すばるPFSによるサイエンス検討会（2015年7月10日）

PFSで探る銀河・銀河団の進化

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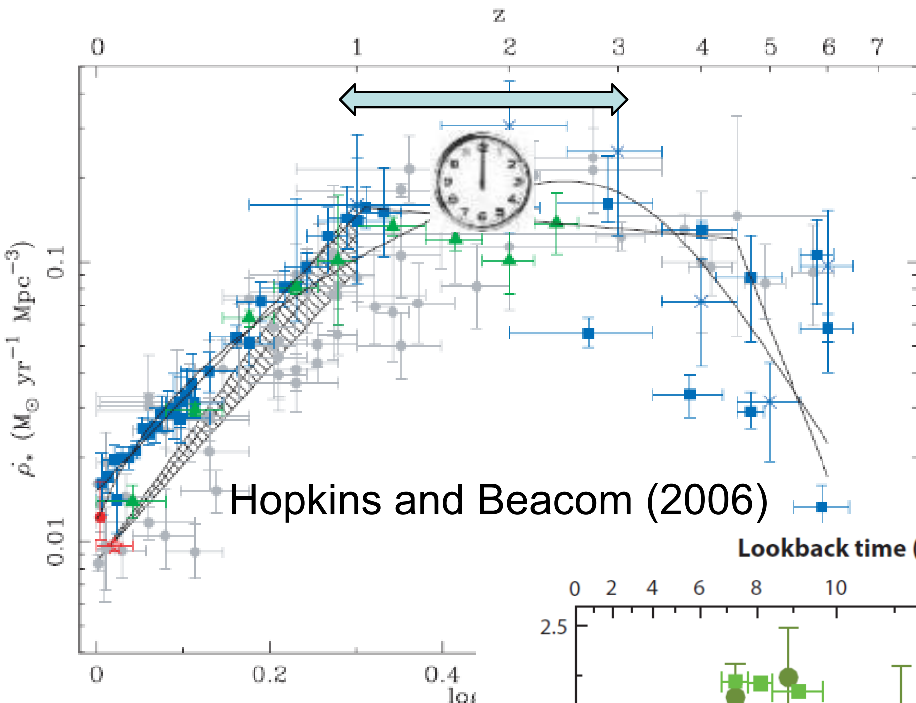
NGC2403 (Subaru/Suprime-Cam)

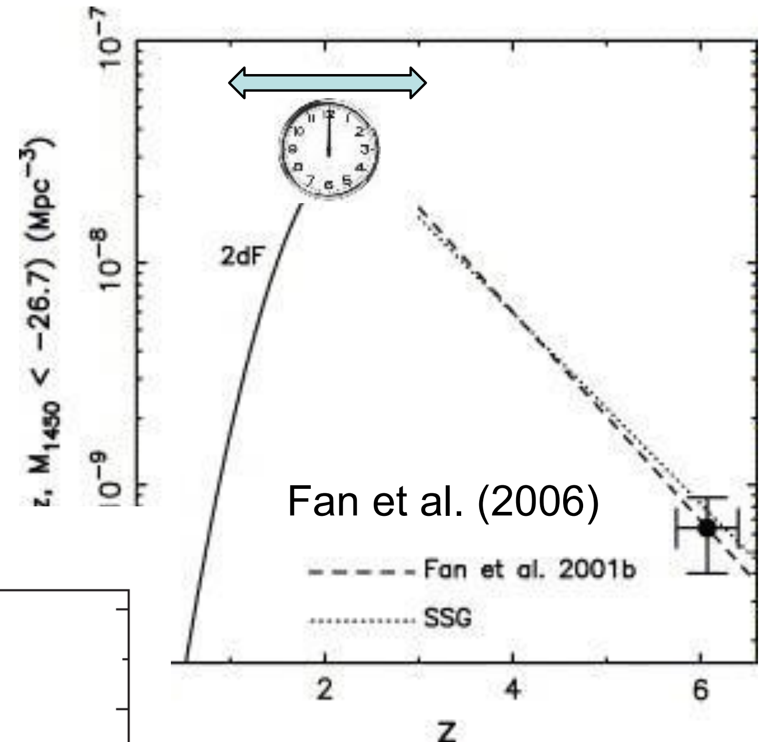
"COSMIC HIGH NOON"『銀河宇宙の白昼』

The peak epoch of galaxy/SMBH formation/dust extinction: 1<z<3 (6>T_{cos}(Gyr)>2)



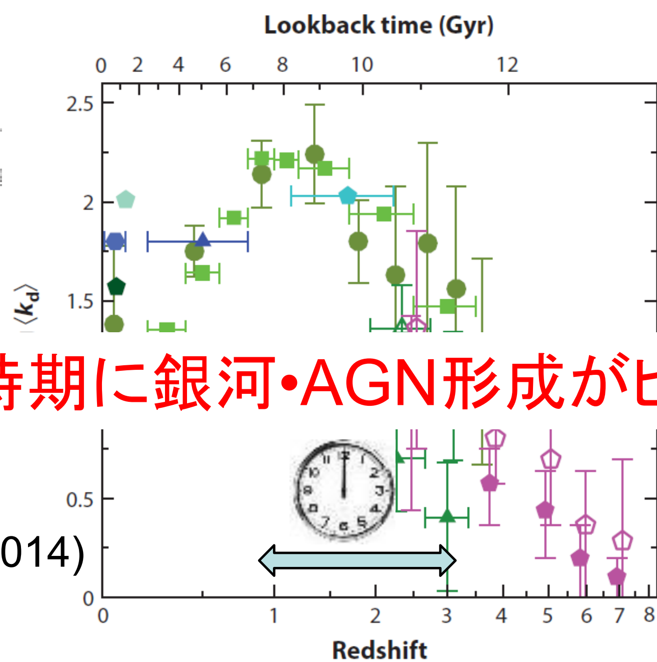
Hopkins and Beacom (2006)

Star formation



Fan et al. (2006)

BH accretion (AGN/QSO)



Madau & Dickinson (2014)

Dust extinction

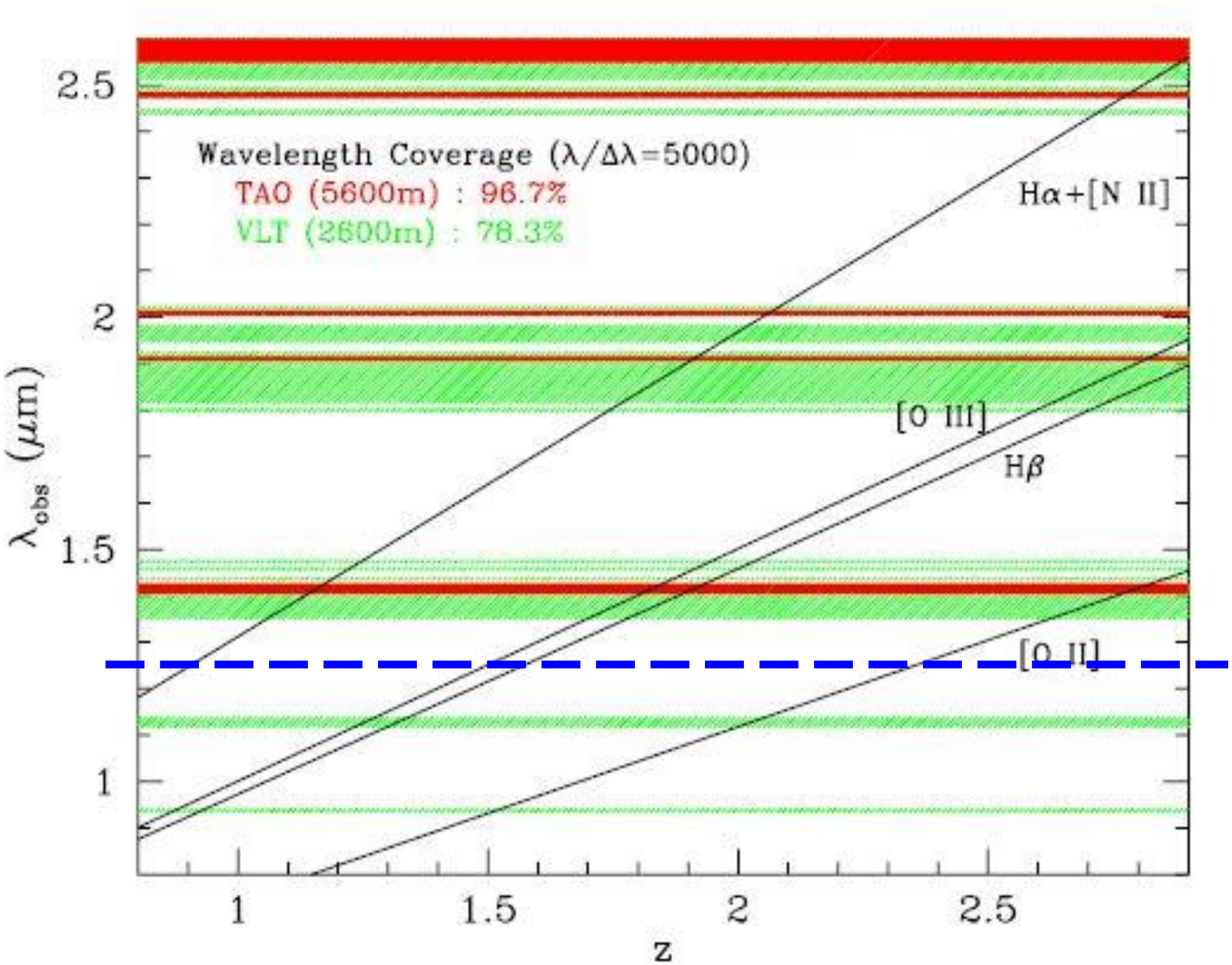
どうしてこの時期に銀河•AGN形成がピークになったのか？

今後の課題

形成最盛期にある銀河の、形態獲得、星形成、AGN、フィードバックが、「いつ」、「どこで」、「どのように」起き、どう「相互に関連」しているのか？

- バルジ形成の謎。クランプ移動か、銀河の合体か？
- 銀河形成（星形成）のモード？継続的進化とバースト・フェーズの相対寄与は？
- 星やガスの内部運動は？形態獲得との関係は？
- 星形成活動とAGN活動とのリンクおよびフィードバック？
- 銀河のIMFは？時間変化？モード依存性？
- 遠方銀河の物理状態（温度、密度、電離状態、重元素量）？
- これら全ての環境と質量への依存性は？その理由は？

PFS line detectability（λ <1.26 μ m）



z(Hα) < 0.92

z(Hβ) < 1.59

z([OIII])< 1.52

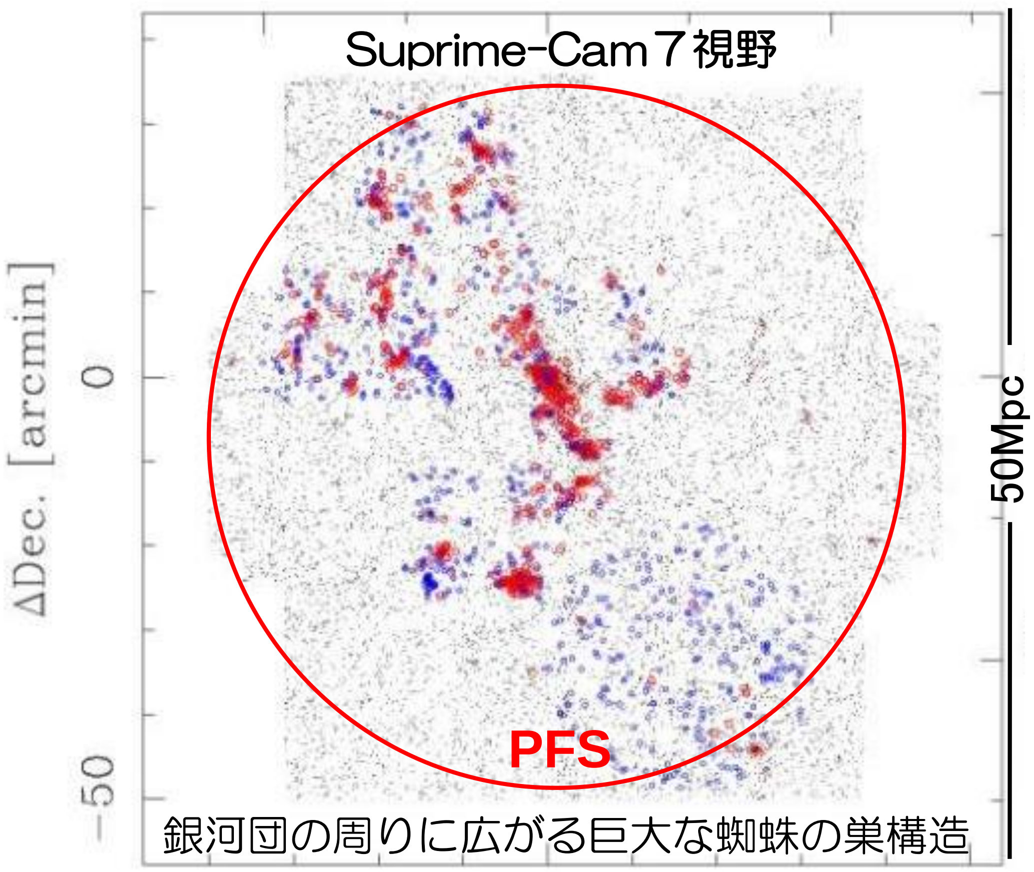
z([OII]) < 2.38

遠方銀河の星形成史/重元素量/力学質量とその環境依存性

1.3° = 75 Mpc (z=1), 100 Mpc (z=1.5), 118 Mpc (z=2): co-moving

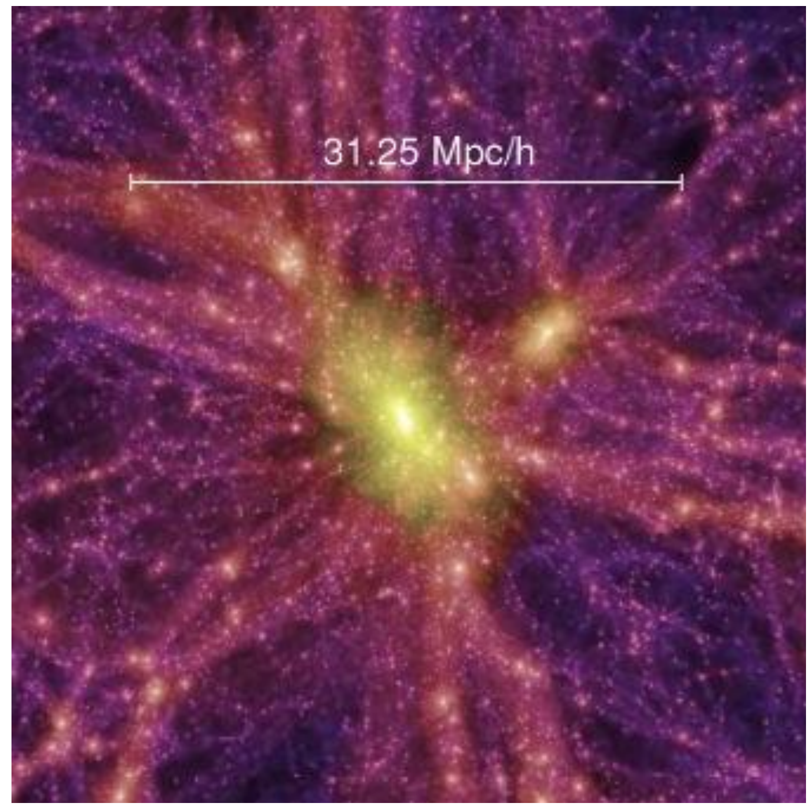
HSC + PFS will easily map out LSSs

CL0016 cluster (z=0.55)
(Tanaka, M. et al. 2009)



1200 個の銀河を分光し距離を測定。
赤が銀河団メンバーで、青は非メンバー。

ミレニアム・シミュレーション
(Springel et al. 2005)



Subaru-HSC Legacy Surveys

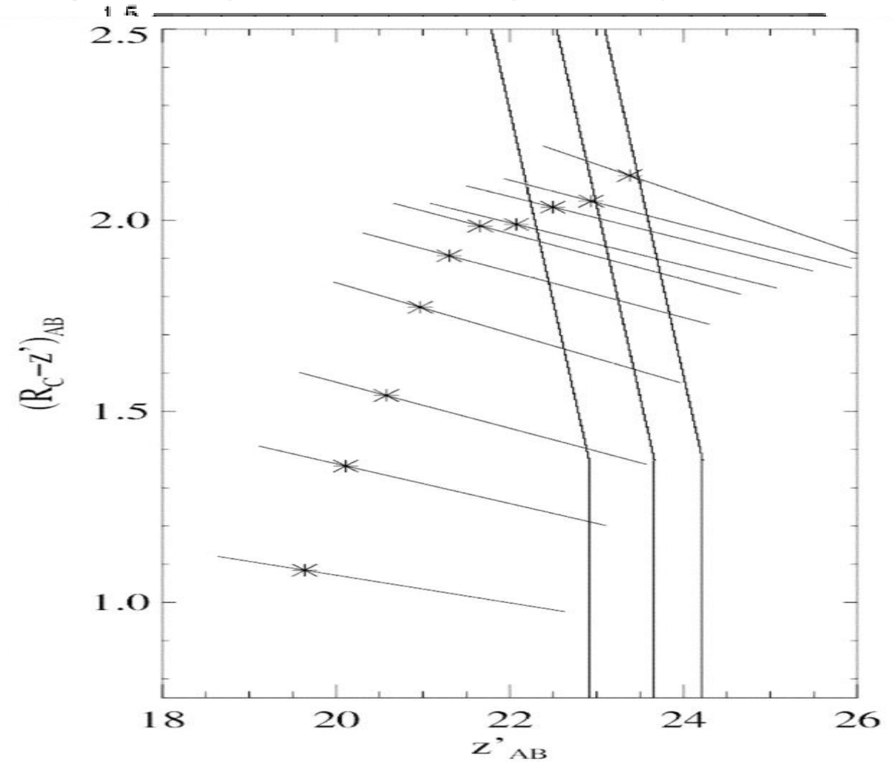
Layer	Area [deg^2]	# of HSC fields	Filters & Depth	Comoving volume [h^{-3}Gpc^3]
Wide	1400	916	$grizy$ ($r \simeq 26$)	$\sim 4.4\,(z < 2)$
Deep	27	15	$grizy$+3NBs ($r \simeq 27$)	$\sim 0.5\,(1 < z < 5)$
Ultradeep	3.5	2	$grizy$+3NBs ($r \simeq 28$)	$\sim 0.07\,(2 < z < 7)$

survey	area	cluster number (dn/dz)
HSC-Deep	27 deg^2	200 ($>10^{14}$ $M_\odot$) at z=1
		6 ($>10^{14.5}M_\odot$) at z=1
HSC-Wide	1400 deg^2	10,000 ($>10^{14}$ $M_\odot$) at z=1
		300 ($>10^{14.5}M_\odot$) at z=1

Hybrid Search for Clusters with HSC (HSC-HSC)

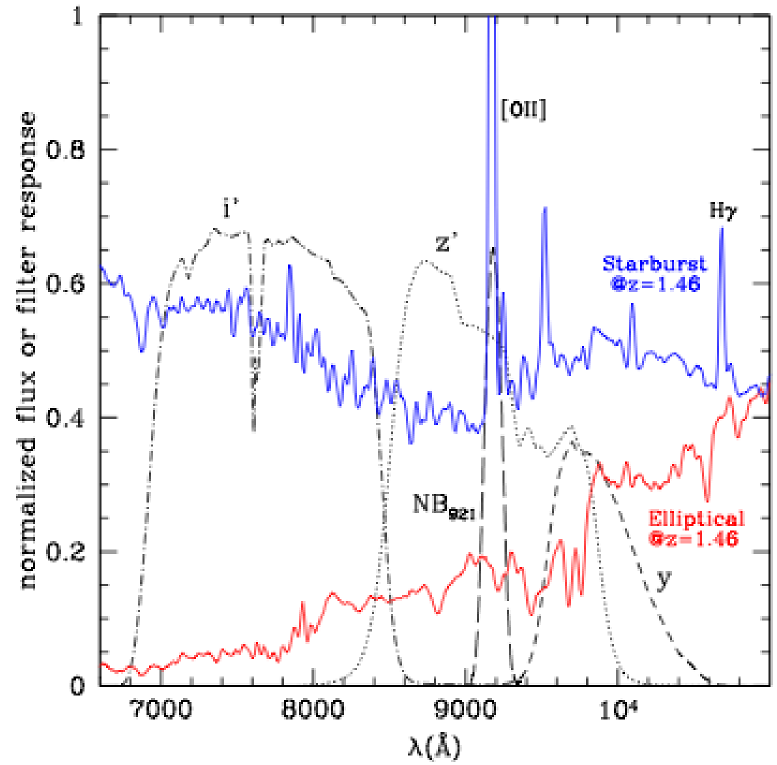
"red sequence" survey (passive galaxies)

phot-z (or color-color) survey to z~1.5



"blue sequence" survey (SF galaxies)

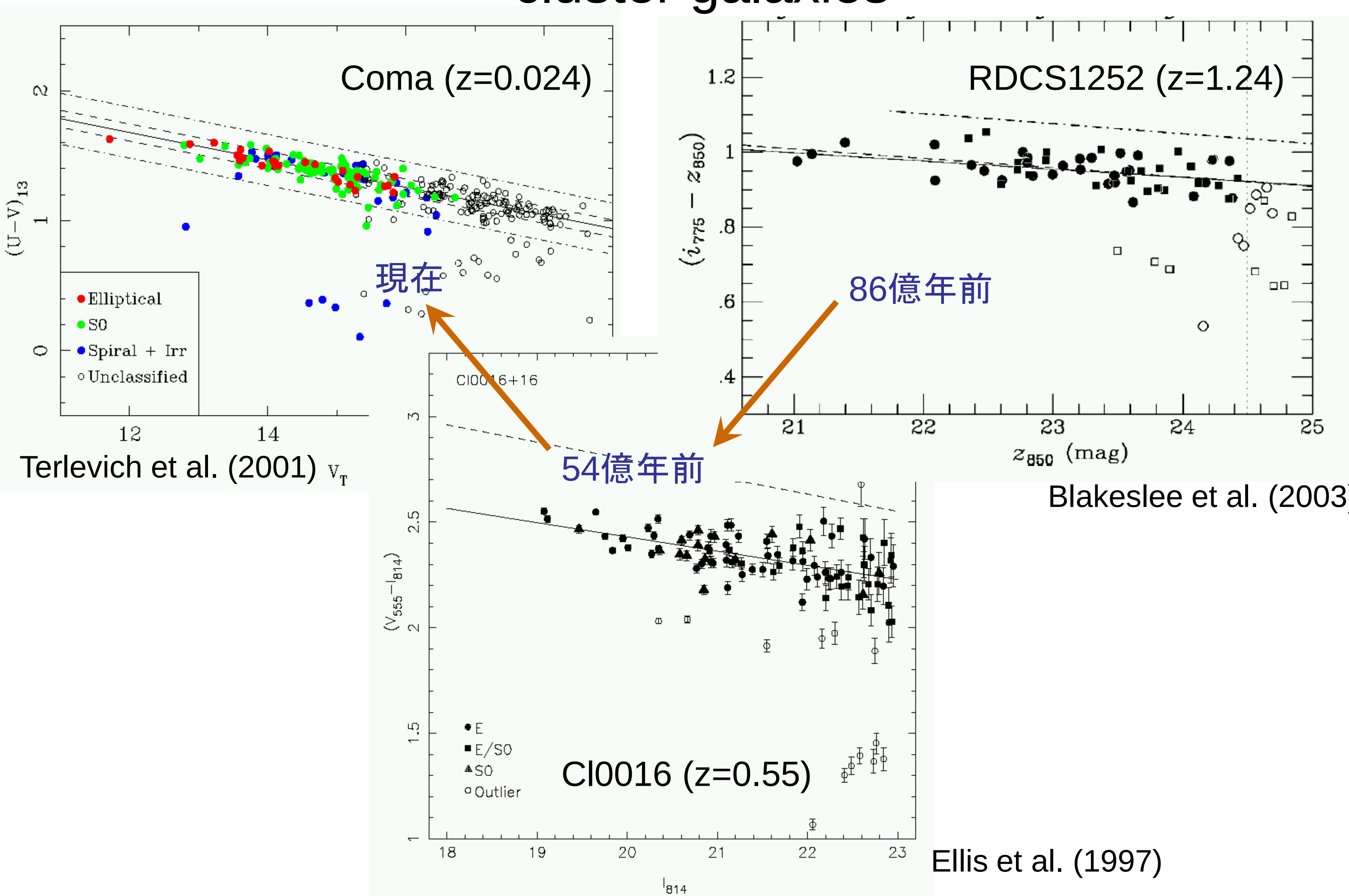
NB [OII] emitter survey to z~1.7



HSC NB filters

Filter	CW [Å]	FWHM [Å]	z(Lyα)	z([OII])	z(Hβ)	z([OIII])	z(Hα)
NB816	8160	120	5.711±0.049	1.189±0.016	0.679±0.012	0.630±0.012	0.243±0.009
NB921	9210	131	6.574±0.054	1.471±0.018	0.895±0.013	0.839±0.013	0.403±0.010
NB973	9730	138	7.002±0.057	1.611±0.019	1.002±0.014	0.943±0.014	0.483±0.011
NB101	10095	143	7.302±0.059	1.709±0.019	1.077±0.015	1.016±0.014	0.538±0.011

Red sequence (colour-magnitude relation) of cluster galaxies



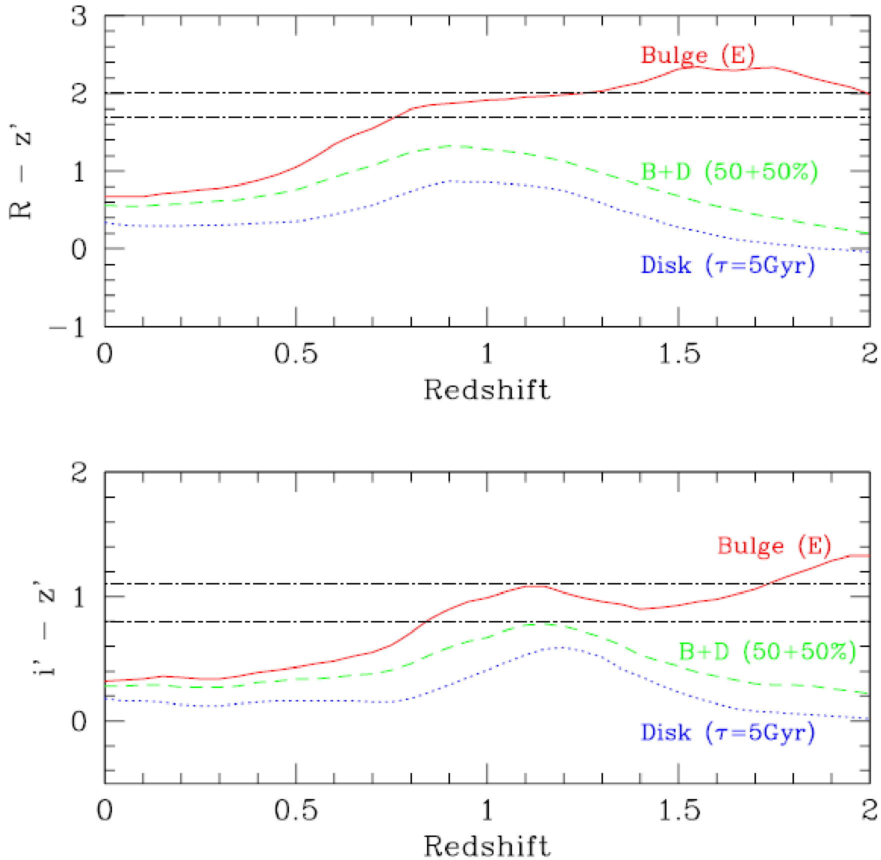
Terlevich et al. (2001)

Blakeslee et al. (2003)

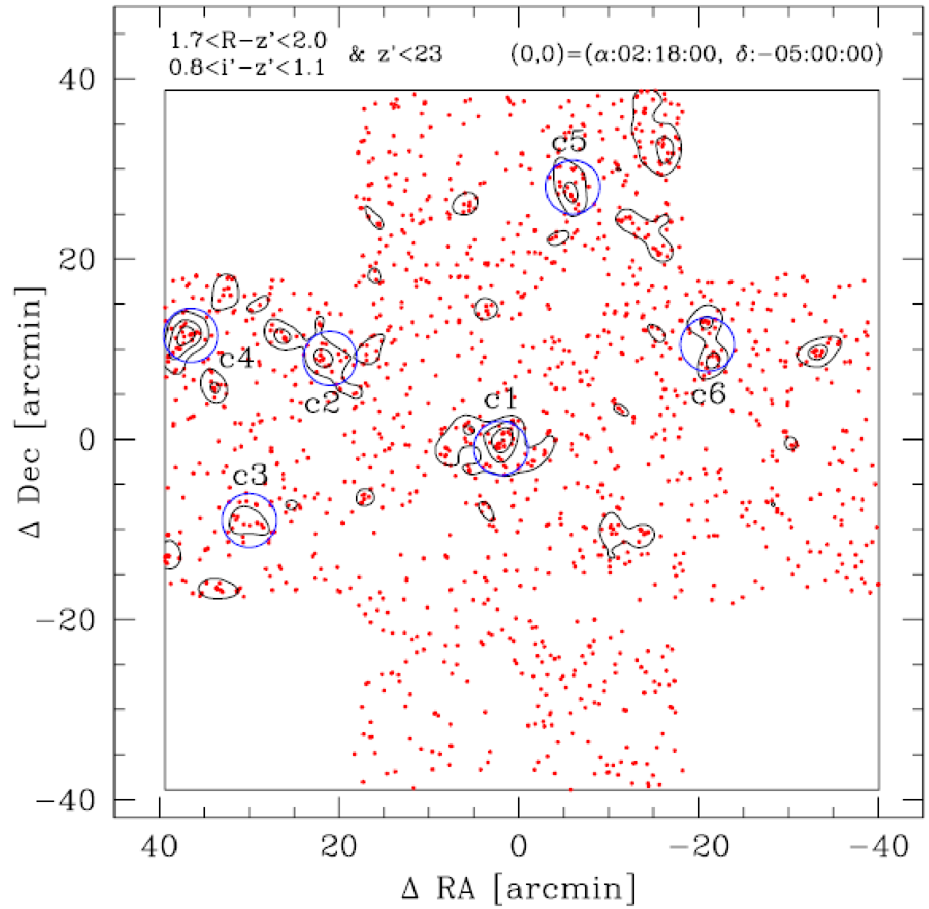
Ellis et al. (1997)

Red sequence survey of high-ρ regions (galaxy clusters)

The combination of R, i' and z' photometries is effective to cull out galaxies at 0.9<z<1.3.



SXDF



Kodama et al. (2004b)

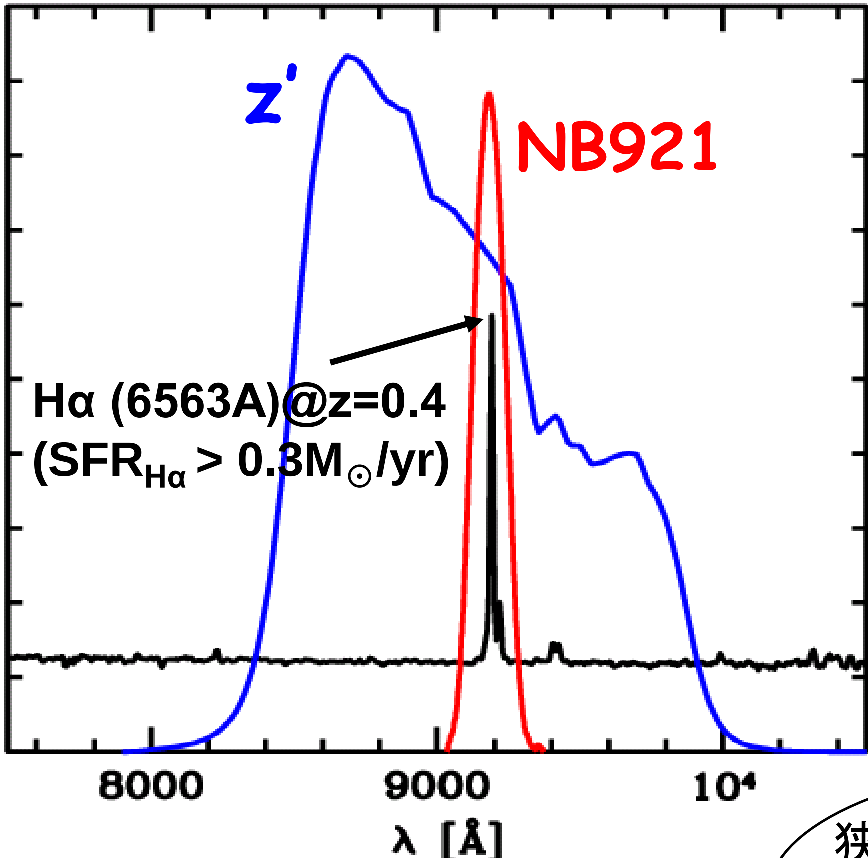
Dual Cluster Finding Approach

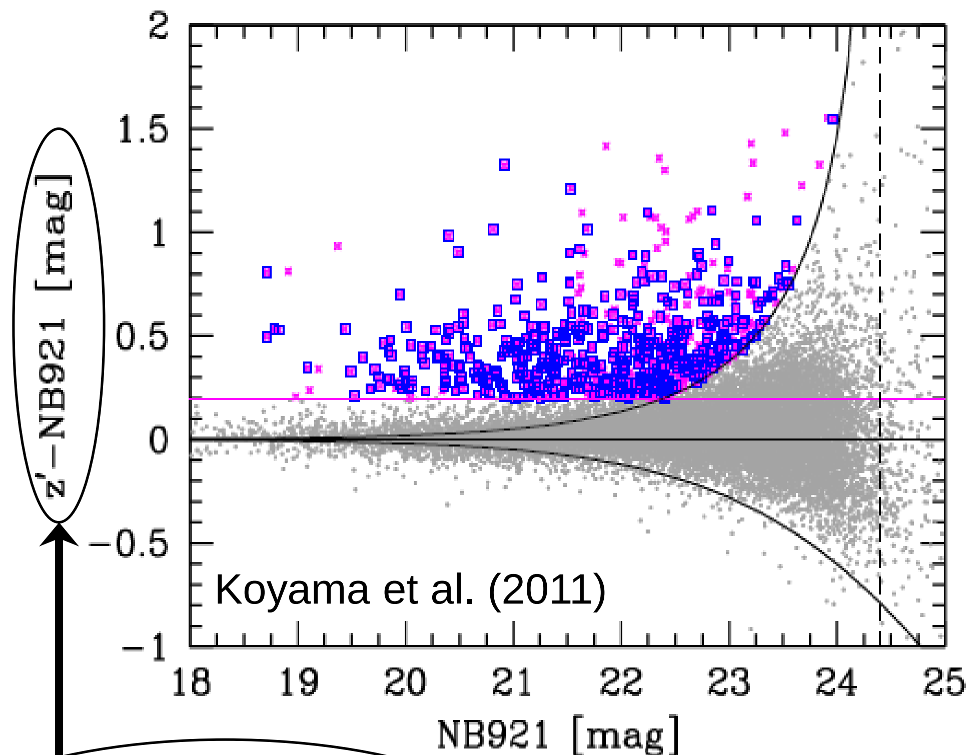
- The red sequence survey will be biased to well-evolved rich clusters at any time, since it is sensitive to passively evolving galaxies, and would miss young clusters with only weak red sequence.

→ By combining with blue sequence survey with narrow-band filters, we can be also sensitive to young, actively star-forming clusters, which are common at high-z (>1).

狭帯域撮像による輝線銀河探査

狭帯域フィルターを使った撮像観測によって、ある特定の赤方偏移にある輝線銀河（星形成銀河）を一網打尽に捕えることができる。





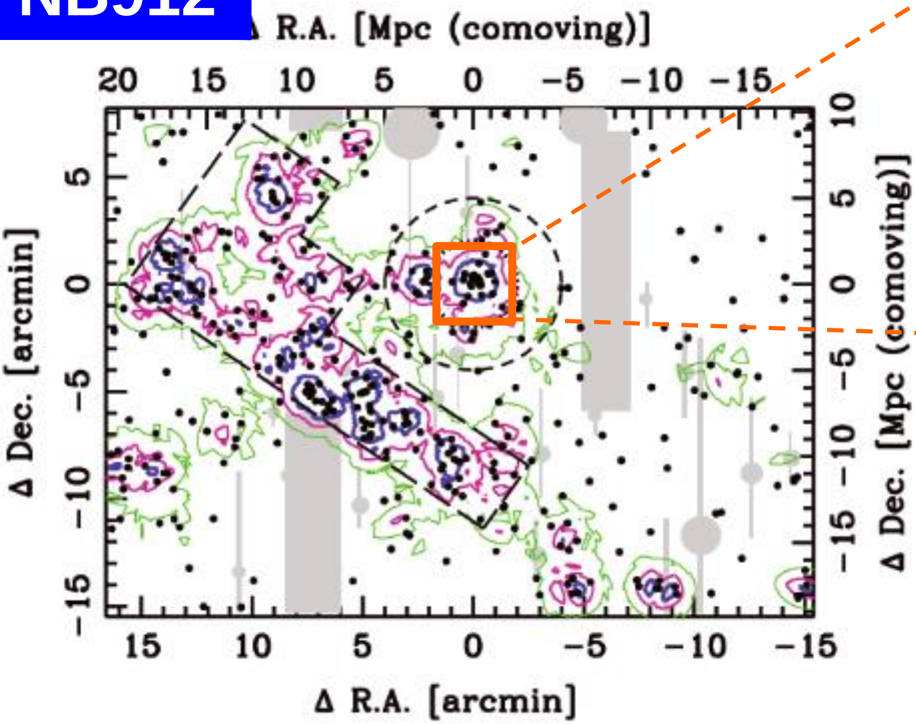
狭帯域フィルター(NB921)と広帯域フィルター(z')との明るさの比（対数）に対応

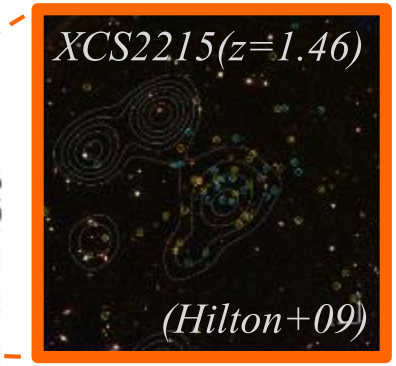
NB921での明るさ

LSSs around two x-ray clusters at z~1.5 traced with [OII] emitters

Suprime-Cam/Subaru
30' ~ 30-40 Mpc
(co-moving) on a side

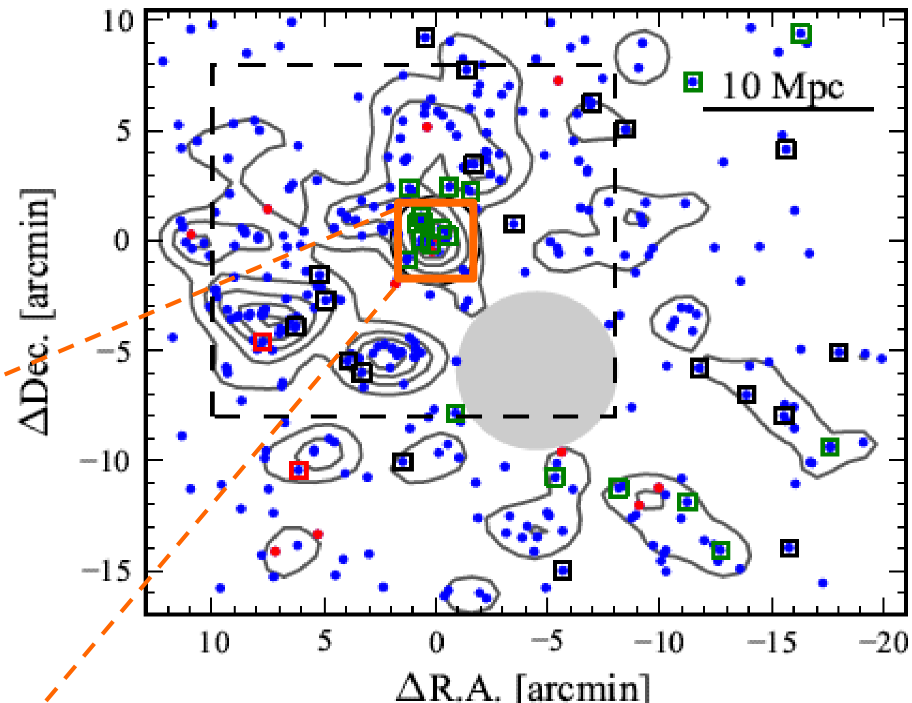
NB912





Hayashi et al. (2011)

NB973



Tadaki et al. (2012)

Panoramic Follow-up Spectroscopy with PFS (PFS-PFS)

- Resolving Star Formation History in Finer Time Scale

  Hα + Balmer absorption + SED

  10^7 yr 10^{8-9} yr $>10^9$ yr

  Starburst? Truncation timescale? → Physical mechanisms

- Dust extinction

  Hα/Hβ (Balmer decrement) → Dust extinction

- Chemical Evolution of Interstellar Gas

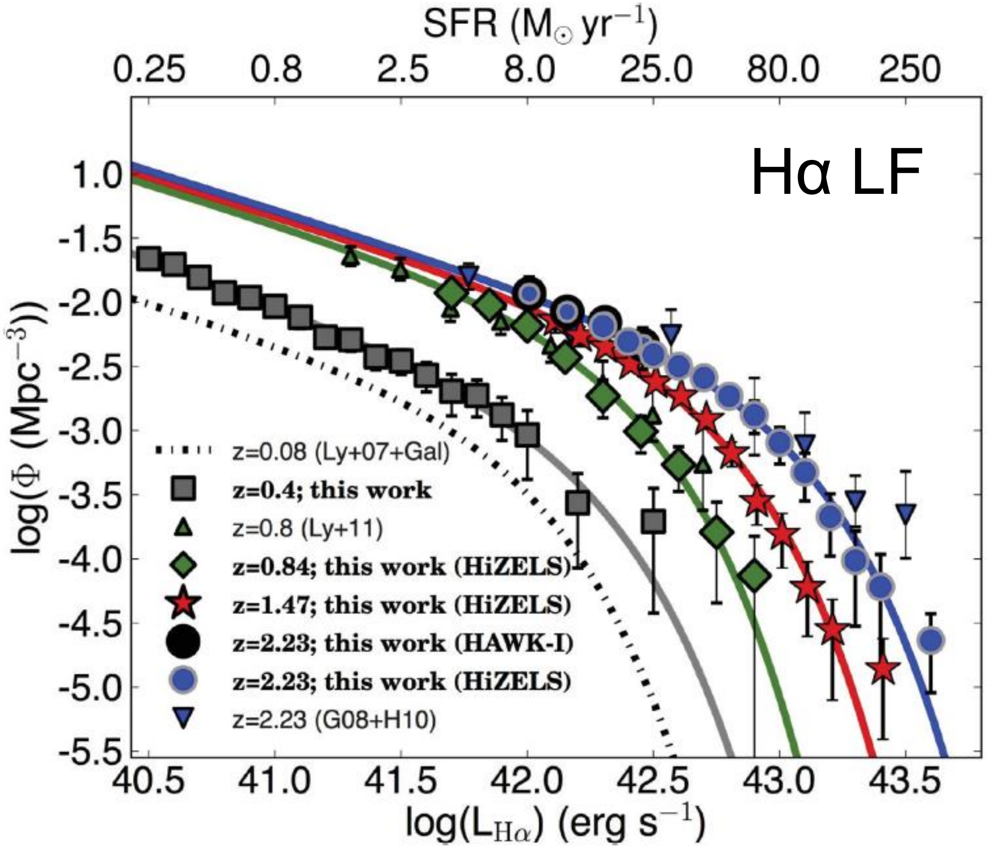
  N2, R23, [OIII]λλ4959,5007/[OIII]λ4363 (T_e) → Gaseous metallicity

- AGN / SB separation, ionization state

  BPT diagram → AGN contribution (environment and time)

- Electron density

  [OII]λ3726,3729 → electron density of HII region and PDR



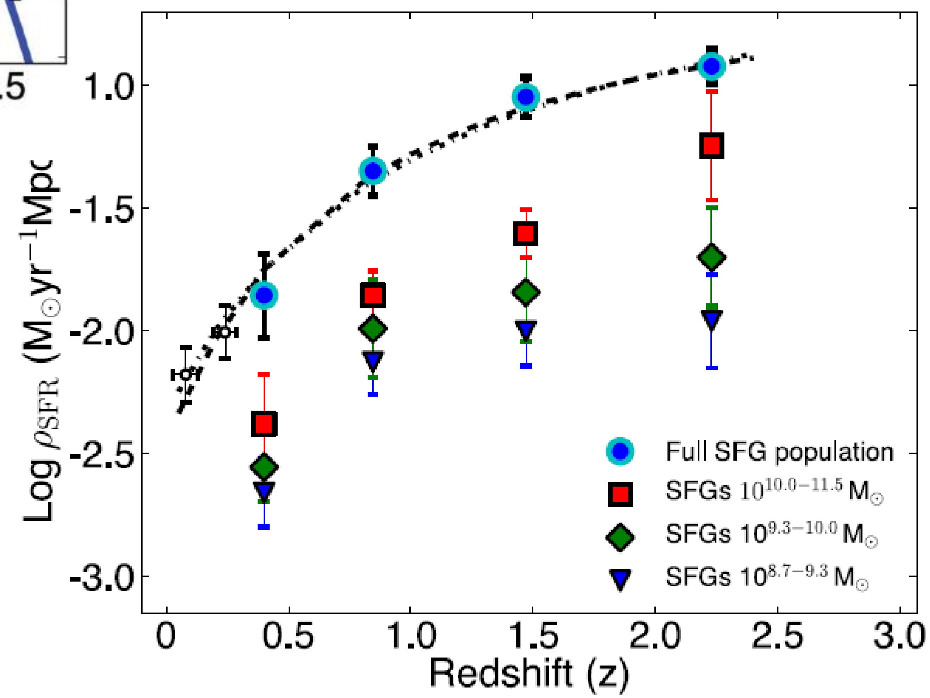
HiZELS

High redshift (Z) Emission Line Survey on UKIRT/WFCAM

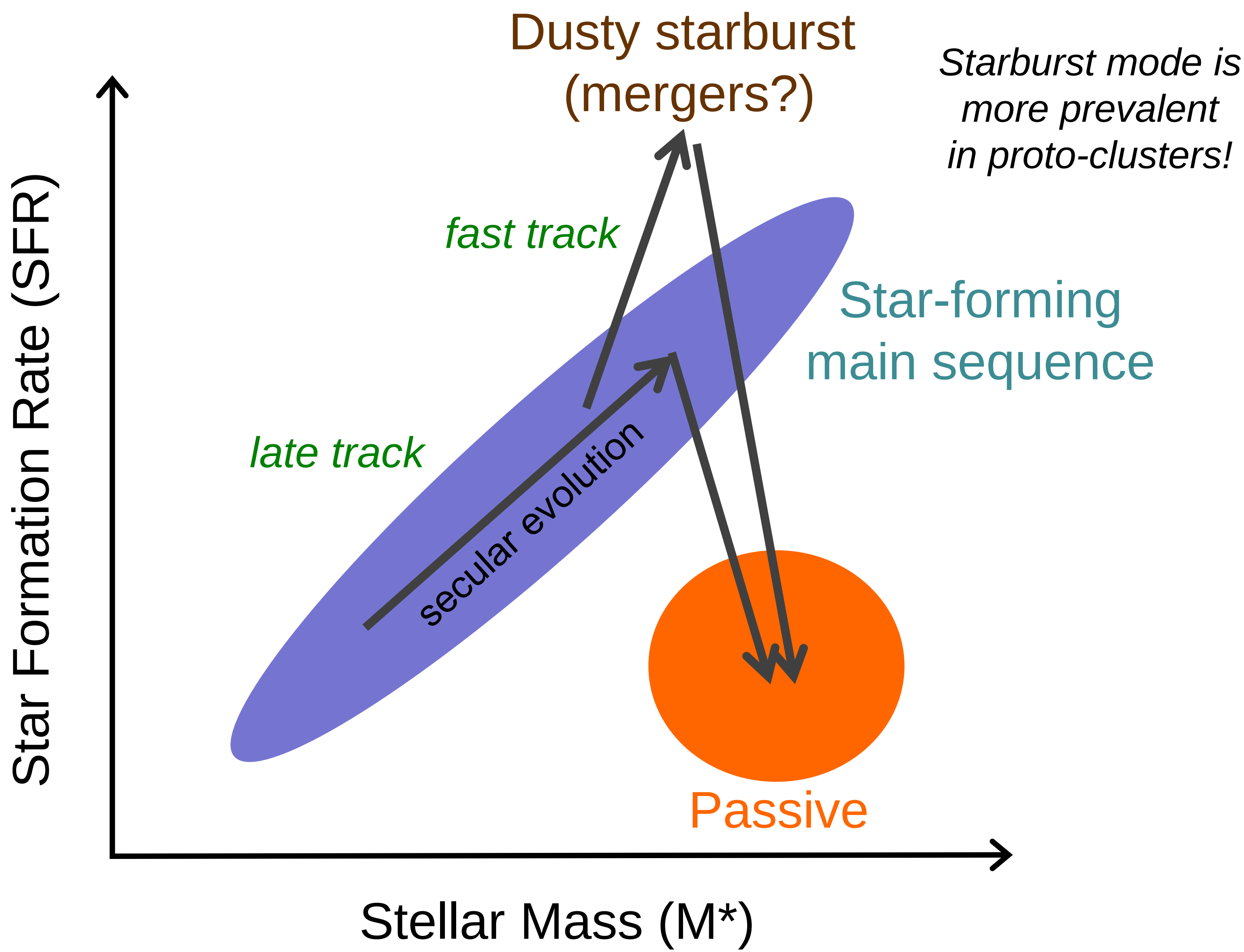
Sobral et al. (2013)

NB selected Hα emitters (1742, 637, 515 and 807) at z=0.4, 0.84, 1.47, and 2.23 over 2 deg^2.

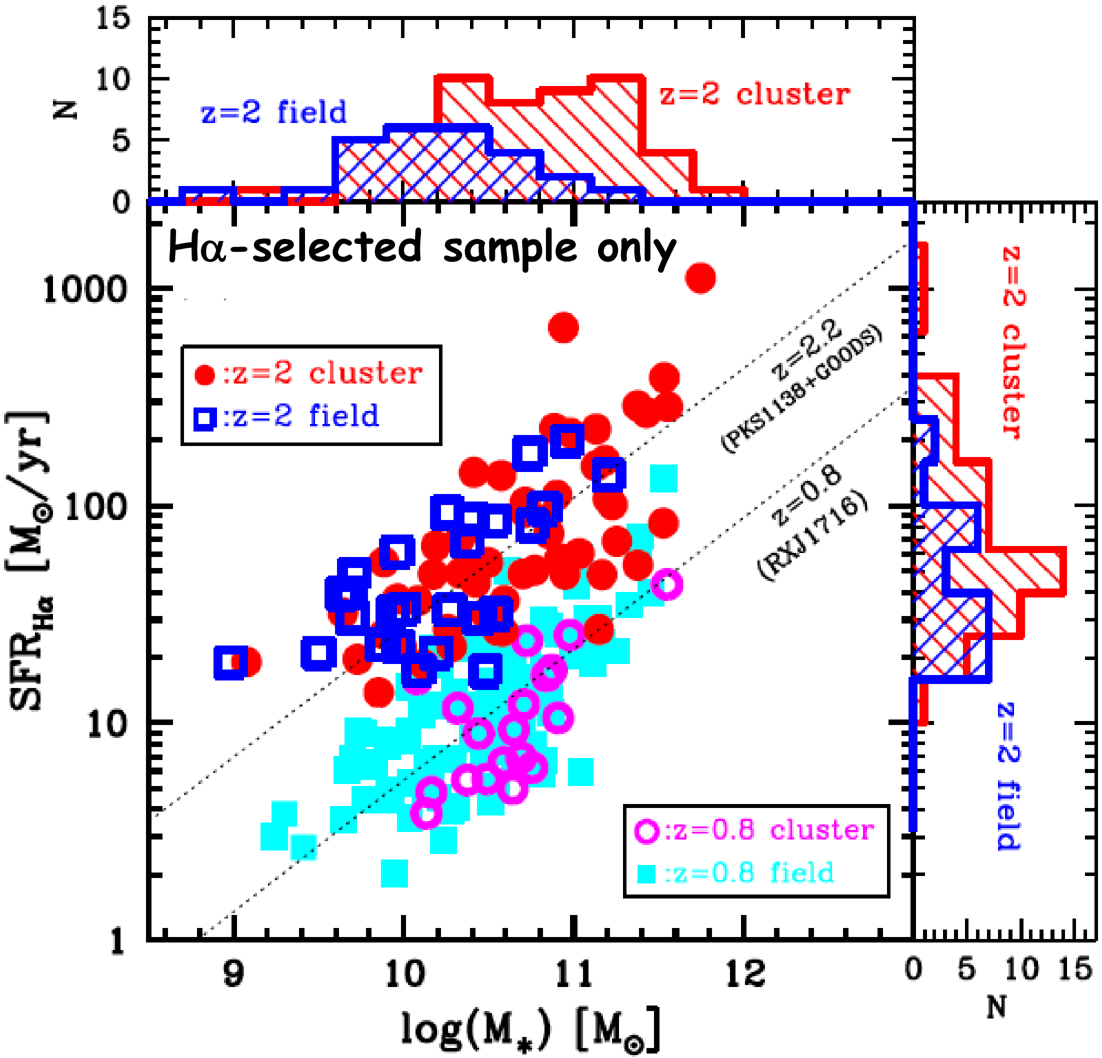
Star Formation History back to z~0.9 (Hα)
1.5 ([OIII])
2.4 ([OII])



Galaxy evolution on the main sequence diagram



Environmental (In-)dependence of the Star-Forming Main-Sequence at z>2?



M*-scaled dust correction for Ha is applied.
(Garn & Best 2010)

The same location of MS.
But cluster galaxies tend to be more massive.

Dusty starbursts and truncation may be environmental dependent

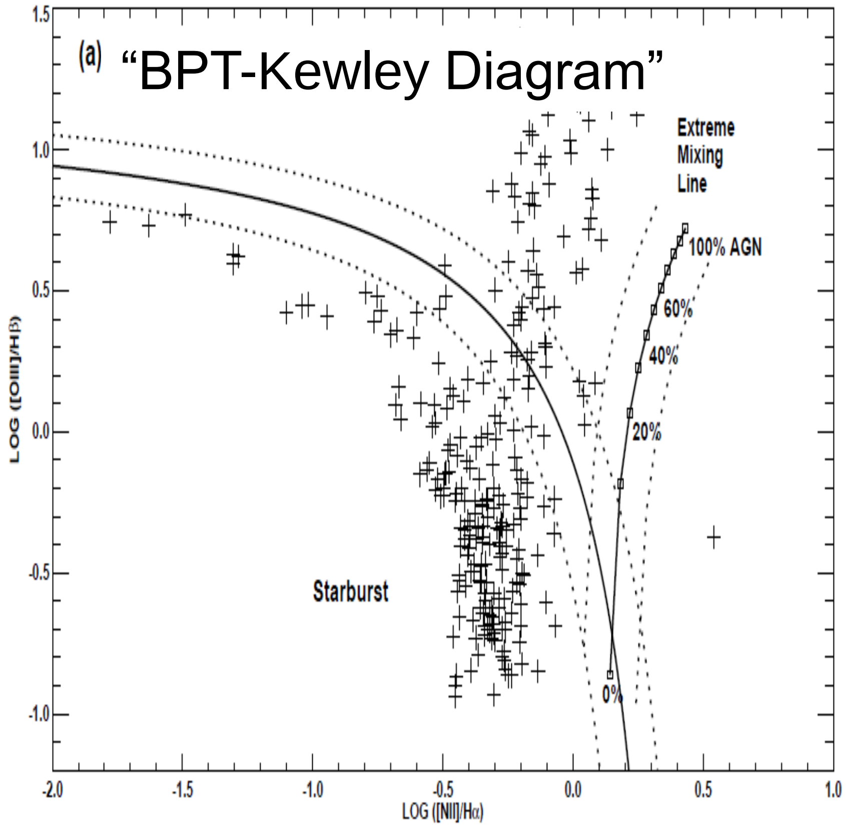
→ Large scatter around MS for cluster galaxies?

Koyama et al. (2013a)

Line diagnostics

AGN / Star-formation separation

Kewley et al. (2001)



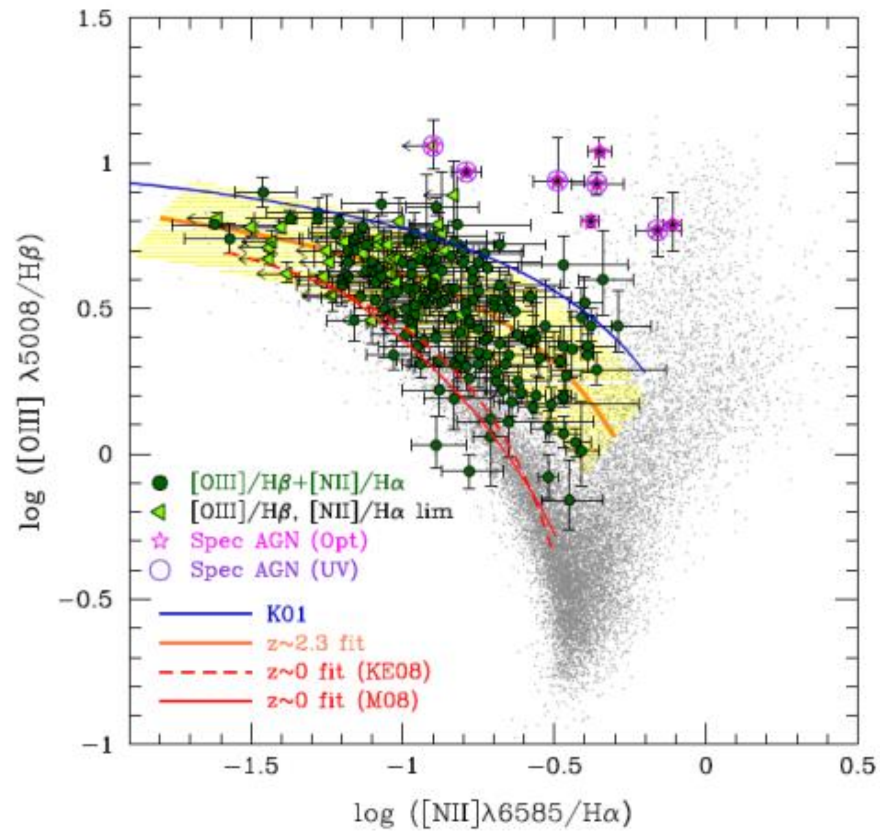
log [OIII]/Hβ

log [NII]/Hα

Relationship between SF and AGN?
SB or AGN driven wind?

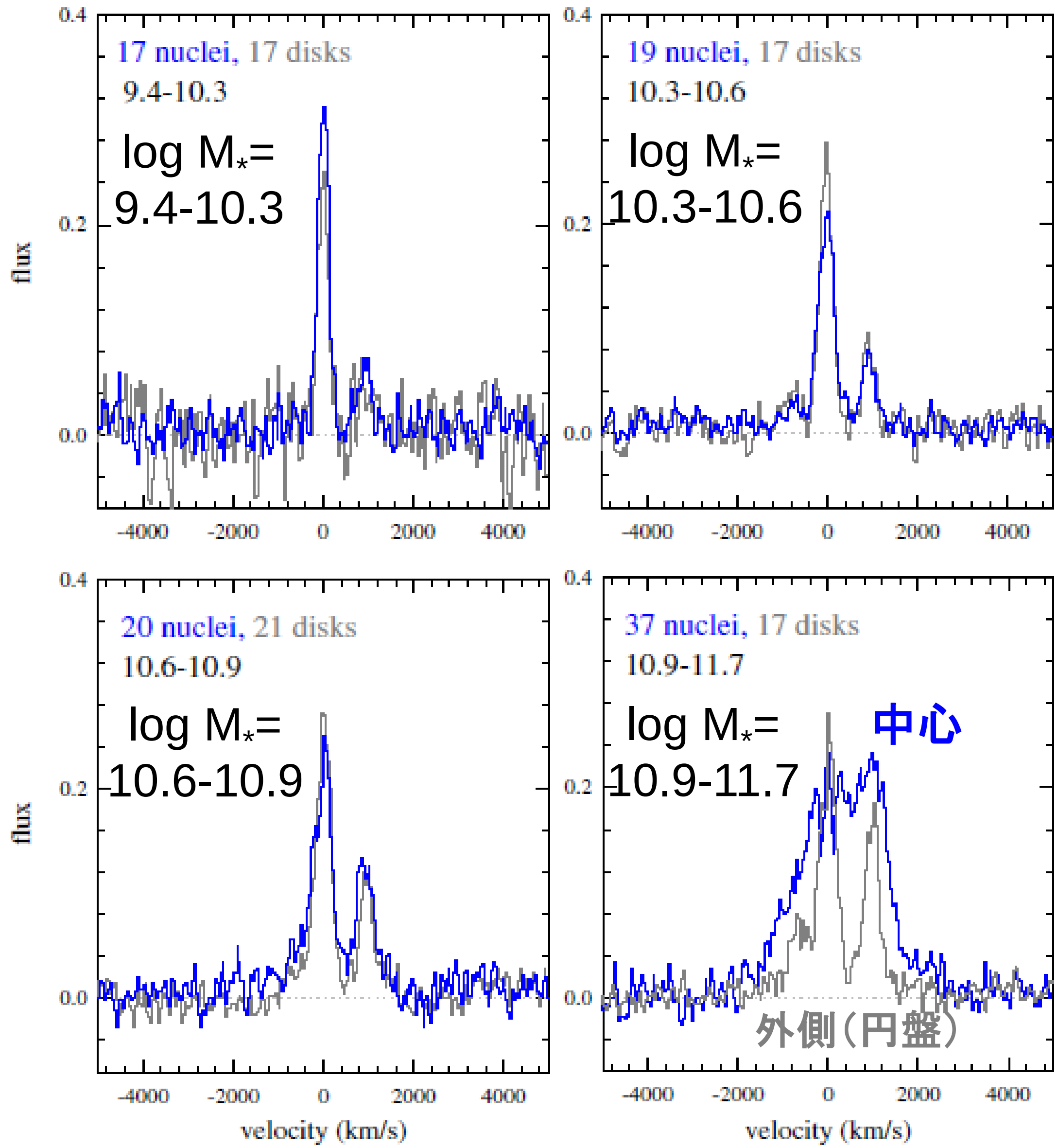
Ionization/excitation state

Steidel et al. (2014)
KBSS-MOSFIRE



High ionization state (strong [OIII]) at high-z
due probably to high SFR and lower metallicity.

星形成＆AGNによるアウトフロー（feedback）



小質量（log M*<10.9）
SFR driven outflow
(Δv_{broad}~300km/s)

大質量（log M*<10.9）
AGN driven outflow

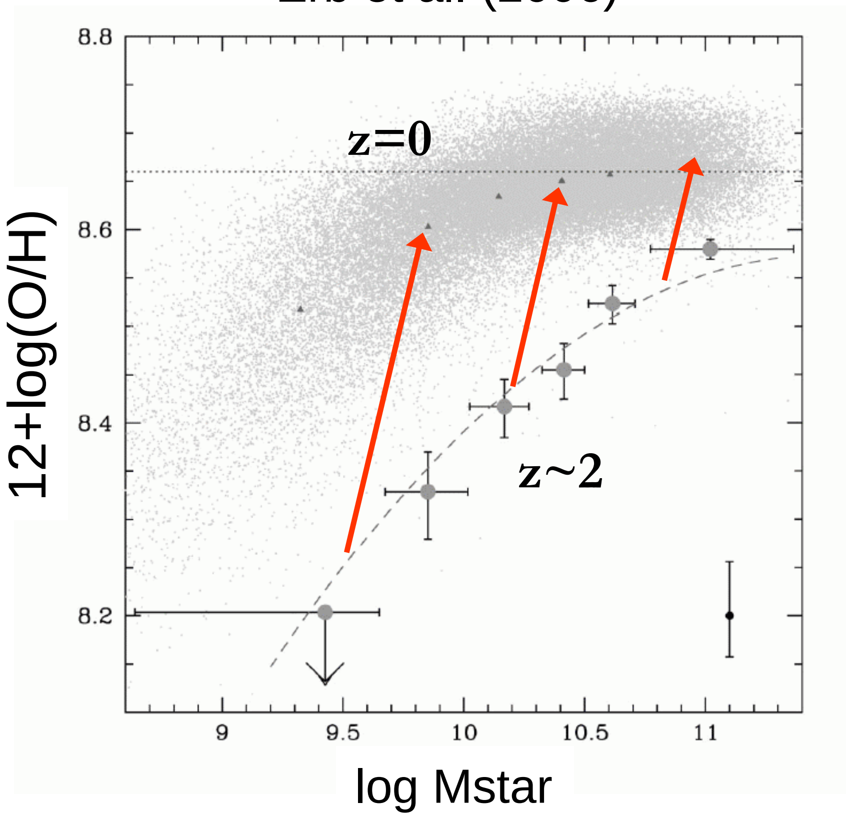
Genzel et a. (2014)

PFS: R=3000-5000 ⇔ ΔV=60-100km/s

Gaseous metallicity (Star formation + gaseous flows)

M-Z relation and its evolution

Erb et al. (2006)

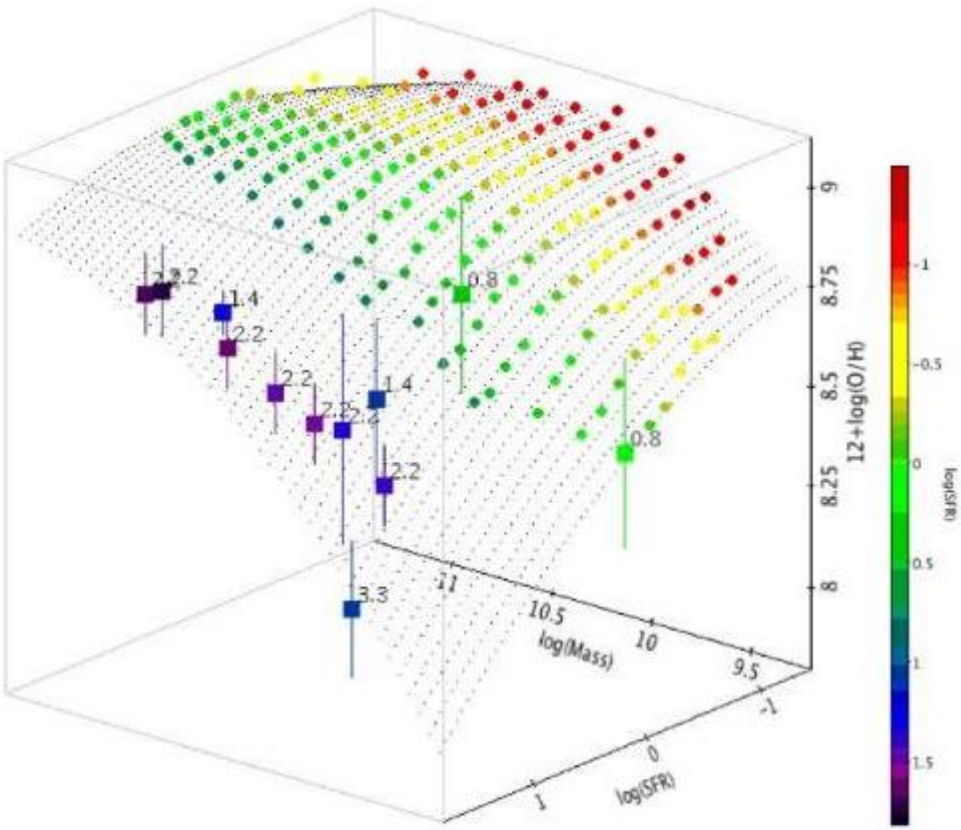


N2 = [NII] / Hα

$$\log R_{23} \equiv \frac{I_{[\mathrm{O\,II}]\lambda3727} + I_{[\mathrm{O\,III}]\lambda4959} + I_{[\mathrm{O\,III}]\lambda5007}}{I_{\mathrm{H}\beta}}$$

Fundamental metallicity relation (FMR)

Mannucci et al. (2010)



Metallicity also depends on SFR as well as M_{stars}. Galaxies with large SFR are in earlier evolution phase and contain more gas, and thus are metal poorer.

Direct Method (gaseous metallicity)

Electron temperature (Te) measurements

from [OIII]$\lambda\lambda$4959,5007/[OIII]λ4363

[OIII]λ4363 is ~1/100 of [OIII]λ5007 !

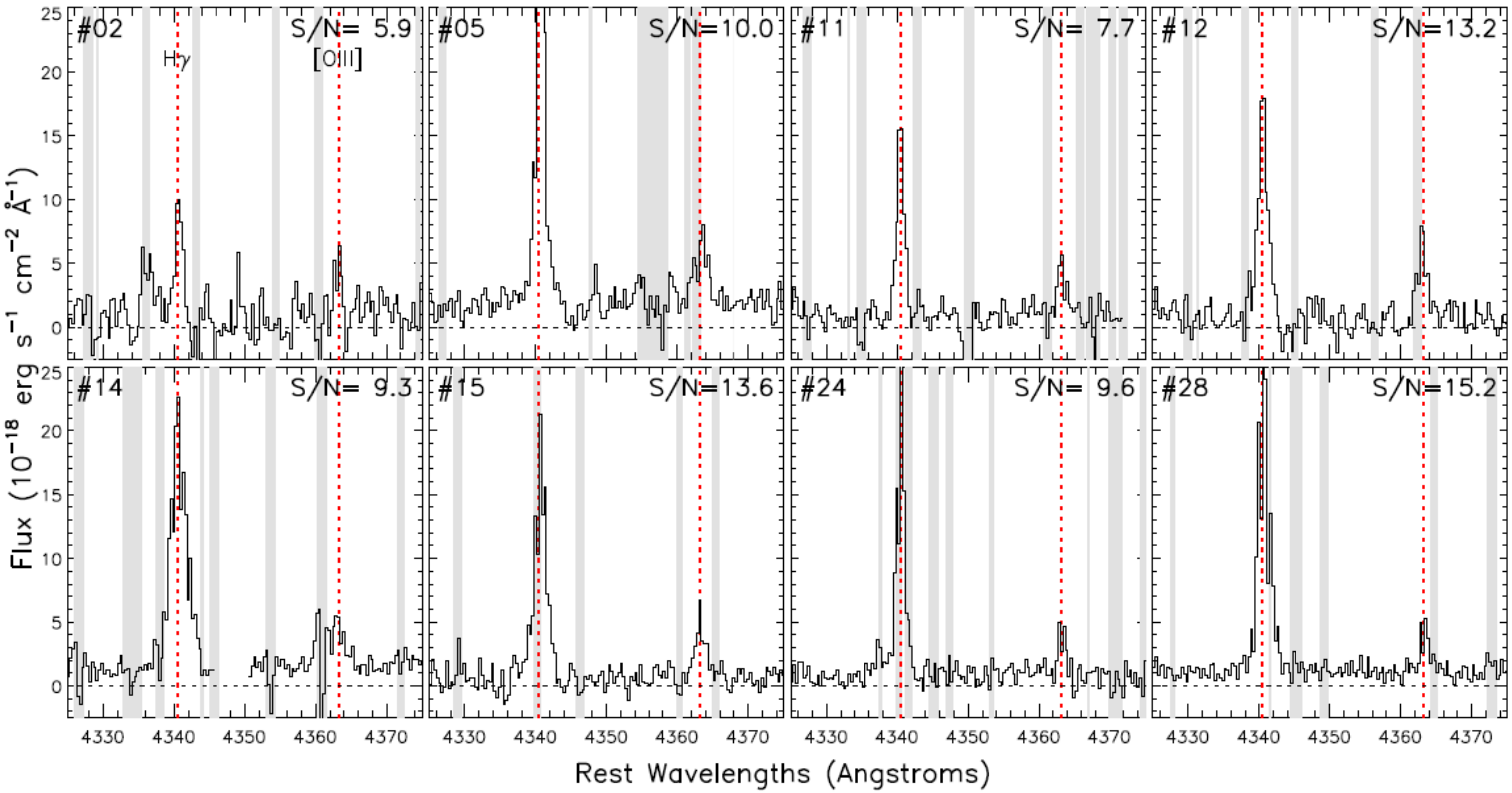
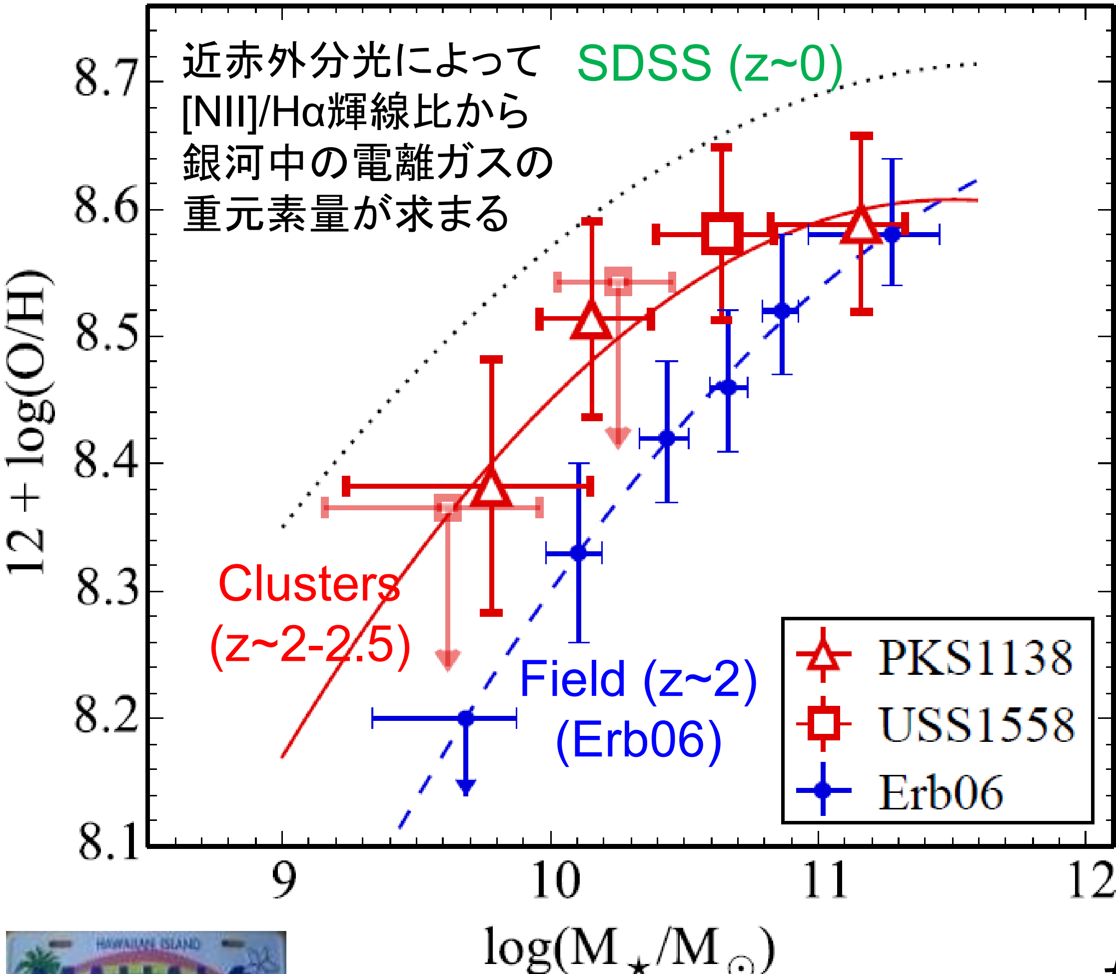


FIG. 1.— Detections of [O III]λ4363 in $z \sim 0.8$ DEEP2 galaxies. The Keck/DEIMOS spectra for 8 of 28 galaxies are shown by the solid black lines, with vertical red dashed lines indicating the locations of H$\gamma\lambda$4340 and [O III]λ4363. OH skylines are indicated by the grey shaded regions. The signal-to-noise of [O III]λ4363 detections is reported in the top right.

z=0.8 DEEP2 galaxies, Ly et al. (2014), Keck/DEIMOS

化学進化の環境依存

星の中で合成された重元素が星の死と共に放出され周りのガスを汚染する。
星形成活動が進行するにつれ銀河ガスの化学進化が進む。



Shimakawa et al. (2014b)

銀河団銀河はフィールド銀河
より同じ質量でも重元素量が高い
（大質量銀河を除く）

銀河団環境では、

より低質量の銀河まで進化が早く、
化学進化が進行している？
（ガスが少なく、重元素量が多い）

または

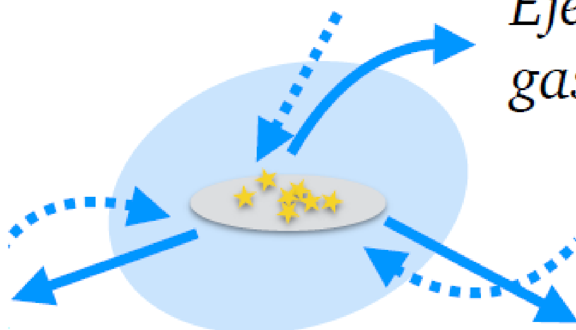
重元素量の少ない外側のガスが
はぎ取られる？

または

周りの圧力が高いため、超新星爆発
などによって銀河のガスが飛びにくく、
出戻って来て化学進化が進む？

ガスの出入りに影響を及ぼす環境効果

General field



Ejecting enriched gas selectively

Stochastic, rapid, cold gas accretion through filaments

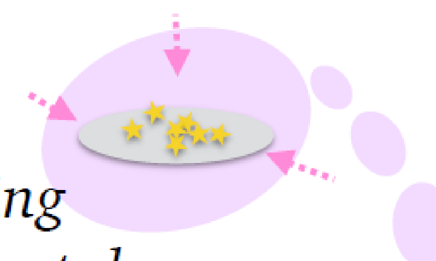
Metal dilution by primordial gas inflow

(Proto)cluster

Recycling of metal enriched gas

Stripping of metal poor gas from the reservoir

Steady but slow(?) gas accretion from a common halo

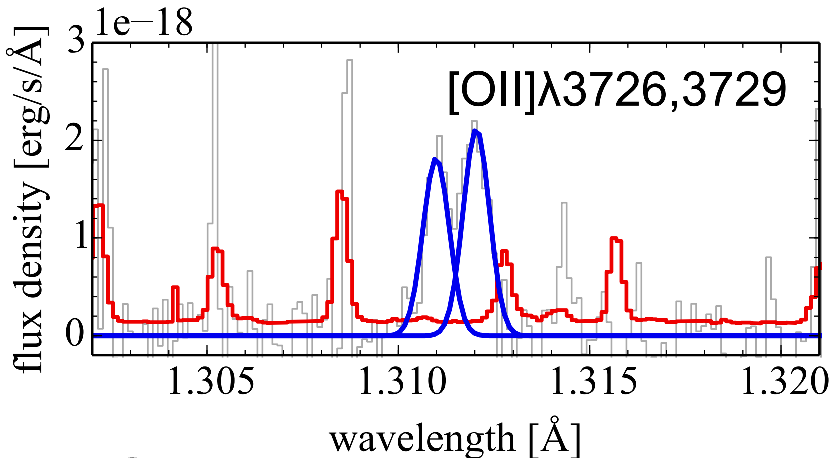


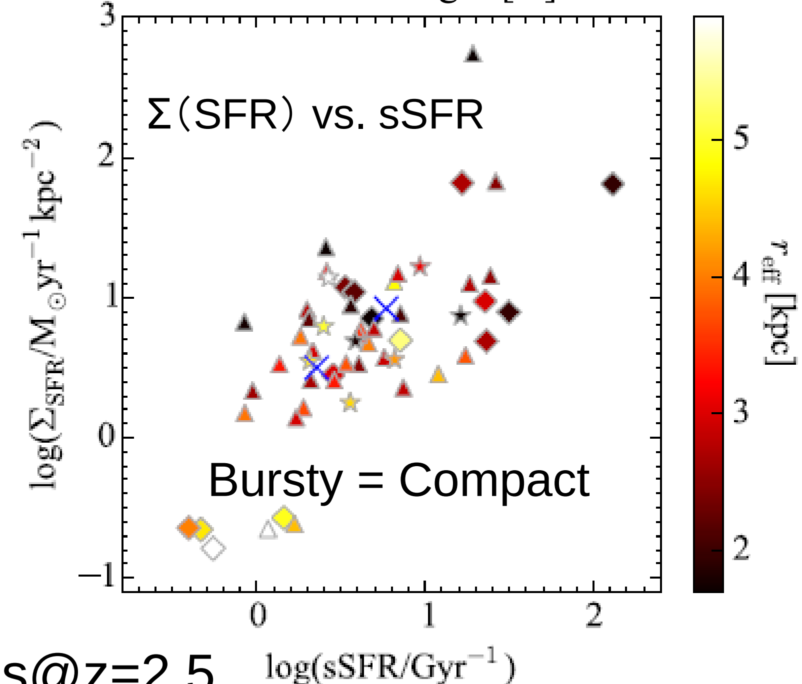
Stripping outer metal-poor gas

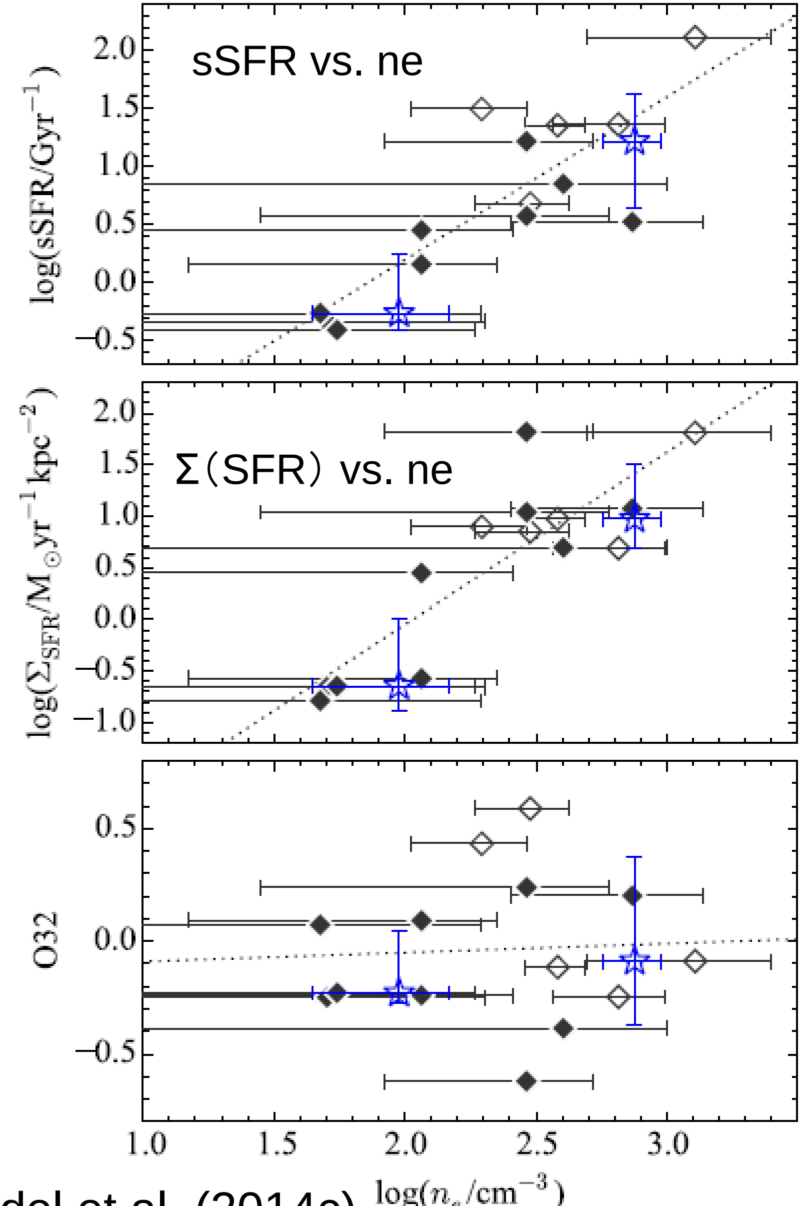
enriched gas falls back

(Dave+ '11; Kulas+ '13)

Electron density and the Schmidt-type law







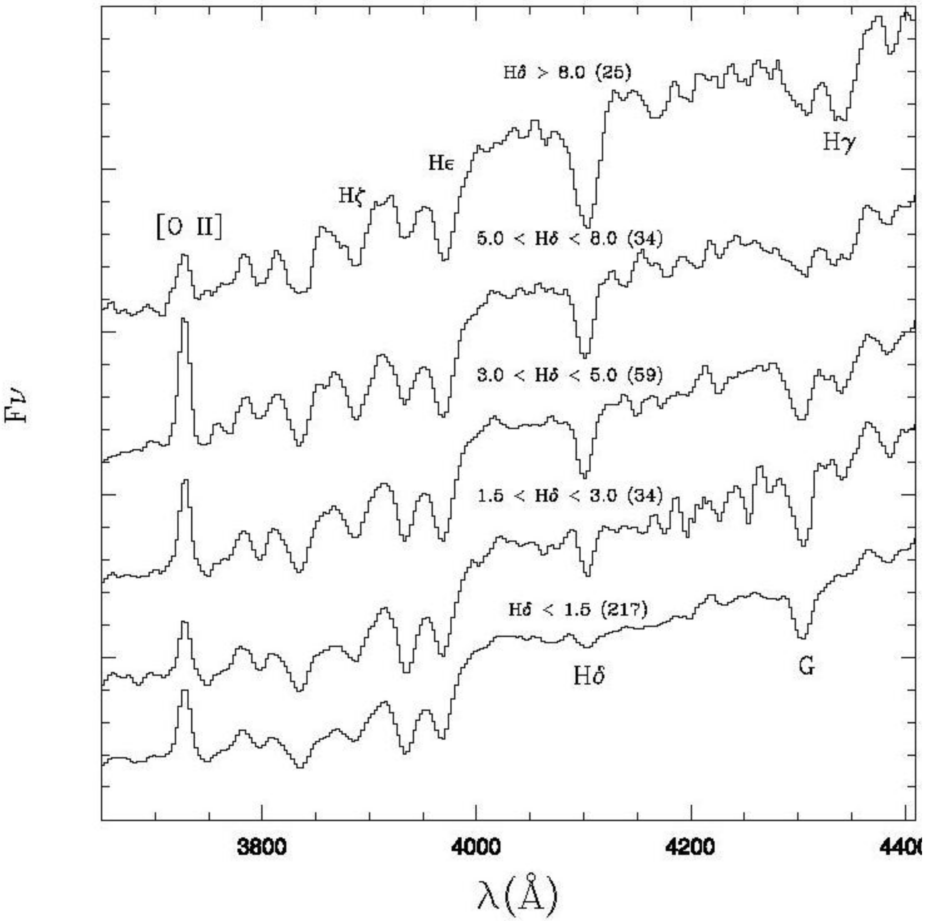
HAEs@z=2.5

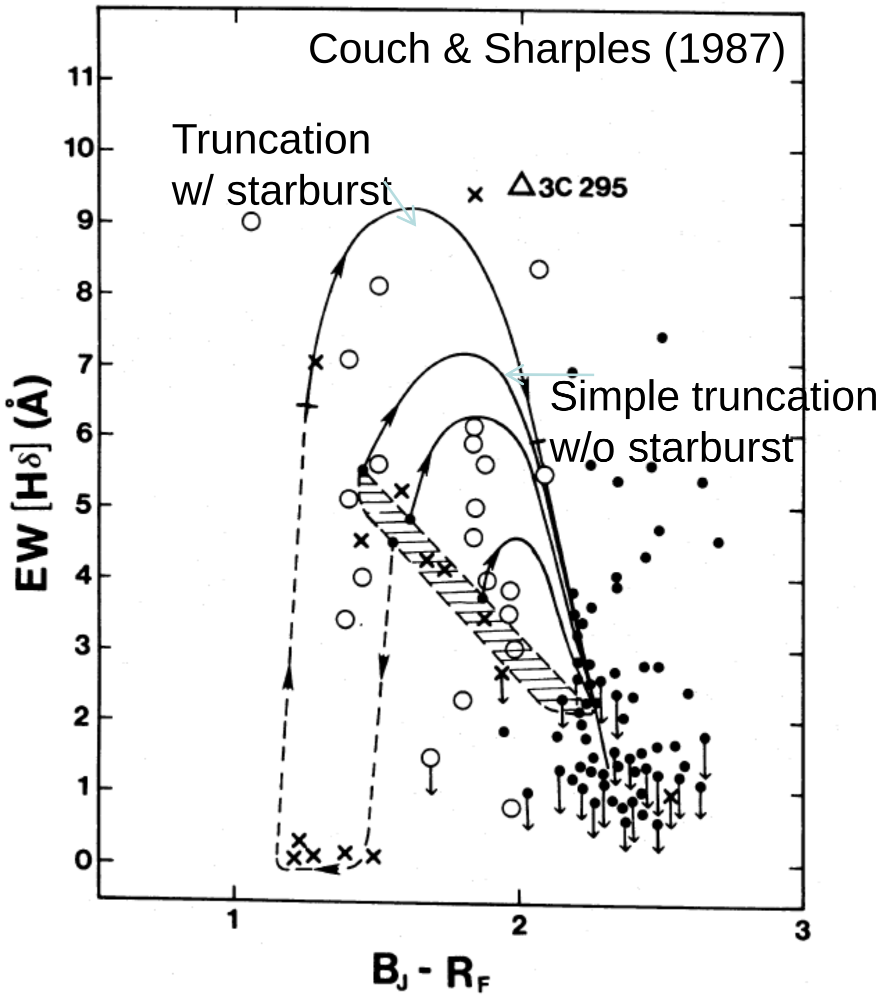
Keck/MOSFIRE

Shimakawa, Kodama, Steidel et al. (2014c)

E+A galaxies (post-starburst galaxies)

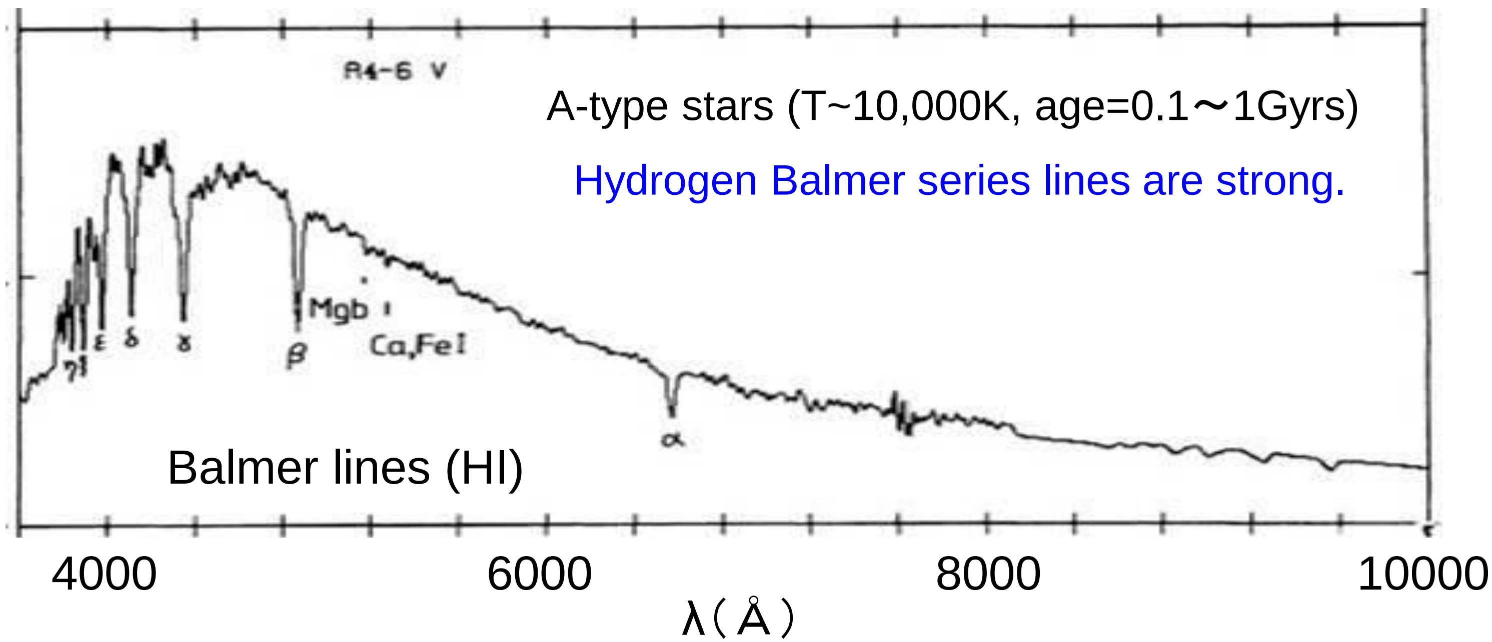
K-type red continuum + strong Balmer absorption lines

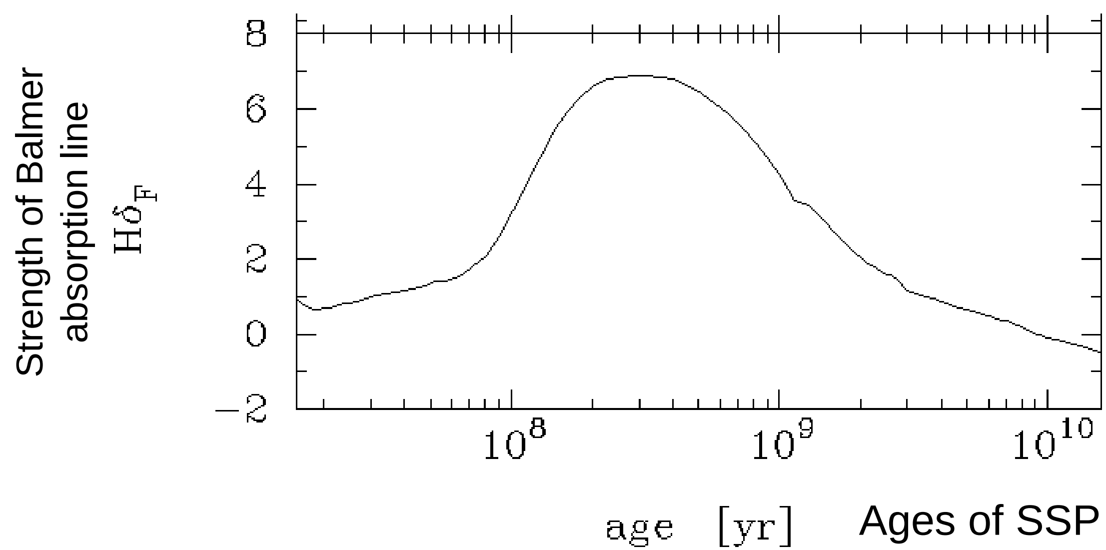




Distant clusters contain increased fraction of galaxies with strong Balmer absorption lines which have truncated star formation recently (within a Gyr). The strongest lines require starbursts just before truncation.

H Balmer absorption line is a good tracer for recent SF quenching



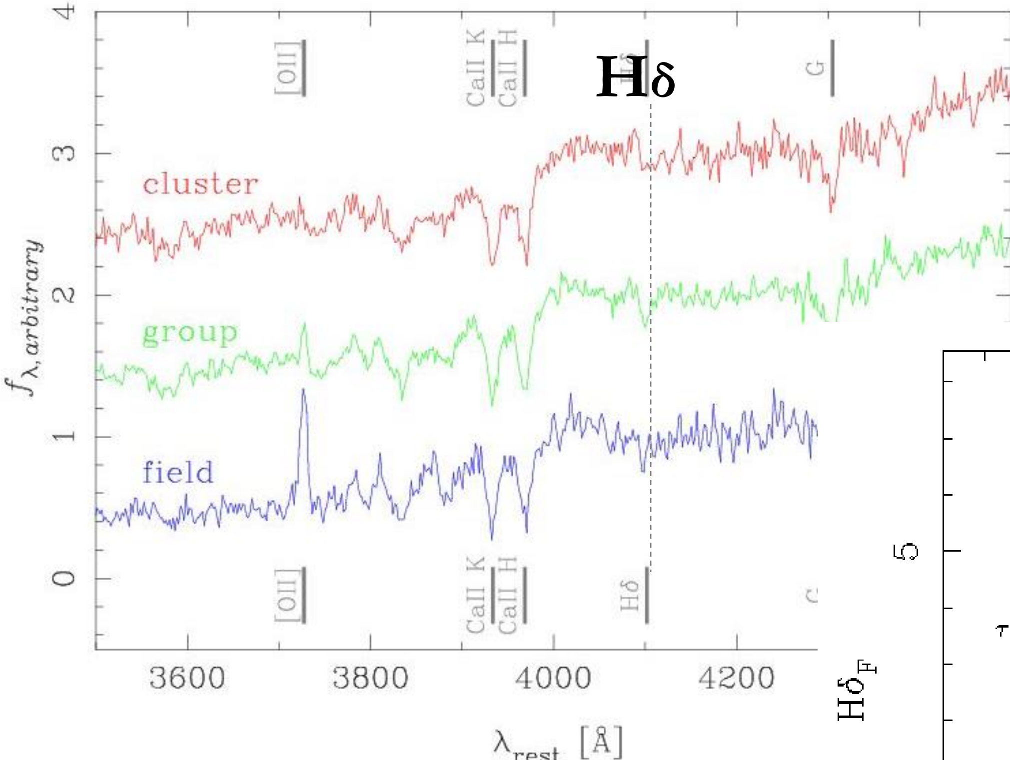


Ages of SSP models

Balmer absorption lines become strong at the age of 0.1-1Gyr when the A-type stars dominate the integrated spectra, and then declined afterwards.

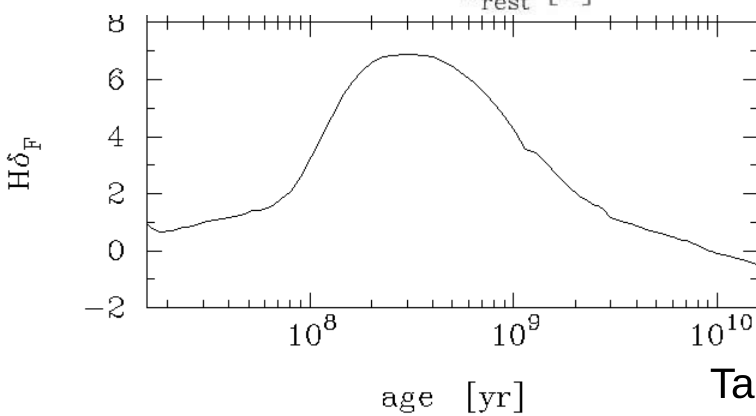
Post-starburst galaxies in group environment

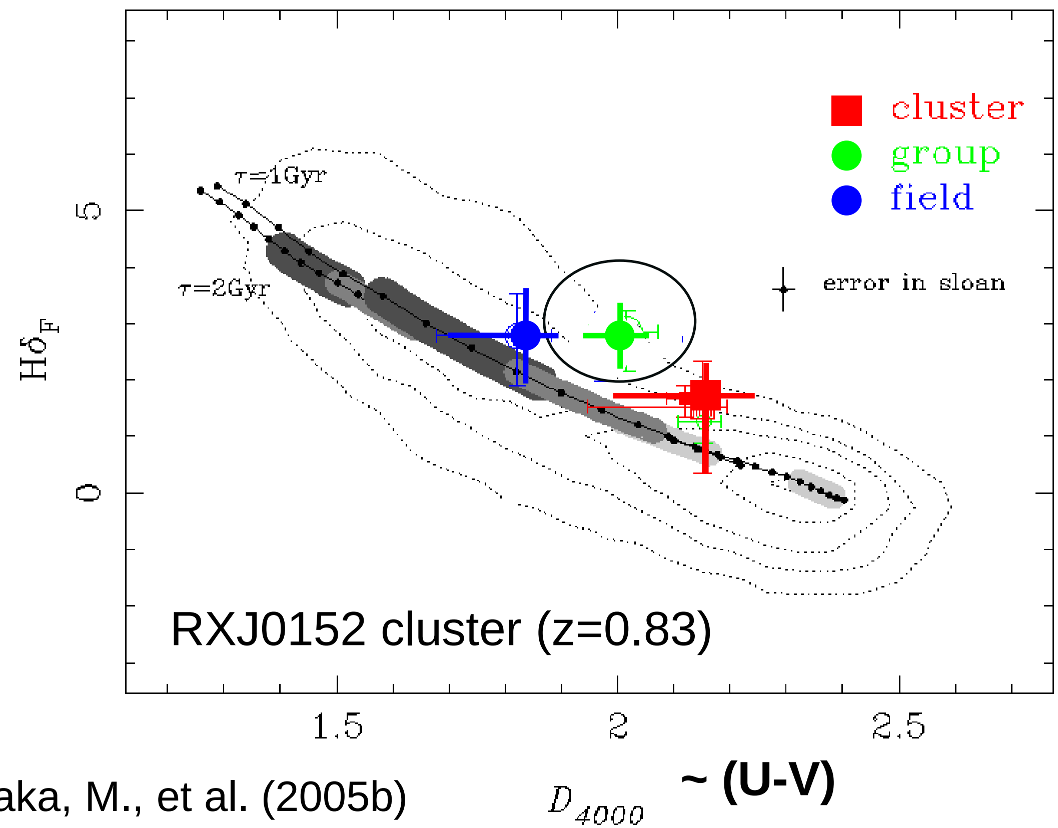
Comparison of stacked spectra of red galaxies at different environments



Stacked spectra of 10 galaxies each with 2 hrs exposure each.

Relatively strong Balmer absorption lines are seen, suggesting recent, intensive star formation activities.





Tanaka, M., et al. (2005b)

~ (U-V)

What quenches star formation in cluster galaxies?

- Ram-Pressure Stripping (～10^7 yrs)

  The gas in a galaxy is stripped off by the ram-pressure of ICM when it falls into a cluster.

- Galaxy-Galaxy Mergers (～10^8 yrs)

  The gas is stripped off by the tidal force or consumed rapidly during mergers.

- Suffocation (～10^9 yrs)

  The gas trapped weakly in galaxy haloes can be easily stripped off by tidal interactions with other galaxies or by ram-pressure of ICM. The remaining gas in the disk is consumed rapidly without a supply of fresh gas any more and the galaxy “suffocates” and the star formation is eventually truncated.

- AGN/SB feedback (～$10^{8\text{-}9}$ yrs)

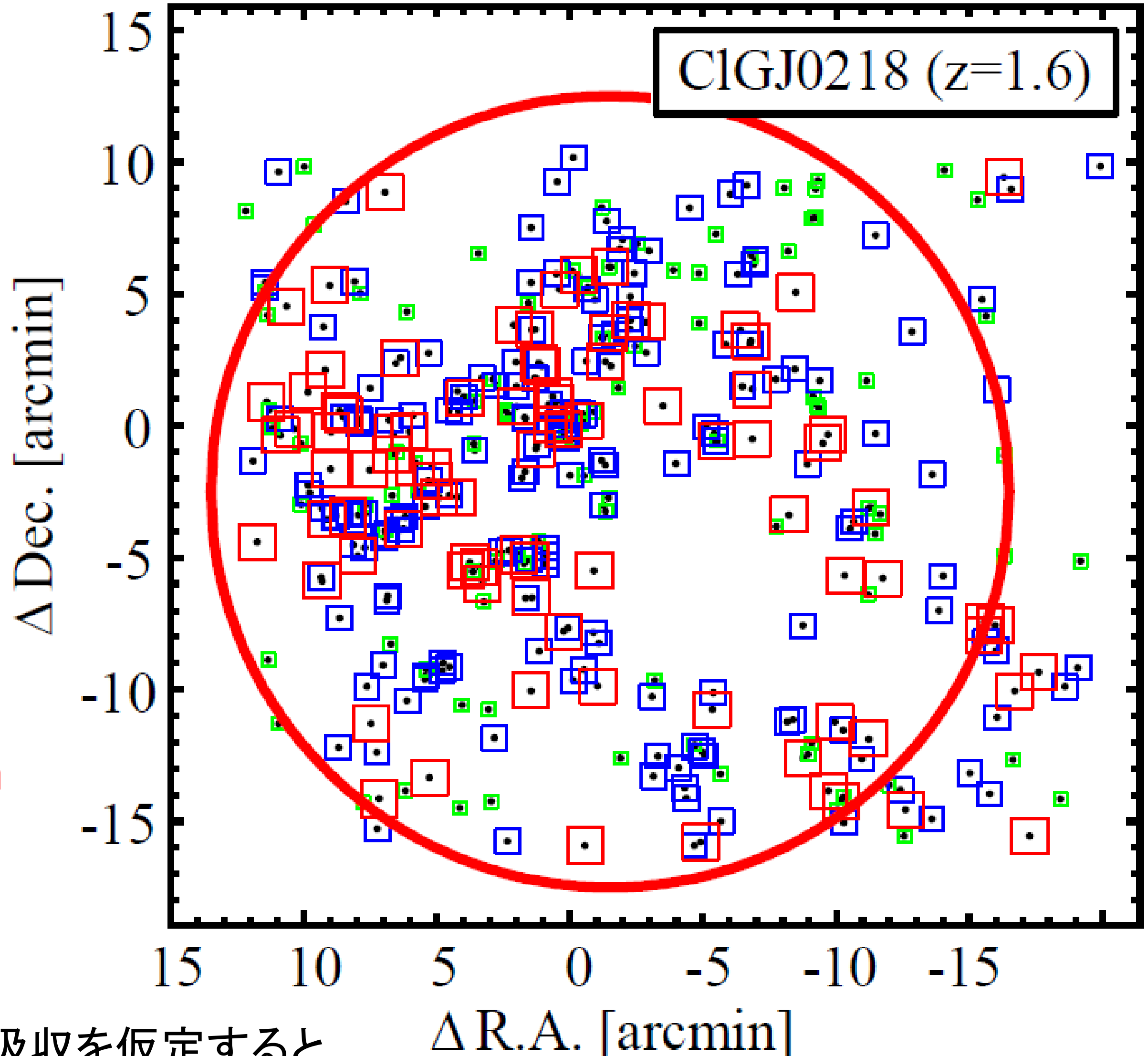
  Galaxy mergers often induce starbursts and AGN activities which can expel the gas out of the system due to large energy input.

FMOSの例

H-long (Hα, [NII]) で
4 hrs exposure
2 configurations

J-long (Hβ, [OIII]) で
6 hrs exposure
1 configuration

※Minimum separation
FMOS: 12arcsec
PFS: 30arcsec



Hαで1等級のレベルの吸収を仮定すると、

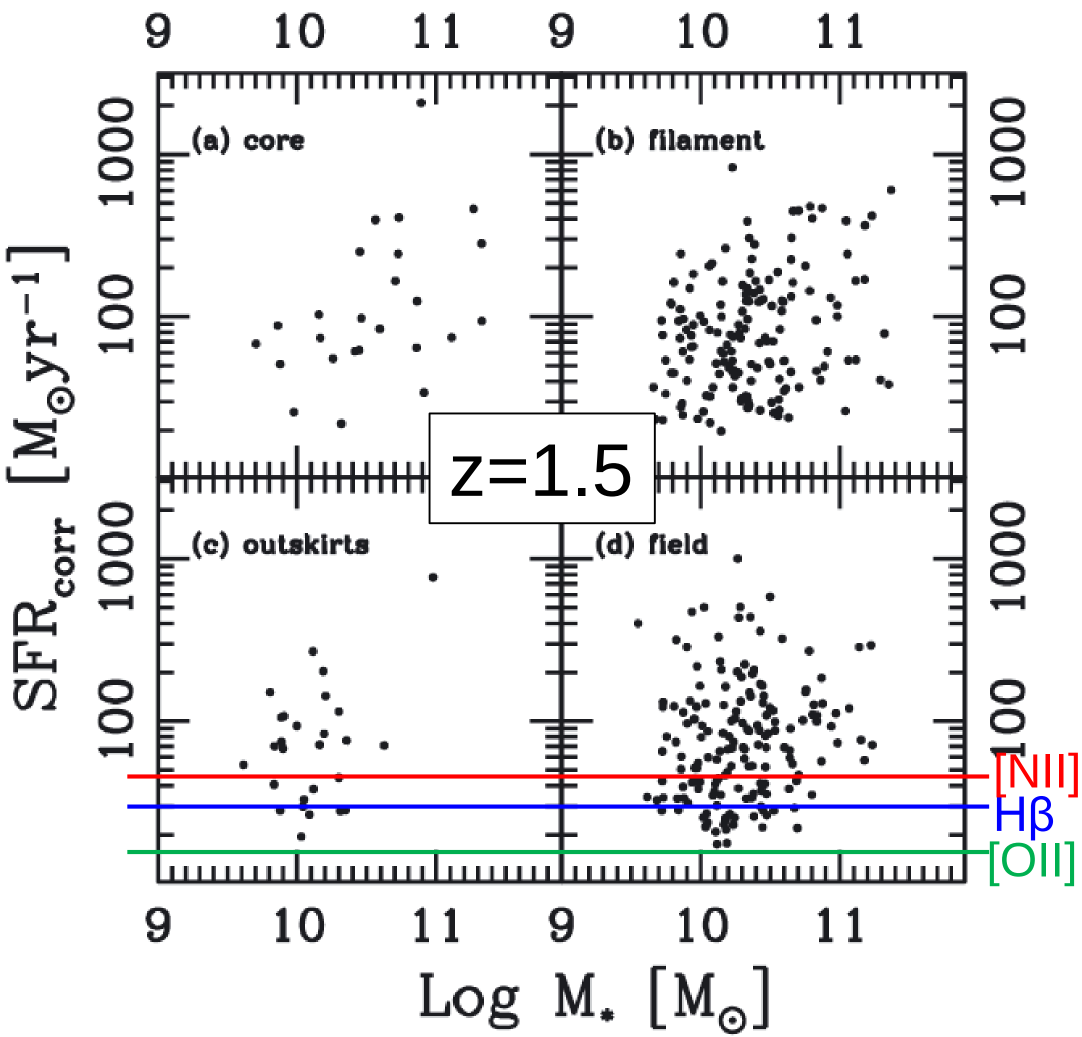
赤□：Hα, [NII], Hβ が検出可能（91個）

青□：Hα, Hβ が検出可能（171個）

緑□（小）：Hα　のみが検出可能（95個）

PFS 1 hour exposure ⇔ 1.8×10^{-17} erg/s/cm^2 (5σ) at 1-1.26μm

⇔ SFR(Hα, [OIII])$_{corr}$ ~ 7$M_\odot$/yr @ z=1.5



Observed line flux ratios
(no dust correction)

Hα/[OIII] ~ 1
Hα/Hβ ~ 4-5 (4)
[OIII]/Hβ ~ 2-6 (4)
Hα/[NII] ~ 3-15 (6)
Hα/[OII] ~ 2-3 (2.5)
(Steidel+14,Hayashi+11)

For absorption lines, 6 hrs exposure will achieve 5σ at J* (passive) at z=1.5, still requiring stacking analyses (20σ with 16 galaxies).

Hayashi et al. (2011), XMM2215-17 cluster (z-1.47)

Summary

- PFS-PFS on HSC-HSC

→ ~200 clusters at z~1 ($\Delta z=1$) in HSC-Deep

- Star formation history, Dust extinction, Chemical evolution, AGN-Galaxy co-evolution, and Physical States (electron density, electron temperature, ionization state),
  and their Environmental Dependence.

Truly statistical analyses (including stacking analyses) to z<1.5 across various environments!