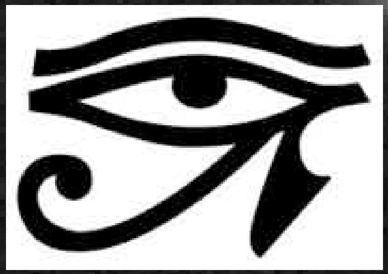
Gas and star-formation in the Cosmic Eye

Stretched & magnified lyman break galaxy at z=3

Central lens at z=0.7

HST snapshot F606W imaging of cluster at z=0.33
Two non-concentric arcs in periphery (75" from central cD elliptical at z=0.73)
Named after the Egyptian `Eye of Horus'



~ Kristen Coppin (Durham University) ~

Collaborators: Mark Swinbank, Ian Smail, James Geach, Alastair Edge, Johan Richard (Durham), Roberto Neri & Pierre Cox (IRAM), Richard Ellis (Caltech), Brian Siana & H.Teplitz (Spitzer), Simon Dye (Cardiff), Jean-Paul Kneib (Marseille)

Talk Outline

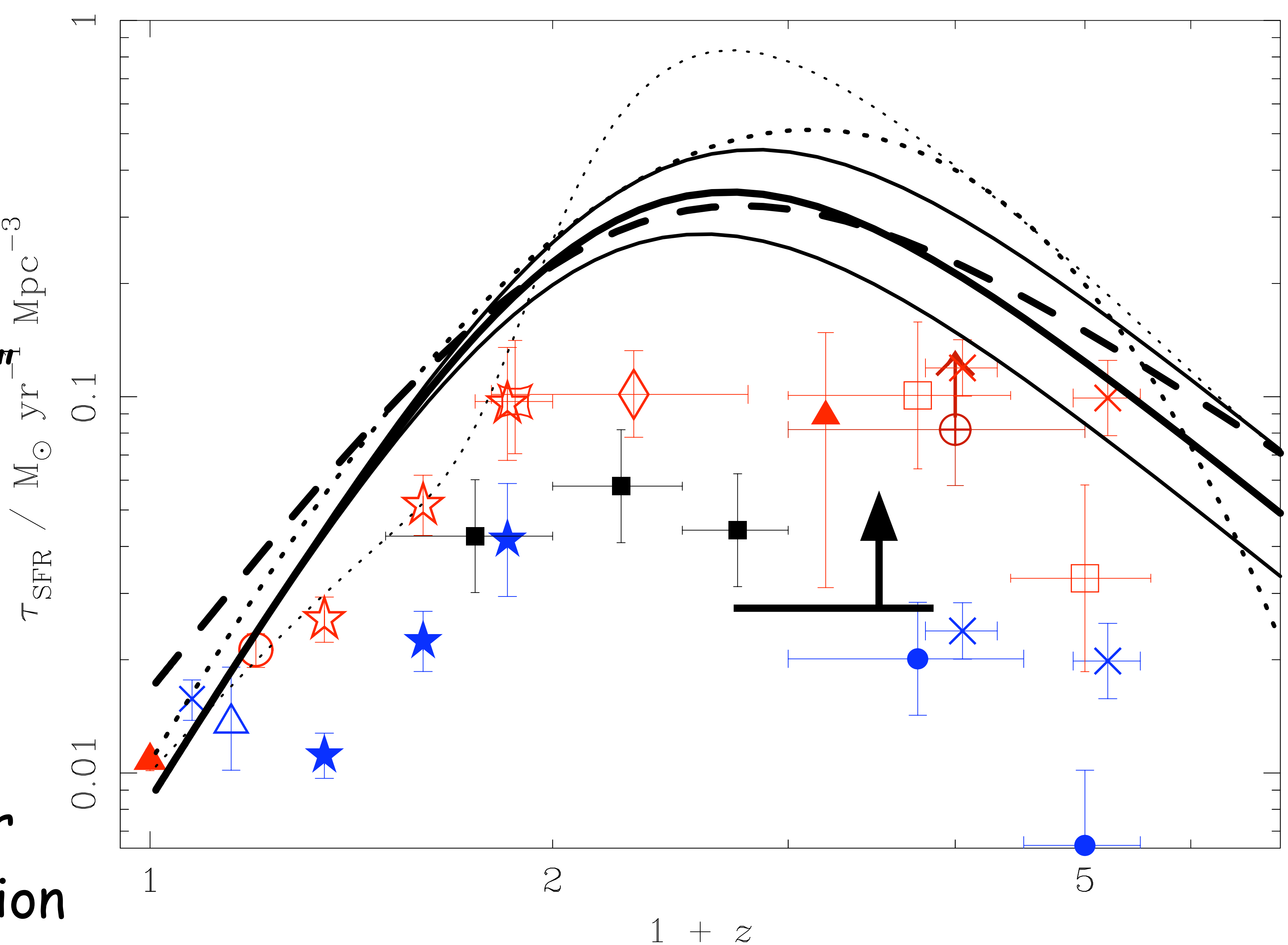
- Background:
  - What are Lyman Break Galaxies and why do we want to study their gas and Star Formation?
- A Detailed study of the "Cosmic Eye":
  - rest-frame UV spectral properties
  - lensing model
  - gas mass & dynamics using IRAM PdBI
  - SFR/stellar mass using Spitzer
- How does the Eye compare with other galaxies (local + high-z)?
- Summary

Epoch of Galaxy Formation

- Galaxy formation was much more efficient at high-z

- Most of todays "normal" galaxies were being assembled at z=1-3

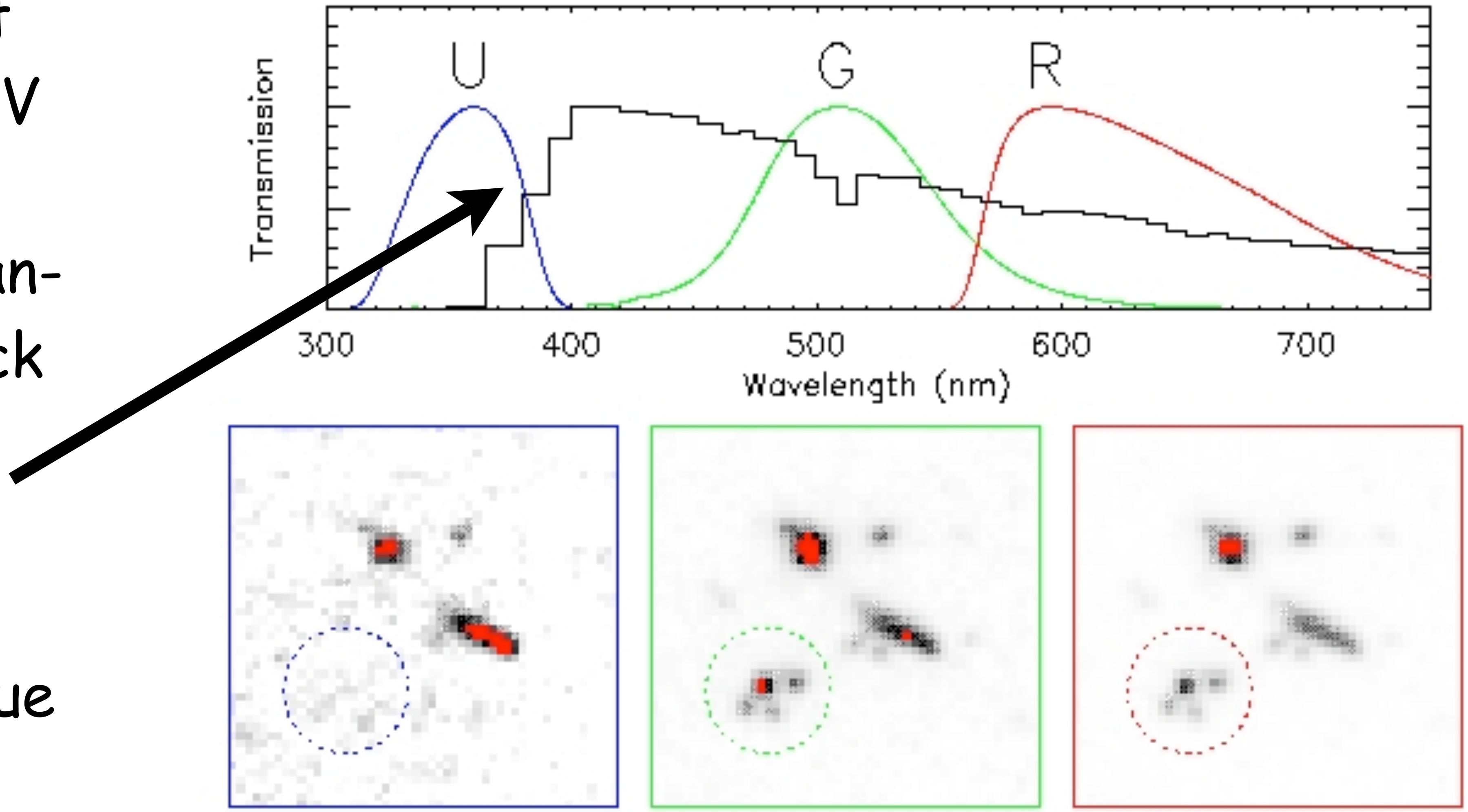
- Can we identify galaxy populations at these redshifts and probe their properties (e.g. distribution of SF, dynamics, gas & stellar masses, timescales) to constrain models?



History of energy generation rate in Universe (Blain et al. 2002)

Identifying high-z Galaxy Populations

- Significant population of "normal" galaxies at z~3 identified using UV colours near the redshifted 912A Lyman-continuum break (Chuck Steidel & co.)
-the Lyman break is about an order of magnitude deep & is due to atmospheres of massive stars present in the galaxy & due to absorption of neutral hydrogen gas in these young galaxies



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

Probing the gas content of LBGs

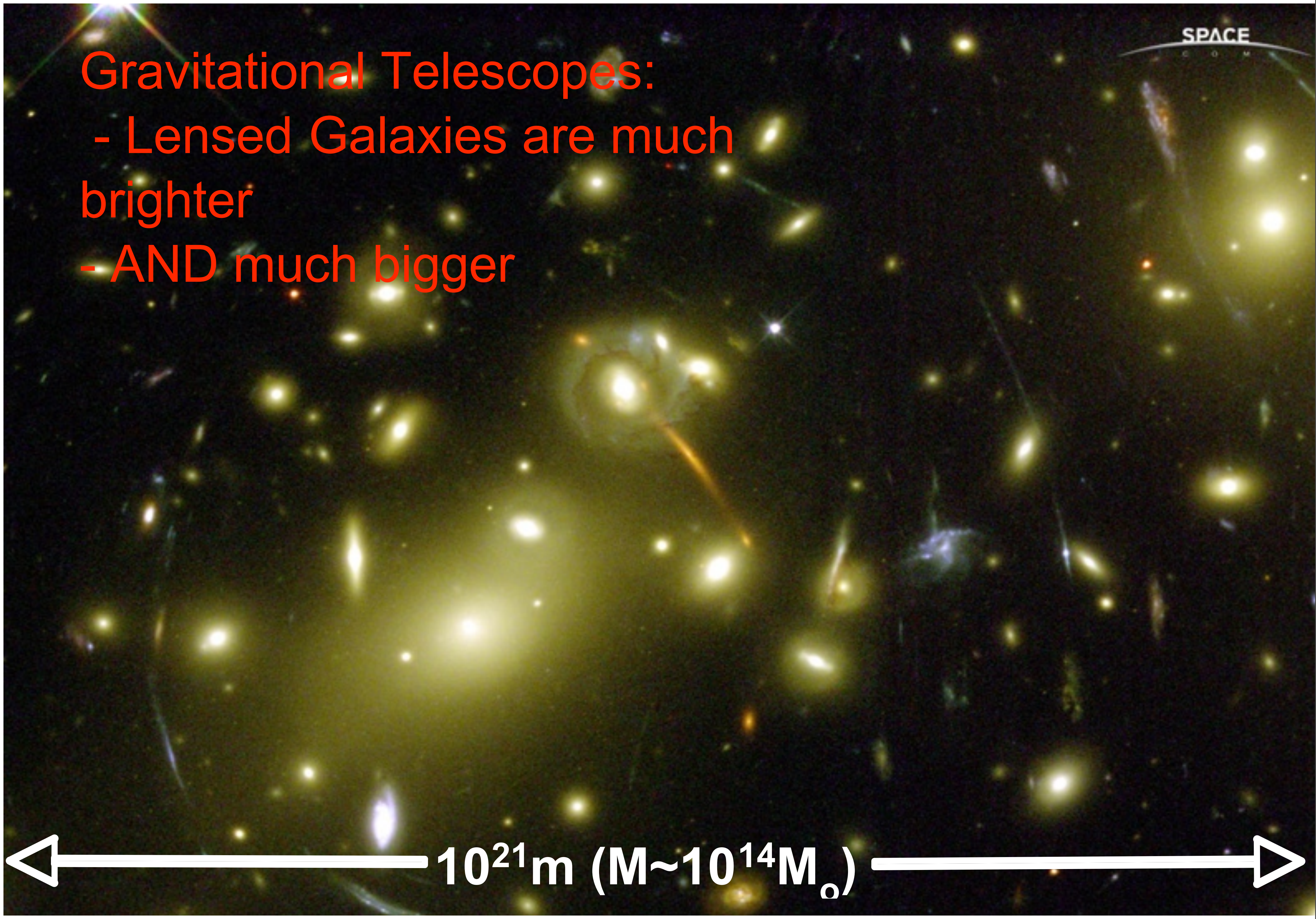
- LBGs are forming lots of stars, so they must have 'fuel' for this SF activity --> CO emission in mm is a key observable!
  - traces cold/dense gas content of high-z sources
  - gas provides the reservoir for SF activity
  - CO provides both a reliable measure of gas mass & is an unbiased tracer of its dynamics and hence the dynamical mass of the host galaxy
- but CO emission is predicted to be very faint for typical LBGs!
- DO WE GIVE UP? That's no fun!
- DO WE BUILD A BIGGER TELESCOPE? Not very feasible..

We can cheat a little...

Measuring faint CO on the cheap

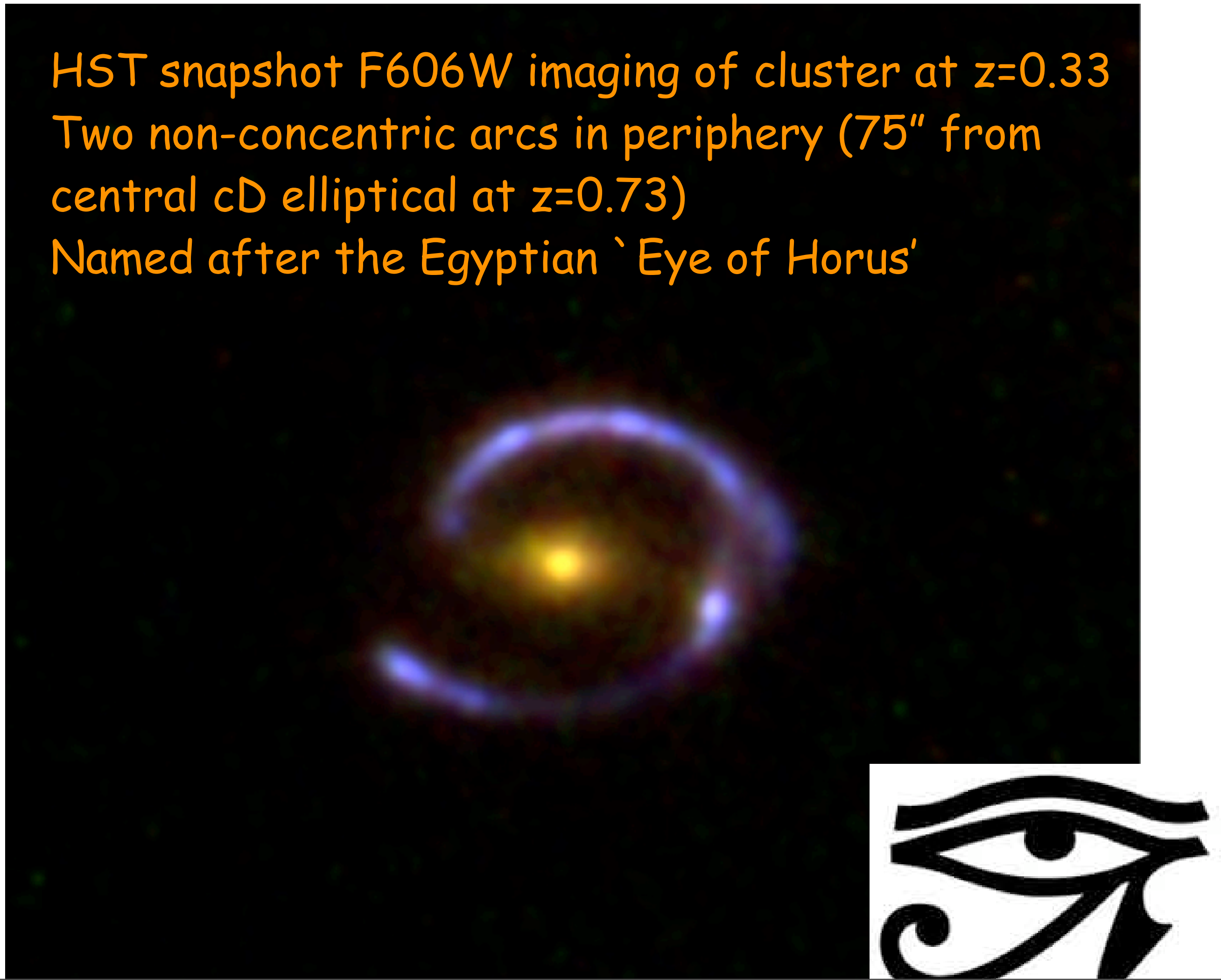
ANSWER:

Use a BIG telescope that nature has already provided!



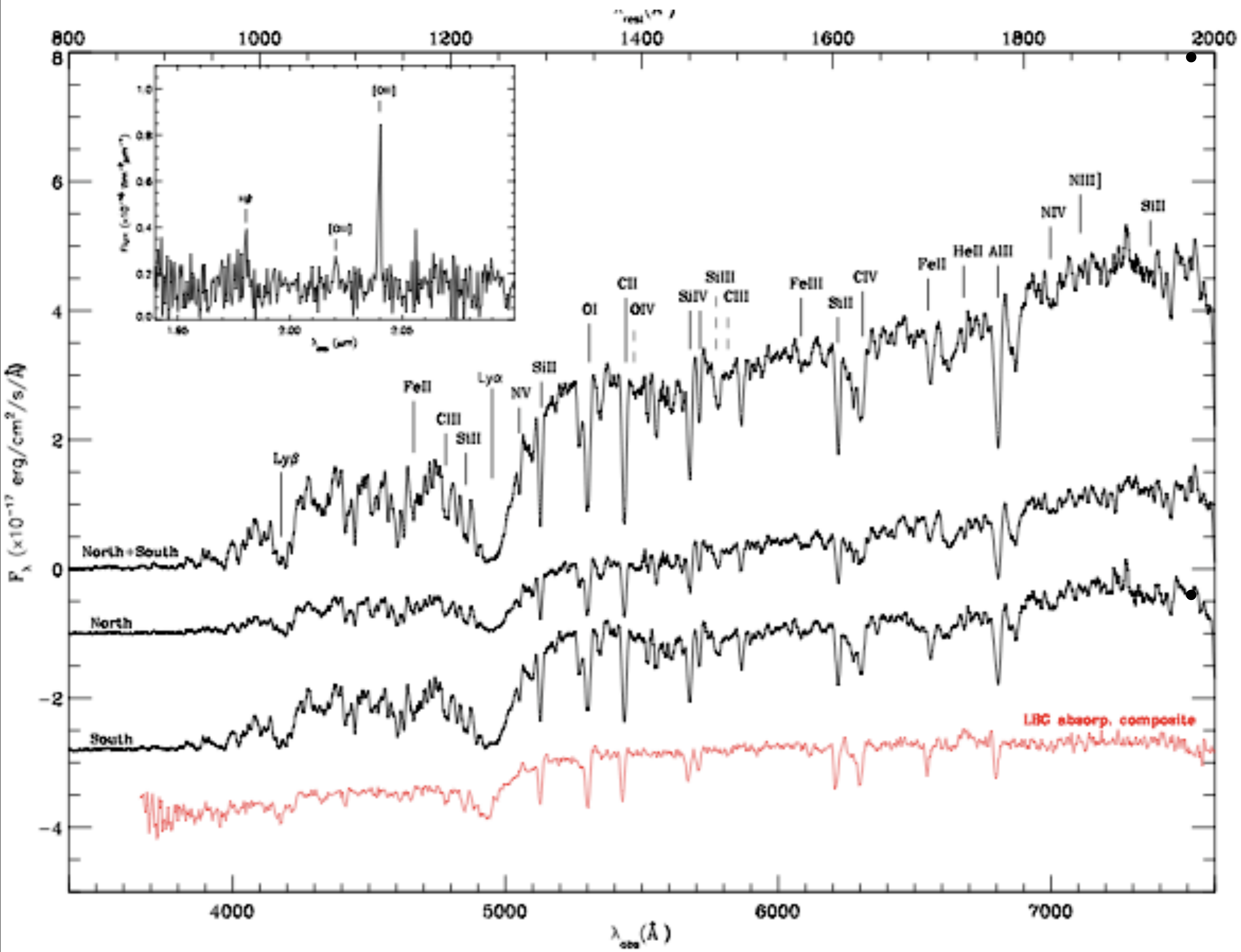
Lensed LBGs

- MS 1512-cB58:
  - boosted brightness from cluster lens (Yee et al. 96)
  - Z~1/2 solar starburst galaxy (UV spec; Pettini et al. 00,02)
  - 1st & only CO detection from an LBG (Baker et al. 2004)
- BUT dangerous to draw conclusions about LBG pop from just one object!
- we need more examples....



Smail et al. 2007

UV view of the Eye

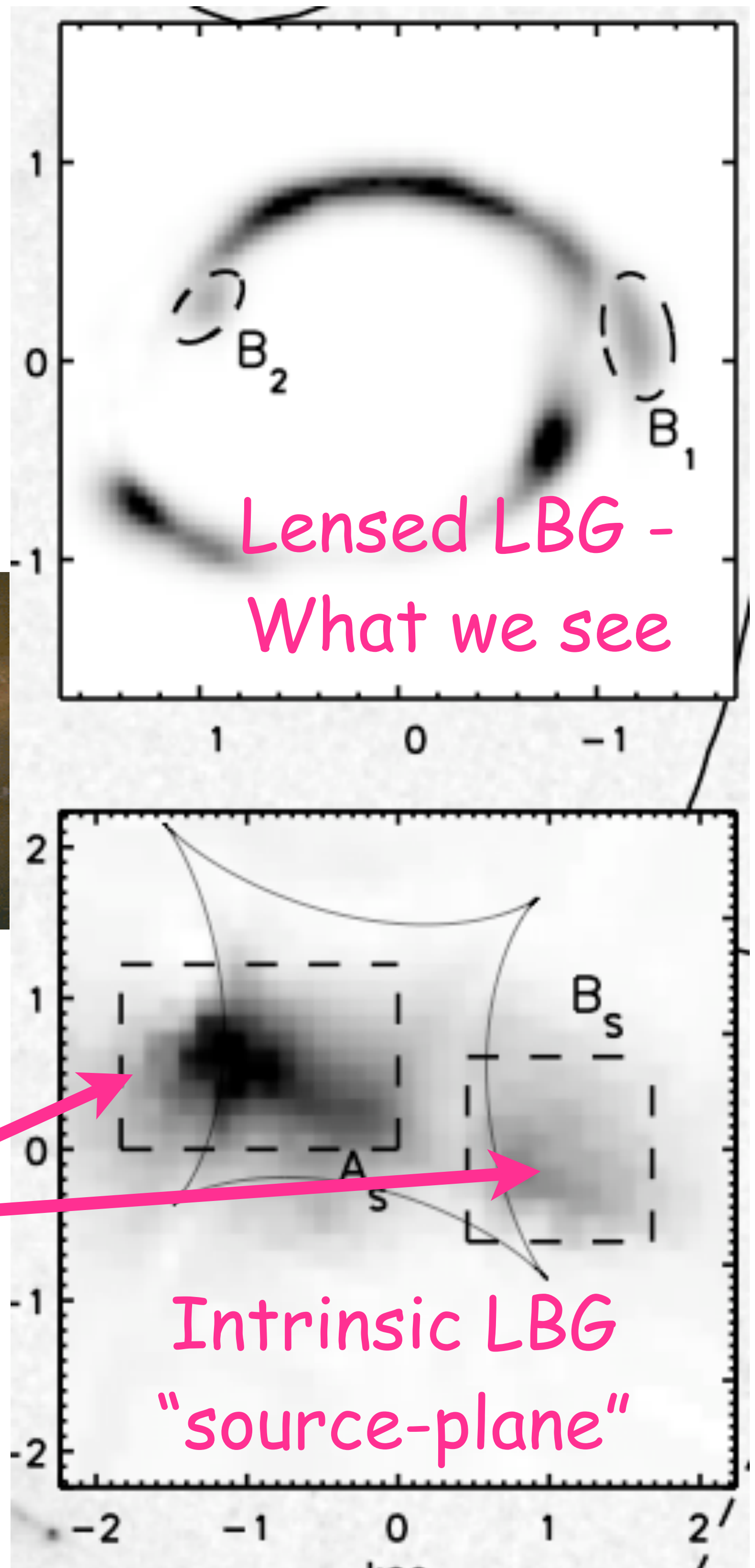


- Strength of CIV(1549) and SiIV suggest luminosity dominated by B-type giants (indicating a 10Myr burst), or an on-going activity of 10Myr with stellar IMF deficient in O-type stars.
- No significant velocity offset between N & S (expected if it's multiply imaged --> 2 components w/ in a single galaxy?)
- Hbeta SFR = 100Mo/yr

restframe Keck LRIS UV spectra: Smail et al. 2007

Lens Model for the Cosmic Eye

2 star forming knots within same galaxy?

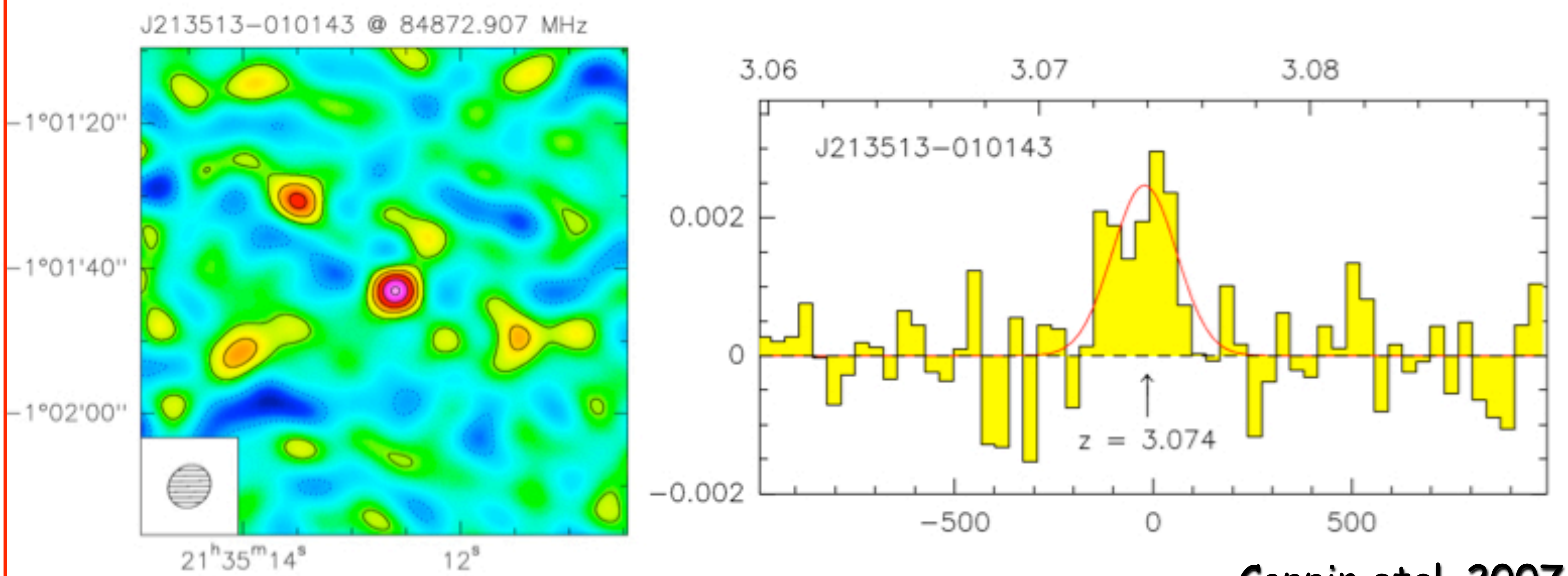


- Lens model suggests amplification factor 28x (Dye et al. 2007)
- Source-plane reconstruction suggests galaxy comprises 2 components separated by ~2kpc
- Intrinsically ~L* LBG

CO in the Cosmic Eye

- IRAM PdBI observations of redshifted CO(3-2) at 85 GHz in 580MHz Rx band in D configuration (most sensitive) in 10 hrs in 2006

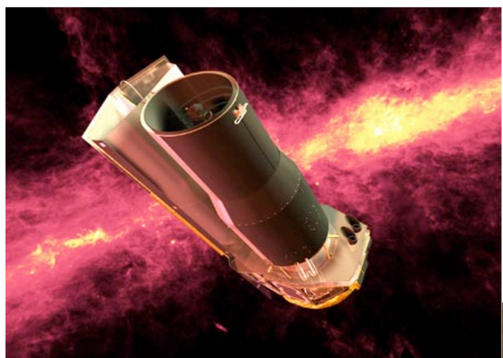
- synthesized beam FWHM 6.3"x5.5", PA=44deg
- Velocity integrated line flux=0.5+/-0.07 Jykm/s (7sigma)
- CO luminosity L'CO=3.0d9 K km/s pc^2 (unlensed) suggests gas mass ~2.4d9Msun
- Assuming gas is distributed in a 1kpc disk --> gas surface density ~760 Msun/pc^2
- CO line width (FWHM=190+/-24km/s) suggests dynamical mass=1d10Msun

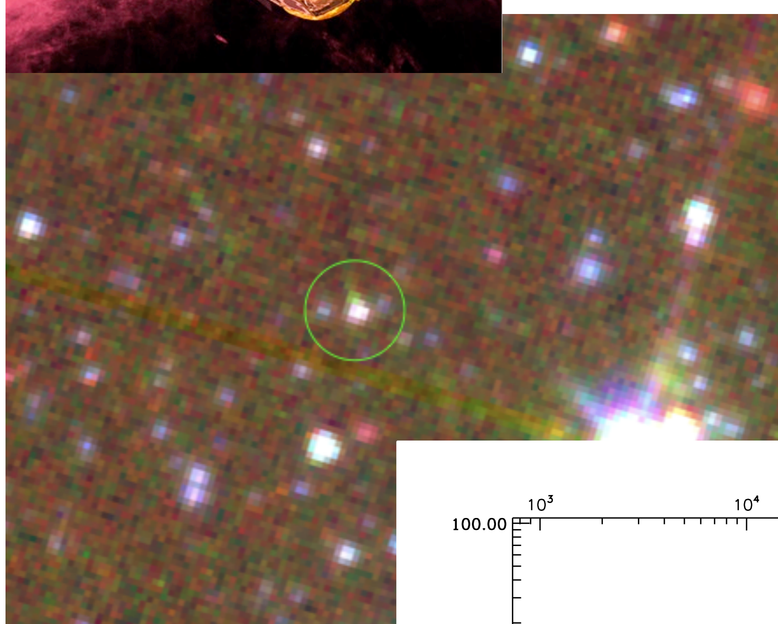


Coppin etal. 2007

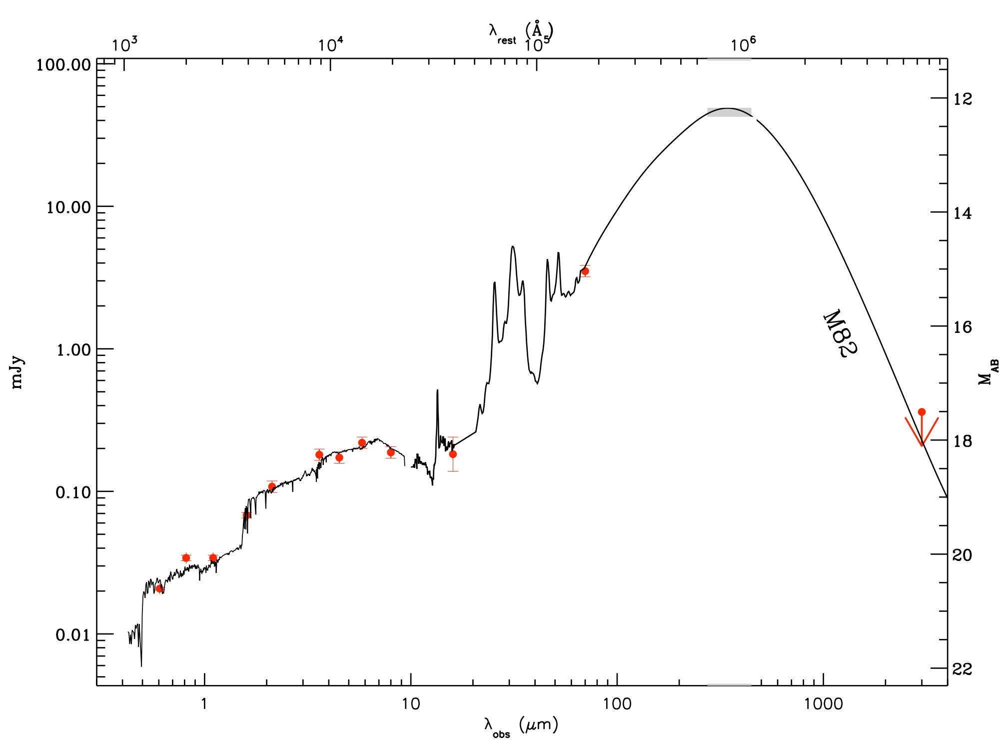
Stellar Mass

- Next step is to compare cold gas mass to dynamical and stellar mass in this LBG





Spitzer IRAC/MIPS (3.6, 4.5, 5.8, 8.0 & 24um) observations to derive stellar mass and SFR



- restframe unlensed: M_K=-22.2+/-0.2 (from SED)
- Using light-to-mass ratio of ~2.5 --> Mstellar ~ $6\times10^9 M_\odot$

--> CO + stellar mass comparison tells us that 75% of the baryons are in the form of stars --> CO dynamical mass consistent with total baryonic mass ~ 1d10Msun

- SFR(24um)=60-100$M_\odot$/yr
- SF efficiency --> Lfir/M(H2)= 140 Lsun/Msun
- gas-to-dust ratio~100

Summary of properties

- Correcting for lensing:
- Lco=3.0d9 K km/s pc^2; Gas mass=2.4d9 Msun
- Gas surface density=(760+/-130) Msun/pc^2 with r=1kpc
- Dynamical mass~8.4d9 csc(i)^2 Msun; Stellar Mass ~ 6d9Msun
- UV SFR ~ 100 Msun/yr; FIR SFR~60 Msun/yr
- SFE (Lfir/MH2)=140 Lsun/Msun (w/in factor of 3)
- Gas/dust ~ 100 (w/in factor of 6)
- When will all the gas be consumed? Reservoir depletion timescale = Gas mass/SFR = 40Myr
- How long did it take to build up the current stellar mass?
  SF timescale = Stellar mass/SFR = 100Myr
- The cosmic eye is a relatively massive galaxy hosting an equally massive gas reservoir & has significant on-going SF, with most of the baryons in the form of stars. It appears we are seeing the LBG in last 1/2-1/3 of its life.

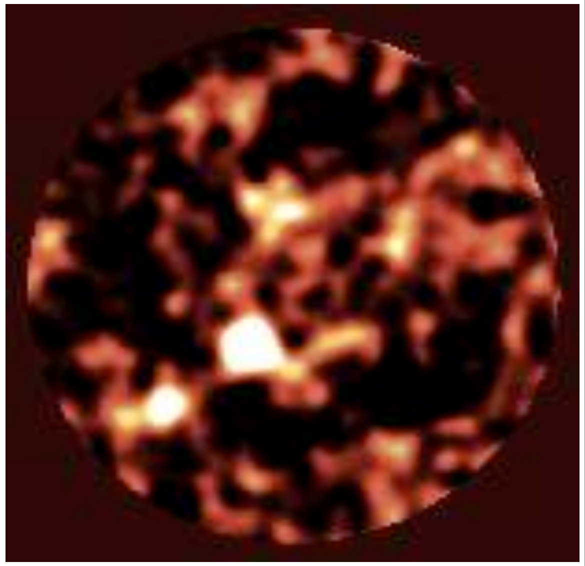
Comparison with other LBGs

- cB58:
  - ~7x less cold gas than the Eye
  - SFR~24 Msun/yr (Baker etal. 2004) (3x less than Eye)
  - gas depletion time ~15 Myr (compared with the Eye's <40Myr)
  - similarly massive L* LBGs, but Eye appears younger, more gas rich & forming more stars than cB58
  - differences reflect brevity of SF event / variation w/in population

Comparison with other galaxy populations

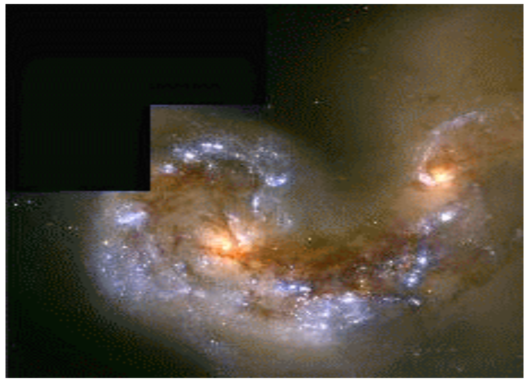
High-z Universe: Submm Galaxies (Greve etal 05,Tacconi etal 06) --> most extreme SF galaxies known (z~2-3)

- SMGs are only other pop with LARGE numbers of sources having reliable cold gas masses
- L'CO & M(H2) is 20x more than LBGs (but probably due to selection effects b/c our LBG is lensed)!
- gas surface densities 4x higher than LBGs; SFE~4x more than LBGs
- line 3x wider than LBGs & from regions 2x larger!
- Comparison suggests that LBGs + SMGs are equally evolved (have similar fractions of baryons in form of gas/stars)...but that the cold gas reservoirs in LBGs resides in less massive systems than SMGs, with lower surface densities & forming stars 4x less efficiently, suggesting less vigorous activity.



HDF-N: 1st deep submm map 50 hrs, 100" radius, a few strong sources

Comparison with other galaxy populations

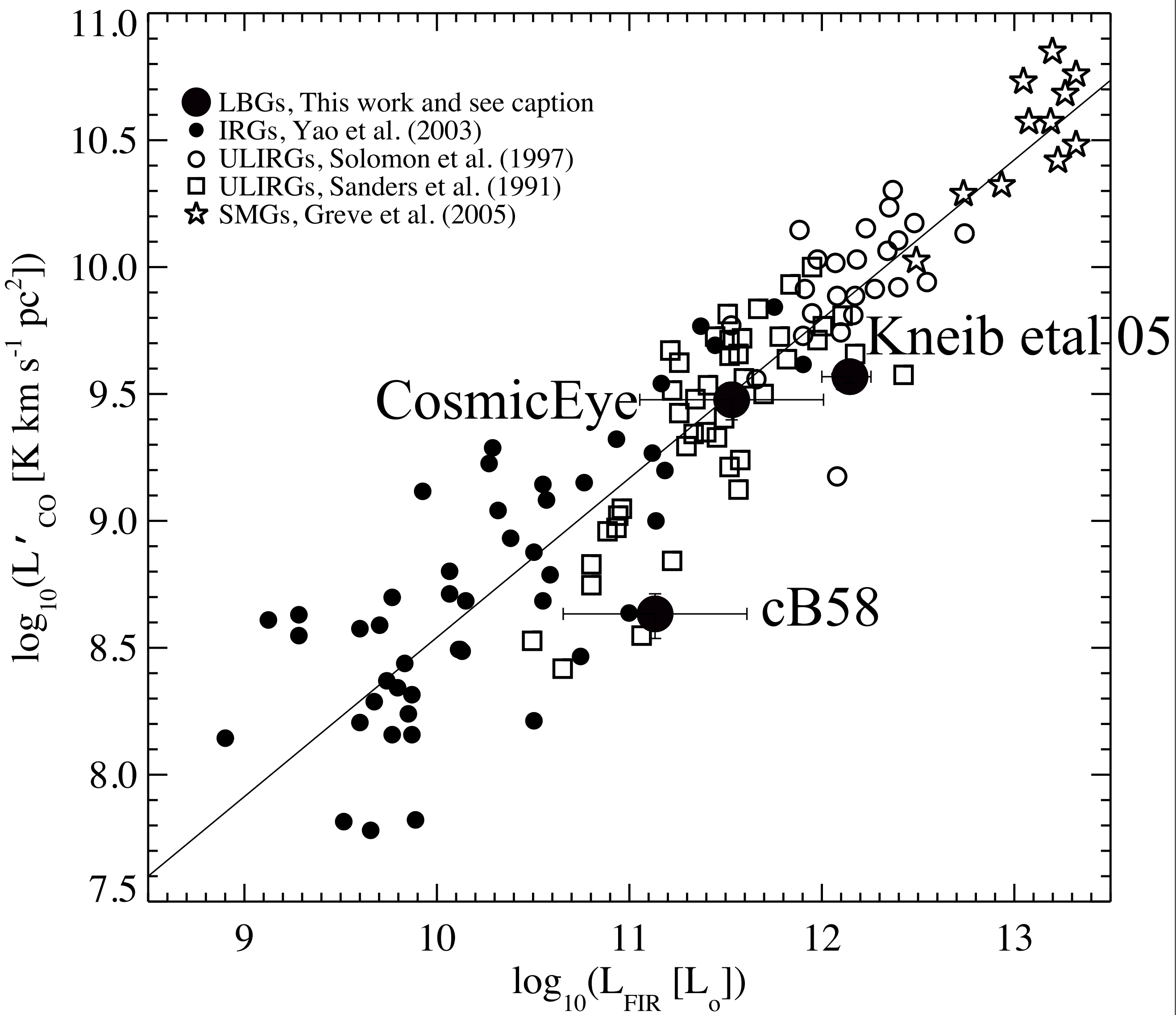


Compare with Local Universe populations: ULIRGs/LIRGs

- -Eye's far-IR Lum similar to LIRGs'
- -LIRG linewidths ~200km/s
- -SFE LIRGs 1-50 Lsun/Msun

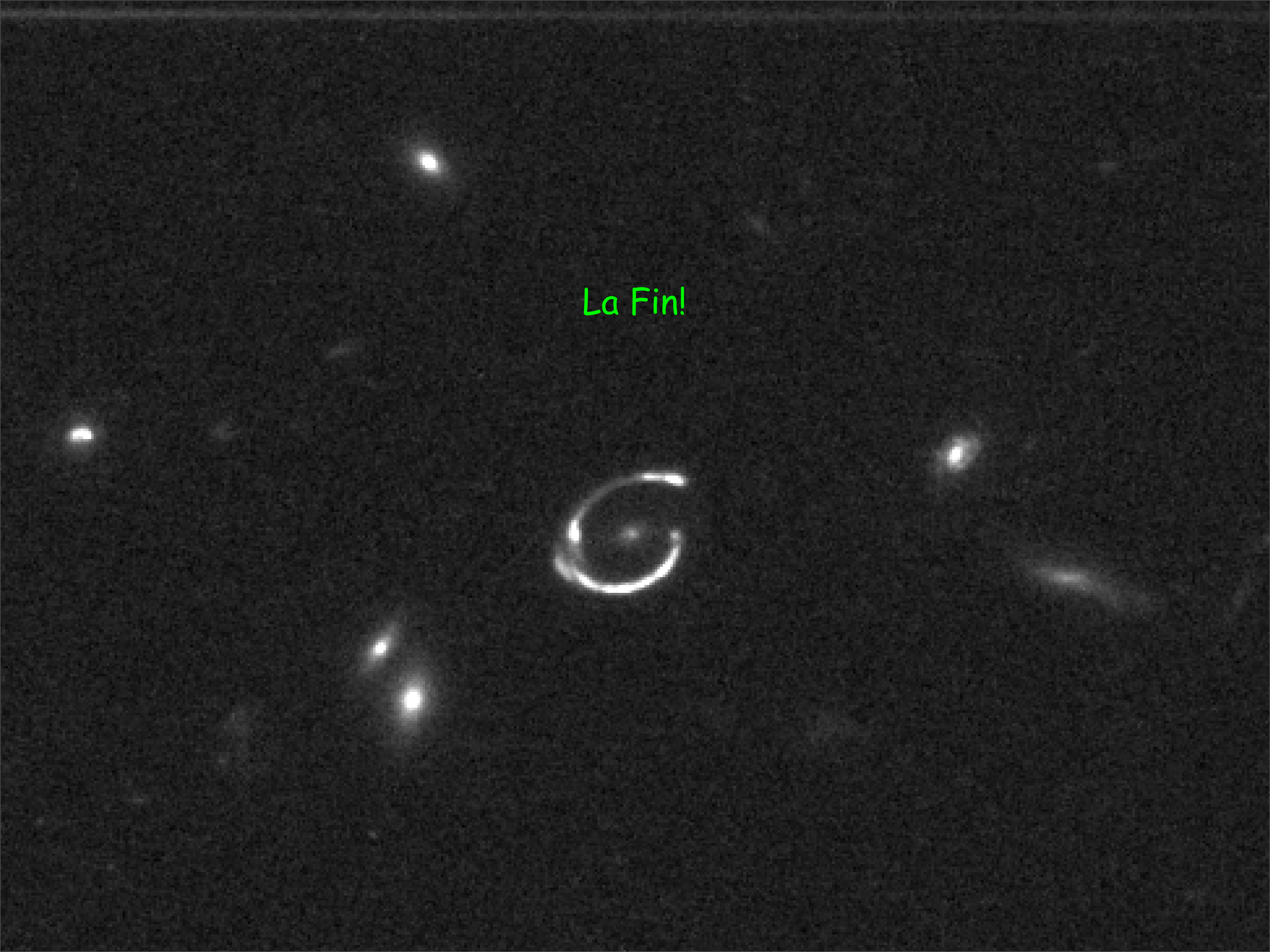
-Are LBGs gas-rich/higher SFE high-z analogues of LIRGs?

-Eye may be occurring in an intense central starburst, similar to activity in LIRGs/ULIRGs



Conclusions

- Detect CO(3-2) in a lensed z~3 LBG with line width of 190+/-24 km/s, inferring gas mass of ~2d9 Msun and Mdyn~8d9 (csc(i))^2 Msun within R<1kpc
- gRK+IRAC photometry --> stellar mass of ~6d9 Msun
- MIPS 24um --> far-IR Luminosity of ~ 3d11 Lsun, SFR~60 Msun/yr, SFE~100 Lsun/Msun, gas/dust~100, Tform~100Myr, Tdepl~40Myr
- gas mass is 7x higher than for cB58, but similar line widths
- Eye at z=3 has many features similar to local LIRGs - SF activity related to SF mode in LIRGs?
- Next step: Observe the system at higher resolution with IRAM PdBI (FWHM~0.6") in order to dissect the gas & yield insights into kinematics of ISM in a normal young galaxy seen 12 billion years ago! (a preview of the capabilities of ALMA!)


La Fin!