"GiGa": the Billion Galaxy HI Survey —
Tracing Galaxy Assembly from Reionization to the Present

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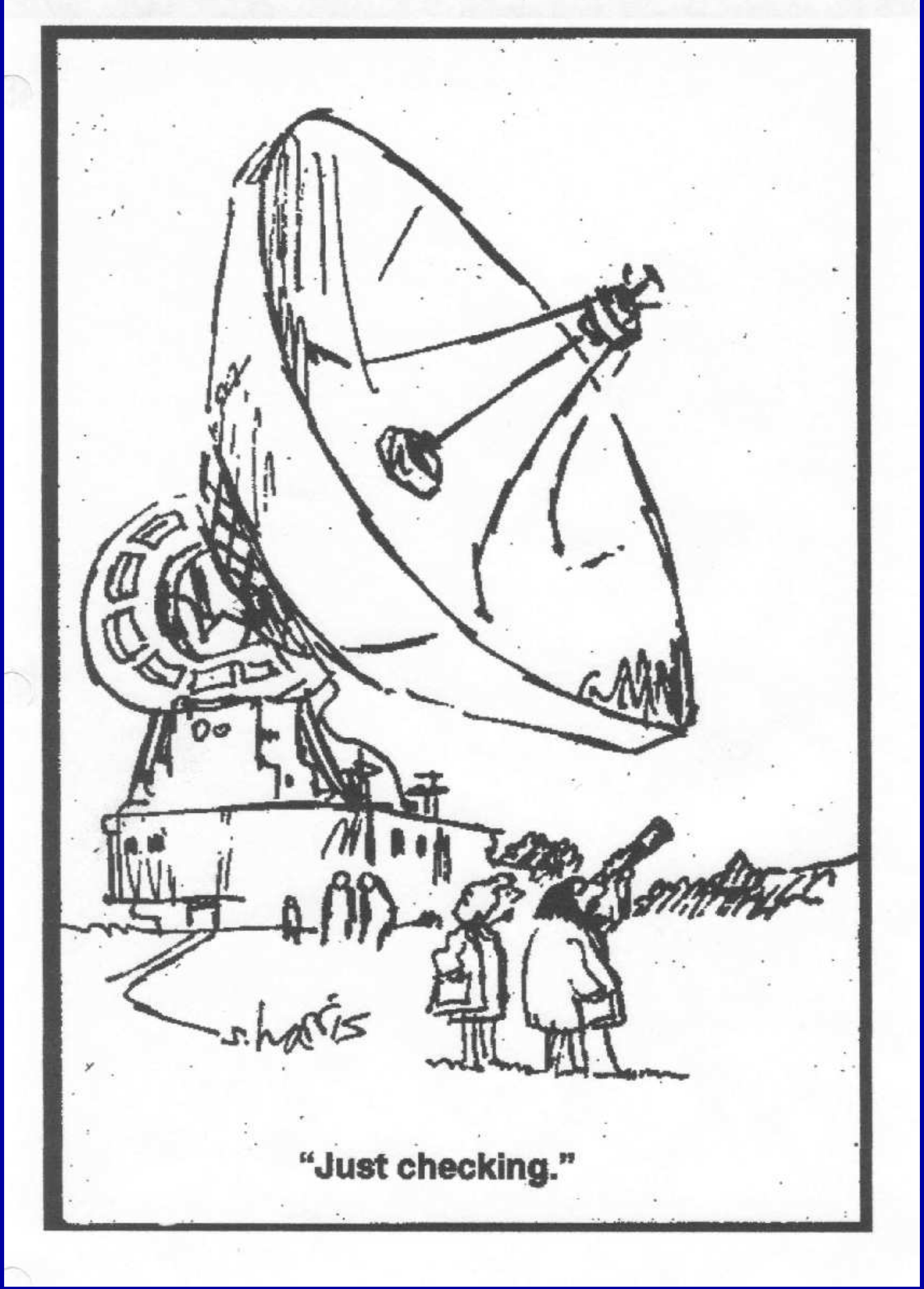


Radio community must: 1) Unify behind current & future radio facilities.
2) Define essential synergy with other future facilities.

WHAT ARE CRITICAL SCIENCE DRIVERS FOR RADIO TELESCOPES OF THE NEXT DECADE?

A) HIERARCHICAL GALAXY FORMATION & GALAXY ASSEMBLY:

• How do HI clouds at z$\gtrsim$6 transform into the giant spirals and ellipticals seen today?

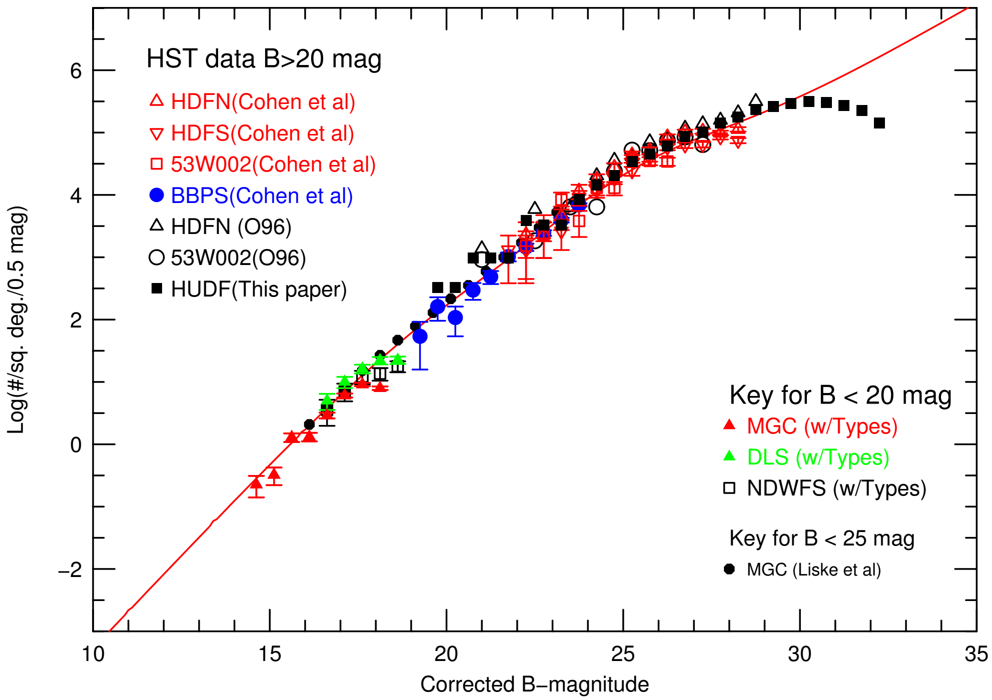
• How and why did the (dwarf dominated!) galaxy luminosity function and mass function evolve with epoch?

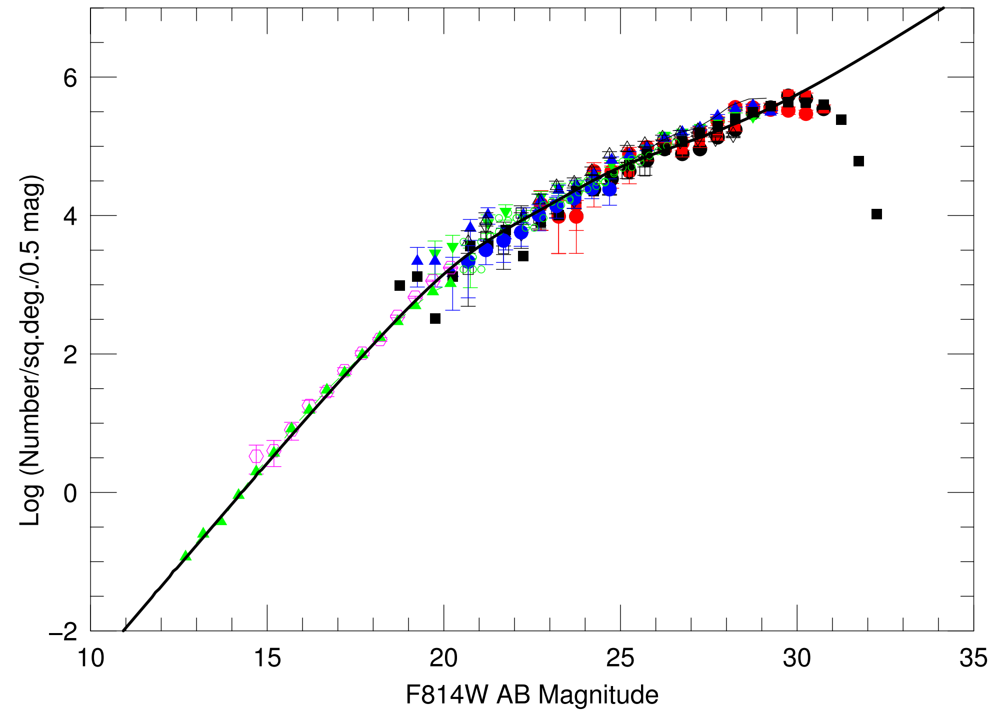
• (How) did feedback from SNe (Type Ia; Type II; Pop III?) shape the faint-end slope-evolution of the dwarf galaxy LF from z$\gtrsim$6 to z=0?

B) THE GALAXY FORMATION–AGN PARADIGM:

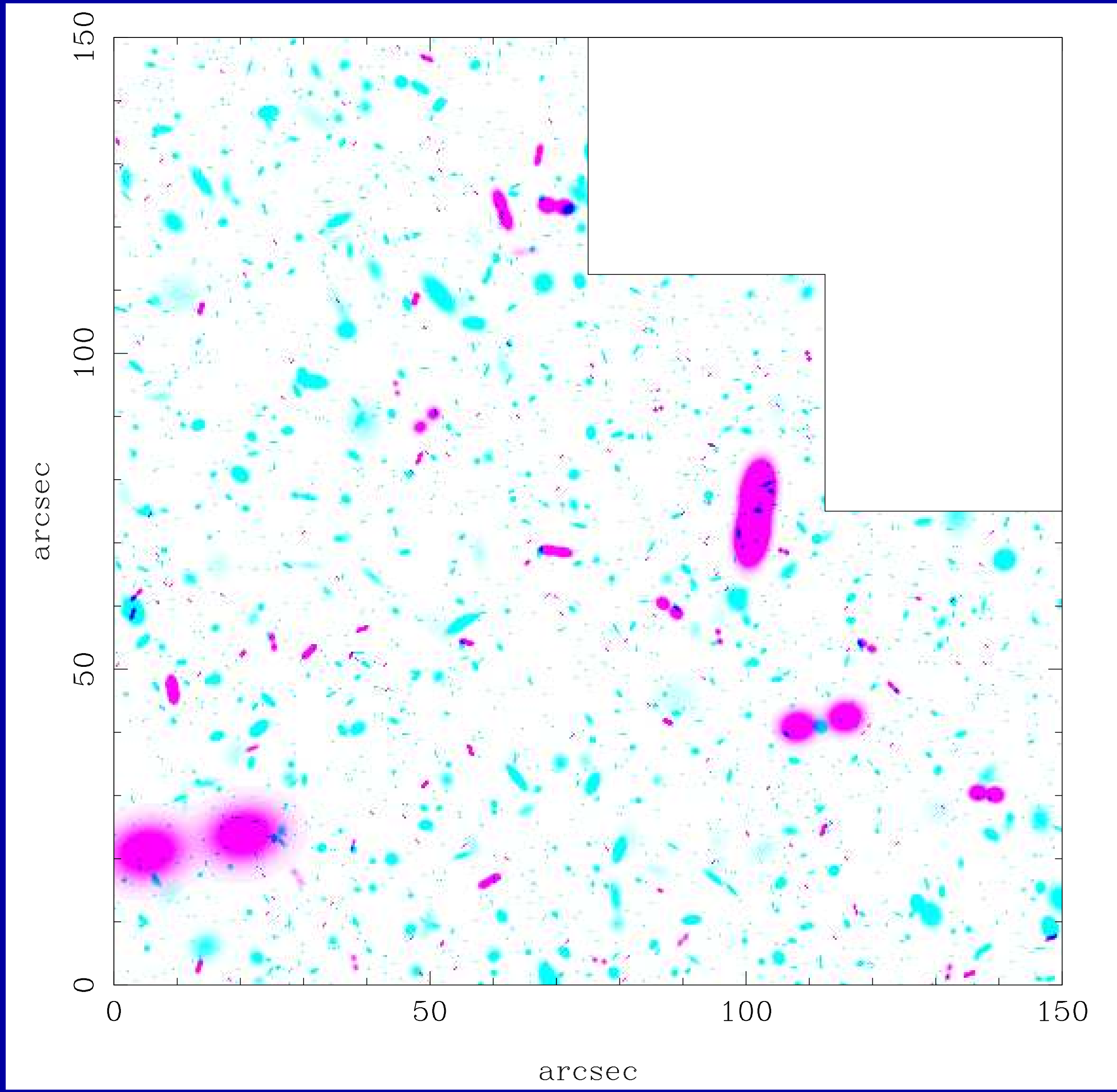
• How did supermassive black hole growth keep up with galaxy assembly?

• How did AGN feedback control the bright-end evolution of the galaxy LF from z$\gtrsim$6 to z=0?



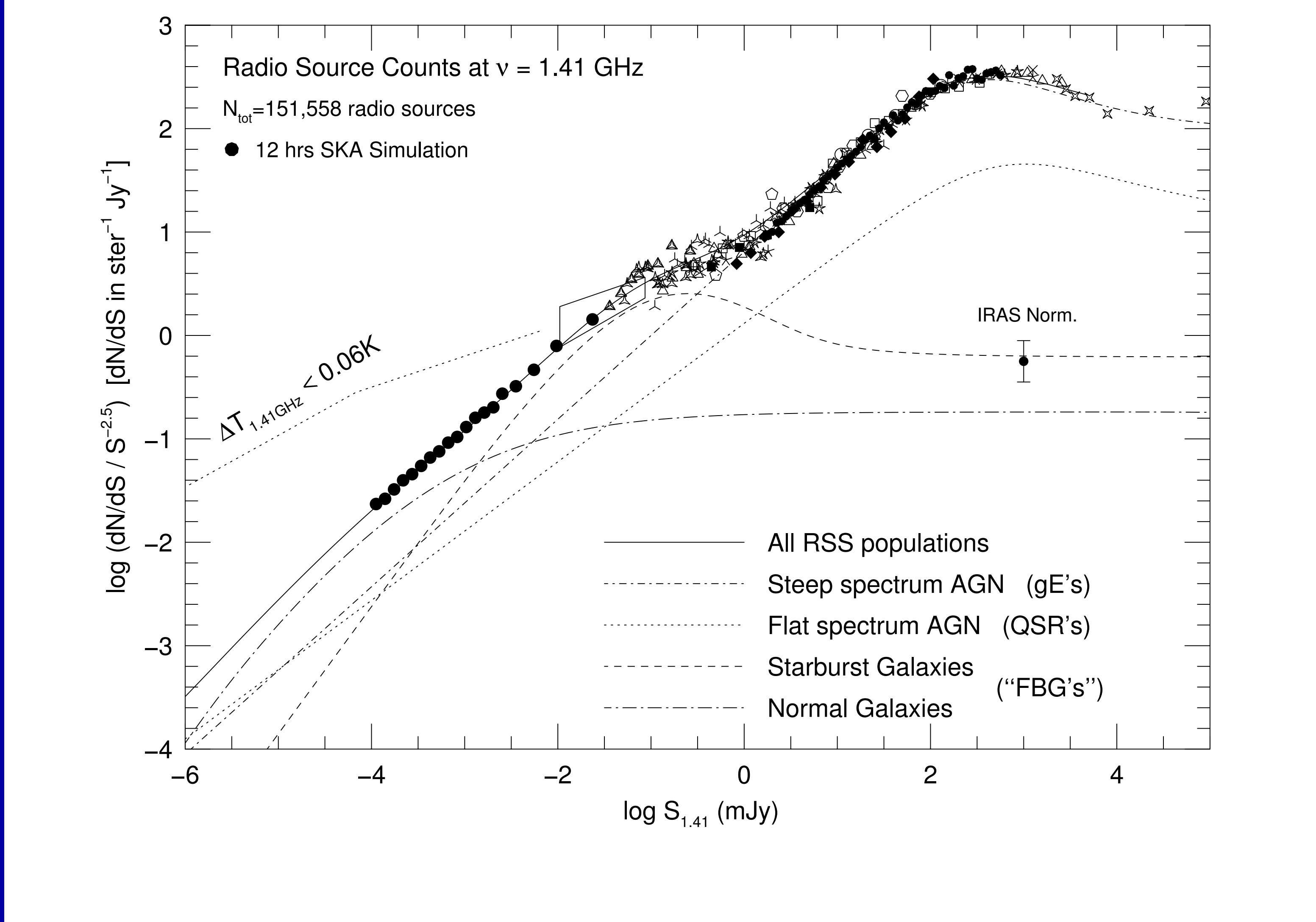


- One "Giga" Galaxy: How to survey a billion galaxies with SKA?
- HUDF galaxy counts (Cohen et al. 2006): expect $\gtrsim 2\times10^{6}$ galaxies/deg^{2} to AB=31.5 mag ($\simeq$ 1 nJy at $\lambda\simeq1\mu$m) $\Rightarrow$ Must survey $\sim10^{3}$ deg^{2}.
- SKA sees similar densities to $S_{1.4}\simeq$1–10 nJy $\Rightarrow$ 1 object/$2\farcs5\times2\farcs5$
- $\Rightarrow$ Must carry out SKA nJy-surveys with sufficient spatial resolution to avoid object confusion: SKA-FWHM$\lesssim0\farcs3$. (For HST: FWHM$\lesssim0\farcs08$).
- $\Rightarrow$ Always obtain SKA HI line channels, so can disentangle overlapping continuum sources in redshifts space, and find all the enclosed HI.



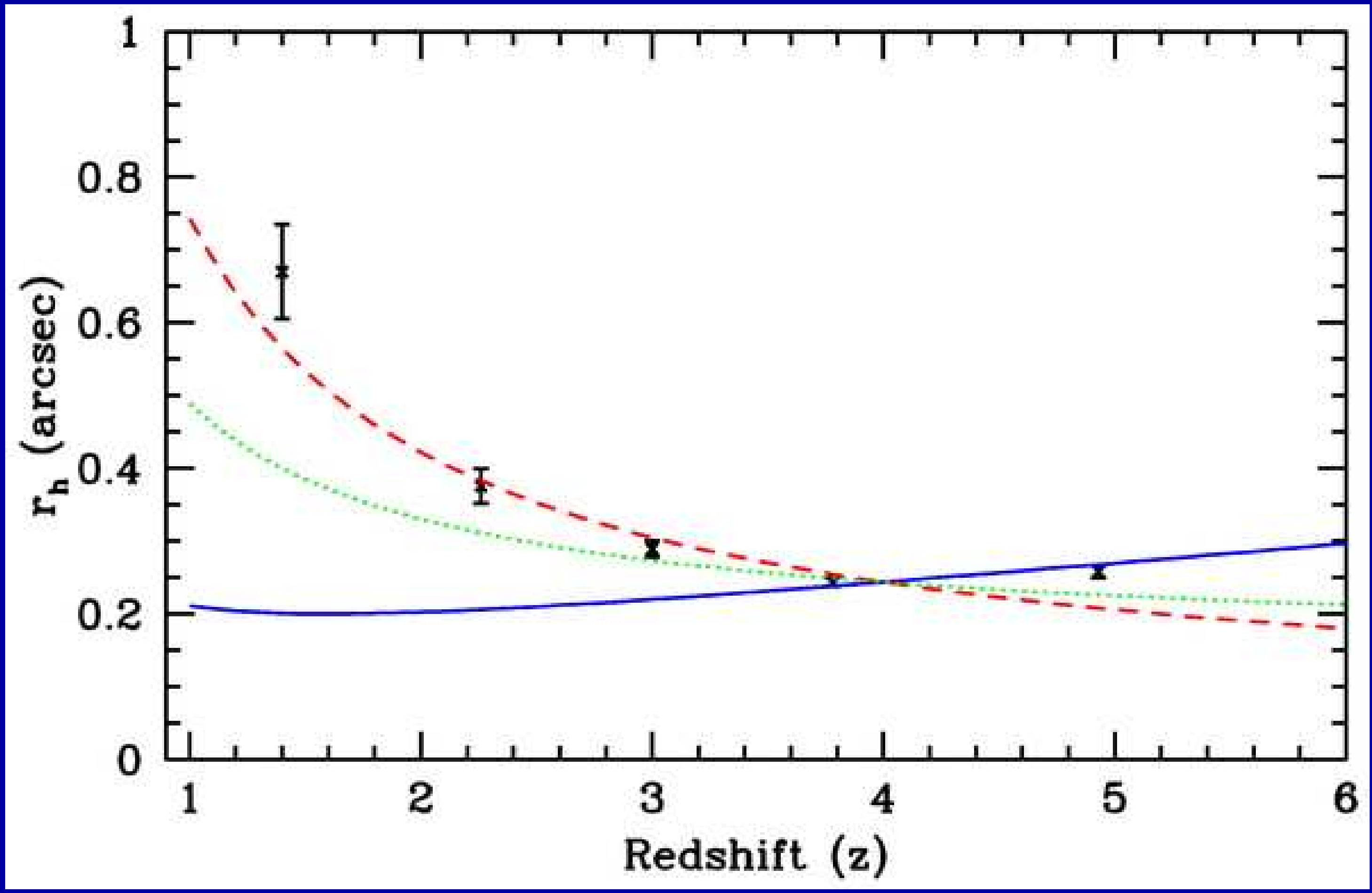
Simulated 12-hr SKA 1.4 GHz image: FWHM$\simeq$0$''\!.$1 and flux limit $\mathbf{0.1}$ $\boldsymbol{\mu}$Jy (5-$\boldsymbol{\sigma}$). Of the 1 deg$^{\mathbf{2}}$ FOV, only an HST/HDF area is shown (2$'\!.$5$\times$2$'\!.$5).

Red extended radio sources are AGN in early-type galaxies. Blue mostly point-like or disk-shaped sources reside in star-forming galaxies, which dominate the counts below 1 mJy. (Hopkins et al. 2000).



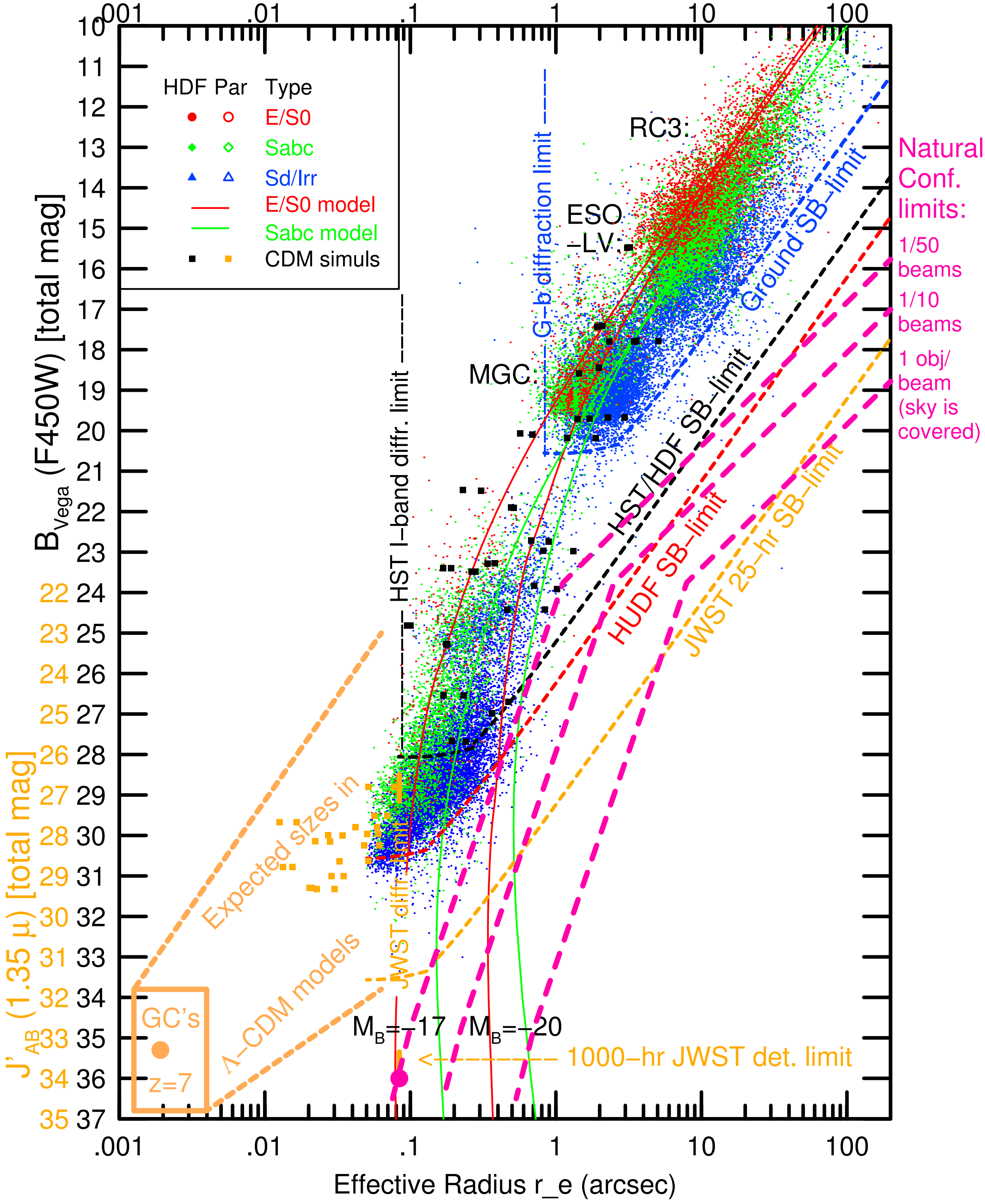
Normalized differential 1.41 GHz source counts (Windhorst et al. 1993, 2003; Hopkins et al. 2000) from 100 Jy down to 100 nJy. Filled circles below 10μJy show the 12-hr SKA simulation of Hopkins et al. (2006).

Models: giant ellipticals (dot-dash) and quasars dominate the counts to 1 mJy, starbursts (dashed) below 1 mJy. Spirals and SB's at z$\gtrsim$0.3 (dot-long dash) to dominate the SKA counts below 100 nJy (slope $\gamma\simeq$1.5–1.8).

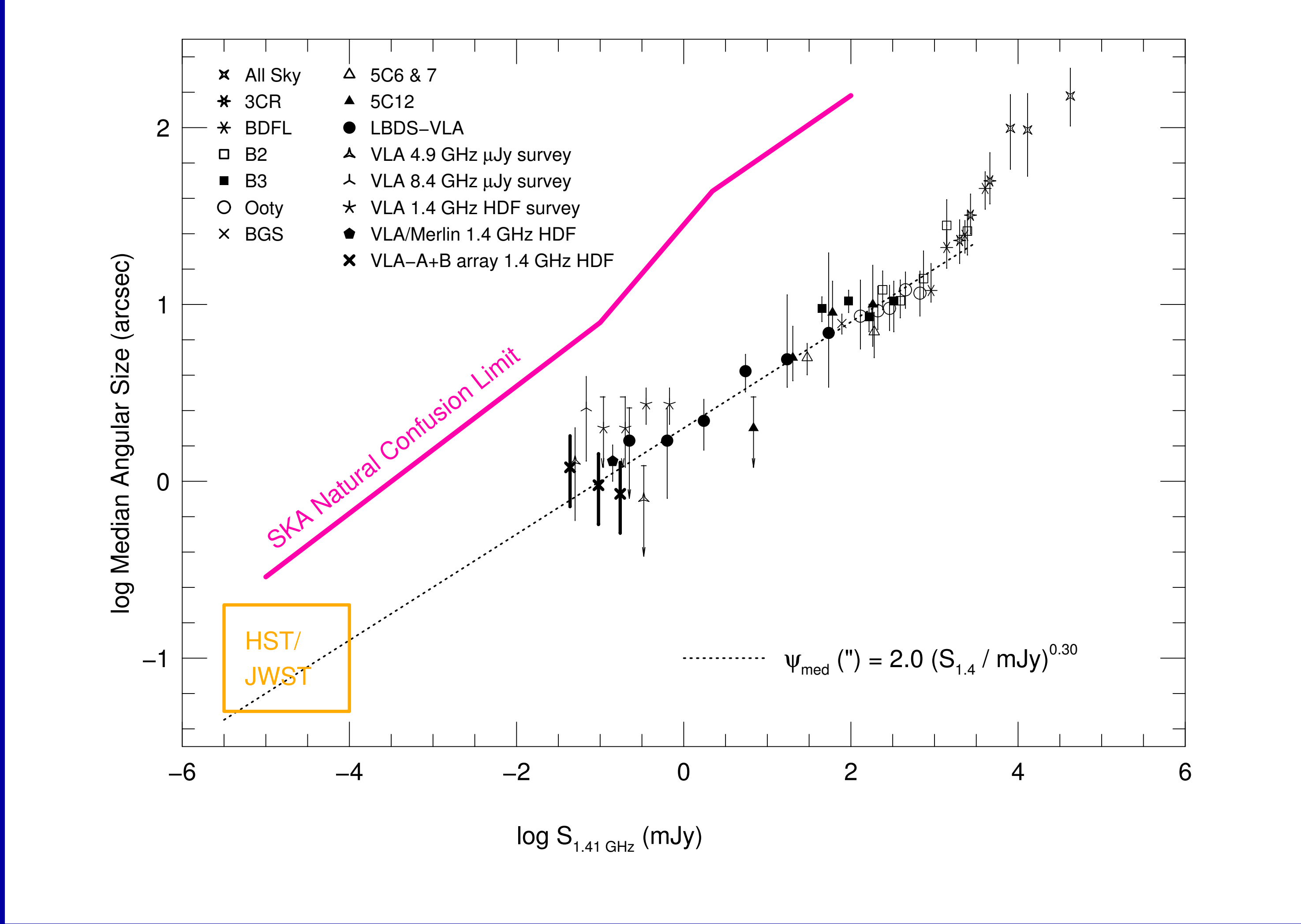


HST GOODS measured galaxy size evolution (Ferguson et al. 2004 ApJL):

- Median galaxy sizes decline steadily at higher redshifts, despite the cosmological Θ–z relation that minimizes at z$\simeq$1.6 in ΛCDM-cosmology.
- Evidence of intrinsic size evolution: $r_{hl}(z) \propto r_{hl}(0)\ .\ (1{+}z)^{-s}$, $s \simeq 1$.
- Caused by hierarchical formation of galaxies, leading to intrinsically smaller galaxies at higher redshifts, where fewer mergers have occurred.
- SKA must anticipate the small $\lesssim 0\overset{''}{.}3$ radio sizes of faint SF-galaxies.



HDF Par Type
E/S0
Sabc
Sd/Irr
E/S0 model
Sabc model
CDM simuls
RC3:
ESO
-LV:
MGC:
G–b diffraction limit
Ground SB–limit
HST I–band diffr. limit
HST/HDF SB–limit
HUDF SB–limit
JWST 25–hr SB–limit
JWST diff. limit
Natural
Conf.
limits:
1/50
beams
1/10
beams
1 obj/
beam
(sky is
covered)
Expected sizes in
Λ–CDM models
GC's
z=7
M_B=–17
M_B=–20
<----------- 1000–hr JWST det. limit
B_{Vega} (F450W) [total mag]
J'_{AB} (1.35 μ) [total mag]
Effective Radius r_e (arcsec)



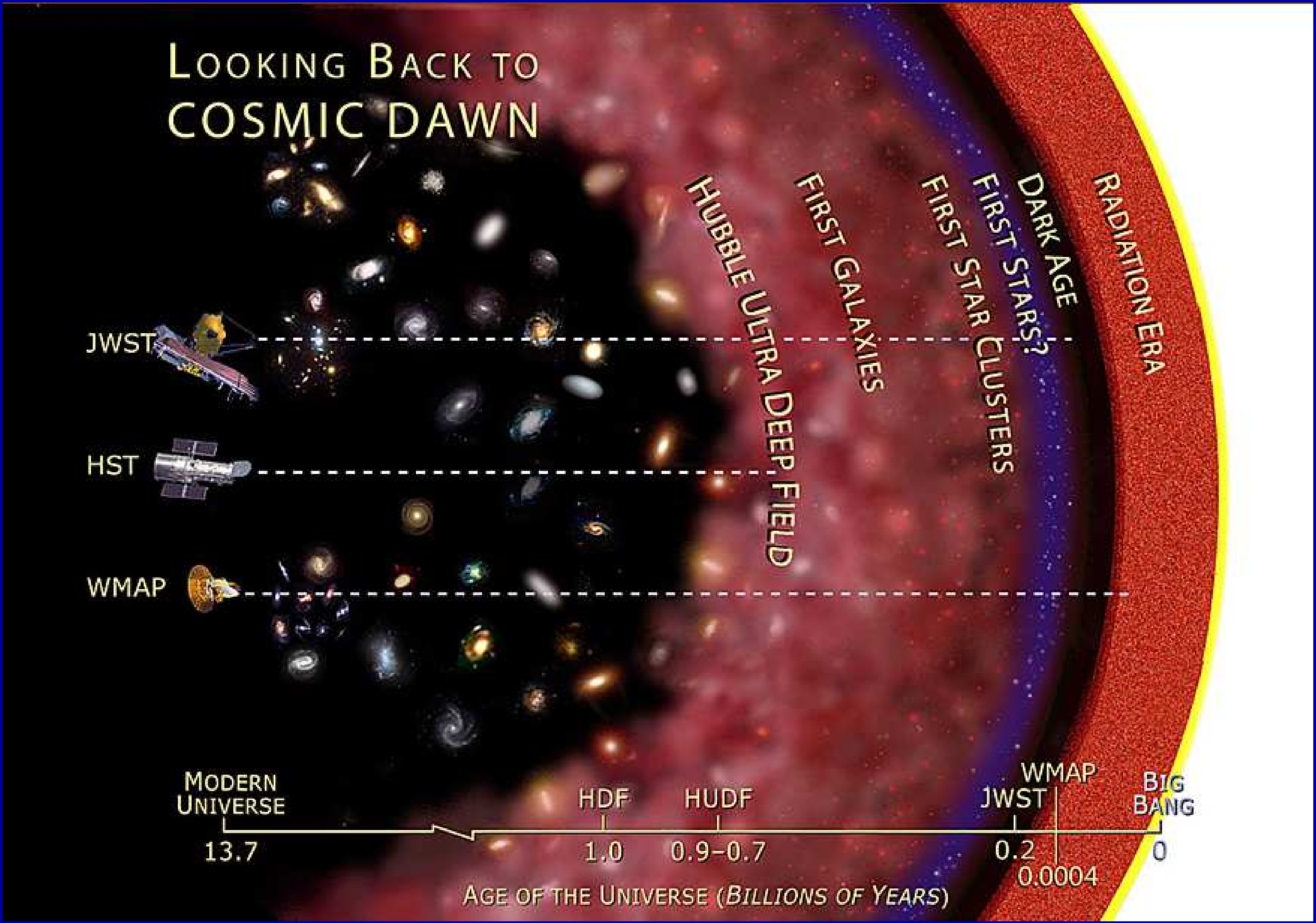
Median Θ vs. $S_{1.4}$ flux from 100 Jy to 30 μJy (Windhorst et al. 2003).

• SKA sizes at 10–100 nJy estimated from the HST N(r_{hl}) to AB=30 mag (3 nJy), reaching $\gtrsim 10^6$ objects/deg^2.

• Purple line: natural confusion limit due to intrinsic source sizes: above this sources unavoidably overlap.

SKA needs $\sim 0\farcs3$ FWHM to match the HI and radio continuum sizes.

SKA will trace HI from the EOR till today, complementing ...



NASA Telescopes penetrating Cosmic Dawn, First Light, & Recombination.

HIERARCHICAL GALAXY FORMATION AND GALAXY ASSEMBLY:

• Galaxies of various Hubble types formed over a wide range of cosmic time, but with a notable transition around redshifts 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 redshifts z$\simeq$1. These evolved mostly passively since then — their merger rate tempered by the expansion (and by Λ?) — resulting in the giant galaxies that we see today.

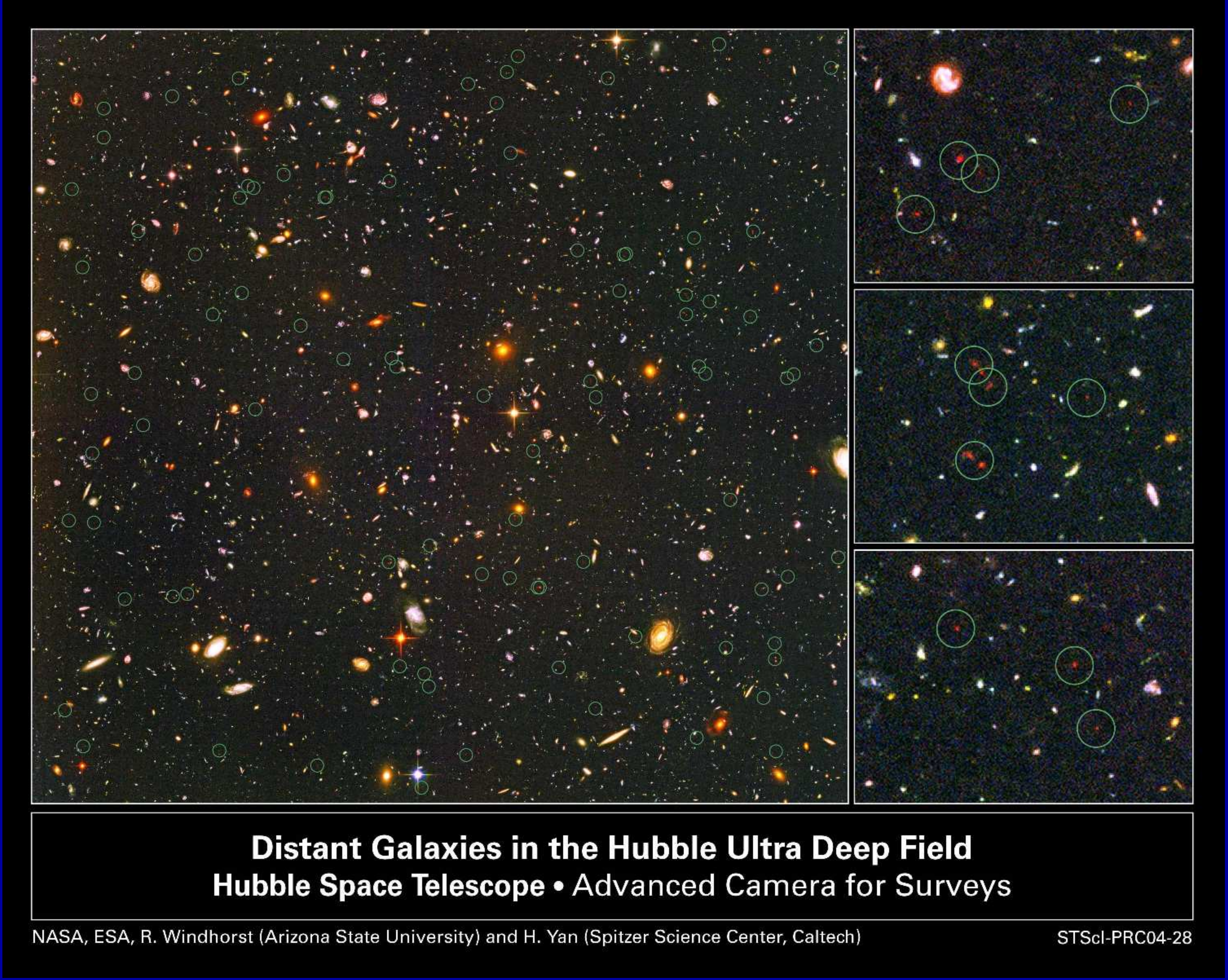
• SKA will measure how galaxies of all types assembled their HI and turned it into stars over a wide range of cosmic time: from z$\sim$6 to z$=$0.

• HI and radio continuum sizes of 10^7–10^9 $M_\odot$ starforming objects are small enough, that with $\sim$0$''\!\!.$3 FWHM resolution, SKA will:

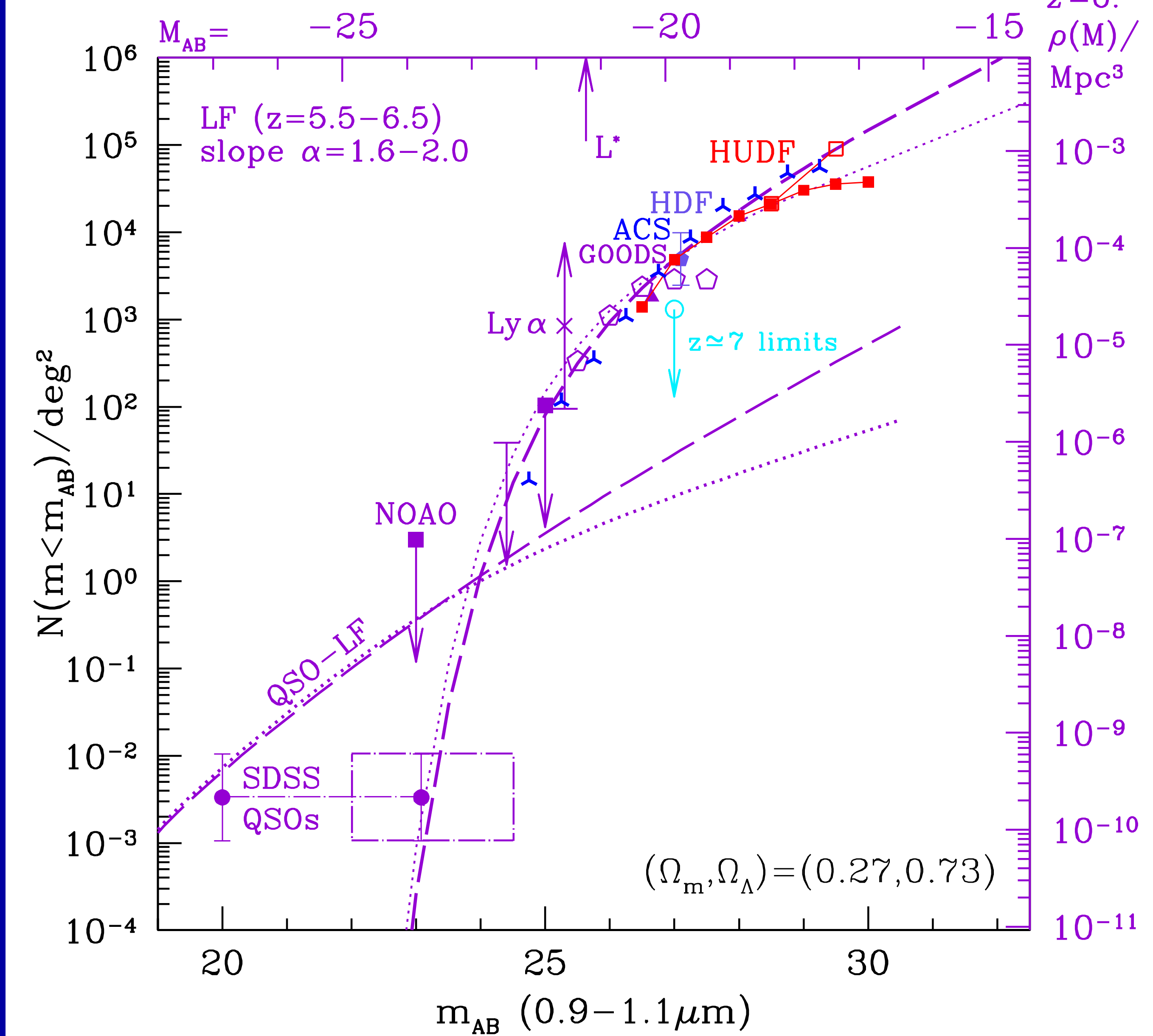
1) properly separate them from neighbors without major confusion; &

2) not resolve them, hence mitigating effects from cosmological SB-dimming.

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

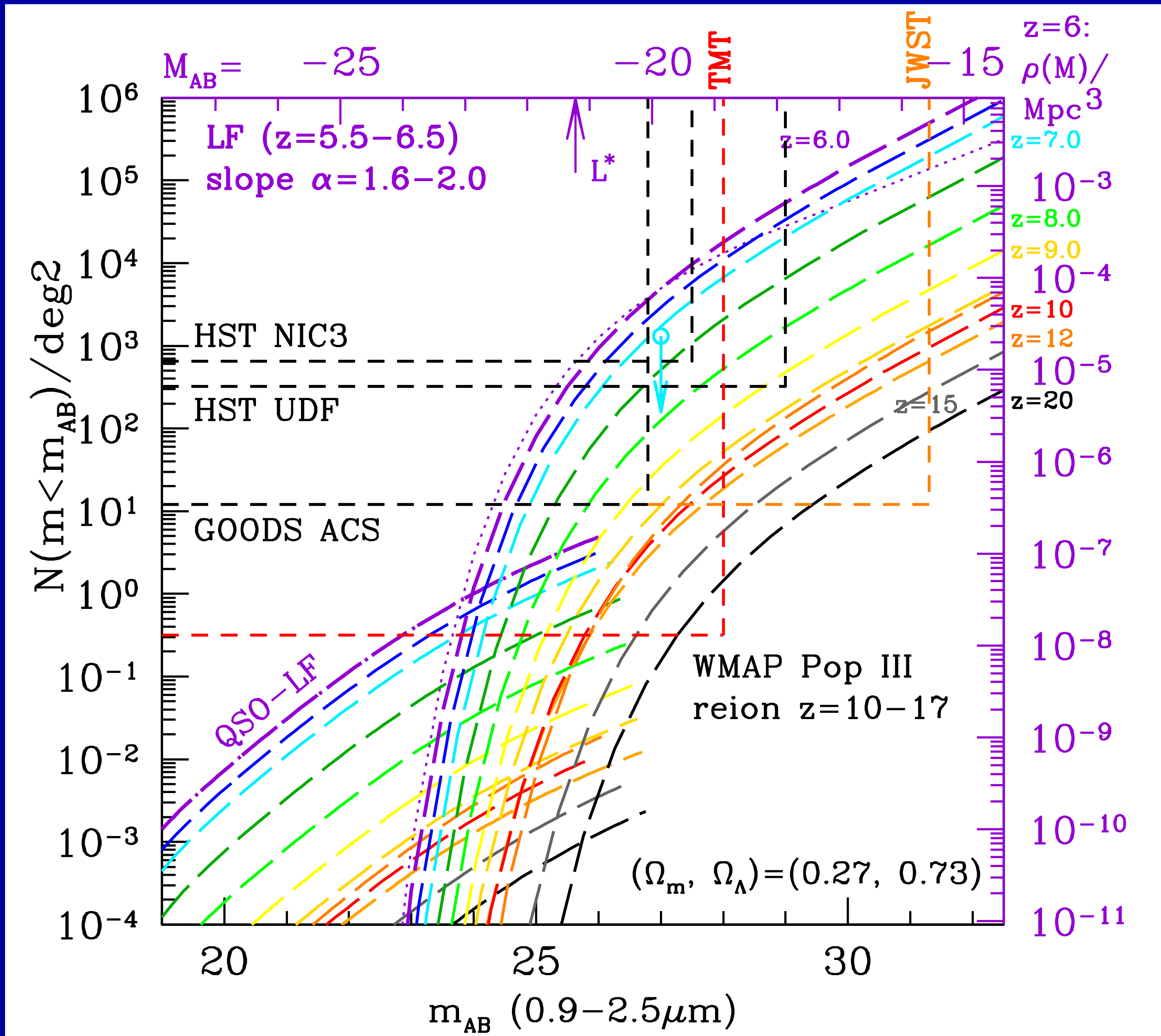


HUDF i-drops: faint galaxies at $z \simeq 6$ (Yan & Windhorst 2004), most spectroscopically confirmed at $z \simeq 6$ to $AB \lesssim 27.0$ mag (Malhotra et al. 2005).



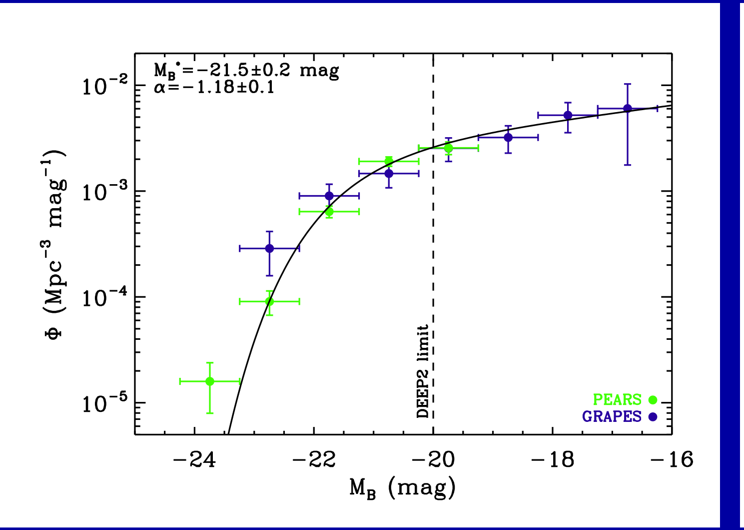
HUDF shows that luminosity function of z≃6 objects (Yan & Windhorst 2004a, b) is very steep: faint-end Schechter slope $|\alpha|\simeq 1.8\pm 0.2$.

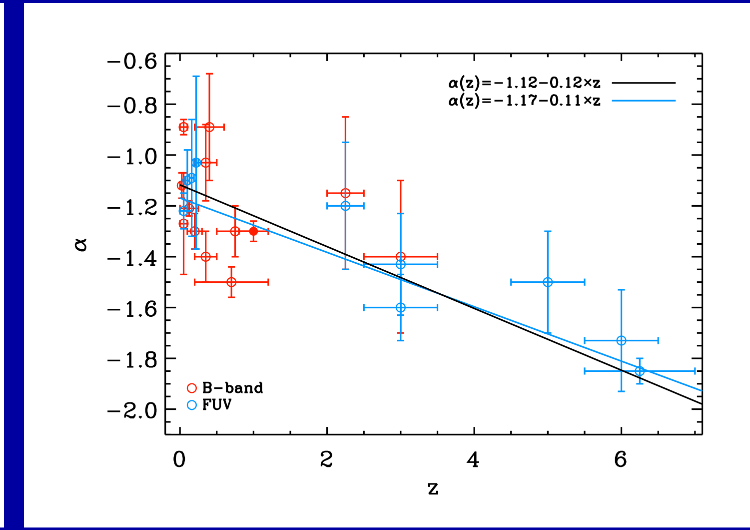
$\Rightarrow$ Dwarf galaxies and not quasars likely completed the reionization epoch at z≃6. This is what JWST will observe for z≃7–20, and SKA for z$\lesssim$6.

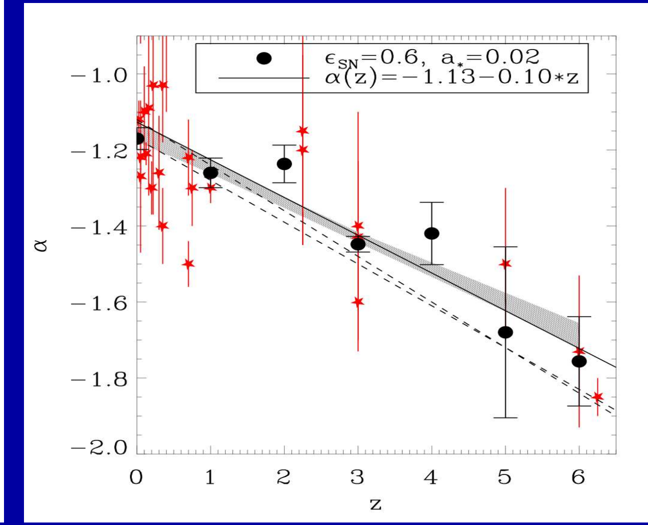


- With proper survey strategy (area & depth), JWST will trace the entire reionization epoch at $z \simeq 7$–20, but cannot search for AGN $z \gtrsim 6$ efficiently.
- With proper survey strategy (area & depth), SKA will trace the HI-LF for $z \simeq 0$–6, and **can** do continuum searches for weaker AGN at $z \gtrsim 7$–10.

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





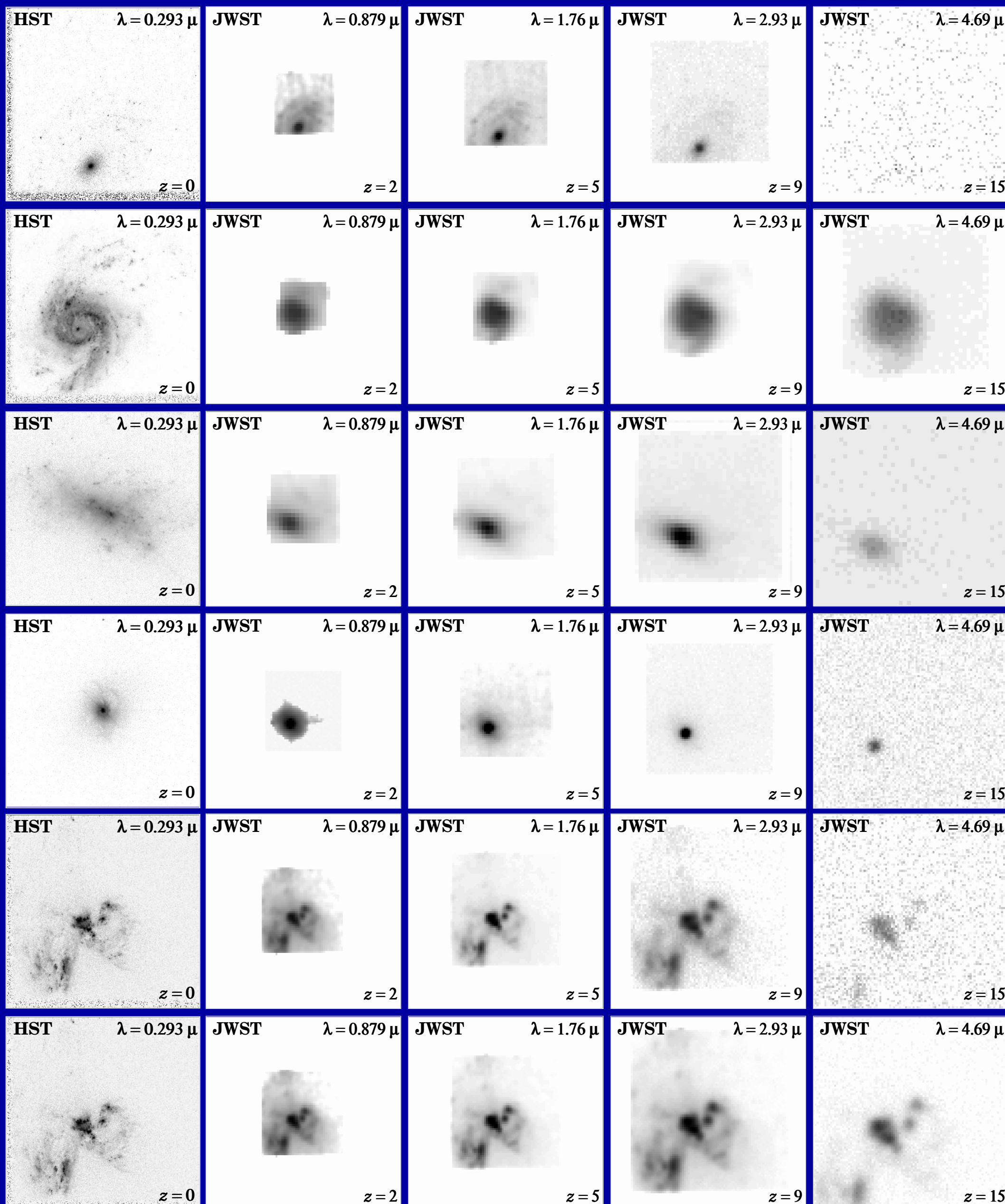


Faint-end LF-slope at $z \gtrsim 1$ with accurate ACS grism z's to $AB \lesssim 27$ (Cohen et al.; Ryan et al. 2007, ApJ, 668, 839) constrains hierarchical formation:

- Star-formation and SN feedback produce different faint-end slope-evolution: new physical constraints (Khochfar ea. 2007, ApJL, 668, L115).
- JWST will trace faint-end LF-slope α-evolution for $z \lesssim 12$.
- SKA will trace low-mass-end of HI-MF slope-evolution for $z \lesssim 6$.
- Can measure environmental impact on faint-end LF-slope α directly.
- Expect convergence to slope $|\alpha| \simeq 2$ at $z > 6$ before feedback starts.
- Constrain onset of Pop III SNe epoch, Type II & Type Ia SN-epochs.

Predicted Galaxy Appearance for JWST and SKA at z≃1–15

HST z=0 JWST z=2 z=5 z=9 z=15



SKA will observe HI and continuum structures over a wide range of cosmic time. If these trace UV-starlight, then SKA will observe that:

- (1) Most disks will SB-dim away at high z, but most formed at z_{form}≃1–2.
- (2) High SB structures are visible to very high z.
- (3) Point sources (AGN) are visible to very high z.
- (4) Unresolved high SB-parts of mergers/train-wrecks are visible to very high redshifts.

SUMMARY: SKA's IMPACT ON GALAXY ASSEMBLY

The SKA Billion Galaxy survey "GiGa" will:

1) Find all baryonic (Hydrogen) mass in the universe from the end of reionization until today.

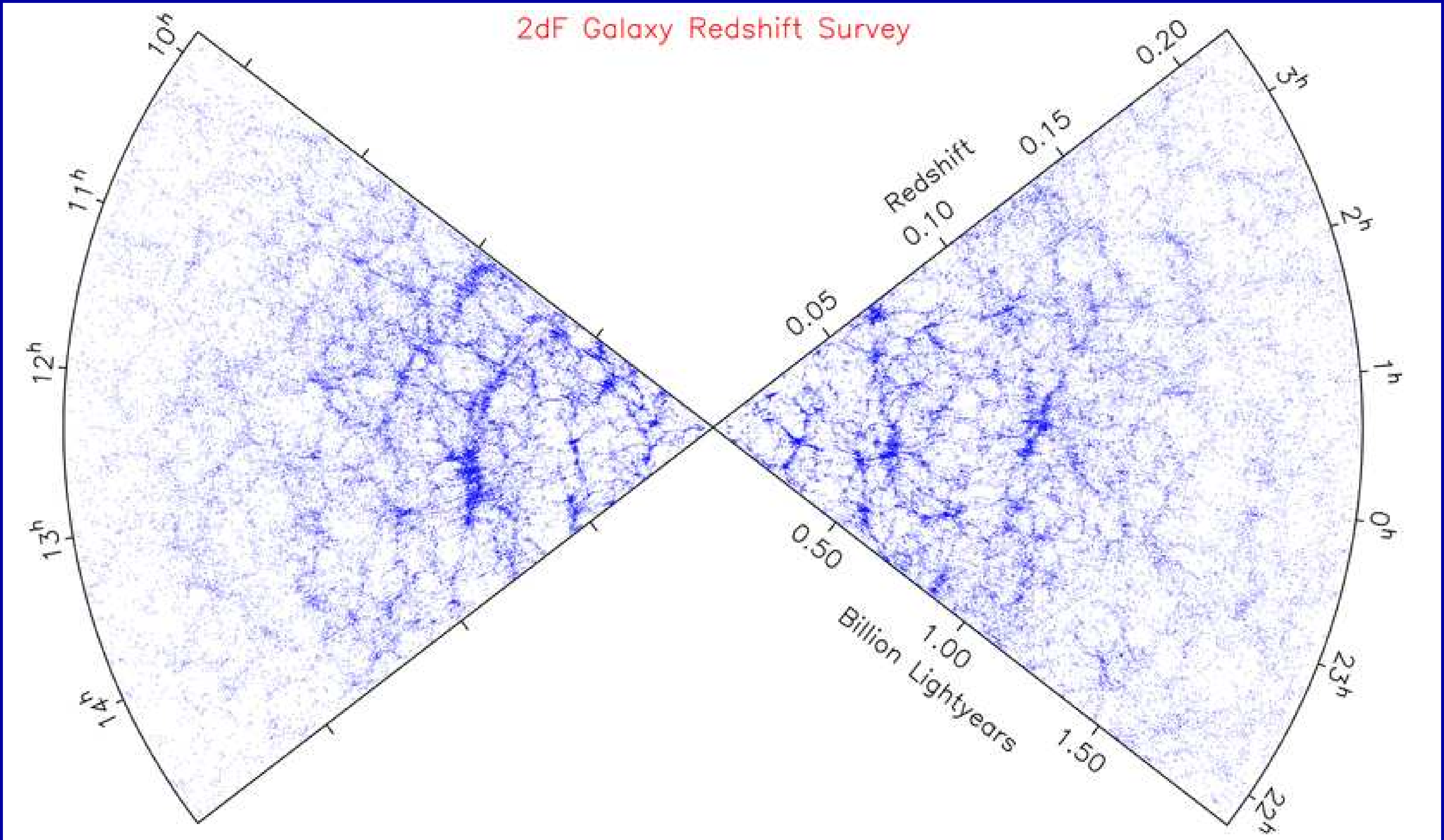
2) Map the mass-assembly and gas-assembly of galaxies since the end of reionization until today.

3) Trace the assembly of galaxies and growth of supermassive black holes over most of cosmic time.

4) Find the first supermassive black holes inside the first galaxies.

Community needs SKA-slogan, e.g.: "FROM PROTONS TO PLANETS."

SPARE CHARTS



Large Scale Structure on 100's of Mpc scales from 2dF Redshift Survey.

The SKA GiGa survey will be done in wedding-cake approach:
10's–1000's deg^2 to 1–10 nJy, resp.

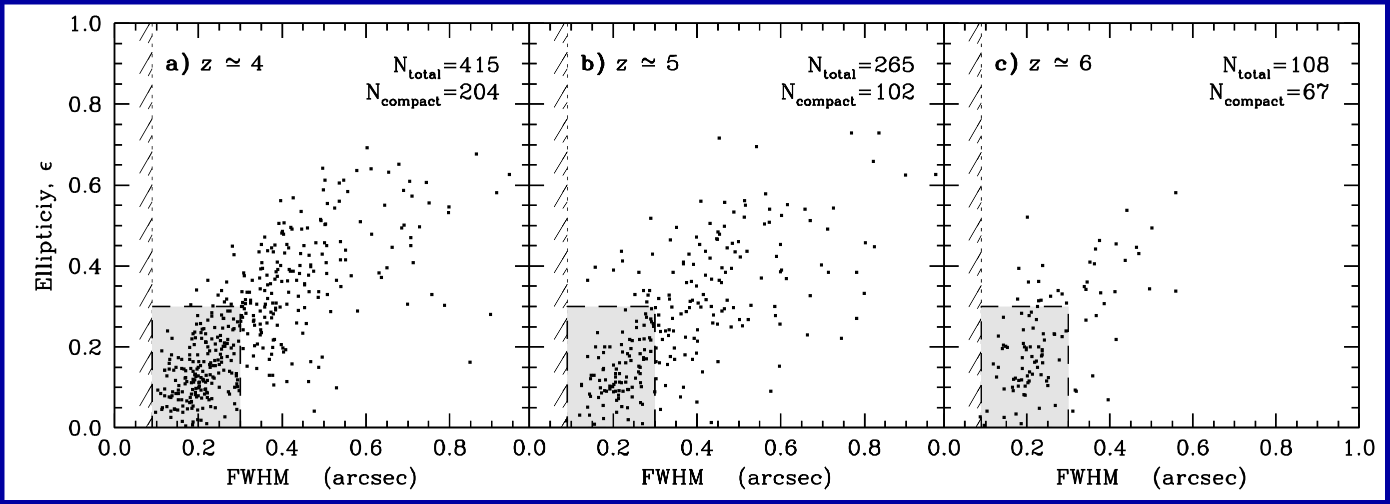
Combination of ground-based and space-based HST surveys show:

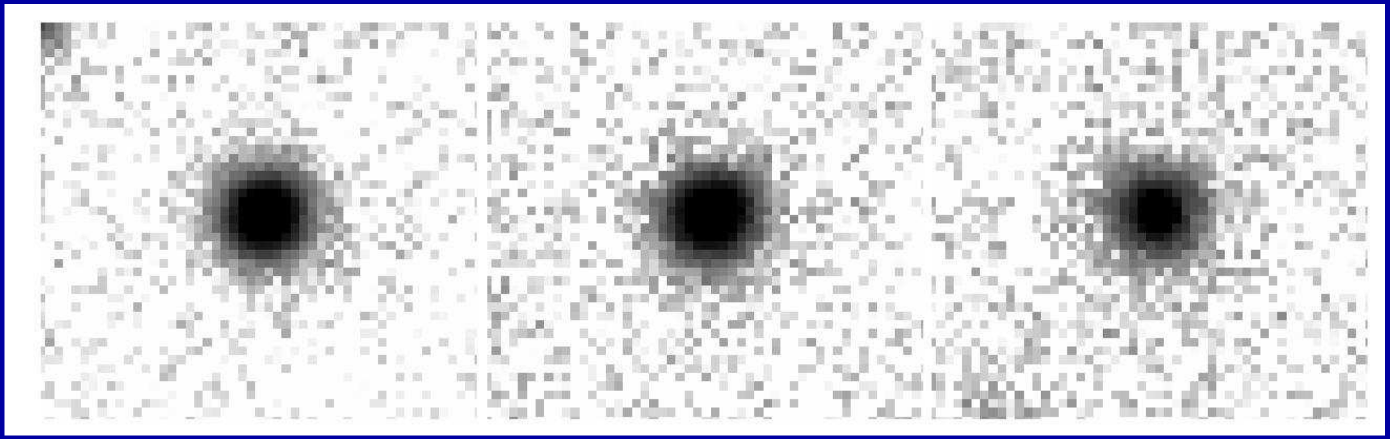
- (1) Apparent galaxy sizes decline from the RC3 to the HUDF limits:
- (2) At the HDF/HUDF limits, this is *not only* due SB-selection effects (cosmological $(1{+}z)^4$-dimming), but also due to:
- (2a) hierarchical formation causes size evolution: $r_{hl}(z) \propto r_{hl}(0).(1{+}z)^{-s}$ with $s \simeq 1$.
- (2b) increasing inability of object detection algorithms to deblend galaxies at faint fluxes ("natural" confusion $\neq$ "instrumental" confusion).
- (3) At AB$\gtrsim$30 mag, JWST — and at $\gtrsim$10 nJy, SKA — will see more than $2{\times}10^6$ galaxies/deg^2. Many of these will be unresolved at $\lesssim 0\farcs1$ FWHM. At $z_{med} \gtrsim 1.5$, this helps mitigate the $(1{+}z)^4$-dimming.

SKA needs to strike the right balance between having a resolution that is:

- High enough to disentangle the expected faint small HI and continuum sources from their neighbors, but ...
- Not so high that small HI and continuum sources at very redshifts are highly resolved, hence mitigating the SB-dimming as much as possible.

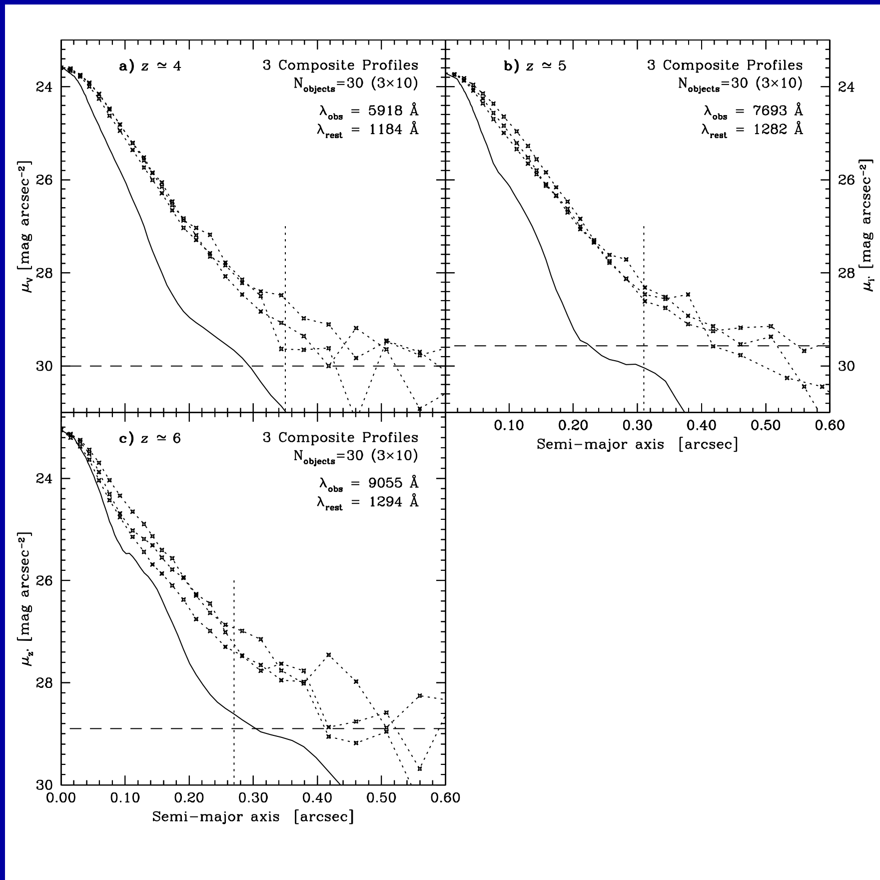
Dynamical ages of Dwarf Galaxies at z≃4–6?

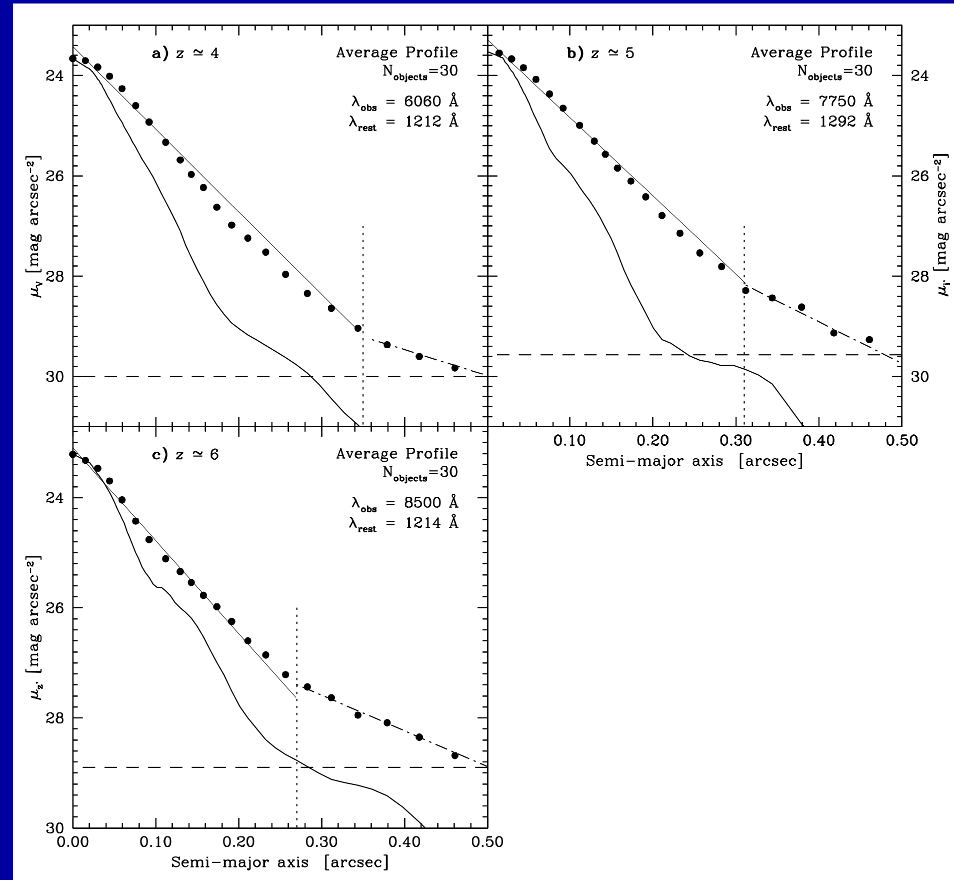




- Select all isolated, nearly unresolved ($2r_e \lesssim 0\farcs3$), round ($1-b/a \lesssim 0.3$) HUDF B-drops, V-drops, and i-drops. to AB=29.0 mag
- Construct average image stack and light-profiles of these dwarf galaxies at z≃4, z≃5, and z≃6.
- If these compact, round objects are intrinsically comparable, each stack has the S/N of ∼5000 HST orbits (≃300 JWST hrs; Hathi et al. 2007).

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

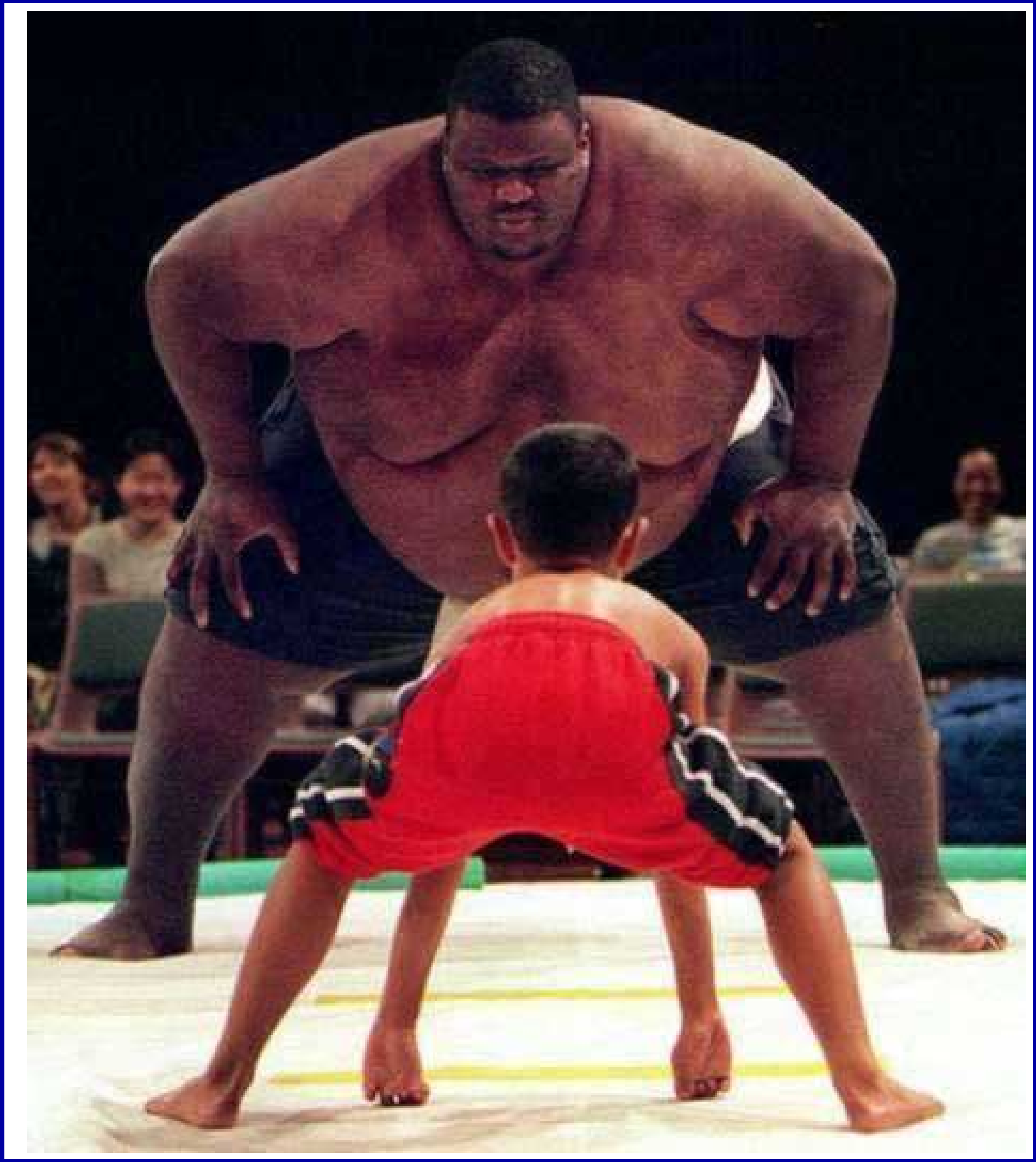




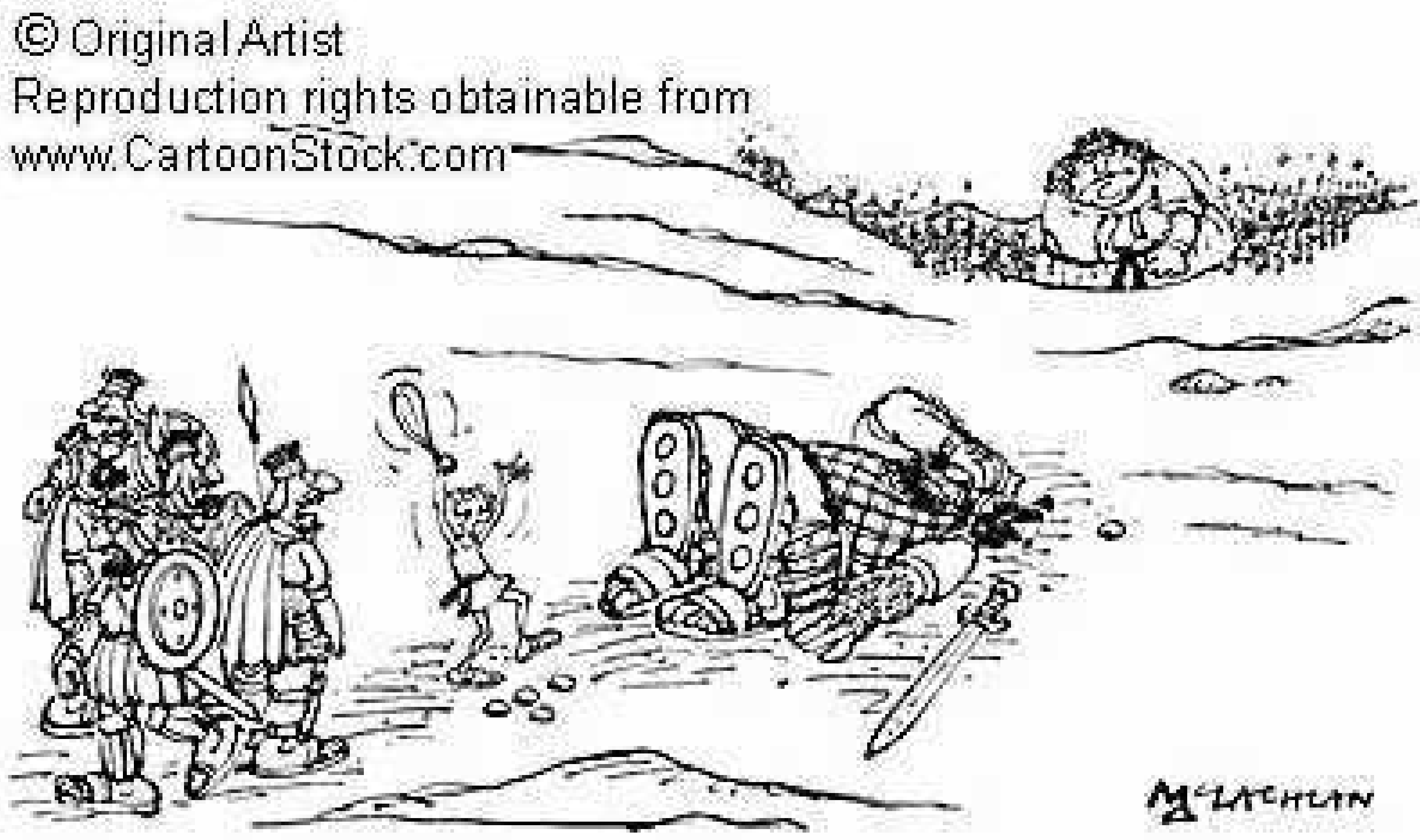
- HUDF sky-subtraction error is 2–3.10^{-3} or AB≃29.0–30.0 mag/arcsec^2
- Average 5000-orbit compact, round dwarf galaxy light-profile at z≃6–4 deviates from best fit Sersic n≃1.0 law (incl. PSF) at r$\gtrsim$0$''$.27–0$''$.35.
- If interpreted as virial radii in hierarchical growth, these imply dynamical 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, AJ; astro-ph/0710.0007).

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



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



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

What goes around, comes around ...

Technical Requirements for SKA (Aug. 06 Tucson Conf.)

1) WAVELENGTH RANGE: 200 MHz – 2.0 GHz.

- Consider hybrid array: 10% of dishes up to 22 GHz (costs 25% more?).

2) SPECTRAL RESOLUTION: 1.0*(1+z) km/sec FWHM

- Needed for spectral line work at z$\simeq$0–10.

3) SPATIAL RESOLUTION: 0.1–1.0" FWHM, but:

- $\lesssim$10 mas ($\lesssim$10 pc) FWHM to separate AGN from starbursts at z=1–10.
- 10–60" FWHM to detect low-mass HI clouds at z$\lesssim$0.05.
- Need a logarithmic or geometric baseline-distribution, ranging from 10's of meters to 1000's of km, heavily weighted towards the central 50 km.

4a) CONTINUUM SENSITIVITY: 10–100 nJy at 1.4 GHz (5 sigma)

- Need nJy sensitivity to see the relevant objects to z$\lesssim$10.

4b) LINE SENSITIVITY: 1.0 μJy sensitivity (5 sigma 12 hrs) in 1 km/sec line channels. Needed to detect a M$\simeq 3\times10^9$ $M_\odot$ galaxy in HI at z$\sim$1.

5) POLARIZATION: Need Stokes I, Q, U, V to measure RM for $\lesssim$2 GHz.