Surface-brightness and Star-Formation Profiles of Galaxy Disks

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Three main classes of profiles

Type I:
Single-exponential
(Freeman 1970)

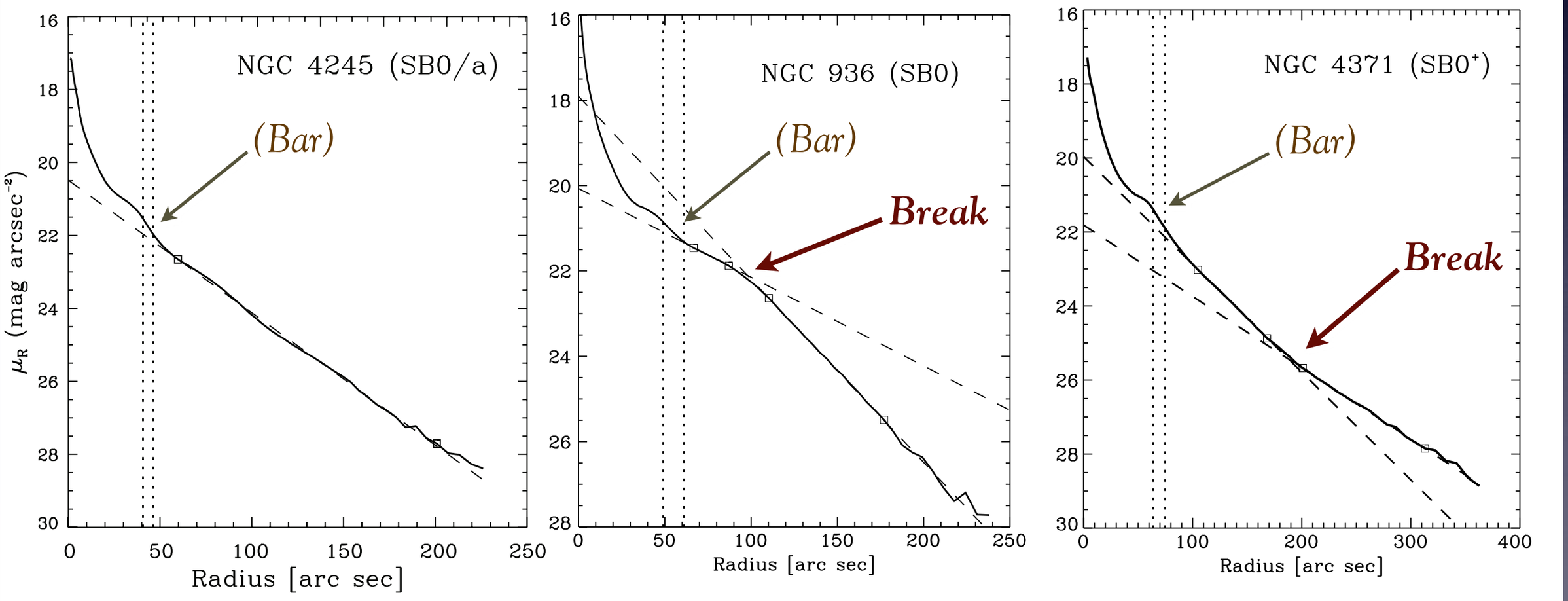
Type II:
includes "Truncations"
(Freeman 1970; van der Kruit & Searle 1981)

Type III:
"Antitruncations"
(Erwin+2005)

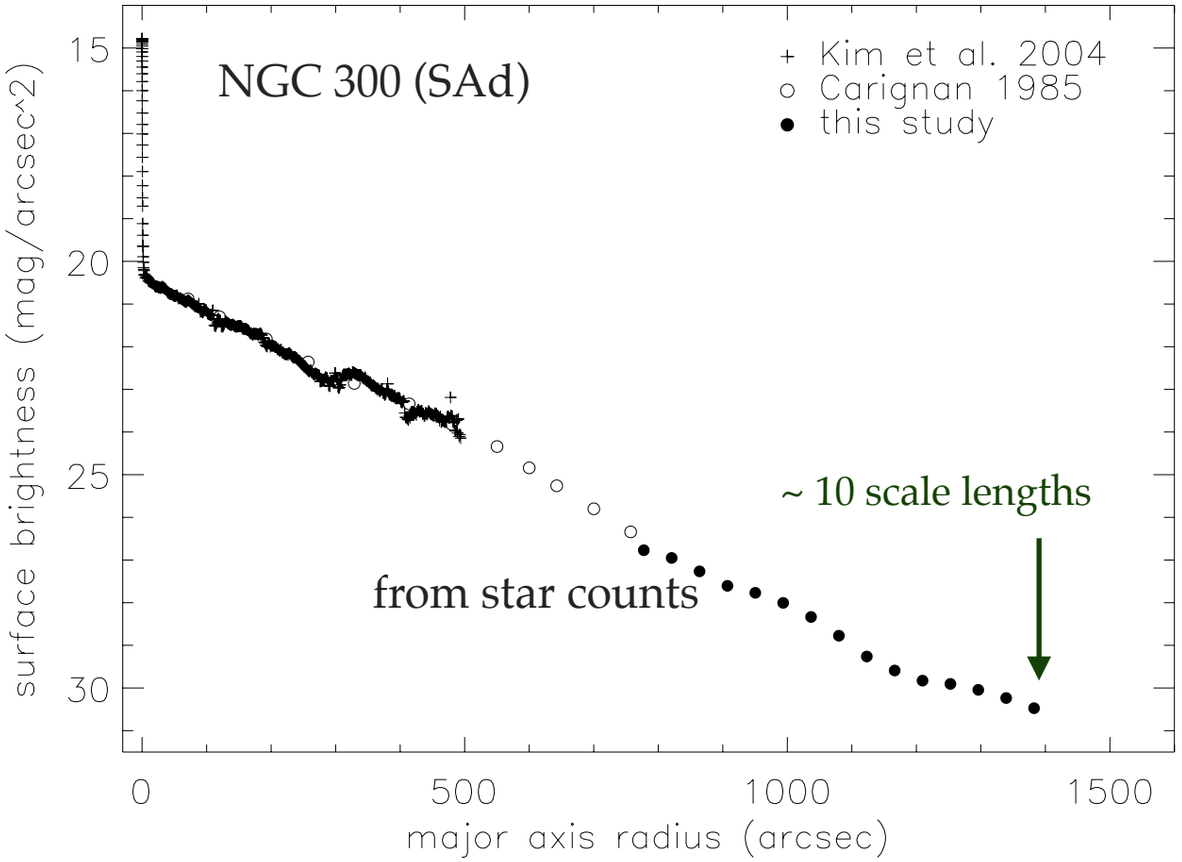
No Break

"Downbending" Break

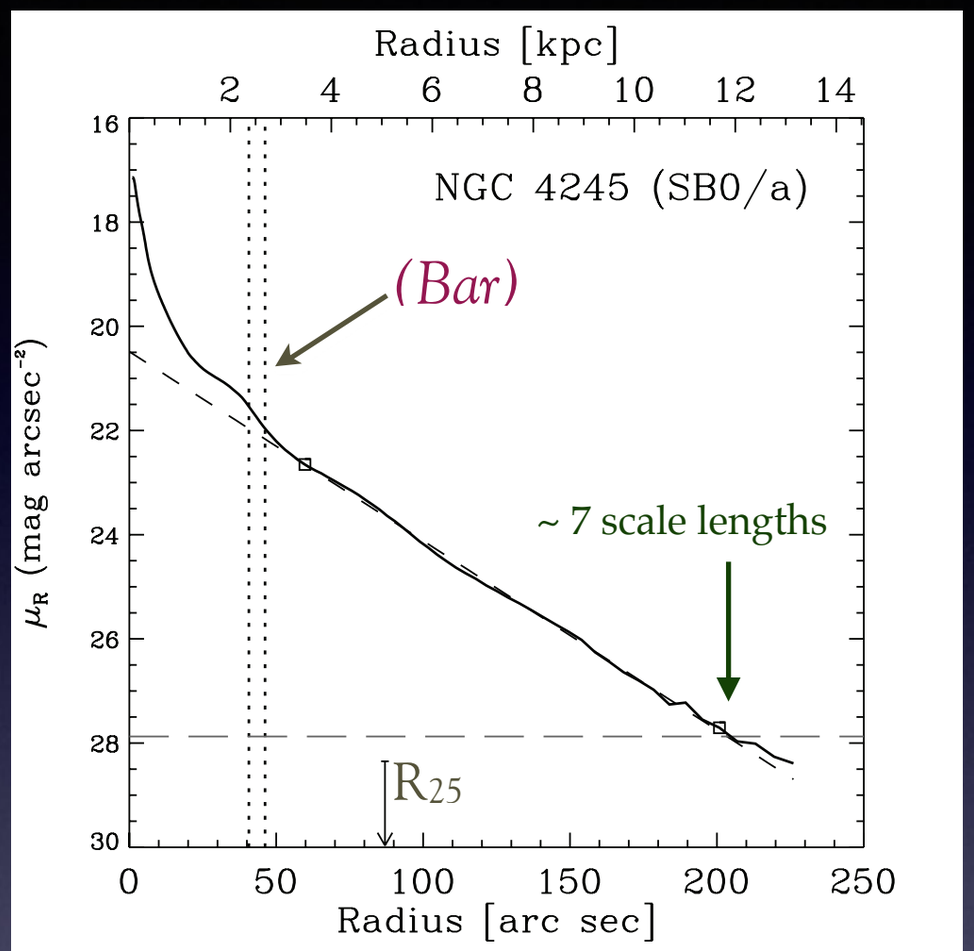
"Upbending" Break



Type I (No Break): Simplest Case



Bland-Hawthorn+2005



Erwin+2008

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

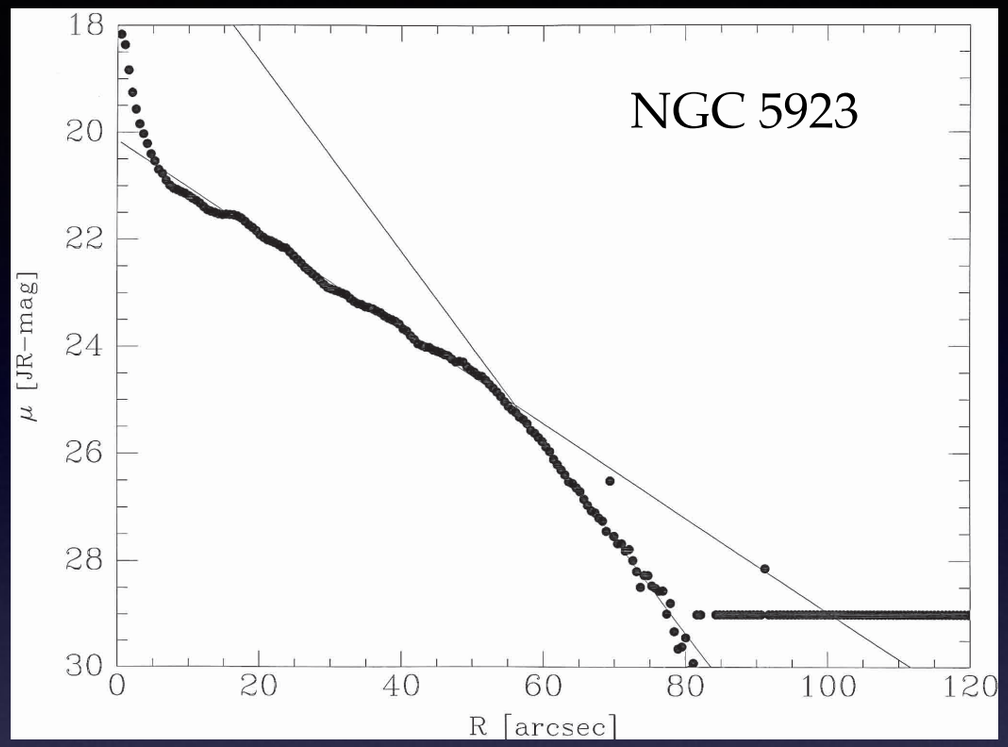
21% of local bright ($M_B < -18.4$) S0–Sm galaxies; most common in S0–Sa

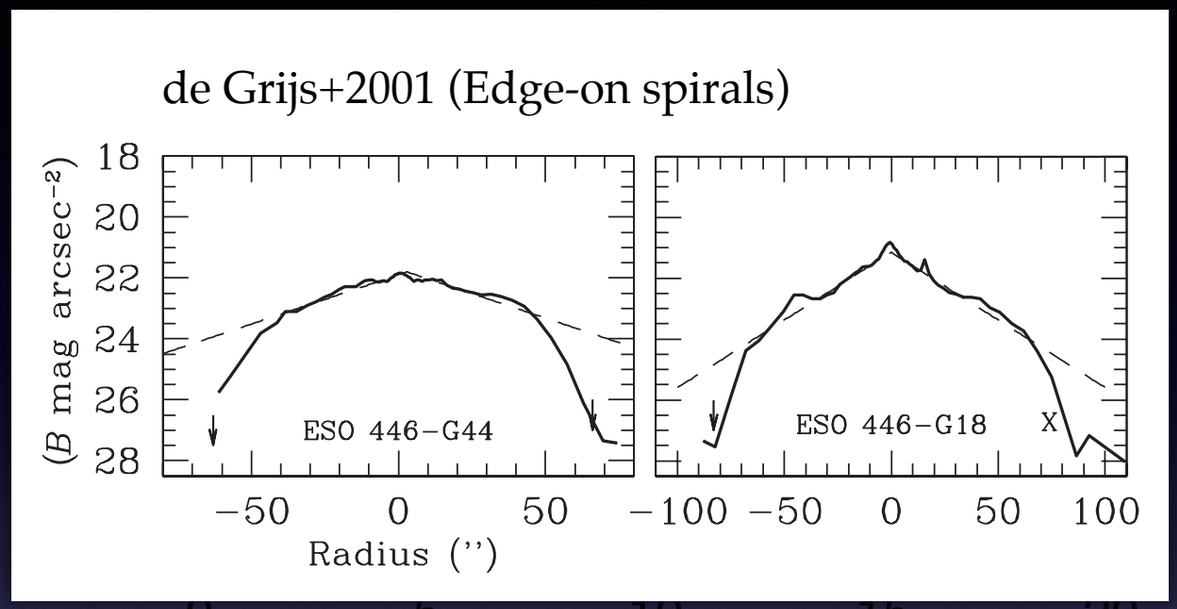
At least some are quite extended: no breaks visible out to limits of 10–11 scale lengths (Weiner et al. 2001; Bland-Hawthorn et al. 2005; Vlajic et al. 2011)

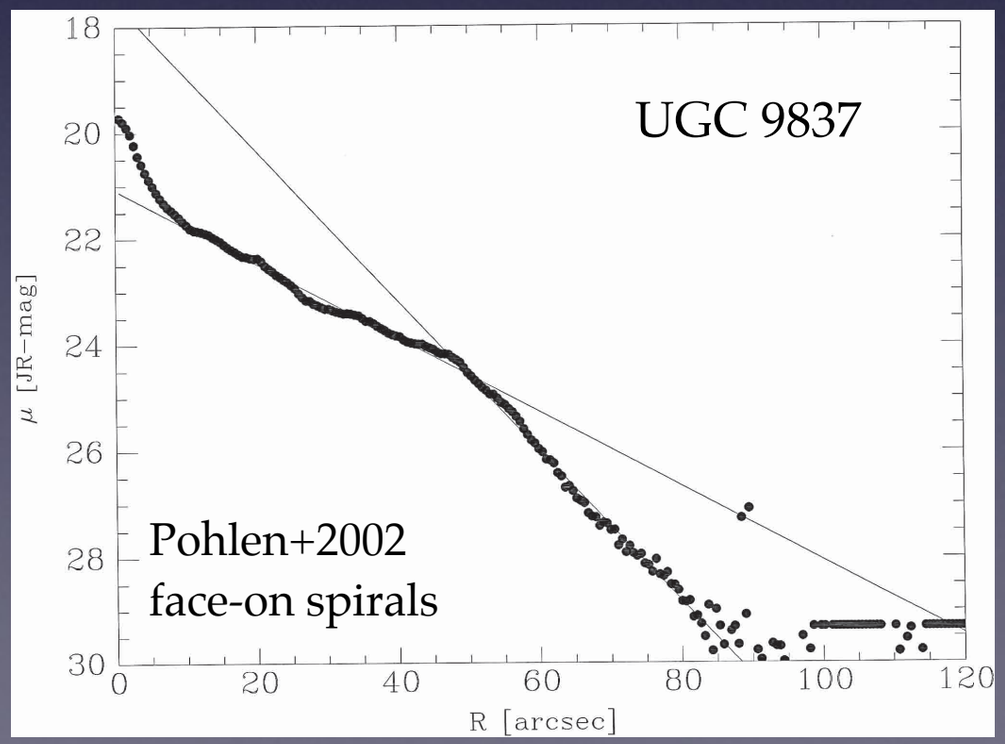
Type II Profiles (including "Truncations")

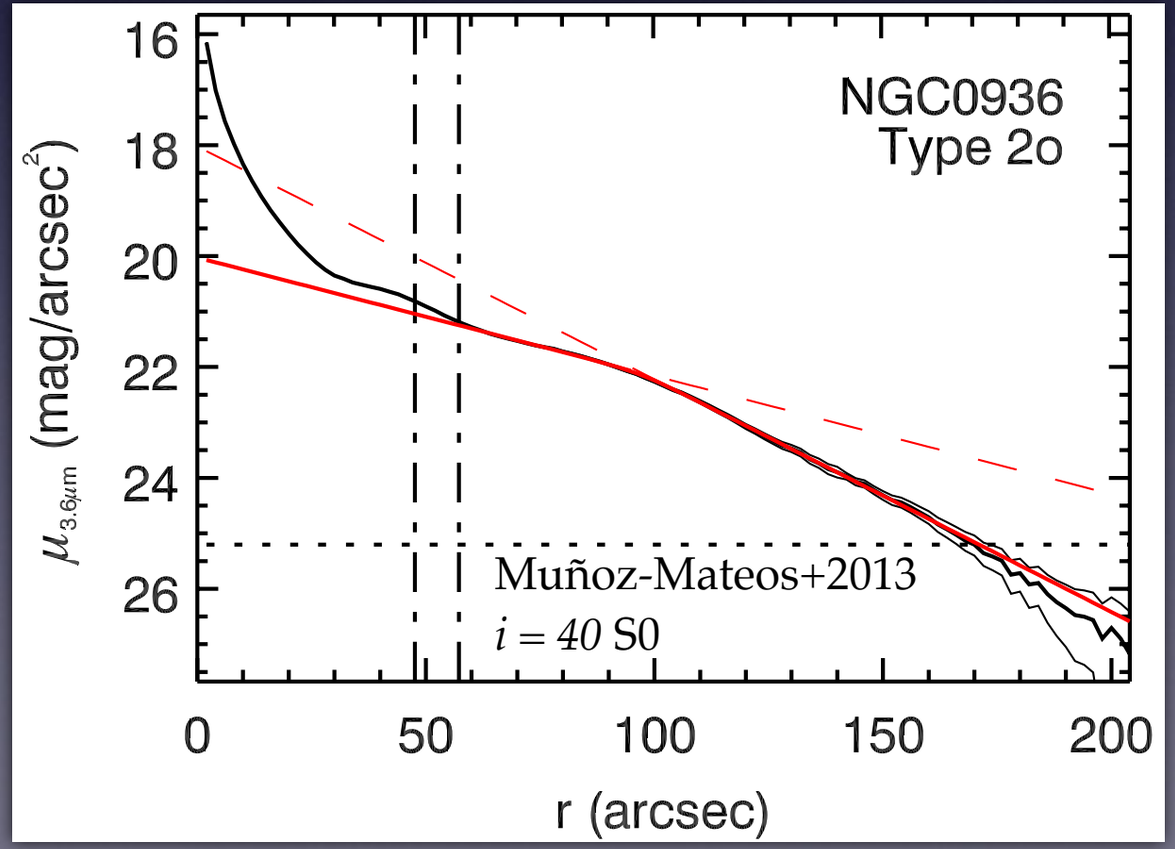
- Freeman 1970: Some disks have inner "deficit" relative to outer exponential = "Type II"
- van der Kruit & Searle (1981): edge-on disks are not single-exponential out to detection limits — instead, they are "truncated"
- Pohlen+2002: deep imaging of 3 face-on spirals shows broken-exponential profiles: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

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









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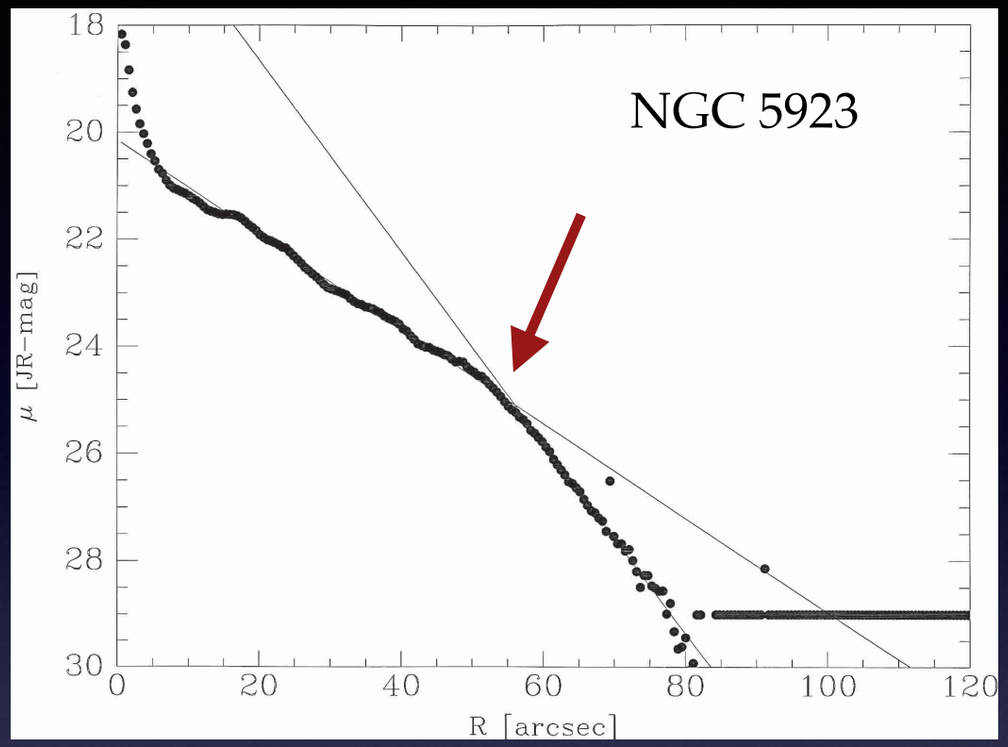

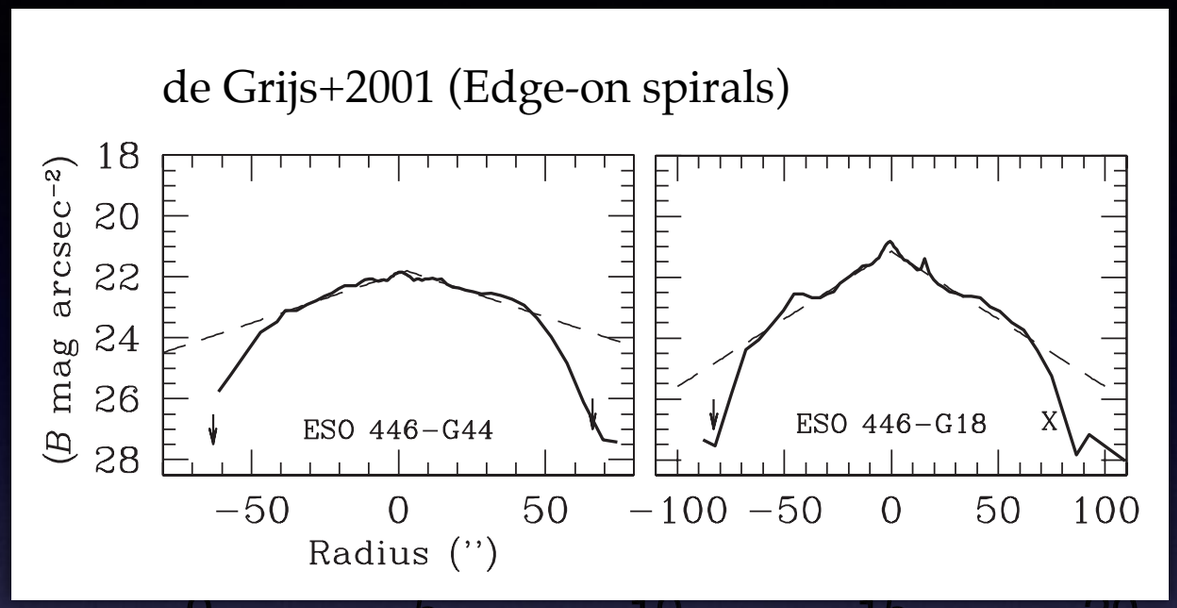

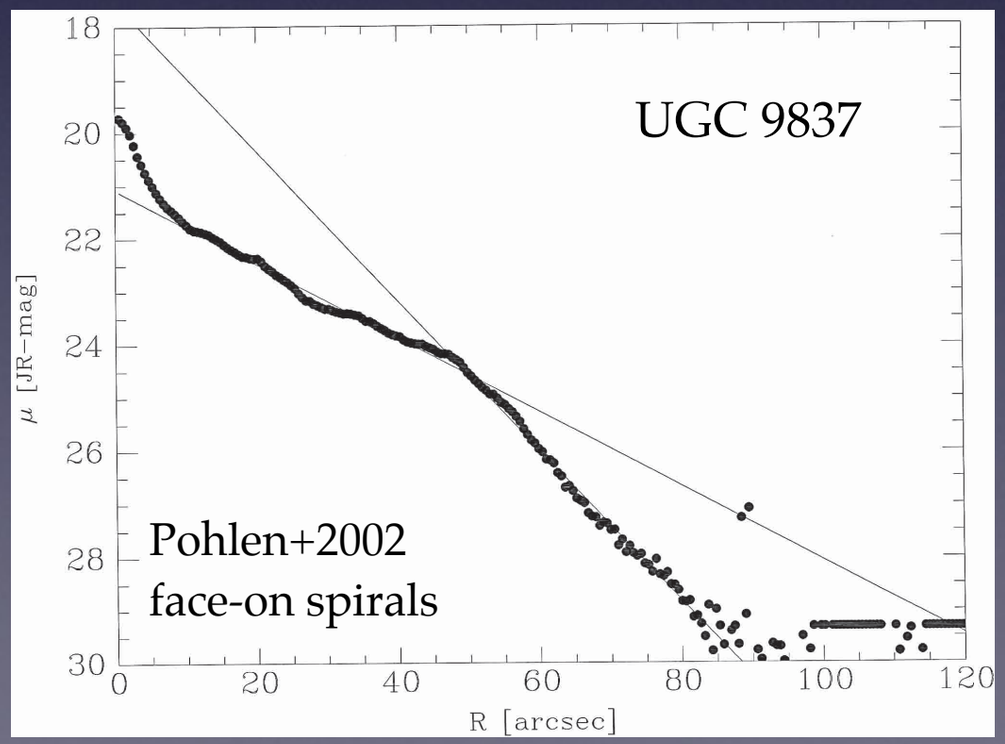

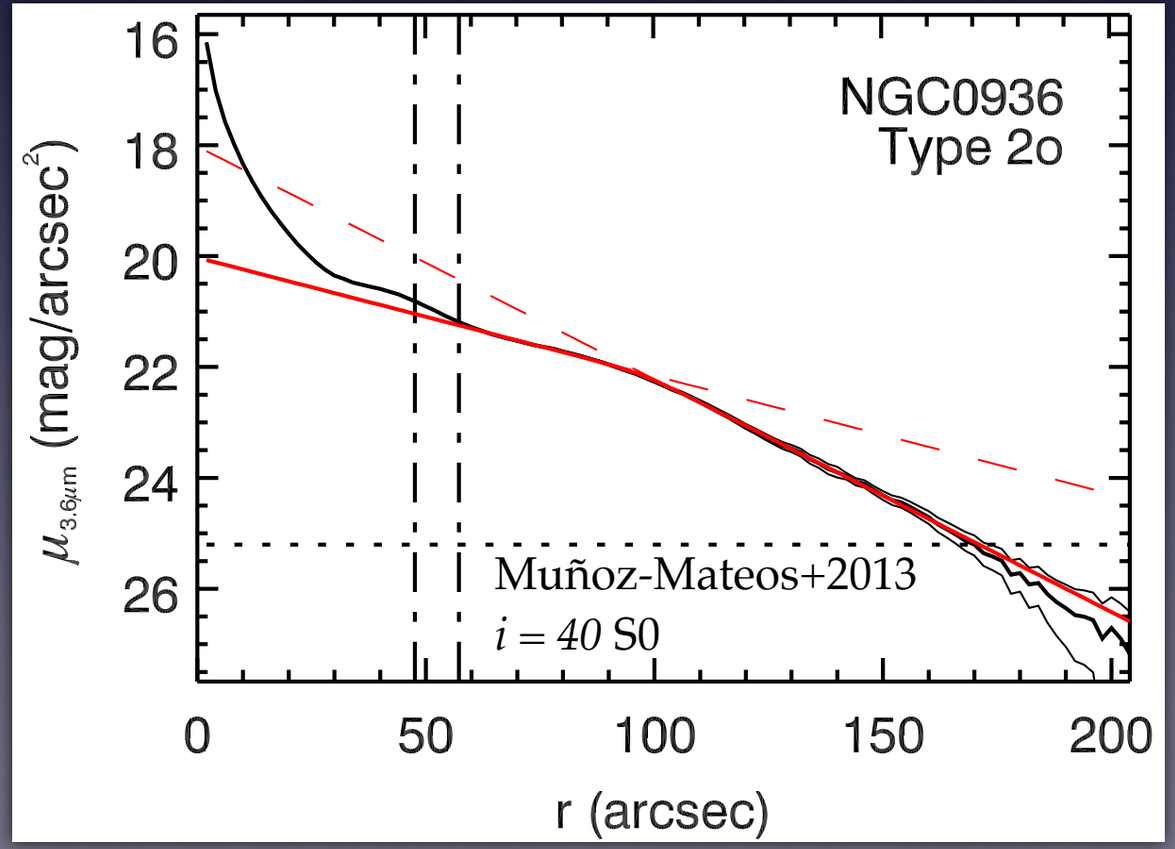

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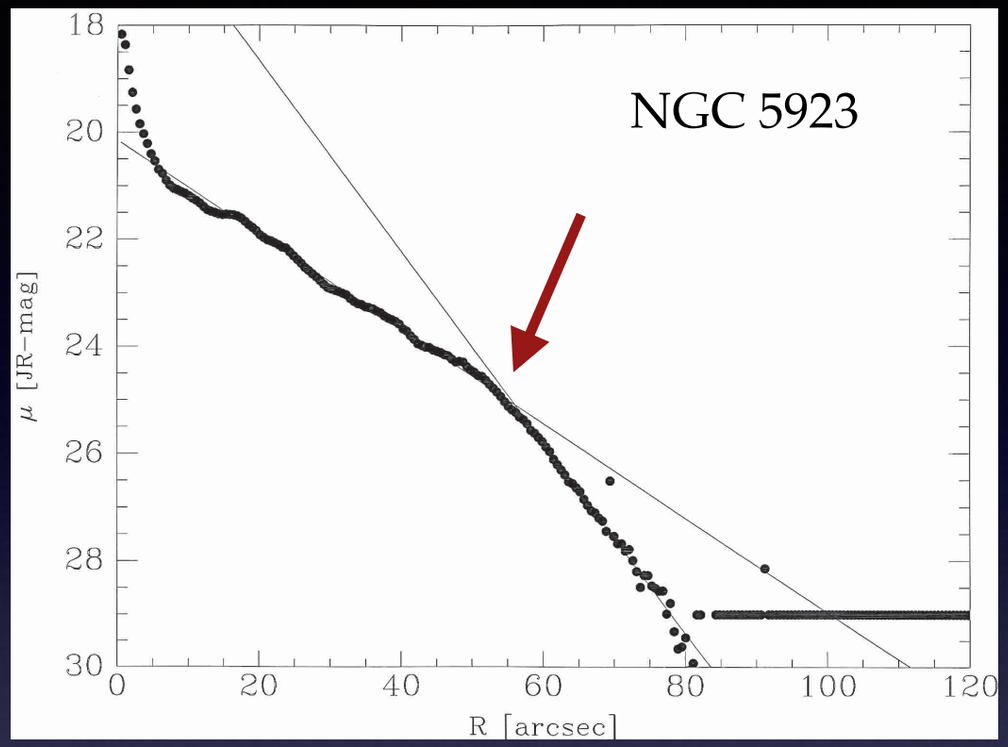

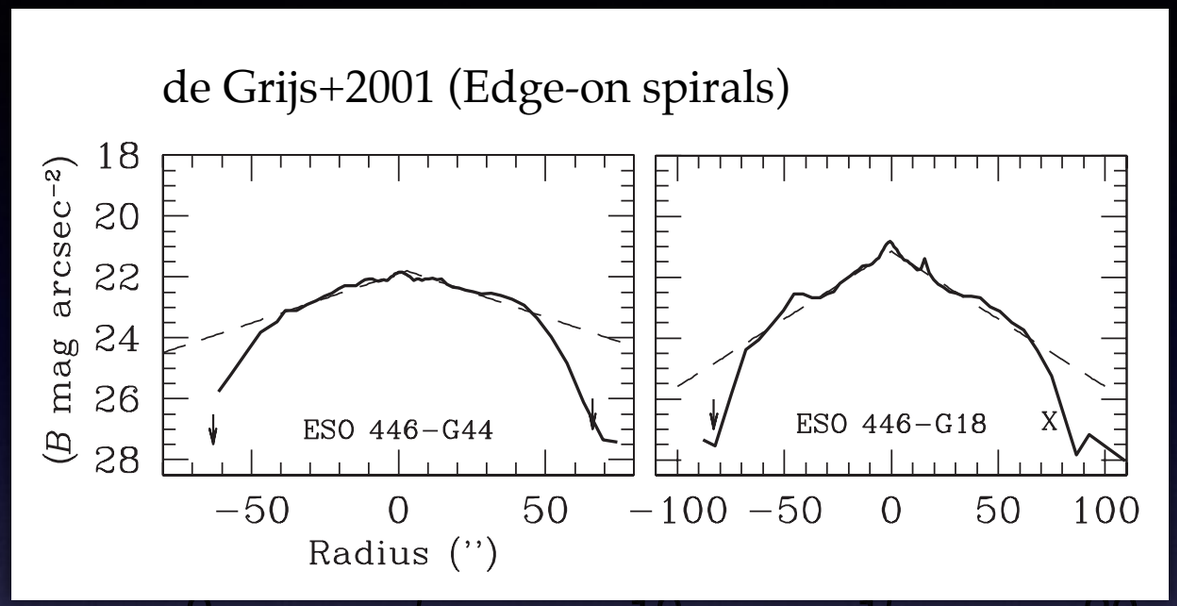

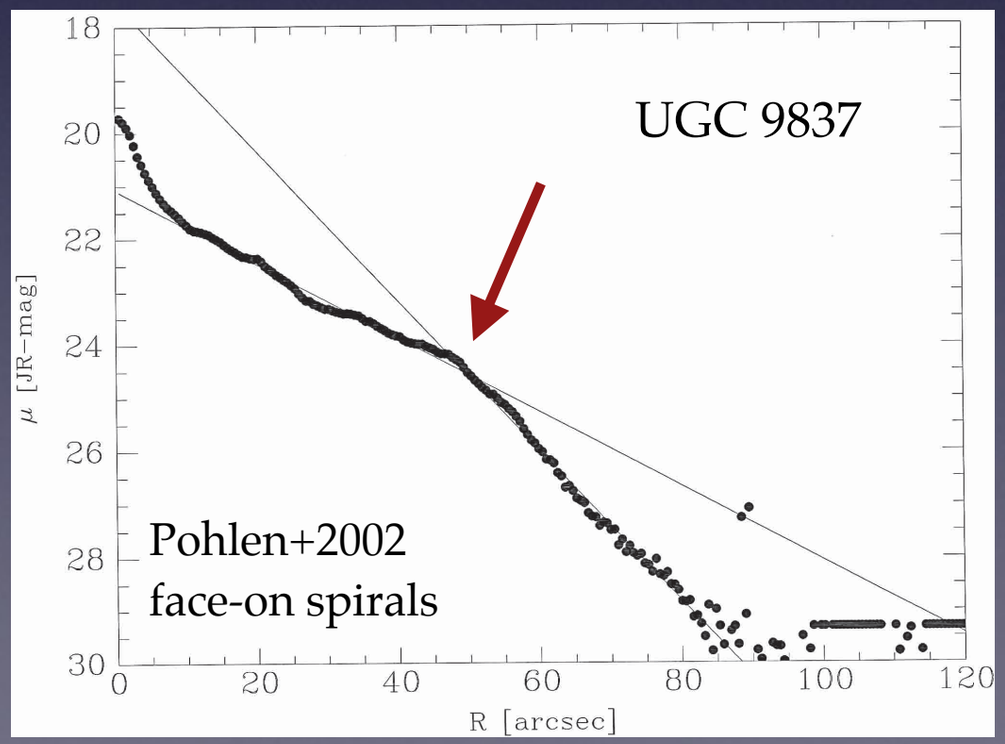

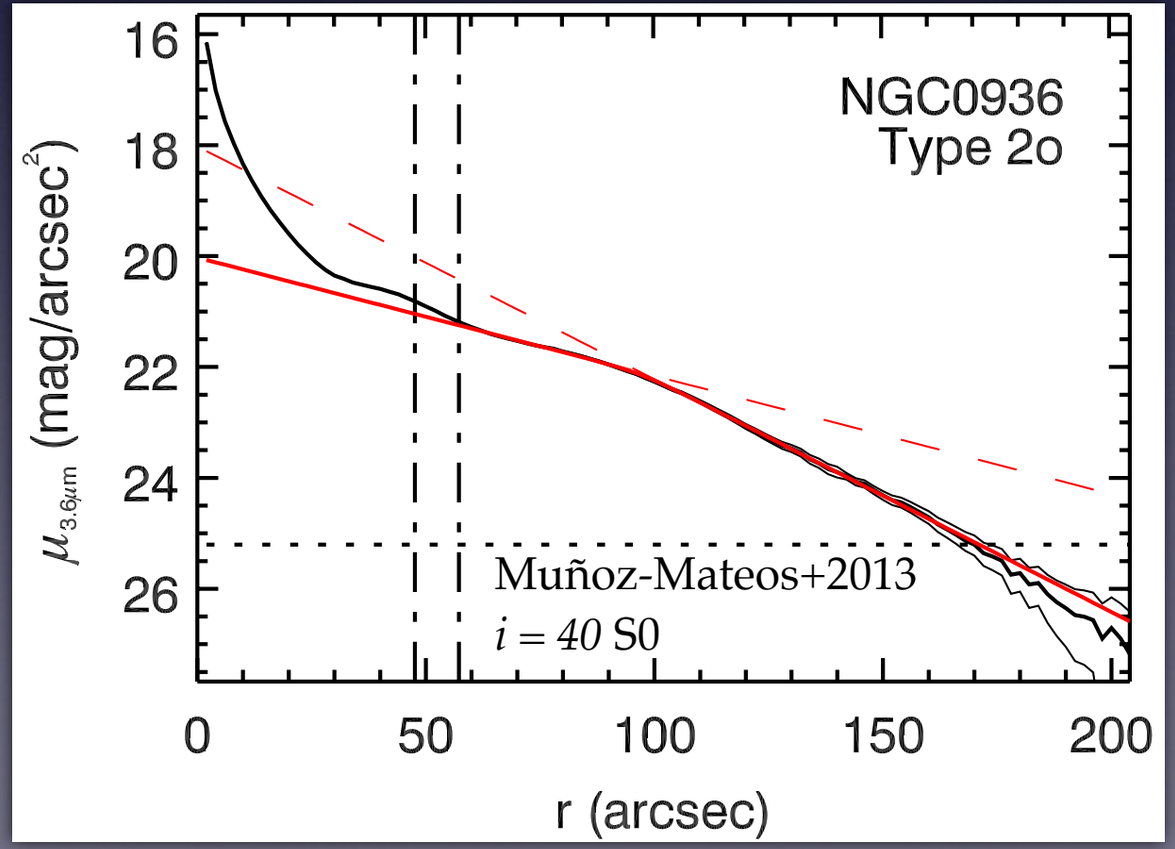

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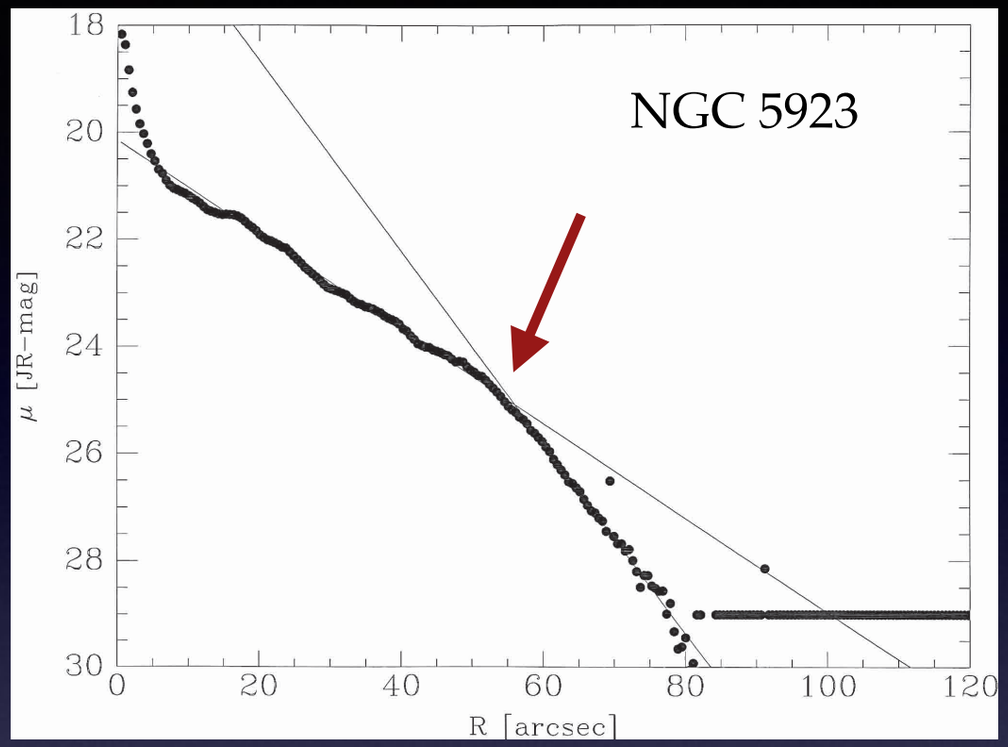

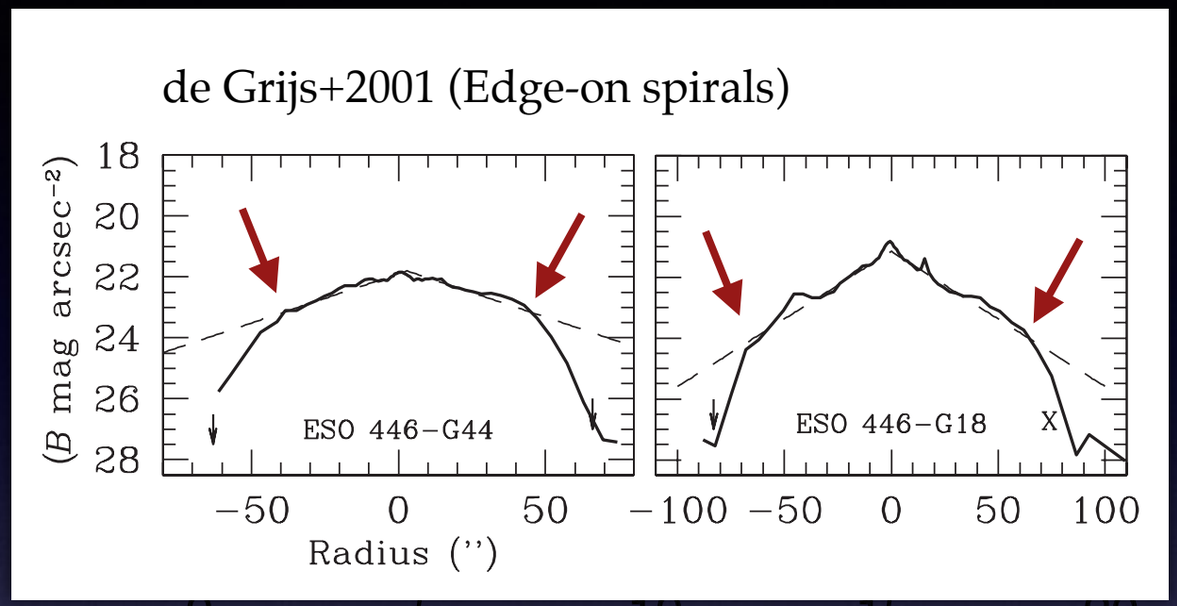

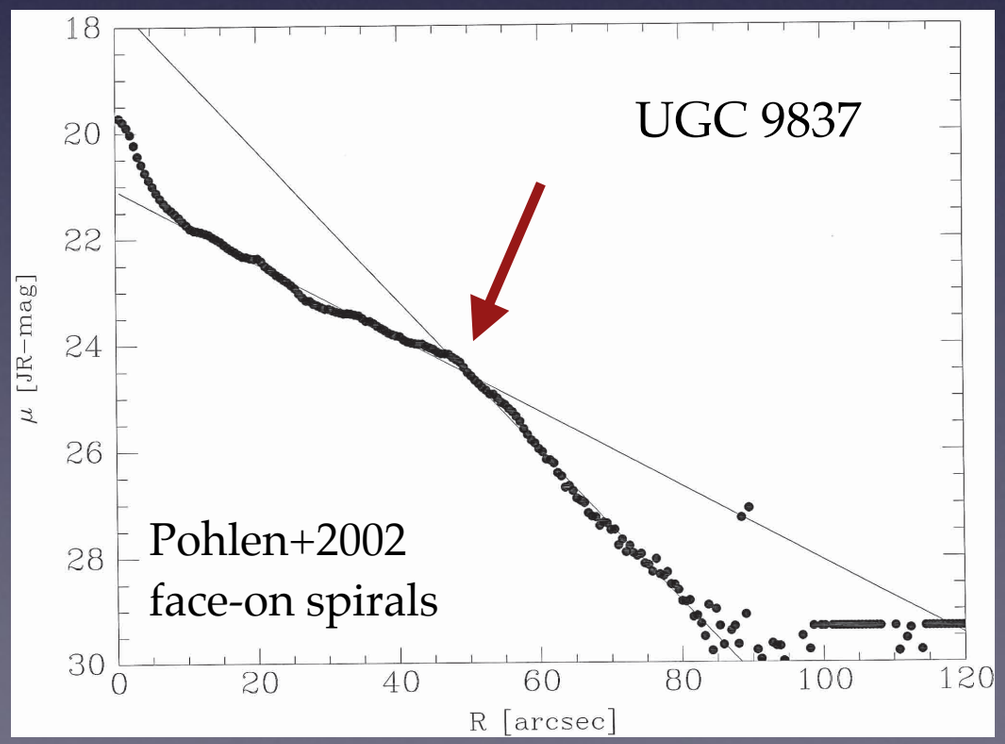

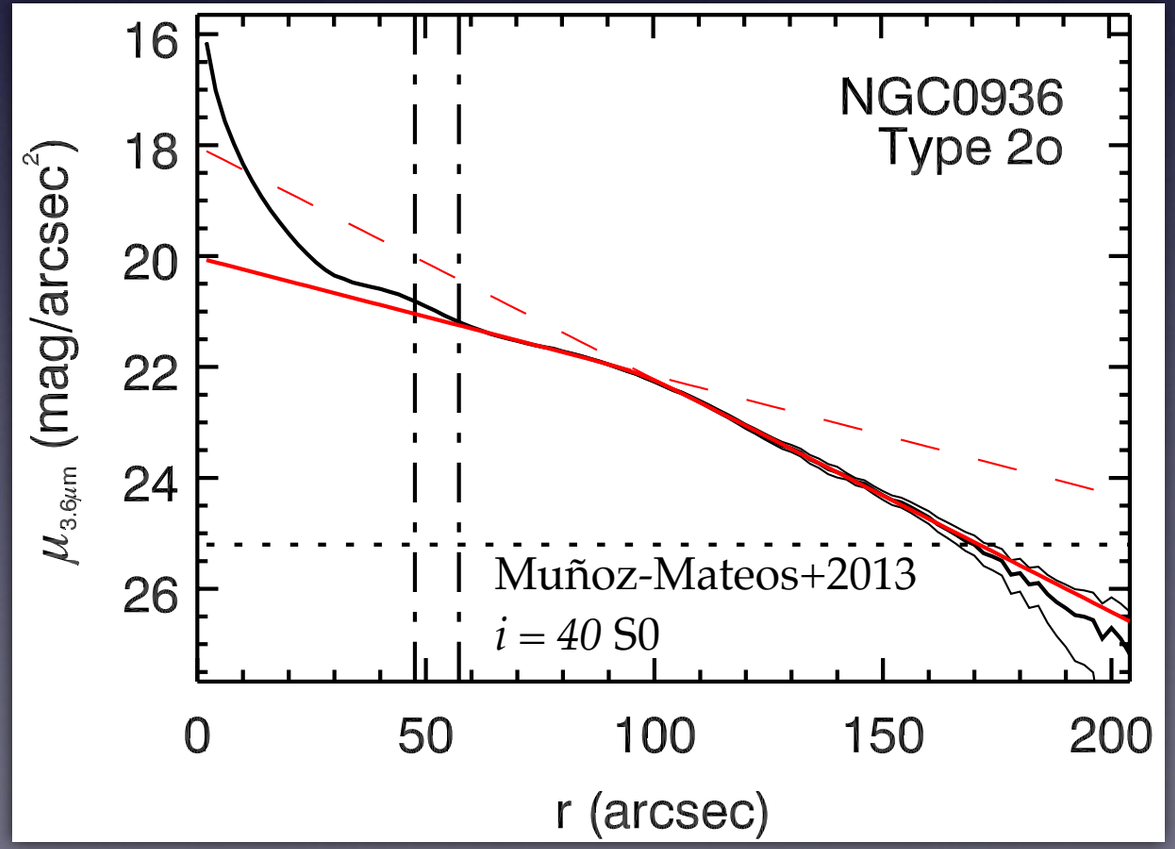

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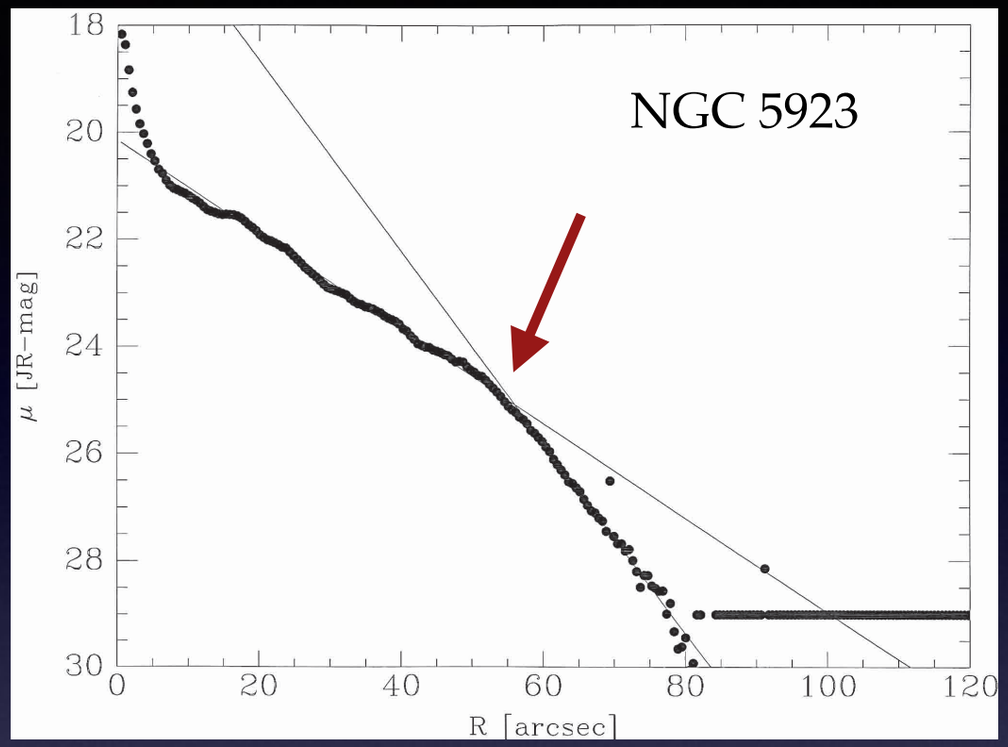
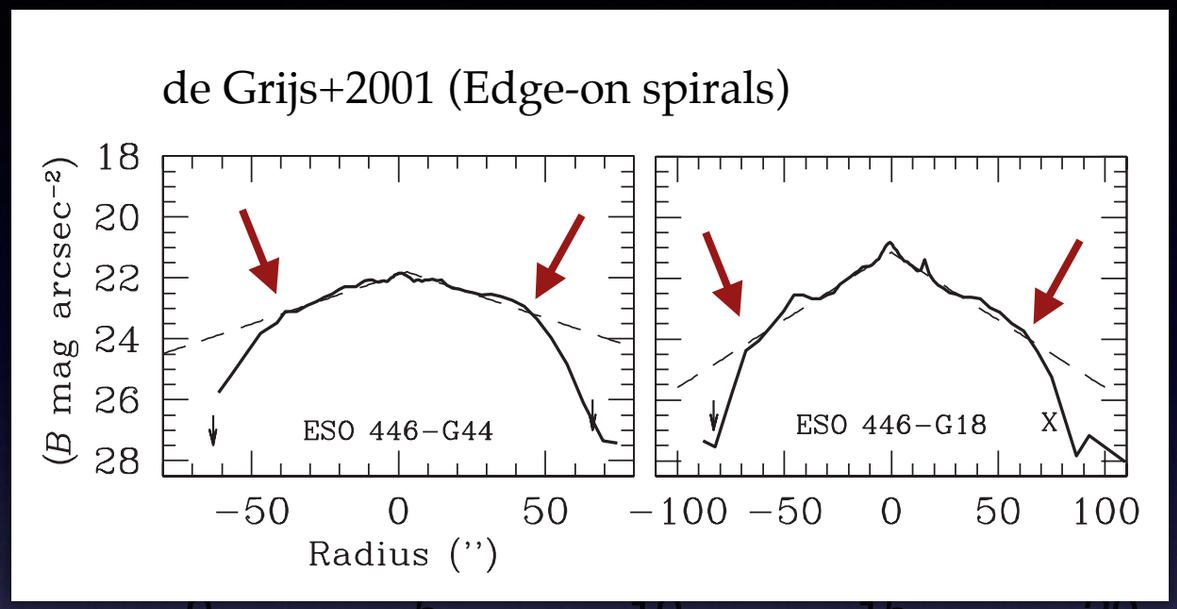
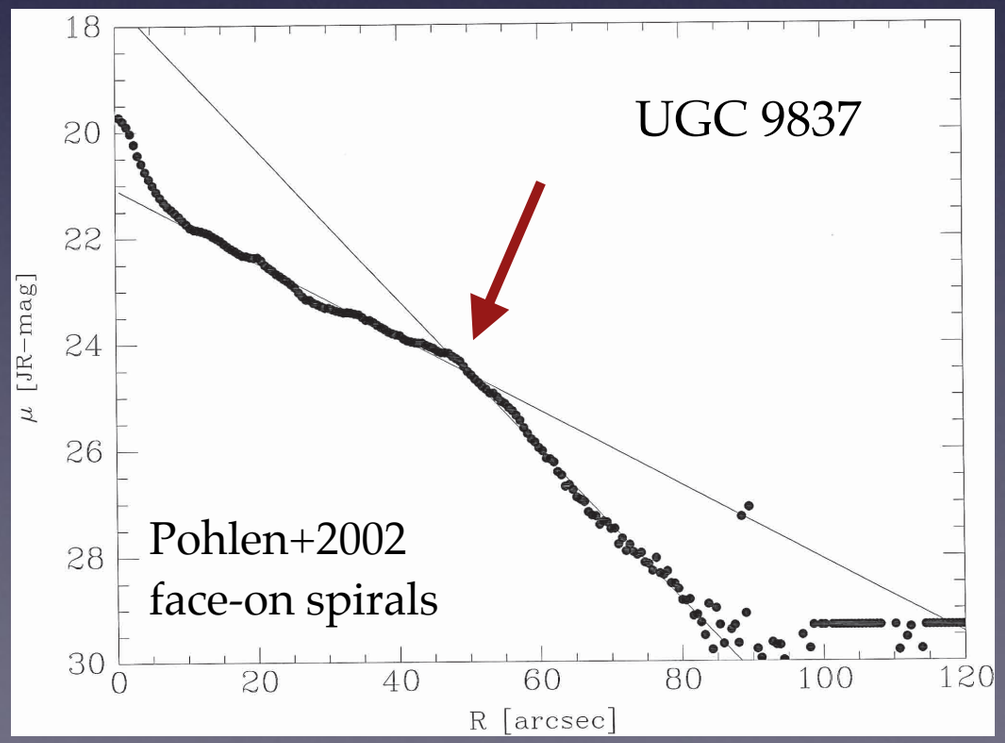
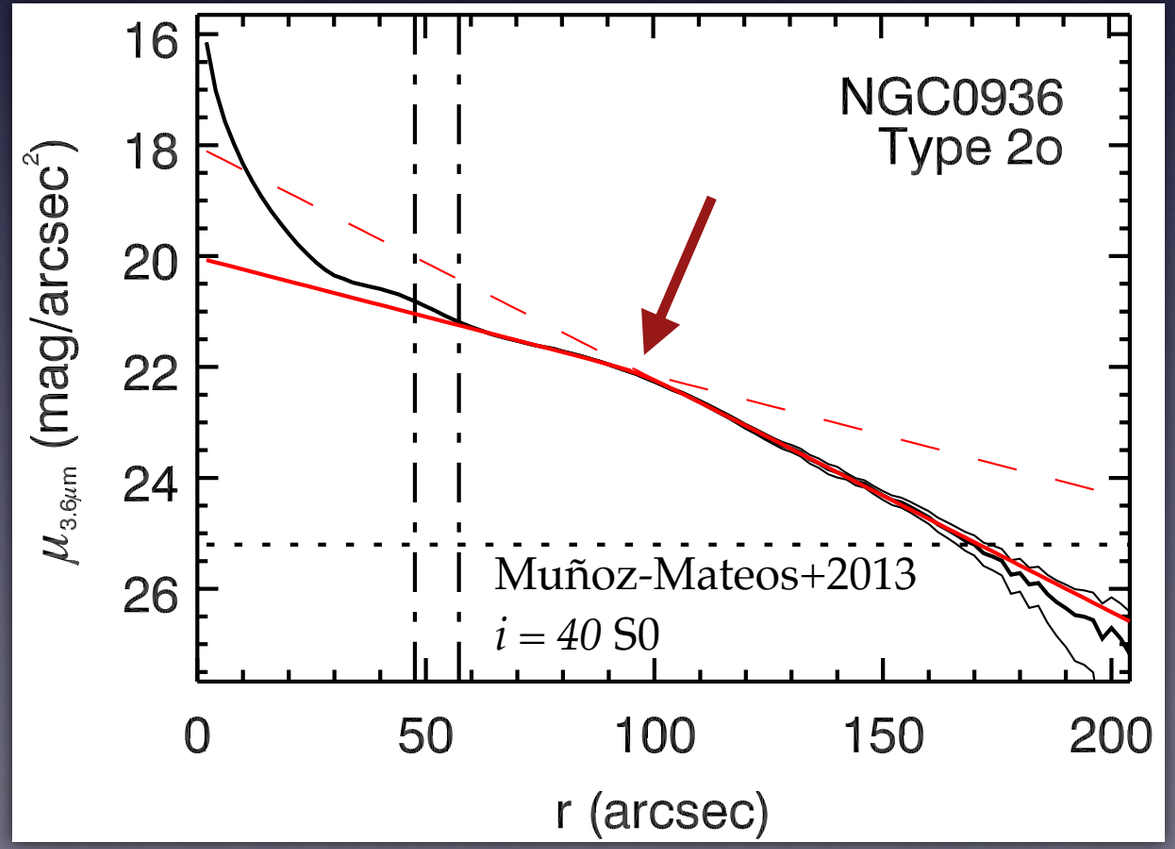
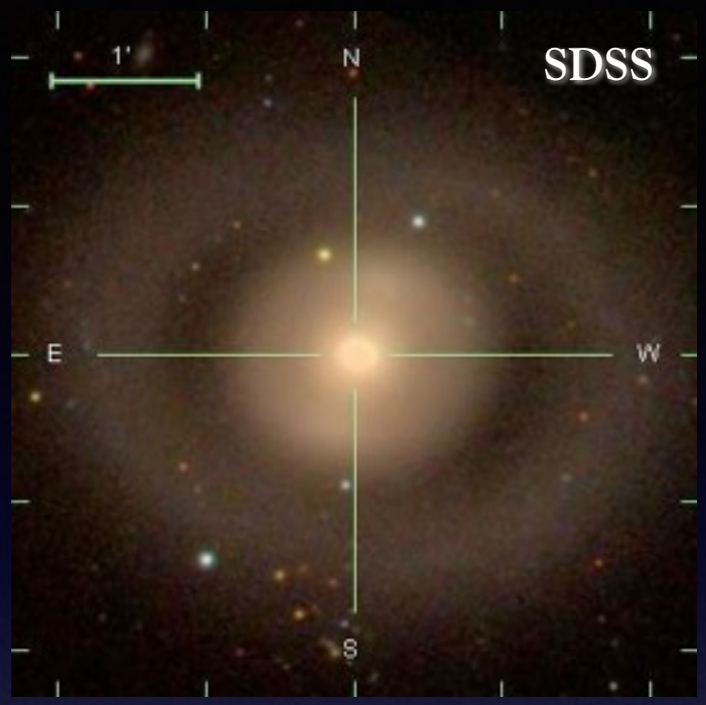






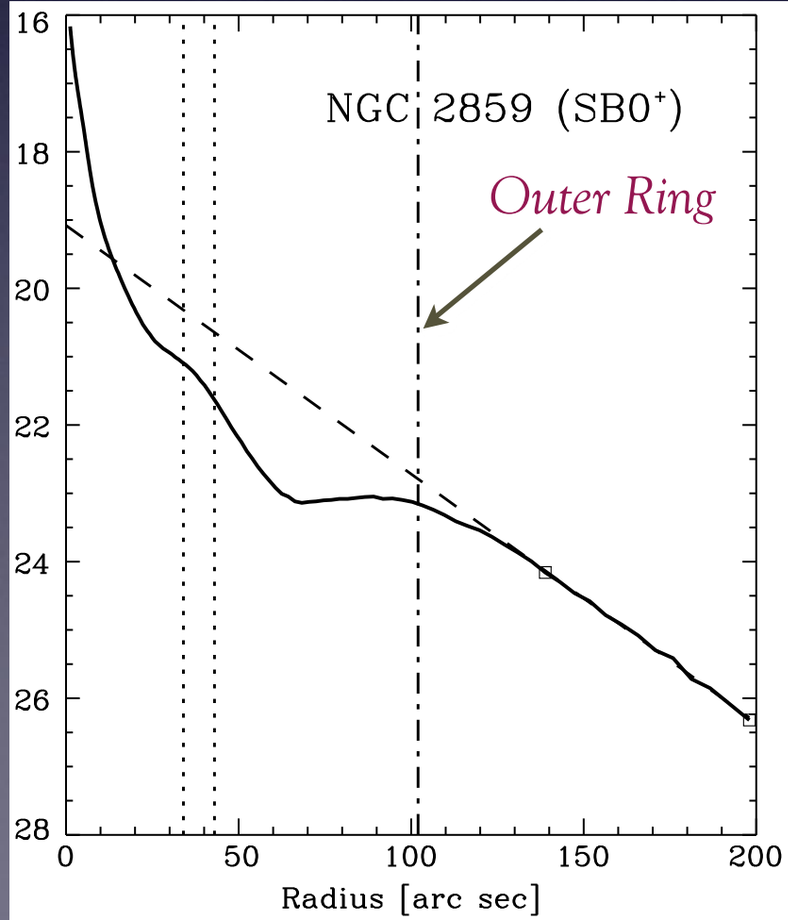


Type II-OLR: Linked to Outer Rings (and Outer Lindblad Resonance?)



"Extreme" Outer Rings

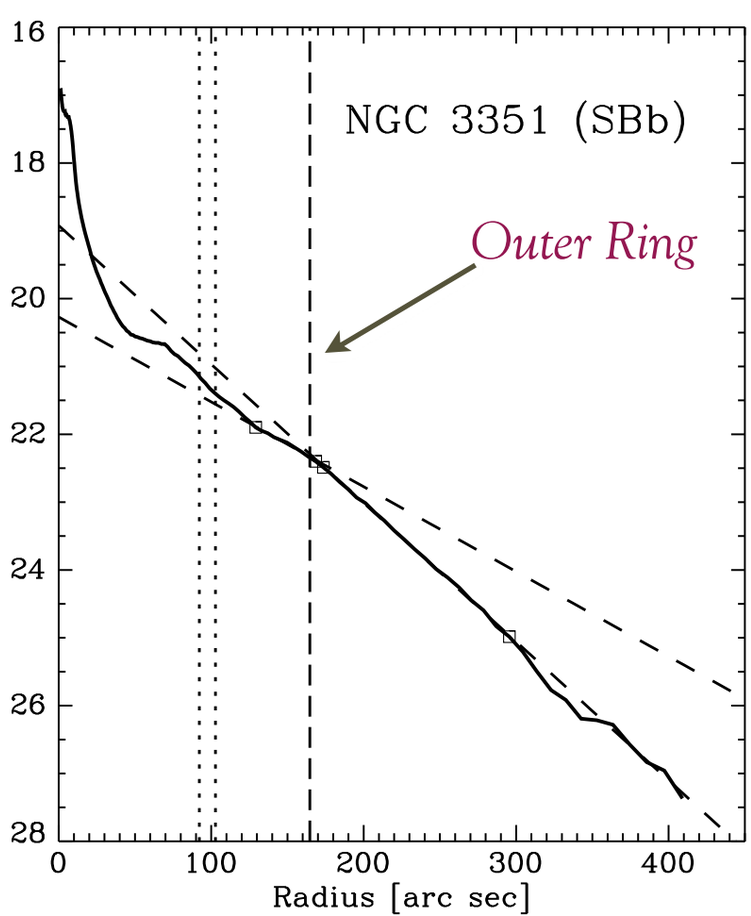
"Normal" Outer Rings



Outer rings: usually the result of gas interacting with bar's Outer Lindblad Resonance (OLR).

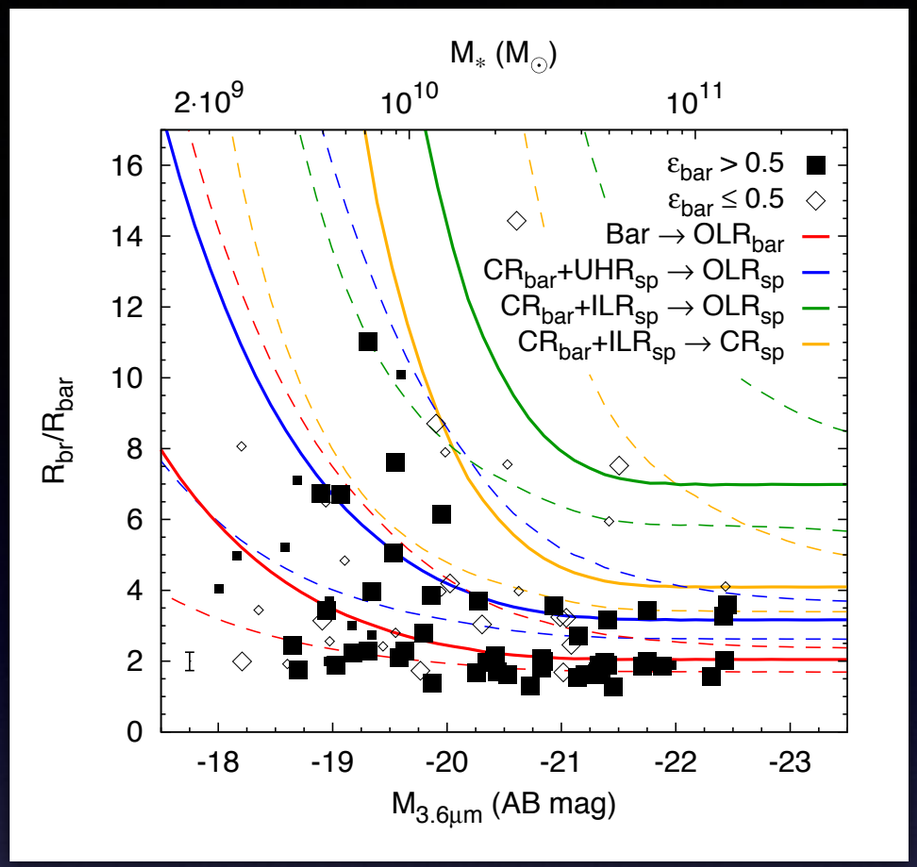
In ~ 45% of barred S0-Sb Type II profiles, break coincides with a visible outer ring.

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



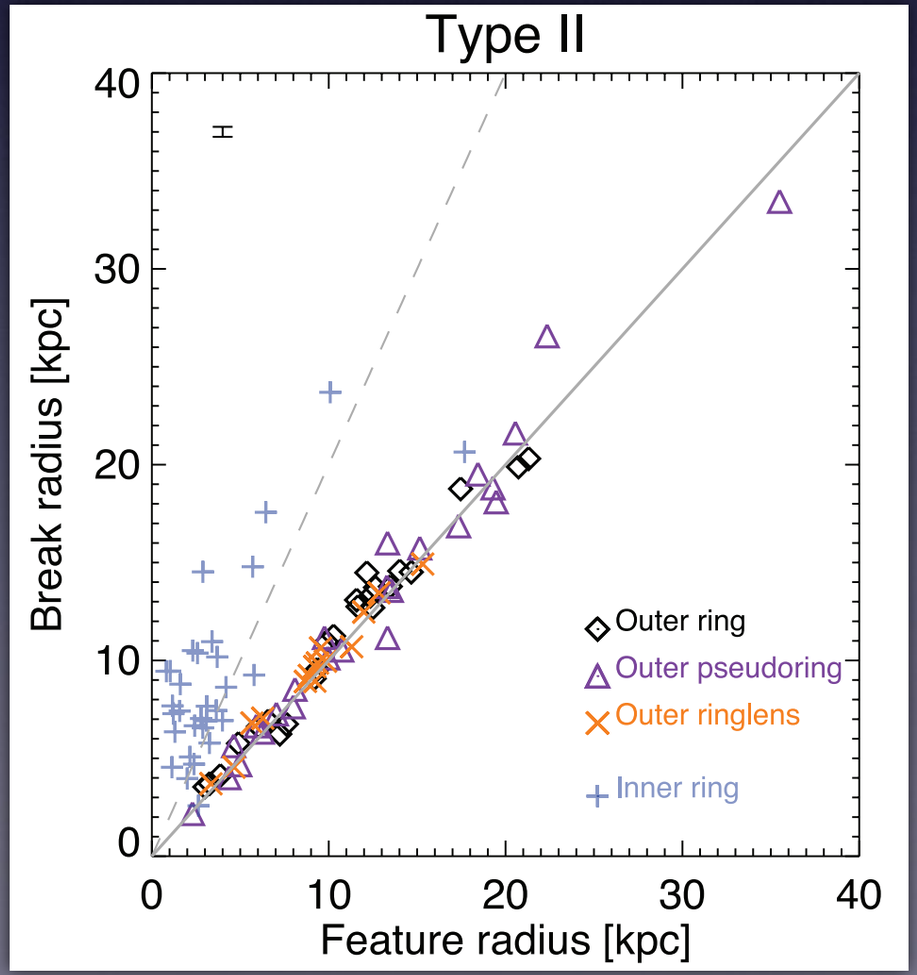
Muñoz-Mateos+2013 (S4G Spitzer IRAC)

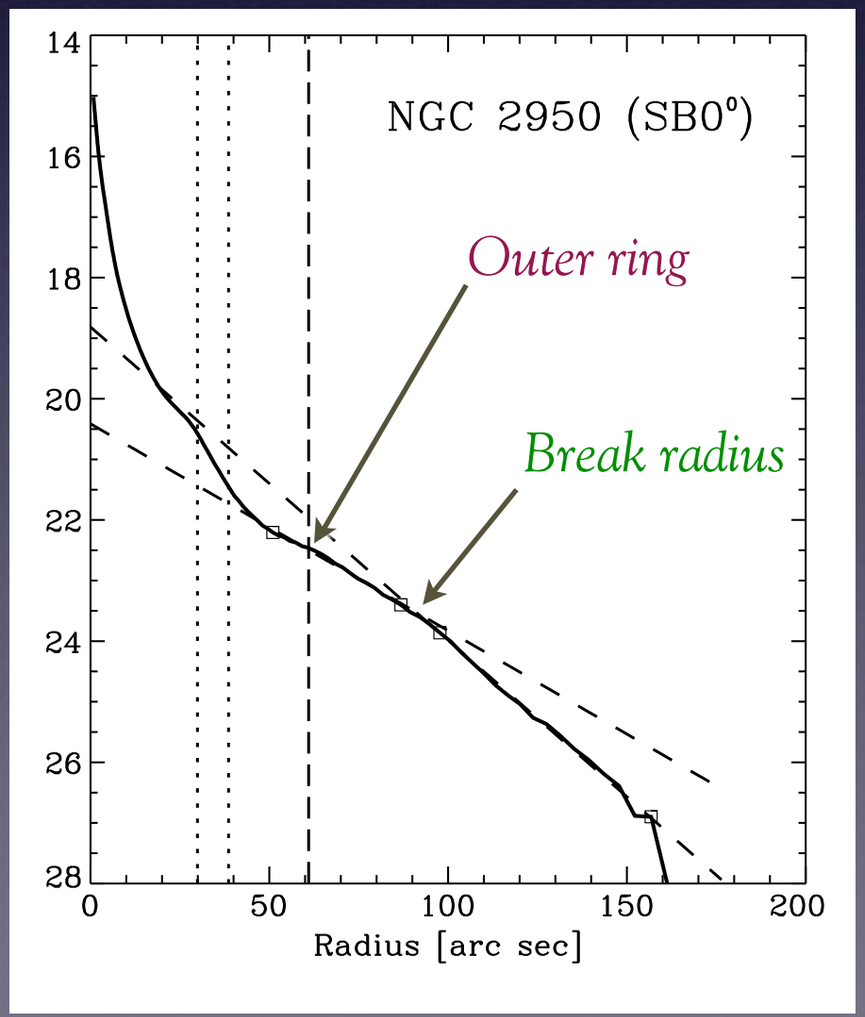
R_{brk} is typically ~ 2 R_{bar}, consistent with bar OLR
[*or* ~ 3–4 R_{bar}, consistent with coupled spiral OLR;
as in Debattista+2006 simulation]



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

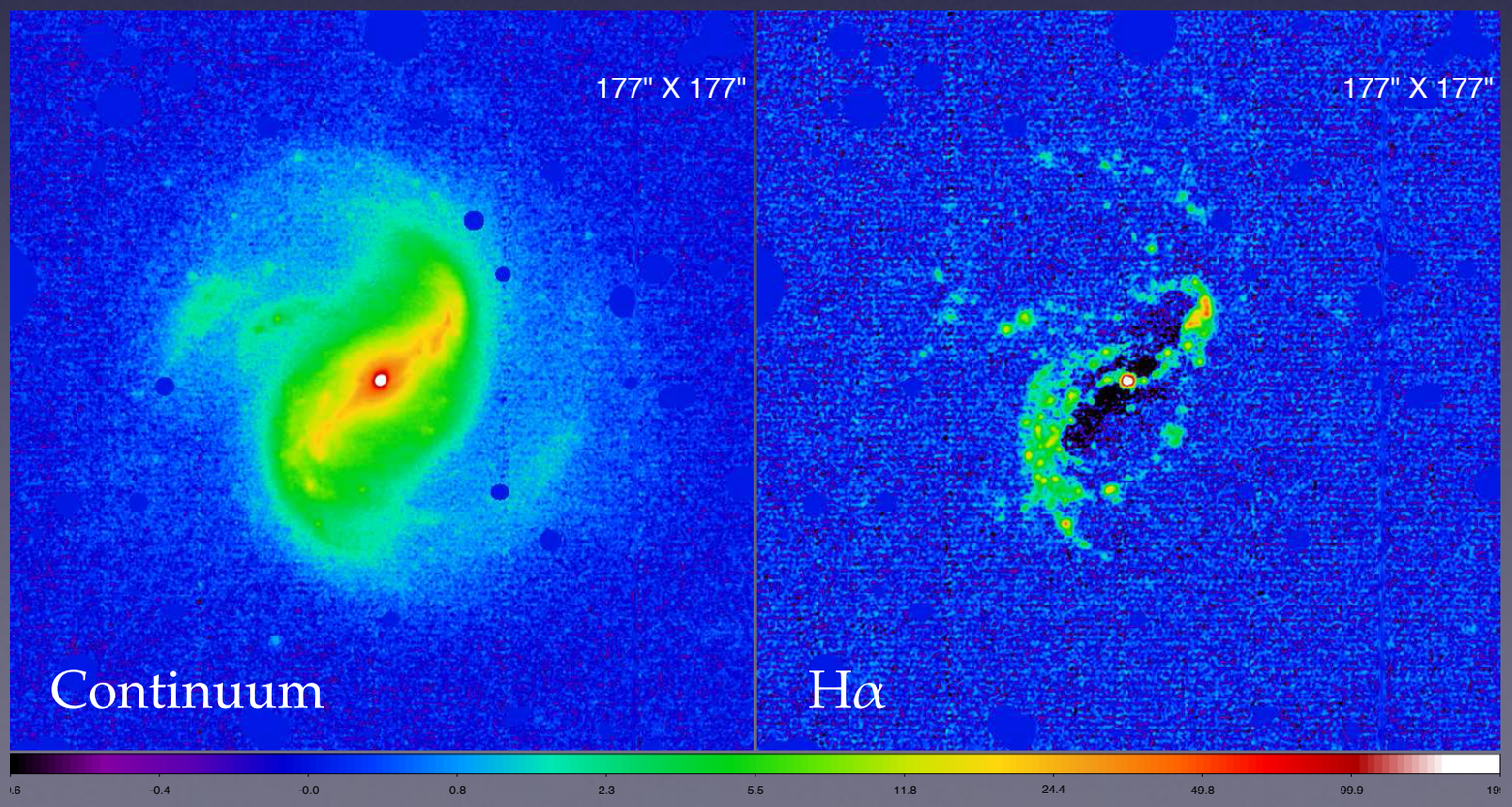
Hα Galaxy Groups Imaging Survey (HAGGIS)

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

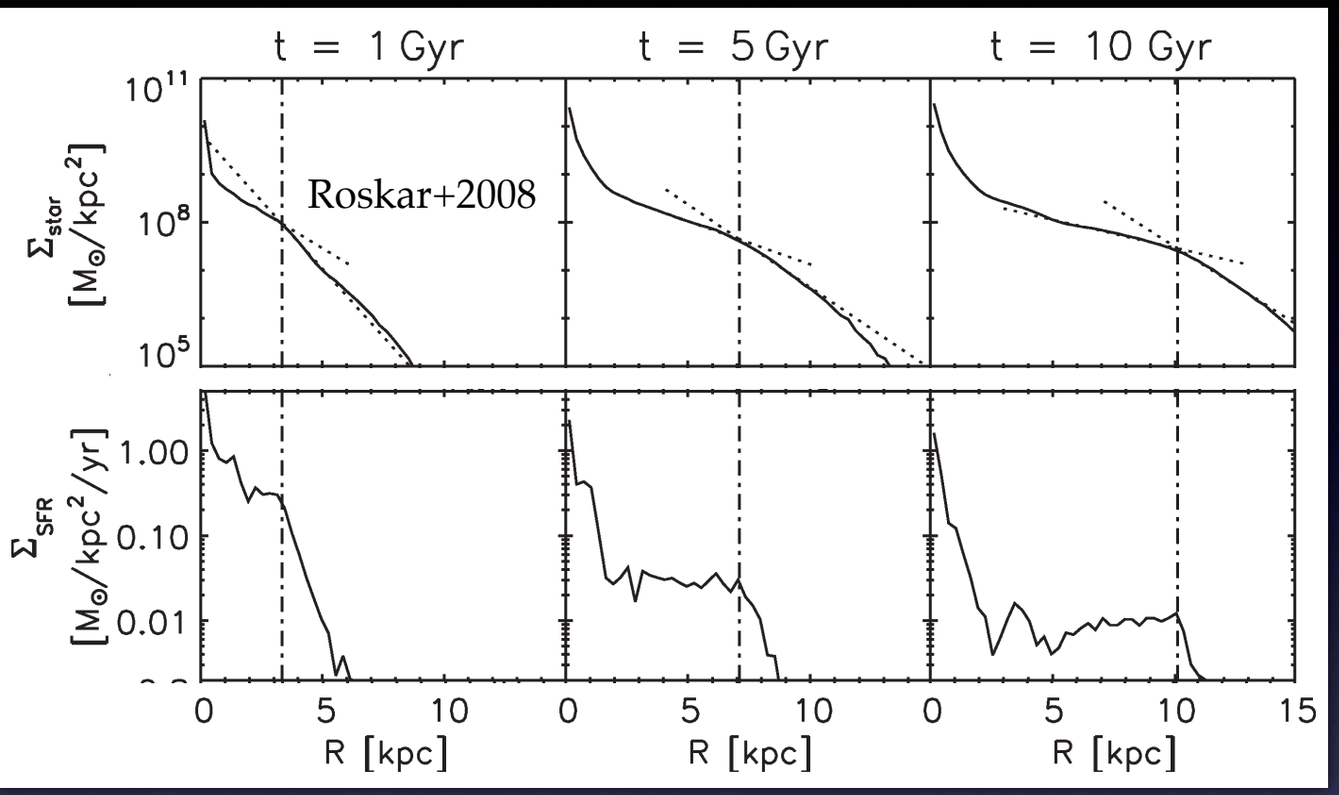
Hα imaging of ~ 100 nearby (z ~ 0.02–0.05) Yang+2007 galaxy groups, spanning halo masses 10^{12}–10^{14} $M_\odot$ (~500 galaxies)

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

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

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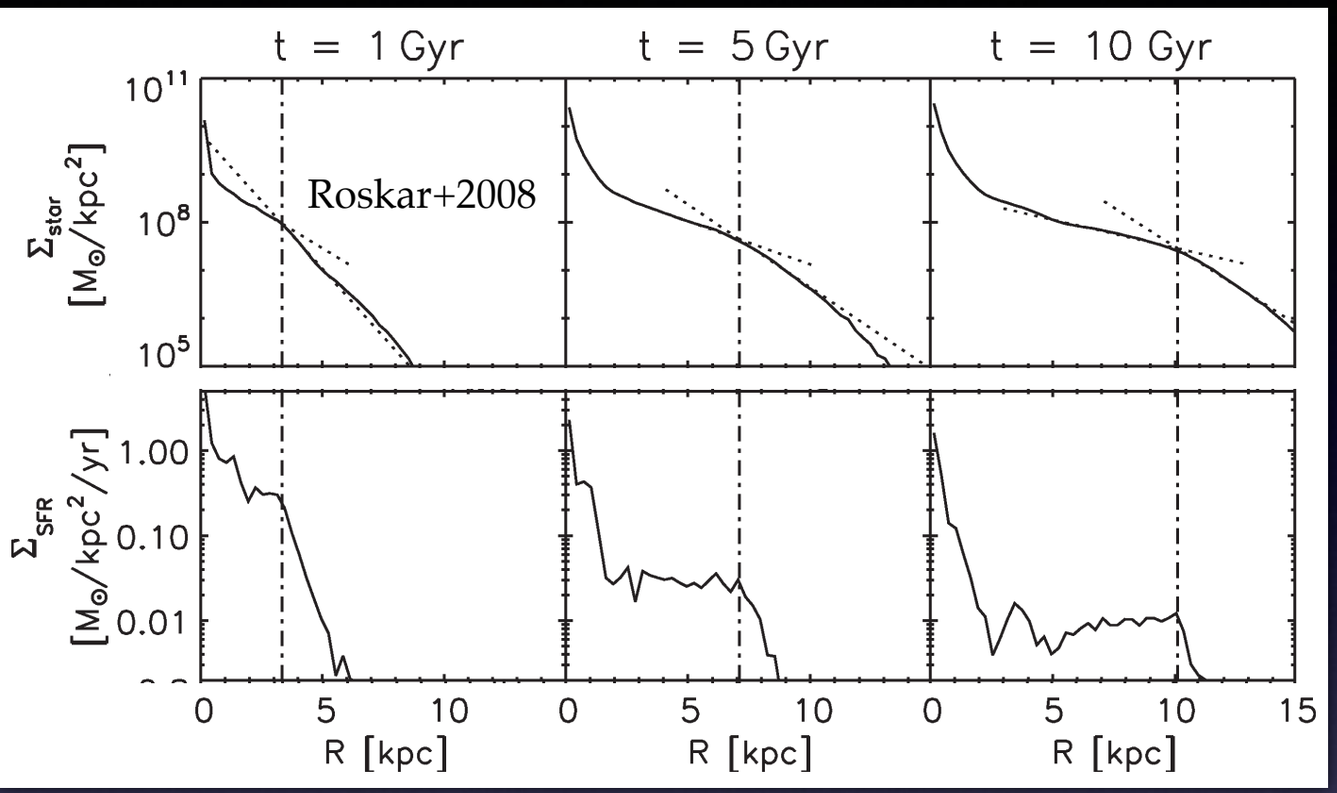

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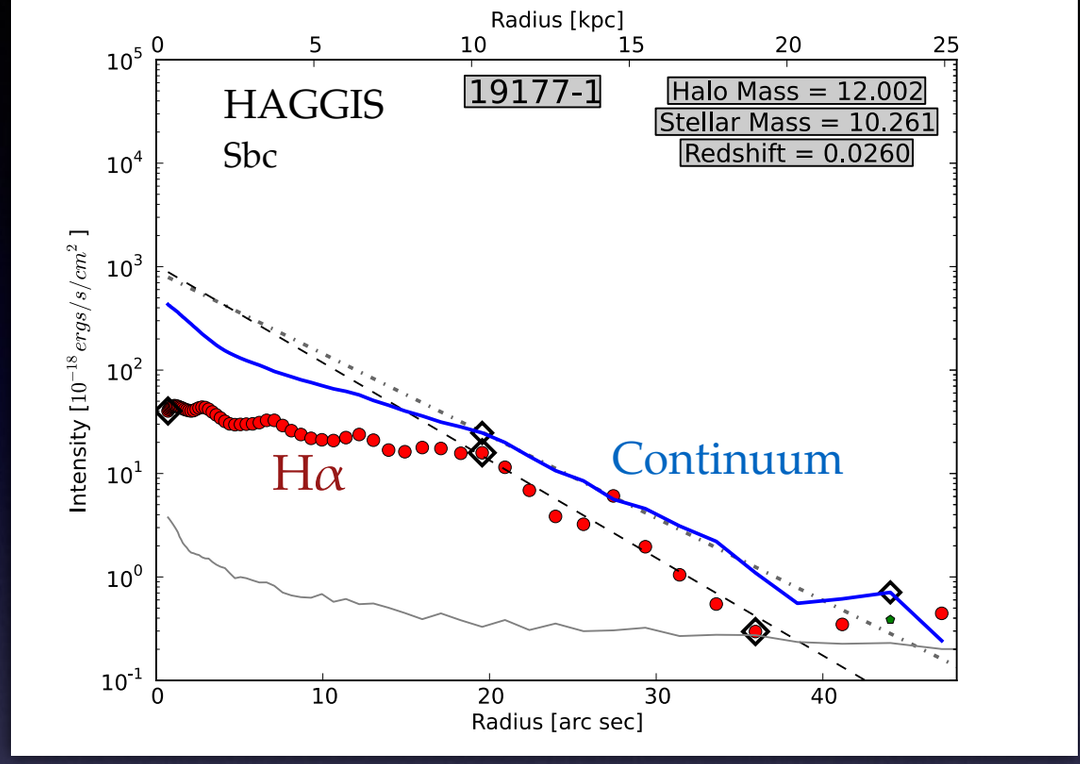

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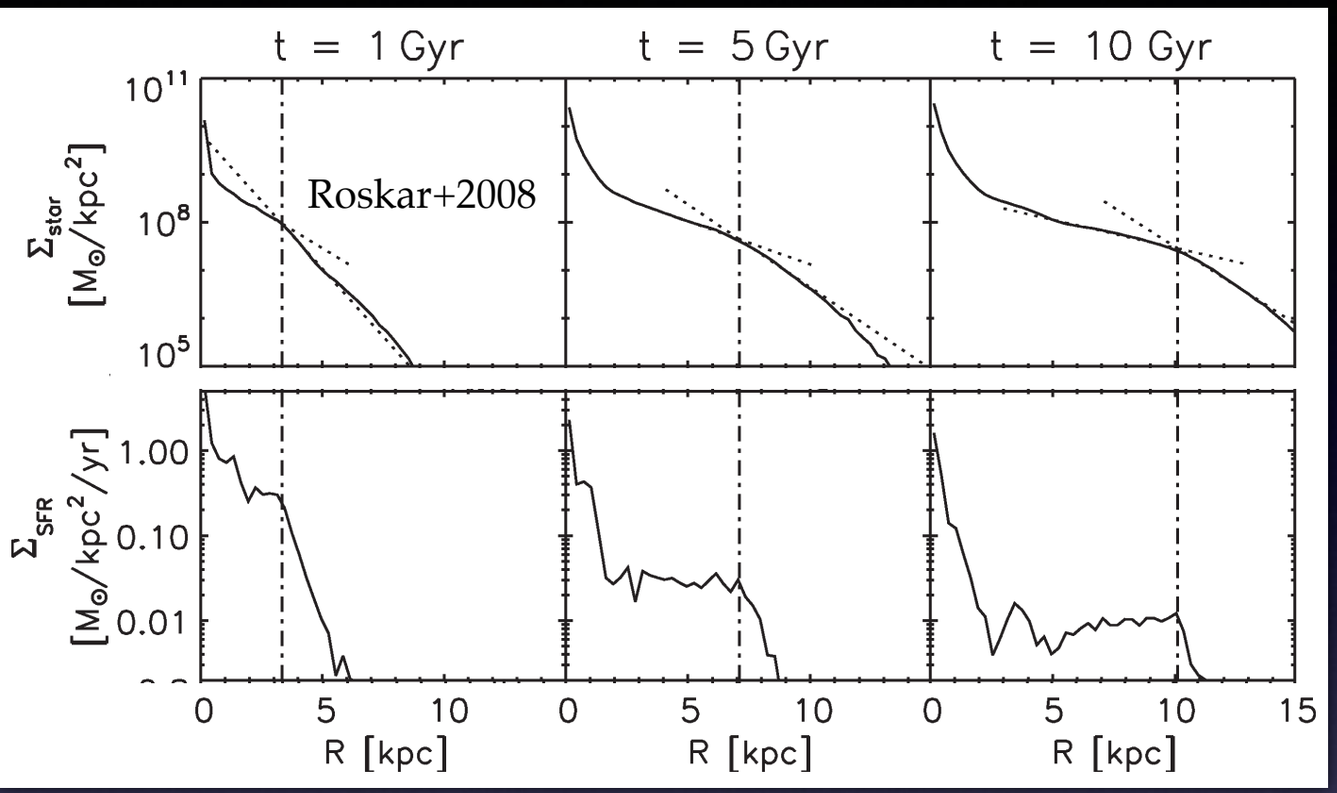

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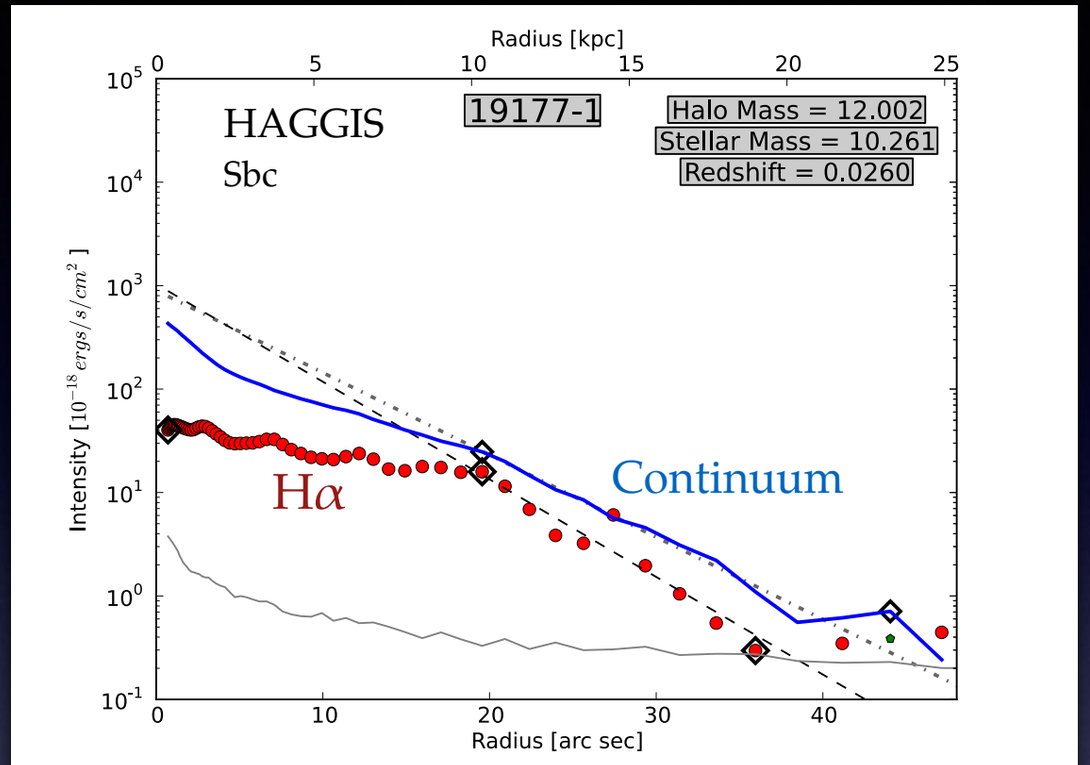

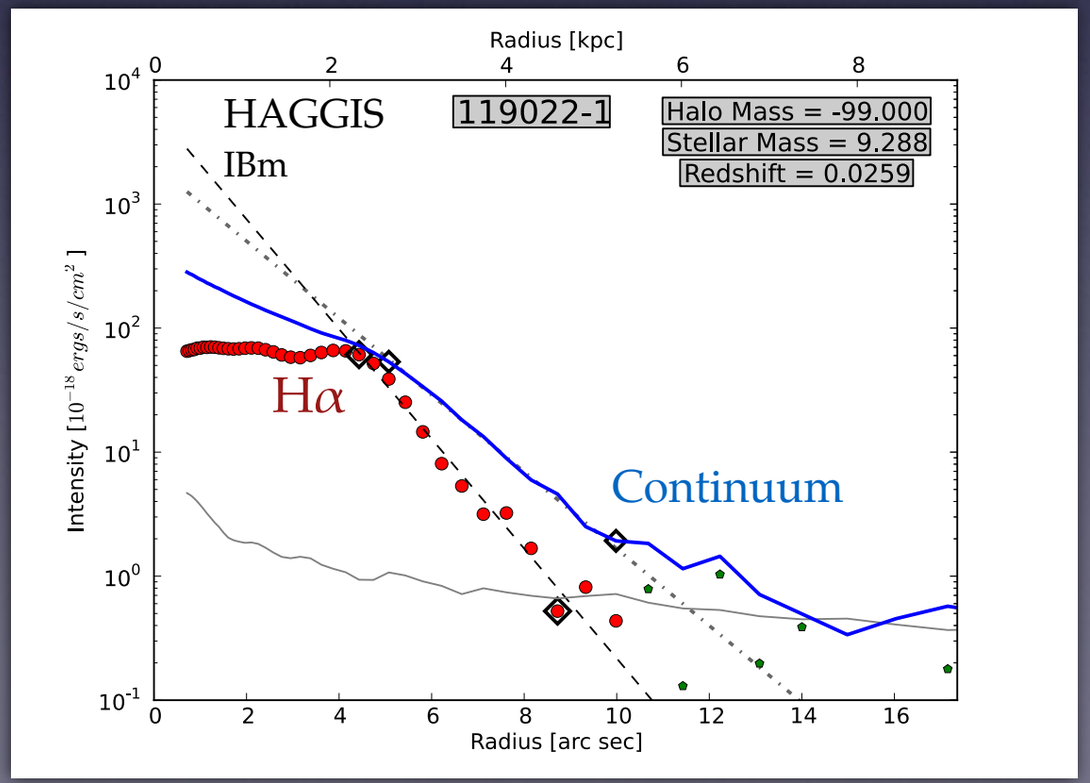

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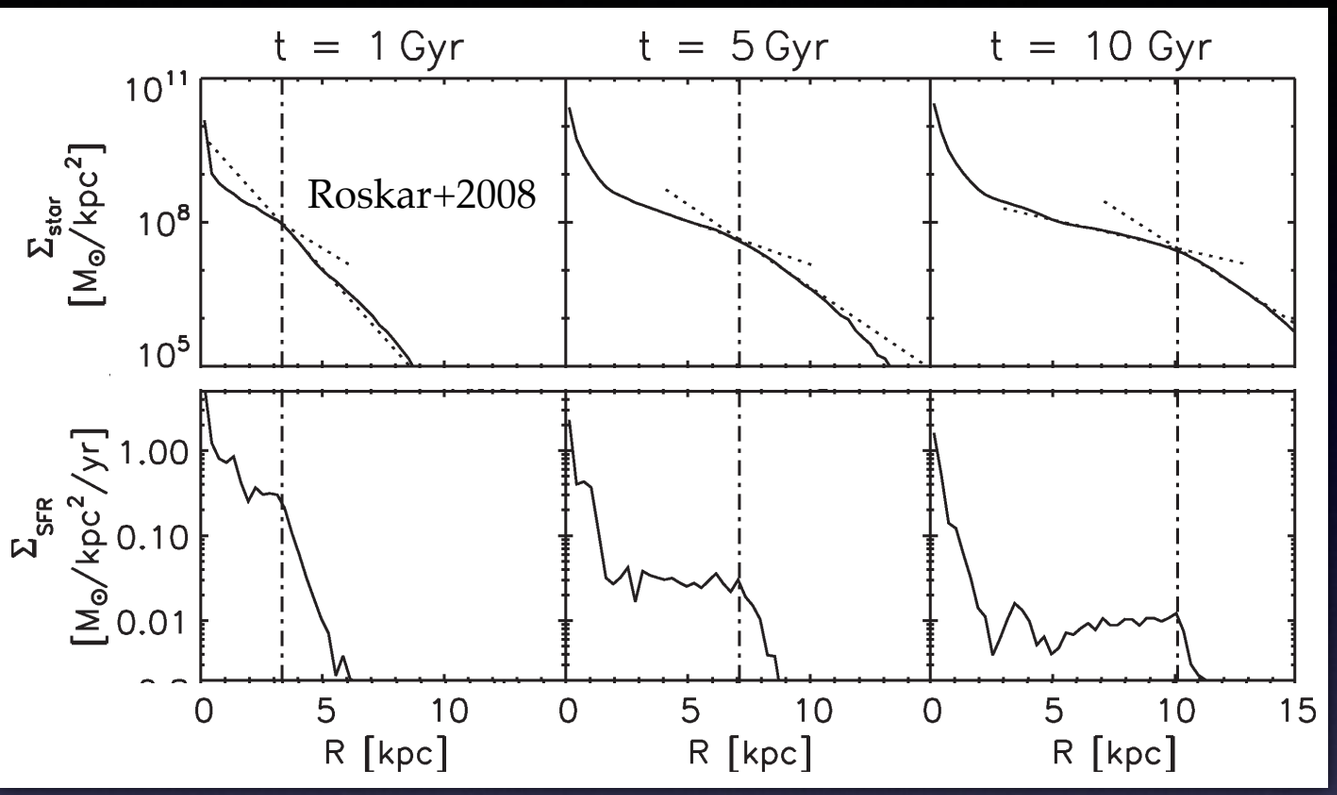

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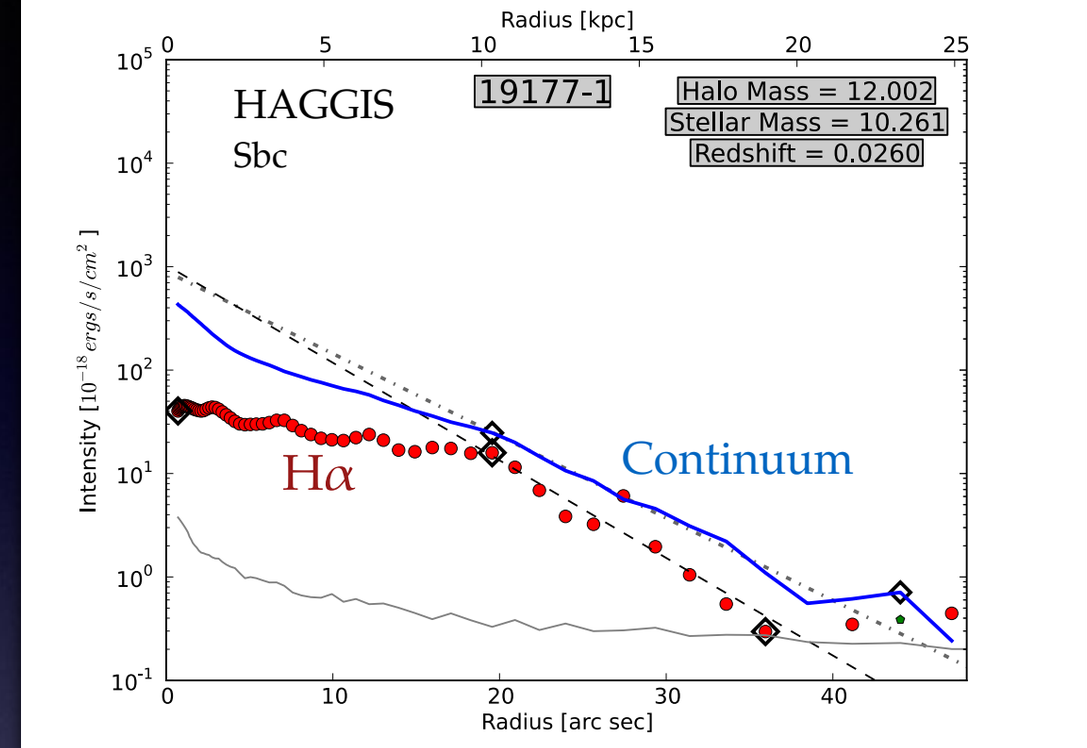
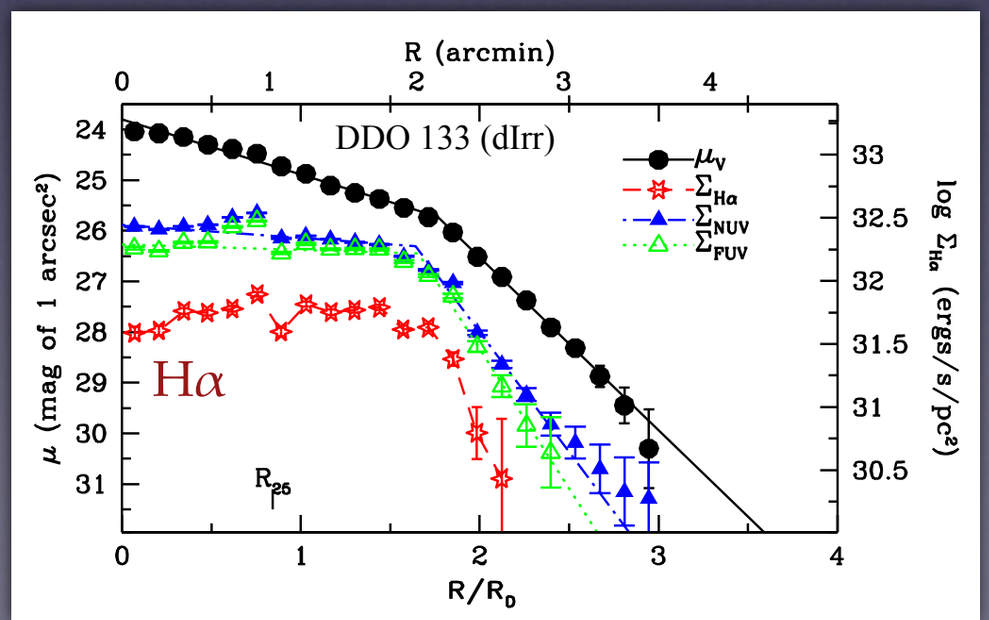
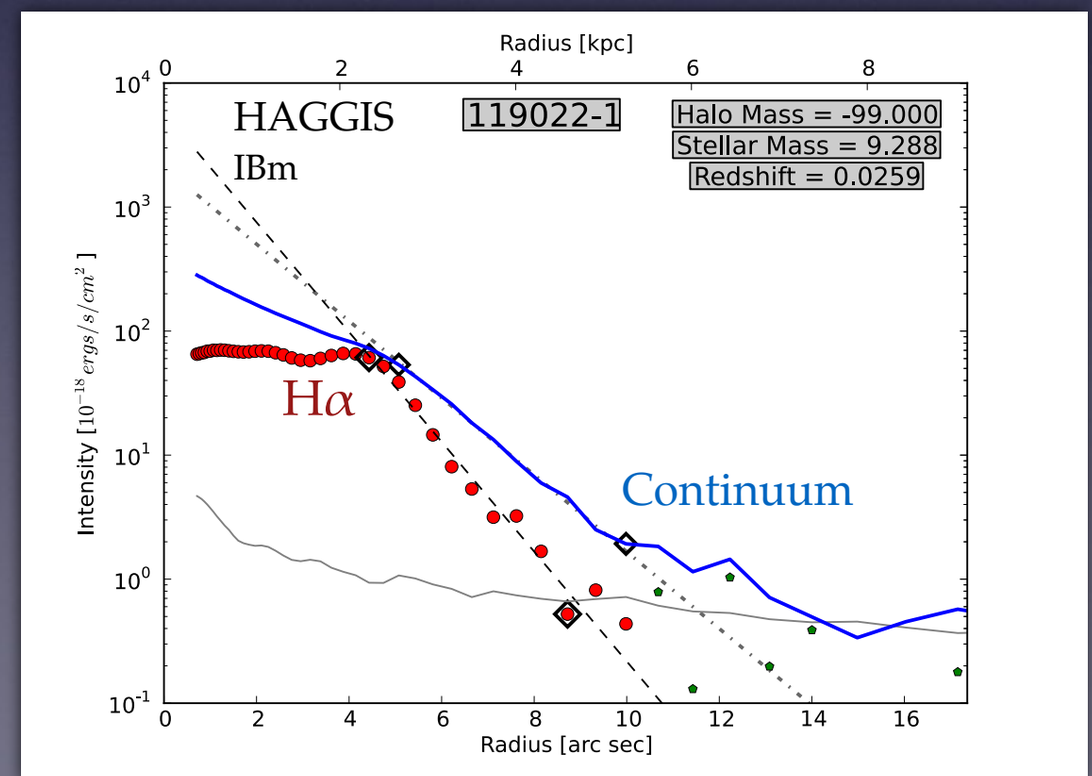


See also:

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

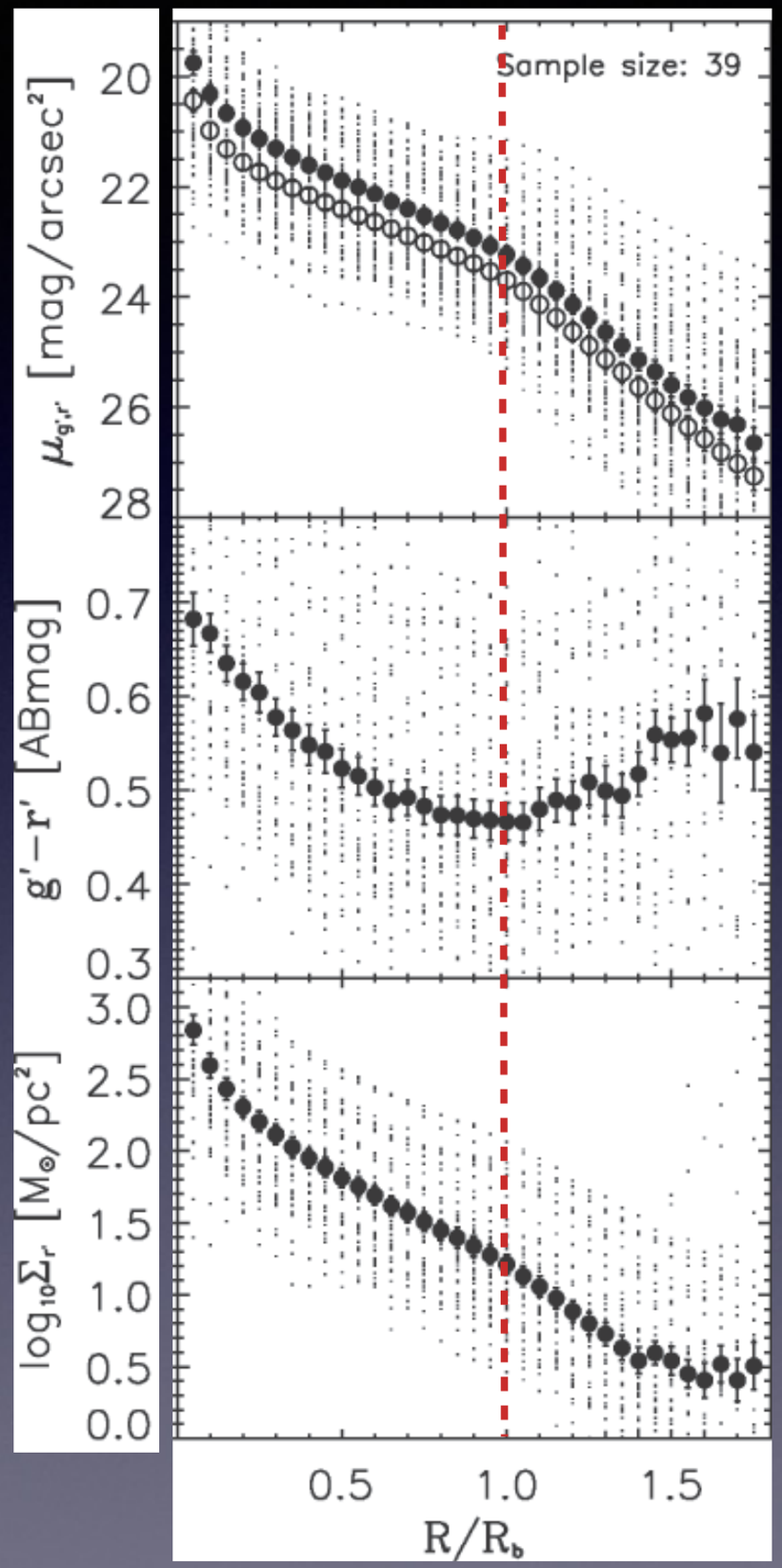
e.g., Roskar+2008; Martínez-Serrano+2009

Sánchez-Blázquez+2009: warp outside break

Leads to age minimum (= blue) at break

Stellar-mass profile is *flatter* than surface-brightness; sometimes/often break disappears! (Type II⇒I)
(e.g. Zheng+2015 analysis of PanSTARRS images)

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



But not all Type II are like that…

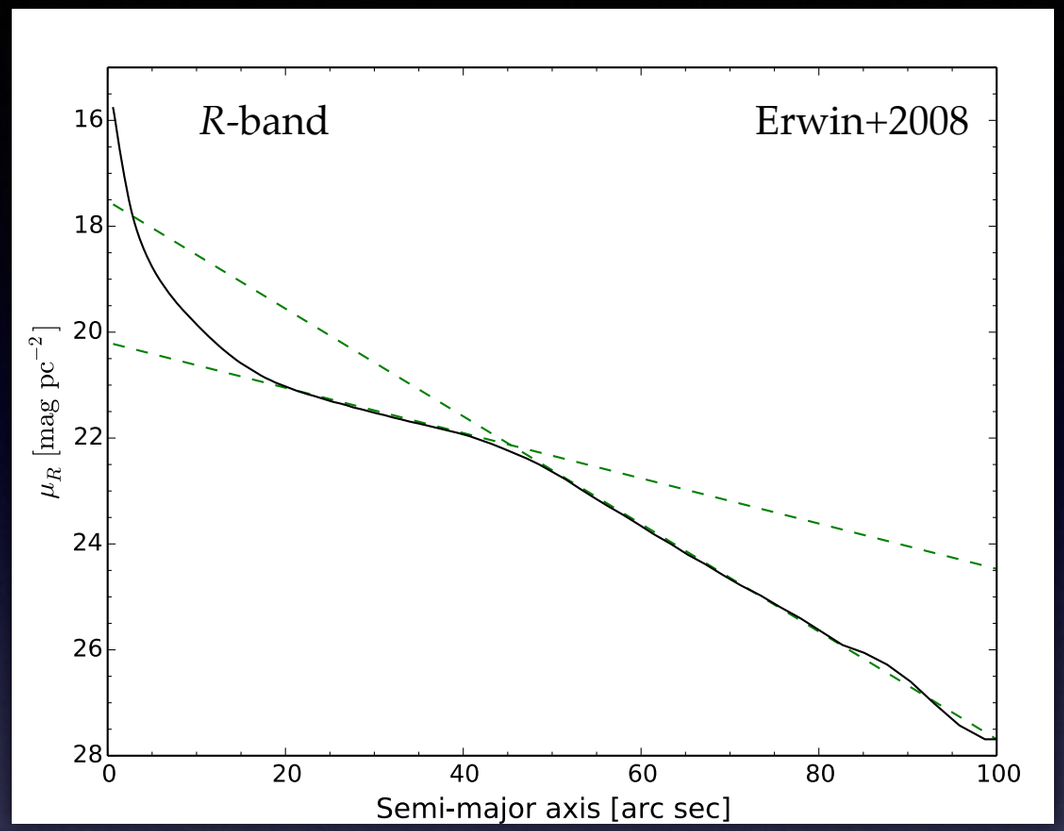
Yoachim+2012: large-FOV IFU observations, fitting multiple stellar populations to optical spectroscopy (late-type spirals)

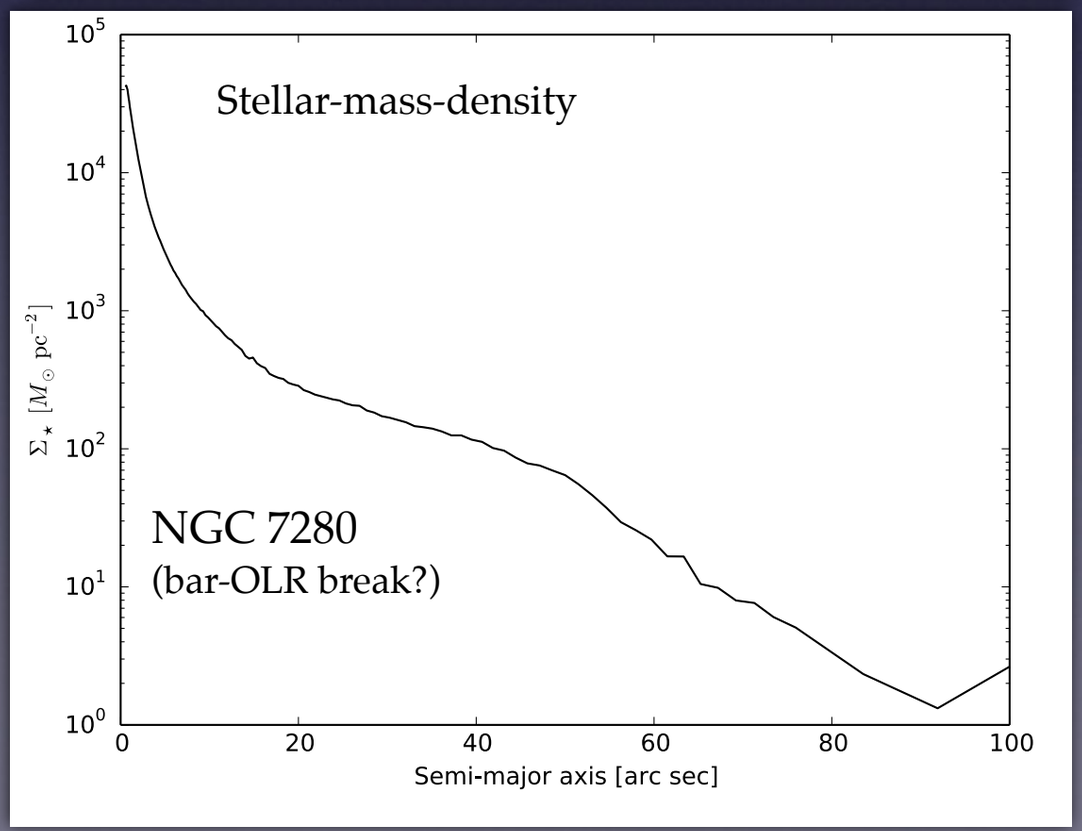
- 6 late-type spirals with Type II profiles:
  - Half show age minimum near or at the break!
  - BUT: other half did *not*

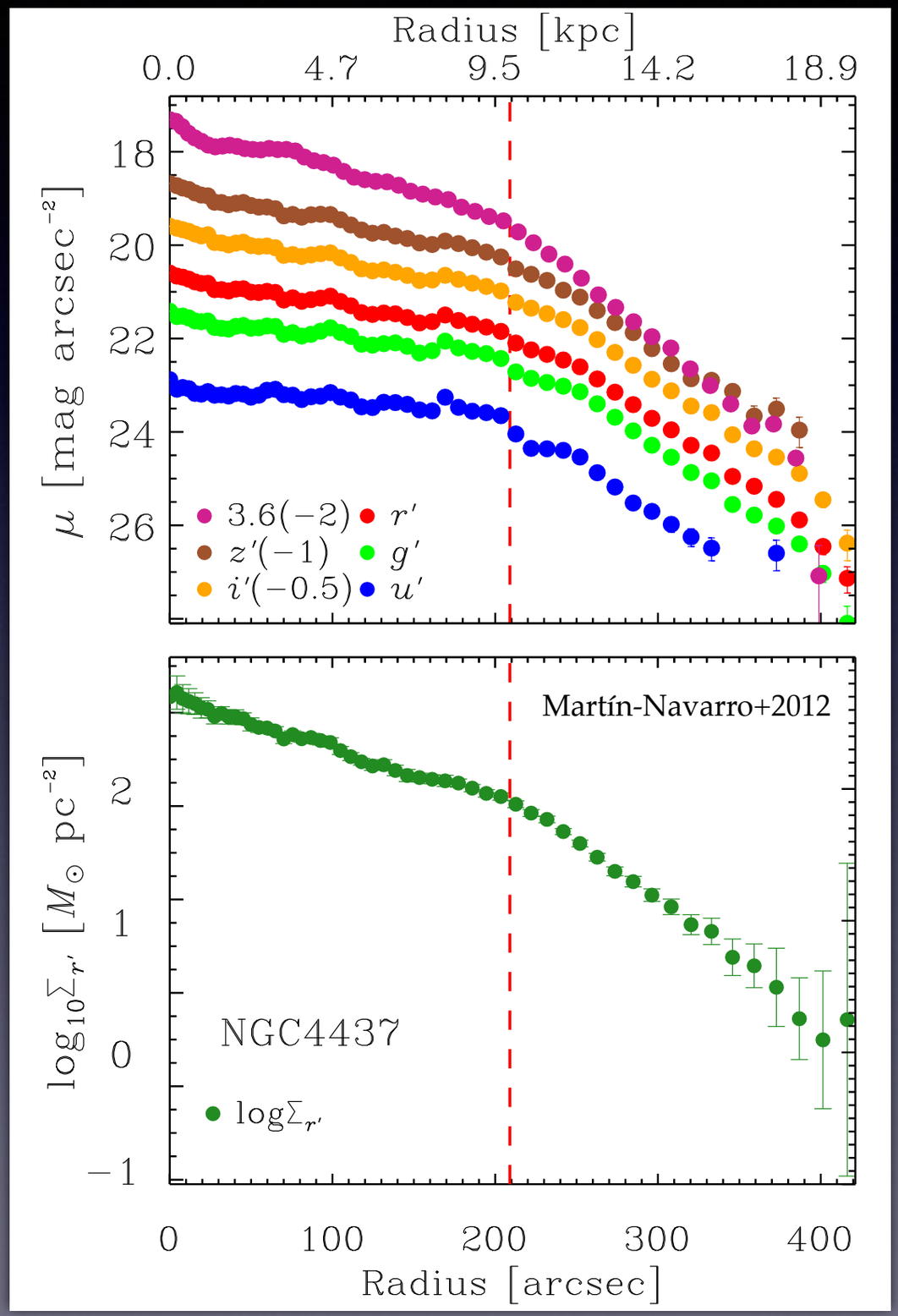
Roediger+2012: analysis of multicolor (*griH)* profiles in Virgo spirals:

- 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?) *three* sub-types of Type II breaks in S0s + spirals!

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

   Circumstantial argument — no models yet

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

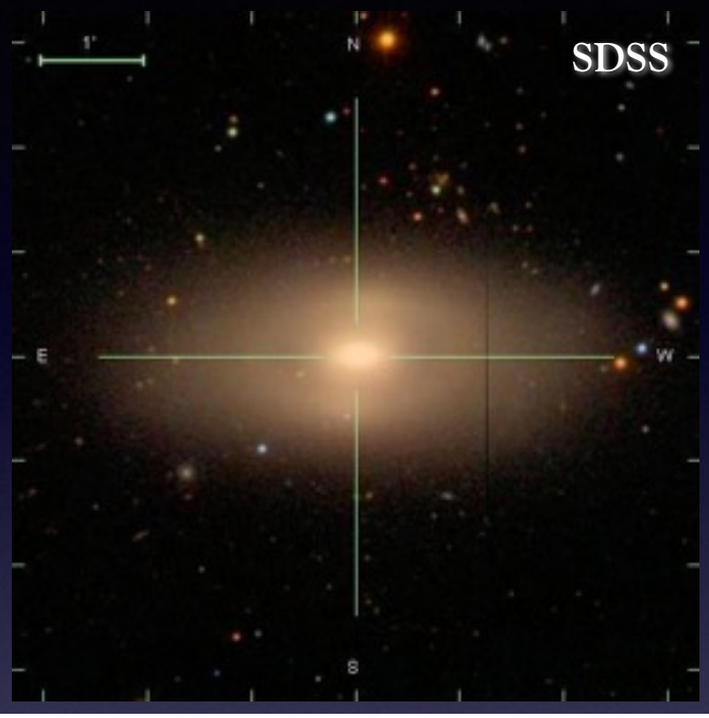
   Predicted by at least one *N*-body model (Debattista+2006)

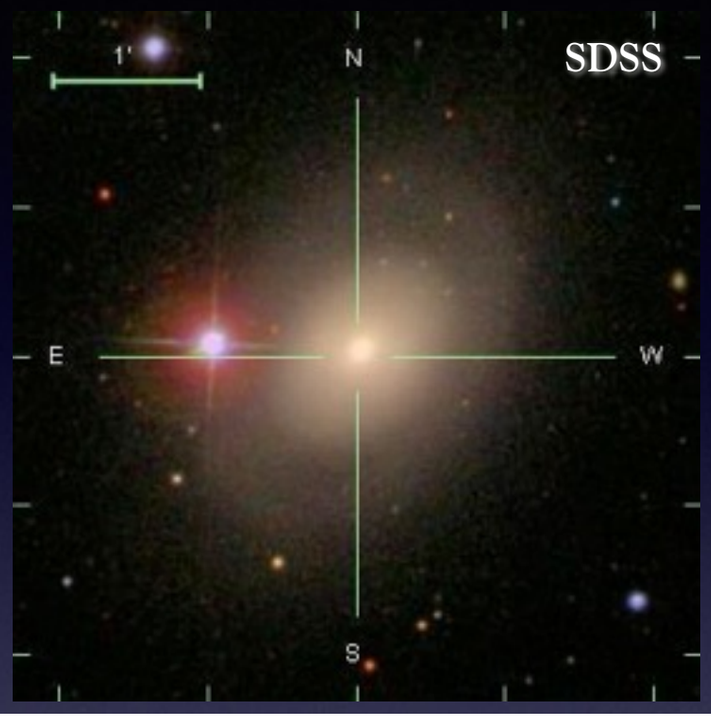
3. SF threshold + radial migration: broken-exp; mostly late-type disks

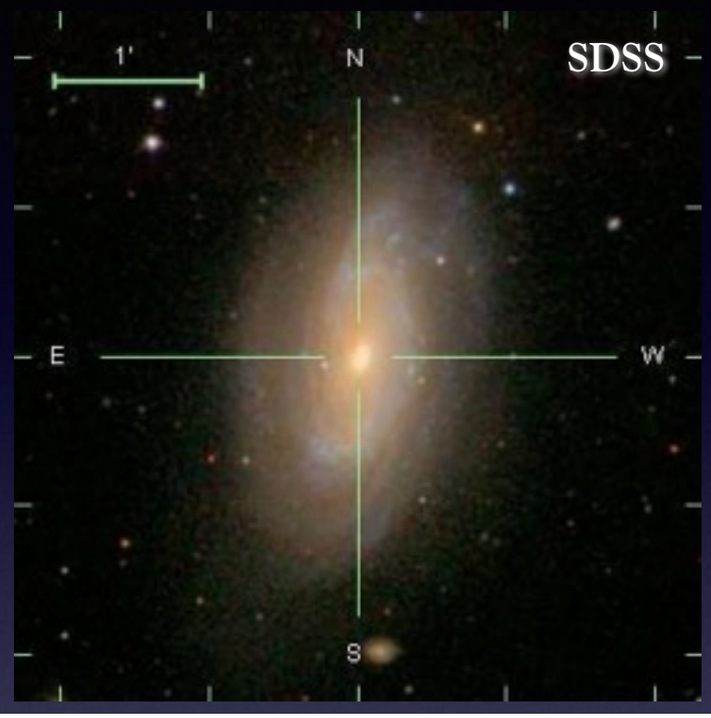
   Best-developed theory, with some predictions matched by observations (age minimum at break, flattening of break with age, break in star-formation rate)

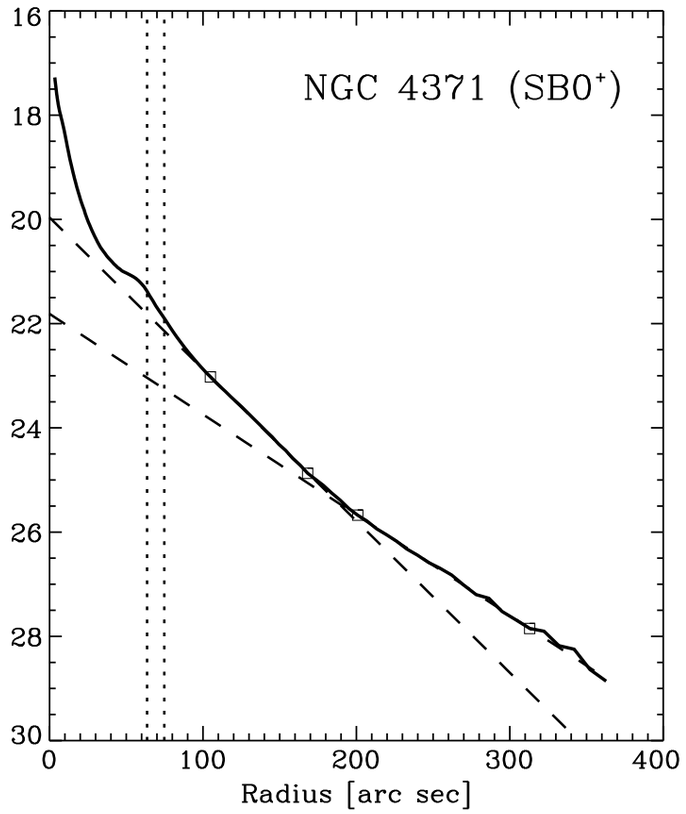
Type III ("Antitruncations")

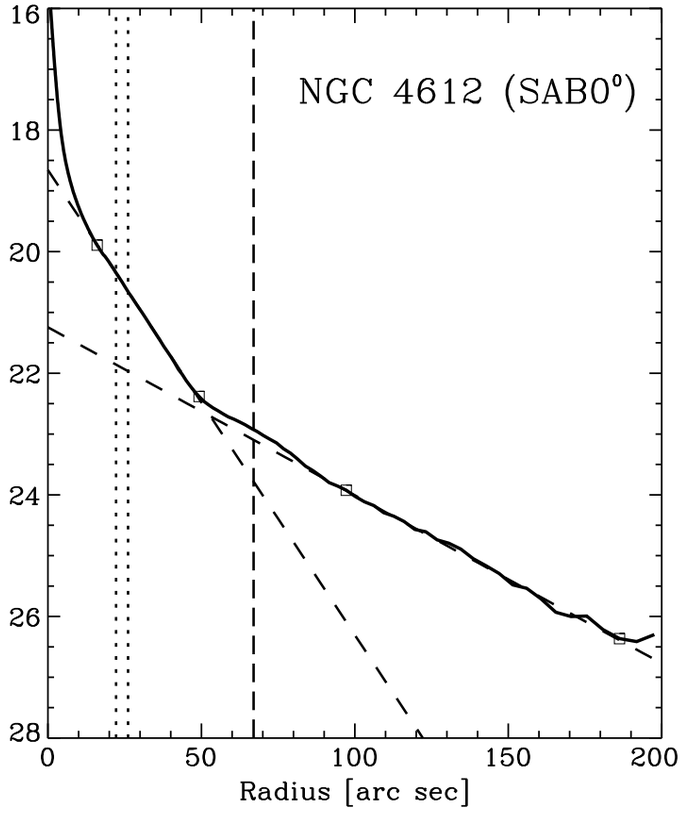
Erwin, Beckman, & Pohlen (2005, ApJL 626: L81)

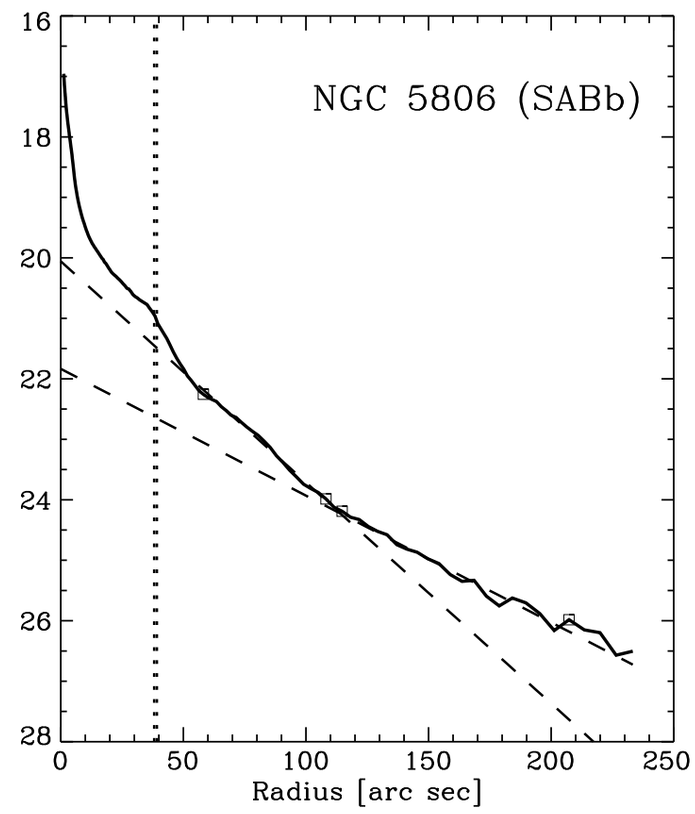






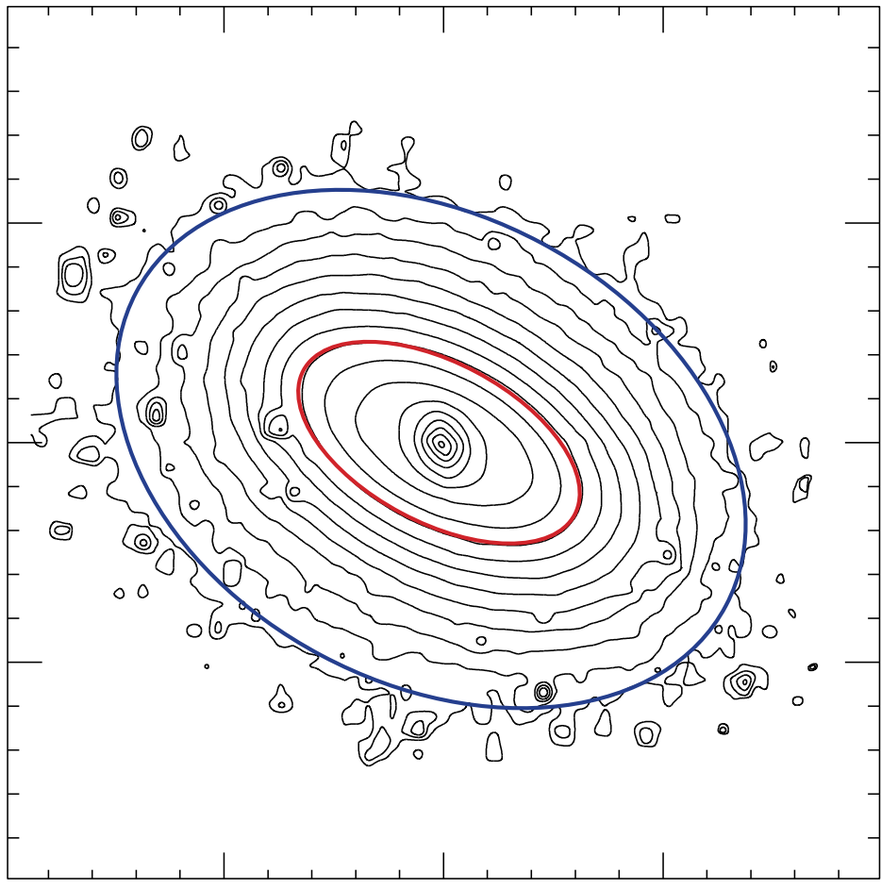


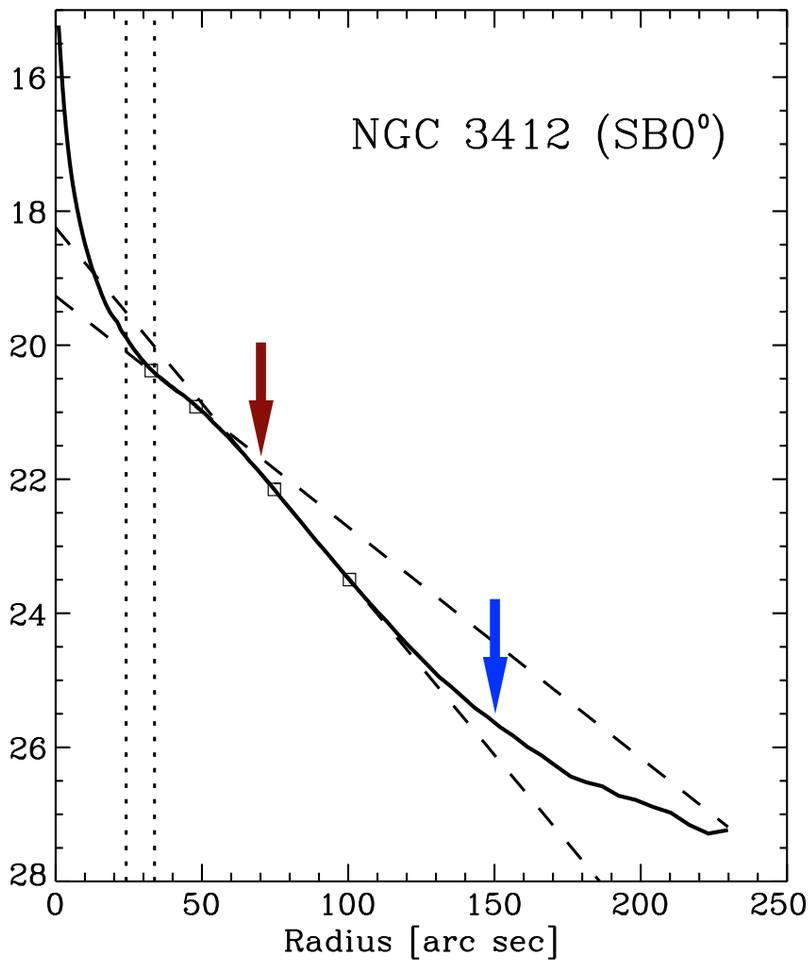




Bulge or Halo Light at Large Radii?

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).

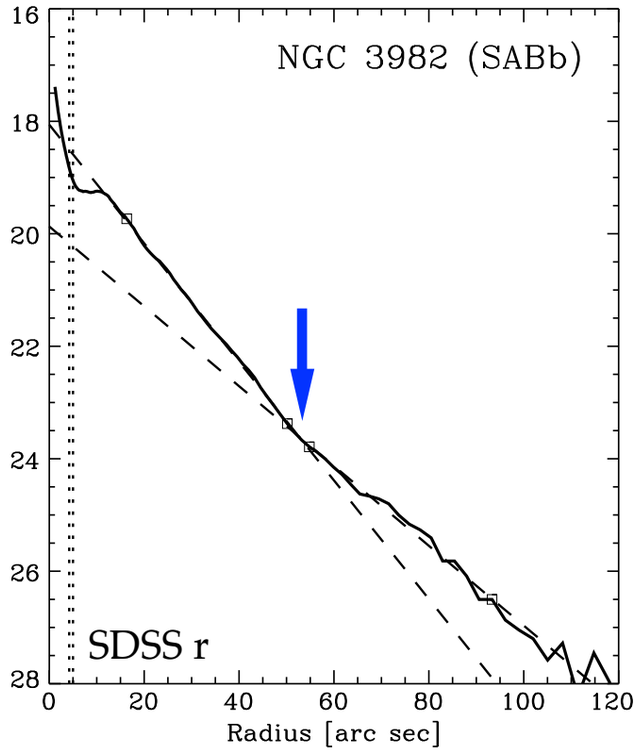
5. Antitruncation seen in *edge-on* disks by Pohlen+2007, Comerón+2012

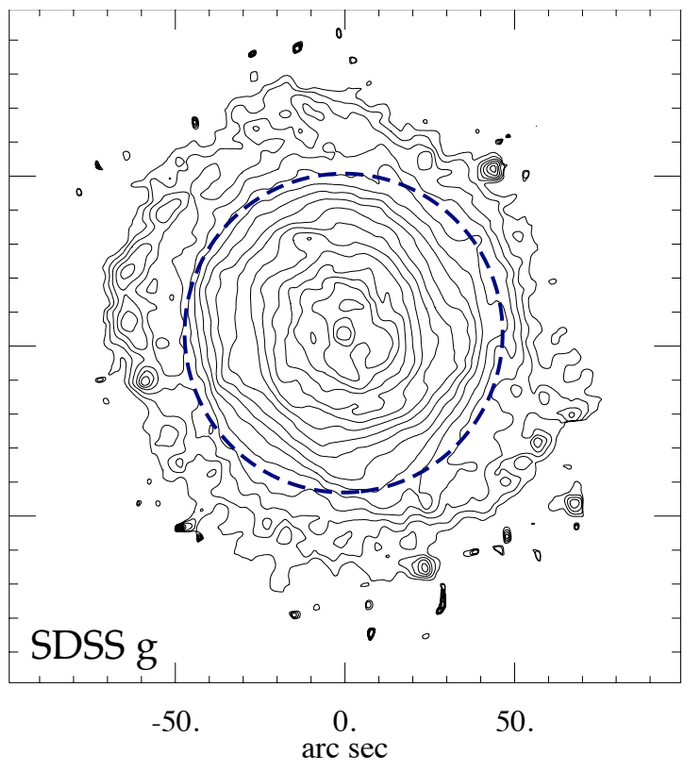
Erwin+2008/Gutiérrez+2011 S0–Sb galaxies with $i > 30°$:

S0: 47% of Type III are III-d (= outer disk, not bulge/halo)

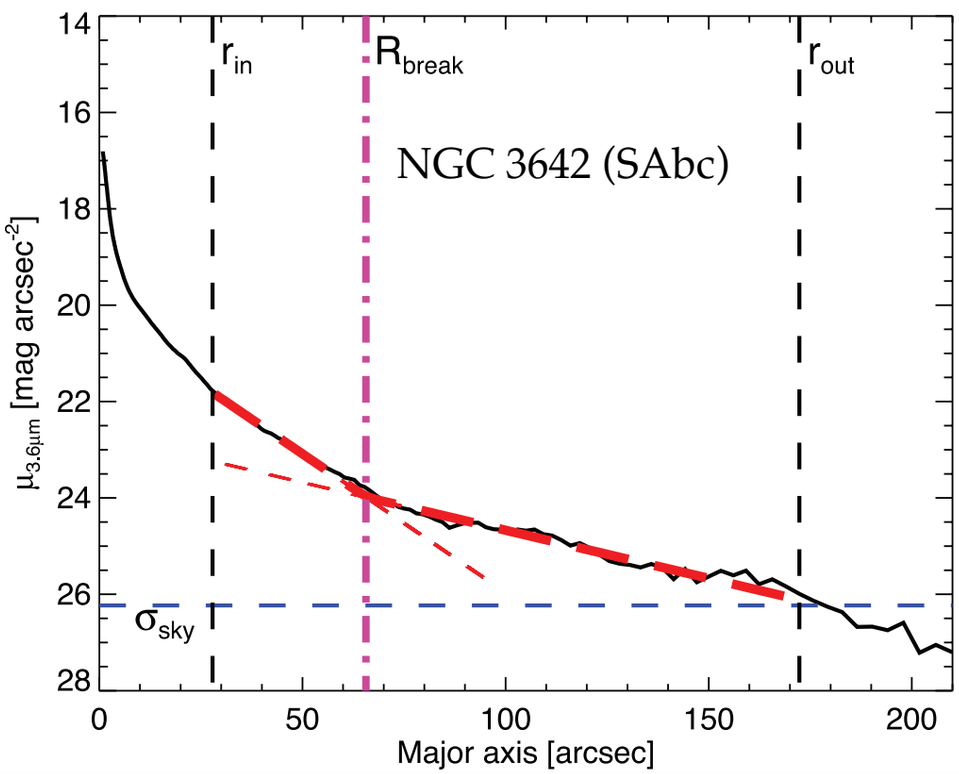
S0/a–Sb: 71% of Type III are III-d

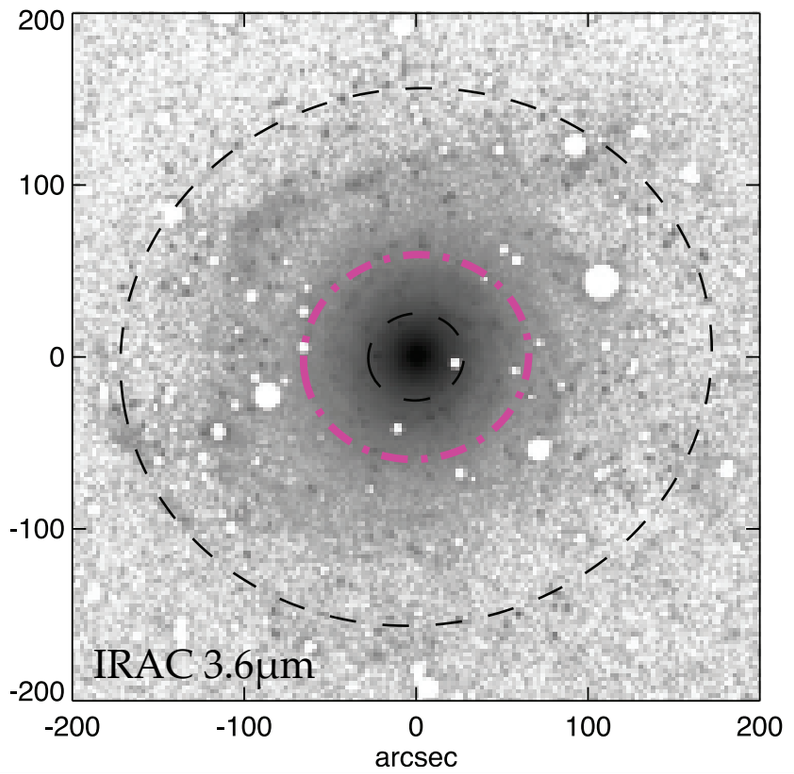
Spirals beyond the break radius





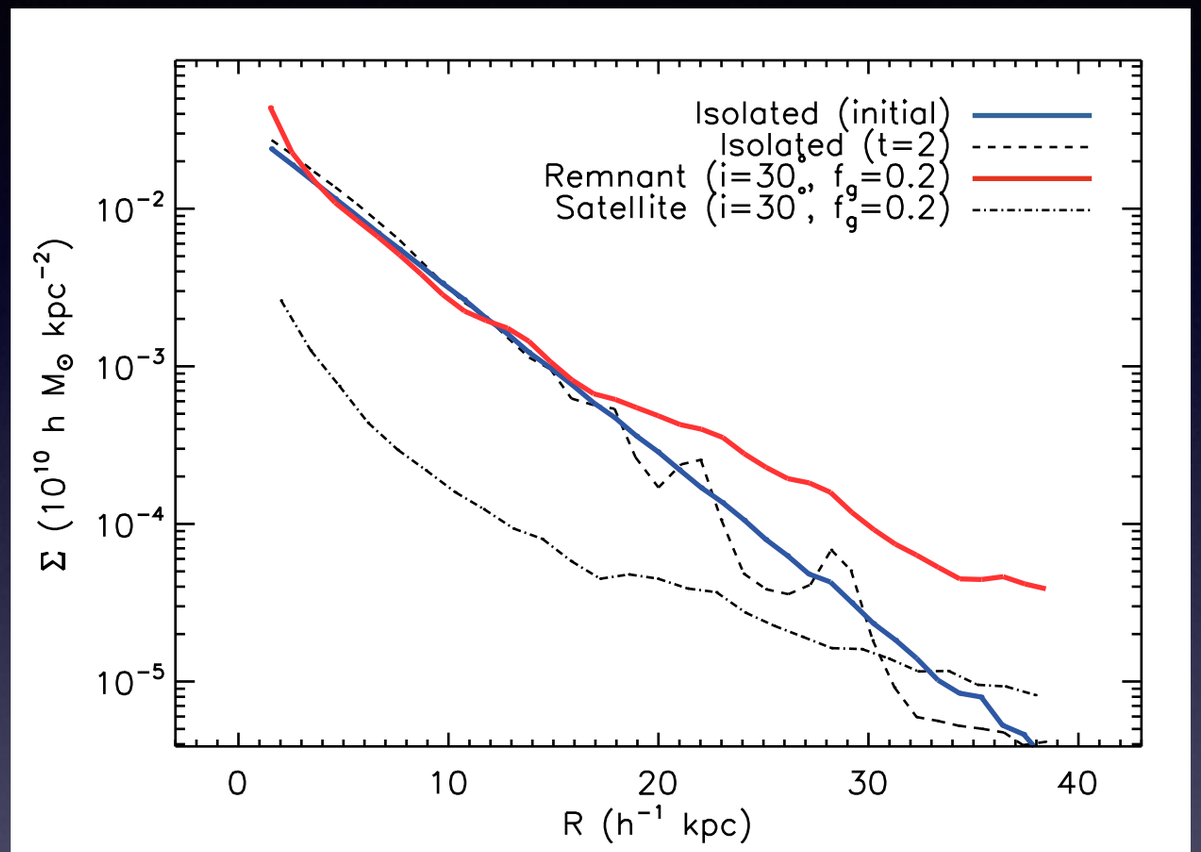
Erwin+2008



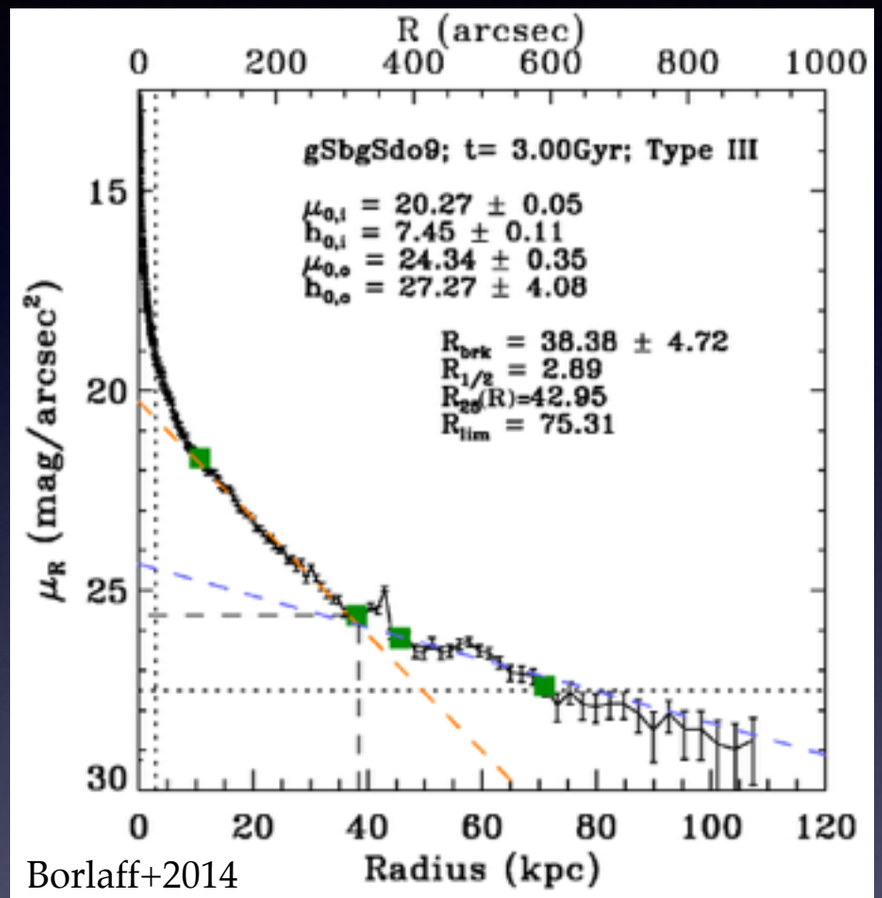


Laine+2014

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



Younger+2007



Borlaff+2014

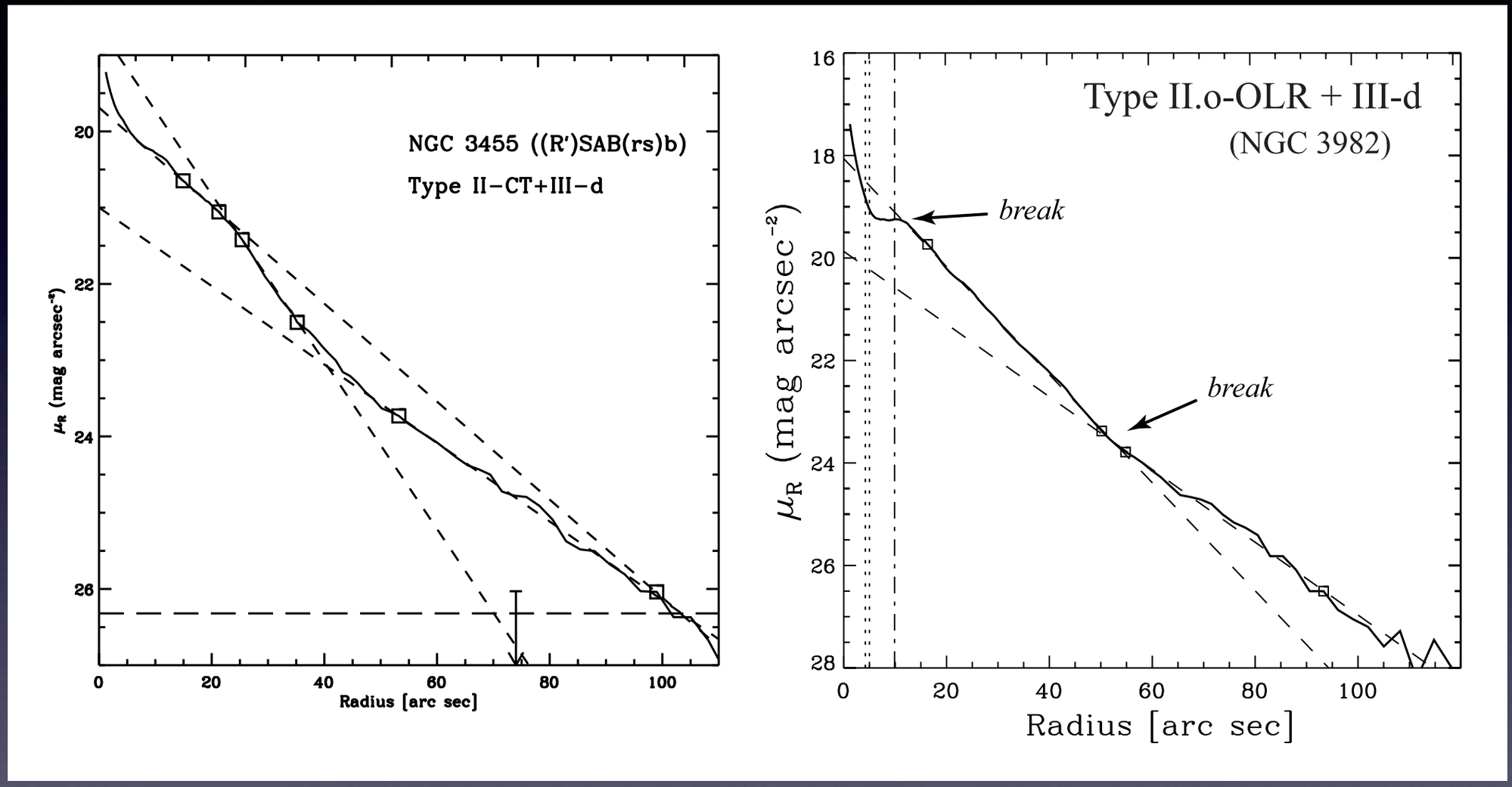
Younger+2007: gas-rich, prograde minor mergers can produce antitruncations

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

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…

Halo Spin as the Key?

Herpich+2015: Simulations of isolated galaxy formation ($M_\star \sim 2–3 \times 10^{10}\ M_\odot$), varying only by halo spin parameter λ

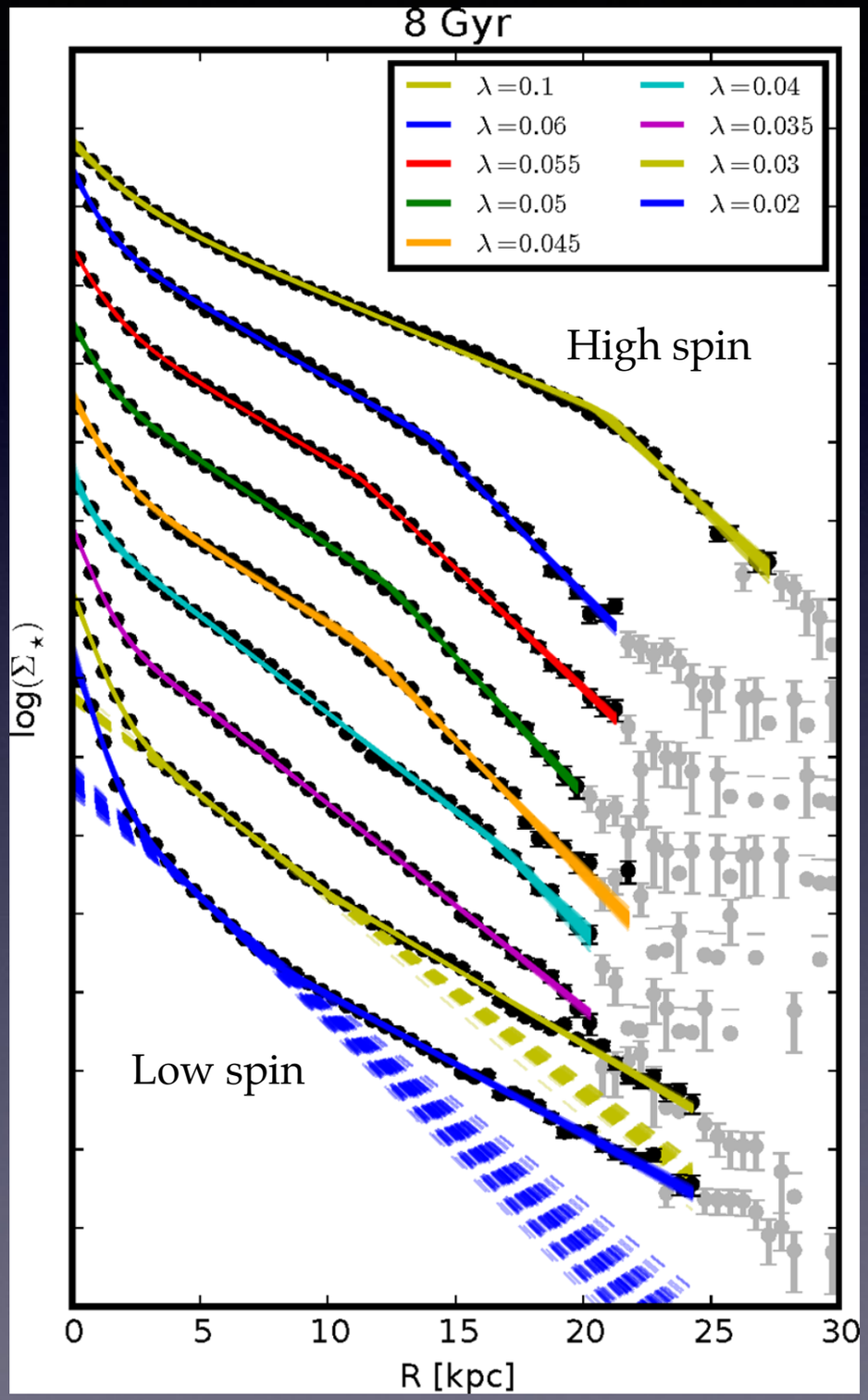
Clear trend in stellar-mass-density profiles:

High spin = Type II

int. spin = Type I

low spin = Type III (no mergers involved…)

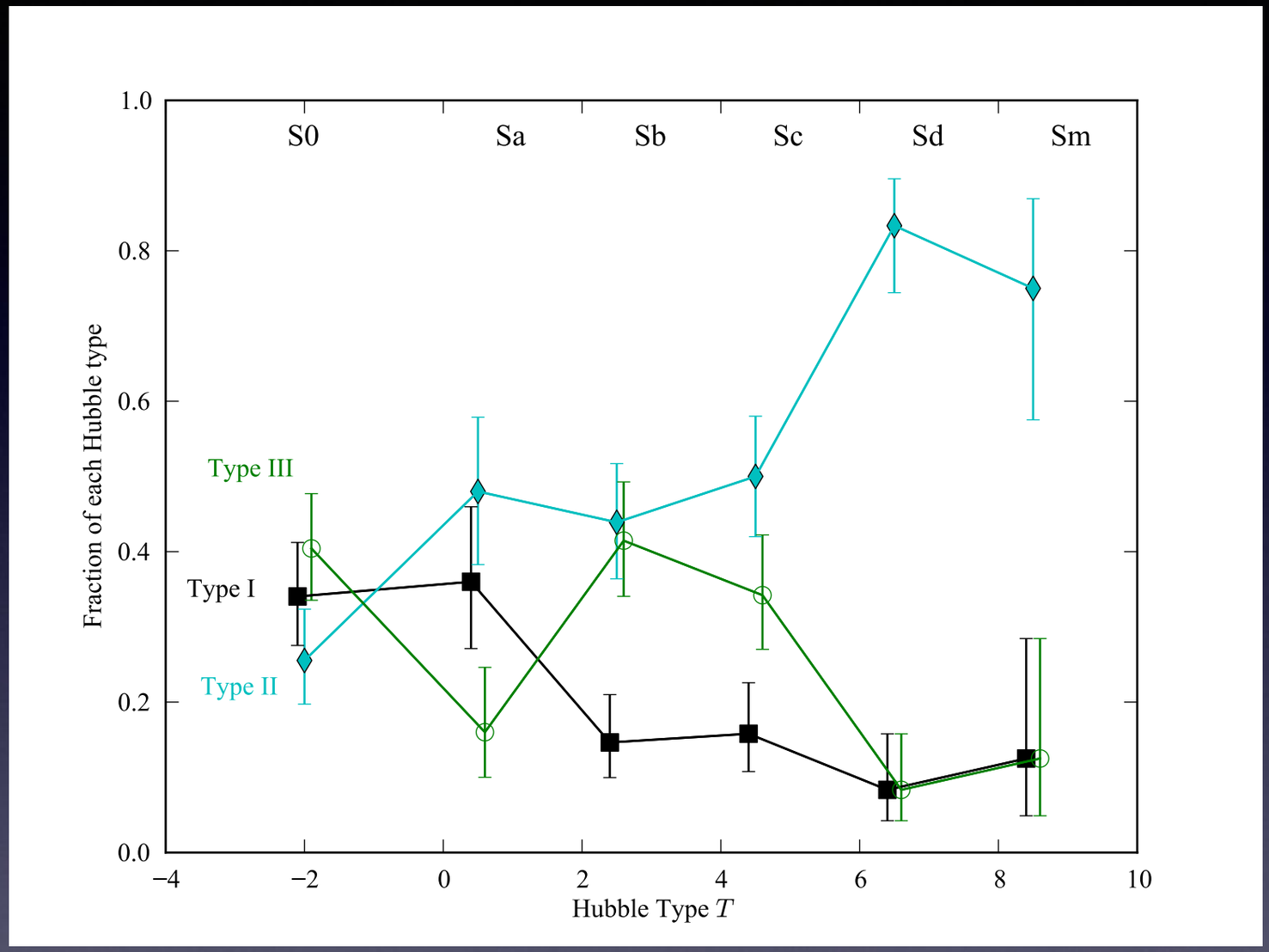
Underlying reasons not clear yet (just a Letter…)



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

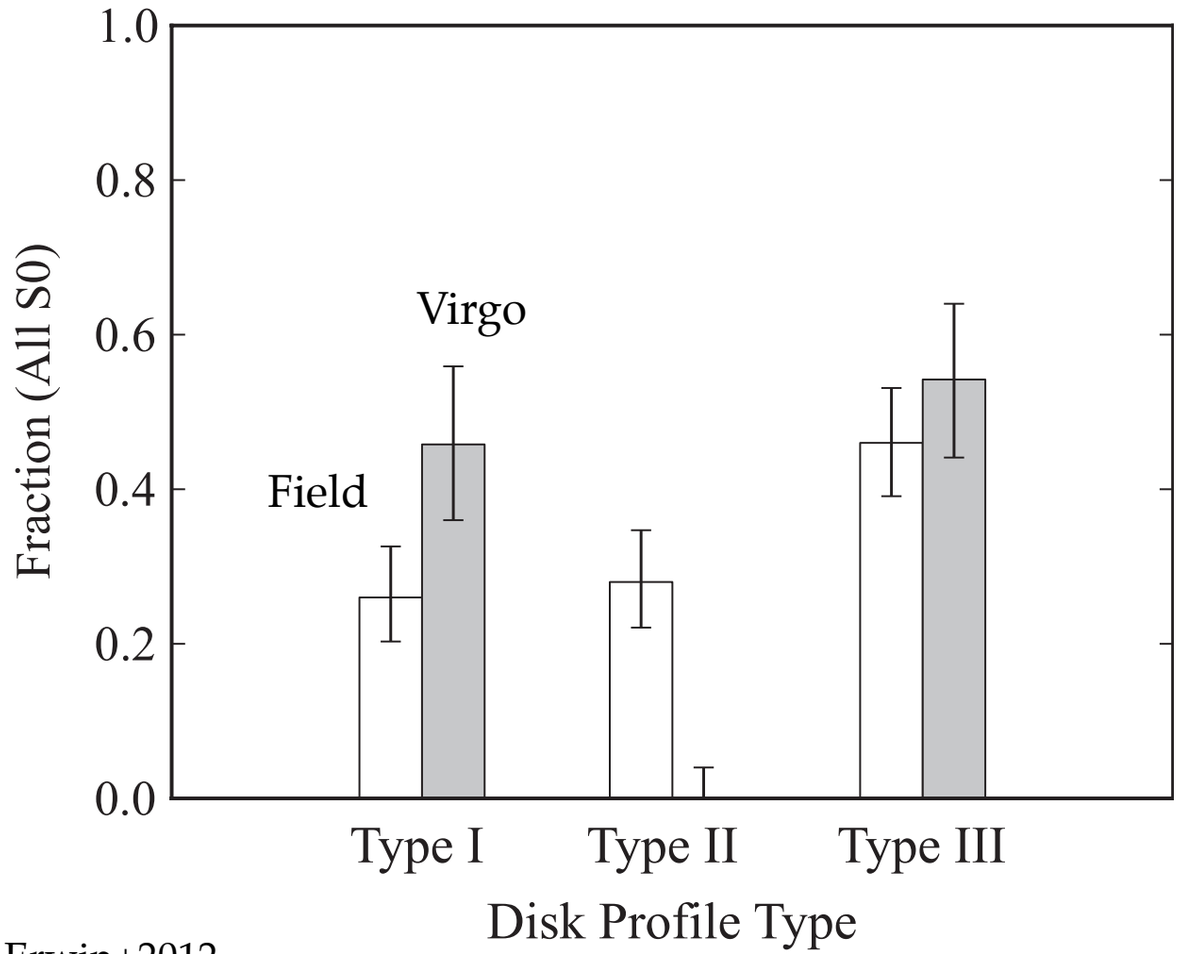


Gutiérrez+2011 (incl. data from Pohlen & Trujillo 2006, Erwin+2008)

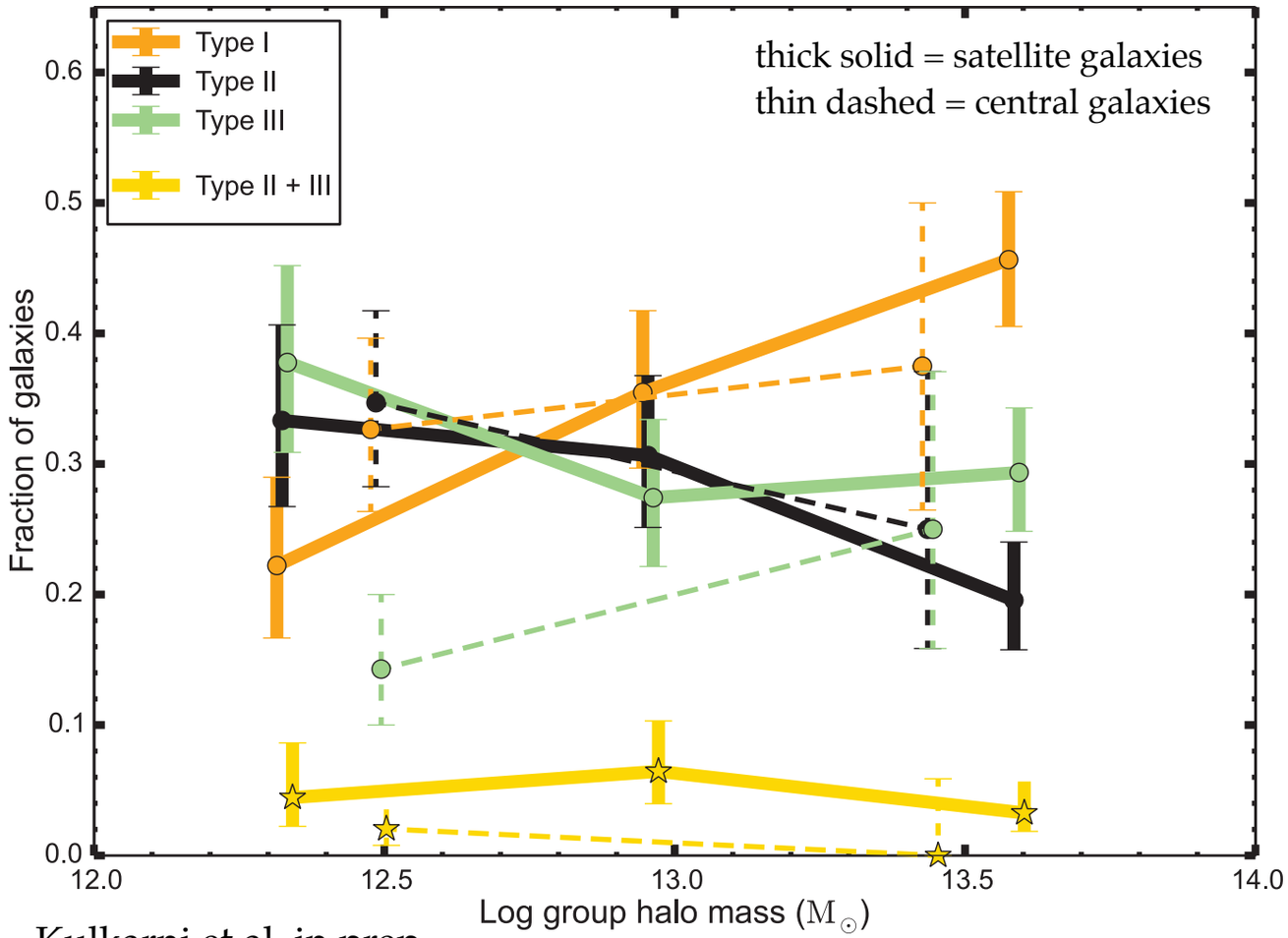
Type I favor early types; late-type spirals are predominately Type II
Similar results found with S4G data by Muñoz-Mateos; consistent with Zheng+2015 results using galaxy concentration

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

Profile Types vs Environment



Erwin+2012



Kulkarni et al. in prep

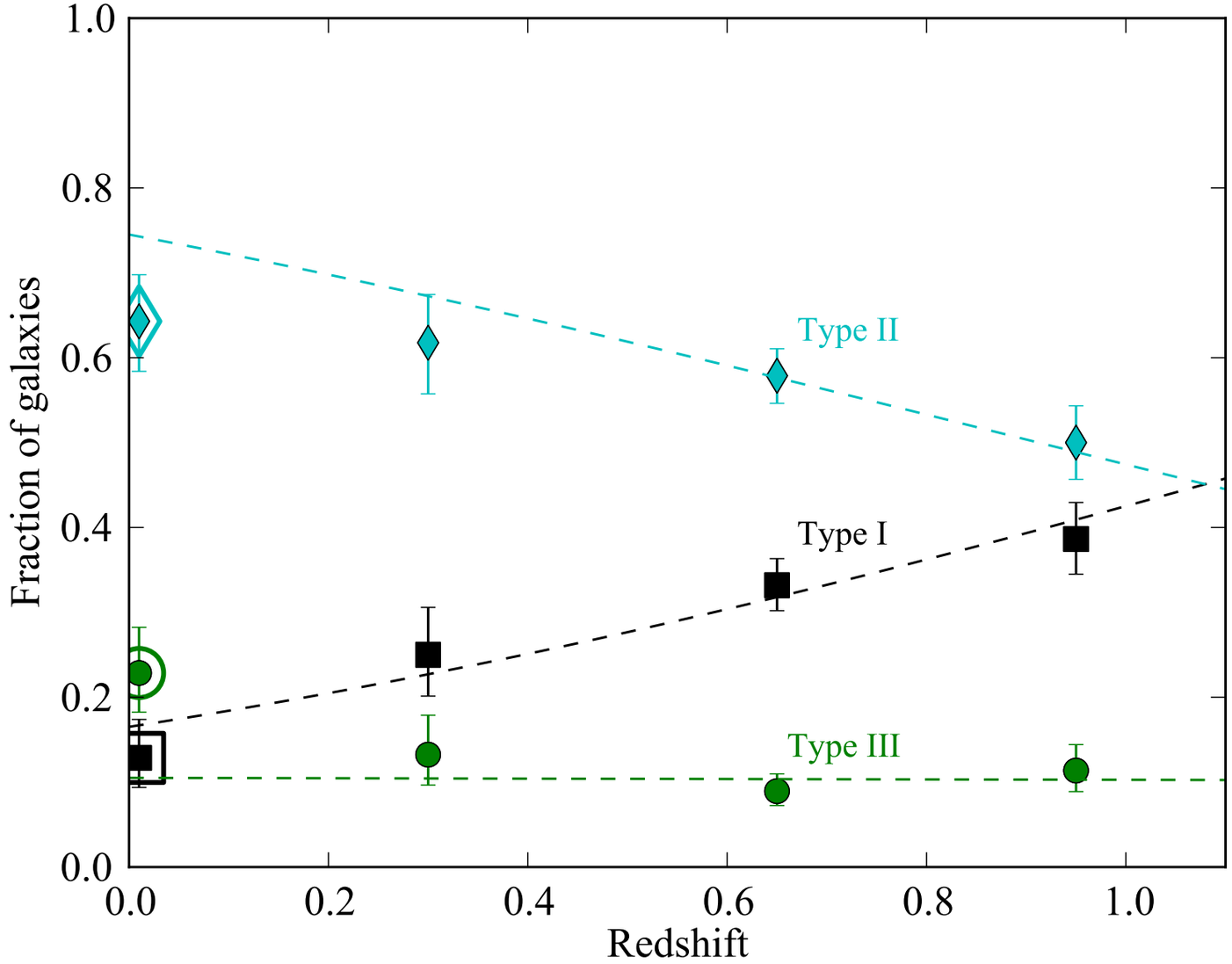
Erwin+2012: Type II profiles absent Virgo S0s!
("Missing" Type II are Type I instead)

Roediger+2012: Type II less common in Virgo vs. field
(34% Type II, vs 49% of field spirals)

HAGGIS: Type II frequency declines with increasing group mass, Type I frequency increase — consistent with Virgo vs "field" results

Dense environments suppress Type II formation (make 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

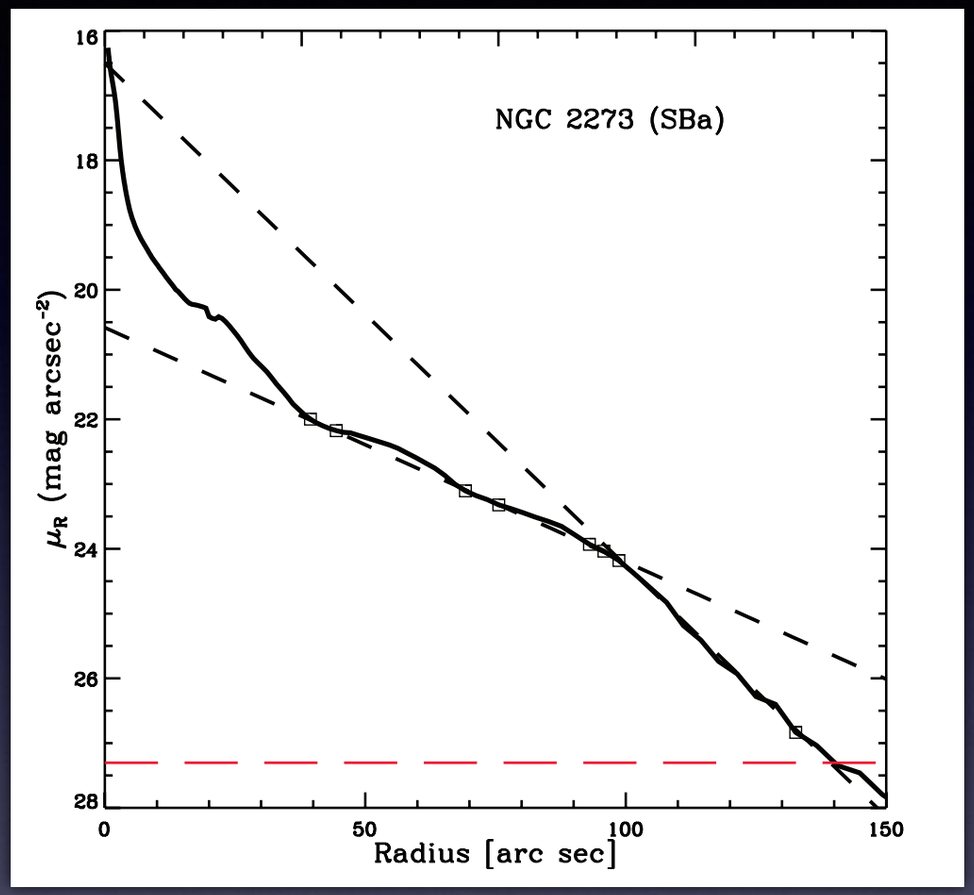
- Three main classes of outer-disk profiles/breaks
  - Type I (~ 20% of spirals): simple (can extend to ~ 10 scale lengths); more common in S0 and early spirals
  - Type II (49% of spirals): more common in late types; probably multiple origins
    - Two broad subtypes/mechanisms: Bar-related resonances; 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 ⇒ I in massive groups, clusters)
- Some evidence for evolution with redshift (cause unknown)

Outstanding Issues

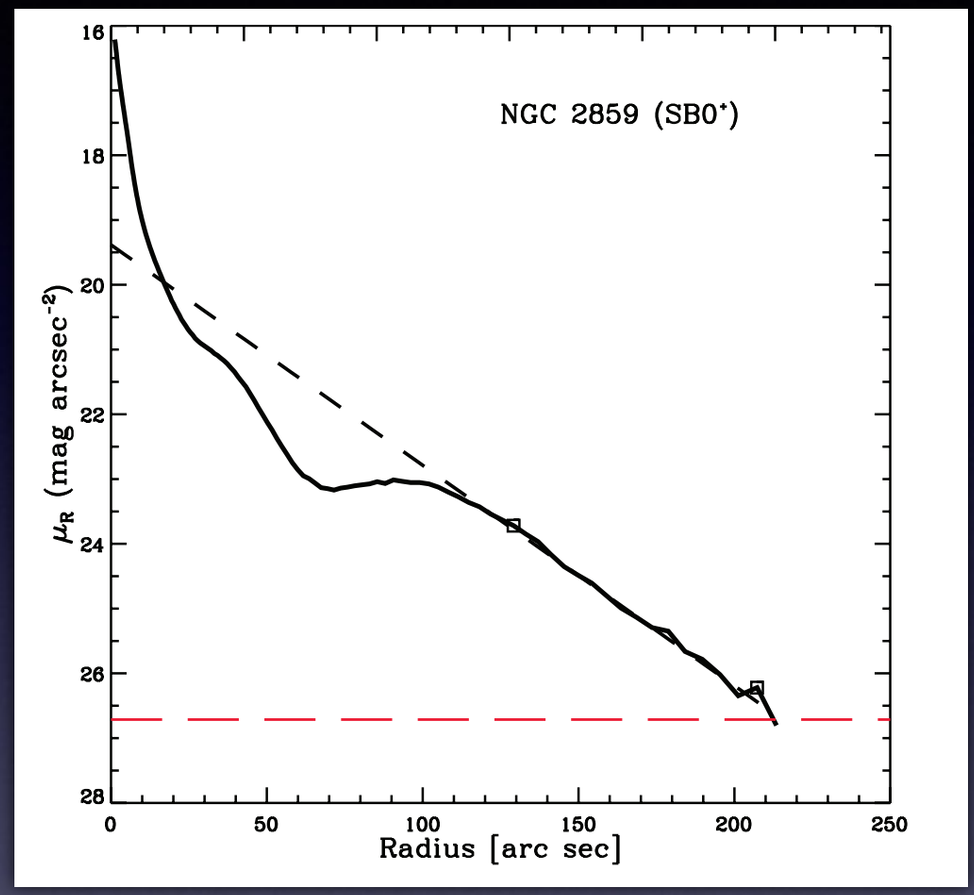
- How many different mechanisms produce Type II/ truncations?
  - Similar to "pseudobulges" — e.g., perhaps several different phenomena lumped together?
- Why is there a *diversity* of types?
  - e.g., SF threshold + radial migration models might explain truncations, but why does this only happen to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

Additional slides

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!)

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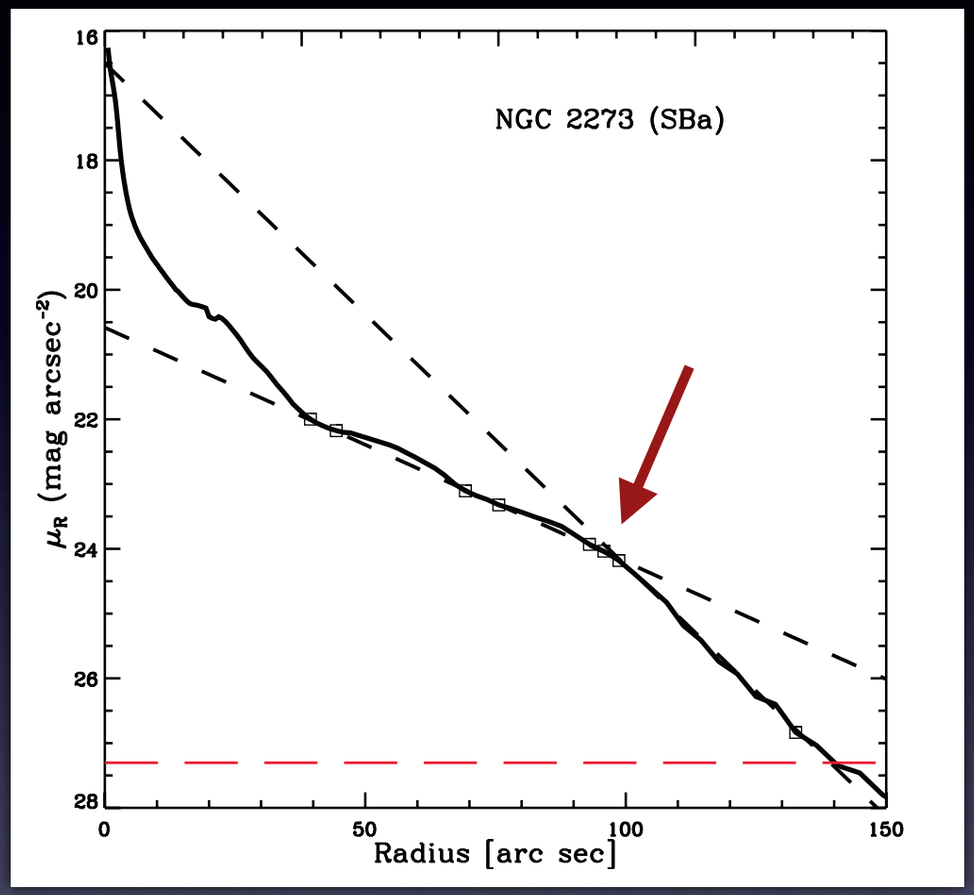

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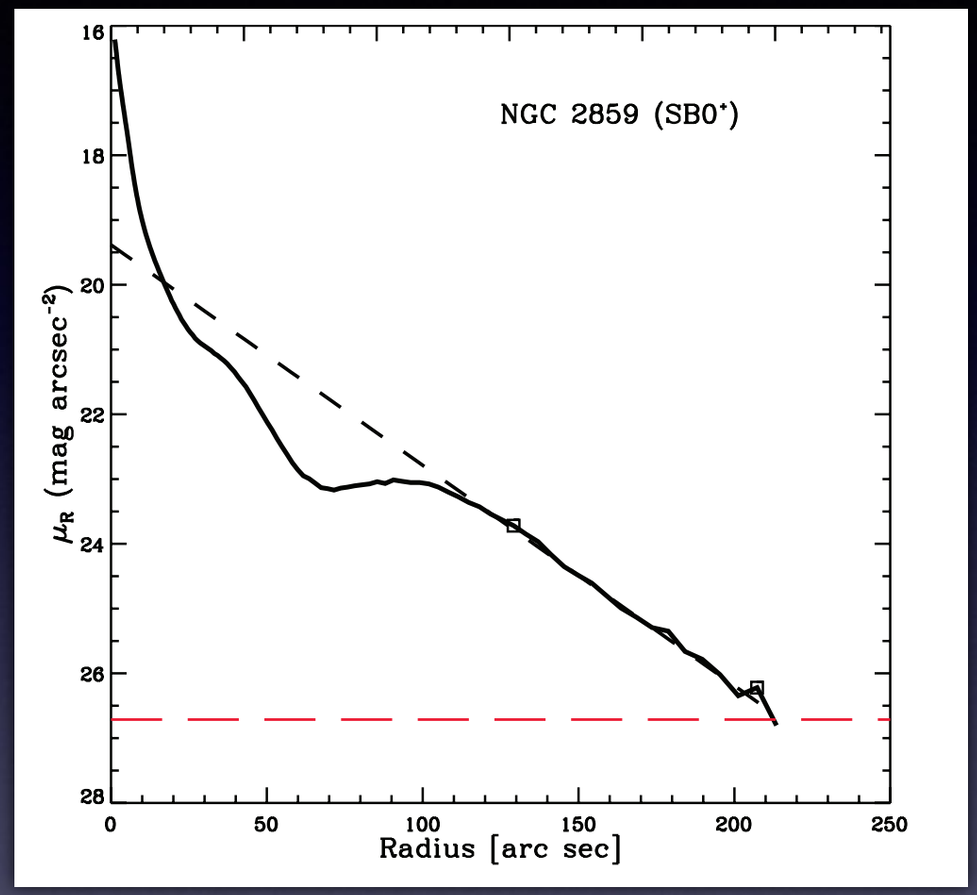

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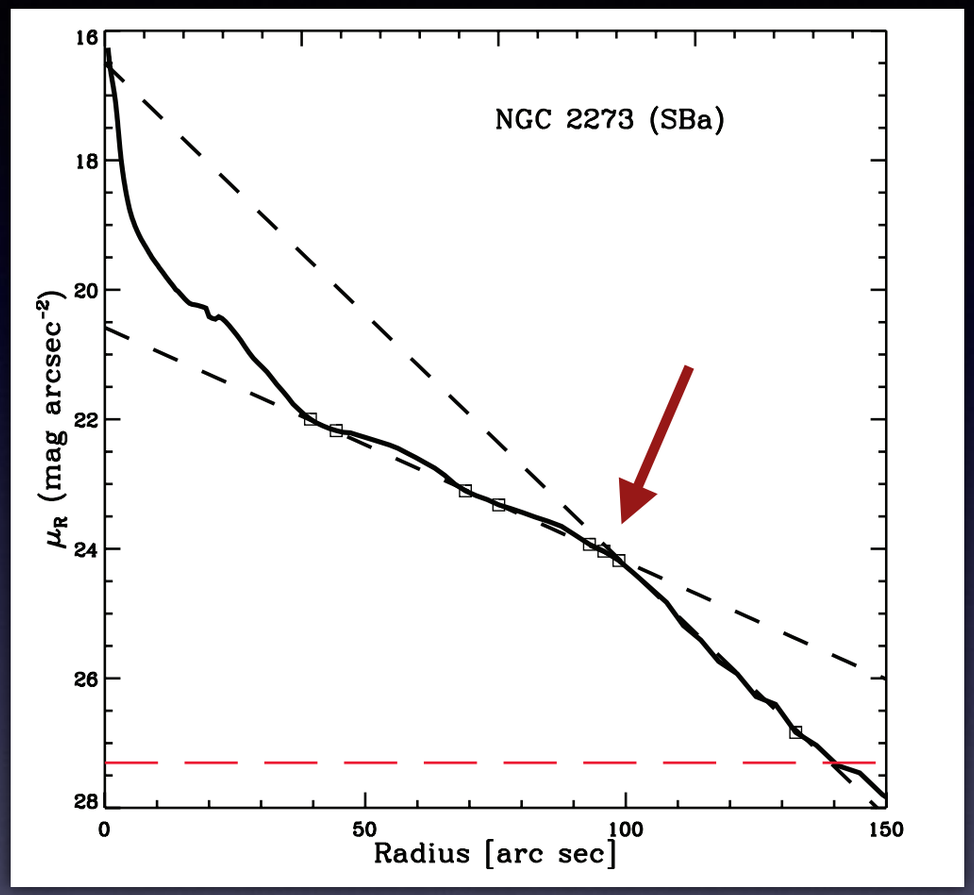

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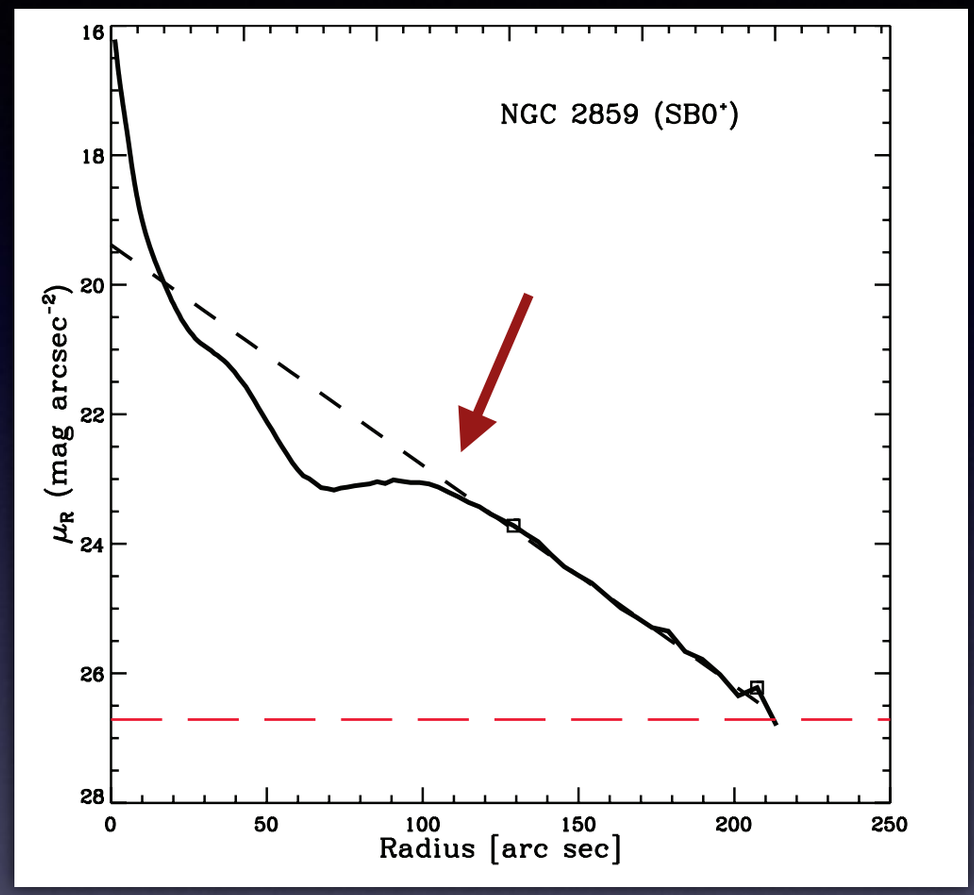

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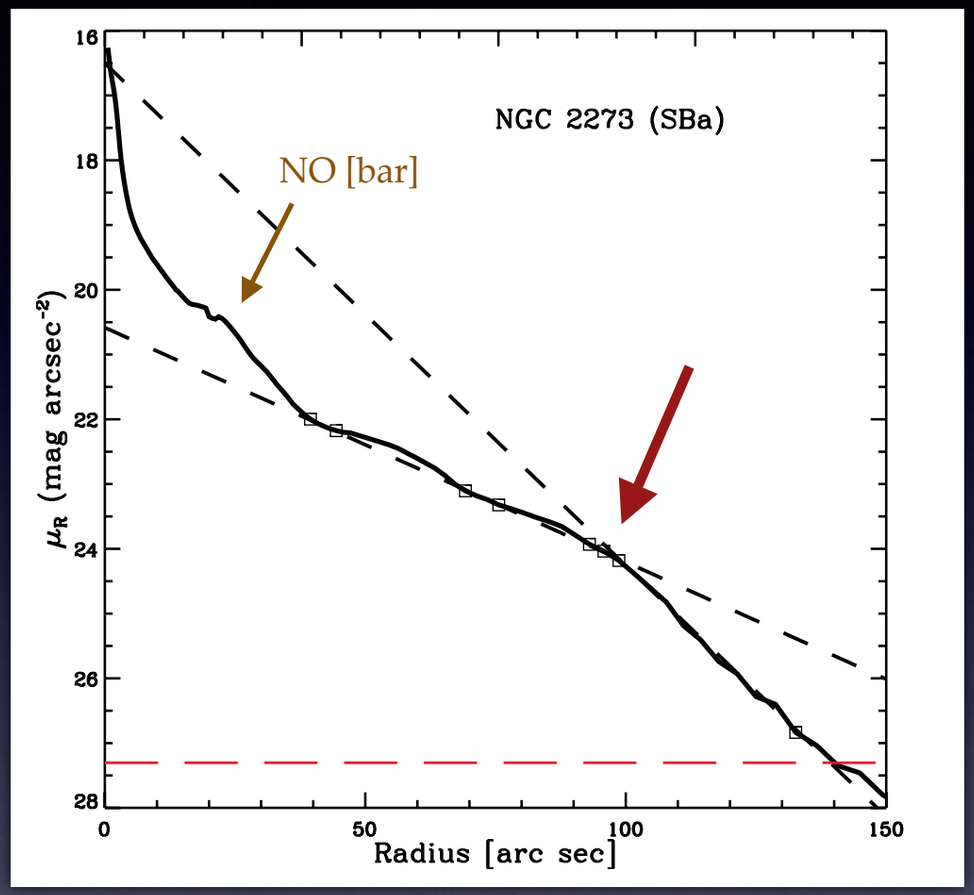

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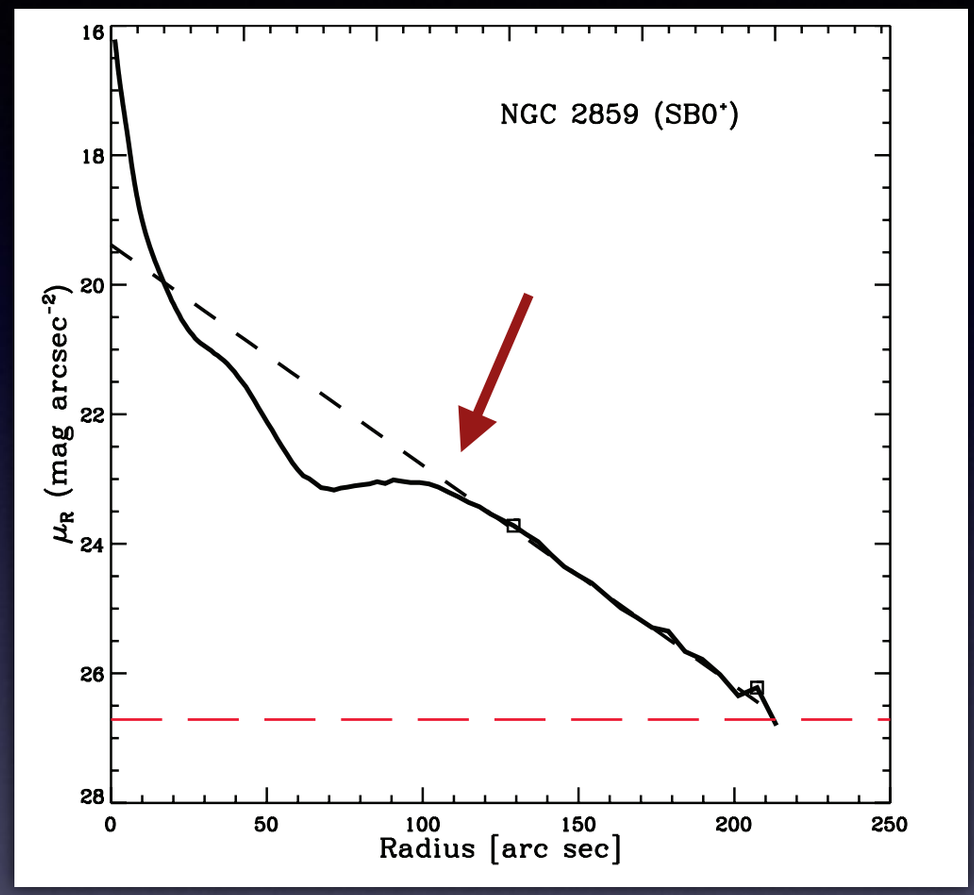

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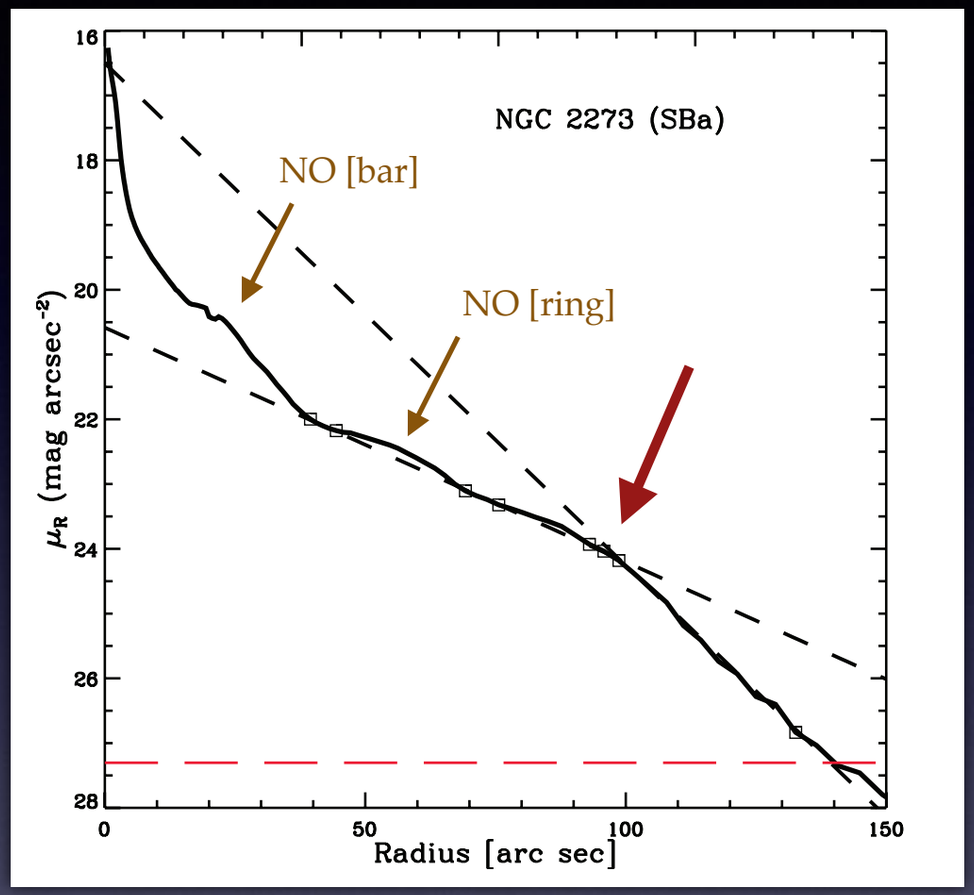

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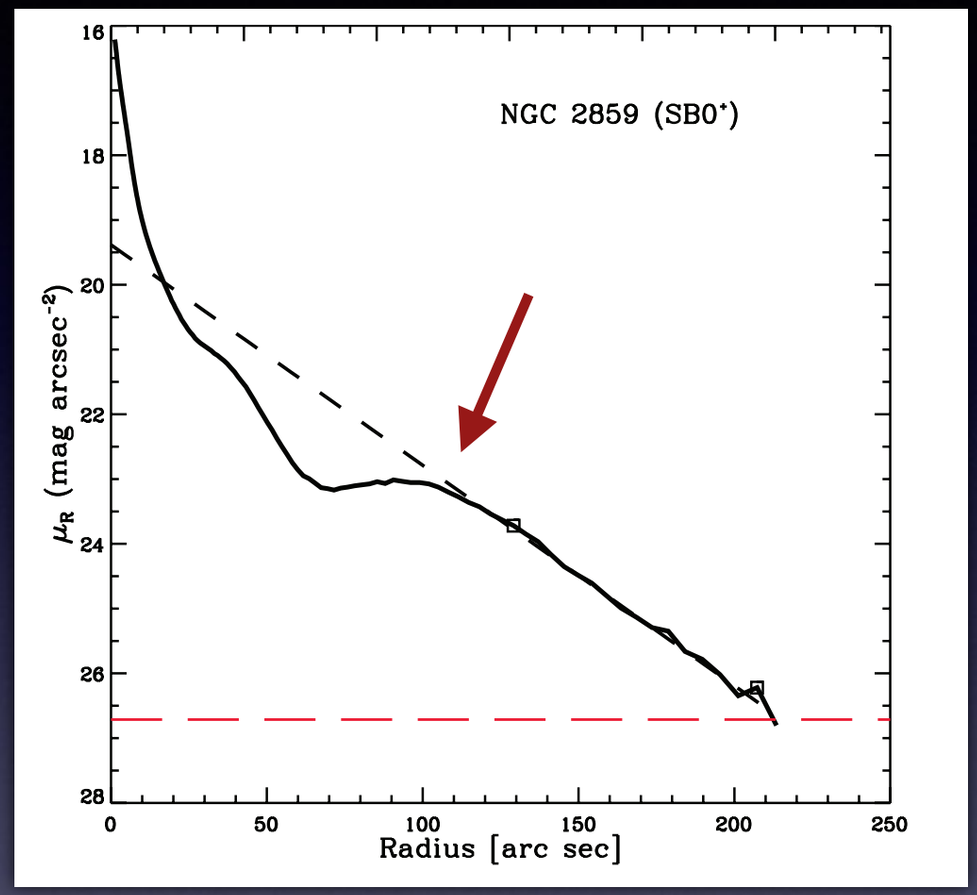

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Type III Formation: In-Situ Star Formation?

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

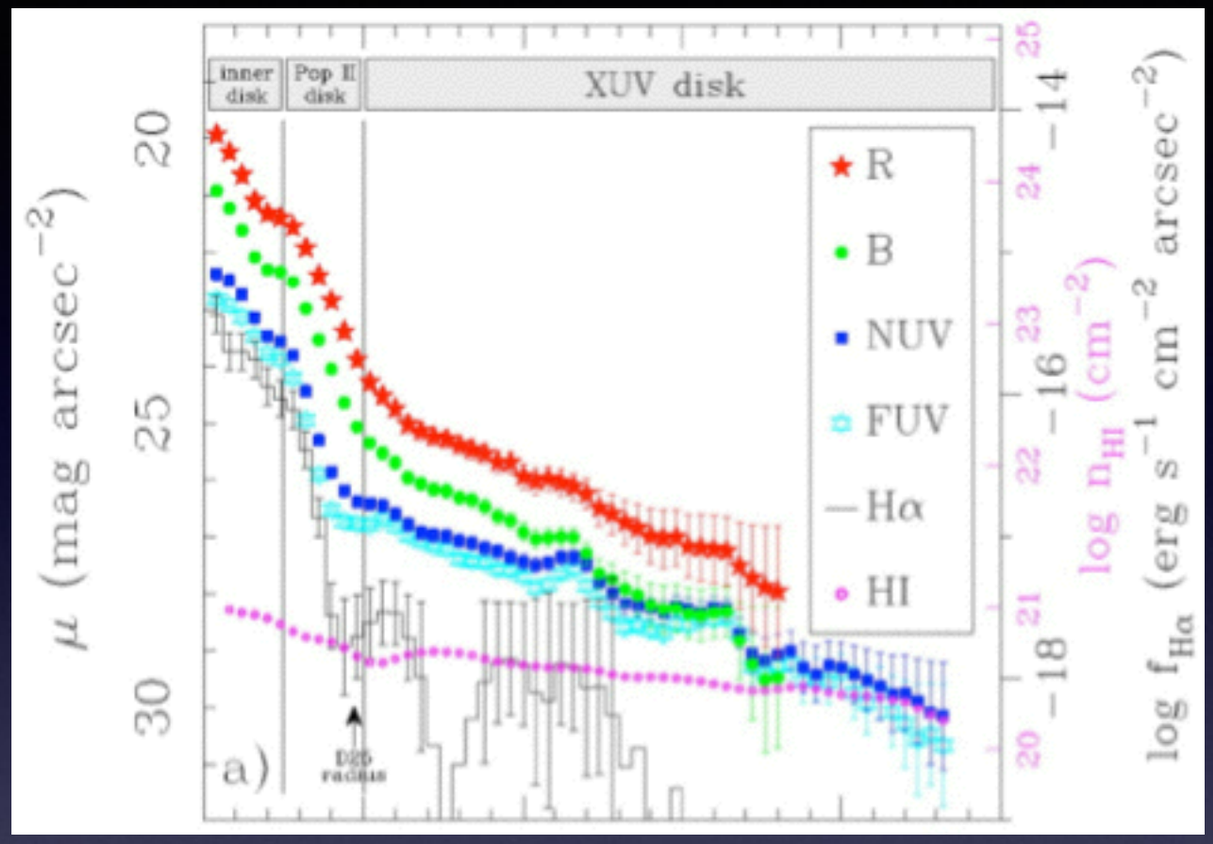
Type III profile in R (older stars, red) and in UV (young stars, blue)

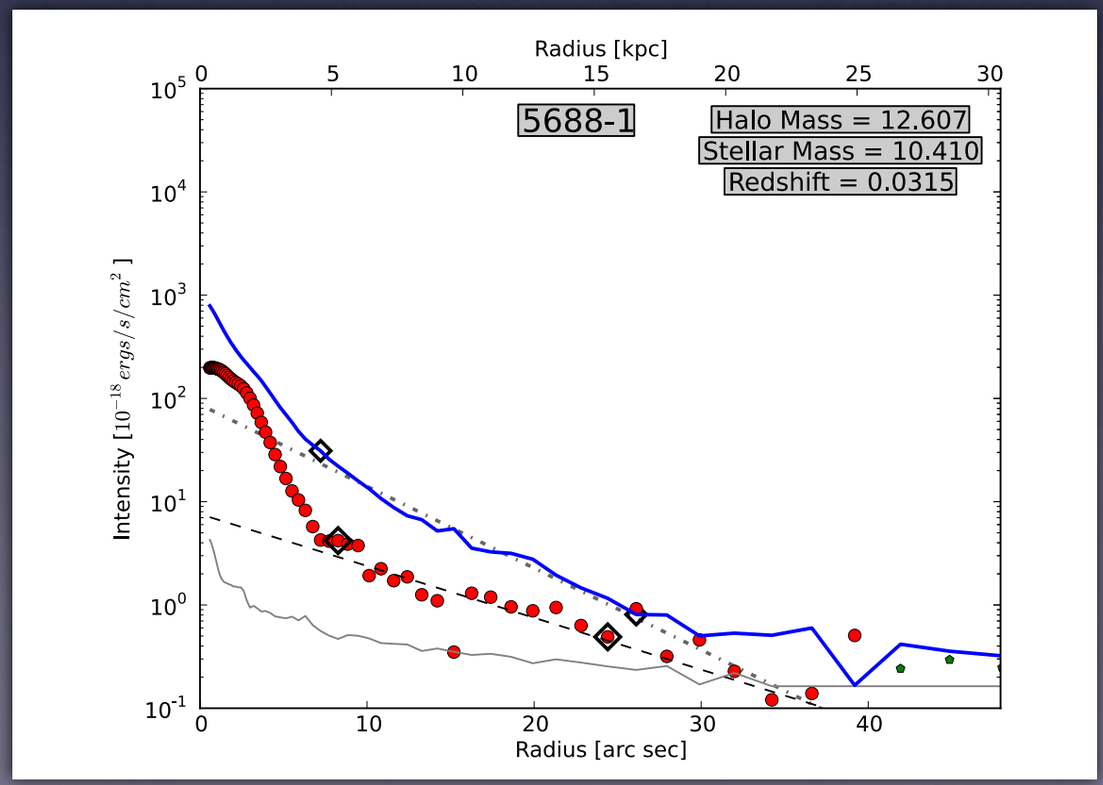
So Type III profile in both older stars and recent star formation!

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…)

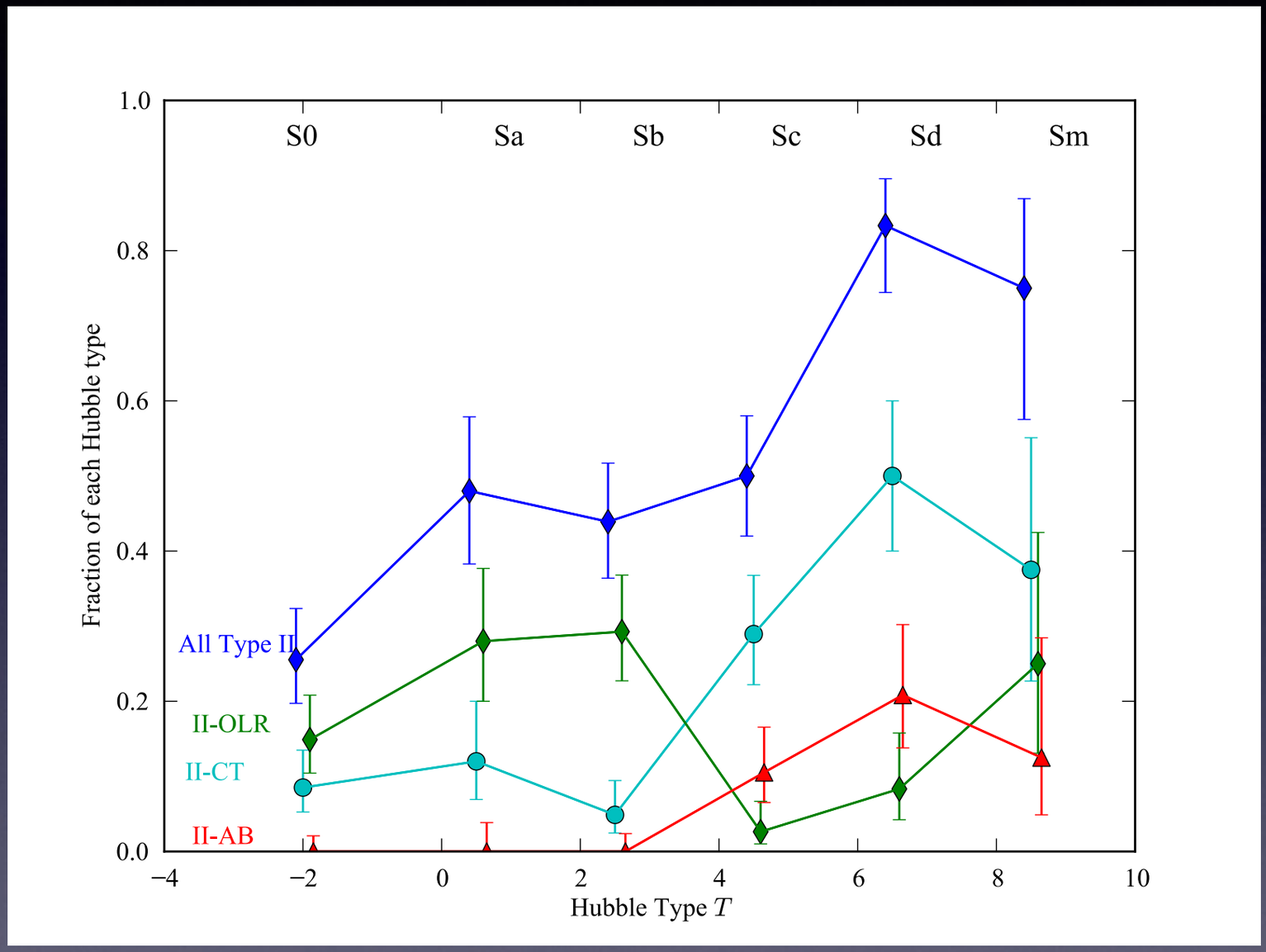




Type II Trends with Hubble Type

Type II-OLR is most common for early-type disks

Type II-CT ("classical truncation") is most common for late-type spirals



Data from Pohlen & Trujillo 2006, Erwin+2008, Gutiérrez+2011