2014年度 天文天体物理若手の会夏の学校 (2014/7/30, 戸倉上山田温泉)

マクロとミクロな視点で解き明かす銀河進化と環境効果

小山佑世 (ISAS/JAXA)

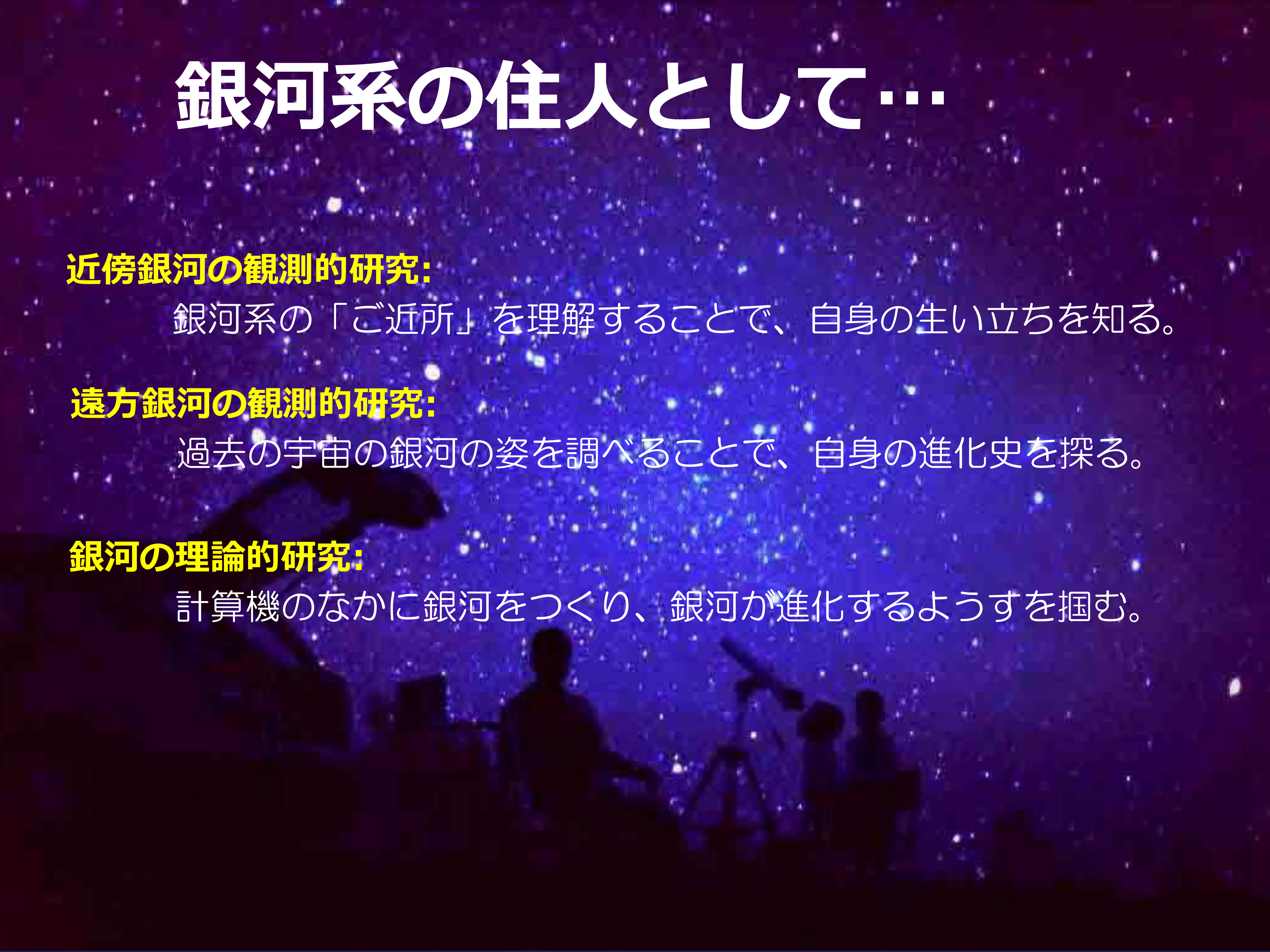
MAHALO-Subaru collaboration

なぜ銀河を研究するのか？

「我々はどこから来たのか, 我々は何者か, 我々はどこへ行くのか」

ポール・ゴーギャン (1897)

銀河系の住人として…



近傍銀河の観測的研究:

銀河系の「ご近所」を理解することで、自身の生い立ちを知る。

遠方銀河の観測的研究:

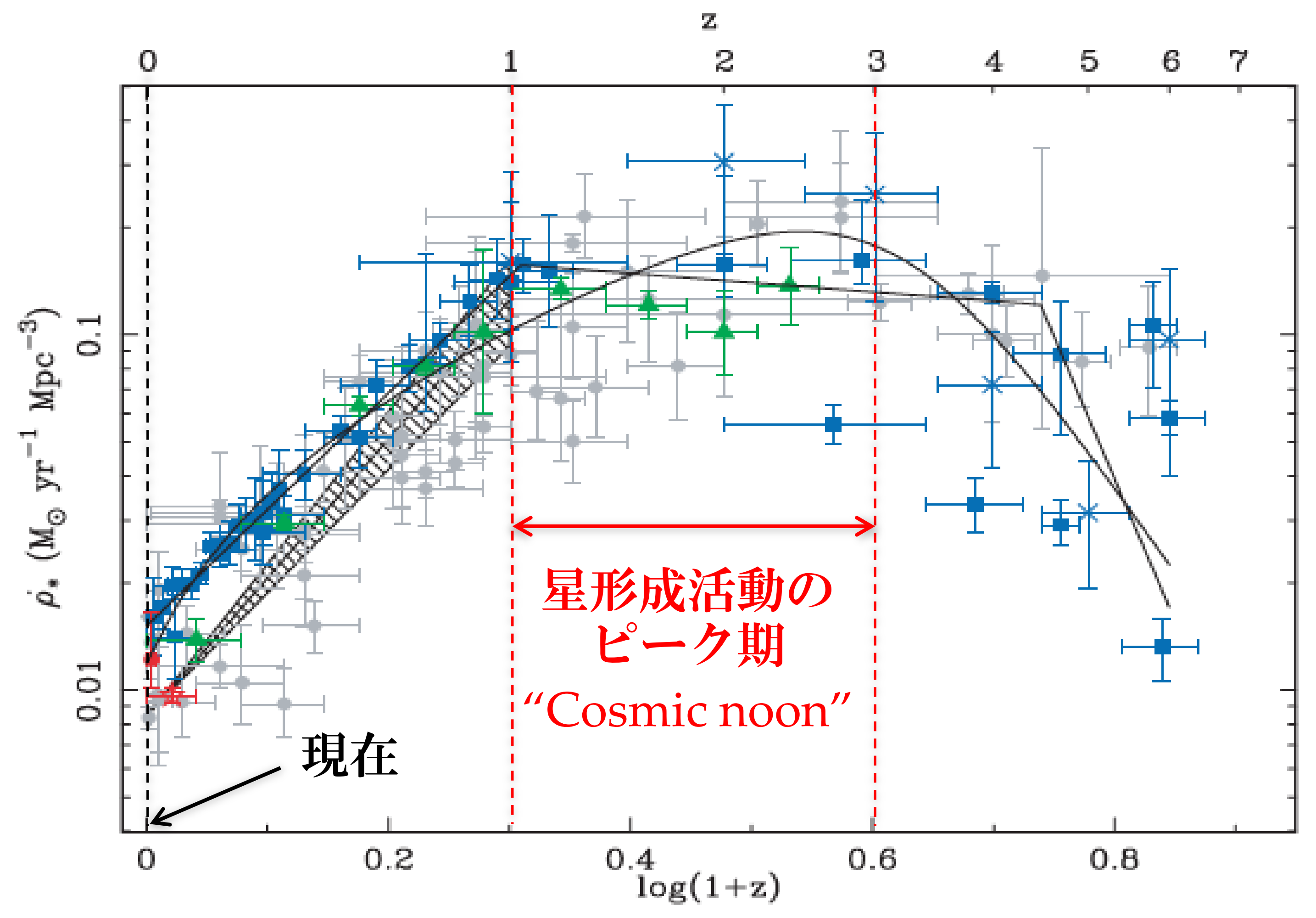
過去の宇宙の銀河の姿を調べることで、自身の進化史を探る。

銀河の理論的研究:

計算機のなかに銀河をつくり、銀河が進化するようすを掴む。

銀河の進化: 二つの側面

(1) (星)質量獲得の歴史 = 星形成史



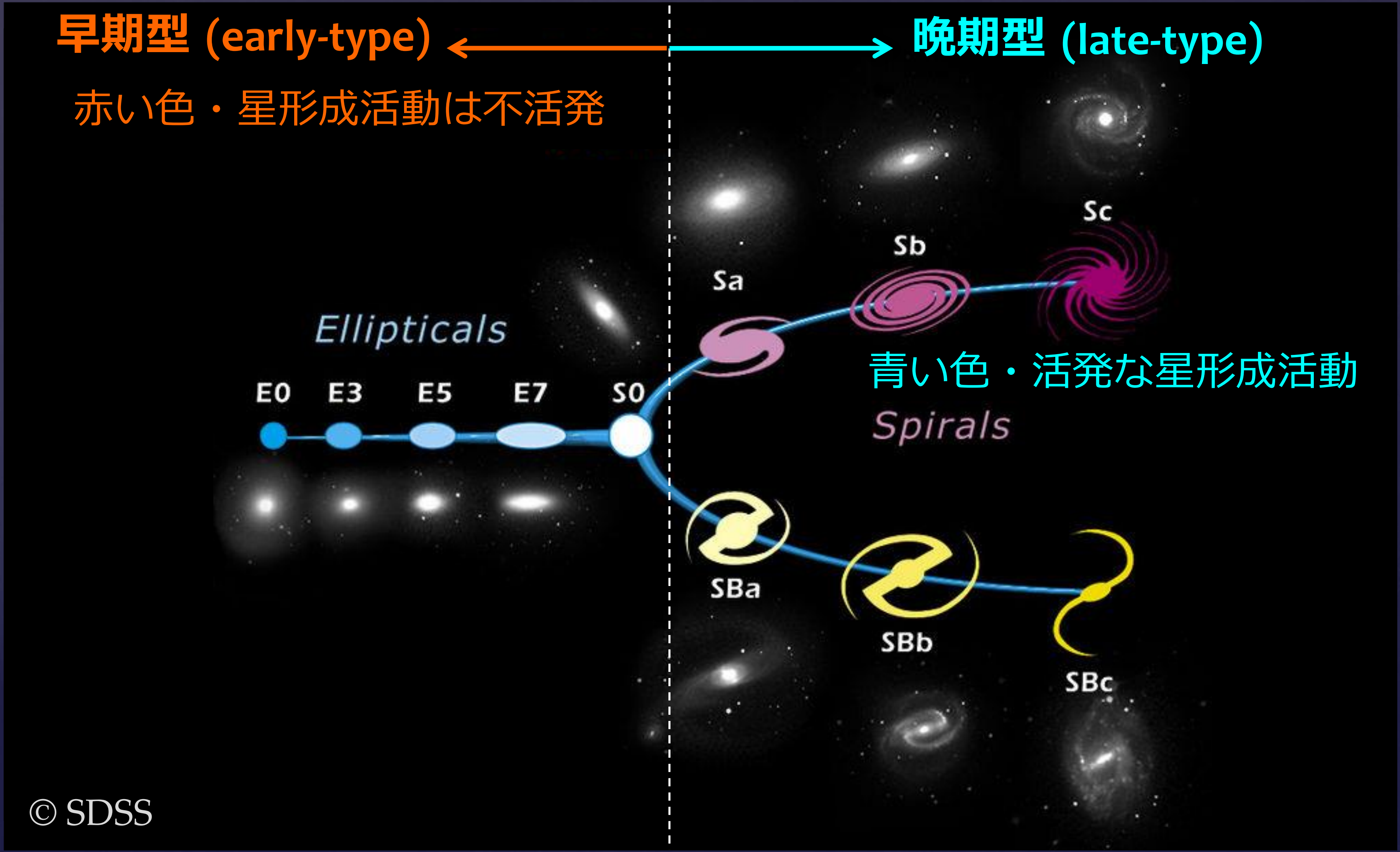
星形成活動の
ピーク期
“Cosmic noon”

現在

Hopkins & Beacom (2006)

銀河の進化: 二つの側面

(2) 形態獲得の歴史 = ハッブル系列の形成



早期型 (early-type) ←

赤い色・星形成活動は不活発

→ **晩期型 (late-type)**

青い色・活発な星形成活動

© SDSS

銀河の進化: 二つの側面

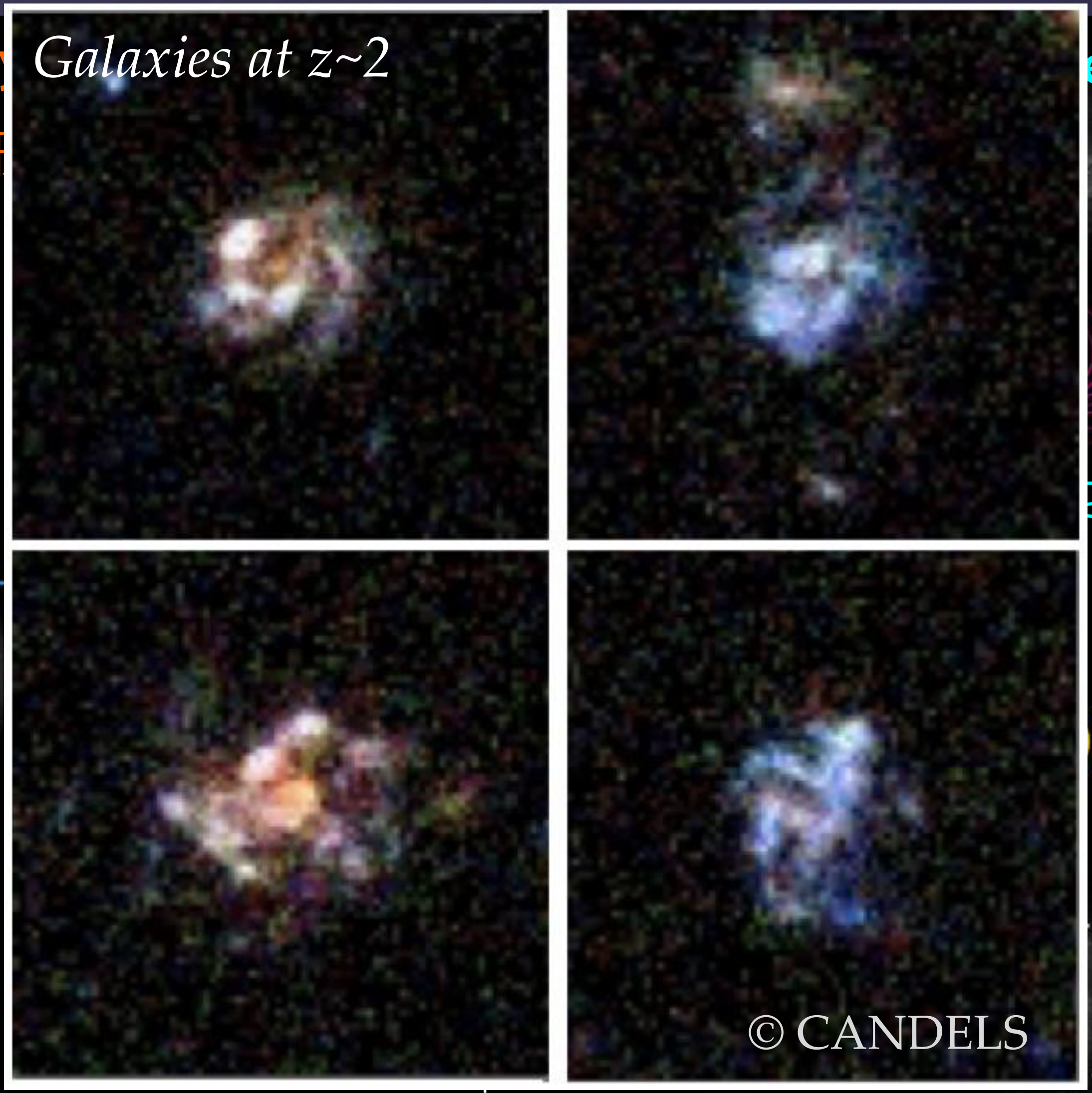
(2) 形態獲得の歴史 = ハッブル系列の形成

早期型 (early

赤い色・星

e-type)

な星形成活動



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1. マクロな視点

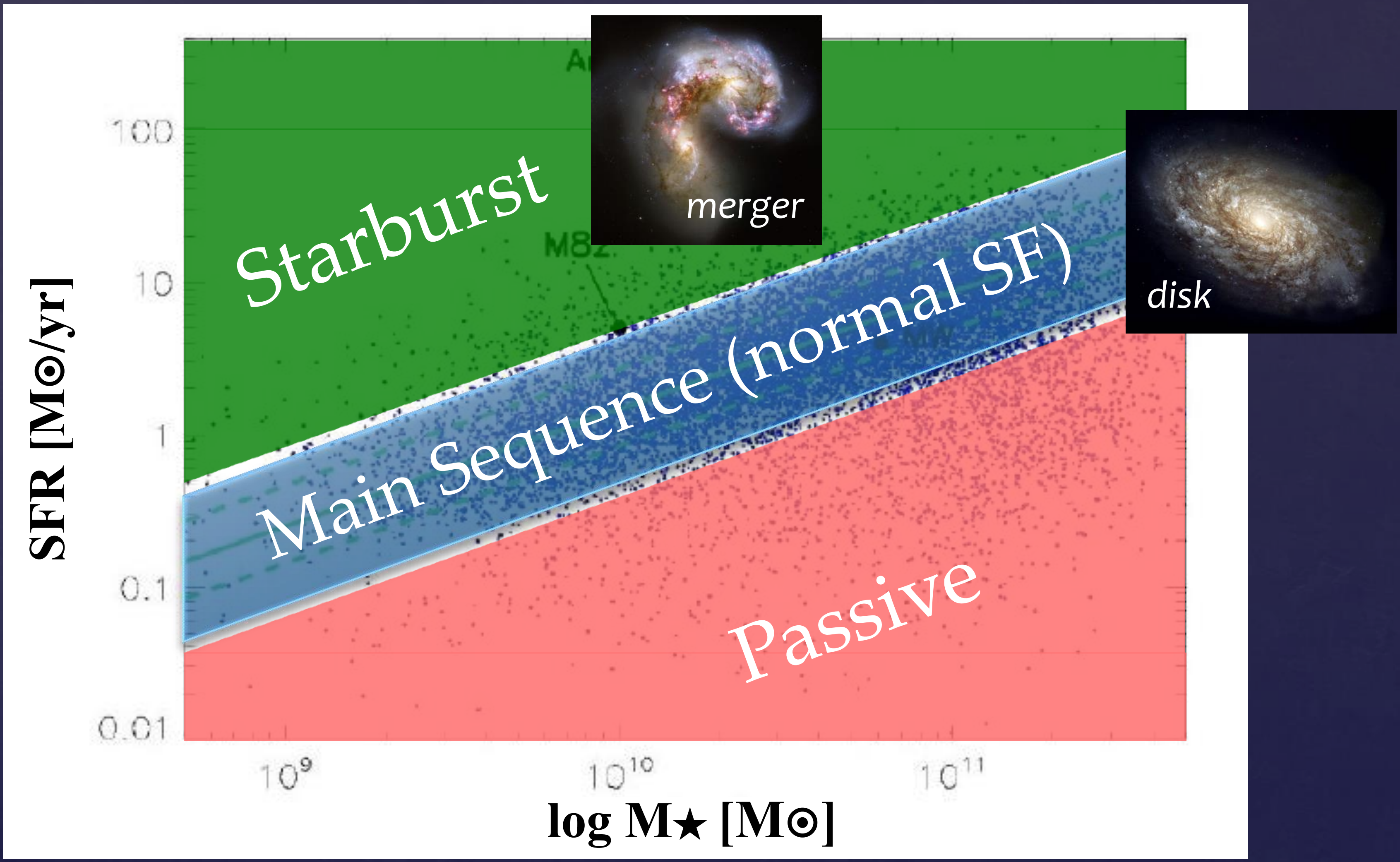
遠方銀河を一つのソース(点源)と捉え、その性質を探る。

2. ミクロな視点

遠方銀河を空間的に分解し、銀河内部の物理状態を探る。

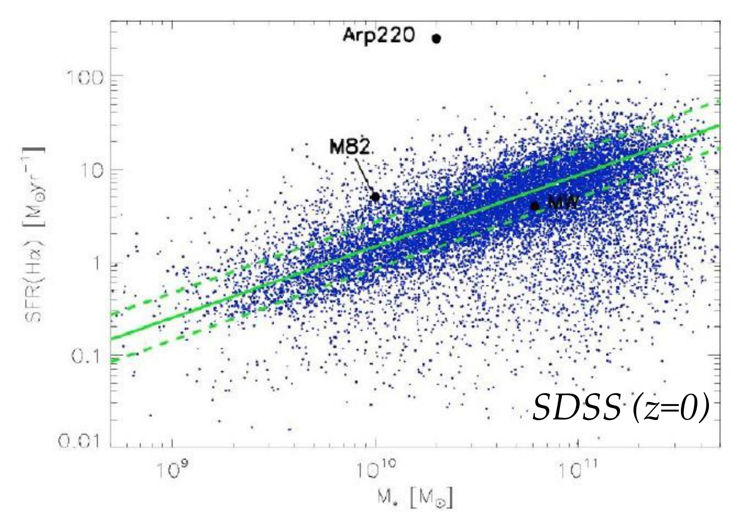
Star Formation “Main Sequence”

= SFR-$M_\star$ relation for star-forming galaxies



Elbaz et al. (2007)

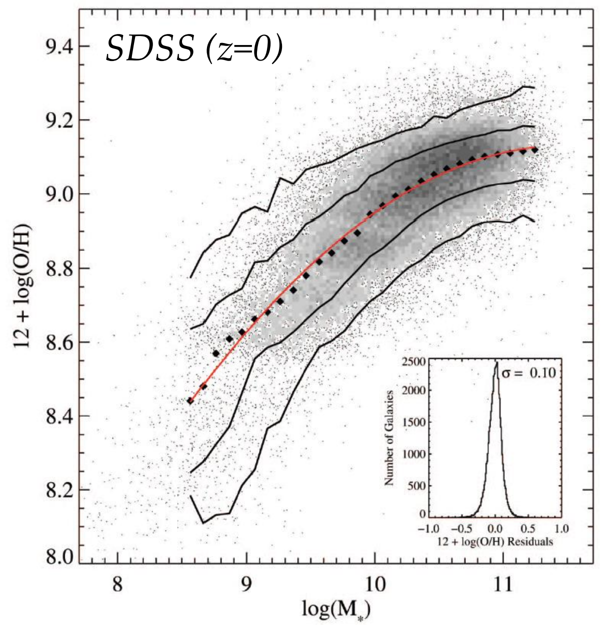
Stellar mass is the king?



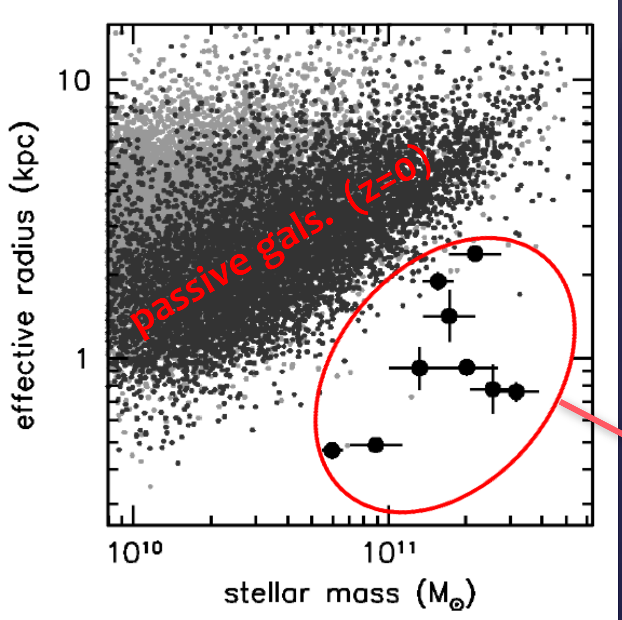
SFR-M* relation

Elbaz et al. (2007)

Mass-metallicity relation



Tremonti et al. (2004)

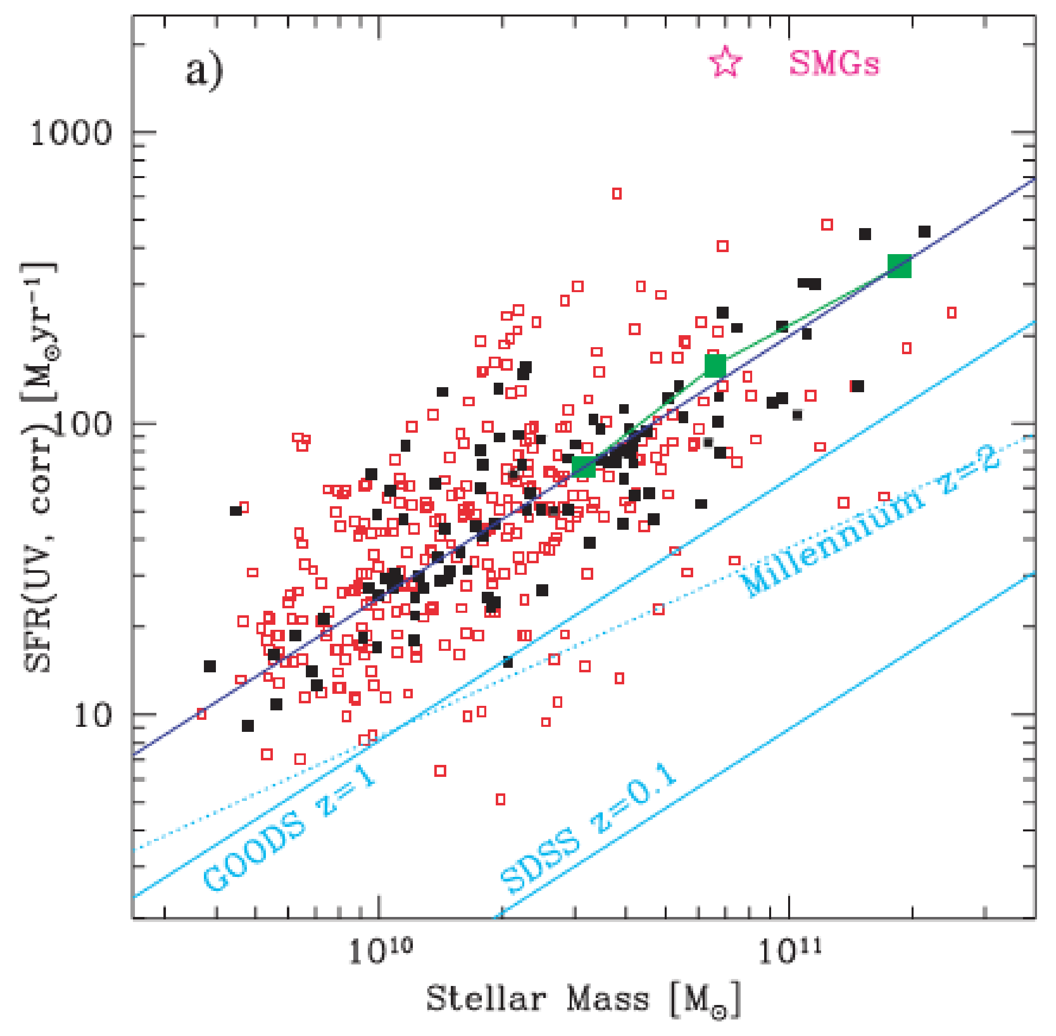


High-z compact
passive galaxies

Mass-size relation

van Dokkum et al. (2008)

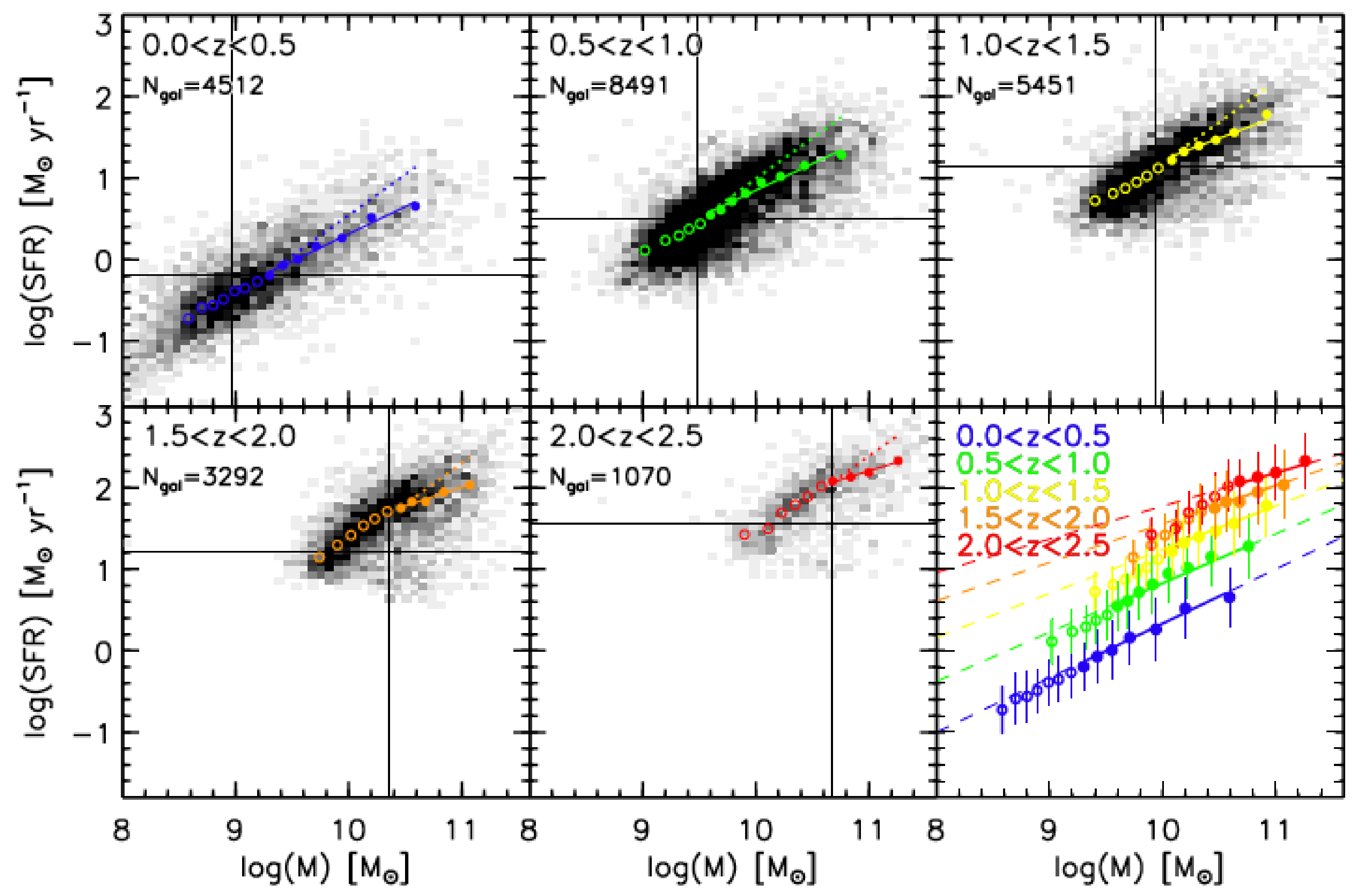
SF main sequence out to z>2



Daddi et al. (2007)

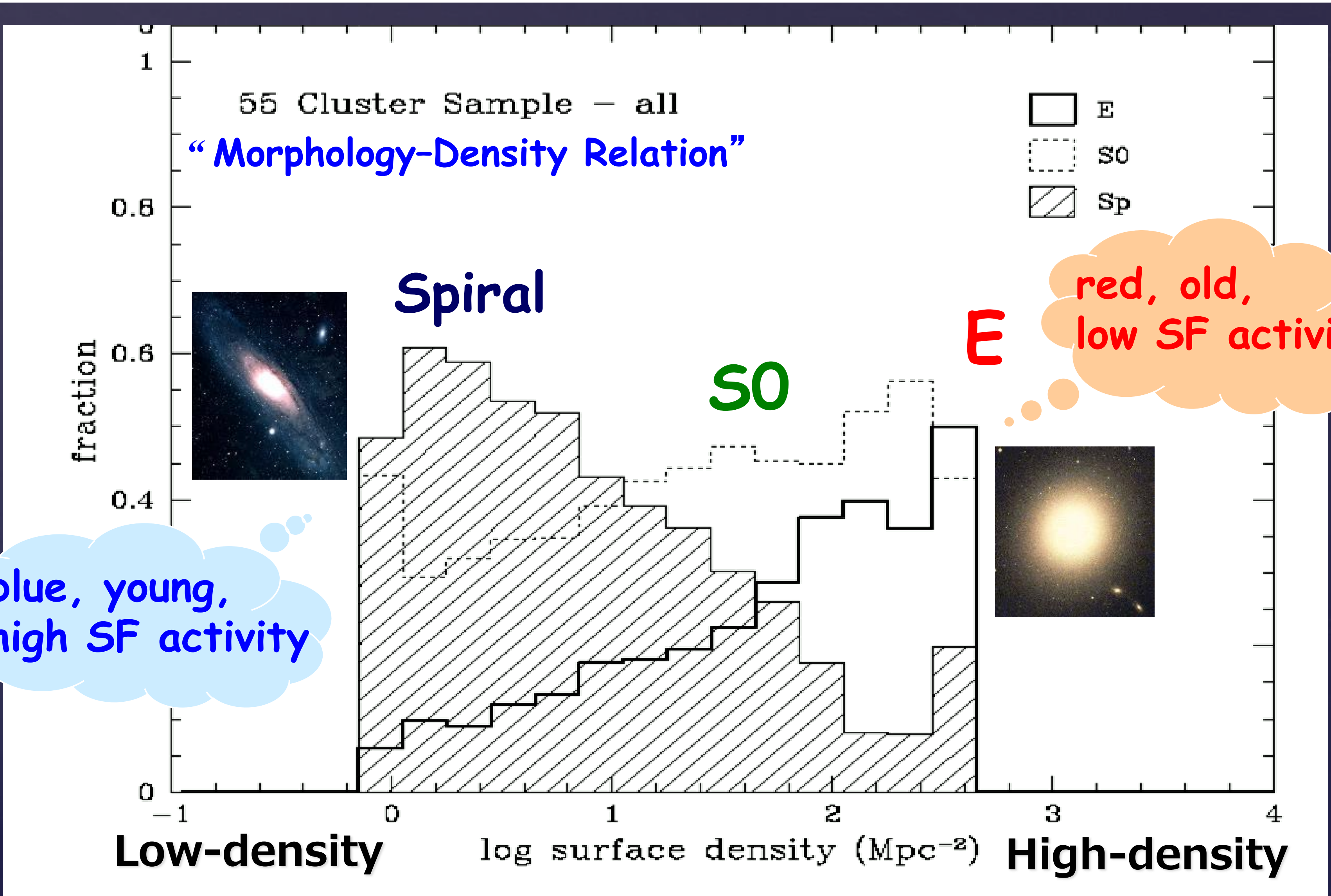
- ✓ MS exists at z~2
- ✓ SFR ∝ $M_\star^{0.9}$
- ✓ scatter always small (~ 0.3 dex)
- ✓ "starbursts" are rare (e.g. SMGs)
- ✓ ULIRGs are not necessarily "starbursts" at z~2.

SF main sequence out to z>2



From NEWFIRM medium-band survey (Whitaker et al. 2012)

Galaxy evolution & environment



"Morphology-Density Relation"

blue, young,
high SF activity

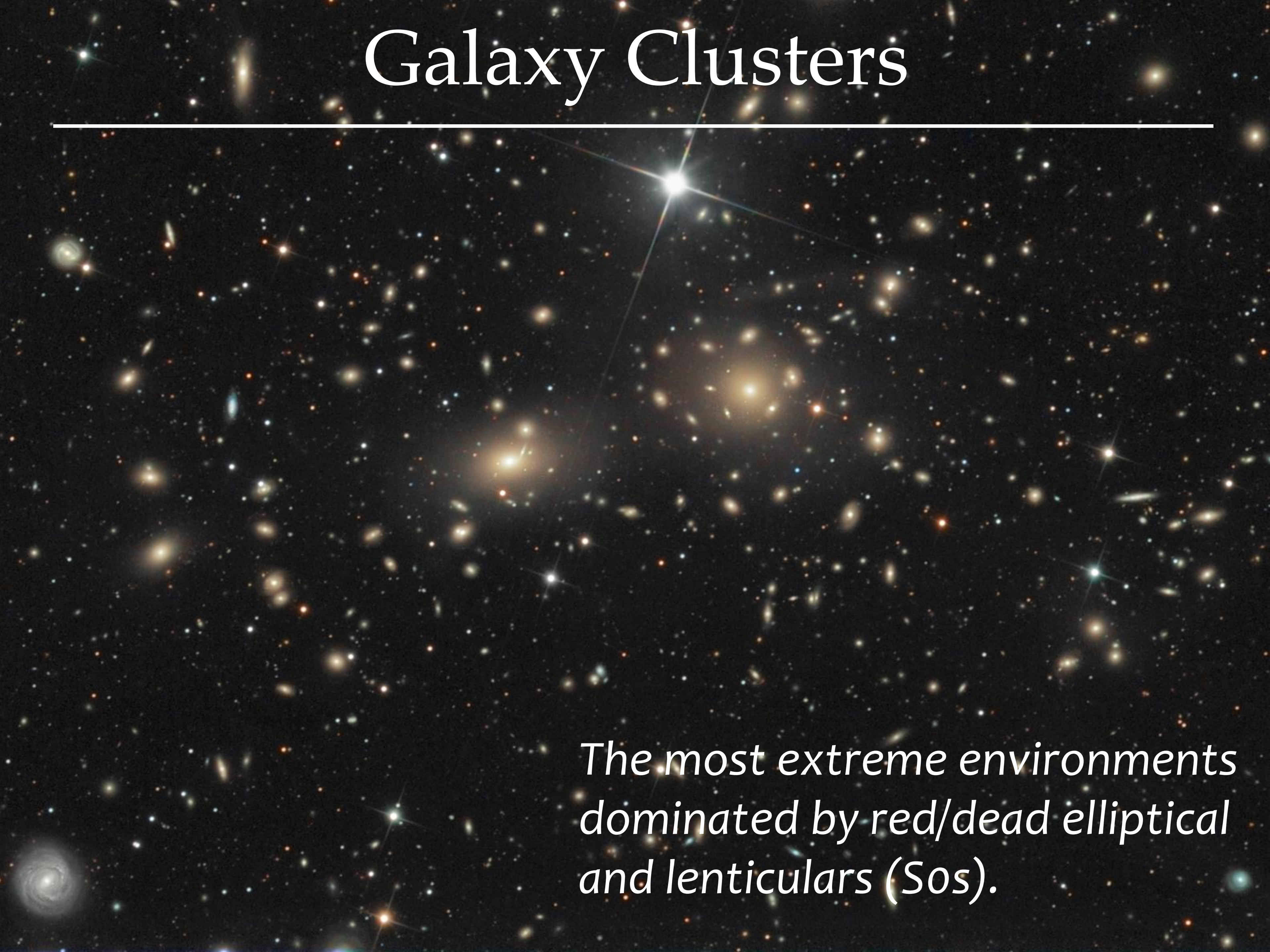
red, old,
low SF activity

Low-density

High-density

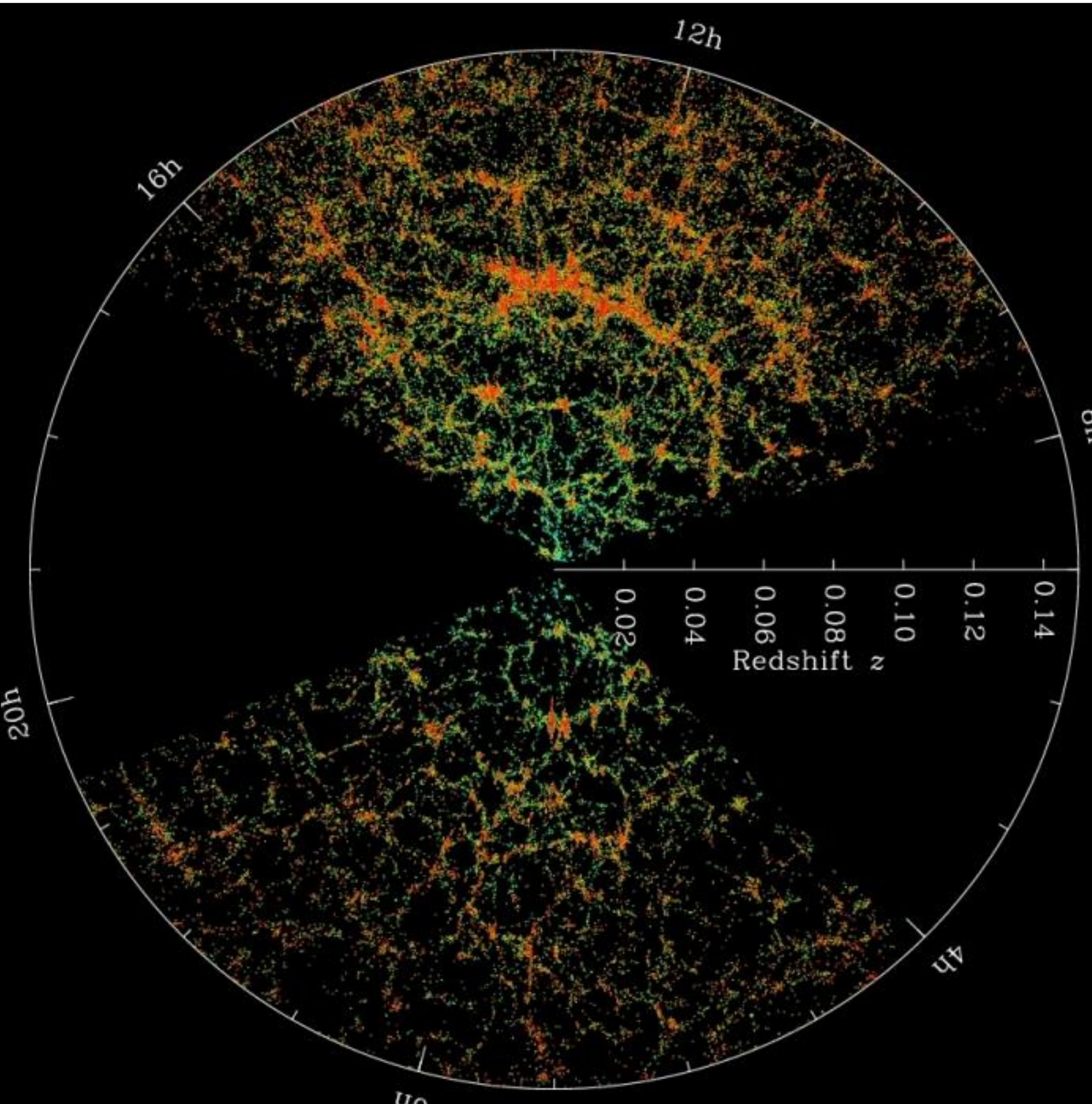
(Dressler 1980)

Galaxy Clusters



The most extreme environments dominated by red/dead elliptical and lenticulars (S0s).

Large-scale structure (*z=0*)



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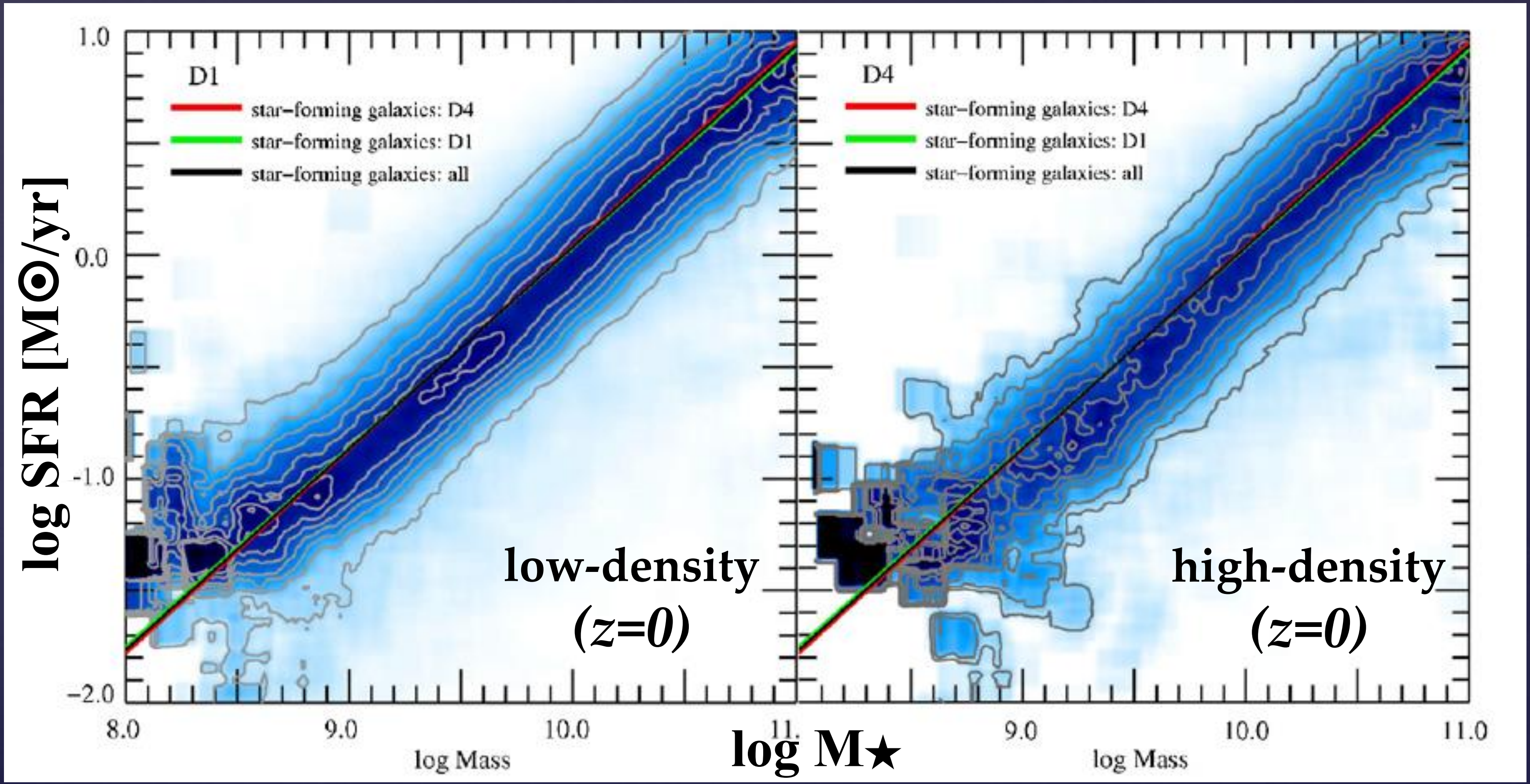
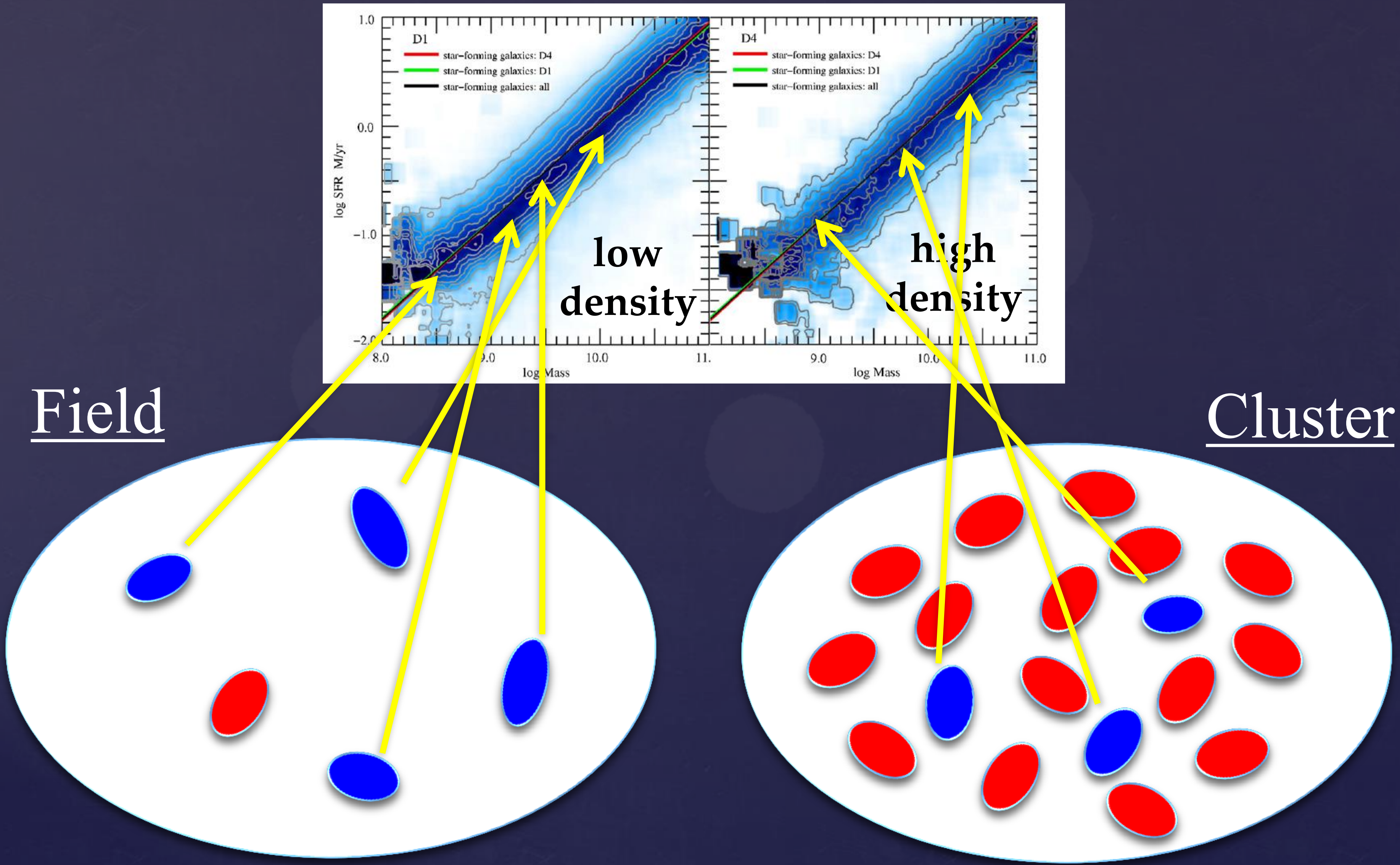
Main sequence vs. environment

SF main sequence is “independent” of environment at z=0



Local star-forming galaxies from SDSS (Peng et al. 2010)

Any trick… ?


D1
star–forming galaxies: D4
star–forming galaxies: D1
star–forming galaxies: all
log SFR M/yr
1.0
0.0
−1.0
−2.0
8.0
9.0
10.0
11.
log Mass
low density
D4
star–forming galaxies: D4
star–forming galaxies: D1
star–forming galaxies: all
9.0
10.0
11.0
log Mass
high density
Field
Cluster

Q: How about in distant universe?

Two big challenges

(1) Distant clusters (z>>1) are very rare.

→ The number of known (proto-)clusters is now increasing.

Galaxy clusters at z>1.5

Spec-z confirmed & X-ray detected clusters only

(candidates are much more)

image by Hilton et al. (2009)

CL J1449+0856	z=2.00	Gobat et al. (2011; 2013)
JKCS 041	z=1.80	Newman et al. (2013)
IDCS J1426.5+3508	z=1.75	Stanford et al. (2012)
XMMU J105324+572348	z=1.75	Henry et al. (2010)
SpARCS J022427-032354	z=1.63	Muzzin et al. (2013)
ClG J0218.3-0510	z=1.62	Tanaka et al. (2010), Papovich et al. (2010)
CL J033211.67 274633.8	z=1.61	Tanaka et al. (2013)
XMMU J0044.0-2033	z=1.58	Santos et al. (2011)
XMM J1007+1237	z=1.56	Fassbender et al. (2011)
XMMU J0338.8+0021	z=1.49	Nastasi et al. (2011)
XMMXCS J2215.9-1738	z=1.46	discovery by Stanford et al. (2006)

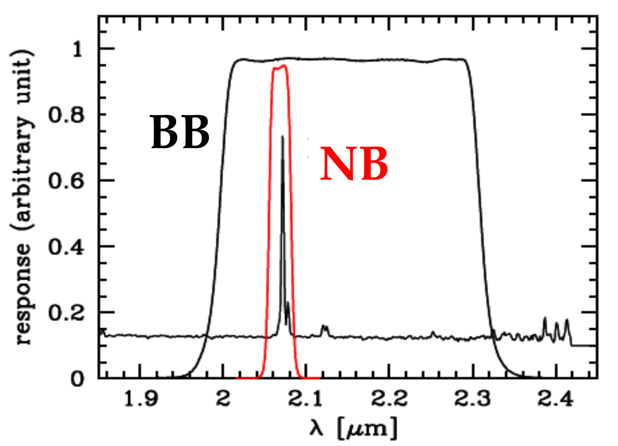
Two big challenges

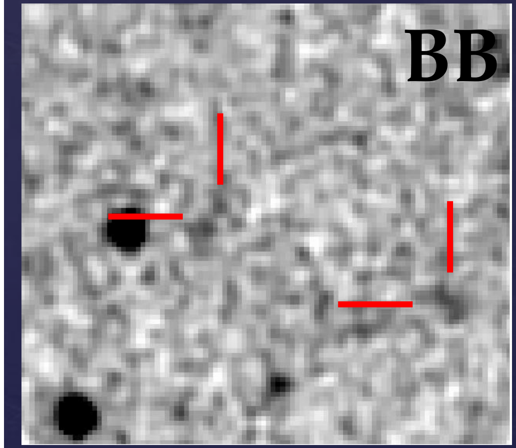
(1) Distant clusters (z>>1) are very rare.

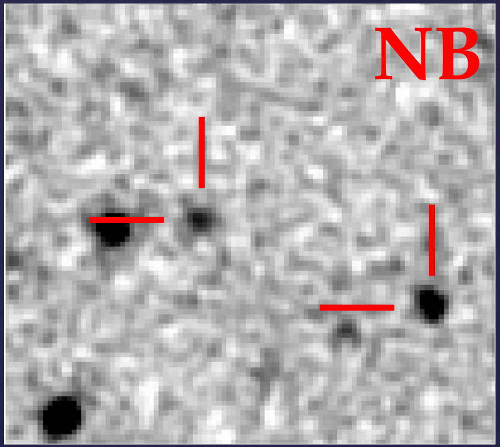
→ The number of known (proto-)clusters is now increasing.

(2) Large uniform sample of SF galaxies required.

→ NB emission-line survey is an ideal solution !







MAHALO-Subaru project

Collaborator: T. Kodama (PI), M. Hayashi, K. Tadaki, I. Tanaka, R. Shimakawa, T. Suzuki, M. Yamamoto

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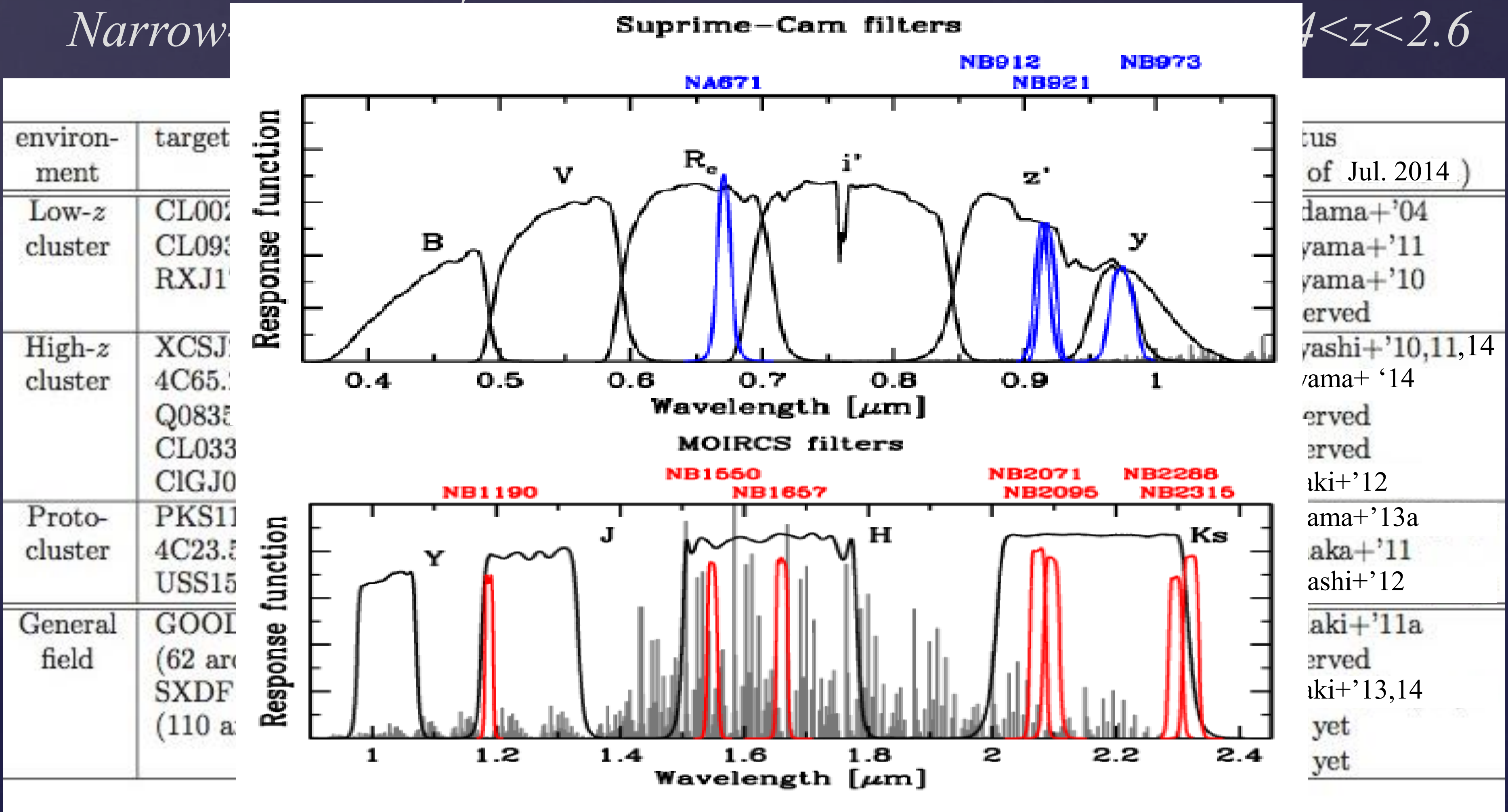
MApping H-Alpha and Lines of Oxygen with Subaru

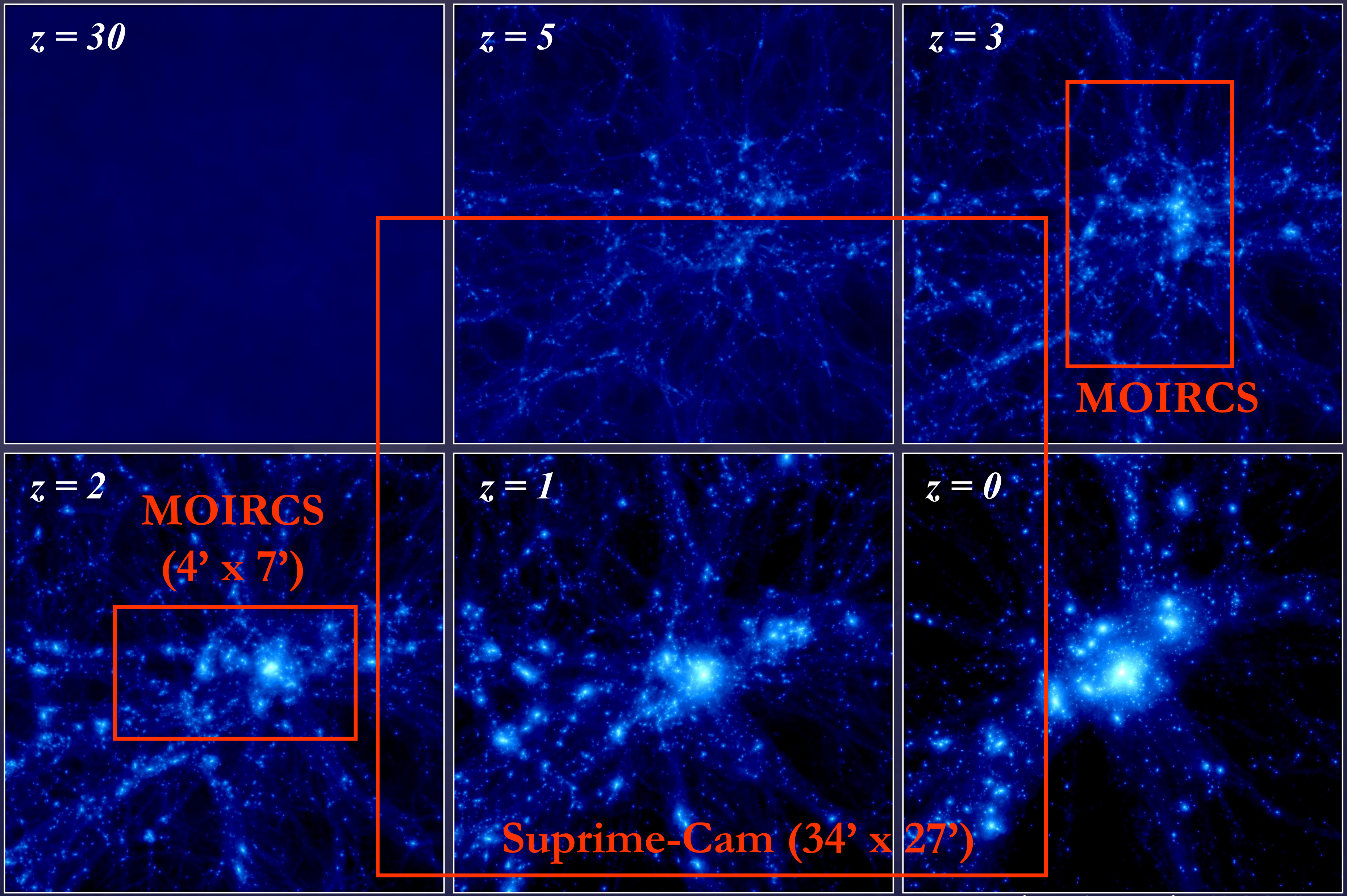
Narrow-

$4<z<2.6$



environ-ment	target	tus of Jul. 2014)
Low-z cluster	CL002 CL093 RXJ1	dama+'04 yama+'11 yama+'10 erved
High-z cluster	XCSJ 4C65. Q0835 CL033 ClGJ0	yashi+'10,11,14 yama+ '14 erved erved aki+'12
Proto-cluster	PKS11 4C23.5 USS15	ama+'13a aka+'11 ashi+'12
General field	GOOI (62 ar SXDF (110 a	aki+'11a erved aki+'13,14 yet yet

Big advantage of Subaru

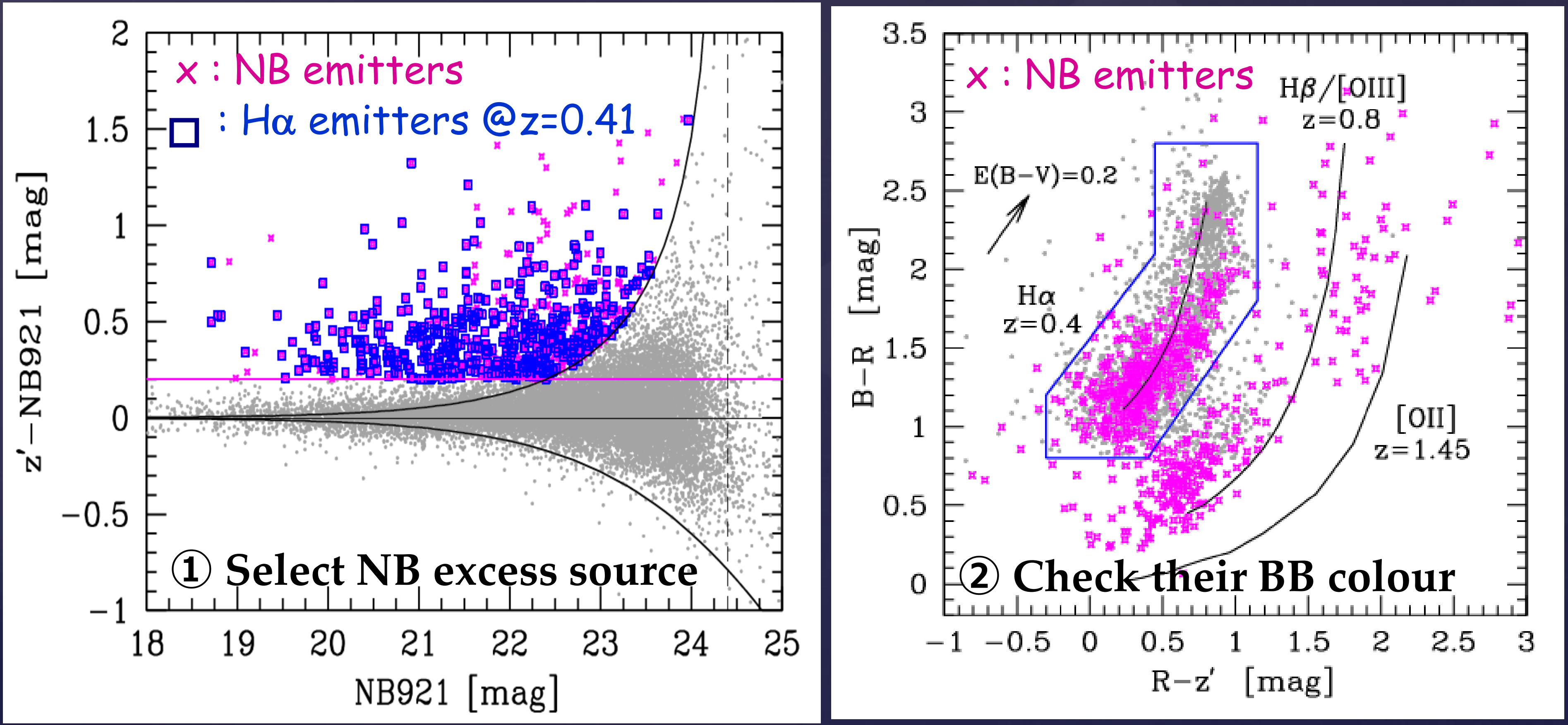


M=6×10^{14} Msun, 20Mpc×20Mpc (co-moving)

Yahagi et al. (2005)

NB survey: powerfulness & Recipe

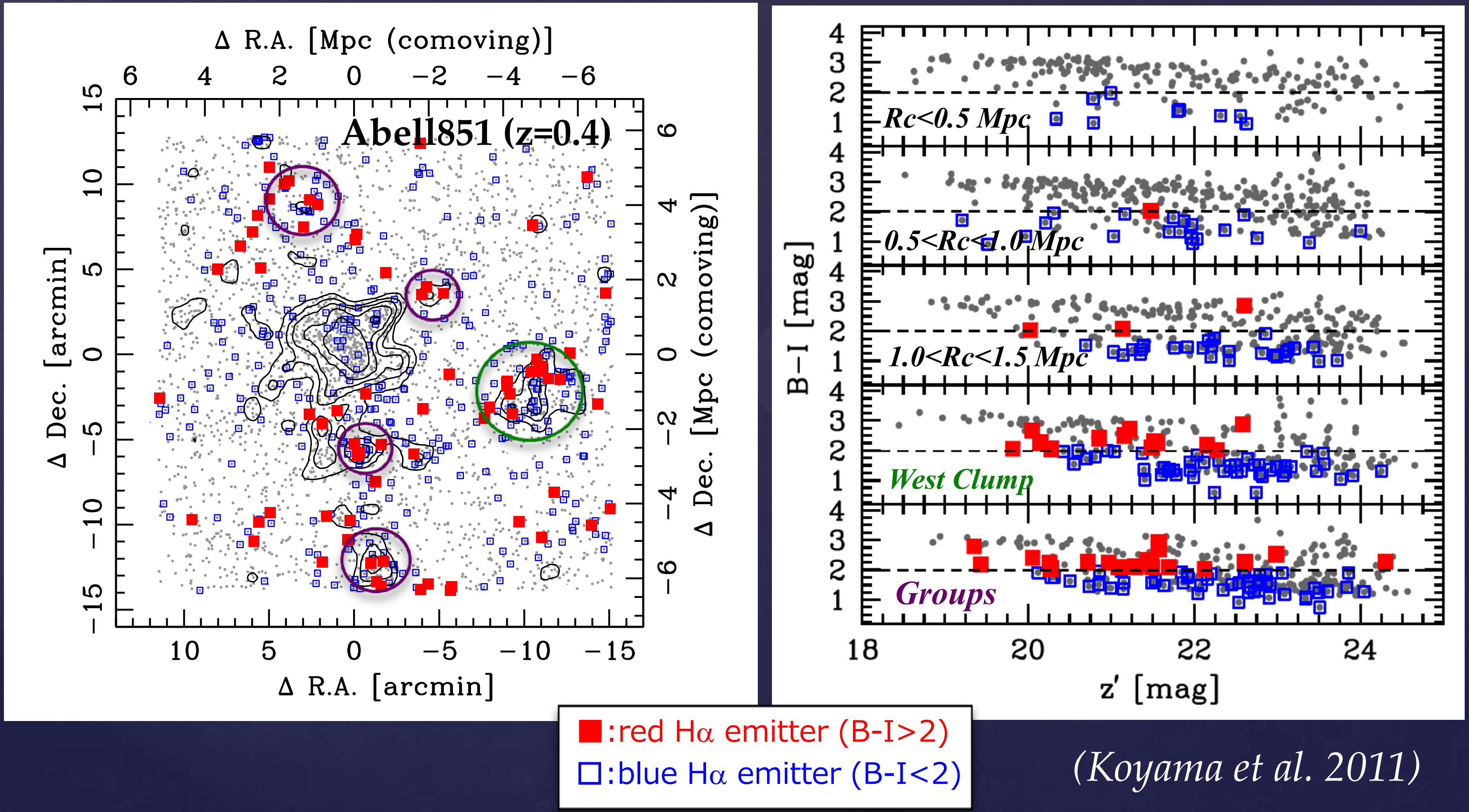
- ✓ Easy selection of (star-forming) cluster members
- ✓ Measure line fluxes (SFR) for “all” galaxies within FoV



An example: z=0.4 Hα emitter survey by Koyama et al. (2011)

Some MAHALO Highlights

Red Hα emitters strongly clustered in group-scale environments

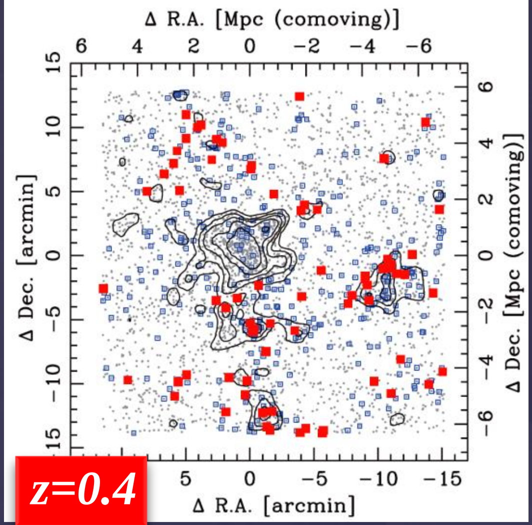


🟥:red Hα emitter (B-I>2)

☐:blue Hα emitter (B-I<2)

(Koyama et al. 2011)

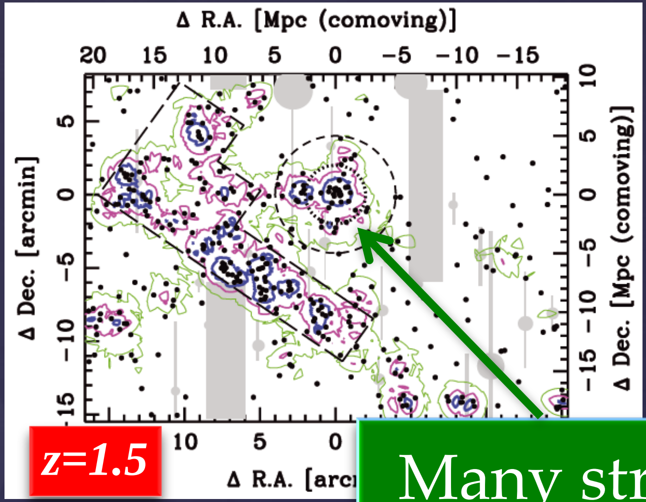
High-z structures revealed by MAHALO



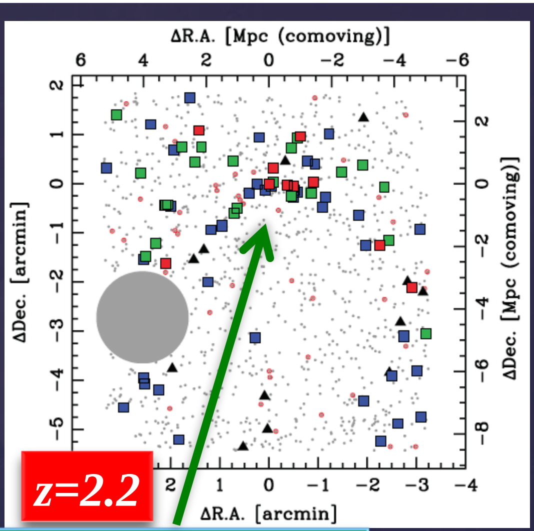
z=0.4

(Koyama+11)

(Hayashi+10, 11)

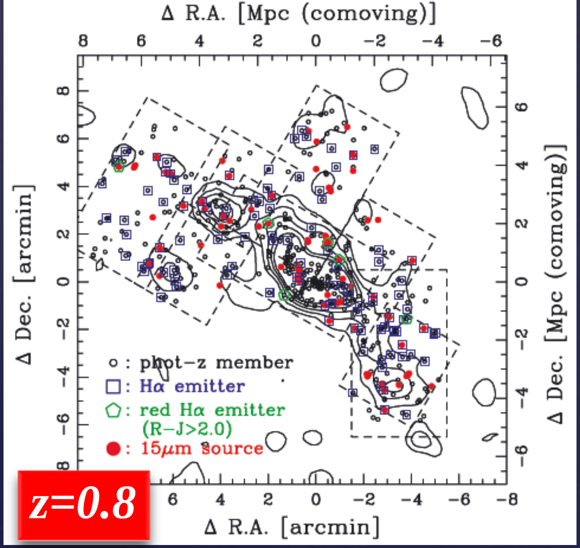


z=1.5



z=2.2

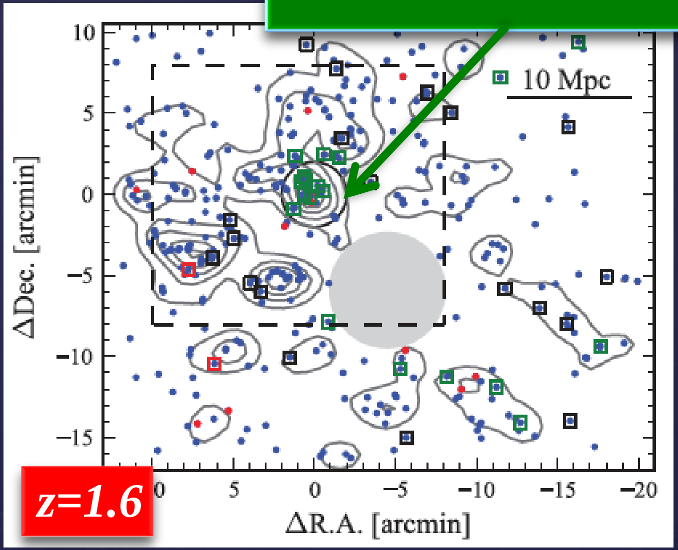
Many strong emitters in z>1.5 cluster cores



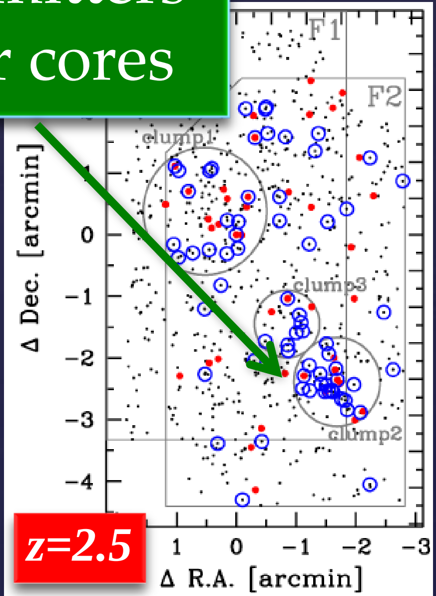
z=0.8

(Koyama+10)

(Ta



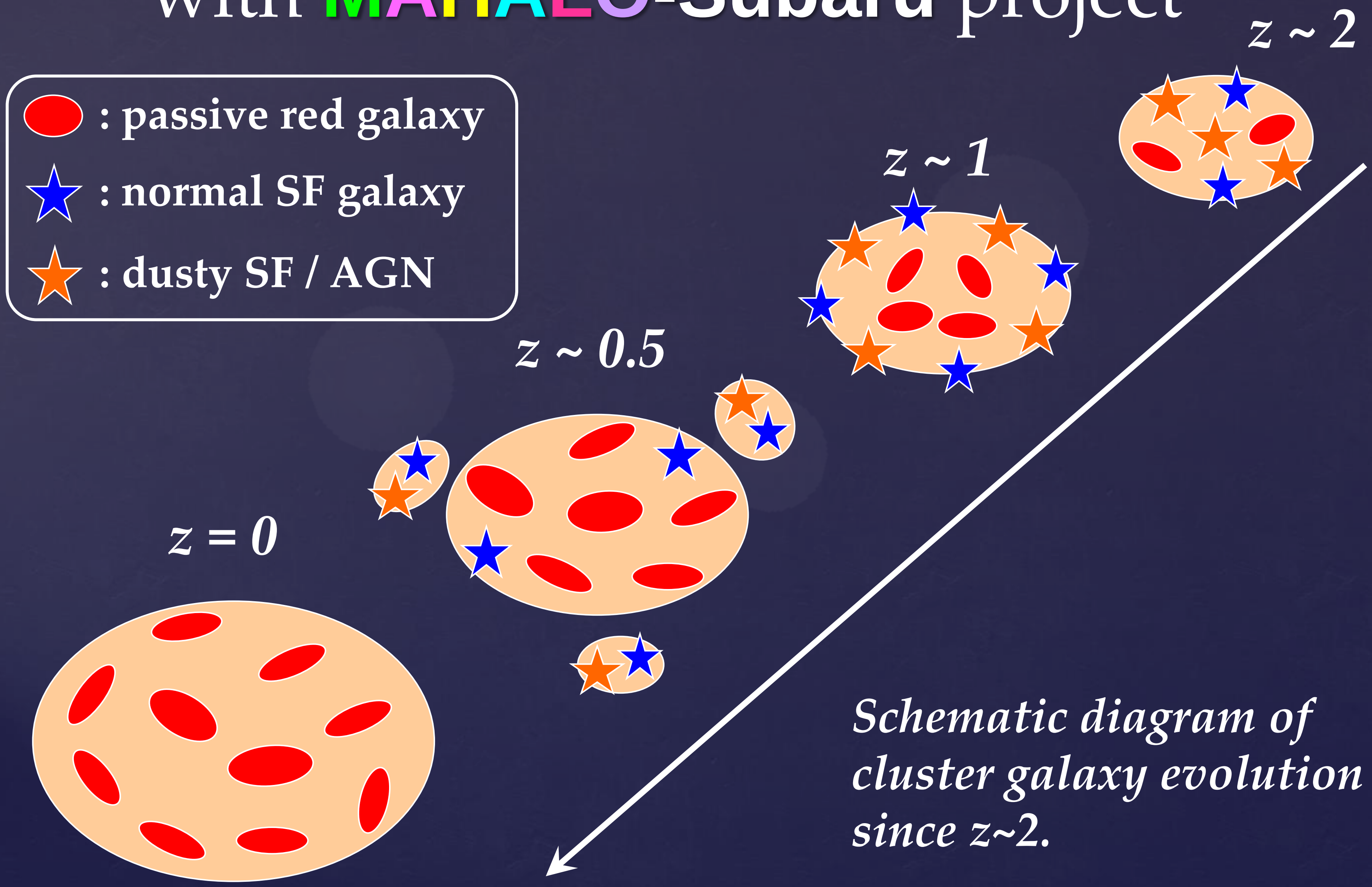
z=1.6



z=2.5

(Hayashi+12)

Cluster galaxy evolution revealed with **MAHALO-Subaru** project



● : passive red galaxy

★ : normal SF galaxy

★ : dusty SF / AGN

z ~ 2

z ~ 1

z ~ 0.5

z = 0

Schematic diagram of cluster galaxy evolution since z~2.

HiZELS: *High-Z Emission-Line Survey*

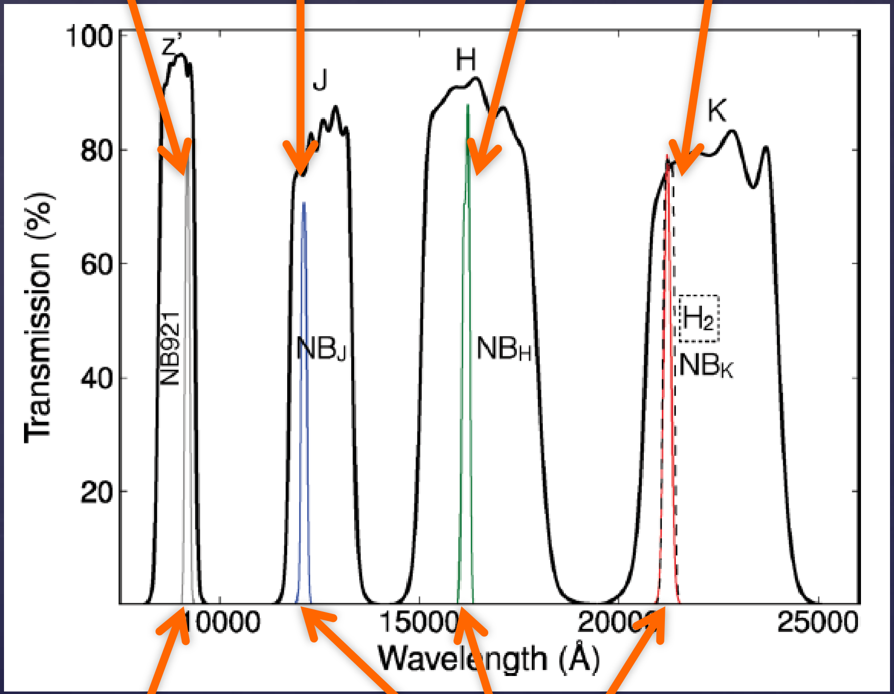
Collaborator: I. Smail (Durham), D. Sobral (Lisbon), J. Geach (Herts), M. Swinbank (Durham), P. Best (Edinburgh)

Hα @ z=0.4

Hα @ z=0.8

Hα @ z=1.5

Hα @ z=2.2

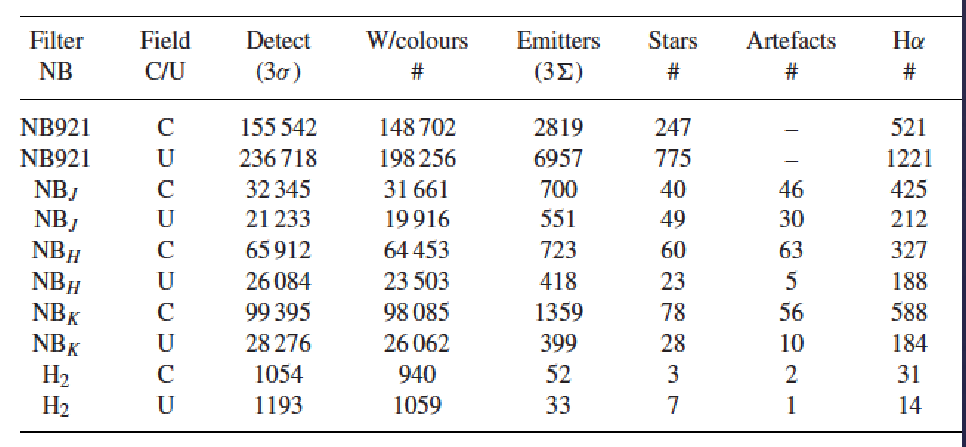


Subaru filter

UKIRT filter

Total ~2 deg² survey in COSMOS & UDS

 # now further extending the survey area.



Filter NB	Field C/U	Detect (3σ)	W/colours #	Emitters (3Σ)	Stars #	Artefacts #	Hα #
NB921	C	155 542	148 702	2819	247	–	521
NB921	U	236 718	198 256	6957	775	–	1221
NB_J	C	32 345	31 661	700	40	46	425
NB_J	U	21 233	19 916	551	49	30	212
NB_H	C	65 912	64 453	723	60	63	327
NB_H	U	26 084	23 503	418	23	5	188
NB_K	C	99 395	98 085	1359	78	56	588
NB_K	U	28 276	26 062	399	28	10	184
H_2	C	1054	940	52	3	2	31
H_2	U	1193	1059	33	7	1	14

~500-2000 Ha emitters at each redshift, providing excellent comparison sample for our MAHALO cluster samples.

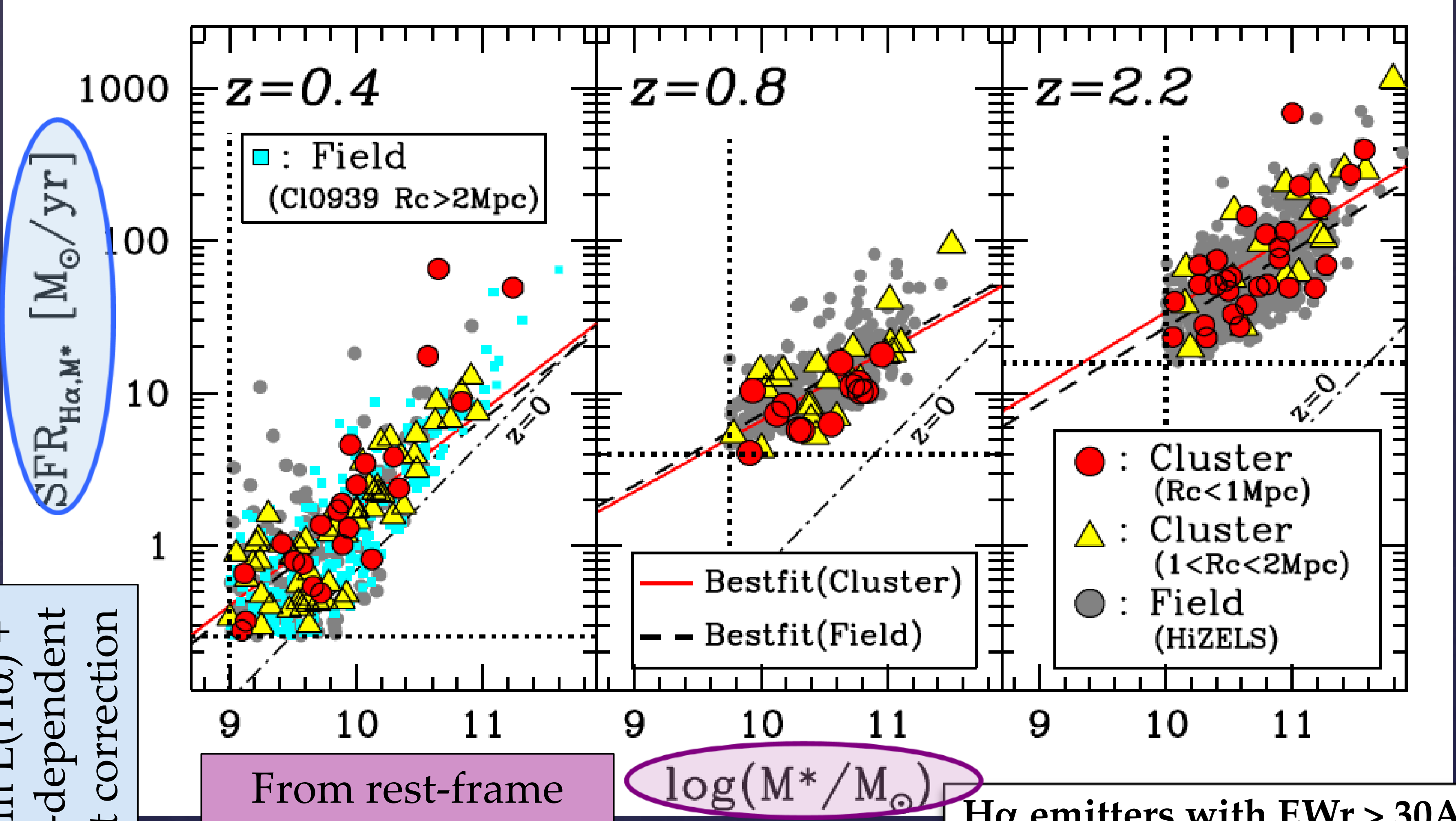
Sobral et al. (2013)

Durham (U.K.)

2011~2013 (JSPS fellow)

Cluster vs. Field comparison out to z~2

The MS location is always independent of environment since z~2 !



From L(Hα) + M★-dependent dust correction

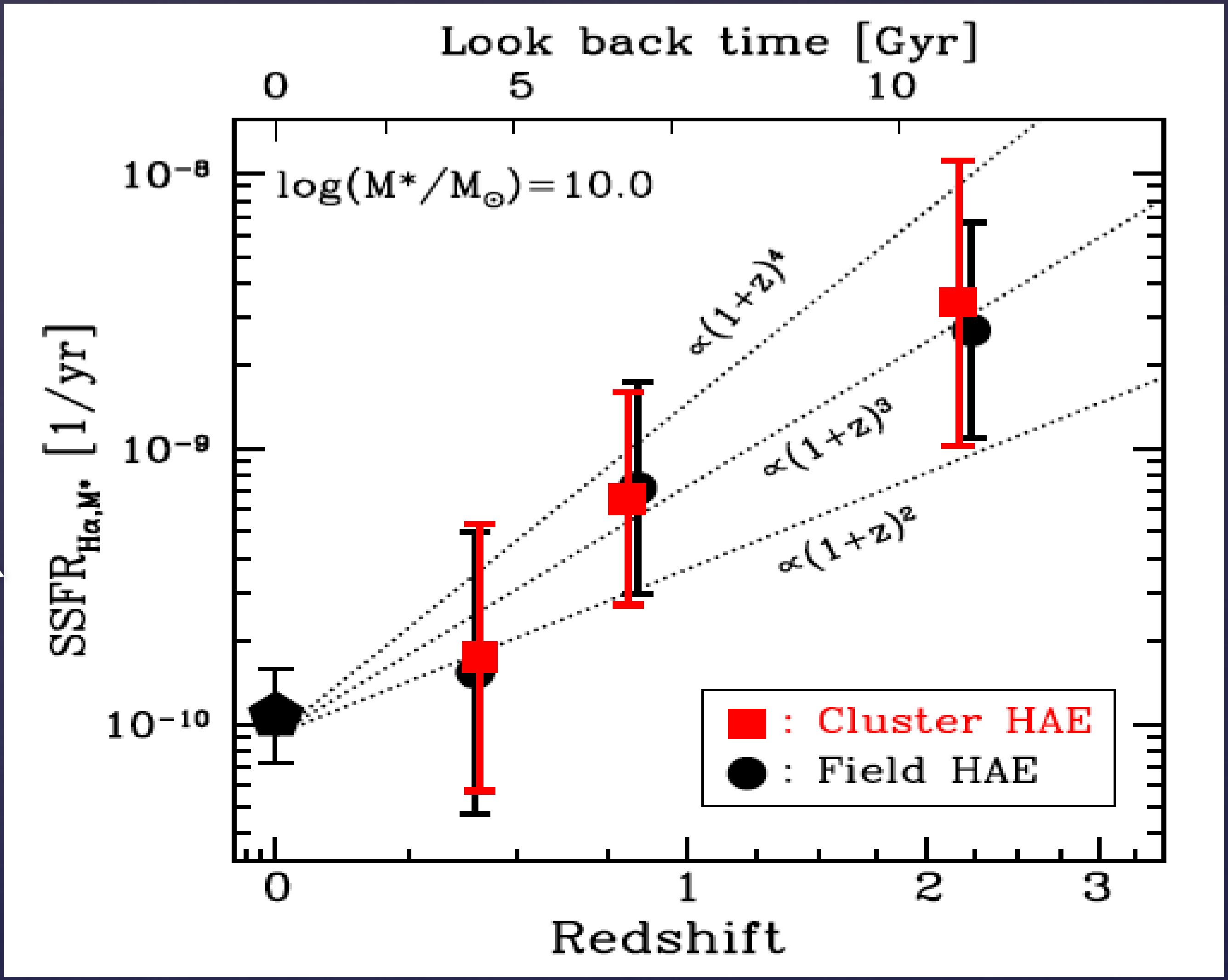
From rest-frame R-band photometry + M/L correction

Hα emitters with EWr > 30A

(Koyama et al. 2013b, MNRAS, 434, 423)

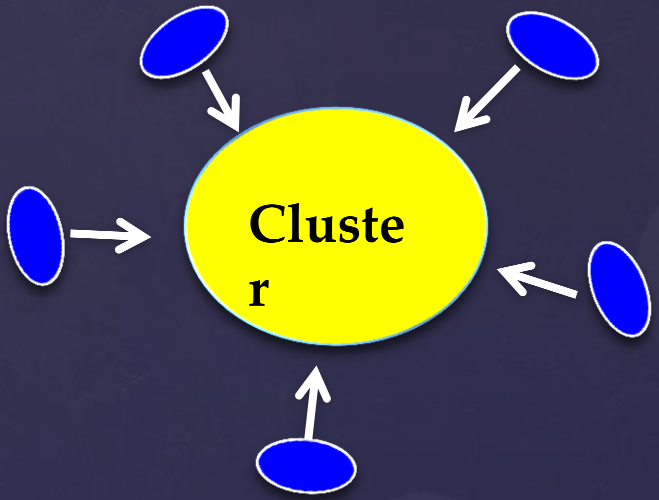
SSFR evolution: following $\propto (1+z)^3$

SSFR = SFR/M★

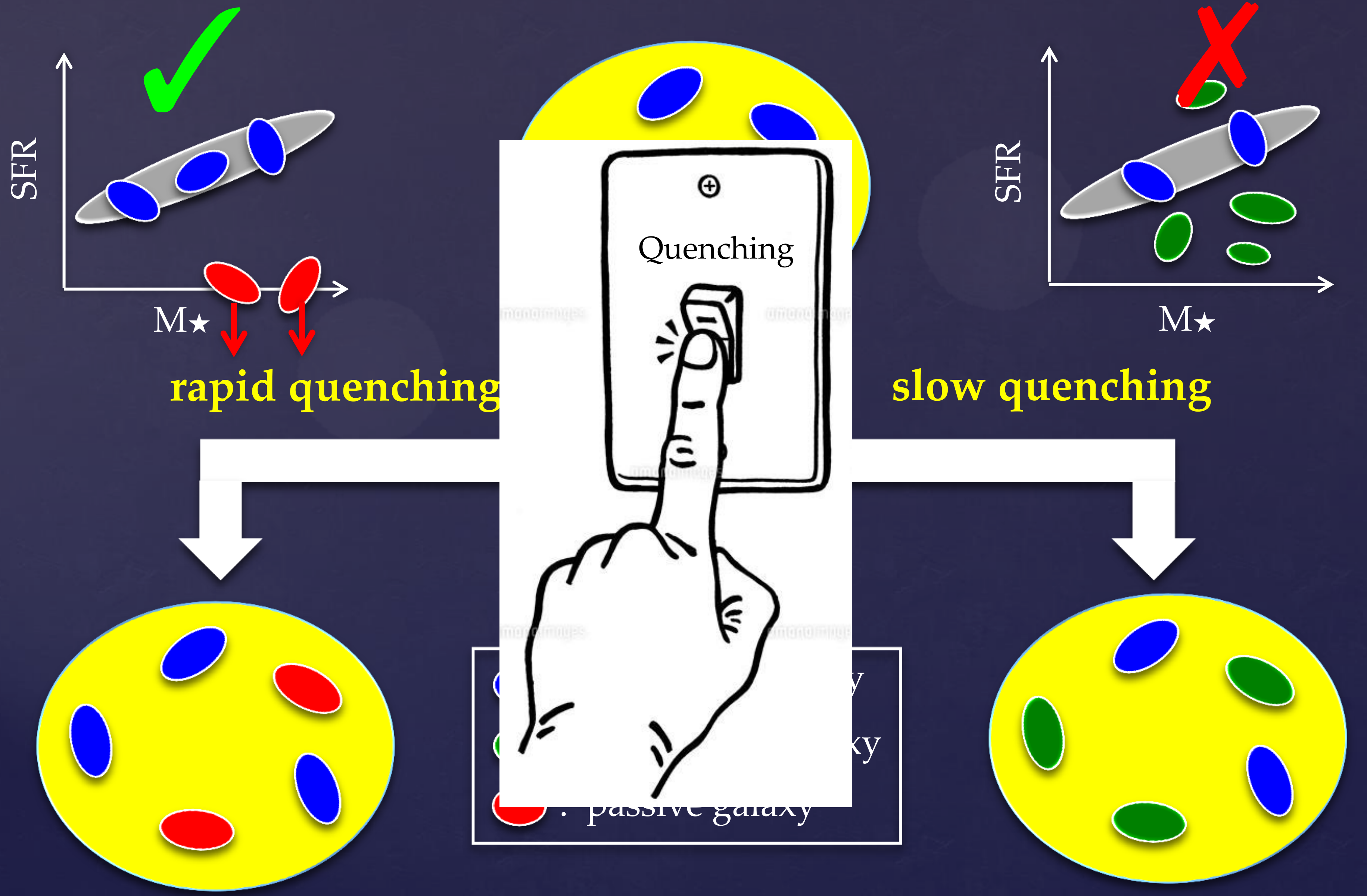


(Koyama et al. 2013b, MNRAS, 434, 423)

Interpretation: rapid SF quenching ?



Interpretation: rapid SF quenching ?



rapid quenching

slow quenching

y

xy

🟥 : passive galaxy

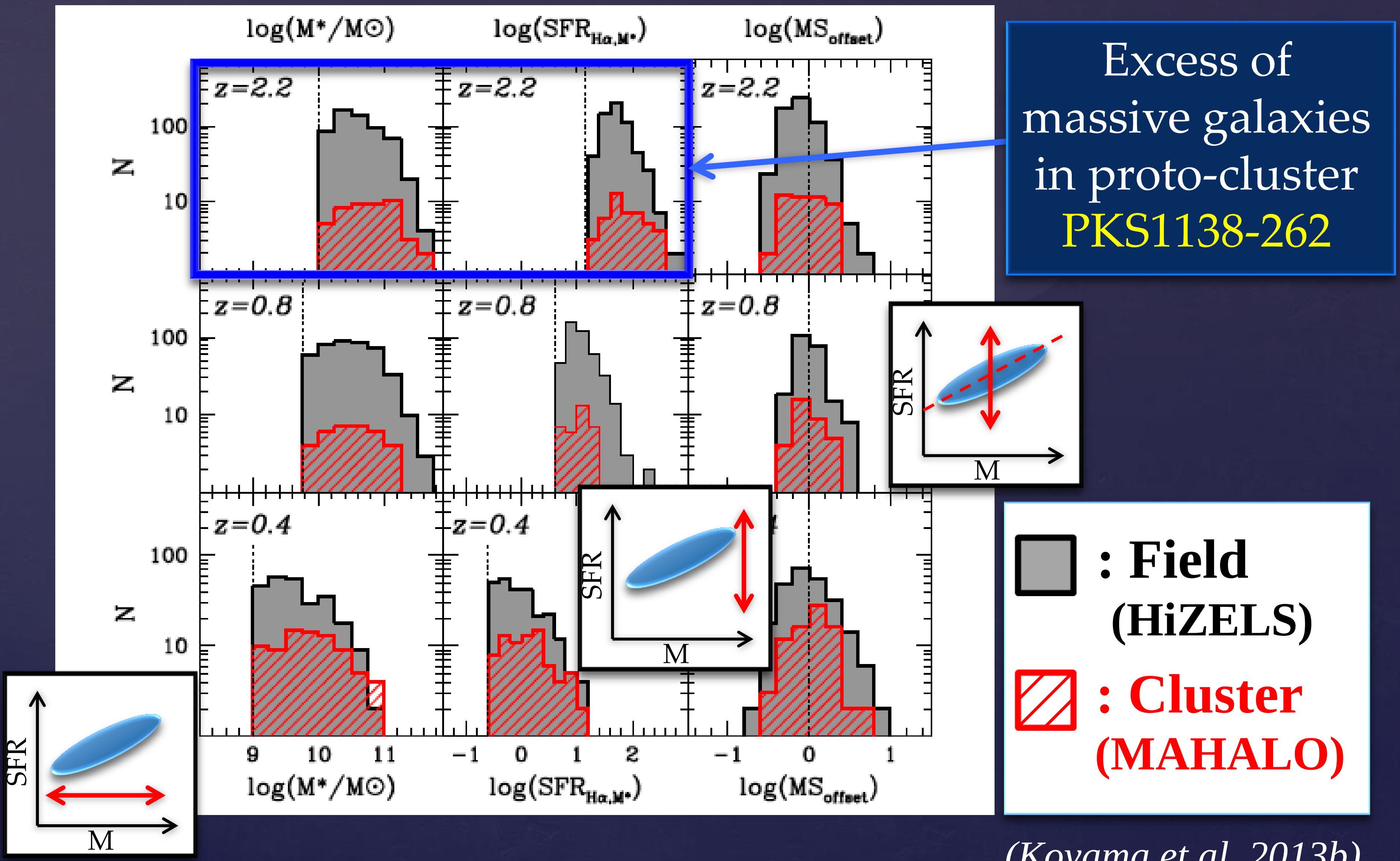
Looking for signs of environmental effects…

(1) Stellar mass

(2) Dust extinction

(3) Metallicity

M★, SFR, ΔMS distribution



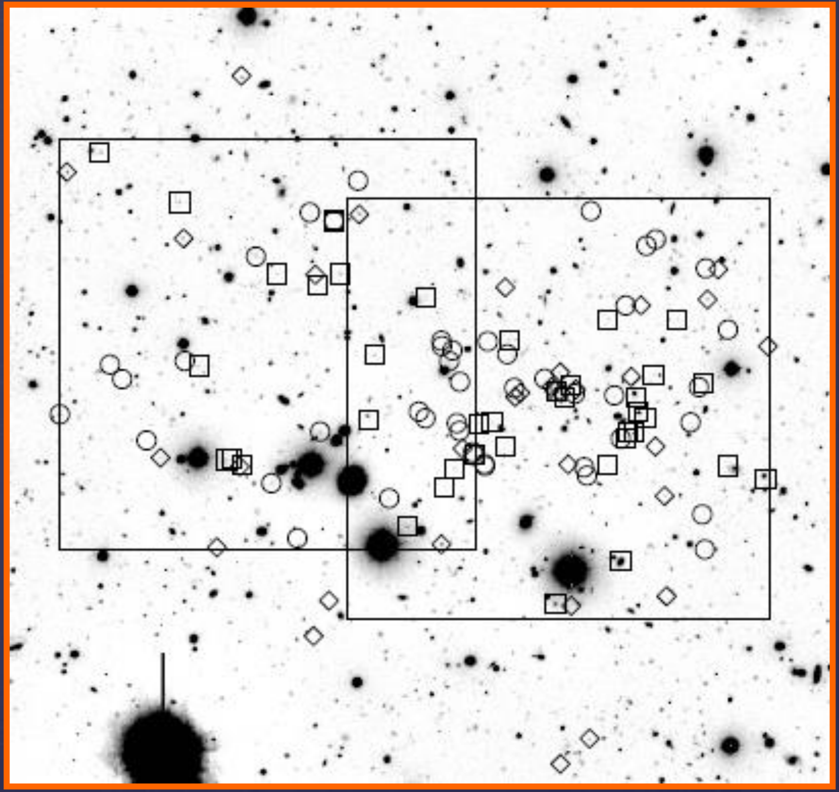
Excess of massive galaxies in proto-cluster PKS1138-262

▨ : Field (HiZELS)

▨ : Cluster (MAHALO)

(Koyama et al. 2013b)

PKS1138-262: a proto-cluster @ z=2.2

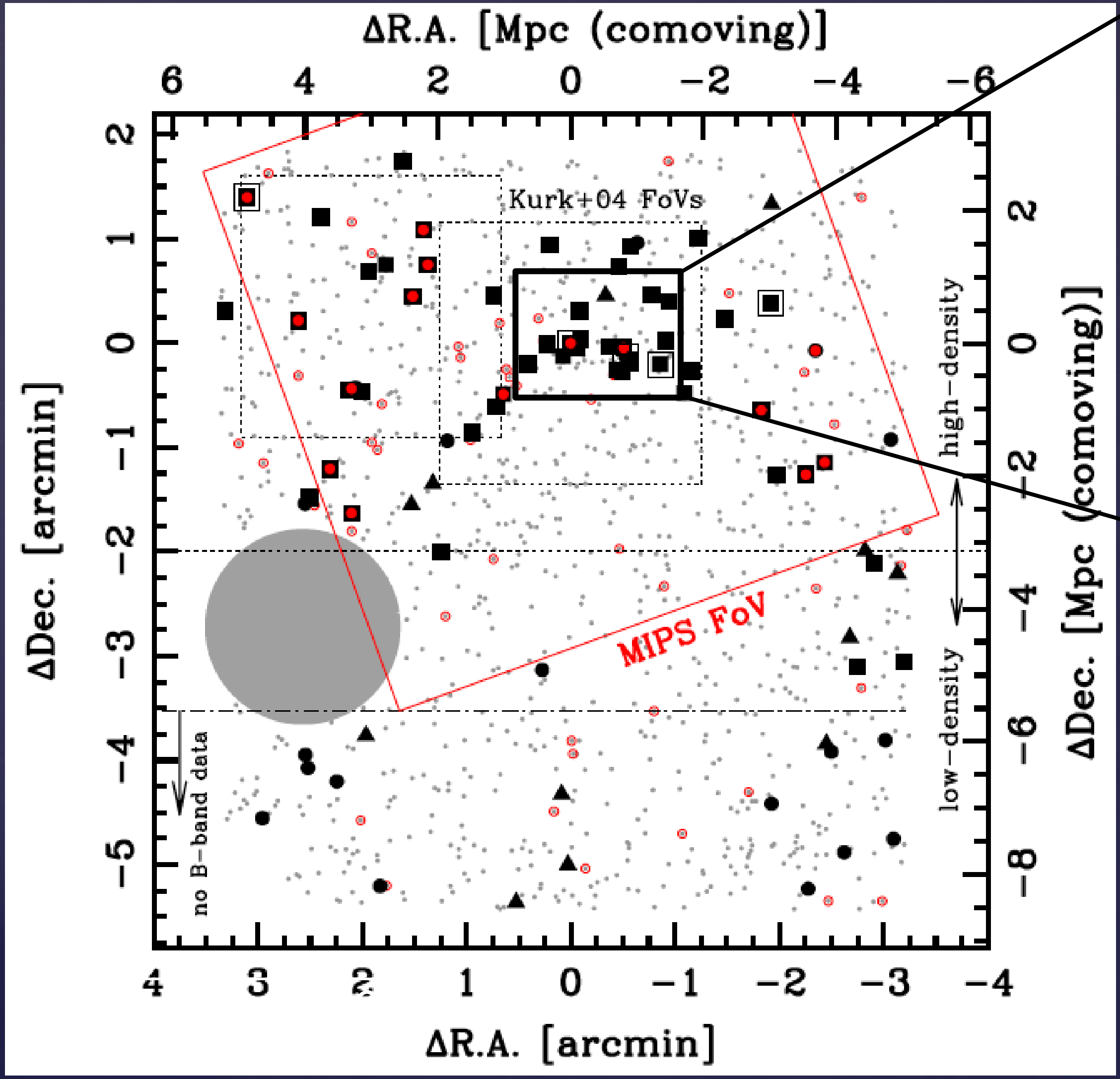


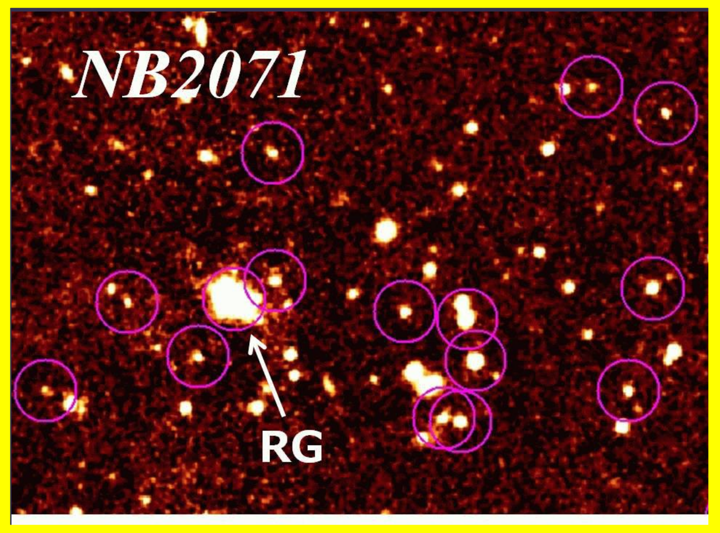
◇: LAE, □: HAE, ○: ERO

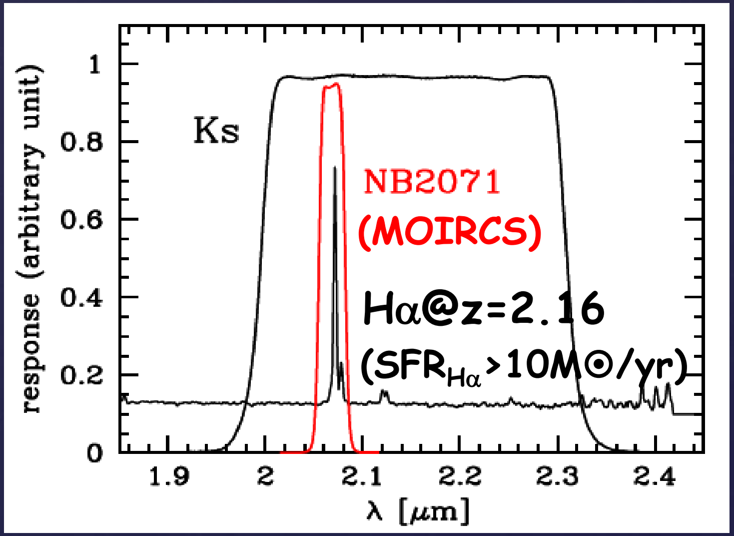
(Kurk et al. 2004)

- A famous over-dense region at z=2.2 (radio galaxy field)
  - first identified as over-density of LAEs *(Kurk et al. 2000)*
- Multi-wavelength follow-up
  - optical/NIR spectroscopy *(e.g. Pentericci+00, Kurk+04, Croft+05, Tanaka+13)*
  - X-ray *(Pentericci et al. 2002)*
  - Hα survey *(Kurk et al. 2004)*
  - DRG *(Kodama et al. 2007)*
  - SED analysis *(Tanaka et al. 2010)*
  - morphology *(Zirm et al. 2008; 2012)*

MOIRCS Hα survey in z=2.2 proto-cluster

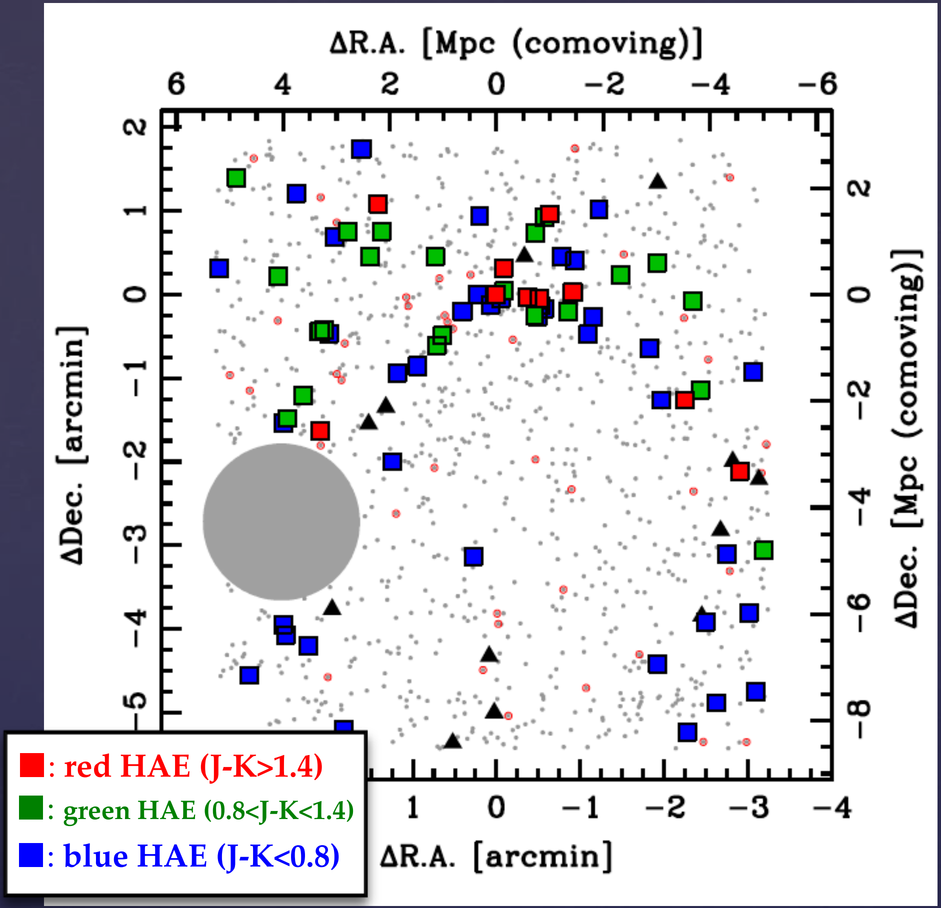




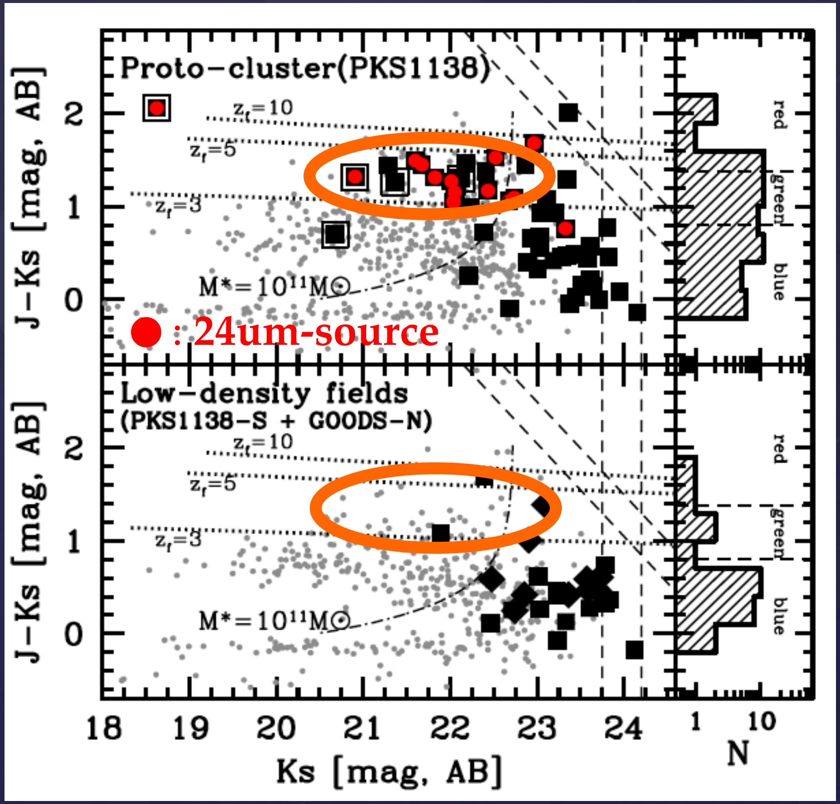


(Koyama et al. 2013a, MNRAS, 428, 1551)

Massive SF galaxies in z>2 proto-cluster



Our MOIRCS+NB(Hα) survey revealed red Hα emitters dominate the core of z=2.16 proto-cluster (PKS1138-262).



Red emitters are massive (M★ >10^{11}M⊙), and clearly dominate dense environment at z~2.

(Koyama et al. 2013a)

Looking for signs of environmental effects…

(1) Stellar mass

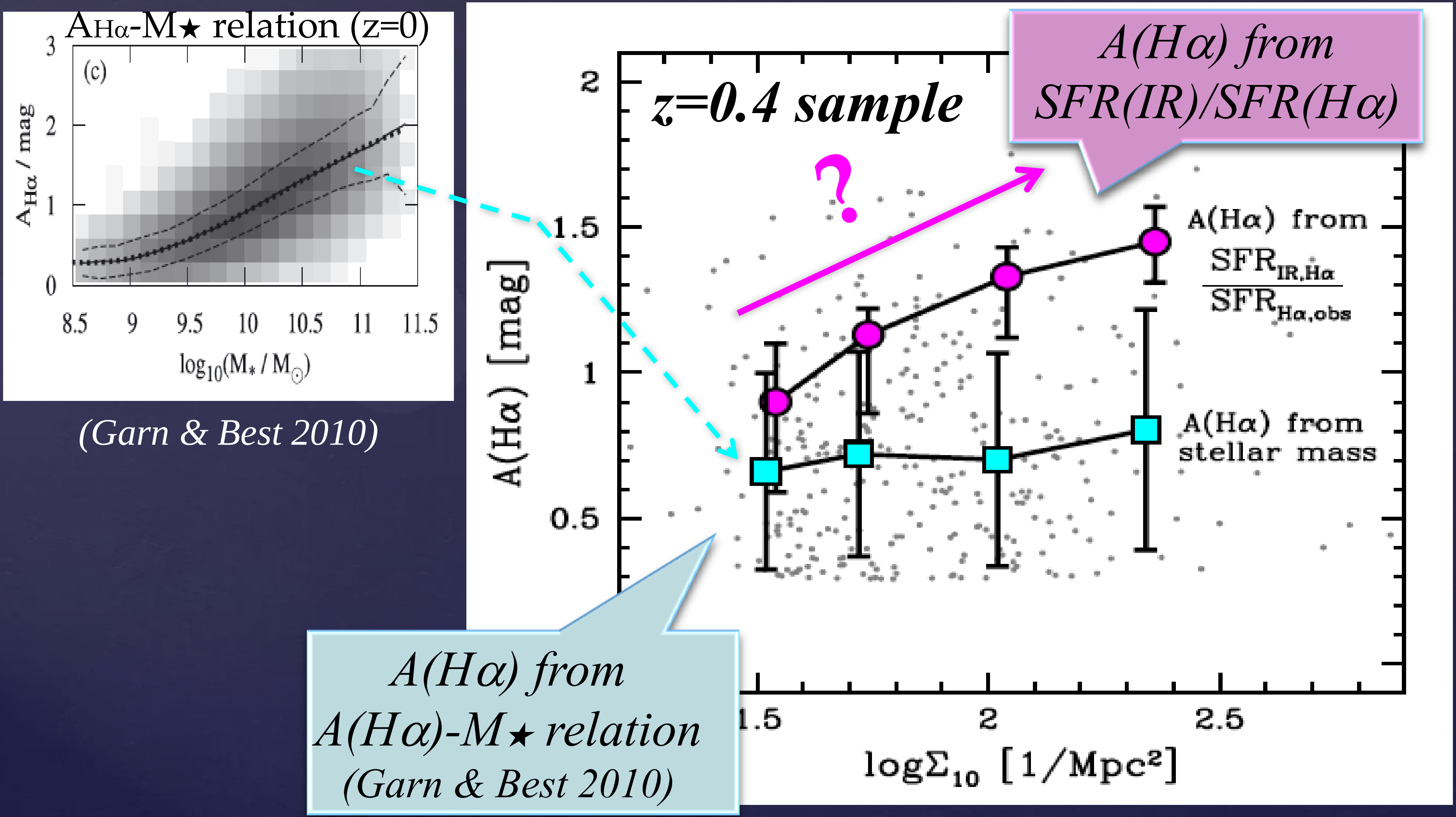
→ At z~2, SF galaxies in cluster environments tend to be more massive (& redder) than those in underdense environments.

(2) Dust extinction

(3) Metallicity

Dust extinction vs. environment (*z=0.4*)

Higher dust extinction (different SF mode) in high-density env?



(Garn & Best 2010)

A(Hα) from SFR(IR)/SFR(Hα)

A(Hα) from A(Hα)-M★ relation (Garn & Best 2010)

(Koyama et al. 2013b)

Looking for signs of environmental effects…

(1) Stellar mass

→ At z~2, SF galaxies in cluster environments tend to be more massive (& redder) than those in underdense environments.

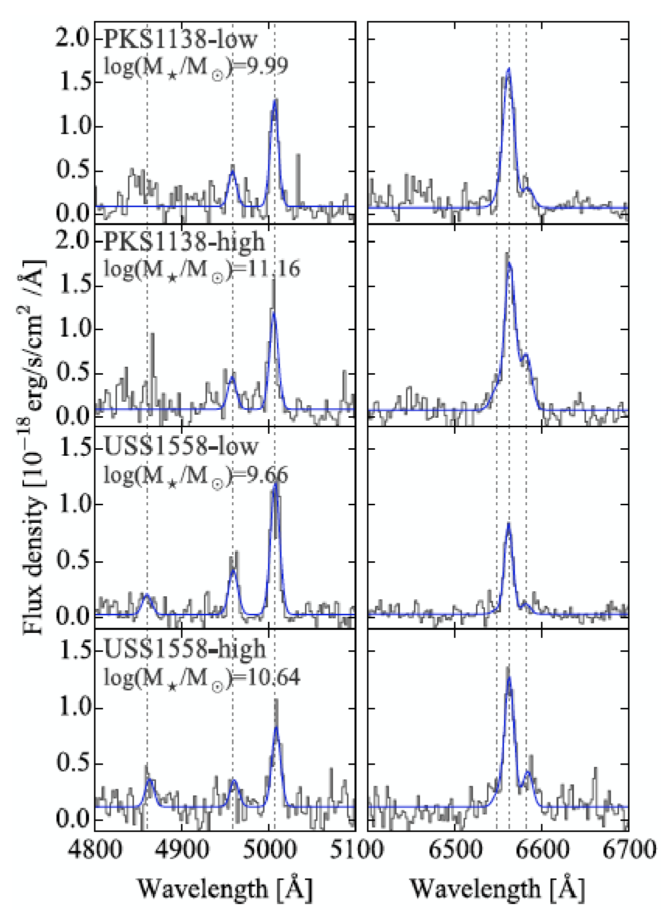
(2) Dust extinction

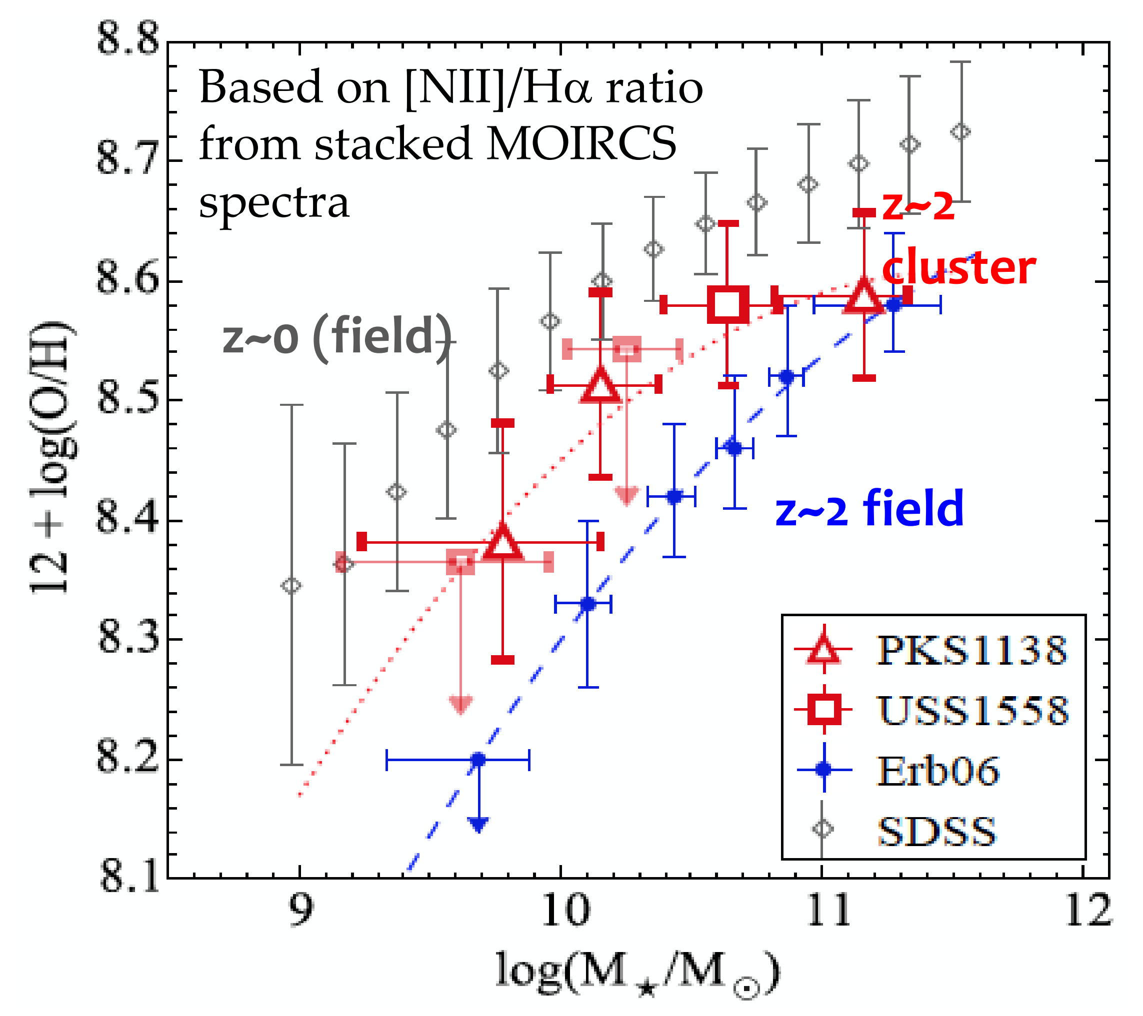
→ SF galaxies in cluster environment may be dustier.

(3) Metallicity

Metallicity vs. environment

Proto-cluster galaxies are more metal-rich particularly at low-mass end ?




Based on [NII]/Hα ratio from stacked MOIRCS spectra

(Shimakawa et al. 2014b, MNRAS submitted)

Looking for signs of environmental effects…

(1) Stellar mass

→ At z~2, SF galaxies in cluster environments tend to be more massive (& redder) than those in underdense environments.

(2) Dust extinction

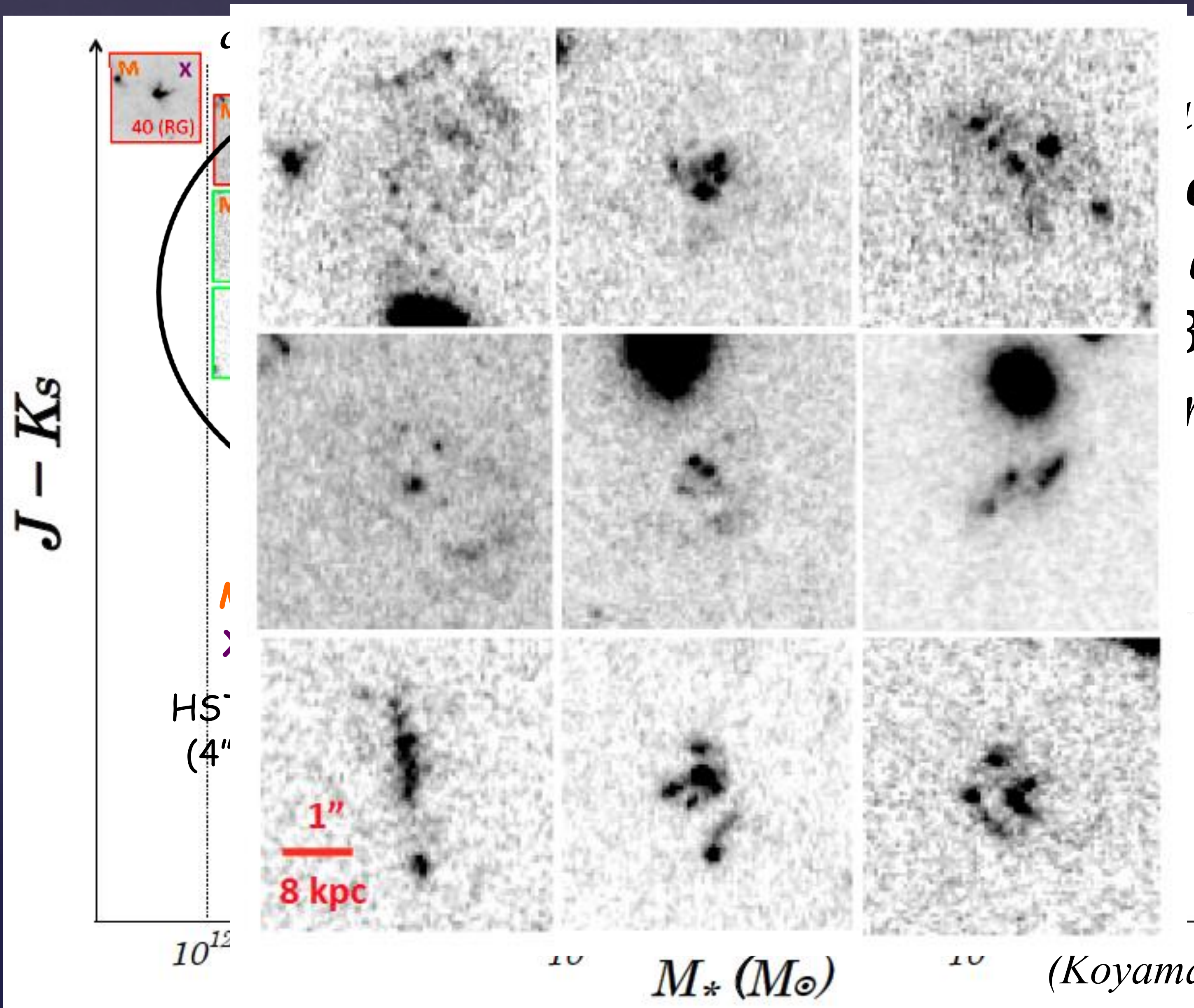
→ SF galaxies in cluster environments may be dustier.

(3) Metallicity

→ High-z cluster galaxies may be more metal-rich, particularly for low-mass systems.

What’s next?

What's next (1) – morphologies



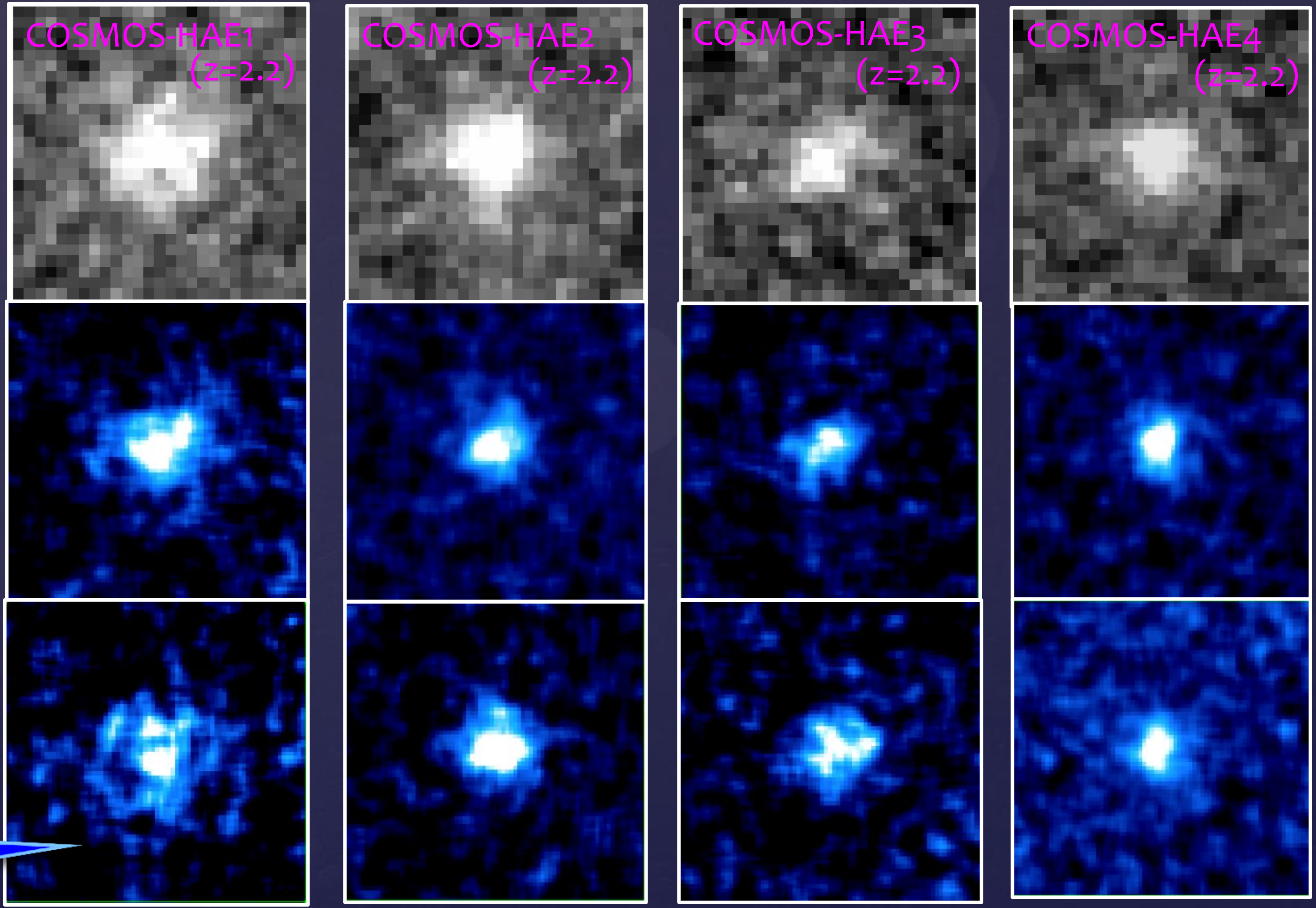
me UV
ogies of
emitters
38 proto-
r env.

(Koyama et al. 2013a)

GANBA-Subaru

Collaborator: Y. Minowa, MAHALO-Subaru team, HiZELS team

Galaxy Anatomy with Narrow-Band AO imaging with Subaru



CFHT K-band
(seeing ~0.7”)
4”x 4”

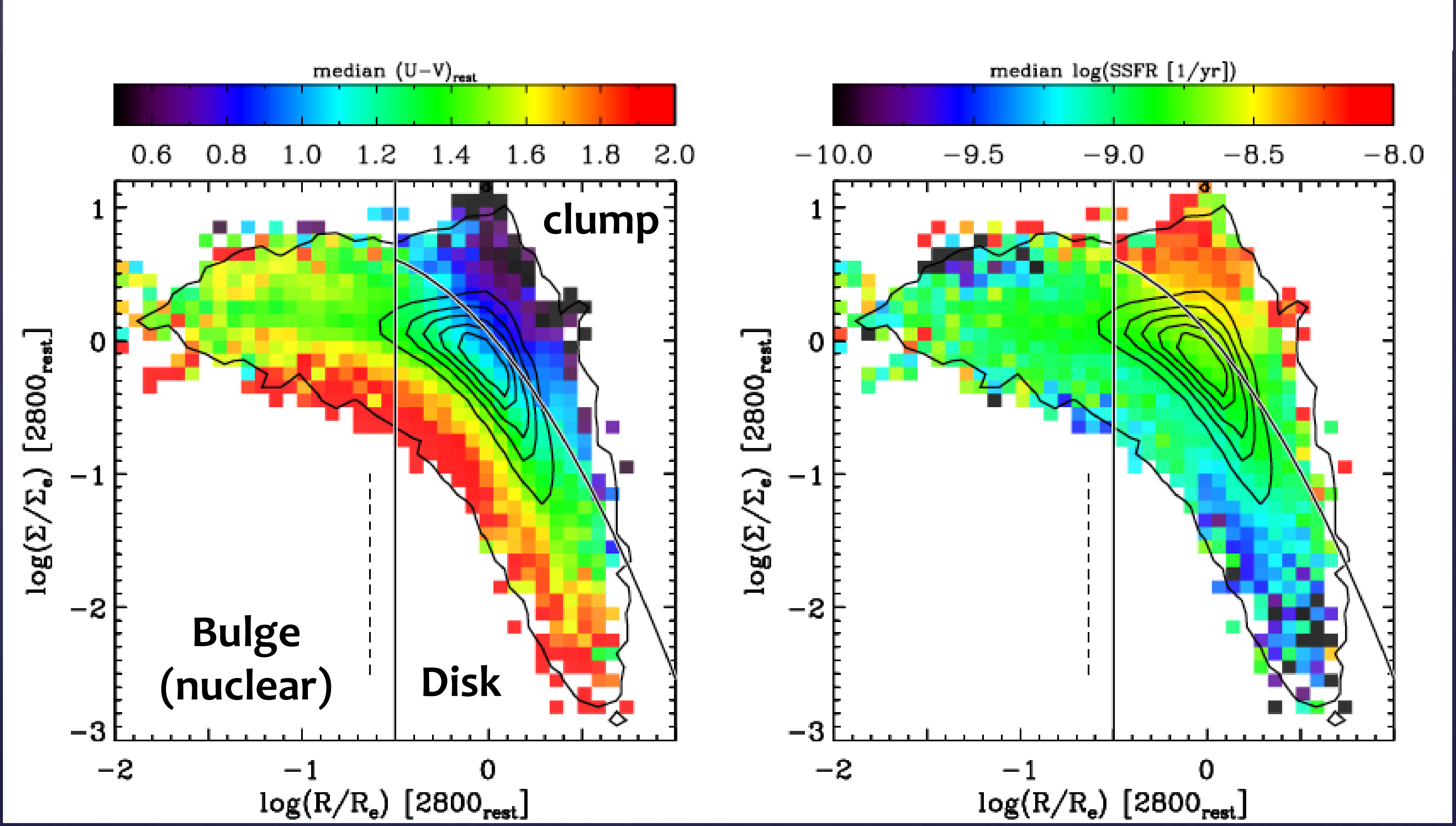
IRCS K’-band
(AO ~0.2”)
4”x 4”

IRCS NB(H2)
(AO ~0.2”)
4”x 4”

Hα map

Pinpointing the site of stellar build-up

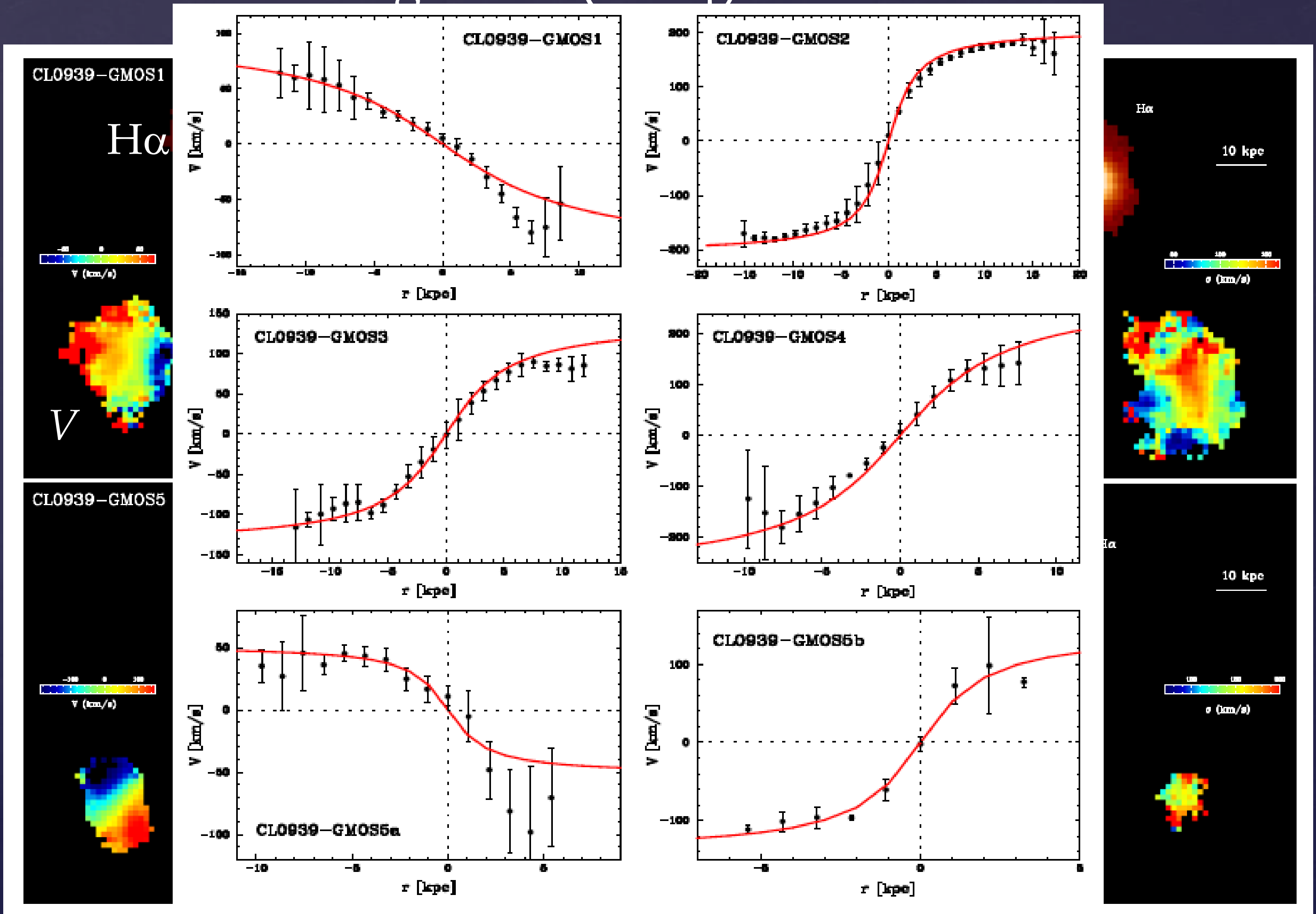
Galactic centre? On disk? In clumps? Any environmental dependence?



From CANDELS 3D-HST by Wuyts et al. (2013)

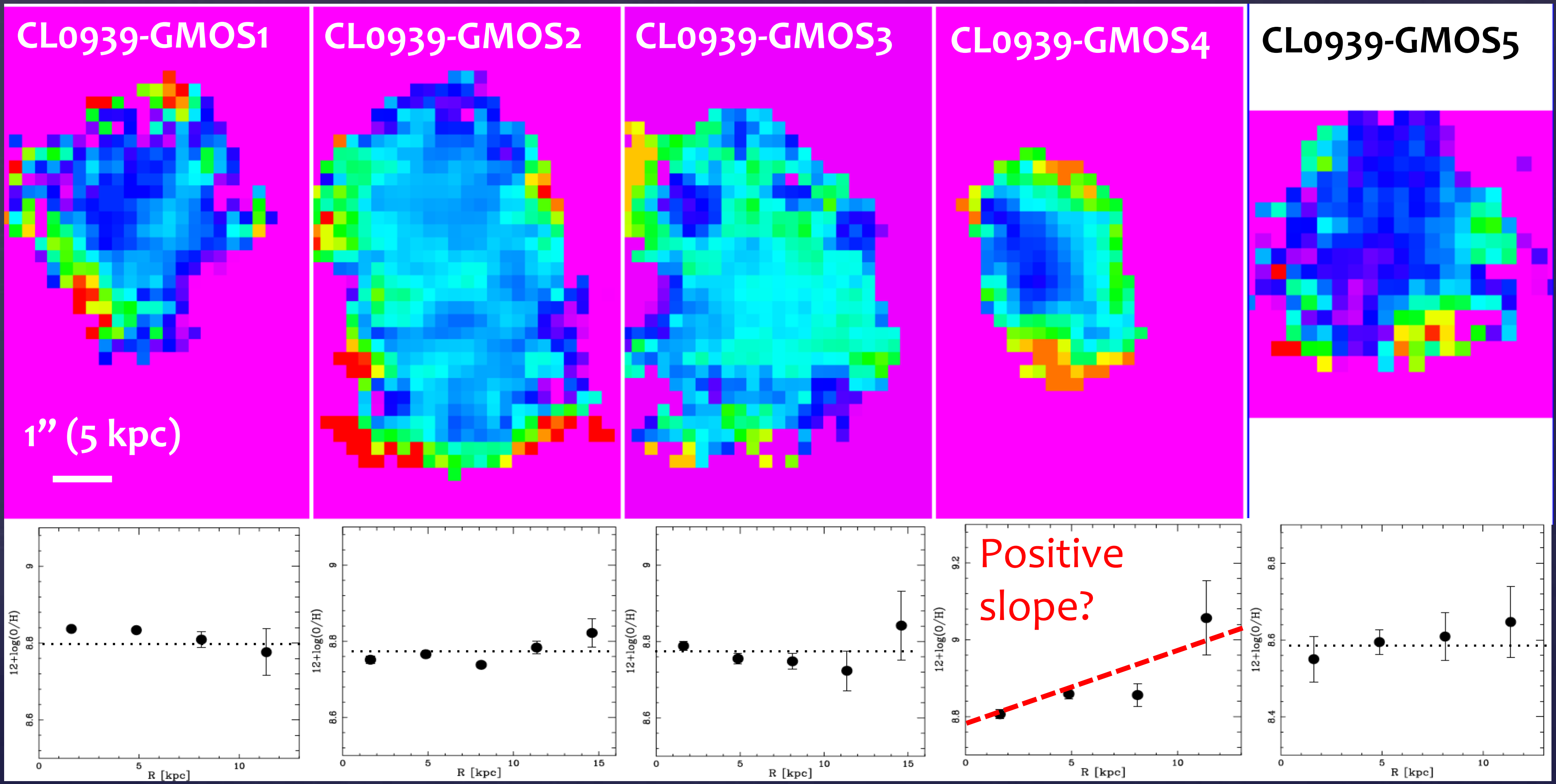
What's next (2) – 3D spectroscopy

3D views of cluster SF galaxies (z=0.4) with GMOS+IFU observation.



What’s next (2) – 3D spectroscopy

The first [NII]/Hα map of transitional galaxies in distant cluster env.



What’s next (2) – 3D spectroscopy

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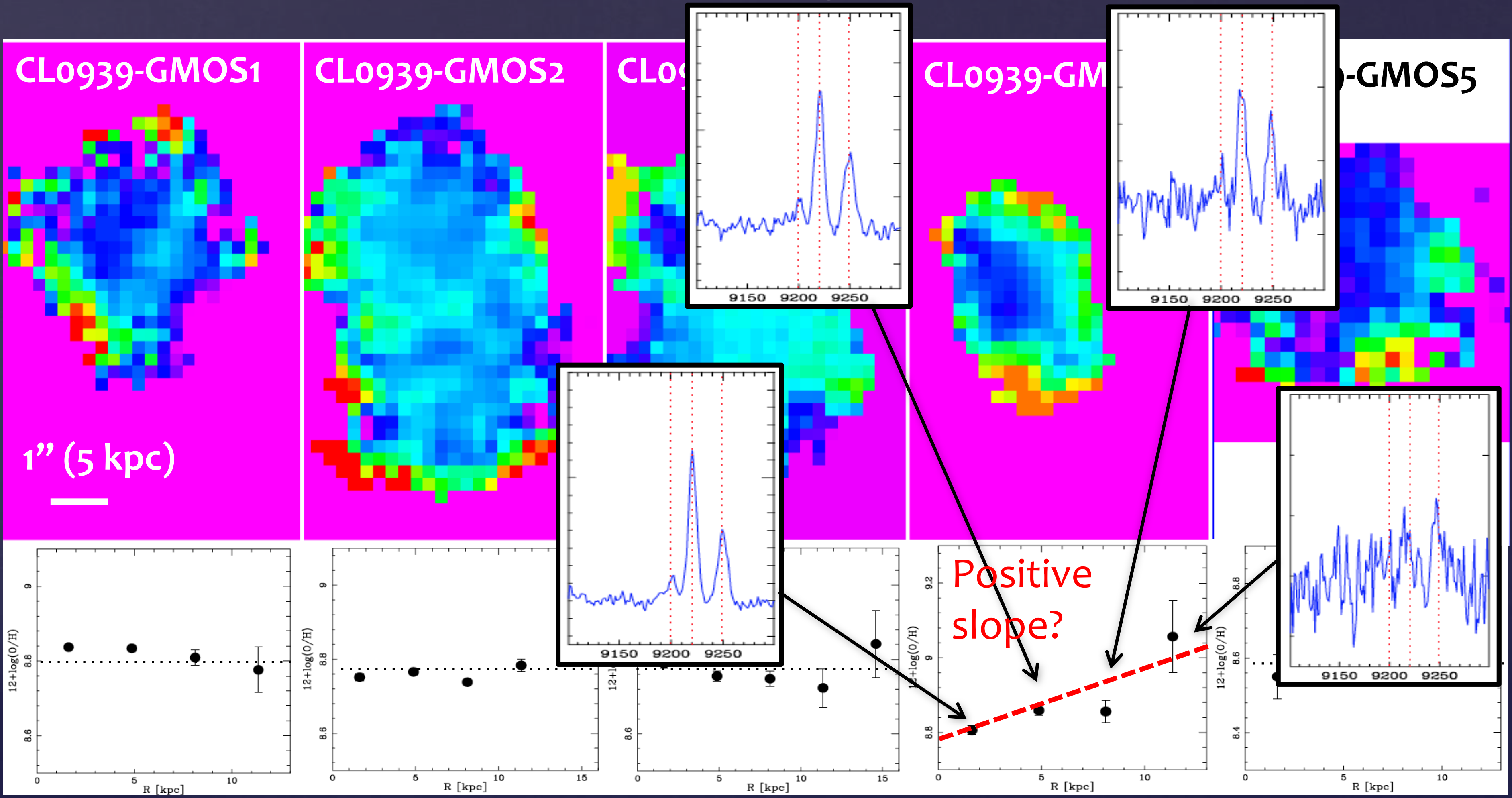
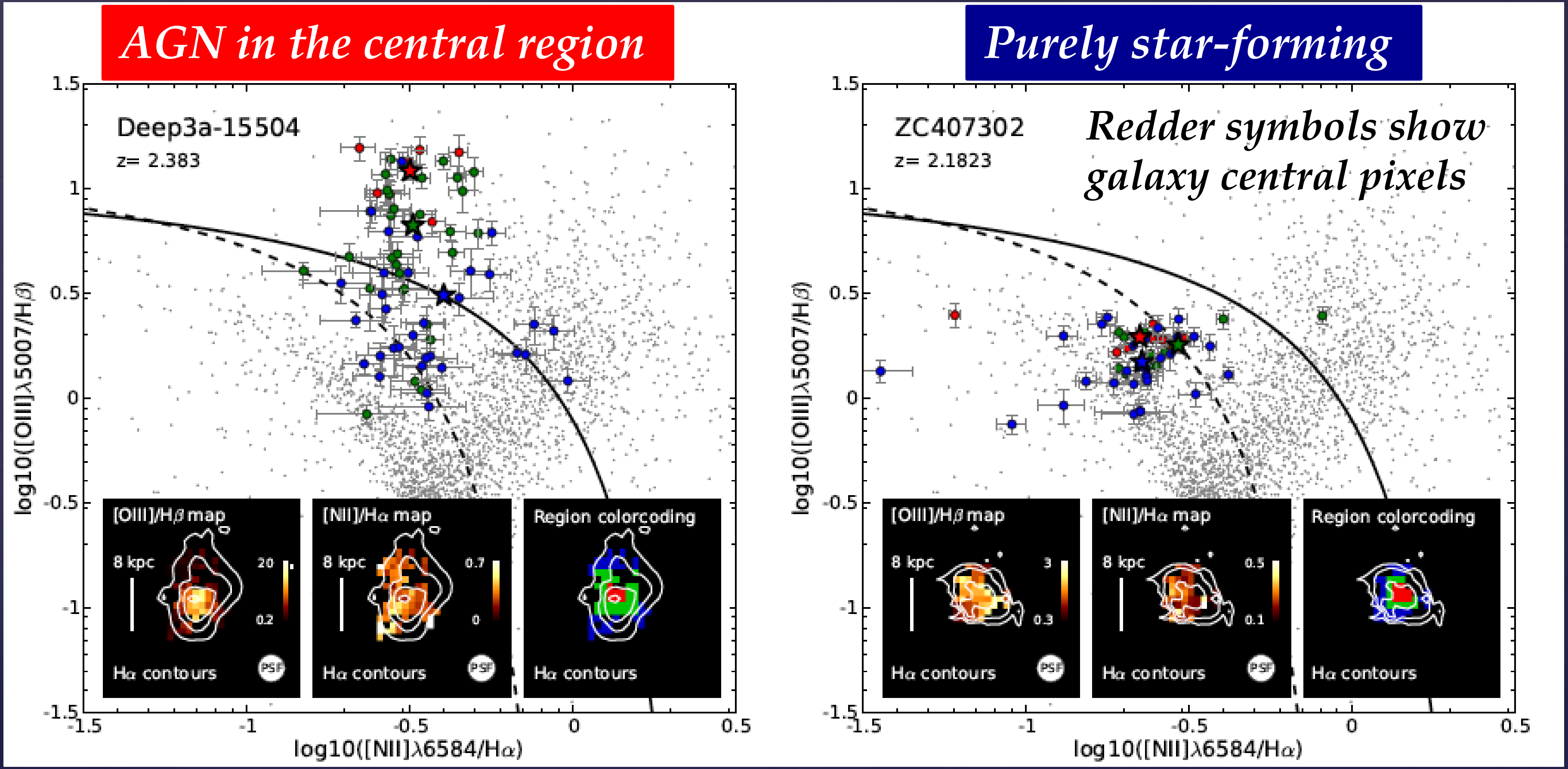


Positive slope?

Spatially resolved line ratios with TMT

Mapping multiple emission-lines over the galaxies to unveil central AGN, metallicity gradient, excitation states… etc.



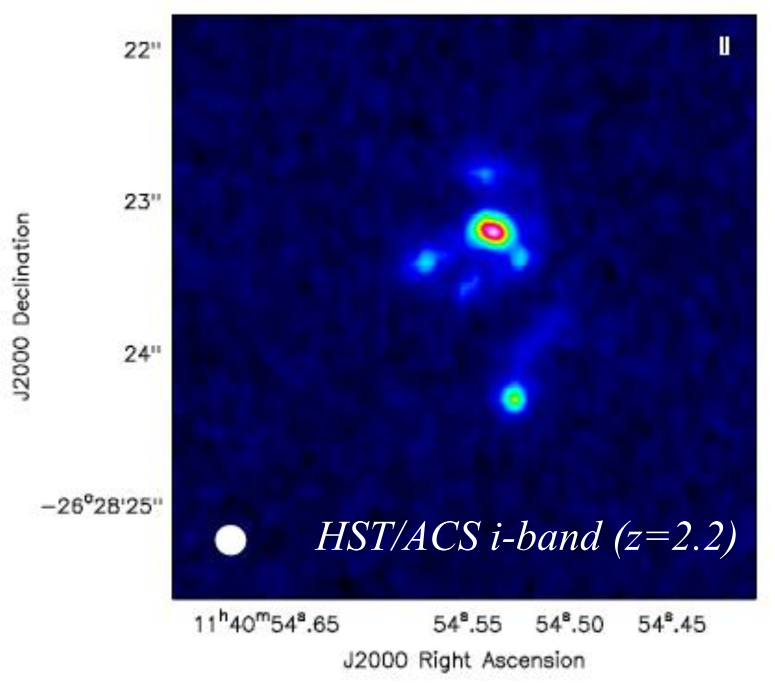
AGN in the central region

Purely star-forming

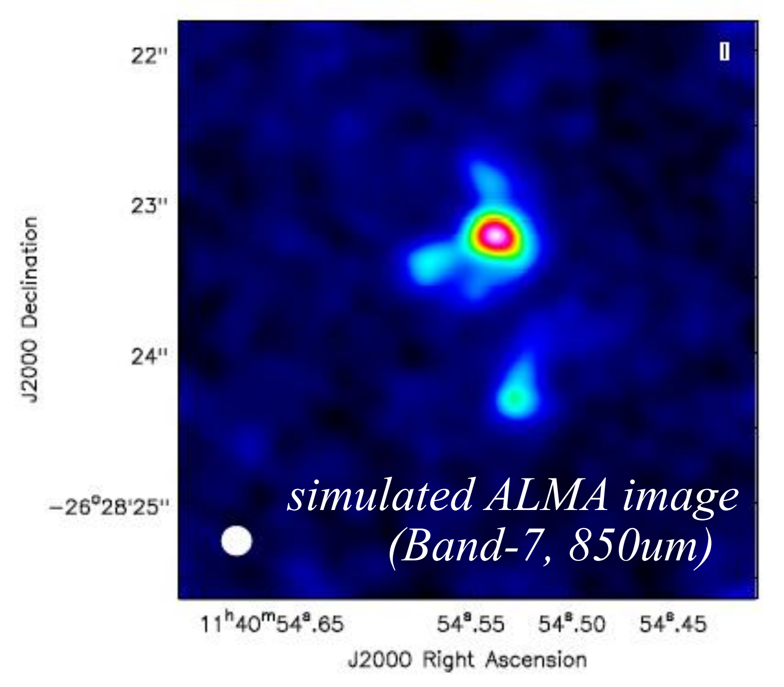
Redder symbols show galaxy central pixels

Pixel-by-pixel BPT diagram from SINFONI+AO observation (Newman et al. 2013)

What's next? (3) – gas/dust with ALMA



HST/ACS i-band (z=2.2)



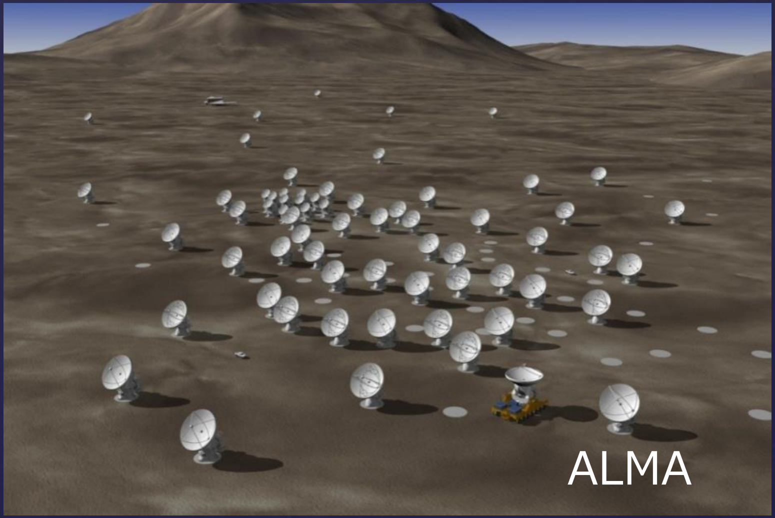
simulated ALMA image (Band-7, 850um)

✓ CO line observations:

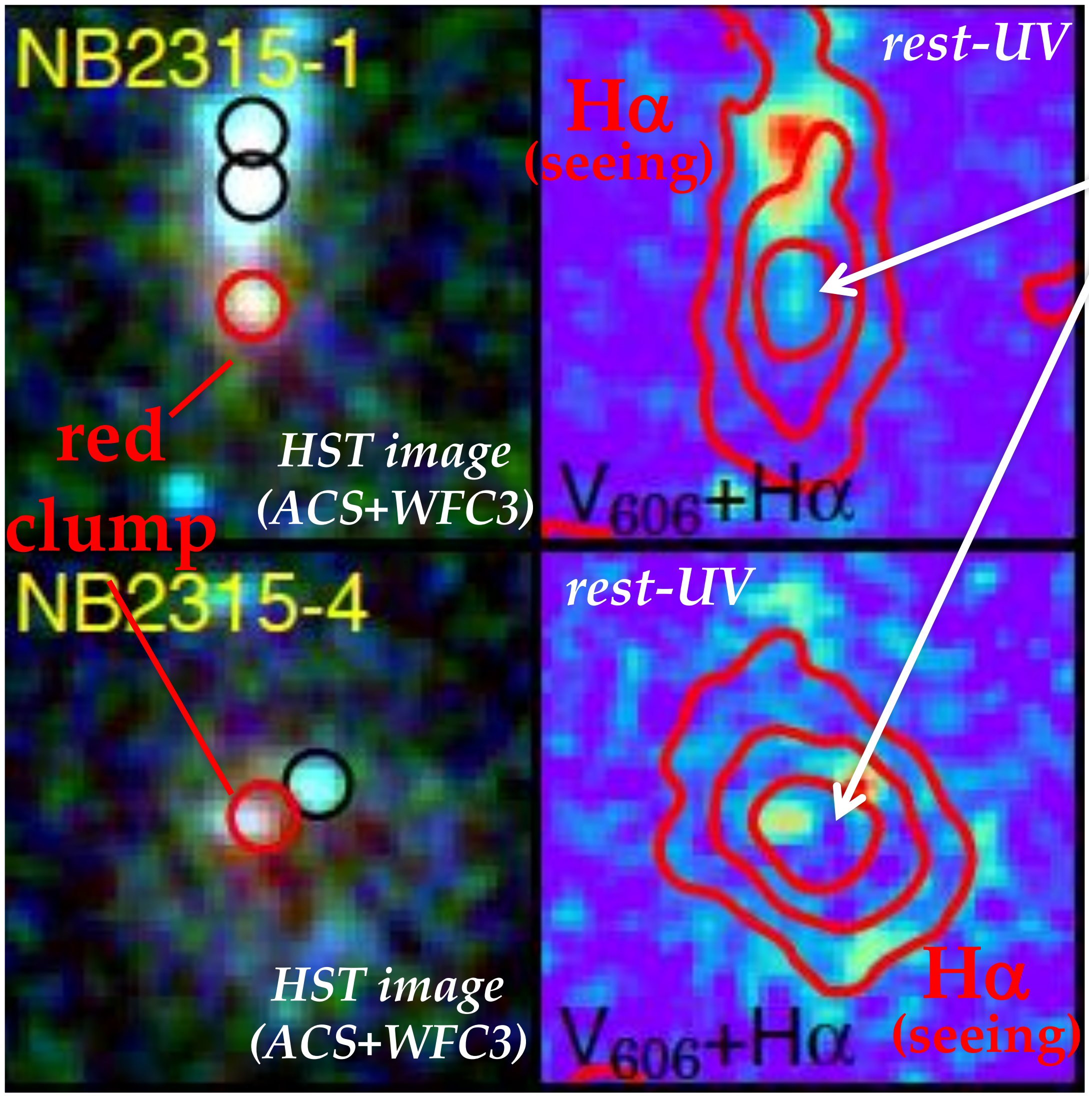
→ molecular gas mass & SF efficiency

✓ sub-millimeter continuum:

→ Spatially resolve dusty SF regions



Dusty SF clumps in high-z SF galaxies



Hα-strong (but UV-faint) dusty red clumps. Responsible for major SF activity in these galaxies?

ALMA will allow us to directly test the nature of these Hα strong clumps.

Hα emitters at z=2.5 in SXDF/CANDELS from Tadaki et al. (2013)

Summary

(1) 銀河進化の研究とは我々のルーツを探ることであり、その大目標は、銀河の星形成史(質量集積史)と形態獲得の歴史を司る物理過程を解明することにある。

(2) 銀河の性質を決める重要なパラメータは銀河の質量と、その銀河の住む環境である。ただし近年の研究から星形成銀河のメイン・シーケンス(星質量ー星形成率関係)は環境に依存しないことが示されている。

(3) 私たちがすばる望遠鏡のナローバンドを用いた輝線銀河探査の結果によれば、赤方偏移~２の宇宙でも同様の結果が得られており、星形成銀河のメイン・シーケンスはいつの時代も環境とは無関係に見える。このことから、環境効果は短いタイムスケールで銀河に作用していると解釈できる。

(4) ただし、星形成銀河について銀河の質量だけでは説明できないような、環境による明らかな性質の違いも見えている。たとえば銀河団の銀河には重いものが多く、またダスト吸収量や金属量にも一般のフィールド銀河とは異なる素性をもっている可能性が示されている。

(5) 遠方銀河を点源と捉える「マクロな視点」から、銀河を空間的に分解してその内部構造と物理状態にせまる「ミクロな視点」で銀河進化を読み解いていくことが、今後の銀河研究の主軸になりつつある。