Reionization — Who Dunnit? Quasars or Dwarf Galaxies?

or: "Did Galaxy Assembly and Supermassive Black-Hole Growth go Hand in Hand?

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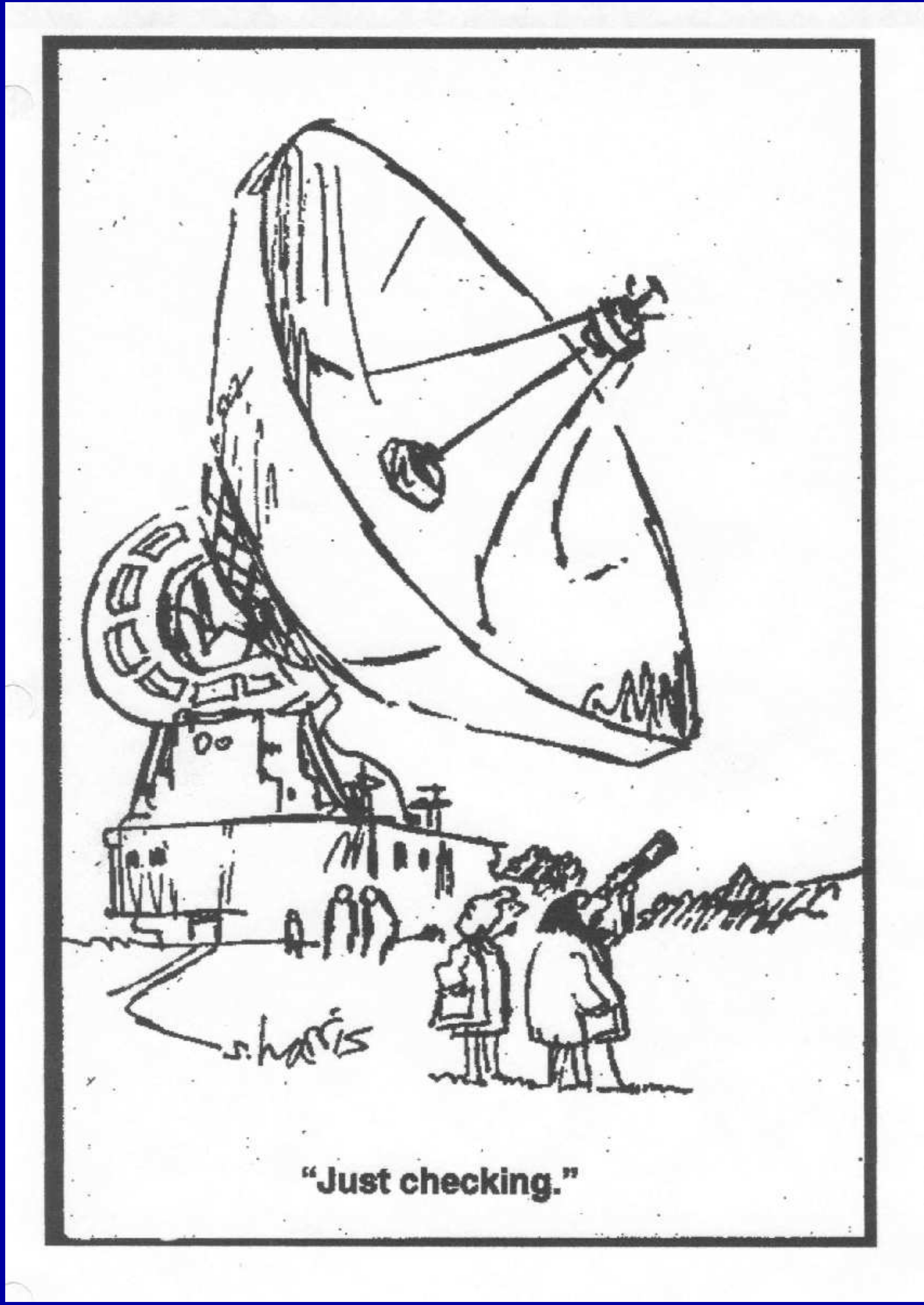
hubblesite.org/newscenter/archive/2004/28/   *hubblesite.org/newscenter/archive/2006/04/*

Colloquium at the University of Washington, Thursday May 17, 2007

"For God's sake, Edwards. Put the laser pointer away."

The danger of having Quasar-like devices too close to home ...



HST and JWST changed the career of this radio astronomer ...

Outline

- (0) Introduction: Galaxy Assembly and Supermassive Black Hole Growth
- (1) Scientific Background and Goals:
- (1.a) Can we quantitatively establish if/how SMBH growth went hand-in-hand with galaxy assembly?
- (1.b) Was the epoch dependent rate of (minor) mergers the major driver of galaxy assembly, and also of SMBH growth & AGN activity?
- (2) Tadpole Galaxies in the HUDF: A measure of Galaxy Assembly?
- (3) A Study of Variable Objects in the HUDF: A measure of AGN Growth?
- (4) Future studies with Hubble Wide Field Camera 3 and James Webb
- (5) Summary and Conclusions

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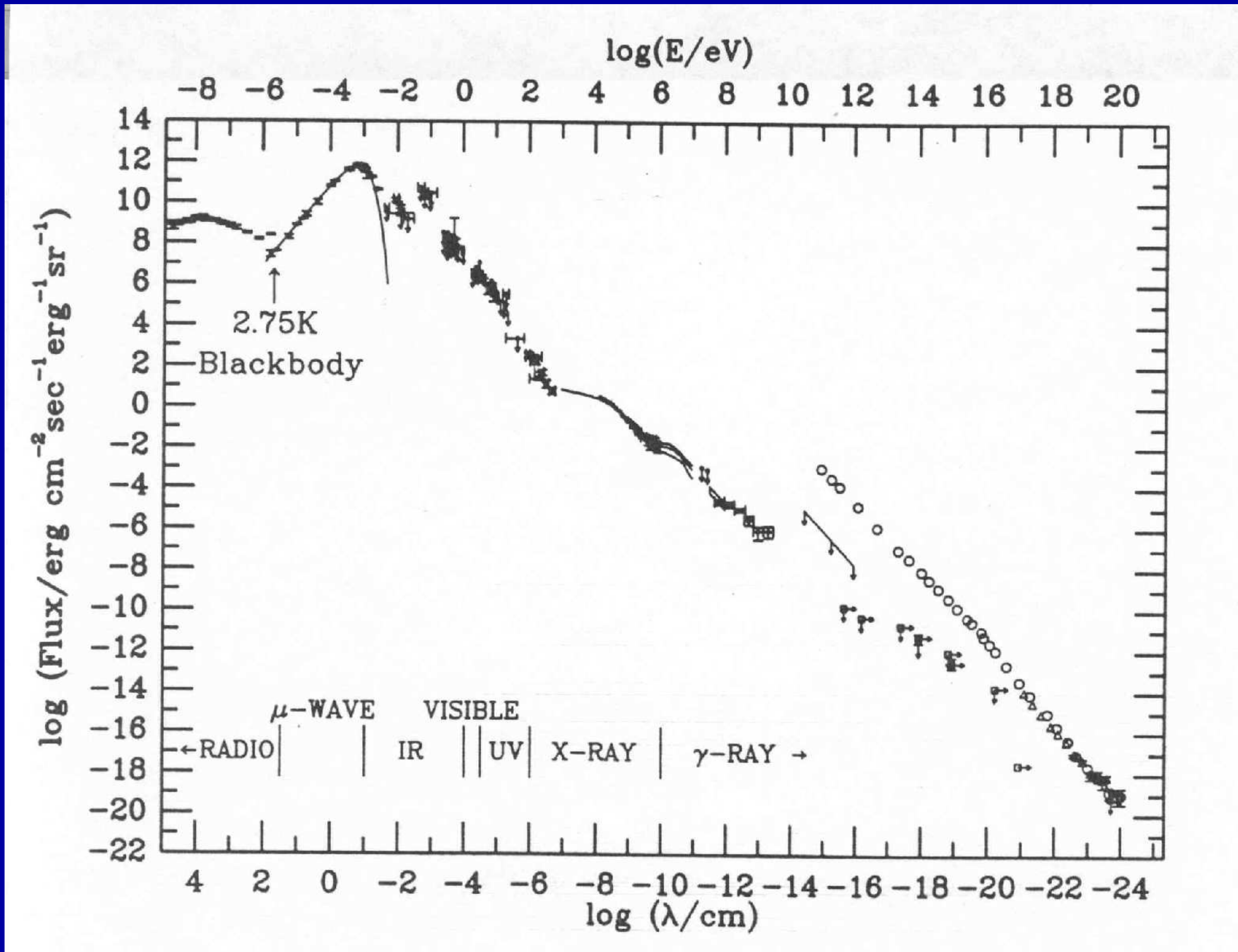
(0) The Cosmic Expansion and Contents of the Universe

Expansion $\Rightarrow$ redshift	$\lambda_{obs} = \lambda_{rest}$. (1+z)
Hubble's Law:	D $\simeq$ v / $H_o \simeq$ (c/H_o) . z = R_o . z
Item:	Numbers inside R_0=(c/H_0)$\simeq$13.7 Glyr:
Photons:	$N_{h\nu} \sim 10^{89}$
Baryons:	$N_b \sim 10^{80}$
η=Photons/Baryons	$\eta \sim 10^9$
Energy Density:	as fraction of critical closure density (WMAP):
Baryons:	$\Omega_b = \rho_b/\rho_{crit} \simeq 0.042$
Dark Matter:	$\Omega_d = \rho_d/\rho_{crit} \simeq 0.20$
Dark Energy:	$\Omega_\Lambda = \rho_\Lambda/\rho_{crit} \simeq 0.76$
(Supermassive) black holes:	$\Omega_{smbh} = \rho_{smbh}/\rho_{crit} \simeq 0.0001$
Total	$\Omega_{tot} = \rho_{tot}/\rho_{crit} \simeq 1.00 \pm 0.02$ ($\rho_{crit} \simeq 10^{-29}$ gr/cm^3)

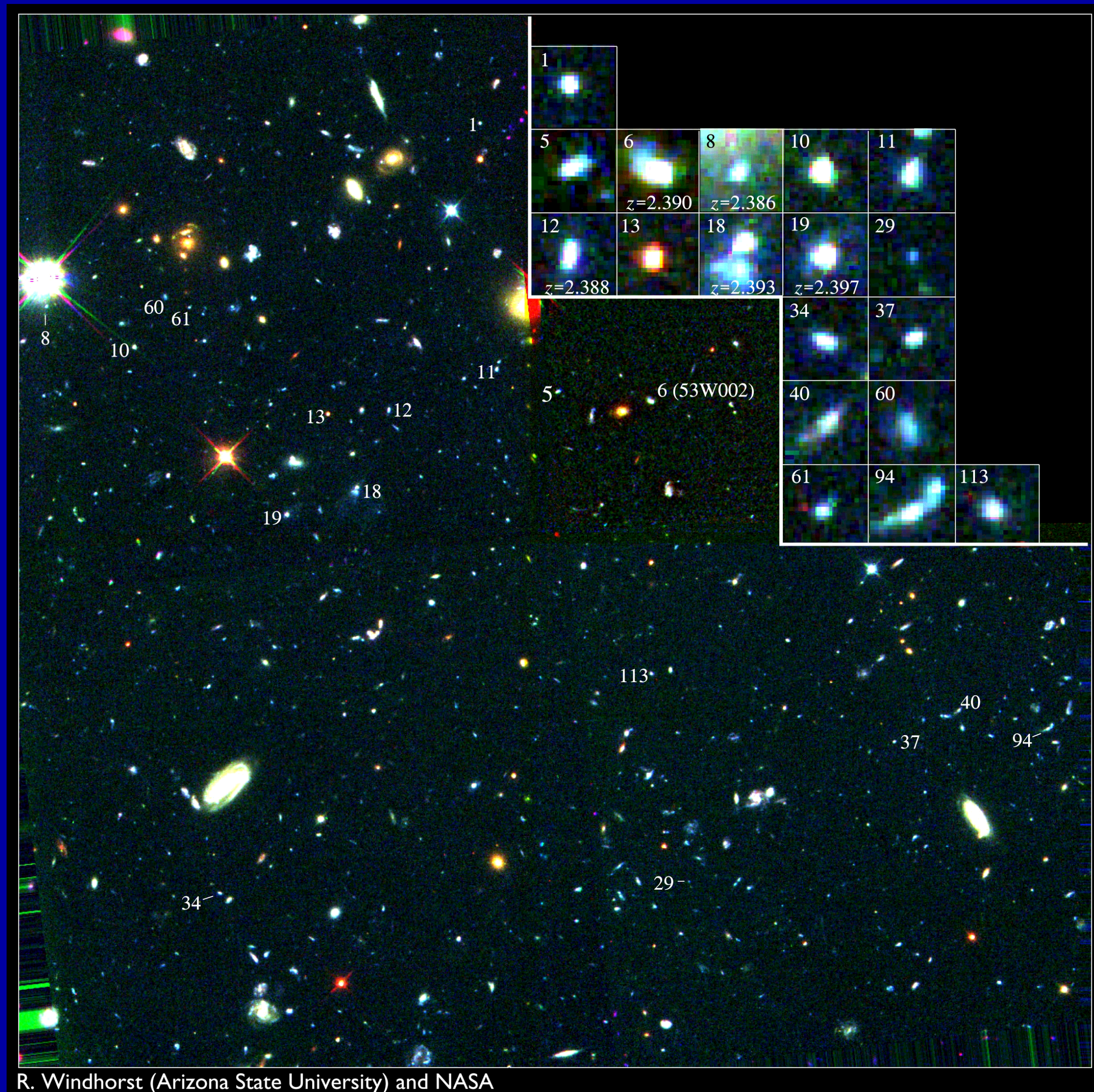
(0) Integrated EM Background: almost a power-law over $\lesssim$30 dex in $\boldsymbol{\lambda}$!



(Except for CMB), most photons in universe are produced by weak AGN and faint star-forming objects. Both have an N(z) that peaks at z$\simeq$1–2.

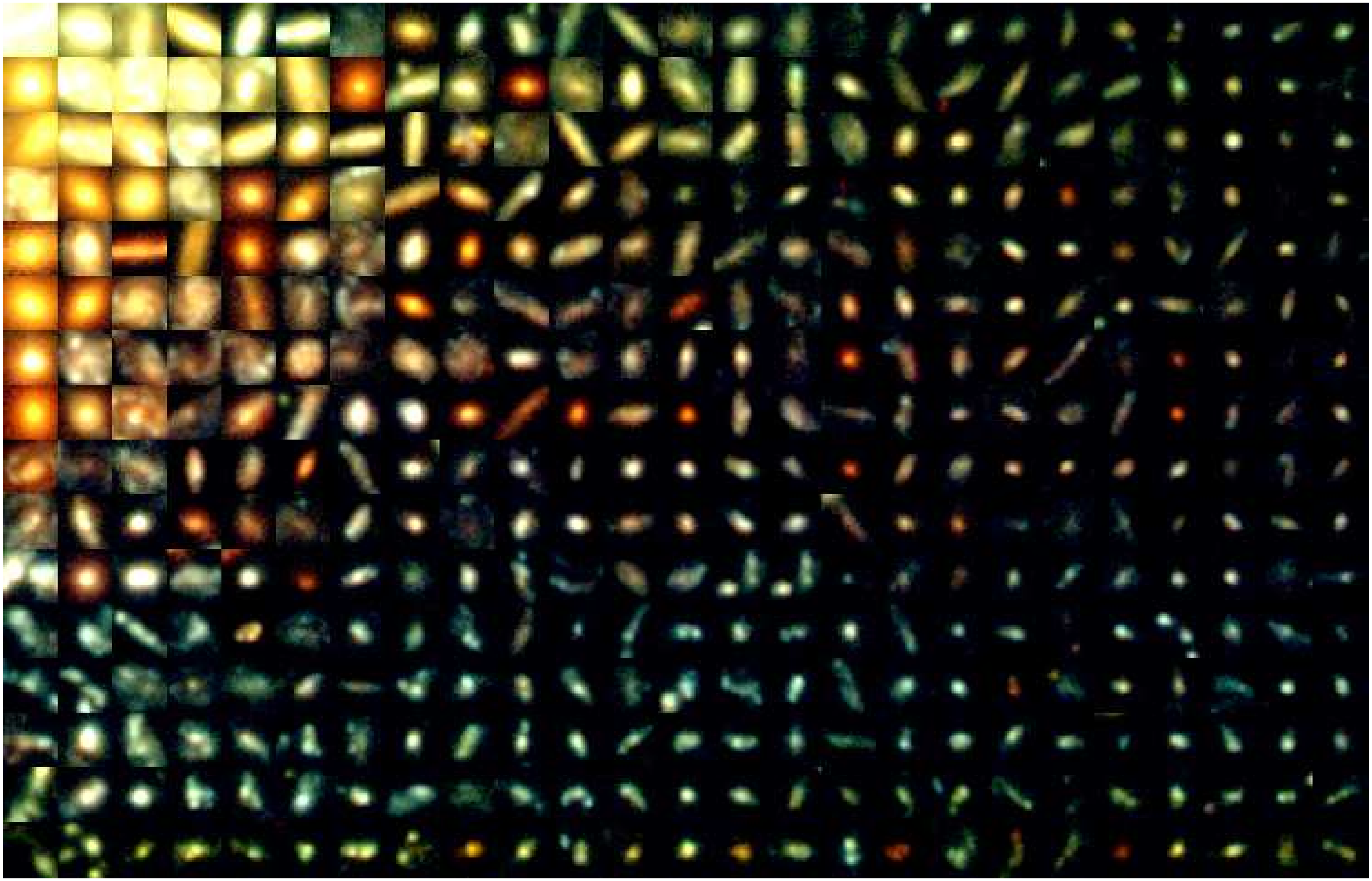
$\Rightarrow$ Most (radio) photons in Universe at z$\lesssim$6 generated by $<$1% of mass!

• (0) Galaxy Assembly in a nutshell



One of the remarkable discoveries of HST was how numerous and small faint galaxies are — the building blocks of the giant galaxies seen today.

THE HUBBLE DEEP FIELD CORE SAMPLE ($I < 26.0$)



z	Age ($q_o = 0.5$)
0.19	77%
0.44	58%
0.54	52%
0.64	48%
0.74	44%
0.87	39%
0.97	36%
1.03	35%
1.14	32%
1.24	30%
1.41	27%
1.61	24%
1.76	22%
2.05	19%
2.57	15%
3.59	10%

• (0) Galaxy Assembly — Summary from Hubble:

• Galaxies of all Hubble types formed over a wide range of cosmic time, but with a notable transition around $z \simeq 0.5$–1.0:

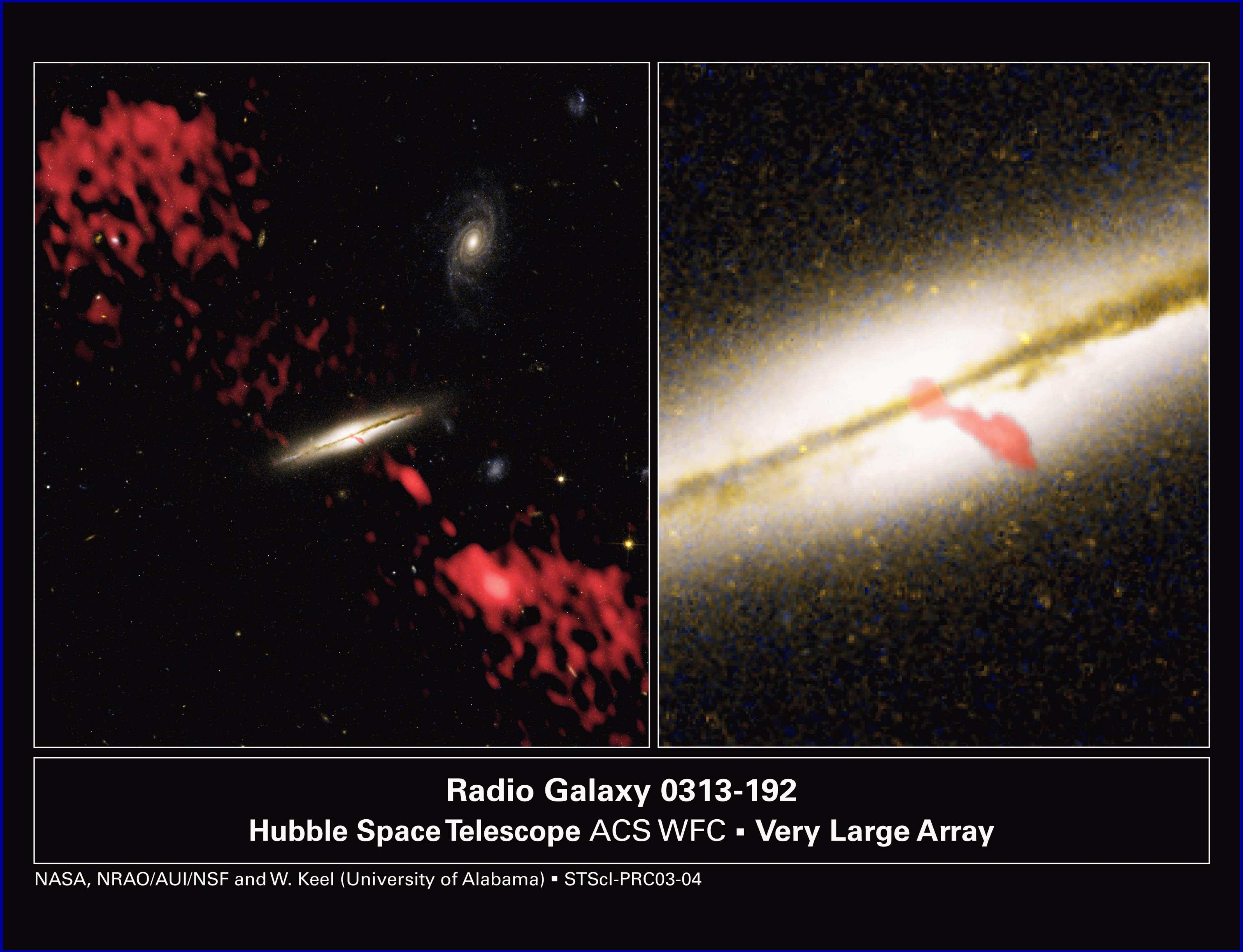
(1) Subgalactic units rapidly merge from $z \simeq 7 \longrightarrow 1$ to grow bigger units.

(2) Merger products start to settle as galaxies with giant bulges or large disks around $z \simeq 1$. These evolved mostly passively since then, resulting in the giant galaxies that we see today.

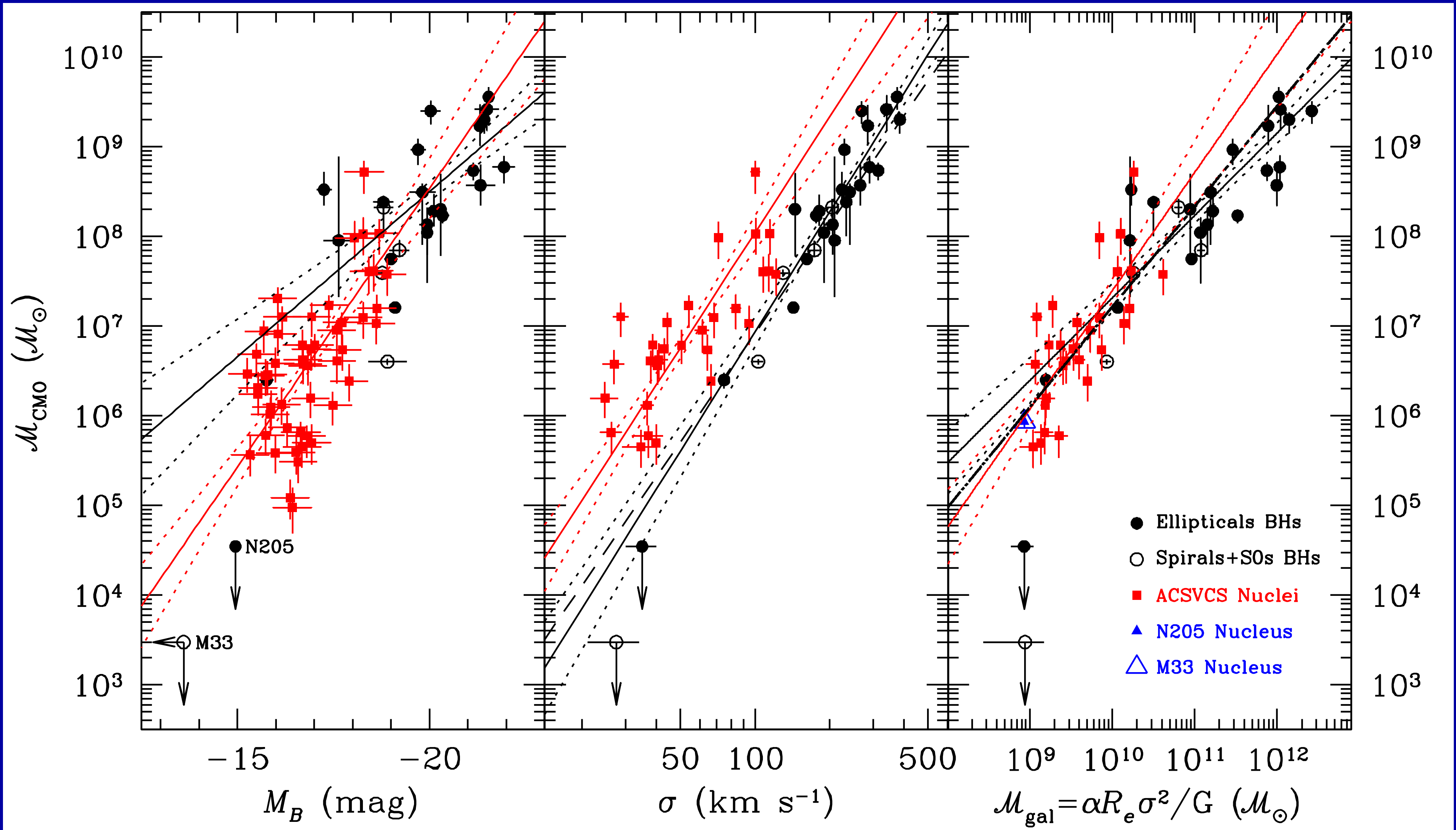
Driver et al. 1998, ApJL, 496, L93 (astro-ph/9802092): Evolution of Hubble Sequence.

• Was Λ a major driver/cause of the declining galaxy merger rate, AGN activity (cosmological evolution), and galaxy evolution for $z \lesssim 1$?

(0) Supermassive Black Hole (SMBH) growth in a nutshell



HST+VLA image of 0313-192: optical galaxy (color) and radio source (red).



SMBH mass vs. bulge-mass relation, measured via corrected velocity dispersion $\boldsymbol{\sigma}$ (Ferrarese et al. 2006, ApJL, , 644, L21; also Nuker team):

On average: $M_{bulge} \simeq 10^{11}\ M_\odot$ produces $M_{smbh} \simeq 10^{8.3}\ M_\odot$

$\Rightarrow$ On average, 0.2% of galaxy bulge mass ends up in central SMBH.

HST and Keck-AO near-IR images of luminous radio galaxy Cen-A:

AGN triggered by minor merger (Canalizo et al., 2003, ApJ, 597, 823)?

CARDINAL QUESTIONS: If all galaxies formed by hierarchical mergers, and SMBH's grew hierarchically as well:

- How exactly did go SMBH growth keep pace with galaxy assembly?
- And how do we observe this (since we don't live long enough)?

Growing a $\sim$100 $M_{\odot}$ Pop III star BH at z$\sim$15 into a 10^9 $M_{\odot}$ SMBH at z=0 requires 23 equal-mass mergers, or one every $\sim$0.58 Gyr.

(1) Scientific Background and Goals

• The HST Ultra Deep Field (HUDF) is the deepest field ever taken. It covers 400 orbits, approximately over 4 epochs each about 1 month apart.

• The combined HUDF detection limit is AB=29.1 mag (= 10 nJy = 10^{-34} W/m^2/Hz; 10-σ). For each of these 4 epochs it is AB$\gtrsim$28.0 mag.

GOAL 1: Unique opportunity for faint variability study on months timescales.

• The HUDF shows a plethora of faint galaxy morphologies/structure also seen in the Deep Fields, but at much higher S/N. A large number of "tadpole" galaxies is seen: highly elongated AND asymmetric galaxies.

• Cowie et al. (1995, 1996)'s first noted chain galaxies. They may be early stage mergers, like Luminous Diffuse Objects (Conselice 2004) or "clump-clusters" (Elmegreen et al. 2004). They have few nearby counterparts.

GOAL 2: Study tadpole galaxies in HUDF and find clues to their nature, redshift distribution, and epoch dependent merger rate.

TADPOLE GALAXIES IN THE *HUBBLE ULTRA DEEP FIELD*

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ABSTRACT

The Hubble Ultra Deep Field ("UDF") presents a wealth of galaxies, some very oddly shaped. In particular, many galaxies that appear to have a bright knot at one end with an extended tail at the other. These objects are presumably in a dynamically unrelaxed state. In this paper, we systematically select these "tadpole galaxies" from the UDF and study them as a function of their photometric redshifts. We find that in general the redshift distribution of these tadpole galaxies follows the distribution of all galaxies in the UDF field. The ratio of tadpole galaxies to field galaxies is found to peak at a redshift of z$\sim$1.8, and the percentage of tadpole galaxies at this redshift is $\sim$2.7%. This is $\sim$3$\times$larger than the percentage of variable galaxies found in the Hubble Deep Field in a similar redshift region. Further study should be performed on these tadpole galaxies to determine if they are in fact variable and contain (hidden) AGN.

Subject headings: galaxy mergers: general — Hubble UltraDeep Field — cosmology

Rhoads et al. 2005, ApJL, 621, 582 (astro-ph/0408031): Tadpole at z=5.49.

(2) A study of Tadpole Galaxies in the HUDF

- Many of these tadpole galaxies have a bright knot at one end with an extended tail at the other, and often two un-centered knots.

- They are presumably dynamically unrelaxed, early-stage mergers.

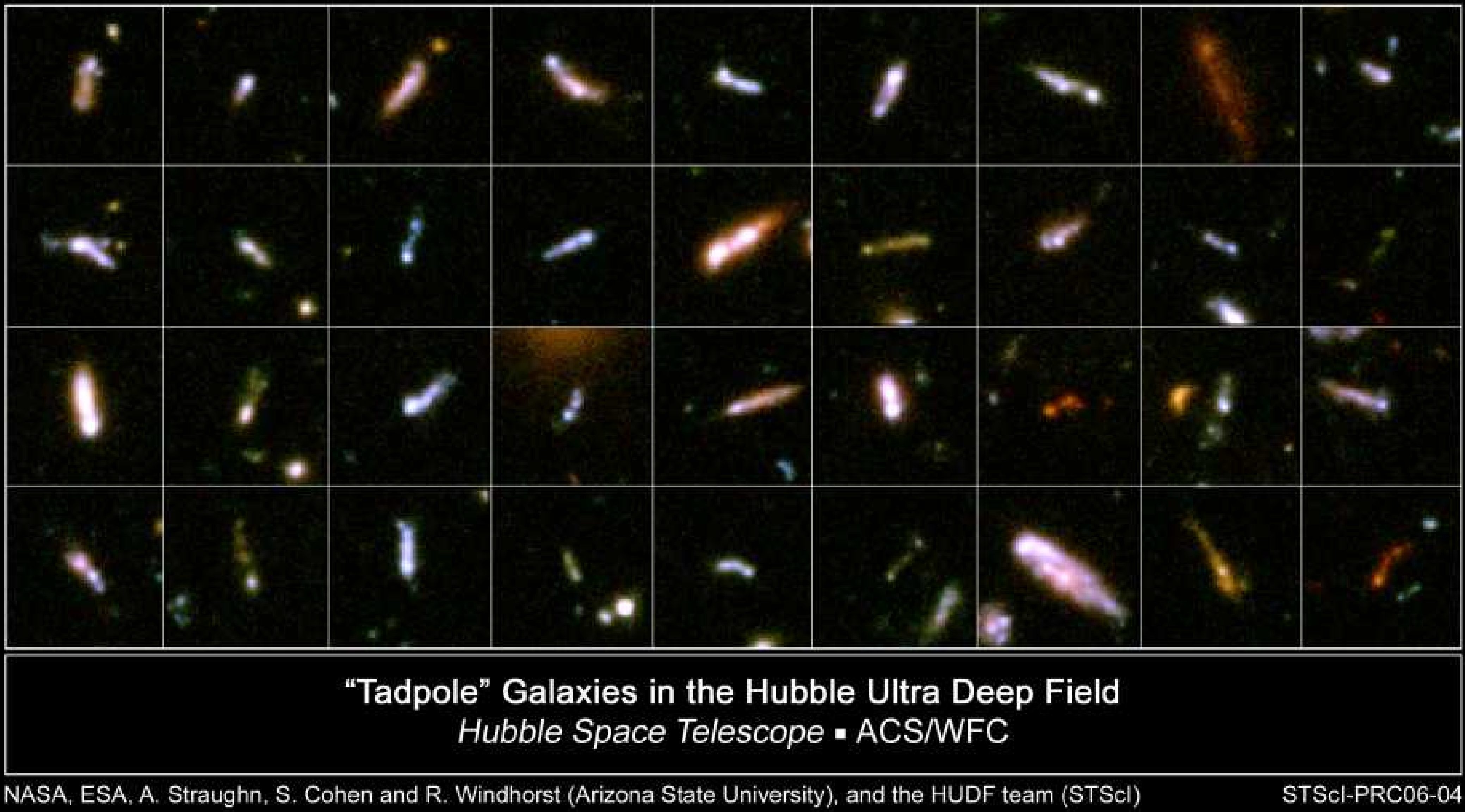
We select them as following:

(A) Make a lowly de-blended object catalog and find all highly inclined systems $\Rightarrow$ first pass of tadpole candidates or "tails".

(B) Make a highly de-blended object catalog and find all clumps rounder than a certain limit located inside sample (A) that are:

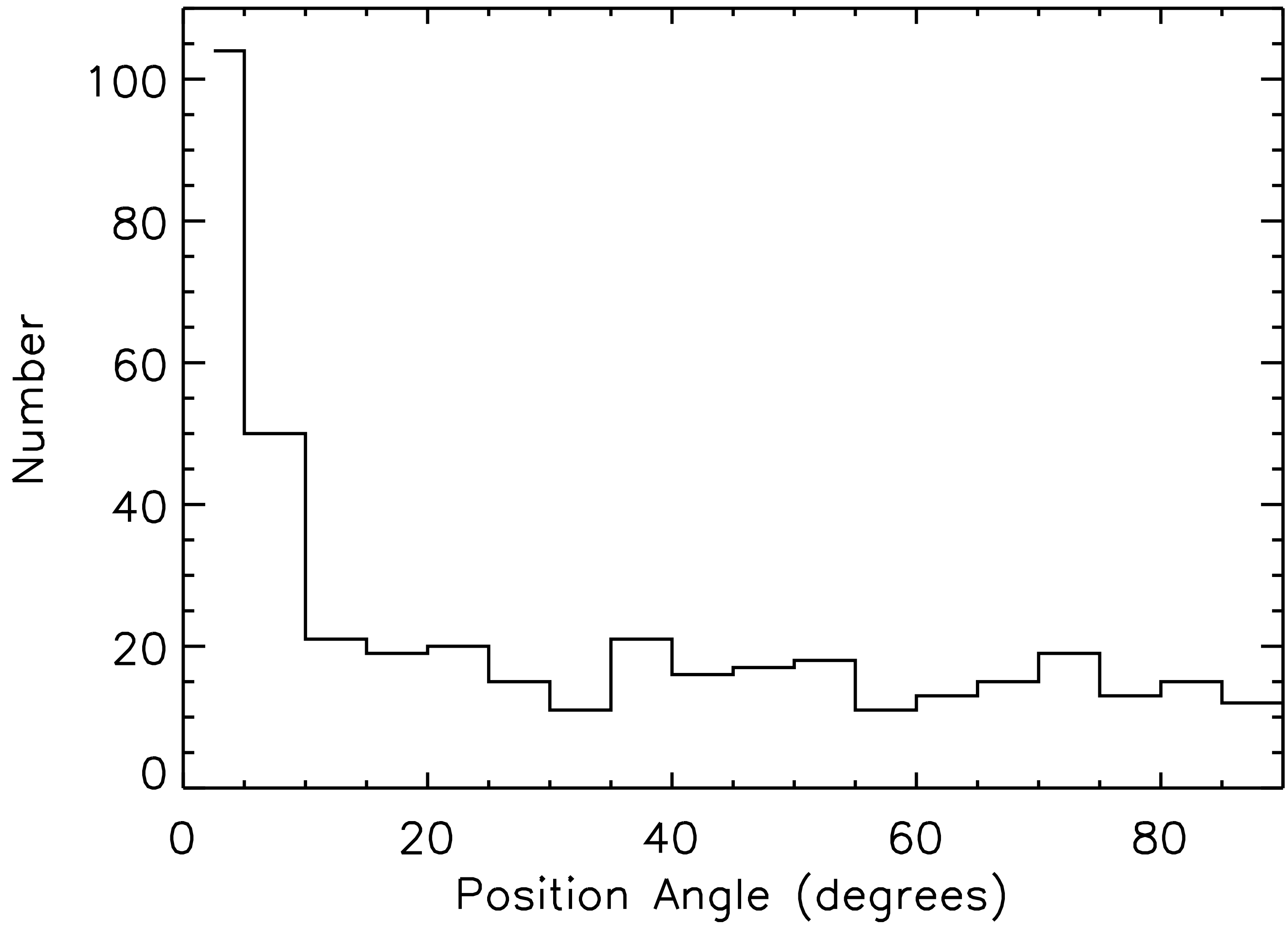
(1) Dislocated from the tail's geometric center by a certain amount, AND

(2) Not displaced in position angle from the tail's major axis by more than a certain amount.



Tadpole galaxies in press release: hubblesite.org/newscenter/archive/2006/04/

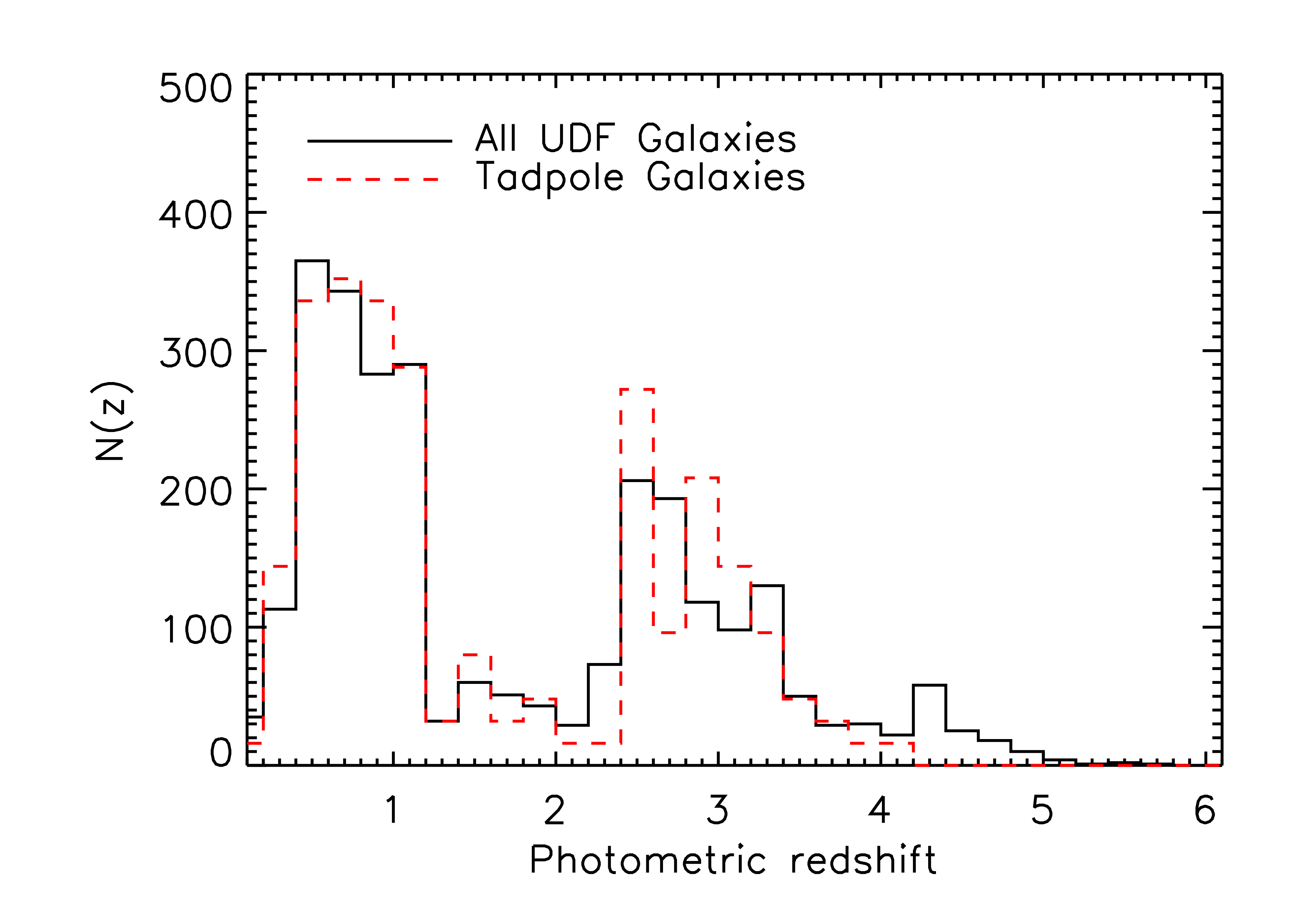
Straughn, A. N., et al. 2006, ApJ, 639, 724 (astro-ph/0511423)



ΔPA(off-axis knot—tail) distribution of tadpole galaxies in the HUDF:

- Clear excess of knots at $|\Delta\text{PA}| \lesssim 10\ \mathbf{deg}$, nearly linear structures.

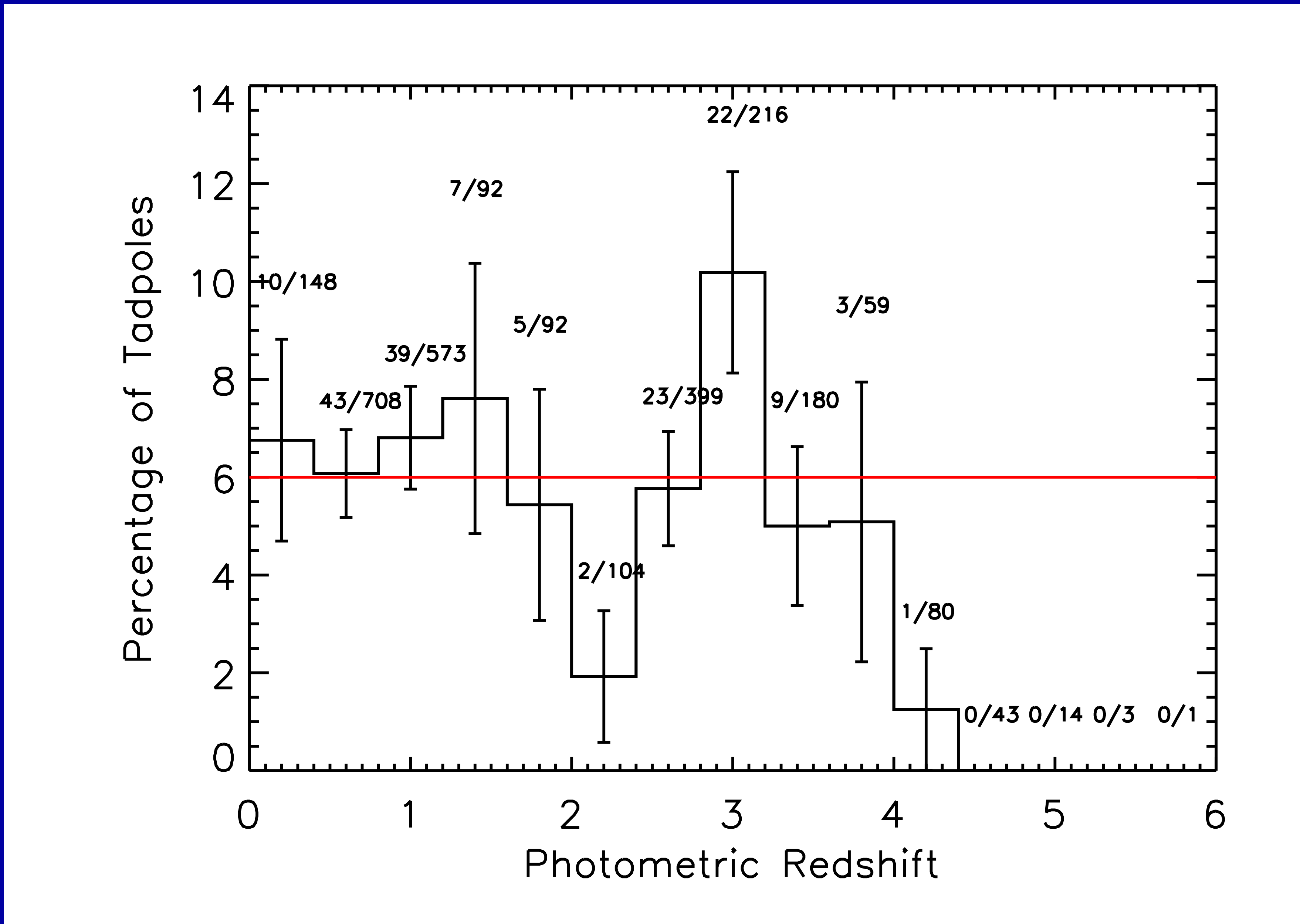
$\Rightarrow$ Most tadpoles are likely real, rather than chance superpositions.



BViz(JH) photo-z distribution of galaxies in the HUDF:

Full drawn: all HUDF field galaxies.

Dashed: HUDF tadpole galaxies ($\times 16$ for comparison with field galaxies).



Fractional redshift distribution of tadpoles compared to all HUDF galaxies.

- To first order, shape of tadpole galaxy redshift distribution is the same as that of field galaxies: average $N(z)_{tadpoles} \simeq 6\% \cdot N(z)_{field}$.

(2) Summary of Tadpole Galaxies in the HUDF

The tadpole photo-z distribution follows the N(z) of all HUDF galaxies, which peaks at z$\sim$1–2. Tadpole fraction is $\sim$6% of all HUDF galaxies.

Each tadpole is $\sim$1"$\simeq$8 kpc across. At the median z$\sim$1.5, these objects are $\sim$3.6 Gyr old if born at z$\sim$7. If each clump in a tadpole has M$\sim 10^8$–10^9 $M_\odot$ then τ(merging) is $\lesssim 10^8$ years ($\lesssim$few% of the galaxy lifetime).

$\Rightarrow$ If each galaxy underwent a several $\sim$equal mass (major) mergers during its lifetime, $\sim$6% of HUDF all galaxies could be seen as tadpoles.

- Majority of tadpoles likely not edge-on disk galaxies, but rather linear structures of "sub-galactic clumps" on moving past/through each other.

- Did the merger rate peak at z$\sim$1–2, before effects from Λ kicked in?

- Was Λ itself responsible for dramatically winding down the epoch dependent merger rate at z$\lesssim$0.5–1?

Clues to Galaxy Formation from Variable Objects In The Hubble Ultra-Deep Field

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ABSTRACT

We present a photometric study of galaxies in the Hubble Ultra Deep Field by splitting the data into four sub-stacks of approximately equal exposure times. Variable objects are selected by studying the error distribution between different epochs and selecting $3 - -3.5\sigma$ outliers. The analysis is performed in both the i' and z' bands separately and together. We find 337 objects in the i'-band, 222 in z'-band and 66 in the combined sample.

Subject headings: galaxies, variable objects

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(3) A Study of Variable Objects in the HUDF

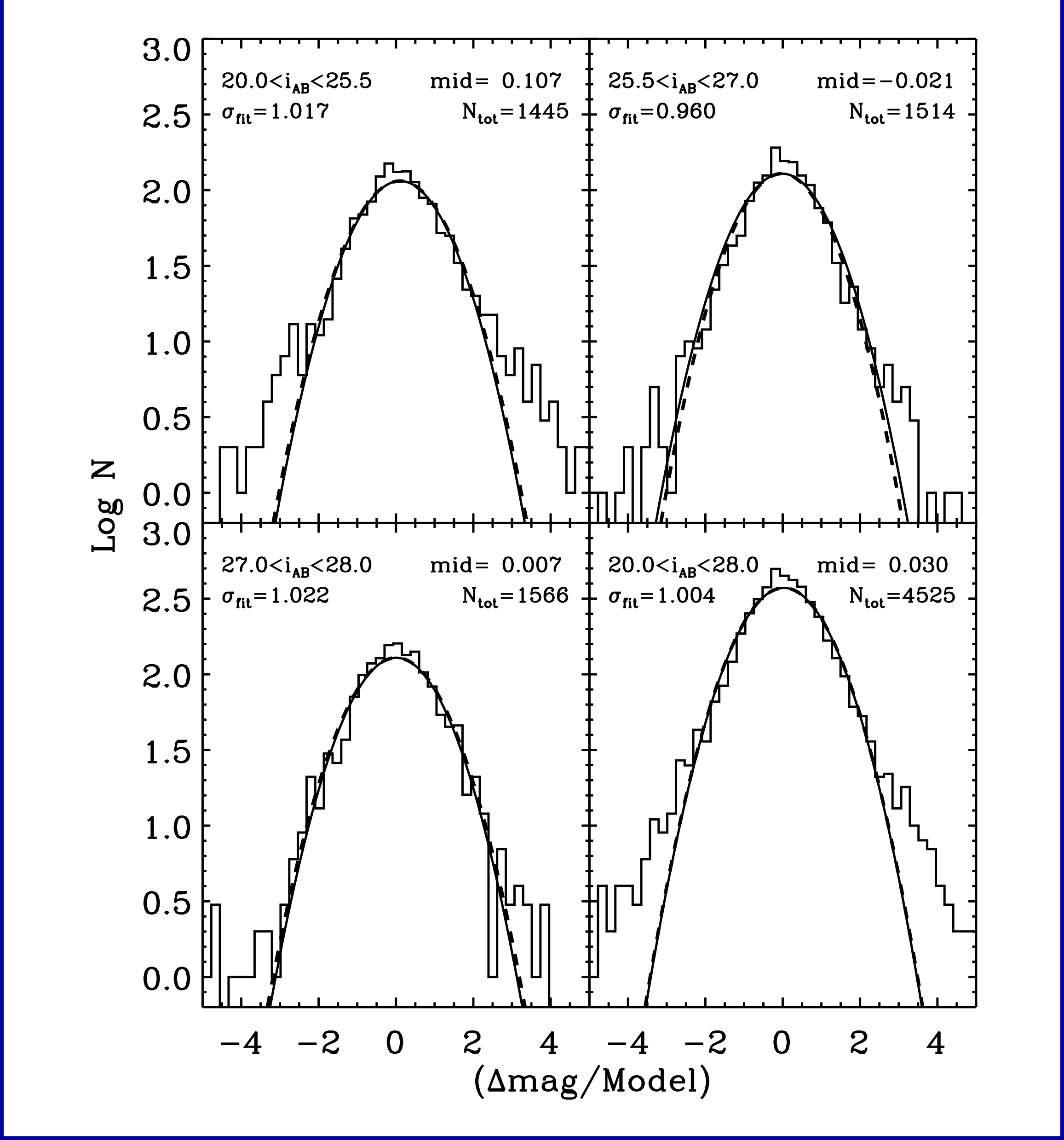
- Split the HUDF into 4 sub-stacks of $\sim$equal exposure times each $\sim$1 month apart. Treat both i' and z' bands separately as well as together. The i'-band is so much deeper than z' that i'-band is the primary filter.

- Define significantly de-blended object apertures in total HUDF image. Use "dual input mode" to get **equal-aperture** fluxes in all epochs, using HUDF weight-maps for errors. Use also sliding box method.

- Use the error distribution between epochs to select $\gtrsim 3.0\boldsymbol{\sigma}$ outliers.

- Among HUDF objects studied to $\boldsymbol{i_{AB}}$ =28.0 mag ($\gtrsim 10\boldsymbol{\sigma}$), expect $\lesssim$13 bogus detections if the noise were purely Gaussian. The noise is not entirely Gaussian, although the HUDF is as close to Gaussian as it gets in any astronomical CCD applications.

- $\sim$45 contain believable variable point sources at $\gtrsim 3.0\boldsymbol{\sigma}$, most of which seen at $\gtrsim$2 epoch pairs. Another 57 possibly variable candidates.



Is the HUDF noise really as Gaussian as it gets?

$\exists$ non-Gaussian noise at Δmag$\simeq$0 $\Leftrightarrow$ CCD A/D-converter issue?

$\exists$ non-Gaussian noise at $|\Delta \text{mag}| \gtrsim 2\sigma$ $\Leftrightarrow$ real variables and splitting issues.

(3) Variable Objects in the HUDF:

Faint variable objects in HUDF could in principle be:

(1) Weak AGN.

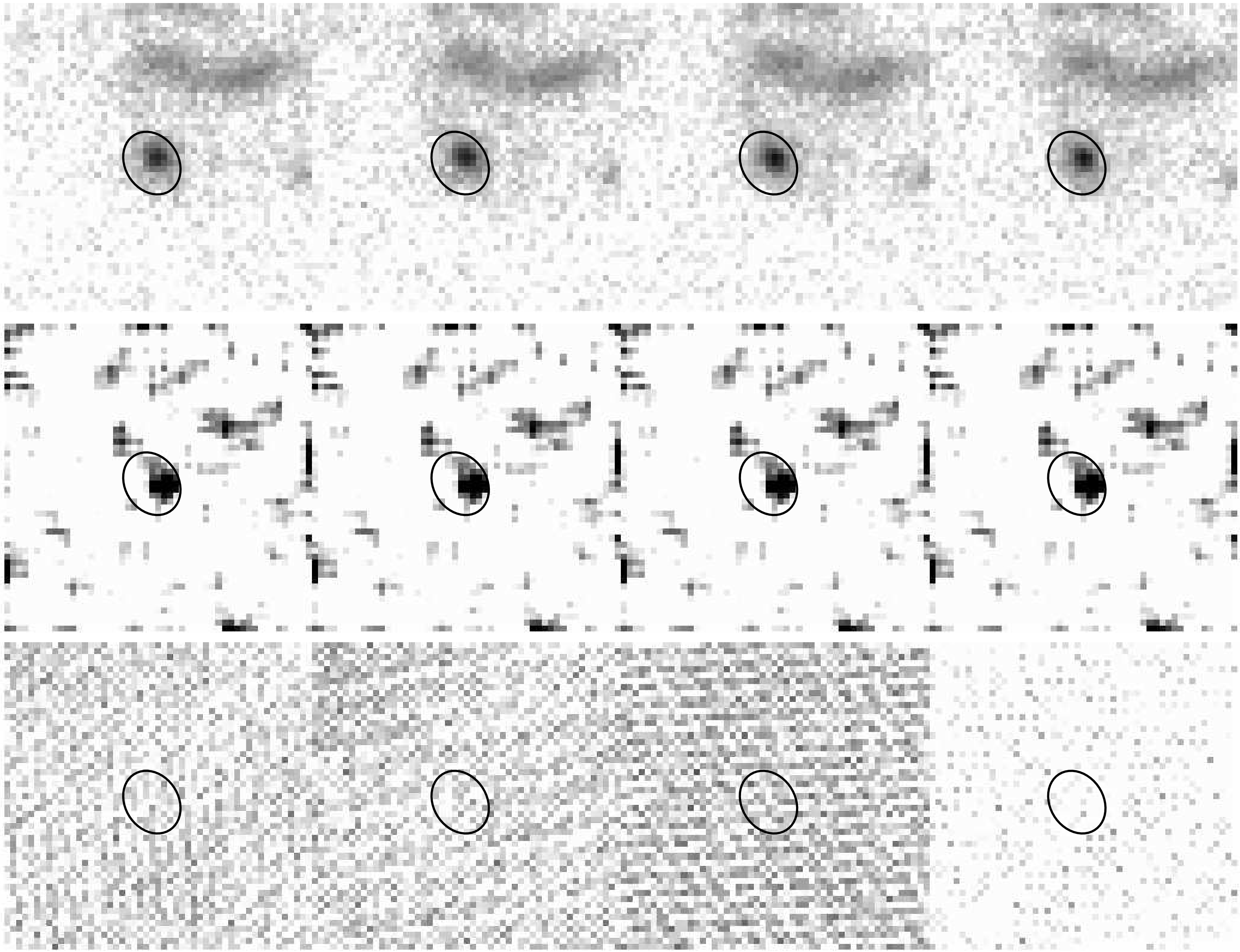
(2) SNe in distant galaxies (see Strolger and Riess 2004).

(3) Perhaps Novae or other Long Period Variables in very nearby galaxies (only visible if z$\lesssim$0.03)

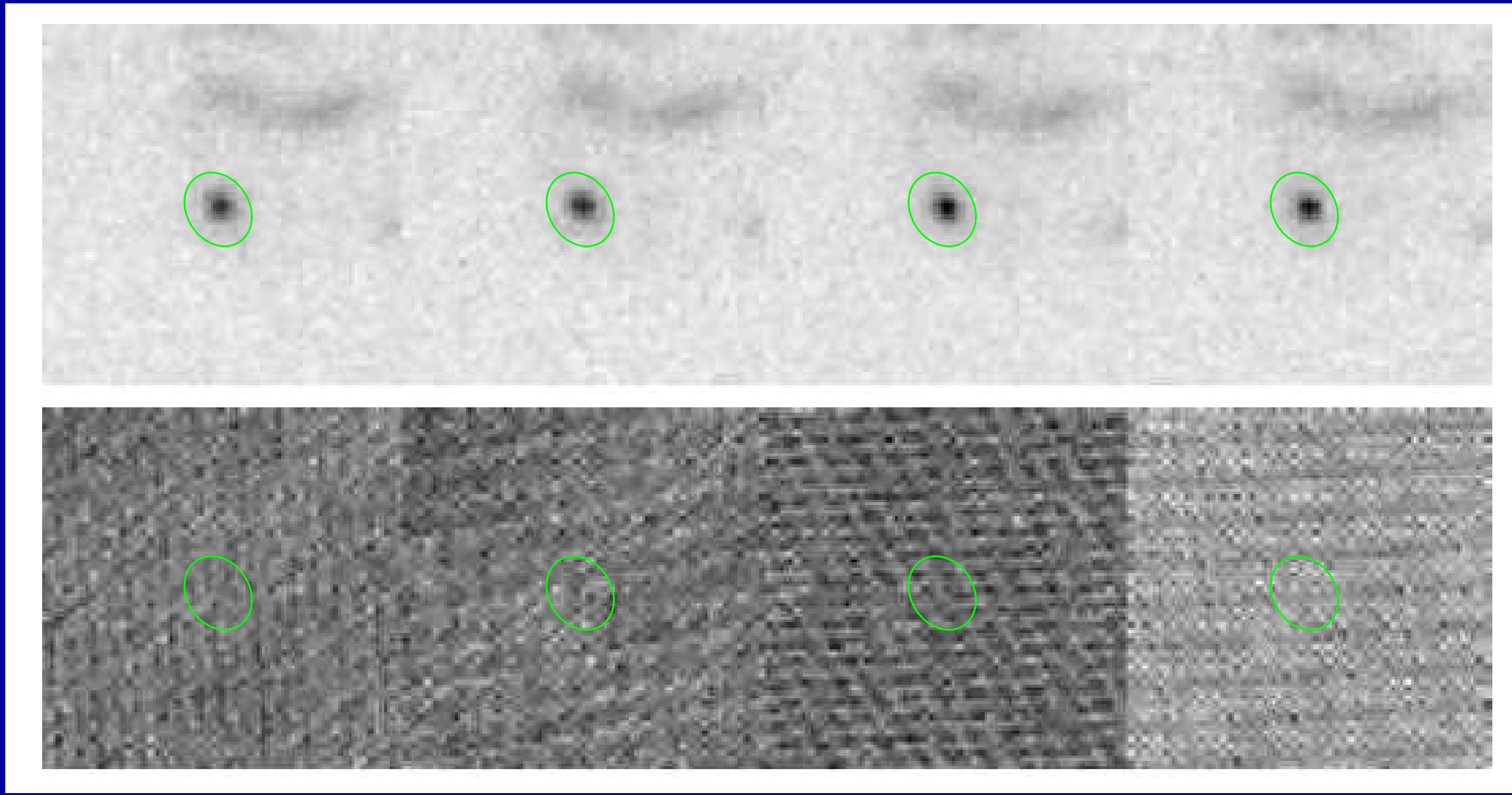
(4) Faint high proper motion objects (KBO's, etc) [None found thus far].

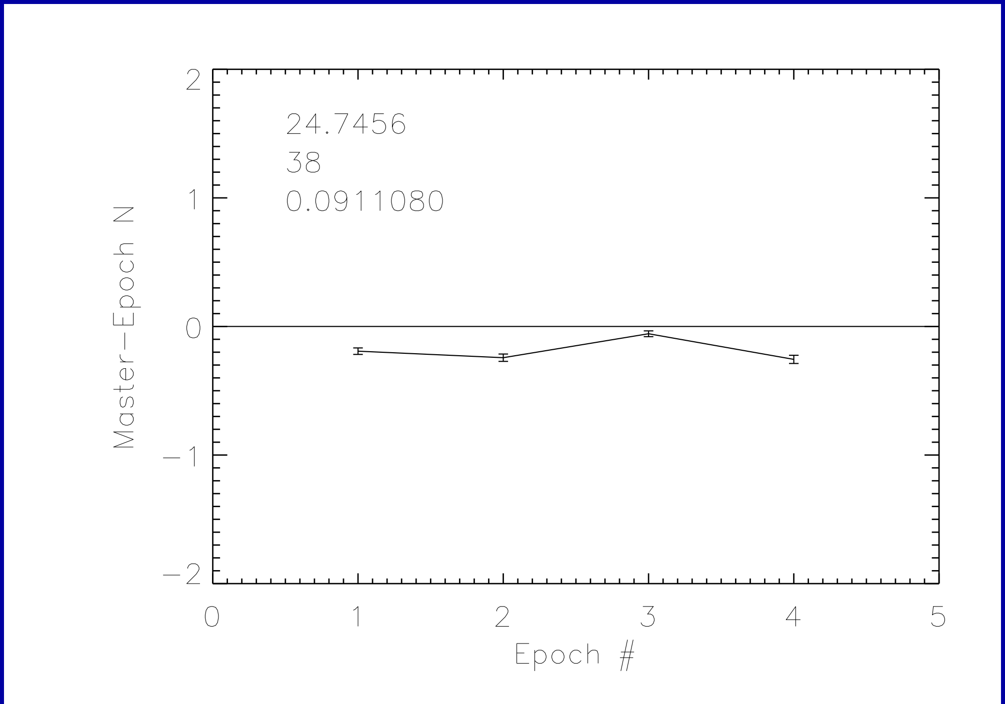
$\Rightarrow$ Only (1) AGN and NONE of (2), (3), (4) were seen as variable objects in the HUDF thus far.

Cohen, S. H., et al. 2006, ApJ, 639, 731 (astro-ph/0511414)



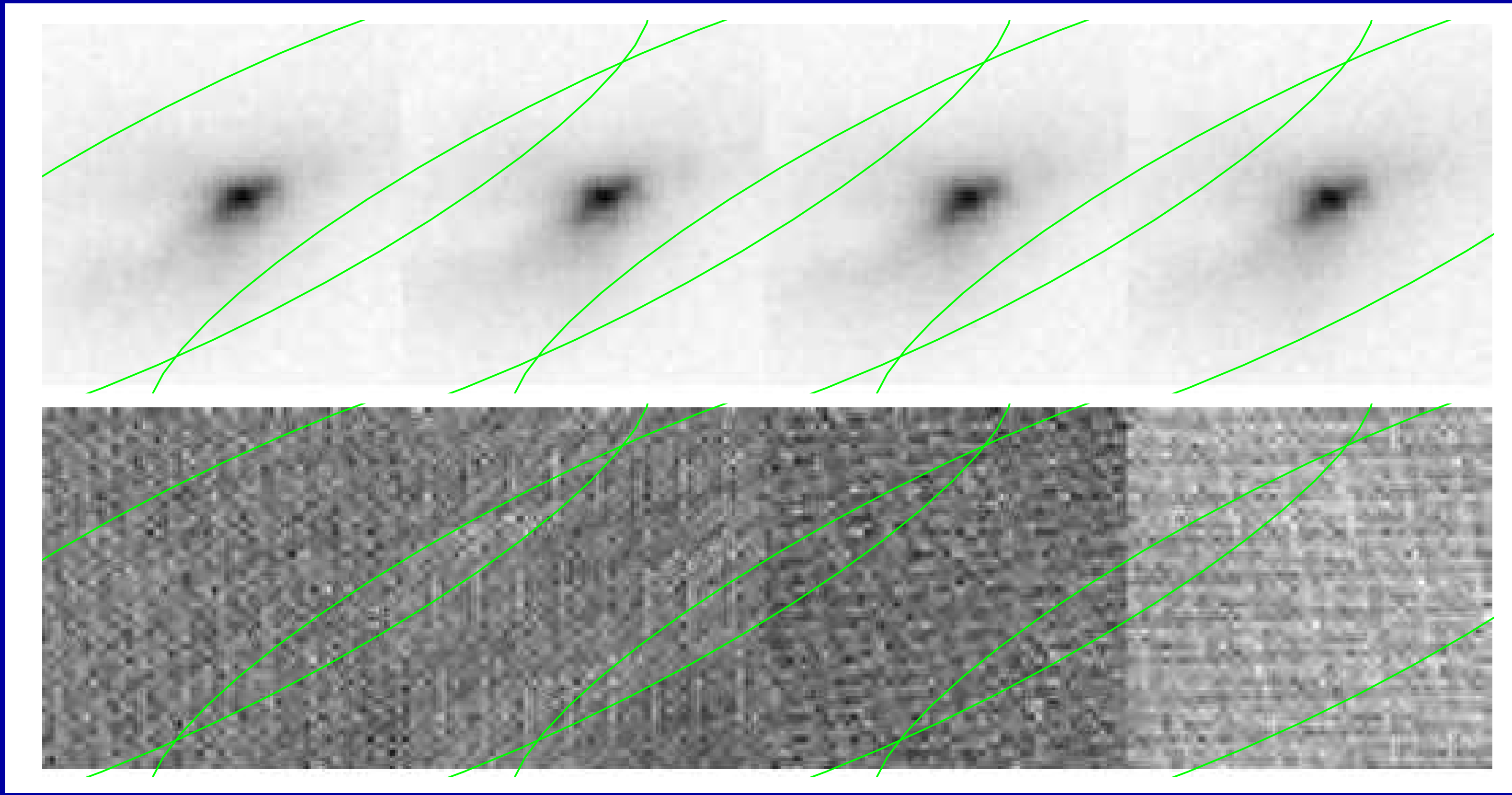
Top: 4 HUDF Epochs; Middle: 1 Variance map; Bottom: 4 Weight-maps.

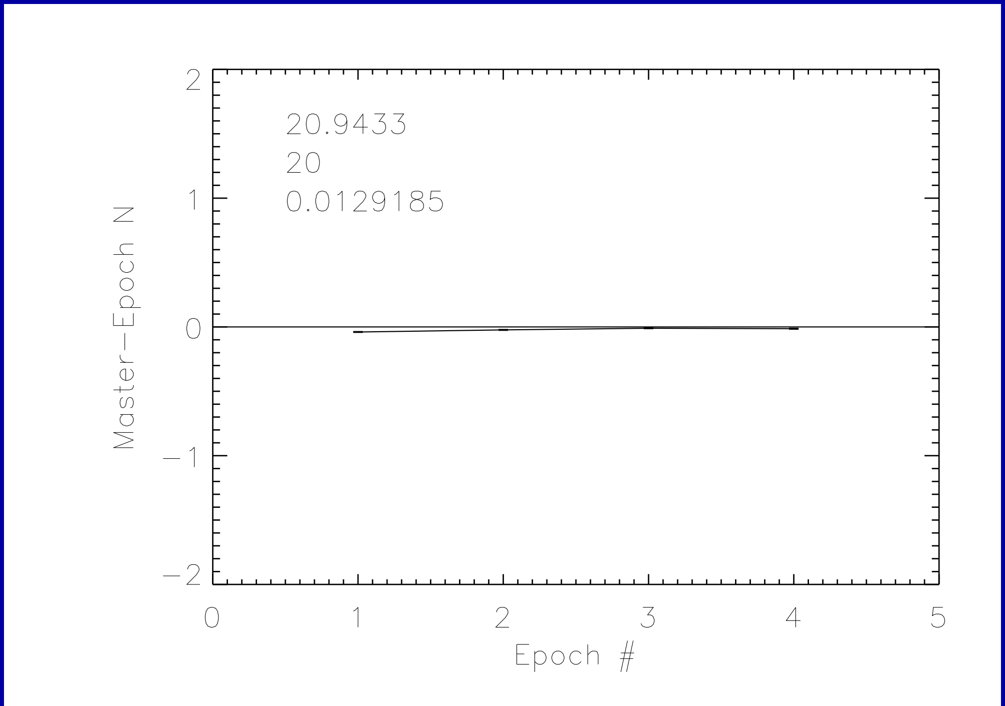




i'-Var Cand # 38 (z=1.122):

9% variability, weak AGN

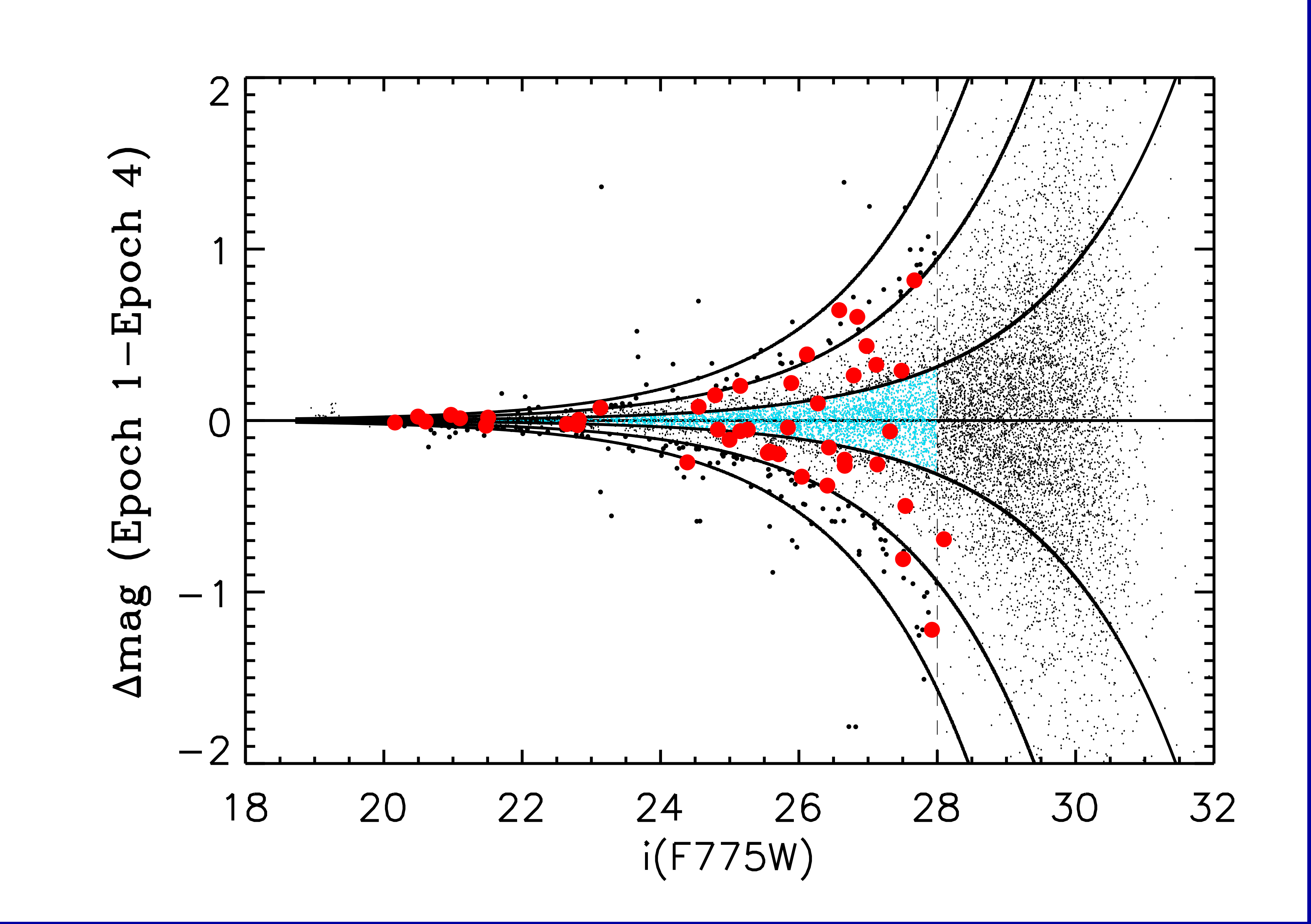




i'-Var Cand # 20 (z=0.906):

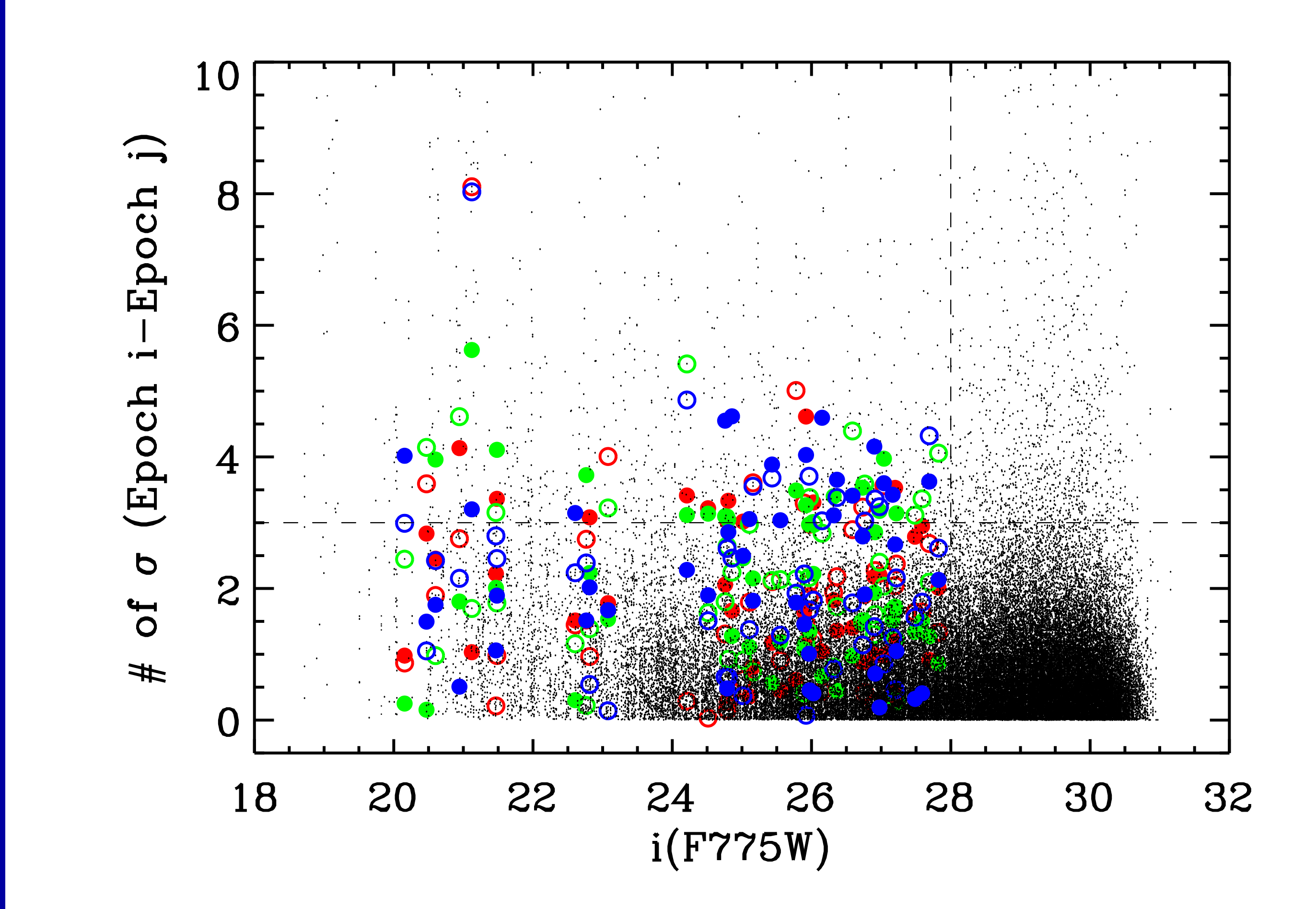
1% var (3-σ!), weak AGN

Faint Chandra X-ray source!
(Koekemoer et al. 2004)



Flux ratio of all objects between two HUDF epochs plotted vs. total i-band flux. Lines are at $\pm 1.0\sigma$ (blue), $\pm 3.0\sigma$, $\pm 5.0\sigma$.

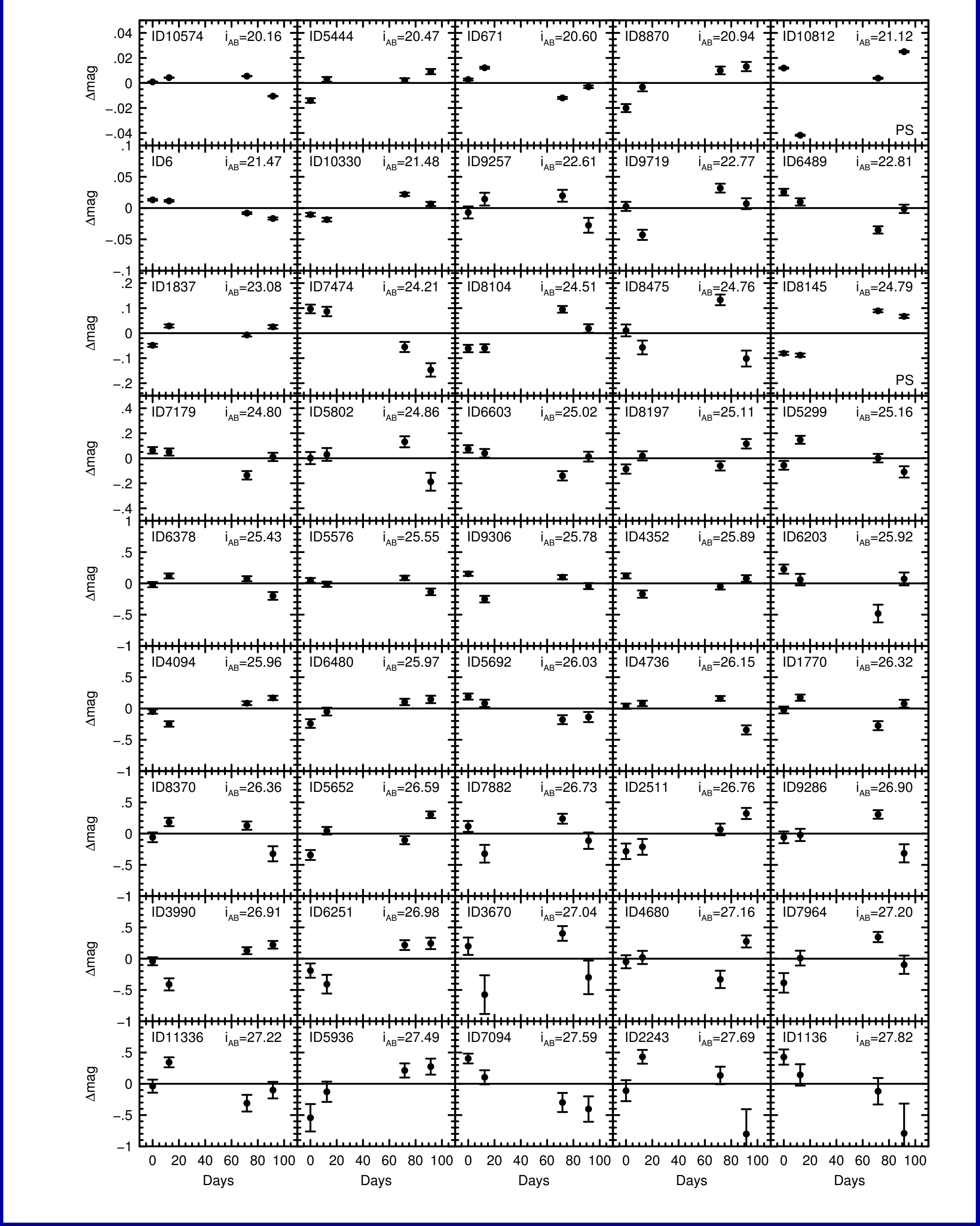
- All objects with |Delta mag|$\geq 3.0\sigma$ were inspected for plausible variability. This will yield $\lesssim$13 bogus detections if the noise were purely Gaussian.



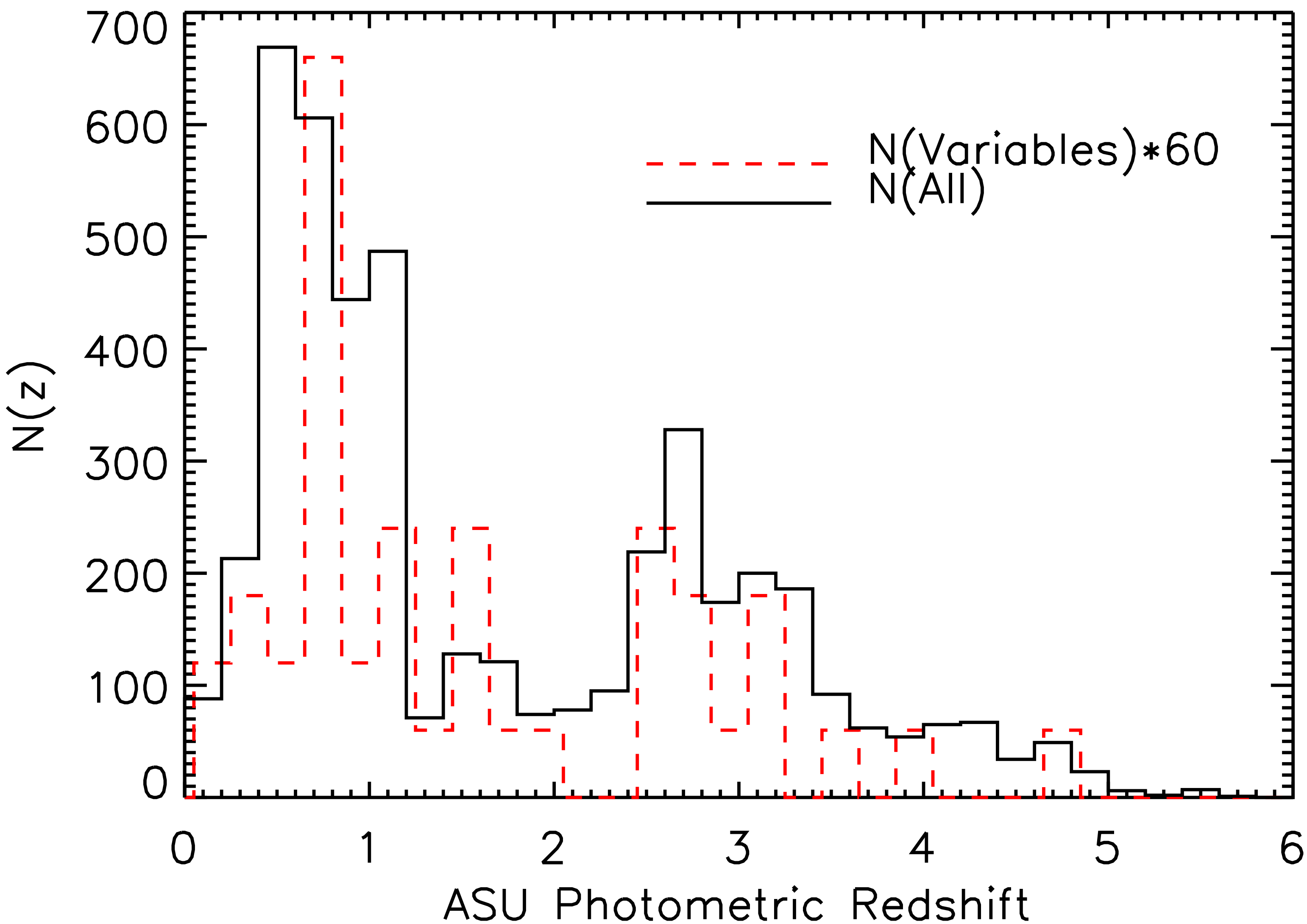
Main contamination are brighter objects over-deblended by object finder, *e.g.*, pieces of spiral arms — must weed these out visually.

- 4 out of 16 Chandra sources are faint point-like variable objects at $\gtrsim 3.0\boldsymbol{\sigma}$. Other 12 Chandra sources are mostly brighter (early-type) galaxies, one is $\gtrsim 3.0\boldsymbol{\sigma}$ variable $\Rightarrow$ Variable point sources are valid AGN candidates.

- We only sample $\boldsymbol{\Delta}$Flux $\gtrsim$10%—30% on timescales of months. The AGN sample is not complete — we miss all non-variable and the obscured AGN.



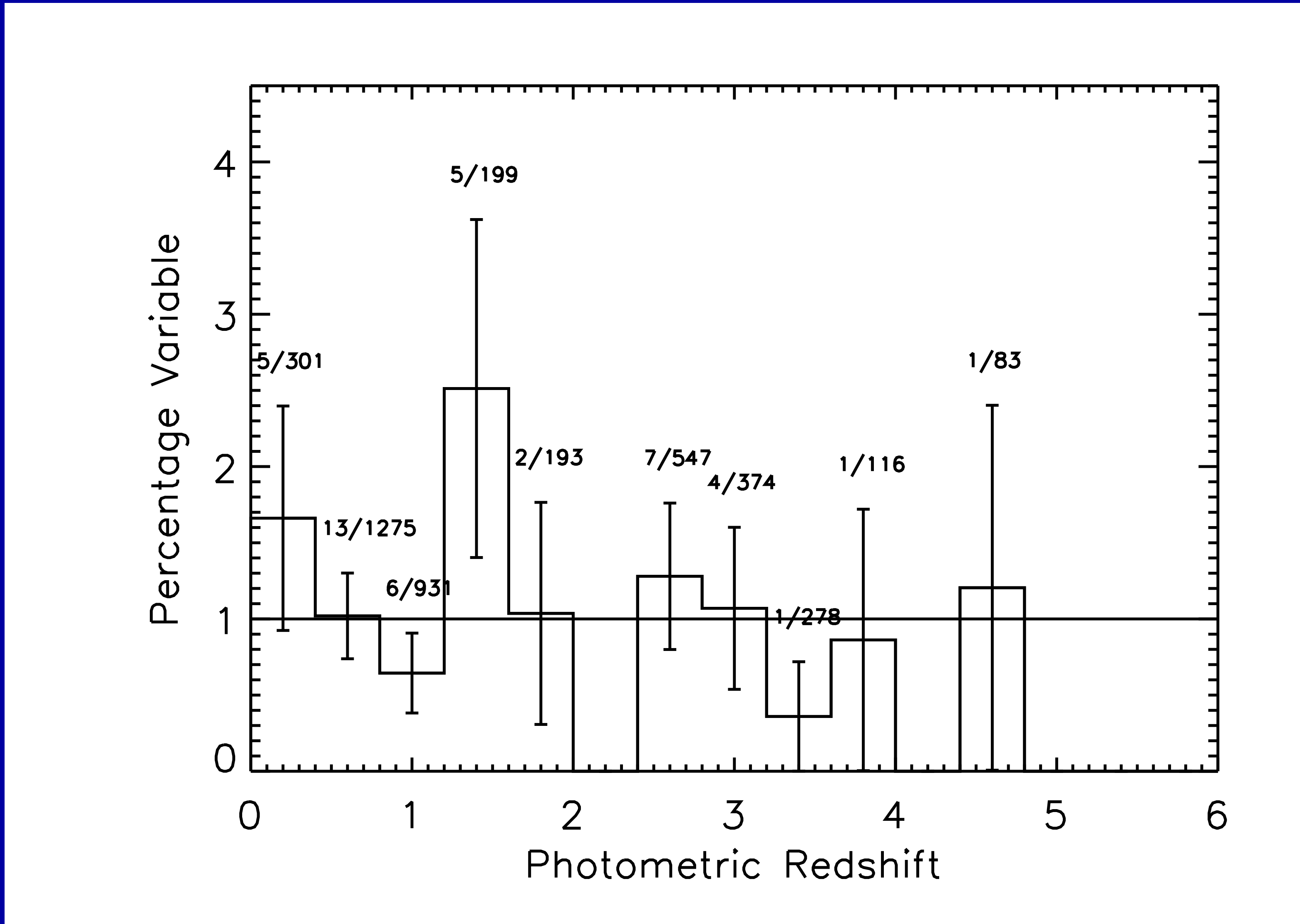
- Light curves: Can detect bright HUDF variables even if $|\Delta\text{mag}| \lesssim$1–2% !



BViz(JH) Photo-z distribution of variable objects in the HUDF:

Full drawn: All HUDF field galaxies.

Dashed: HUDF variable objects ($\times$60 for comparison with field galaxies).



Fractional N(z) of HUDF variable objects compared to all HUDF galaxies.

- Variable objects show a similar N(z) as field galaxies. About 1% of all field galaxies have variable weak AGN at all redshifts.

$\Rightarrow$ If variable objects are representative of all weak AGN, SMBH growth keeps pace with the cosmic SFR (which peaks at $z \simeq 1$–2).

(3) A Study of Variable Objects in the HUDF

- HUDF variable fraction to AB$\lesssim$28.0 mag is $\sim$1% of all objects.

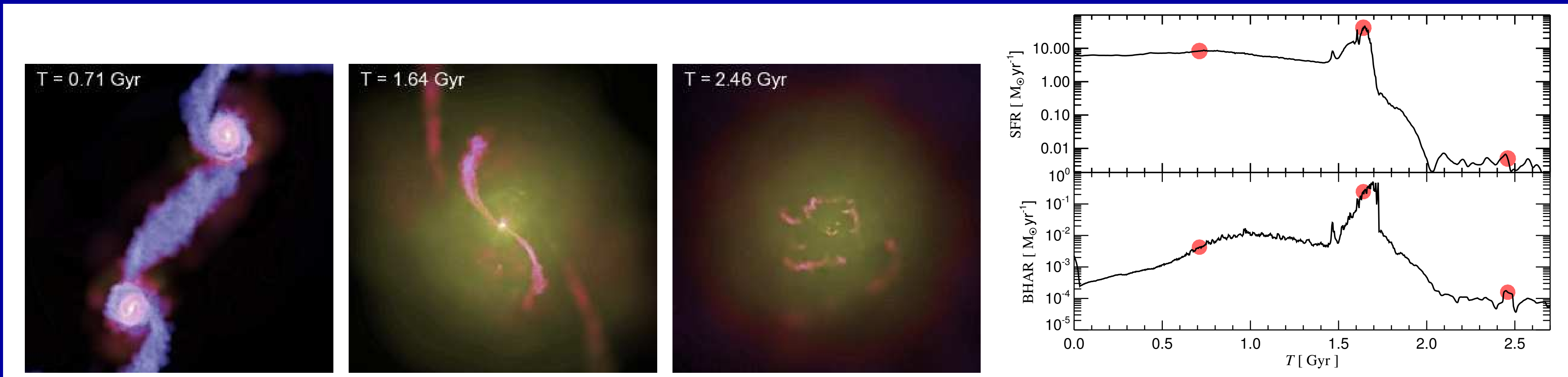
- These are likely a combination of weak AGN. None were SNe in distant galaxies (Strolger & Riess et al. 2004). None were novae and/or Long Period Variables in nearby galaxies (z$\lesssim$0.03).

- Accounting for limited time span sampled, the real fraction of AGN in the HUDF that is variable on timescales of months is likely $\sim$2%.

- The variable-object N(z) follows that of all HUDF galaxies.

- At the median z$\simeq$1.5, objects are $\sim$3.6 Gyr old if born at z$\sim$7. If AGN life-time is several$\times 10^7$ years then $\sim$1–2% of all galaxies may be AGN.

- In AGN unification picture, $\lesssim$1/3 of these are seen as "face–on", consistent with the $\lesssim$1% variable AGN fraction observed in the HUDF.

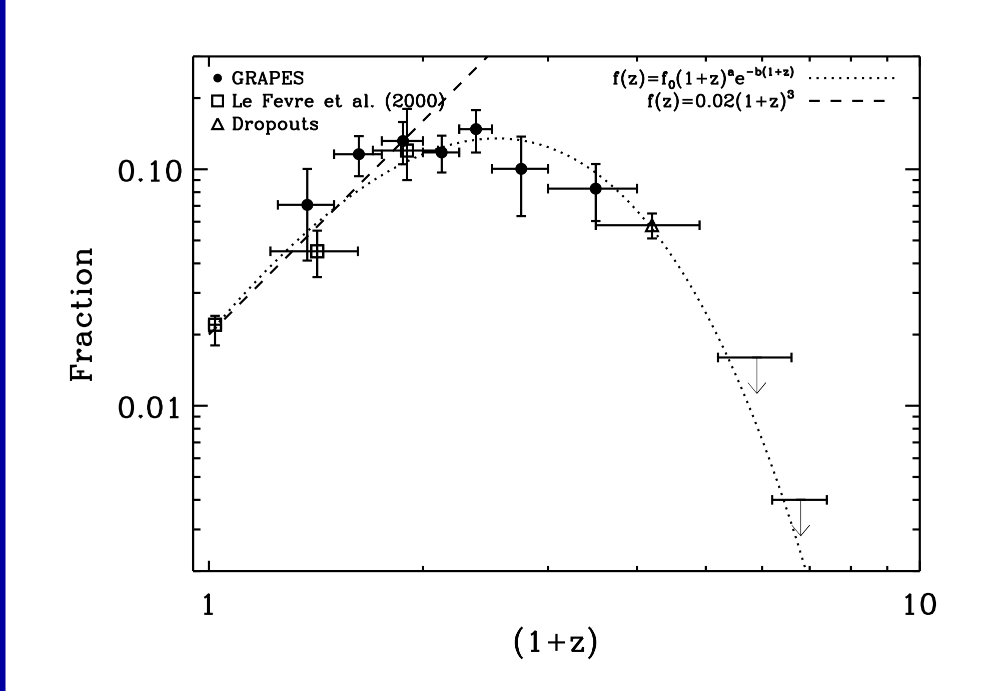


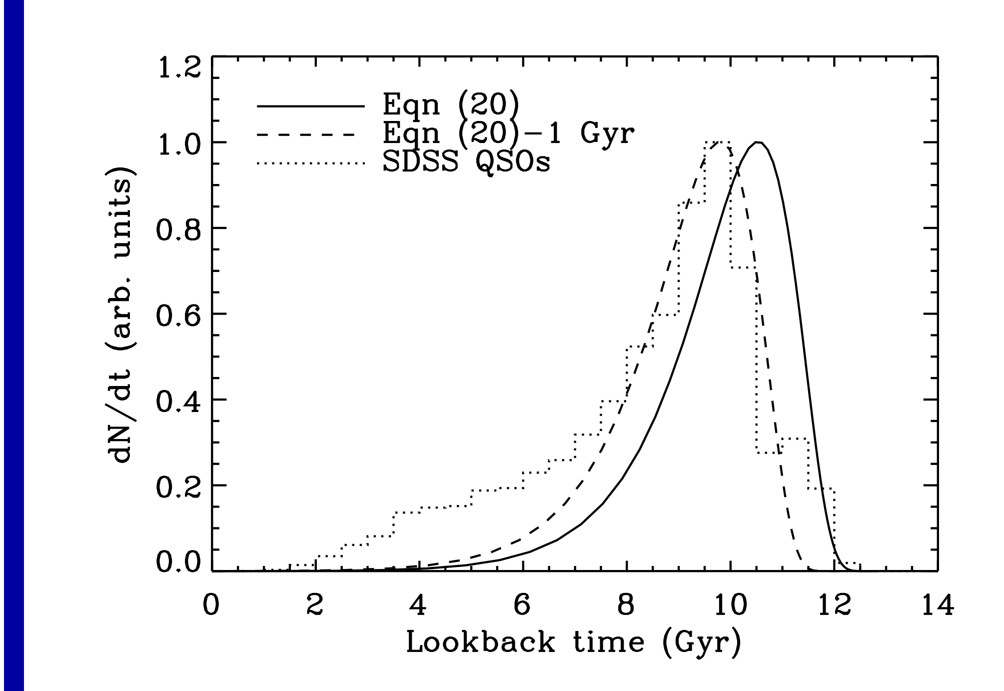
- [LEFT] Simulated merger of two disk galaxies at three different stages, including the effects of SMBH growth and AGN feedback (Springel, di Matteo, Hernquist, 2005, ApJ, 620, 79). Color indicates temperature, while brightness indicates gas density.

- [RIGHT] Evolution of the accretion rate onto the black holes (top) and the star formation rate (bottom). Red ● 's mark the times shown in the three simulated images.

- Overlap between Tadpoles and Variables is very small — 1 object!

$\Leftrightarrow$ In hydrodynamical simulations, the object resembles a tadpole galaxy $\sim$0.7 Gyr after the merger starts, and the AGN is triggered $\gtrsim$1.6 Gyr after it starts, *i.e.*, $\gtrsim$1 Gyr after the early-merger stage.





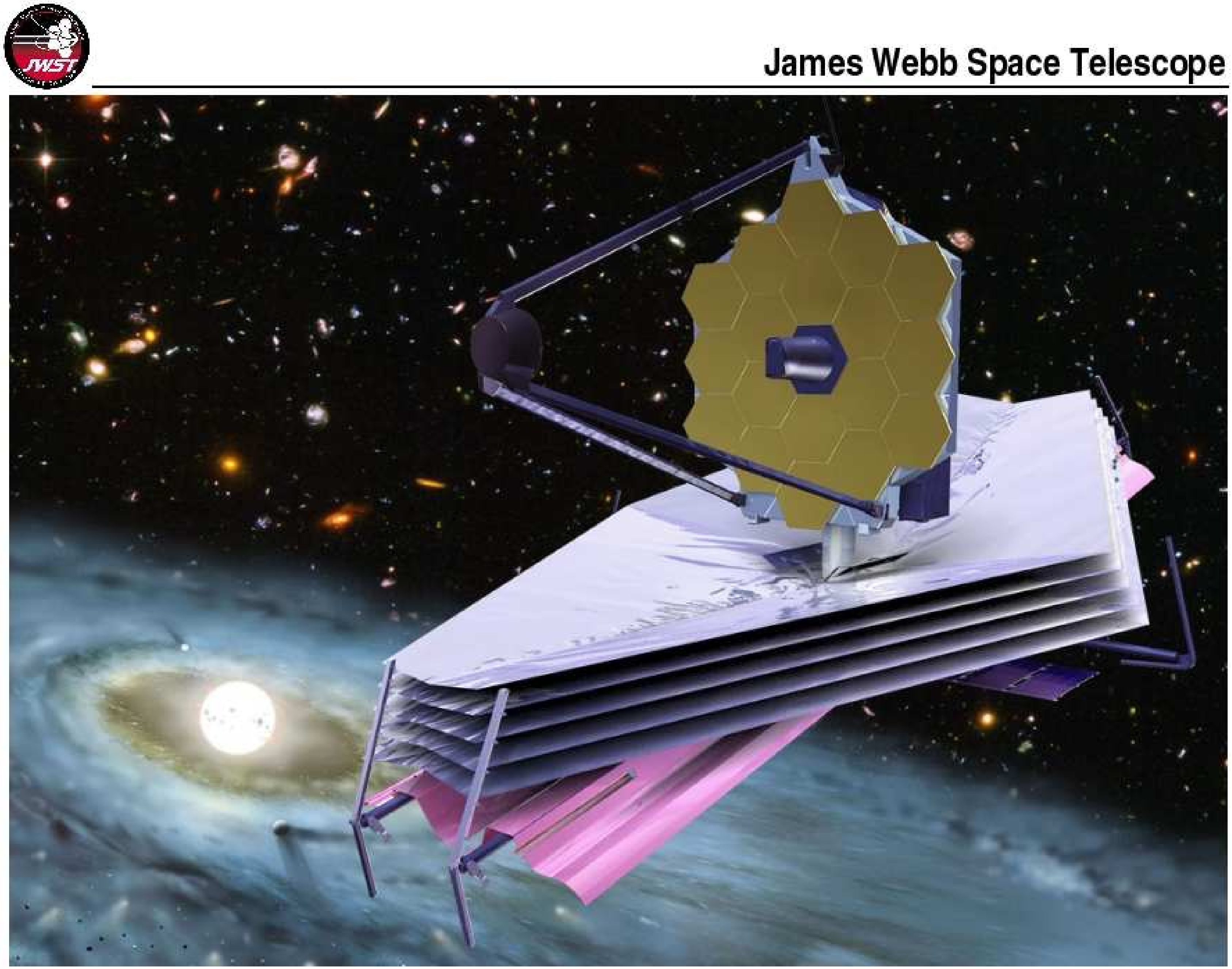
Ryan et al. (2007): Analytical model for epoch dependent merger rate (Conselice 2003) follows observed pair counts from HST/ACS grism survey.

Galaxy merger rate — based on mean-free-path between galaxies in a ΛCDM universe (Ryan et al. 2007) — compared to SDSS QSO counts vs. look-back time: fairly similar curves except for ∼1 Gyr offset.

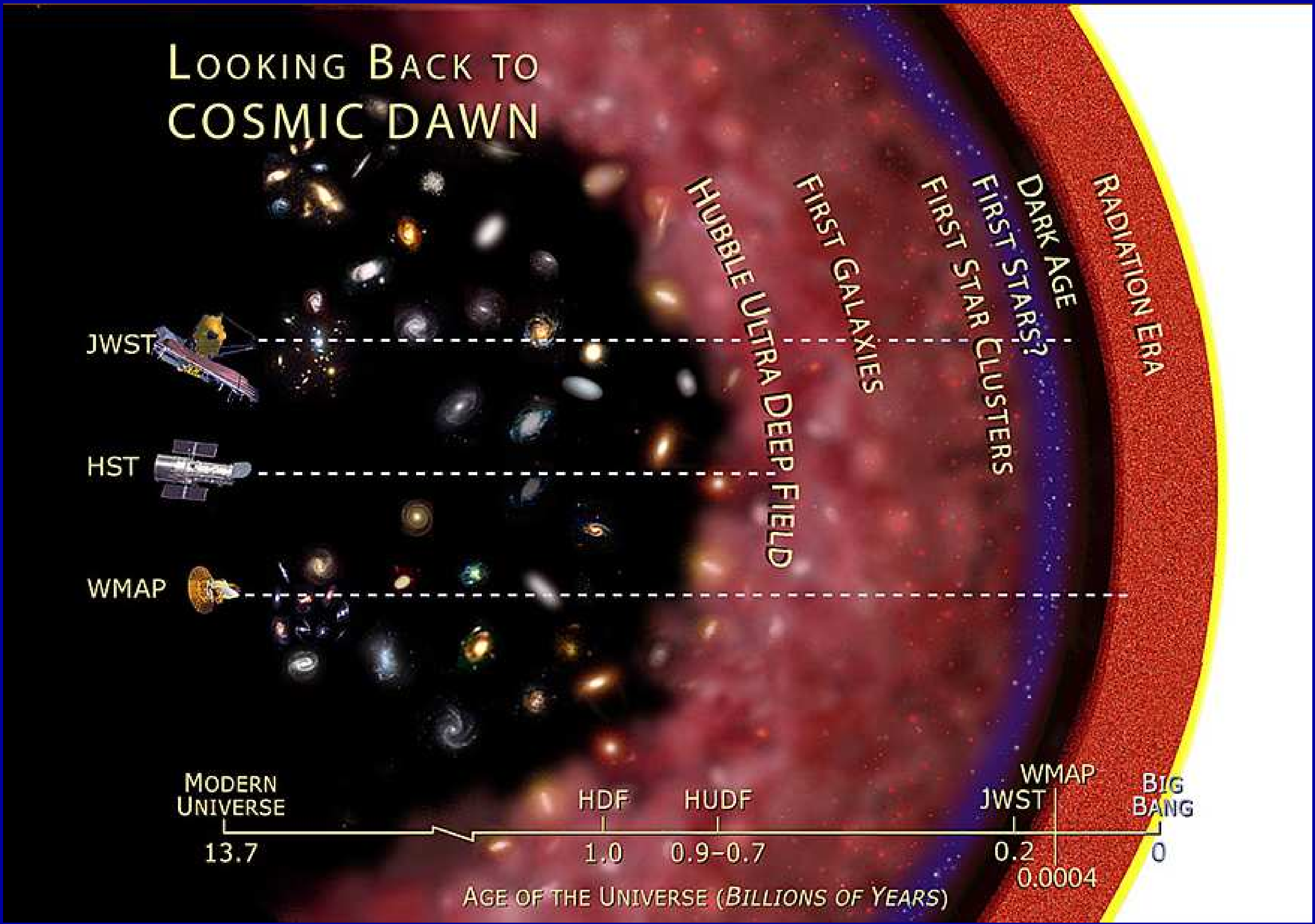
⇒ This qualitatively supports the presented picture: there may be a ∼1 Gyr delay between (major) galaxy merger and SMBH feeding.

• The Beast feeds like fireflies in the night, and well after the Beauty produces its spectacular galaxy merging (typically 1 Gyr later).

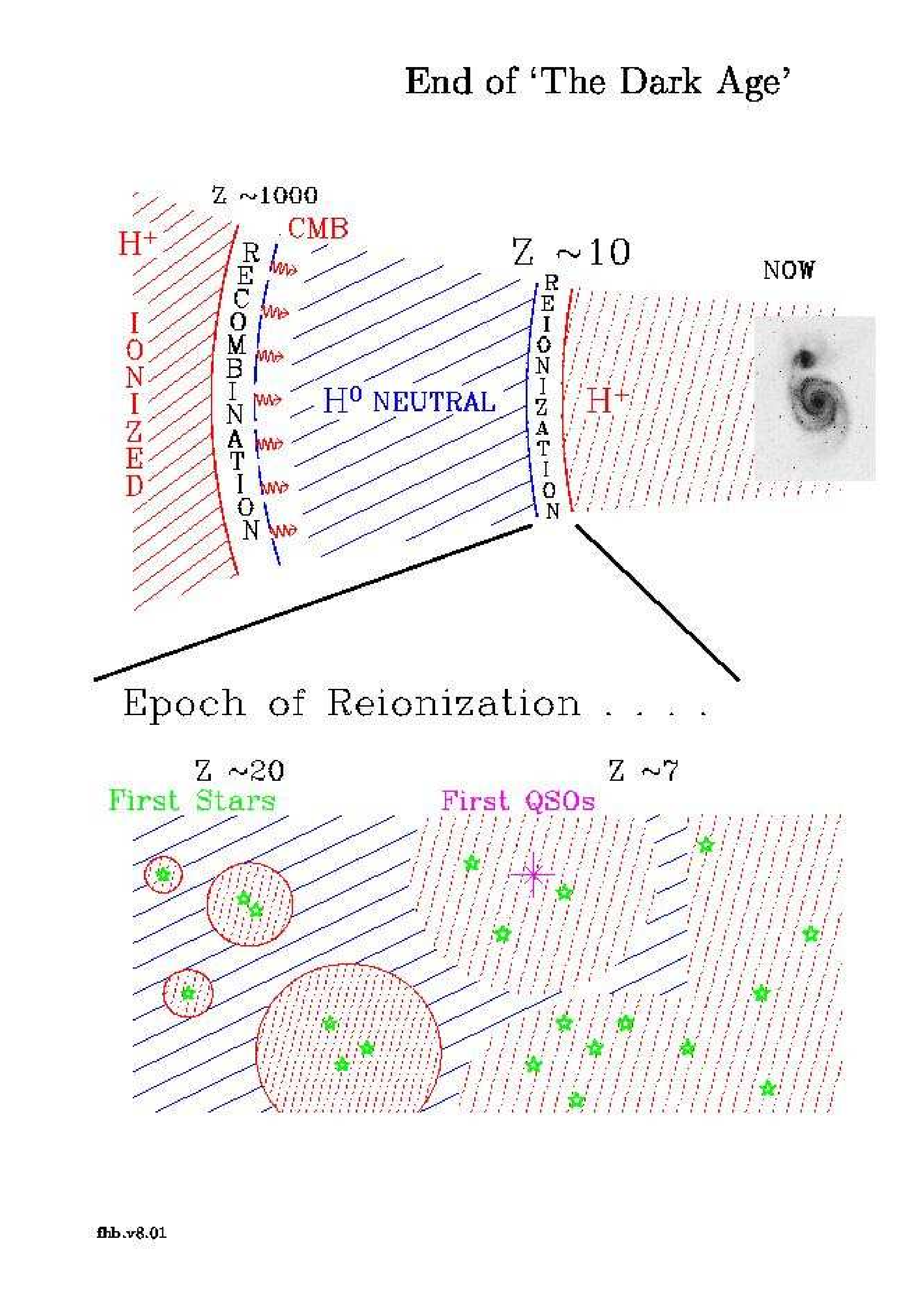
(4a) Future studies with the James Webb Space Telescope



JWST tracing First Light, Reionization, and Galaxy Assembly.



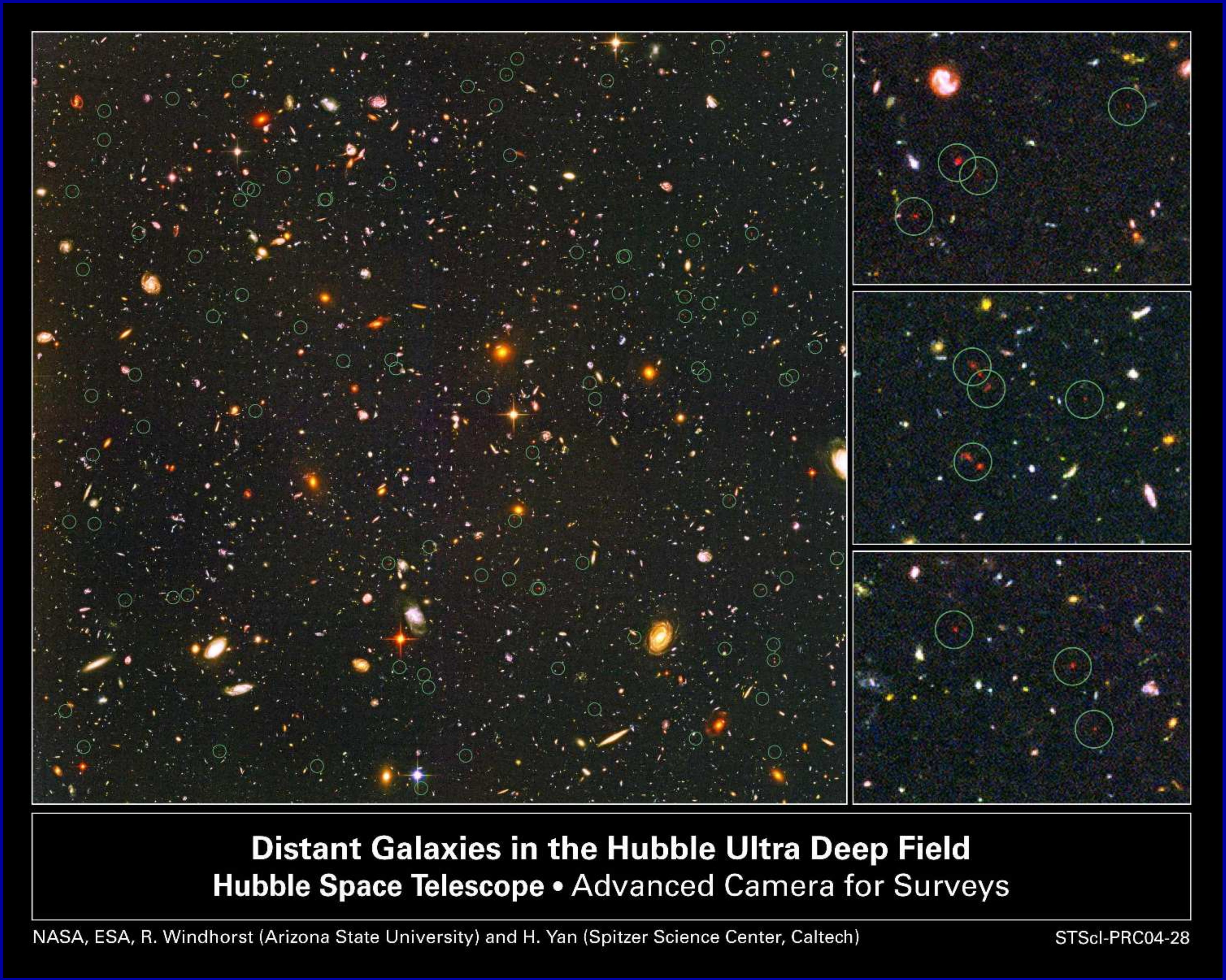
NASA telescopes penetrating Cosmic Dawn, First Light, & Recombination



WMAP: First Light may have happened as following:

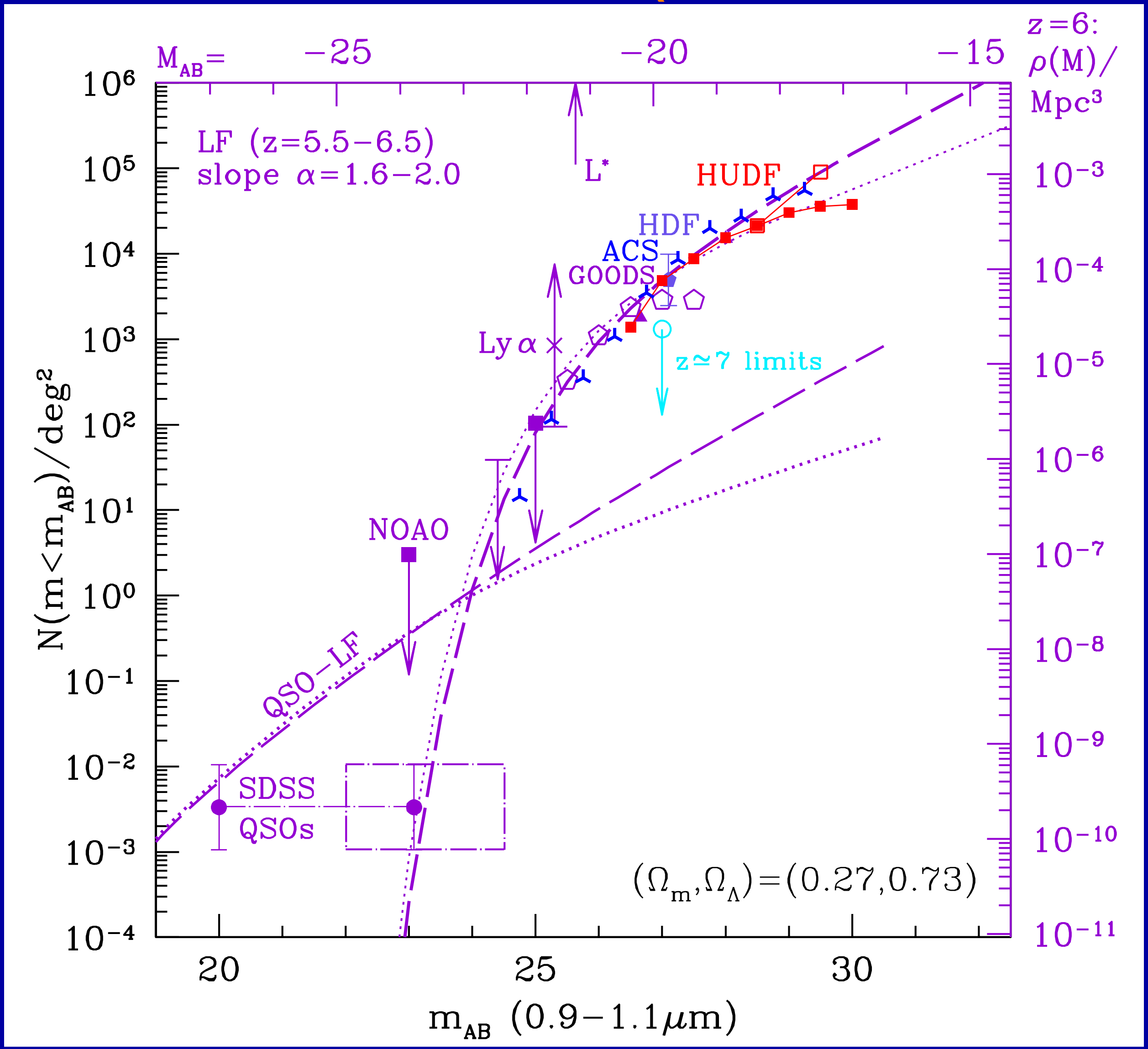
- (0) Dark Ages since recombination (z=1089) until First Light objects started shining (z=11–20).
- (1) First Light when Population III stars start shining with mass $\gtrsim$100–200 $M_\odot$ at z$\simeq$11–20.
- (2) Pop III supernovae heated IGM, which could not cool and form normal Pop II halo stars until z$\simeq$9–10 (Cen 2002).
- (3) This is followed by Pop II stars forming in dwarf galaxies (mass$\simeq$$10^7$–$10^9$ $M_\odot$) at z$\simeq$6–9, ending the epoch of reionization.

(Fig. courtesy of Dr. F. Briggs)



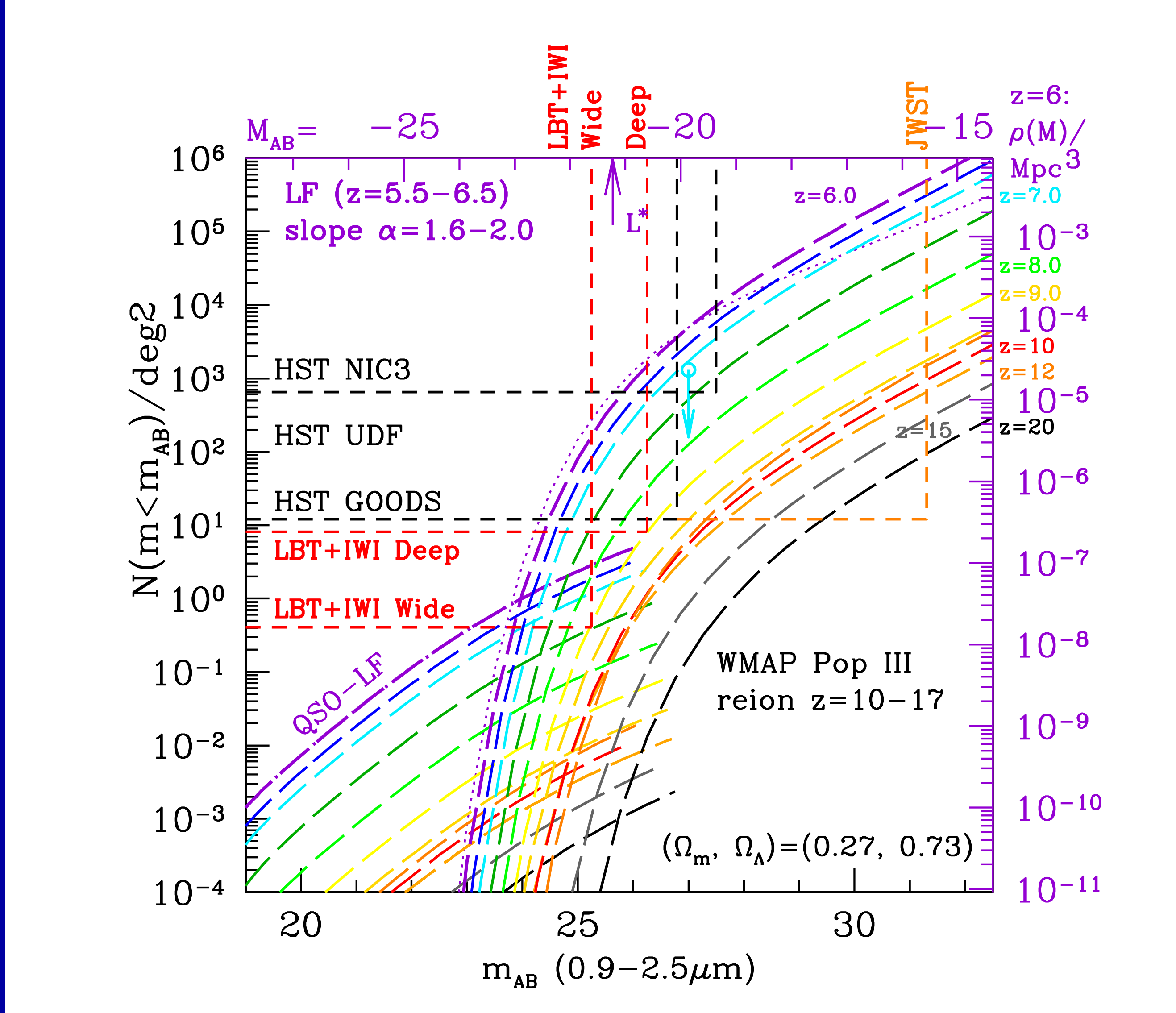
HUDF i-drops: faint galaxies at z$\simeq$6 (Yan & Windhorst 2004), most spectroscopically confirmed at z$\simeq$6 to AB$\lesssim$27.0 mag (Malhotra et al. 2005).

• Reionization — Who Dunnit? Quasars or Dwarf Galaxies?



HUDF shows that luminosity function of z≃6 objects (Yan & Windhorst 2004a, b) may be very steep: faint-end Schechter slope $|\alpha|\simeq$1.6–2.0.

⇒ Dwarf galaxies and not quasars likely completed the reionization epoch at z≃6. This is what JWST will observe in detail to z≳10–20.

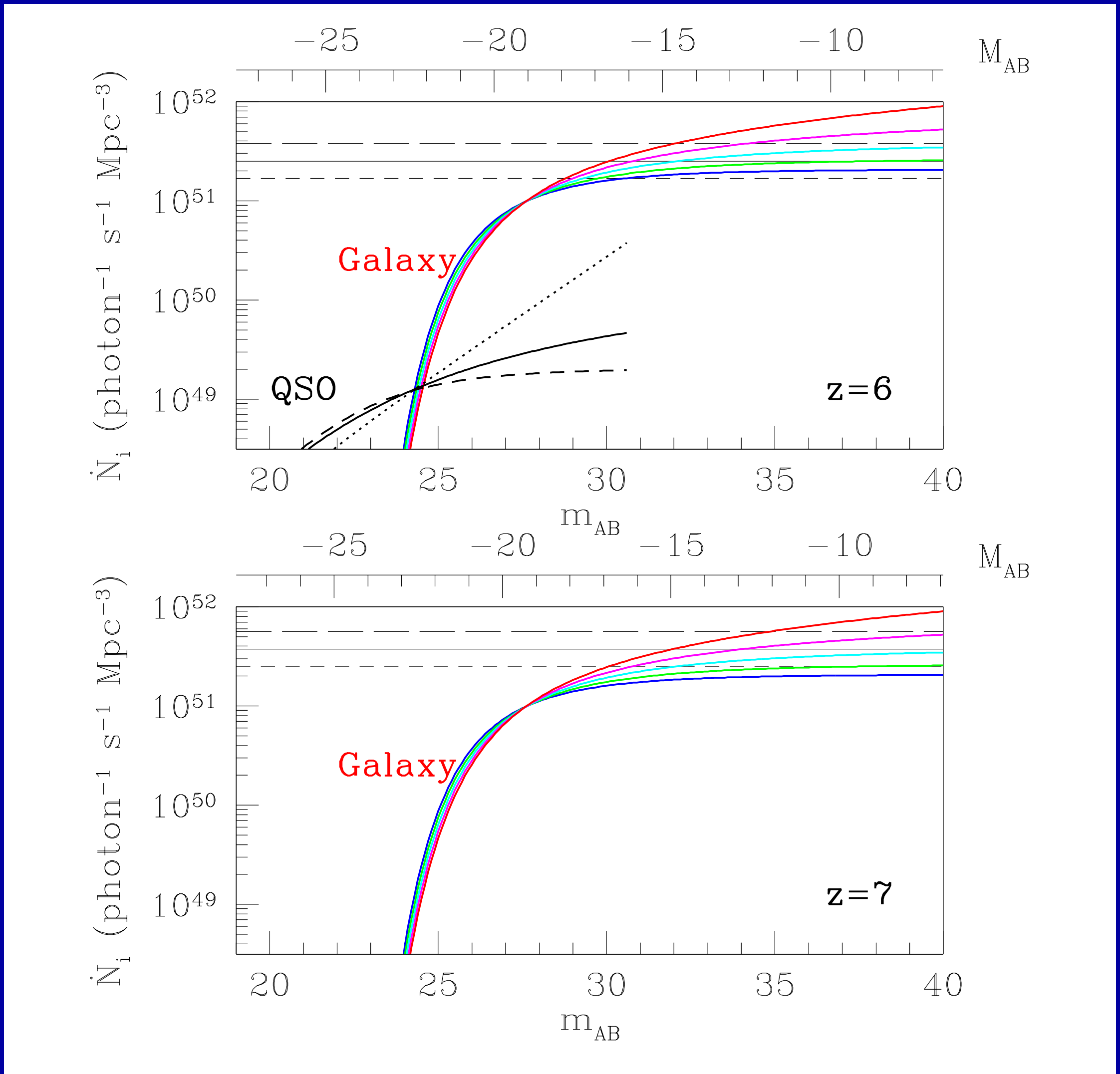


• With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.

• A ground-based wide-field near-IR survey to AB$\lesssim$25–26 mag and z$\lesssim$10 (red lines) is an essential complement to JWST First Light studies:

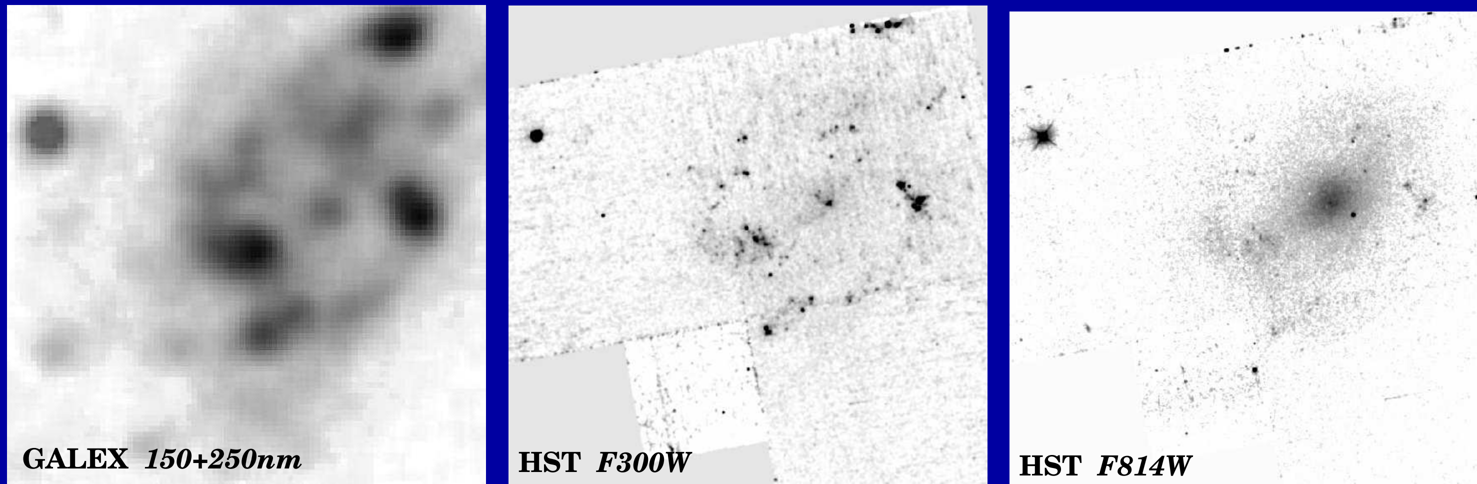
• Co-evolution of supermassive black-holes and proto-bulges for z$\lesssim$10.

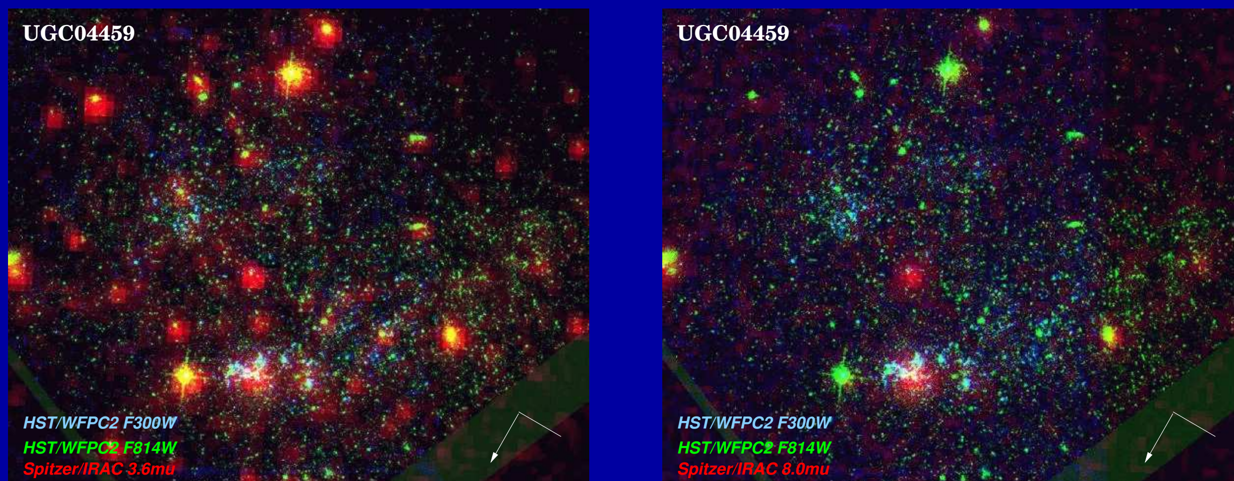
• Reionization — Who Dunnit? Quasars or Dwarf Galaxies?



- The steep LF of dwarf galaxies at z≃6 (Yan & Windhorst 2004a, ApJL, 600, L1) can provide enough UV-photons to complete reionization by z≃6.
- Pop II dwarf galaxies may not have started shining *pervasively* much before z≃7–8, or no H-I would be seen in the foreground of z≳6 quasars.
- QSO's and weak AGN likely do not provide enough UV photons at z∼6 to finish reionization, unless their LF is unphysically steep (*i.e.*, $|\alpha|\gtrsim 2.5$).

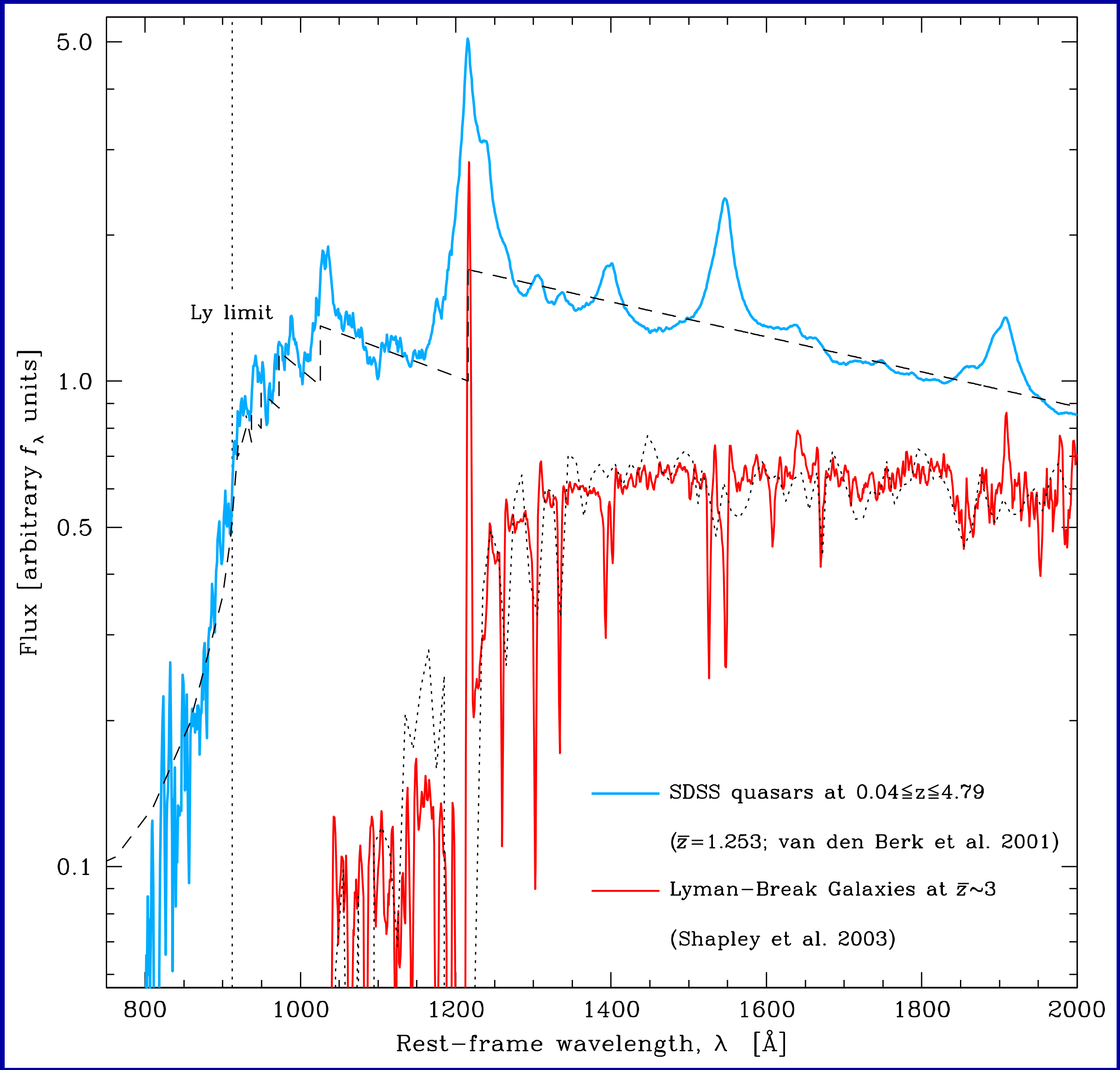
Caveat: What is the UV escape fraction of Dwarf Galaxies?





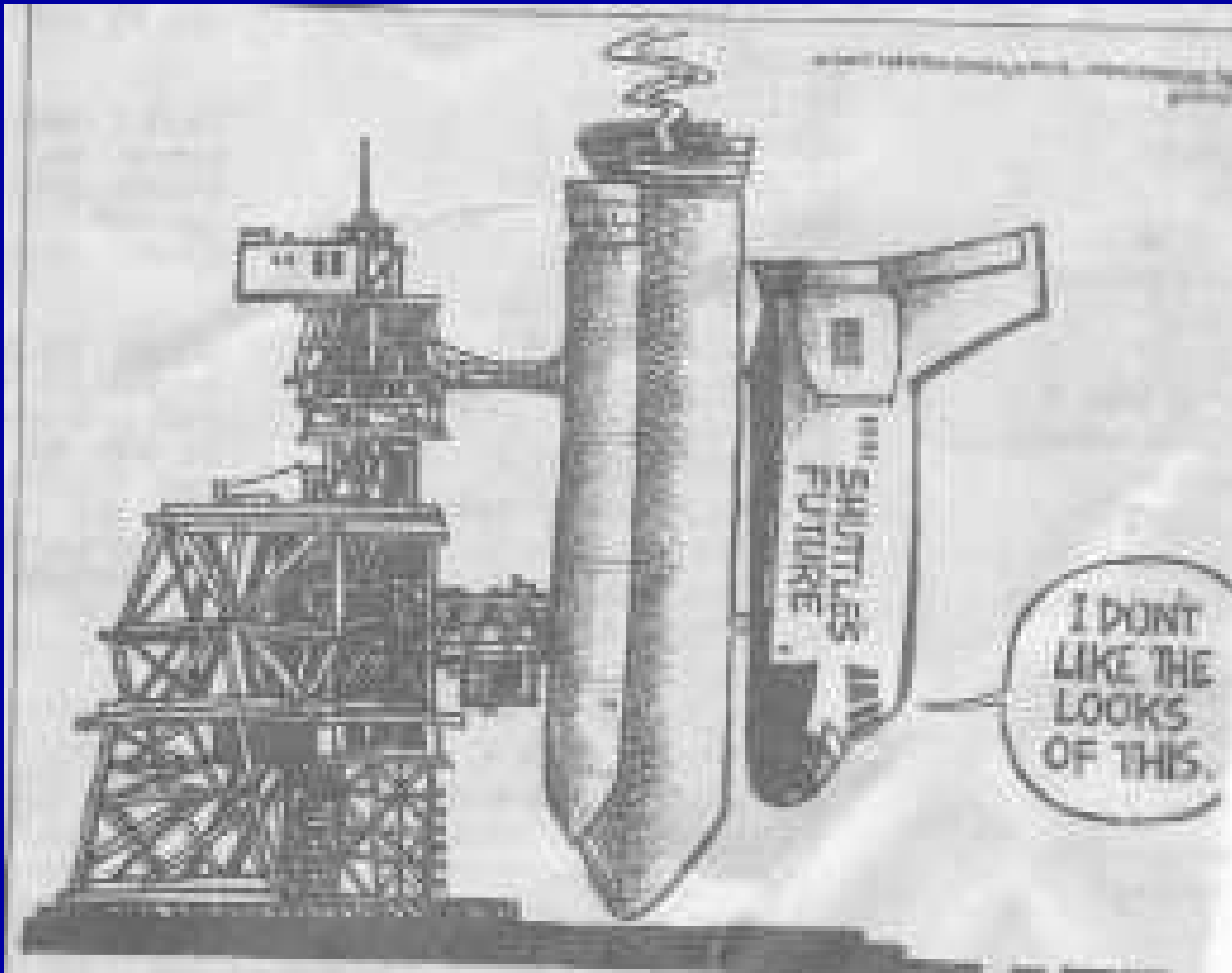
- GALEX, HST/UV and Spitzer IRAC images of nearby late-type dwarf galaxies show enough (SN-driven?) holes between their dust that UV-photons can escape: covering factors or escape fractions $f_{esc} \gtrsim 20\%$?
- Steidel et al. (2001): z$\simeq$3 LBG's have UV-escape fraction $f_{esc} \simeq 10\%$.
- Yan & Windhorst (2004) assume that f_{esc} at z$\simeq$6 is at least as high.

Caveat: Can the Hard-UV of weak AGN outshine Dwarf Galaxies?



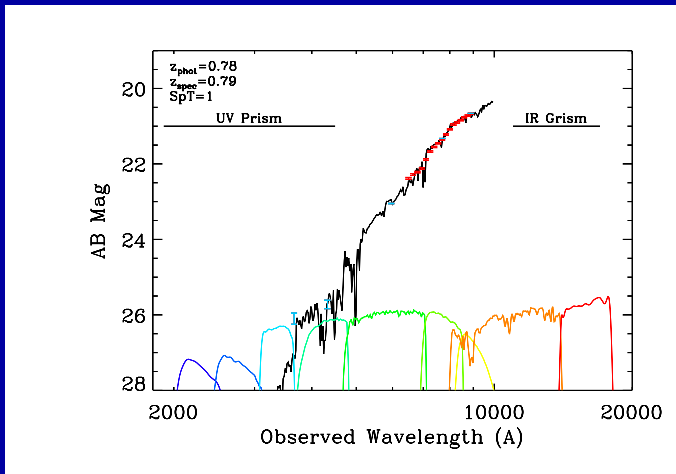
- In principle, the hard-UV of QSO's and weak AGN can outdo the young SED's of LBG's or dwarf galaxies, but likely by no more than $\gtrsim$1 dex.

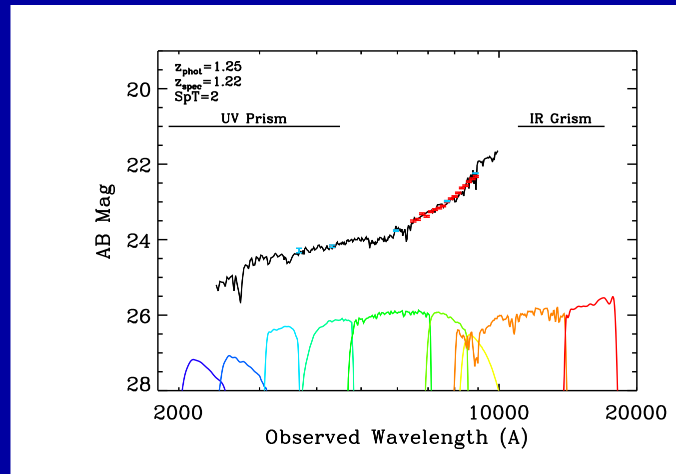
(4b) Future studies with the Hubble Wide Field Camera 3

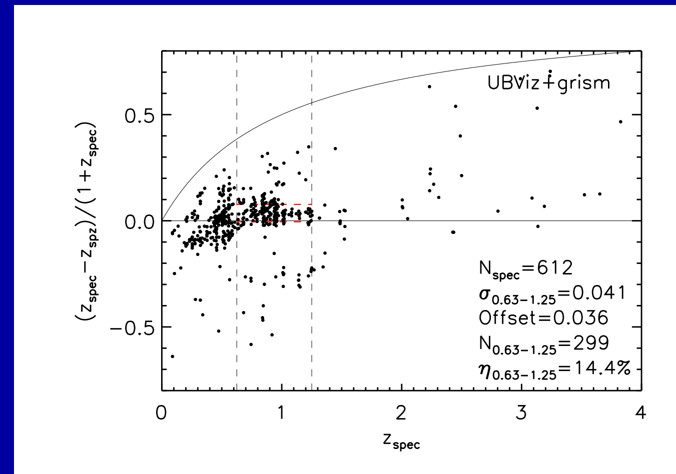


If there are no further Shuttle issues, WFC3 will get launched in Sep. 2008 ...

Power of combination of Grism and Broadband for WFC3



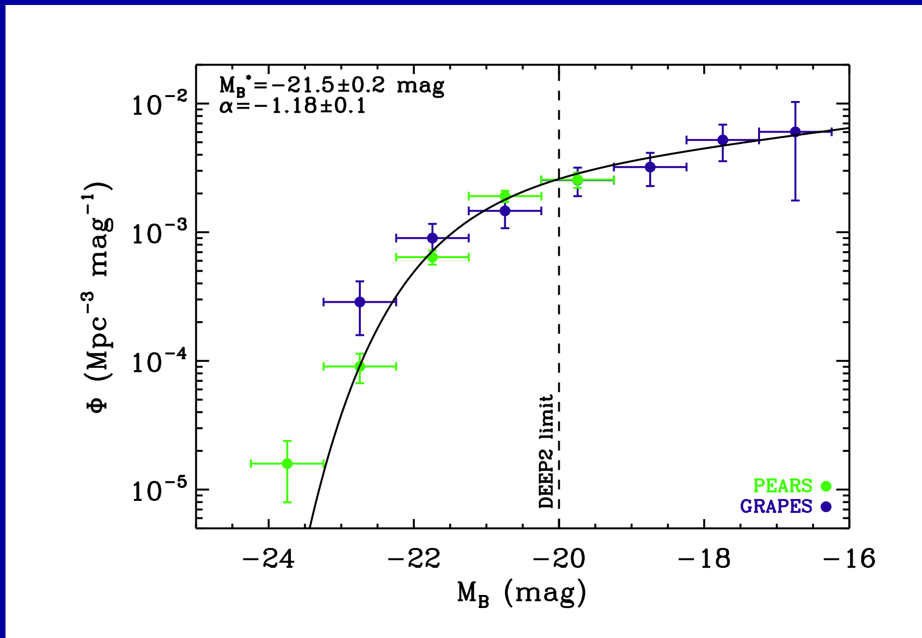


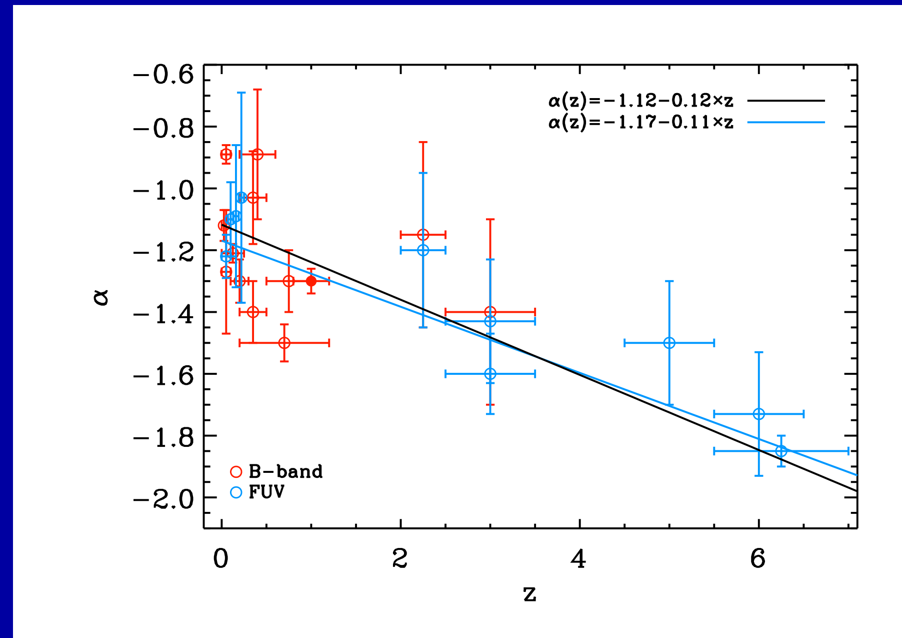


Lessons from the Hubble ACS grism surveys "GRAPES" and "PEARS" (Malhotra et al. 2005; Cohen et al. 2007; Ryan et al. 2007):

- (a) Spectro-photo-z's from HST grism + BViz(JH) considerably more accurate than photo-z's alone, with much smaller catastrophic failure %.
- (b) Redshifts for $\gtrsim$13,000 objects to AB$\gtrsim$27.0–27.5 mag; $\sigma_z/(1+z)\lesssim$0.04.
- (c) Expect $\lesssim$0.02–0.03 accuracy when including new capabilities of WFC3: UV and near-IR broad-band imaging and low-res grism spectroscopy.
- WFC3 will provide full panchromatic sampling of faint galaxy spectra from 0.2–1.7 μm, permitting high accuracy photo-z's for faint galaxies of all types to AB$\simeq$27.0 mag.

LF Faint-end Slope Evolution (fundamental, like local IMF)





Measuring the faint-end LF-slope at z$\gtrsim$1 with accurate z's to AB$\lesssim$27 (Ryan ea. 2007, Cohen ea. 2007) constrains hierarchical formation theories:

- AGN and star-formation feedback processes (SNe) produce different faint-end slopes and slope-evolution — new physical constraints.
- WFC3 and JWST will complement the ACS grism, provide deeper low-resolution spectra than ground-based, and trace α for $1 \lesssim z \lesssim 12$.
- Will measure environmental impact on LF faint-end slope directly.
- Expect convergence to slope $|\alpha| \equiv 2$ at $z > 6$ before feedback starts.

(5) Summary and Conclusions

• Tadpole galaxies make up about 6% of the total HUDF galaxy sample.

• Tadpoles have a redshift distribution very similar to that of field galaxies $\Longleftrightarrow$ Tadpole galaxies may be good tracers of the galaxy assembly process.

• Variable objects make up ~1% of the total HUDF galaxy sample. Weak variable AGN comprise likely $\gtrsim$3–6% of total HUDF galaxy sample, when accounting for the missed long-period variable and obscured AGN.

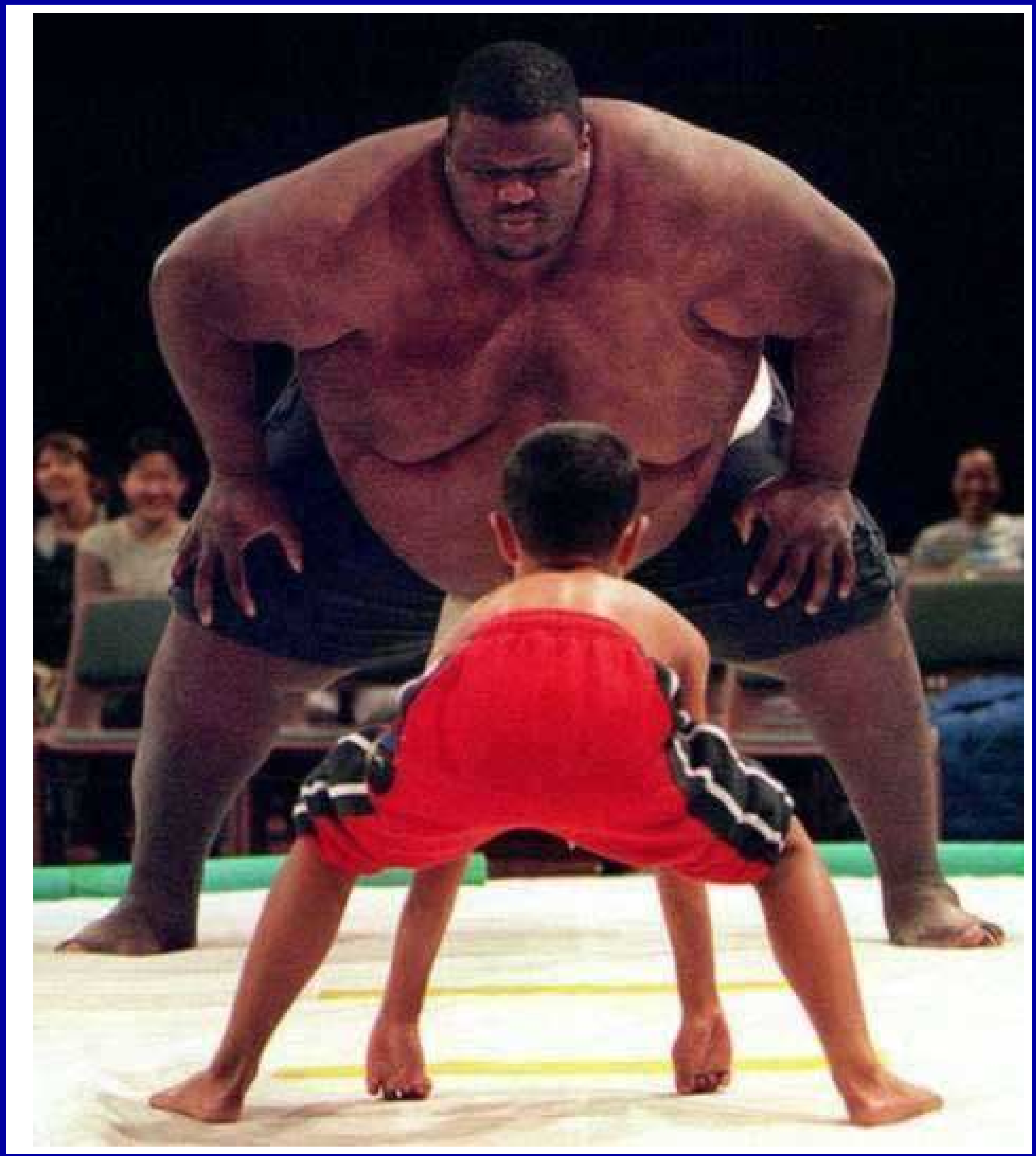
• Variable objects have a redshift distribution similar to that of HUDF field galaxies $\Leftrightarrow$ They likely trace brief(!) episodes of SMBH growth.

• Both the HUDF Tadpoles and objects with Variable point sources have similar redshift distributions N(z), both of which peak around z$\simeq$1–2.

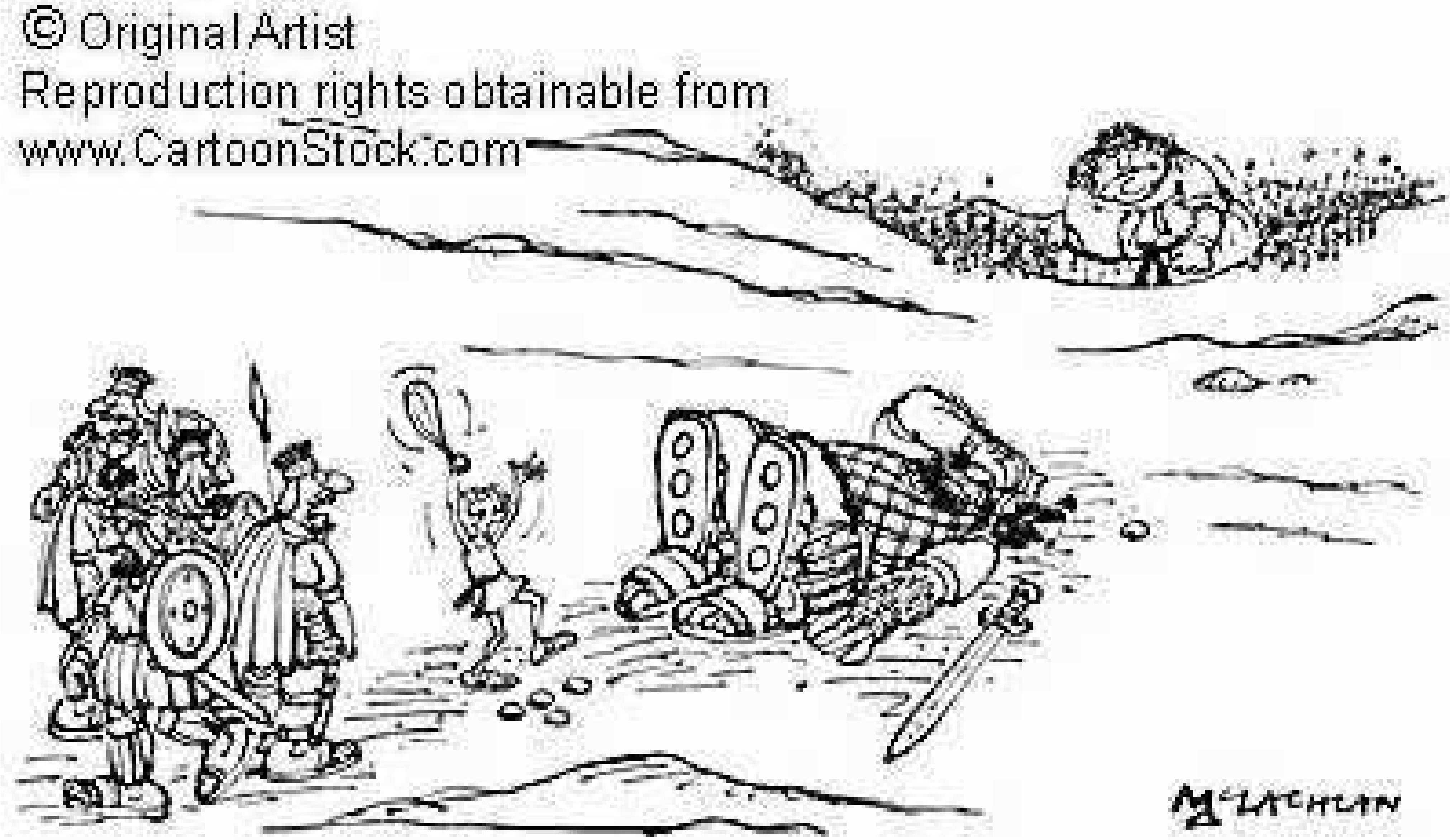
$\Rightarrow$ AGN GROWTH STAYS ~IN PACE WITH GALAXY ASSEMBLY.

• THE (EVOLVING) STEEP FAINT-END LF-SLOPE ($|\alpha|\gtrsim$1.8–2) OF DWARF GALAXIES AT z$\gtrsim$6 LIKELY COMPLETED REIONIZATION.

SPARE CHARTS



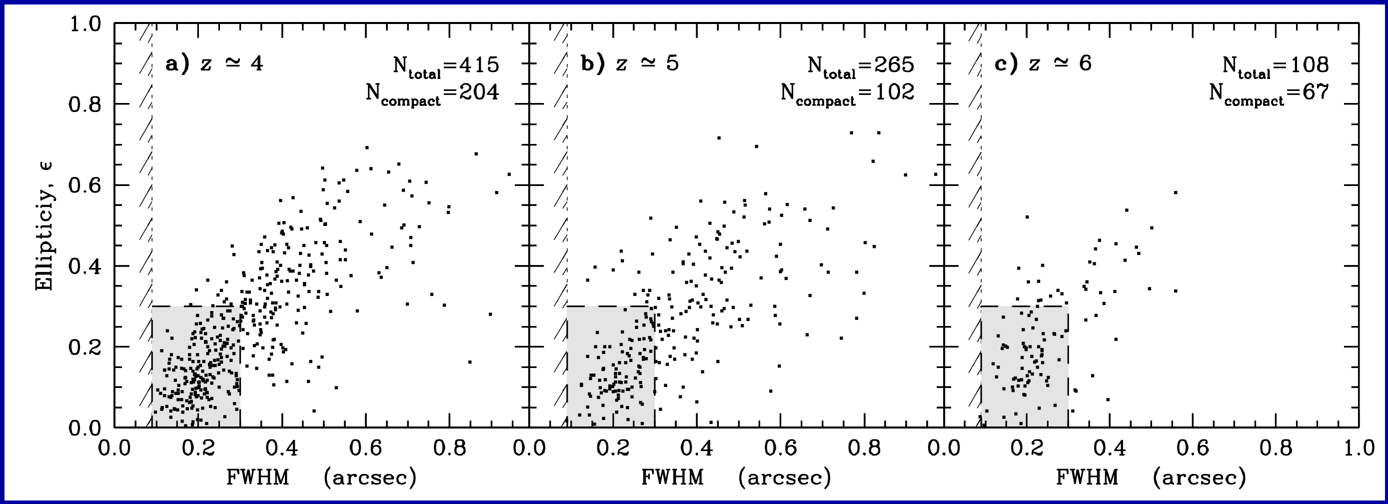
At the end of reionization, dwarfs had beaten the Giants, but ...

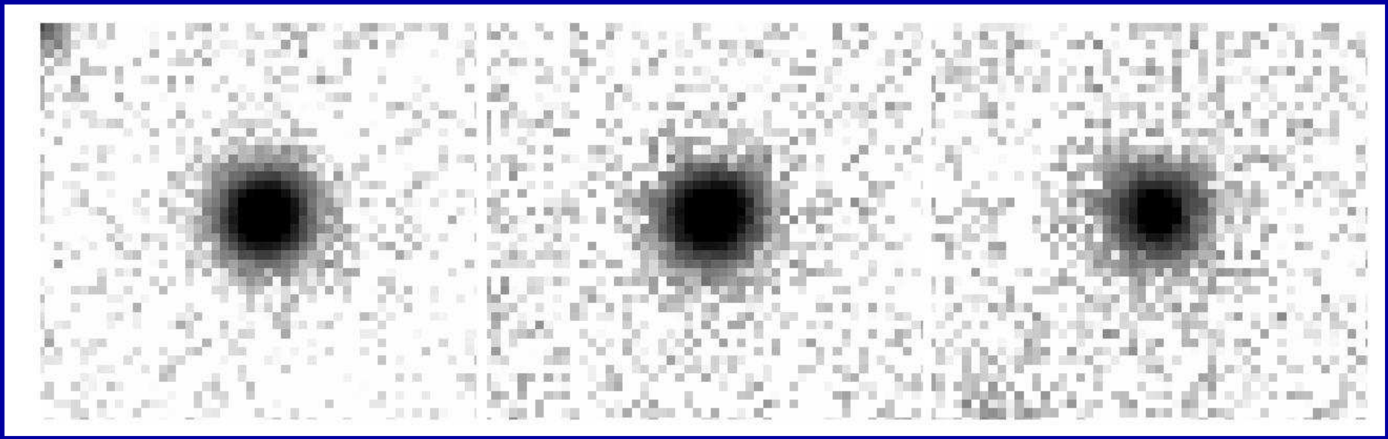


"You've done it now, David - Here comes his mother."

What comes around, goes around ...

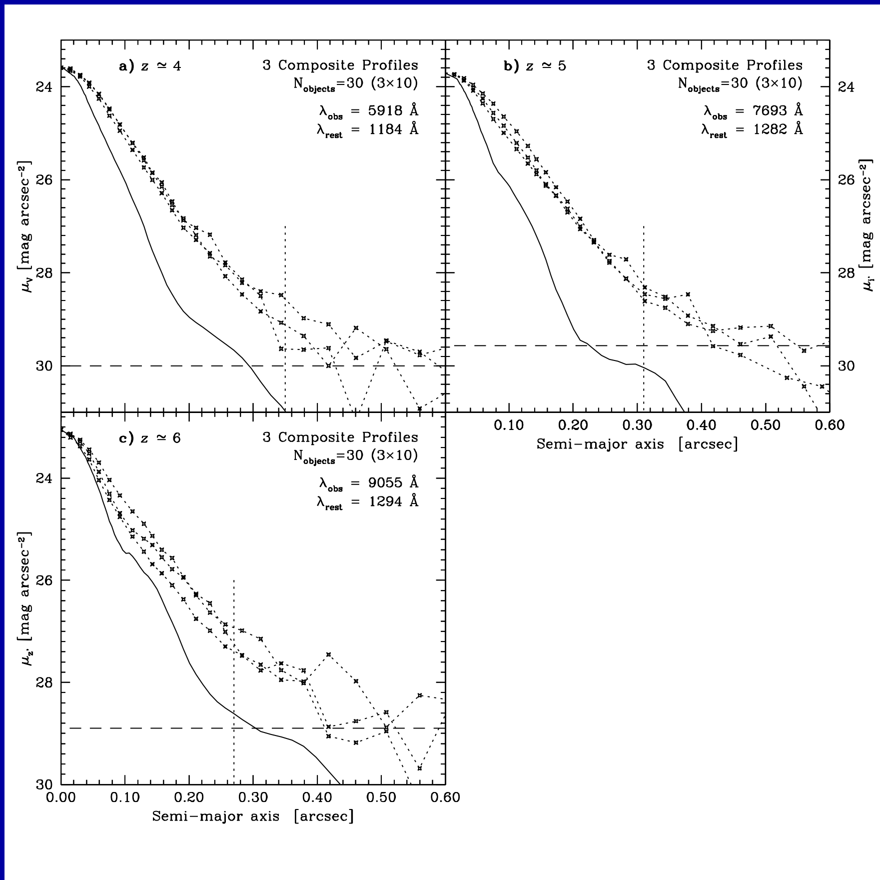
Dynamical ages of Dwarf Galaxies at z≃4–6?

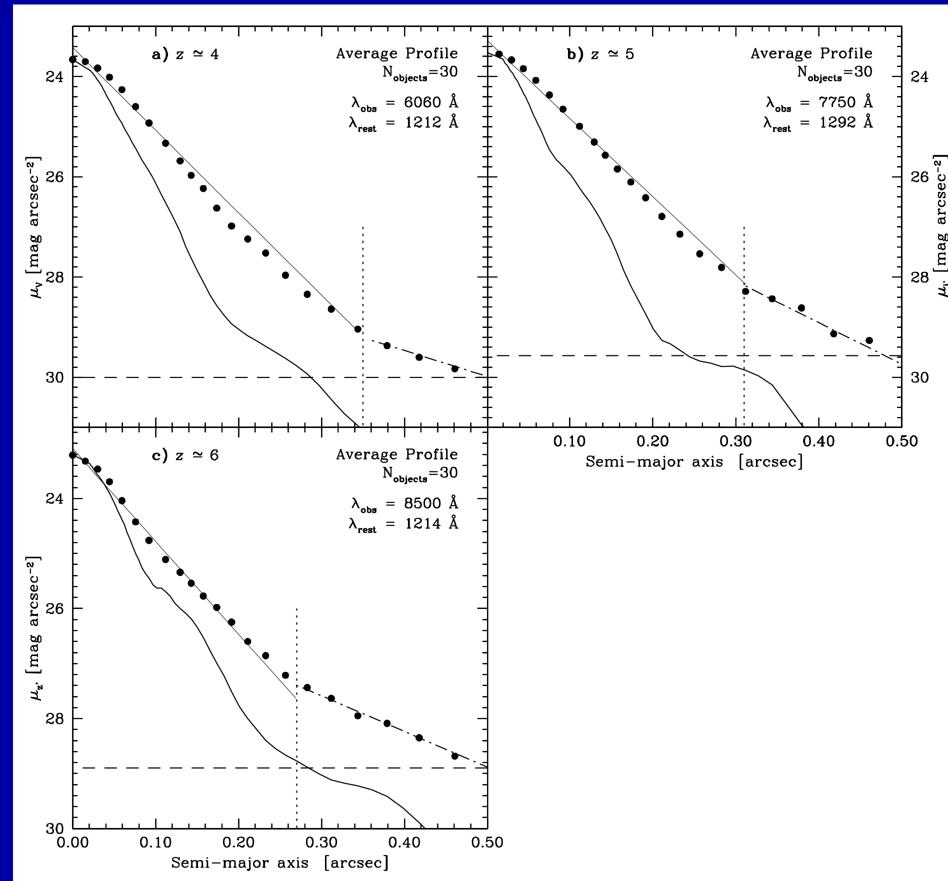




- Select all isolated, nearly unresolved ($2r_e \lesssim 0''.3$), round ($1-b/a \lesssim 0.3$) HUDF B-drops, V-drops, and i-drops.
- Construct average image stack and light-profiles of these dwarf galaxies at z≃4, z≃5, and z≃6.
- If these compact, round objects are intrinsically comparable, each stack has the S/N of ∼5000 HST orbits (Hathi et al. 2007).

Dynamical ages of Dwarf Galaxies at z≃4–6?





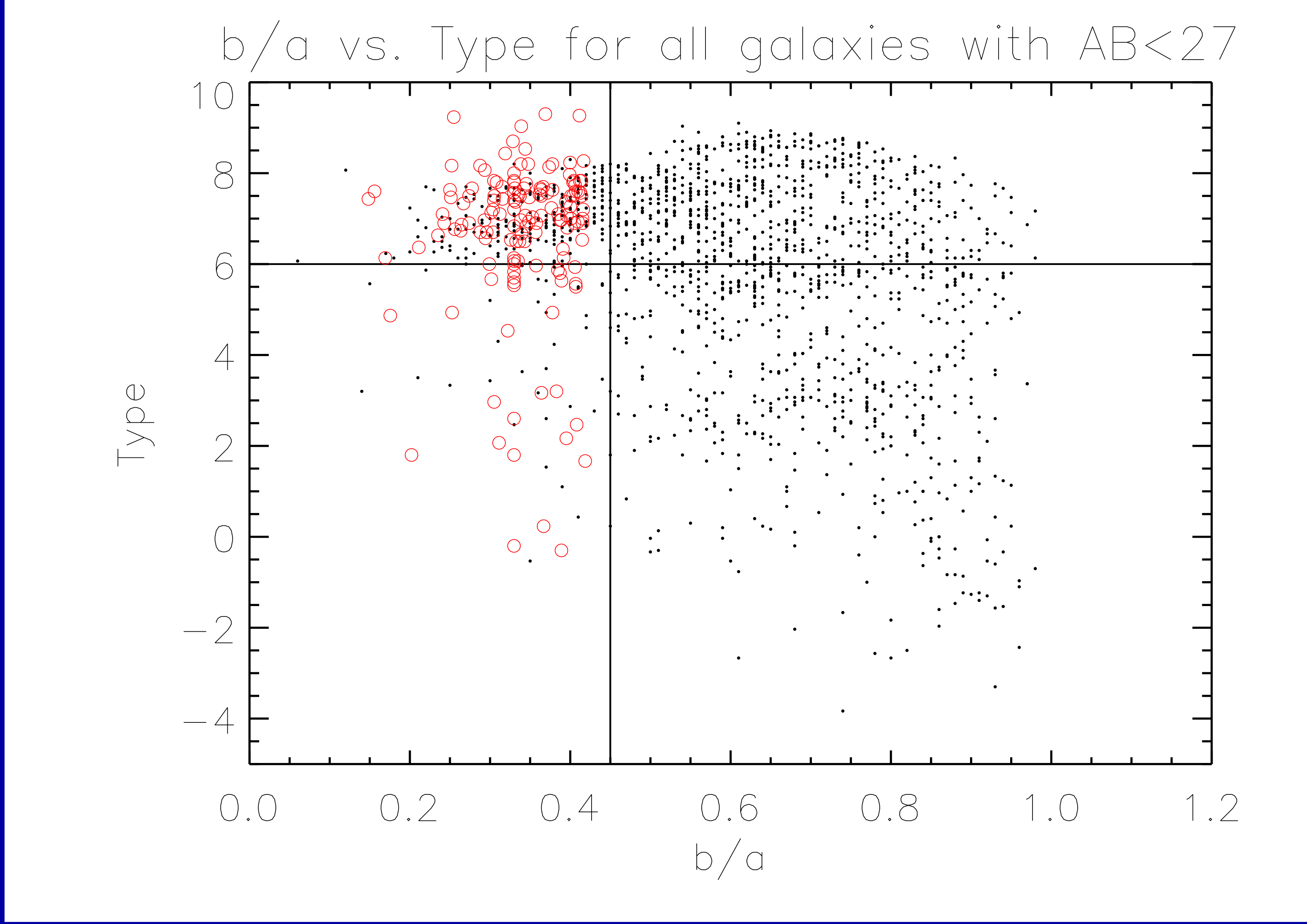
- HUDF sky-subtraction error is 2–3 10^{-3} or AB≃29.0–30.0 mag/arcsec^2
- Average 5000-orbit compact, round dwarf galaxy light-profile at z≃6–4 deviates from best fit Sersic n≃1.0 (incl. PSF) at r≳0.″27–0.″35.
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of τ_{dyn}≃0.1-0.2 Gyr at z≃6–4 for the enclosed masses.

⇔ Comparable to their SED ages (Hathi et al.2007).

⇒ Global starburst that finished reionization at z≃6 started at z≃6.6.

Input Parameters for IDL Tadpole Finder script:

Parameter	Value
(A) b/a limit: knots	>0.70
(B) b/a limit: tails	<0.43
(1) Distance to center (in a-axis units)	<4
(2) PA difference (tail-knot in degrees)	<30
Total number of tadpoles selected by script	140
Total number of tadpoles selected by eye	25
Total number of tadpoles selected	165

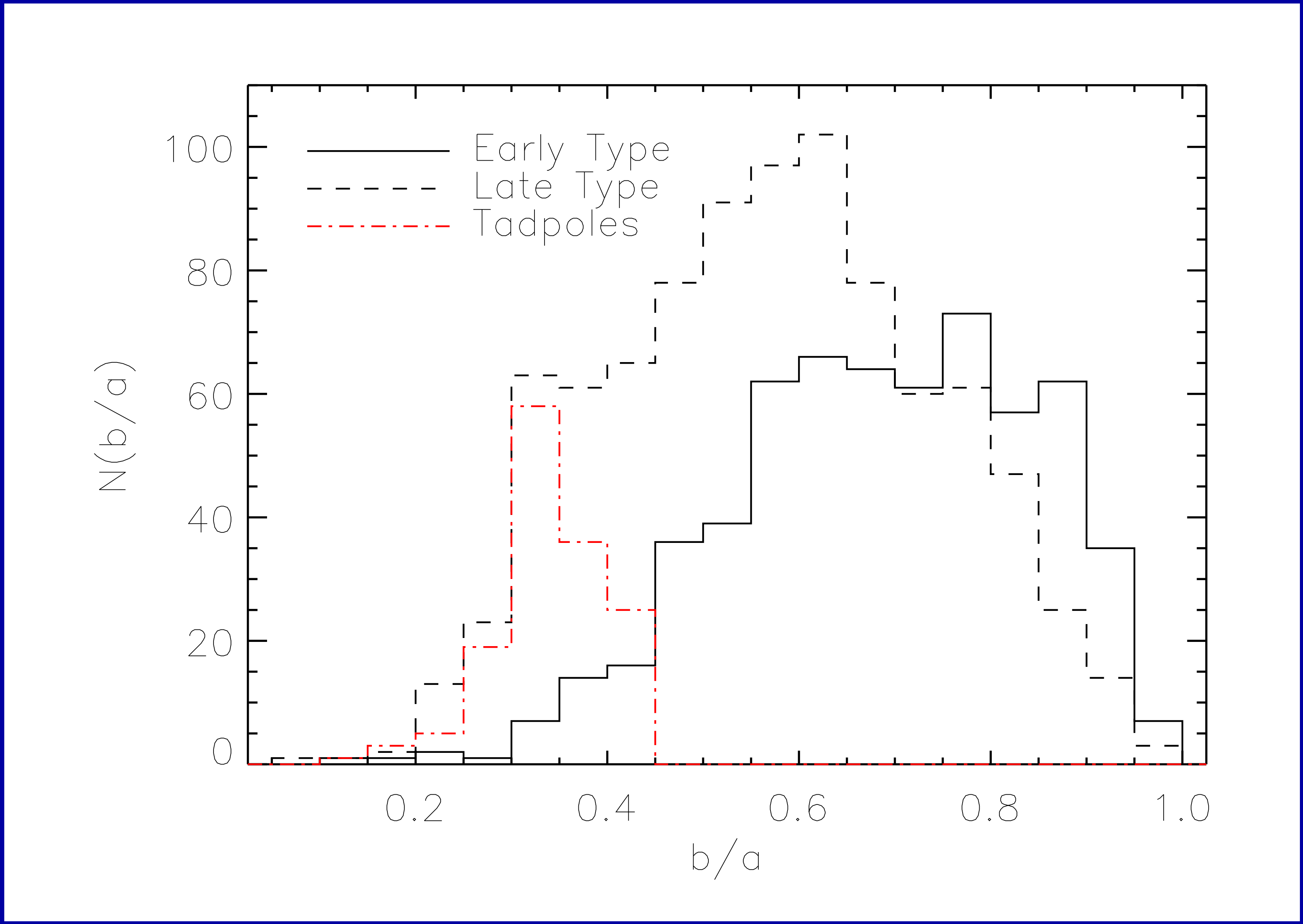


Ellipticity vs. rest-frame HUDF Type to i_{AB} =27 mag:

- Fraction of Flat Late-Types/All Late-Types = 26%
- Fraction of Flat Early-Types/All Early-Types = 7%

⇒ ∃ likely an excess of truly linear structures among flat late-type objects.

⇒ Not all tadpoles are edge-on late-type disks.



Ellipticity distribution to i_{AB} =27 mag:

⇒ ∃ likely an excess of truly linear structures among flat late-type objects.

⇒ Not all tadpoles are edge-on late-type disks.

Summary of HUDF Data and Epochs Used

Observation dates/Orbits:	B	V	i	z	Total
09/24/2003-10/02/2003	6	18	18	50	50
10/03/2003-10/28/2003	22	20	58	56	156
12/04/2003-12/22/2003	6	8	18	20	52
12/23/2003-01/15/2004	22	20	50	50	142
TOTAL ORBITS:	56	56	144	144	400
Total number of exposures	112	112	288	288	800
Total exposure time (s)	134880	135320	347110	346620	963930

(6) Work in Progress

- TADPOLES:
- Do C-A-S type search for asymmetry/clumpiness, etc.
- Address selection effects from SB-dimming quantitatively.
- Include NIC3 J+H images to constrain K-morph effects.
- Investigate edge-on disk contamination following Odewahn et al. (1997).

- VARIABLE OBJECTS:
- Study galaxy cores with 5x5 pix apertures or by differencing images.
- Test all variable candidates for stellarity $\Rightarrow$ Likely AGN.
- Compare to statistics on variability timescales on nearby objects (depends on luminosity). Cross-check with known X-ray variability in CDF-S.
- Get better N(z_{phot}) from BViz and JHK. Use all GRAPES redshifts for AB$\lesssim$27.5 mag. Find any nearby novae (none so far).
- Check for non-zero proper motion objects (none so far).