Constraining the Cosmological Evolution of Disks

Kartik Sheth
Associate Astronomer, National Radio Astronomy Observatory

Cosmological Evolution / High Redshift

Bob Abraham, Lia Athanassoula, Richard Ellis, Bruce Elmegreen, Debra Elmegreen, Karin Menendez-Delmestre, Juan Carlos Munoz-Mateos, Kimberly Scott, Nick Scoville, Linda Strubbe, Diana Powell + **COSMOS Team**

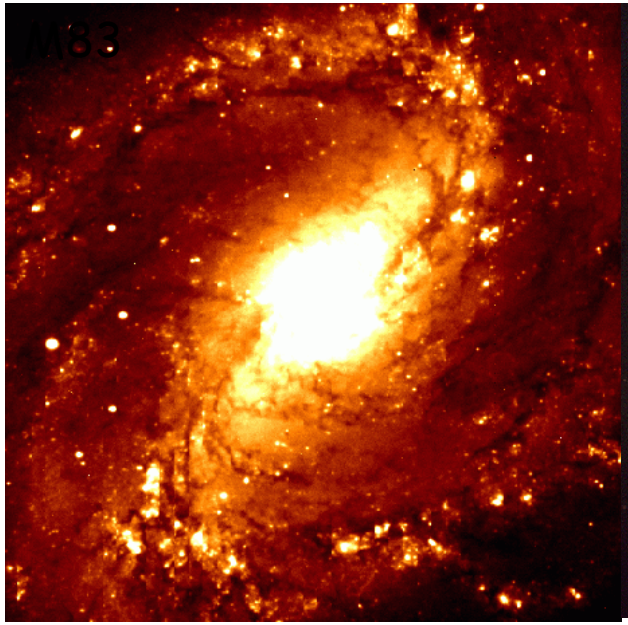
Local Universe / Secular Evolution

Taehyun Kim, Naftali Kimani, Ayodotun Agbale, Juan Carlos Munoz-Mateos, Kotaro Kohno, Andreas Lundgren, Kyoko Onishi, Mike Regan, Eva Schinnerer + **S^{4}G Team**

Magellanics / Late Types

Eric Wilcots, Elena D'Onghia, Stephen Pardy, Bonita de Swardt, ++

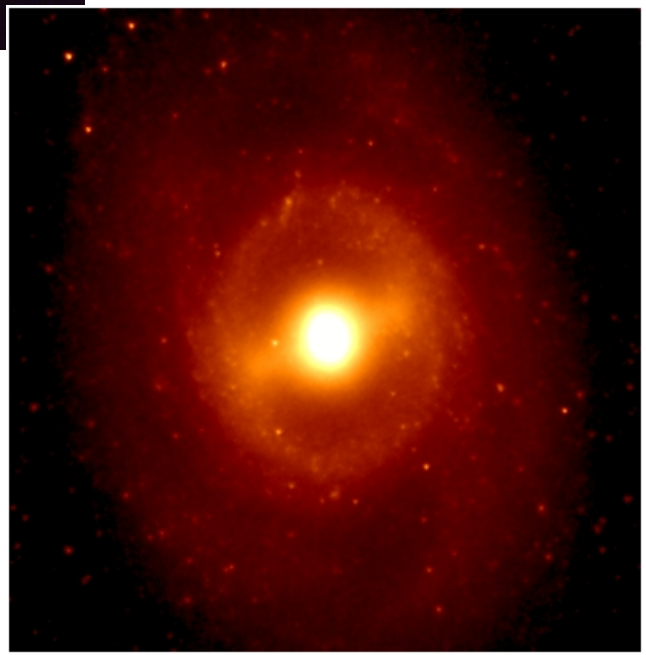
You wanna' go where everybody knows your name…



- **27.6% SAB**
- **36.8% SBs**

(RC3, De Vaucouleurs '63)

- Tri-axial non-axisymmetric stellar structures
- Dust lanes -> pipelines for gas inflow
  (Sheth et al. '00, 02, '05; Regan et al. '95, 99)
- Rings + lenses common in barred spirals
  (Buta & Combes ' 96, S^{4}G --> Comeron et al. 2013)
- Distinct differences in bar properties between early and late Hubble types (e.g., Elmegreen ' 96; **S^{4}G --> Kim et al. 2013a,b**)



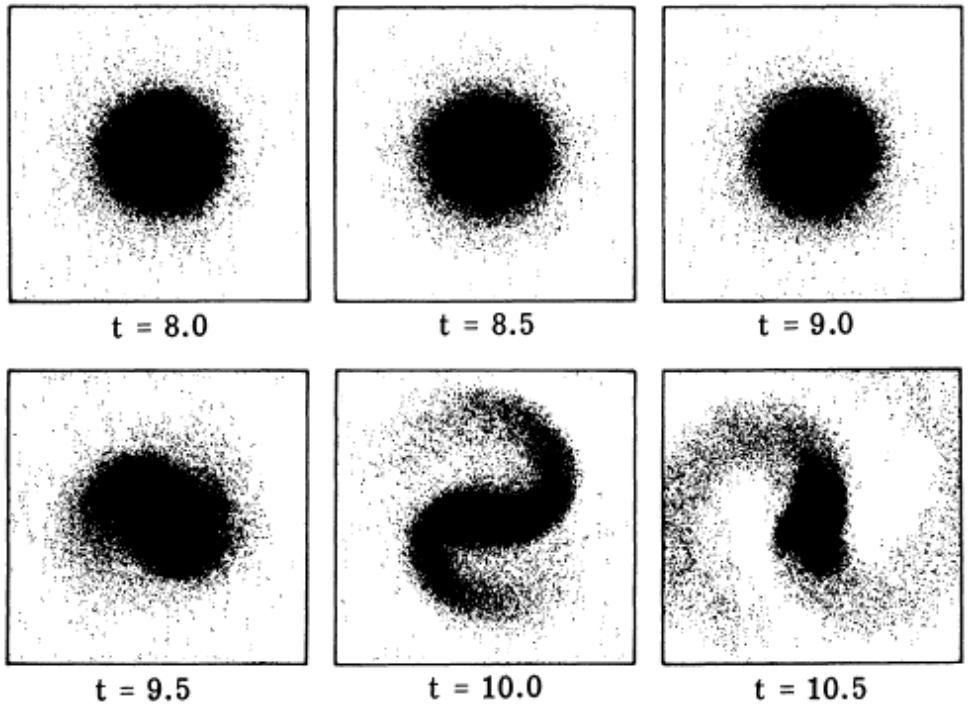
Bars: A Cosmological Signpost of Disk Maturity

A "troublesome" mode
(Kalnajs '72)

Bars always form (quickly) in isolated, cold, massive, rotationally-supported disks
(Ostriker & Peebles '73)

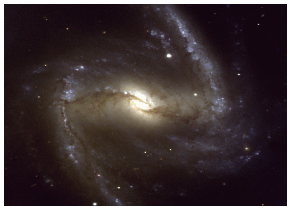
Even in disks originally dominated by dark matter - bars form
(Athanassoula '02,' 03;Athanssoula & Sellwood '86)

Hohl '71



- **Epoch of Bar Formation & Evolution of bar fraction -> dynamically cold, massive disks -> assembly of Hubble sequence**
  - *mergers / interactions

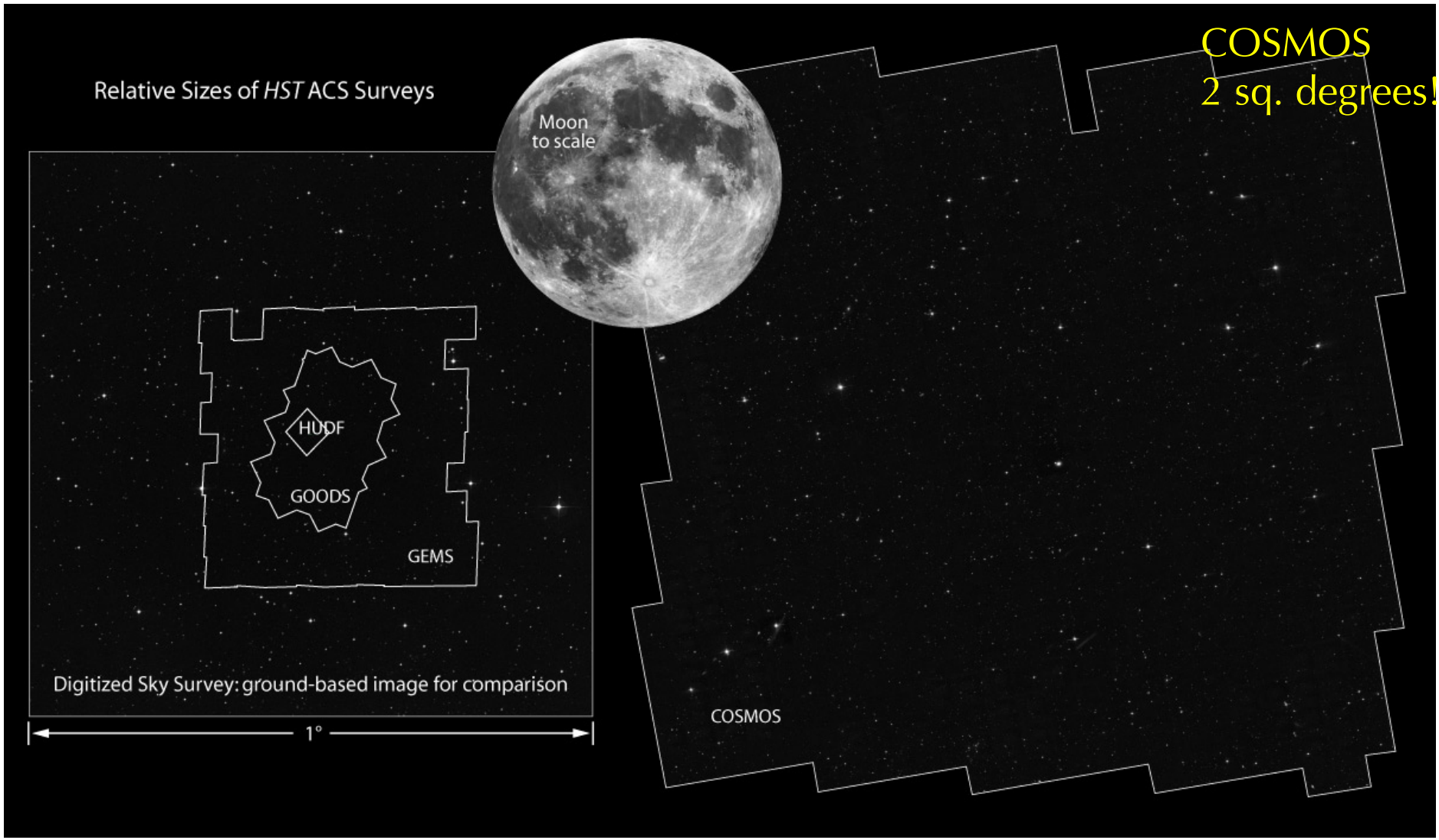
Using Bars to Infer Galaxy Disk Assembly



- **How does the bar fraction vary with redshift?**
- A decade of controversy before our COSMOS work:
  - Dramatic paucity of bars at z > 0.5 (van den Bergh '96; Abraham et al. '99)
  - Large bar fraction similar at high and low-z in NICMOS-HDF (Sheth et al '03)
  - Bar fraction constant to z~1 but small samples, poor selection / completeness (Elmegreen et al '04; Jogee et al '04)
- **What is the relationship between bars and the host galaxy disk?**

Ongoing / possible future studies:

- How do bar properties (length, ellipticity) vary w/ z?
- Bars & AGN activity, star formation
- Bars & environment
- 5% NICMOS / CANDLES parallels --> analysis to z > 0.835

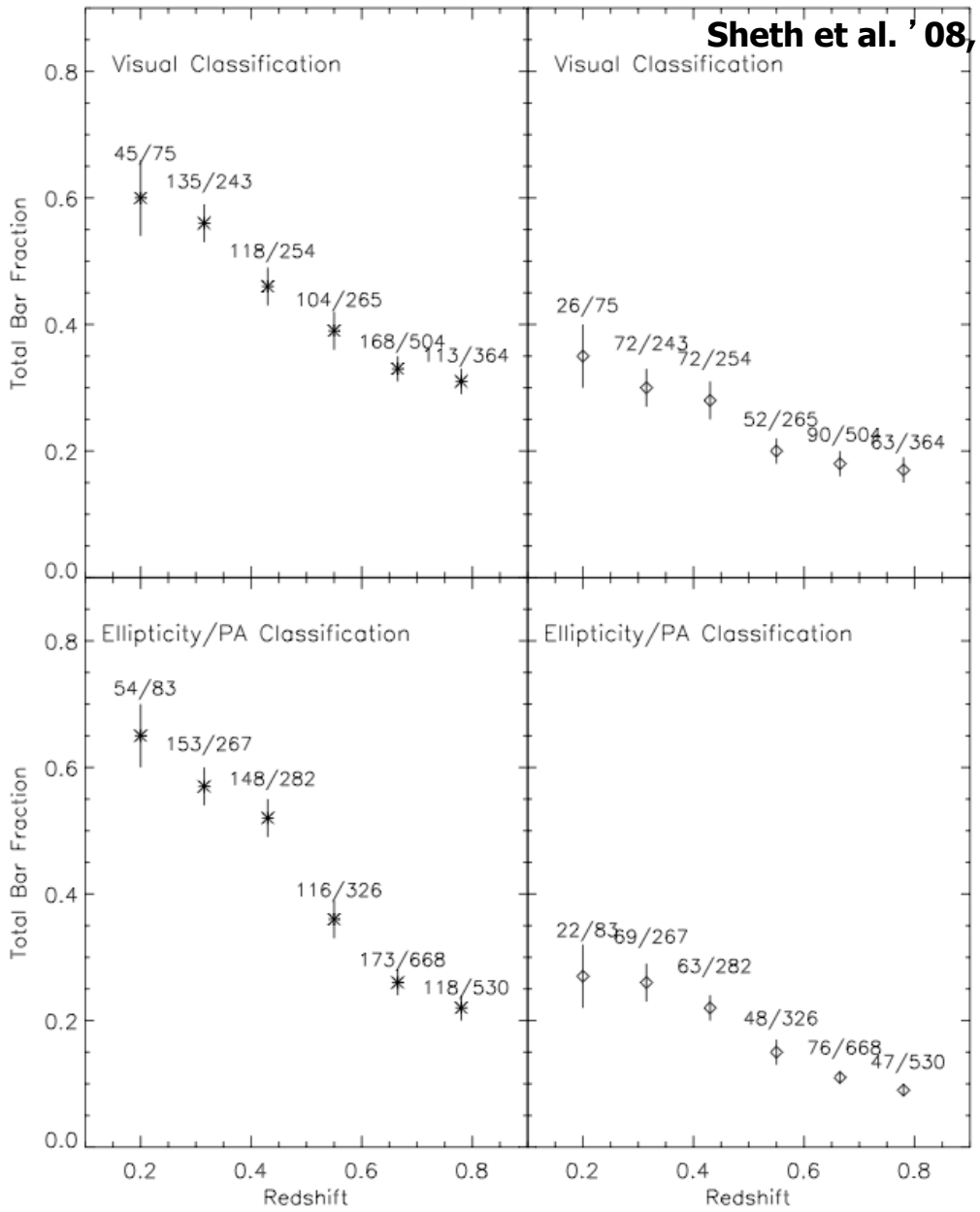


590 orbits ==> 2 square degrees

-- 9 x any previous HST image

2 million galaxies at z ~ 0.2 to 5 (SDSS at high z)

The Cosmological Evolution of Barred Spirals



A Steadily Declining Bar Fraction!

- L* and brighter **disk** galaxies
- $z < 0.85$
- Complete sample for $D < 20$ kpc
- Complete sample for $M > 1\text{--}3 \times 10^{10} M_{\odot}$
- $i < 65$
- 2,157 disks, 10x previous studies

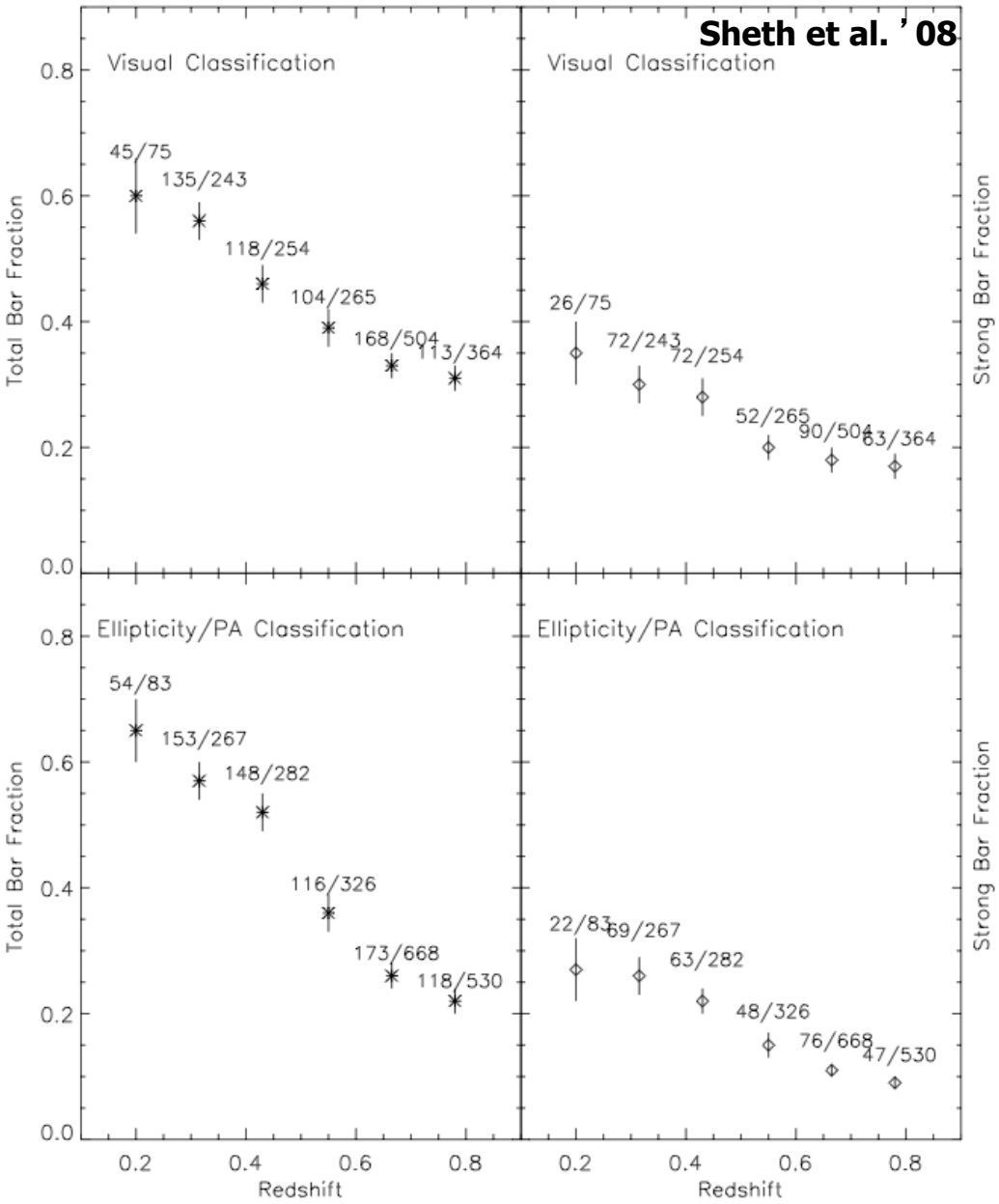
F_{bar} = Barred / Disk Galaxies

Disk galaxies --> Sa - Sd (color priors).

Contrary to previous results, we find:

- **Significant evolution**
- **$f_{bar} = 0.65 \rightarrow 0.22$**
- **$f_{stbrs} = 0.27 \rightarrow 0.09$**

The Cosmological Evolution of Barred Spirals



A Steadily Declining Bar Fraction!

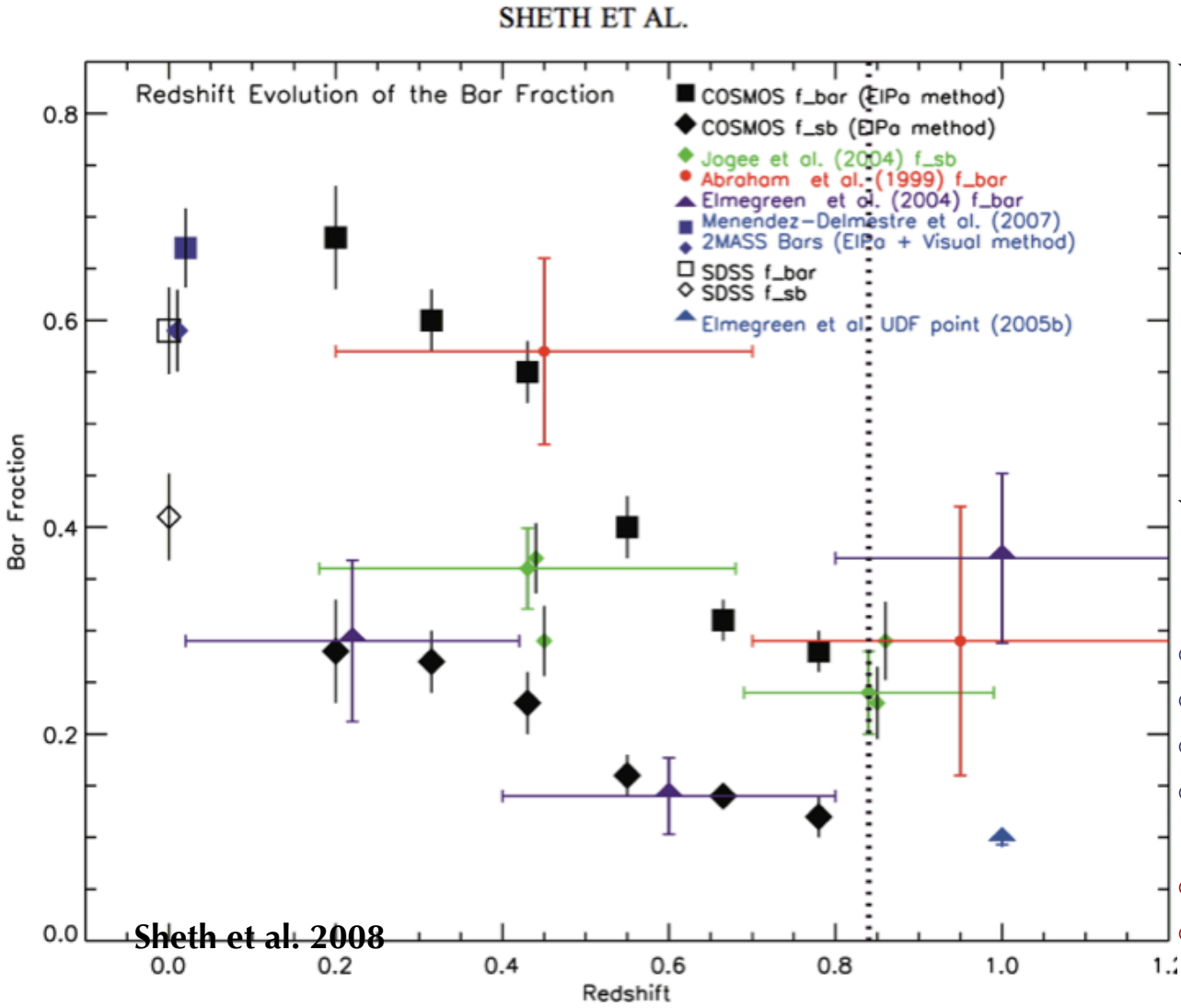
- Careful analysis of completeness and selection effects:

- Number statistics / errors
- K-correction / band shifting
- Surface brightness dimming
- Resolution/PSF effects
- Peculiar / merging galaxies

SIGNIFICANT DECLINE IN THE BAR FRACTION

- $f_{bar} = 0.65 \rightarrow 0.22$
- $f_{stbrs} = 0.27 \rightarrow 0.09$

A Decade of Controversy Laid to Rest



Sheth et al. 2008

★Consistent with previous HDF & NICMOS studies (Abraham '99, Sheth '03)

★ALL data from past studies in line with the detailed 1 Gyr bin evolution with COSMOS from our work!

★ Multiple follow-on studies confirm results:

- Cameron et al. 2010
- Masters et al. 2011
- Melvin et al. 2013
- Harrington et al. 2013

- Kraljic et al. 2012
- Athanassoula 2012, 2013a,b

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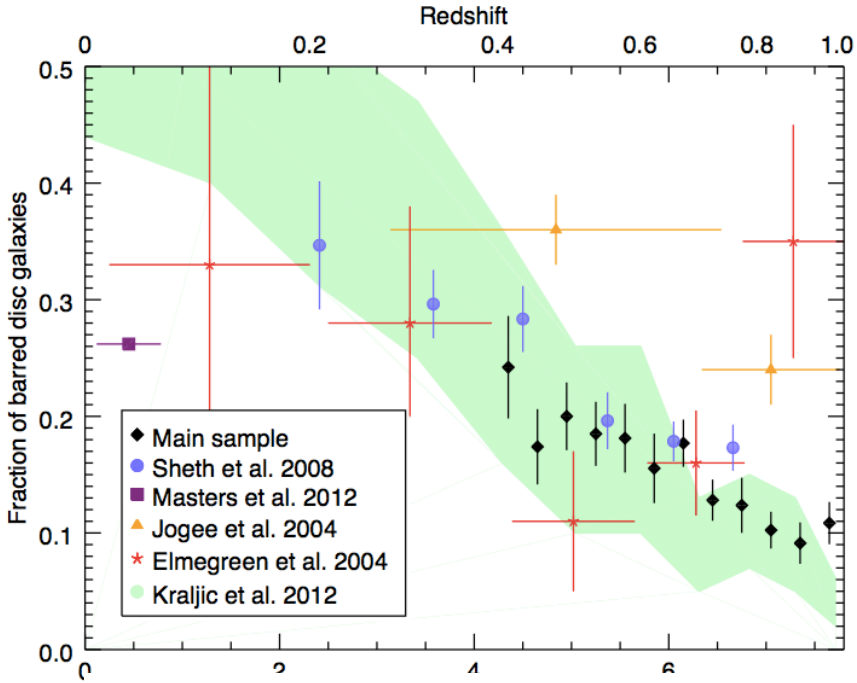
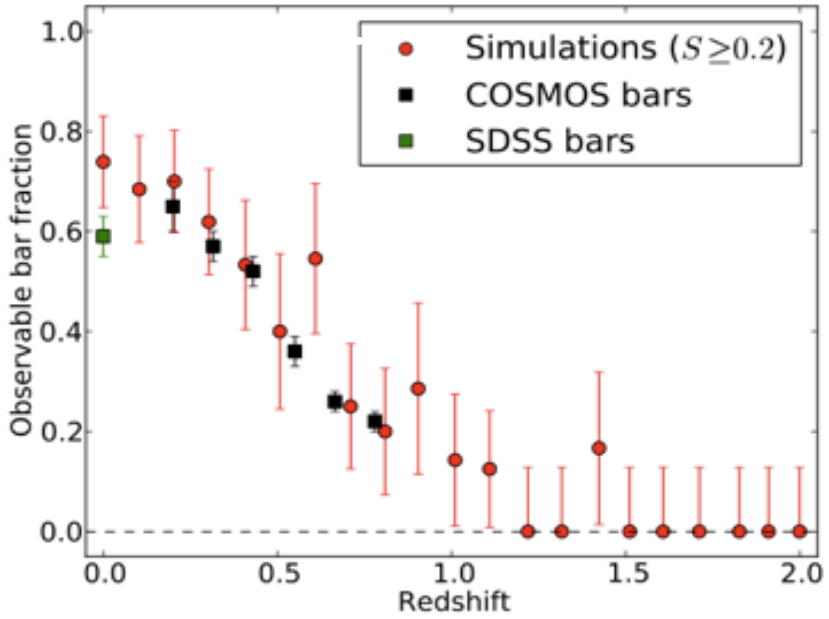
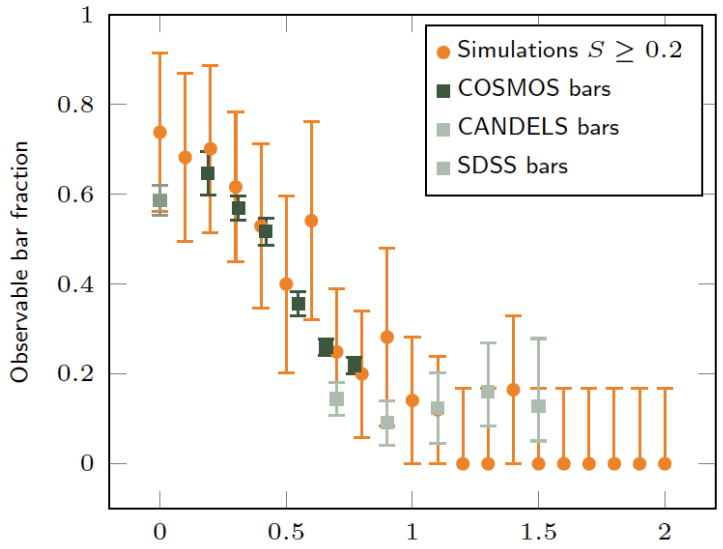


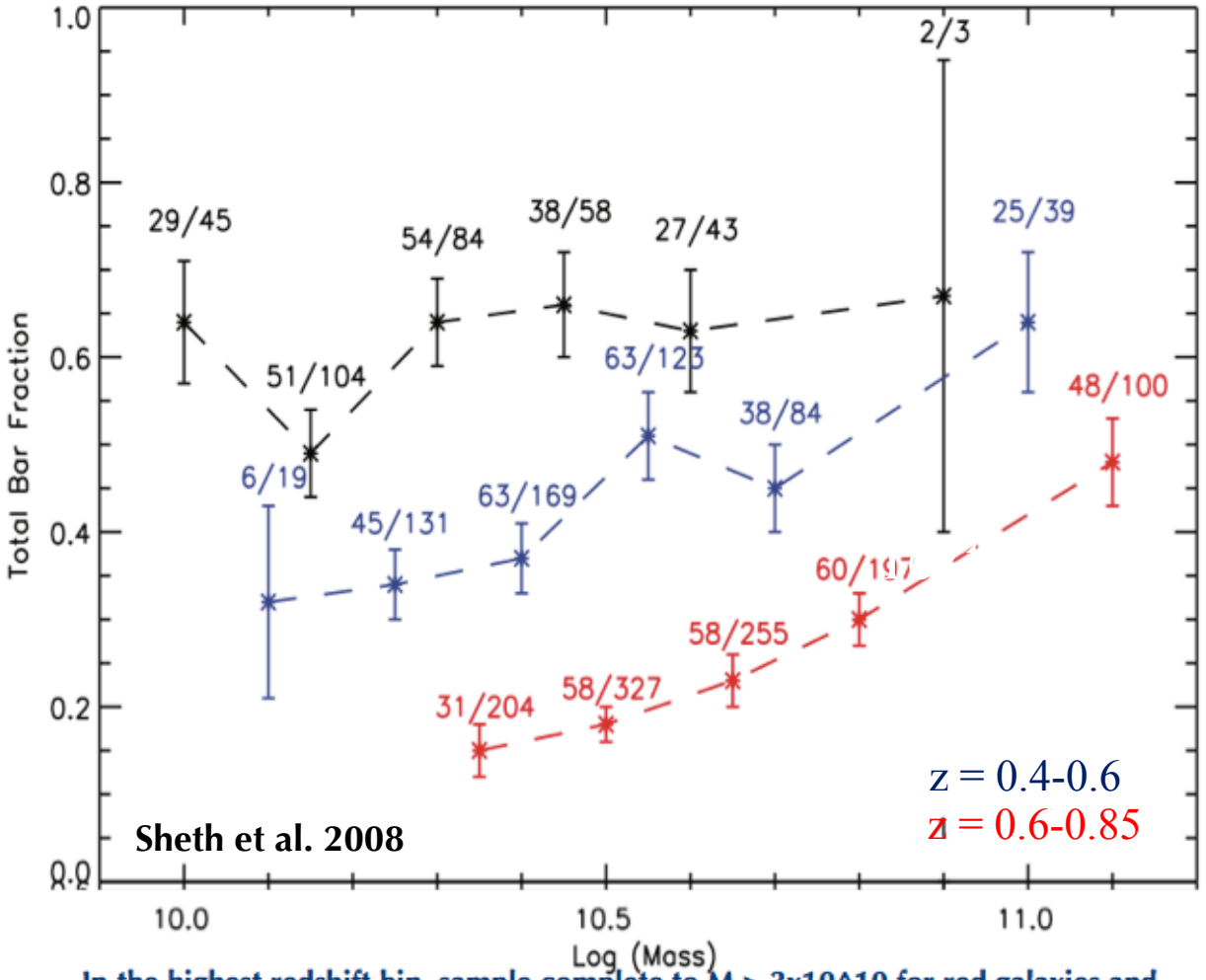




- **Melvin et al. 2013**
- **Harrington et al. 2013**

- **Kraljic et al. 2012**
- **Athanassoula 2012, 2013a,b**

Evolutionary Trends: Clues towards Downsizing

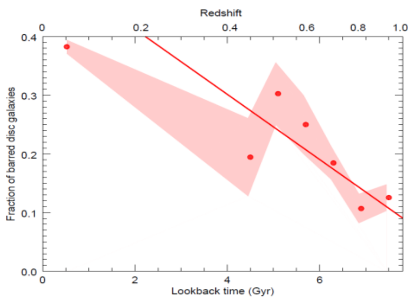


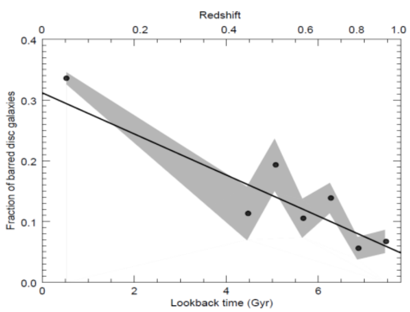
In the highest redshift bin, sample complete to M > 3x10^10 for red galaxies and 10^10 for the blue galaxies (Bell et al. '05 & Maraston et al. 2005 models)

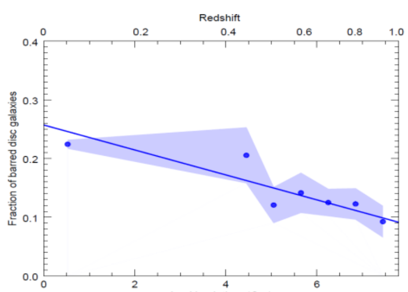
Bar fraction vs. M_V /Mass

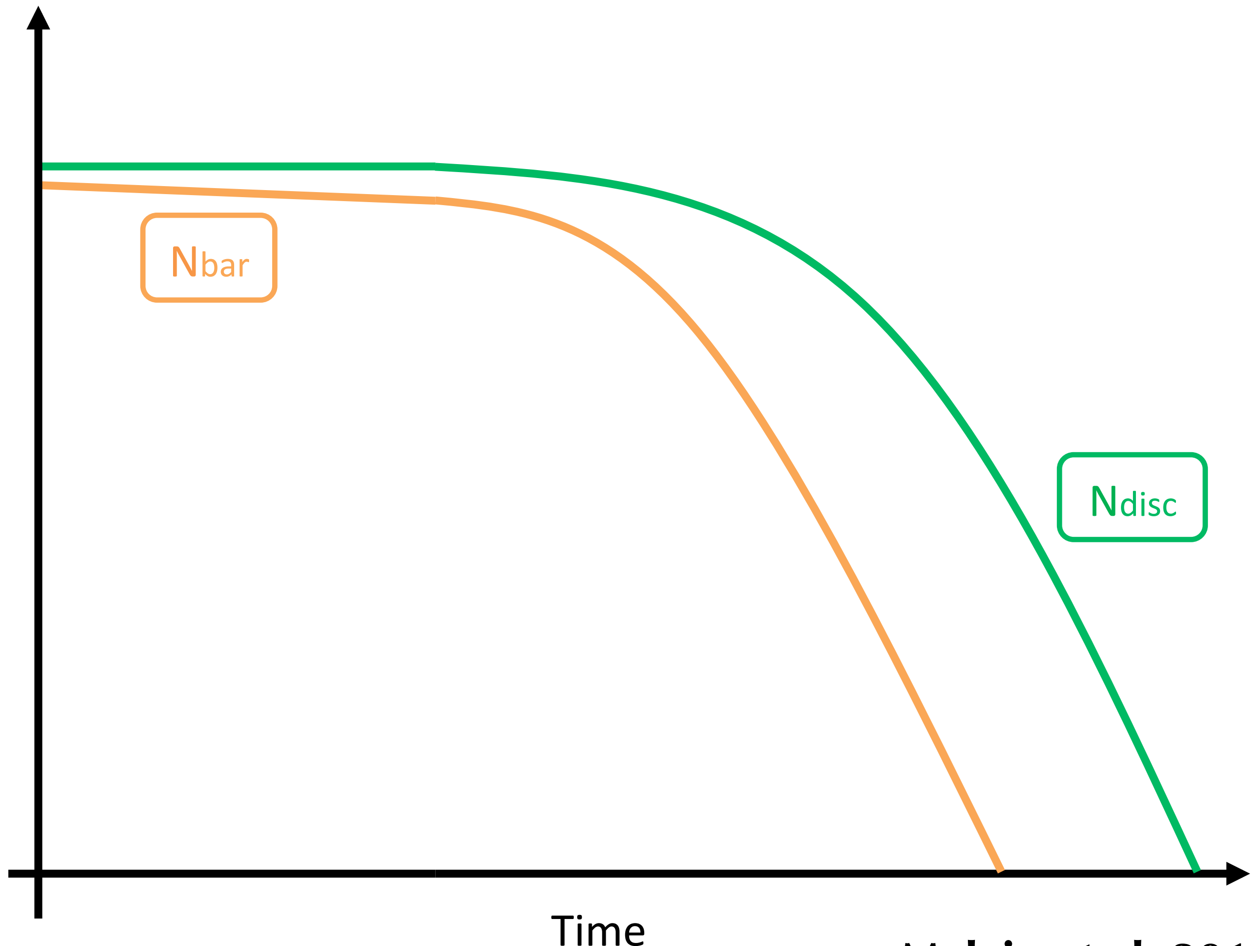
- Bar fraction is high in massive / bright galaxies in the high-z bin
- Majority of the evolution is taking place in the lower mass bins
- Evolution must be continuing today - need to check the lower mass bins

What drives the mass evolution of f_b?









- **Melvin et al. 2013**

tom.melvin@port.ac.uk

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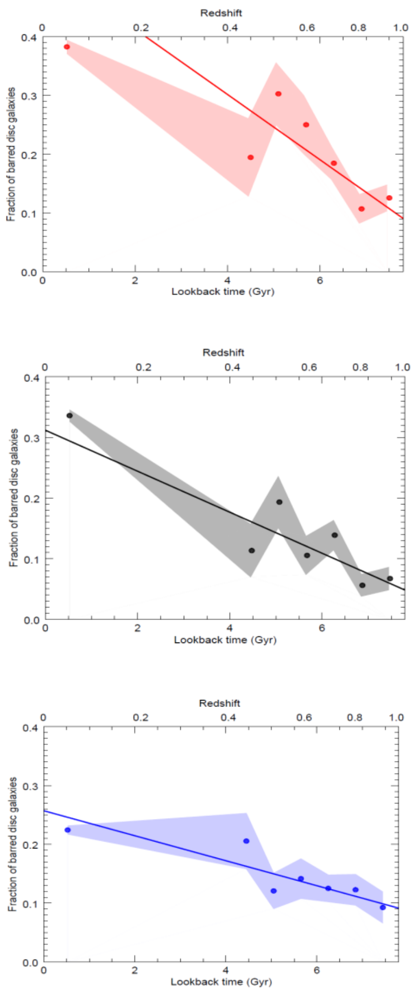

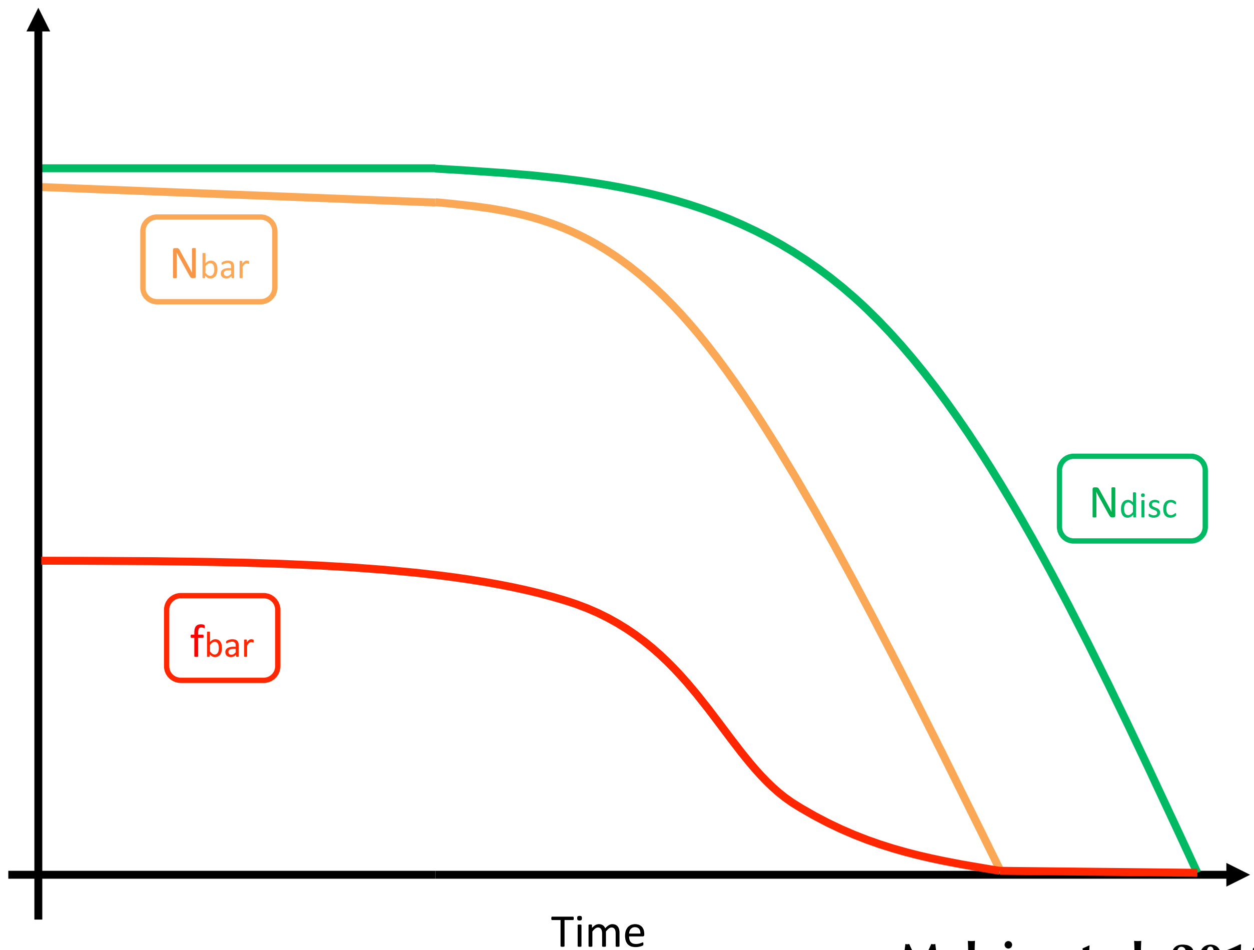

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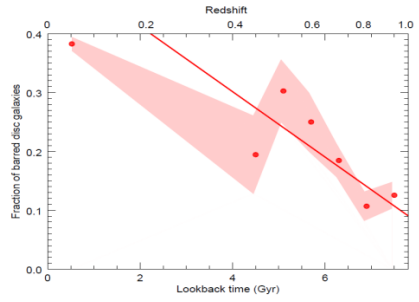

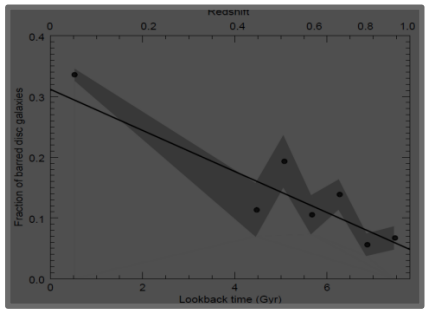

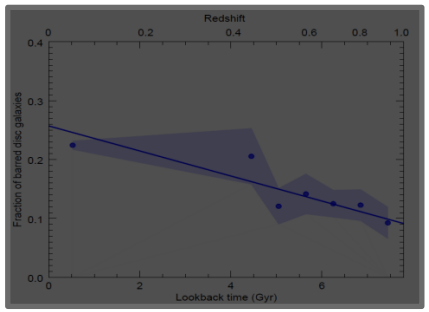

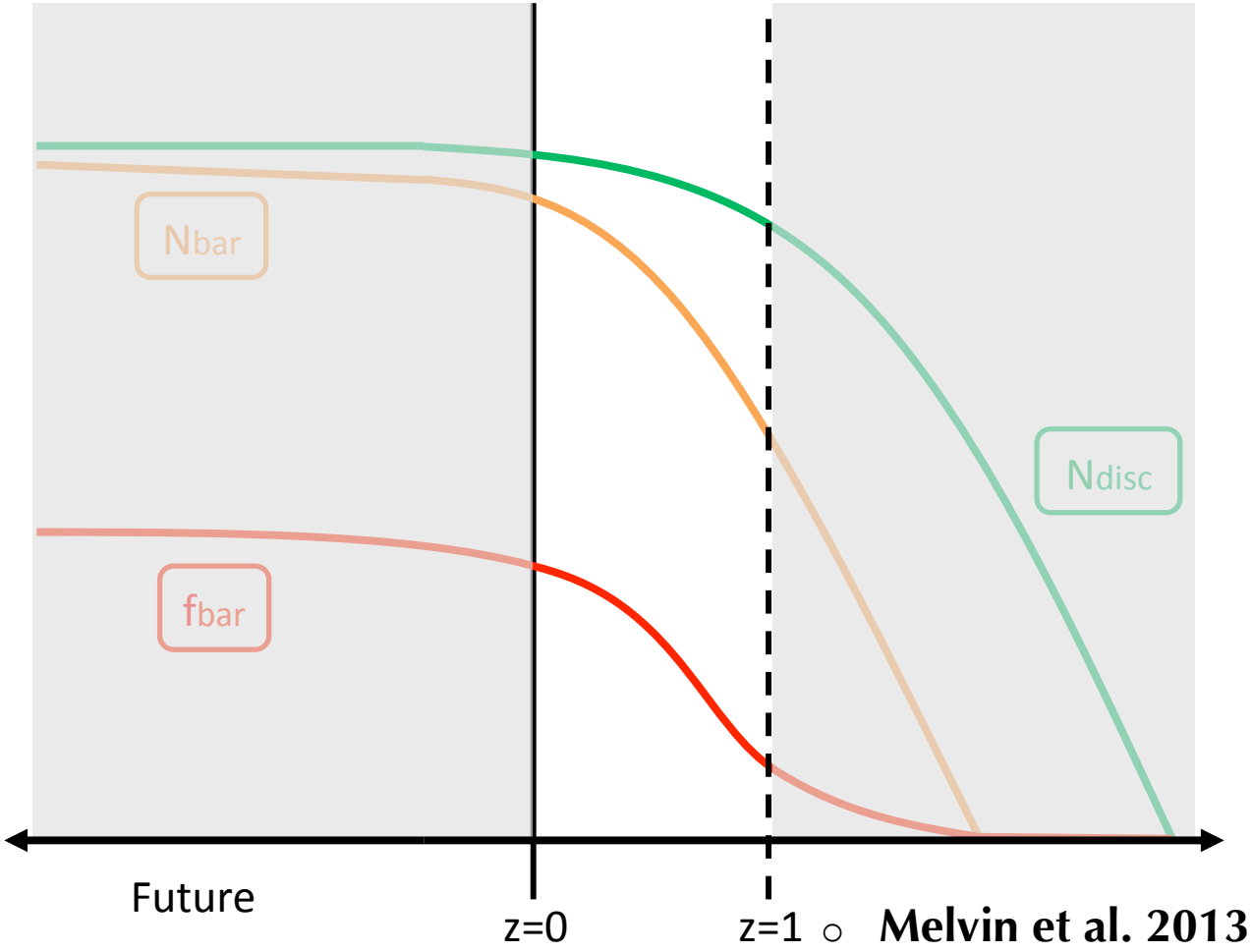

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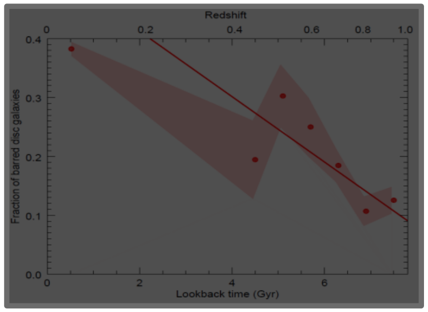

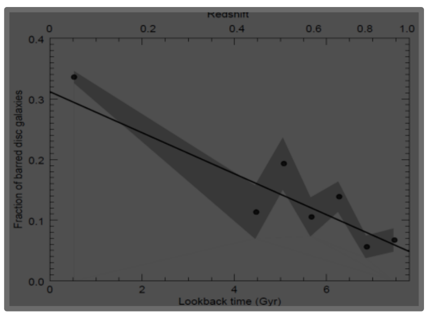

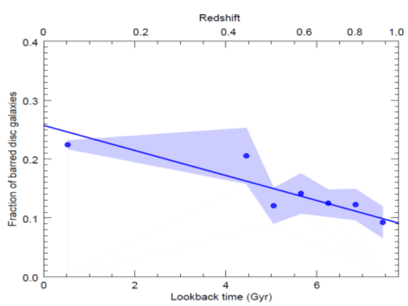

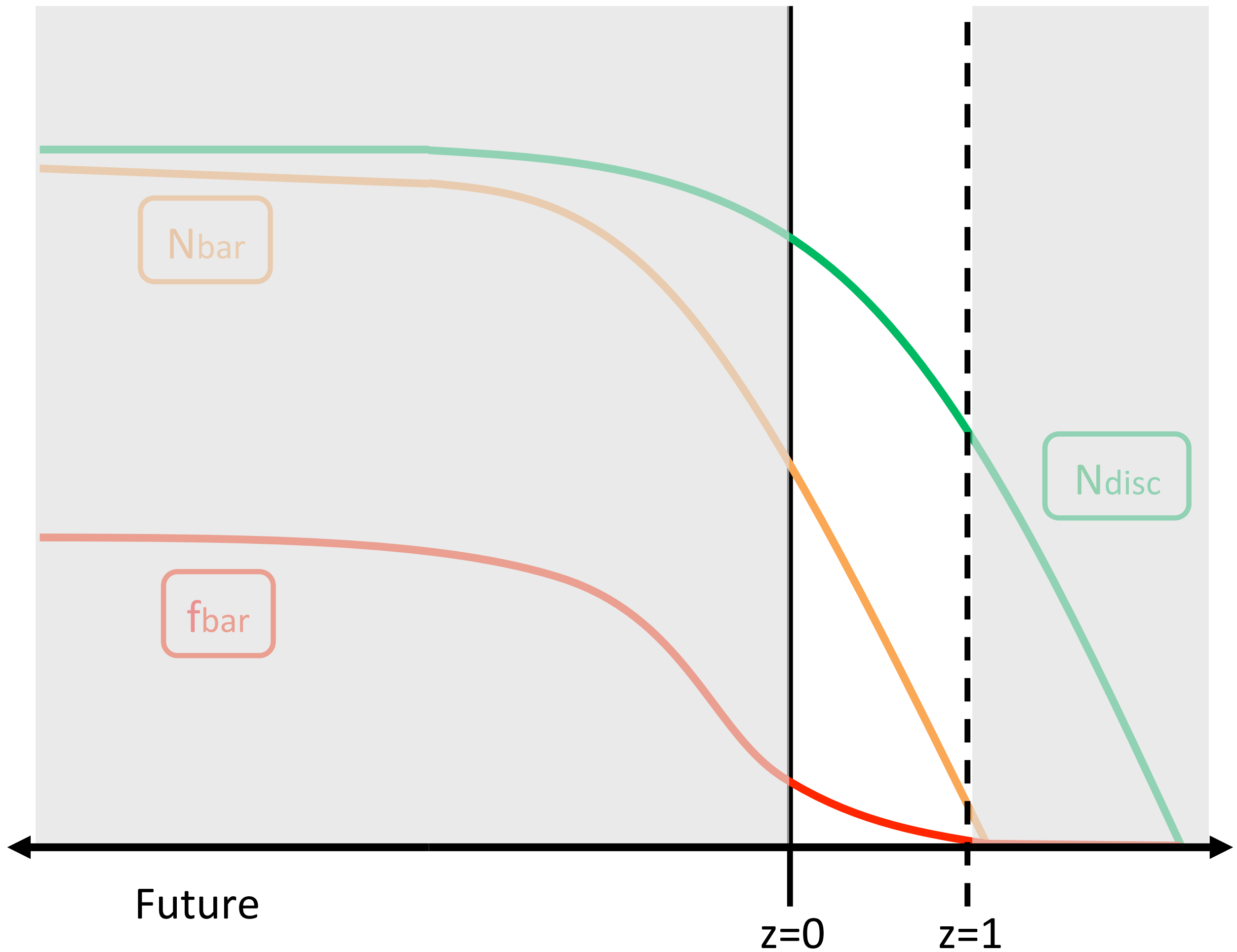

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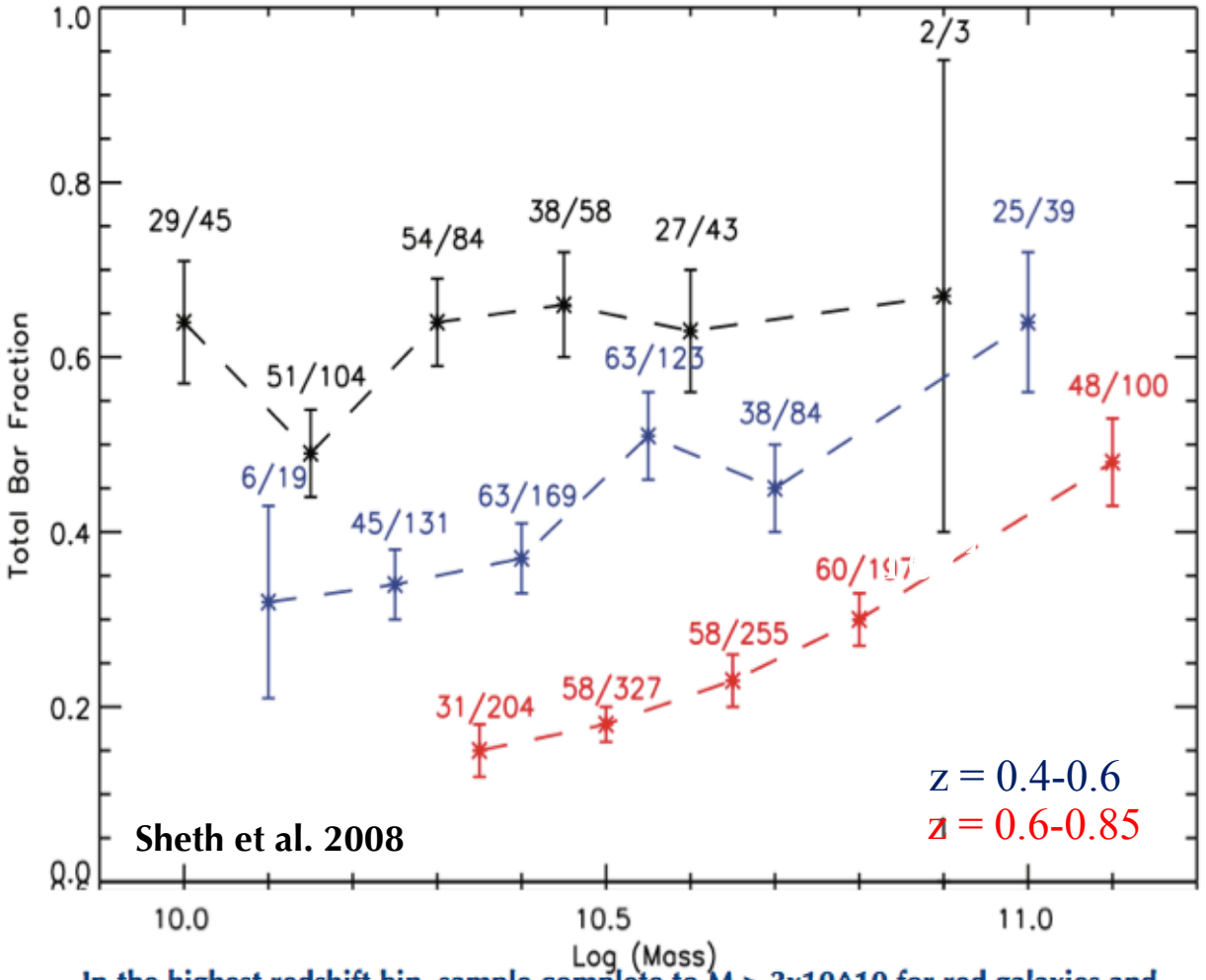
Evolutionary Trends: Clues towards Downsizing



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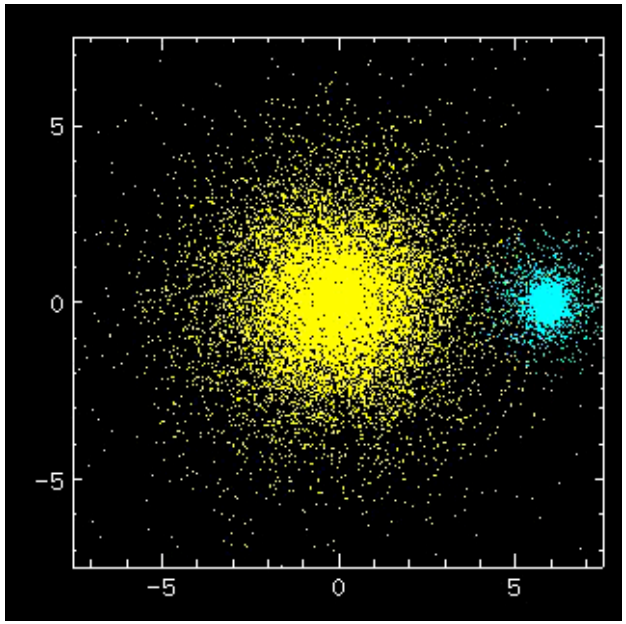
Interpretation of the Cosmological Evolution

In the framework of classical bar formation:

- Sufficiently hot disks embedded in massive halos can remain unbarred for a long time.
- To get observed slope, most bars should take between 3--7 Gyr to form (if t_{form} at z~2)



Interactions / Mergers:

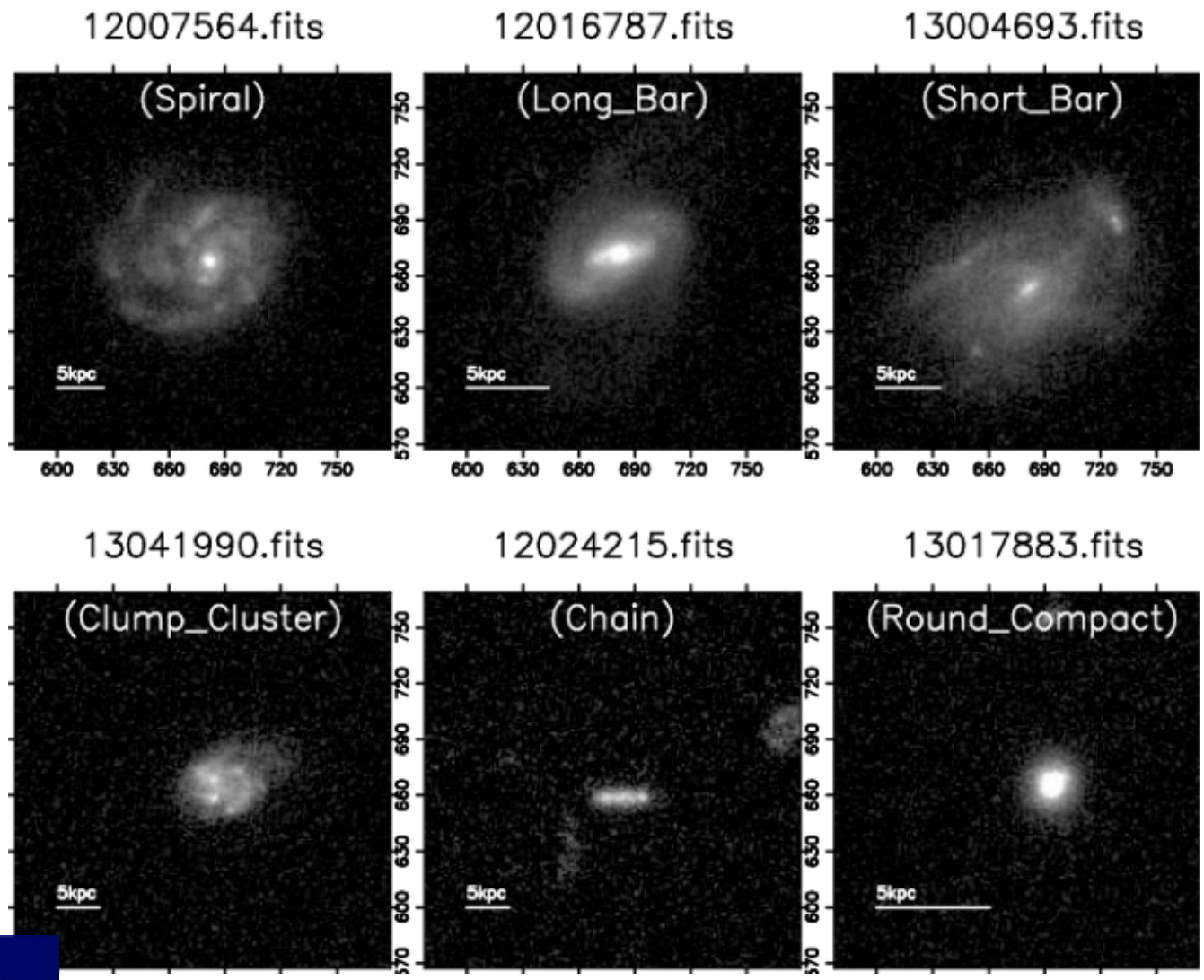
- Create and destroy bars
- Full parameter space remains unexplored - theorists rejoice!
- Requires detailed modeling

It may be that the low mass systems are dark matter dominated and therefore take longer to form structures (favored by theorists)

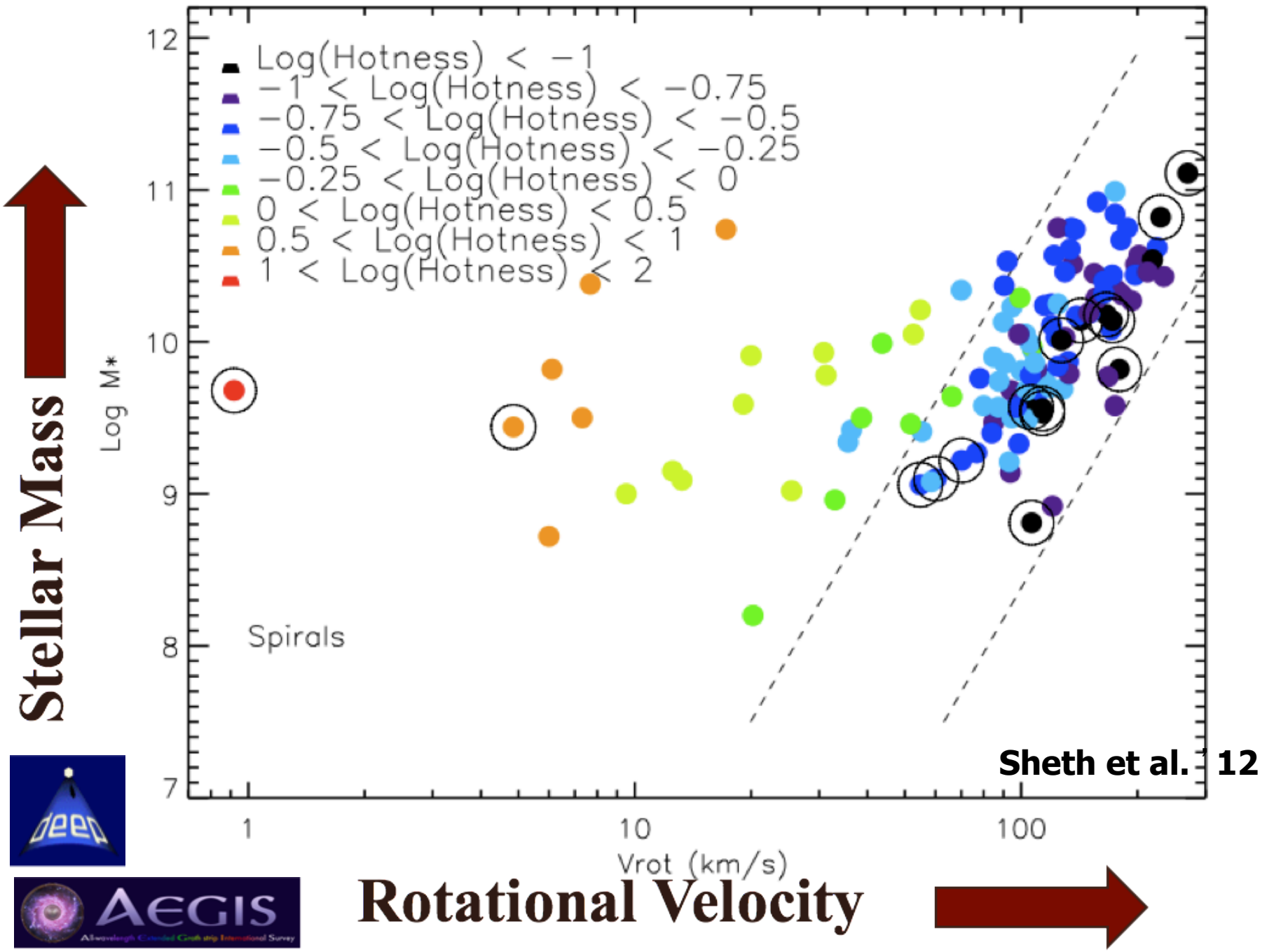
Or it may be that at higher redshifts, smaller and less massive galaxies experience higher levels of harassment and therefore may remain dynamically hot and therefore bar-free?

Are Dynamically Hot Disks Preventing Bar Formation?

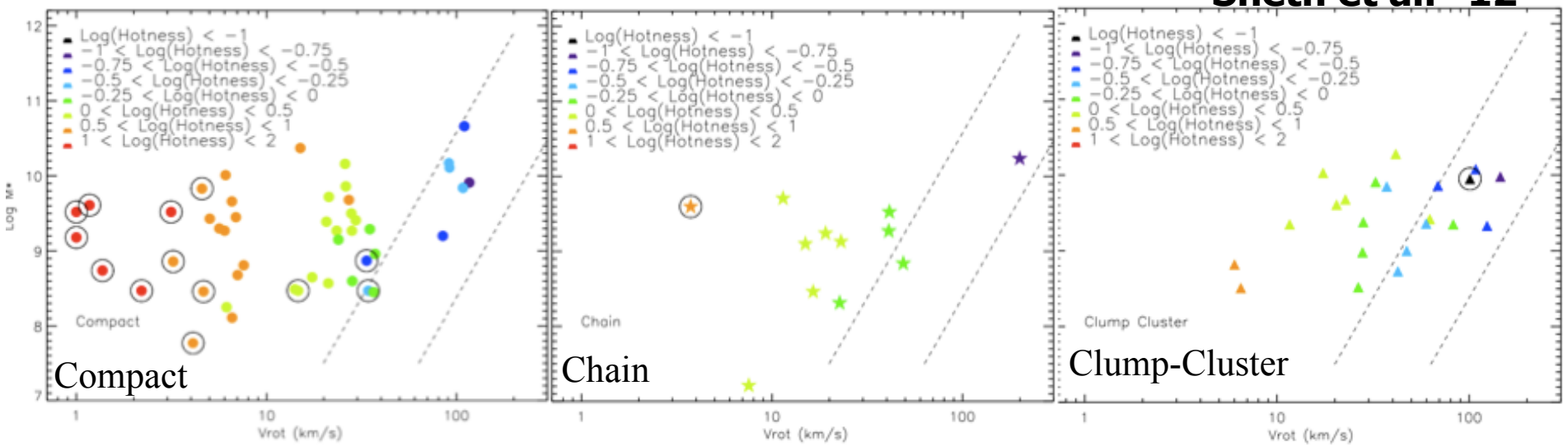
- Initial sample: 544 emission line galaxies from the DEEP2 / AEGIS field (Weiner et al. 06a,b; Kassin et al. '07)
- Chose all L* & brighter, non-interacting, face-on systems, as in COSMOS
- $0.2 < Z < 0.85$
- Classified them into spirals, bars, compacts
- Compared to previously measured dynamical properties



Sheth et al. 2012

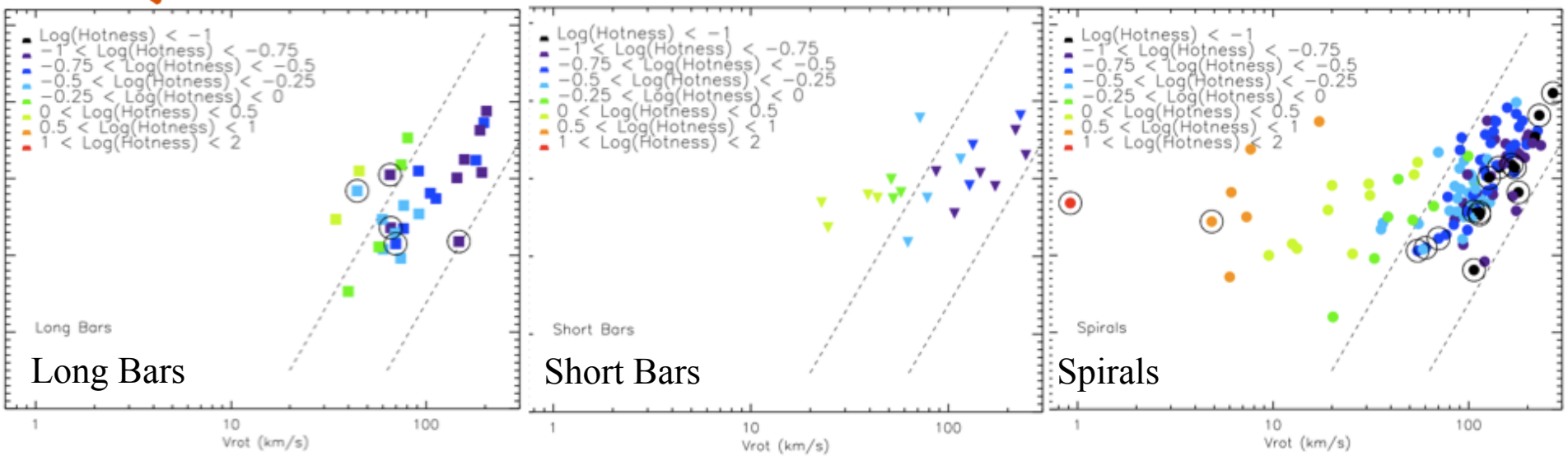

Log(Hotness) < −1
−1 < Log(Hotness) < −0.75
−0.75 < Log(Hotness) < −0.5
−0.5 < Log(Hotness) < −0.25
−0.25 < Log(Hotness) < 0
0 < Log(Hotness) < 0.5
0.5 < Log(Hotness) < 1
1 < Log(Hotness) < 2
Spirals
Log M*
Vrot (km/s)
12
11
10
9
8
7
1
10
100
Stellar Mass
Rotational Velocity
Sheth et al. '12

Sheth et al. ’12



Compact Chain Clump-Cluster

Evolutionary Sequence?

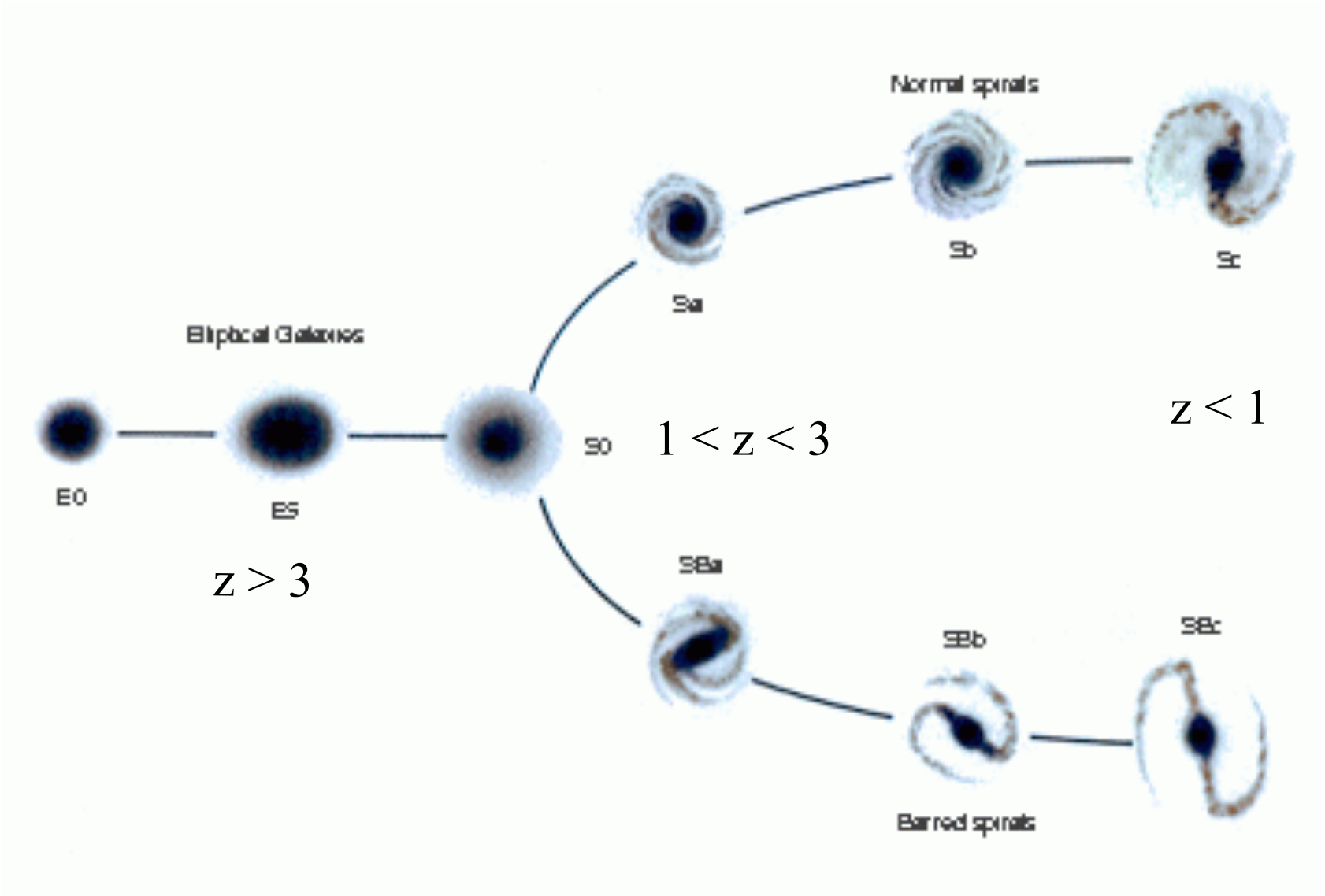


Long Bars Short Bars Spirals

Bar Formation & State of Disks

- Bars are not present in dispersion-dominated disk galaxies.
- Data suggest an evolutionary sequence:
  - Clump-cluster &chain galaxies → rotationally-supported disks on the TF
  - But the precise migration to the TF not well-understood
- No obvious difference in the placement of barred and unbarred spirals on the TF, as in local Universe (Courteau 2003).
- Interaction history between the baryonic matter and the dark matter halo, especially in the inner parts of disks,critical for formation of bars.

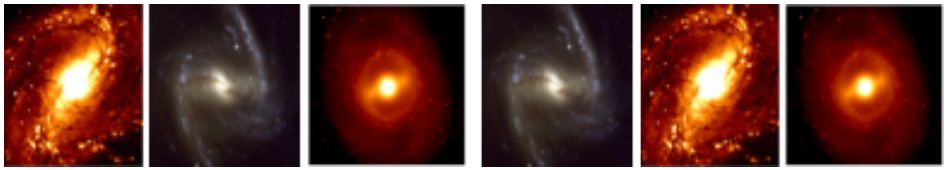
Assembly History of the Hubble Sequence



What we know (and don't know)

- The total bar fraction in >L* disks declines by x3 over the last 7 Gyr.
  - f_{bar} = 0.65 -> 0.22, f_{stbrs} = 0.27 -> 0.09
  - HDF, NICMOS-HDF, GEMS, UDF, COSMOS - all are consistent
  - **Need JWST for pushing further in redshift space**.
- The decline is stellar mass (and color, bulge-domination) dependent
  - More massive galaxies formed their bars first (Downsizing!)
- Bars are **not** present in dispersion-dominated galaxies
  - Evolutionary sequence from clump cluster -> disks -> bars?
  - Being on TF is a necessary but not sufficient condition
  - Evolution / interaction with DM halo likely plays a role in bar formation
- Simulations beginning to reproduce observations
  - Gas fraction may also play an important role in slowing bar formation
- Is there a ceiling to bar fraction?
  - What fraction of bars are destroyed but leaves behind a disk / can they reform?
  - How does the fraction vary within groups and clusters?
- How do bar **and gas** properties vary with redshift?
- How do bars influence AGN & star formation activity?

The Local Bar Fraction



What is the precise local bar fraction?
What is the distribution of bar properties
How do these vary with galaxy host & environment?

Bar Fractions:

60-70% (a majority of the studies - (deVaucouleurs et al ' 63, Eskridge et al. '02, Menendez-Delmestre et al. '07, Marinova et al. ' 07, Sheth et al. ' 08)

25-40% (some reasonable, some delusional studies)

A variety of factors affect measurement of this value *f_bar*
Different definitions of a bar.
Sample size and completeness
Sample selection criteria (esp. the denominator)
Quality of data.

Since bars are stellar structures you need a large, homogenous, deep, infrared survey to settle these simple but fundamental questions?

THE SPITZER SURVEY OF STELLAR STRUCTURE IN GALAXIES (S^4G)

is the largest and deepest, homogeneous survey of nearby galaxies at mid-infrared wavelengths!

S^4G was the **only** nearby galaxies Exploratory Program chosen in Cycle 6 (first Warm Mission cycle)

THE S^{4}G TEAM

Kartik Sheth, NRAO/Caltech, PI
Michael Regan, STScI (D-PI, SAC) + Pipe 1
Joannah Hinz, MMTO/U. AZ, (D-PI, SAC)

S^{4}G Data Products brought to you by..

Core Data Team
Taehyun Kim, NRAO/SNU - Pipe 2
Juan Carlos Munoz–Mateos, NRAO - Pipe 3
Eija Laurikainen, University of Oulu - Pipe 4
Heikki Salo, University of Oulu - Pipe 4
Dimitri Gadotti, ESO - Pipe 4
Sebastien Comeron, Oulu - Pipe 4
Jarkko Laine, University of Oulu - Pipe 4
Sharon Meidt (MPIA) - Pipe 5
Miguel Querejeta (MPIA) – Pipe 5
Mauricio Cisternas (IAC) - Pipe 5
Armando Gil de Paz, UCM, Madrid (SAC)
Karin Menendez–Delmestre, U. Valongo
Mark Seibert, OCIW
Trisha Mizusawa, Florida Institute of Tech

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Debra Elmegreen, Vassar College
Eva Schinnerer, MPIA, Heidelberg
Dennis Zaritsky, U. Arizona

THE S^{4}G TEAM

Active team members

Ron Buta, U. of Alabama
Luis Ho, OCIW
Bruce Elmegreen, IBM
Lia Athanassoula, OAMP, France
Albert Bosma, OAMP, France
Tom Jarrett, Caltech
Lee Armus, Caltech
Barry Madore, OCIW
Bonita de Swardt, SAAO
George Helou, Caltech
Chien Peng, OCIW
Benne Holwerda, SAAO - Guest
Sabrina Stierwalt, U. Va - Guest
Manuel Aravena, ESO – Guest
Brent Tully, U> Hawaii – Guest
Helene Courtois, IAP – Guest
Jenny Sorce, IAP - Guest

Core Team Members

Jason Surace, IPAC
Karen Masters, U. Portsmouth
Bahram Mobasher, U. Riverside
Jin Koda, SUNY
Peter Capak, IPAC
Patrick Ogle, IPAC

Motivation

- Nearby galaxies are the "fossil" records of galaxy evolution
- S^{4}G provides a wealth of detail to test current models of galaxy formation and evolution
- Create the ultimate survey of the distribution of stellar structures, their masses and properties in the nearby Universe.
- S^{4}G is a volume-, magnitude- and size- limited survey of 2300+ galaxies with IRAC at 3.6 and 4.5 μ m (240s, 637.2 hrs)
  - 3.6 and 4.5 μ m provides a dust-free view of the old stars (color independent of population changes, metallicity etc.)
  - The bst tracer of stellar mass (Eskew et al 2012, Meidt et al. 2012 a,b)

An Ultimate Survey Of Stellar Structure & Mass in Nearby Galaxies

All galaxies that meet the following criteria were chosen:

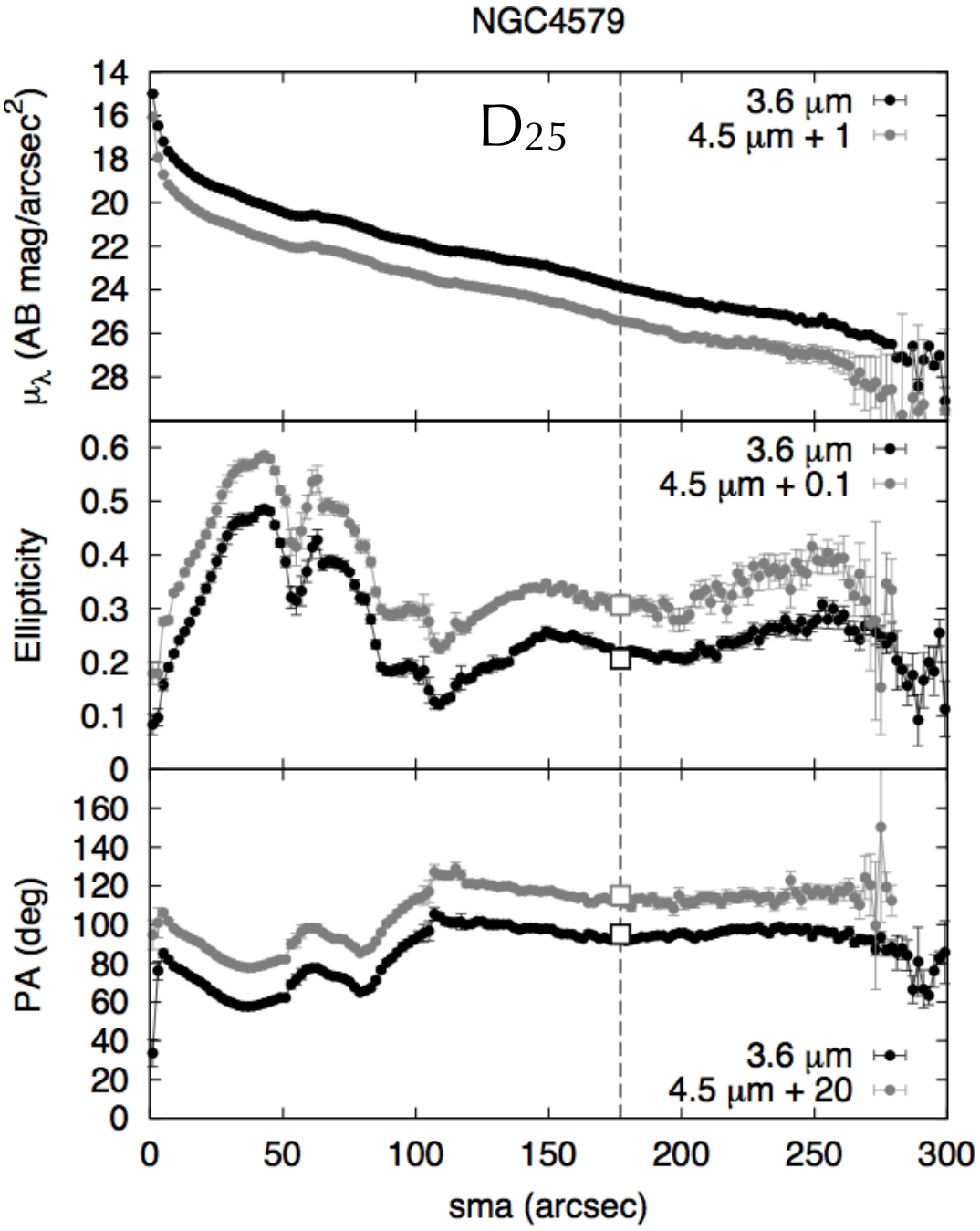
- $V^*_{hel} < 3000$ km/s (D < 40 Mpc)
- $m_B < 15.5$
- $D_{25} > 1'$
- $|b| > 30°$

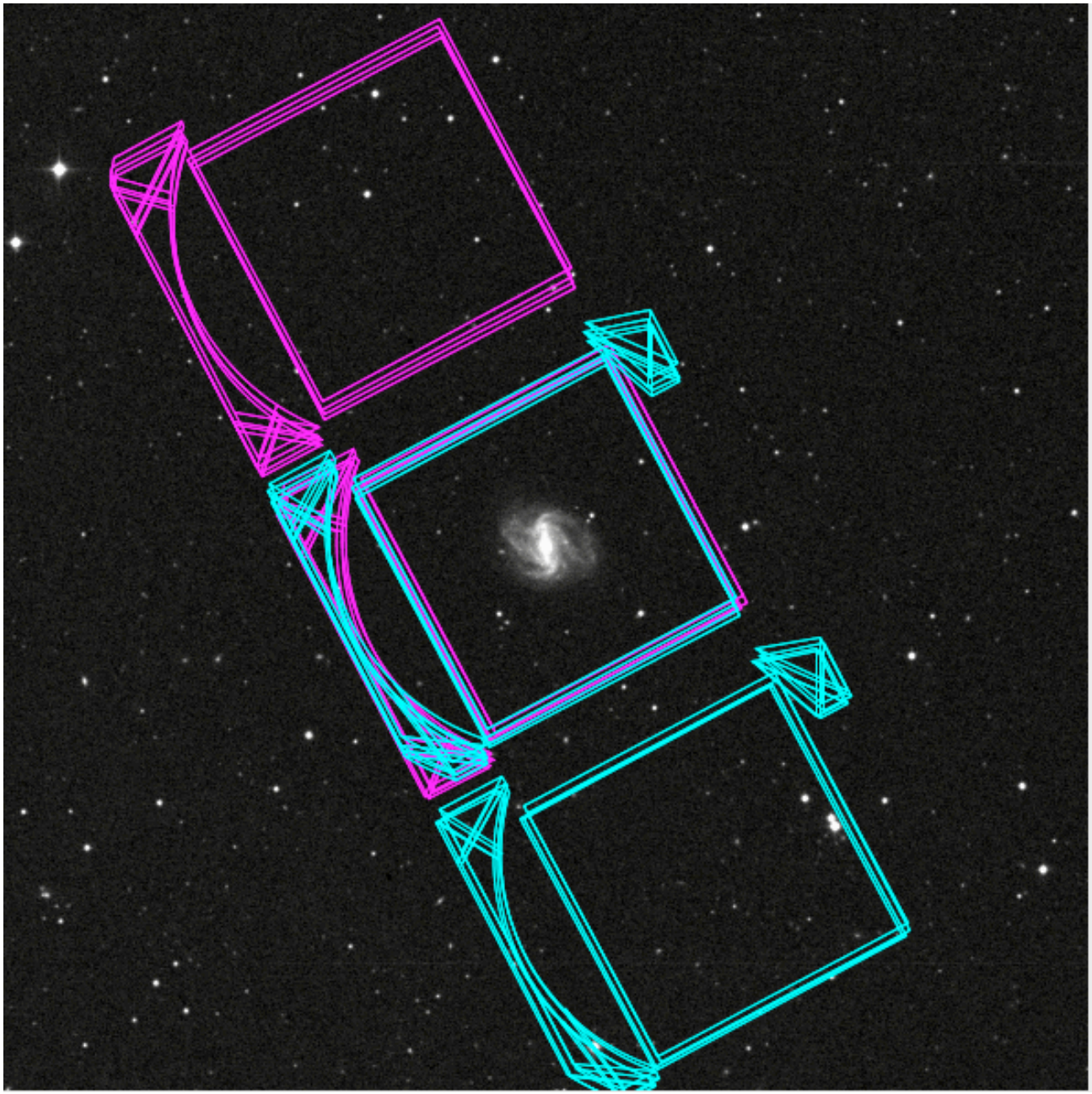
- **637.2 hrs**
- 2352 galaxies (1,809 in warm mission)
- Mosaicked or mapped to 1.5 x D_{25}
- 240s per pixel
- 1σ = 0.00722, 0.0093 MJy /sr / $m_{(AB)}$ ~ **27 mag arcsec^{-2}**
- **Σ_* << 1 $M_\odot$ pc^{-2} !**

- **3.6 + 4.5 μm critical for removing effects of PAH emission, for better modeling of stellar light and removal of systematics**

An Ultimate Survey Of Stellar Structure & Mass in Nearby Galaxies

- All galaxies at 1.5x D_{25}
- $\Sigma_* << 1\ M_\odot\ pc^{-2}$!
- Depth impossible from ground for such a large survey!

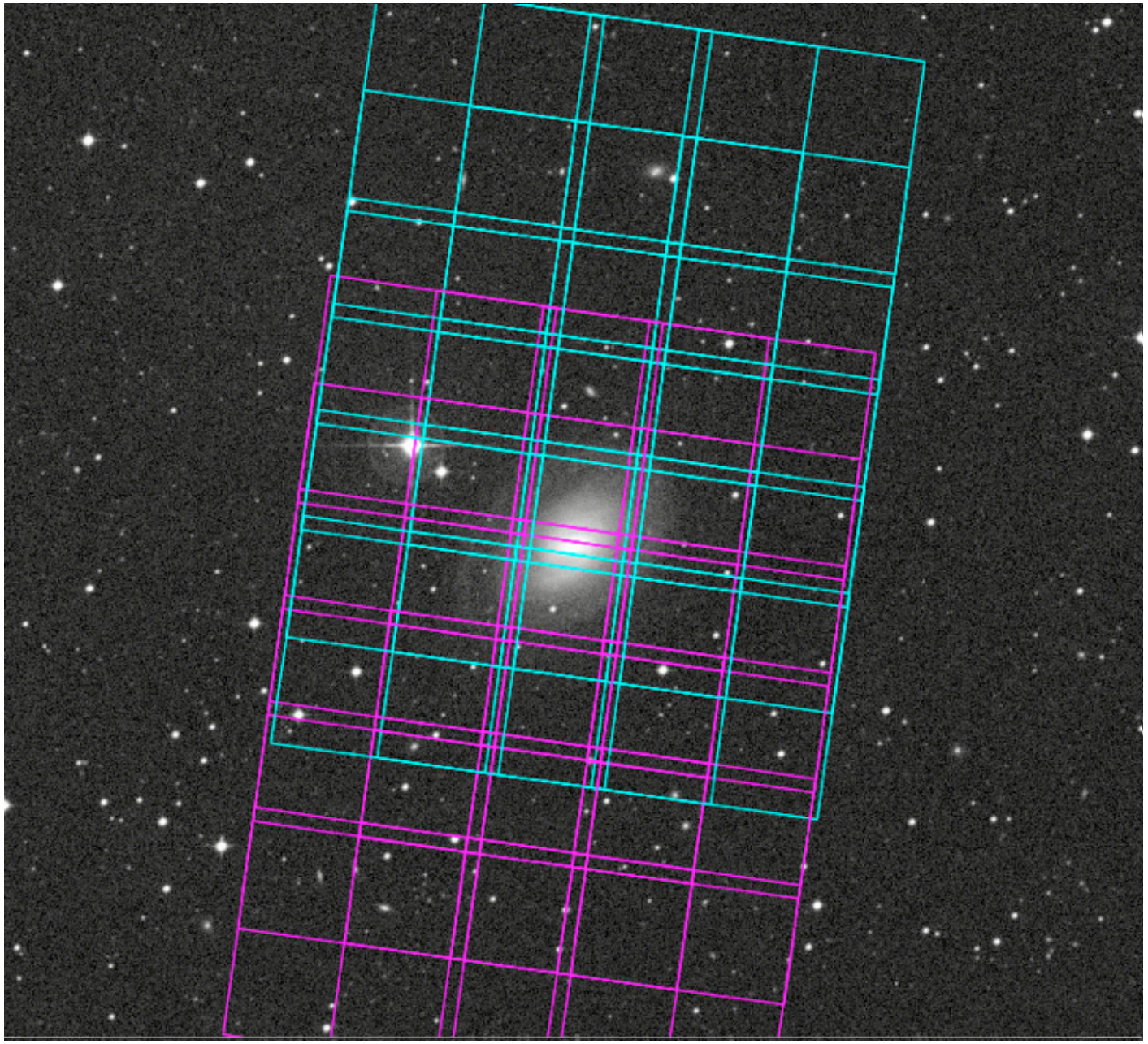




Small galaxies are observed with a dither map

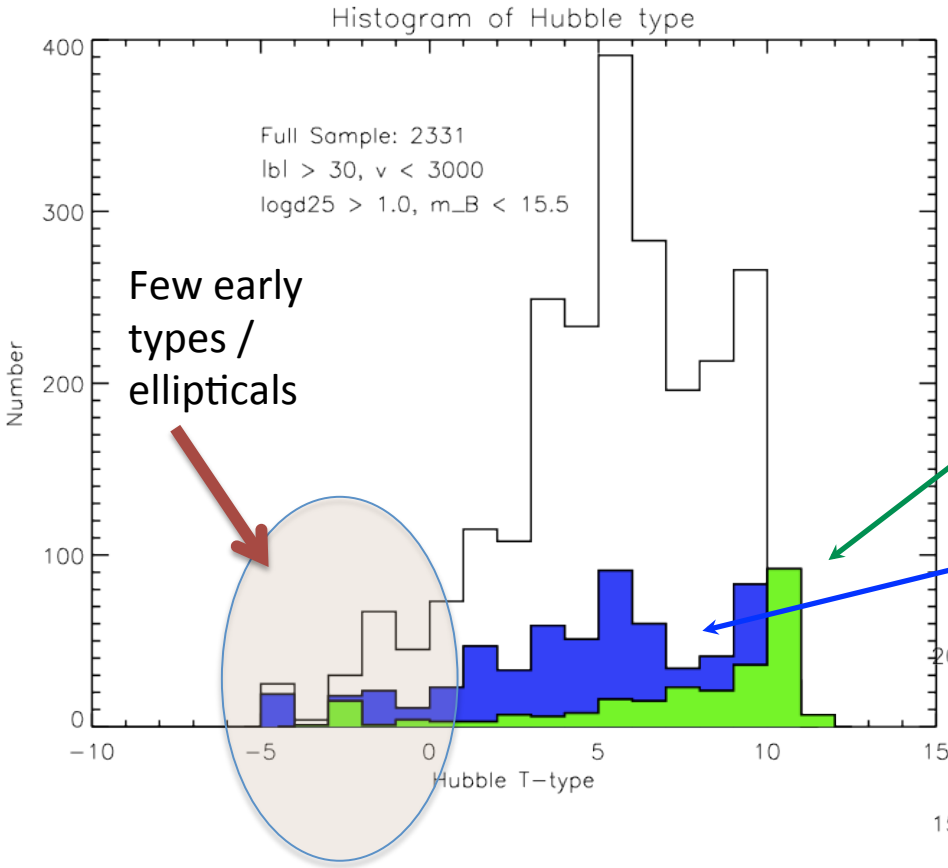
Background from adjacent FOV

Scattered light from stars a problem



Big galaxies are mosaicked with 146.6” steps,

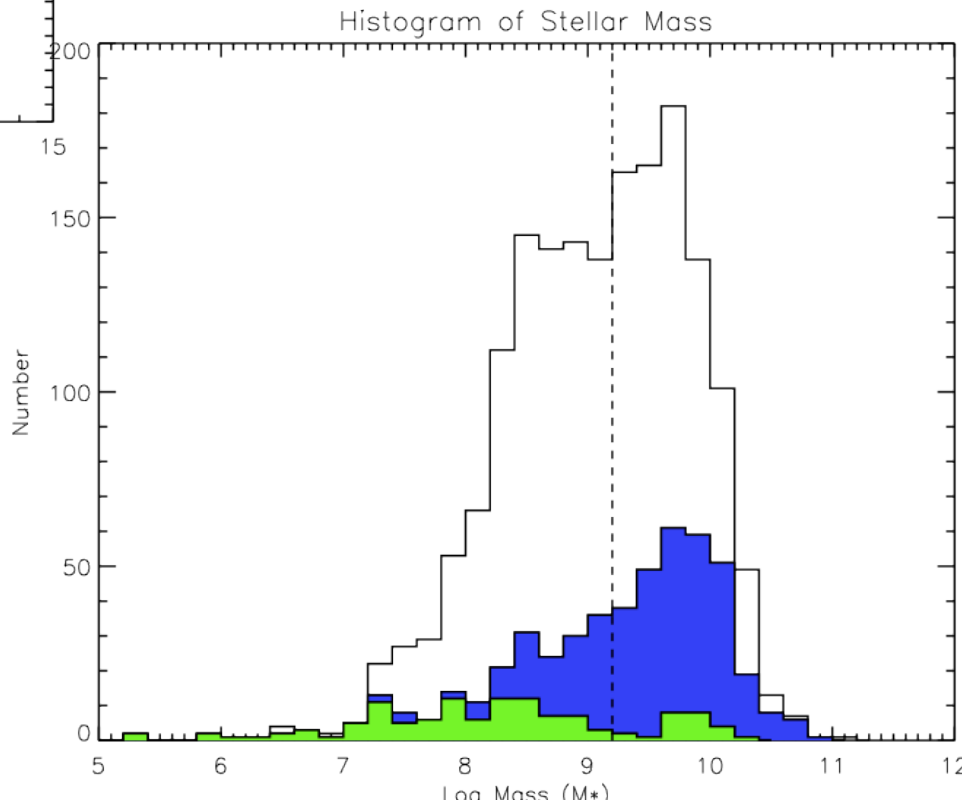
And with a slight offset from galaxy center



Few early types / ellipticals

Local Galaxy Volume (3 Mpc) survey (258 galaxies)

SINGS + GO + GTO (339 galaxies)

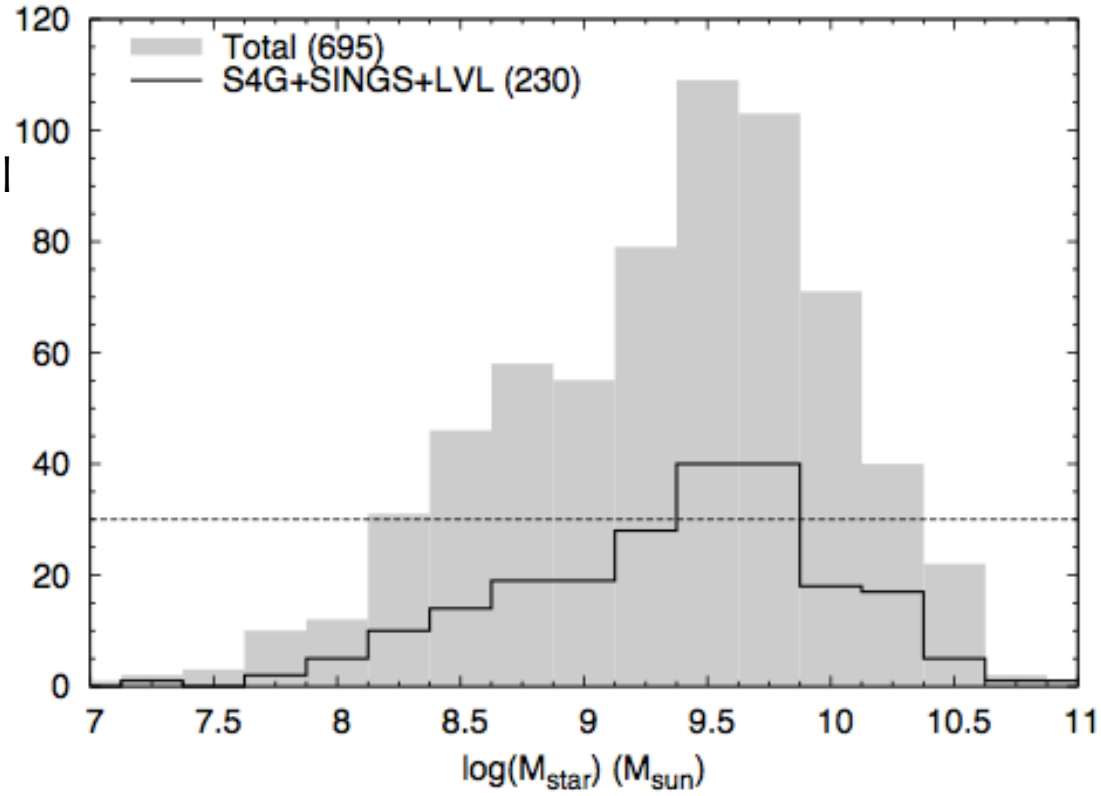


★ S^{4}G explores the full mass and T-type space.

ETGs: Not Dead Yet!

- All remaining ETGs with the same selection criteria as original survey
- **695 total ETGs**

- **188 hrs – Spitzer Cycle 10**
- Mosaicked or mapped to 1.5 x D_{25}
- 240s per pixel
- 1 σ = 0.00722, 0.0093 MJy / sr / $m_{(AB)}$ ~ **27 mag arcsec^{-2}**
- **Σ_* << 1 $M_\odot$ pc^{-2} !**



Just starting these observations now. Will be looking for a postdoc depending on Spitzer funding for this newest Cycle 10 awards.

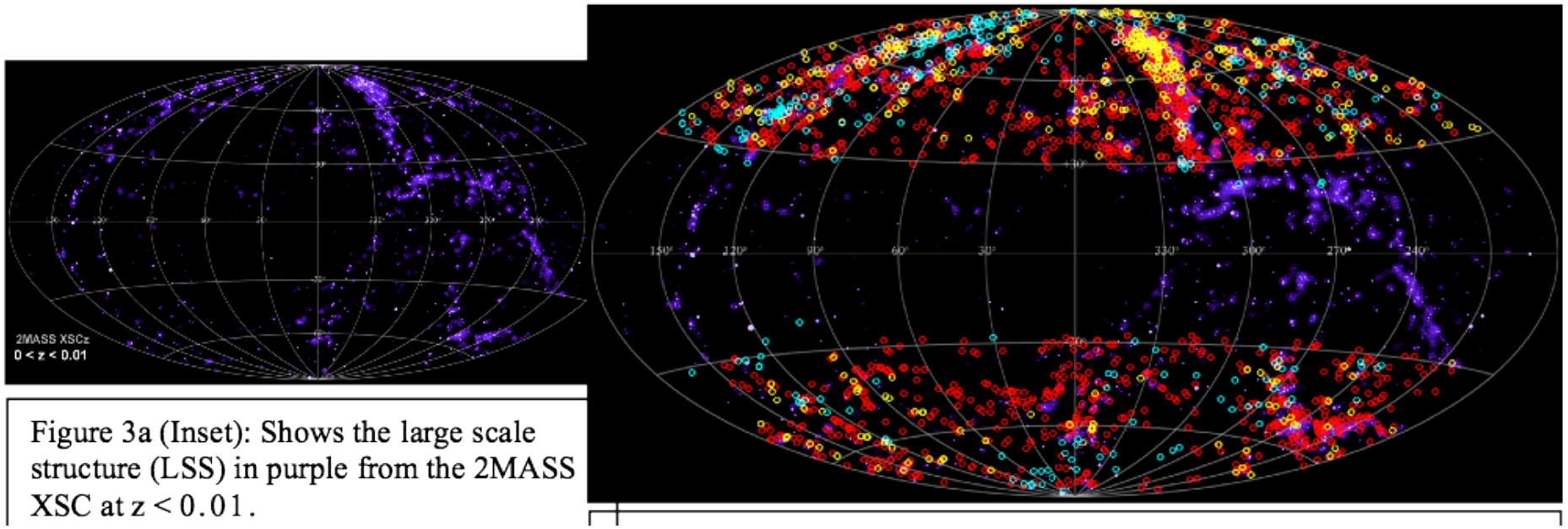
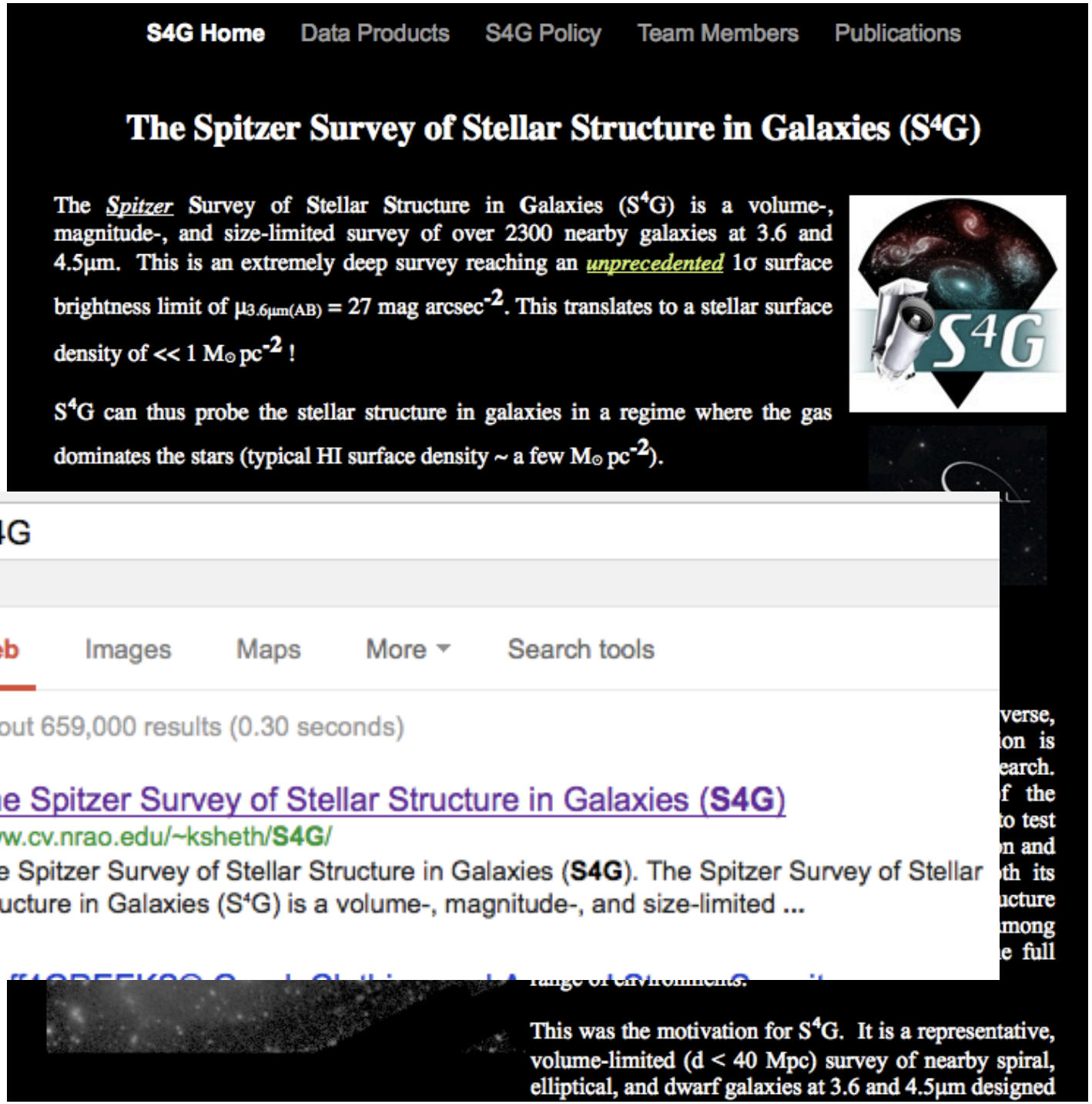


Figure 3a (Inset): Shows the large scale structure (LSS) in purple from the 2MASS XSC at $z < 0.01$.

★ S^{4}G explores a wide range of large scale structure!

All S^{4}G data + P1-P3 products released at the AAS in Long Beach in January

http://www.cv.nrao.edu/~ksheth/S4G



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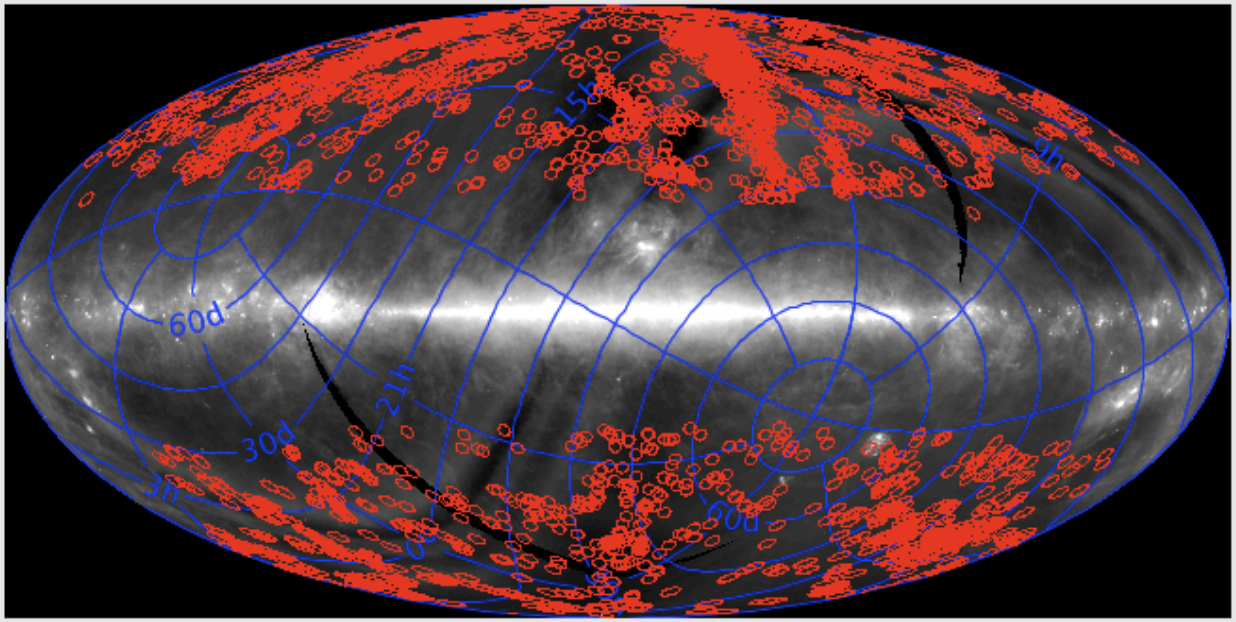
Spitzer Survey of Stellar Structure in Galaxies (S4G)

S4G consists of a sample of 2,331 galaxies, which have been mapped with IRAC channels 1 and 2 (3.6 and 4.5 microns).

IRSA hosts the complete S4G project data set, including results from galaxy modeling using ellipse fitting and Galfit.



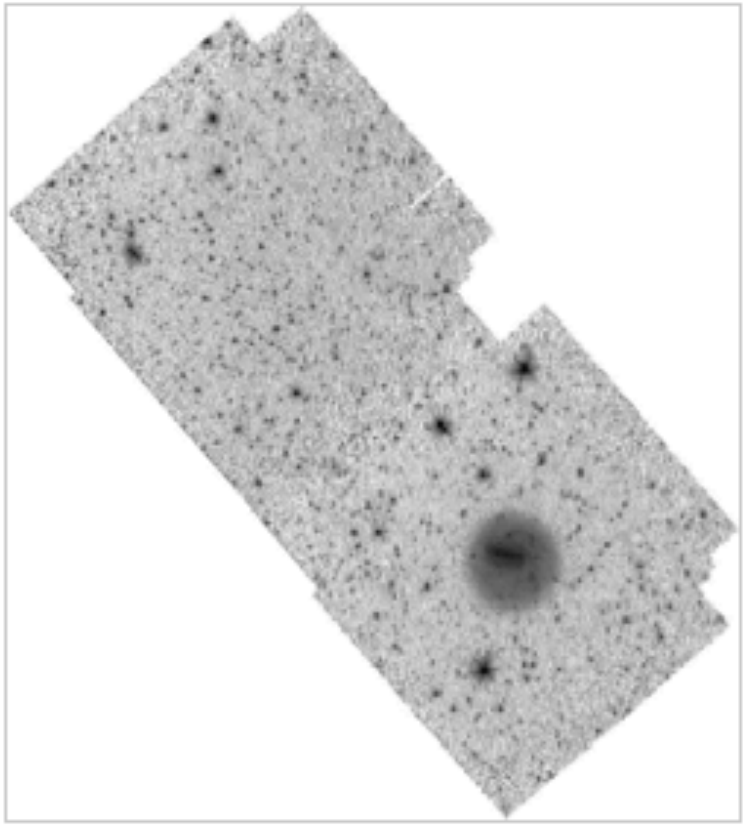
You can get a close-up map of a region by clicking on any of the red overlays on the above image, or by typing a coordinate below.

[Documentation: Pipelines | Galfit Models | S4G Home Page | Spitzer Exploration Science Programs]

The 2,331 S4G galaxies are represented as overlays in red on the all-sky ISSA image above. Use the form below to enter a coordinate or object name to search for data, or click on any red region to

Galaxy: NGC3906

IRAC Data



NGC3906 IRAC Ch1 Preview

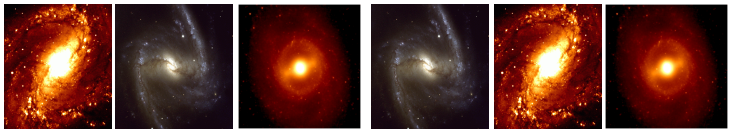
Download IRAC images:

- **IRAC 1:** FITS, Preview JPEG
- **IRAC 1 Mask:** FITS
- **IRAC 2:** FITS, Preview JPEG
- **IRAC 2 Mask:** FITS

Ellipse Fits:

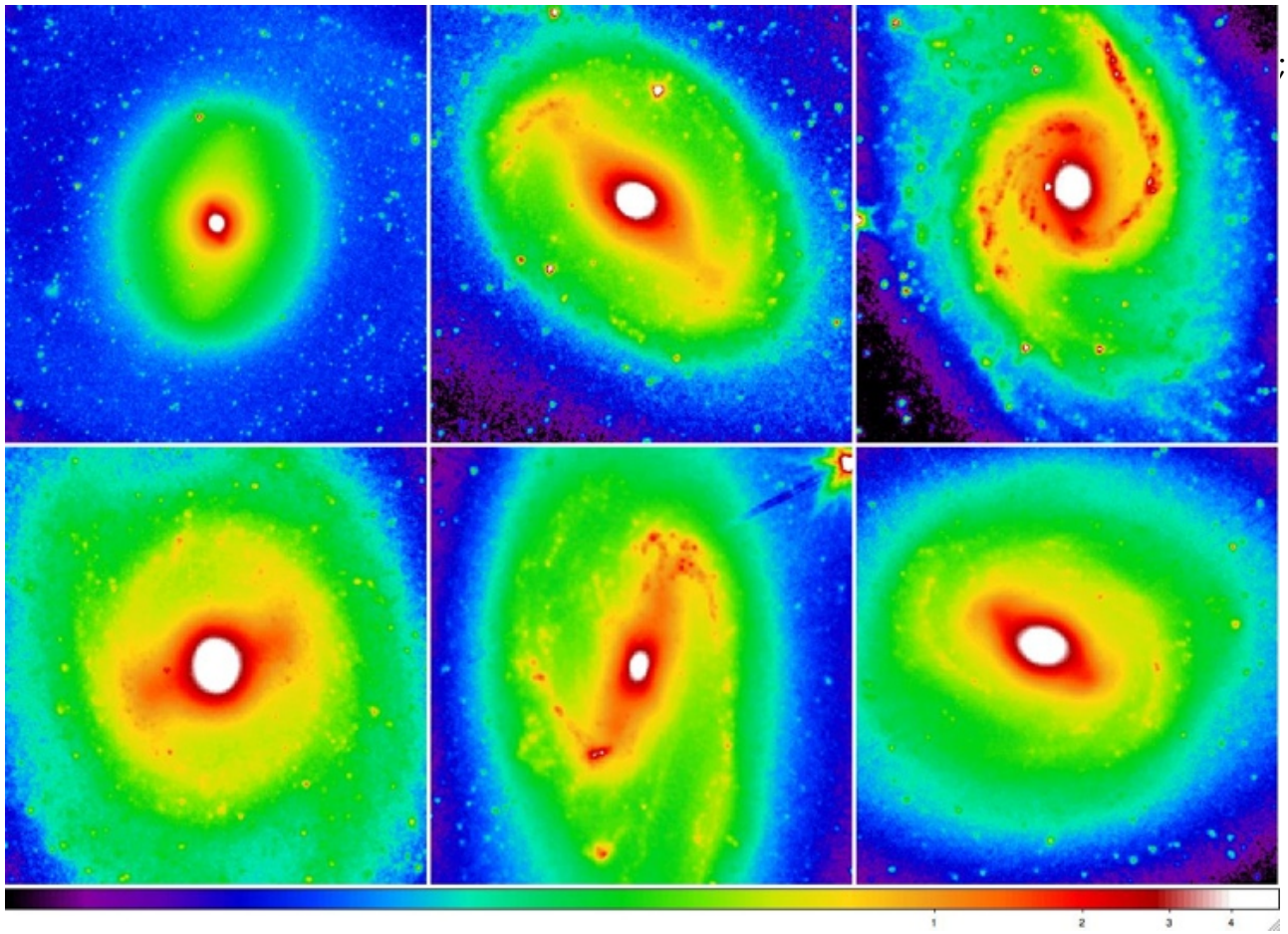
Download Ellipse fit output

The Local Bar Fraction



What is the precise local bar fraction?
How does it vary with galaxy host & environment?

- Two Factions:

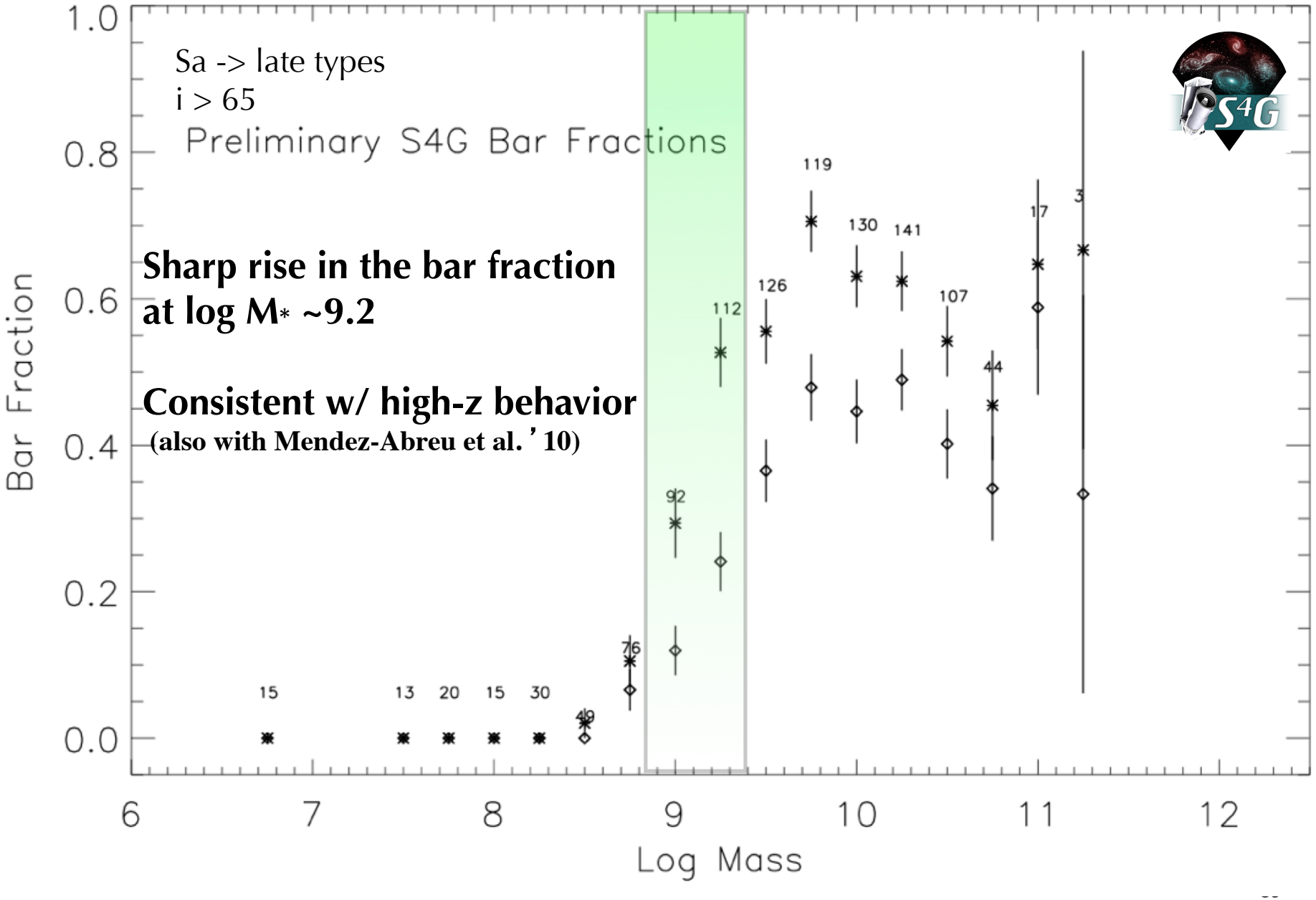


Census of local bars

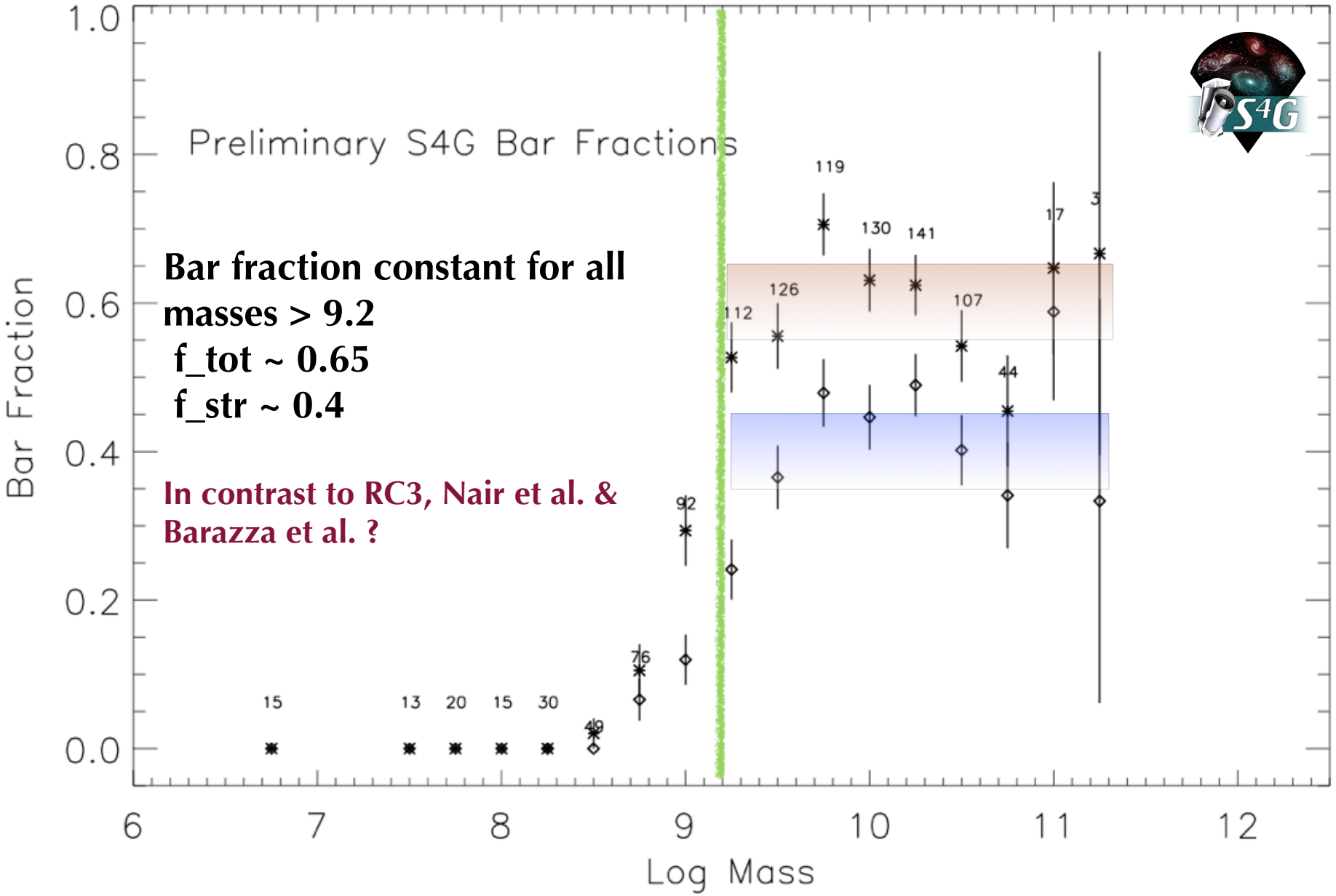
- Bar frequency
- Bar lengths
- Bar strengths
- Nuclear bars
- Lenses
- Correlation with rings & spiral arms

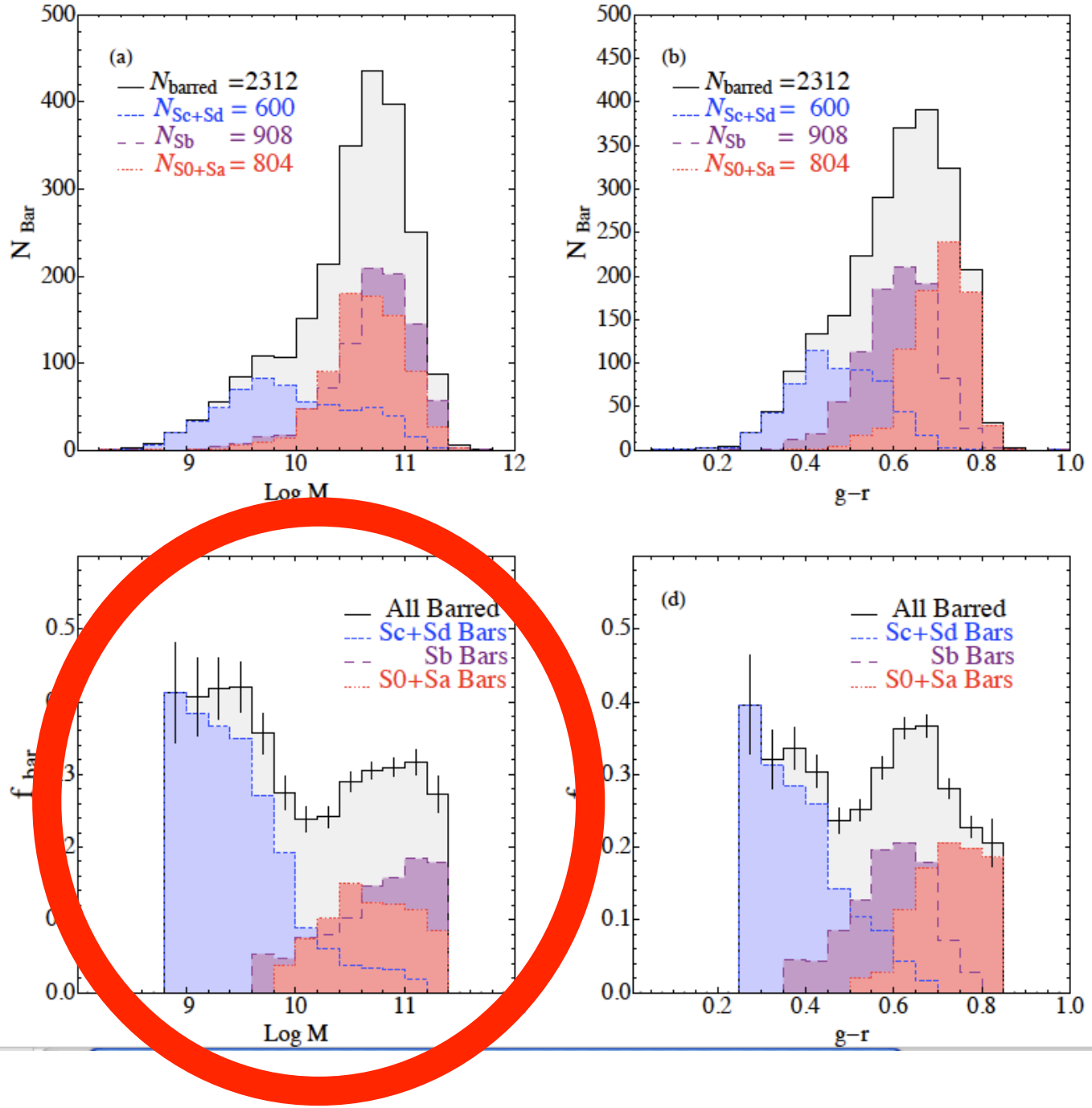
- Bar properties as a f(galaxy properties)

Sheth et al. ’13



Sheth et al. ’13

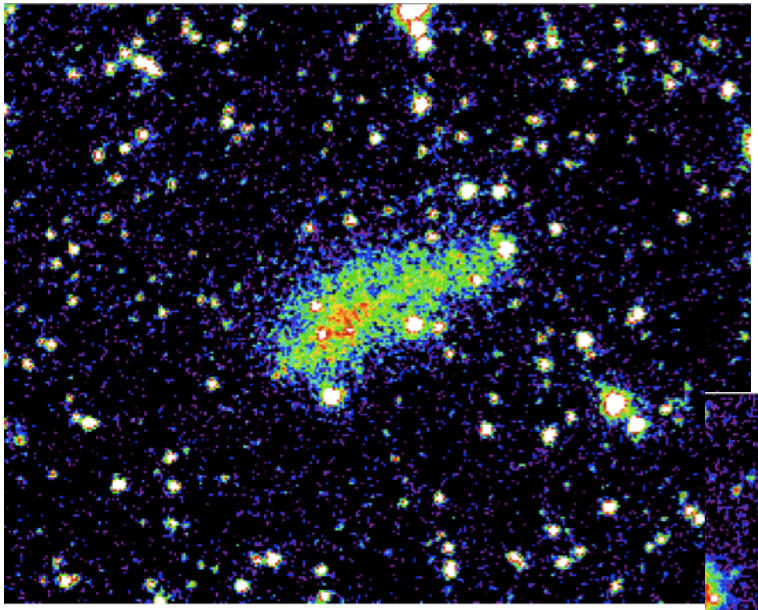


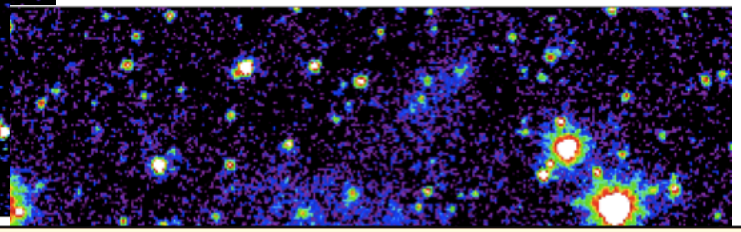


Nair et al. 2010

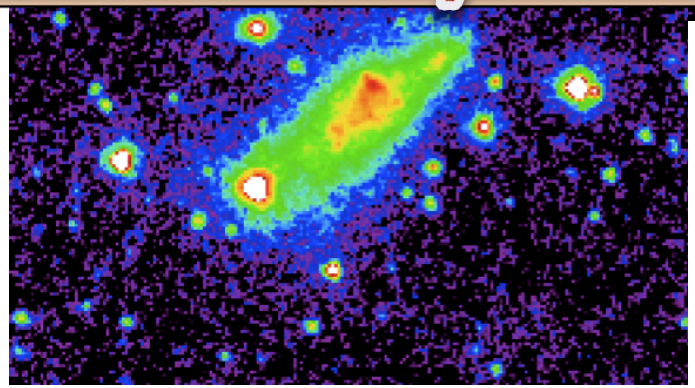
Caution - against using this catalog blindly

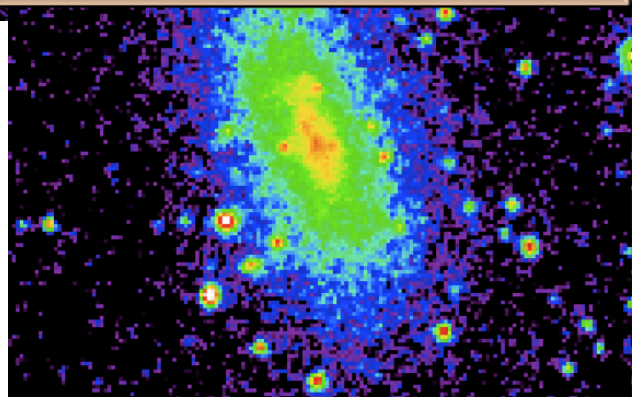
S^{4}G Images of typical RC3 Magellanic "Bars"





So at least some Magellanic bars may not be "real" bars



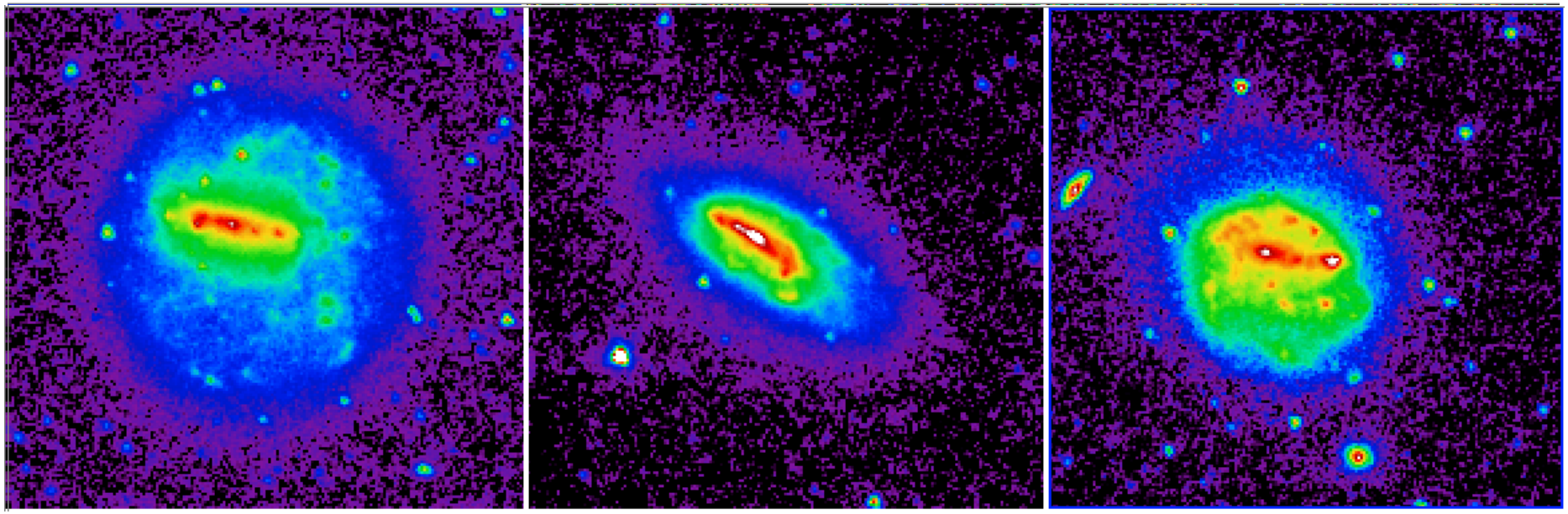


And at least some Magellanic bars are just plain different

What about the LMC bar?

- No evidence of a bar in gas kinematics but we count it as a bar in our bar fraction analysis

S4G Offset Bars



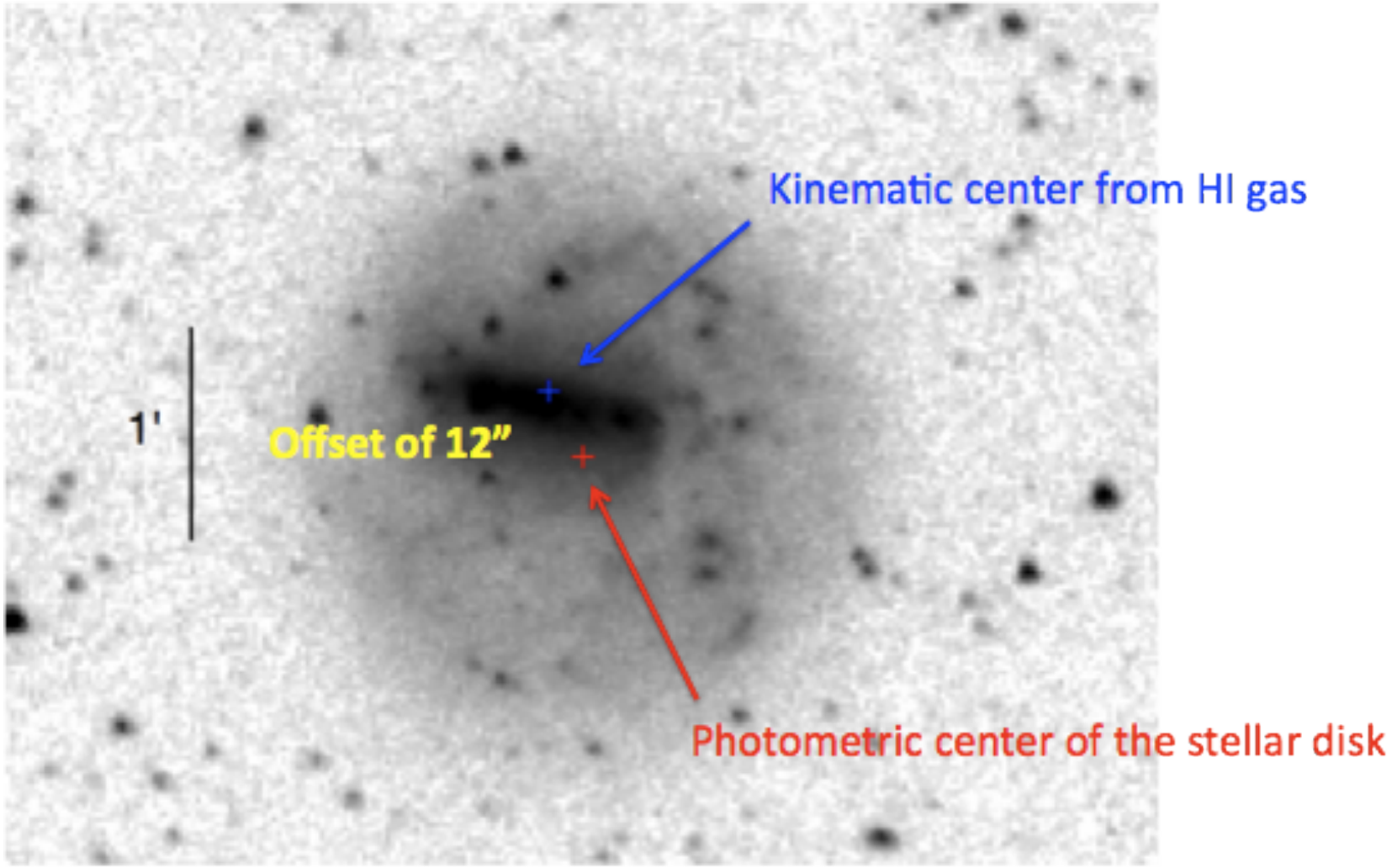
- In our measurement of the S4G Bar fraction we include these offset bars.

- The LMC bar would be considered a bar using the visual and ellipse/pa classification method.
  - **I will refer to these as "wine bars" later!**

Off-center Bars

de Swardt, Sheth + S4G et al. 2012

Interaction with DM sub-halos ?



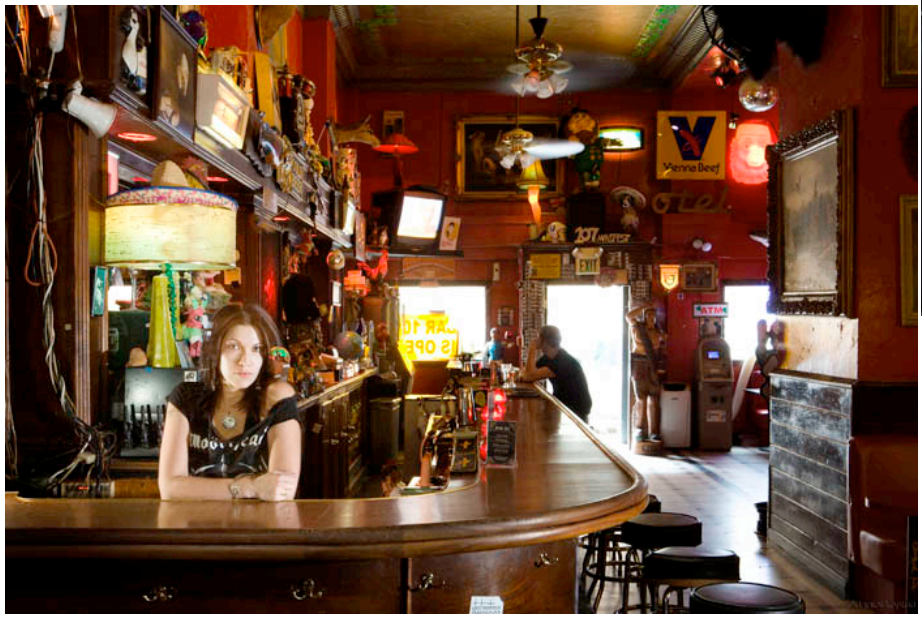
Key Take-Home Points on Bars

- We should be more careful and consistent in defining "bars"
  - Visual classification alone should be viewed with extreme caution especially for late type systems
  - Beware of Galaxy Zoo type studies – ok in some cases but not all (e.g. intermediate bars in the optical or late type bars)

- Bar fraction strongly depends on the sample, the sample size and completeness of data, not to mention classification methodology, bar definition, image quality, rest-frame band, etc.

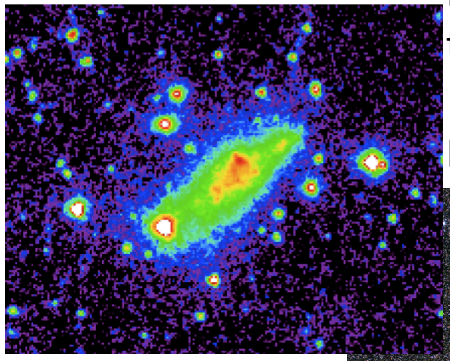
- Perhaps we should adopt a different nomenclature to avoid confusion with visually classified / Magellanic / offset bars?

"Dive" Bars vs. "Wine" Bars



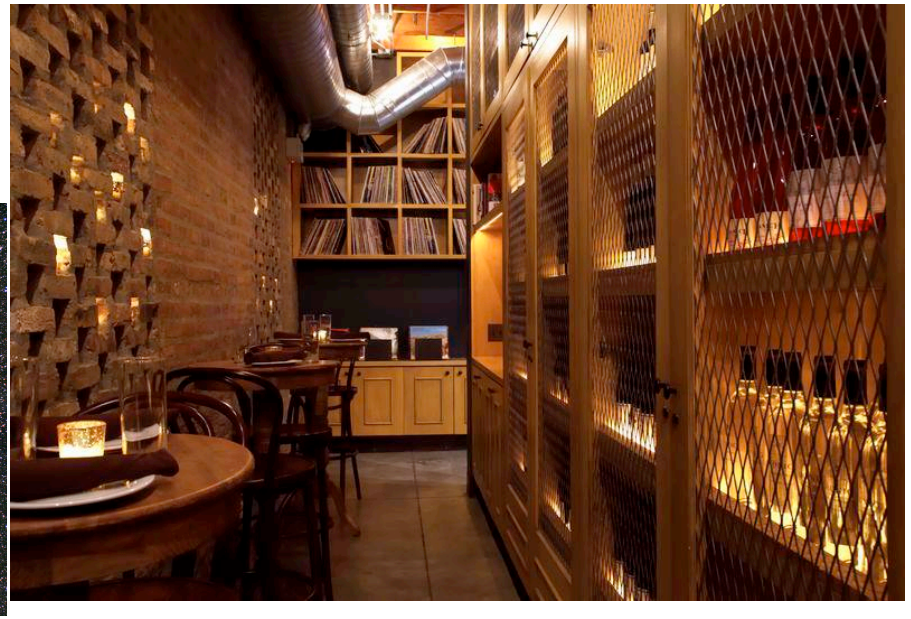
RELEVANT TO COSMOLOGY STUDIES

The quintessential theoretical bar (x1)



Probably don't deserve the label "bars"

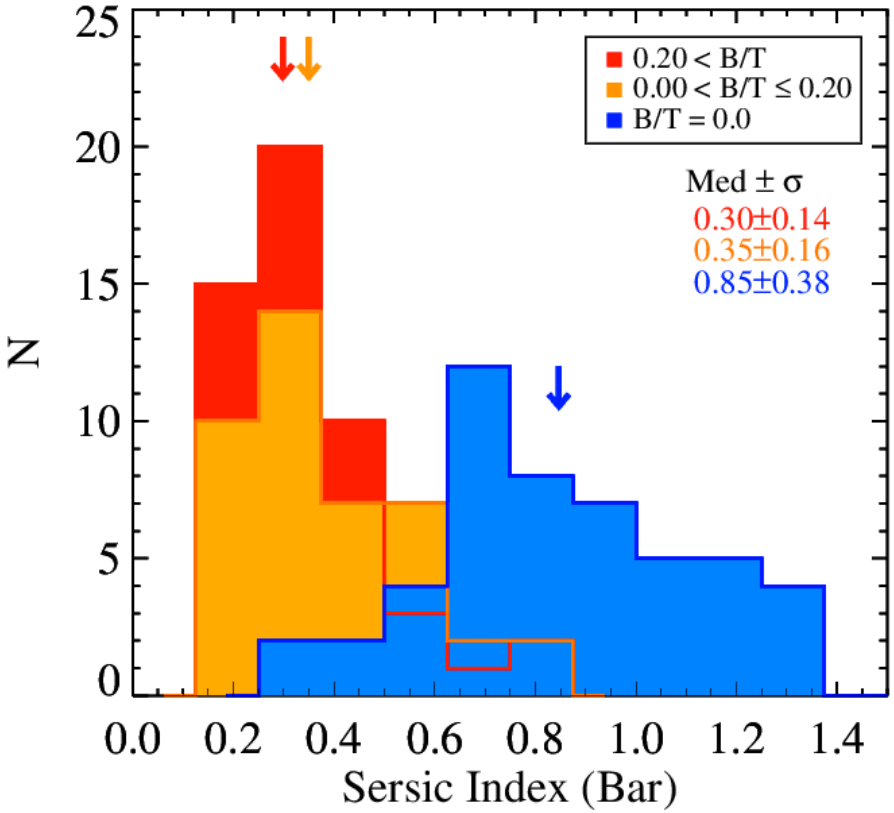
Needlessly confusing!

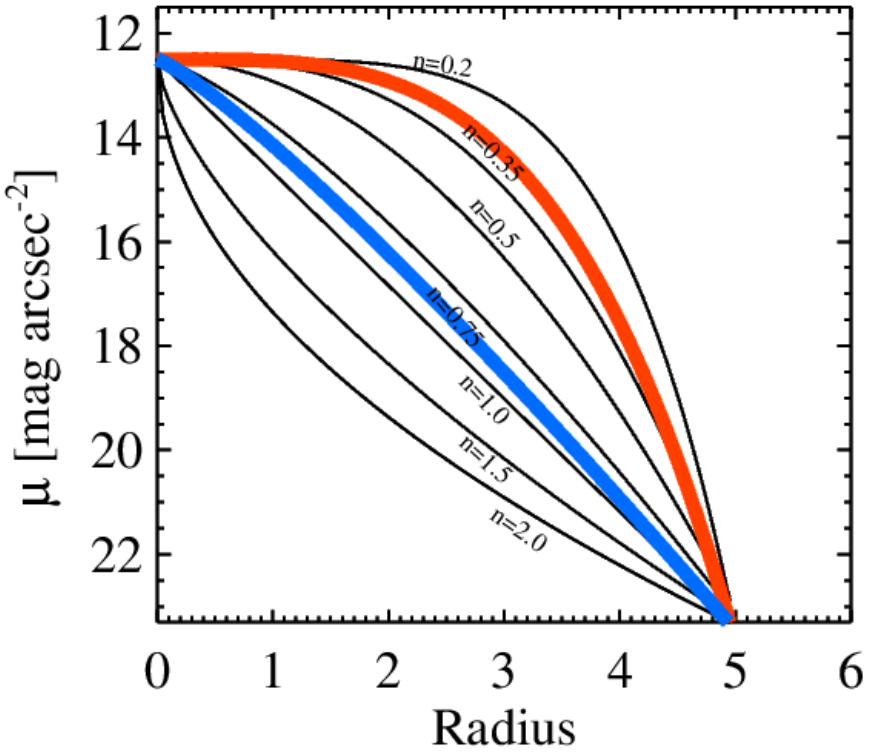


Early vs. Late type bars

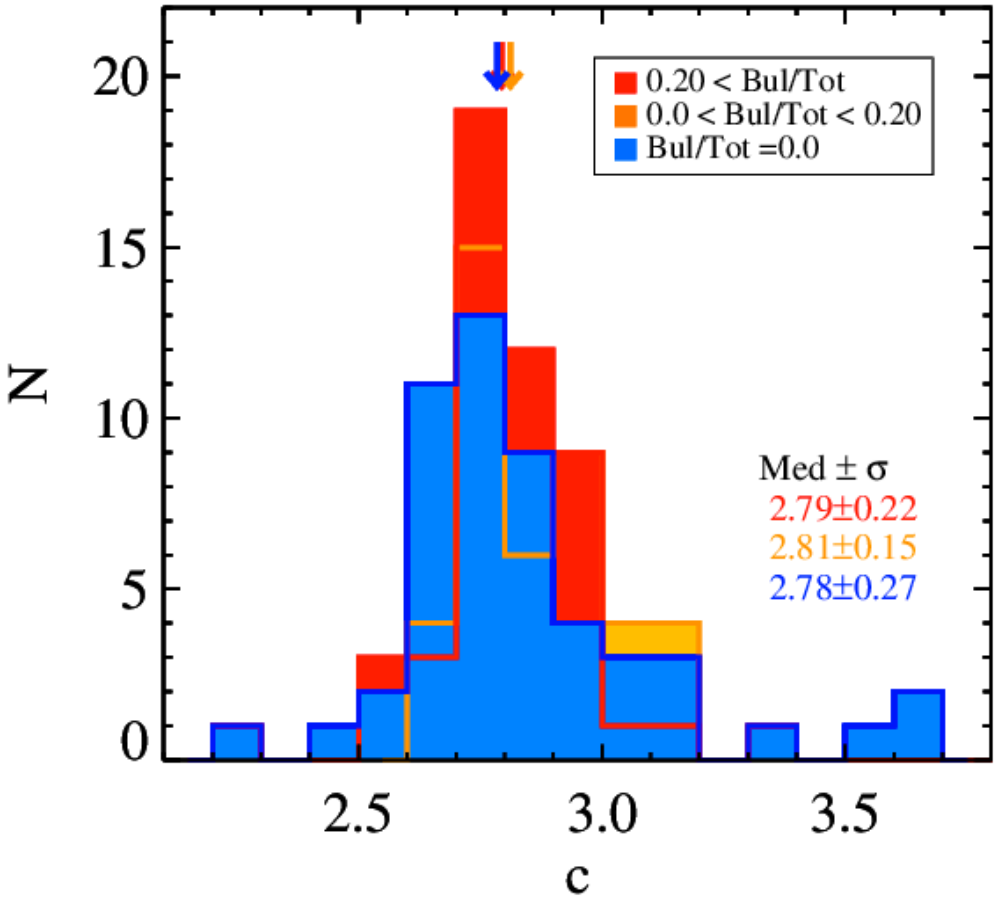
--> Taeyhun Kim's thesis (2013 a,b)

Detailed structural decomposition of 144 S^{4}G spirals





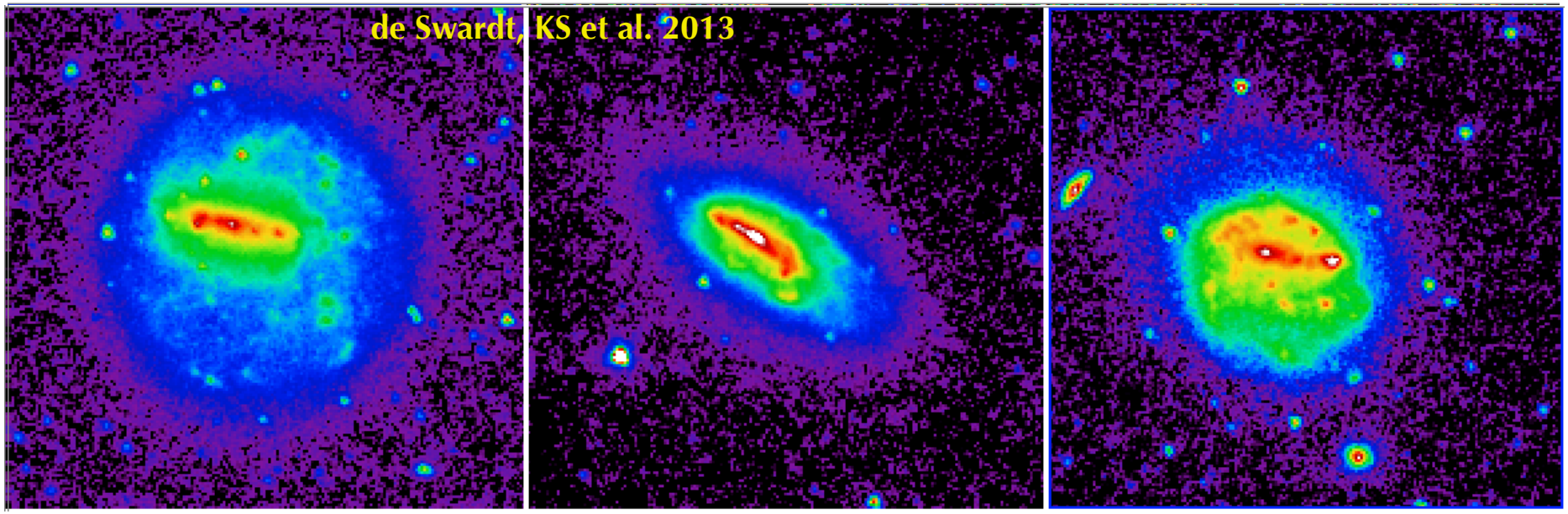
Bars are boxy in shape!



Taeyhun Kim's thesis (2013 a,b)

- **Consistent with the evolutionary history of bars and disks derived from COSMOS, NICMOS, DEEP2, AEGIS and S4.**

The Puzzle of Offset Bars



- A very small fraction of galaxies exhibit these offset bars (or disk offsets)
- Ongoing work with ***de Swardt, Wilcots, D'onghia, Pardy,*** (SALT + VLA)

- **Some in interacting systems but MANY in apparently isolated systems!**

- New, relatively unexplored area - see simulations by Pardy, Athanassoula, Hernquist, Bekki & others..

What we know (and don't know)

- Bar fraction today declines sharply at log M < 9.2
  - consistent with cosmological evolution / high redshift COSMOS work
- "Dive" bars, the cosmologically important ones, all seem to be boxy irrespective of whether the galaxy is early or late!
- Bar structure consistent with theoretical models (x1 orbits) and profiles evolve with time - consistent with theory & COSMOS results
- Greater care and consistency is a must in defining "Bars"
- "Wine" bars are enjoyable but probably different from the "Dive" bars
- Bar fraction is a very loose term and literature shows confusion due to differences introduced by selection effects, sample sizes, sample imhomogenity, completeness, bar identification criteria

- What are the "wine bars"? Are they an intermediate stage of bar evolution?
- What are the offset bars?
- Is there a ceiling to bar fraction? Why are there unbarred massive, disks?
- What is the structure of bars? Relation to bulges, spirals?
- How do bars influence AGN & star formation activity?
- At what rate does gas flow and accumulate in the center?

THE SPITZER SURVEY OF STELLAR STRUCTURE IN GALAXIES (S^{4}G)

contains a treasure trove of beautiful, very deep and uniform mid-infrared data on all kinds of galaxies (edge-ons, lenticulars, bulgeless galaxies, low mass dwarfs)

All data are now publicly available with enhanced data products! (and more coming...)

Webpage: http://www.cv.nrao.edu/~ksheth/S4G/

Data access: http://irsa.ipac.caltech.edu/data/SPITZER/S4G/

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