Breaks in Disk Profiles: Observational Perspectives

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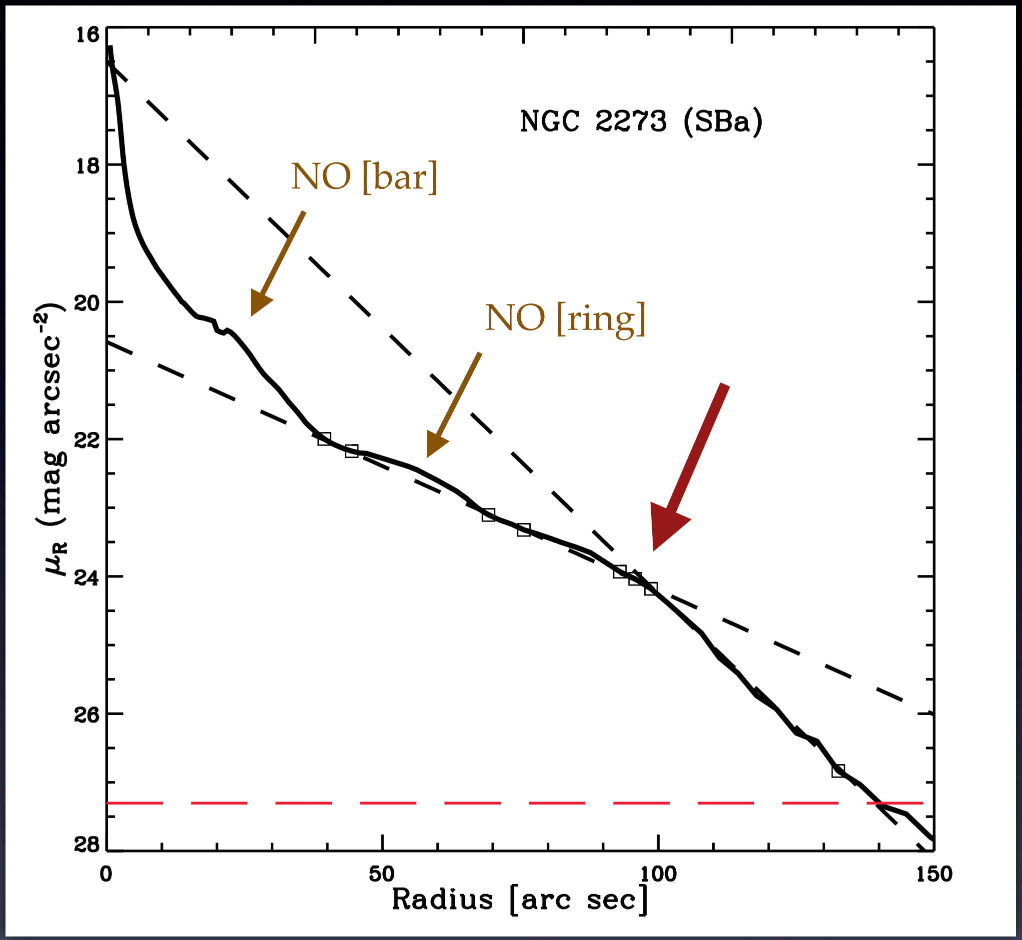
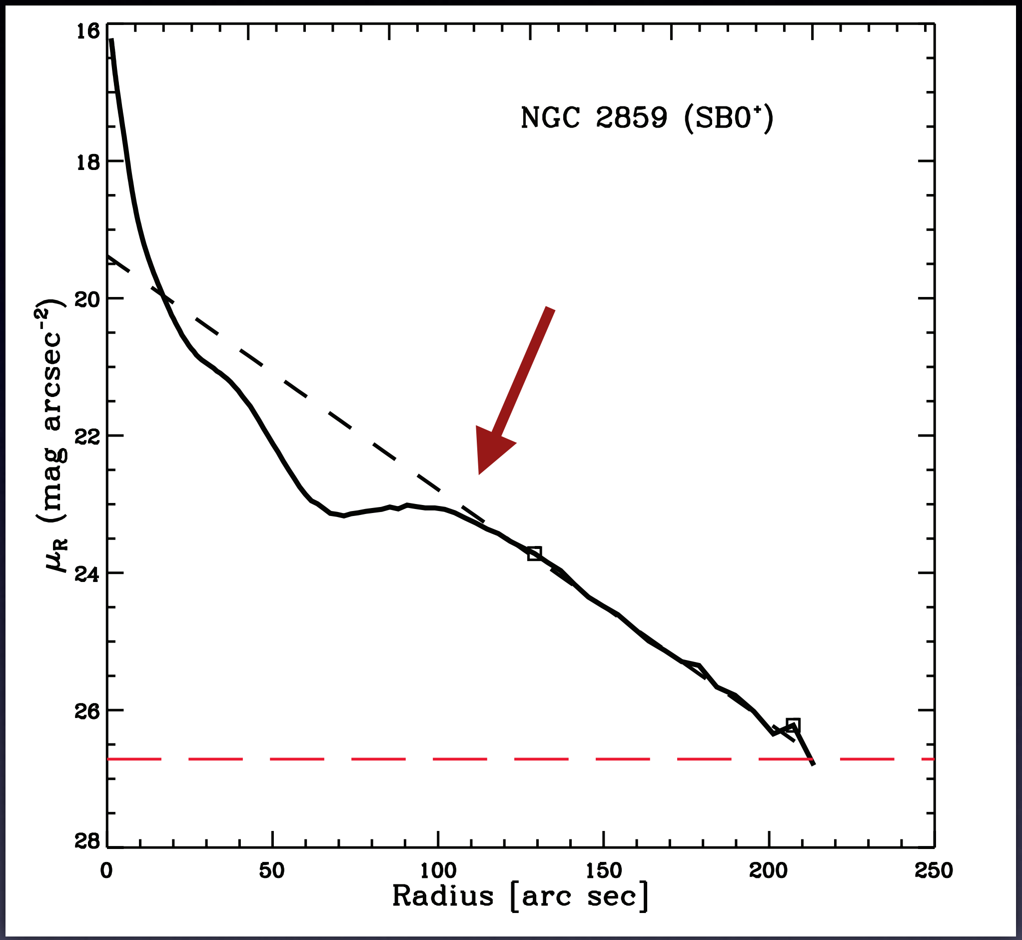
What Do We Mean by “Break”?



Broken exponential



Inner non-exponential zone

1. Two extended exponential zones in disk with transition between them (the break in “broken exponential”)

2. Where outer exponential gives way to *deficit* relative to its inward extrapolation (inner region may not be exponential!)

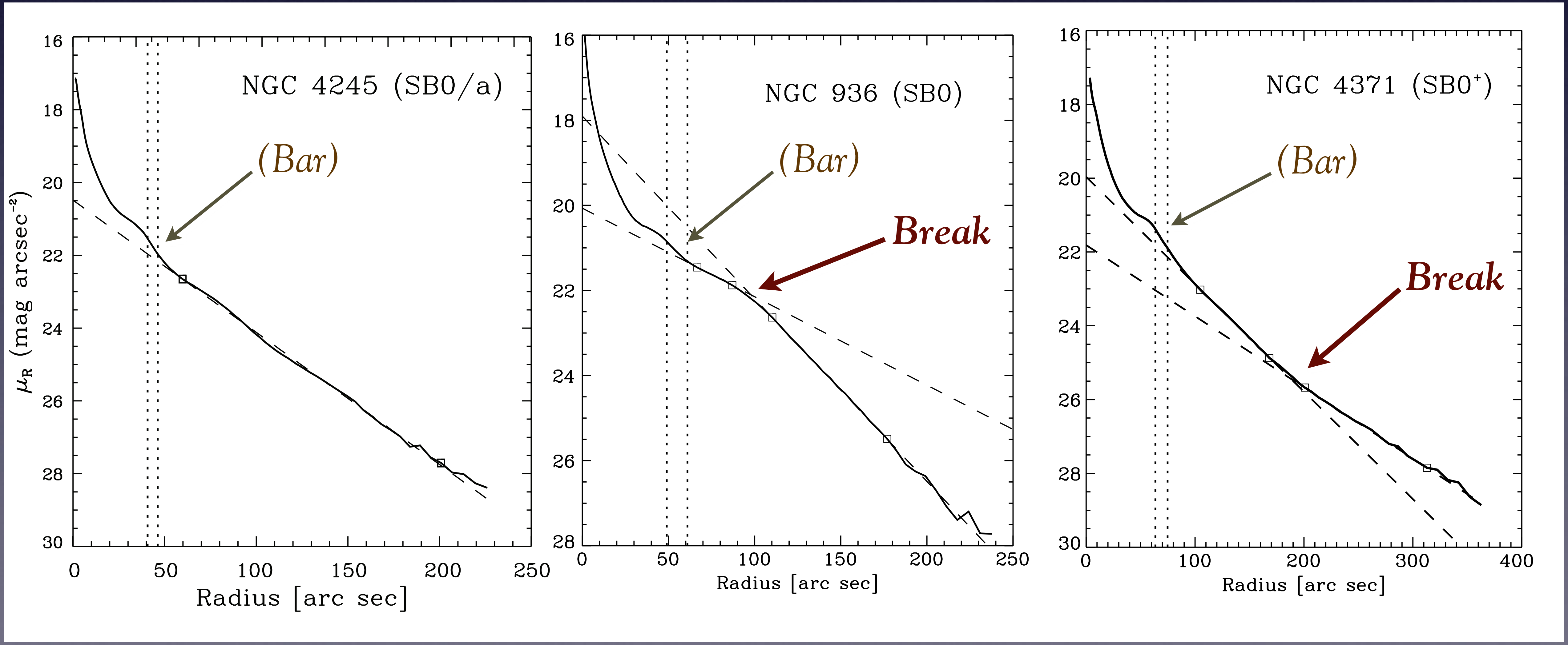
Three main classes of profiles

Type I:
Single-exponential
(Freeman 1970)

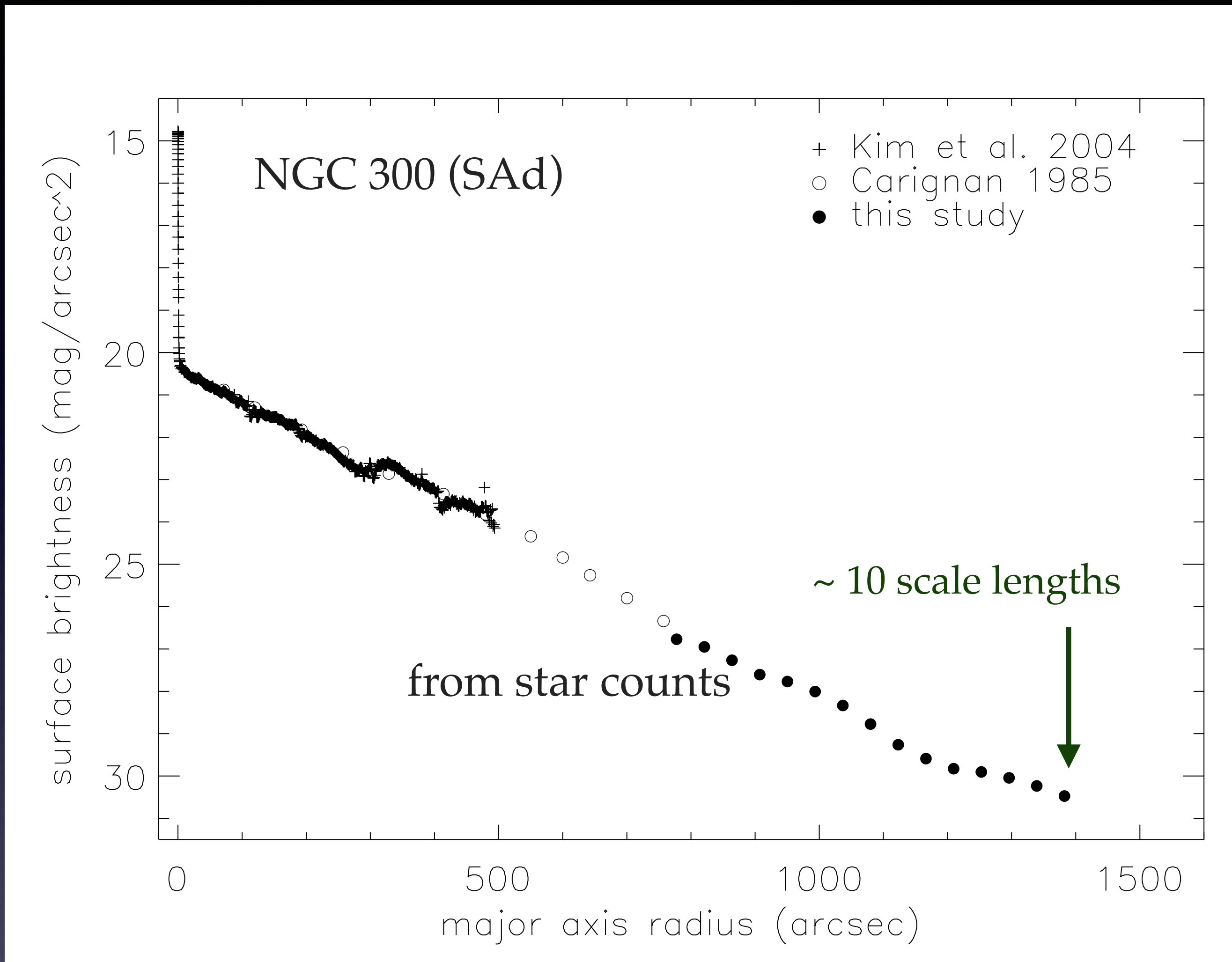
Type II:
includes "Truncations"
(Freeman 1970; van der Kruit & Searle 1981)

Type III:
"Antitruncations"
(Erwin+2005)

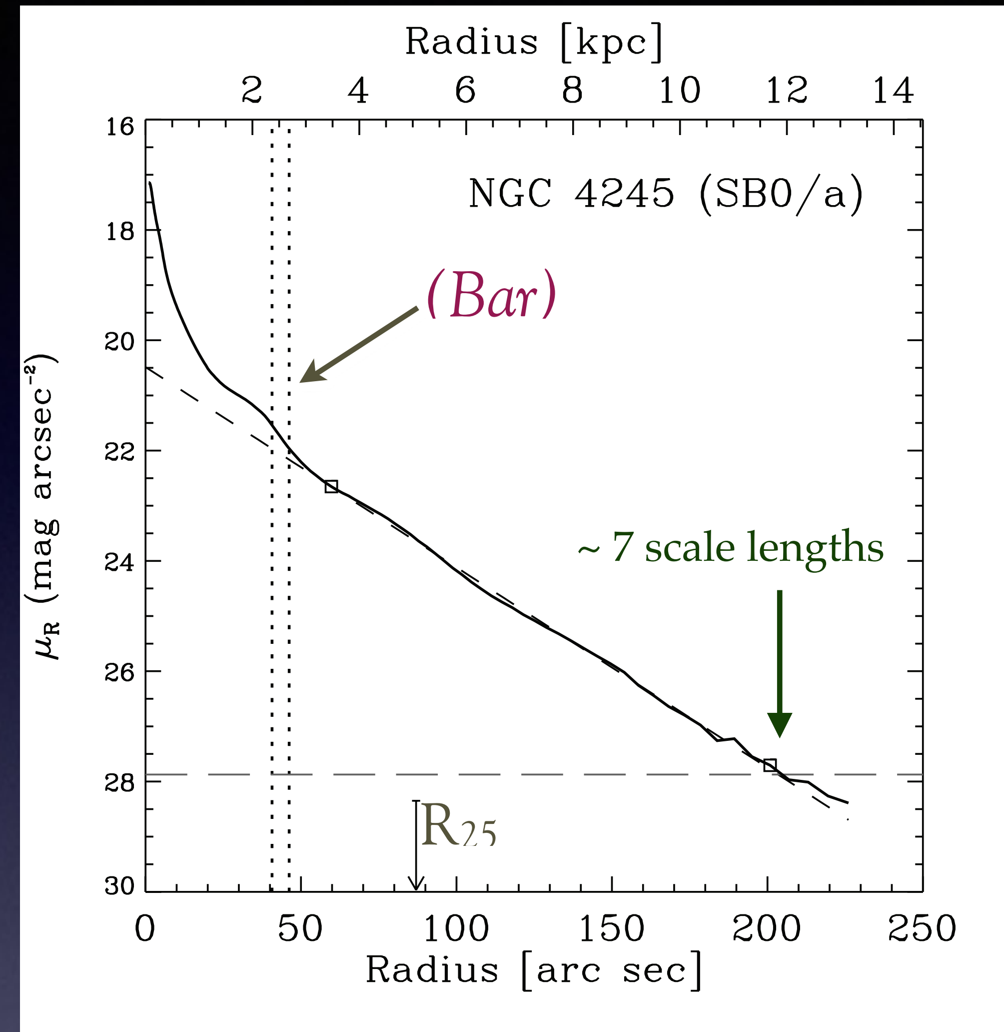
No Break | "Downbending" Break | "Upbending" Break



Type I (No Break): Simplest Case



Bland-Hawthorn+2005



Erwin+2008

Classic single-exponential disk (e.g., Freeman 1970)

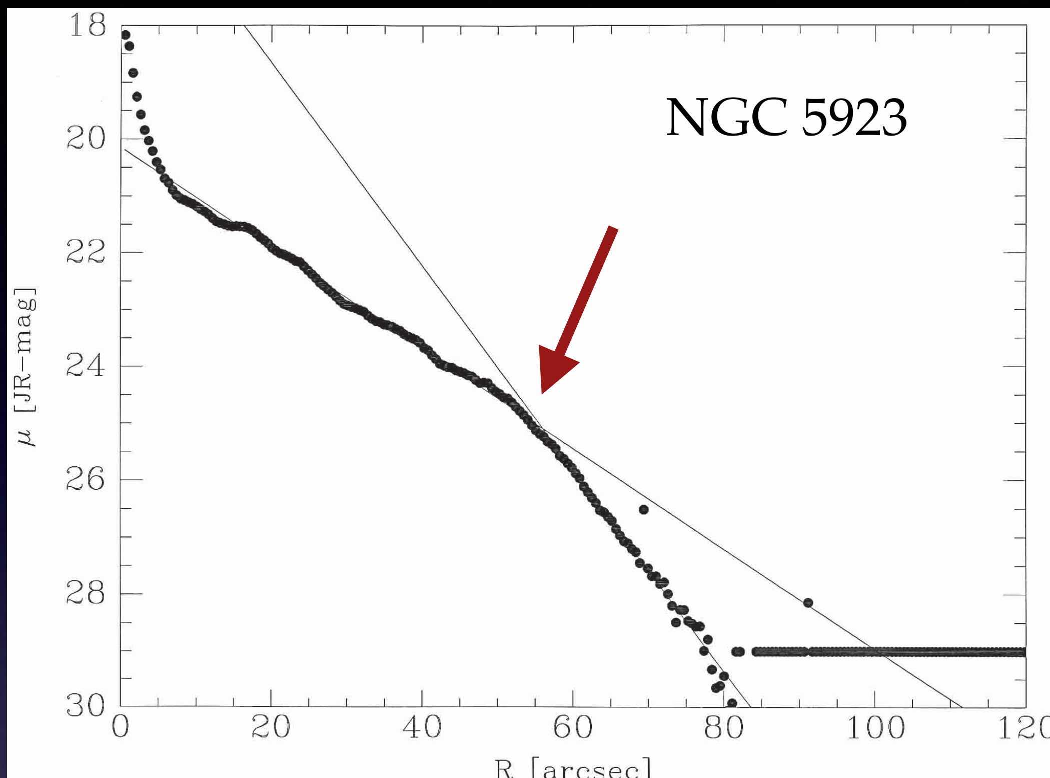
21% of local bright (M_B < -18.4) S0–Sm galaxies; most common in S0–Sa

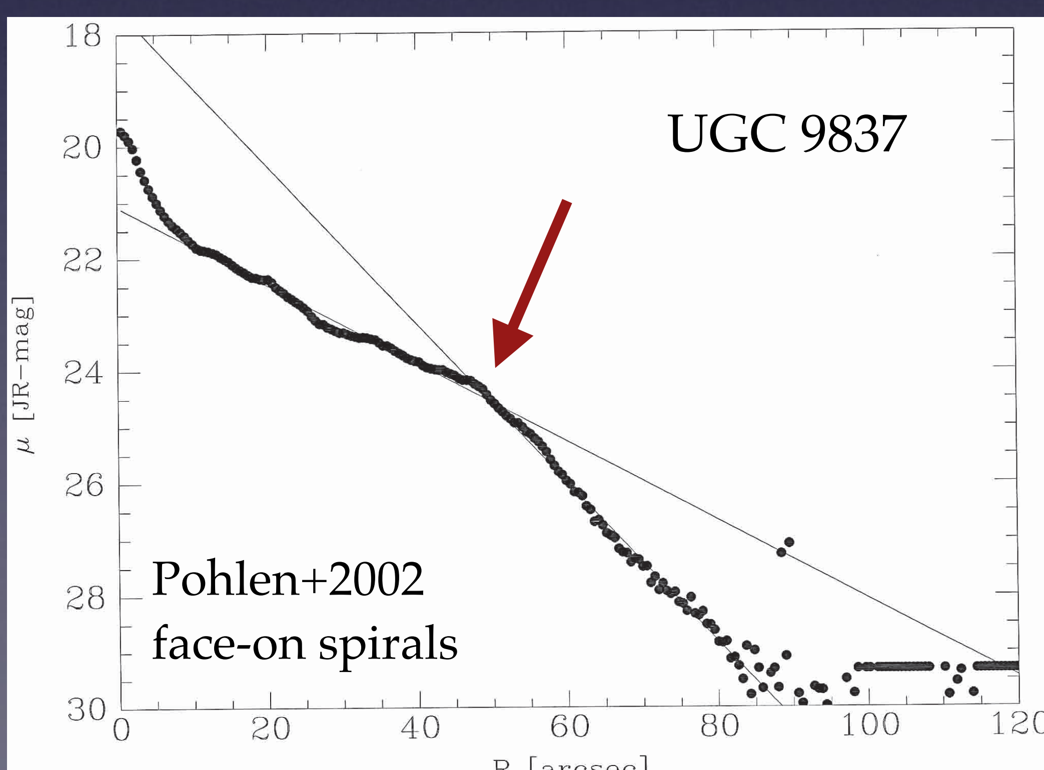
Some, at least, are quite extended: no breaks visible out to limits of ~ 8.5 scale lengths (Barton & Thompson 1997; Hunter+2011) and even 10–11 scale lengths (Weiner et al. 2001; Bland-Hawthorn et al. 2005; Vlajic et al. 2011)

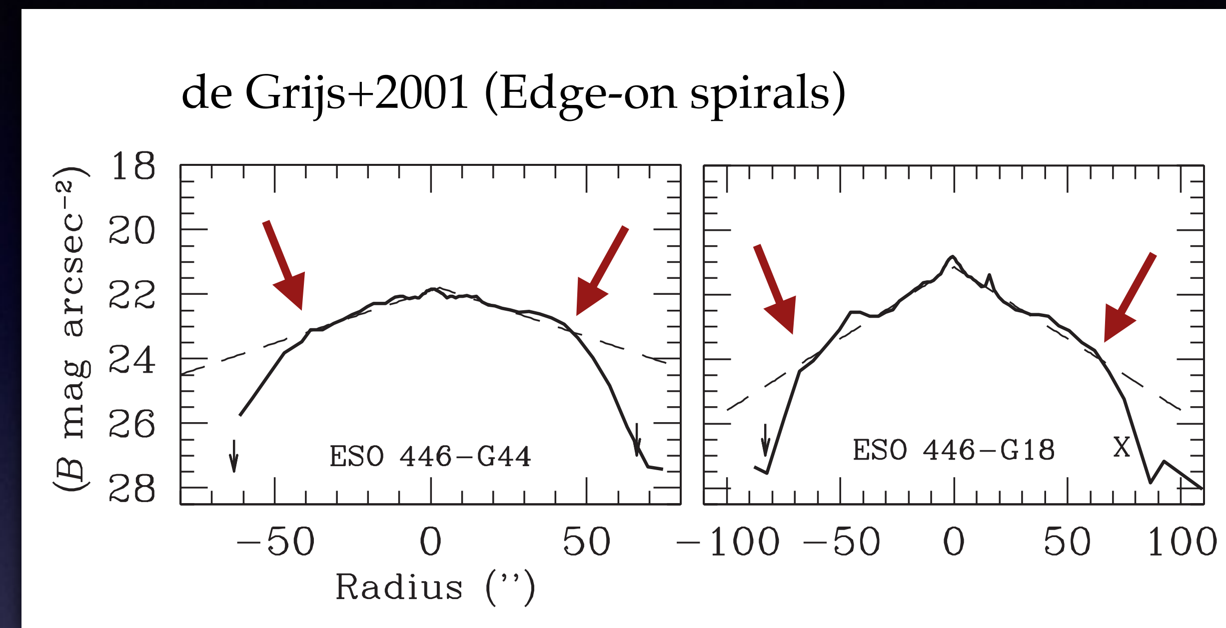
Type II Profiles (including "Truncations")

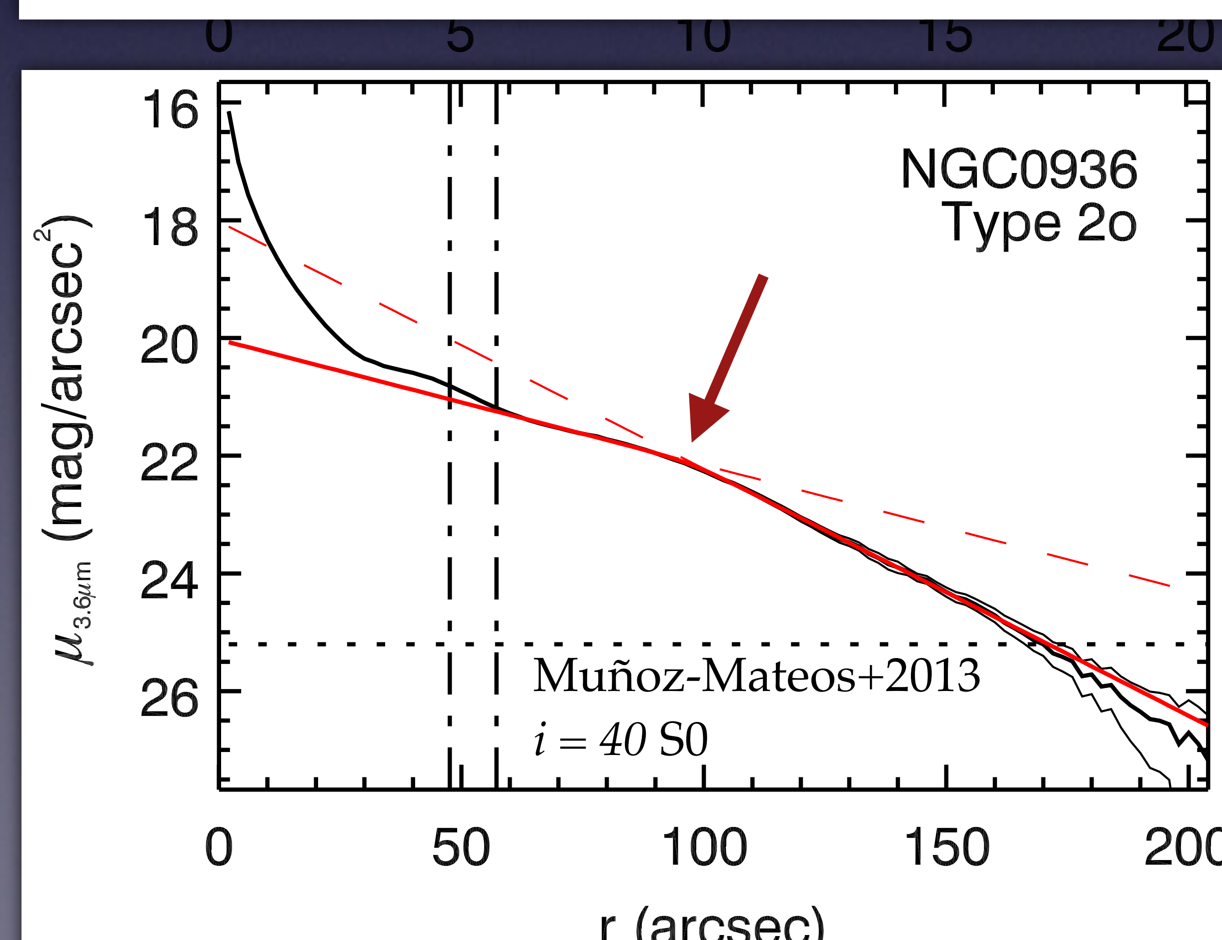
- Freeman 1970: Some disks have inner "deficit" relative to outer exponential = "Type II"
- van der Kruit & Searle (1981): edge-on disks are not single-exponential out to detection limits — instead, they are "truncated"
- Pohlen+2002: deep imaging of 3 face-on spirals shows broken-exponential profiles: break = "truncation"
- SO: Lump them together as "downbending breaks": profile is shallow inside break, steeper outside

Type II Examples (Face-on and Edge-on)







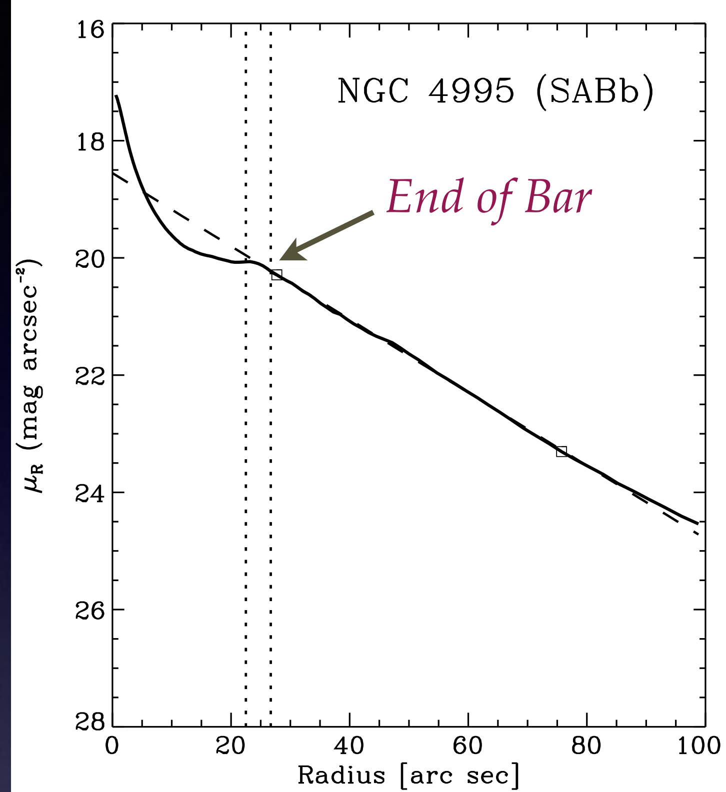


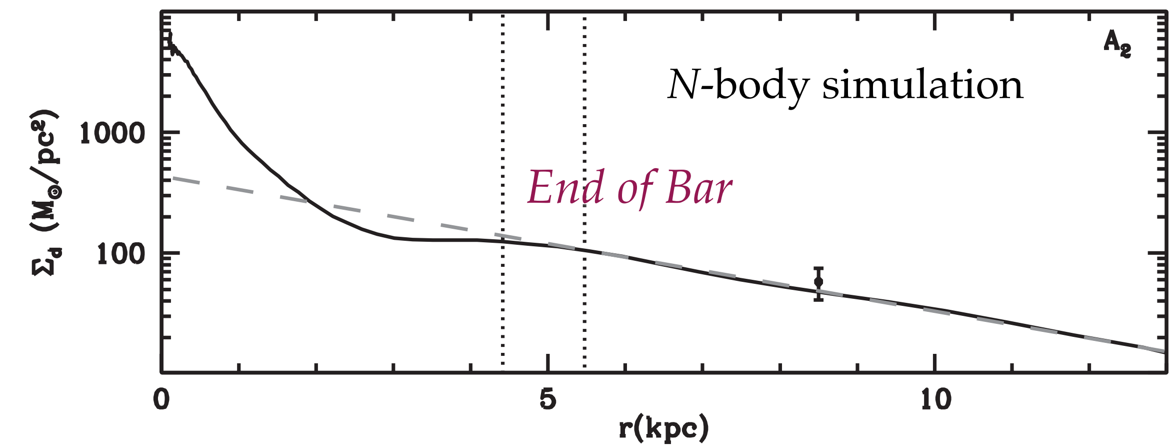
Type II Profiles: Oddities

Type II.i

Break is ~ at end of bar
Similar to some *N*-body simulations

Only ~5% of local S0–Sdm (Gutiérrez+11; Laine+14)

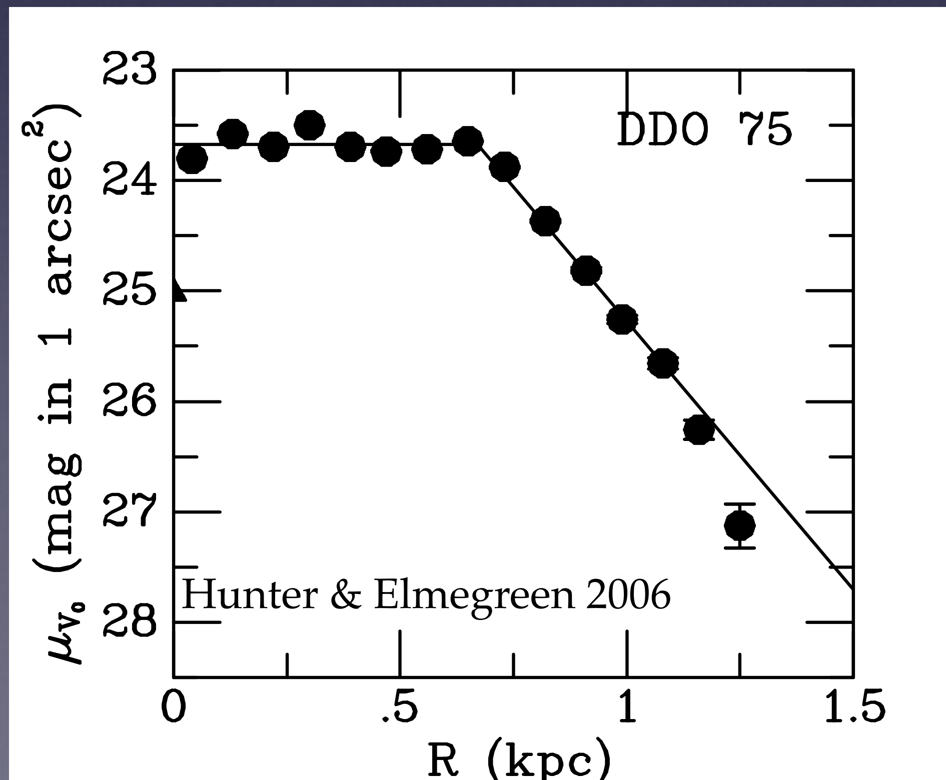




Adapted from Valenzuela & Klypin (2003)

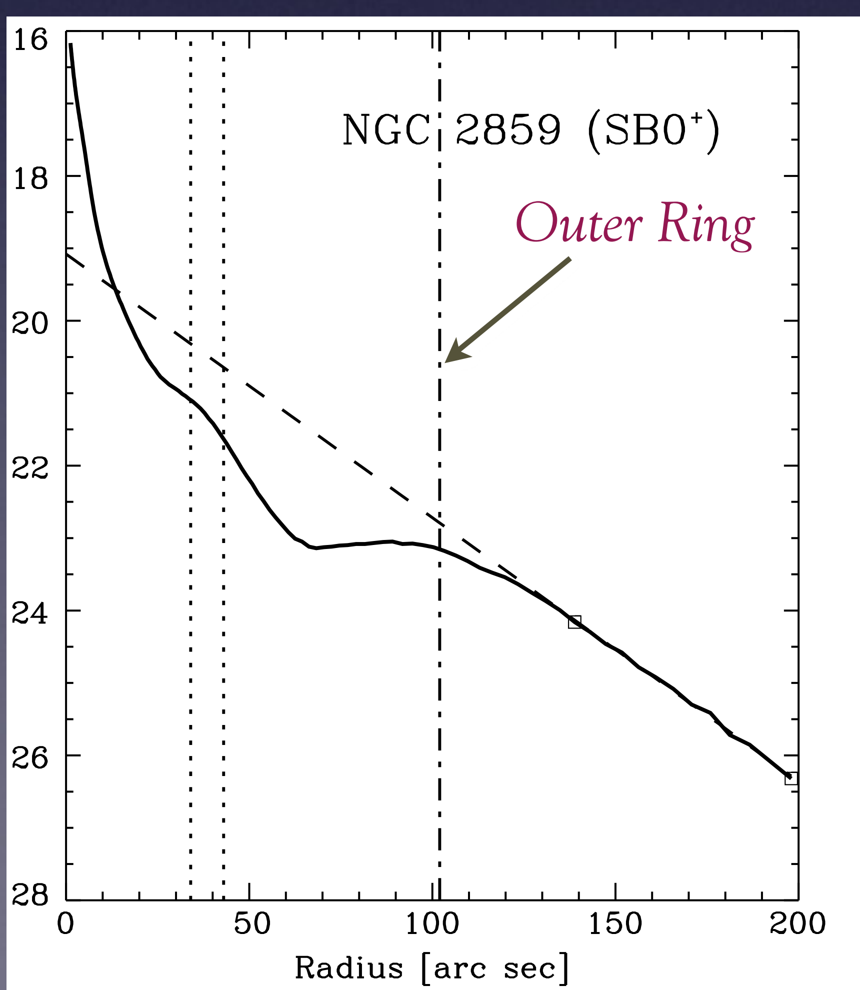
Type II-FI

Inner profile is *flat* or even *increasing* before break;
late-type dwarfs only(?)
(Hunter & Elmegreen 2006; Herrmann+2013)

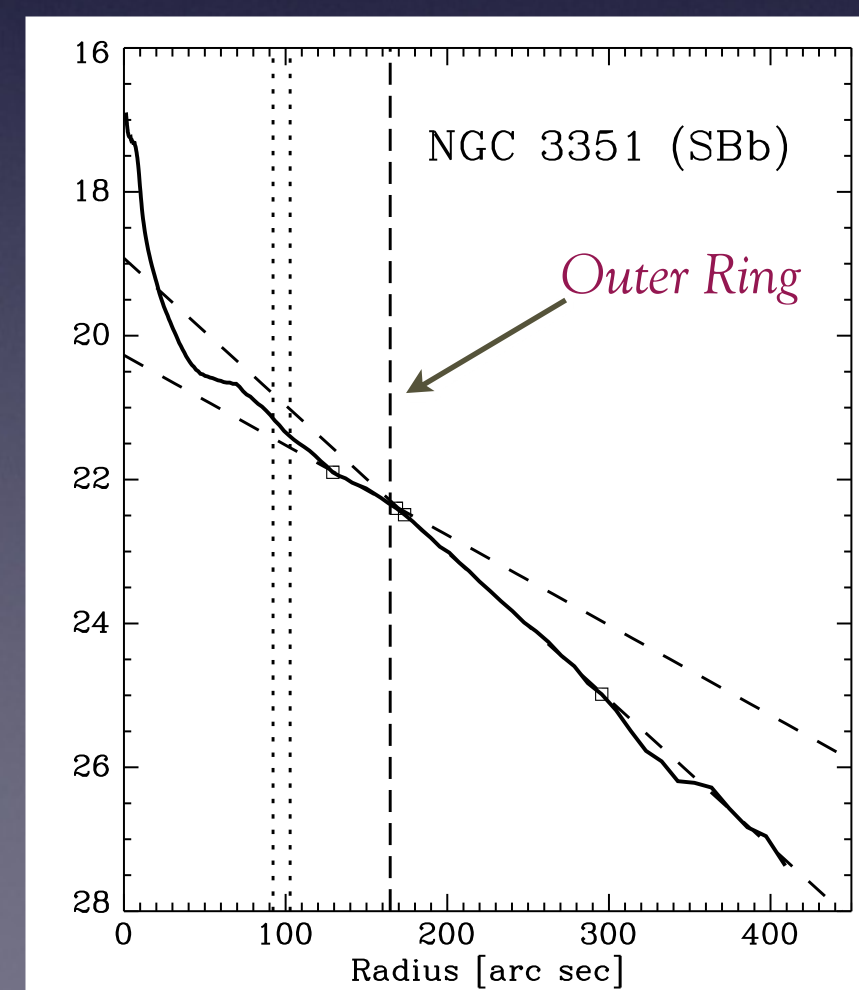


Type II-OLR: Linked to Outer Rings (and Outer Lindblad Resonance?)

“Extreme” Outer Rings



“Normal” Outer Rings



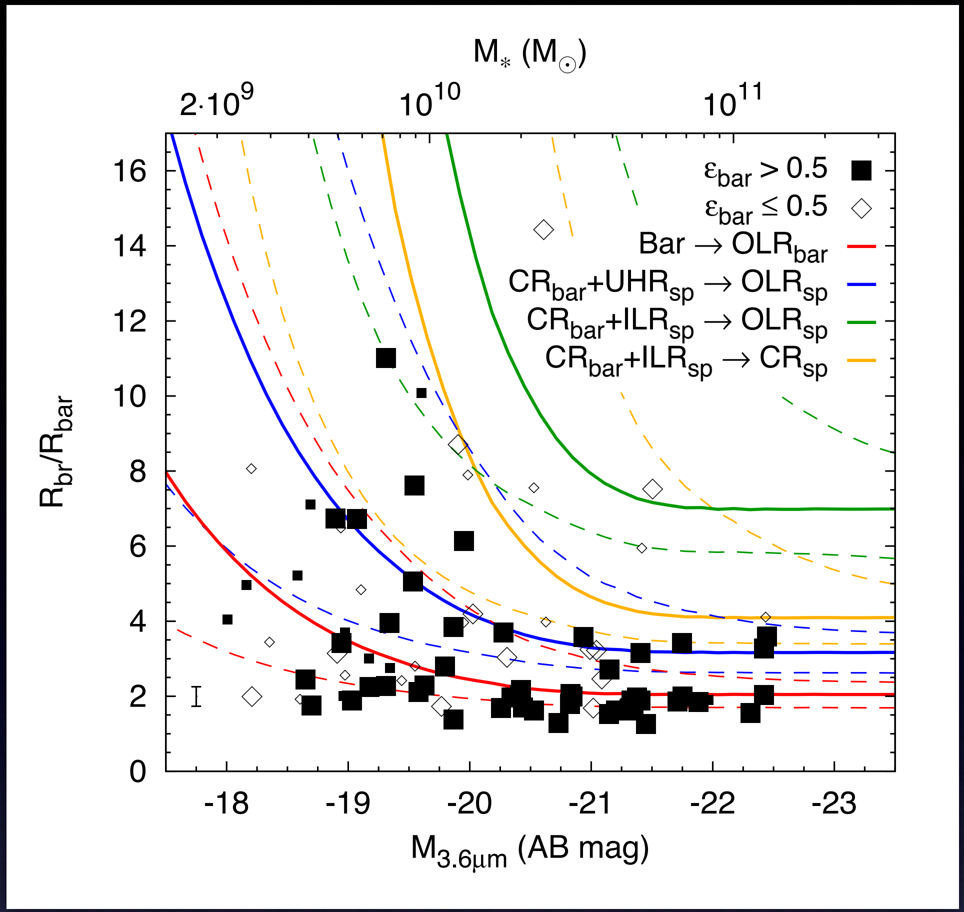
Outer rings believed to result of gas interacting with bar’s Outer Lindblad Resonance (OLR).

In ~ 45% of barred S0-Sb Type II profiles, break coincides with a visible outer ring.

Laine+14: 48% of S0–Sab Type II breaks correspond with outer rings/pseudorings/“ringlenses”

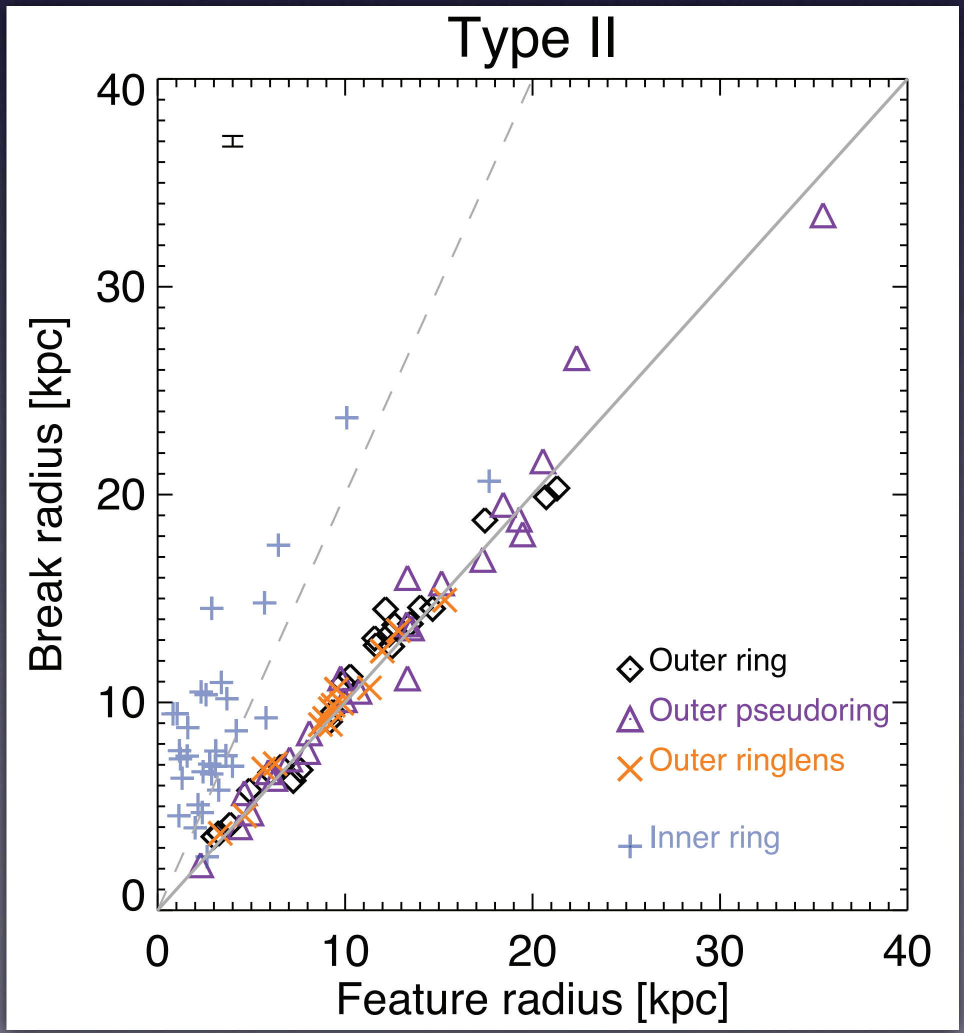
Muñoz-Mateos+2013 (S4G Spitzer IRAC)

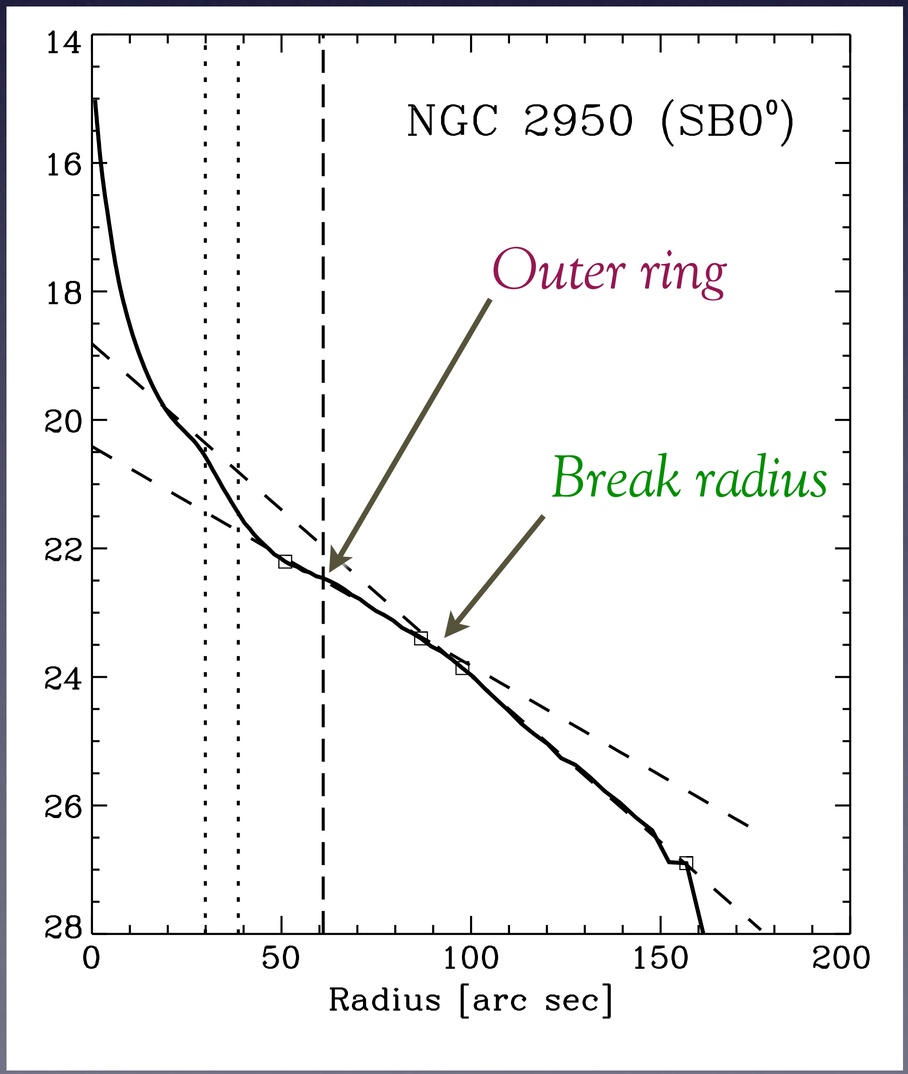
R_brk is typically ~ 2 R_bar, consistent with bar OLR [*or* ~ 3–4 R_bar, consistent with coupled spiral OLR; Debattista+2006]



Laine+2014 (also S4G data)

R_brk correlates *very* well with outer rings (not with inner rings)





Classical Truncations

In some barred galaxies, break is clearly *outside* outer ring (or outside expected OLR radius)

Type II also in *unbarred* galaxies — and late-type spirals, where bars are small and outer rings are rare

Probably different phenomenon from OLR (or other resonance) breaks

Since "truncations" seen by van der Kruit and collaborators in 1980s–2000s are typically at large radii in late-type spirals, we call these "classical truncations"

Best explanation: star-formation threshold + radial scattering of stars

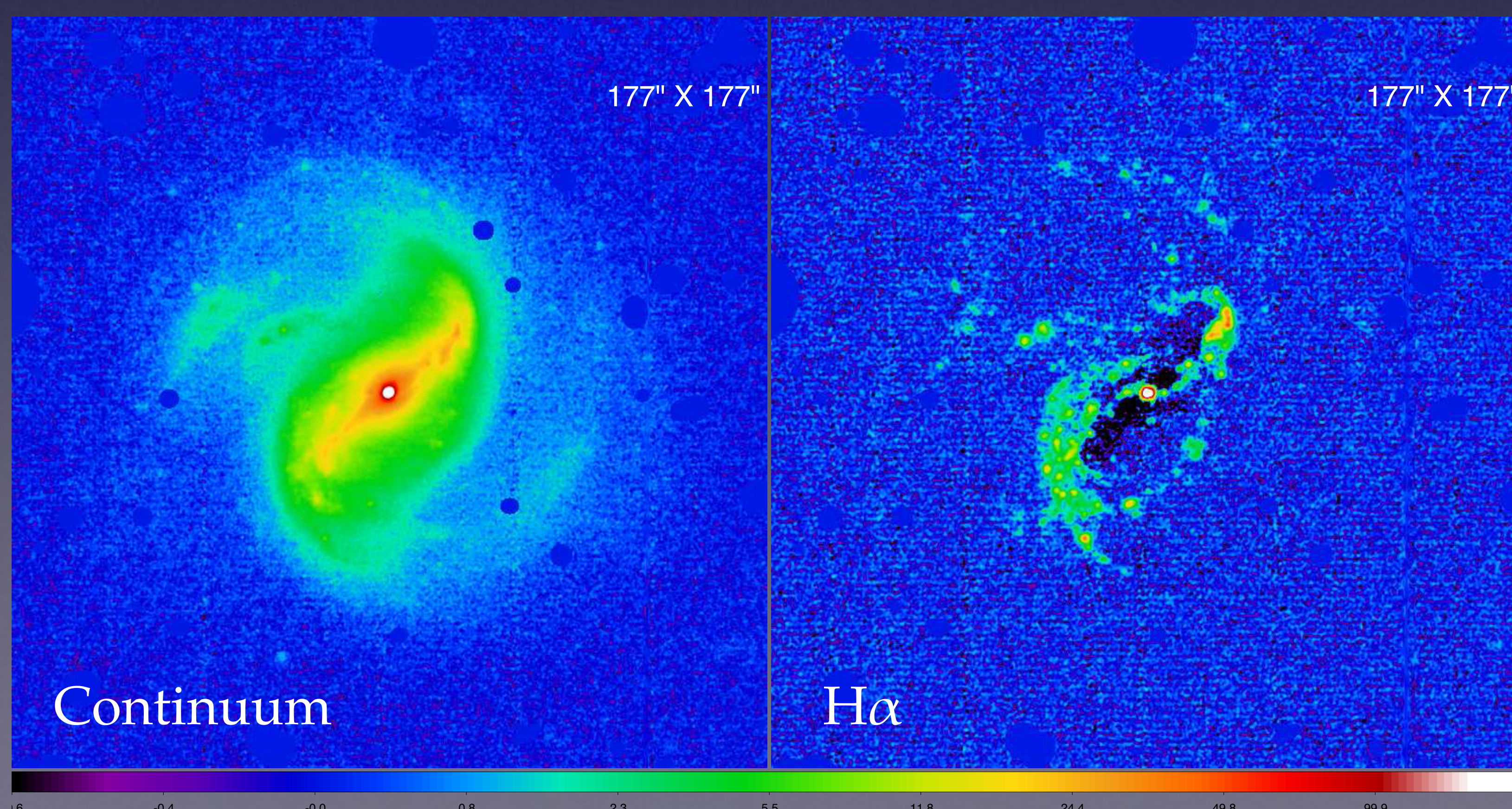
Hα Galaxy Groups Imaging Survey (HAGGIS)

PE, David Wilman, Sandesh Kulkarni (MPE), Leonel Gutierrez (UNAM), John Beckman (IAC)

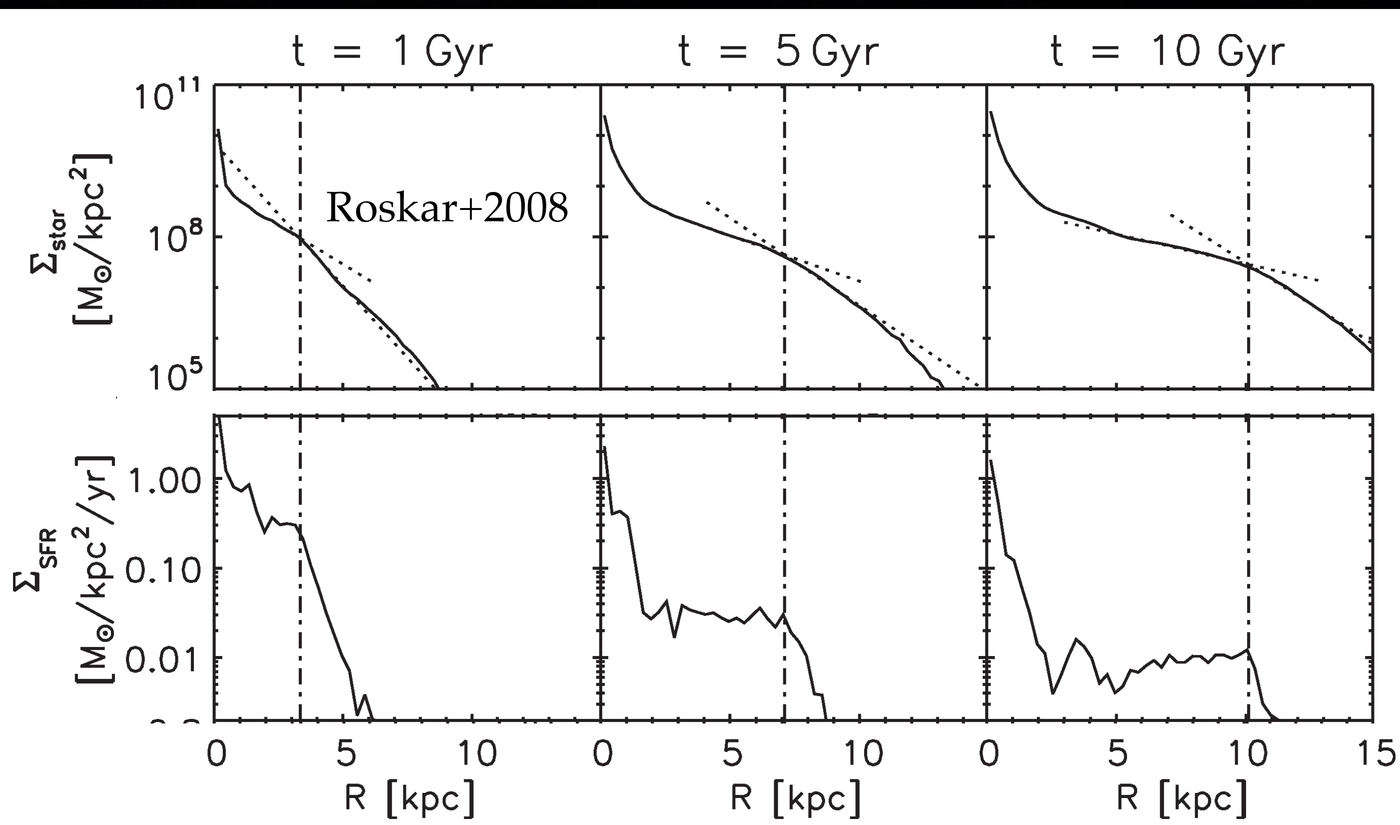
Hα imaging of ~ 100 nearby (z ~ 0.02–0.05) Yang+2007 galaxy groups, spanning halo masses 10^12–10^14 M_sun (~500 galaxies)

INT-WFC (La Palma) and ESO/MPI-2.2m WFI (~0.8″ FWHM)

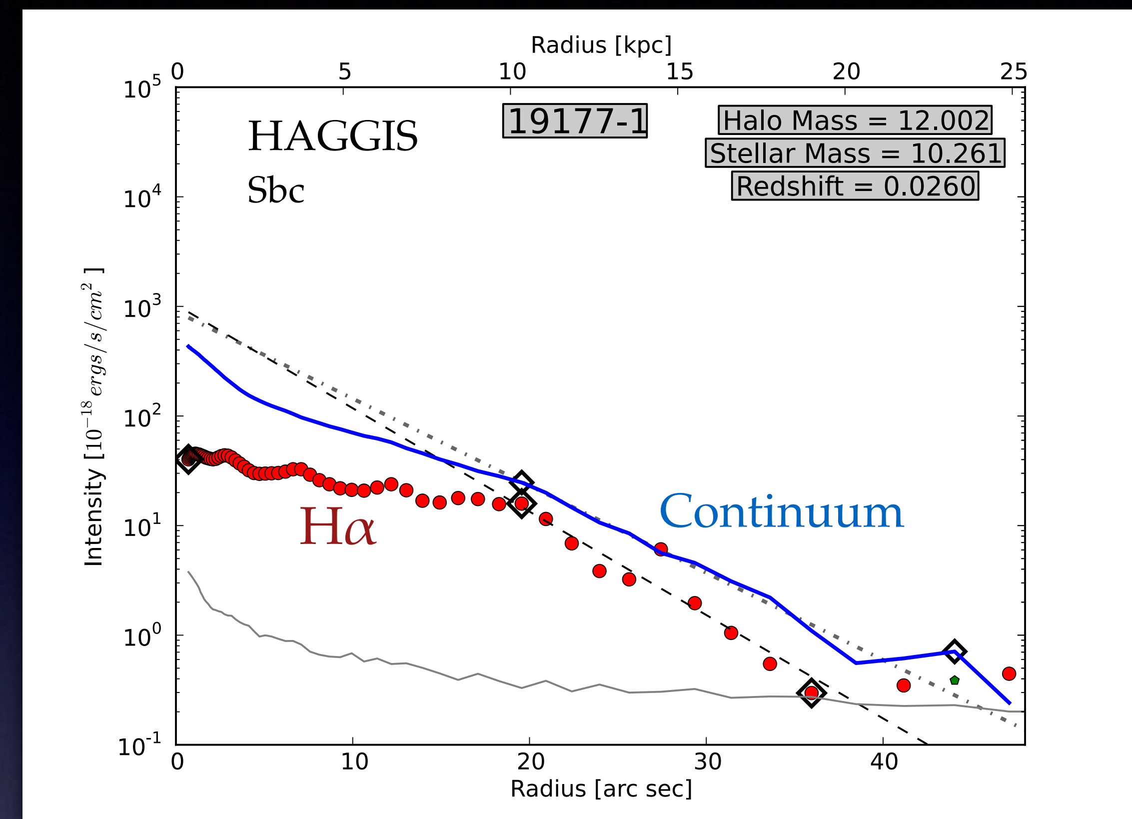
Narrow-band Hα *and* continuum filters + calibration with SDSS spectra



SB Profile Breaks = Star Formation Breaks

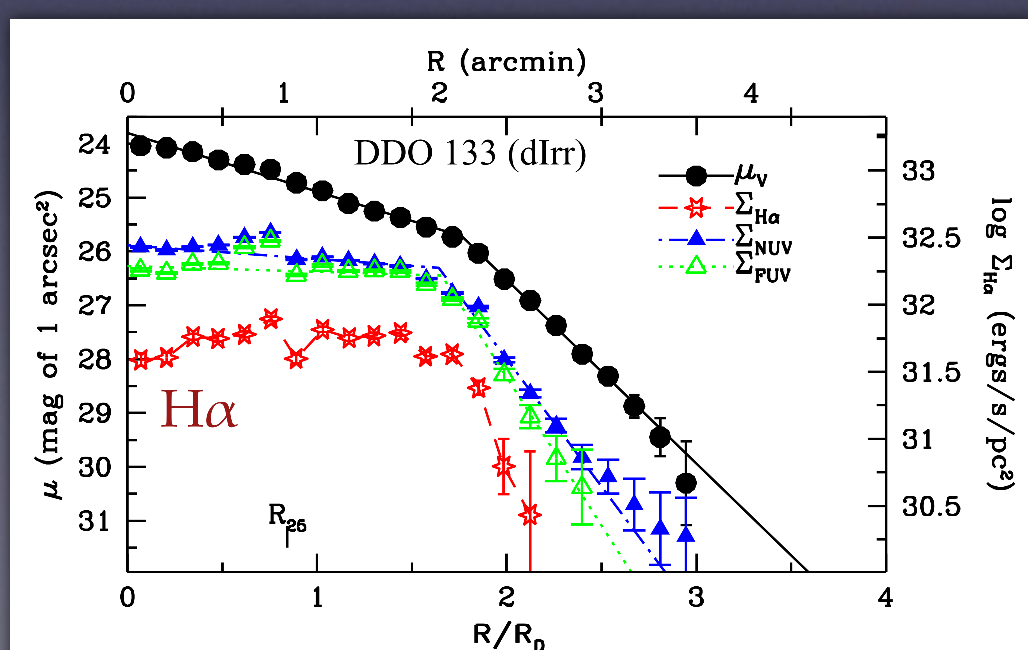


Simulations (e.g., Roskar+2008; Sánchez-Blázquez+2009) show break in SFR ~ break in stellar continuum

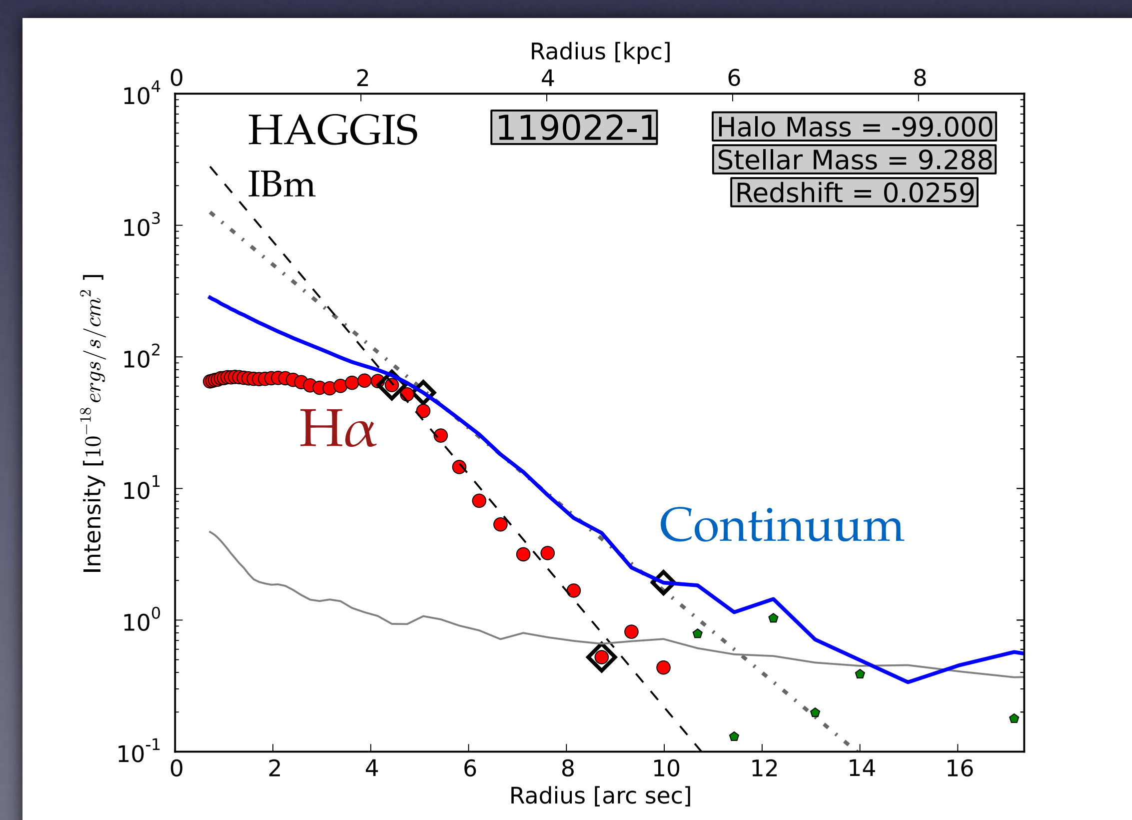


See also:

Christlein+2010; Herrmann+2013



Hunter+2011



Are Breaks Purely a Stellar Population Effect?

Bakos+2008: *g-r* color profiles for late-type spirals:

Type II profiles tend to show *blue minimum at the break!*

Azzollini+2008 see this in late-type spirals out to z ~ 1

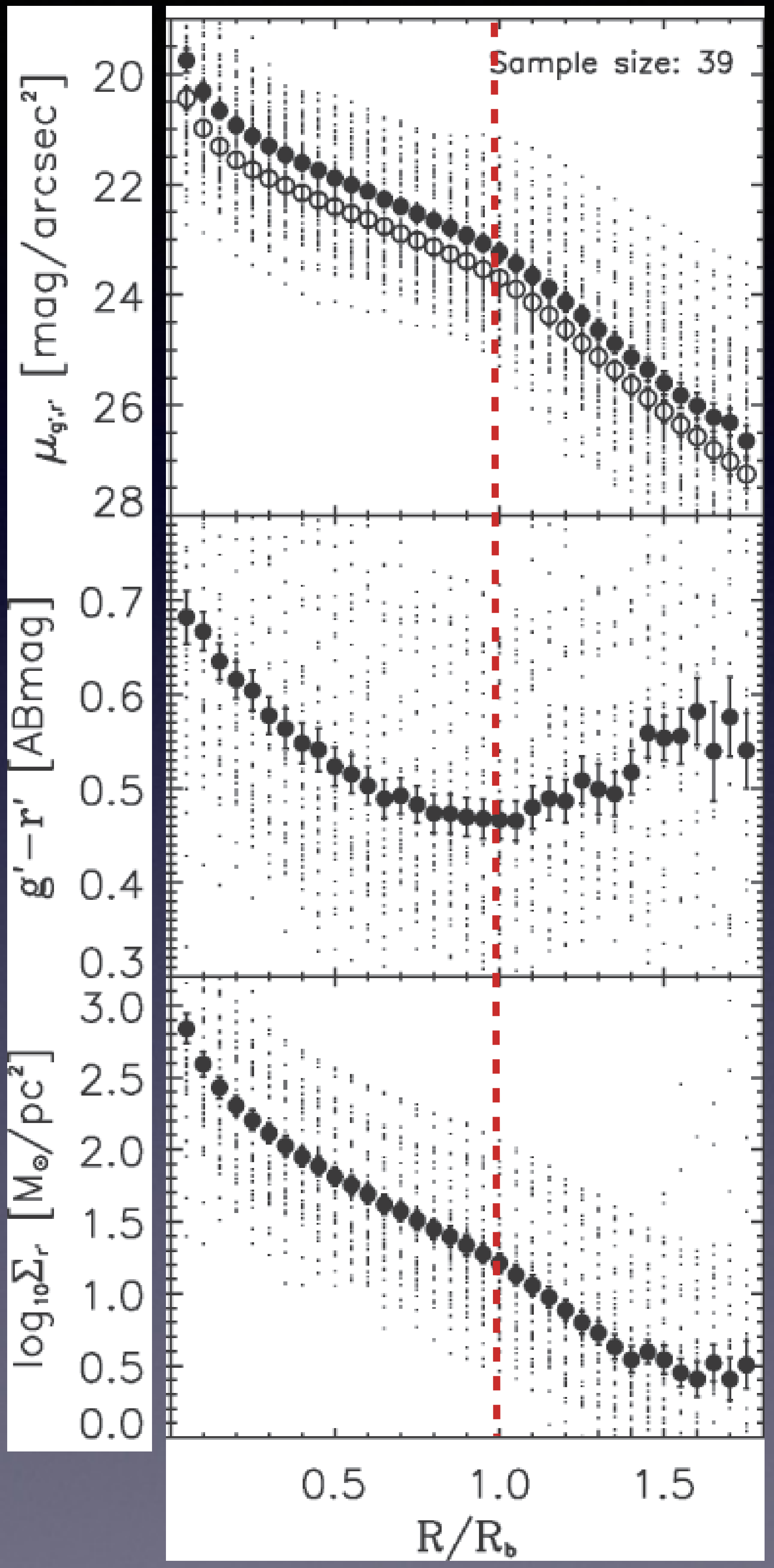
Modeling suggests scenario of star-formation threshold + radial migration of stars

e.g., Roskar+2008; Martínez-Serrano+2009; Sánchez-Blázquez+2009

Leads to age minimum (= blue) at break

Stellar-mass profile is *flatter* than surface-brightness; sometimes break disappears!

Evidence for age-reversal at break in star-count data for M33 (Barker+2007; Williams+2009, 2011)



Not all Type II are like that…

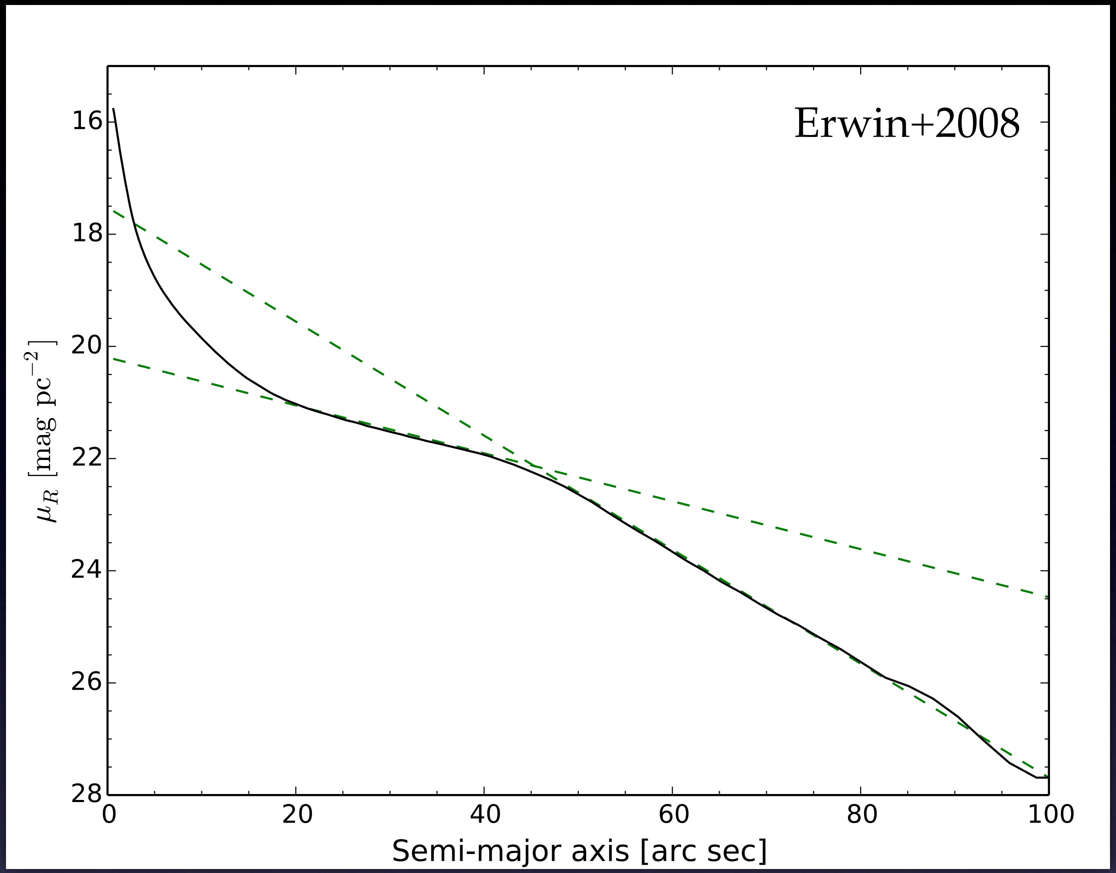
Yoachim+2012: large-FOV IFU observations, fitting multiple stellar populations to optical spectroscopy (late-type spirals)

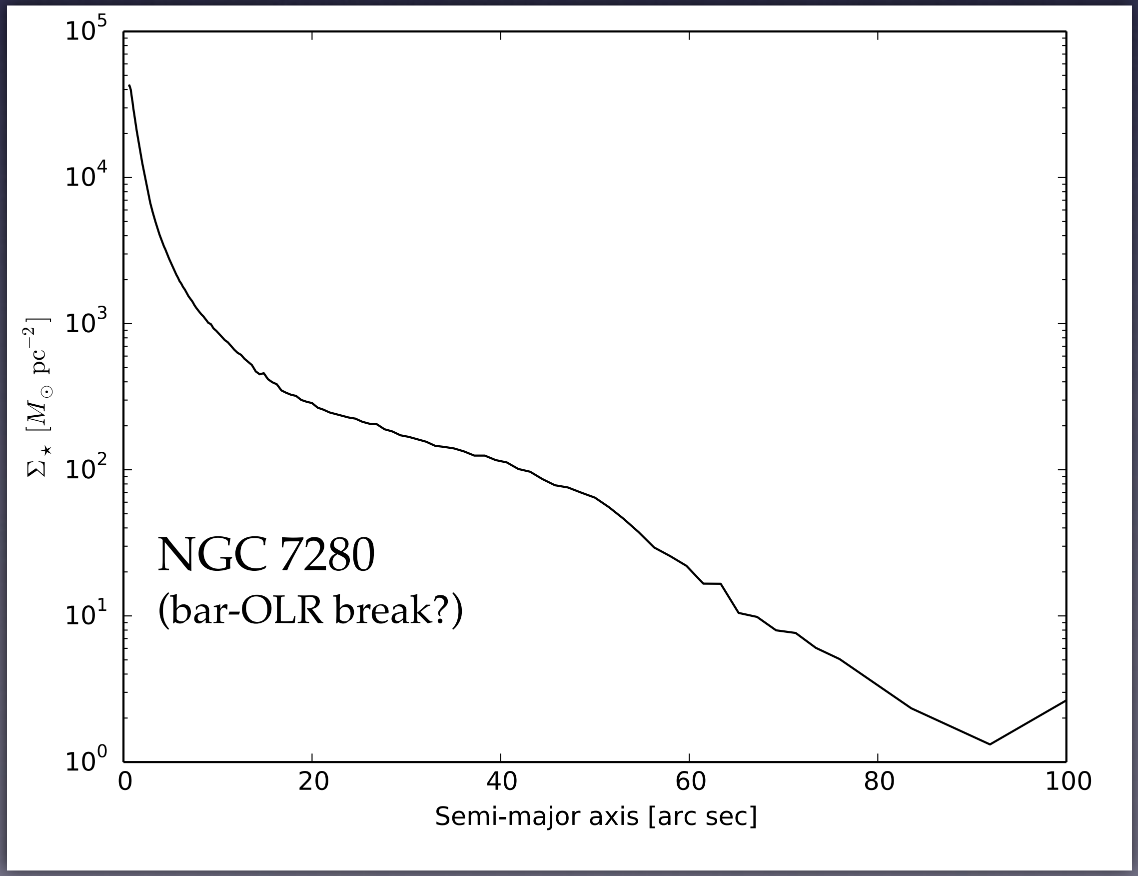
- 6 late-type spirals with Type II profiles:
  - Half show age minimum near or at the break!
  - BUT: other half did *not*

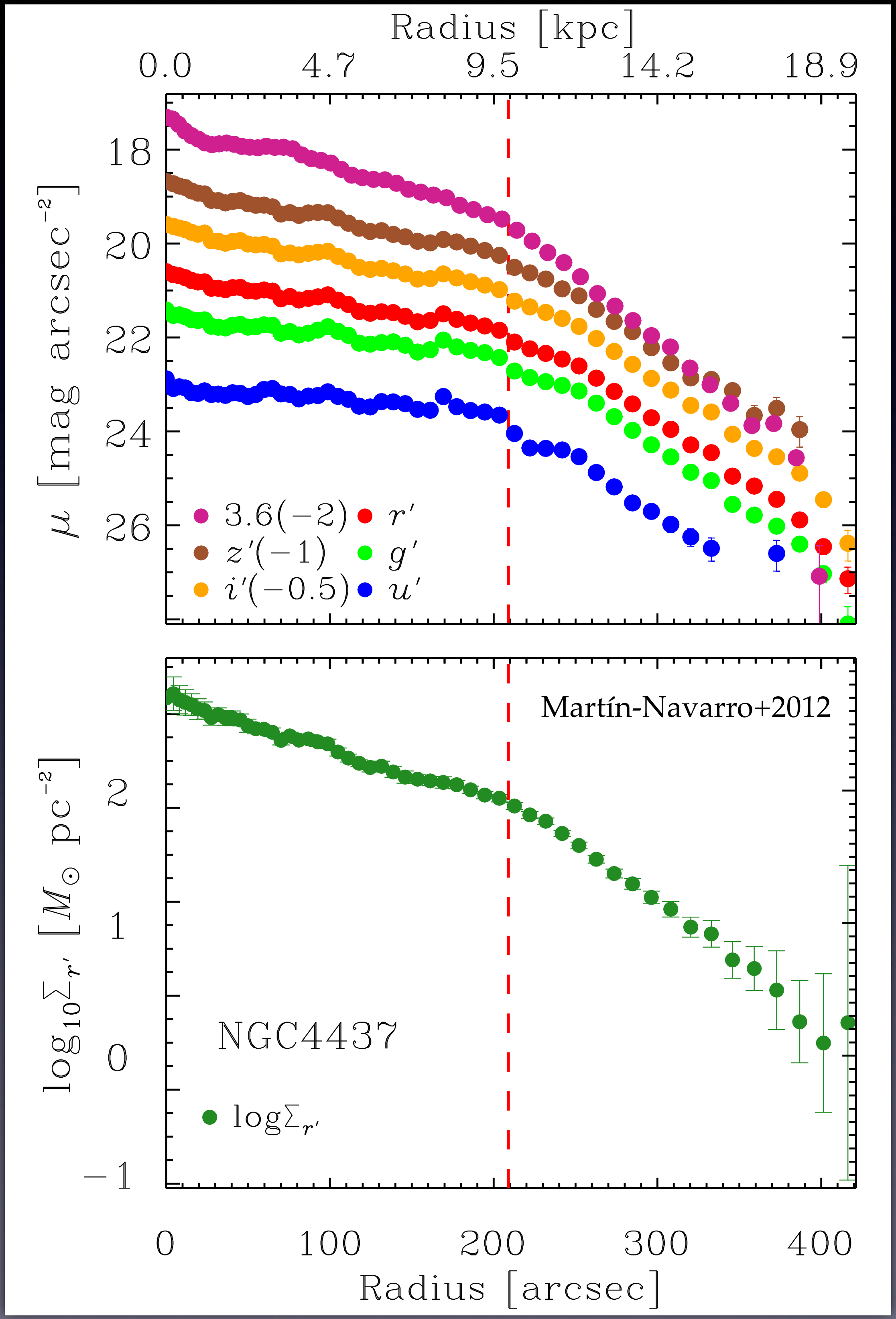
Roediger+2012: analysis of multicolor (*griH)* profiles in Virgo spirals:

- 1/3 of 21 Type II profiles show age minimum near or at the break (Some Type I profiles also show age minima…)
- BUT: rest did *not*

Type II Breaks *Do* Exist in Stellar Profiles







Type II Summary

Apparently (at least?) *four* sub-types of Type II breaks in S0s + spirals!

1. II.i (inside bar): usually *not* broken-exp; rare

   Predicted by some *N*-body models? (mostly ignored)

2. Bar OLR: sometimes not broken-exp; mostly early-type disks; common

   Circumstantial argument — no models yet

3. Spiral OLR(?): broken-exp; somewhat rare?

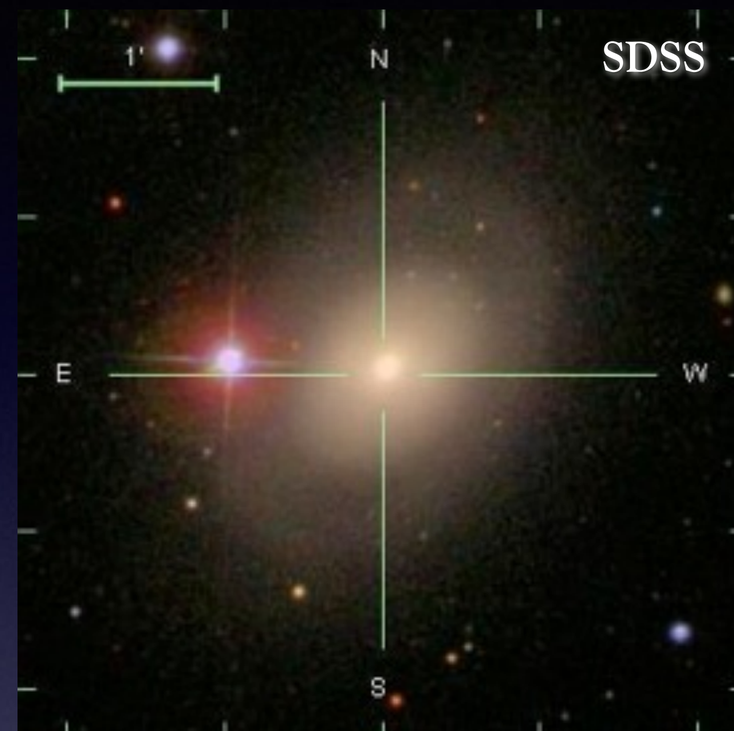
   Predicted by at least one *N*-body model (Debattista+2006)

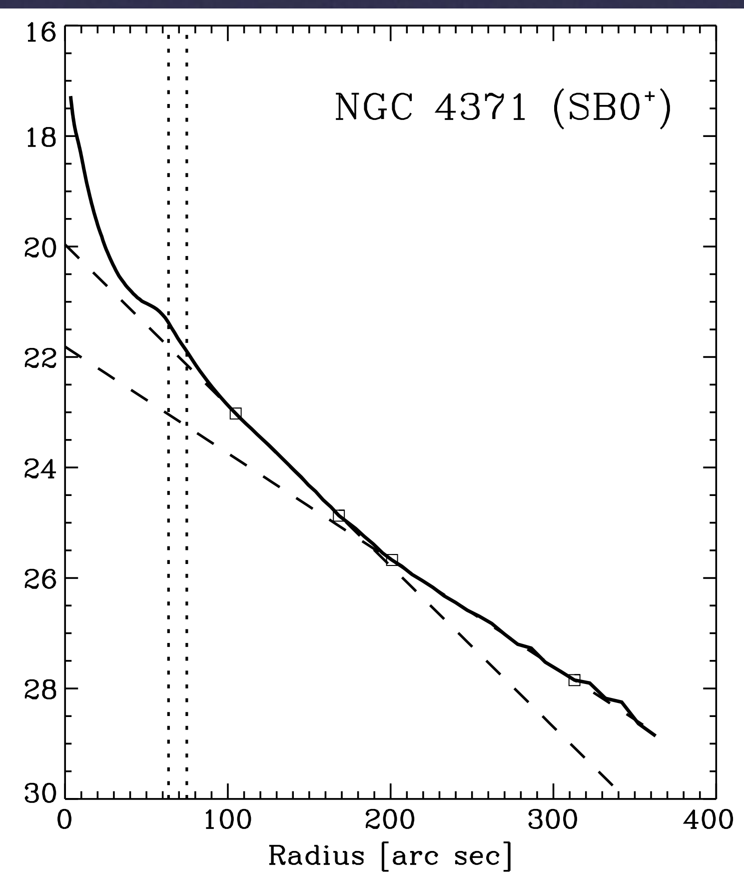
4. SF threshold + radial migration: broken-exp; mostly late-type disks

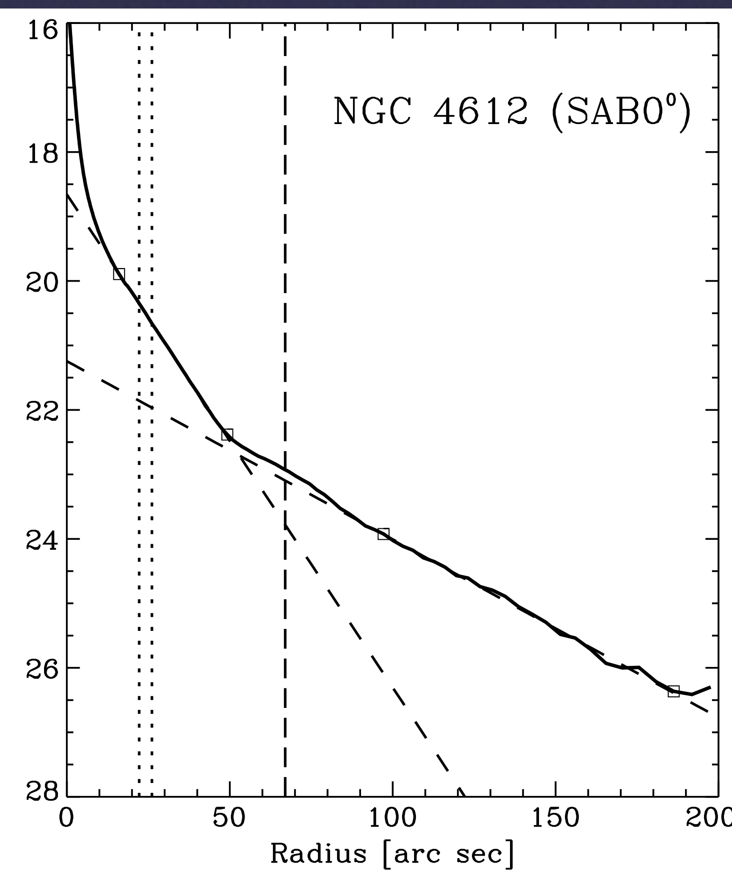
   Best-developed theory, with some predictions matched by observations (age minimum at break, flattening of break with age, SFR break)

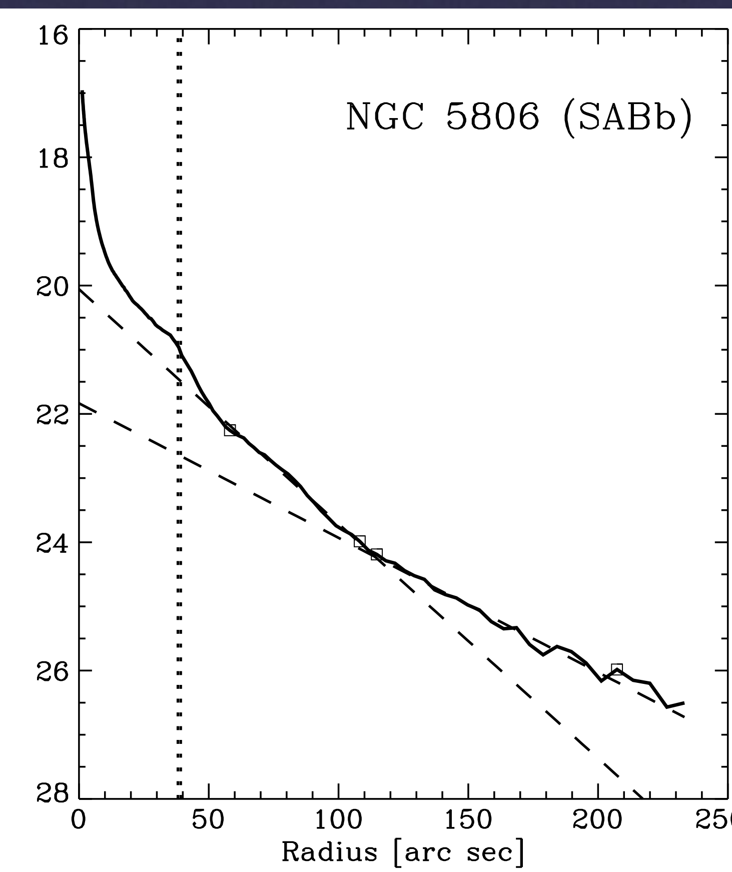
Type III ("Antitruncations")

Erwin, Beckman, & Pohlen (2005, ApJL 626: L81)



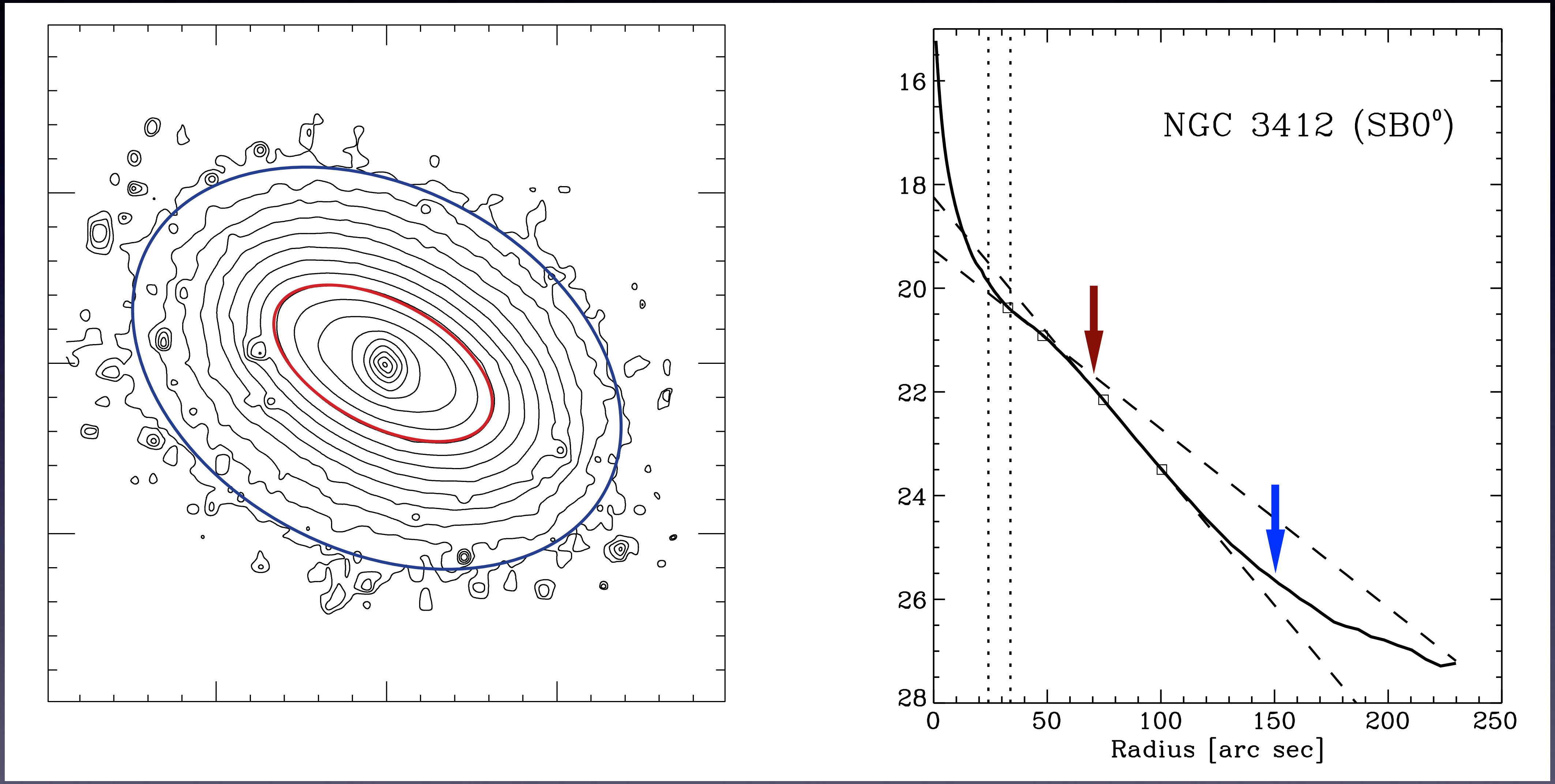






Bulge or Halo Light at Large Radii?

For *some* galaxies, yes…



1. Outer isophotes are rounder.
2. Smooth transition in SB profile; suggests addition of two co-extensive components.
3. Outer profile not exponential.

A *minority* of Type III profiles are like this ("Type I + bulge/halo")

38% of Type III in local S0–Sb

15% of Type III in z~0.17 Sa–Sd (Maltby+2012, assuming R^1/4 bulges)

...but for majority, outer excess light is apparently still part of the disk

1. Inclined galaxies: outer isophotes ~ same ellipticity as inner disk.

2. Sharp transitions in profile: not sum of 2 exponentials, so prob. not outer bulge or halo light.

3. Spiral structure in outer disk.

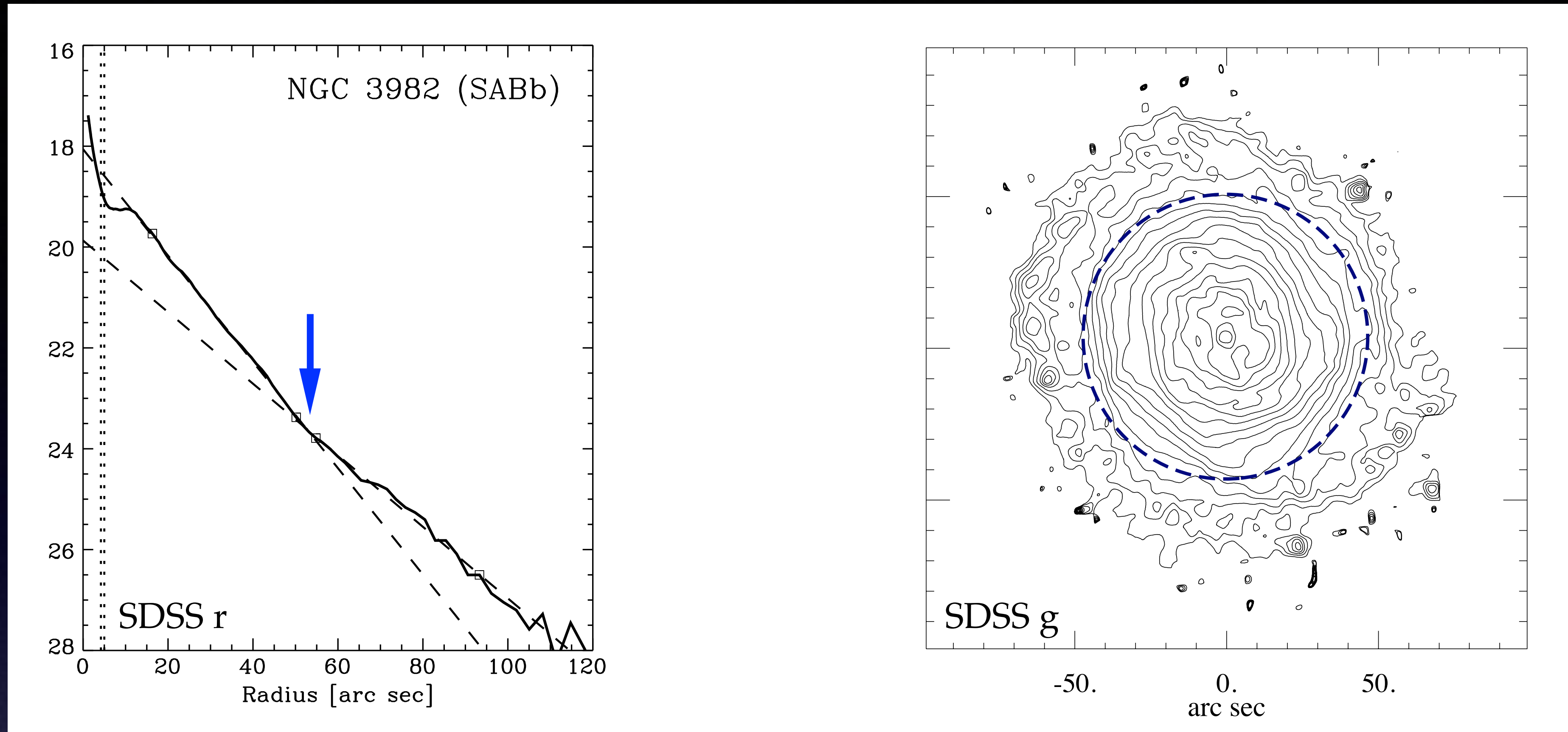
4. Appear in later Hubble types, where bulges are less prominent or absent (Pohlen & Trujillo 2006; Hunter & Elmegreen 2006).

5. Antitruncation seen in *edge-on* disks by Pohlen+2007, Comerón+2012

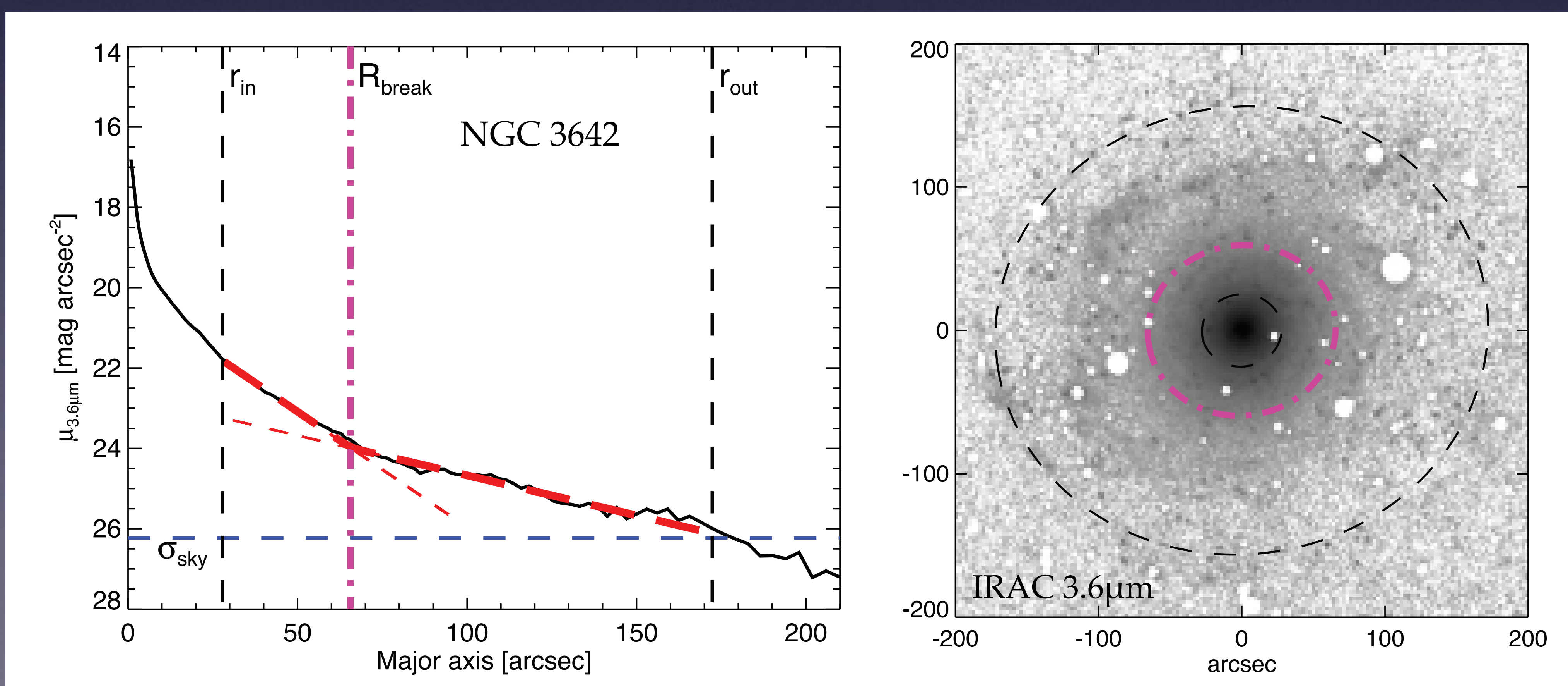
Erwin+2008/Gutiérrez+2011 S0–Sb galaxies with $i > 30°$:

S0: 47% of Type III are III-d

S0/a–Sb: 71% are III-d

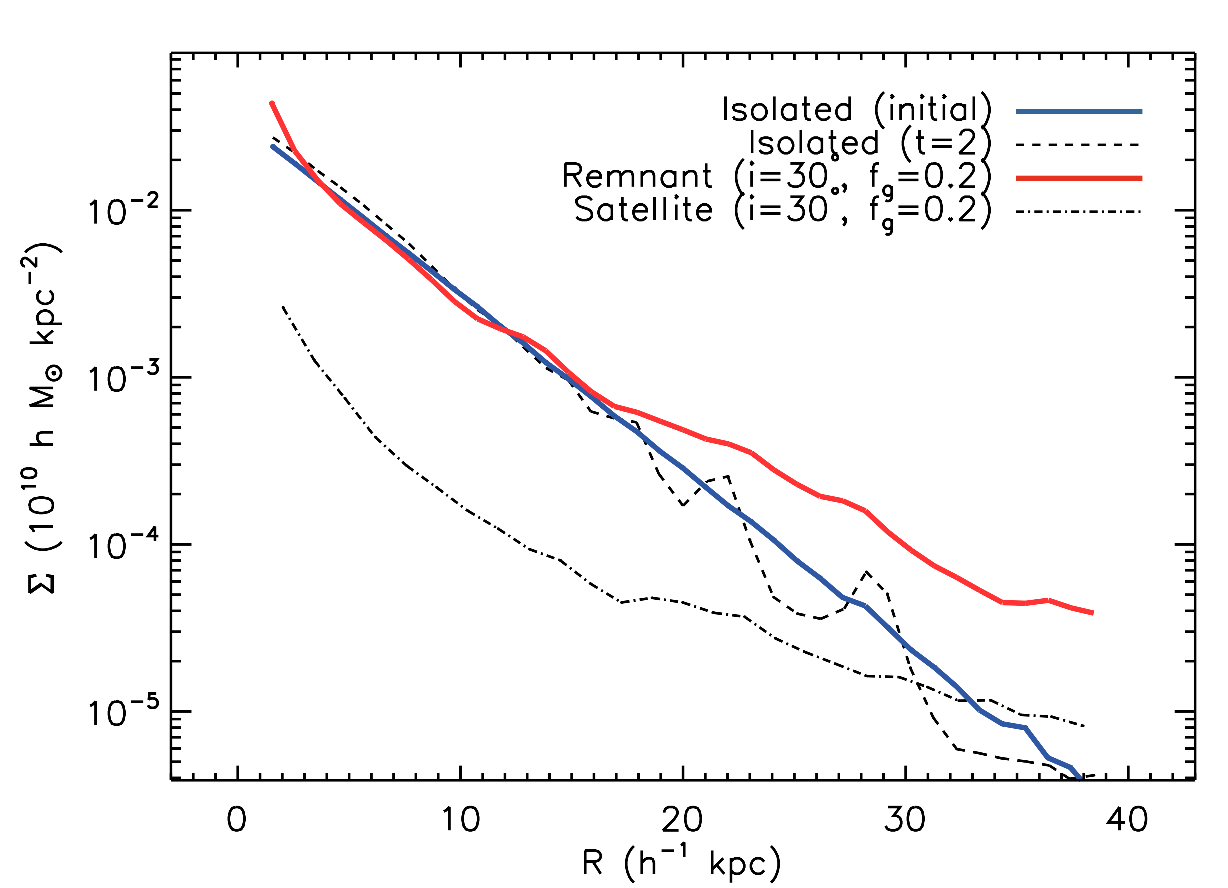


Erwin+2008

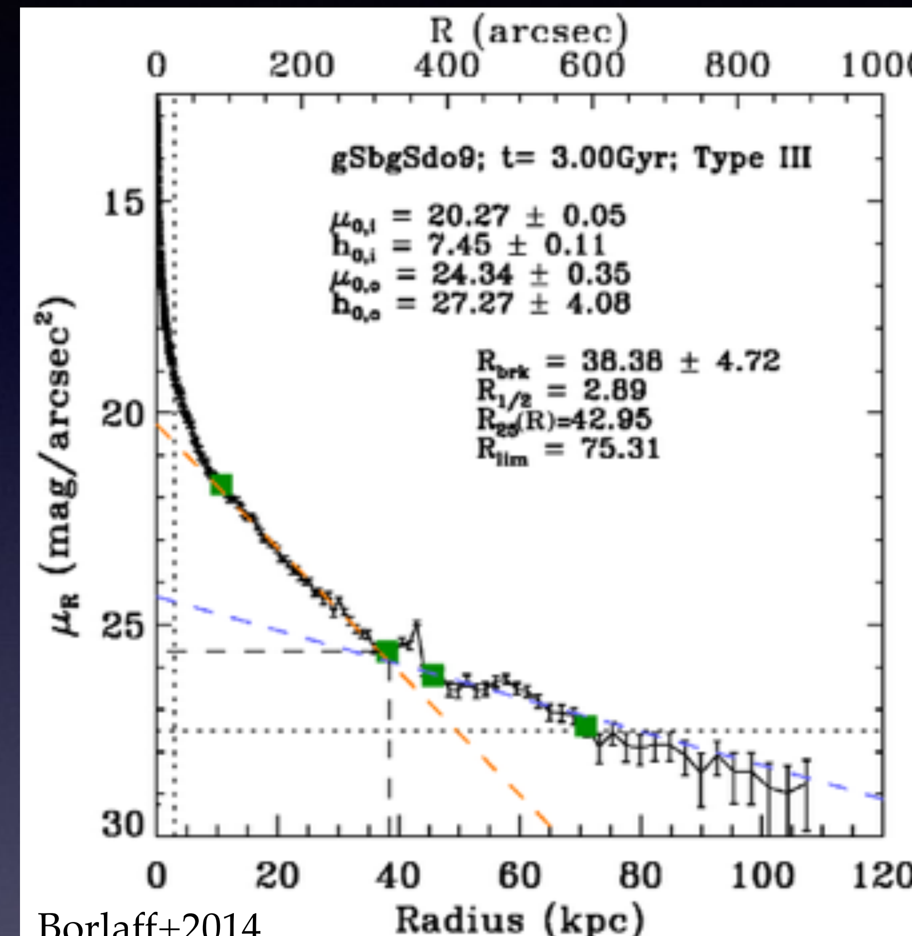


Laine+2014

Type III Formation: Minor (or even Major) Mergers?



Younger+2007



Borlaff+2014

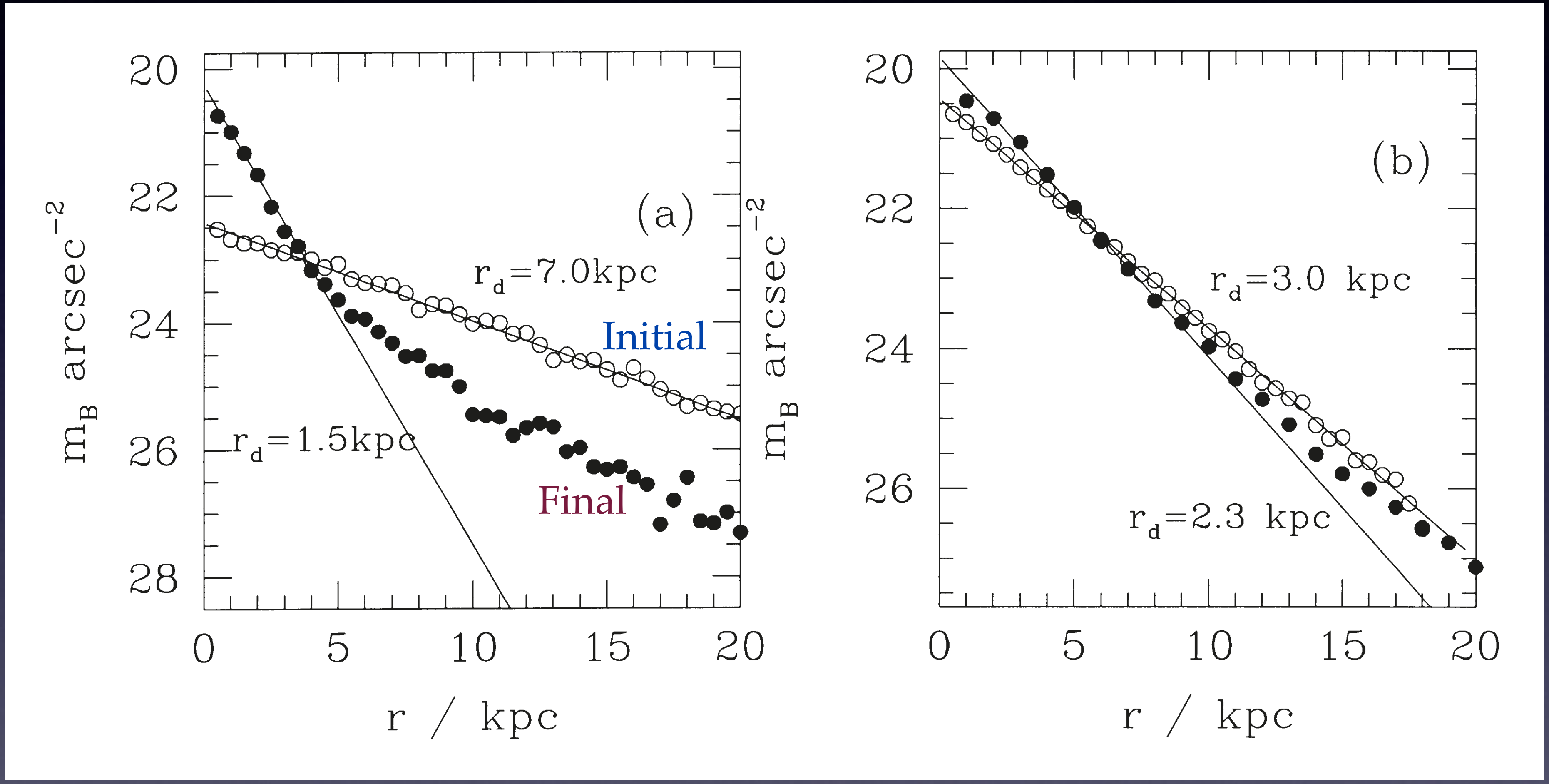
Younger+2007: gas-rich, prograde minor mergers can produce antitruncations

Ang.mom. of secondary transferred to primary stars, but gas inflow deepens inner potential well, so inner stars keep ~ same radii (also: Laurikainen & Salo 2001)

Outer stars are from primary's disk

Borlaff+2014: major mergers can sometimes produce rotating S0 remnants; many of these have antitruncated disks

Type III Formation: Tidal Harassment?



Moore+1999: Harassment from cluster tidal field

Problem: this can't explain Type III profiles in late-type spirals (and irregulars) outside clusters

Type III Formation: In-Situ Star Formation?

NGC 4625 (SABm)
Gil de Paz et al. (2005) GALEX obs.

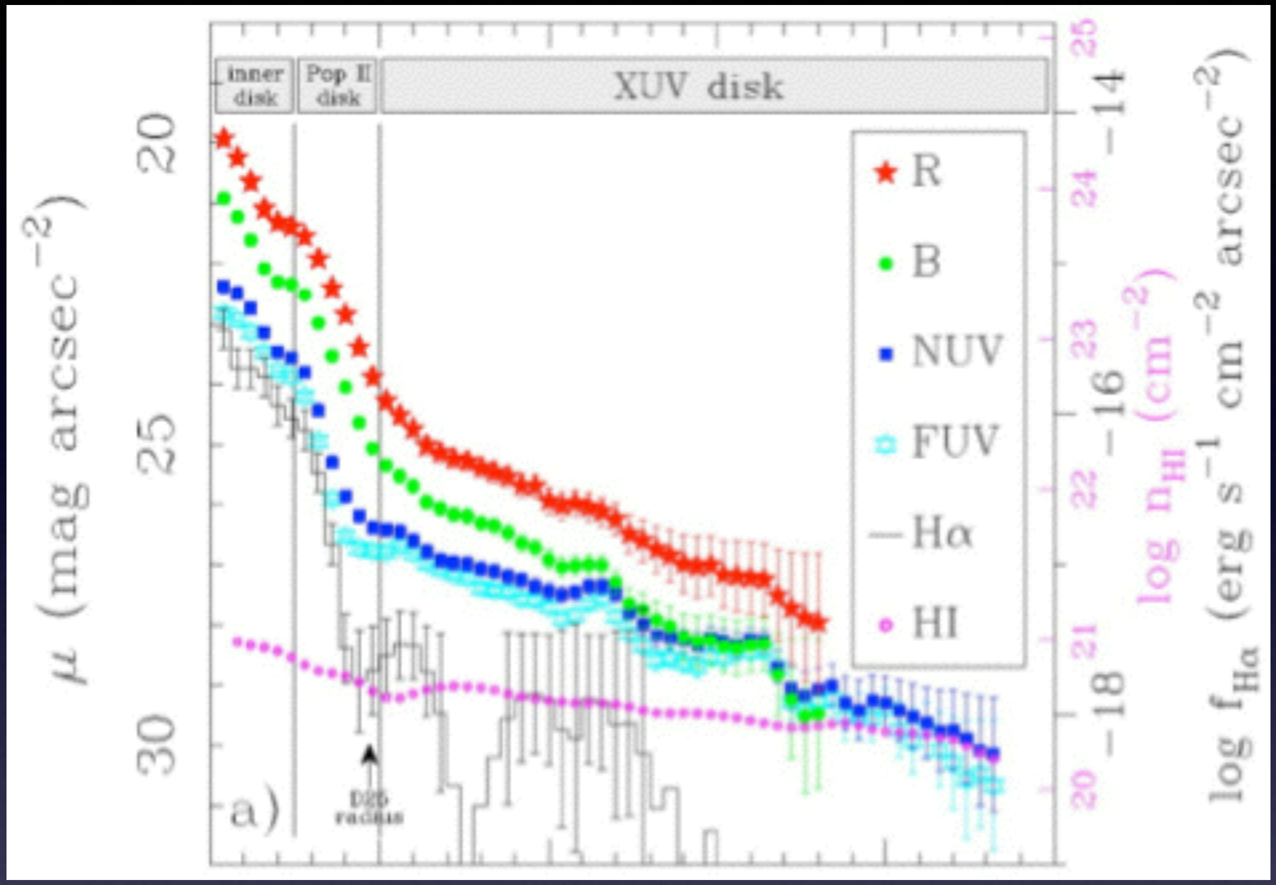
Type III profile in R (older stars, red) and in UV (young stars, blue)

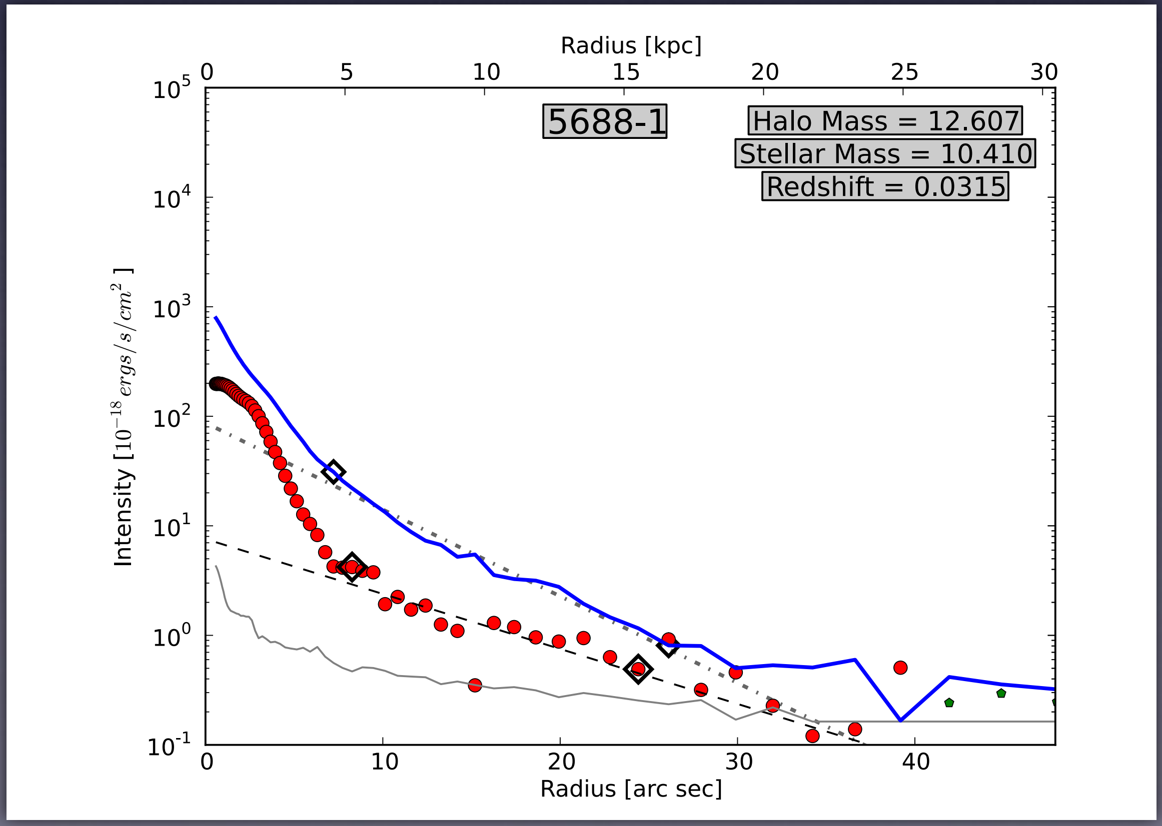
So Type III profile in both older stars and recent star formation!

Antitruncations seen in HAGGIS Hα profiles

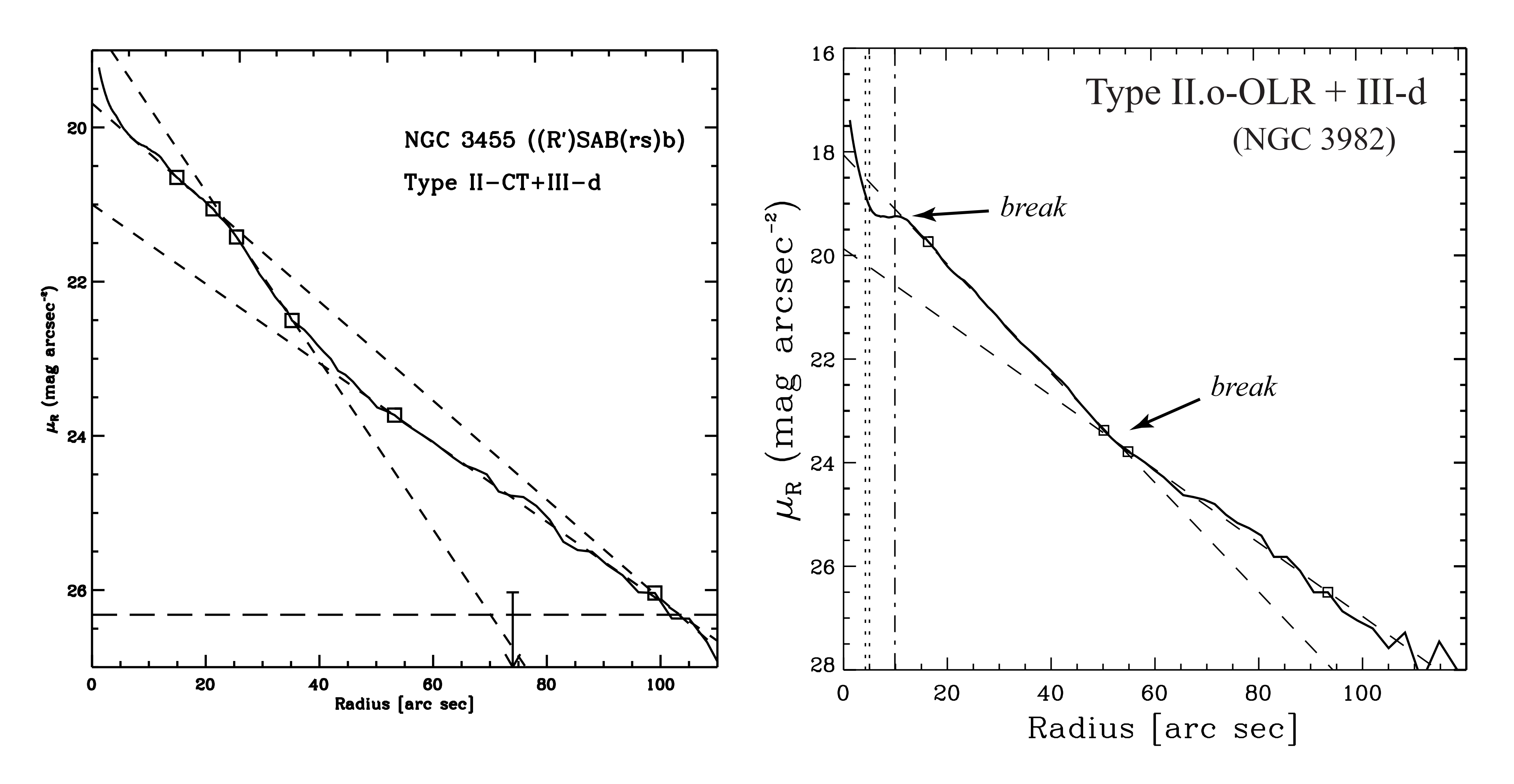
But only ~2% of galaxies, so < 10% of Type III (SB) profiles

(Elmegreen & Hunter 2006: Given the right ad-hoc initial gas profile, you can end up with antitruncated stellar profile…)





Multiple Breaks: Type II + III



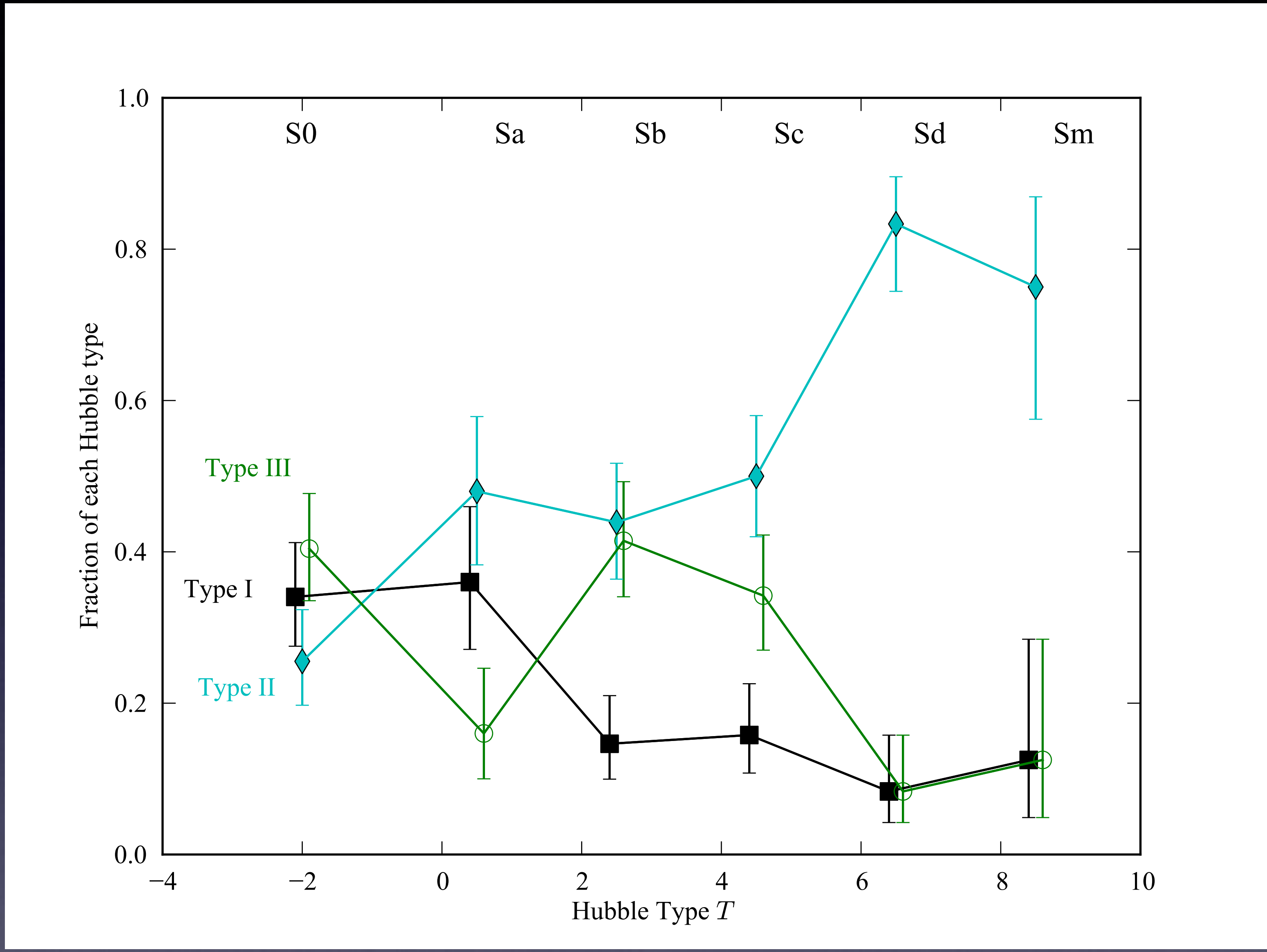
About 8% of local S0–Sdm galaxies show a *composite* profile:
Inner Type II profile with outer excess = "Type II+III"
Herrmann+2013 find "III+II" or "II+II" in 4% of dwarfs

Suggests that whatever mechanisms are involved are *not* always exclusive…

Correlations with Galaxy Properties?

- No clear correlations of profile type with galaxy luminosity, mass, or V_{rot}
- Strong correlation with *bars*
  - Barred galaxies more likely to have Type II profiles
  - Unbarred galaxies more likely to have Type III
    - Even in barred galaxies, the weaker the bar, the more likely a Type III profile is

Profile Types vs Hubble Type



Gutiérrez+2011 (incl. data from Pohlen & Trujillo 2006, Erwin+2008)

Type I favor early types; late-type spirals are predominately Type II
Similar results found with S4G data by Muñoz-Mateos

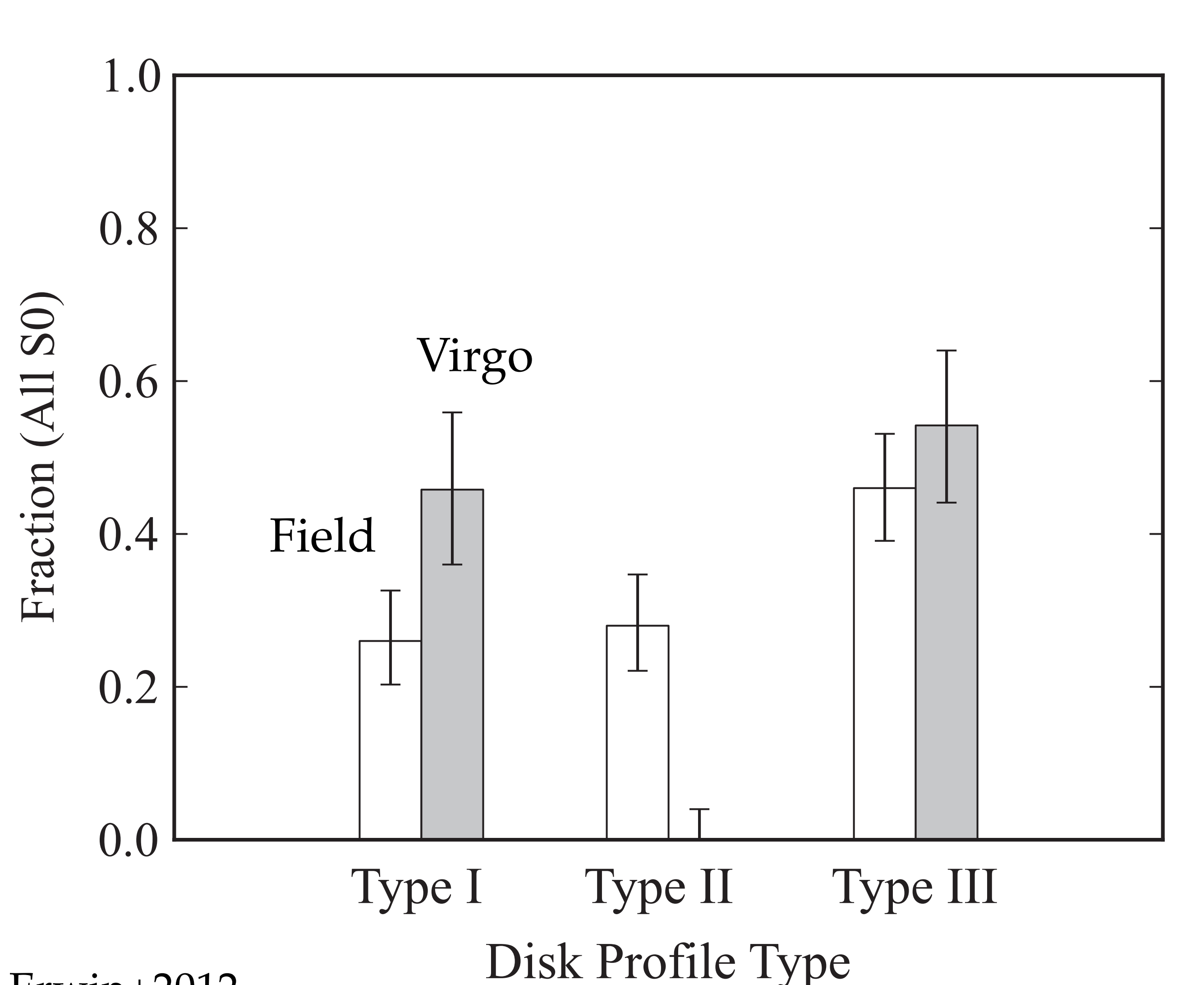
Late-type dwarfs (Sm, Im, BCDs): Herrmann+2013 find 8%, 61%, 16% for Types I, II, III

Profile Types vs Environment

Erwin+2012: Type II profiles common in field S0s, but absent in Virgo S0s! ("Missing" Type II are Type I instead)

Roediger+2012: Type II profiles exist in Virgo *spirals*, but appear *less common*: 34% of Virgo spirals are Type II, vs 49% of field

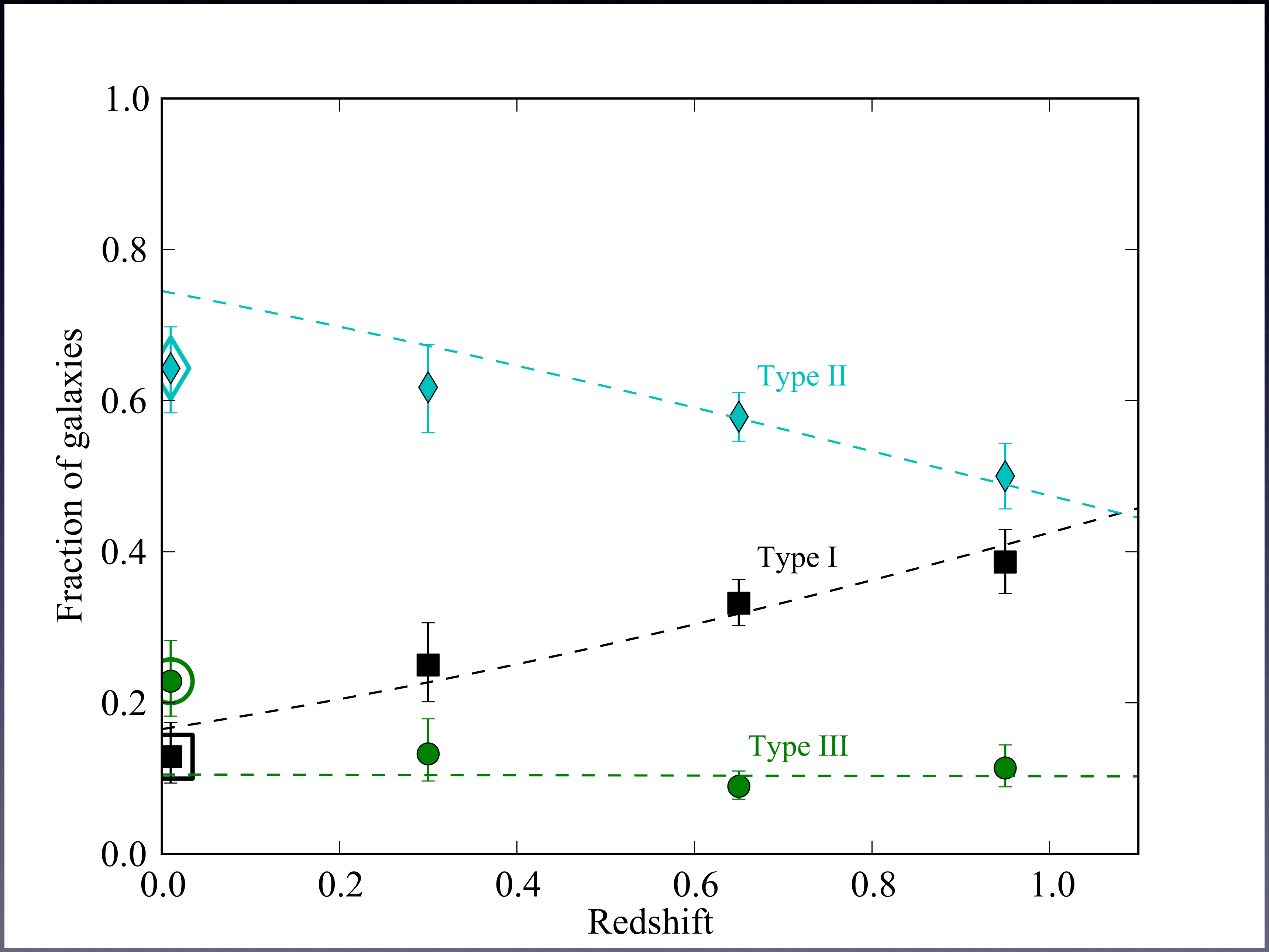
Maltby+2012: no difference between cluster and non-cluster environment in Abell 901/2 — but restricted definition of Type II makes comparison hard



Erwin+2012

Cluster environment suppresses Type II formation (makes Type I instead?)

Evolution of Late-type Spiral Disk Types with Redshift



Data from Azzollini+2008 ($z > 0.1$; GOODS-S ACS images); Pohlen & Trujillo 2006 ($z \sim 0.01$)

Logistic regression shows evidence for evolution with redshift for Types I and II (P = 0.006, 0.009)

No evidence for trend in Type III fraction

Trujillo & Pohlen 2005, Azzollini +2008: evidence for evolution in Type II break radius (smaller at higher z)

SF threshold + scattering model would predict *opposite* trend for Types I and II:
Type II should turn into Type I as SFR declines and populations age (plus shift from *B* to *r*)

What Might Be Happening?

- Type I *turning into* Type II?
  - Interesting, but not predicted by models(?)
- Late-forming galaxies more likely to be Type II?
  - galaxies too low in mass or L at z ~ 1 to be in that sample
- Change in mass/luminosity distribution with z?
  - Azzollini+2008 sample biased against low L at high z
  - BUT: no evidence at z ~ 0 for Type I/II L difference
- High-z Type I galaxies preferentially evolve to earlier types and/or higher Sérsic *n*?

Summary

- Three main classes of outer-disk profiles/breaks
  - Type I (~ 20% of spirals): simple (can extend to ~ 10 scale lengths); more common in S0 and early spirals
  - Type II (49% of spirals): more common in late types; probably multiple origins
    - Two broad subtypes/mechanisms: Bar-related resonances; SF thresholds + radial migration
  - Type III (28% of spirals): most are extended disk, not bulge/halo
- Strong dependence on Hubble type (and on bars)
- May depend on environment (Type II rare in clusters?)

Outstanding Issues

- How many different mechanisms produce Type II/ truncations?
  - Similar to "pseudobulges" — e.g., perhaps several different phenomena lumped together?
- Why is there a *diversity* of types?
  - e.g., SF threshold + radial migration models might explain truncations, but why does this only happen to *some* galaxies?
- What is detailed relation between profiles and environment?
- What is the redshift evolution of disk profiles in early-type spirals and S0s?