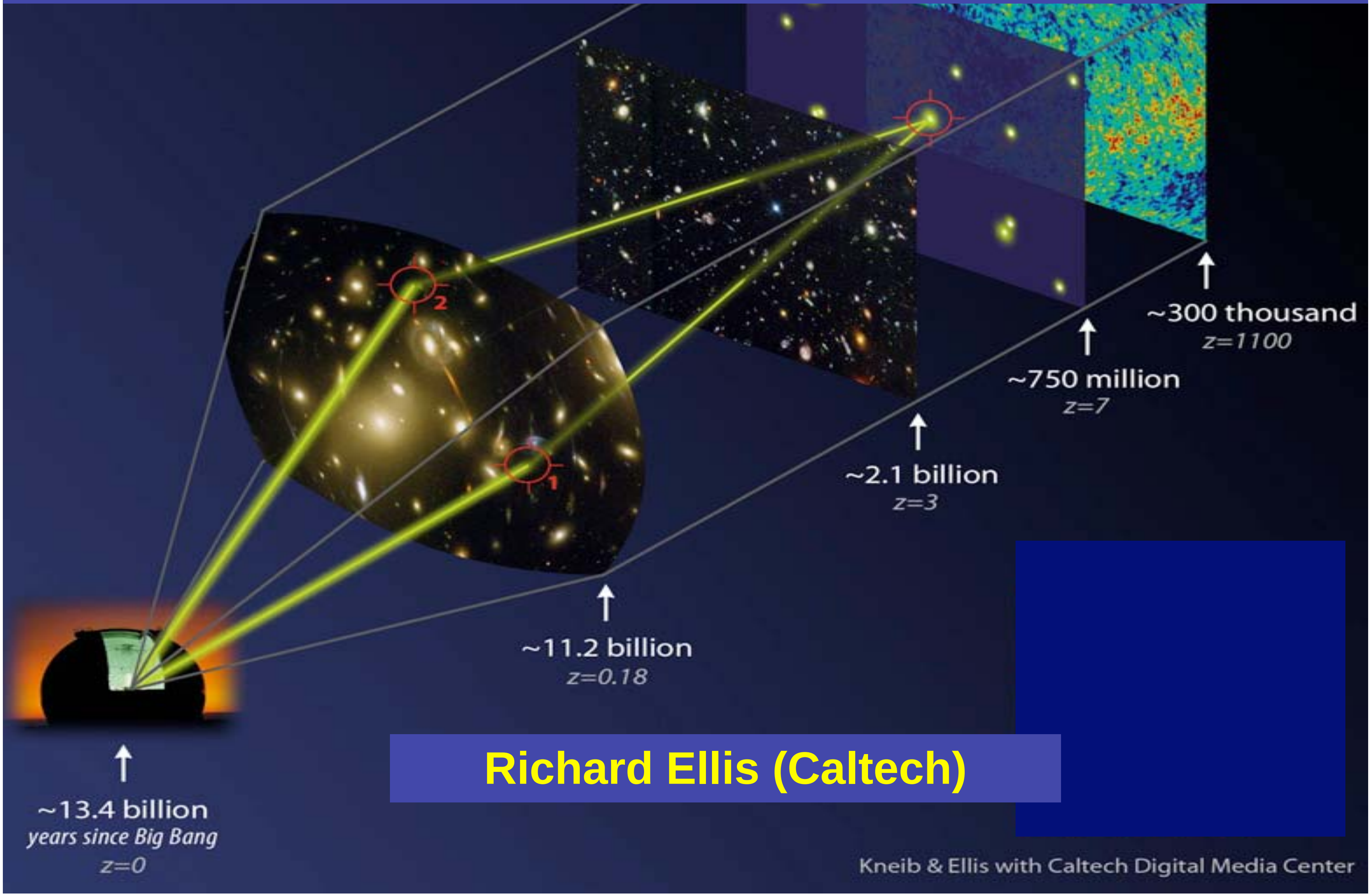
Probing Early Galaxy Formation with Gravitational Lensing



Richard Ellis (Caltech)

Opening Up the High z Universe

Astron. Astrophys. 200, L17–L20 (1988)

Letter to the Editor

ASTRONOMY AND ASTROPHYSICS

Faint distorted structures in the core of A 370: Are they gravitationally lensed galaxies at $z \simeq 1$?*

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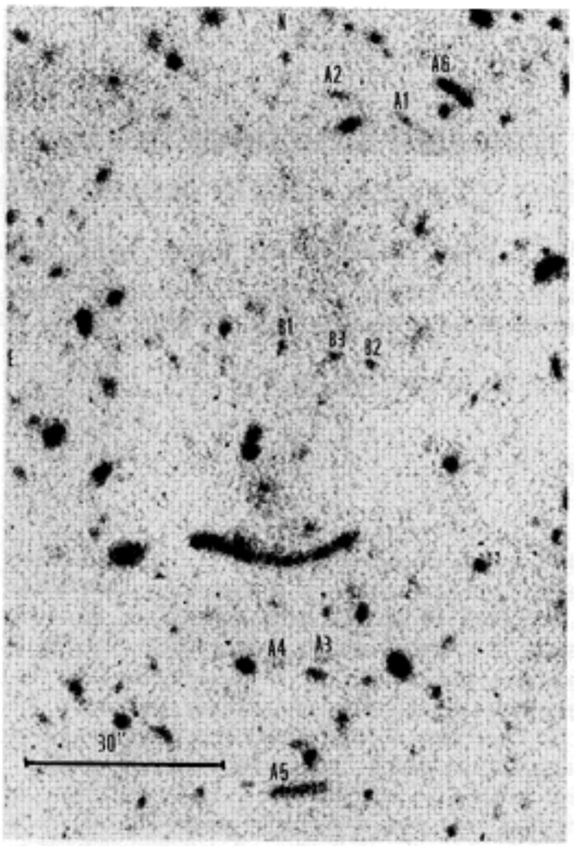
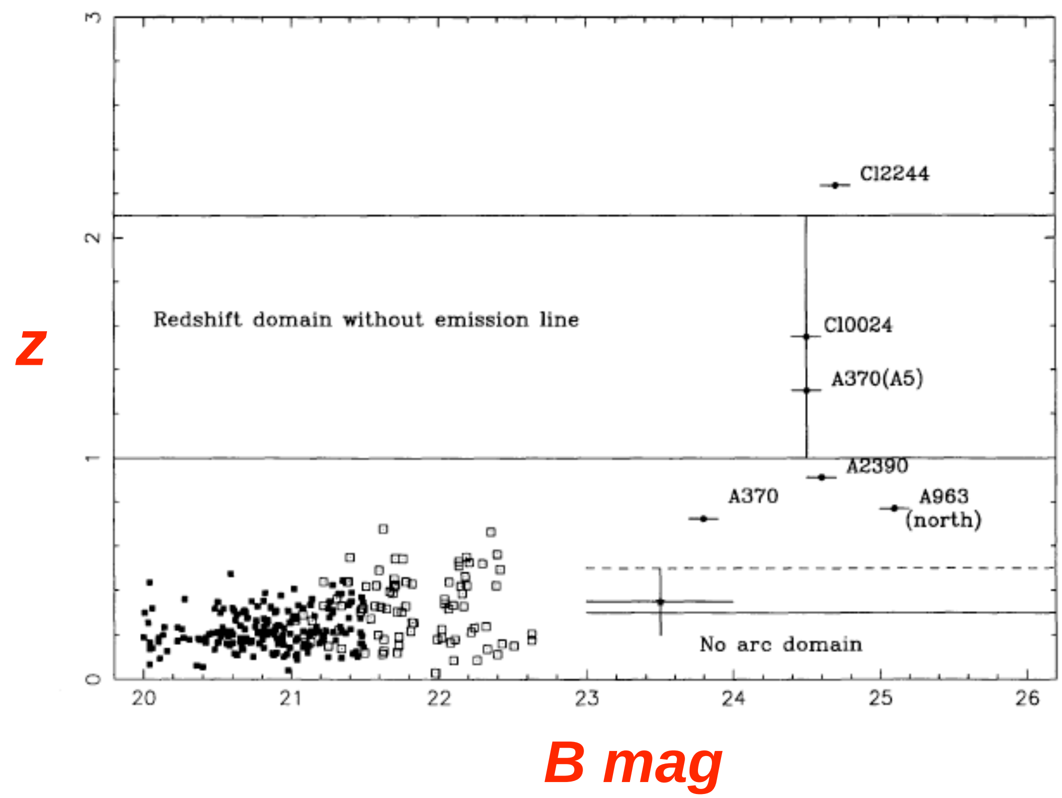


MELLIER ET AL. (1991)



Toulouse: September 1989

Applications of Lensing to Early Galaxy Formation

Motivation:

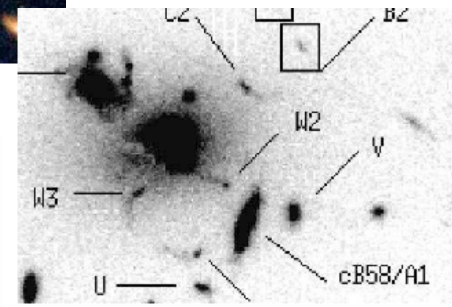
- Complete inventory of star formation and mass assembly history from z~10 to present epoch
- Contribution of early SF sources to cosmic reionization
- Detailed astrophysical properties of selected high z sources (winds, feedback, dynamics etc)

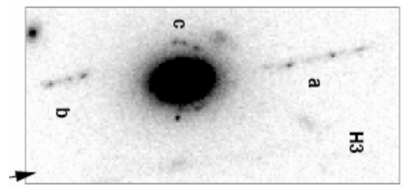
Two approaches:

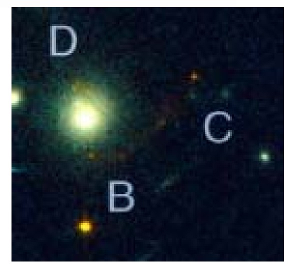
- Detailed study of individual lensed z>2 galaxies (any λ)
  - magnification: integrated properties (cB58-like)
  - angular enlargement: resolved spectra/dynamics (AO)
- Surveys conducted through clusters
  - SCUBA imaging to extend sub-mm counts
  - Ground and space-based optical-IR imaging
  - Critical line spectroscopic mapping

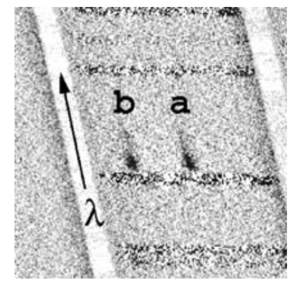
High Redshift Arcs: Record Breakers (1991-2005)

- Cl2244-02 (z=2.237); Mellier et al 1991
- A2218 #384 (z=2.515); Ebbels et al 1996
- MS1512 cB58 (z=2.72); *Yee et al 1996*,
  Seitz et al 1998
- A2390 (z=4.05); Frye et al 1998,
  Pellò et al 1999

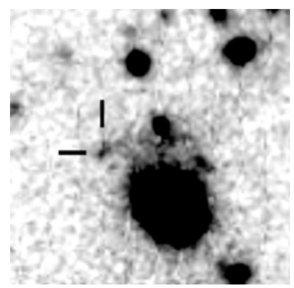


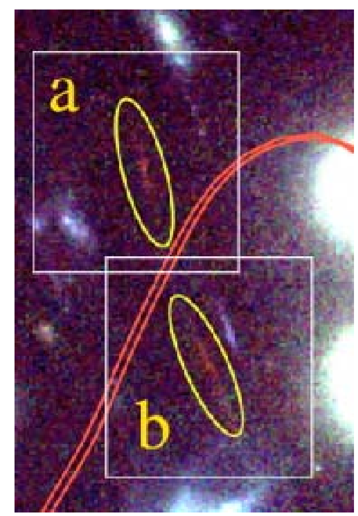






- MS1358+62 (z=4.92); Franx et al 1997
- A2218 (z=5.7); Ellis et al 2001
- A370 (z=6.56); Hu et al 2002
- A2218 (z~7); Kneib et al 2005





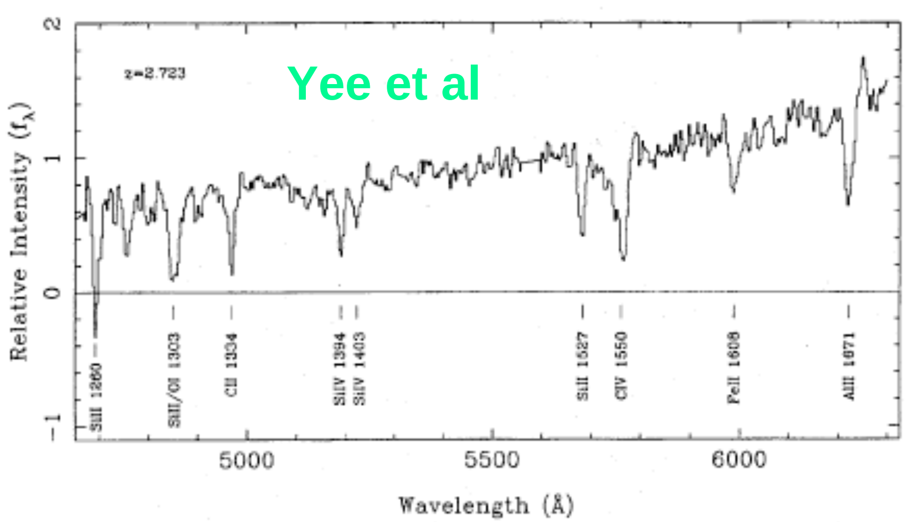
Spectroscopic verification has always been the challenge!

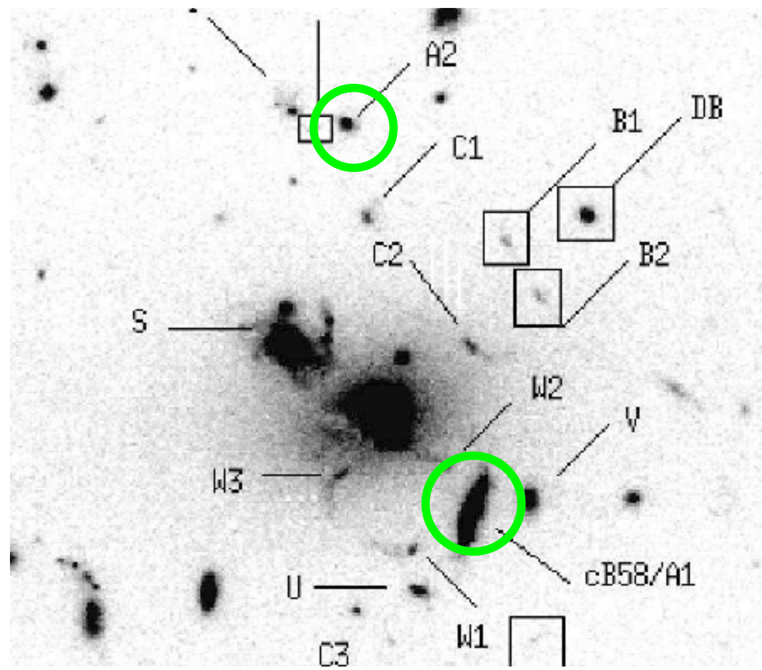
Applications - I: Integrated Properties of High z Sources

The most strongly magnified sources enable detailed studies of (presumed typical) distant galaxies (e.g. cB58)

Seitz et al (1998): HST demonstration of strong-lensing (mag ~ ×20-40)

Pettini et al (2002): exploitation via Keck Echelle Spectroscopic Imager (ESI)

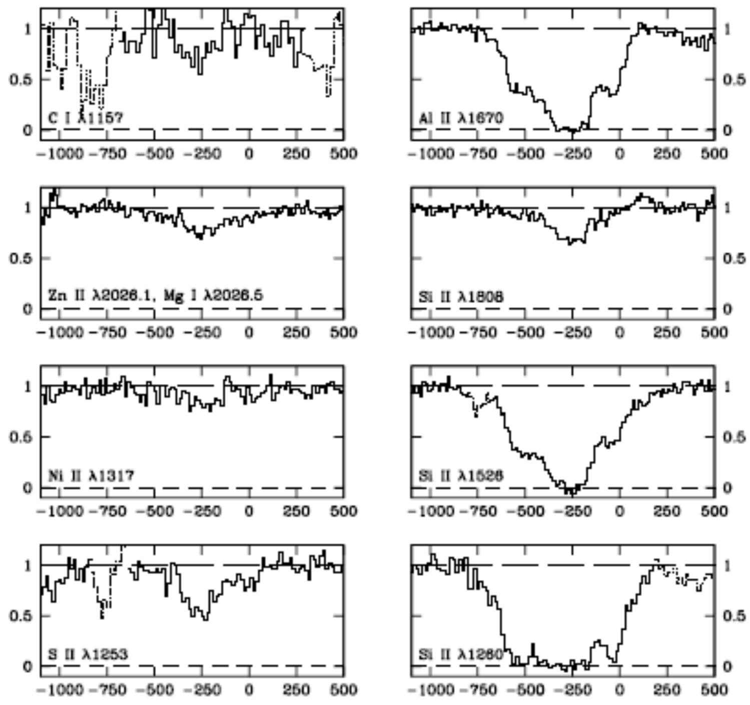




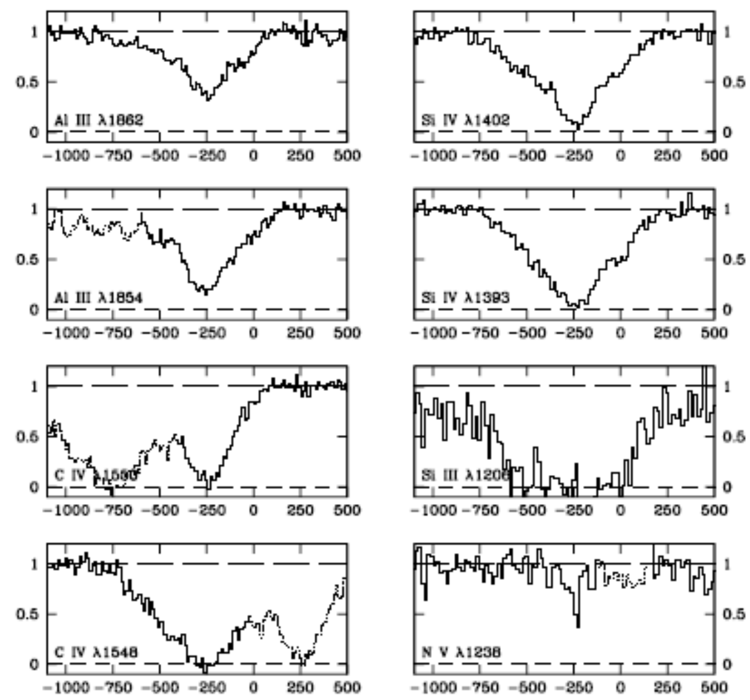
See also Rowan-Robinson et al (1991) IRAS 10214+4724 z=2.286
Lensed AGN mag ~ × 50

Keck ESI spectrum of cB58 (Pettini et al 2002)

Low ionisation



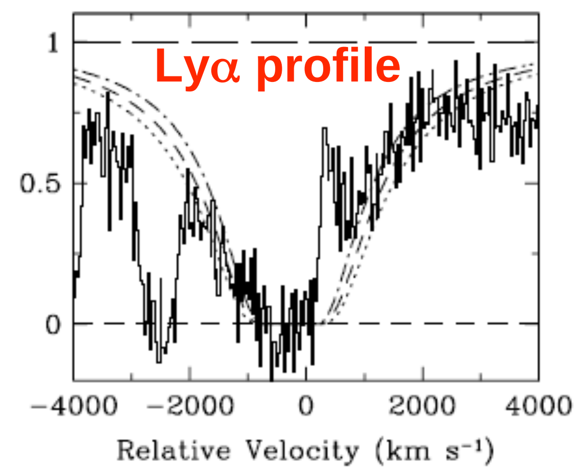
High ionisation



ESI: 10 orders, 4000Å -1μm,11.5kms s^{-1} pix^{-1}

Abundances & outflow kinematics for ~40 interstellar species from H through Zn

ISM enriched by SNII (2/3 solar) in past 300Myr

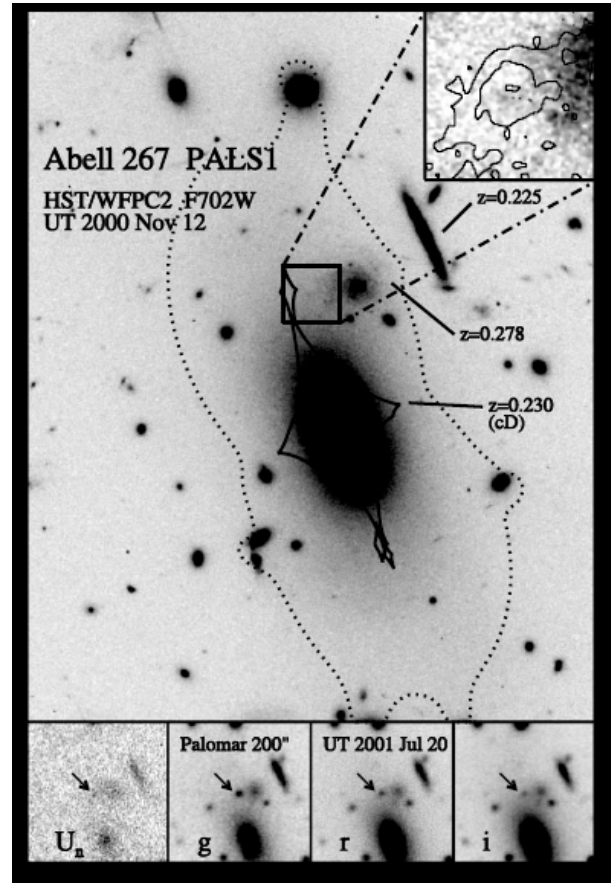


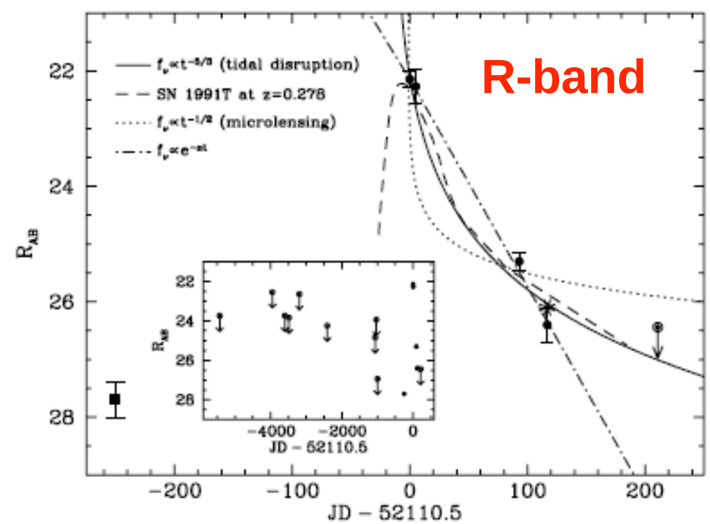
Can we find more examples of lensed LBGs?

Systematic Searches for Lensed LBGs

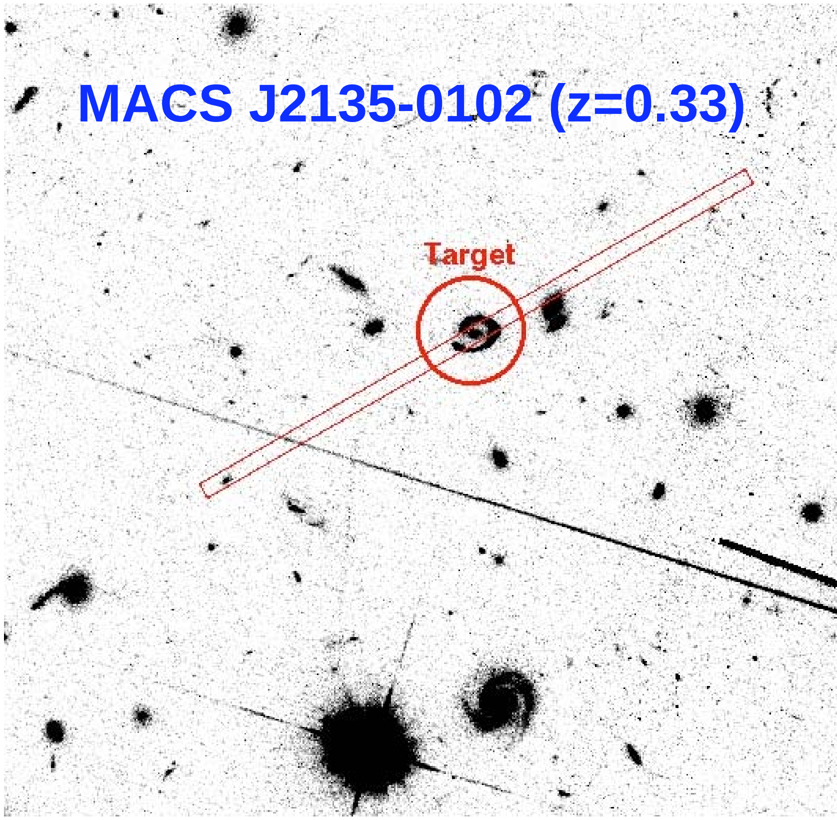
<u>Palomar Amplified Lyman Break Survey (PALS)</u>

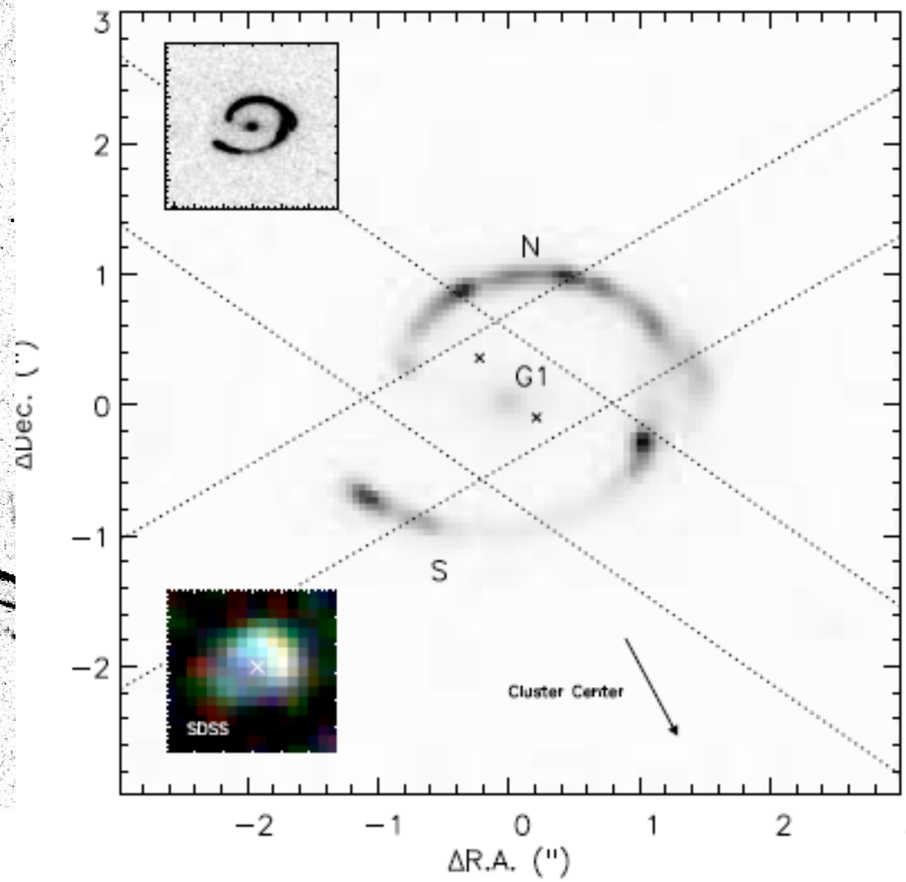
- Ugri snapshot imaging of ~100 X-ray selected lensing clusters (PI: Dave Sand)
- To first locate LBGs at Palomar, Steidel used15000s (U), 10000 (g), 5000s (r, i)
- To find magnified examples, we used 900s (U), 600s (g), 240s (r, i)
- But despite two years of searching (in poor weather), no more lensed LBGs were found (in ~30 clusters)!
- See Stern et al (2004) for the only `science deliverable' from this heroic effort: a lensed transient (possibly a flare from a tidally-distributed star at z=3.3) or SN1991T-like SN in the foreground cluster





The `Cosmic Eye'





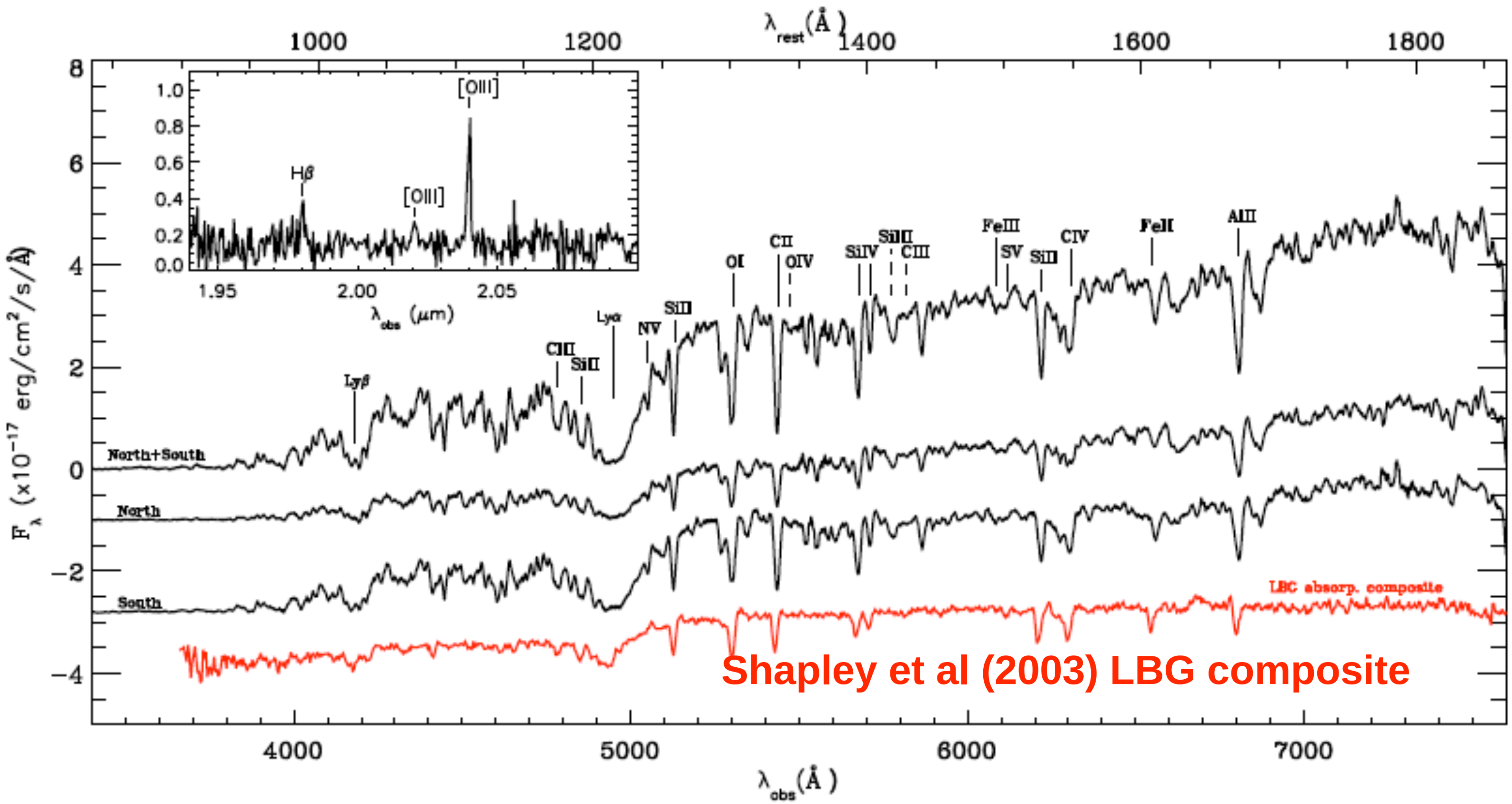
HST snapshot F606W imaging of MACS clusters (PI: Ebeling)

Two non-concentric arcs in periphery (75” from cD)

Named after the Egyptian `Eye of Horus'

Smail et al (2007)

Keck Follow-up



LRIS: 2 × 1hr : arcs have same redshift, z=3.0747(±5)

subtle differences in Lyα, Lyβ profiles,

z(G1)=0.7268 (not a cluster member!)

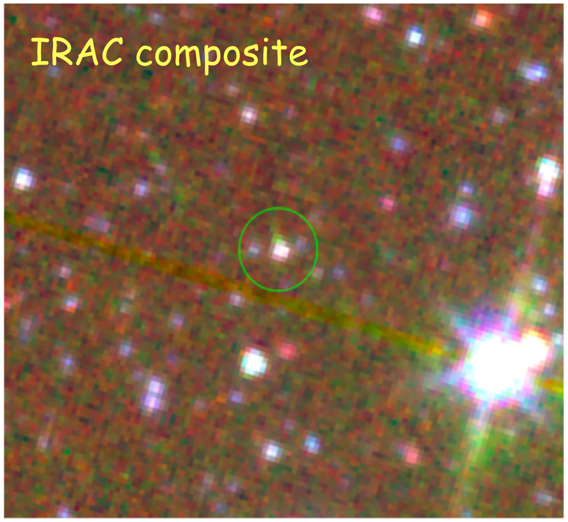
NIRSPEC: 40m, [O III], Hβ emission, z=3.0743(±1)

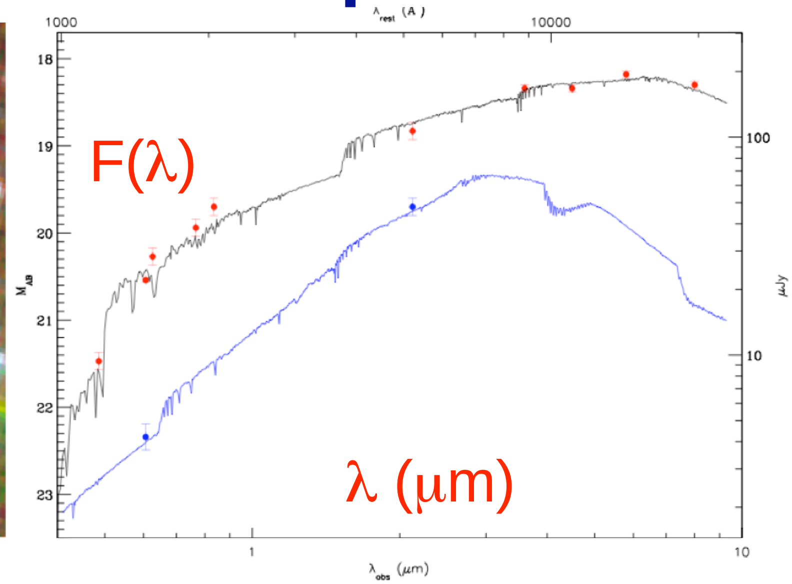
NIRC-K: 1000s, R_{606}-K colors of arcs identical, K(G1)=19.7 (L*)

Spitzer and IRAM Follow up

Stellar mass & SFR:

M_K = -22.2±0.2
$M_* \sim 8 \times 10^9 M_\odot$
SFR(24μm) $60 M_\odot$/yr

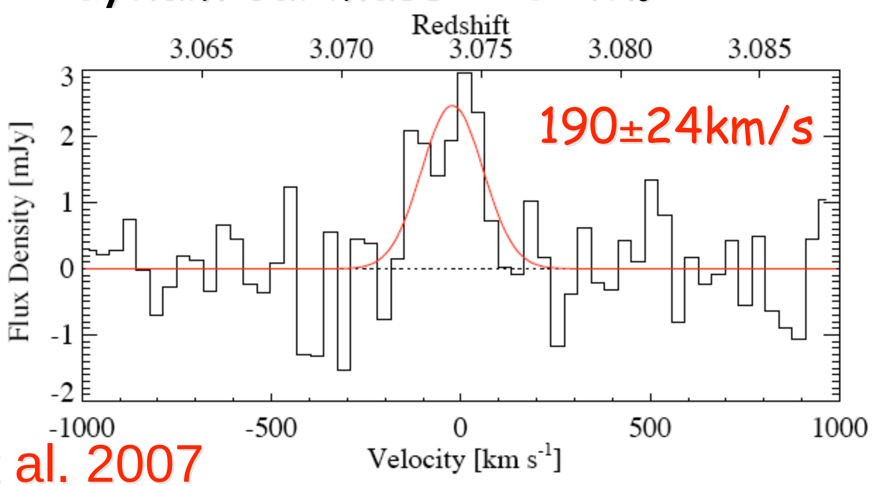


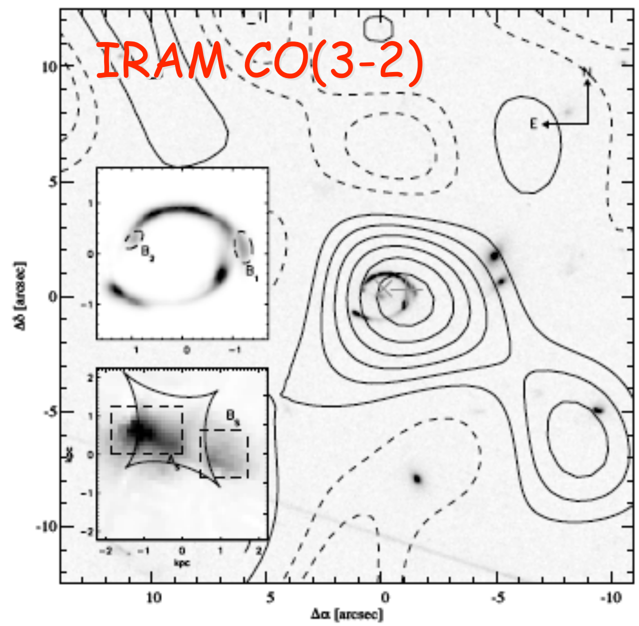


IRAM CO(3-2) data:

Luminosity → gas mass $\sim 5 \times 10^8 M_\odot$

Line width → dynamical mass $\sim 10^{10} M_\odot$





Coppin et al. 2007

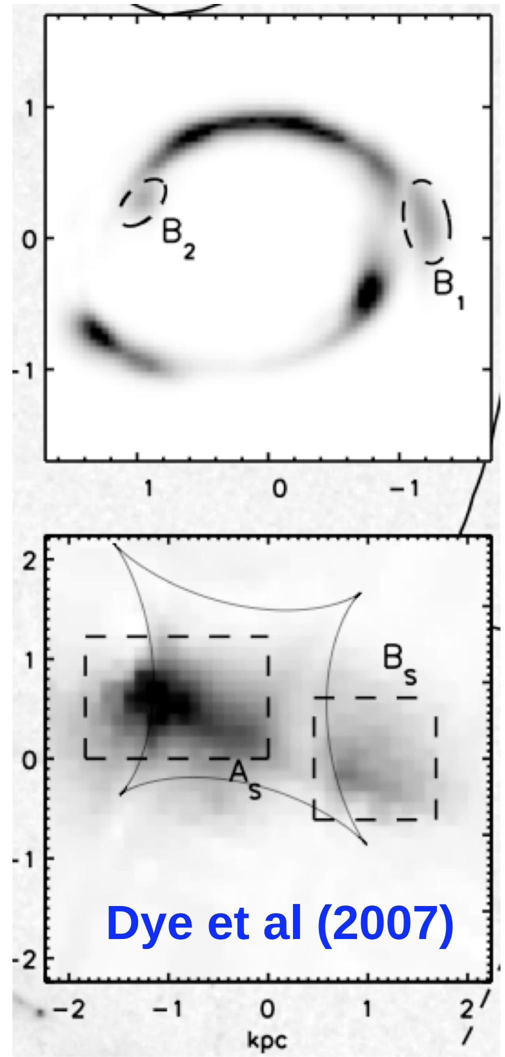
`Cosmic Eye' - Preview of ALMA science

What is gas content of early galaxies?

z~3.07 LGB pair lensed by
L^*_K z=0.73 galaxy + z=0.33 cluster
Cluster provides ~30% boost & induces non-concentricity of arcs
Magnification = × 28 ± 3
Sources 1.5 kpc apart (< 1kpc in size)

<u>Intrinsic properties:</u>

L_K = 22.6 ± 0.2 (AB), M_K=-22.2+/-0.2 (~L_K*)
SFR ~ 100 $M_o yr^{-1}$
Masses: $1\times10^{10} M_o$ (dynamics)
$7\times10^9 M_o$ (stellar)
$5\times10^8 M_o$ (gas)
Timescale = Gas mass/SFR = 40Myr!



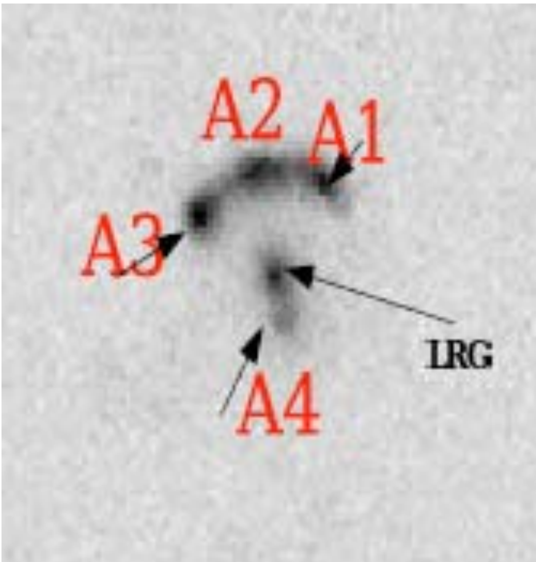
Gas-rich & similar (less vigorous) to sub-mm popn.

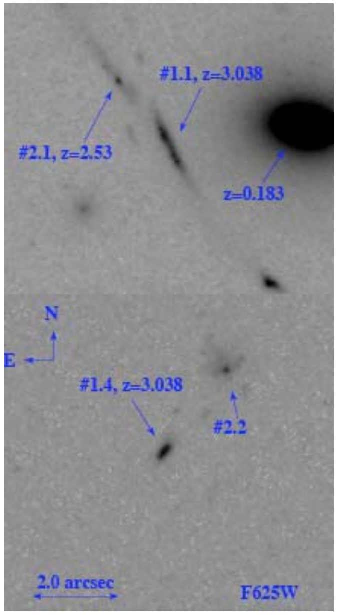
Smail et al 2007; Coppin et al 2007

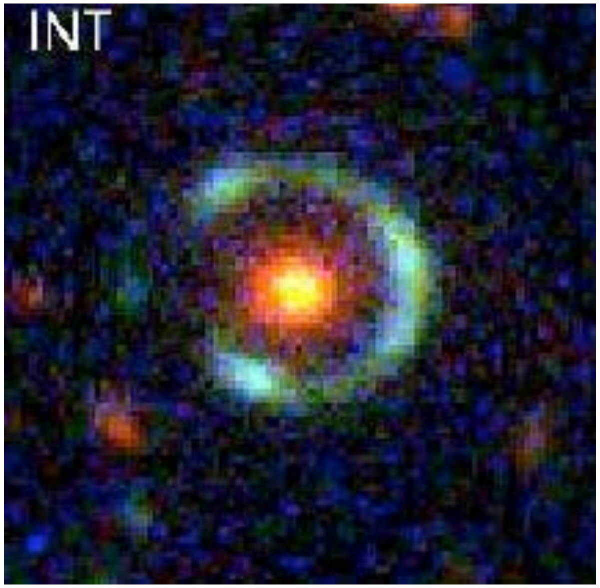
Some Newly-Discovered Highly-Magnified z>2 Galaxies

- cB58 (Yee et al 1996) z=2.76, r~21, m ~ ×20-40
- Cosmic Eye (Smail et al 2007) z=3.07, r~20.3, m ~ ×30

- 8 o'clock arc (Allam et al 2007) z=2.72, r~19.2, m ~ ×12
- Sextet arcs (Frye et al 2007) z=3.04, r~21.7, m ~ ×16
- Cosmic horseshoe (Belokurov et al 2007) z=2.38, r~19.0, m ~ ×35



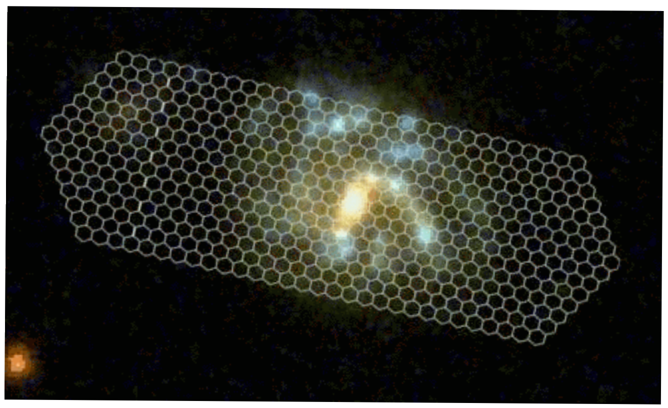


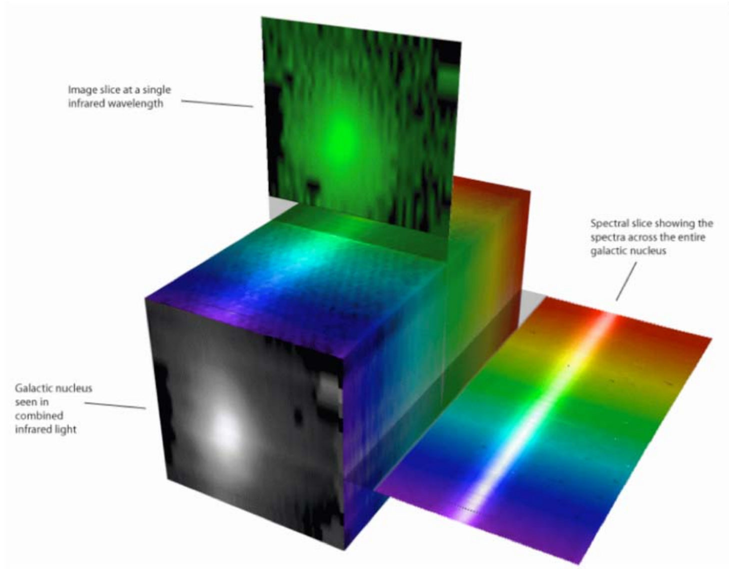


SDSS & upcoming multi-color surveys will generate ~30-100 cases

Applications - II: Resolved Spectroscopy of High z Sources

- Seek to characterize *velocity field* of selected z > 2 star forming galaxies
- Data gives information on winds (feedback), onset of disk/bulge formation
- Integral field units enable 2-D spectroscopic mapping essential for complex, asymmetric systems





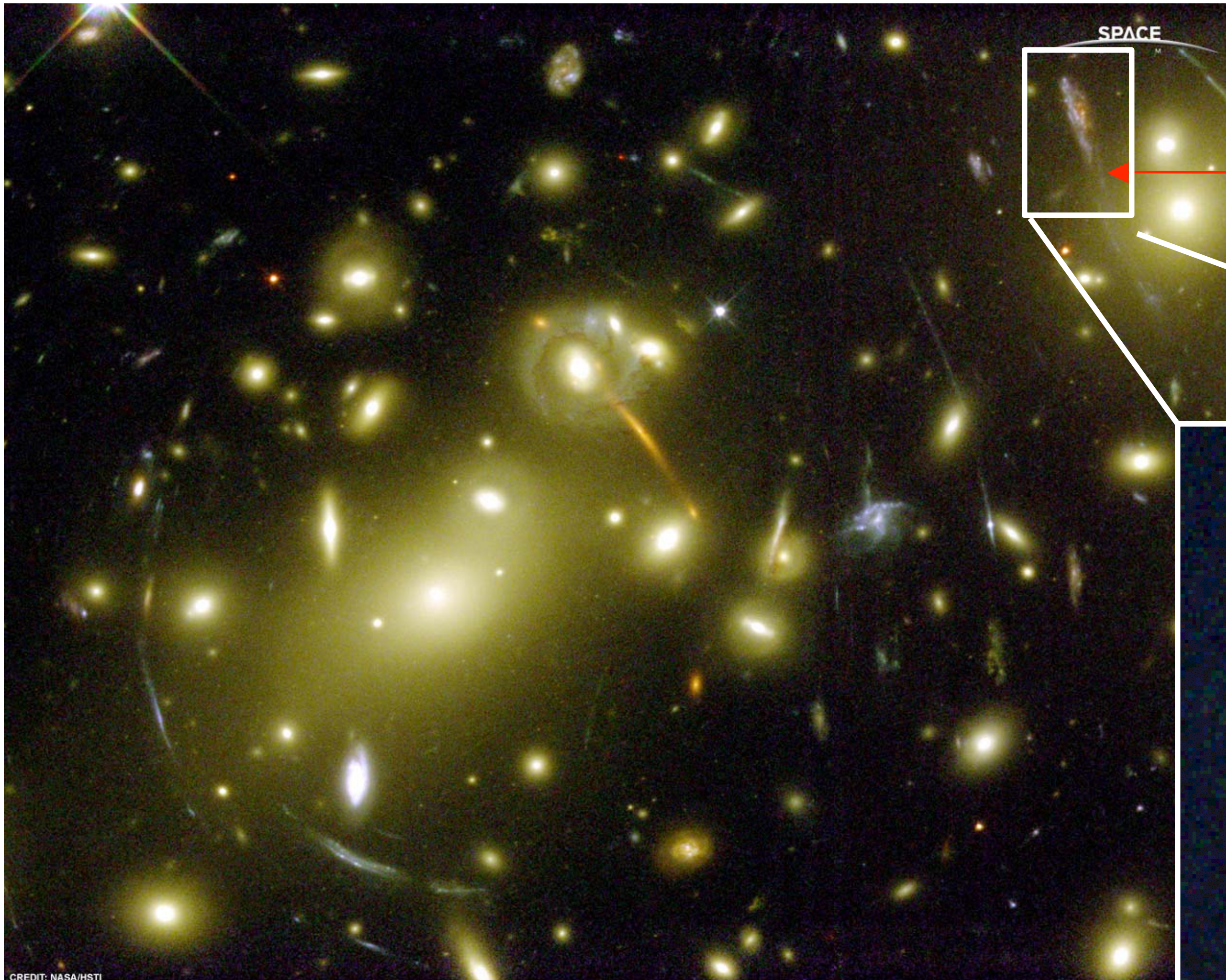
- Lensing improves physical resolution; gains + adaptive optics even larger

At z~3 for a source magnified ×5, 1 arcsec is 1.6 kpc

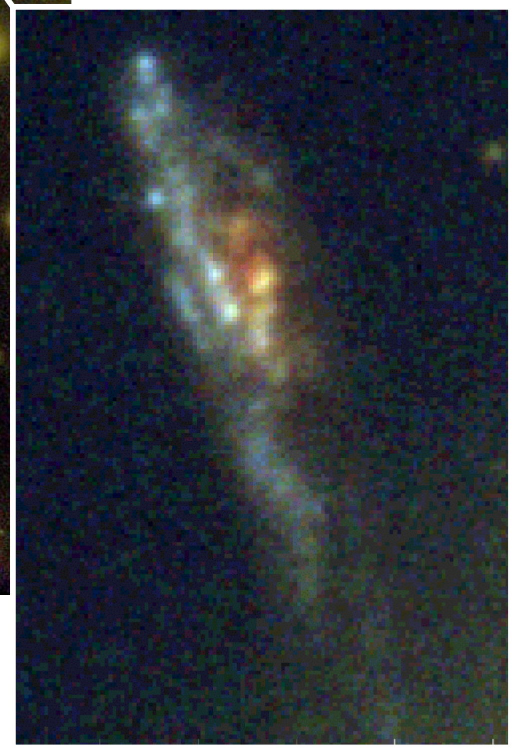
IFU sampling: non-AO = 300pc, LGS AO = 75pc

- Challenge: to find suitable systems with strong and extended emission lines (clearly a sample biased to strong SF systems)

Proof of Concept: Abell 2218 arc #289 z=1.034



magnified ×5

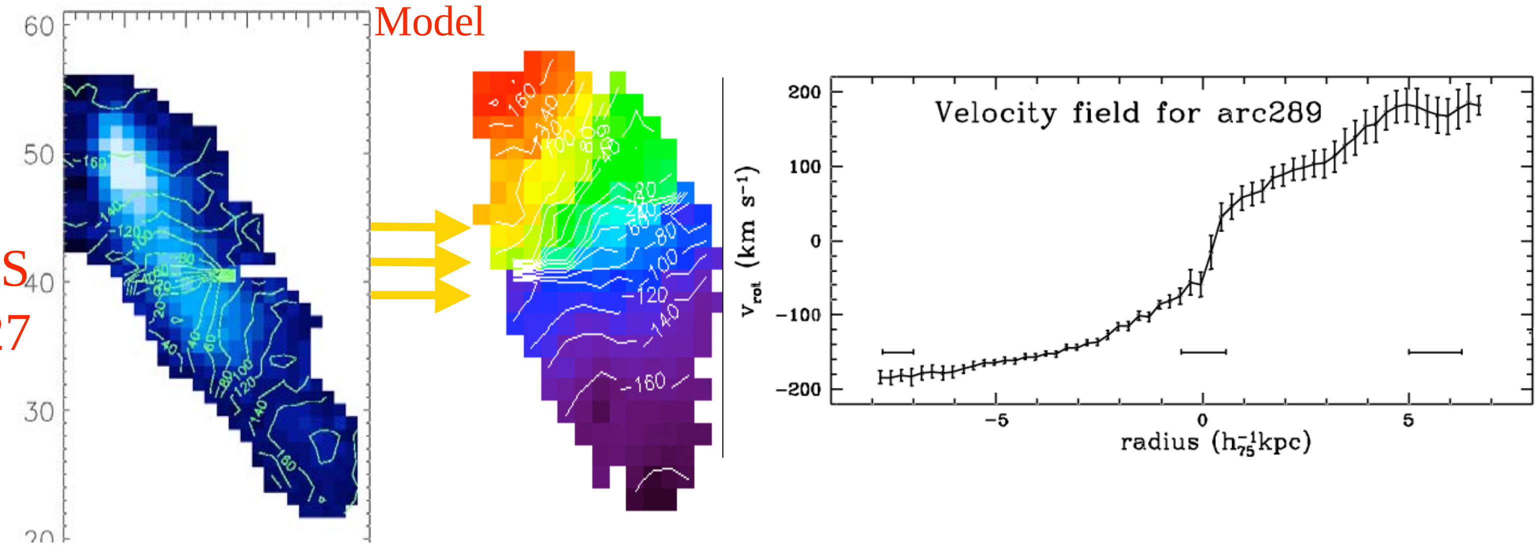


1 arcsec ~ 7.7 kpc (no lens); 1.5 kpc (lensed)

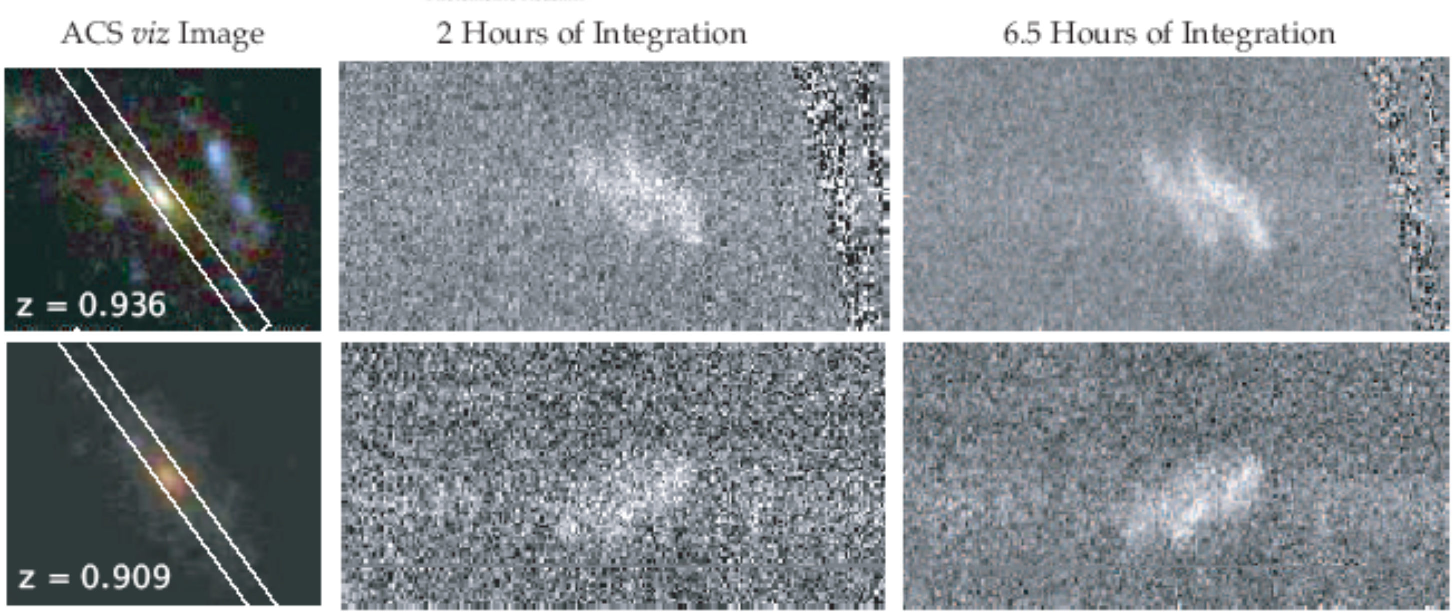
Swinbank et al (2003)

Rotation Curves of z~1 Field Galaxies

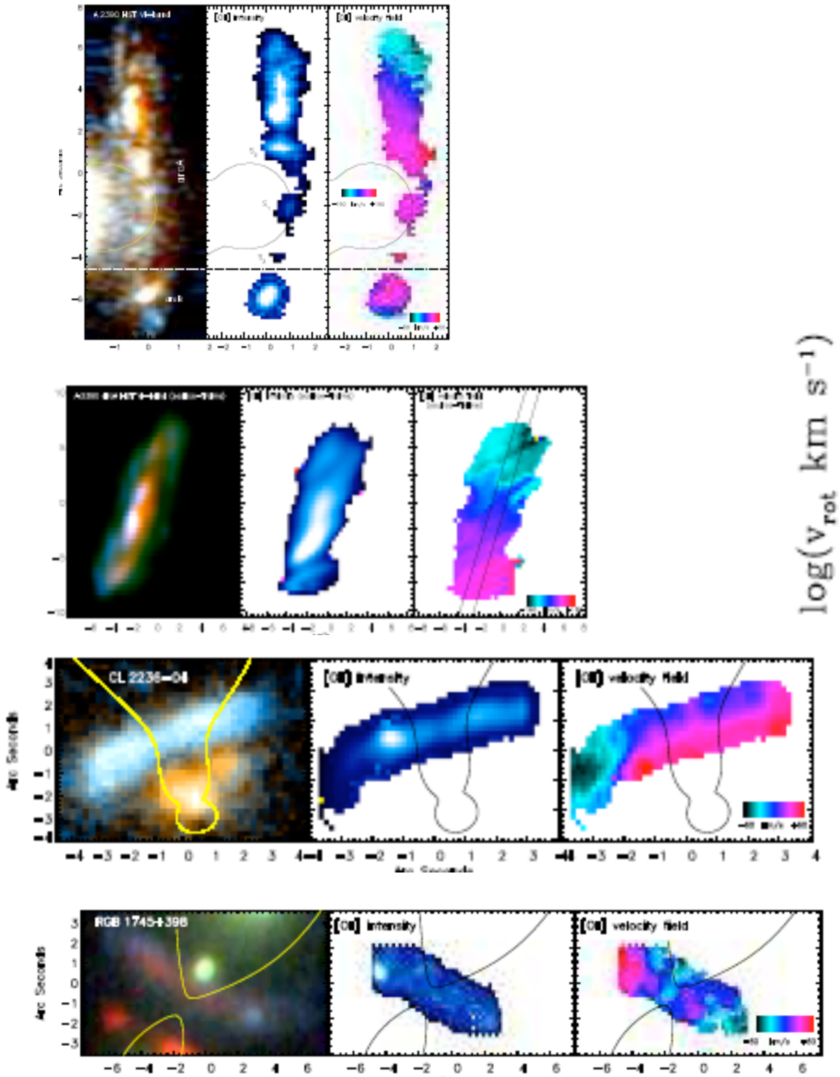
Lensed method: Gemini GMOS IFU [OII] 3727 map

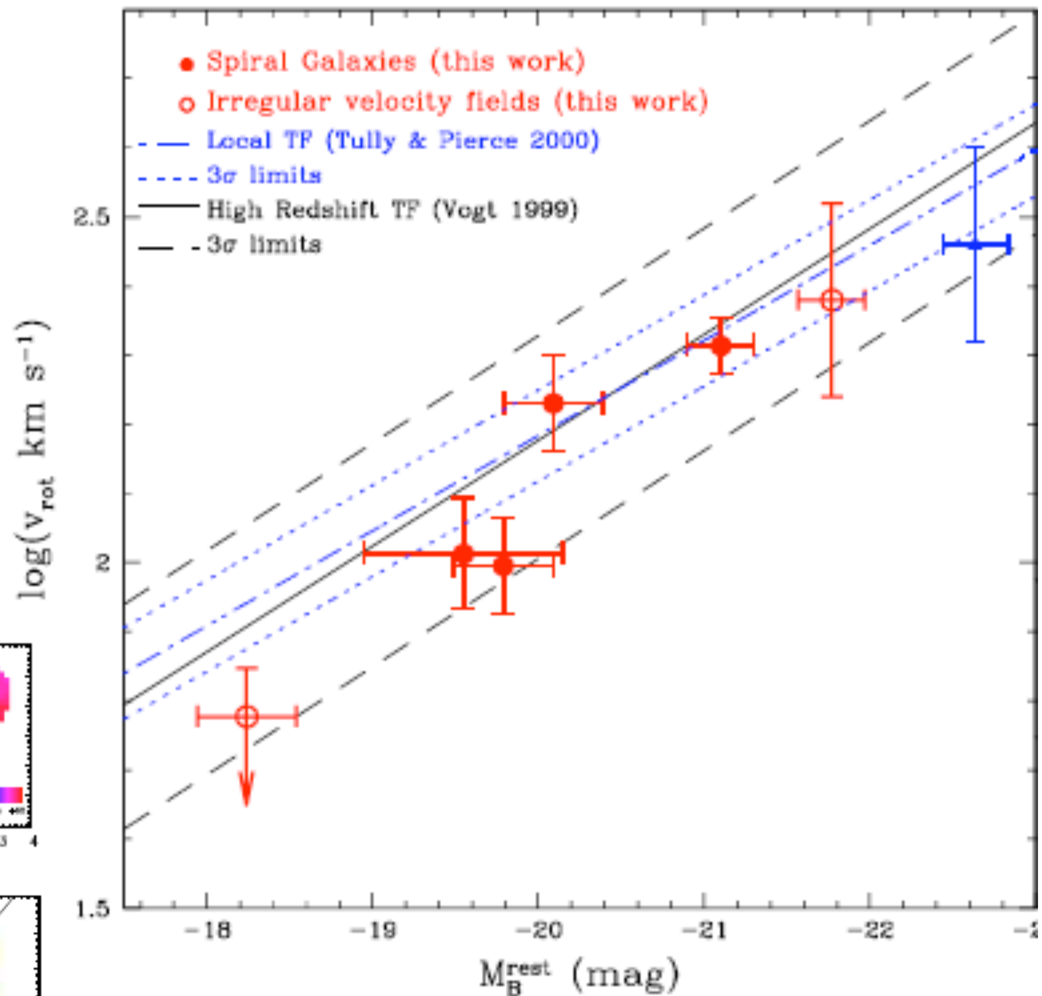


Traditional method: Keck DEIMOS rotation curves of GOODS spirals at z=1 (Bundy et al, in prep)



The High Z Tully-Fisher Relation



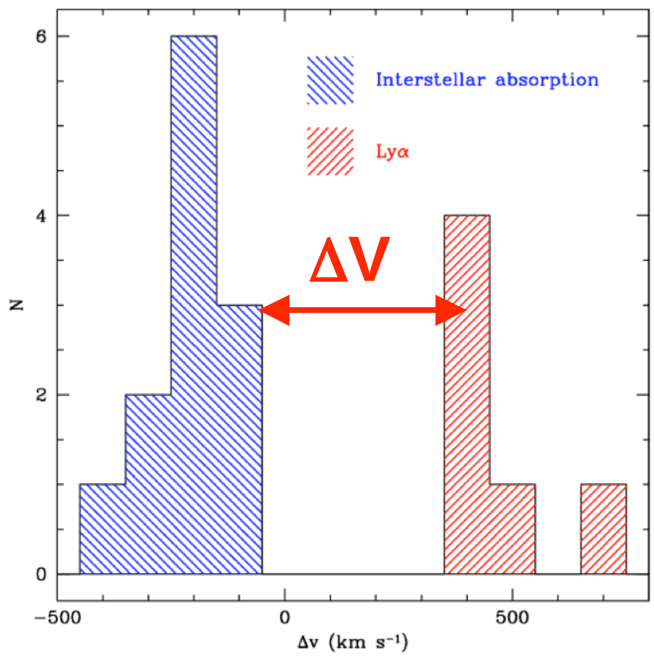


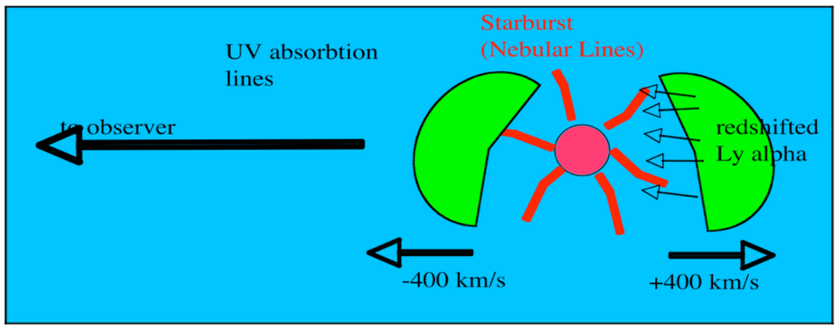
Swinbank et al 2006

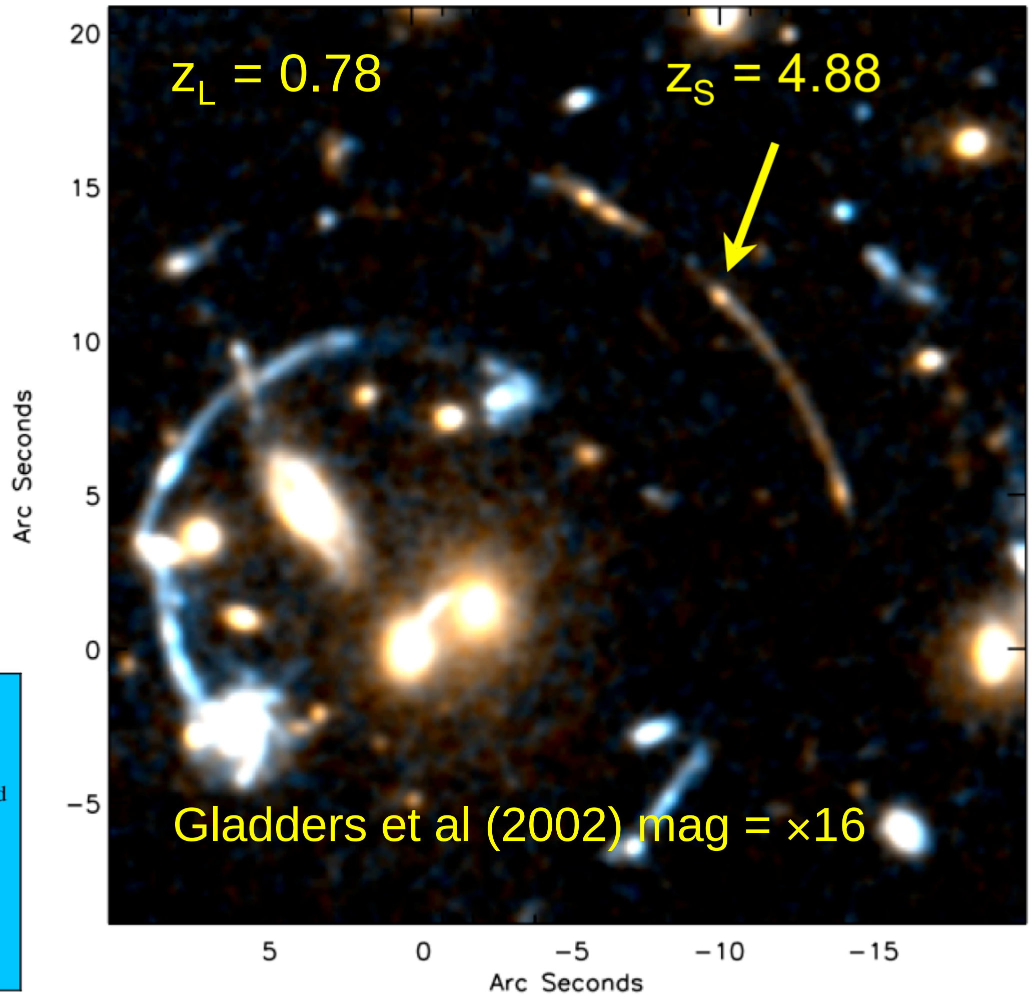
RCS0224-002: feedback in z=4.88 galaxy

Offset between ISM absorption & Lyα emission → superwind/outflows

Do these escape galaxy or return as part of a cycle of activity?





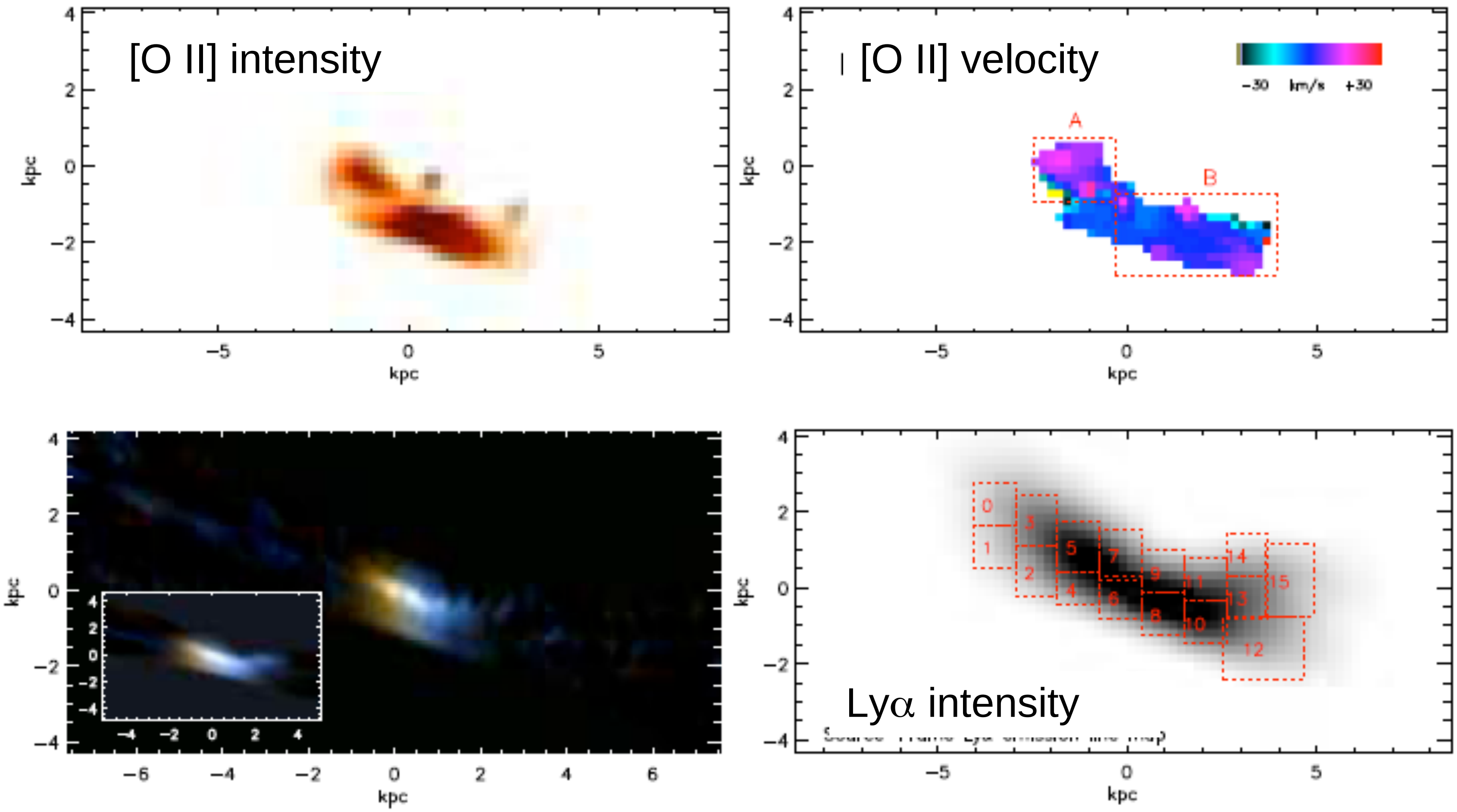


Can we resolve outflows to get scale, energies & masses?

VLT Optical & IR IFU Observations

VLT VIMOS IFU (16 hrs): Lyα & ISM
5000A & 1um at R~2000; 0.67" per pixel

VLT SINFONI IFU (18 hrs): [O II]
1.5- 2.4um at R~2000; 0.25" per pixel

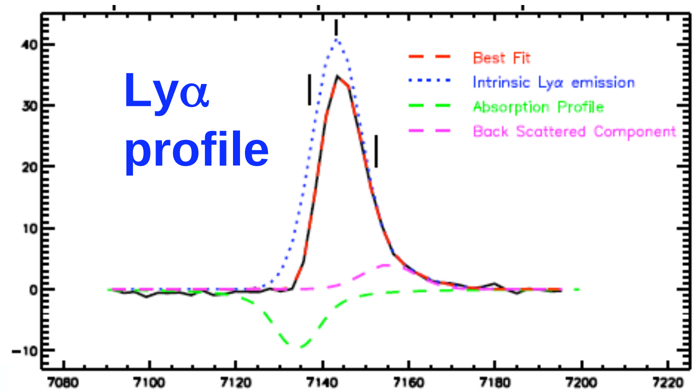


Lyα more extended than [OII] with constant line profile (Δv<10km/s)

Lyα - [OII] = +200+/-40 ; [OII] - UV ISM= -400+/-100 km/s

A Simple Picture for the ISM, Lyα & [O II] Data

Reconstruct source properties at 200pc resolution!

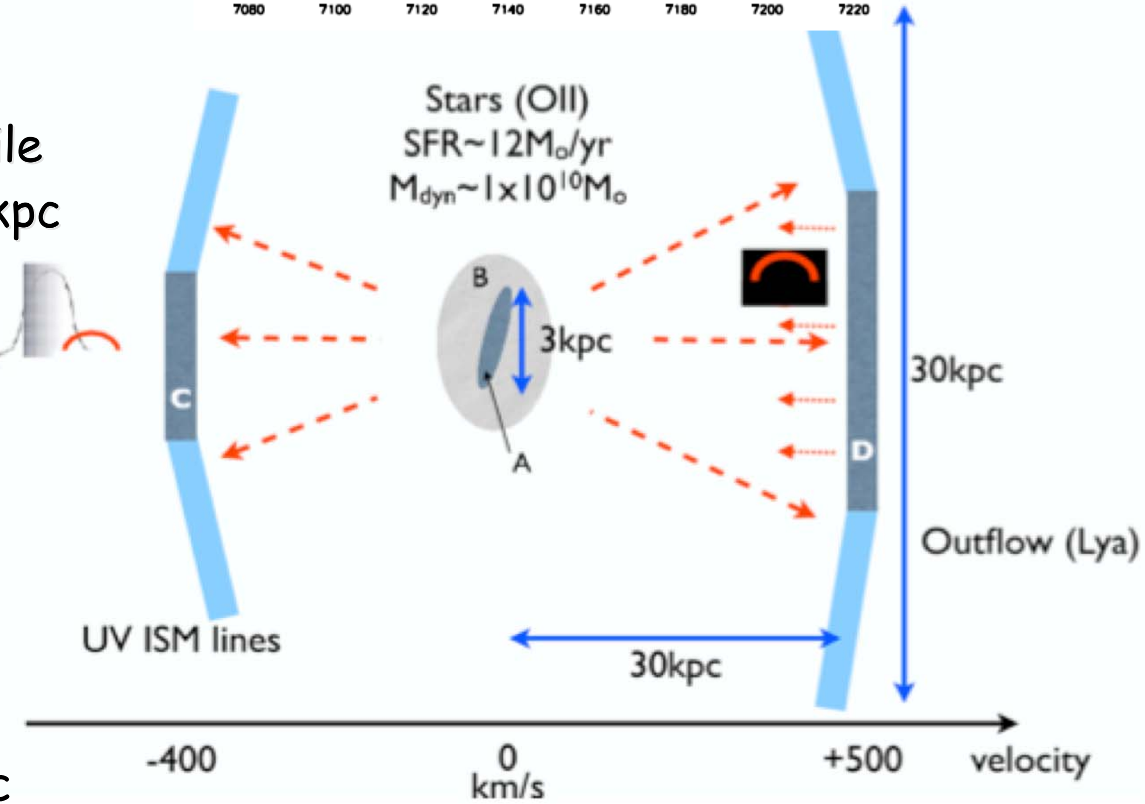


<u>Key results</u>:

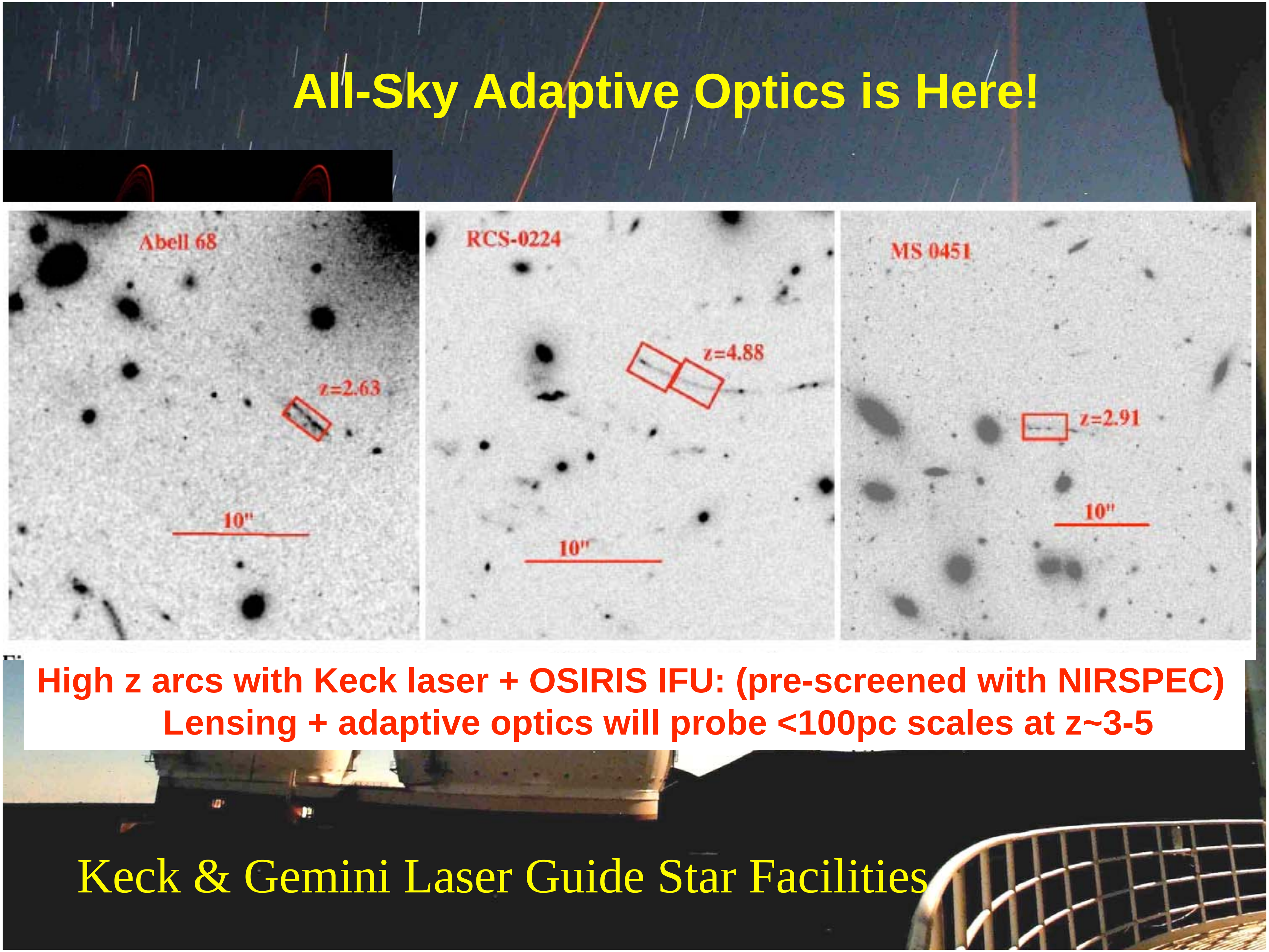
Source ~3kpc across
SFR~12+/-2 Mo/yr
ΔV (Lyα-OII) ~ 200km/s
Spatially-independent Lyα profile
Bi-conical outflow, extent >>10 kpc

<u>Energetics:</u>

Age of outflow ~60Myr
Mass swept up 2. 10^8Mo
Outflow rate ~ 3 Mo/yr
KE ~ 5 x 10^{56} ergs
Outflow escape to several ~Mpc



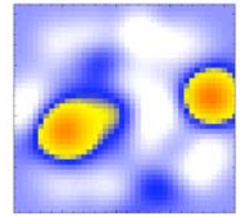
Swinbank et al (2007)


All-Sky Adaptive Optics is Here!
Abell 68
z=2.63
10"
RCS-0224
z=4.88
10"
MS 0451
z=2.91
10"
High z arcs with Keck laser + OSIRIS IFU: (pre-screened with NIRSPEC)
Lensing + adaptive optics will probe <100pc scales at z~3-5
Keck & Gemini Laser Guide Star Facilities

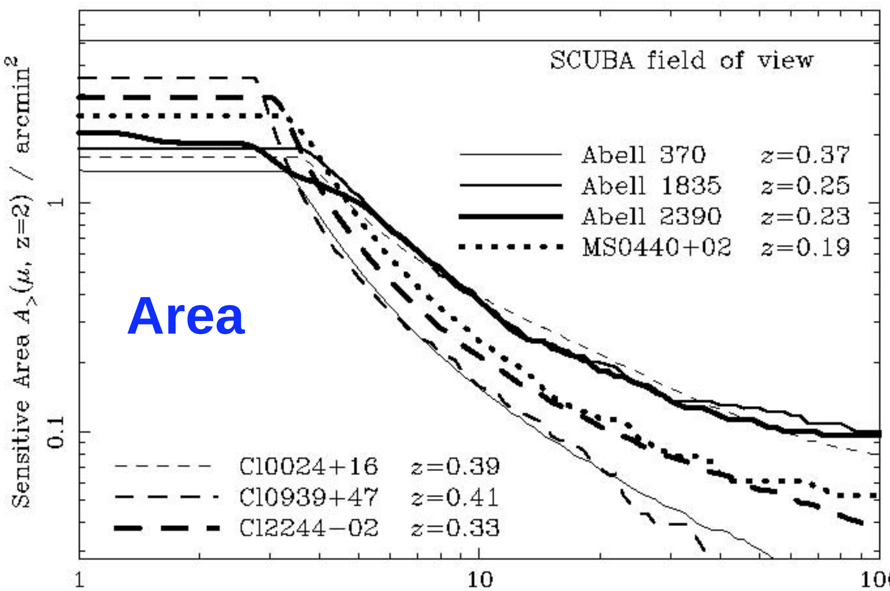
Lensed Surveys - I: Sub mm Counts & Sources

- Submm survey through lensing clusters
- Boost sensitivity of maps by >×2-10
- Increase spatial resolution of maps – lower confusion limit
- Correct for amplification using detailed mass models built from HST imaging
- Boost sensitivity of follow-up observations
- Reach below 1mJy in the source plane

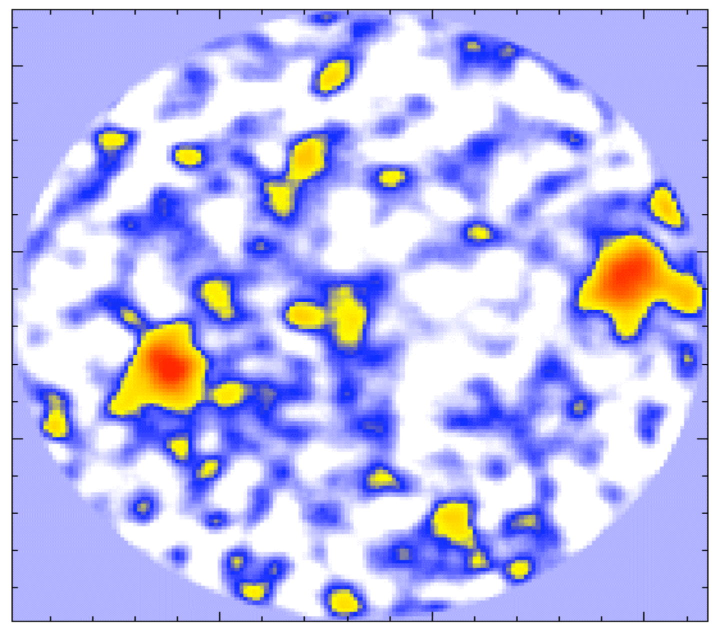
Blank Field



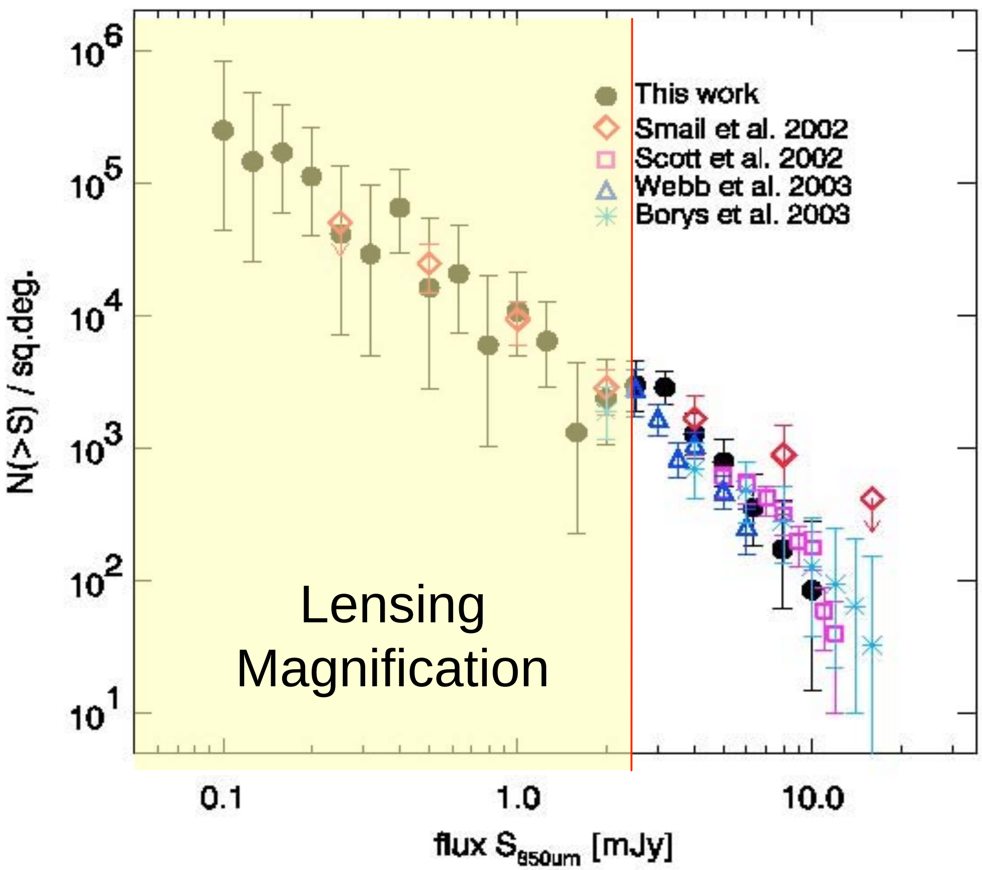
Lensed Field



Magnification



Resolving the Sub-mm (850 μm) Background

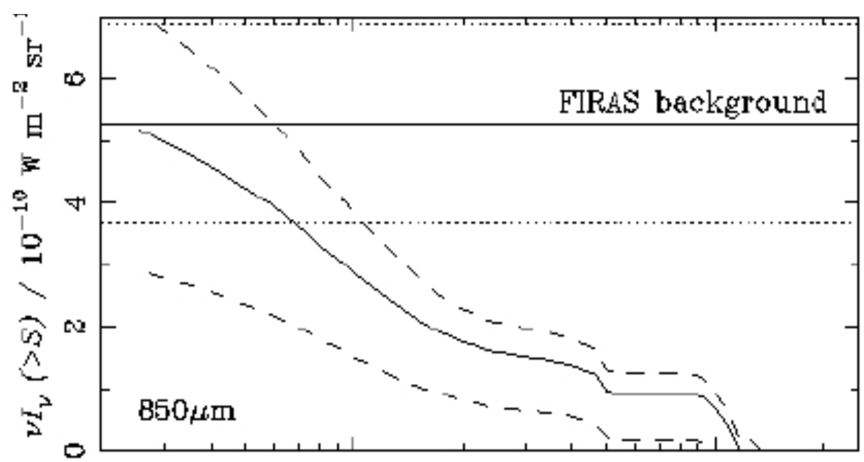


Results:

- 58 sources
- tripled no. of sub-mJy sources
- observed: 2.8 < S_{850} < 25 mJy
- unlensed: 0.1 -19 mJy

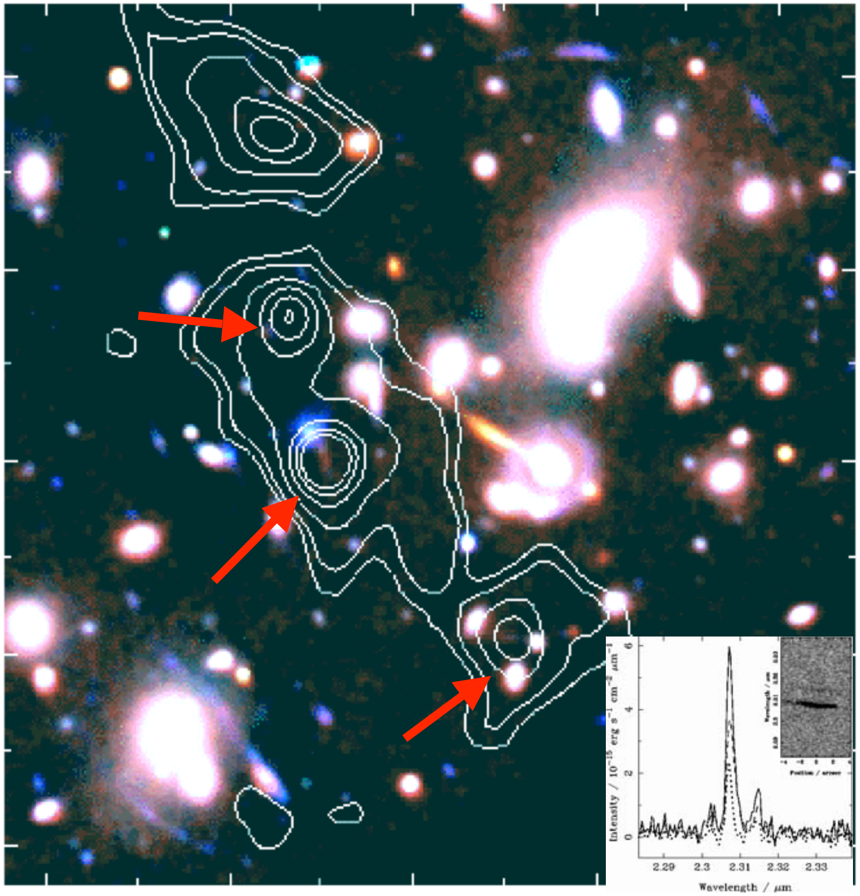
Implication:

- Strong evoln ($\times 10^{2\text{-}3}$!)
- 80% of FIRB resolved @ 0.5 mJy

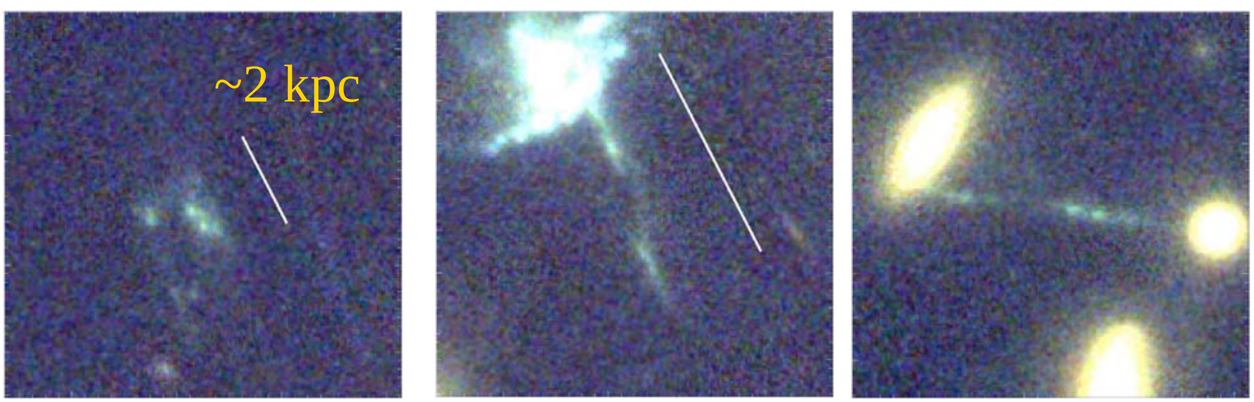


Knudsen et al 2006

Multiply-imaged Sub-mm Galaxy - I



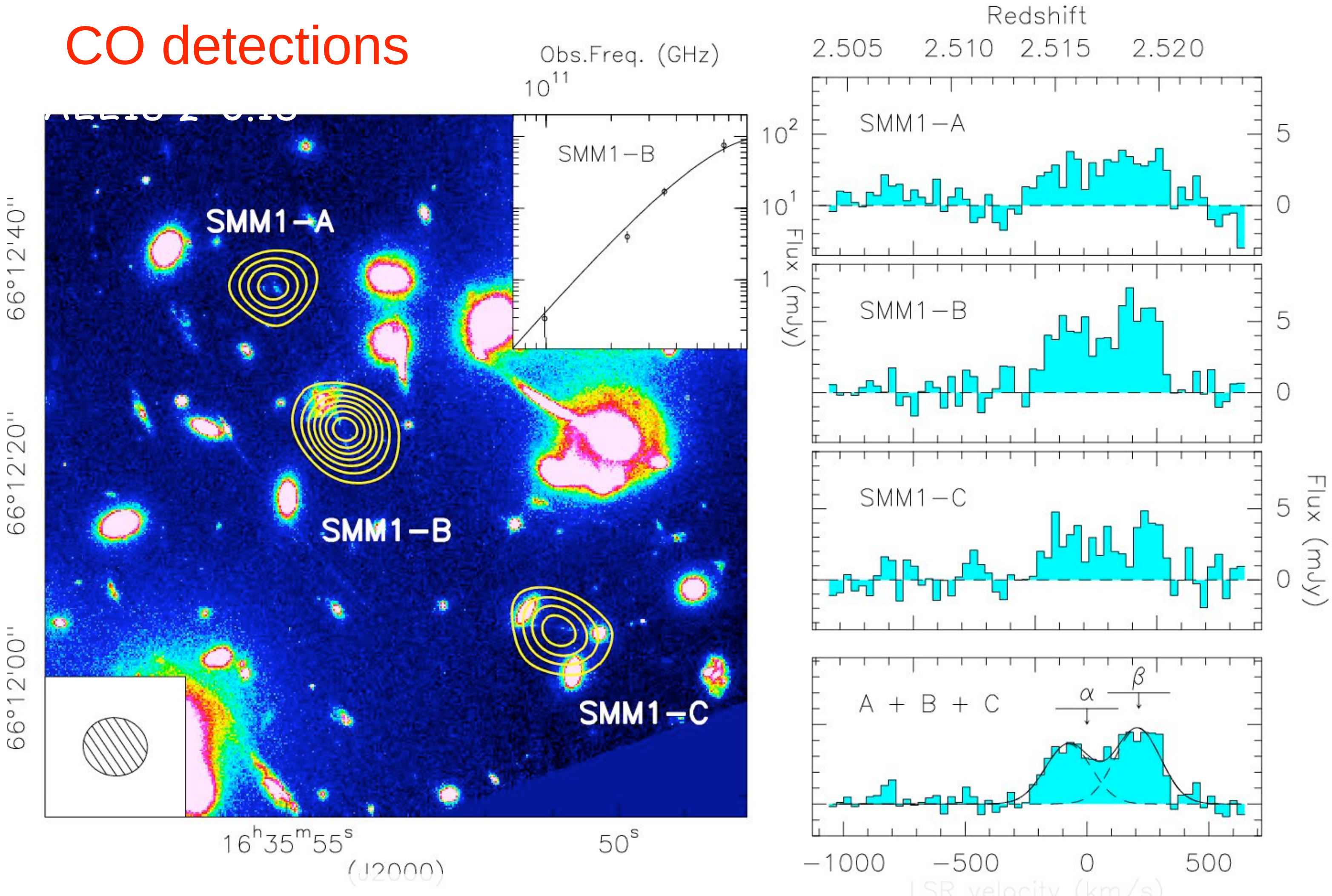
- A2218 shows 4 submm sources – 3 with similar counterparts
- Multiple images of sub-mJy K~22/I~26 galaxy magnified 40x
- Lens model predicts z=2.6+/-0.2
- Keck spectroscopic z=2.515
- Magnification reveals complex & compact (2 kpc) morphology with 3 subunits



(Kneib et al. 2004,2005)

Multiply-imaged Sub-mm Galaxy - II

CO detections



- $H\alpha$ & CO: Δv between sub-units ~ 200 km/s, line widths ~260 km/s
- Two velocity components are spatially offset by 2" = 1.5kpc
- Detailed kinematics in a merging sub-mJy SMG - mass $1.5x10^{10}M_o$

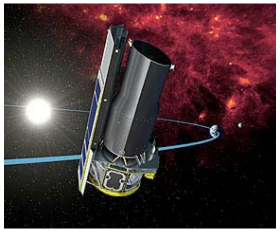
Lensed Surveys - II: Census of z>7 Galaxies

Motivation:

- Seek star forming sources responsible for cosmic reionization via direct imaging/spectroscopy in near-IR
- Lensing allows access to lower luminosity systems missed by traditional surveys, but only if their surface density is high

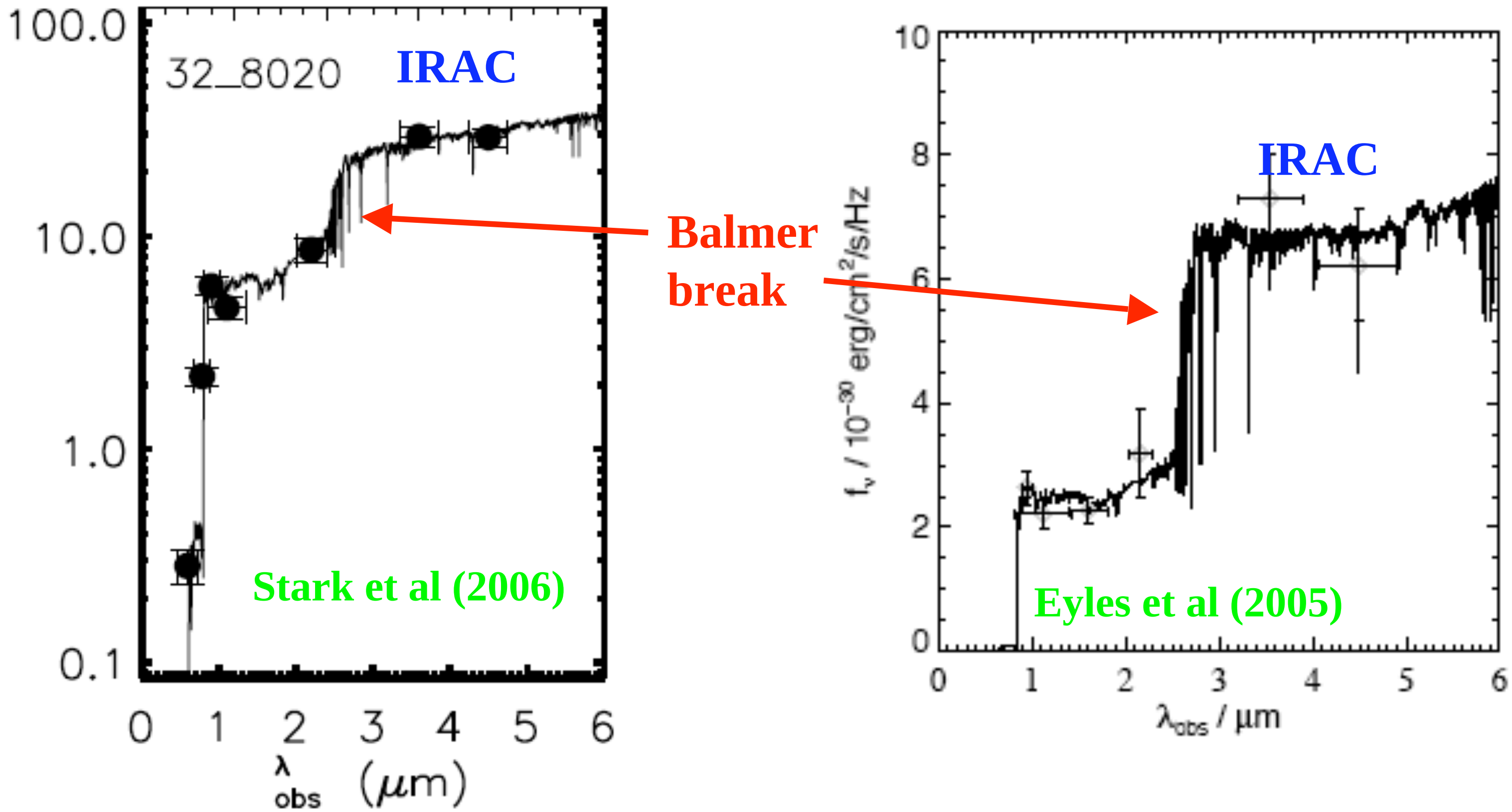
Blind searches are risky but can expect to find higher z sources

- Surprisingly mature galaxies at z~5-6 exist with established (>100Myr) stellar populations (Spitzer/HST)
- Present of metals in intergalactic medium in spectra of highest z QSOs
- Evidence faint end of LF is steepening with z ($3<z<6$)
  - Critical line mapping of lensed Lyα emitters
  - Searches for lensed continuum dropouts (Richard, Pellò)

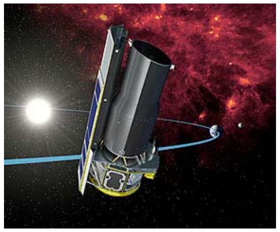


Established Stellar Populations at z~5-6

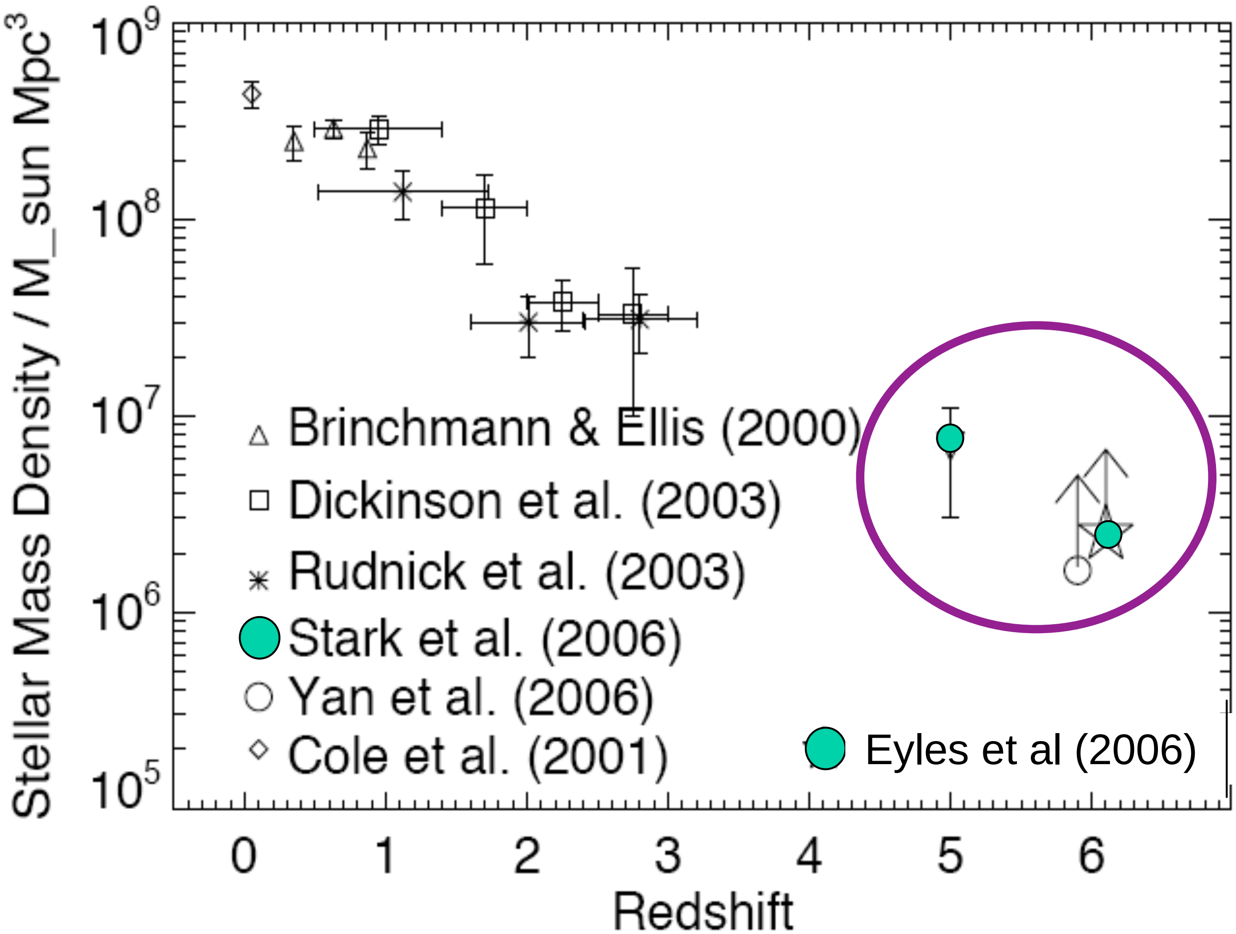
z=5.55 M = 1.1 10^{11} $M_{\odot}$ | **z=5.83 M= 2-4 10^{10} $M_{\odot}$**



`Balmer break' in many (~20) spectroscopically-confirmed z~5-6 galaxies points to significant star formation in earlier progenitors

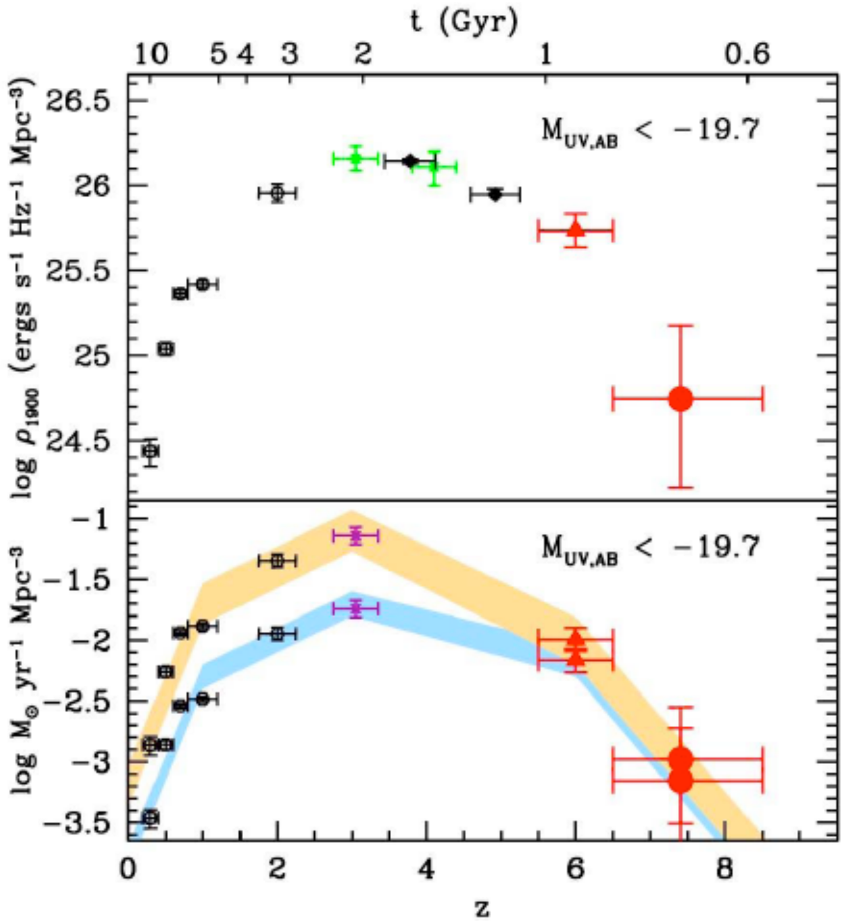


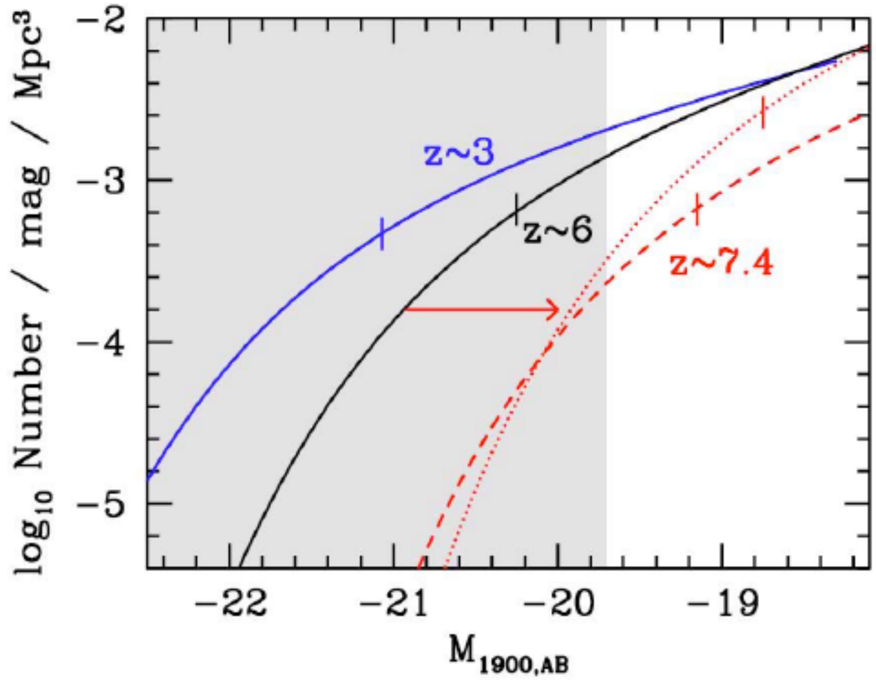
Stellar Mass Assembly History



Assembled stellar mass density at z~5-6 is surprisingly high
Possibly a lower limit (although estimates v. uncertain)
Can this be reconciled with earlier observed star formation?

Declining UV luminosity density of dropouts





Bouwens & Illingworth (2006)

Rapid decline in UV luminosity density 3<z<7
Possible steepening of LF faint end slope with increasing z

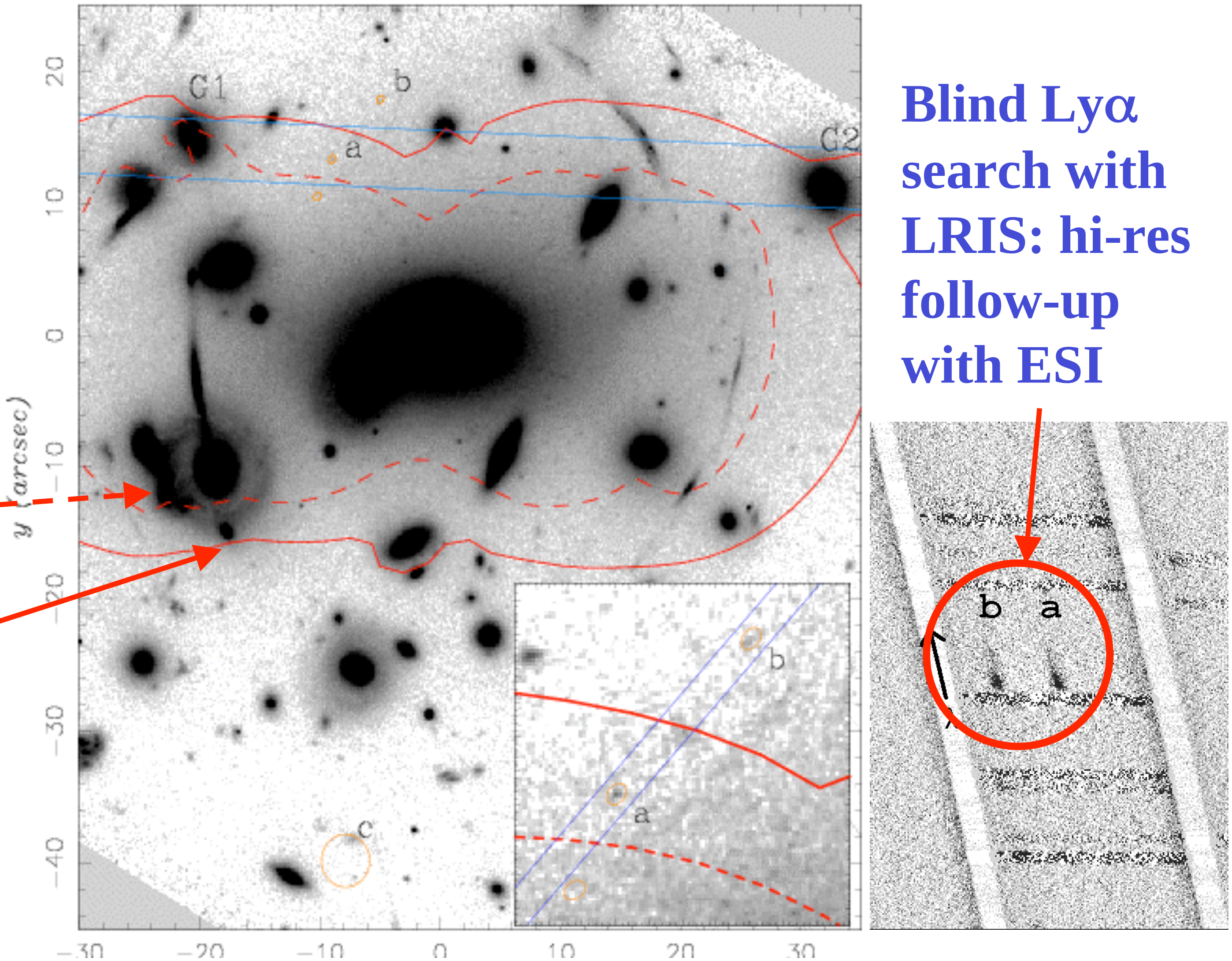
Critical Line Mapping with Keck

From arclet spectroscopy the location of the “critical lines” is known precisely for

z=1

and for

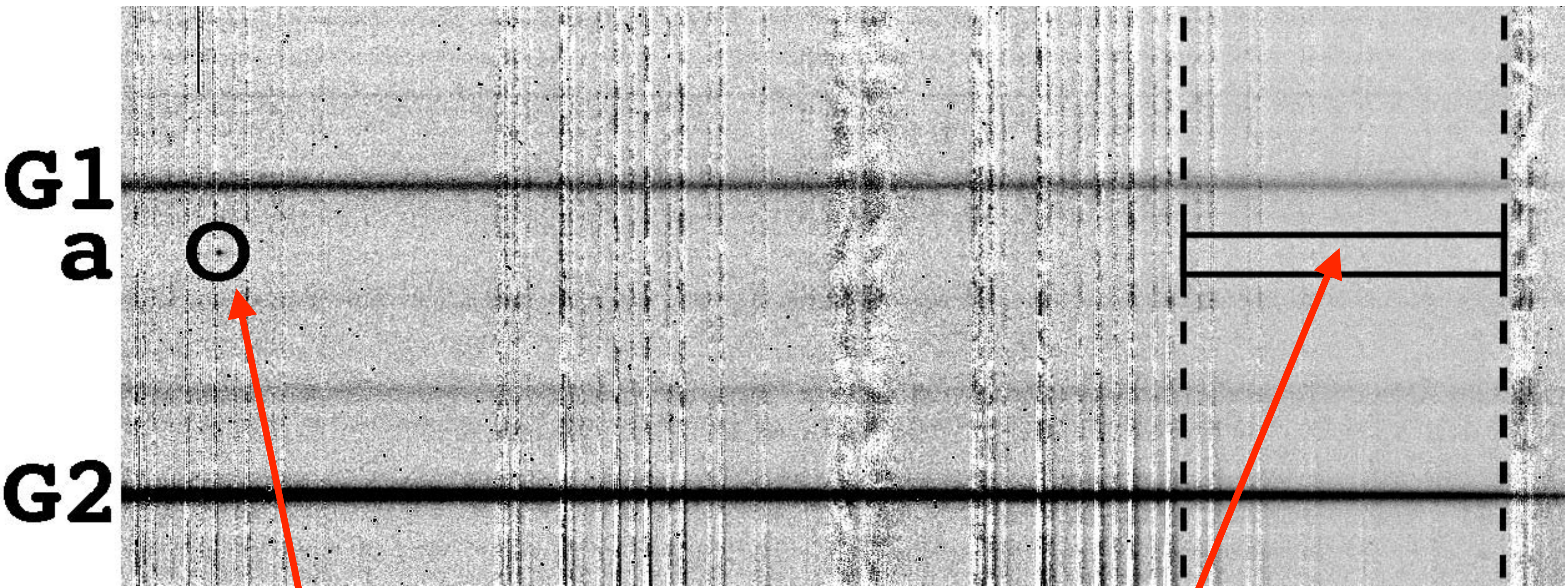
z=5



Blind Lyα search with LRIS: hi-res follow-up with ESI

Utilizing strong magnification (×10-30) of clusters, probe much fainter than other methods in small areas (<0.1 arcmin^2 cluster^{-1})

Blind longslit search with LRIS



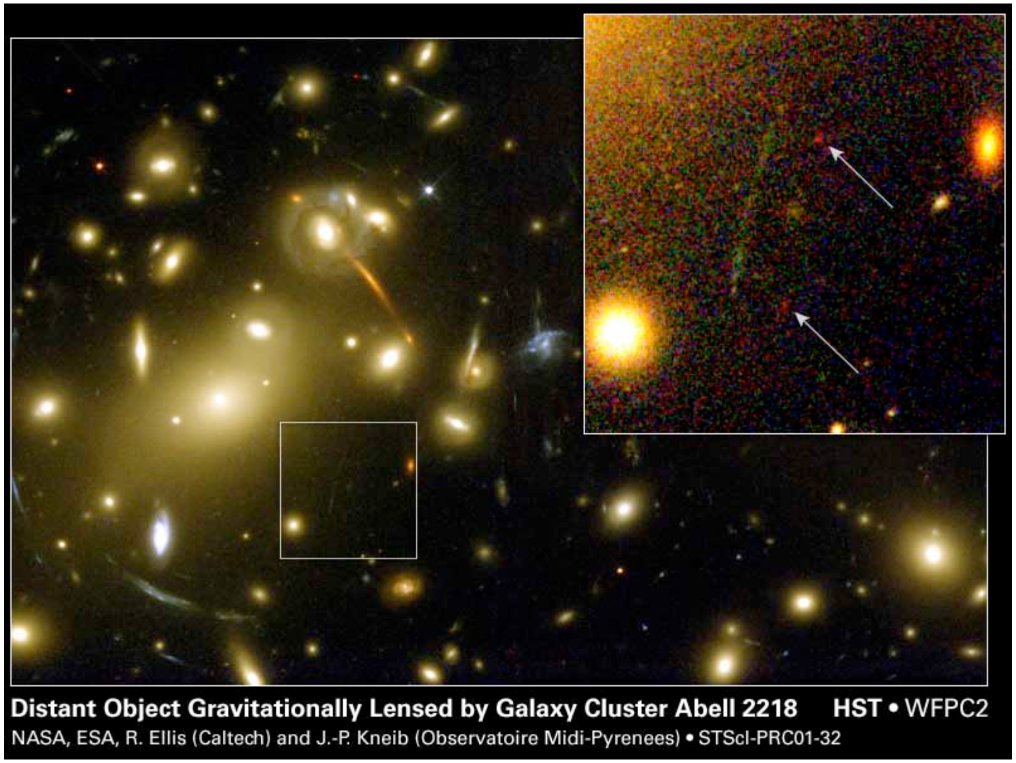
Candidate Lyman alpha (z=5.7) with no detectable stellar continuum

Young Globular Cluster at z~5.7?

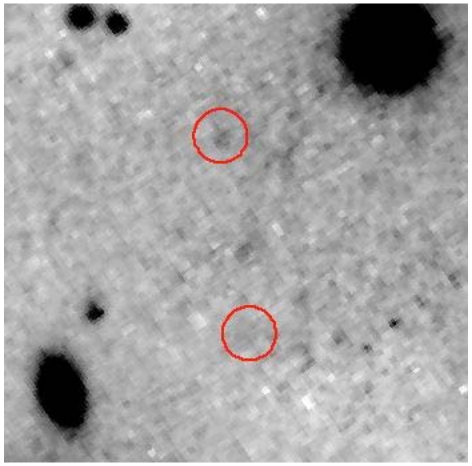
• Magnification of ×30 in Abell 2218 → unlensed Lα flux is 2. 10^{-18} cgs; 20 × fainter than limit for unlensed searches

• Unlensed Lα luminosity (10^{42} cgs) implies SFR ≈ 0.5 solar mass yr^{-1}

• Faint stellar continuum (~3. 10^{-21} cgs $Å^{-1}$) implies age < 1-2 Myr; forming globular cluster?



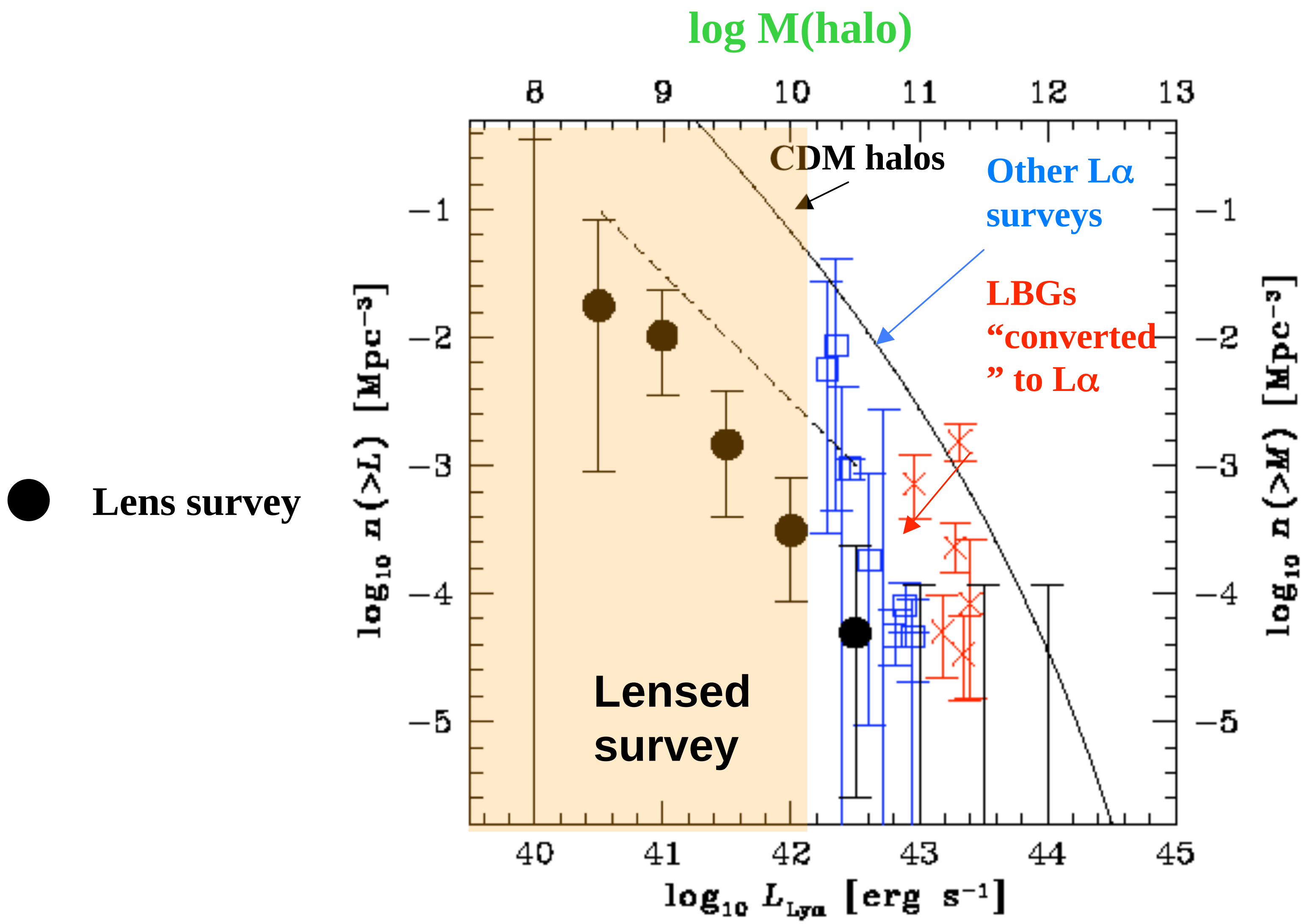
NICMOS J



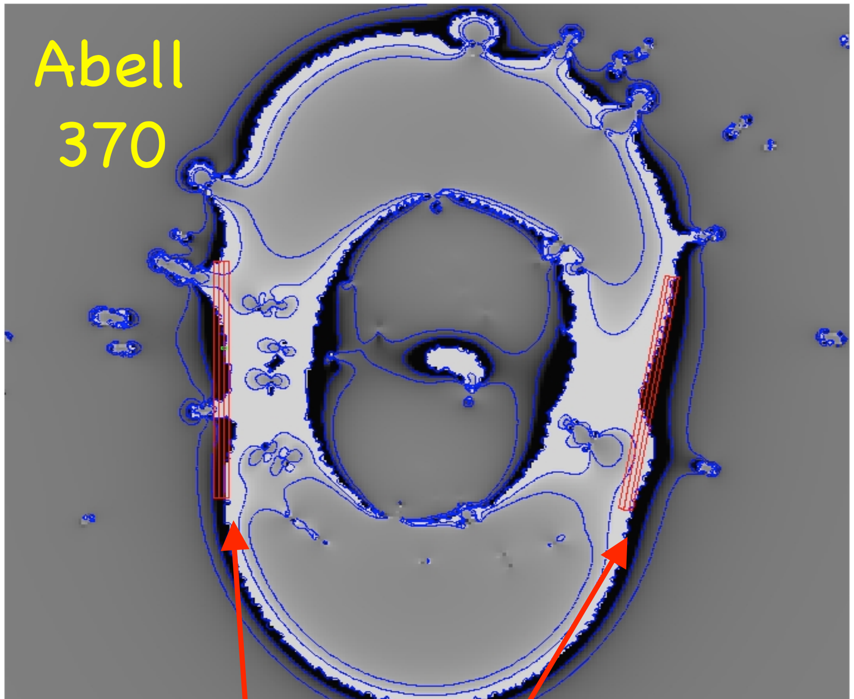
Ellis et al Ap J 560, L119 (2001)

Cumulative Lya LF: 4.7<z<5.7

Santos, Ellis, Kneib & Kuijken Ap J 606, 683 (2004)



Low Luminosity z~10 Lyα Emitters: Critical Line Mapping With Keck



NIRSPEC Slit Positions

Critical line mapping of 9 clusters in J-band, corresponding to Lyα at $8.5 < z < 10.4$

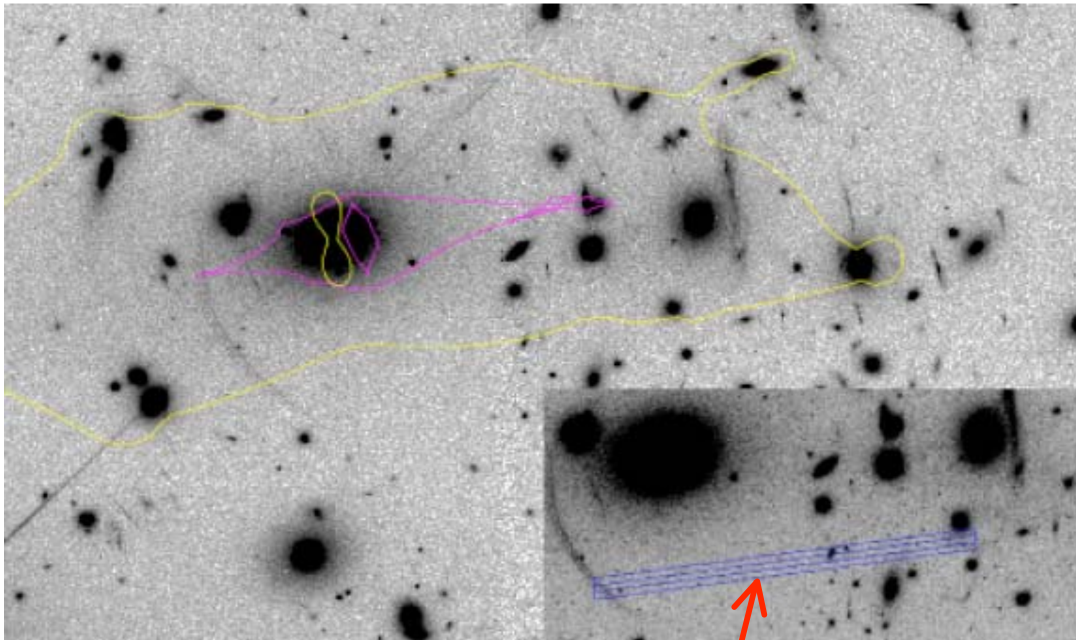
Clusters limited to those where the location of the critical line is precisely known from earlier work

Sensitive to sources magnified by at least ×20 corresponding to intrinsic SFR~0.1 $M_{\odot}$ yr^{-1}

Stark et al Ap J 663, 10 (2007)

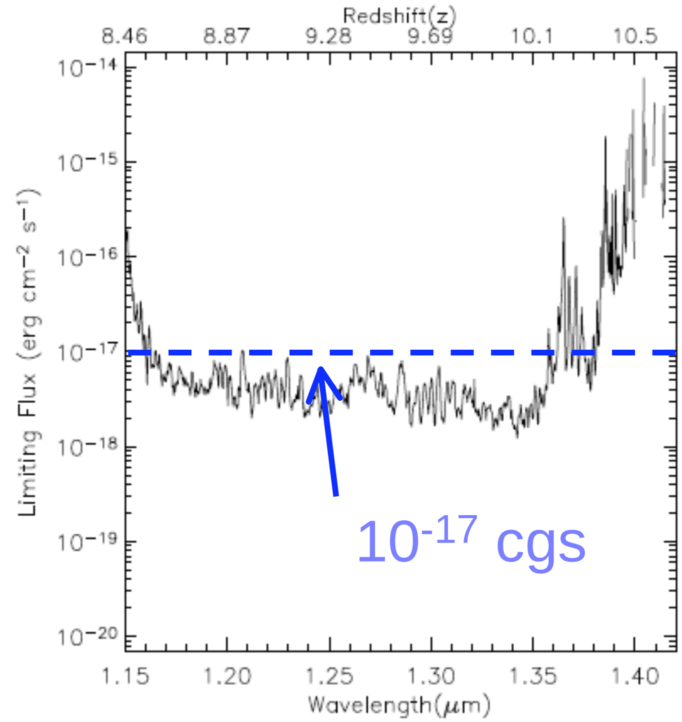
Example: Abell 2390

Cluster critical line for $z_S > 7$



NIRSPEC slit positions

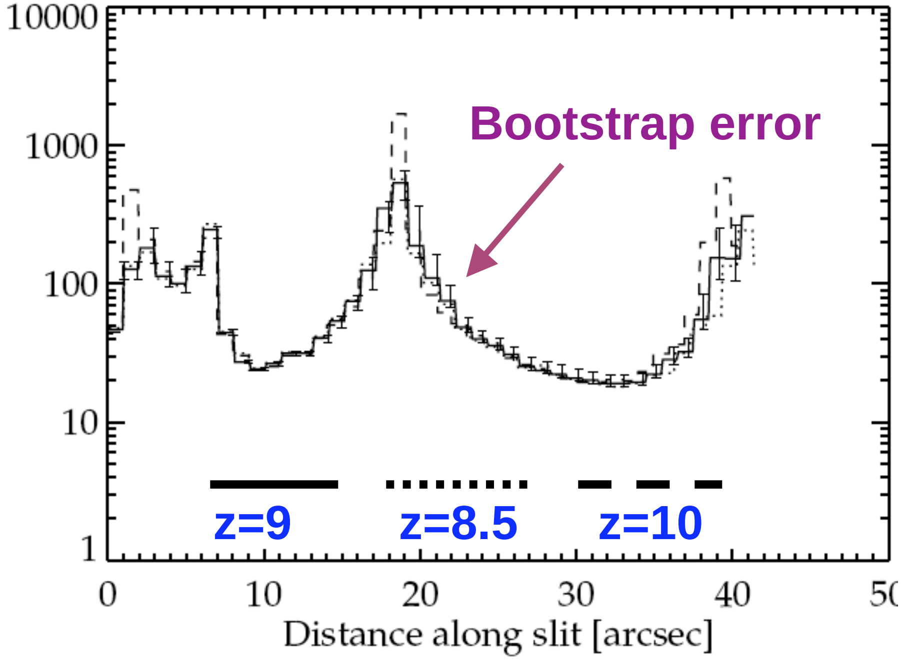
Wavelength sensitivity (1.5hr)



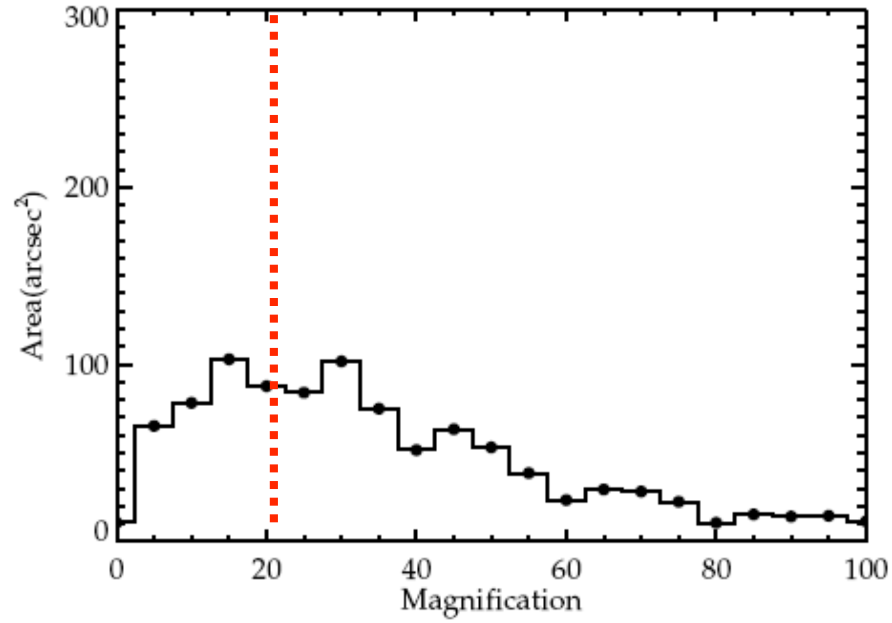
- 9 clusters with well-defined mass models & deep ACS imaging
- Obs. sensitivity ~ 3-9.10^{-18} cgs; magn. > ×15-20 throughout
- Sky area observed: 0.3 $arcmin^2$; V(comoving) ~ 50 Mpc^3
- 6 promising lensed emitter candidates (>5σ)
- $8.6 < z < 10.2$; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 -1 $M_\odot$ yr^{-1}

How Reliable are Mass Models and Magnifications?

Magnification along slit



Sky area versus magnification

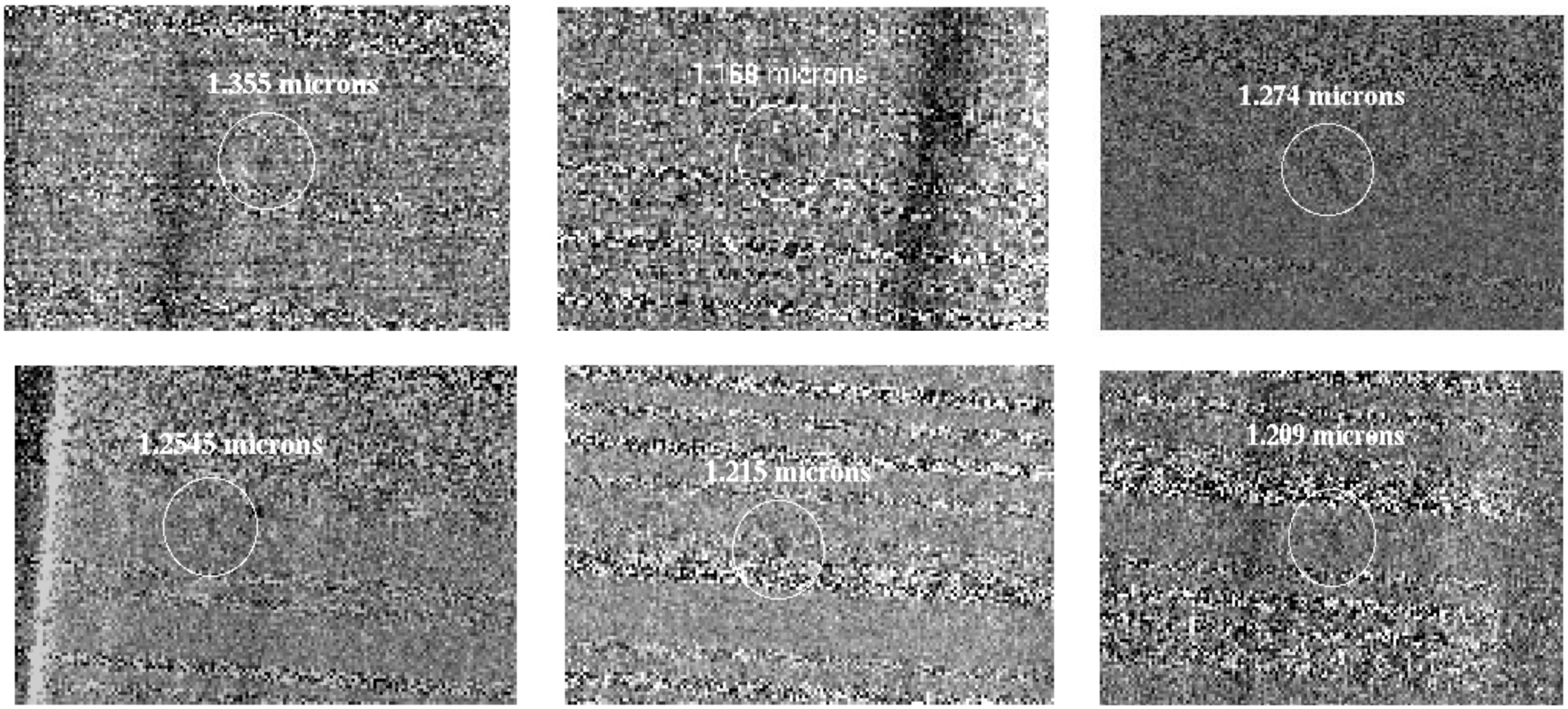


$$\mathcal{M}(\Omega, z) = \frac{1}{[1-\kappa(\Omega,z)]^2 - \gamma(\Omega,z)^2}$$

- Magnification $\mathcal{M}$ depends strongly on position Ω, less so on z
- Error in magnification $\mathcal{M}$ determined by Markov Chain MC sampling of multiple images of known spectroscopic redshift
- Bulk of survey has magnification $\mathcal{M}$ > ×20 and error in $\mathcal{M}$ is ~20%

Candidate Lyα Emitters

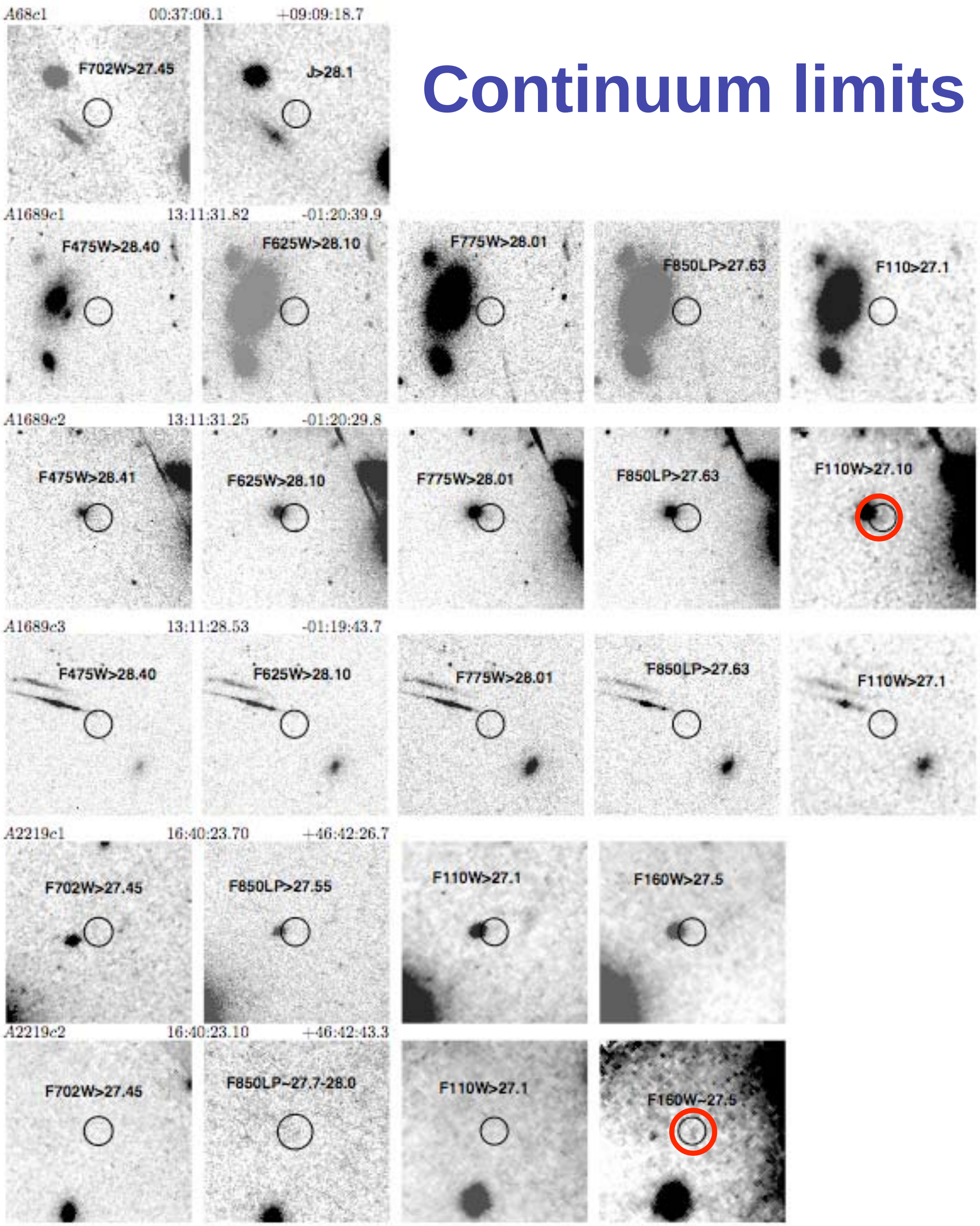
$8.6 < z < 10.2$; $L \sim 2 - 10.\ 10^{41}$ cgs; SFR ~ $0.2 - 1\ M_\odot\ yr^{-1}$



Recognize burden of proof that these are z~10 emitters is high

Each detection is > 5σ, seen in independent exposures/visits

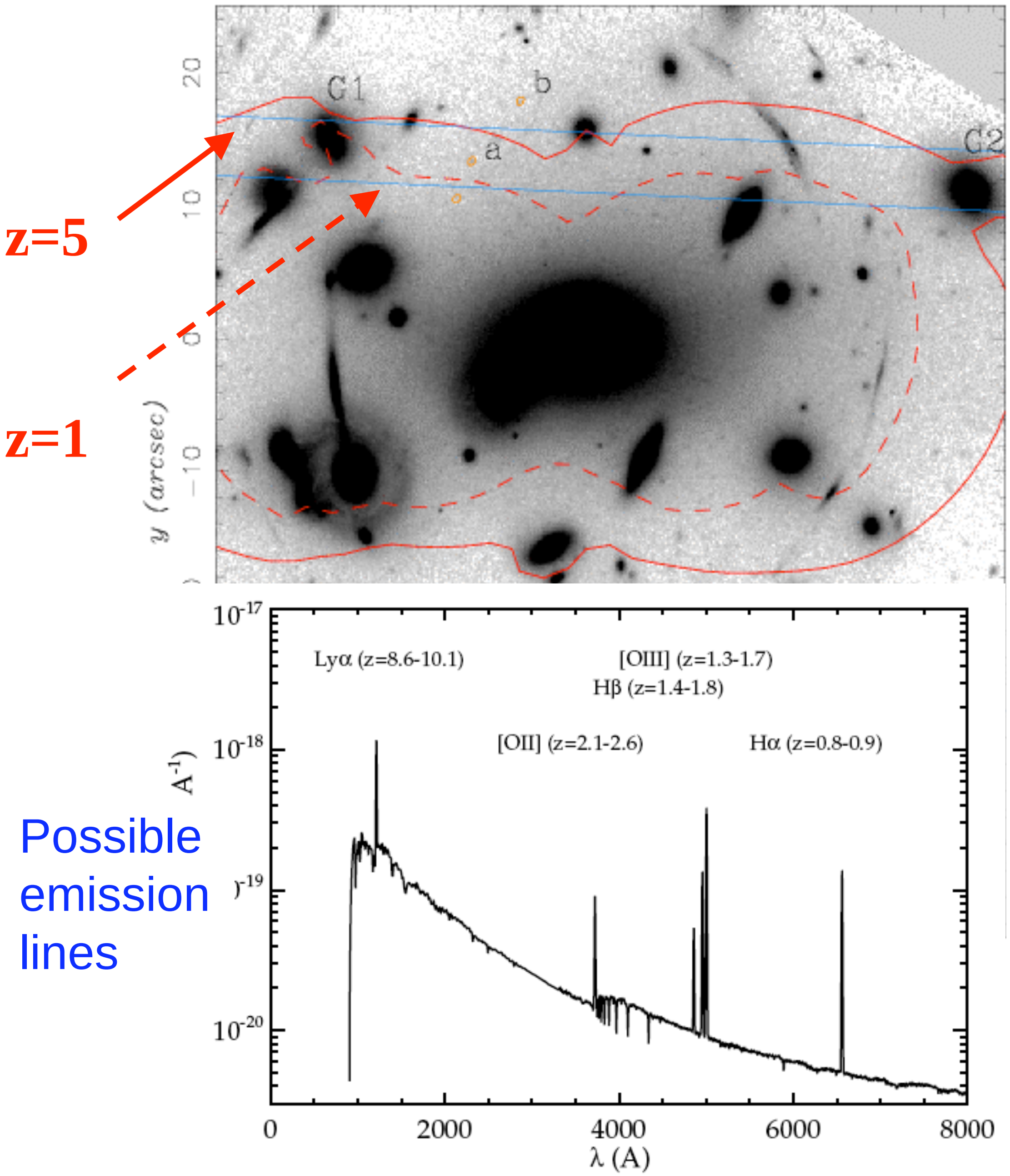
Continuum limits from z~10 candidates



Very deep ACS and NICMOS imaging is available for most clusters with z~10 candidates:

- no optical detections to $m_{AB} > 27$
- two marginal J, H detections: still consistent with high z & modest SFR

Interlopers? Critical Line Location Depends on z



<u>Bonus of strong lensing:</u>

By only searching the z>5 critical line, we minimize contamination from magnified interlopers at 1<z<3 which would lie elsewhere in the image plane.

So contamination is <u>less likely</u> than in non-lensed searches

Spectroscopic Elimination of Interlopers

Various explanations for a single emission line in the J-band

Line	Redshift	λ Lyα (μm)	λ [OII] (μm)	λ Hβ (μm)	λ [OIII] (μm)	λ Hα (μm)
Hα	0.91	0.2324	0.7124[a]	0.9292	0.9479/0.9571	1.2545
[O III]	1.51[b]	0.3047	0.9338	1.2179	1.2425/1.2545	1.6444
	1.53[c]	0.3076	0.9428	1.2297	1.2545/1.2666	1.6603
Hβ	1.58	0.3138	0.9618	1.2545	1.2797/1.2922	1.6937
[O II]	2.37	0.4093	1.2545	1.6362	1.6692/1.6854	2.2091
Lyα	9.3	1.2545	3.8388	5.0149	5.1160/5.1655	6.7708

- Deeper LRIS spectroscopy (Santos et al 2004) from 4000-9400Å eliminates Hα and [O II] as source of emission (4/6 candidates)
- H-band spectra eliminates [O III] as source (3/6 candidates)
- IRS spectroscopy (~7μm) is in progress to verify Hα at z~10 (2/6 candidates)

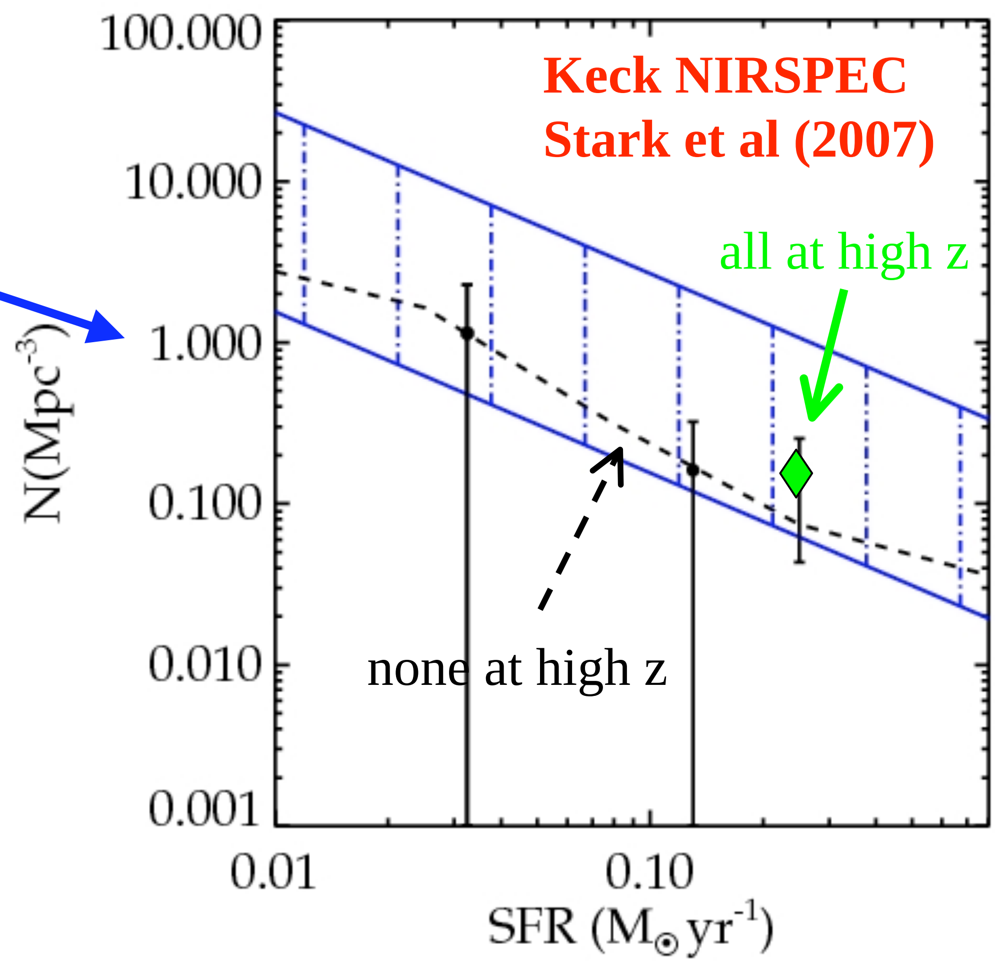
Now believe >3/6 candidates likely to be 8<z<10 sources

Did faint SF galaxies at z~10 cause reionization?

$$n = \left(\frac{B}{10}\right)\left(\frac{n_H}{10^{-7}\ \mathrm{cm}^{-3}}\right)\left(\frac{f_c}{0.1}\right)^{-1}\left(\frac{\mathrm{SFR}}{1.0\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-1}\left(\frac{n_c}{3\times10^{53}}\right)^{-1}\left(\frac{\Delta t}{575\ \mathrm{Myr}}\right)^{-1}$$

Consider range:

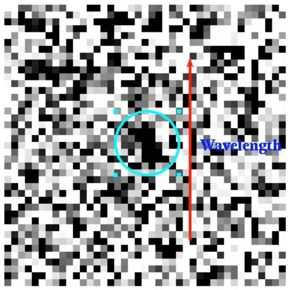
f_c ~ 0.02-0.5
Δt ~ 250-575 Myr
B ~ 5-10

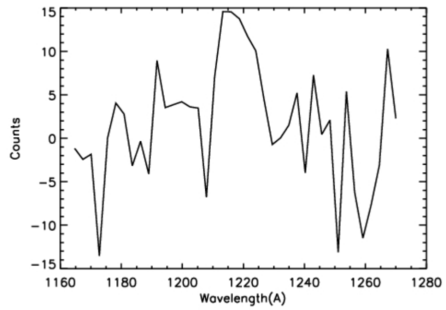


If >3 of our 6 candidates are at high z, low luminosity galaxies may play a dominant role in cosmic reionization

Further Confirmation of z>8 Candidate Lyα Emitters?

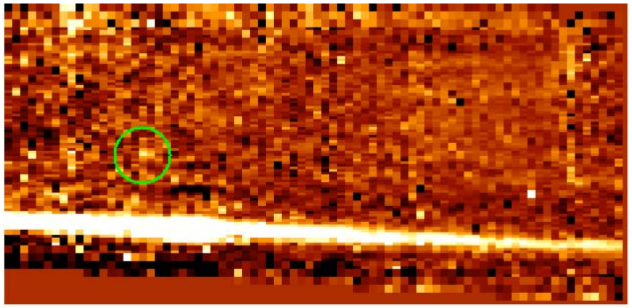
- Stacking spectra to see if line profile is asymmetric?





- NIRSPEC R~2000 too coarse
- How to centroid faint line?

- Detecting Hα at λ ~ 6 μm in deep IRS data?

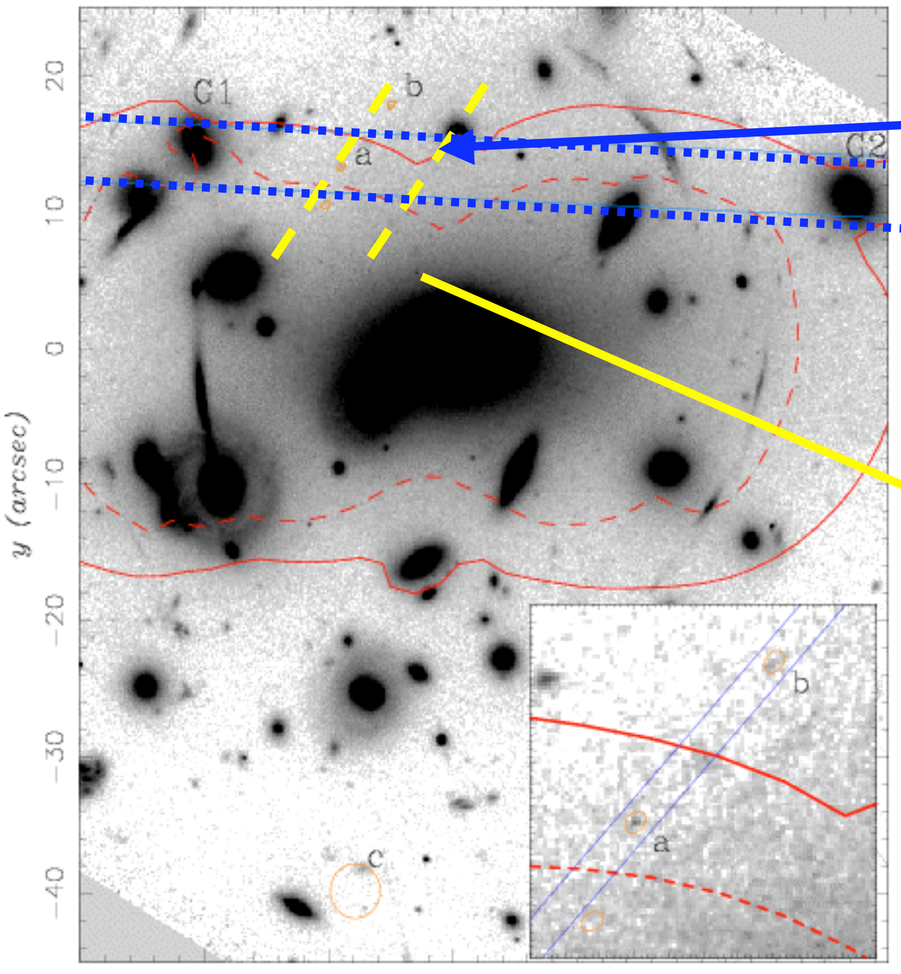


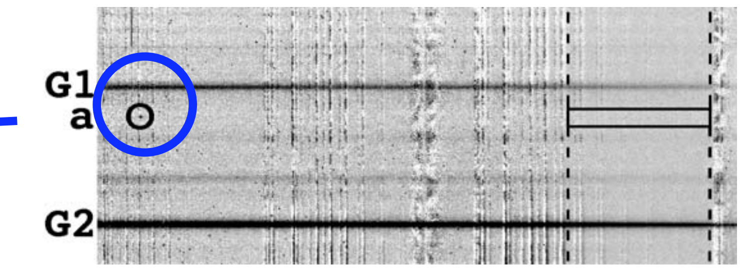
- IRS 24hr exposures of 2 candidates
- Will only see Hα if Lyα/Hα ~1, i.e. if Lyα is suppressed

- More ambitious follow-up with NIRES R~4000 echellette (requires 8-10hrs per target)…coming soon!

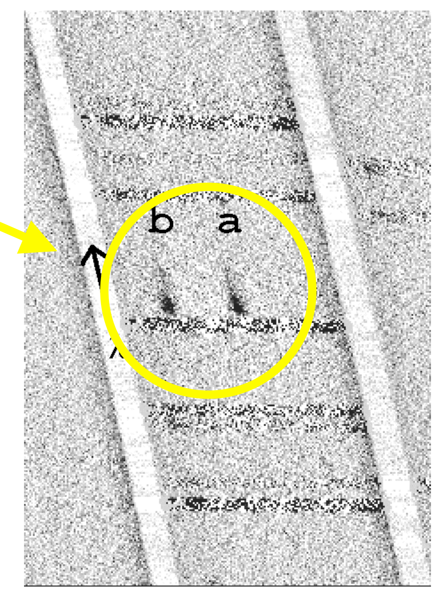
A Multiply-Imaged Source Would Be Convincing

Previous examples identified with aid of broad-band images





LRIS: Single line detection



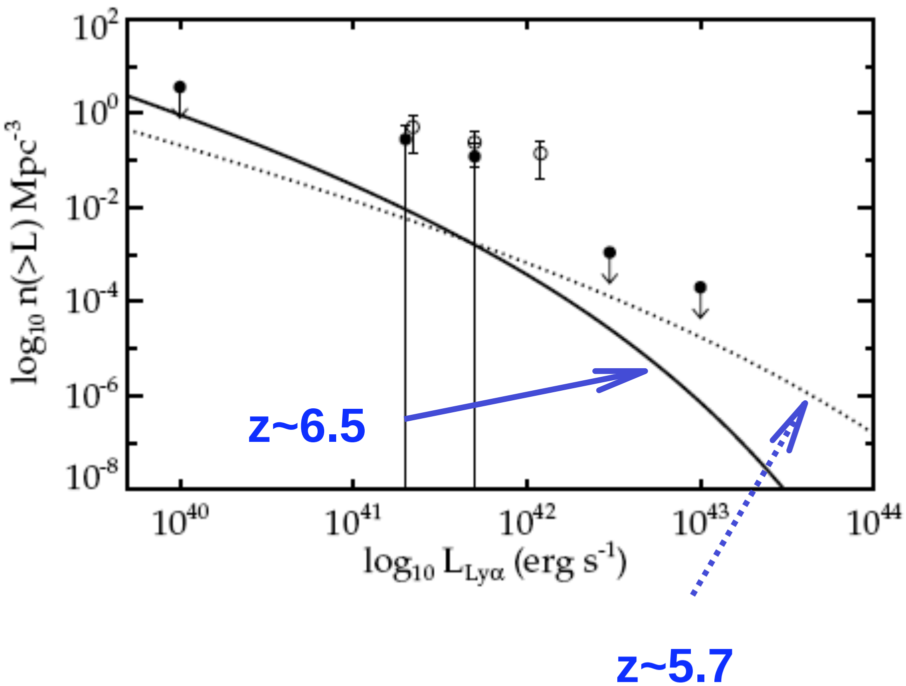
Will align slit appropriately with NIRES

ESI: Pair confirmation

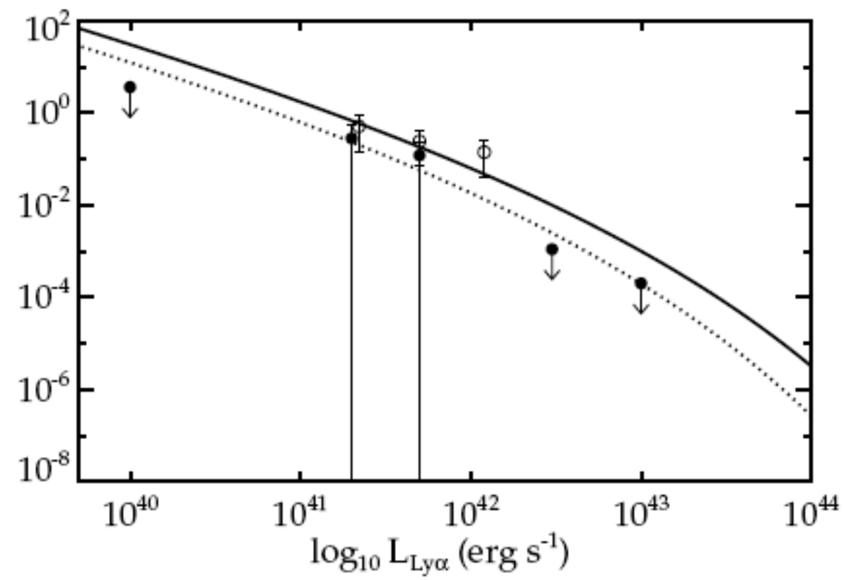
Is High Abundance of z~10 Lyα Emitters Plausible?

Predicted z~10 LF based on semi-analytic fit to lower z LFs

Standard model (f_*~0.15, ε~0.25)



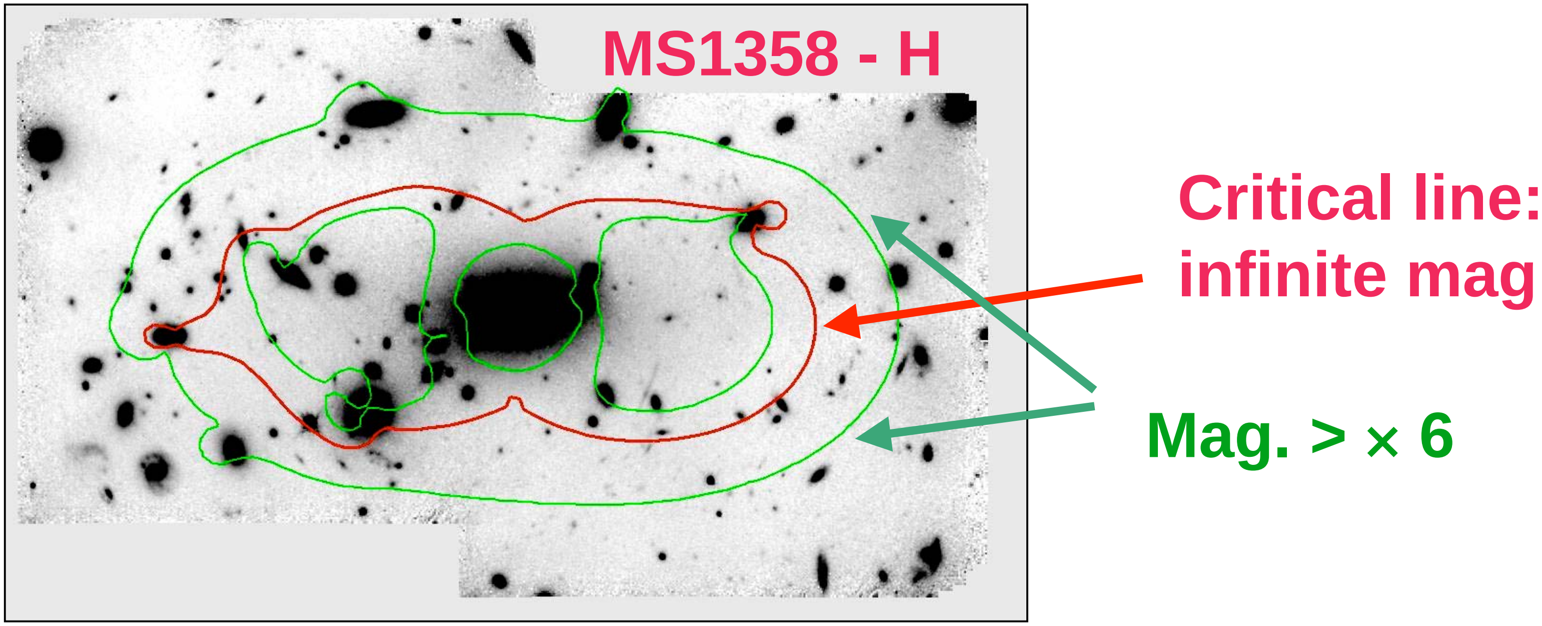
Higher SF efficiency or Pop III IMF



If 3 of the 6 candidates are at high z, the LF is only marginally consistent with semi-analytic extrapolation of that observed at z~6 but compatible with change to a Pop III (Schaerer) IMF or an increase in SF efficiency at z~10

Stark, Loeb & Ellis (in press, astro-ph/0703.xxxx)

Searching for Lensed Dropouts with HST/Spitzer



- 8 well-constrained clusters with deep IRAC imaging (Egami & Rieke)
- 11 NICMOS pointings in 6 clusters (4 orbits F110W, 5 orbits F160W)
- ACS/F850LP imaging of all 8 clusters
- K-band ground based imaging with Keck/NIRC + Subaru/MOIRCS
- 10 low luminosity z-drops (z~8) and 3 J-drops (z~10)
- Spectroscopic confirmation in progress

Richard et al (2007)

Conclusions

Lensing has achieved a lot more than cosmology!

Achievements (1987-2007):

- Opened up high redshift universe at all wavelengths
- Resolved sub-mm background
- Detailed properties of many selected $z>2$ sources
- Located (possibly) most distant sources which contribute to cosmic reionization
- Provided valuable early glimpse of ELT and ALMA science

Future prospects:

- More concerted efforts at finding $z>2$ lensed sources
- Resolved dynamics (especially with LGS AO)
- Dedicated instruments for studying lensed $z\sim10$ sources
- Thirty meter telescopes, JWST and ALMA…

Bernard Fort (1942 -)