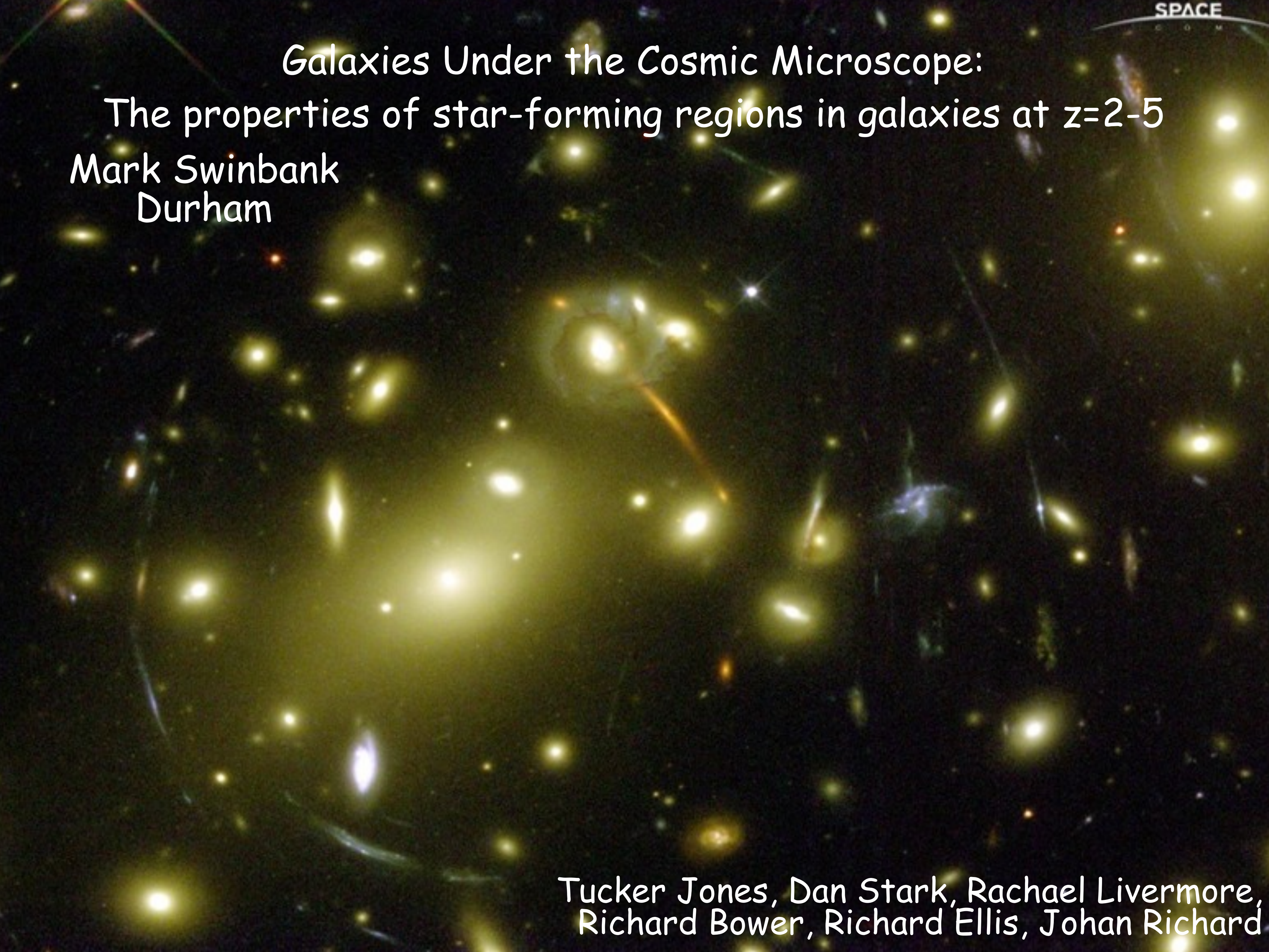
M. Swinbank

The Properties of star-forming regions in high-z star-forming galaxies

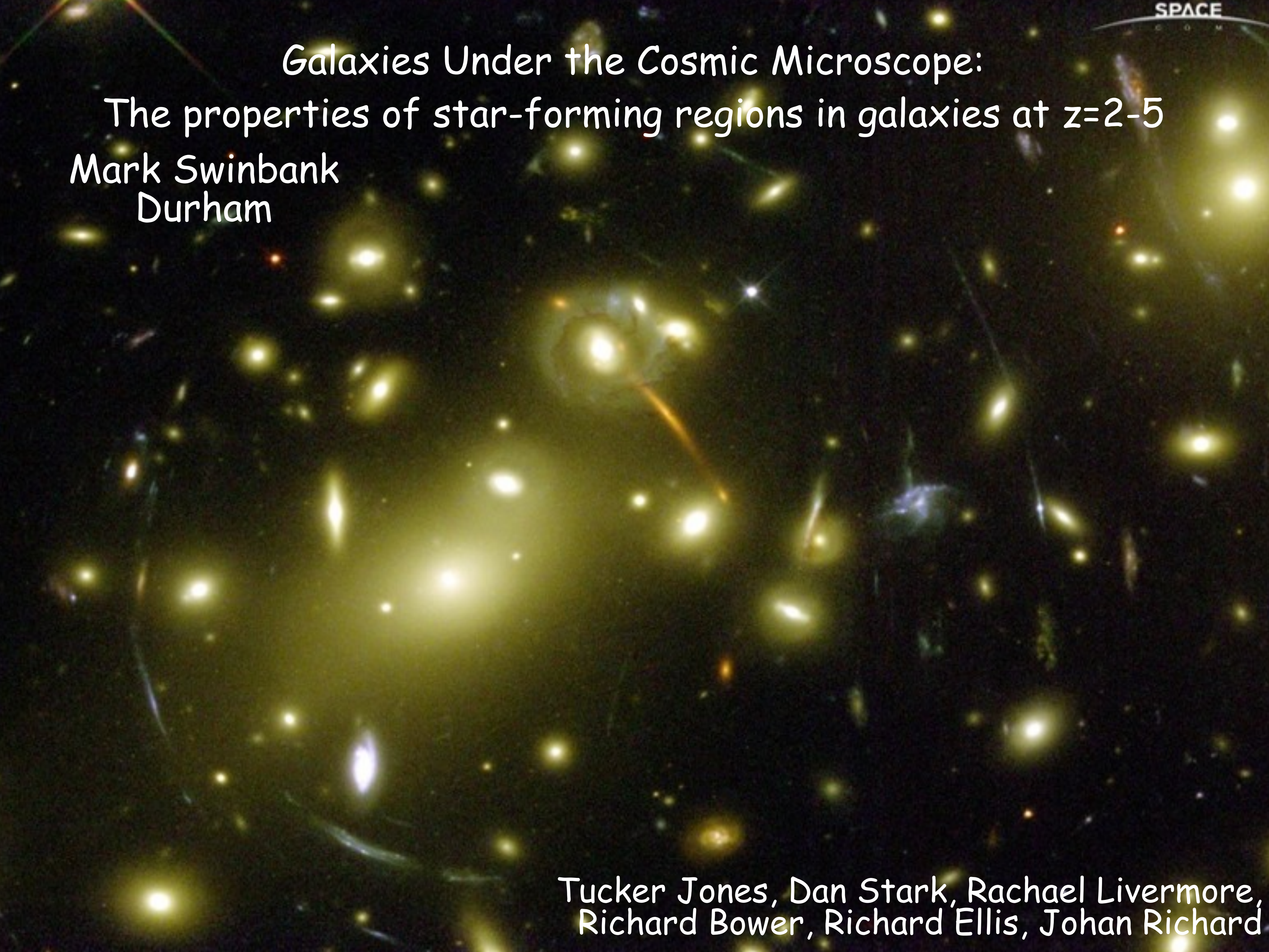
Measuring the properties of star-forming regions in high redshift galaxies (such as sizes, luminosities, and velocity dispersions) define some of the key science drivers for ELT and ALMA. Such observations can tell us how and why the star-formation in distant galaxies is much for efficient than that seen locally, and whether local, intense star-forming regions are good analogs for high-z galaxies. In this talk, I will show some recent observations which have been aided by strong gravitational to probe the properties of star-forming regions within galaxies at z~2--5 on scales of ~100pc. These results show that the mode of star-formation at z~2 is similar to that seen in local ULIRGs, although the energetics are unlike anything seen in the local Universe.



Galaxies Under the Cosmic Microscope: The properties of star-forming regions in galaxies at z=2-5

Mark Swinbank
Durham

Tucker Jones, Dan Stark, Rachael Livermore,
Richard Bower, Richard Ellis, Johan Richard



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Introduction

Studies of high-z galaxies

Detailed Studies of high-z galaxies

Very Detailed Studies of high-z galaxies

Extremely Detailed Studies of high-z galaxies

Summary

Introduction

Studies of high-z galaxies

(Mapping the demographics of the SF population at z=2-3)

Detailed Studies of high-z galaxies

(Resolved spectroscopy of z=2-3 SF galaxies on 4-8kpc scales)

Very Detailed Studies of high-z galaxies

(AO assisted IFS to provide ~kpc resolution studies)

Extremely Detailed Studies of high-z galaxies

(AO assisted IFS+lensing providing (upto) ~100pc resolution, even out to z=5)

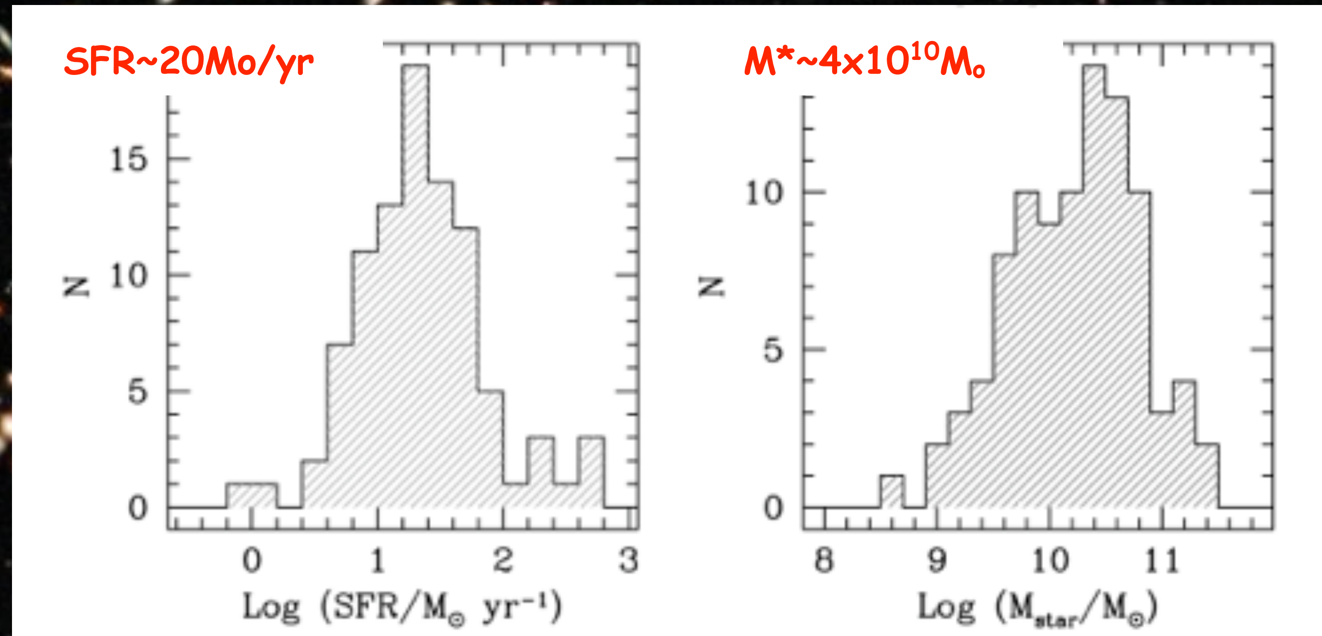
Summary

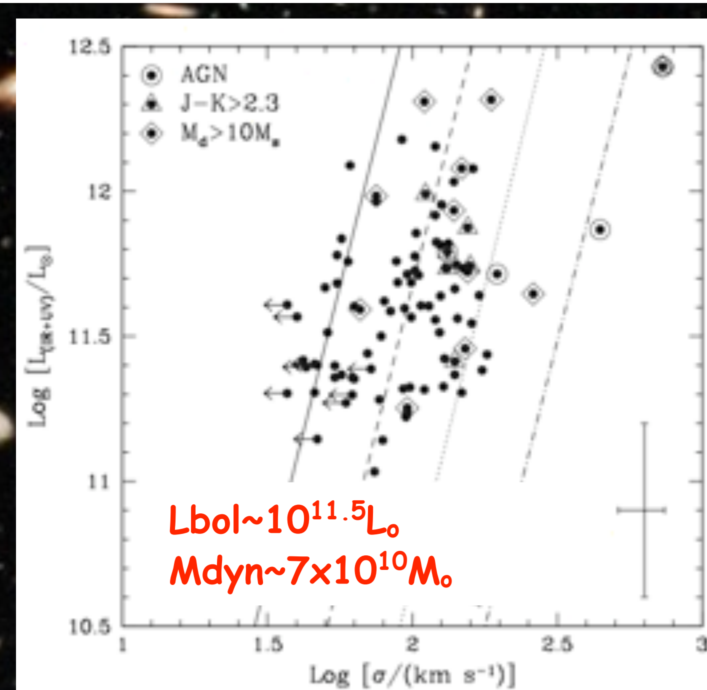
Properties of high-redshift SF galaxies poputions

- Actively SF, low dust, dynamical/stellar masses, chemical properties and space densities expected for local spirals/spheroidals

- Responsible for ~30-40% of the cosmic SF budget between z=2-3

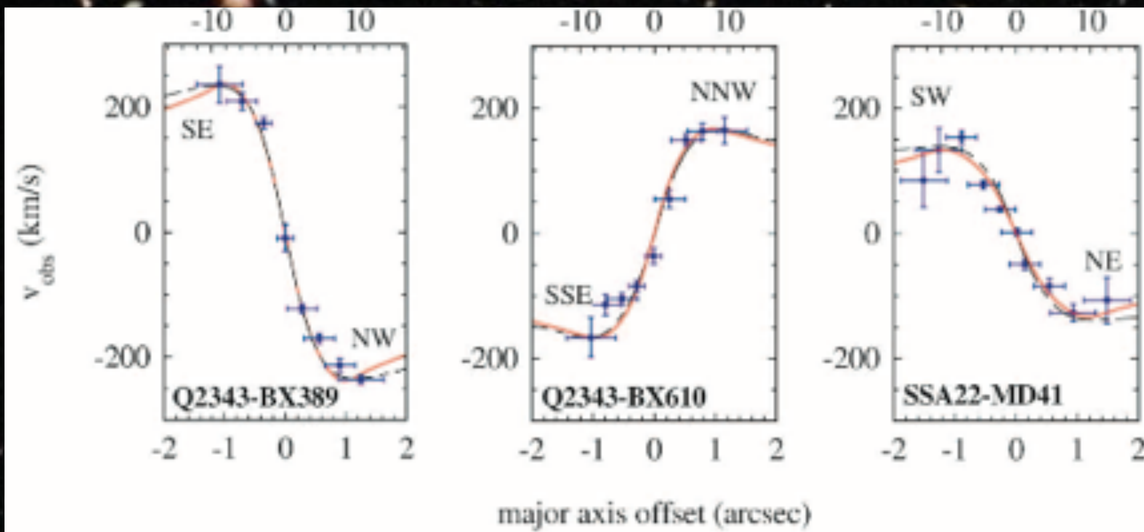
e.g. Shapley et al. 2003, 2006, Erb et al. 2004

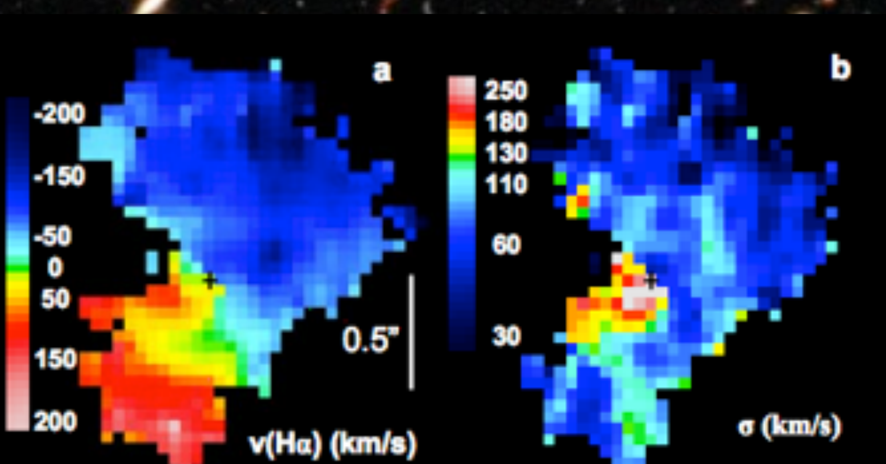




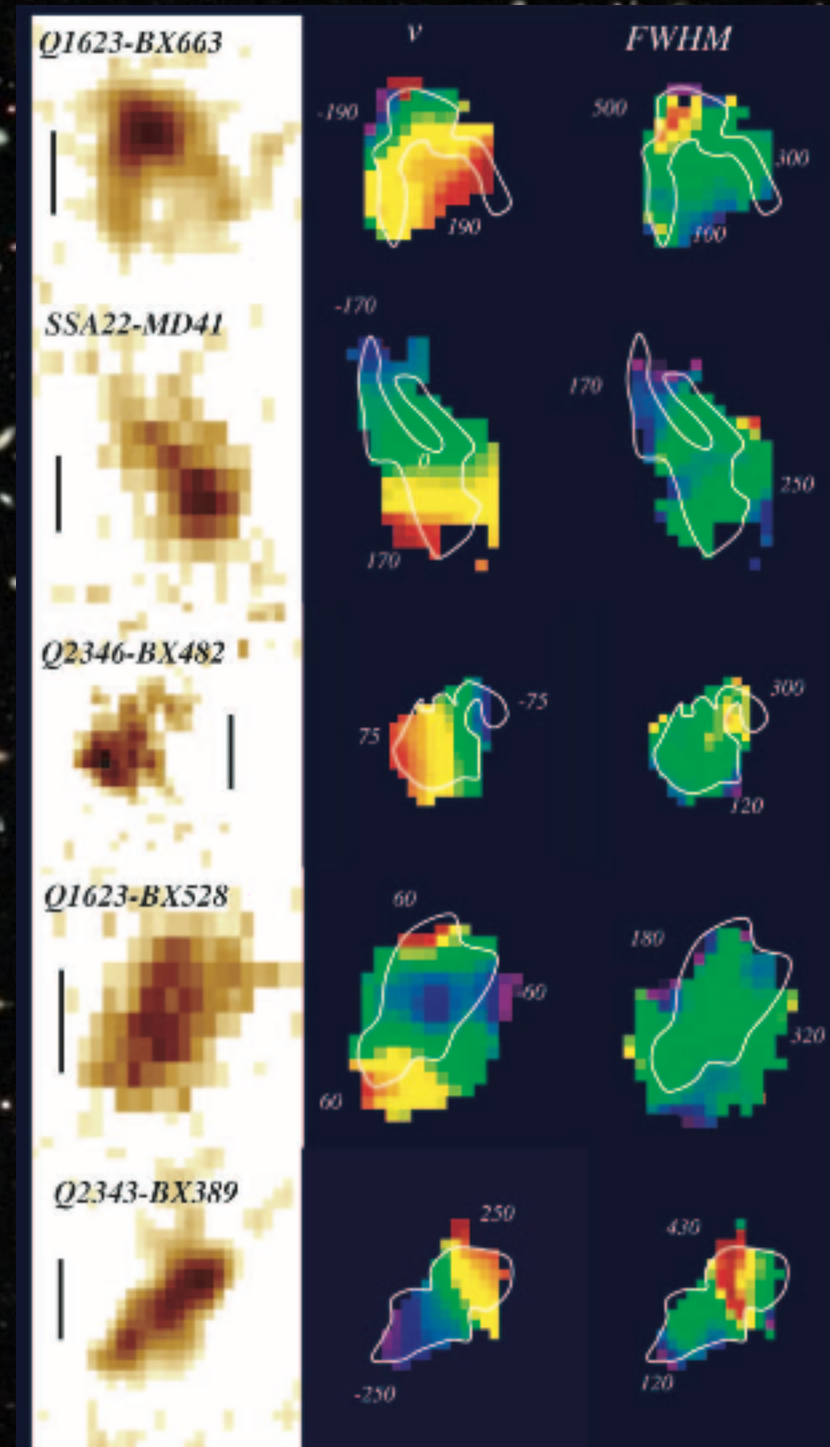
"Very Detailed Studies"

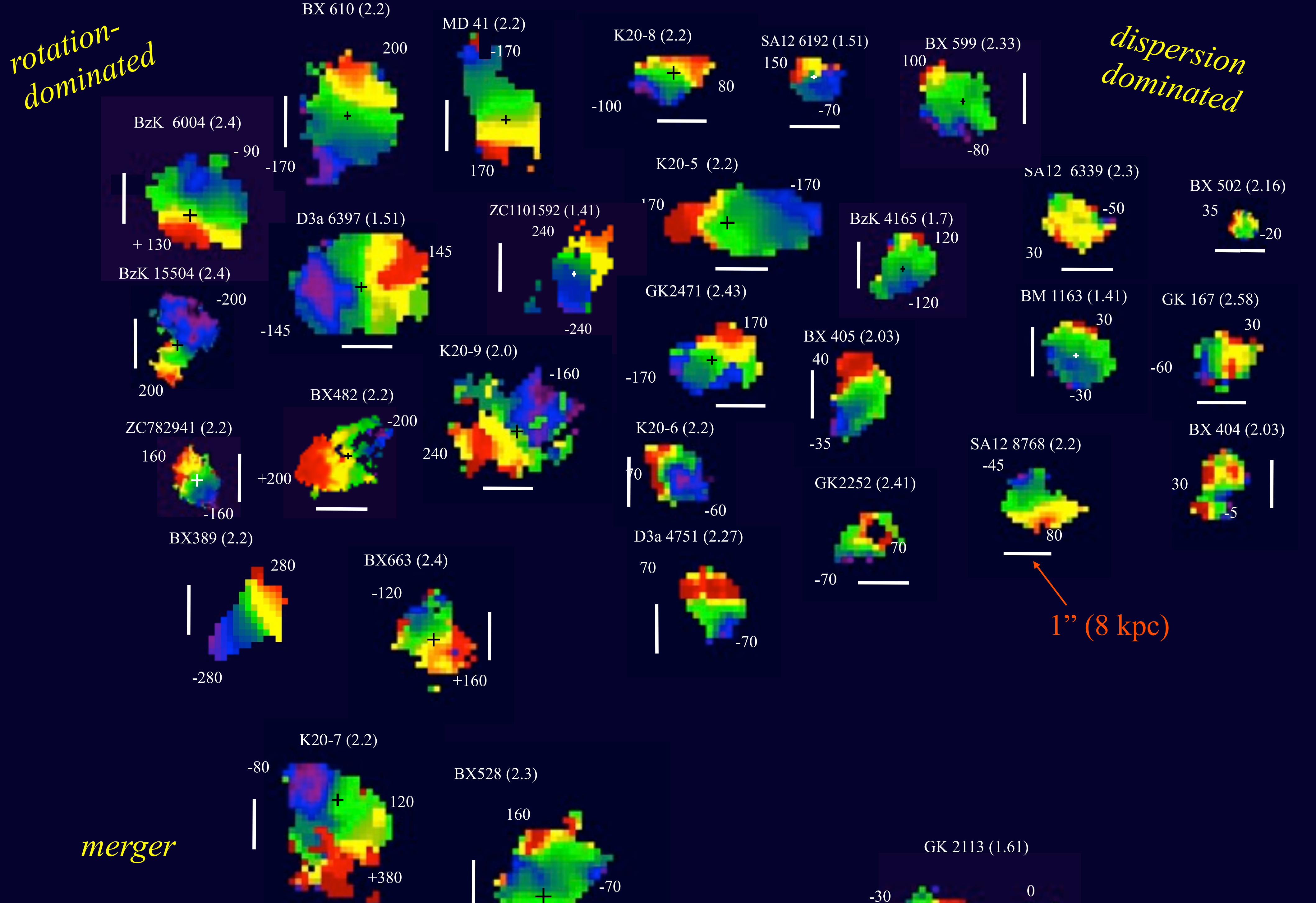
Forster-Schreiber et al. (2006) studied 14 BX/BM galaxies with SINFONI and found evidence for velocity gradients/shears on ~4kpc scales in 9/14 and rotation in 3 galaxies





Genzel et al. (2006) studied unusually large object at z=3 on ~1kpc (0.1") scales and found evidence for rotation.





SINS sample

Forseter-Schreiber et al. 2009

Even with AO correction, studies of high-z galaxies are still limited to ~1.5kpc, which is limited to characteristic size of largest starburst complexes.

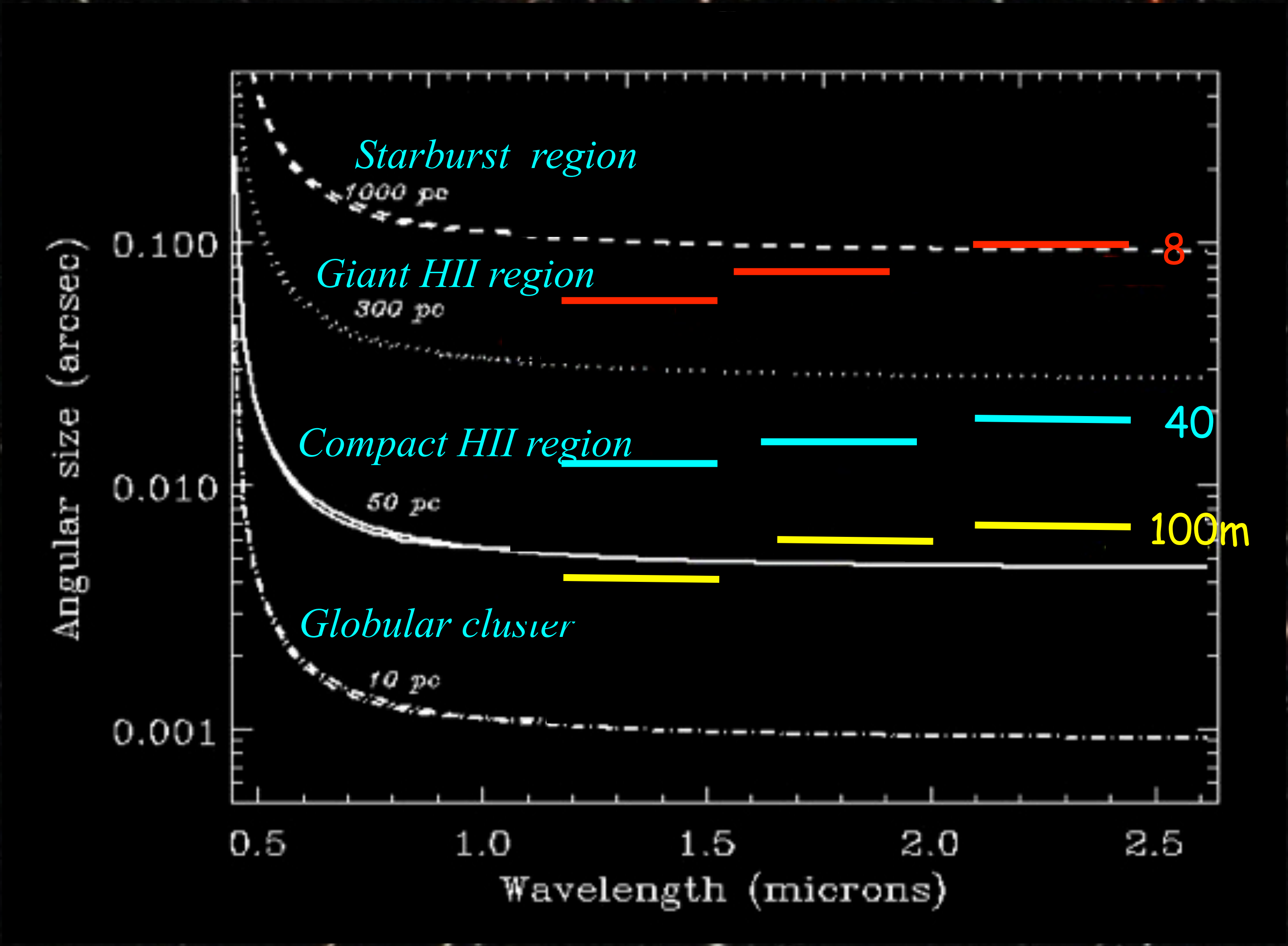
Physical processes within galaxies occur on scales from (non-linear) collapse of gas on scales from individual stars (pc), to HII regions (50pc), to SB complexes (~>kpc)

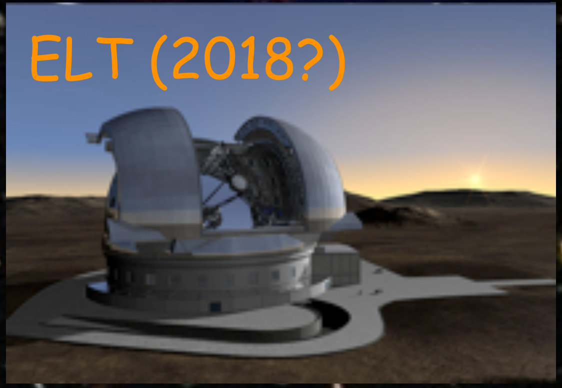
Key extra-galactic science drivers for construction of TMT & ELT is to probe physics on scales comparable to HII regions.

In particular:

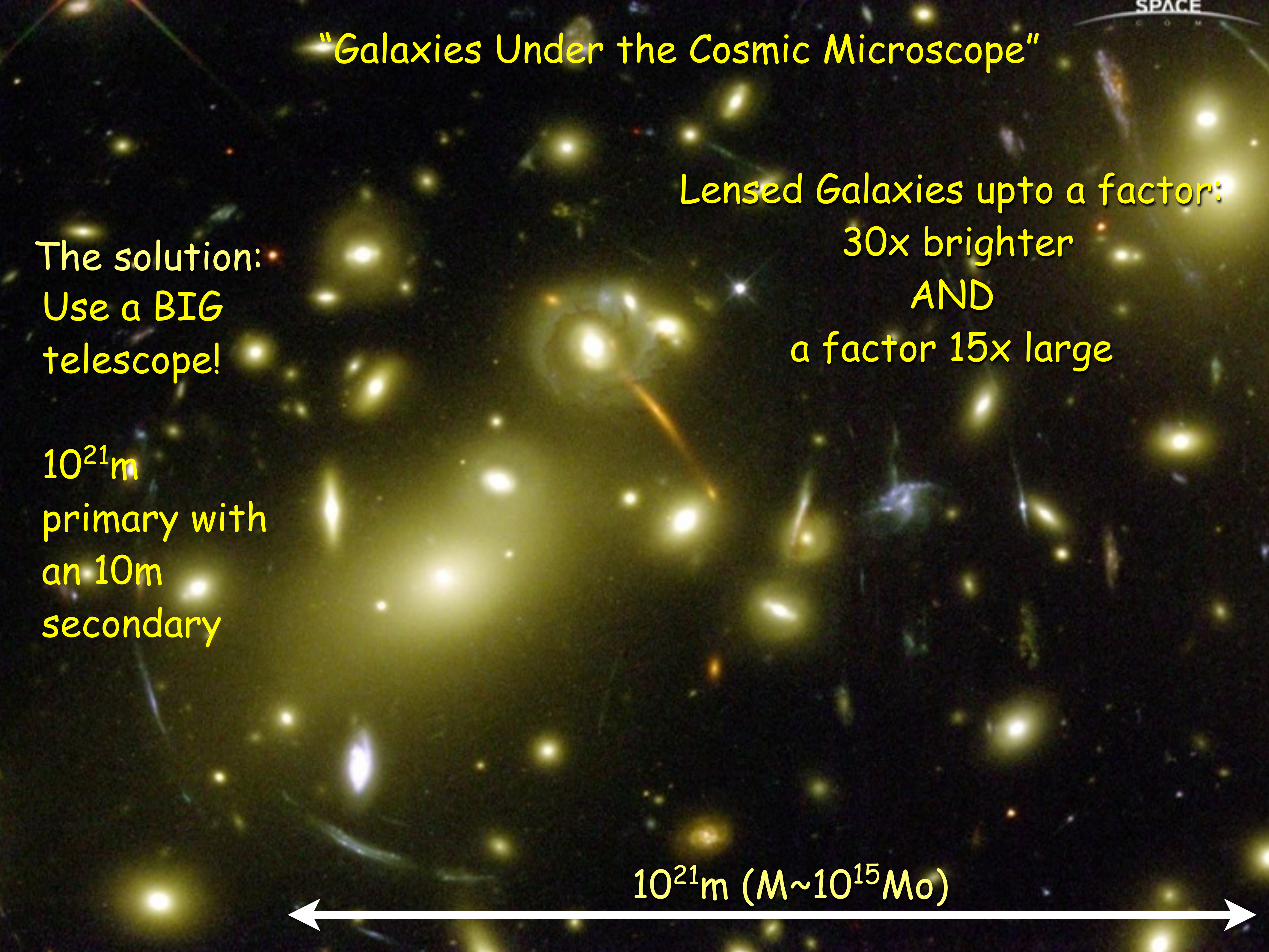
- What are dynamical structures of individual HII regions?
- What are SF densities and SFE's?
- What is jeans mass as a function of environment within galaxies?
- Formation of clumpy structures in disks?
- Gauging importance (impact) of minor mergers
- Mixing of metals and origin of mass-metallicity relation
- Spatially resolved properties of SB driven outflows at high-z. mass loading? energetics?
- Size of compact SBs and how this relates to efficiency driving winds.

The Problem (II):





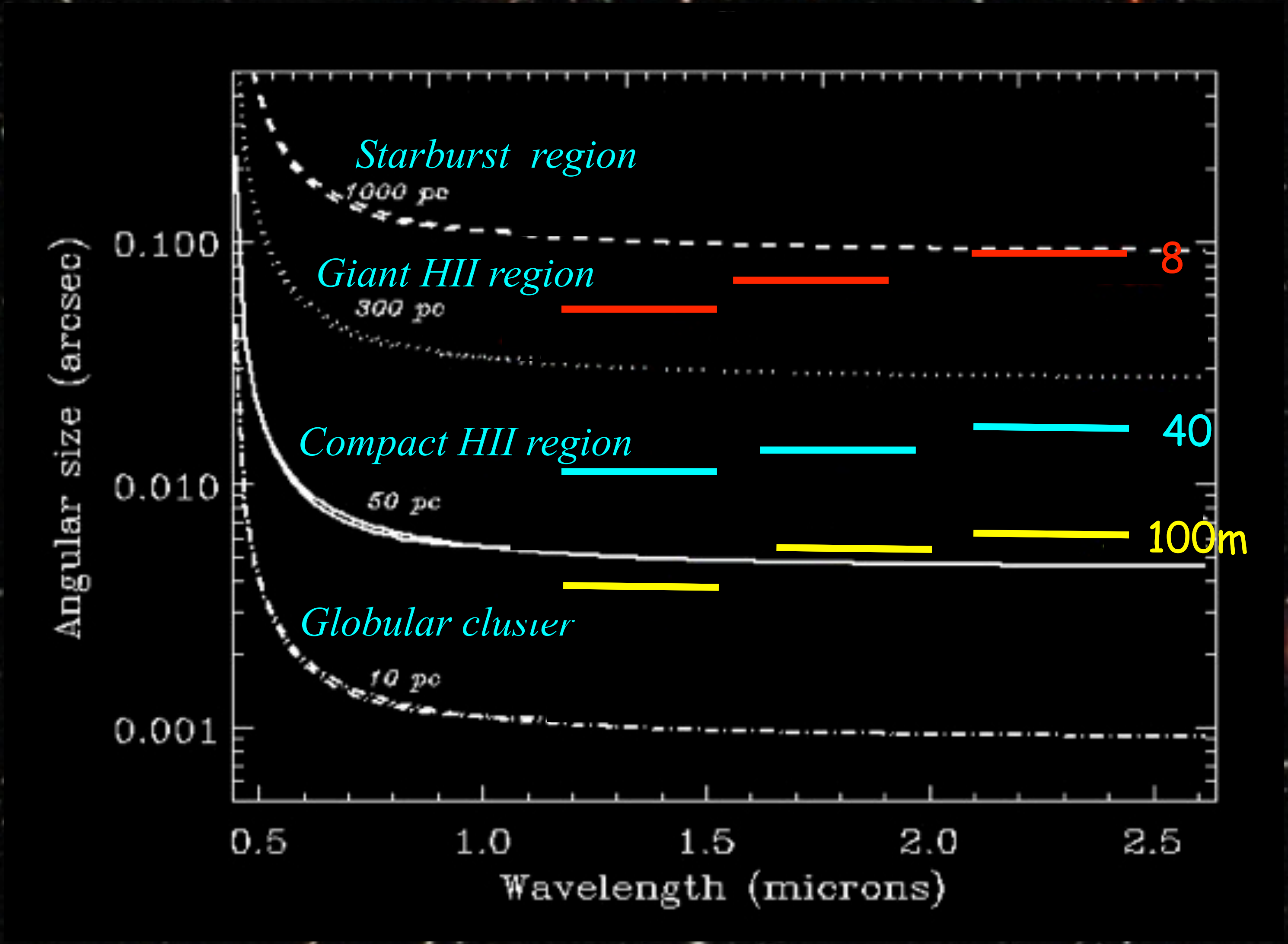
"Galaxies Under the Cosmic Microscope"



Lensed Galaxies upto a factor:
30x brighter
AND
a factor 15x large

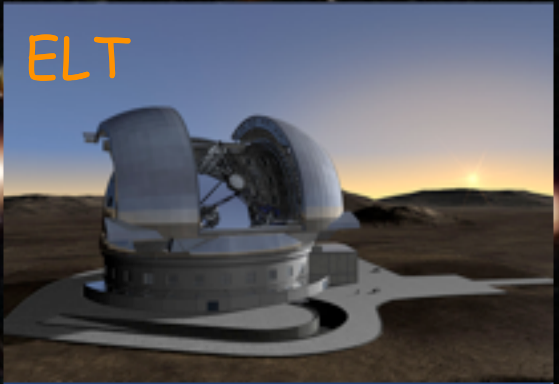
The solution:
Use a BIG telescope!

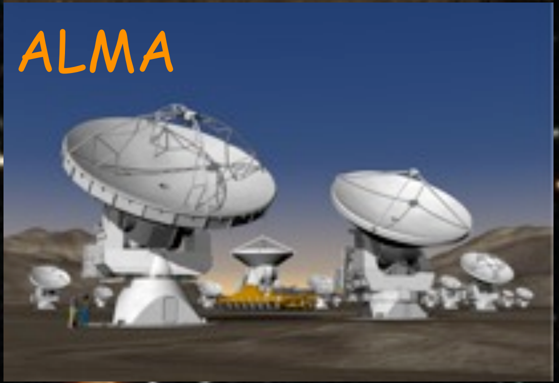
10^{21}m primary with an 10m secondary

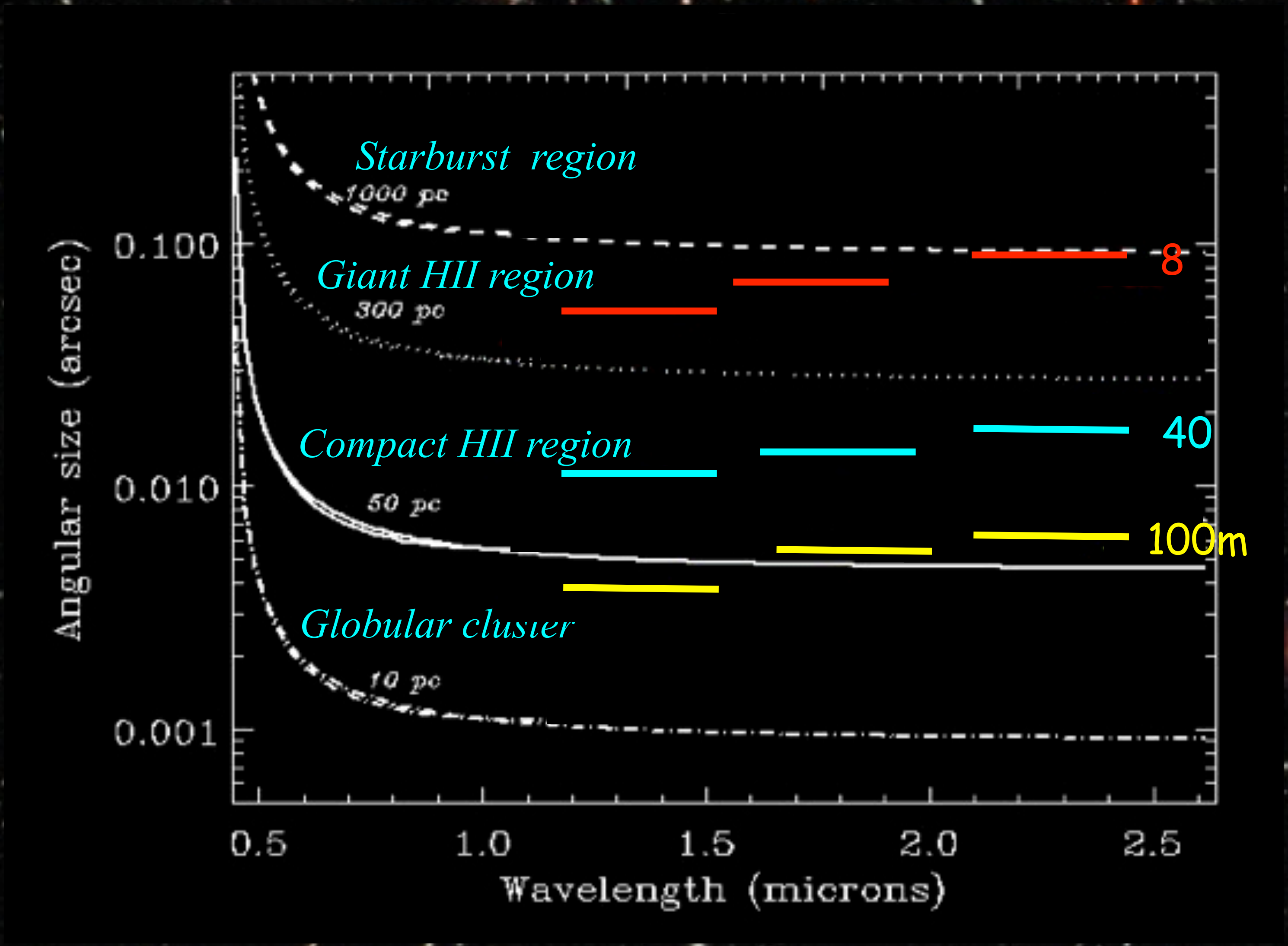

Starburst region
1000 pc
Giant HII region
300 pc
Compact HII region
50 pc
Globular cluster
10 pc
8
40
100m
Angular size (arcsec)
0.100
0.010
0.001
0.5
1.0
1.5
2.0
2.5
Wavelength (microns)


VLT

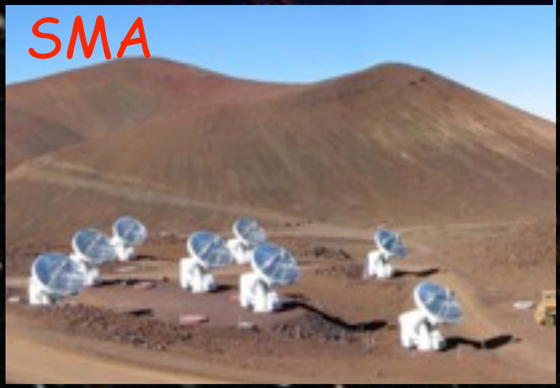

SMA

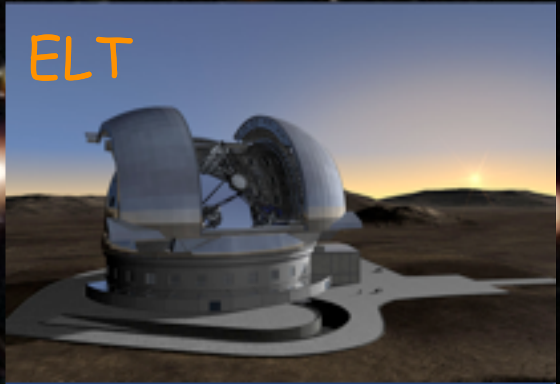

ELT


ALMA

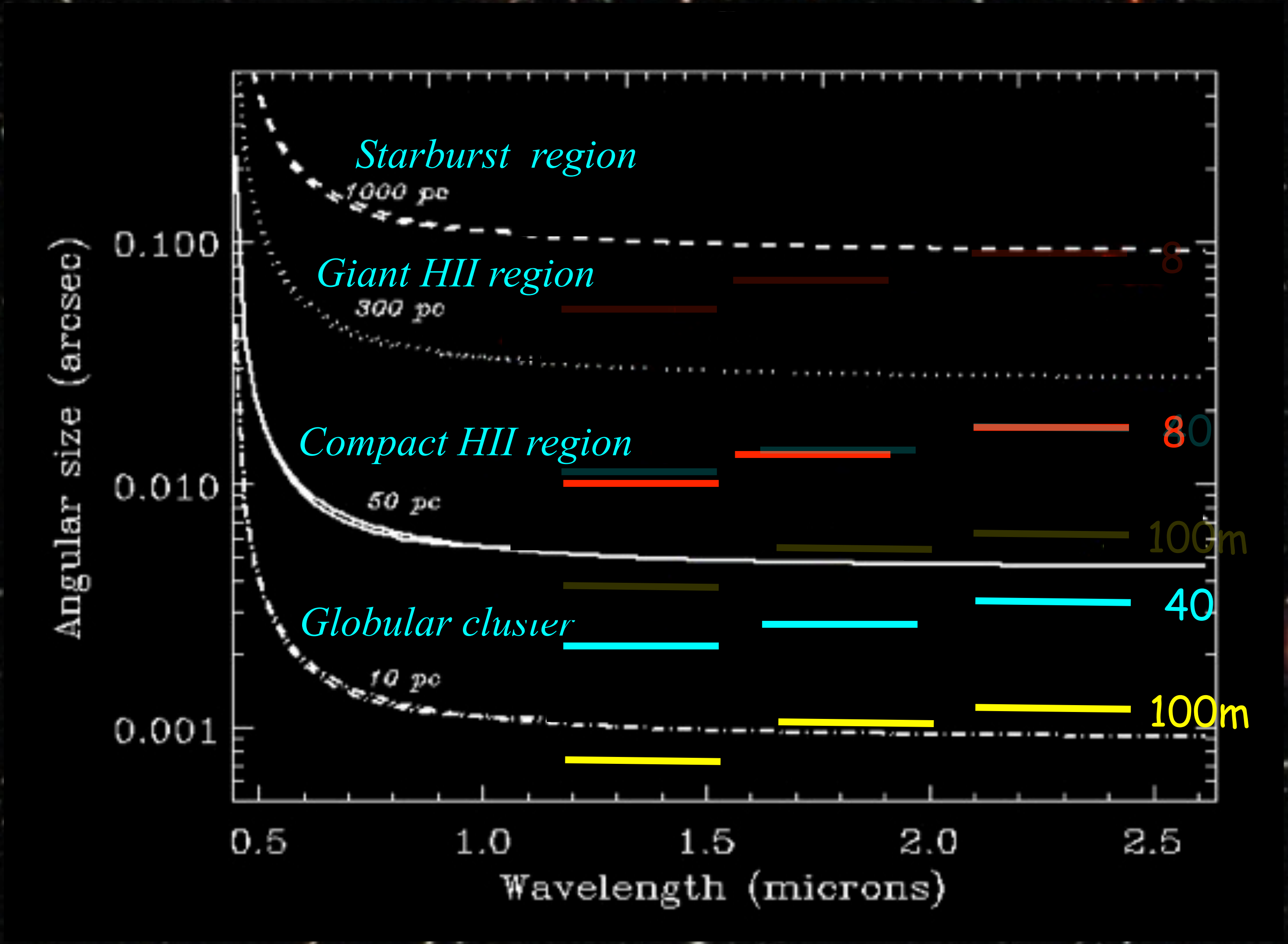

Starburst region
1000 pc
Giant HII region
300 pc
Compact HII region
50 pc
Globular cluster
10 pc
8
40
100m
0.100
0.010
0.001
Angular size (arcsec)
0.5
1.0
1.5
2.0
2.5
Wavelength (microns)


VLT

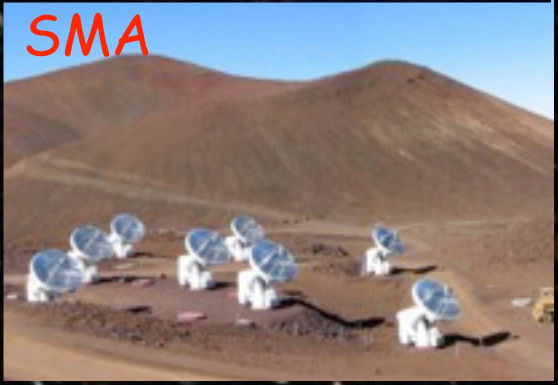

SMA

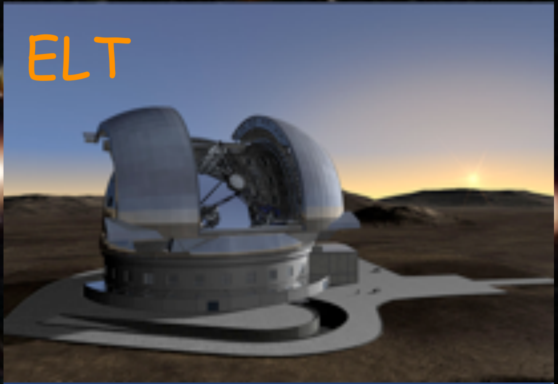

ELT

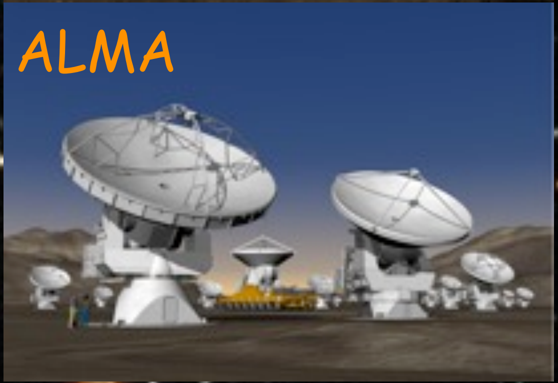

ALMA


Starburst region
1000 pc
Giant HII region
300 pc
Compact HII region
50 pc
Globular cluster
10 pc
8
80
100m
40
100m
0.100
0.010
0.001
Angular size (arcsec)
0.5
1.0
1.5
2.0
2.5
Wavelength (microns)


VLT

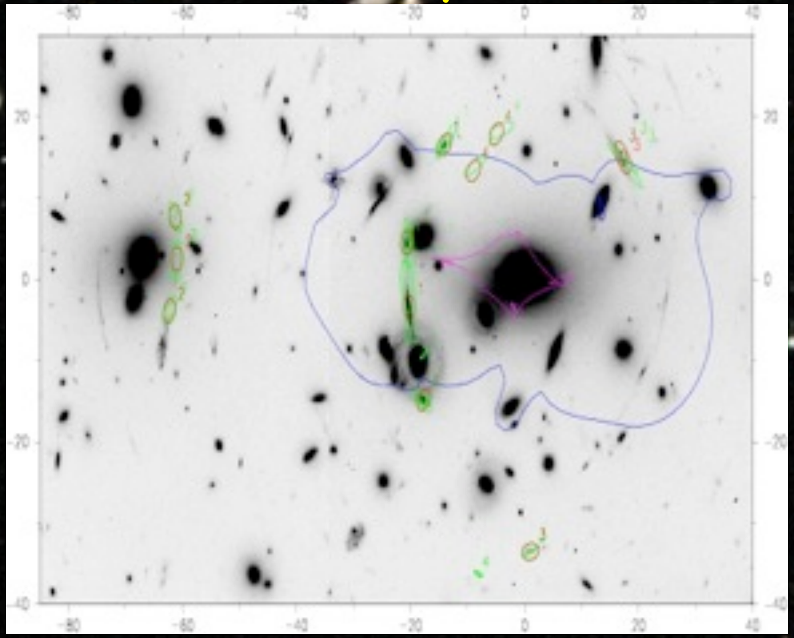

SMA

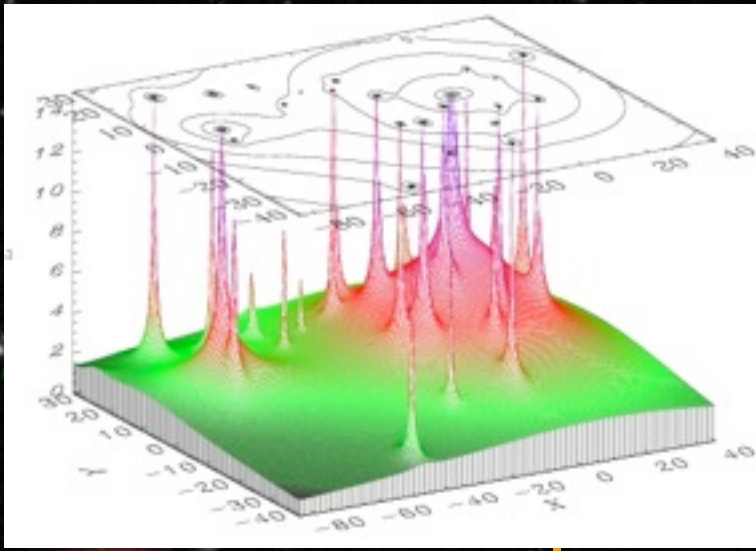

ELT


ALMA

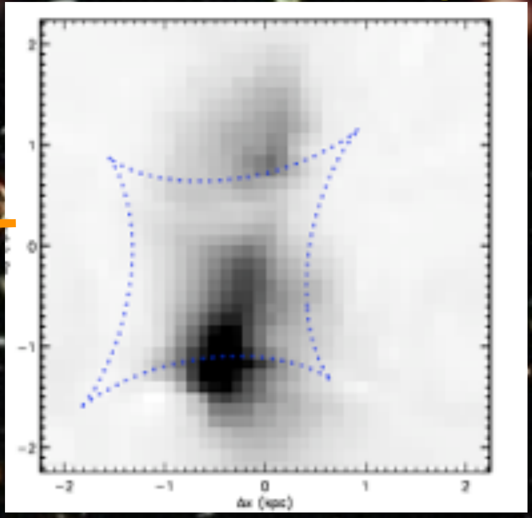
Example: Mass modelling and source plane reconstruction of z=3 galaxy

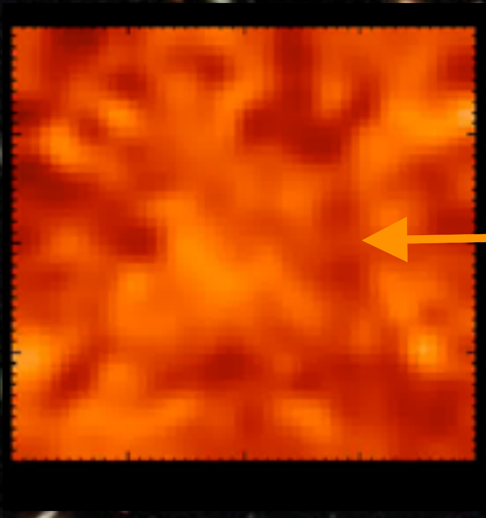
Original image → Galaxy Cluster → Lens model



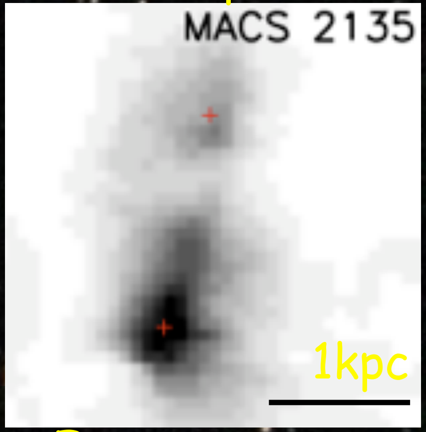


Unlensed Image



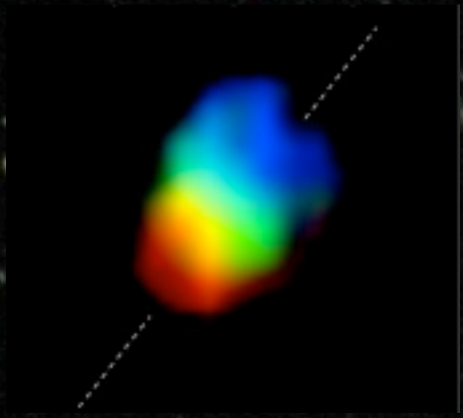


SF and dynamics maps with spatial scale of 100pc!



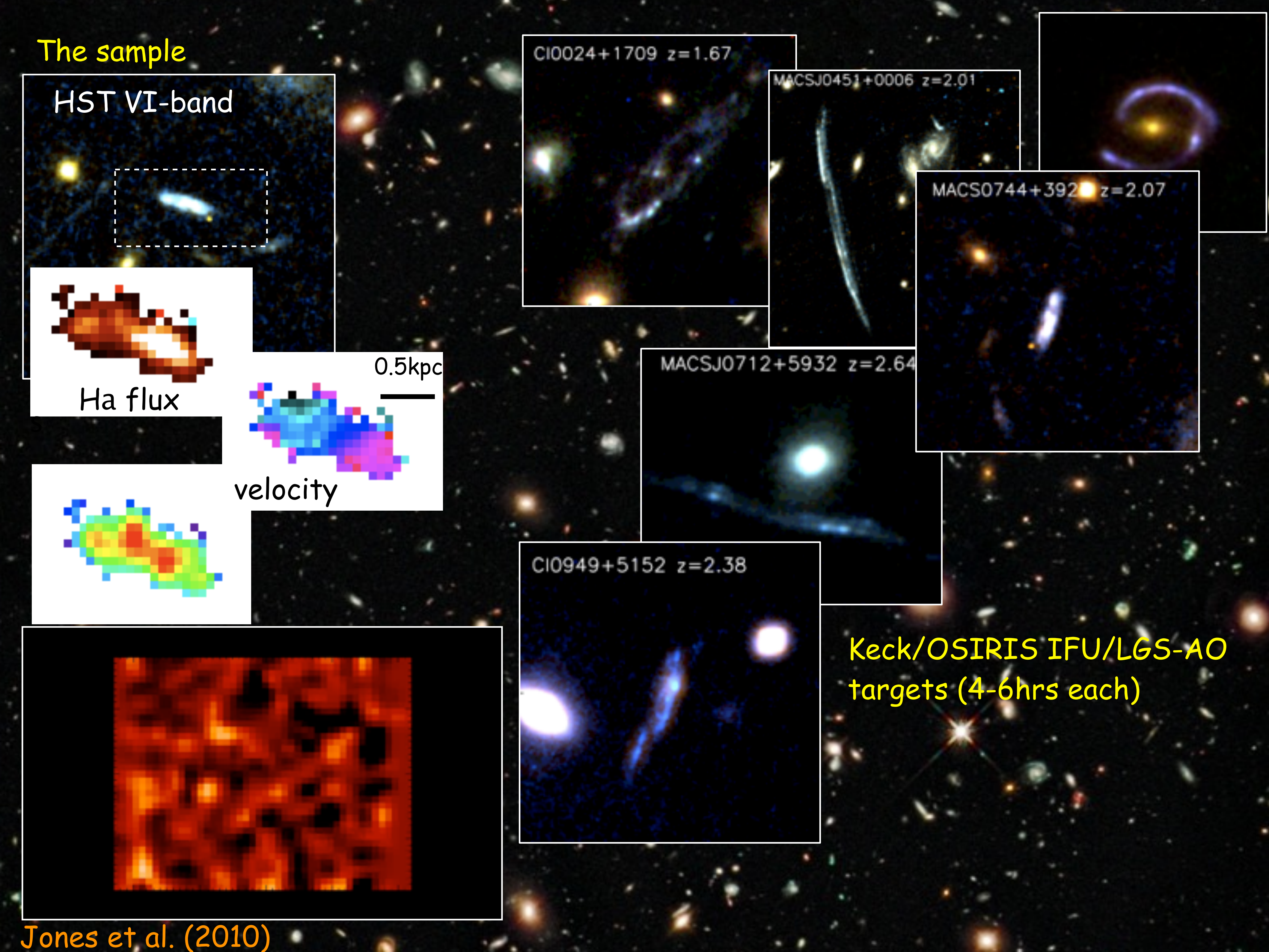
SF map

+



dynamics

Stark, Swinbank et al. 2008 Nature

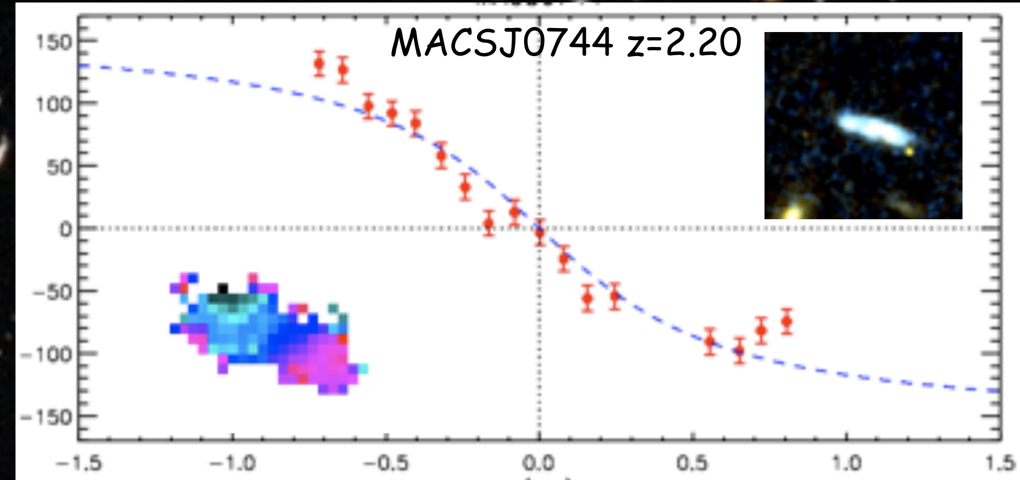


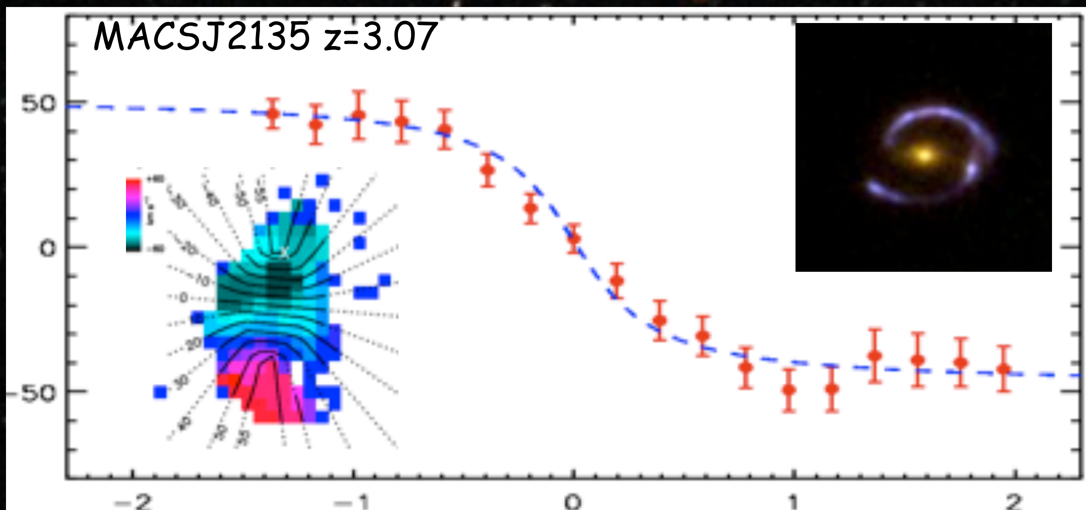
The sample
HST VI-band
Ha flux
velocity
0.5kpc
Cl0024+1709 z=1.67
MACSJ0451+0006 z=2.01
MACS0744+392 z=2.07
MACSJ0712+5932 z=2.64
Cl0949+5152 z=2.38
Keck/OSIRIS IFU/LGS-AO
targets (4-6hrs each)
Jones et al. (2010)

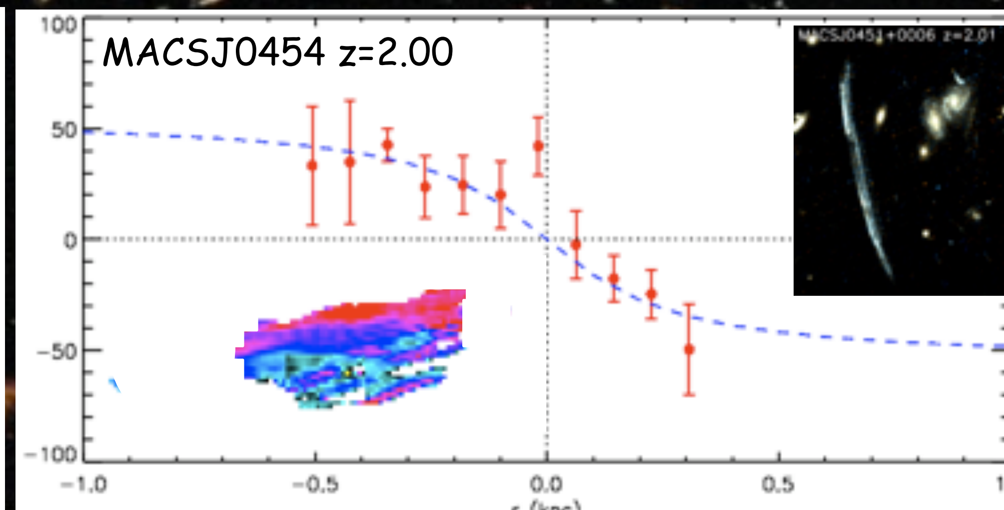
Kinematics

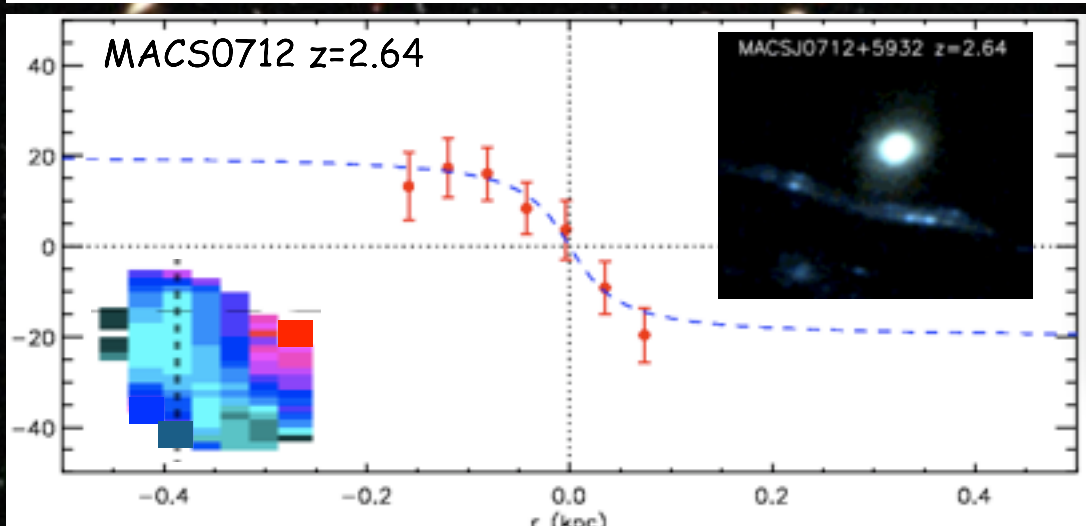
5/6 systems display ‘coherent’ velocity gradients across 2--10kpc in projection

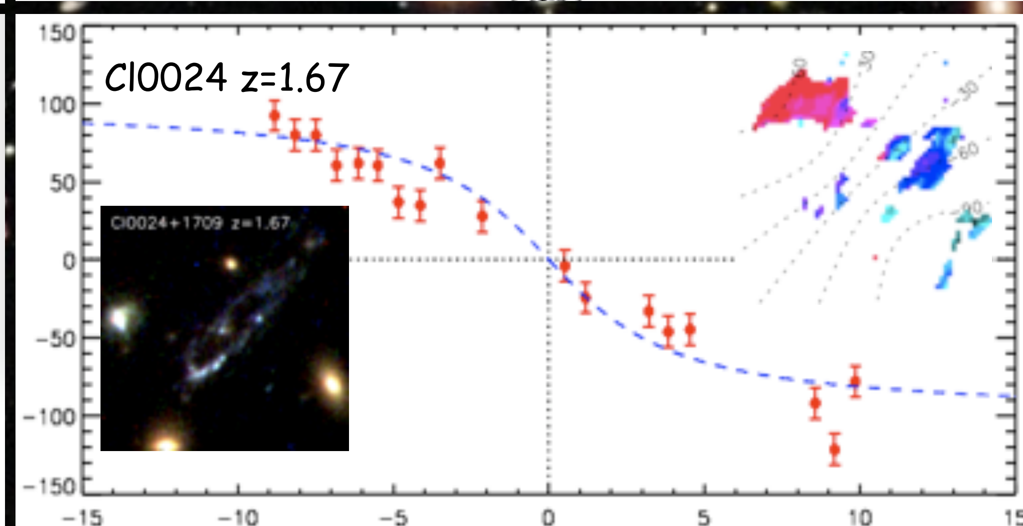
4 consistent with rotation, 1 merger, 1 ambiguous.

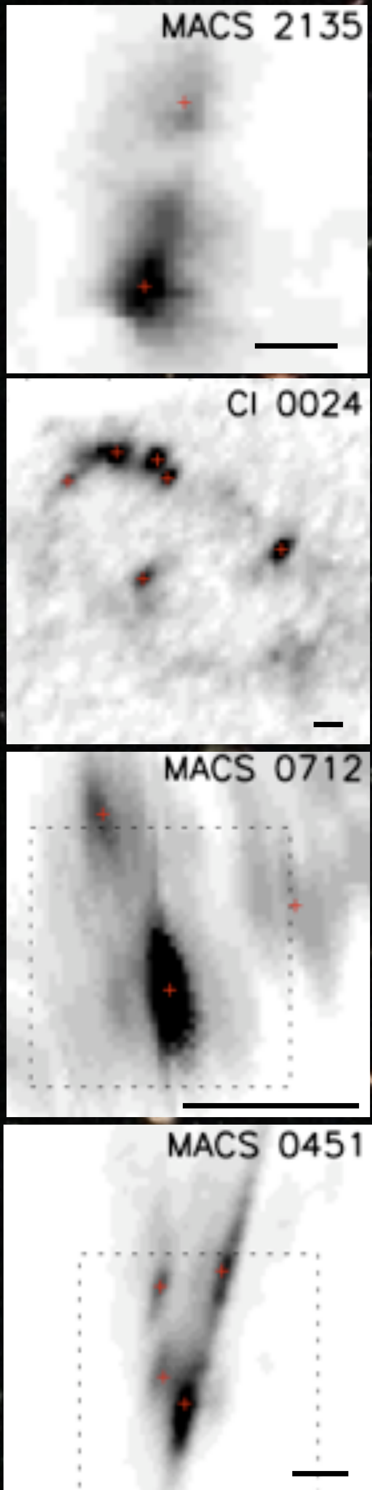












Star-Formation Scales within Disks: back of the envelope calculation

In rotating disk of gas and stars, Toomre criterion is used to test whether perturbations can be stabalised against collapse.

Q<1: gas is unstable and will fragment into giant, dense clumps. Dynamical friction, viscosity and tidal interactions may cause clumps to migrate to center, forming bulges which stabilise the system against further fragmentation.

For galaxies whose velocity field resemble rotation:

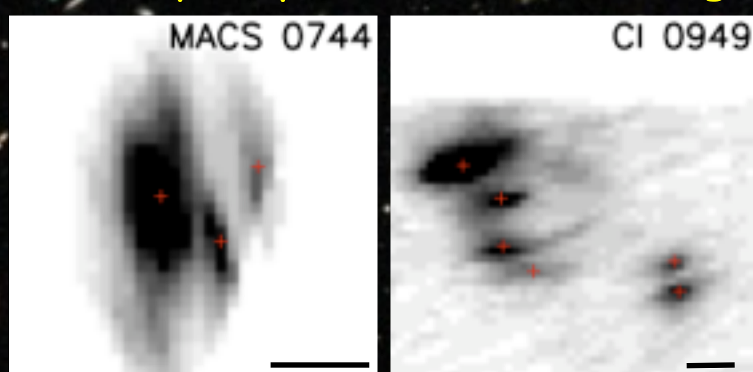
mass surface density

$$Q=s_r k/pGS$$

$1.5V_{max}/R$

For the lensed sample, Q~0.6 (inclination corrected)

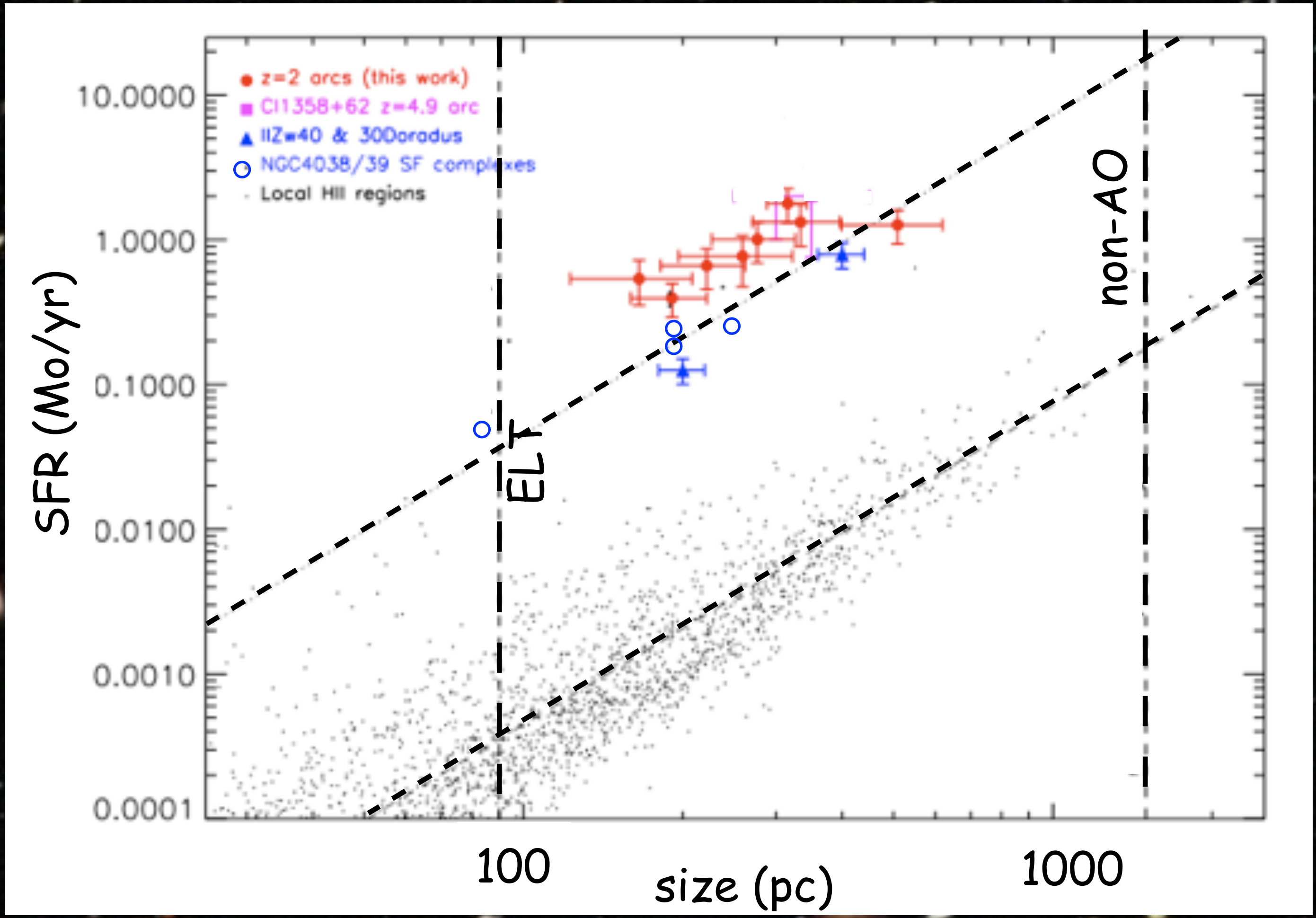
Implies that gas will fragment into massive clumps on scales of Jeans length for dispersion support. In uniform disk, the largest scale for which velocity dispersion stabilises against gravitational collapse is:



$$L_J=ps^2/8GS$$

gives L_J=0.1--1kpc for all galaxies in our sample

Properties of HII regions in SF galaxies at z=2



The luminosities in the HII regions are ~100x larger than in local spirals, but diameters are consistent with the Jeans length for support by velocity dispersion.

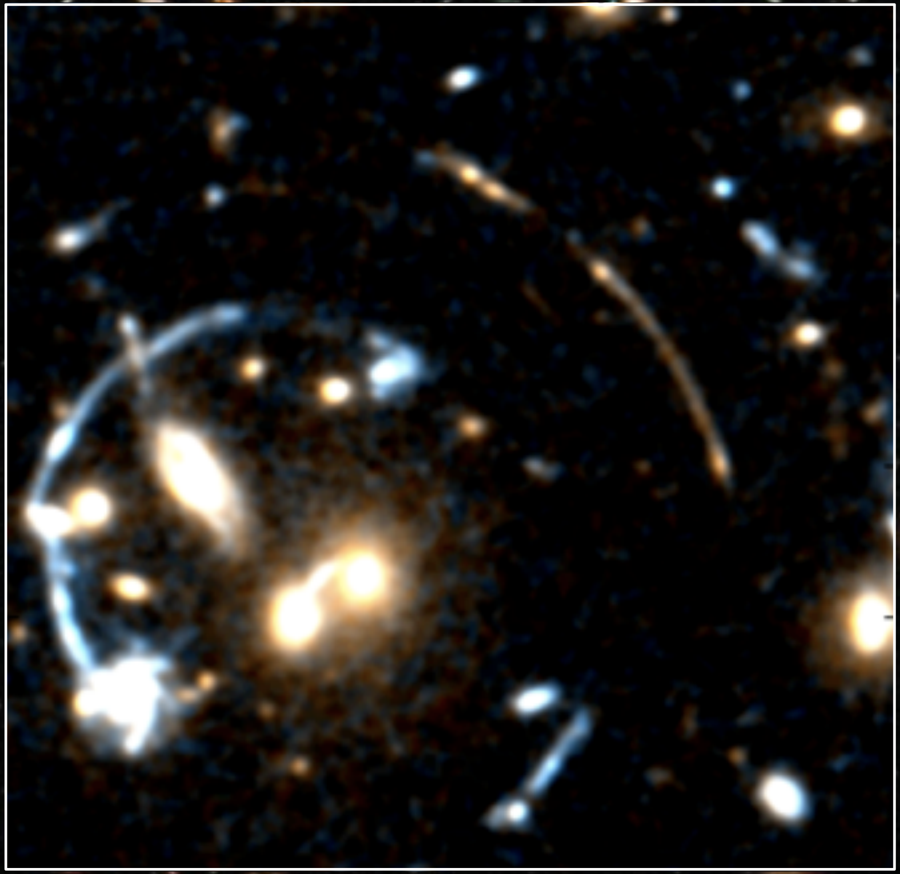
Likely that they collapsed as a result of disk instabilities (expected since the Toomre Q parameter is less than unity for all galaxies in our sample).

Intense star-formation in high redshift galaxies driven by the fragmentation of gravitationally unstable systems due to high gas fractions? high gas surface densities? high velocity dispersions?

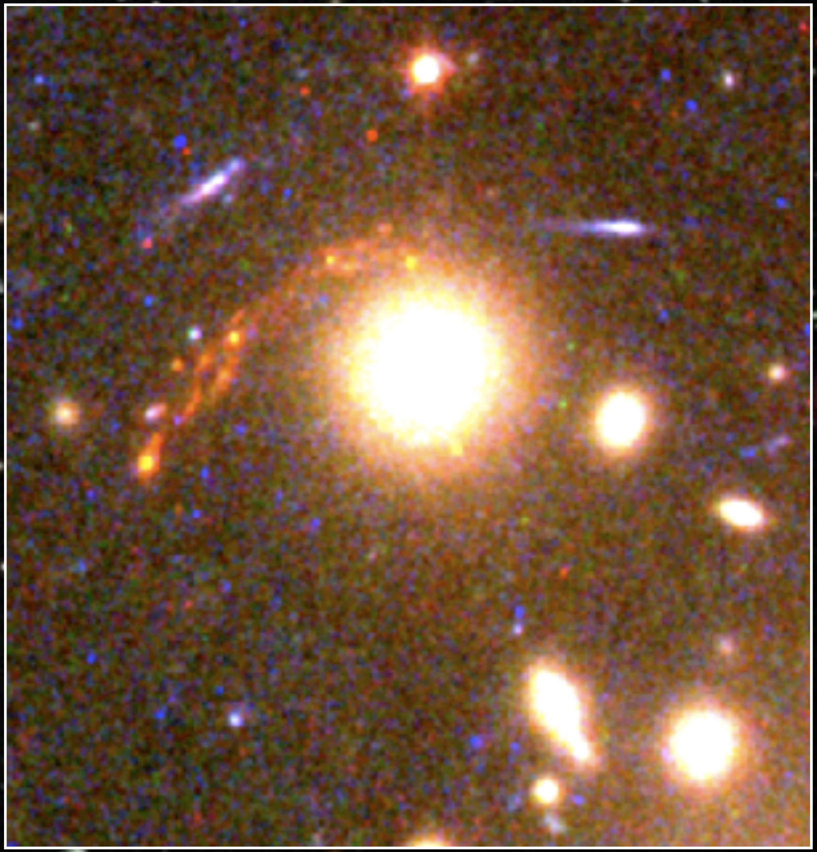
Kennicutt 1988, Gonzalez-Delgado et al. 1997, Lee et al. 2008

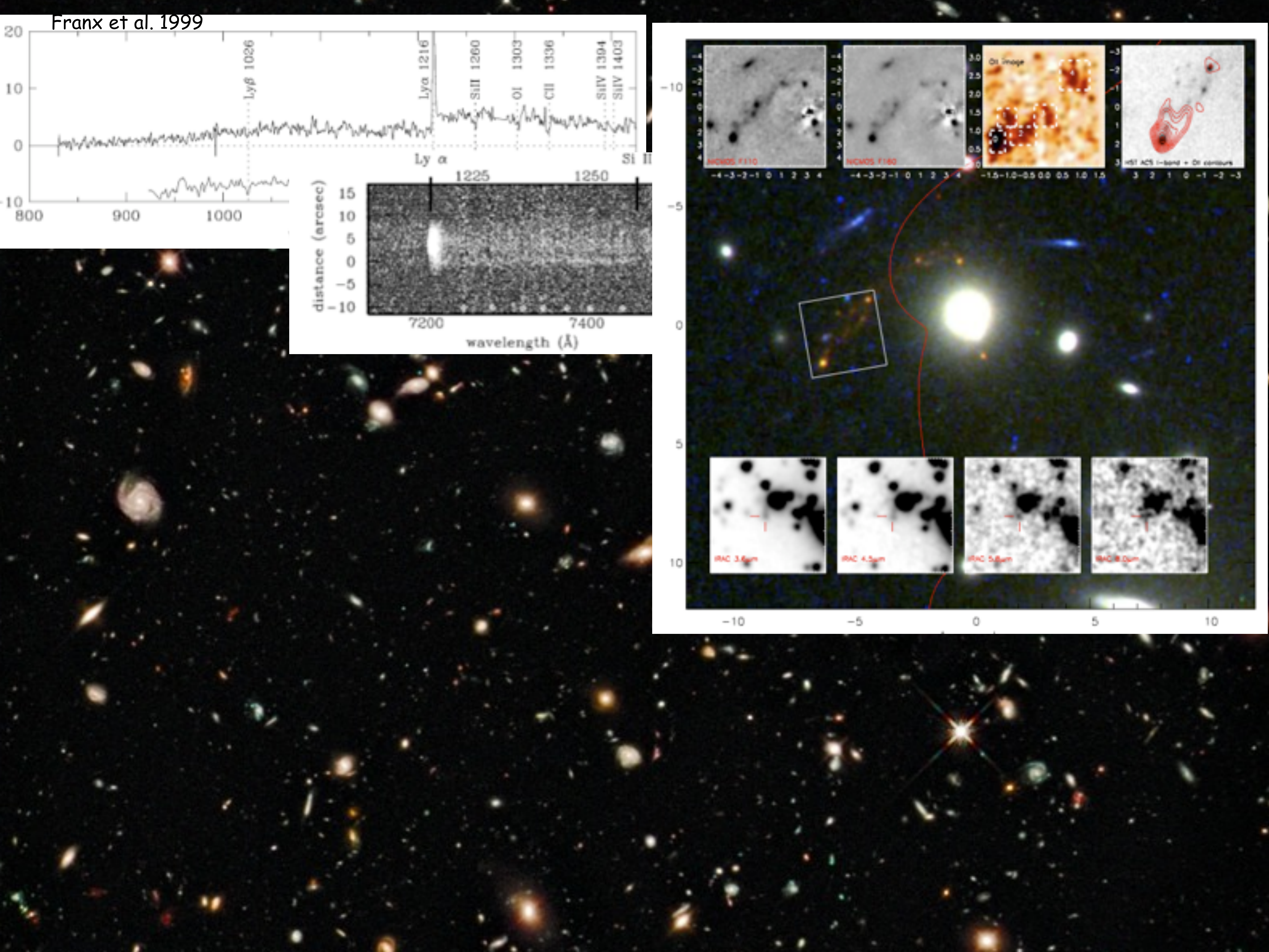
Due to lensing, we can also do this experiment at the highest z's: nebular emission lines are visible to z~5.5

RCS0224-002 z_{cl}=0.78 z_{arc}=4.88
(Gladders et al. 2001)

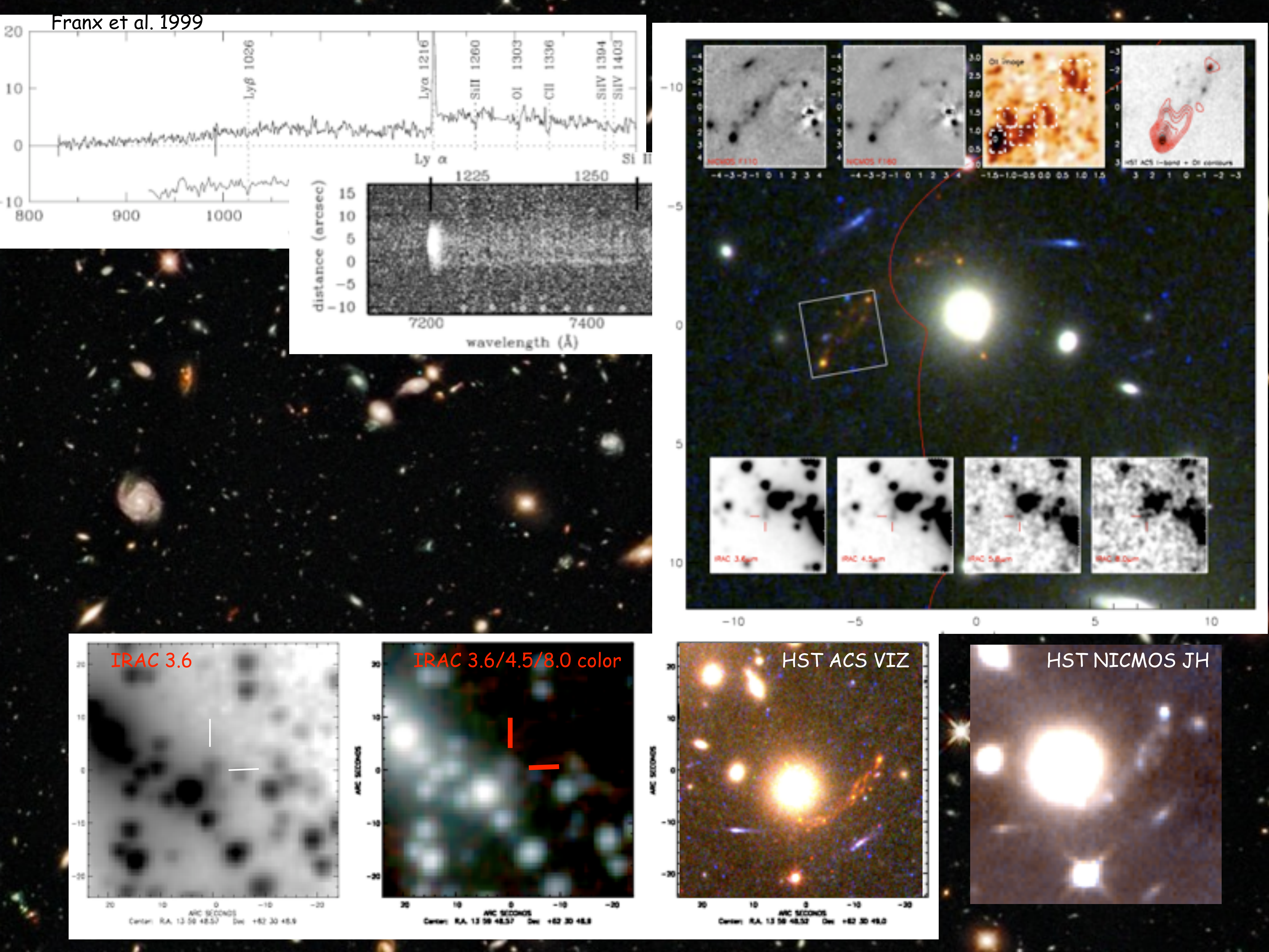


MS1358+62 z=4.92
(Franx et al. 1999)

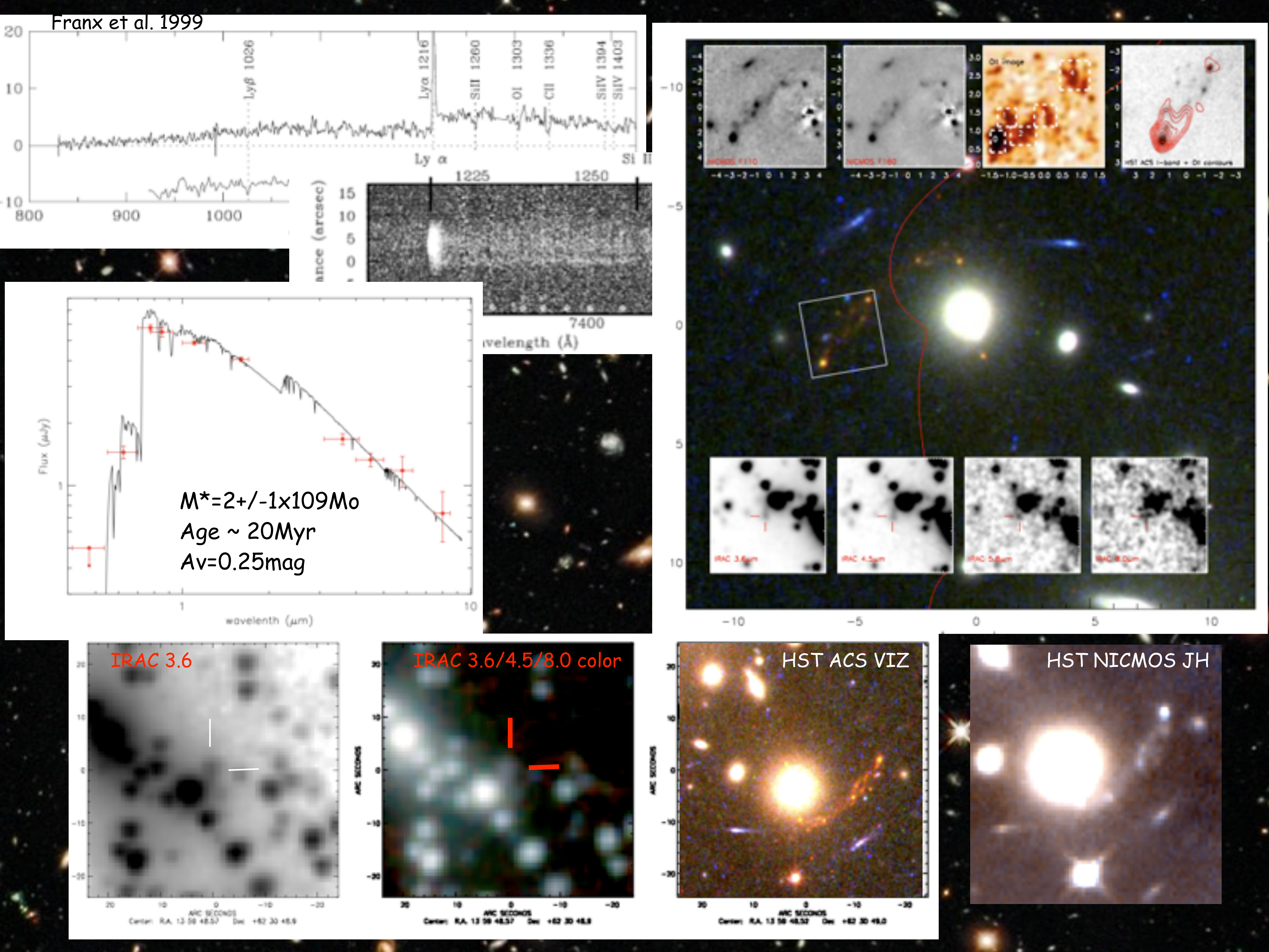




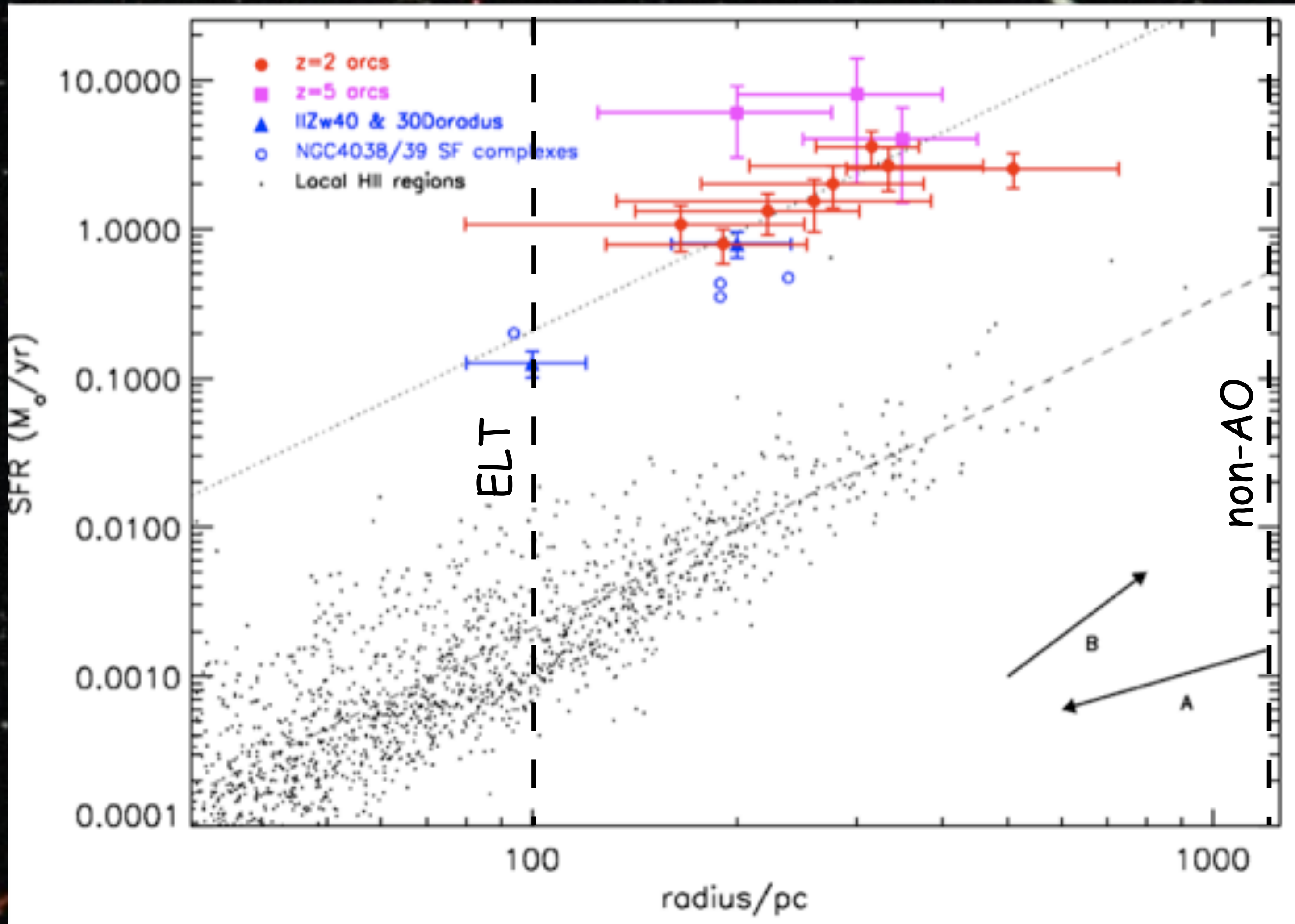
Franx et al. 1999
Lyβ 1026
Lyα 1216
SiII 1260
OI 1303
CII 1336
SiIV 1394
SiIV 1403
Ly α
Si II
distance (arcsec)
wavelength (Å)



Franx et al. 1999
Lyβ 1026
Lyα 1216
SiII 1260
OI 1303
CII 1336
SiIV 1394
SiIV 1403
Ly α
Si II
distance (arcsec)
wavelength (Å)
IRAC 3.6
IRAC 3.6/4.5/8.0 color
HST ACS VIZ
HST NICMOS JH

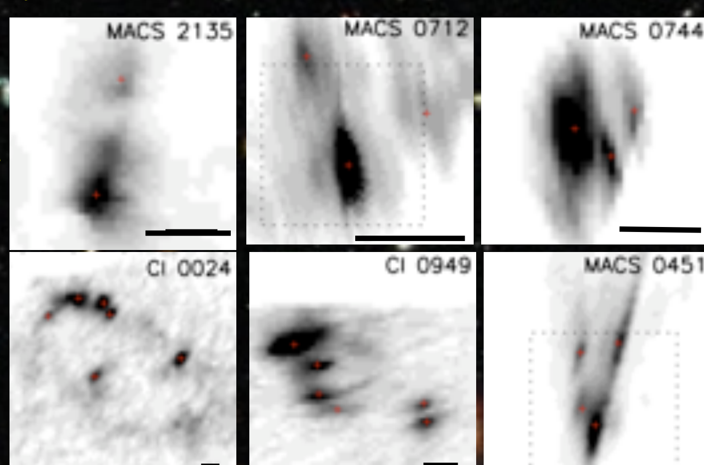


Franx et al. 1999
Lyβ 1026
Lyα 1216
SiII 1260
OI 1303
CII 1336
SiIV 1394
SiIV 1403
Ly α
1225
1250
7400
Flux (μJy)
wavelenth (μm)
M*=2+/-1x109Mo
Age ~ 20Myr
Av=0.25mag
IRAC 3.6
IRAC 3.6/4.5/8.0 color
HST ACS VIZ
HST NICMOS JH

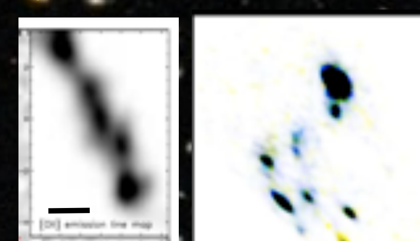


z=2-3

Ha



z=5

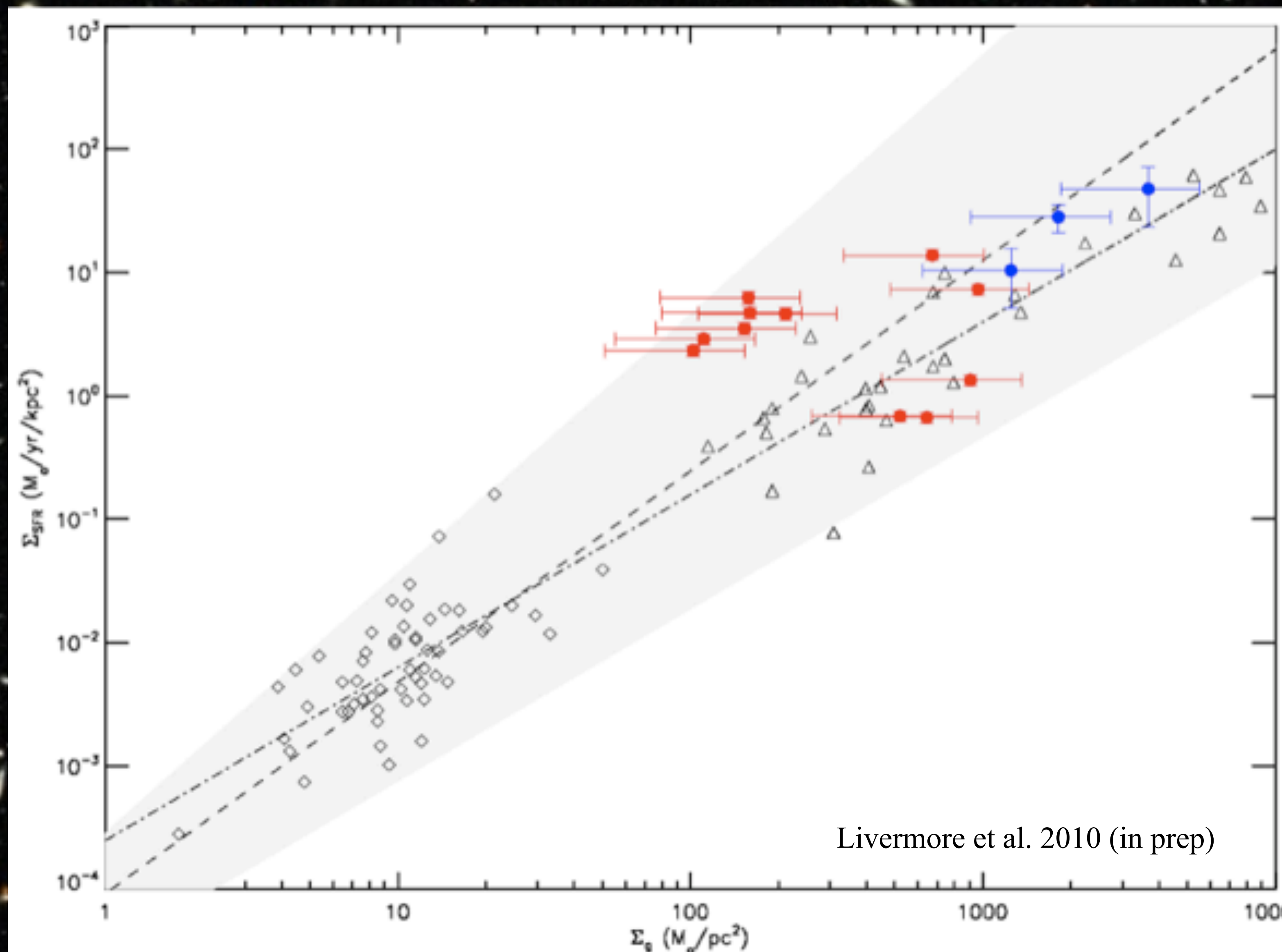


RCS0224 MS1358

Swinbank et al. '07, '09;
Jones, Swinbank et al '10;
Stark, Swinbank '08 Nature

But these SF regions do sit on the KS relation (and we can do this *without* CO!)

Assuming Ha (or OII) velocity dispersion traces dynamics of gas (and clouds are self gravitating), then we can estimate Mgas directly via $M_{gas}=5s^2R/G$



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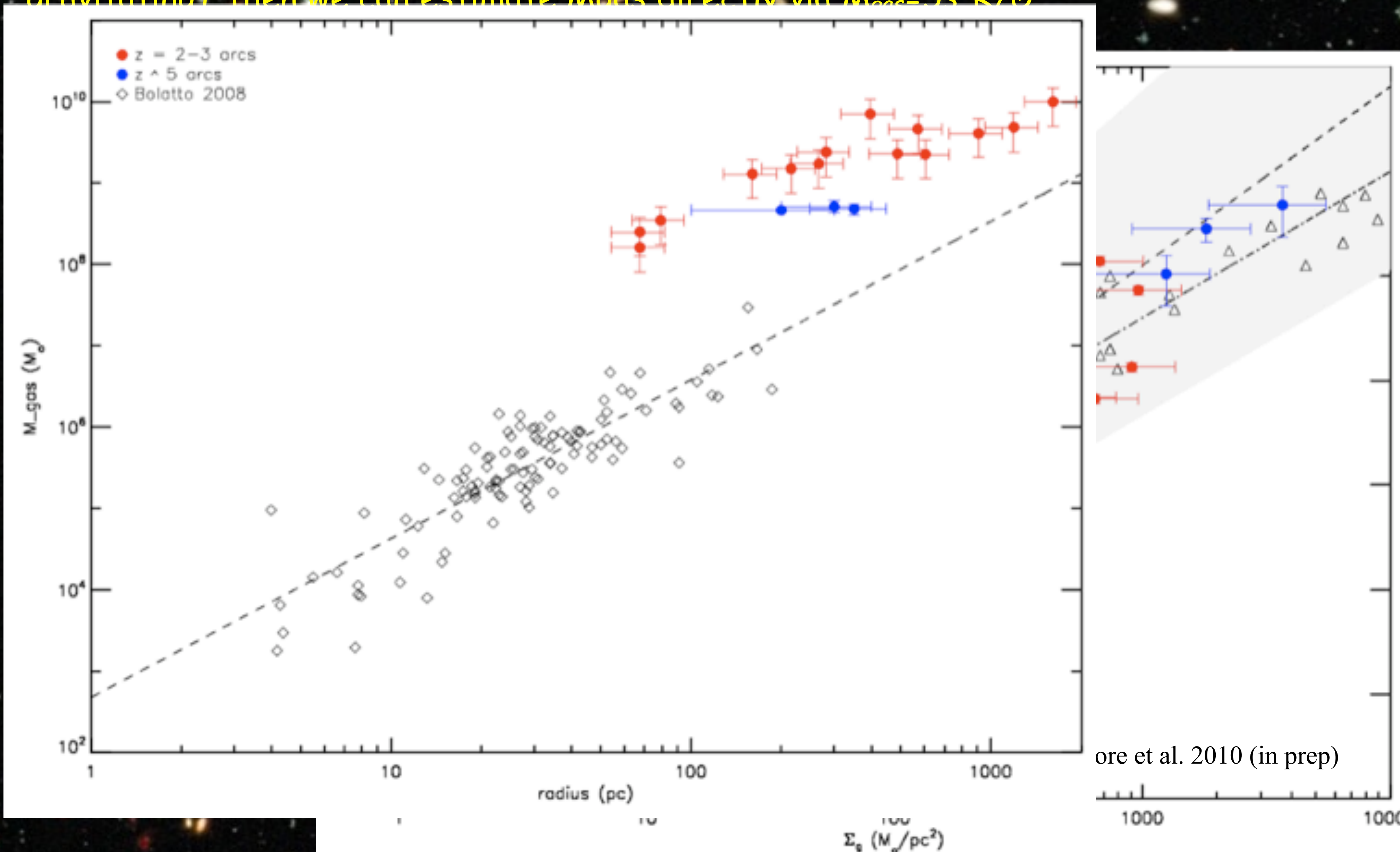


ore et al. 2010 (in prep)

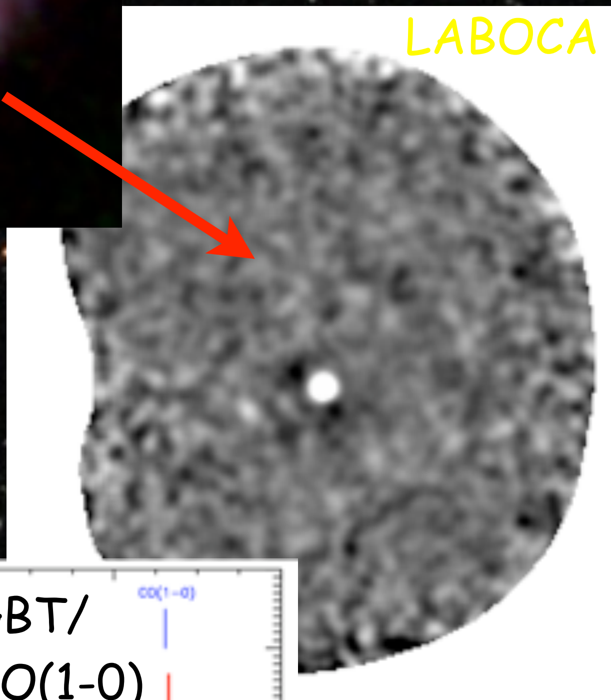
Multi-wavelength serendipity

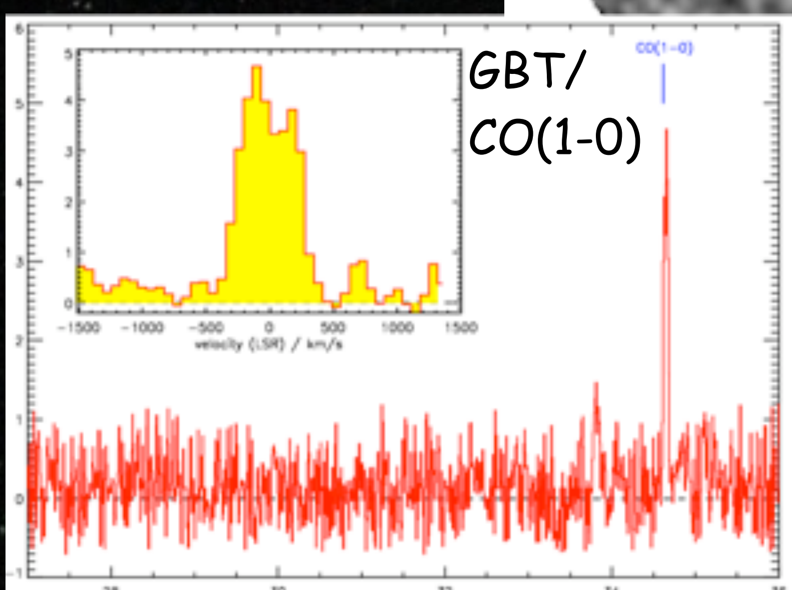
MACS J2135-0102: an X-ray luminous cluster at z=0.32 with a bright lensed LBG at z=3.07 and the brightest SMG, with z=2.32 and S870um=106+/-3mJy (3x brighter than any other SMG)

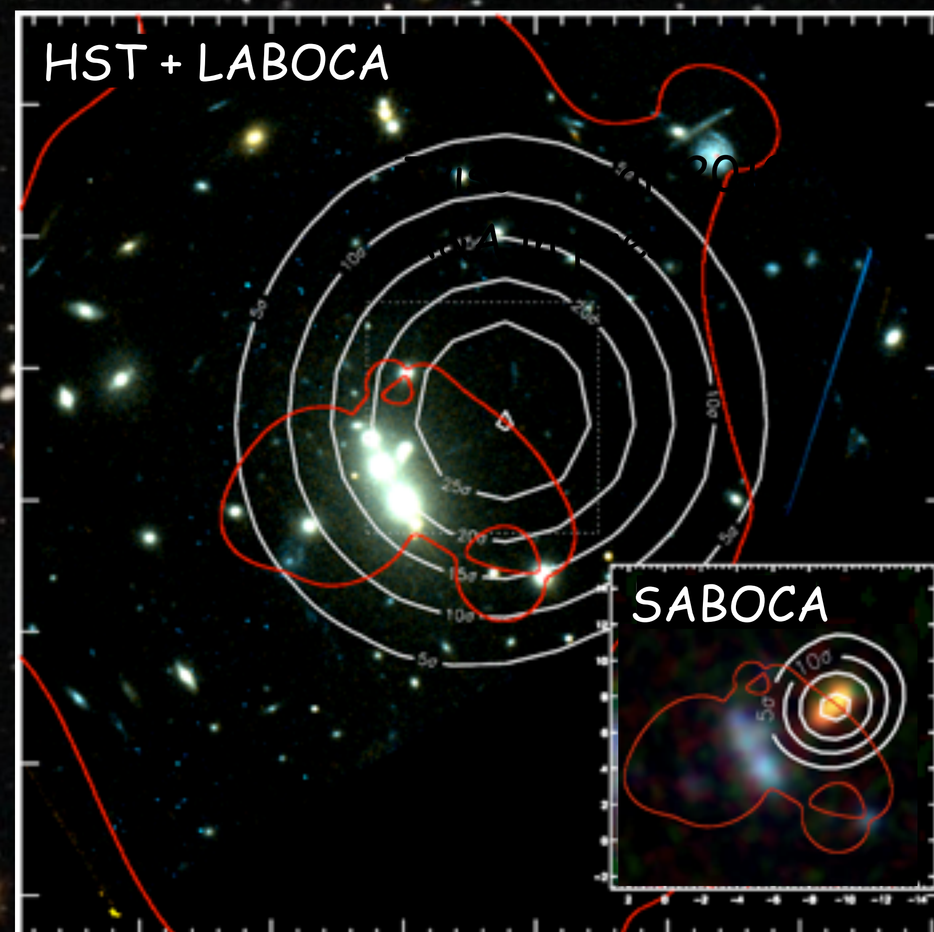
m=32.5+/-4.5

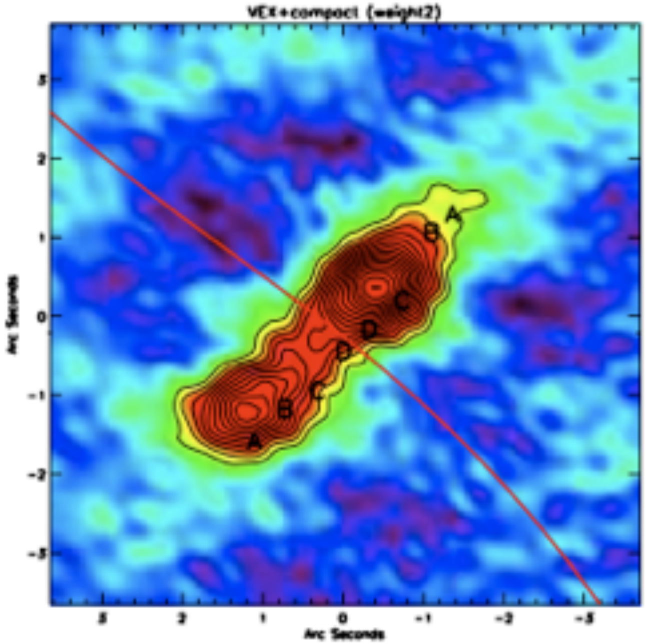
(so intrinsic flux=3mJy; ie a typical high-z ULIRG).

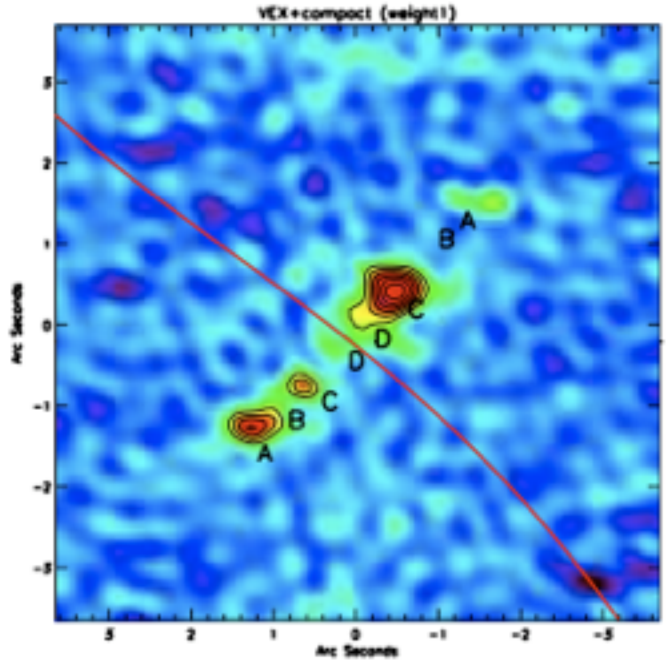
For m=32, 0.2"=100pc (source-plane)

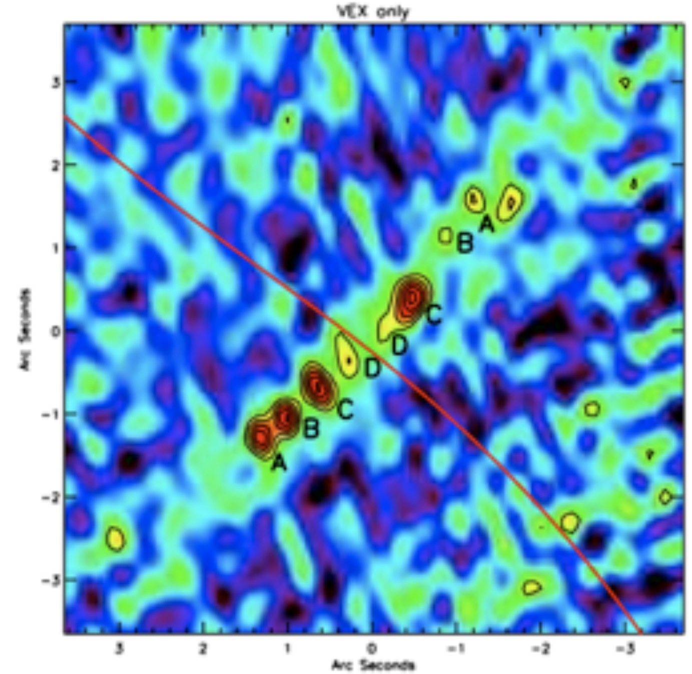








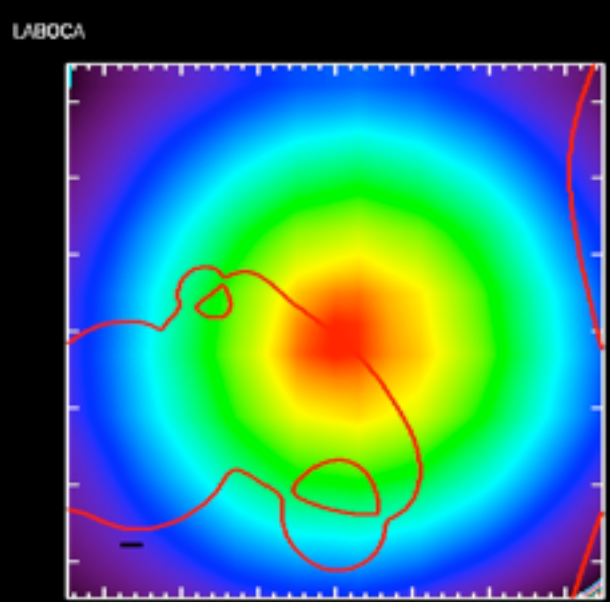




To resolve the star-formation, we used the Smithsonian Sub-mm Array (SMA) at 3 configurations: compact (1.5"), Extended (0.7"), Very Extended (VEX; 0.2")

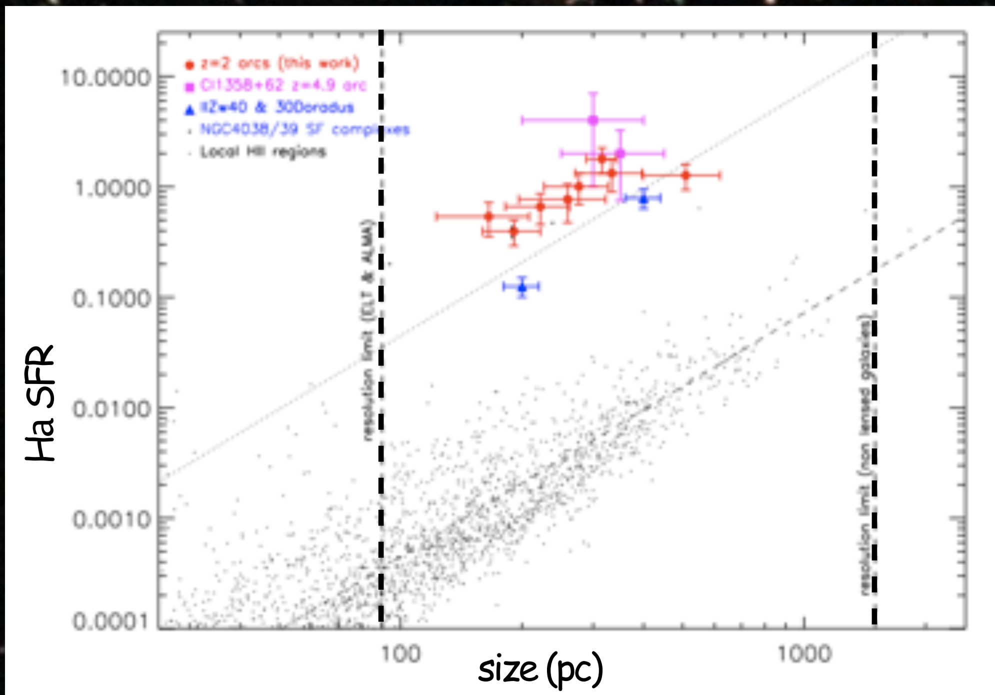
In all configurations, the galaxy continues to break up into smaller clumps

In highest configuration, beam is 0.2" (90-150pc after accounting for lensing).

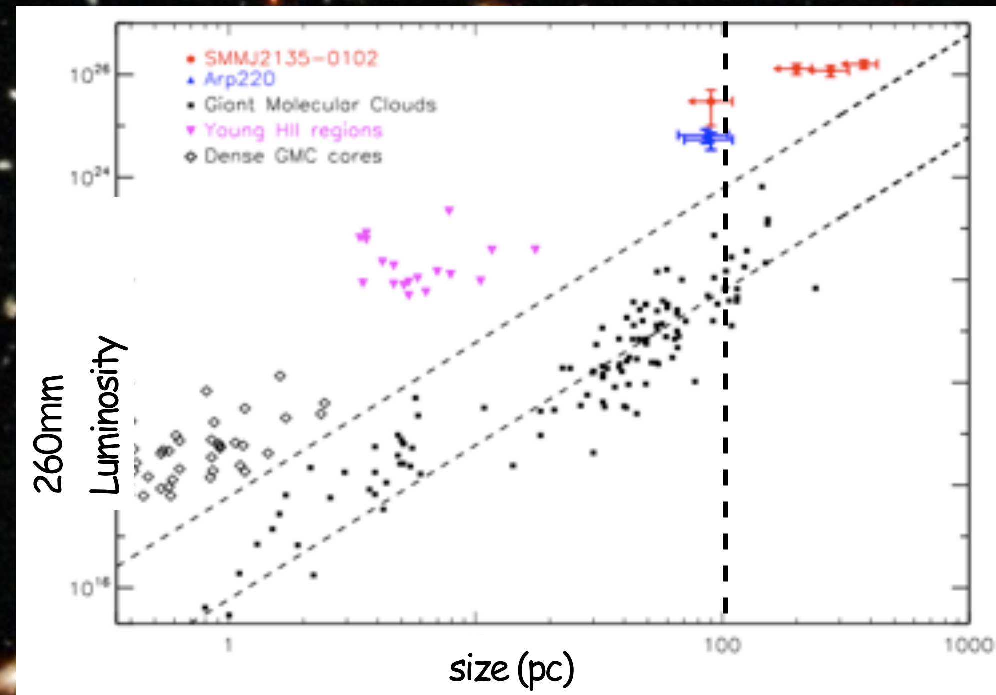


Intense Star-Formation Within Compact Regions in z=2-5 Galaxies

Nebular Emission Lines

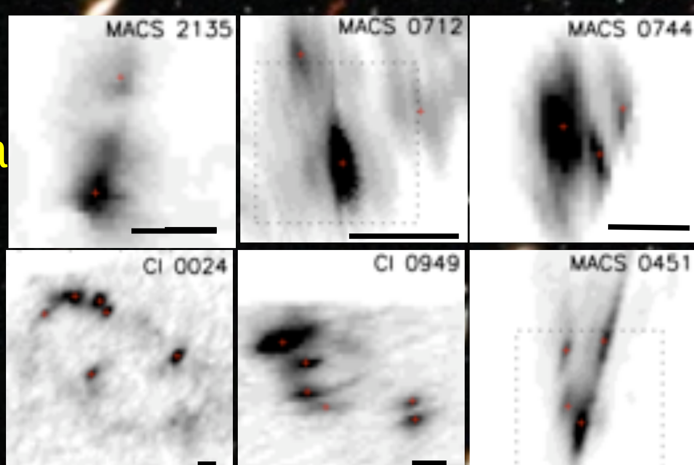


Sub-mm emission

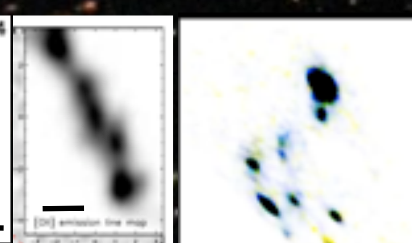


z=2-3 Lensed LBGs

Ha

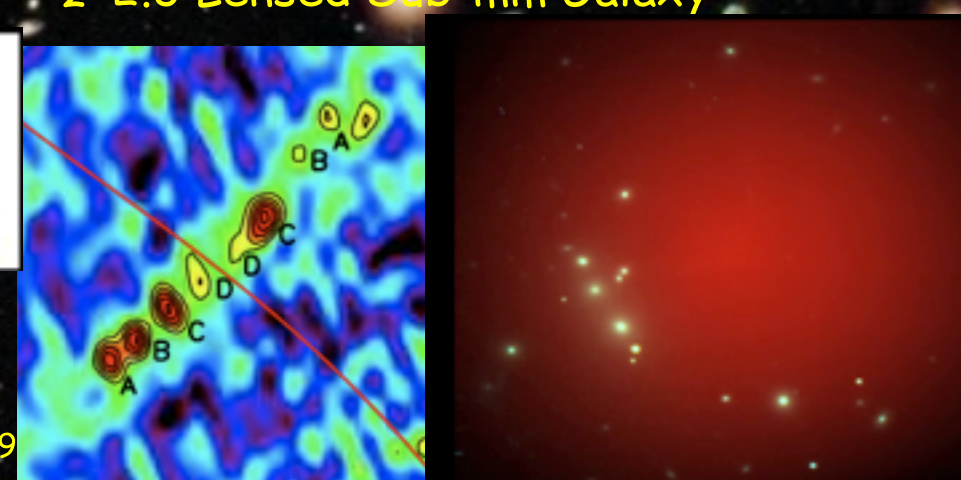


z=5



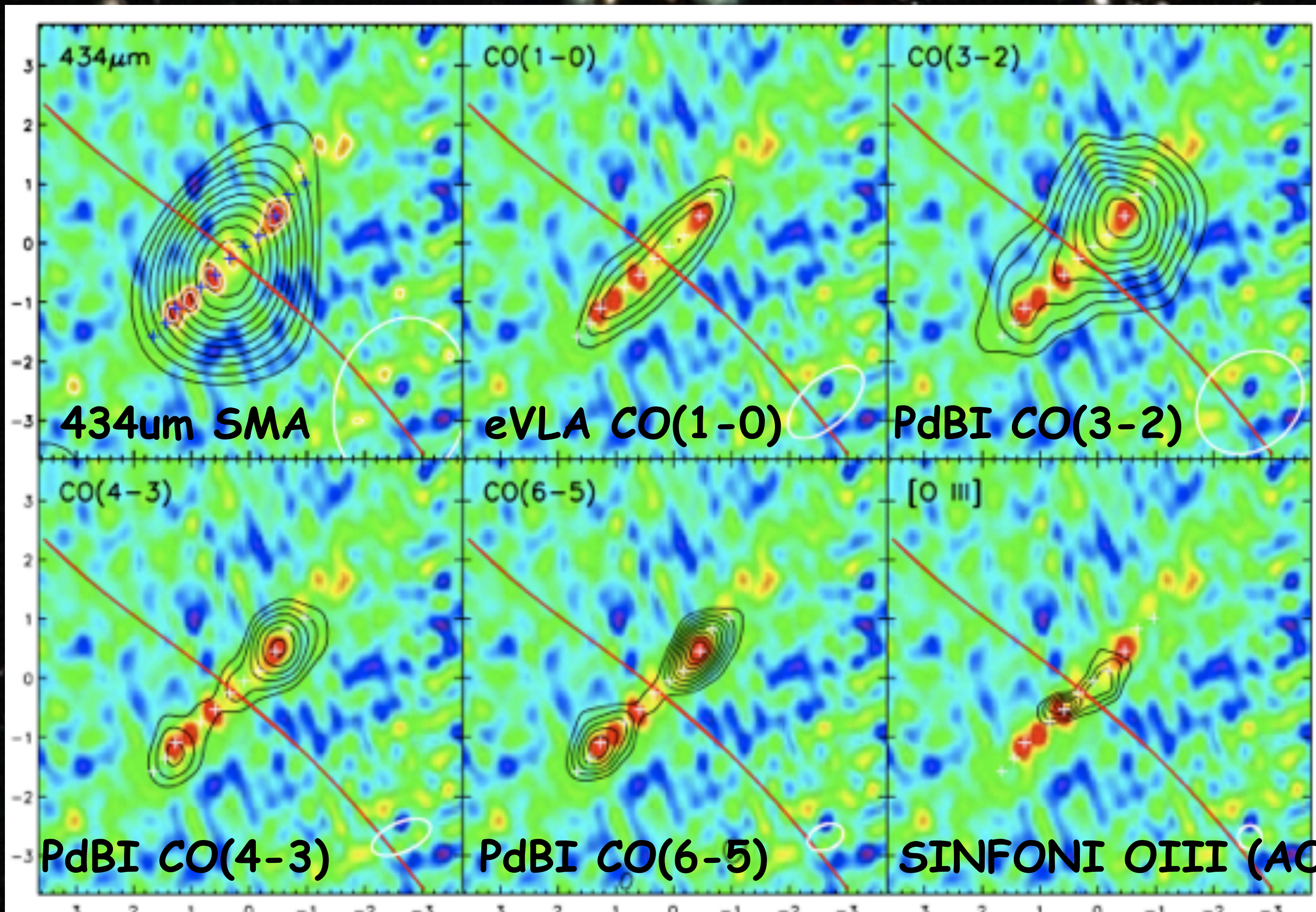
Stark et al. 2008
Jones et al. 2010
Swinbank et al. 2007,2009

z=2.3 Lensed Sub-mm Galaxy



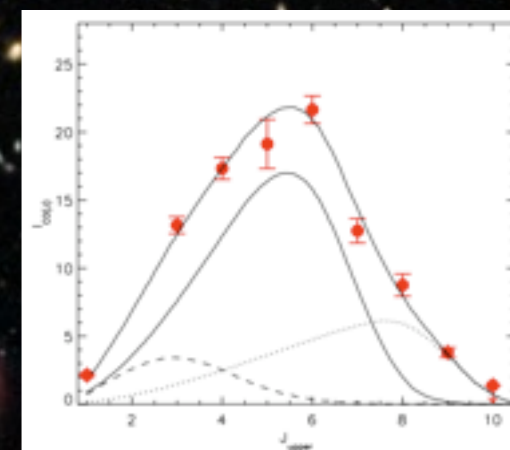
Swinbank et al. 2010 Nature 464 733

Spatially Resolved radio/(sub)-mm:

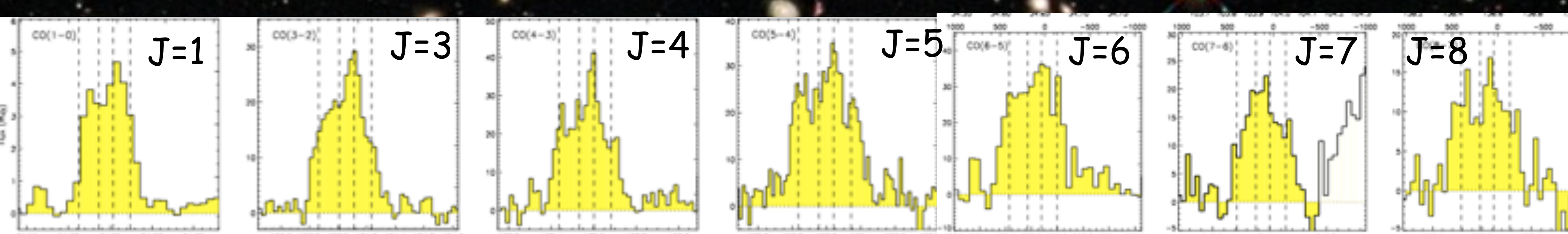


Cox et al. 2010
(in prep)

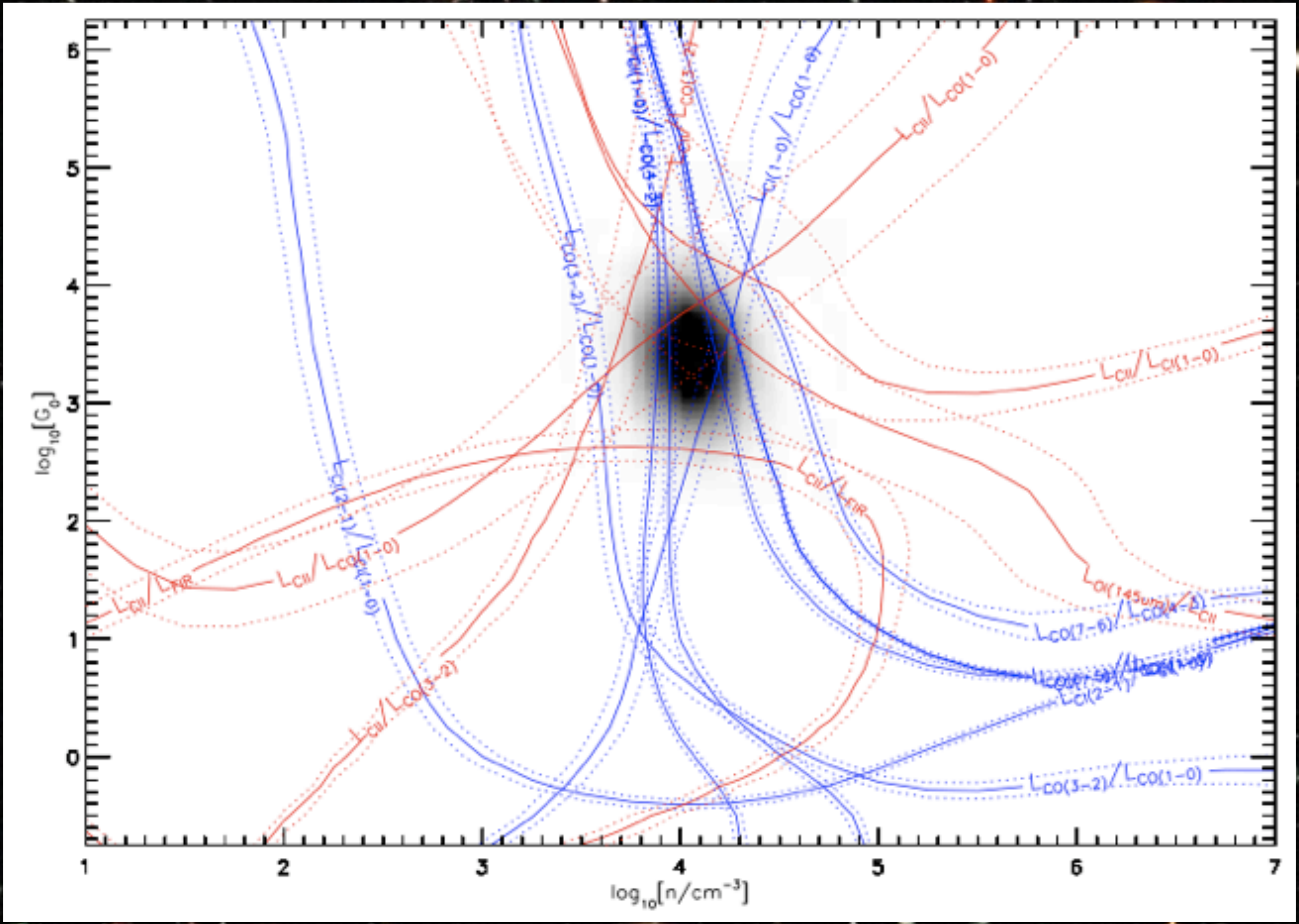
Ivison et al. 2010



Danielson et al. (2010)
submitted



Line ratios can be modelled with PDR models to derive density and strength of radiation field within ISM



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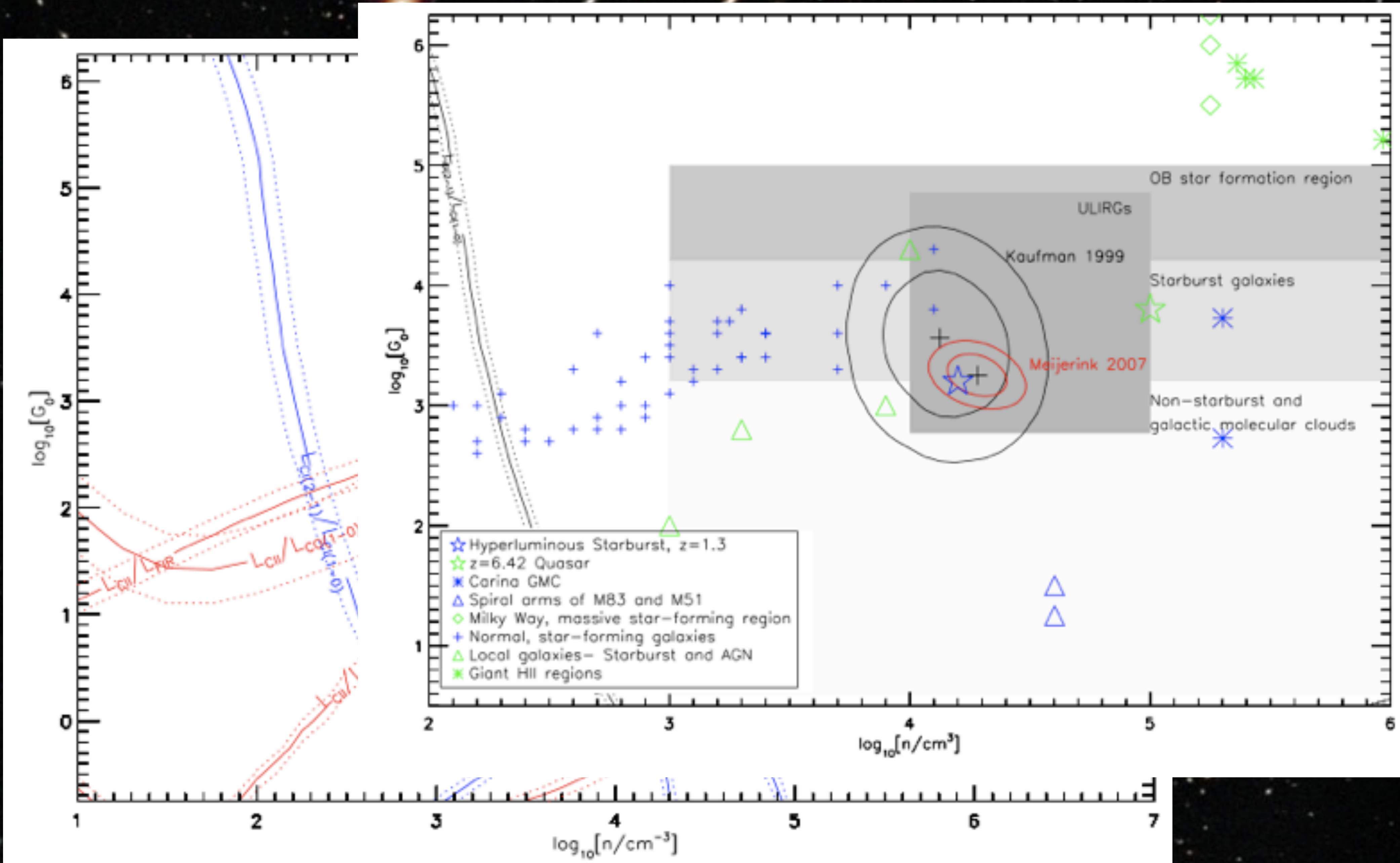
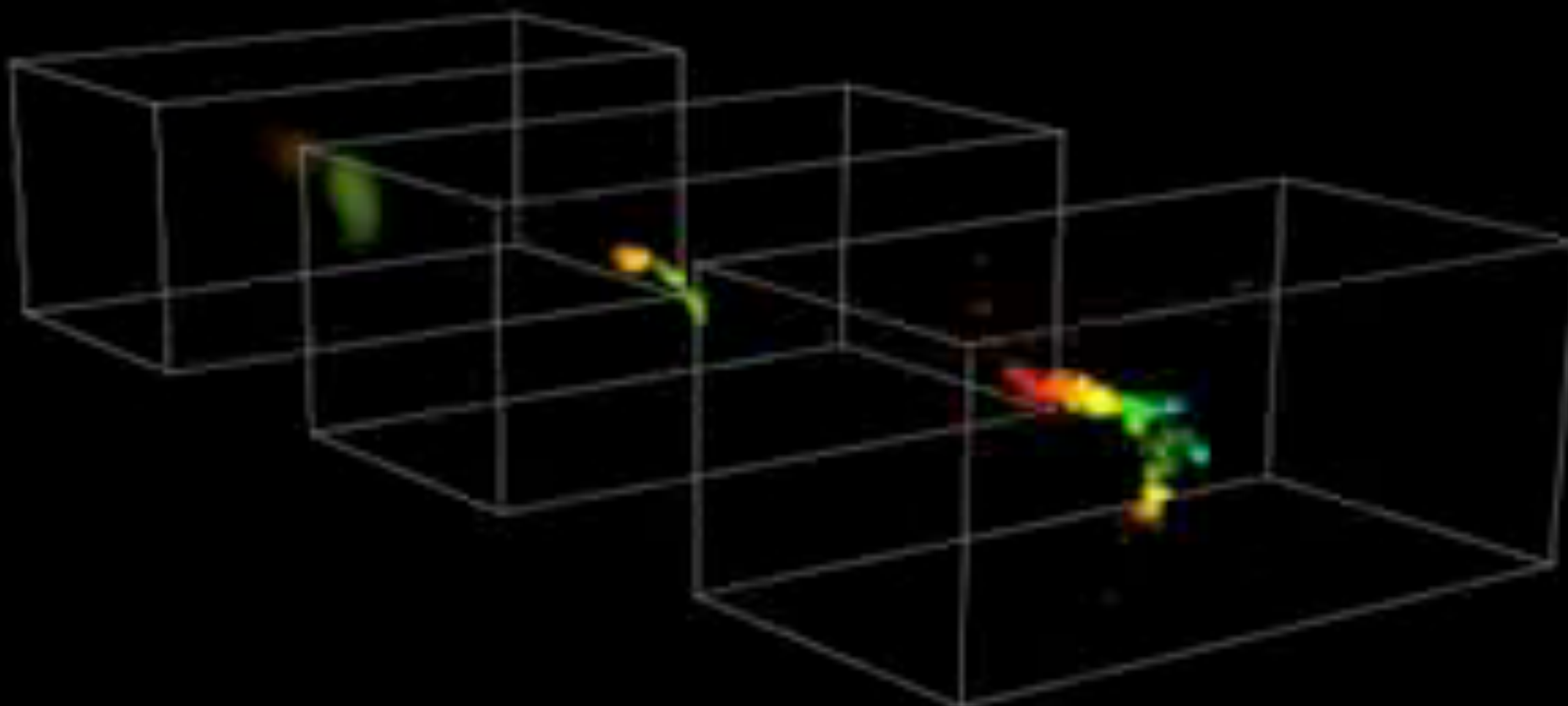
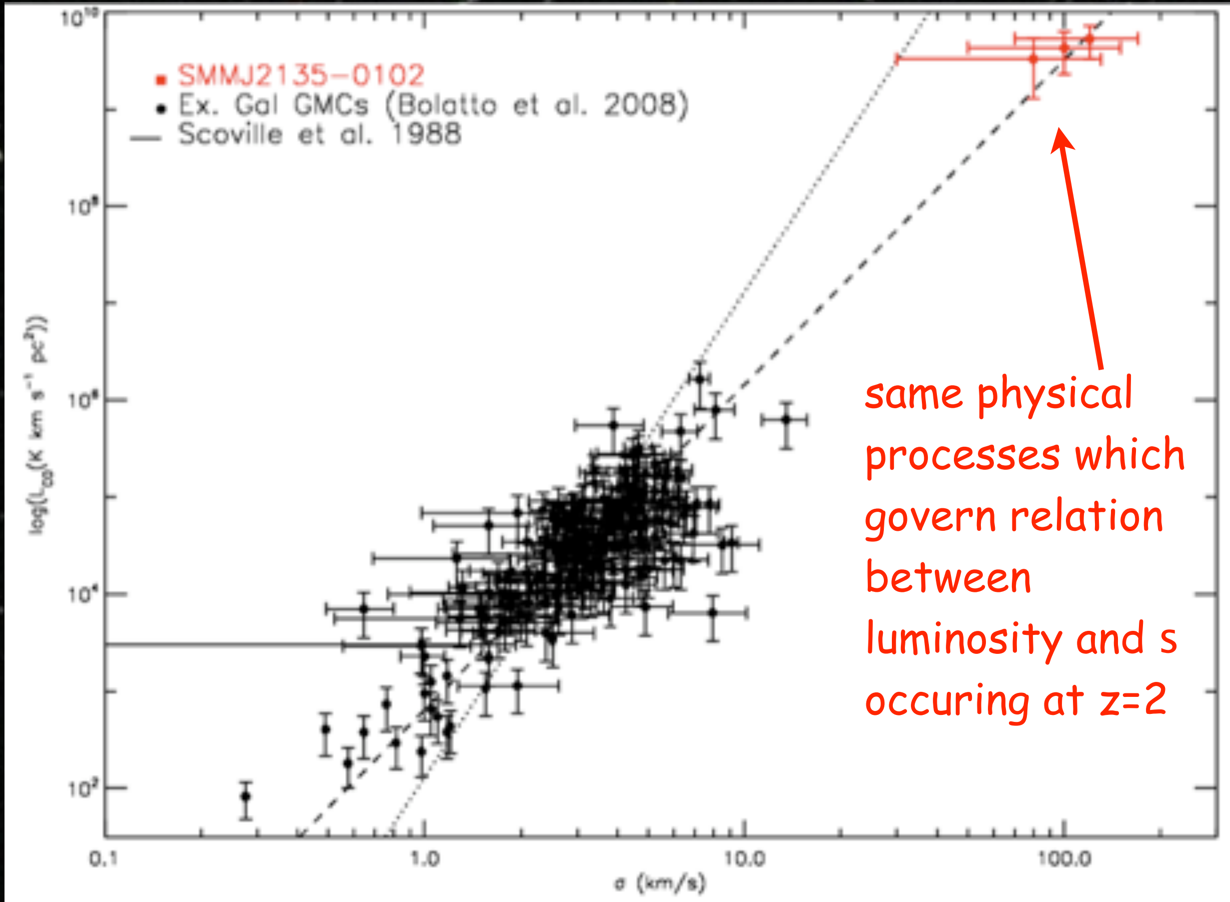
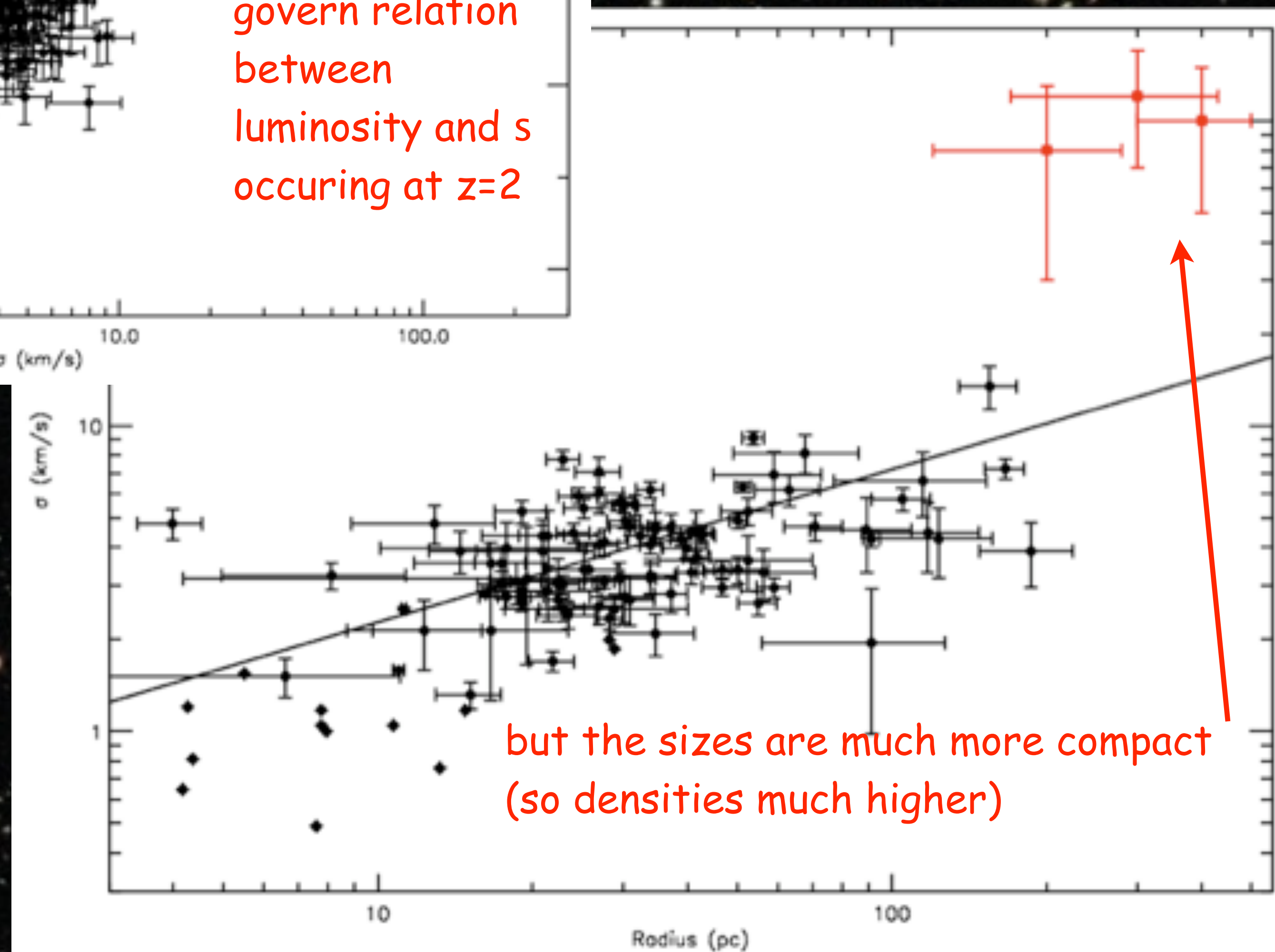




Relation between CO luminosity, size and sigma with gas components (cf those in local galaxies)



same physical processes which govern relation between luminosity and s occuring at z=2



but the sizes are much more compact (so densities much higher)

Danielson et al. (2010 submitted)
Cox et al. (2010 in prep)

What I want you to remember:

- Probing the sub-kpc scale kinematics and distribution of gas and SF within galaxies at z~2--5 is key science driver for ELT and ALMA, but can be achieved now for sources which are highly amplified. Resolution can reach <100pc -- comparable to low-z studies.

- Using Ha and sub-mm luminosities, the GMC within galaxies at z=2-5 appear to be substantially more luminous at fixed size than those in the MW (and local group), although SF regions like those in the Antennae or Arp200 show similar characteristics.

- This could be caused by large increase in star-formation efficiency, metallicity, or even variations in stellar IMF (higher fraction of OB stars per star-forming cloud).

- What is needed? More examples (HST/WF3, Panstarrs, Herschel-ATLAS and SCUBA2 should provide ~10^4 examples over entire sky). Velocity dispersions of individual clouds (hence mass measurements and/or turbulence). Measurements of chemistry.

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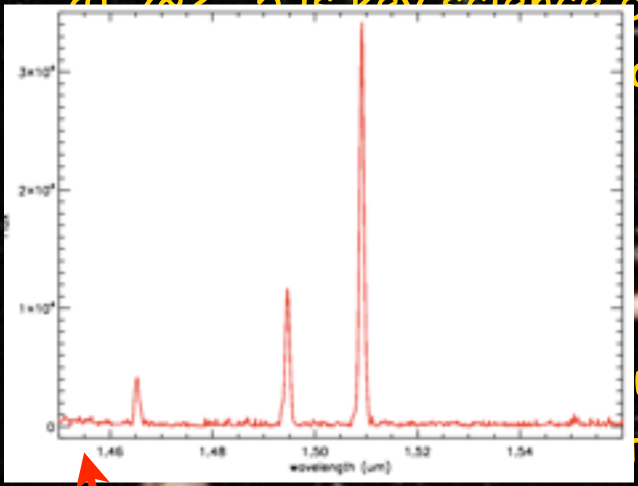

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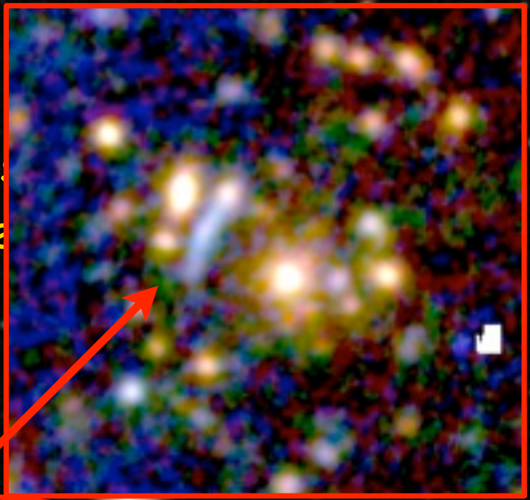

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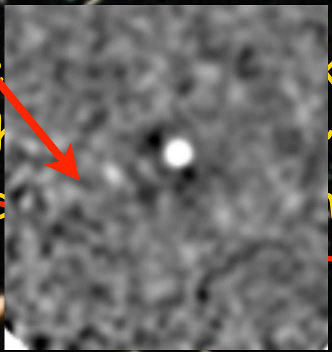
- What is ne  xamples (HST/WF3, Panstarrs, Herschel-ATLAS and SCUBA2 sh ... 10^4 examples over entire sky). Velocity dispersions of individual c ... mass measurements and/or turbulence). Measurements of chemistry.

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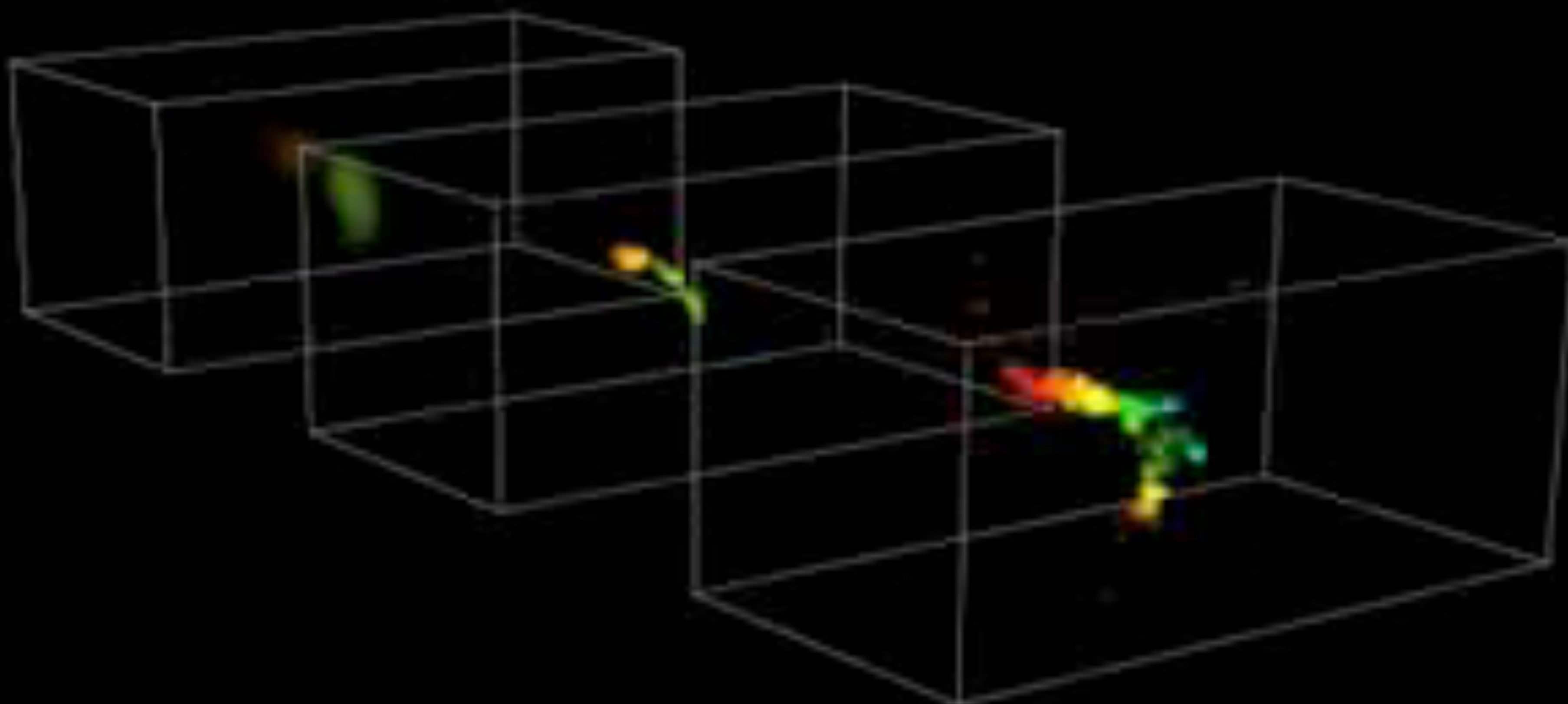
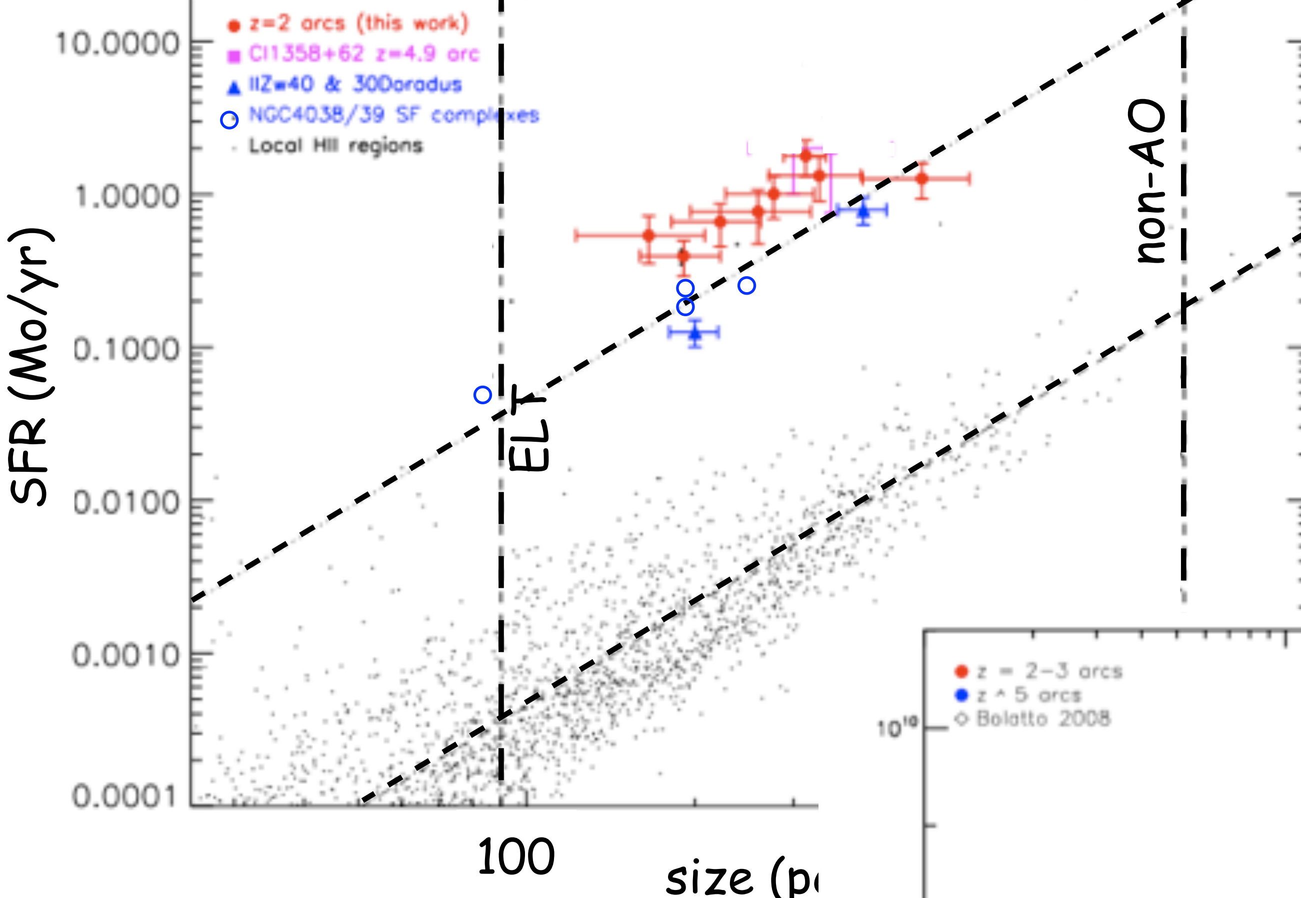
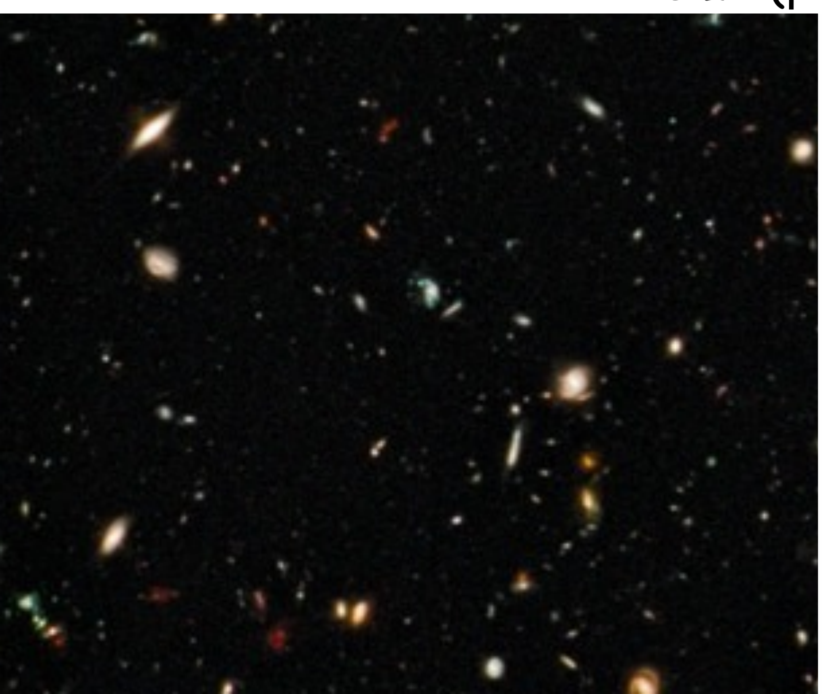
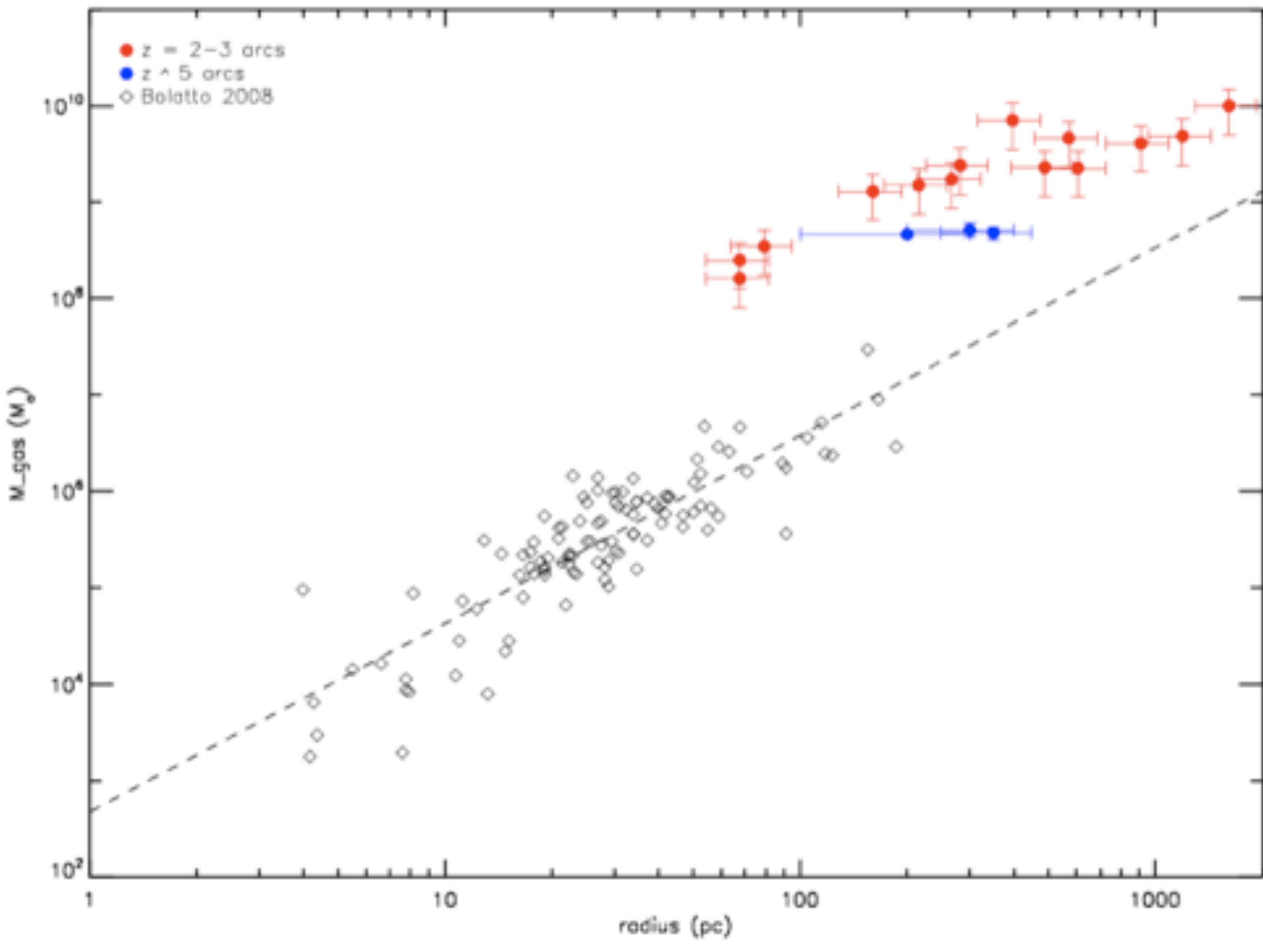
The End




z=2 arcs (this work)
Cl1358+62 z=4.9 arc
IIZw40 & 30Doradus
NGC4038/39 SF complexes
Local HII regions
SFR (Mo/yr)
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
100
size (p
ELT
non-AO




z = 2-3 arcs
Bolatto 2008
M_gas
radius (pc)
1
10
100
1000