Star Formation over Cosmic Time

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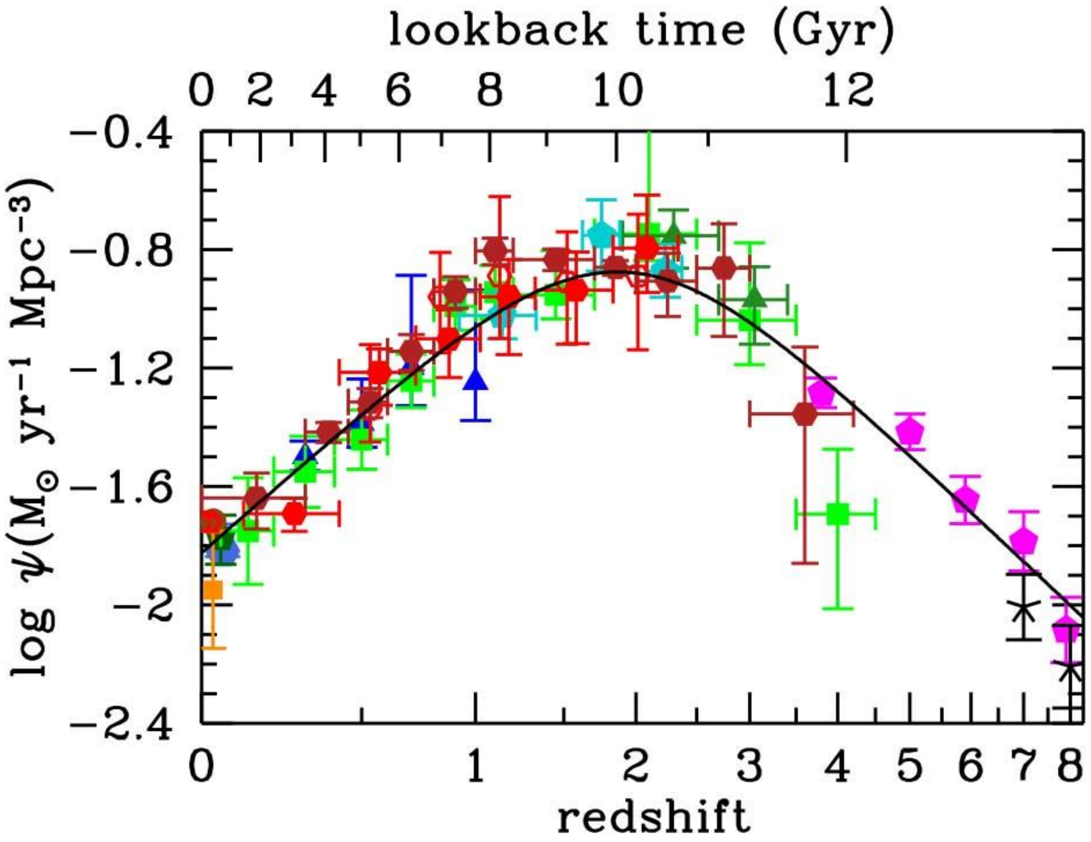
1993 La Palma



Star Formation Rate Density

Madau & Dickinson 2014, ARAA

What can we learn from this? What has Hans contributed?

Start with something simpler:
the Dark Matter accretion rate.

Dekel +13 “Toy Model”

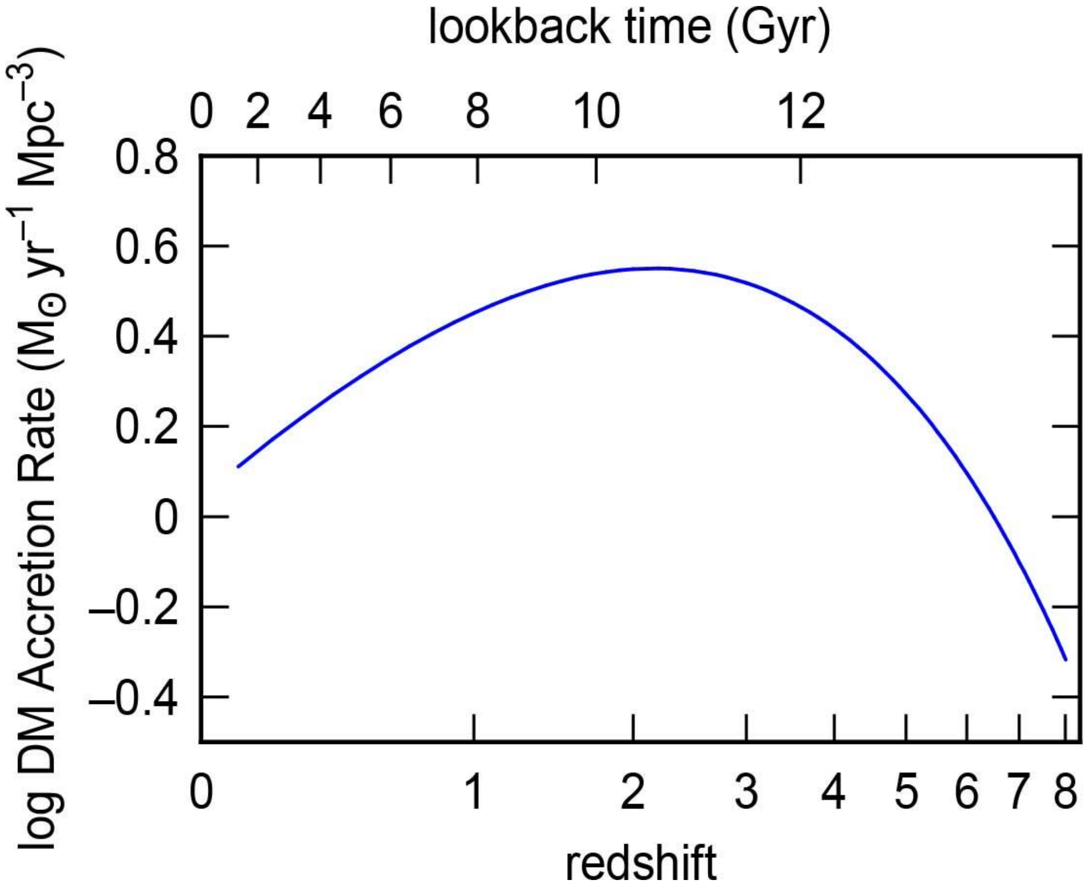
$$\frac{1}{M(z)}\frac{dM(z)}{dt} \approx 0.03(1+z)^{2.5}\ \mathrm{Gyr}^{-1}$$

- the collapse rate increases with z a little faster than sqrt(density), which goes as $(1+z)^{1.5}$

Solve for M(z,t) and then take dM/dt:

$$\frac{dM(z)}{dt} \approx 0.03 M_0 e^{-0.79z}(1+z)^{2.5}\ \mathrm{Gyr}^{-1}$$

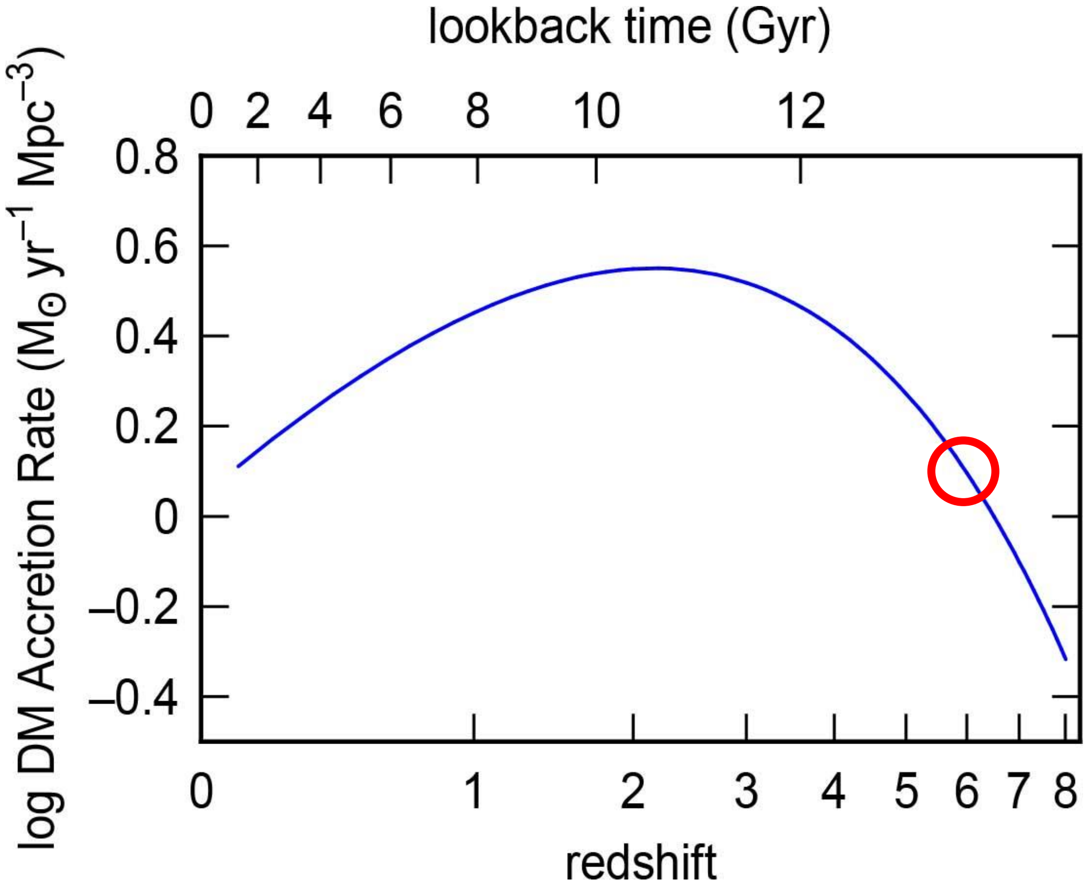
Integrate over the halo mass function $n(M_0)$ and divide by volume to get the density:



Dark Matter Accretion Rate Density

$$\frac{d\rho(z)}{dt} \approx 0.03 \rho_0 e^{-0.79z}(1+z)^{2.5}\ \mathrm{Gyr}^{-1}$$

The rate is small at first because the virial horizons are small: only a small fraction of the total universe mass has reversed its expansion and is collapsing.



Dark Matter Accretion Rate Density

The mass of the Milky Way halo at z=6 was

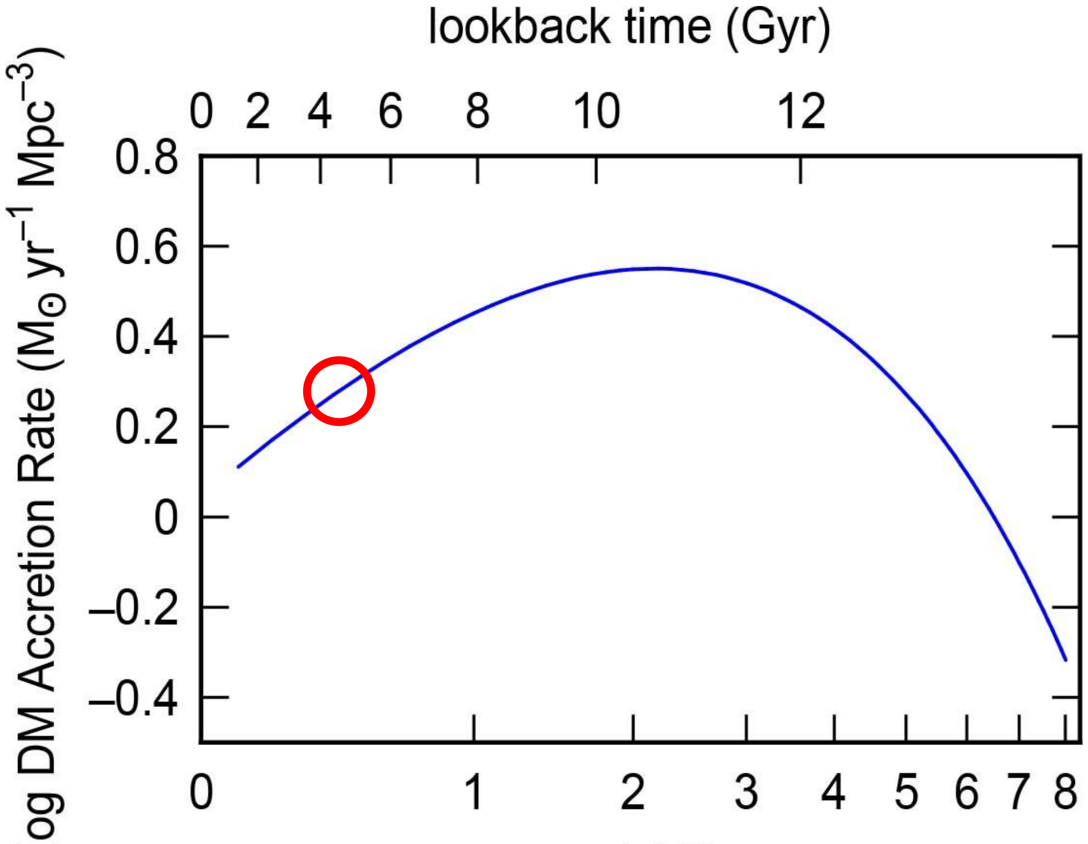
$M(z) = 2x10^{12}\ e^{-0.79x6} = 1.7 \times 10^{10}\ M_O$

and the disk radius was

$R_d \sim 0.05\ R_V = 560$ pc

A dwarf galaxy.

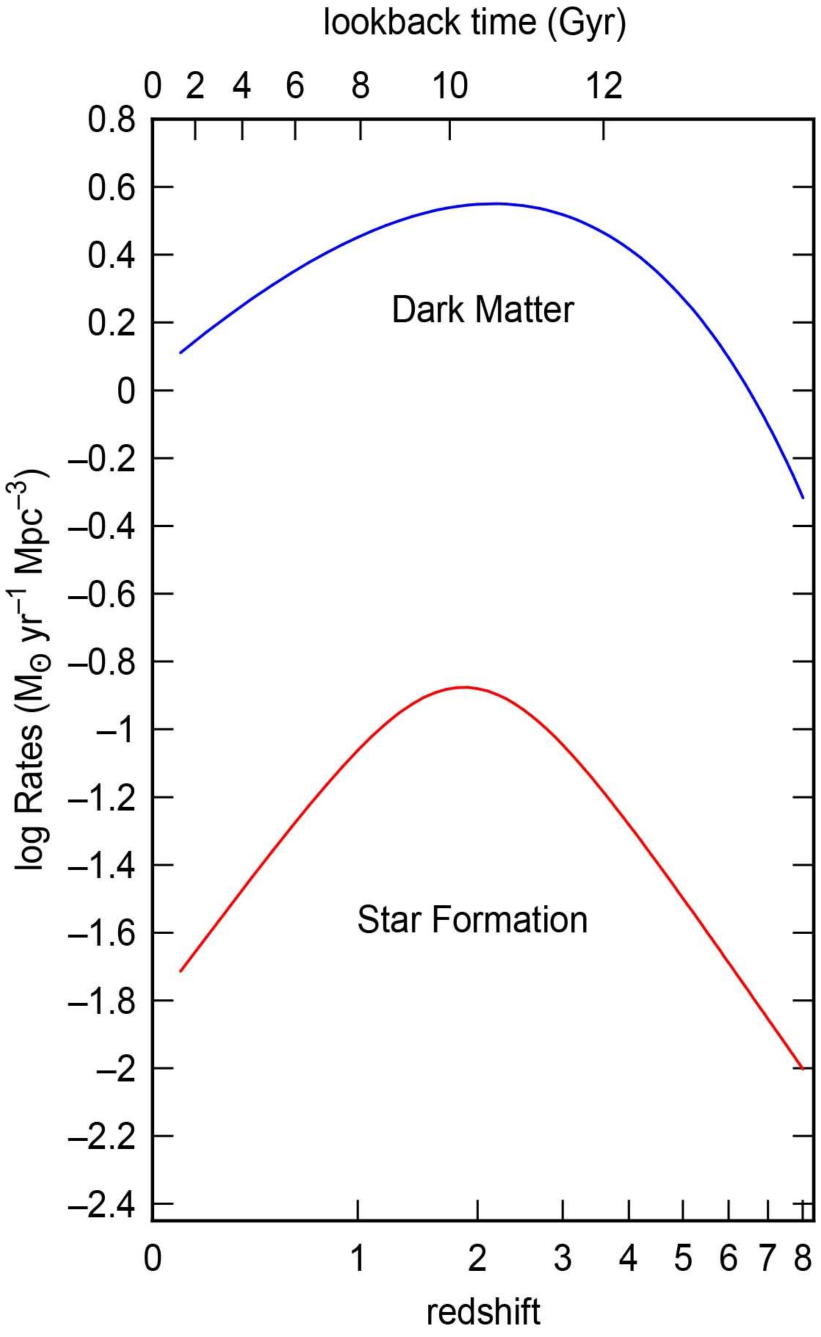
The rate is small recently because the density of the universe is low and the gravitational timescale is long.



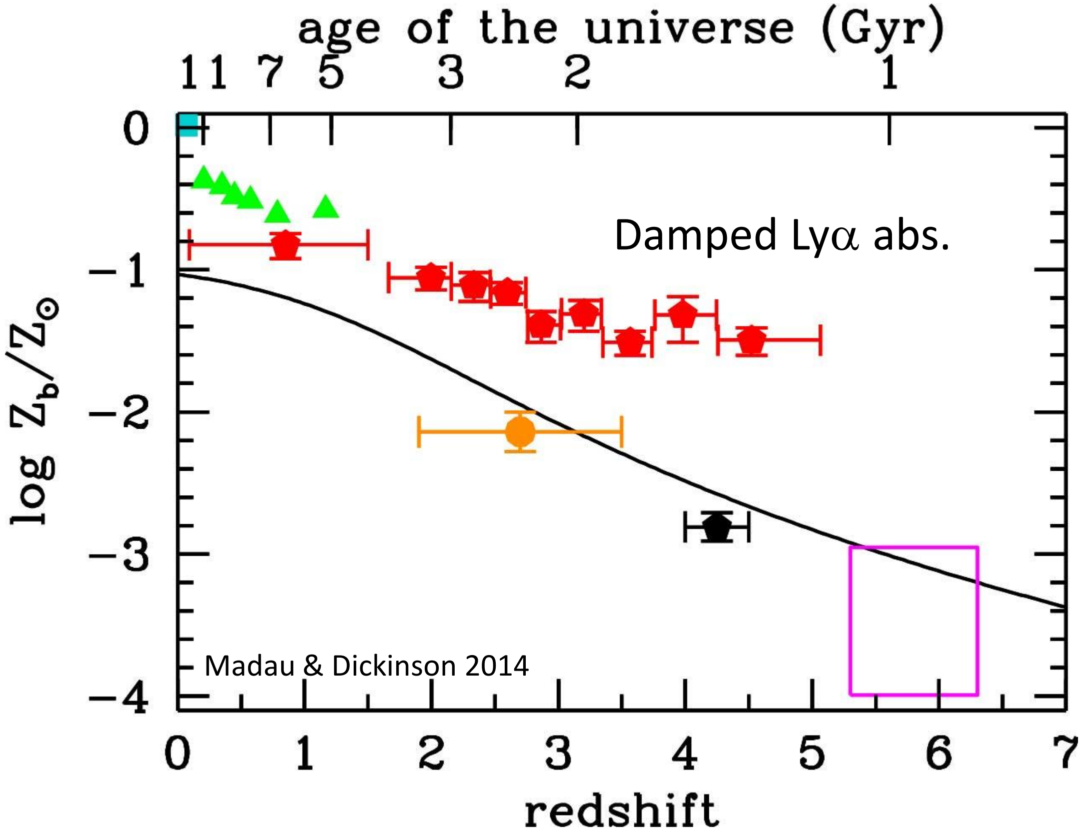
Dark Matter Accretion Rate Density

The star formation rates are smaller than the DM rates because the baryon fraction is low,

and star formation is regulated or quenched by baryon physics
  - AGNs, stripping, star formation feed back, ...



What is the metallicity?

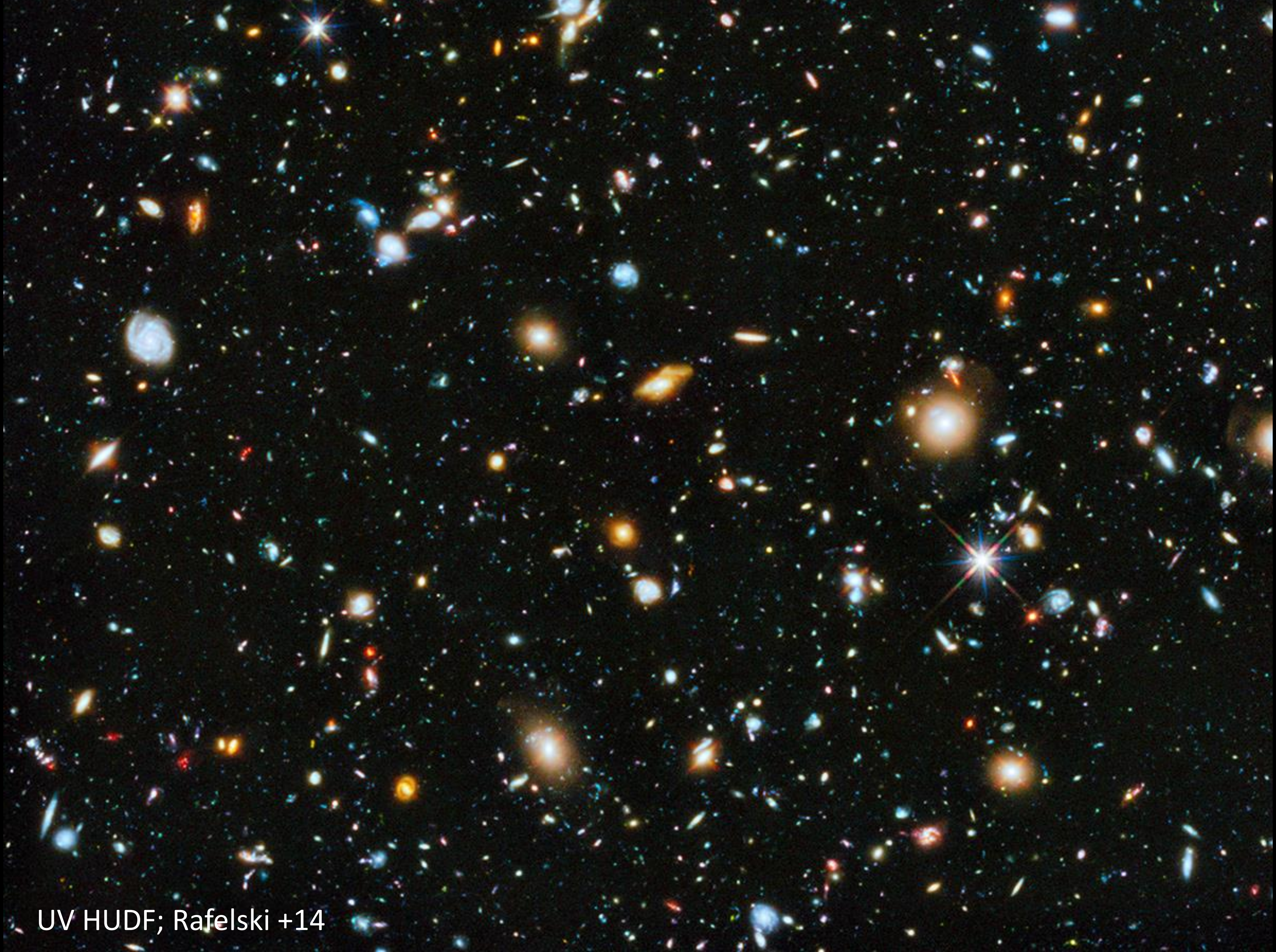


Also at z > 2:

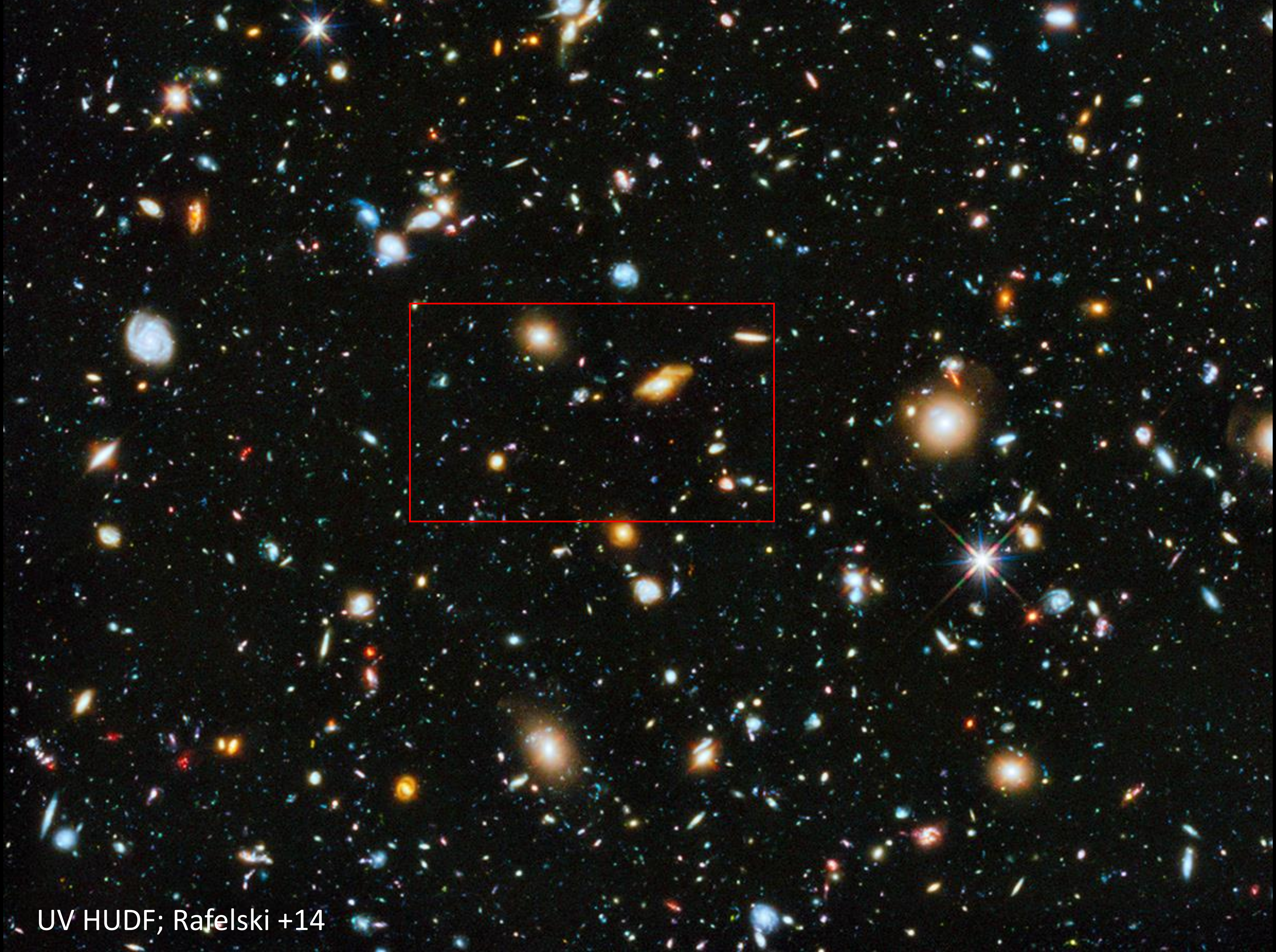
Metallicity associated with galaxies is ~10% solar

Metallicity associated with IGM is ~0.1% solar at the same redshift

solid curve: SFR Density with conventional metal yields;
turquoise: local SDSS (Gallazzi +08); green: galaxy clusters (Balestra +07);
red: damped Lyα absorption systems (Rafelski +12)
orange: OVI absorption from IGM in Lyα forest (Aguirre +08)
black: CIV absorption from IGM (Simcoe +11)
magenta: CIV and CII absorption from IGM (Ryan-Weber +09, Simcoe +11, Becker +11)

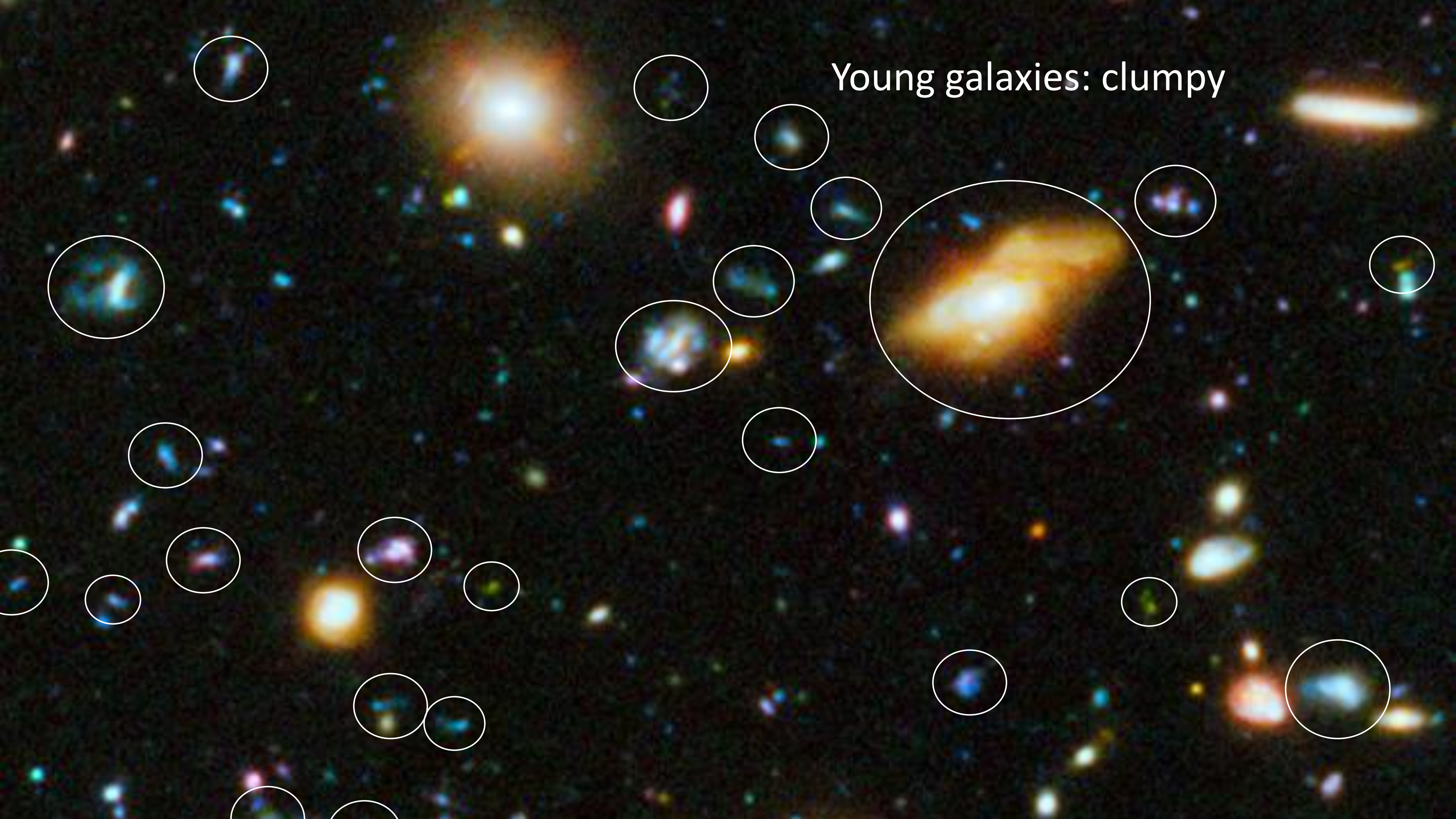


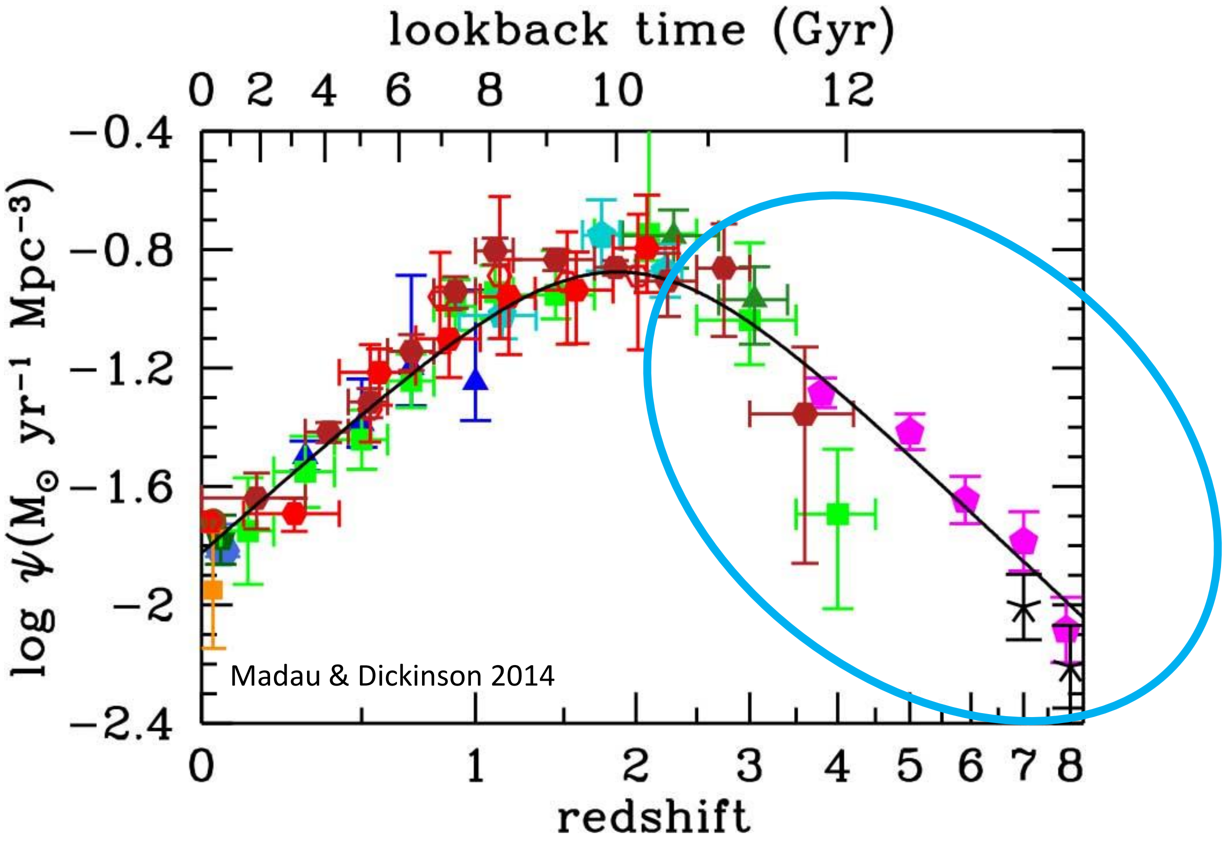
UV HUDF; Rafelski +14



UV HUDF; Rafelski +14

Young galaxies: clumpy





Star Formation Rate Density

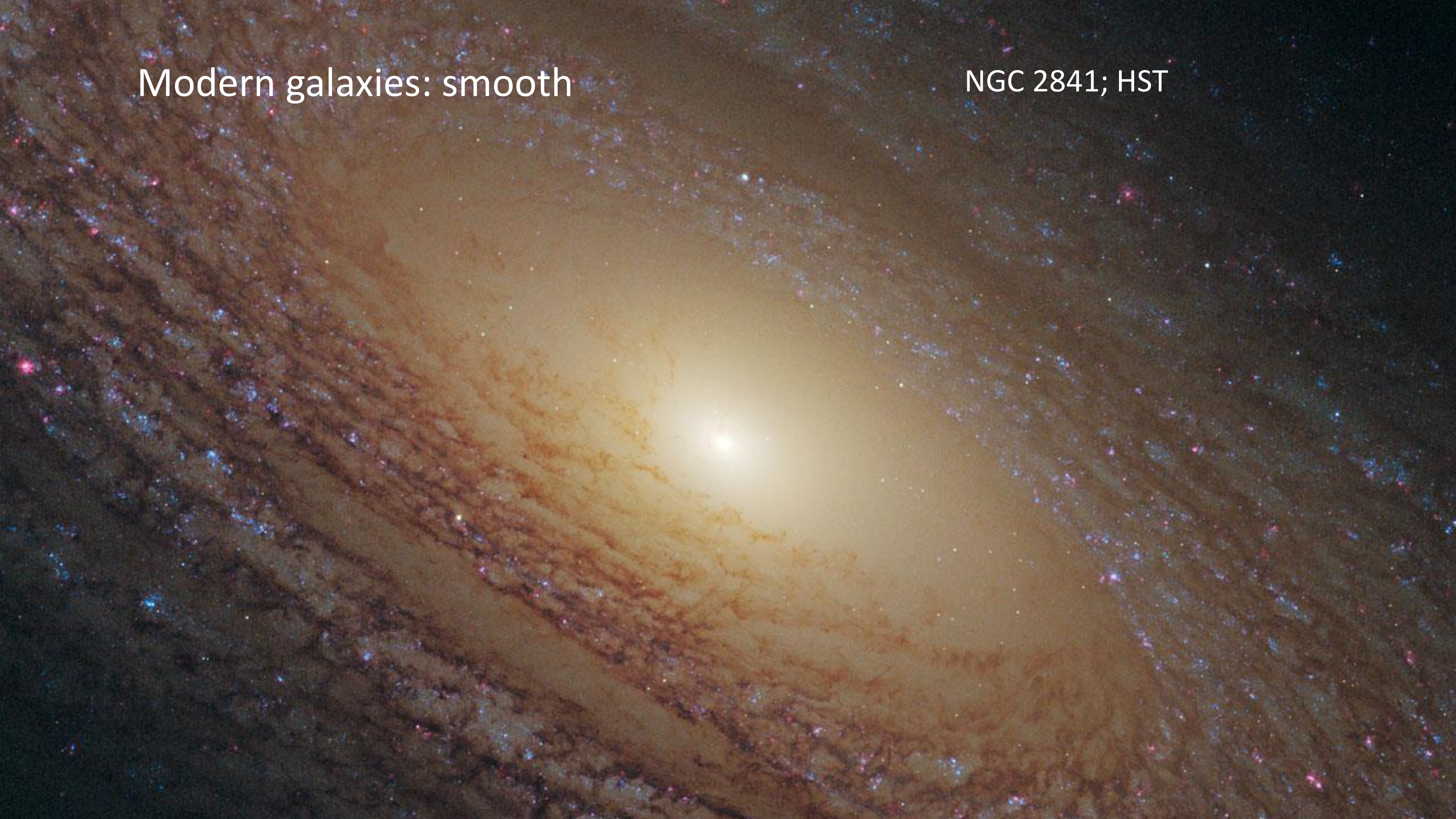
Morphology

High turbulence:
- Accretion
- Intense SF feedback
- Gravitational instab.

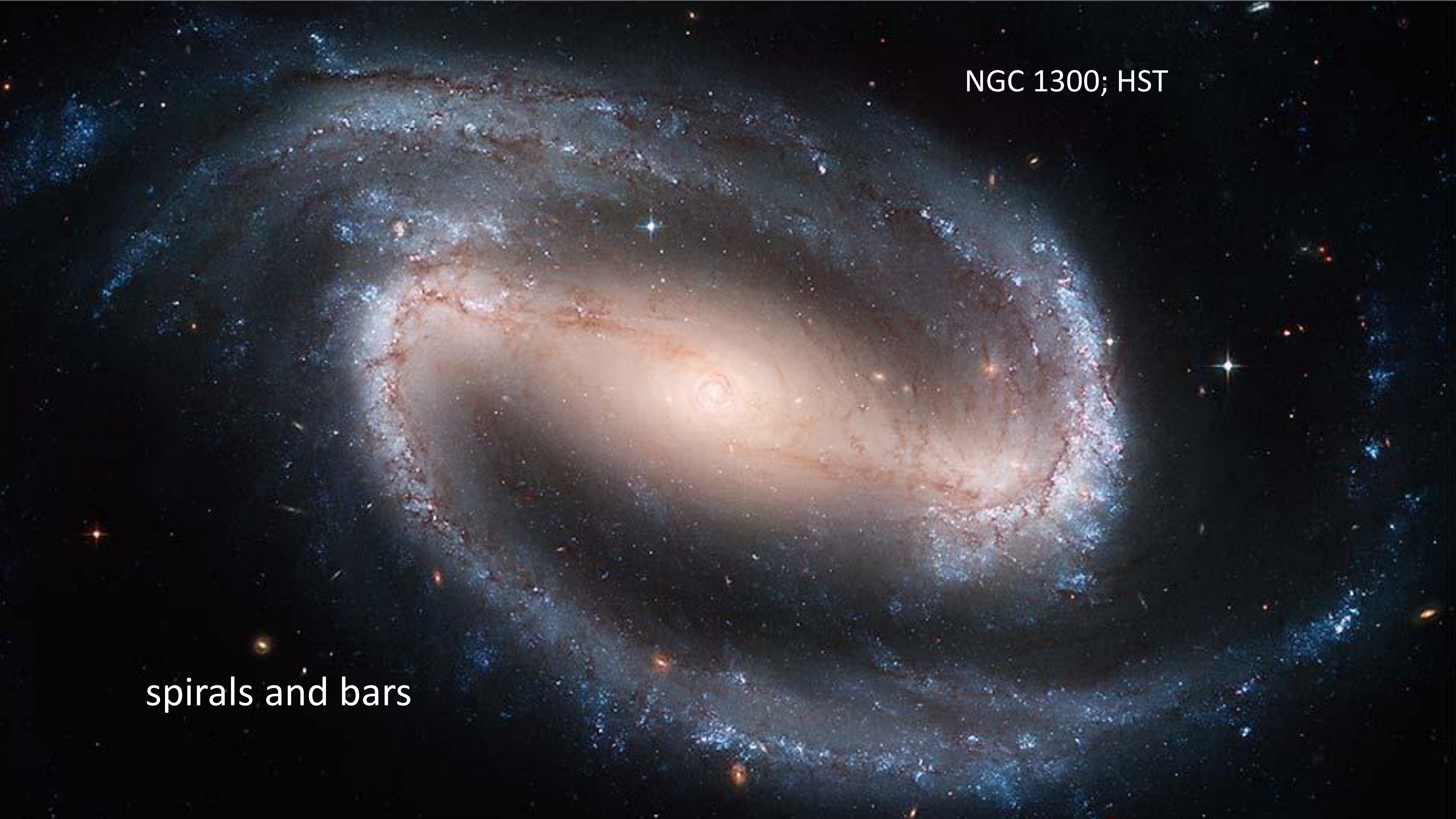
Large Jeans length
- Massive SF clumps
- Thick disks
- Large disk torques and radial migrations

QSOs/mergers

Modern galaxies: smooth



NGC 2841; HST

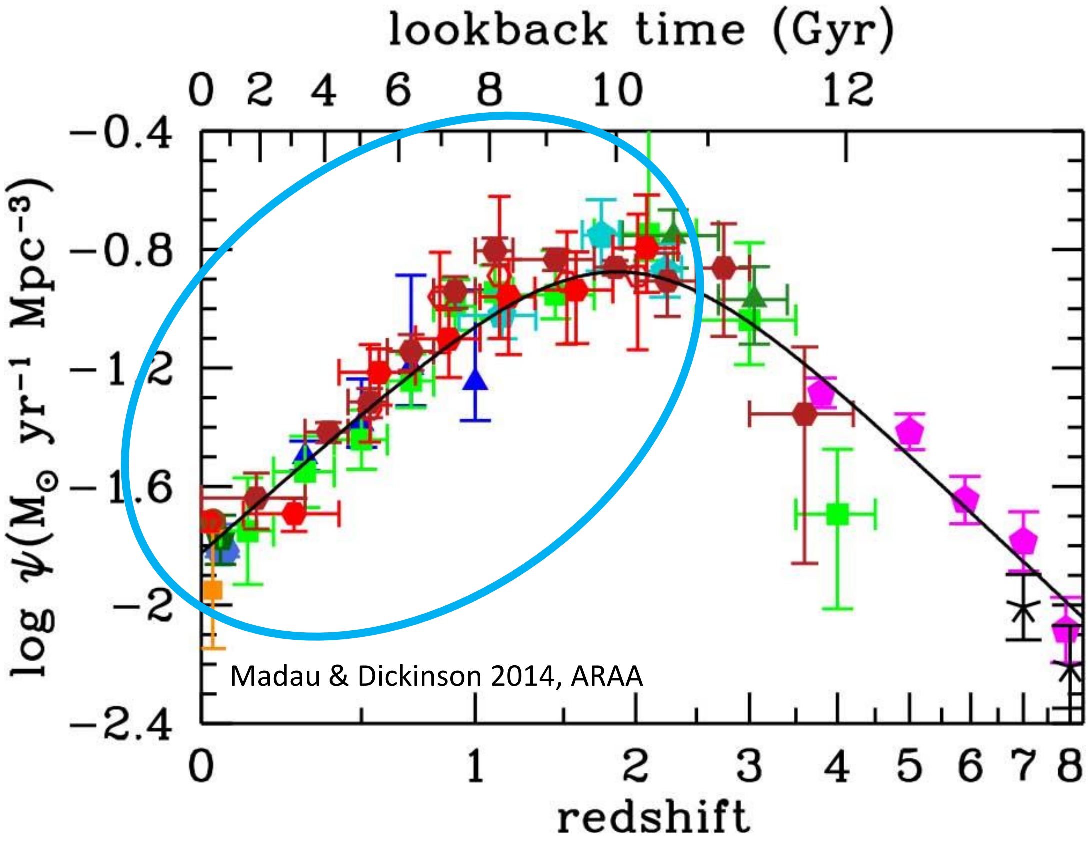

NGC 1300; HST

spirals and bars

Quiescent disks:
- Low accretion
- Low SF feedback
- Marginal grav. equilibrium

Stellar gravity exceeds gaseous gravity
- Spiral arms
- Bars
- Weak torques with random stellar scattering

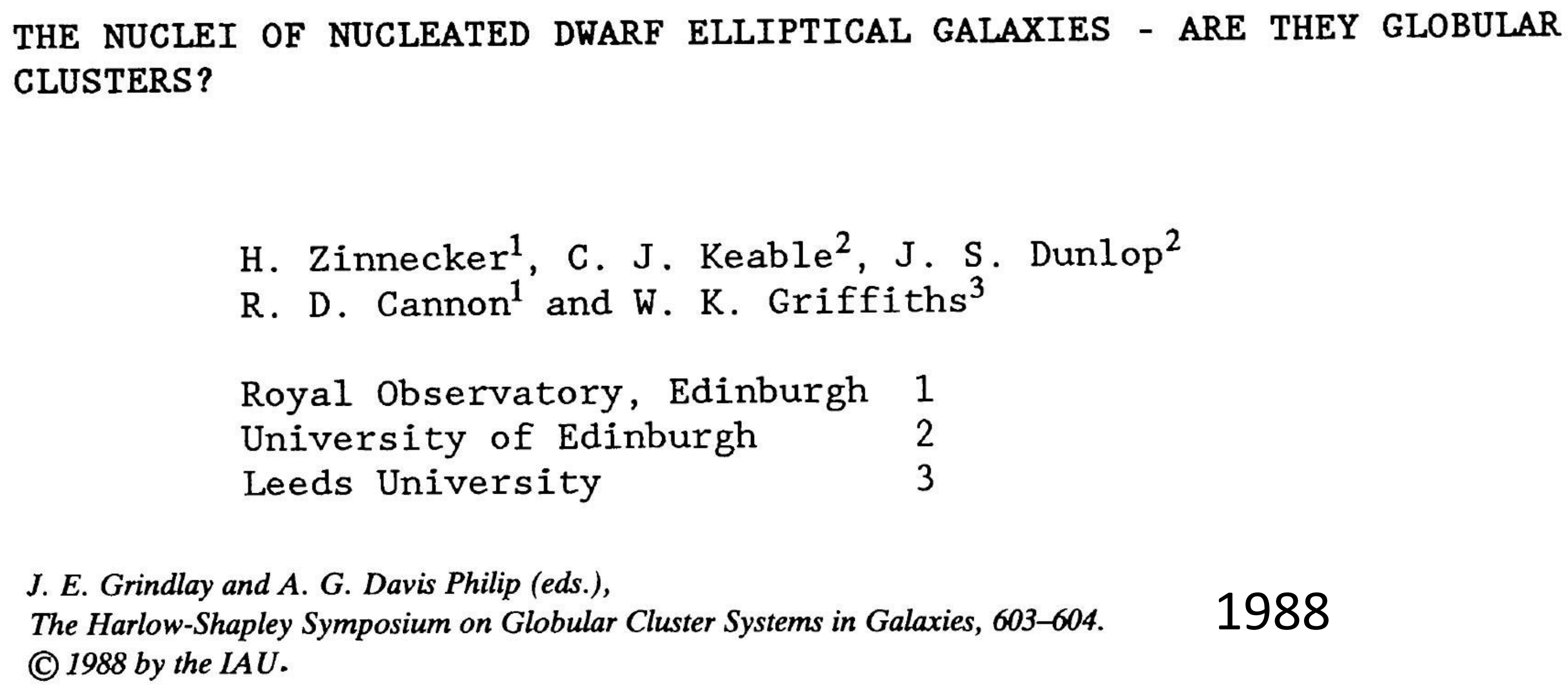
“Red & dead” ellipticals,
Massive galaxy clusters



Madau & Dickinson 2014, ARAA

Star Formation Rate Density

Morphology



THE NUCLEI OF NUCLEATED DWARF ELLIPTICAL GALAXIES - ARE THEY GLOBULAR CLUSTERS?

H. Zinnecker[1], C. J. Keable[2], J. S. Dunlop[2]
R. D. Cannon[1] and W. K. Griffiths[3]

Royal Observatory, Edinburgh 1
University of Edinburgh 2
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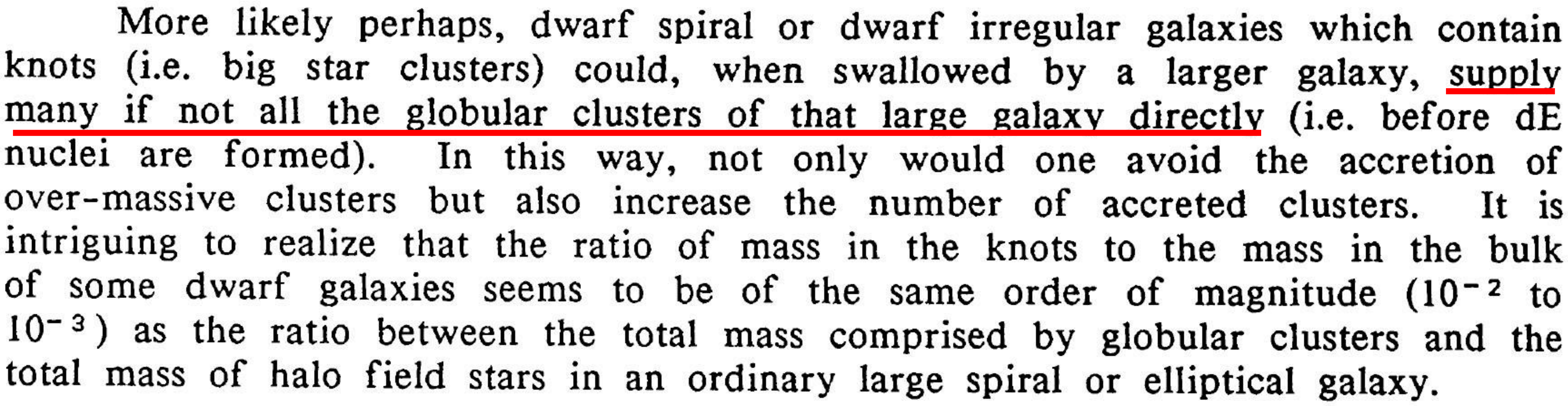
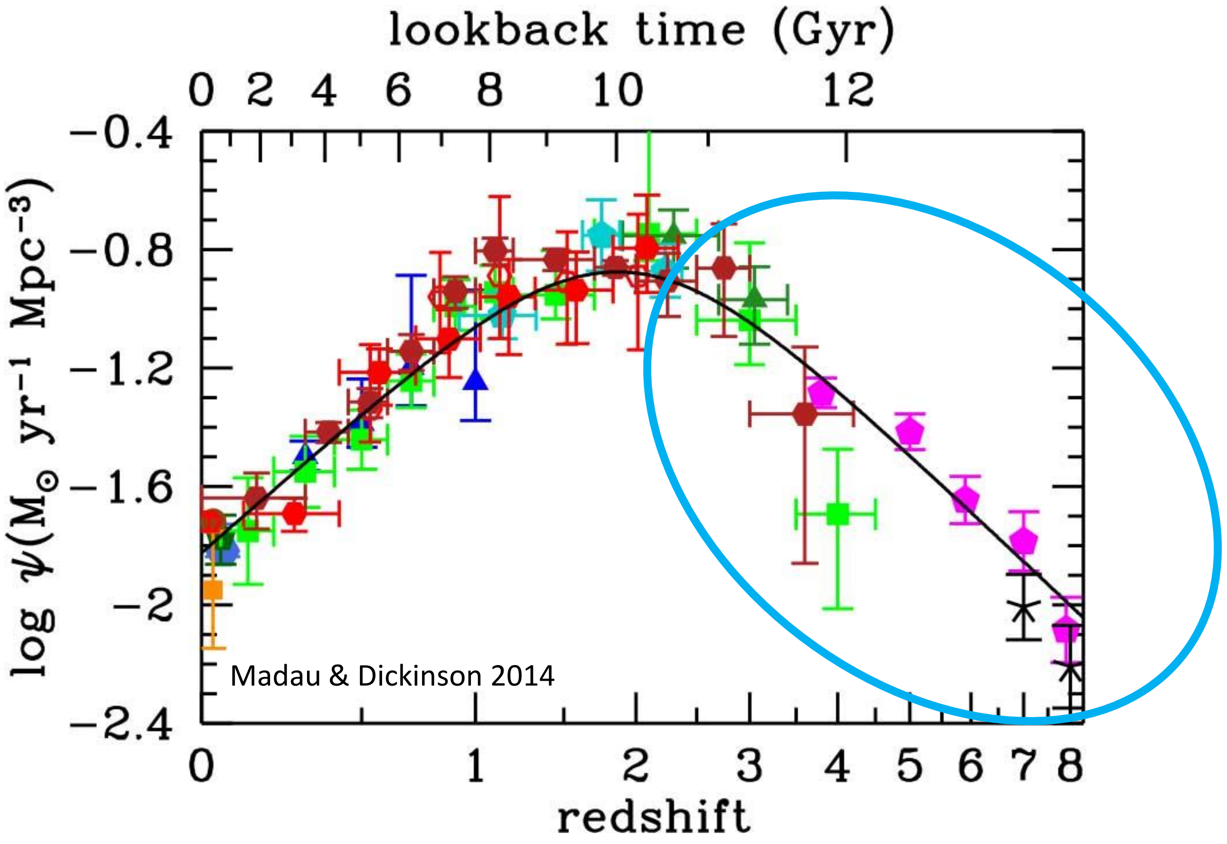
J. E. Grindlay and A. G. Davis Philip (eds.),
The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, 603–604.

1988



More likely perhaps, dwarf spiral or dwarf irregular galaxies which contain knots (i.e. big star clusters) could, when swallowed by a larger galaxy, supply many if not all the globular clusters of that large galaxy directly (i.e. before dE nuclei are formed). In this way, not only would one avoid the accretion of over-massive clusters but also increase the number of accreted clusters. It is intriguing to realize that the ratio of mass in the knots to the mass in the bulk of some dwarf galaxies seems to be of the same order of magnitude (10^{-2} to 10^{-3}) as the ratio between the total mass comprised by globular clusters and the total mass of halo field stars in an ordinary large spiral or elliptical galaxy.



Star Formation Rate Density

Era of Globular Cluster formation

How important were they to the SFR density?

Metal Poor GCs formed in low-mass galaxies (or in low-mass versions of today's large galaxies) that got captured and destroyed by the halos of large-mass galaxies

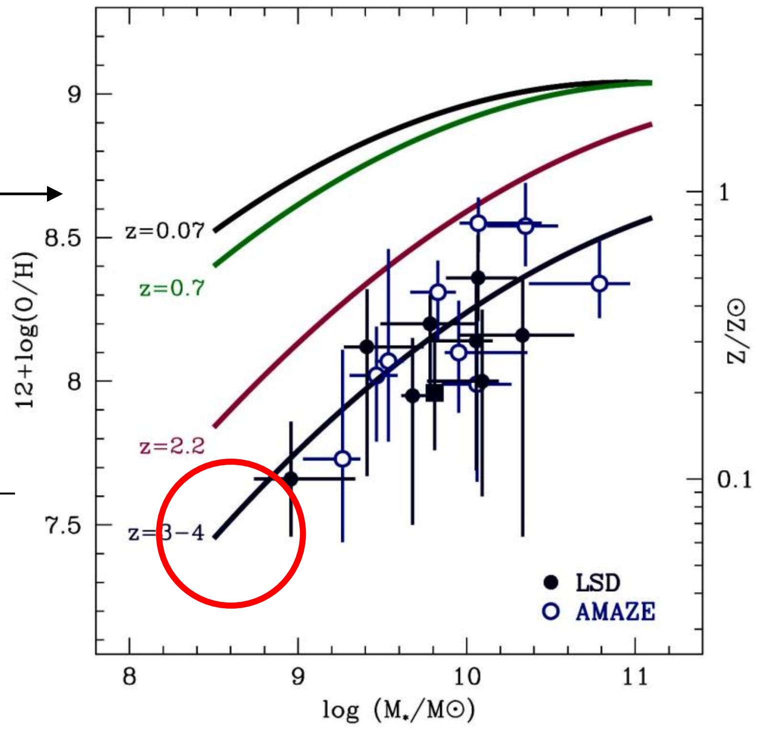
(Searle & Zinn '78; **Zinnecker '88**, Cote '98, Elmegreen +12, … Li & Gnedin `14, El'Badry +18)

The low metallicity of halo GCs comes from the mass-metallicity relation of galaxies at intermediate to high redshift: requires a galaxy $M_* < 3\times10^8\ M_O$

solar abundance

0.1 Z_O

metal-poor GCs



Mannucci +09

(See also Mouhcine '06 for a similar result with galaxy halo stars; but see Pastorello +15 who find similar color gradients for blue and red GCs in ETG)

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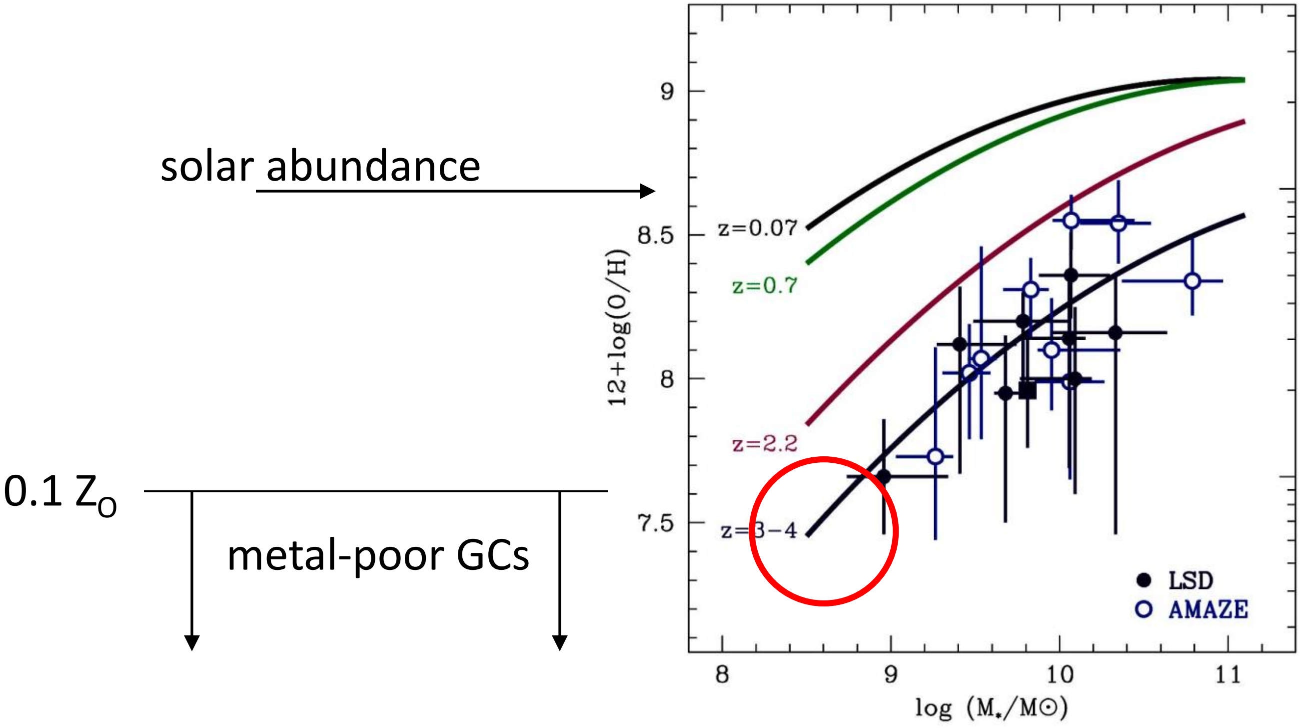
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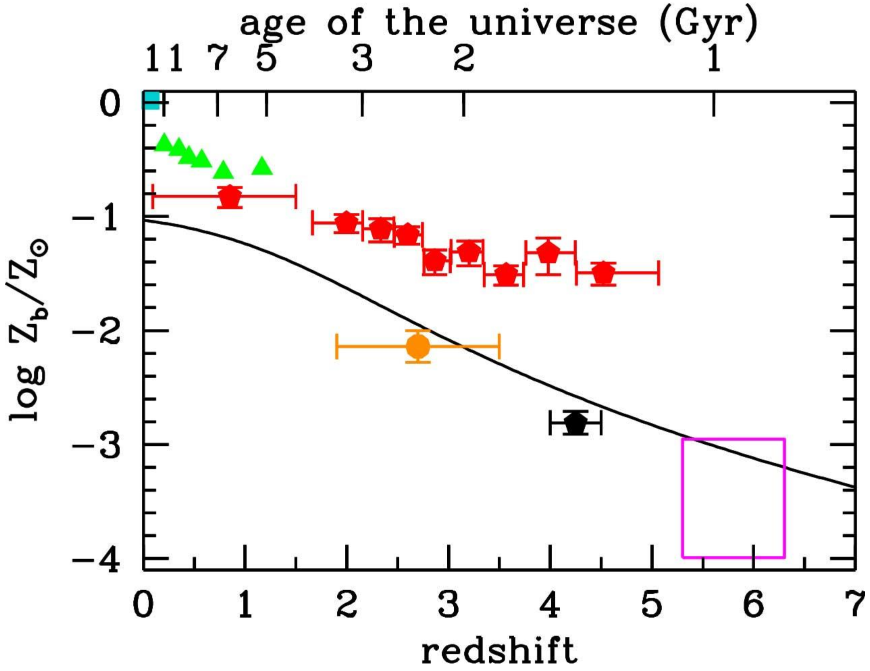


Ibata, Gilmore, Irwin 94

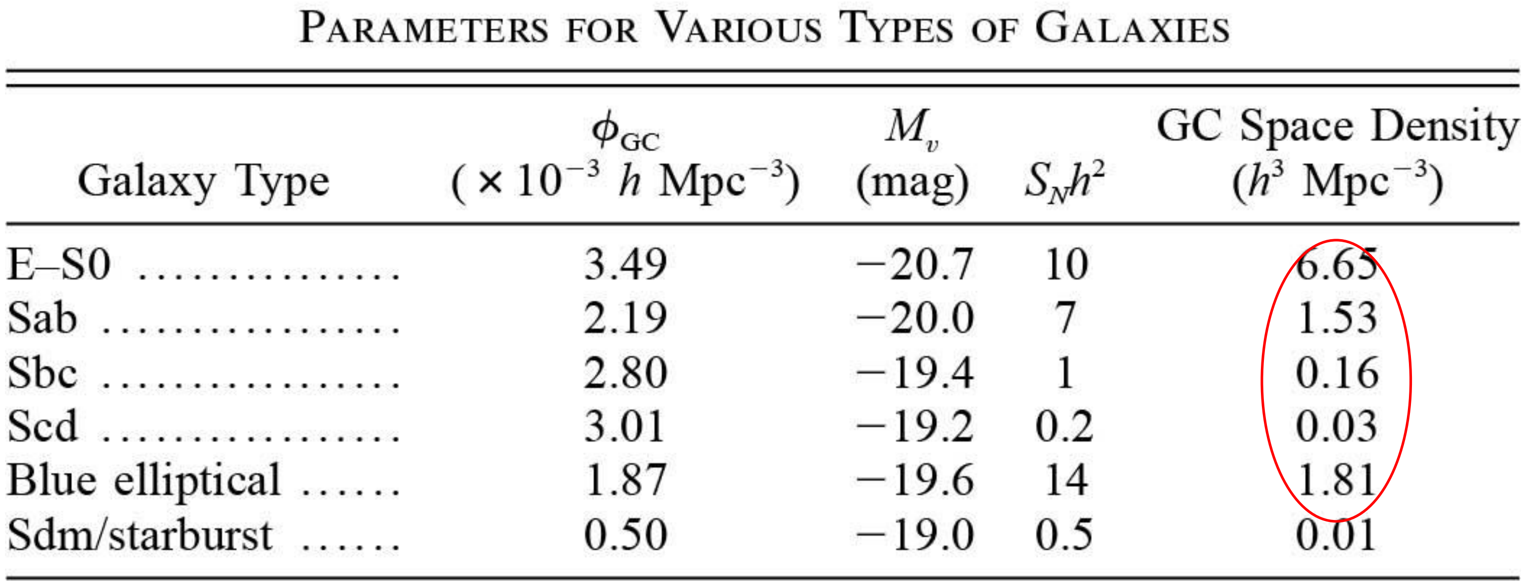
Associated GCs:
Terzan 7, Terzan 8,
Arp 2, M54,
Whiting 1

NASA, ESA

e.g.: the Sagittarius Dwarf Galaxy

- Proves some halo GCs enter the MW in dwarfs

The space density of metal-poor GCs



Parameters for Various Types of Galaxies

Galaxy Type	ϕ_{GC} ($\times 10^{-3}$ h Mpc^{-3})	M_v (mag)	$S_N h^2$	GC Space Density (h^3 Mpc^{-3})
E–S0	3.49	−20.7	10	6.65
Sab	2.19	−20.0	7	1.53
Sbc	2.80	−19.4	1	0.16
Scd	3.01	−19.2	0.2	0.03
Blue elliptical	1.87	−19.6	14	1.81
Sdm/starburst	0.50	−19.0	0.5	0.01

Portegies Zwart & McMillan ‘00

The space density of all GCs is ~8/Mpc^3. Considering evaporation, it was ~16/Mpc^3 in the early Universe. Half are metal-poor (8/Mpc^3 at formation) and of these 25% are above the peak in the GCLF → 2/Mpc^3 massive metal-poor GCs at time of formation

(Boylan-Kolchin ‘17 estimate 2/Mpc^3 metal-poor GCs also. They consider all masses but ignore evaporation)

Elmegreen ‘12

What SFR is needed to form a massive GC? What is the total SFR Density?

Integrating a power law (-2) CMF up to a most massive $M_{max} = 2x10^{6}\ M_{O}$,

and assuming a cluster formation fraction of $\Gamma = 0.25$, requires $M_{star} = 5x10^{7}\ M_{O}$.

With 2% SF efficiency on large scales, the molecular mass would be $2.5x10^{9}\ M_{O}$.

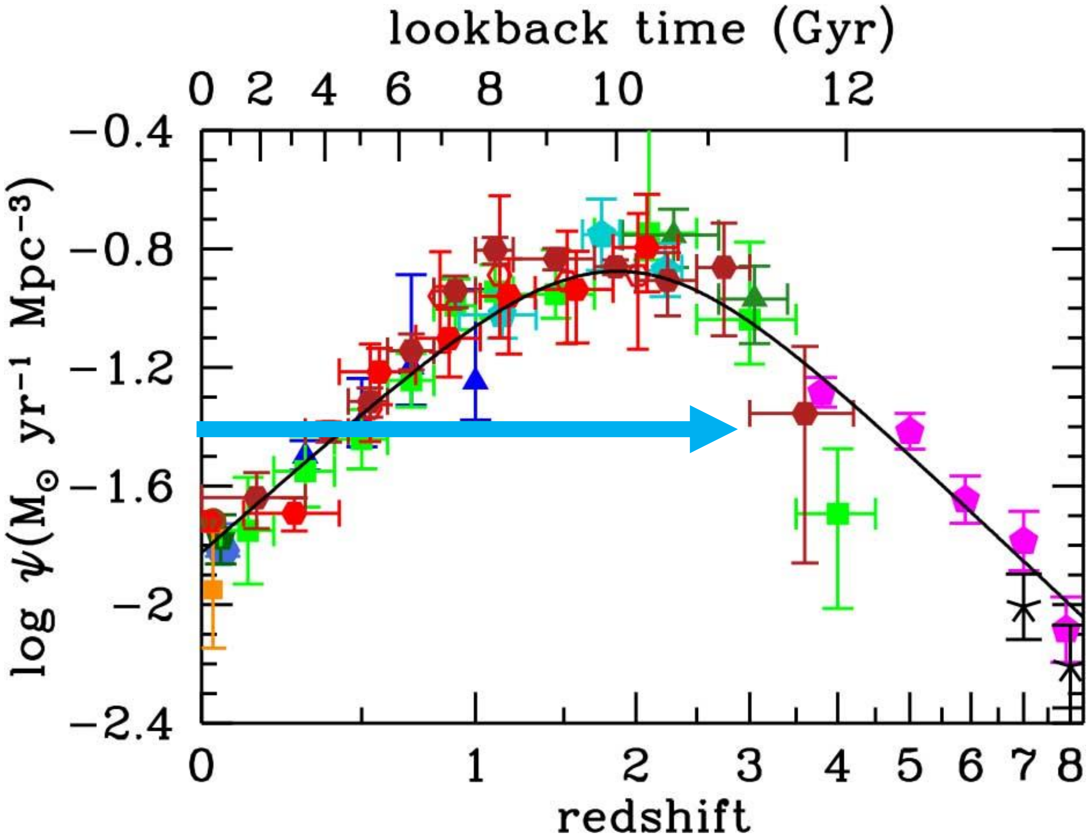
For a 2 Gyr consumption time, that mass produces a SFR of $\boxed{\sim 1\ M_{O}/yr.}$

Or, can consider that the SF event lasts ~50 Myr, giving the same SFR.

The duration of the GC formation epoch from z=7 to 2 is 2.6 Gyr, ~50x larger, a 2% duty cycle

→ SFR density forming massive MP-GCs is $1\ M_{O}/yr$ x 2% x 2 MP-GC/Mpc^{3} = $\boxed{0.04\ M_{O}/yr/Mpc^{3}}$

Elmegreen ’12,18



The formation rate of stars directly connected with metal-poor GCs is a high fraction of the total.

Doubling this to include the metal-rich GCs suggests that most early-universe star-forming regions made GCs.

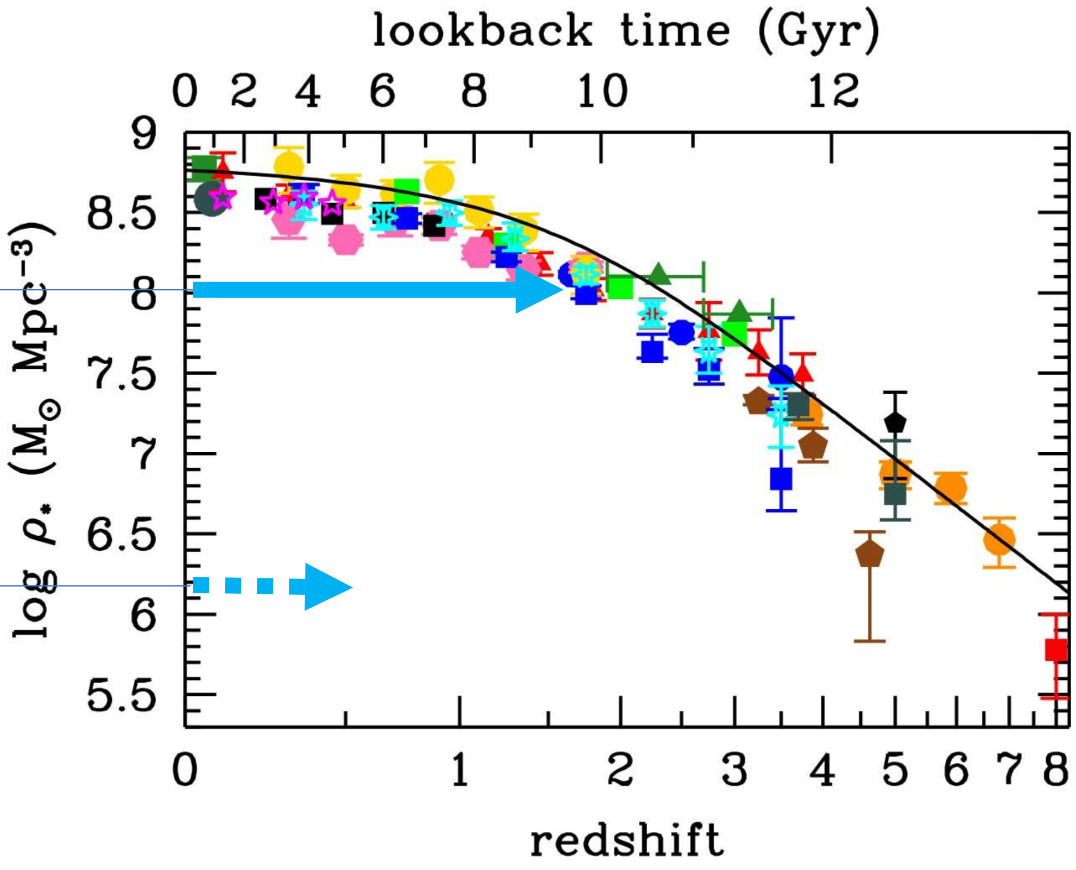
What is the cosmic stellar density of regions that formed massive metal-poor GCs?

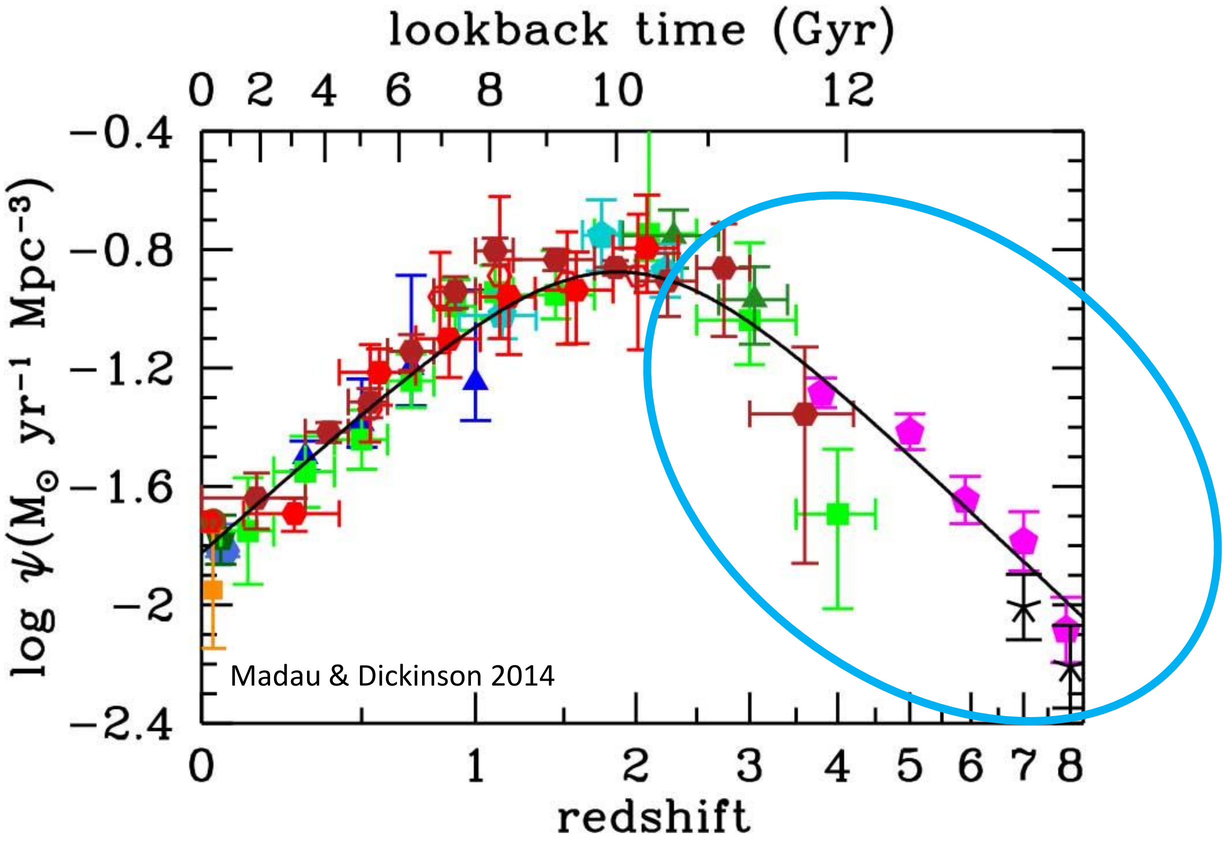
Total stellar mass associated with a 2x10^{6} M$_{O}$ GC: 5x10^{7} M$_{O}$

Space density ~ 2 MP-GC/Mpc^{3}

Product = 10^{8} M$_{O}$/Mpc^{3} of stars directly associated with MP-GC formation

1.6 x 10^{6} M$_{O}$/Mpc^{3} in GCs today
~ 0.3% of all stars

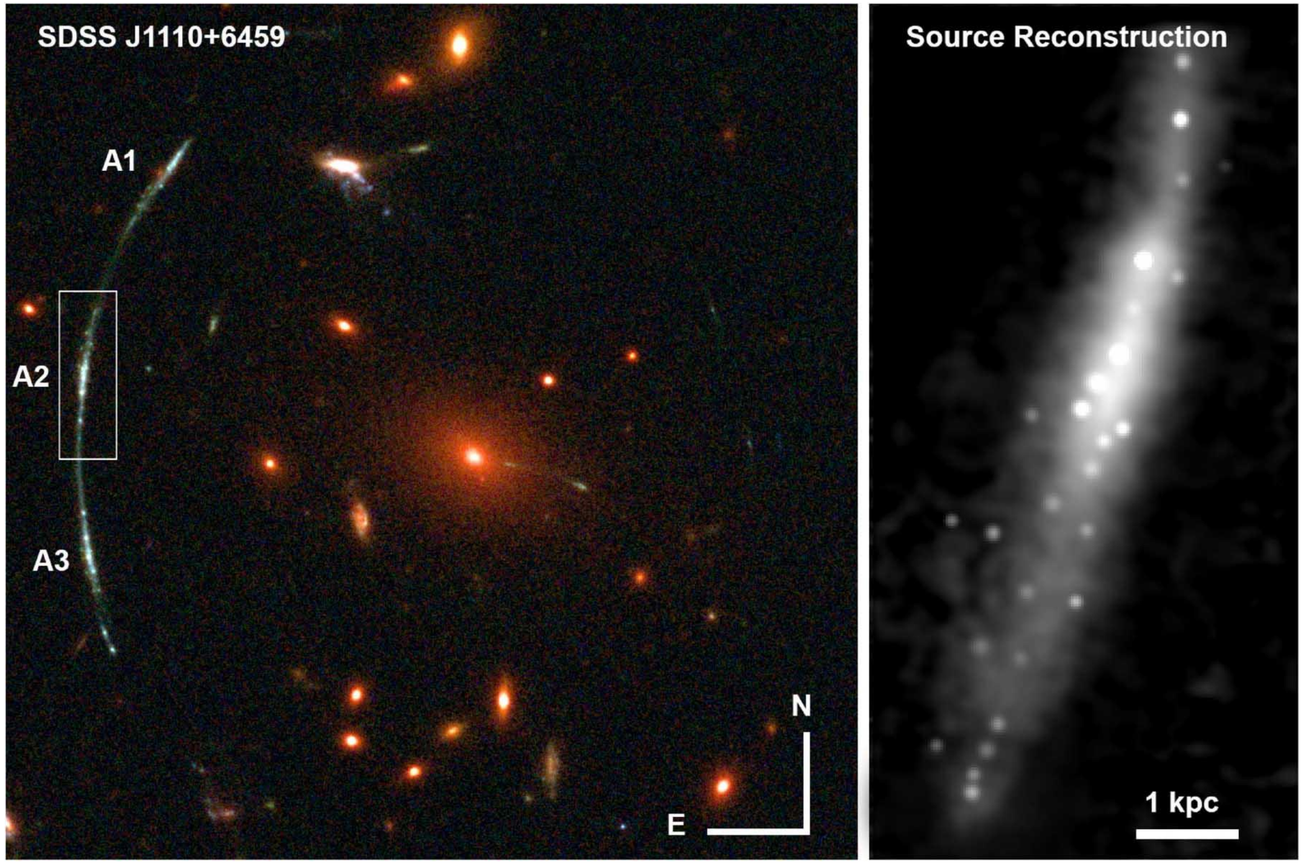


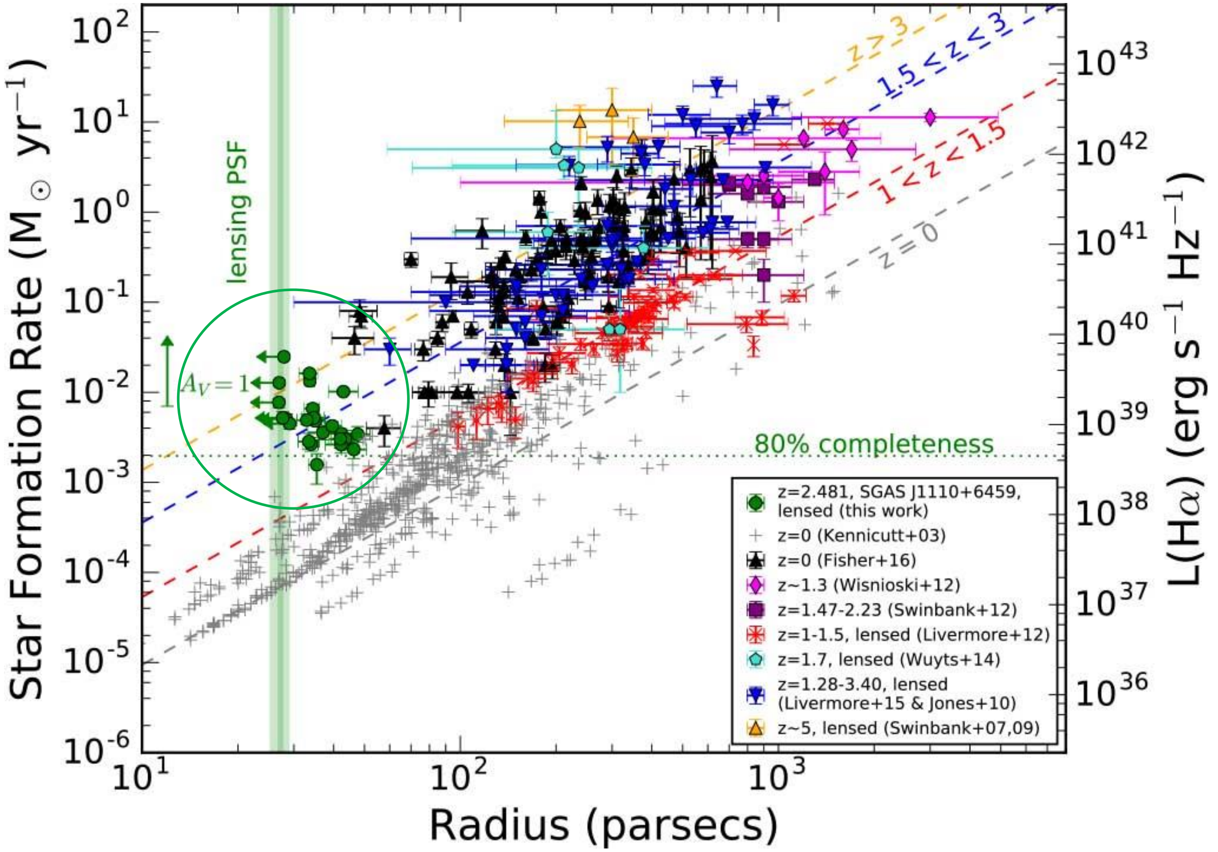


Star Formation Rate Density

Era of Globular Cluster formation

<u>Most SF resulted in a massive GC</u>



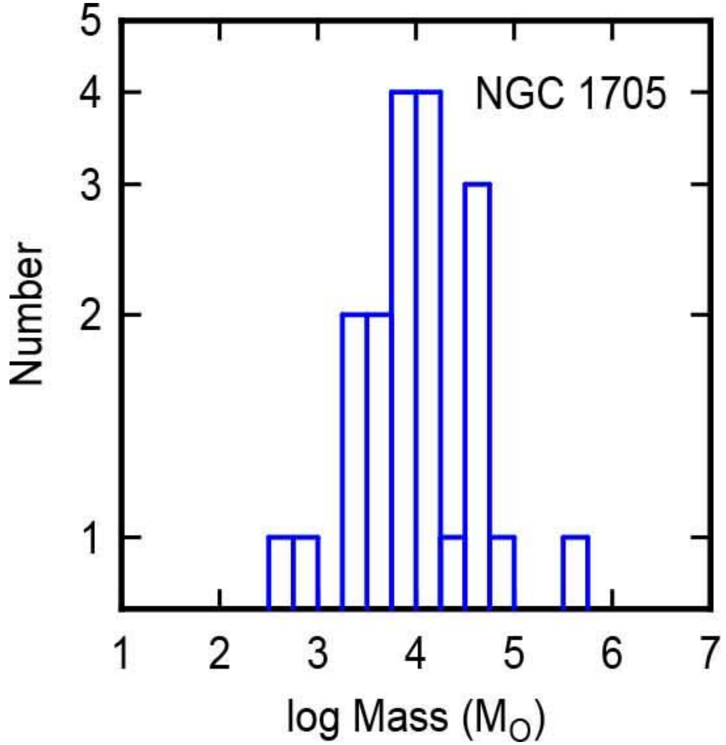


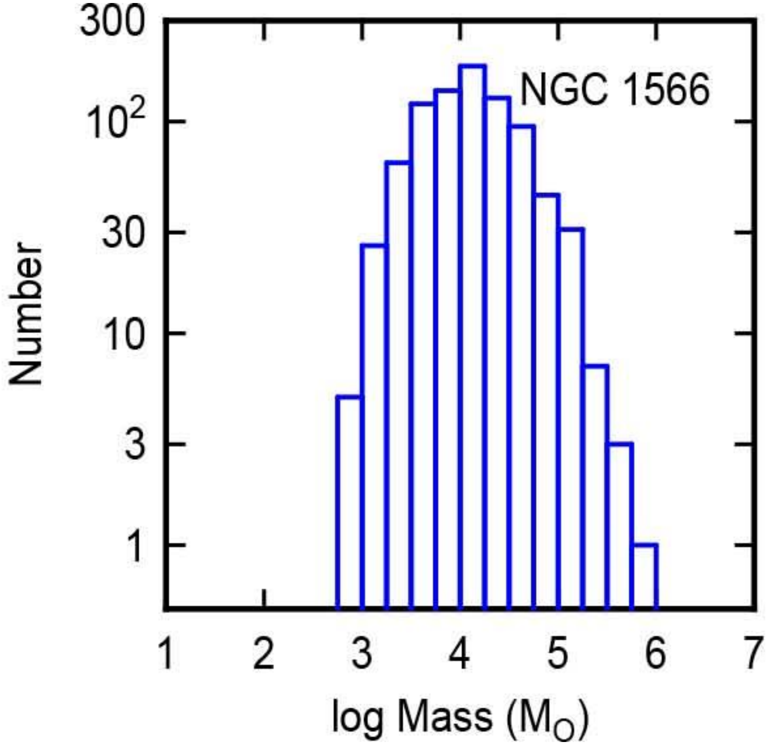
Traci Johnson +17: HST image of lensed galaxy on SDSS
z=2.481, magnification = 28 +- 8

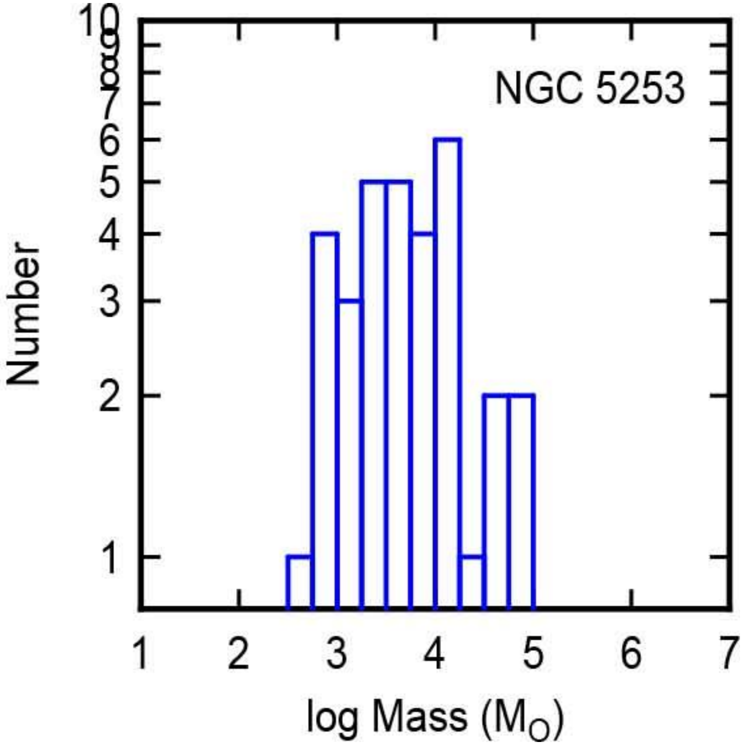
Source size = 10's pc: smaller than clumps found by other means.

SFR ~ 0.01 M_O/yr means 10^5 M_O in 10 Myr
x40 or so to include the other SF with each one.

LEGUS survey; Calzetti +15

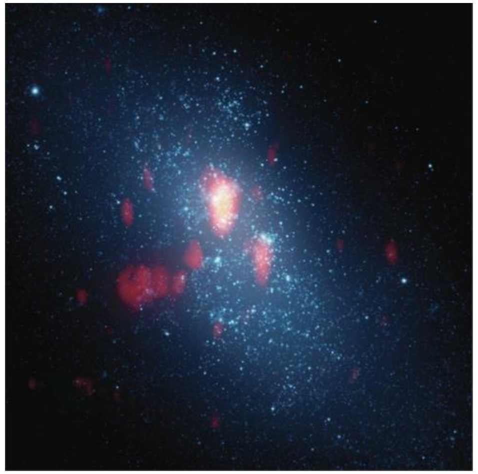






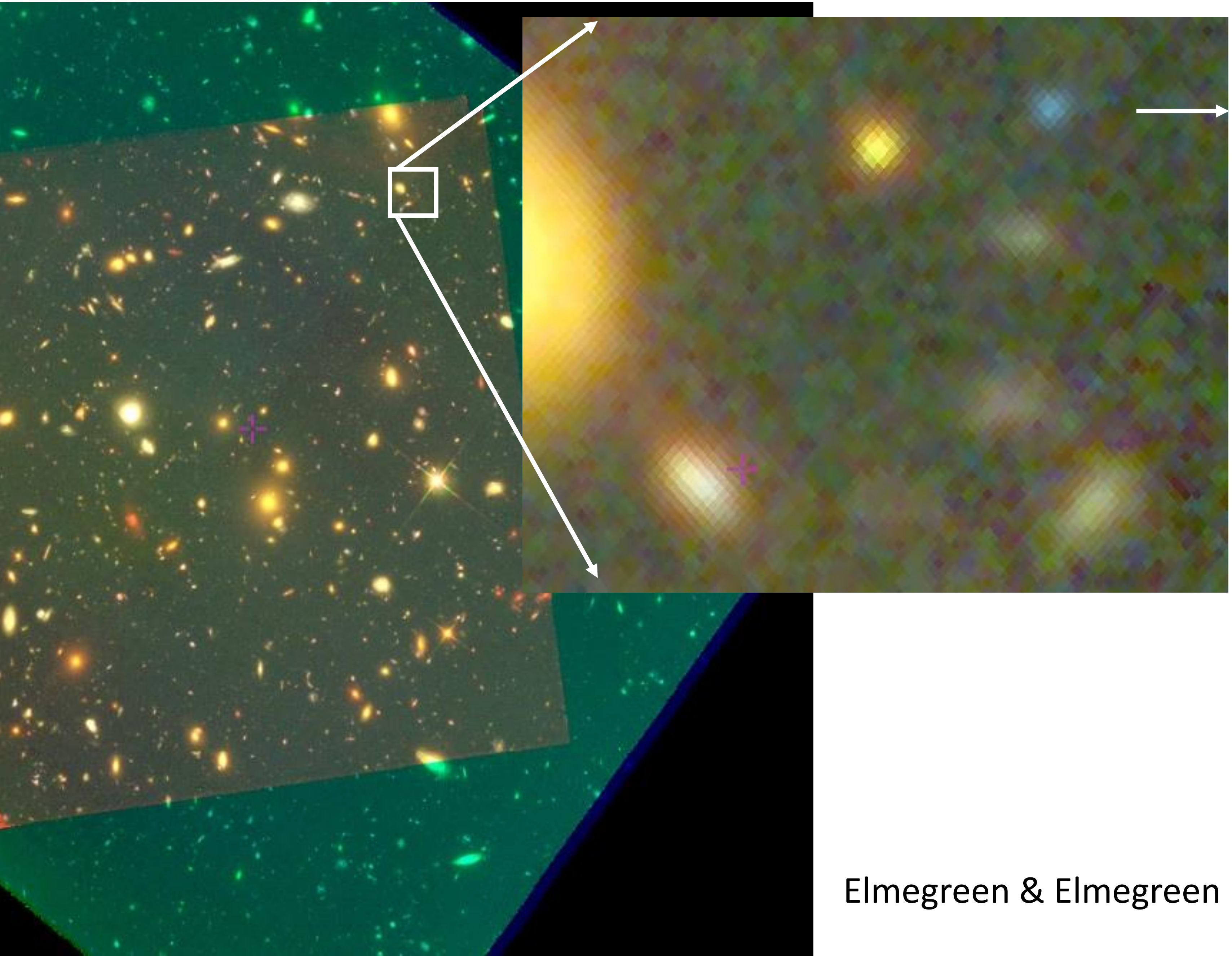
NASA-HST

NASA-HST



Lopez-Sanchez +12

The HST Frontier Field Parallels



60 “Little Blue Dot” galaxies

z ~ 1 - 4

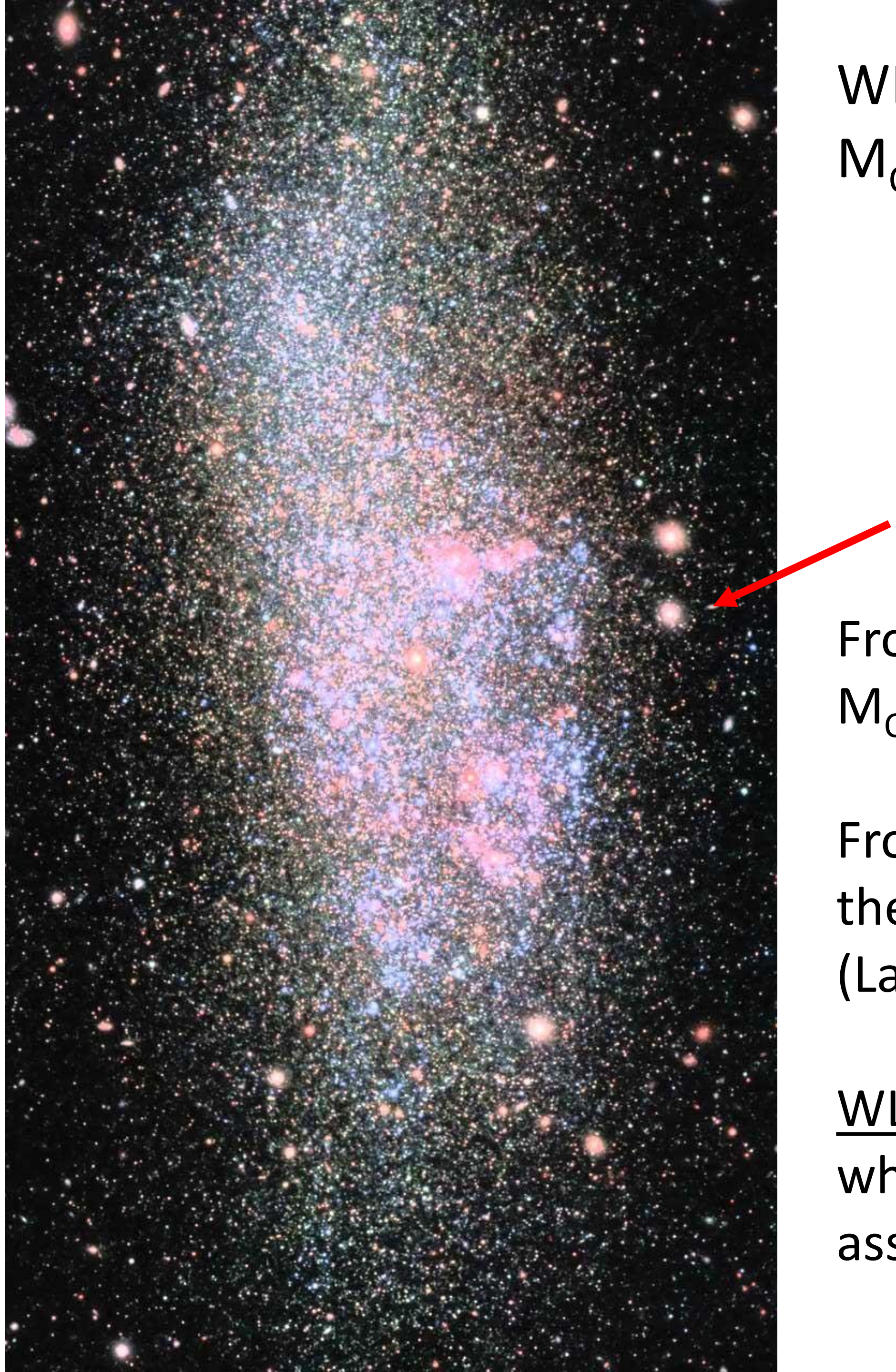
R ~ 150 pc from deconvolved stacked images (3 redshift bins)

Mstar ~ 10^6-10^7 M_O

1/sSFR ~ 10 Myr

SFR ~ 1 M_O/yr

Elmegreen & Elmegreen ‘17



WLM galaxy: A local dwarf (M_*=1.6x10^7 M_O; Zhang +12) with a metal-poor GC

~14 Gyr old GC (Hodge +99)
Fe/H = -1.63+-0.14,
M_V~-8.8 mag suggests 10^6 M_O

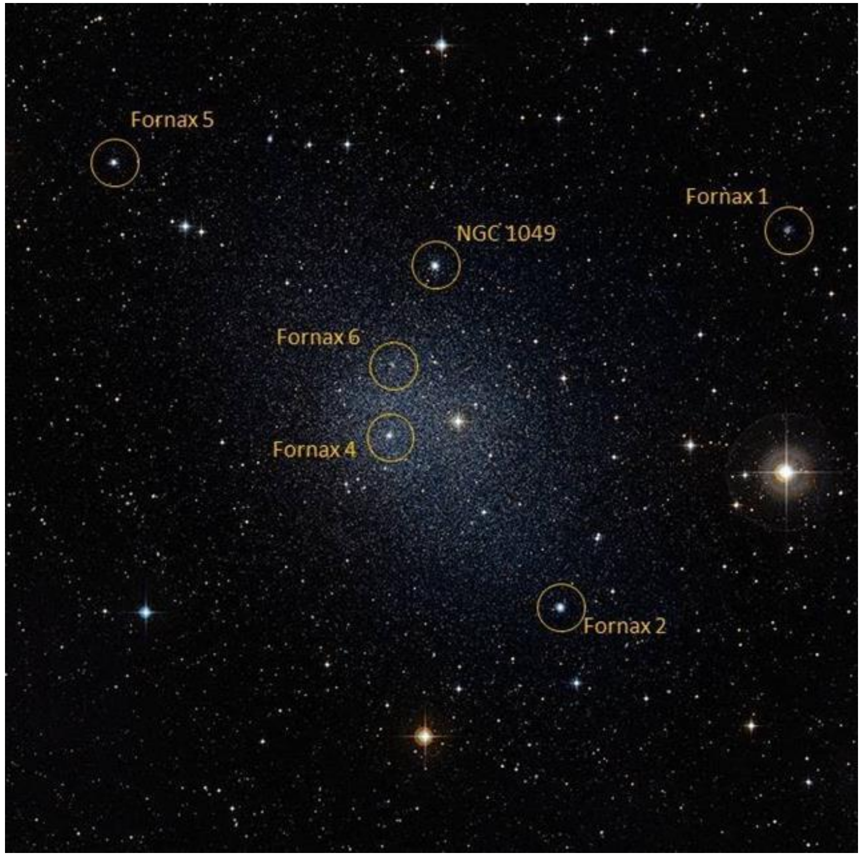
From the SFH, WLM stellar mass was also 10^6 M_O when GC formed (Leaman +12)

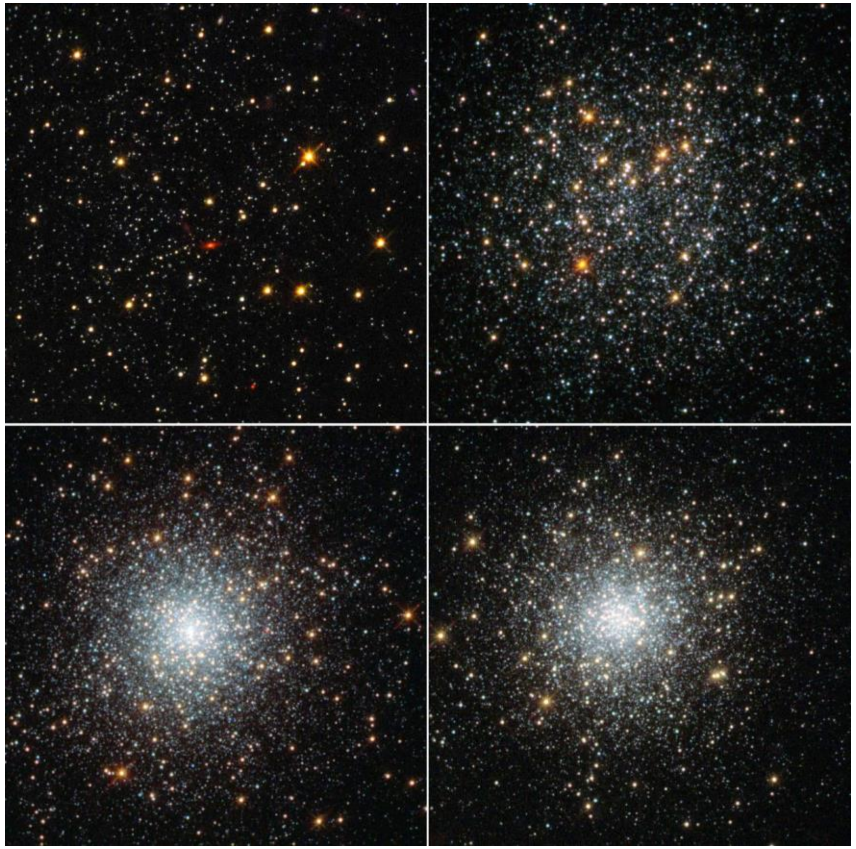
From the metallicity distribution, WLM was 4x the current GC mass when the GC formed (Larsen +14)

<u>WLM was dominated by the massive cluster</u> when the cluster formed (even without all the associated SF)

Larsen +12: Fornax dwarf: the summed GC mass is ~$1x10^6 M_O$ and the summed mass of all stars in Fornax with the same metallicity as the GCs was $3.1x10^6 M_O$.

Larsen +14: Fornax GCs





- Larsen +14: IKN dwarf: MP GC mass ~ the MP star mass
- Larsen +18: NGC 147: MP GC mass is 6% of MP star mass

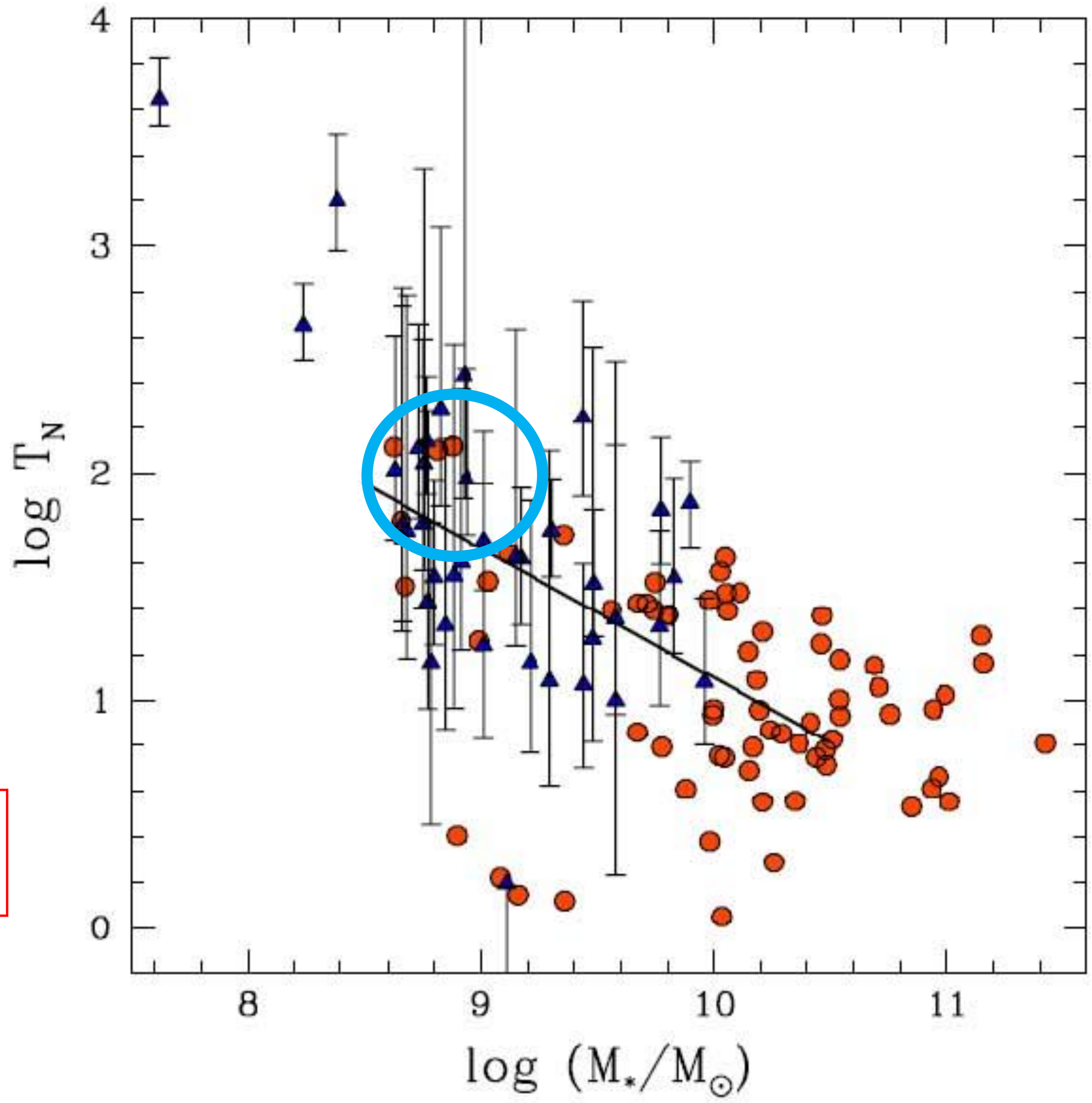
Zaritsky +15: GCs in the S^4G survey of spiral galaxies (3.6μ Spitzer IRAC)

T_N = Number of GCs per 10^9 M_O of galaxy.

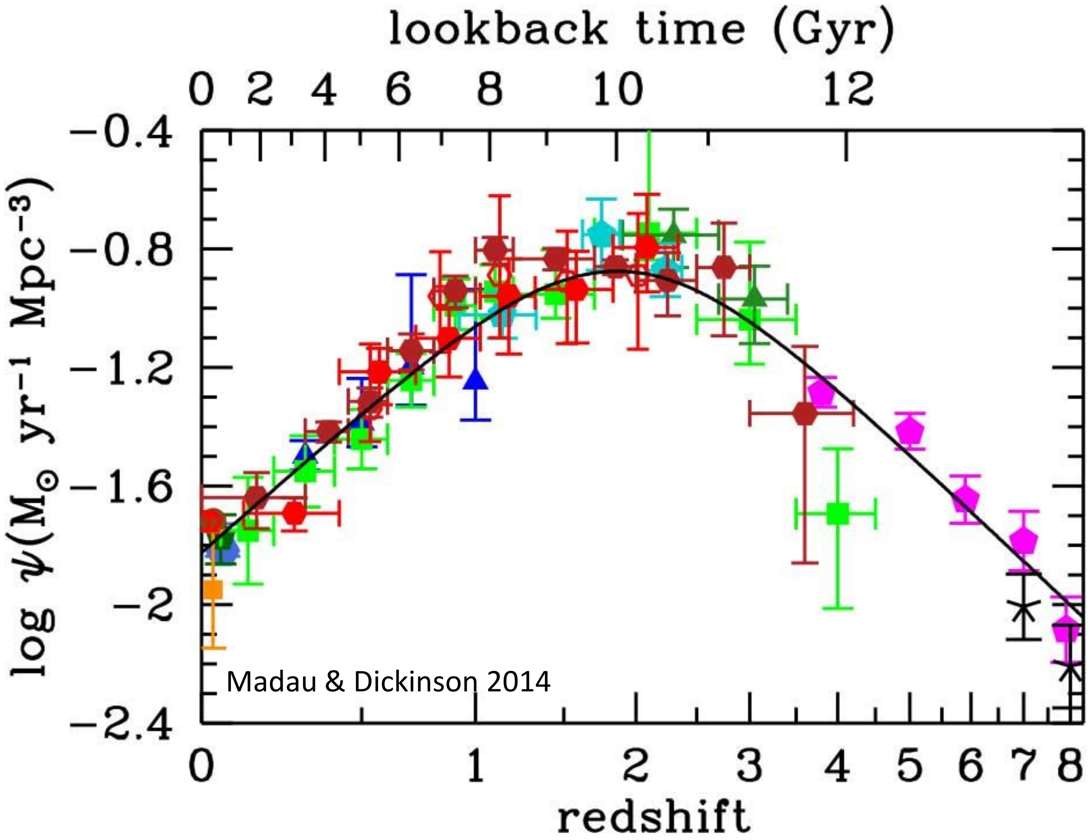
For dwarfs, 2% of today's mass is in GCs (@2×10^5 M_O each).

At 10% of the universe age, and for 10x initial GC mass (constrained by dual populations or by integrating the CMF), the total GC mass then was comparable to the galaxy mass at GC formation

GC formation was a whole-galaxy event



Summary



Madau & Dickinson 2014

Massive spiral and elliptical galaxies with almost no 10^6 M_O clusters forming, and old remnants from the GC-era in their halos and bulges

⇐

Small, dense, turbulent, clumpy galaxies commonly forming today's GCs, with the M-P GCs dominating the smallest galaxies *ala Hans Z. et al. 1988*

Thanks for 41 years of friendship and inspiration!

2017,
Prague