The First Appearance of the Red Sequence of Galaxies in Proto-Clusters at 2<z<3

T. Kodama, I. Tanaka, M. Kajisawa, et al.

"Mac Naught from the Andes above Santiago" (22/01/07)

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Subaru's Great Contribution to Cluster Studies

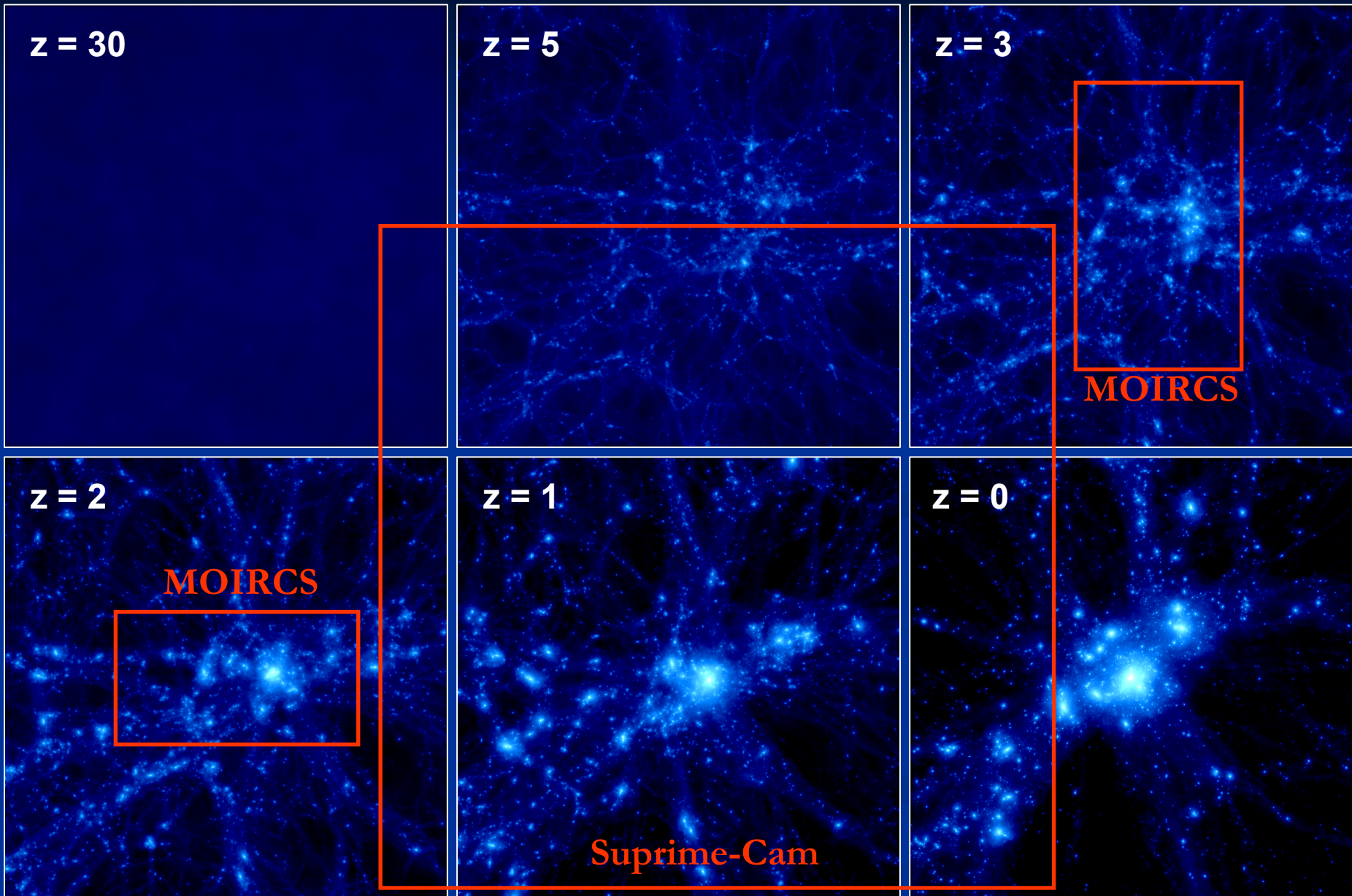## Panoramic views of distant clusters with its wide field instruments!

- Suprime-Cam (34'×27') Optical imaging
- MOIRCS (7'×4') NIR imaging/spectroscopy
- FMOS (30' ϕ) NIR spectroscopy

$$30' = 30\text{Mpc} @ z=1$$
$$7' = 13\text{Mpc} @ z=3$$

→ **Assembly of galaxies from surrounding filaments to cluster cores, and environmental influences on galaxies.**

Build-up of Cluster of Galaxies – Dark Matter Simulation (ΛCDM)

z = 30

z = 5

z = 3

MOIRCS

z = 2

MOIRCS

z = 1

z = 0

Suprime-Cam

$M = 6 \times 10^{14}$ Msun, $20 \text{Mpc} \times 20 \text{Mpc}$ (co-moving)

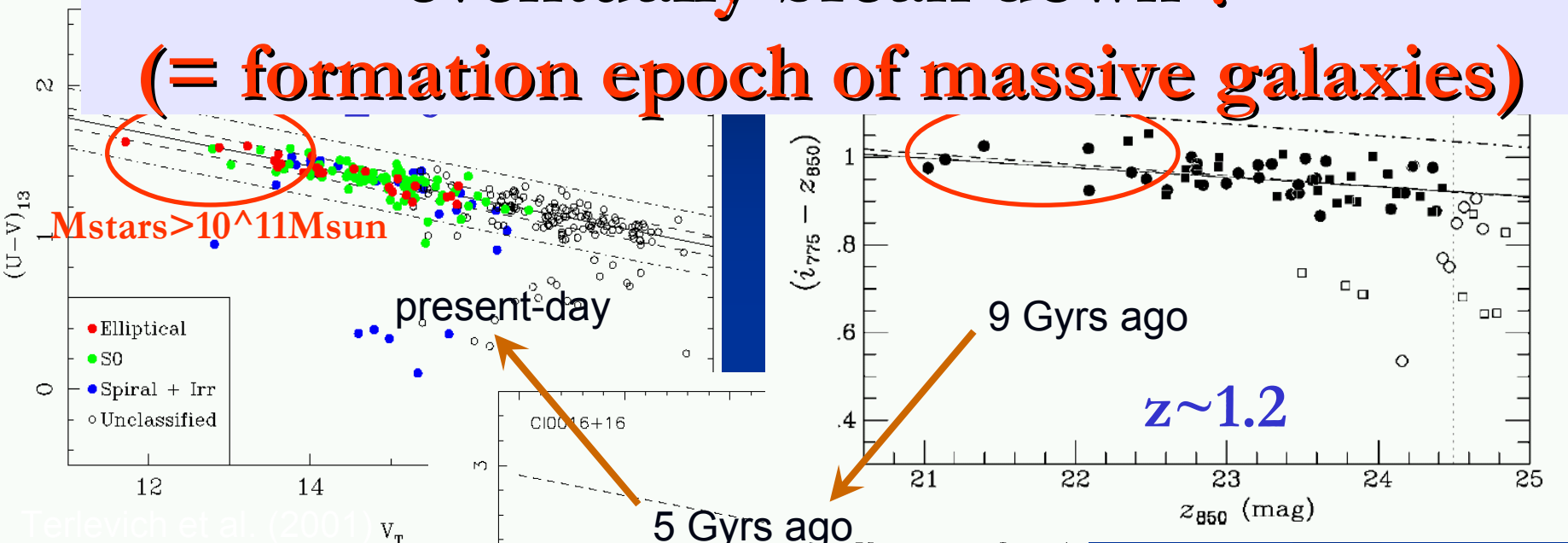Yahagi et al. (ν GC; 2005)

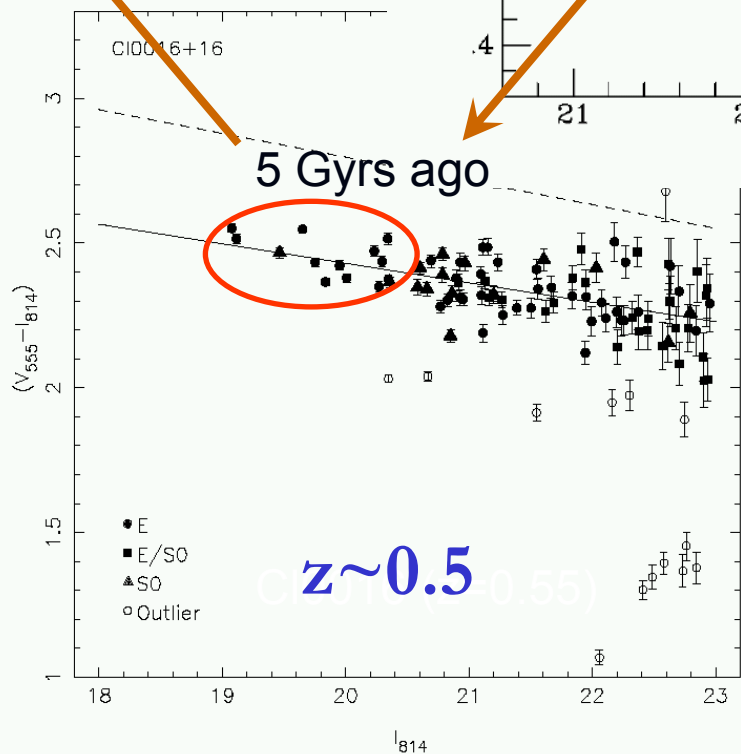# Why Proto-Clusters

despite this is an ultimate "biased" survey?

- CMR/FP analyses of z<1.3 clusters require that (massive) cluster galaxies should have had major star formation activity at z>2. Therefore a transition from active phase to passive phase (ie. appearance of the red sequence) is expected to be observed at z>2. (direct determination of the formation epoch of cluster early-type galaxies).

- Large scale distribution of galaxies in clusters at different epochs will tell us how the clusters of galaxies are assembled over the Hubble time. (witnessing the build-up of clusters).

When does the colour-magnitude relation eventually break down ?
(= formation epoch of massive galaxies)

Mstars>10^11Msun

present-day

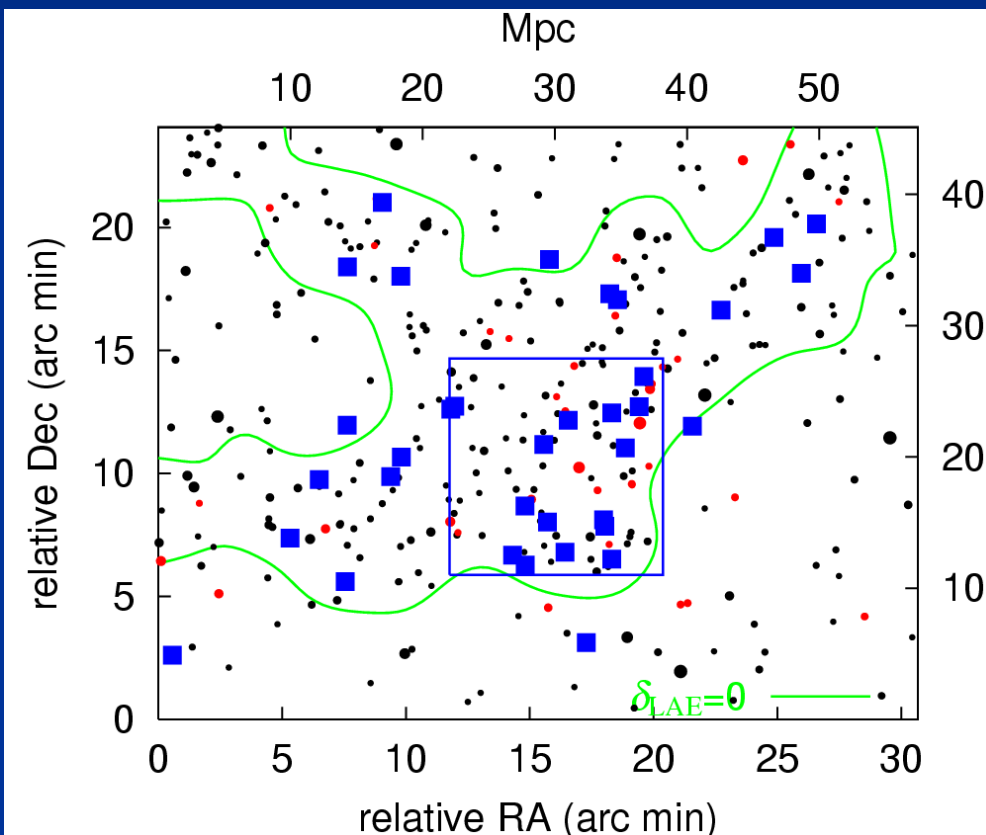- Elliptical
- S0
- Spiral + Irr
- Unclassified

Terlevich et al. (2001)

9 Gyrs ago

$z \sim 1.2$

Blakeslee et al. (2003)

5 Gyrs ago

CI0016+16

$z \sim 0.5$

- E
- E/S0
- S0
- Outlier

Ellis et al. (1997)

Evolution of CMR of cluster early-types.

$z(SF)>2$
$z(assembly)>1$

LSS in the early Universe traced by Ly α emitters

z~4.86 (~1Gyr)

z~3.09 (~2Gyr)

SSA22 （Matsuda et al. 2005）

SDF （Shimasaku et al. 2003）

Map of star formation → Map of stellar mass

3+1 known proto-clusters around high-z radio galaxies at 2<z<3

Subaru/MOIRCS observations (except for 1558)

$4.0' \times 7.0'$ (0.117'/pix), 7'=10-15Mpc@z=2-3

Targets (radio galaxies)	redshift (z)	J	H	Ks	PSF
PKS 1138-262	2.156	83 min	____	55 min	0.5"~0.7"
USS 1558-003 (5' x 5')	2.527	180min (SOFI)	____	175min (SOFI)	0.7"
USS 0943-242	2.923	118min	68 min	63 min	0.4"~0.6"
MRC 0316-257	3.130	78 min	60 min	55 min	0.6"~0.7"

J=23.5, H=22.3, K=22.0 (5 sigma, Vega)

Kodama et al. (2006) in prep.

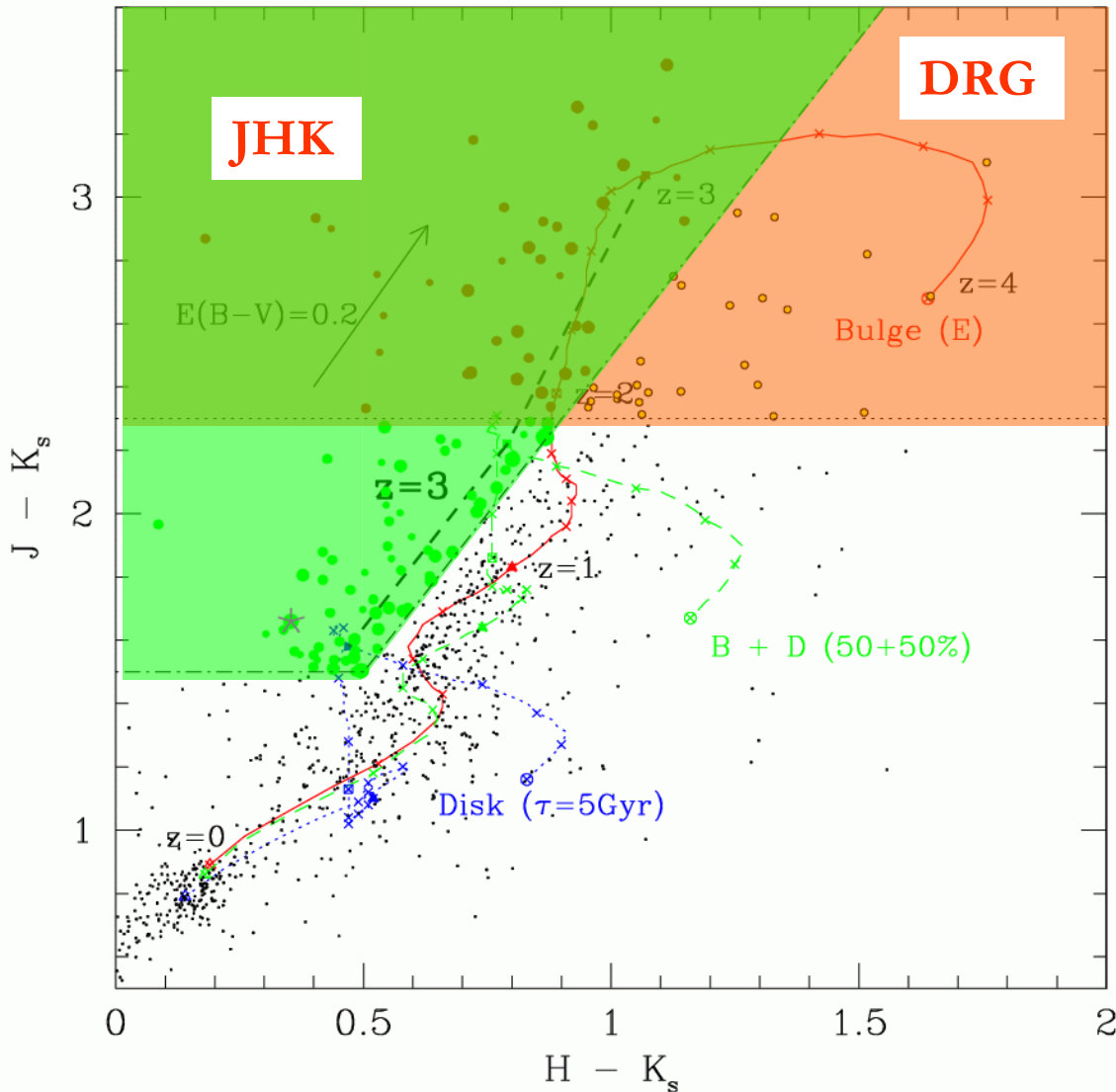# "A Proto Cluster"   PKS1138-262 (z=2.156)

MOIRCS   J : 83 min   Seeing ~ 0.5-0.7"

4' x 7'   Ks : 55 min   Courtesy: Ichi Tanaka

JHK selection of 2<z<3 galaxies
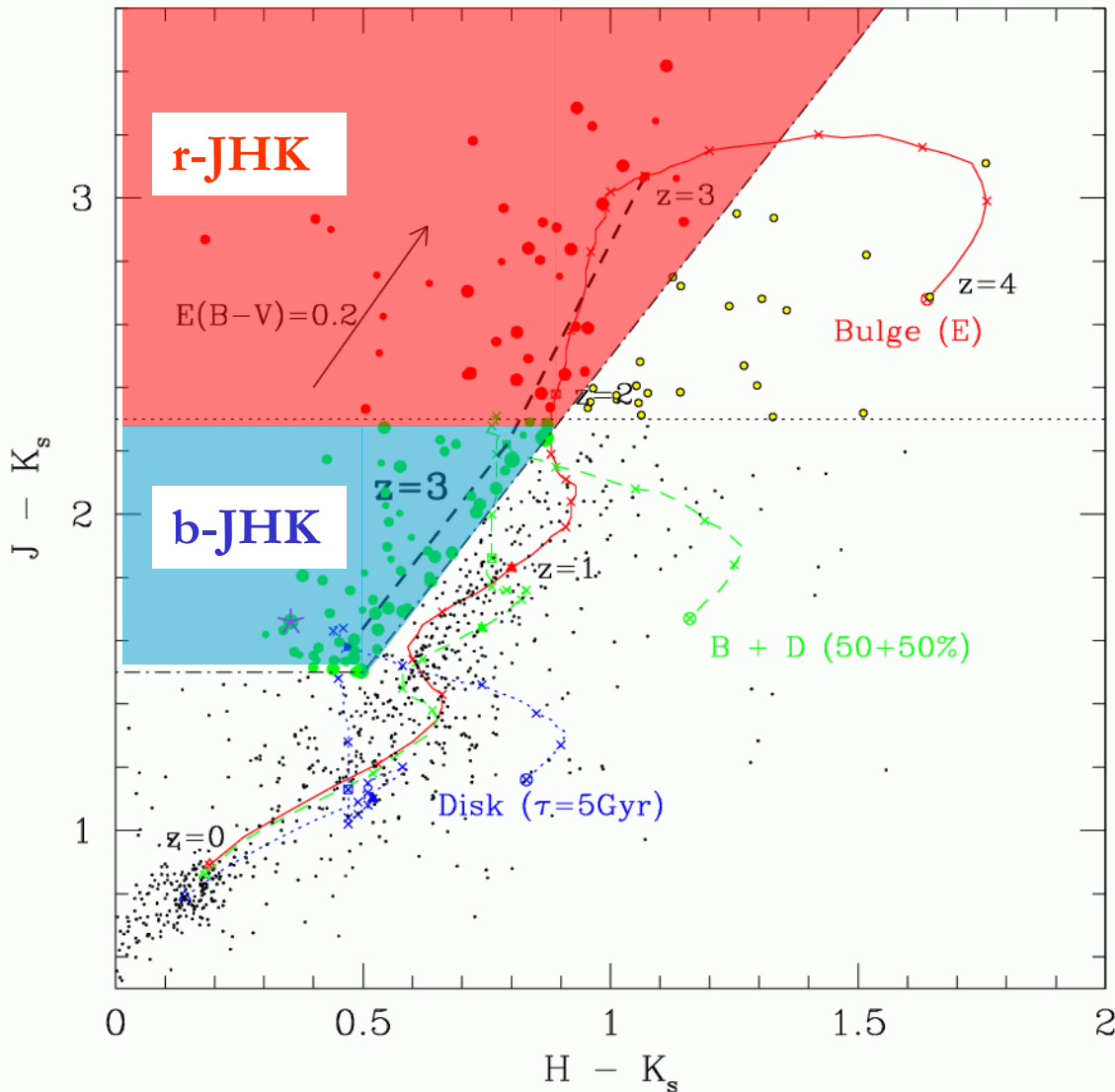

Classical criteria (DRG):
J-K>2.3
passive/dusty gals at z>2

↓

Our new criteria (JHK):
(J-K)> 2(H-K)+0.5
&& J-K>1.5
passive/dusty +
star-forming gals at 2<z<3

Kajisawa et al. (2006), Kodama et al. (2006)

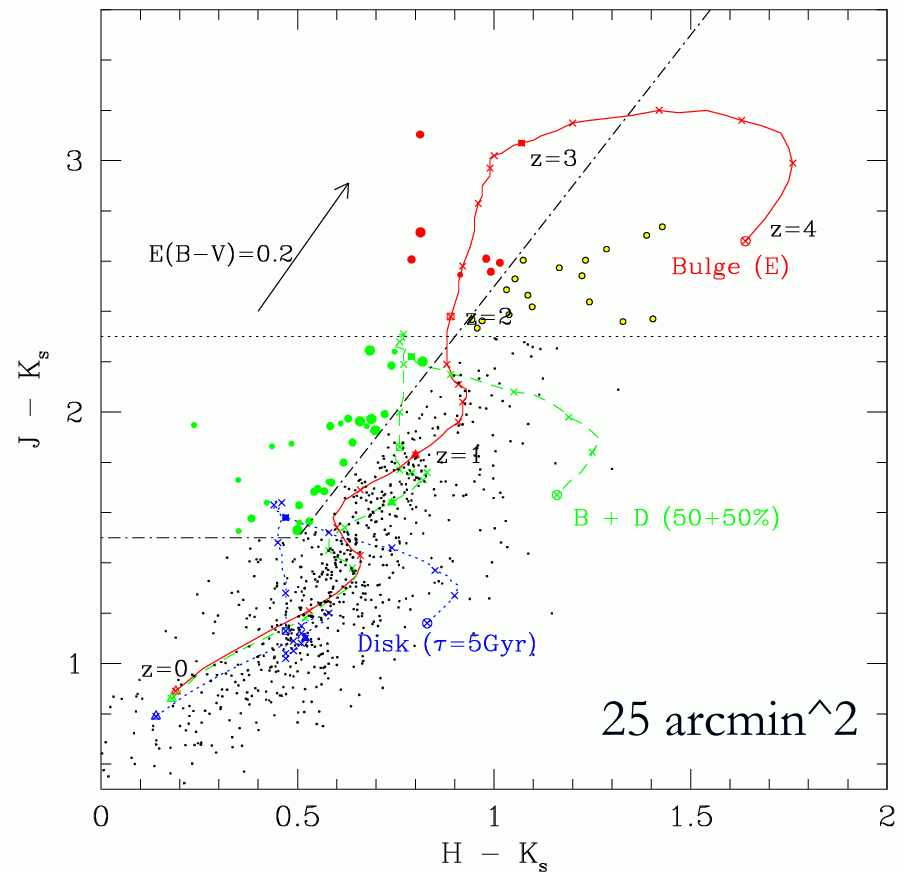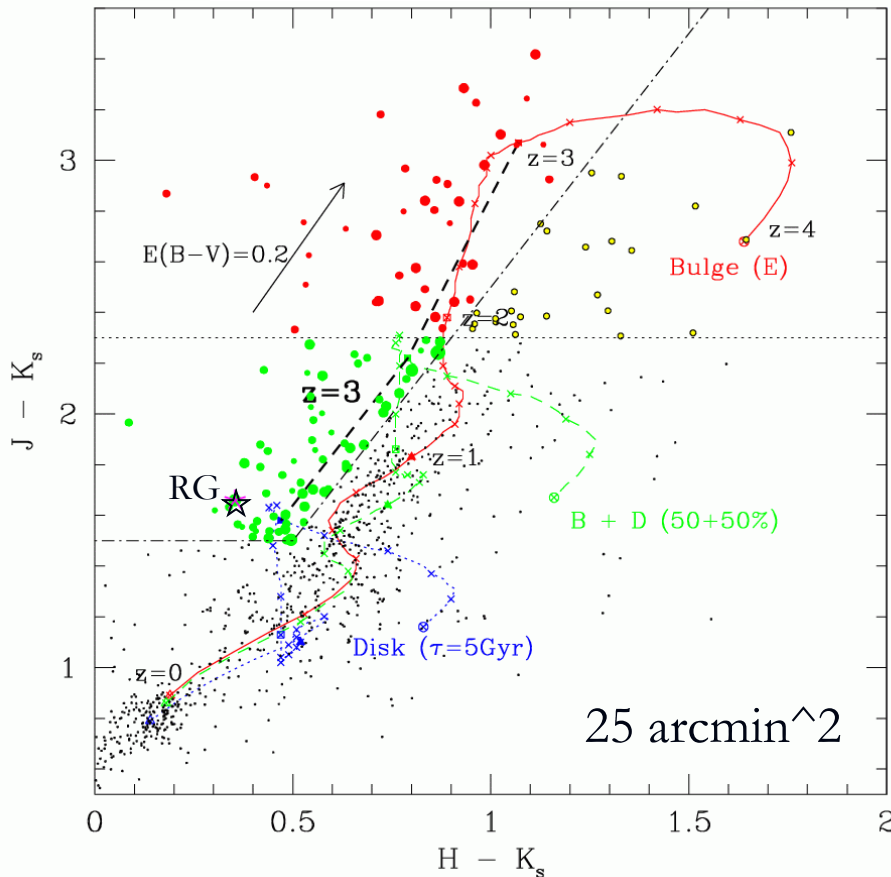# JHK selection of 2<z<3 galaxies

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J-K>2.3 -- r-JHK
J-K<2.3 -- b-JHK

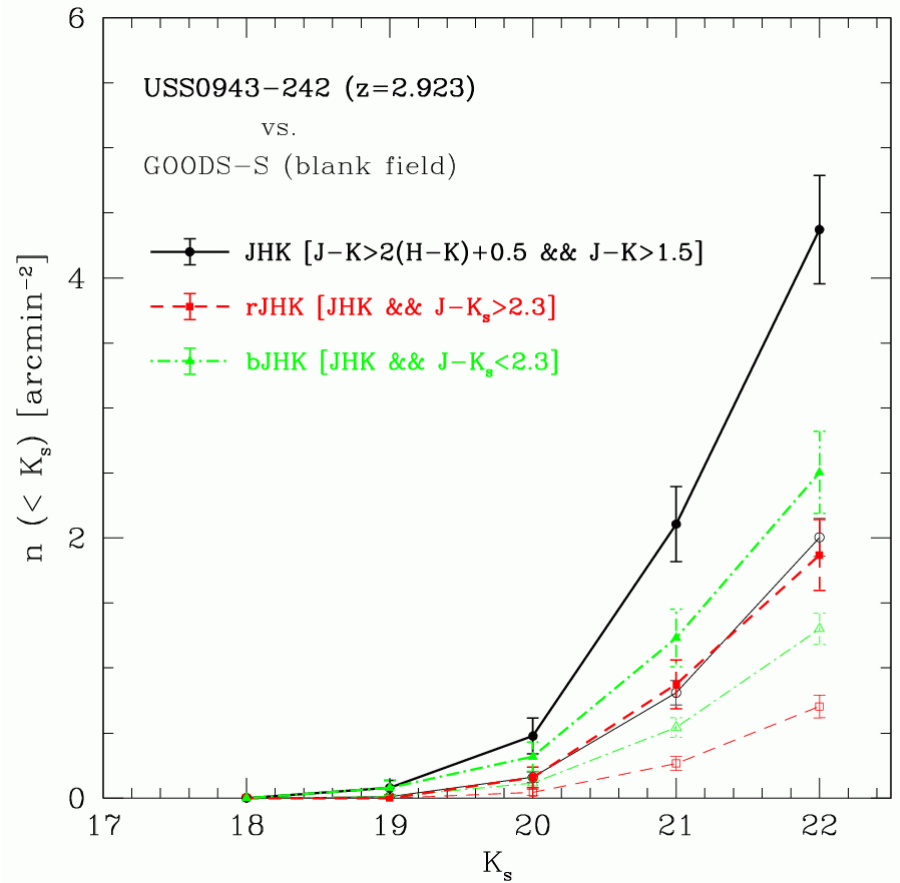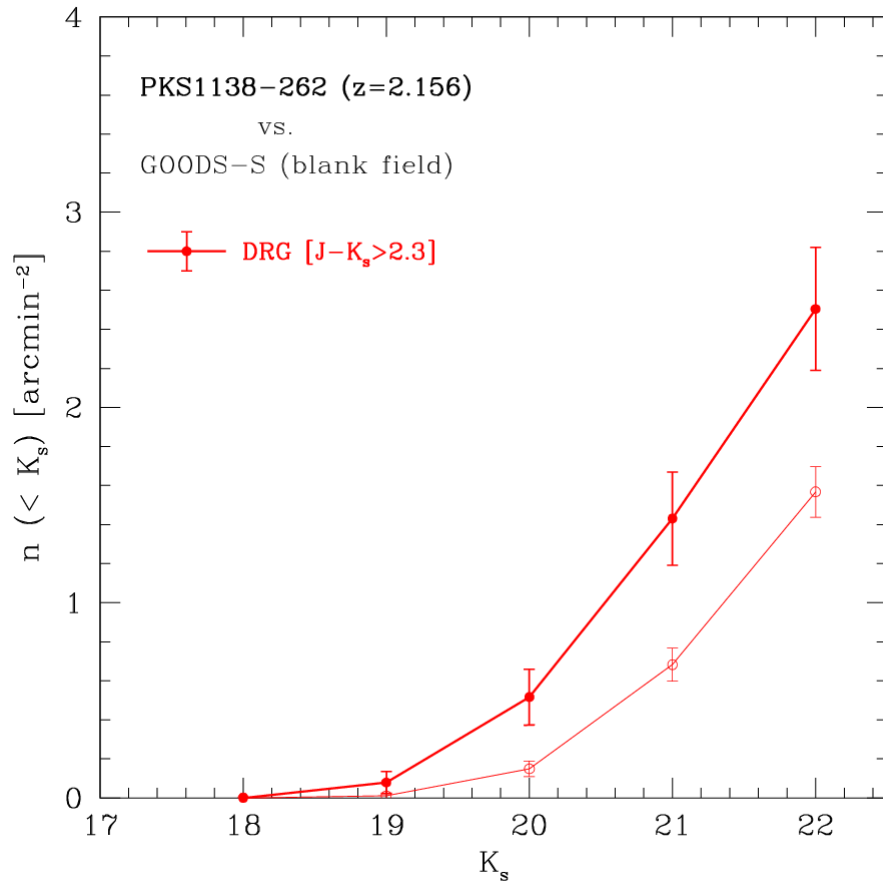# JHK diagram (0943@z=2.923)

USS0943 (z=2.923)

GOODS-S (blank field)

Excesses of both r-JHK and b-JHK are clearly seen (factor>2.5).

Kodama et al. (2006)

Statistical Excess of DRGs/JHKs around PKS1138 (z=2.156) / USS0943 (z=2.923)
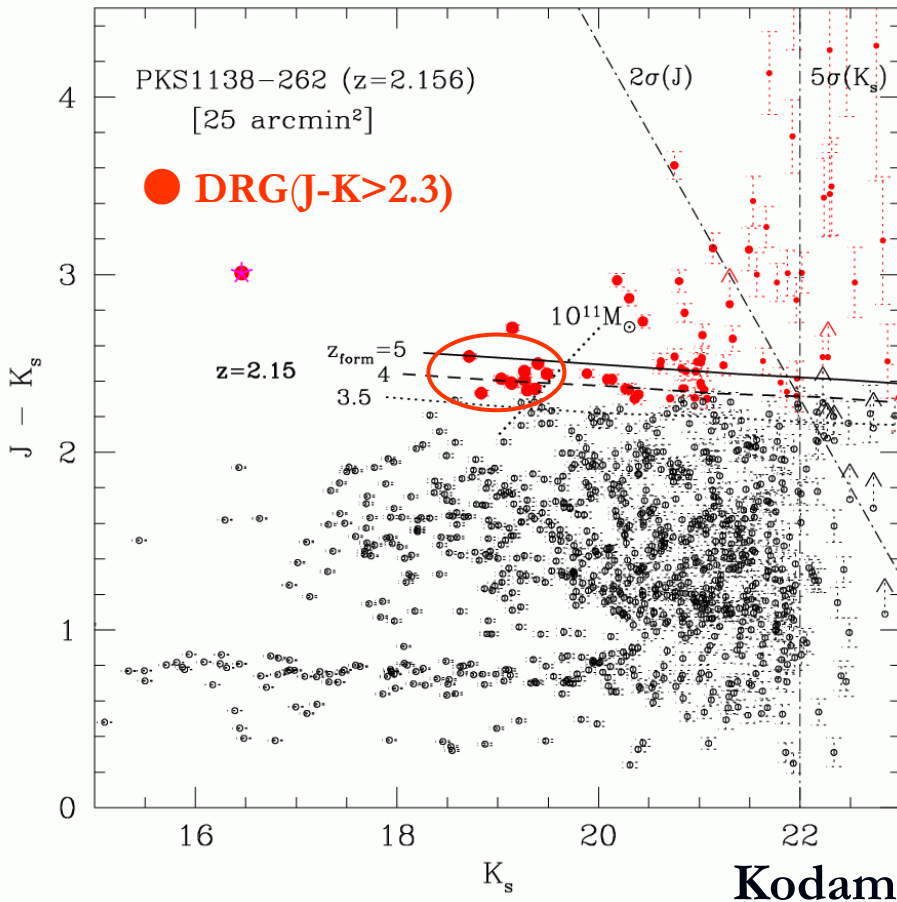
PKS1138 (z=2.156)

USS0943 (z=2.923)

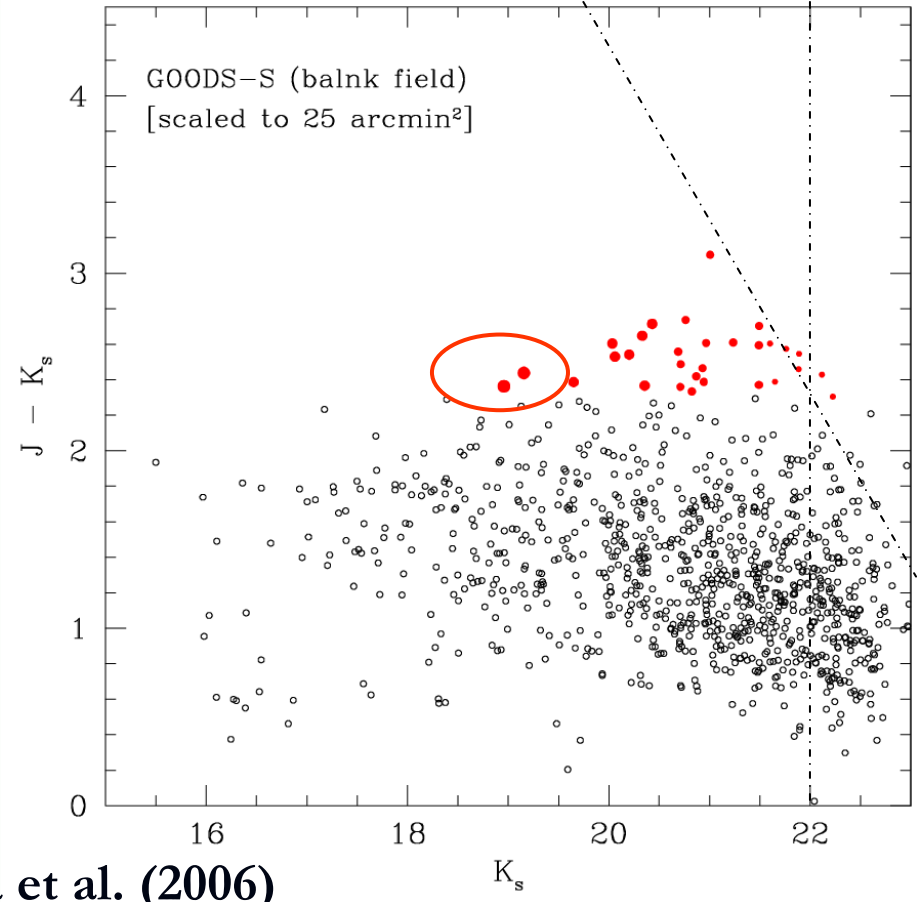**Factor 2~3 in excess of DRGs/JHKs compared to GOODS-S.**

Colour-Magnitude (1138@z=2.156)
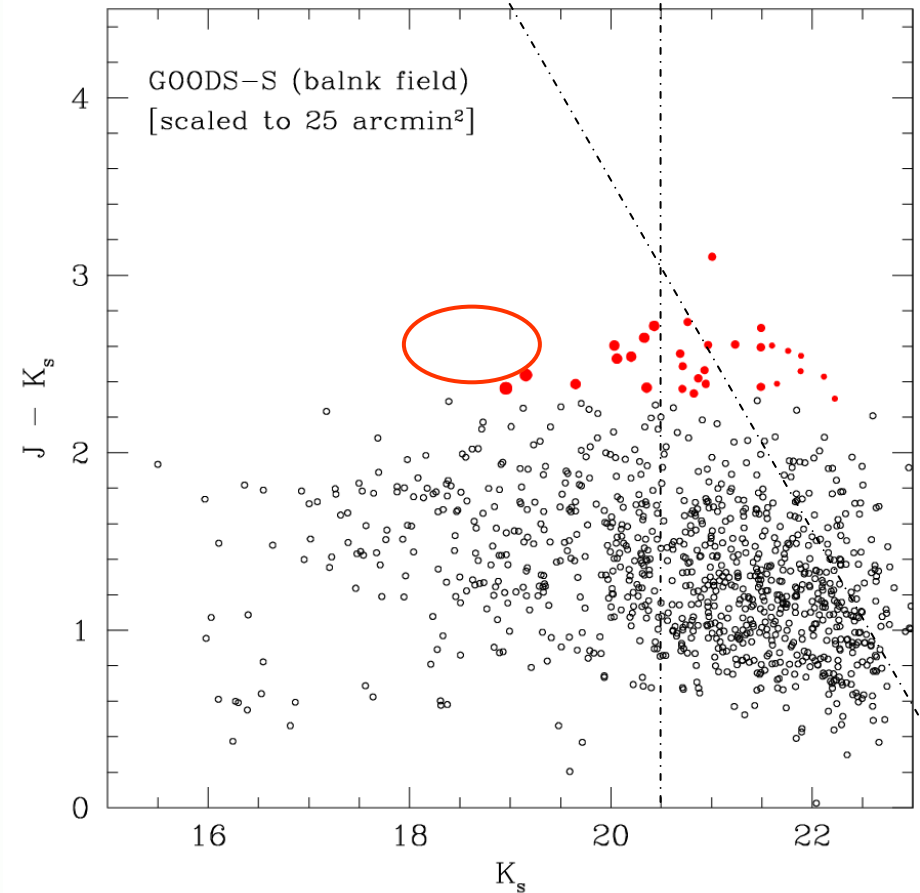
PKS1138 (z=2.156)

GOODS-S (blank field)

PKS1138−262 (z=2.156)
[25 arcmin²]

● DRG(J−K>2.3)

$2\sigma(J)$ $5\sigma(K_s)$

$10^{11}M_\odot$

$z_{form}=5$
$z=2.15$ 4
              3.5

$J − K_s$

K_s

GOODS−S (balnk field)
[scaled to 25 arcmin²]

$J − K_s$

K_s

Kodama et al. (2006)
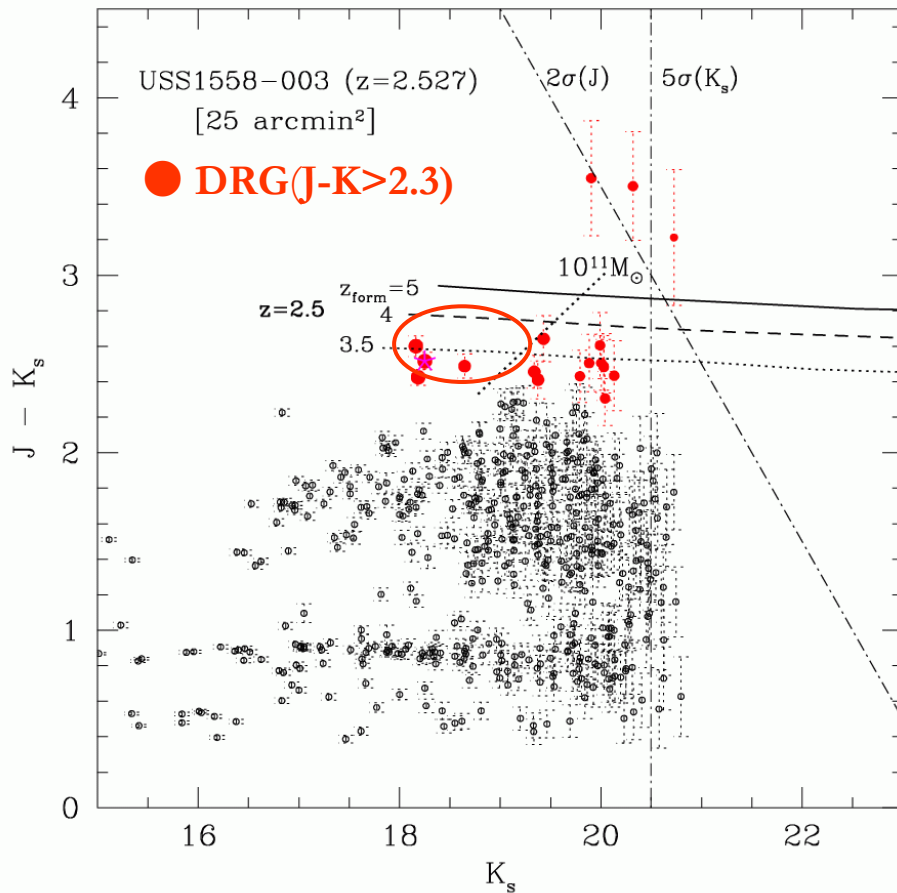
Well-visible red sequence consistent with passive evolution formed at z~4-5.
They are very massive (>10^11Msun) !

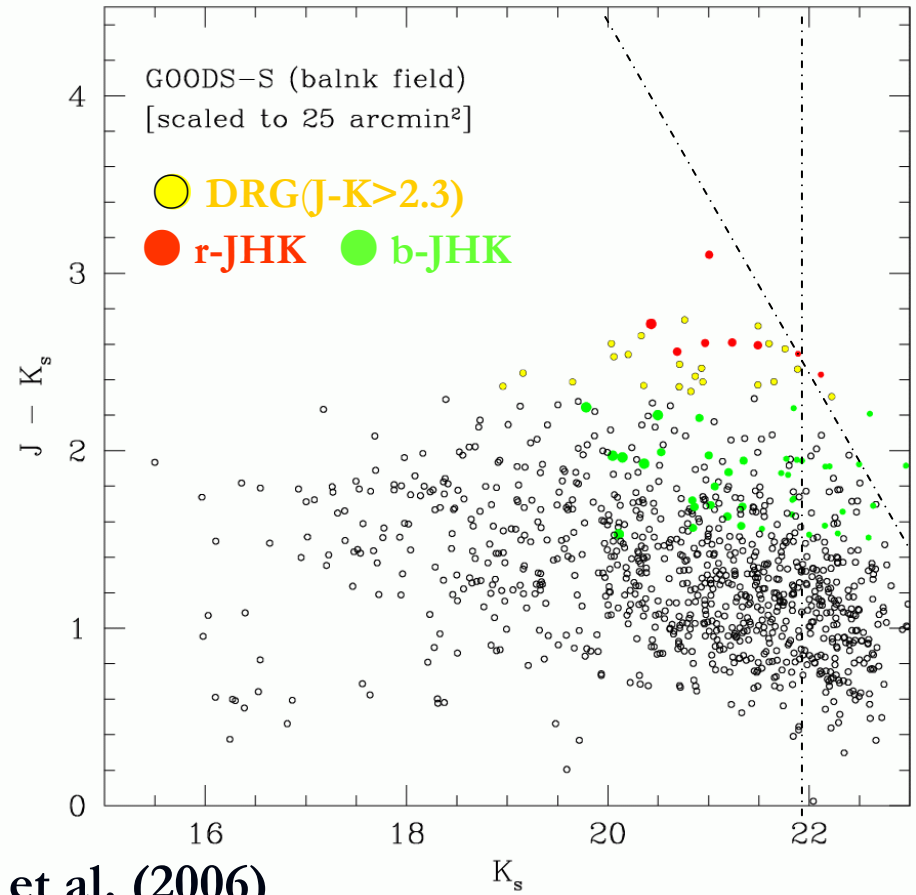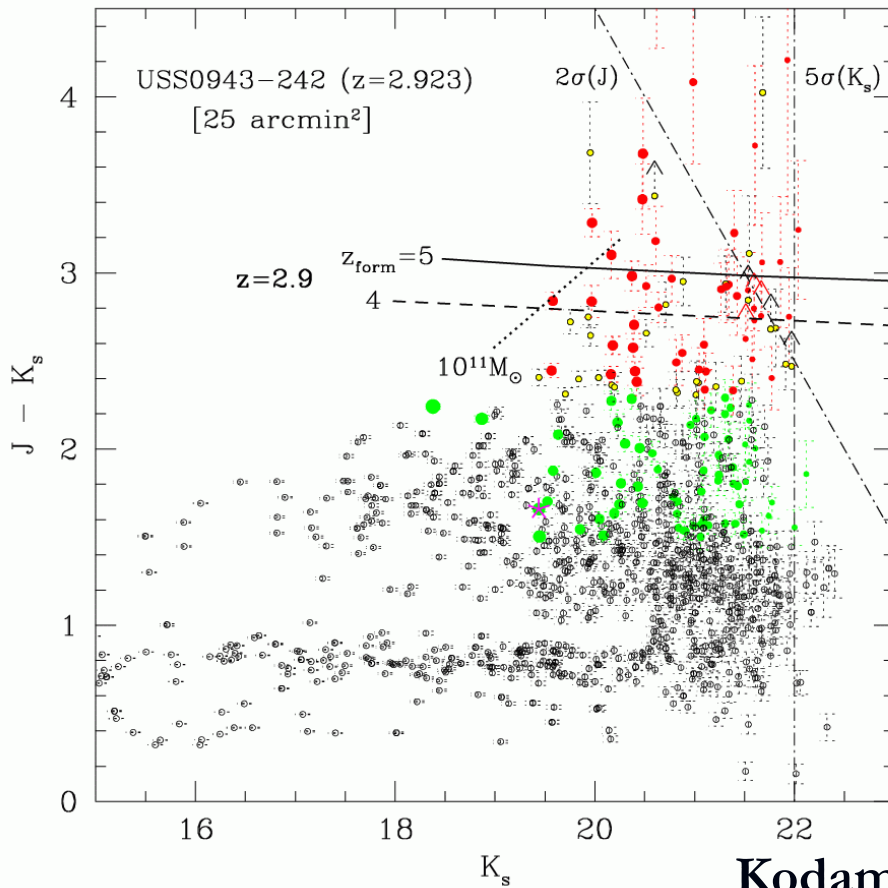# Colour-Magnitude (1558@z=2.527)

USS1558 (z=2.527)

GOODS-S (blank field)

Well-visible "red finger" consistent with passive evolution formed at z~3.5!
They are very massive (>10^11Msun) !

Colour-Magnitude (0943@z=2.923)

USS0943-242 (z=2.923)
[25 arcmin²]

$2\sigma(J)$ $5\sigma(K_s)$

$z=2.9$ $z_{form}=5$

4

$10^{11}M_\odot$
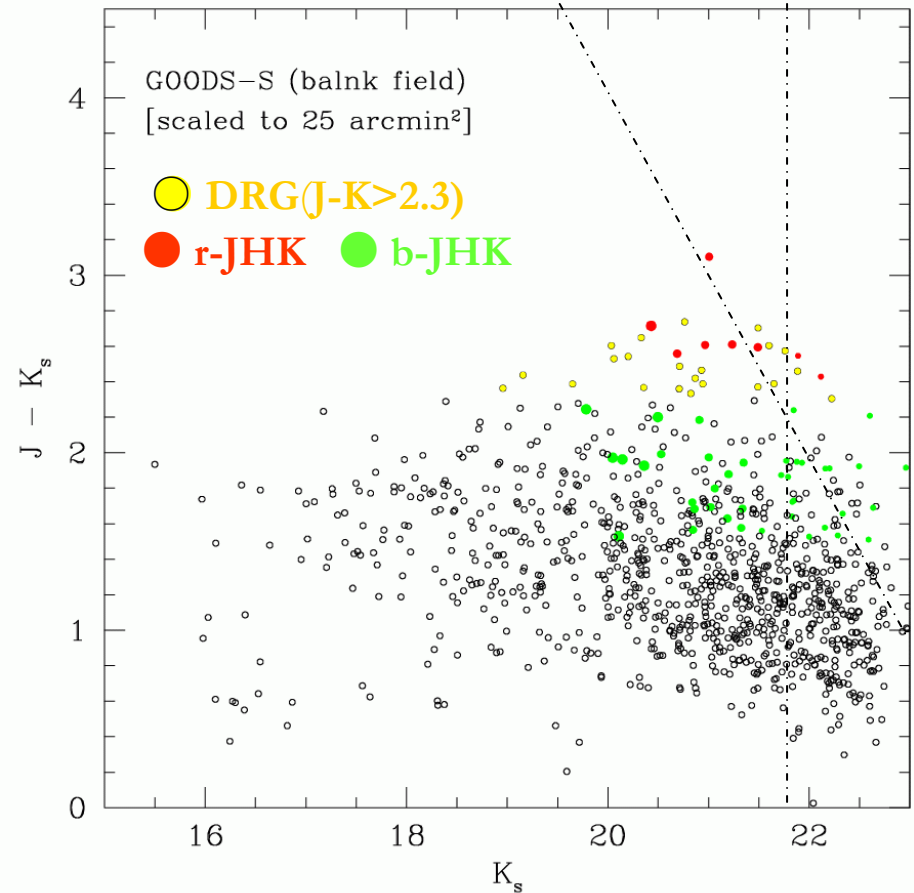
GOODS-S (balnk field)
[scaled to 25 arcmin²]

DRG(J-K>2.3)

r-JHK   b-JHK

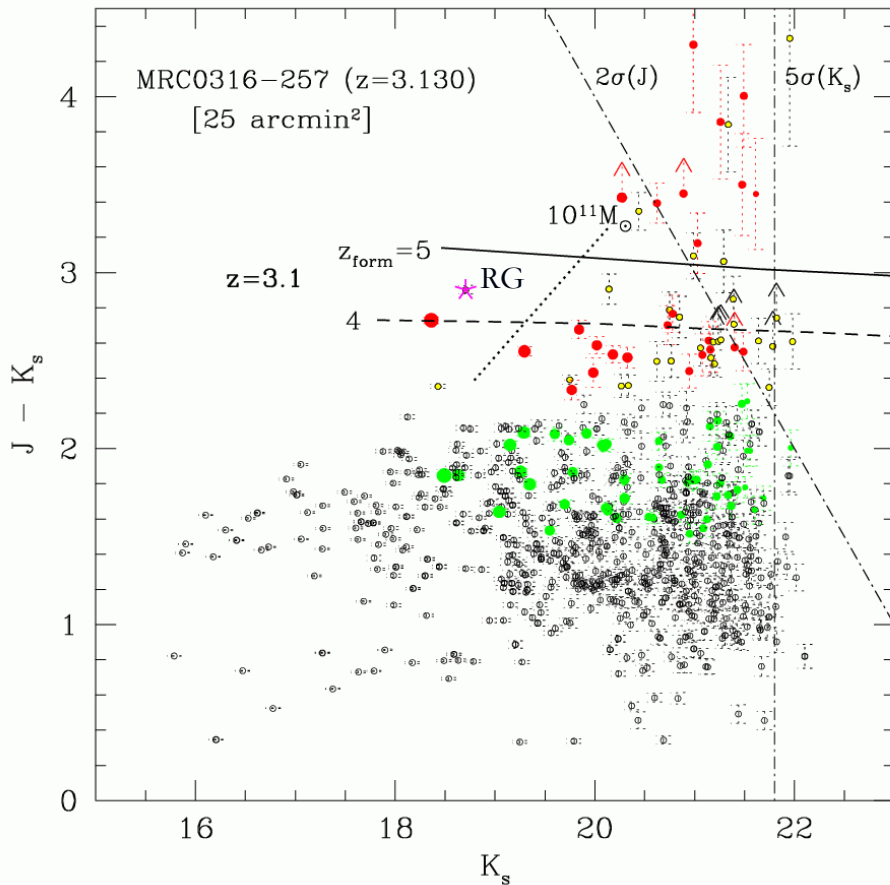Kodama et al. (2006)

Clear excess of red galaxies consistent with passive evolution formed at z>4,
but few massive ones (>10^11Msun) ! → not assembled yet !?
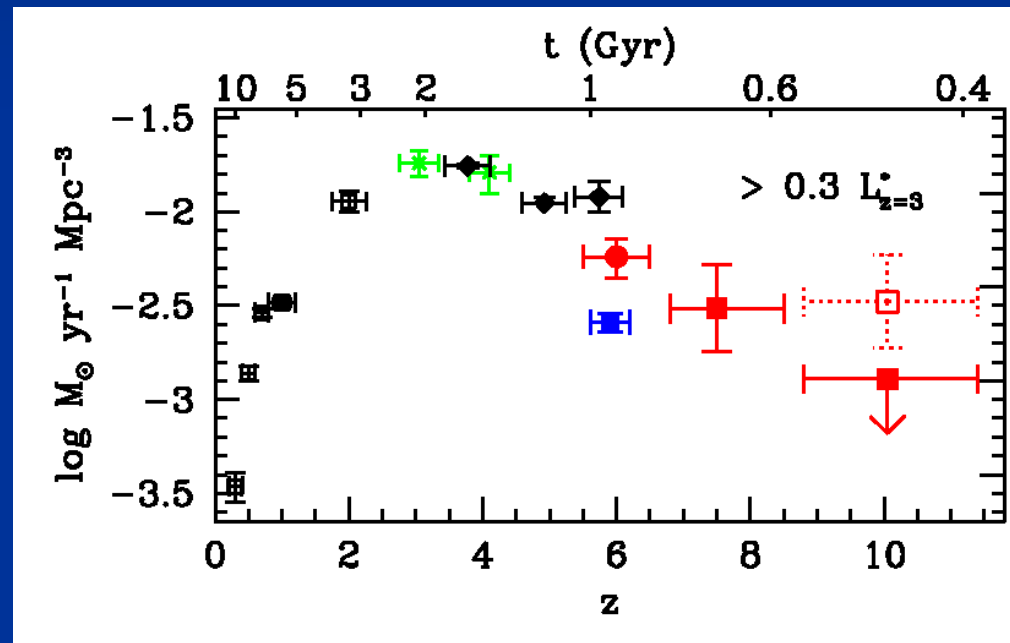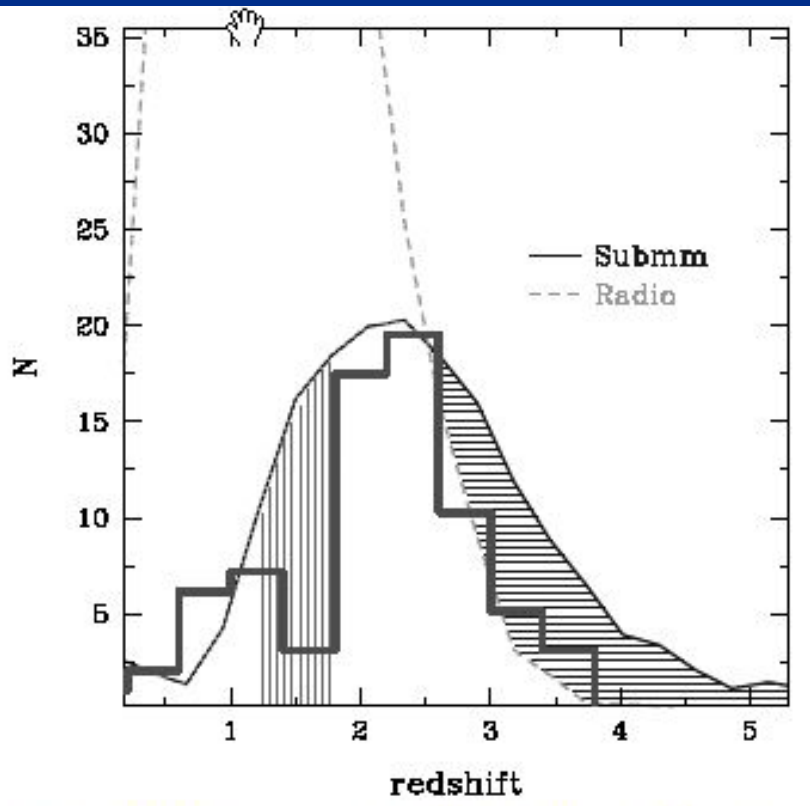
Colour-Magnitude (0316@z=3.130)

Some massive red galaxies including the RG formed at z~4 !

What's the era of $2 < z < 3$?
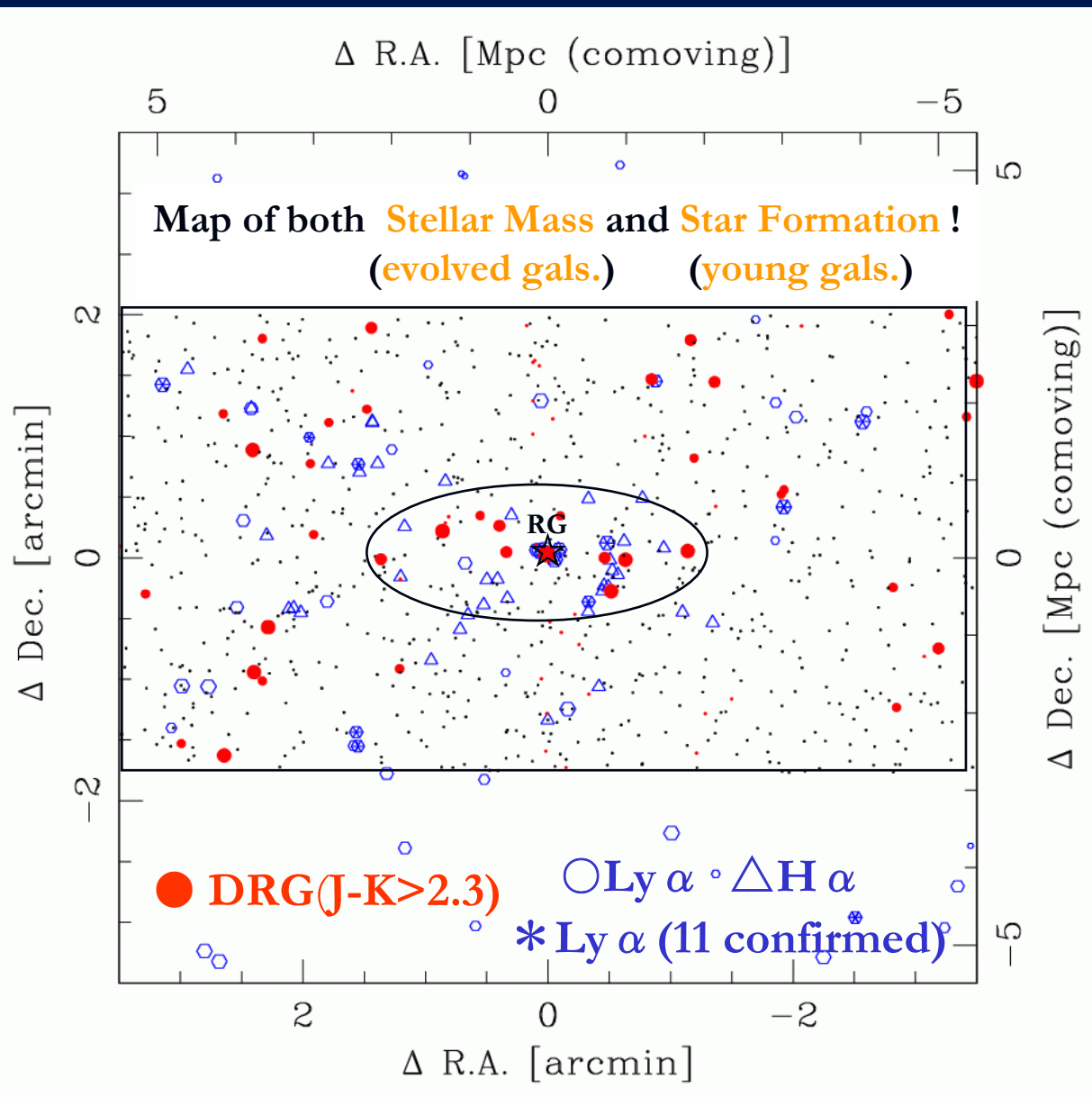
SCUBA sources peak at z~2.4

Cosmic SFR peaks at z~3

Chapman et al. (2005)

Bouwens et al. (2005)

$\triangle$t(2<z<3)

100 Msun/yr $\times$ 1 Gyr = 10^11 Msun

2-D Structure of PKS1138 (z=2.156)

Map of both **Stellar Mass** and **Star Formation** !
(evolved gals.)   (young gals.)

RG

● **DRG(J-K>2.3)**   ○ Ly α ○ △ H α
                            ✱ Ly α (11 confirmed)

Δ R.A. [Mpc (comoving)]

Δ Dec. [arcmin]

Δ R.A. [arcmin]

Δ Dec. [Mpc (comoving)]

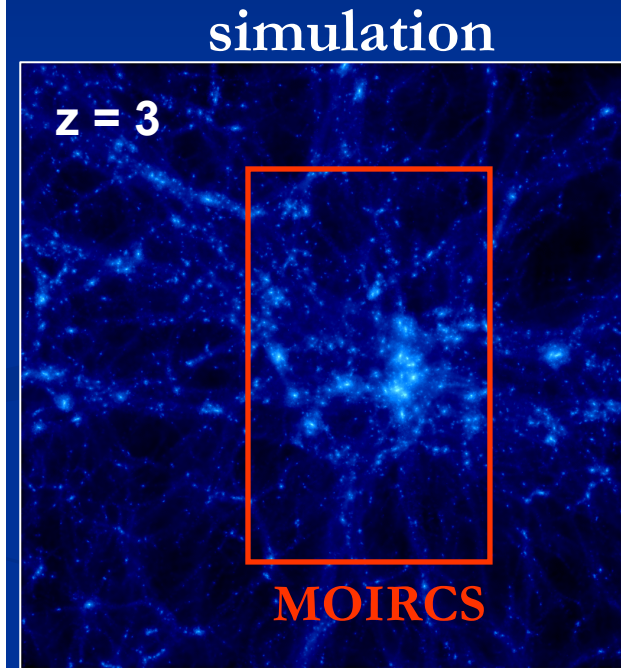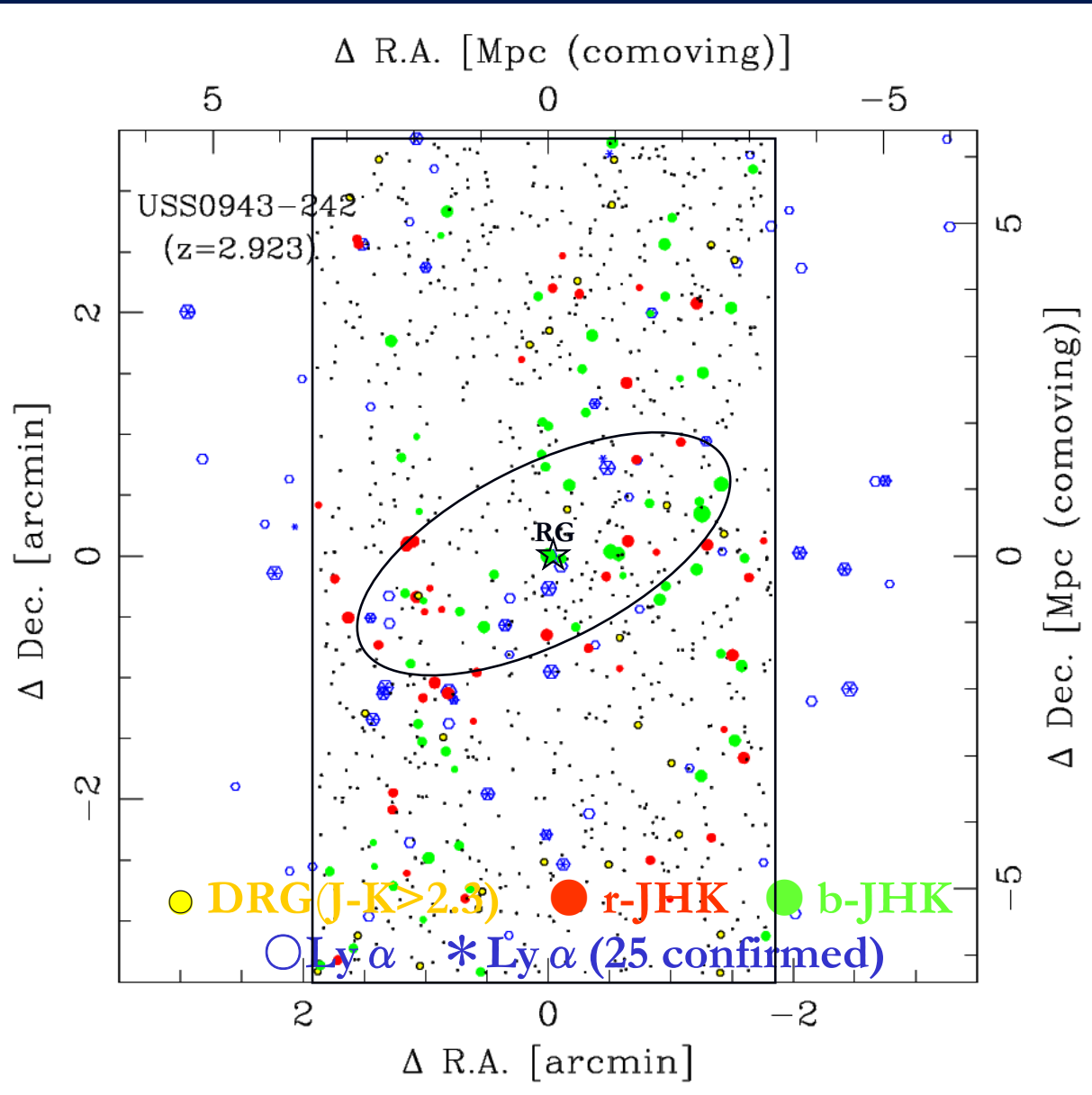**simulation**

z = 2

MOIRCS

see also
Kurk et al. (2004)
Croft et al. (2005)

2-D Structure of USS0943 (z=2.923)

Summary

◆ **Large excesses of evolved populations (NIR-selected galaxies) are found in the known proto-clusters around high-z radio galaxies (2<z<3), which form band-shape structures on scales of >10Mpc.**

◆ **The first appearance of red massive galaxies between z=3 and 2?**

◆ **Spectroscopic surveys (optical/NIR) are underway in order to confirm the structures/red sequence.**