Herschel and ALMA reveal the hidden side of star formation in the distant Universe

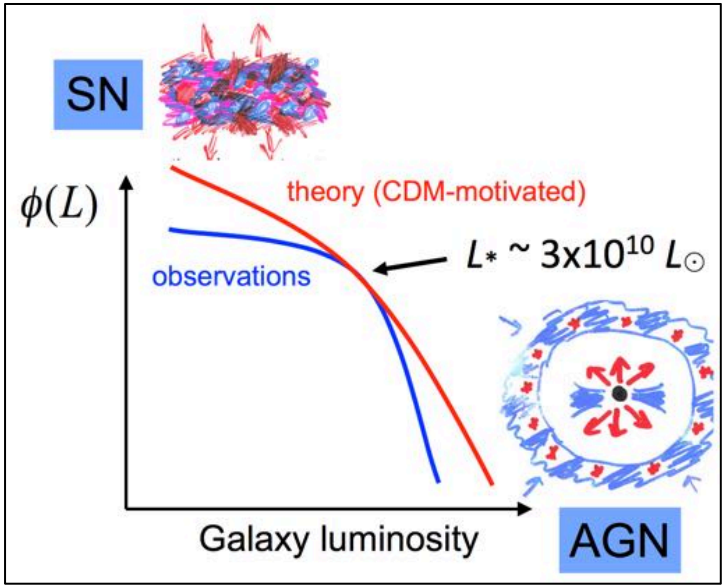
David Elbaz, CEA Saclay

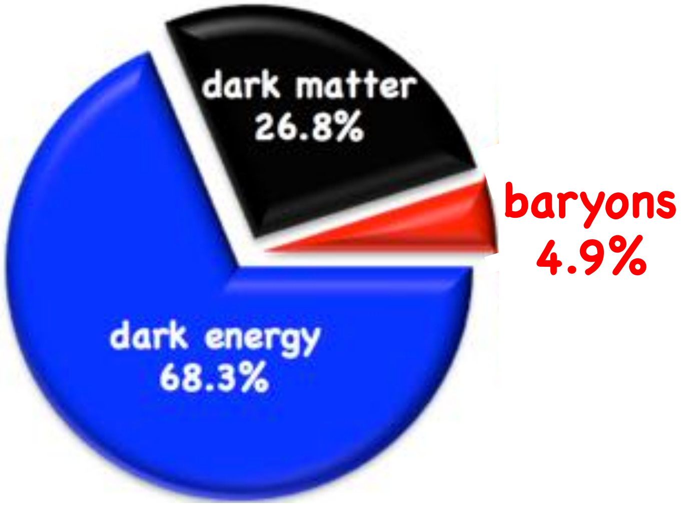
with

C.Schreiber (PhD)

T.Wang, M.Pannella, X.Shu (postdocs)

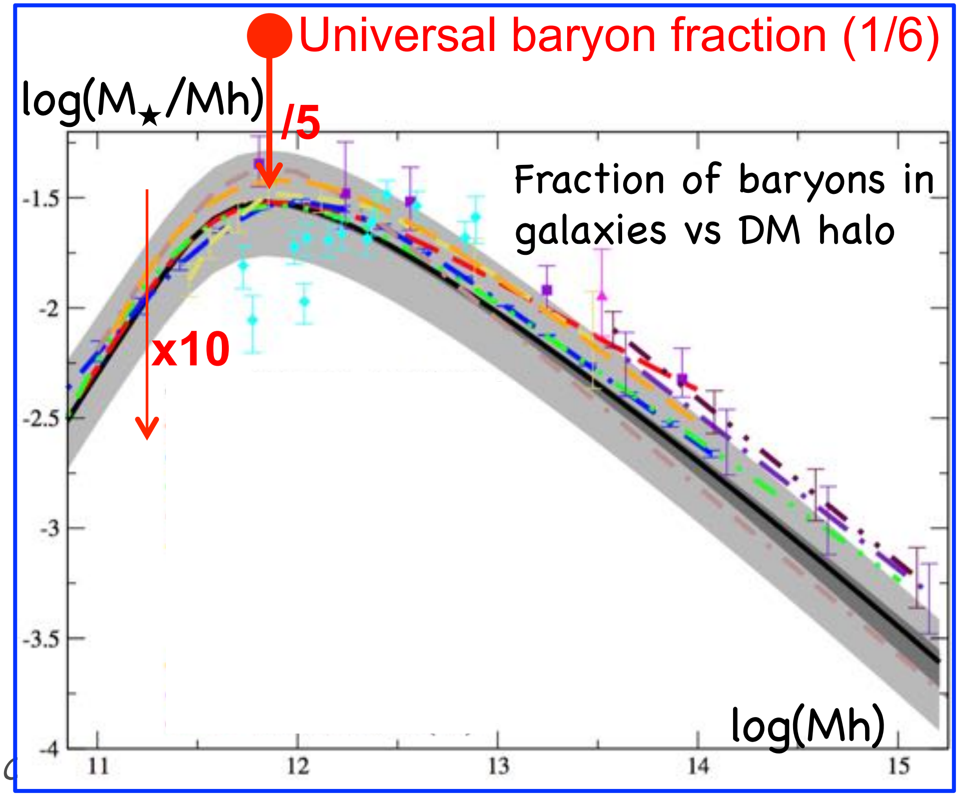
E.Daddi, M.Dickinson



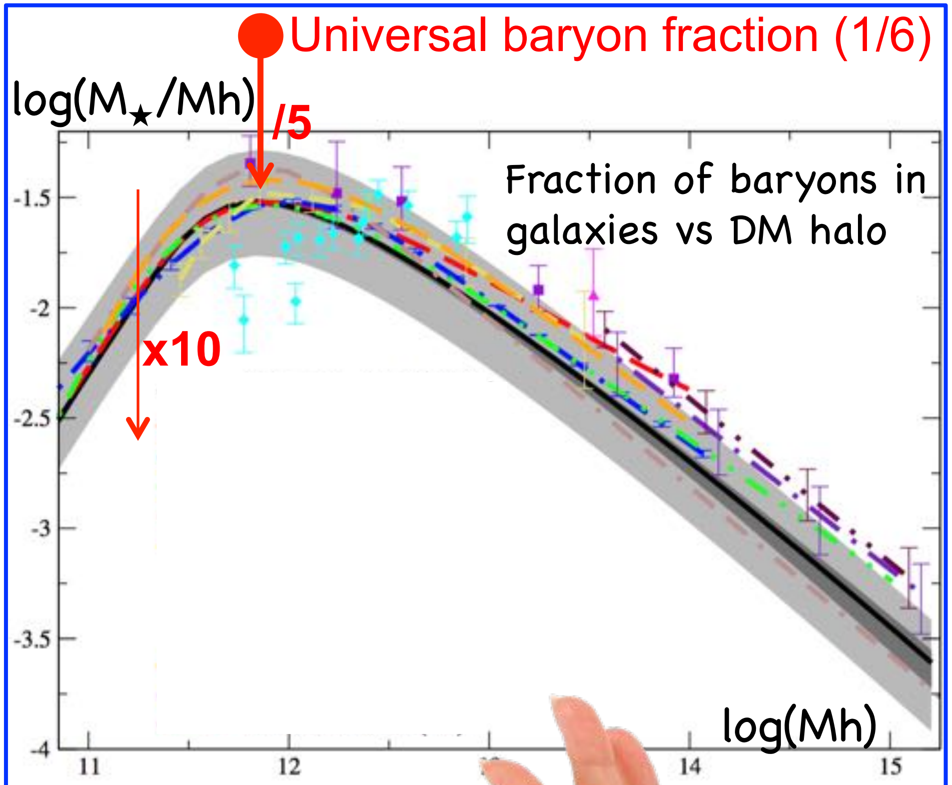


MW:
1/5th of universal baryon/DM

MW/10:
1/50th of universal baryon/DM

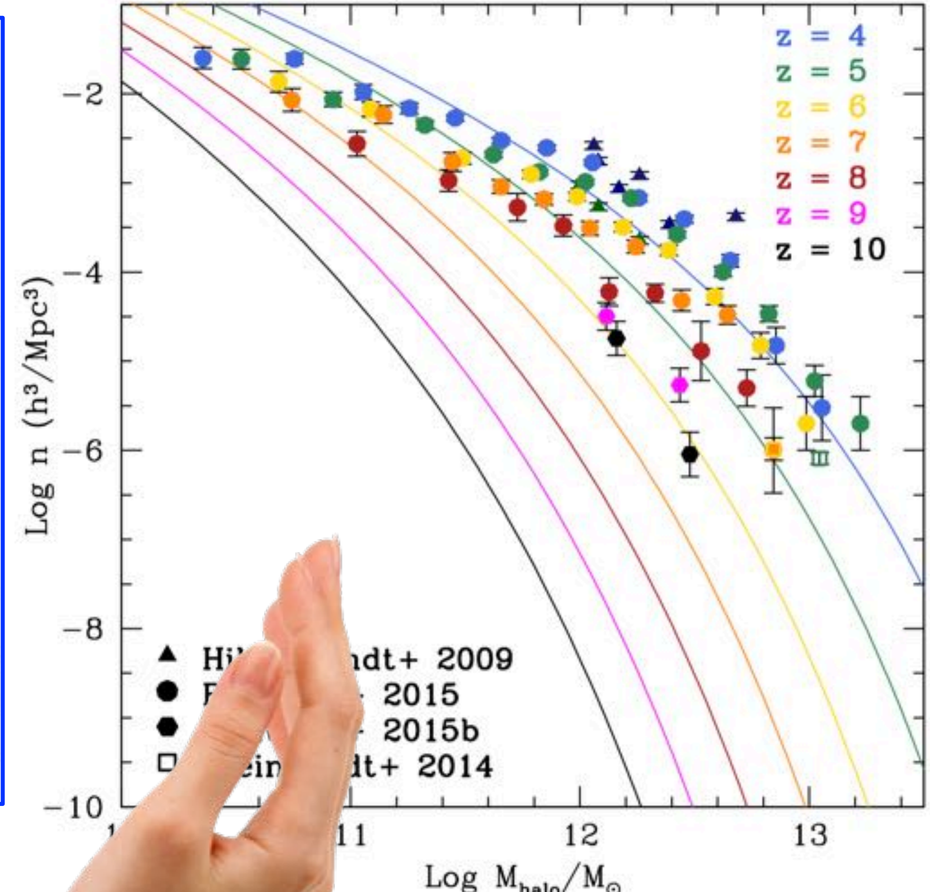


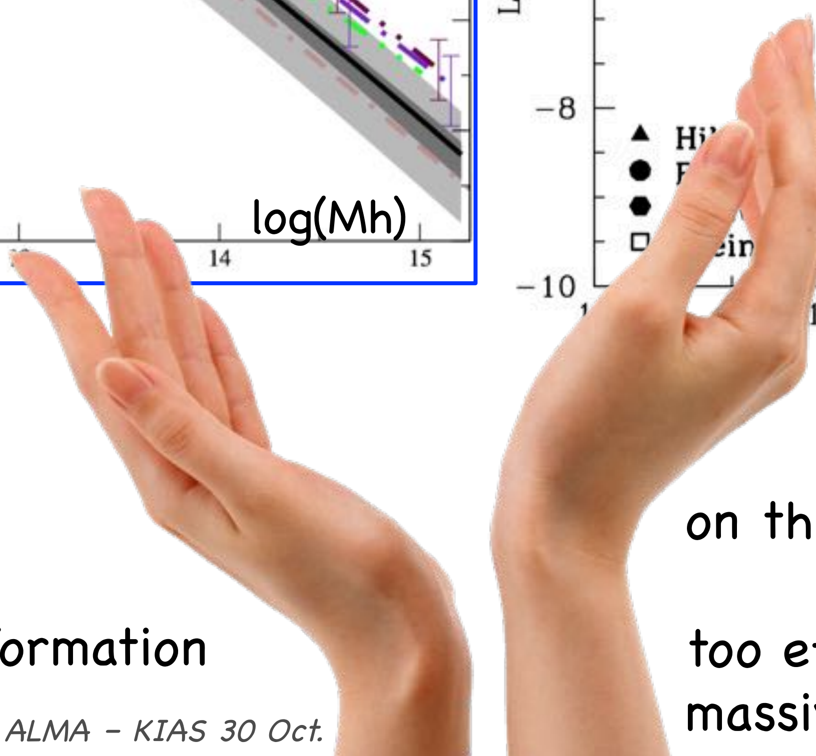
Paradoxical galaxy formation



THE IMPOSSIBLY EARLY GALAXY PROBLEM

CHARLES. L. STEINHARDT [1,2], PETER CAPAK[1,2], DAN MASTERS[1,2], JOSH S. SPEAGLE[3,2,4]





on one hand...

inefficient galaxy formation

on the other hand...

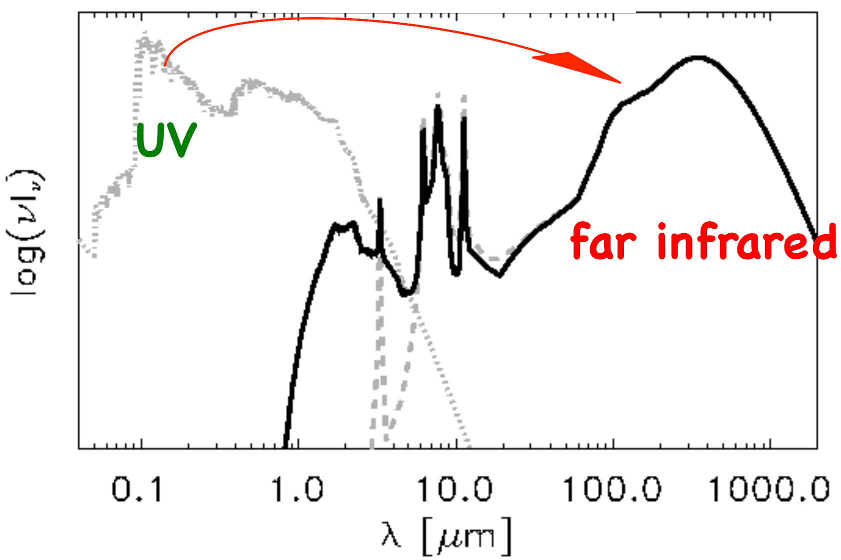
too efficient high-z massive galaxy formation

Why is the Universe so inefficient in forming galaxies ?
What regulates the efficiency of galaxy/star formation ?

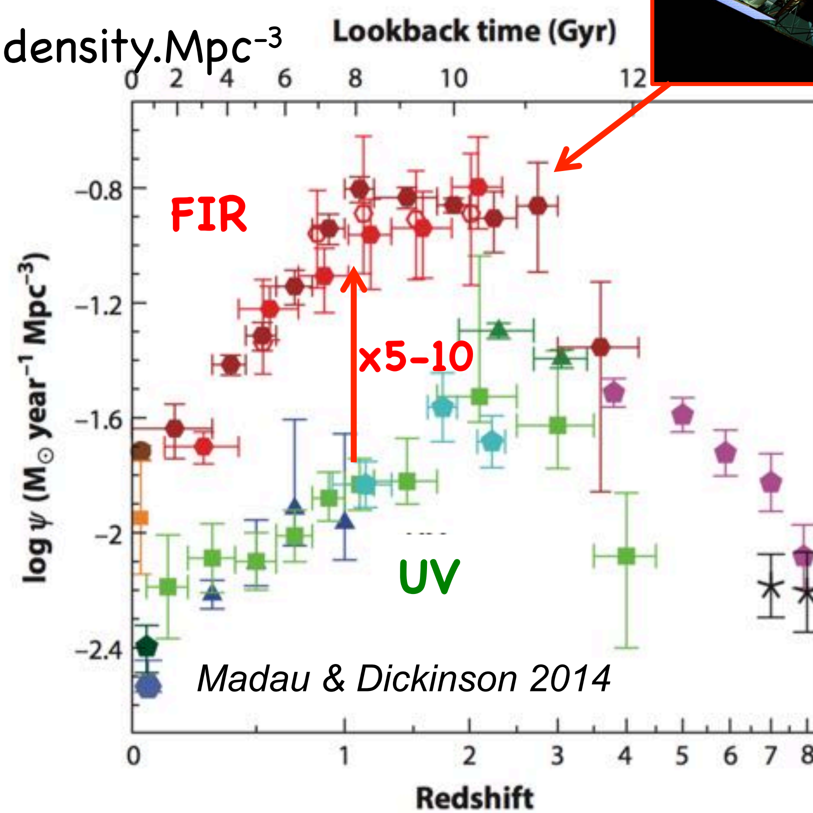
Total far infrared luminosity + **uncorrected UV**

→ total UV emission from OB stars

→ star-formation rate , f(IMF)



SFR density.Mpc^{-3}

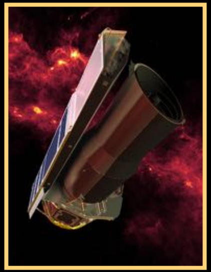


IRAS 1985
57 cm
41" fwhm

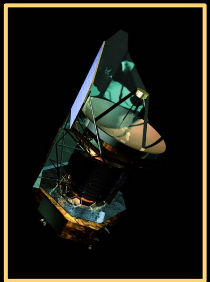
100 μm

ISO 1995
60 cm

100μm



Spitzer 2003
85 cm



Herschel 2009
350 cm

FWHM
100μm=6.7 arcsec

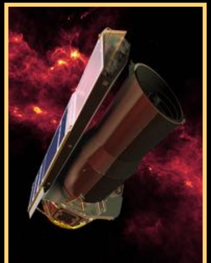
0.2 arcsec

IRAS 1985
57 cm
41" fwhm

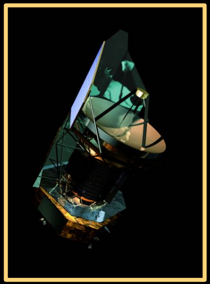
100 µm

ISO 1995
60 cm

100µm



Spitzer 2003
85 cm



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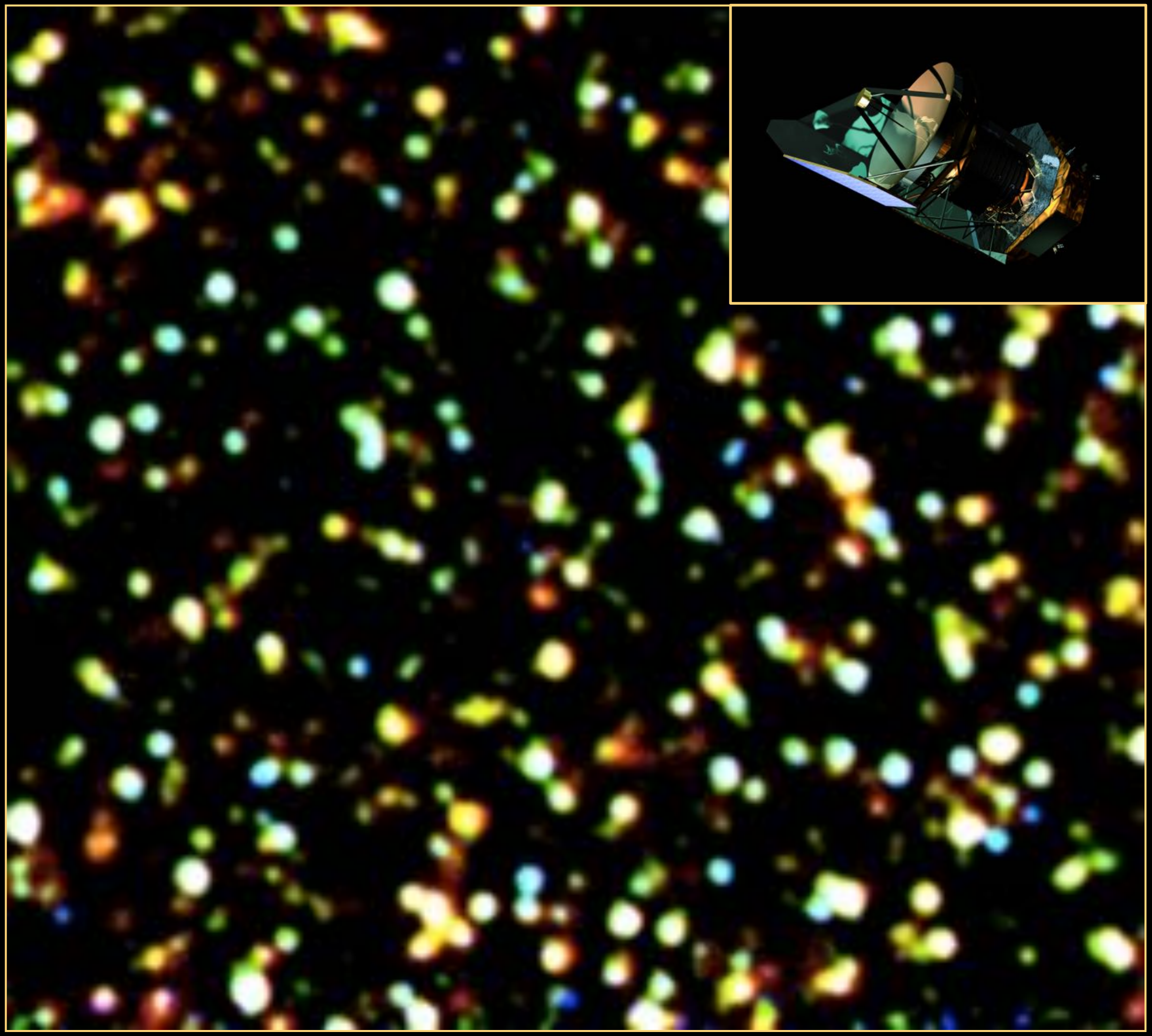
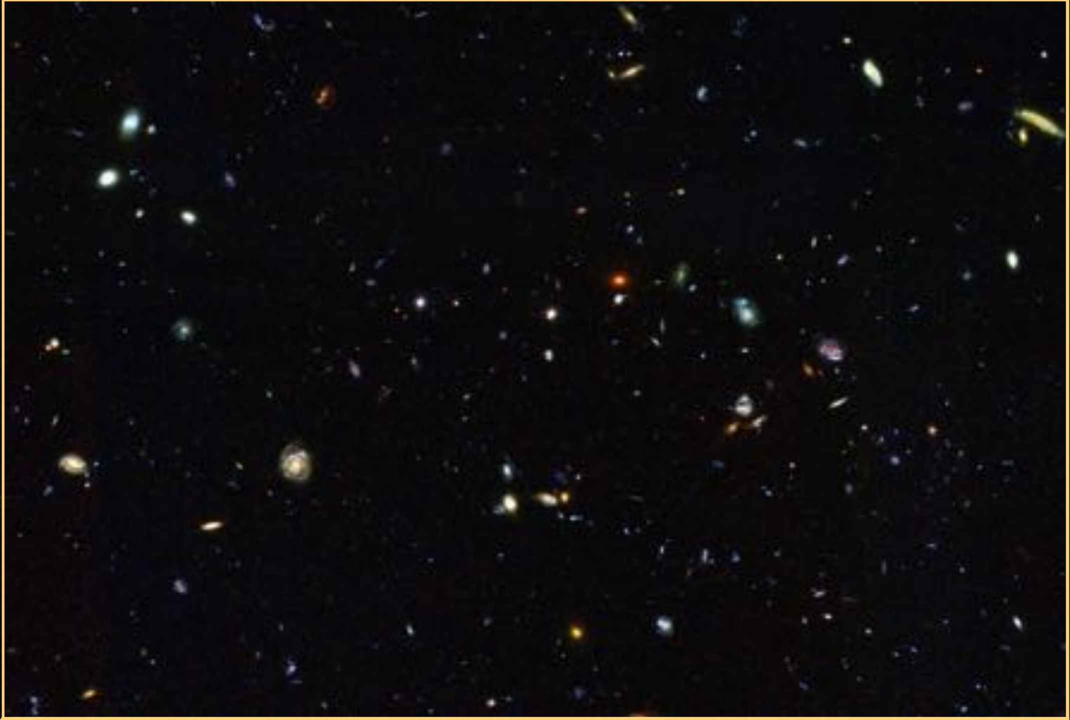
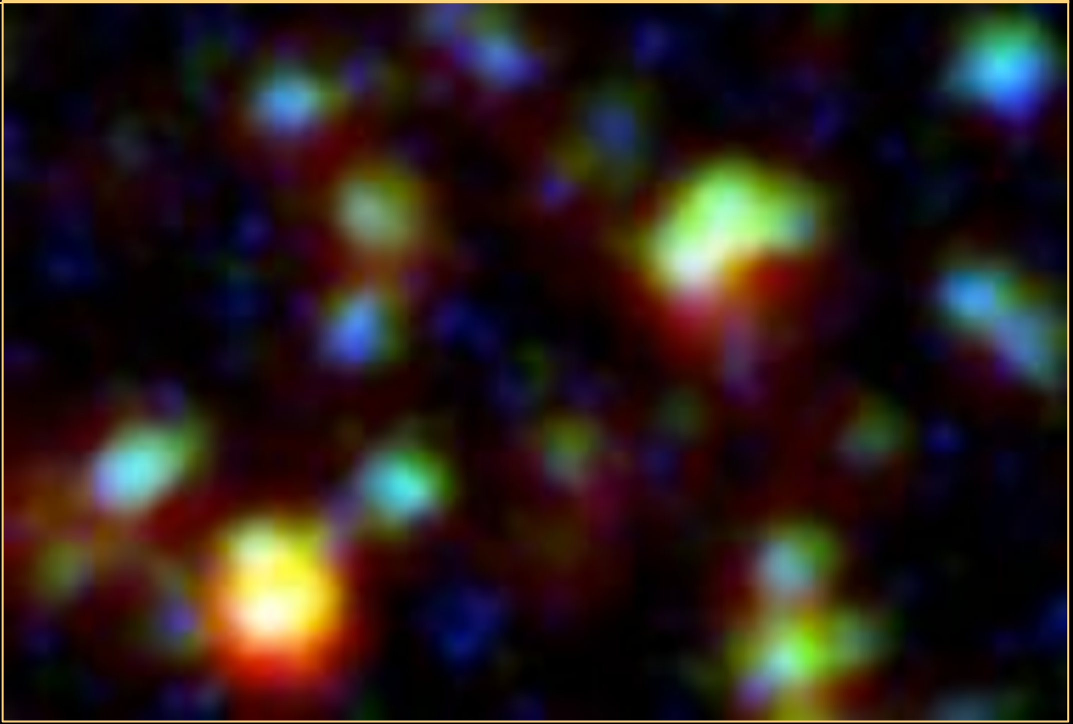
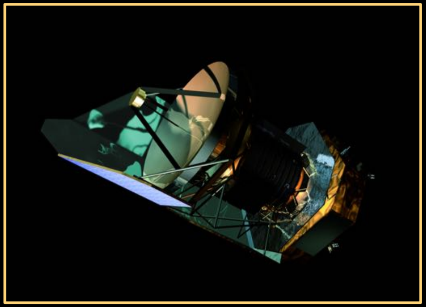
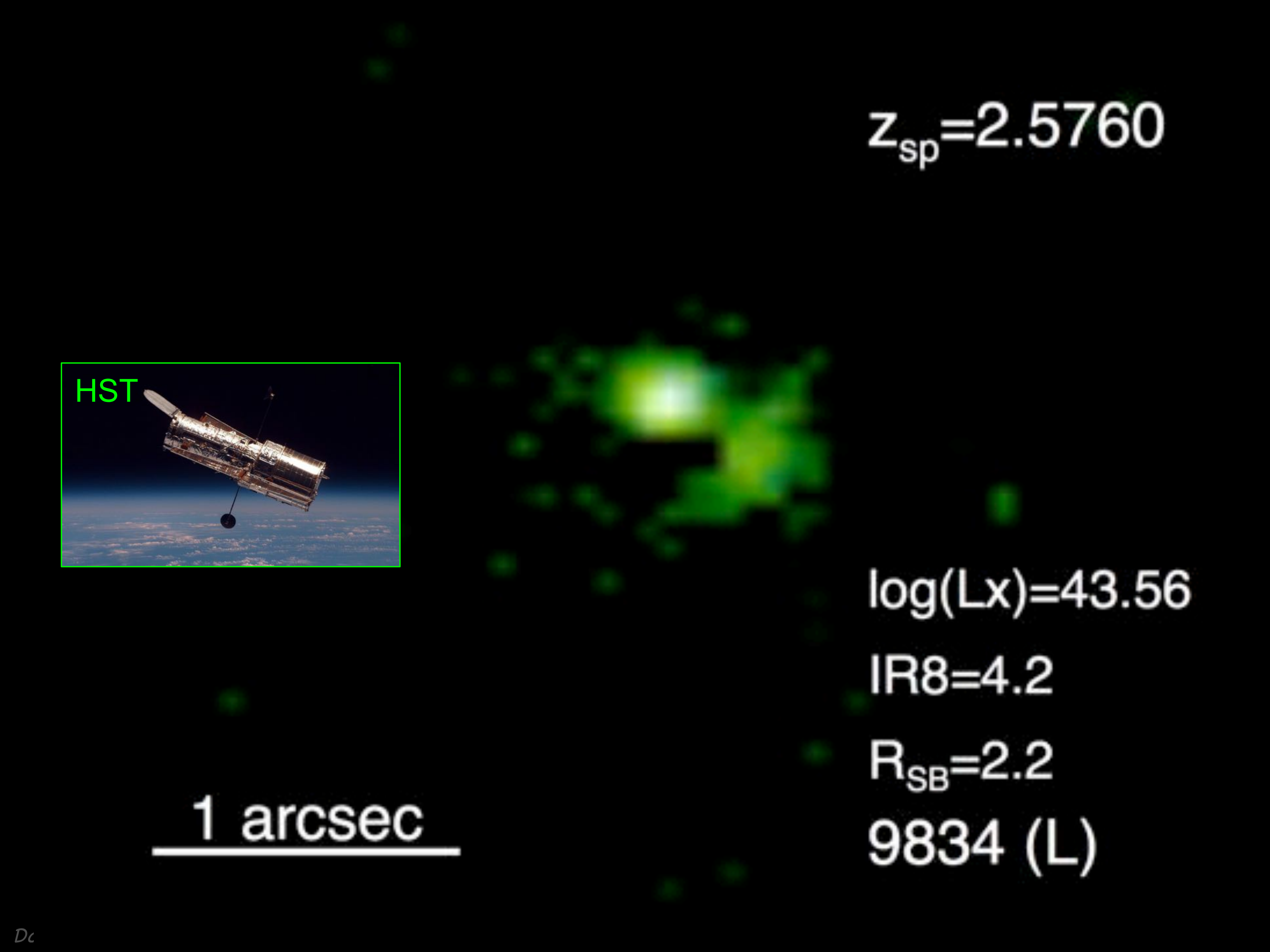
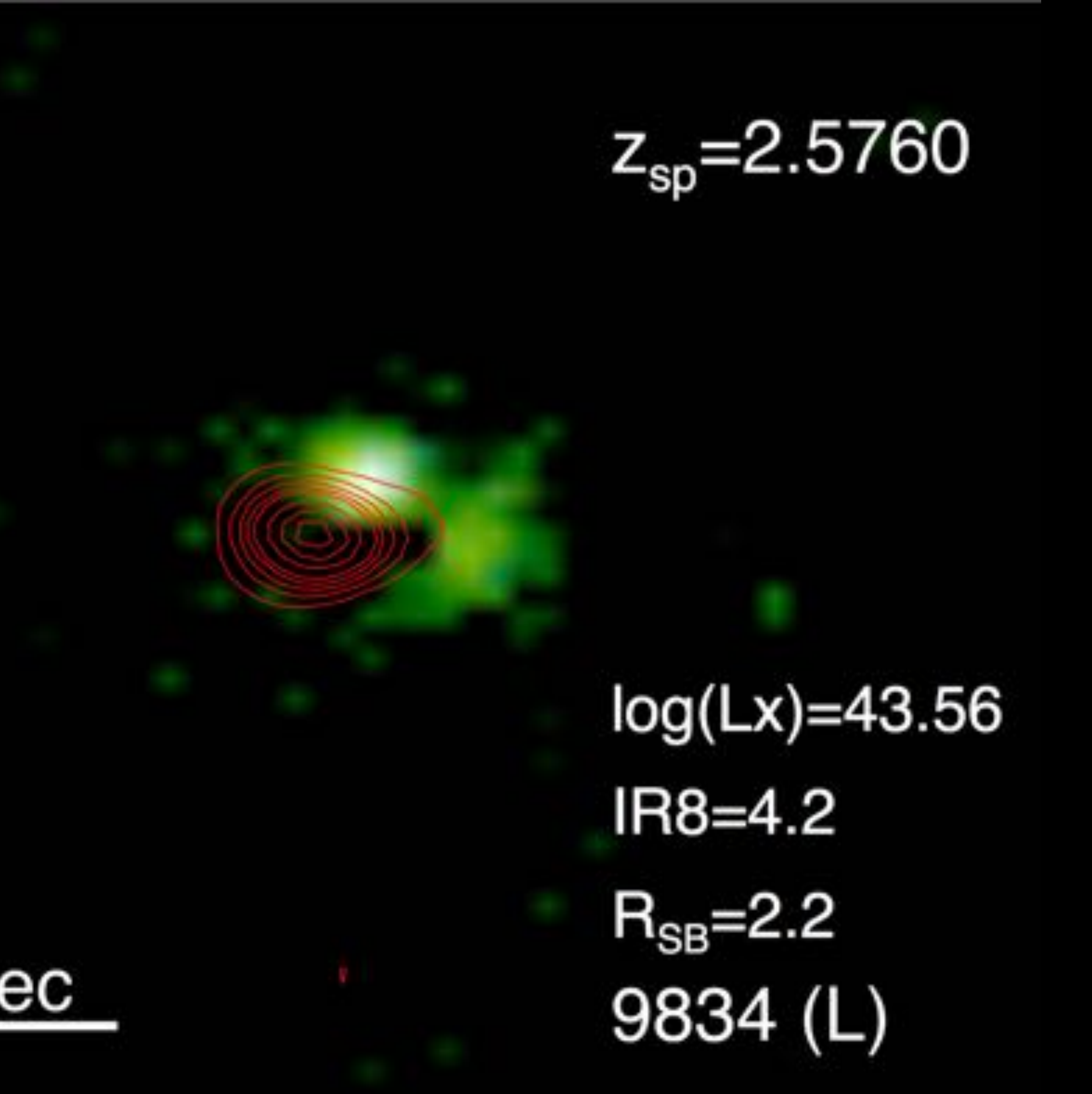


Elbaz +11

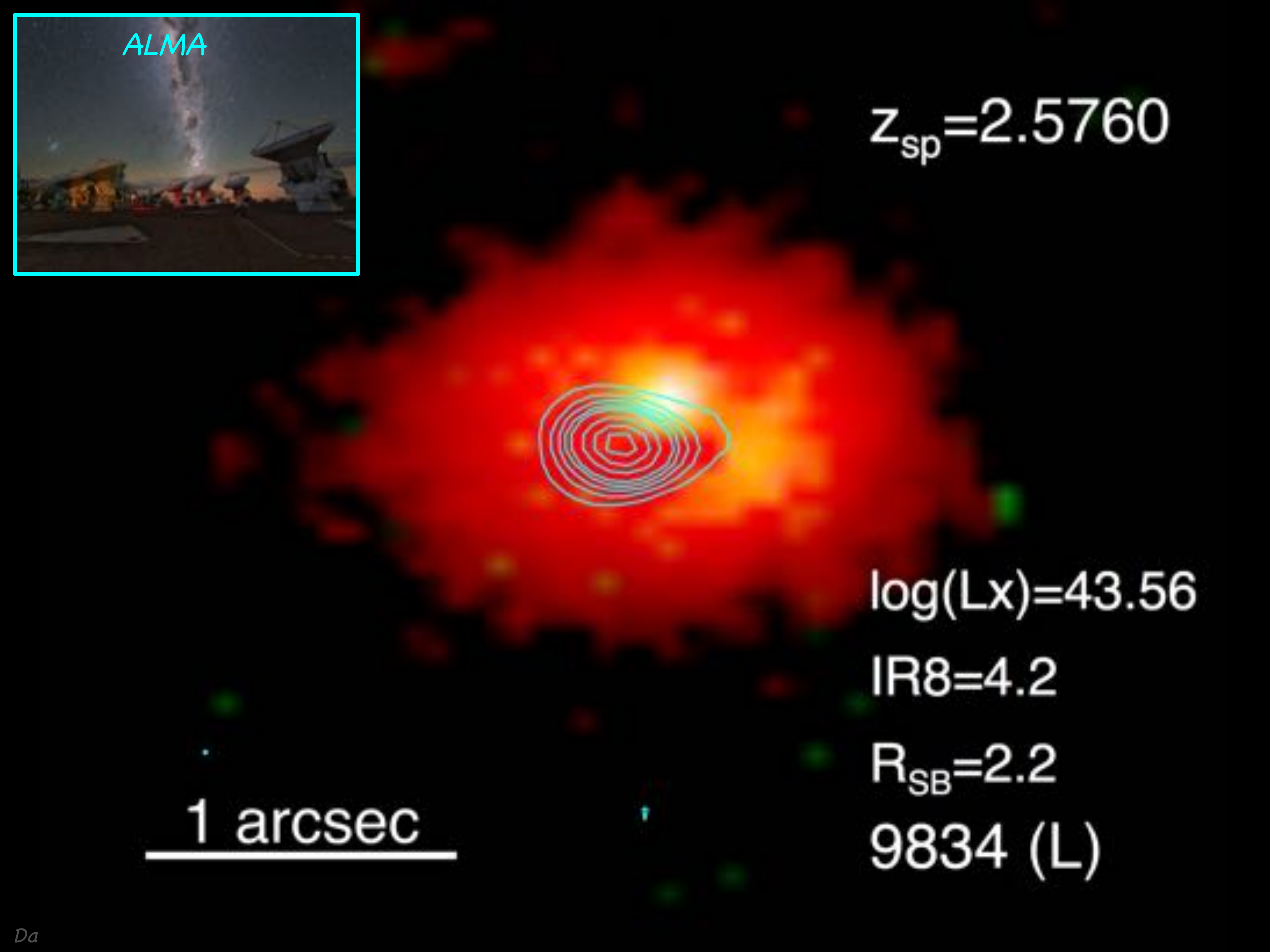


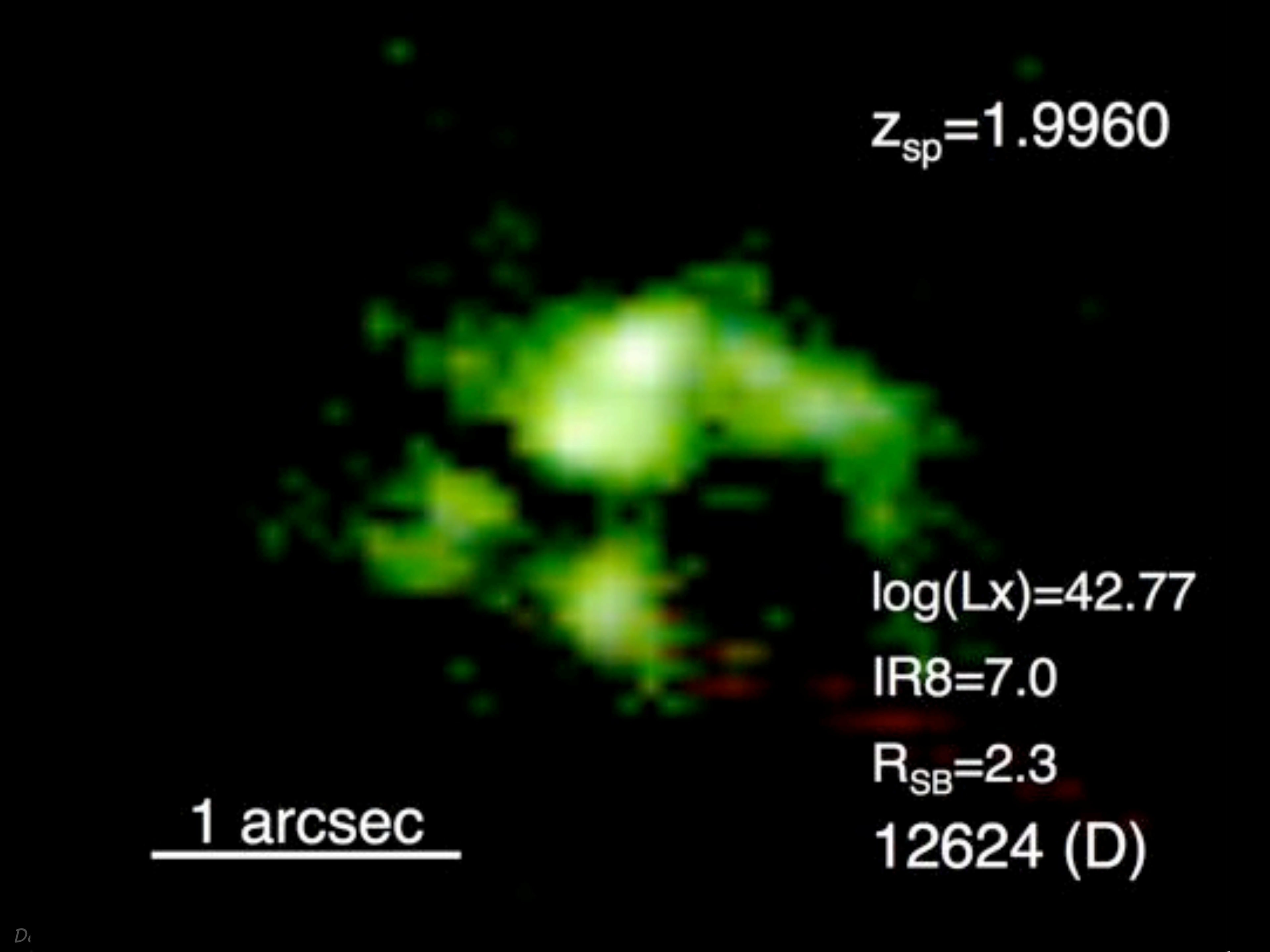




z_{sp}=2.5760
HST
log(Lx)=43.56
IR8=4.2
R_{SB}=2.2
9834 (L)
1 arcsec

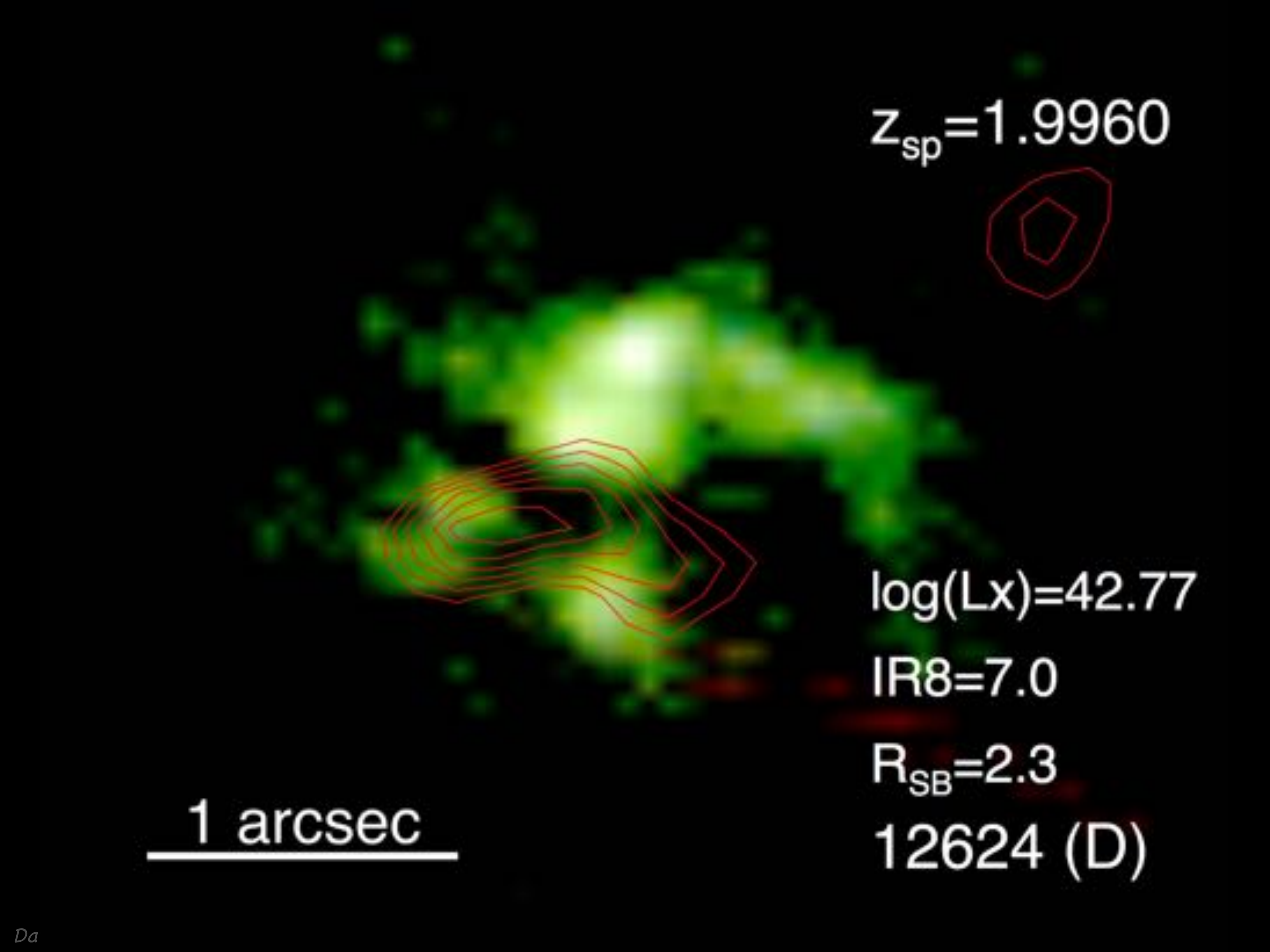


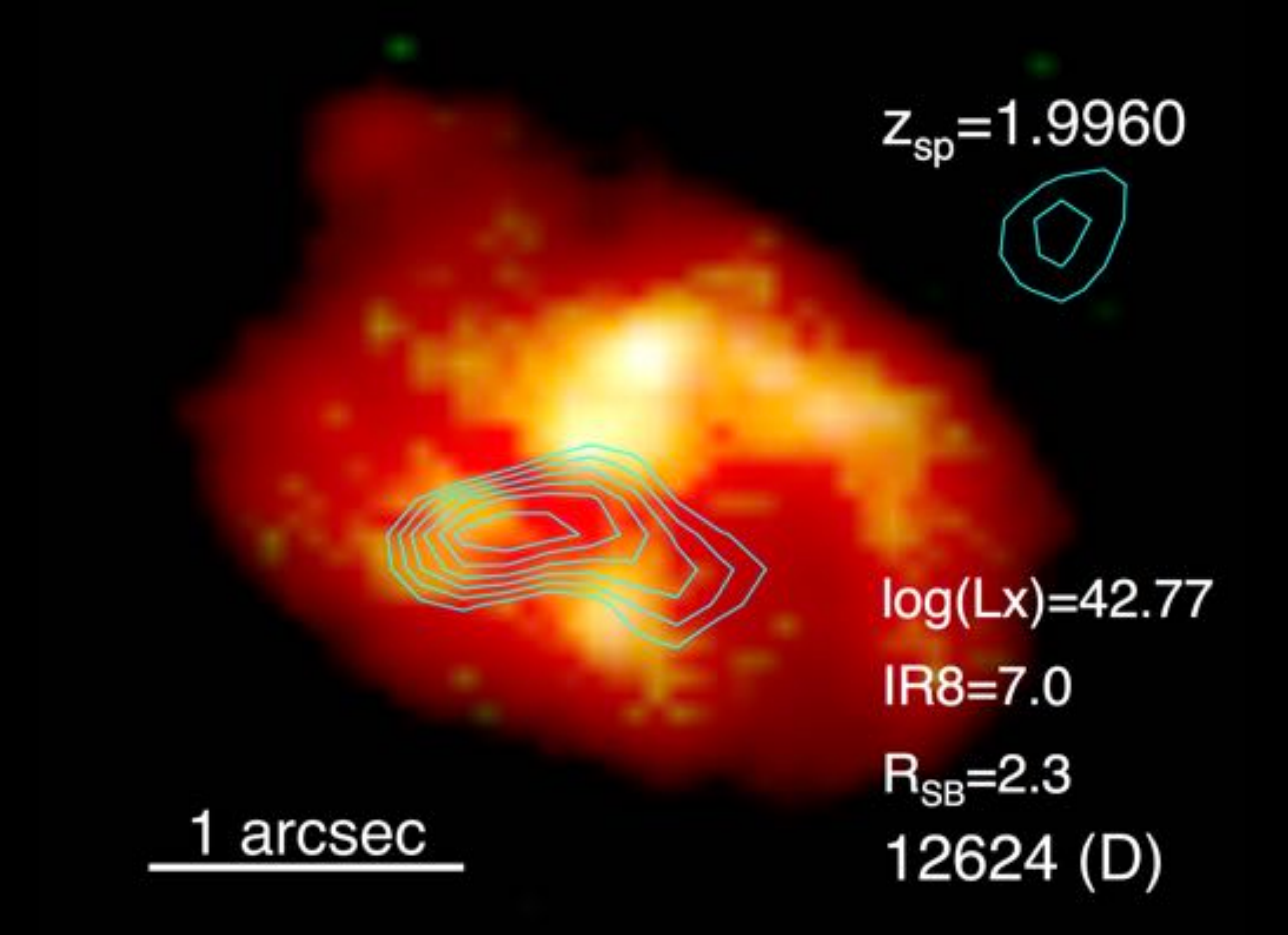
Da


ALMA
z_sp=2.5760
log(Lx)=43.56
IR8=4.2
R_SB=2.2
9834 (L)
1 arcsec
Da



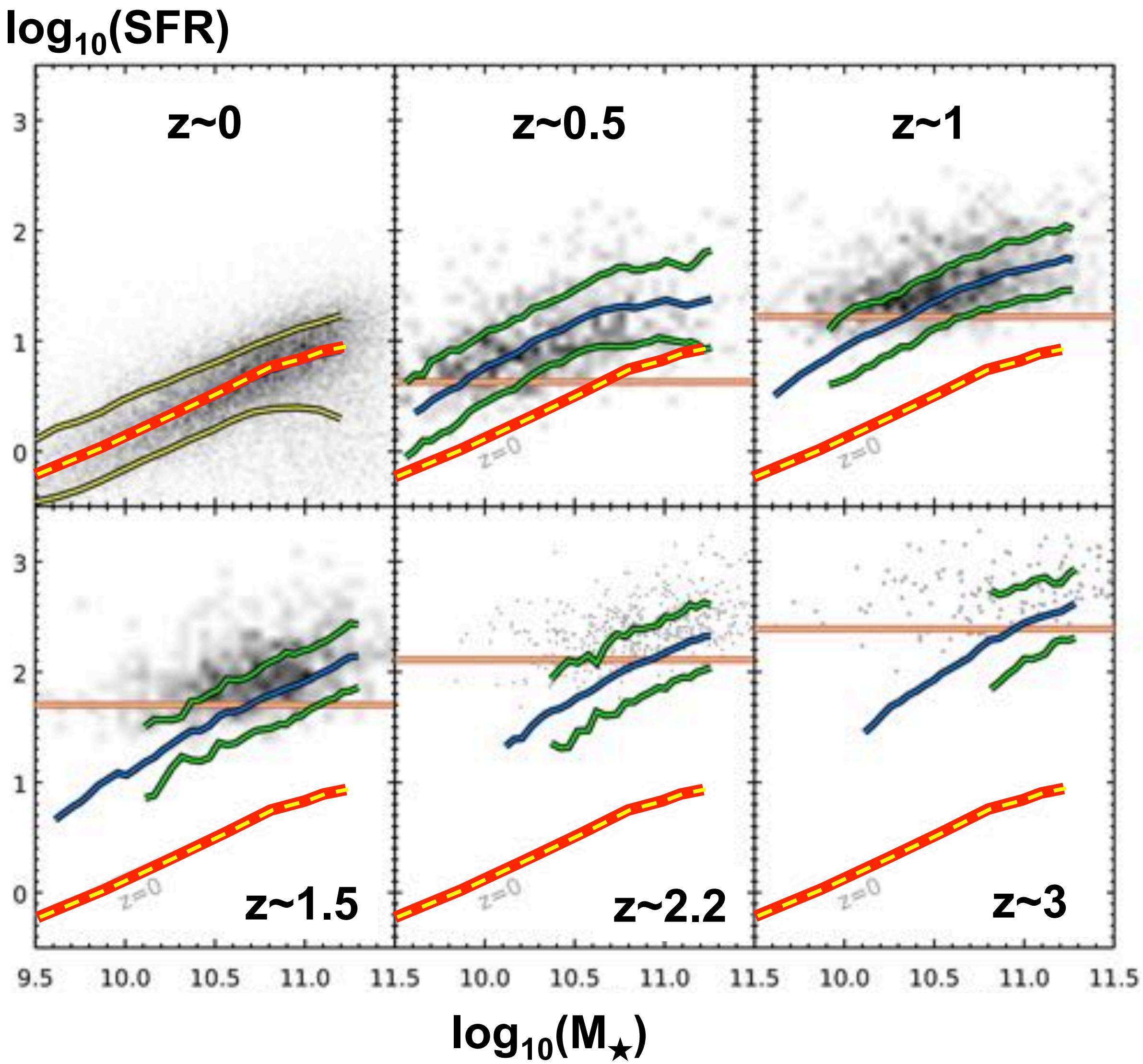
z_{sp}=1.9960
log(Lx)=42.77
IR8=7.0
R_{SB}=2.3
12624 (D)
1 arcsec

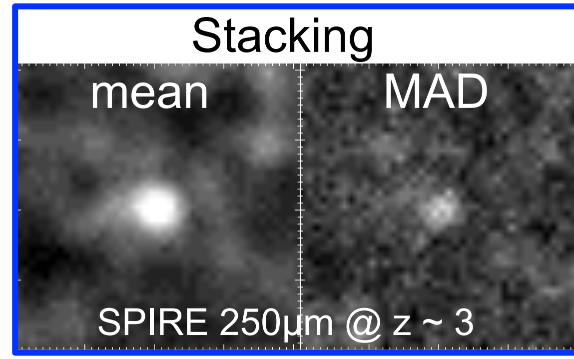

z_{sp}=1.9960
log(Lx)=42.77
IR8=7.0
R_{SB}=2.3
1 arcsec
12624 (D)
Da



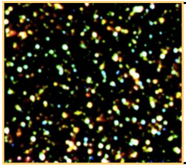
Da

The main sequence of star-formation
as viewed by Herschel





Schreiber +2015



The main sequence of star-formation
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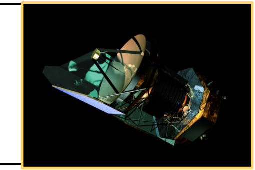
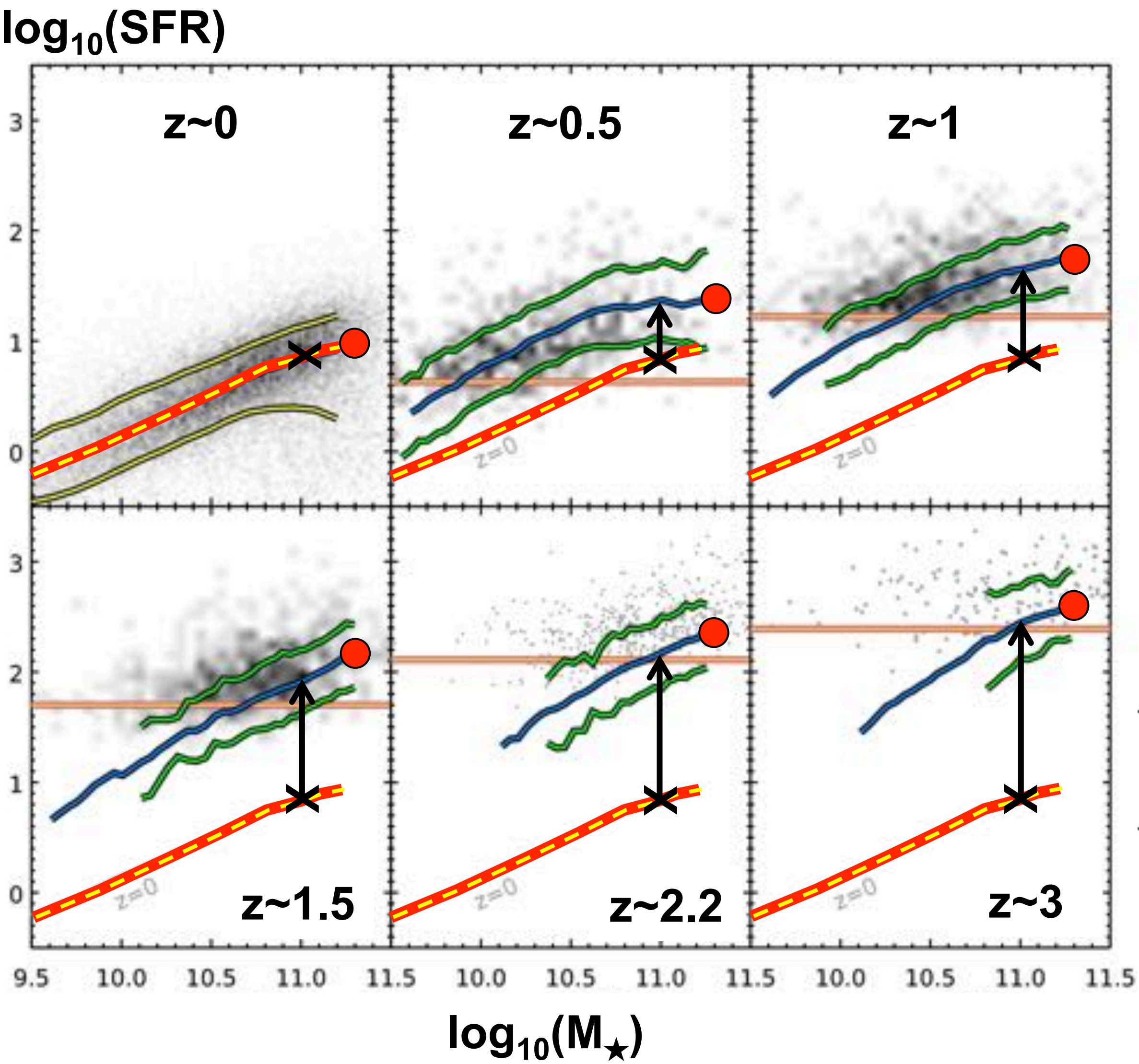
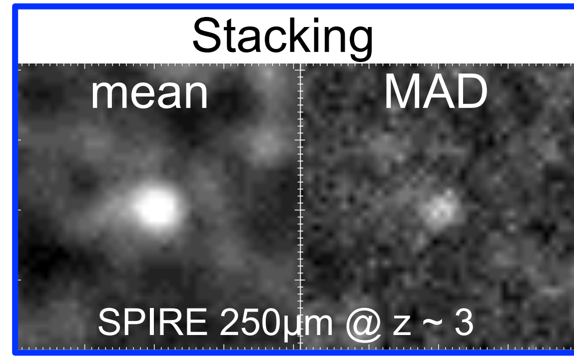
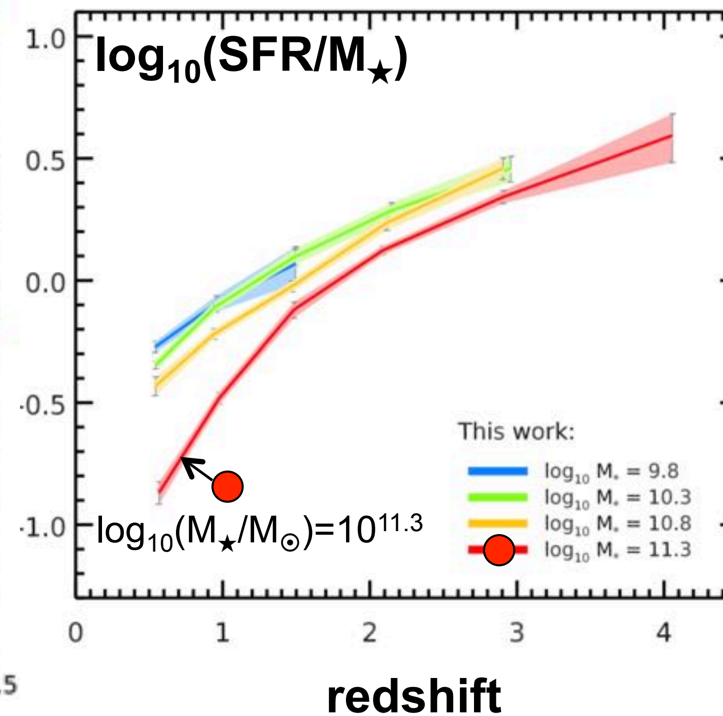


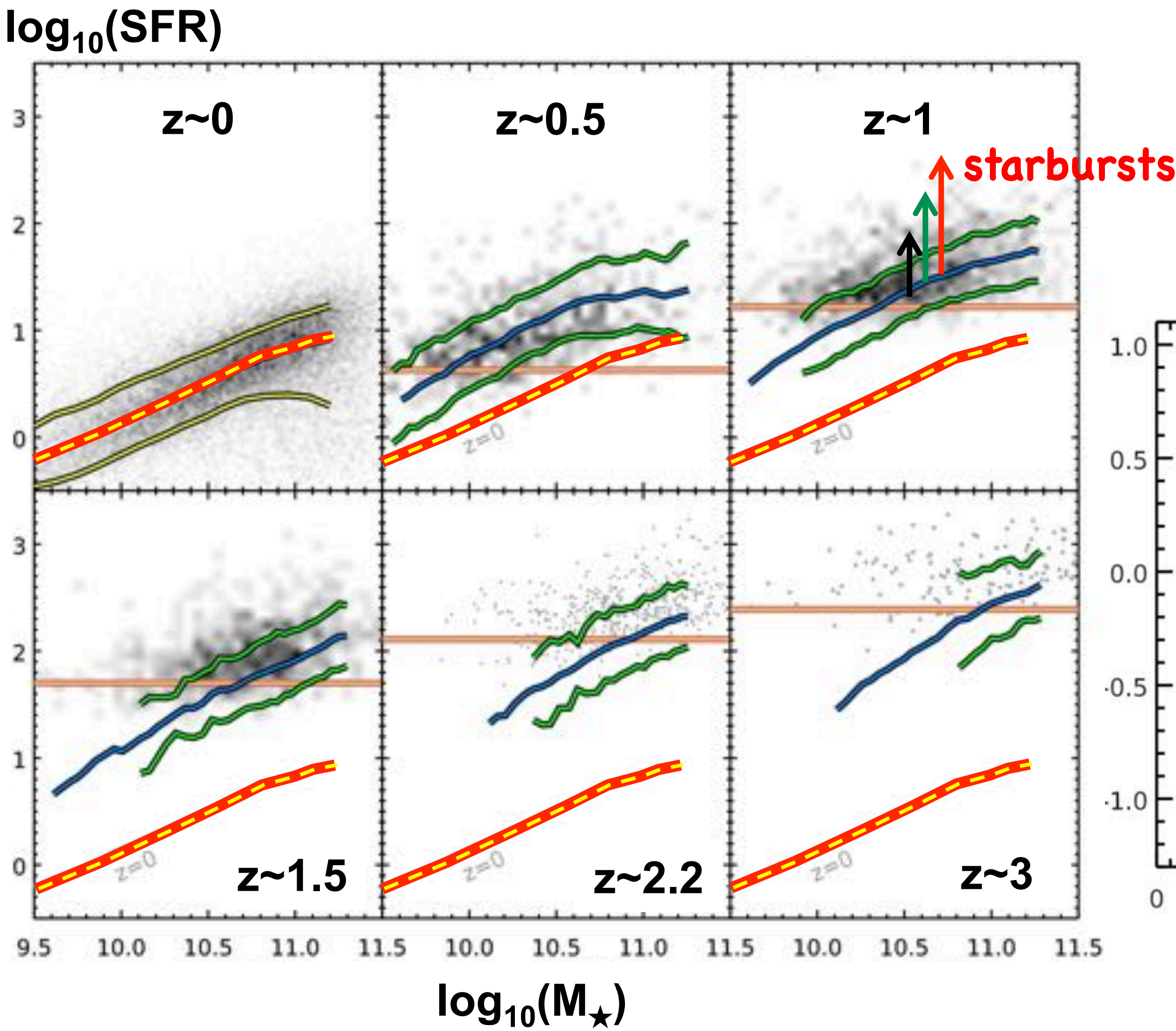


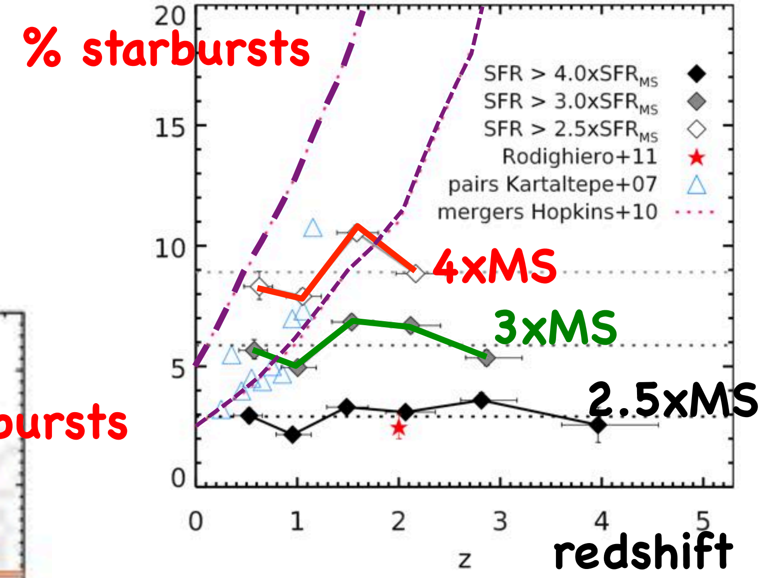


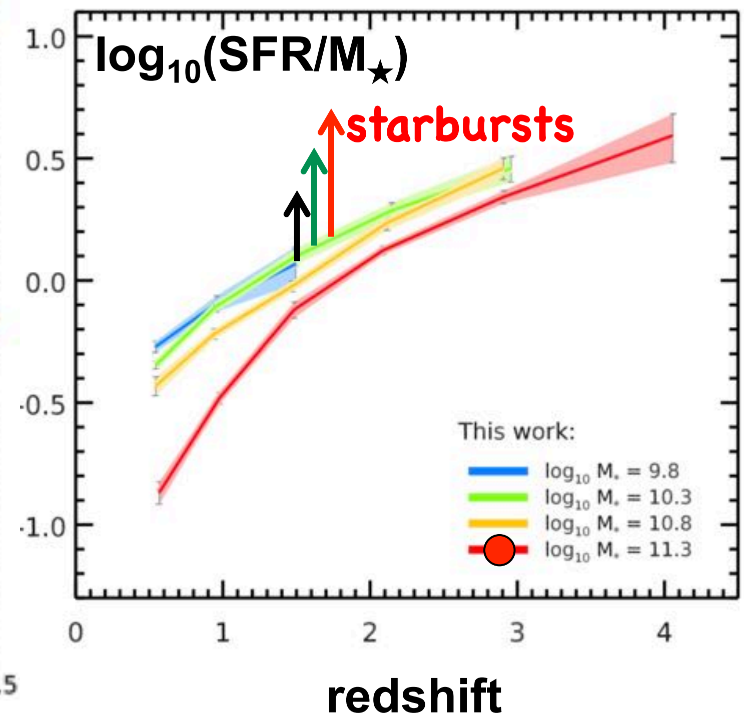


Schreiber +2015

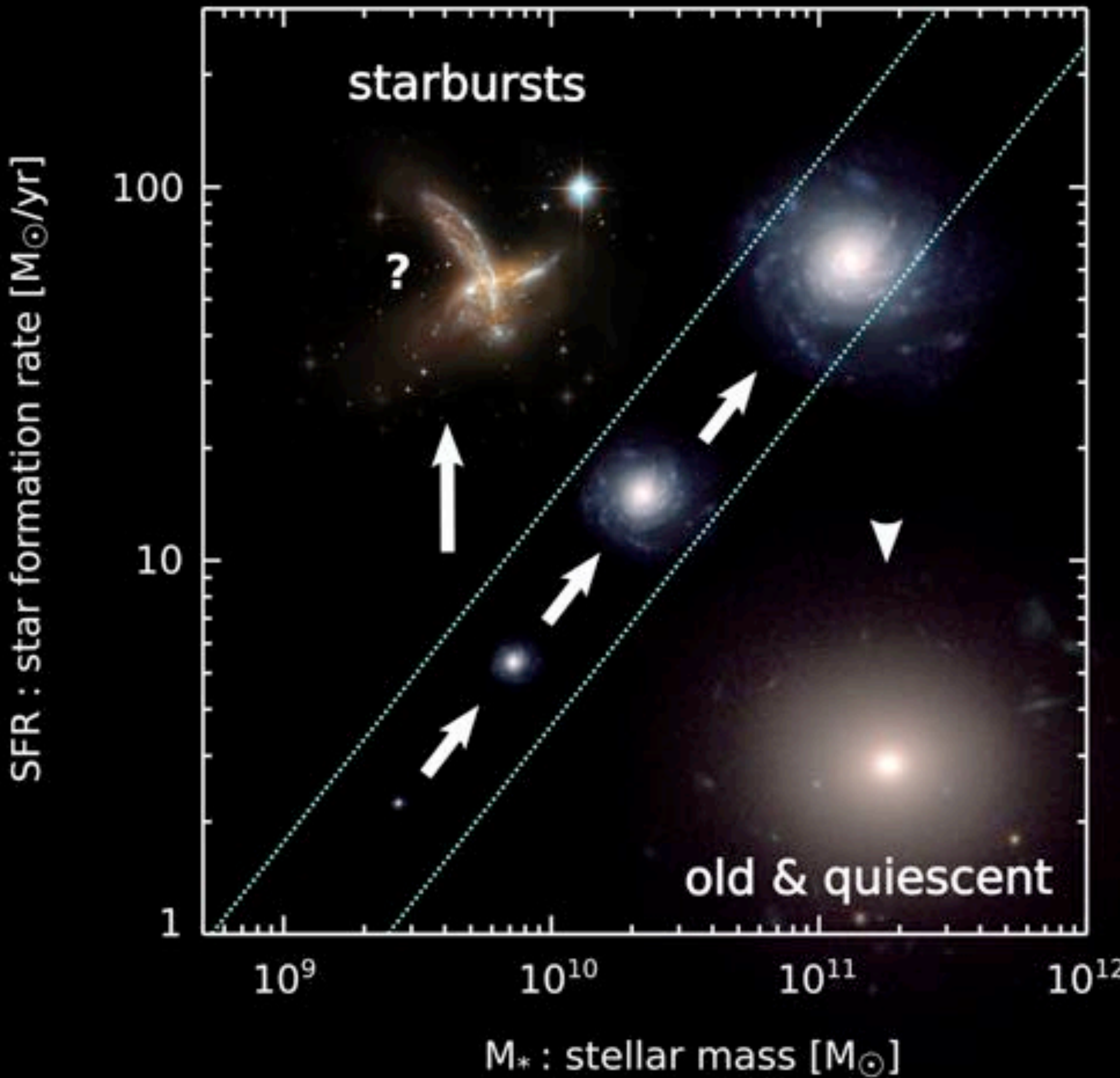
Starbursts and main sequence



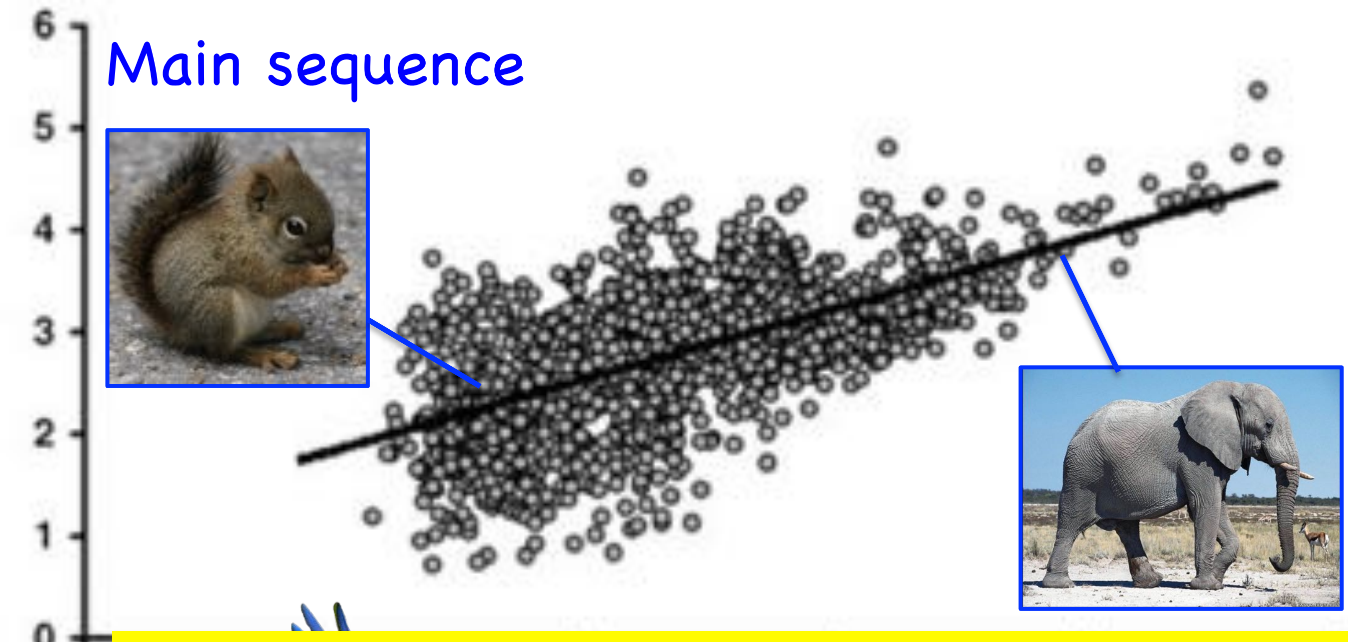




Schreiber +2015


starbursts
?
old & quiescent
100
10
1
SFR : star formation rate [M⊙/yr]
10^9
10^10
10^11
10^12
M* : stellar mass [M⊙]

David Elbaz

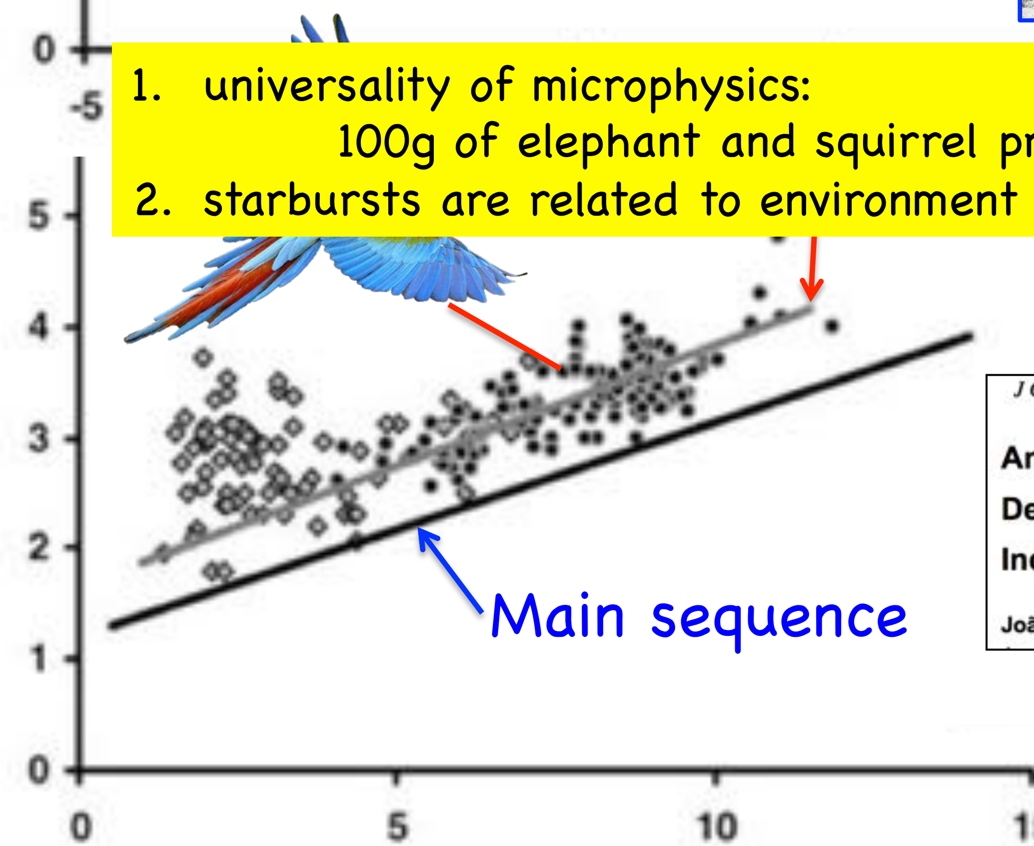


longevity

~1 billion heart beats

heart rate ~ 1/SFR

1. universality of microphysics:
   100g of elephant and squirrel produce energy with the same efficiency
2. starbursts are related to environment effects



J Gerontol A Biol Med Sci. 2007 February ; 62(2): 149–160.

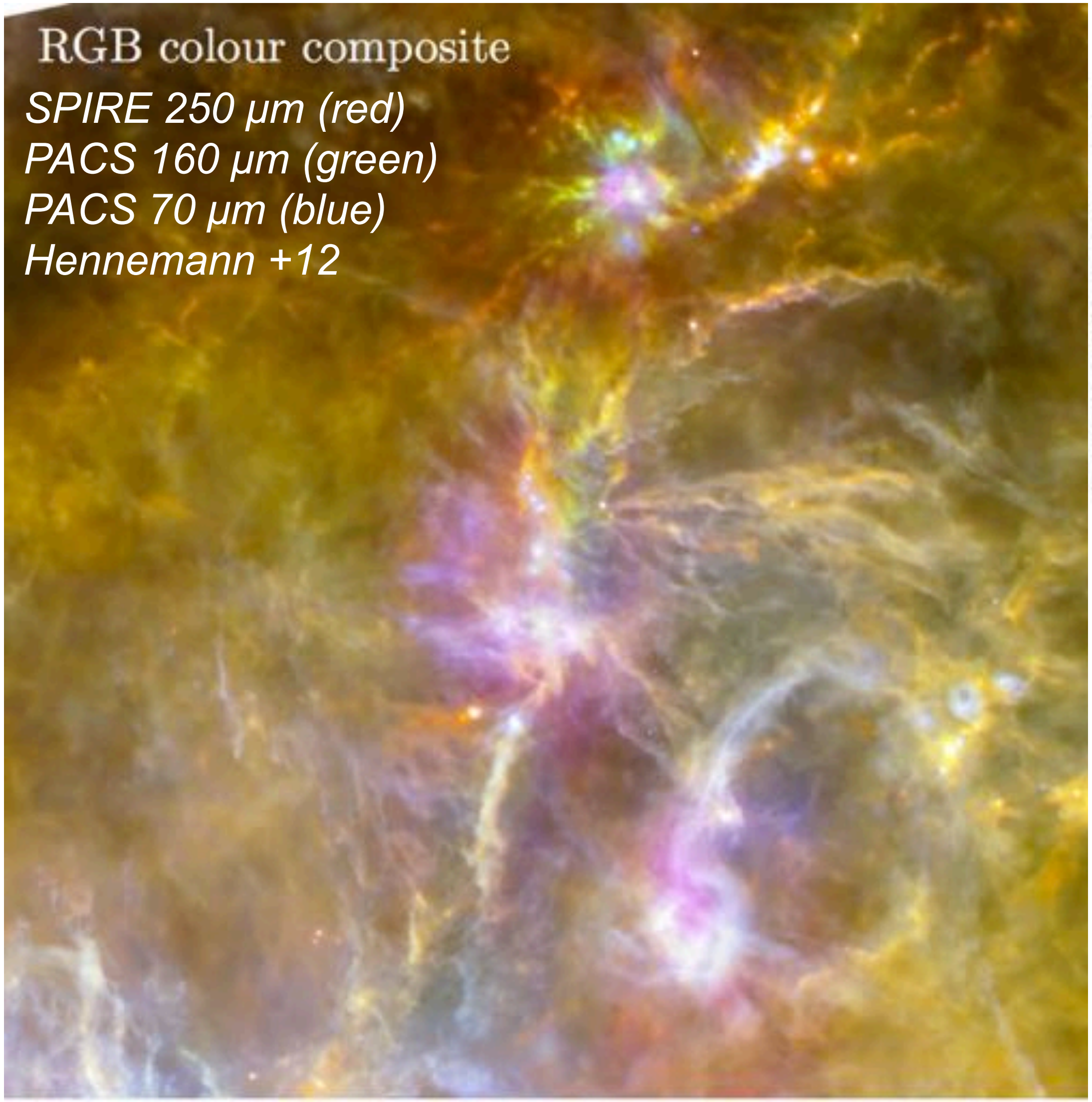
An Analysis of the Relationship Between Metabolism, Developmental Schedules, and Longevity Using Phylogenetic Independent Contrasts

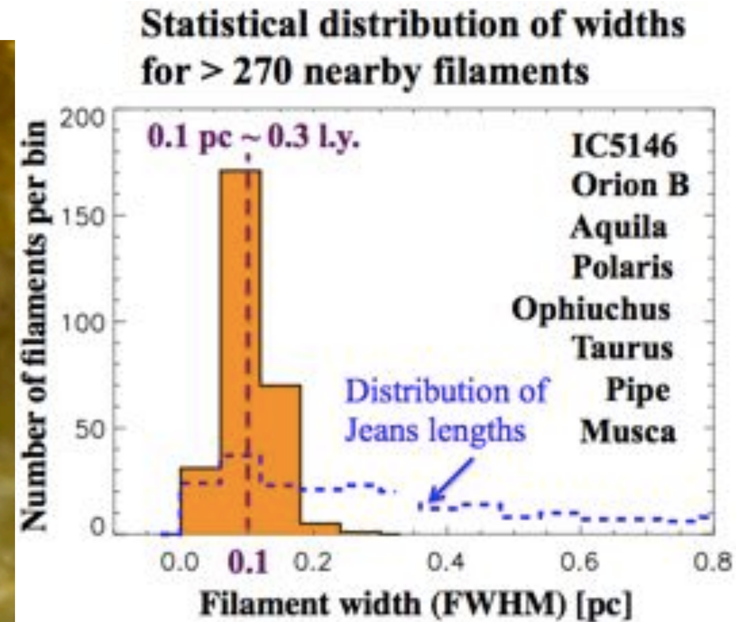
João Pedro de Magalhães[1], Joana Costa[2], and George M. Church[1]

1456 mammals, birds, amphibians, reptiles

mass

The "microphysics": universal SF efficiency in filaments
self-regulation by turbulence





Arzoumanian +11

SFR = [1.8-4.5]x10^{-8} M$_{dense}$

at GMC scale *(Andre +13)*
and at galaxy scale
(Gao & Solomon 04)

origin of turbulence ? differential rotation vs stellar feedback…

A fundamental consequence of the MS:
what drives galaxy evolution is their replenishment of gas from the **outside** !

Galaxies spend most of their lifetime on the SFR-$M_\star$ MS

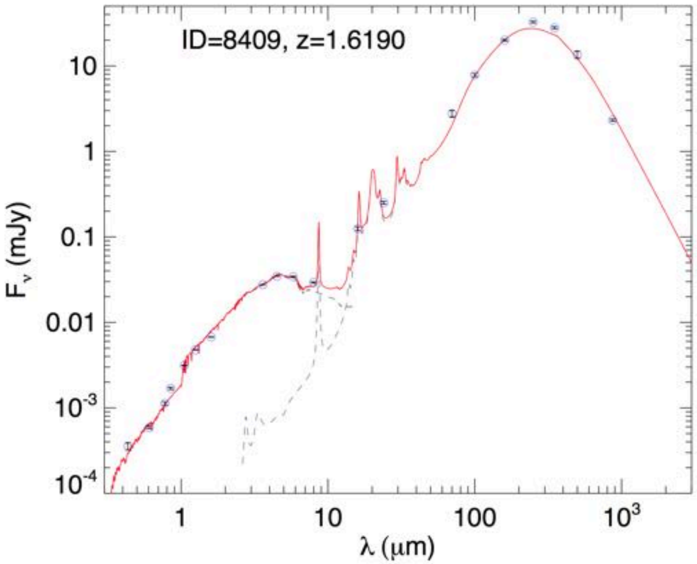
→ SFR given by $M_\star$ within a factor 2

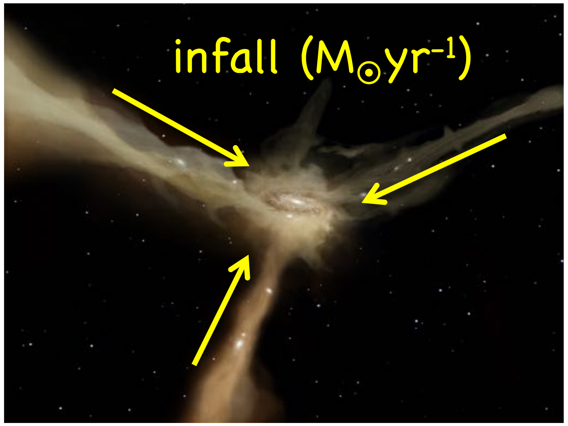
Herschel + ALMA → M_{dust}

optical + NIT → $M_\star$ → metallicity → gas to dust ratio

} M_{gas}

} depletion time τ~SFR/M_{gas} (Myr)

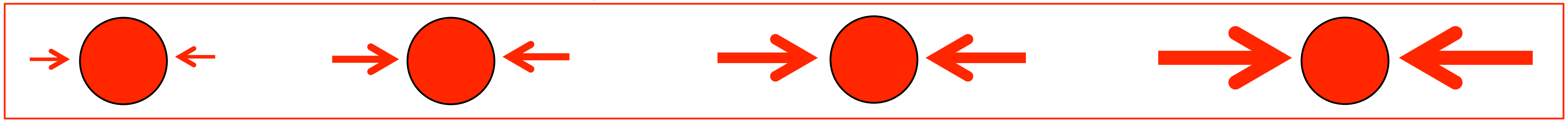




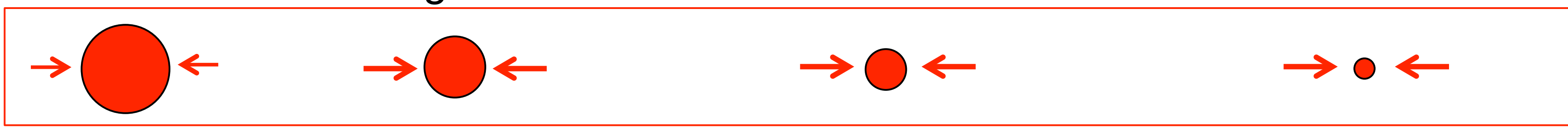
τ(depletion)~600 Myr on the main sequence
=> best evidence for the need of gas replenishment

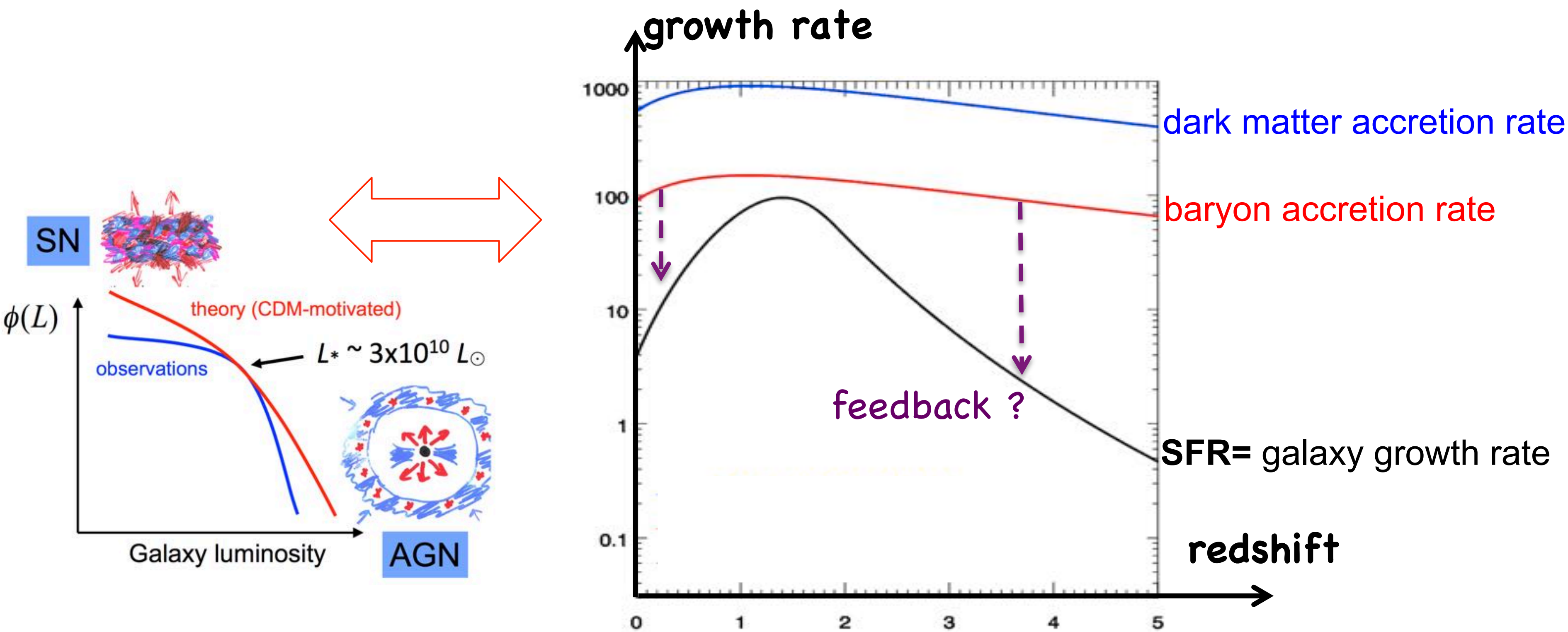
The main sequence view on the low baryonic content of gals

same halo mass at all z: stronger accretion in the past



follow the same halo growth with z: same accretion over time



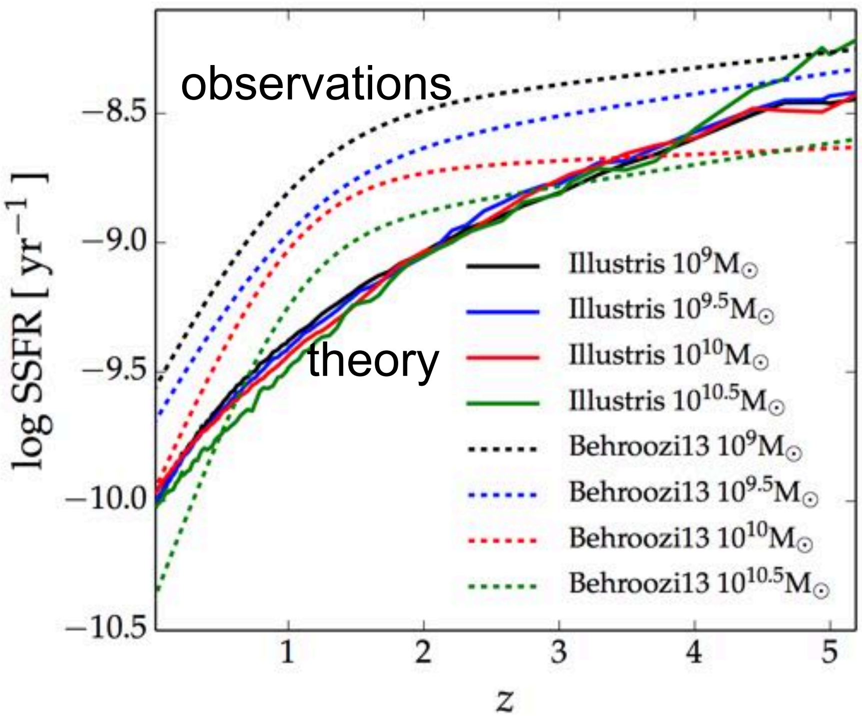


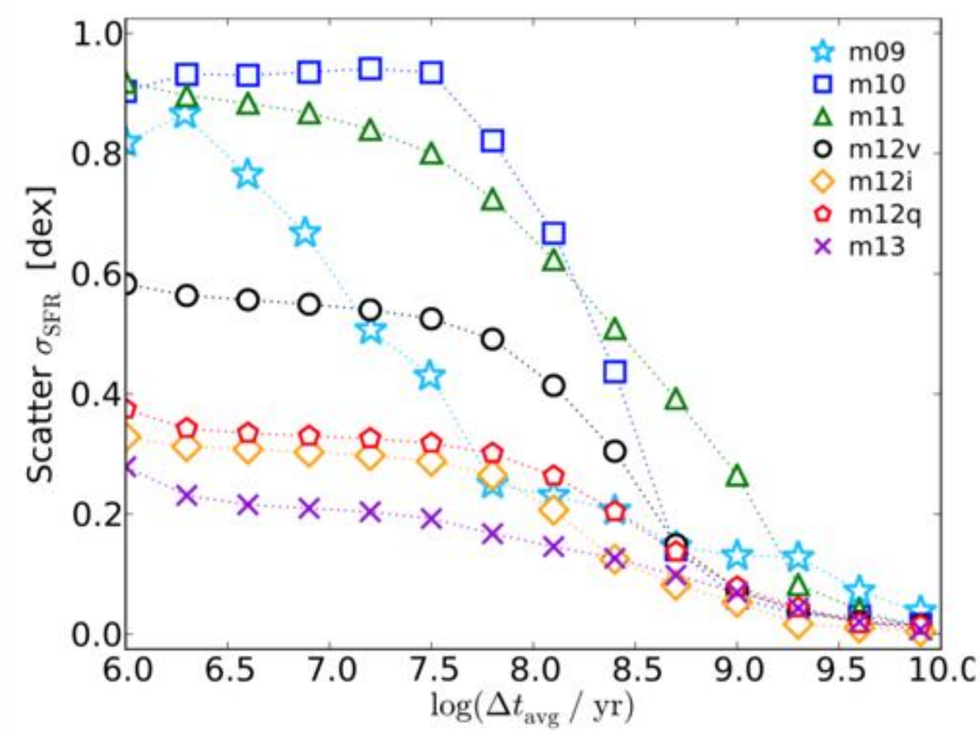
Can feedback save our representation of the Universe ?

difficult to account for the right SF efficiency over the whole cosmic history with the same recipee

The strong feedback required induces a scatter of the SFR that depends on M★ ! → not seen rms(MS) constant with z and M

redshift evolution of sSFR=SFR/M*



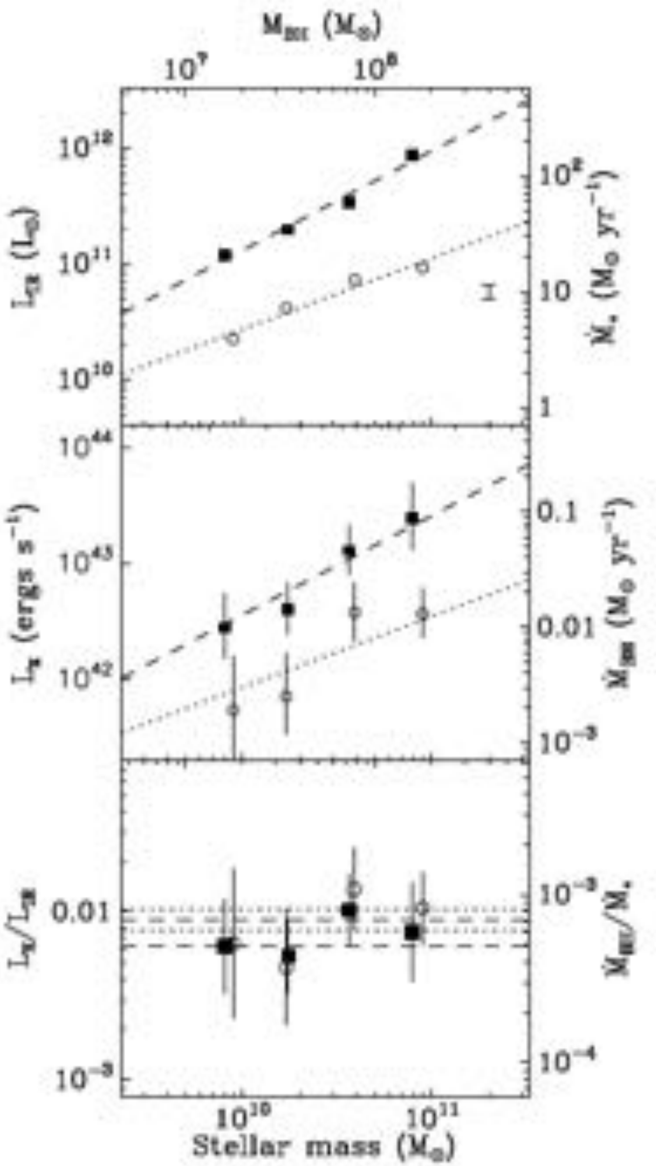


Illustris simulation
Vogelsberger +2014, Nature

galaxies on FIRE simulation
Hopkins +2014, MNRAS

Is AGN feedback a good way to quench star formation ? Generally not.
Black Hole accretion rates (BHAR) and SFRs go along together

(Mullaney et al. 2012; Chen et al 2013; Delvecchio et al 2015, etc)

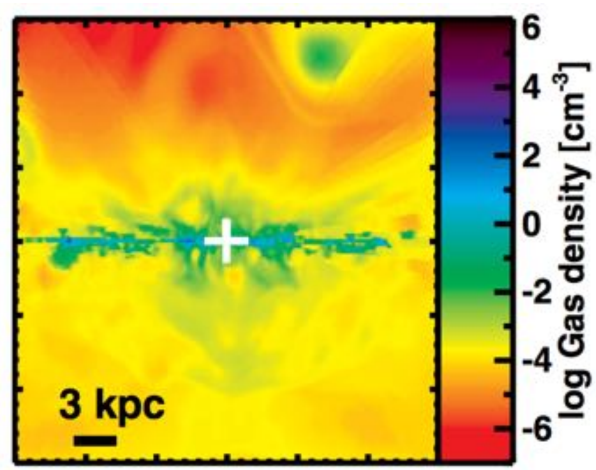


There is a Main Sequence also for AGNs!

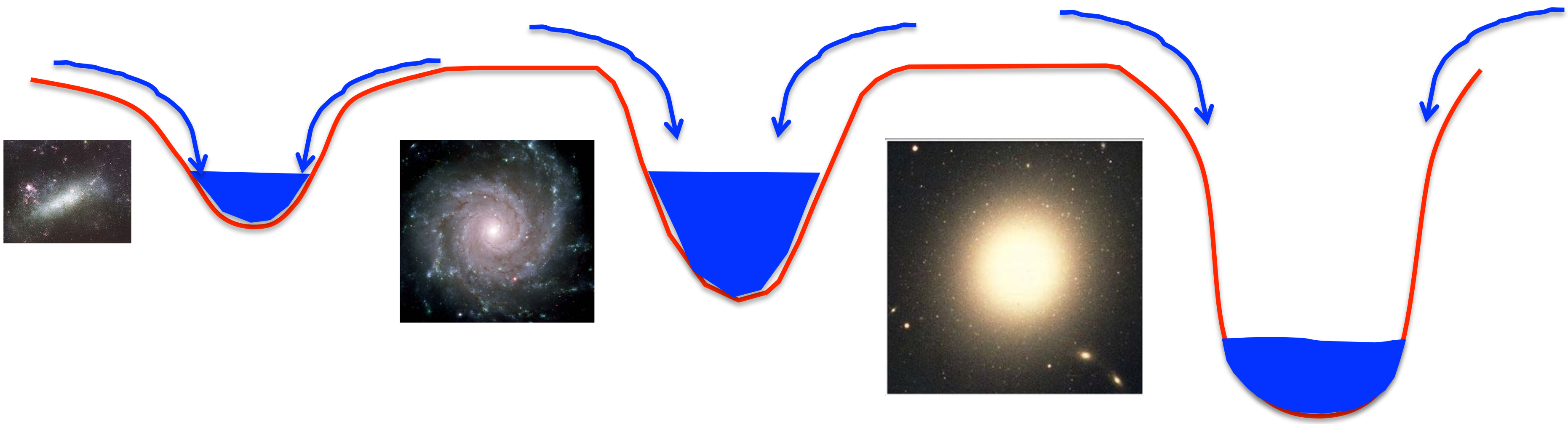
When eliminating short-time fluctuations
doing ensemble averages (→ time averages)

Ratio of BHAR/SFR Level is ~ Magorrian

Gas reservoir regulating both SFR/AGN activity

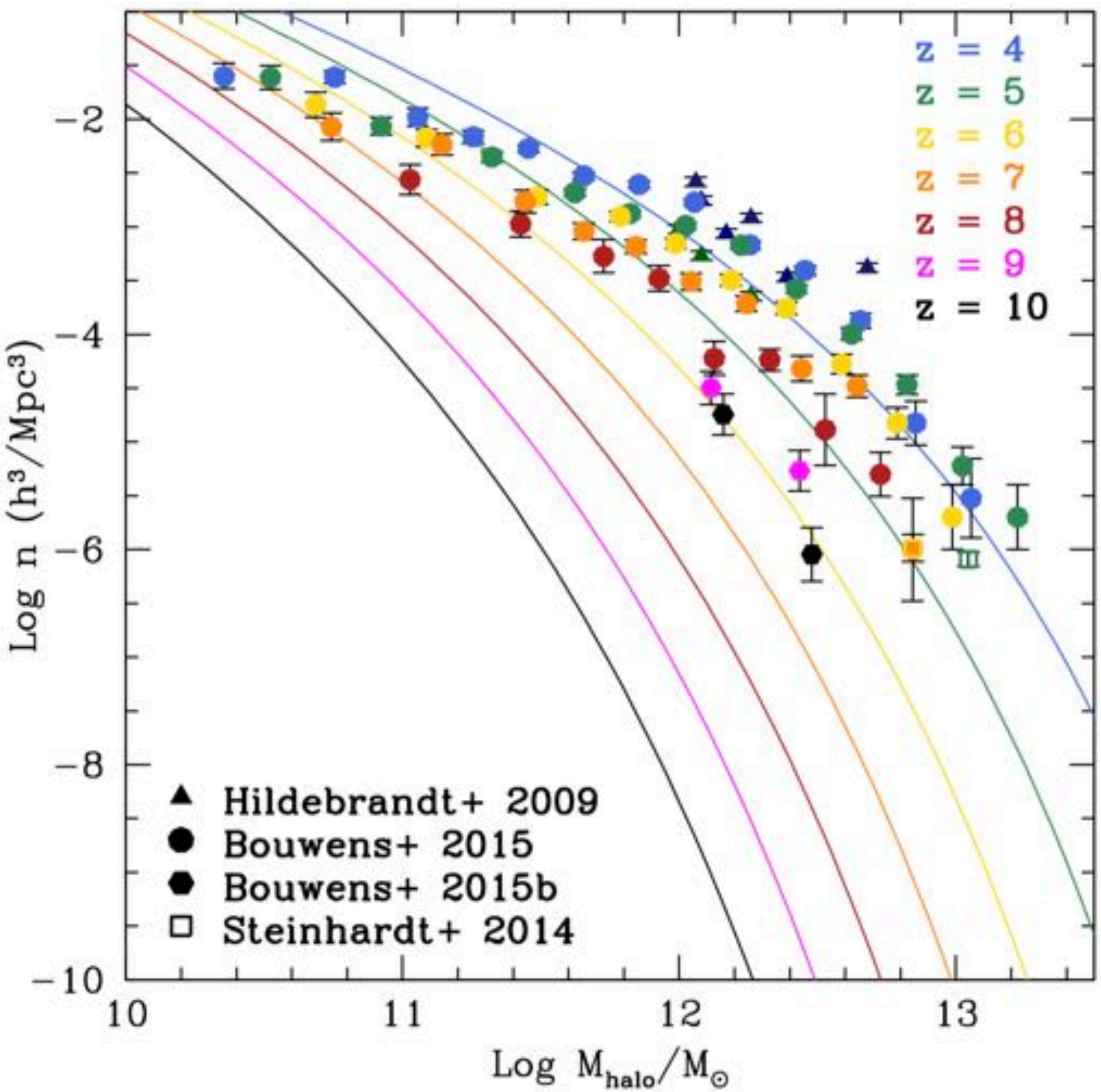


Simulations support this scenario (Roos +2015, etc)



THE IMPOSSIBLY EARLY GALAXY PROBLEM

Charles. L. Steinhardt [1,2], Peter Capak[1,2], Dan Masters[1,2], Josh S. Speagle[3,2,4]



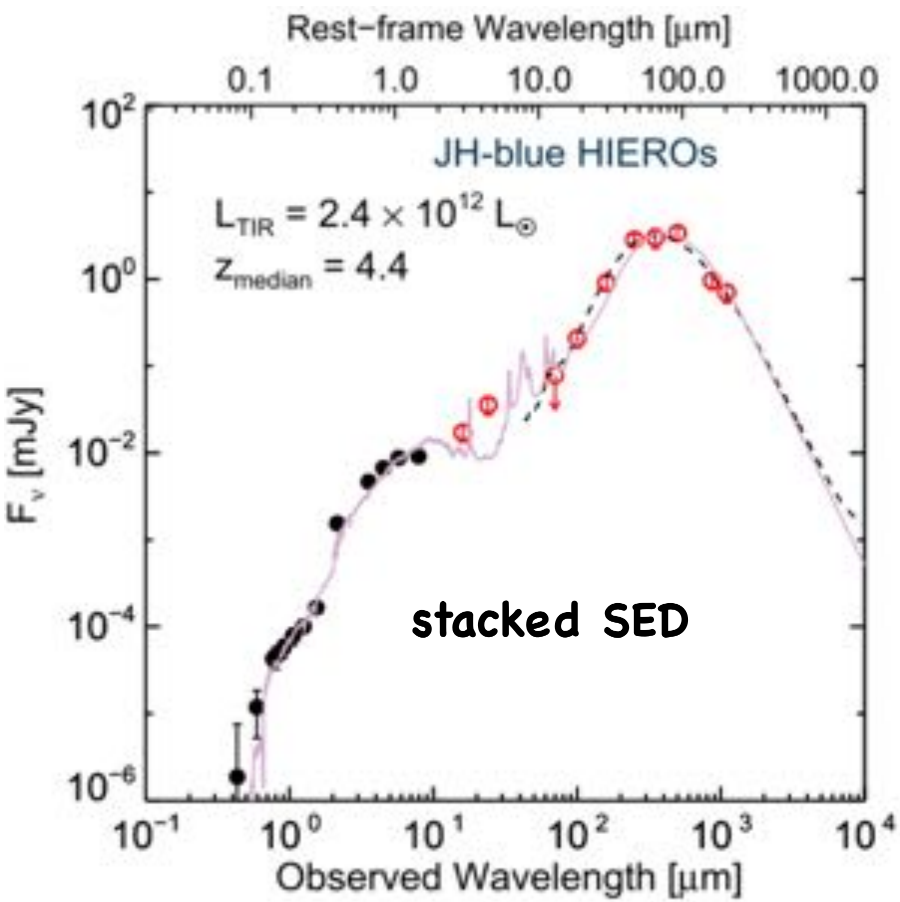
Halo masses estimated using:
clustering (triangle)
stellar masses and $M_H / M_* \sim 70$ (square)
lower-z abundance matching (circle)

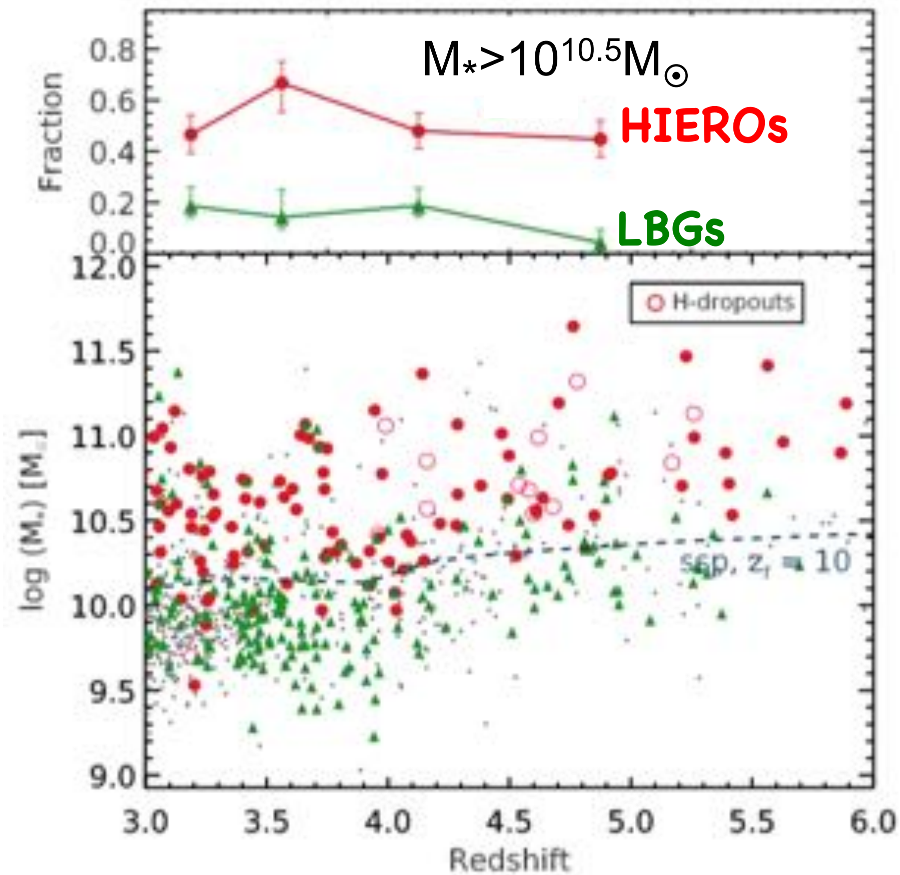
INFRARED COLOR SELECTION OF MASSIVE GALAXIES AT $z > 3$

The Astrophysical Journal, 816:84 (17pp), 2016

T. Wang (王涛)[1], D. Elbaz[1], C. Schreiber[1], M. Pannella[1], X. Shu[2], S. P. Willner[3], M. L. N. Ashby

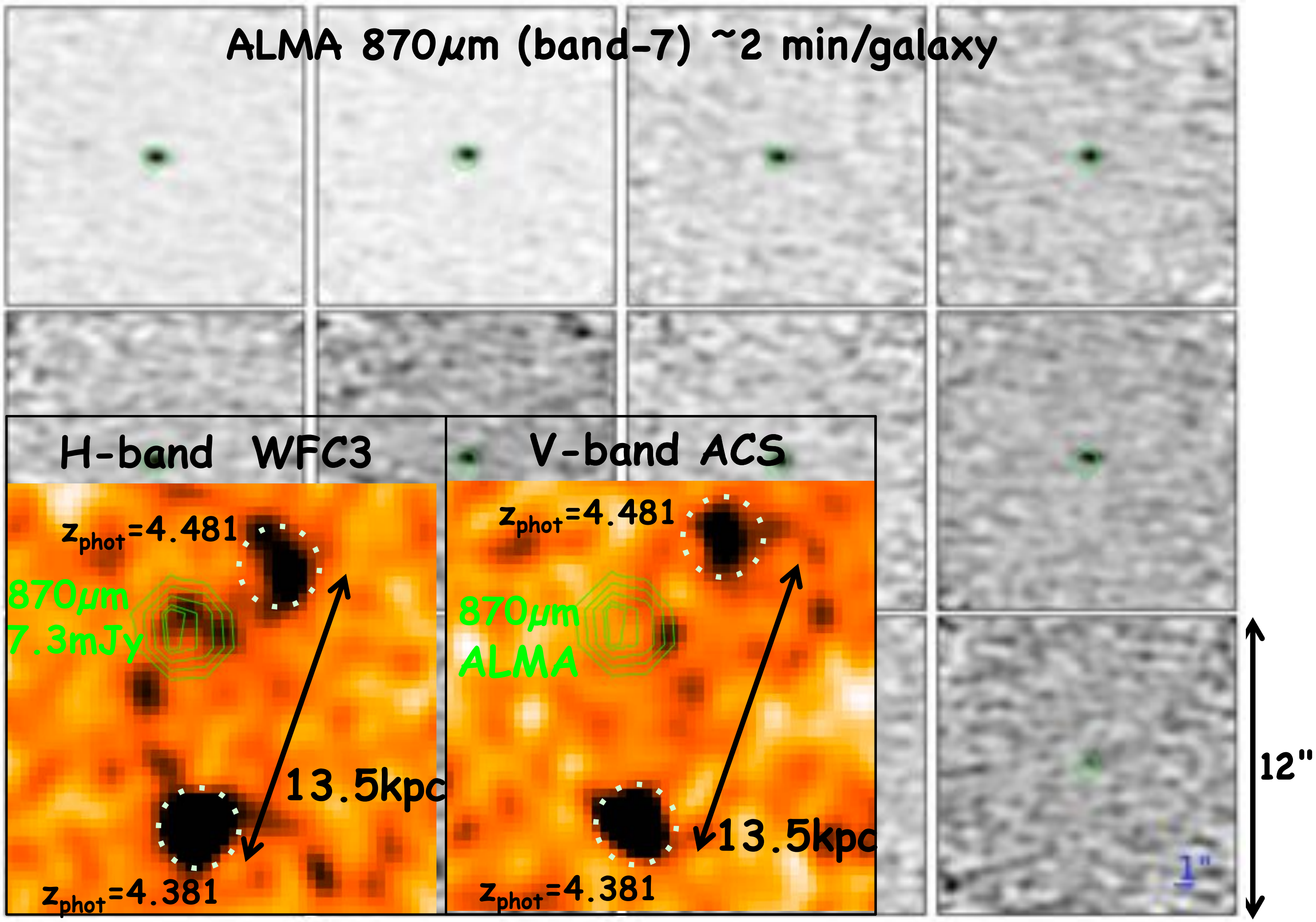
At $M_* > 10^{10.5} M_\odot$, HIEROs make ~4-5 x more SF than LBGs !





ALMA Cycle 3 (**Wang**, Elbaz in prep): Are the most massive z>4 galaxies hidden from HST even in H?

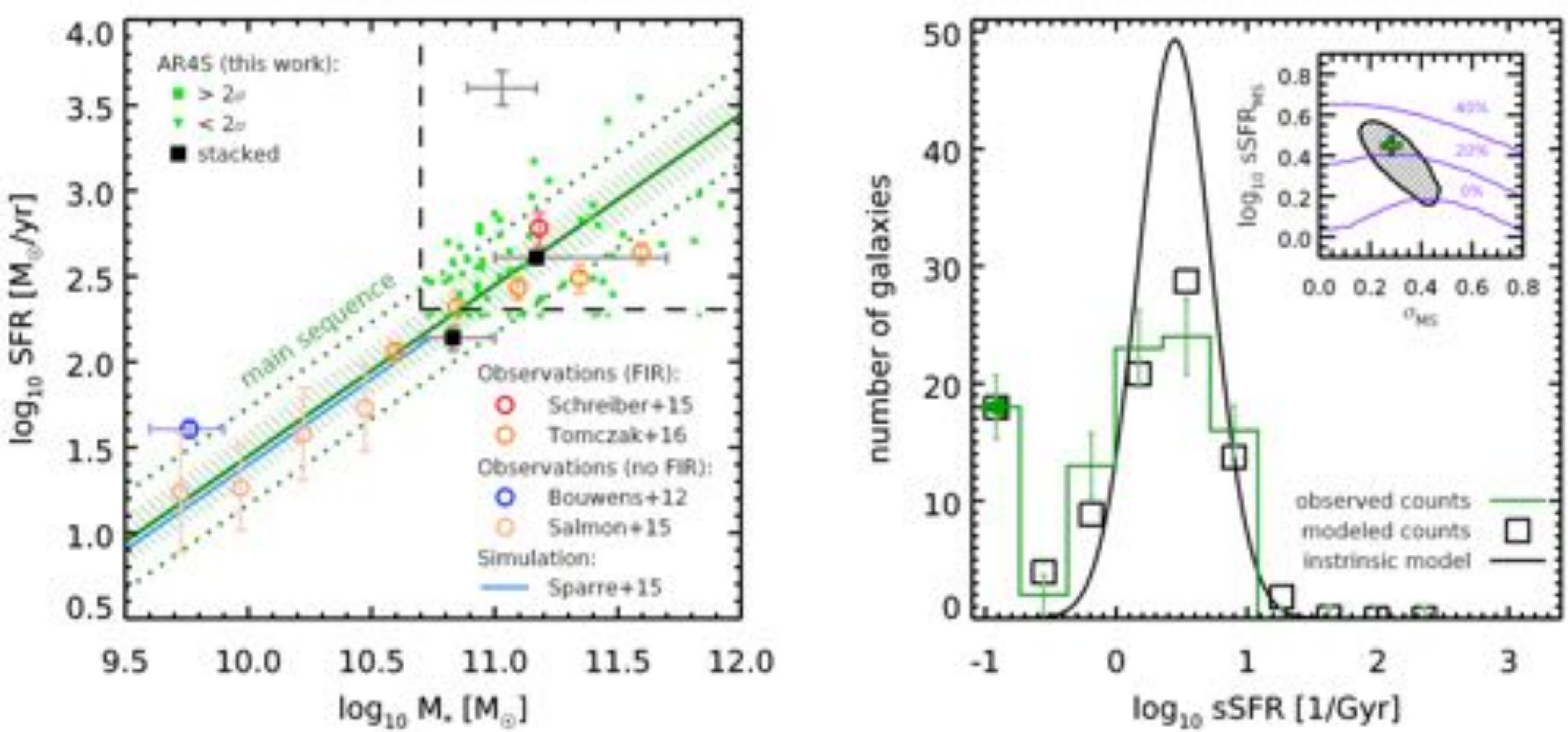
candidates from Wang, Elbaz (+2015)



The ALMA Redshift 4 Survey (AR4S).
I. The massive end of the $z = 4$ main sequence of galaxies

C. Schreiber[1,2], M. Pannella[3,2], R. Leiton[4,5], D. Elbaz[2], T. Wang[2,6], K. Okumura[2] and I. Labbé[1]

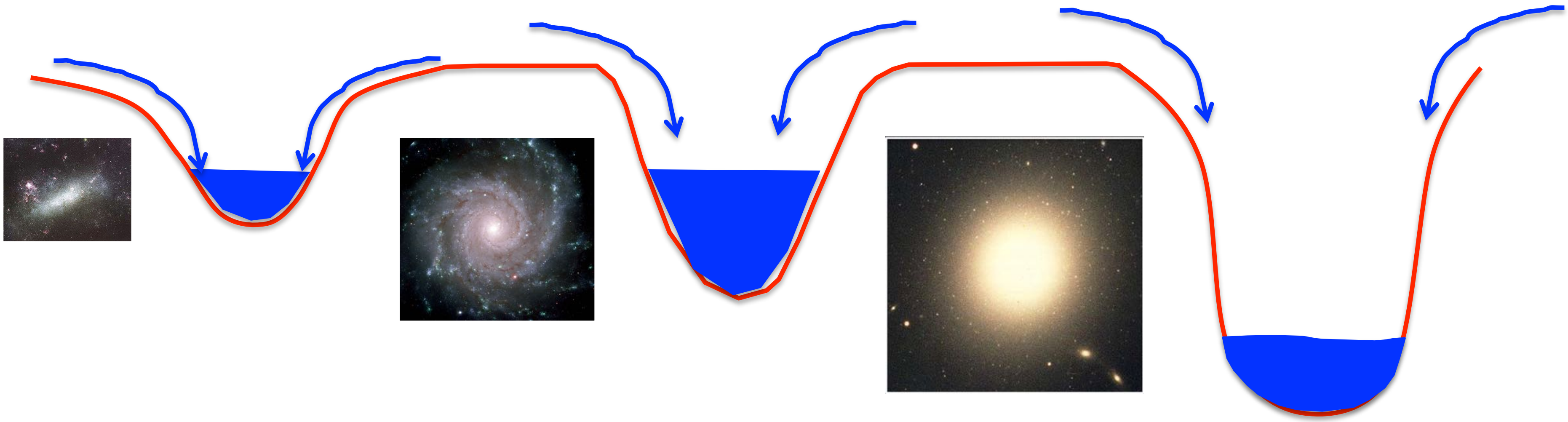
systematic ALMA survey of all known galaxies with M*> 5 × 10^{10} M⊙ at 3.5 < *z* < 5
in the GOODS–*South*, UDS & COSMOS CANDELS fields
96 galaxies at 890 µm (180 µm rest-frame) with an on-source integration time of 1.3 min/gal



Summary: a double tension between model and observations

SFR-$M_\star$ main sequence => strong universality among star-forming galaxies
→ best evidence that galaxies are regularly fed by external diffuse matter
→ no variation of rms(SFR-$M_\star$) with $M_\star$ and z => feedback violence << cosmo.models

The low baryonic content of DM halos must come from large-scales
Some missing process is preventing baryons from infalling in DM haloes…

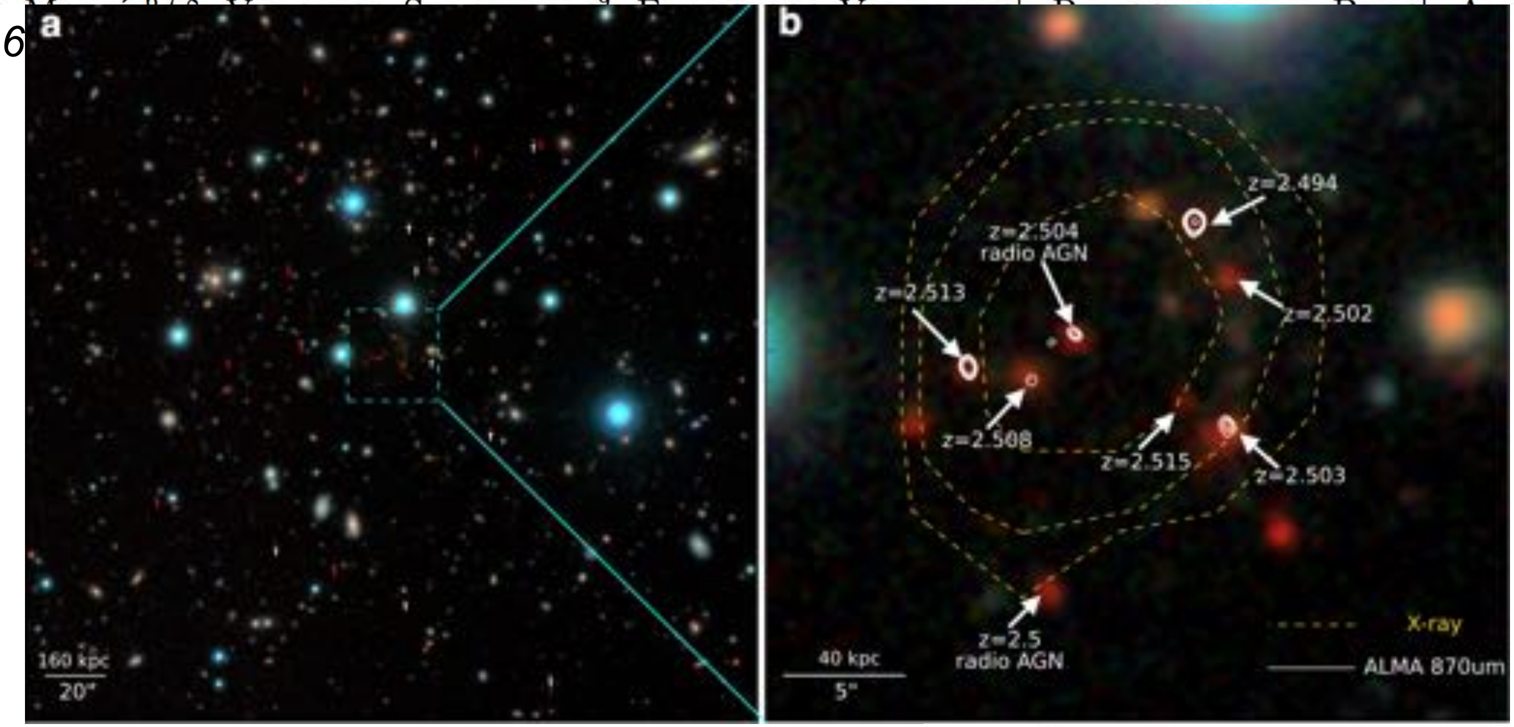


On the other hand, there is an excess of z~4 massive galaxies, high-z supermassive black holes and z~2.5 cluster
→ some missing process make the Universe more efficient in forming high-z structures !

DISCOVERY OF A GALAXY CLUSTER WITH A VIOLENTLY STARBURSTING CORE AT $z = 2.506$

TAO WANG[1,2], DAVID ELBAZ[1], EMANUELE DADDI[1], ALEXIS FINOGUENOV[2], DAIZHONG LIU[4], CORENTIN SCHREIBER[5],

ApJ 2016

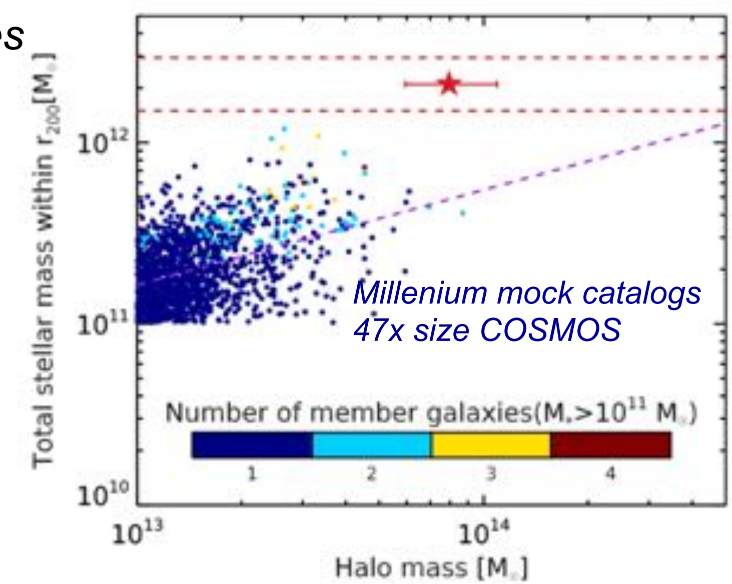


systematic study of overdensities of Distant Red Galaxies with J - K_s > 1.3 in the COSMOS field

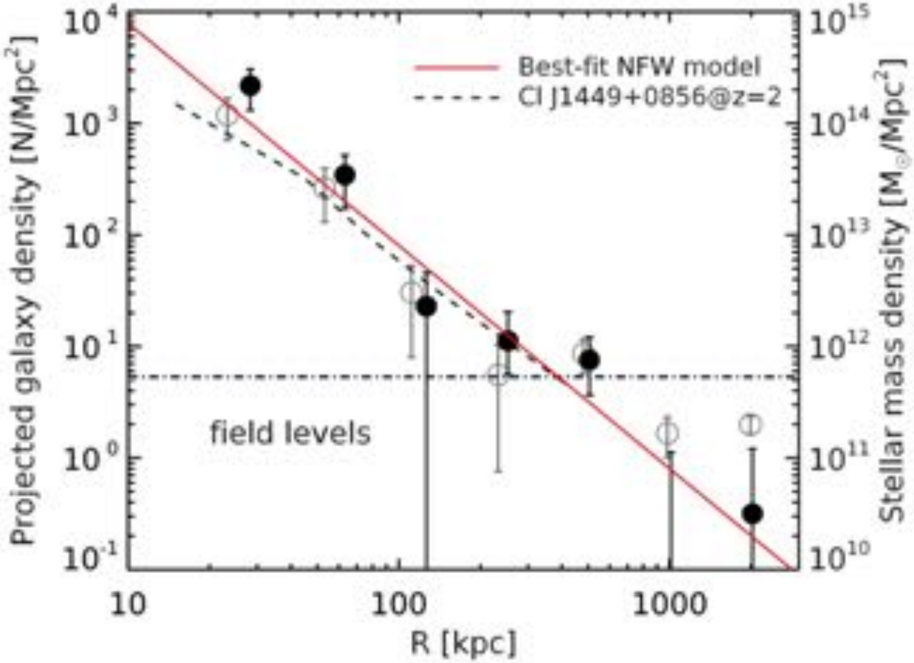
follow-up with IRAM, JVLA, ALMA, VLT-KMOS + Chandra-XMM detection

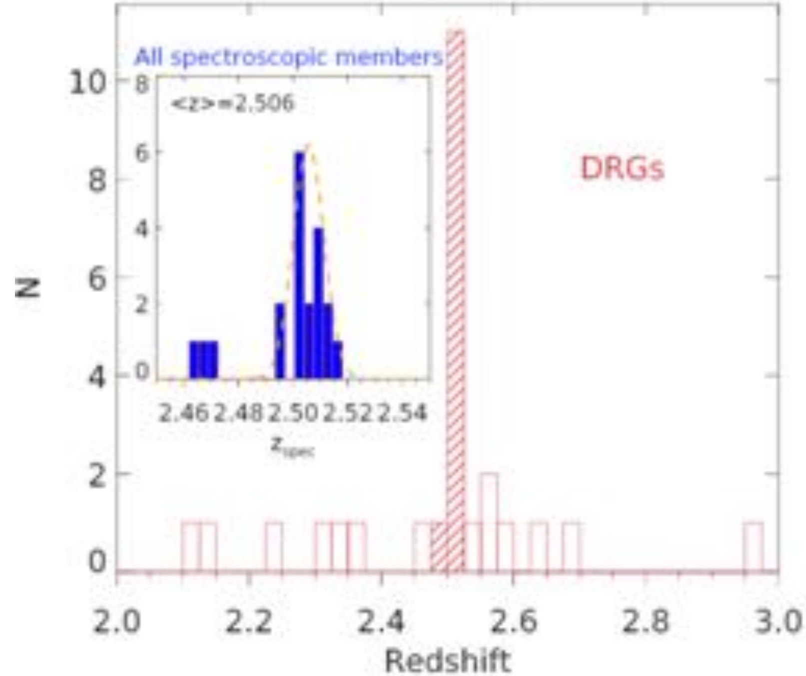
z=2.506 M_{tot}~10^{14} $M_\odot$ cluster
(X-rays, velocities, core mass profile)

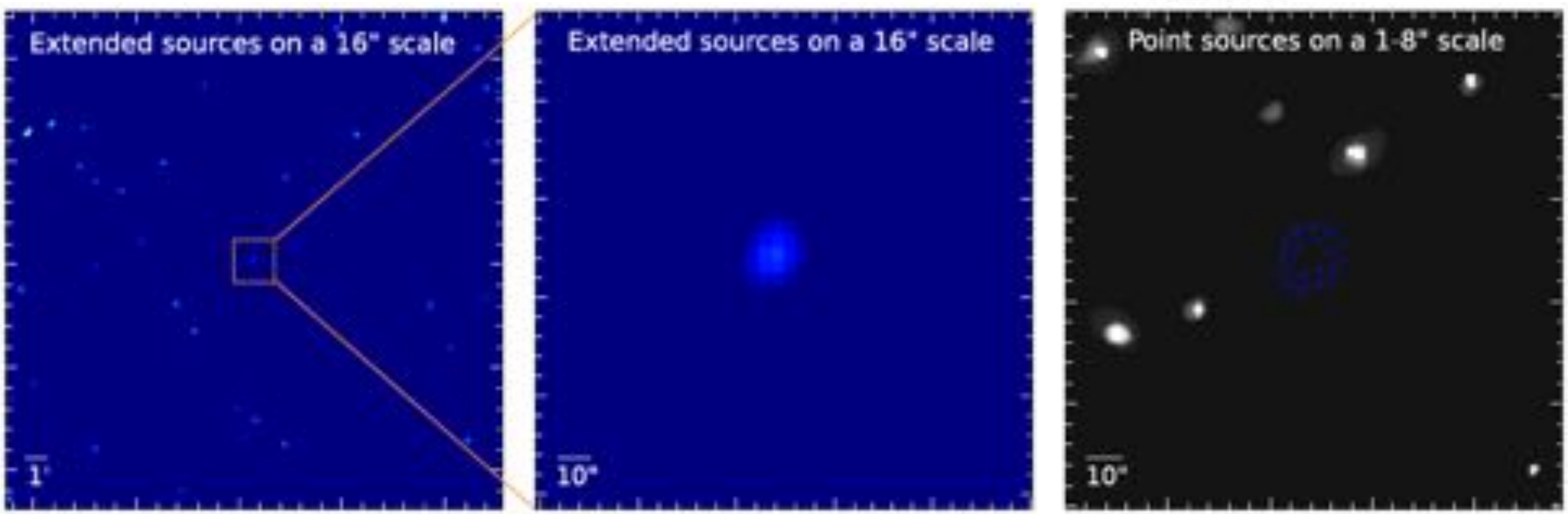
Total SFR~3400 $M_\odot$/yr in central ~200kpc



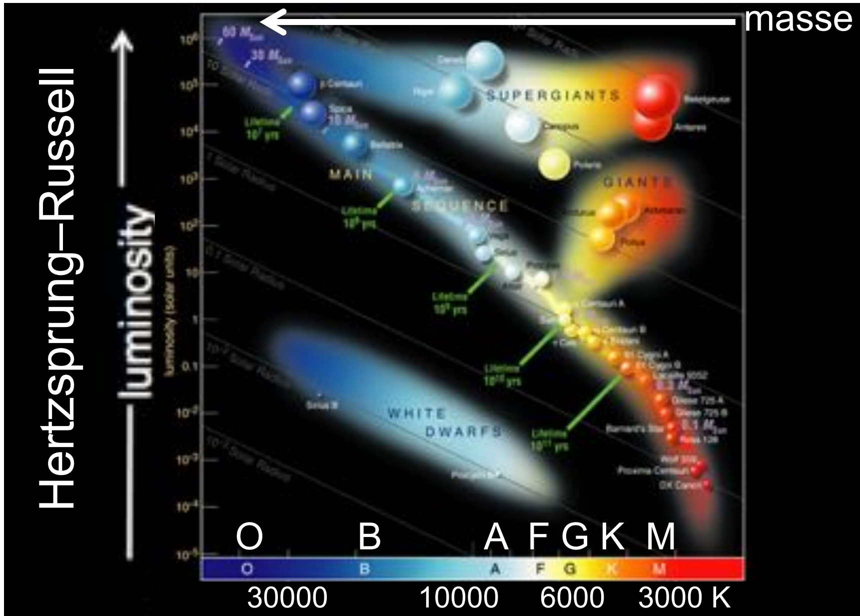
z=2.506 cluster (Wang, Elbaz +2016)

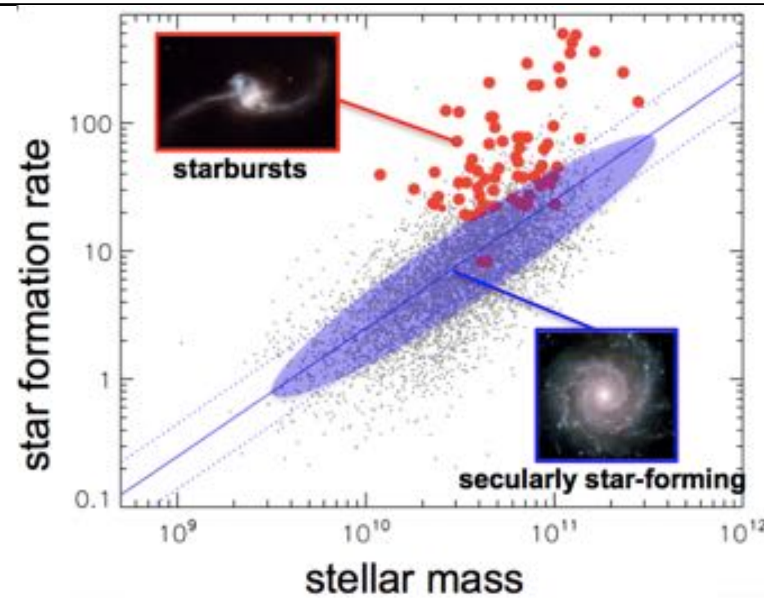






Analogy between the stellar and galaxies main sequences





Stars spend most of their life on the MS

Massive stars exhaust quickly their reservoirs

Stars loose a large % of their mass in winds

Red stars (giants, AGB) are
less common, more luminous and dusty

Universal efficiency of light production :
$0.007\ \Delta m\ c^2 \rightarrow$ light

Massive stars produce massive black holes

Stars become more luminous before dying
AGB, SN

Galaxies spend most of their life on the MS

Massive gals exhaust quickly their reservoirs

Galaxies loose a large % of their mass in winds

Starbursts are red,
less common, more luminous and dusty

Universal efficiency of light production :
$SFR = 4\times10^8\ M_{dense}$

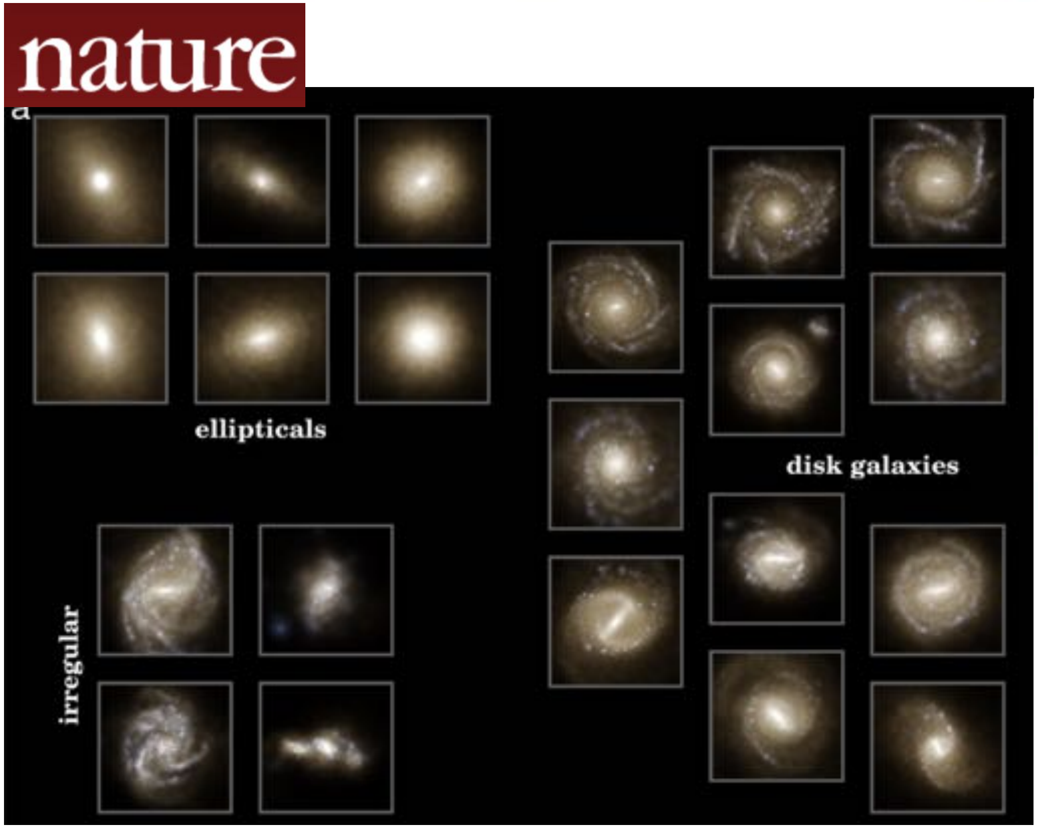
Massive galaxies produce supermassive BH

Do galaxies become starbursts before dying ?

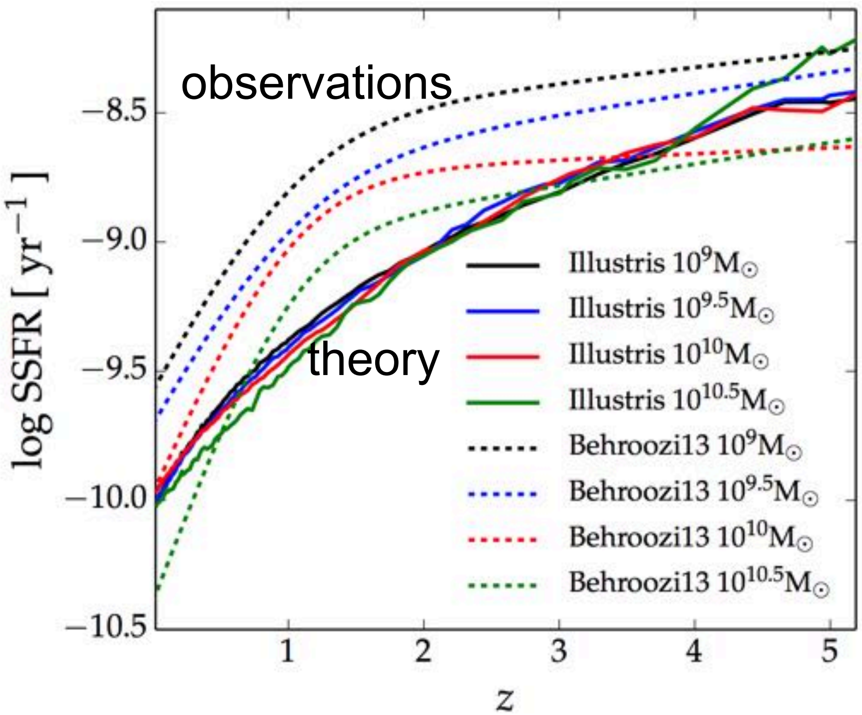
Properties of galaxies reproduced by a hydrodynamic simulation

Nature **509**, 177–182 (08 May 2014)

M. Vogelsberger[1], S. Genel[2], V. Springel[3,4], P. Torrey[2], D. Sijacki[5], D. Xu[3], G. Snyder[6], S. Bird[7], D. Nelson[2] & L. Hernquist[2]



redshift evolution of sSFR=SFR/M*

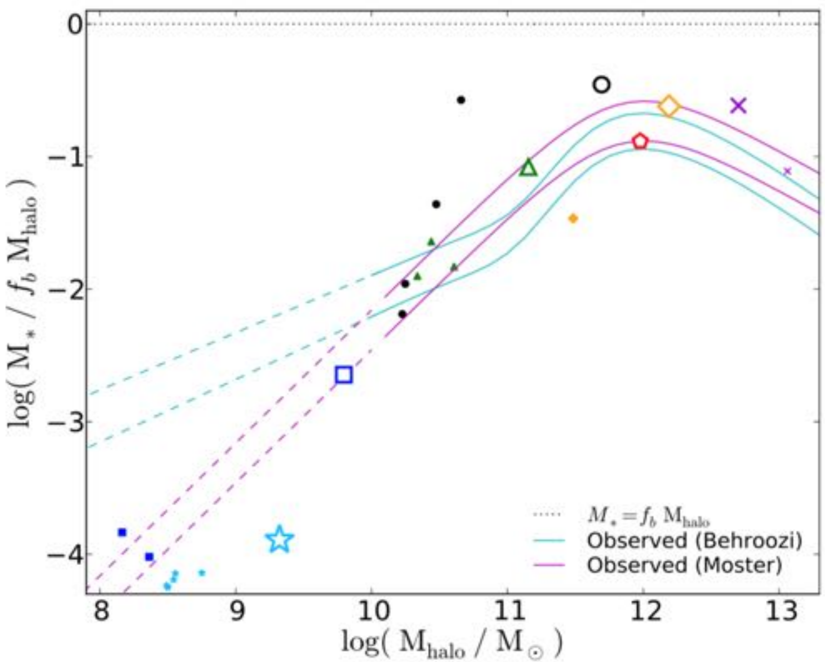


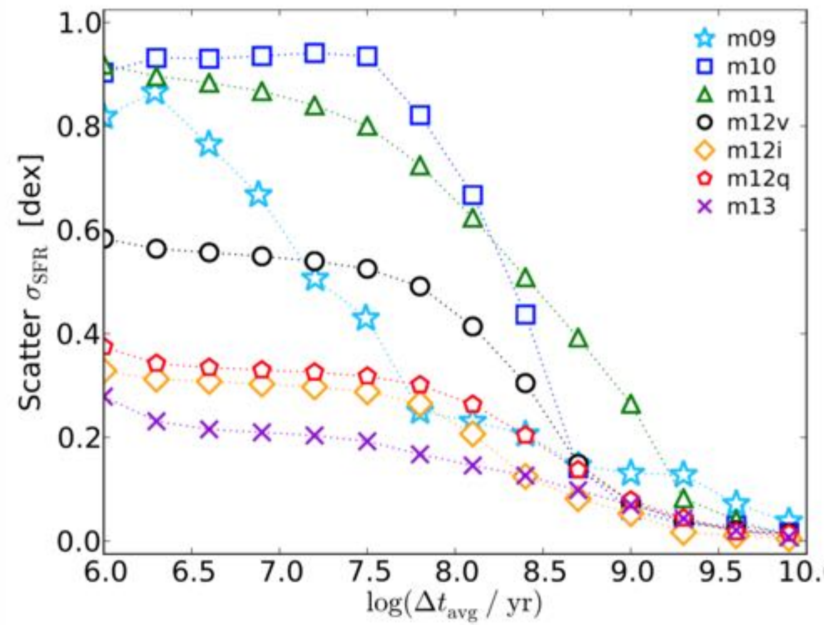
Galaxies on FIRE (Feedback In Realistic Environments): Stellar Feedback Explains Cosmologically Inefficient Star Formation

Philip F. Hopkins*[1,2], Dušan Kereš[3], José Oñorbe[4], Claude-André Faucher-Giguère[2,5], Eliot Quataert[2], Norman Murray[6,7], & James S. Bullock[4]

MNRAS 2014

succeeds to explain the drop in baryon/halo mass





but with such a strong feedback that :
(i) this model predicts a different dispersion as a function of galaxy mass
(ii) thin disks are destroyed → no Milky Way – like galaxies…