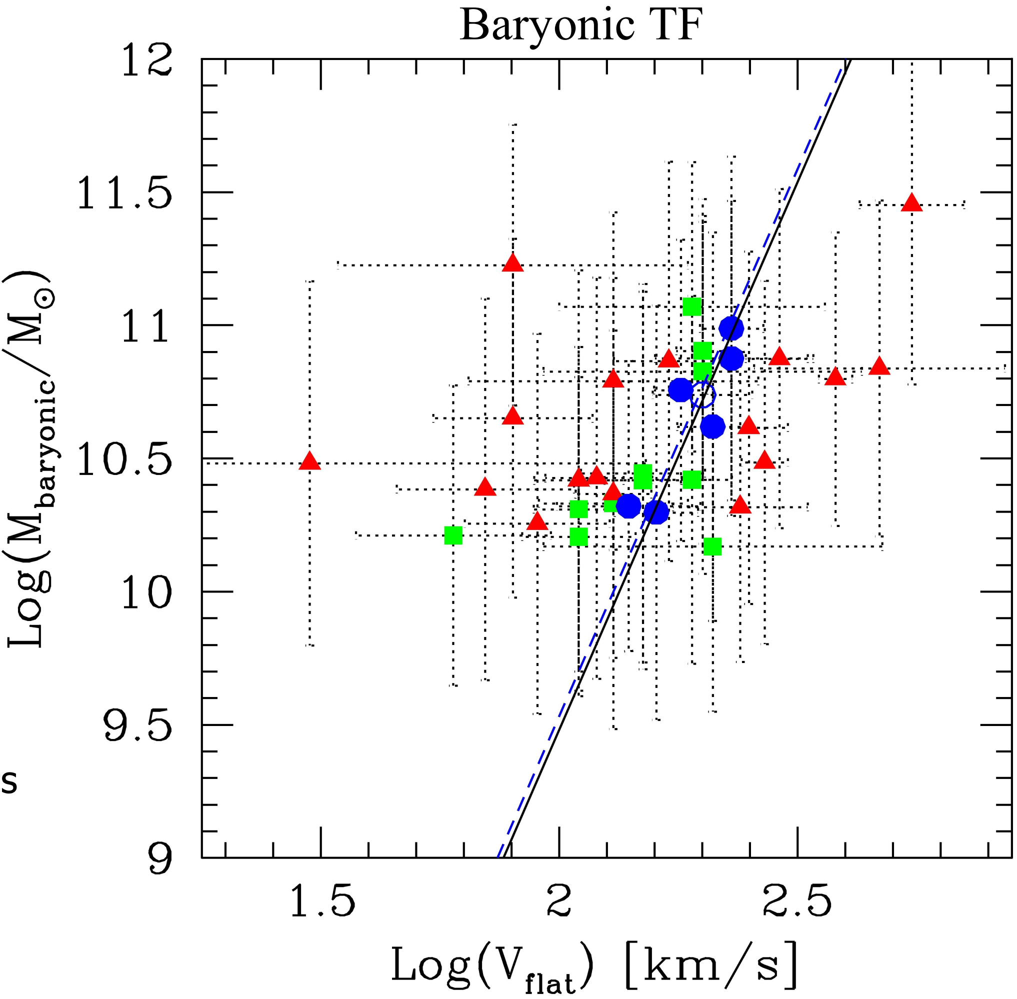
Yang et al (2008)



▲ Complexe Kinematics
■ Perturbed Rotation
● Rotating Disk

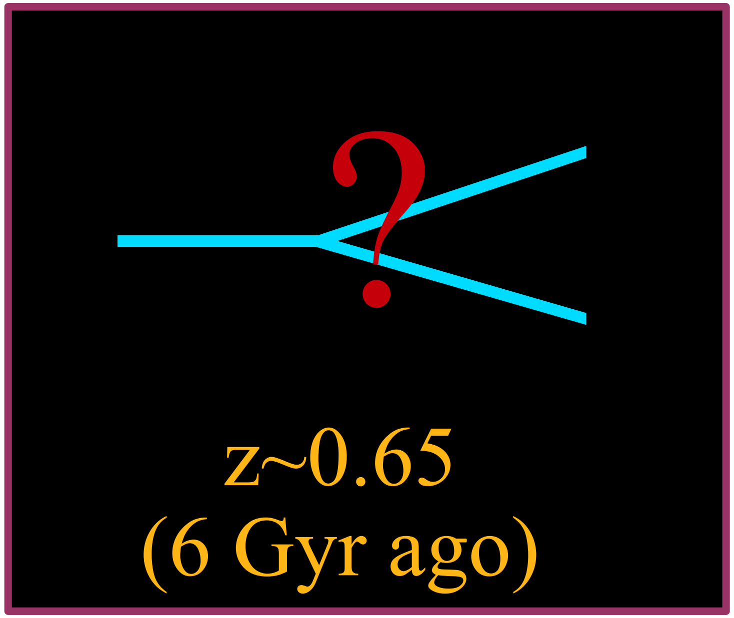
Puech et al. (2010)

Dynamics can explain the dispersion.
What about galaxy morphology?

Morphological classification:

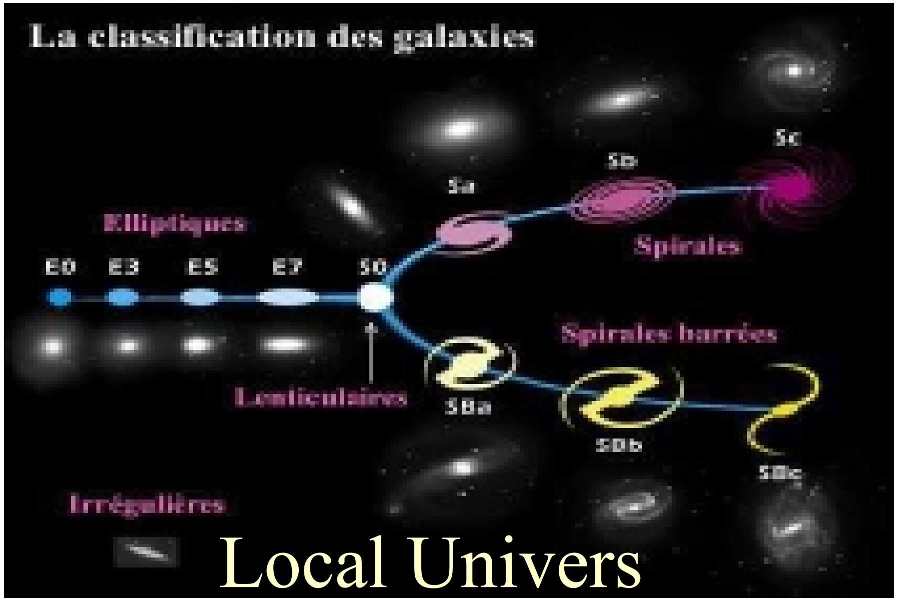
Much more than observing the beauty of galaxies

How were the galaxies of the Hubble sequence 6 Gyrs ago?



z~0.65
(6 Gyr ago)

Evolution?



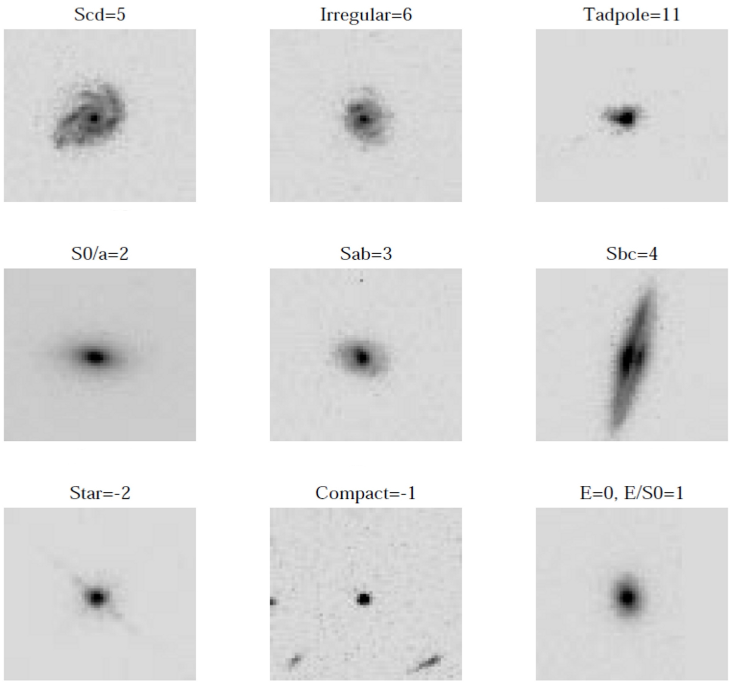
Local Univers

The link between distant and local galaxies is affected by:

- **Selection and observational biases**
- **The transformation of galaxies through time: stellar evolution, gaz supply, mergers ===> Change of type**

Methodological Bias

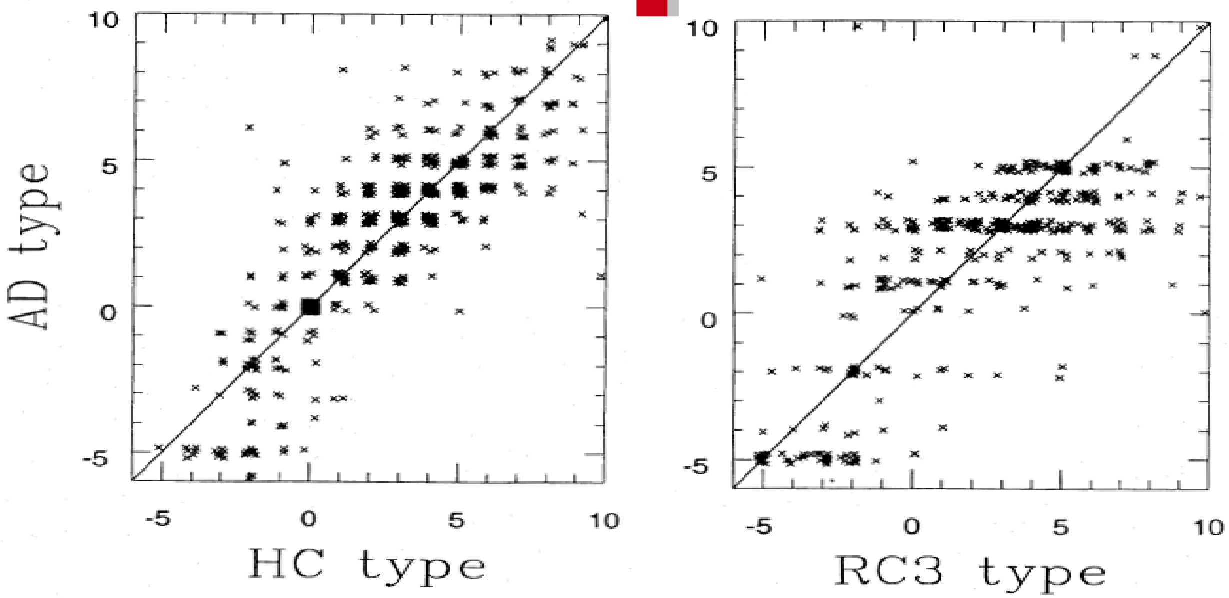
The standard method

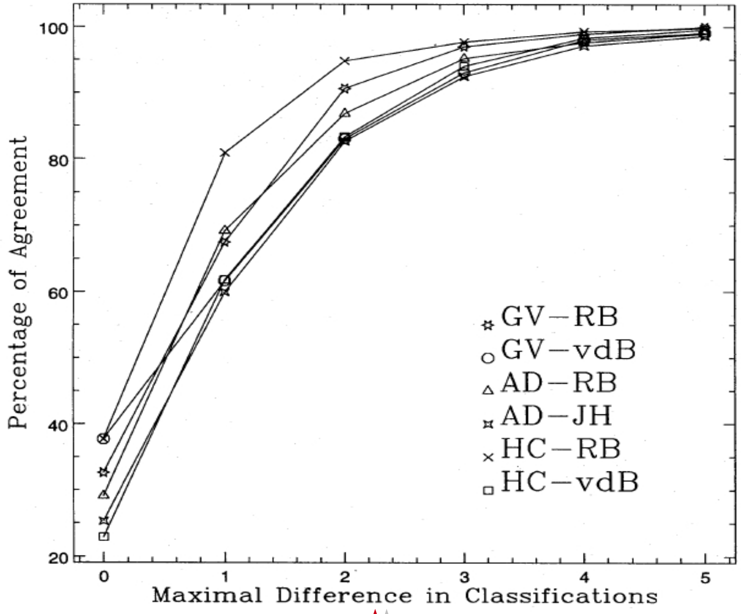


Brinchmann et al. (1998)

...and the humain bias ==> subjectivity

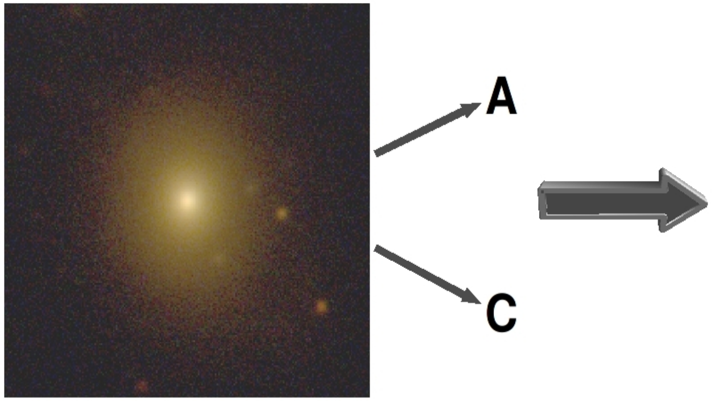
Naim et al. (1995)

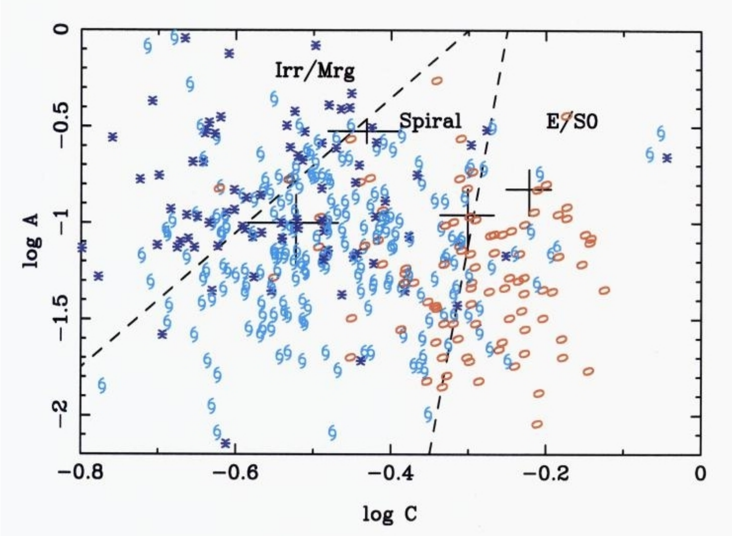




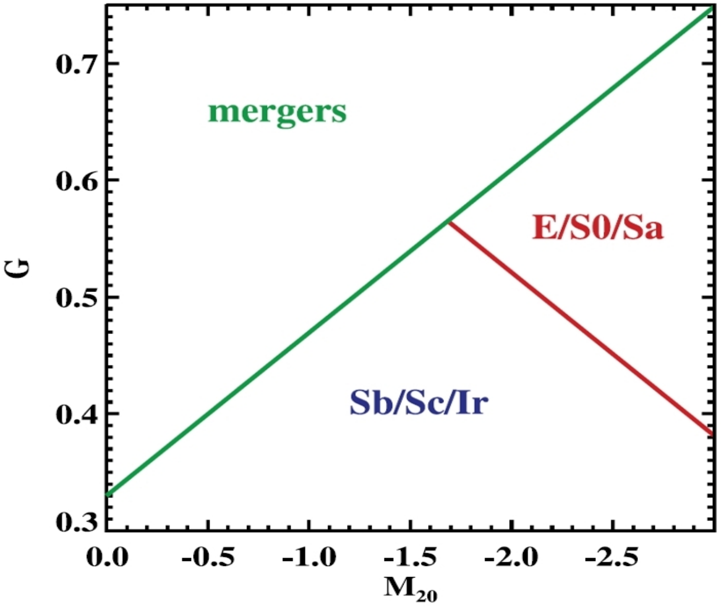
Methodological Bias

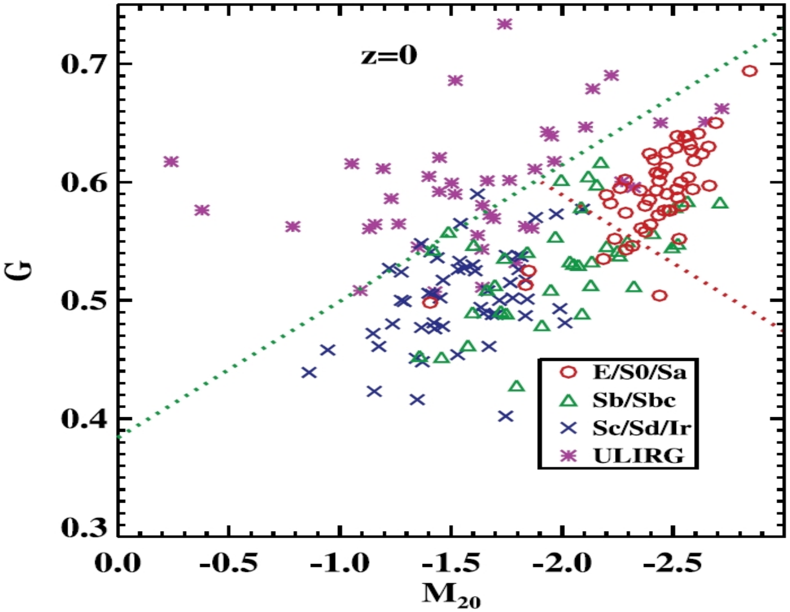
The automatic methods





Abraham et al. (1996b)





Lotz et al. (2008)

Morphological Classification vs Kinematic Classification

The case A-C :

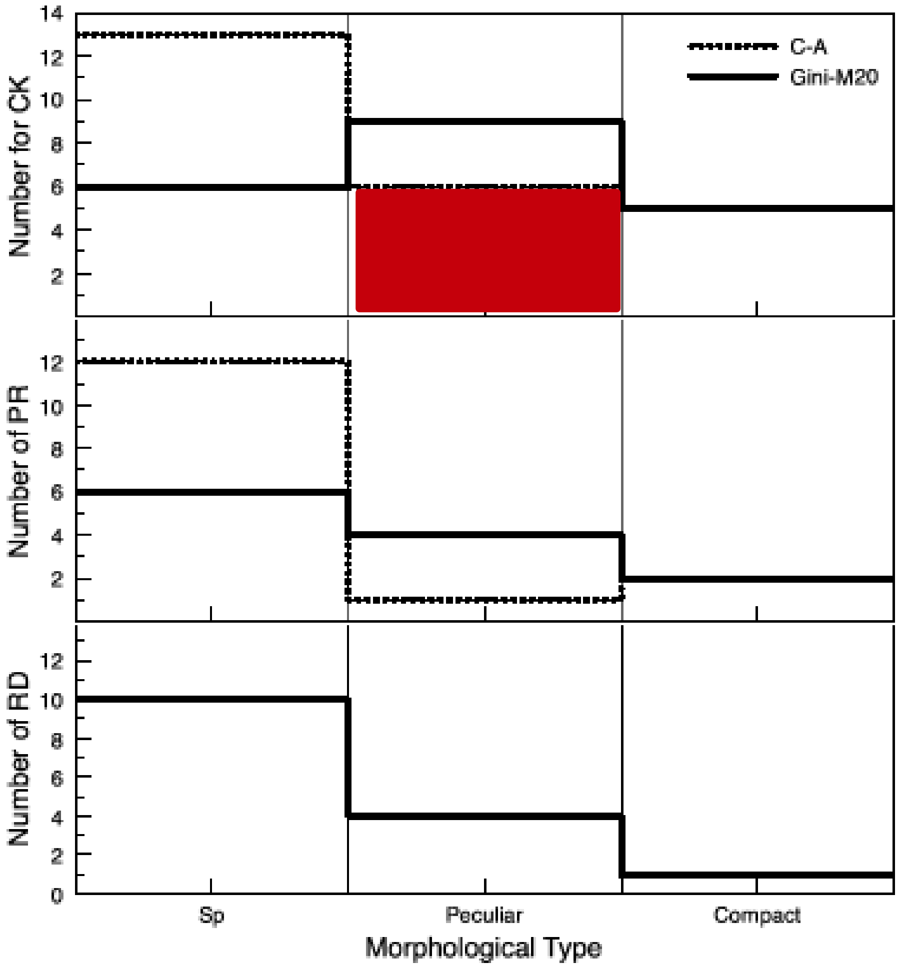
- Any Rotating Disk was classified as Spiral

- 68% of unnormal Dynamics do not have an unnormal morphology.

The case Gini-M_{20} :

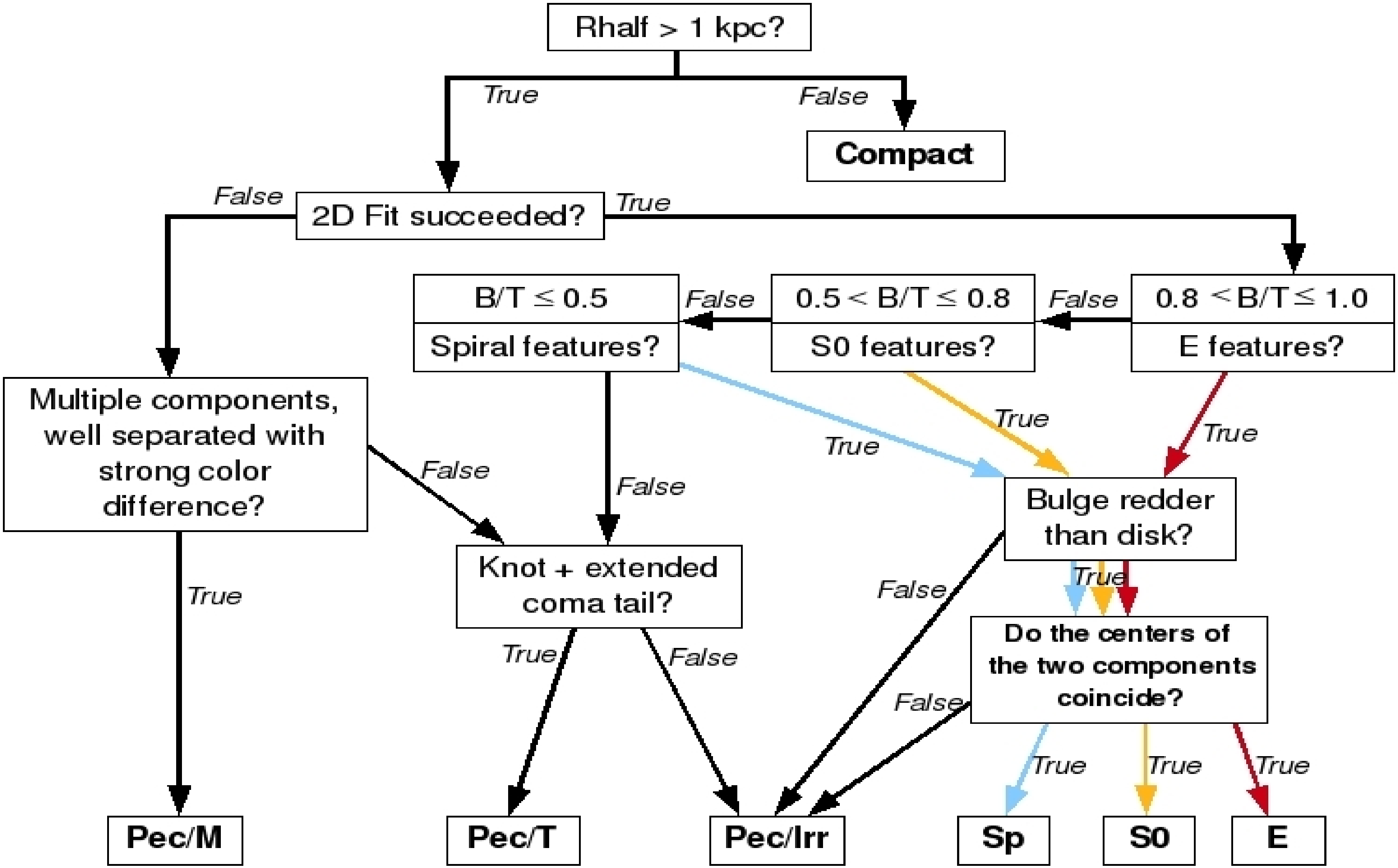
- 35% of Rotating Disks are not Spirals

- 30% of unnormal Dynamics do not have an unnormal morphology.



Neichel et al. (2008)

Decision Tree



Rhalf > 1 kpc?

Compact

2D Fit succeeded?

$0.8 < B/T \leq 1.0$

E features?

$0.5 < B/T \leq 0.8$

S0 features?

$B/T \leq 0.5$

Spiral features?

Multiple components, well separated with strong color difference?

Knot + extended coma tail?

Bulge redder than disk?

Do the centers of the two components coincide?

Pec/M

Pec/T

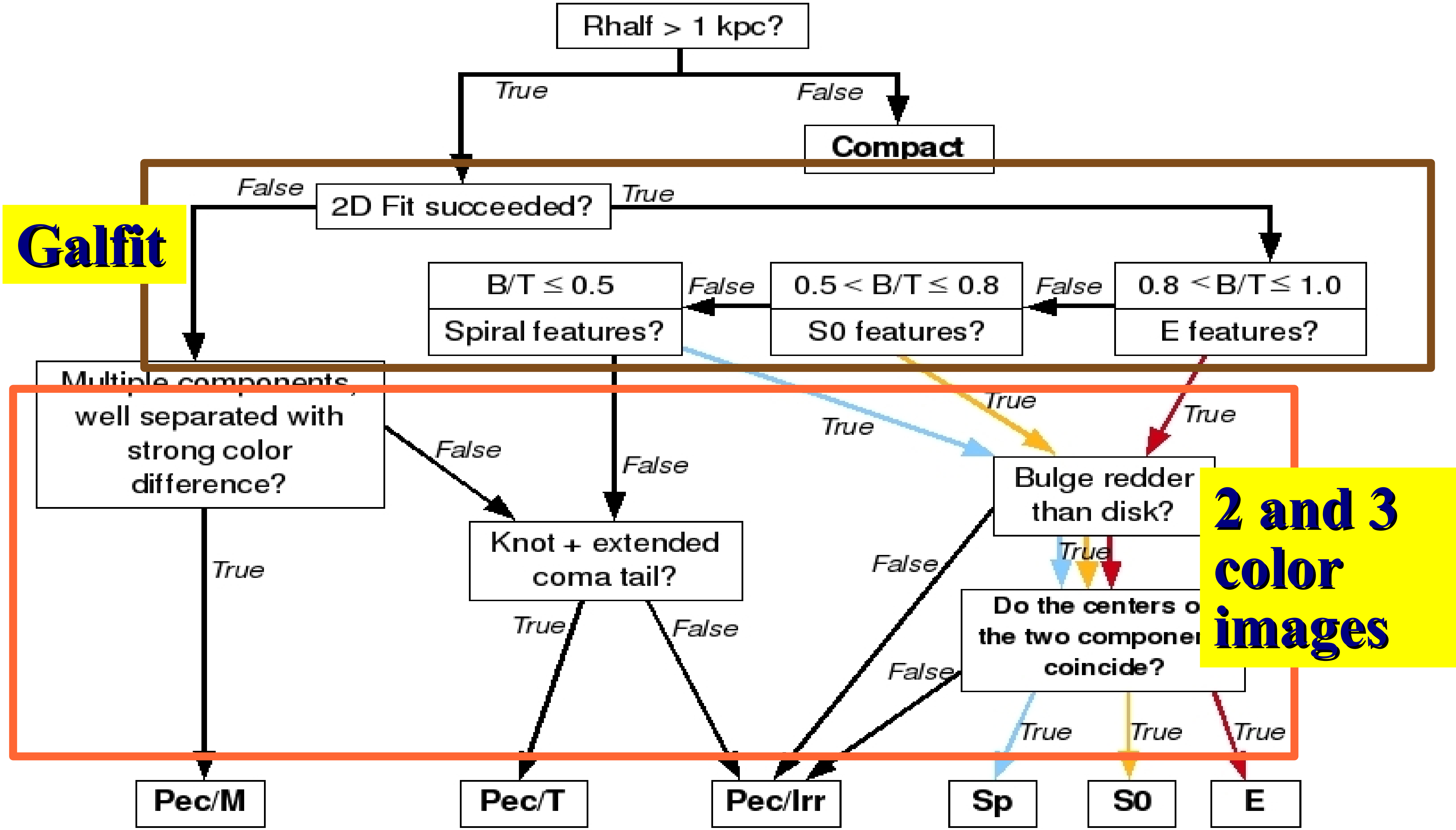
Pec/Irr

Sp

S0

E

Decision Tree



Rhalf > 1 kpc?

True

False

Compact

Galfit

False

2D Fit succeeded?

True

B/T ≤ 0.5

Spiral features?

False

0.5 < B/T ≤ 0.8

S0 features?

False

0.8 < B/T ≤ 1.0

E features?

Multiple components, well separated with strong color difference?

False

False

True

True

True

Bulge redder than disk?

2 and 3 color images

True

Knot + extended coma tail?

False

Do the centers o the two componen coincide?

False

True

False

True

True

True

True

Pec/M

Pec/T

Pec/Irr

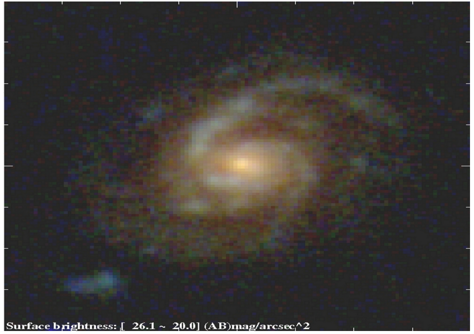
Sp

S0

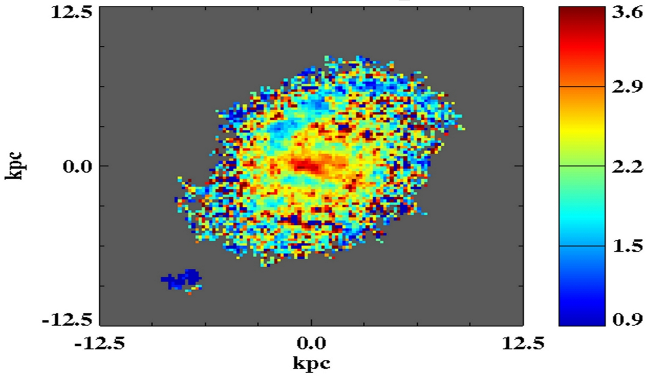
E

Full Morphological Analysis

3 color image



2 color map



One band image

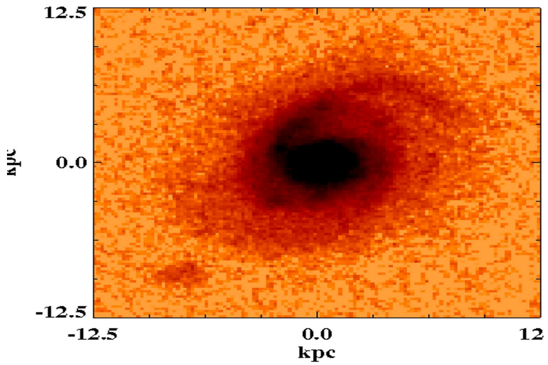
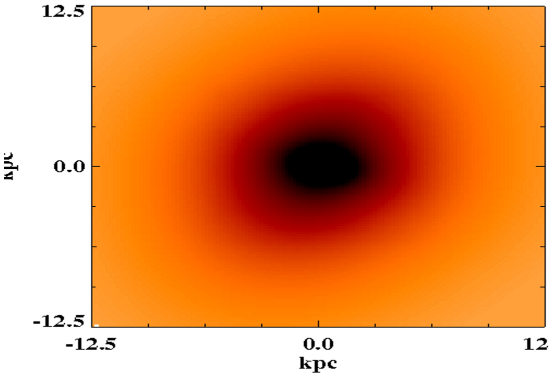
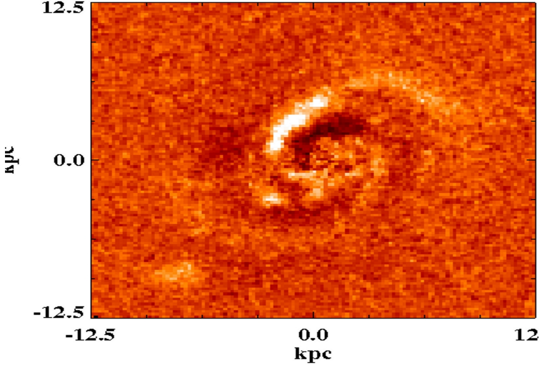


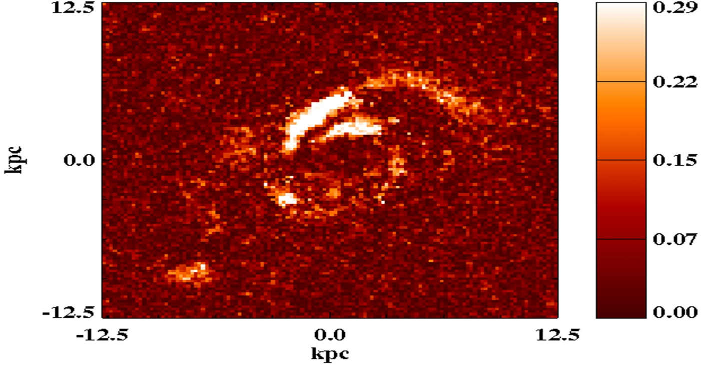
Image of the fit

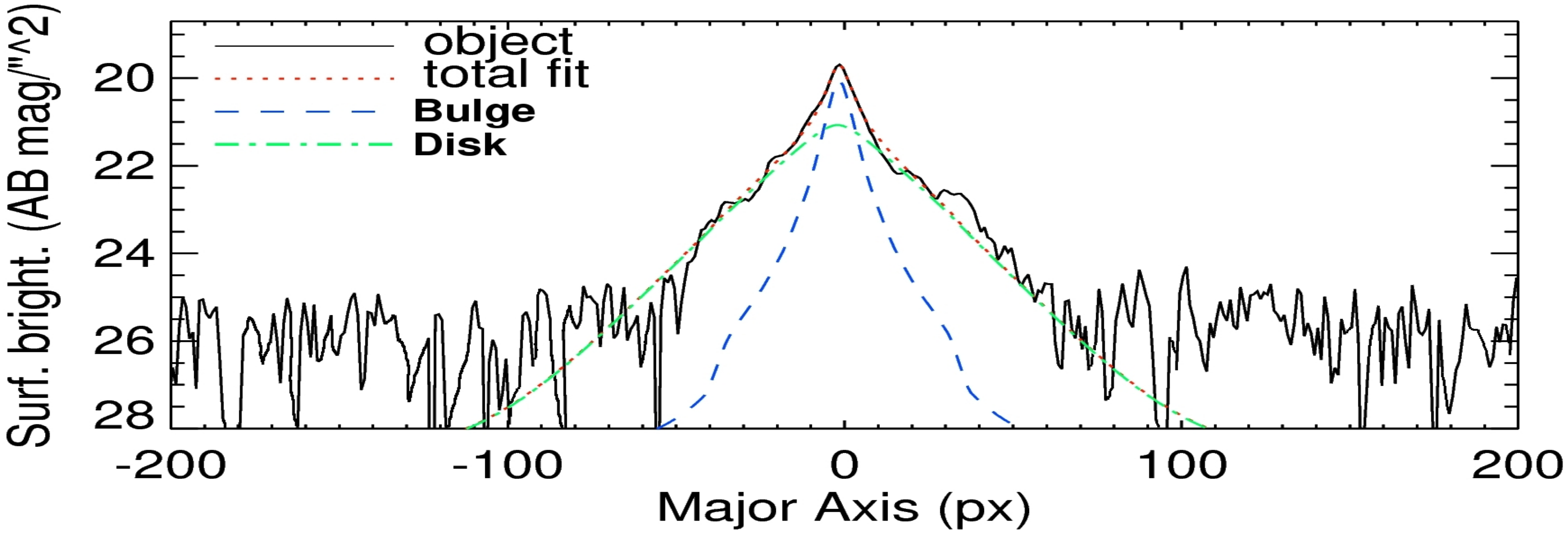


residual images

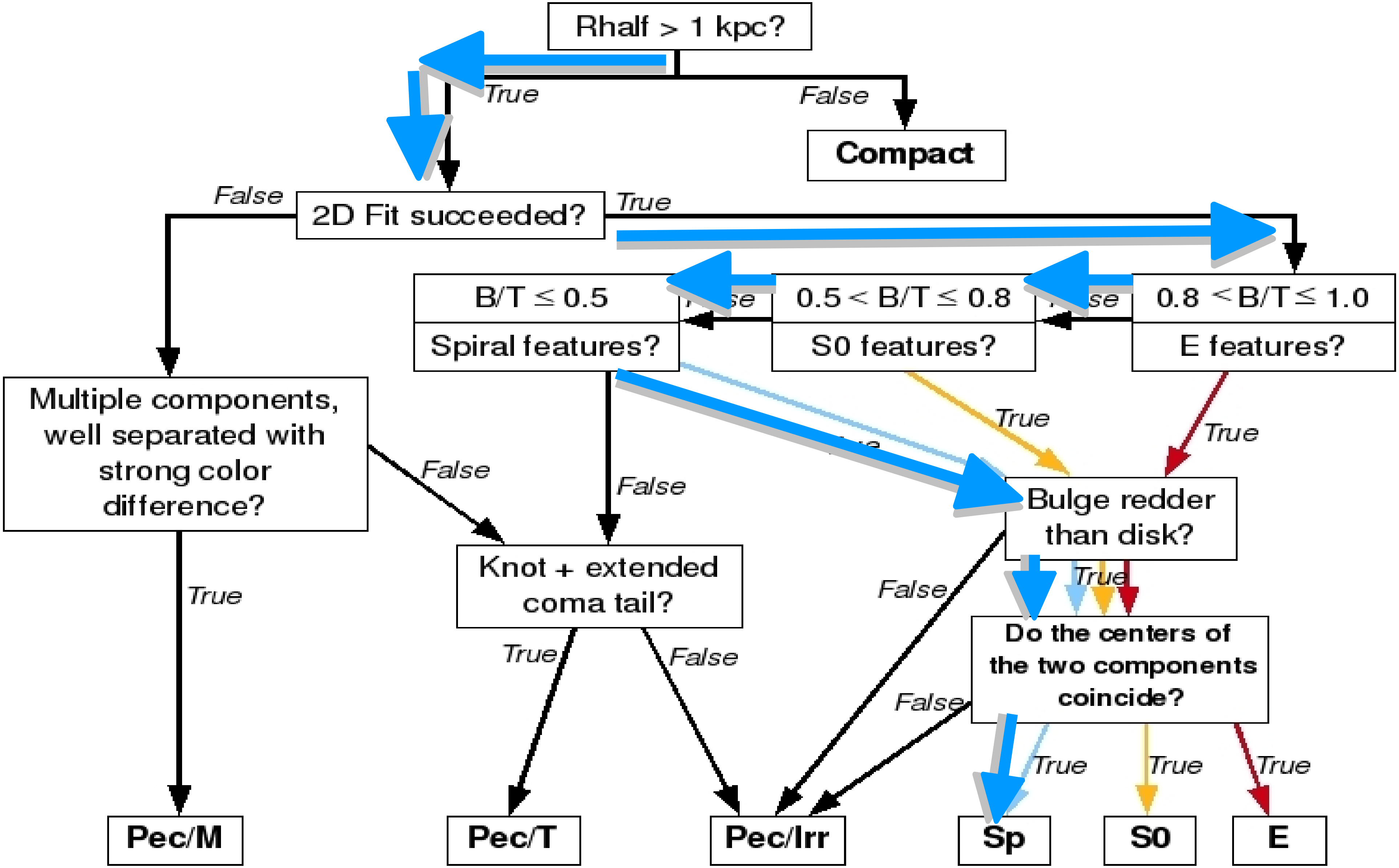


error image





Decision Tree



Rhalf > 1 kpc?

True

False

Compact

False

2D Fit succeeded?

True

B/T ≤ 0.5

Spiral features?

0.5 < B/T ≤ 0.8

S0 features?

0.8 < B/T ≤ 1.0

E features?

Multiple components, well separated with strong color difference?

False

False

True

True

Bulge redder than disk?

True

Knot + extended coma tail?

True

False

False

True

Do the centers of the two components coincide?

False

True

True

True

Pec/M

Pec/T

Pec/Irr

Sp

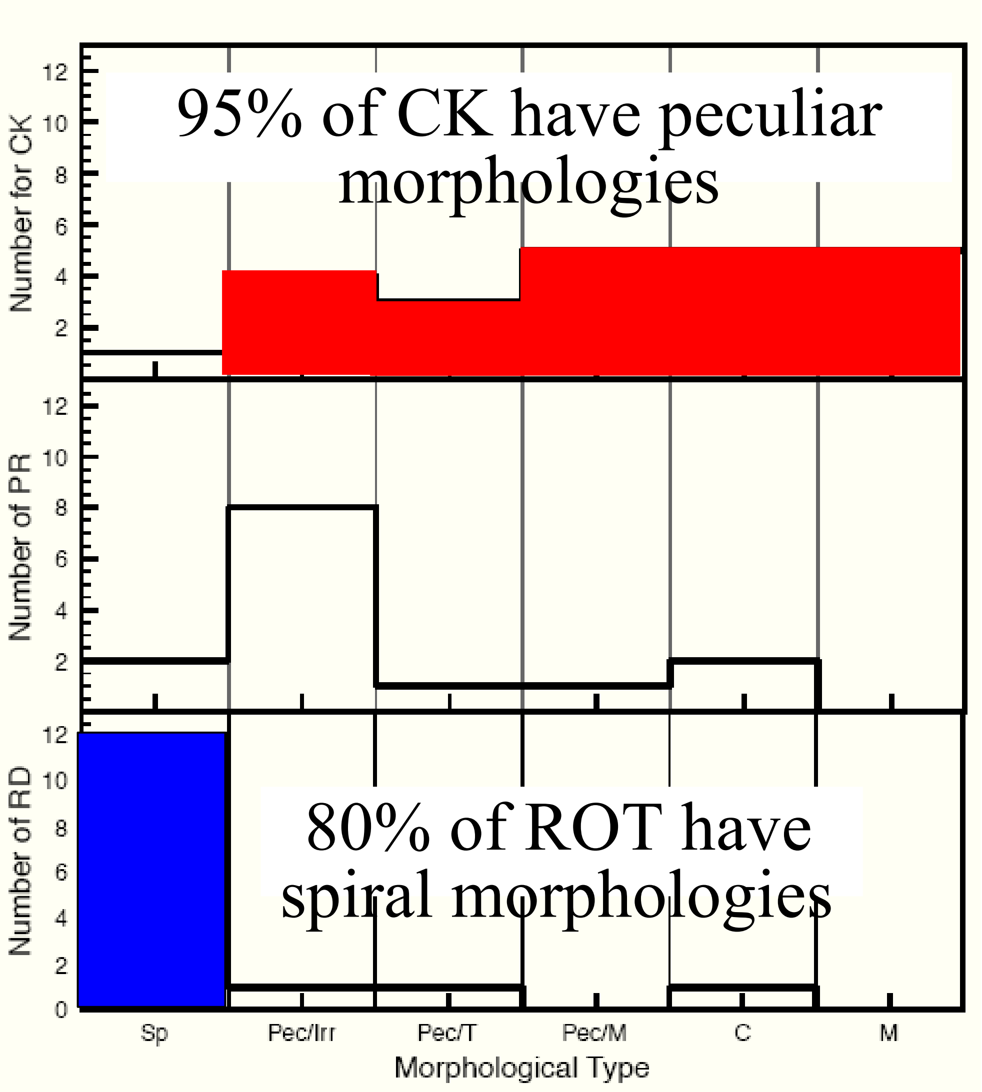
S0

E

Morphology versus kinematics

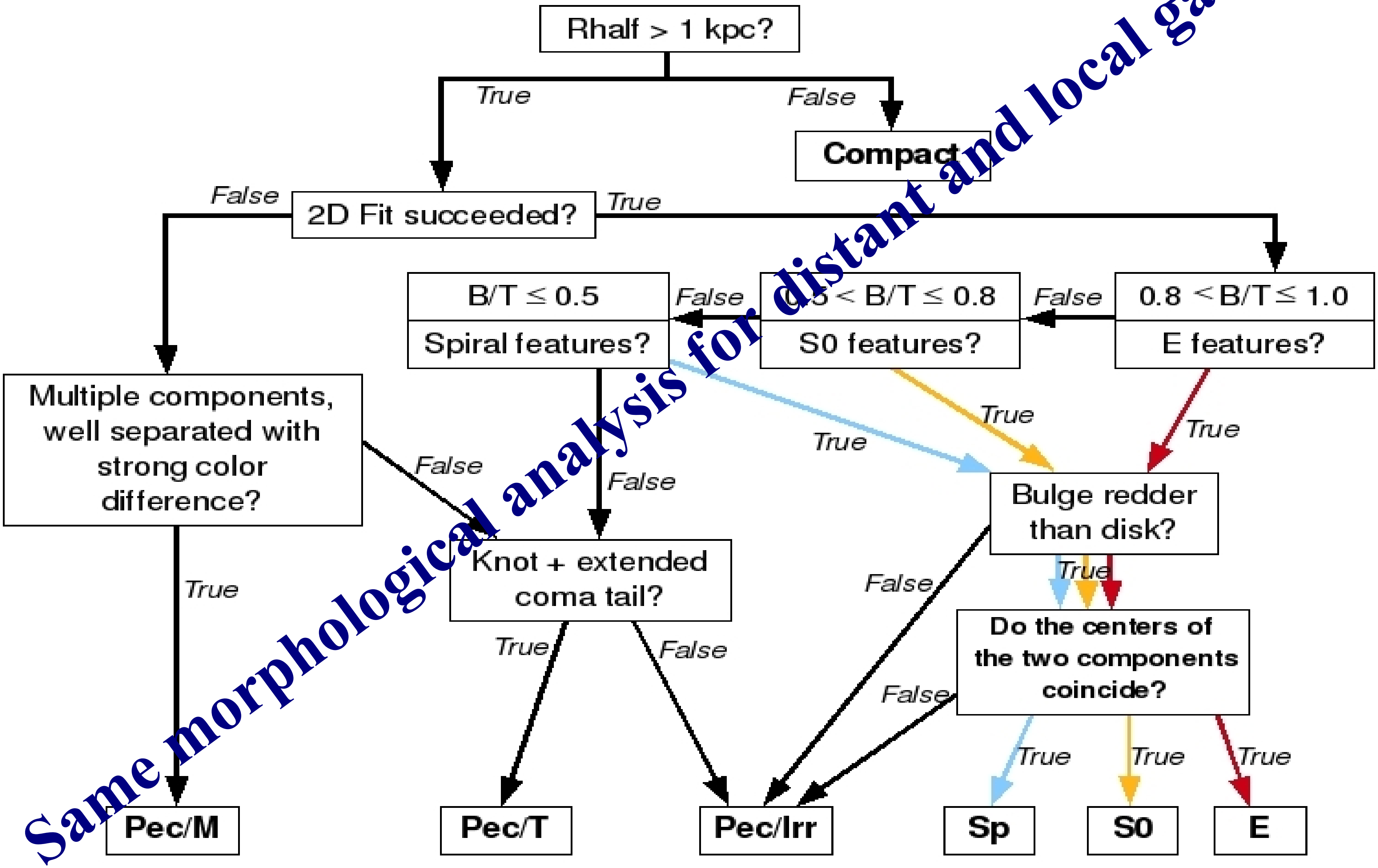
Neichel et al (2008)

Agreement between kinematics and morphological classifications



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

Decision Tree



Rhalf > 1 kpc?

True

False

Compact

2D Fit succeeded?

False

True

B/T ≤ 0.5

Spiral features?

False

0.5 < B/T ≤ 0.8

S0 features?

False

0.8 < B/T ≤ 1.0

E features?

Multiple components, well separated with strong color difference?

False

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True

Bulge redder than disk?

Knot + extended coma tail?

True

True

False

False

Do the centers of the two components coincide?

False

True

True

True

Pec/M

Pec/T

Pec/Irr

Sp

S0

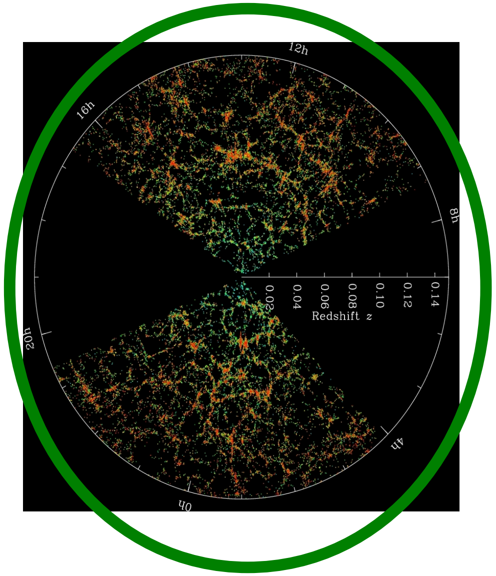
E

Same morphological analysis for distant and local galaxies

Samples of comparison

SDSS survey

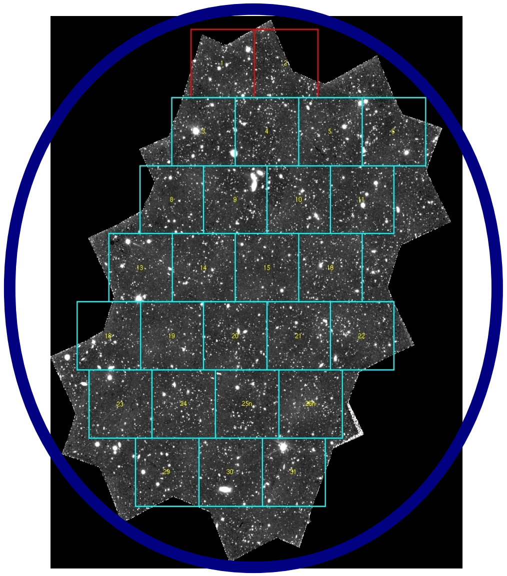
Local



0.0207 < *z* < 0.030

CDFS survey

Distant



0.4 < *z* < 0.8

Criteria for the selection:

- **M_J(AB)< -20.3**

- good quality spectra including [OII] λ3727
- At least three optical bands images (SDSS: u, g, r bands; CDFS: v, i, z bands)

Samples representativeness

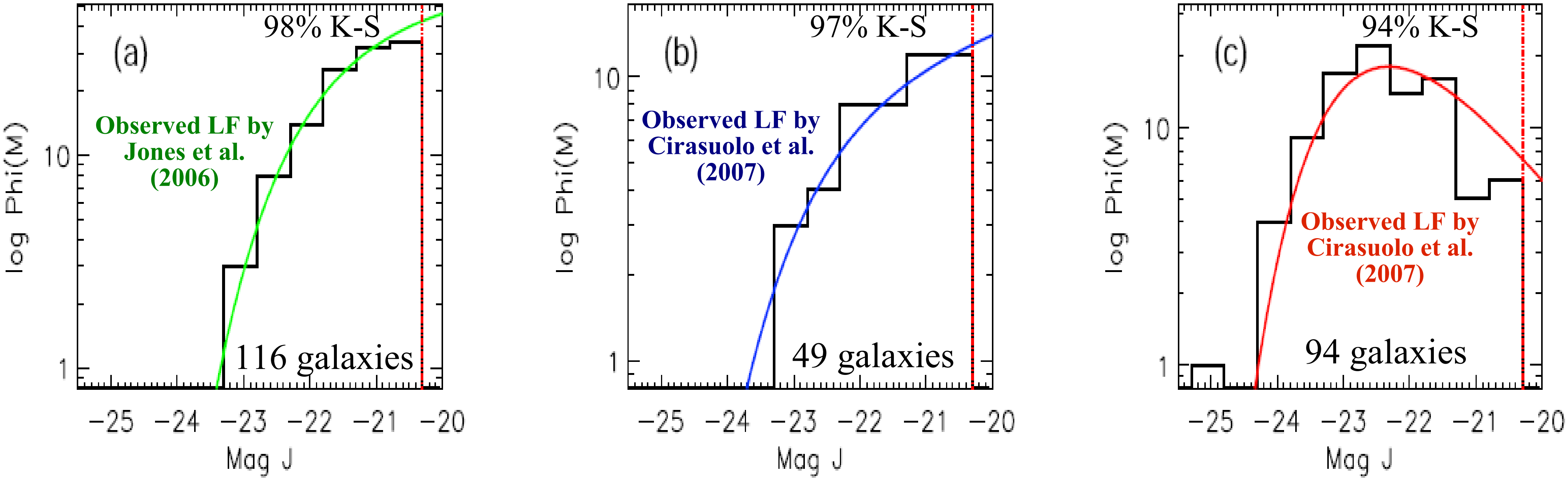
SDSS survey

CDFS survey

Local

Distant Starburst
EW[OII]>15 Å

Distant Quiescent
EW[OII]<15 Å



$0.0207 < z < 0.030$

$0.4 < z < 0.8$

$M_J(AB) < -20.3$

Spatial Resolution

SDSS survey

Local
(2.5 m ground telescope)

$z \sim 0.025$

FWHM = 1.4 arsec ===>> 0.72 kpc

0.396 "/pix

3.5 pix / resolution element

CDFS survey

Distant
(HST/ACS)

$z \sim 0.65$

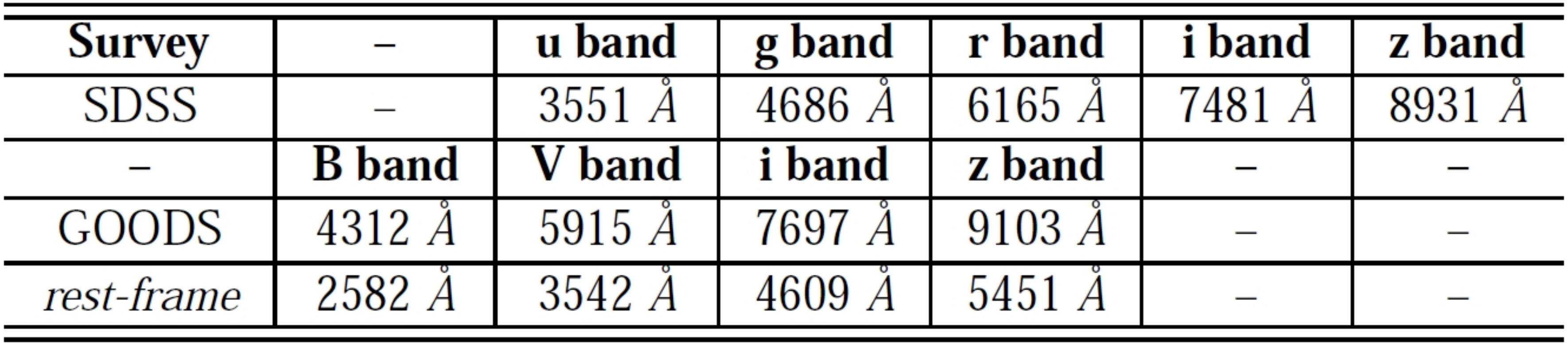
FWHM = 0.108 arsec ===>> 0.75 kpc

0.03 "/pix

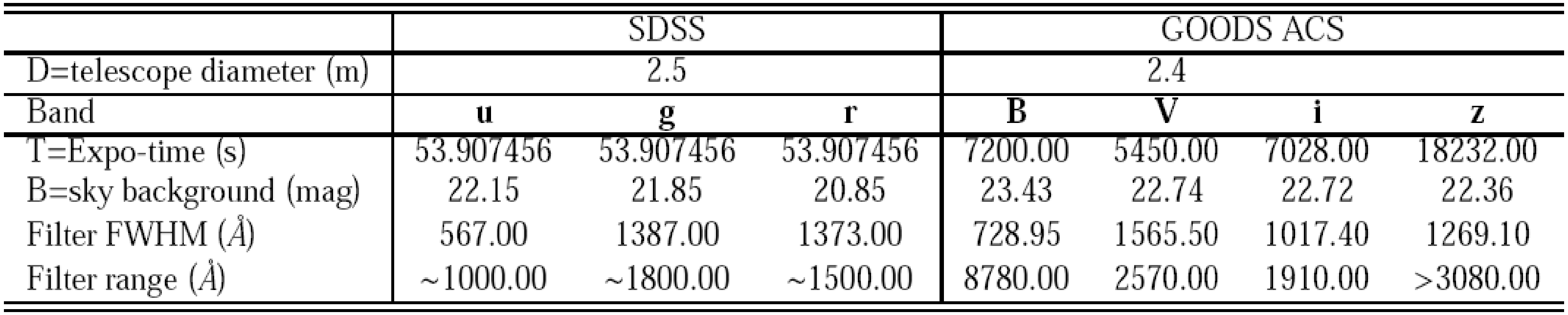
3.6 pix / resolution element

… K-correction, cosmological dimming or instrument differences?

K-correction, cosmological dimming or instrument differences



Survey	–	u band	g band	r band	i band	z band
SDSS	–	3551 Å	4686 Å	6165 Å	7481 Å	8931 Å
–	**B band**	**V band**	**i band**	**z band**	–	–
GOODS	4312 Å	5915 Å	7697 Å	9103 Å	–	–
rest-frame	2582 Å	3542 Å	4609 Å	5451 Å	–	–



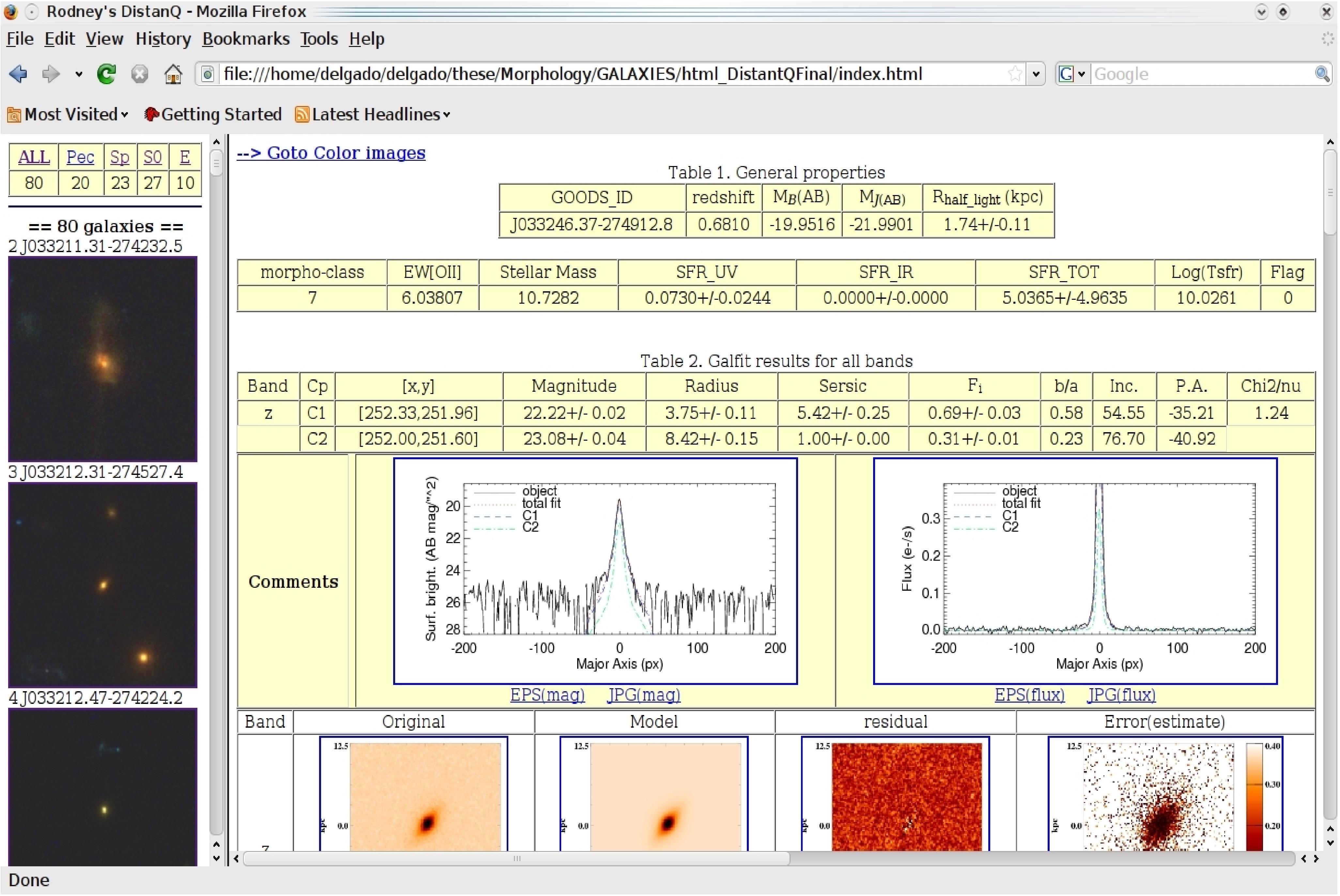
	SDSS			GOODS ACS			
D=telescope diameter (m)	2.5			2.4			
Band	**u**	**g**	**r**	**B**	**V**	**i**	**z**
T=Expo-time (s)	53.907456	53.907456	53.907456	7200.00	5450.00	7028.00	18232.00
B=sky background (mag)	22.15	21.85	20.85	23.43	22.74	22.72	22.36
Filter FWHM (Å)	567.00	1387.00	1373.00	728.95	1565.50	1017.40	1269.10
Filter range (Å)	~1000.00	~1800.00	~1500.00	8780.00	2570.00	1910.00	>3080.00

$$\frac{SNR^{HST}}{SNR^{SDSS}} = \sqrt{\frac{FWHM^{HST}}{FWHM^{SDSS}}} * \sqrt{\frac{T^{HST}}{T^{SDSS}}} * \frac{D^{HST}}{D^{SDSS}} * \sqrt{\frac{B^{SDSS}}{B^{HST}}} * \frac{f_{\lambda}^{HST_{z=0.0}}}{f_{\lambda}^{SDSS}} * \frac{1}{(1+z)^{5}}$$

mag difference :

u (V)	0.52
g (i)	0.08
r (z)	1.02

Data base



file:///home/delgado/delgado/these/Morphology/GALAXIES/html_DistantQFinal/index.html

ALL	Pec	Sp	S0	E
80	20	23	27	10

== 80 galaxies ==

2 J033211.31-274232.5

3 J033212.31-274527.4

4 J033212.47-274224.2

--> Goto Color images

Table 1. General properties

GOODS_ID	redshift	M_B(AB)	M_J(AB)	R_{half_light} (kpc)
J033246.37-274912.8	0.6810	-19.9516	-21.9901	1.74+/-0.11

morpho-class	EW[OII]	Stellar Mass	SFR_UV	SFR_IR	SFR_TOT	Log(Tsfr)	Flag
7	6.03807	10.7282	0.0730+/-0.0244	0.0000+/-0.0000	5.0365+/-4.9635	10.0261	0

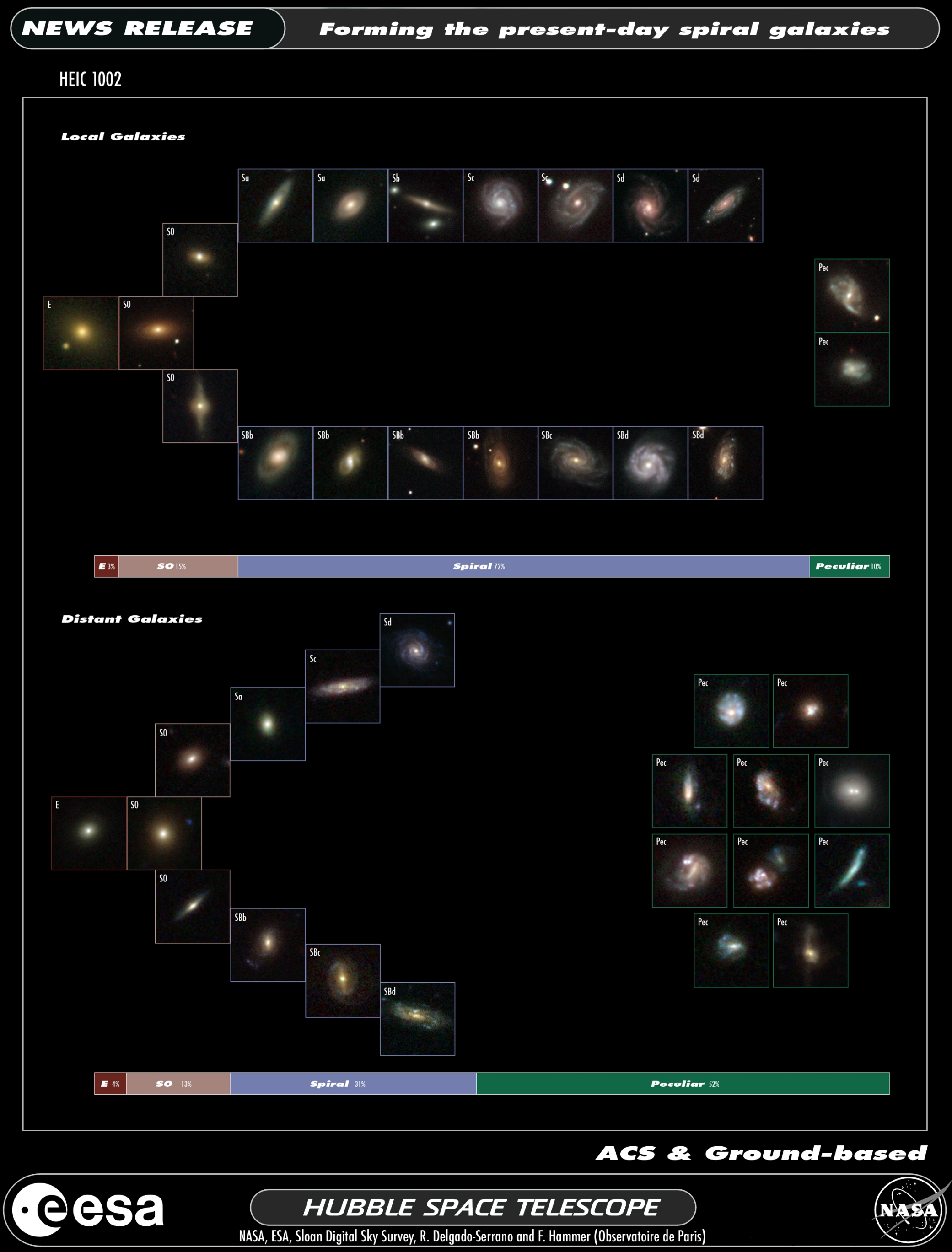
Table 2. Galfit results for all bands

Band	Cp	[x,y]	Magnitude	Radius	Sersic	F_i	b/a	Inc.	P.A.	Chi2/nu
z	C1	[252.33,251.96]	22.22+/- 0.02	3.75+/- 0.11	5.42+/- 0.25	0.69+/- 0.03	0.58	54.55	-35.21	1.24
	C2	[252.00,251.60]	23.08+/- 0.04	8.42+/- 0.15	1.00+/- 0.00	0.31+/- 0.01	0.23	76.70	-40.92	

Comments

Band	Original	Model	residual	Error(estimate)
z				

Results


NEWS RELEASE — Forming the present-day spiral galaxies

HEIC 1002

ACS & Ground-based

HUBBLE SPACE TELESCOPE

NASA, ESA, Sloan Digital Sky Survey, R. Delgado-Serrano and F. Hammer (Observatoire de Paris)

PR heic1002a

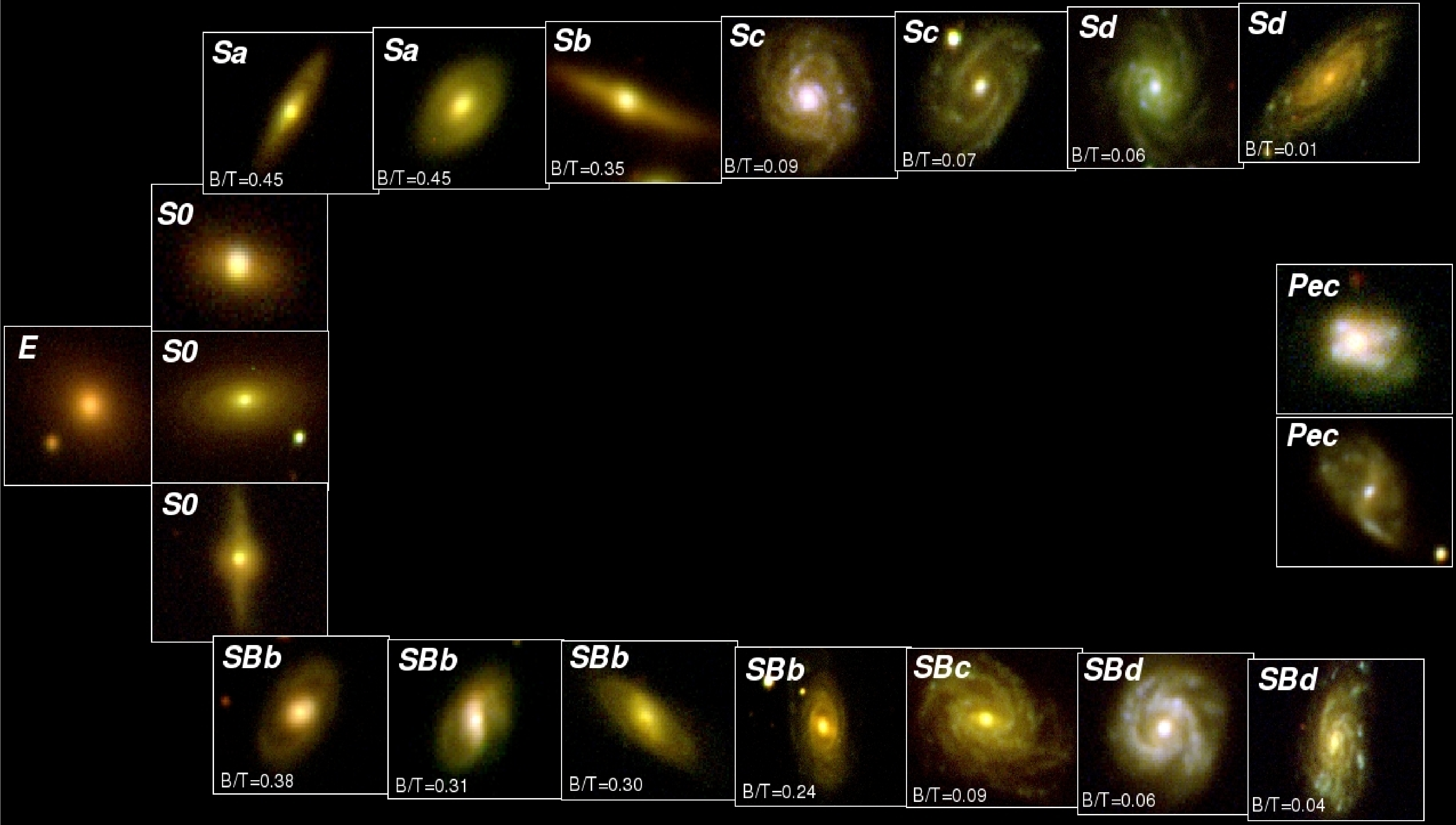
Results

	Local		
Type	Total (%)	Quiescent (%)	Starburst (%)
E	3±1	3±2	0±0
S0	15±4	14±4	20±10
Spiral	72±8	76±10	55±17
Peculiar:	10±3	7±3	25±11
P/Irr	4±2	2±1	15±9
P/Tad	0±0	0±0	0±0
P/Mer	4±2	4±2	5±5
P/C	2±1	1±1	5±5

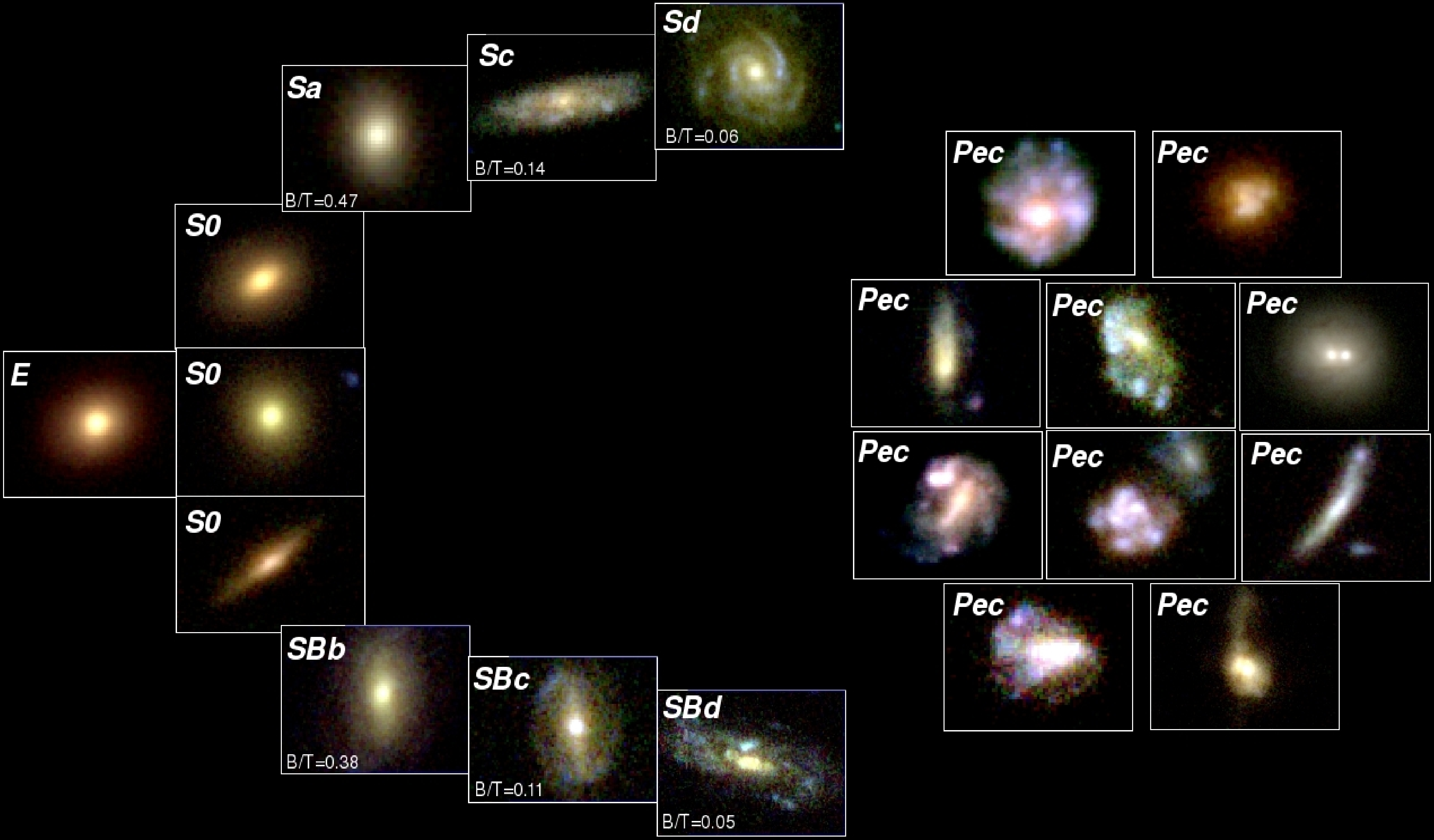
	Distant		
Type	Total(%)	Quiescent (%)	Starburst (%)
E	4±1	11±3	0±0
S0	13±2	33±6	0±0
Spiral	31±7	31±6	31±8
Peculiar:	52±9	25±5	69±12
P/Irr	26±7	21±5	29±8
P/Tad	6±3	0±0	10±5
P/Mer	20±6	4±2	30±8
P/C	0±0	0±0	0±0

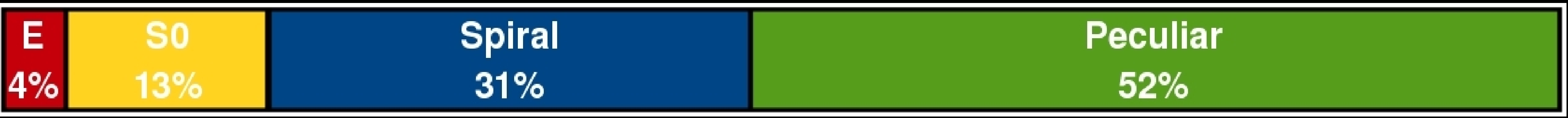
Delgado-Serrano et al. (2010)

Local Galaxies



Distant Galaxies



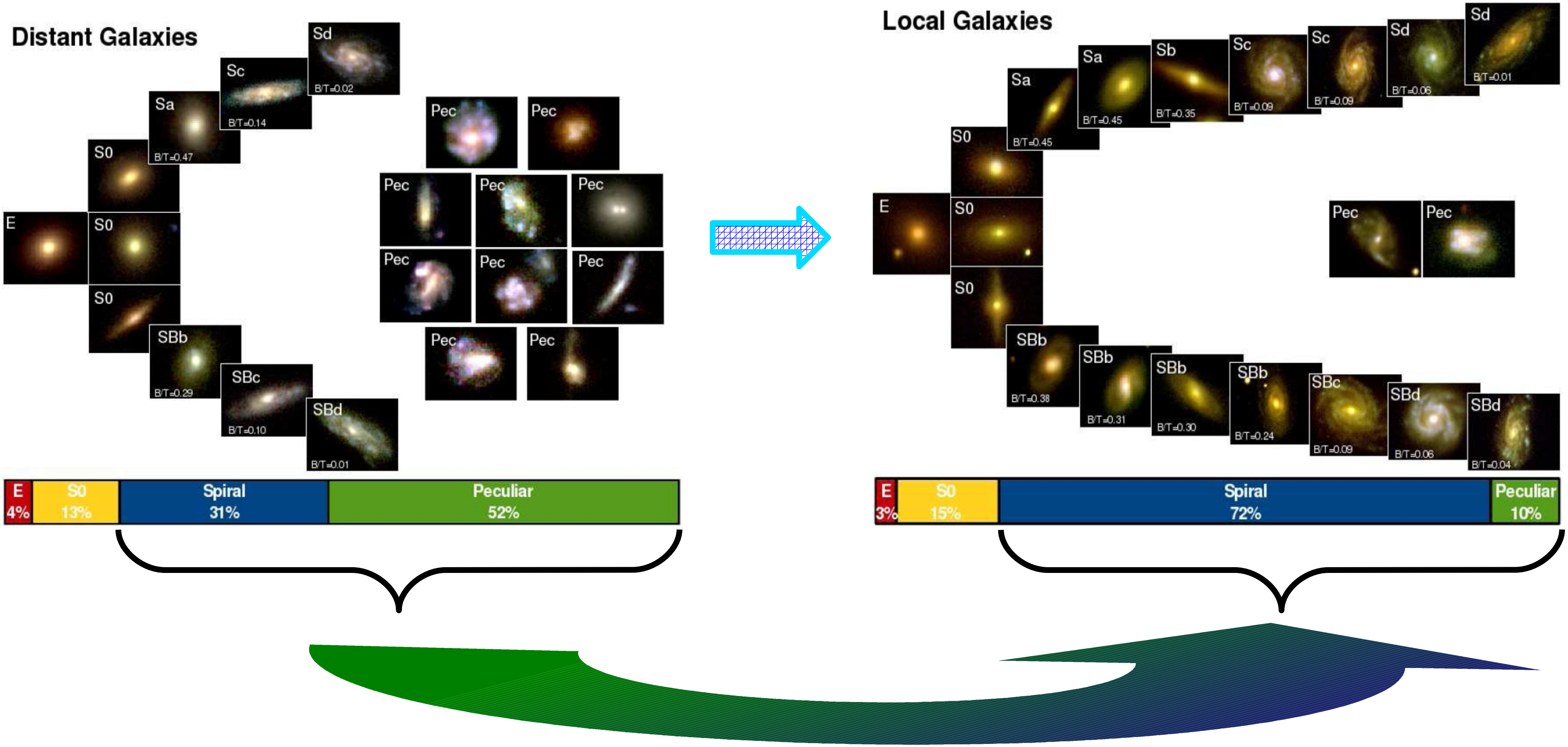


Hubble sequence evolution

6 Gyrs ago

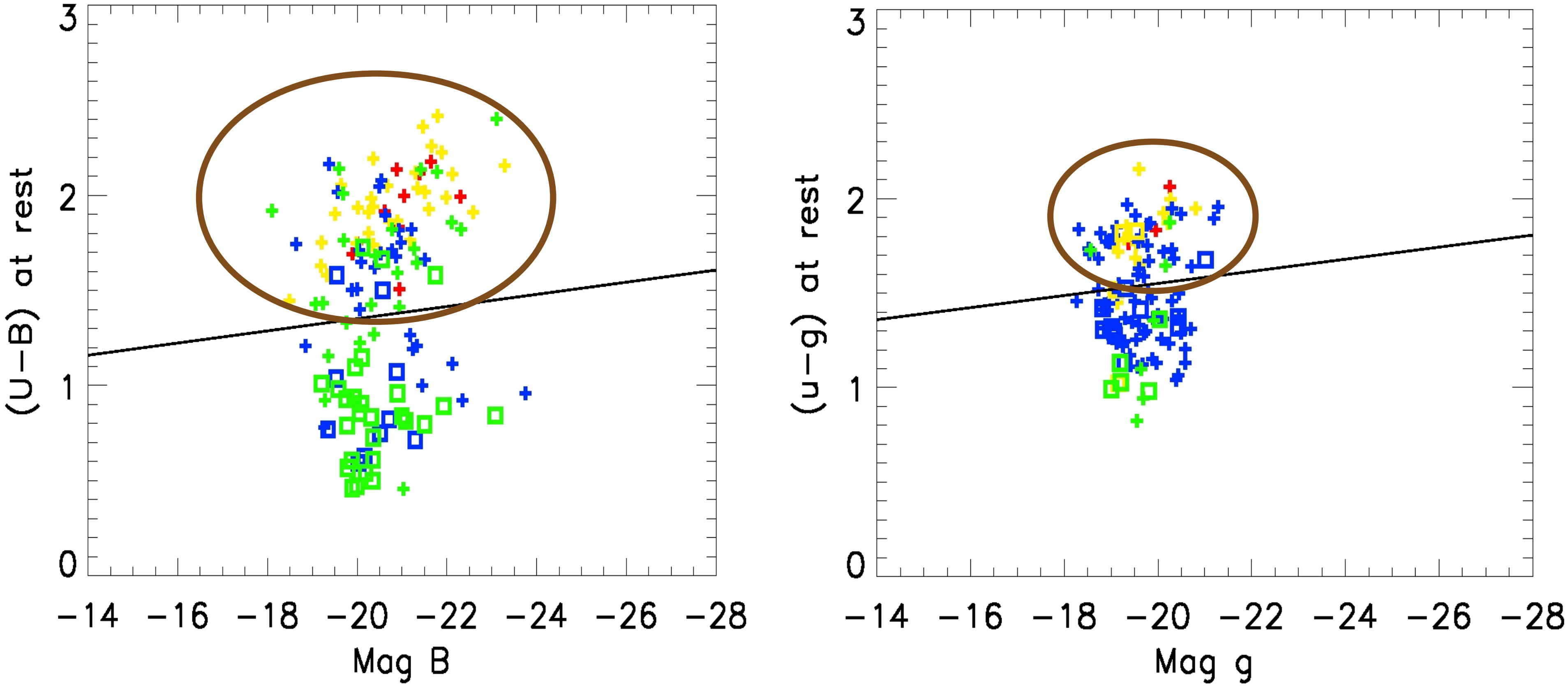
Present-day

Delgado-Serrano et al. (2010)



- **2.3 times more regular spiral galaxies**
- **5.2 times less peculiar galaxies**
- **No fraction evolution of E/S0 galaxies**

The “Red Sequence” and galaxy morphology

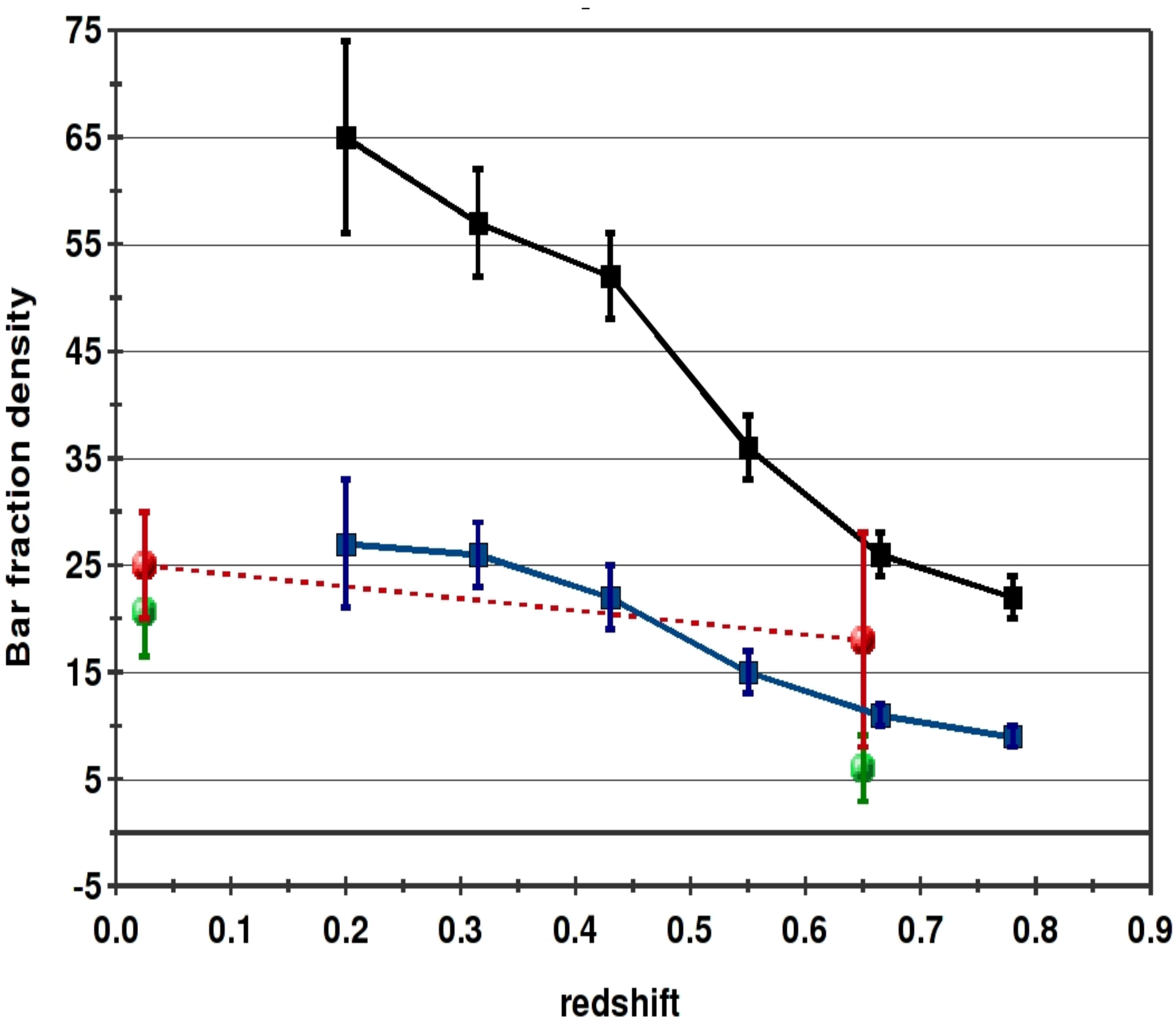


The bimodality is not a good morphological discriminante:

	Distant «Red Sequence»	Local «Red Sequence»
Red/Yellow ===>> E/S0	49 ± 8 %	33 ± 8 %
Blue ===>> Spirals	25 ± 6 %	61 ± 11 %
Green ===>> Peculiar	26 ± 6 %	6 ± 3 %

Contamination!

Barred Galaxy fraction



Results from Sheth et al. (2008)

Blue line → strong bar detection ($\varepsilon > 0.4$, $\delta\varepsilon > 0.1$, P.A. ≥ 10°)

Black line → strong bar + weak bar

Results with our samples

Green Circles → bar detection in Sp and S0 galaxies within the whole sample

Red Circles → bar detection in Sp and S0 galaxies compare to the total number of Sp and S0 galaxies in the sample

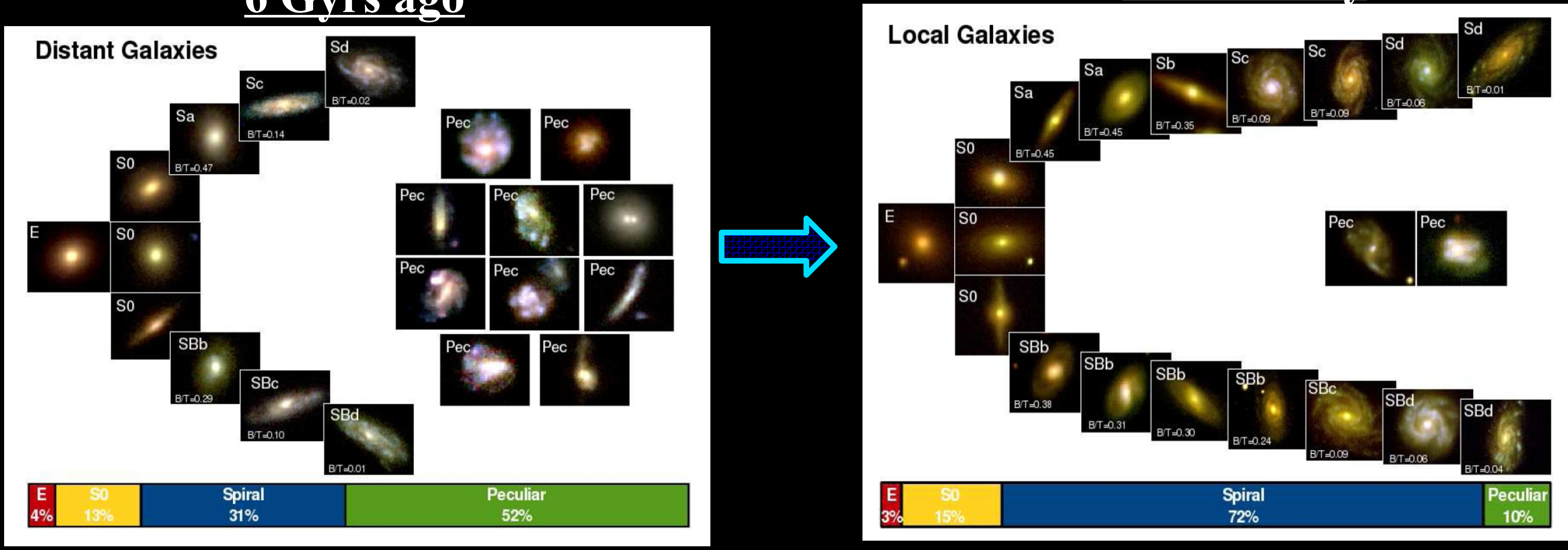
Conclusions

- **We have established a first approximation of what would be the progenitors, 6 Gyrs ago, of the galaxies of the present-day Hubble sequence.**
- **E/S0 galaxy populations show no evidence for a number evolution during the last 6 Gyrs;**
- ***Slightly more than half of the distant galaxies have peculiar morphologies, that is likely associated to anomalous kinematics according to Neichel et al. (2008)*;**
- **The fraction of regular spiral was 2.3 times lower 6 Gyrs ago than at the present epoch;**
- ***Morphology statistics strongly shows that almost all the galaxy evolution, since 6 Gyr ago, is caused by the transformation of galaxies with peculiar morphologies to regular spiral galaxies at present epoch*;**
- ***The transformation of peculiar distant galaxies to regular spiral in the present-day Hubble sequence should be addressed by current scenarios of galaxy evolution and formation.***

Delgado-Serrano et al. (2010)

6 Gyrs ago

Present-day



Technological University of Panama
Panama's Observatory

Thank You!!