The GALEX View of Star Formation in the LSB regime

David Thilker, JHU

+ GALEX Science Team

Outline

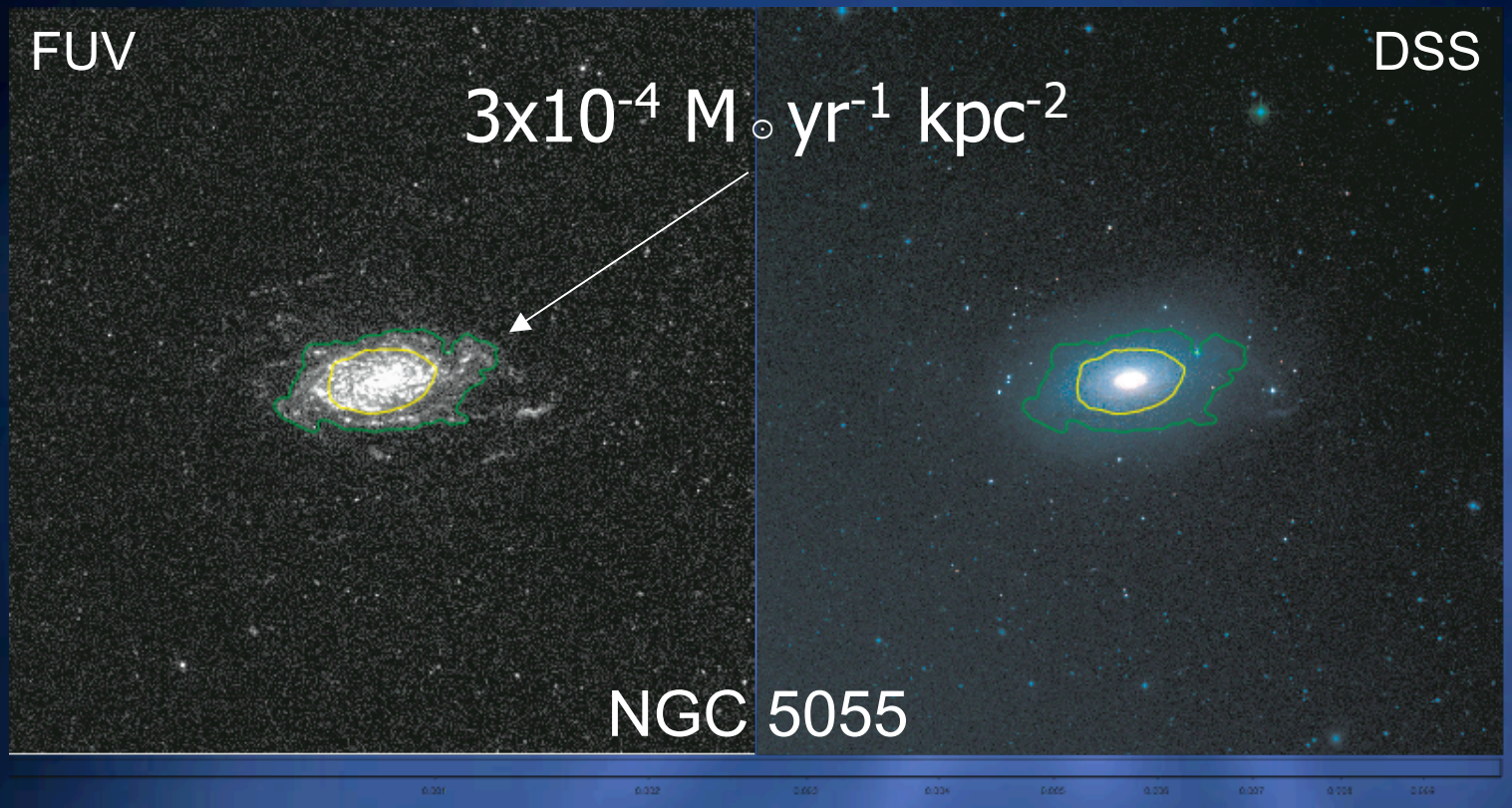
- What key advantage does GALEX offer?
- Where does LSB star formation occur?
  … and, why is it significant?
  - Extended UV disk (XUV-disk) galaxies (e.g. M83)
  - Early-type (spherodial) galaxies (e.g. NGC 404)
  - Massive, giant LSB galaxies (e.g. Malin 1)
  - LSB dwarfs / extreme gas-rich objects
    - Sometimes "failed" XUV-disks (e.g. NGC 2915)
  - Intergalactic gas & dwarf formation (e.g. Leo Ring)
- GALEX Deep Galaxy Survey
- UV PDF rather than "SF threshold"

Why use GALEX?

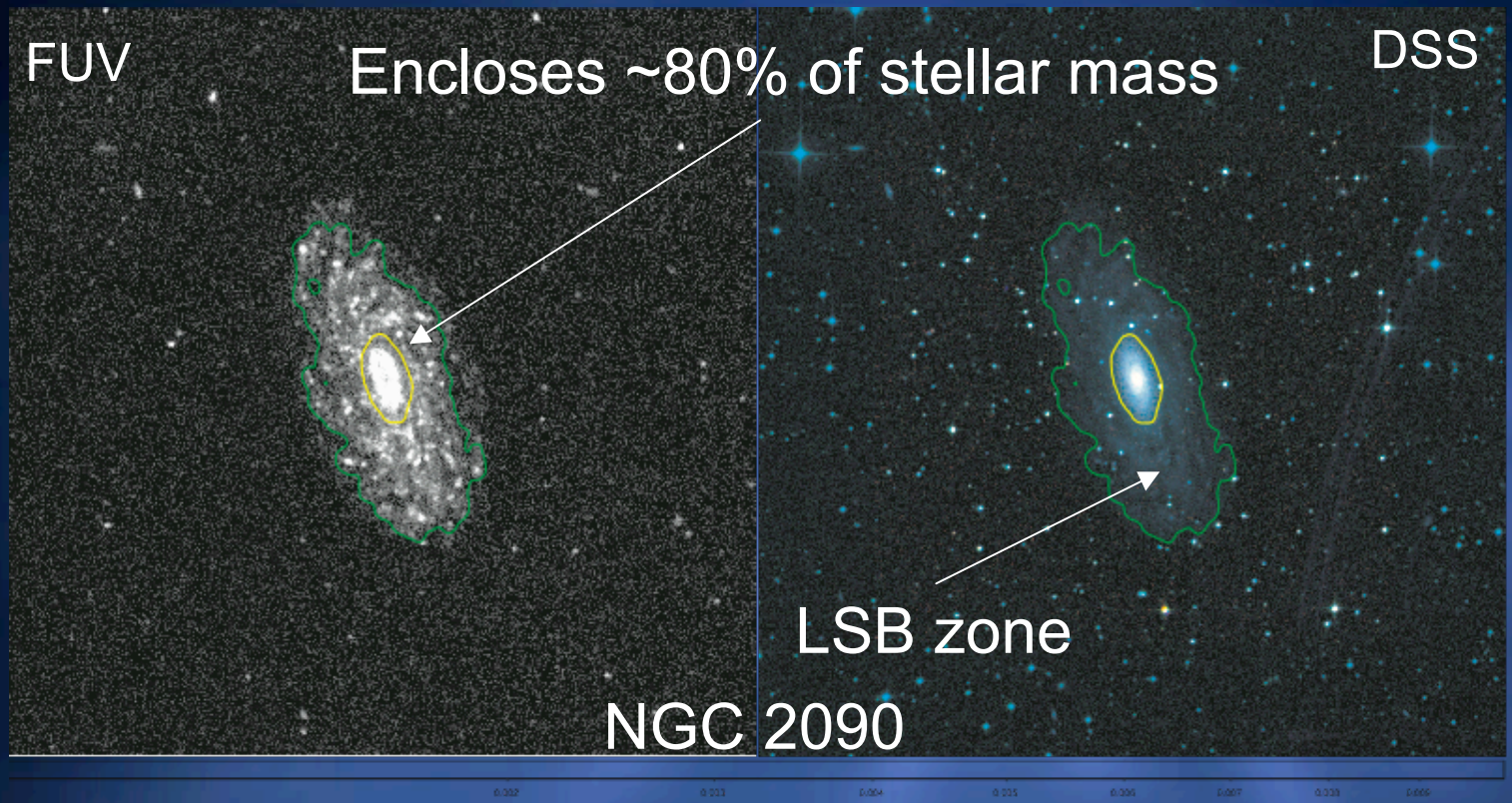
- GALEX is exceptionally sensitive to sources with low SFR or intermittent SF
  - Timescales of few x 10^8 yr
    - "Recent", not "current" like Hα
  - UV limited to <SFR> ~10^{-5} $M_\odot$ yr^{-1} (MC sim.)
    - Hα <SFR> ~$10^{-3.5}$ $M_\odot$ yr^{-1} (Thilker et al. '07)
  - Important caveats (later in talk)
- Wide-field (1.2° diam.), survey data
- New discovery space being exploited

Extended UV disk (XUV-disks)

- 20-30% of nearby disk galaxies have spatially extended UV emission typically reaching two optical radii
  - Zaritsky & Christlein (2007)
  - Thilker et al. (2007)
- Galaxy disks are much larger (2x) than appreciated and still growing!
  - Anti-truncated disk profiles (e.g. Pohlen & Trujillo '06)
- Two basic types (e.g. M83, NGC 2090) were found in our survey



- Type 1 XUV-disks have structured, UV-bright emission complexes beyond the anticipated location of the SF threshold.

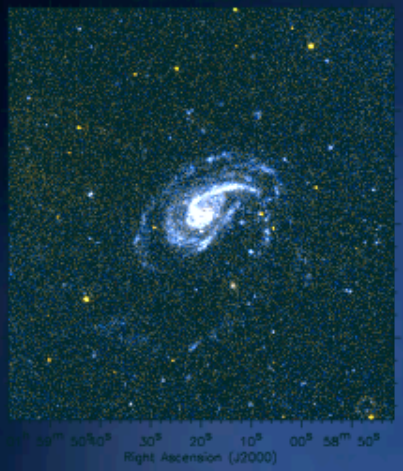


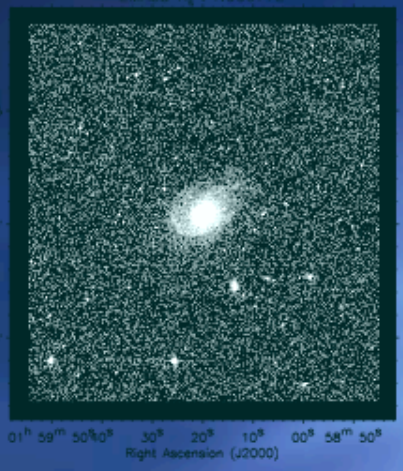
- Type 2 XUV-disks have blue UV-NIR within an exceptionally large, outer, optically-LSB zone.

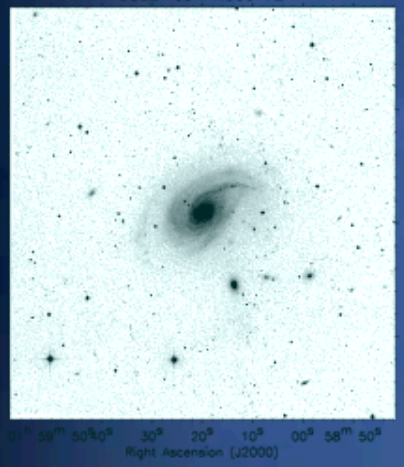
- Zaritsky & Christlein: conclusion was based on angular correlation function analysis of color-selected GALEX pipeline sources normalized by R25

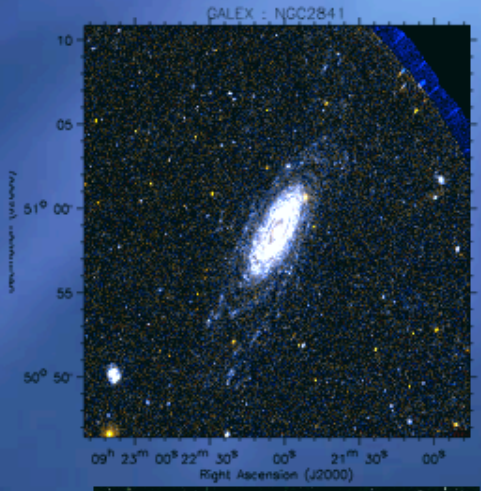
- We applied a morphological method:
  - UV threshold contour --> optically independent!
    - Boissier et al. '07: At the apparent Hα threshold radius, GALEX UV Σ_{SFR} is generally $\sim 3 \times 10^{-4}$ $M_\odot$ yr^{-1} kpc^{-2}.
    - Spatially-resolved Schmidt Law analysis (Thilker et al. '07b) shows that for the critical N(HI) allowing the CNM phase (Schaye '04), we expect comparable Σ_{SFR} levels
  - Type 2 LSB zone definition guided by models of inside-out disk formation

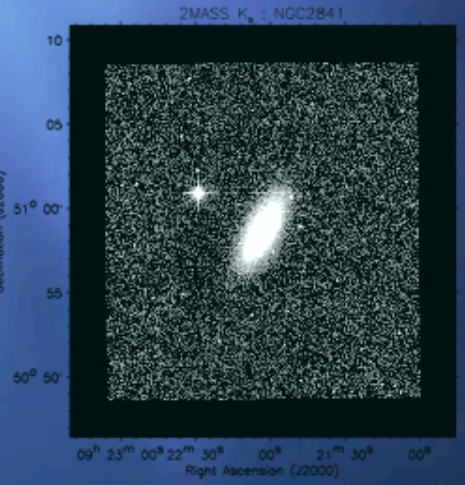
- Very similar estimate of XUV incidence





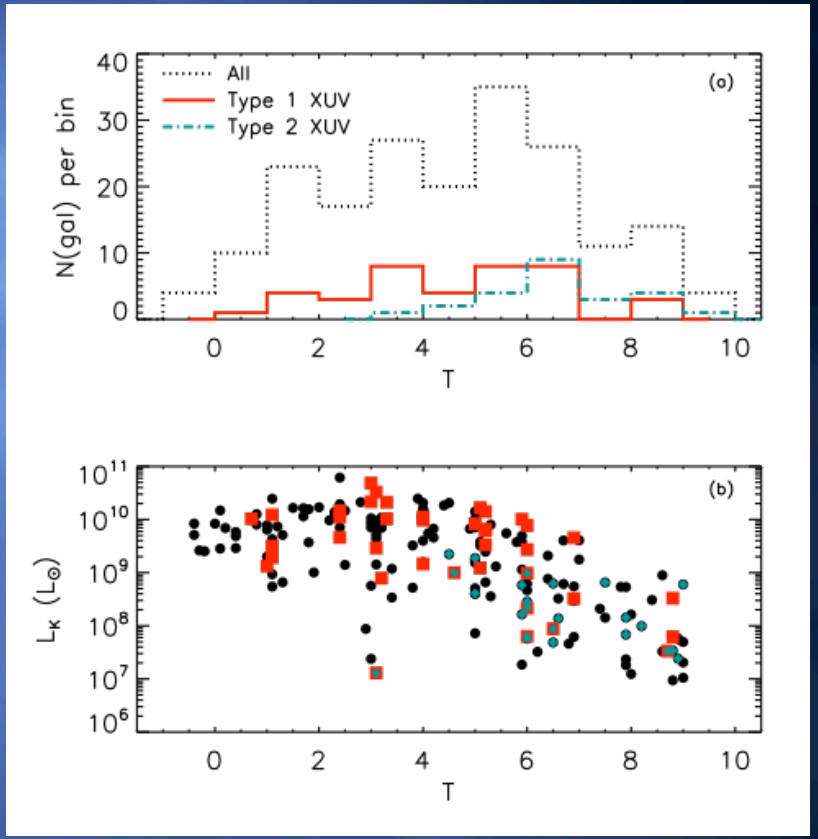


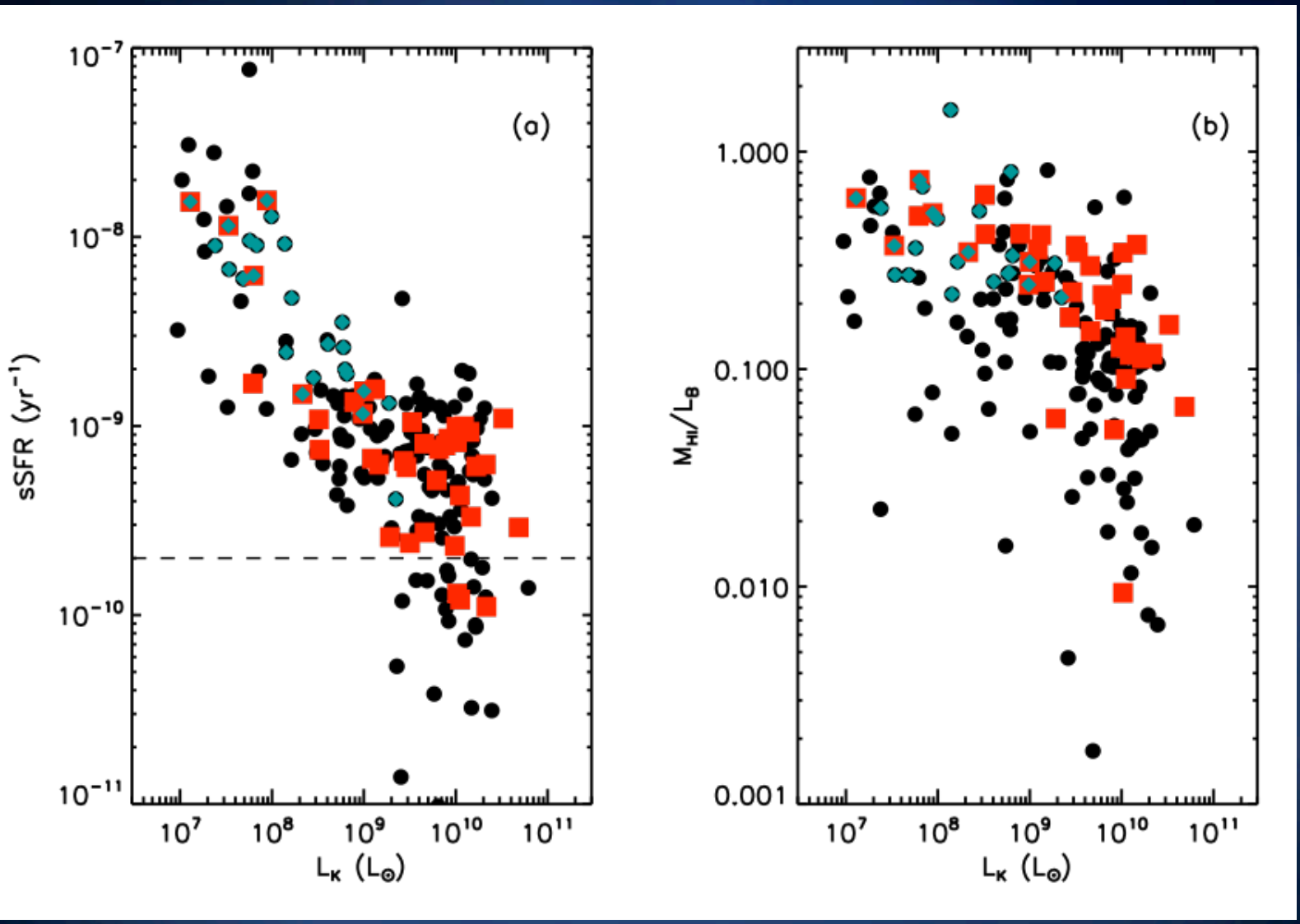




More examples…

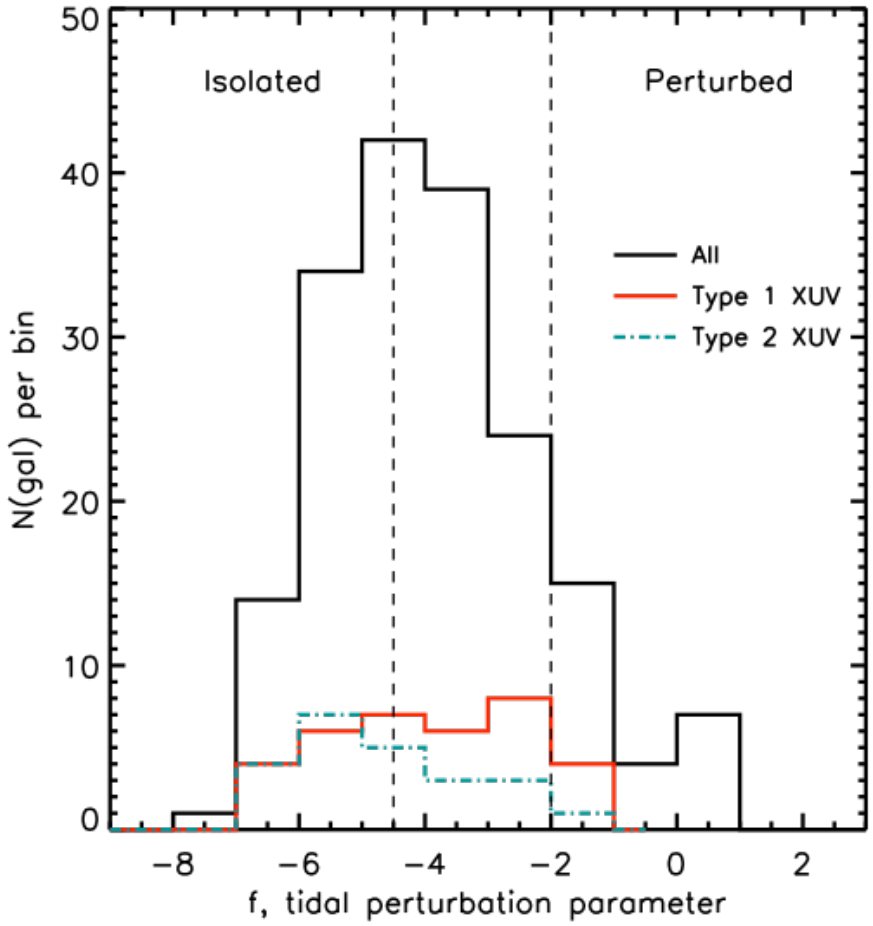
- Type 1: sporadic SF tracing filaments in extended HI disk
  - no preferred spiral type
  - incrementally augmenting disk
- Type 2: non-linear inside-out growth
  - classified as late-type spirals
  - transforming disk structure





Very high *sSFR* for Type 2, $t_{form} < 1$ Gyr

XUV-disks are ~2x more gas-rich on average



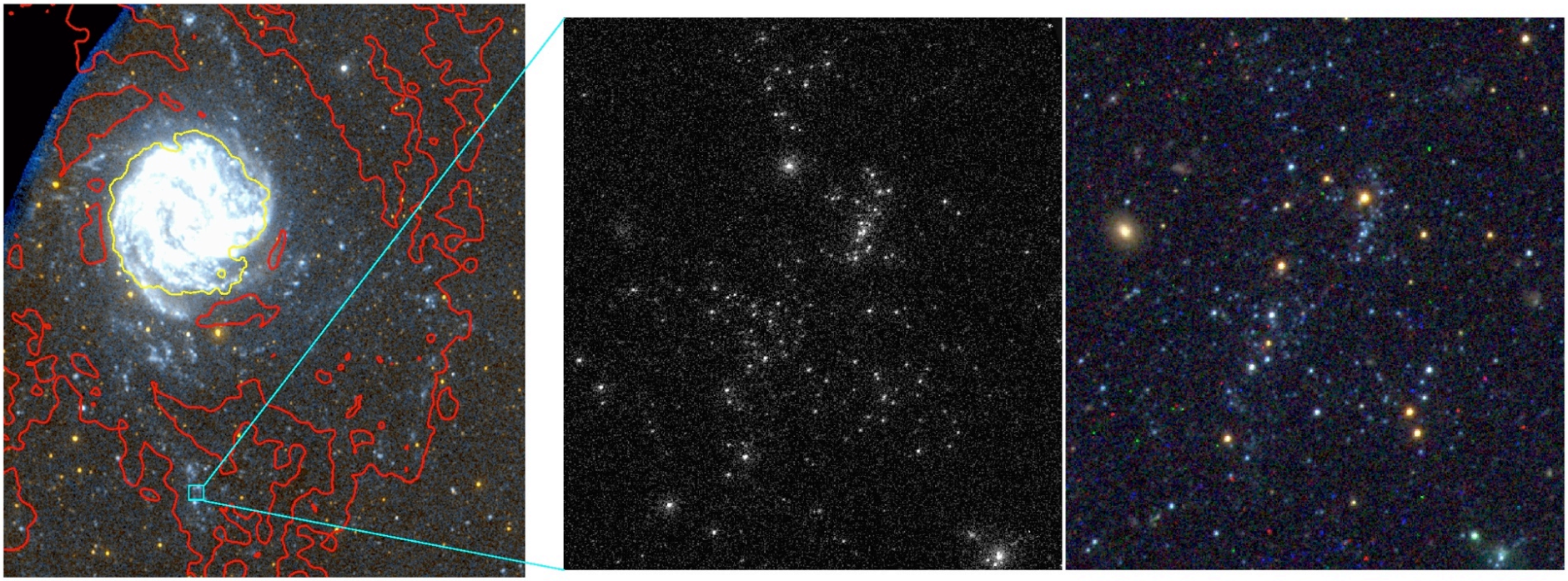
Type 1 XUV-disks are *more perturbed* than the overall sample.

Type 2 galaxies are *comparatively isolated*.

HST imaging of XUV-disks

- FUV, F435W, F606W, F814W observations
  - 8 fields in M83, one each in NGC 5055 & NGC 2090
- GOALS:
  - Constrain spectral type of individual stars contributing to XUV clumps
  - Use CMD to model the overall SFH within HST fields
  - Examine spatial clustering properties in comparison to inner disk

HST imaging of XUV-disks

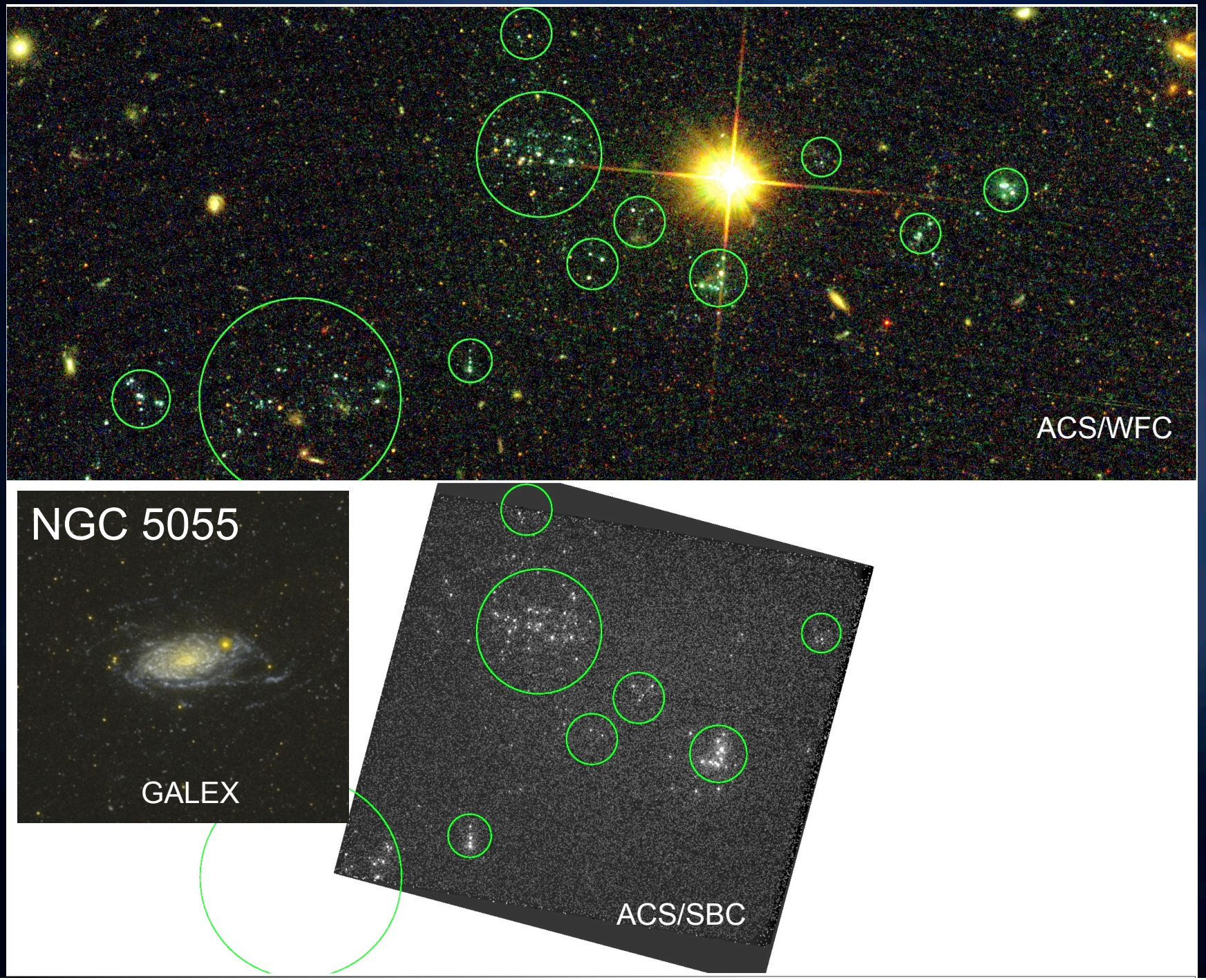


GALEX with HI
4-5” res.

HST/SBC 1500Å
0.1” res.

HST/ACS

- HST resolves the GALEX XUV-disk UV sources into loosely clustered complexes of individual stars.
- These complexes, likely evolved OB associations, are low mass ($<10^3$ $M_\odot$), intermediate age structures.
- Observed association sizes vary from 100 pc to ~500 pc with significant internal sub-clustering.
  - The largest groupings may be several blended associations.

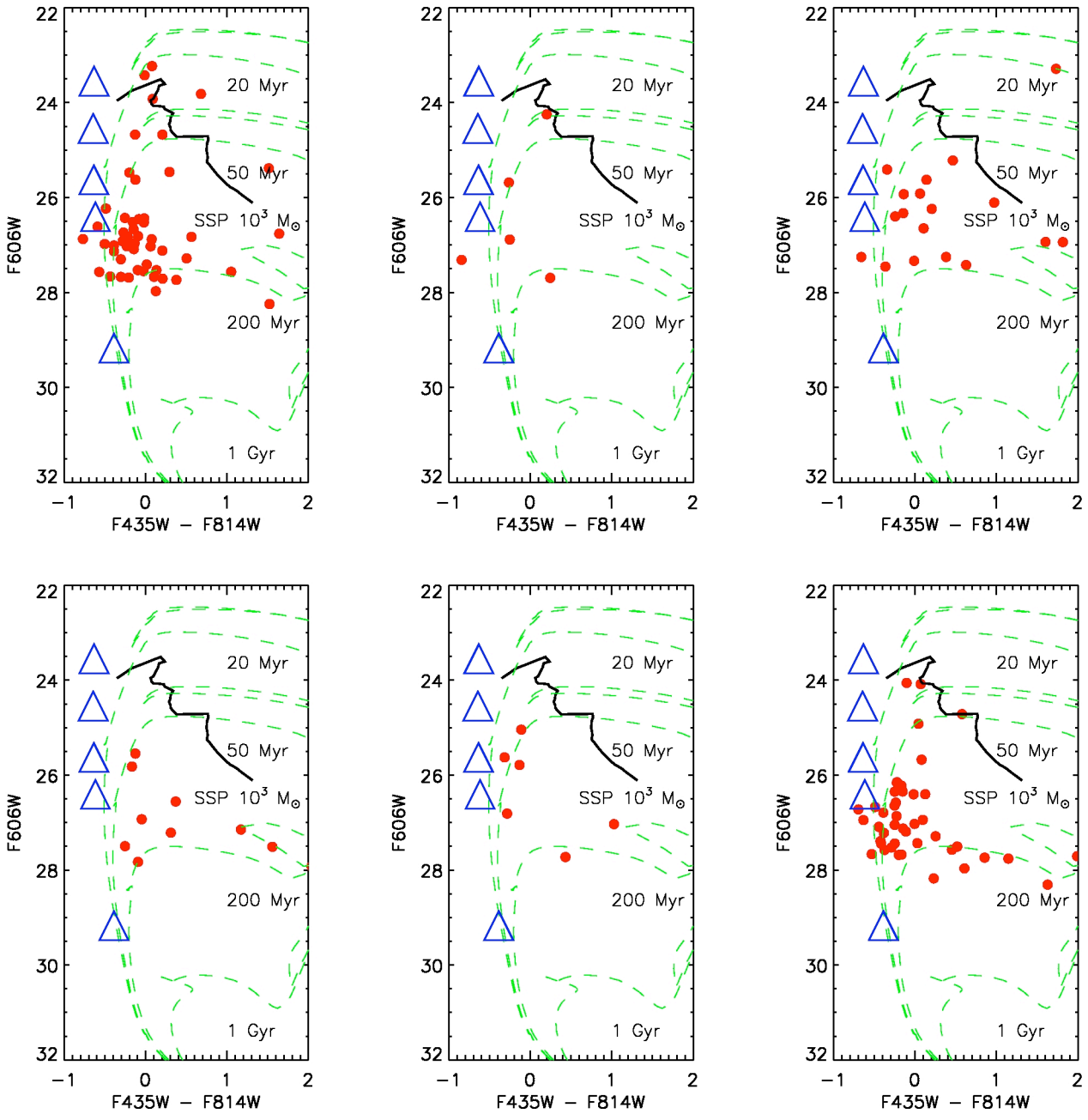

ACS/WFC
NGC 5055
GALEX
ACS/SBC

NGC 5055 XUV-disk HST CMDs

Padova isochrones (Girardi '02 +)

ZAMS positions marked with triangles: (5,15,20,30,40 $M_\odot$)

Solid line is a 10^3 $M_\odot$ cluster (5 Myr - 1 Gyr)



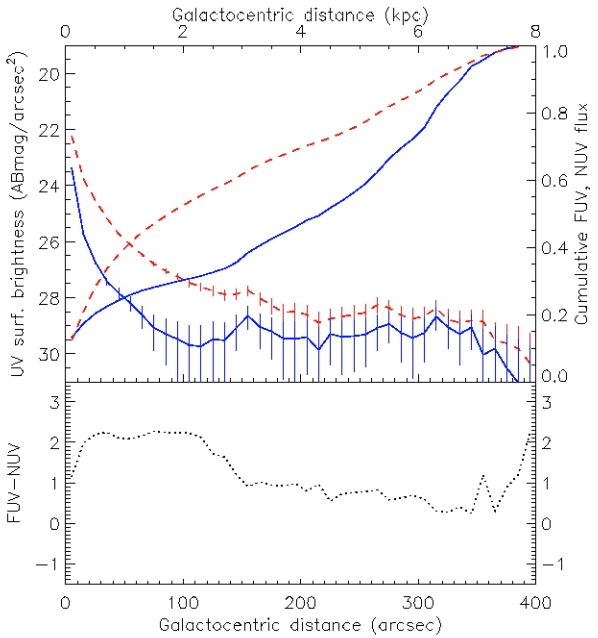
CMD analysis of XUV-disk complexes

- Very few sources are consistent with being zero-age upper-MS stars having M >15 $M_\odot$.
  - Hα emission is detected from complexes in which they are found.
- CMDs suggest multiple generations within larger complexes (up to age of ~200 Myr).

XUV-disk galaxies… the next step

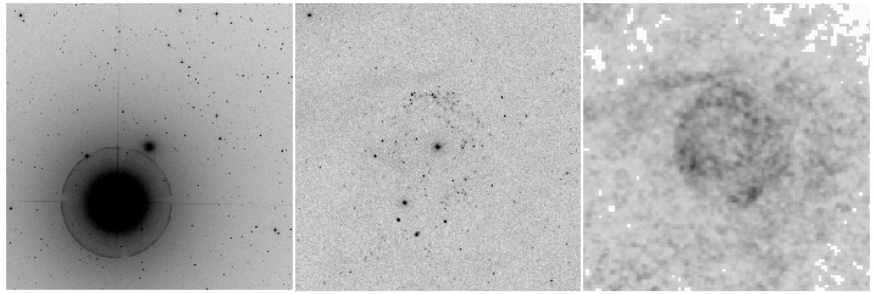
- Now extending T07 survey (sample of 189 S0-Sdm galaxies, D<40 Mpc) considering:
  - New MIS-depth GALEX data
    - Good for ID purposes, need deeper for low dens. SFL
  - All galaxy types (E and Irr too, not just Sp)
  - Relaxing distance limit
- Aim: Unified interpretation amongst all extended and LSB objects.
- Surprises already!

- NGC404, E-S0
- HI suggestive of merger event (del Rio et al. '04) even though now isolated
- Type 1 XUV
- Most FUV from ring despite Σ_{SFR} ~ 2e-5 Ms yr^{-1} kpc^{-2}



Thilker et al. (2009) in prep.

DSS FUV HI (WHISP)

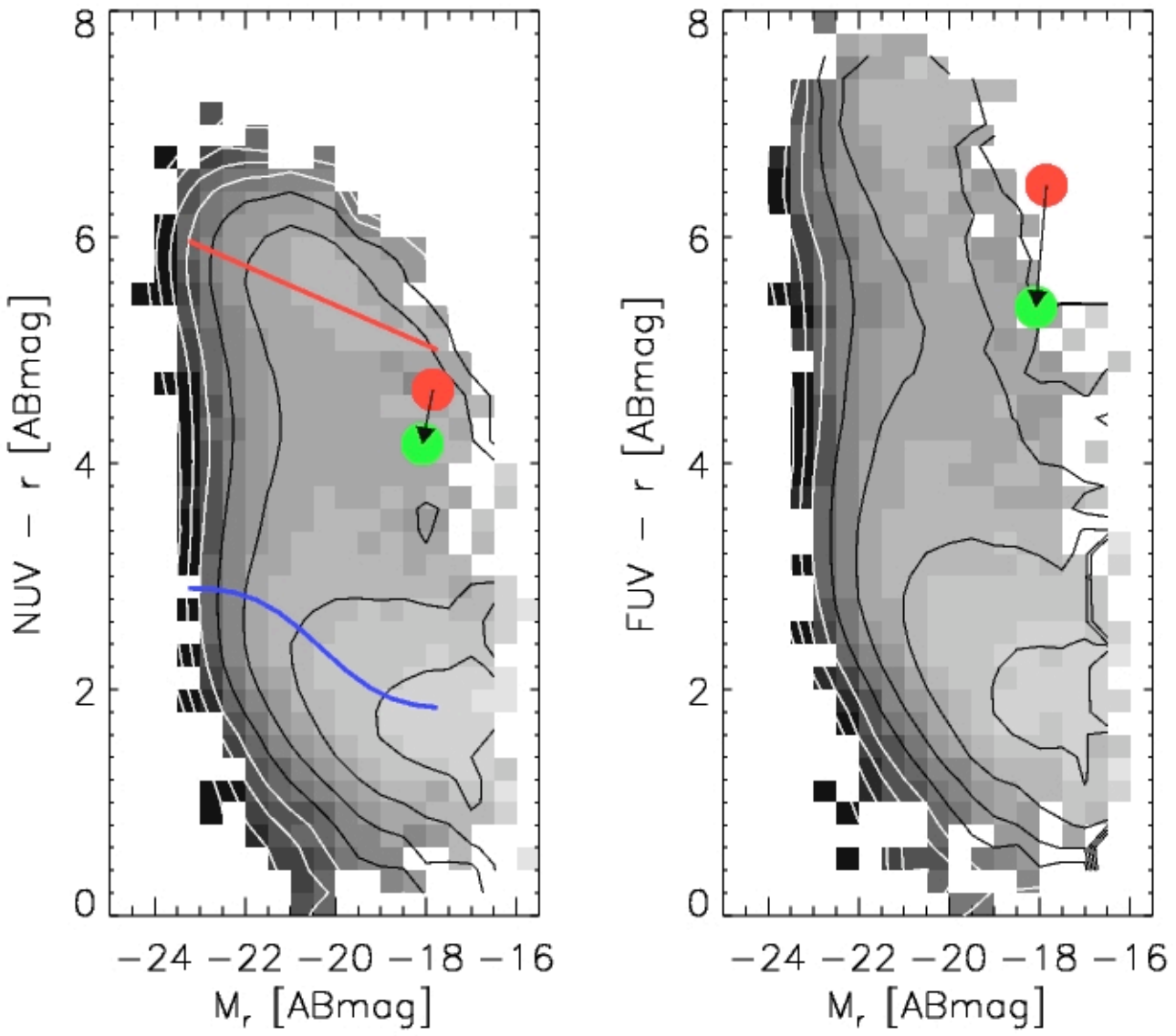


[UV-r,r] galaxy CMD from Wyder et al. (2007)

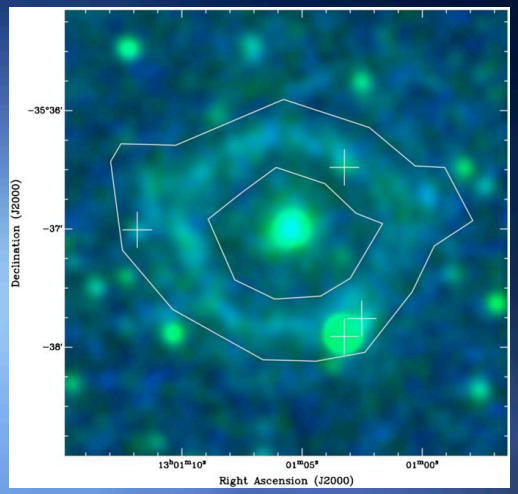
Red sequence
Blue sequence
Green valley

NGC 404 has/is transitioning back into green valley
after merger

Thilker et al. (2009) in prep.

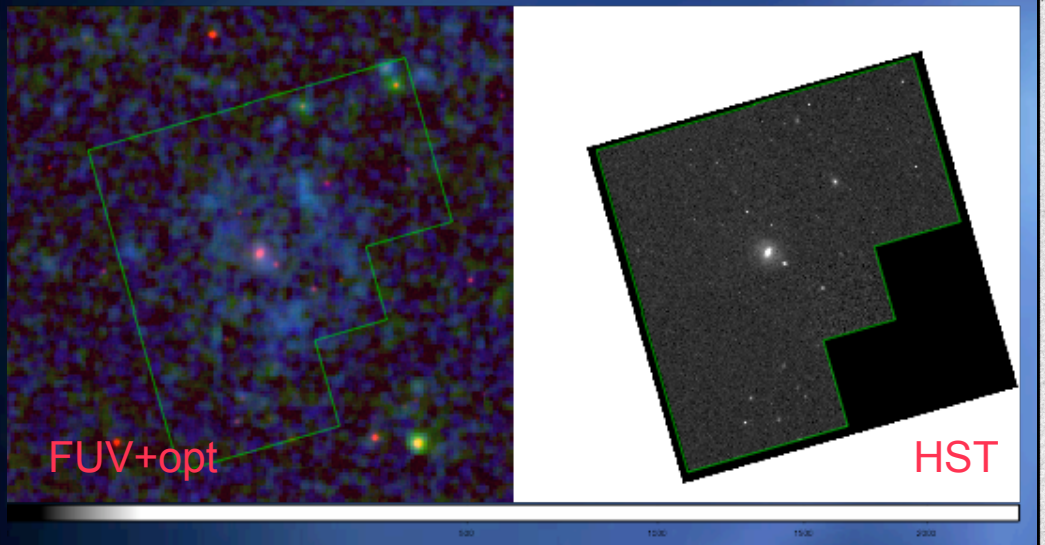


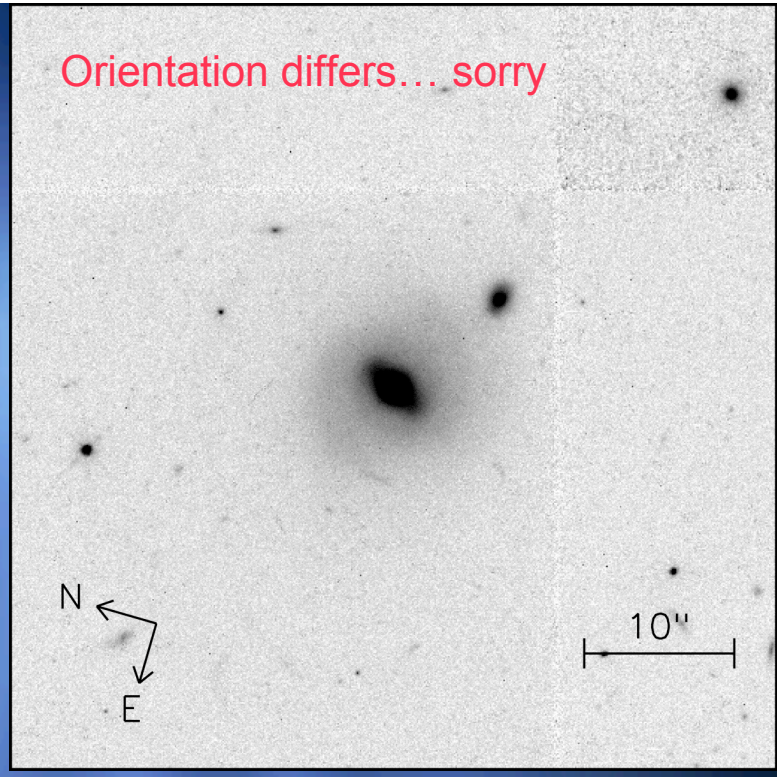
- Rejuvenated disk formation via merger events



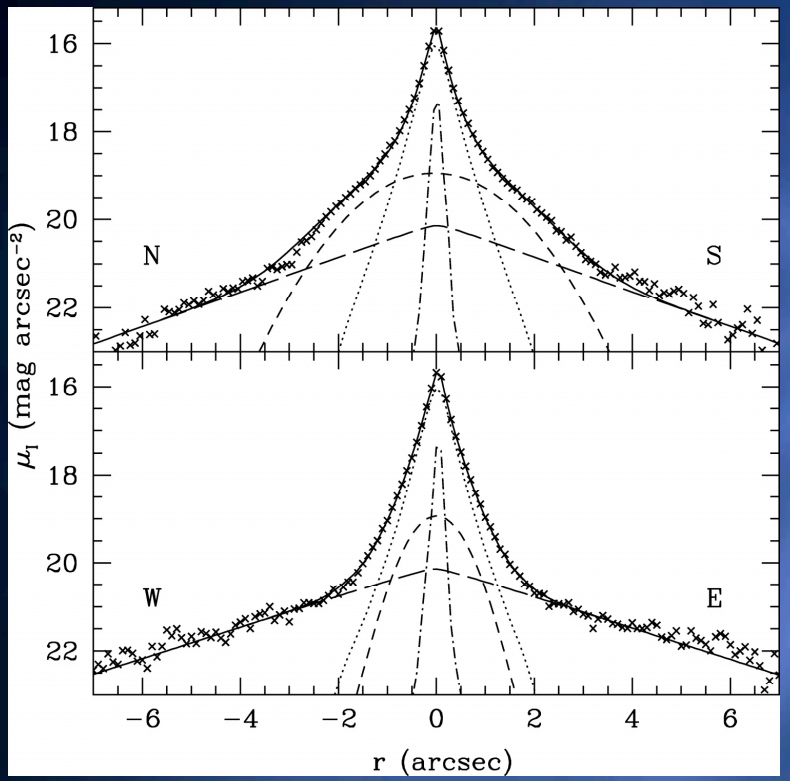
- Not the only one
  - Donovan et al. 2009 (ESO 381-47, above)
  - Kannappan et al. 2009 (blue seq. ETGs)
  - Rich (in prep… same process at z=0.1)
  - LGLA (Seibert & Madore, in prep.)

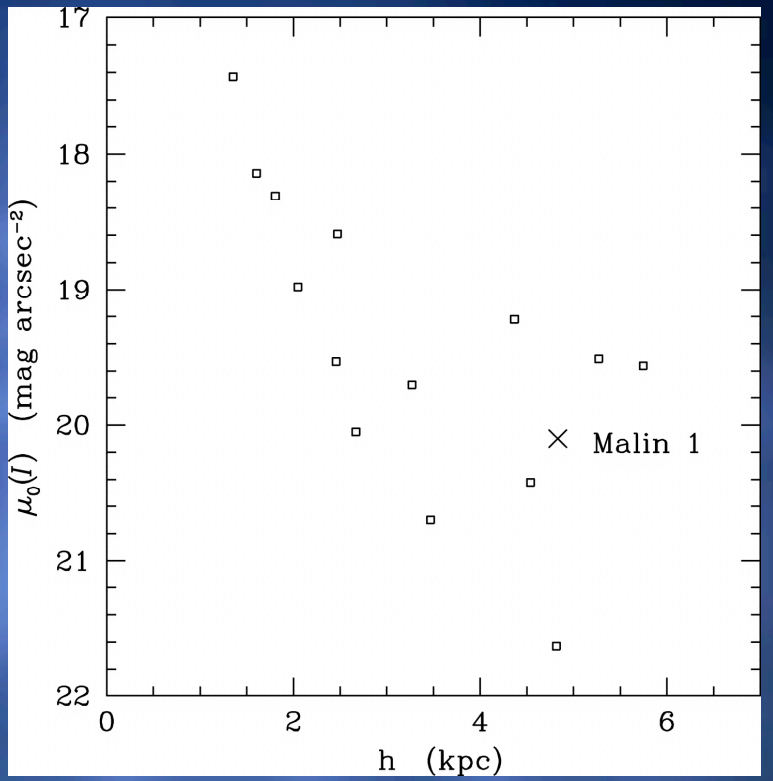
Giant LSB = XUV-disk?





- Barth (2007): HST shows Malin 1 has a typical S0-like disk within separate LSB outer component. See also, Sancisi & Fraternali rotation curve analysis.
- Massive LSBs are likely extreme XUV-disks with anomalously high M(HI).



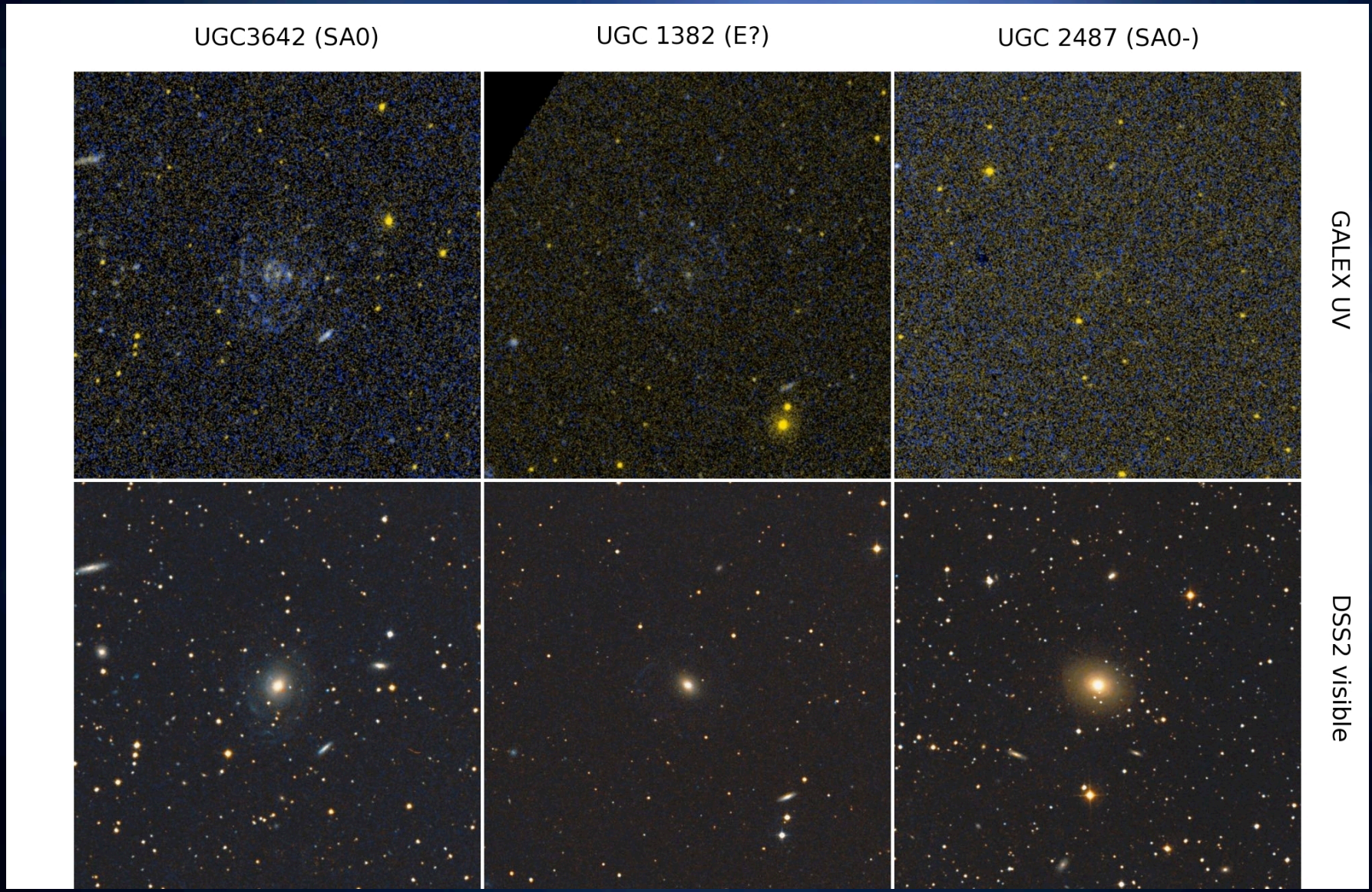


- Barth (2007): HST shows Malin 1 has a typical S0-like disk within separate LSB outer component.
- Massive LSBs are likely extreme XUV-disks with anomalously high M(HI)

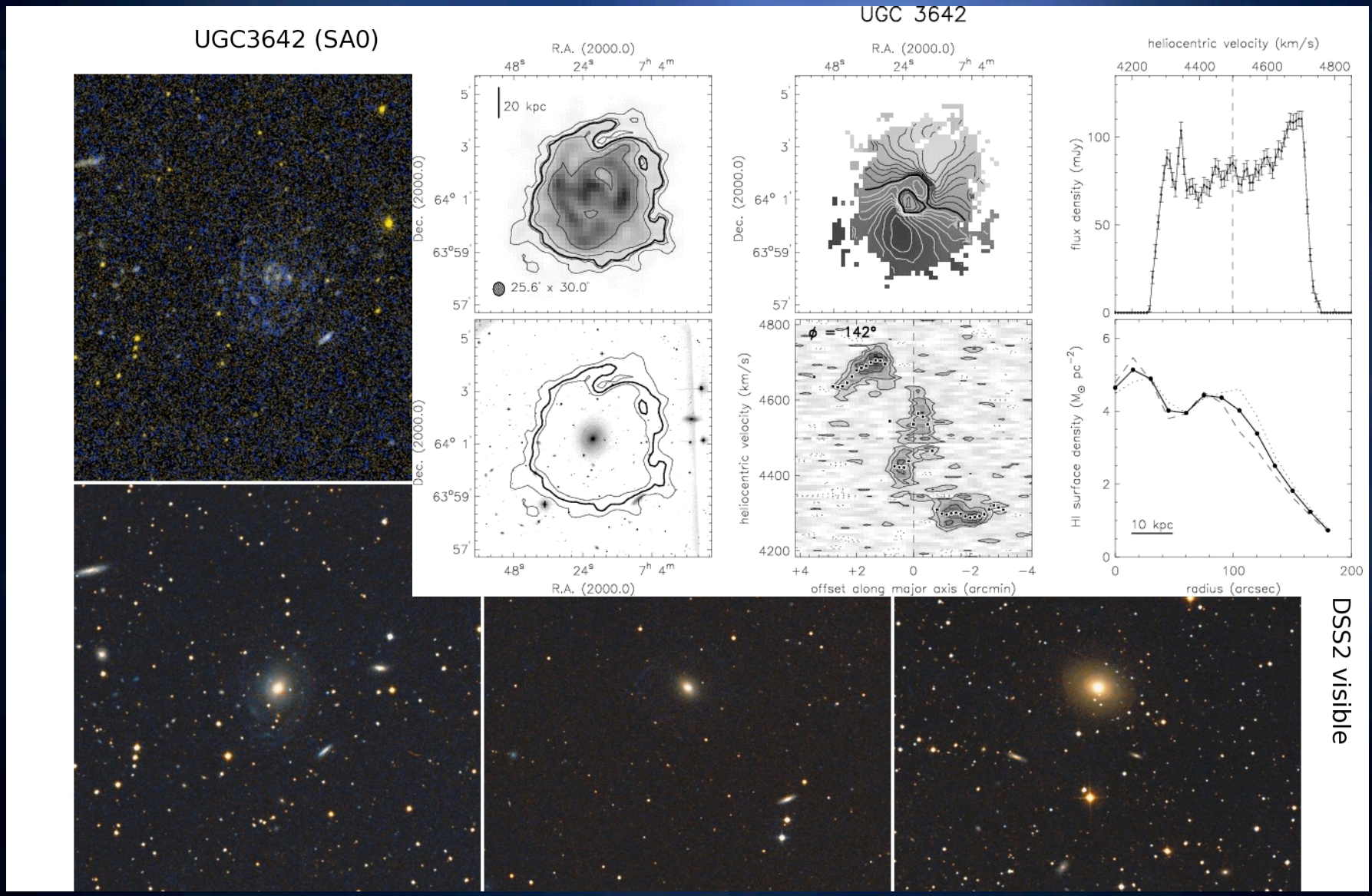
Massive LSB galaxies

- Two-stage (half-delayed) formation?
  - First make "host" object
    - HSB disk + bulge,
    - Or, red/dead E (like NGC 404 but massive)
  - This ordinary E or Sp is later dumped upon
  - High angular momentum accretion required to retain gas at large radii, not consumed in a quick burst of SF

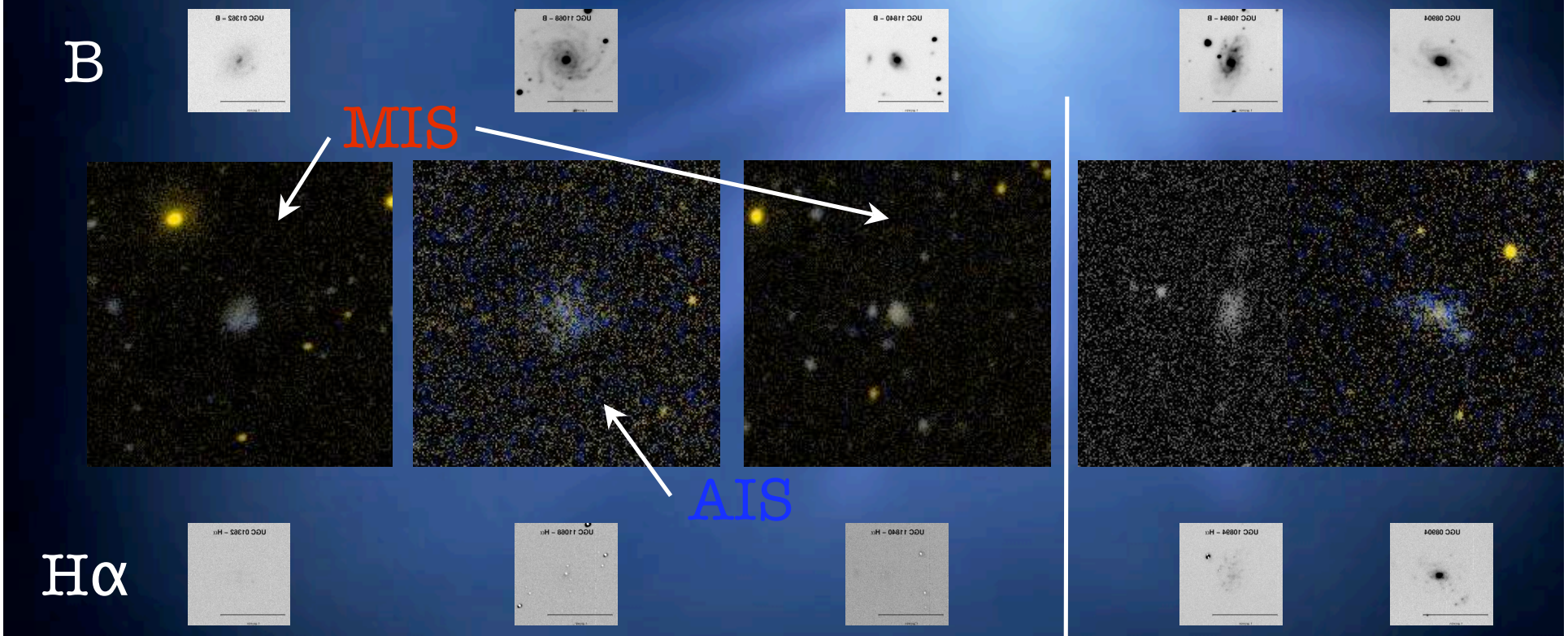
mLSB galaxies in formation about E or S0 hosts.
Rivaling Malin 1… log M(HI)>10 and diameter 100-150 kpc



mLSB galaxies in formation about E or S0 hosts.
Rivaling Malin 1… log M(HI)>10 and diameter 100-150 kpc



GALEX + future UV missions are critical to the study of mLSB SF activity

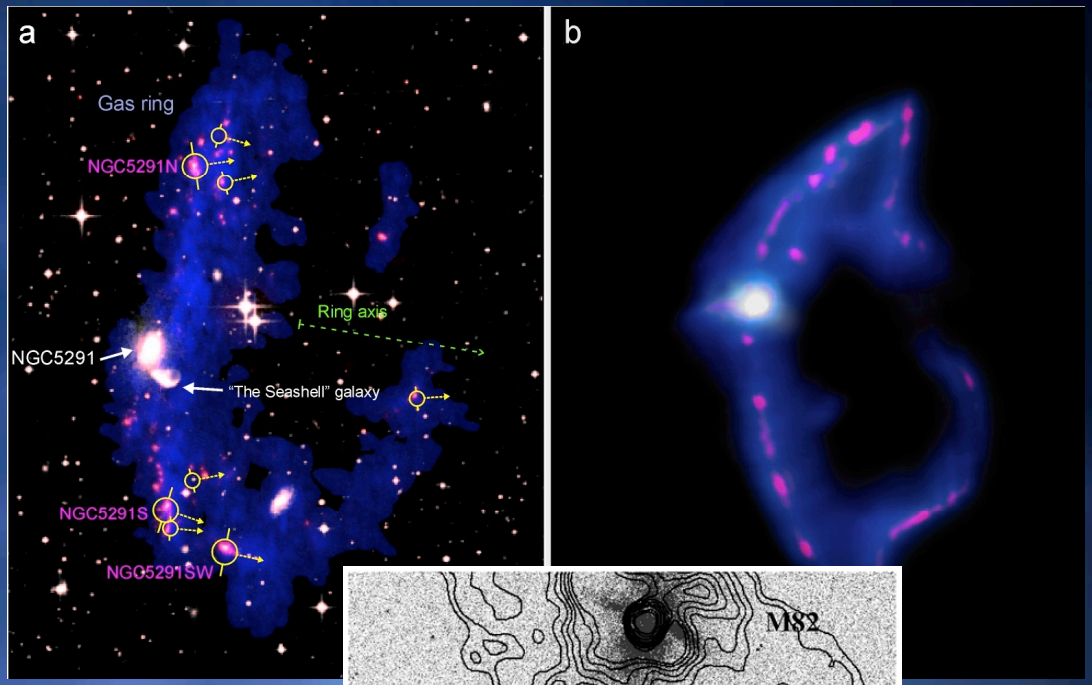


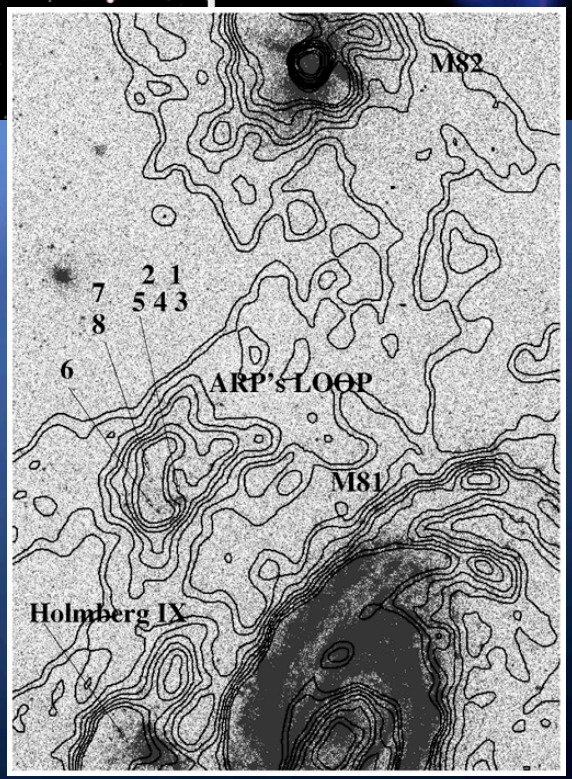
Don't forget the little ones…

- Hα imaging = limited representation of recent SF in dwarf LSBs [stochastic incompleteness at low SFR, possible Integrated Galactic IMF issues]
  - see Boissier et al. '07, Thilker et al. '07
  - IGIMF (Weidner poster here!)
- A large sample of dwarf LSBs must be analyzed in UV to assess their true SFR distribution, checking assumed SFR calib. with full SED modeling or resolved CMD modeling for a subset.
  - Implications for SFR density vs. z
  - Hunter et al. (today)
  - LVL survey results forthcoming (Lee et al.)

Entirely new galaxies

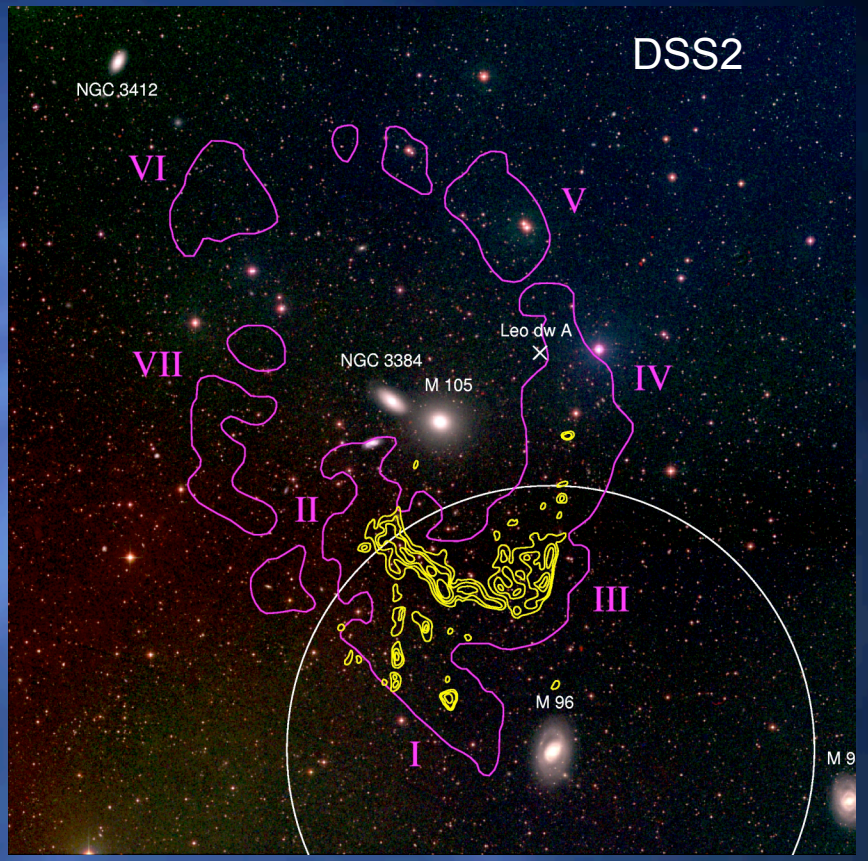
- e.g. tidal dwarf galaxies, TDGs
- NGC 5921
  - Boquien et al. '07
- M81 group
  - de Mello et al. '08
- NGC 1533
  - Werk '09 + today!





SF in the Leo Ring

- Intergalactic SF
  - Intragroup environ.
- Dwarf formation in <u>potentially</u> pristine gas ring
- Clumps w/o DM?
  - New route to objects similar to TDGs
  - But in this case, no pre-enrichment

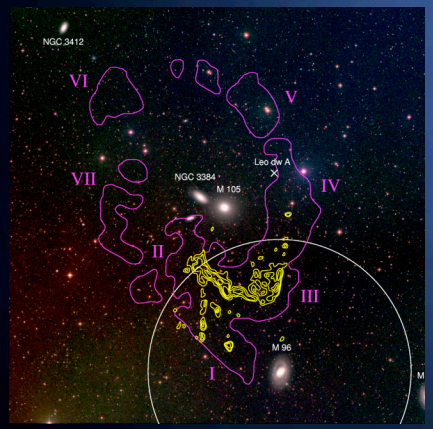


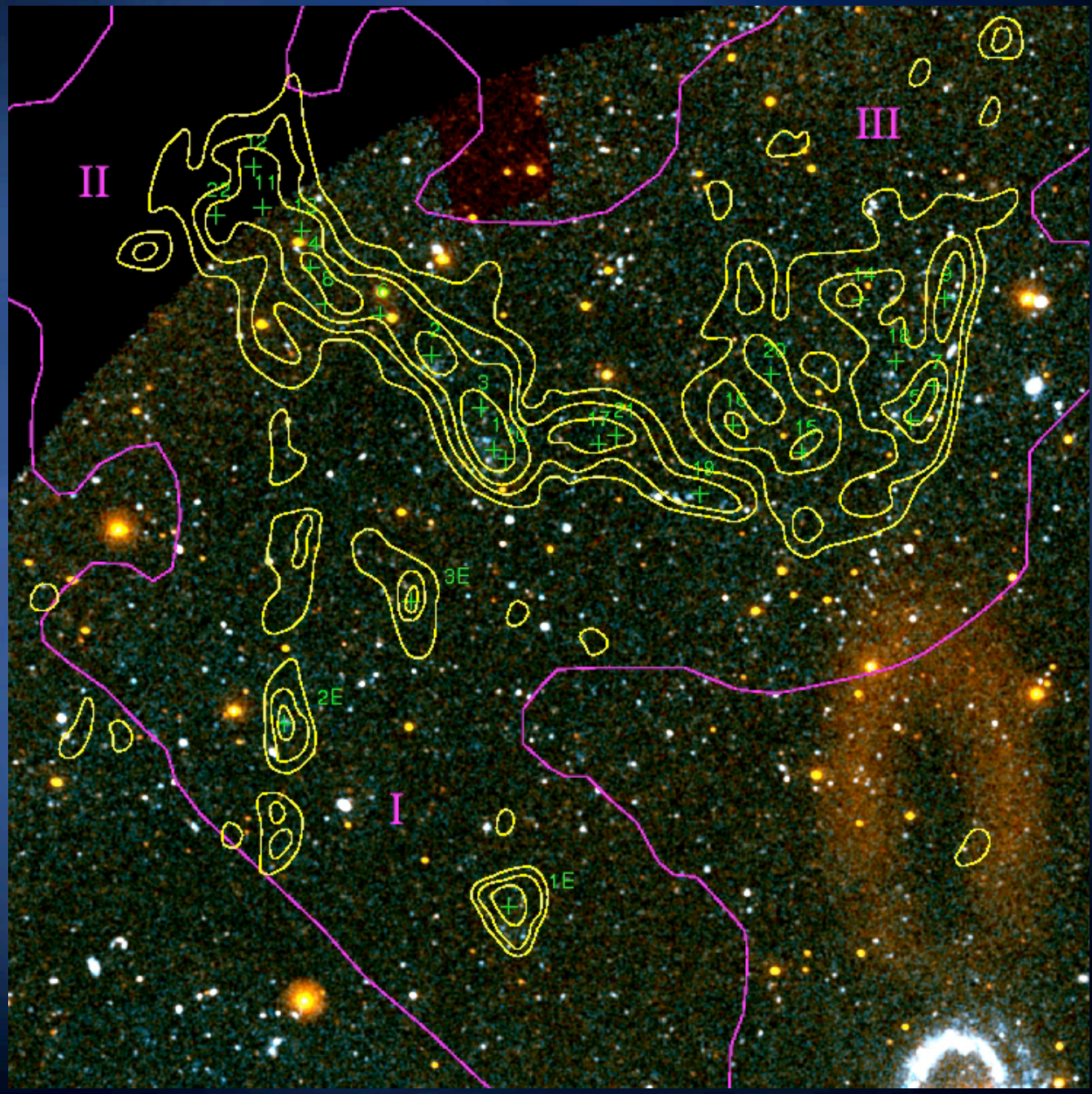
350 kpc
4 Gyr orbital timescale

Thilker et al. (2009)

GALEX discovery image

- Aricebo HI 2×10^{18} cm^{-2}
- VLA 45" HI $0.1\text{-}2 \times 10^{20}$ cm^{-2}

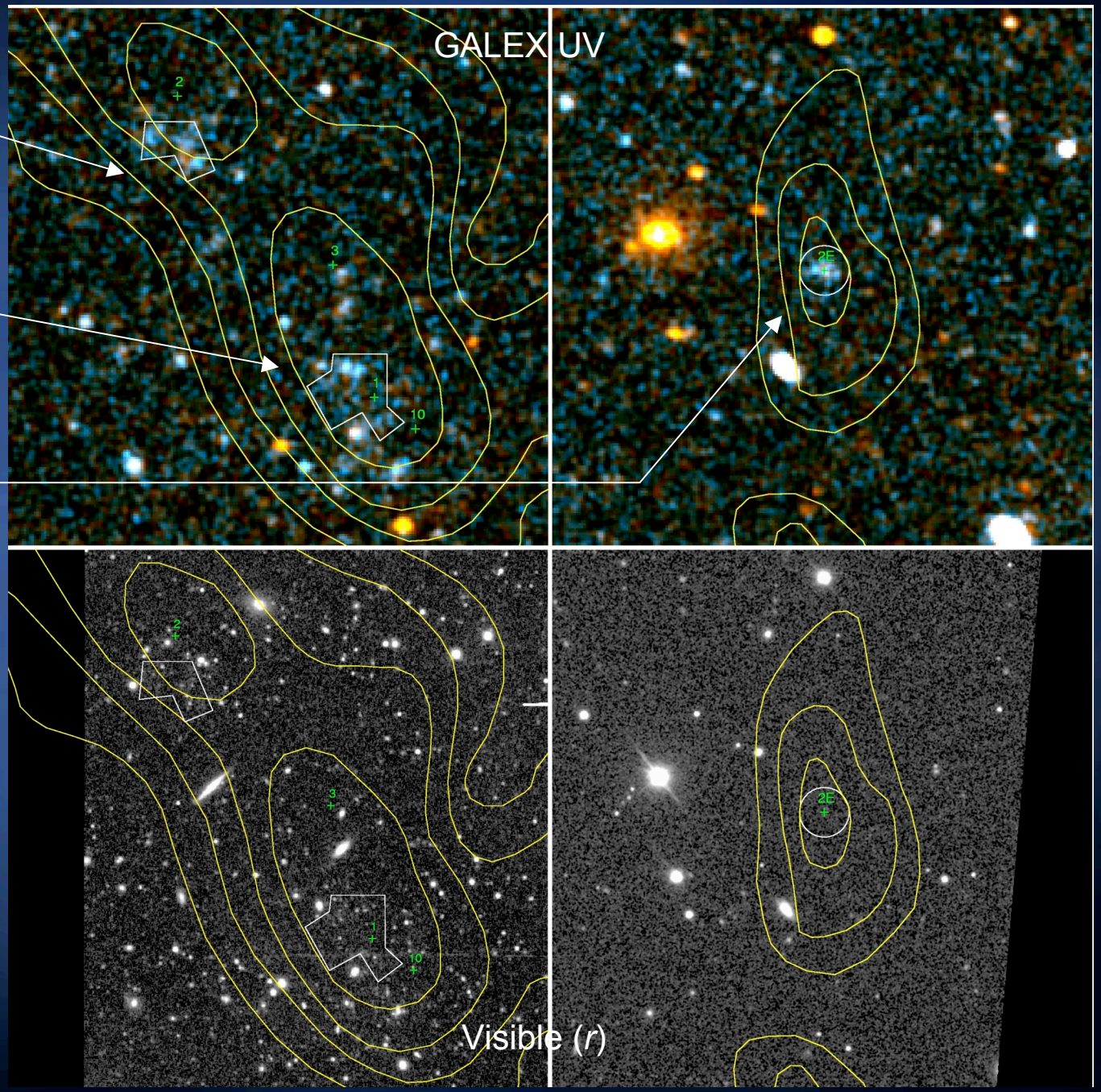




~1 Gyr

550 Myr

150 Myr



Σ_{HI} ~ 1 Ms pc^{-2}

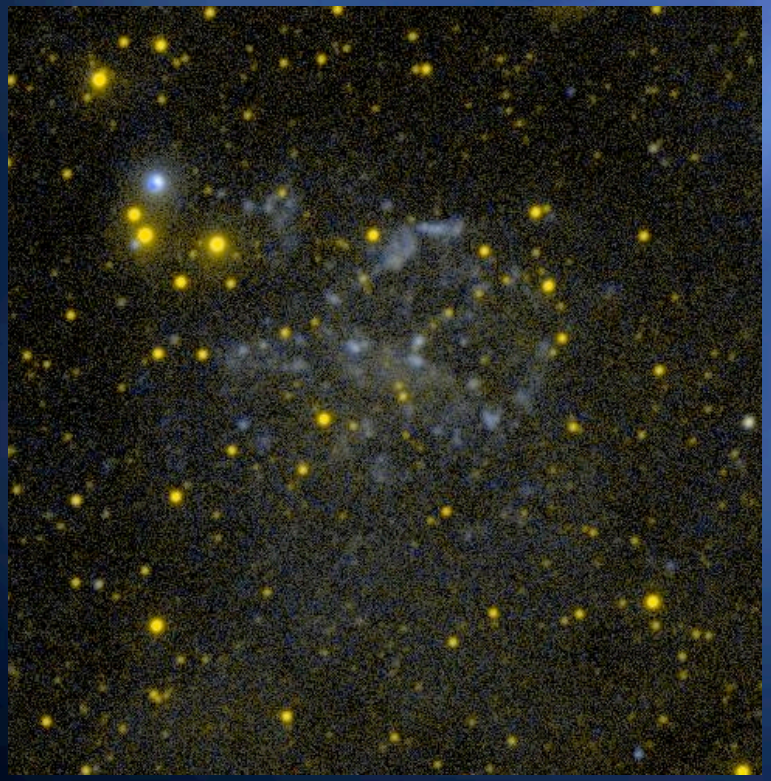
Σ_{SFR} 0.0001-0.0002 Ms yr^{-1} kpc^{-2}

VLA follow-up underway…
Deep GALEX and Magellan too!

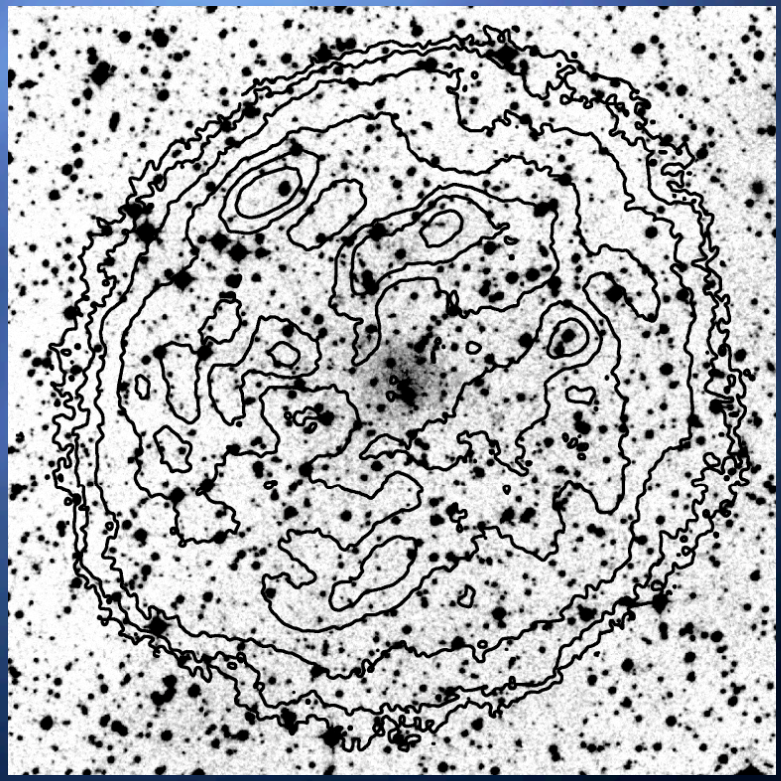
16 kpc FOV / panel

GALEX Deep Galaxy Survey

- 15ks per galaxy (10x normal NGS exposure)
- Small pilot sample, eventually ~100 targets
- Science goals: XUV, low dens. SFL, extraplanar dust in edge-ons, extreme HI-rich dwarfs, massive LSB galaxies



GALEX DGS



Warren et al. '04

ESO 215-G?009: highest M(HI)/L(B) known - almost no Hα

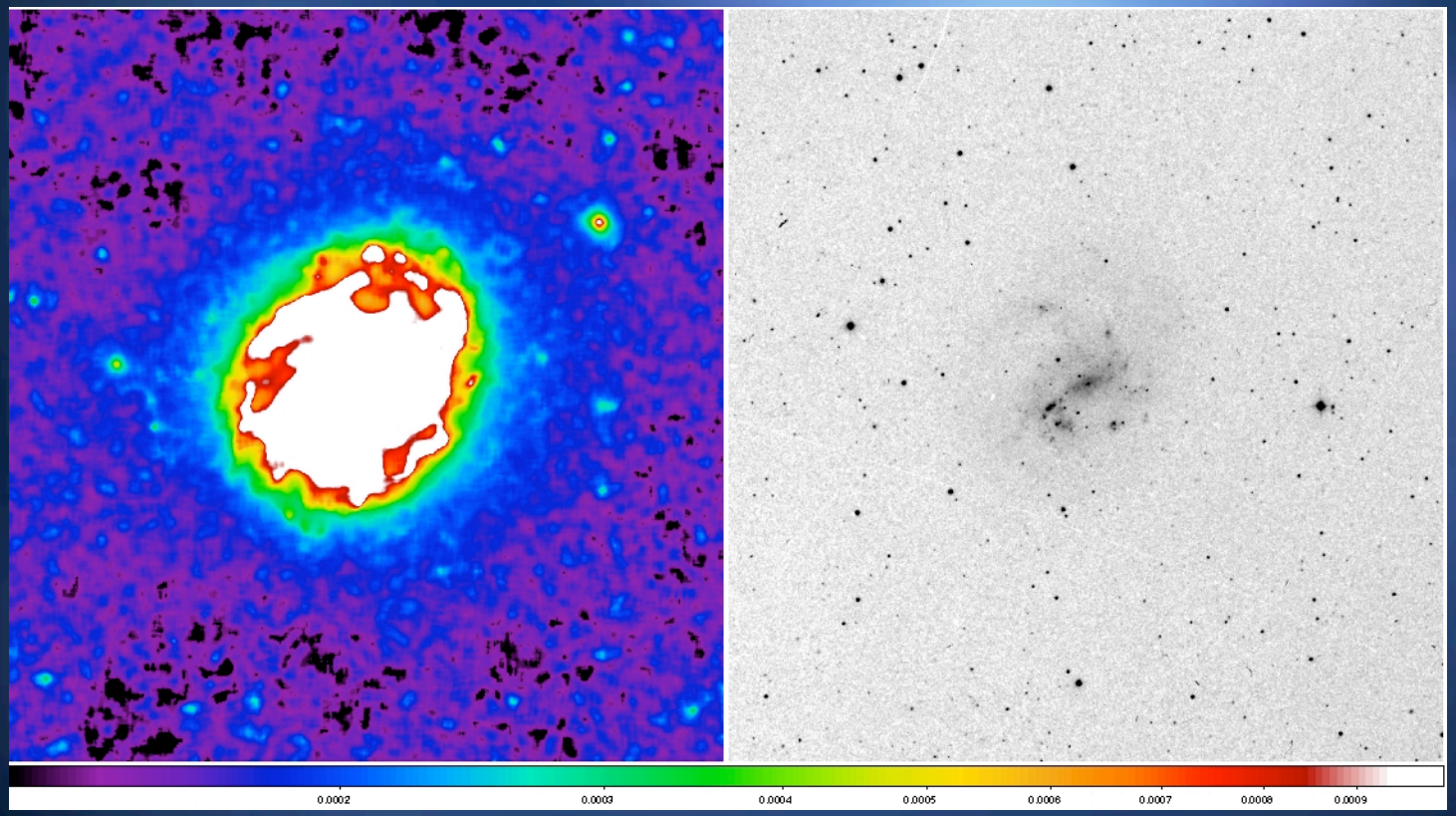
UV prob. distrib. function at low Σ_{HI}

- Probabilistic SF recipe, instead of a "threshold"
  - SF more likely for log N(HI)=20 at 1 kpc res. than log N(HI)=20 at 100 pc res. assuming similar struct
  - Unresolved CNM cores matter most
    - Note, they may come and go on *t* short vs. UV
- Based on HI cubes, and deep FUV, 3.6 μm images
  - Select HI-dominated environments only
  - Measure bkgd-corrected PDF(I_{FUV}) as a function of:
    - Σ_{gas} , P_{ext} , spat. scale, stability param.

UV prob. distrib. function at low Σ_{HI}

- Complications
  - Background galaxies
    - Flag with deep, high-resolution opt. imaging
  - Scattered UV light from dust
    - NGC 253, M82 : Hoopes et al. ‘05 (SB outflow)
  - Multiple age stellar populations
    - Distinguish by morphology? clumpy vs. smooth
    - Distinguish by (UV, UV-opt.) colors?
  - Cirrus from MW
    - Map foreground IR, HI
    - Target high-latitude galaxies

Outer, diffuse UV emission past detected HI



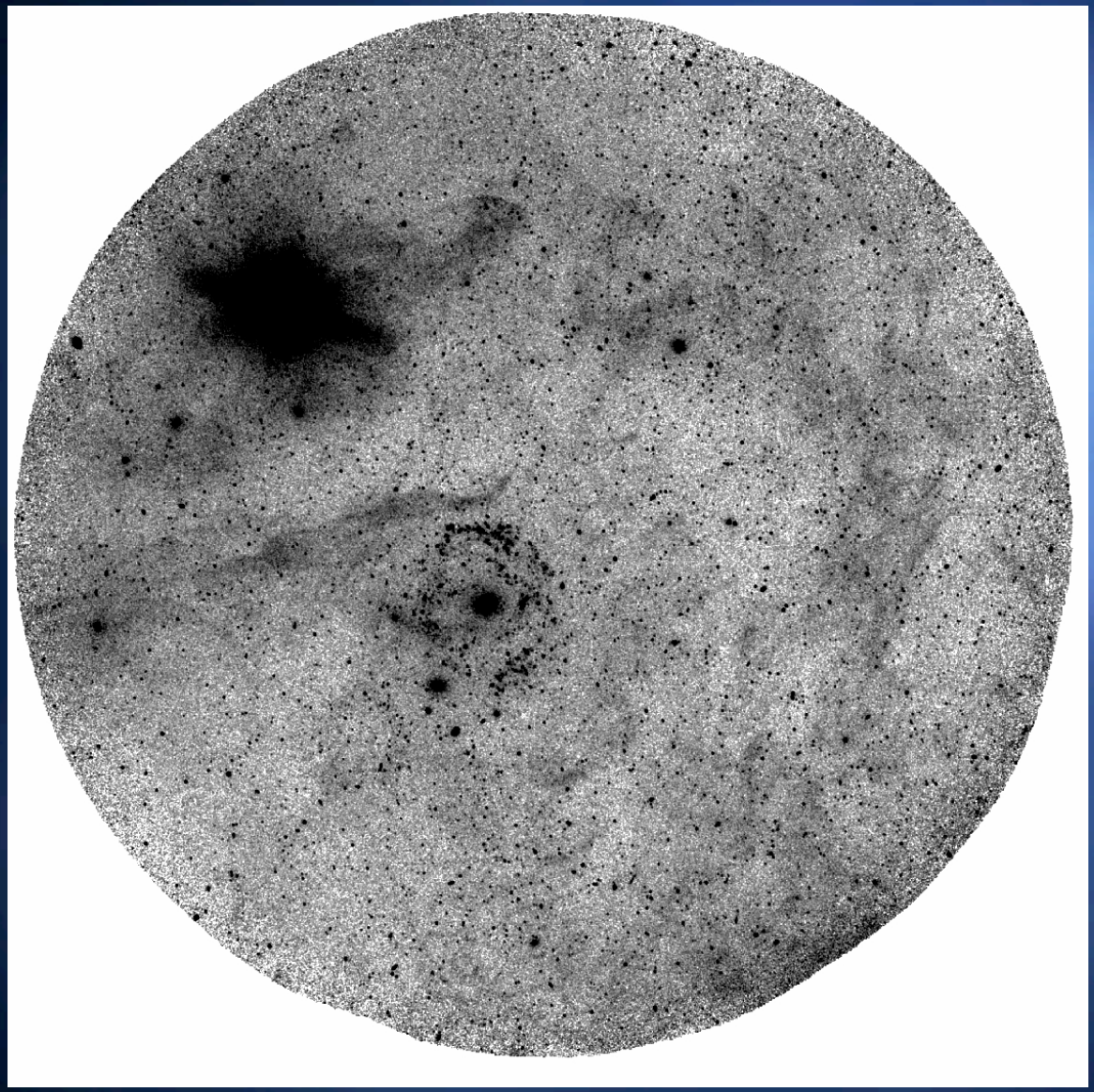
40ks GALEX FUV NGC 4395

DSS2

Thilker et al. (sometime soon)

UV prob. distrib. function at low Σ_{HI}

- Complications
  - Background galaxies
    - Flag with deep, high-resolution opt. imaging
  - Scattered UV light from dust
    - NGC 253, M82 : Hoopes et al. ‘05 (SB outflow)
  - Multiple age stellar populations
    - Distinguish by morphology? clumpy vs. smooth
    - Distinguish by (UV, UV-opt.) colors?
  - Cirrus from MW
    - Map foreground IR, HI
    - Target high-latitude galaxies



NGC 404: 13.4ks GALEX FUV

MW cirrus!

Summary

- LSB SF is common in a variety of low density environments and traces important phases of galaxy evolution
  - Inside-out disk formation continues in XUV-disks
  - Evolution in the galaxy CMD is not purely one way
    - Rejuvenated ETGs can also have XUV structure, sometimes even forming disks
    - External origin of gas more obvious for RS galaxies
  - Massive [giant] LSB galaxies may be extreme cases of the XUV-disk phenomenon + formed in two stages
    - Ordinary disk or E separate from ext. LSB compon.
  - Intergalactic (tidal, or unenriched) gas spawns dwarf galaxies more often than thought, survival?
- New deep GALEX survey, but interpret w/ care.
- Upcoming…Much more comprehensive XUV-disk census & probabilistic SF law/thres at low NHI