Galaxy Zoo: Observing Secular Evolution Through Bars

Edmond Cheung (UC Santa Cruz)

Lia Athanassoula
Karen Masters
Bob Nichol
Eric Bell
Sandra Faber
David Koo

GALAXY ZOO

Deconstructing Galaxies
ESO Santiago, Chile
November 21, 2013

Bars are drivers of galaxy evolution

Bars are drivers of galaxy evolution

Bars are drivers of galaxy evolution

- Observational evidence of bar-driven secular evolution

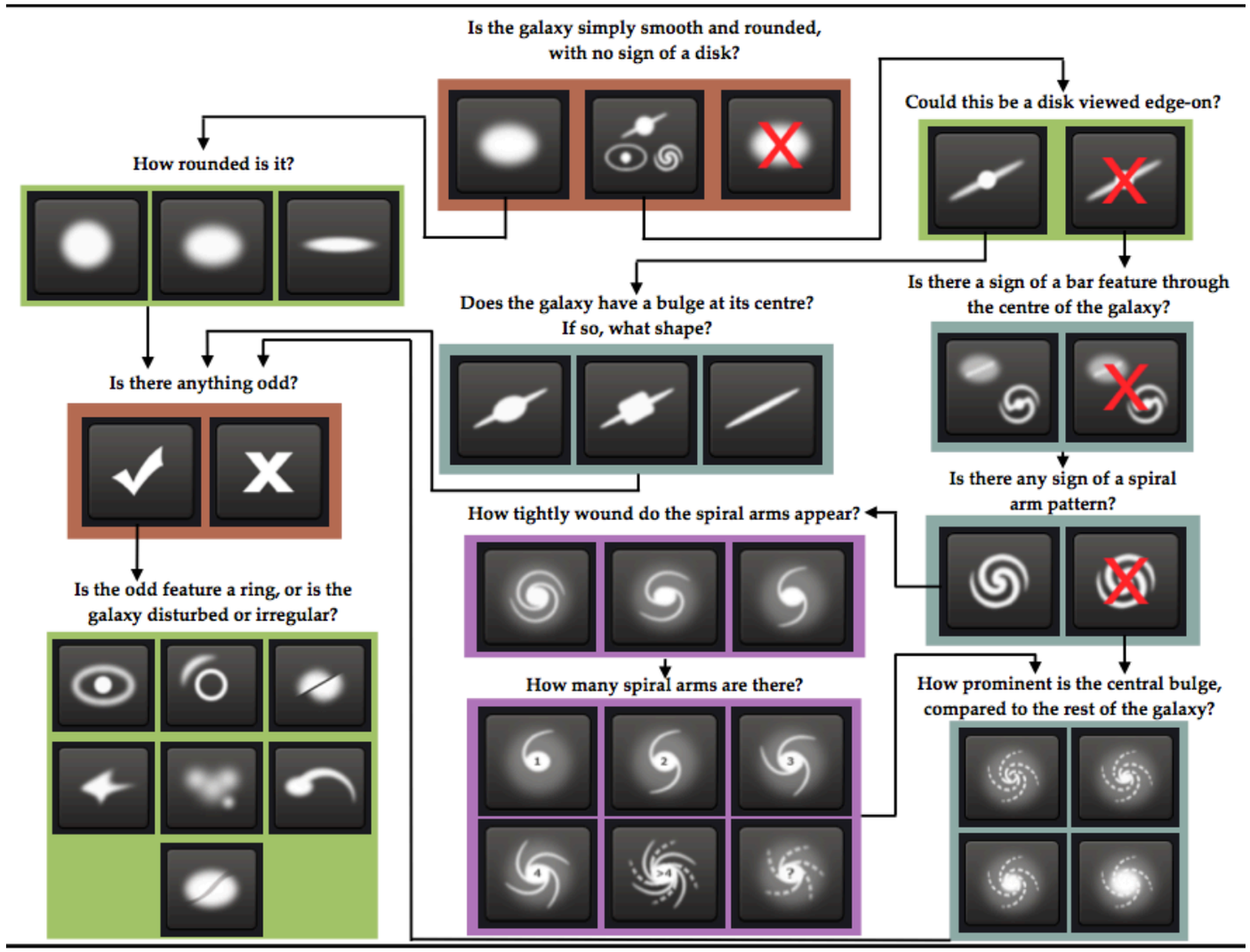
Bars are drivers of galaxy evolution

- Observational evidence of bar-driven secular evolution
  - Galaxy Zoo 2

Galaxy Zoo 2

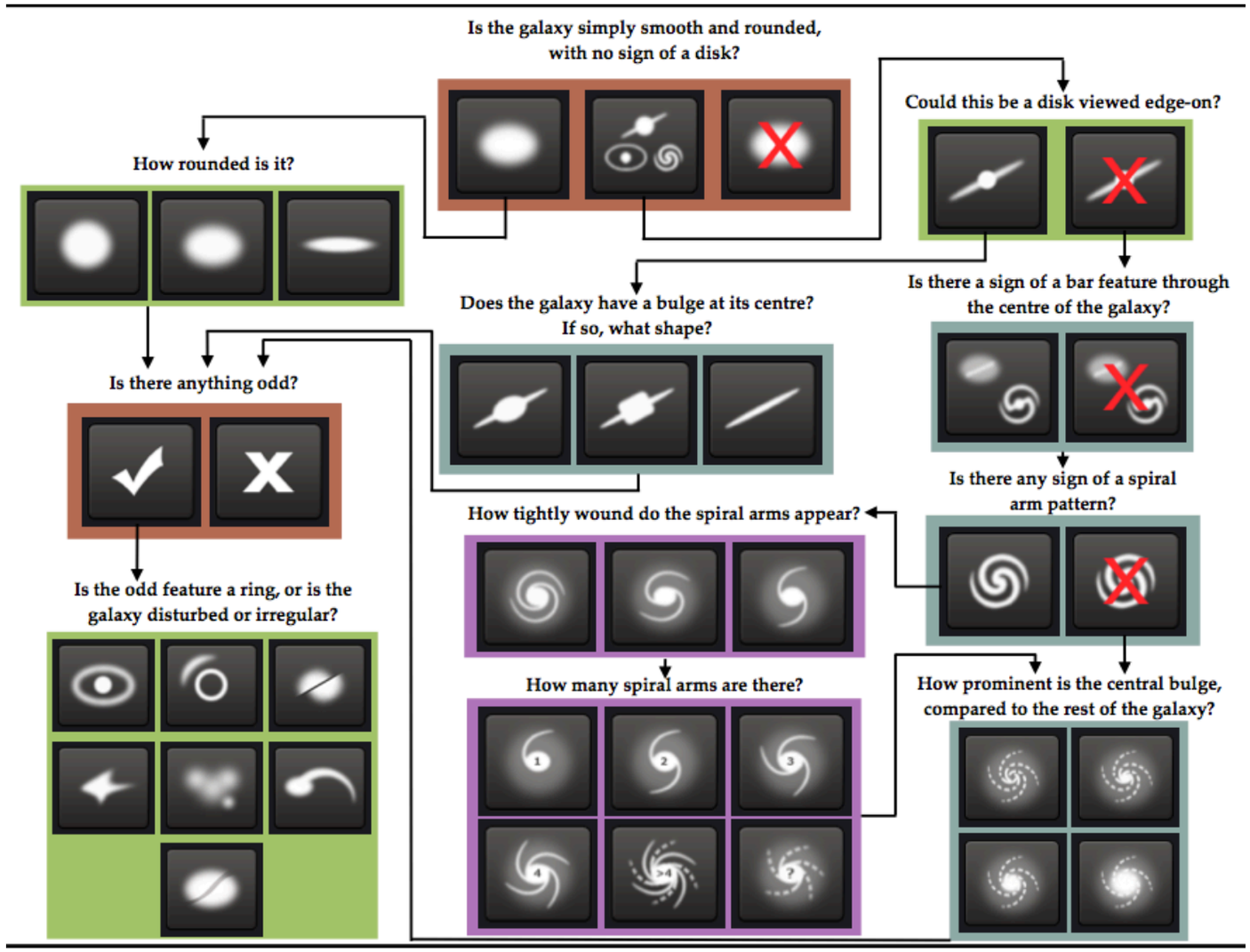
Galaxy Zoo 2

- 84,000 `citizen scientists'
- over 16 million classifications of 300,000 SDSS galaxies



Galaxy Zoo 2

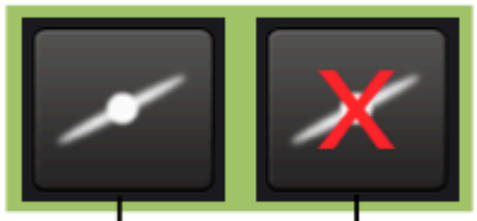
- 84,000 `citizen scientists'
- over 16 million classifications of 300,000 SDSS galaxies



Is the galaxy simply smooth and rounded, with no sign of a disk?

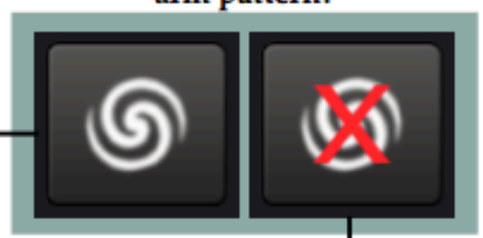
How rounded is it?

Could this be a disk viewed edge-on?



Is there a sign of a bar feature through the centre of the galaxy?

Is there any sign of a spiral arm pattern?



Does the galaxy have a bulge at its centre? If so, what shape?

How tightly wound do the spiral arms appear?

How many spiral arms are there?

How prominent is the central bulge, compared to the rest of the galaxy?

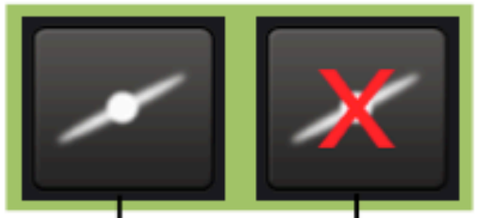
Is there anything odd?

Is the odd feature a ring, or is the galaxy disturbed or irregular?

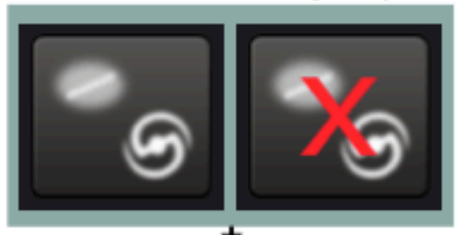
Is the galaxy simply smooth and rounded, with no sign of a disk?

How rounded is it?

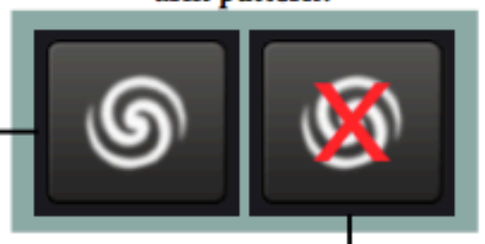
Could this be a disk viewed edge-on?



Is there a sign of a bar feature through the centre of the galaxy?



Is there any sign of a spiral arm pattern?

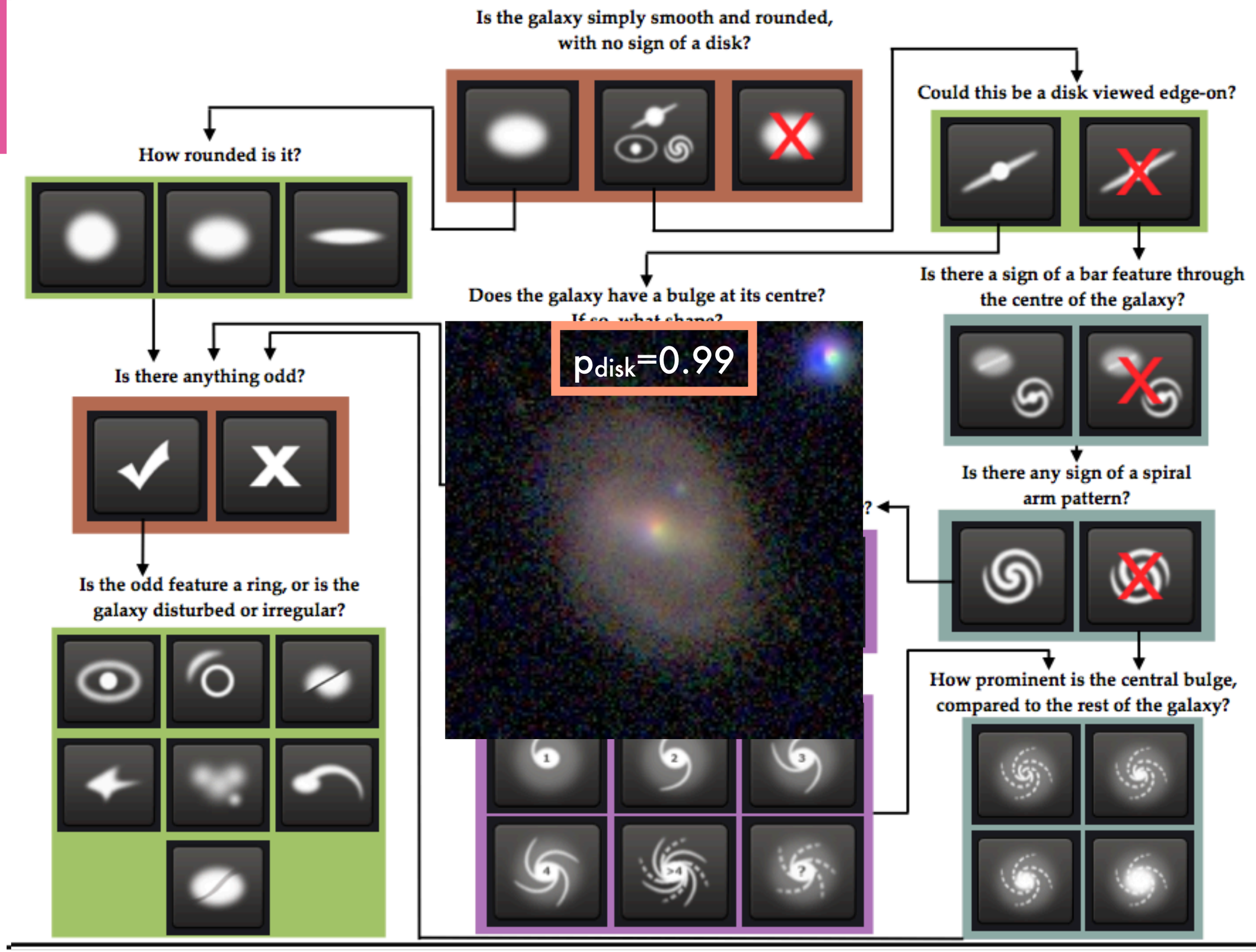


Does the galaxy have a bulge at its centre? If so, what shape?

How prominent is the central bulge, compared to the rest of the galaxy?

Is there anything odd?

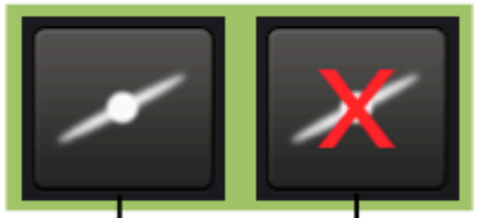
Is the odd feature a ring, or is the galaxy disturbed or irregular?


Is the galaxy simply smooth and rounded, with no sign of a disk?
Could this be a disk viewed edge-on?
How rounded is it?
Does the galaxy have a bulge at its centre?
If so, what shape?
p_{disk}=0.99
Is there a sign of a bar feature through the centre of the galaxy?
Is there anything odd?
Is there any sign of a spiral arm pattern?
Is the odd feature a ring, or is the galaxy disturbed or irregular?
How prominent is the central bulge, compared to the rest of the galaxy?
1
2
3
4
>4
?

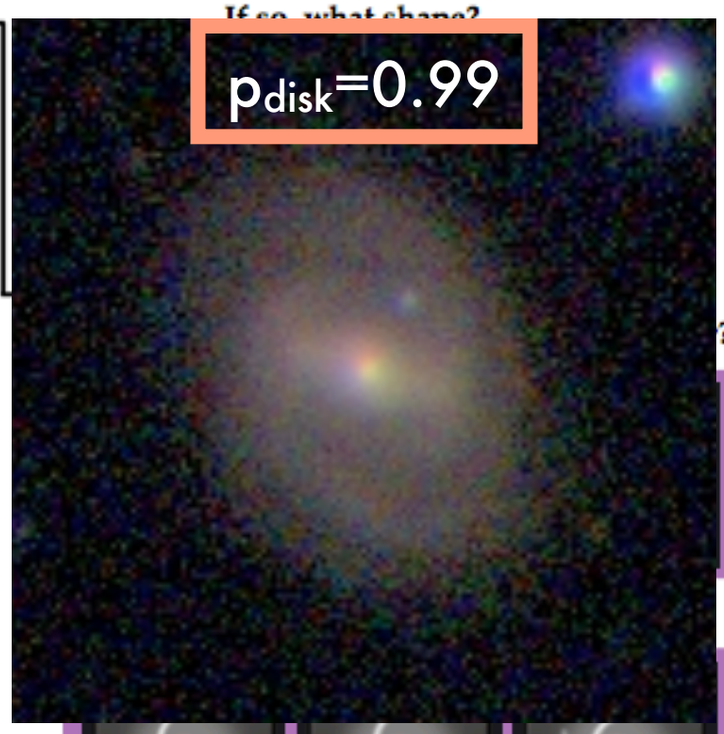
Is the galaxy simply smooth and rounded, with no sign of a disk?

How rounded is it?

Could this be a disk viewed edge-on?



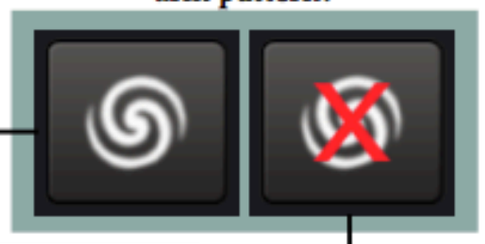
Does the galaxy have a bulge at its centre? If so, what shape?



Is there a sign of a bar feature through the centre of the galaxy?

Is there anything odd?

Is there any sign of a spiral arm pattern?

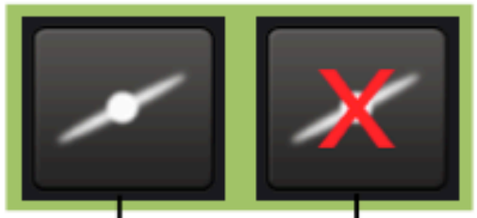


Is the odd feature a ring, or is the galaxy disturbed or irregular?

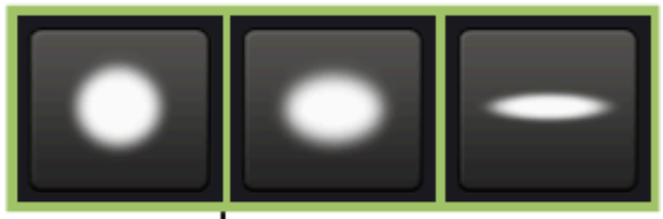
How prominent is the central bulge, compared to the rest of the galaxy?

Is the galaxy simply smooth and rounded, with no sign of a disk?

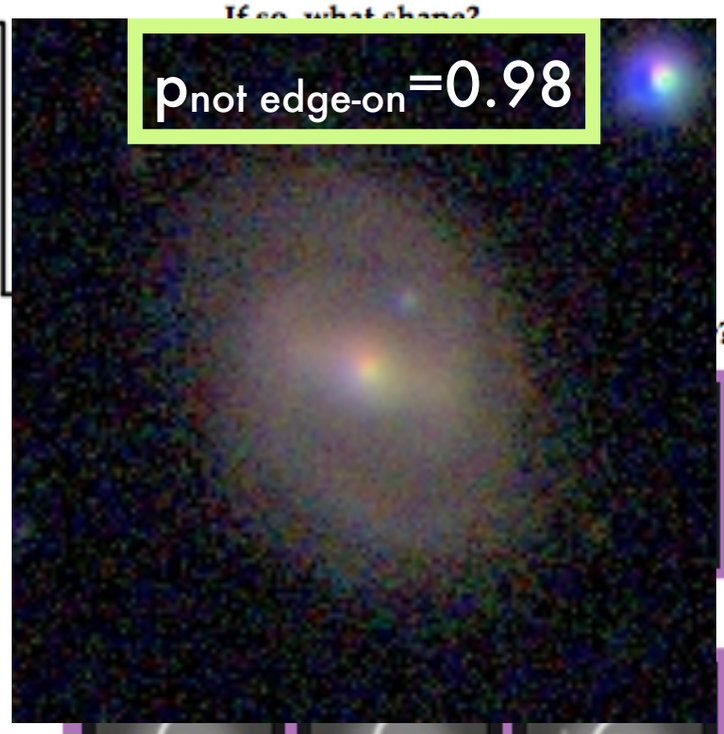
Could this be a disk viewed edge-on?



How rounded is it?



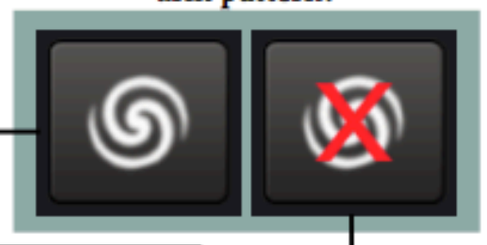
Does the galaxy have a bulge at its centre? If so, what shape?



Is there a sign of a bar feature through the centre of the galaxy?

Is there anything odd?

Is there any sign of a spiral arm pattern?

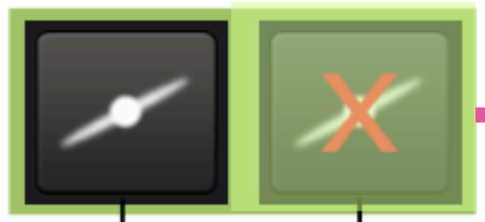


Is the odd feature a ring, or is the galaxy disturbed or irregular?

How prominent is the central bulge, compared to the rest of the galaxy?

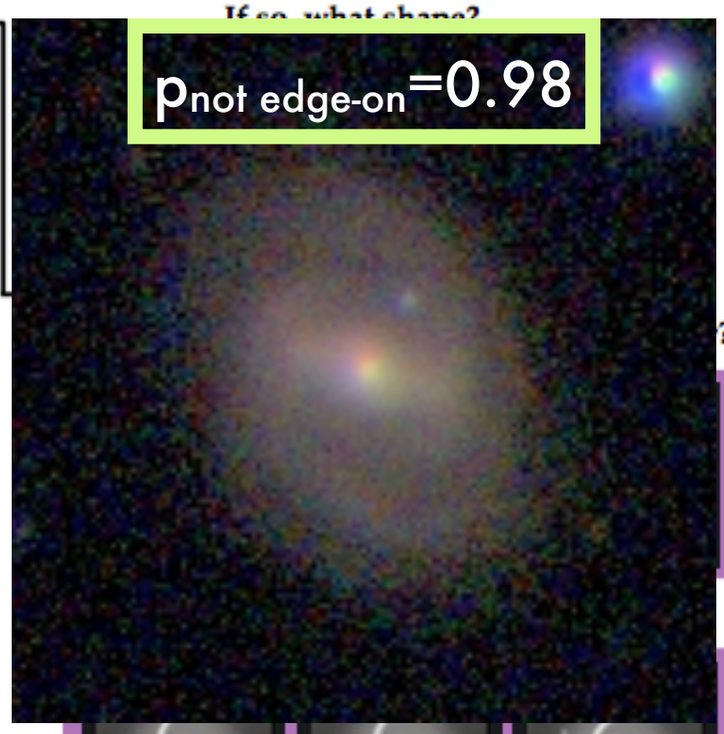
Is the galaxy simply smooth and rounded, with no sign of a disk?

Could this be a disk viewed edge-on?



How rounded is it?

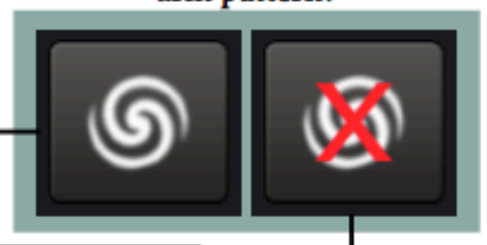
Does the galaxy have a bulge at its centre? If so, what shape?



Is there a sign of a bar feature through the centre of the galaxy?

Is there anything odd?

Is there any sign of a spiral arm pattern?



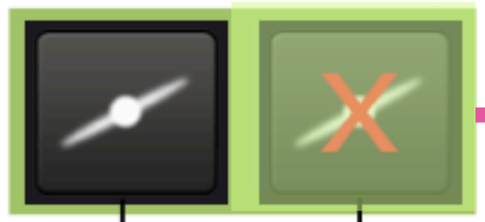
Is the odd feature a ring, or is the galaxy disturbed or irregular?

How prominent is the central bulge, compared to the rest of the galaxy?

Is the galaxy simply smooth and rounded, with no sign of a disk?

How rounded is it?

Could this be a disk viewed edge-on?

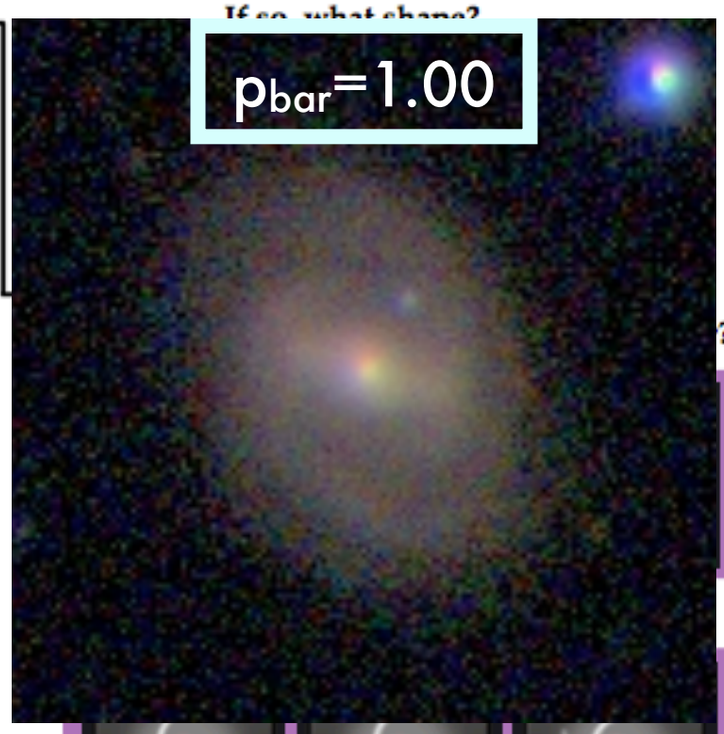


Is there a sign of a bar feature through the centre of the galaxy?

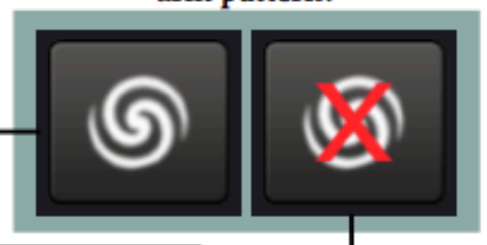
Is there anything odd?

Is the odd feature a ring, or is the galaxy disturbed or irregular?

Does the galaxy have a bulge at its centre? If so, what shape?



Is there any sign of a spiral arm pattern?

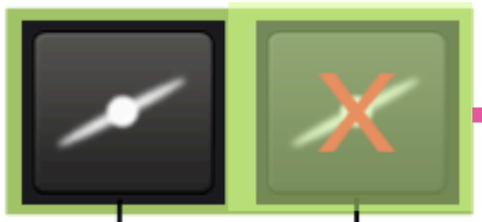


How prominent is the central bulge, compared to the rest of the galaxy?

Is the galaxy simply smooth and rounded, with no sign of a disk?

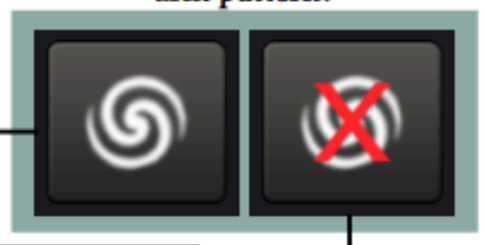
How rounded is it?

Could this be a disk viewed edge-on?



Is there a sign of a bar feature through the centre of the galaxy?

Is there any sign of a spiral arm pattern?



How prominent is the central bulge, compared to the rest of the galaxy?

Does the galaxy have a bulge at its centre? If so, what shape?

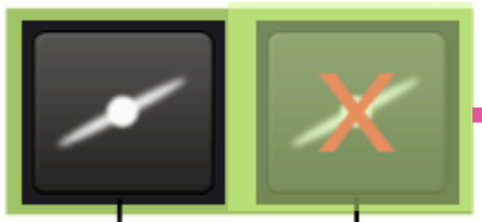
Is there anything odd?

Is the odd feature a ring, or is the galaxy disturbed or irregular?

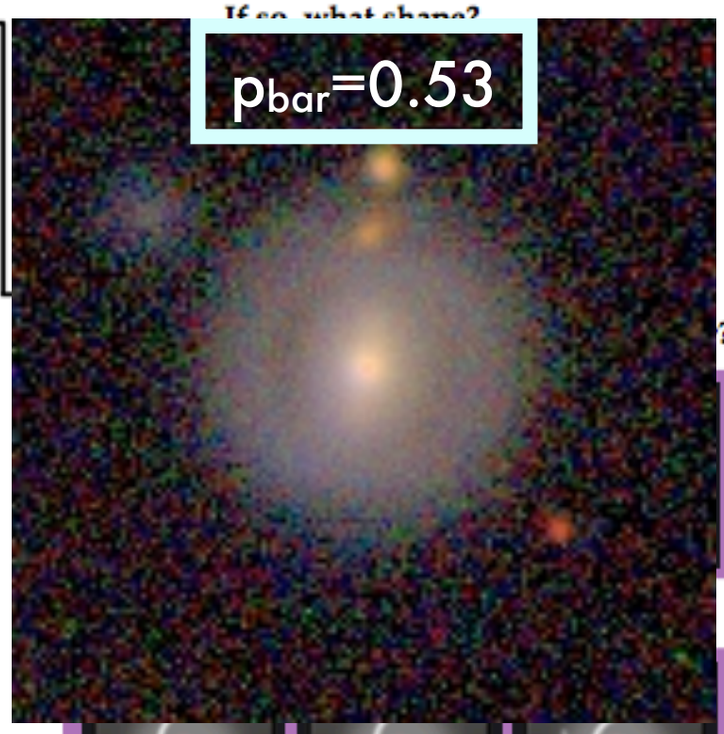
Is the galaxy simply smooth and rounded, with no sign of a disk?

How rounded is it?

Could this be a disk viewed edge-on?



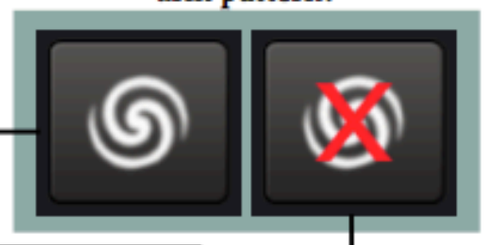
Does the galaxy have a bulge at its centre?
If so, what shape?



Is there a sign of a bar feature through the centre of the galaxy?

Is there anything odd?

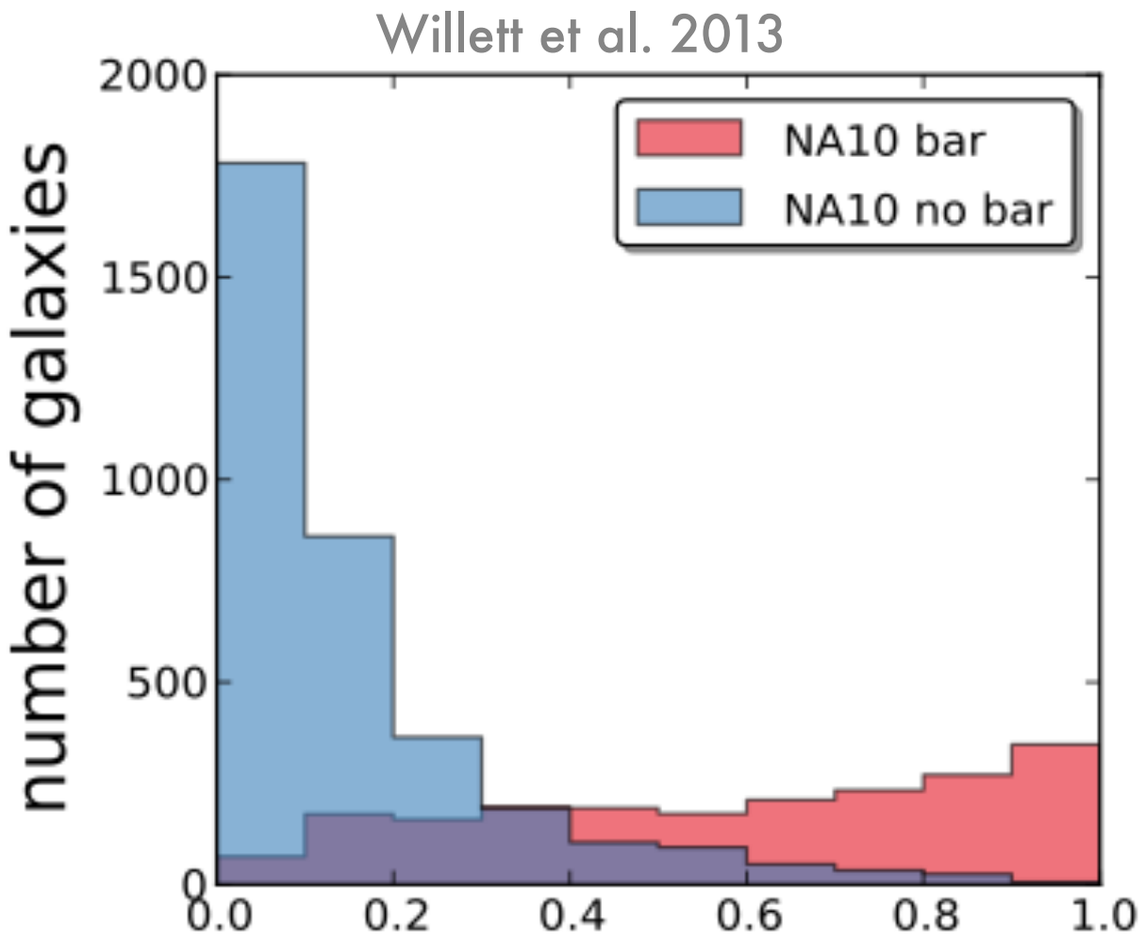
Is there any sign of a spiral arm pattern?



Is the odd feature a ring, or is the galaxy disturbed or irregular?

How prominent is the central bulge, compared to the rest of the galaxy?

Galaxy Zoo 2


Willett et al. 2013
NA10 bar
NA10 no bar
number of galaxies
2000
1500
1000
500
0
0.0
0.2
0.4
0.6
0.8
1.0
P_{bar} (Bar Likelihood)

Sample Selection

Sample Selection

- $0.01<z<0.06$
  - $M_r<-20.15$; volume-limited

Sample Selection

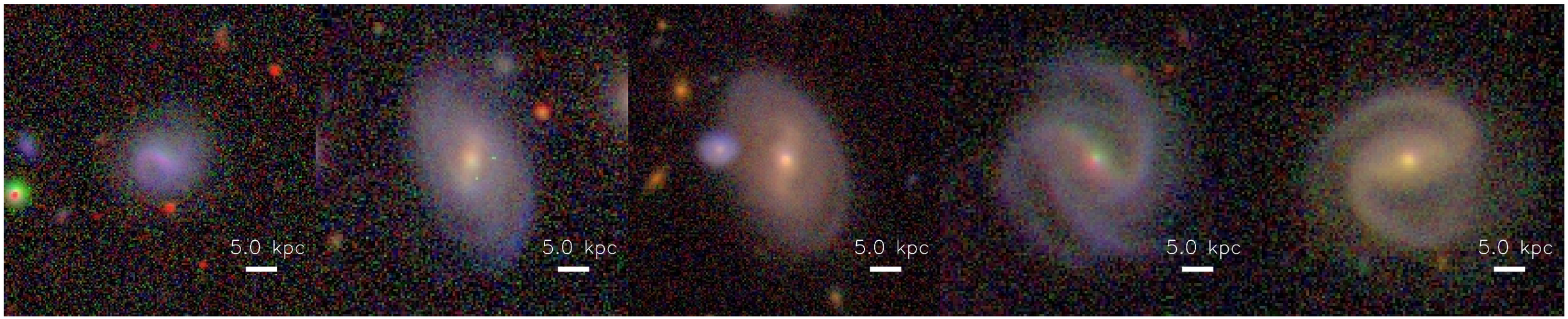
- $0.01<z<0.06$
  - $M_r<-20.15$; volume-limited
    - 1/4 of all classifications answers bar question
      - selects non-edge-on disk galaxies

Sample Selection

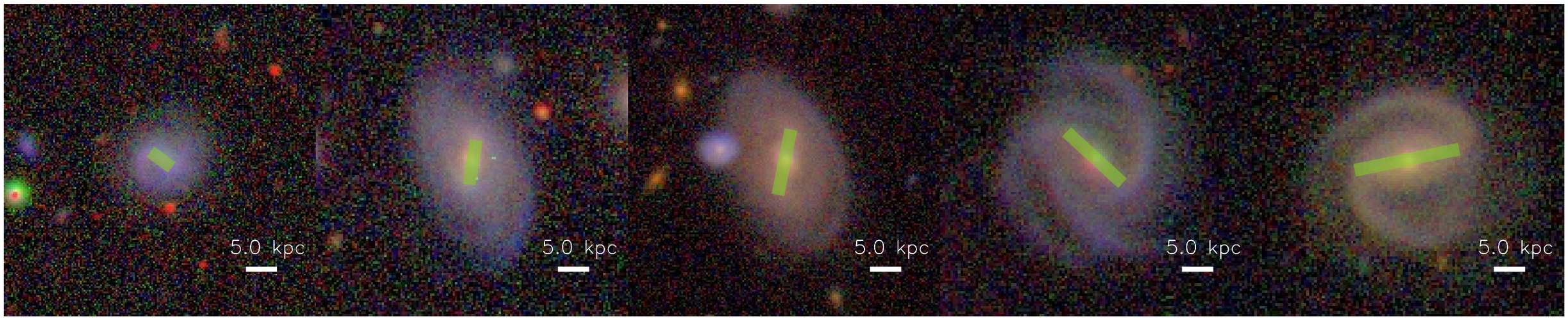
- $0.01<z<0.06$
  - $M_r<-20.15$; volume-limited
    - 1/4 of all classifications answers bar question
      - selects non-edge-on disk galaxies

- **13,295** disk galaxies

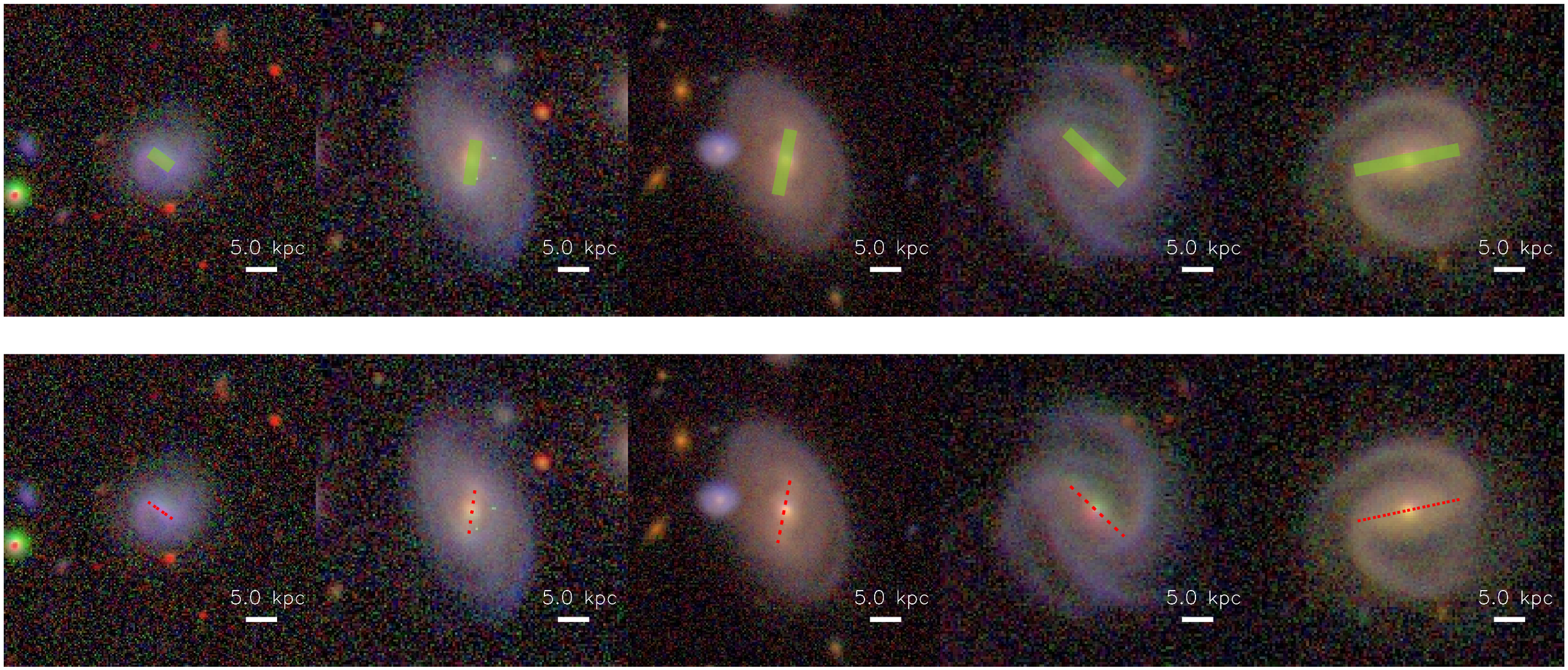
Bar Lengths



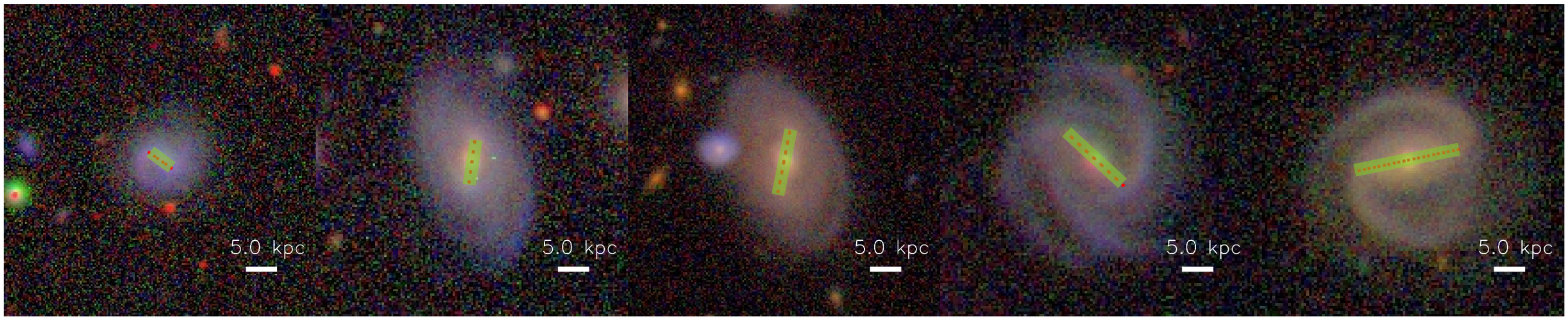
Bar Lengths



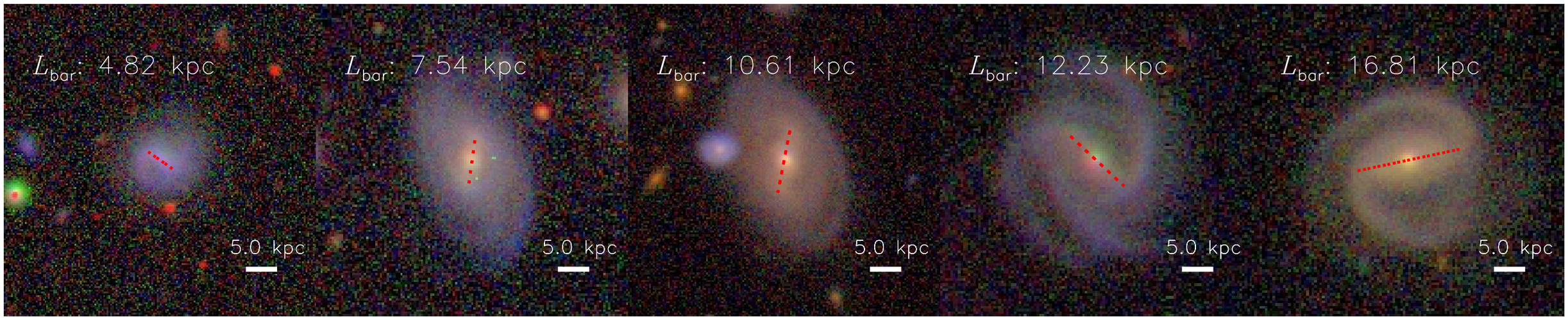
Bar Lengths


5.0 kpc
5.0 kpc
5.0 kpc
5.0 kpc
5.0 kpc
5.0 kpc
5.0 kpc
5.0 kpc
5.0 kpc
5.0 kpc

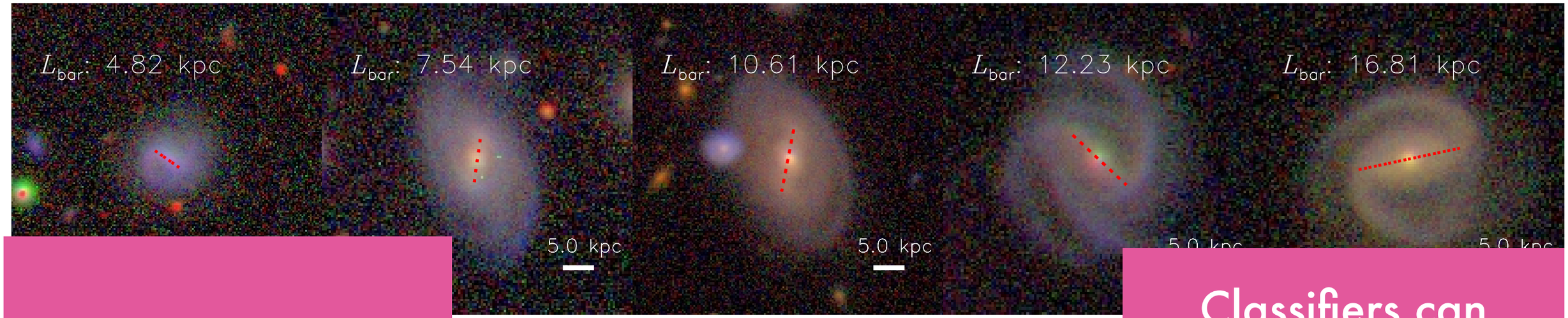
Bar Lengths



Bar Lengths


L_{bar}: 4.82 kpc
5.0 kpc
L_{bar}: 7.54 kpc
5.0 kpc
L_{bar}: 10.61 kpc
5.0 kpc
L_{bar}: 12.23 kpc
5.0 kpc
L_{bar}: 16.81 kpc
5.0 kpc

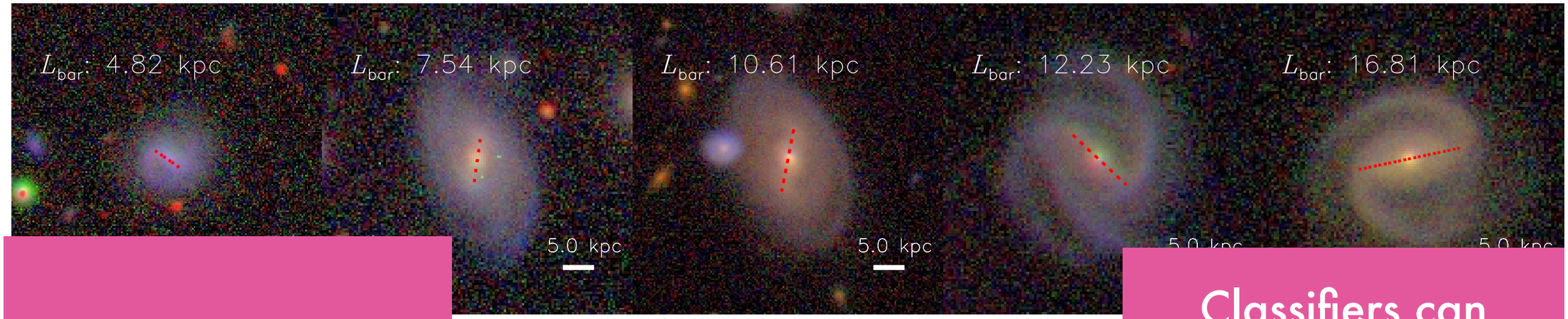
Bar Lengths



Minimum of 3 measurements

Classifiers can reproduce own result to within 3%, and to others within 20%

Bar Lengths



Minimum of 3 measurements

Classifiers can reproduce own result to within 3%, and to others within 20%

- 1,154 barred galaxies

Bars are drivers of galaxy evolution

Bars are drivers of galaxy evolution

- Observational evidence of bar-driven secular evolution
  - Galaxy Zoo 2

Bars are drivers of galaxy evolution

- Observational evidence of bar-driven secular evolution
  - Galaxy Zoo 2
  - explore how p_{bar} and L_{sbar} behave under 2 parameters are predicted to affect bar-driven secular evolution

Bars are drivers of galaxy evolution

- Observational evidence of bar-driven secular evolution
  - Galaxy Zoo 2
    - explore how p_{bar} and L_{sbar} behave under 2 parameters are predicted to affect bar-driven secular evolution
      - gas content

Bars are drivers of galaxy evolution

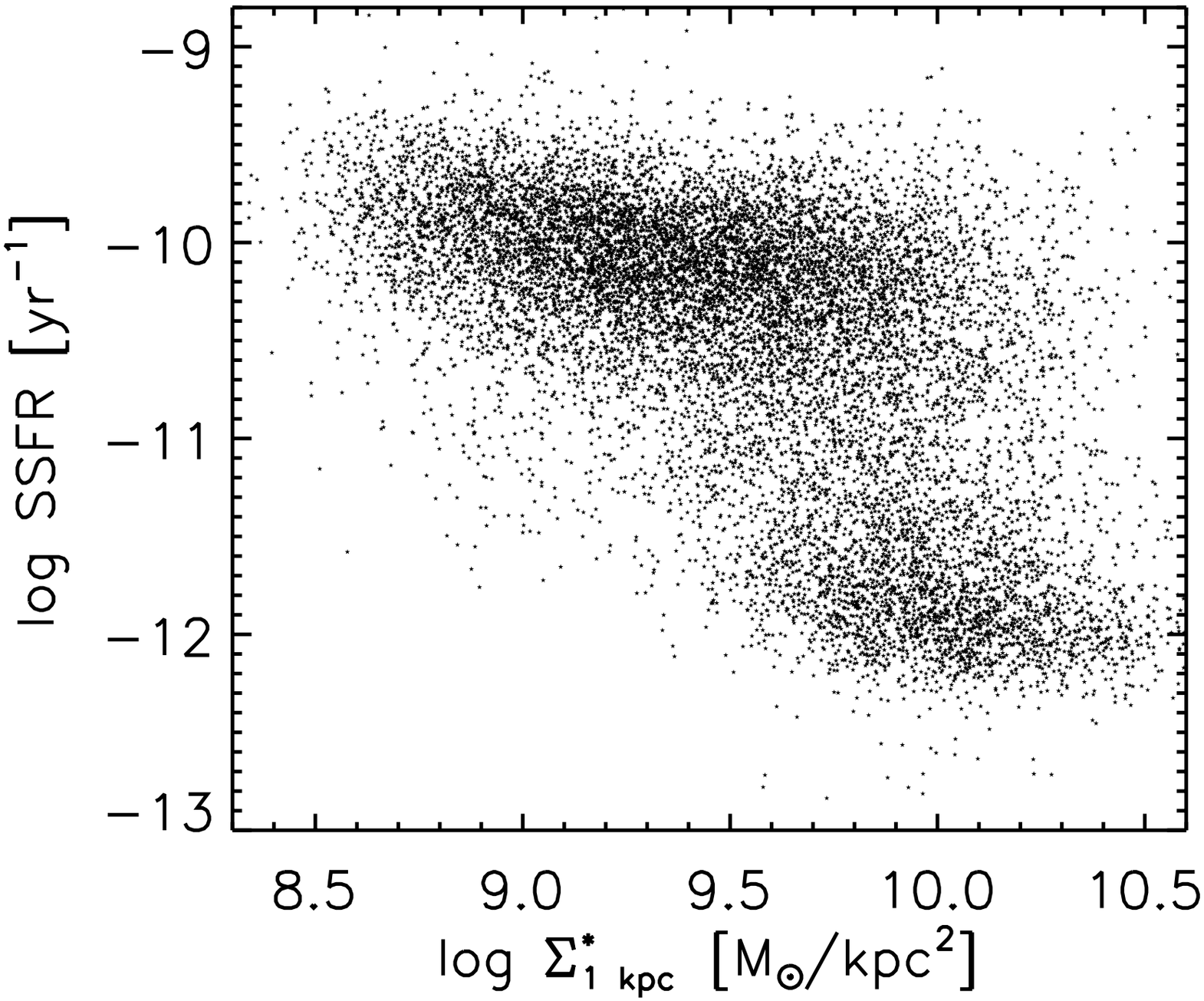
- Observational evidence of bar-driven secular evolution
  - Galaxy Zoo 2
  - explore how p_{bar} and L_{sbar} behave under 2 parameters are predicted to affect bar-driven secular evolution
    - gas content
    - bulge mass density

Evidence of secular evolution

Evidence of secular evolution

Cheung et al. 2013

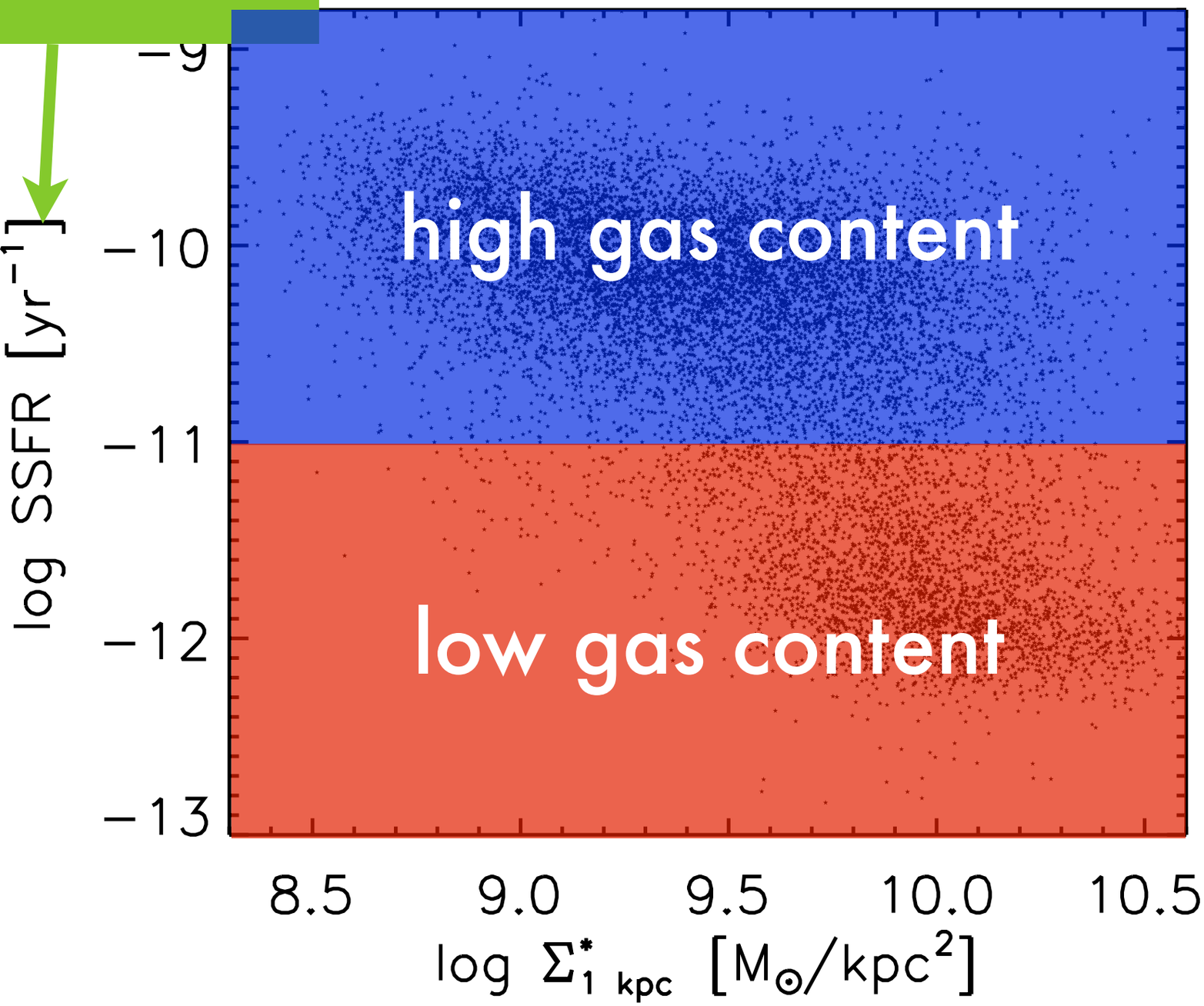
Evidence of secular evolution



Cheung et al. 2013

e of secular evolution

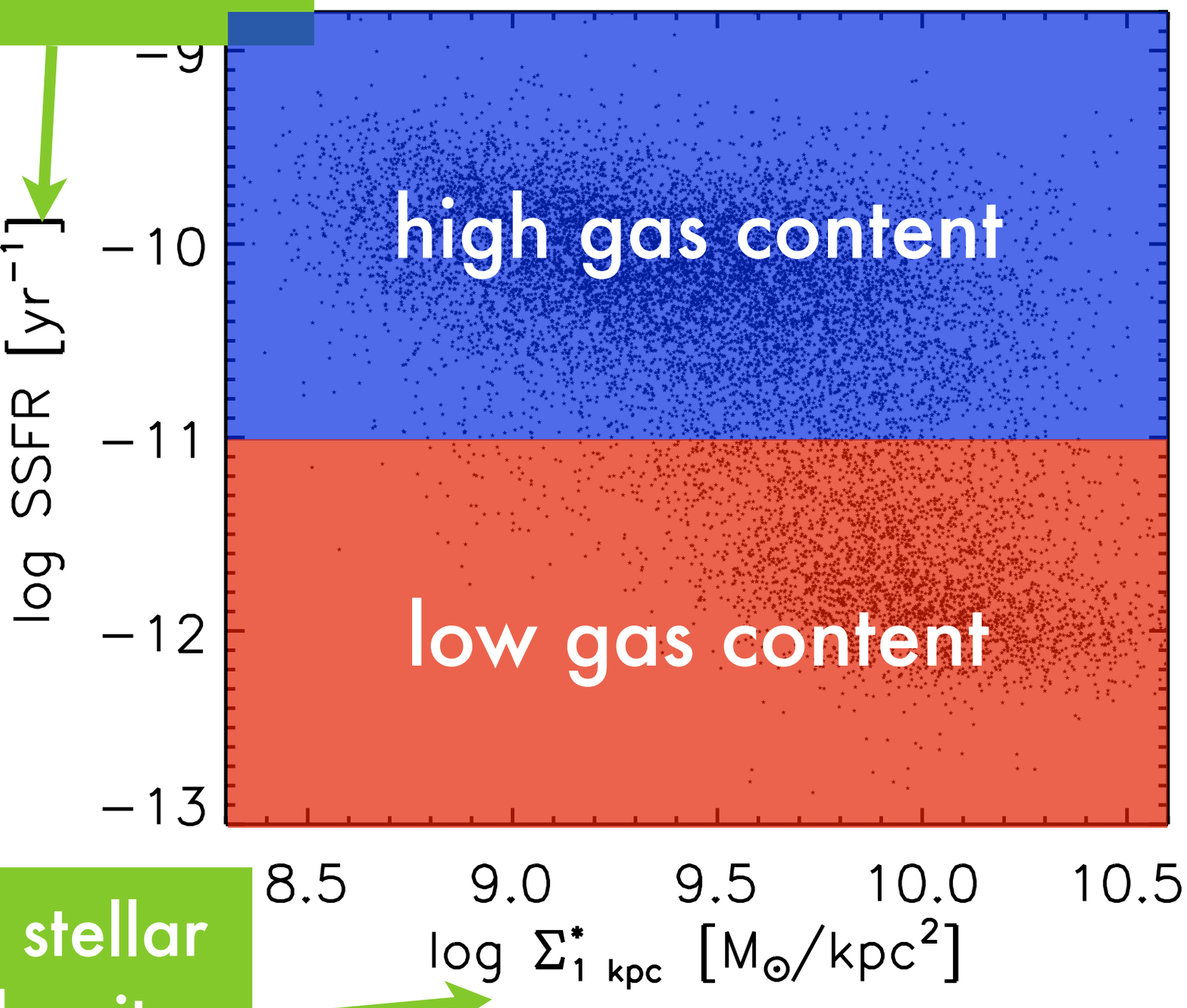
tracer of gas content



Cheung et al. 2013

e of secular evolution

tracer of gas content



surface stellar mass density within 1 kpc

Cheung et al. 2013

e of secular evolution

tracer of gas content

high gas co

low gas co

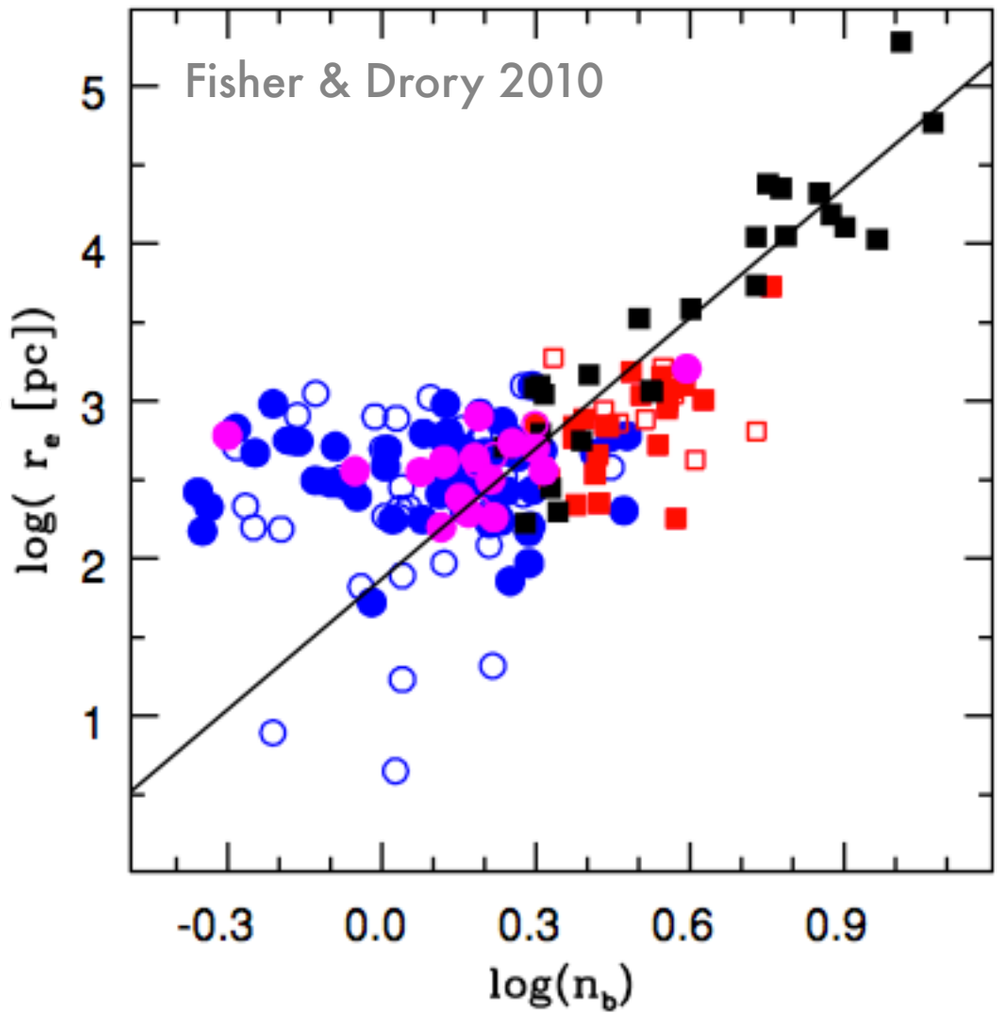
log SSFR [yr^{-1}]

−9
−10
−11
−12
−13

8.5 9.0 9.5 10.0 10.5

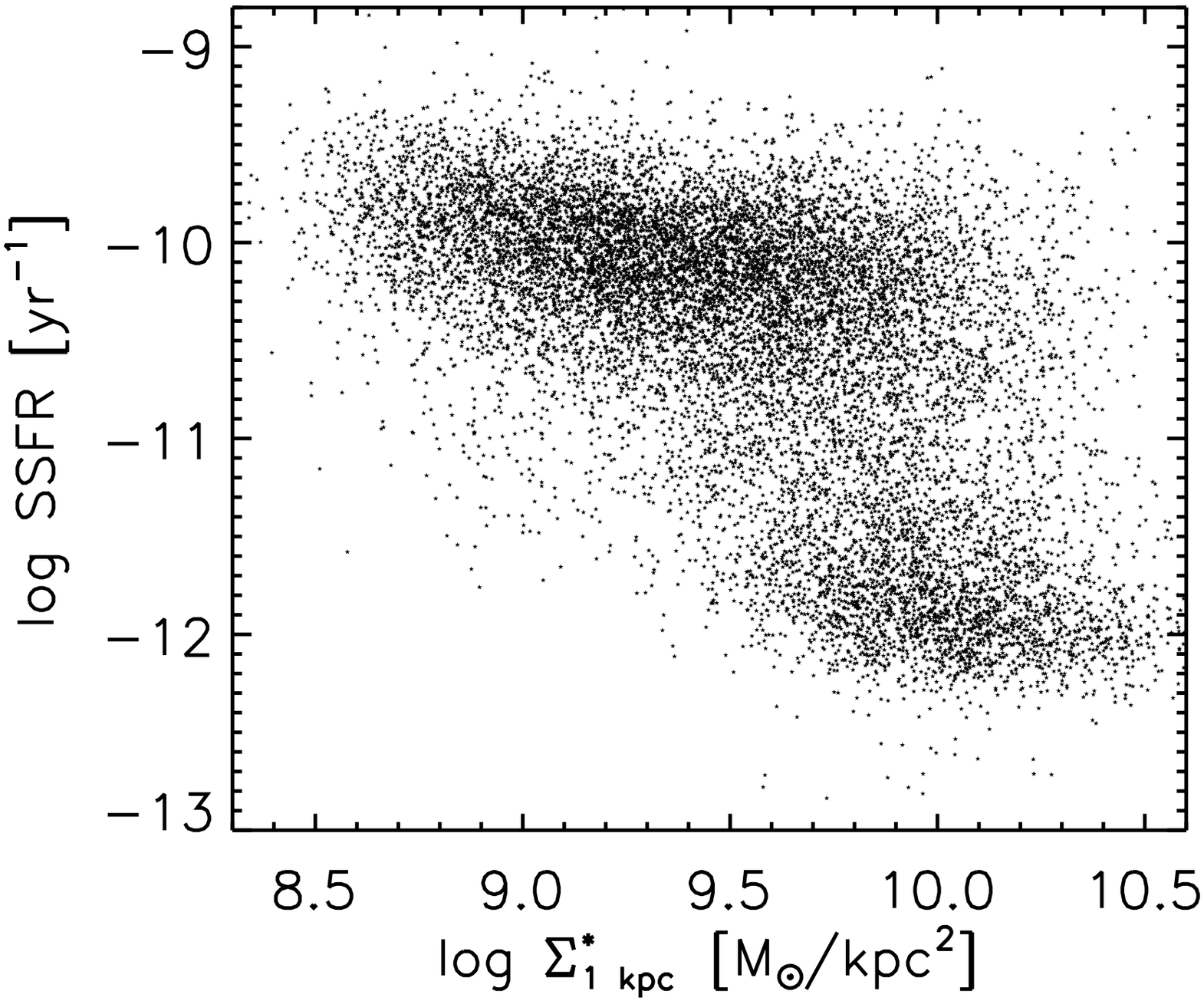
log $\Sigma^*_{1\ kpc}$ [$M_\odot/kpc^2$]

surface stellar mass density within 1 kpc



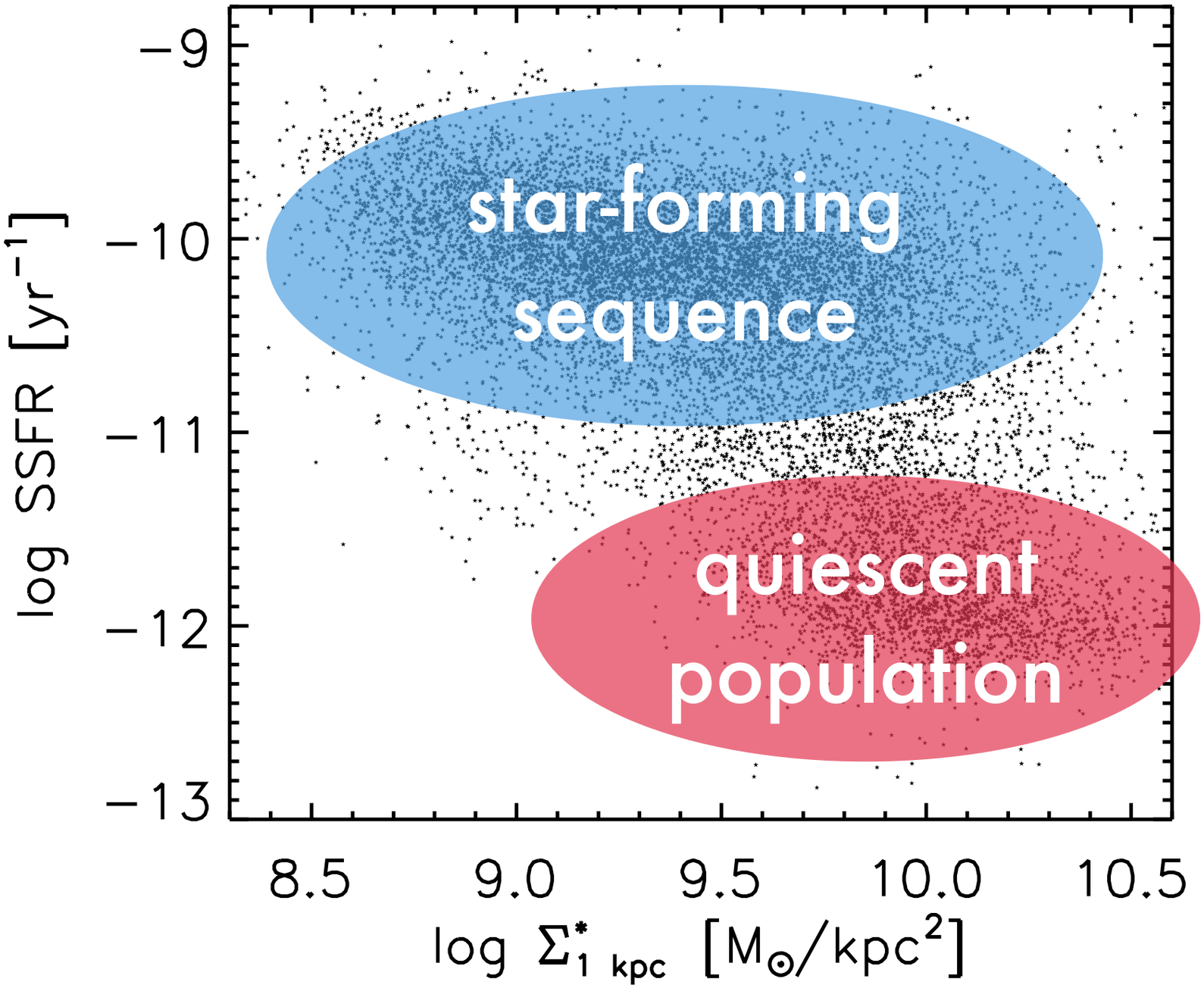
Cheung et al. 2013

Evidence of secular evolution



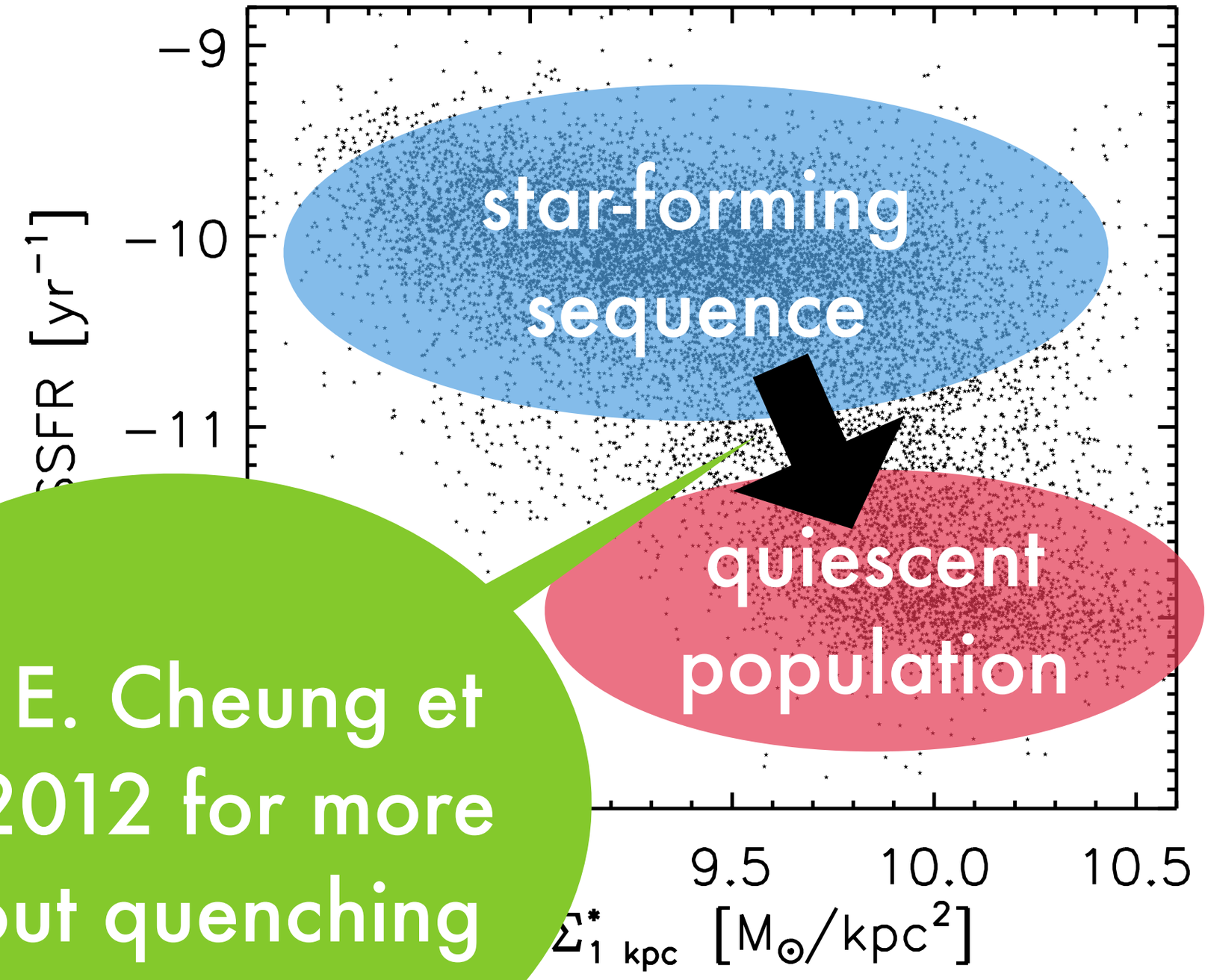
Cheung et al. 2013

Evidence of secular evolution



Cheung et al. 2013

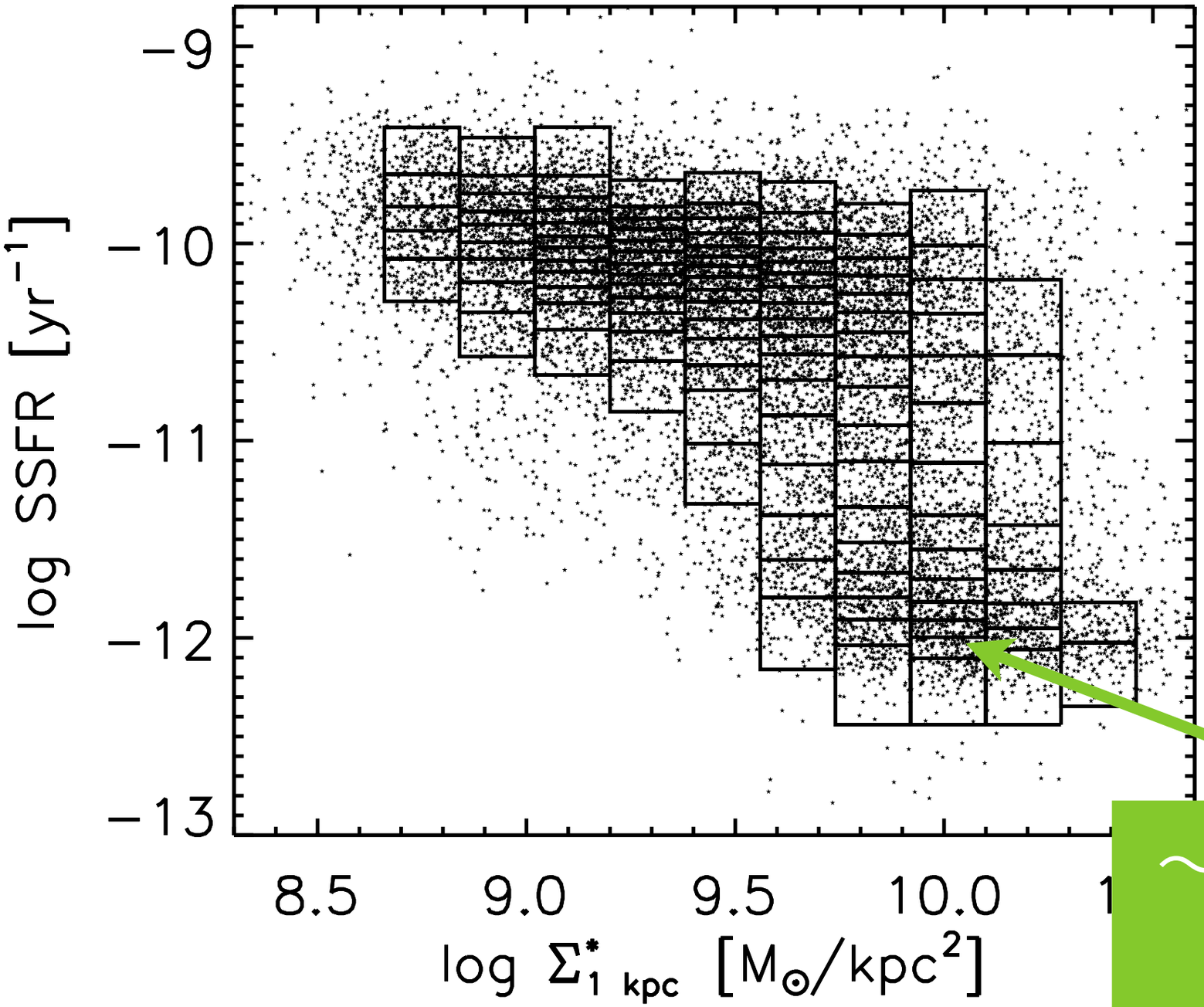
Evidence of secular evolution



see E. Cheung et al. 2012 for more about quenching

Cheung et al. 2013

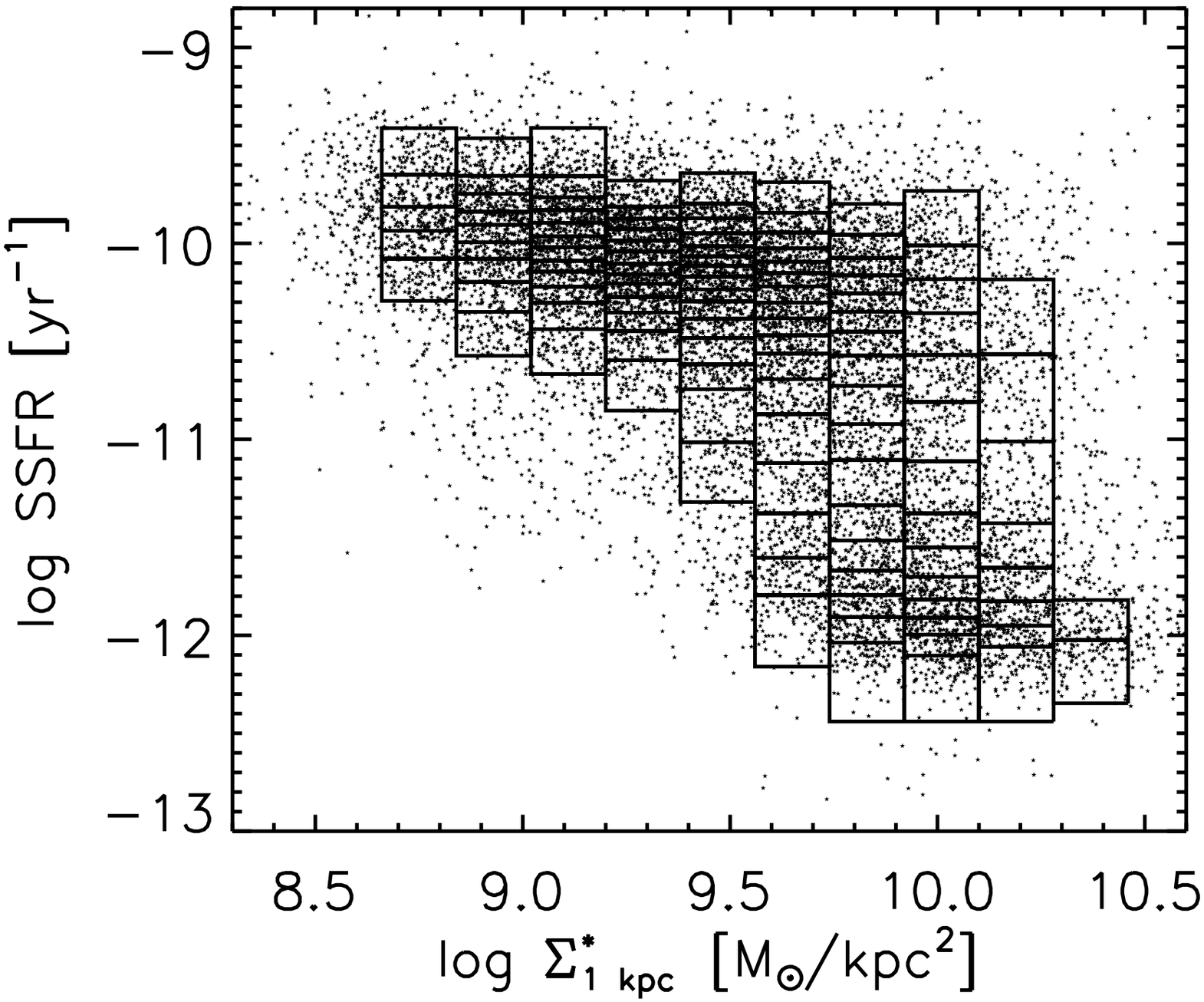
Evidence of secular evolution



~100 galaxies each

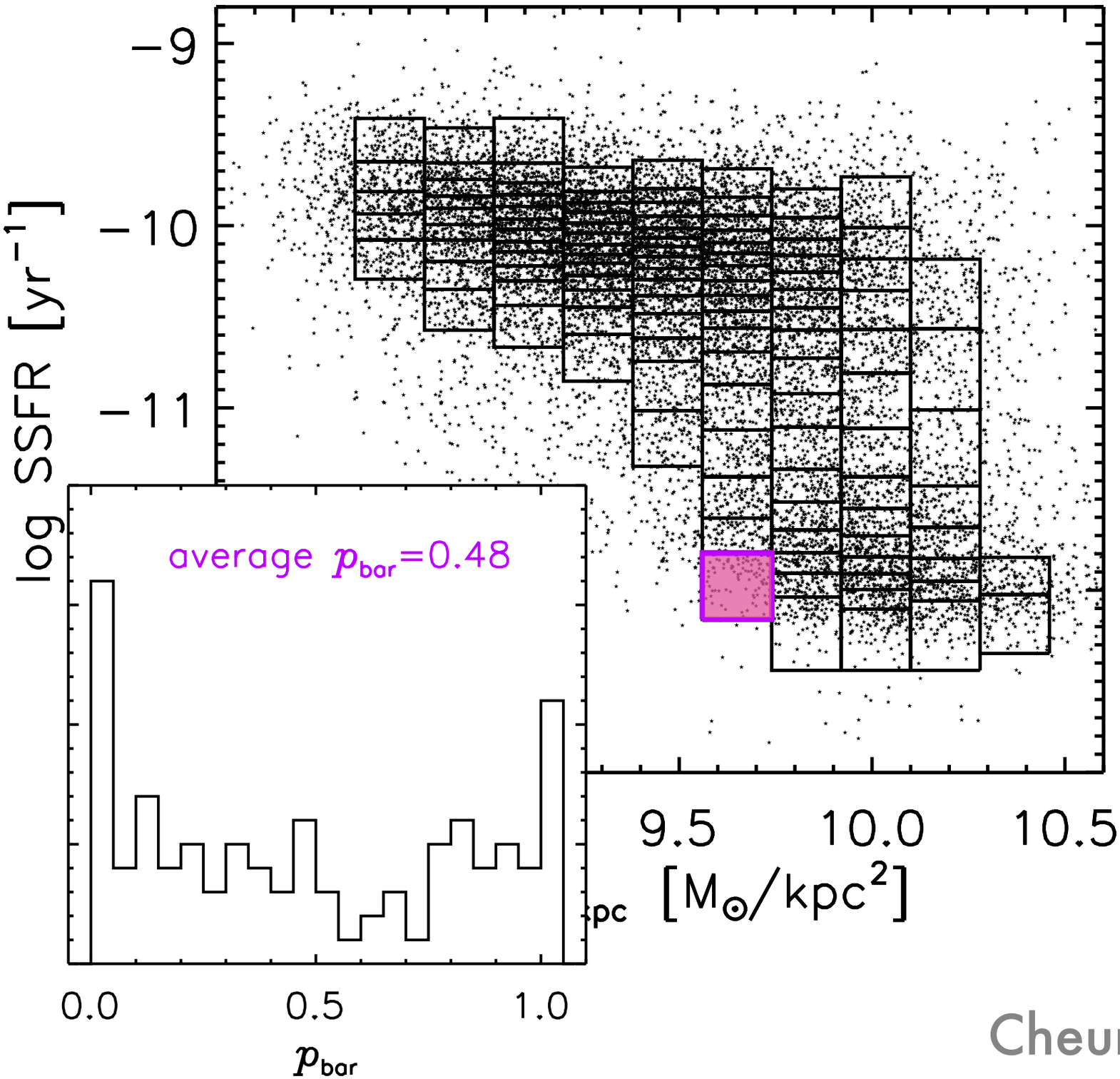
Cheung et al. 2013

Evidence of secular evolution



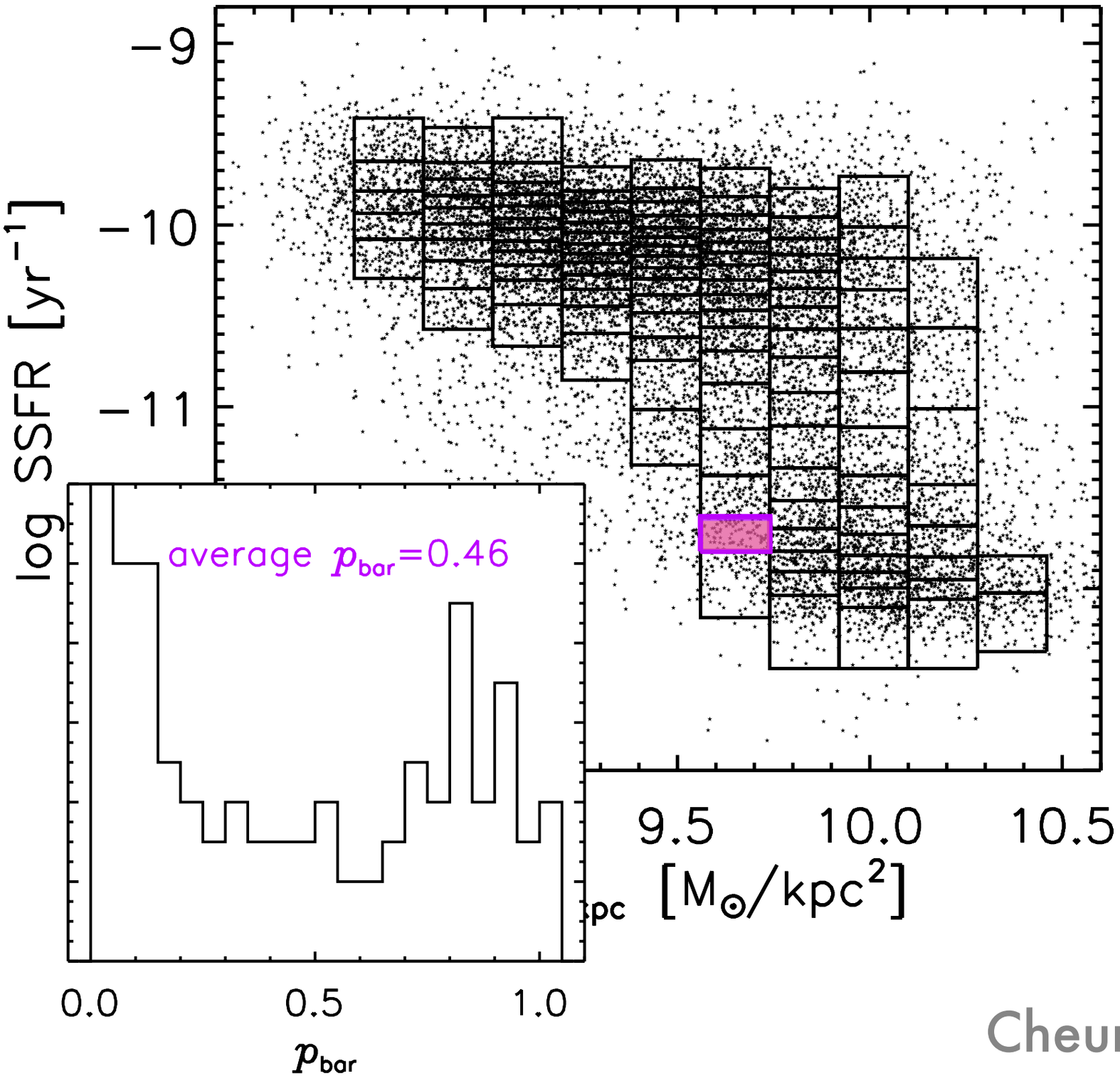
Cheung et al. 2013

Evidence of secular evolution



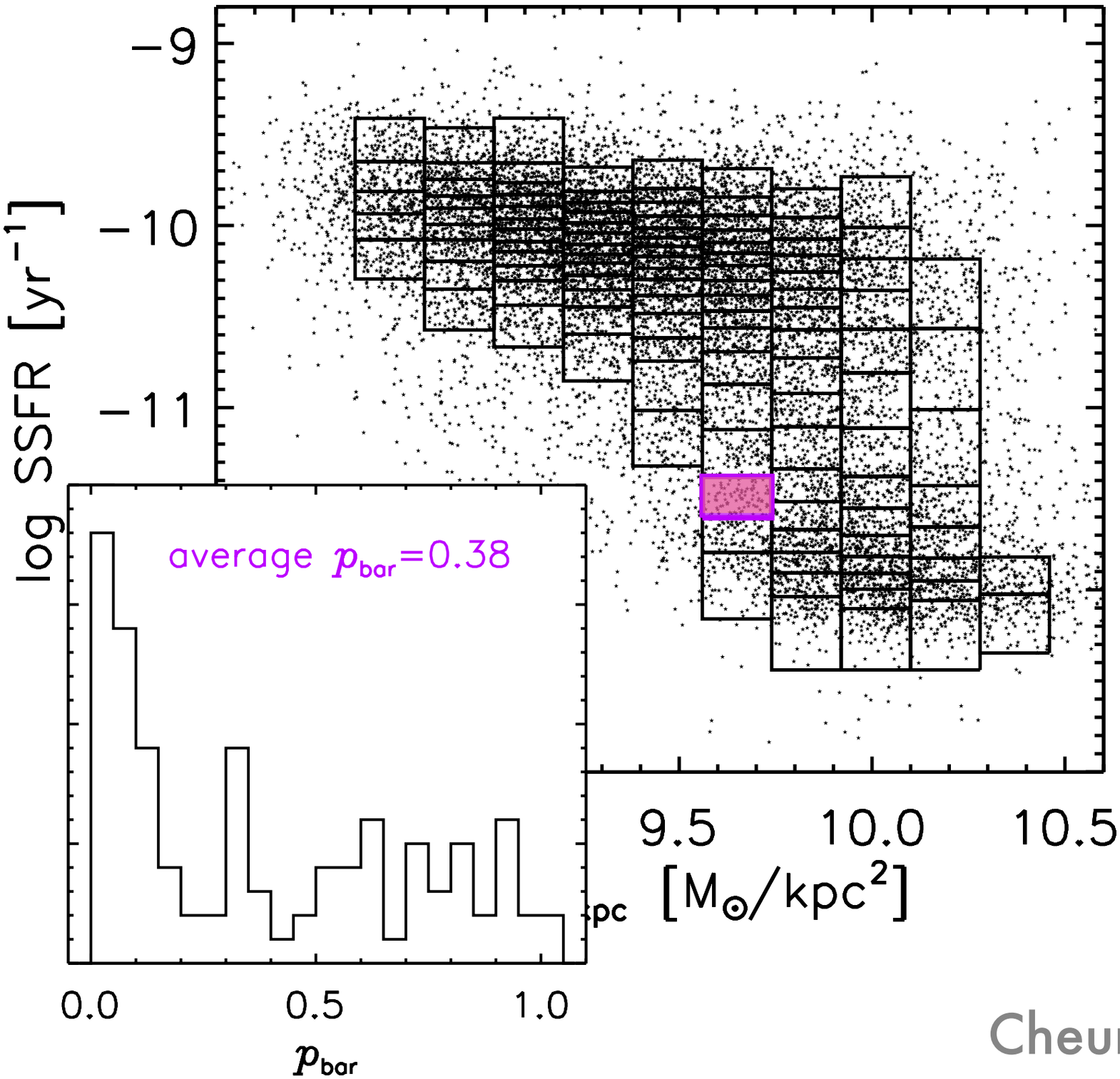
Cheung et al. 2013

Evidence of secular evolution



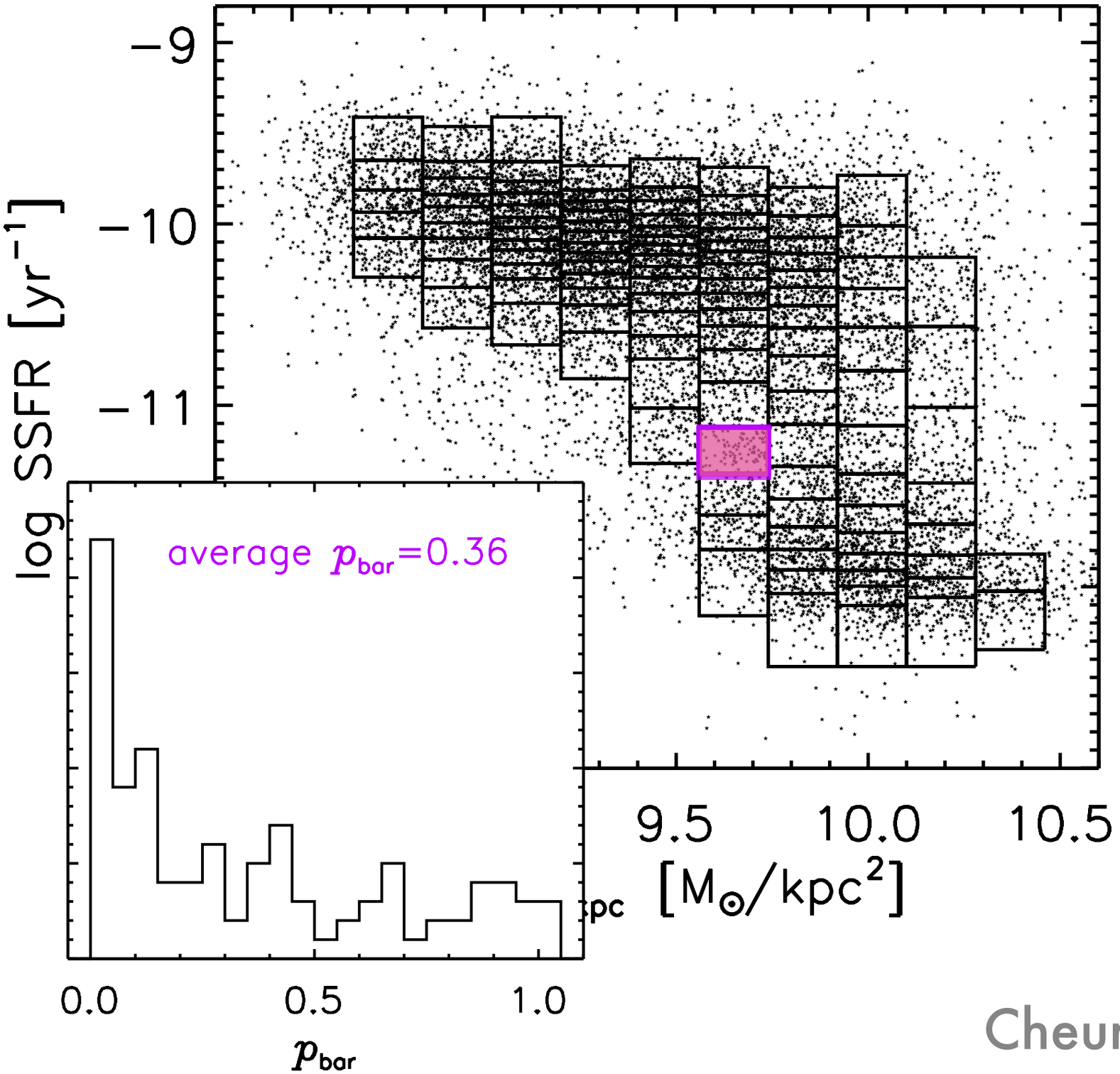
Cheung et al. 2013

Evidence of secular evolution



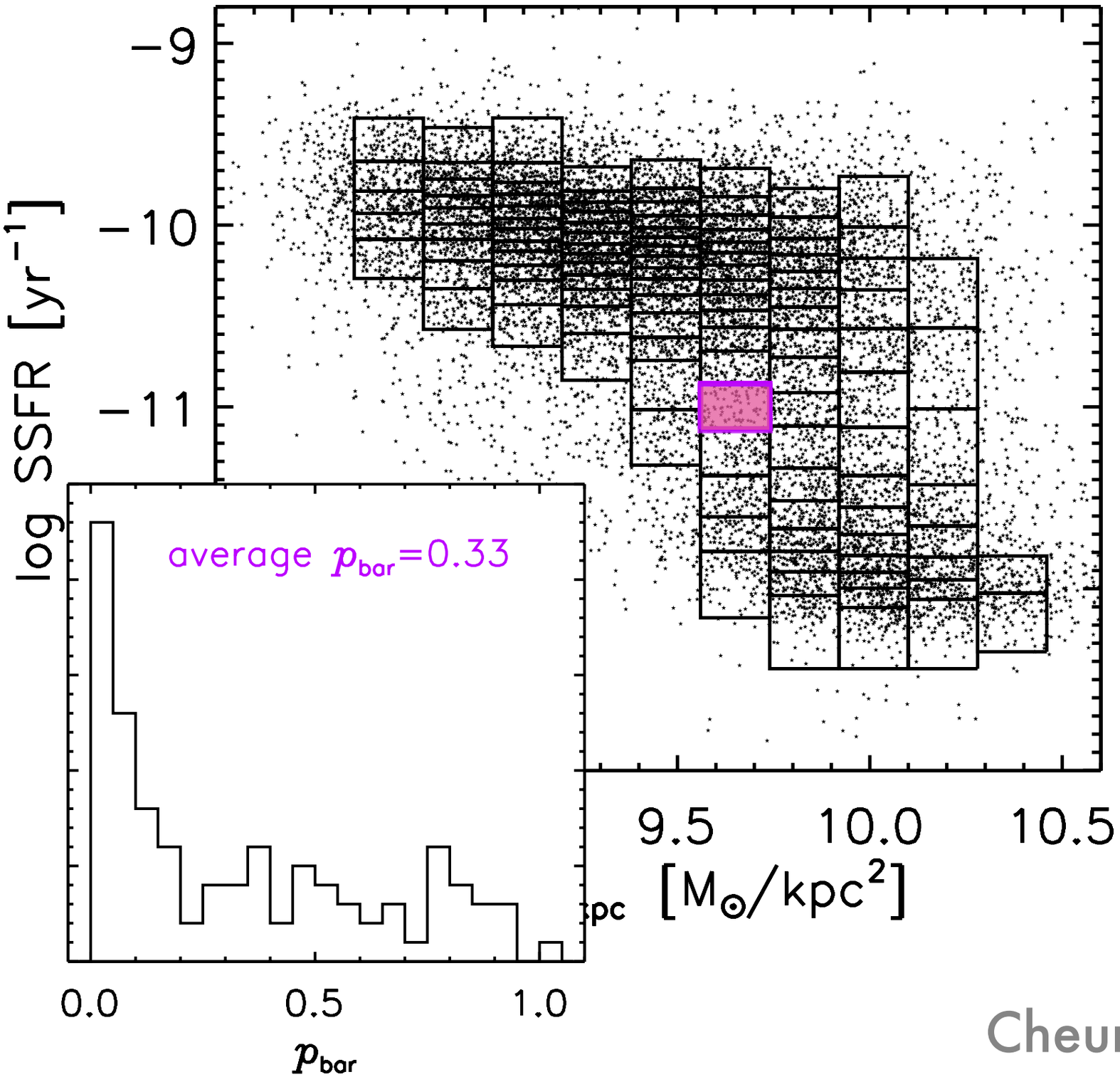
Cheung et al. 2013

Evidence of secular evolution



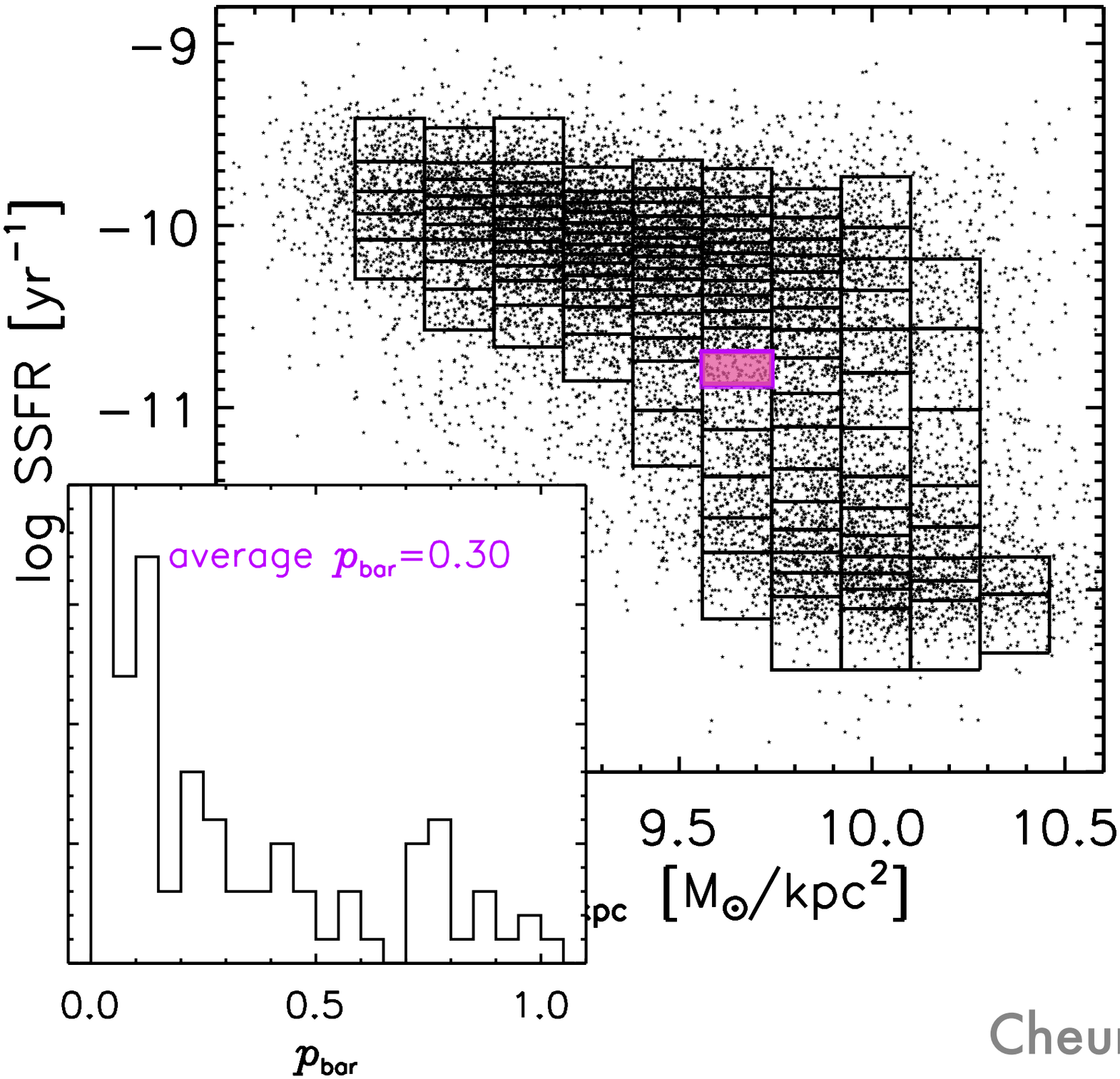
Cheung et al. 2013

Evidence of secular evolution



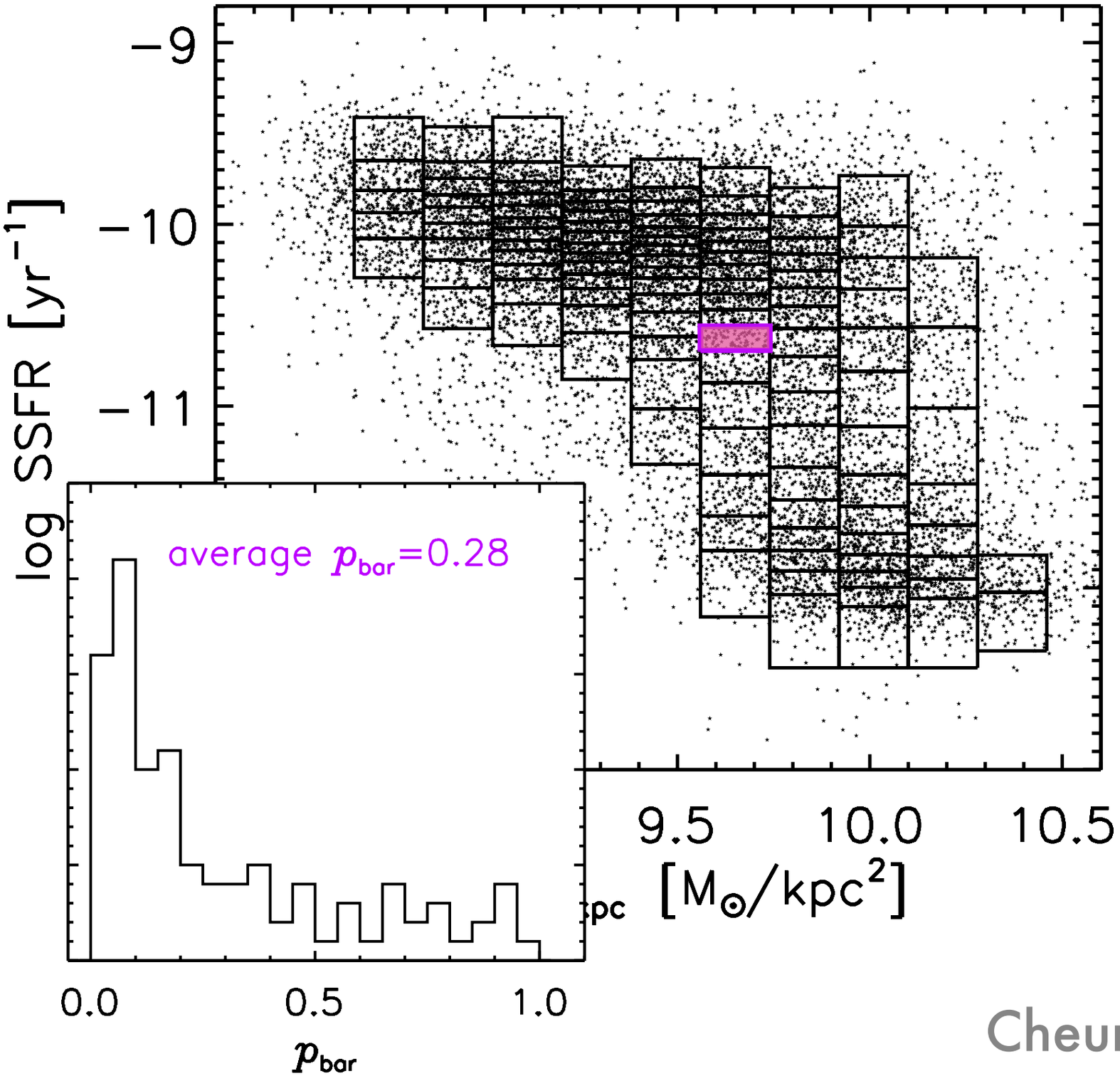
Cheung et al. 2013

Evidence of secular evolution



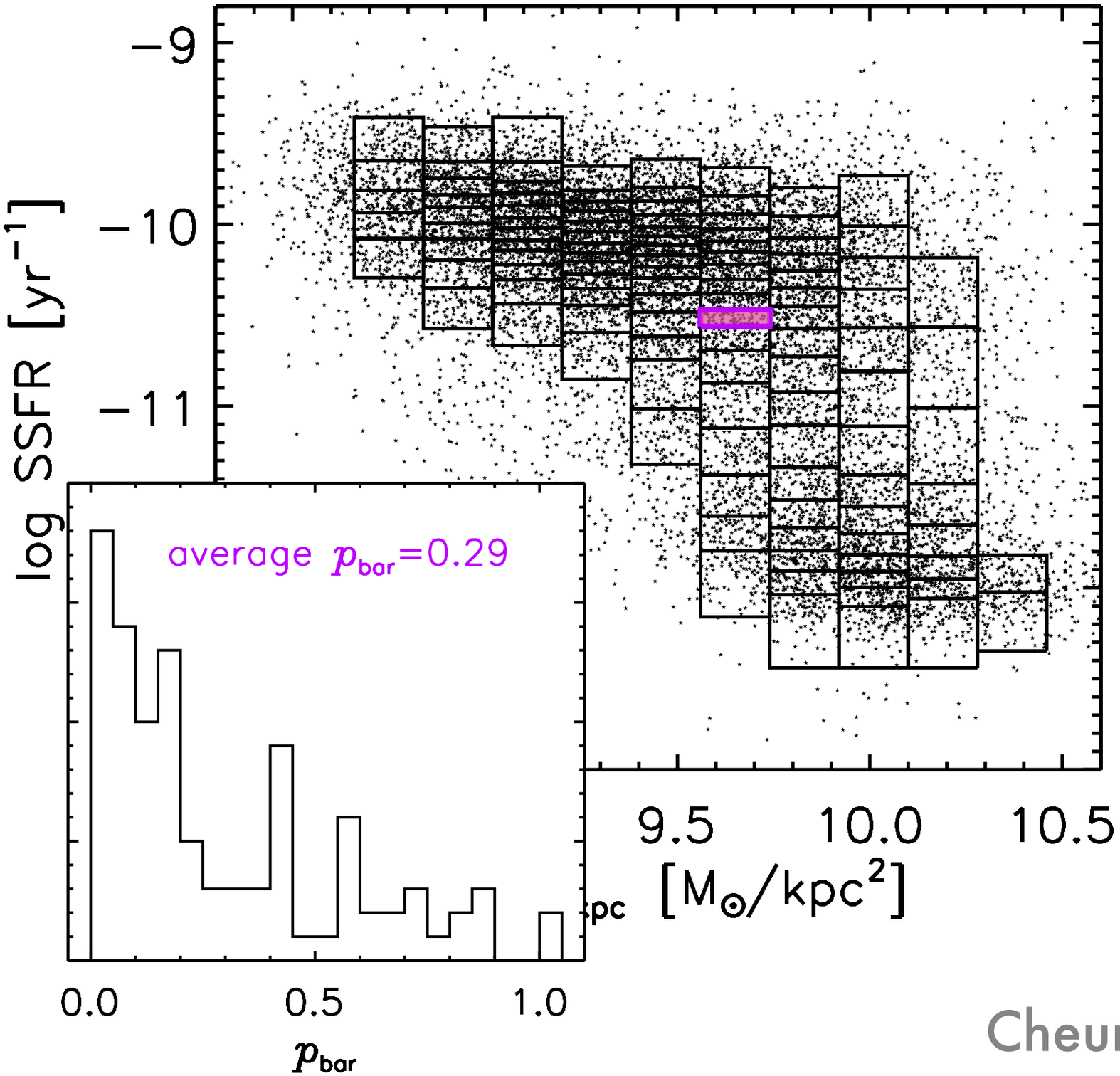
Cheung et al. 2013

Evidence of secular evolution



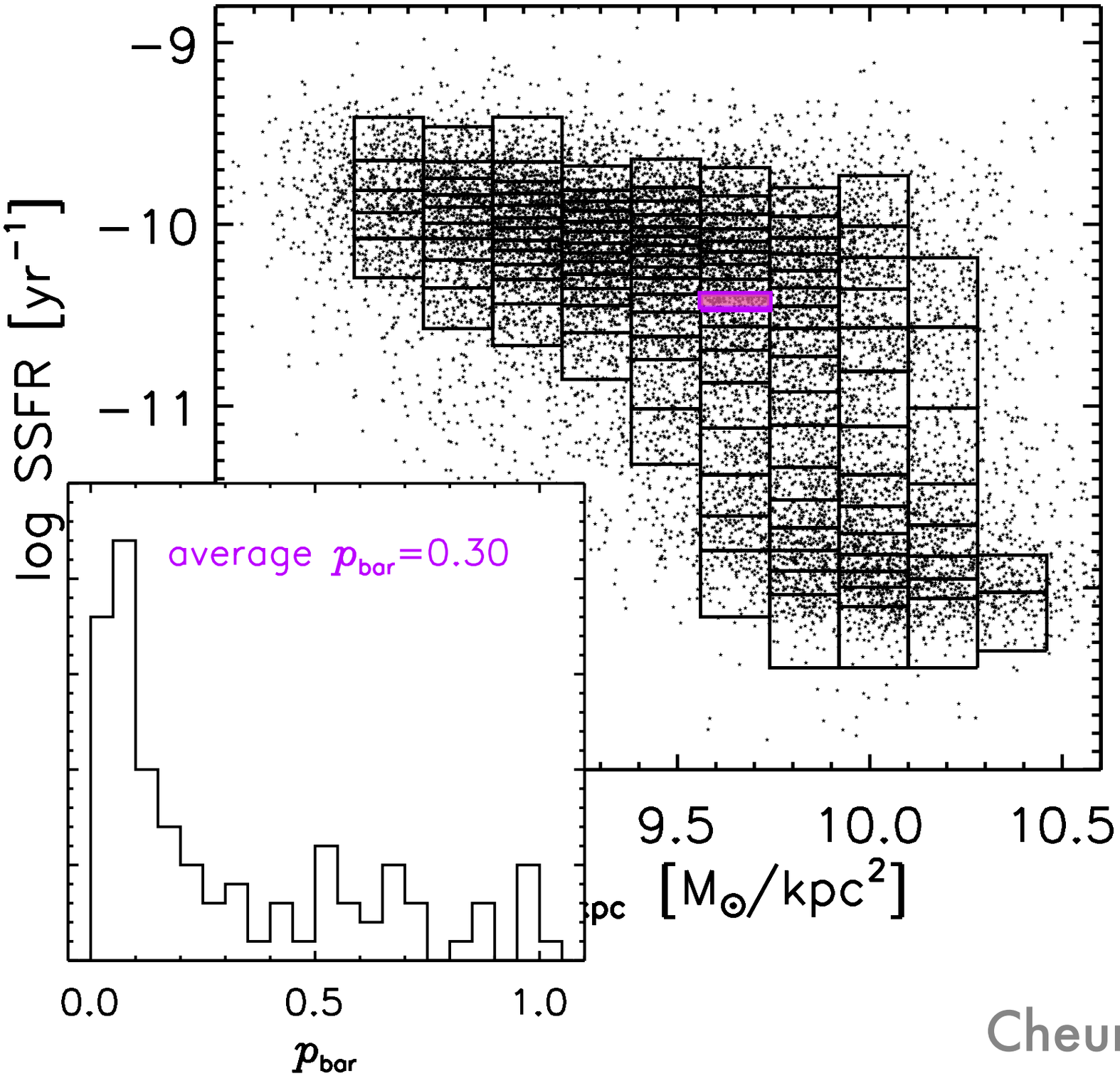
Cheung et al. 2013

Evidence of secular evolution



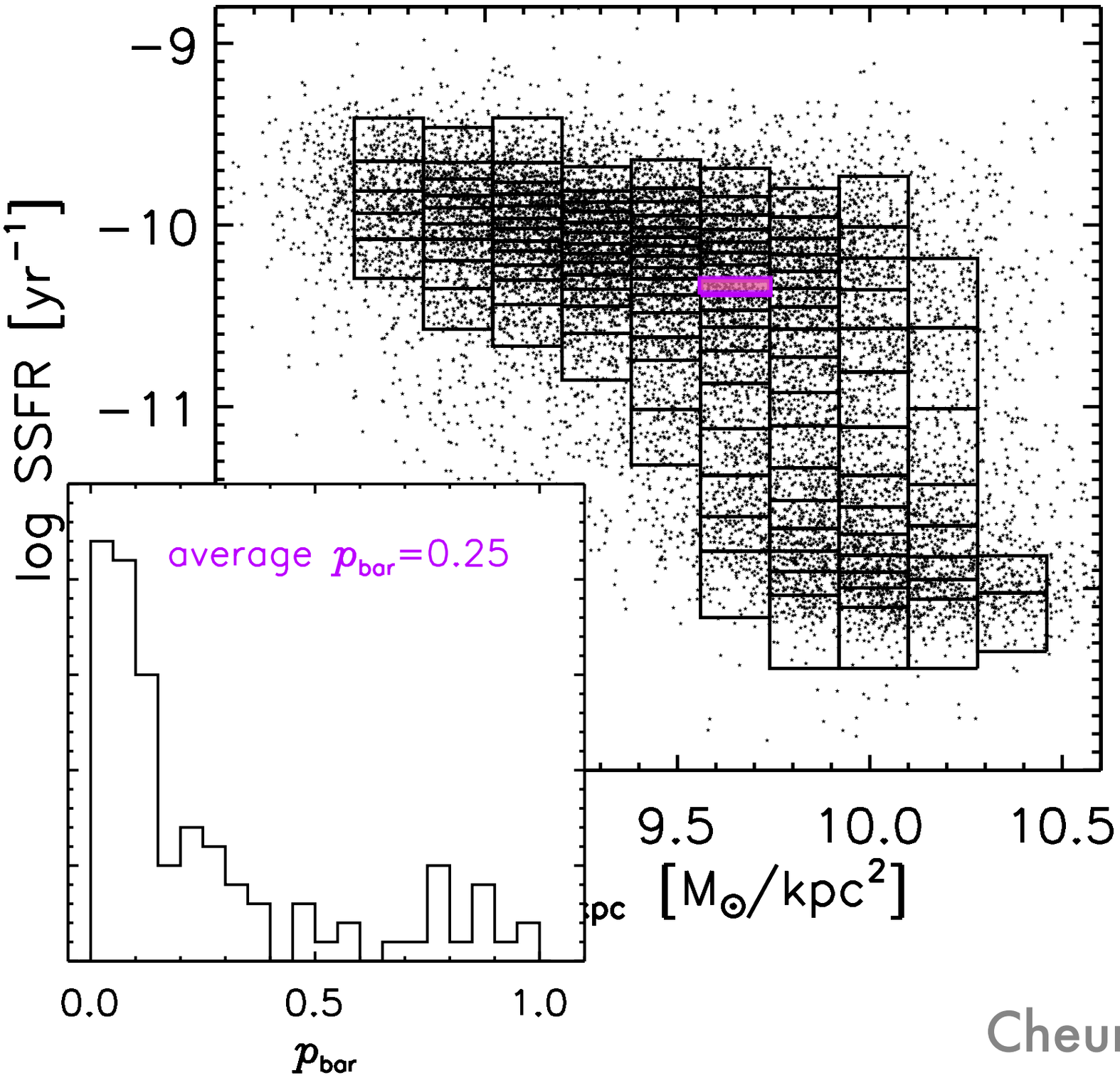
Cheung et al. 2013

Evidence of secular evolution



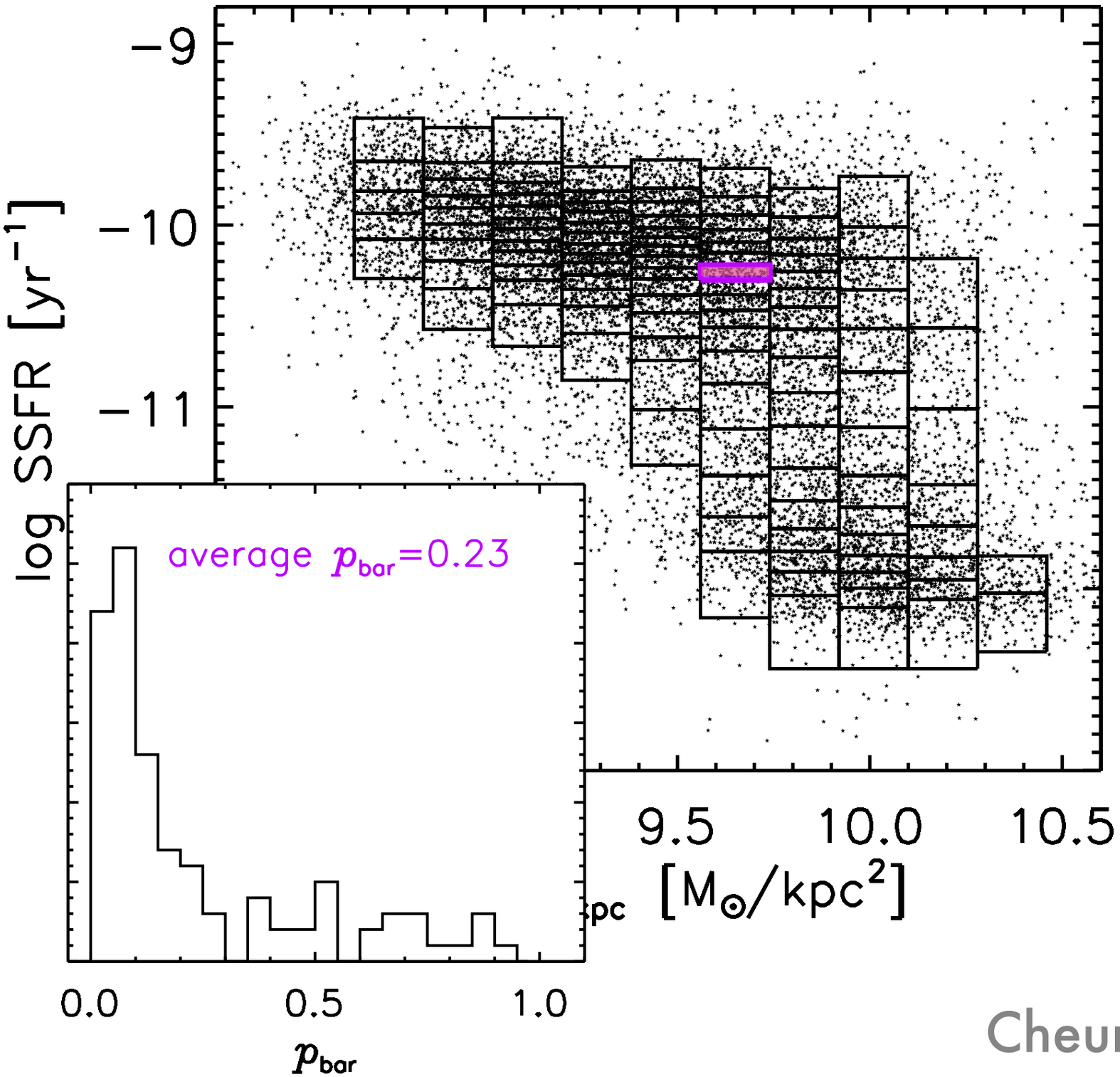
Cheung et al. 2013

Evidence of secular evolution



Cheung et al. 2013

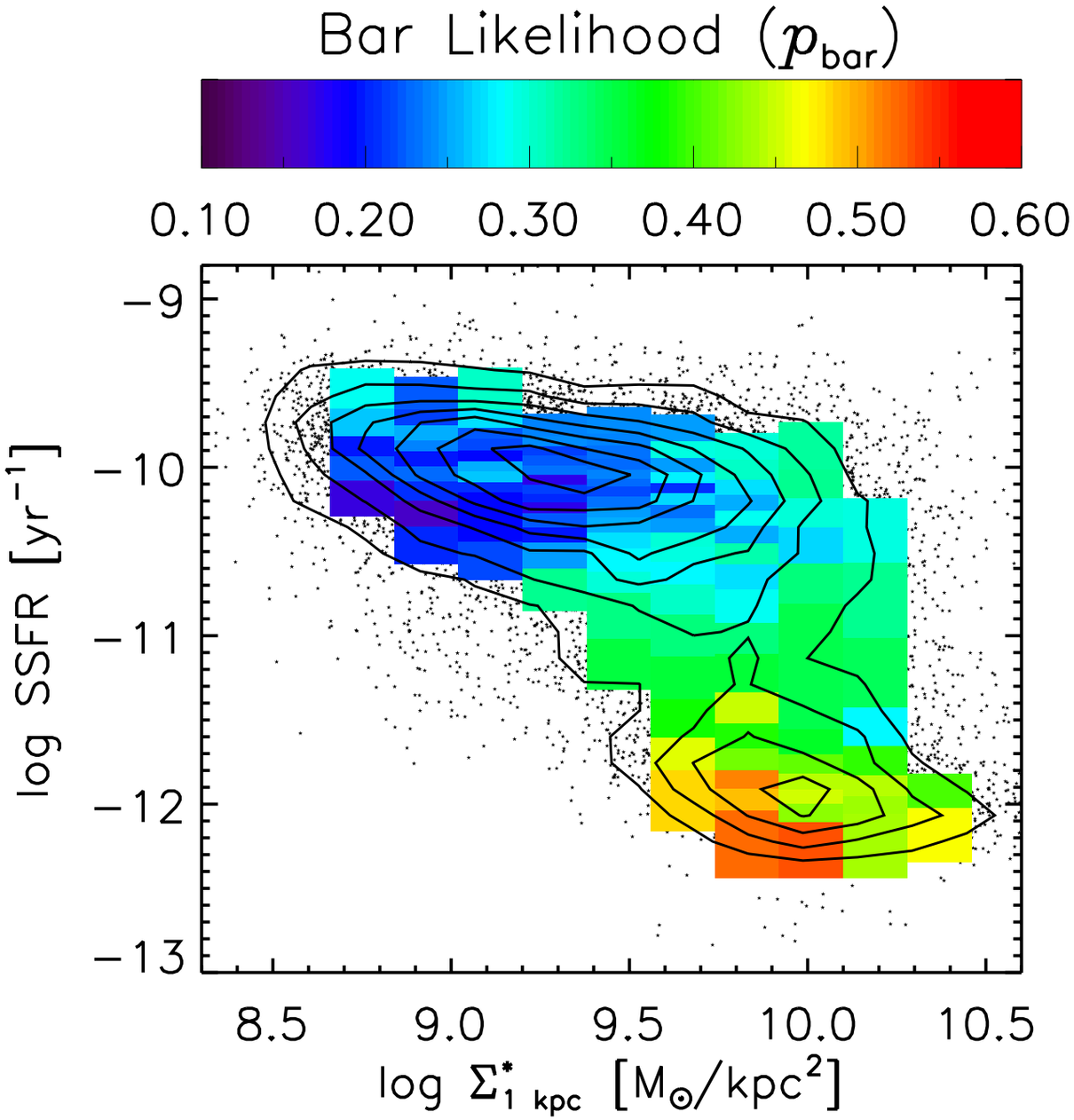
Evidence of secular evolution



Cheung et al. 2013

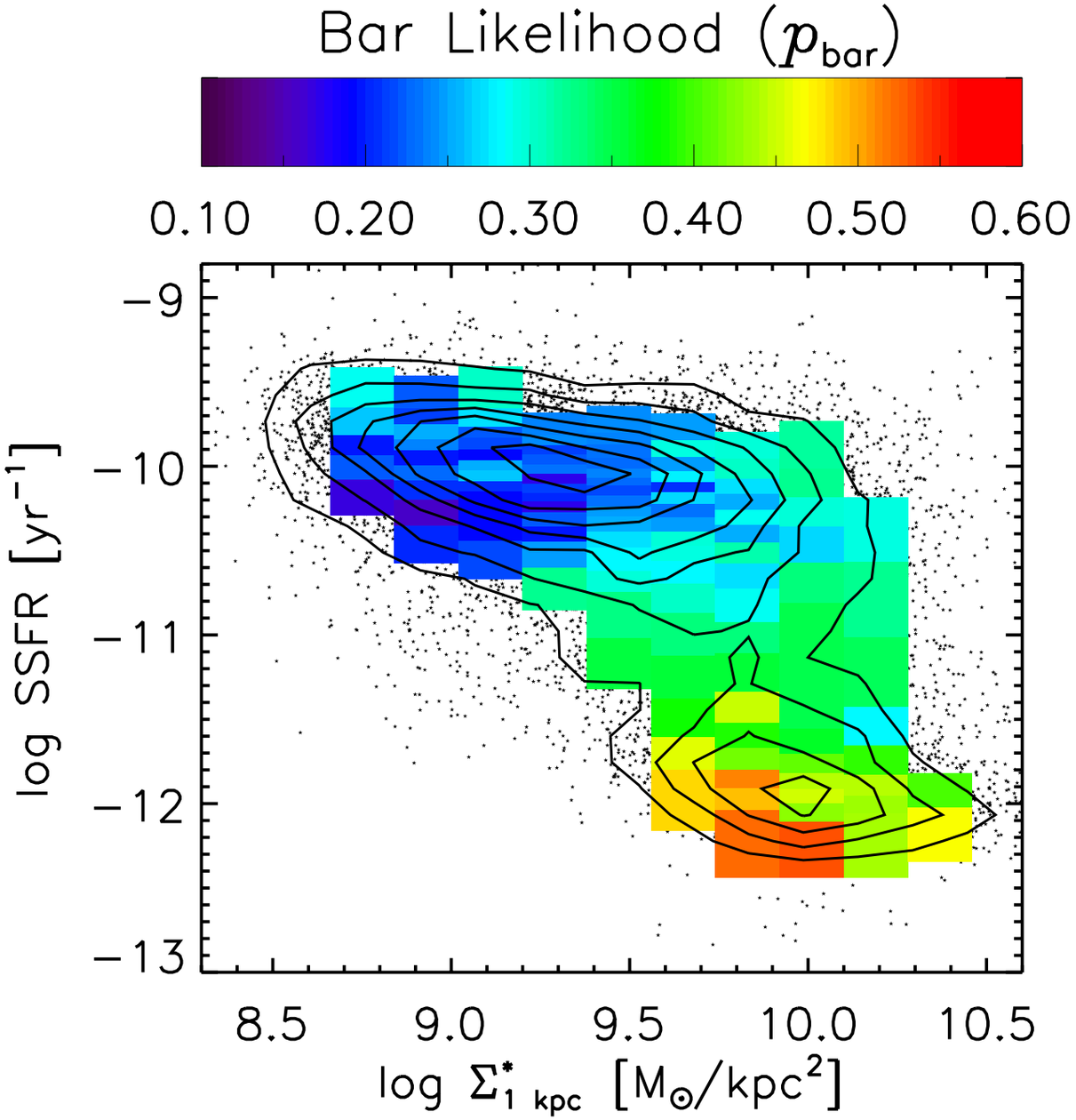
Evidence of secular evolution

Cheung et al. 2013



Evidence of secular evolution

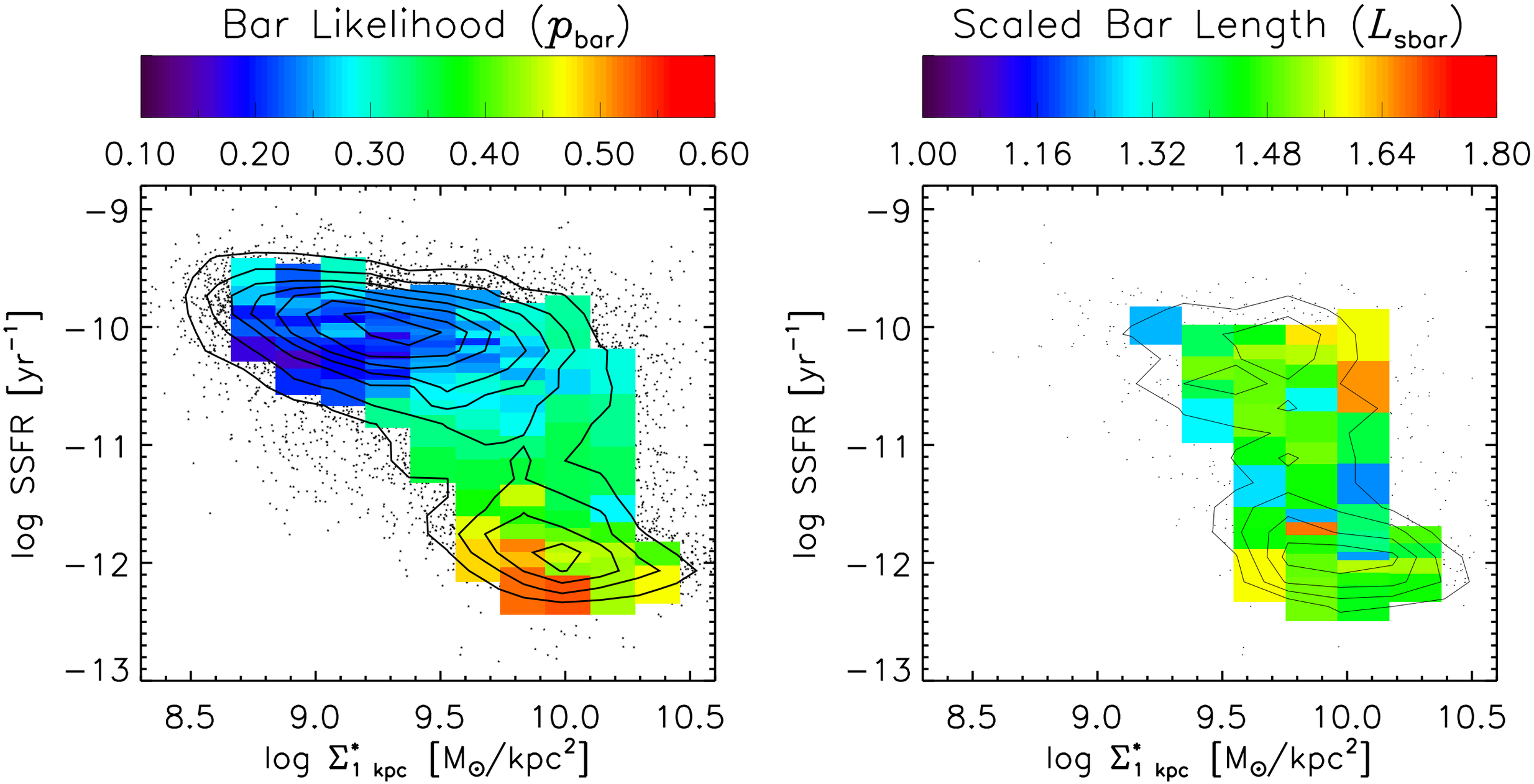
Cheung et al. 2013



- p_{bar} is strongly anti-correlated with SSFR

Evidence of secular evolution

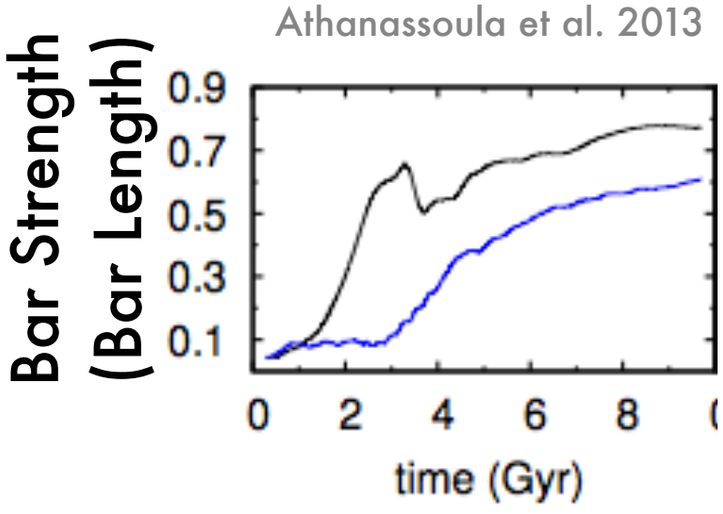
Cheung et al. 2013

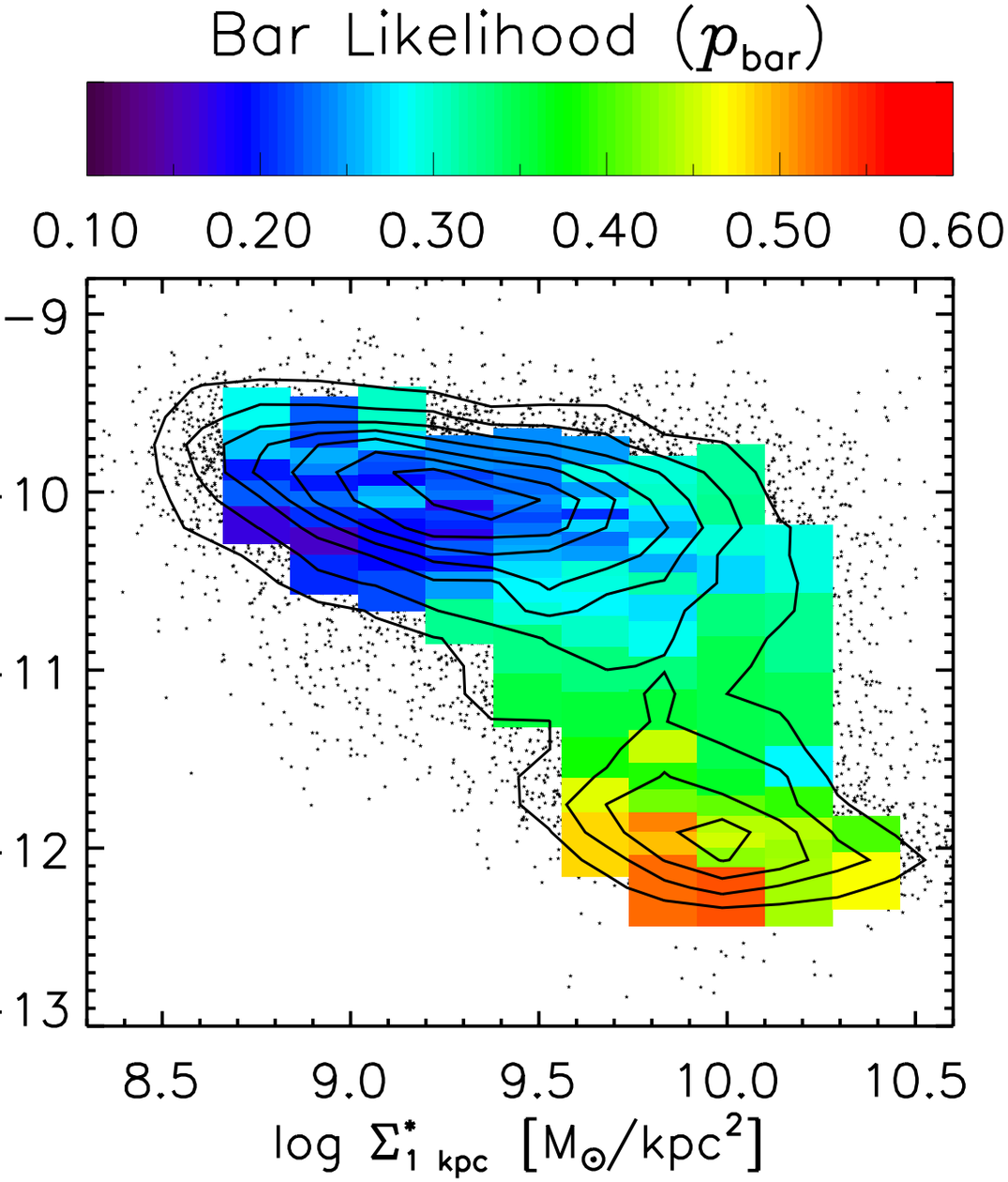


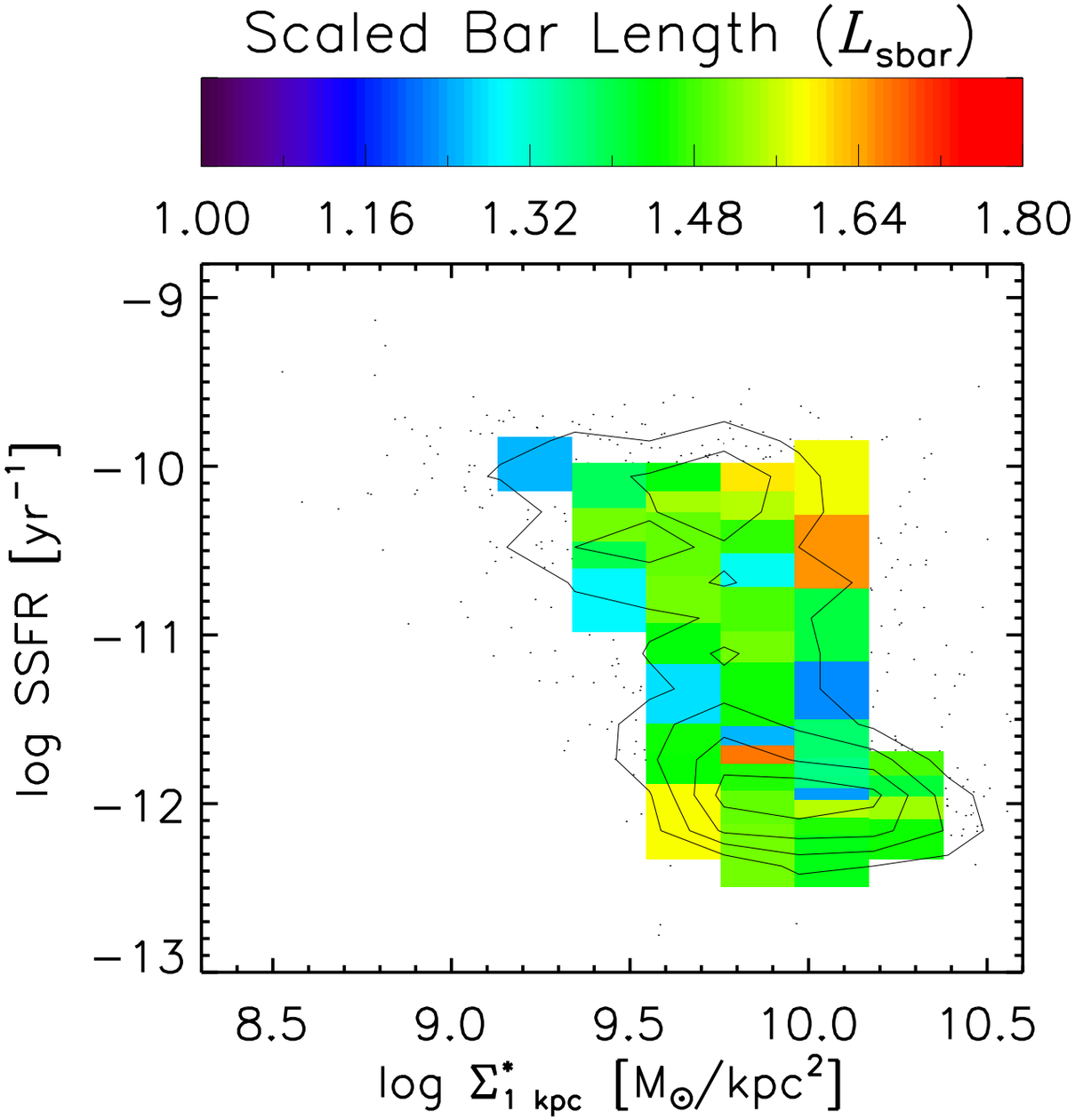
Evide ution

Cheung et c

Consistent with effects of gas on bar formation



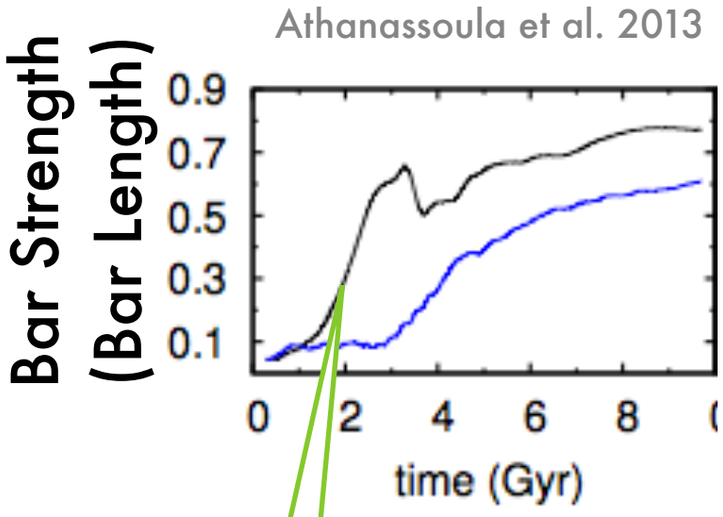


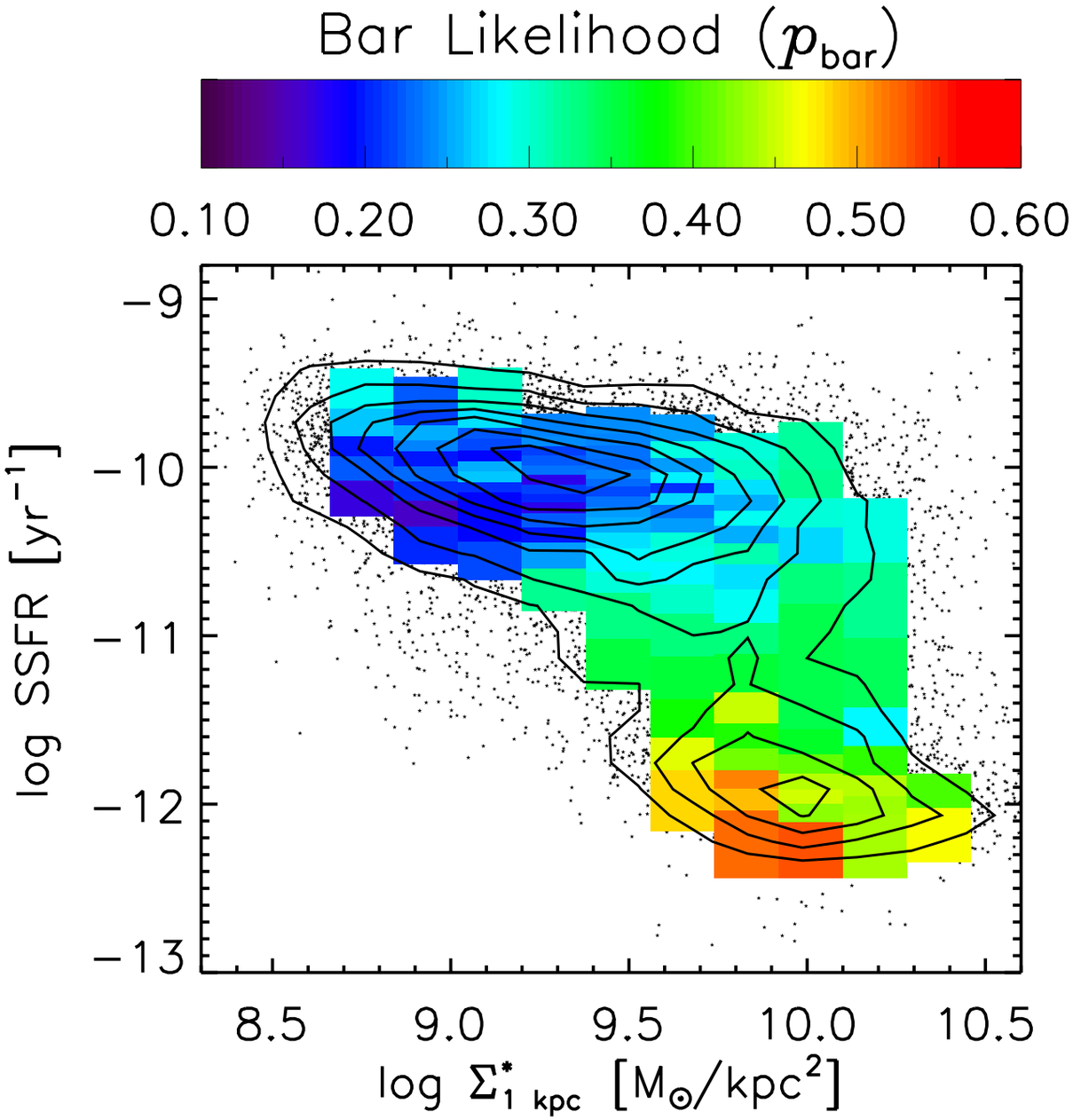


Evide ution

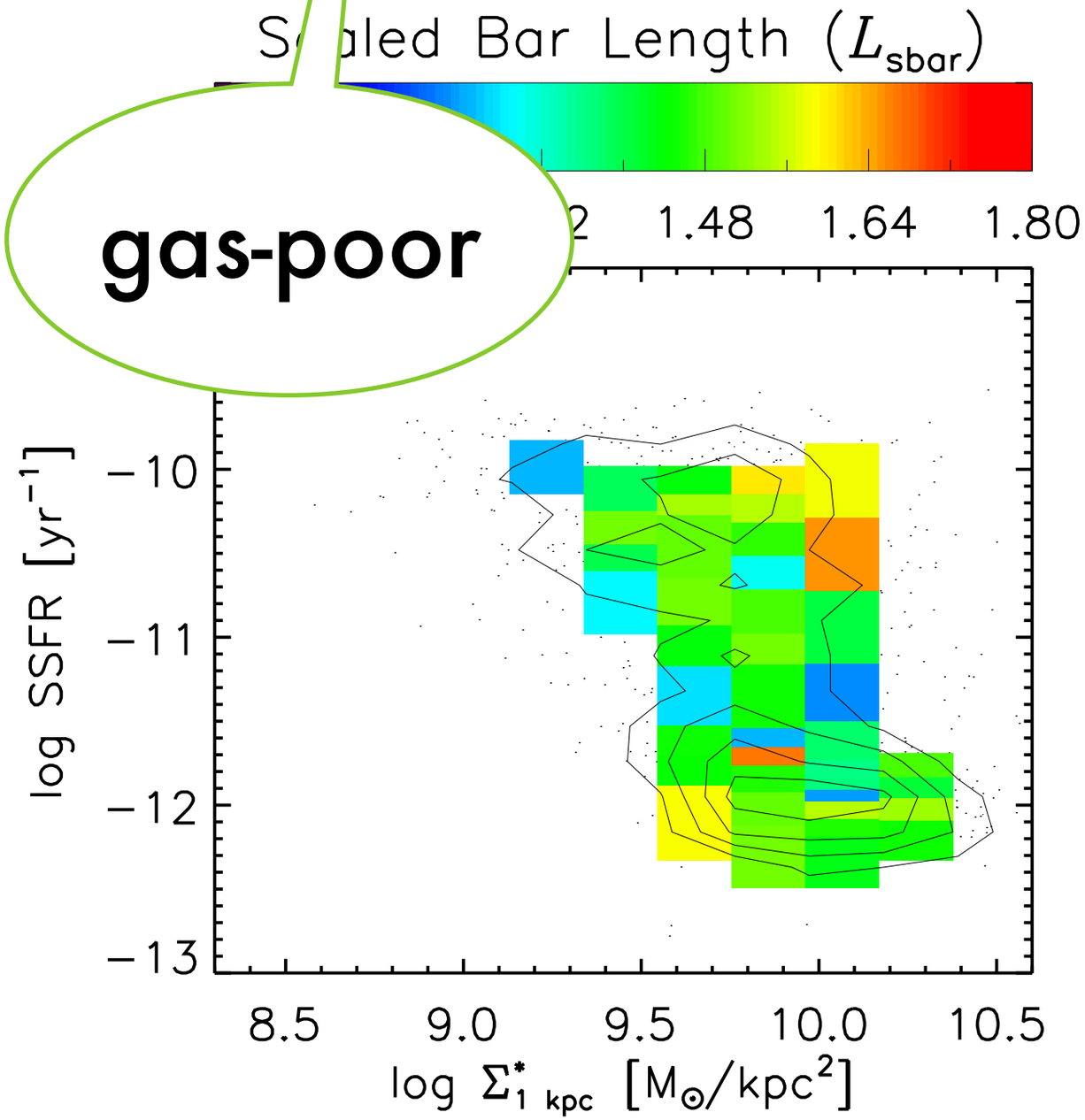
Cheung et c

Consistent with effects of gas on bar formation





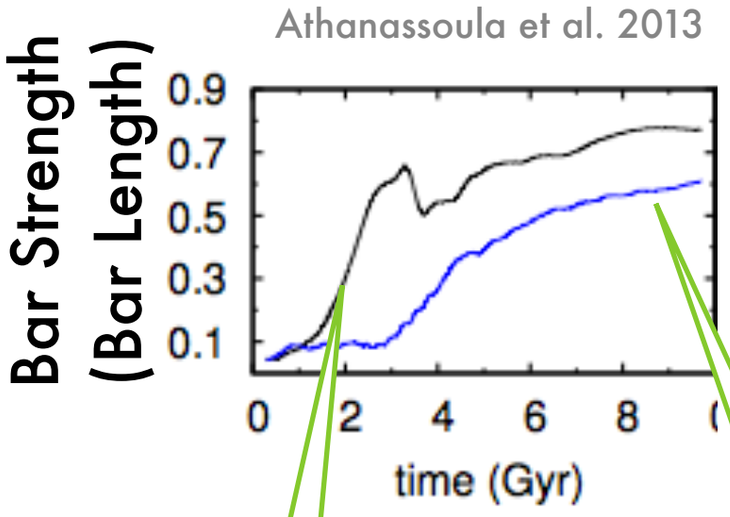
gas-poor

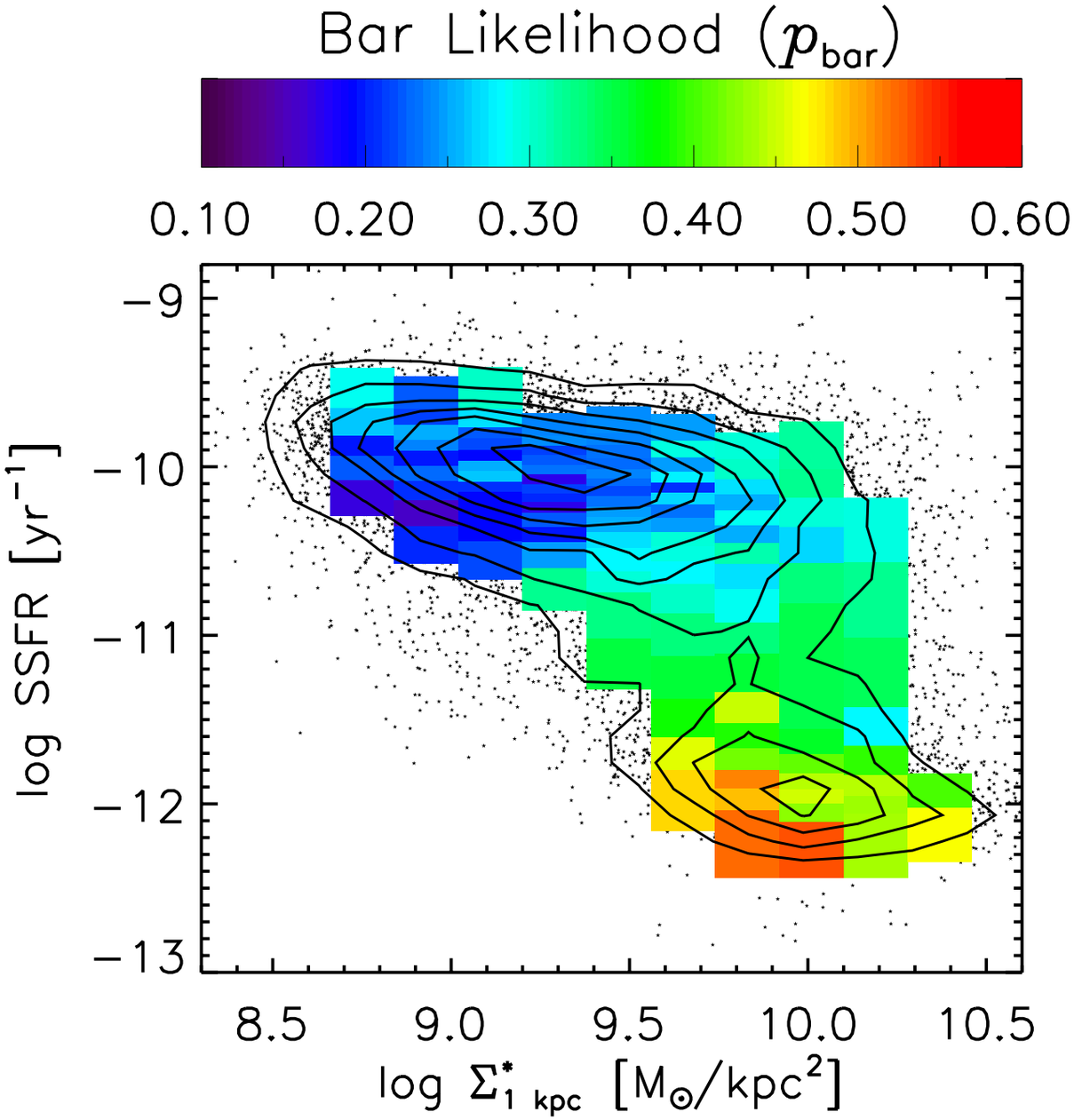


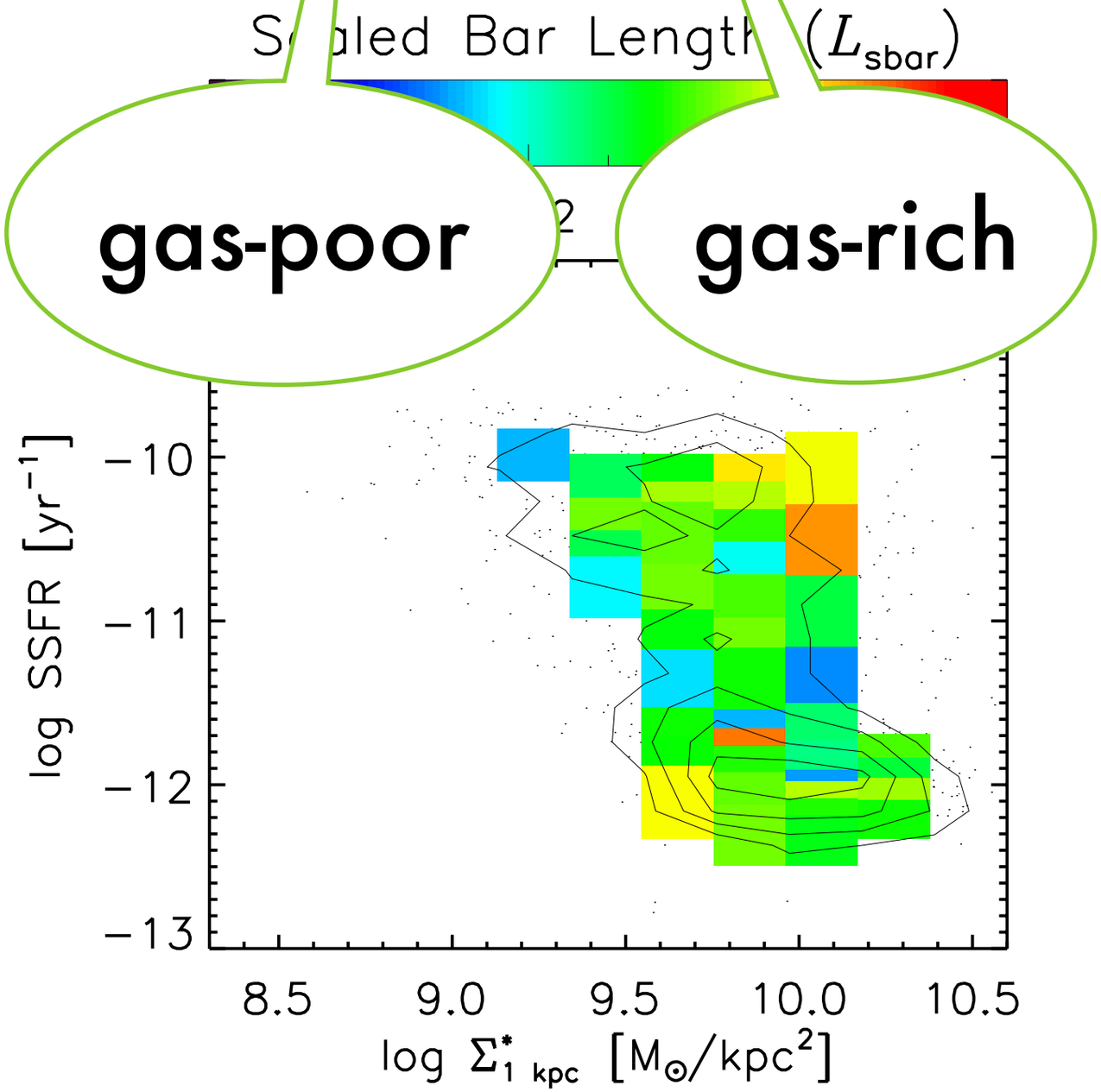
Evide ution

Cheung et c

Consistent with effects of gas on bar formation





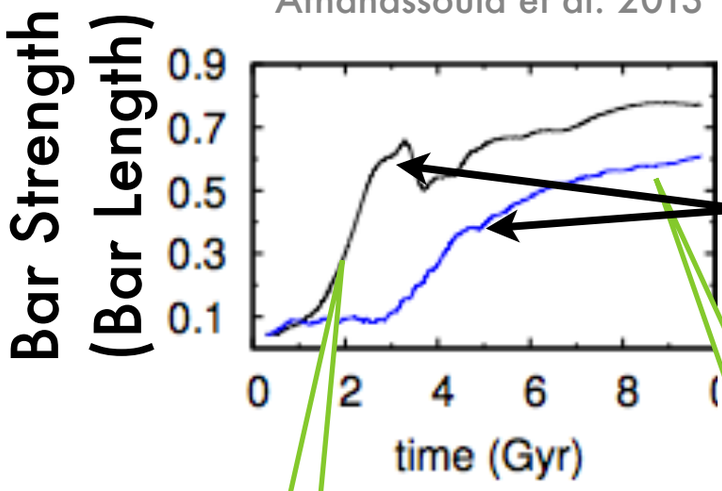


Evide

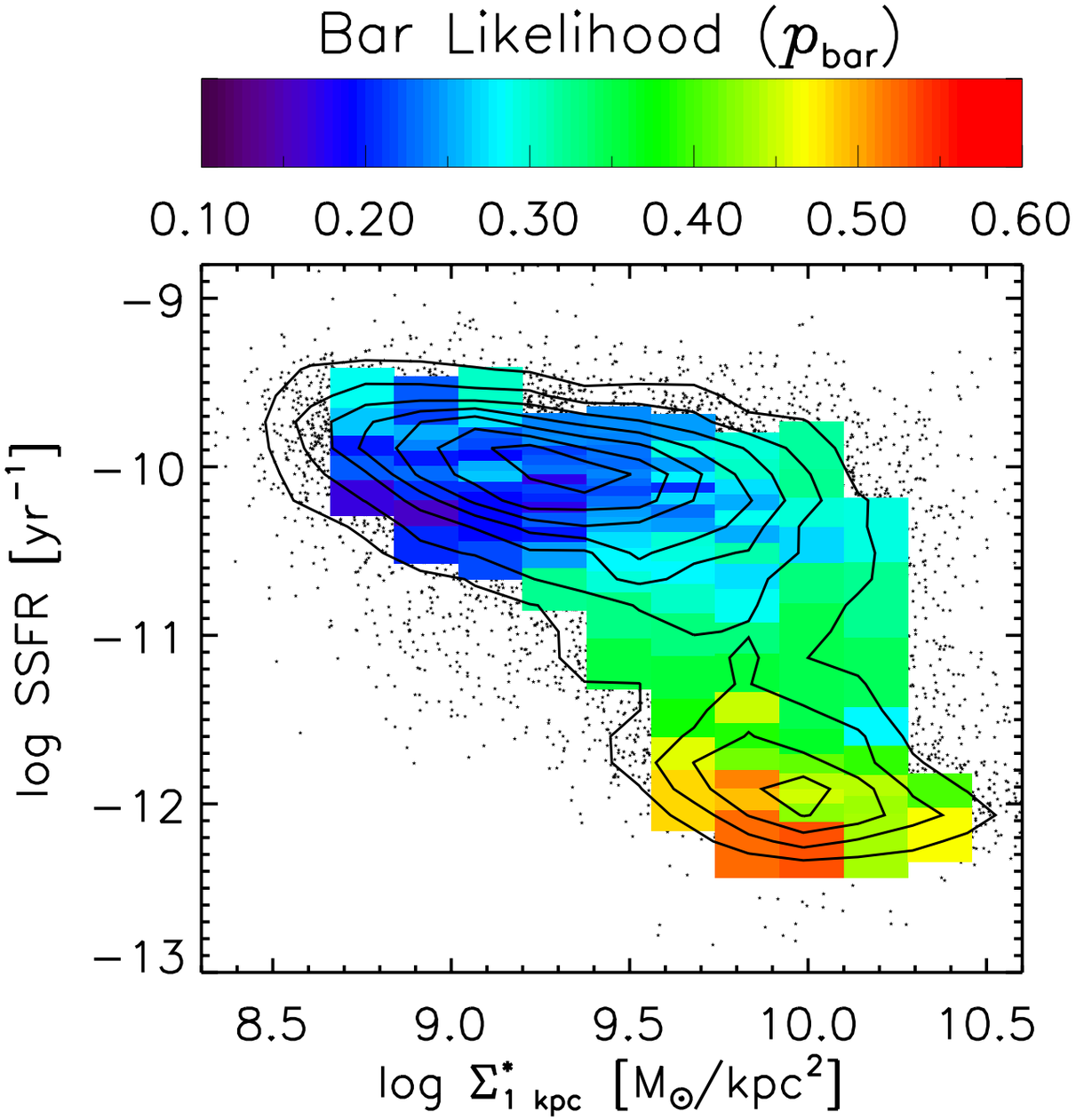
Cheung et c

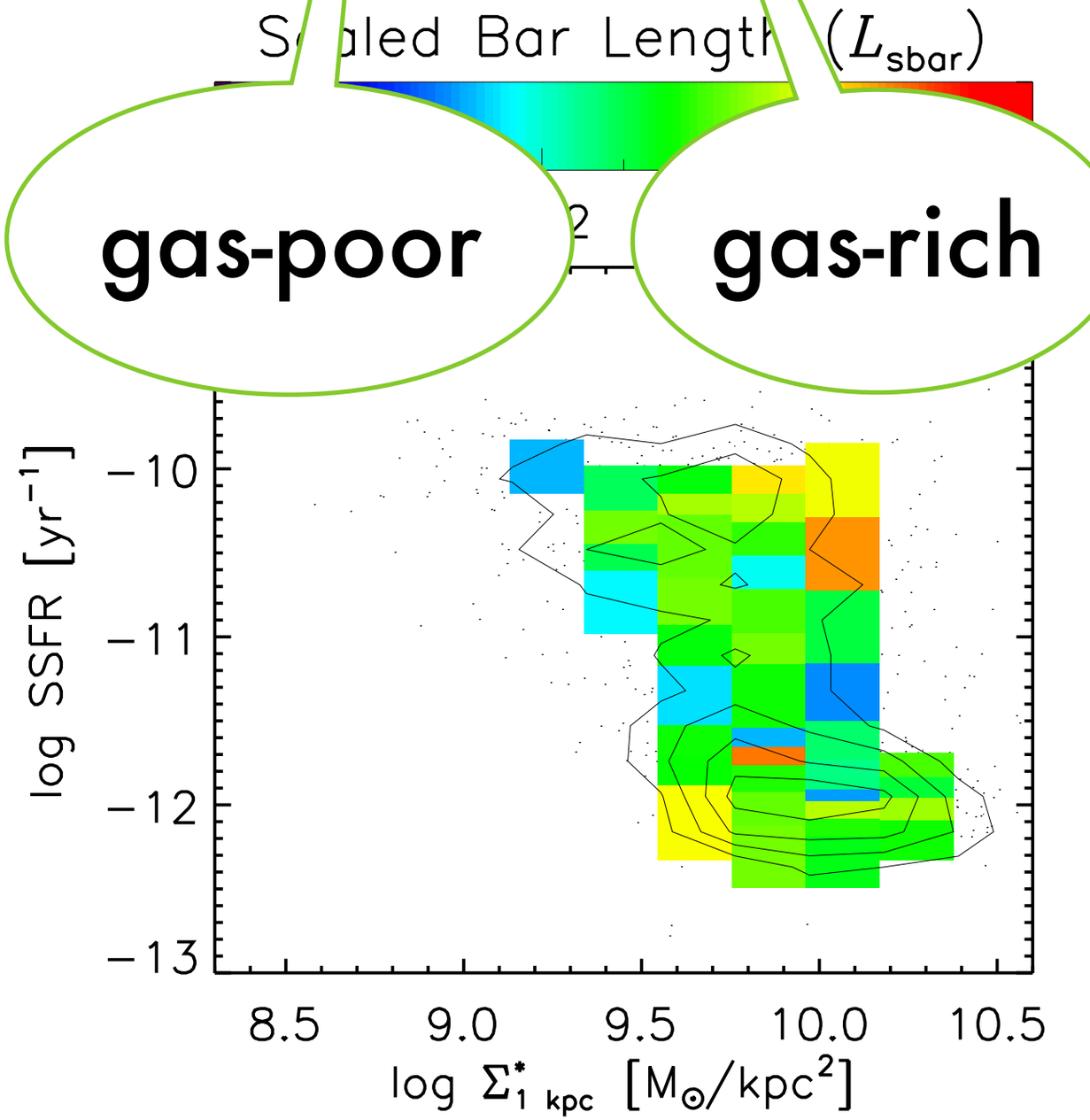
Consistent with effects of gas on bar formation

Athanassoula et al. 2013



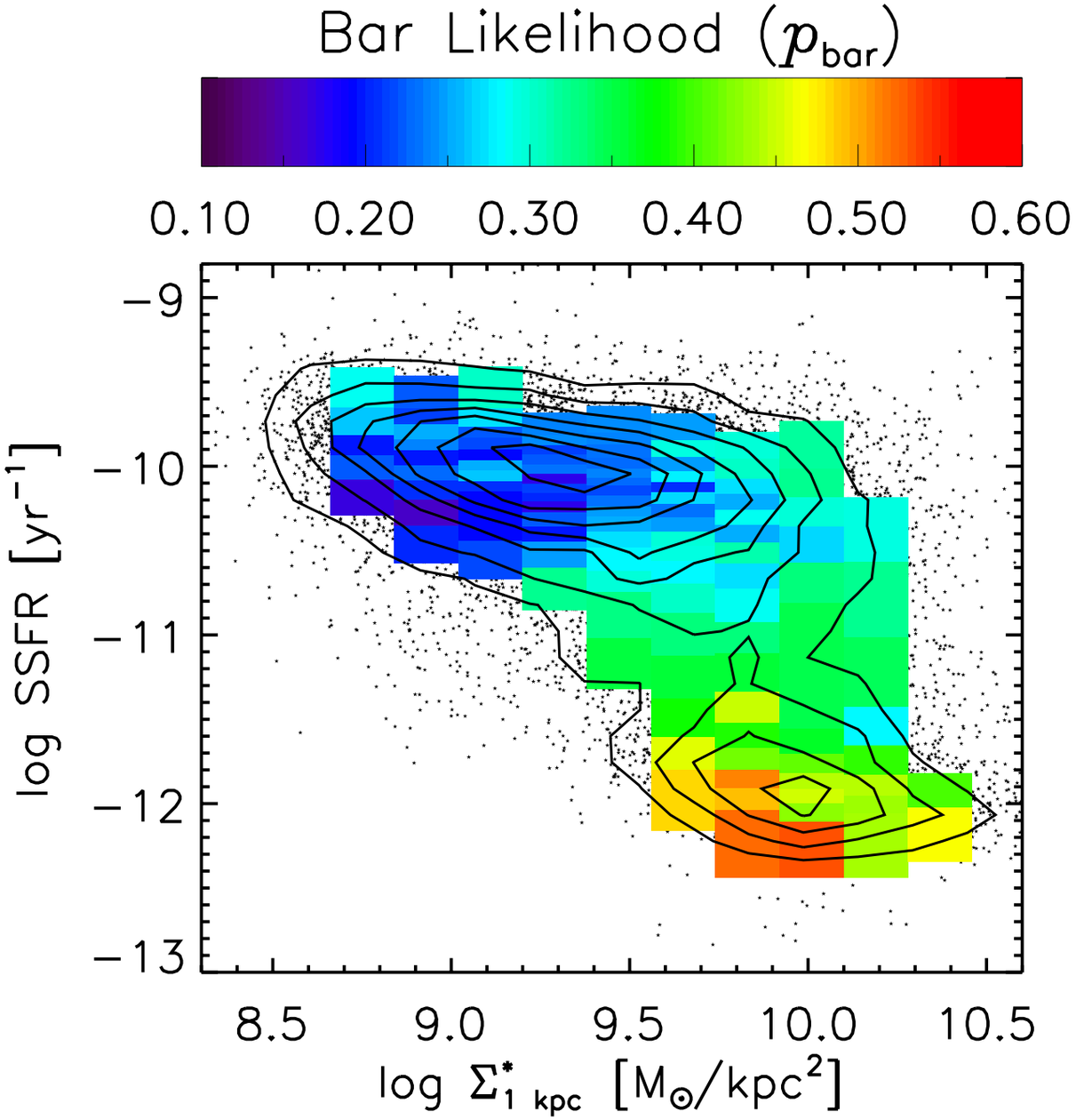
Bar forms





Evidence of secular evolution

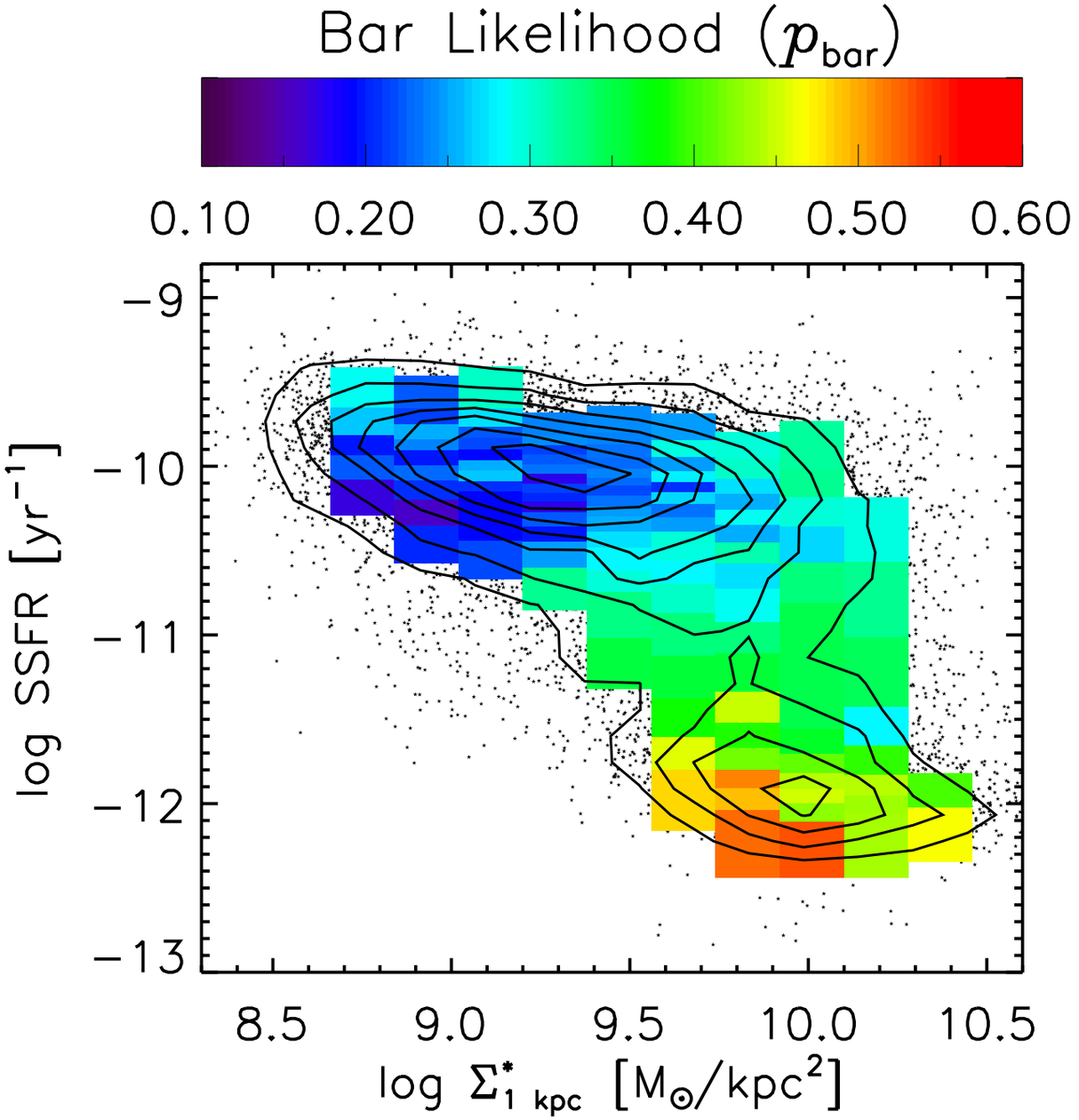
Cheung et al. 2013



- p_{bar} is strongly anti-correlated with SSFR
- due to bar formation

Evidence of secular evolution

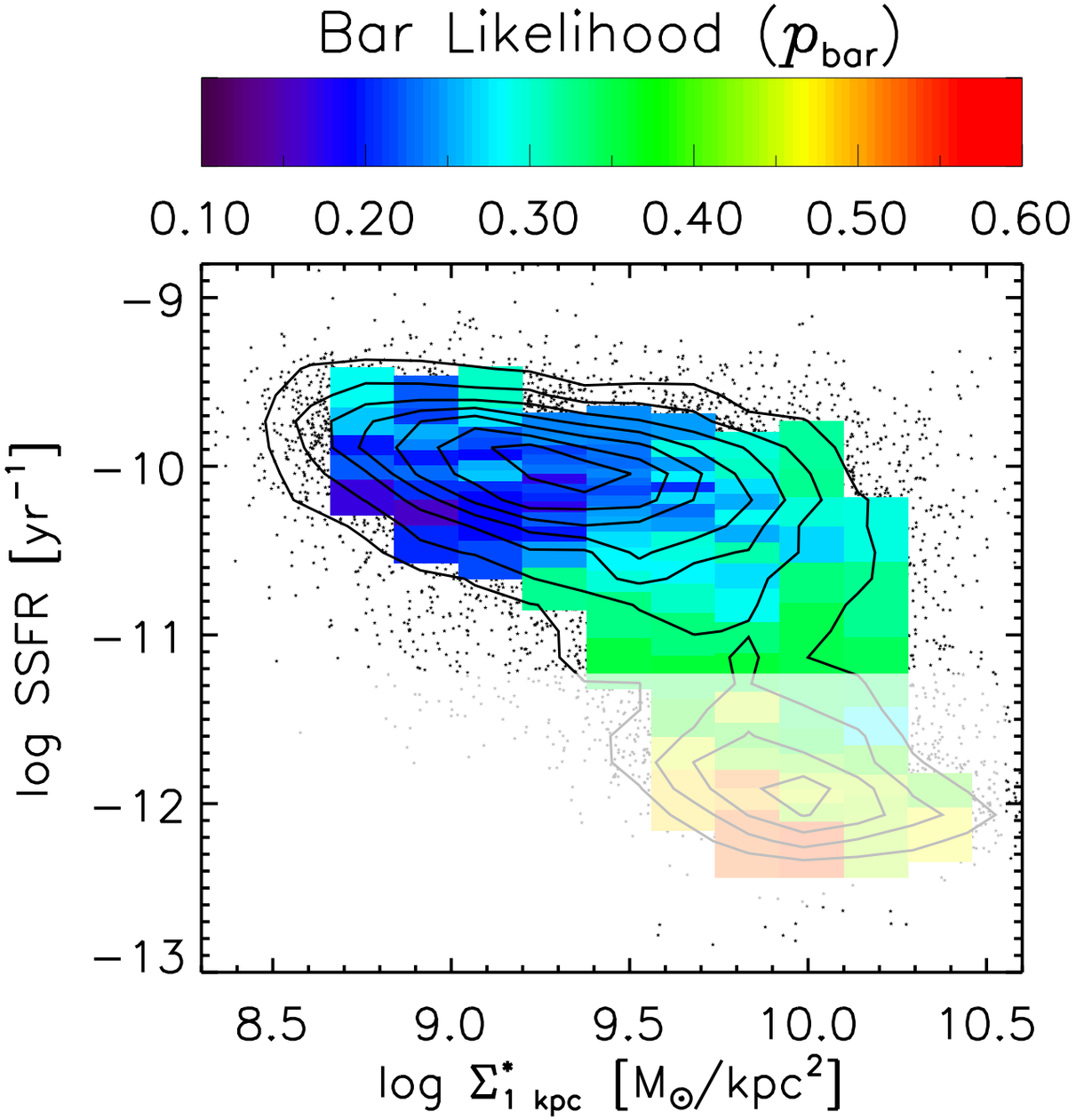
Cheung et al. 2013



- p_{bar} is strongly anti-correlated with SSFR
  - due to bar formation
- The correlations between p_{bar} and $\Sigma_{1\ kpc}{}^*$ is bimodal

Evidence of secular evolution

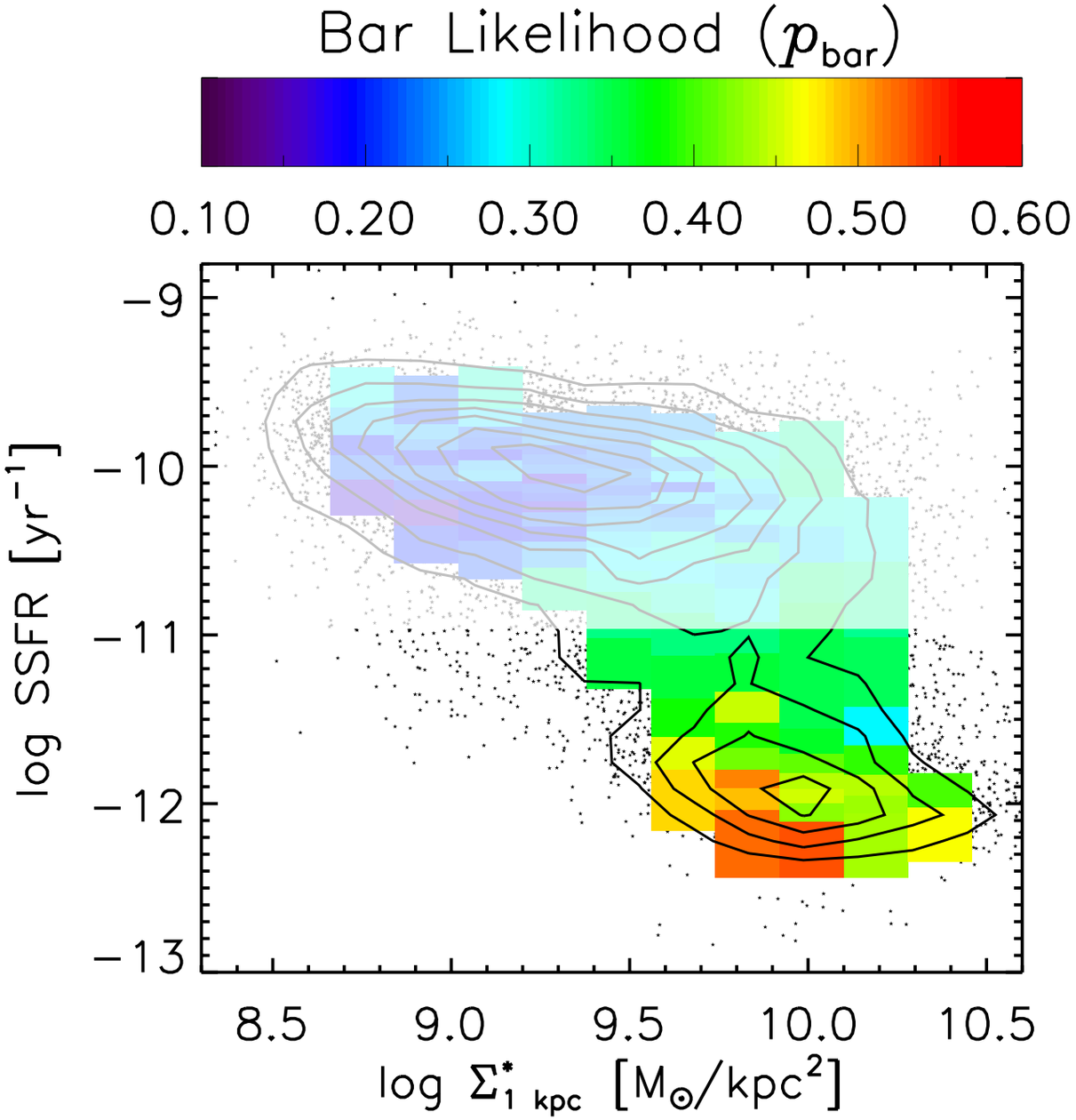
Cheung et al. 2013



- p_{bar} is strongly anti-correlated with SSFR
  - due to bar formation
- The correlations between p_{bar} and $\Sigma_{1\ kpc}{}^*$ is bimodal

Evidence of secular evolution

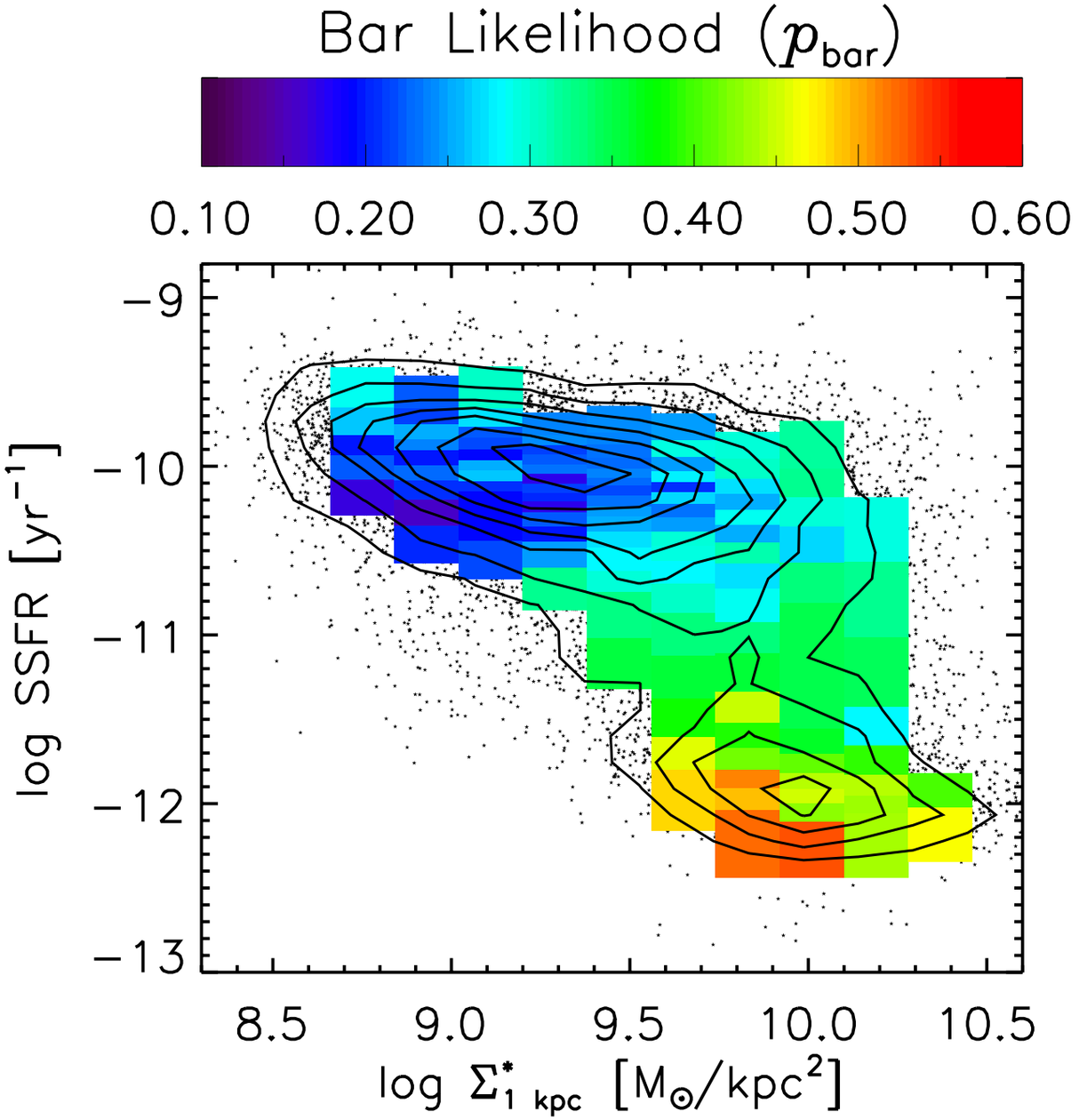
Cheung et al. 2013



- p_{bar} is strongly anti-correlated with SSFR
  - due to bar formation
- The correlations between p_{bar} and $\Sigma_{1\ kpc}{}^*$ is bimodal

Evidence of secular evolution

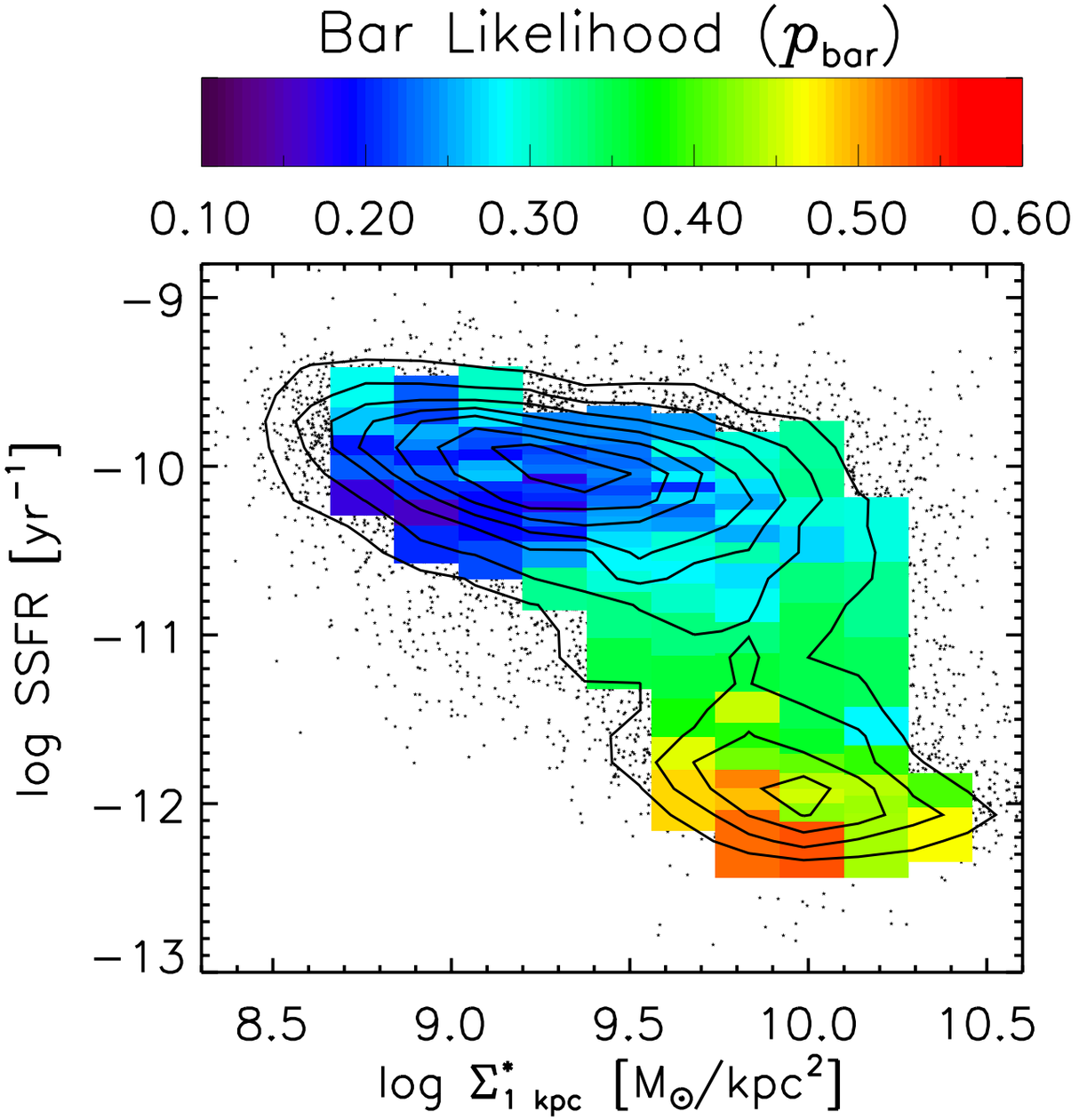
Cheung et al. 2013



- p_{bar} is strongly anti-correlated with SSFR
  - due to bar formation
- The correlations between p_{bar} and $\Sigma_{1\ kpc}{}^*$ is bimodal

Evidence of secular evolution

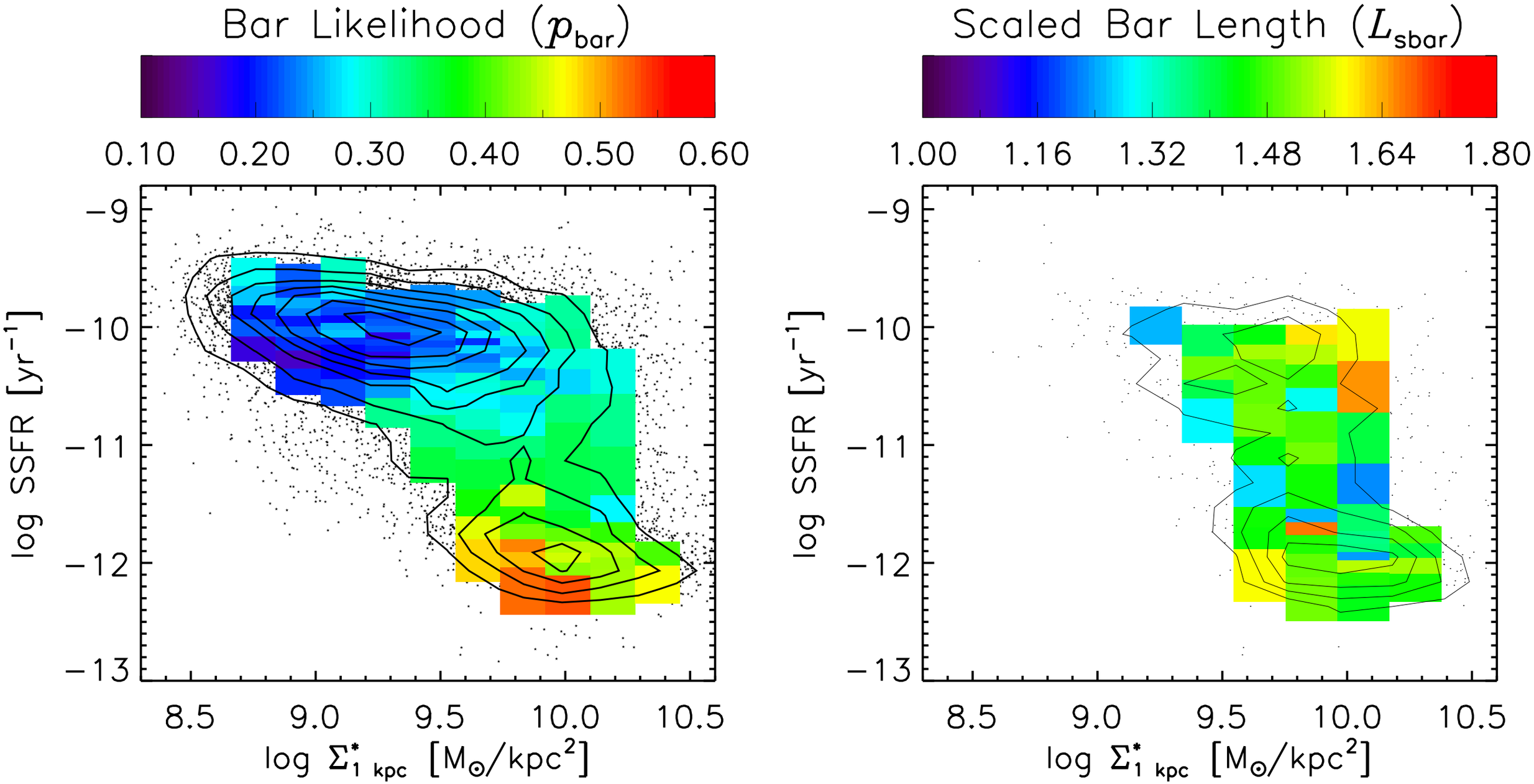
Cheung et al. 2013



- p_{bar} is strongly anti-correlated with SSFR
  - due to bar formation
- The correlations between p_{bar} and $\Sigma_{1\ kpc}{}^*$ is bimodal
  - due to bar evolution

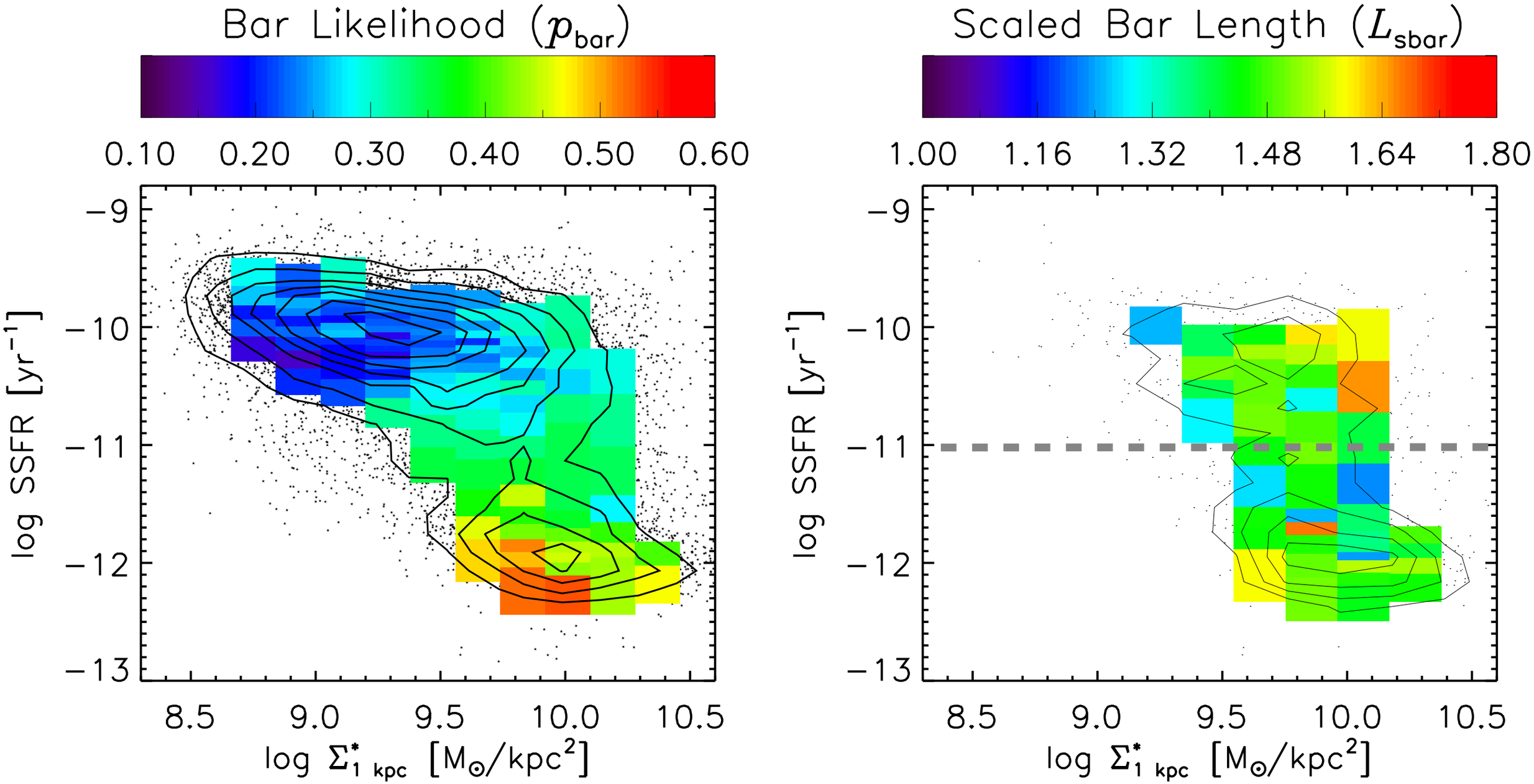
Evidence of secular evolution

Cheung et al. 2013



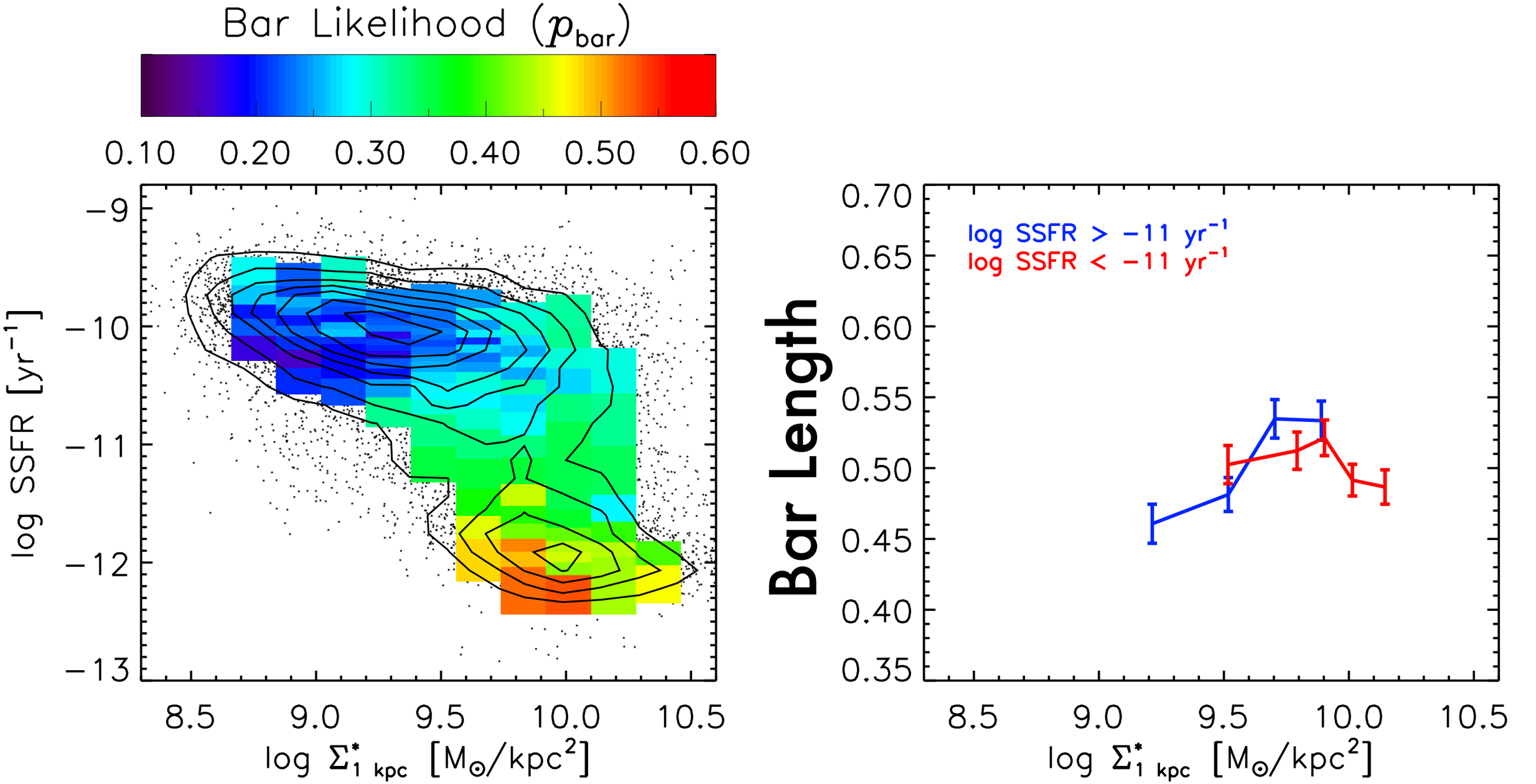
Evidence of secular evolution

Cheung et al. 2013



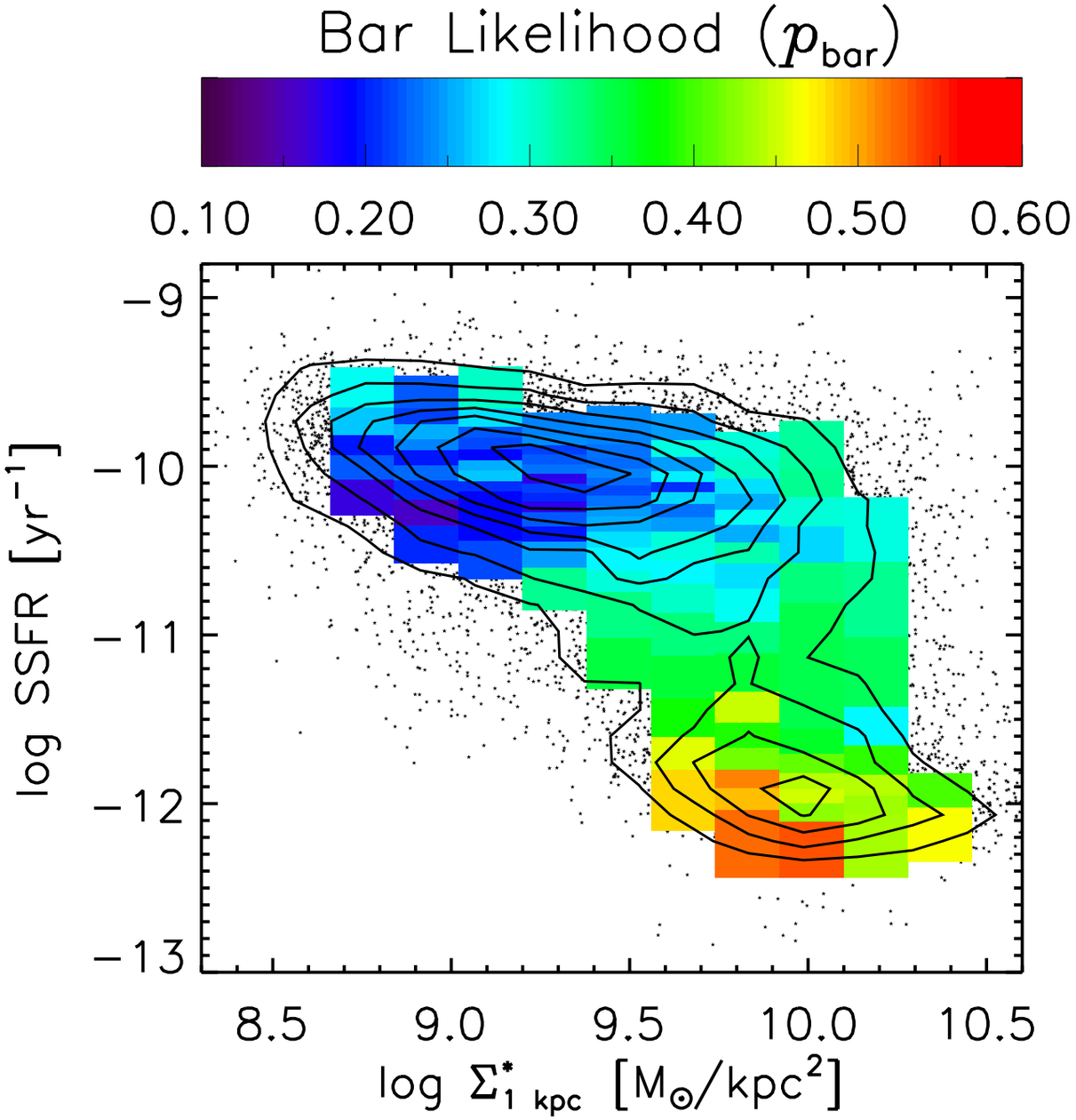
Evidence of secular evolution

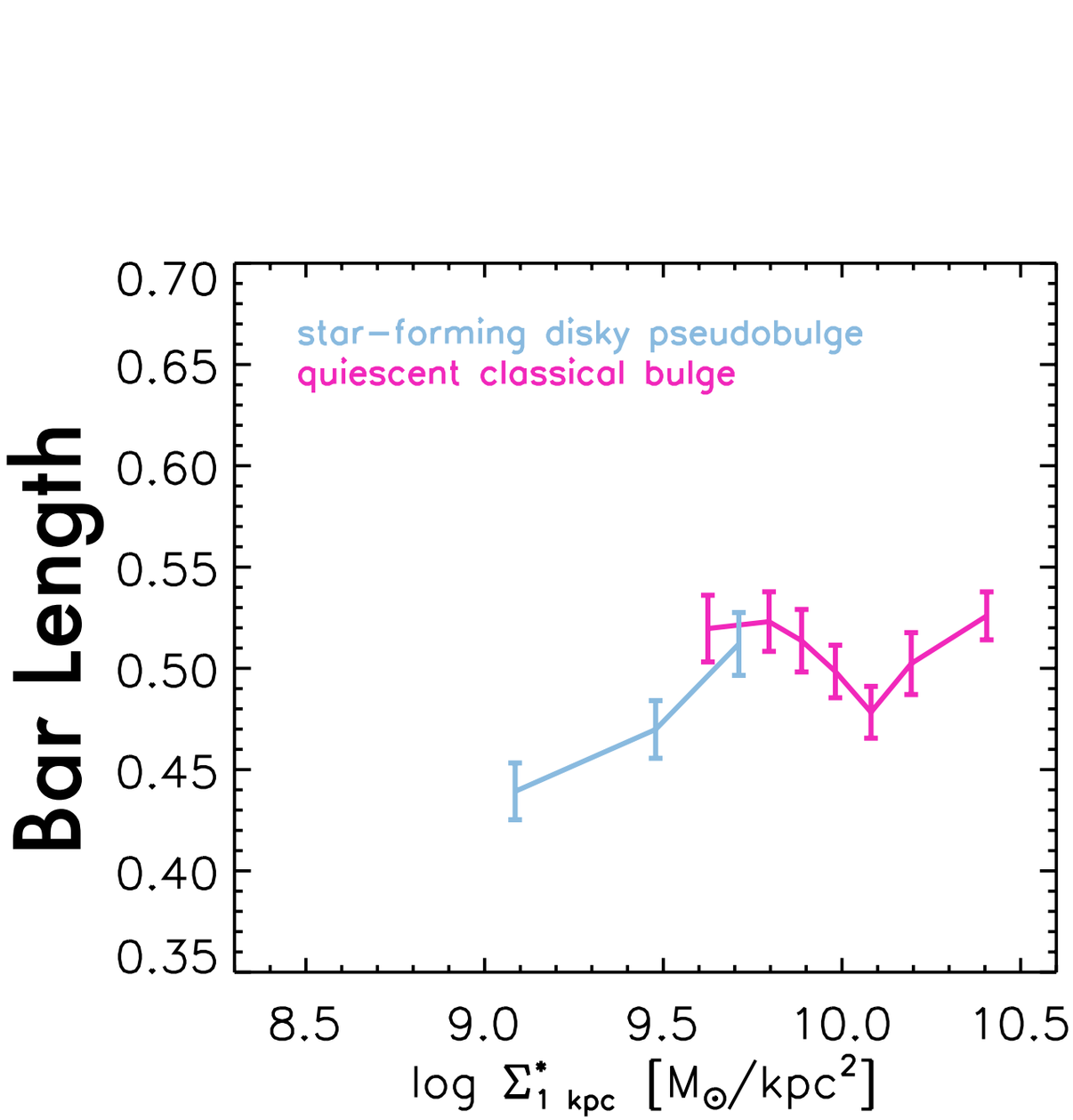
Cheung et al. 2013



Evidence of secular evolution

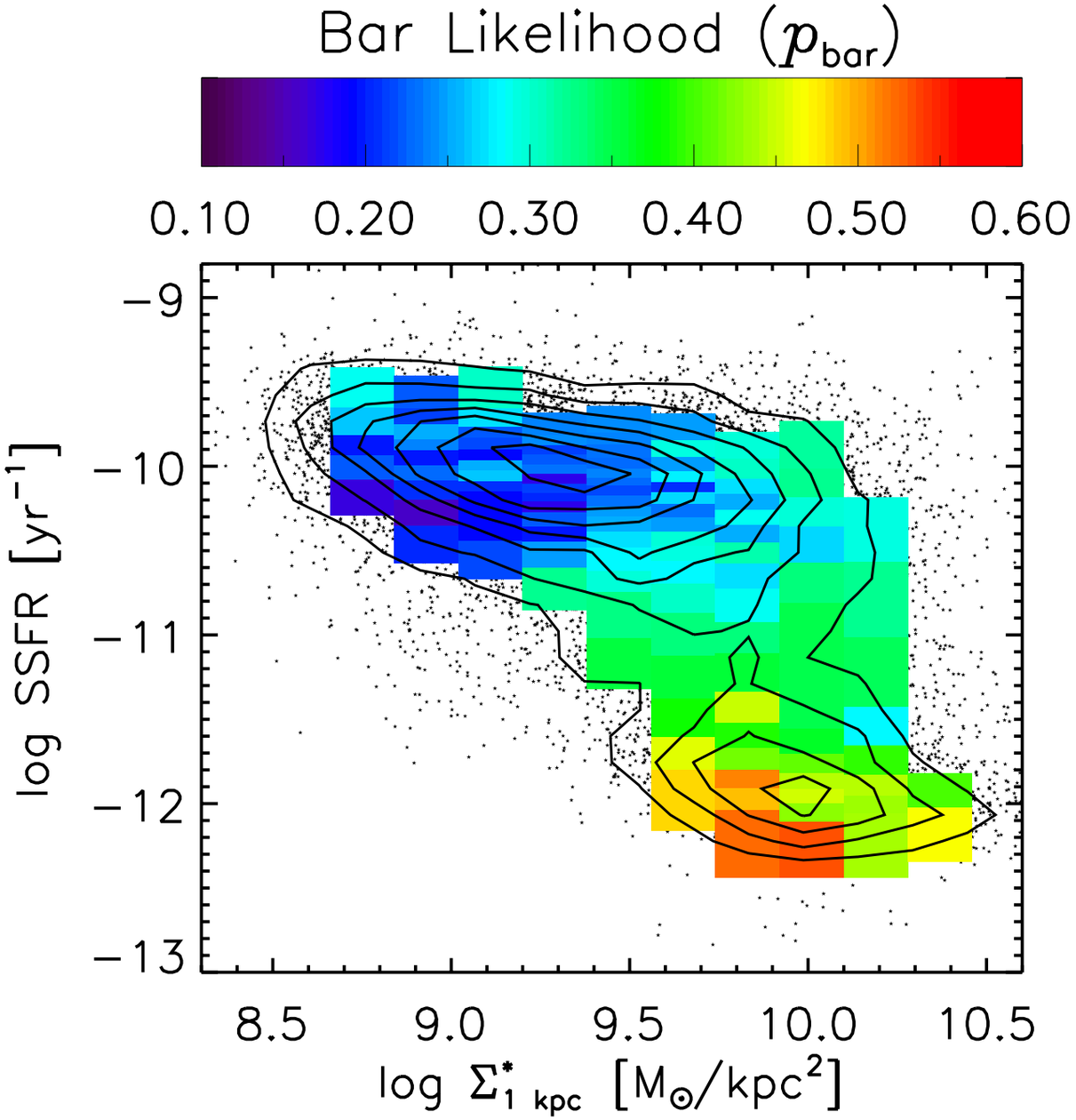
Cheung et al. 2013

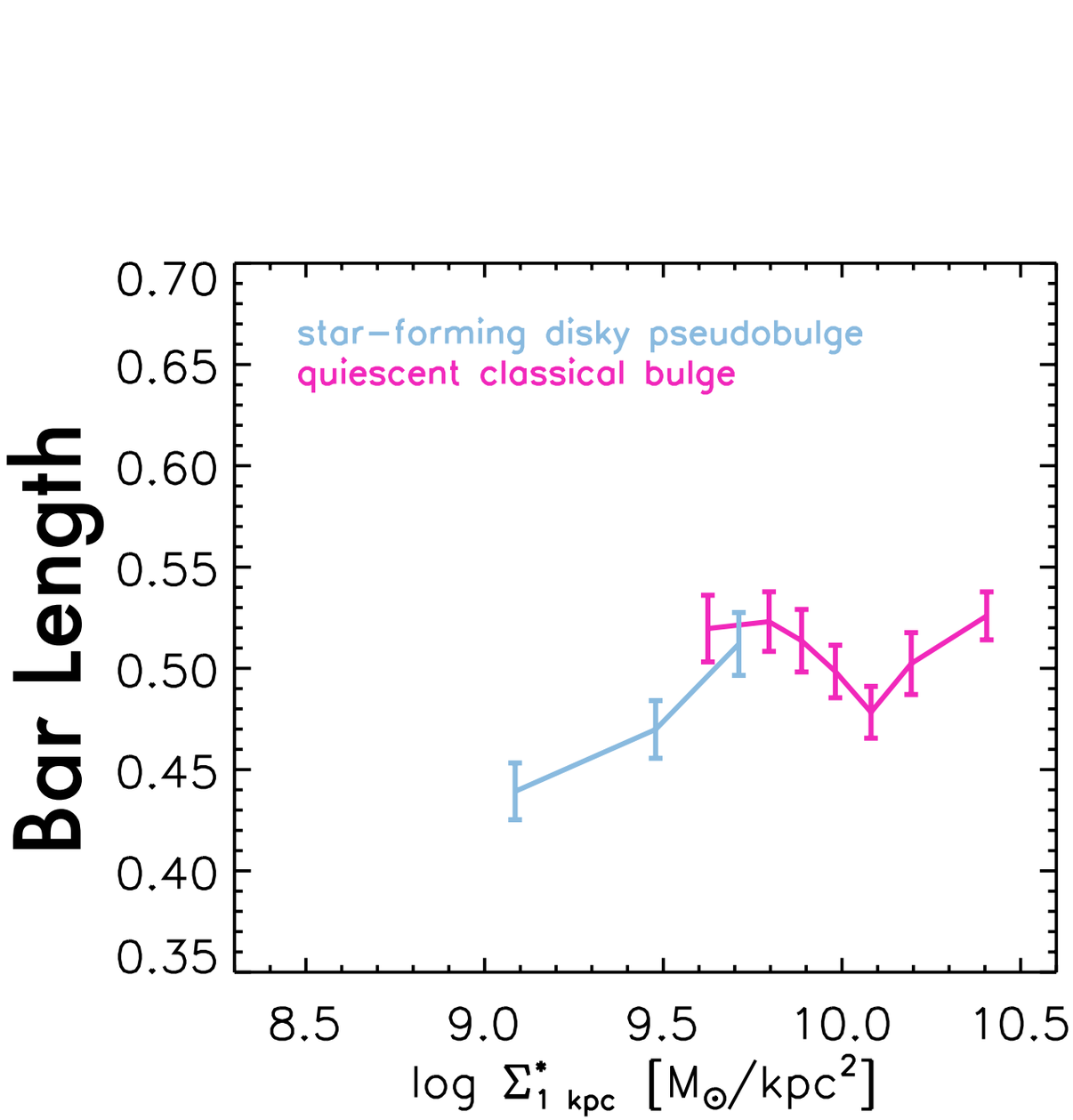




Evidence of secular evolution

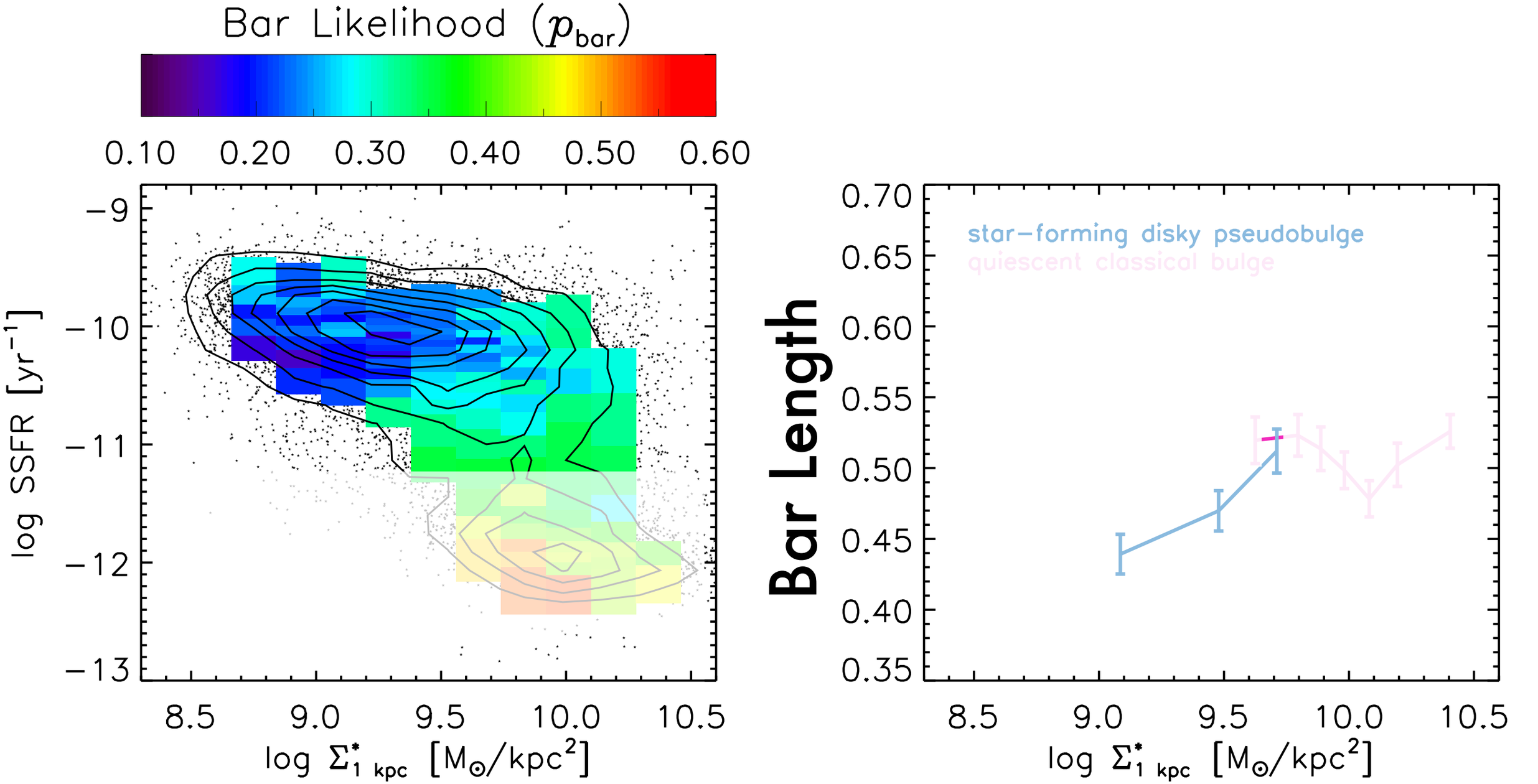
Cheung et al. 2013





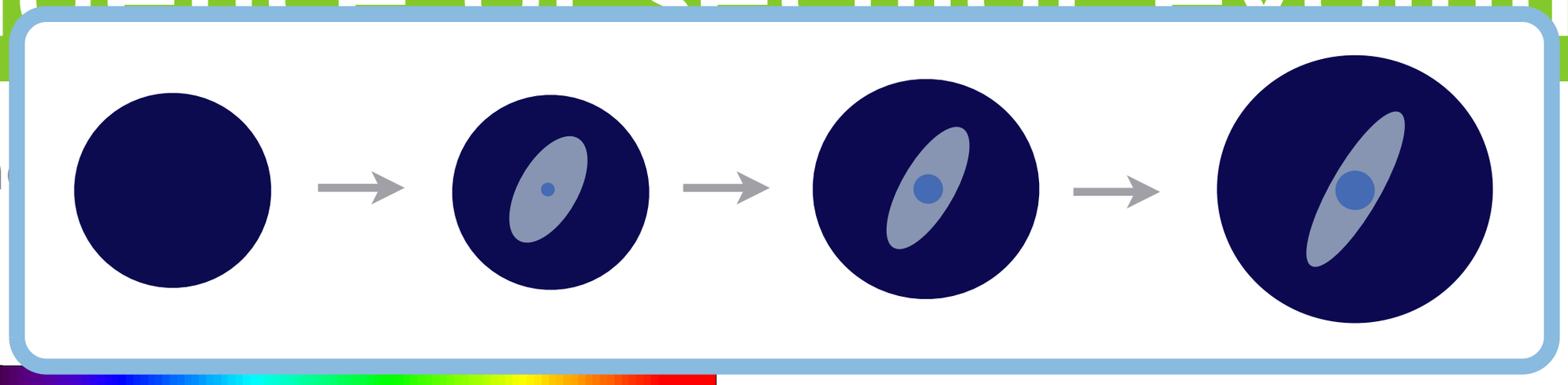
Evidence of secular evolution

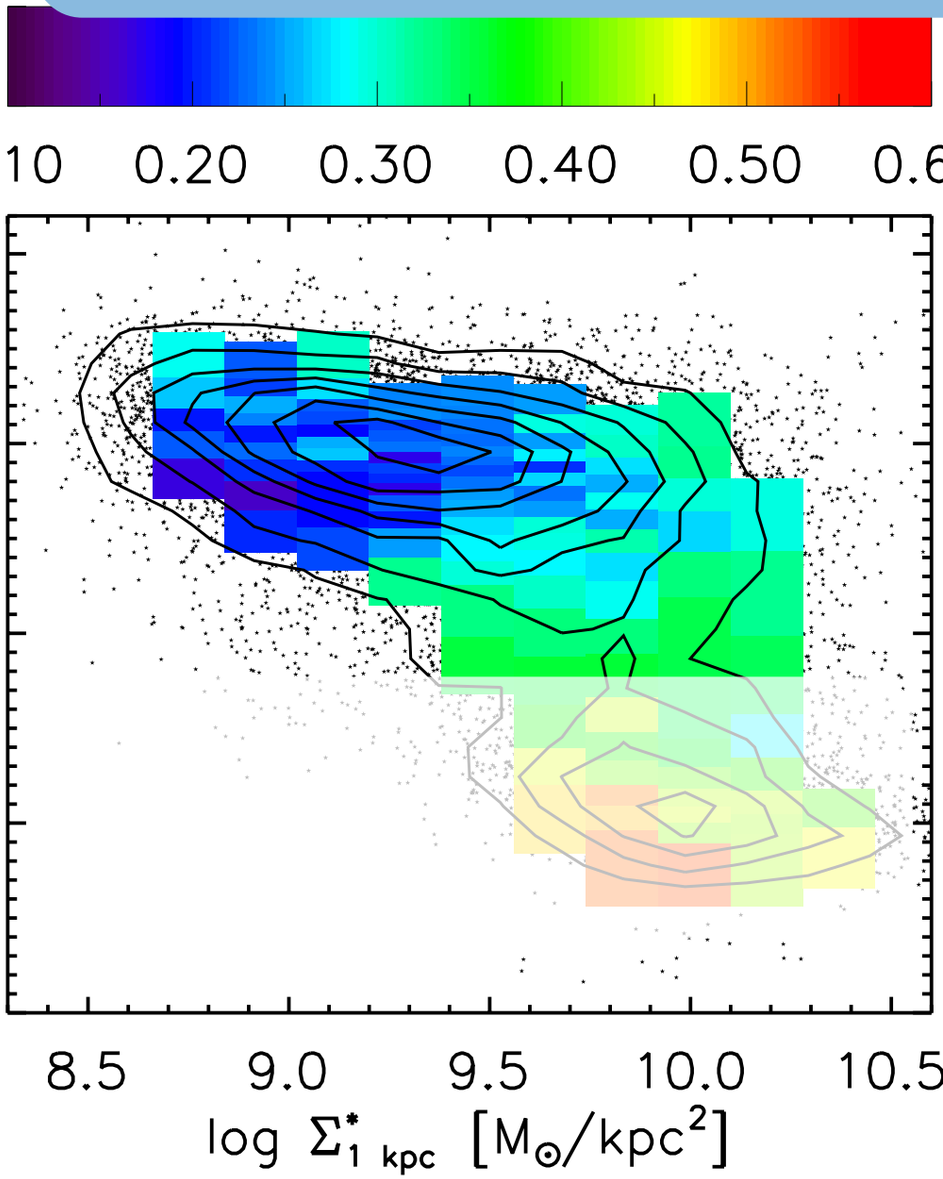
Cheung et al. 2013

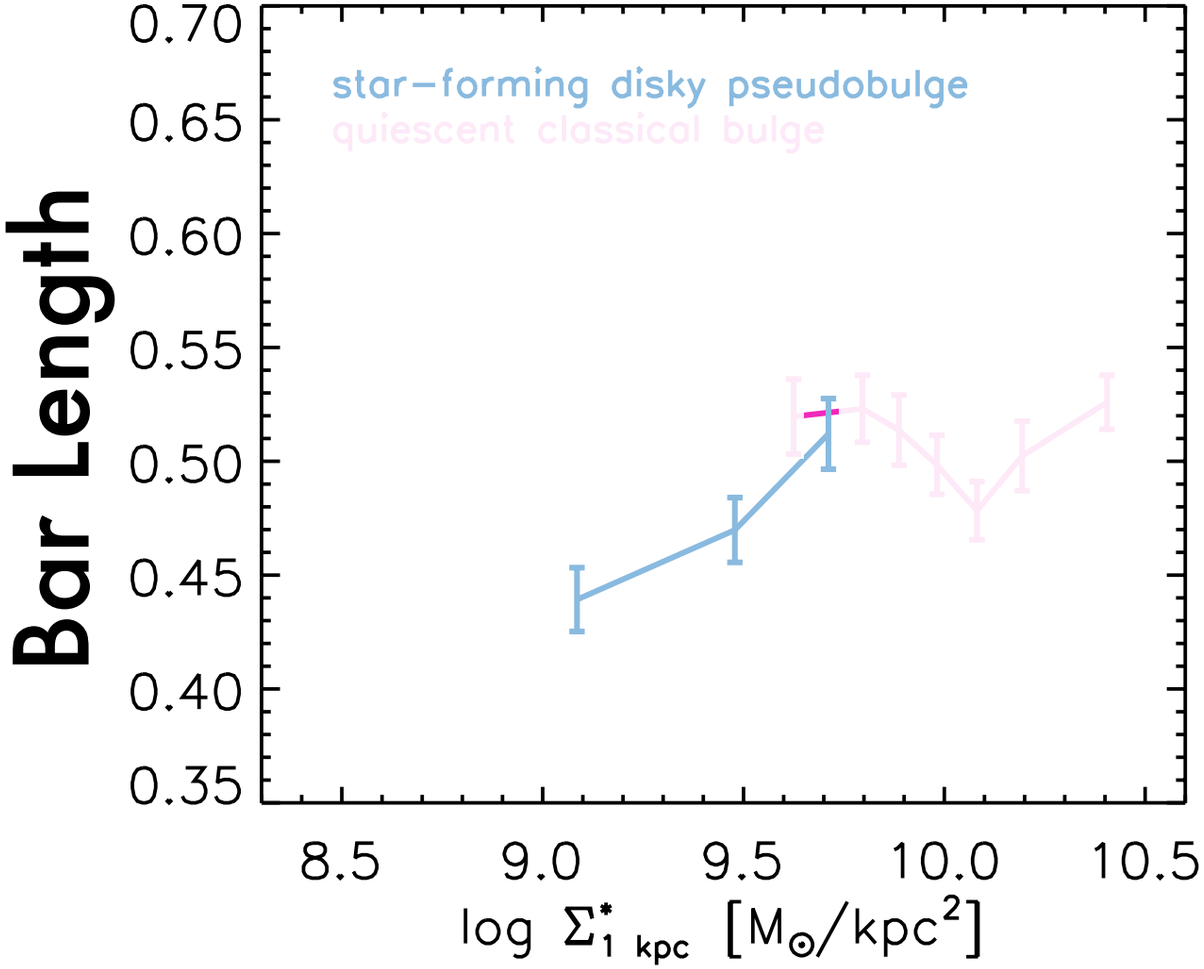


Evidence of secular evolution

Cheun

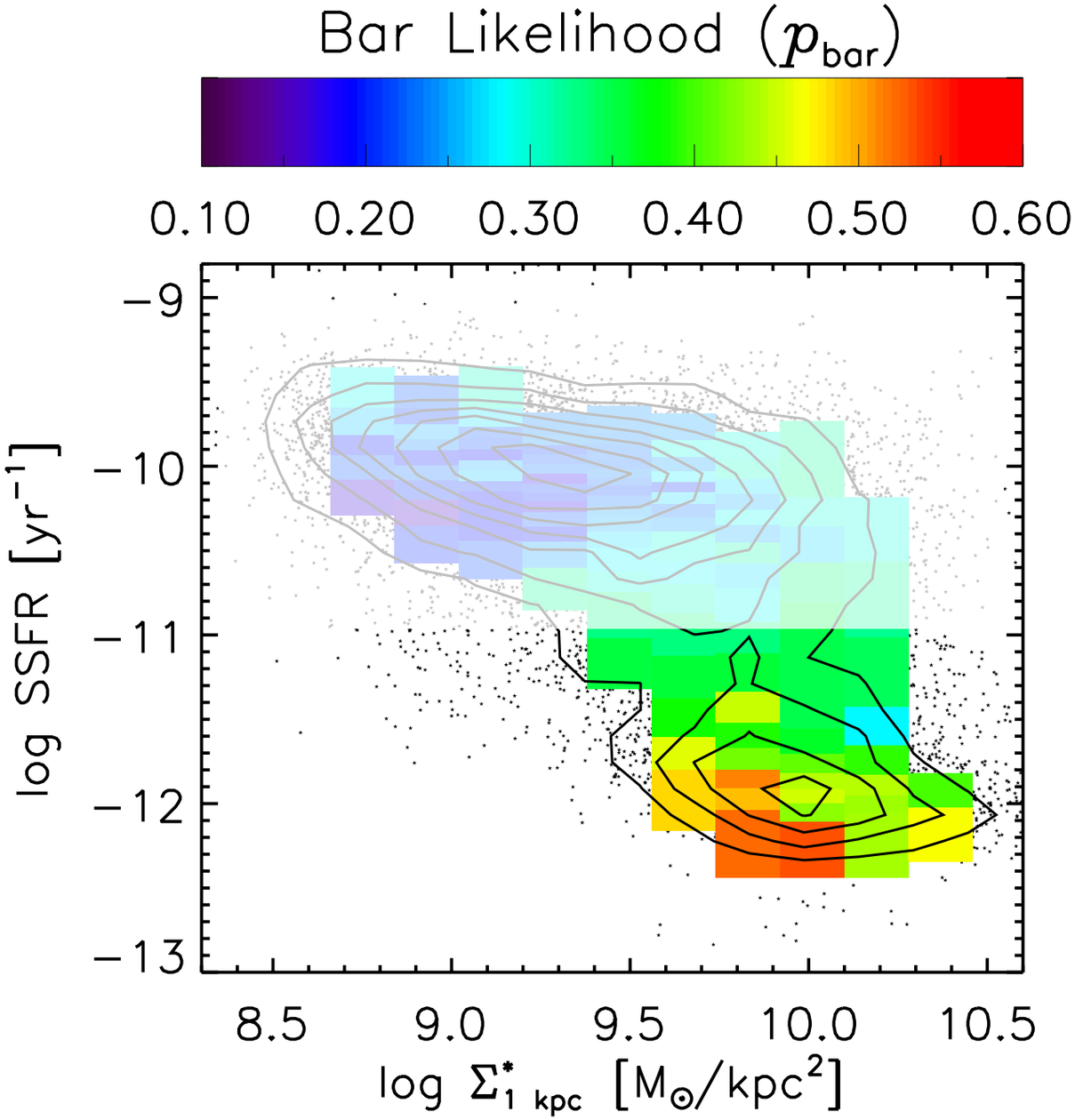


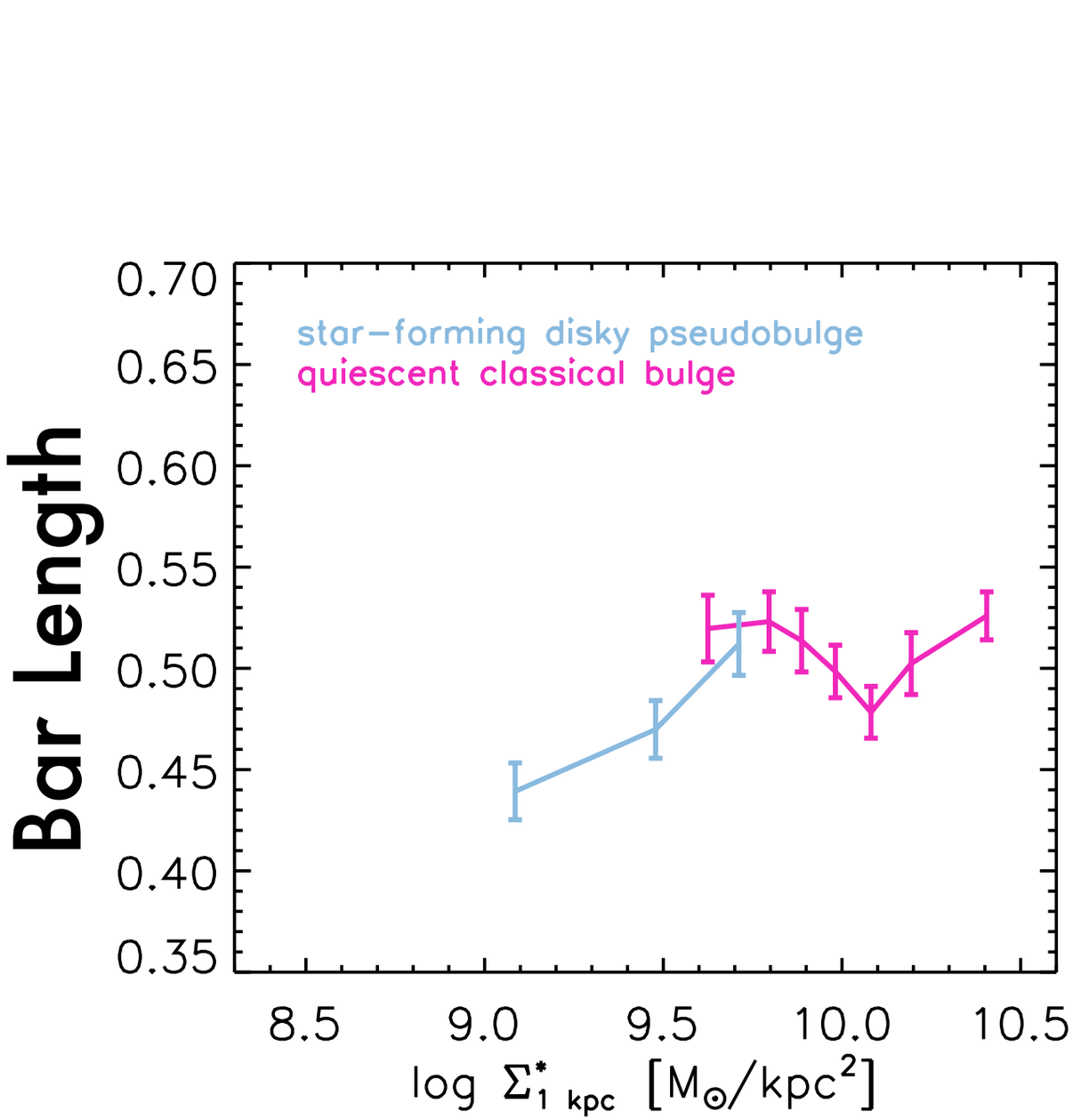




Evidence of secular evolution

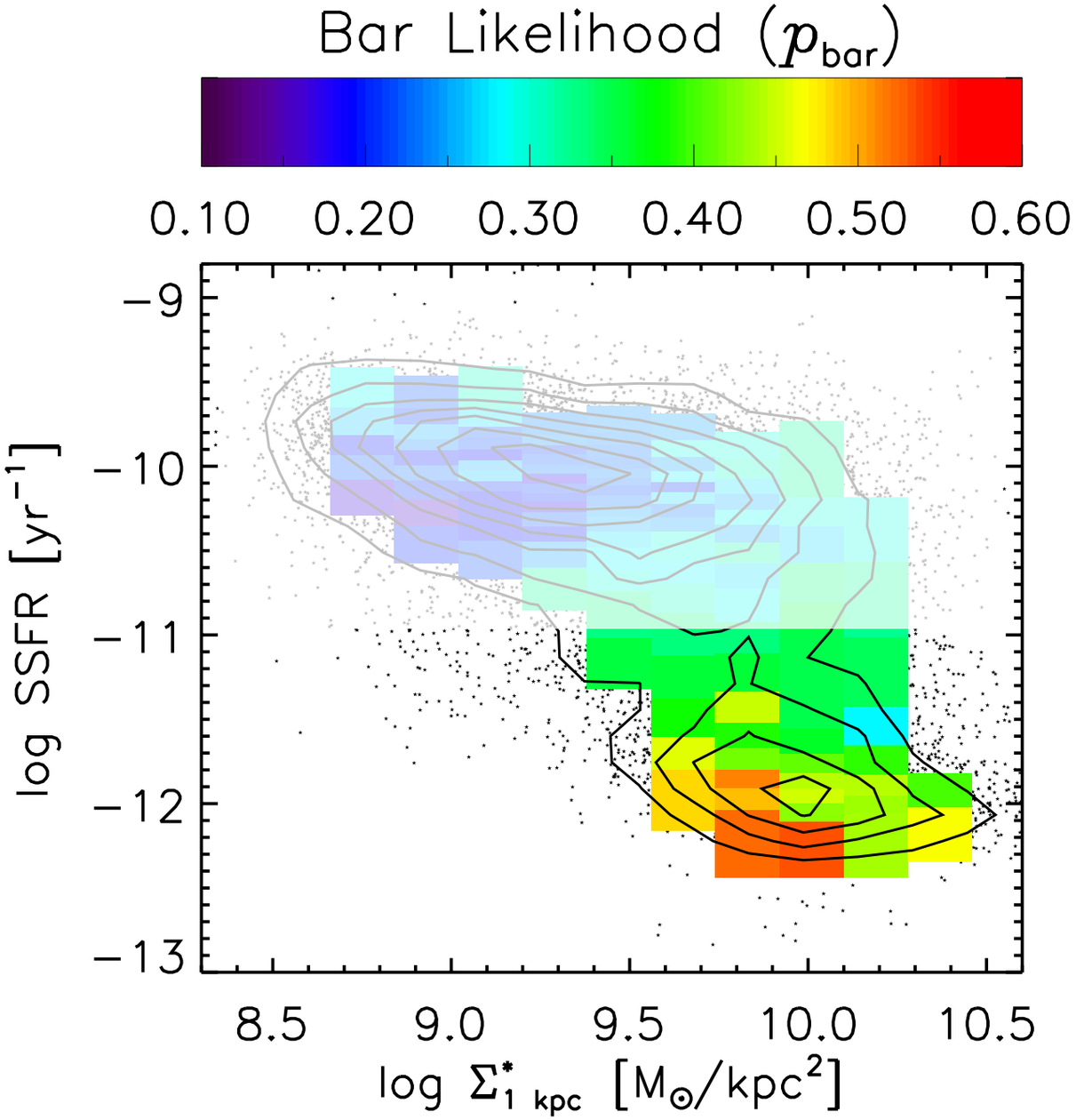
Cheung et al. 2013

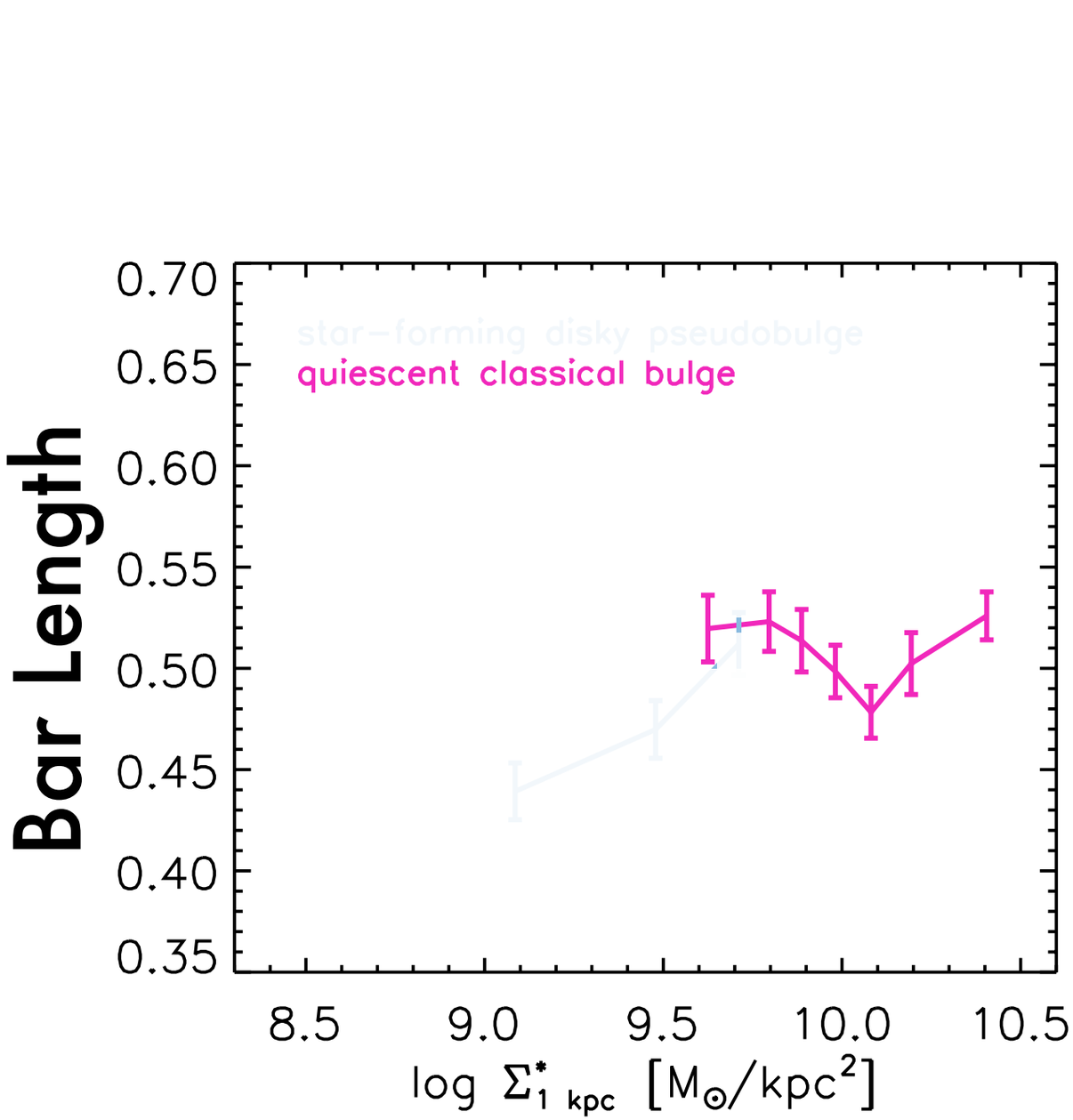




Evidence of secular evolution

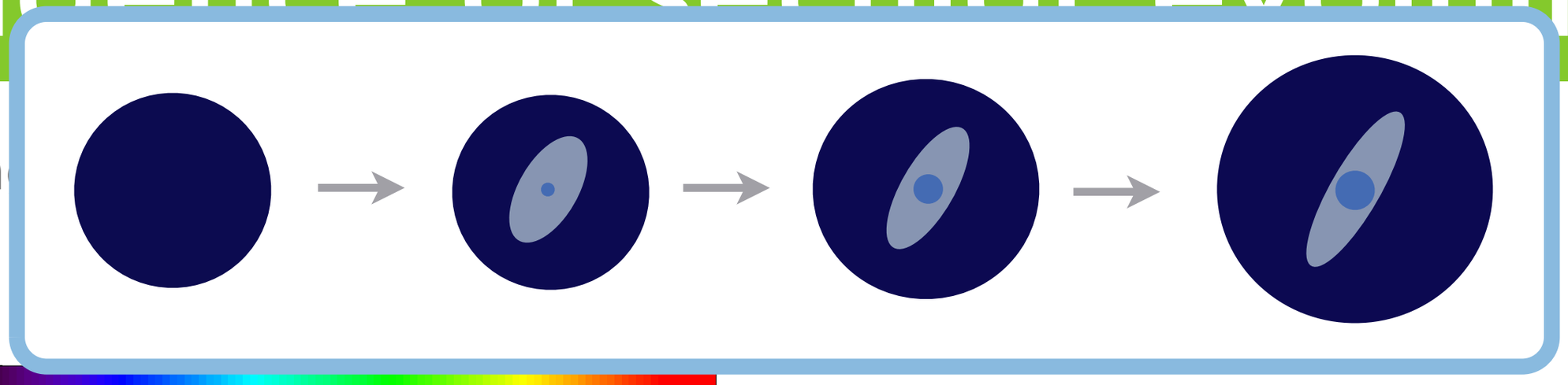
Cheung et al. 2013

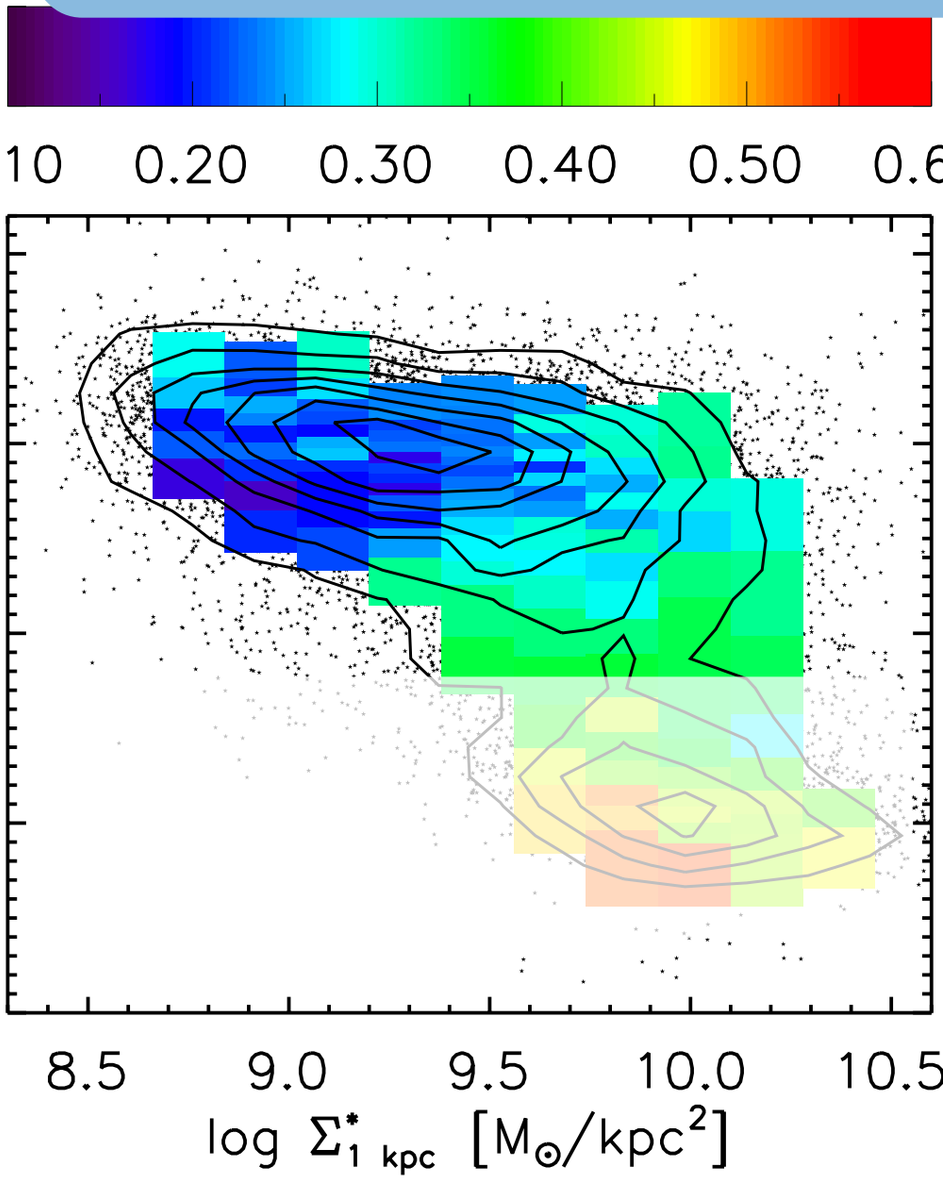


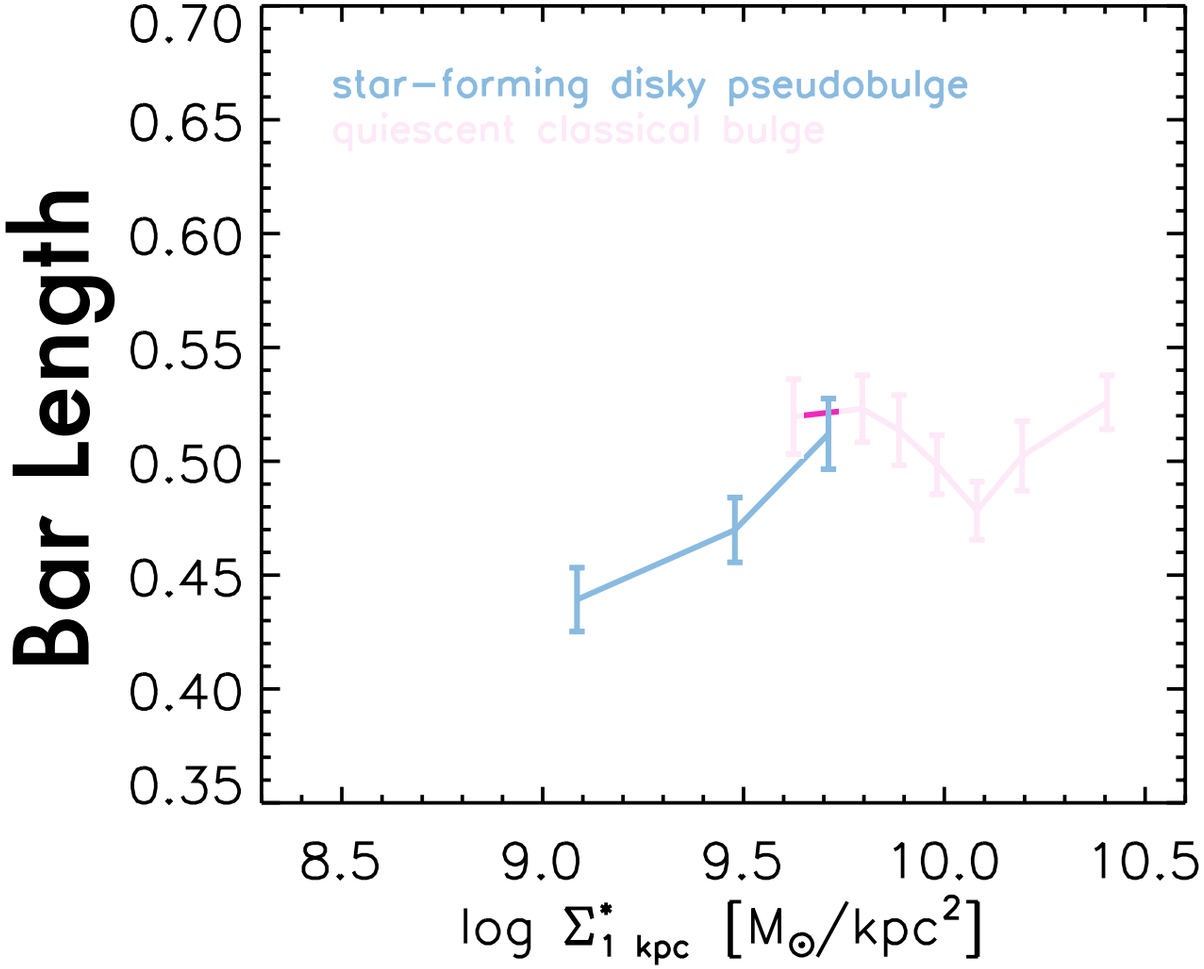


Evidence of secular evolution

Cheun







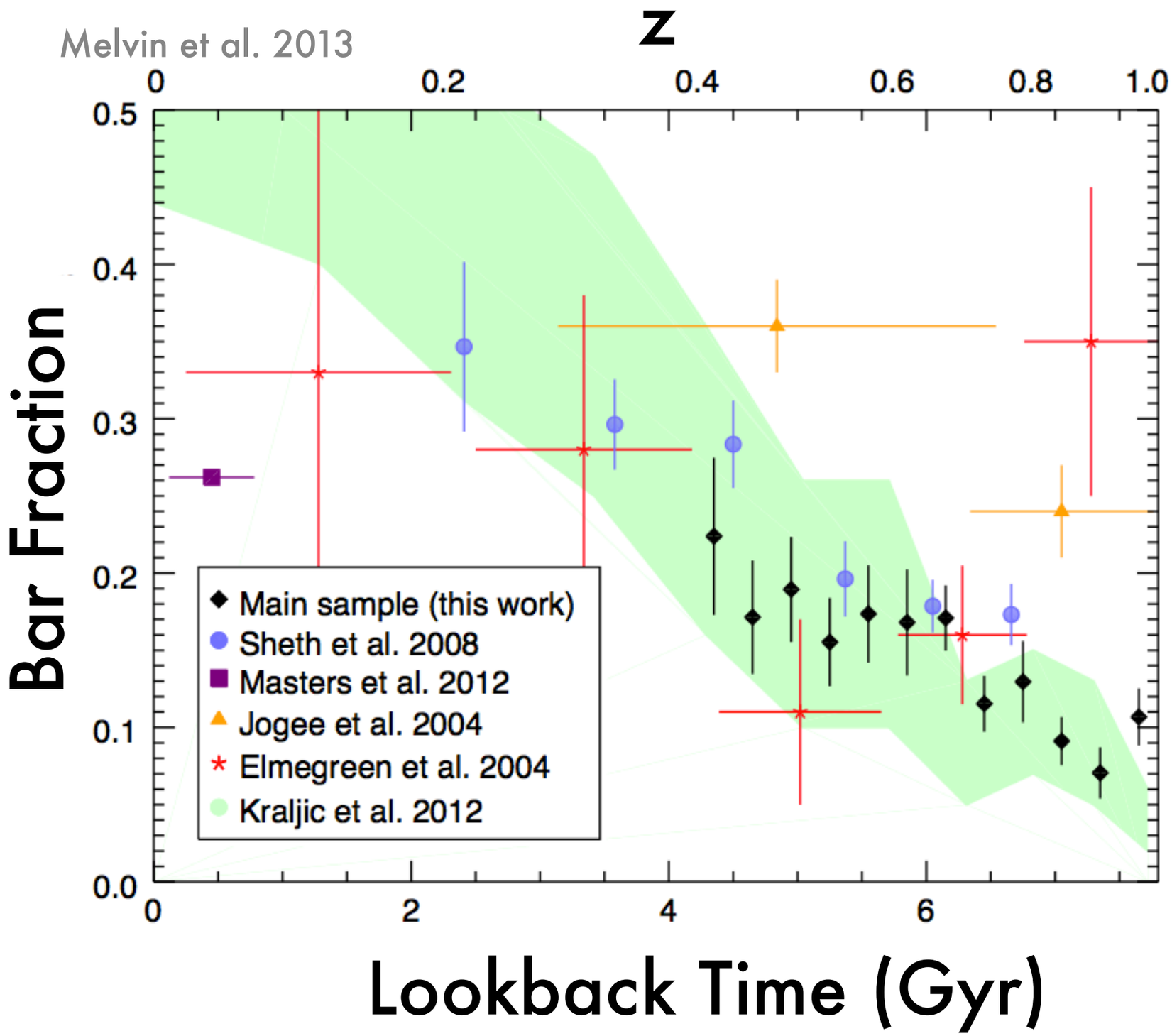
Are we observing secular evolution?

Are we observing secular evolution?

The Mice • Interacting Galaxies NGC 4676
Hubble Space Telescope • Advanced Camera for Surveys

NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI) and the ACS Science Team • STScI-PRC02-11d

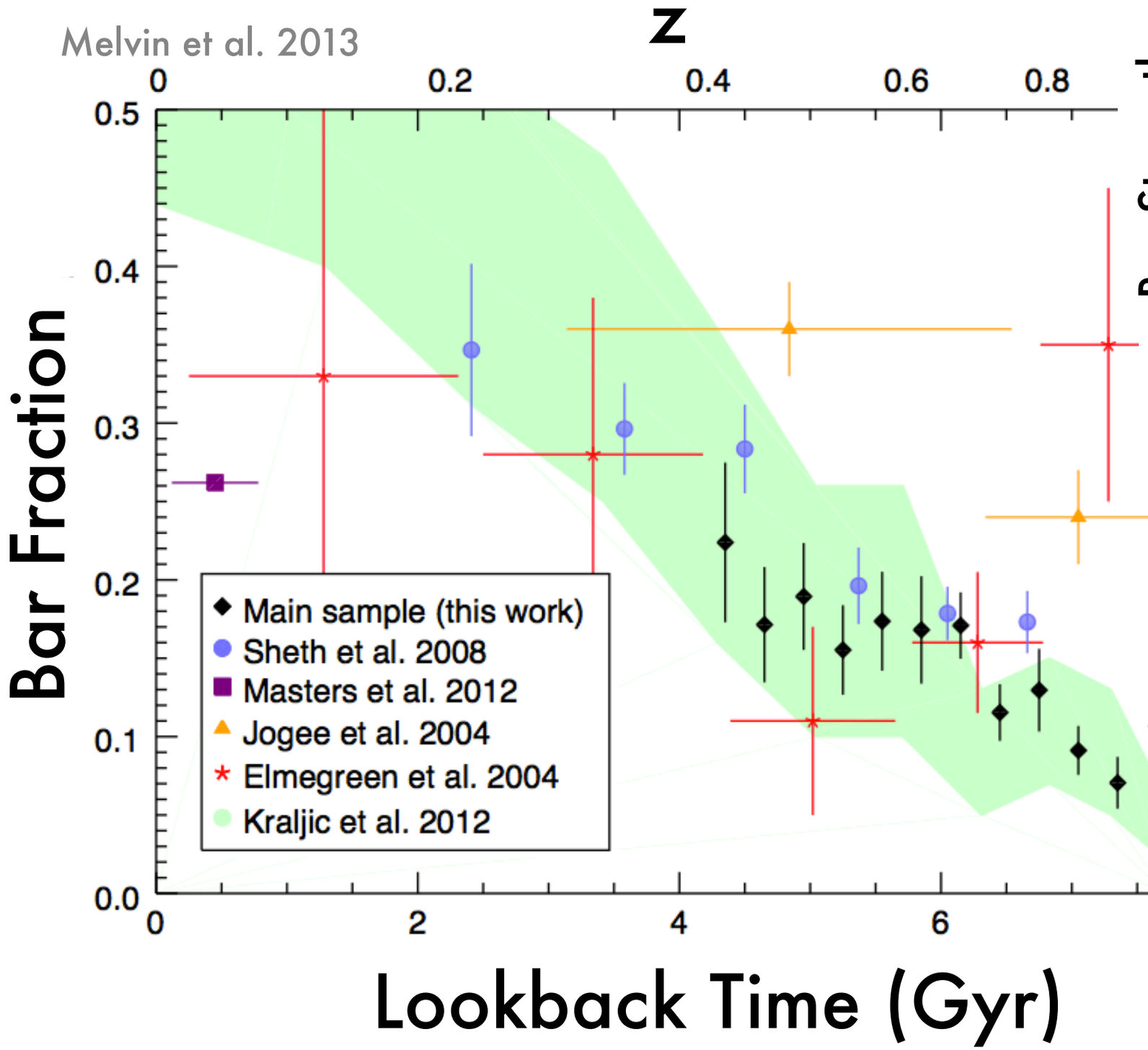
Are we observing secular evolution?



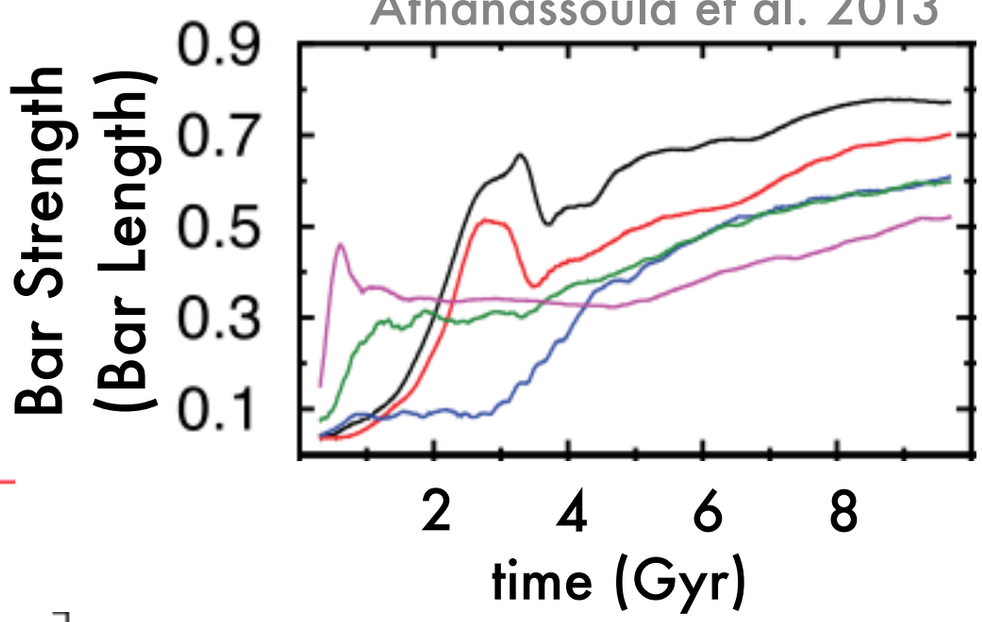
- Observations show bars since z~1

Are we observing secular evolution?

Melvin et al. 2013



Athanassoula et al. 2013



- Observations show bars since z~1
- Theory show bars to be long-lived and to grow

Are we observing secular evolution?

- We believe we are `observing' secular evolution

Are we observing secular evolution?

- We believe we are `observing' secular evolution
- Bars are not stagnant structures

Are we observing secular evolution?

- We believe we are `observing' secular evolution
- Bars are not stagnant structures
- Bars are dynamic, evolving structures that directly influence the evolution of their host galaxies

Bars are drivers of galaxy evolution

Thank you!

Bar Likelihood ($p_{\rm bar}$)

0.10 0.20 0.30 0.40 0.50 0.60

log SSFR [$\rm yr^{-1}$]

−9 −10 −11 −12 −13

8.5 9.0 9.5 10.0 10.5

log $\Sigma^*_{1\ \rm kpc}$ [$\rm M_\odot/kpc^2$]

Scaled Bar Length ($L_{\rm sbar}$)

1.00 1.16 1.32 1.48 1.64 1.80

log SSFR [$\rm yr^{-1}$]

−9 −10 −11 −12 −13

star−forming disky pseudobulge

quiescent classical bulge

$L_{\rm sbar}$

1.4 1.3 1.2 1.1 1.0 0.9 0.8 0.7

8.5 9.0 9.5 10.0 10.5

log $\Sigma^*_{1\ \rm kpc}$ [$\rm M_\odot/kpc^2$]