Did AGN Growth and Galaxy Assembly go hand-in-hand?

"NSinc: Galaxy Assembly and Black Hole Growth?"

Rogier A. Windhorst (ASU)

Amber Straughn, Seth Cohen, Russell Ryan Jr., Nimish Hathi (ASU)

A. Koekemoer, N. Pirzkal, C. Xu, S. Malhotra, B. Mobasher, J. Rhoads,
L. Strolger, other GRAPES co-I's (STScI)

and Haojing Yan (SSC, Caltech)

Sponsored by NASA & STScI *hubblesite.org/newscenter/archive/2004/28/*

Leiden Lorentz Workshop on QSO Hosts, Aug. 26, 2005

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

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

Outline

- (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 SMBH growth, AGN activity, and also of galaxy assembly?

- (1.c) Was Λ the major driver/cause of the declining galaxy merger rate, AGN activity (cosmological evolution), and of the passive nature of galaxy evolution for $z \lesssim 1$?

- (2) Tadpole Galaxies in the UDF: A Measure of Galaxy Assembly?

- (3) A Study of Variable Objects in the UDF: A Measure of AGN Growth?

- (4) Conclusions and Implications for JWST

Sponsored by NASA

ARIZONA STATE UNIVERSITY

(1) Scientific Background and Goals

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

- The combined UDF detection limit is i_{AB} =29.1 mag (10-σ). For each of these 4 epochs it is i_{AB} $\gtrsim$28.0 mag.

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

- The UDF shows a plethora of faint galaxy morphologies/structure also seen in the HDF's, 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 edge-on Luminous Diffuse Objects (Conselice 2004) or "clump-clusters" (Elmegreen et al. 2004). They have no counterparts in nearby surveys.

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

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

(2) A study of Tadpole Galaxies in the UDF

- 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 in a dynamically unrelaxed state.

We select them as following:

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

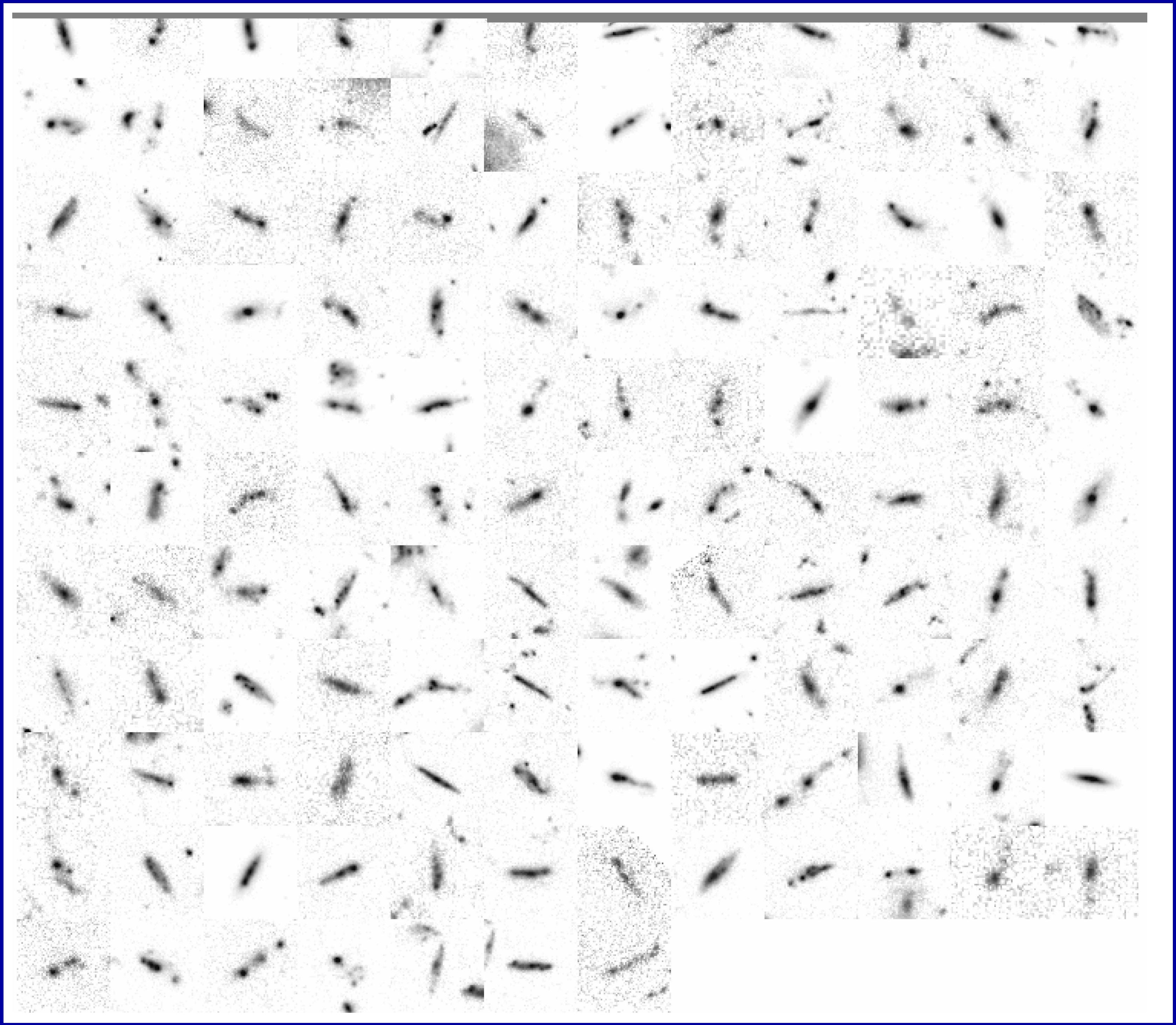
(B) Make a highly de-blended SExtractor catalog and find all clumps rounder than a certain limit located inside sample (A) that are:

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

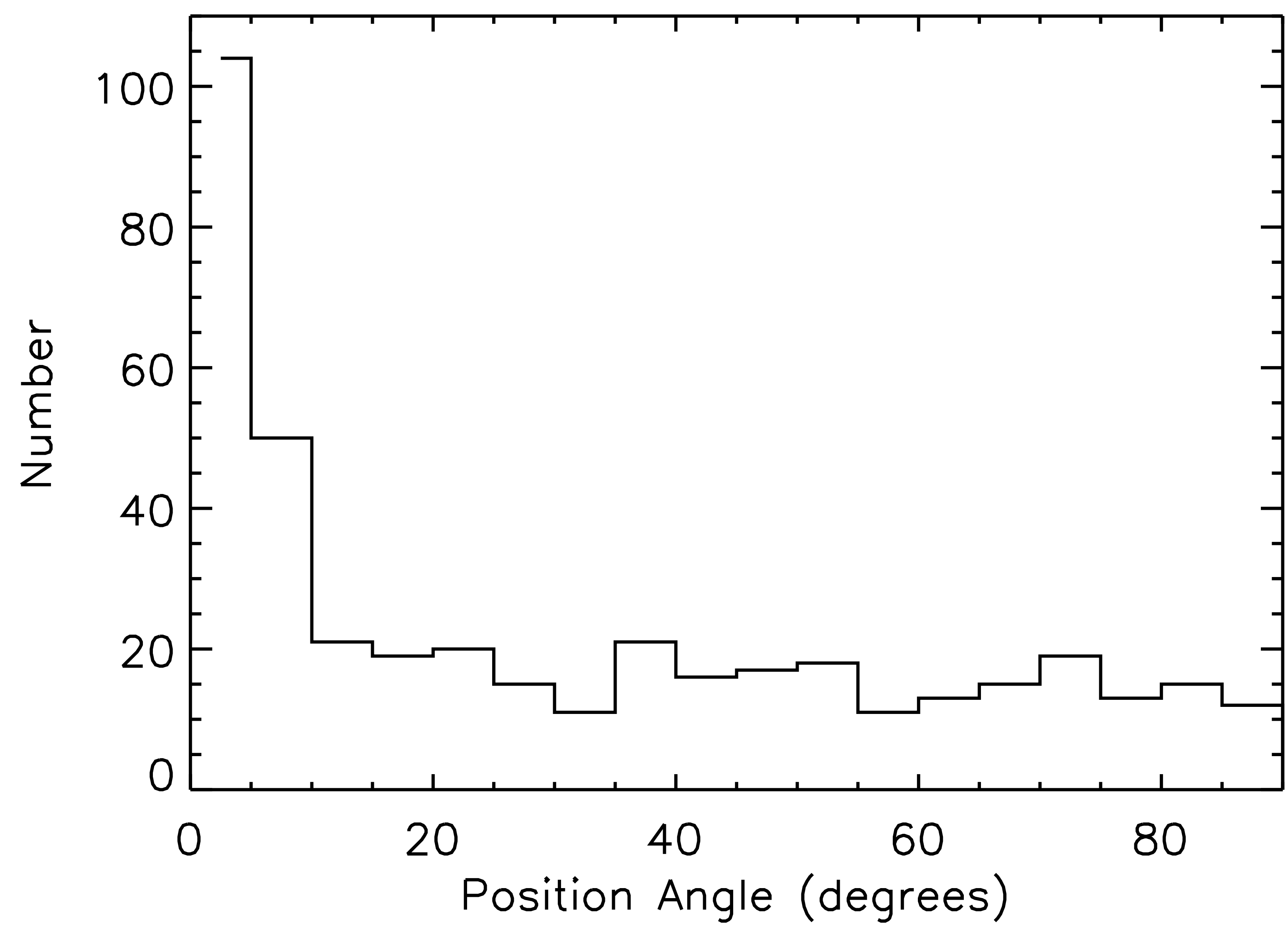
(2) Not displaced in position angle from the tail's major axis by more than a certain amount.

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



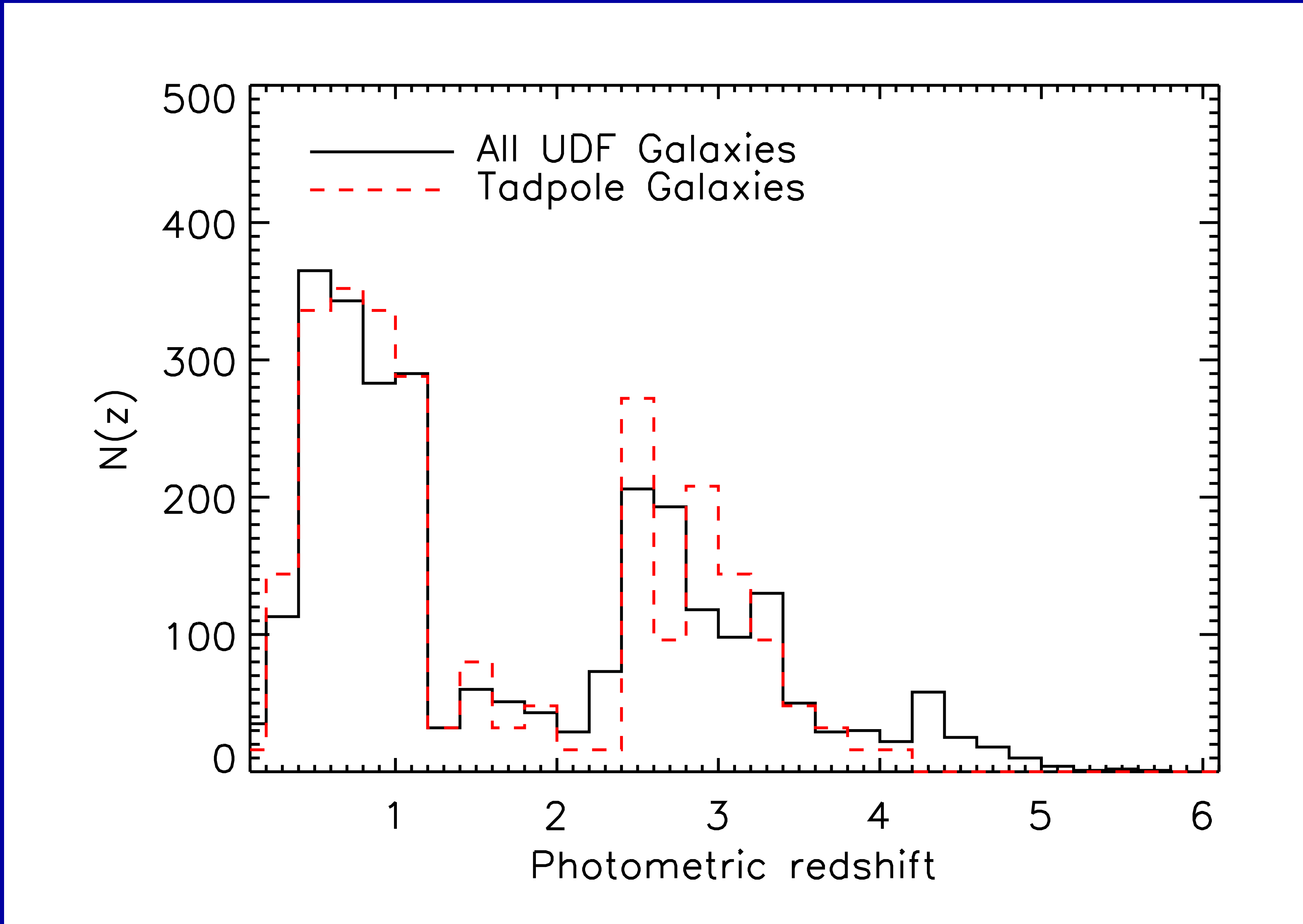
The UDF tadpole galaxies selected by the IDL script.



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

- Clear excess of knots at $|\Delta \mathrm{PA}| \lesssim 10$ **deg**.

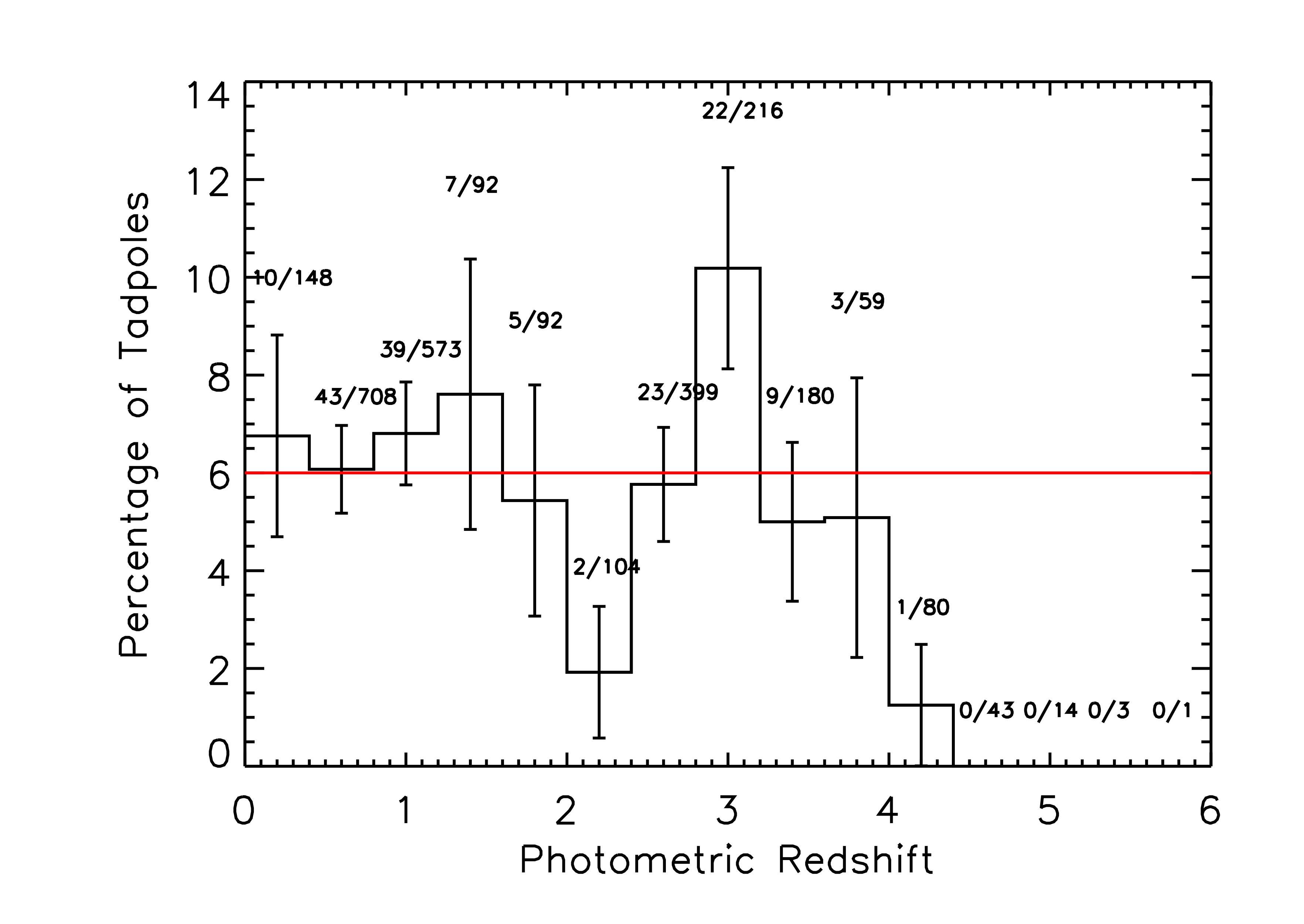
$\Longrightarrow$ Most tadpoles are likely real, rather than chance superpositions.



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

Full drawn: all UDF field galaxies.

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



Fractional redshift distribution of tadpoles compared to all UDF galaxies.

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

(2) Summary of Tadpole Galaxies in the UDF

IDL script: found 140 tadpoles to i_{AB} (total)$\lesssim$27.0 mag.
Visually: identified another 25 similar objects.
Total: $\sim$165 tadpoles.

The tadpole photo-z distribution follows the N(z) of all UDF galaxies.
Average tadpole fraction is $\sim$6% of all UDF 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).

$\Longrightarrow$ If each galaxy underwent a few $\sim$equal mass (major) mergers during its lifetime, $\sim$6% of UDF 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.

(3) A Study of Variable Objects in the UDF

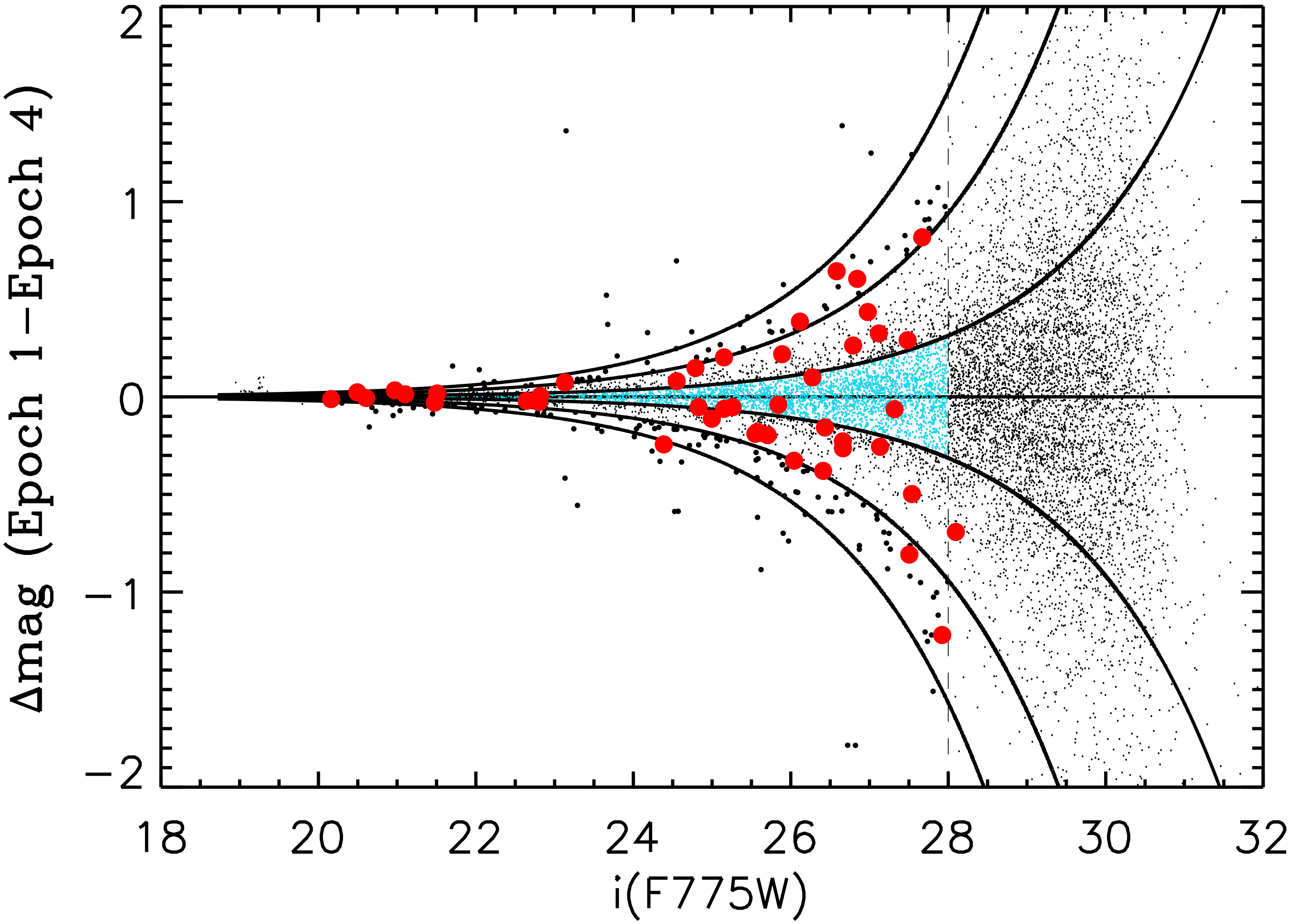
- Split the UDF into 4 sub-stacks of ∼equal exposure times each ∼1 month apart. Treat both i' and z' bands separately as well as together.
The i'-band is so much deeper than z' that i'-band is the primary filter.

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

- Use the error distribution between epochs to select $\gtrsim$3.0–3.5σ outliers.

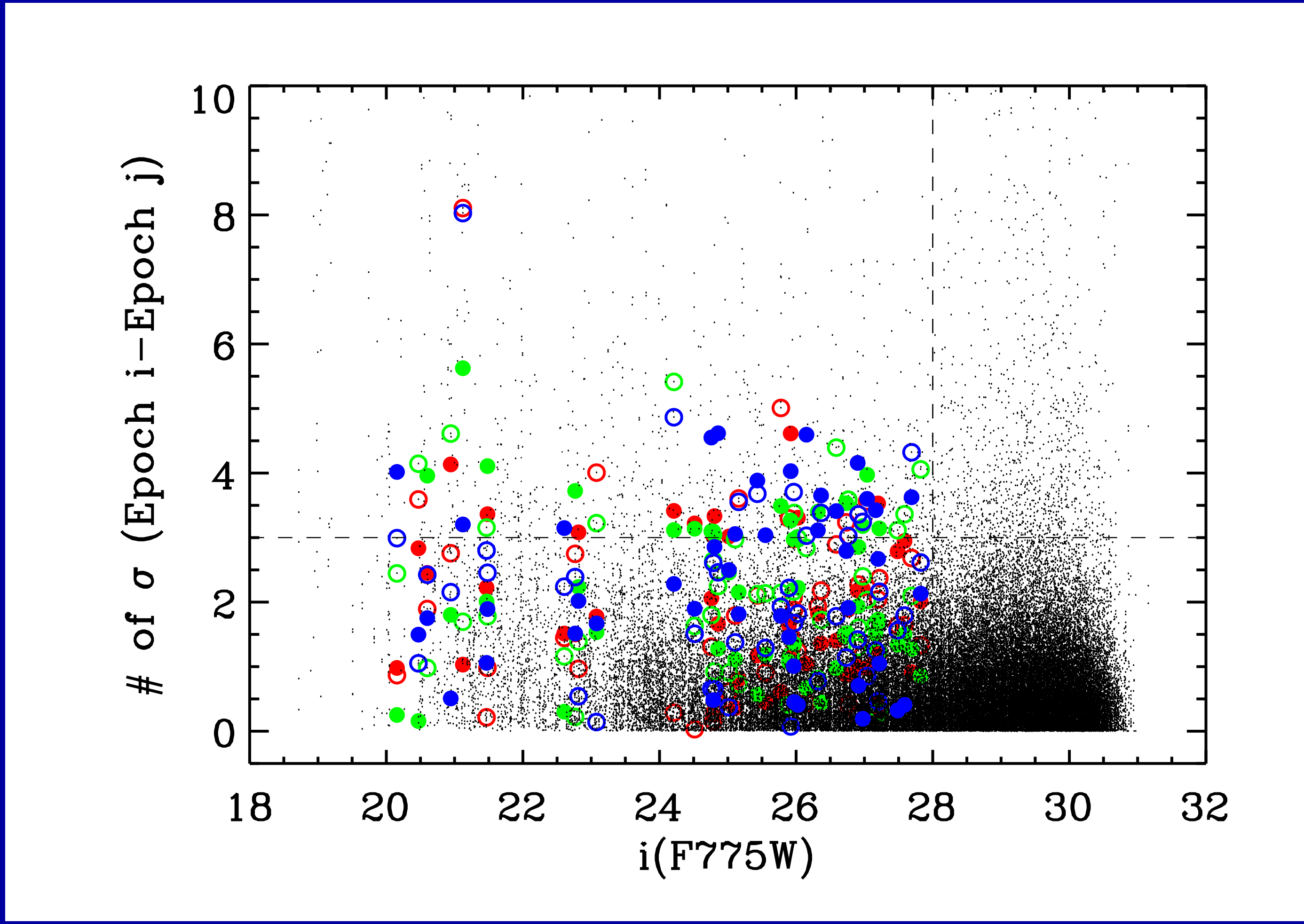
- Among UDF objects studied to i_{AB} =28.0 mag ($\gtrsim$10σ), expect $\lesssim$13 bogus detections if the noise were purely Gaussian.
The noise is not entirely Gaussian, although the UDF is as close as it gets.

- ∼45 contain believable variable point sources at $\gtrsim$3.0σ, most of which seen at $\gtrsim$2 epochs. Another 57 possibly variable candidates.



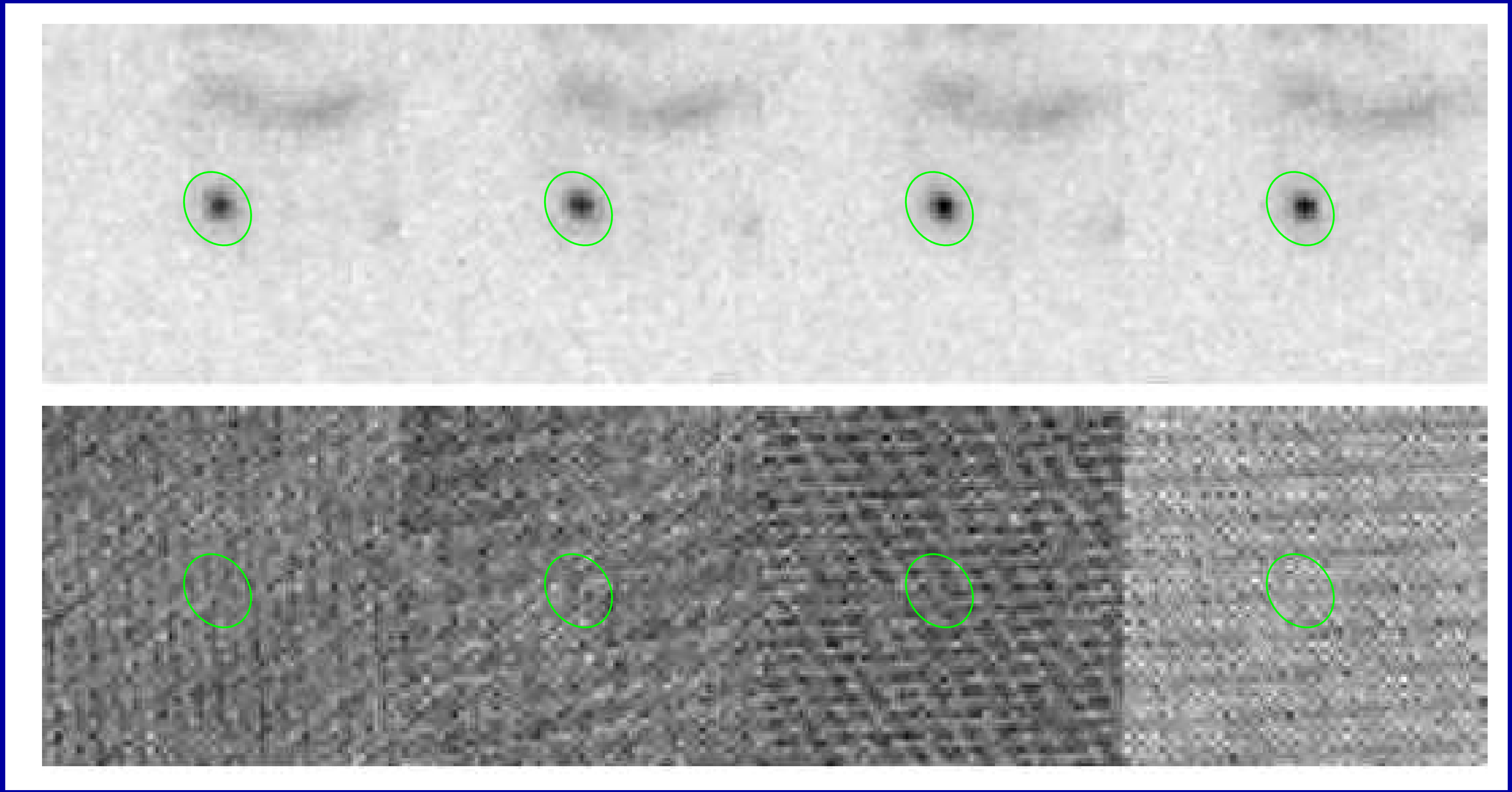
Magnitude difference of all objects between two UDF epochs plotted against their total i-band magnitude. Lines are at $\pm 1.0\sigma$ (blue), $\pm 3.0\sigma$, $\pm 5.0\sigma$.

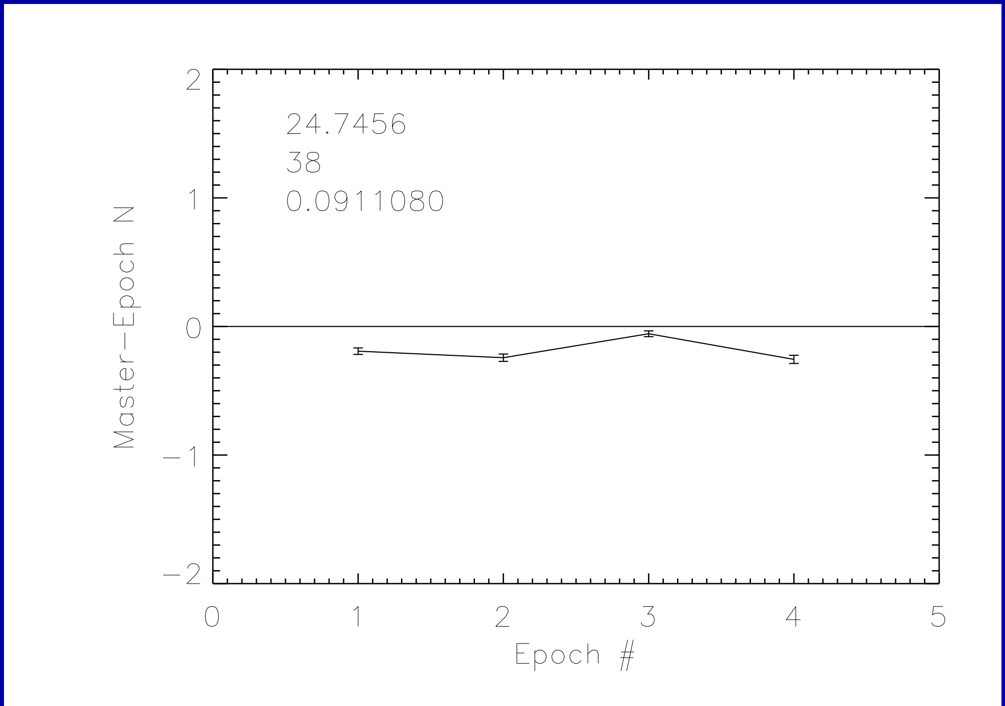
- All objects with $|\text{Delta mag}| \geq 3.0\sigma$ were inspected for plausible variability. This will yield $\lesssim$13 bogus detections if the noise were purely Gaussian.



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

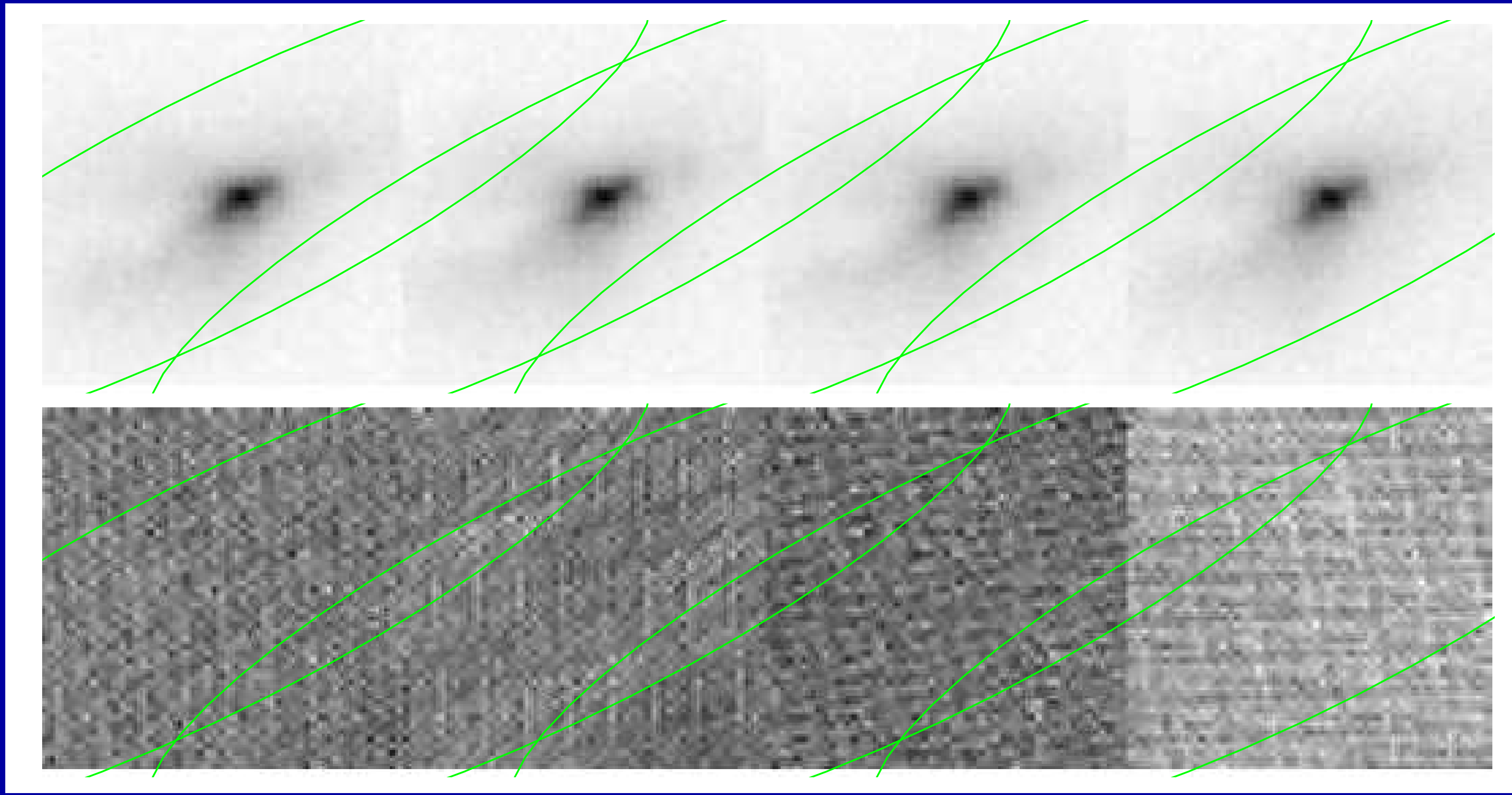
- 6 out of 16 Chandra sources are faint point-like variable objects at $\gtrsim 3.0\boldsymbol{\sigma}$. Other 10 Chandra sources are mostly brighter (early-type) galaxies, one is $\gtrsim 3.0\boldsymbol{\sigma}$ variable $\Rightarrow$ Variable point sources are valid AGN candidates.
- We only sample $\boldsymbol{\Delta}$Flux $\gtrsim$10%—30% on timescales of months. The AGN sample is not complete — we miss all non-variable and the obscured AGN.

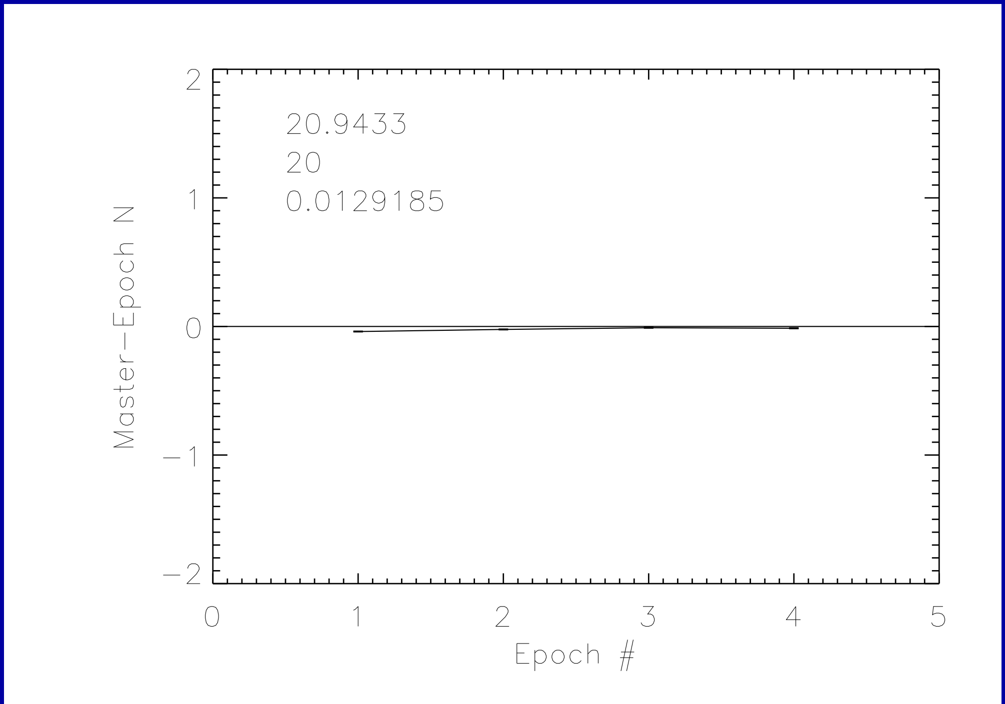




i'-Var Cand # 38 (z=1.122):

AGN

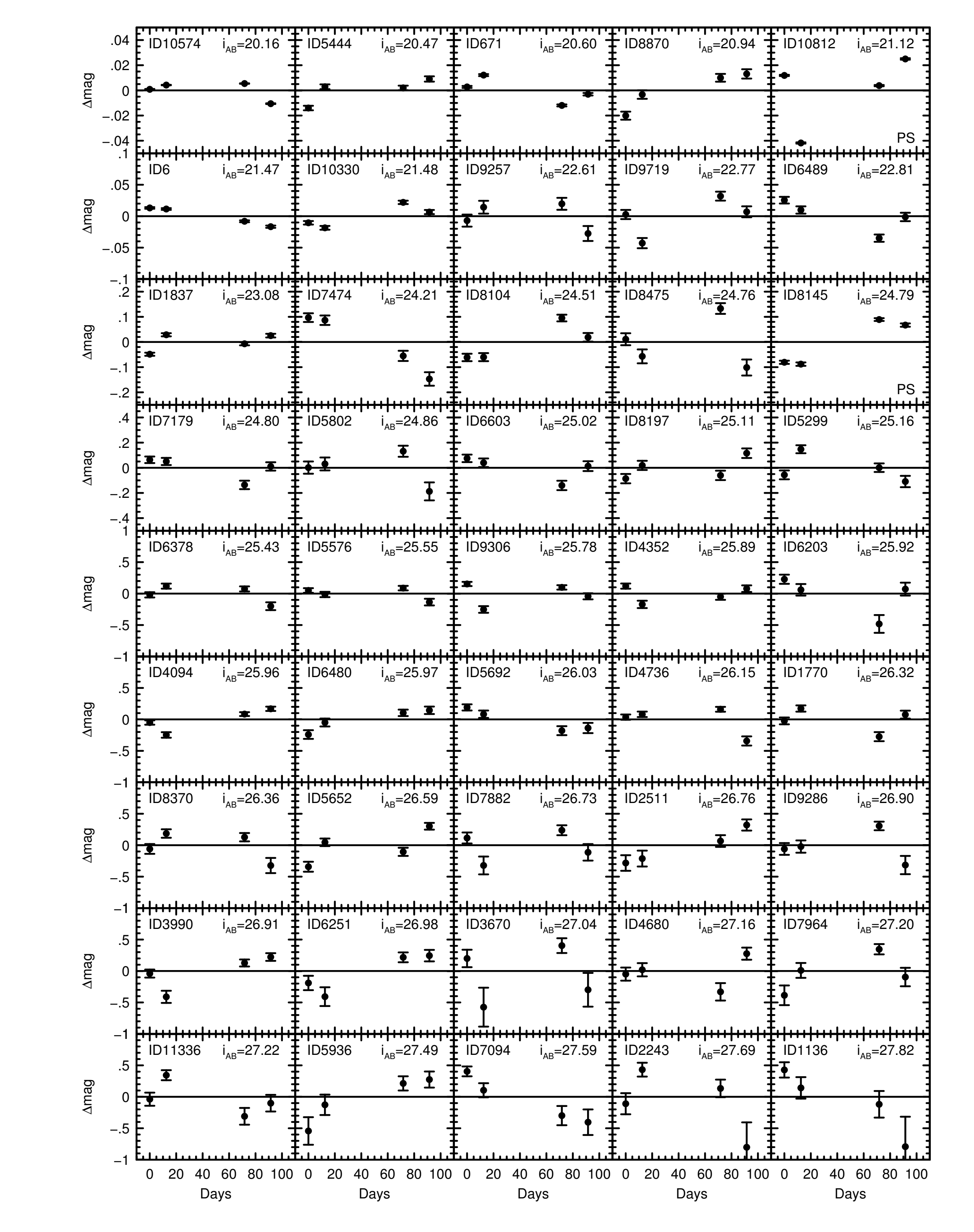




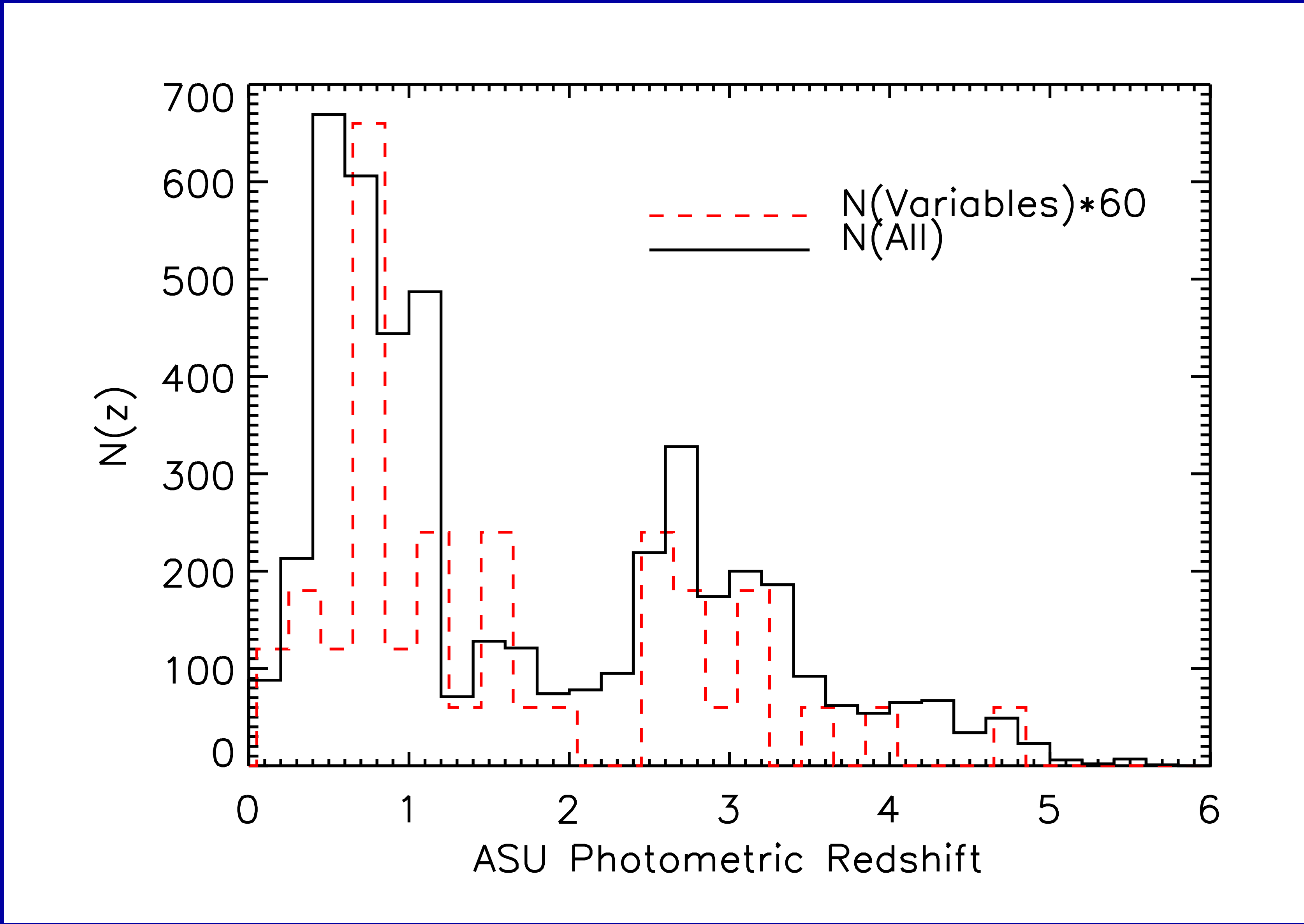
i'-Var Cand # 20 (z=0.906):

Weak AGN

also faint Chandra source! (Koekemoer et al. 2004)



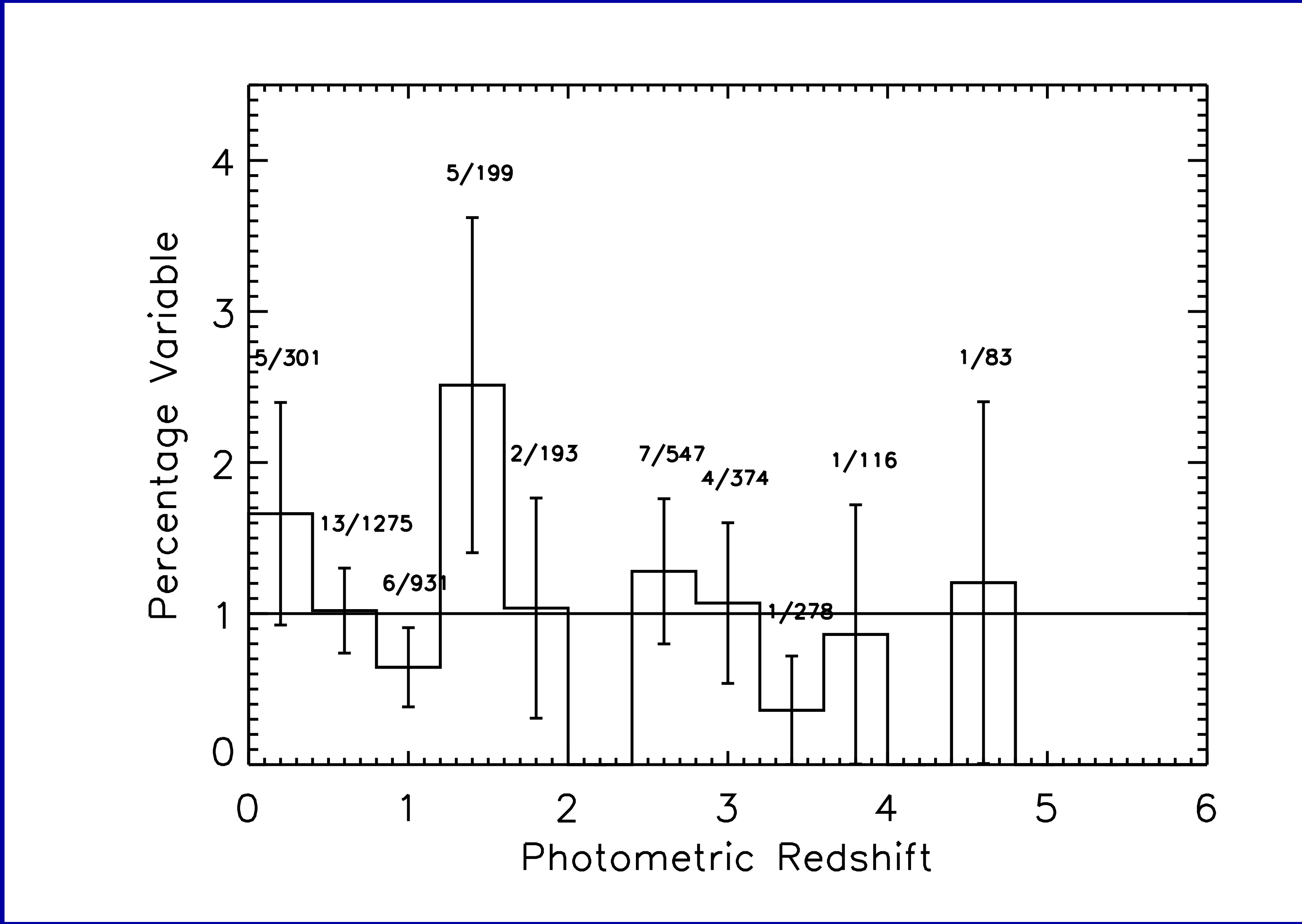
- Light curves: Can detect bright HUDF variables if Δmag$\lesssim$1–2% !



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

Full drawn: All UDF field galaxies.

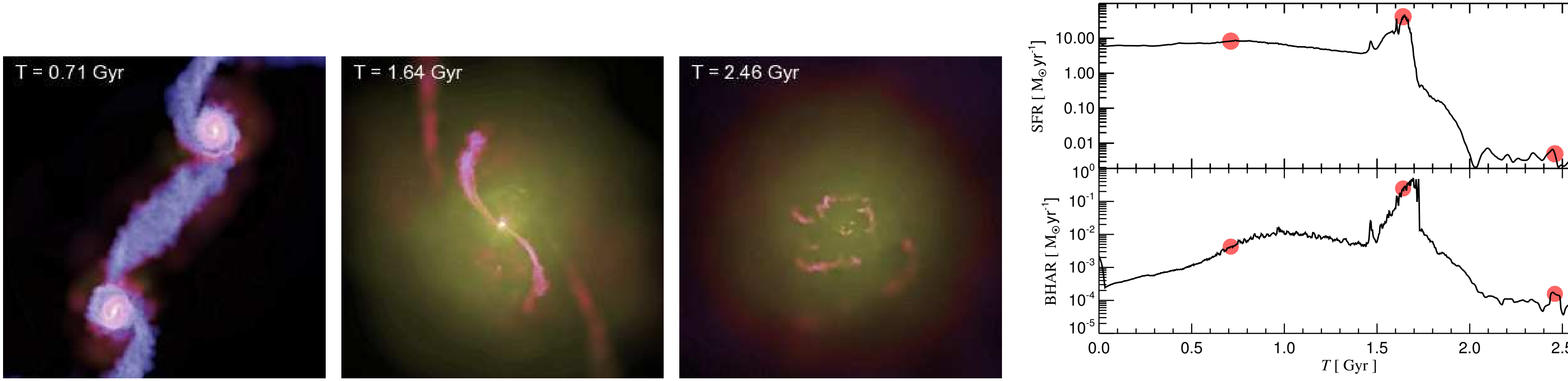
Dashed: UDF variable objects (×60 for comparison with field galaxies).



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

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

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



• [LEFT] Simulated merger of two disk galaxies at three different stages, including the effects of black hole growth and AGN feedback by Springel et al. (2004). The images show the gas distribution in the two disks at three different times, with color encoding temperature, while brightness measures gas density.

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

• Overlap between Tadpoles and Variables is very small — 1 object! $\Longleftrightarrow$ In hydrodynamical simulations, the object resembles a tadpole galaxy ~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 tadpole stage.

(4) Summary and Conclusions

- Tadpole galaxies make up about 6% of the total UDF 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.

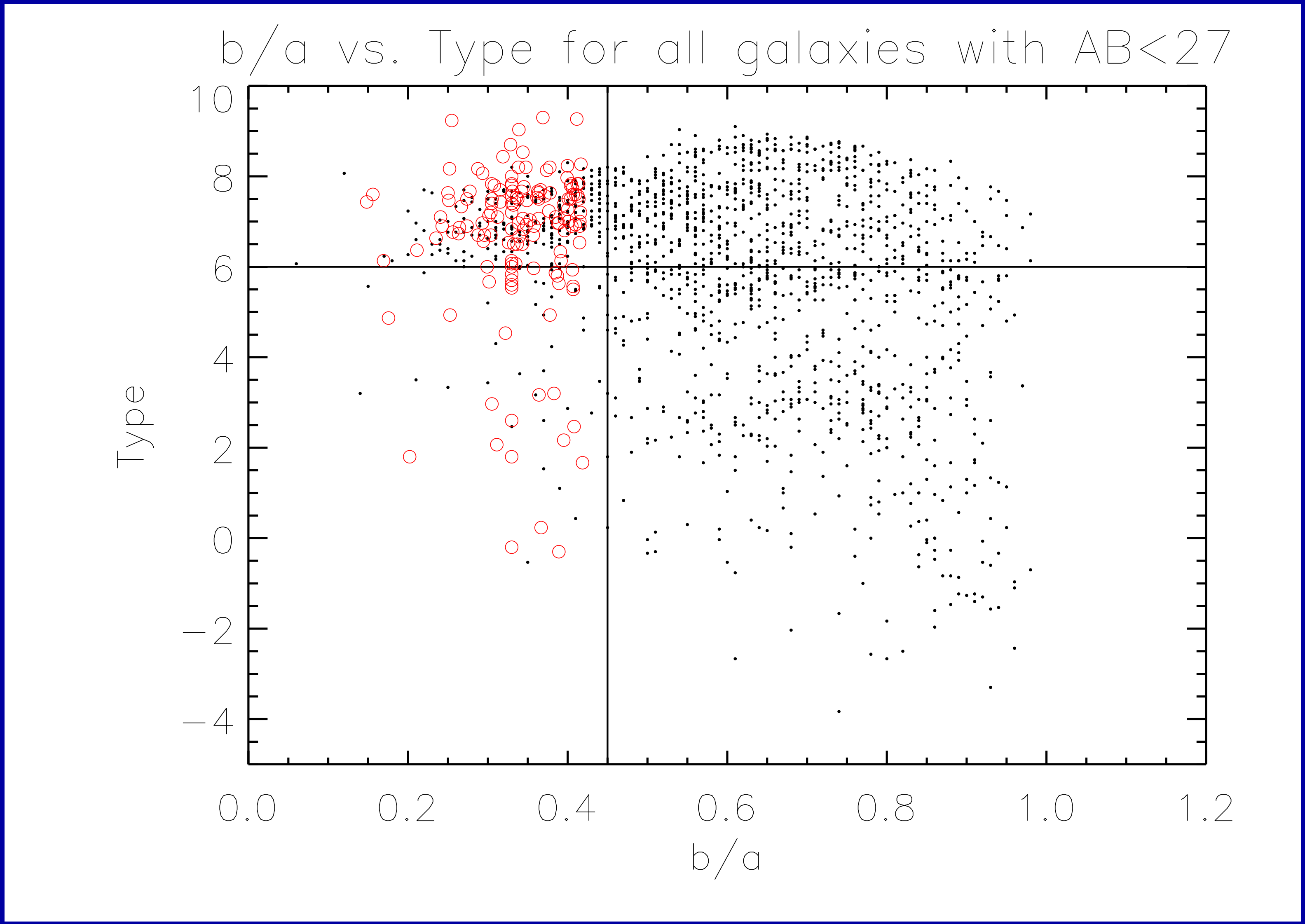
- Variable objects make up $\sim$1% of the total UDF galaxy sample. Weak variable AGN comprise likely $\gtrsim$3–6% of total UDF galaxy sample, when accounting for the missed long-period variable and obscured AGN.

- Variable objects have a redshift distribution similar to that of UDF field galaxies $\Longleftrightarrow$ They may trace the process of black hole growth.

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

$\Longrightarrow$ AGN GROWTH STAYS $\sim$IN PACE WITH GALAXY ASSEMBLY.

SPARE CHARTS

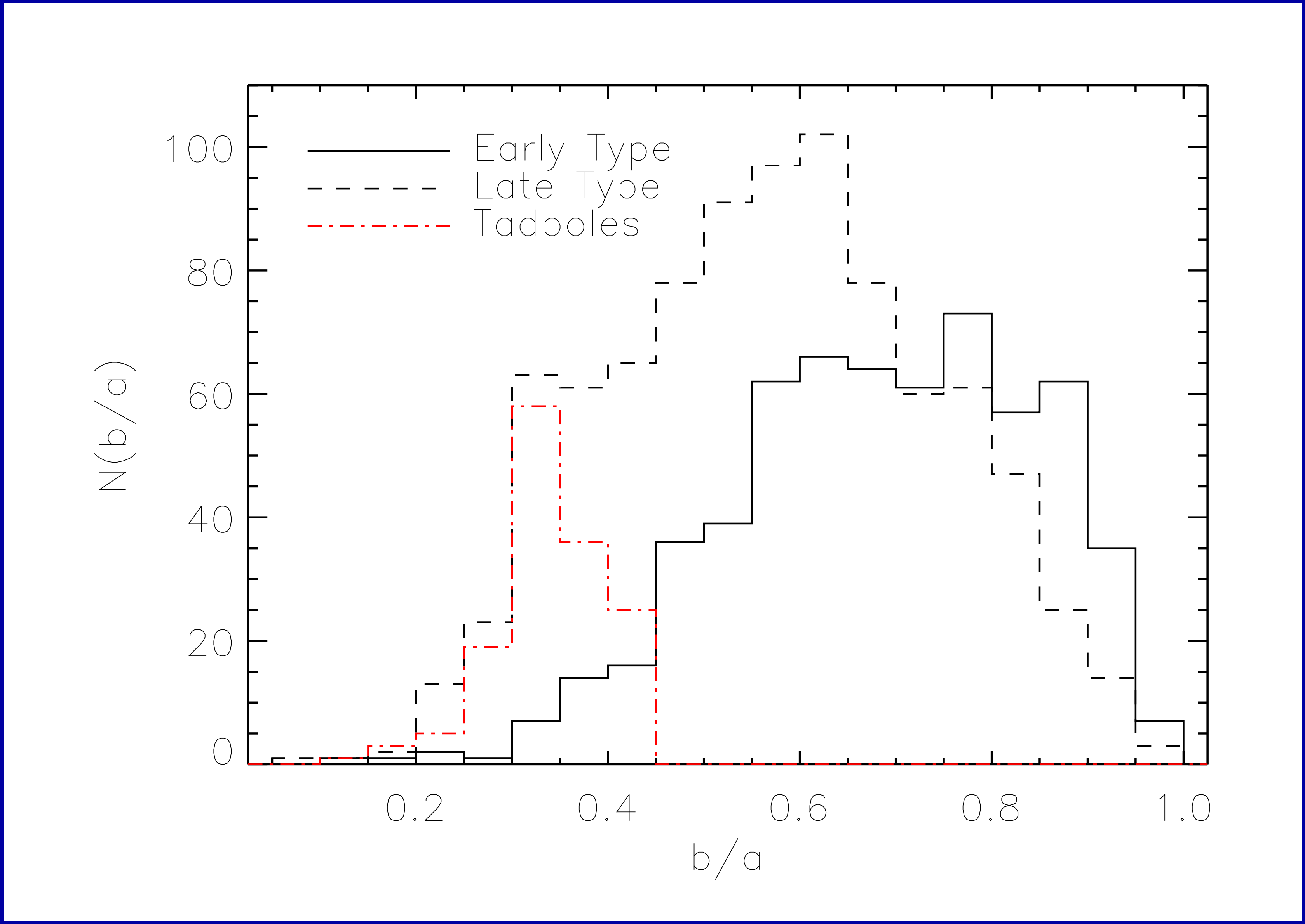


Ellipticity vs. rest-frame UDF Type to i_{AB} =27 mag:

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

$\Rightarrow$ $\exists$ likely an excess of truly linear structures among flat late-type objects.

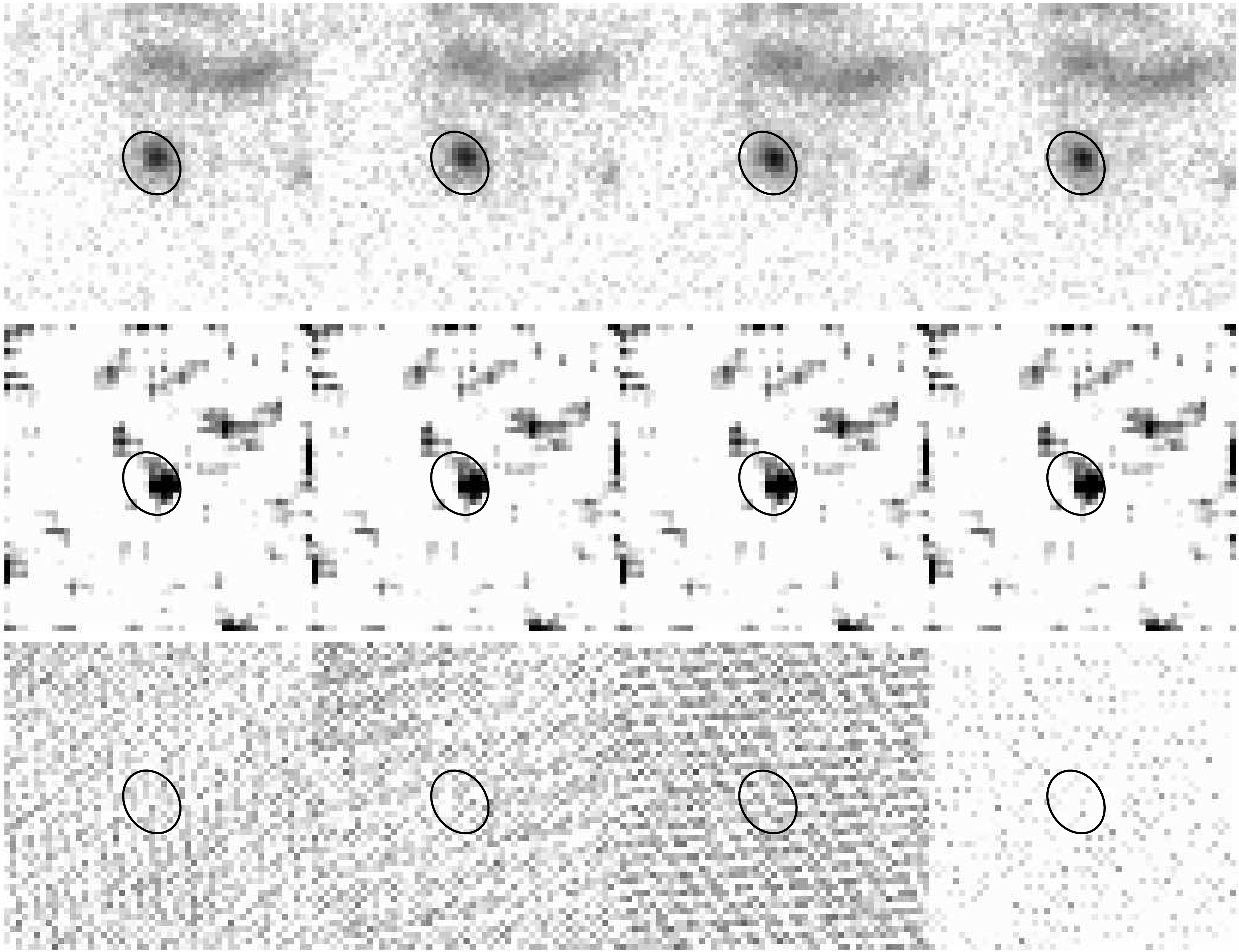
$\Rightarrow$ Not all tadpoles are edge-on late-type disks.



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.



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

(4) Implications for JWST Requirements

- For studying "Madau diagram" of black-hole growth, JWST must be able to measure faint-source IR-variability on timescales of months–years.

- Critical to be able to measure JWST fluxes with a relative accuracy of $\lesssim$2% on timescales of months–years (BRIGHTEST believable variable source in UDF has 1 μmvariability of a few %).

- Relative PSF effects on total JWST fluxes should therefore be kept to $\lesssim$2% on timescales of months–years (months necessary, years preferable). [this relates to the ability to do relative, not absolute photometry].

- For optimal and unbiased search of tadpoles at all PA's (and other similar dynamically young objects), the FWHM of the JWST PSF needs to be kept round to within a few % in b/a.

(5) 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.

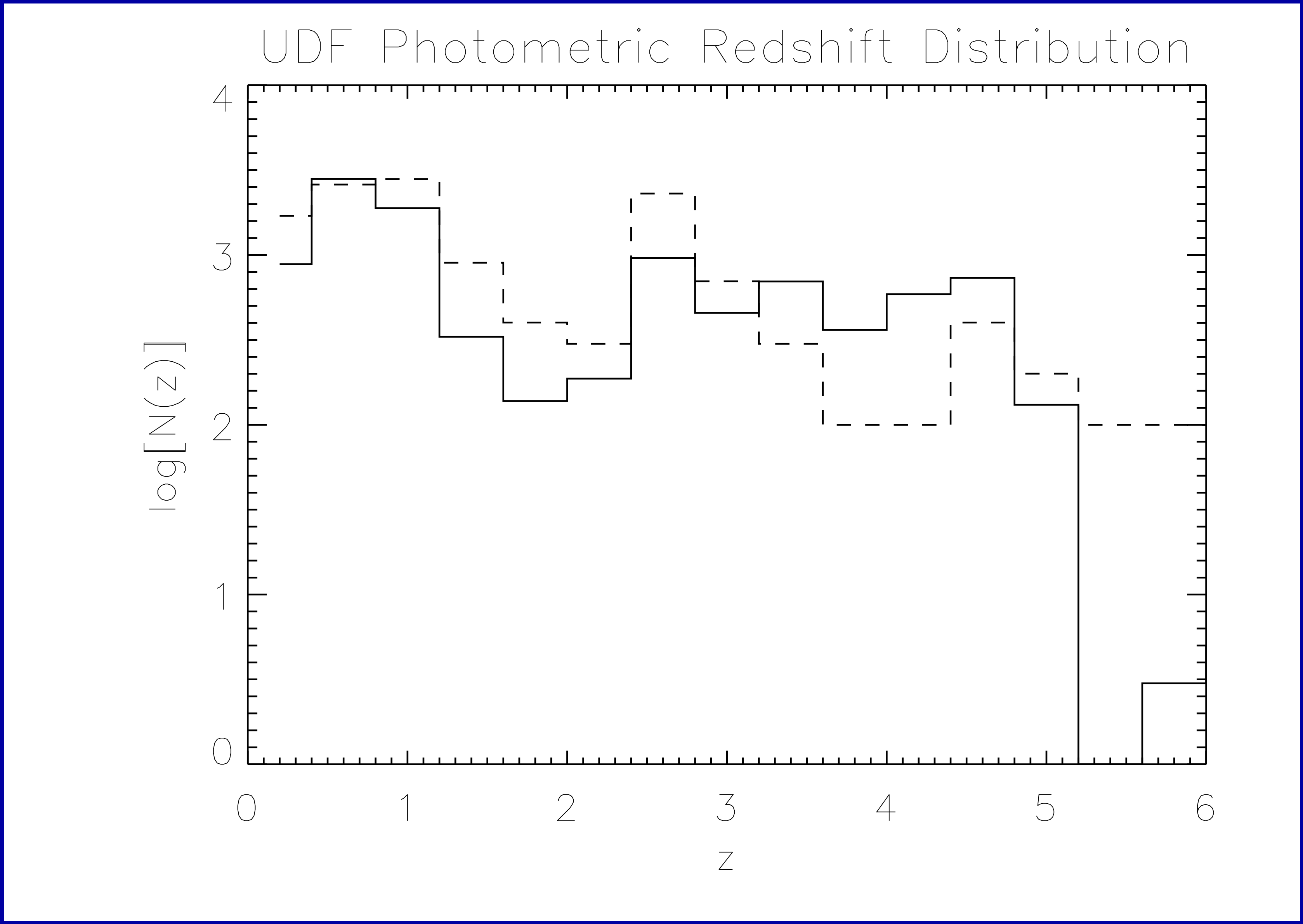
- Test all variable candidates for stellarity $\Rightarrow$ Likely AGN.

- 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).

Other UDF Tadpole galaxies selected by eye, visually obeying the same criteria as the IDL script intended to find, but not found by the script.



Logarithmic redshift distribution of galaxies in the UDF.

Full drawn: all UDF field galaxies.

Dashed: UDF tadpole galaxies ($\times 80$ for comparison with field galaxies).

(3) Conclusions from Tadpole Galaxies in the UDF

Compared to the general SFH of UDF field galaxies, tadpole galaxies may have had maximum SF activity at z$\simeq$1.8 (*i.e.*, peak in Madau diagram).

- Is this the epoch of maximum merging in progress, before the effects from $\mathbf{\Lambda}$ kick in?

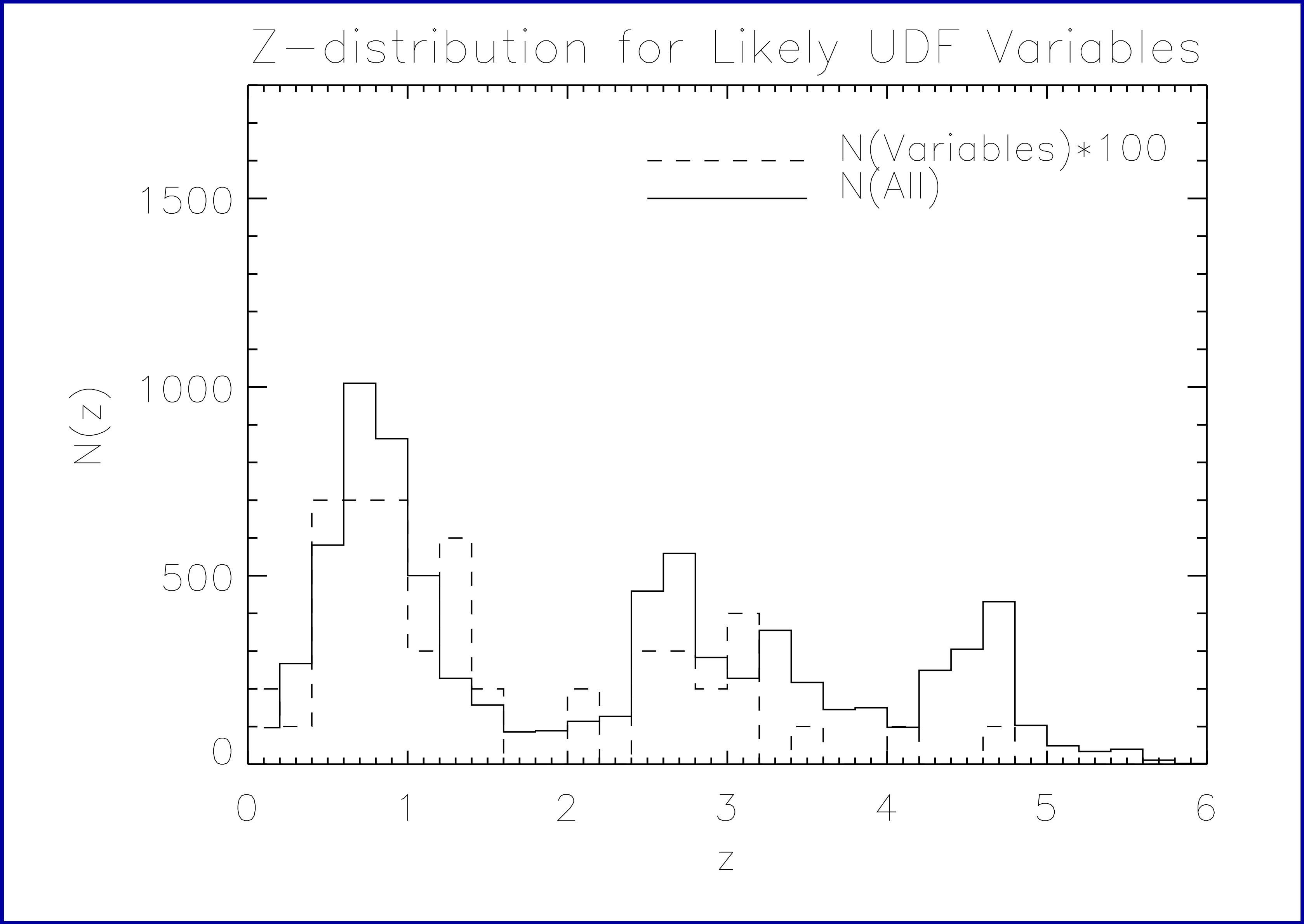
- Was $\mathbf{\Lambda}$ itself responsible for dramatically winding down the epoch dependent merger rate at z$\lesssim$0.5–1?

Caveat: $(1{+}z)^4$ SB-dimming will prevent selecting tadpole galaxies to very high z ($\gtrsim$4–5), hence biasing their N(z).

Counter: This is true — perhaps even more so — for regular field galaxies, since most are fully resolved. (Some tadpoles are unresolved in one direction, resulting in $\sim(1{+}z)^3$-dimming). Most tadpoles are also fully 2-dim resolved, however, hence comparing their N(z) is fair.

Summary of UDF 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	
Total exposure time (s)	134880	135320	347110	346620	



BVizJH Photo-z distribution of variable objects in the UDF.

Full drawn: all UDF field galaxies.

Dashed: UDF variable objects (×100 for comparison with field galaxies).

(4) A Study of Variable Objects in the UDF

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

- These are likely a combination of weak AGN and a few SNe in distant galaxies (see Strolger & Riess et al. 2004), and PERHAPS some novae and/or Long Period Variables in very nearby galaxies (if z$\lesssim$0.03).

- The real fraction of AGN in the UDF that is variable on timescales of months is likely $\lesssim$2%, constraining the frequency of weak AGN activity and the fraction of hidden AGN.

- The variable-object N(z) follows that of all UDF 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 $\lesssim$1–2% of all UDF galaxies may be AGN. In AGN unification picture, $\lesssim$1/3 of these are seen as "face–on", consistent with the $\lesssim$1% UDF variable AGN fraction (*IF* most weak AGN variable on months time-scales; but see Psaltis et al.).

(4) Variable Objects in the UDF

The Likely Variable Objects

These 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 (if $z \lesssim 0.03$)??

(4) Faint high proper motion objects (KBO's, etc).

(5) UVO's ("Unidentified but Variable Objects").