

The structure of barred galaxies:

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Main collaborators:

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Heikki Salo

Ronald Buta

Samples:

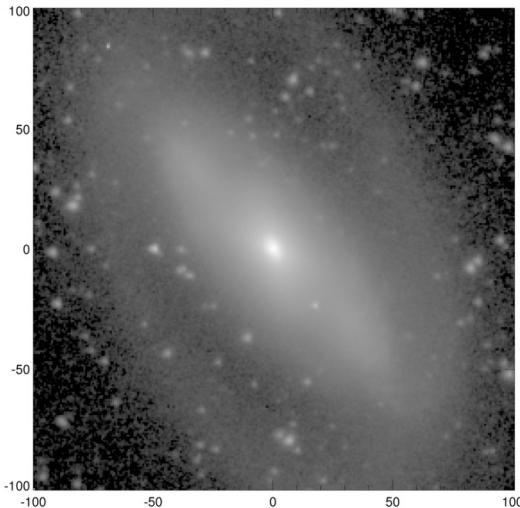
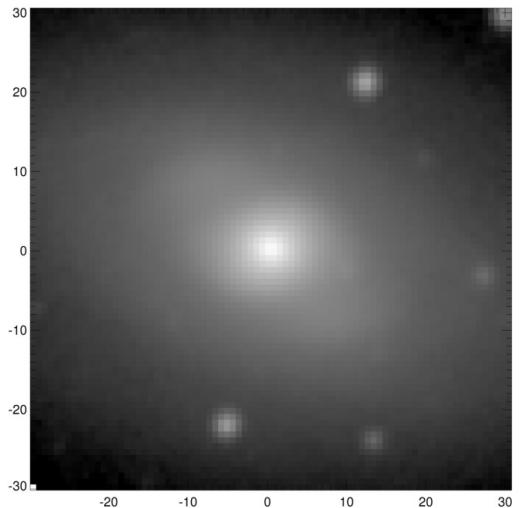
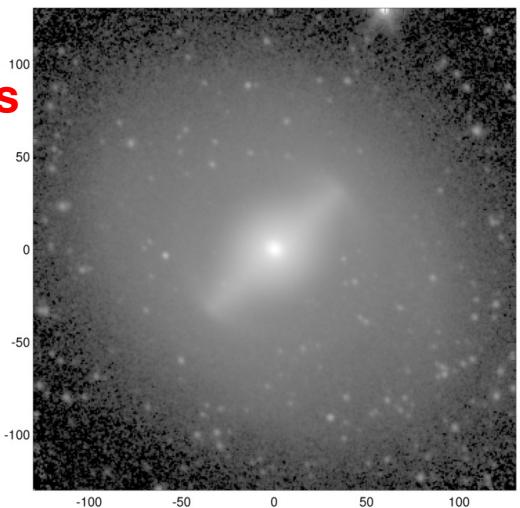
Near InfraRed S0 galaxy Survey (NIRS0S):

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

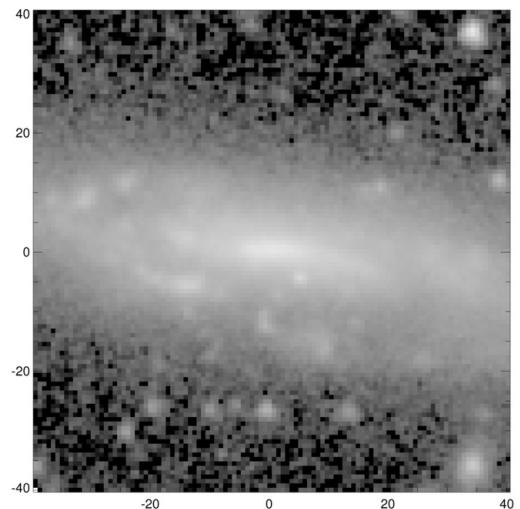
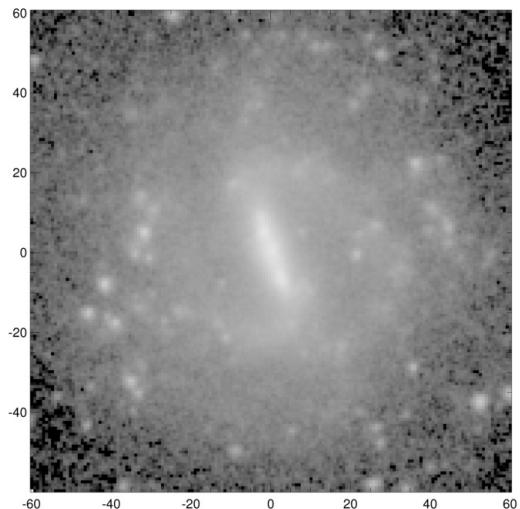
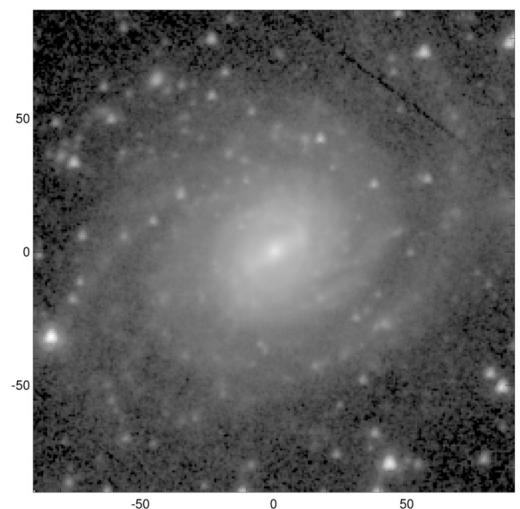
Spitzer Survey of Stellar Structure in Galaxies (S⁴G):

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

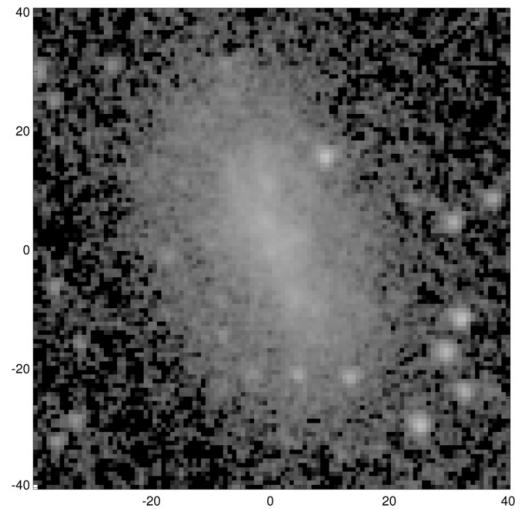
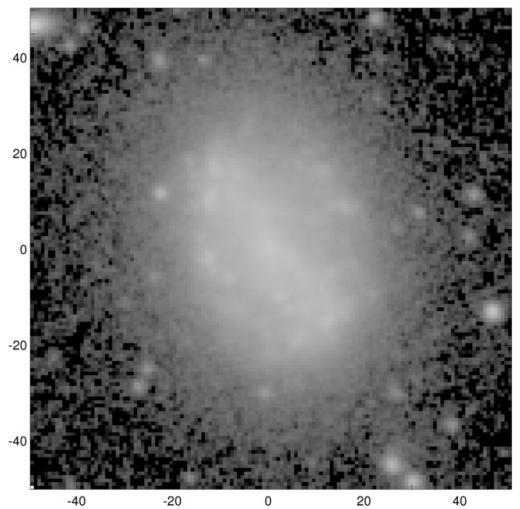
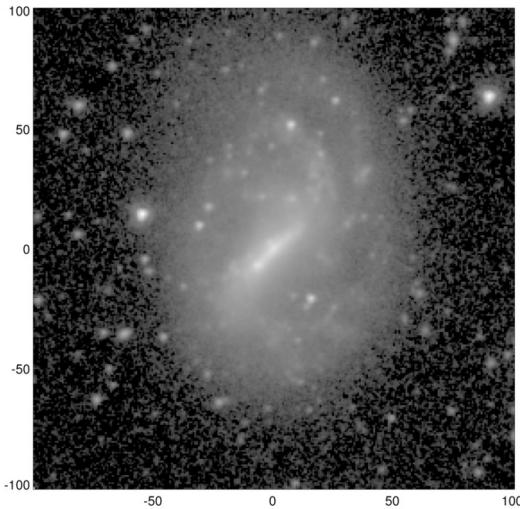
Early-types



Sc-Sd

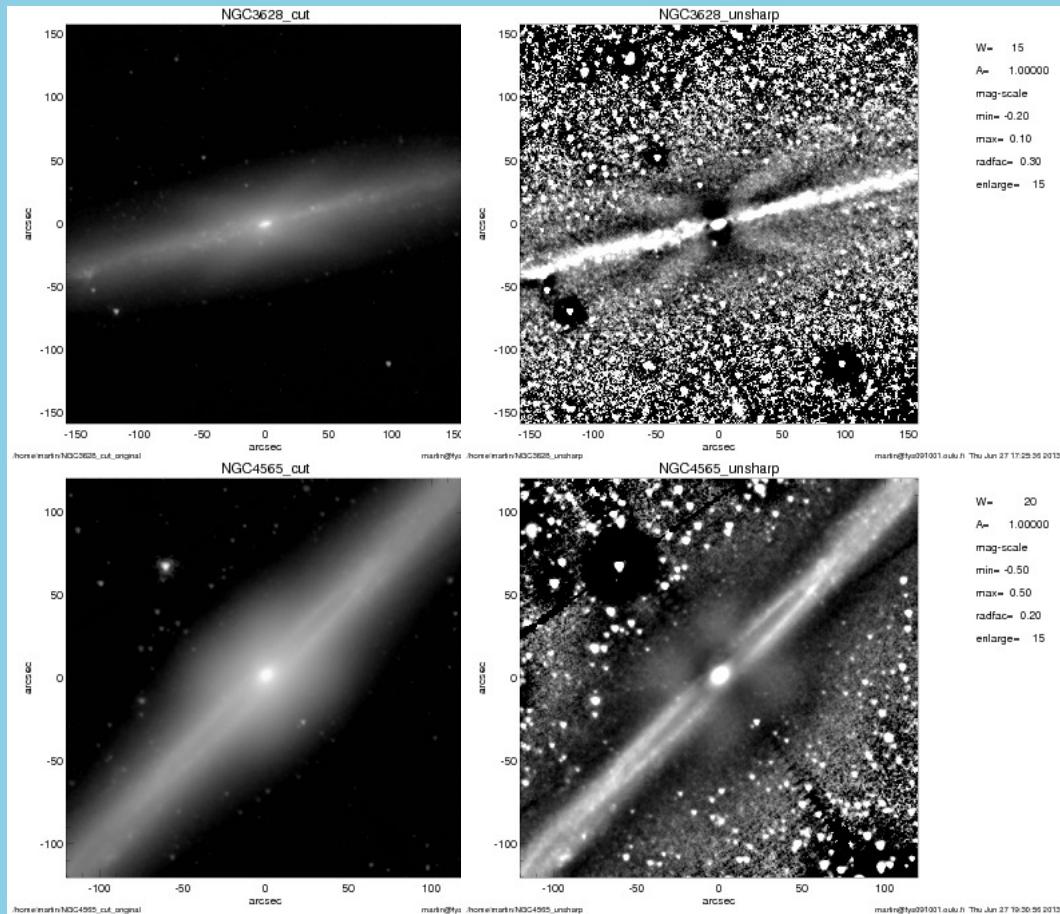


Sm



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 μ m images for:

NGC 3628

NGC 4565

(see also Kormendy & Barentine 2010)

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

Attempts to find them:

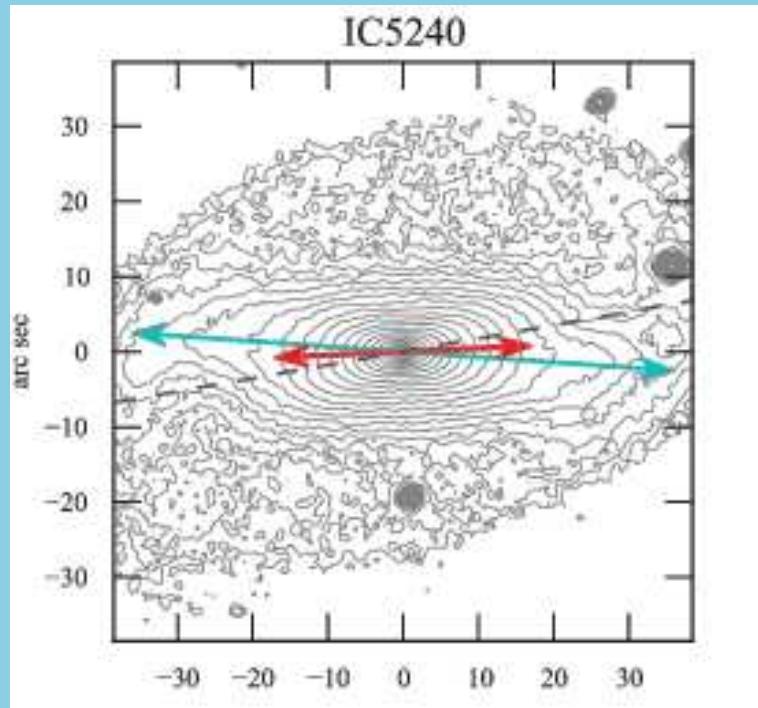
(1) **Cylindrical rotation:** in NGC098 (Mendez-Abreu et al. 2008)

(Bertola & Capaccioli 1977; Kormendy & Illingworth 1982)

(2) **Isophotal analysis (a4, b4, dPA):**

Beaton & Athanassoula (2006); Athanassoula & Beaton (2006)

⇒ Distinguish boxy bulge in M31, $i(\text{disk})=77.5^\circ$



Erwin & Debattista (2013):

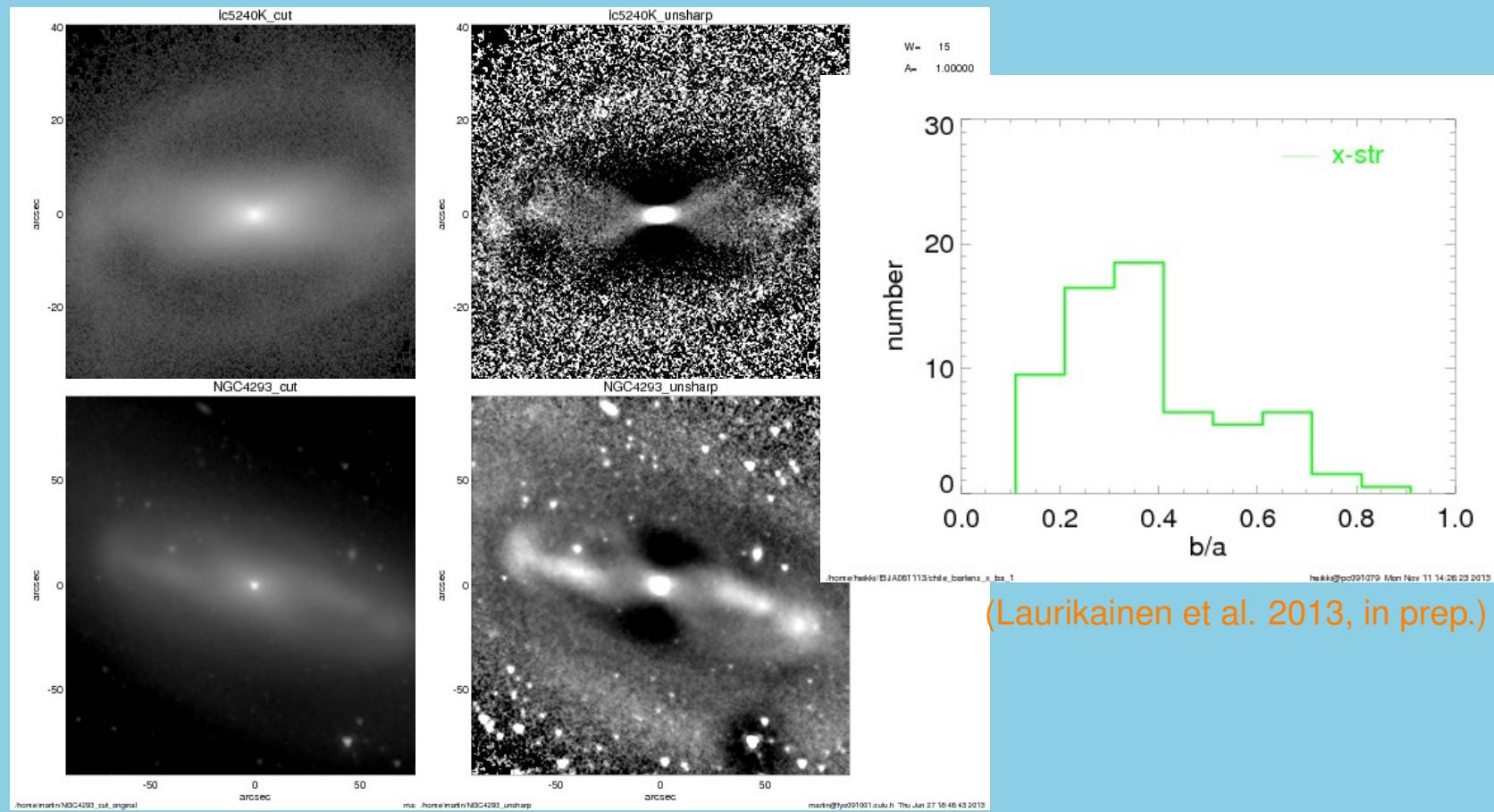
Analysis for ~ 80 S0-Sb galaxies:

⇒ boxy/spurs best visible when:

$i_{\text{disk}}=45-75^\circ$, $dPA < 45^\circ$ (bar, line of node)

⇒ 2/3 are boxy

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

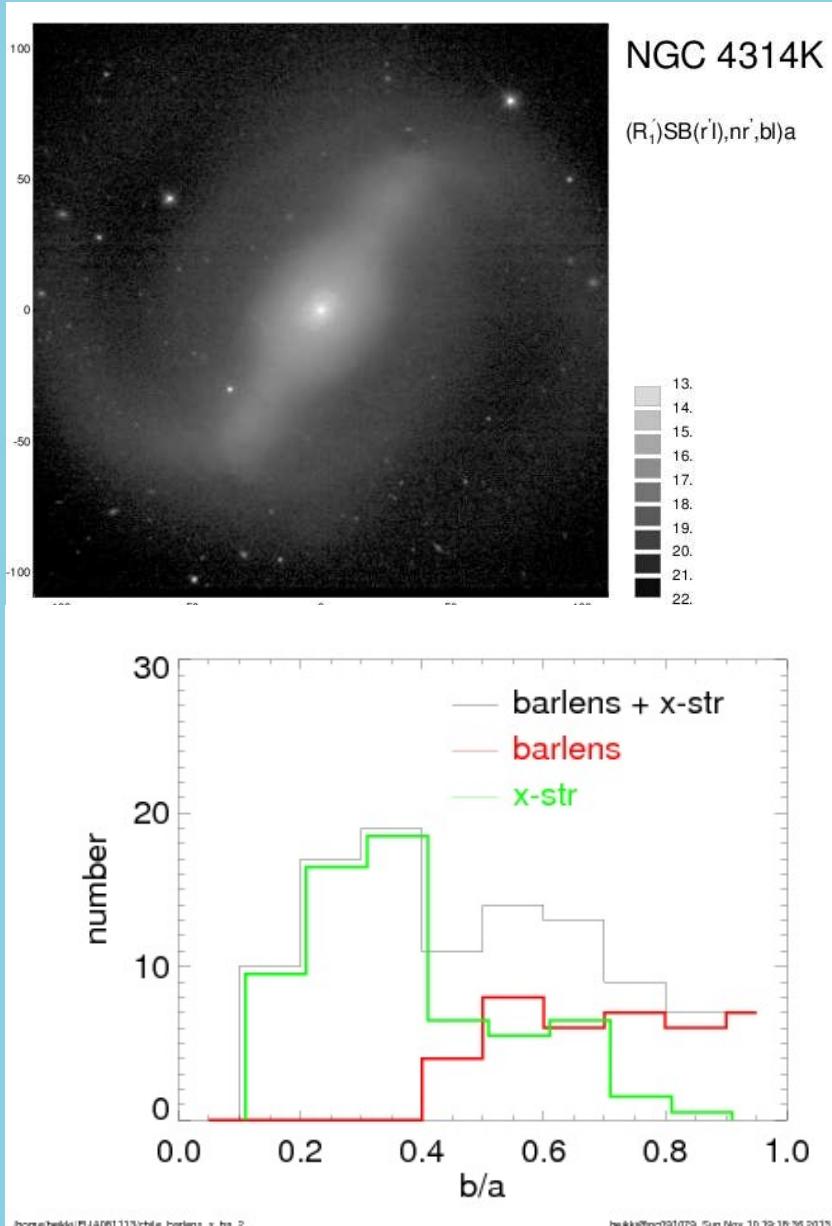


x-shapes in visual classifications (non-edge-on galaxies):

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

Buta et al. (2013) \Rightarrow classification in S⁴G

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



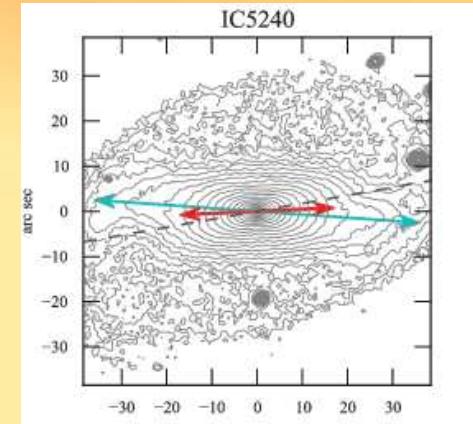
- Classical bulges (Peletier)
 - Inner disks (NGC 2787, NGC 3945; Erwin et al. 2003)
 - Barlenses (Laurikainen et al. 2011):
 lens-like structures embedded in bars,
 form part of the bar
 - ⇒ systematic classification for S0-Sa galaxies
 - ⇒ Laurikainen et al. (2007): some of those suggested to be vertically thick
- ⇒ galaxies with bl+x-strs cover the full range of disk inclinations

Observational properties of barlenses

(Laurikainen et al. 2013, in prep.)

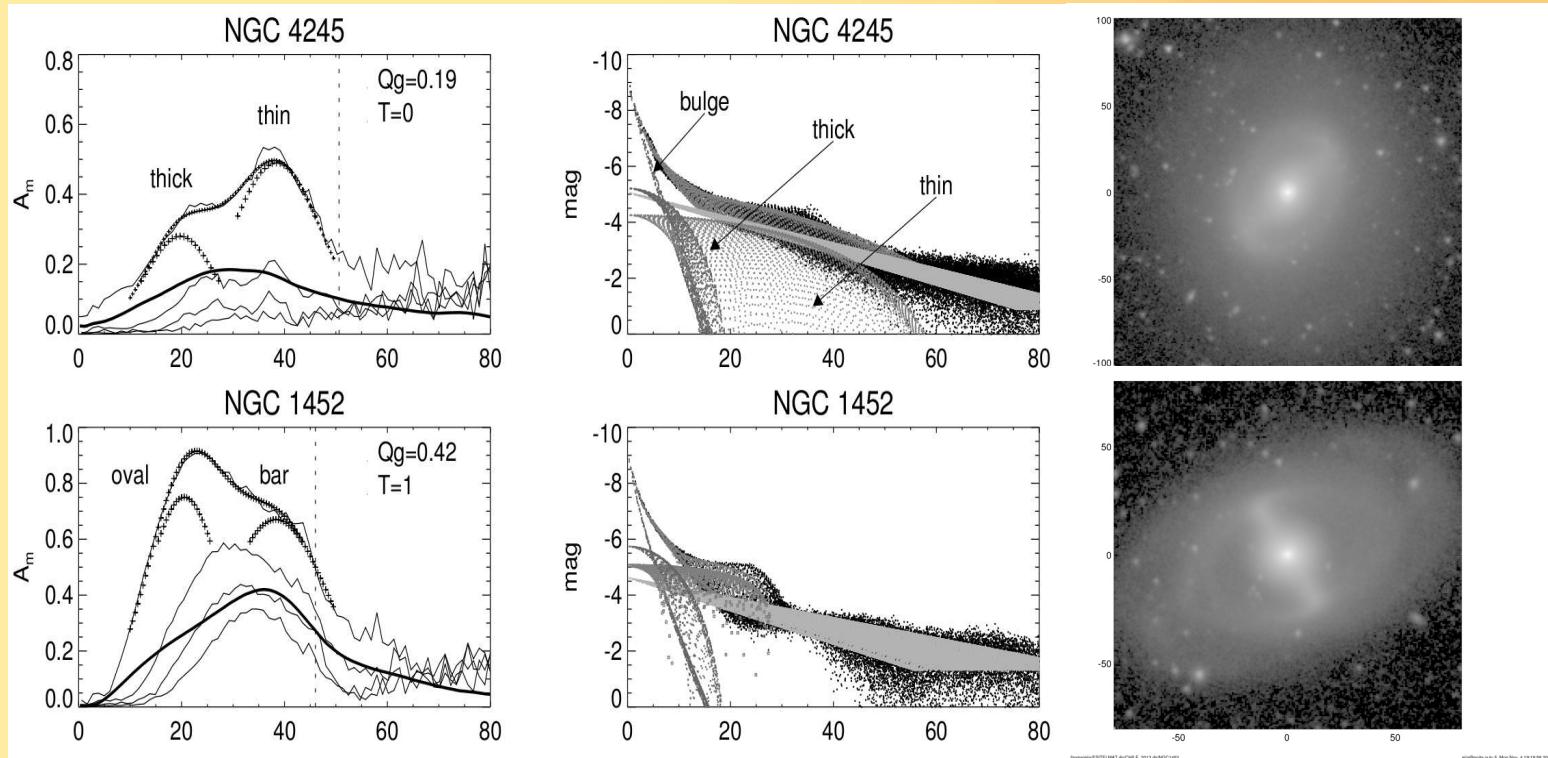
1. Detectable in isophotal analysis?

- Carried out to all barlens galaxies in NIRS0S (=36/215):
Use ellipse fitting from Laurikainen et al. (2011;
ell, PA, b4-profiles, dPA)
⇒ only 25% are boxy (34% if marginal cases included)
- Comparison with ED(2013): 38/78 galaxies common with NIRS0S
⇒ 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)

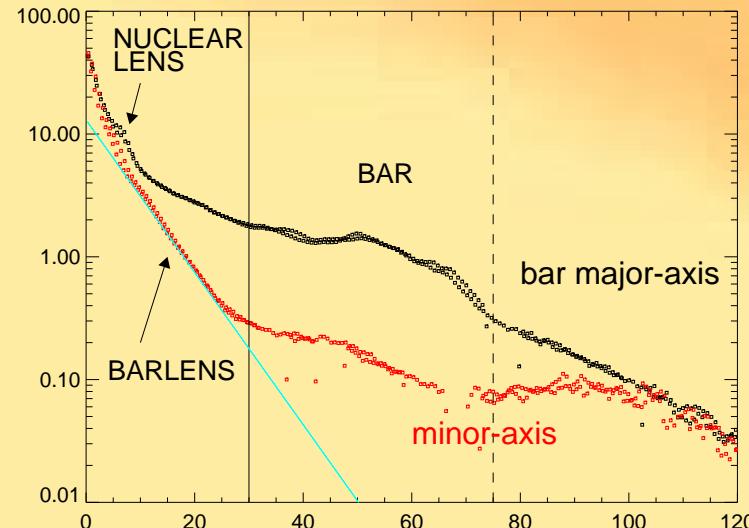
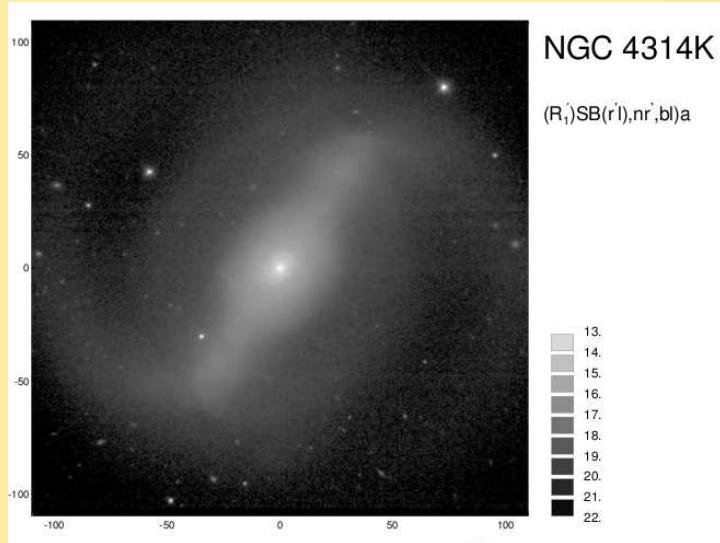


Left: Fourier amplitudes of density ($m=2, 4, 6, 8$) and $Q=(F_{tangential}/F_{radial})$

Middle: bulge/disk/bar/barlens decompositions

⇒ barlenses appear in Fourier analysis (even if not visible in isop. anal.)

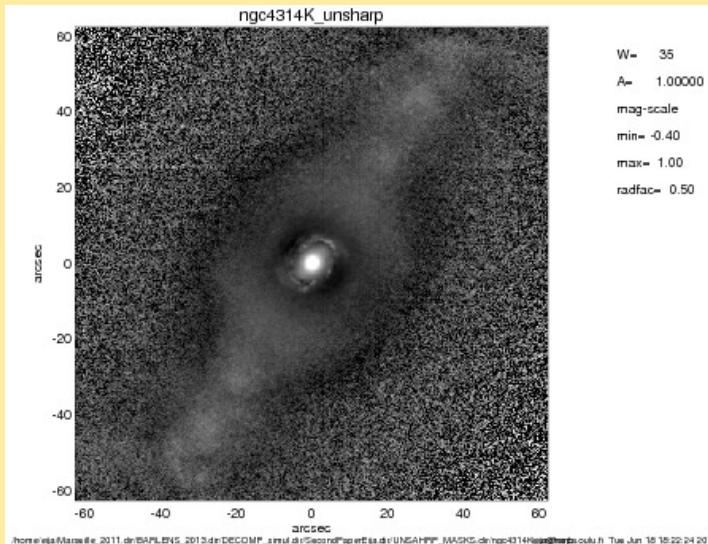
3. Surface brightness profiles



⇒ exponential surface brightness profile, cannot be a classical bulge

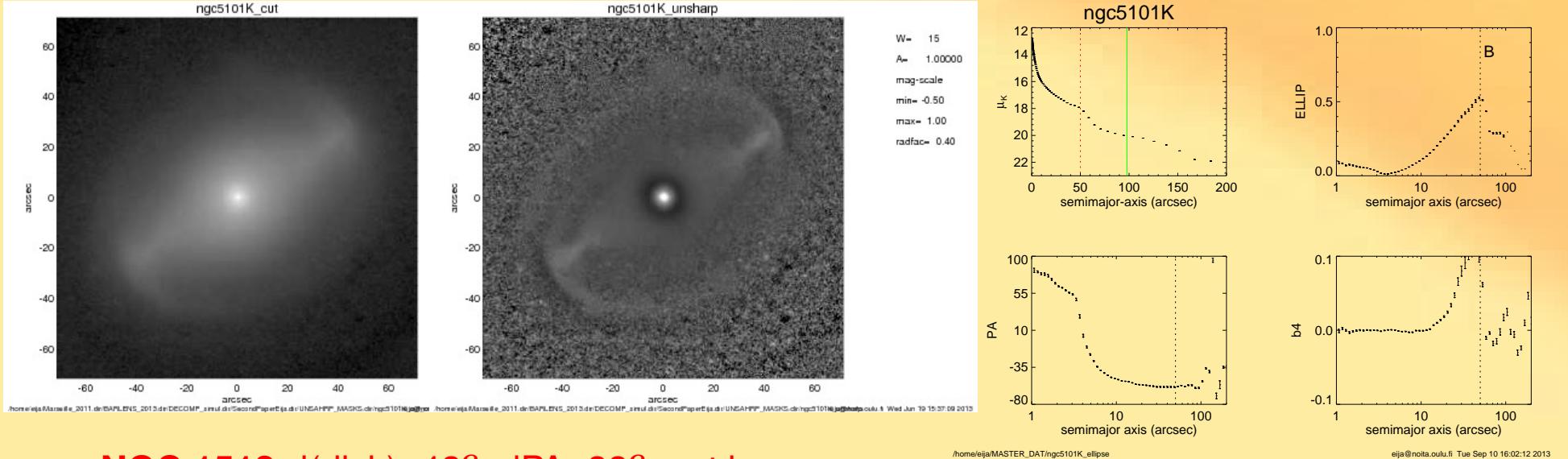
4. Unsharp masks

⇒ barlens form part of the bar,
not boxy, no spurs, $i(\text{disk})=20.4^\circ$
(ED2013, NIRS0S)

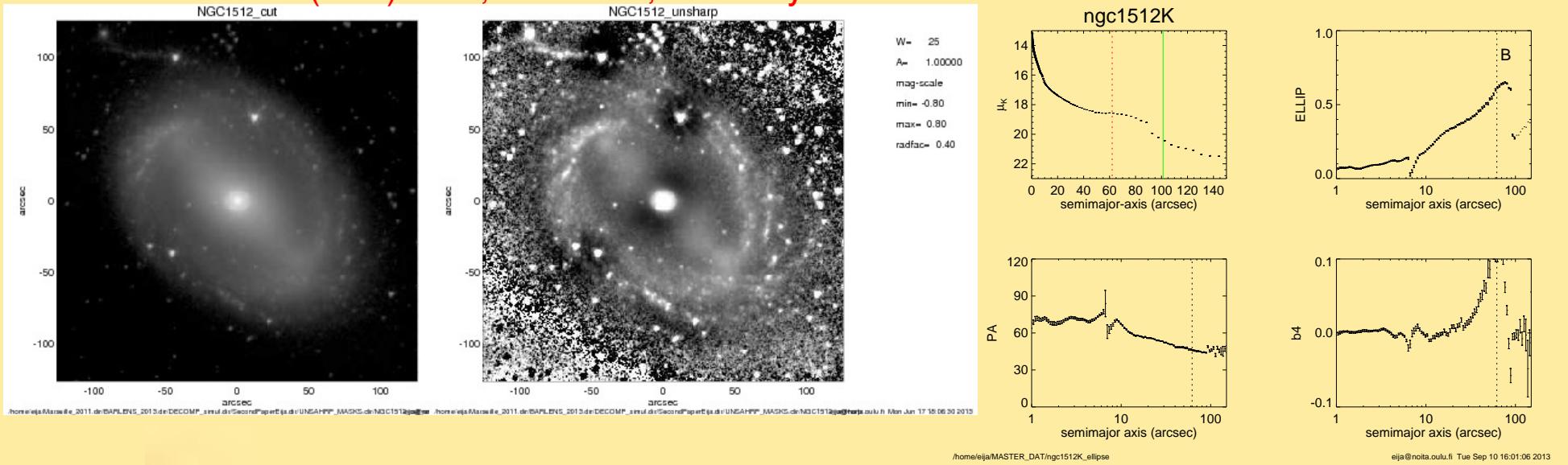


Barlenses form part of the bar...

NGC 5101: $i(\text{disk})=22^\circ$, $dPA=26^\circ$, not boxy

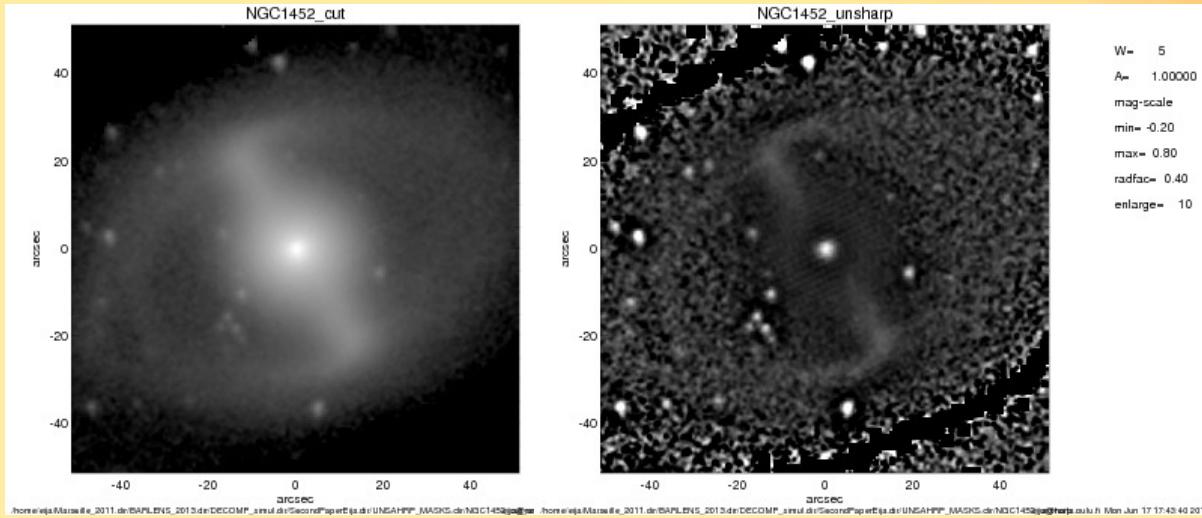


NGC 1512: $i(\text{disk})=42^\circ$, $dPA=22^\circ$, not boxy

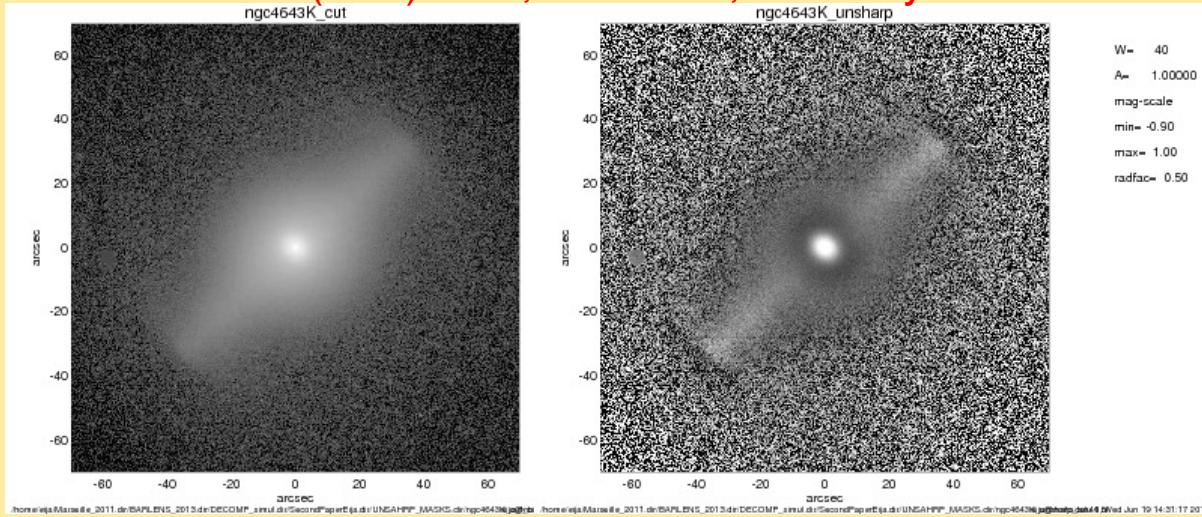


Barlens form part of the bar: not elongated along the disk plane, μ -profiles

NGC 1452: $i(\text{disk})=53^\circ$, $\text{dPA}=10^\circ$, not boxy

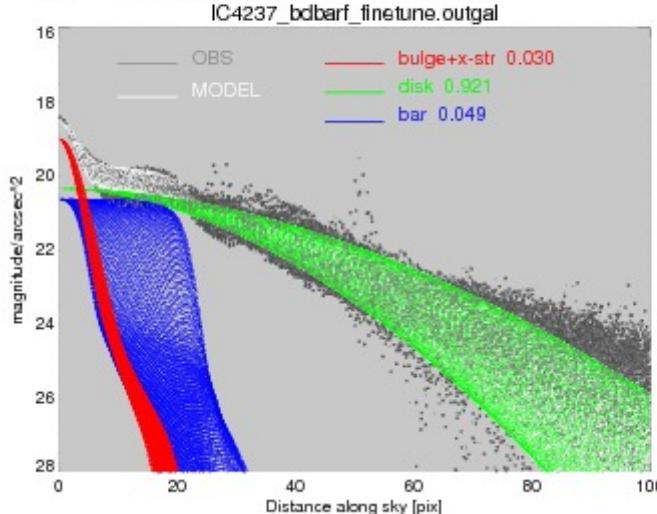


NGC 4643: $i(\text{disk})=37^\circ$, $d\text{PA}=18^\circ$, not boxy

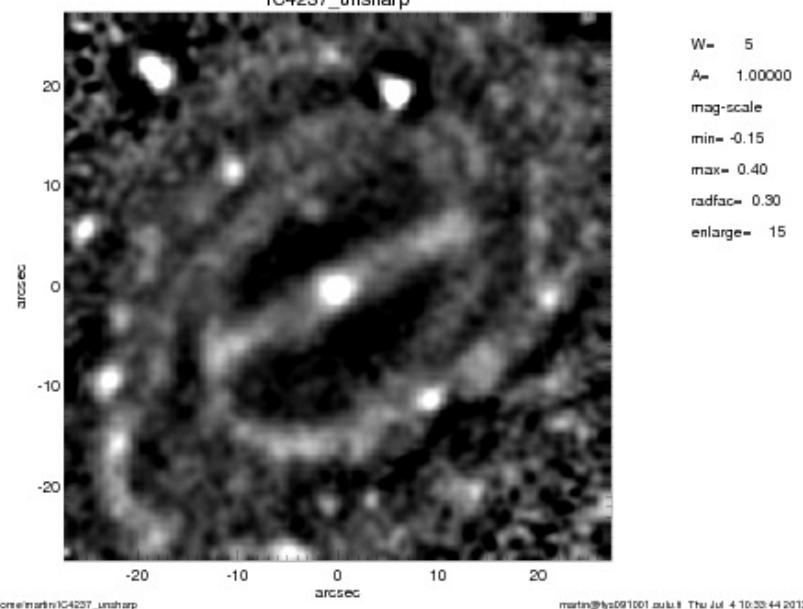
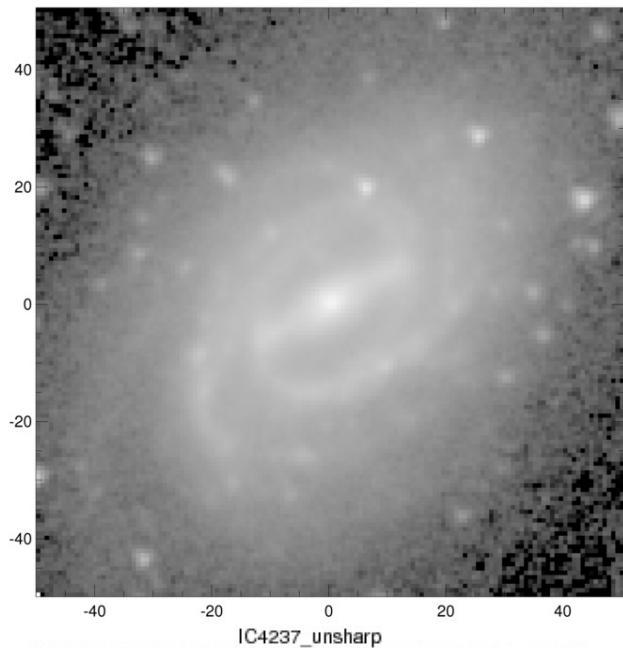
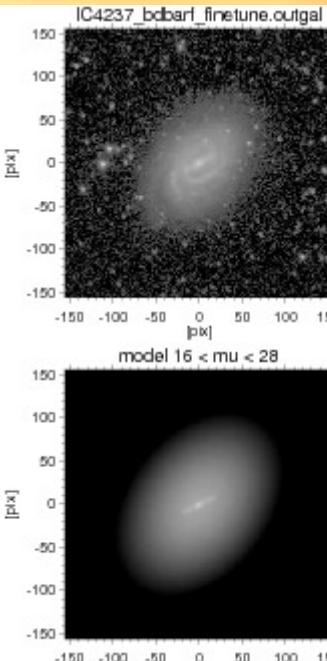


6. Structural decompositions

```
INITFILE= IC4237_bdbarf_finetune.outgal
DATAIN = IC4237_phot1_noman.fits
SIGMA = IC4237_sigma2012.fits_ns
PSF = PSF-1.composite.fits
CONSTRAINT= none
MASK = IC4237.1.linmask_noman.fits
```



```
FITSECT = '[124:436,635:947]
CONVBOX = 50, 50
MAGZPT = 21.097
INFILE: 2013-Aug-22
PLOT: 22-Aug-2013 16:36:33.00
eija@nolta.cuulu.fi
```



IC 4237: SB_x(r)b

⇒ x-shaped 'thick bar', but no bulge?

```

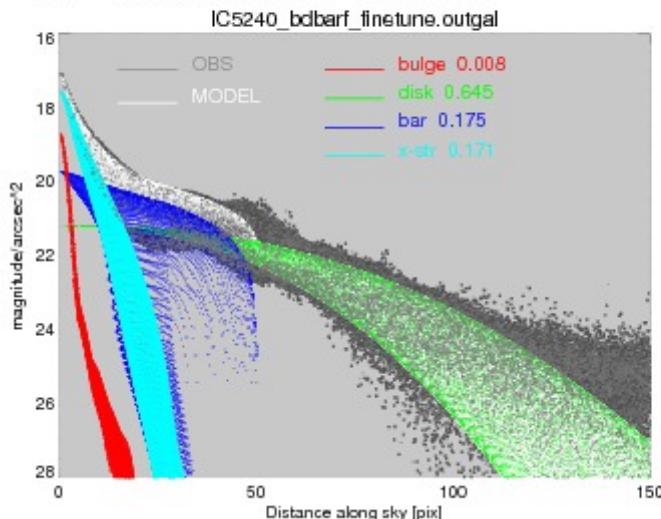
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CONSTRAINT= none
MASK = IC5240.1.timmask_noman.fits

```

```

FITSECT = [433.953,417.937]
CONVBOX = 50, 50
MAGZPT = 21.097
INFIL: 2013-Aug-22
PLOT: 22-Aug-2013 16:38:13.00
eija@noita.celu.fi

```



```

COMP_1 = s@r
1_XC = 693.1
1_YC = 677.1
1_MAG = 16.4
1_RE = 0.391
1_N = [1.093
1_AR = [0.825
1_PA = [-83.4

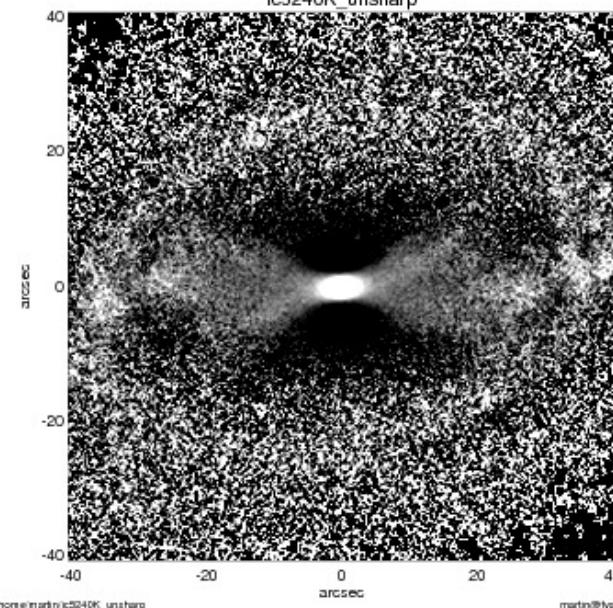
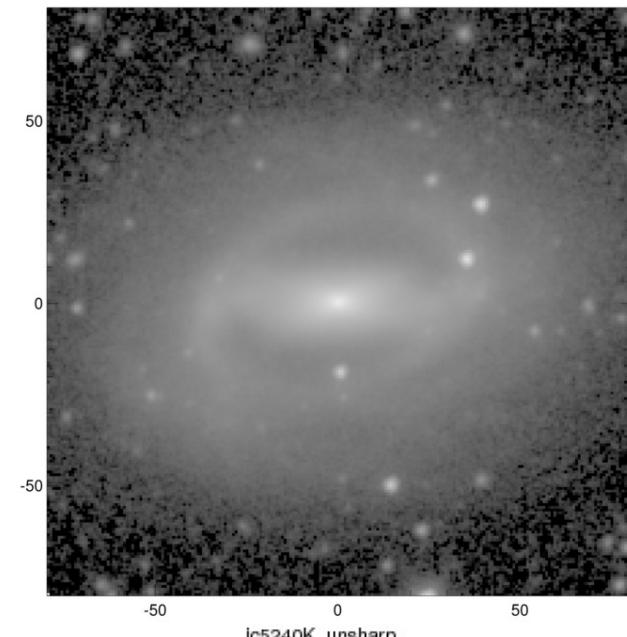
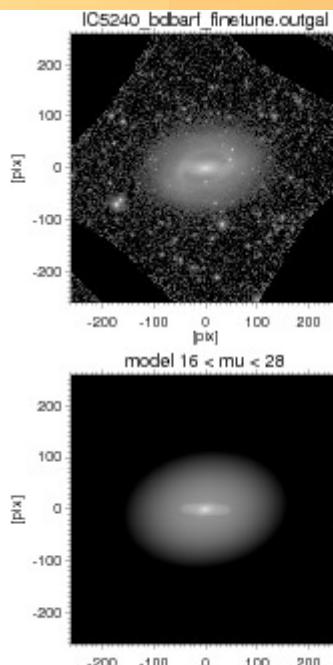
COMP_2 = s@r
2_MAG = 11.6
2_RE = 58.49
2_N = [0.429
2_AR = [0.701
2_PA = [-81.4

COMP_3 = f@rr
3_MU_0 = 16.4
3_ROOT = [50.
3_ALPHA = [0.5
3_BETA = 1.95
3_AR = [0.250
3_PA = [88.45
3_CO = [1.030

COMP_4 = f@rr
4_MU_0 = 13.8
4_ROOT = [30.
4_ALPHA = 2.5
4_BETA = 1.86
4_AR = [0.600
4_PA = [-79.5
4_CO = 1.436

ERROR = Con
Chi2/nu = 16.

```



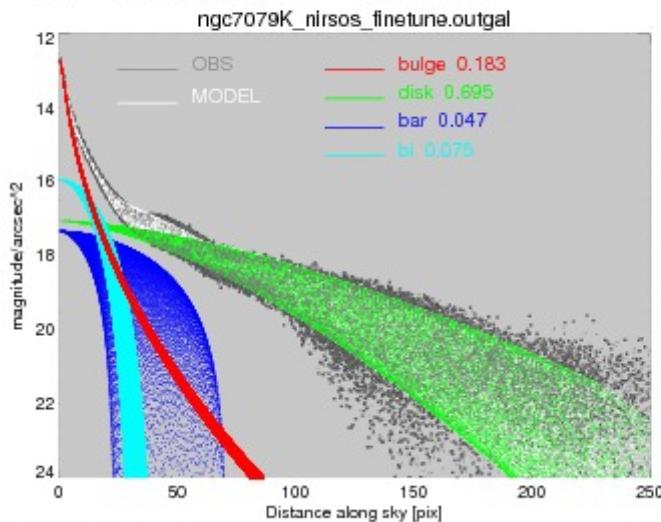
IC 5240: SB_x(r)0/a

- ⇒ x-shaped 'thick bar'
- ⇒ a small pseudobulge or no bulge at all

```

INITFILE= ngc7079K_nirsos_finetune.outgal FITSECT = [203 643 312:752]
DATAIN = ngc7079K.fits CONVBOX = '50, 50'
SIGMA = ngc7079K_sigma.fits MAGZPT = 24.375
PSF = ngc7079K_psf.fits INFIL: 2013-Aug-22
CONSTRAINT= none PLOT: 22-Aug-2013 16:28:17.00
MASK = ngc7079K_dummymask.fits eija@noita.culu.fi

```



```

COMP_1 - sersic
1_XC = 423.4
1_YC = 532.8
1_MAG = 10.4
1_RE = [8.01]
1_N = [2.172]
1_AR = [0.938]
1_PA = [85.05]

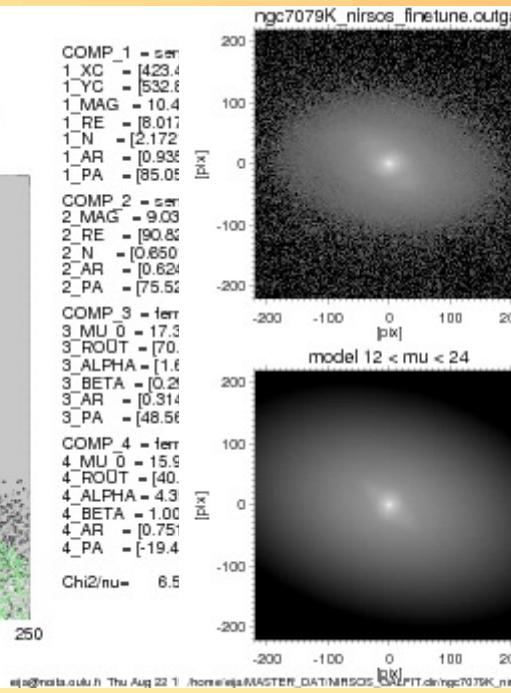
COMP_2 - sersic
2_MAG = 9.03
2_RE = [90.82]
2_N = [0.650]
2_AR = [0.624]
2_PA = [75.52]

COMP_3 - terry
3_MU_0 = 17.3
3_ROOT = [70.
3_ALPHA = [1.6
3_BETA = [0.21
3_AR = [0.314
3_PA = [48.5t

COMP_4 - terry
4_MU_0 = 15.9
4_ROOT = [40.
4_ALPHA = 4.3
4_BETA = 1.00
4_AR = [0.75]
4_PA = [-19.4

Chi2/nu = 6.5

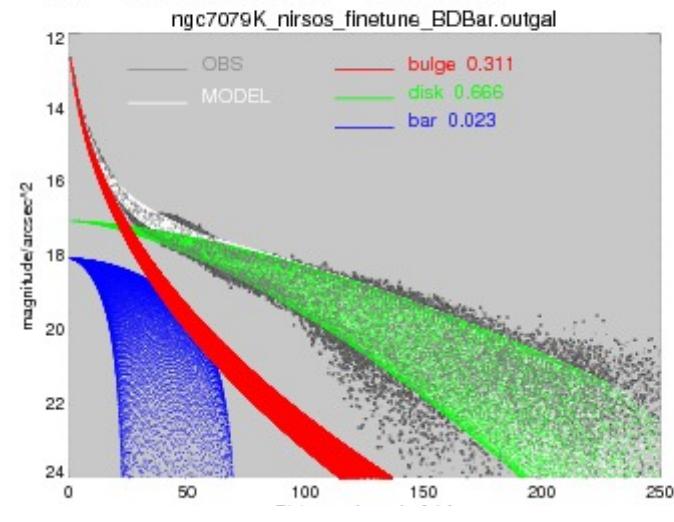
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```

INITFILE= ngc7079K_nirsos_finetune_BDBar.outgal FITSECT = [203 643 312:752]
DATAIN = ngc7079K.fits CONVBOX = '50, 50'
SIGMA = ngc7079K_sigma.fits MAGZPT = 24.375
PSF = ngc7079K_psf.fits INFIL: 2013-Aug-27
CONSTRAINT= none PLOT: 27-Aug-2013 11:01:58.00
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```



```

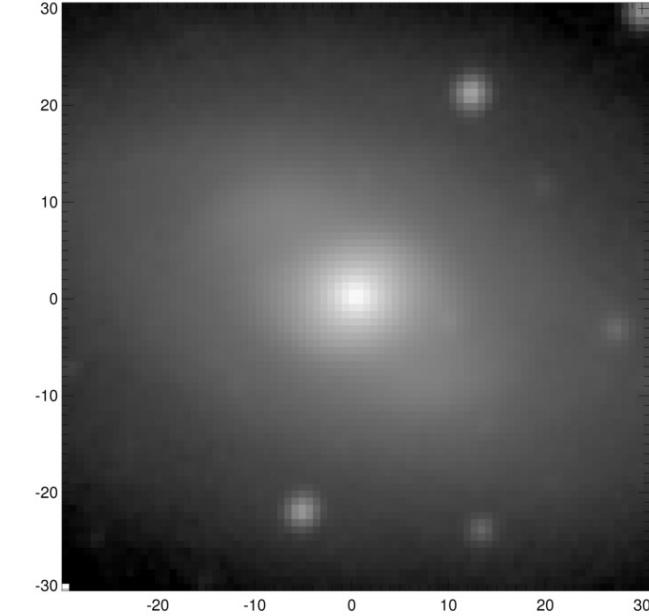
COMP_1 - sersic
1_XC = [423.4740]
1_YC = [532.8780]
1_MAG = 9.8717
1_RE = 13.0681
1_N = 2.2377
1_AR = 0.8401
1_PA = 86.4806

COMP_2 - sersic
2_MAG = [9.0366]
2_RE = [90.8293]
2_N = [0.6501]
2_AR = [0.6246]
2_PA = [75.5224]

COMP_3 - terry2
3_MU_0 = 18.0564
3_ROOT = [70.9375]
3_ALPHA = [1.6538]
3_BETA = [0.2988]
3_AR = [0.3143]
3_PA = [48.5875]

Chi2/nu = 5.89045

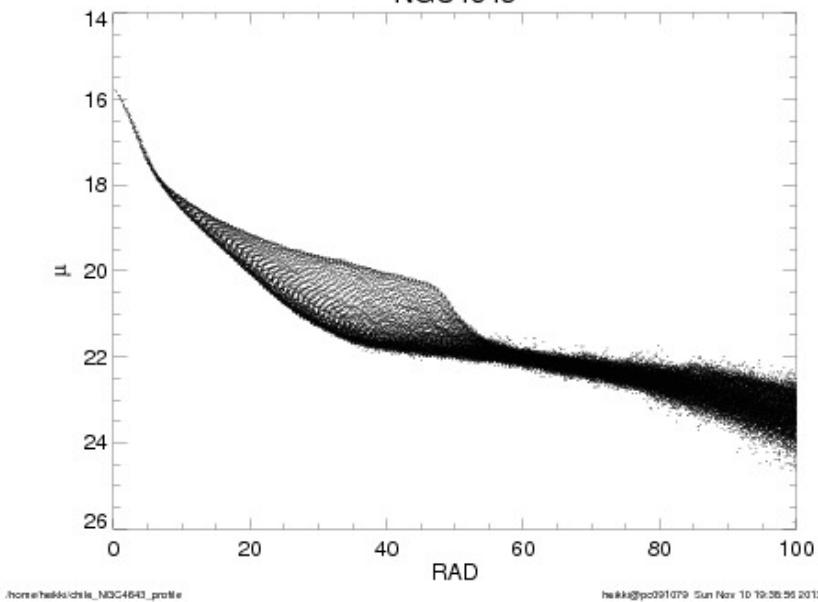
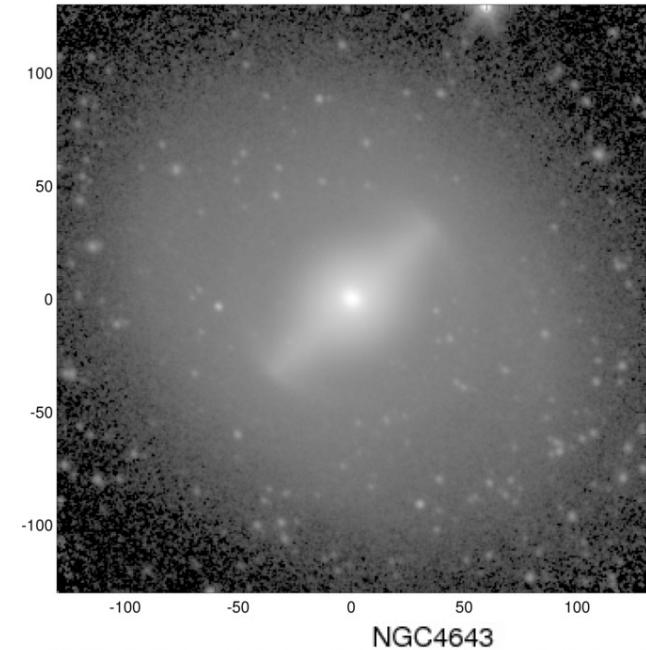
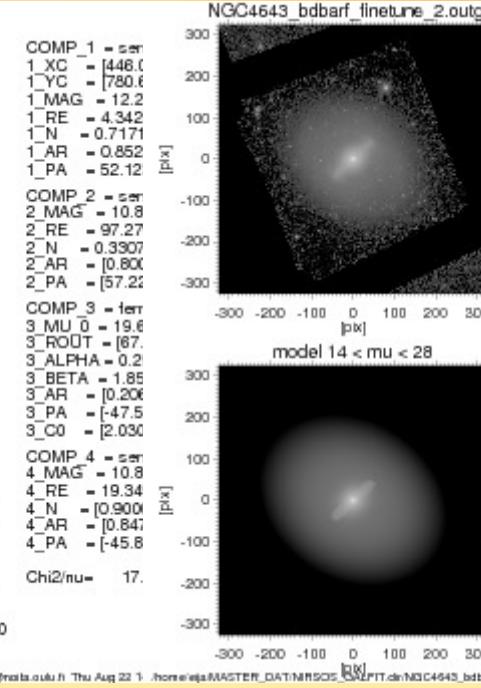
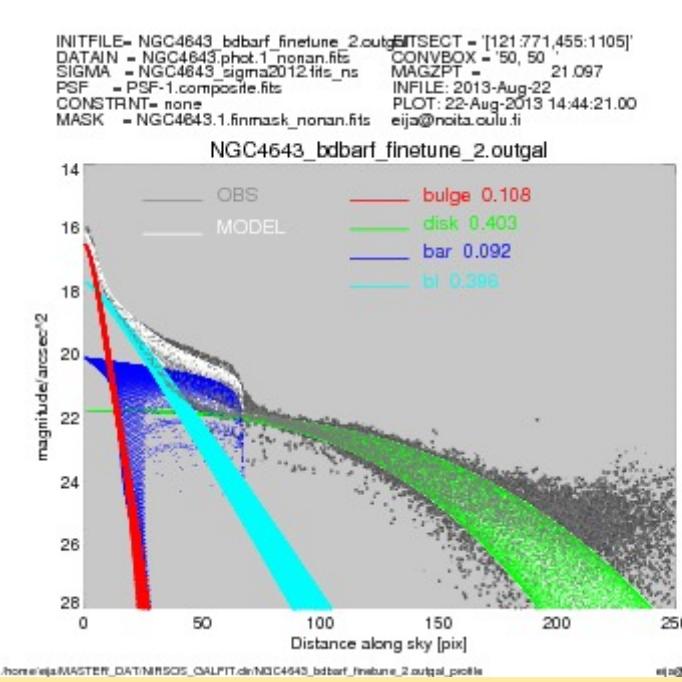
```



NGC 7079: (L)SB_a(s:,bl)0°

Fitting also barlens:

⇒ reduces the B/T flux-ratio (0.31 ⇒ 0.18)



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):

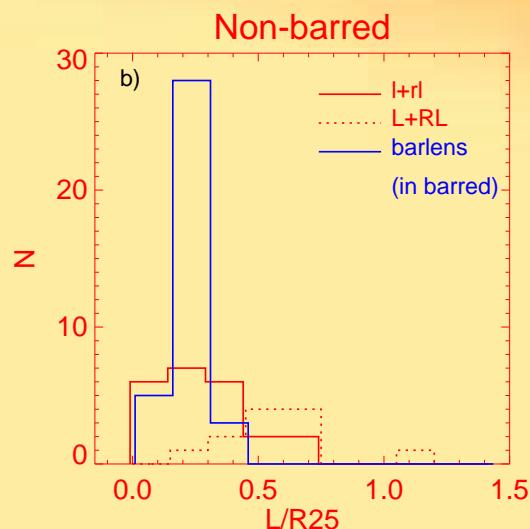
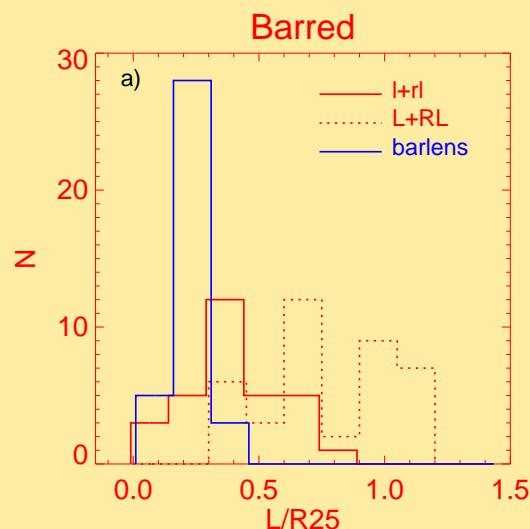
	bl (Sérsic) N=14	x-str (Sérsic) N=14
$F(\text{bl})/F(\text{tot})$	0.18 ± 0.11	0.08 ± 0.02
$F(\text{bl})/F(\text{thin-bar})$	2.35 ± 0.32	0.76 ± 0.15
$F(\text{bulge})/F(\text{tot})$	0.12 ± 0.02	0.08 ± 0.01
Sérsic n (bulge)	1.5 ± 0.1	1.4 ± 0.2

- ⇒ Barlenses brighter than x-shaped structures:
absolutely (0.18 vs. 0.08), and in respect of the bar flux (2.35 vs. 0.76)
- ⇒ In both structures similar central peaks (~ 0.1)

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

- ⇒ Barlenses affect the estimated $F(\text{bulge})/F(\text{tot})$

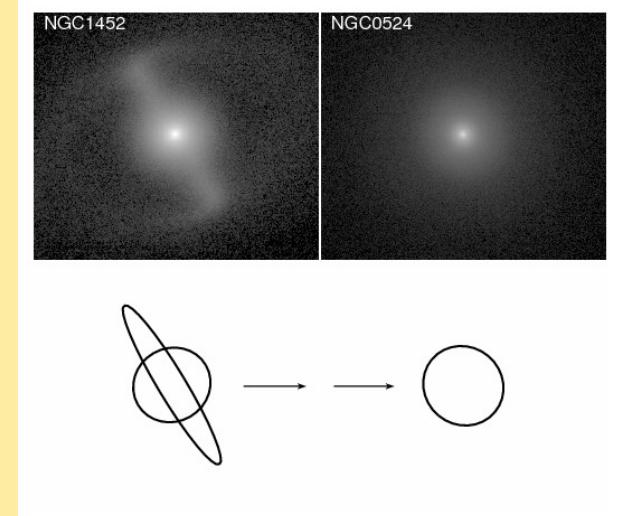
Barlenses without 'thin bars'?



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

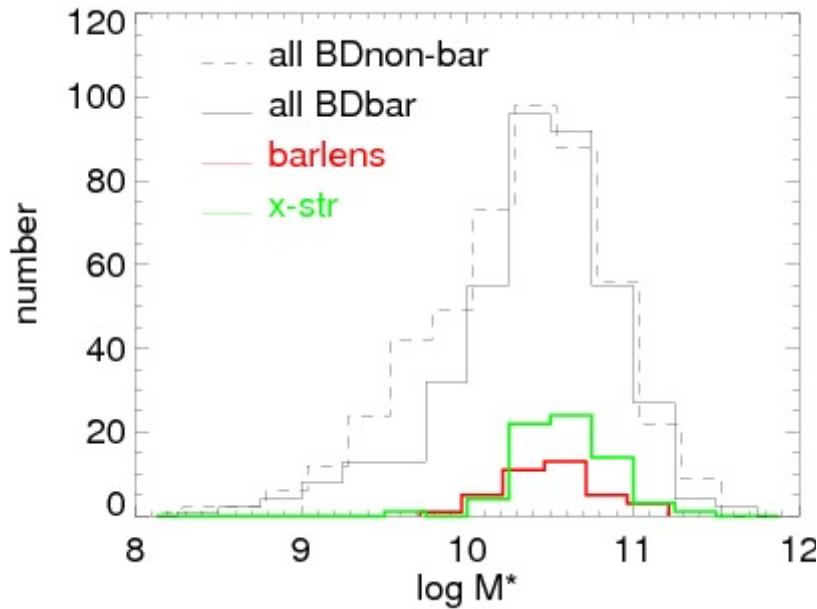
Barlens galaxies (N=38, Laurikainen et al. 2013:)

- 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)

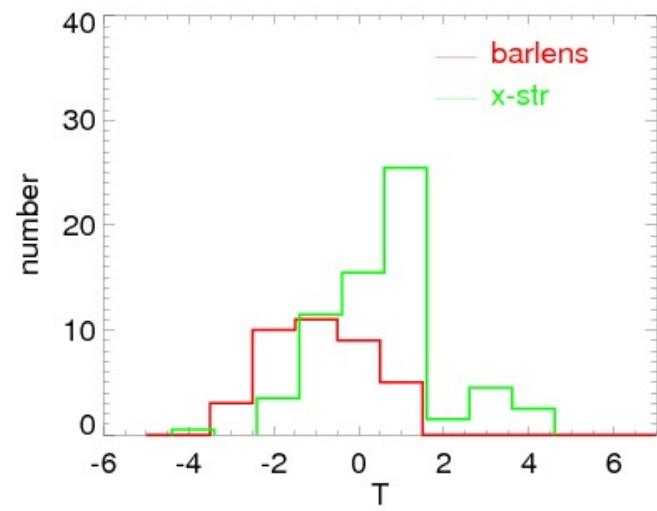
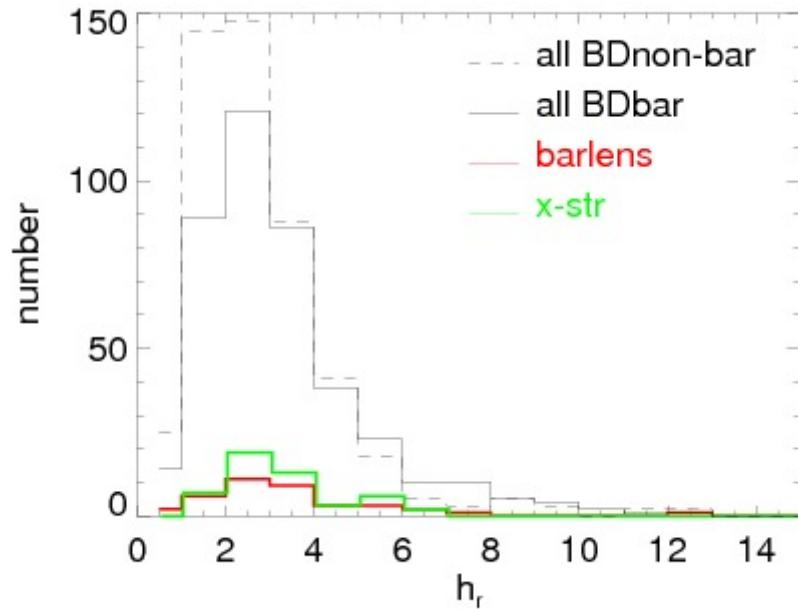
x-shaped galaxies (N=66):

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

Parent galaxy masses

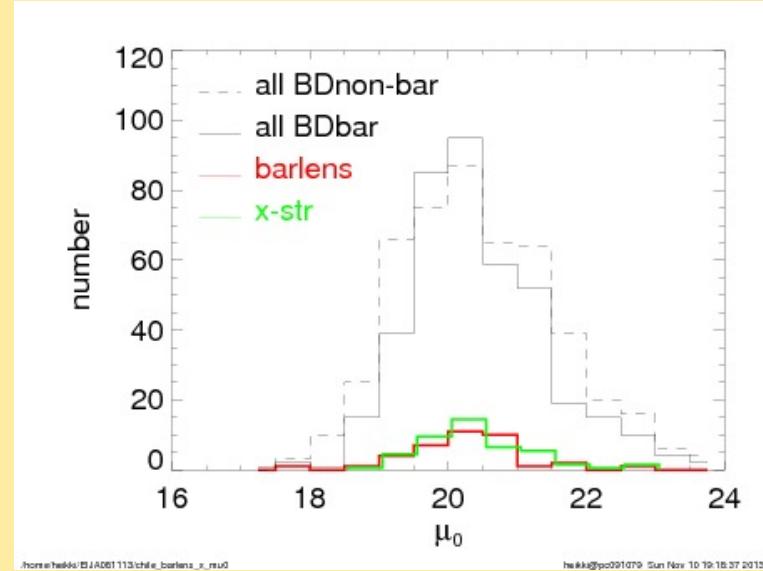


Parent galaxy sizes

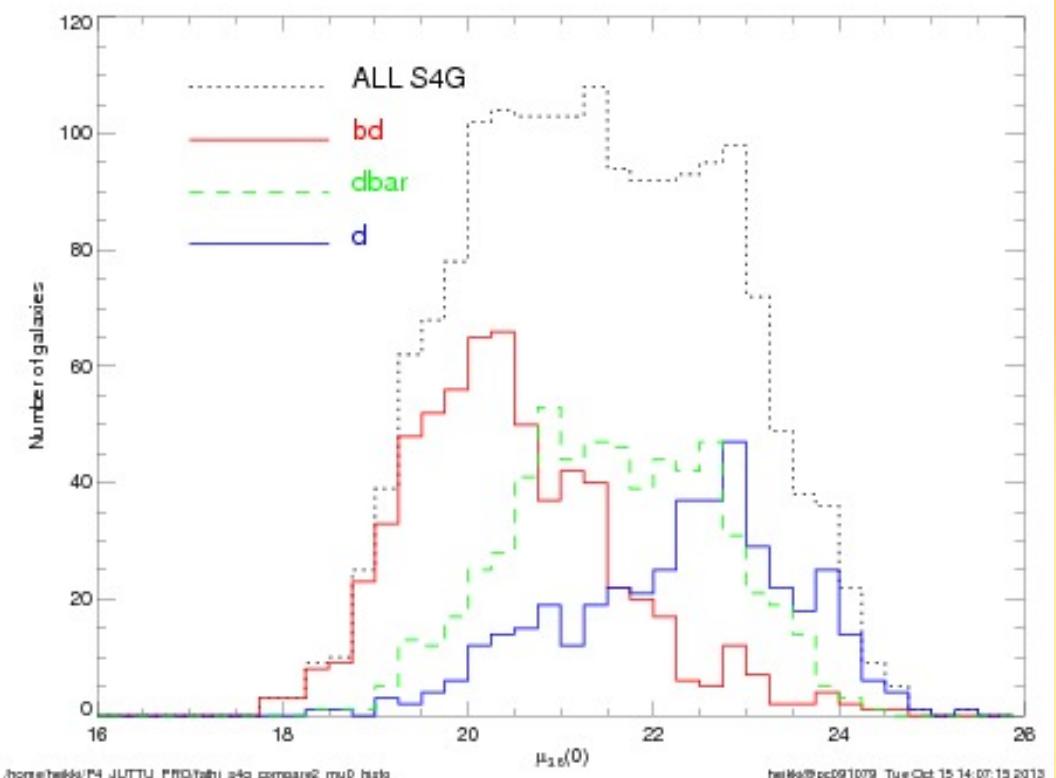


- ⇒ bl, x-str appear in bright galaxies
- ⇒ have normal h_R
- ⇒ bl peaked to earlier Hubble types

Parent galaxy disks (μ_0)



Compared to complete S⁴G

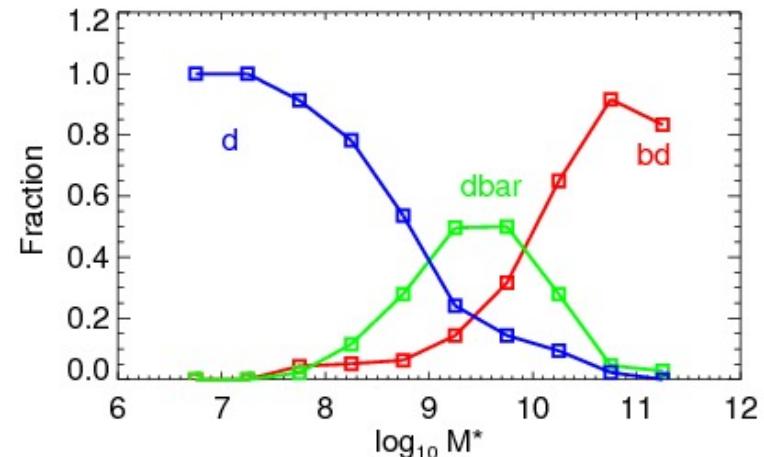
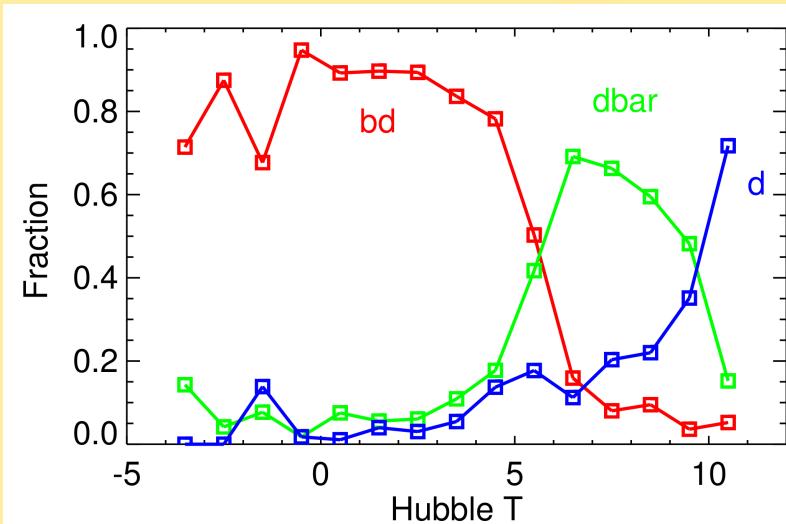


(Salo et al. 2013, in prep.)

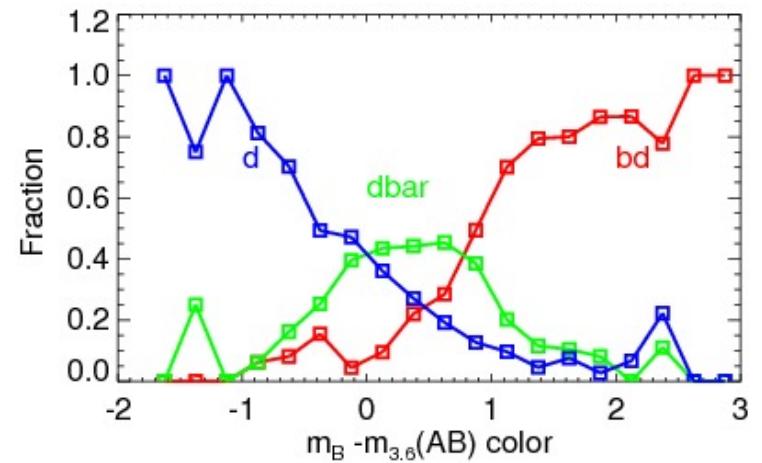
- ⇒ bl/x-str appear in bright disks (μ_0 as in normal BD-galaxies)
- ⇒ they do not appear in dbar-galaxies
- ⇒ In the complete S⁴G: $\mu_0(\text{bd}) \Rightarrow \mu_0(\text{dbar}) \Rightarrow \mu_0(\text{d})$

BBar (bl, x-str) vs. dbar in S⁴G:

(Salo et al., in prep.)



⇒ BDbar/dbar: strong function of
Hubble type, galaxy mass and color

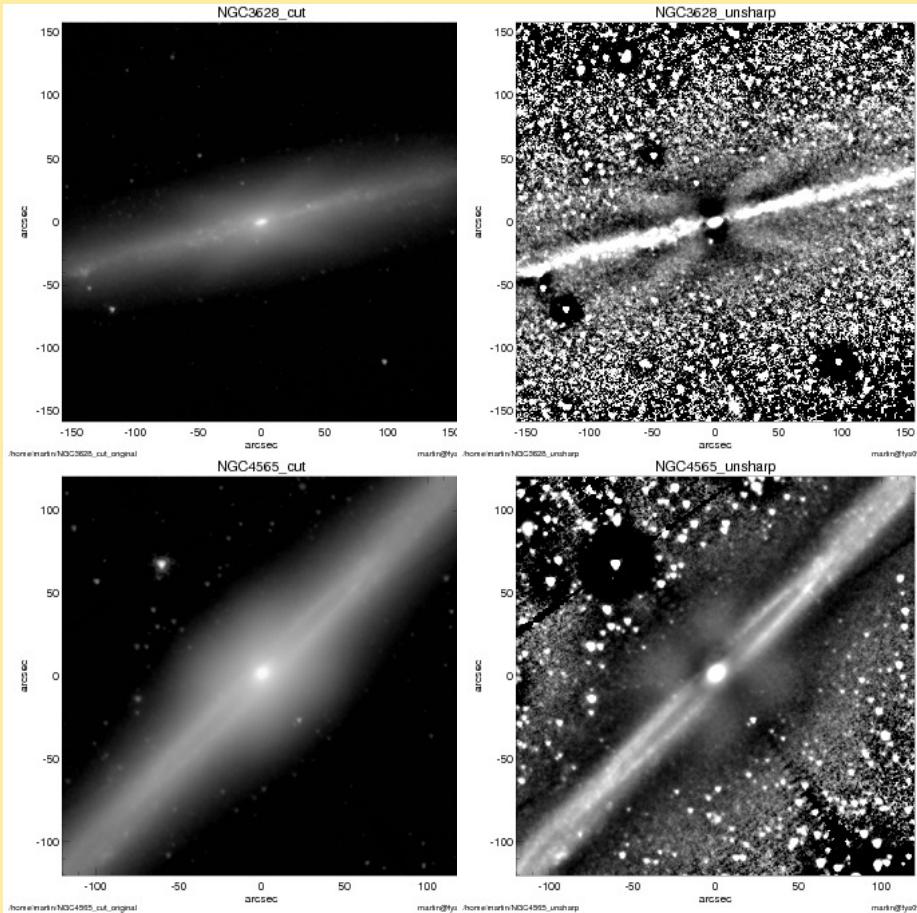


/home/heikkil/14_JUTTU_Proj/yihui/s4g_COMPARE2_bulge_fraction_vs_mass

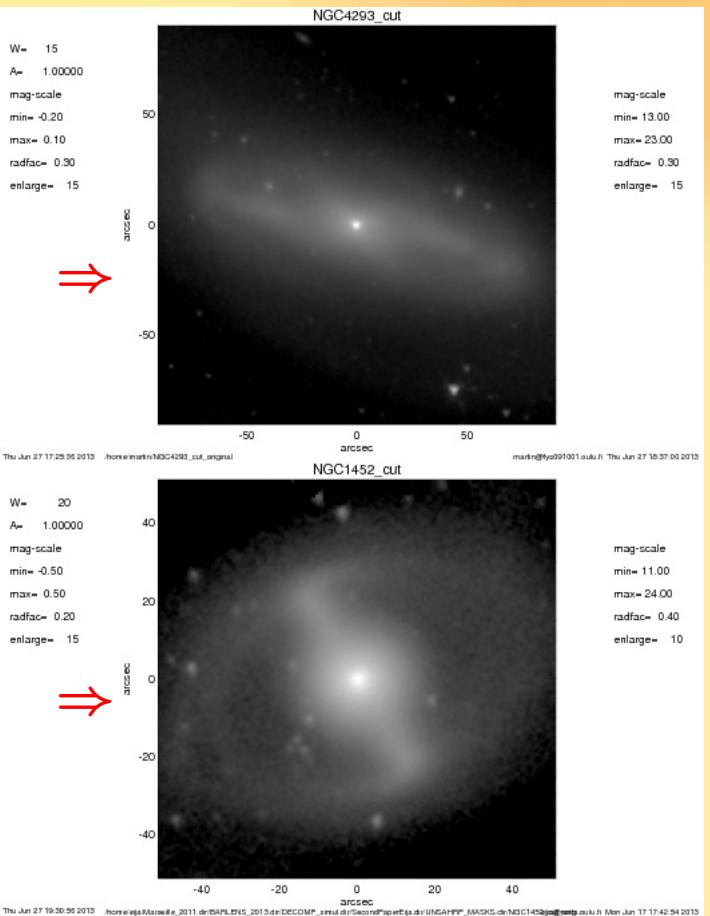
heikkil@pc091079 Wed Oct 16 13:23:51 2013

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 ($F/F(\text{tot})=0.2$ vs. 0.1)
- Both have similar small central peaks ($F/F(\text{tot}) \sim 0.1$)
- 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