The structure of barred galaxies:

Eija Laurikainen
Univ. of Oulu; FINCA, Univ. of Turku

Main collaborators:

Evangelie Athanassoula

Heikki Salo
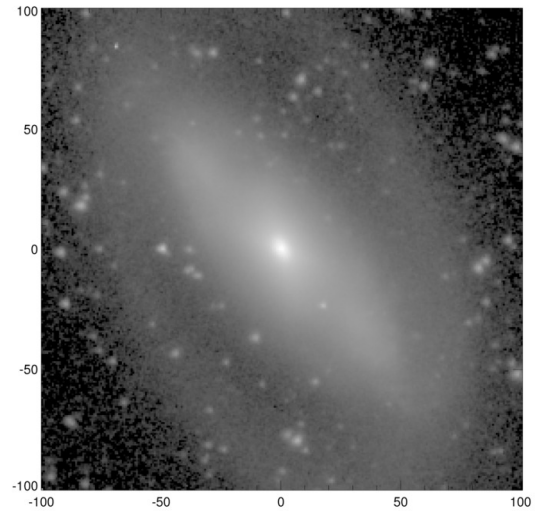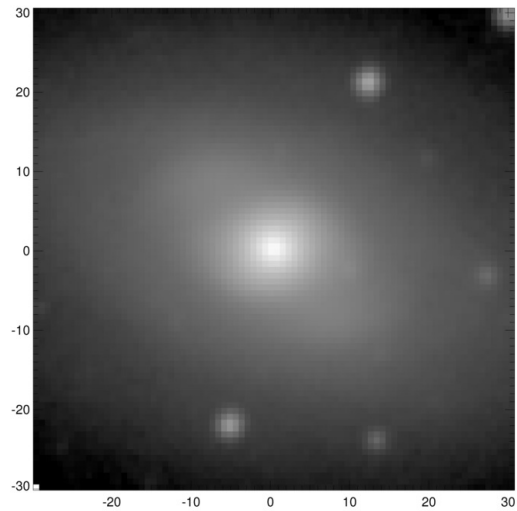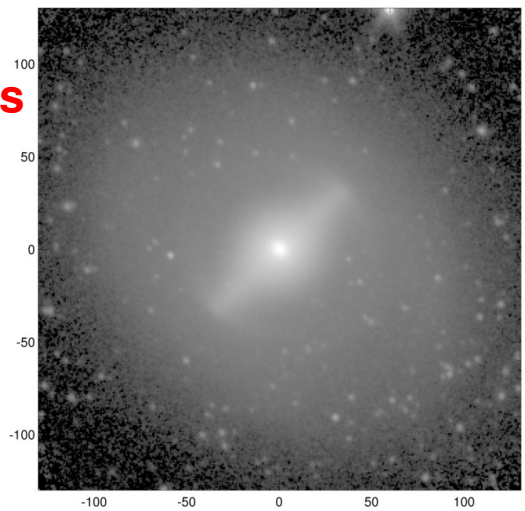
Ronald Buta

Samples:

Near InfraRed S0 galaxy Survey (NIRS0S):

- $B_T \leq 12.5$ mag
- $-3 \leq T \leq 1$, include 25 E^+
- INC $< 65^o$
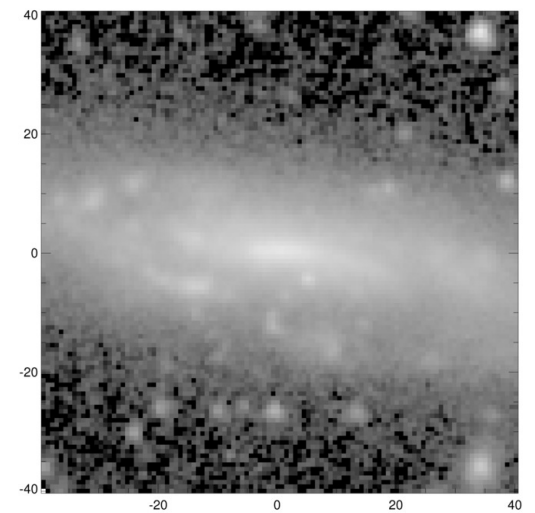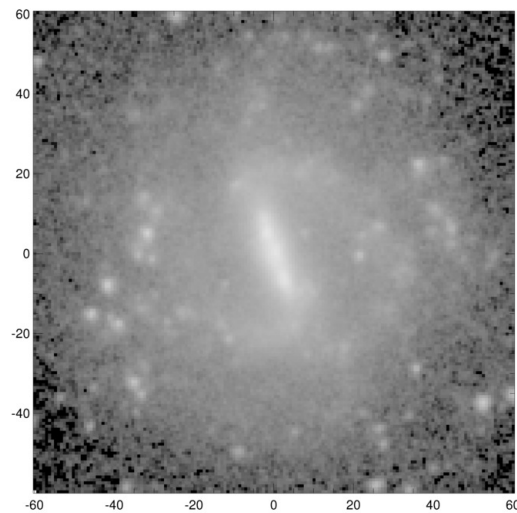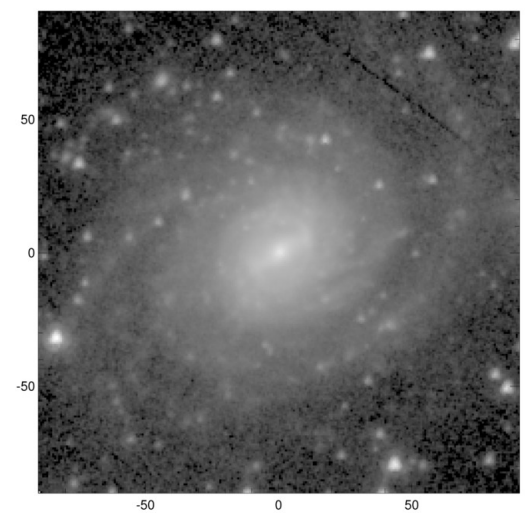   - $\Rightarrow$ 215 galaxies: N(E)=13, N(S0-S0/a)=169, N(Sa)=33

Spitzer Survey of Stellar Structure in Galaxies (S^{4}G):

- Radial velocity in radio $\nu < 3000$ km s^{-1} (equivalent to D=41 Mpc)
- Integrated blue magnitude $m_{Bcorr} < 15.5$ mag
- Angular diameter $D_{25} > 1'$
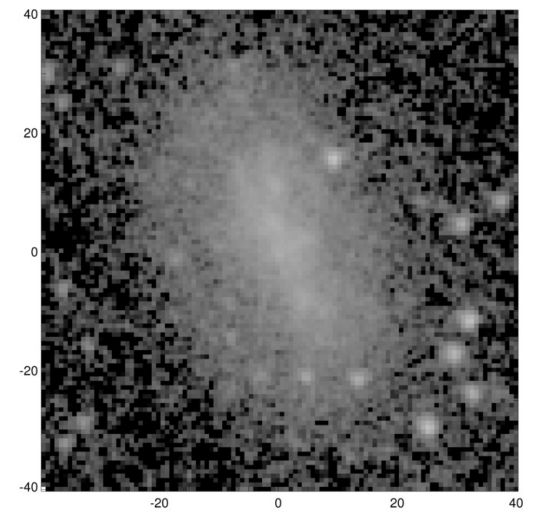- Galactic latitude $> 30^0$
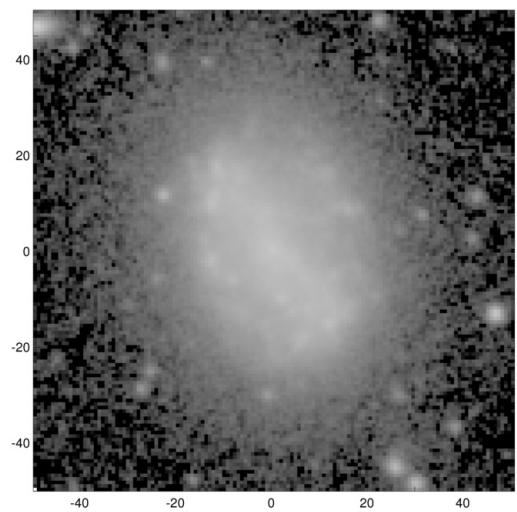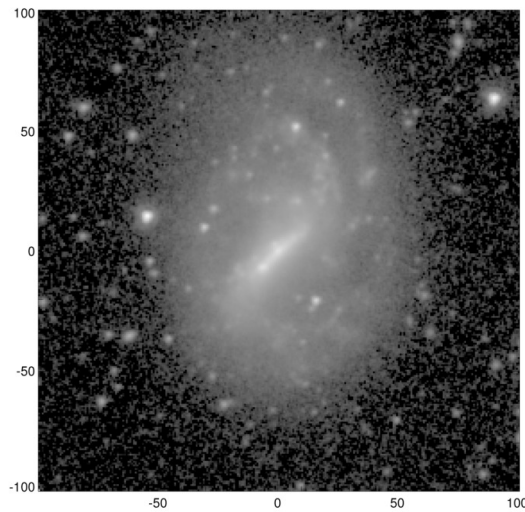
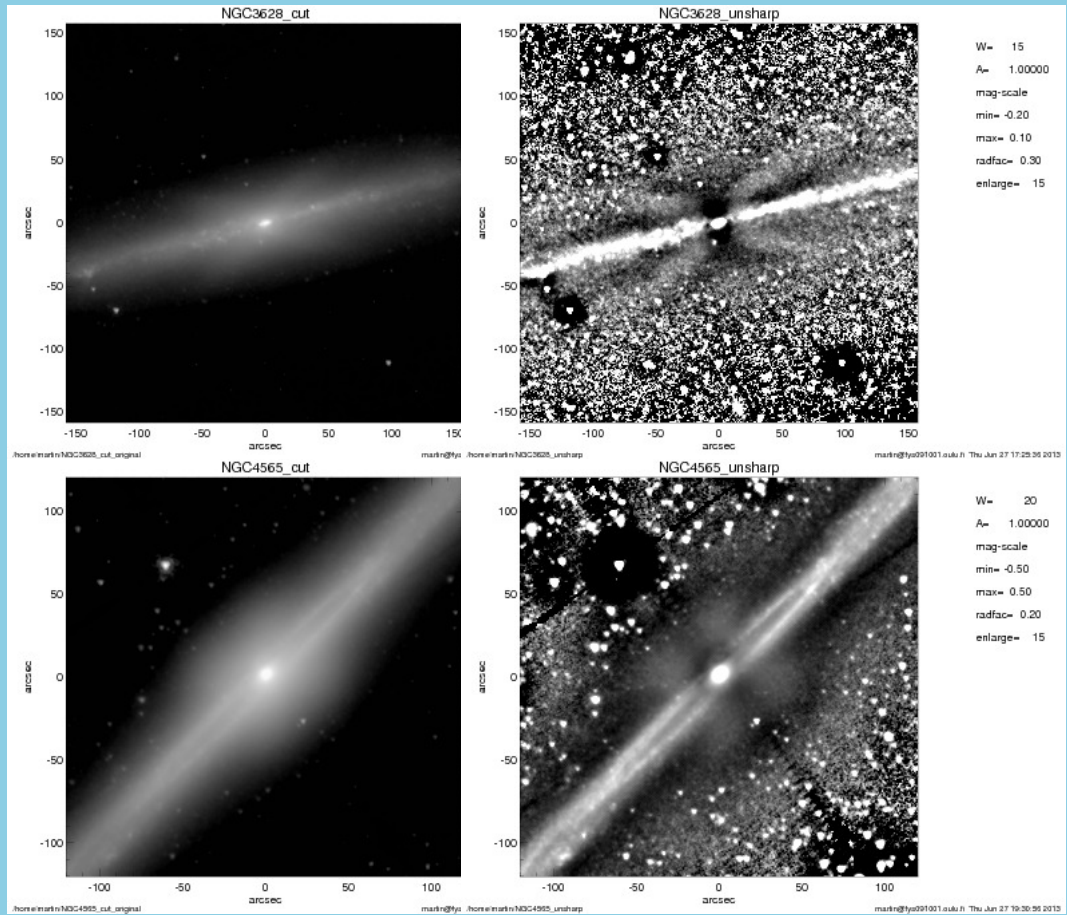   - $\Rightarrow$ N=2352 galaxies

Early-types

Sc-Sd

Sm

2

Bars in edge-on view:

- Lüttice et al. (2000): even 45% of S0-Sd galaxies have boxy bulges
  Compare: 56% of disk galaxies have strong bars (Eskridge et al. 2000)
- Shaw (1993), Bureau et al. (2006): b/p show x-shaped residuals
- Combes & Sanders (1981): b/p/x-str form part of the bar

3.6 μm images for:

NGC 3628

NGC 4565
(see also Kormendy & Barentine 2010)

3

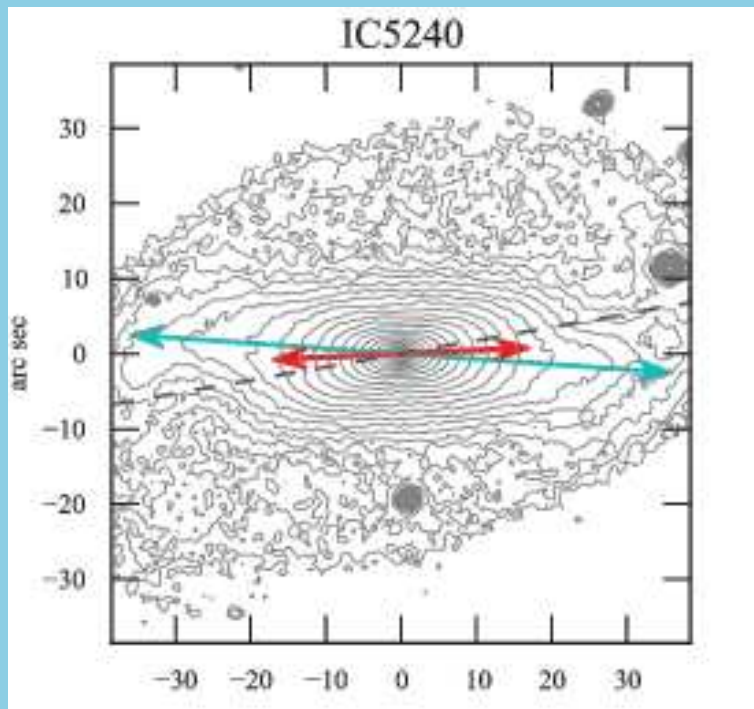# Where are b/p/x-structures in more face-on view?:

Attempts to find them:

(1) Cylindrical rotation: in NGC098 (Mendez-Abreu et al. 2008)
(Bertola & Capaccioli 1977; Kormendy & Illingworth 1982)

(2) Isophotal analysis (a4, b4, dPA):
Beaton & Athanassoula (2006); Athanassoula & Beaton (2006)
$\Rightarrow$ Distinguish boxy bulge in M31, i(disk)=77.5^o
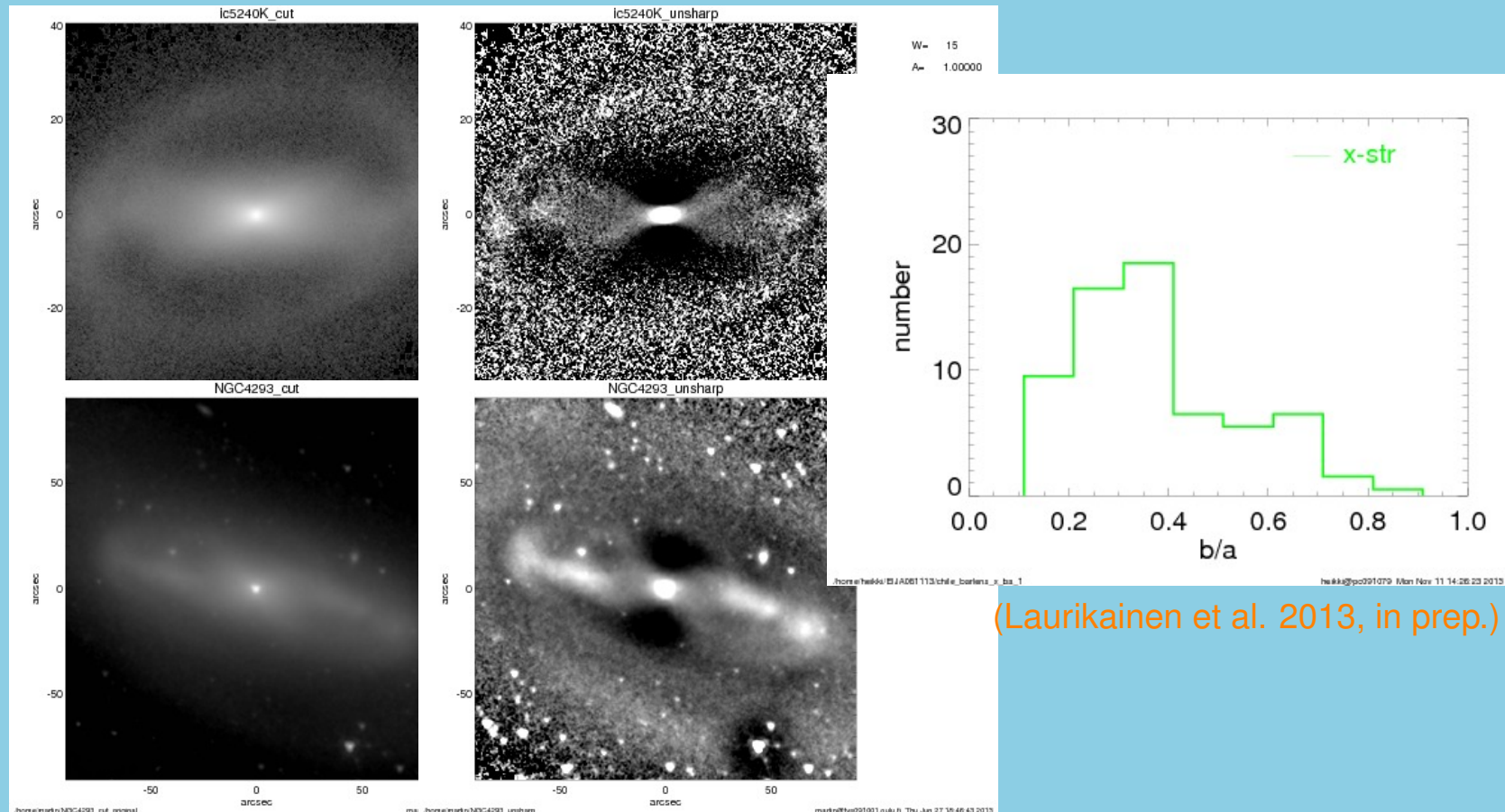

IC5240

Erwin & Debattista (2013):
Analysis for $\sim$ 80 S0-Sb galaxies:

$\Rightarrow$ boxy/spurs best visible when:

i_{disk}=45-75°, dPA<45° (bar, line of node)

$\Rightarrow$ 2/3 are boxy

4

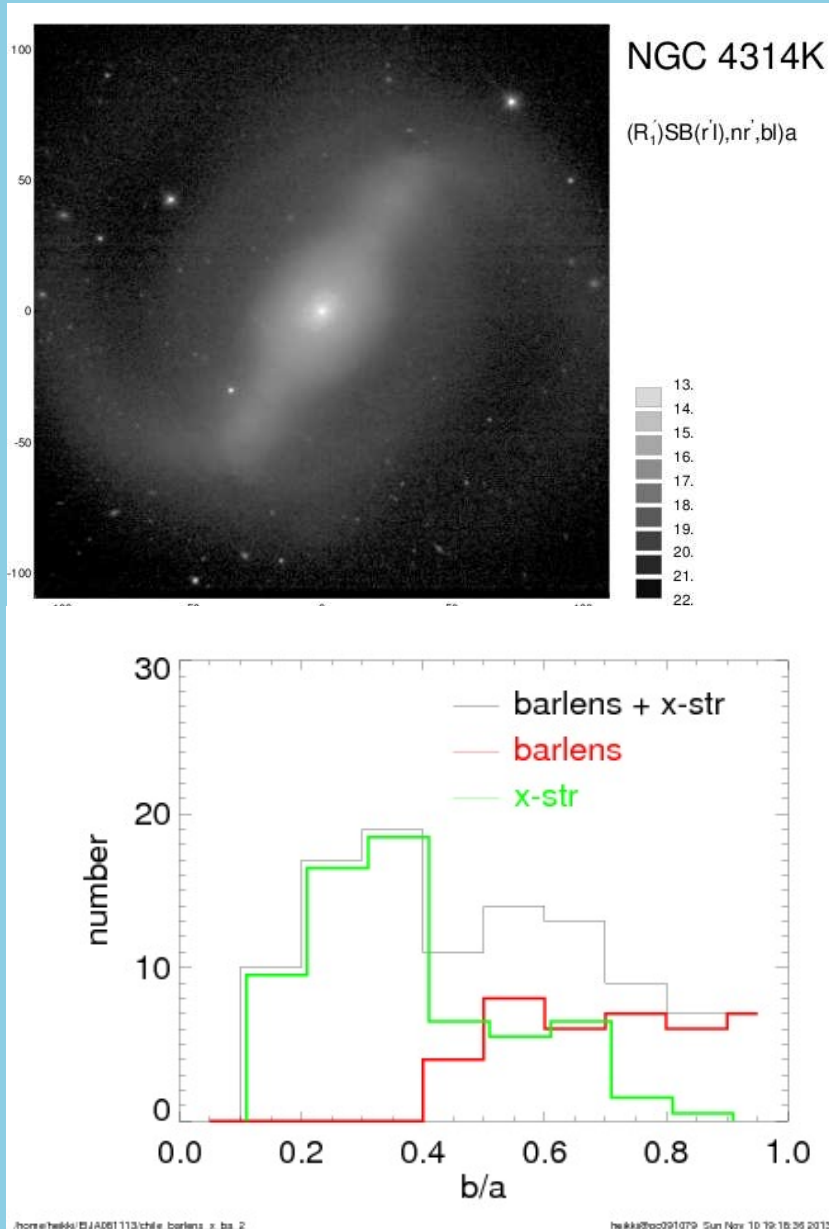**(3) Direct evidence of x-shapes at different viewing angles:**

(Laurikainen et al. 2013, in prep.)

x-shapes in visual classifications (non-edge-on galaxies):

Buta et al. (2010), Laurikainen et al. (2011) $\Rightarrow$ a few cases detected

Buta et al. (2013) $\Rightarrow$ classification in S^4G

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(4) Barlenses (bl) - a manifestation of the same phenomenon?


- Classical bulges (Peletier)

- Inner disks (NGC 2787, NGC 3945; Erwin et al. 2003)

- Barlenses (Laurikainen et al. 2011):
  lens-like structures embedded in bars,
  form part of the bar

  ⇒ systematic classification for S0-Sa galaxies
  ⇒ Laurikainen et al. (2007): some of those
     suggested to be vertically thick

  ⇒ galaxies with bl+x-strs cover
     the full range of disk inclinations

6

Observational properties of barlenses

(Laurikainen et al. 2013, in prep.)

1. Detectable in isophotal analysis?

IC5240

- Carried out to all barlens galaxies in NIRS0S (=36/215):
  Use ellipse fitting from Laurikainen et al. (2011;
  ell, PA, b4-profiles, dPA)

  $\Rightarrow$ only 25% are boxy (34% if marginal cases included)

- Comparison with ED(2013): 38/78 galaxies common with NIRS0S

  $\Rightarrow$ only in 21% (8/38) boxy/spurs detected by ED2013
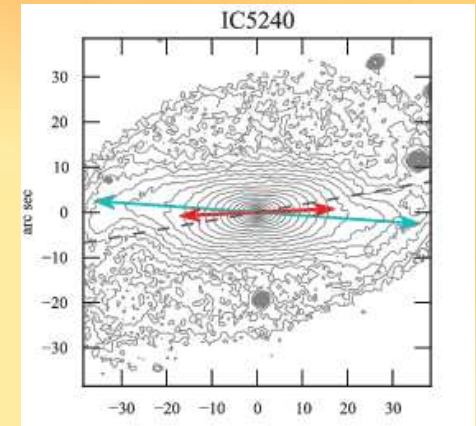
Isophotal analysis does not find a large majority of barlenses.
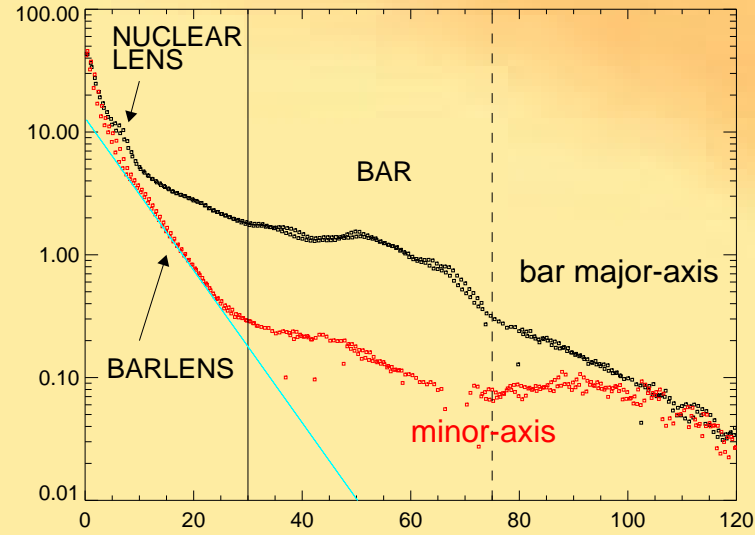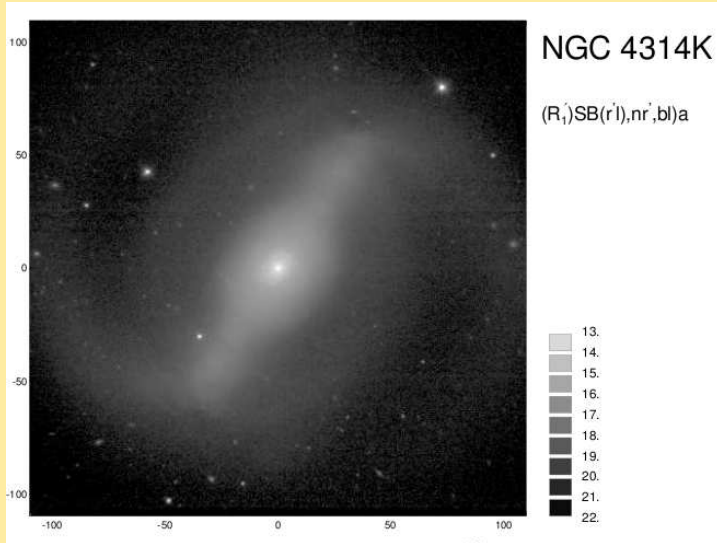
2. Fourier analysis (Laurikainen et al. 2007)
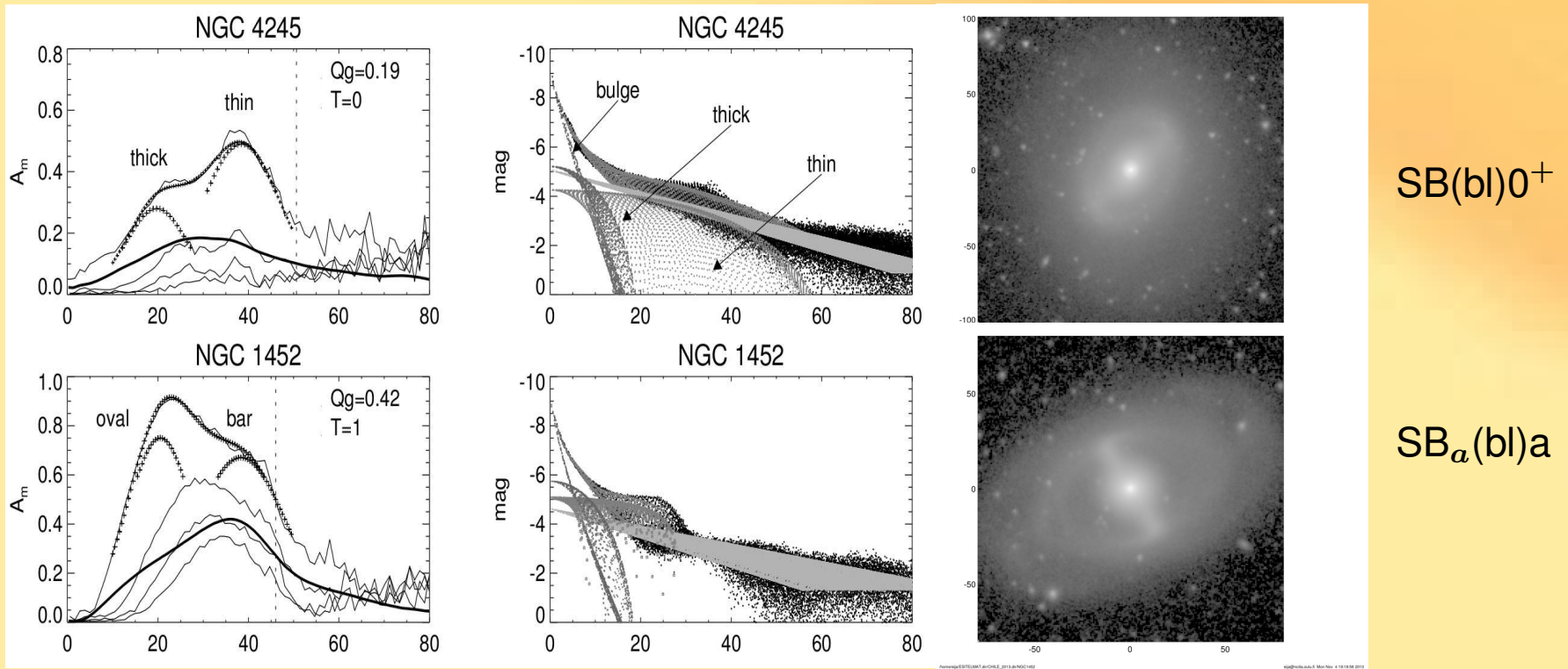
Left: Fourier amplitudes of density (m=2, 4, 6, 8) and Q=($F_{tangential}/F_{radial}$)

Middle: bulge/disk/bar/barlens decompositions

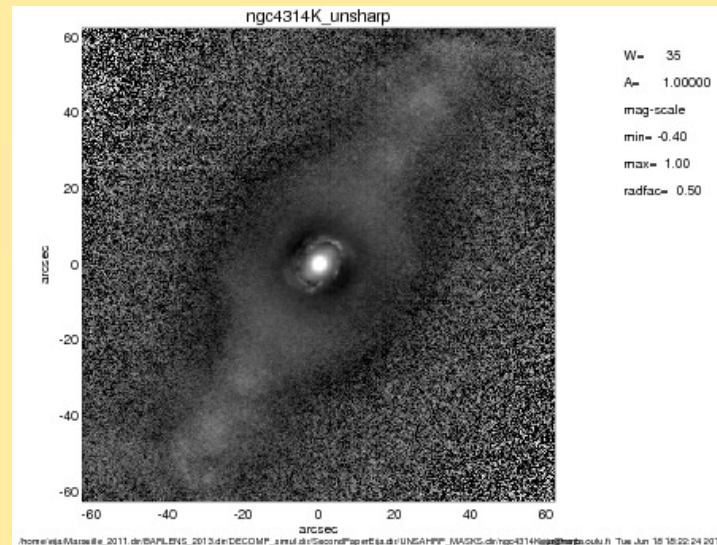$\Rightarrow$ barlenses appear in Fourier analysis (even if not visible in isop. anal.)

3. Surface brightness profiles

NGC 4314K

$(R'_1)SB(r'l),nr',bl)a$

⇒ exponential surface brightness profile, cannot be a classical bulge

4. Unsharp masks

⇒ barlens form part of the bar,
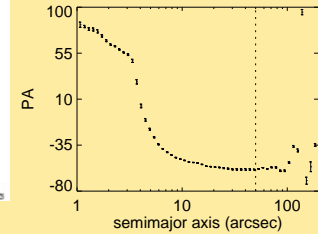   not boxy, no spurs, i(disk)=20.4^o
   (ED2013, NIRS0S)

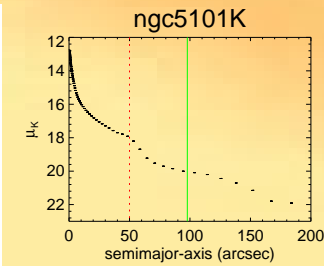# Barlenses form part of the bar...

NGC 5101: i(disk)=22°, dPA=26°, not boxy
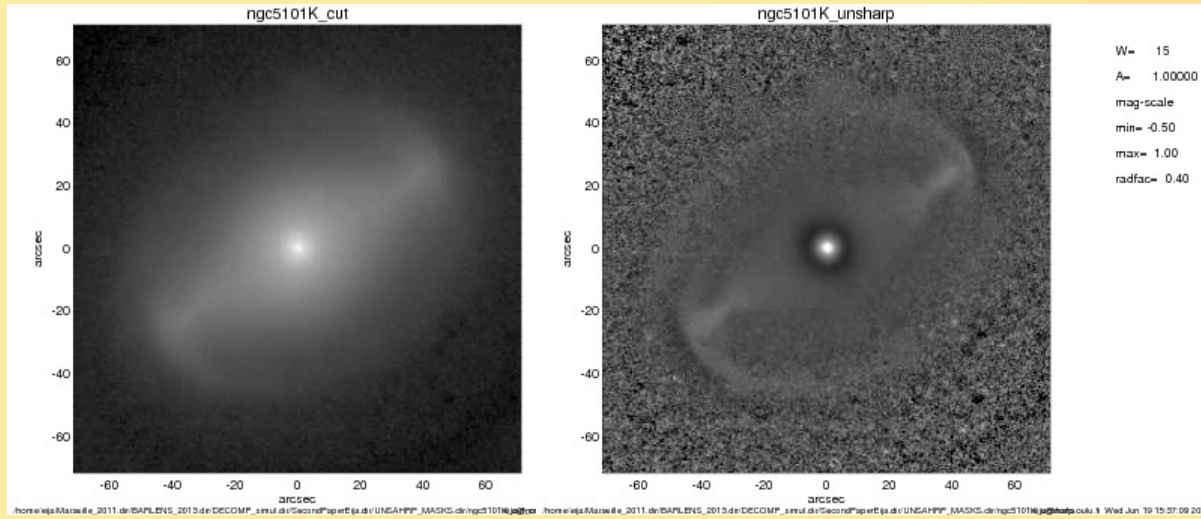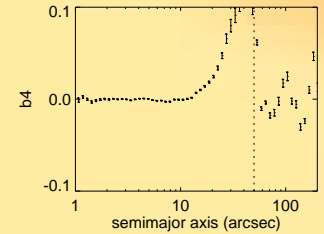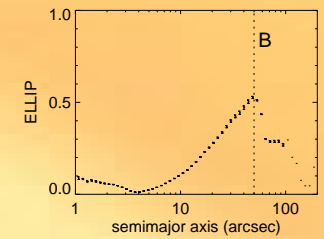
NGC 1512: i(disk)=42°, dPA=22°, not boxy
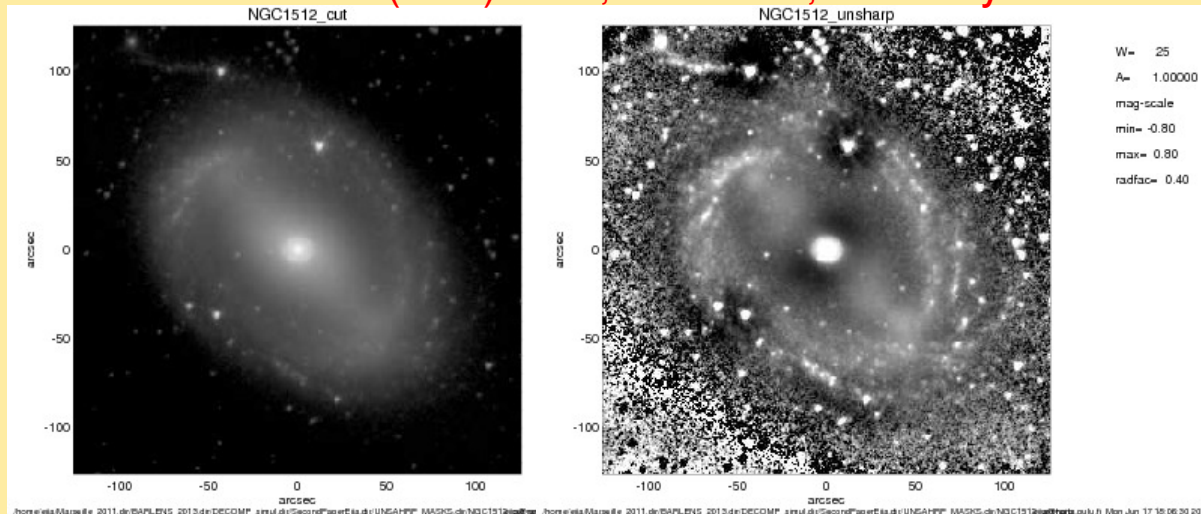
10
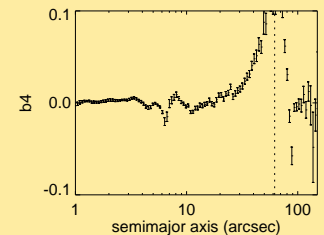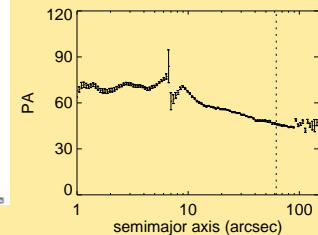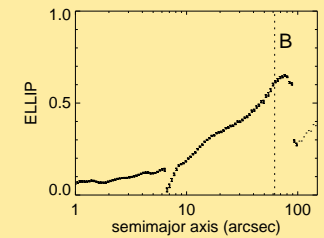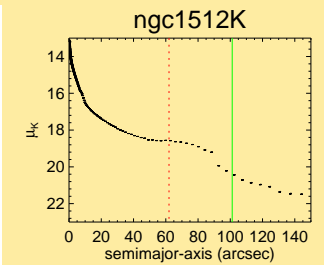
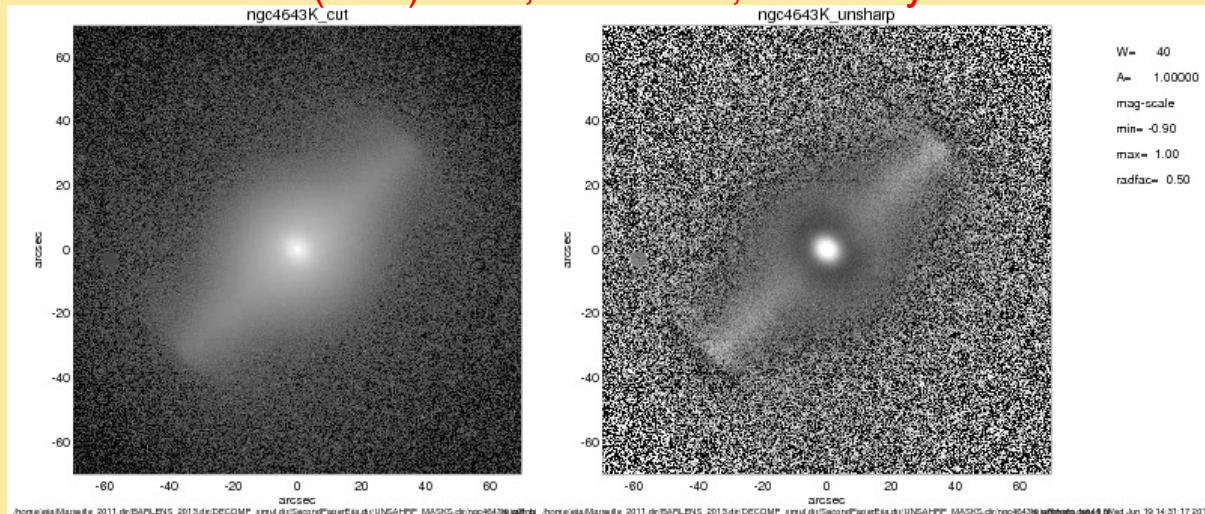# Barlens form part of the bar: not elongated along the disk plane, μ -profiles

NGC 1452: i(disk)=53°, dPA=10°, not boxy
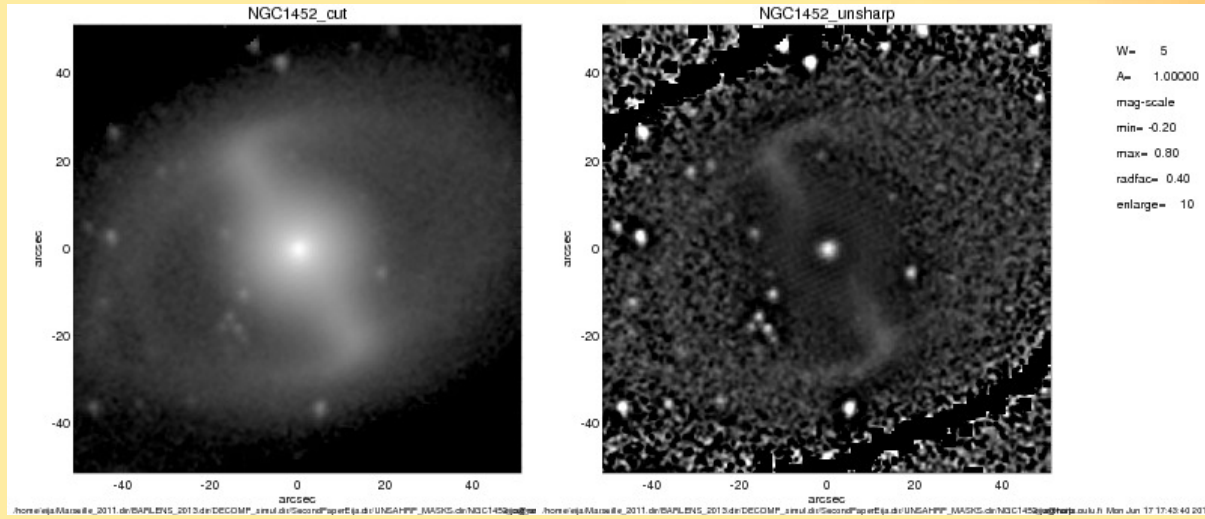
NGC 4643: i(disk)=37°, dPA=18°, not boxy

6. Structural decompositions
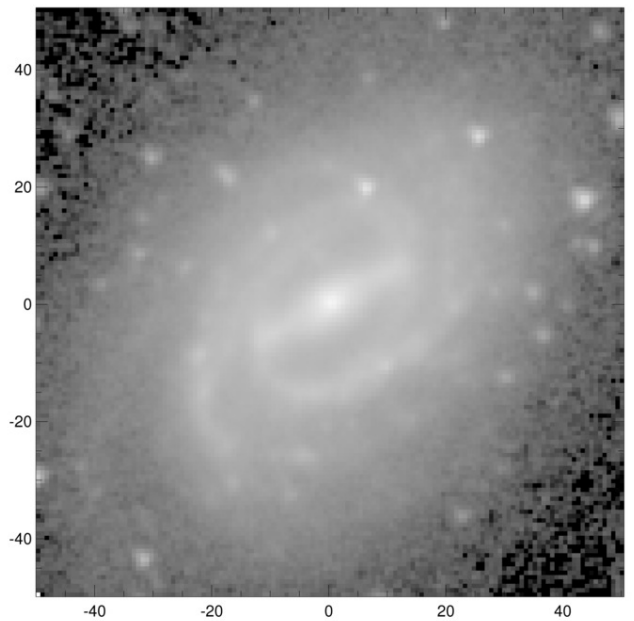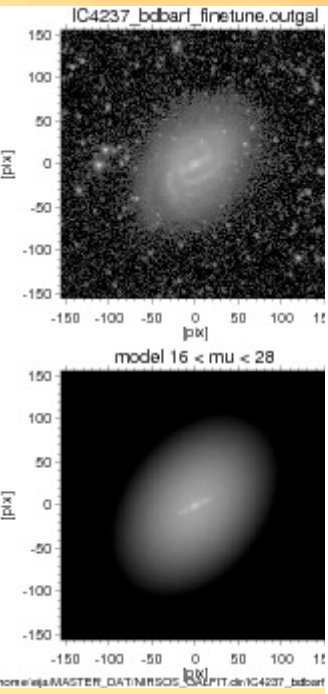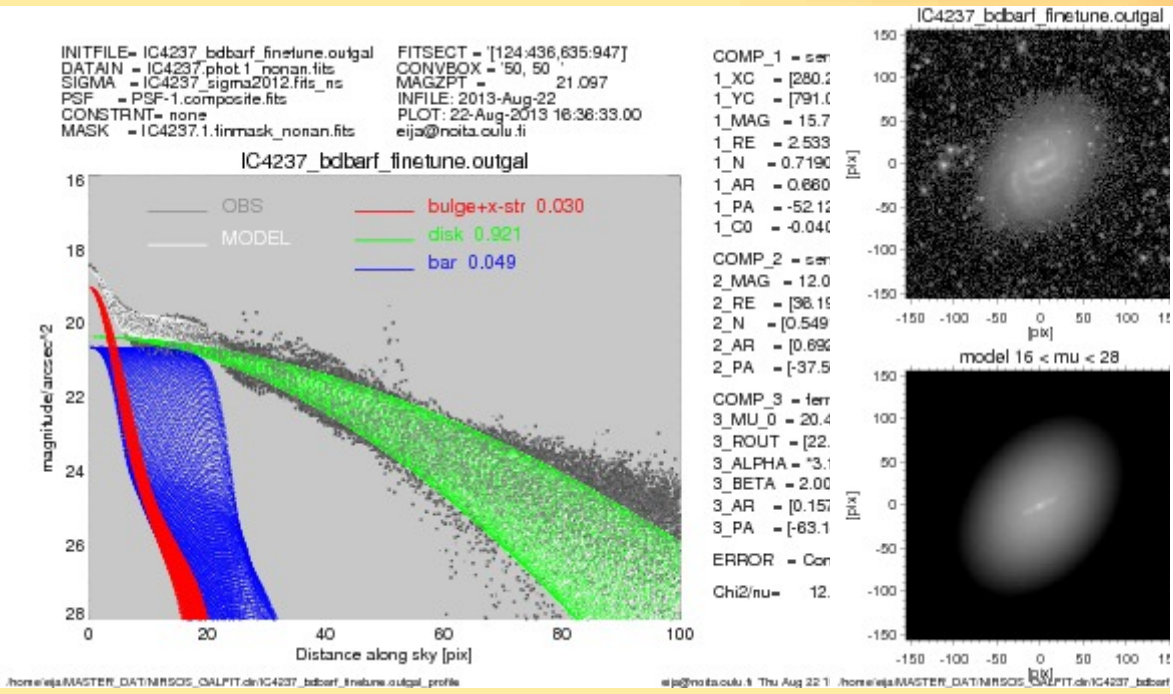
IC 4237: SB$_x$(r)b

$\Rightarrow$ x-shaped 'thick bar', but no bulge?
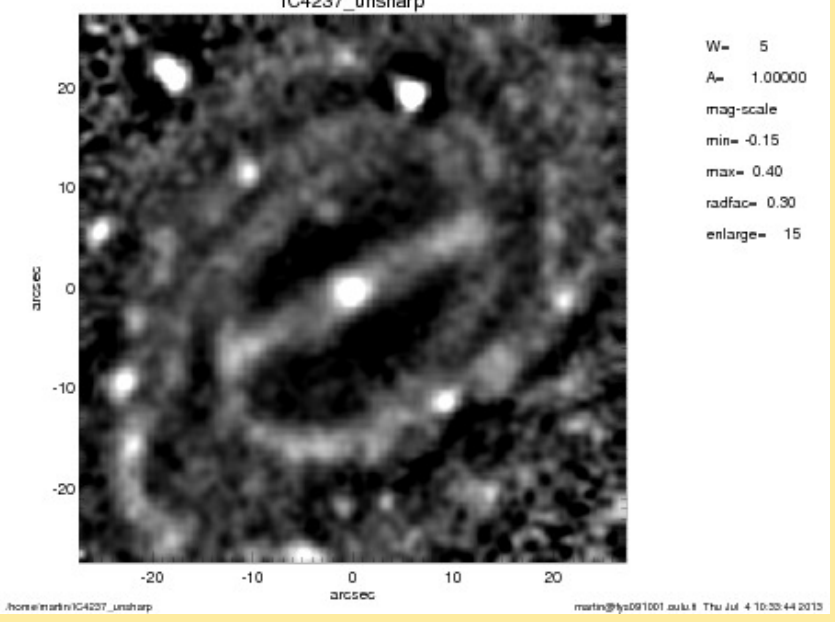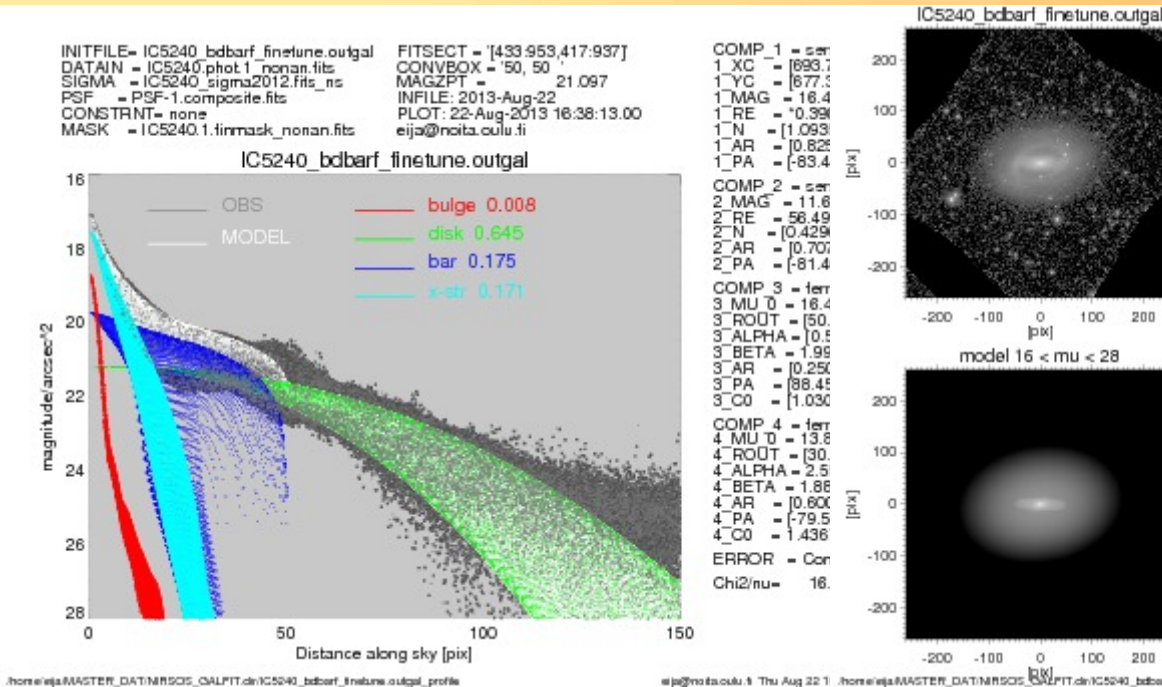
IC 5240: SB$_x$(r)0/a

$\Rightarrow$ x-shaped 'thick bar'

$\Rightarrow$ a small pseudobulge or no bulge at all
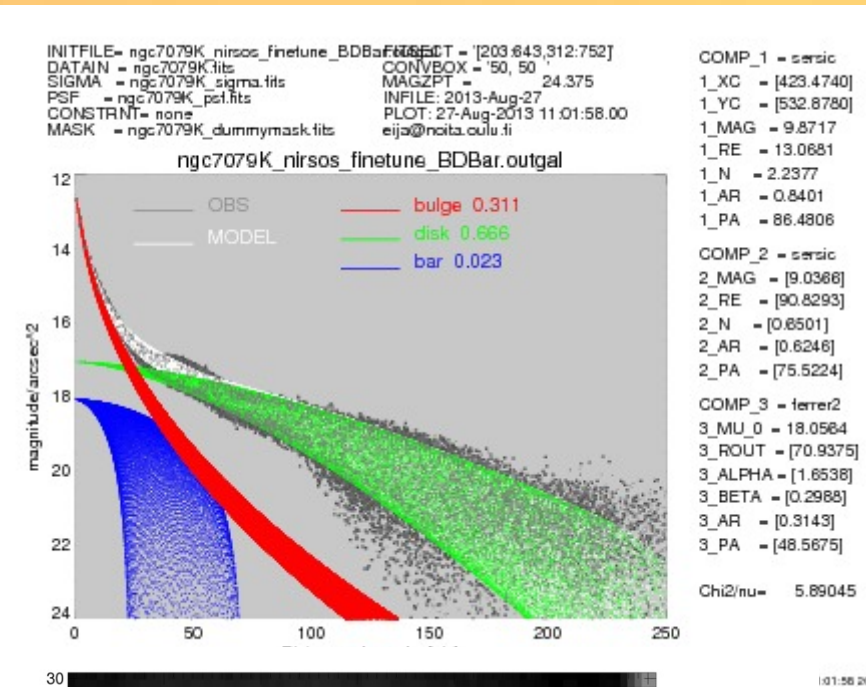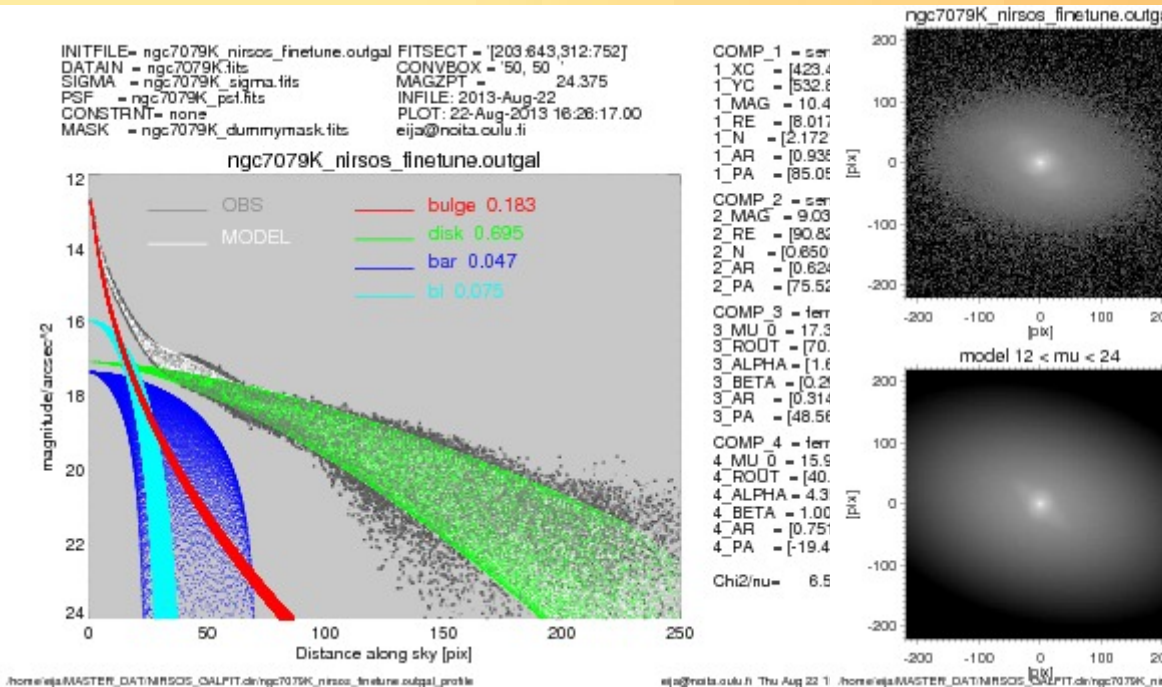
NGC 7079: (L)SB$_a$(s:,bl)0°

Fitting also barlens:

$\Rightarrow$ reduces the B/T flux-ratio (0.31 $\Rightarrow$ 0.18)

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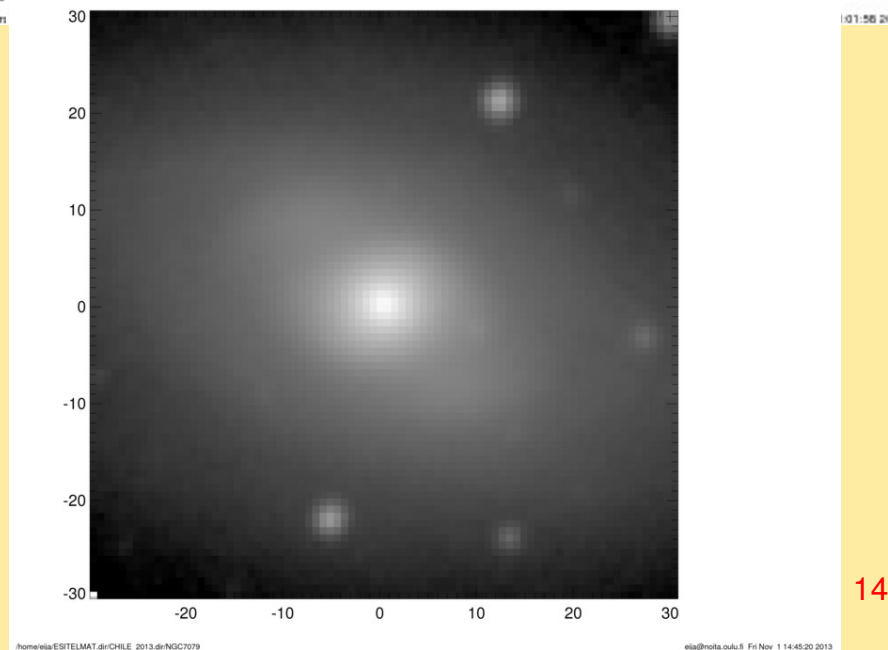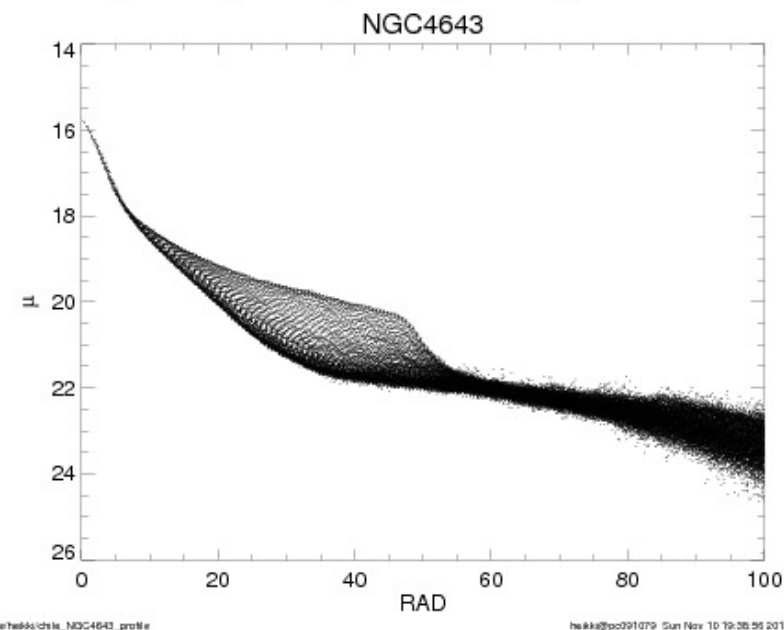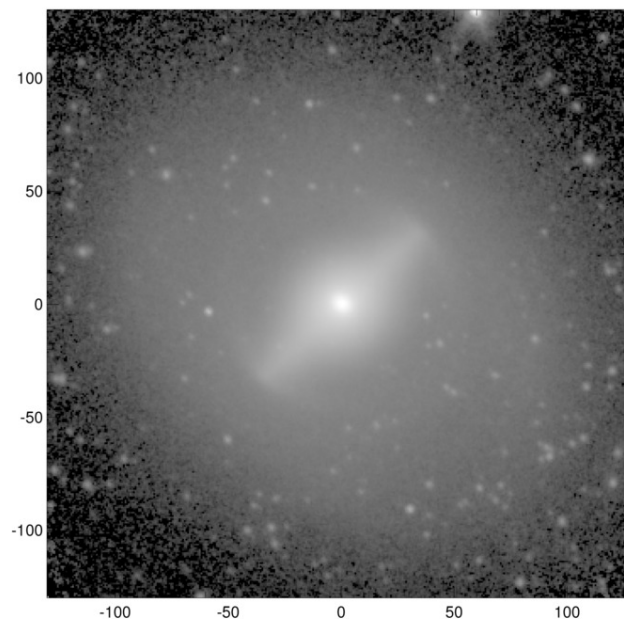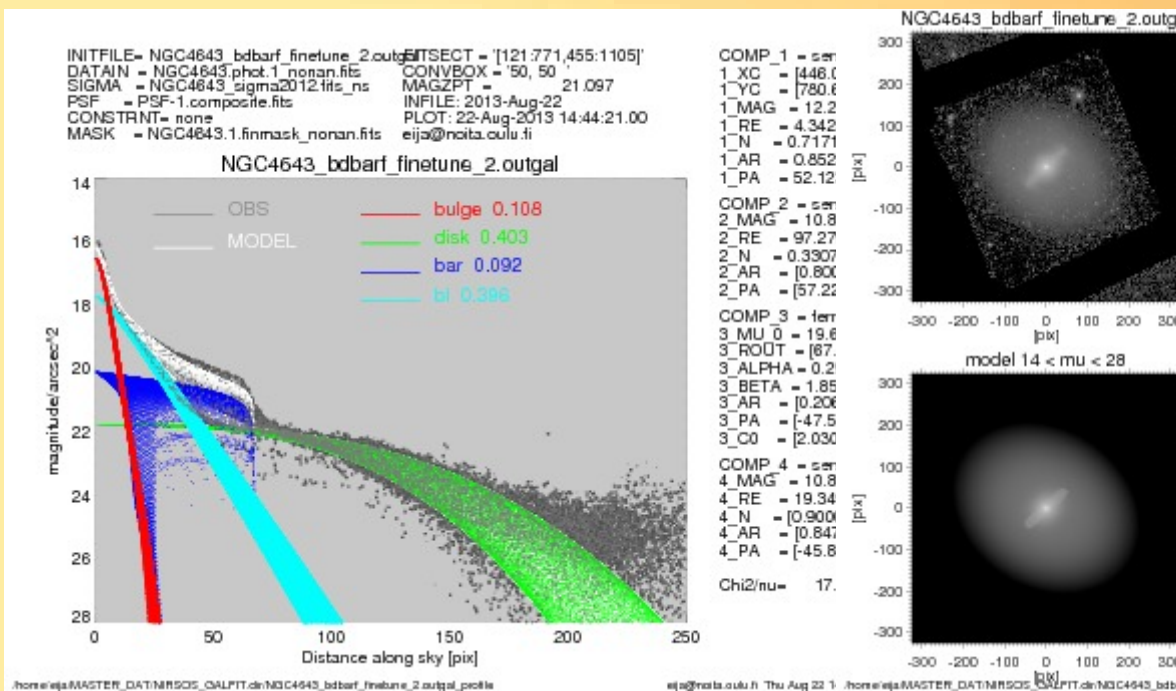
NGC 4643: (L)SB(r,nl,bl)0°

Central component different from a barlens:

⇒ smooth continuation from barlens to thin-bar
⇒ barlens profile is exponential (Ferrers, Sérsic)
     (as in NGC 4314 before)

Barlenses (bl) vs. x-shaped structures (x-str):

	bl (Sérsic) N=14	x-str (Sérsic) N=14
F(bl)/F(tot)	0.18±0.11	0.08±0.02
F(bl)/F(thin-bar)	2.35±0.32	0.76±0.15
F(bulge)/F(tot)	0.12±0.02	0.08±0.01
Sérsic n (bulge)	1.5±0.1	1.4±0.2

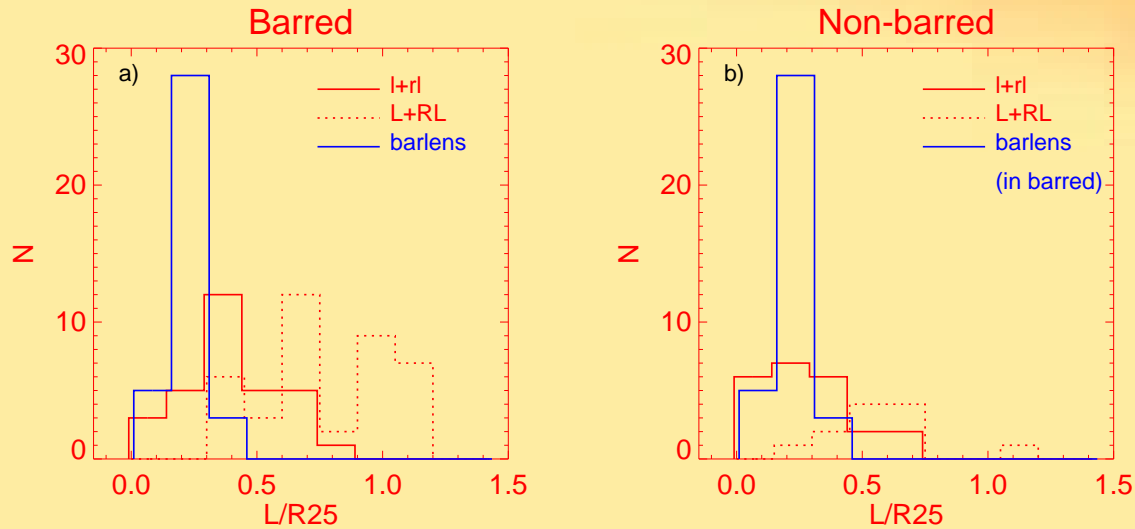$\Rightarrow$ Barlenses brighter than x-shaped structures:
absolutely (0.18 vs. 0.08), and in respect of the bar flux (2.35 vs. 0.76)

$\Rightarrow$ In both structures similar central peaks ($\sim$0.1)

Barlens gal.	bulge/disk/bar N=14	bulge/disk/thin-bar/barlens N=14
Sérsic n (bulge)	2.6	1.5
F(bulge)/F(tot)	0.35	0.12

$\Rightarrow$ Barlenses affect the estimated F(bulge)/F(tot)

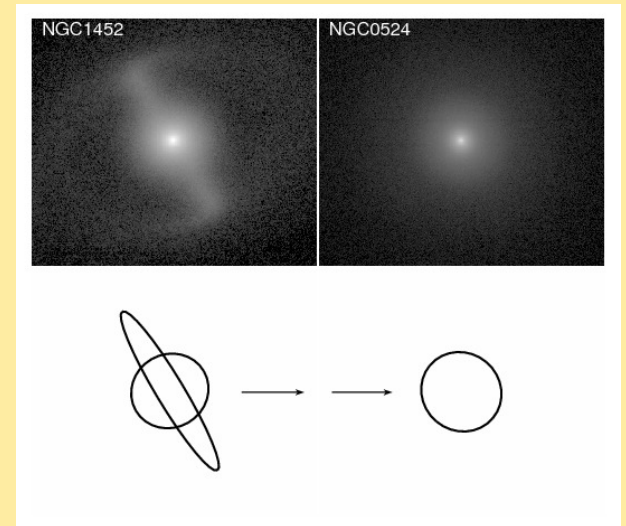# Barlenses without 'thin bars'?

Barred

Non-barred

Analysis of NIRS0S

(Laurikainen et al. 2011, 2013)

In principle yes:

⇒ sizes of inner lenses in non-barred galaxies
  similar to those of barlenses in barred galaxies

⇒ what does it mean?

Parent galaxy properties
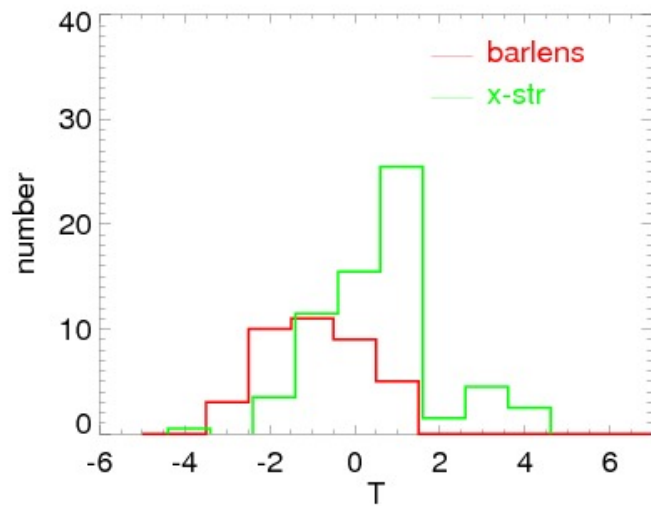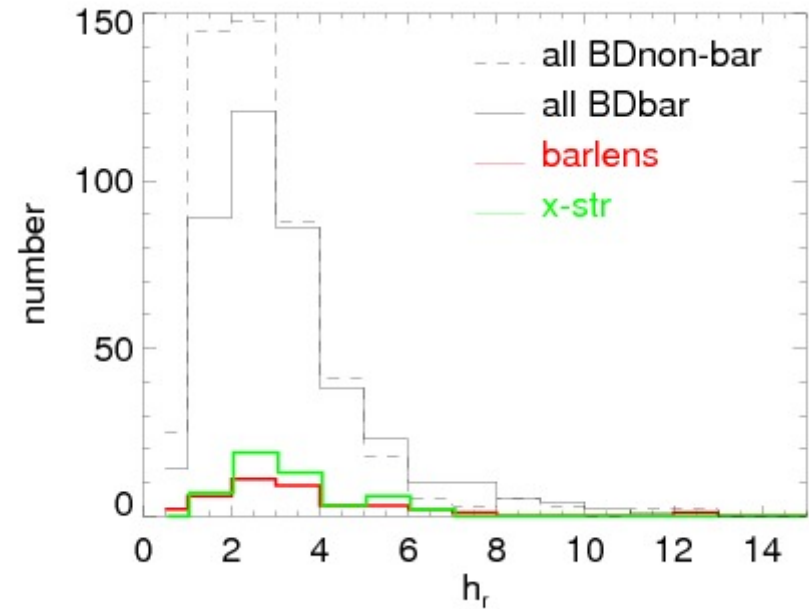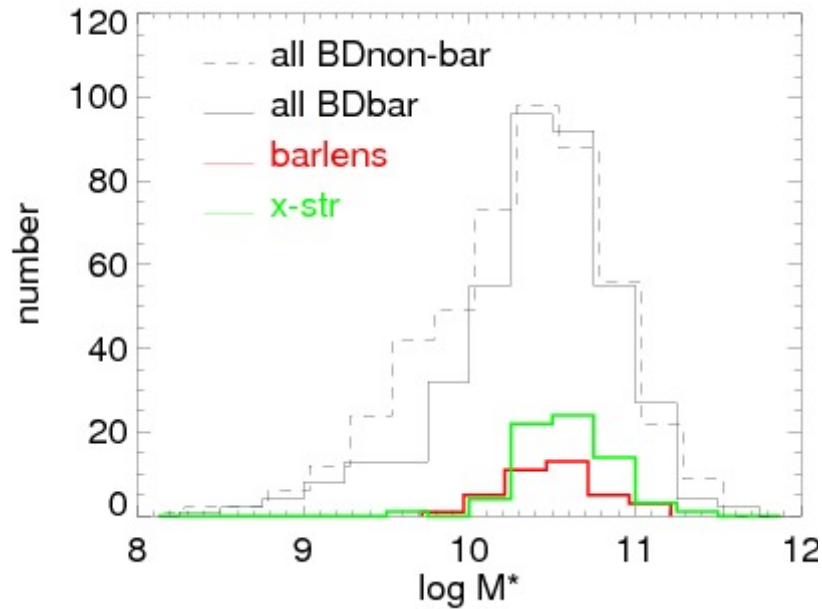
Barlens galaxies (N=38, Laurikainen et al. 2013:)

- 25-34% of NIRS0S galaxies have barlenses
- appear mainly in **strong bars**: 62% (B), 38% (AB)
- typically have **ansae bars**: 52% (compared to 24% of bars without bl)

x-shaped galaxies (N=66):

- appear often in **strong bars**: 56% (B), 44% (AB)
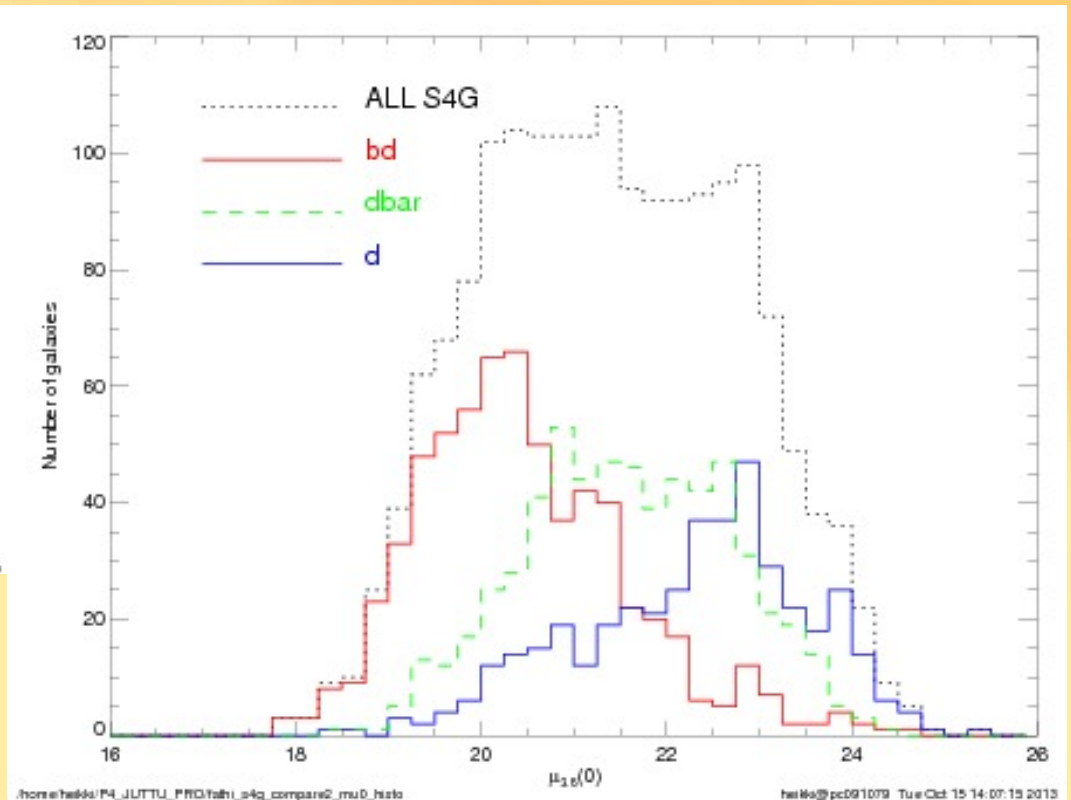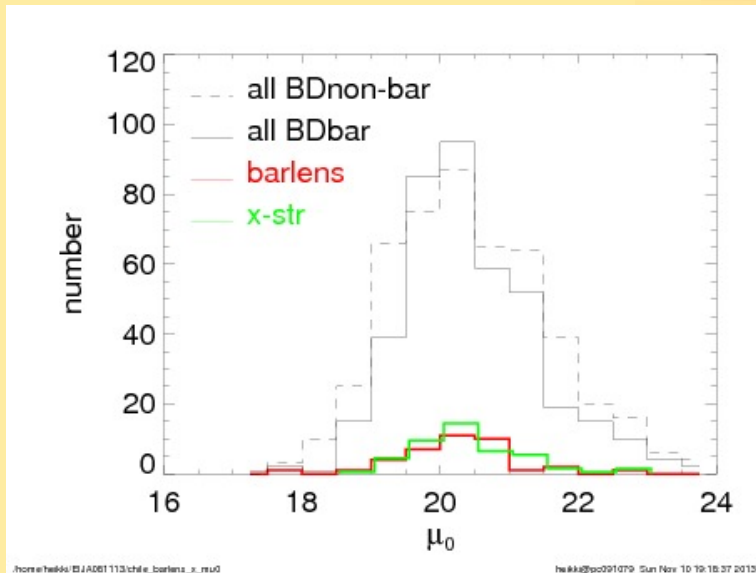- only 15% have ansae bars

Parent galaxy masses   Parent galaxy sizes

⇒ bl, x-str appear in bright galaxies

⇒ have normal h_R

⇒ bl peaked to earlier Hubble types

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Parent galaxy disks (μ_0)   Compared to complete S^{4}G

(Salo et al. 2013, in prep.)

$\Rightarrow$ bl/x-str appear in bright disks (μ_0 as in normal BD-galaxies)

$\Rightarrow$ they do not appear in dbar-galaxies

$\Rightarrow$ In the complete S^{4}G: μ_0(bd) $\Rightarrow$ μ_0(dbar) $\Rightarrow$ μ_0(d)

BDbar (bl, x-str) vs. dbar in S^{4}G:

(Salo et al., in prep.)
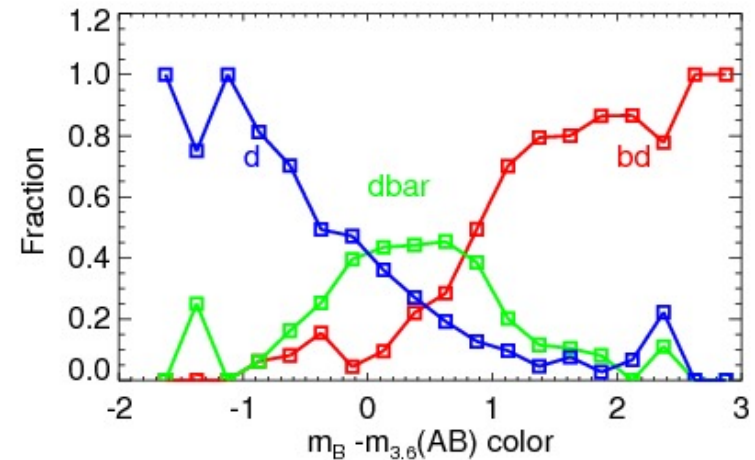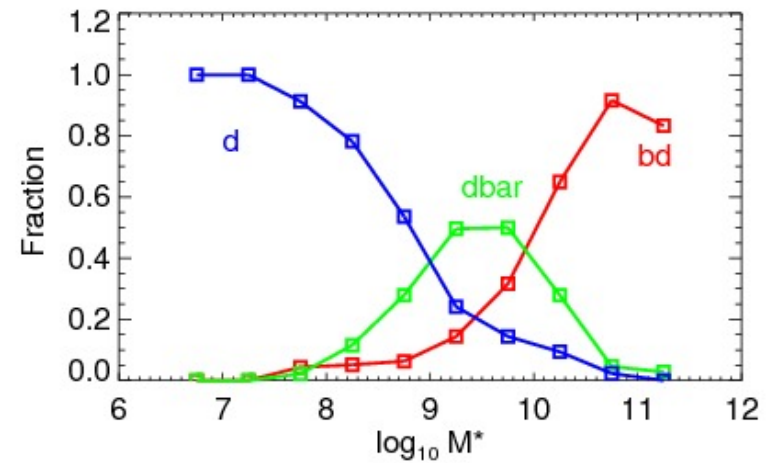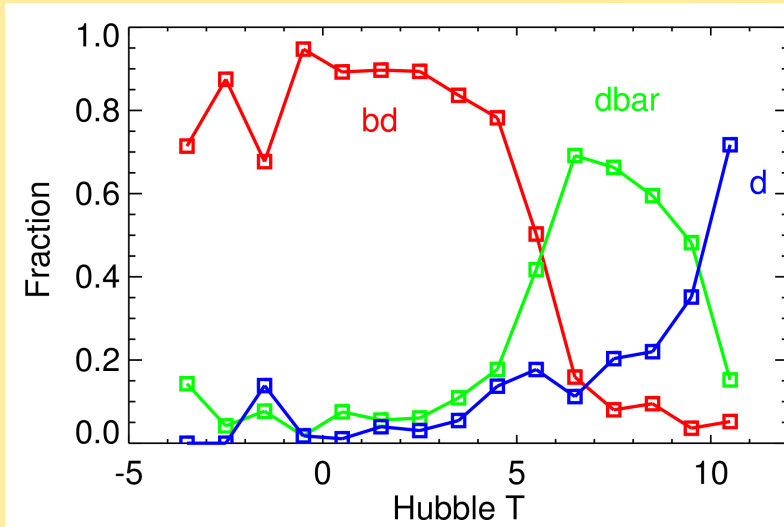
⇒ BDbar/dbar: strong function of Hubble type, galaxy mass and color

Analog between bl and x-shaped str?

Edge-on view

More face-on view

Conclusions

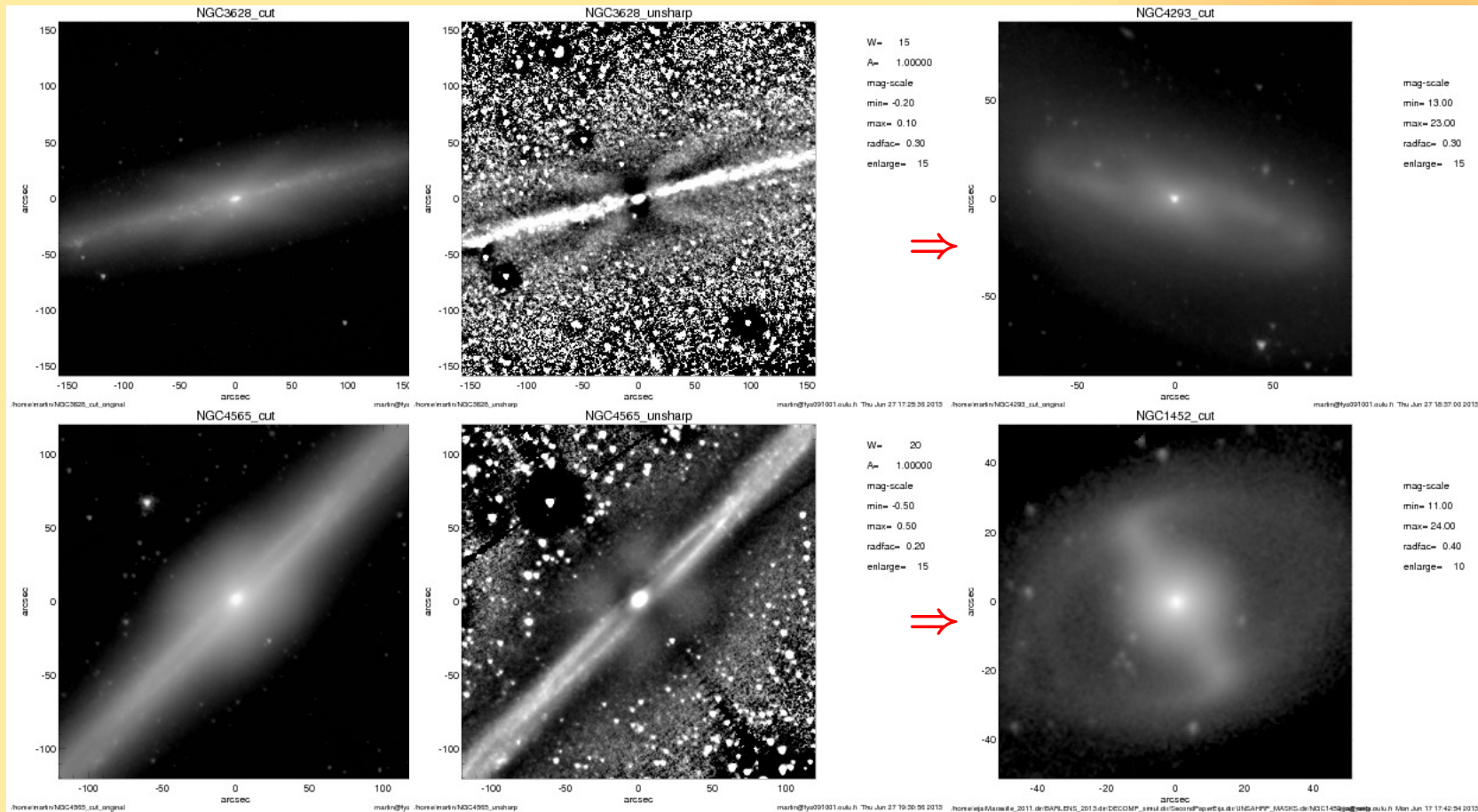**Barlenses:** identified as lens-like structures embedded in bars.
Suggested to be vertically thick in a similar manner as b/p/x bulges,
but needs to be explained with theoretical models.

- Isophotal analysis: detects only 25% of all barlenses
- Fourier analysis: double peaks in density amplitude profiles
- Barlenses are not classical bulges (unsharp masks, μ-profiles)
- Most barlenses are not inner disks (unsharp masks, not elongated along the disk plane)

Compared to x-shaped bars:

- Barlenses are brighter (F/F(tot)=0.2 vs. 0.1)
- Both have similar small central peaks (F/F(tot) $\sim$ 0.1)
- Barlenses have ansae 'thin bar' morphology (52%), lacking in x-shaped bars (15%)

Mean B/T reduced from 0.35 to 0.12, when barlens taken into account