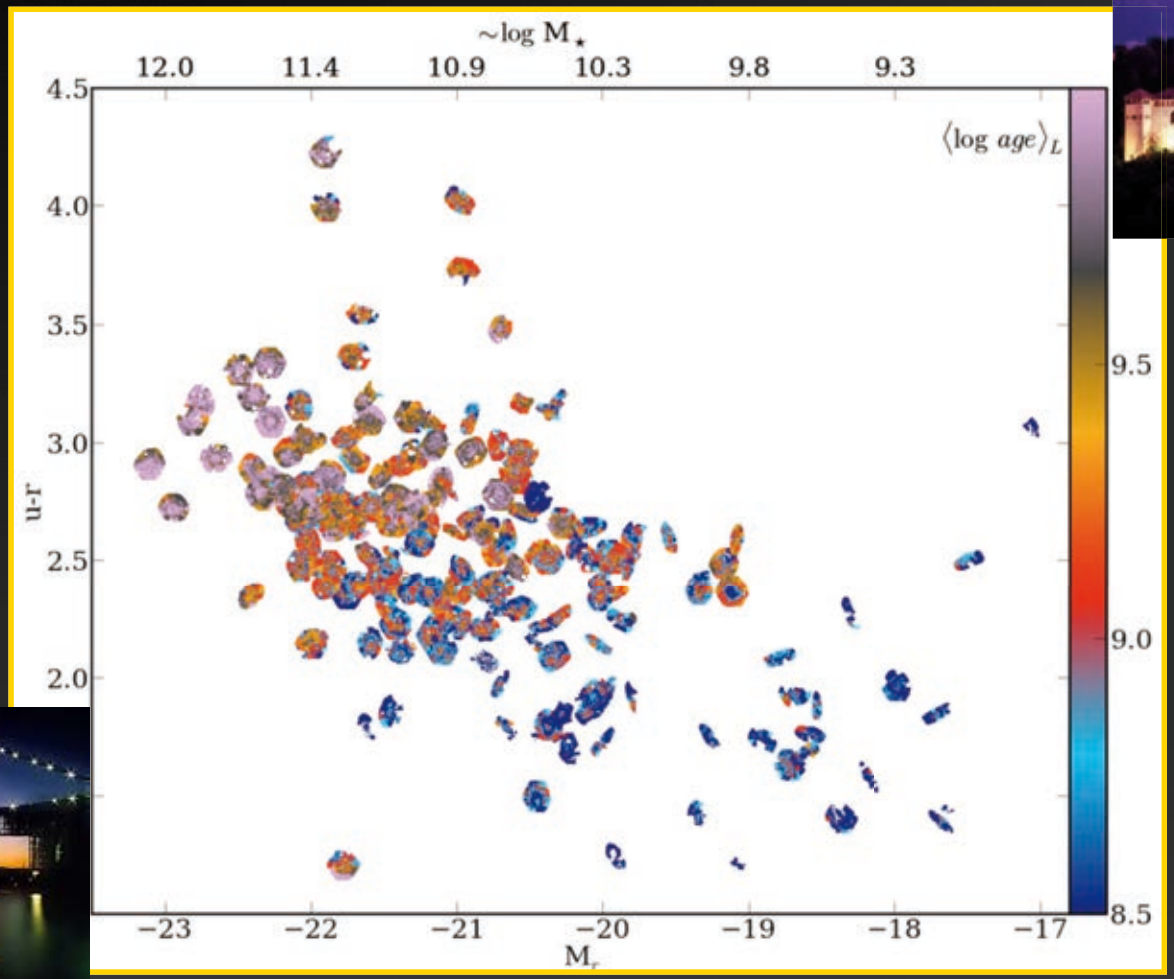
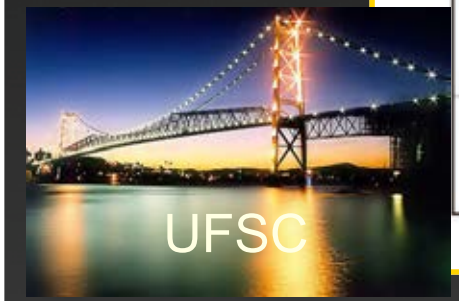
A journey through the amazing new world of stellar populations in 2D:
1st results on galaxy growth from the CALIFA survey



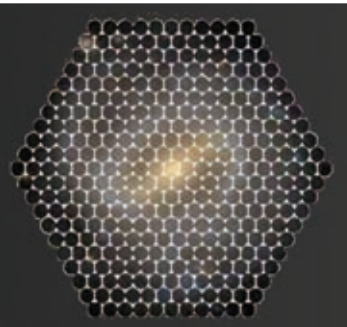


Outline

1 – Spectral synthesis w/STARLIGHT

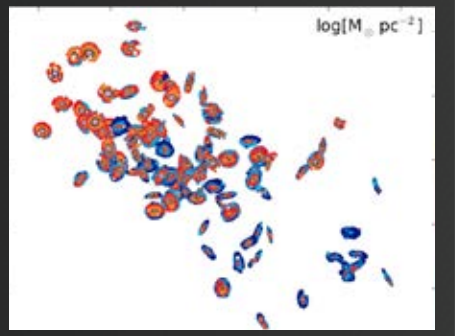
- Basics & example results

...a preamble to the main feature:



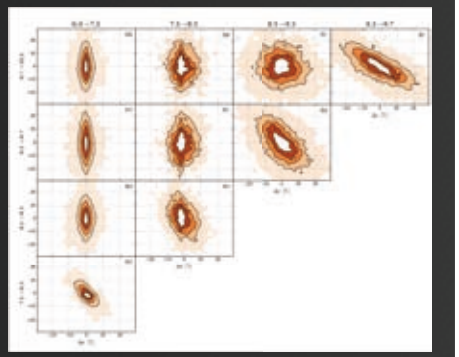
2 – Galaxy evolution in 2D: CALIFA

- PyCASSO & 1st results



THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: AN INSIDE-OUT GROWTH VIEW FROM THE CALIFA SURVEY

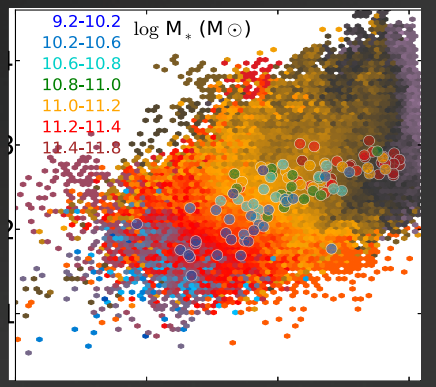
E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4],



Resolving galaxies in time and space: I:

Applying STARLIGHT to CALIFA datacubes

R. Cid Fernandes[1,2], E. Pérez[1], R. García Benito[1], R. M. González Delgado[1], A. L. de Amorim[2], S. F. Sánchez[1,3], B. Husemann[4], J. Falcón Barroso[5,6], P. Sánchez-Blázquez[7], C. J. Walcher[4], and D. Mast[1,3]



Resolving galaxies in time and space: II:

Uncertainties in the spectral synthesis of data cubes

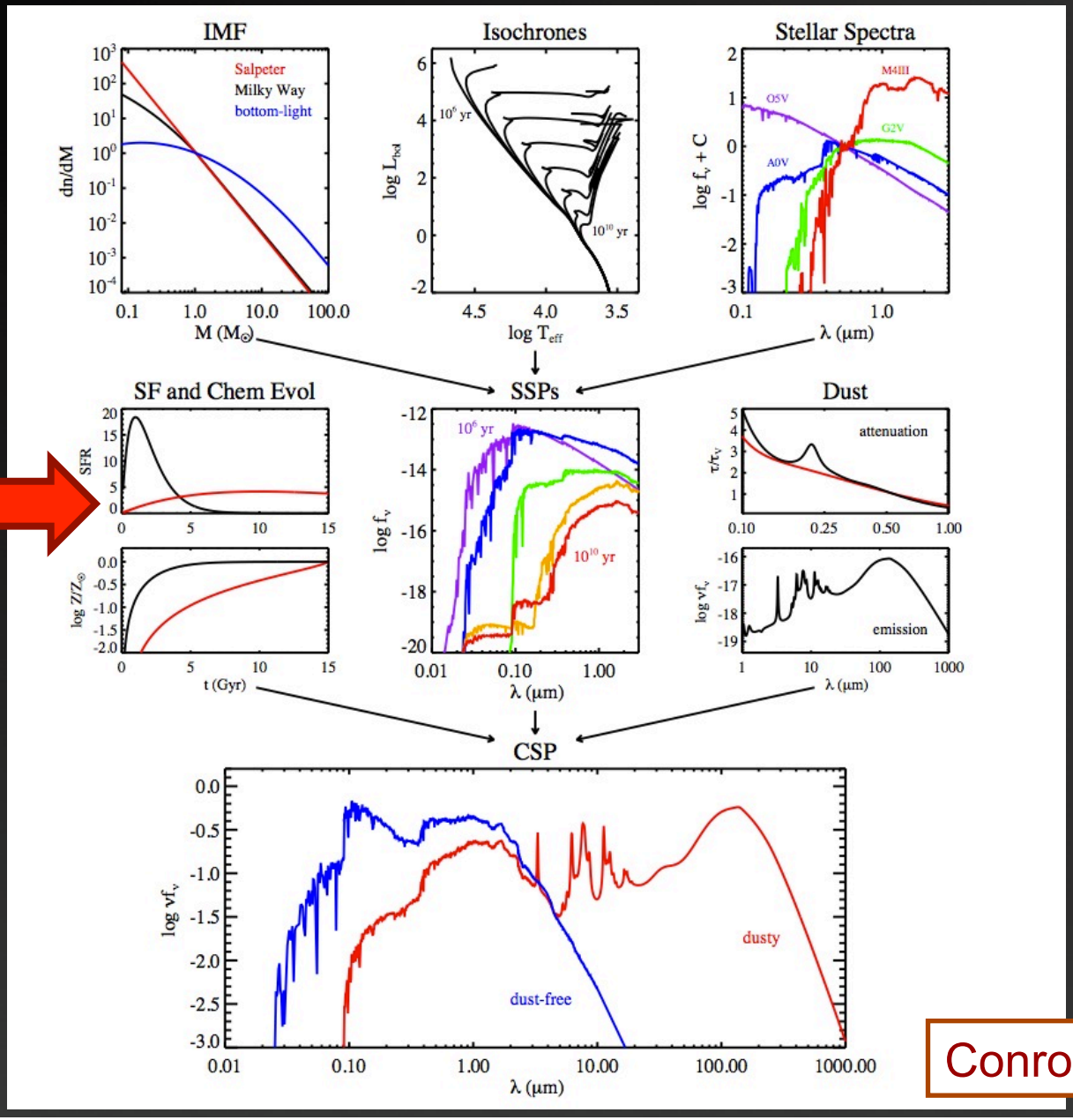
R. Cid Fernandes[1,2], R. M. González Delgado[2], R. García Benito[2], E. Pérez[2], A. L. de Amorim[1,2], S. F. Sánchez[2,3], B. Husemann[4], R. López-Fernández[2], N. Vale Asari[1], J. Falcón Barroso[5,6], P. Sánchez-Blázquez[7], C. J. Walcher[4], and D.

The star formation history of CALIFA galaxies: Radial structures

R. M. González Delgado[1], E. Pérez[1], R. Cid Fernandes[1,2], R. García Benito[1], A. L. de Amorim[2], S. F. Sánchez[1,3], B. Husemann[4], C. Cortijo-Ferrero[1], R. López Fernández[1], P. Sánchez-Blázquez[5], S. Bekeraite[4], C. J. Walcher[4], J.

Forward spectral synthesis

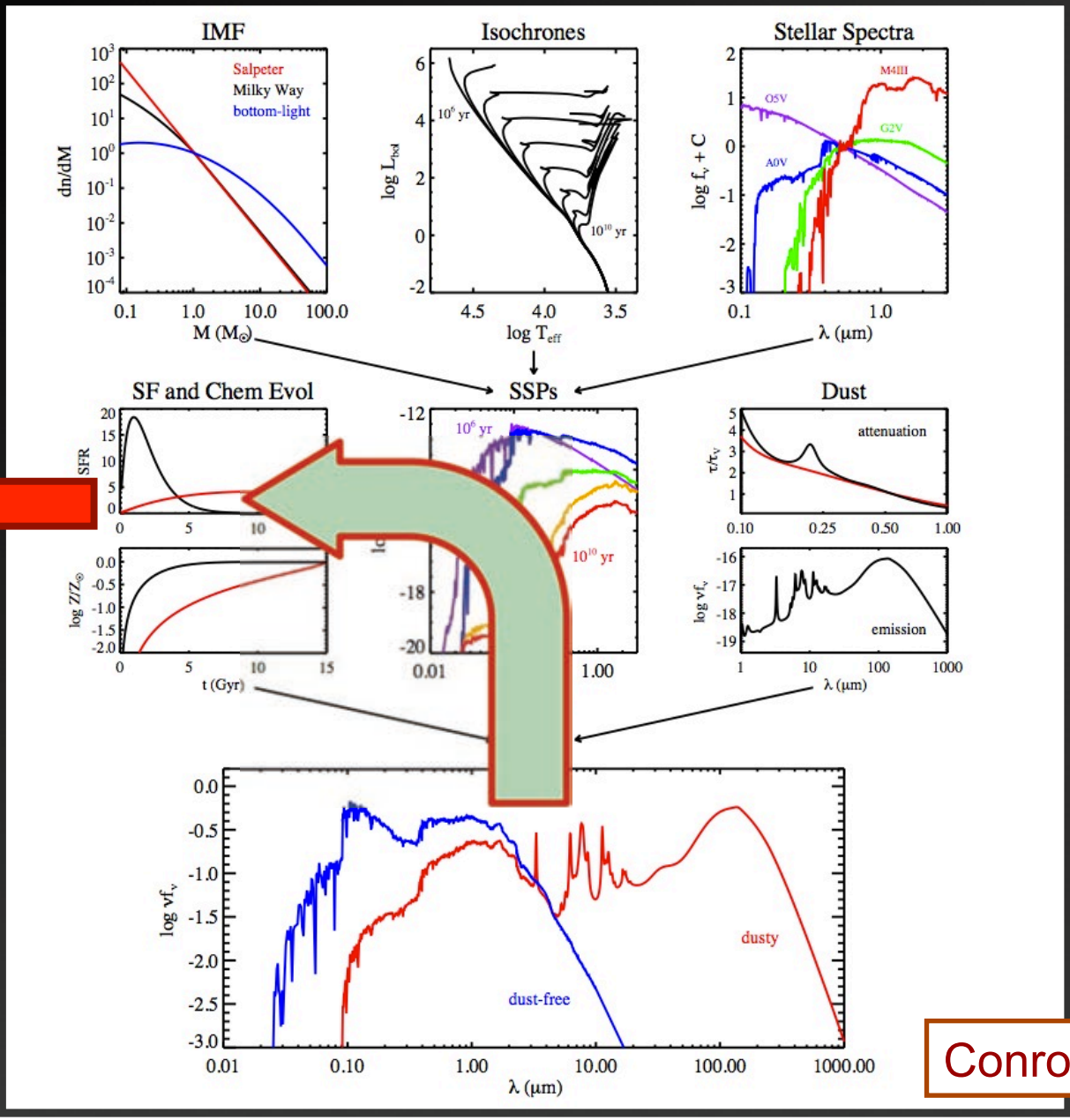
ASSUME
Star Formation History



Conroy 2013

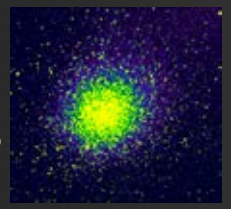
Inverse spectral synthesis

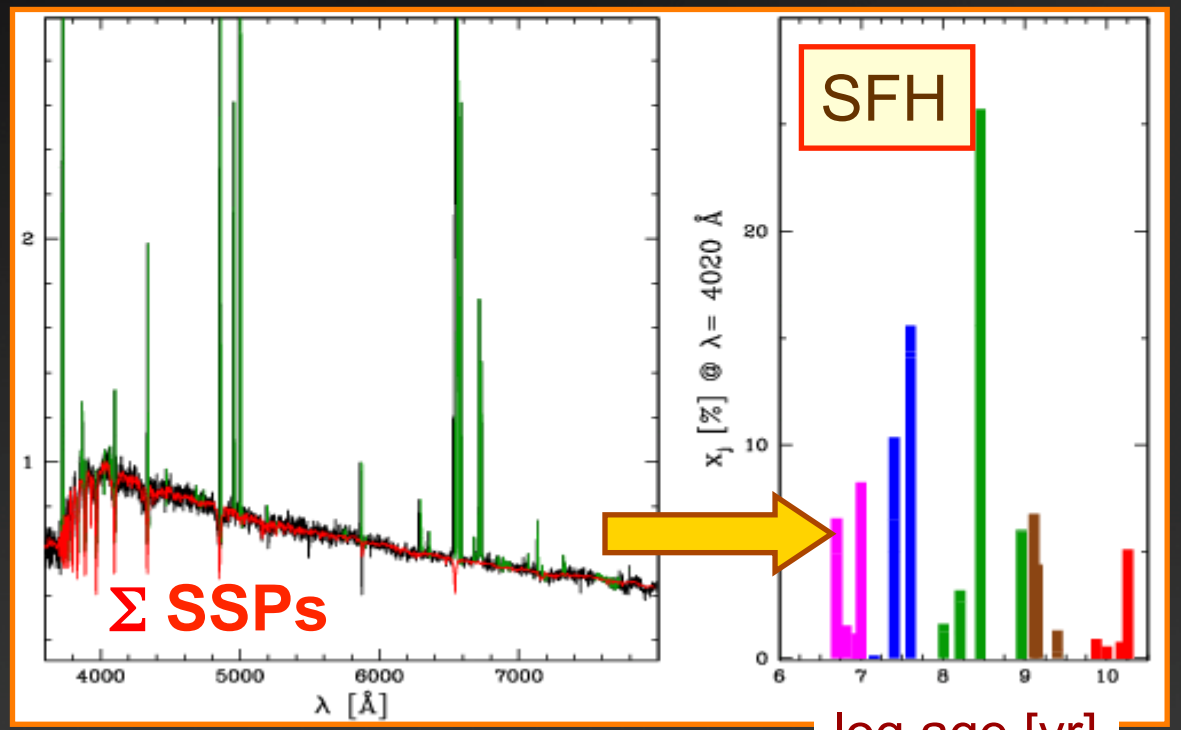
DERIVE
Star
Formation
History



Conroy 2013

1 – STARLIGHT basics: old idea / new skin

$= M_1$  $+ M_2$  $+ M_3$  $+ \ldots$

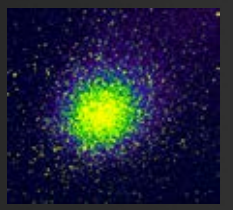


CF 04, 05

Decomposing galaxy spectra: The basics...


= M_1

+ M_2

+ M_3

+ ...

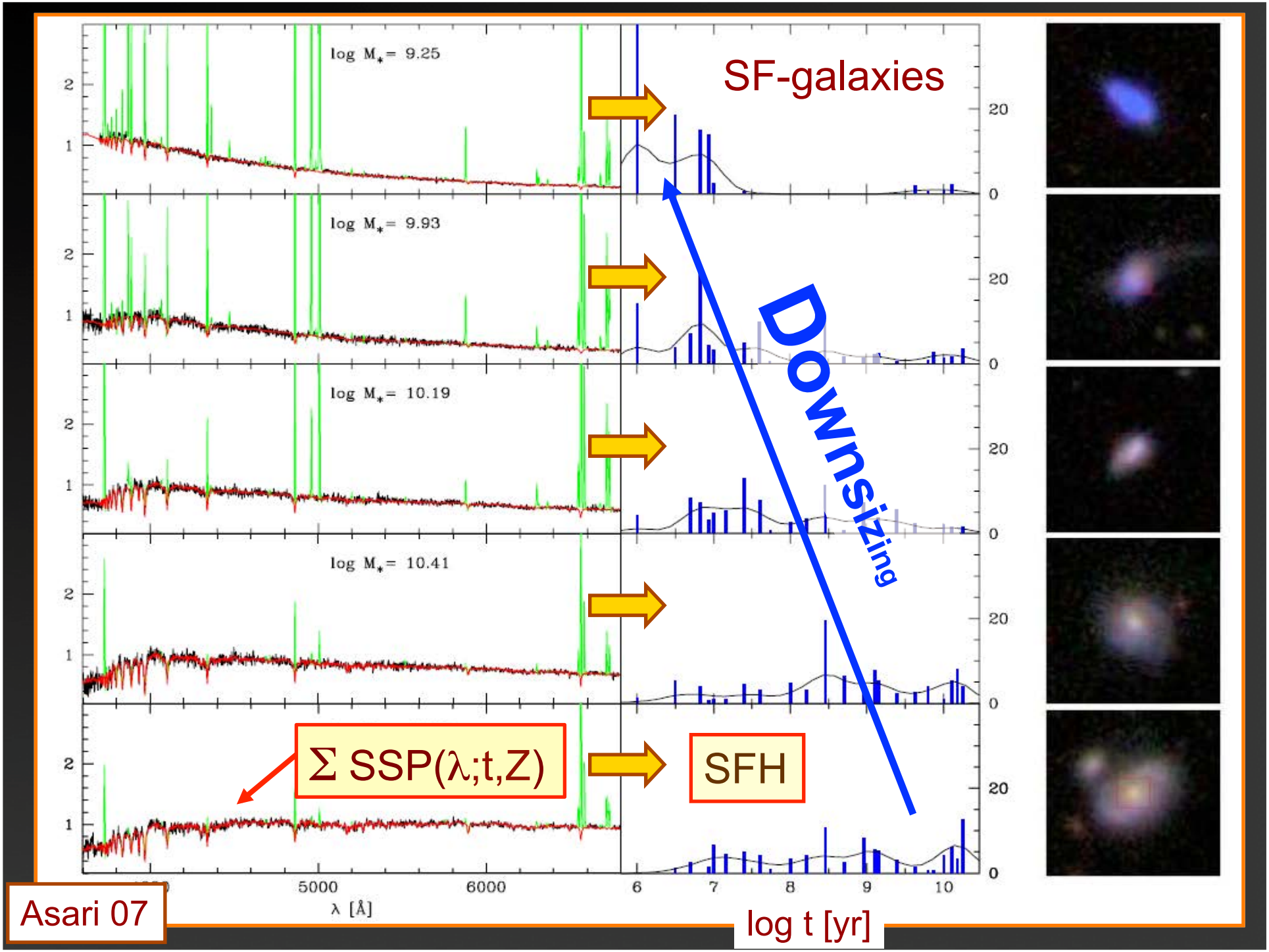
$$L_{gal}(\lambda) = \sum_{t,Z} M_{SSP}(t,Z) \times SSP(\lambda;t,Z) \times e^{-\tau(\lambda)}$$

Observables
Full spectrum:
F_λ

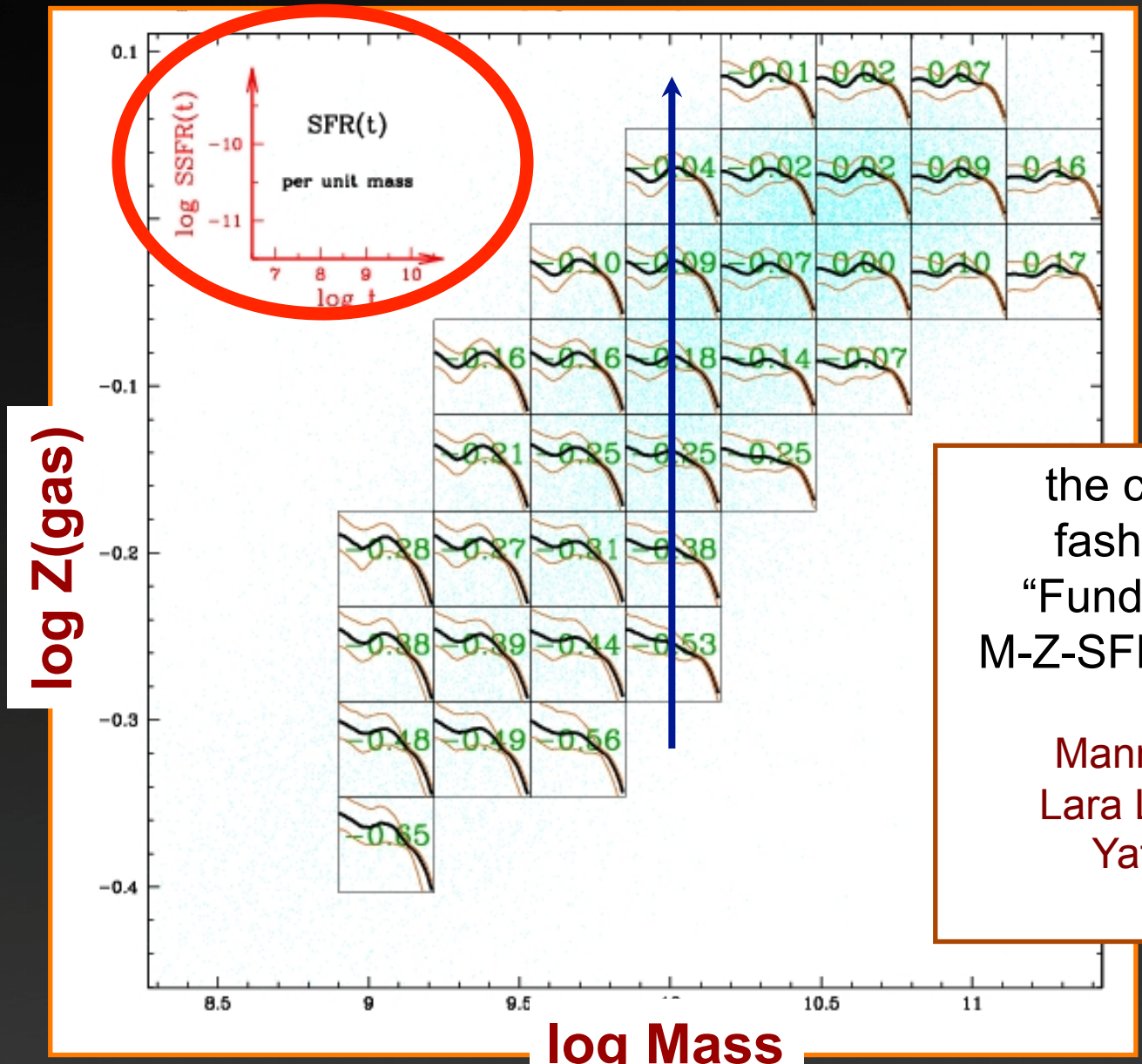
SFH:
mass or light fractions
➔ ***Pop vector***

Spectral Base
SSPs from
BC03, Granada,
Pegase, "CB07",
Vazdekis, …

Dust
…


log M*= 9.25
log M*= 9.93
log M*= 10.19
log M*= 10.41
SF-galaxies
Downsizing
Σ SSP(λ;t,Z)
SFH
λ [Å]
log t [yr]
Asari 07

The M_*–Z_{gas}–SFH relation



the currently fashionable "Fundamental" M-Z-SFR relation…

Mannucci 10
Lara López 10
Yates 12
…

Semi
Empirical
Analysis of (SDSS)
Galaxies

The SEAGal team

RCF (Florianópolis)

Abilio Mateus
(Florianópolis)

William Schoenell
(Florianópolis)

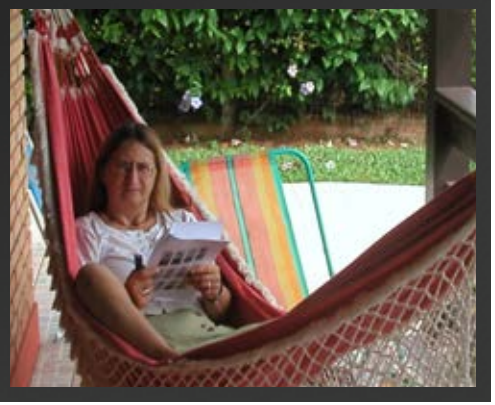
Jean Gomes
(CAUP, Portugal)

Laerte
Sodré
(São Paulo)

Natalia Vale Asari
(Florianópolis)

Marielli Schlickmann
(Florianópolis)

Grażyna
Stasińska
(Meudon)



Flori-where?


www.guiafloripa.com.br


www.guiafloripa.com.br

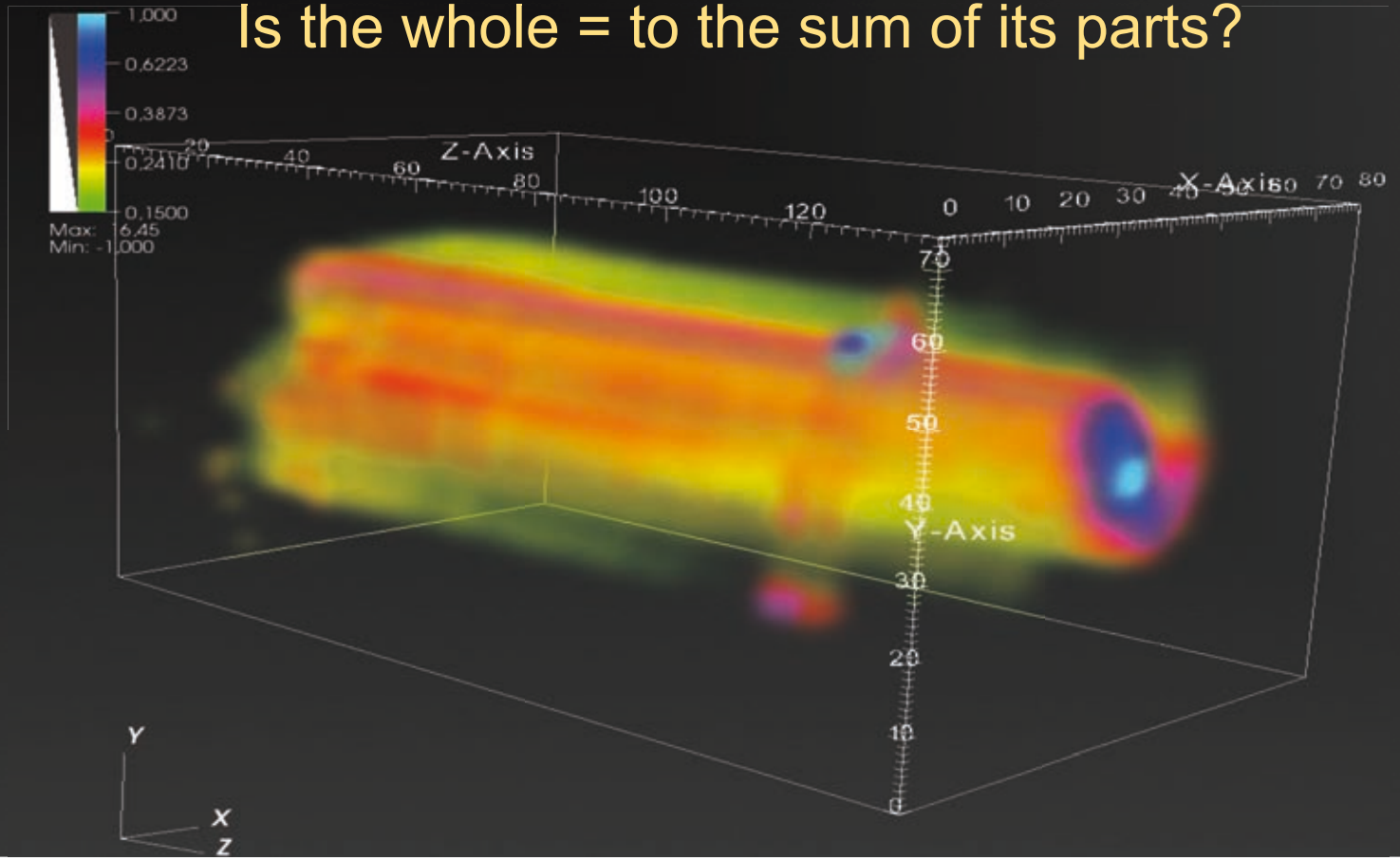

www.guiafloripa.com.br

Deadline
=
TODAY!

Fine, but this is all **“0D”** (integrated spectra)!

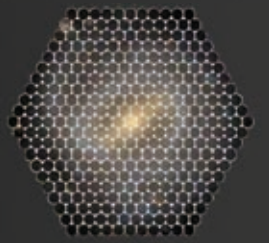
Does size / shape / looks matter?

Can galaxies be treated as point sources?
What can we learn from **F(λ,x,y)** ?
Is the whole = to the sum of its parts?



2 – Galaxy evolution in 2D

The brave new world of spatially resolved star formation histories



Calar Alto Legacy Integral Field Area survey

~ 80 members / 13 countries

- PI: S. F. Sánchez
- PS: C. J. Walcher

250 dark nights:

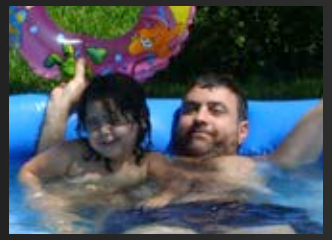
- PPAK@3.5m CAHA
- Full optical wavelength range
- ~2000 spectra per galaxy

Sample:

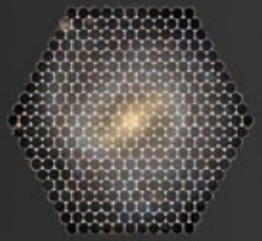
- ~20 galaxies per 1x1 mag bin in the CMD
- + diameter selection …

Enrique Pérez

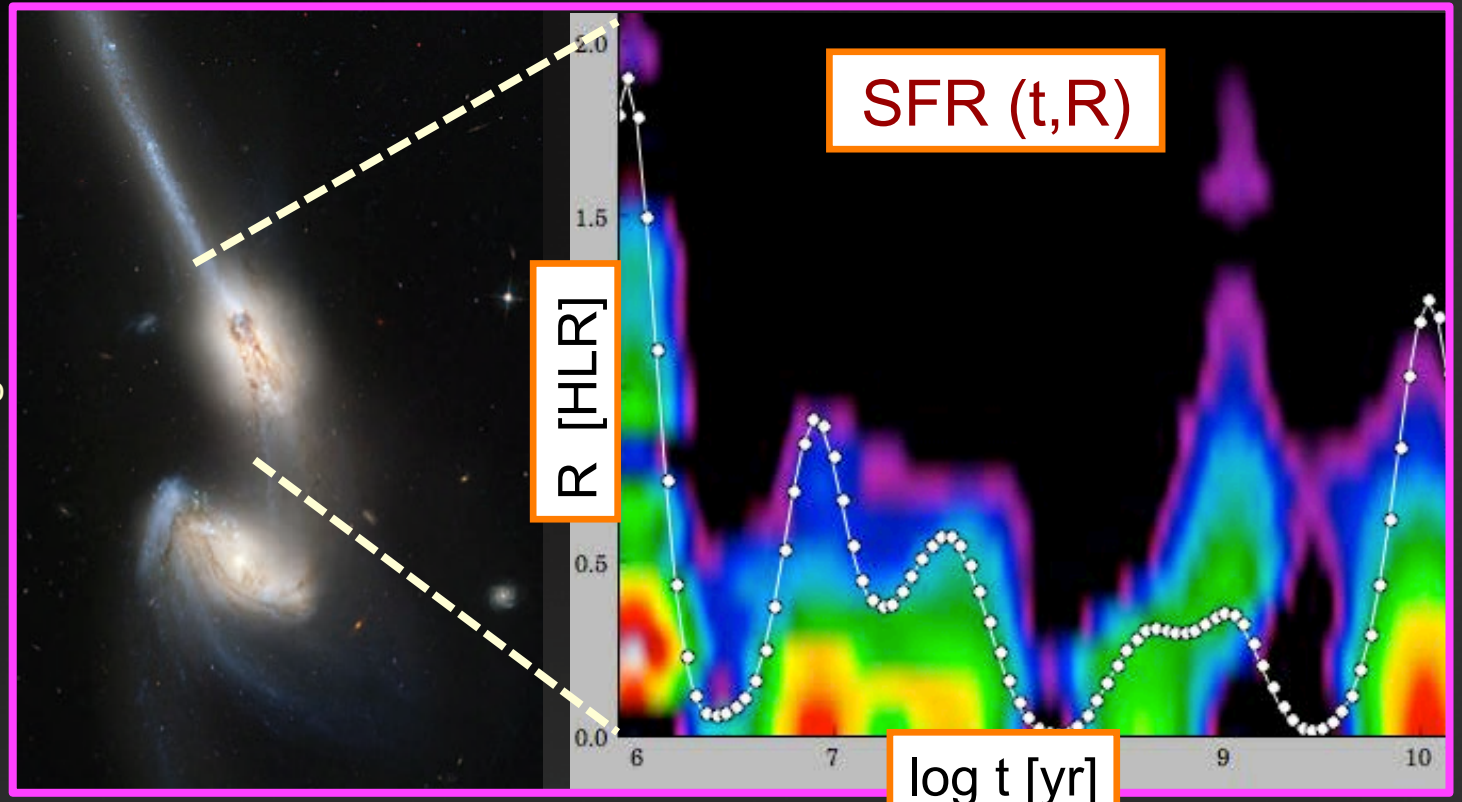
Rosa González Delgado



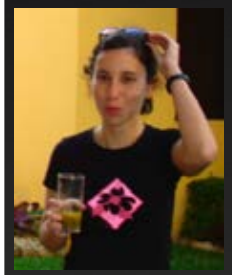
Helena (+ me)



Rubén García-Benito



André Amorim



Natalia Vale Asari

Rafael López

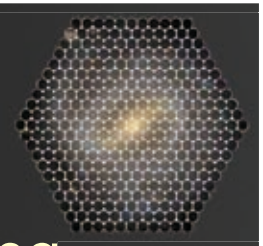
Bernd Husemann

Sebastián F. Sánchez

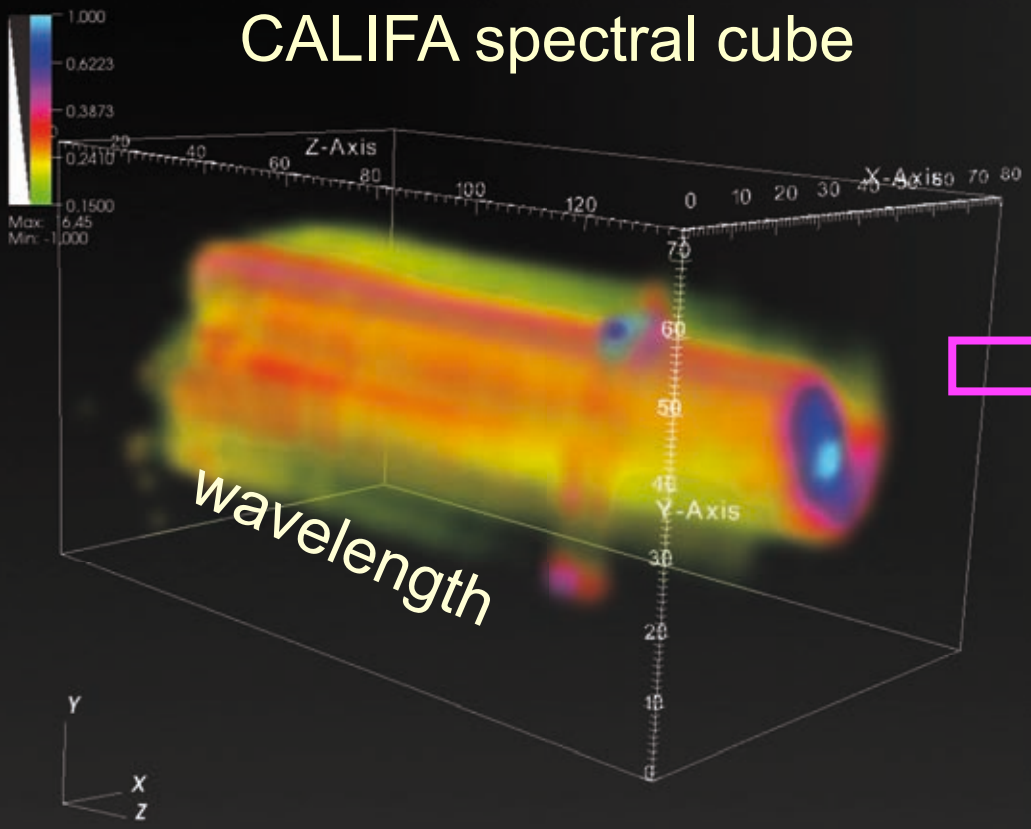
Clara Cortijo

The **PyCASSO** pipeline

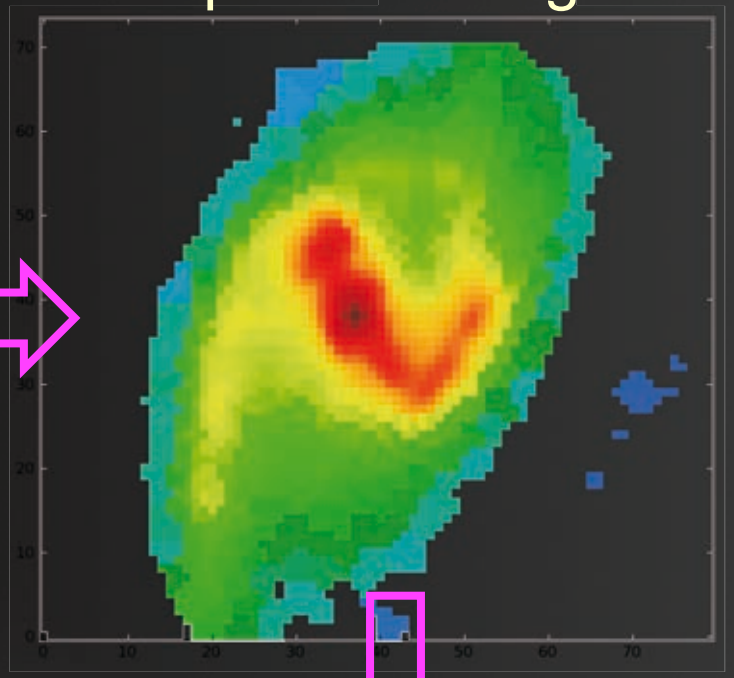
Python **CA**lifa **S**tarlight **S**ynthesis **O**rganizer



CALIFA spectral cube



spatial binning



M_* , v_* , σ_*, A_V,
<age>, <Z_*>, SFH, ...

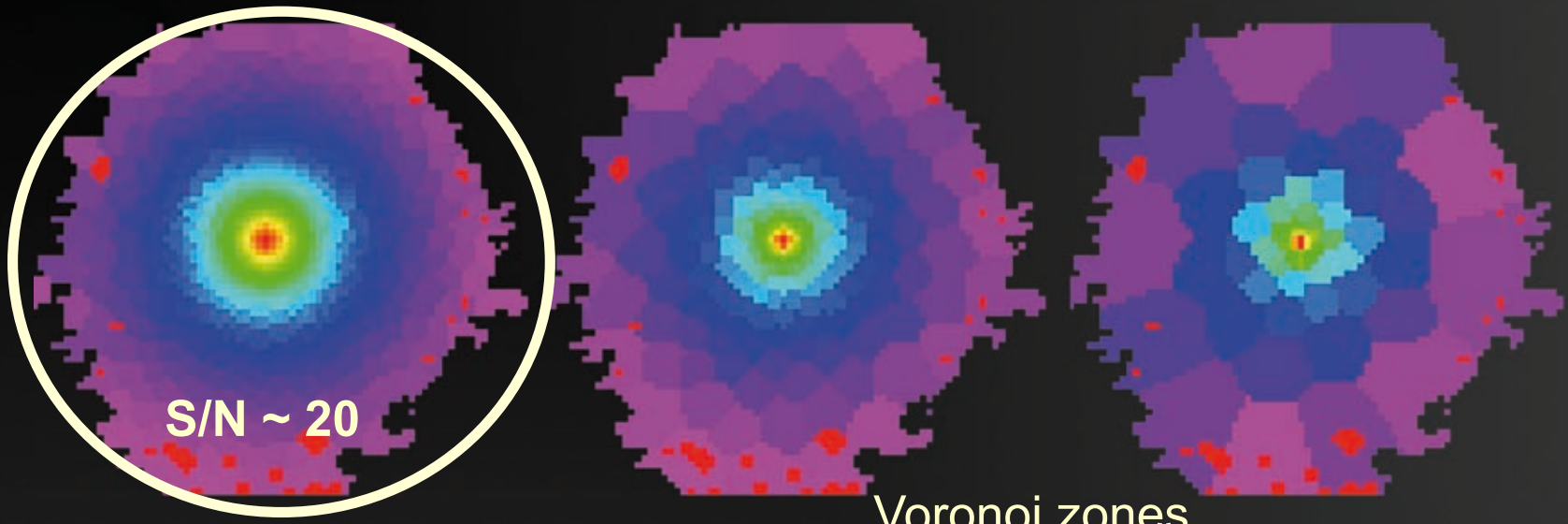
as a function of (x,y) !!

STARLIGHT

Output spectra corrected for:

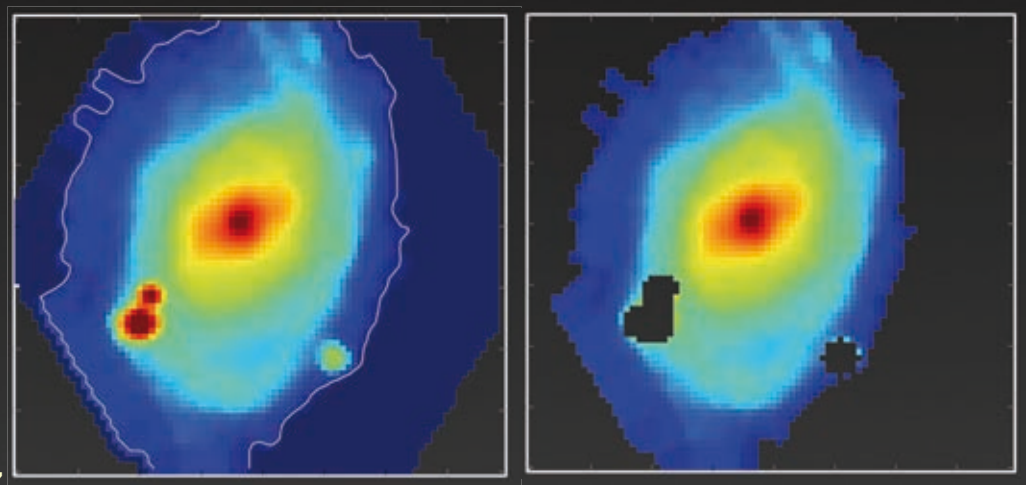
- redshift
- Galactic extinction
- etc …

PyCASSO: Some “technical details”



Voronoi zones
(“segmentation maps”)

Spatial masks



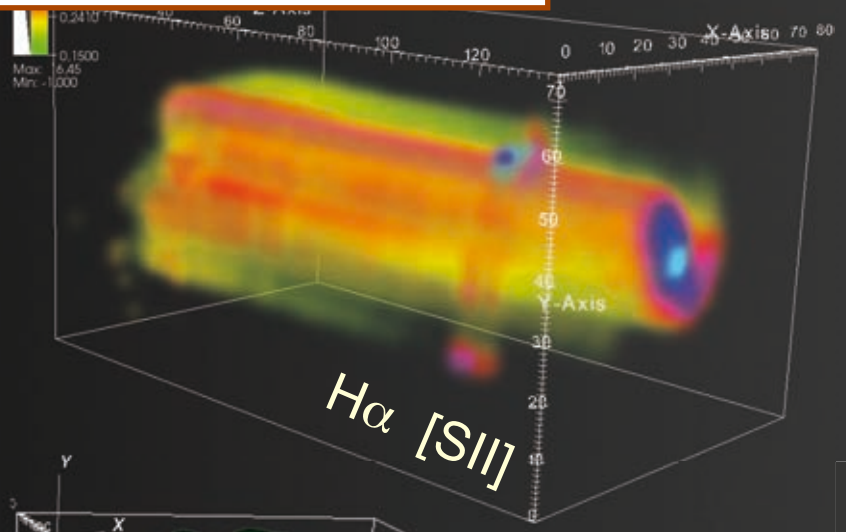
+
Spectral masks
Bad pixel flags
Correlated errors
Calibration issues
…

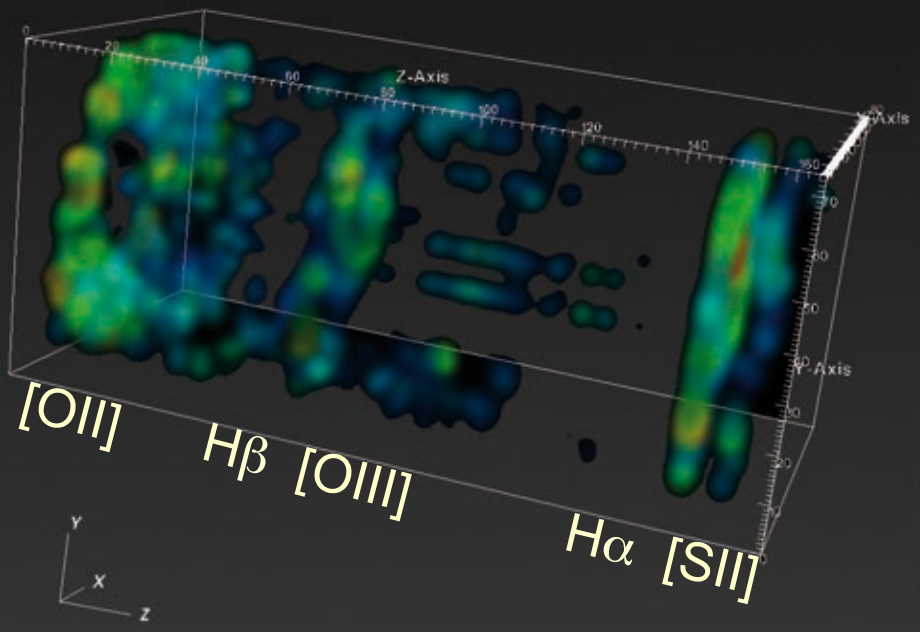
PyCASSO: spectral products

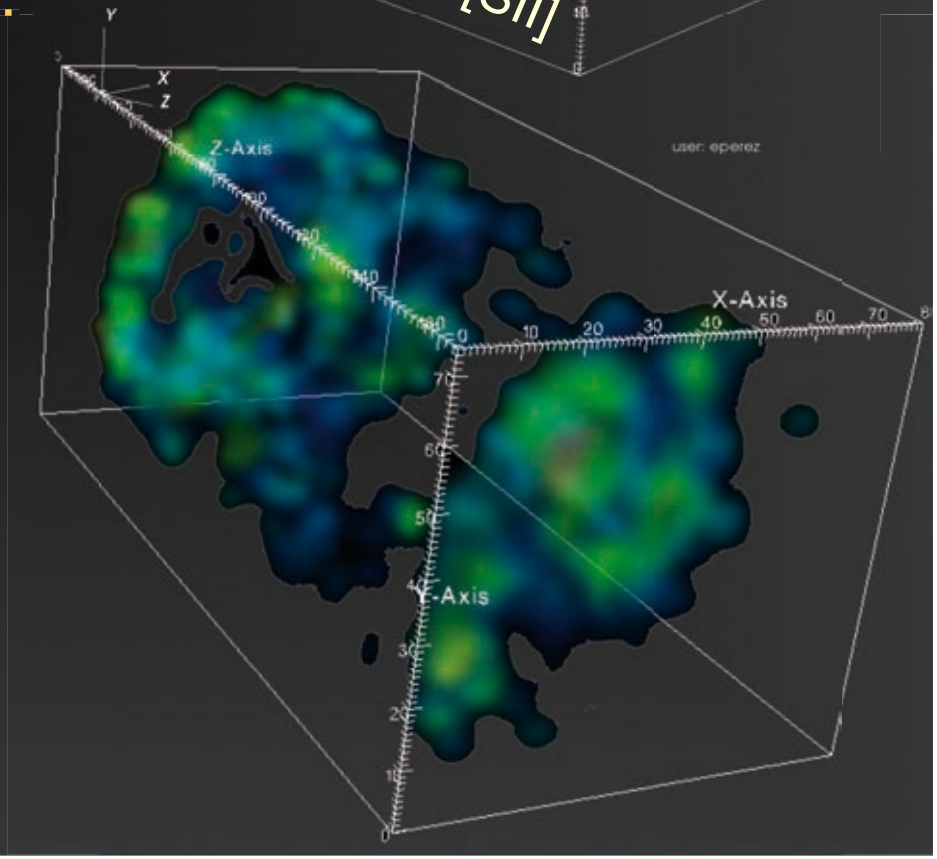
Spectral cubes:

- Data
- Fit: stellar “continuum”
- Residual: gas

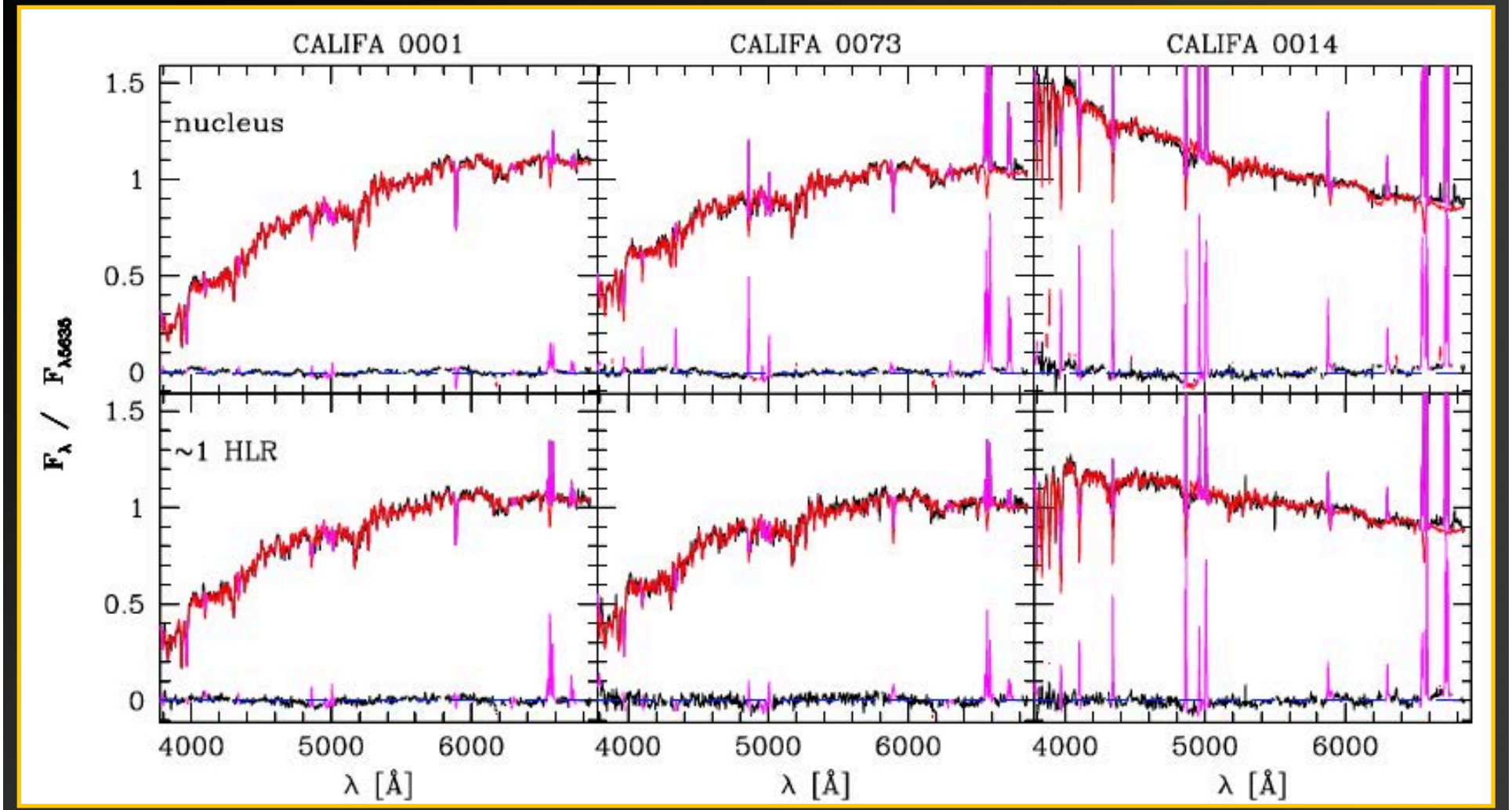
➔ Useful for emission line work…







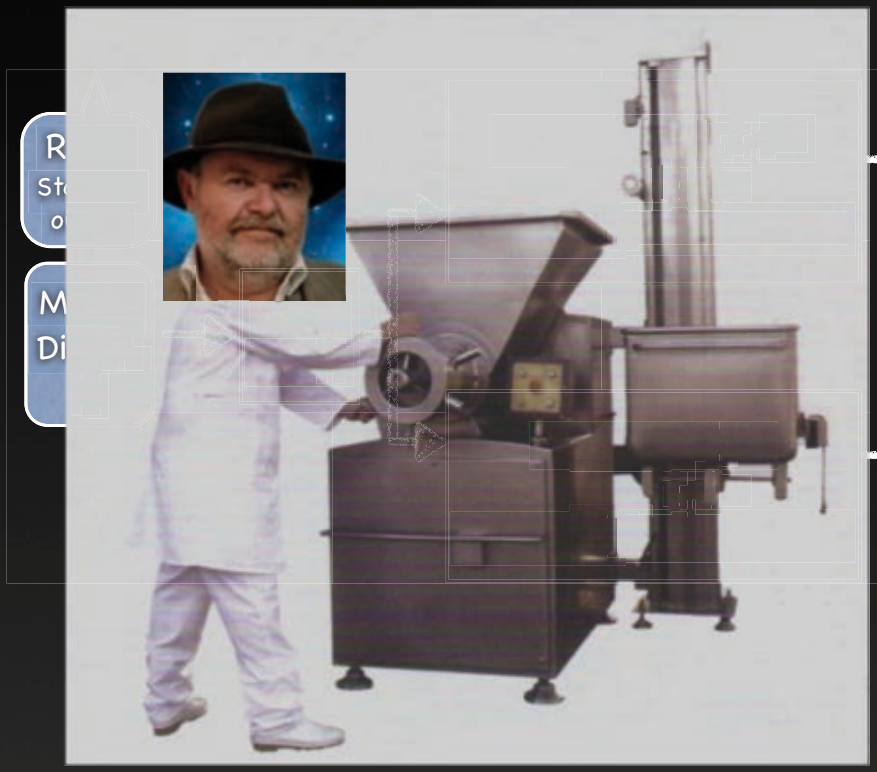
Example spectral fits: Nucleus and @ R = 1 HLR

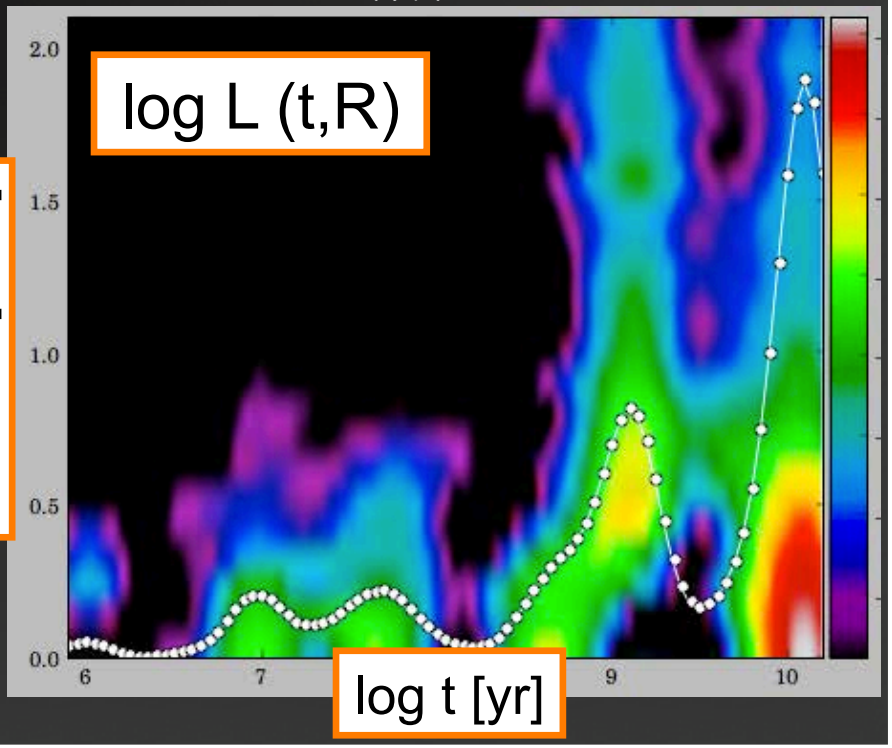


➔ Spectral residuals of 1 – 4%.

➔ Fits are as good/bad as for SDSS spectra…

PyCASSO: SFH products



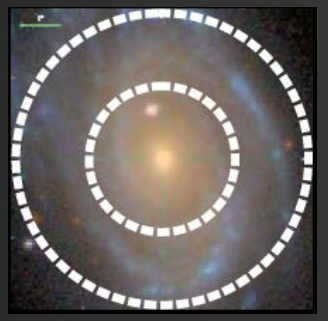


L(x,y,t)
M(x,y,t)
Z(x,y,t)

Resolving galaxies in time and space: I:

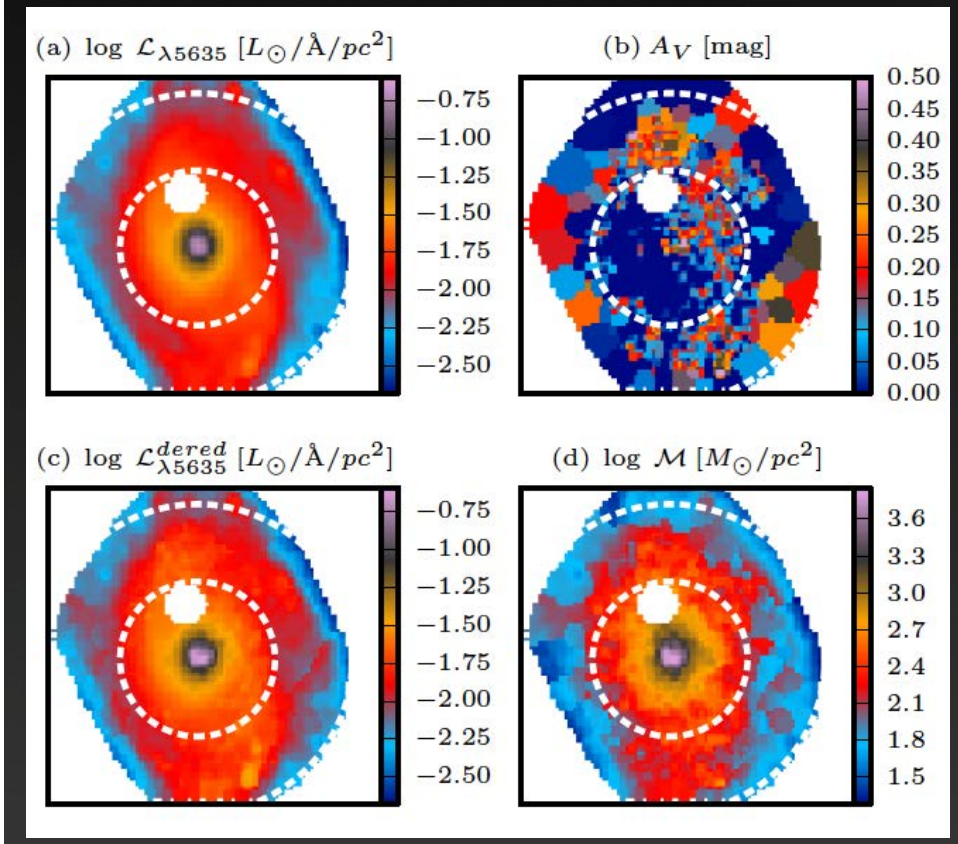
Applying STARLIGHT to CALIFA datacubes

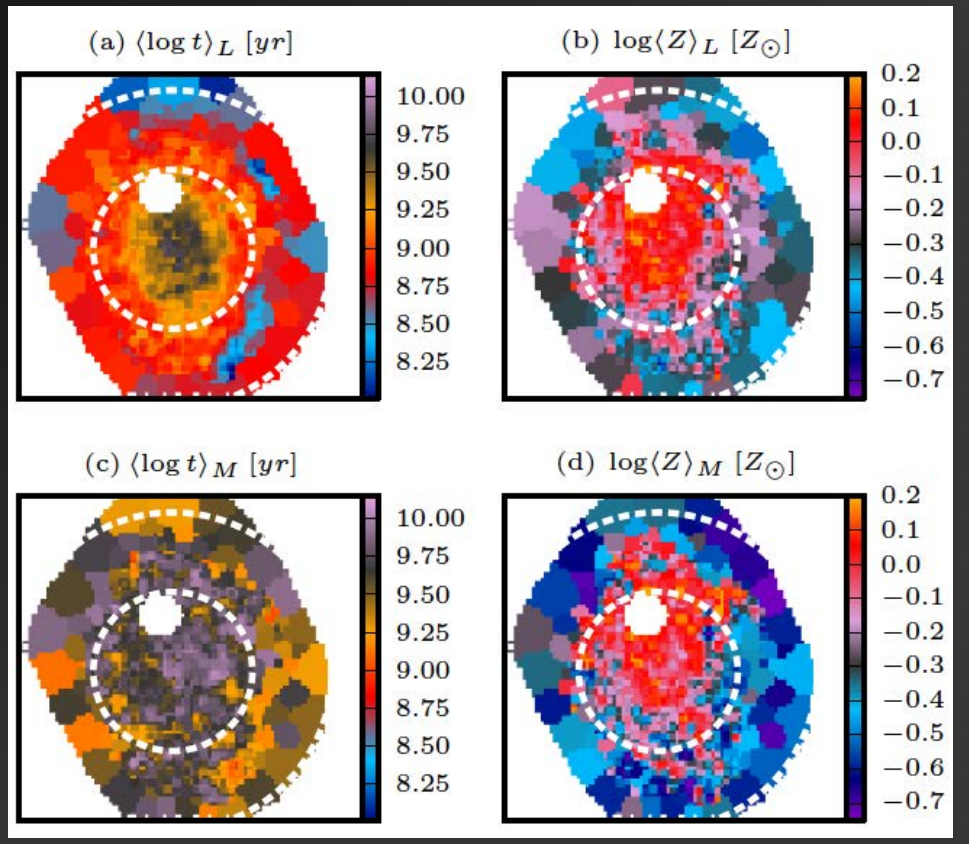
R. Cid Fernandes[1,2], E. Pérez[1], R. García Benito[1], R. M. González Delgado[1], A. L. de Amorim[2], S. F. Sánchez[1,3], B. Husemann[4], J. Falcón Barroso[5,6], P. Sánchez-Blázquez[7], C. J. Walcher[4], and D. Mast[1,3]



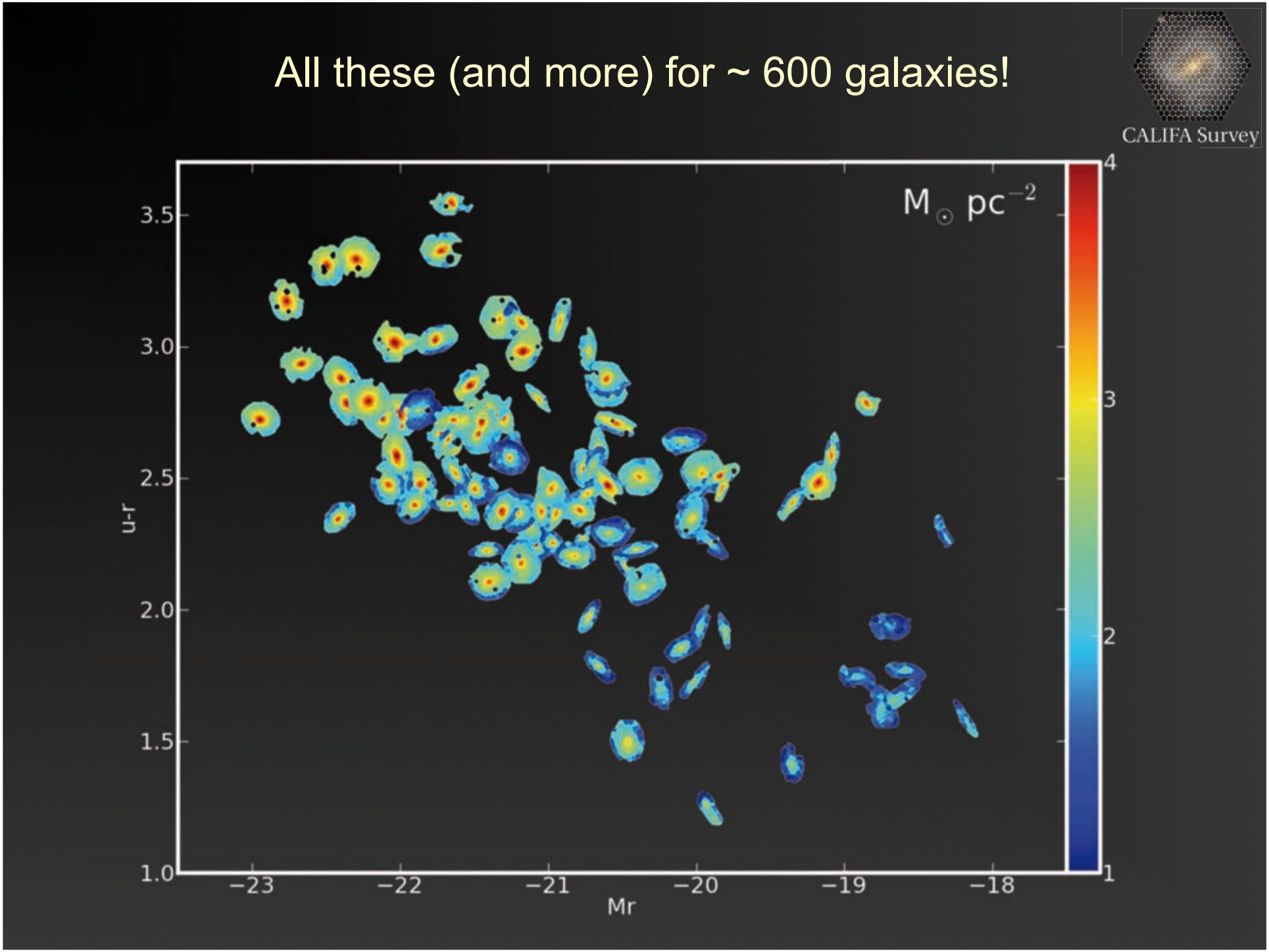
CALIFA 277

+ 2D maps of A_V, mass, mean ages, Zs, kinematics, SFRs …

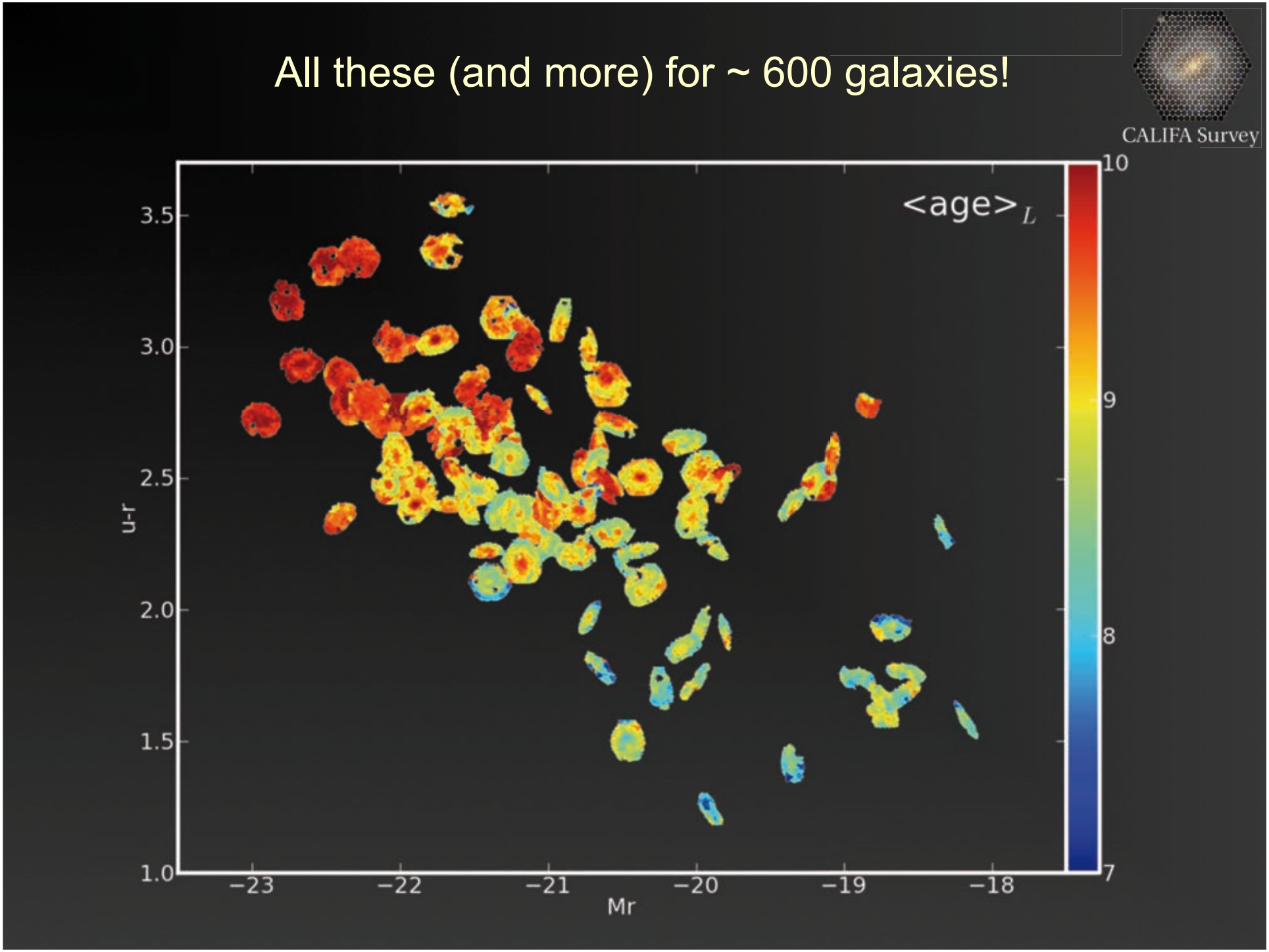




All these (and more) for ~ 600 galaxies!



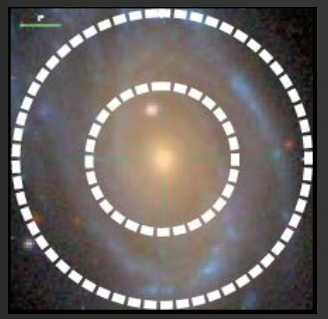
All these (and more) for ~ 600 galaxies!



Resolving galaxies in time and space: I:

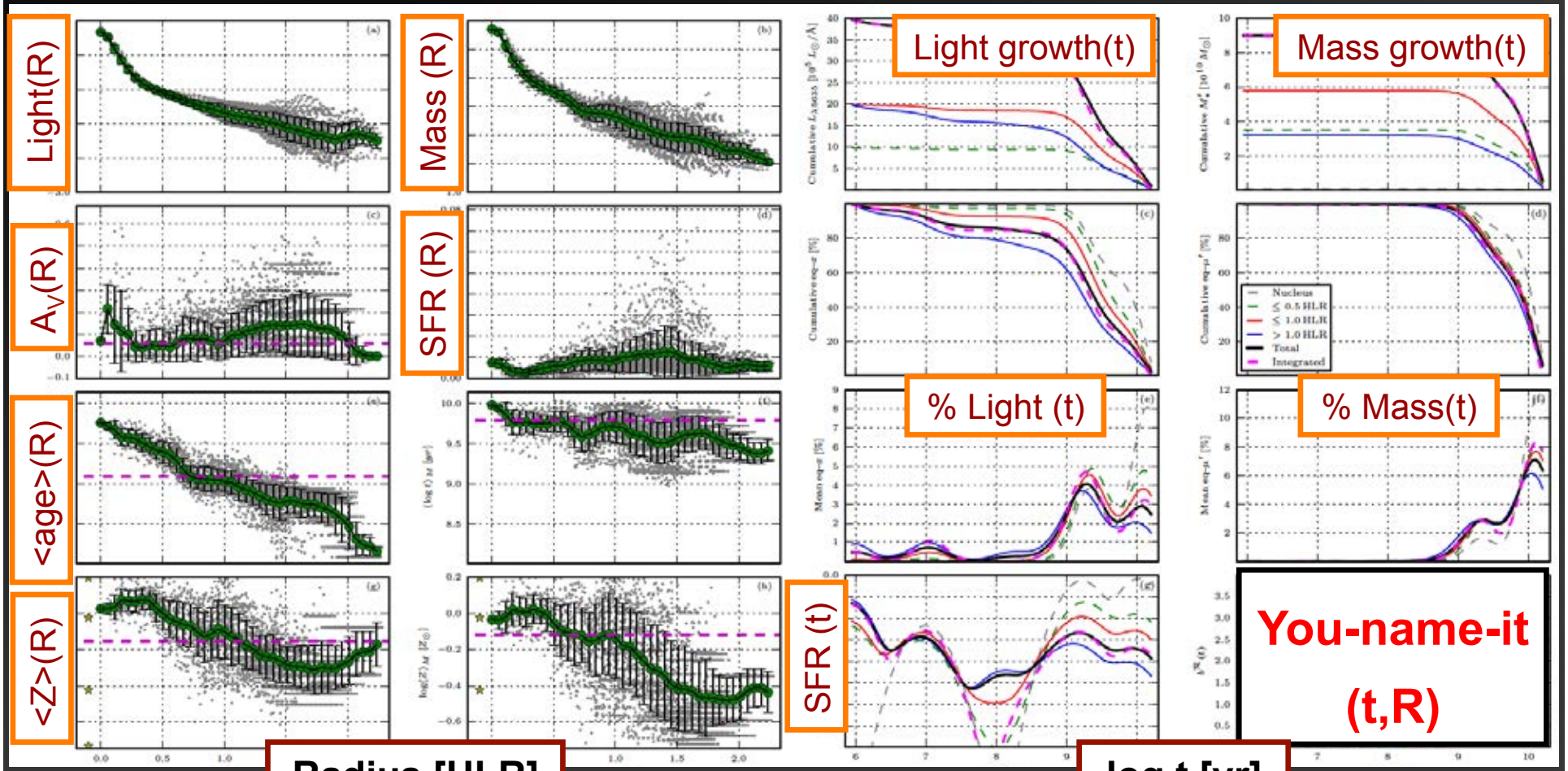
Applying STARLIGHT to CALIFA datacubes

R. Cid Fernandes[1,2], E. Pérez[1], R. García Benito[1], R. M. González Delgado[1], A. L. de Amorim[2], S. F. Sánchez[1,3], B. Husemann[4], J. Falcón Barroso[5,6], P. Sánchez-Blázquez[7], C. J. Walcher[4], and D. Mast[1,3]



CALIFA 277

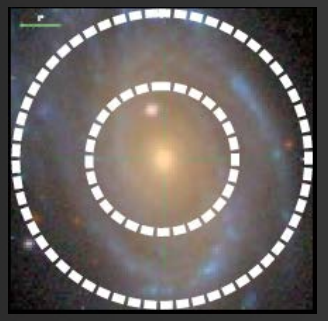
+ 1D radial & age profiles



Resolving galaxies in time and space: I:

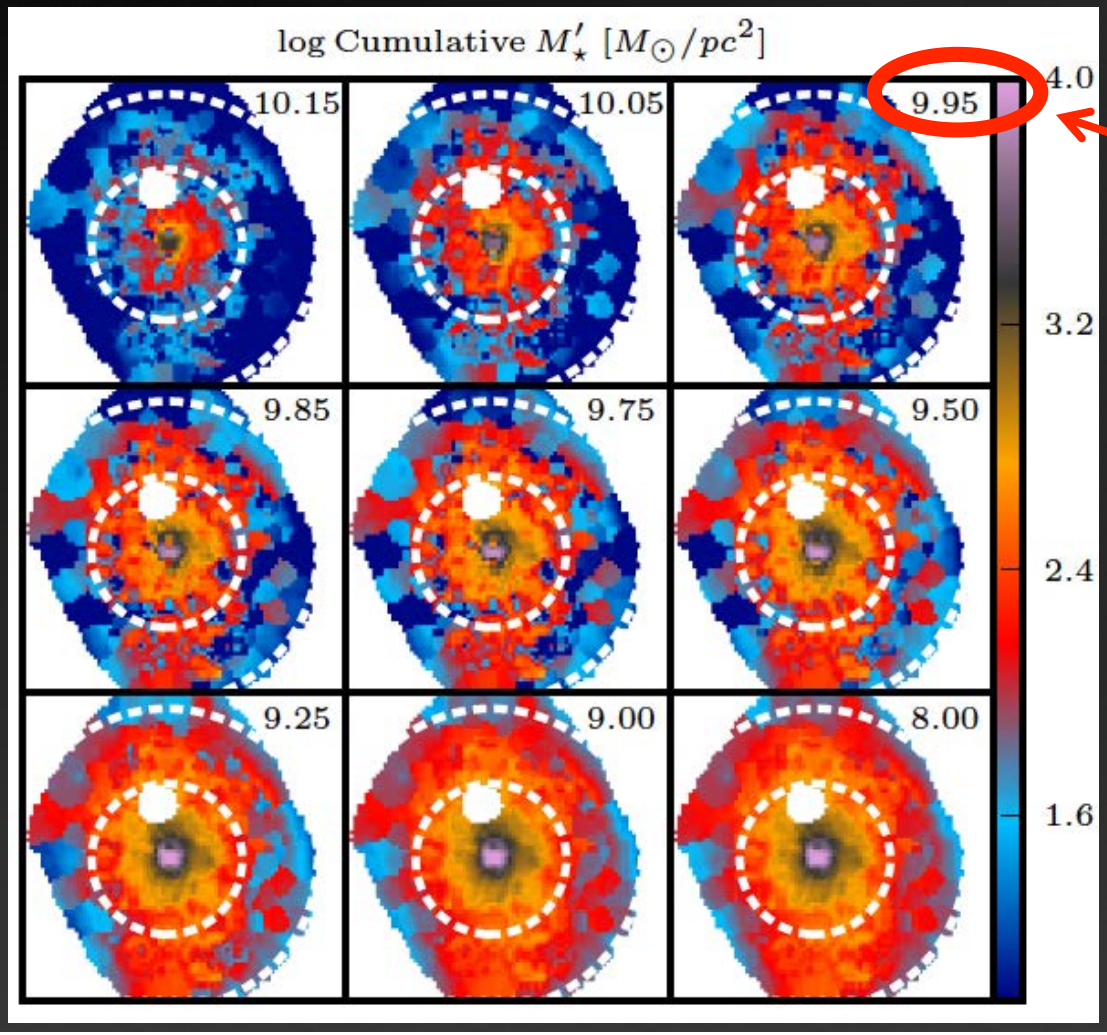
Applying STARLIGHT to CALIFA datacubes

R. Cid Fernandes[1,2], E. Pérez[1], R. García Benito[1], R. M. González Delgado[1], A. L. de Amorim[2], S. F. Sánchez[1,3], B. Husemann[4], J. Falcón Barroso[5,6], P. Sánchez-Blázquez[7], C. J. Walcher[4], and D. Mast[1,3]



CALIFA 277

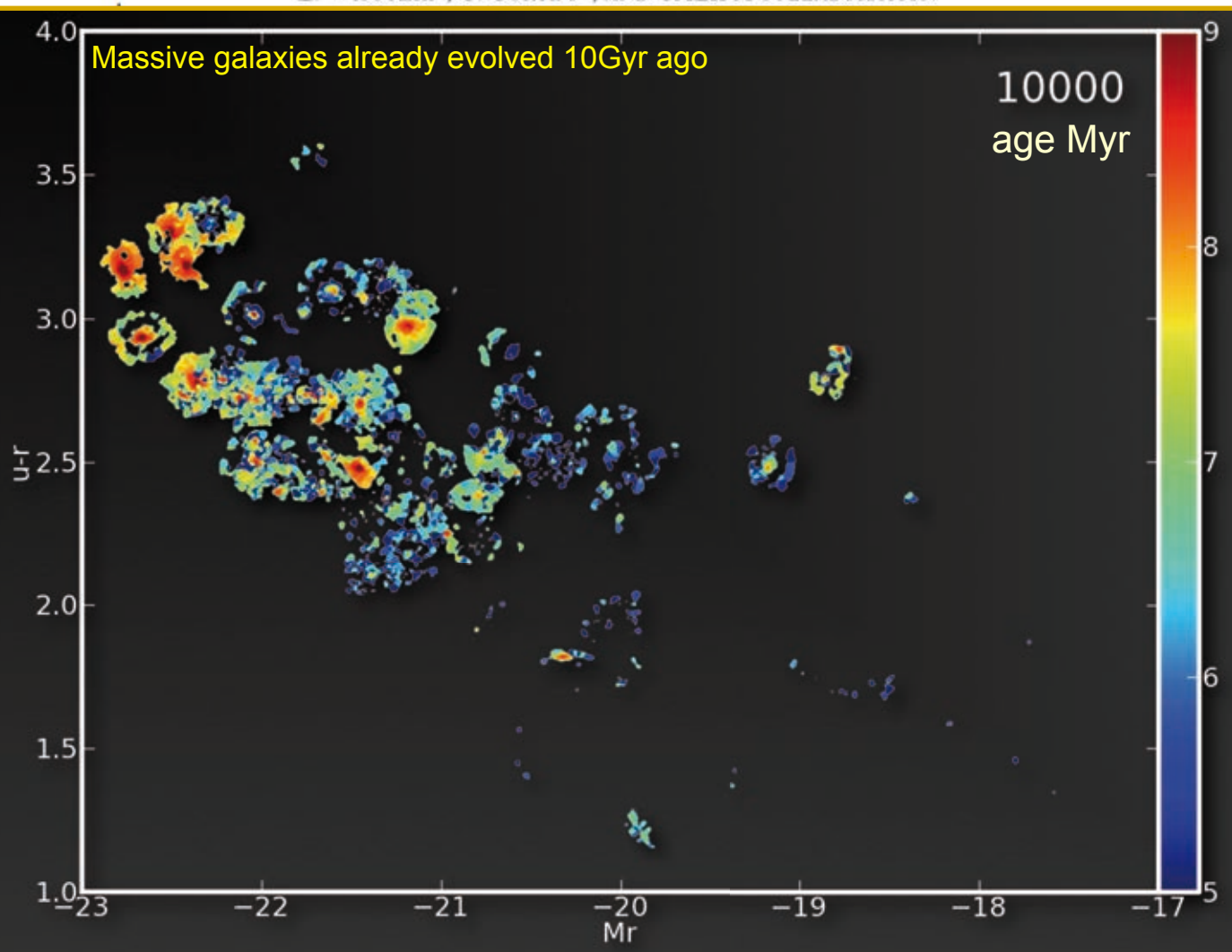
+ Mass assembly history in 2D!

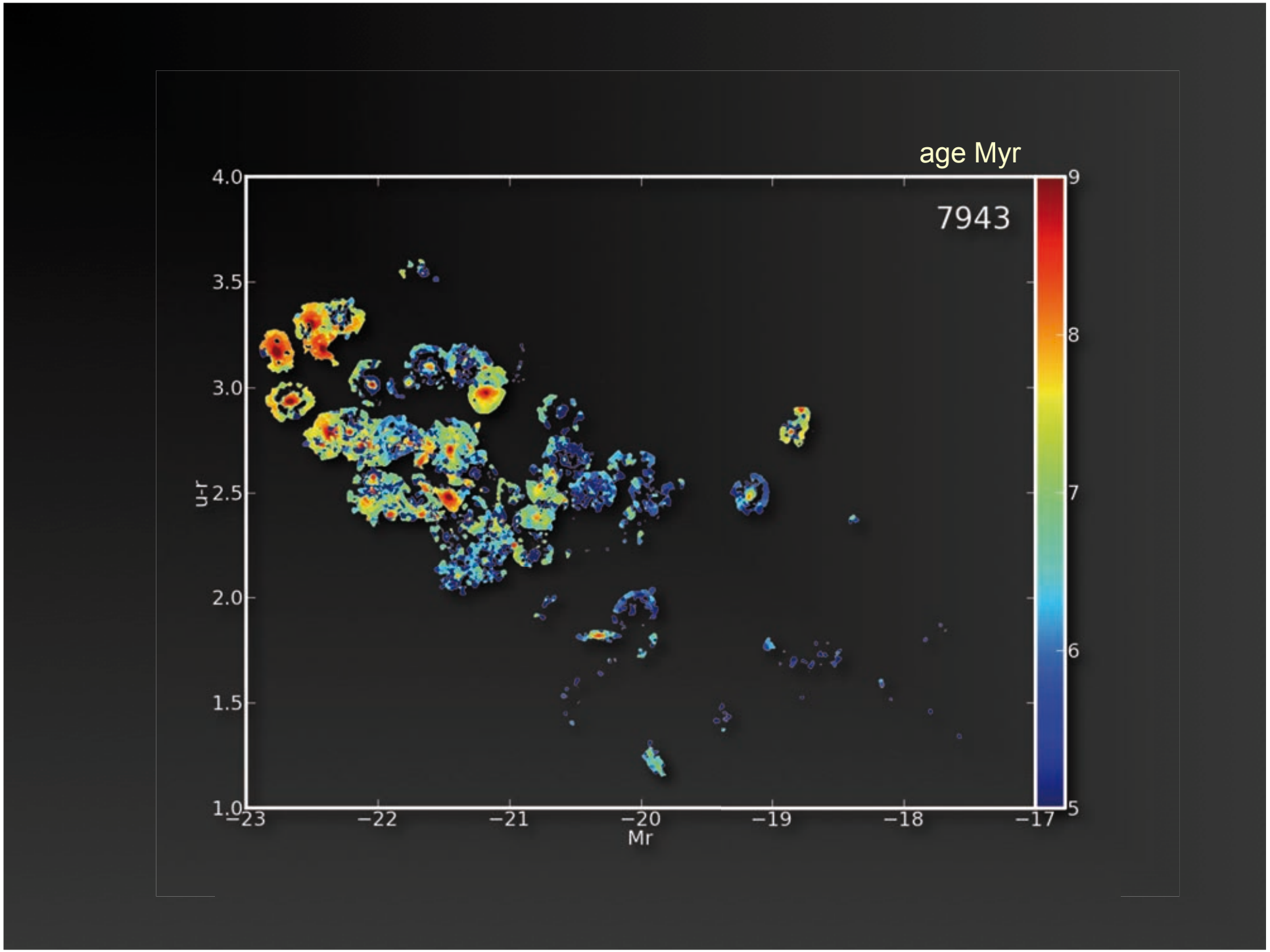


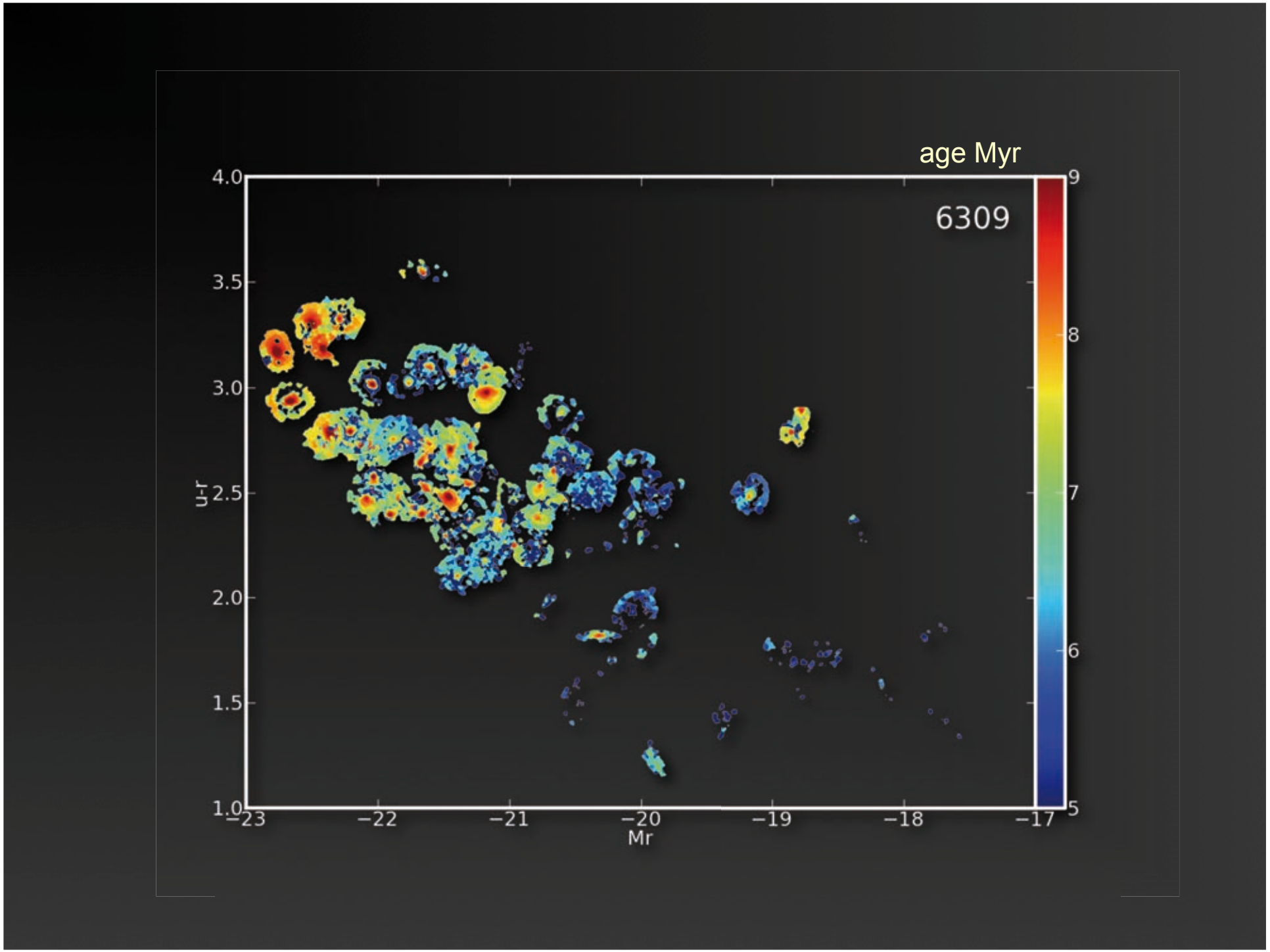
log age [yr]

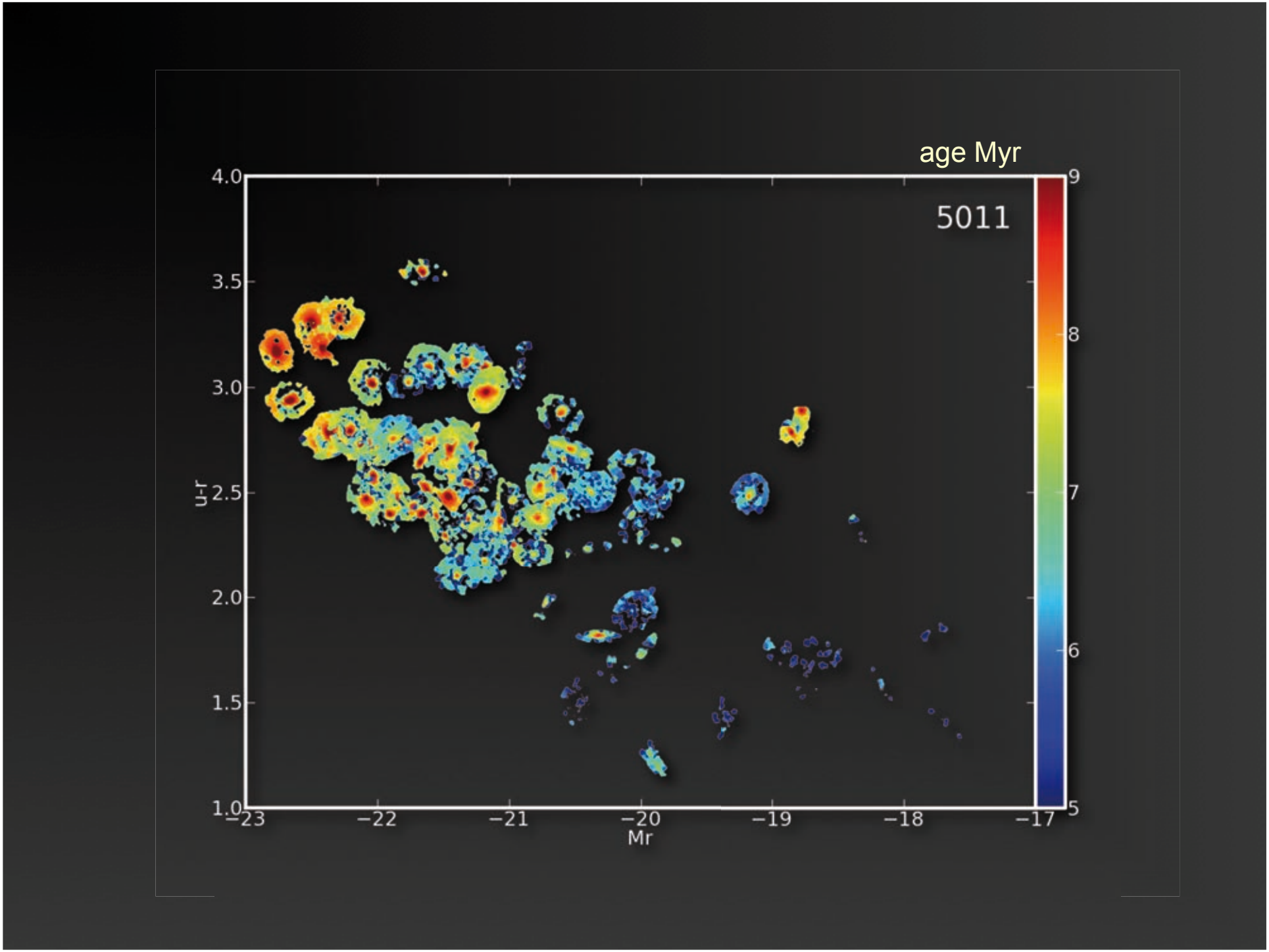
THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: AN INSIDE-OUT GROWTH VIEW FROM THE CALIFA SURVEY

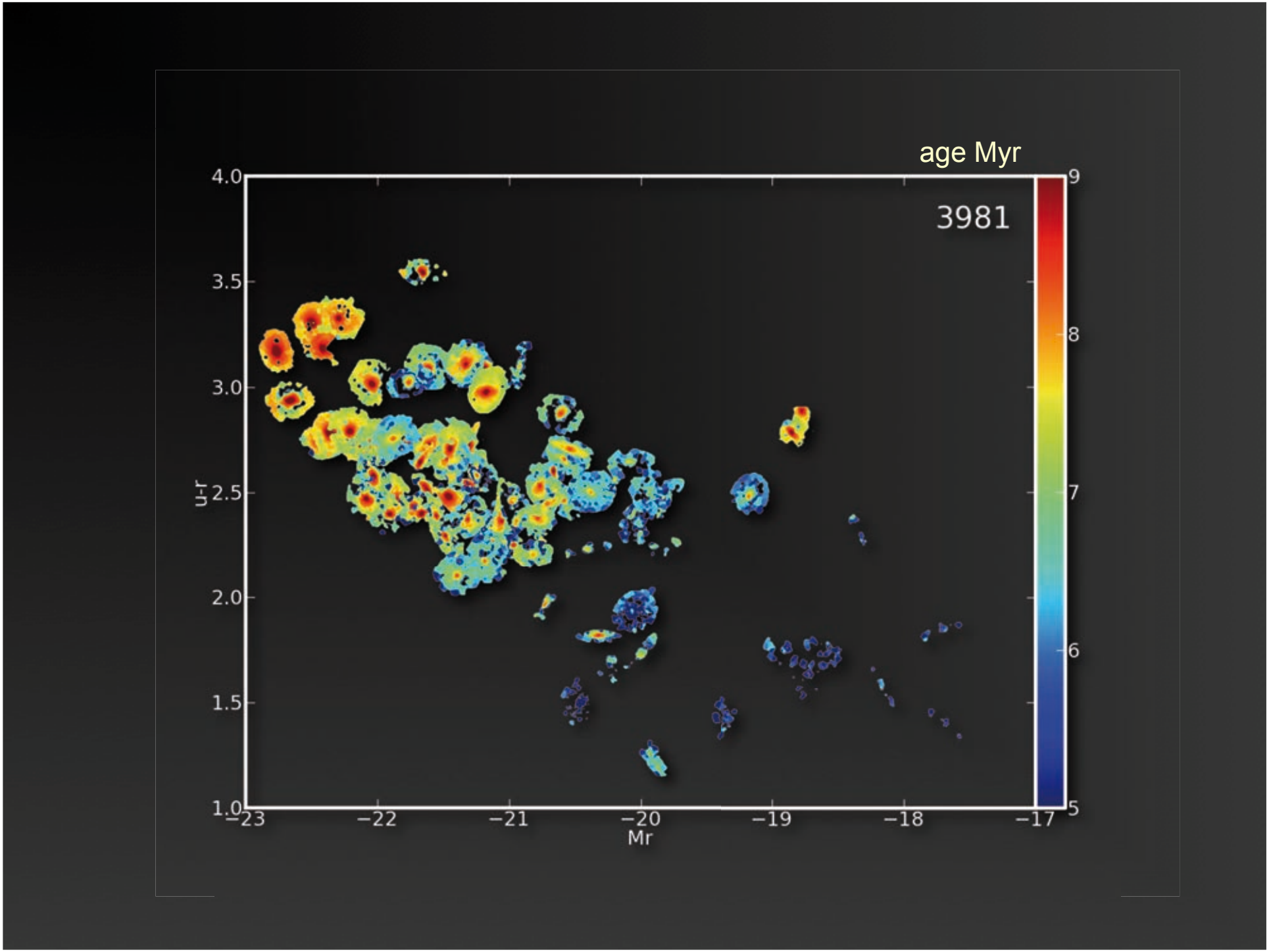
E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4], L. Wisotzki[4], C. Cortijo[1], and CALIFA collaboration[6]

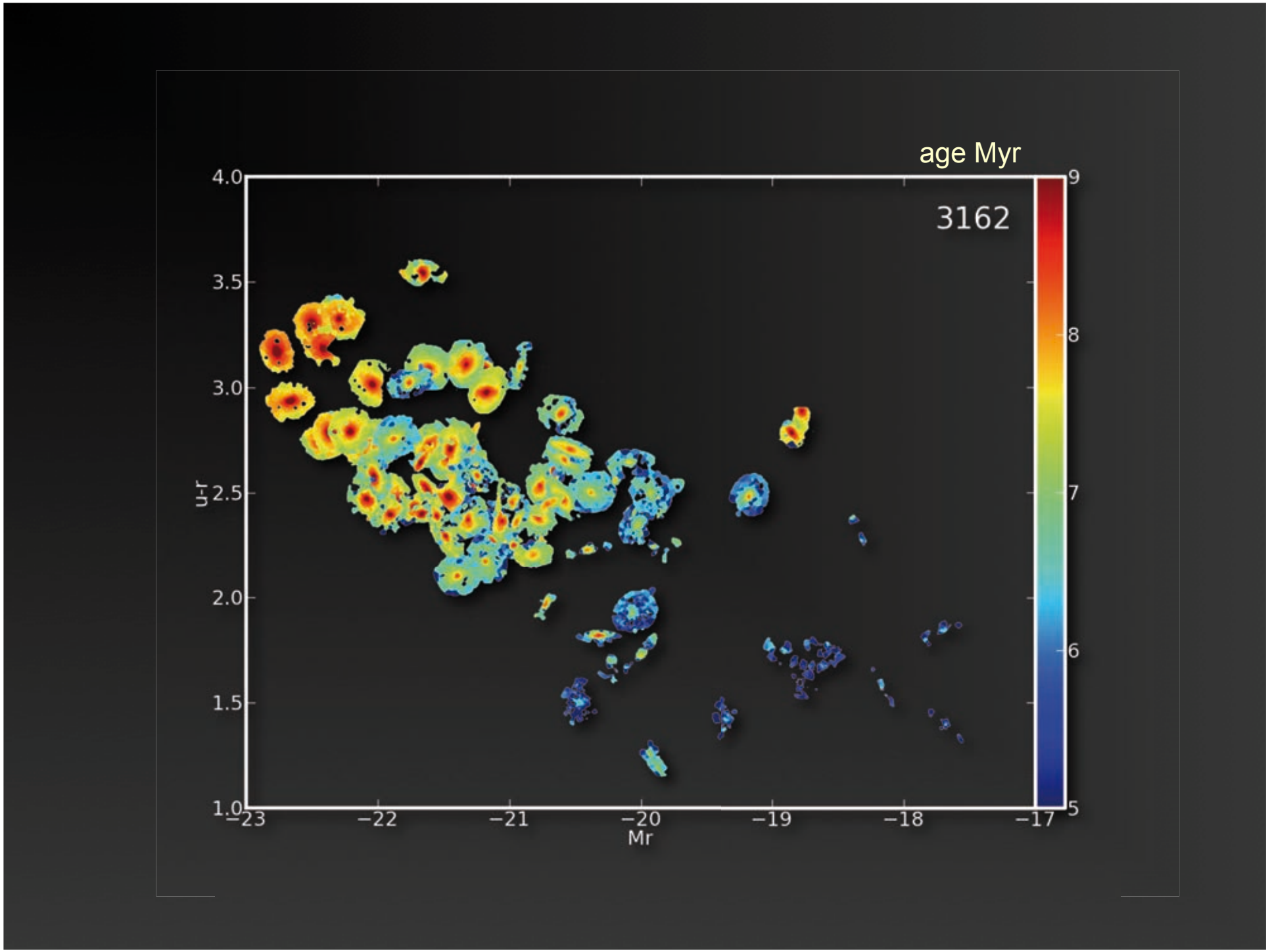


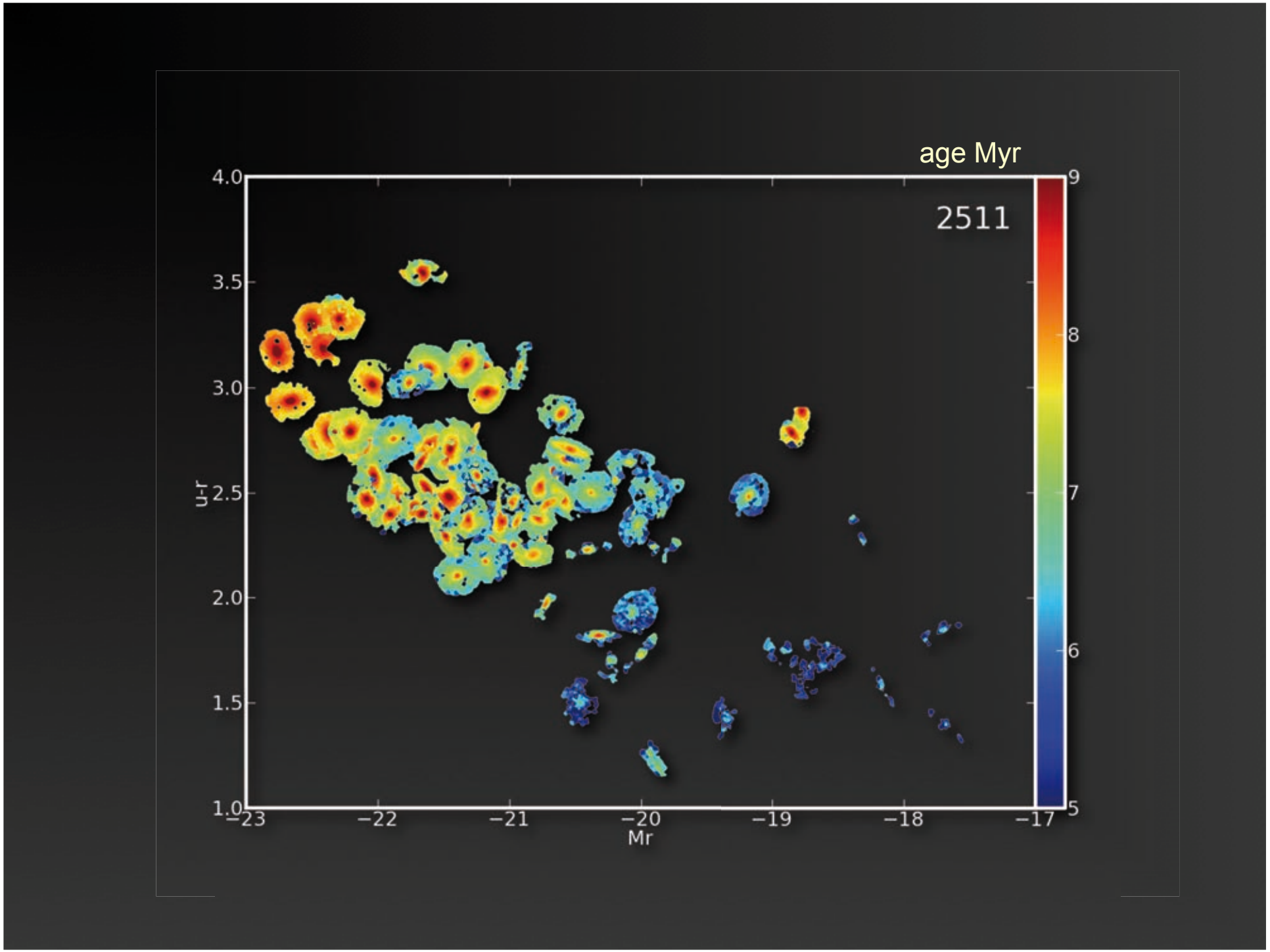

age Myr
7943
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

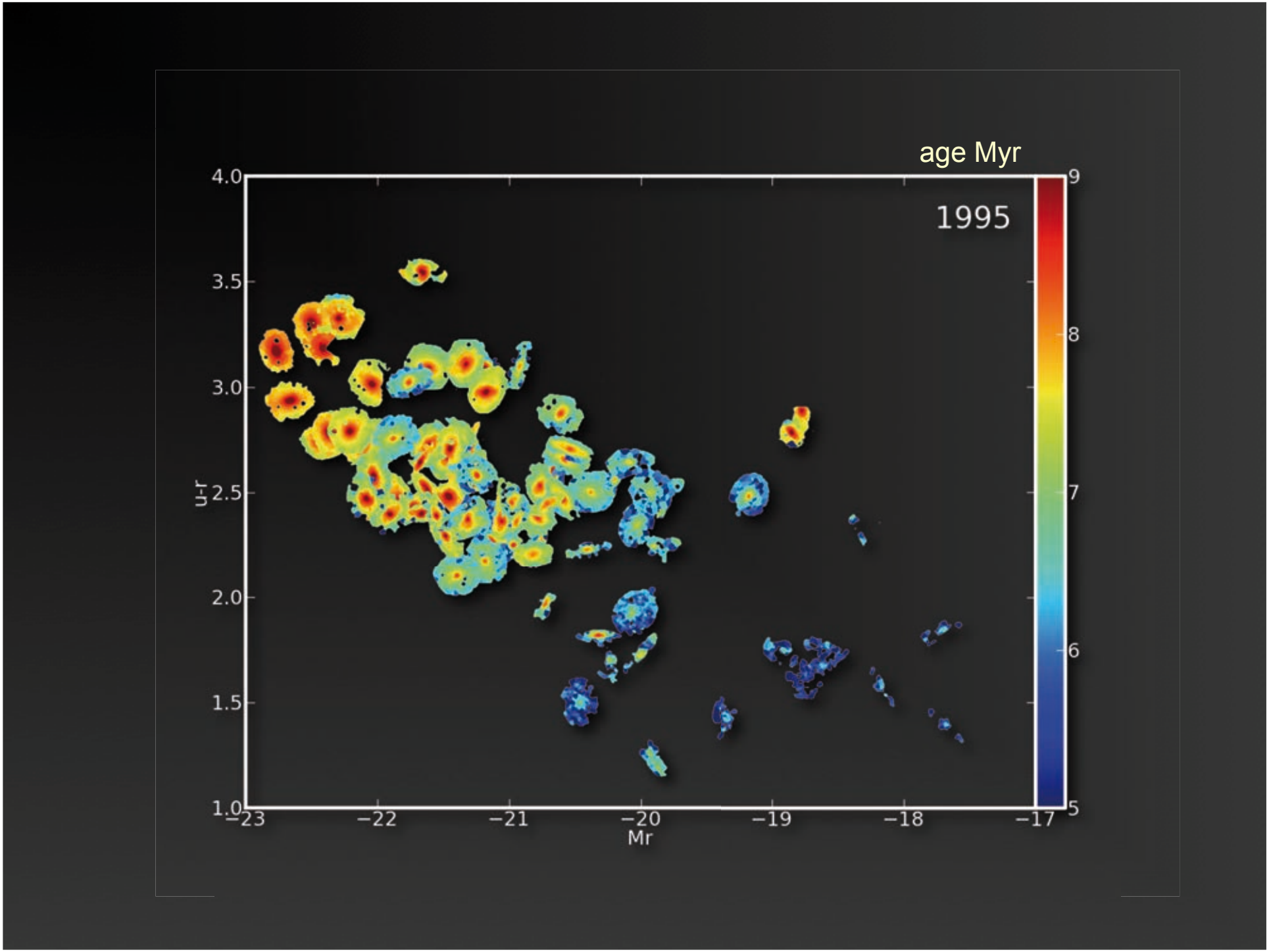

age Myr
6309
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

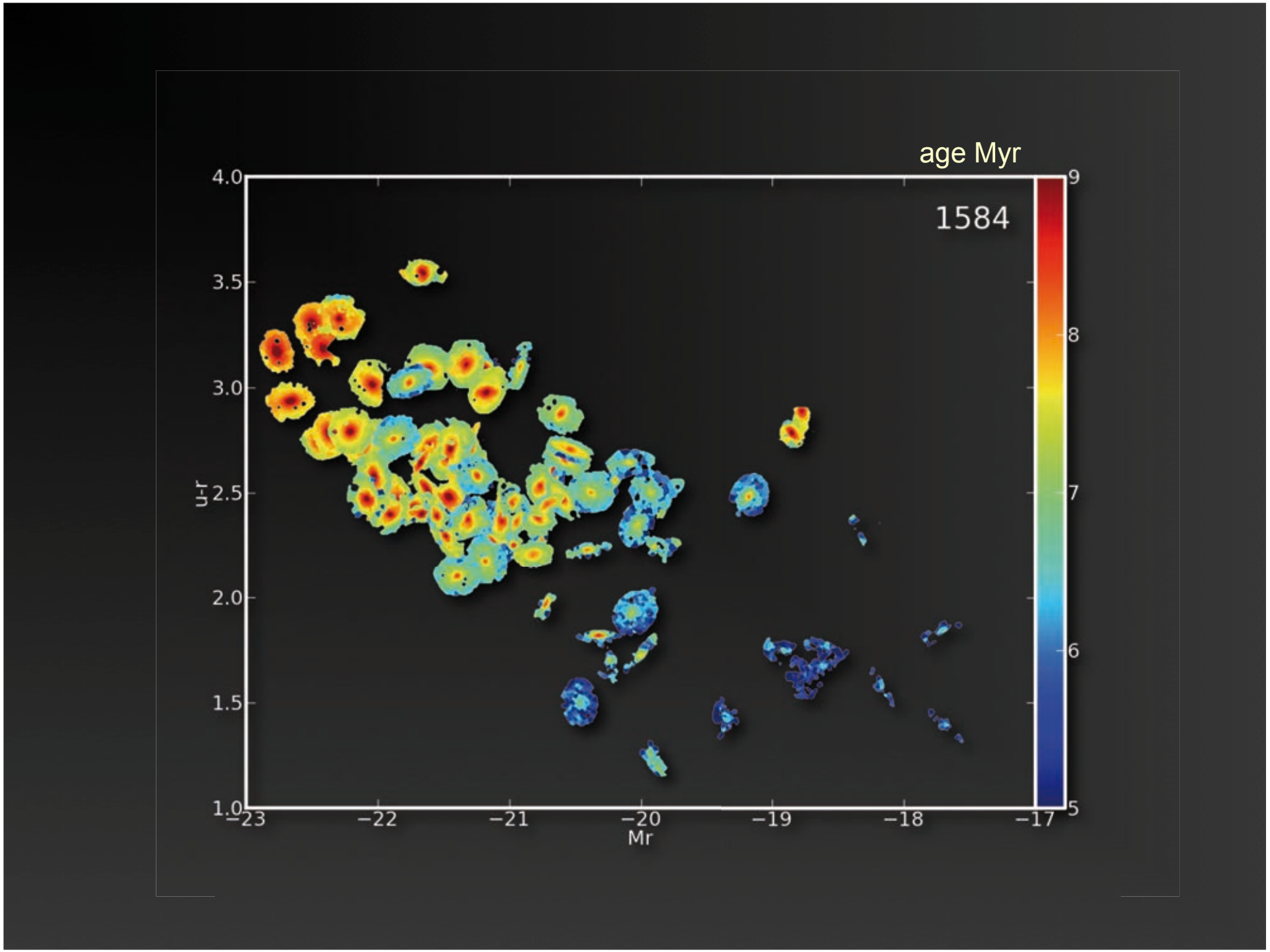

age Myr
5011
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

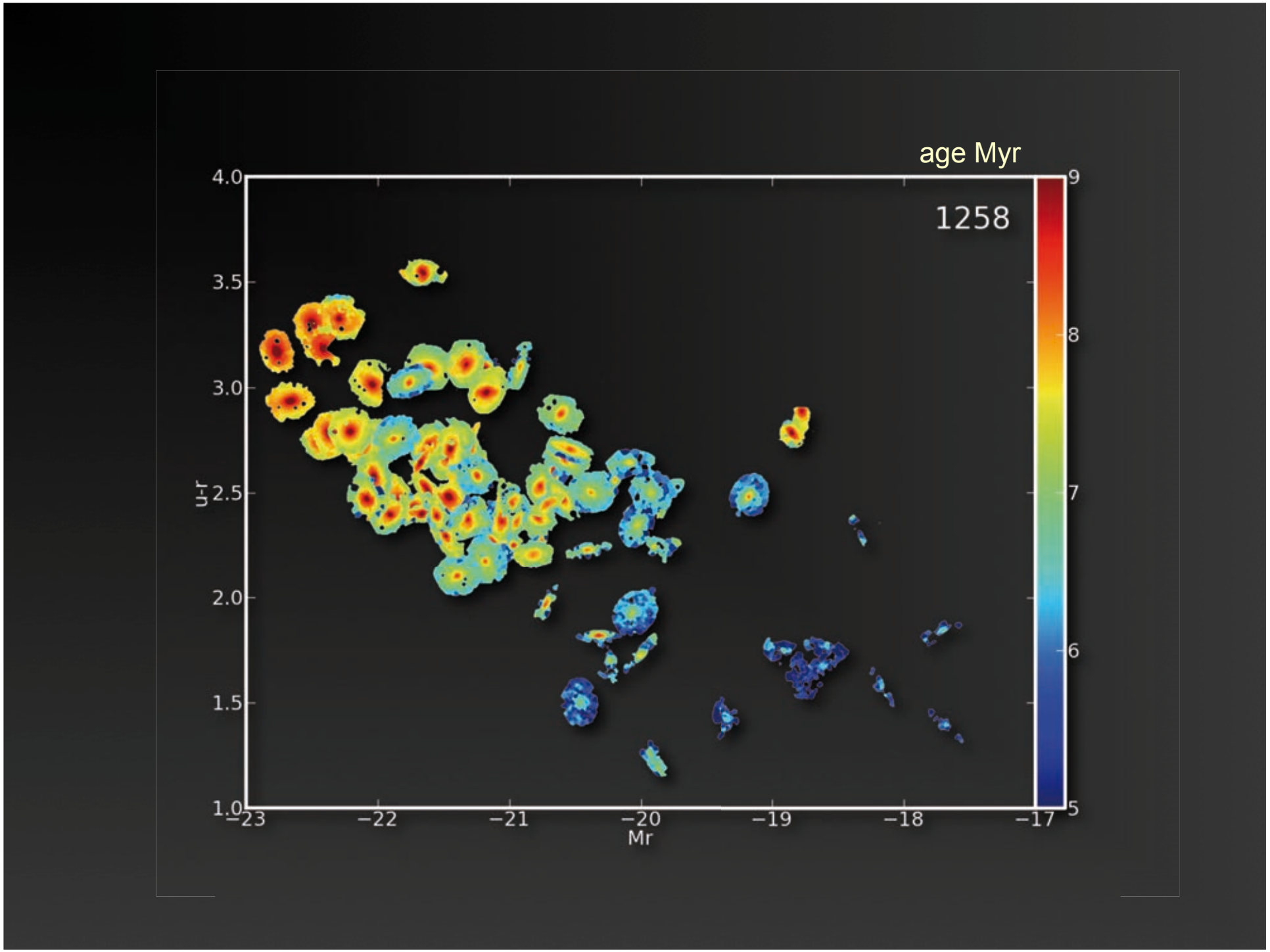

age Myr
3981
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

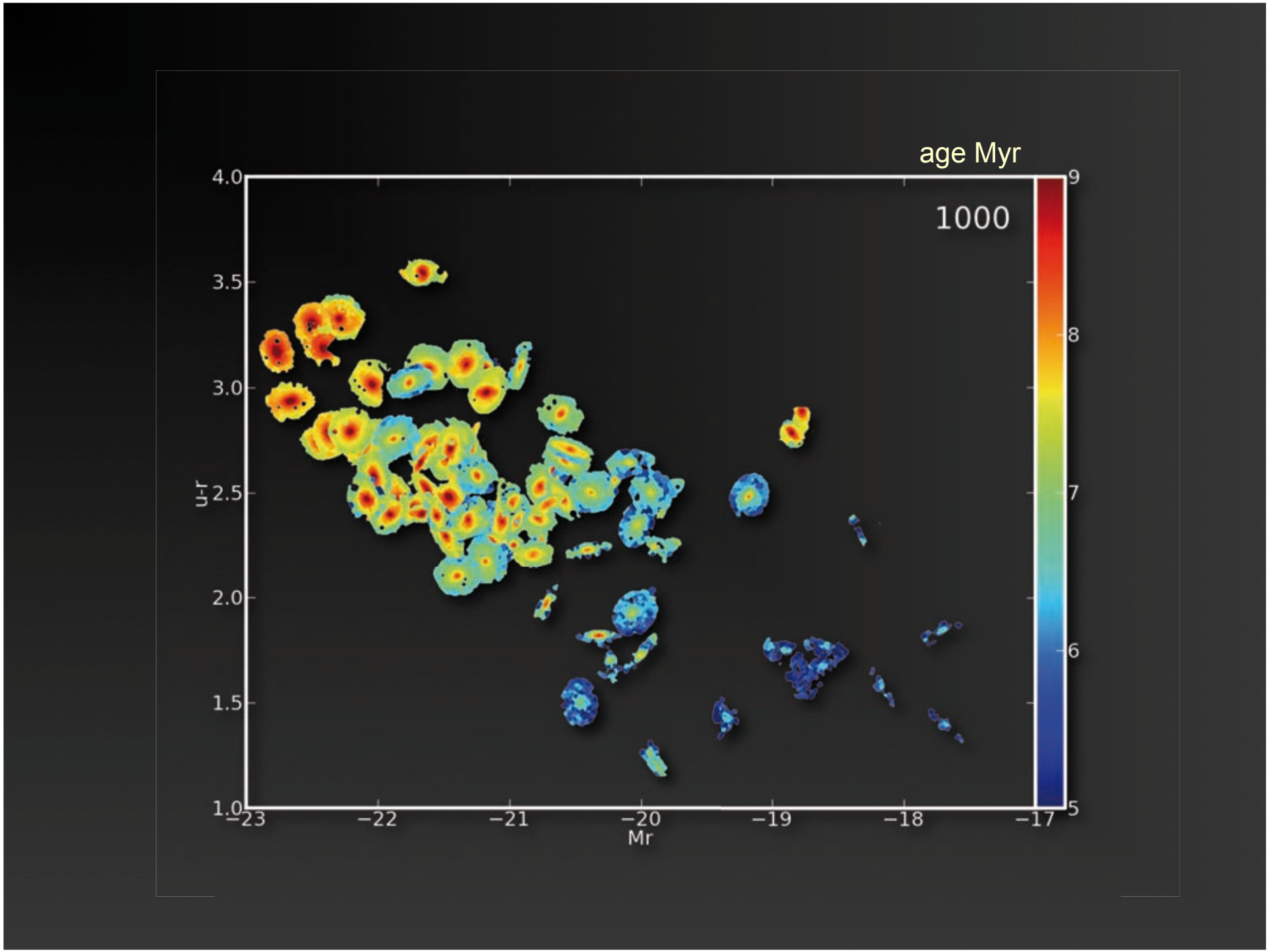

age Myr
3162
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

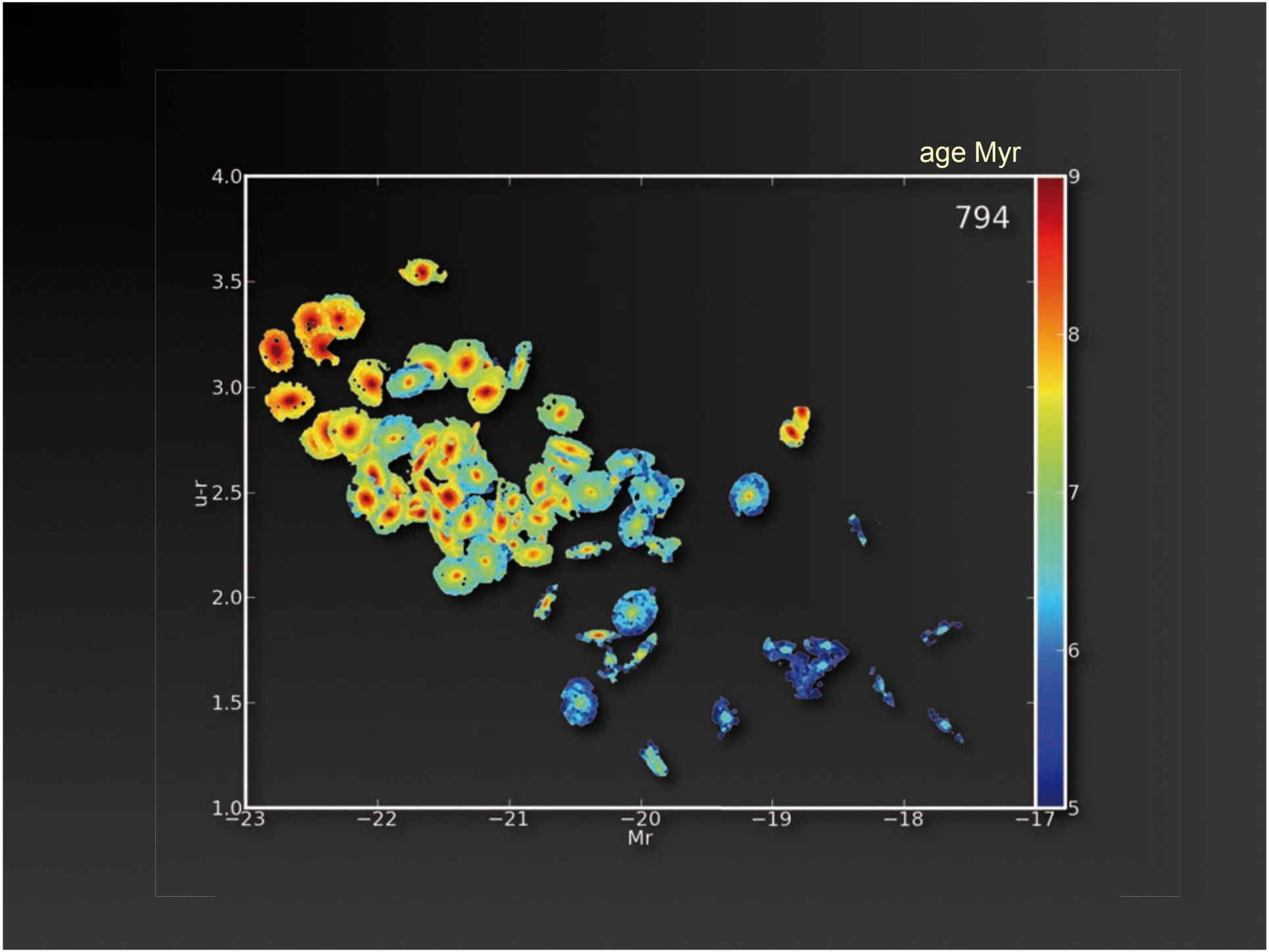

age Myr
2511
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

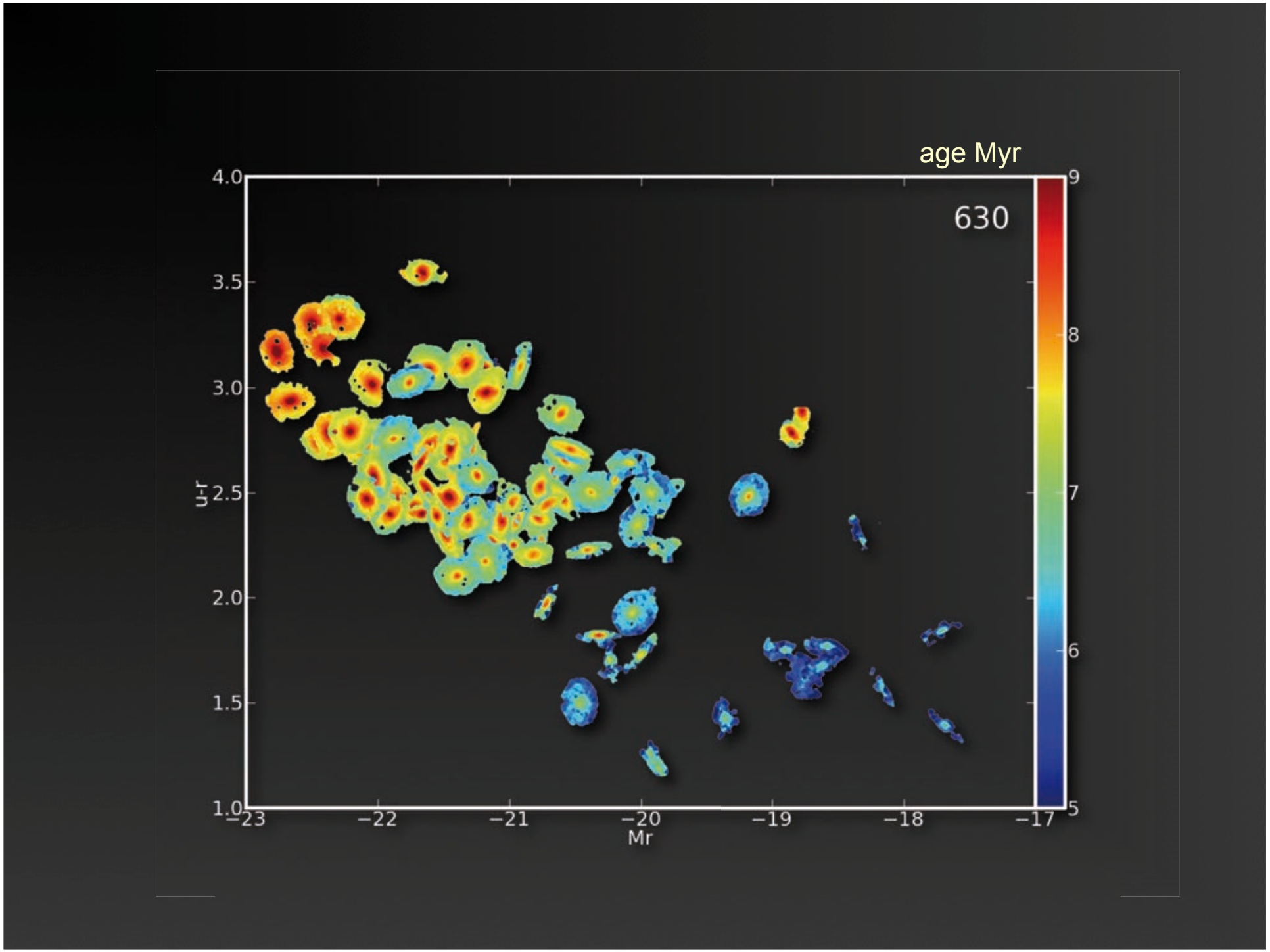

age Myr
1995
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

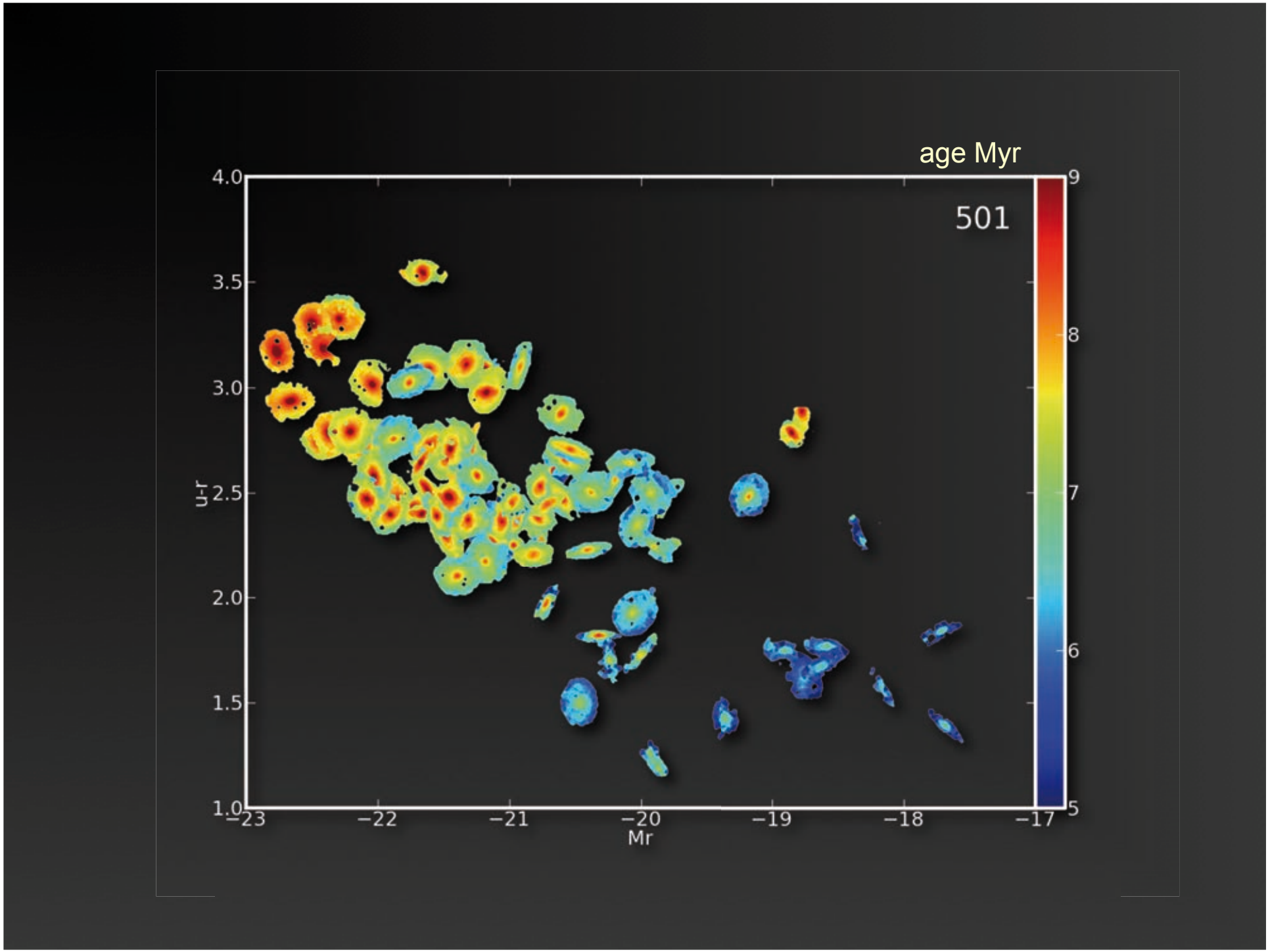

age Myr
1584
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

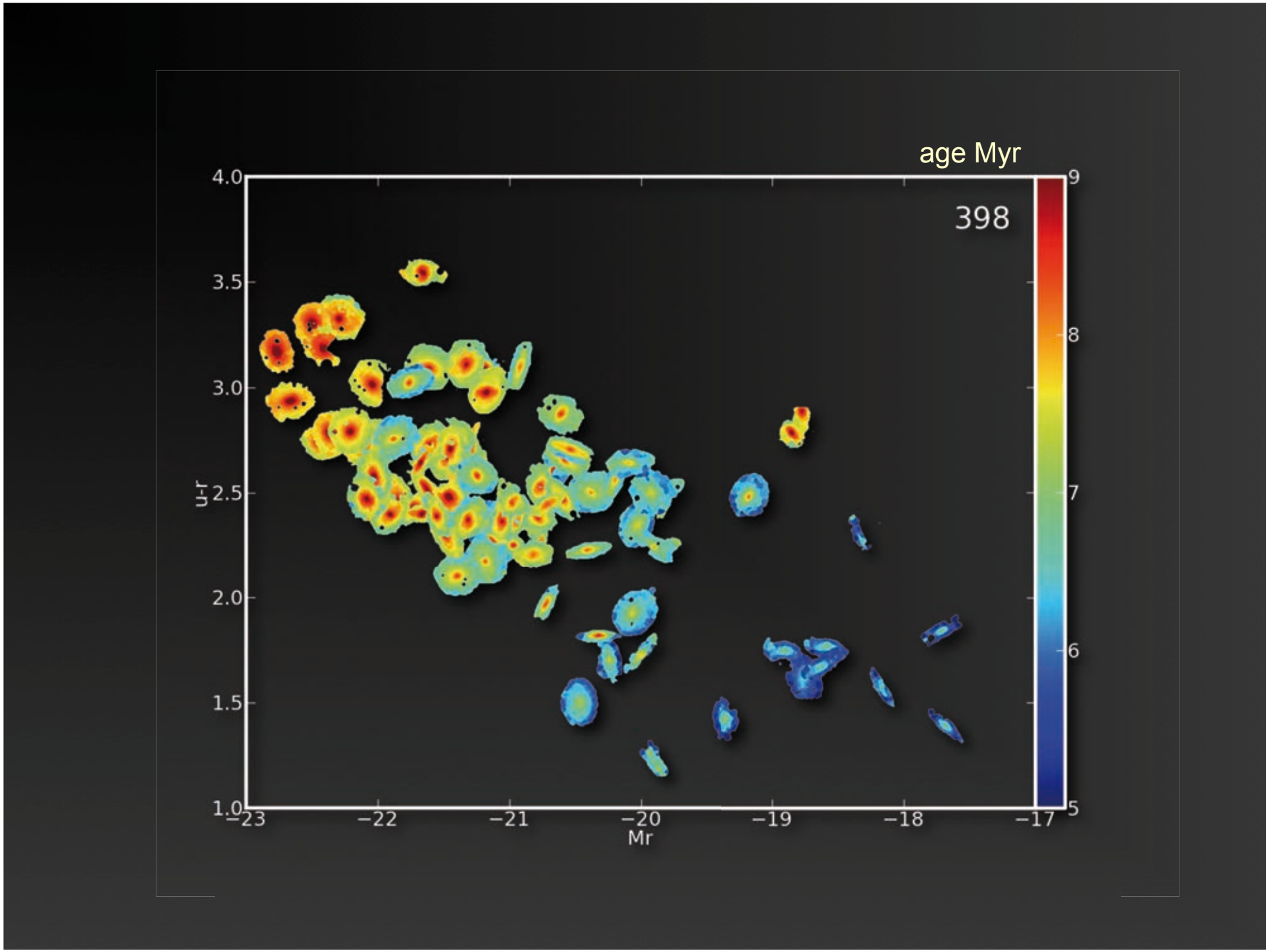

age Myr
1258
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

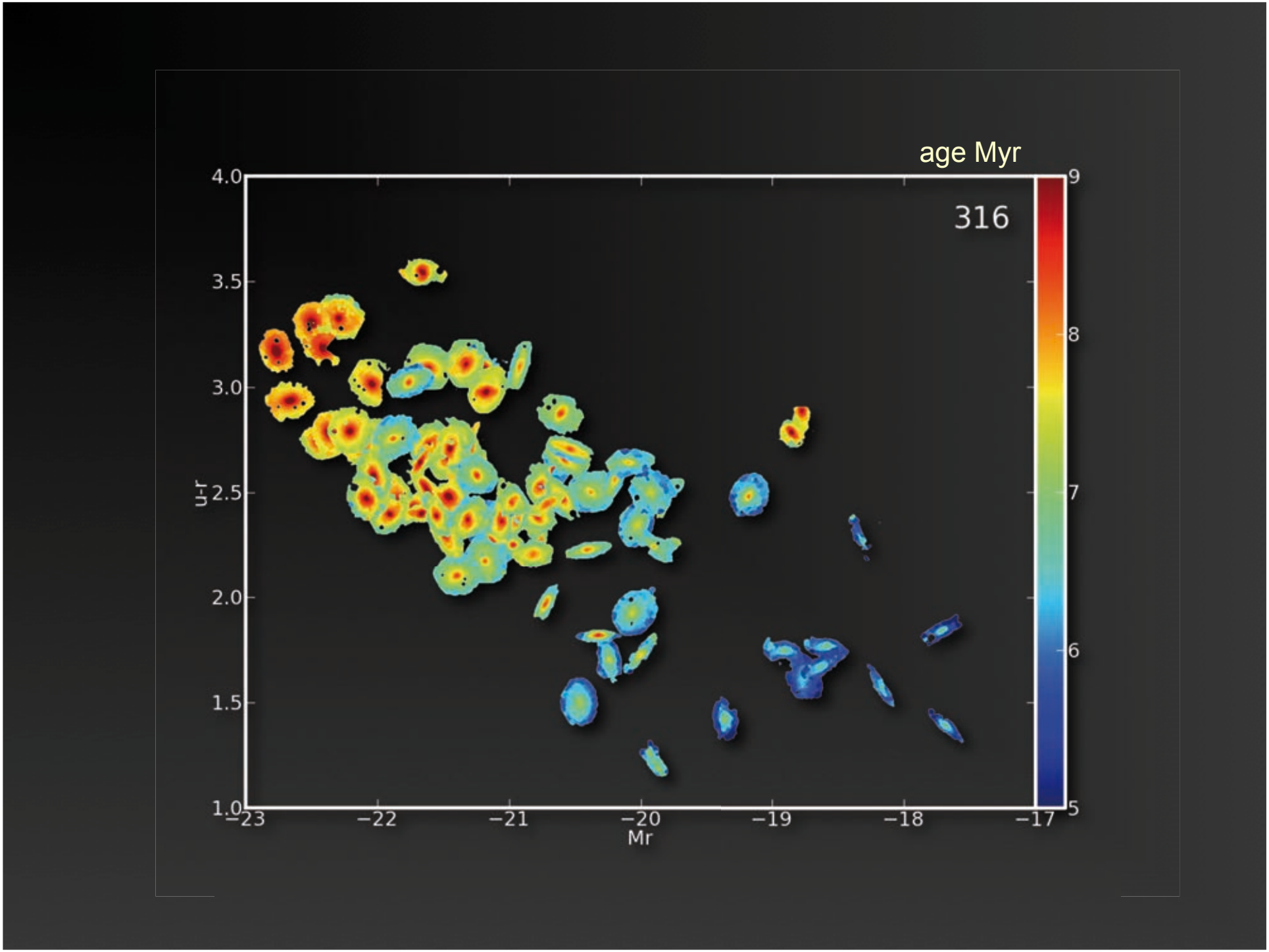

age Myr
1000
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

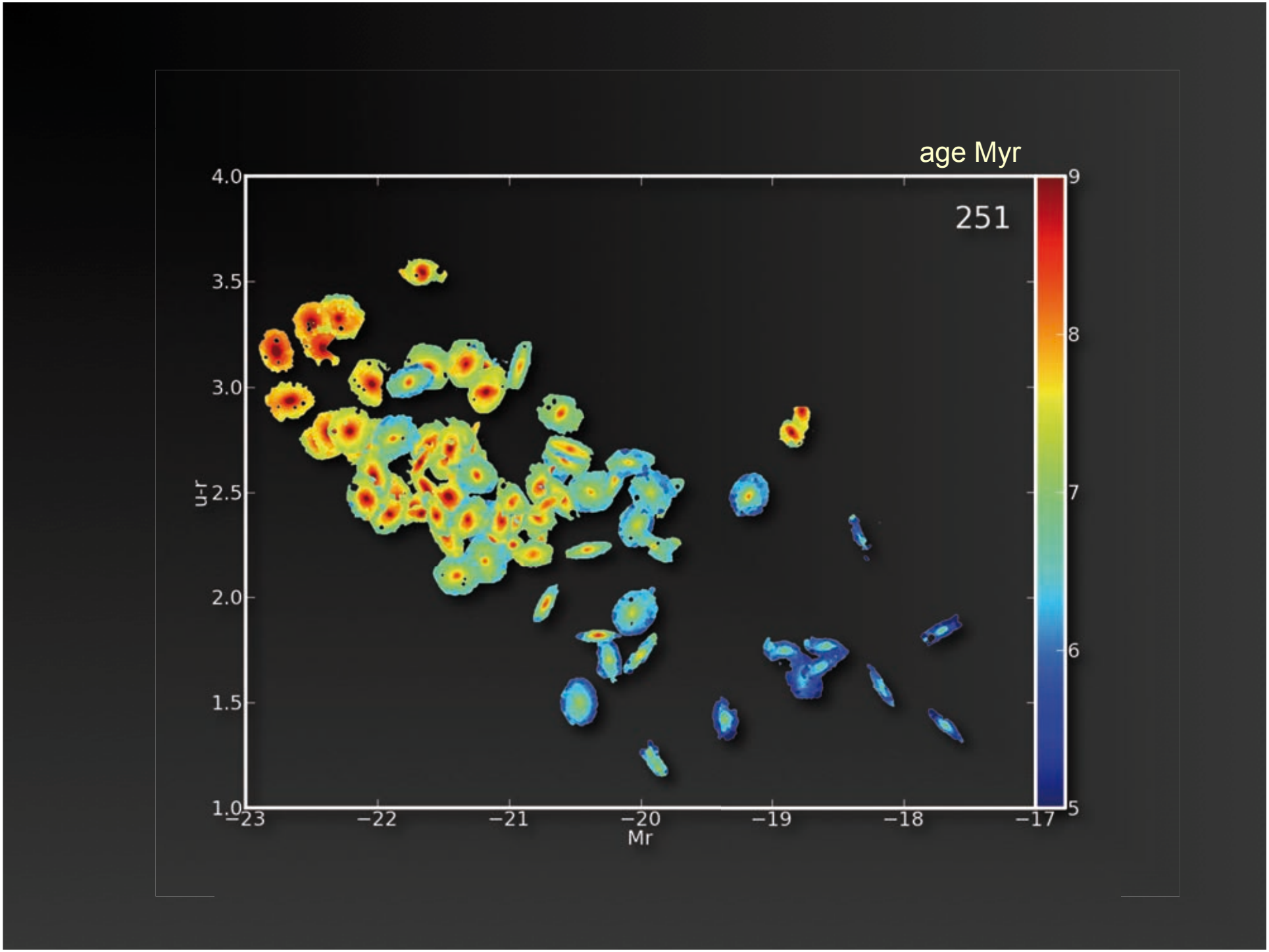

age Myr
794
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

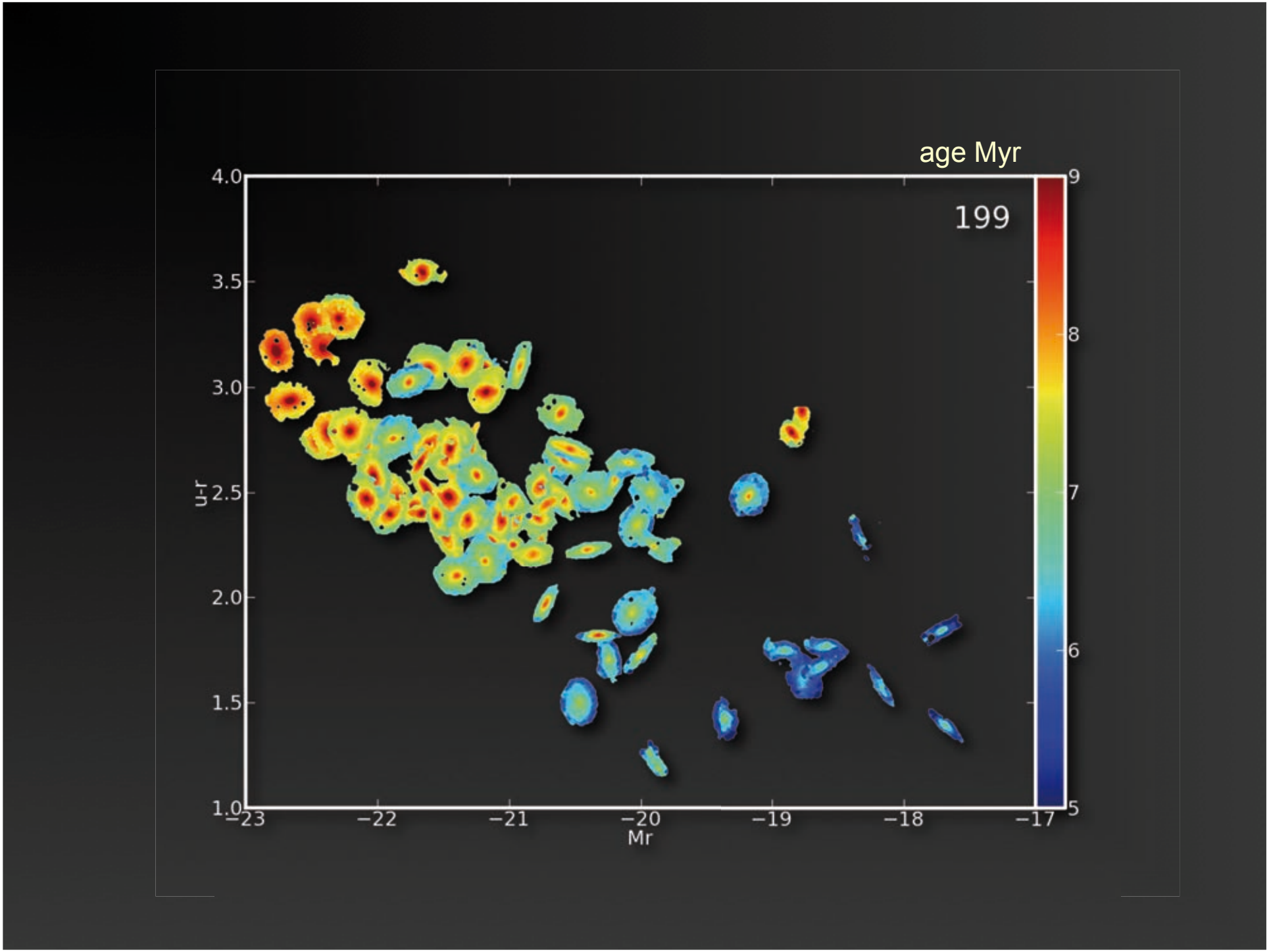

age Myr
630
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5


age Myr
501
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5


age Myr
398
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5


age Myr
316
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

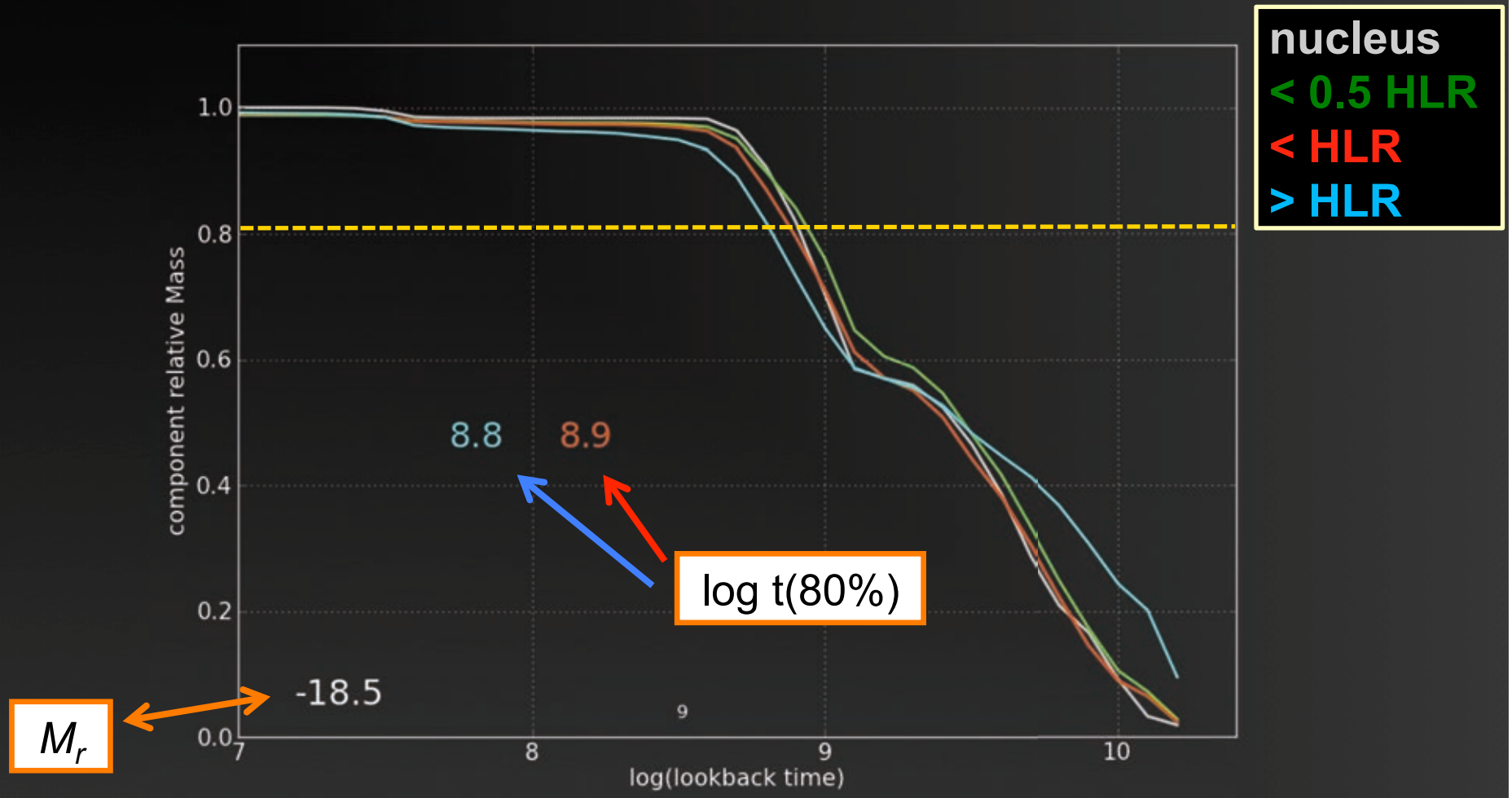

age Myr
251
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5


age Myr
199
4.0
3.5
3.0
2.5
2.0
1.5
1.0
u-r
−23
−22
−21
−20
−19
−18
−17
Mr
9
8
7
6
5

THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: AN INSIDE-OUT GROWTH VIEW FROM THE CALIFA SURVEY

E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4], L. Wisotzki[4], C. Cortijo[1], and CALIFA collaboration[6]

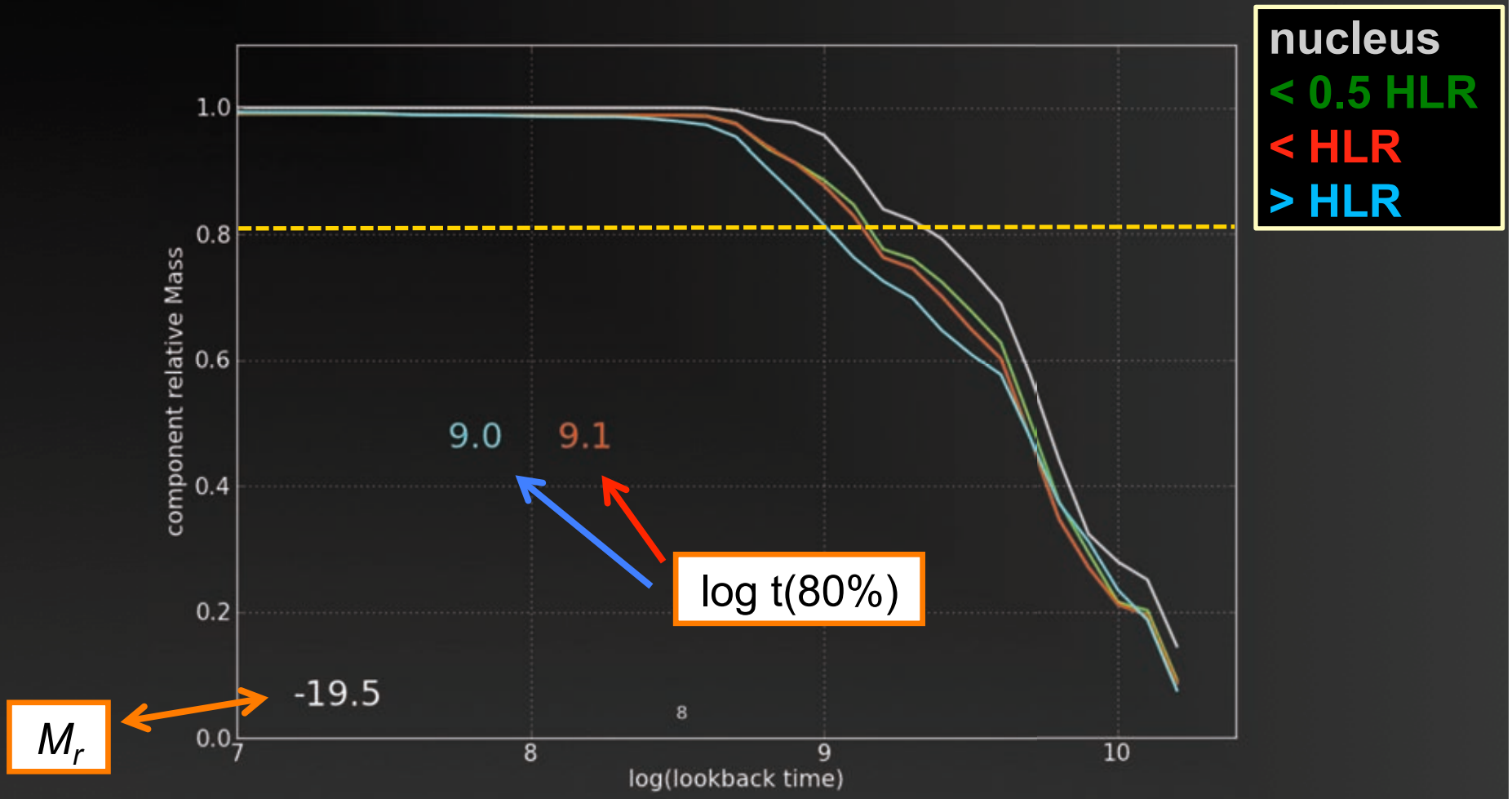
Mass build up as a function of R



THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: AN INSIDE-OUT GROWTH VIEW FROM THE CALIFA SURVEY

E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4], L. Wisotzki[4], C. Cortijo[1], and CALIFA collaboration[6]

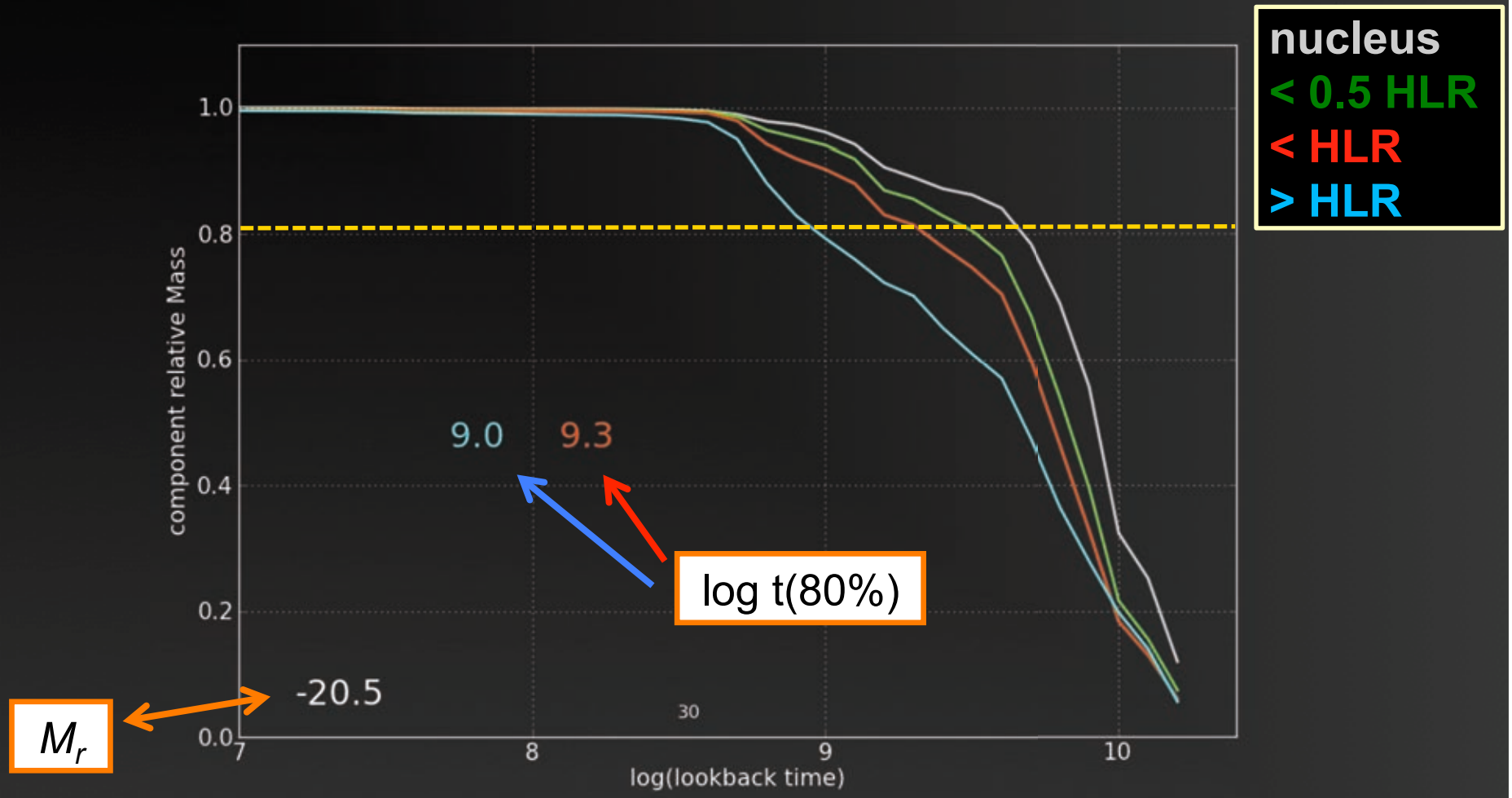
Mass build up as a function of R



THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: AN INSIDE-OUT GROWTH VIEW FROM THE CALIFA SURVEY

E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4], L. Wisotzki[4], C. Cortijo[1], and CALIFA collaboration[6]

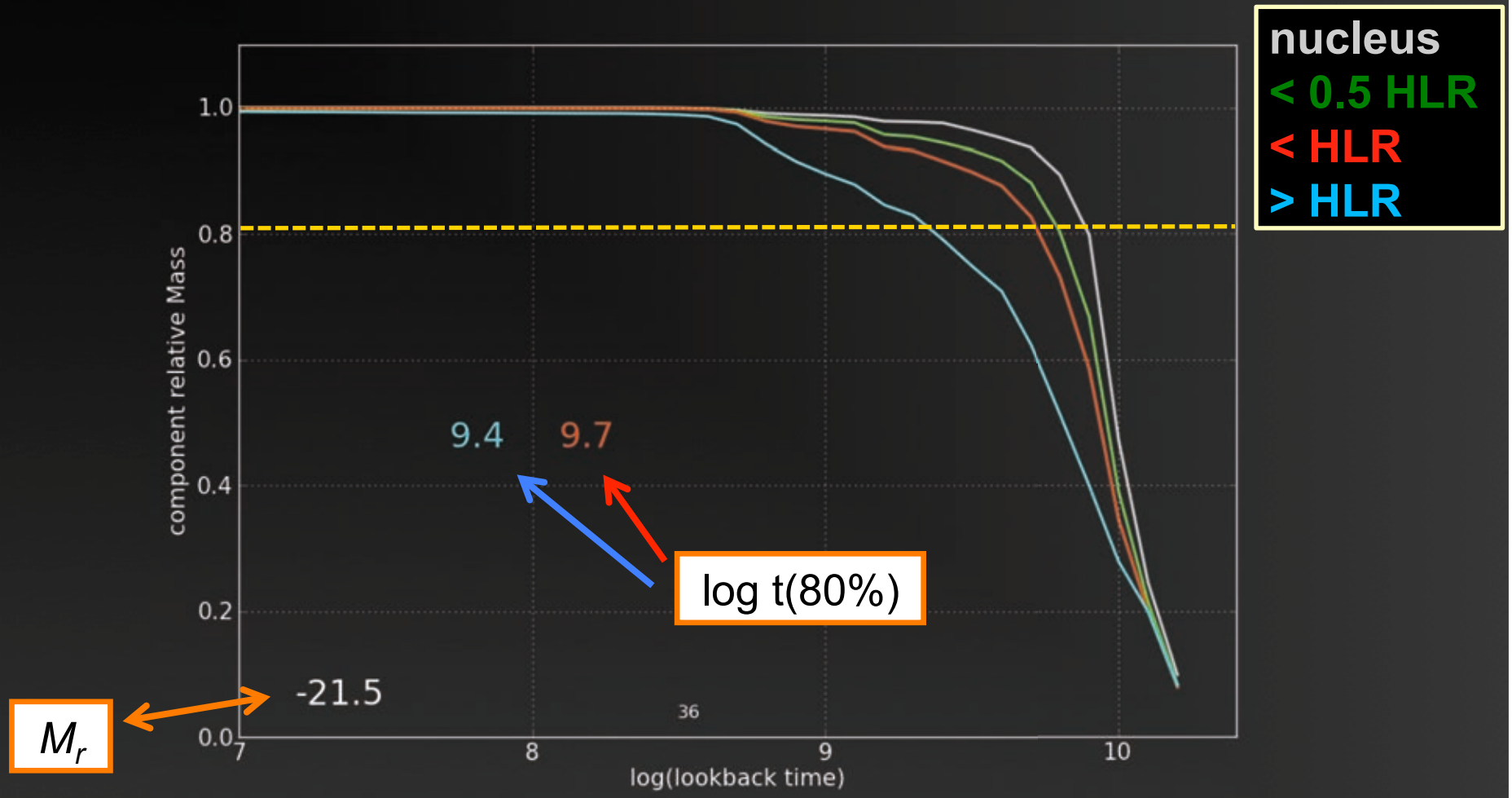
Mass build up as a function of R



THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: AN INSIDE-OUT GROWTH VIEW FROM THE CALIFA SURVEY

E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4], L. Wisotzki[4], C. Cortijo[1], and CALIFA collaboration[6]

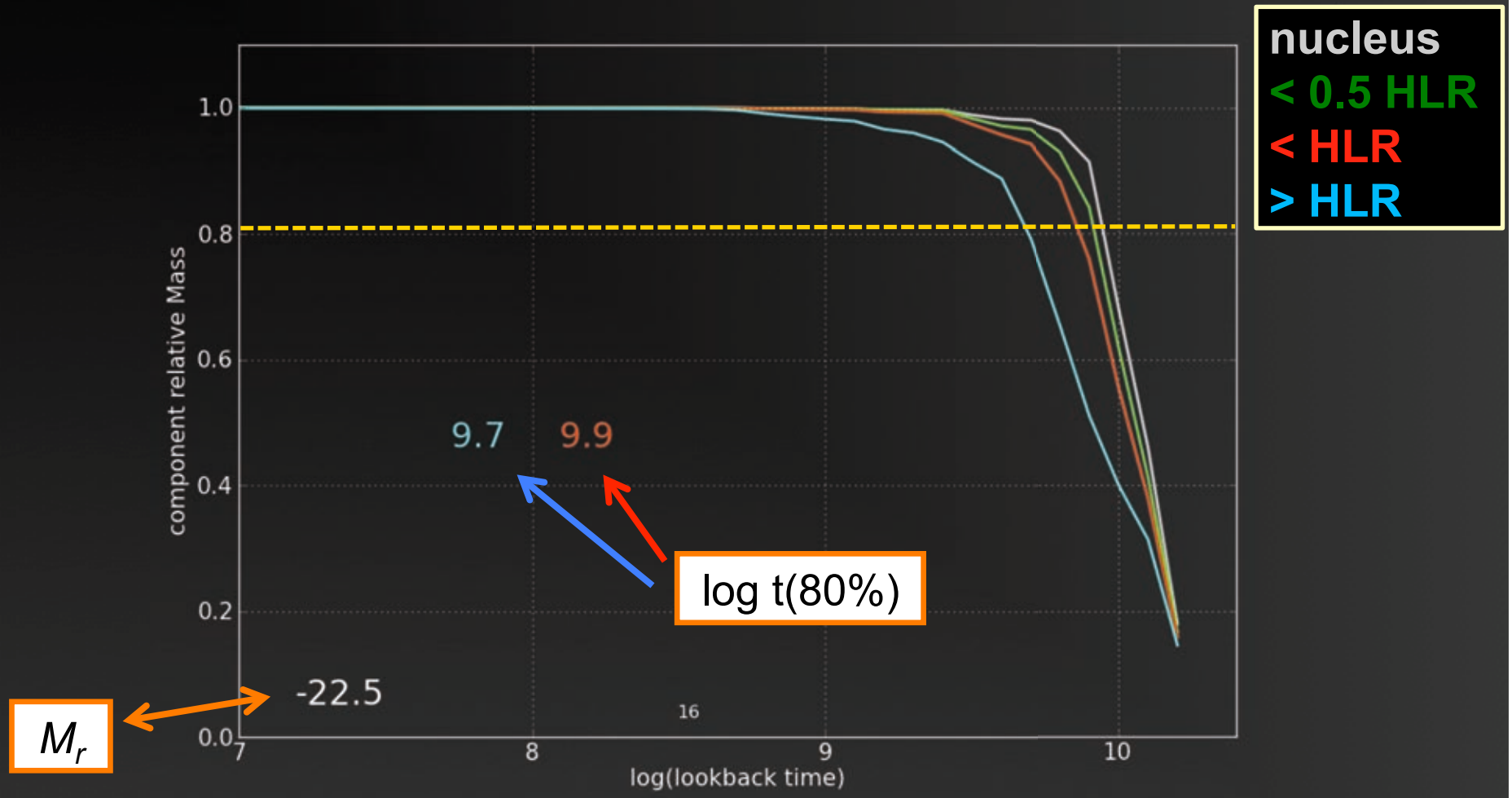
Mass build up as a function of R



THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: AN INSIDE-OUT GROWTH VIEW FROM THE CALIFA SURVEY

E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4], L. Wisotzki[4], C. Cortijo[1], and CALIFA collaboration[6]

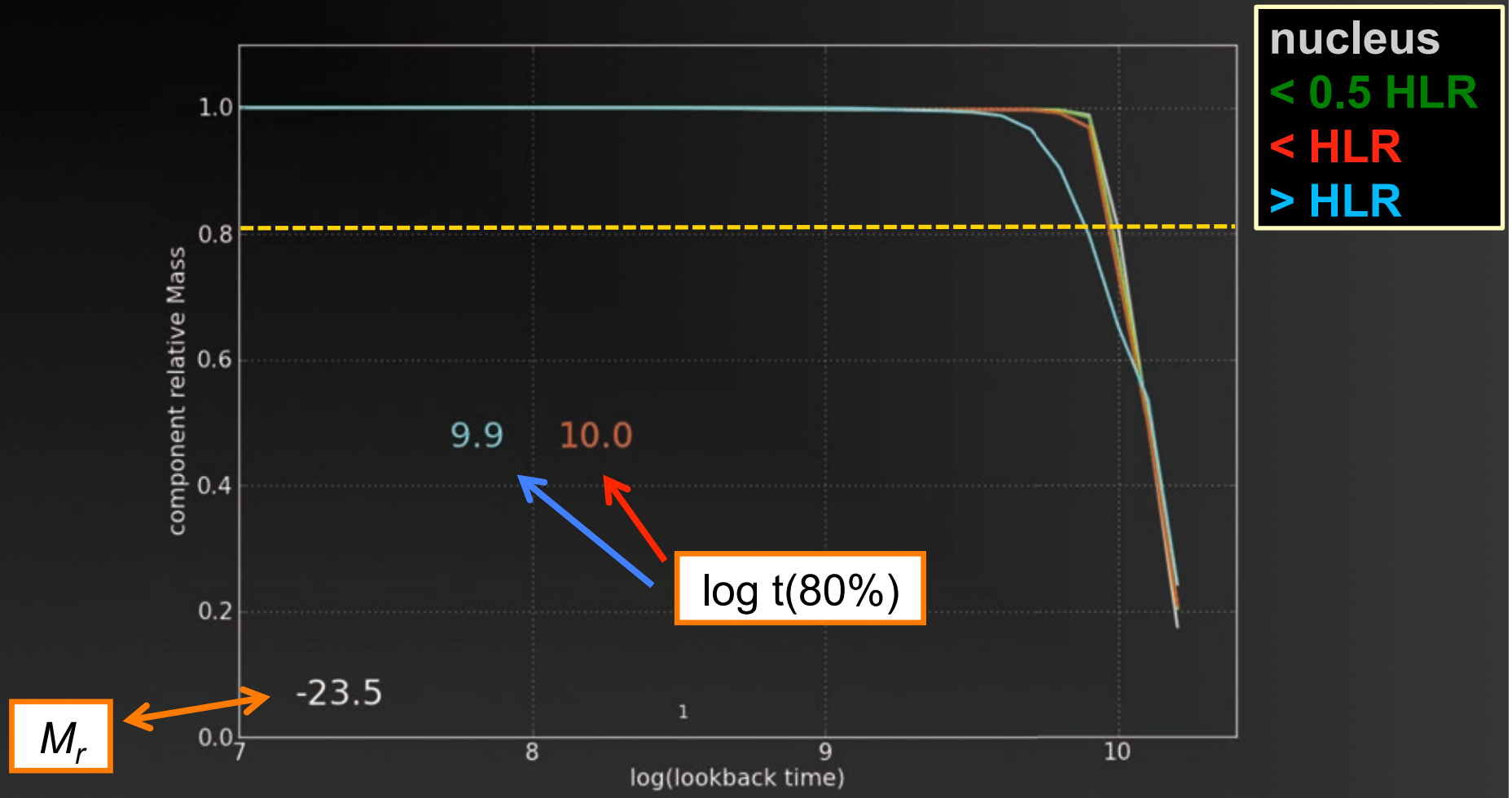
Mass build up as a function of R

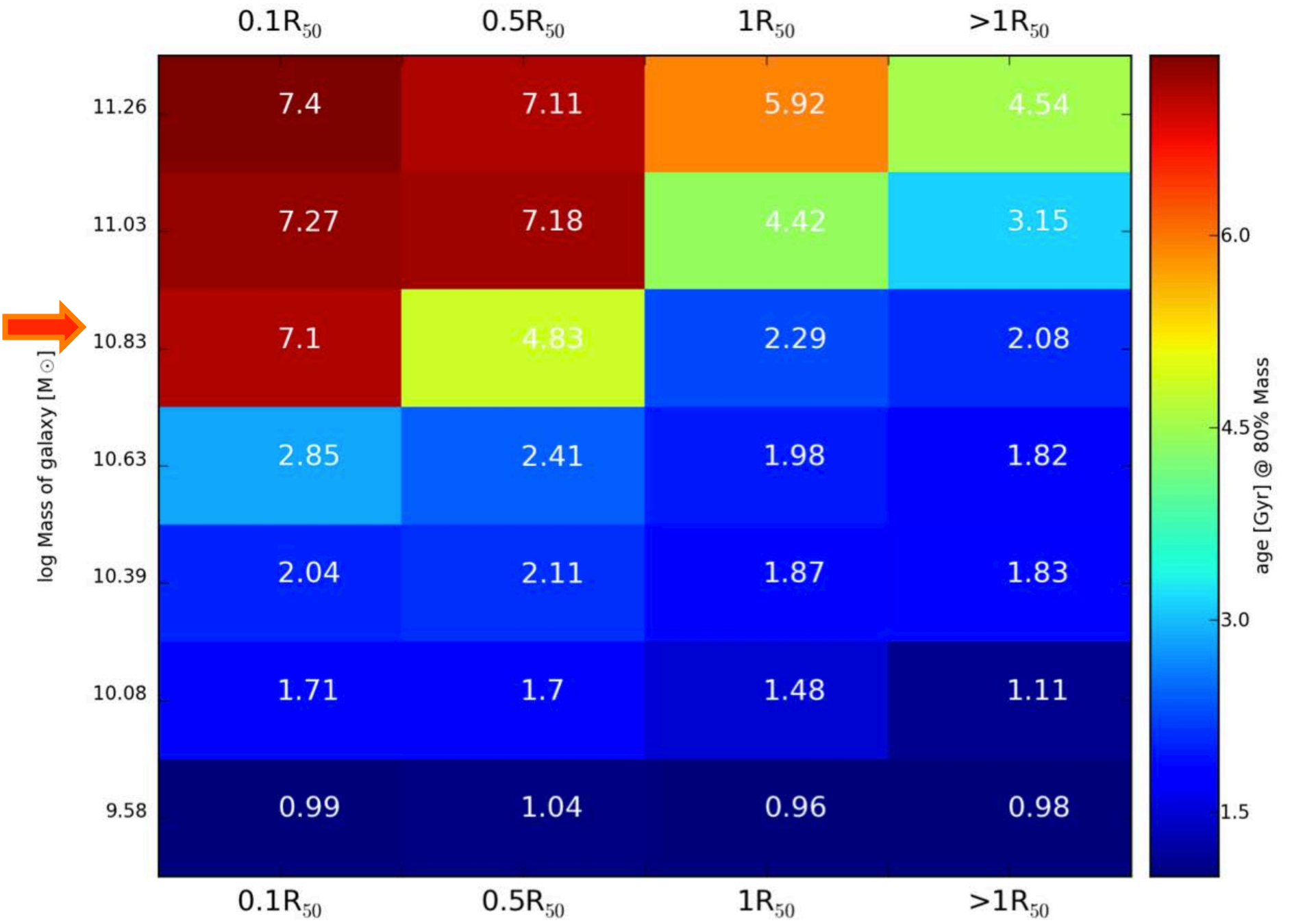


THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: AN INSIDE-OUT GROWTH VIEW FROM THE CALIFA SURVEY

E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4], L. Wisotzki[4], C. Cortijo[1], and CALIFA collaboration[6]

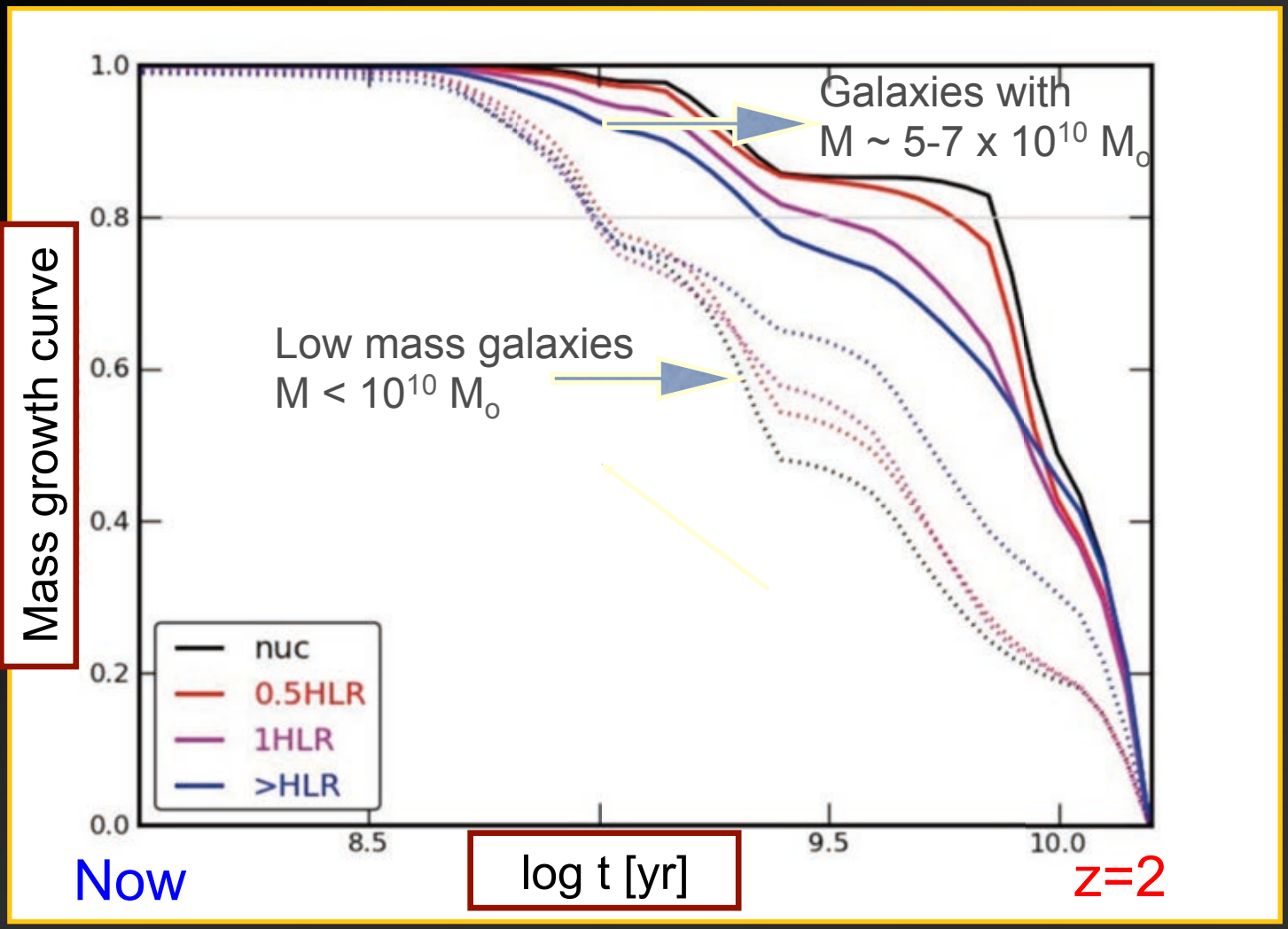
Mass build up as a function of R





Pérez et al. 2013, ApJL,764, L1

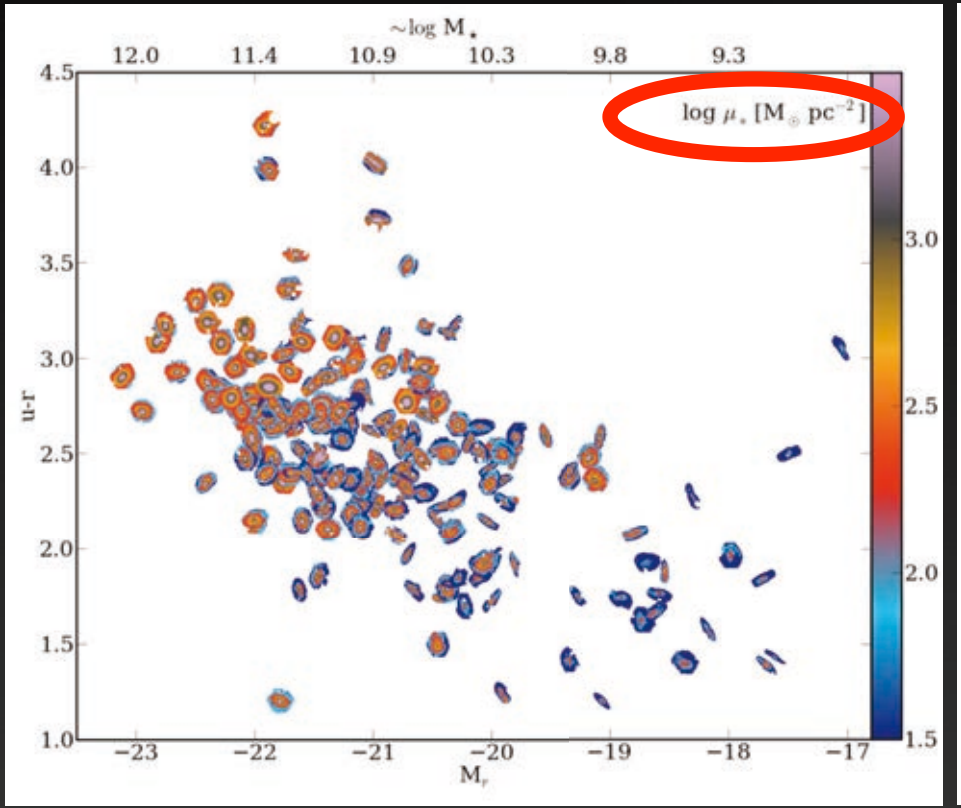
When and where the mass is assembled ?

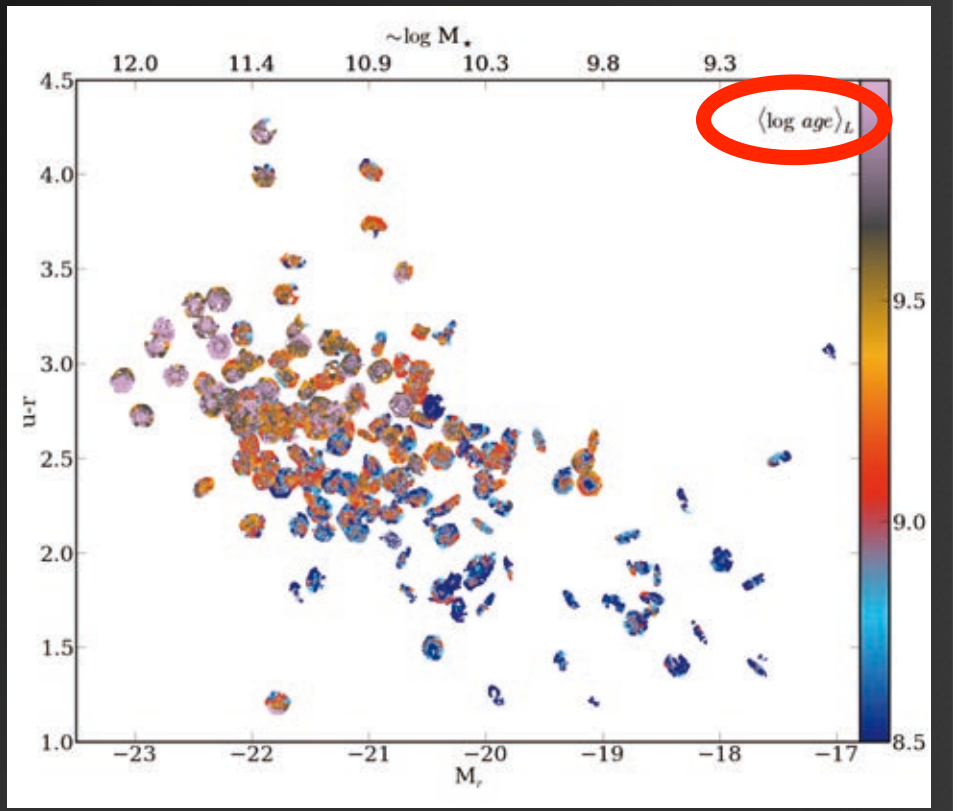


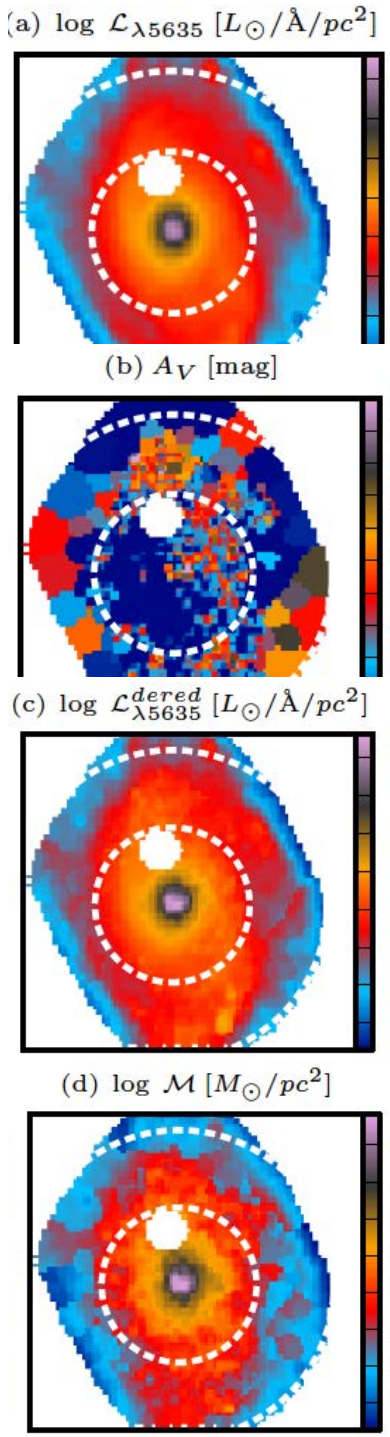
Galaxies with $M > 10^{10} M_o$ grow inside-out
The central core is assembled early ($z > 2$), but their envelope continues to assemble ($z = 2 – 0$)

The star formation history of CALIFA galaxies: Radial structures

R. M. González Delgado[1], E. Pérez[1], R. Cid Fernandes[1,2], R. García Benito[1], A. L. de Amorim[2], S. F. Sánchez[1,3], B. Husemann[4], C. Cortijo-Ferrero[1], R. López Fernández[1], P. Sánchez-Blázquez[5], S. Bekeraite[4], C. J. Walcher[4], J. Falcón-Barroso[6,7], A. Gallazzi[8], G. van de Ven[9], J. Alves[10], J. Bland-Hawthorn[11], R. C. Kennicutt, Jr.[12] D. Kupko[4], M. Lyubenova[9], D. Mast[1,3], M. Mollá[13], R. A. Marino[14], A. Quirrenbach[15], J. M. Vílchez[1], L. Wisotzki[4], and CALIFA collaboration



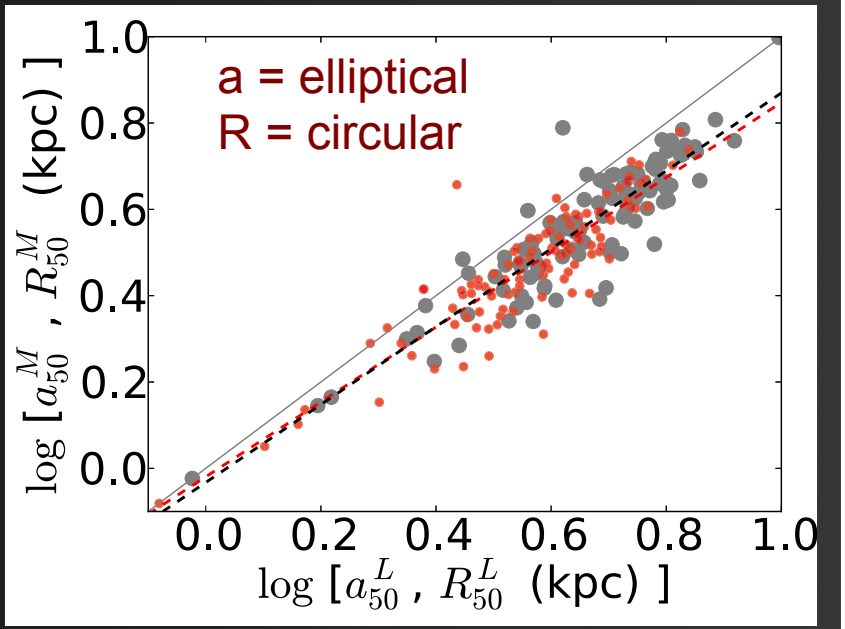


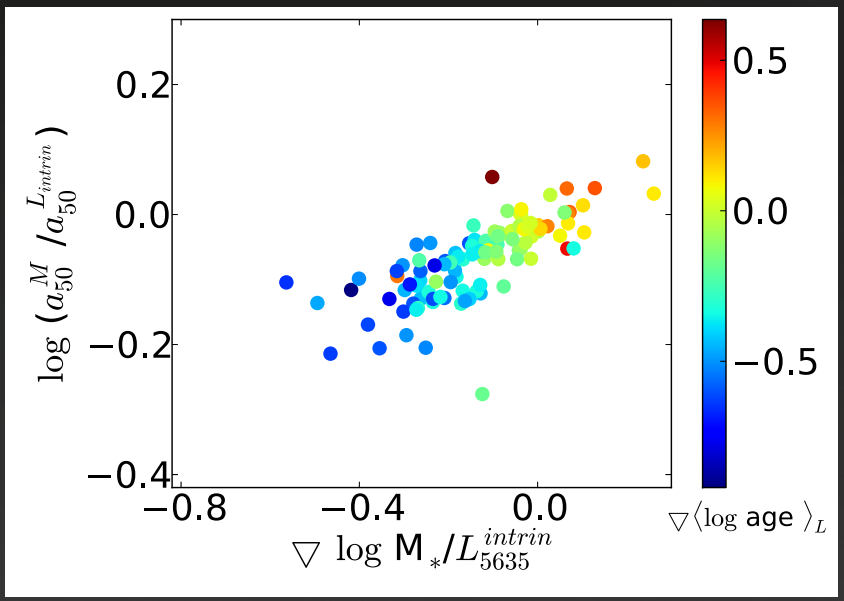


Light x Mass sizes (WYSI *not* WYG!)

➔ Galaxies are **~20%** more compact in mass than in light

Systematic spatial variations in A_V and/or M/L cause the 20% difference in radii.





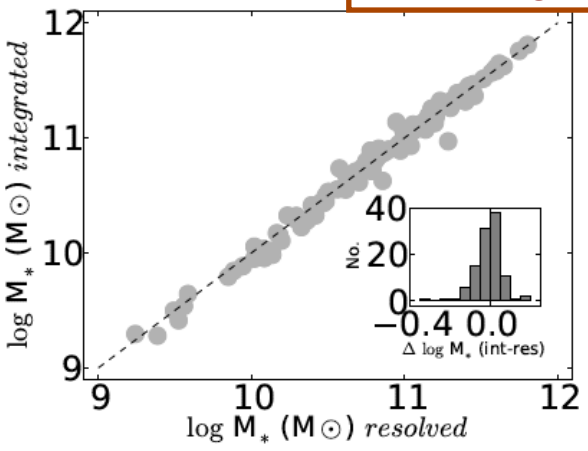
¿∇A_V or ∇M/L?

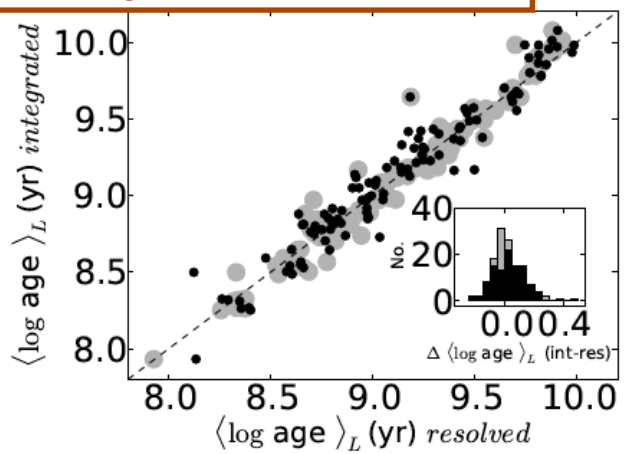
- ~ **5%** due to ∇A_V
- **~15%** due to ∇M/L (age & Z gradients)

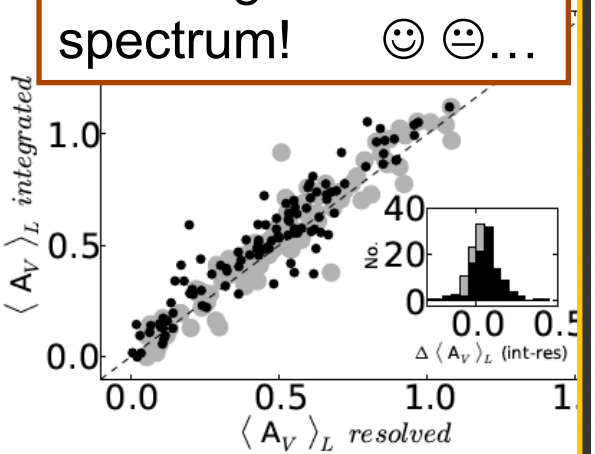
The whole x the sum of the parts
(the meaning of integrated spectra)

➔ Galaxy-wide spatially averaged properties match those obtained from the integrated spectrum! ☺ 😐…

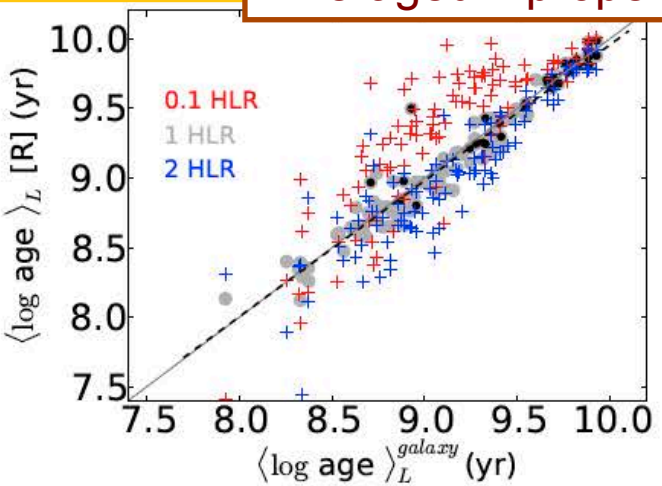
Averaged x integrated properties

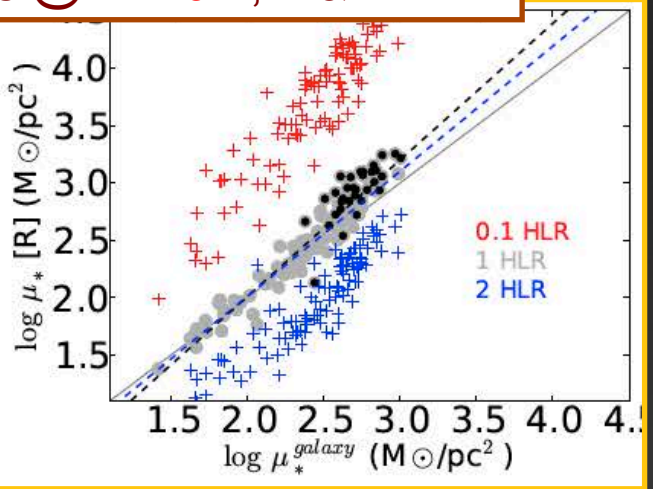






Averaged x properties @ R = 0.1, 1 & 2 HLR

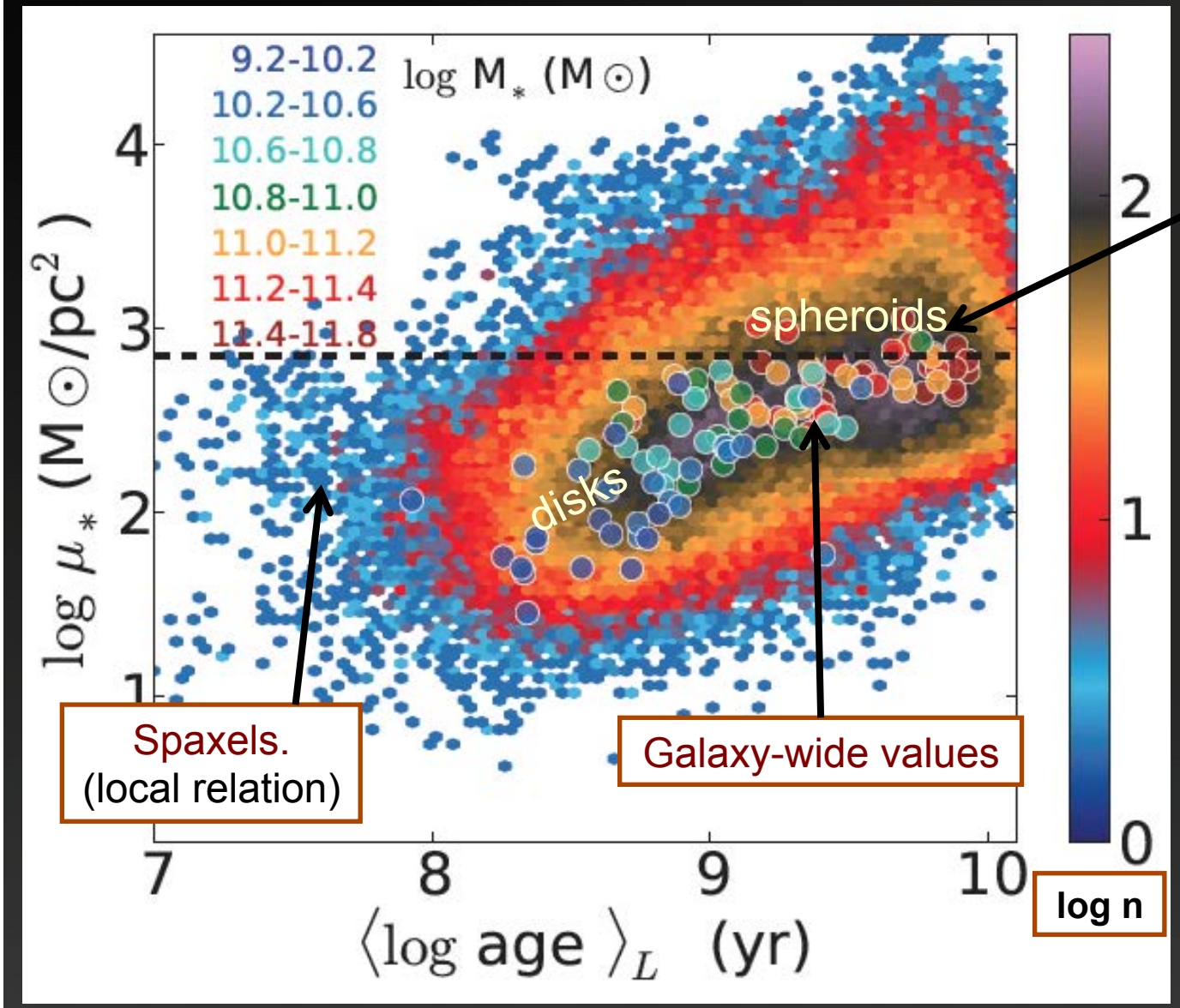




Spatially averaged properties match those at 1 HLR.

➔ Effective radii are really effective!

Global x local: is SFH driven by M_* or μ_* ?



Note log n scale:
Lots of spaxels here!
Mostly @ R ~ 1 HLR

Galaxy-wide values match those at R~1HLR.

Break at

$M_* = 7 \times 10^{10}\ M_o$
$\mu_* = 700\ M_o/pc^2$

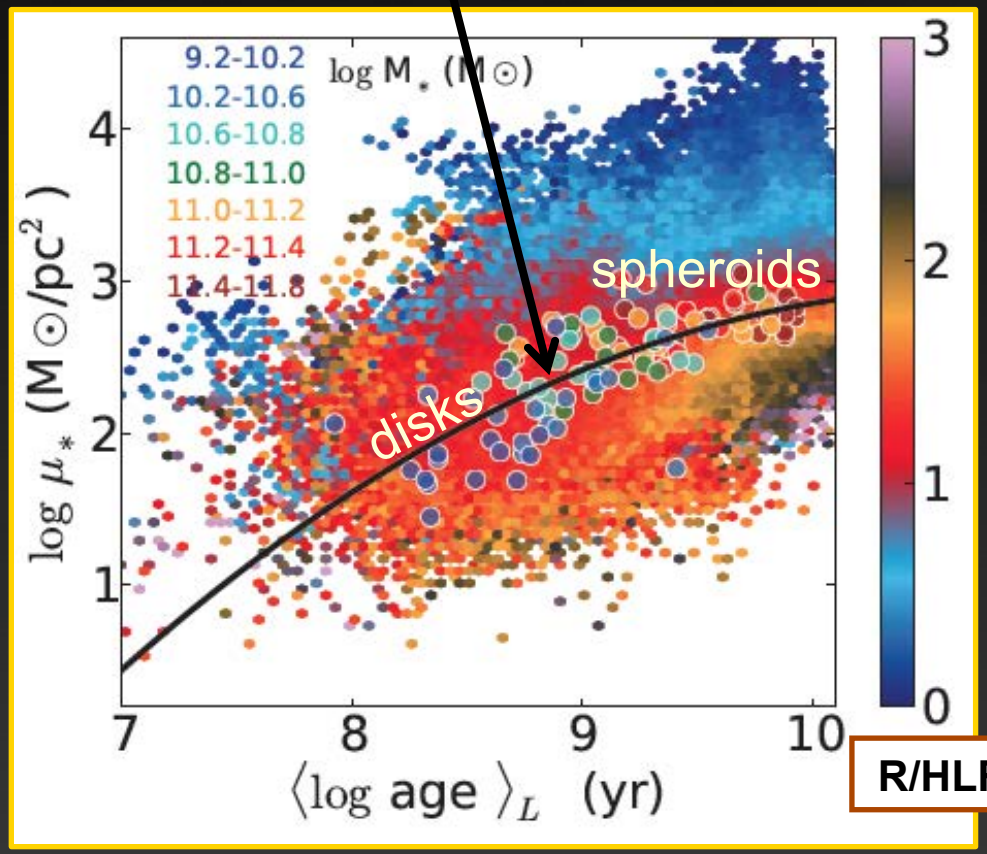
➔ Below 700 M_o/pc^2 μ_* increases with age (low density ⇔ young)

➔ Above μ_*^{crit}, no correlation!

Global x local: is SFH driven by M_* or μ_* ?

➔ Fit to galaxy-wide relation
(or to R~1HLR, it's the same)

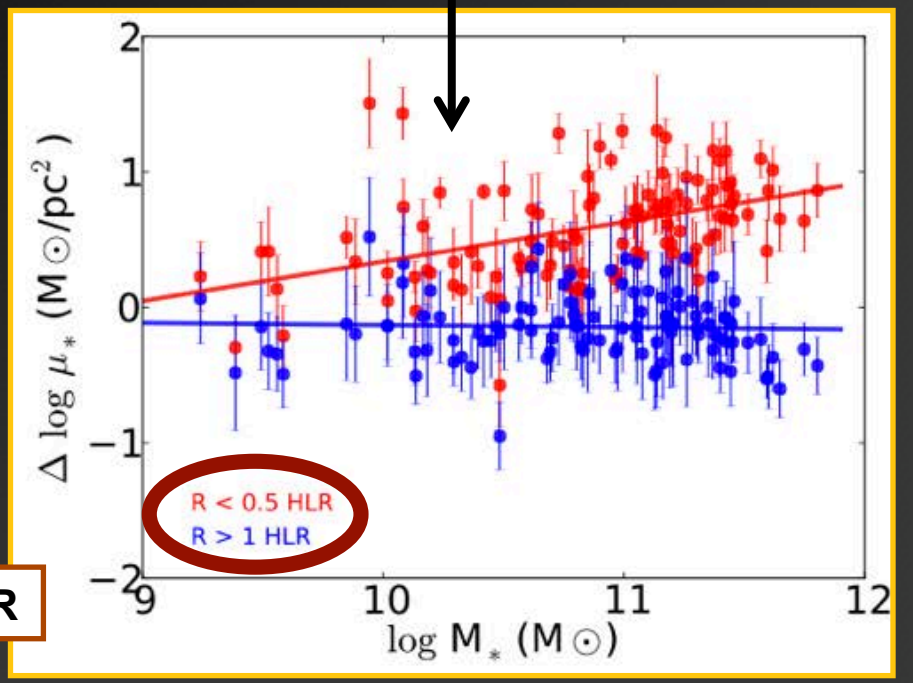
Assuming μ_* controls the SFH, the fit predicts μ_* given the age.



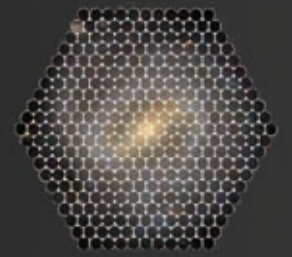
Excess μ_* removes the local forces affecting the SFH.

➔ $\Delta\mu_*$ correlates with total mass only for central regions of massive galaxies!

SFH is driven by M_* in the inner parts and by μ_* at 1 HLR and beyond.
(bulge x disk formation mechanisms)



Summary



- PyCASSO: A powerful tool to digest datacubes
- Galaxies grow inside out
- Mass builds up faster for more massive galaxies, at any R!
  - Downsizing = Downsizing(R)
- Relative inner-outer age difference peaks @ $M_* = 7 \times 10^{10}\ M_o$
  - Theory says this is ~ where AGN and SN (low M) feedback are minimal…
- Galaxies are 20% smaller in mass than in light
  - 3/4 due to ∇age and 1/4 due to ∇A_V
- Spatially averaged and integrated properties correlate very well. Both match the properties at R = 1 HLR
  - Effective radii are more effective than you may have thought!
- The local stellar mass density drives the SFH is disks, but in bulge dominated systems the total stellar mass is a more fundamental property