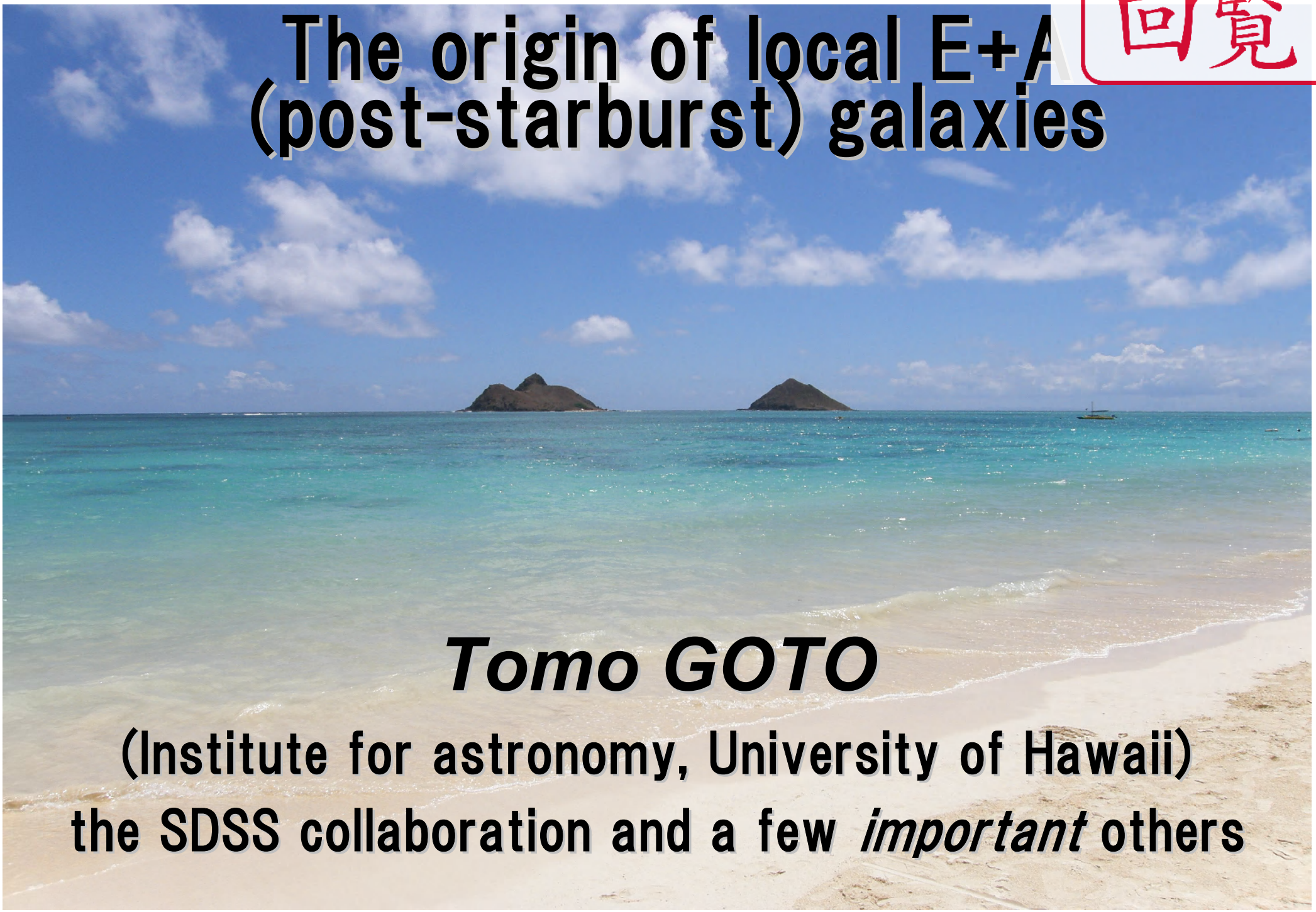
回覧

The origin of local E+A (post-starburst) galaxies



Tomo GOTO

(Institute for astronomy, University of Hawaii)

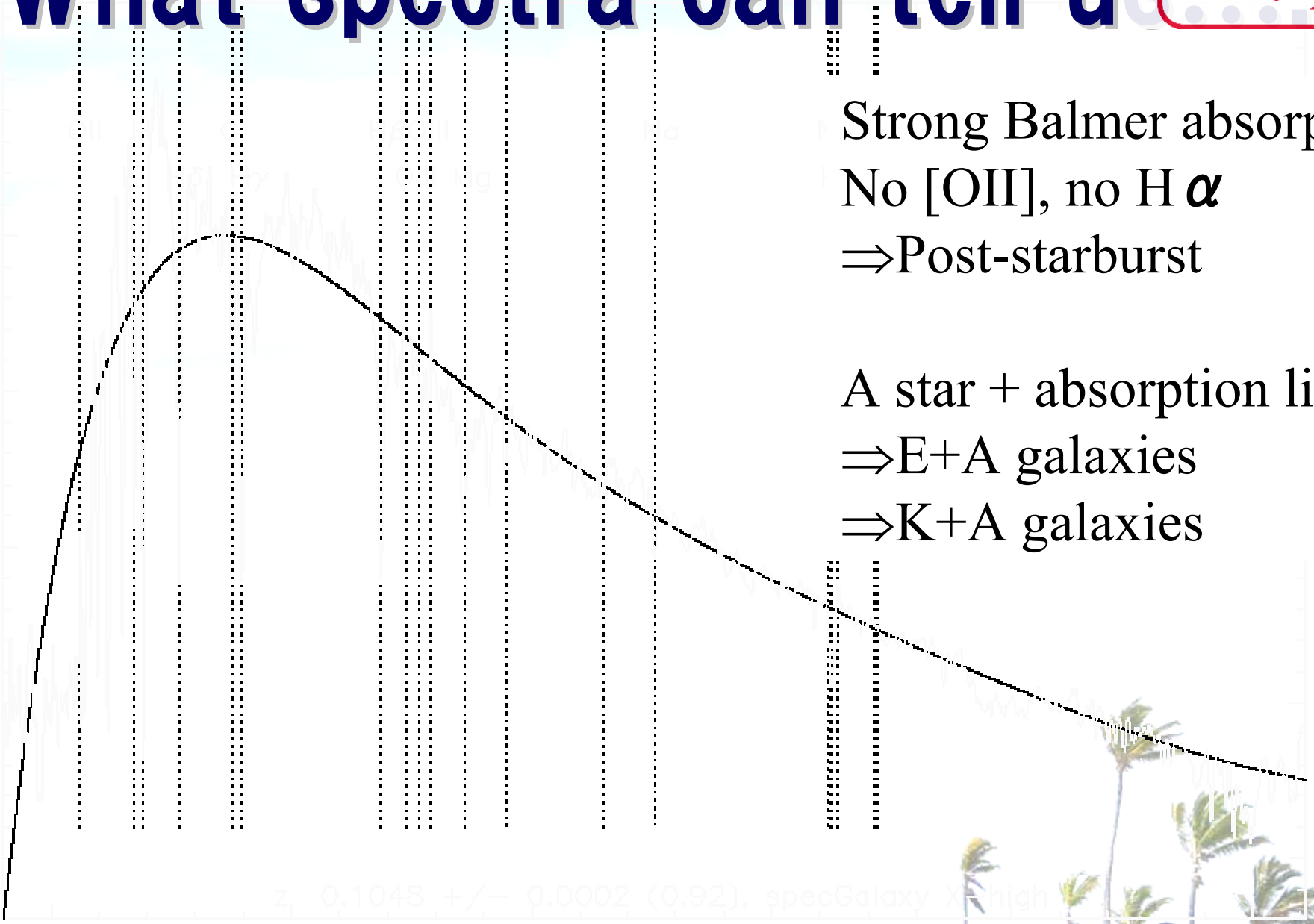
the SDSS collaboration and a few *important* others


KDN NO. PP13566/10/2009(022554)
Your complete daily TV listings inside!
view
TRAVELLER
Post-starburst
for high-z
E+A galaxies
malaysia's best
starts here
galaxy evolution

回覧

What spectra can tell us...

回覧



Strong Balmer absorption
No [OII], no Hα
⇒Post-starburst

A star + absorption lines
⇒E+A galaxies
⇒K+A galaxies

E+A has α enhancement. →Post-starburst

回覧

- α elements (e.g., Mg) are from typeII Super Novae.
- Fe is from type Ia Super Novae with time delay of a few Gyr.
  - i.e., Post-starbursts have no time to create Fe, should have α enhanced. What about E+As?

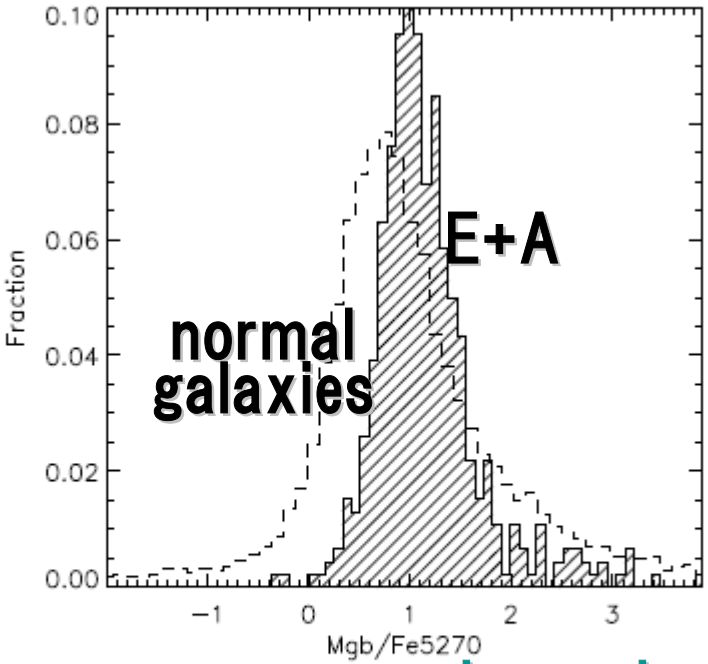


Figure 5. The histogram of the ratio of Mgb to Fe5270 is shown for E+A galaxies in the solid, hashed region, and for star-forming galaxies with the dashed lines. A Kolomogorov-Smirnov test shows these two distributions are significantly different with more than 99.999% confidence level.

Goto, T. 2007,MNRAS.377.1222

- As expected, E+As have α enhancement.
  - Independent evidence of post-starburst.

Two puzzles on E+A(post-starburst)

回覧

- What caused star burst?
- What stopped it?

- Cluster related. Found to live in cluster region (MORPHS, Dressler & Gunn 83)
- Dust enshrouded star formation.(Poggianti et al. 1999; Smail et al. 1999)
- Merger/Interaction (Zabludoff et al 1996)

Still puzzles

- Very rare(21/11113 in LCRS). Phase is short(1Gyr). Million spectra of SDSS provide good opportunity to address this 25-year-old puzzle.

What happens when starburst shut off...

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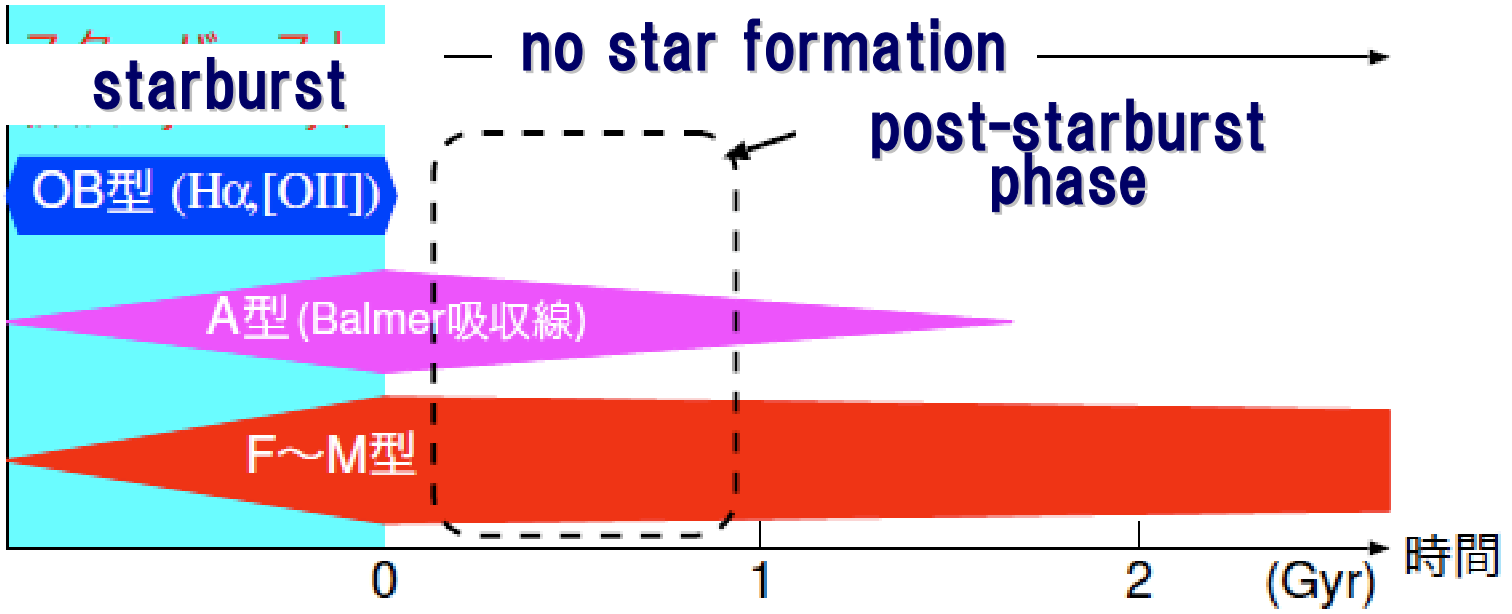
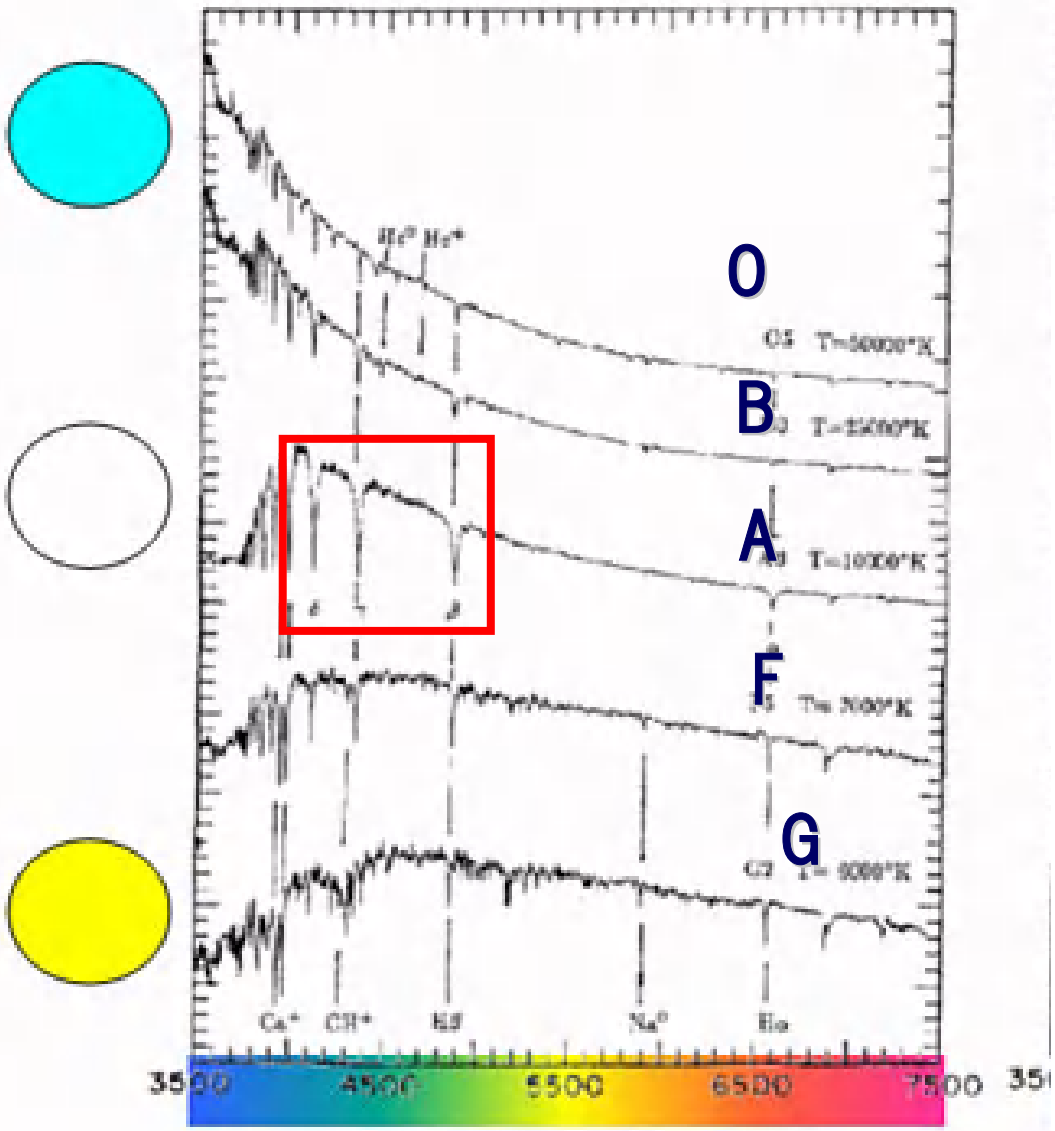


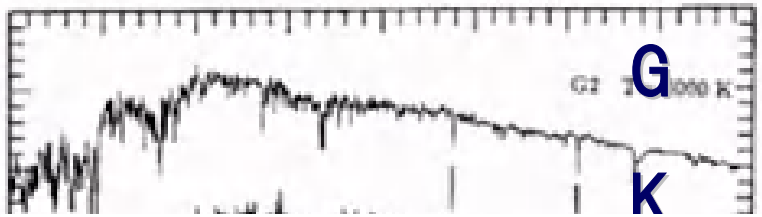
- Lifetime of OB stars: 0.01 Gyr, A stars :1Gyr
- No [OII], no Hα emission →no OB stars
- Balmer absorption →A stars

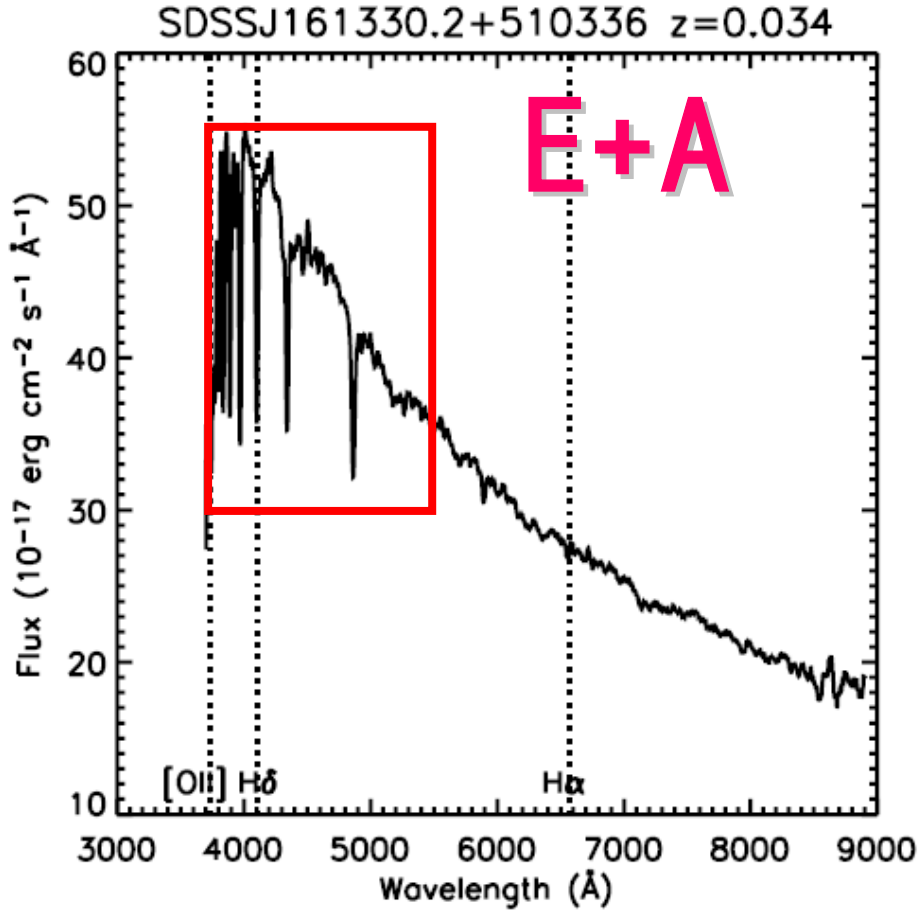
©C.Yamauchi

A stars have strong Balmer absorption

回覧







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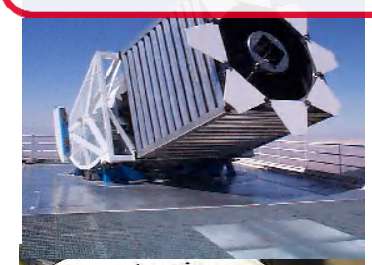
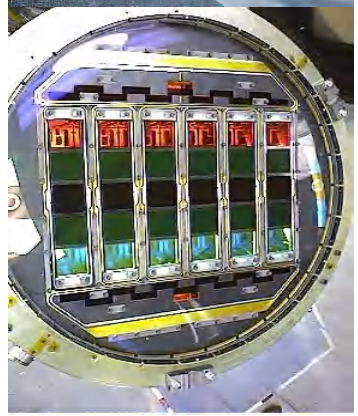
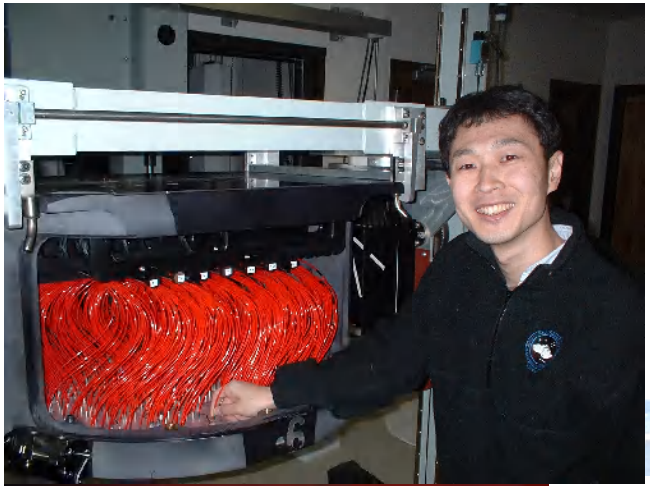
Sloan Digital Sky Survey (SDSS)

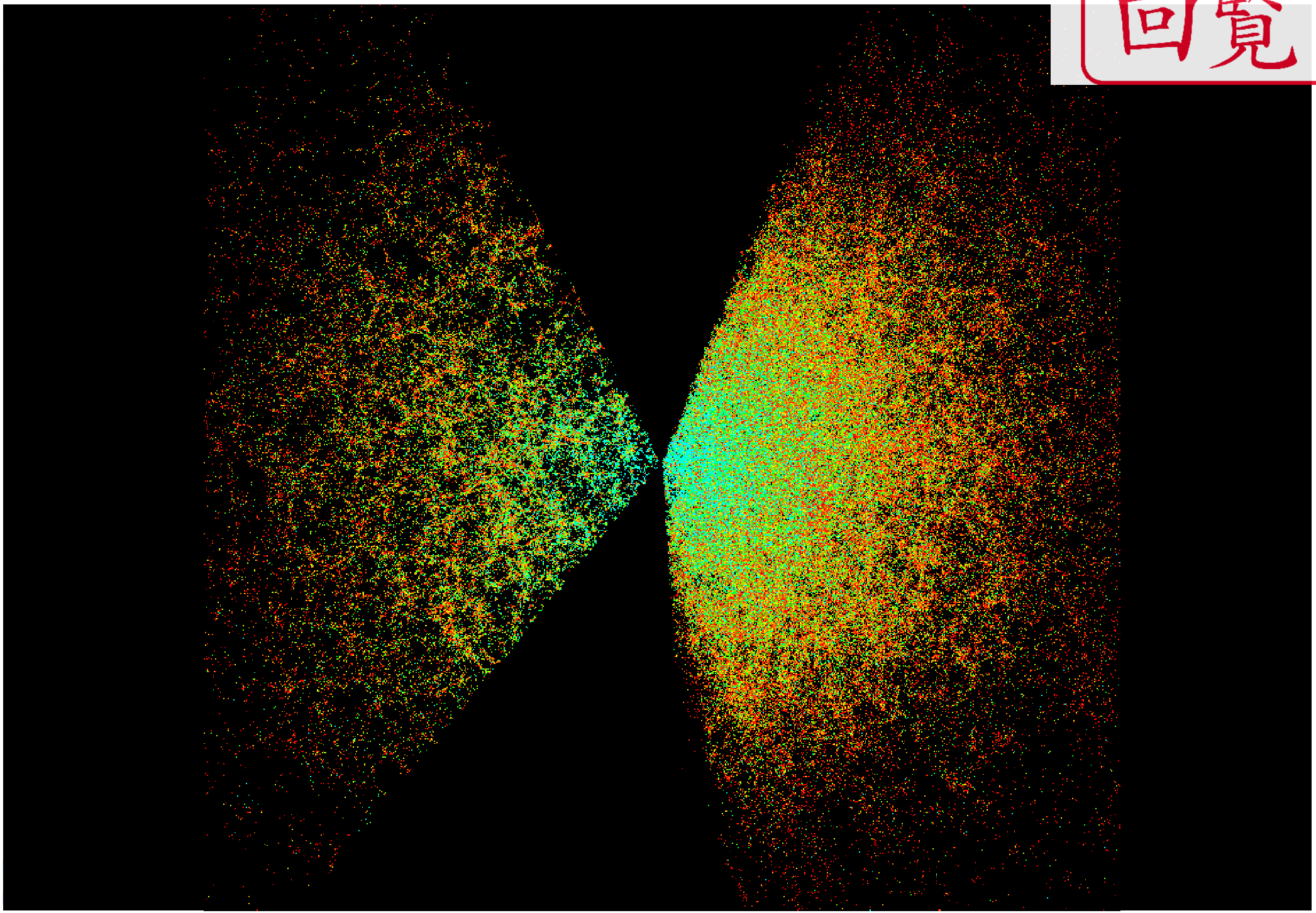




- SDSS will produce
  - Imaging of 10,000 sq.deg *r*~23.1
    In 5 optical bands (*ugriz*)
  - Spectra of $1.0\times10^{6}\,galaxies$
    and $1.5\times10^{5}\,QSOs$
    in 5 years



Using 2.5m telescope at APO.



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Evolution is difficult to observe.

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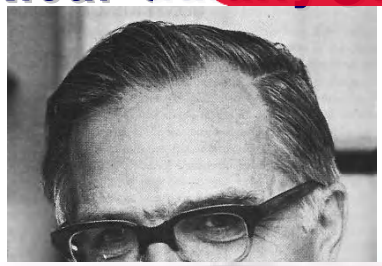
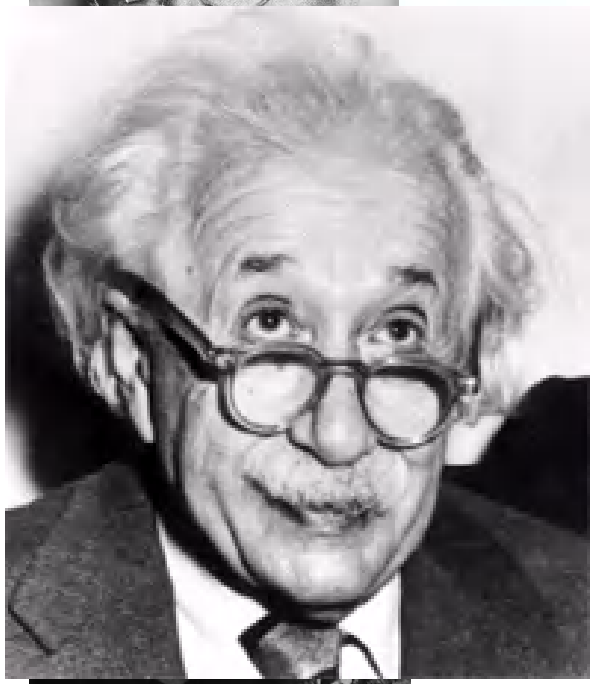
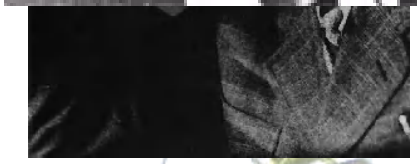
Elliptical Galaxy@z=0



Important Transition Stage

popⅢ galaxy@z=10





Spiral galaxy@z=0

It is important to observe galaxy evolution in action→ E+As

How to find E+As

Goto, T. et al. 2003, PASJ, 55, 771
Goto, T. 2005, MNRAS, 357, 937

回覧

- Hδ EW>4 Å (2.42%)
- 4 categories.
  - E+A: Hα<1σ, [OII]<1σ, No emission lines. (0.04%)
  - HDS+[OII]: Hα<1σ, [OII]$\geqq$1σ (0.09%)
  - HDS+Hα: H$\alpha$$\geqq$1$\sigma$, [OII]<1$\sigma$ (0.04%)
  - HDS+em: H$\alpha$$\geqq$1$\sigma$, [OII]$\geqq$1$\sigma$, Significant emission lines. (2.25%)

The largest catalog of 1284 E+As out of 700,000 galaxies of SDSS DR6.

E+A Spectra

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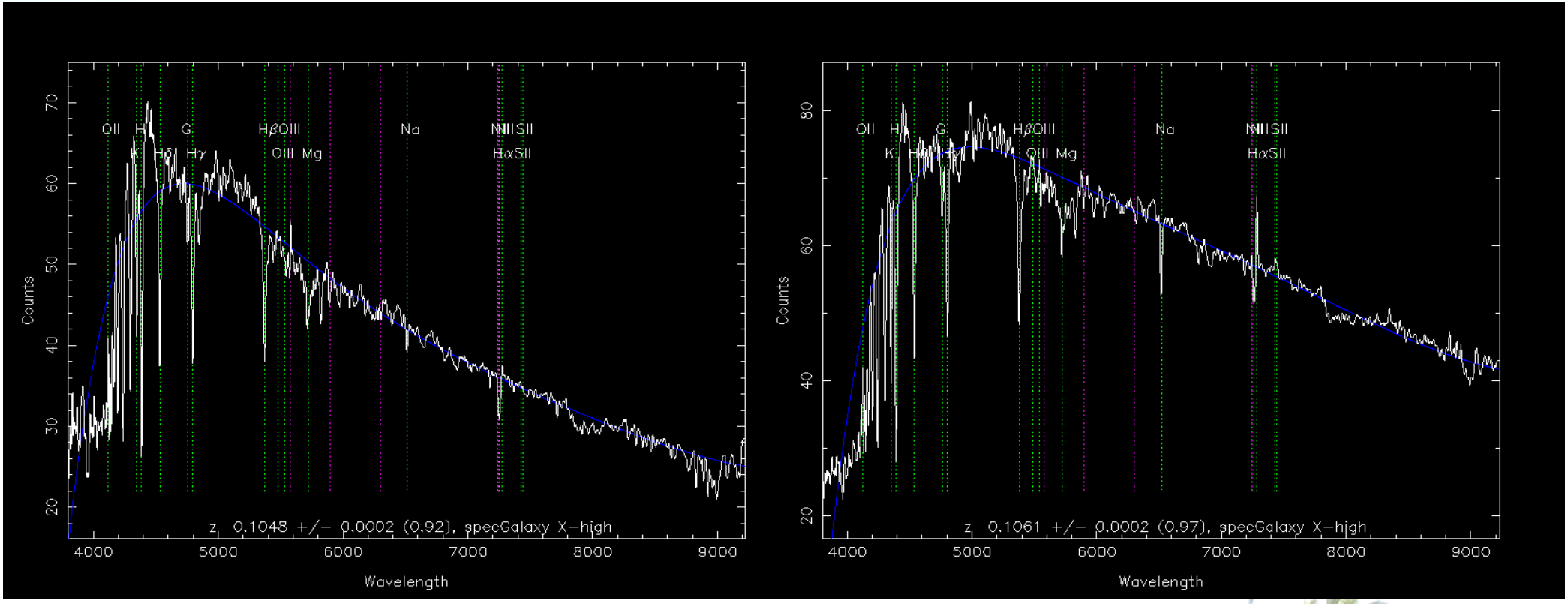

E+A Atlas Images

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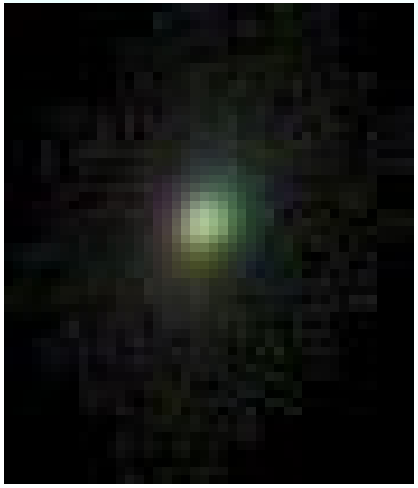
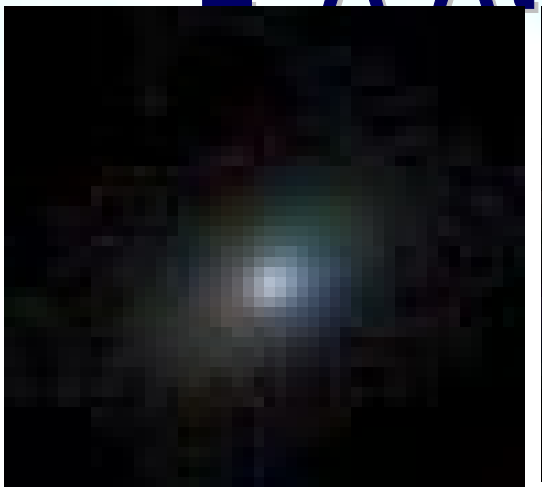
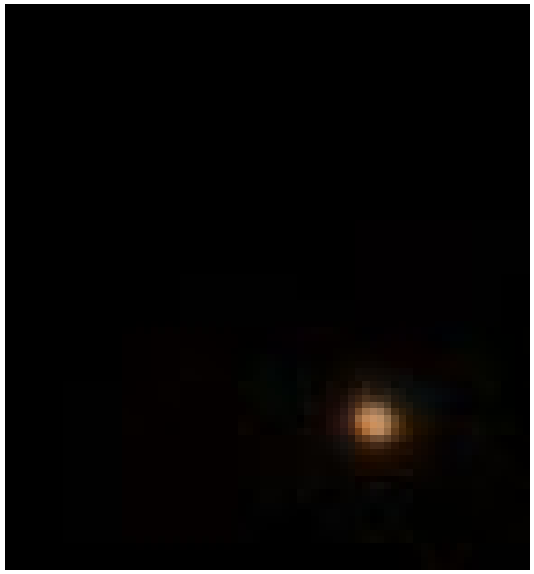
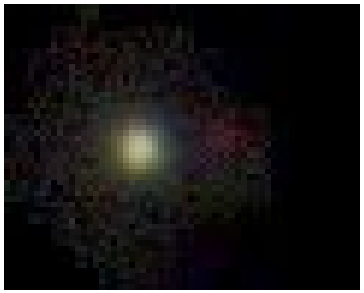
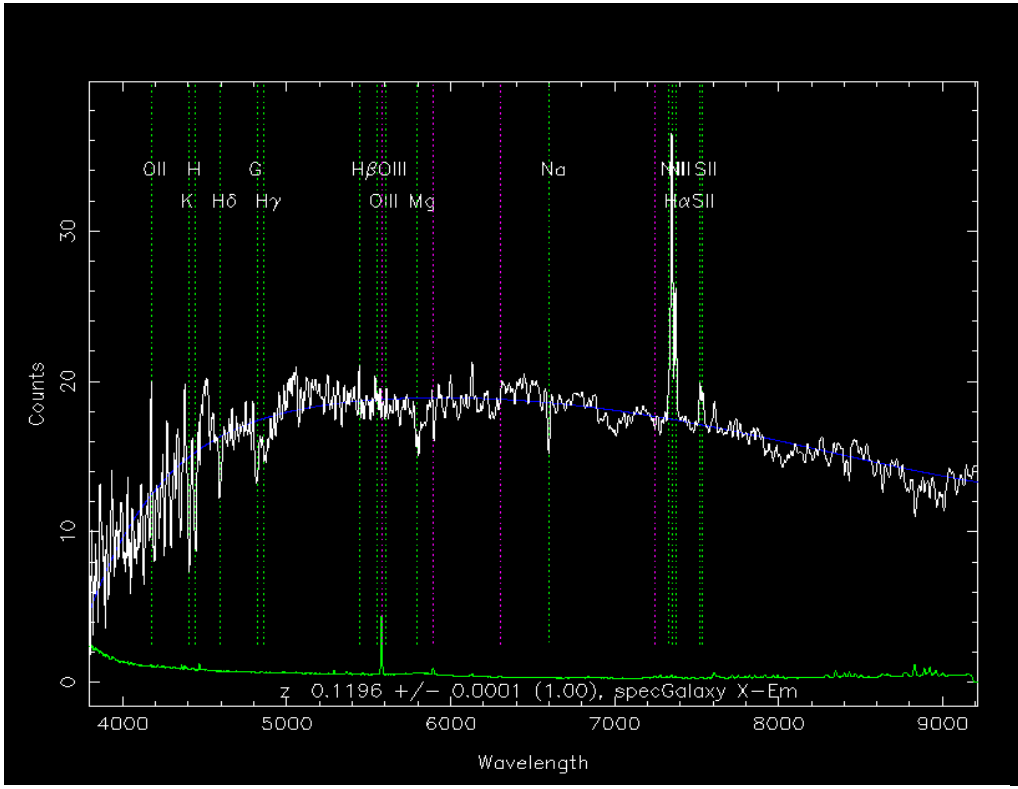



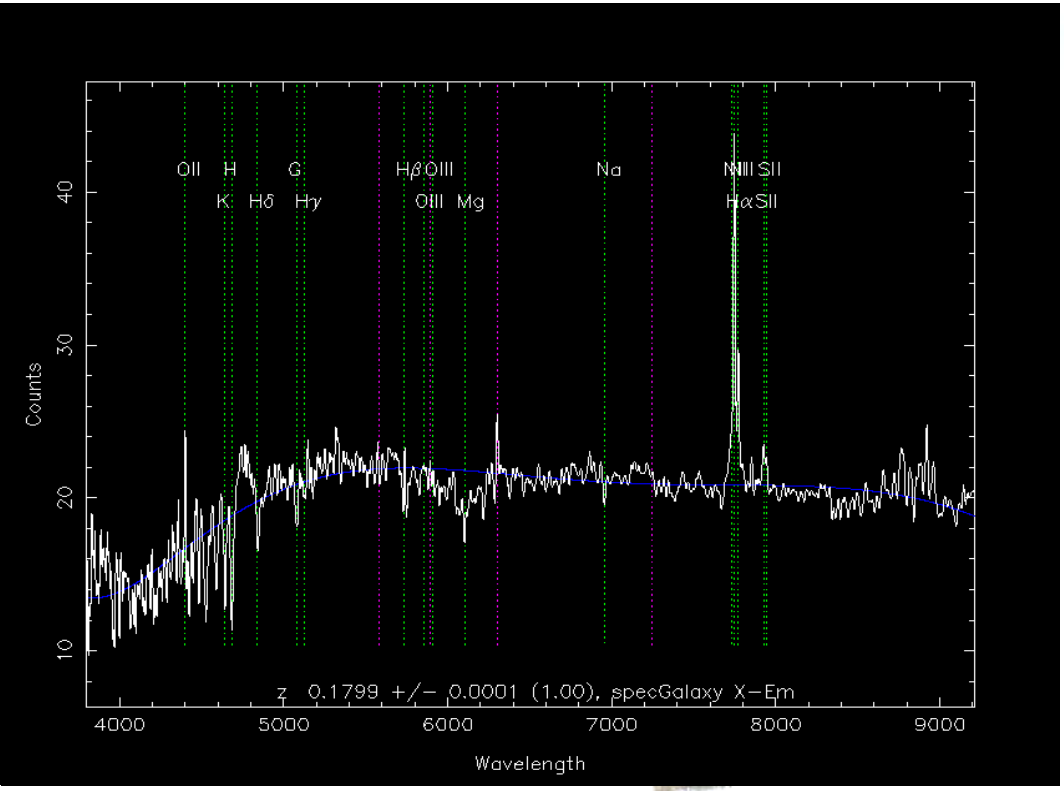



HDS+em Spectra

回覧



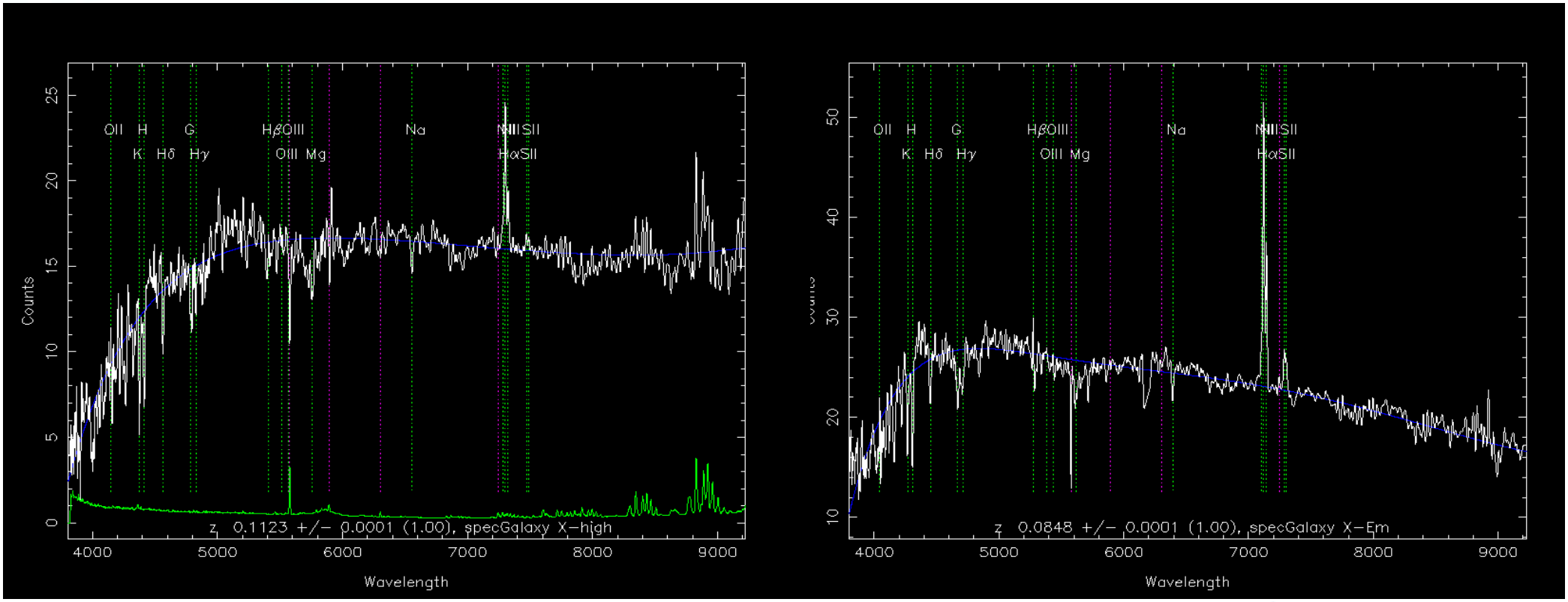


HDS+em Sample Atlas Images

回覧

HDS+Hα Spectra

回覧



- [OII] has been used as SF indicator.
- Could be dust? Metallicity effect?
- Possible 52% contamination in high-z work

HDS+Hα Atlas Images

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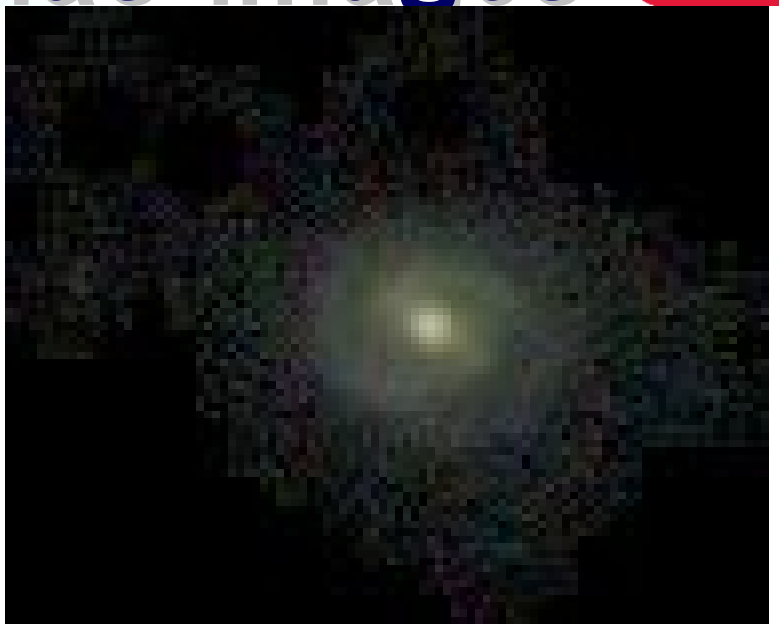

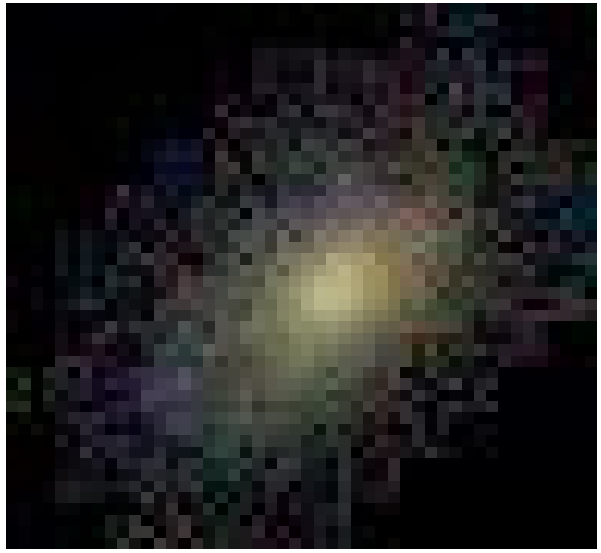

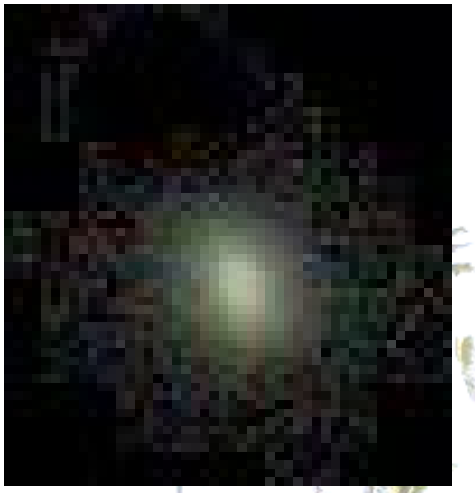

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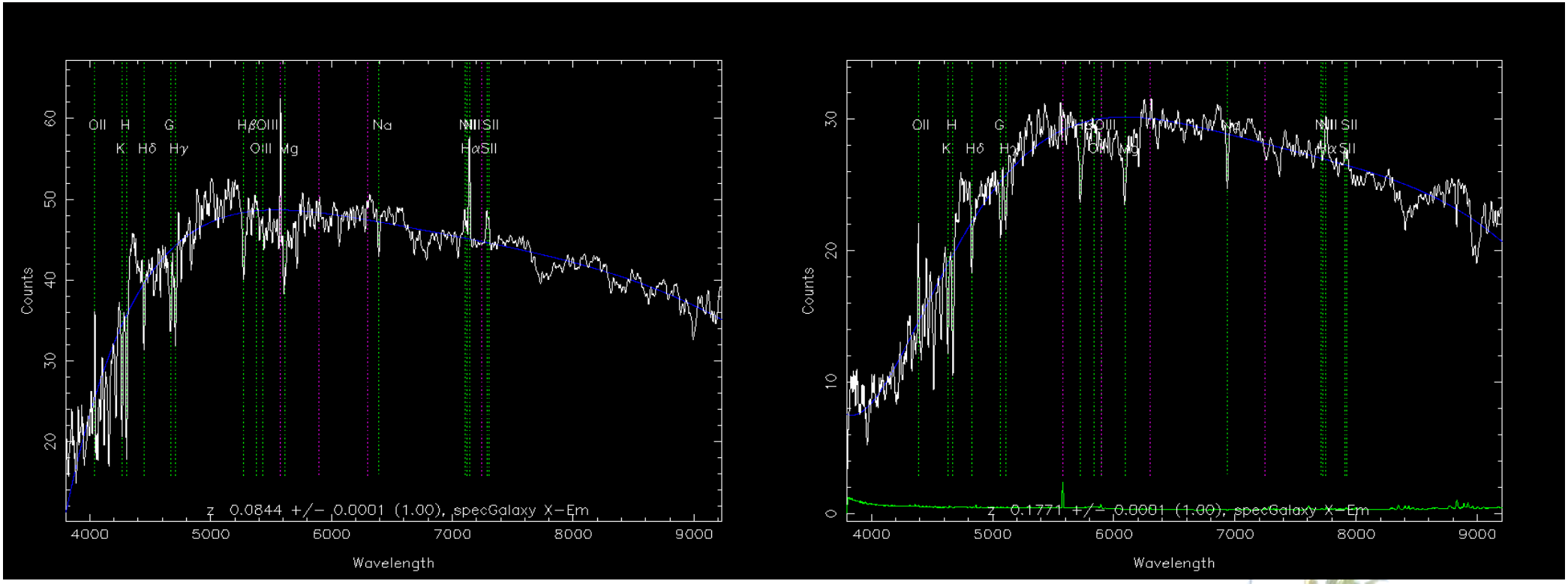
HDS+[OII] Spectra



- Could be self-absorption?

HDS+[OII] Atlas Images

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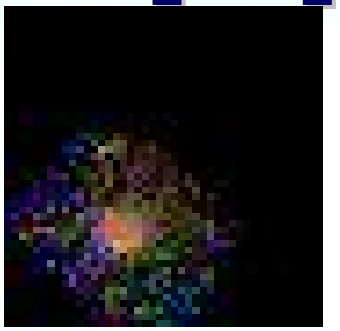
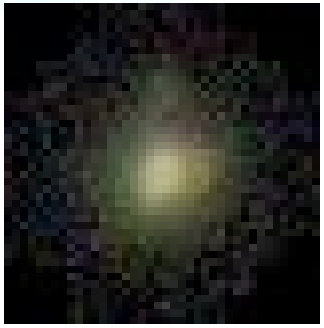

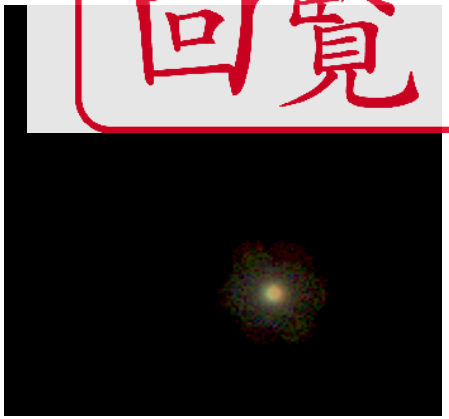

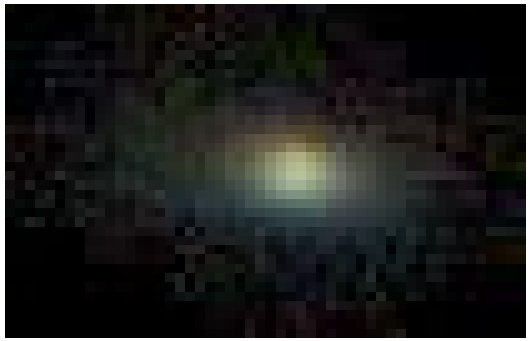
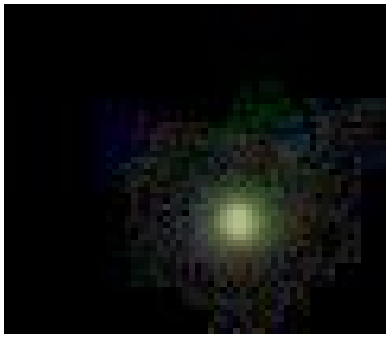

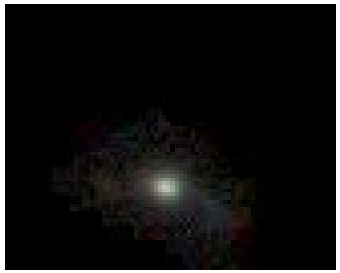
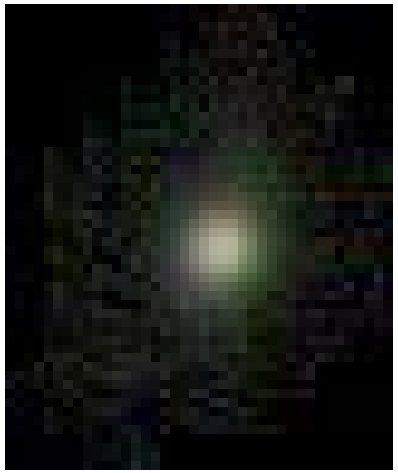

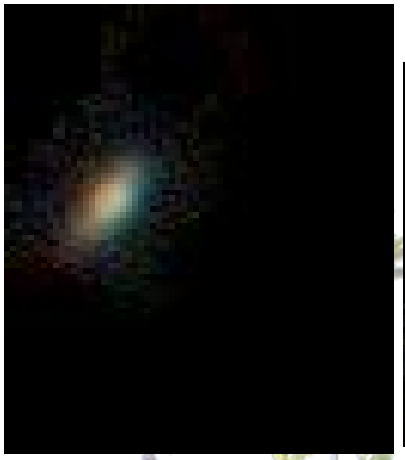
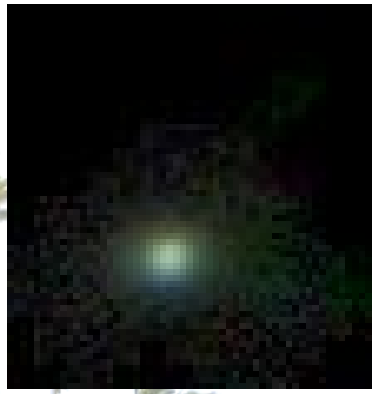

Color-magnitude diagrams

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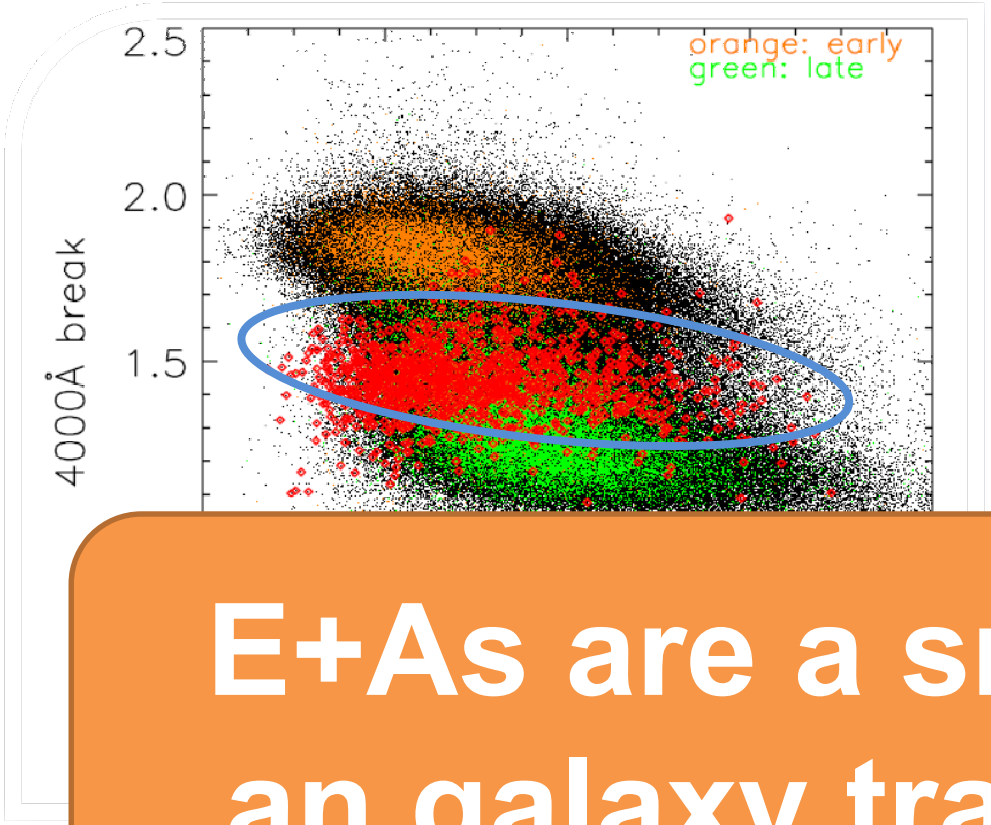
Red : E+A
Orange : all gals have C >3.3,aka, earl-type
Green: all gals have C<2.0,aka, late-type

4000 Å break



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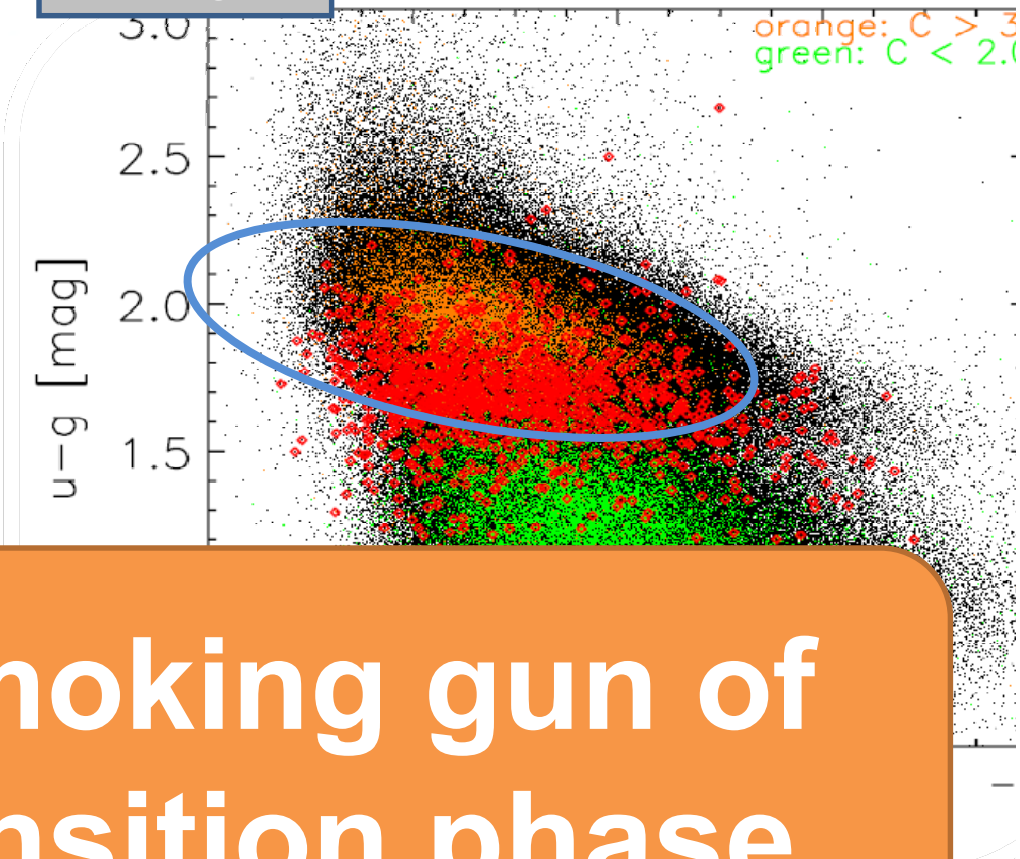

E+As are a smoking gun of an galaxy transition phase

E+A LF:

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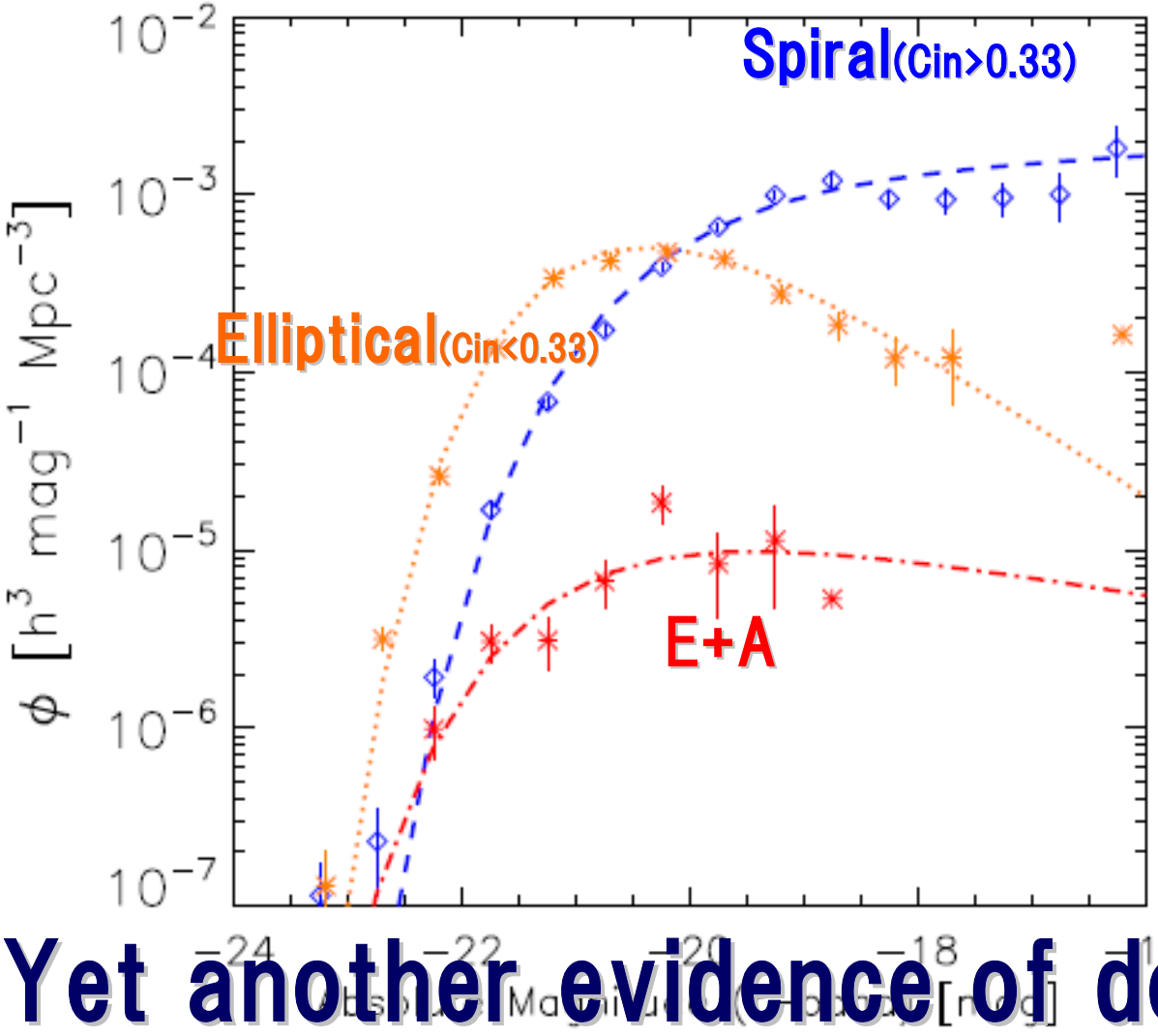
Inami & Goto et al. in prep.



Yet another evidence of downsizing.

Three Scenarios for E+A

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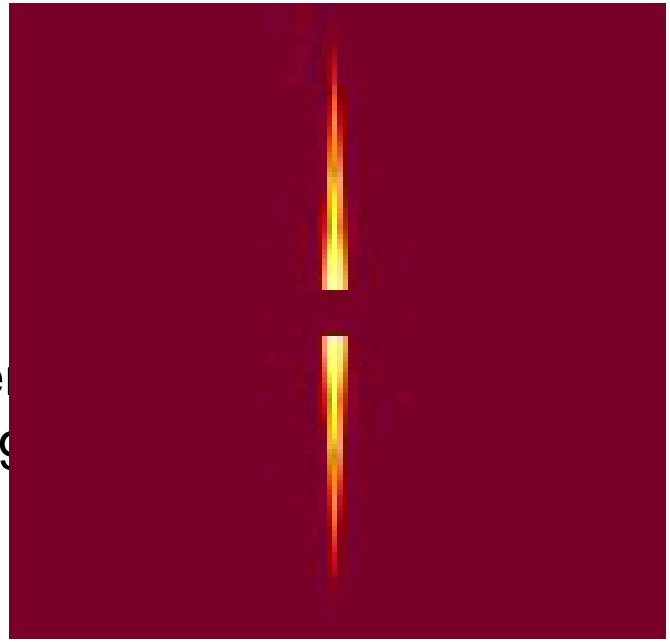
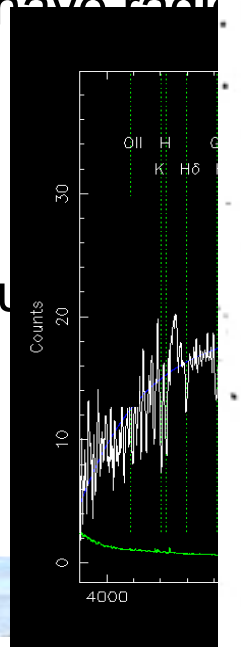
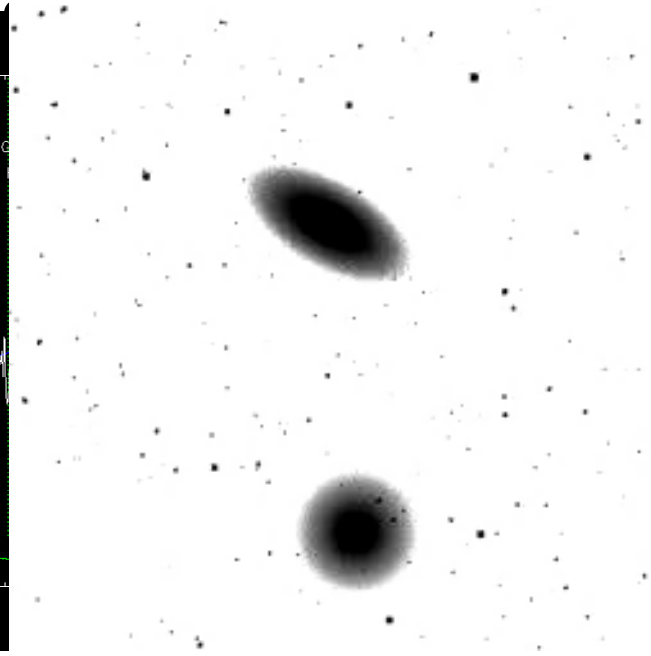


1. **Cluster Related** (ram pressure, tidal inte
potential, …etc; Dressler et al. 1999; Poggianti et al. 19

2. **Dusty Starburst** (2/15 of E+As have radi
Smail et al. 1997;)

3. **Interaction/Merger** (tidal featu
1996)





E+A is E+A

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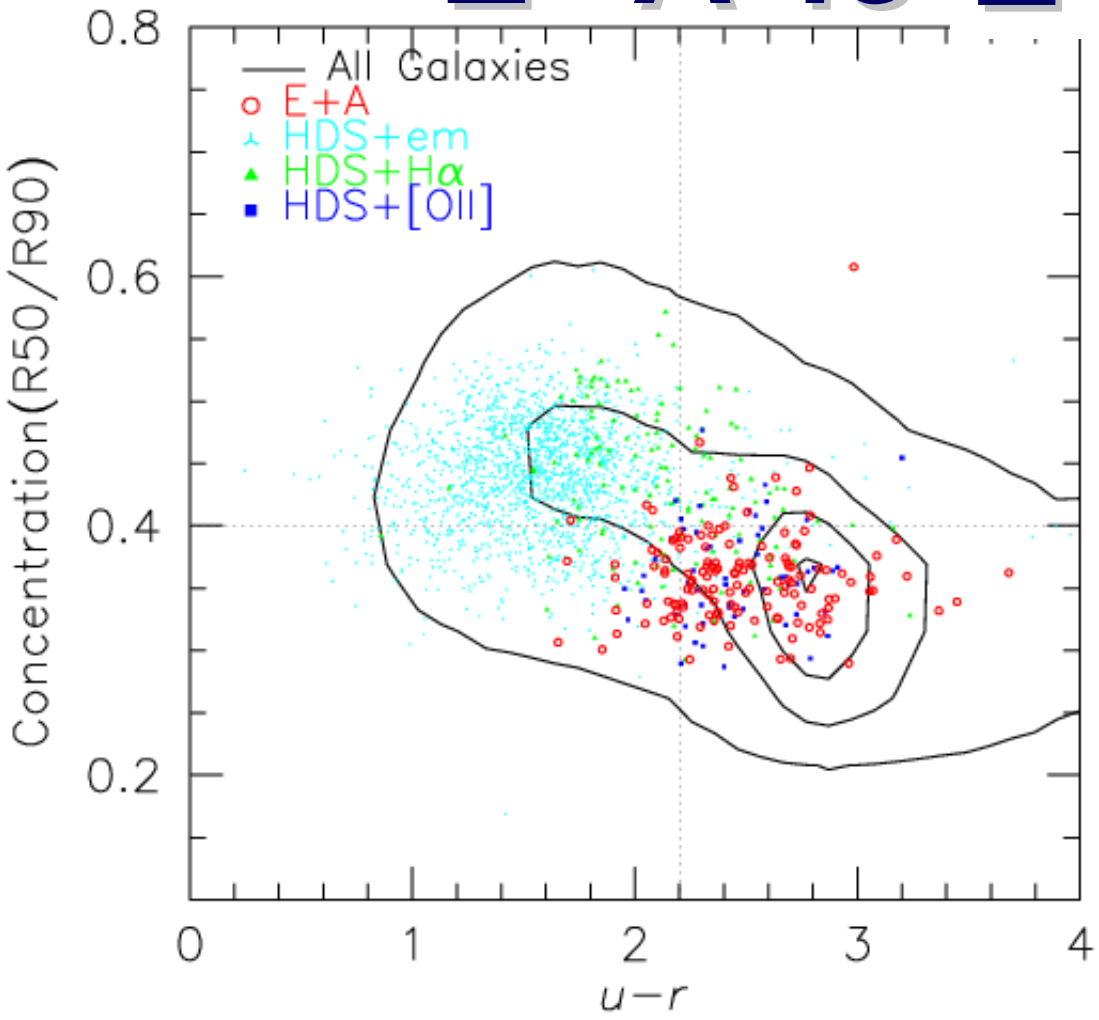

"E+A" is sometime called "K+A" because of its disk-like morphology.
However,…

Previous sample might be contaminated by HDS+H α

Fig. 5. Distributions of each subclass of galaxies in *Cin* v.s. $u-r$ plane. The contours show the distribution of all 94770 galaxies. The large open circles, triangles, squares, and small dots represent E+A, HDS+[OII], HDS+Hα and HDS+em galaxies, respectively.

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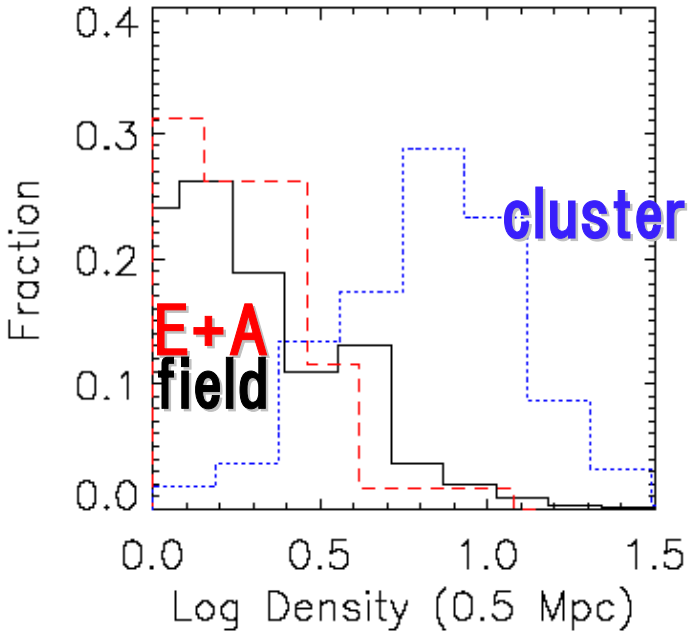
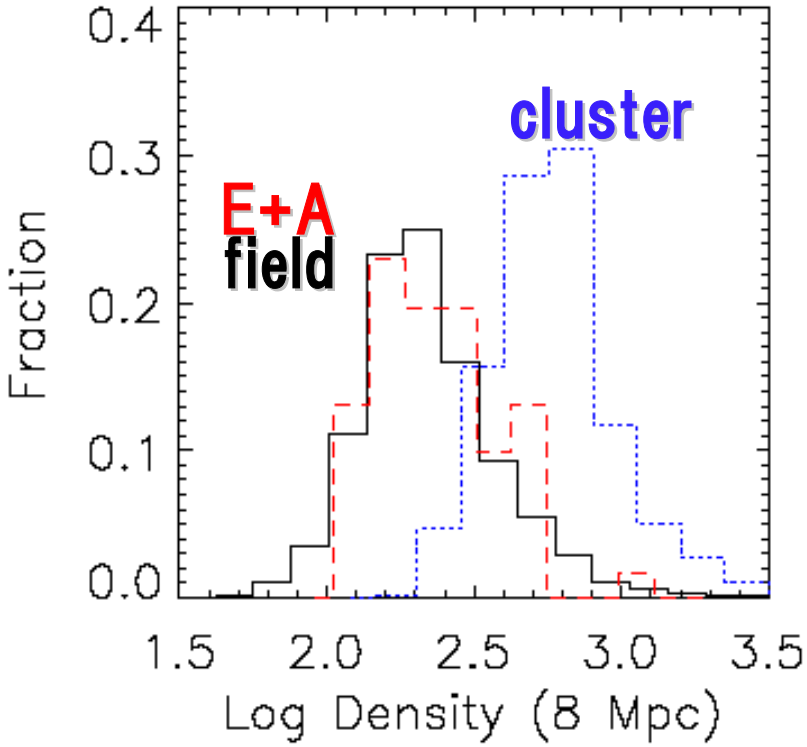
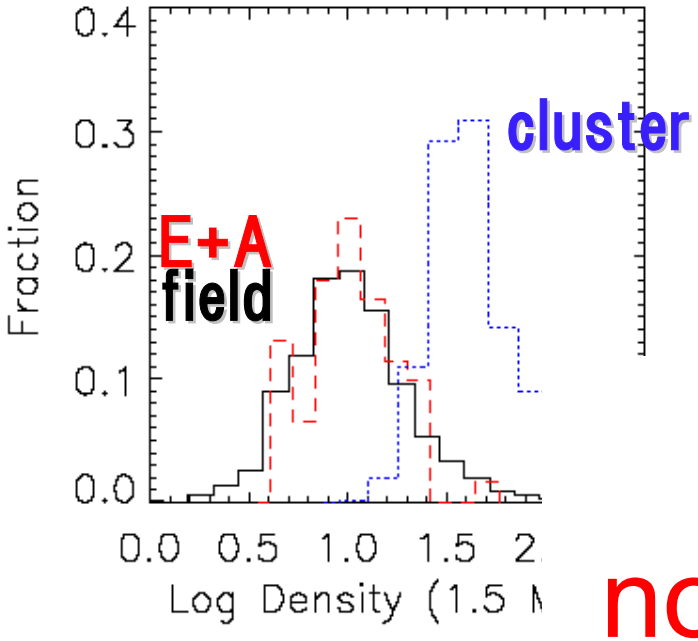
Environment of E+A Galaxies

Goto, T. 2005, MNRAS, 357, 937







Not by cluster,

not by large-scale structure

回覧

Three Scenarios for E+A

1. Cluster related (ram pressure, tidal interaction, merging…etc; Dressler et al. 1999; Poggianti et al. 1999)

2. Dusty Starburst (2/15 of E+As have radio SF; Miller et al. 2002; Smail et al. 1997;)

3. Interaction/Merger (tidal features in 5/21 E+As in Zabludoff et al. 1996)

Optical-Infrared color: $r-K$

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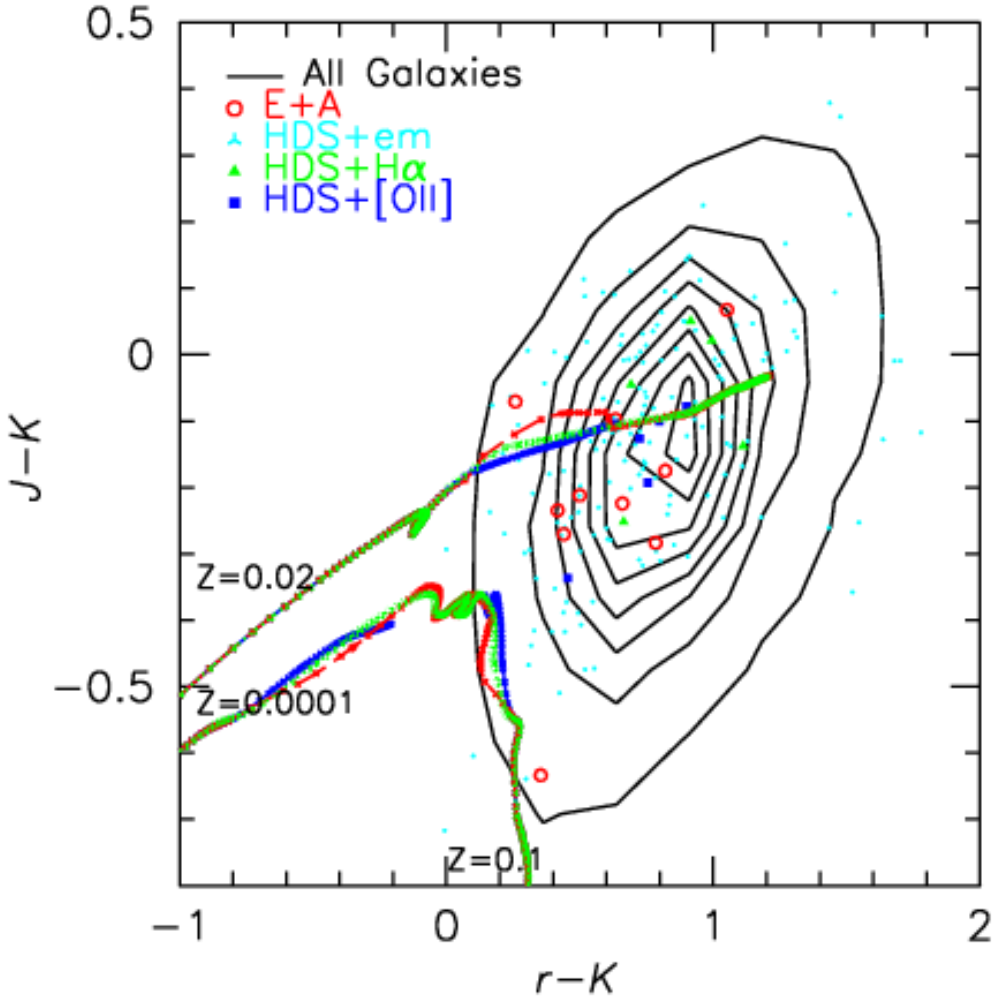

Fig. 12. $J-K$ is plotted against $r-K$. All magnitudes are in restframe AB system. The contours show the distribution of all galaxies in our sample. The open circles, small dots, triangles and squares represent E+A, HDS+em, HDS+Hα and HDS+[OII], respectively. The dashed, solid and dotted lines show the models with instantaneous burst, constant star formation and exponentially decaying star formation rate. Three sets of the models are plotted for different metallicities.

E+As are not dustier.

(c.f., 5 dusty starbursts in Smail et al. are ~1mag redder.)

Radio Estimated SFR

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Goto, T. 2004, A&A, 427, 125

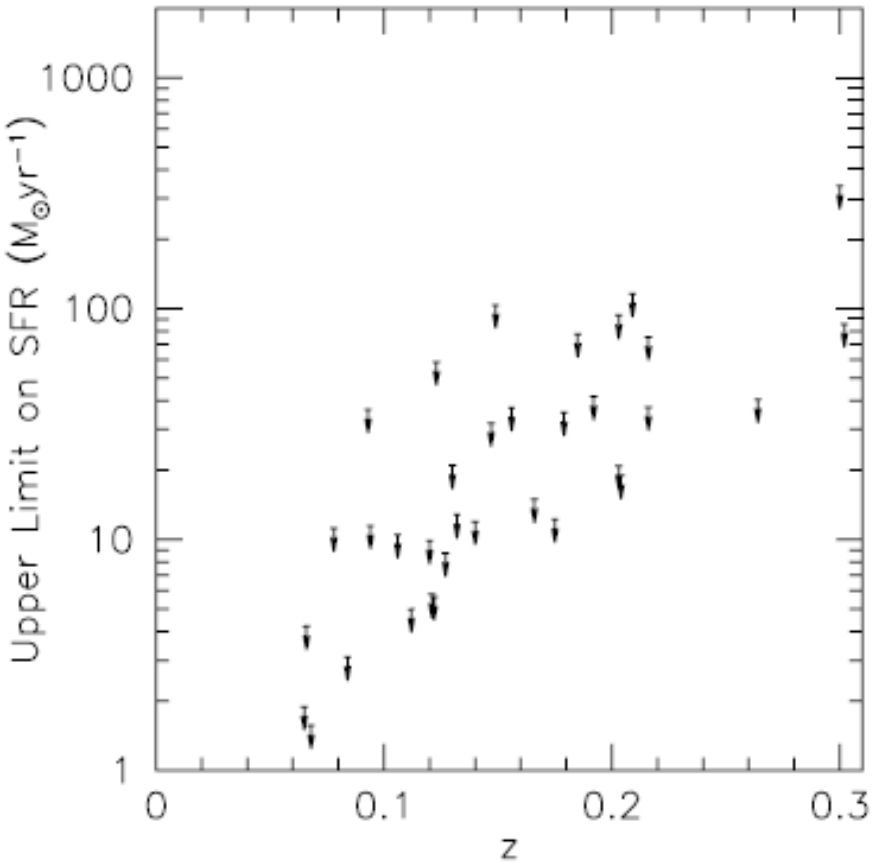


Fig. 3. Upper limits on SFR calculated using the radio 20cm continuum are plotted against redshift. None of our target galaxies were detected in the observation. Therefore, all data points show upper limit on the radio estimated star formation rate calculated from the 3 σ of the rms sky noise. Note that the SFR is computed by integrating IMF over 0.1-100 $M_\odot$. The SFR over 5-100 $M_\odot$ is 5.5 times smaller than our value.

No evidence that E+As are not dusty starbursts.

Goto

回覧

Three Scenarios for E+A

1. **Cluster related** (ram pressure, tidal interaction, merging…etc; Dressler et al. 1999; Poggianti et al. 1999)
2. **Dusty Starburst** (2/15 of E+As have radio SF; Miller et al. 2002; Smail et al. 1997;)
3. **Interaction/Merger** (tidal features in 5/21 E+As in Zabludoff et al. 1996)

回覧

Hδ_EW vs Time

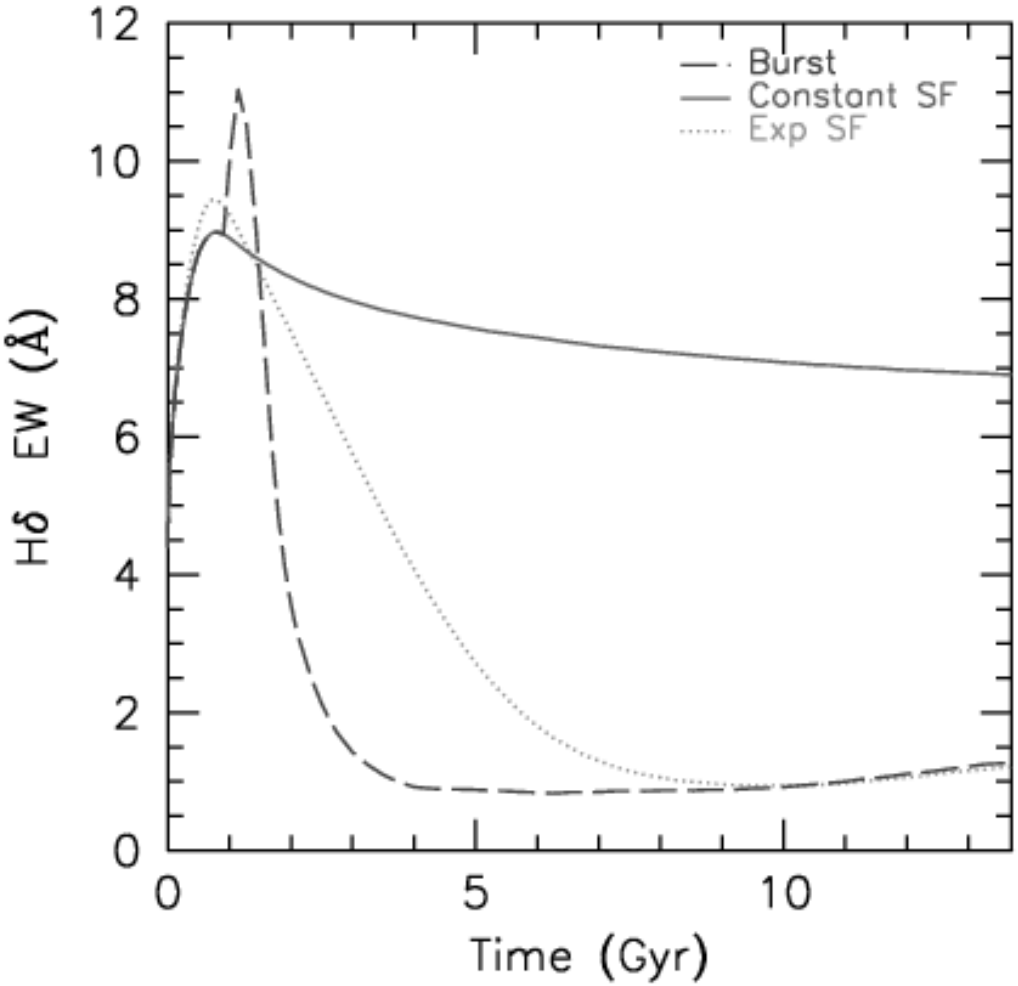
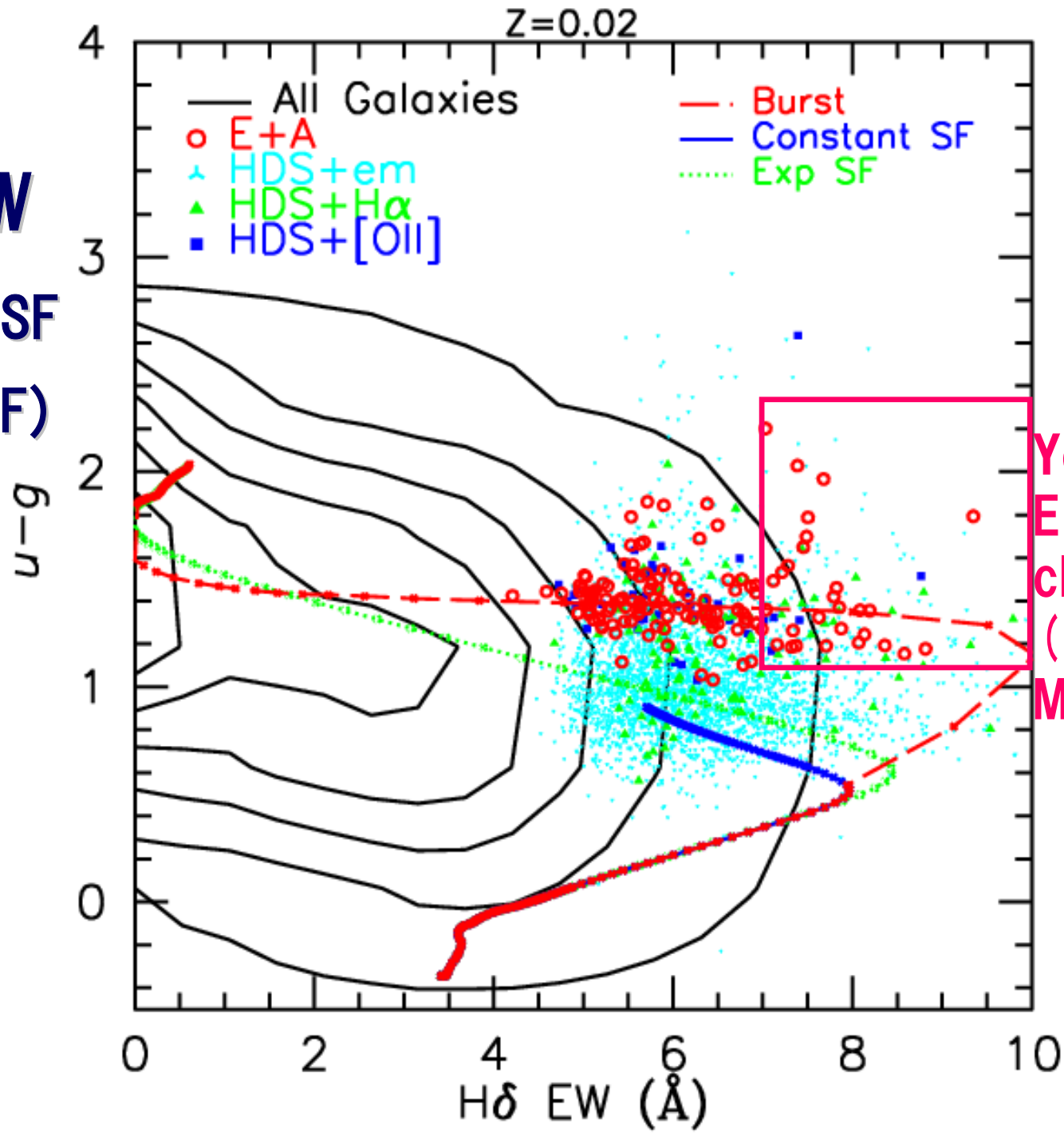


Fig. 10. Hδ EWs are plotted against time (age) for three star formation histories with the GISSEL model. The dashed, solid and dotted lines show the models with instantaneous burst, constant star formation and exponentially decaying star formation rate. The models in this figure assume Salpeter IMF and solar metallicity.

回覧

u-g vs Hδ EW

(current SF vs recent SF)



Young/strong E+As: closer to burst (130-470 Myrs)

Young/strong E+A Spectra (Hδ EW>7 Å)

回覧

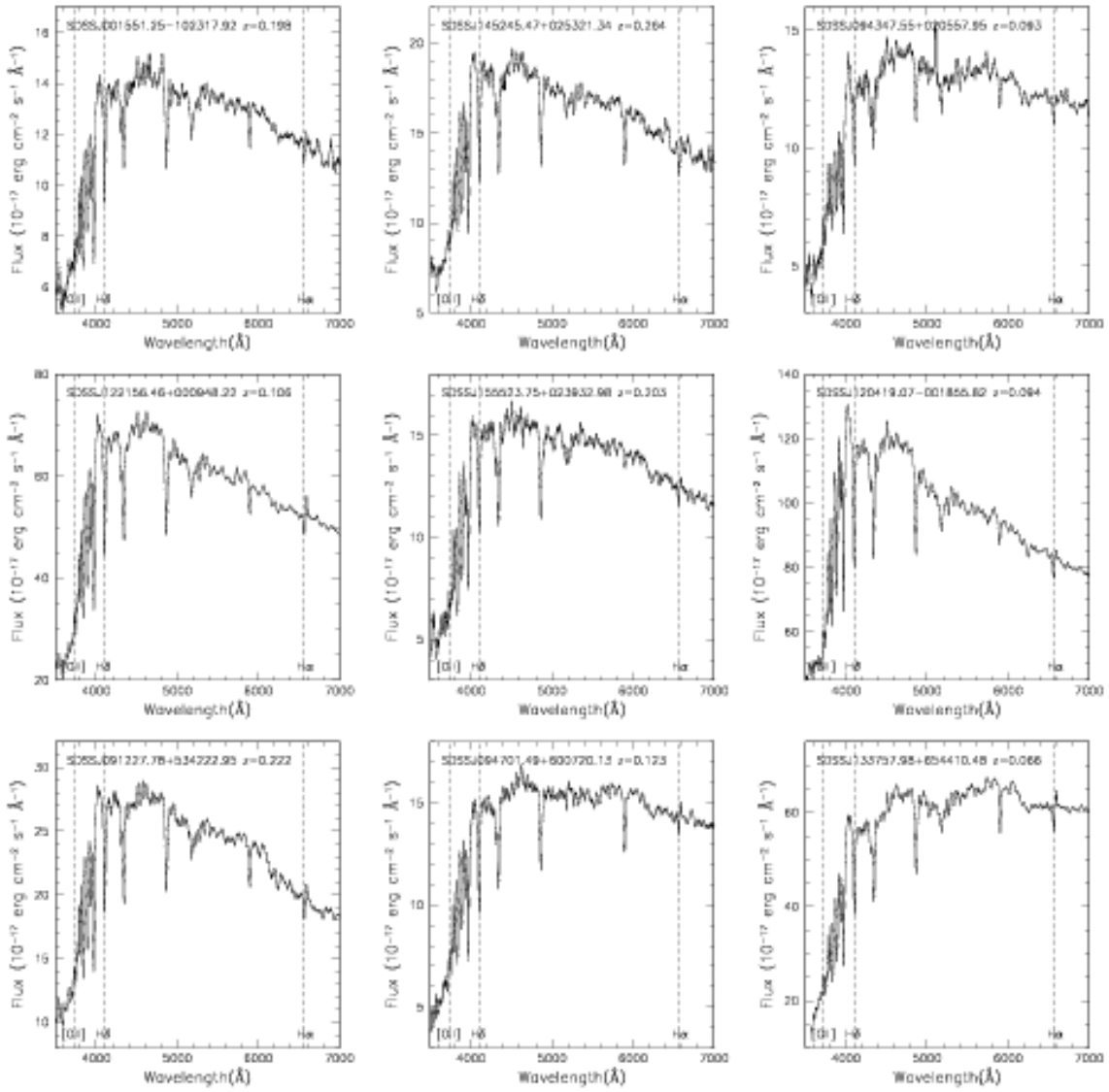


Fig. 16. Nine example spectra of young E+A galaxies (E+As with Hδ EW >7 Å). Spectra are shifted to restframe and smoothed using a 20Åbox.

Atlas Image of Young/strong E+A

回覧

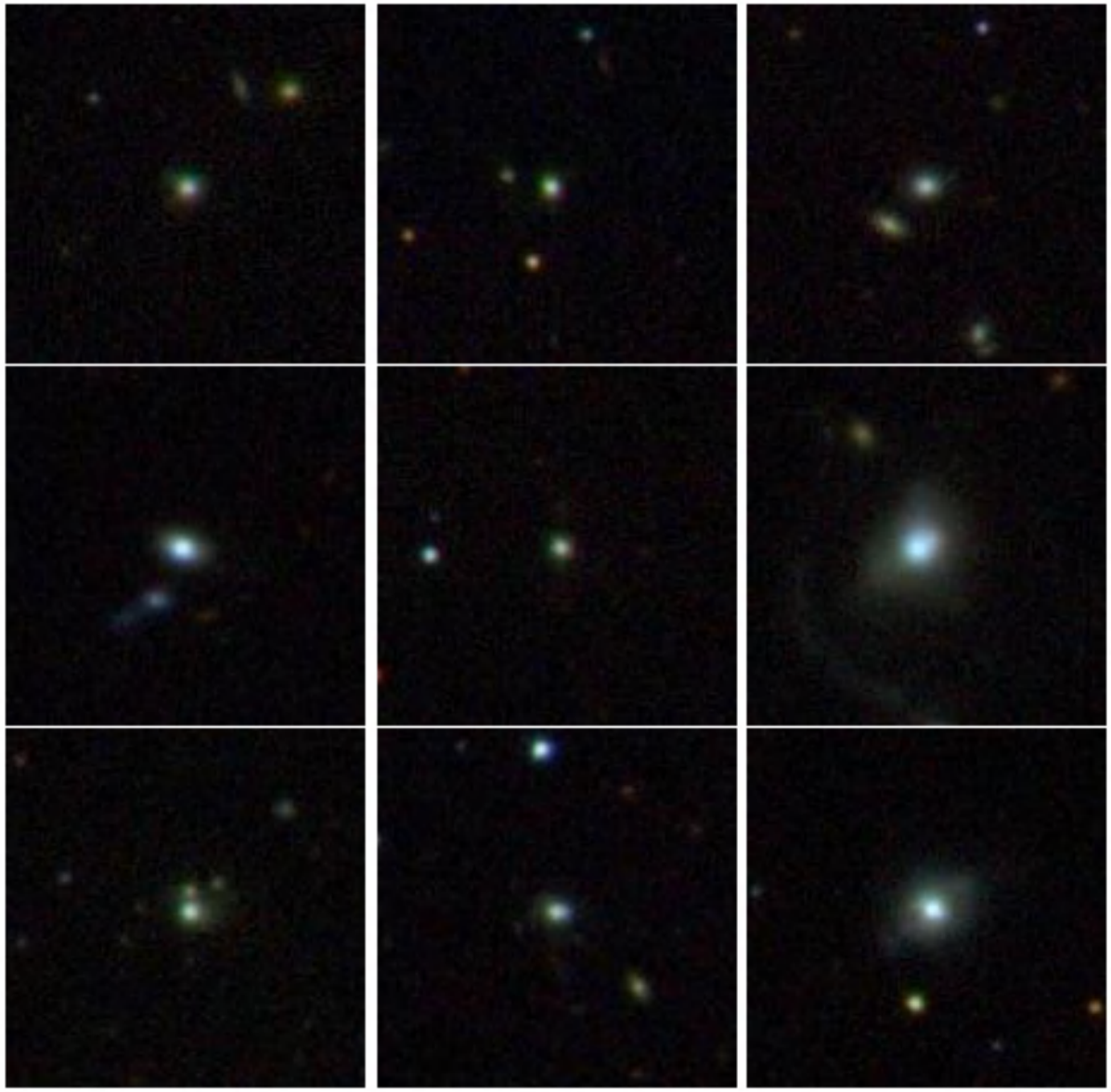


Fig. 17. Nine example images of young E+A galaxies (E+As with Hδ EW >7 Å). Image size is 60"×60" and north is up. Each panel corresponds to that in figure 16.

回覧

$N_{accompanying\ galaxies}$

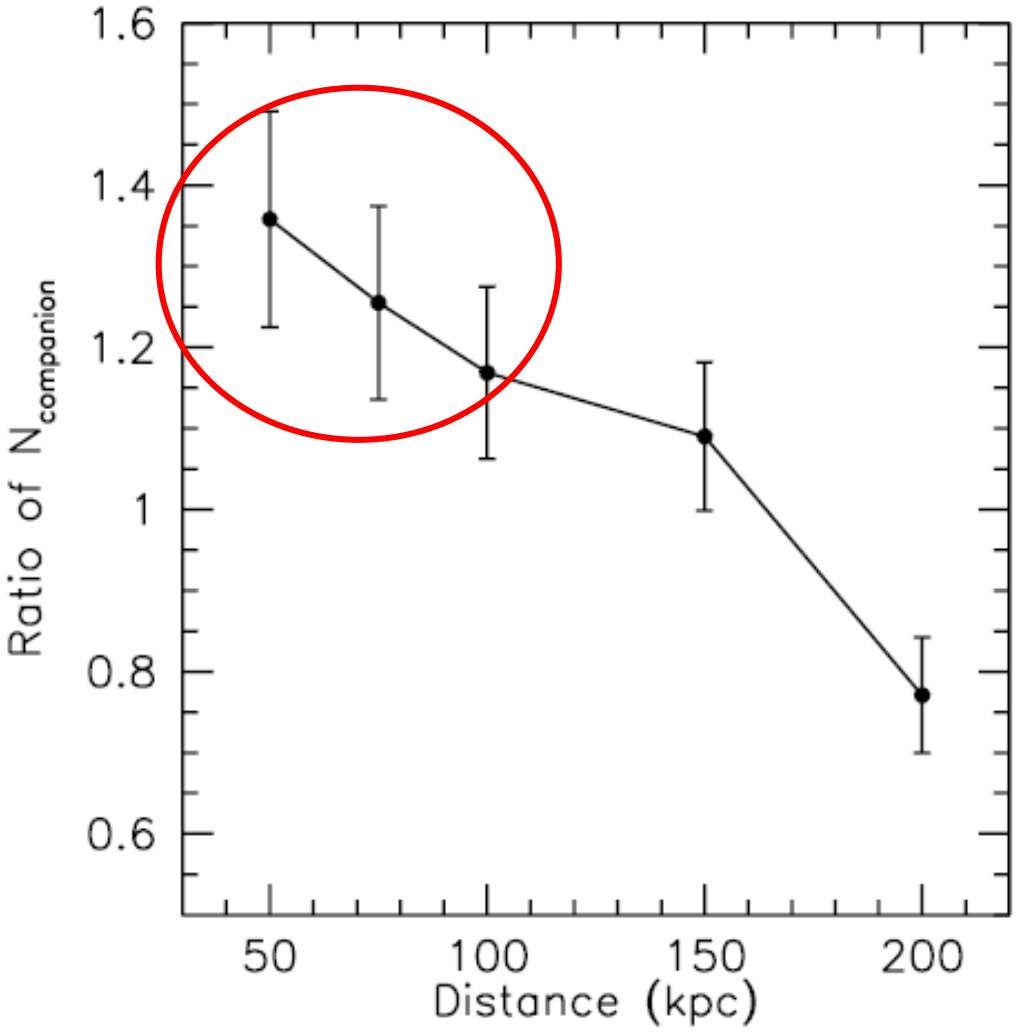


Figure 3. The number ratio of companion galaxies of E+As to that of random (field) galaxies.

More accompanying galaxies for young E+As at <100kpc scale.

Goto, T. 2005, MNRAS, 357, 937

This is now spectroscopically confirmed.

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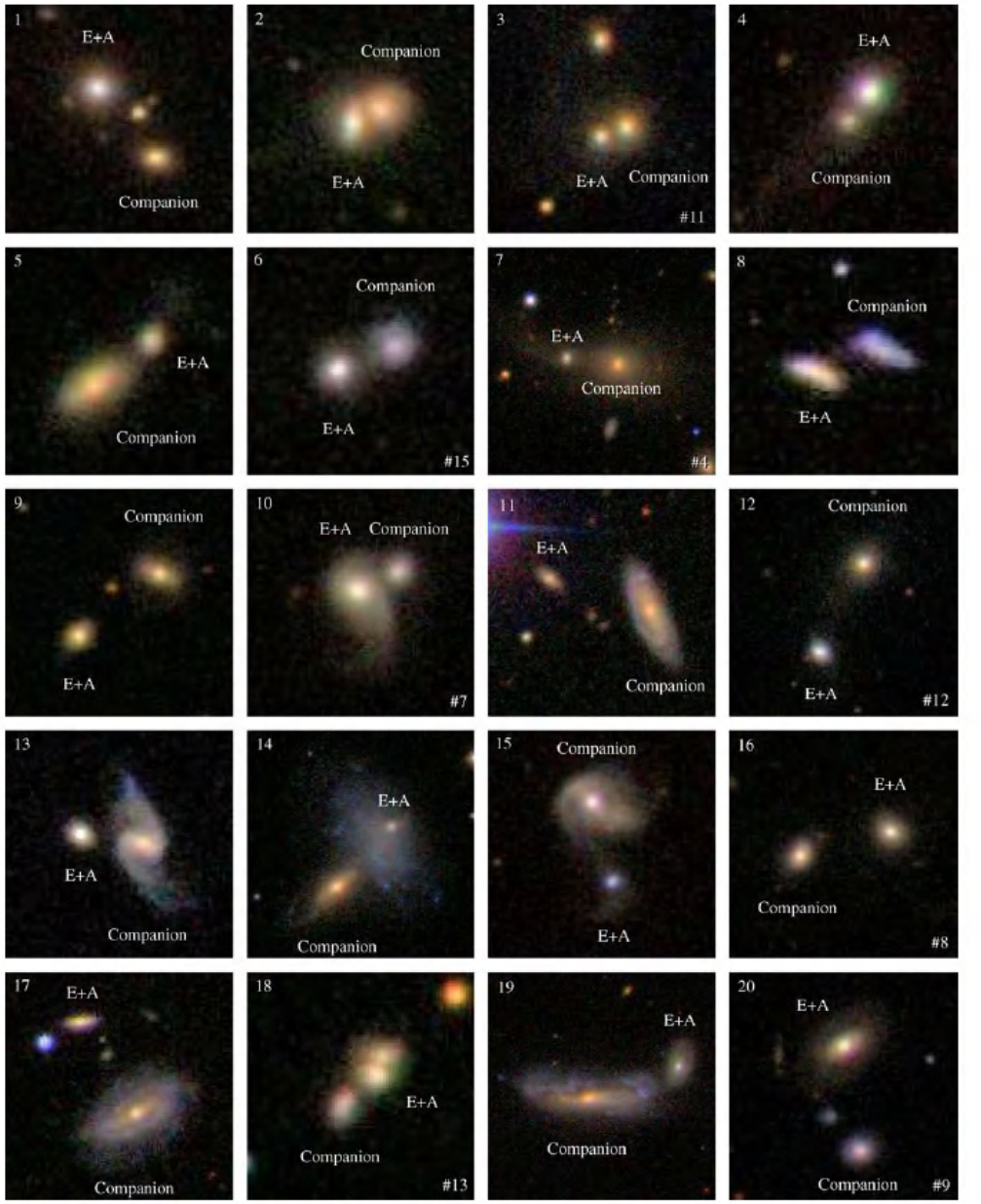
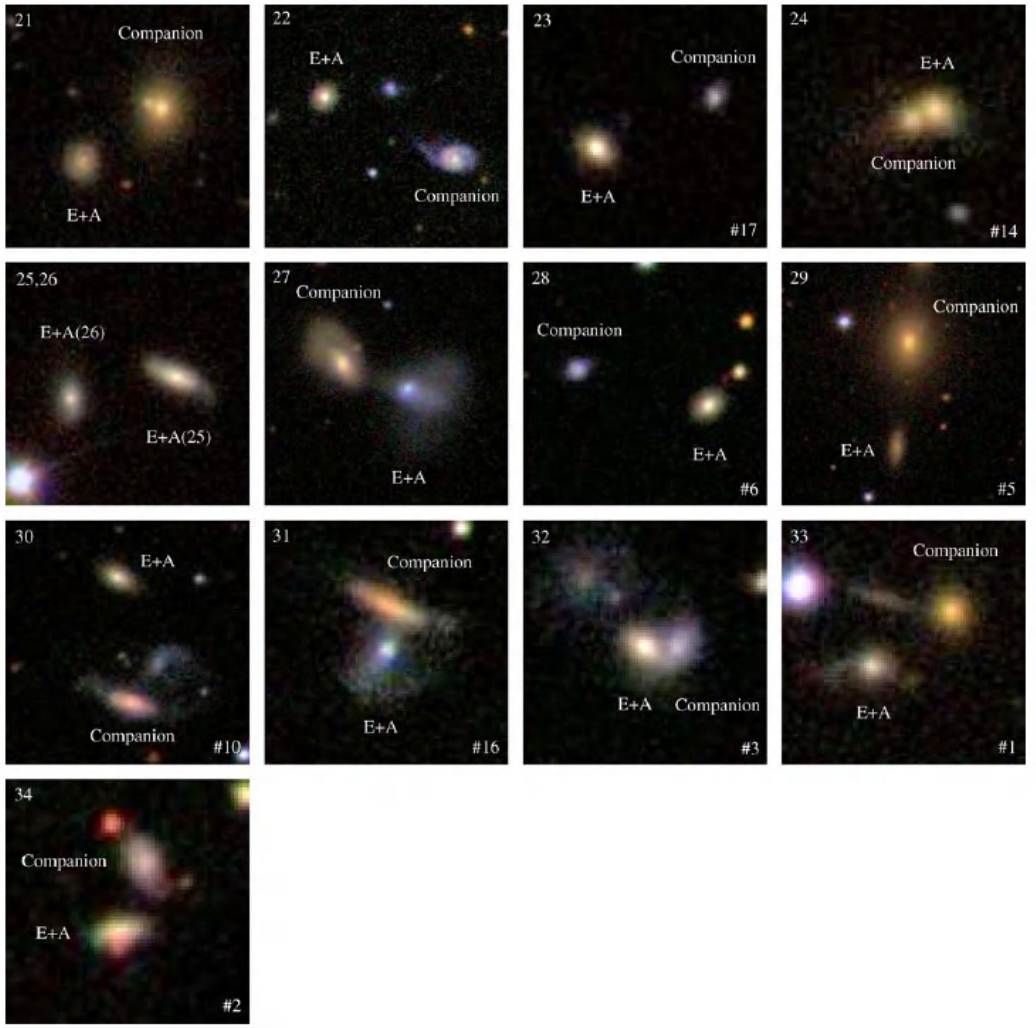


Figure 4. SDSS *g*, *r*, *i*-composite images of E+A and companion pairs taken from SDSS CAS. The inlaid number at the bottom right-hand panel in each image is the target ID of our KPNO observation.



E+A has 54% larger probability to have a companion.

Yamauchi, Yagi, Goto, 2008, 390,383

回覧

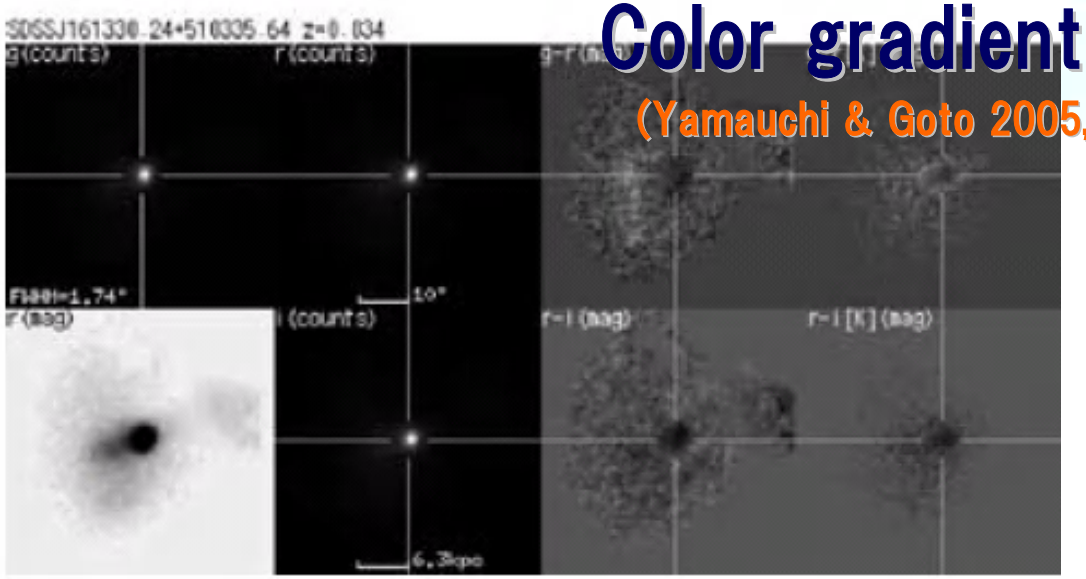
Three Scenarios for E+A

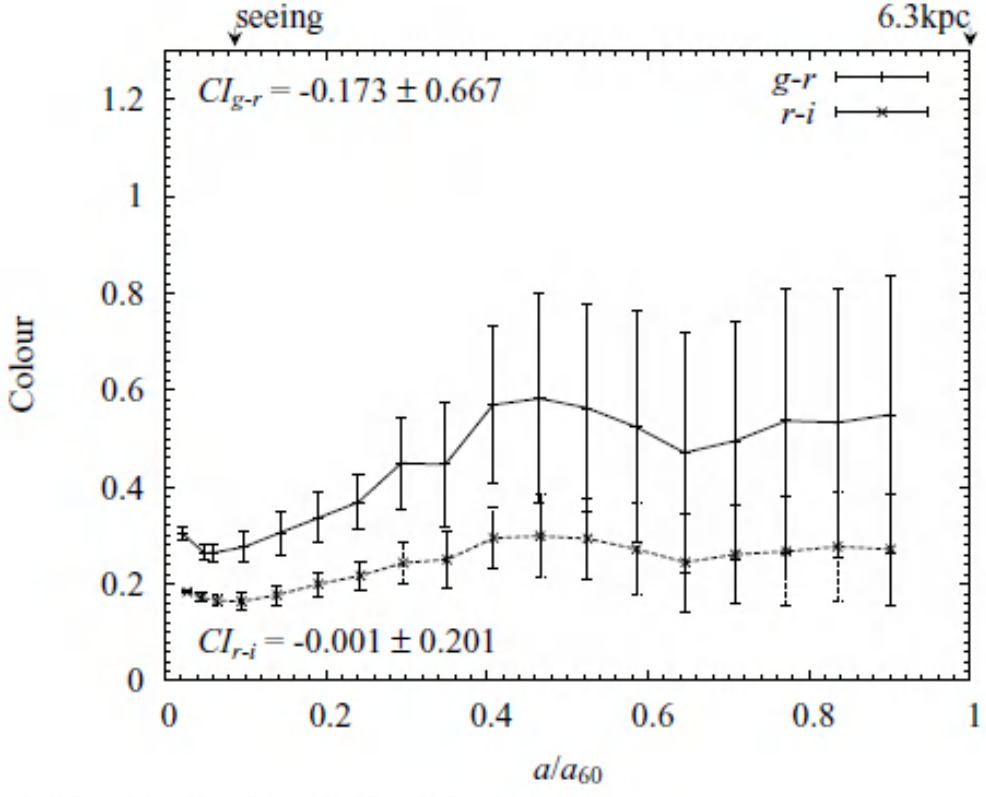
1. Cluster related (ram pressure, tidal interaction, merging…etc; Dressler et al. 1999; Poggianti et al. 1999)
2. Dusty Starburst (2/15 of E+As have radio SF; Miller et al. 2002; Smail et al. 1997;)
3. Interaction/Merger (tidal features in 5/21 E+As in Zabludoff et al. 1996)

Color gradient of E+As :

(Yamauchi & Goto 2005,MNRAS,359,1557)

回覧





Bluer core in >60% of local E+As

→central starburst of infalling gas due to the merger/interaction

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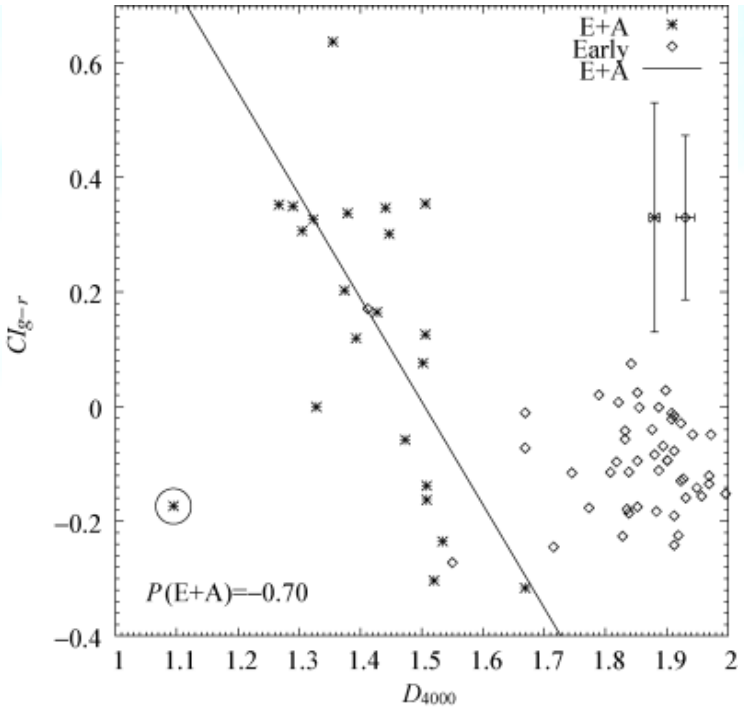
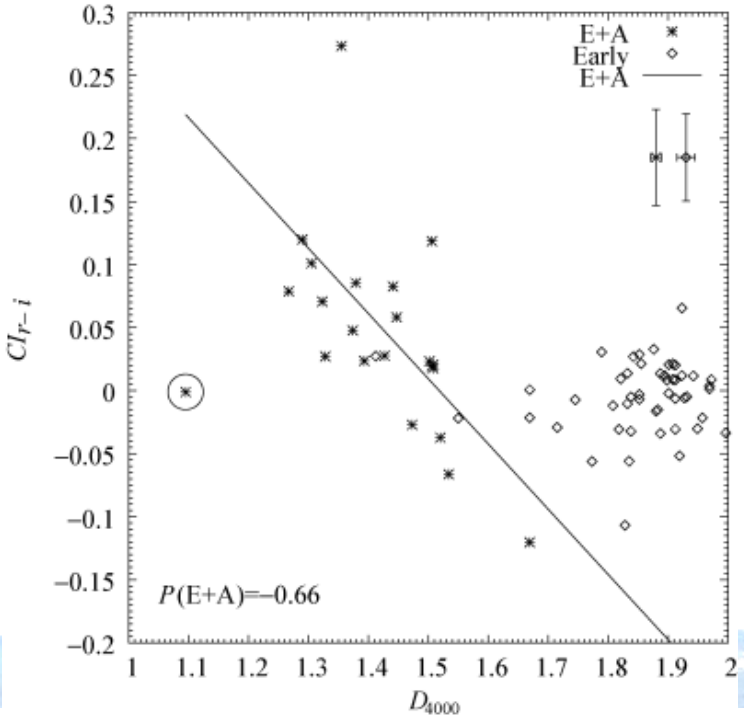
Correlation between color-gradient and D4000:

possible merger time clock.

(Yamauchi & Goto 2005,MNRAS,359,1557)





blue color gradient to flatter
→consistent with merger

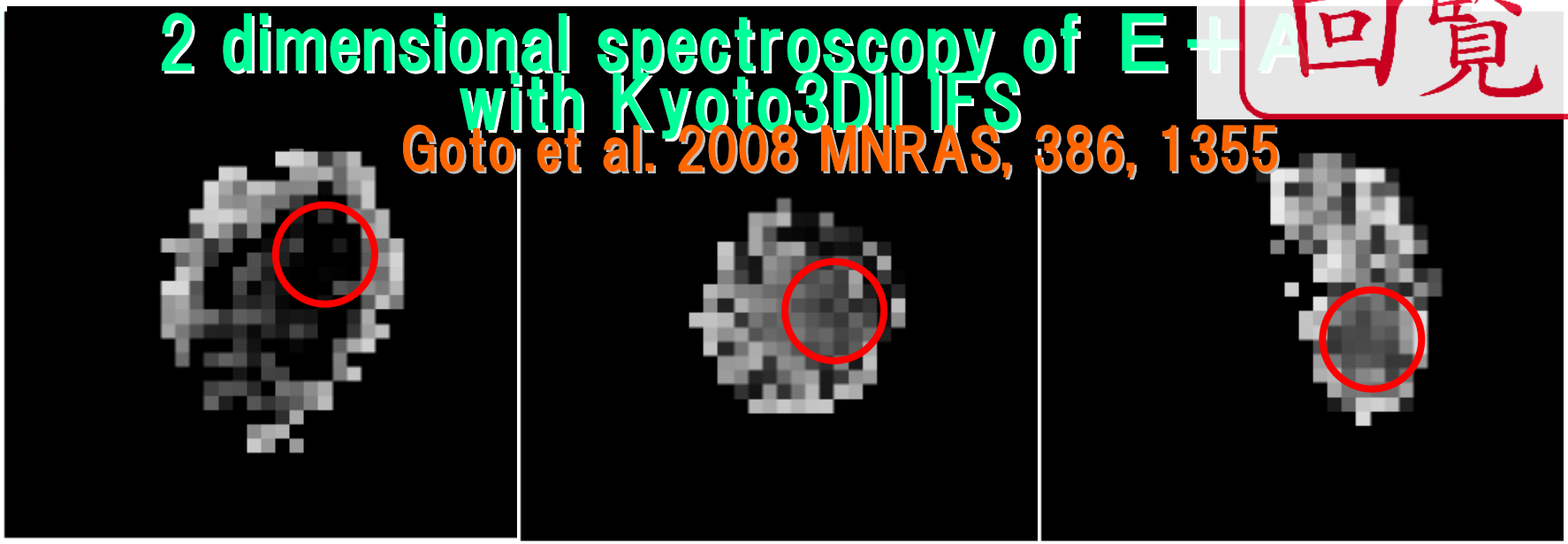
Special thanks to H.Sugai,A. Kawai,A.Shimono

2 dimensional spectroscopy of E+A with Kyoto3DII IFS

Goto et al. 2008 MNRAS, 386, 1355

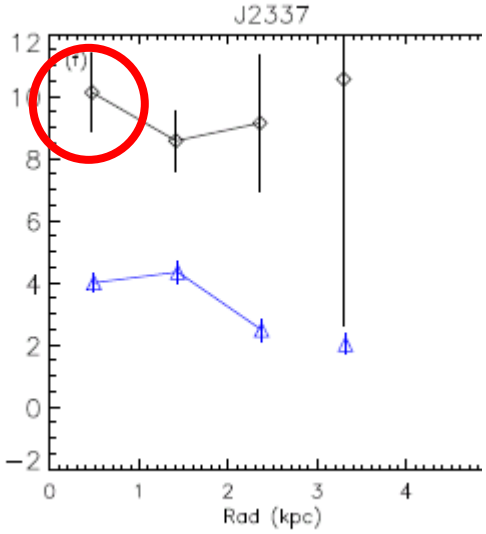
回覧

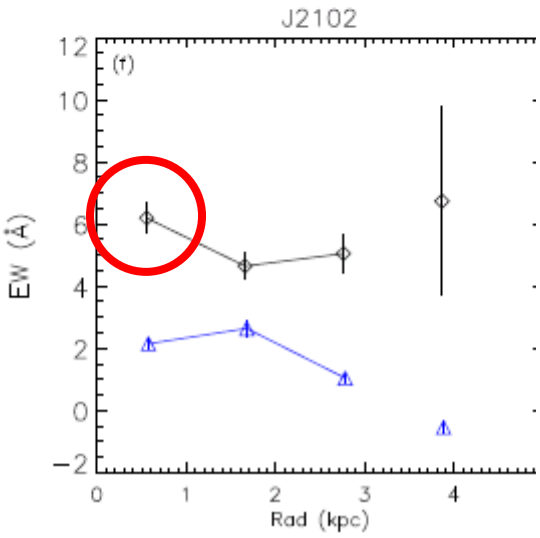
Hδ/continuum

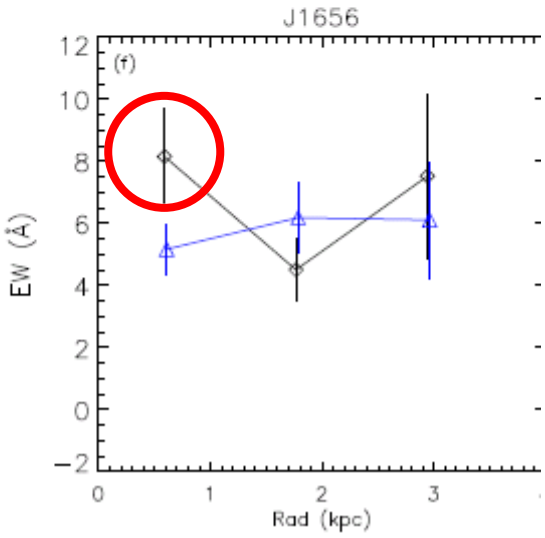


Hδ EW

Hγ EW







Hδ is stronger at center (although quite extended).

→supports merger scenario

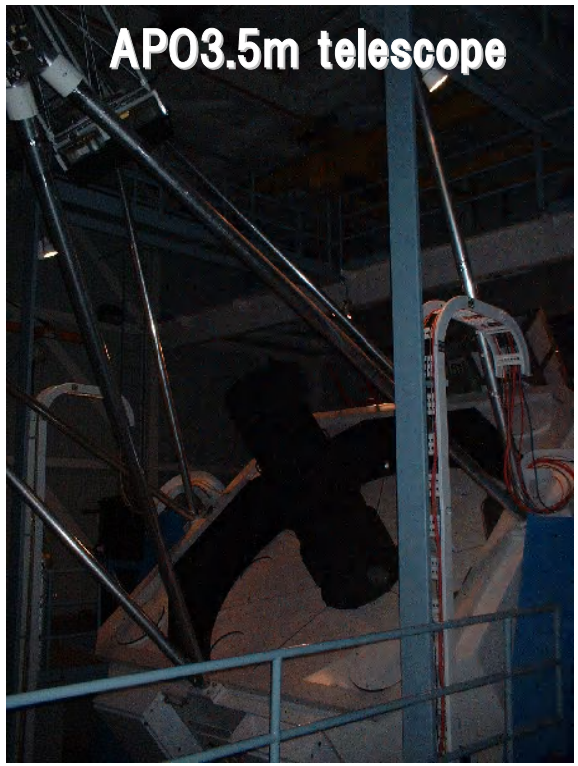
(gas infalls by losing angular momentum)

Spatially resolved spectroscopy

(Yagi & Goto 2006,ApJ,642,152, 2006,AJ,131,2050)

回覧

Position	Hδ EW (Å)
x0.89kpc/pix	
1	
0	7.1 ± 0.3
±1	6.4 ± 0.2
±2–3	6.6 ± 0.1
±4–6	5.9 ± 0.3
x0.39kpc/pix	
2	
0	7.4 ± 0.2
±1	7.8 ± 0.1
±2–3	6.6 ± 0.1
±4–6	3.5 ± 0.3
x0.72kpc/pix	
3	
0	7.3 ± 0.2
±1	7.1 ± 0.1
±2–3	7.1 ± 0.1
±4–6	6.4 ± 0.2



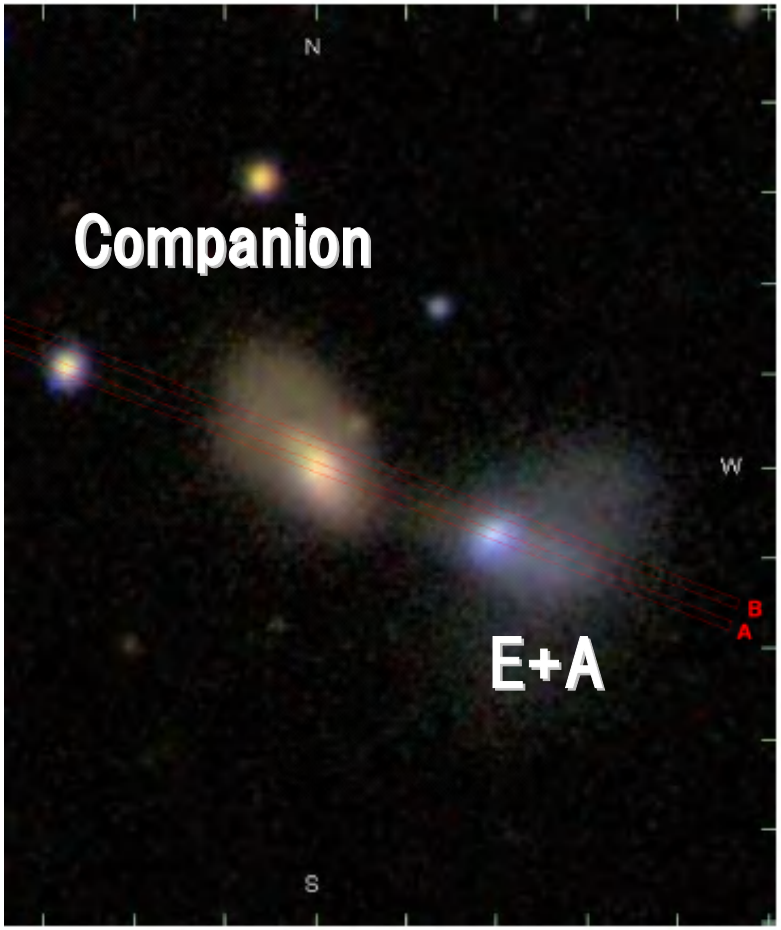
Poststarburst is centered at the core, but spatially extended.

→ rather a merger product than a truncated spiral arm.

Spatially resolved spectroscopy

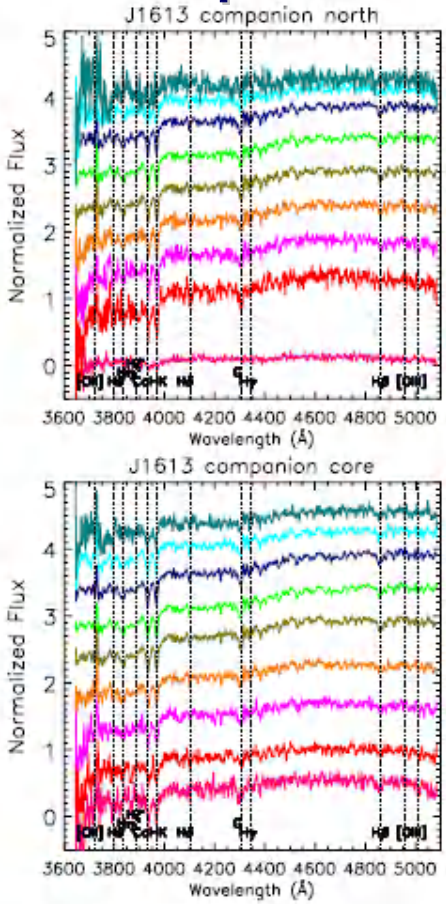
(Goto et al. 2008,MNRAS, 391, 790)

回覧



he SDSS *g*-, *r*-, *i*-composite image of the J1613+5103. The
itions are overlaid. The E+A galaxy is to the right (west), with
. The companion galaxy is to the left (east).

Companion



E+A

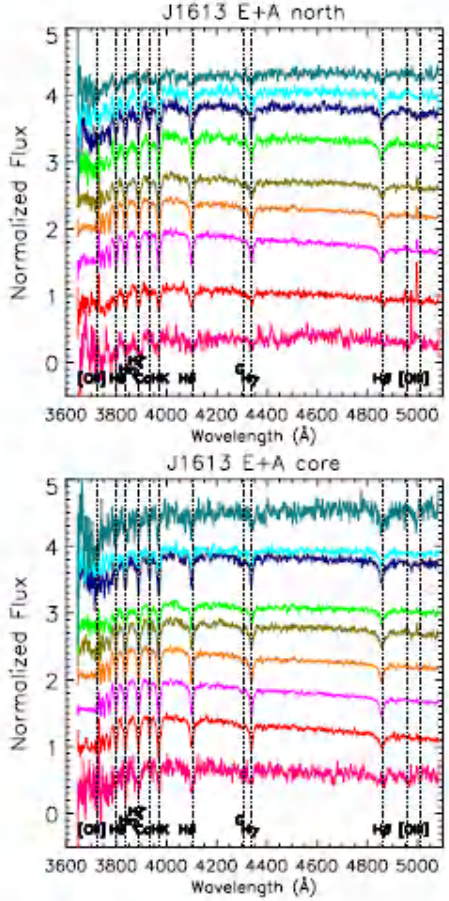


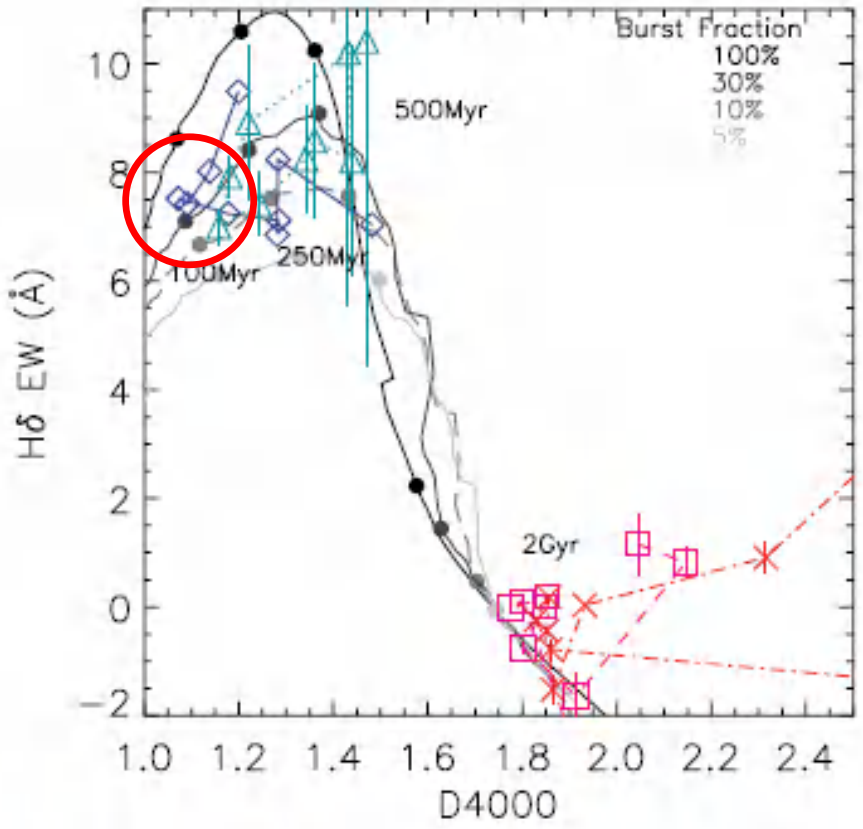
Figure 3. Spectra in each aperture. Right-hand panels are for the E+A galaxy. Left-hand panels are for the companion galaxy. Bottom panel
core. Top panels are shifted by 2 arcsec to the north. Each spectrum is spatially divided into nine equally spaced bins. In each panel, these ni

Younger Age at the center

(Goto et al. 2008,MNRAS, 391, 700)

回覧

Younger age at the center



8. Hδ EW is plotted against D4000. The diamonds and triangles are E+A core/north spectra, respectively. The squares and crosses are for npanion galaxy's core/north spectra. Grey lines are population syn- models from BC03 with 5–100 per cent delta burst population added

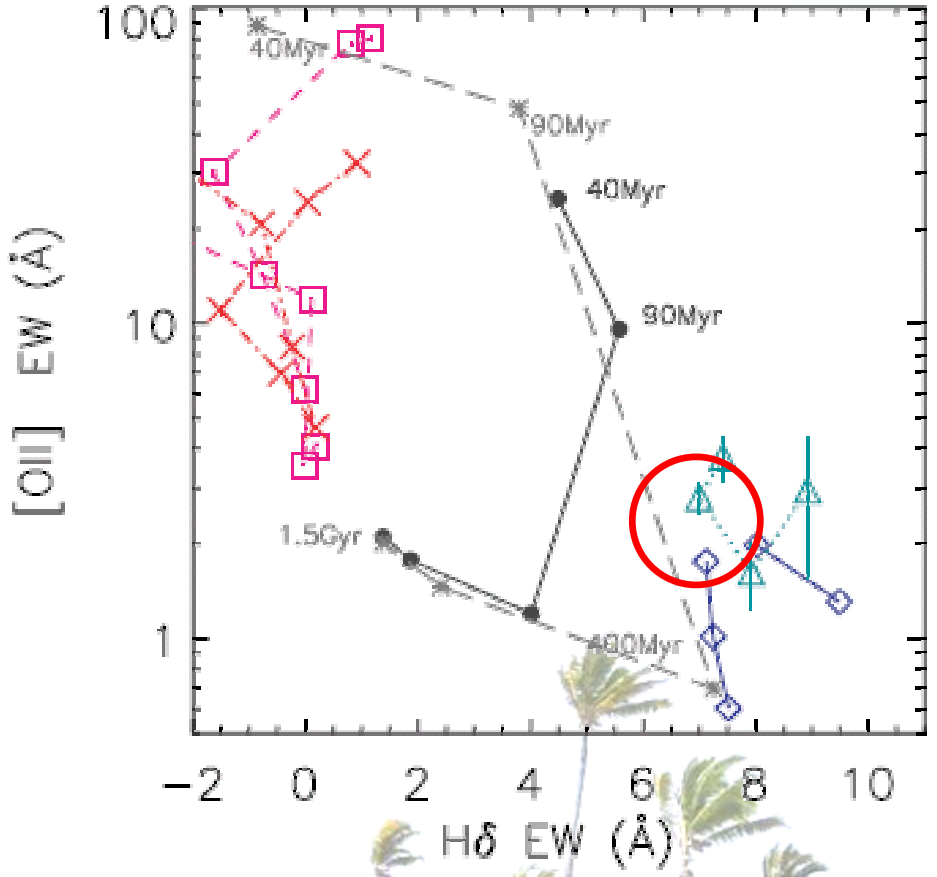


Figure 9. Hδ EW is plotted against [O II] EW. The diamonds and trian are for the E+A core/north spectra, respectively. The squares and cro are for the companion galaxy's core/north spectra. Only data points v

The Origin of local E+As

回覧

- ✓ E+As are in all environment including the field.
  - ➔E+As are not cluster/LSS origin.
- ✓ Optical-IR color is not redder; radio SFR<10Msun/yr.
  - ➔E+As are not likely to be Dusty Starburst.
- ✓ Excess in $N_{accompanying\ galaxies}$.
  - ➔Merger/interaction is most likely to be responsible for the E+As.
    - →Consistent with E morphology, younger age at the center by 2D-spectorsopy.

回覧

End

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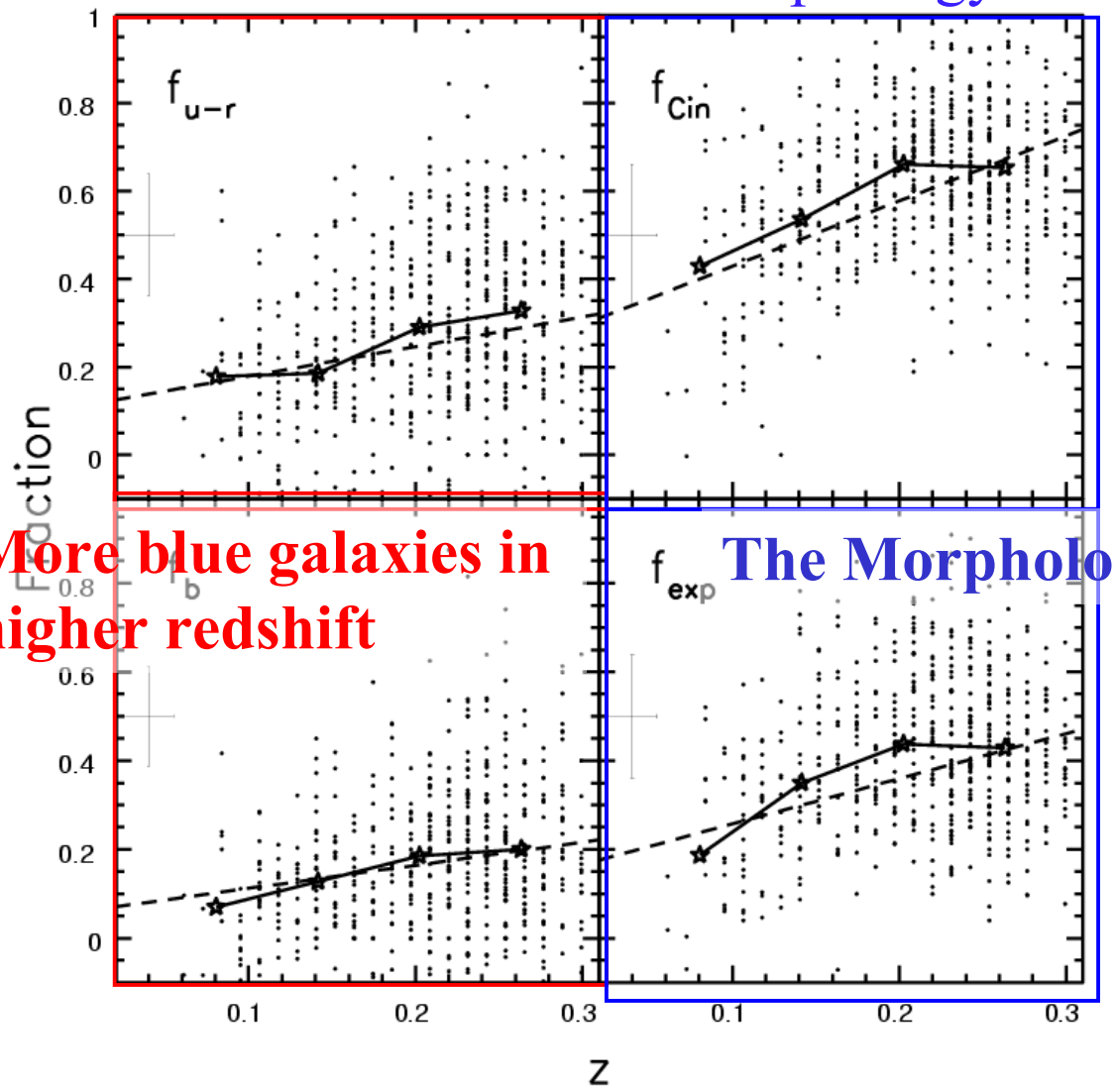
- post-starburst gum
- subaru picture
- bekki radial profile

回覧

color

morphology



Morphological Butcher-Oemler effect in CE

(Goto, et al. 2003, PASJ, 55,755)

More blue galaxies in higher redshift

The Morphological BO Effect

Fig. 1. Photometric and morphological Butcher-Oemler effect from the 514 SDSS Cut & Enhance clusters. f_b, f_{Cin}, f_{exp} and f_{u-r} are plotted against redshift. The dashed lines show the weighted least-squares fit to the data. The stars and solid lines show the median values. The median values of errors are shown in the upper left corners of each panel. The Spearman's correlation coefficients are shown in Table 1.

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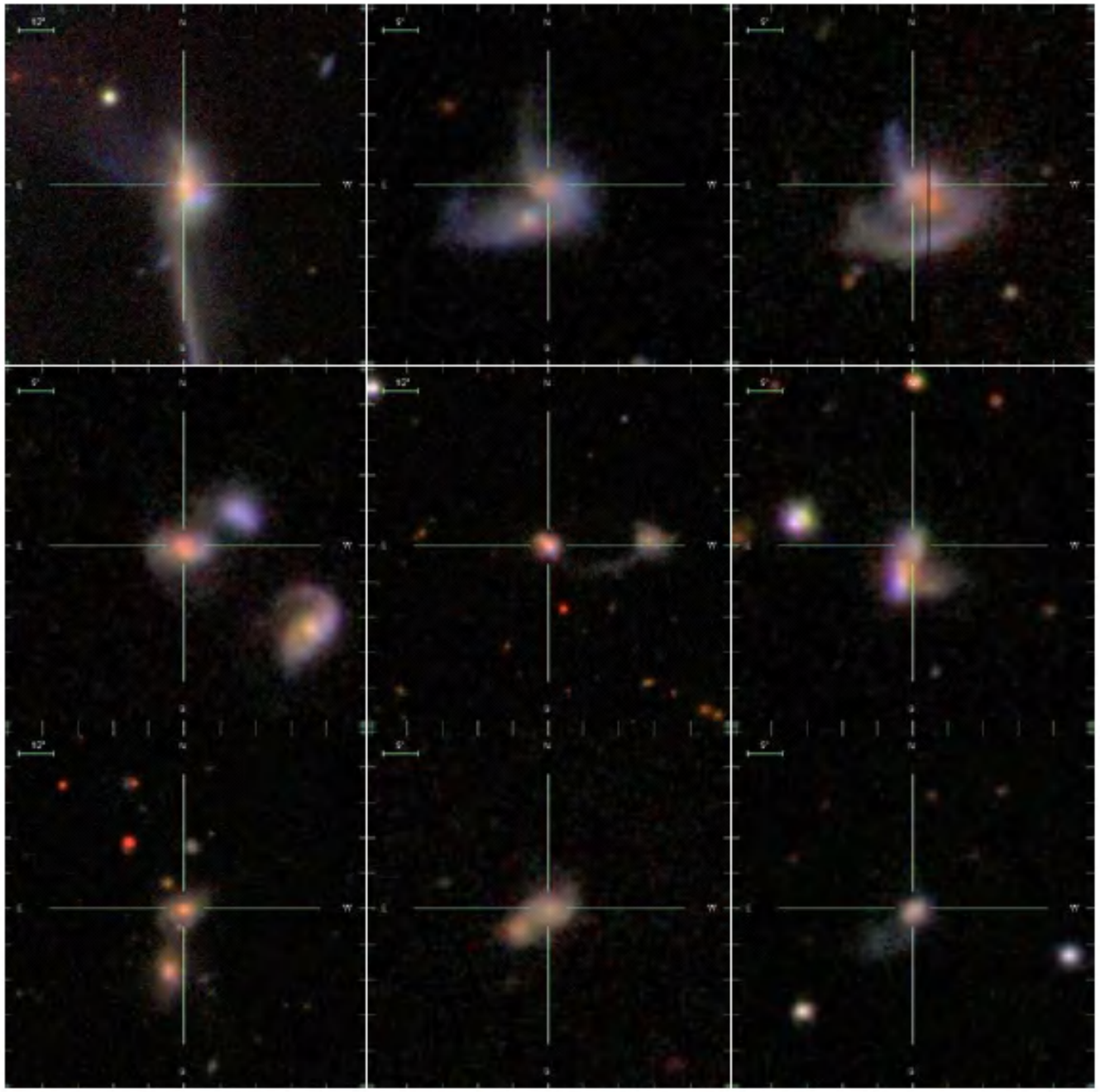


Figure 3. Examples of g, r, i-composite images of ULIRGs ($10^{12.0} < L_{ir} \leqslant 10^{13.0} L_{\odot}$). The images are sorted from low to high redshift. Only the nine lowest-redshift galaxies are shown. The corresponding spectra with name and redshift are presented in Fig. 4. (The spectrum of the same galaxy can be found in the same column/row panel of Fig. 4.)

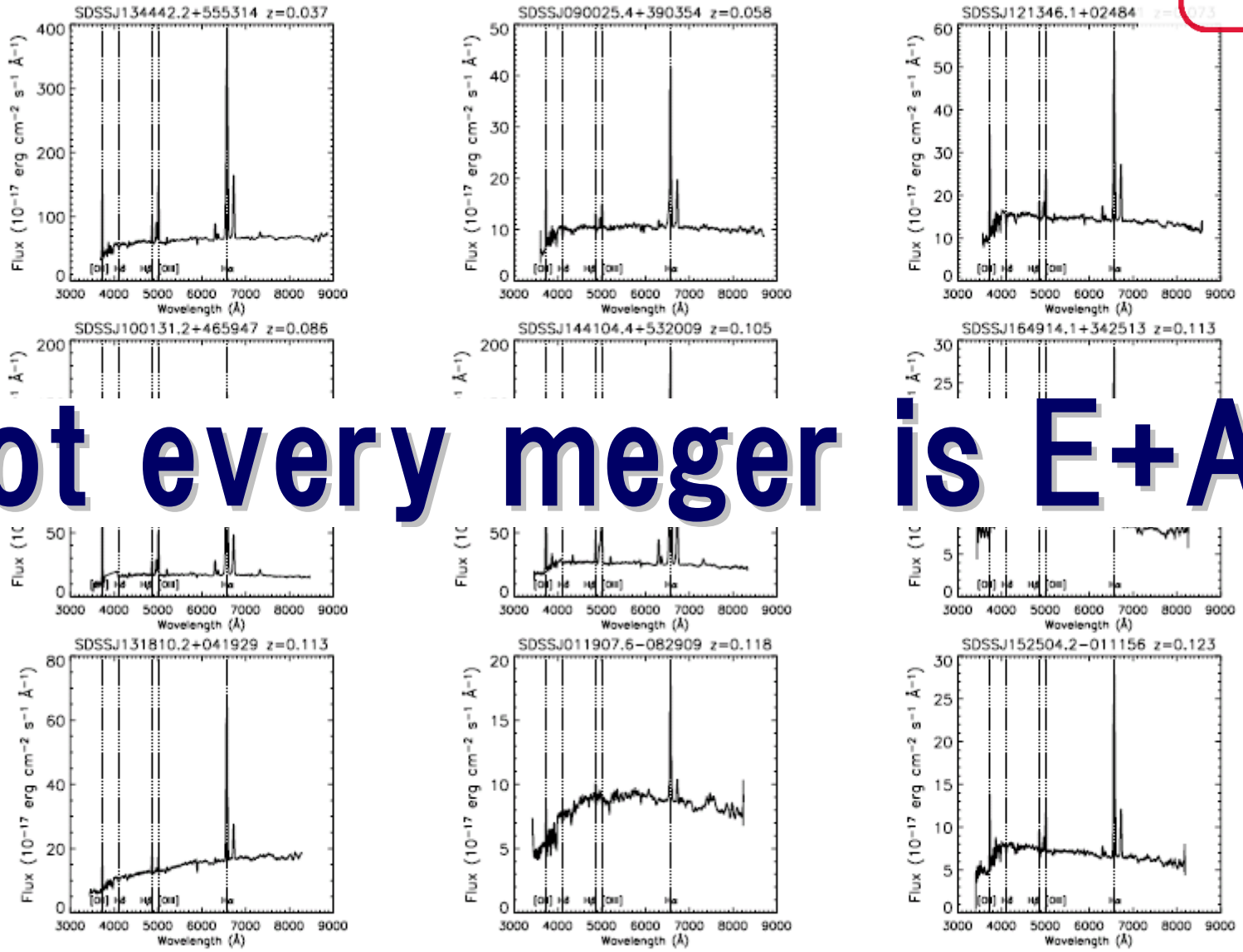
178 Ultra Luminous Infrared Galaxy (ULIRG)

$10^{12} L_{sun} < L_{ir} < 10^{13} L_{sun}$

Largest Sample of ULIRG before AKARI

Goto, T. 2005, MNRAS, 360, 322

回覧



Not every meger is E+A.

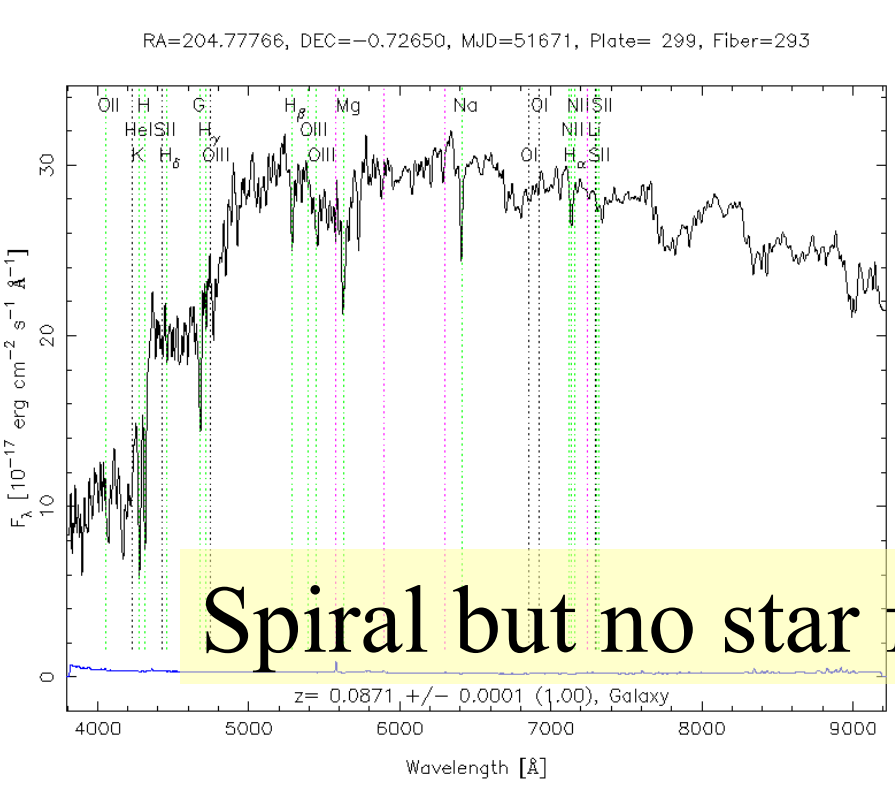
Figure 4. Example spectra of the nine lowest-redshift ULIRGs. The spectra are sorted from low redshift. Each spectrum is shifted to the restframe wavelength and smoothed using a 20-Å box. The corresponding images are shown in Fig. 3. (The image of the same galaxy can be found in the same column/row panel of Fig. 3.)

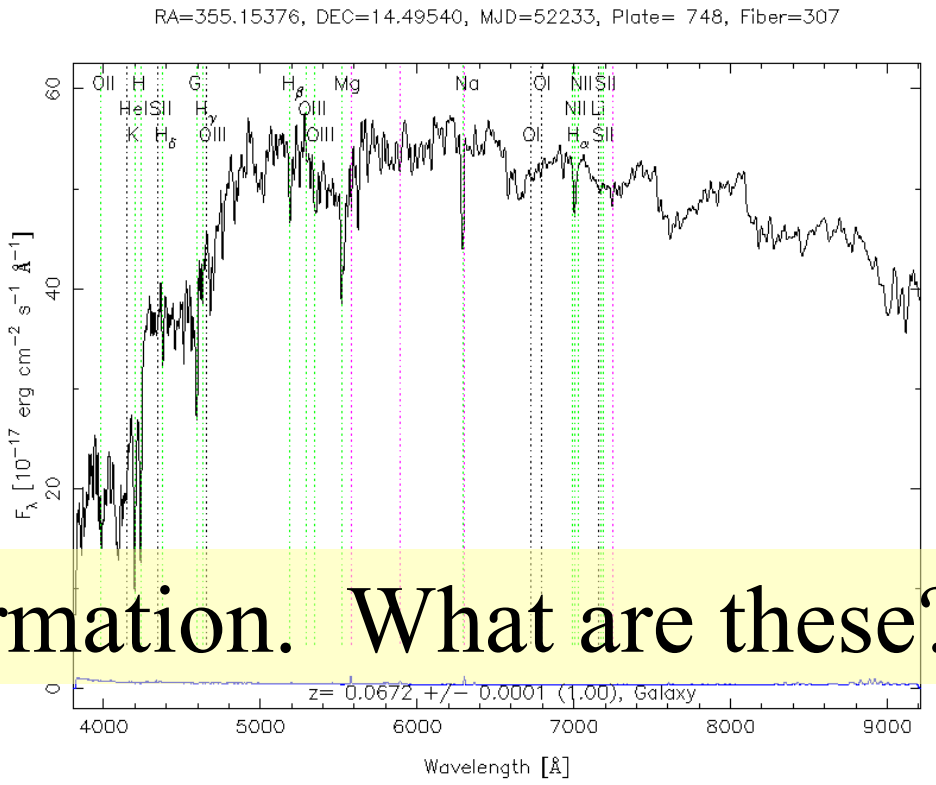
Goto, T. 2005, MNRAS, 360, 322

Passive Spiral Galaxies in the SDSS

(Goto et al. 2003,PASJ,55,757)

回覧





Spiral but no star formation. What are these?

Optical-IR color --- not dustier

回覧

-

PS do not look like dusty star forming galaxies.

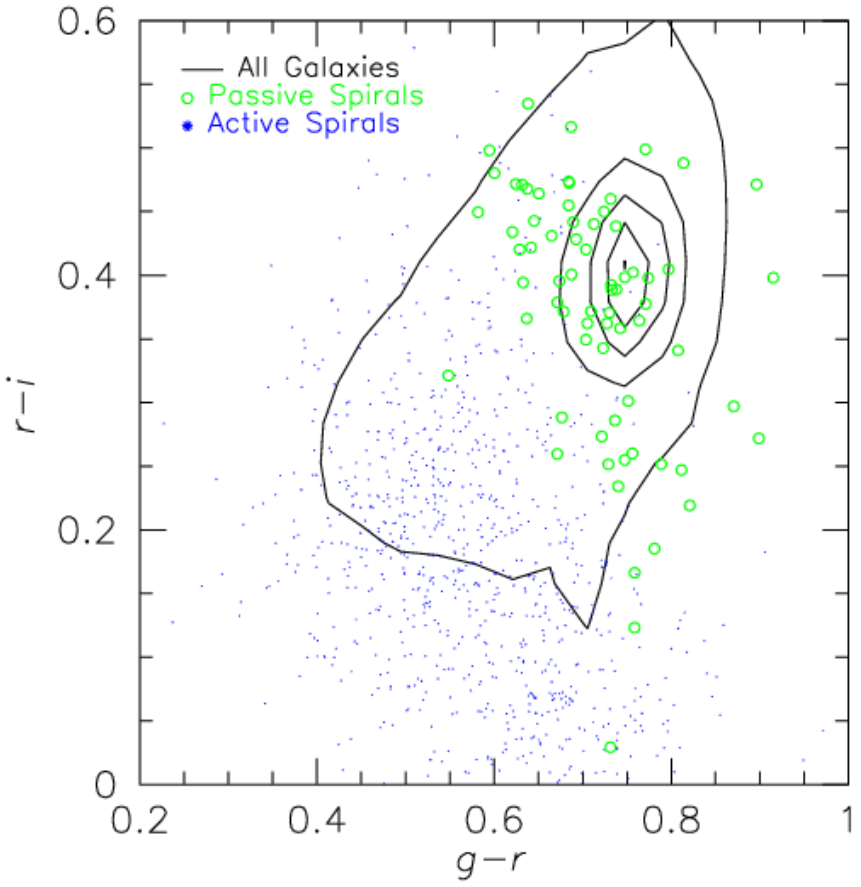
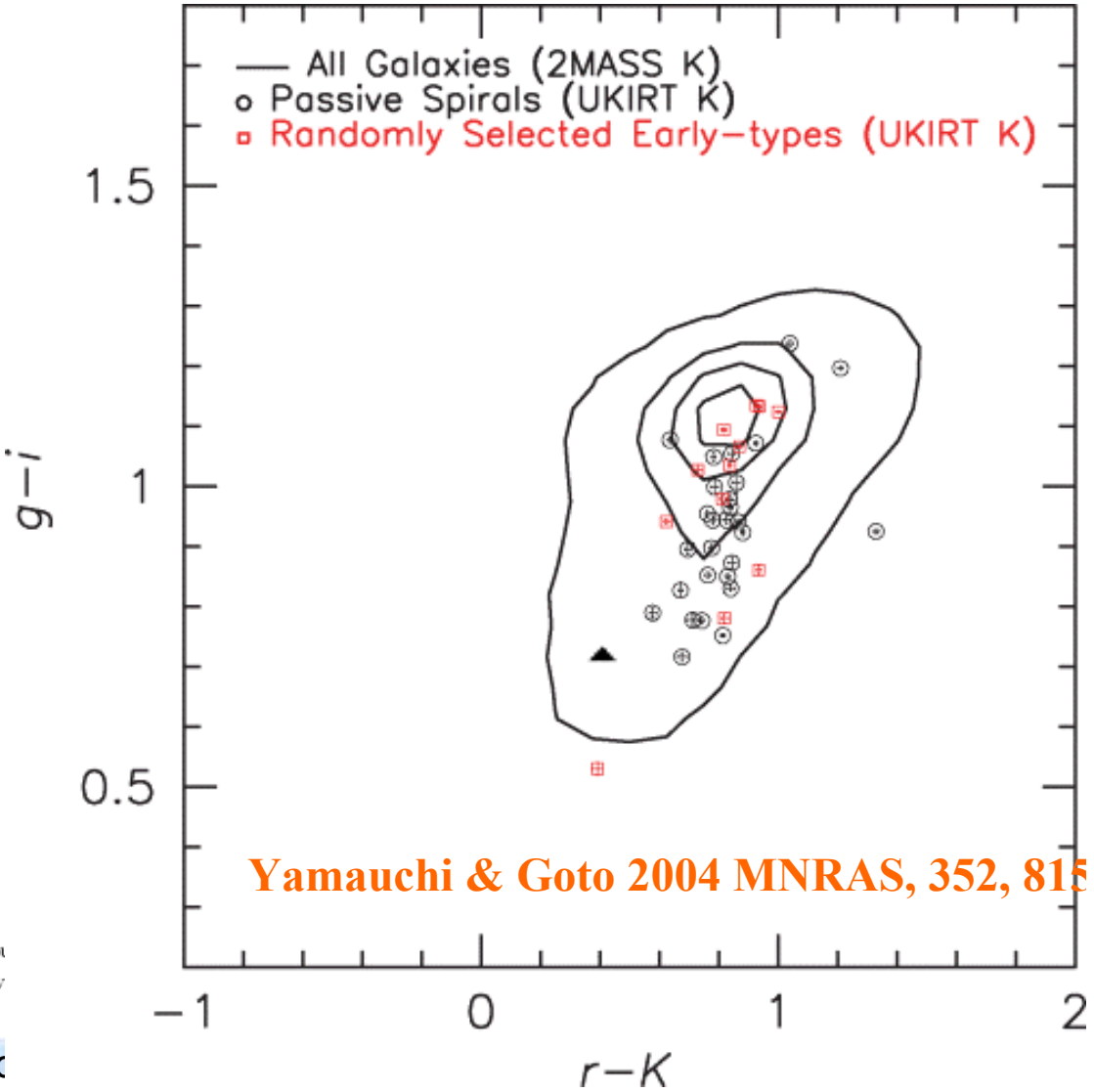


Fig. 9. The distribution of passive spirals in restframe $g-r-i$ plane. Contours show the distribu all galaxies in our volume limited sample. Open circle and filled dots represent passive and activ galaxies, respectively.



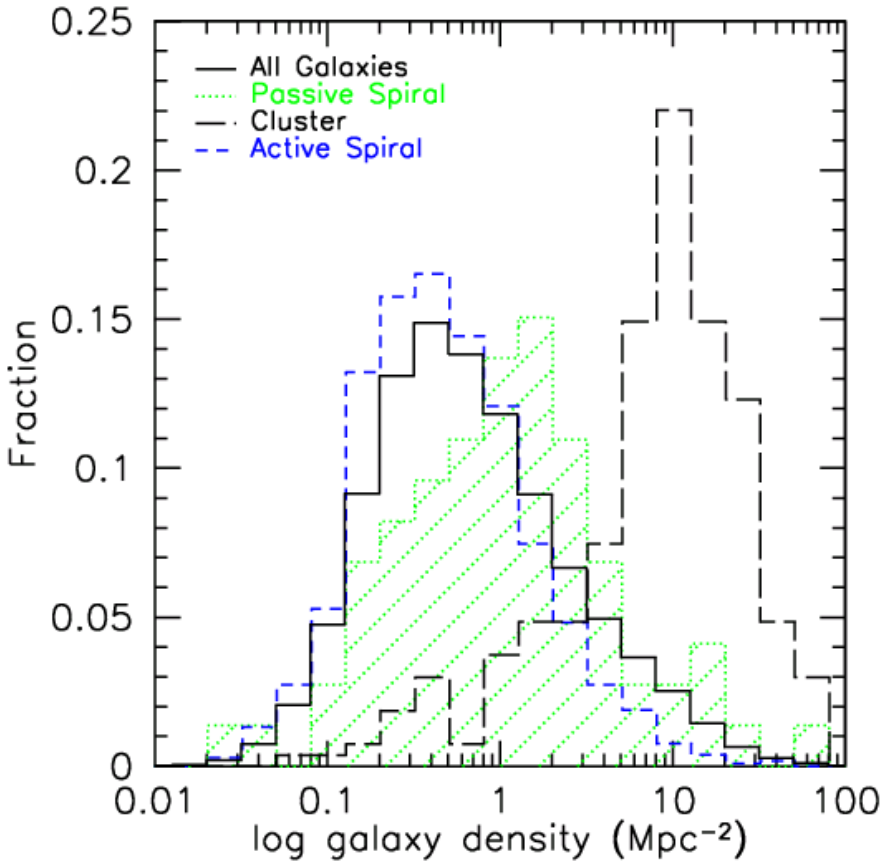
Yamauchi & Goto 2004 MNRAS, 352, 815

The Environment of Passive Spirals

(Goto et al. 2003,PASJ,55,757)

Passive spirals may be a smoking gun in cluster galaxy evolution.

回覧



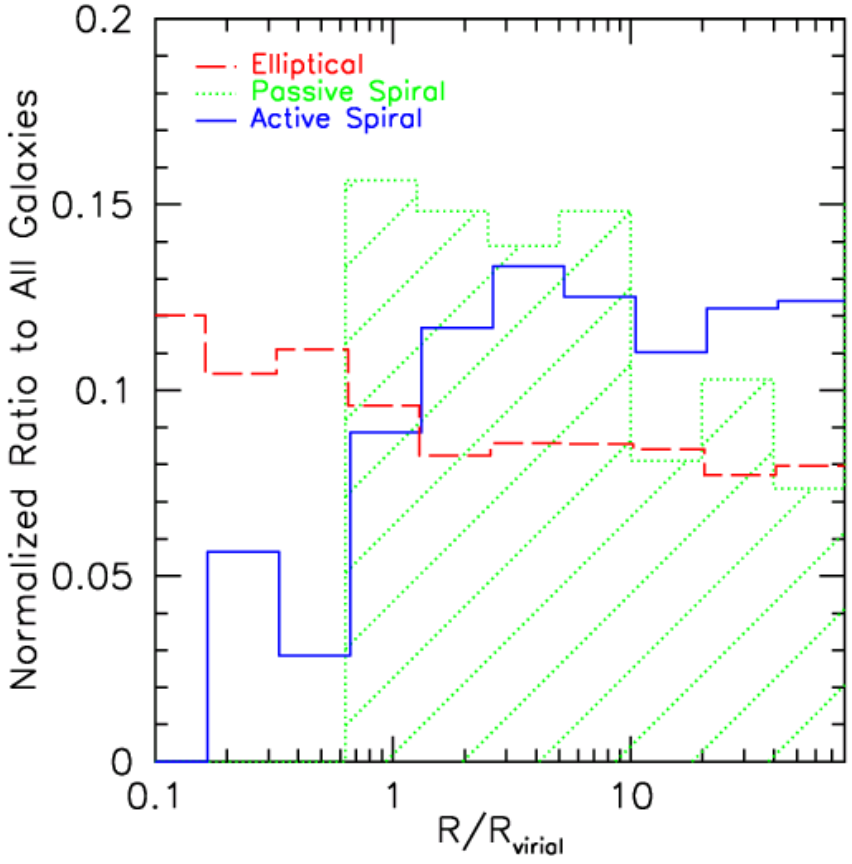


Fig. 7. The distribution of densities for passive spiral galaxies (hashed region) and all galaxies (solid line) in a volume limited sample. A Kolomogorov-Smirnov test shows distributions of passive spirals and all galaxies are from a different distribution. A long dashed line shows the distribution of cluster galaxies. A short dashed line shows that of active spiral galaxies.

g. 8. The distribution of passive spiral galaxies as a function of cluster-centric-radius. A solid, dashed d dotted lines show the distributions of passive spiral, elliptical and active spiral galaxies, respectively. e distributions are relative to that of all galaxies in the volume limited sample and normalized to be 1 clarity. The cluster-centric-radius is measured as a distance to a nearest C4 cluster (Miller et al. 2003) within ±3000 km/s, and normalized by virial radius (Girardi et al. 1998).

Morphology Radius Relation
(Goto et al. 2003, MNRAS, 346, 601,)

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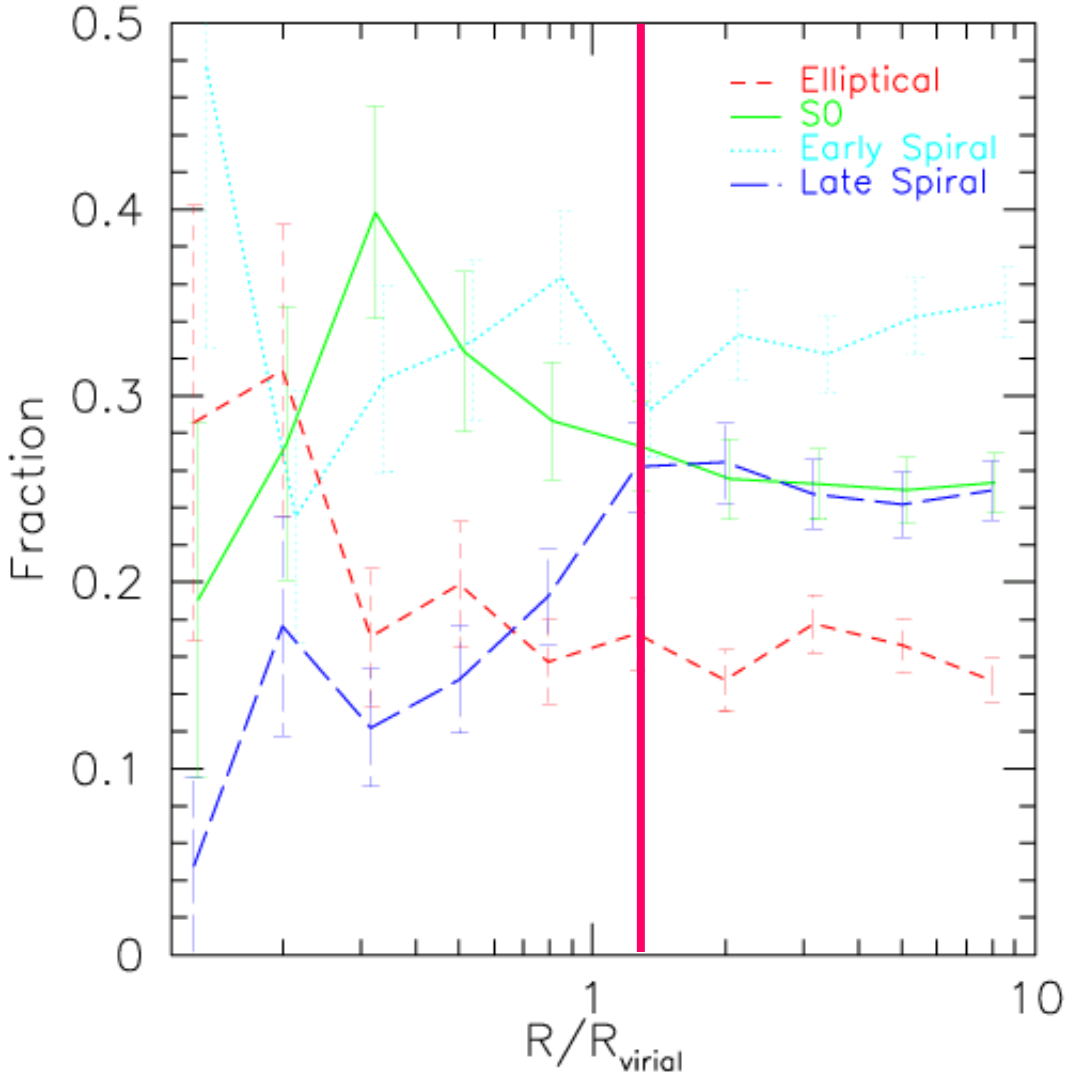
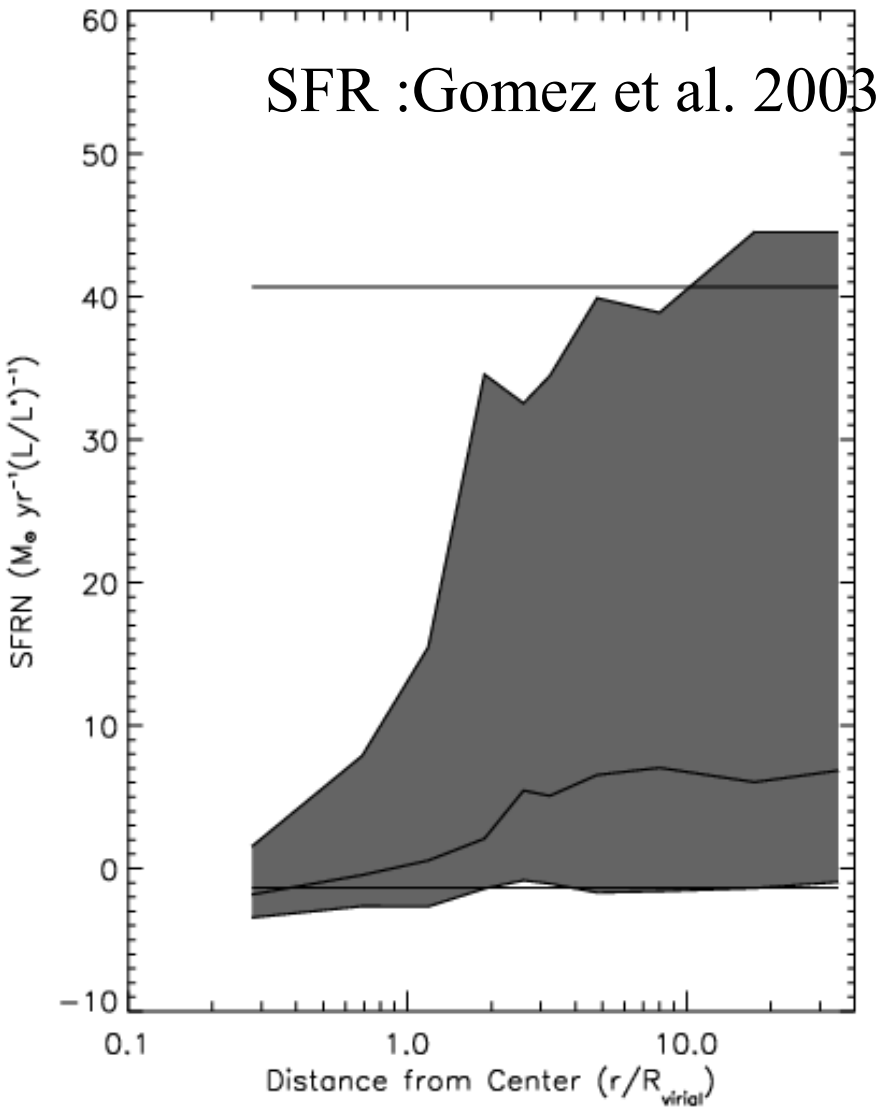


Fig. 15.— The morphology-radius relation. Fractions of each type of a galaxy is plotted against cluster centric radius to the nearest cluster. short-dashed, solid, dotted and long-dashed lines represent elliptical, S0, early-spiral and late-spiral galaxies, respectively.

SFR :Gomez et al. 2003



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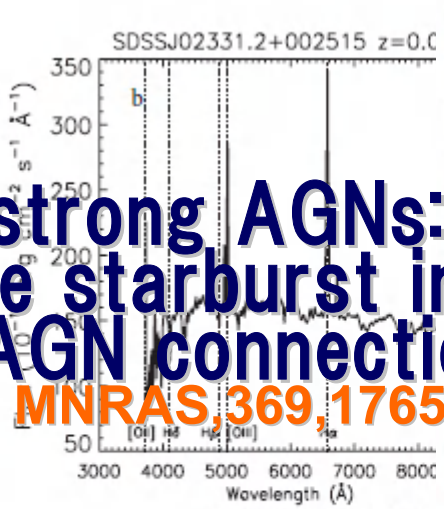
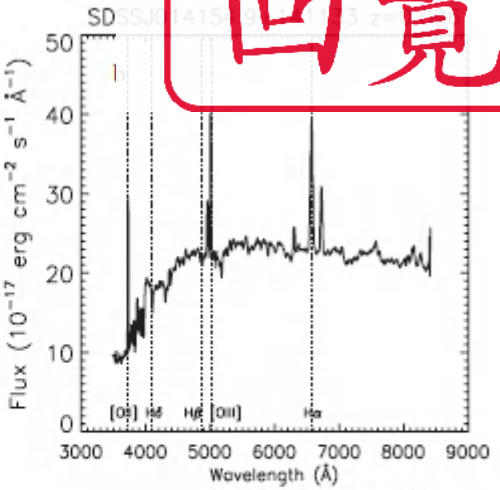
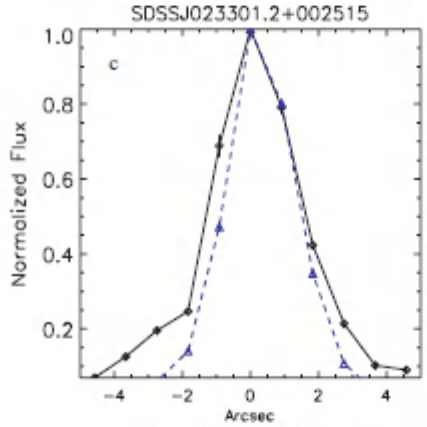
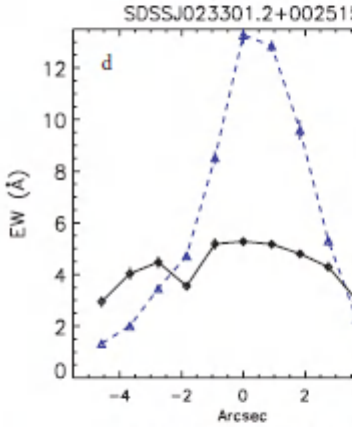
Hdelta-strong AGNs: AGNs outlive starburst in the starburst-AGN connection?

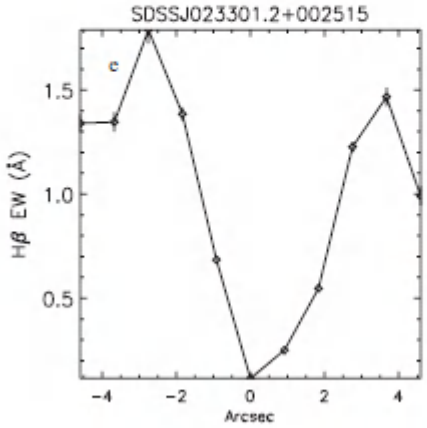
(Goto 2006, MNRAS,369,1765)

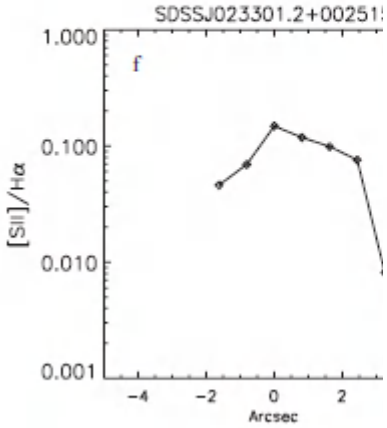


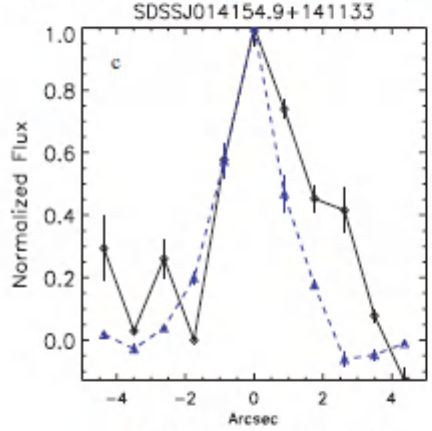


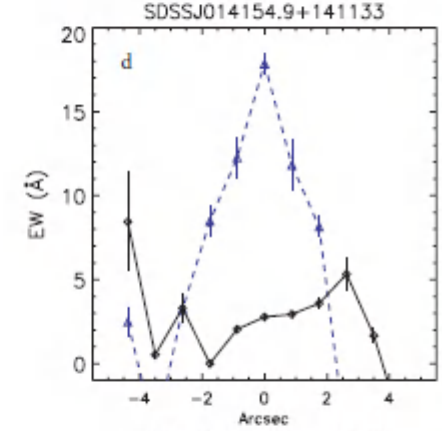


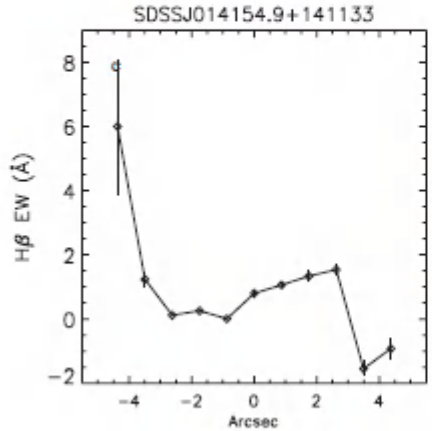


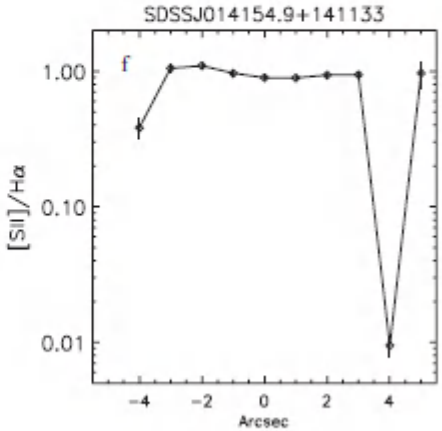












SS J023301.2+002515. Panel (a) shows *g*, *r*, *i*-composite image taken with the SDSS. Panel (b

Figure 3. As Fig. 1, but for SDSS J014154.9+141133.

Hδ strong-AGNs

回覧

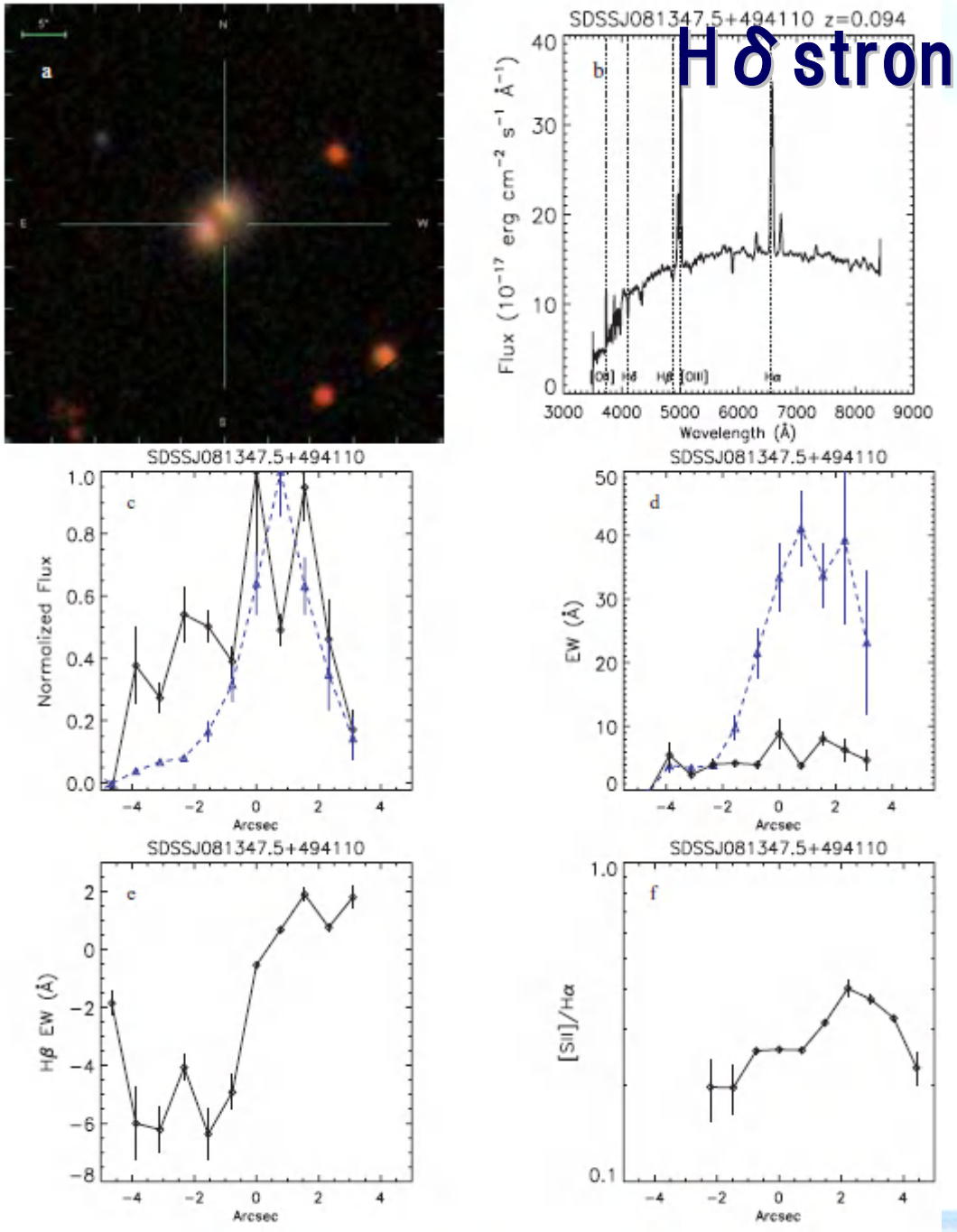


Figure 2. As Fig. 1, but for SDSS J081347.5+494110.

- Poststarburst & AGN are spatially correlated, suggesting underlying physical connection.
- The existence of poststarburst-AGN suggests that AGNs outlive starburst. Hdelta/D4000 can possibly used as a time clock to understand the AGN lifecycle.

Schechter parameters

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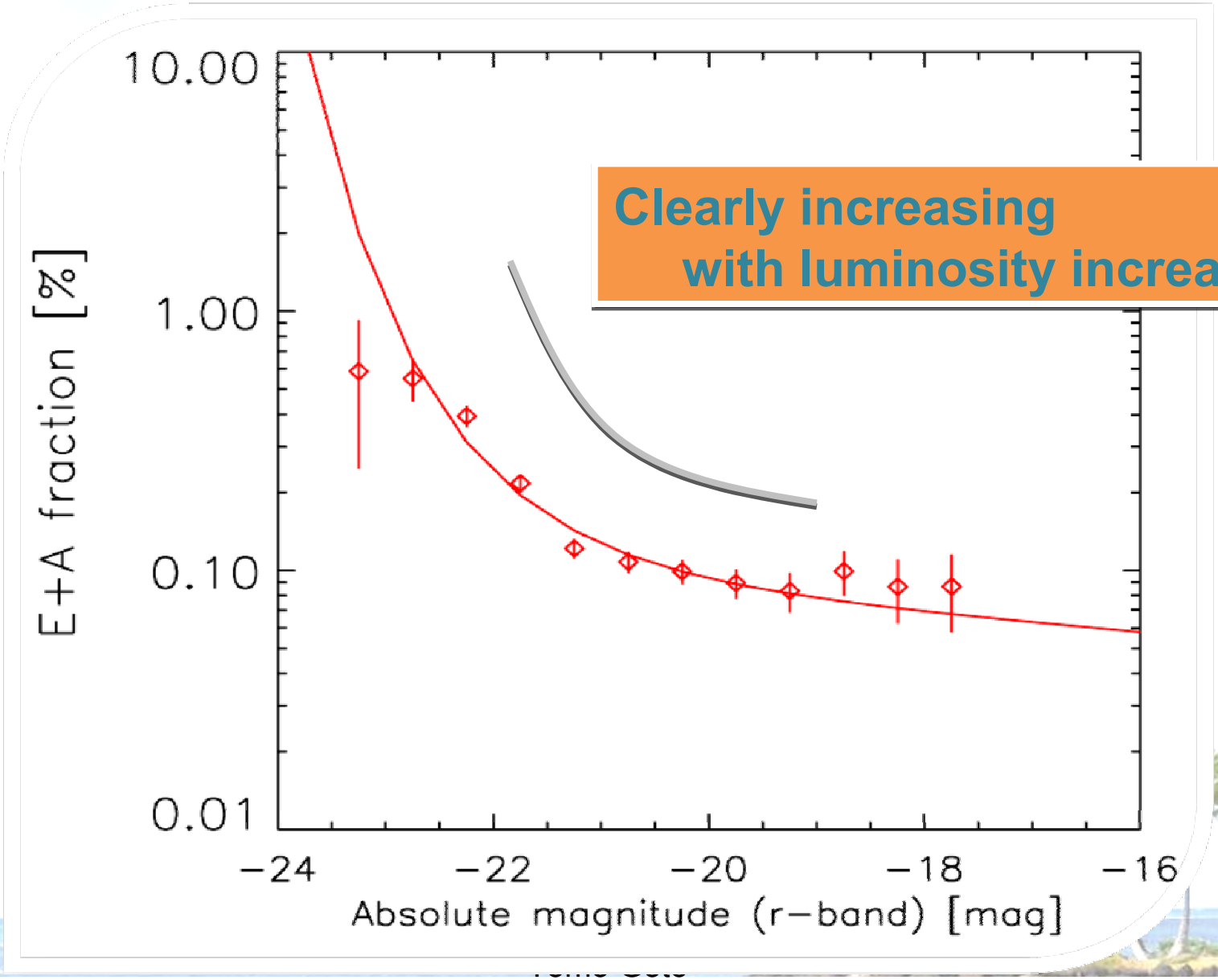
	$M_r - 5 \log h$ [mag]	α	ϕ^* [0.01 h^3 Mpc^{-3}]
E+A 銀河	-21.26+/-0.07	-1.07+/-0.08	(7.39+/-0.77)e-4
SDSS DR6 全銀河	-20.84+/-0.01	-1.16+/- 0.01	0.88+/-0.04

回覧

LF fraction



Clearly increasing with luminosity increasing

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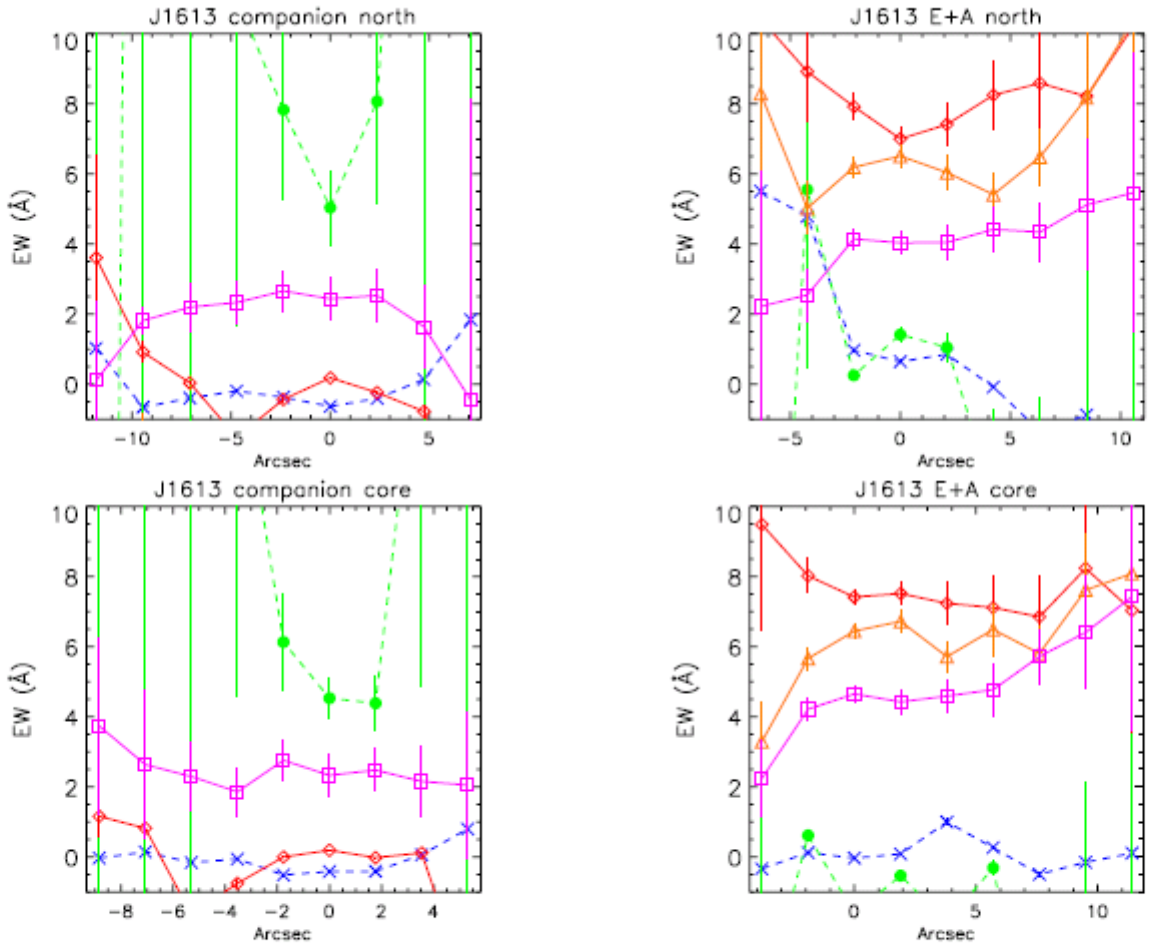

Figure 5. EW profiles. The right-hand panels show the EW profiles for the E+A core (lower) and north (upper) spectra. The left-hand panels show the EW profiles for the companion core (lower) and north (upper) spectra. The diamond (red), triangle (orange) and square (magenta) symbols are for Hδ, Hγ and Hβ, respectively. These absorption lines are connected with the solid lines. The cross (blue) and filled (green) circle are for [O III] and [O II] emission lines, which have positive sign in this plot. The emission lines are connected with the dotted lines. 1 arcsec corresponds to 0.66 kpc at this redshift.

回覧

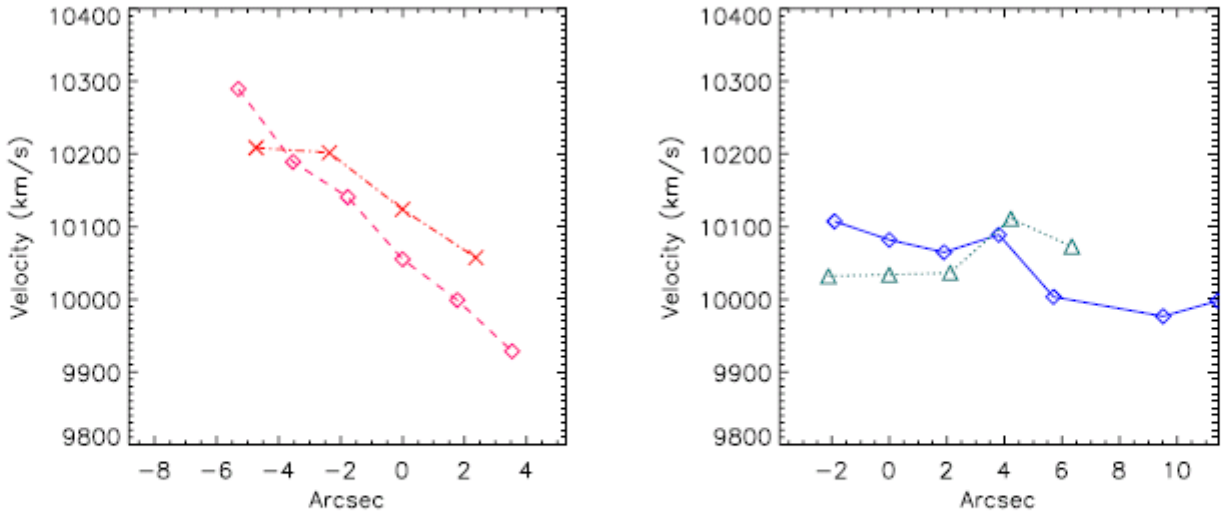

Figure 6. Recession velocity. We plot recession velocity of the Hδ line. The diamonds and triangles in the right-hand panel are for the E+A core/north spectra, respectively. The squares and crosses are for the companion galaxy's core/north spectra in the left-hand panel. We visually checked the Gaussian fits, and only data points based on a reasonably good fit are shown. 1 arcsec corresponds to 0.66 kpc at this redshift.

Time sequence of truncation

(Yagi & Goto 2006,ApJ,642,152, 2006,AJ,131.2050)

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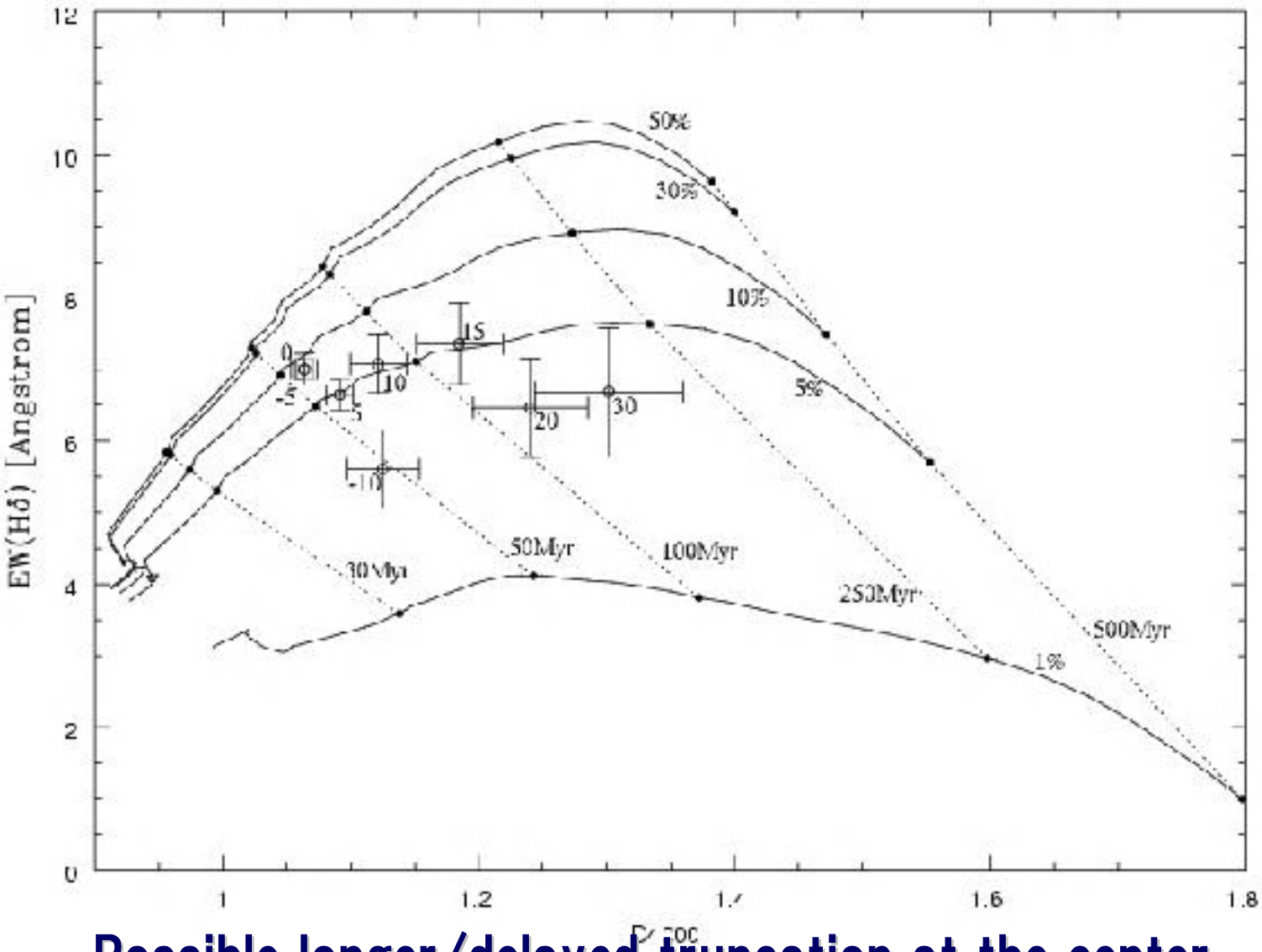

Possible longer/delayed truncation at the center.

Spatially resolved spectroscopy

(Yagi & Goto 2006,ApJ,642,152, 2006AJ....131.2050)

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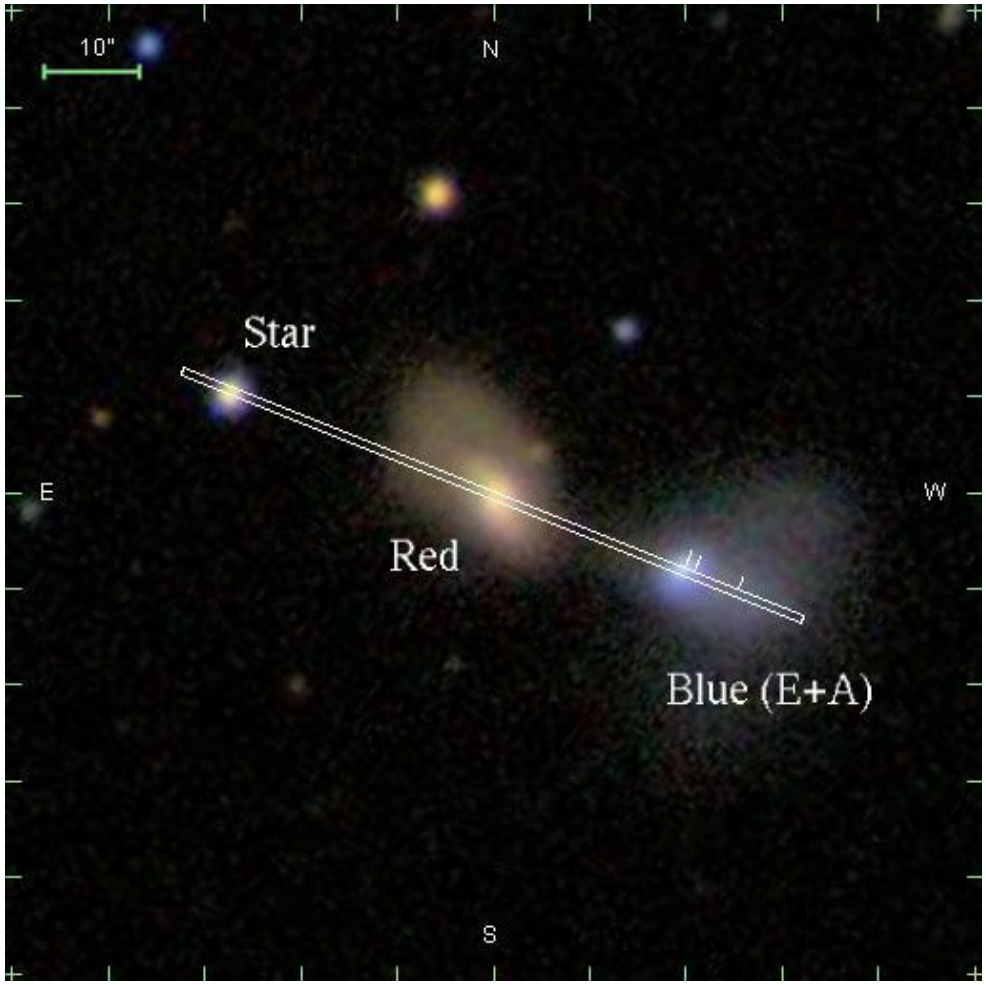

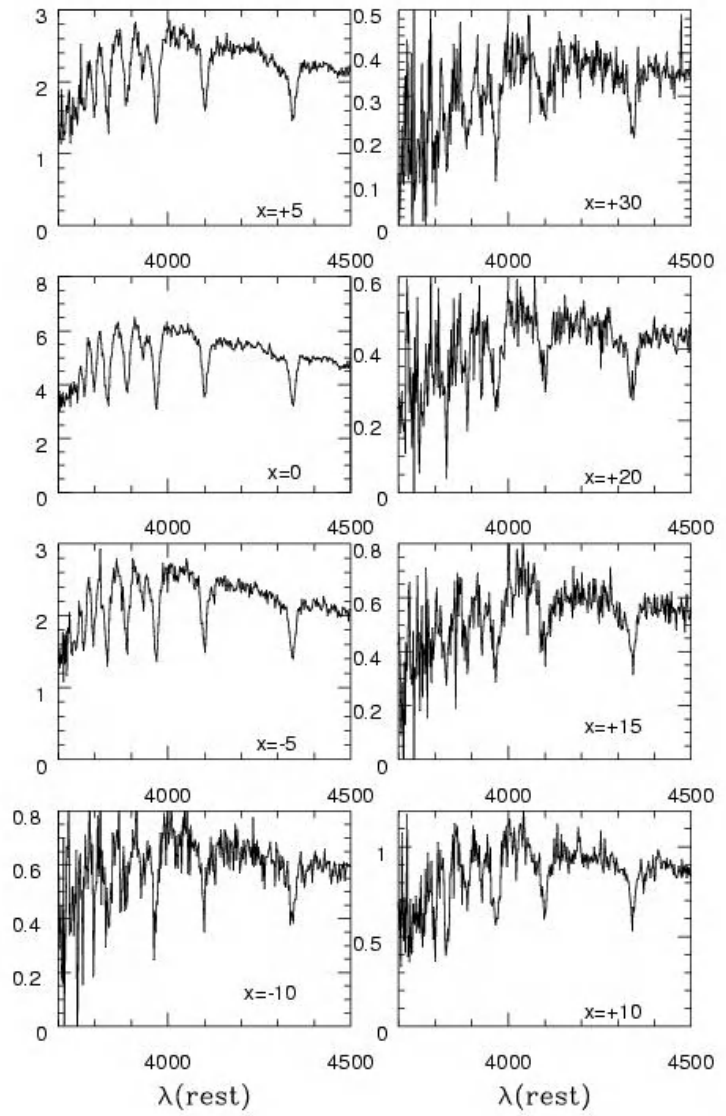

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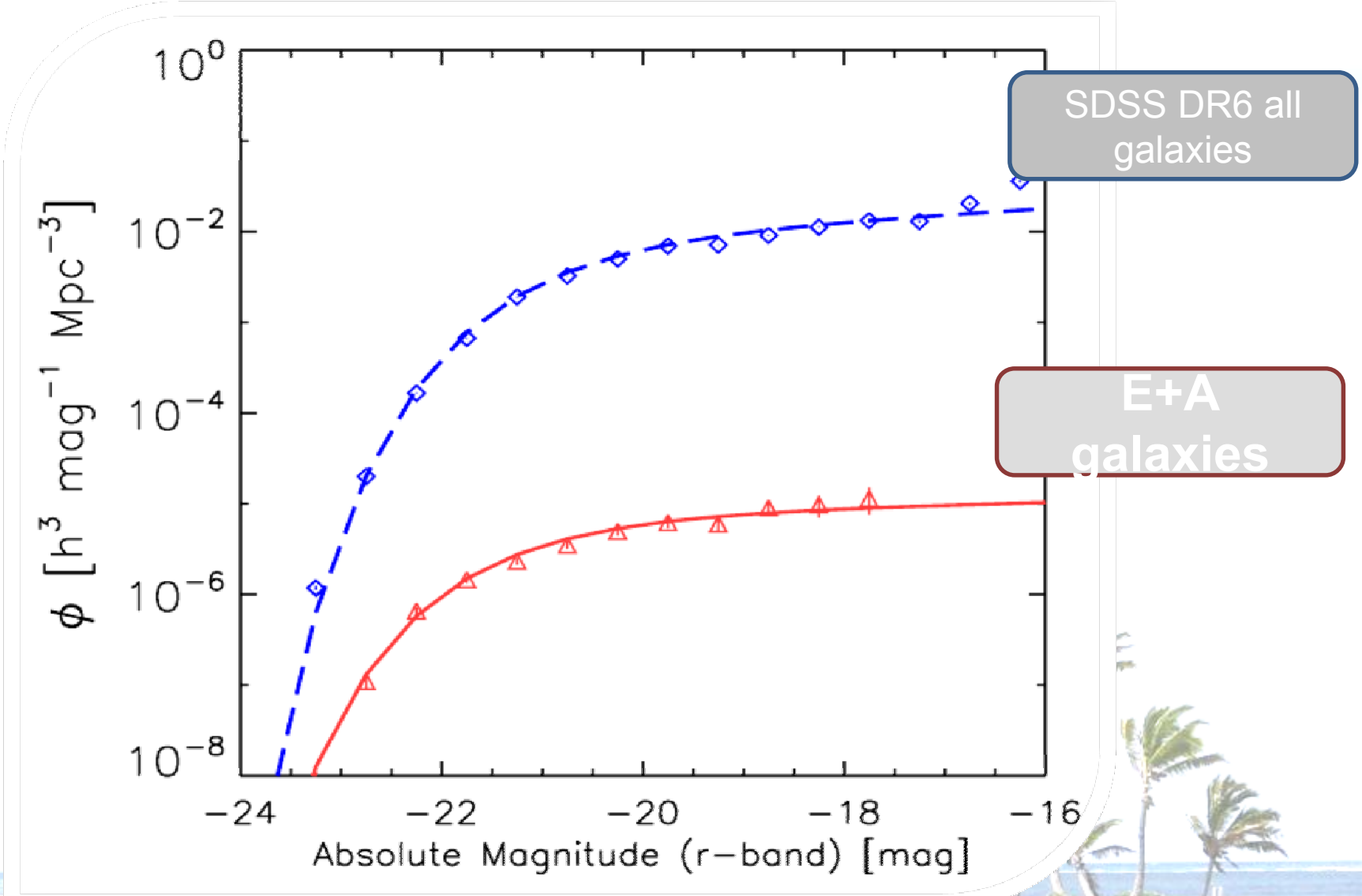
E+A LF

Inami & Goto et al. in prep.



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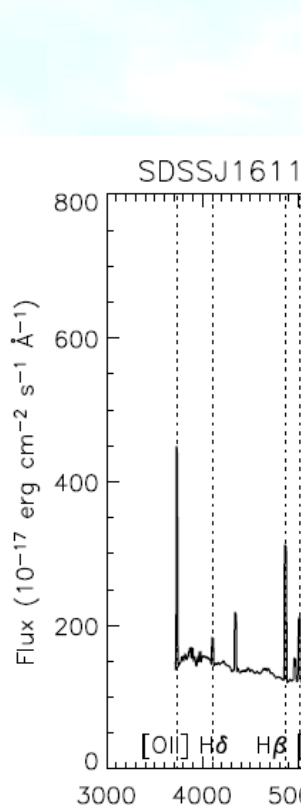
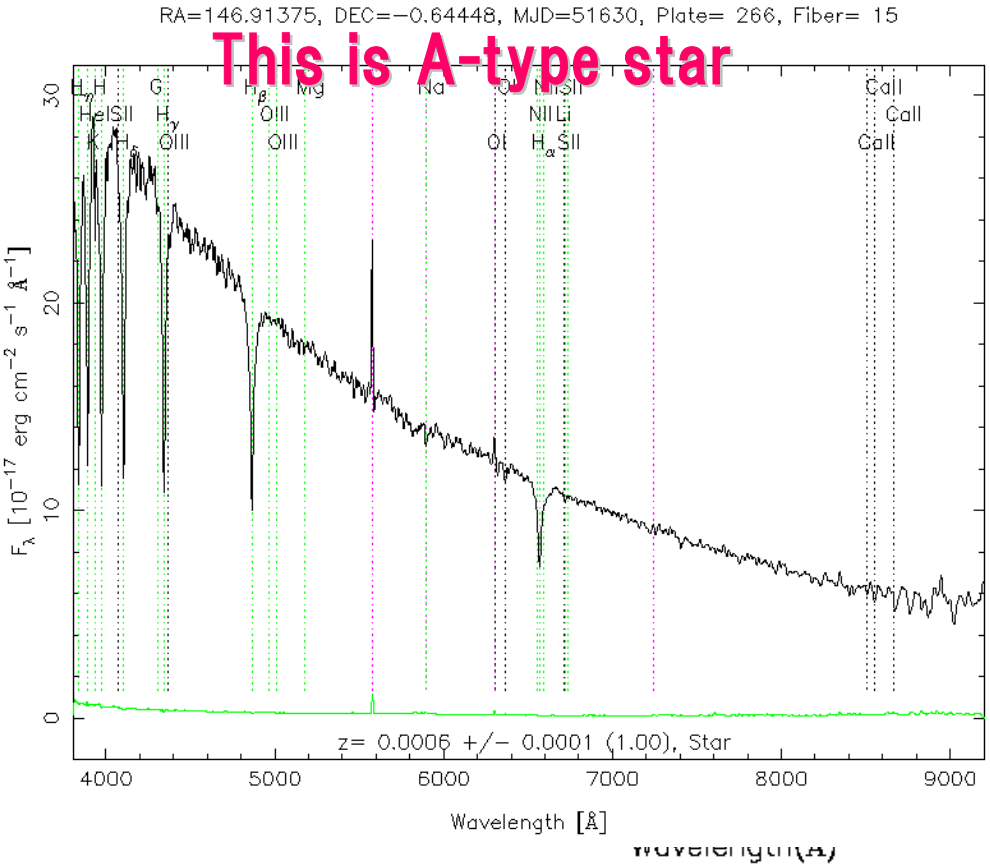
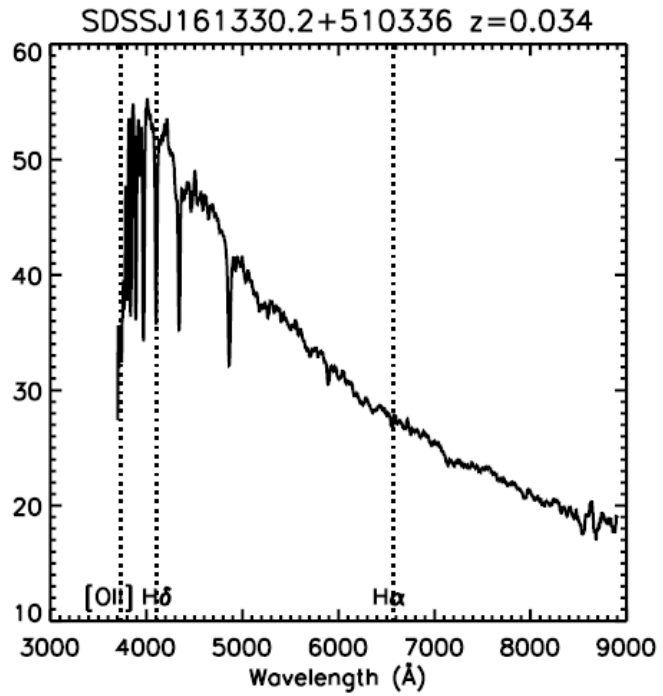




This is a galaxy



- Not much information on past SFH
- Truncation of SF: galaxy evolution in action