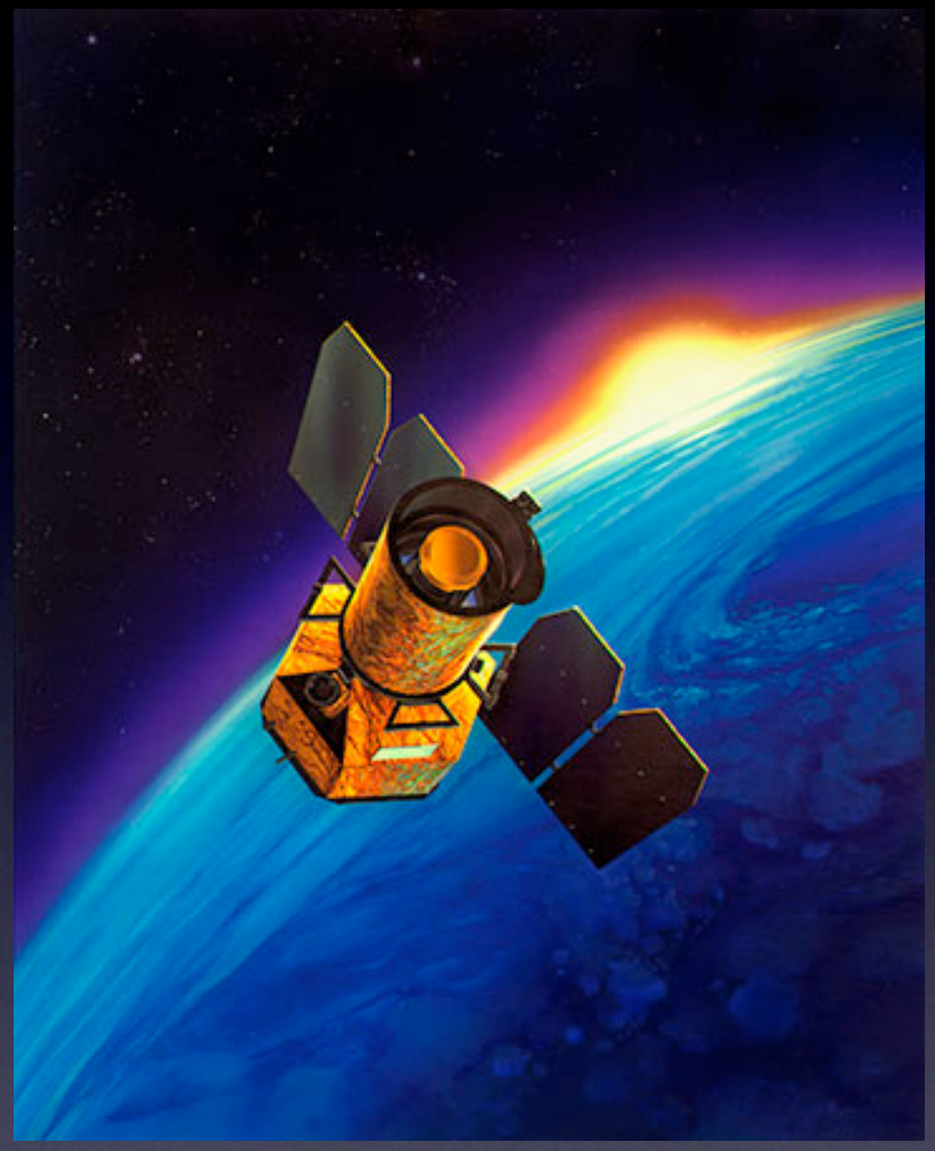
*Outer Disks of Nearby Galaxies*

# Ultraviolet Insight from GALEX



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- GALEX - mission specifics
- UV-traced SF reflects the presence of extended gas distributions, acquisition and removal processes, and the overall role of gas in galaxy evolution and transformation
- Highlighted results [and processes]:
  - Extended UV disk (XUV-disk) galaxies [accretion]
  - The Green Valley and early-type rejuvenation [merger]
  - On the late formation of giant LSB disks [TBD??]
  - SF intergalactic structures and tidal dwarf galaxies [collision, interaction]
  - Timing gas removal in cluster environments [stripping]

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# GALEX Galaxy Evolution Explorer

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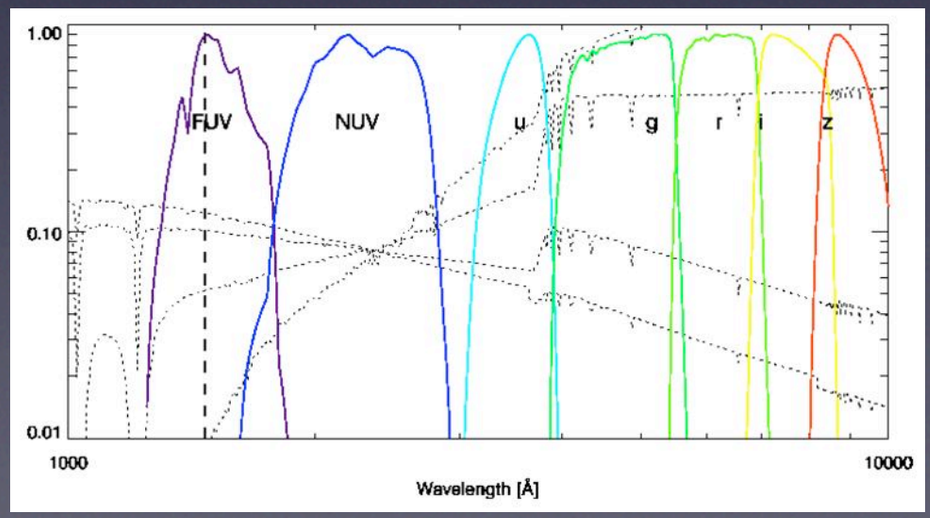
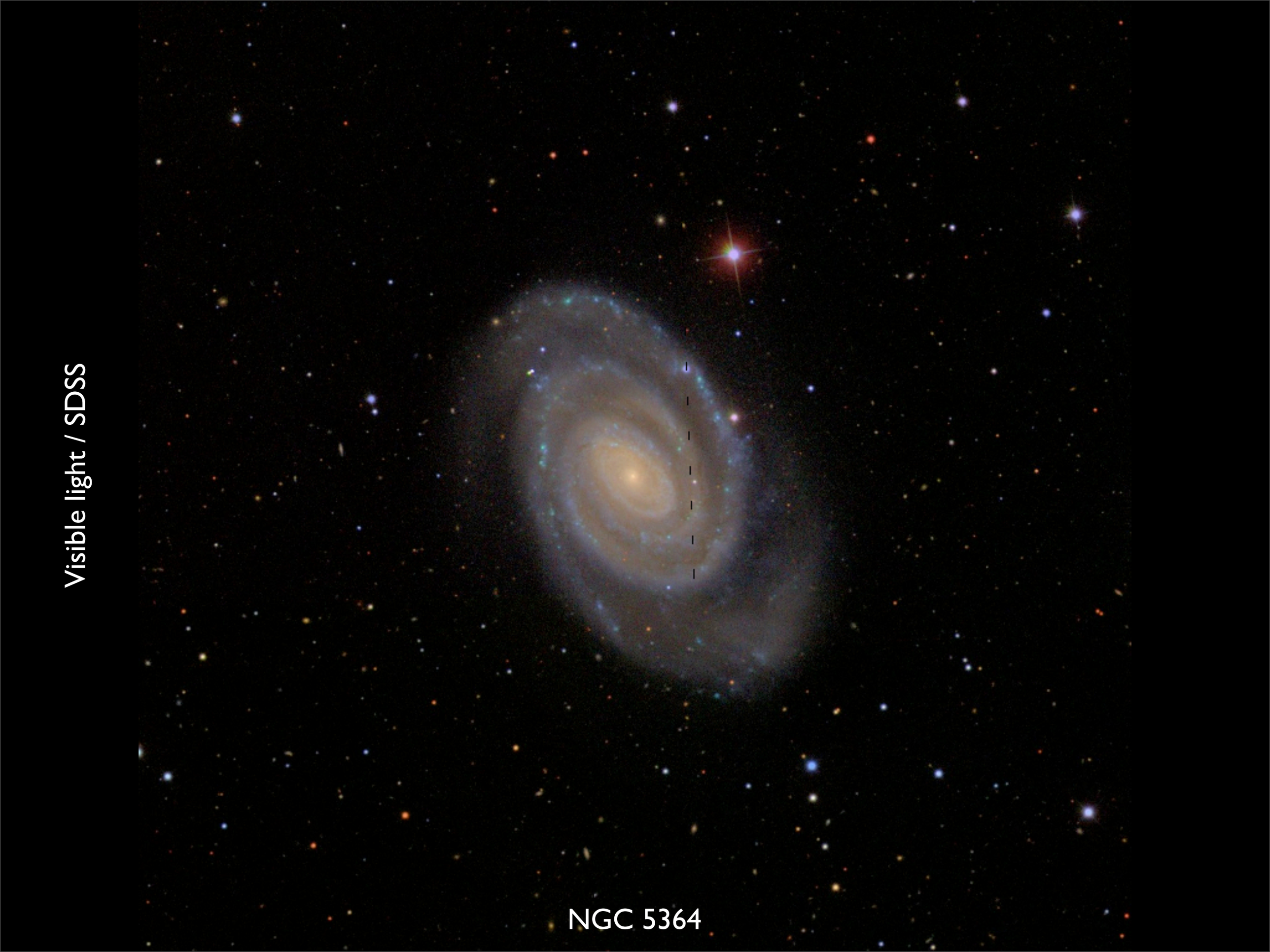
- GALEX = UV "sky survey" mission / 50 cm aperture
  - All-sky Imaging Survey (AIS), Medium Imaging Survey (MIS), Nearby Galaxy Survey (NGS), Deep Imaging Survey (DIS)
  - current "Legacy" surveys
    - formerly - guest investigator program
- Two simultaneous detectors (~~FUV 1539A~~, NUV 2316A)
- Imaging + grism modes
- 4 - 5" resolution
- 1.2° diameter circular FOV




Visible light / SDSS
NGC 5364

UV light / GALEX

NGC 5364

Visible light / SDSS

NGC 4656

UV light / GALEX

NGC 4656

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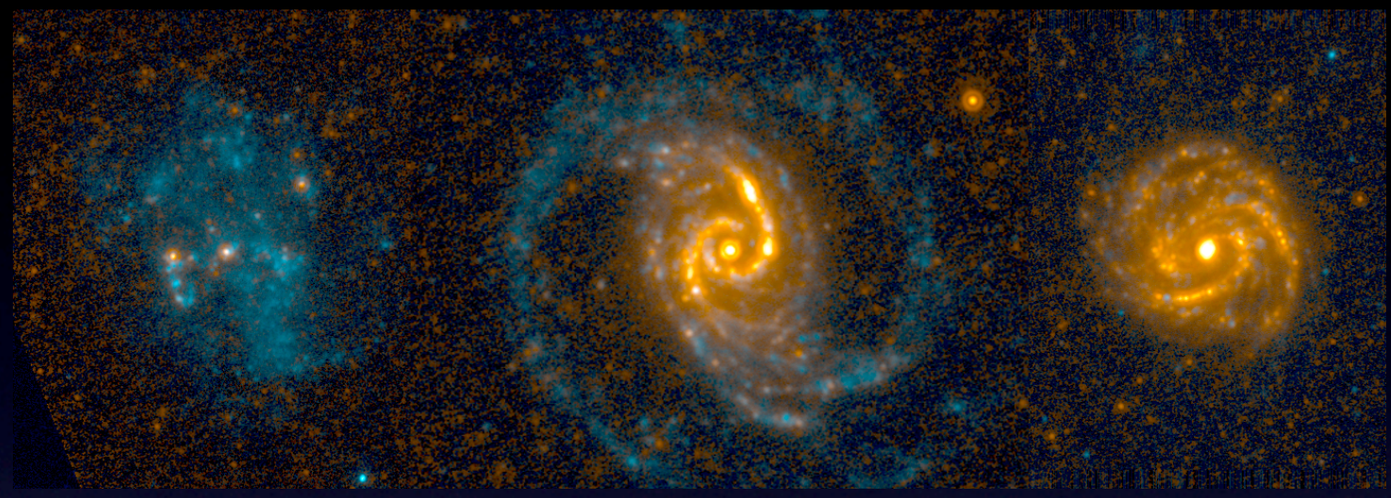

FUV / 24μm

- Key advantages
  - wide-field = serendipity
  - very low sky bkgd
  - high sensitivity to locales of *recent* SF (few 100 Myr)
- Limitations
  - modest angular resolution, brightness limit
  - potentially dust censored
    - true synergy with Spitzer and Herschel in IR

# GALEX Galaxy Evolution Explorer



Discovery - Thilker et al. (2005) / Deep Image - Bigiel et al. (2010)

## Extended Disk of Galaxy M83

GALEX • NUV • FUV
VERY LARGE ARRAY • RADIO

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- Long known that HI disks are larger than optical extent, but such extensive SF was a surprise
  - Early VLA and WSRT maps -- now THINGS / LVHIS
  - Deep census: HALOGAS, soon MHONGOOSE
- Next generation all-sky HI surveys = unbiased picture
  - ASKAP (WALLABY) and WSRT (WNHS)
- GALEX *already* provides a view of associated SF activity
  - Gas consumption, enrichment + improved SFL
  - Follow-up optical spec. of youngest reg. to pin down metallicity
  - GALEX can also supply QSO sightlines for absorption spec.

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# THINGS

## The HI Nearby Galaxy Survey

NGC 2841
NGC 3621
NGC 7331
NGC 4826 (M64)
NGC 6946
NGC 3184
NGC 925
NGC 3351 (M95)
NGC 3198
NGC 5194 (M51)
NGC 5236 (M83)
NGC 3521
NGC 4214
NGC 2976
DDO 53
NGC 1569
M81dwB
M81dwA
NGC 2366
Our Galaxy HI stars
IC 2574
NGC 4449
NGC 3627 (M66)
Holmberg II
NGC 7793
DDO 154
NGC 4736 (M94)
NGC 3077
Holmberg I
NGC 5055
NGC 2903
10 kpc
NGC 628 (M74)
NGC 5457 (M101)
NGC 3031 (M81)
NGC 2403

THINGS
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

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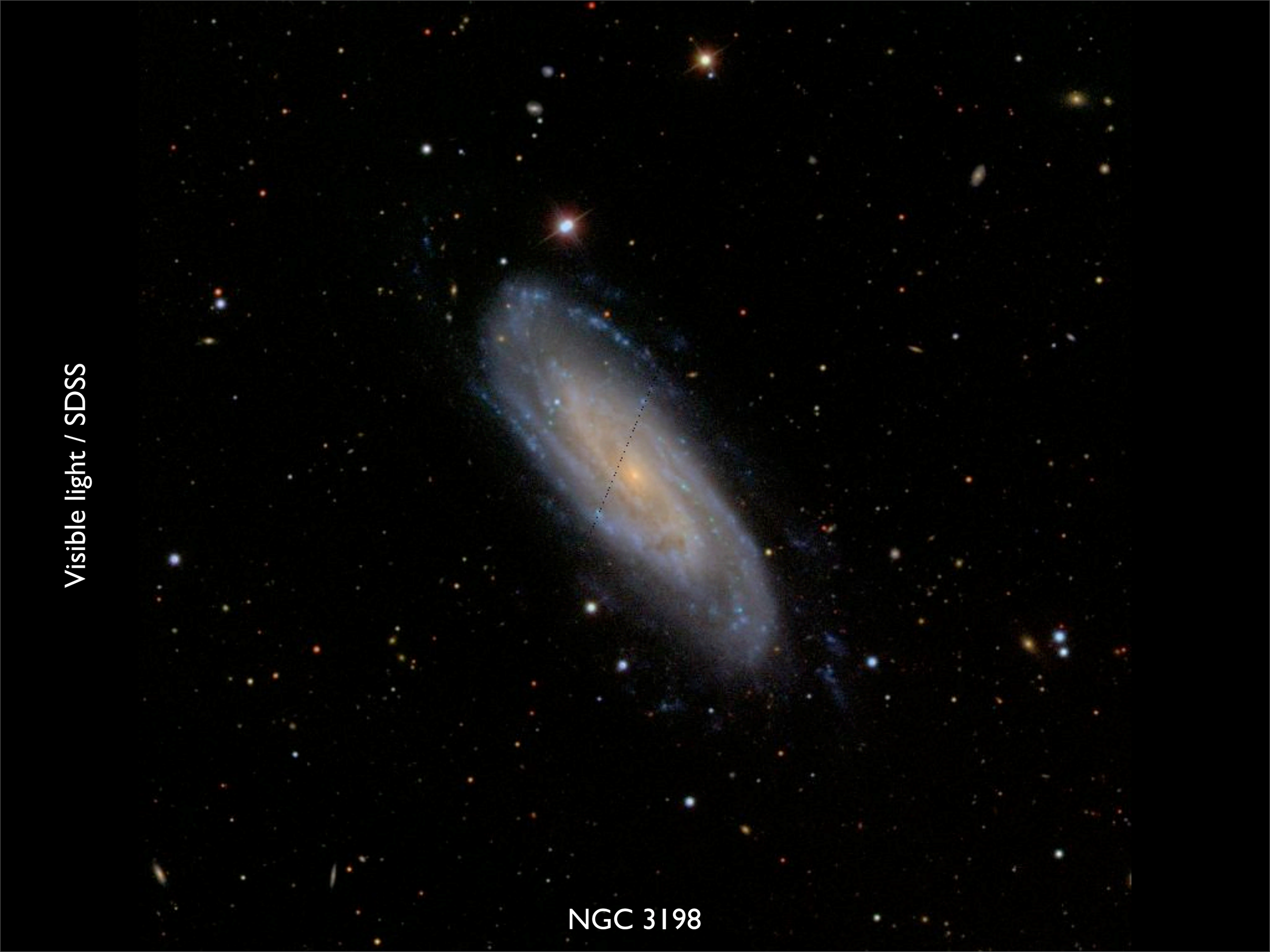
- Extended UV disk (XUV-disk) galaxies
  - Outer disk, low density star formation within HI reservoir
    - Highly structured distribution of UV-bright clumps
    - Spatial correlation on kpc scales between HI and UV
    - Azimuthally averaged $\Sigma_{SFR} < 10^{-4}$ $M_\odot$ / yr / kpc$^2$ but bright exceptions
  - Limited HII reg. originally seen in H$\alpha$ by Ferguson et al. (1998)
  - XUV portion = few to 50+% of $L_{UV,\,tot}$ = diverse morphology
  - XUV features evidently commonplace, but when to call it ...
    - Significant? (only if morphologically transformative?)
    - Outer? (past stellar body or main area of SF?)

Visible light / SDSS

Messier 63

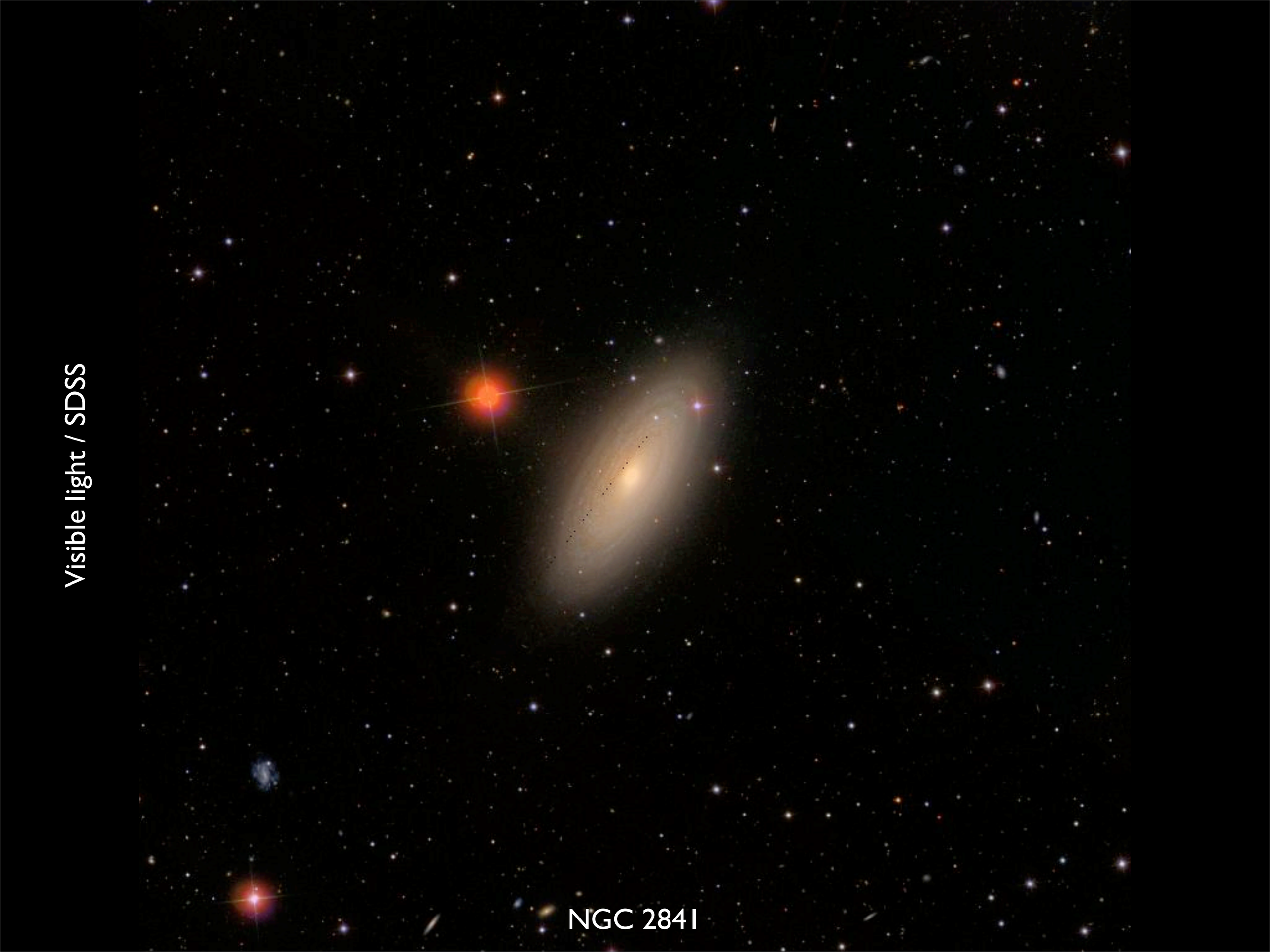
UV light / GALEX

Messier 63


Visible light / SDSS
NGC 3198

UV light / GALEX

NGC 3198


Visible light / SDSS
NGC 2841

UV light / GALEX

NGC 2841

Visible light / SDSS

NGC 3359

UV light / GALEX

NGC 3359

Visible light / DSS2

NGC 628

UV light / GALEX

NGC 628


Visible light / DSS2
NGC 6744

UV light / GALEX

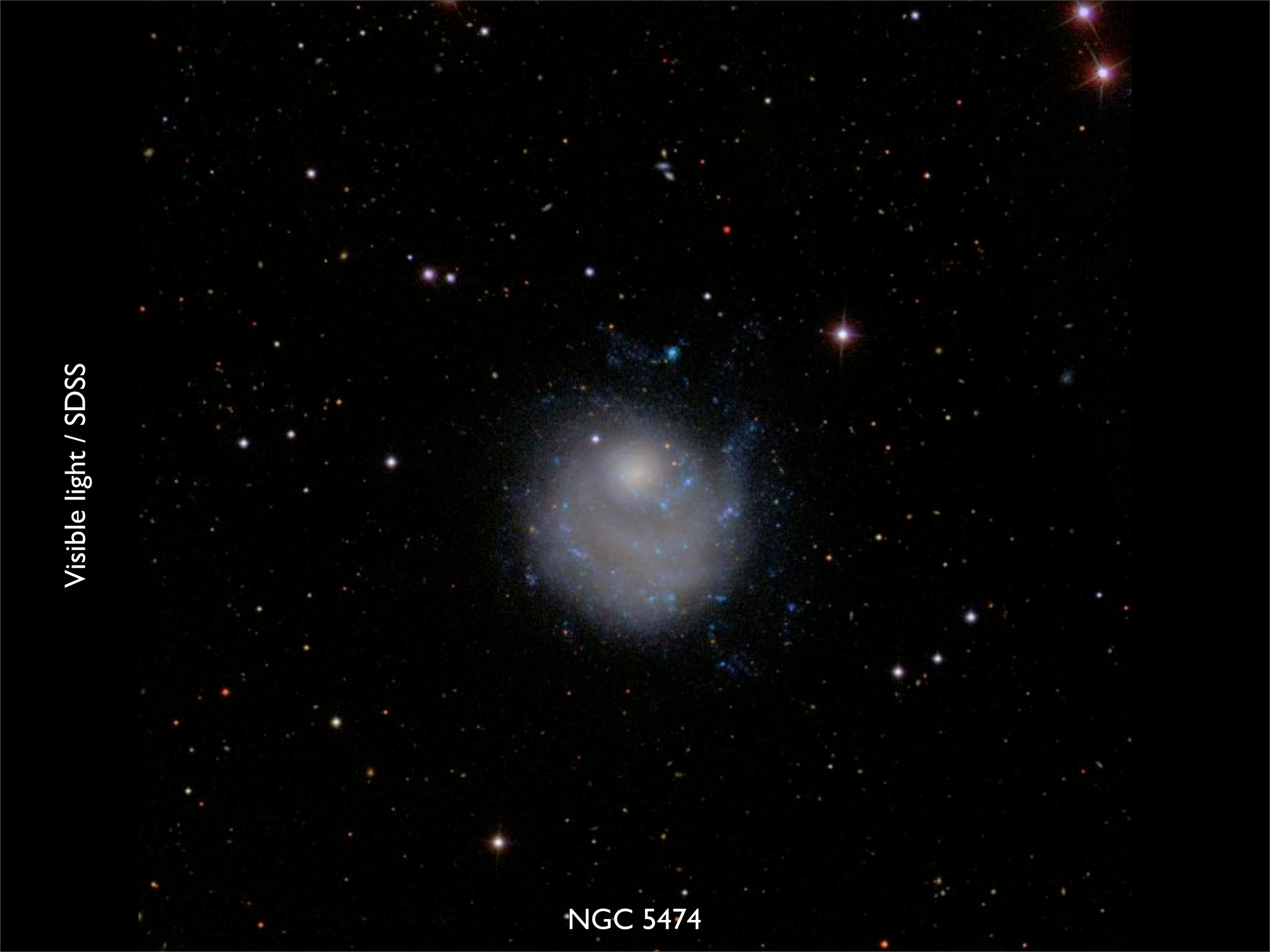
NGC 6744

Visible light / SDSS

NGC 2541

UV light / GALEX

NGC 2541


Visible light / SDSS
NGC 5474

UV light / GALEX

NGC 5474

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- Thilker et al. '07 published classification scheme based on ~200 galaxies drawn from the GALEX Atlas (Gil de Paz et al. '07).
  - Two (non-exclusive) morphological types ... NEXT SLIDE
  - 30% overall XUV-disk incidence at z = 0
    - Type 1 is twice as common as Type 2
    - Disk sparseness and imaging depth influence detection efficiency (eg. NGC 2915)
    - Zaritsky & Christlein (2007) independently derived similar incidence based on a smaller sample, but our survey provided the first large set of objects for detailed study.

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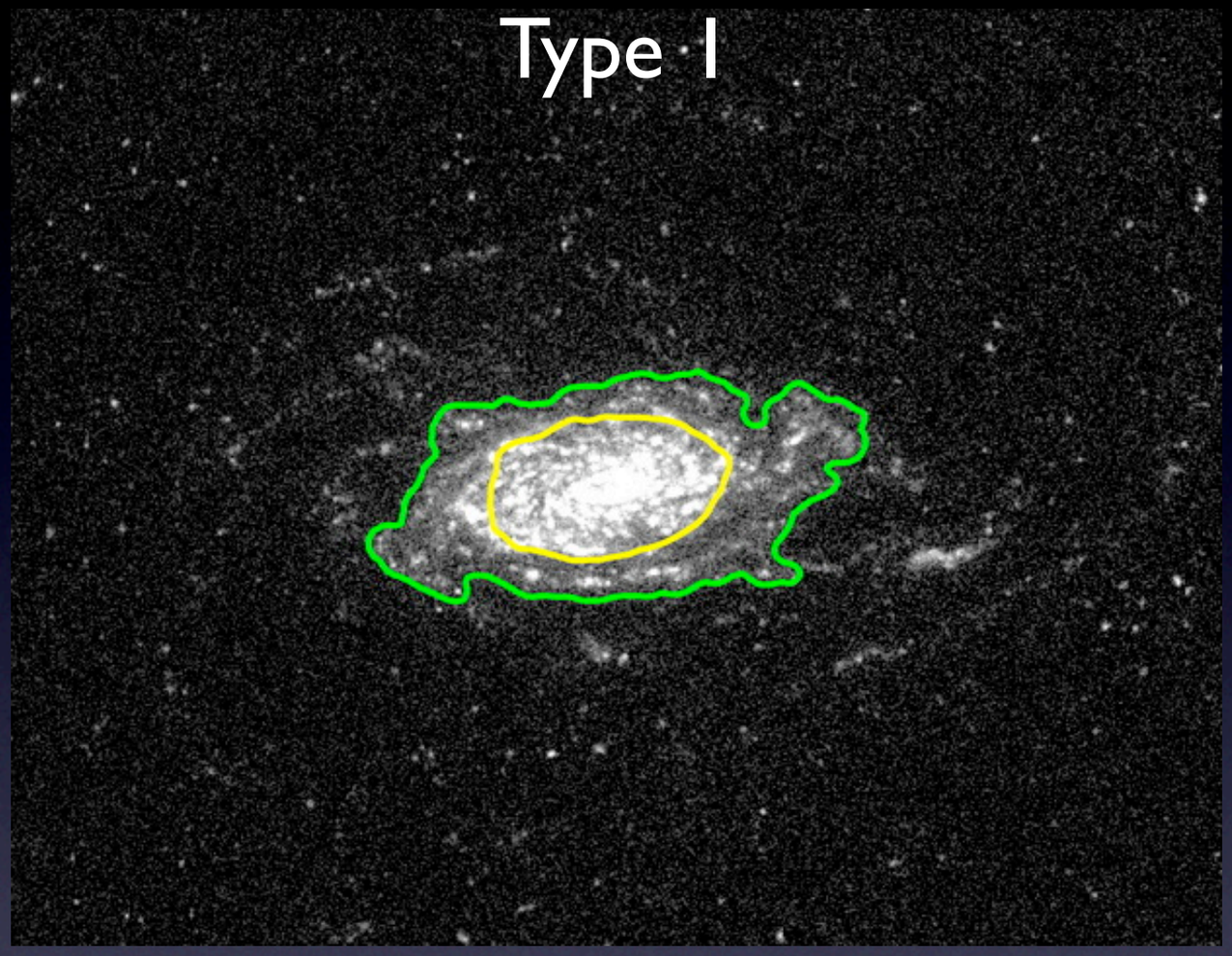
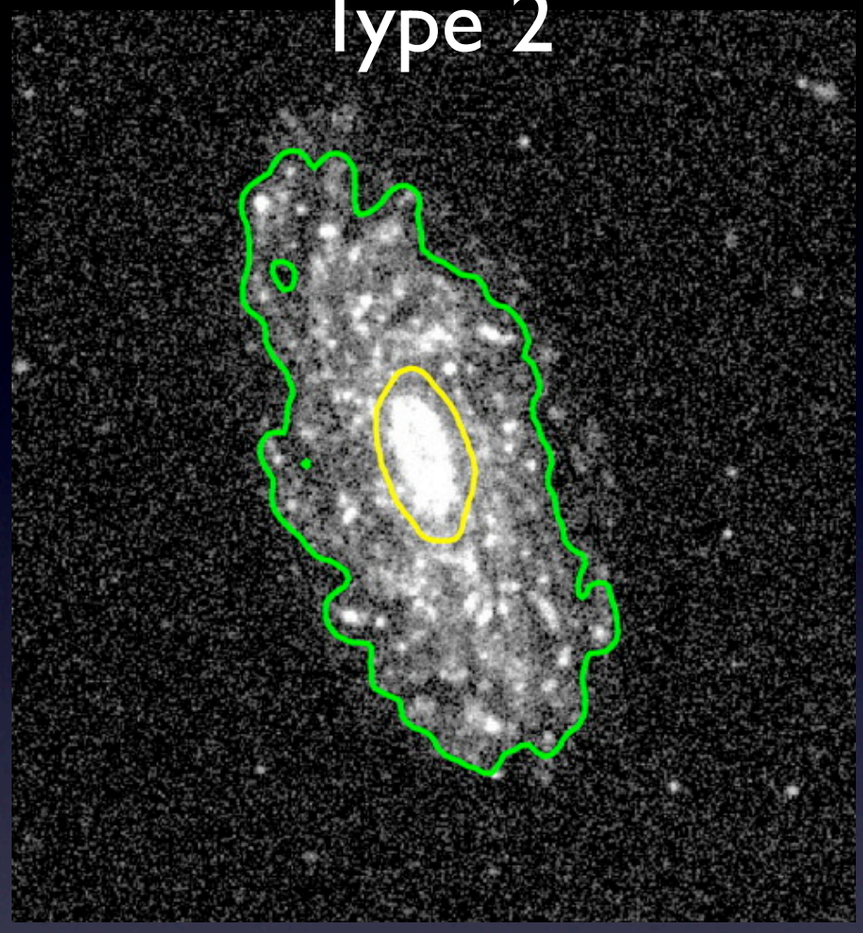
Type 1



Type 2



- Type 1 -- Sparse, structured UV past expected SF threshold
- Type 2 -- Widespread, blue LSB zone inside threshold but beyond 80% of stellar mass

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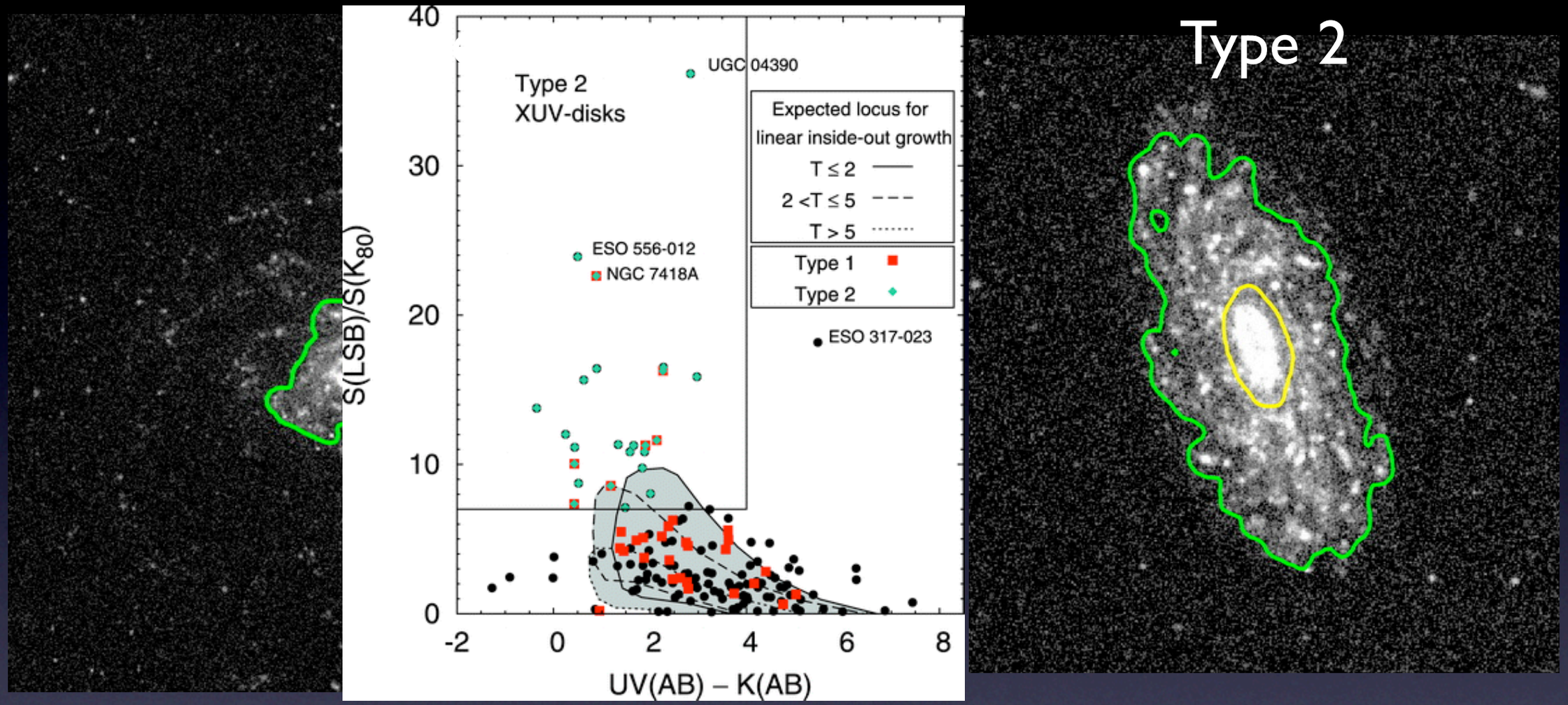


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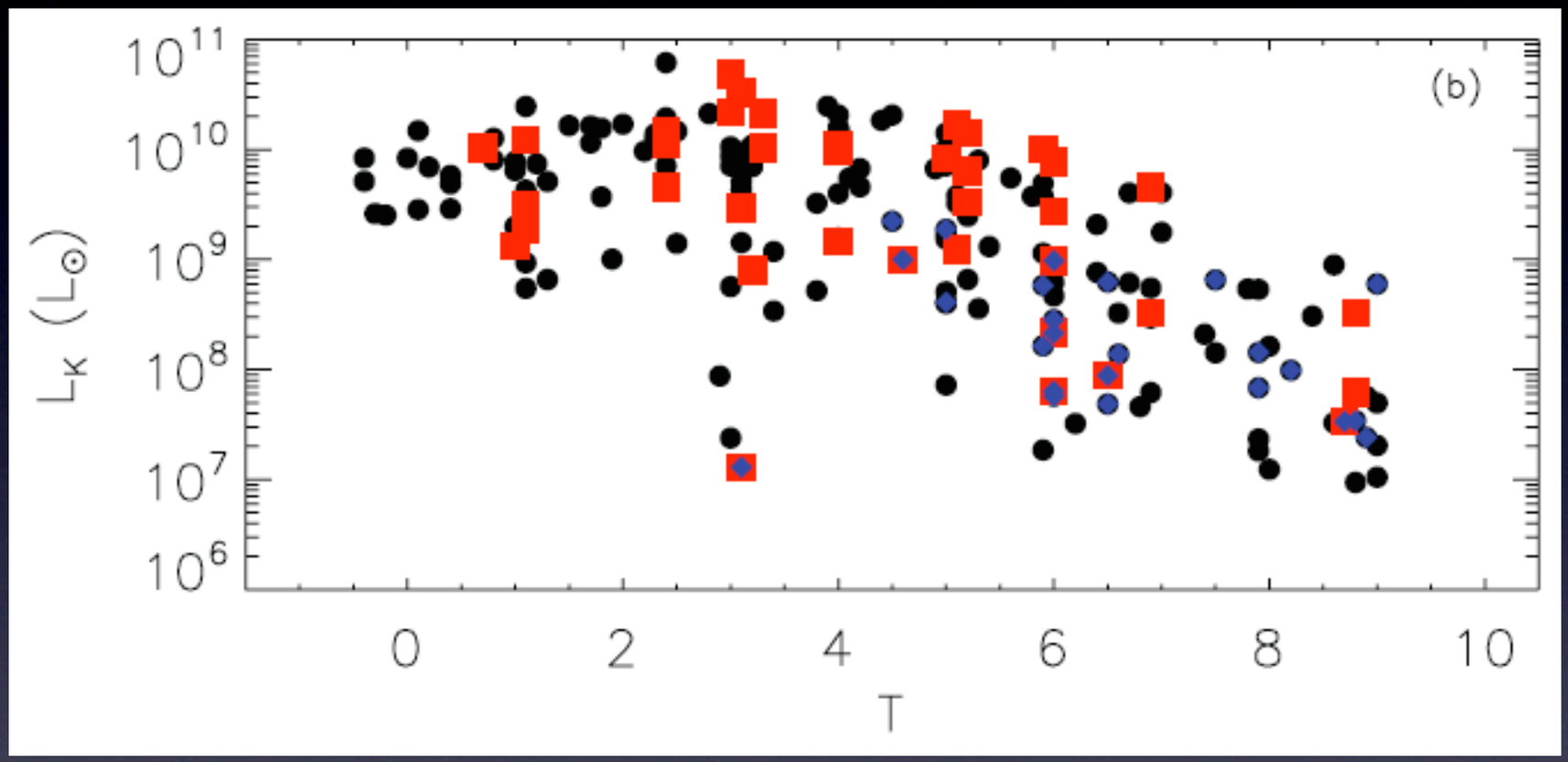
- Type 1 seen in all galaxy disks. Type 2 prefer late-type disks.




- Mergers unlikely the source of all the extended star-forming gas, though perturbation may stimulate SF (75% of XUV Type I have LSB companions or HVCs.)
  - IGM accretion is viable source

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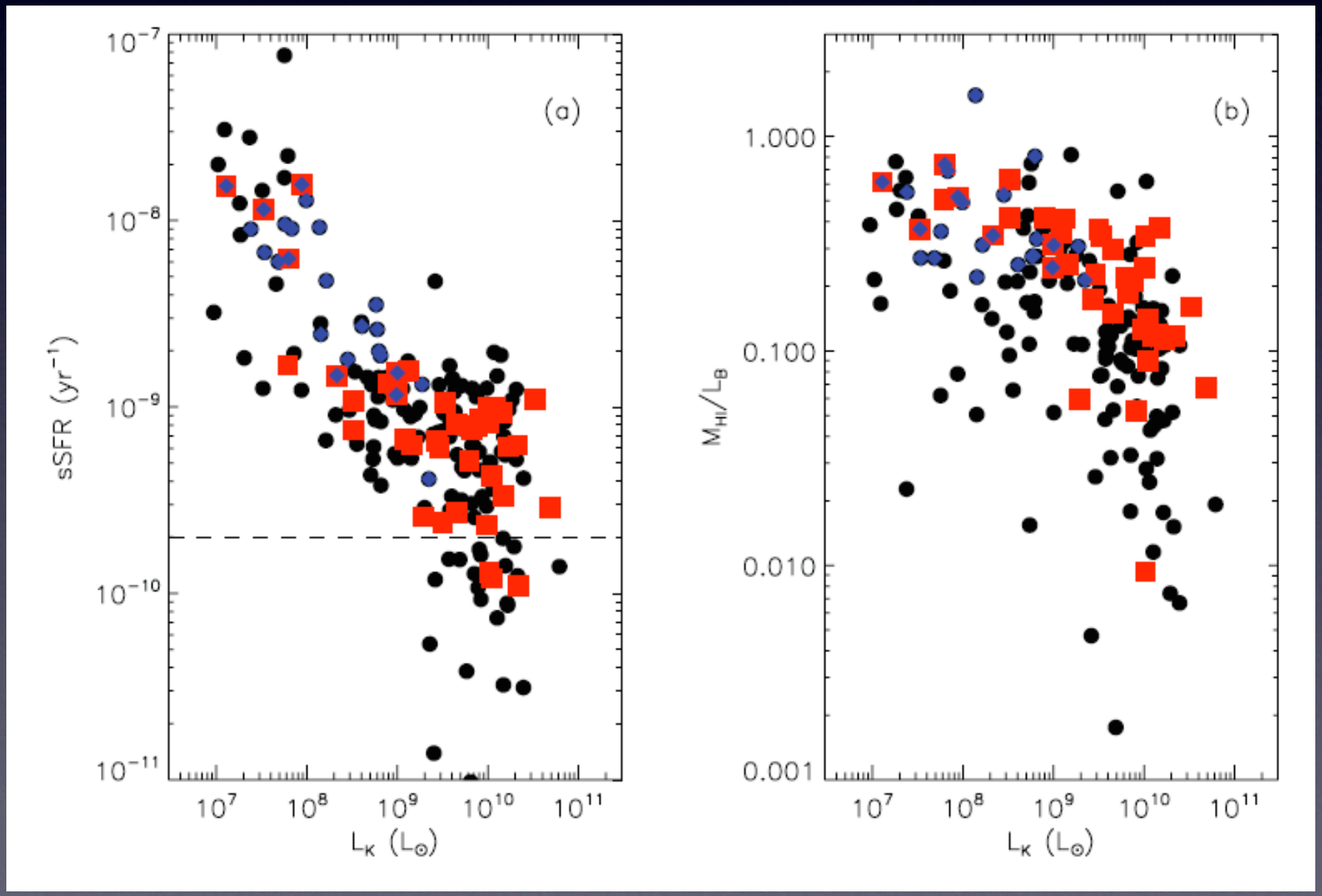
- High specific SFR in Type 2 - doubling of stellar mass in < 1 Gyr
- XUV-disks are 2x more gas rich than non-XUV counterparts at fixed $L_K$ or fixed SFR



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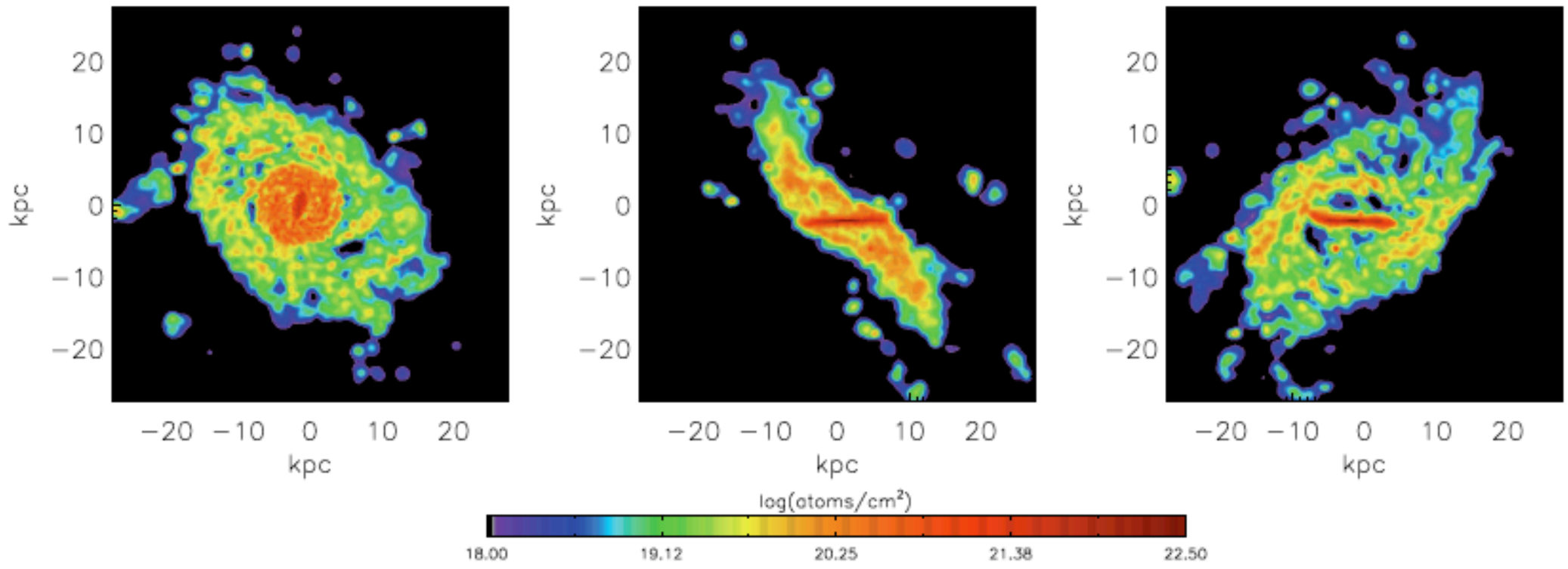
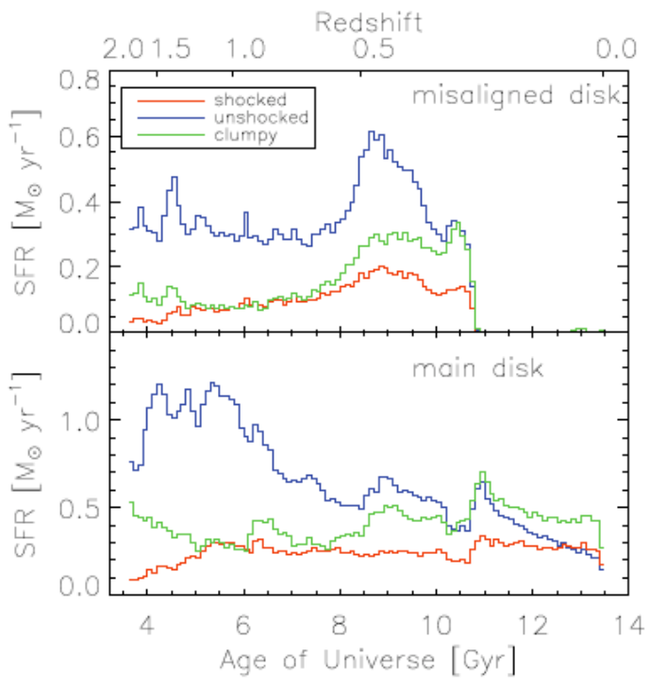



# Roškar et al. (2010)

- Fully cosmological simulation in which a warped, misaligned outer disk is formed via IGM accretion through hot halo
- SFR and metallicity tracked separately in main disk and outer area



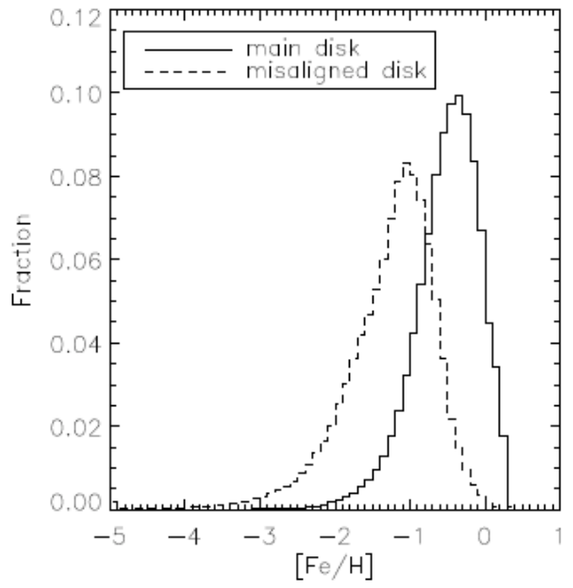




**Figure 11.** Mass-weighted metallicity distribution function for the st

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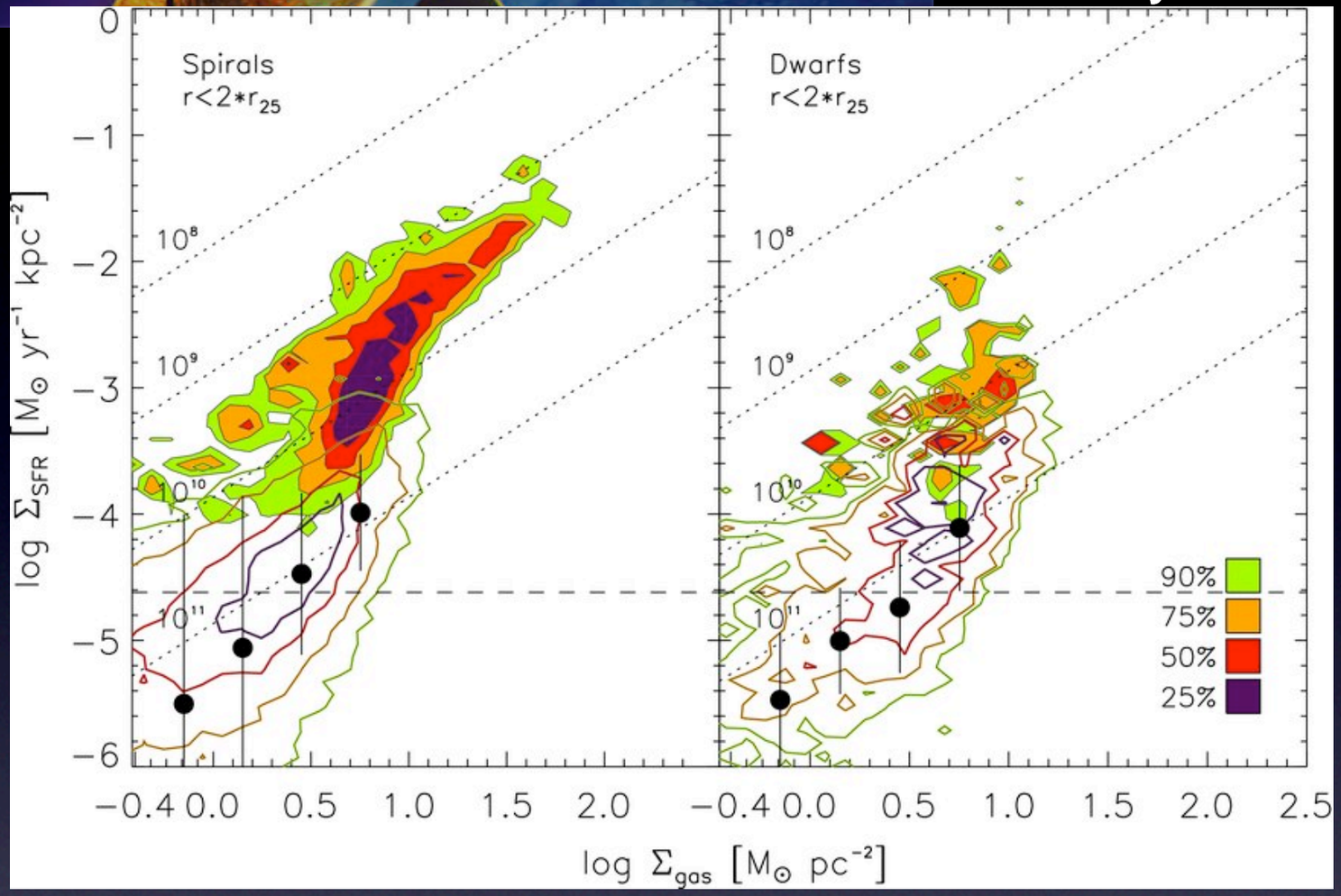
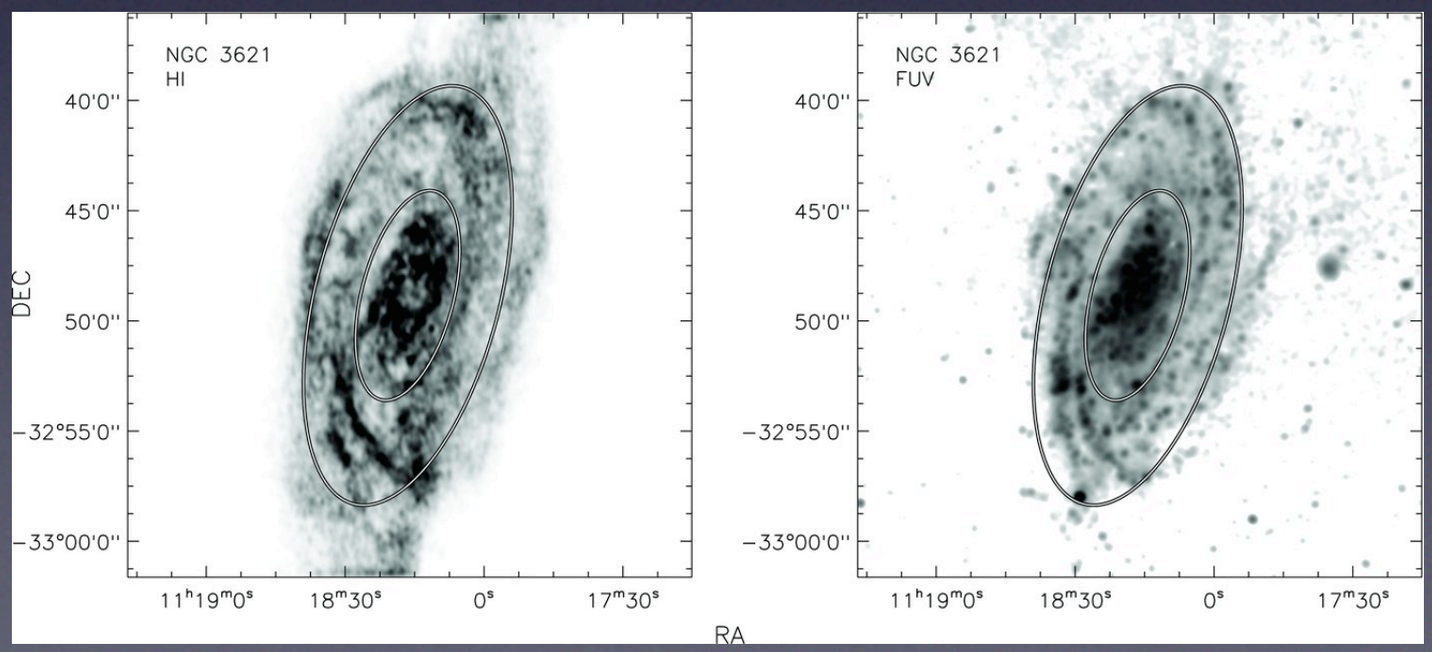
- Bigiel et al. (2010) composite SFL
- GALEX FUV + Spitzer 24μm
- vs. HI + CO ($H_2$)
- Total gas SFE is 30x lower in Type 1 XUV-disks compared to high density environments
  - Formation of molecular gas is rate limiting process (eg. Schruba et al. 2011)
- Possible change in IMF, cluster/association demographics?



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- *IMPROVED XUV-SURVEY UNDERWAY*
  - Dramatically more GALEX data are now available!
  - Include AIS and new sky coverage at MIS-depth.
  - Previous survey limited to disk-like "host" galaxies
  - Thilker et al. (2011, in prep) analyzes a sample of 3000+ nearby galaxies, selecting XUV-disks following T07 rules
    - Deep multi-wavelength follow-up for best examples
    - Several surprises already
  - *SEE ALSO - Lemonias et al. (2011) - GALEX DIS XUV-disks*

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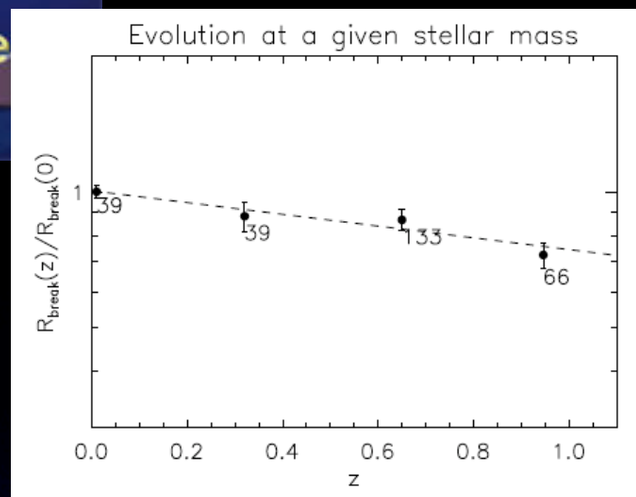
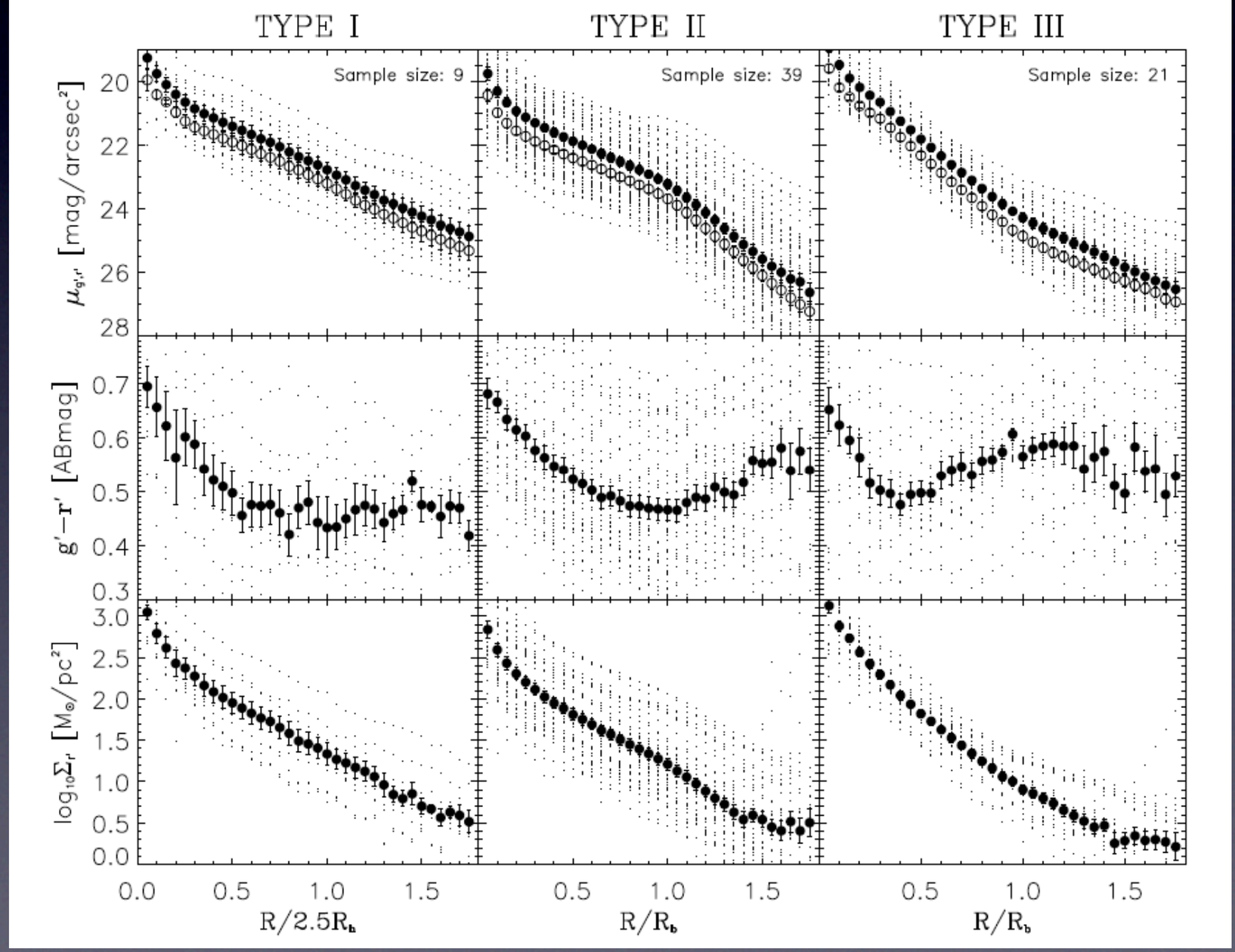



- Complicated relation with optical SB profiles
- Bakos et al. (2010)
- Following Pohlen, Erwin, & Trujillo
  - Radial migration of stars into outer disk + in-situ SF determines profile shape / color
  - Type III showing long-term effect of XUV SF?
- Z. Zheng, Pan-STARRS1 dissertation project -- correlation of optical + UV disk type



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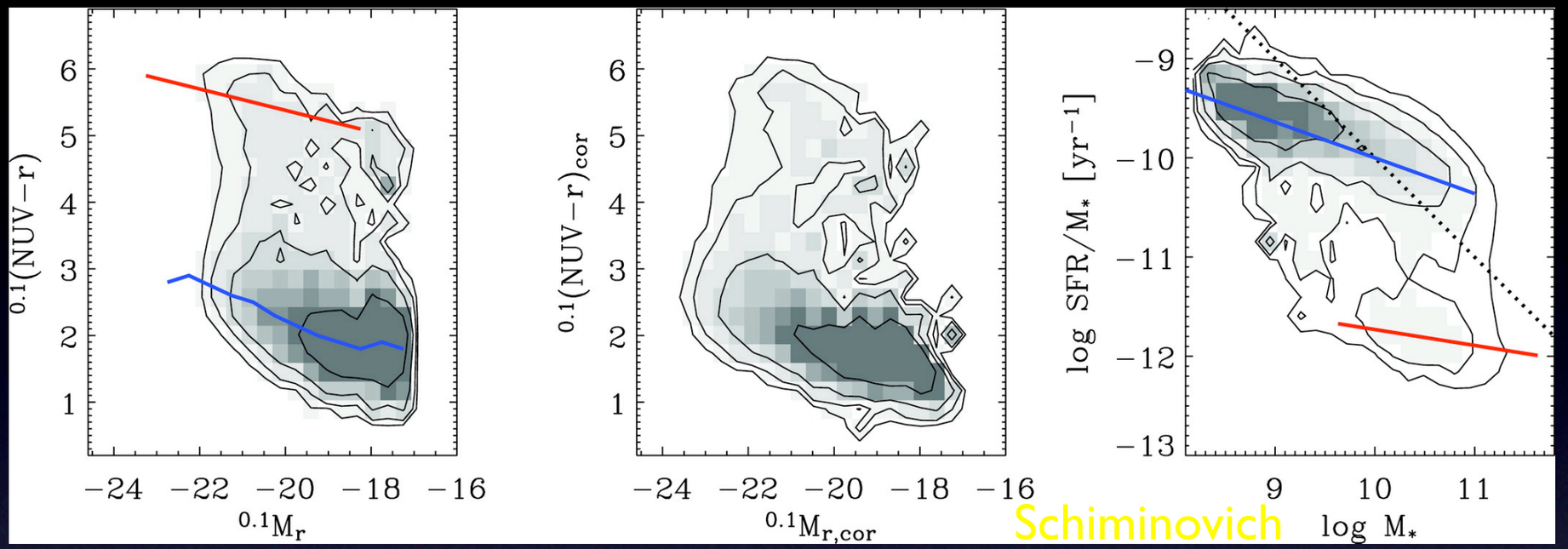
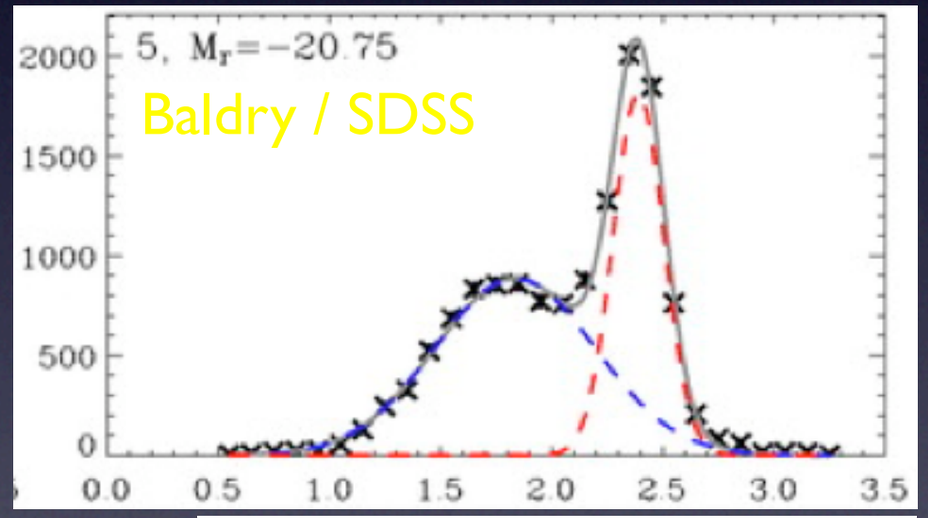
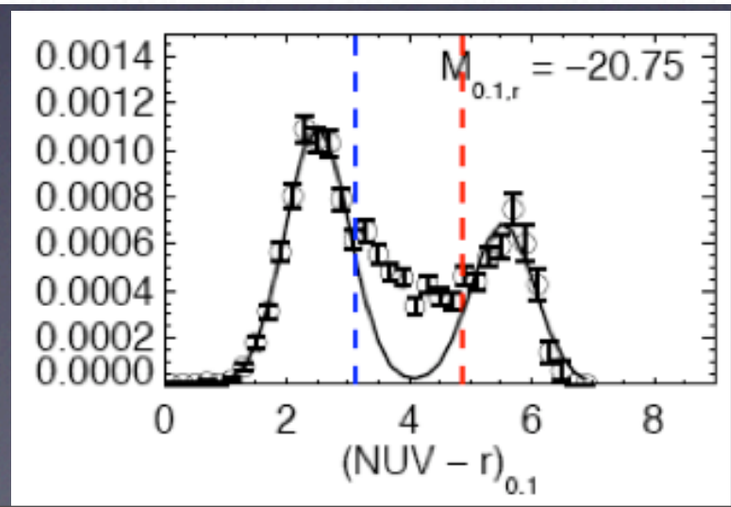
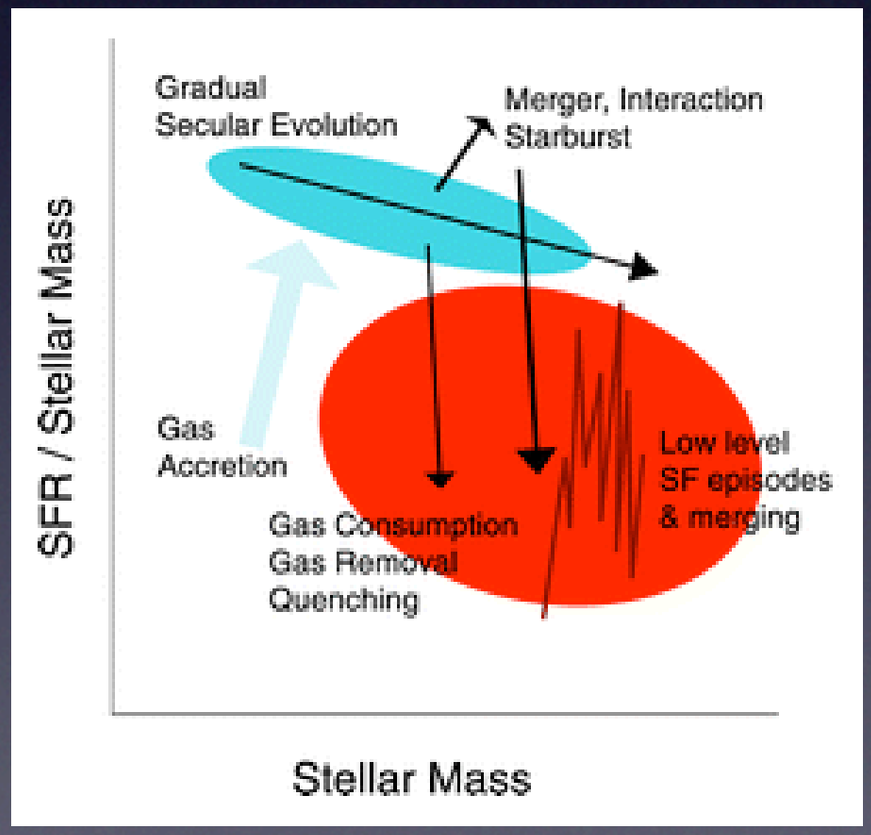
- Baldry et al. '04
- Galaxies migrate from blue to red sequence
- Wyder, Schiminovich, Martin papers in 2007 GALEX ApJS issue
- Green valley galaxies are likely transition objects




Wyder / GALEX+SDSS

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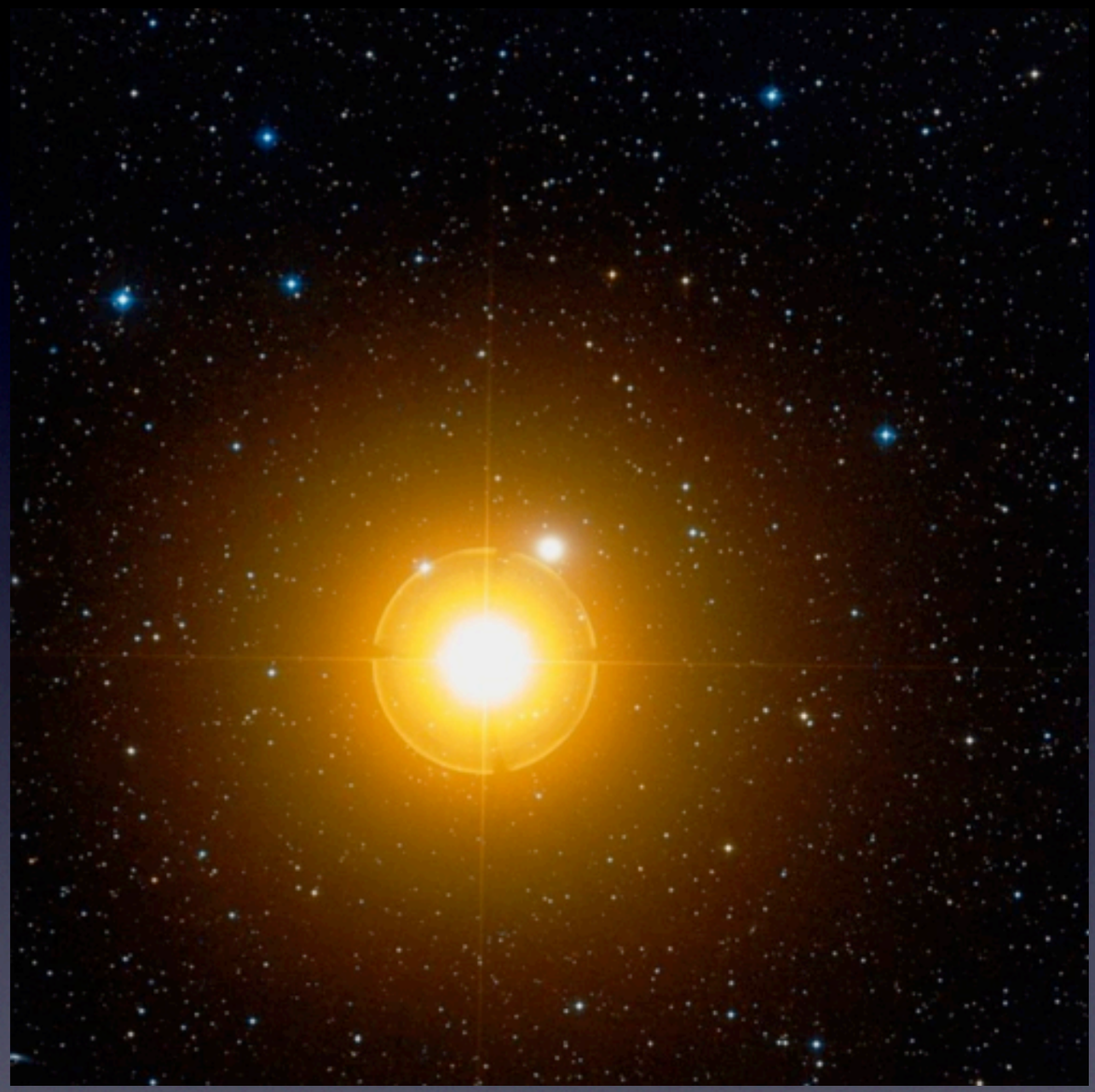
- NGC 404
- Nearby, low mass S0
  - $M_* = 7e8\ M_\odot$
  - $M_{HI} = 1.5e8\ M_\odot$
- Isolated …now
- No other galaxy within 1.1 Mpc radius
- Group remnant? (Karachentsev et al. 2002)



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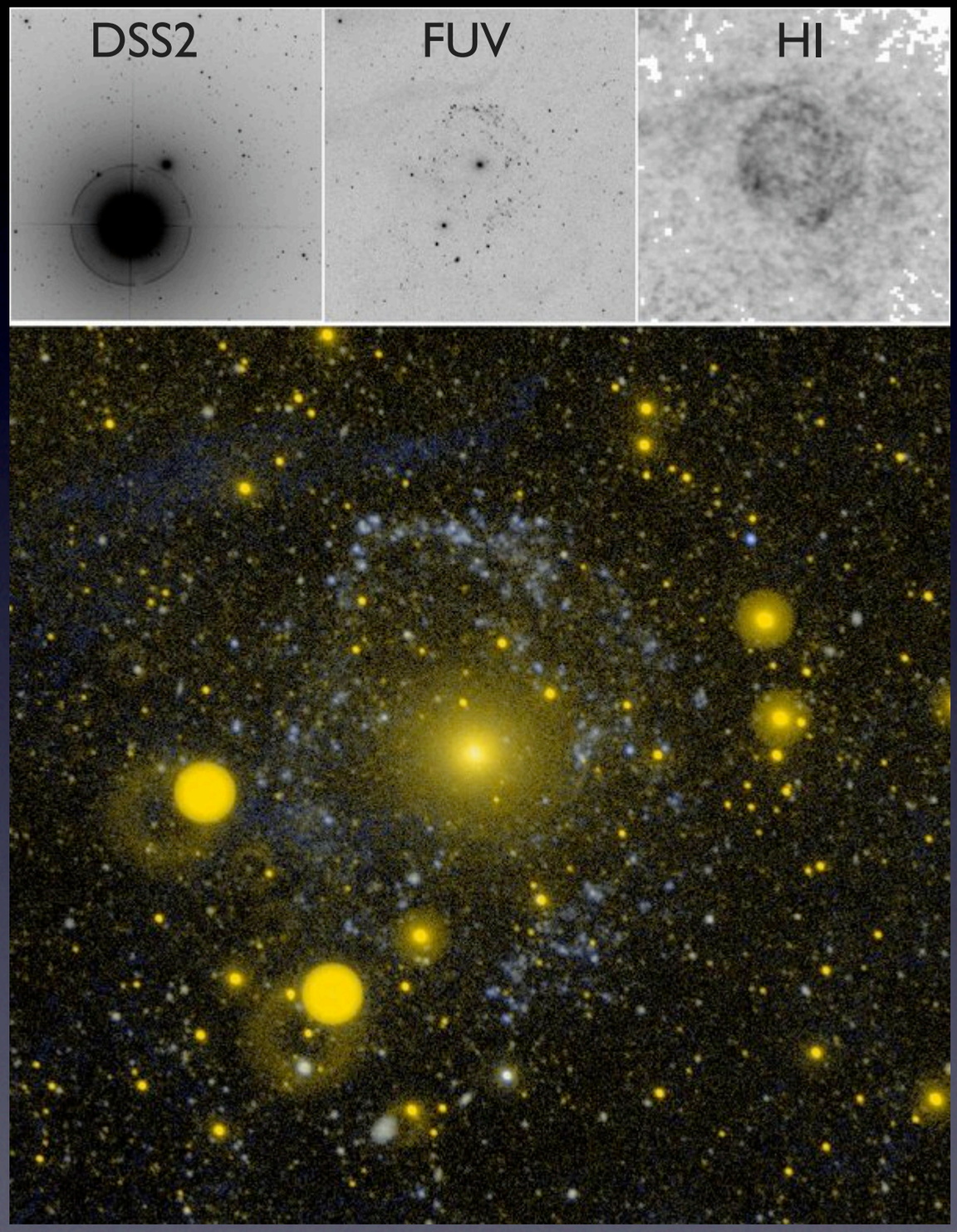
- NGC 404: nearby ETG galaxy w/ XUV-disk
  - Merger origin for HI ring (del Rio et al. '04)
- First such merger?
  - Maybe the S0 disk formed this way…
- Is this event transformational?
  - Available HI gas could augment stellar mass by 20% if all converted
  - More important-- change in B/D ratio?




Thilker et al. (2010)

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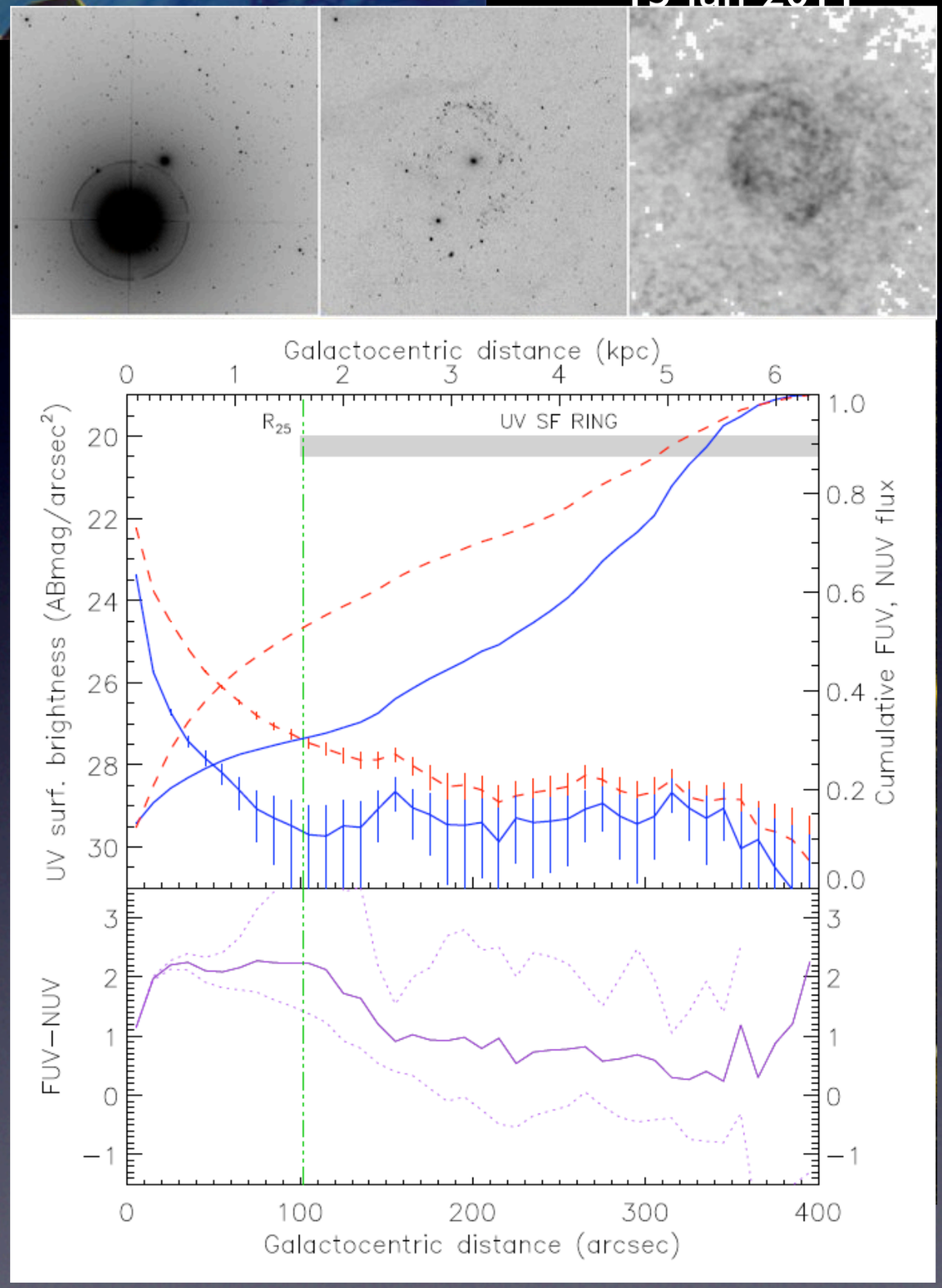
- NGC 404: nearby ETG galaxy w/ XUV-disk
  - $\Sigma_{SFR}$ = 2x10$^{-5}$ $M_\odot$/yr/kpc$^2$
  - SFR = 0.0025 $M_\odot$/yr
  - 70% from XUV-disk despite low $\Sigma$(SFR)
  - $\tau_{dep}$ ~ 60 Gyr, equiv. SFE$_{HI}$ = 2x10$^{-11}$ yr$^{-1}$
  - non-transformational -- but the potential is there if stimulated
- UV color gradient due to underlying S0 disk
  - Outer color agrees with merger dating




Thilker et al. (2010)

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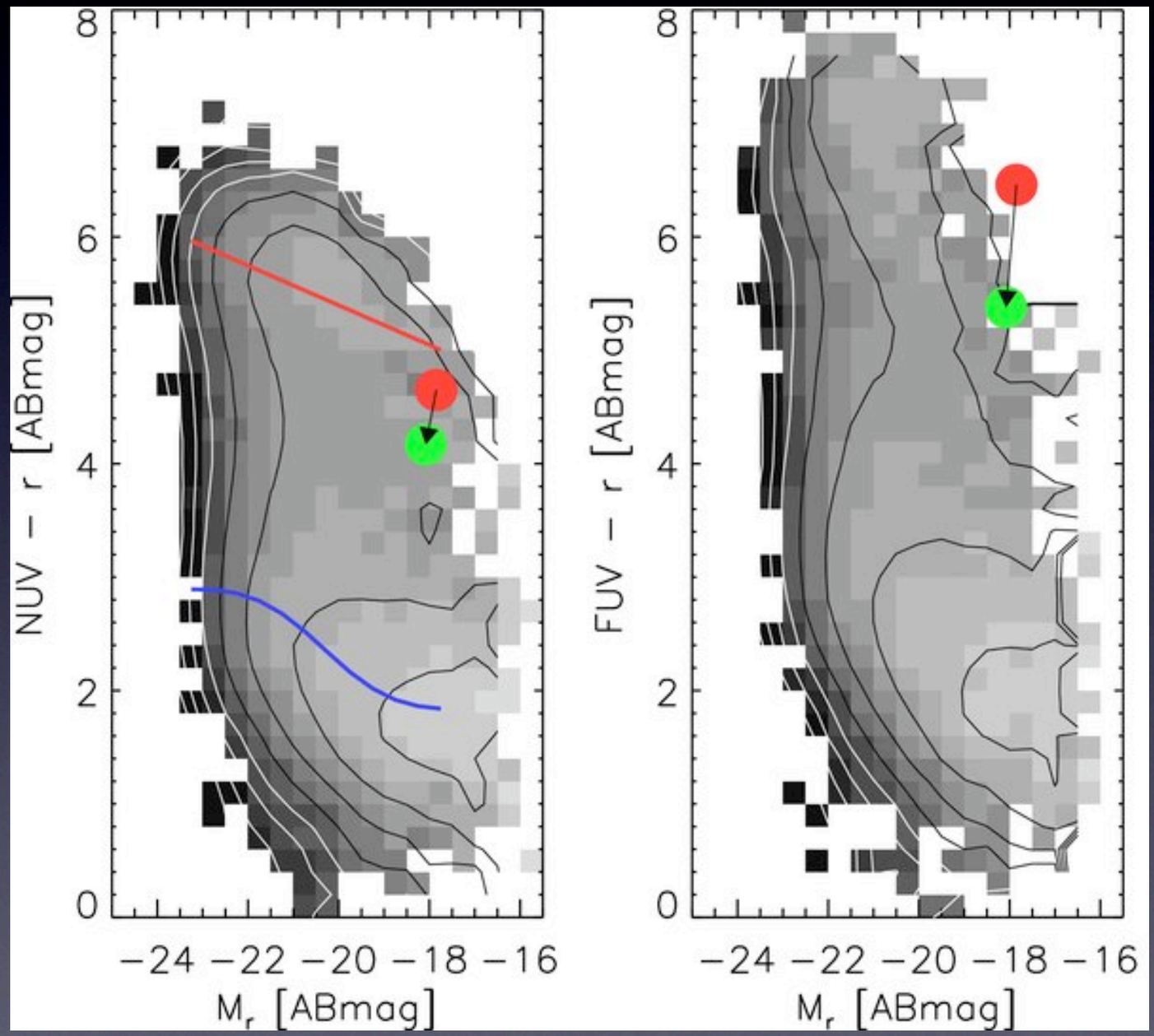
- Inferred motion in the UV-opt galaxy CMD
- CMD from Wyder et al. '07
- Thilker et al. (2010) show that the presence of the SF ring changes the position of the galaxy (red seq. to green valley)

Without SF ring / "before"

Including SF ring / "after"



Visible light / SDSS

NGC 934

UV light / GALEX

NGC 934

Visible light / SDSS

NGC 4262

UV light / GALEX

See also, Bettoni et al. (2010)

NGC 4262

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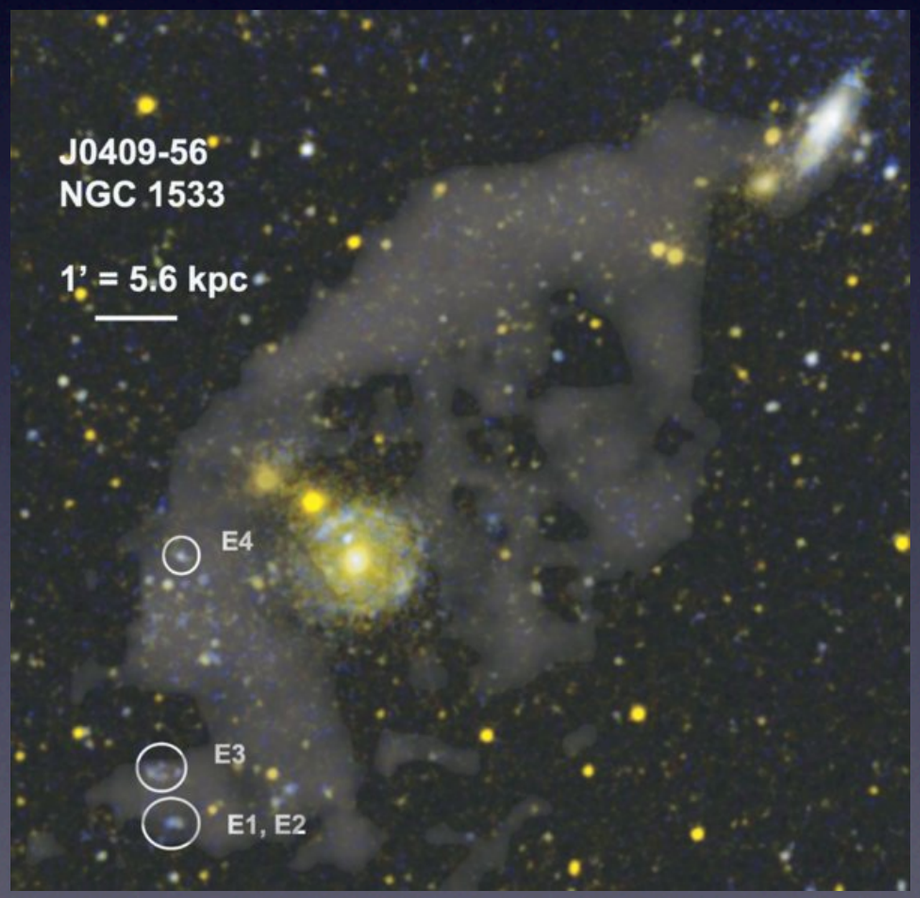
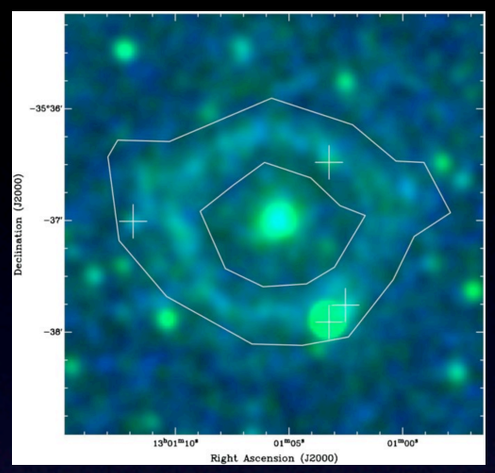
- GV is partially two-way!
- Mixed mergers in RS, or other accretion mechanism, are responsible

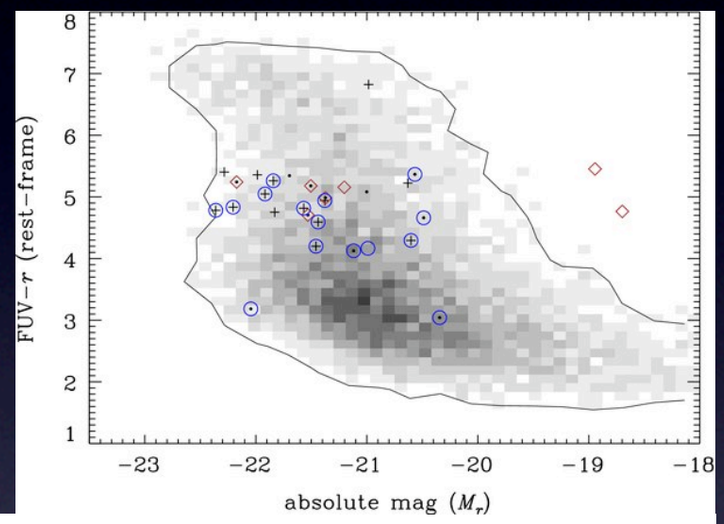


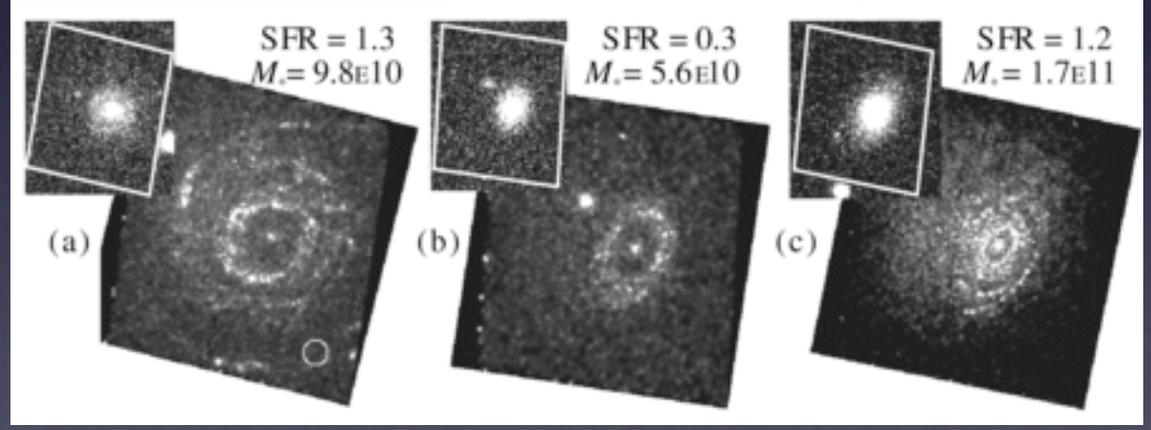

Werk et al. '09
HI arc = early-stage remnant?




Donovan et al. '09
ESO381-G047

Salim & Rich '10
same process at z~0.1




- see also: Cortese & Hughes '09, Kannappan et al. '09 (BS ETGs), Moffet et al. '10, Zernow et al. 2010

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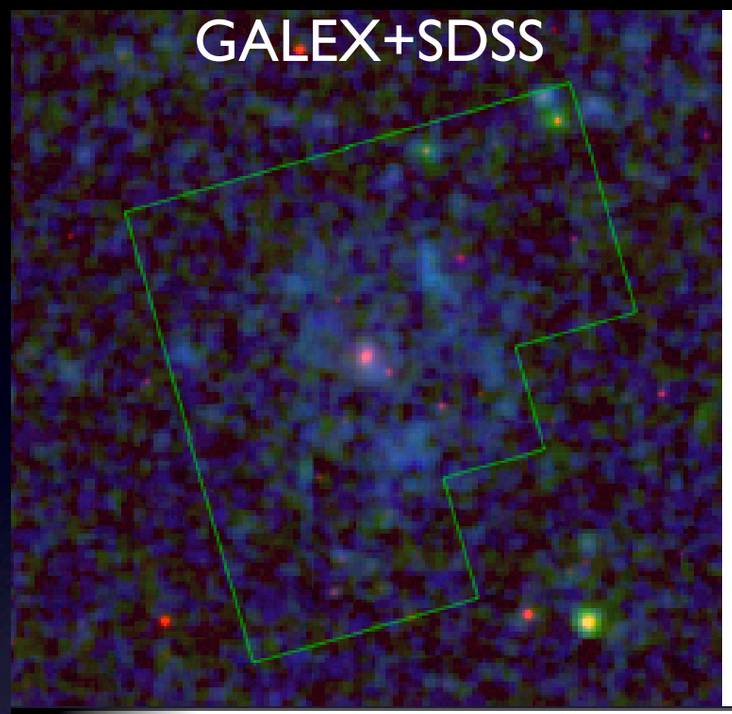
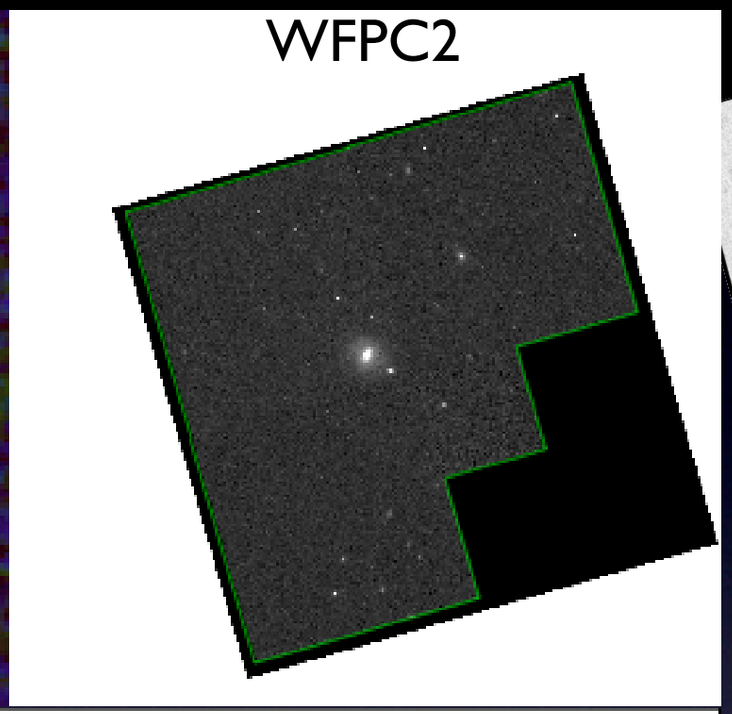
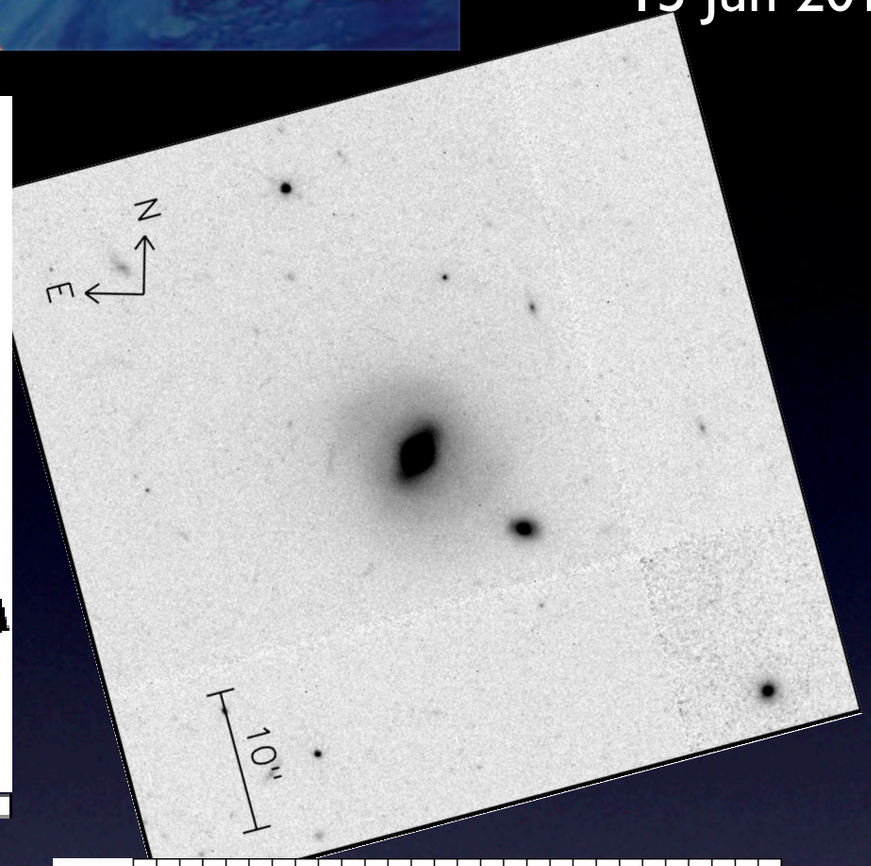
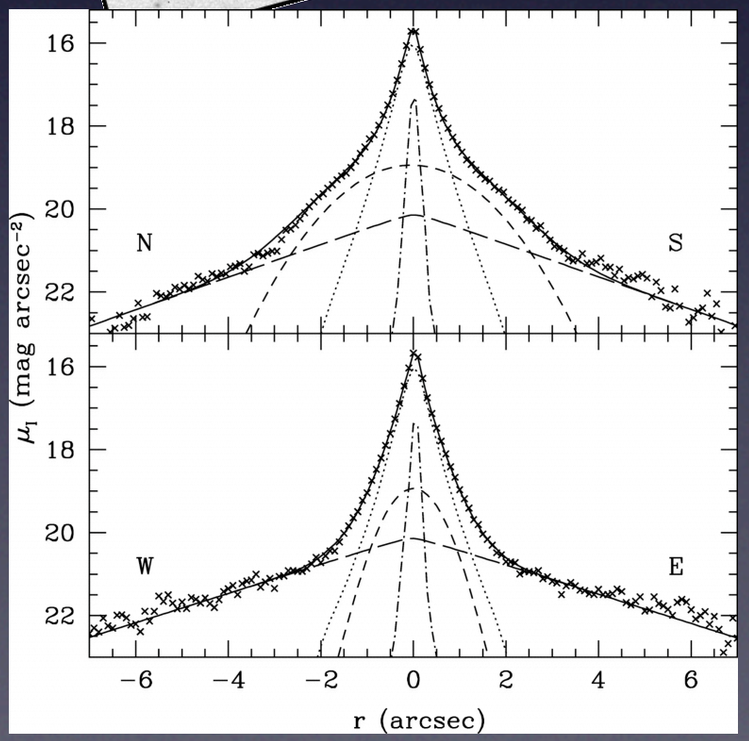



- Barth (2007): HST shows Malin 1 has a typical HSB S0 disk within separate LSB outer component.
- Massive LSBs are likely extreme XUV-disks with anomalously high M(HI) obtained *somehow*.



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- Two-stage formation scenario likely for at least some mLSBs
- First make "host" object through typical process
  - (a) HSB disk + bulge, or... (b) red/dead early-type
- An ordinary host later acquires <u>much</u> more gas, enabling it to build the (a) hybrid disk or (b) singular LSB component
  - similar to Type 2 XUV-disk gas budget
- High angular momentum accretion required to retain gas at large radii, not consumed in a quick burst of SF

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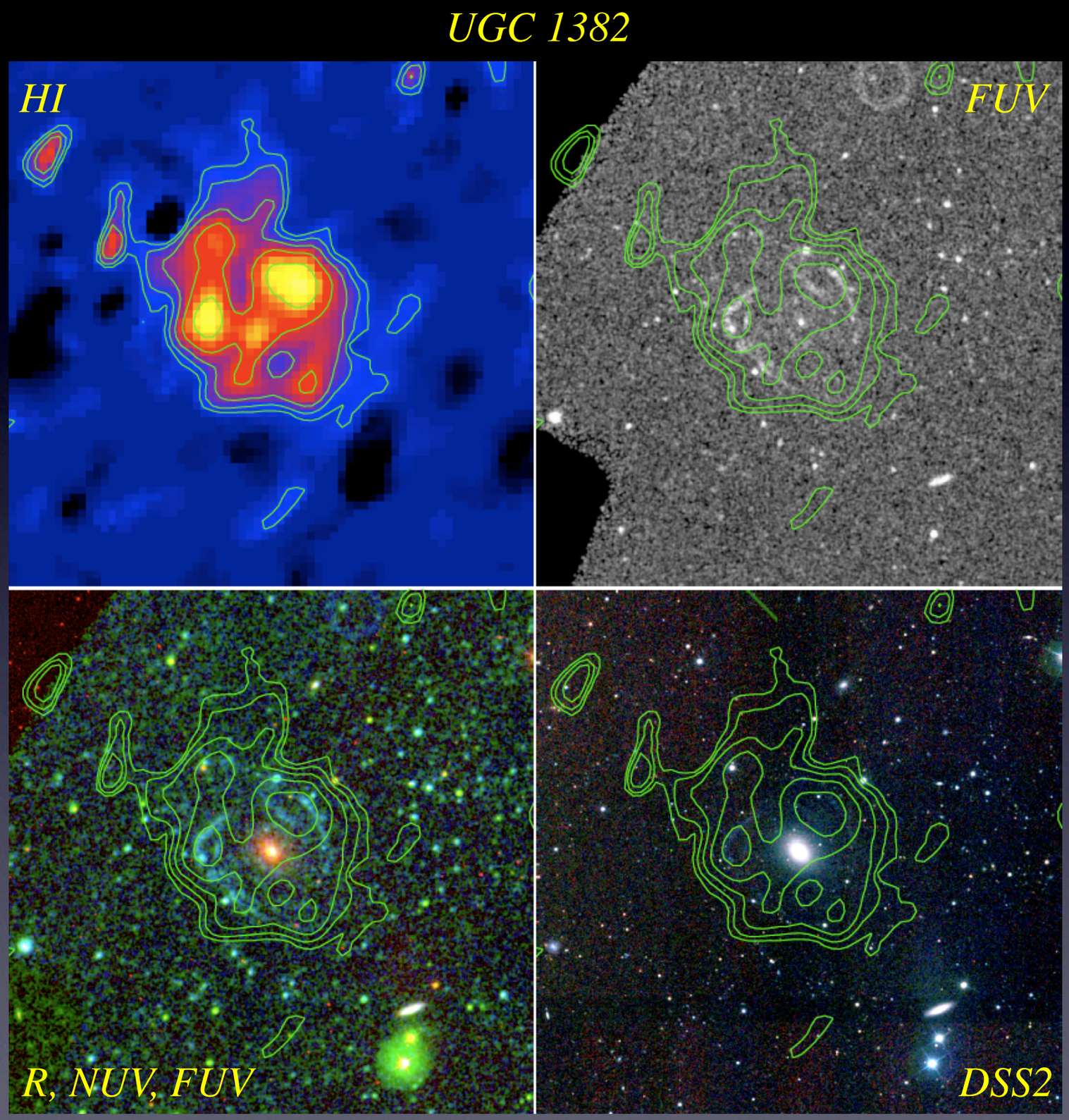
GALEX Galaxy Evolution Explorer

Kloster Seeon
15 Jun 2011

- Massive LSB disk galaxies forming about E or S0 hosts.
- Offshoot of XUV survey, increased dist. limit to examine early types in which log M(HI)>10.
- Found several with XUV-disks of diameter 100-150 kpc



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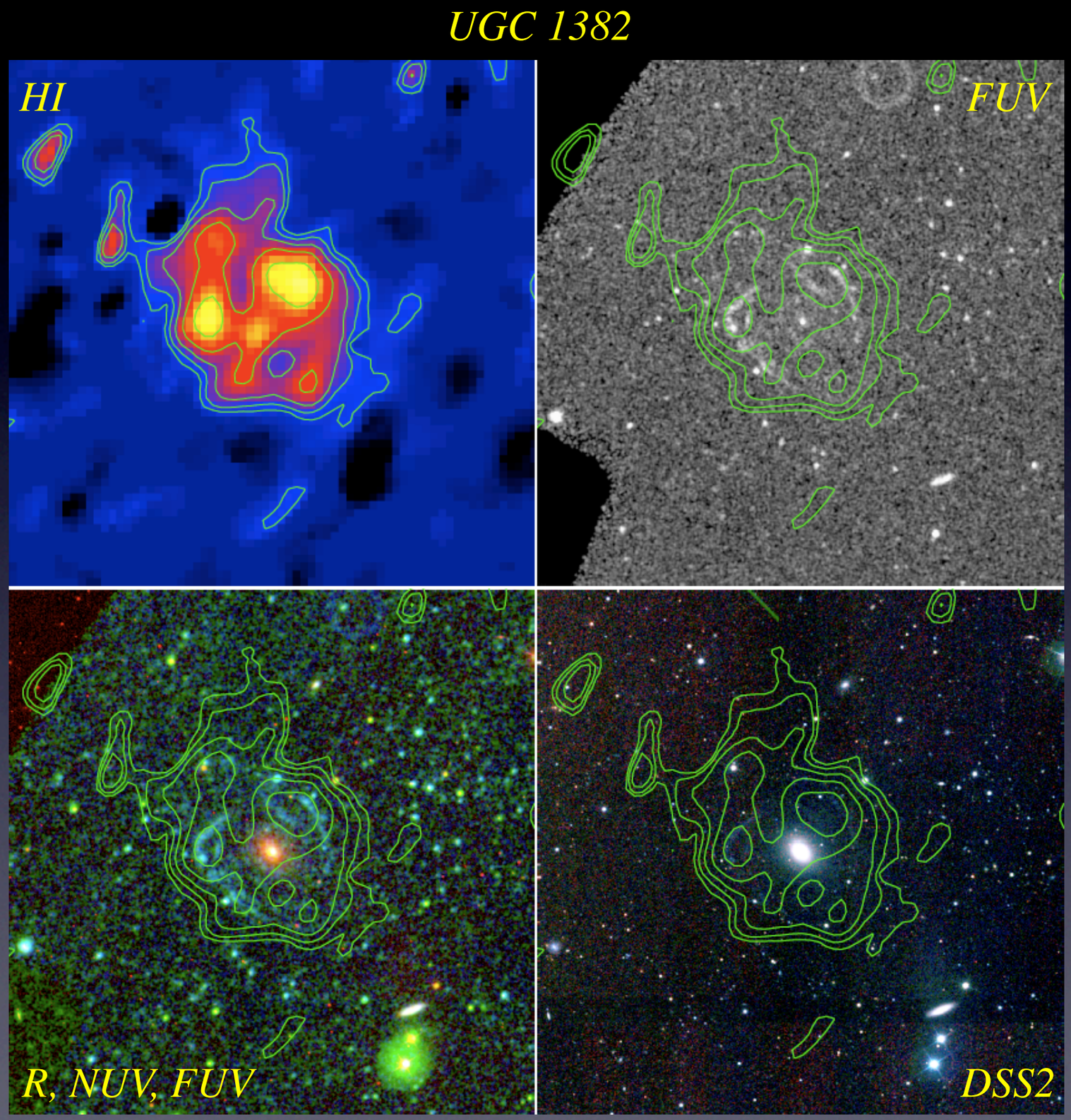
- UGC 1382
  - Elliptical host (T = -5) with $M_* = 4 \times 10^{10} M_\odot$
  - Gas frac. ~ 0.5
  - Spiral structure



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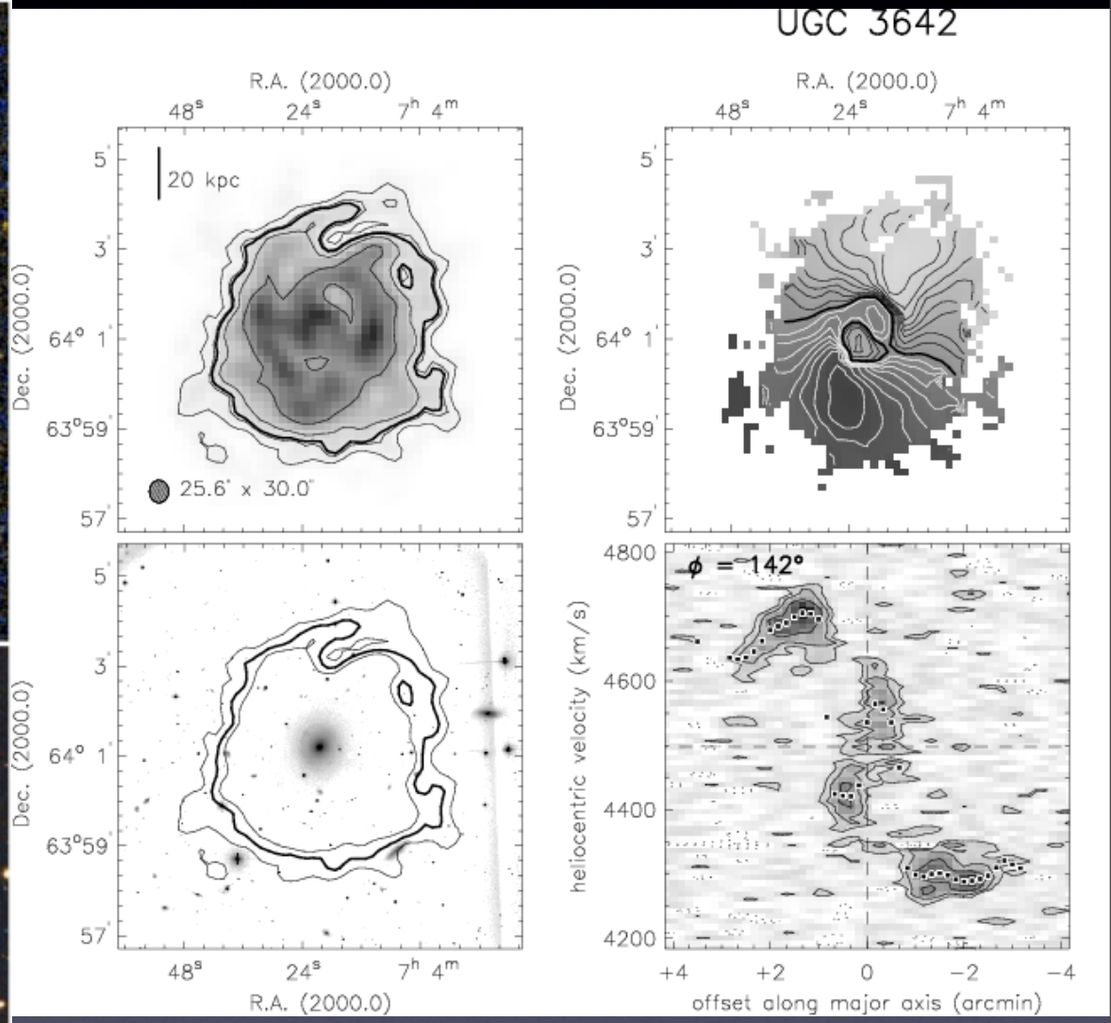
- UGC 3642
  - S0 host (T = -2)
    $M_* = 7 \times 10^{10}\ M_\odot$
  - Opt. brighter, more evolved?
  - Counter-rot. HI evidence for late assembly


HI from WHISP

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- NEW HI SURVEYS WILL FIND MUCH MORE CIRCUMGALACTIC & INTERGALACTIC GAS
  - Possible accreting clouds, collisional rings, TDGs
    - GALEX can find them now
- In the low SFR regime, UV is a more reliable tracer than H$\alpha$ or IR - regardless of IMF
  - stochastic limits: log(SFR) = -3.5 for H$\alpha$, -5 for UV
- What SF might we be missing in H$\alpha$ surveys?
  - ultra-faint dwarf galaxies
  - intragalactic debris

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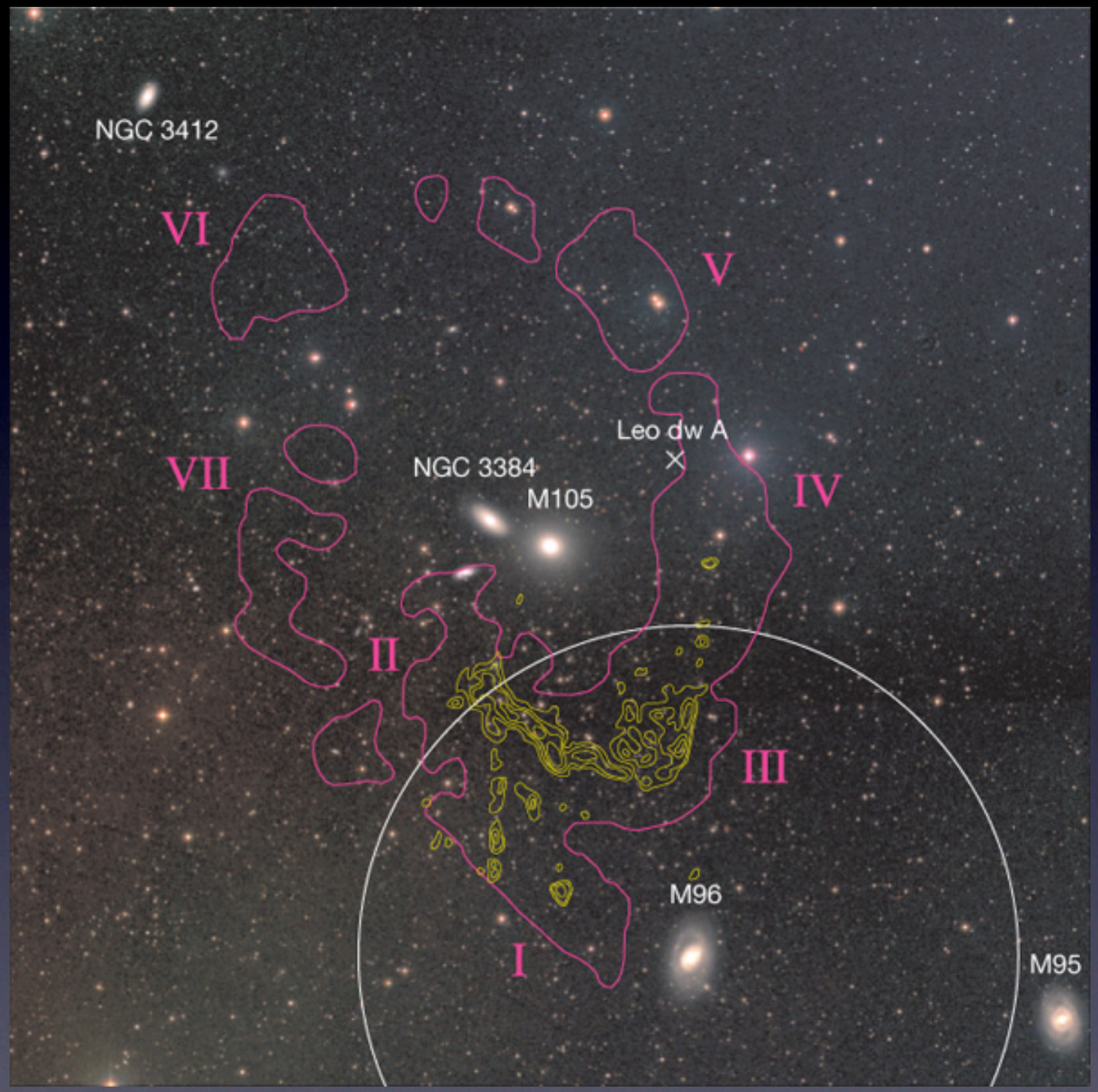
- The Leo Ring (Thilker et al. '09)
- Putative fossil intragroup structure contains $2 \times 10^9$ $M_\odot$ of HI
- Several sites of intergalactic SF found with GALEX



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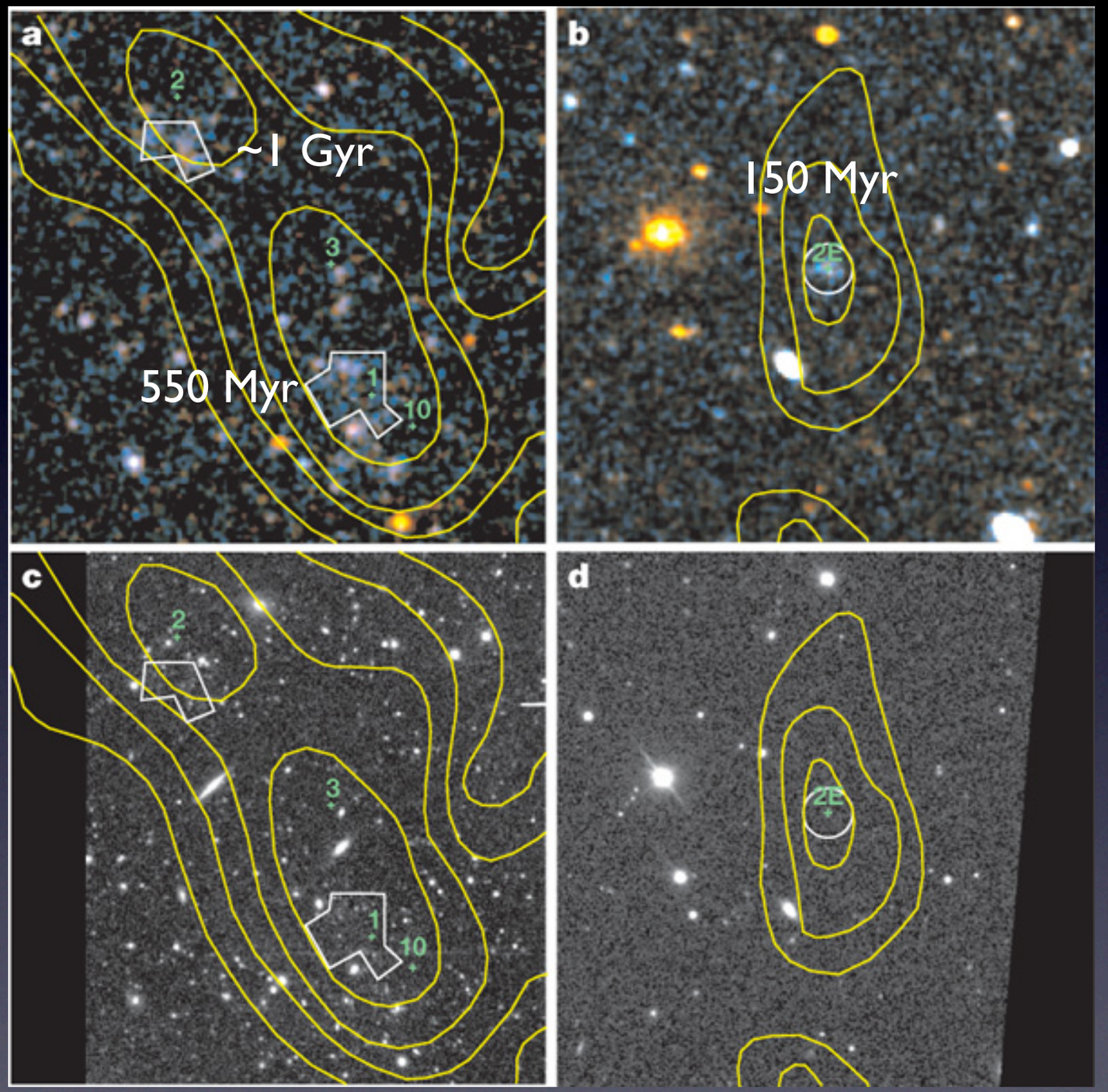
- UV-opt color-color ages
- SFR < 0.001 $M_\odot$ $yr^{-1}$
- Leo Ring Clumps lack DM (Schneider et al. 1989)
- Objects similar to TDGs
  - Metallicity TBD w/ HST



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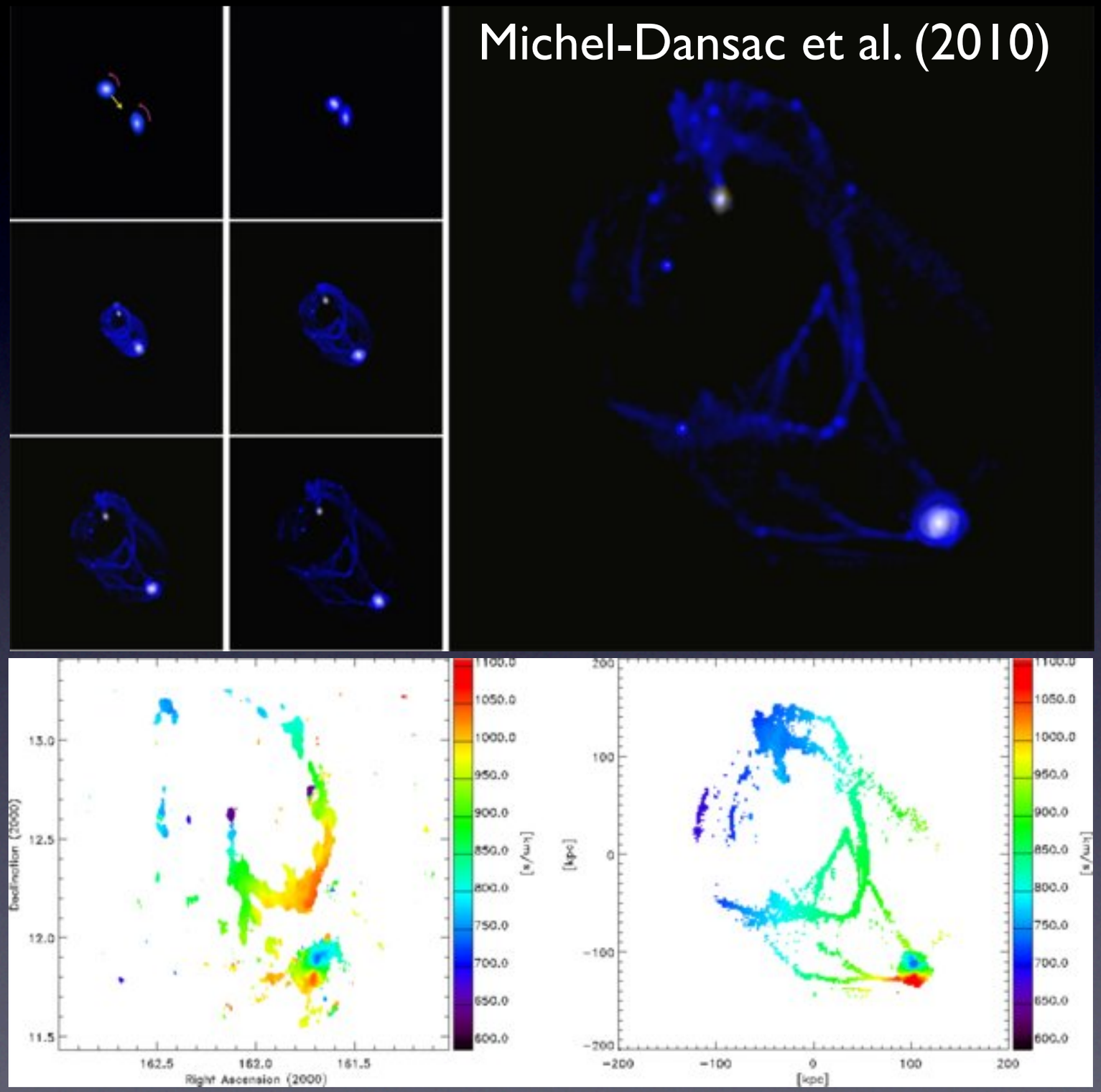
# Collisional model

- If verified as true origin, then possibly the oldest known collisional ring
- Do any faint dwarfs survive from prior SF events?
  - Perhaps a better chance than traditional TDGs
- Probe of group "pollution" mechanism
  - stars and enriched gas
  - ring remains distinct



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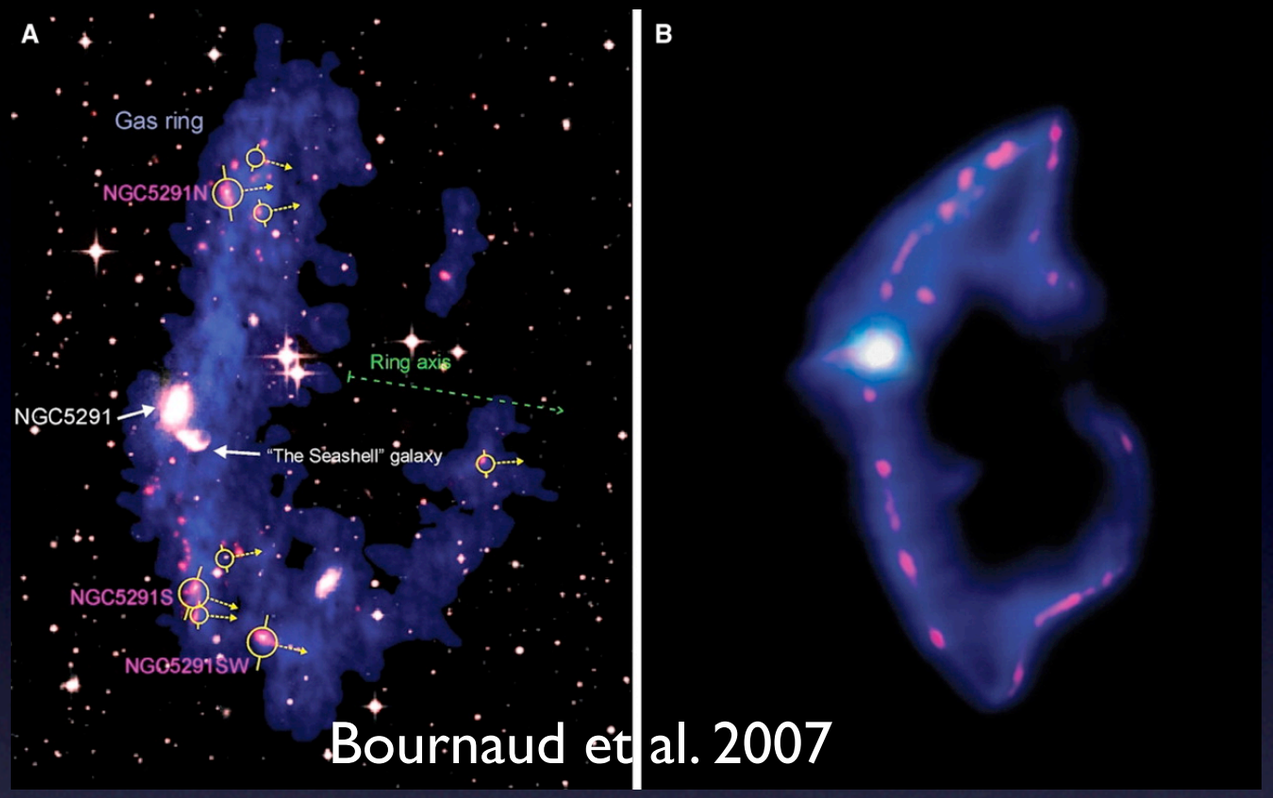
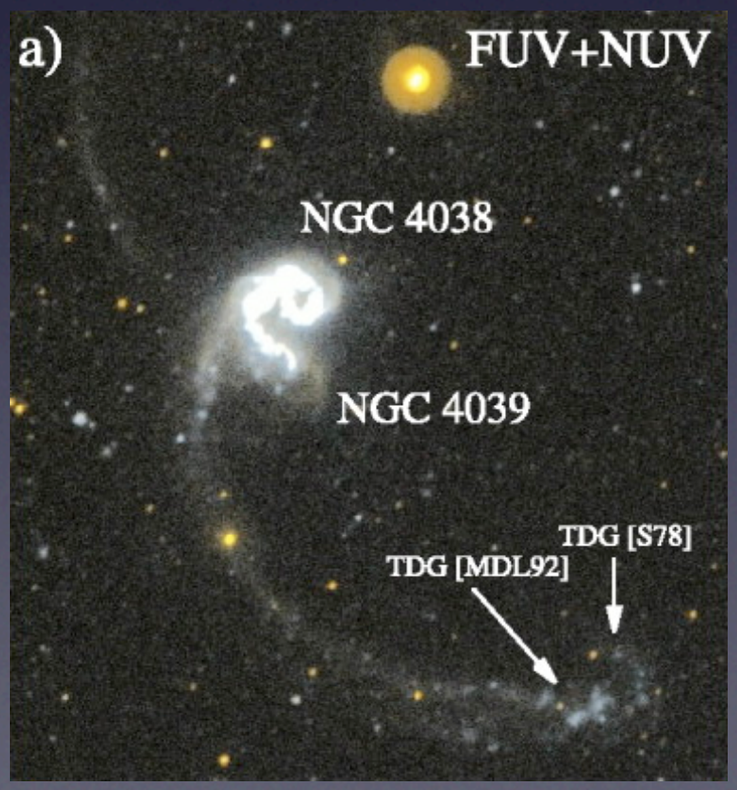
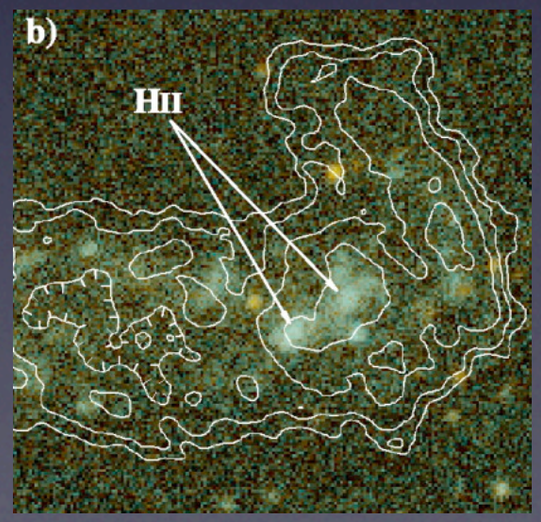
- NGC 5291's collisional ring (Boquein et al. '07 & Bournaud et al. '07)
- Another example: NGC 2292/93 (LGG 138) ring
- GALEX is ideal for finding such SF sites, and following evolution of displaced gas
- Classical TDGs also...



Bournaud et al. 2007




Hibbard et al. '05



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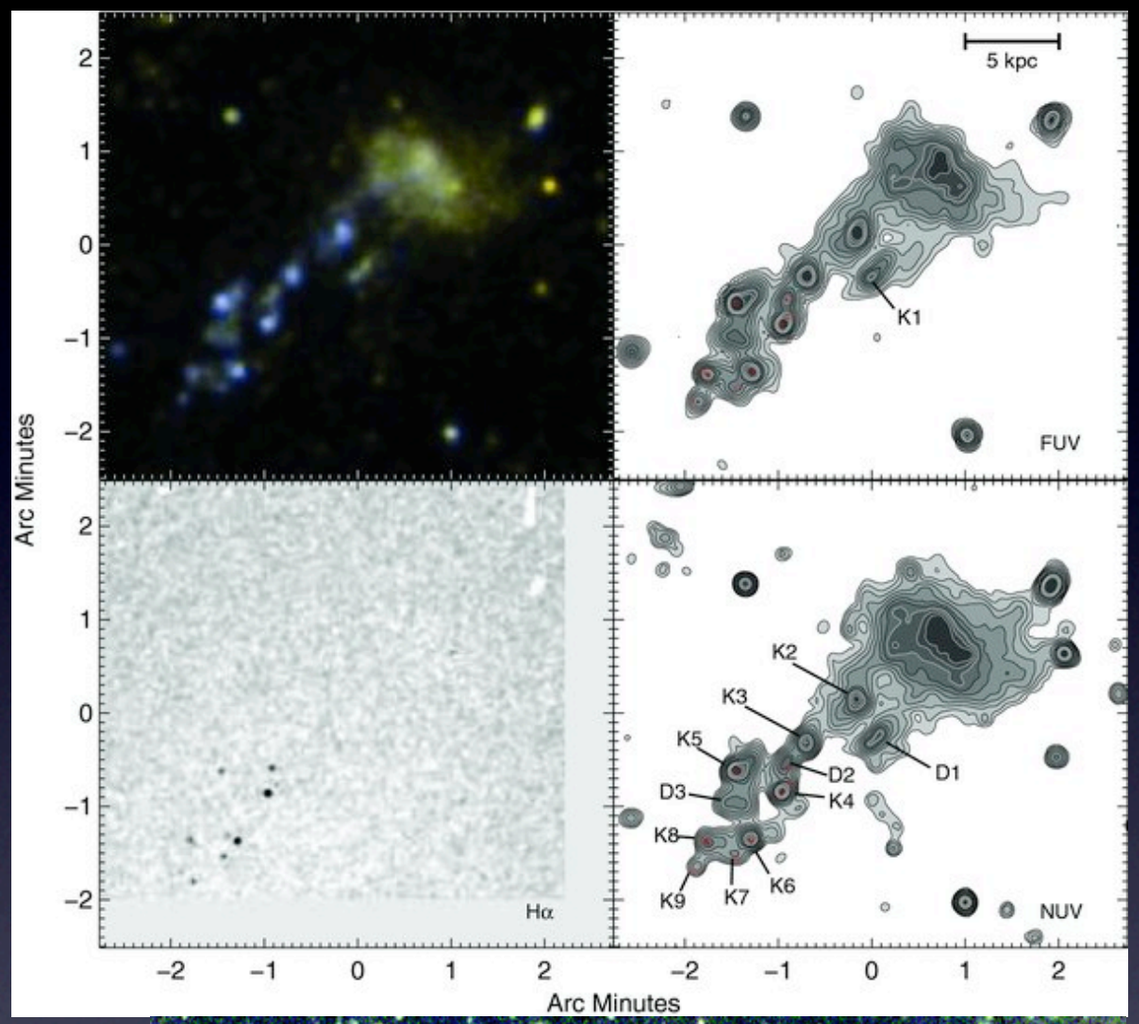
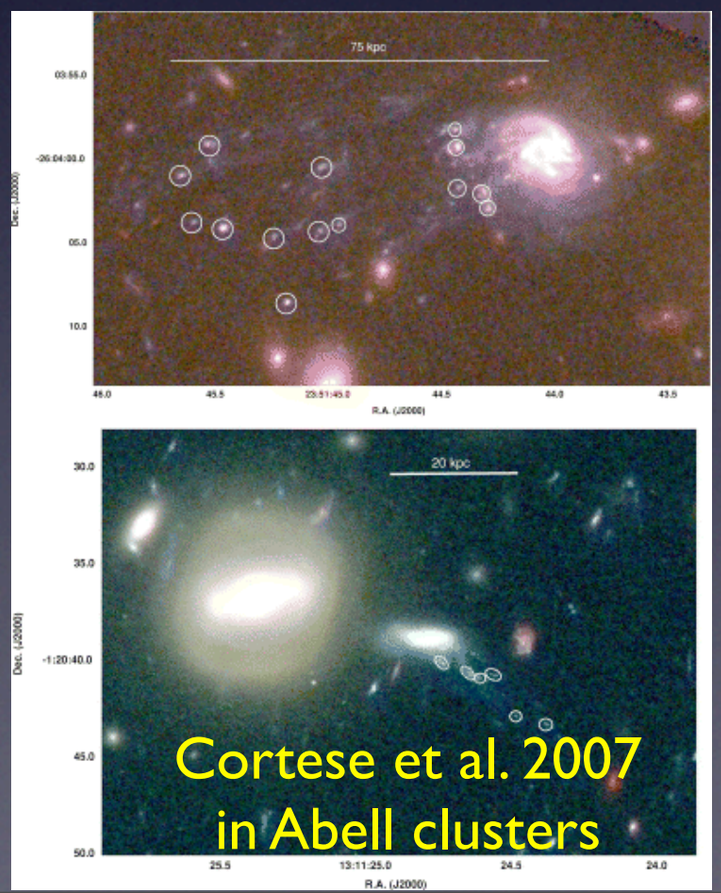
In-situ SF within ram-press. stripped gas

Hester et al. 2010 (IC3418, Virgo Cluster)
XUV-disk NGC 4254 is similar
Smith et al. '10 (UV tails in Coma)

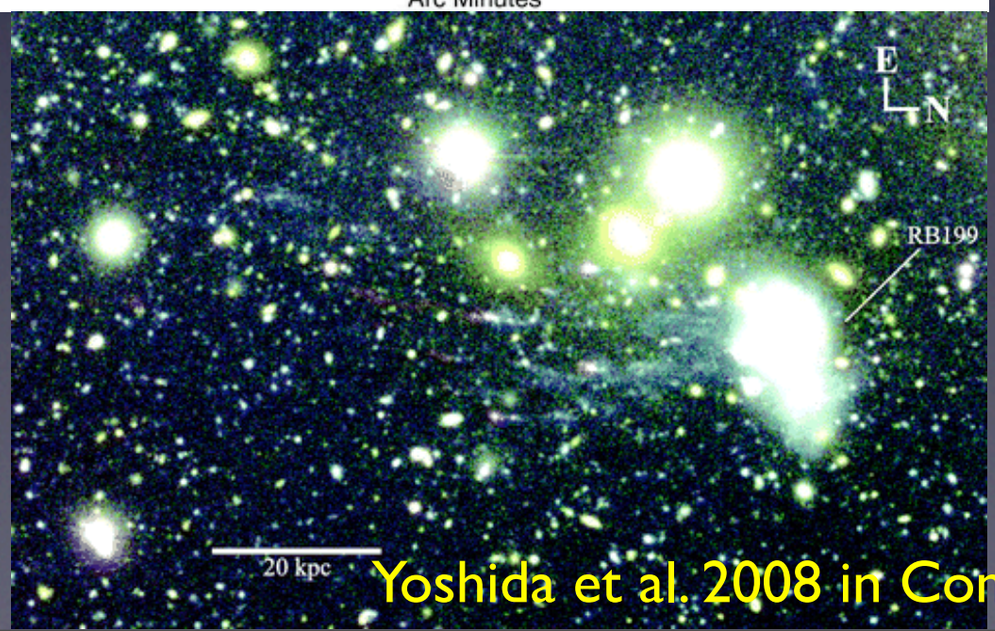
Use UV-opt SED as a timer since RP...

Hester et al. '10




Cortese et al. 2007
in Abell clusters



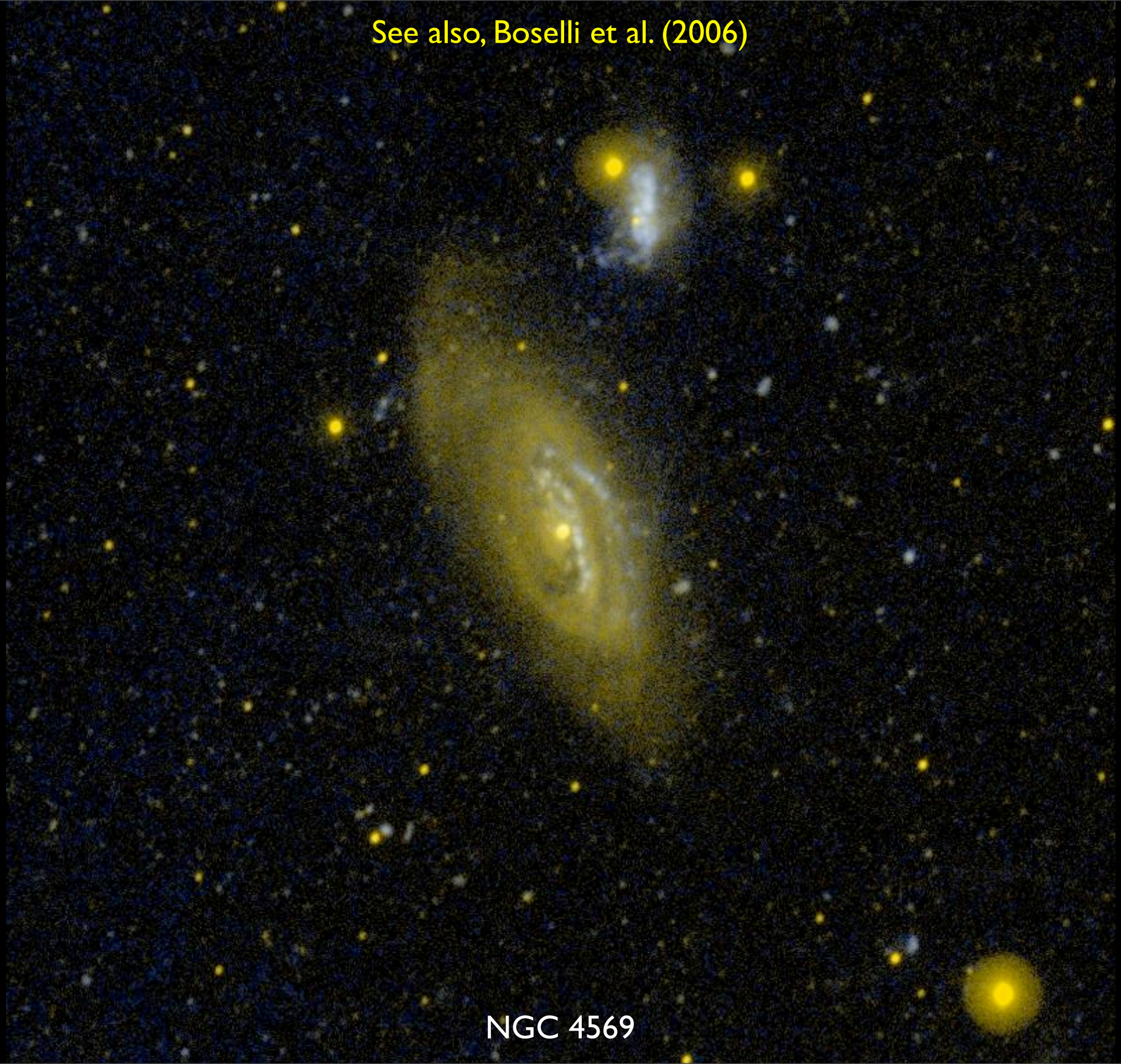

Yoshida et al. 2008 in Coma

Visible light / SDSS

NGC 4569

UV light / GALEX

See also, Boselli et al. (2006)



NGC 4569

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- CONCLUSIONS:
  - XUV-disks are common and trace ongoing inside-out disk formation
  - The Green Valley galaxy pop. is diverse, including rejuvenated SF ETGs
  - At least some massive LSB disk galaxies may have formed in two stages
  - GALEX provides an ideal way to search for TDGs and intergalactic SF
  - Timing gas removal in cluster environ. is feasible with UV-opt SED

- GALEX, the Galaxy Evolution Explorer, has lived up to its name - highlighting disk building and morphological transformation processes, while allowing the study of rate limiting factors inherent to the resolved SFL.