The angular momentum of z=1 star forming galaxies from deep MUSE observations
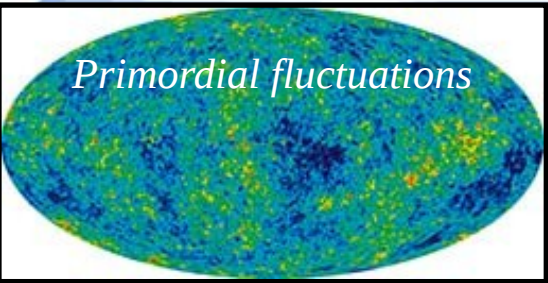
Nicolas Bouché
T. Contini; B. Epinat

+ MUSE team: R. Bacon (PI); E. Emsellem; J. Brinchman; J. Richard; T. Martinsson; D. Krajnovic; P. Weilbacher; L. Wisotski; ...
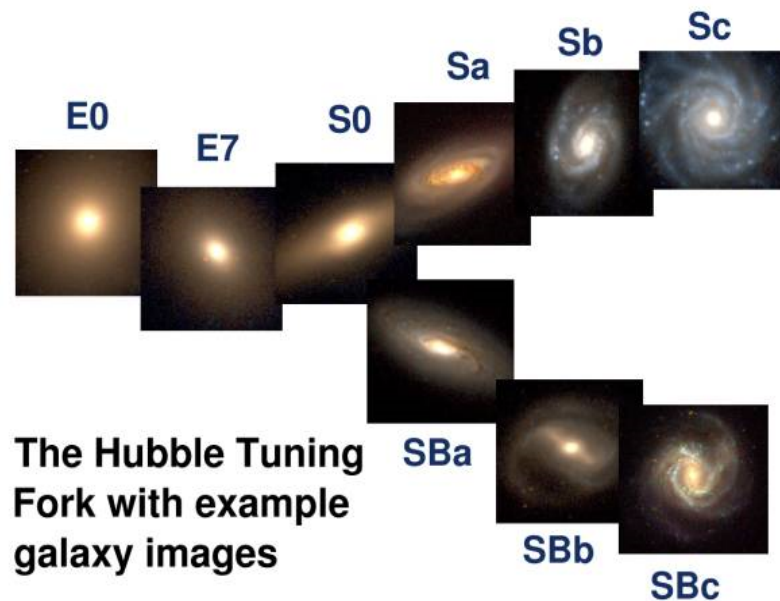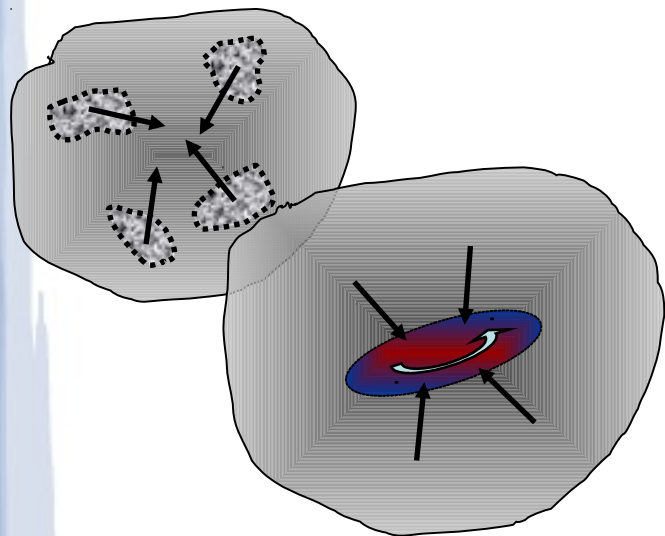
H. Finley; **A. Guerou**; I. Schroetter; E. Ventou;

MULTI-SPIN GALAXIES 2016
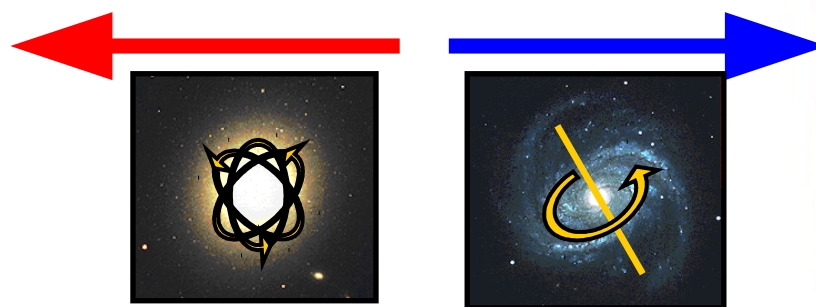
Primordial fluctuations

The growth of galaxies
gas inflows and outflows

The Hubble Tuning Fork with example galaxy images

E0   E7   S0   Sa   Sb   Sc

SBa   SBb   SBc
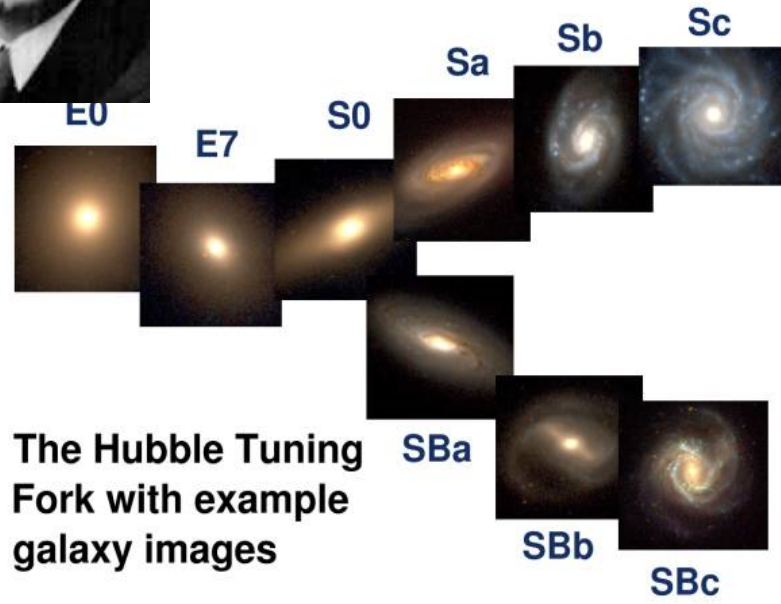
Z=1000   Z=10   Z=1   Z=0
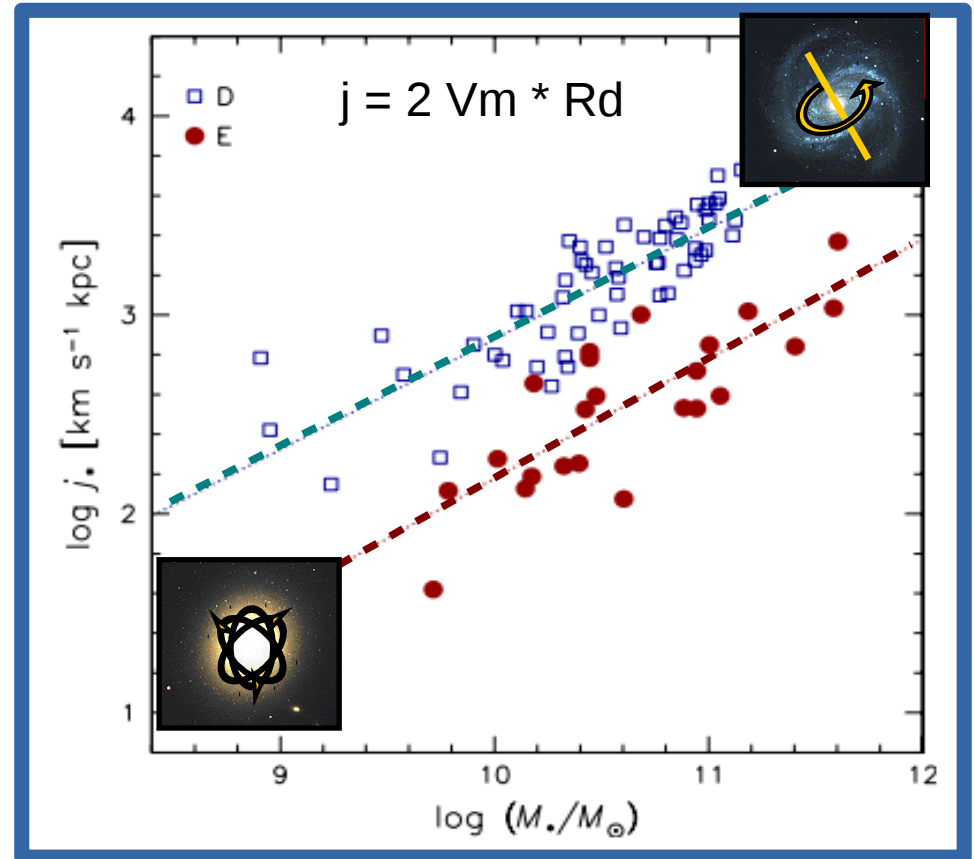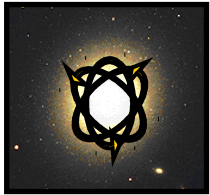
1ˢᵗ stars   Galaxies assemble and take shape
Peak of SFRD
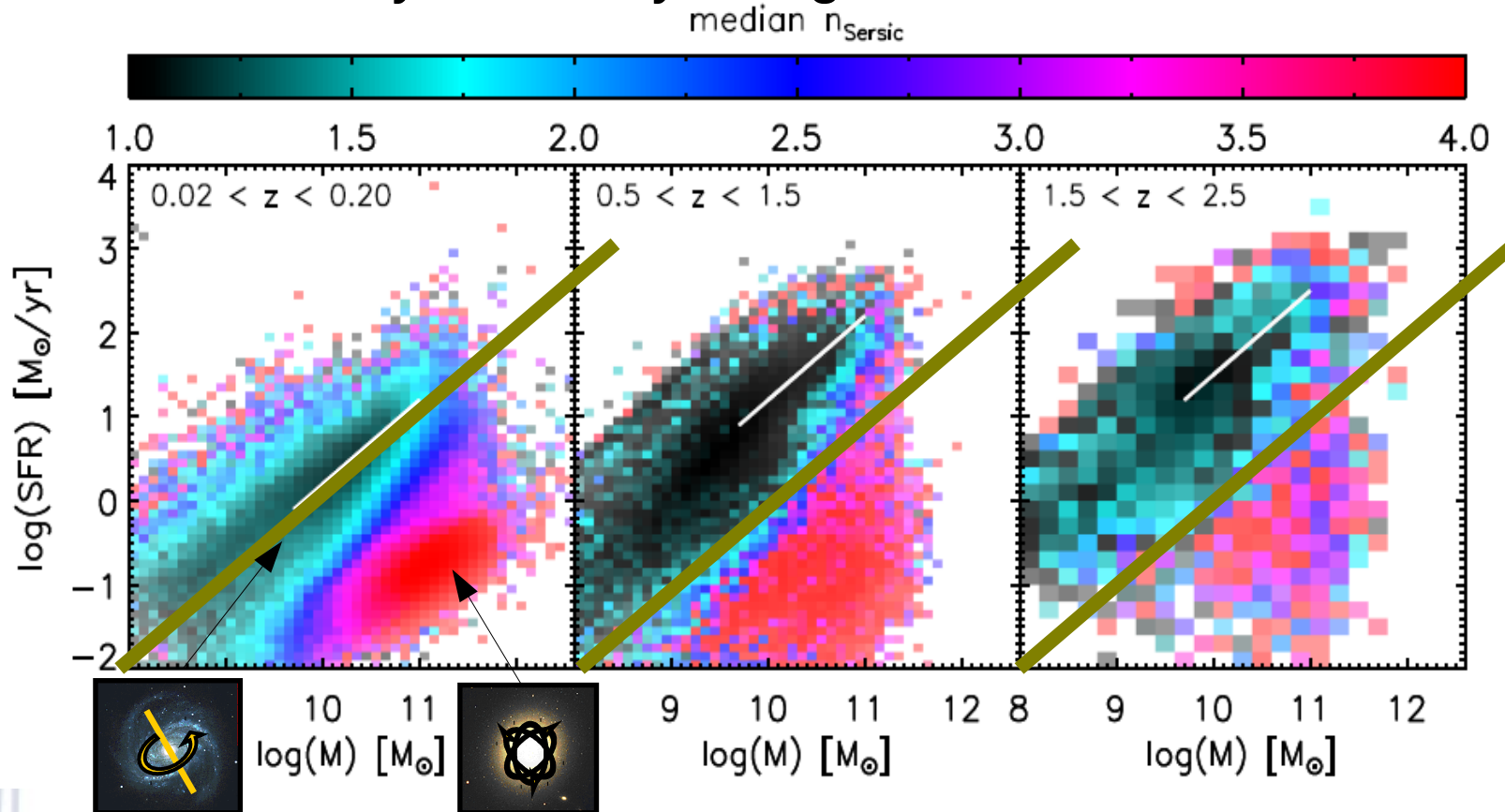
The Hubble diagram

is a spin sequence

z=0 Fall & Romanowsky 2015
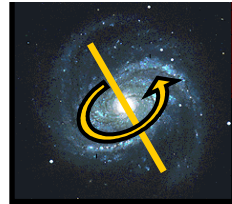
$j = 2 V_m * R_d$

E0 E7 S0 Sa Sb Sc

The Hubble Tuning
Fork with example
galaxy images

SBa SBb SBc

The new Hubble diagram: SFR-M*

The main sequence is a morphology sequence
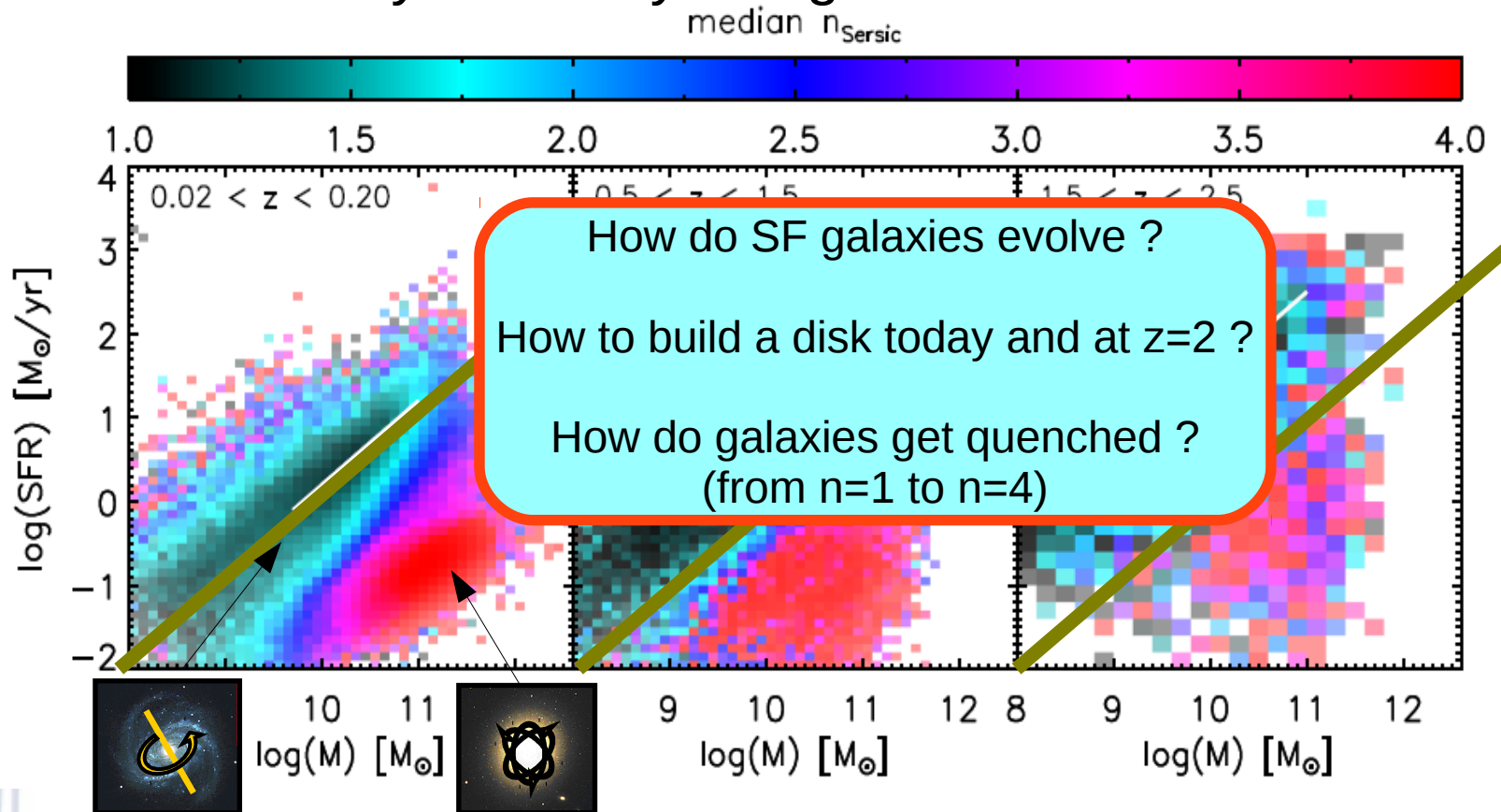### entirely driven by DM growth

S. Wuyts 2011

Daddi 2007 ; Elbaz 2007 ; Noeske 2007 ; Kashino 2013 ; Peng 2010 ; Pannella 2009
Damem 2009 ; Whitaker 2012, 2014, 2015 ;Tomczak 2015 ; Suzuki 2016
[…] Many more
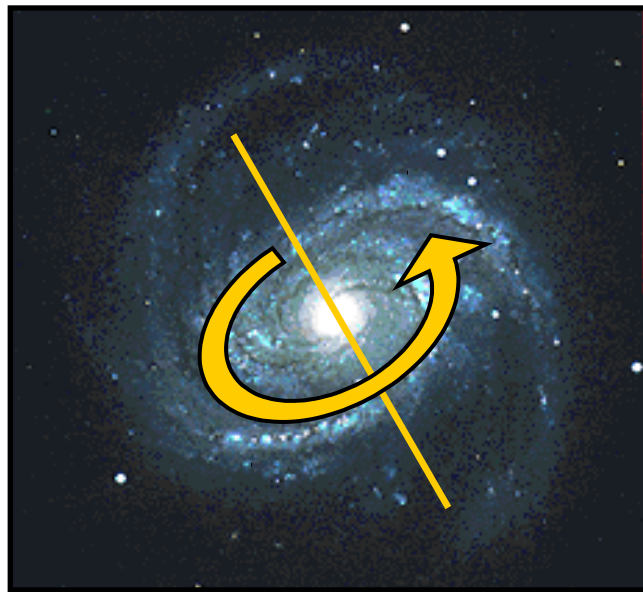
The new Hubble diagram: SFR-M*

The main sequence is a morphology sequence
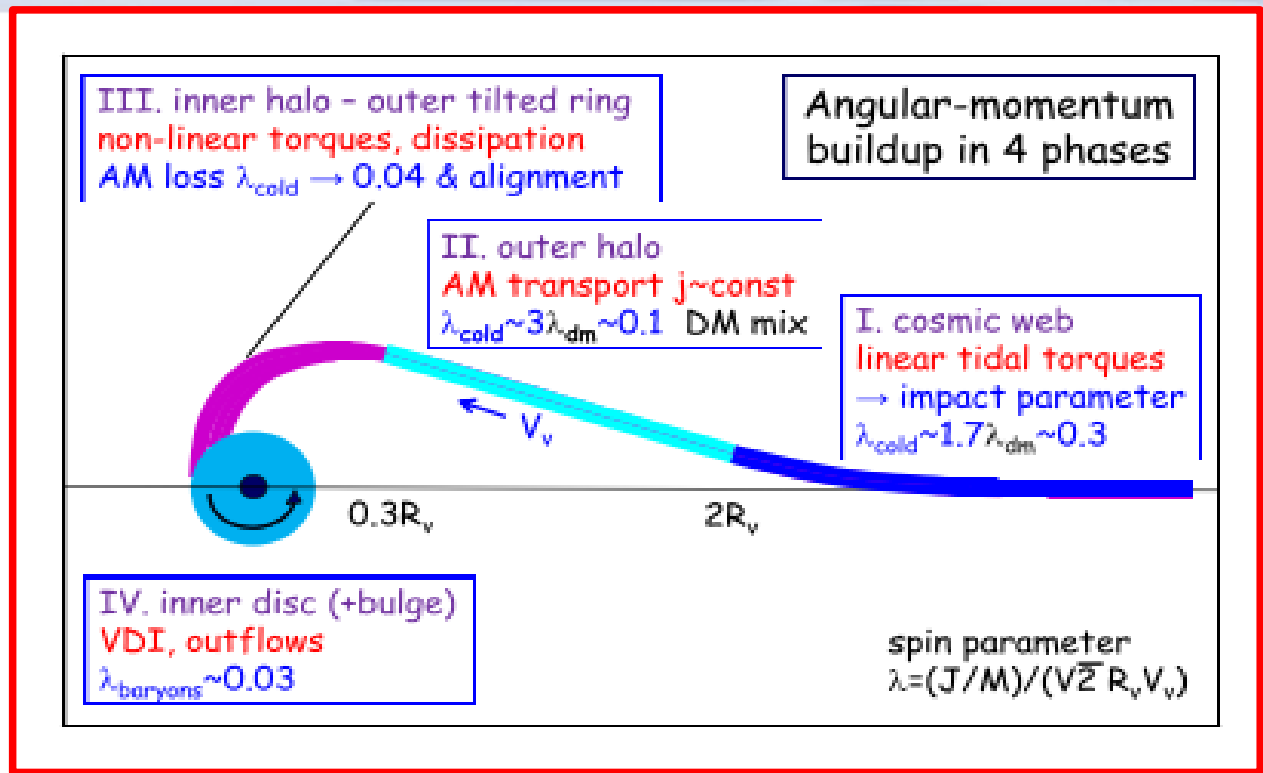entirely driven by DM growth
S. Wuyts 2011

Daddi 2007 ; Elbaz 2007 ; Noeske 2007 ; Kashino 2013 ; Peng 2010 ; Pannella 2009
Damem 2009 ; Whitaker 2012, 2014, 2015 ;Tomczak 2015 ; Suzuki 2016
[…] Many more

DM, Galaxies grow thru accretion, but
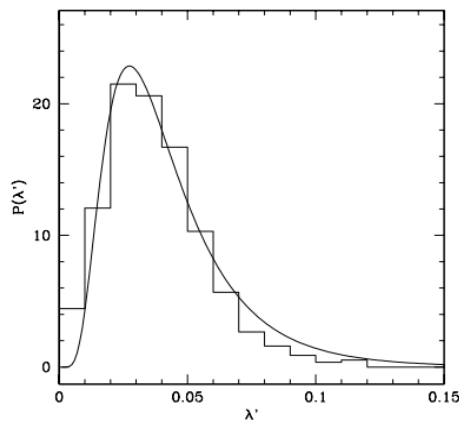# How to build a spinning disc ?
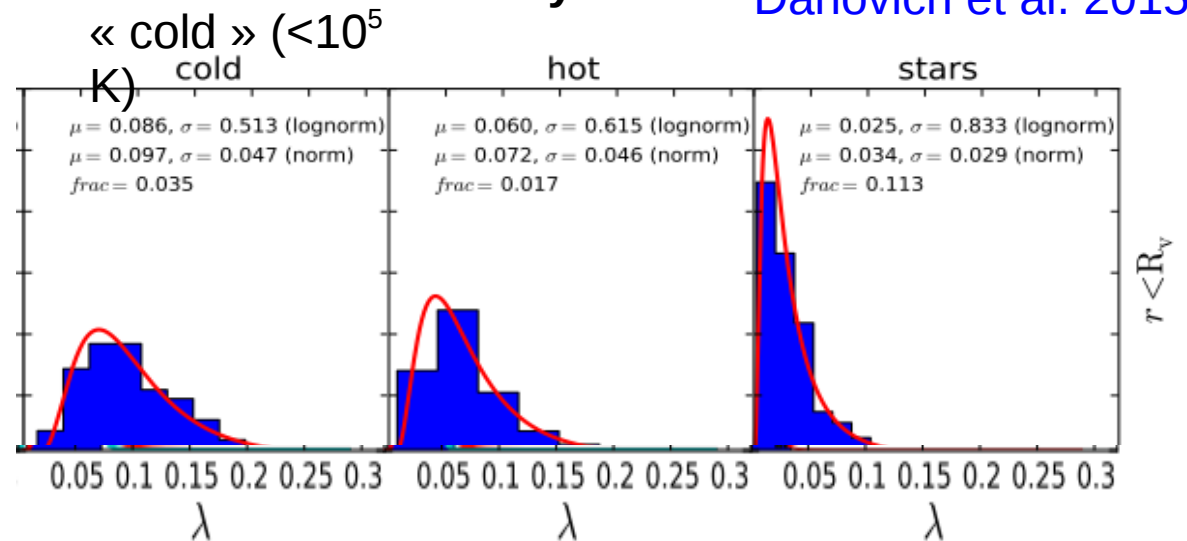
Spins

$$\lambda' \equiv \frac{J}{\sqrt{2}MVR},$$

III. inner halo – outer tilted ring
non-linear torques, dissipation
AM loss $\lambda_{cold} \rightarrow 0.04$ & alignment

II. outer halo
AM transport j~const
$\lambda_{cold} \sim 3\lambda_{dm} \sim 0.1$ DM mix

Angular-momentum buildup in 4 phases

I. cosmic web
linear tidal torques
$\rightarrow$ impact parameter
$\lambda_{cold} \sim 1.7\lambda_{dm} \sim 0.3$

V_v

0.3R_v 2R_v

IV. inner disc (+bulge)
VDI, outflows
$\lambda_{baryons} \sim 0.03$

spin parameter
$\lambda = (J/M)/(\sqrt{2} R_v V_v)$

Dark Matter
Bullock et al. 2001

Baryons
Danovich et al. 2015

« cold » (<10^5 K)

- **Why spin of stars ~ DM ?**

Angular Momentum buildup
from « Cold Flow Disks »

Stewart et al. 2011
See also Shen 2013

Stewart et al. 2016
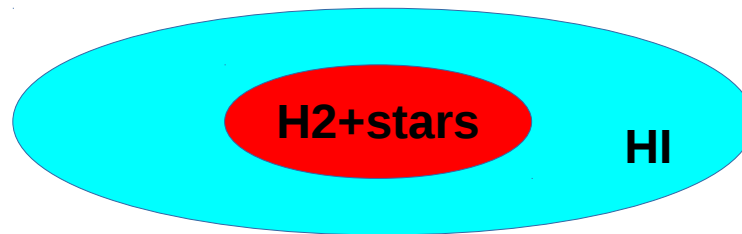
ENZO   ART   RAMSES   AREPO
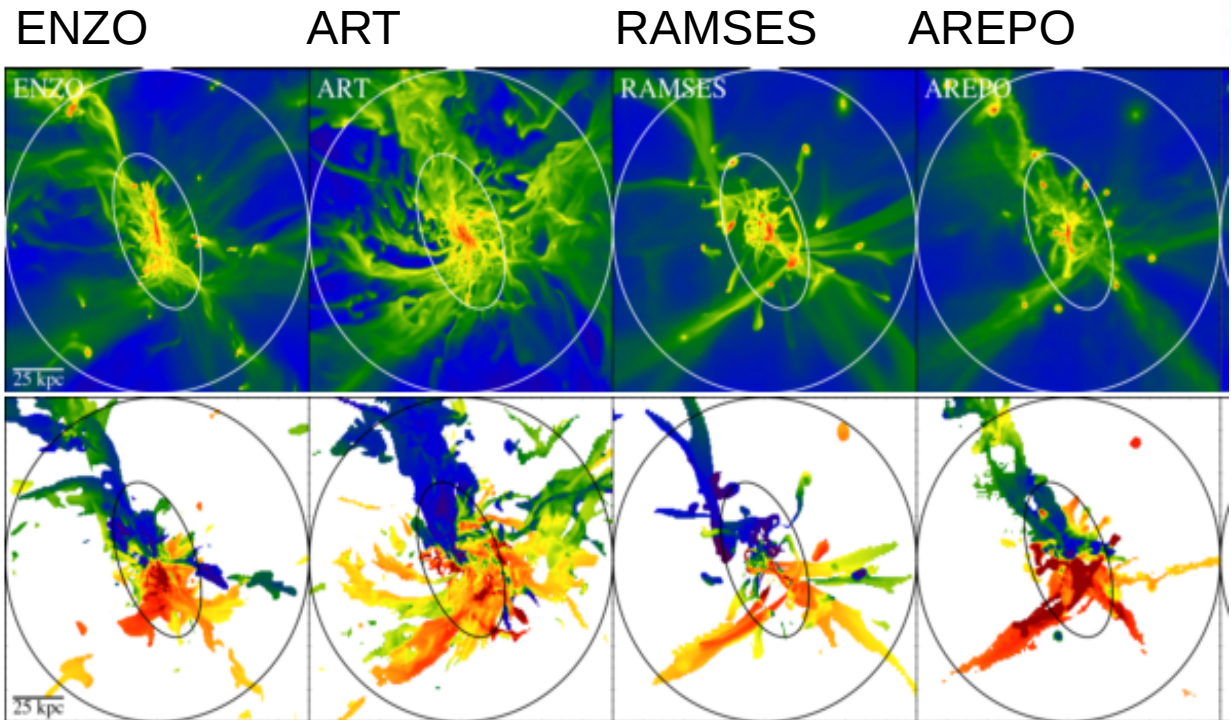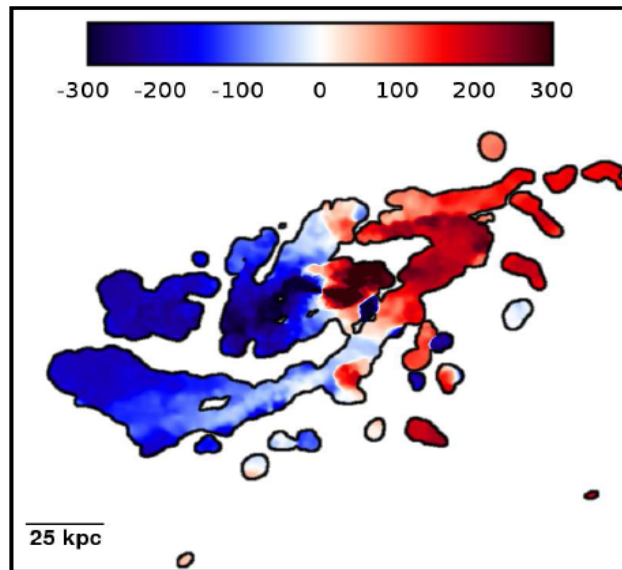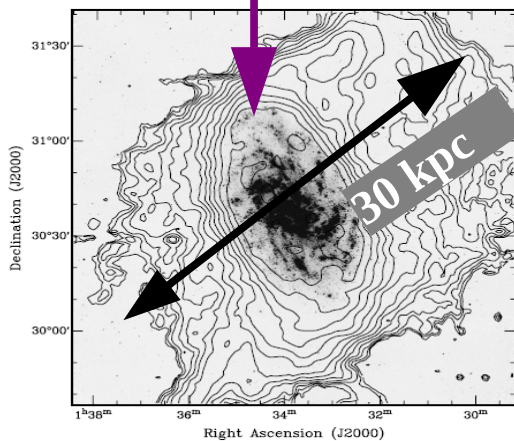

« Cold Flow Disk »
Large rotating co-planar gaseous structure

See also Nelson+15

How to build a disc ?
A cartoon picture

H2+stars
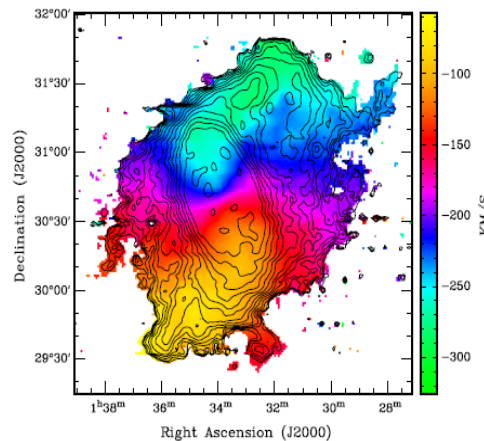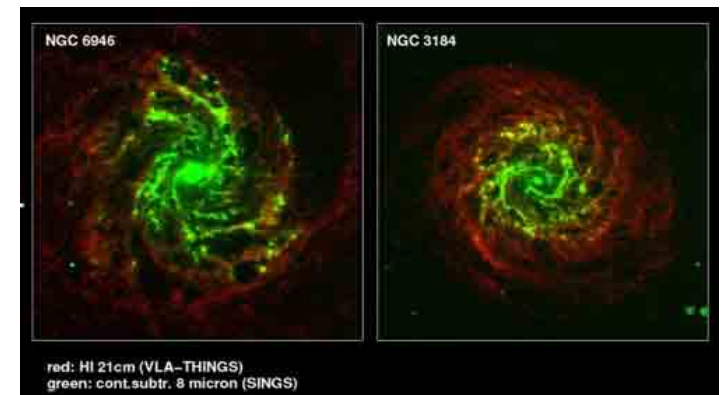
HI

GALEX FUV

Putman 2009

THINGS survey

30 kpc

Outflows are multi-phased!

NGC 891

Wang et al.

NGC 4631

Chandra 0.3-2.0 keV   XMM 0.3-1.2 keV

1'   2 kpc
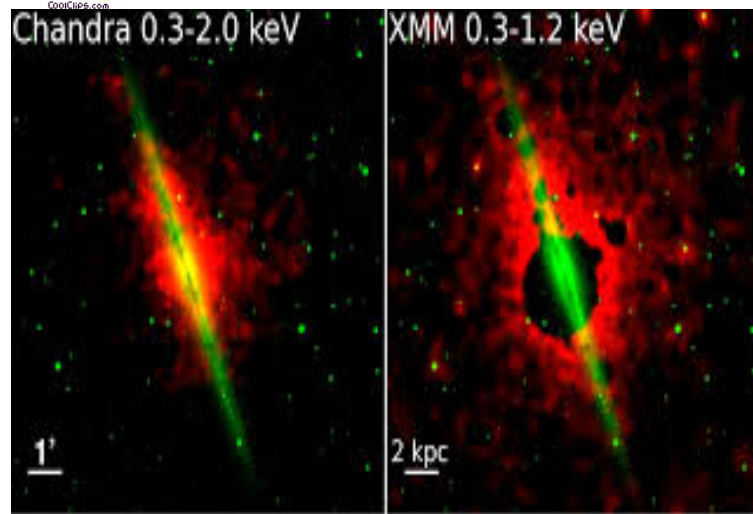
M82
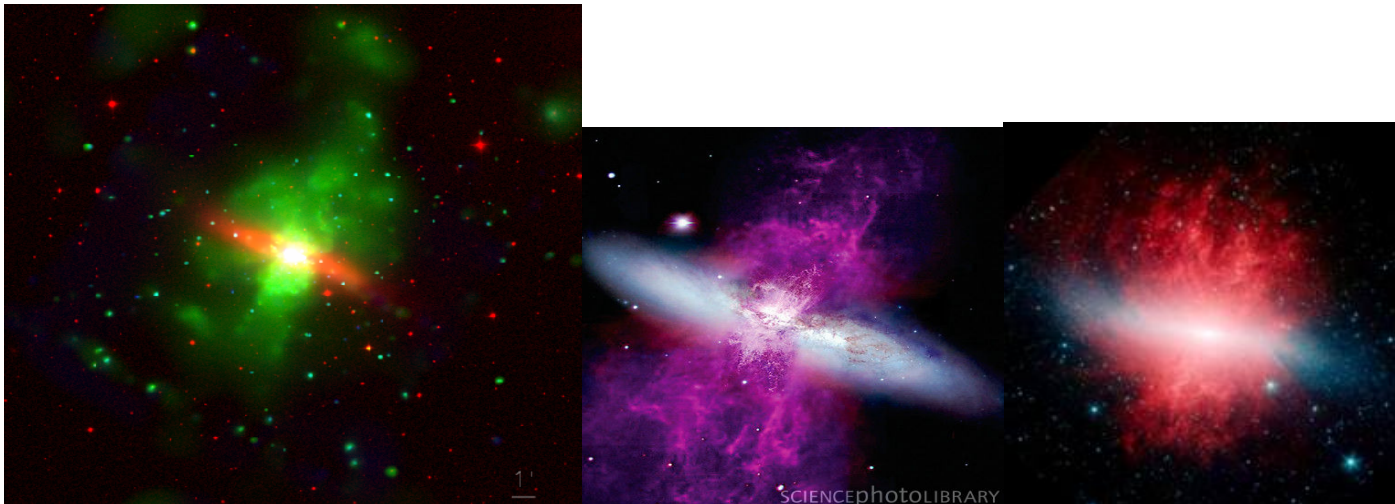
Xray   Halpha   Dust

How to build a disc ?
A cartoon picture
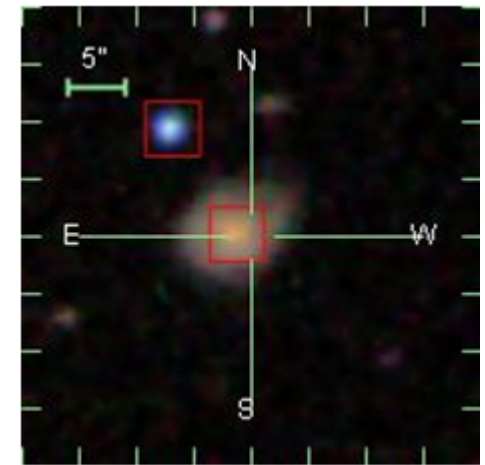

Outflows are
hot (X-ray) ; ionized ;
neutral ; molecular
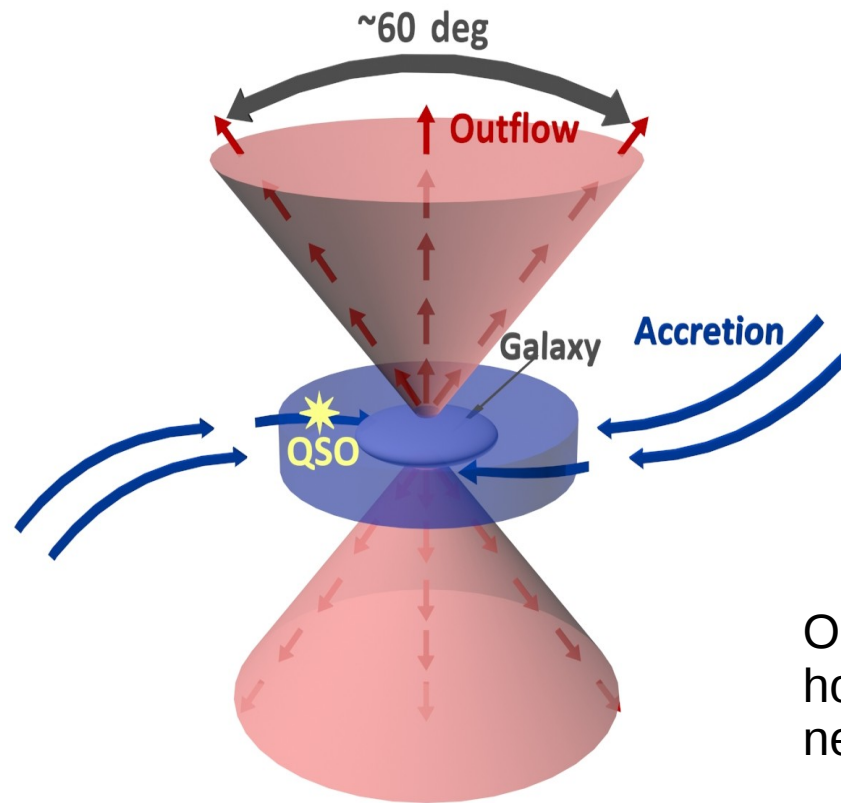
Credit : I. Schroetter

How to build a disc ?
A cartoon picture
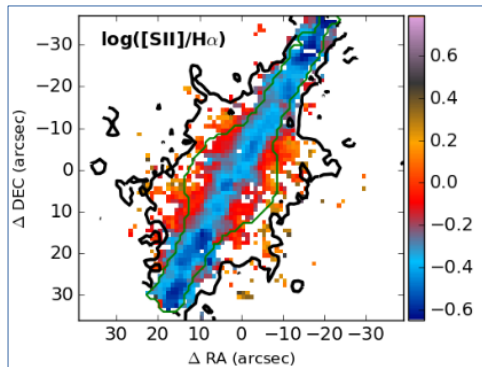
C. Lopez-Coba
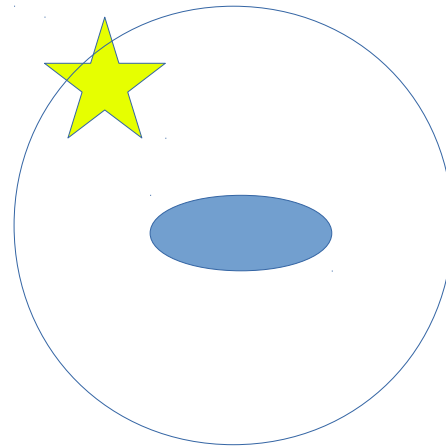(Tomorrow)

Also Moiseev 2010,
Oparin & Moiseev 2015

~60 deg

Outflow

Accretion

Galaxy

QSO
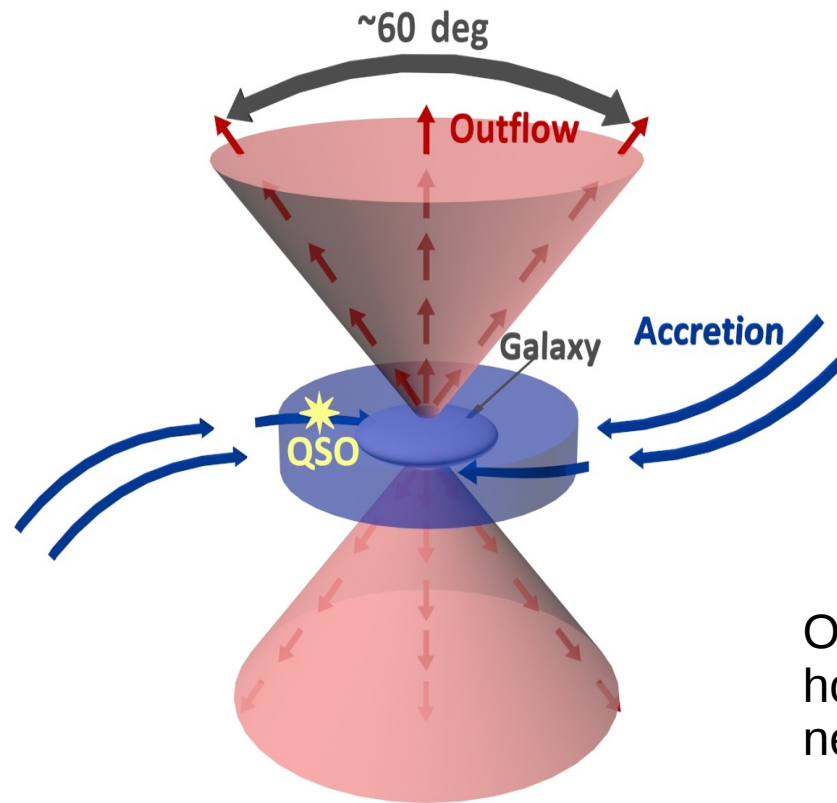
Outflows are
hot (X-ray) ; ionized ;
neutral ; molecular

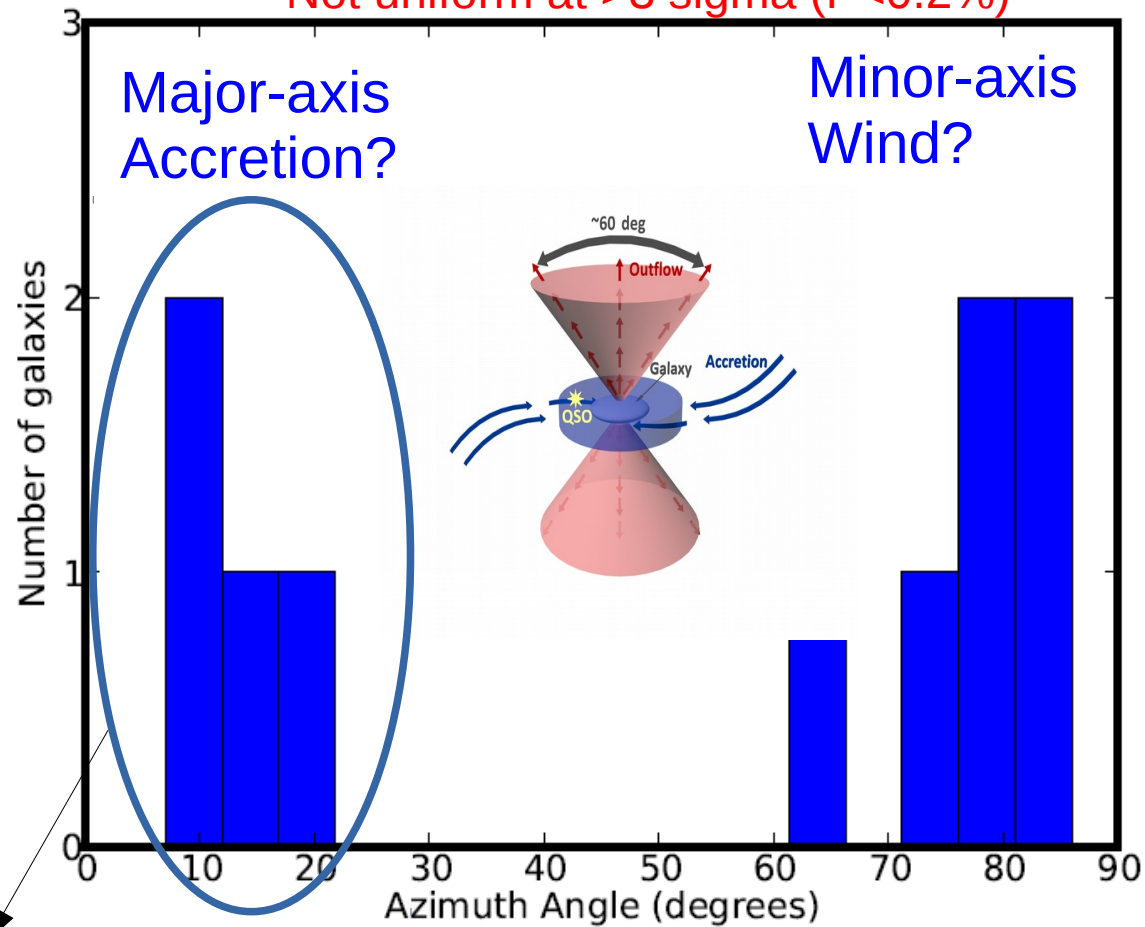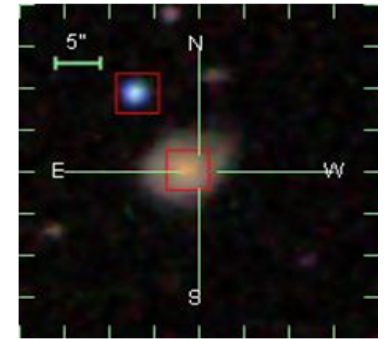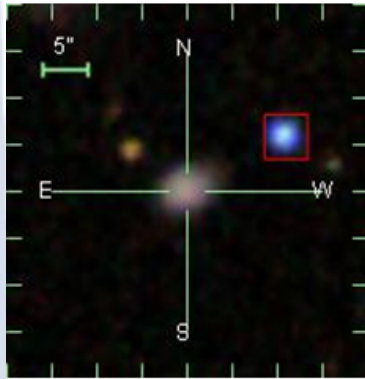Credit : I. Schroetter

« Cold flow disks » at intermediate-z

- Use background quasars around SDSS z=0.2 galaxies
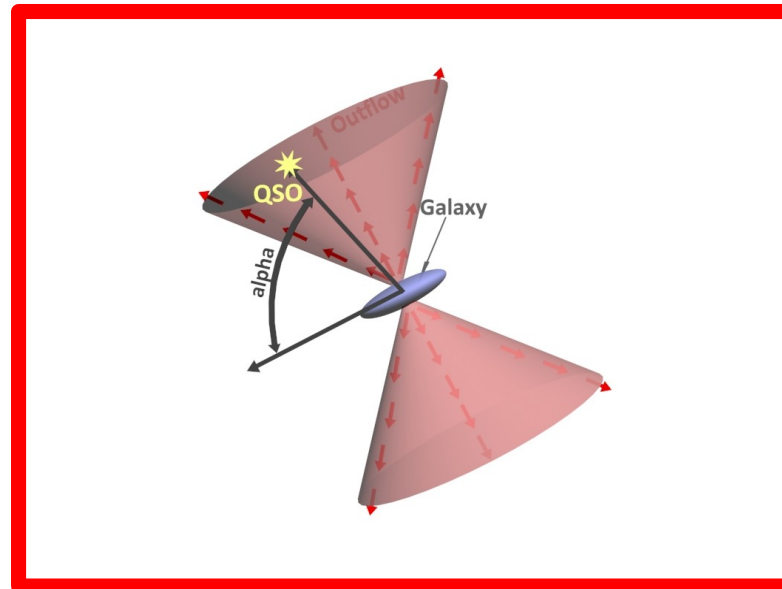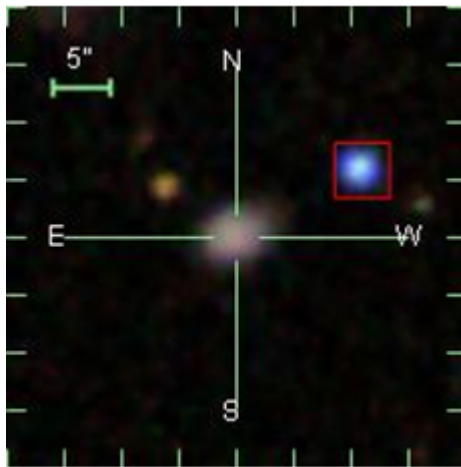
CGM is anisotropic at z=0.2
and z~1

Bouché et al. 2012

Not uniform at >3 sigma (P<0.2%)

Major-axis
Accretion?

Minor-axis
Wind?

Chen Tremonti 2010,
Bordoloi et al. 2011
Rubin et al. 2013
**Lan & Ménard 2014,
Nielsen et al. 2015,
Schroetter+ 2015**

**See** Bouché et al. 2013 *Science* ; Bouché et al. 2016 **for details on accretion**

Spins at z=1–3: State-of-the-art

N=312 'full' MC-NFW no adiabatic contraction
N=304 'full', MC-NFW. with adiabatic contraction
N=256 'full' MC-NFW, no ad.contr., with n_{Sersic}-corrections

Z=1—3 : Burkert et al. 2016

For M*>1e10 :
   KMOS3D (Wuyts 2016)

H2+stars

HI
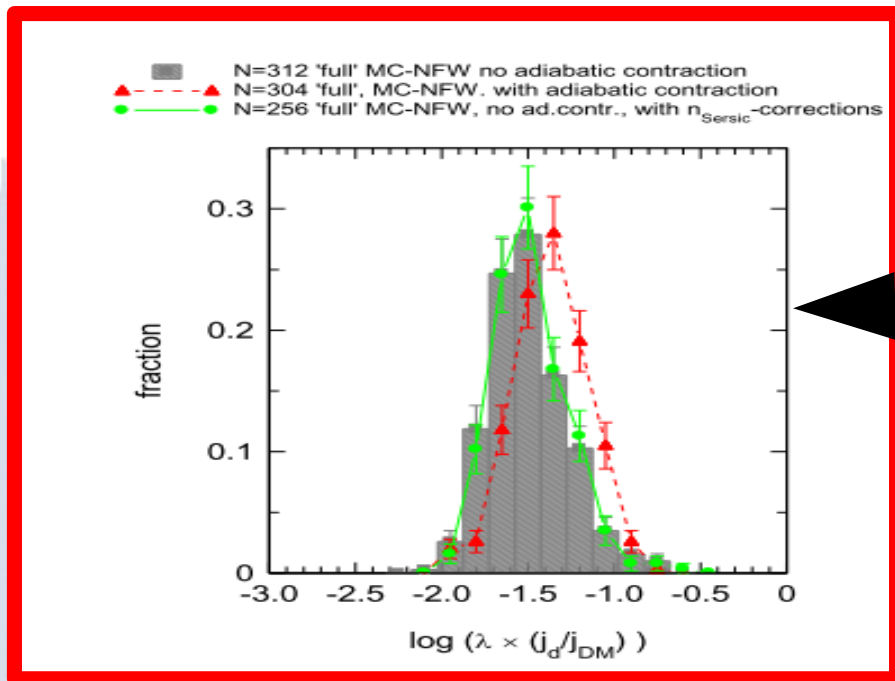
What about low mass galaxies?
1e8<M* <1e10 ?

Low-mass galaxies with MUSE

multi unit spectroscopic explorer

30 hr HDF-S

1'
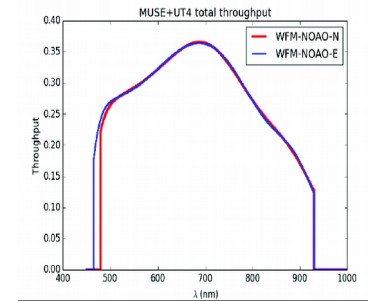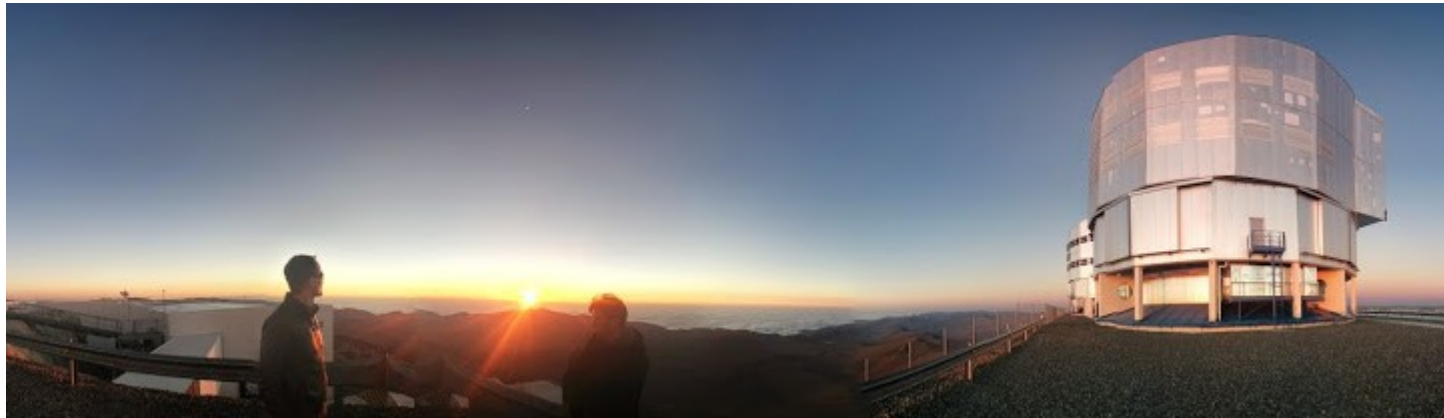
Sensitive to F> few 1e-19 erg/s/cm²/sq''
Soon with AO !
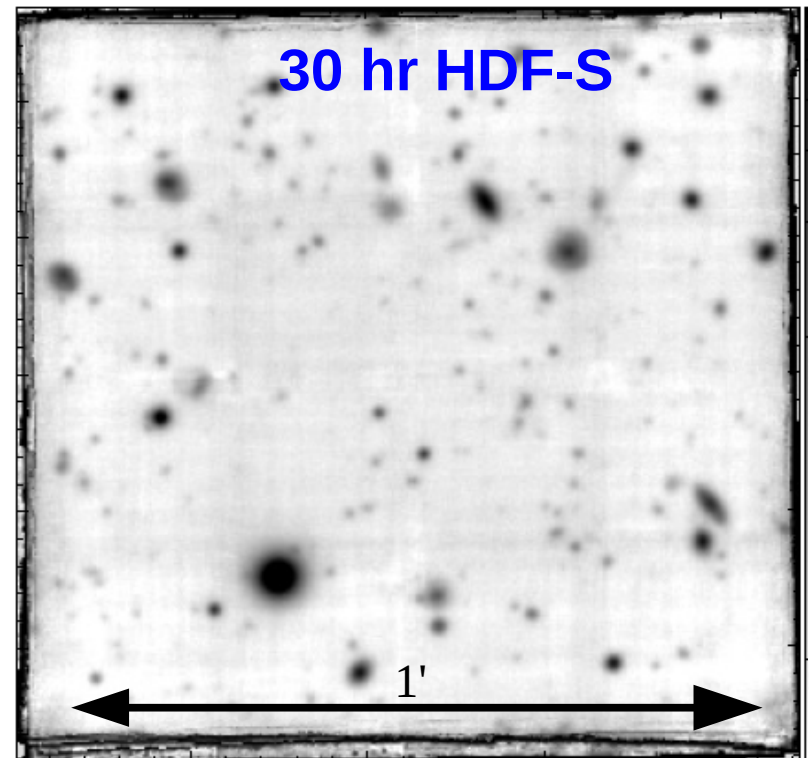
Bacon et. 2015

Low-mass galaxies with MUSE

MUSE+UT4 total throughput

30 hr HDF-S

1'
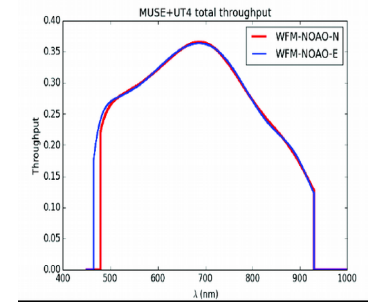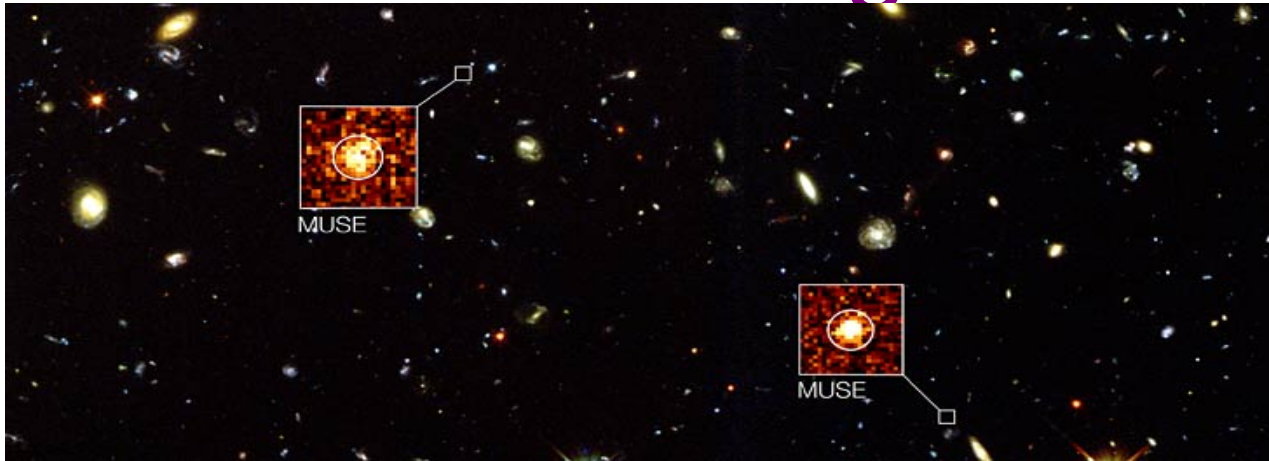
Sensitive to F> few 1e-19 erg/s/cm²/sq''
Soon with AO !
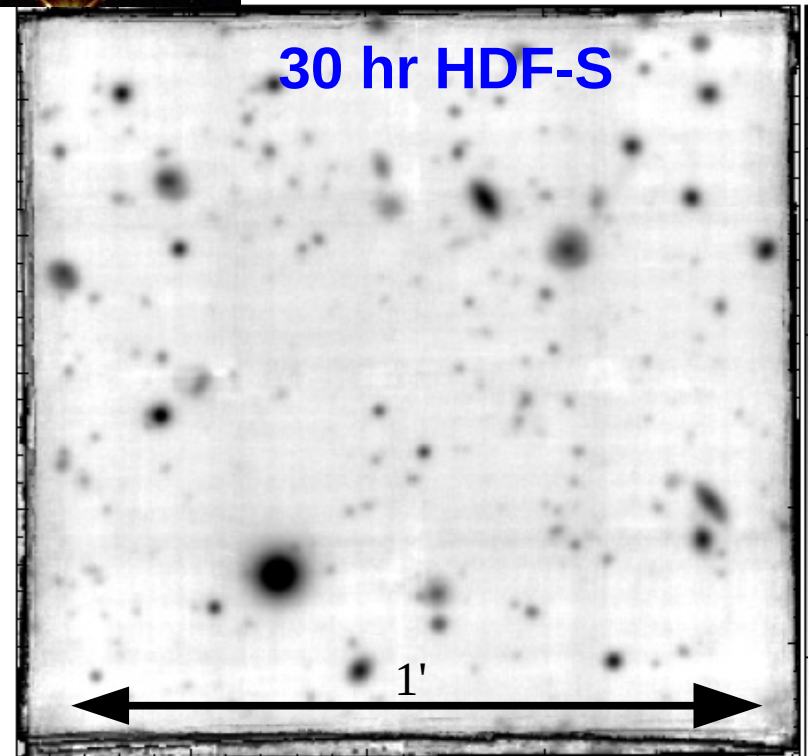
Bacon et. 2015

HDFS 1'x1' Sample Selection
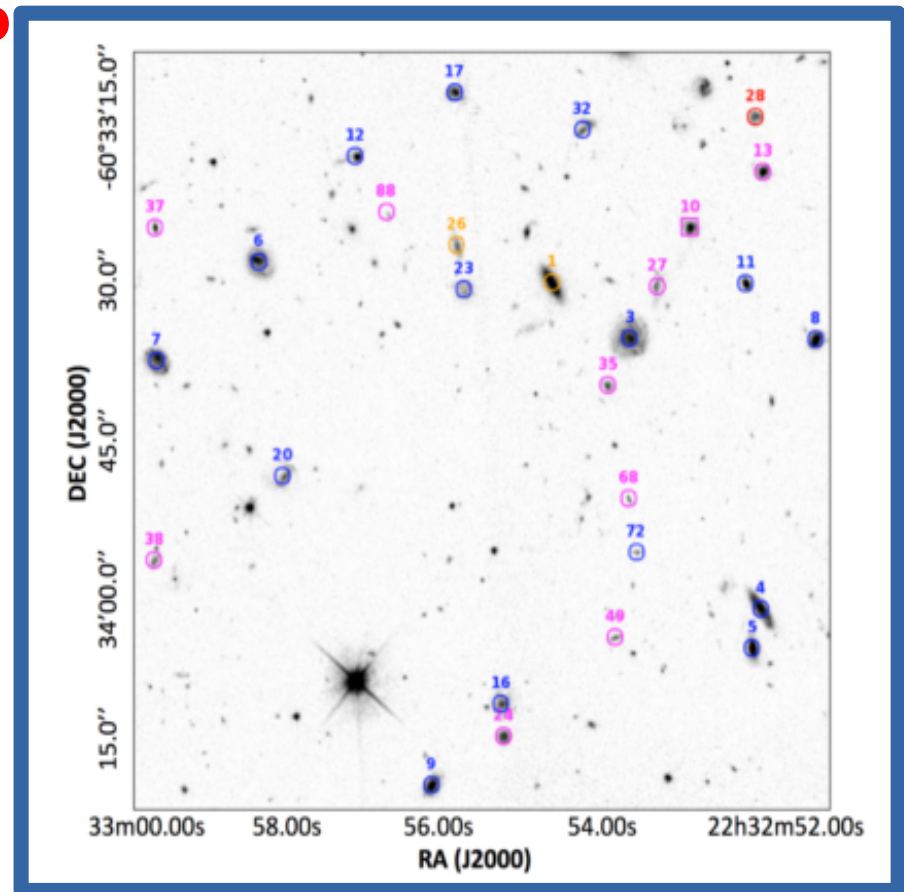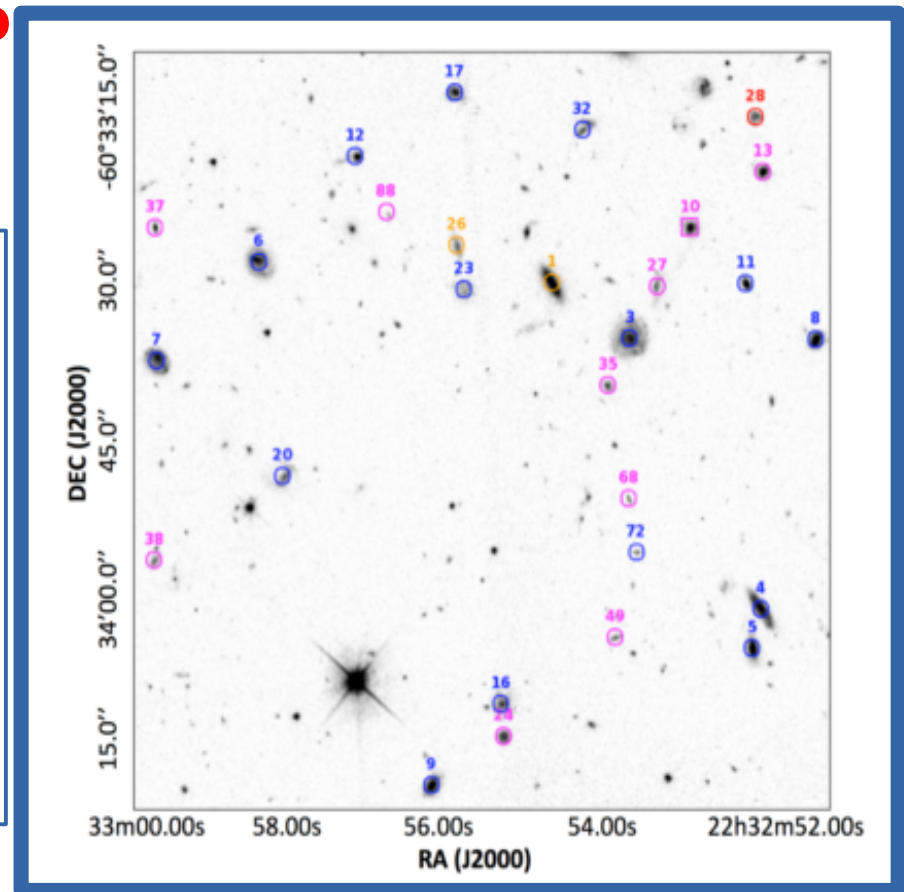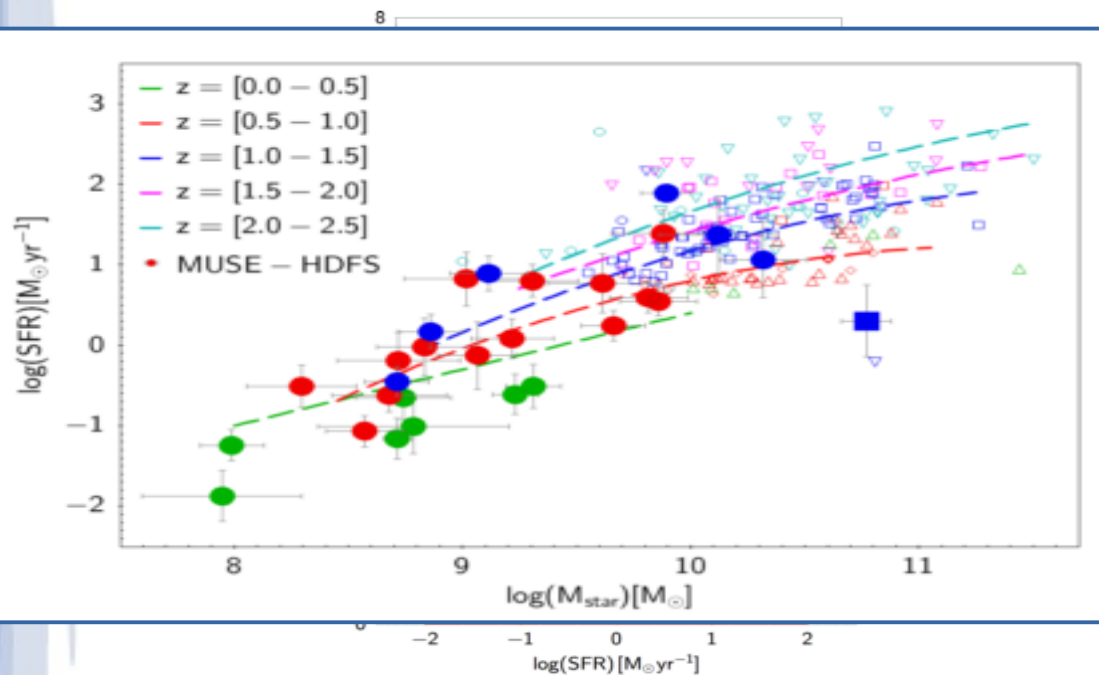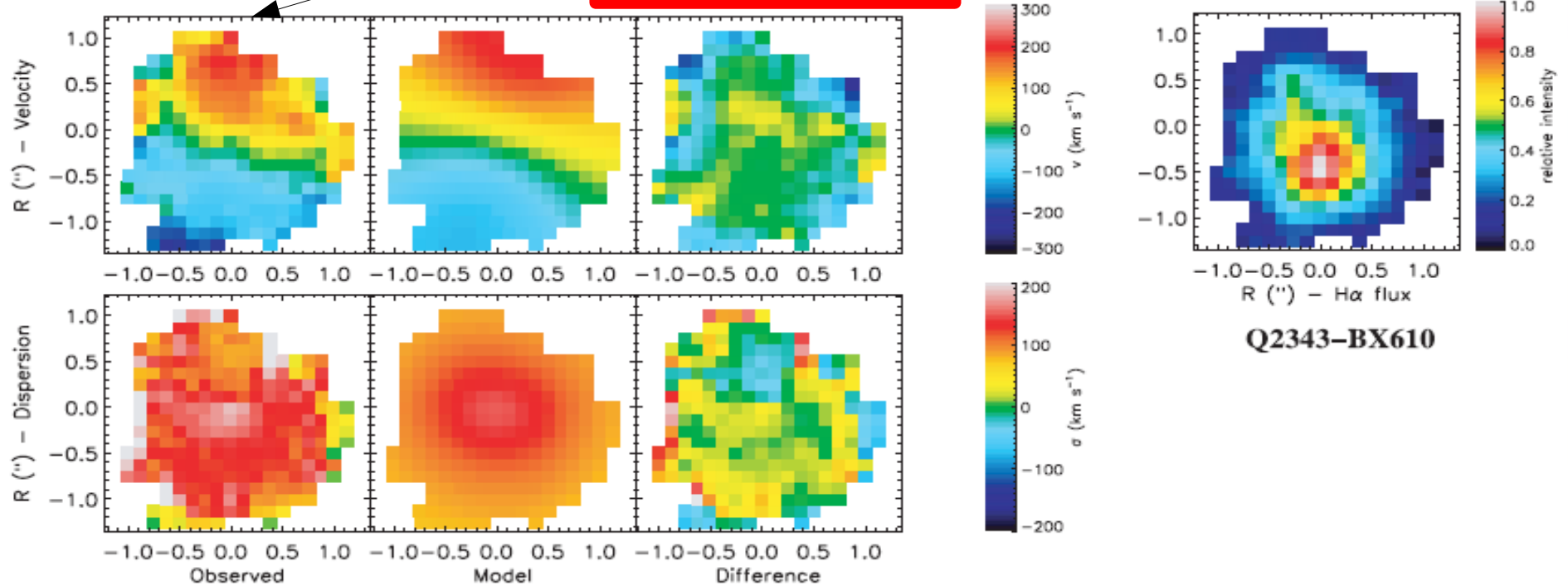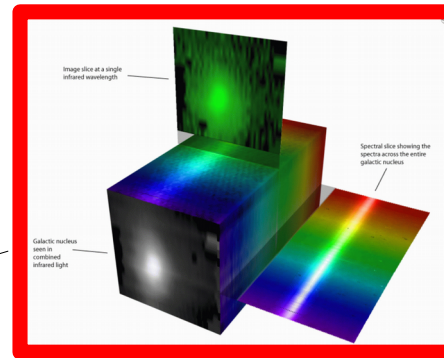
- 28 Star-forming galaxies (OII) at z=0.4—1.4 with

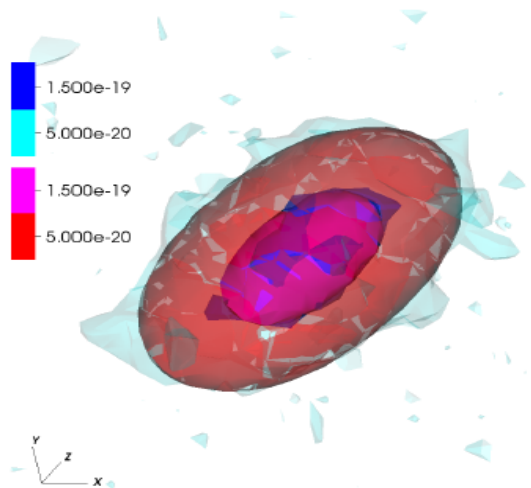 - **> 20 spaxel with SNR>15**

  - 1e8 < M* < 1e11

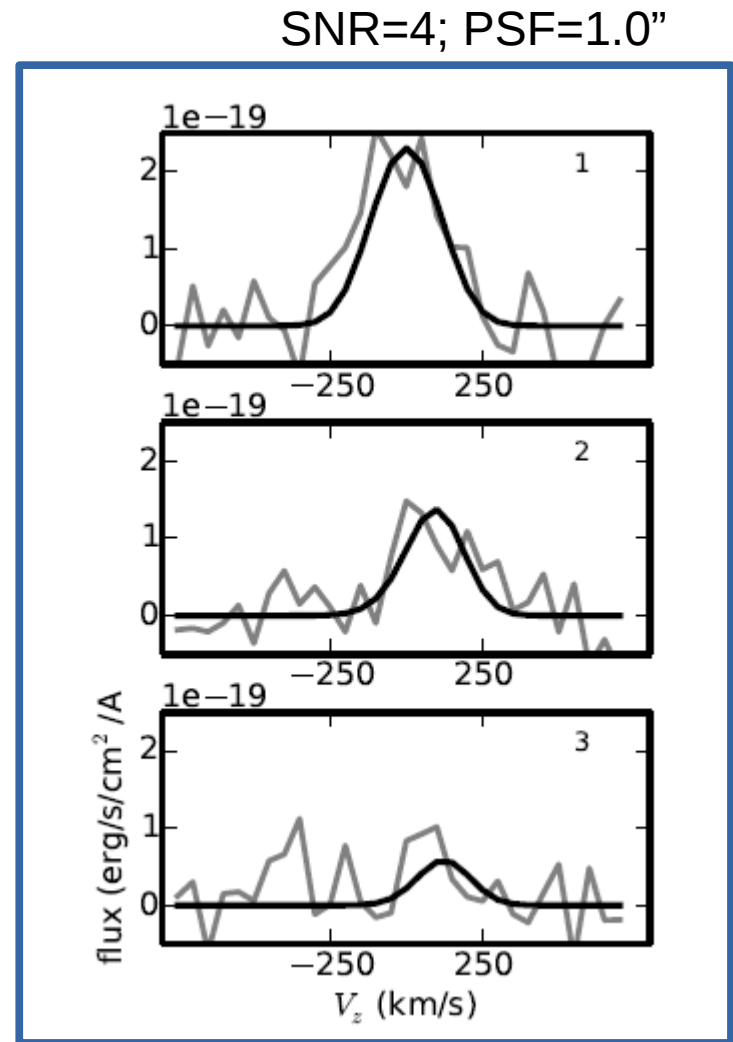 - -2 < log SFR < 2
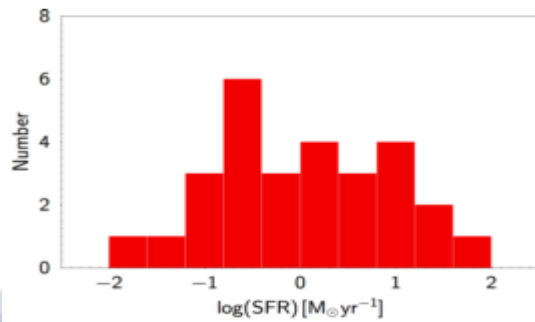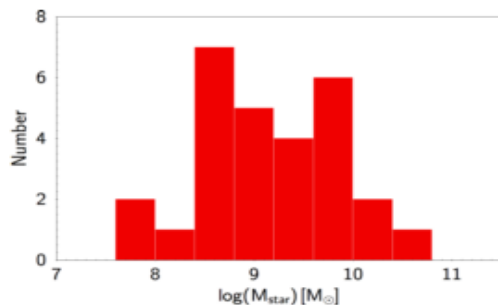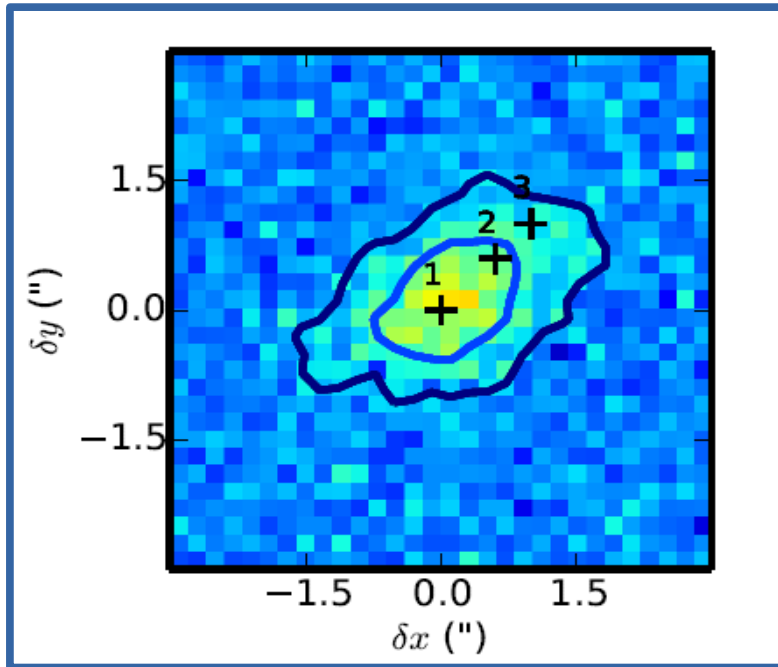
Contini et al. 2016

HDFS 1'x1' Sample Selection

- 28 Star-forming galaxies (OII) at z=0.4—1.4 with

  - **> 20 spaxel with SNR>15**

  - 1e8 < M* < 1e11

Contini et al. 2016

Traditional methods: shortcomings

Cresci et al. 2009

→ **Strong Vmax / inclination degenerancies**

Use all the information available

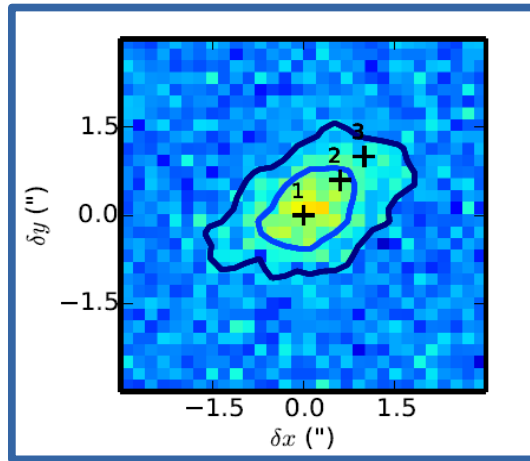SNR=4; PSF=1.0"
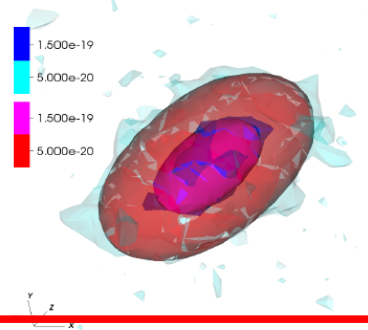

→ **Surface brightness effects!**
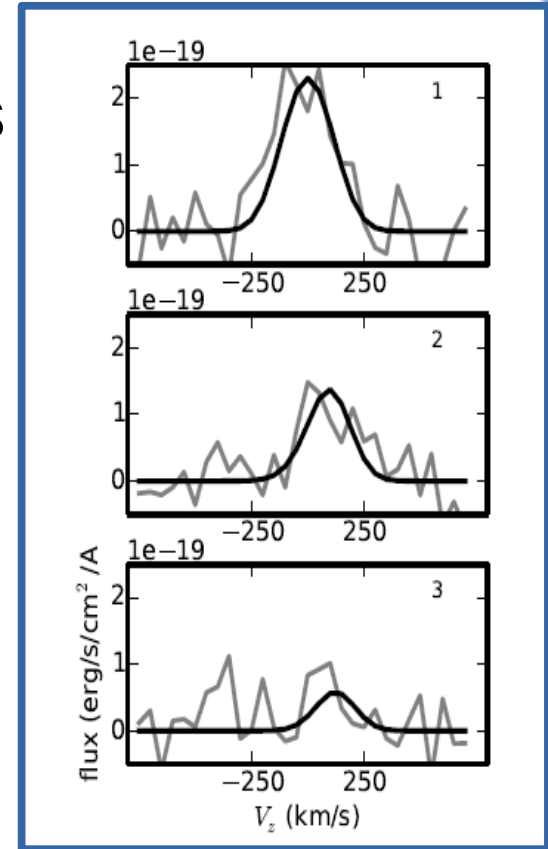
A new 3D method

http://galpak.irap.omp.eu

Constraints on inclinations+kinematics **simultaneously**
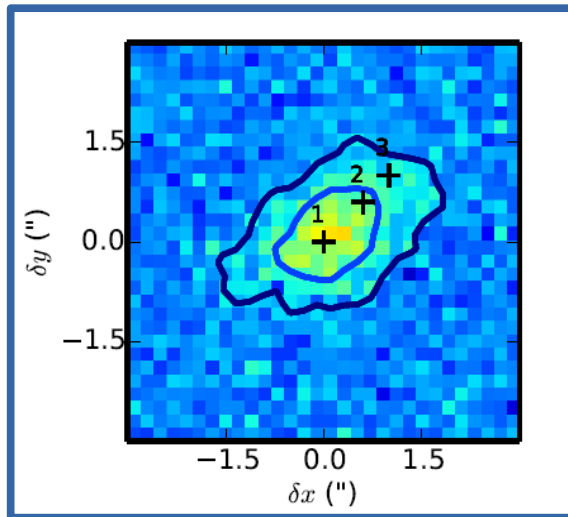– chi^2 fit ?
– MCMC Baysian

3D galaxy model + PSF & LSF

→ Access to `**deconvolved**' properties

Technically difficult (convolution, chi^2 flat hyper-space) …

A new 3D method (GalPaK³ᴰ)

http://galpak.irap.omp.eu

Bouché et al. 2015a
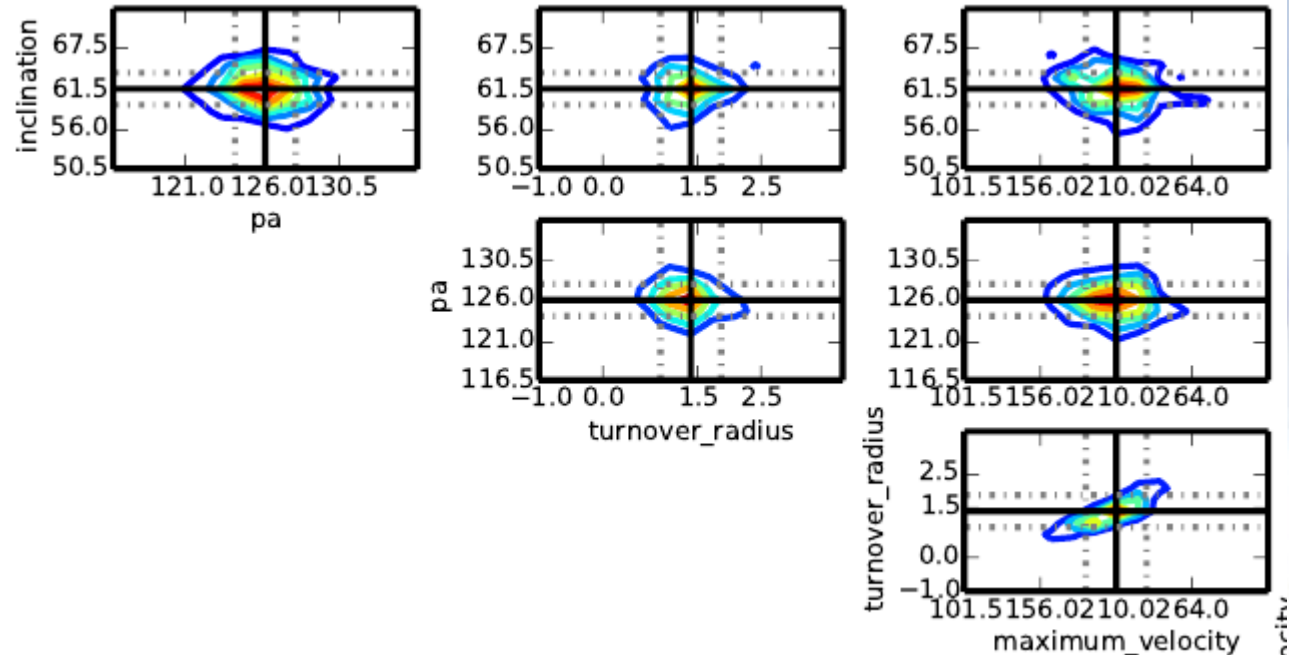
→ Access to `**deconvolved**' properties!

- Technically difficult (convolution, flat hyper-space) ...

Application on HDF-S

Bright Flux cuts = 3, 10 e-20
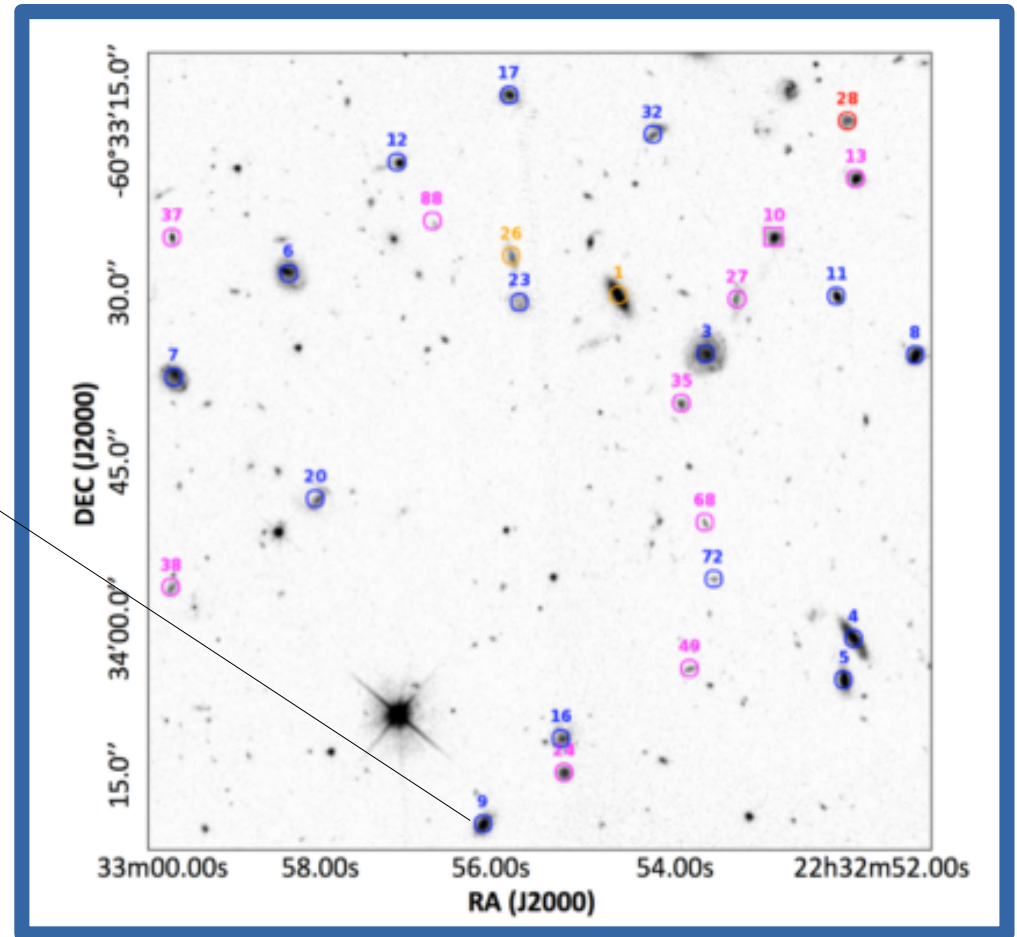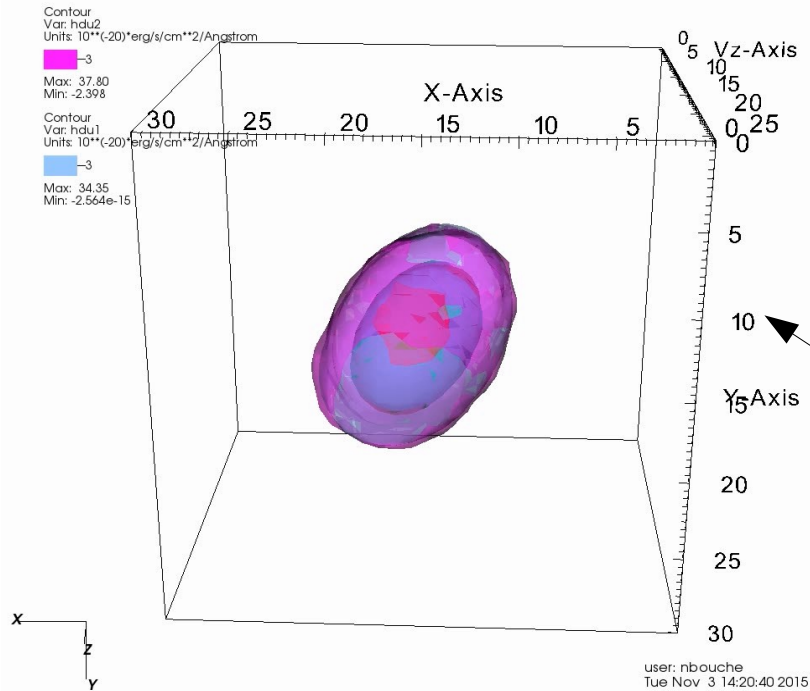
Application on HDF-S
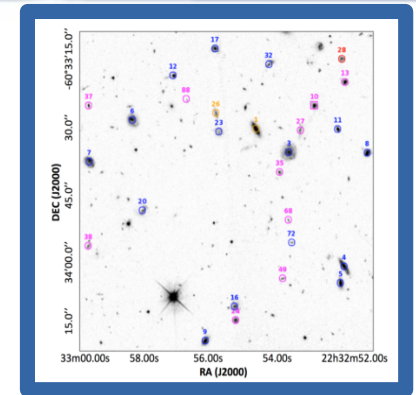
Kinematics Vmax : 2D vs. 3D
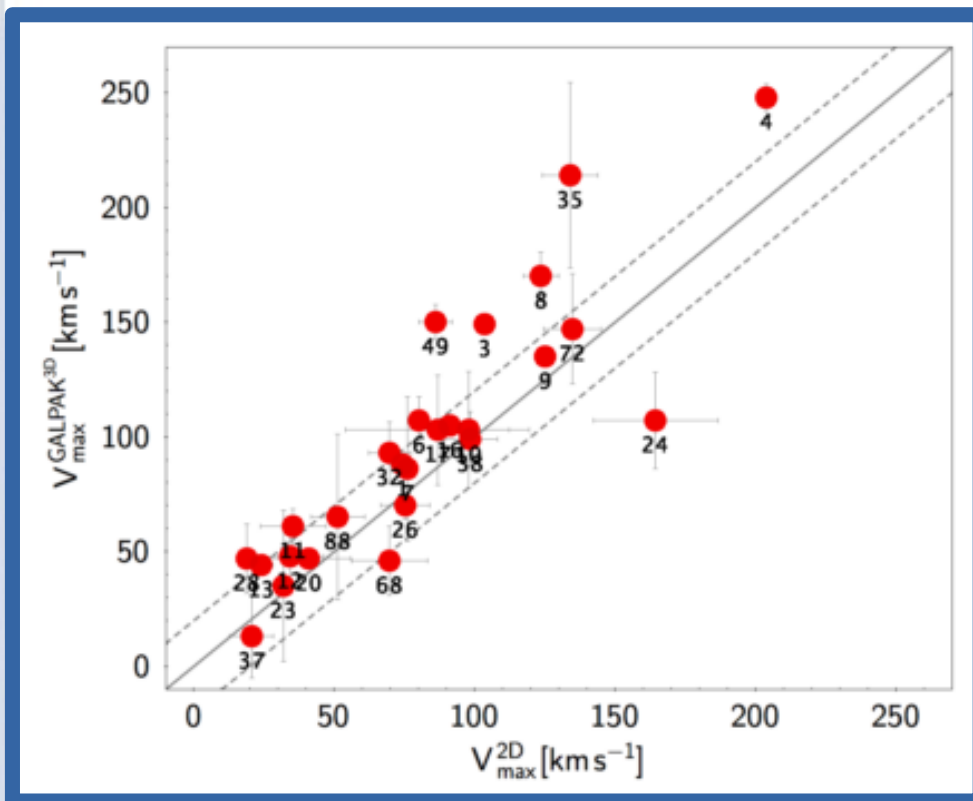
Kinematics PA : 2D vs. 3D

Contini et al. 2016
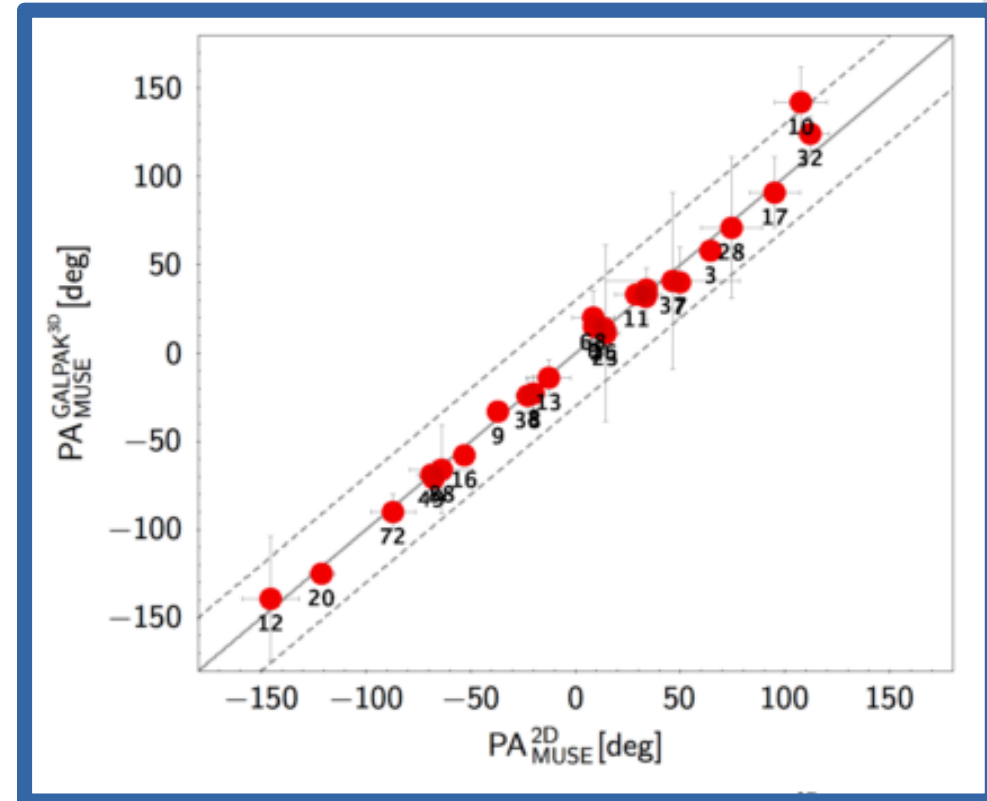
Application on HDF-S
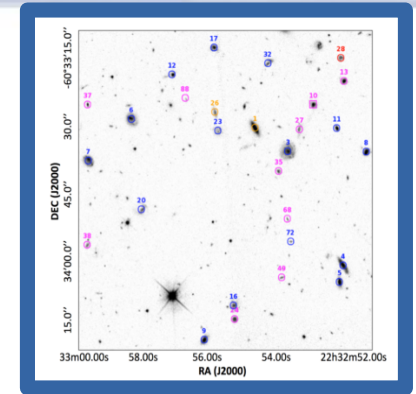
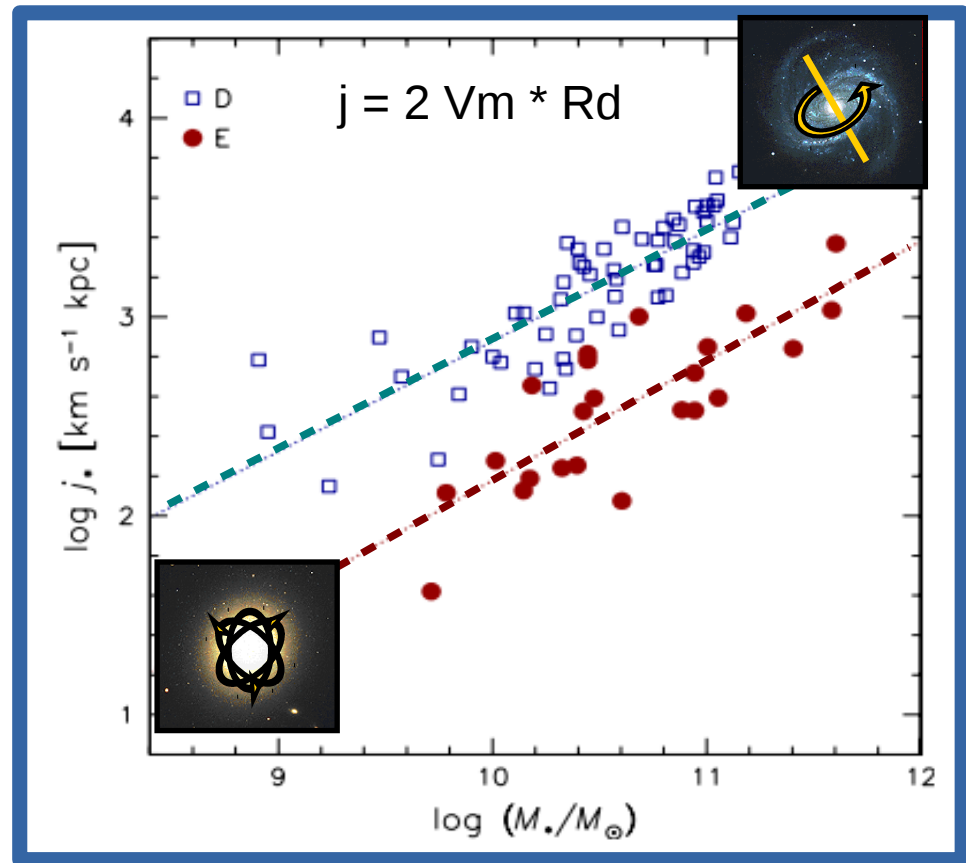**Inclinations :**
MUSE (0.7'') Vs HST (0.15'')
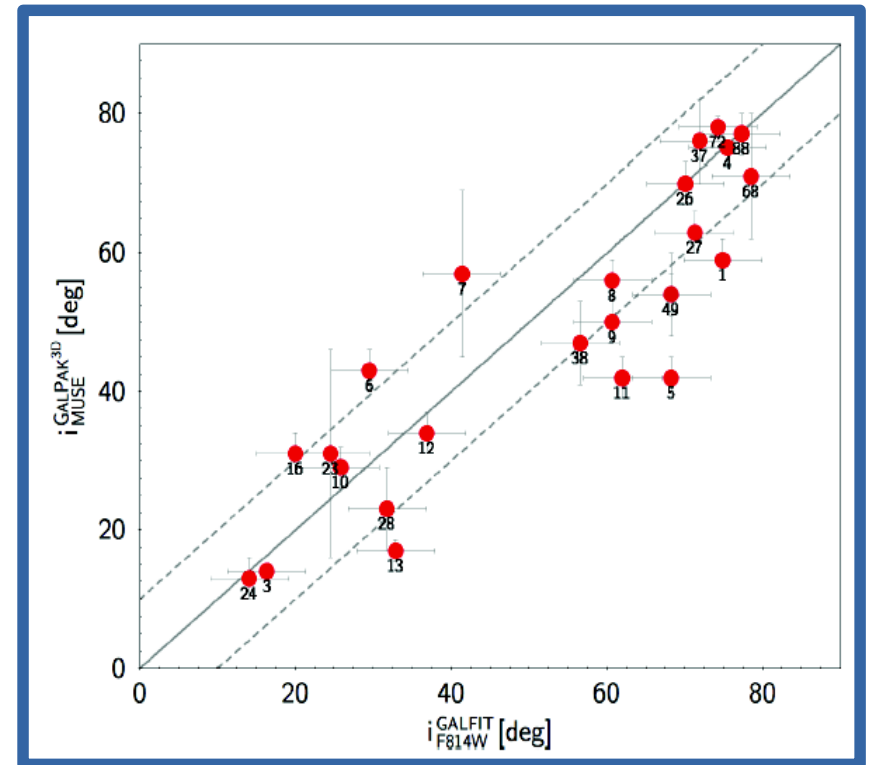
Incl (HST) Galfit2D

Disc Angular Momentum Observations

z=0.4 – 1.4 **HDFS MUSE**
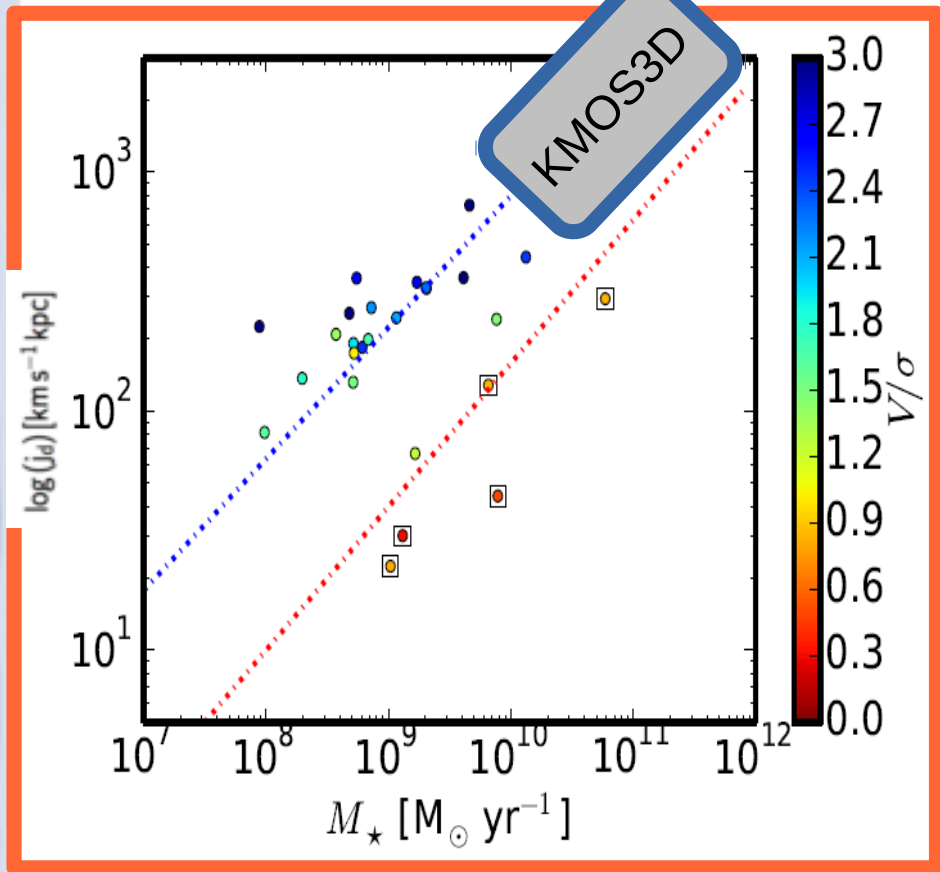
z=0 Fall & Romanowsky 2015

KMOS3D

j = 2 Vm * Rd

MUSE spectrum (not stacked!)

Redshift: **z~0.6 !!!**

Using ppXF   Capellari & Emsellem 2004
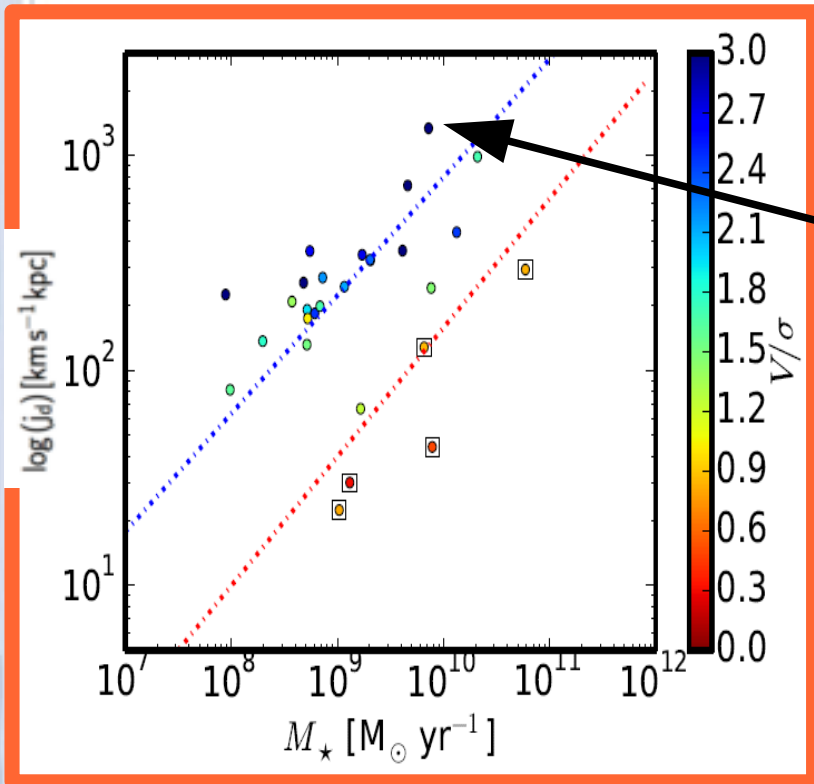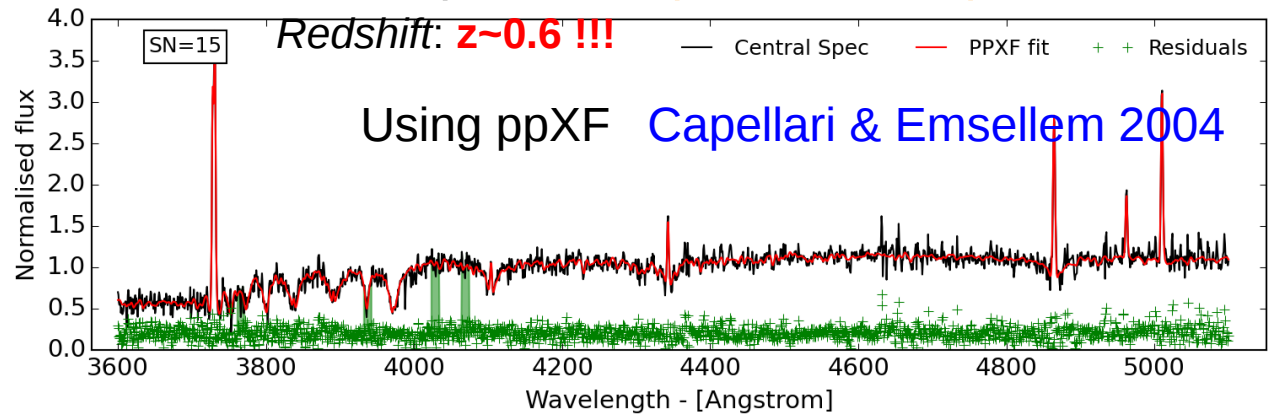
Stellar kinematics   **Gas ([OII] or [OIII]+Hb)**

F814W
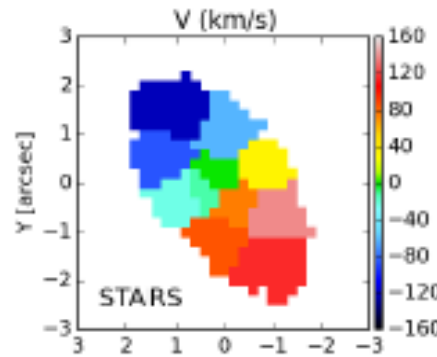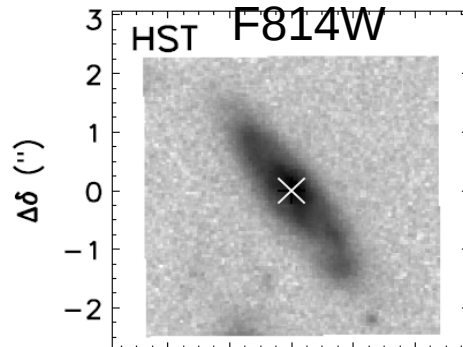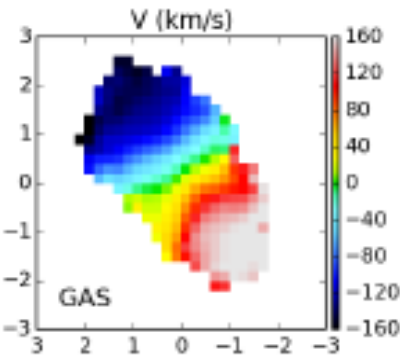
Guérou et al. (in prep.)
Krajnovic et al. (in prep.)

MUSE spectrum (not stacked!)
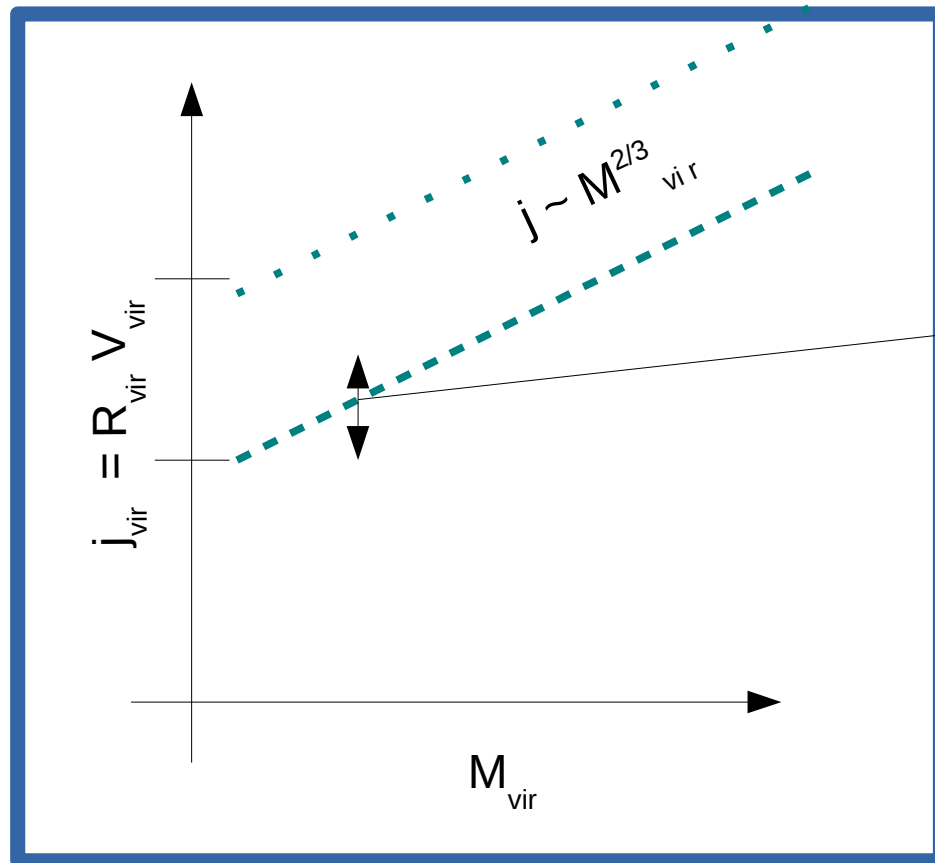

Using ppXF   Capellari & Emsellem 2004

Guérou et al. (in prep.)
Stellar kinematics

Contini et al. (2016)
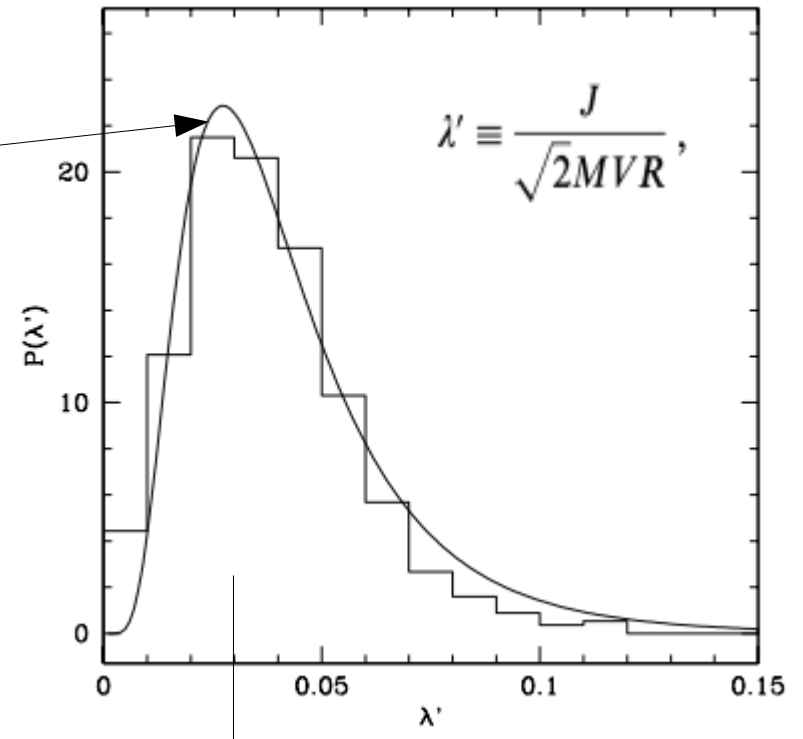**Gas ([OII] or [OIII]+Hb)**
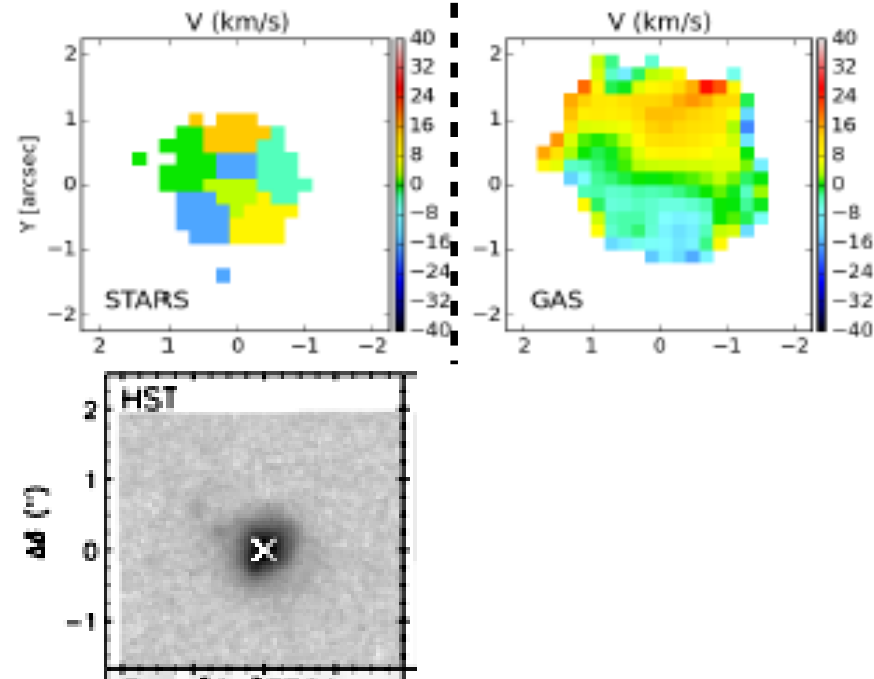
Insights from Angular Momentum DM Scaling Relation
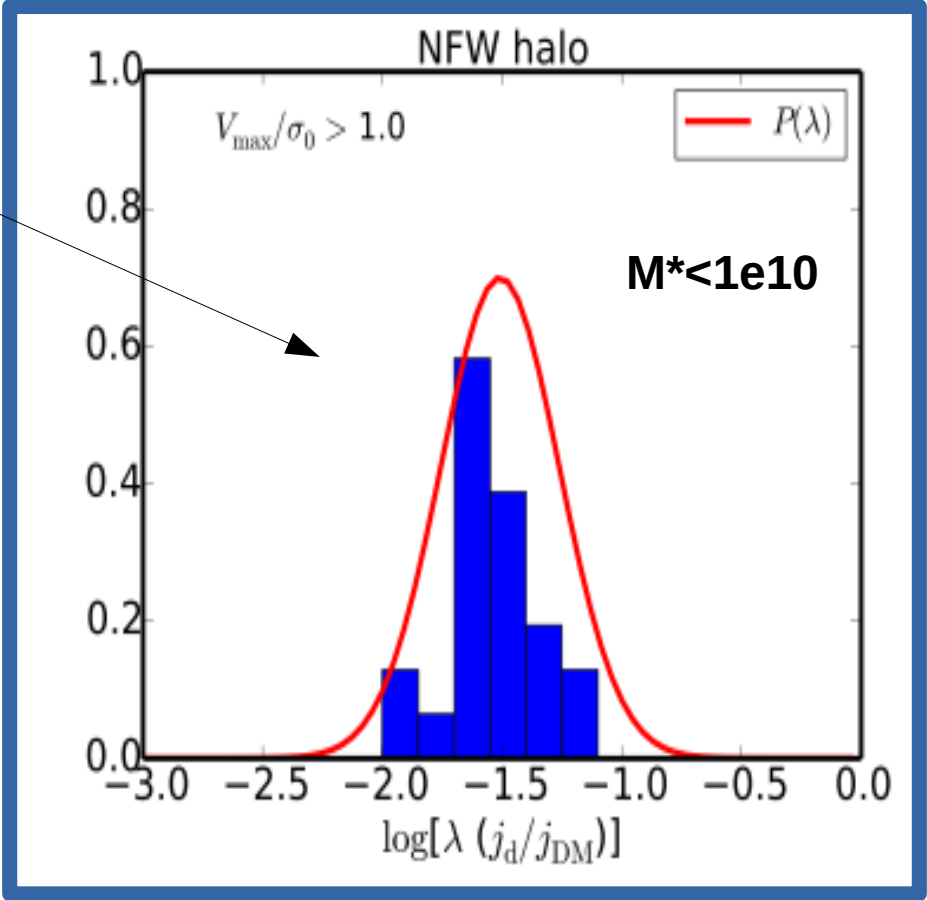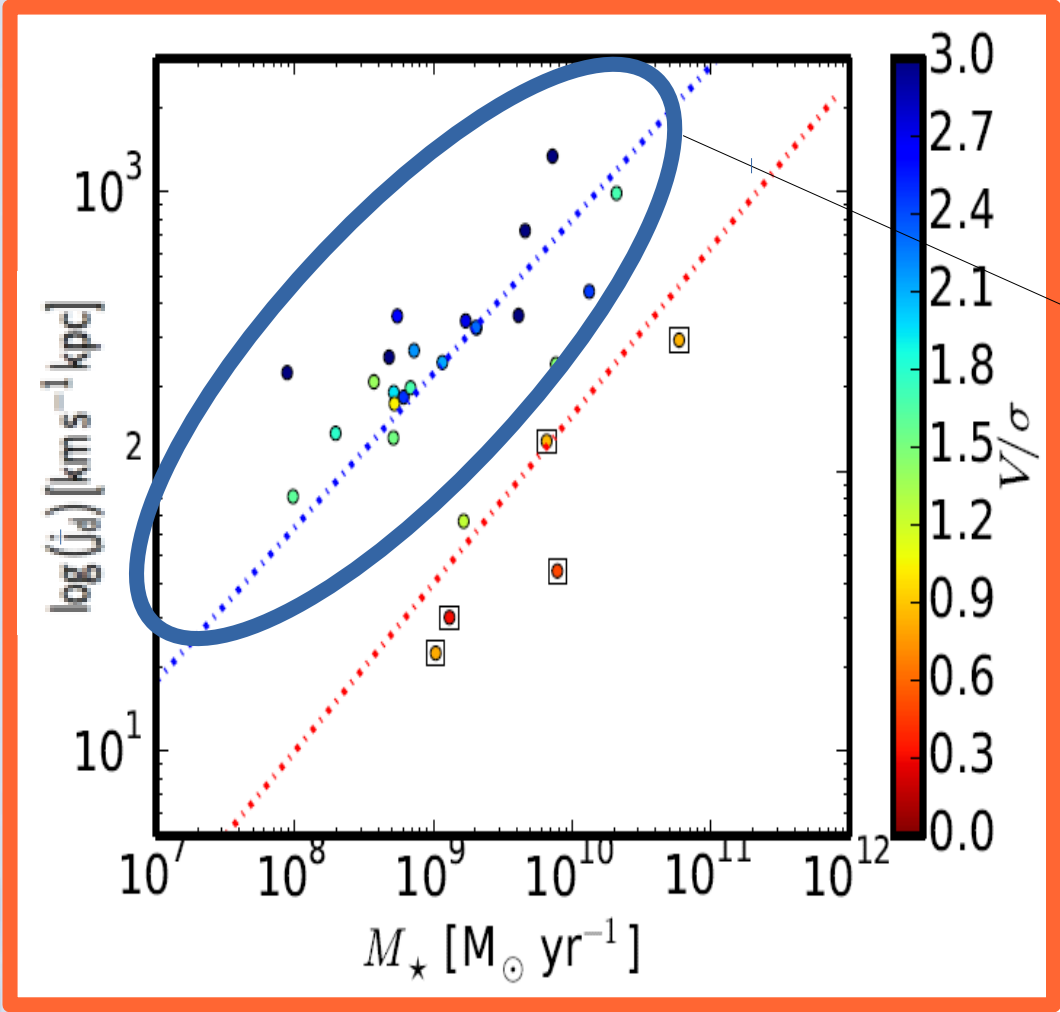
Fall 1983 ; MoMaoWhite 1998 ; Burkert 2015

Bullock et al. 2001

$$\lambda' \equiv \frac{J}{\sqrt{2}MVR},$$
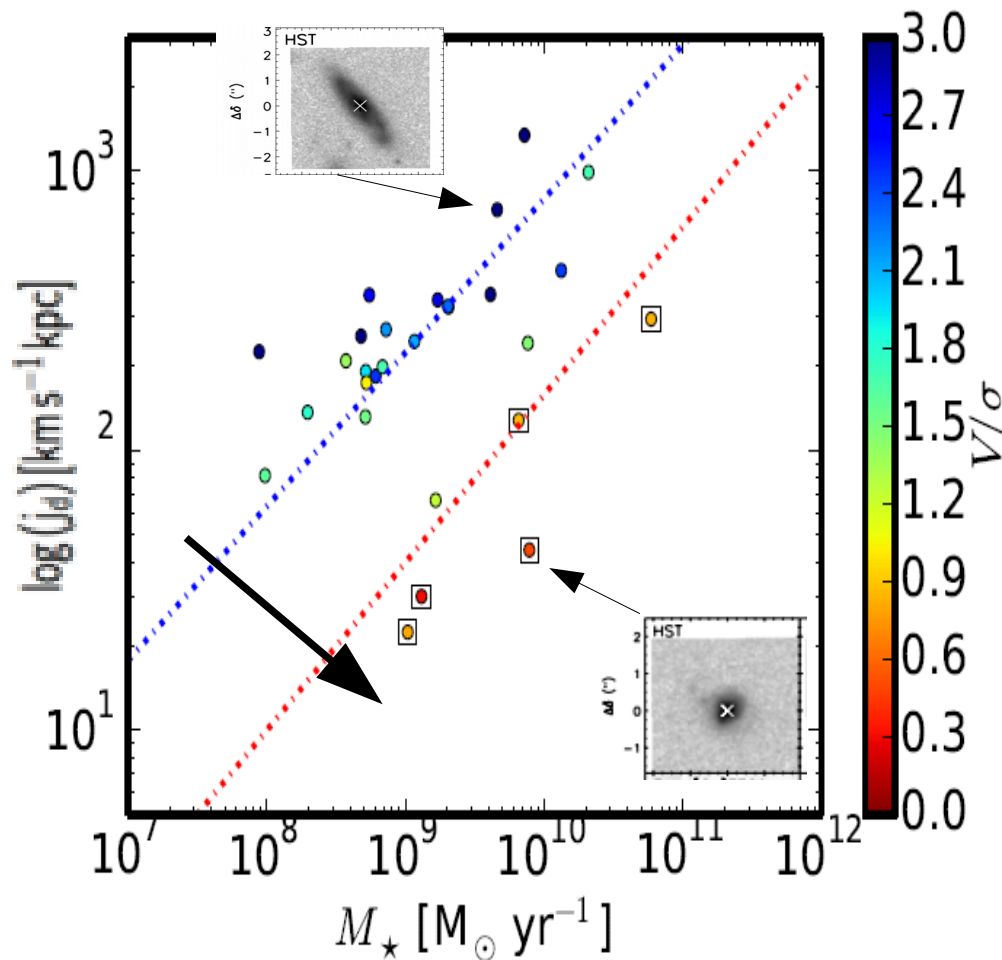
DM has 3 % of max. AM

Disk (gas) Angular Momentum in low-mass galaxies
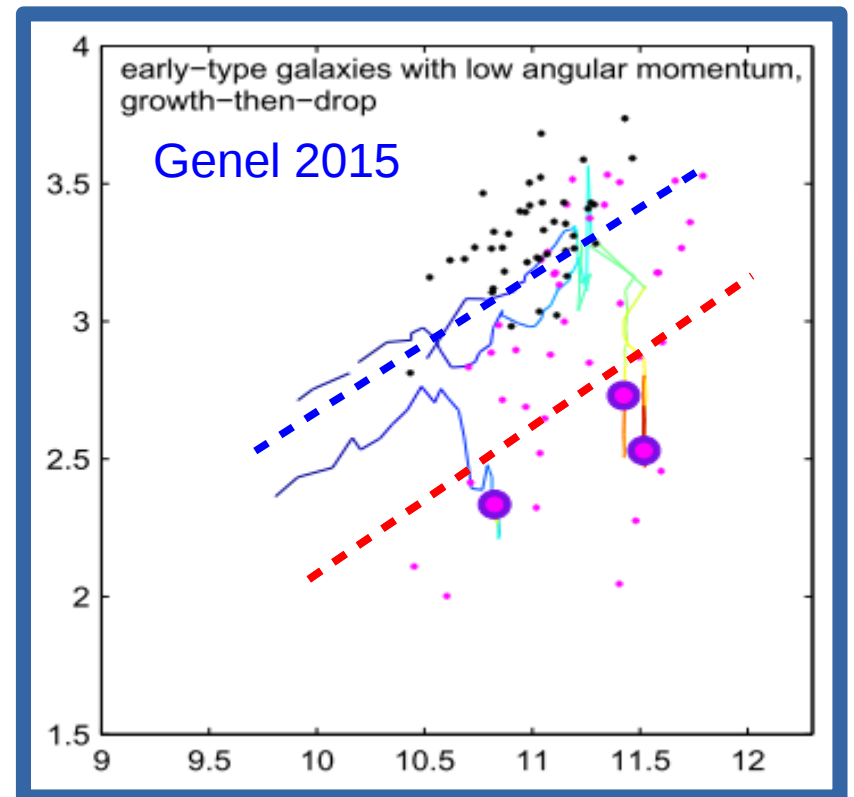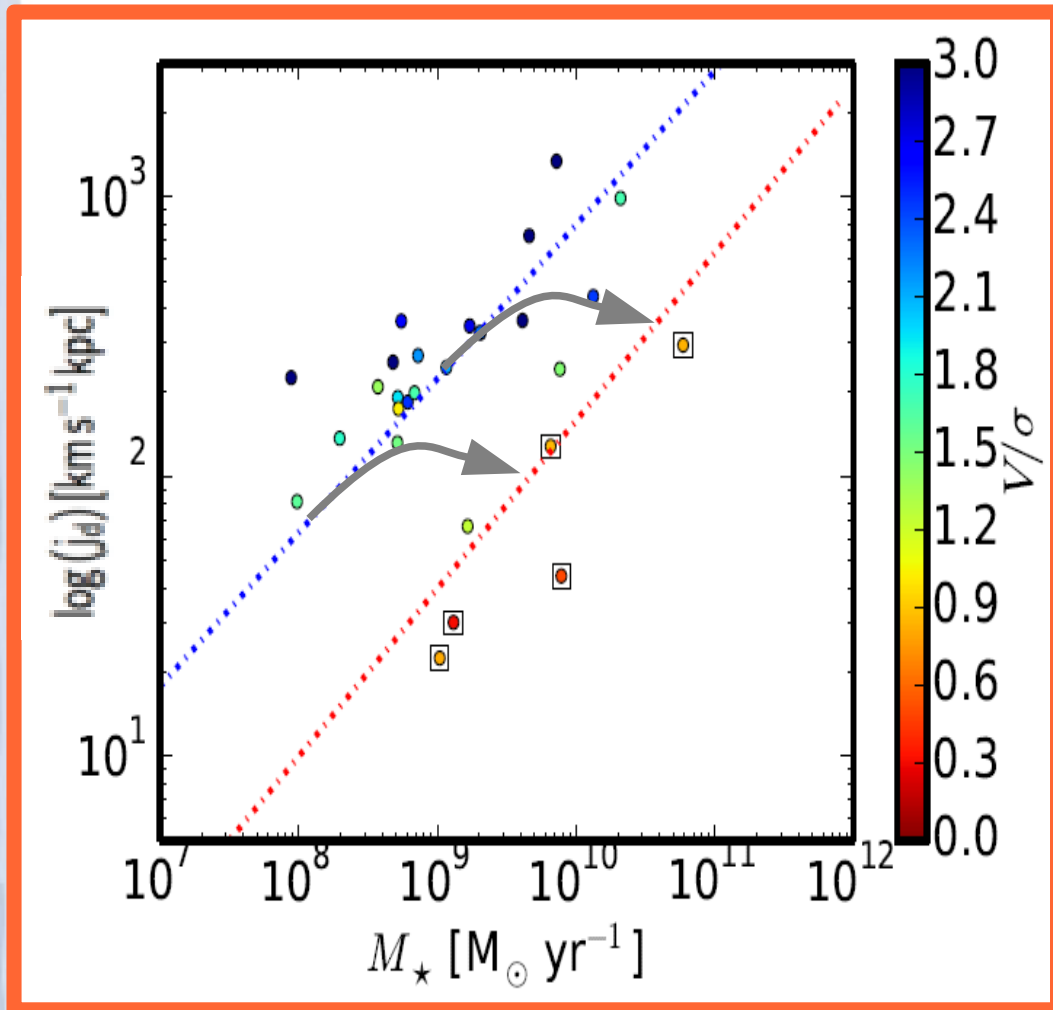
M*>1e10

M*<1e10
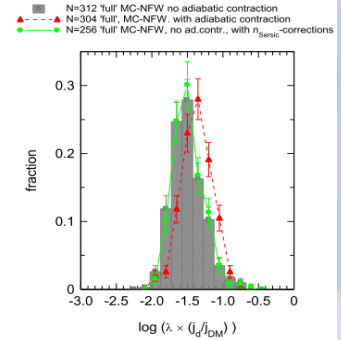
Disk (gas) Angular Momentum
in low-mass galaxies

- Extends j-M* to 1e8 !

- 2 sequences in place !

- Trend with v/sigma !

See Obreschkow& Glazebrook 2016

Disk (gas) Angular Momentum in low-mass galaxies

Genel 2015

Conclusions

- Kinematics of <u>low-mass disks</u> (1e8-1e10)
  - Extends high-mass end scaling relations (>1e10)
  - Well in place at z=0.4—1.4
- Angular Momentum of SFG and v/sigma (B/T)
  - → morphology transformation before quenching !
- Coming Soon
  - UDF 3x3 mosaic with MUSE
  - MUSE w/ AO !