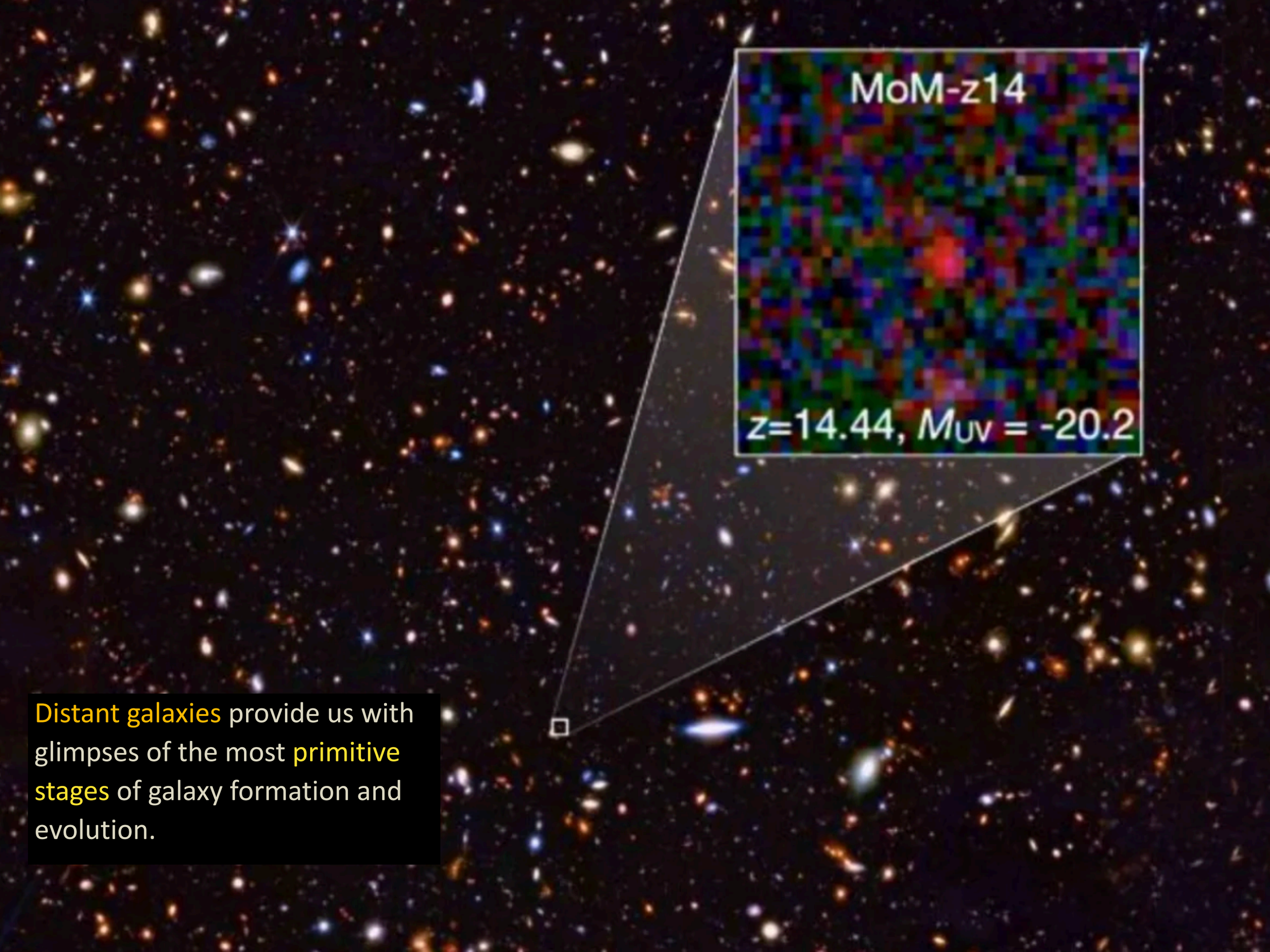
Galaxy Evolution:
Lessons from the Local Universe







Karín Menéndez-Delmestre
Brazilian Center for Research in Physics (CBPF)
Rio de Janeiro, Brazil



Distant galaxies provide us with glimpses of the most primitive stages of galaxy formation and evolution.

Nearby galaxies –
‘fossil record’ of galaxy evolution

SINGS

Ellipticals

Irregulars

Unbarred Spirals

Weak Bulge

Strong Bulge

Intermediate Spirals

Barred Spirals

Nearby galaxies provide a wealth of detail (arrival parameters) to extensively test models of galaxy formation and evolution.

SPITZER SPACE TELESCOPE

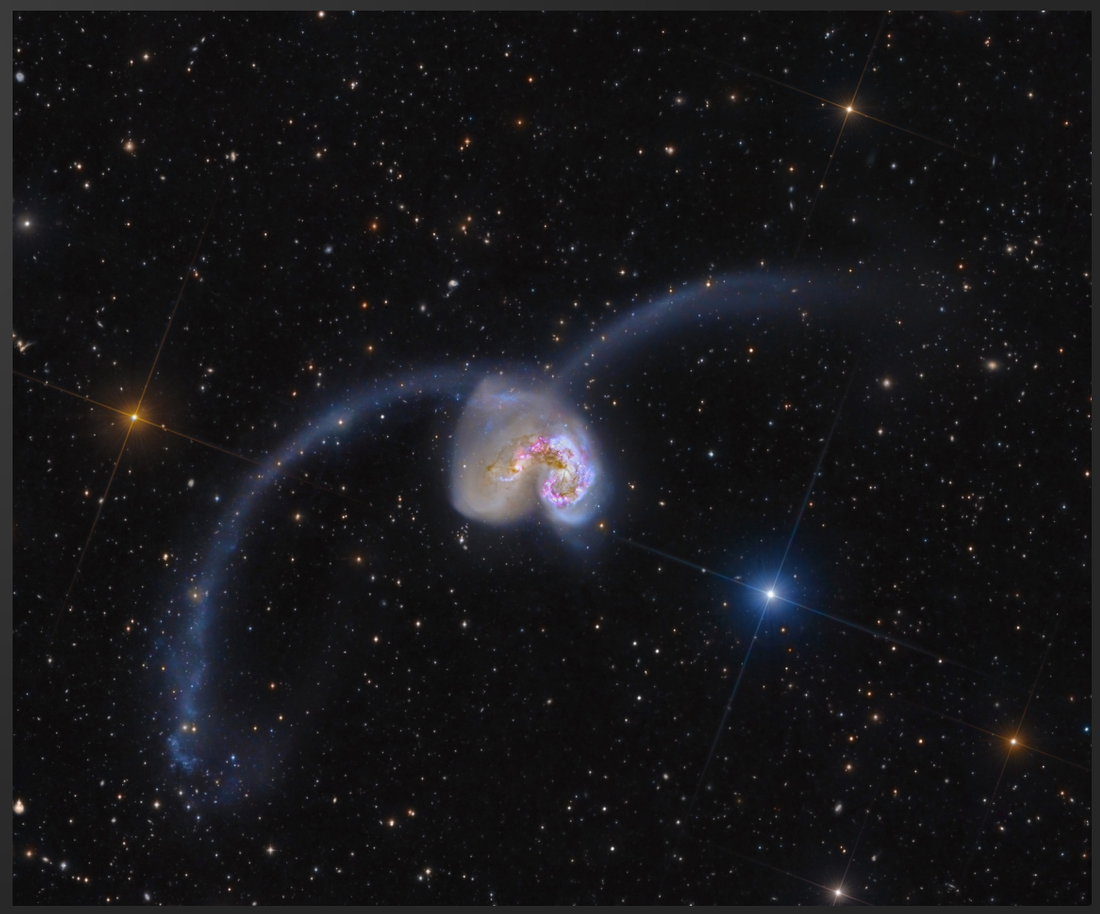
Galaxy global shapes — tell-tale signs of past evolution



"Morphology matters"

A galaxy remembers its dynamic history and the impact it has on its orbits is written onto its morphology

P. Erwin



APOD — Image Data: Subaru, NAOJ, NASA/ESA/Hubble, R.W. Olsen
Processing: Federico Pelliccia and Rolf Wahl Olsen

Galaxy global shapes — tell-tale signs of past evolution

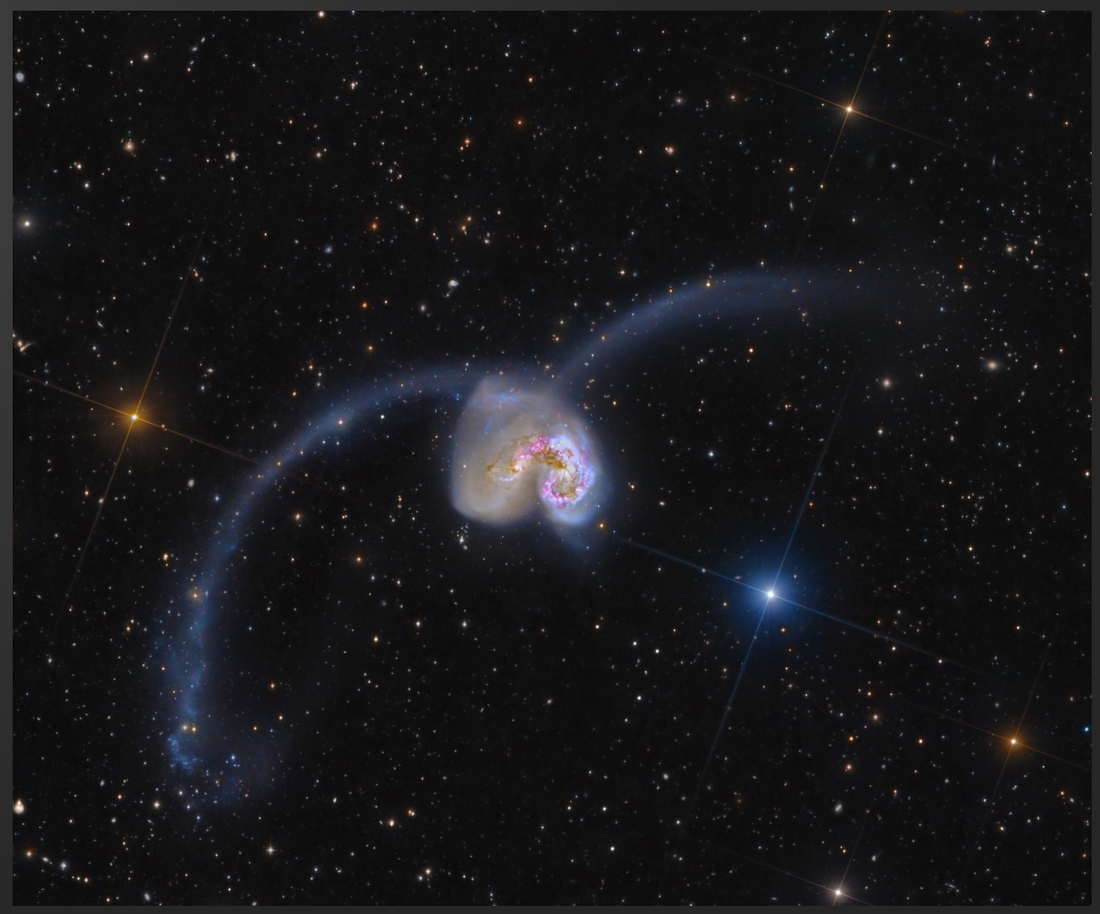
- Galaxy shapes are associated to past events
  - Disks are destroyed in major galaxy fusions



"Morphology matters"

A galaxy remembers its dynamic history and the impact it has on its orbits is written onto its morphology

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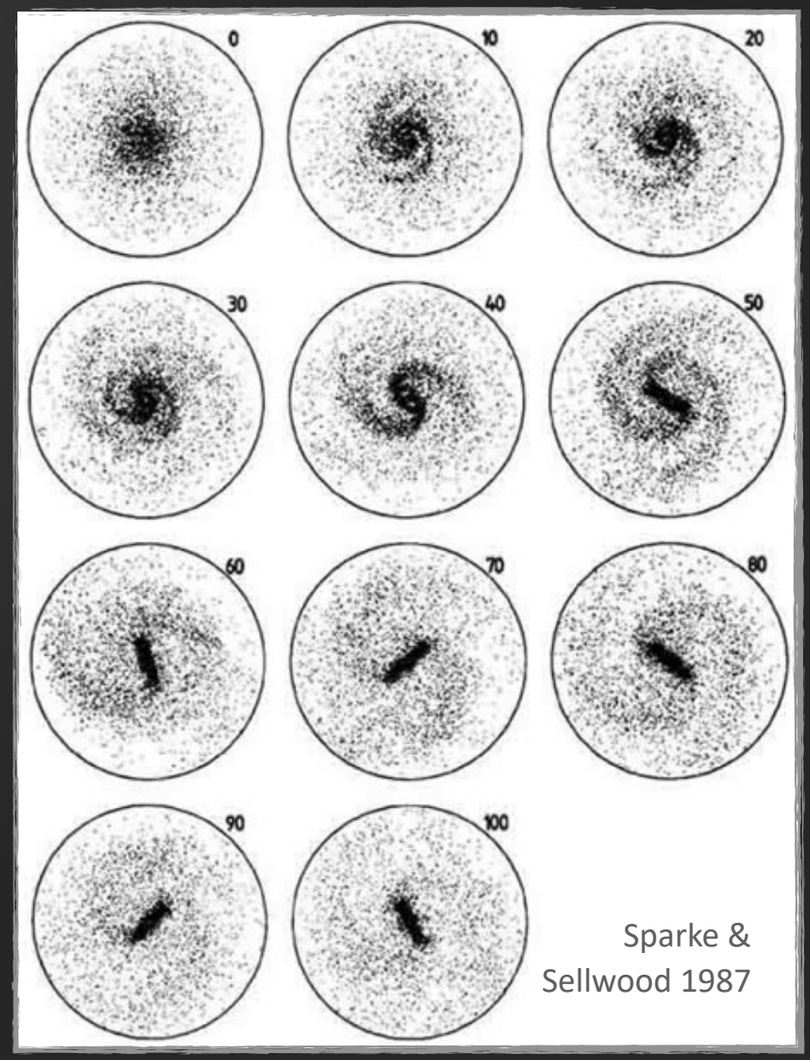
Galaxy global shapes — tell-tale signs of past evolution

- Galaxy shapes are associated to past events
- Presence of sub-galactic structures — disk maturity



Bars are everywhere! 2/3 of spirals are barred

optical: de Vaucouleurs+63;
near-though-midIR: e.g., Menéndez-Delmestre+07, Erwin+18



Disks like forming bars!

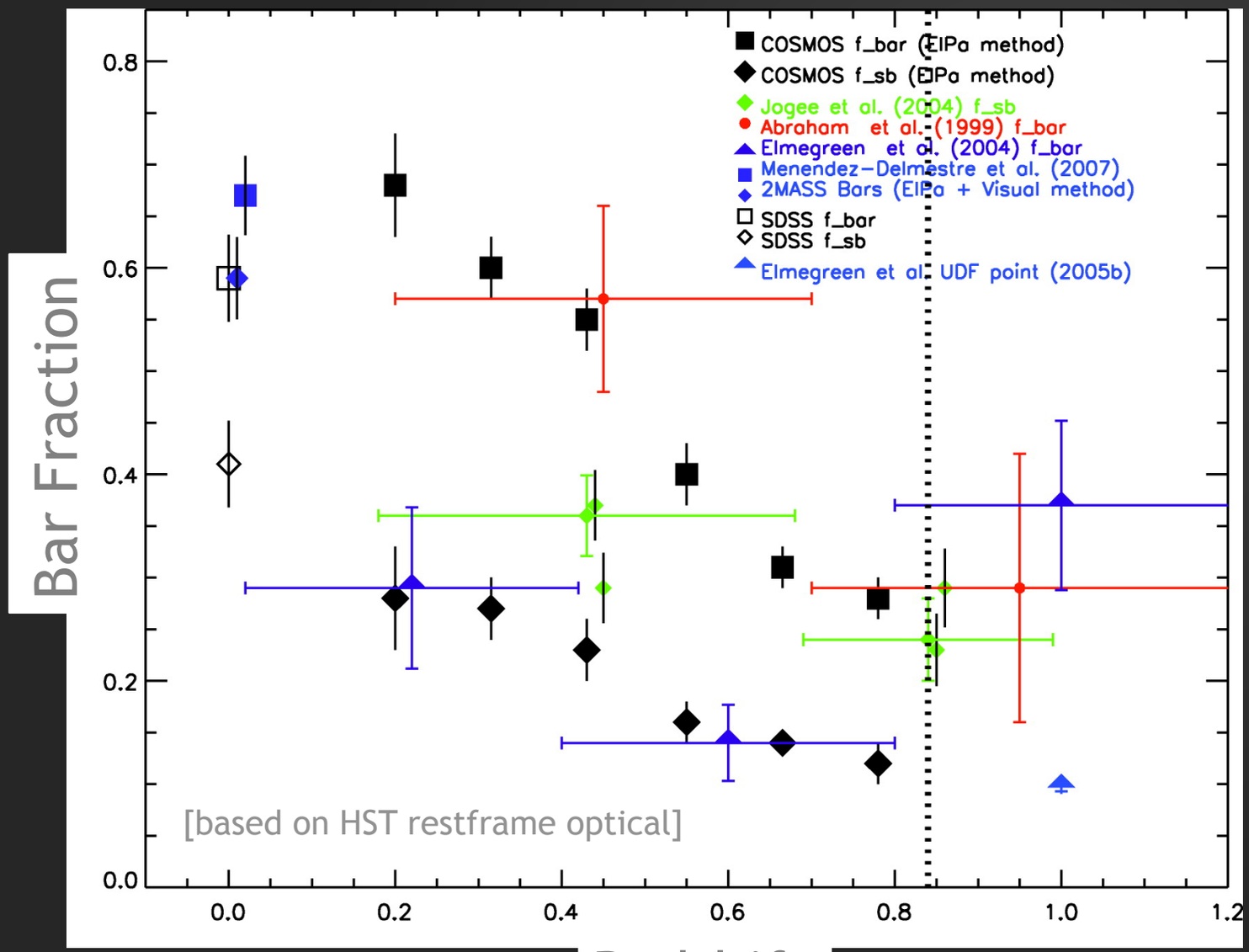
- A disk will naturally form a bar in a couple of Gyrs unless it is particularly rich in gas, dynamically hot or is (centrally-)dominated by dark matter — Athanassoula+ FIRE-2 simulations; Ansar+23

  → The presence of a bar allows us to gauge disk "maturity"

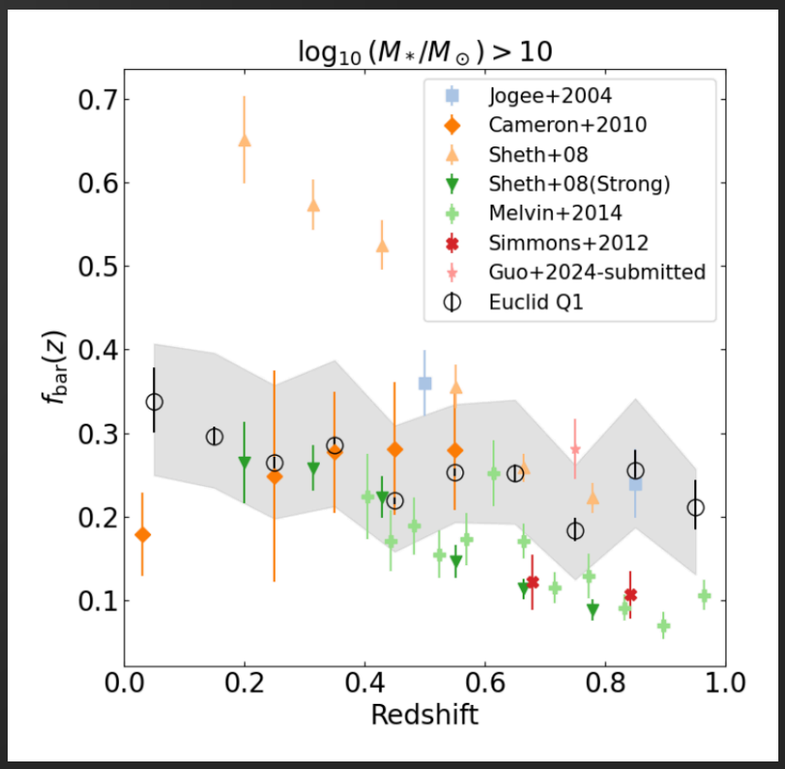
- The presence of a bar and its properties reflect much about the formation history of the galaxy.

Bar fraction evolution with redshift
— bars and disk maturity

Tracing the fraction of disks with bars = tracing disk maturity through cosmic time



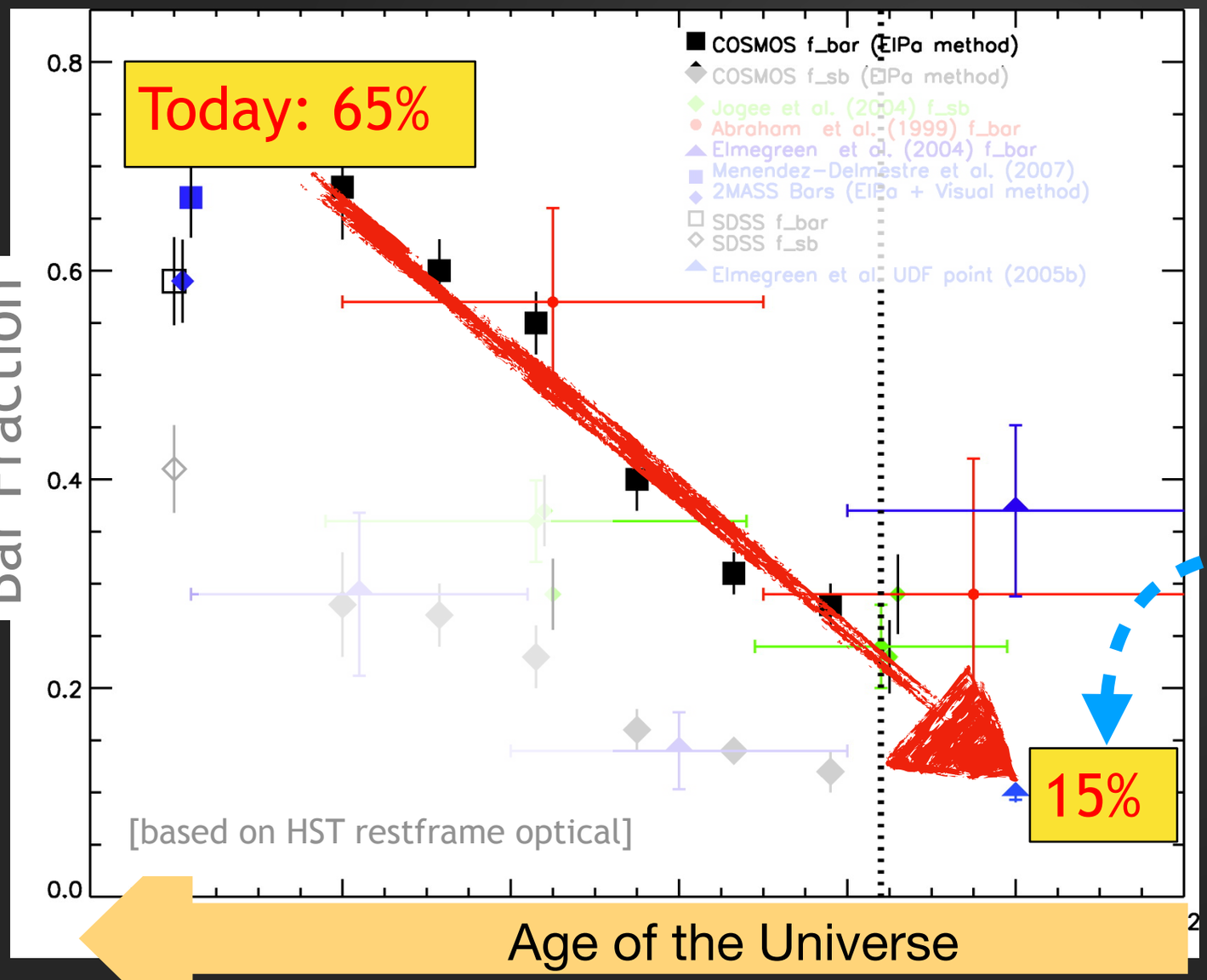
Sheth+08



Euclid+25

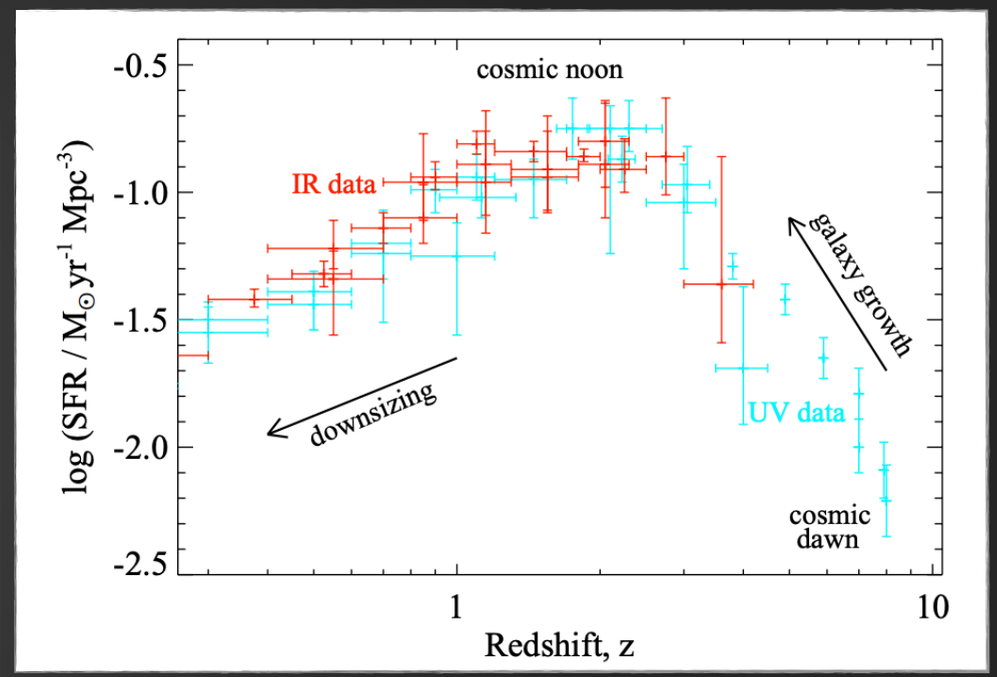
Bar fraction evolution with redshift
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Tracing the fraction of disks with bars = tracing disk maturity through cosmic time



Universe is
~6 Grys old

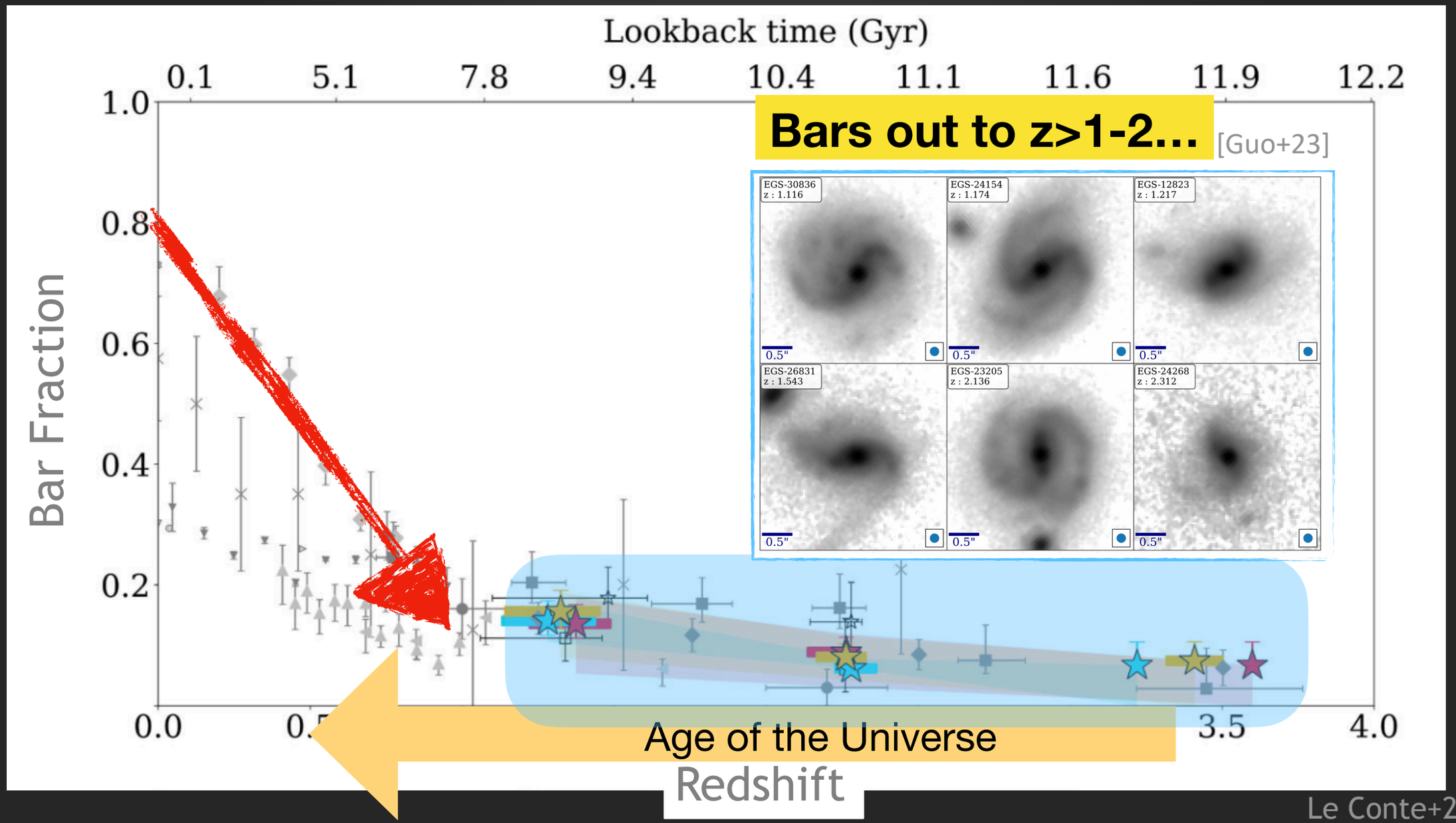
Sheth+08



Stanway+20

Bar fraction evolution with redshift
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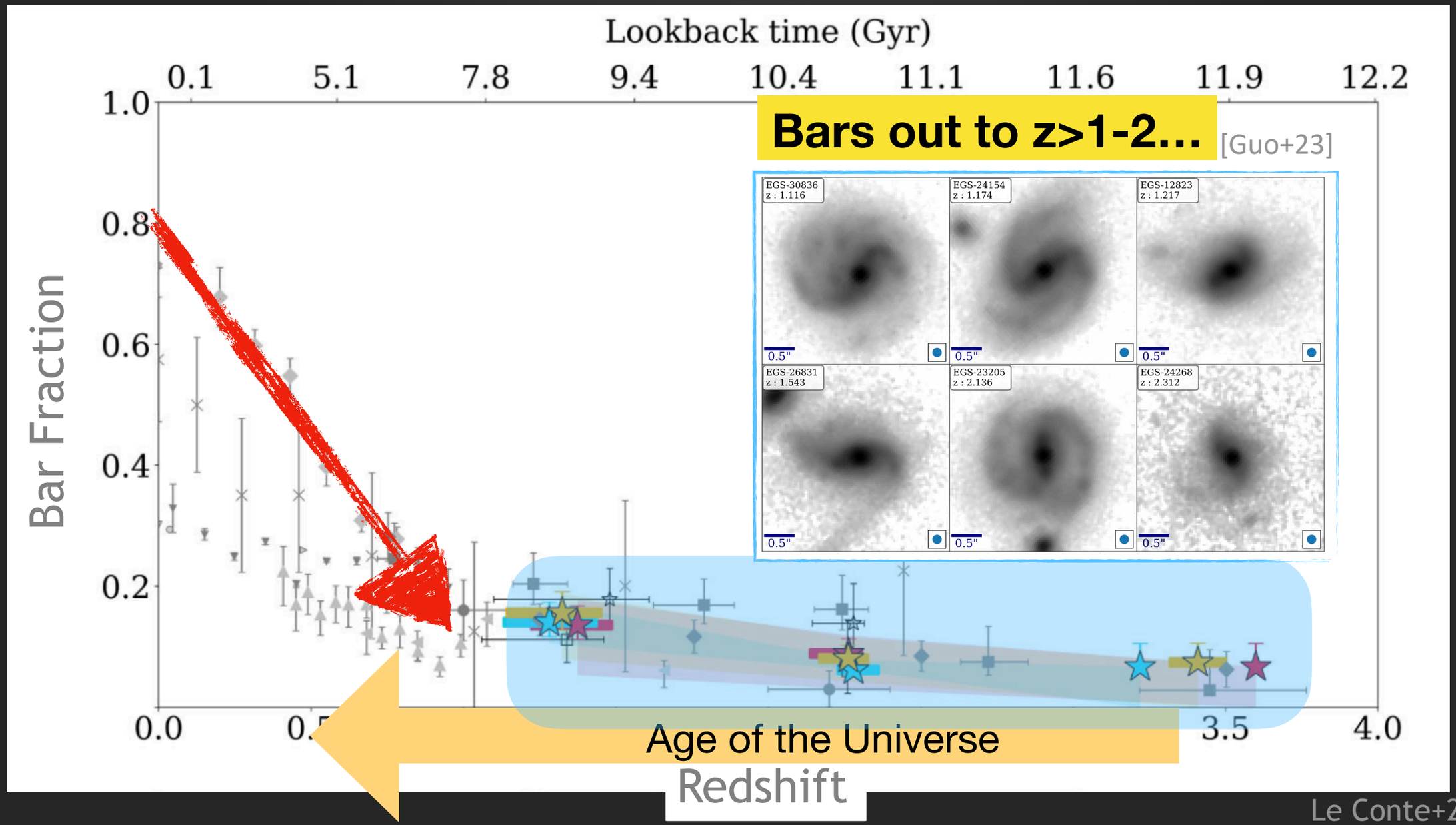
Le Conte+26

Bar fraction evolution with redshift

— bars and disk maturity

Dynamically cold, stable disks way earlier than expected!

Tracing the fraction of disks with bars = tracing disk maturity through cosmic time



Le Conte+26

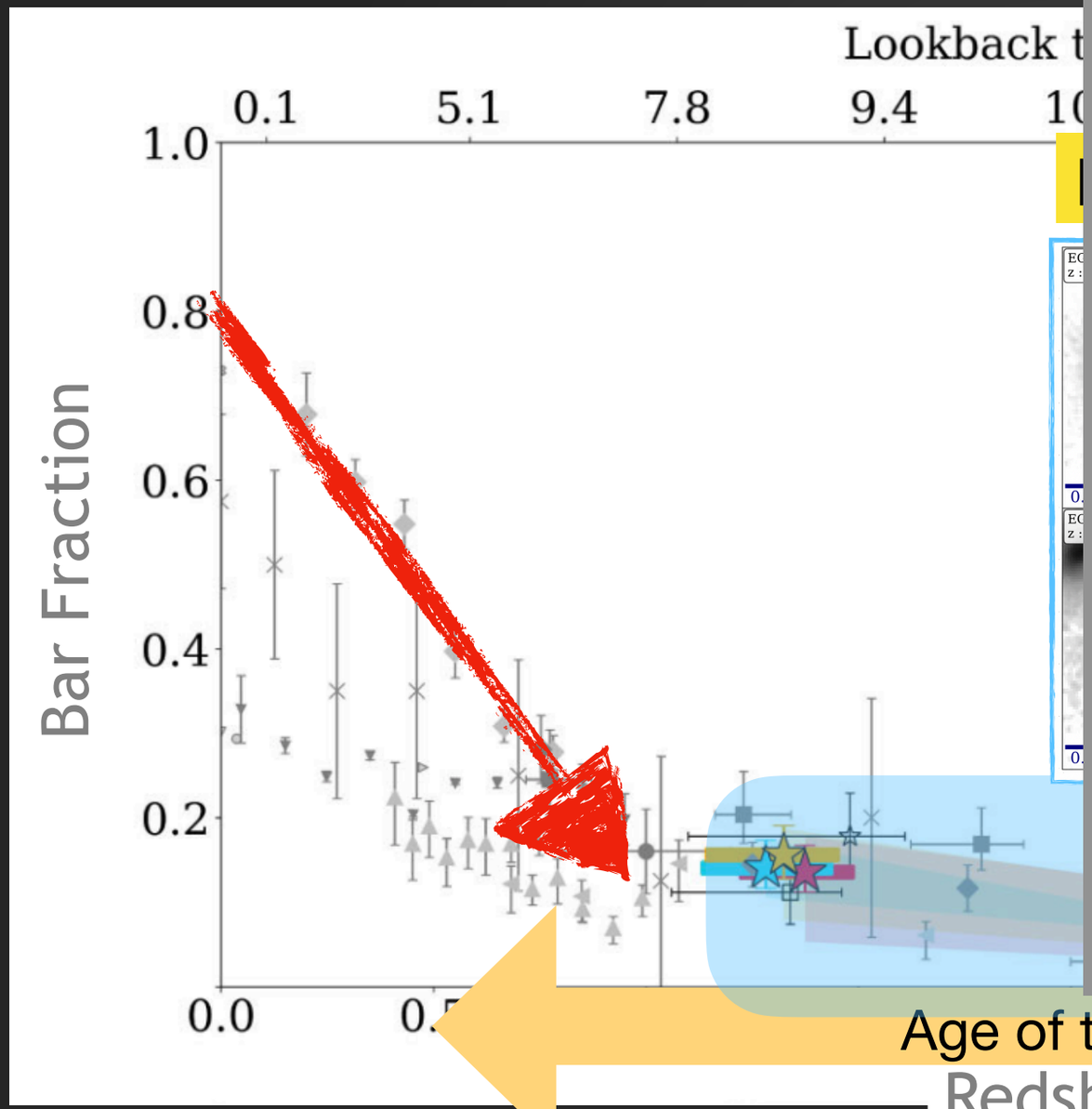
Bar fraction evolution with redshift

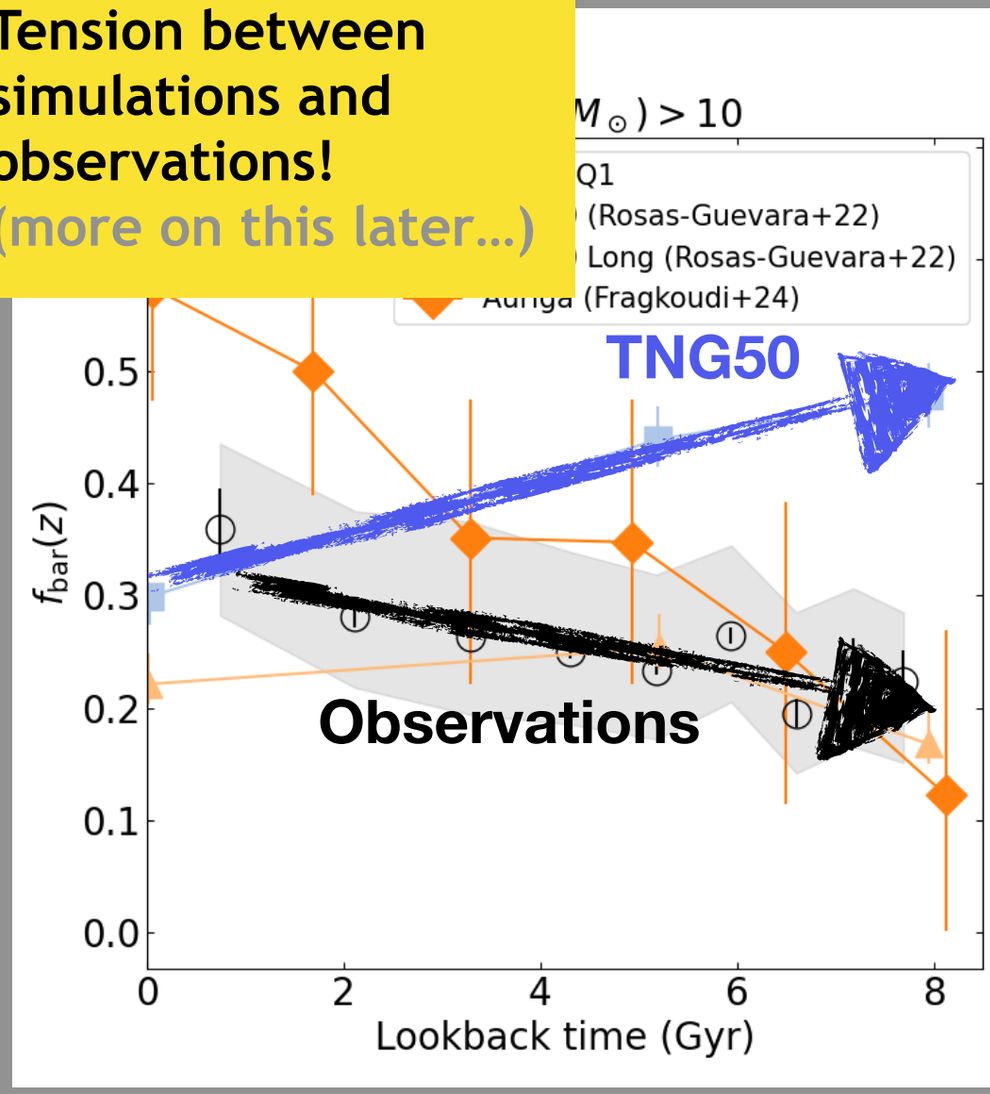
— bars and disk maturity

Dynamically cold, stable disks way earlier than expected!

Tension between simulations and observations!
(more on this later…)

Tracing the fraction of disks with bars = tracing di





Euclid: Huertas-Company+25

Age of the Universe

Redshift

Le Conte+26

Galaxy global shapes — tell-tale signs of past evolution

- Galaxy shapes are associated to past events
- Presence of sub-galactic structures — disk maturity
- Internal galaxy evolution can lead to changes to internal structure

Bars transform their hosts!

- The gas transport triggered by a bar can affect significantly its host

→ wash out metallicity gradient
(Martin & Roy 2004; but Sánchez+14; Zurita+21)

→ central accumulation of gas
(e.g., Sheth+05, Chown+19, Yu+22, PHANGS: Sun+20)

→ nuclear starbursts, pseudobulges
(e.g., Kormendy & Kennicutt 04)

→ Feeding AGN?
(e.g., Laurikainen+04, Cheung+15, Alonso+18, Lima-Silva+22, La Marca+26)



Zooming into sub-galactic structures —
the quest for stellar mass

★ Shapes provide insights to galaxies' history of mass assembly…

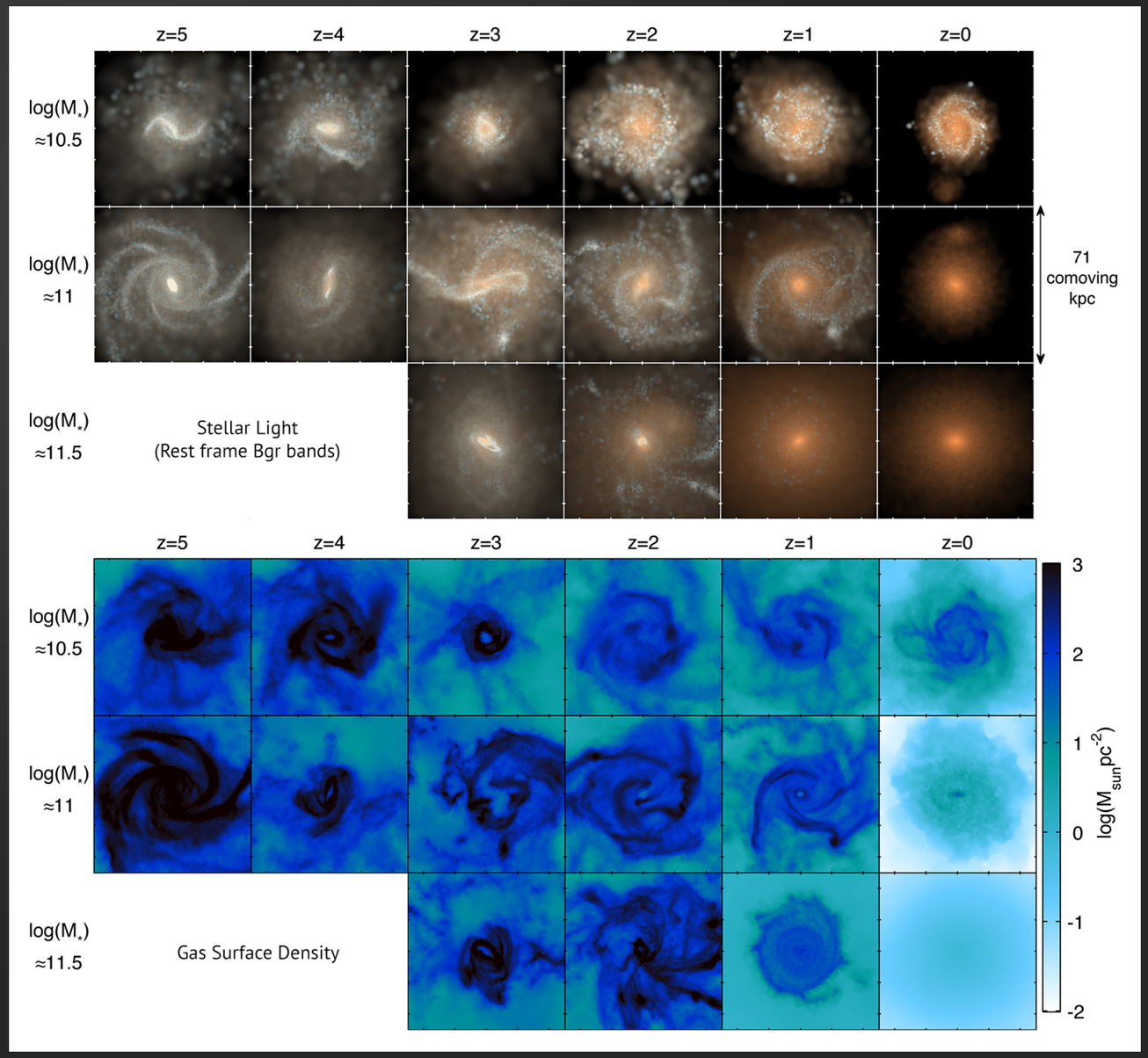
- How much mass is involved in these structures?
  - Stellar mass is the key to compare to simulations

New generation of cosmological simulations (N-body treatment of DM + full hydrodynamical treatment of gas) are starting to reproduce basic galaxy morphology trends

(e.g., Snyder et al. 2015)

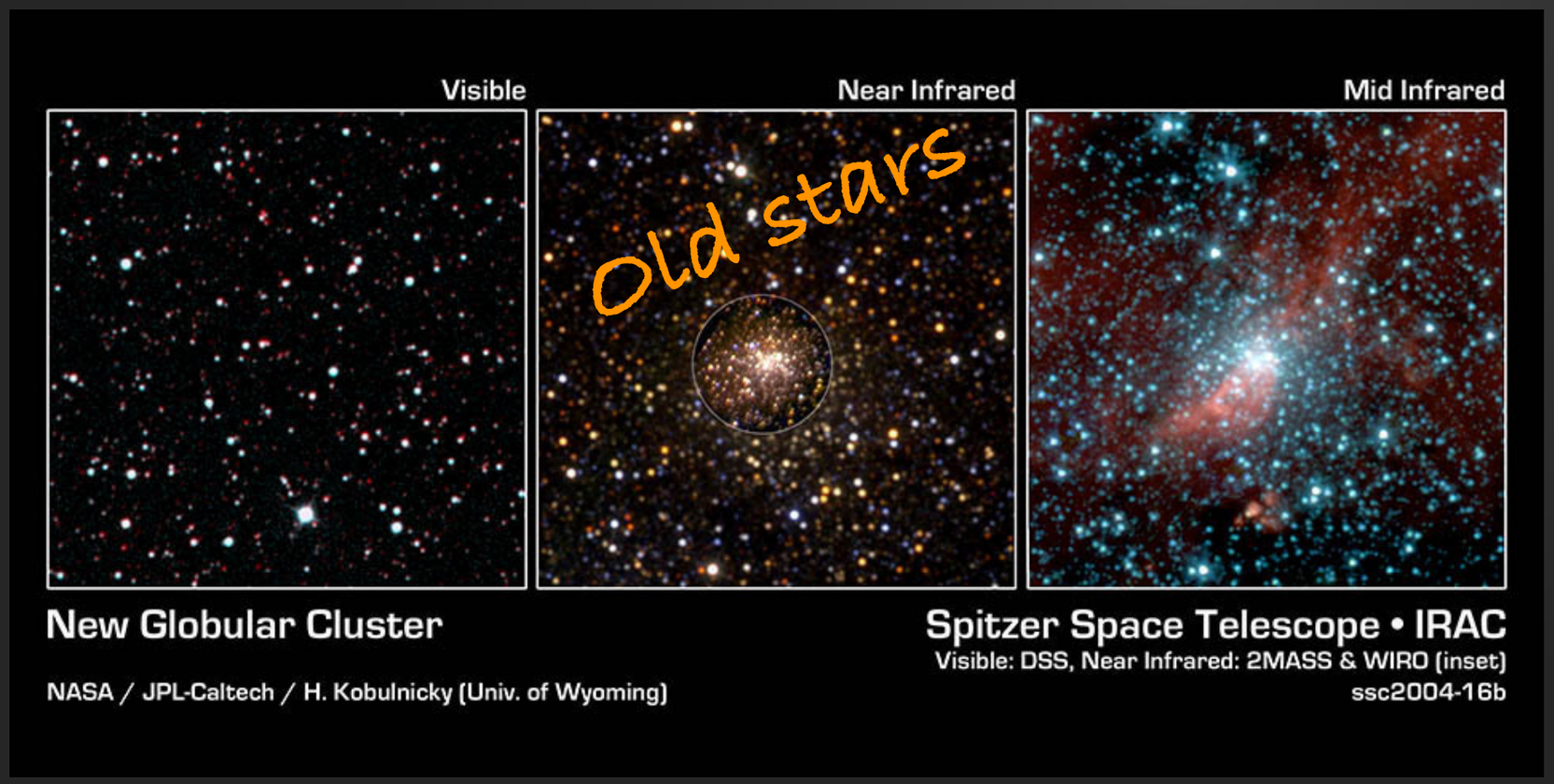
Full hydrodynamical treatment of baryonic physics, including: cooling, star-formation, star-formation feedback, AGN feedback.

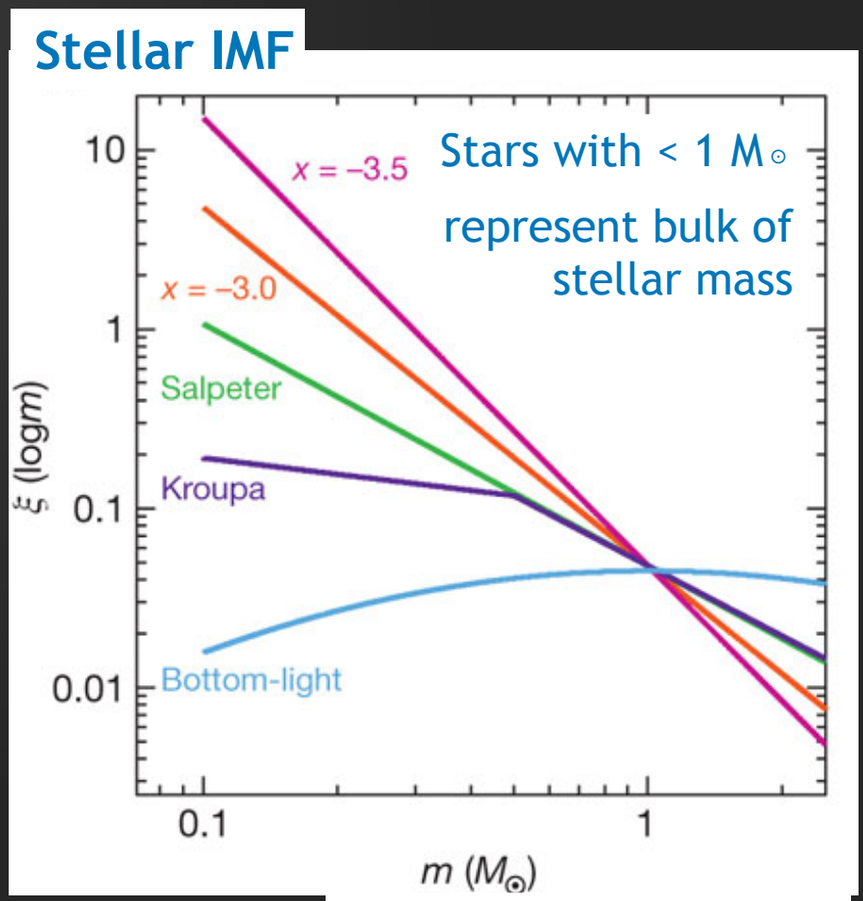
Illustris Collaboration



Nearby galaxies
– the quest for (mass) characterization

- Challenge: observations measure light and not mass
  - need to convert “radiation” into “stellar mass”
  - go infrared!
    - dust extinction minimal
    - infrared luminosity is dominated by old stars - the best marker of the distribution of stellar mass in galaxies.



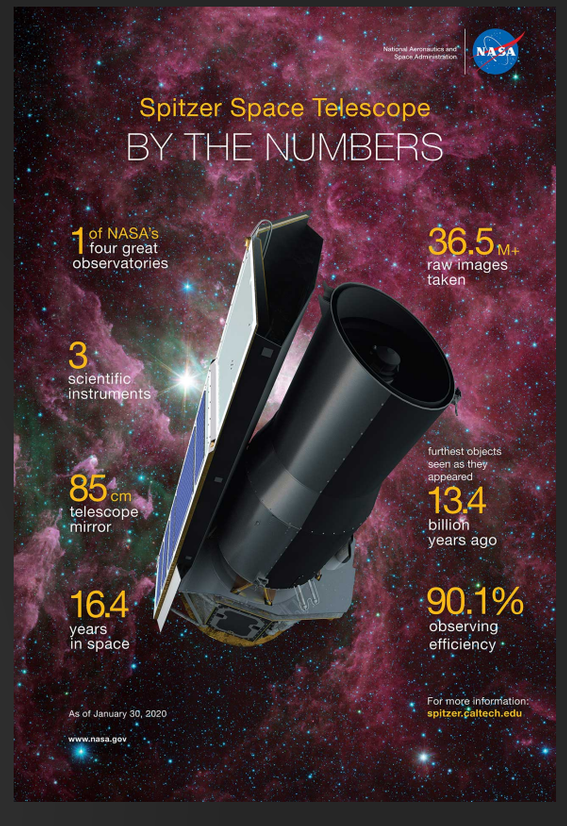


Spitzer Survey of Stellar Structures in Galaxies

- Legacy Survey of the *Warm* Spitzer Mission
  - ✦ >2300 galaxies @ at 3.6/4.5μm
    - $m_B < 15.5$, $D_{25} > 1'$, d <40 Mpc
  - ✦ largest, deepest, most homogeneous survey of nearby galaxies in the mid-infrared: ~27 mag/arcsec^2, $\Sigma_* << 1\ M_\odot\ pc^{-2}$, mosaicked to reach 1.5 x D_{25}

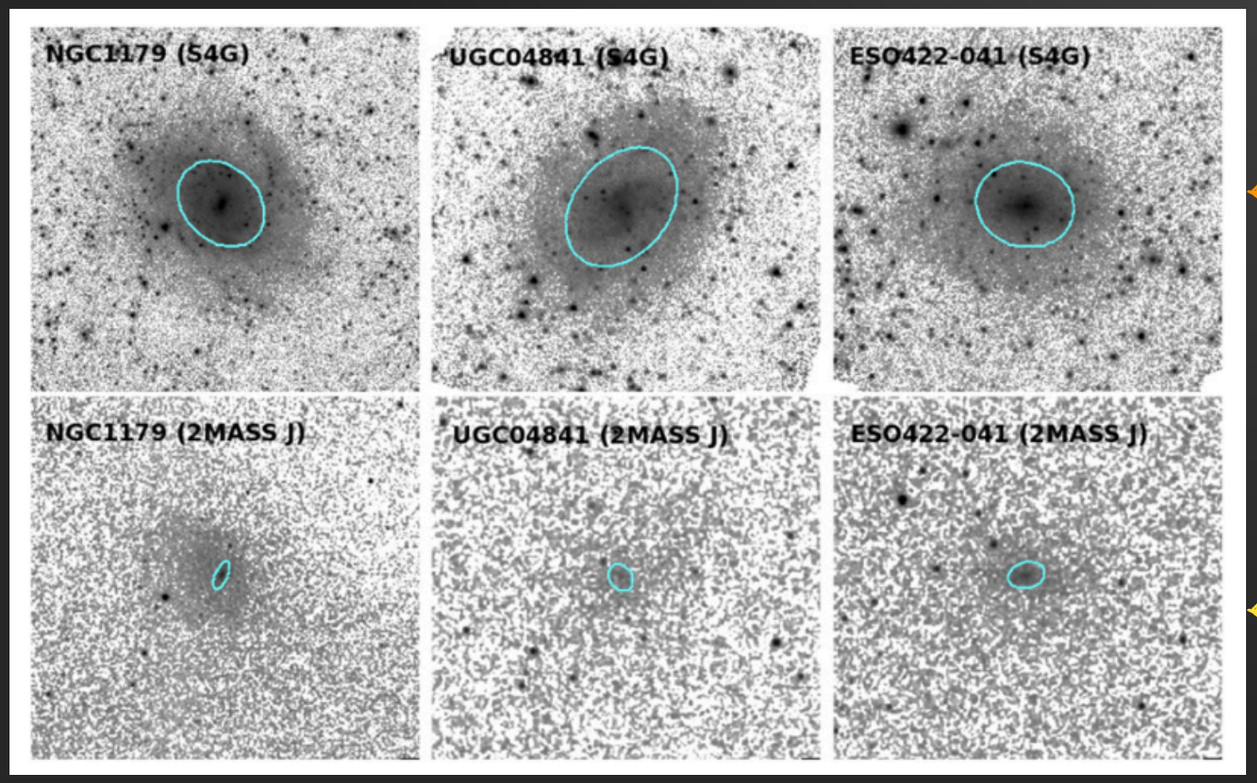
S^{4}G:

- ☐ a deep mapping of low mass regions
- ☐ homogeneity in depth and data processing for entire sample



Light distribution
—> Mass maps!

Eskew+12, Querejeta+15)



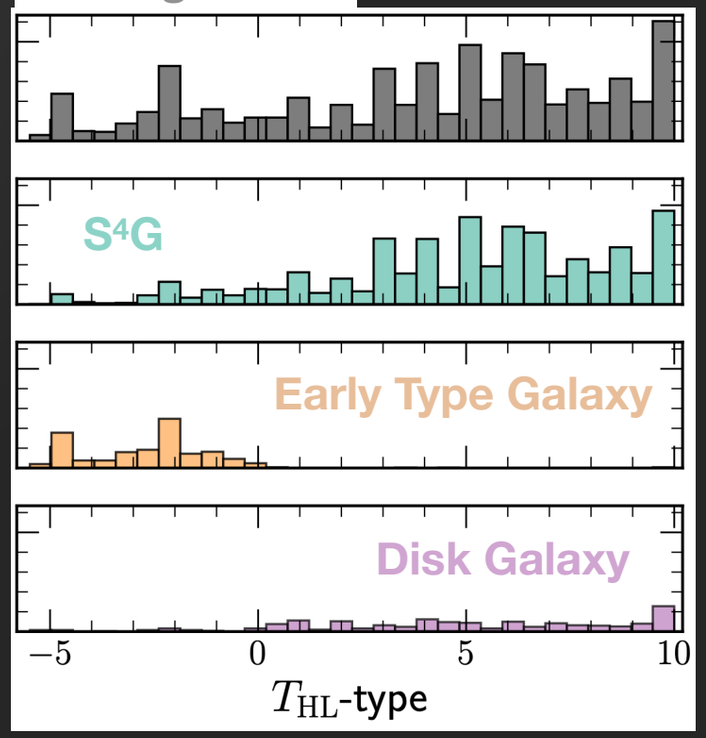
S^{4}G

Sheth+10
Muñoz-Mateos+15
Querejeta+15

2MASS
2 MICRON ALL SKY SURVEY

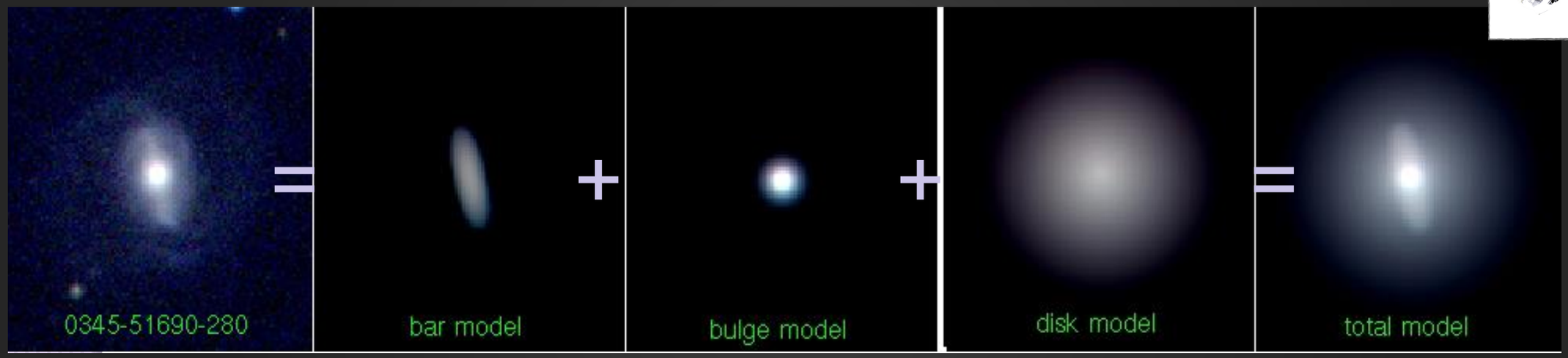
CS^{4}G
3239 galaxies

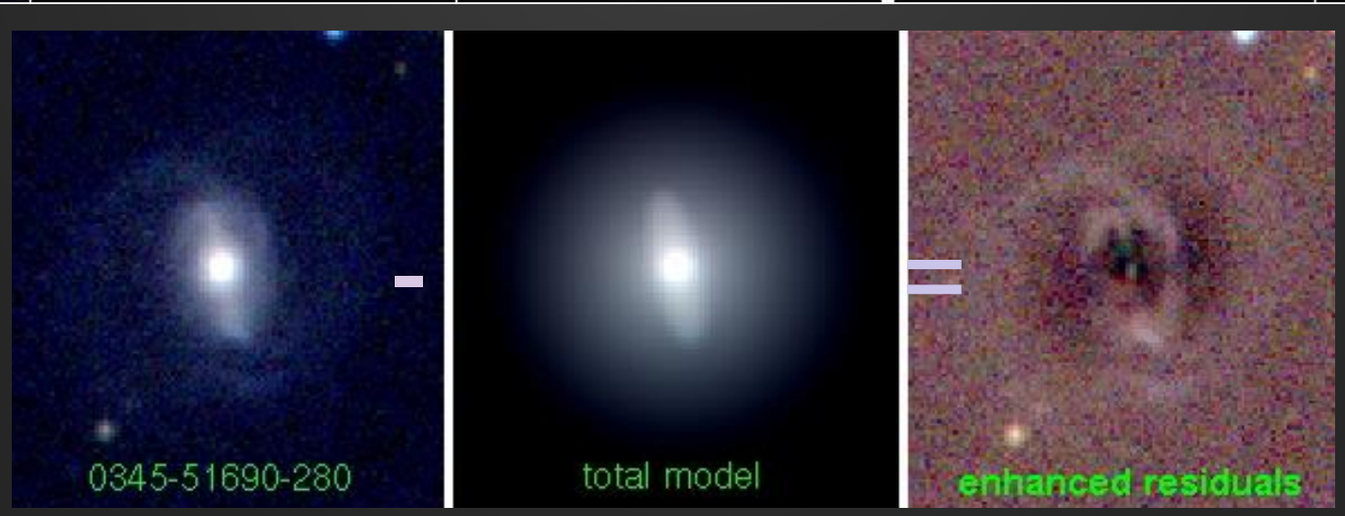
see also
Sánchez-Alracón+25



Stellar Mass in Galaxy Structures

- Specific objetive:
  - Establish what the distribution of stellar mass content is in stellar structures commonly found in galaxies (e.g., bulge, disk, bars)
- Exploit 2D decompositions made by S4G team





GALFIT
(Peng et al. 2002, 2010)
GALFIDL (Salo+15)

✦ Invitation to undertake spatially-resolved studies of galactic substructures

- TIMER (MUSE; PI Gadotti)
- SPLUS (12-filter survey; Lima-Dias+23)

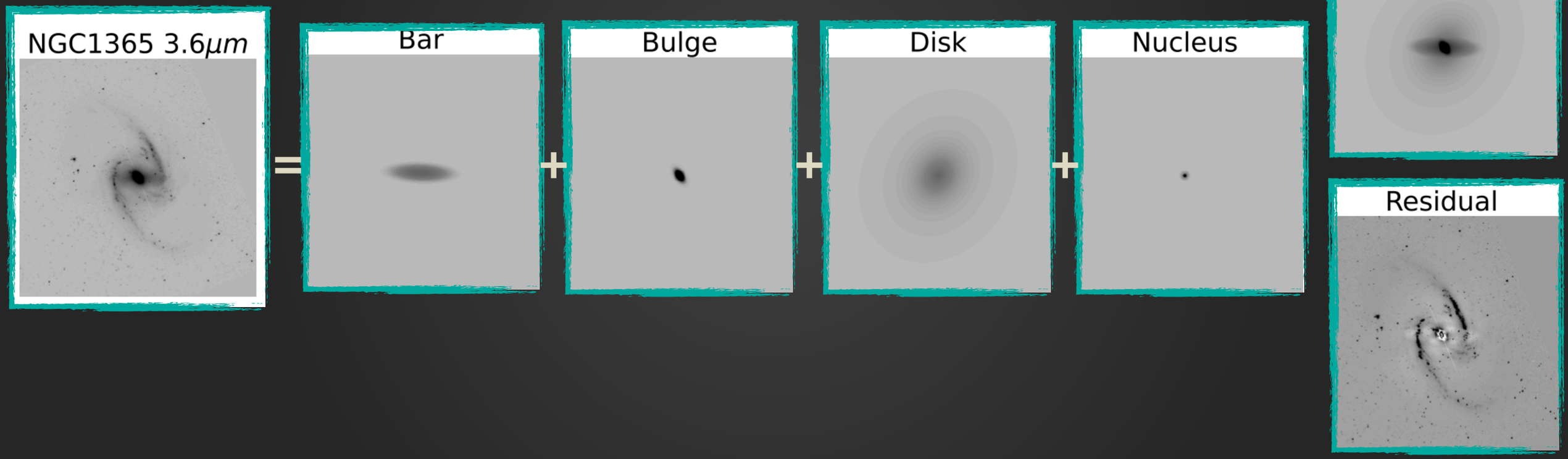
Bars in massive spirals

How much stellar mass within bars?



Yasmin Cavalcante-Coelho
(ESO La Silla School 2024)

- 365 bars out of all massive spirals from S4G
  - ~1-100s billion solar masses
  - not too inclined! (i < 65°)



Cavalcante-Coelho+ in prep.

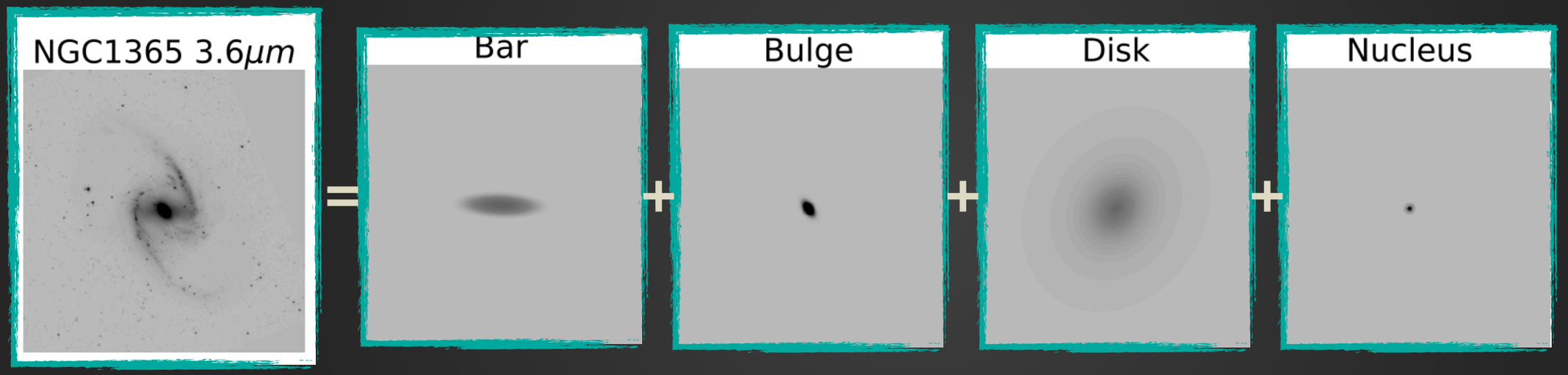
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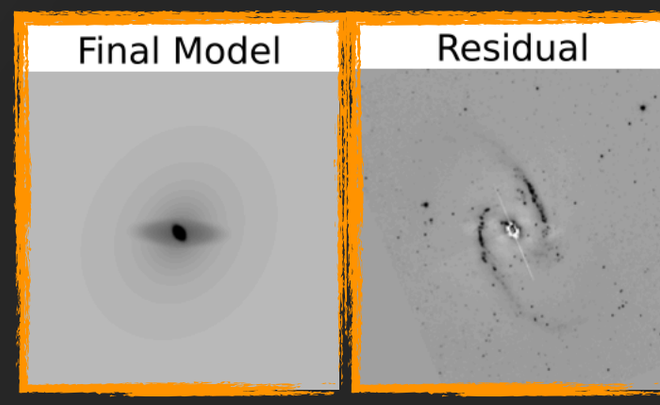


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Light distribution —> Mass maps!

Eskew+12
(see also Querejeta+15)

$$M_* = 10^{5.65} F_{3.6}^{2.85} F_{4.5}^{-1.85} \left(\frac{D}{0.05}\right)^2$$

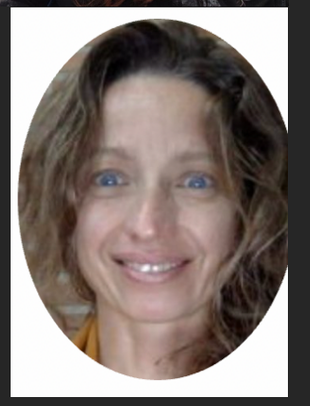
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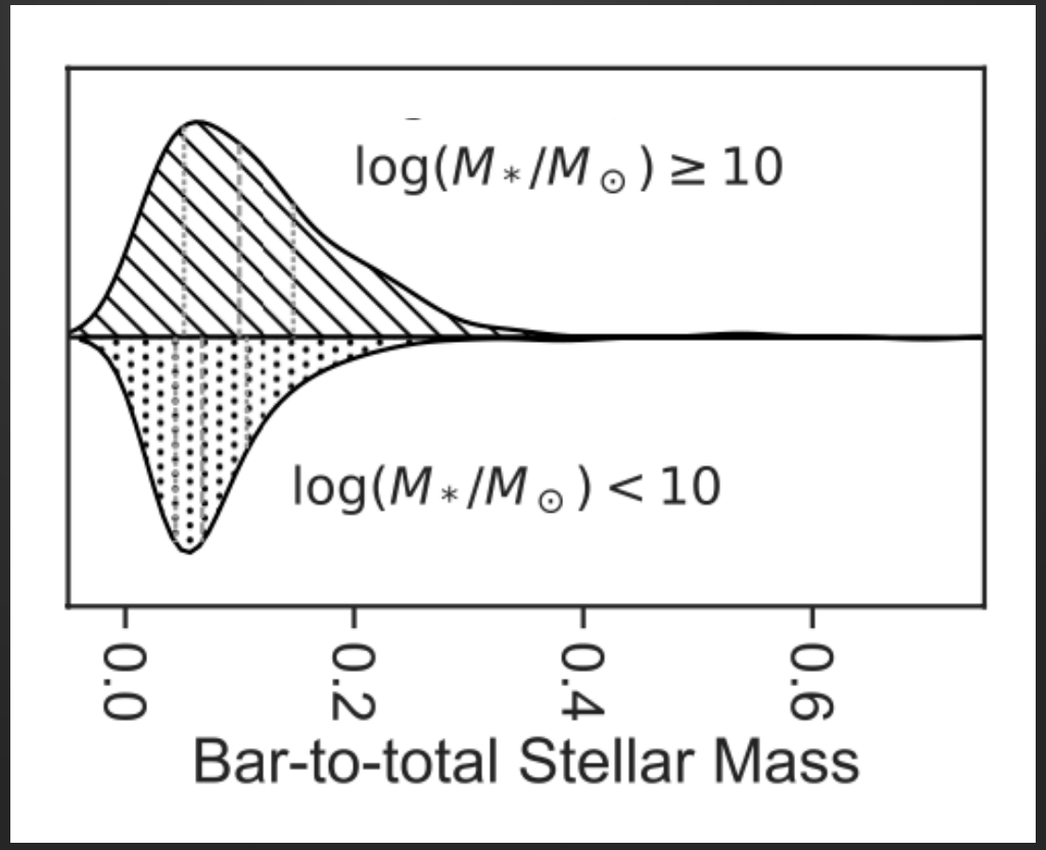


Yasmin Cavalcante-Coelho
[collab. Arianna Cortesi]



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- The bar comprises <1/10 of the galaxy's total stellar mass

✦ Bars in higher-mass disk galaxies enclose a greater proportion of the galaxy stellar mass



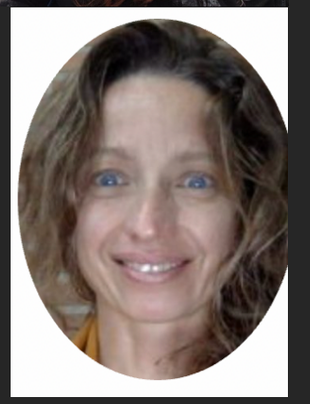
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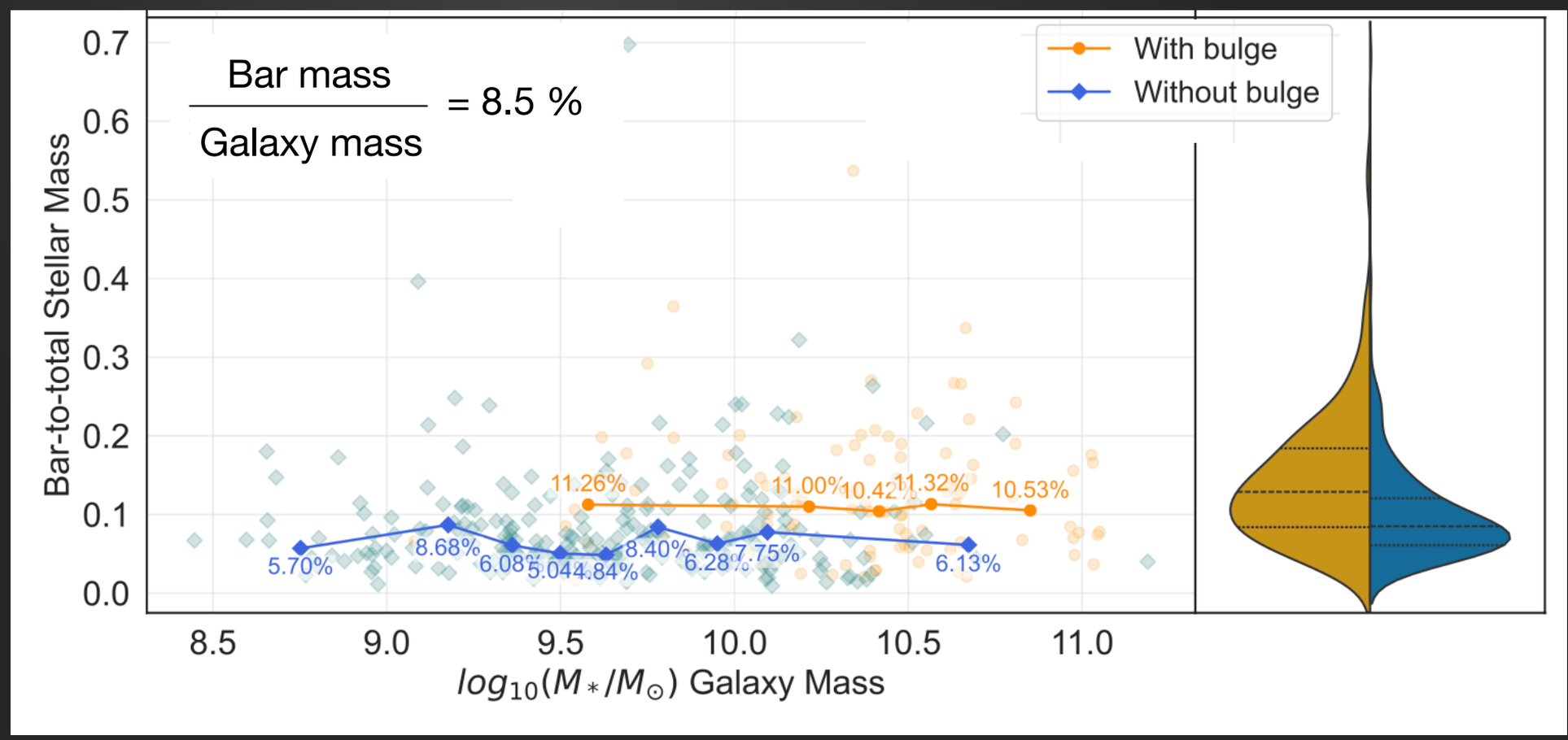


Yasmin Cavalcante-Coelho
[collab. Arianna Cortesi]



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- ✦ More massive bars in disk galaxies with more prominent bulges



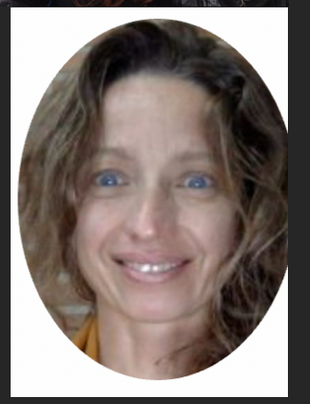
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Bars in massive spirals

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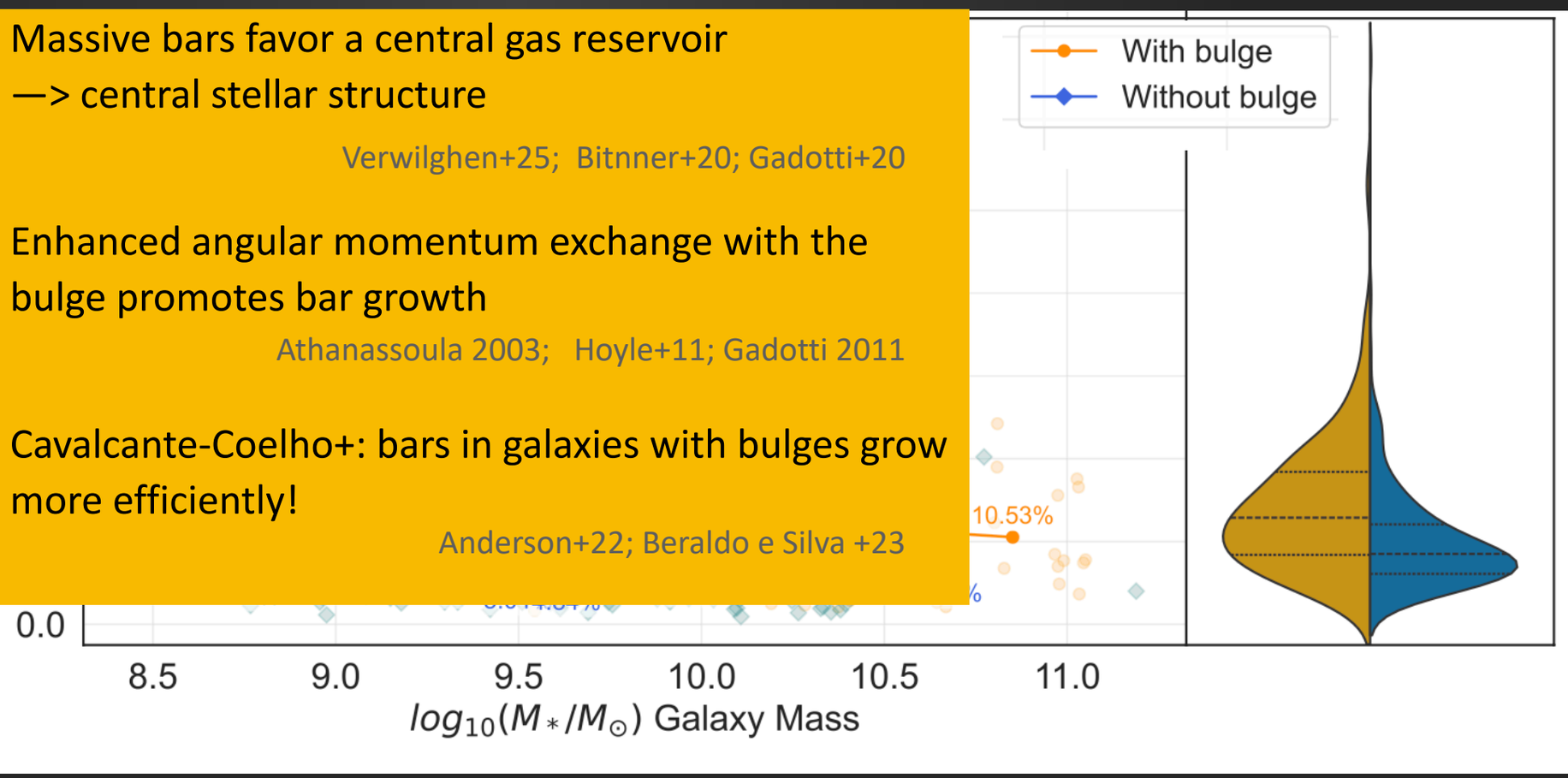
- ✦ Bars in higher-mass disk galaxies enclose a greater proportion of the galaxy stellar mass
- ✦ More massive bars in disk galaxies with more prominent bulges

- ▸ Massive bars favor a central gas reservoir —> central stellar structure

  Verwilghen+25; Bitnner+20; Gadotti+20
- ▸ Enhanced angular momentum exchange with the bulge promotes bar growth

  Athanassoula 2003; Hoyle+11; Gadotti 2011
- ▸ Cavalcante-Coelho+: bars in galaxies with bulges grow more efficiently!

  Anderson+22; Beraldo e Silva +23



Cavalcante-Coelho+ in prep.

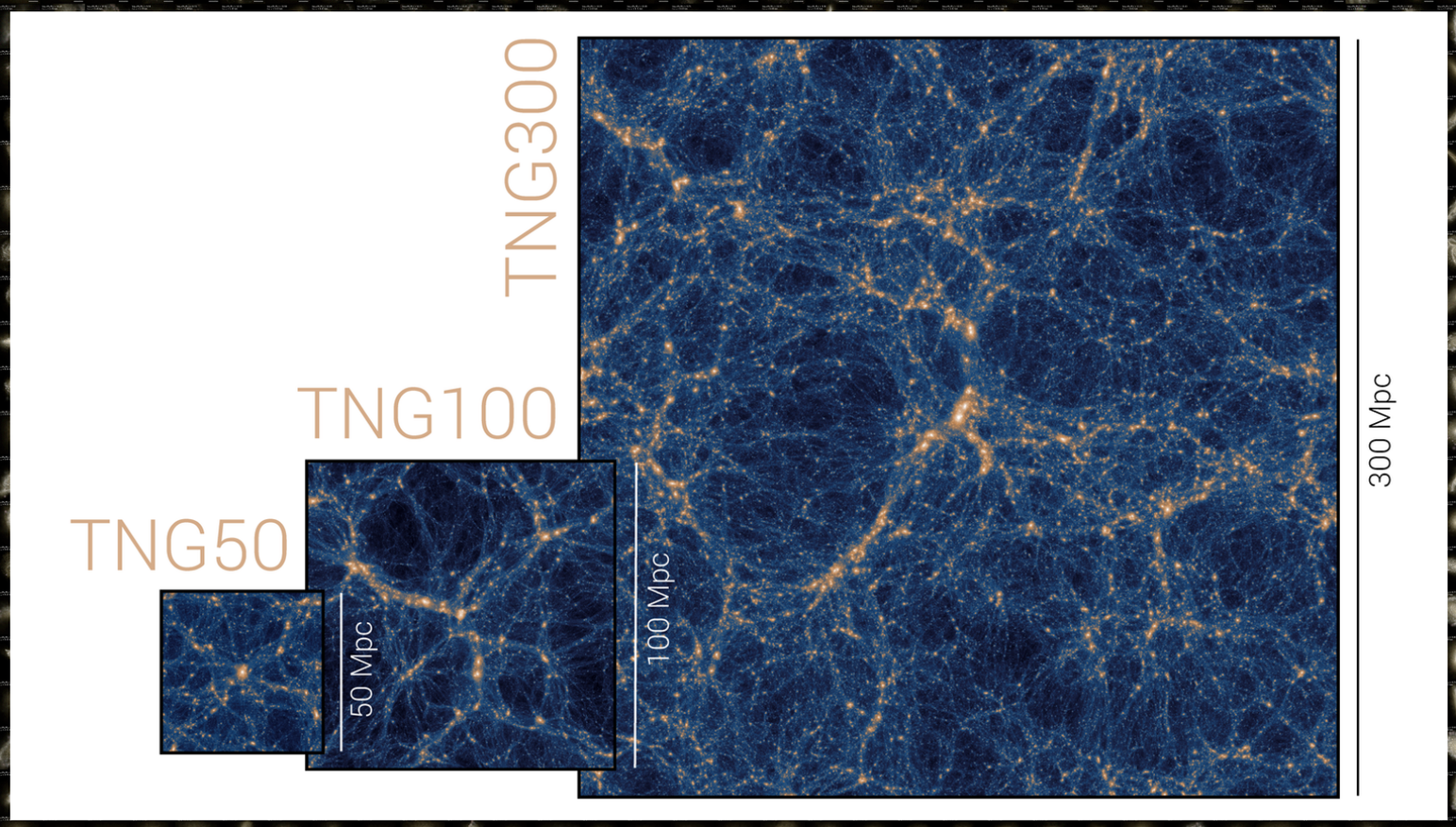
Bar masses in simulated galaxies

A nascent study with Illustris TNG-50



Thiago Bueno Dalpiaz

TNG50: synthetic stellar light images at z~0
Rodriguez-Gómez+18



Bar masses in simulated galaxies

A nascent study with Illustris TNG-50

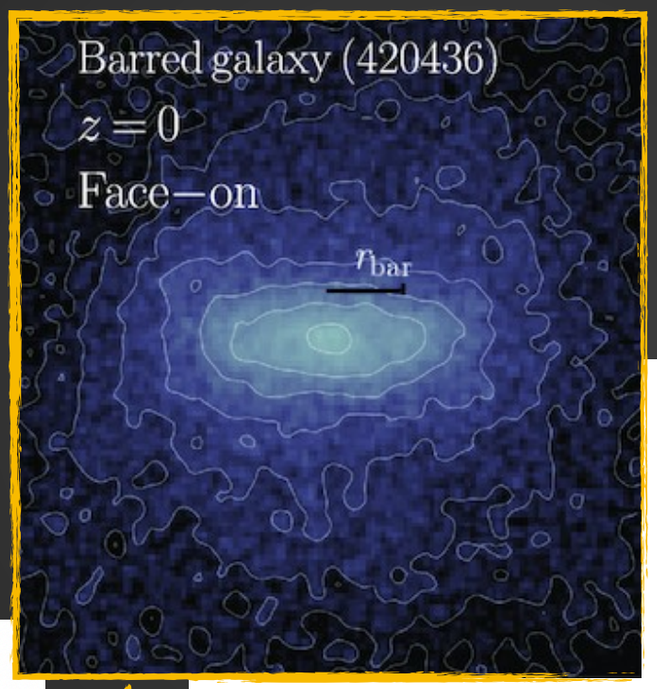


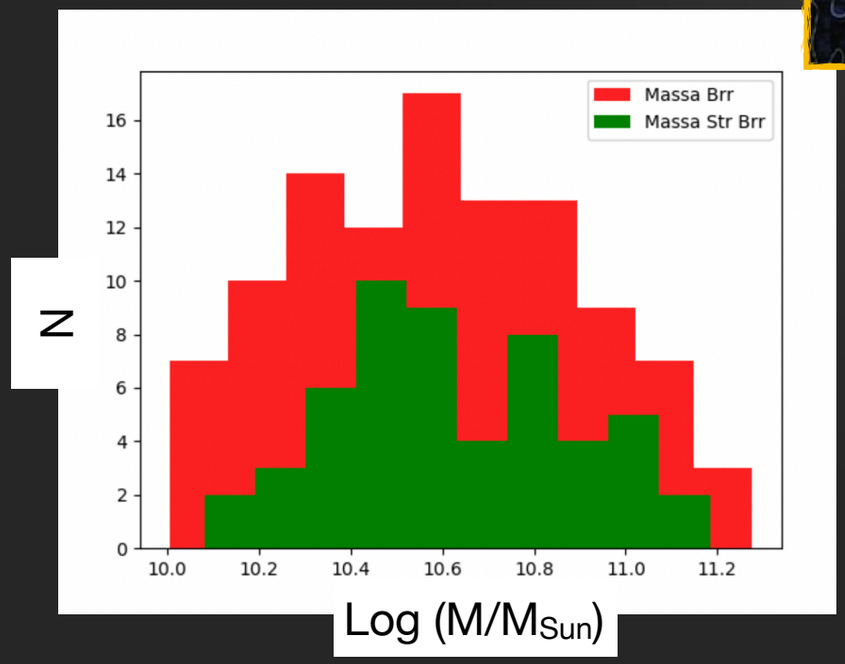
Thiago Bueno Dalpiaz

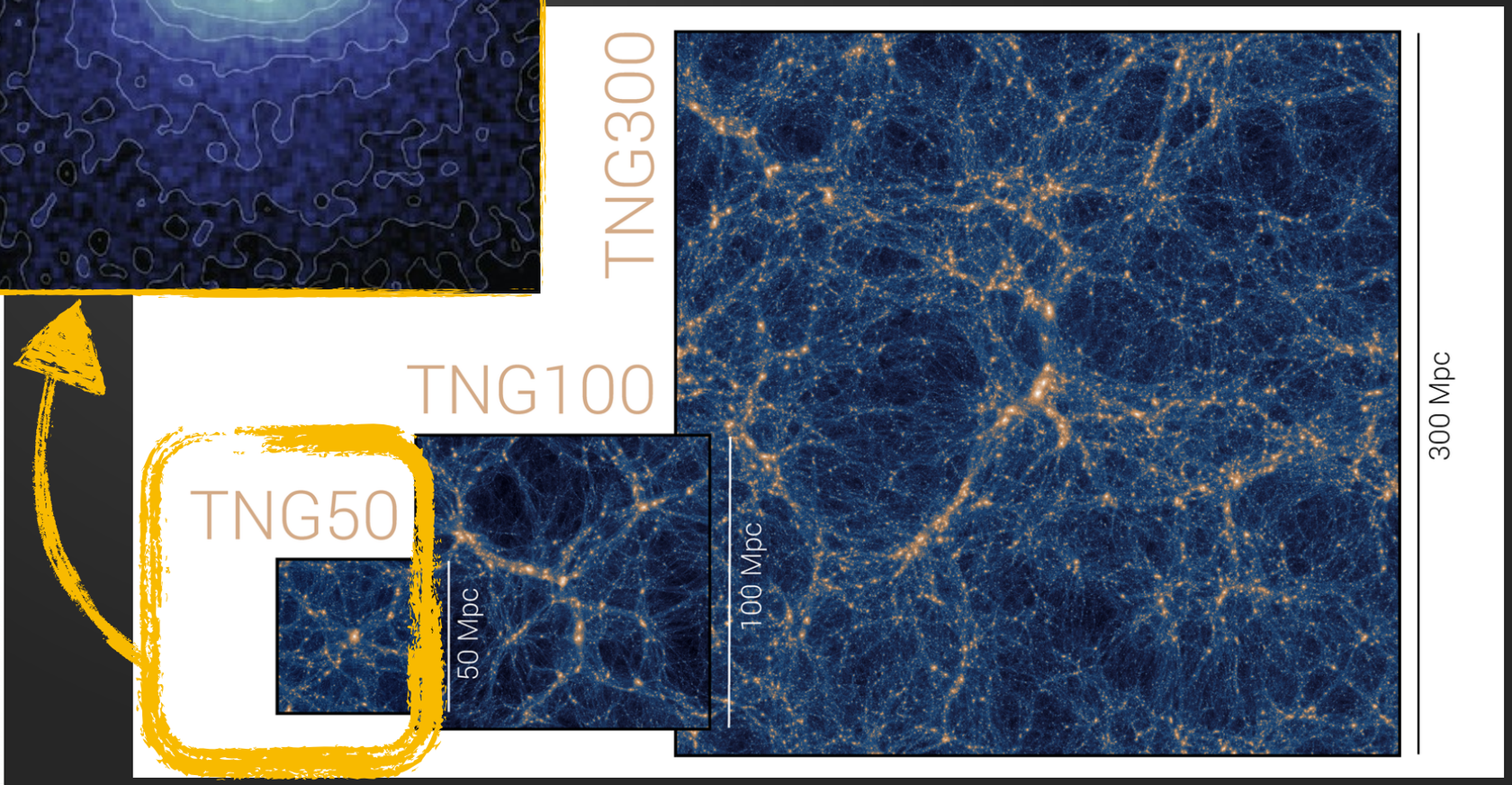
- Barred sample from Rosas-Guevara+22

  ~100 barred disks at z=0

  ~50 strongly-barred systems







Bar masses in simulated galaxies

A nascent study with Illustris TNG-50



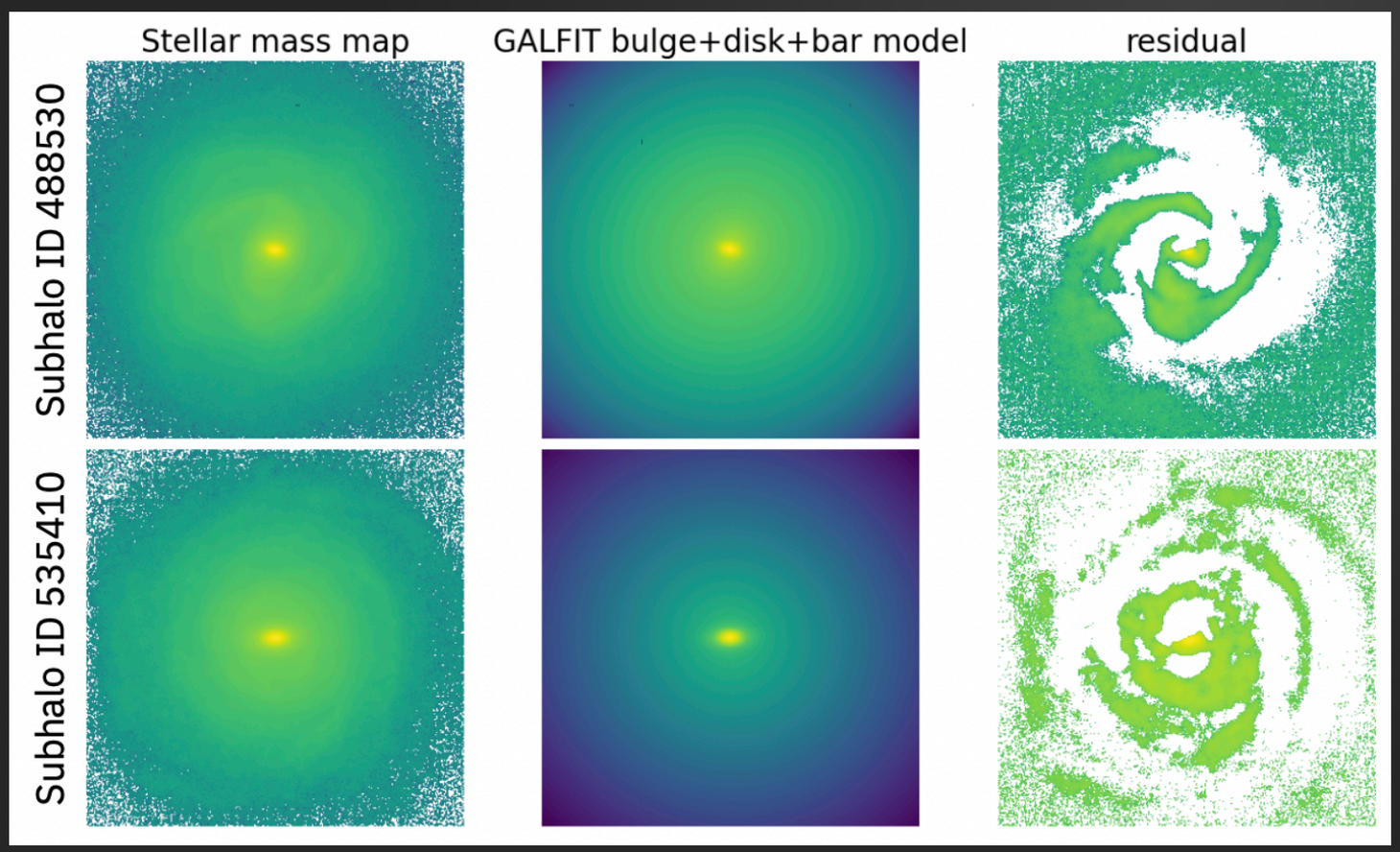
Thiago Bueno Dalpiaz

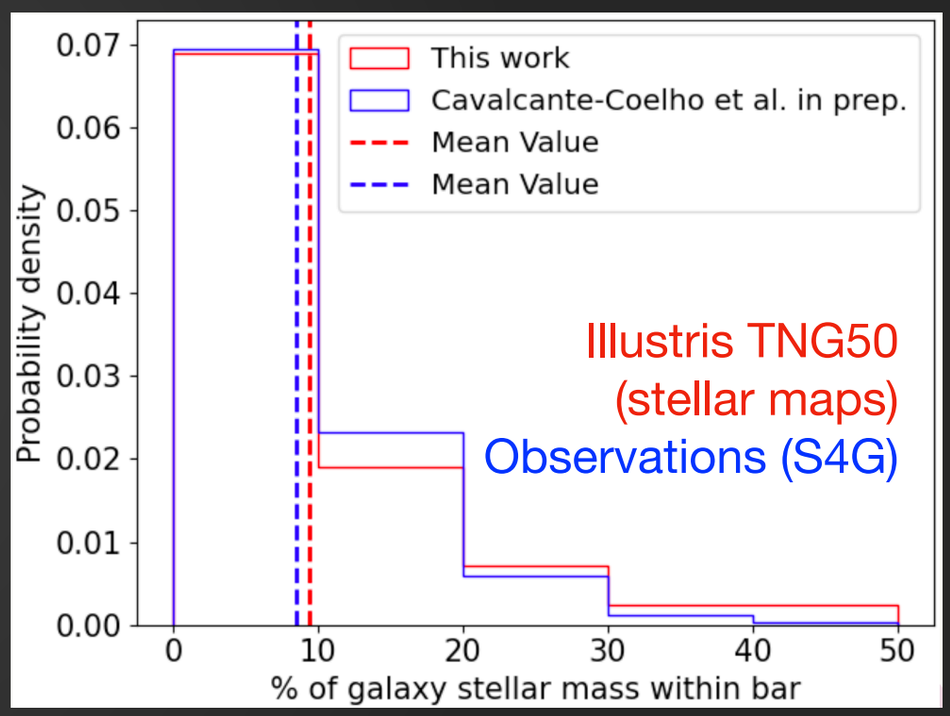
- Barred sample from Rosas-Guevara+22

  ~100 barred disks at z=0

  ~50 strongly-barred systems

  - 2D decomposition of TNG50 stellar mass maps with GALFIT —> bar component —> mass within bars.





M_{bar}/M^*_{gal} ~10.1%

TNG-50

M_{bar}/M^*_{gal} ~8.5%

S4G

Bar masses in simulated galaxies

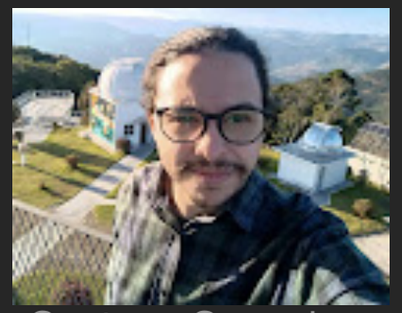
A nascent study with Illustris TNG-50



Rubens Machado
(IAG/USP)



Thiago Bueno Dalpiaz



Gustavo Gonçalves
(UFTPR)

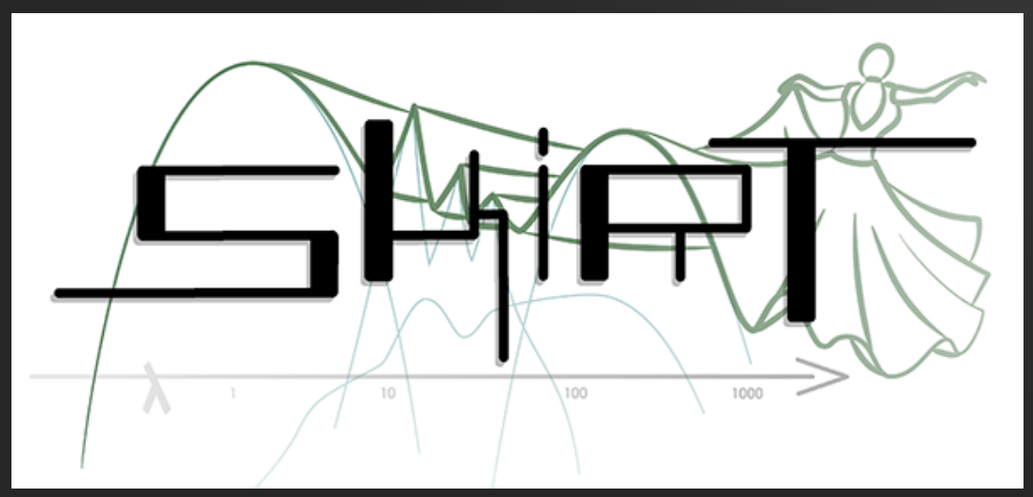
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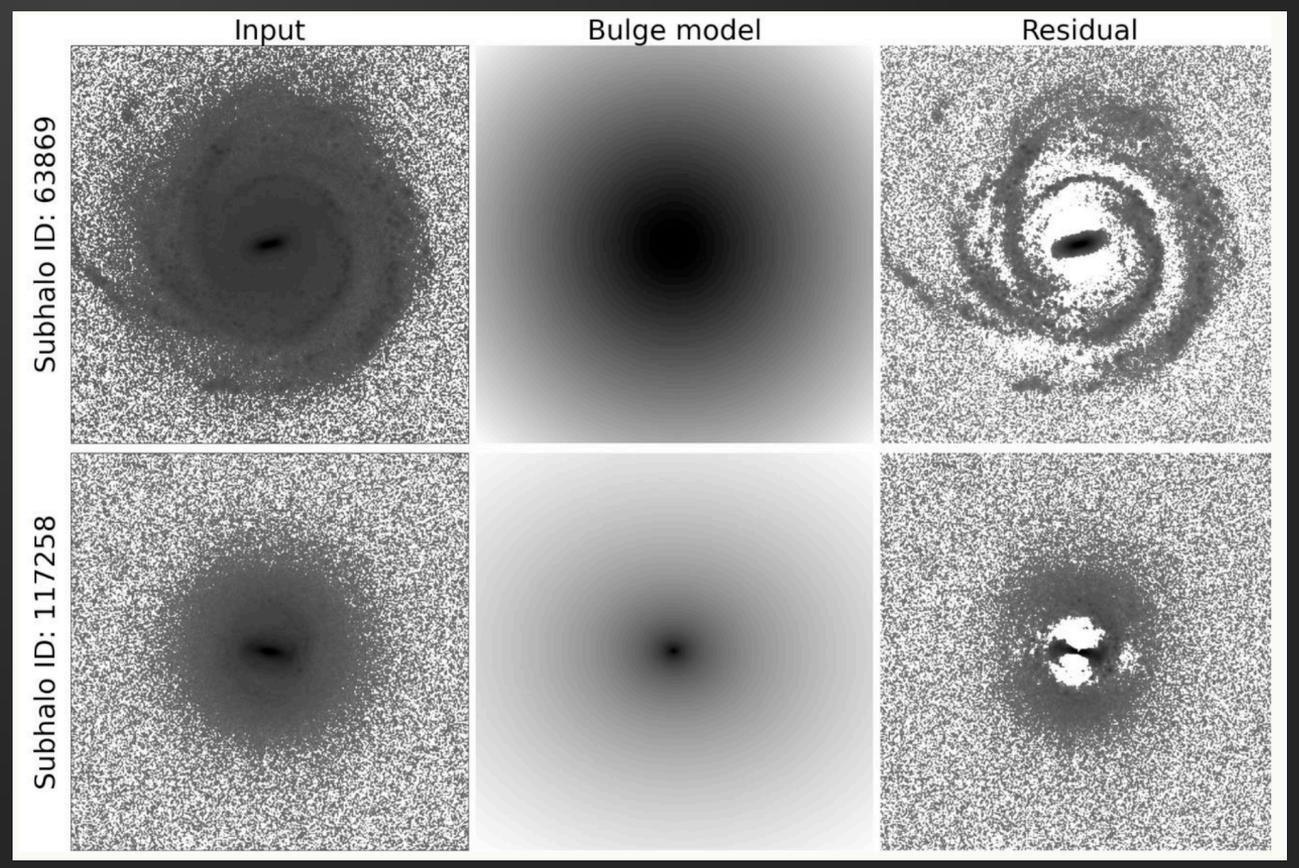
  ~50 strongly-barred systems

- Bar properties as a function of wavelength in Illustris TNG50: analysis of mock images
- Undertake 2D decomposition of mock images with GALFITM —> mass within bars.

[Bueno-Dalpiaz in prep.]



Camps & Baes 2020



Bar fraction evolution with redshift — tensions between observations and simulations

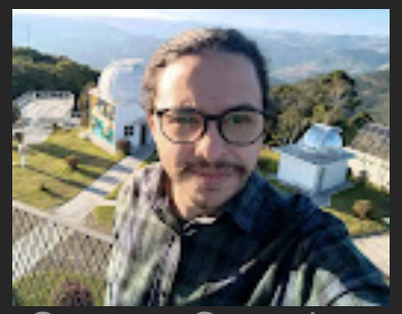
- TNG50 finds many more bars than observations!



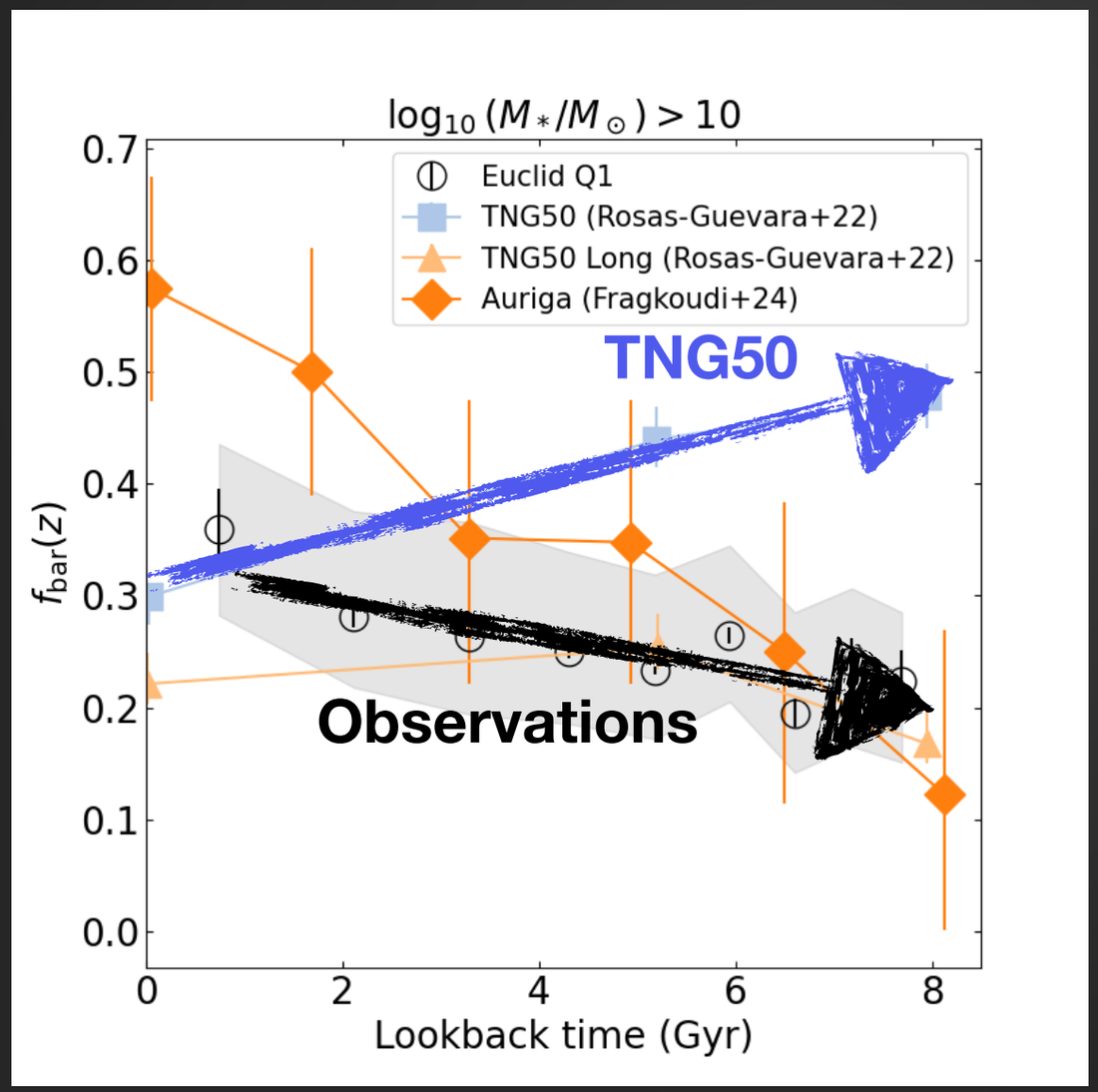
Rubens Machado
(IAG/USP)



Thiago Bueno Dalpiaz



Gustavo Gonçalves
(UFTPR)



Euclid: Huertas-Company+25

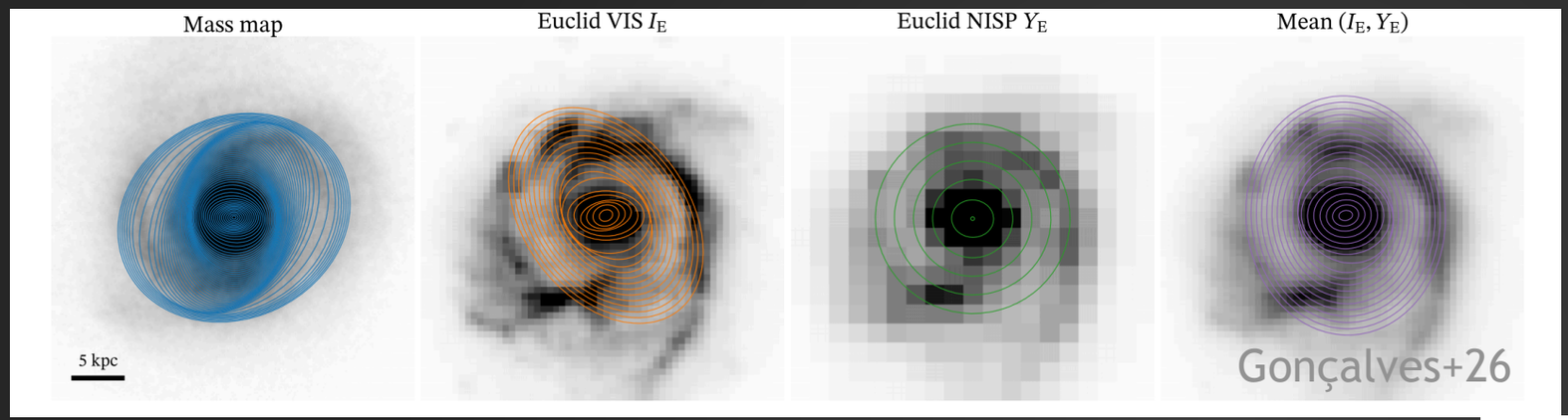
Bars at (very!) high-z:

JWST: Costantin+23; Guo+23+24; LeConte+23+26; Geron+25

ALMA: Tsukui+23

Bar fraction evolution with redshift — tensions between observations and simulations

- TNG50 finds many more bars than observations!

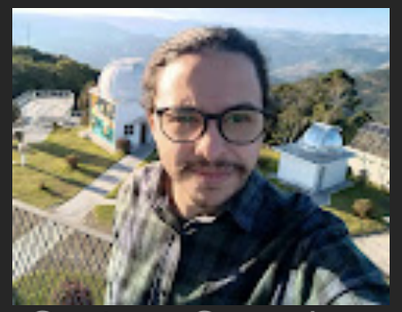




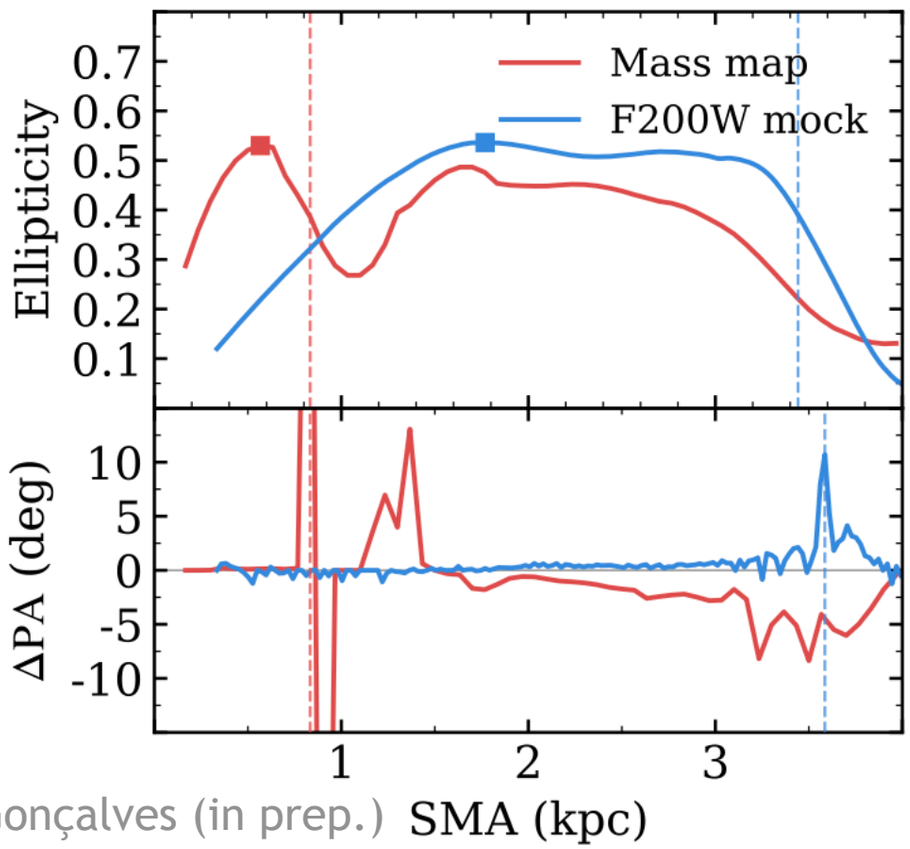
Rubens Machado
(IAG/USP)



Thiago Bueno Dalpiaz



Gustavo Gonçalves
(UFTPR)



Gonçalves (in prep.)

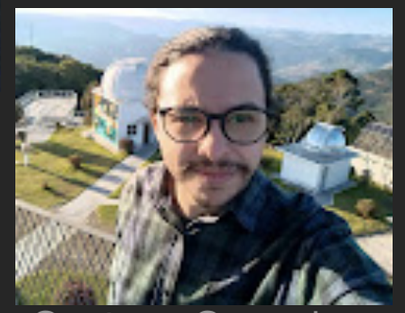
Bar fraction evolution with redshift — tensions between observations and simulations



Rubens Machado
(IAG/USP)

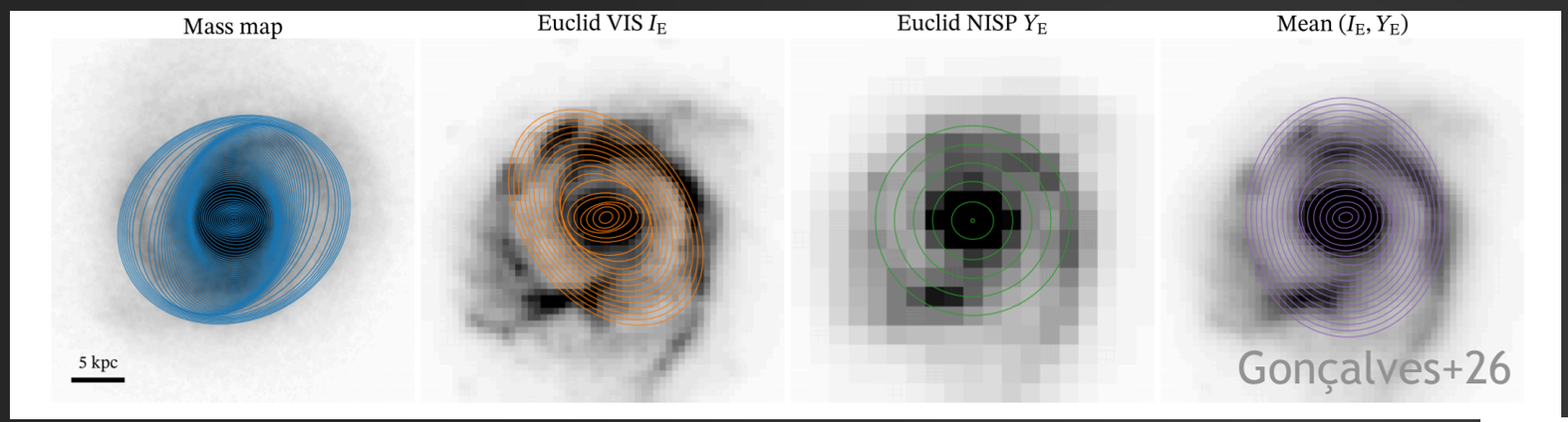


Thiago Bueno Dalpiaz

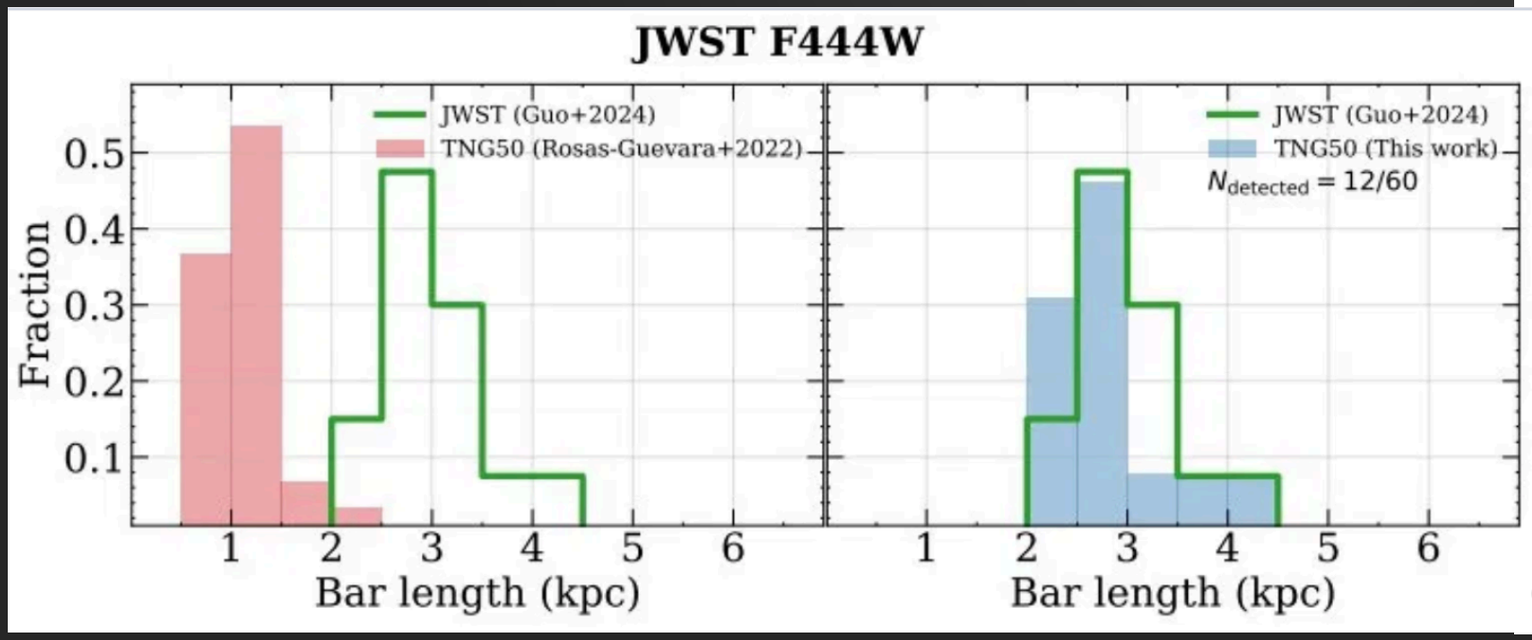


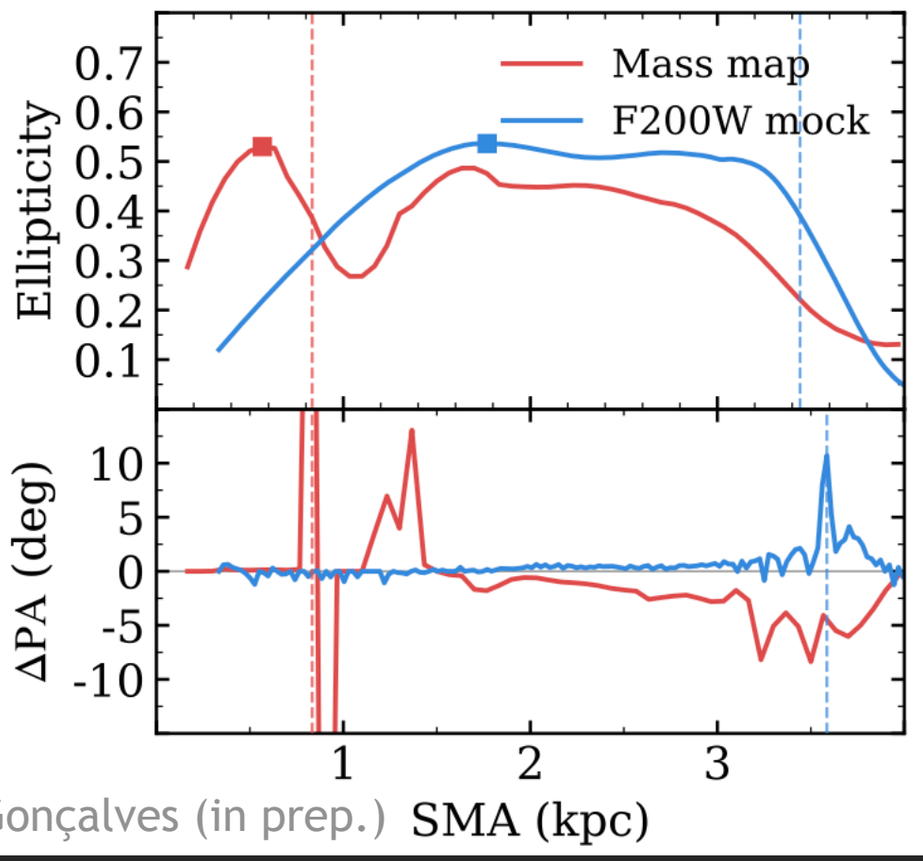
Gustavo Gonçalves
(UFTPR)

- TNG50 finds many more bars than observations!



- TNG50 is picking up many small bars!
- Observational conditions only allow us to pick out the larger structures





Gonçalves (in prep.)

Bar fraction evolution with redshift — tensions between observations and simulations

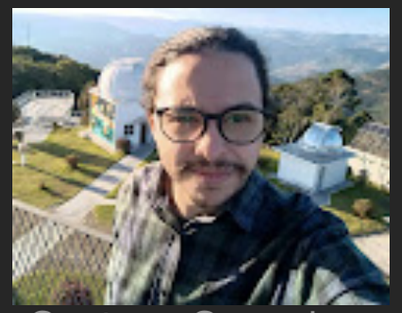
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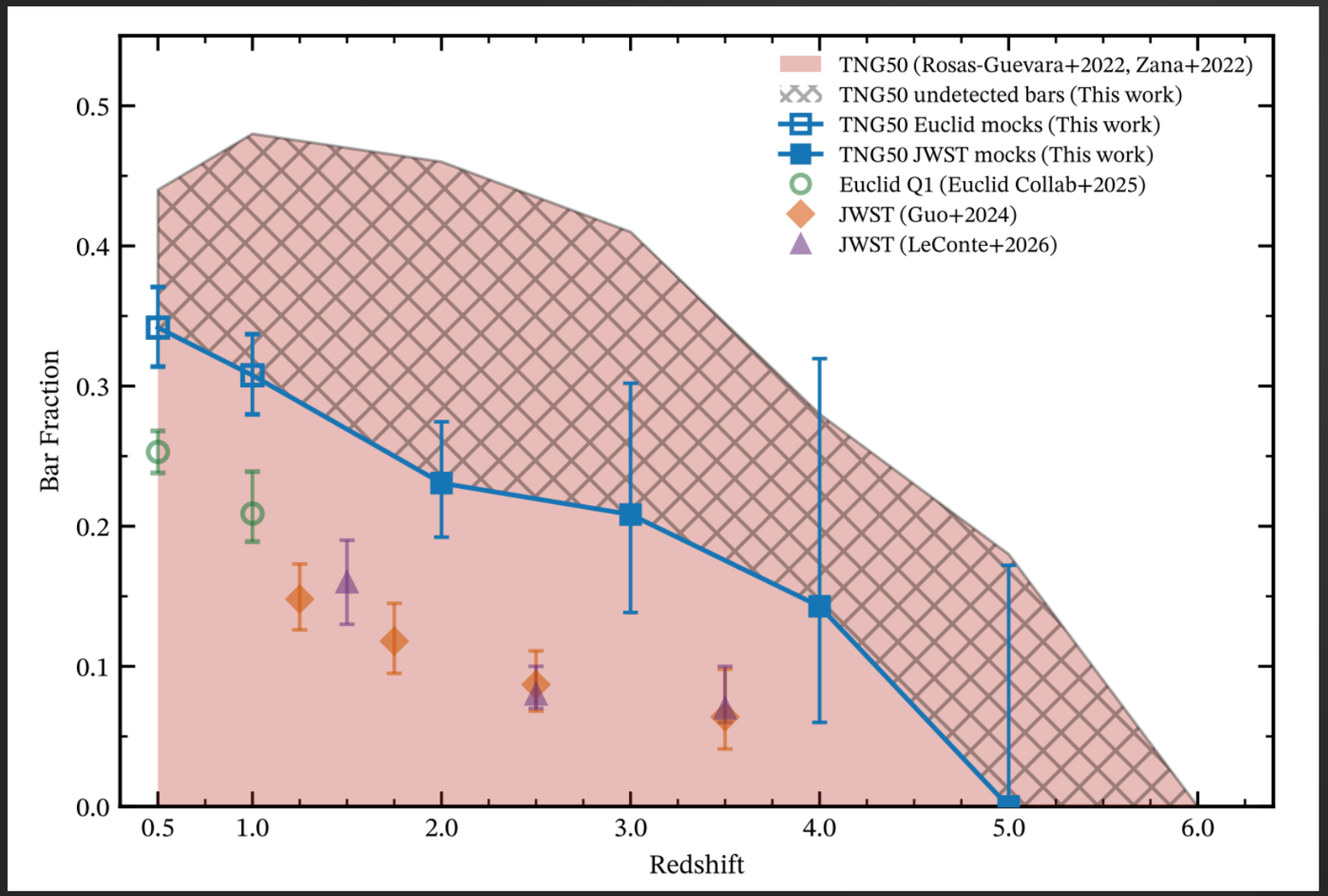
Rubens Machado
(IAG/USP)



Thiago Bueno Dalpiaz



Gustavo Gonçalves
(UFTPR)

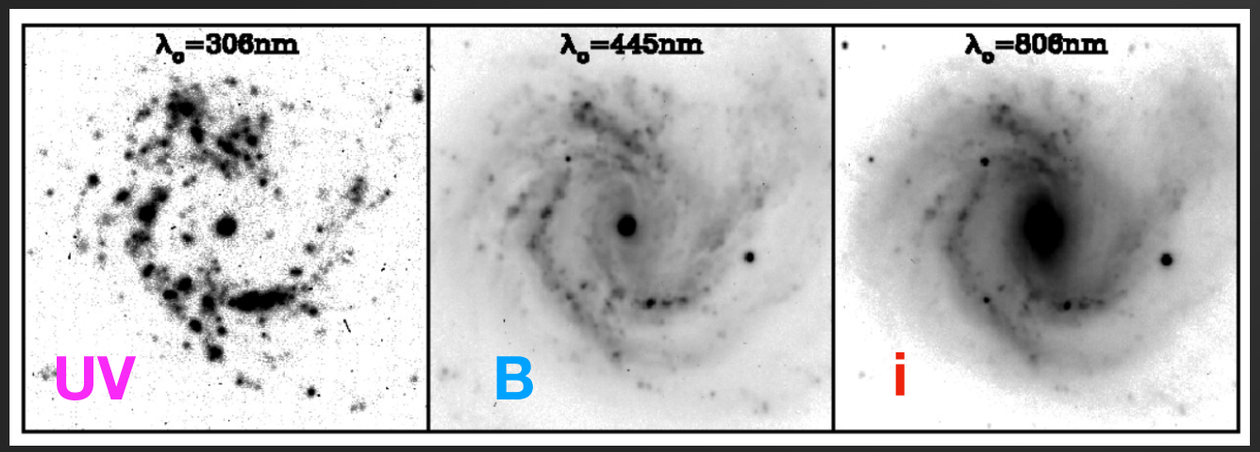


Gonçalves+ in prep

- Tension lessens!
- Crucial to consider resolution and observational effects to compare simulations with the real universe!
- Still tough to pick out weak bars in low-mass galaxies!

Stellar structures with cosmic time —
stellar populations matter!

- Morphology holds clues of galaxies' formation histories
  — but careful! morphology analysis at different bands can be misleading…
- Images of distant galaxies probe bluer bands — as we study stellar structures at higher redshifts, we are prey to band-shifting!



Bars are typically dominated by old stars

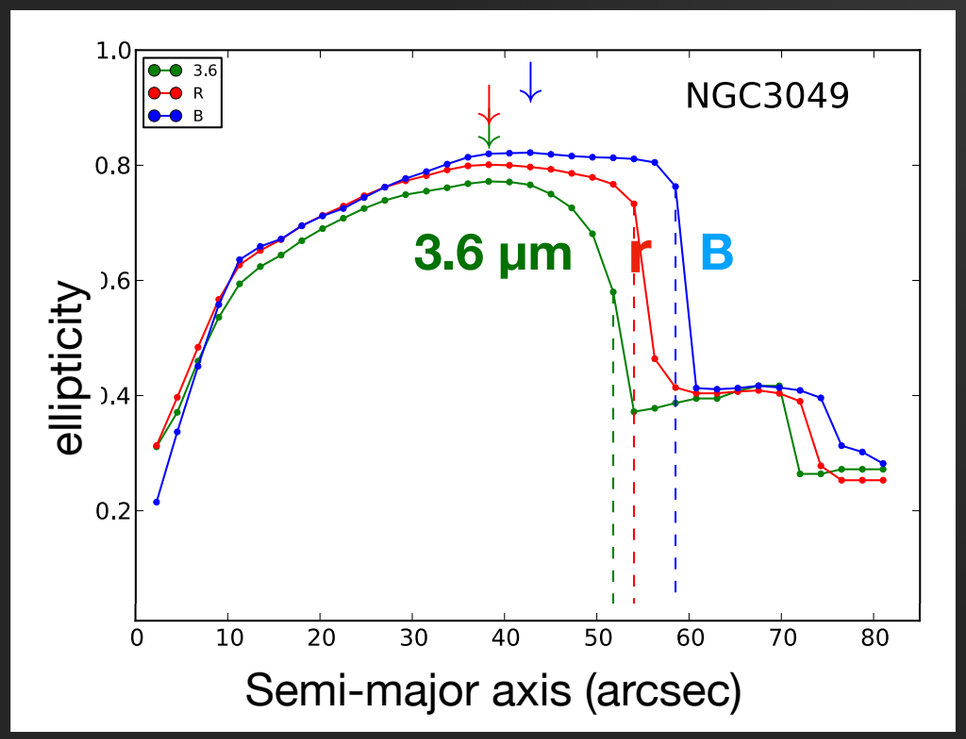
➡ they disappear in the UV

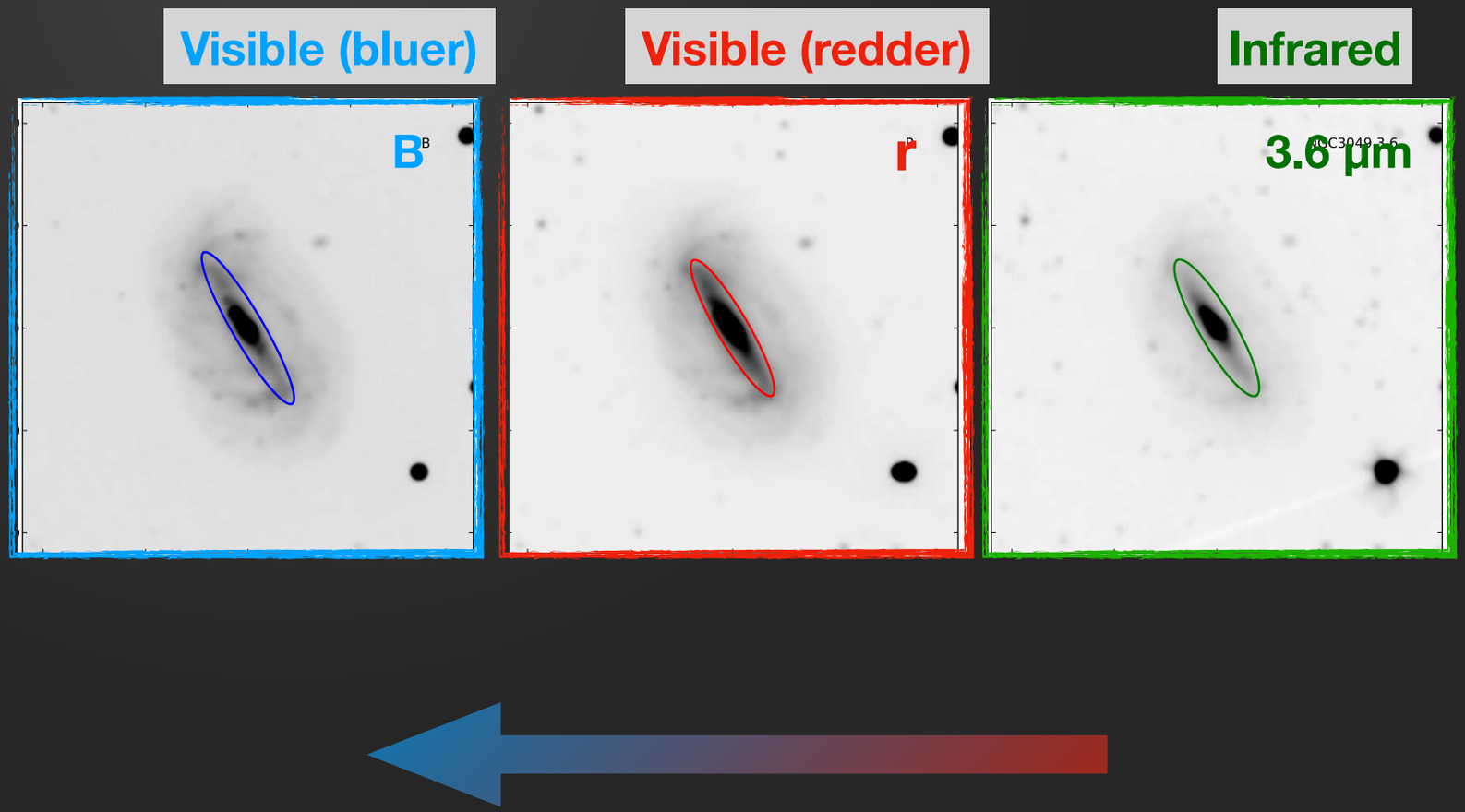
Sheth+03

Multiband studies of bars —
Bars appear thinner and longer in blue

Color variations of morphological parameters

- ✦ We probe for changes in bar properties as a function of band [Menéndez-Delmestre+24]
  - Bars are stellar structures
  - Bar properties change with waveband: the bluer, the longer & thinner

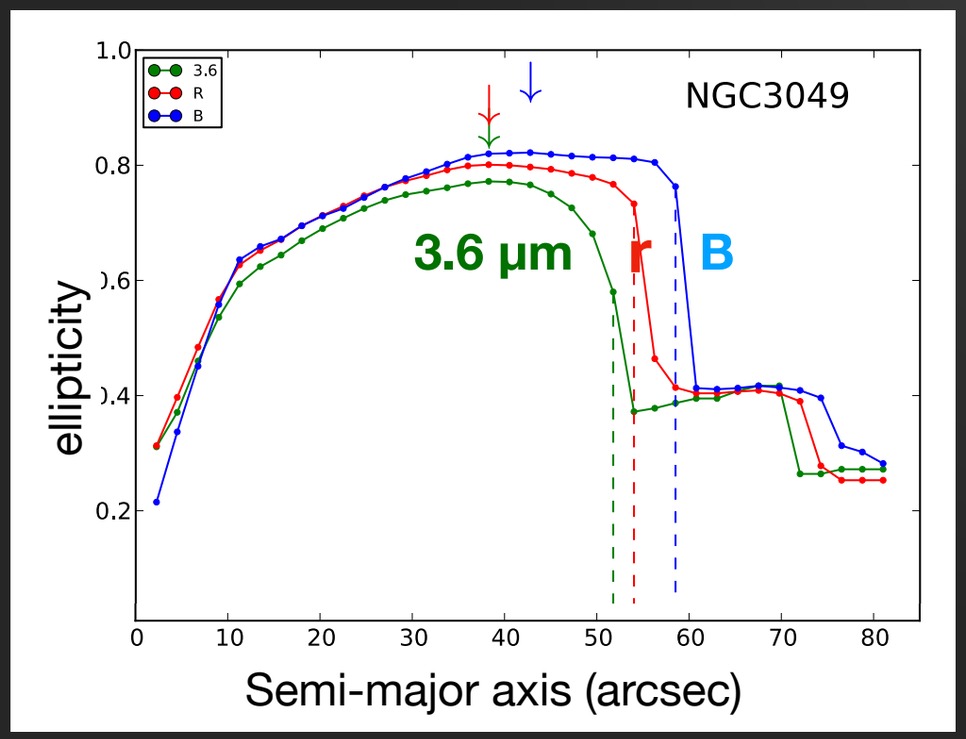


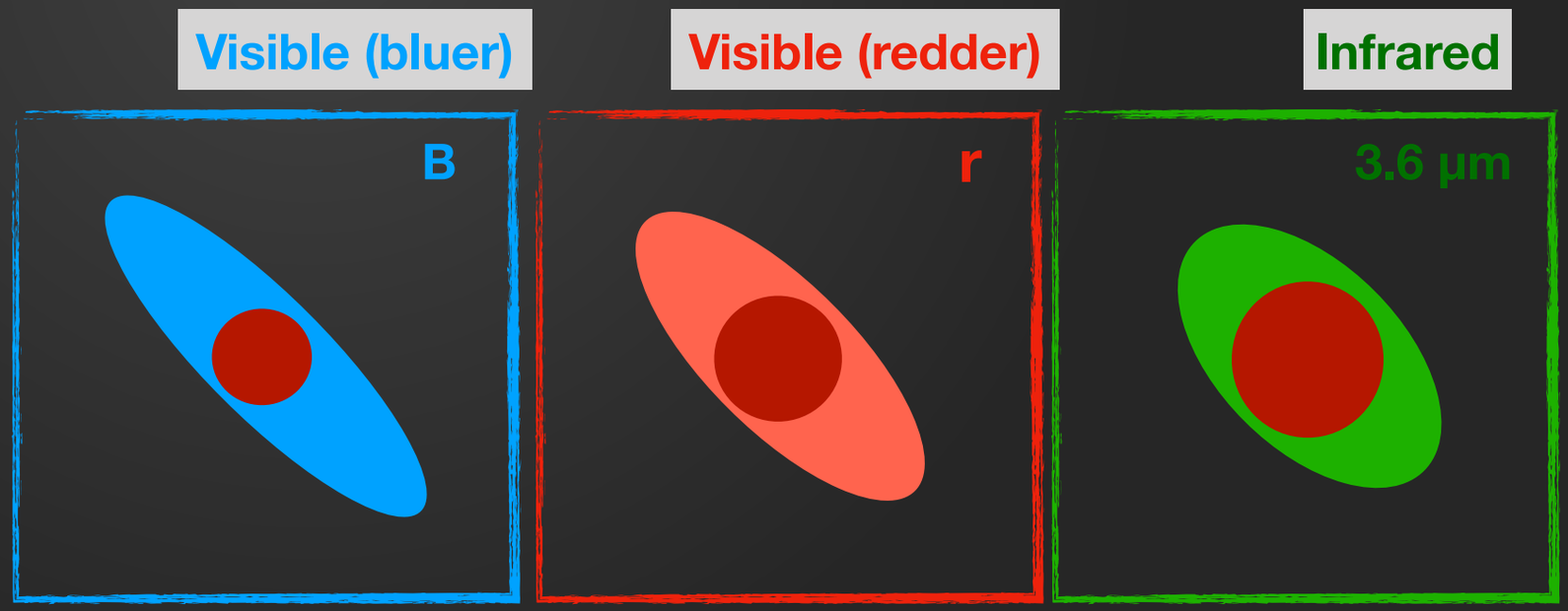


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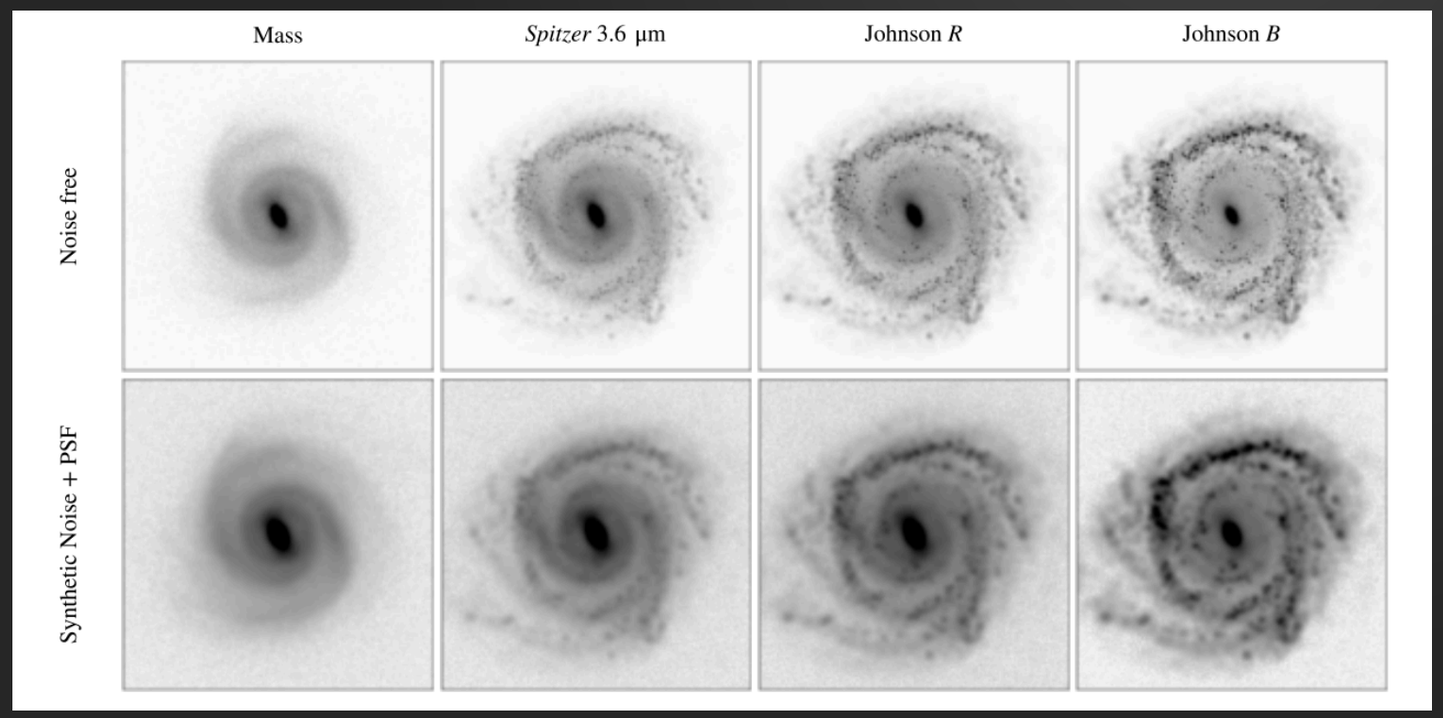
- bars increase their median length & ellipticity ~10% with respect to their canonical “true values” at 3.6 μm.

Multiband studies of bars —
Bars appear thinner and longer in blue

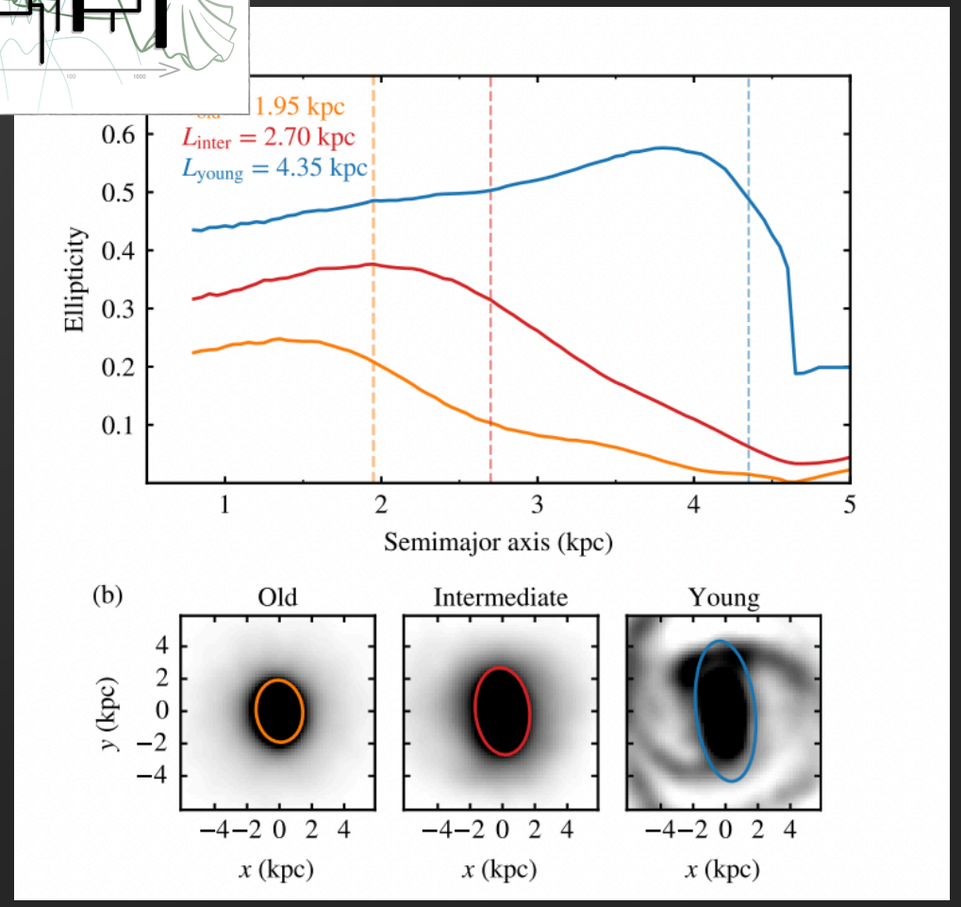
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- Gonçalves+25: We find same thing with Illustris TNG50: analysis of mock images of 50 strong bars



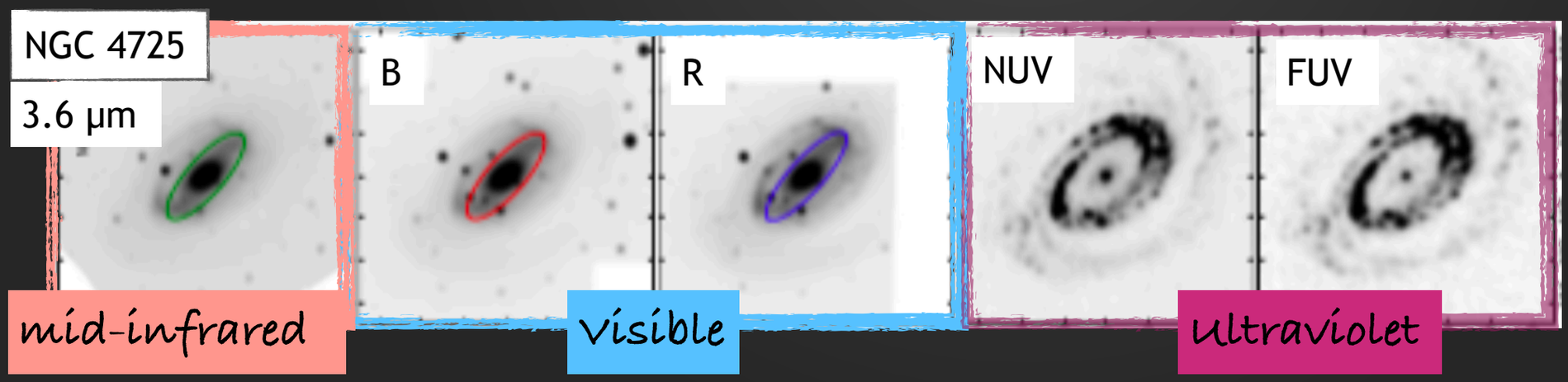
Gonçalves+25



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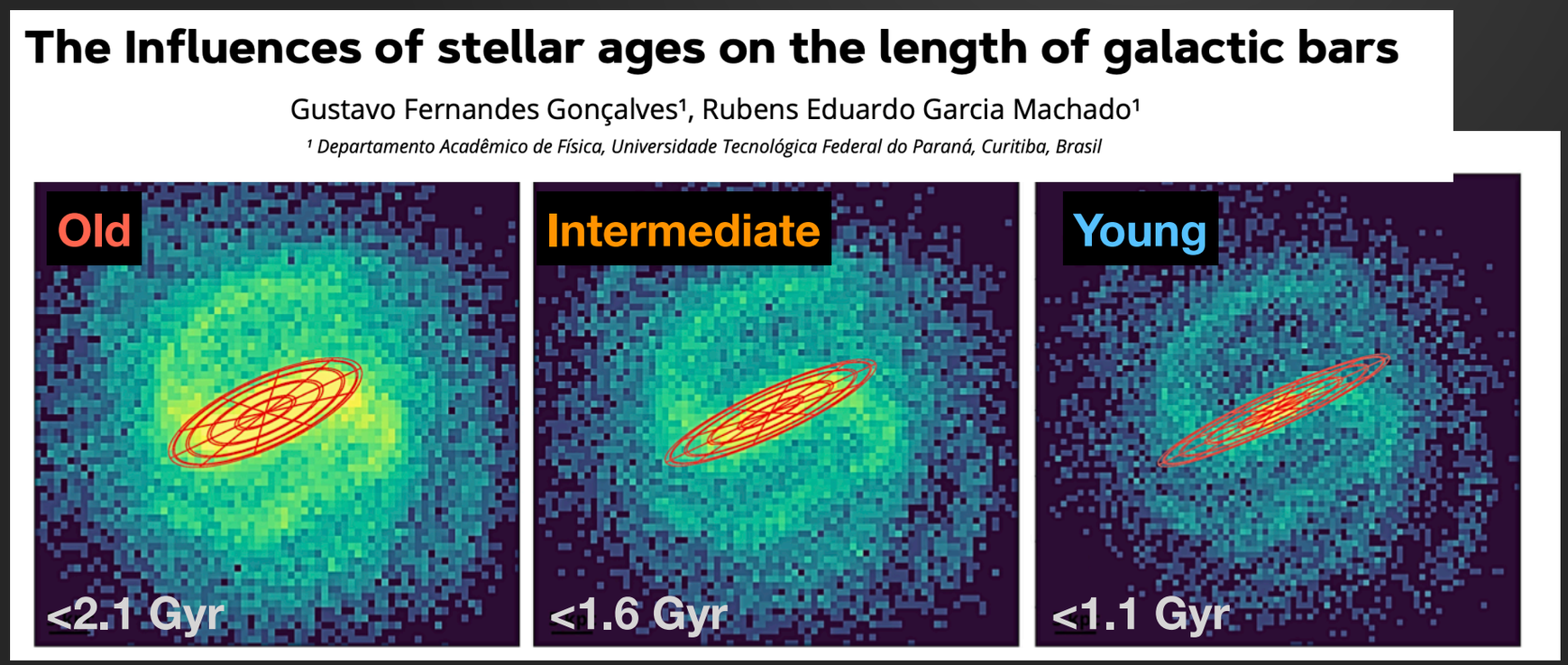
- ✦ We probe for changes in bar properties as a function of band [Menéndez-Delmestre+24]
  - Bars are stellar structures
  - Bar properties change with waveband: the bluer, the longer & thinner
    - ▸ Why longer? Star forming knots at the end of bar delay ellipticity maximum
    - ▸ Why thinner? The bulge is more prominent in redder bands



Bars appear thinner and longer in blue — younger stars uncovered along the bar?

Color variations of morphological parameters

- ✦ We probe for changes in bar properties as a function of band [Menéndez-Delmestre+24]
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Gonçalves+25

- ✦ Also, tracing younger populations along the bar!

Neumann+20, Bittner+21

Bar in simulated galaxies

Exploring larger samples with Illustris TNG-50

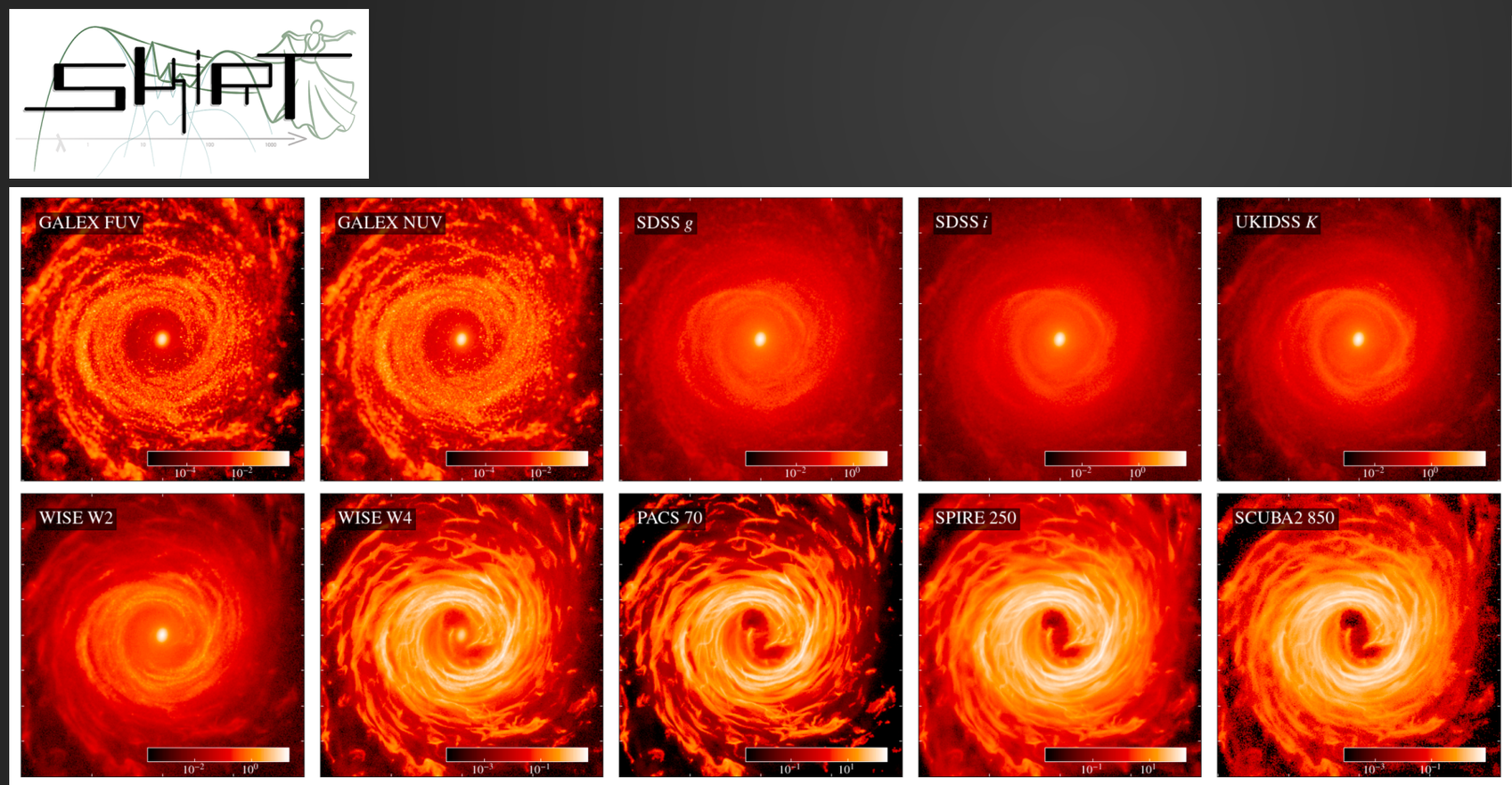
- Hot out of the oven: >400 bars from the TNG-50 Skirt Atlas (TSA-DR2)



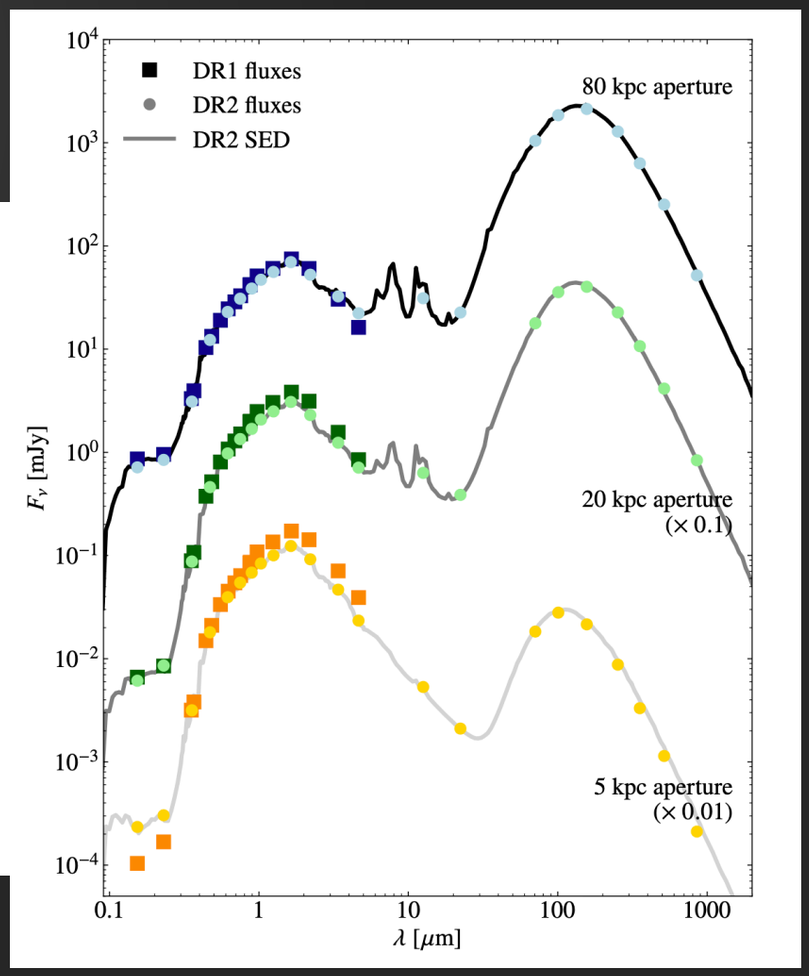


Thiago Bueno Dalpiaz

Maarten Baes (U. Ghent)



Baaes+ (submitted)



Bar in simulated galaxies

Exploring larger samples with Illustris TNG-50



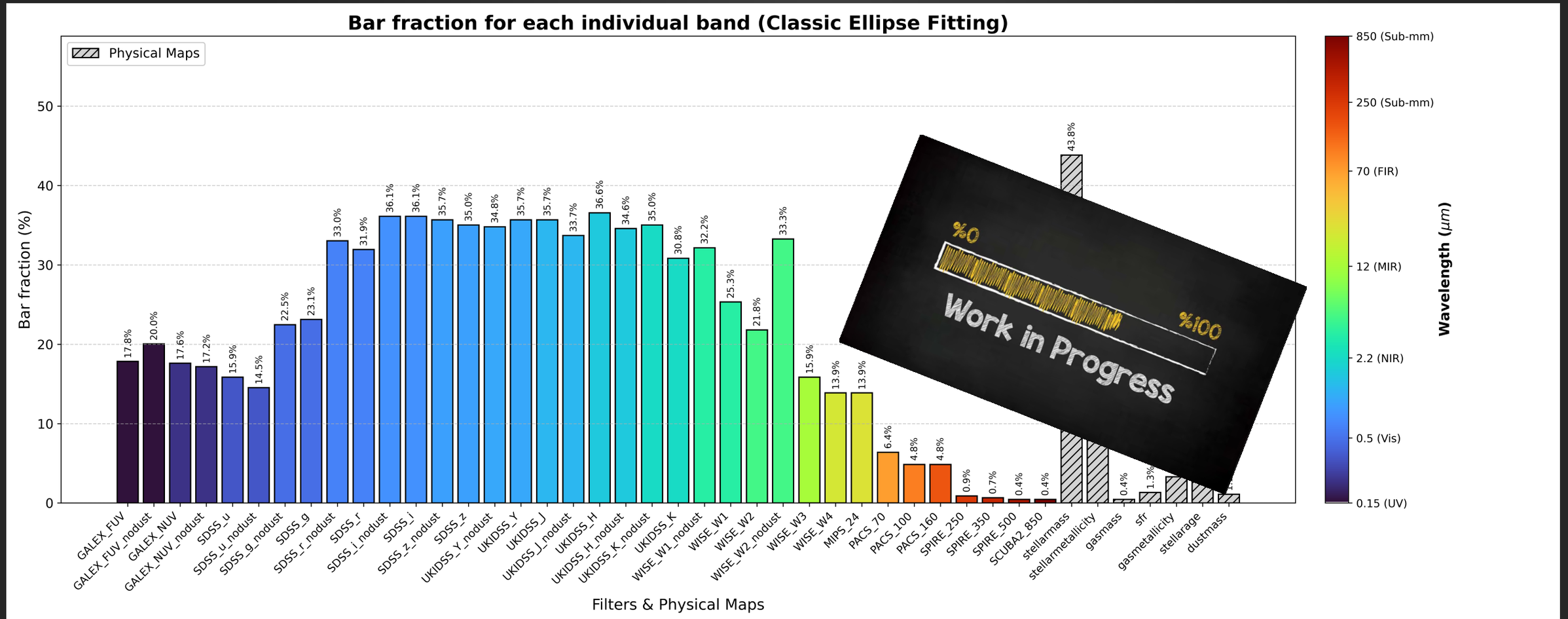


Thiago Bueno Dalpiaz

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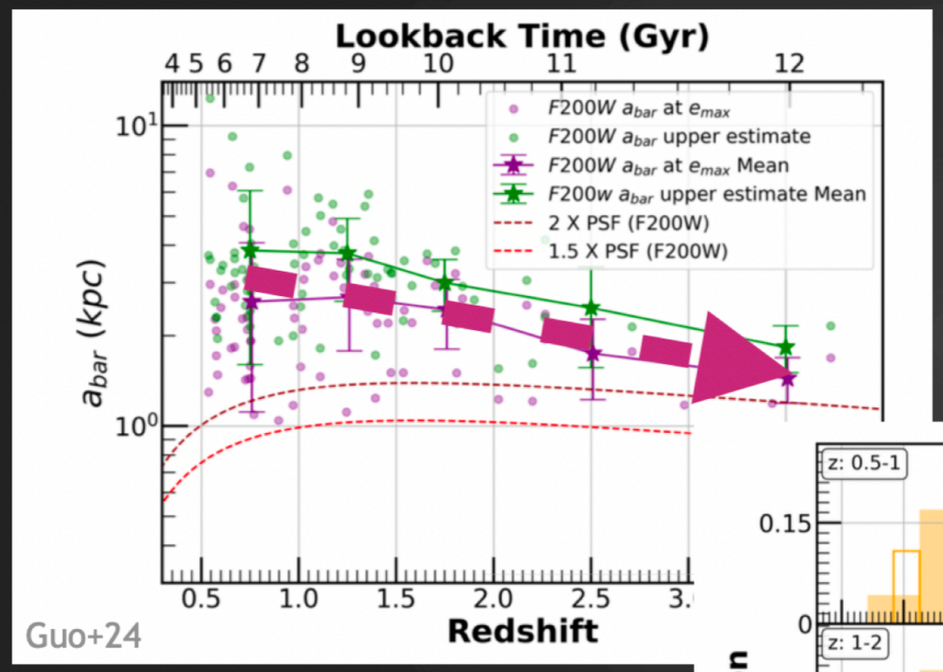
  - Bar properties as a function of wavelength in Illustris TNG50: analysis of mock images



Stellar structures with cosmic time —
many predictions… pending observations!

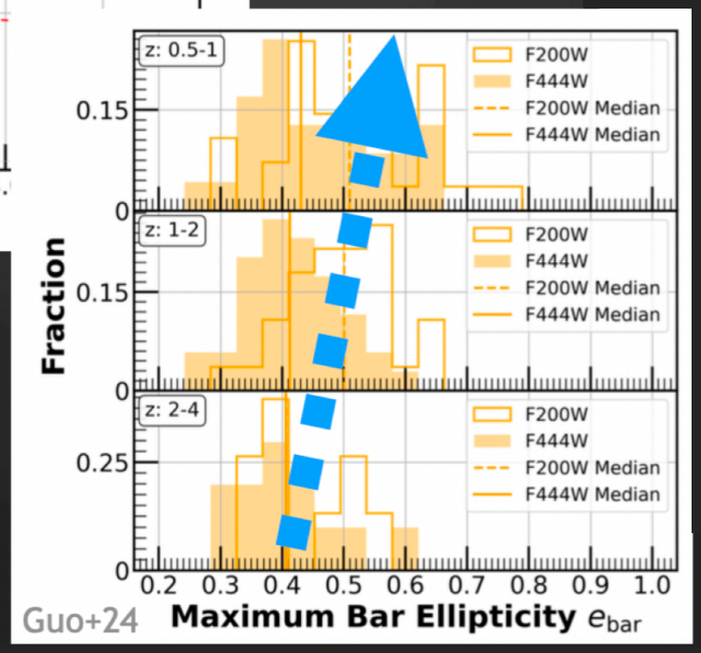
- Images of distant galaxies probe bluer bands — with KMD+24 we create a local benchmark to correct any measured changes in bar properties as a function of cosmic time —> allows for the measure intrinsic changes in bar structural parameters at different cosmological times, free of band- shifting effects.

Extending characterization of bar properties out to higher redshifts



early growth and evolution of barred galaxies

- Impact of deprojection?

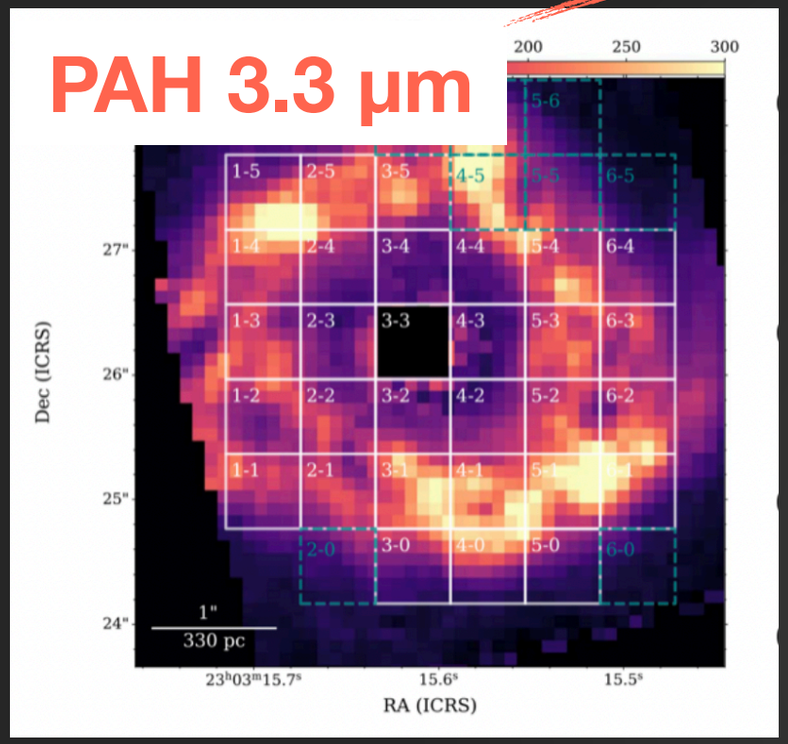


see also Le Conte +26

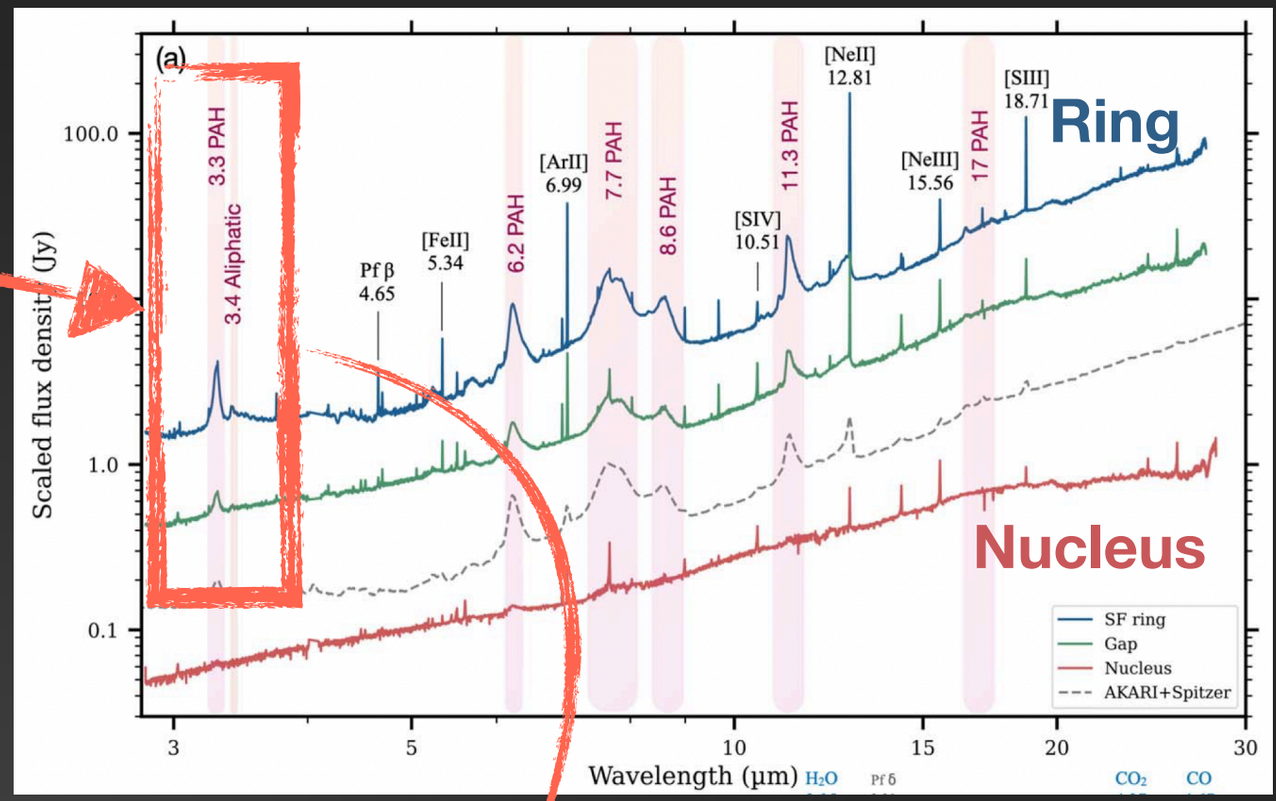
- JWST opens the door to bar identification beyond z~0.8
- mid-IR inspection of bar properties at sub-kpc scales out to cosmic noon!
  - ★ Stellar mass maps based on mid-IR light!
  - ★ Are we tracing the bar formation epoch? young bars?

strengthening early on!

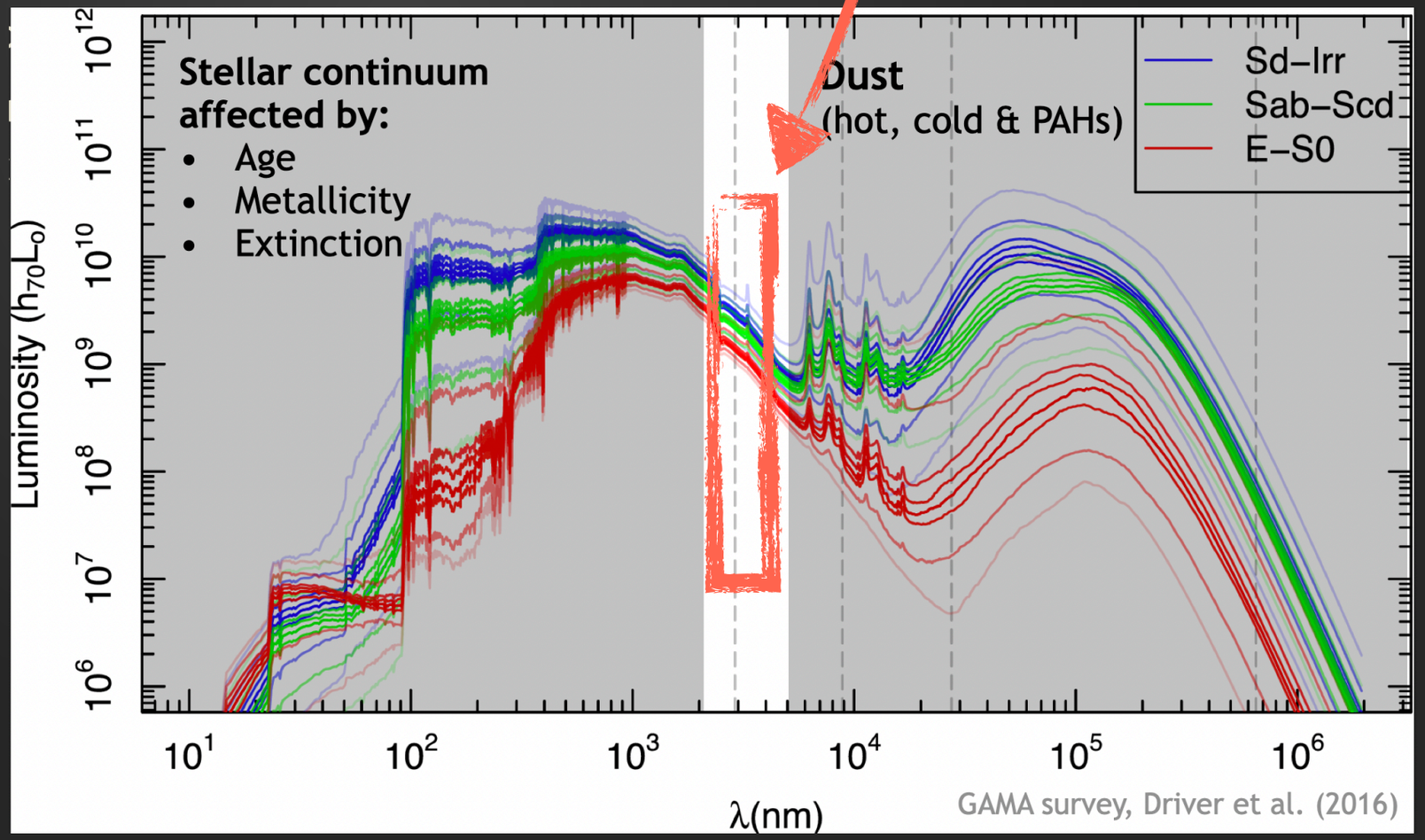
Star-forming regions
– **ALERT** for mass census



NGC 7469
Seyfert



Lai+23



[courtesy of J. C. Muñoz-Mateos]

- ✦ **Caveats** for the 3.6 and 4.5μm bands for tracing the stellar mass
  - 3.3 μm PAH feature affects 4.5μm band
  - Hot dust (Td > 500 K) contributes at 4.5μm
- ✦ Spatially-resolved stellar population studies are important!

The CANGA Survey

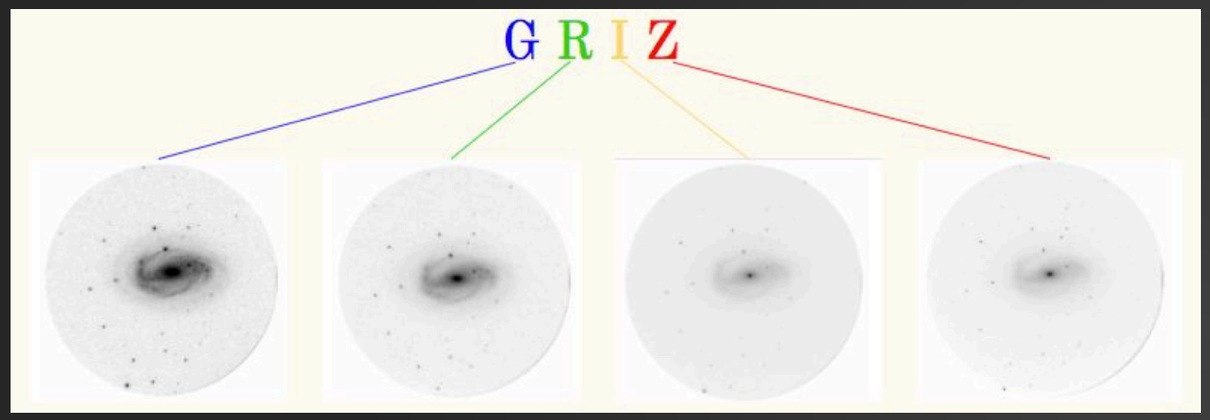
- **C**ensus of **A**ustral **N**earby **Ga**laxies (PIs: KMD + Thiago S. Gonçalves)
  - Multi-band optical imaging of all S^{4}G galaxies in the South (~1000)

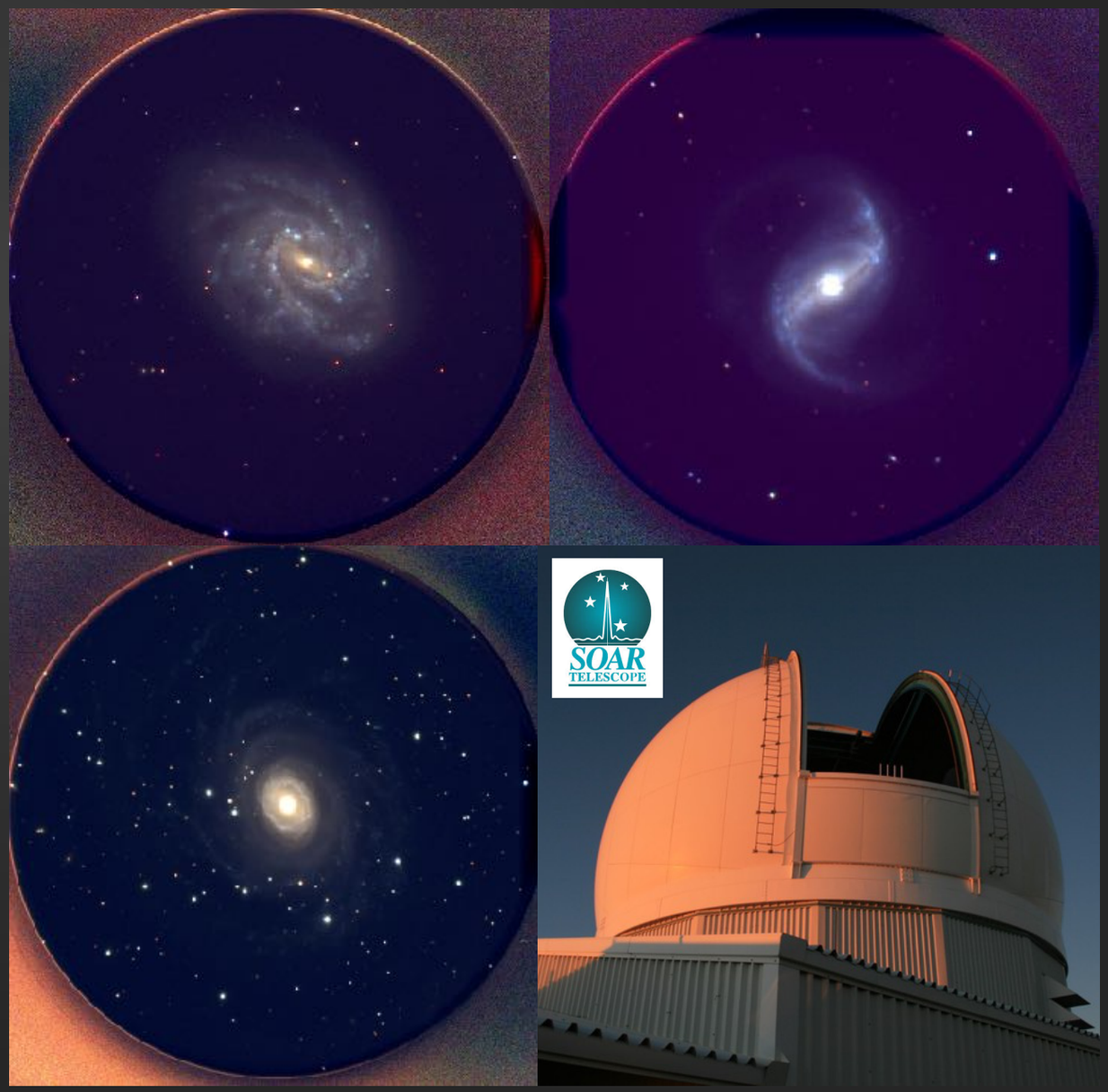




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  - Multi-band optical imaging of all S^{4}G galaxies in the South (~1000)
  - *griz* imaging with Goodman High Throughput Spectrograph (GHTS) on SOAR

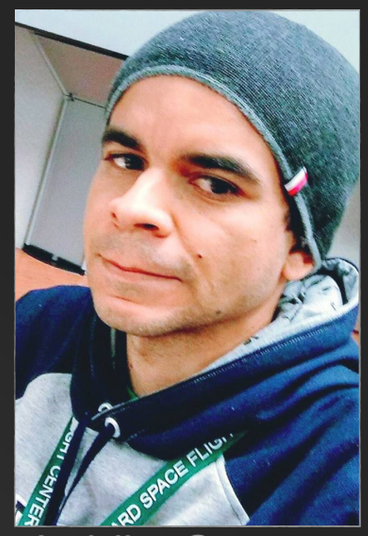




Long-term commitment!

✦ CANGA (opt) + S^{4}G (mid-IR) trace stellar mass distribution out to the faintest outskirts of nearby galaxies and complement this mass census with a detailed analysis of the stellar populations in stellar structures.

Galaxy formation histories —
a spatially-resolved view with CANGA



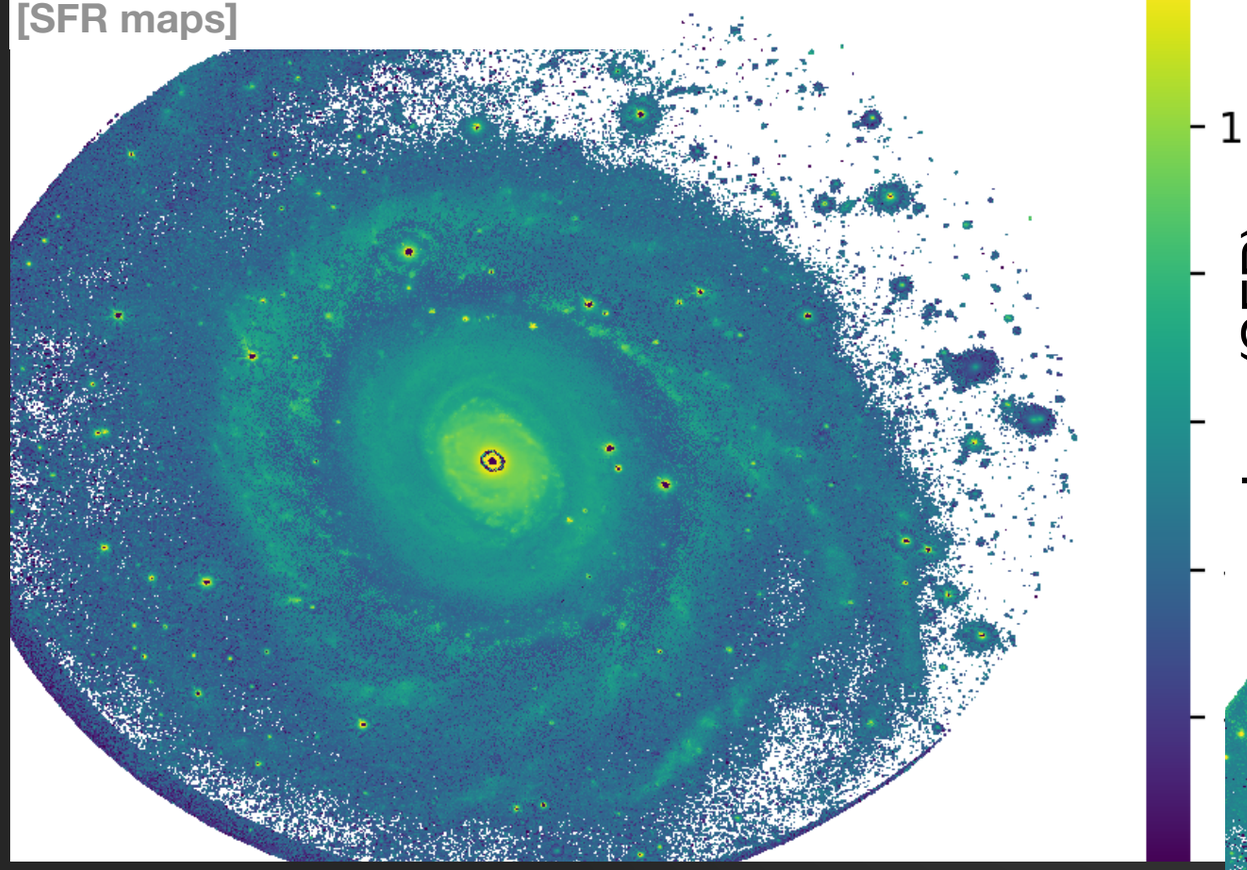
Luidhy Santana
(OV/UFRJ)



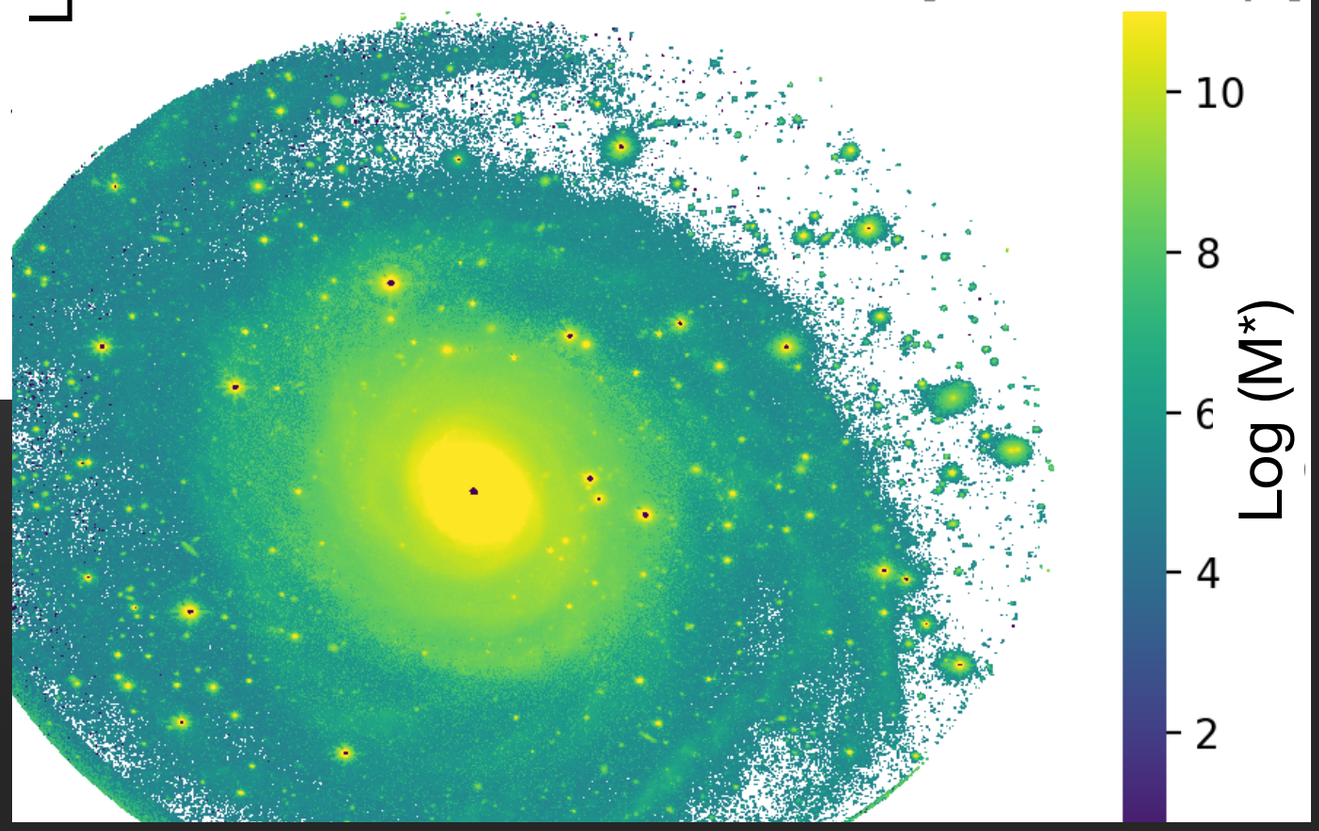
Felipe Almeida-Fernandes
(INPE)

- Spatially-resolved stellar population analysis: **SED fitting**

Where are stars forming NOW?
[SFR maps]



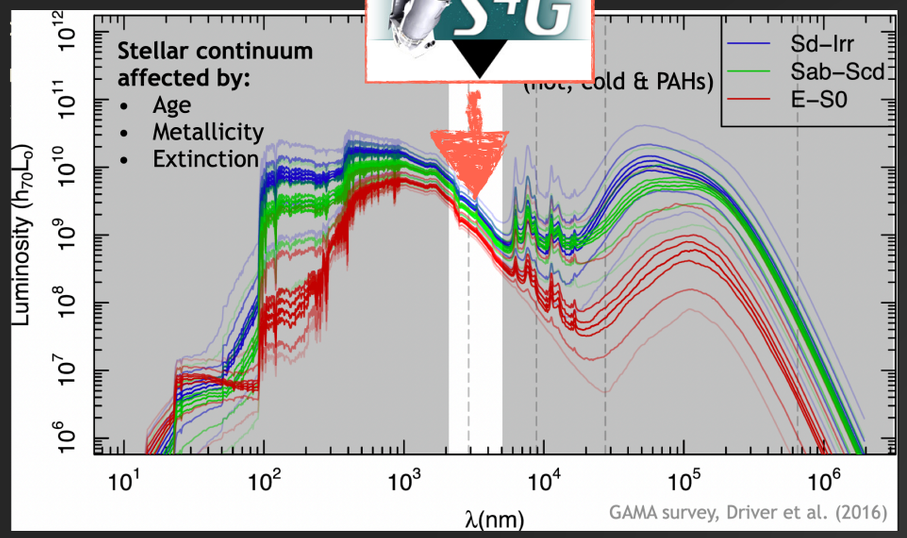
Where are all those stars that were formed up to today?
[Stellar mass maps]



- Spatially-resolved stellar population analysis
  - *LePhare* & *Cigale* SED fitting algorithms

In a nutshell — galactic structures (presence, mass content, +)
all tells us about galaxy evolution

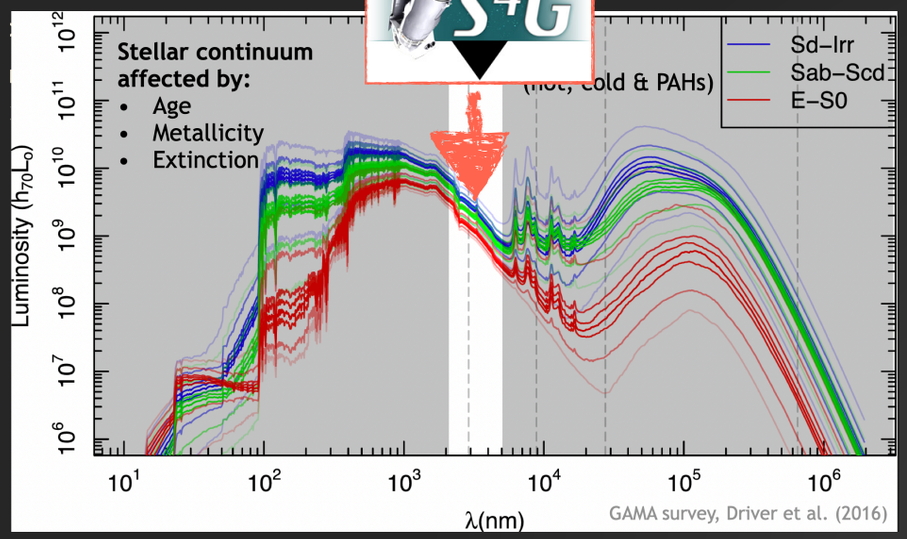
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Where's the mass?

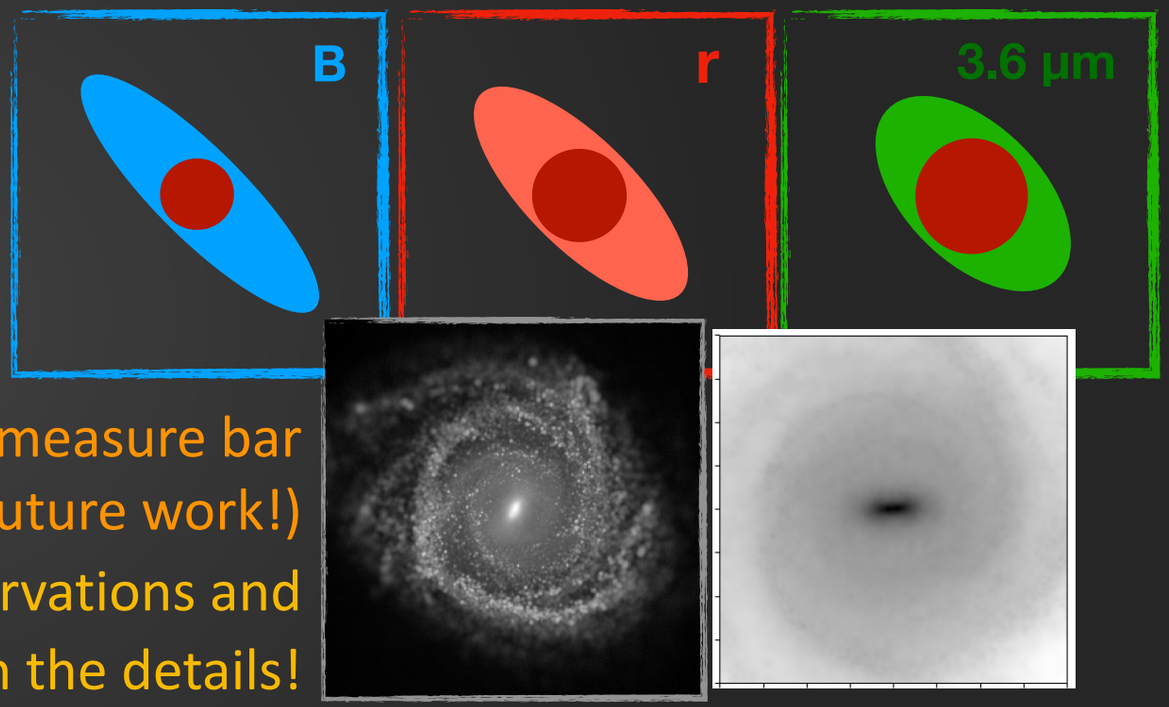
- Galaxy shapes intricately connected to galaxy formation history
- Stellar mass distribution in local galaxies = key benchmarks for galaxy evolution models and simulations
- Mid-infrared = best tracer of stellar mass — S4G for all to use!

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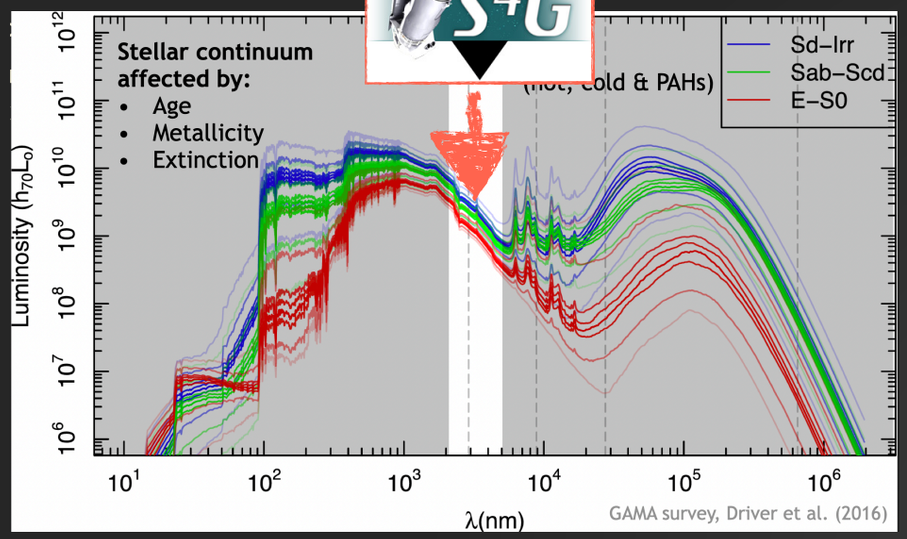
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Simulations — use Illustris TNG50 to measure bar masses and retrace bar mass growth (future work!)

- Bar fraction studies — tensions between observations and simulations… the key is in the details!

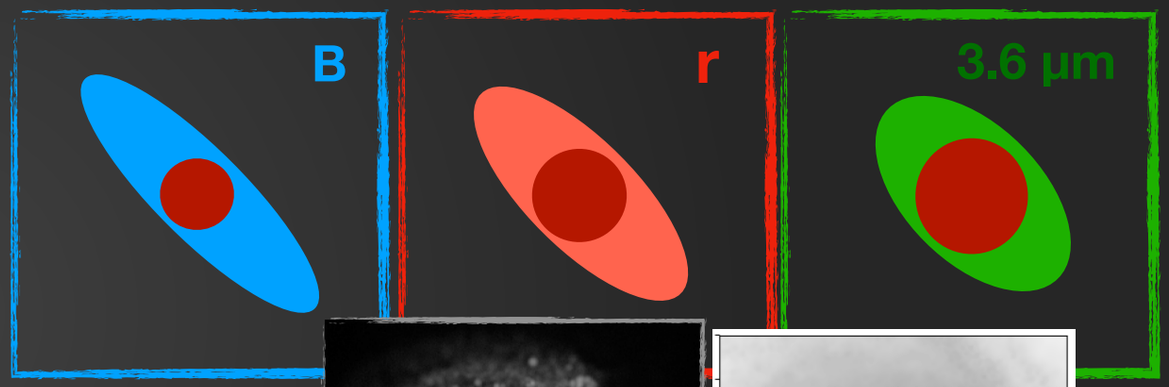
Bars with TNG50

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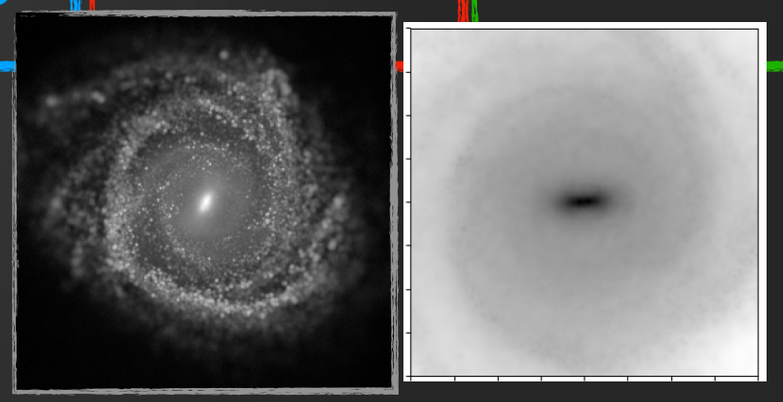
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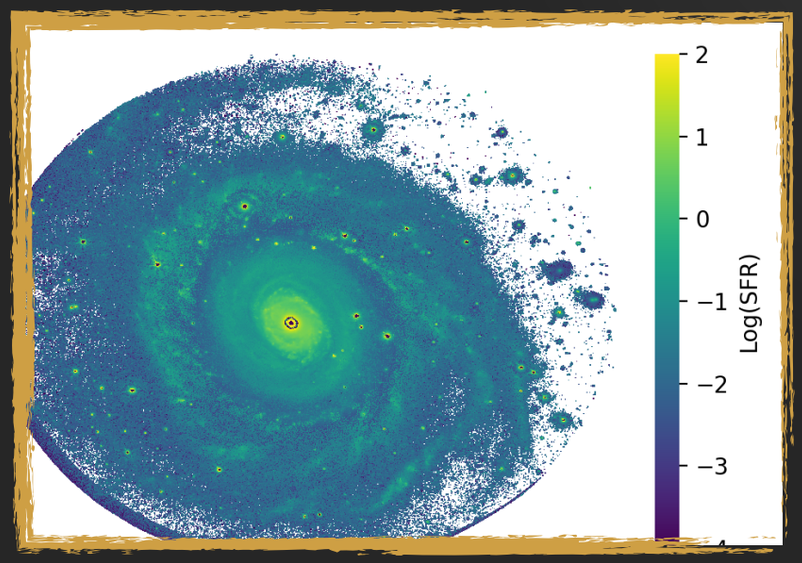
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Bars with TNG50



Formation histories

— *pixel by pixel!*

- Combining mid-infrared with optical, build a stellar mass census with a detailed analysis of the stellar populations in stellar structures
- The CANGA survey — a legacy survey underway mapping galaxies from the southern sky!

Hidden slides

What's up with low-mass systems?
A study of bars in dwarf galaxies



Yasmin Cavalcante-Coelho
(ESO La Silla School 2024)

- 338 dwarf galaxies from the S4G sample

  [less than ~ billion solar masses]

  - ✦ Visual classification [Buta+15]: 38% of dwarfs host a bar (see also Erwin+18)
    - ▸ compared to 65% in massive galaxies [KMD+07]

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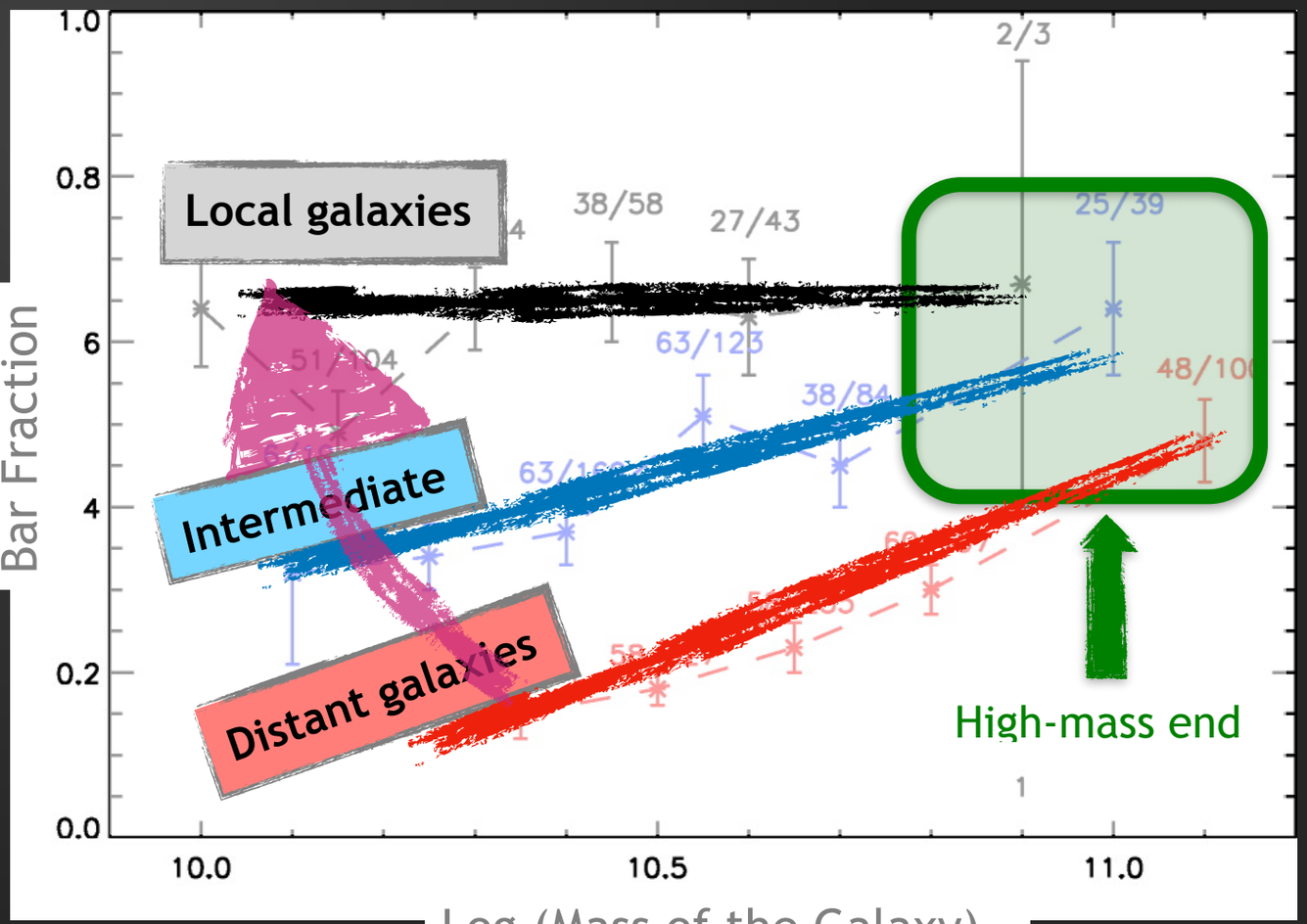
  [less than ~ billion solar masses]

  - ✦ Visual classification [Buta+15]: 38% of dwarfs host a bar (see also Erwin+18)
    - ▸ compared to 65% in massive galaxies [KMD+07]

  - ✦ Together with our result of lower bar-to-total mass ratios in lower-mass galaxies…

Consistent with the trend of low mass galaxies still in the process of forming their bars.

—> **Catching "bar growth" through the growth in stellar mass**



Sheth+08