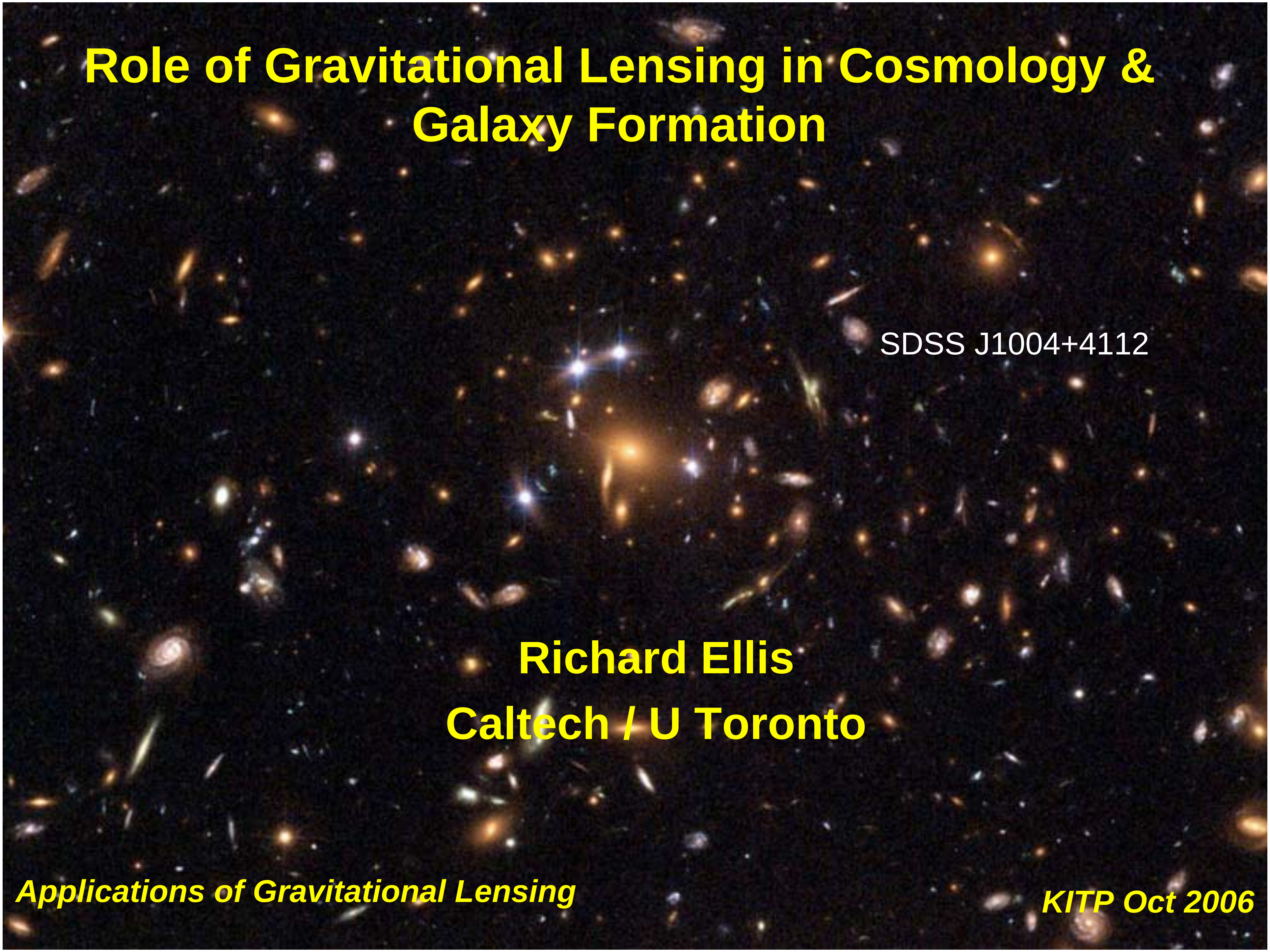
Role of Gravitational Lensing in Cosmology & Galaxy Formation



Richard Ellis

Caltech / U Toronto

Topical Applications of Strong & Weak Lensing

Q: What does the non-lensing community expect of the lensing community?

- **Dark energy:** Weak lensing is thought, by theorists, to play the crucial role in precision studies. But is this a practical proposition?
- **Dark matter:** How can lensing probe the interplay between dark and baryonic matter? Why are the current efforts controversial?
- **Distant galaxies**: Highly magnified $z>2$ galaxies can play a vital role. How can we systematically search for more?
- **Cosmic Reionization**: What are the limitations and advantages of using gravitational telescopes to chart the $z>7$ Universe? Should we be devoting more effort here c.f. blank surveys?

Dark Energy: theorists are having a field day…

***"Dark energy dynamics is perhaps the most pressing today in cosmology"* (Bassett et al 2004)**

Riess et al. 2004, ApJ, 607, 665
"Type Ia Supernova Discoveries…Constraints on Dark Energy Evolution"
w(z)=w(z,w0,w')
"Our constraints are consi
and value of w expected f
inconsistent with very rap

aastro-ph/0311622, revised Apr 2004
"Cosmological parameters from supernova observations"
Choudhury and Padmanabhan

aastro-ph/0405446
Gong
ysis of dark energy I:
t forms
zations, no firm conclusions.

astro-ph/0403292
"New dark energy constraint
supernovae, microwave back
galaxy clustering"
Wang and Tegmark
w(z)=w(z,w1,wa,etc)
"We have reported the most
measurements to date of the
density as a function of time,
universe. We have found tha
constraining power, the spec
high-z supernova measureme
no hints of departures from t
corresponding to Einstein s c
constant."

378
Padmanabhan
traints on low redshift
lark energy"
t combining the supernova
vations {\it with the
om WMAP observations}
icts any possible variation of
edshifts. The results rule out
nge in w(z) in recent epochs
letely consistent with the
constant as the source of

astro-ph/0404468
"No evidence for Dark En
Metamorphosis ?"
Jonsson et al
w(z)=summation(Ak,z), p
"For the ansatz proposed b
energy evolution is both fa
and forced...Our best fit to
additional high redshift su
consistent with the cosmol
the 68% confidence level.

7094
on the dark energy equation
recent supernova data"
,w1)
models for the equation of
ark energy will remain
a mug's game until there
ntially more data at higher
i.e., data not highly

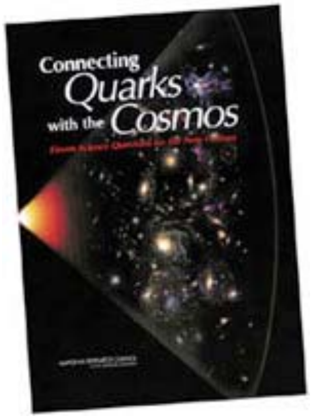
aastro-ph/0407364
"The essence of quintessence and the cost of compression"
Bassett, Corasaniti, Kunz
w(z)=w(a,a_t,w0,wm,delta); allows rapid changes
"Rapid evolution provides a superlative fit to the current SN Ia data...[significantly better than lambda]"

astro-ph/0407372
"Cosmological parameter analysis including SDSS..."
Seljak et al.
w(z)=w(a,w0,w1)
"We find no evidence for variation of the equation of state with redshift.."

astro-ph/0407452
Probing Dark Energy with Supernovae : a concordant or a convergent model?
Virey et al.
w(z)=w(z,w0,w')
Worries that wrong prior on omega_m will bias the result. Suggests weaker prior, data consistent with lambda or significant DE evolution.

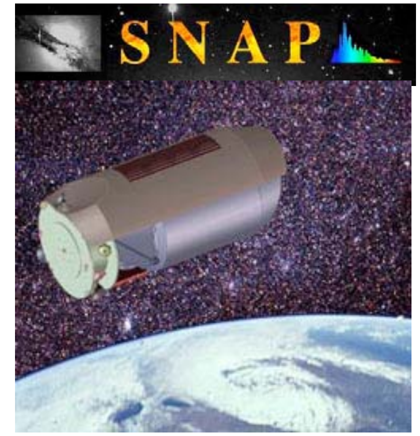
astro-ph/0408112
"Scaling Dark Energy"
Capozziello,Melchiorri,Schirone
w(z)=w(z,zb,zs); phenomenological
"We found that the current data does not show evidence for cosmological evolution of dark energy...a simple but theoretically flawed cosmological constant still provides a good fit to the data."

New Proposals for Tracking Dark Energy



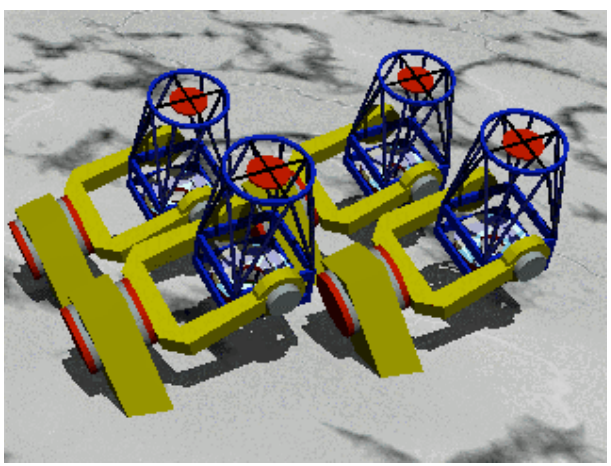
DoE/NASA initiated studies for a Joint Dark Energy space mission (JDEM, 2015+), also ESA/CNES

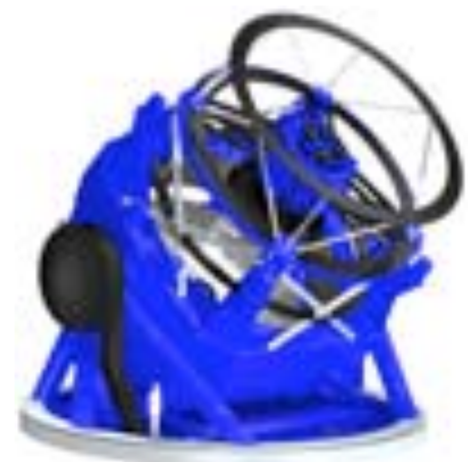
Contenders: SNAP, Destiny, ADEPT. Also GRALE/DUNE



Shorter term initiatives on the ground (DoD/DoE/NSF):

Pan-STARRS (2007) Dark Energy Survey (2009), VISTA-Dark Camera (2011), Subaru HSC/WFMOS (2012), LSST (2013+)





Should Significant Observational Resources be Devoted to DE Studies?

Positive opinions:

• Dark Energy is a very pressing problem in the physical sciences; whatever the outcome, the impact on our view of the Universe will be profound

• We can't ignore what we don't understand; this is the ultimate quest

Negative opinions:

• DE studies, if supported, would dominate our observing facilities for next 20 years & might offer improved precision without any further understanding. If $w = -1.0000$ in 2026 what will we have learned?

• DE will distract resources & young people from more tractable and fruitful astrophysical questions.

• We are becoming particle physicists: `a community chasing one goal'

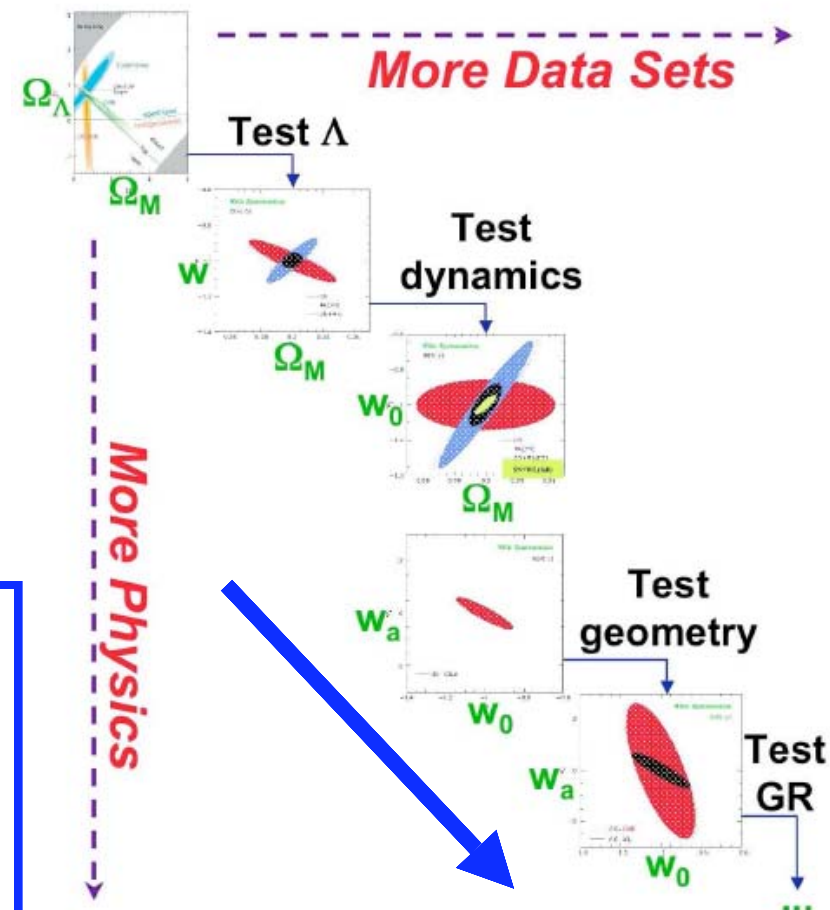
What's the Observer's Target? Stepwise Approach

- Dark energy has no agreed physical basis

  constant $\Lambda \rightarrow$ static $w \rightarrow$ dynamic
  $w = w_0 + w_a (1-a)$
  w(t) has no naturally-predicted form

- Wrong parameterization can lead to incorrect deductions: models are degenerate!

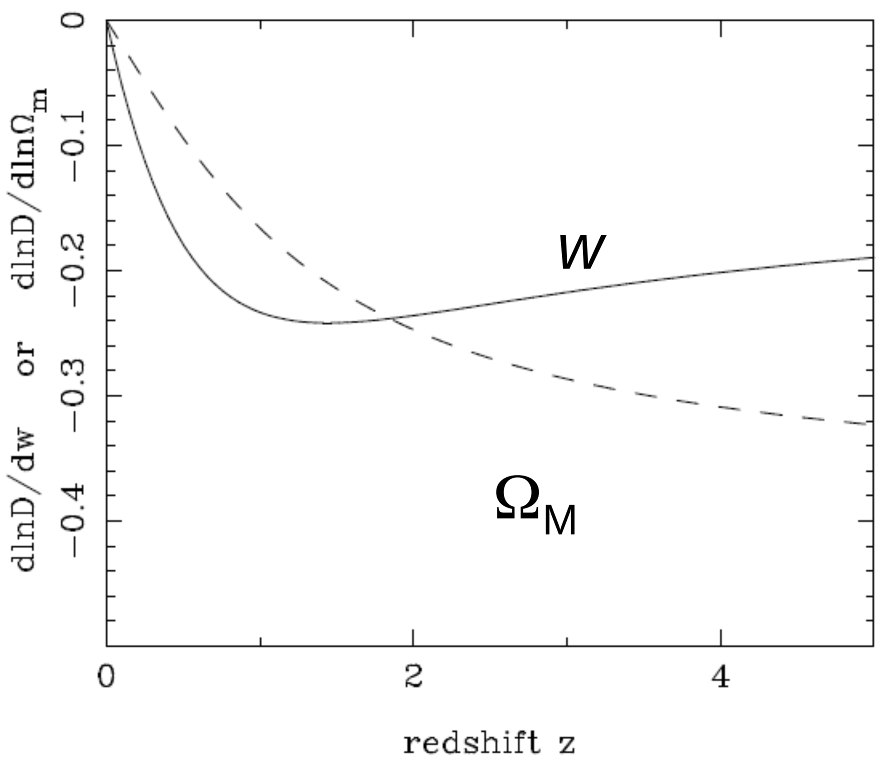
- Incremental approaches:
  - reject null hypothesis of Λ ($w \neq -1$)
  - prove via more than one method $w \neq$ const
  - derive empirical evolution a(t), G(t), $d_A(z)$, so test GR



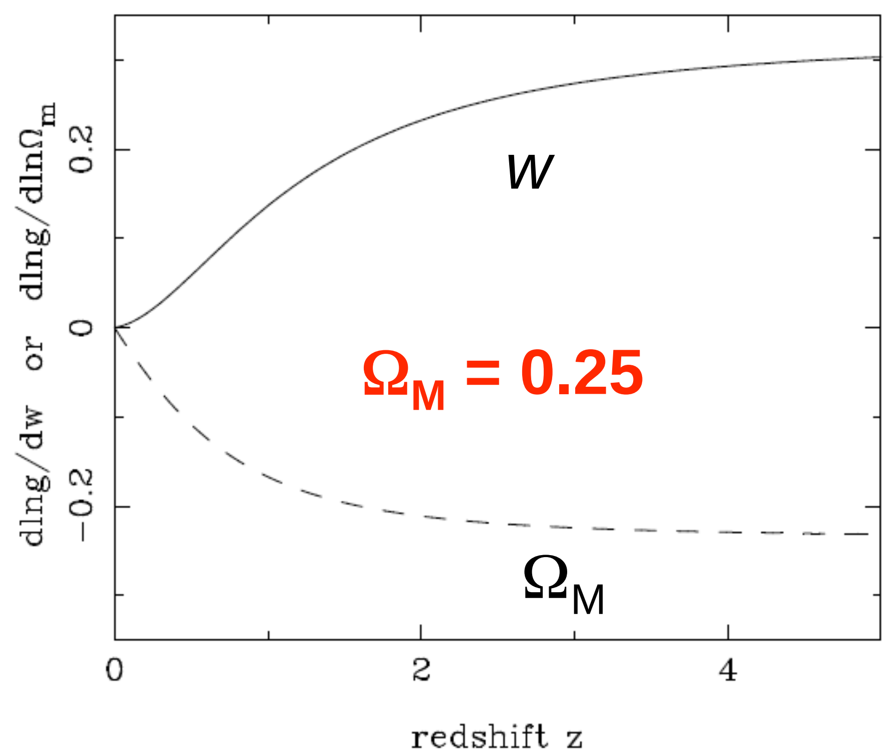
Linder (astro-ph/0511197)

Contrasting Distance & Growth-based Methods

dlnD/dw (SNe/wiggles)



dlng/dw (lensing)



D(z): not v. sensitive to *w*: 1% precision requires D to 0.2%
also *w* degenerate with changes in Ω_M

g(z): *w* has opposite effect to Ω_M
weak lensing could thus play a key role

Is Weak Lensing Going to Cut It..?

Everyone agrees WL is a promising probe….but……

Issues include:

- **Calibration**: Need to measure shear to 10^{-3} & control systematics to $10^{-3.5}$; current best methods 10 x worse. OK if we understand limitations - not clear we do, much work needed (STEP project: Heymans & Massey)
- **PSF correction:** Ground versus space: is space required? (Refregier et al AJ 127, 3102, 2004)
- **Redshift distributions**: require accurate N(z) for background populations (see van Waerbeke et al astro-ph/0603696 for appraisal of issues)
- **Intrinsic Alignments:** e.g. due to tidal torques; ~few % effect mitigated by down-weighting very close pairs or using photo-z information (Heyman & Heavens MN 339, 711 (2003)
- **Shear-Galaxy Correlations:** Subtle bias first noticed by Hirata & Seljak, Phys. Rev D, 70, (2004) due to possible correlation of foreground galaxy with density enhancement which could contaminate cosmic shear at 10% level for typical surveys (Heymans et al (astro-ph/0604001).

Not just simulations but direct observational comparisons

Shear Testing Evaluation Project

Blind comparisons on simulated datasets (Heymans & Massey)

Author	Key	Method
Bergé	JB	Shapelets (Massey & Refregier 2005)
Clowe	C1	KSB+ (same PSF model used for all galaxies)
Clowe	C2	KSB+ (PSF weight size matched to galaxies')
Hetterscheidt	MH	KSB+
Hoekstra	HH	KSB+
Jarvis	MJ	Bernstein & Jarvis (2002)
Jarvis	MJ2	Bernstein & Jarvis (2002) (new weighting scheme)
Kuijken	KK	Shapelets (Kuijken 2006)
Mandelbaum	RM	Reglens (Hirata & Seljak 2003)
Nakajima	RN	Bernstein & Jarvis (2002) (deconvolution fitting)
Paulin-Henriksson	SP	KSB+
Schirmer	MS1	KSB+ (scalar shear susceptibility)
Schirmer	MS2	KSB+ (tensor shear susceptibility)
Schrabback	TS	KSB+
Semboloni	ES1	KSB+ (shear susceptibility fitted from population)
Semboloni	ES2	KSB+ (shear susceptibility for individual galaxies)

PSF correction scheme \ Shear measurement method	Moments	Fitting
Subtraction	KSB+ (various) Reglens (RM) RRG* K2K* Ellipto*	BJ02 (MJ, MJ2)
Deconvolution	Shapelets (JB) im2shape*	Shapelets (KK) BJ02 (RN)

STEP1 (Heymans et al, astro-ph/0506112): ellipsoidal ground-based data

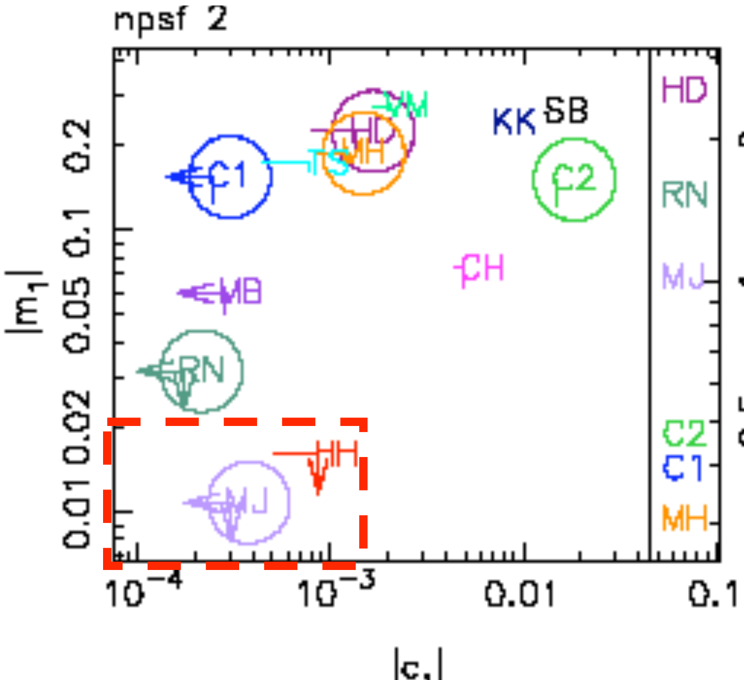
STEP2 (Massey et al, astro-ph/0608643): shapelet ground-based data

STEP3 (in progress): shapelet space-based data

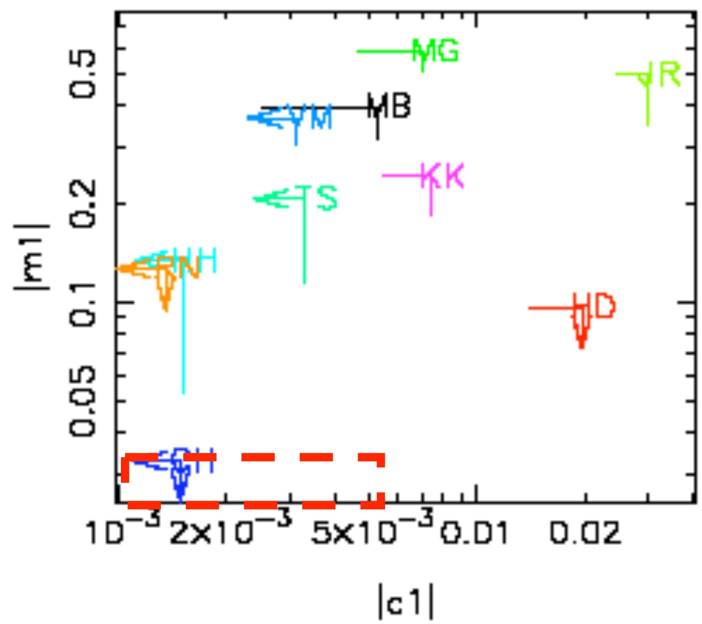
Testing Shear Codes with Simulations

$$\Delta\gamma = m_1\gamma + c_1$$

Ellipsoidal simulations



Shapelet simulations



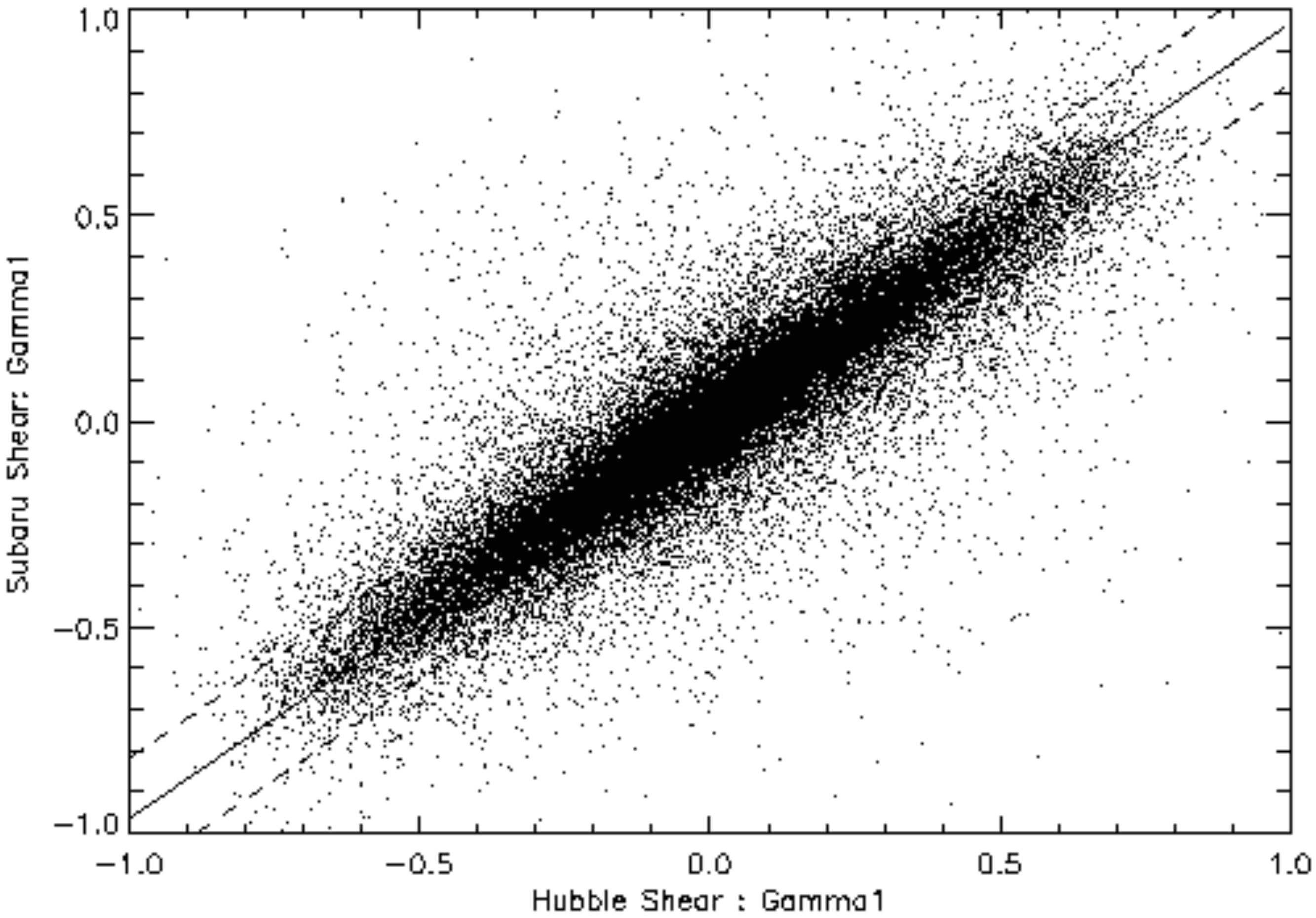
Can we understand the results?

• Groups with acceptable results with one form of simulation perform poorly on another (more realistic?) type - why?

• Many modified algorithms offer no apparent gain over classical formalism (KSB) - why?

Heymans et al ; Massey et al

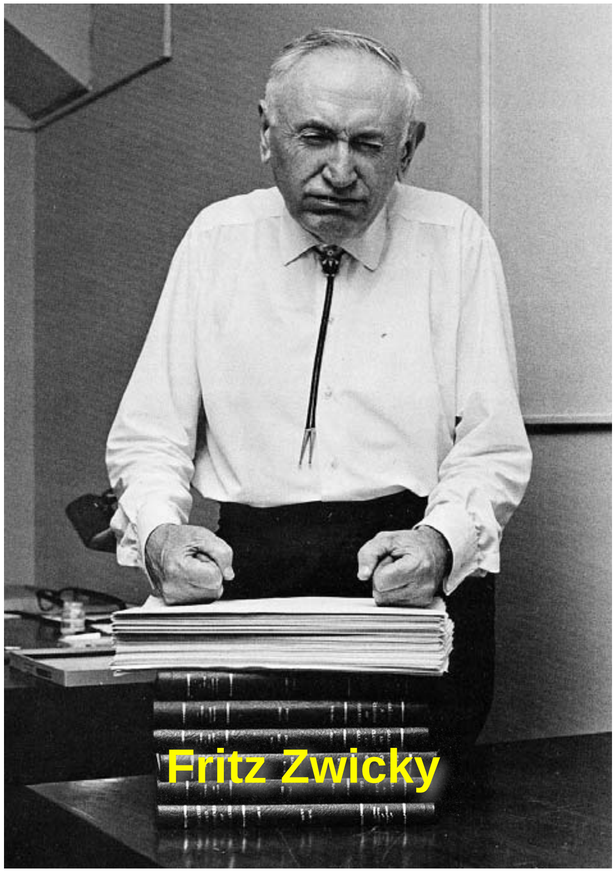
Ground vs Space: Shear-Shear Comparison



COSMOS field 2 deg^2

Kasliwal et al, in prep

Dark Matter

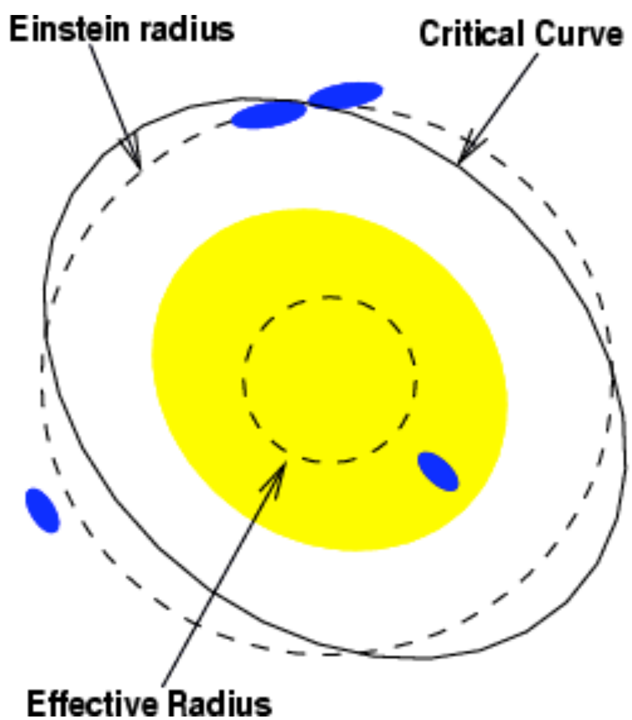


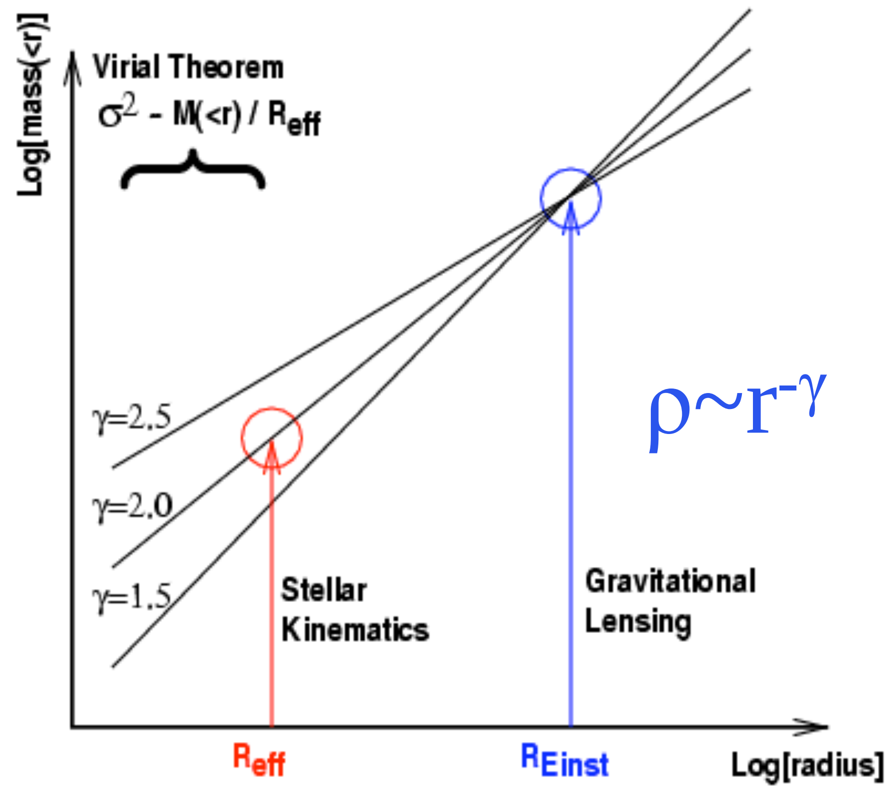
Key role of strong & weak lensing:

- DM distribution on large & small scales

- Relation to baryons: separate using dynamics

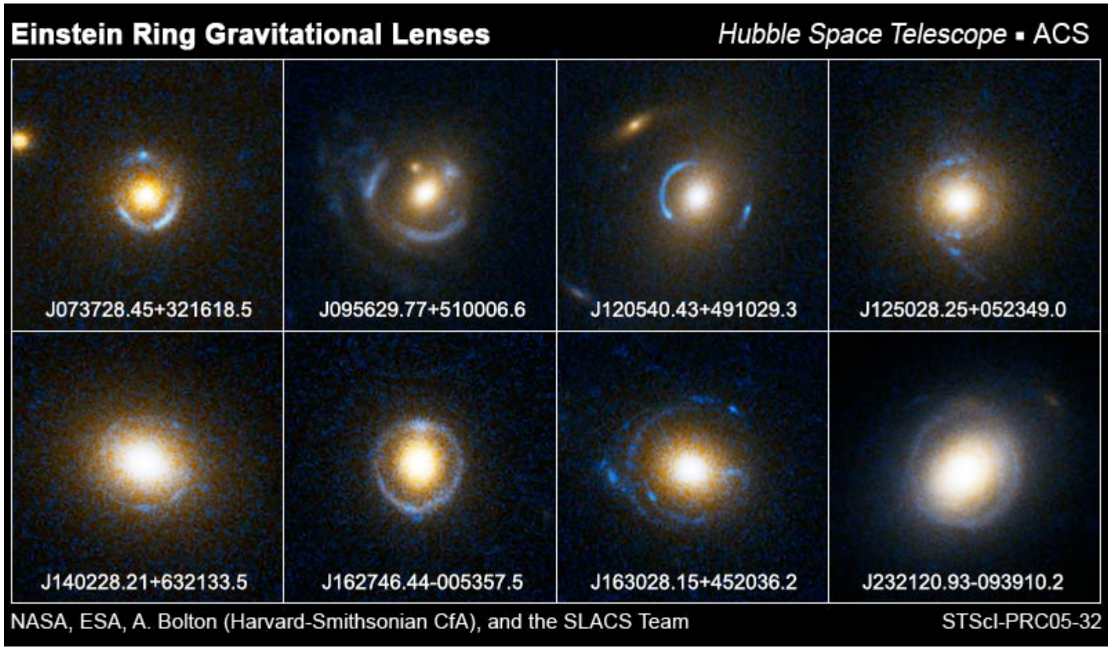
Combining Lensing & Stellar Dynamics: I

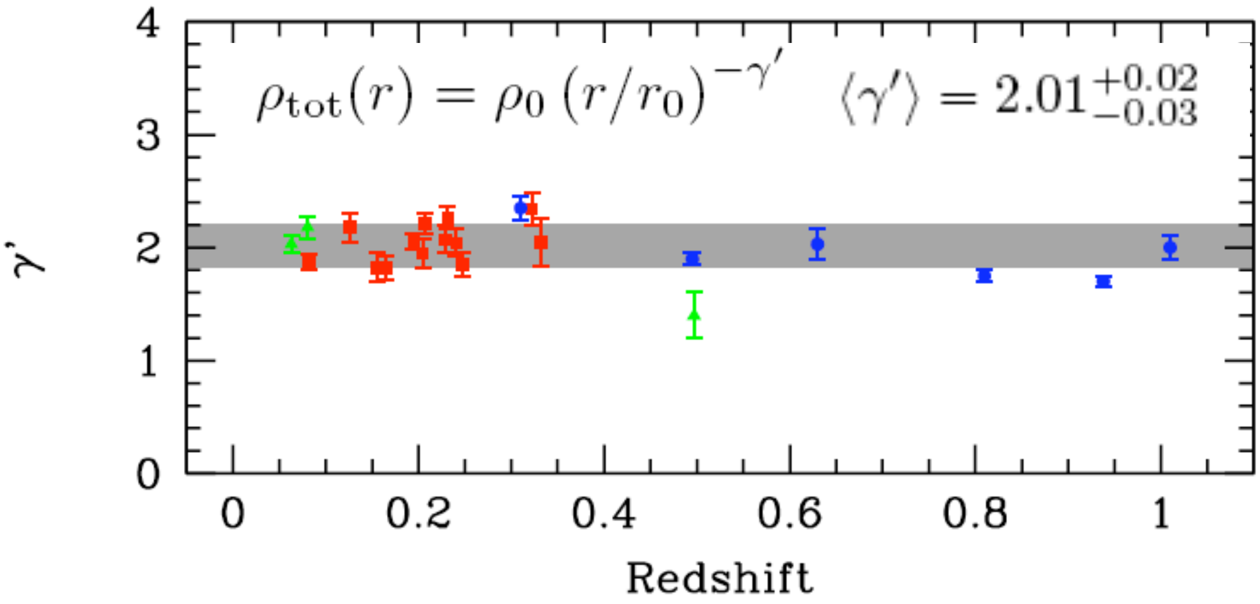




On galactic scales, lensing and stellar dynamics provide complementary constraints on the mass distribution. In combination, therefore, they constrain the slope, γ, of the total mass distribution and can be used to separate baryonic and DM distributions

SLACS: DM as f (L, z)

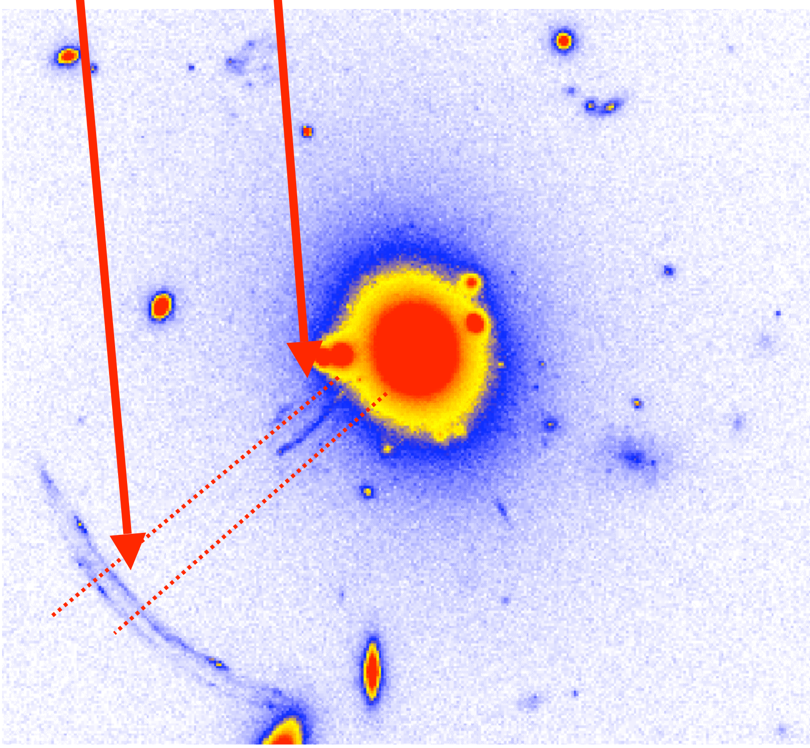




Combining Lensing & Stellar Dynamics: II

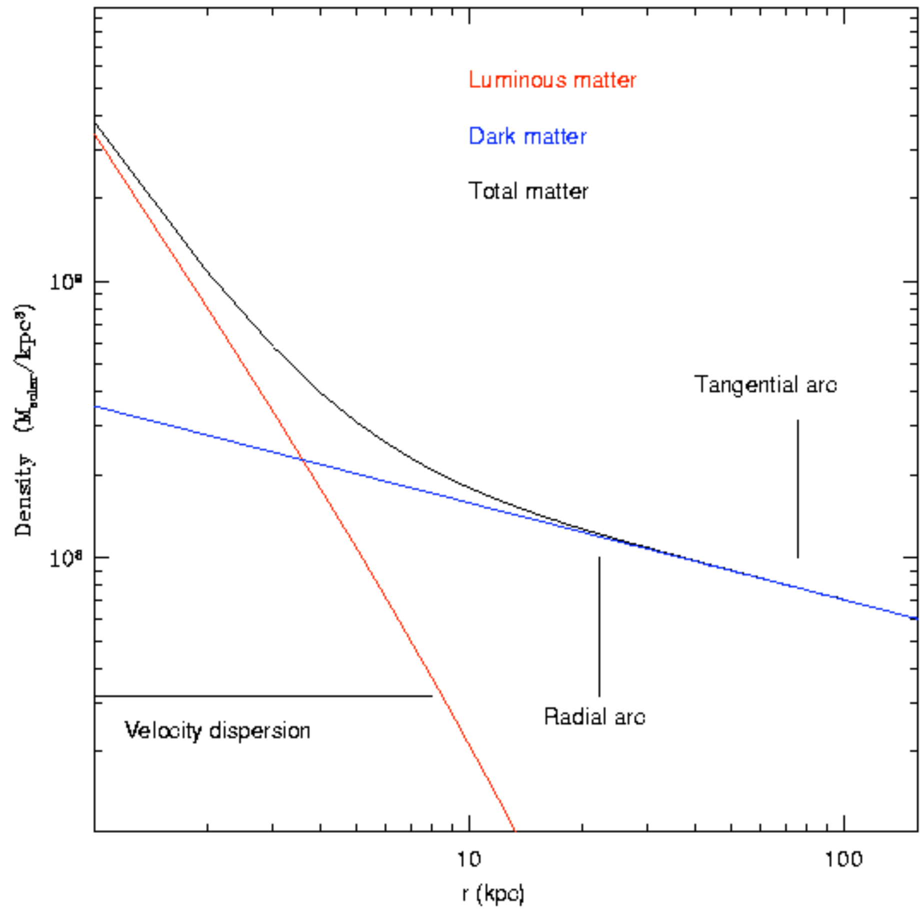
Tangential: M(<r)

Radial: dM/dr



MS2137-23 (z=0.313)

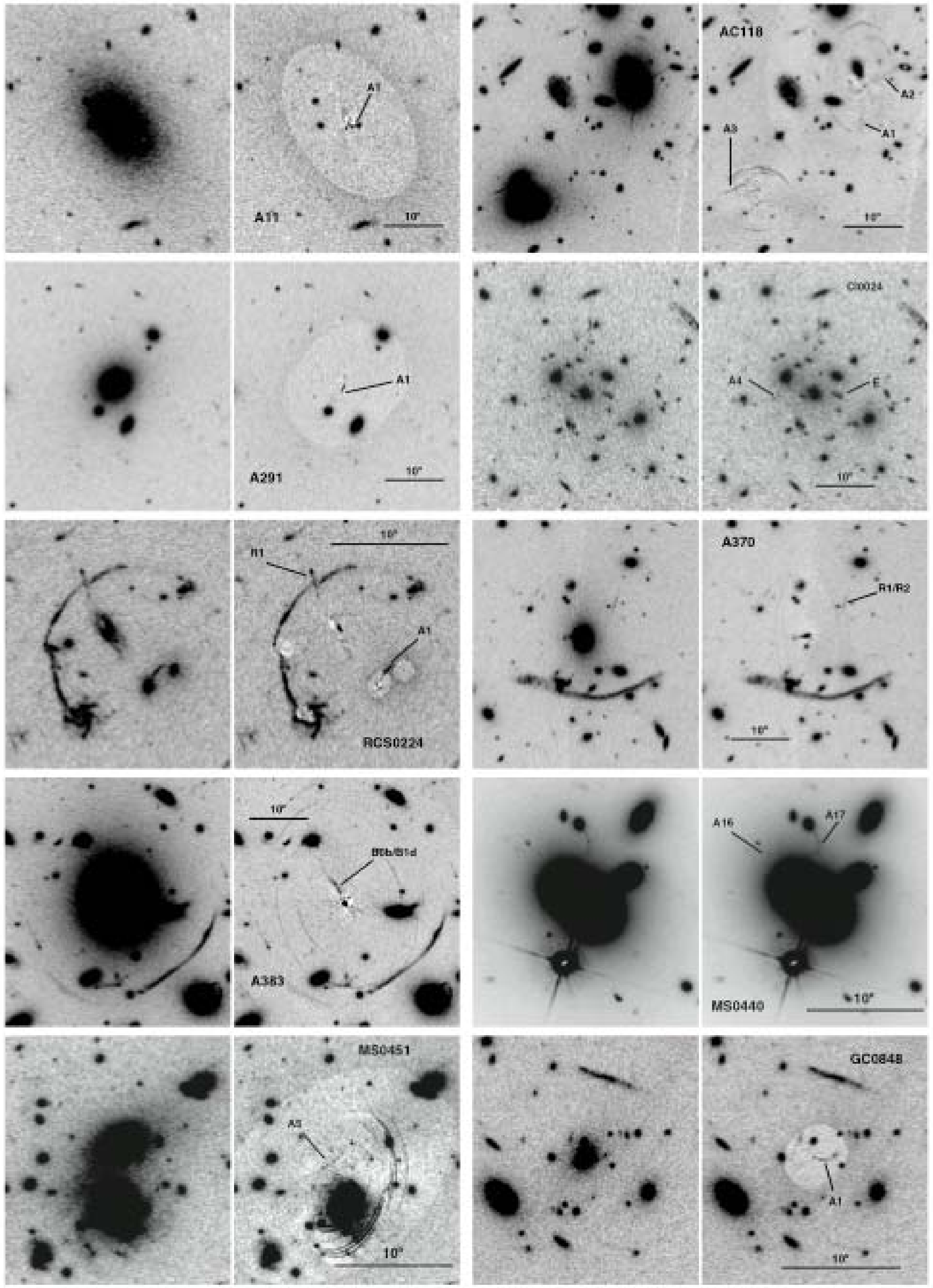
Sand et al



Separating baryons and DM in cluster cores

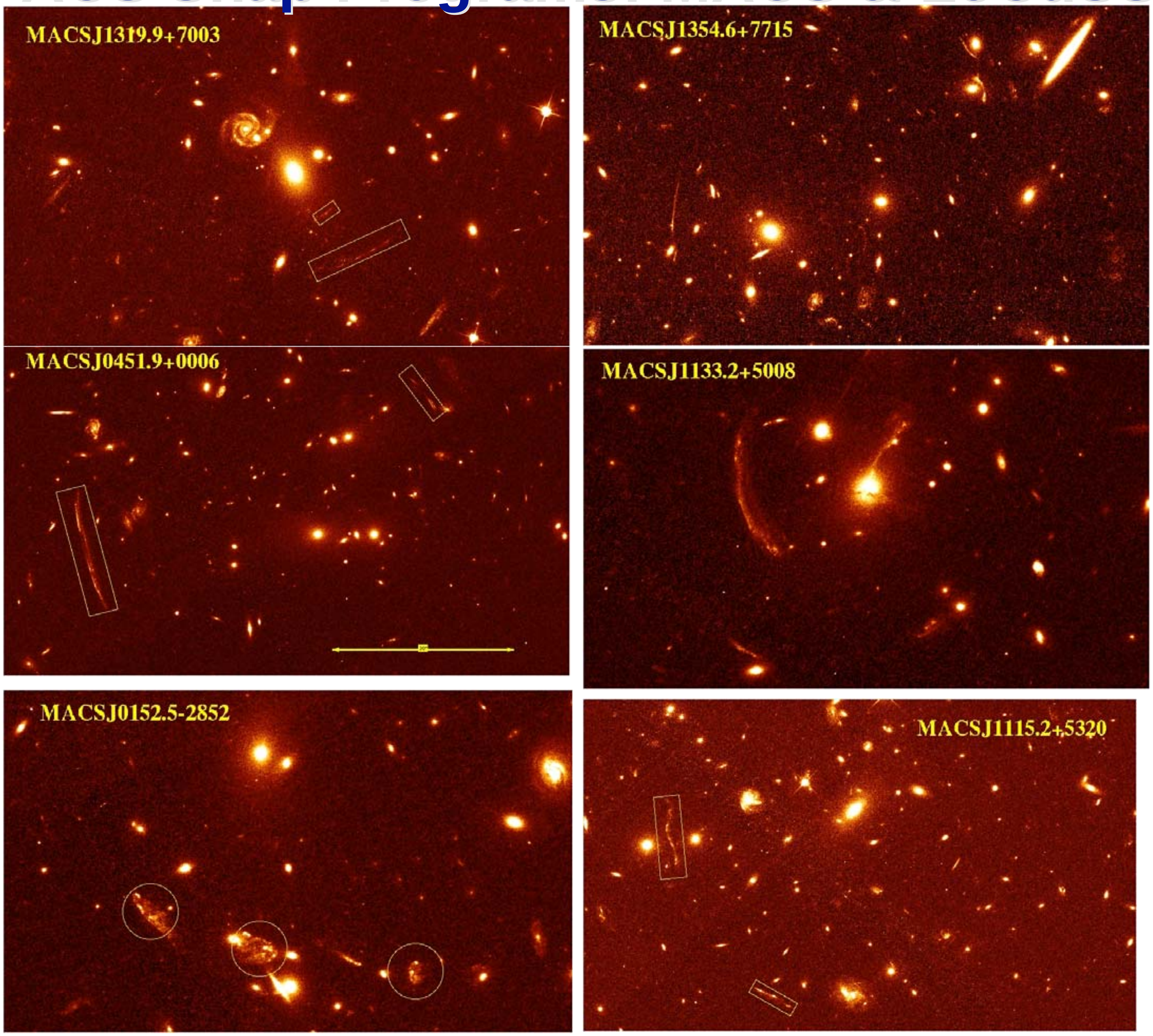
Hubble WFPC2 Archive

- 129 HST clusters
- 105 tangential arcs
- 12 radial arcs
- Key uncertainties:
  BCG mass,
  asymmetries,
  substructure
- Survey worthwhile



Sand et al (2005)

Great Progress Will Follow Spectroscopic Followup of ACS Snap Programs: MACS & LoCuSS

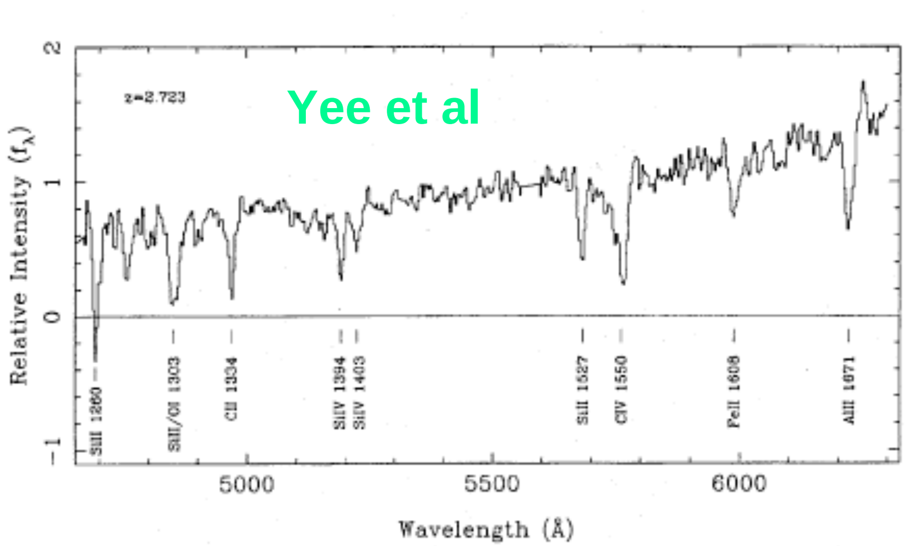


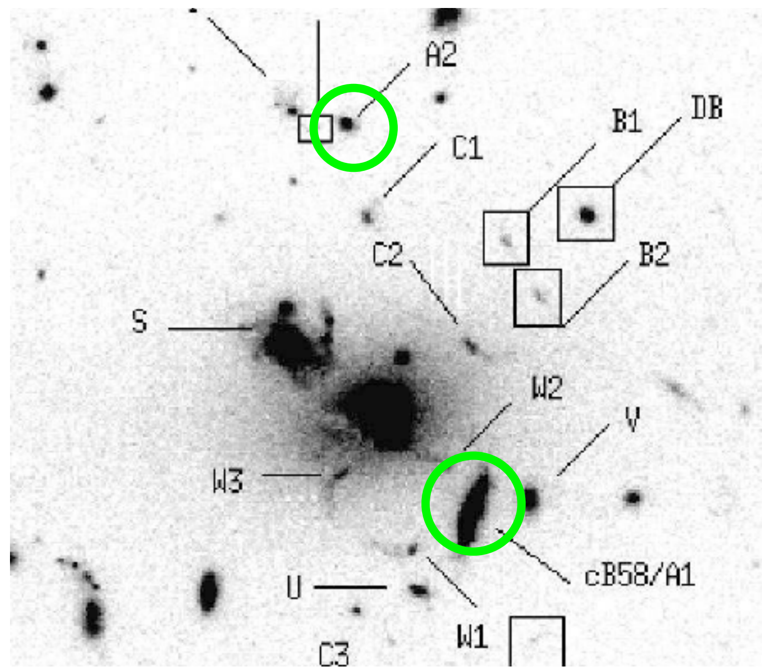
Distant Galaxies: cB58 - the first lensed LBG

Yee et al (1996): serendipitous discovery of z~2.72 V=20.5 source during CNOC cluster survey

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

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

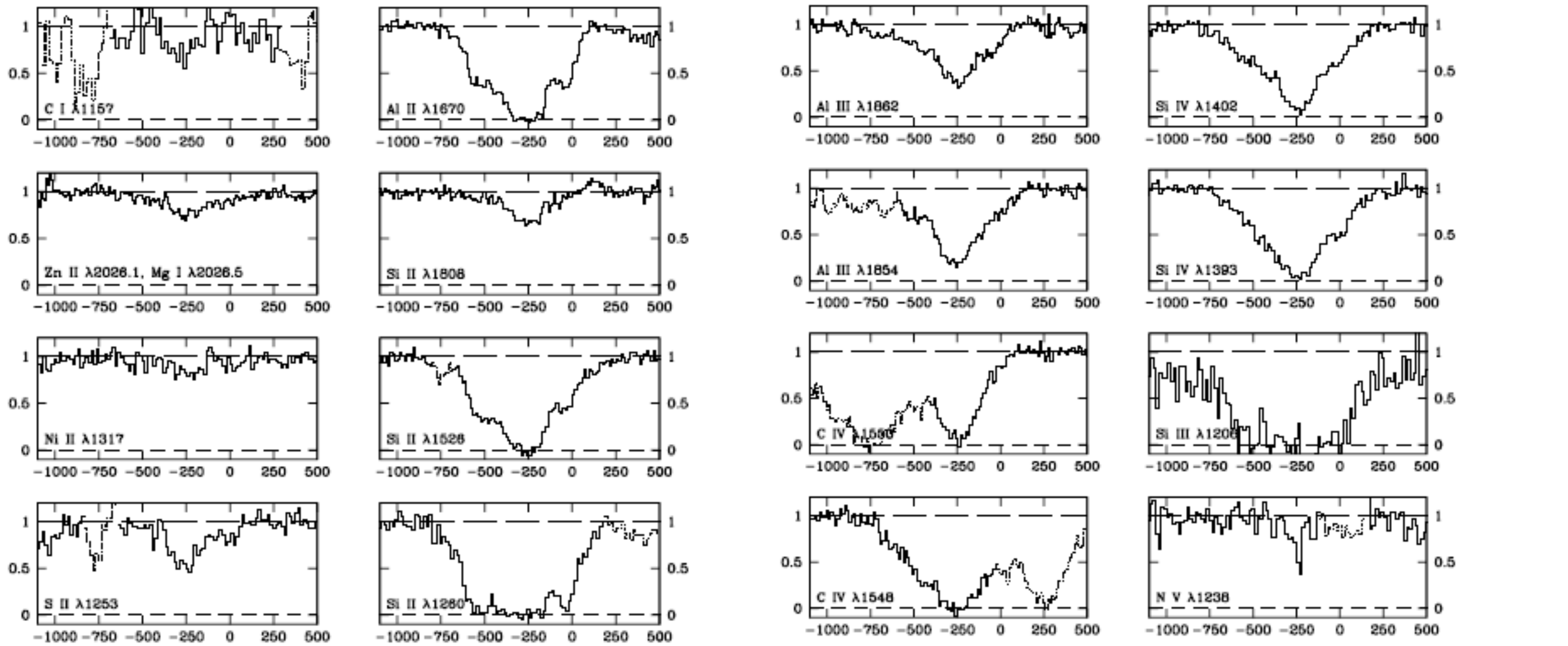




See also Rowan-Robinson et al (1991) IRAS 10214+4724 z=2.286 Lensed AGN mag ~ × 50

Keck ESI spectrum of cB58 (Pettini et al 2002)

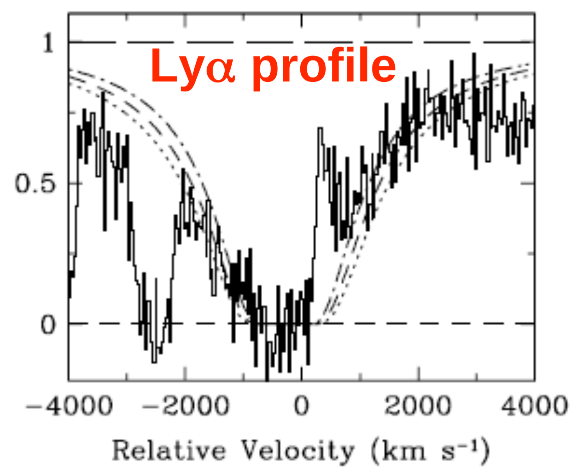
Low ionisation **High ionisation**



ESI: 10 orders, 4000Å -1μm,11.5kms/s/pix

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

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

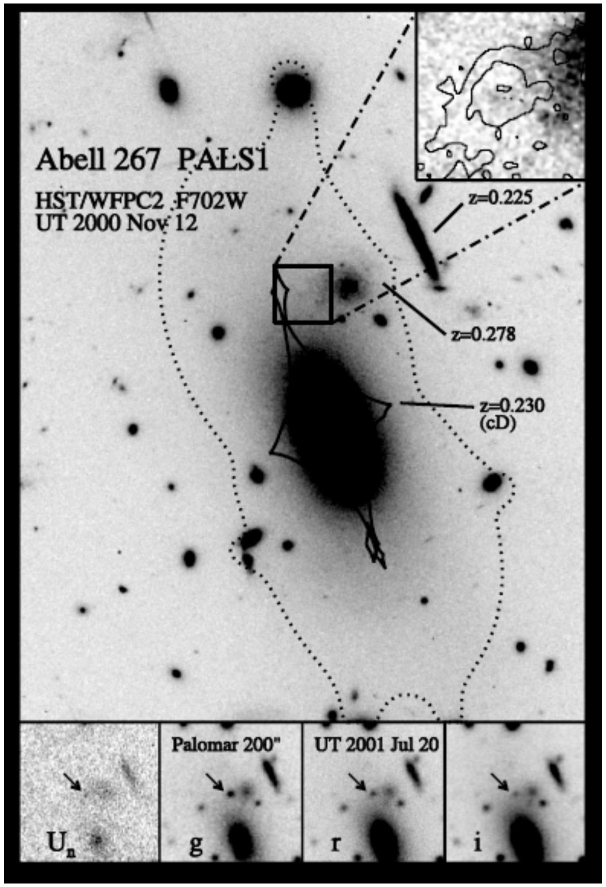


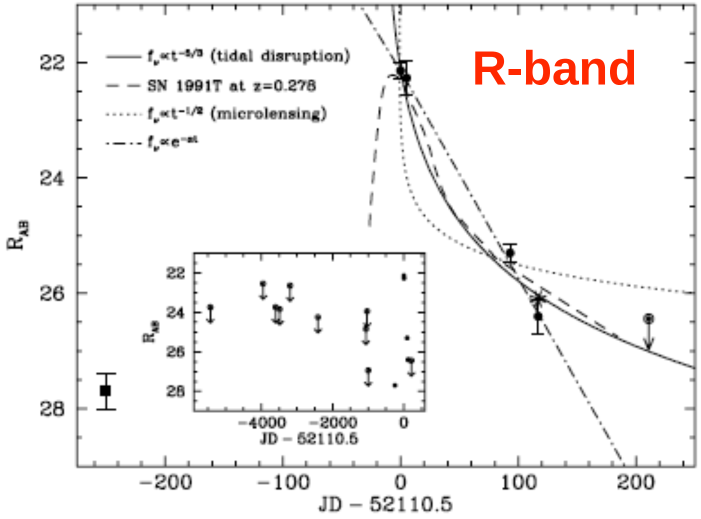
Can we find more examples of lensed LBGs?

Systematic Searches for Lensed LBGs

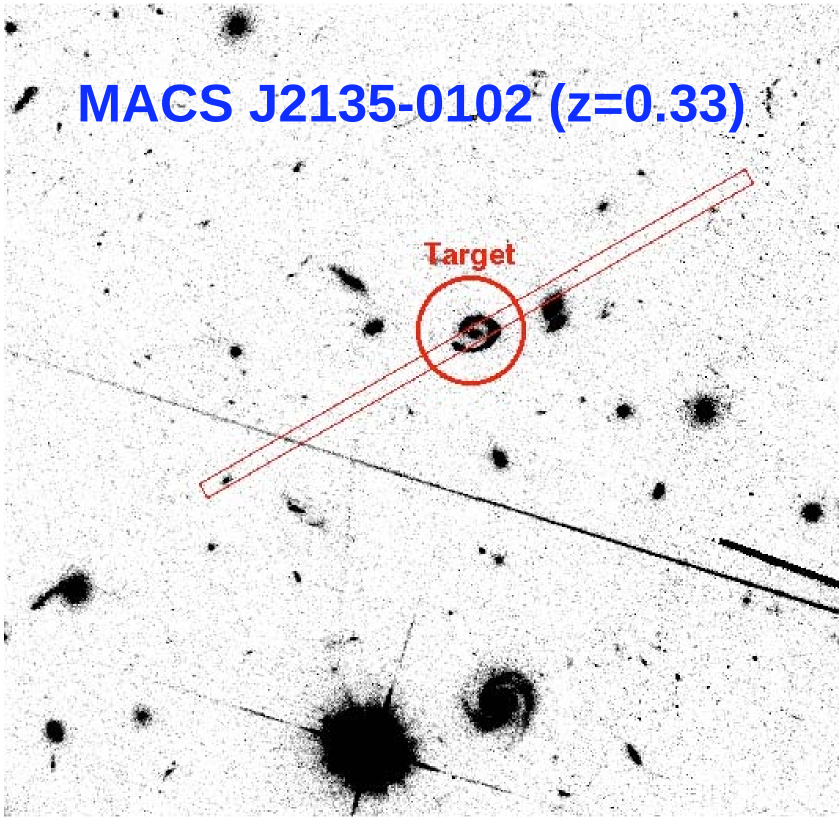
Palomar Amplified Lyman Break Survey (PALS)

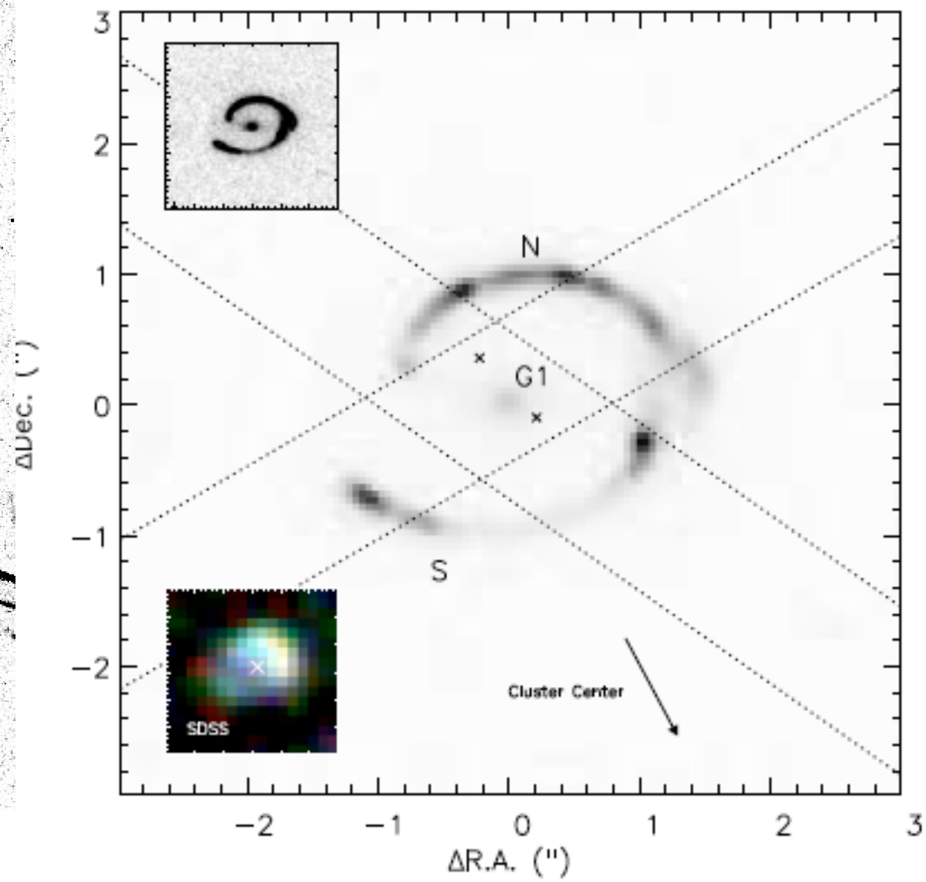
- Ugri snapshot imaging of ~100 X-ray selected lensing clusters (PI: Dave Sand)
- To first locate LBGs at Palomar, Steidel used15000s (U), 10000 (g), 5000s (r, i)
- To find magnified examples, we used 900s (U), 600s (g), 240s (r, i)
- But despite two years of searching, no more lensed LBGs were found (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'



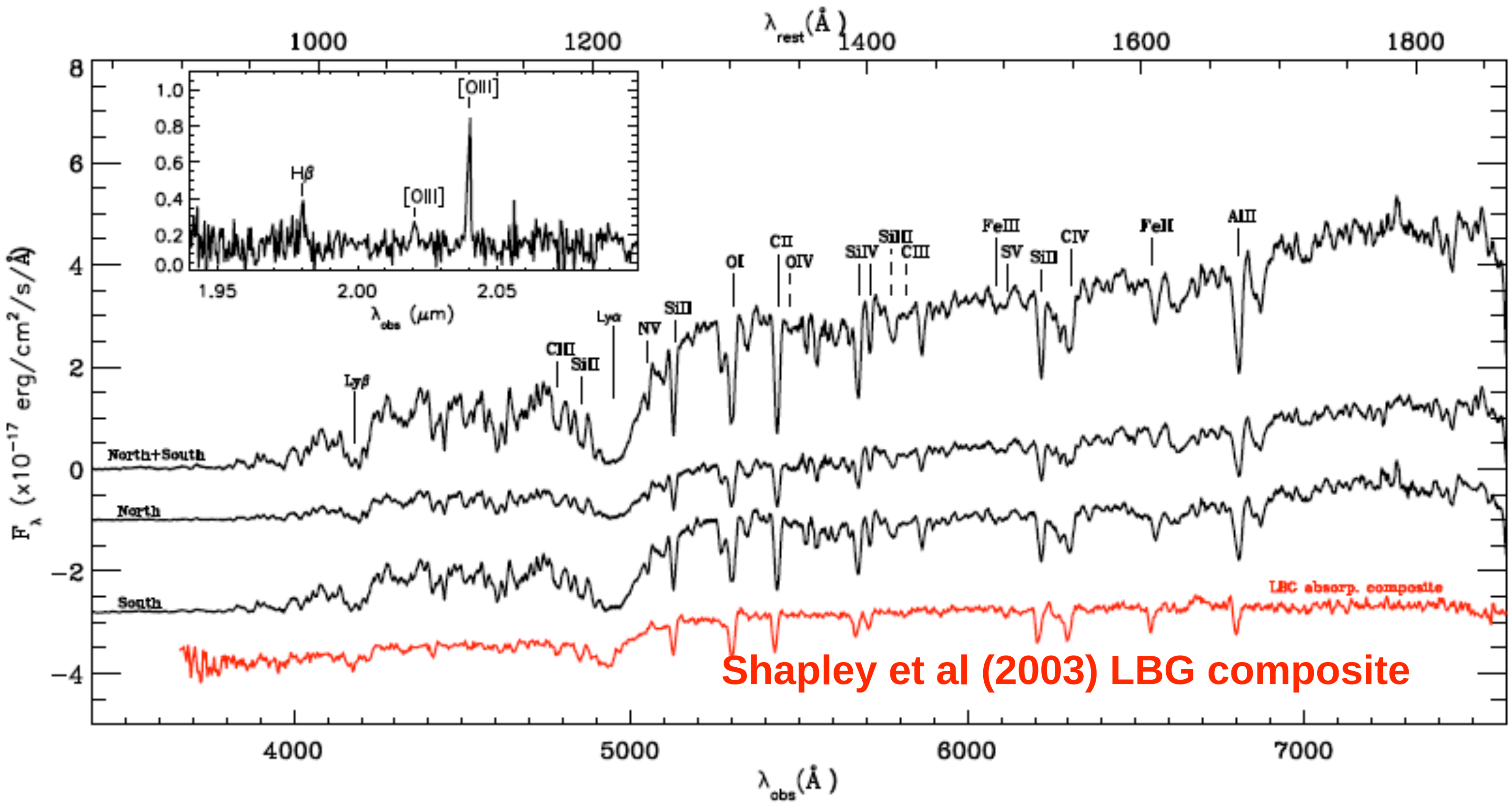


HST snapshot F606W imaging of MACS clusters (PI: Ebeling)

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

Named after the Egyptian `Eye of Horus'

Keck Follow-up



LRIS (JR): June 30, 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 (DPS/RSE): July 24, 40m, [O III], Hβ emission, z=3.0743(±1)

NIRC-K (JR): July 4, 1000s, R_{606}-K colors of arcs identical, K(G1)=19.7 (L*)

Upshot: A Typical LGB Magnified by ×30

Mass model (Kneib et al, in prep) using *LENSTOOL*:

- z~3.07 LGB pair lensed by a combination of a L^*_K z=0.73 galaxy and a z=0.33 cluster
- Einstein radii of arcs ~1.0 arcsec (c.f. 0.73 arcsec implied for G1 alone)
- Boosting by cluster is ~30% effect
- Cluster shear accounts for non-concentric nature of two arcs
- Provisional model gives mag = × 30 ± 5
- Two sources are 1.5 kpc apart in source plane (and <1kpc in size)

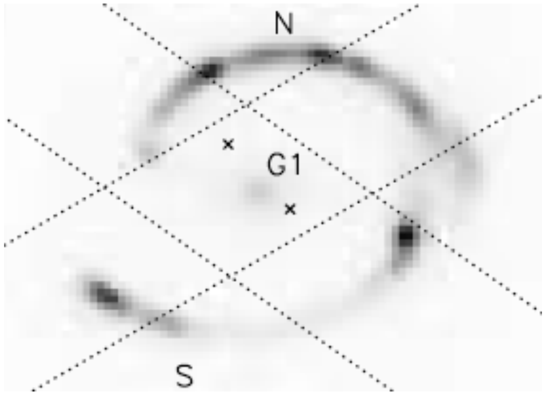
LGB properties

Correcting for lensing, L_K = 22.6 ± 0.2 (AB)

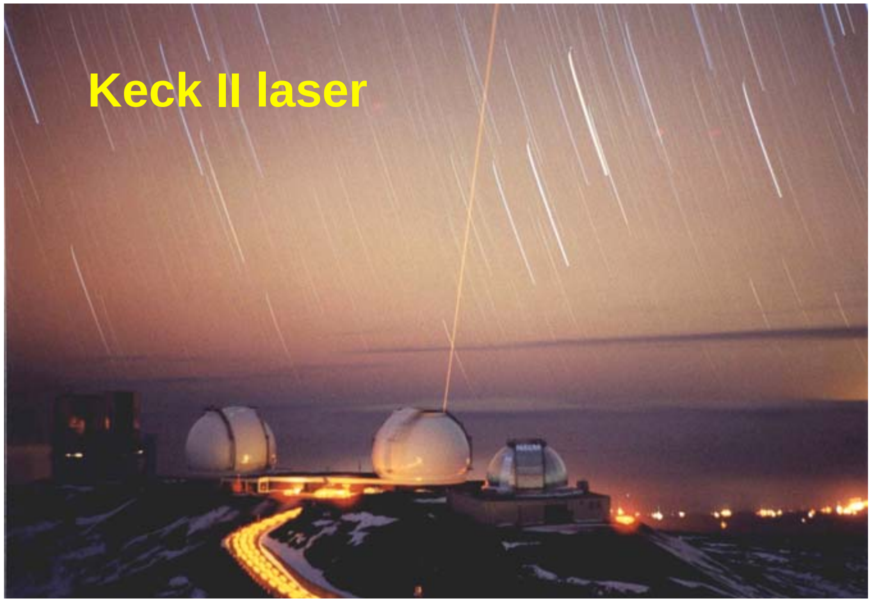
Shapley et al gives $L_K^*(z\sim3)$ = 22.5 ± 0.25 (AB)

R_{606}-K_{AB} ~ 1.6 (c.f. 1.0 ± 0.6 for Shapley et al)

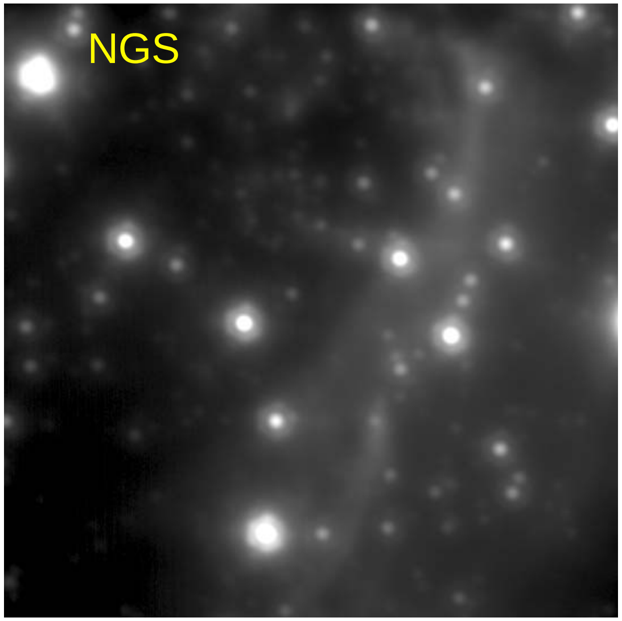
SFR ~ 100 $M_\odot$ yr^{-1}

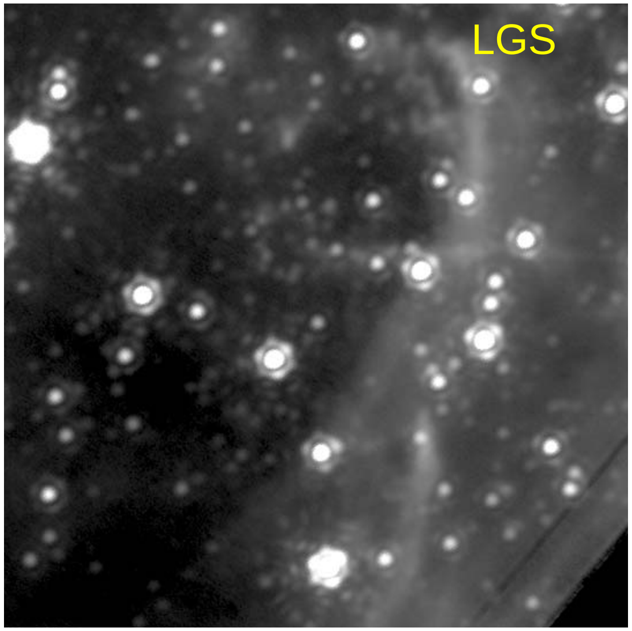


The Era of All-Sky Adaptive Optics Has Arrived!



Natural GS
Strehl=0.34
FWHM: 92
mas

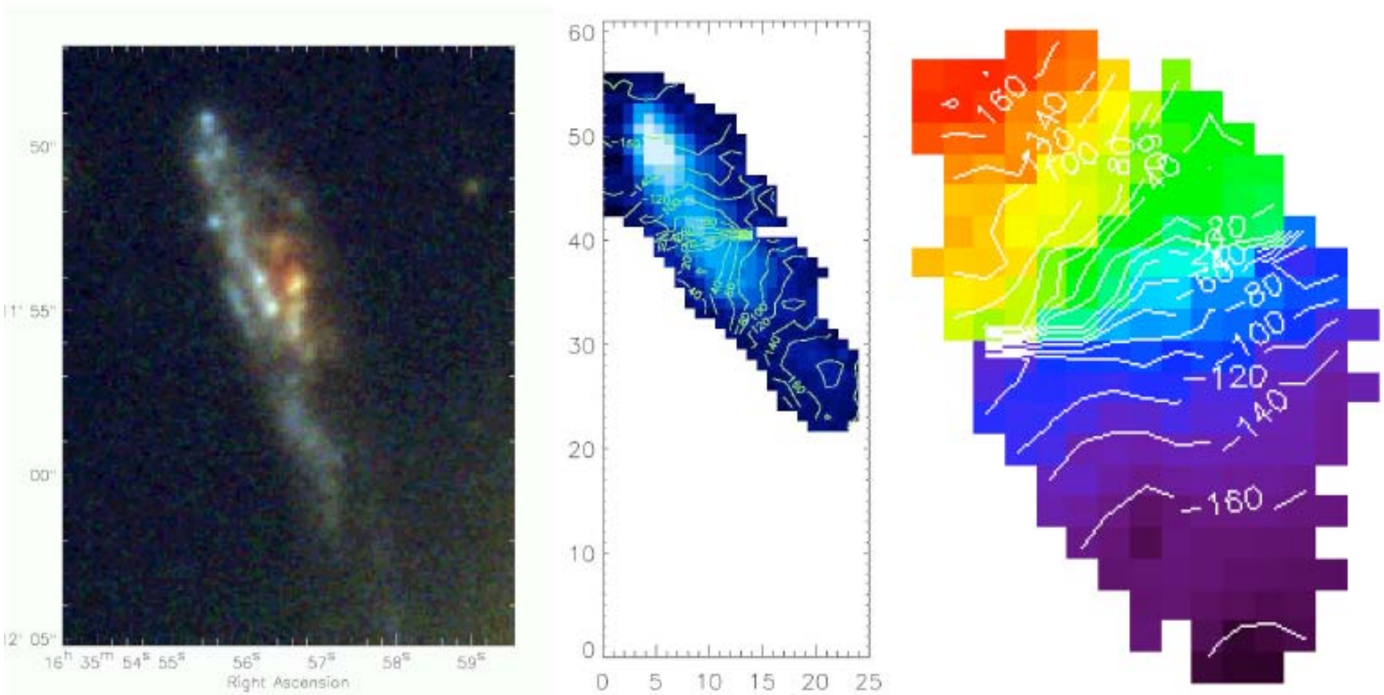




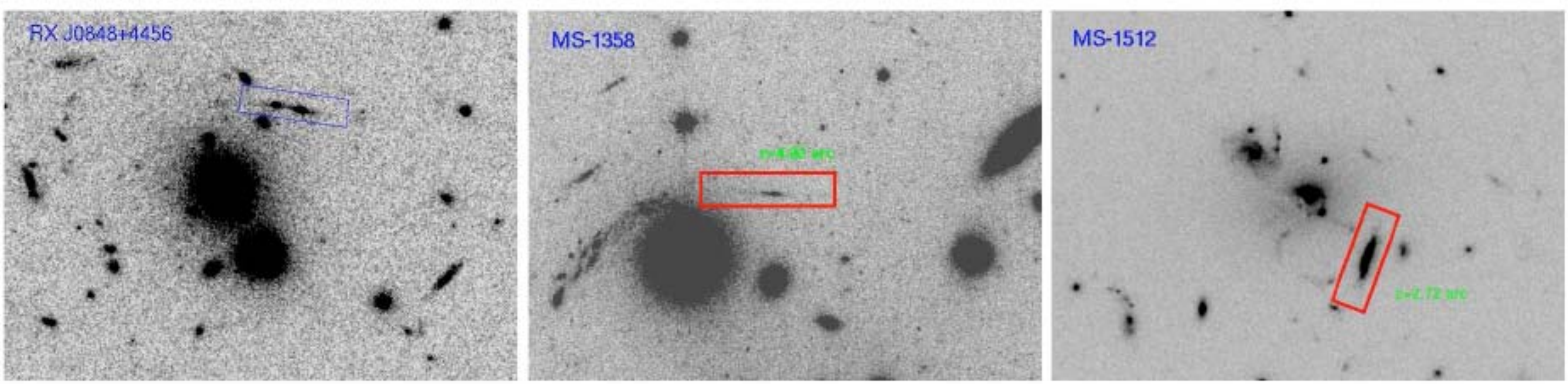
Laser GS
Strehl=0.75
FWHM: 82
mas

Resolved Dynamical Data for z~5 Arcs

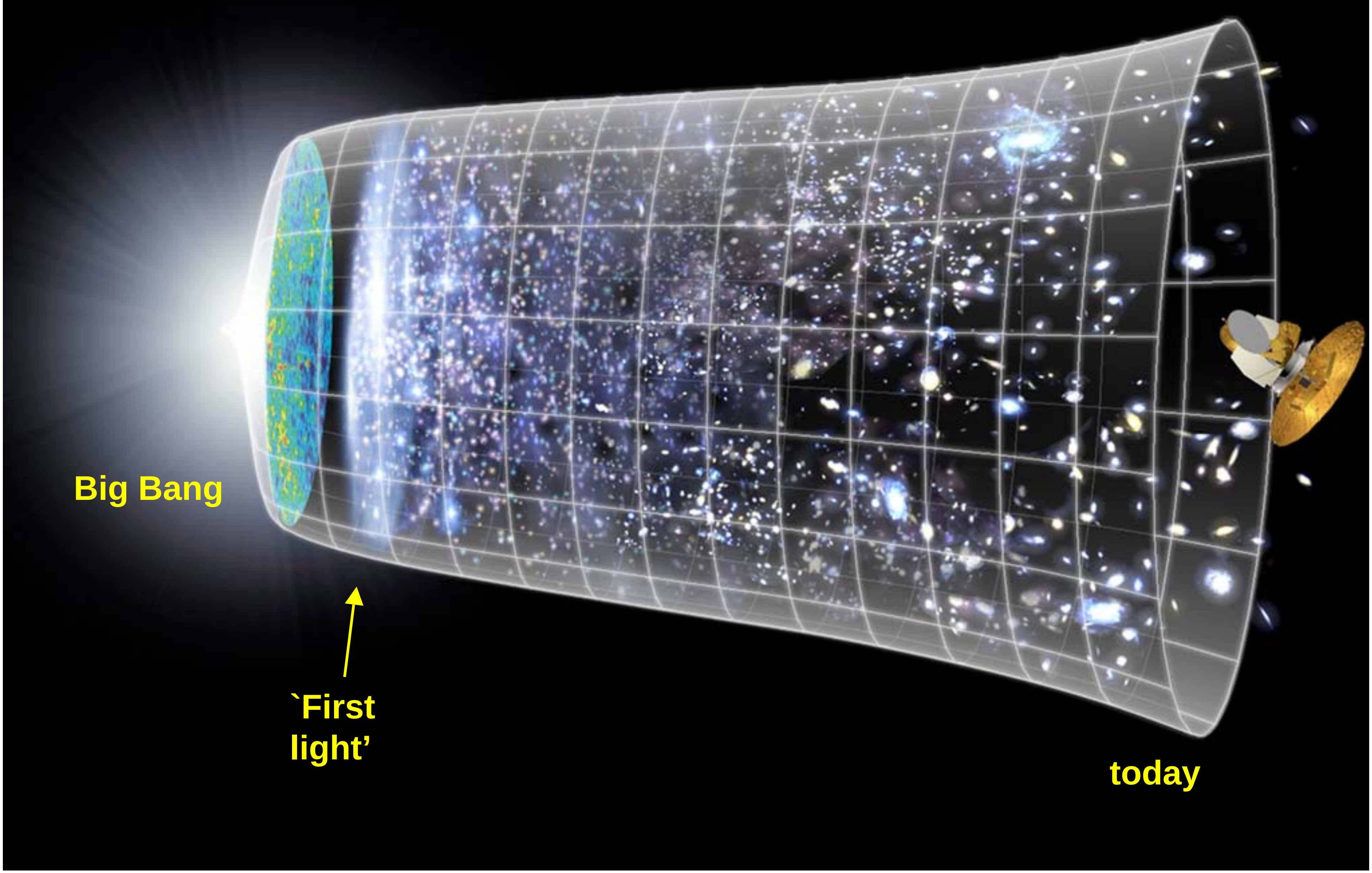
z~1 arc in A2218 (GMOS IFU <u>without AO,</u> Swinbank et al 2004)



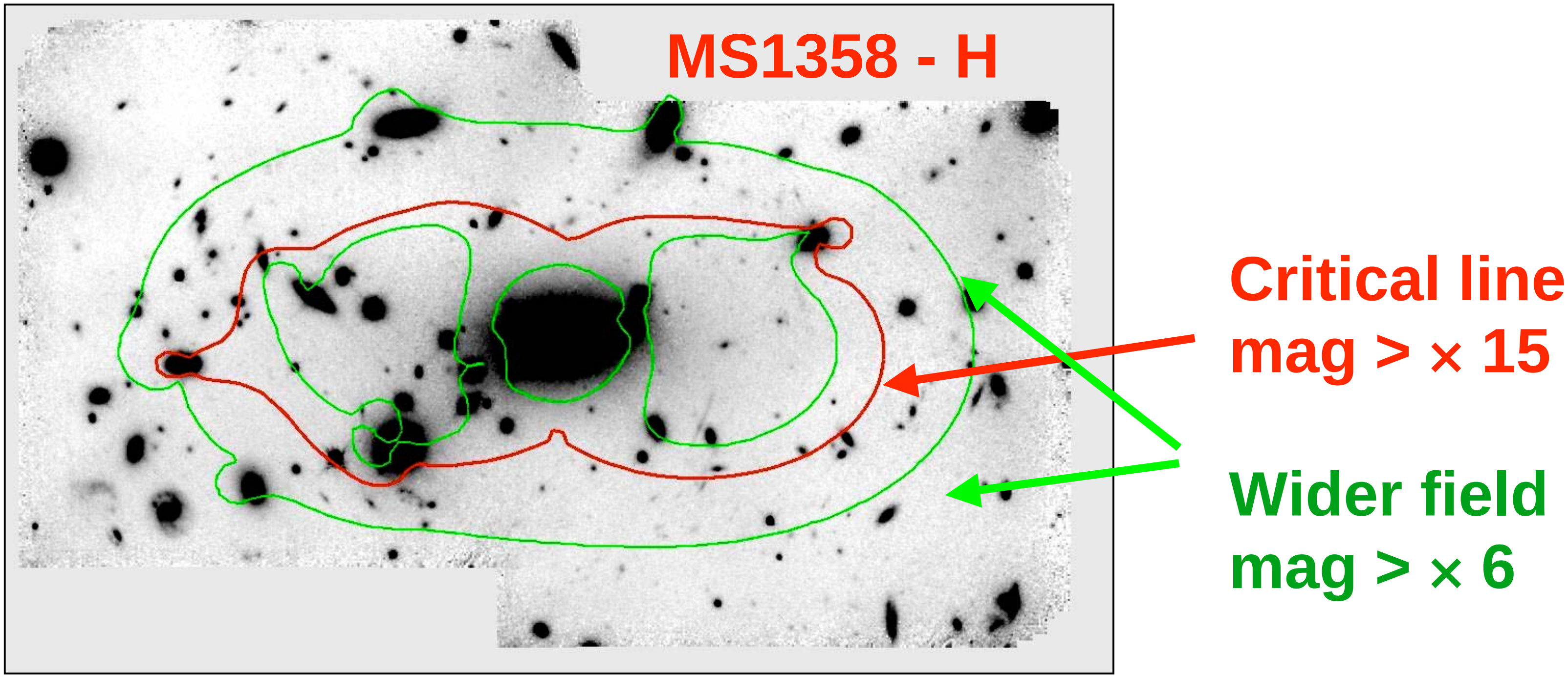
z>4 arcs with OSIRIS IFU: lensing + AO probe 150pc scales at z~5



Searching for Cosmic Dawn



Searching for z>7 Lensed Sources with NICMOS

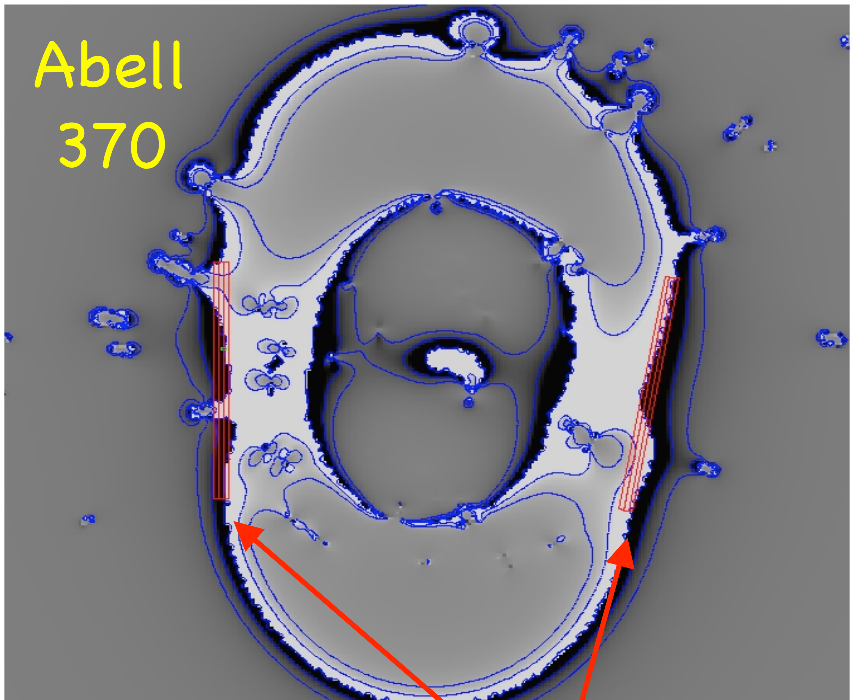


Use of clusters as natural magnifiers:

- moderate field imaging (a la SCUBA)
- critical line searches

Best approach depends on unknown surface density & LF

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 $8.5 < z < 10.4$

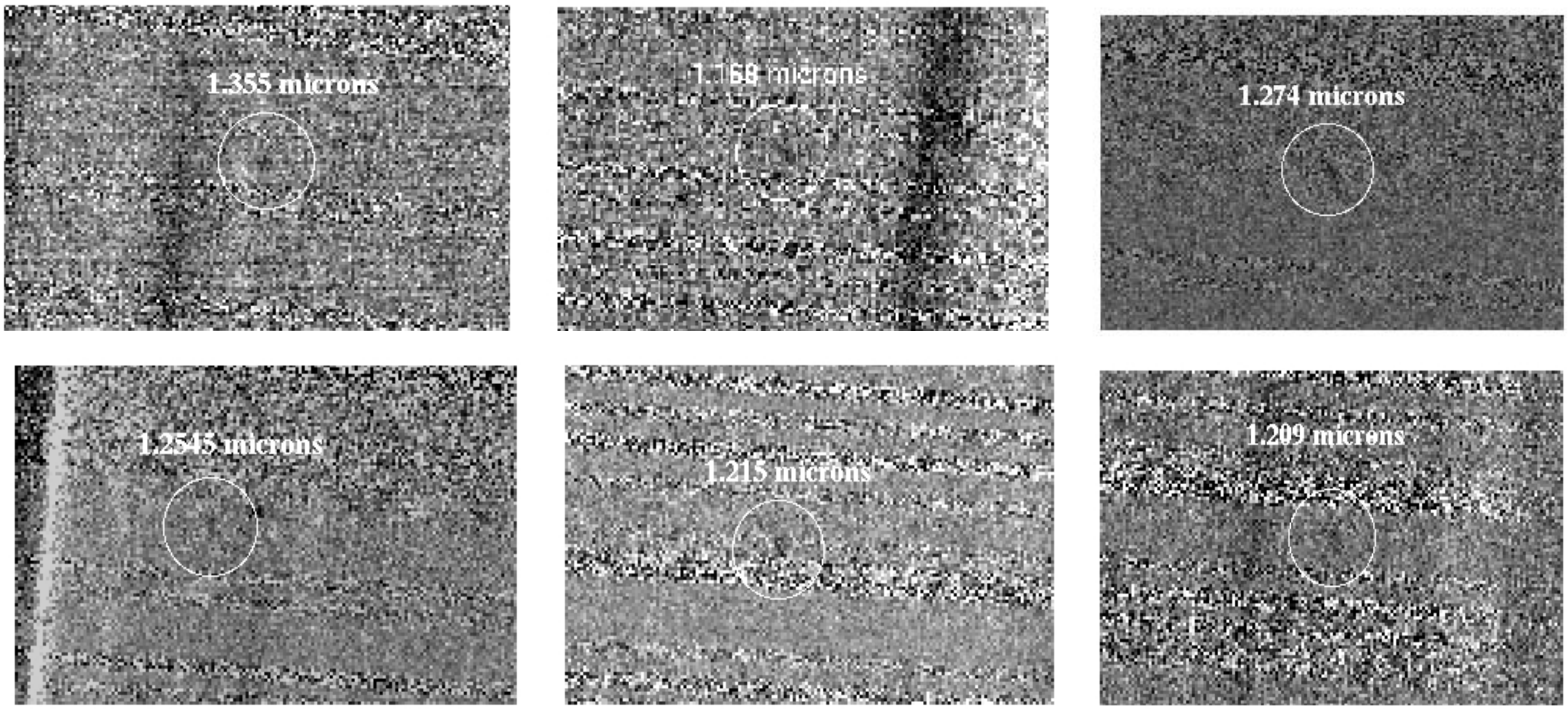
Clusters limited to those where the location of the critical line is precisely known (<20 all-sky).

Sensitive to sources 0.1 $M_{\odot}$ yr^{-1} over 50 Mpc^3 (comoving)

Stark et al (submitted)

Candidate Lyα Emitters

8.6 < z < 10.2; L ~ 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
Can rule out interloper low z via rejection of associated lines

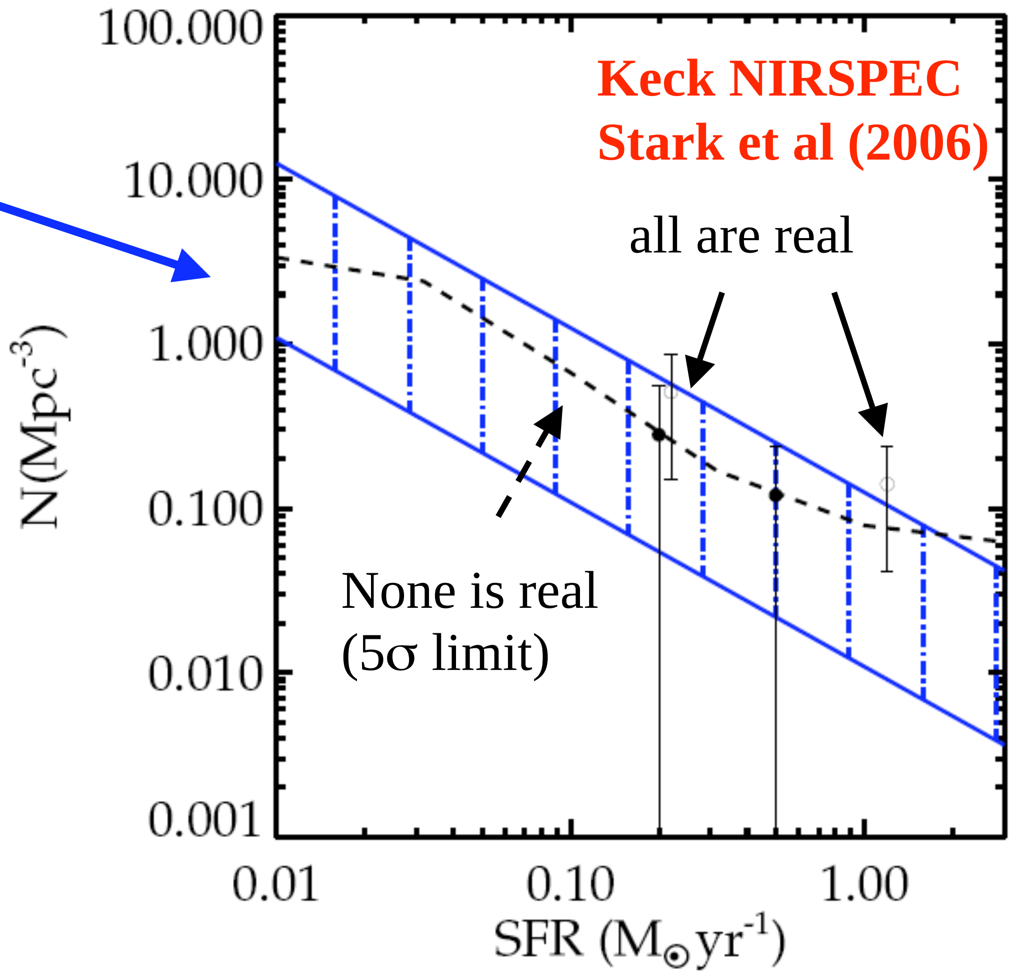
Did faint SF galaxies at z~10 cause reionization?

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

Consider range:

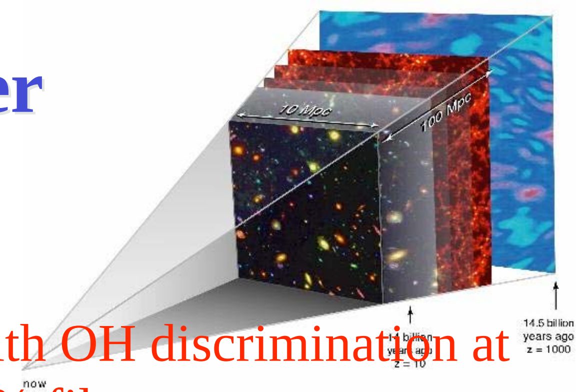
f_c~0.1-0.5
Δt ~250-575 Myr

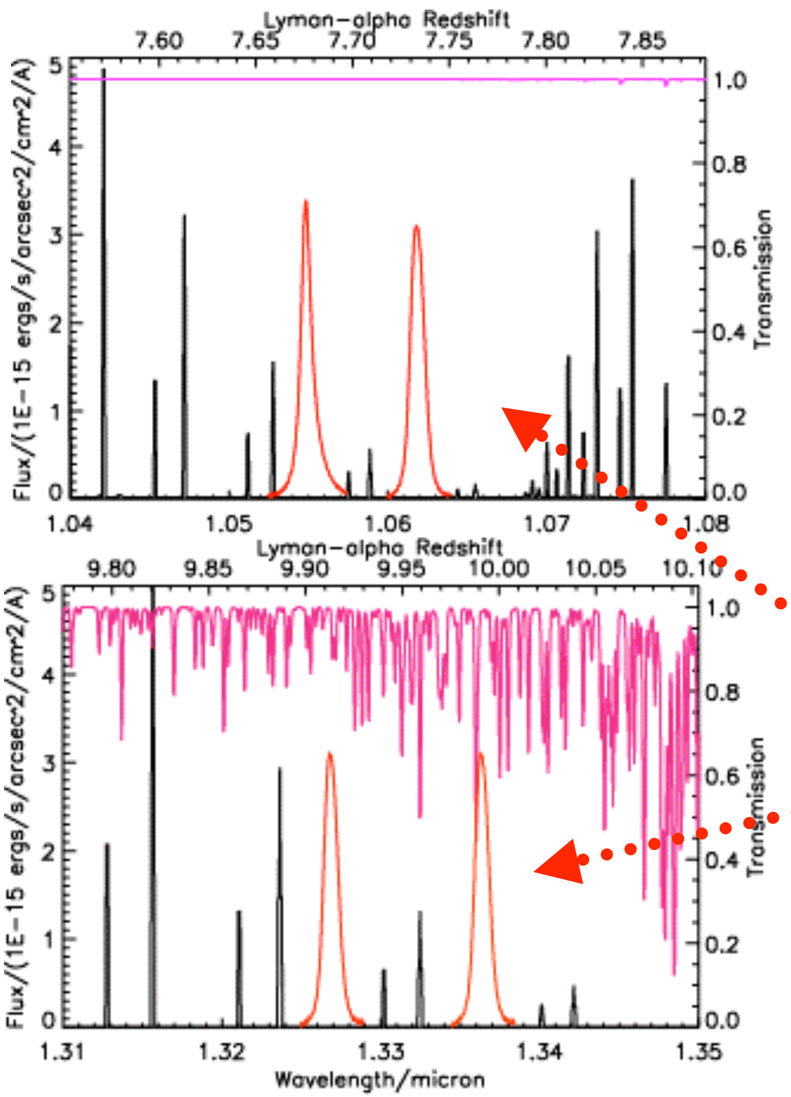
If even 2-3 of our 6 candidates are real, low luminosity galaxies may play a dominant role in cosmic reionization



DAZLE – Dark Age Z Lyman Explorer

McMahon, Parry, Bland-Hawthorn et al





IR nb imager with OH discrimination at R=1000 i.e. 0.1% filter

FOV 6.9 × 6.9 arcmin 2048 Rockwell Hawaii-II 0.2”/pixel

Sensitivity: 2. 10^{-18} erg cm^{-2} sec^{-1}(5σ), 10hrs on VLT i.e. ~1 $M_{\odot}$ yr^{-1} at z=8;

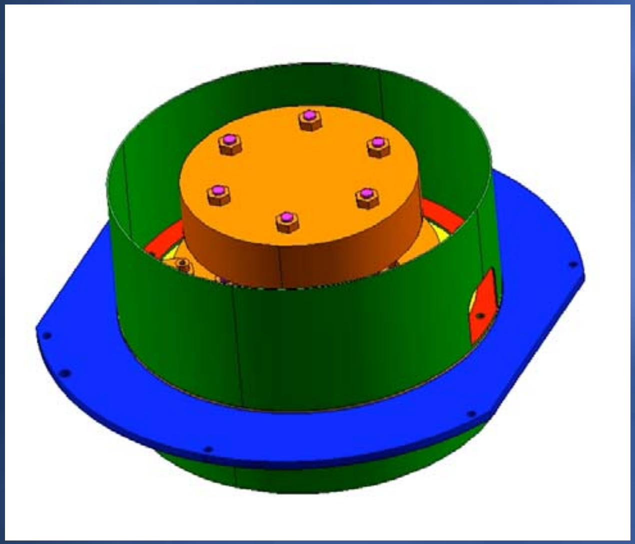
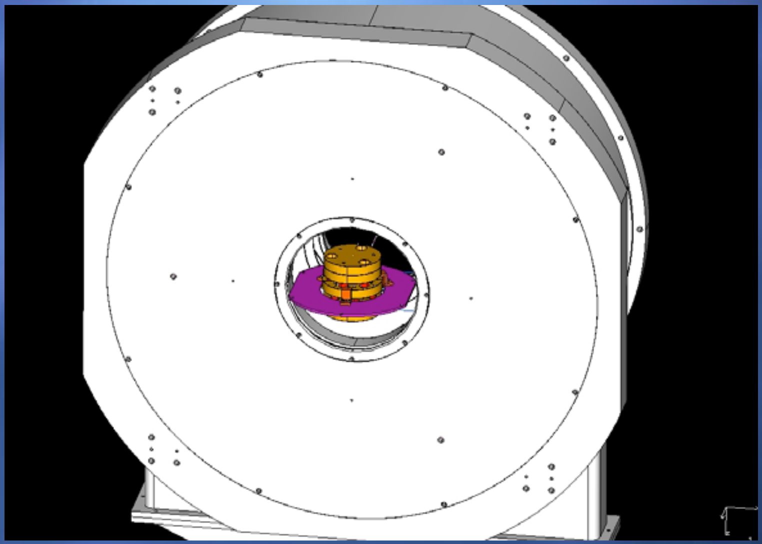
Each filter targets slice of dz=0.011 Comoving volume/exposure ~3000 Mpc^3.

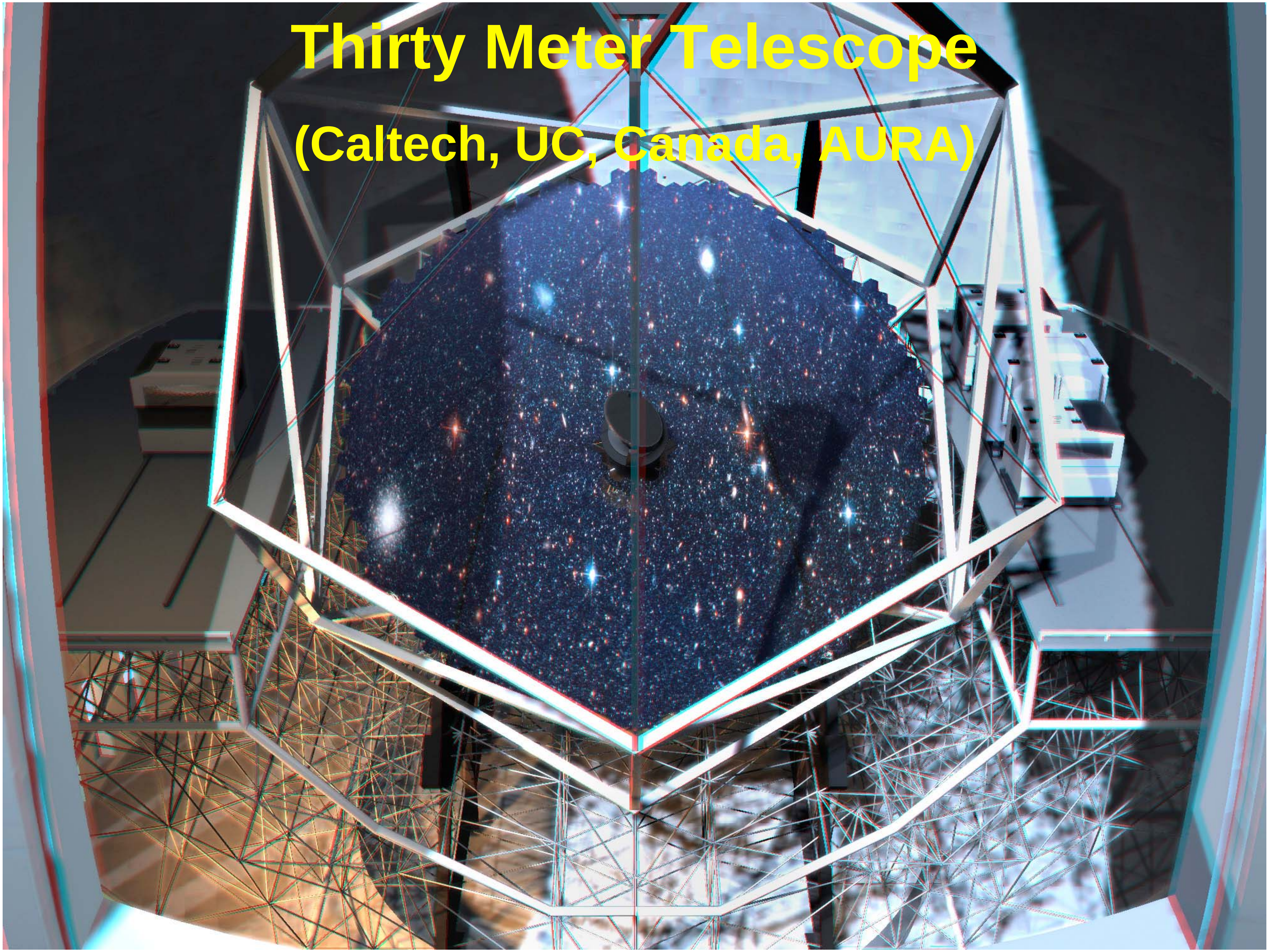
Sky emission and absorption spectrum around 1.06 and 1.33 microns showing DAZLE filter pairs for Lyman α at z=7.7, 9.9; other gaps are at 8.8, 9.2

F2T2 - Gemini Genesis Project

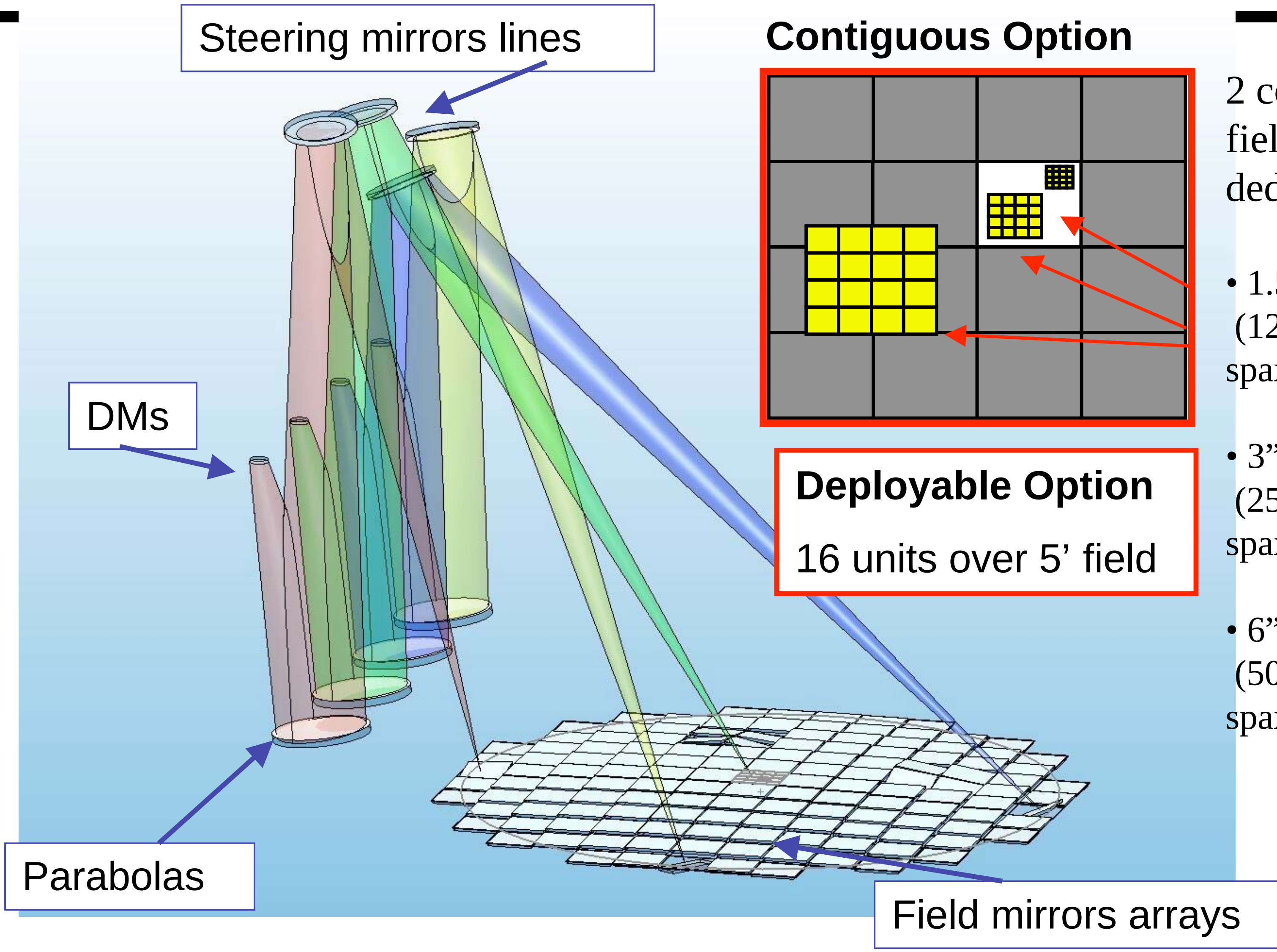
Prototype for the JWST Tunable Filter Imager… F2T2 will be fed by multi-conjugate AO & be facility-class instrument on Gemini

(PI: Bob Abraham)


Thirty Meter Telescope
(Caltech, UC, Canada, AURA)

AO-fed multi-IFU spectrograph



2 contiguous fields sub-tiles dedicated to:

- 1.5" sq. (12.5 mas spaxial)
- 3" sq. (25 mas spaxial)
- 6" sq. (50 mas spaxial)

Epilogue

Dark energy: more cooperation in WL welcome, extend from simulations to independent ground & space-based datasets

Dark matter:

- huge challenge of spectroscopic follow-up of new lens surveys!

- less arguing about flat inner slopes.. separating DM & baryons is a `noble pursuit‘ that should be encouraged (more practical with better data)

Distant galaxies: More HST snapshots & coordinated searches followed by AO-studies

Cosmic Reionization: Adequate support for new instrumentation probing magnified areas in clusters