Lensing with KIDS

studying dark matter and dark energy with light rays

Konrad Kuijken

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Outline:

1. Weak lensing introduction
2. The KIDS survey
3. Galaxy-galaxy lensing (halos)
4. Cosmic shear (large scale structure)
5. Methods

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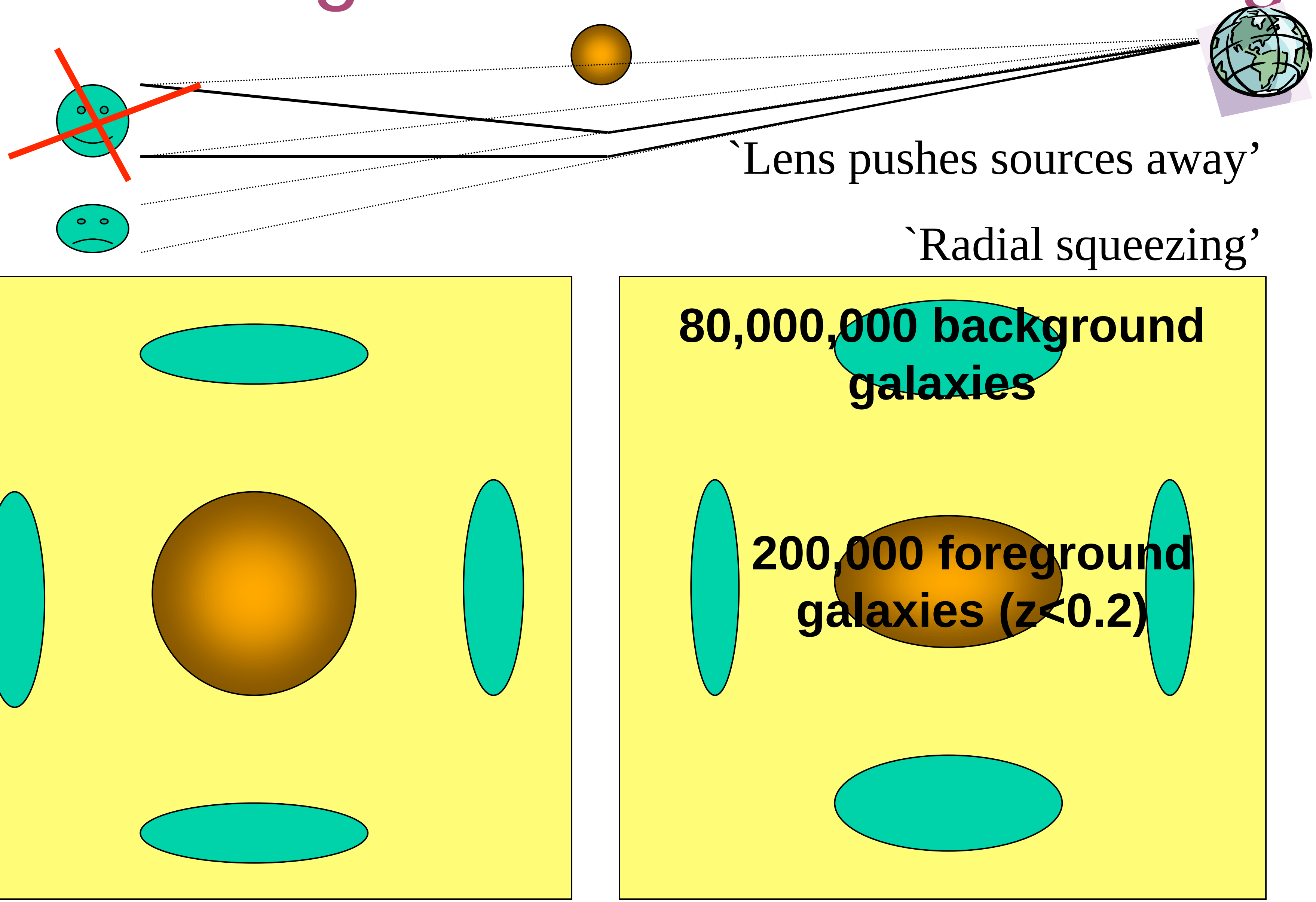
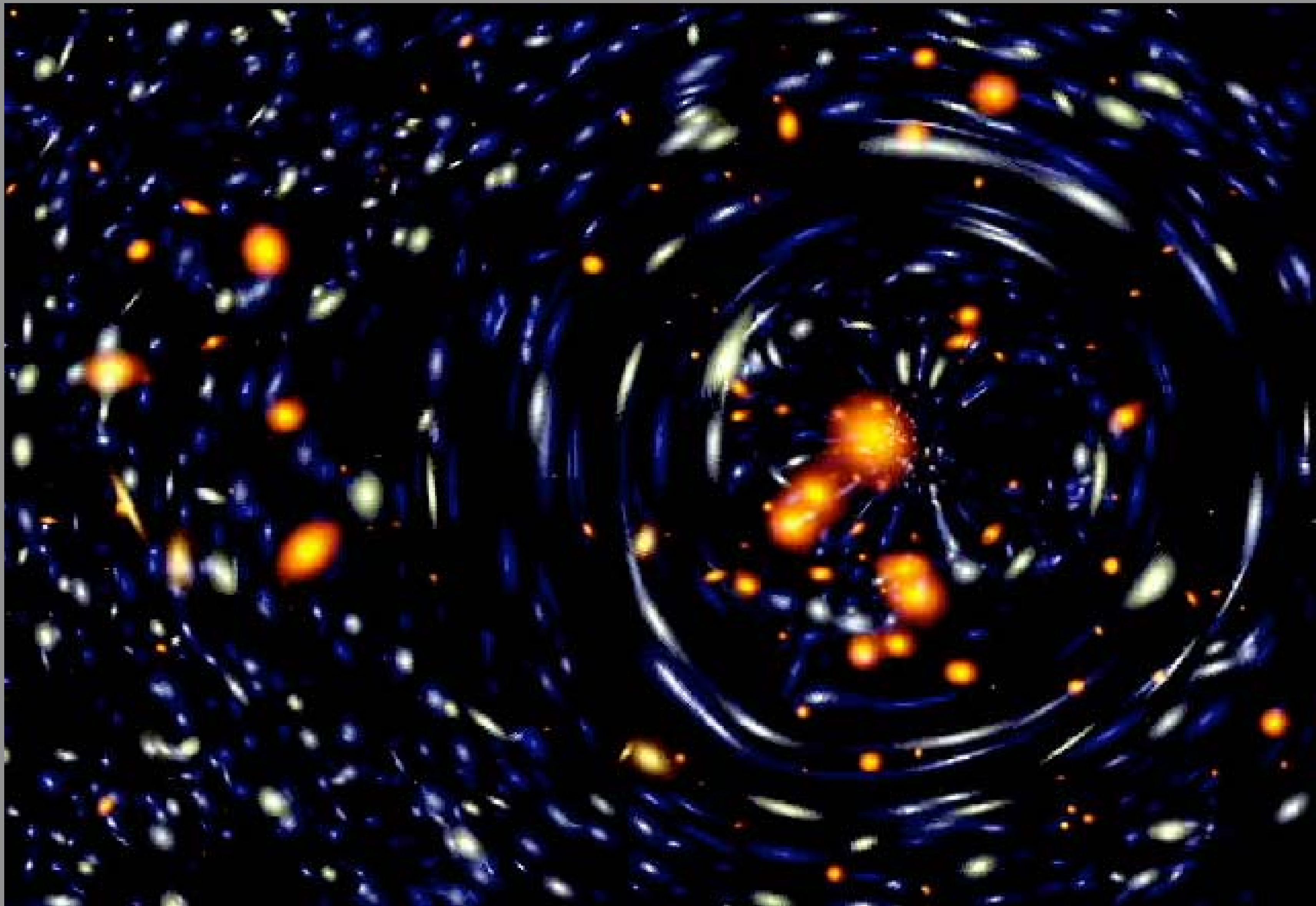
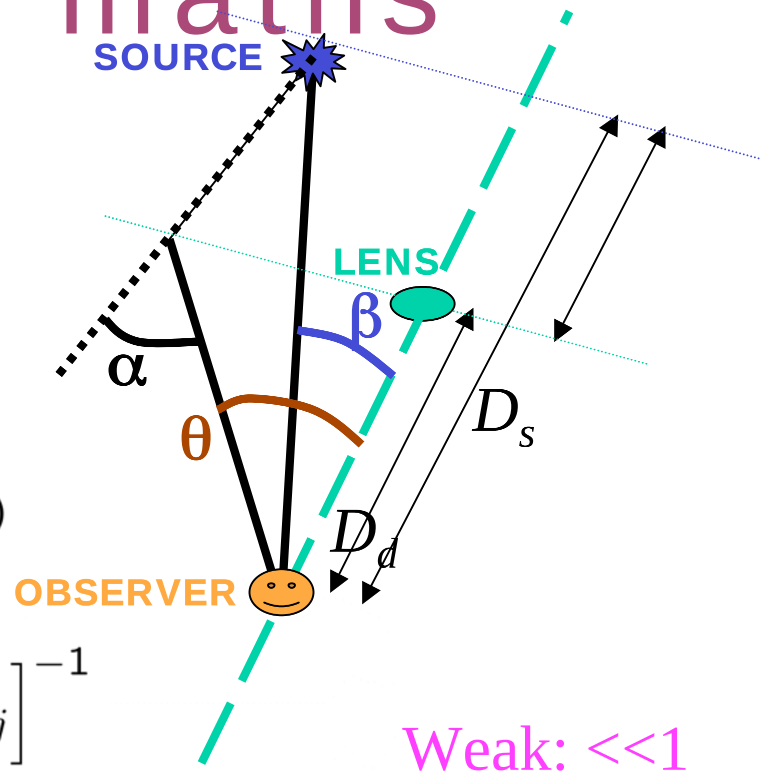
1. Weak gravitational lensing





Weak lensing maths



Lensing potential $\Psi(x,y) = \int \psi dz$

Deflection $\alpha = \frac{2}{c}\int \nabla\psi \frac{dz}{c} \equiv \frac{2}{c^2}\nabla\Psi$

Image shift $\theta - \beta = \frac{D_{ls}}{D_s}\alpha = \frac{2}{c^2}\frac{D_{ls}}{D_s}\nabla\Psi(D_l\theta)$

Distortion $A \equiv \left[\frac{\partial\beta}{\partial\theta}\right]^{-1} = \left[\delta_{ij} - \frac{2}{c^2}\frac{D_{ls}D_l}{D_s}\Psi_{ij}\right]^{-1}$

$$A^{-1} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} \equiv (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$$

Weak: <<1

$$\begin{aligned} \kappa &= \Sigma/\Sigma_{\rm crit} \\ \gamma_1 &= 4\pi G(\Psi_{11}-\Psi_{12})/\Sigma_{\rm crit} \\ \gamma_2 &= 4\pi G(2\Psi_{12})/\Sigma_{\rm crit} \end{aligned} \quad \text{for } \Sigma_{\rm crit} = \frac{4\pi G c^2 D_s}{D_{ls}D_l}$$

Weak lensing pro/con

- Study projected mass distribution directly
  - Independent of whether dark or light

- Technical difficulties:
  - Projection along very long sightline
  - Noisy: each background galaxy is estimator of shear with $\sigma \sim 10\%$ (cf. <1% signal)
  - Very accurate shape measurements require control of systematic distortions in camera, atmosphere, etc.
  - Need source & lens distances (Σ_{crit})

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2. The KIDS survey

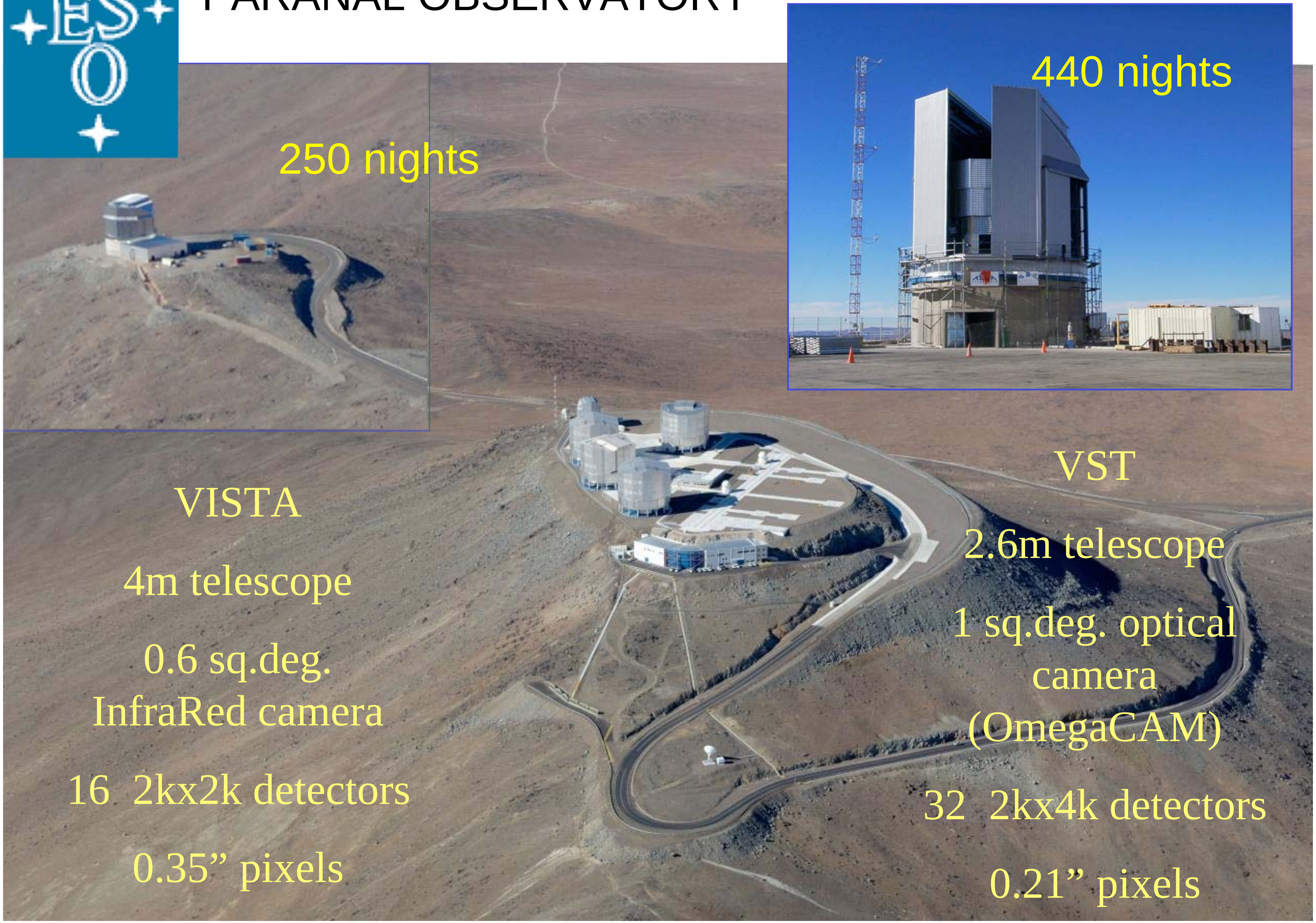
KIDS: a 1500-square degree cosmological survey with VST/OmegaCAM

PI: Konrad KUIJKEN, Leiden Observatory, The Netherlands
Ralf Bender, Hans Böhringer, Massimo Capaccioli, Thomas Erben, Ulrich Hopp, Yannick Mellier, Mark Neeser, John Peacock, Mario Radovich, Roberto Saglia, Peter Schneider, Peter Schuecker, Stella Seitz, Roberto Silvotti, Will Sutherland, Andy Taylor, Edwin Valentijn, Steve Warren

The VISTA Kilo-degree Infrared Galaxy survey (VIKING)

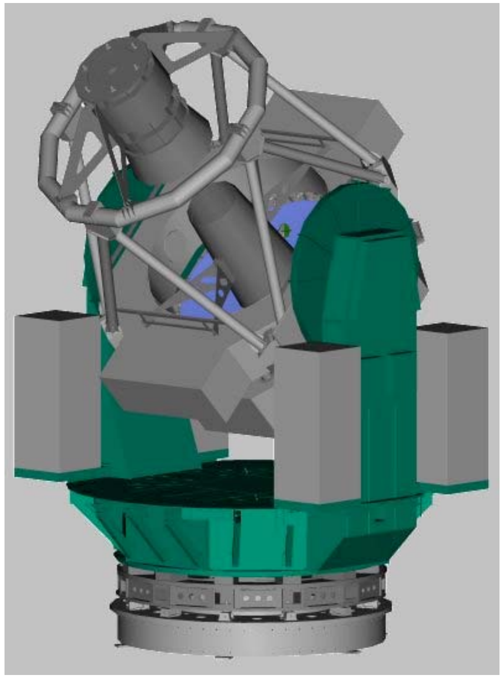
PI: Will Sutherland, Institute of Astronomy, Cambridge, UK
Ralf Bender, Hans Böhringer, Malcolm Bremer, Massimo Capaccioli, Lee Clewley, Gavin Dalton, Simon Driver, Alastair Edge, Jim Emerson, Thomas Erben, Philippe Heraudeau, Ulrich Hopp, Matt Jarvis, Konrad Kuijken, Jochen Liske, Richard McMahon, Yannick Mellier, Mark Neeser, John Peacock, Chris Pearson, Steve Phillipps, Mario Radovich, Kathy Romer, Roberto Saglia, Peter Schneider, Peter Schuecker, Stella Seitz, Roberto Silvotti, Andy Taylor, Edwin Valentijn, Bram Venemans.

PARANAL OBSERVATORY

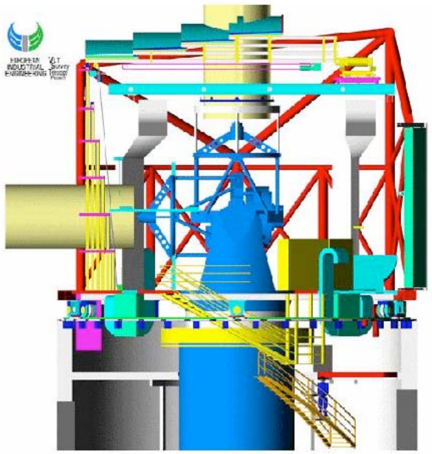


The VST

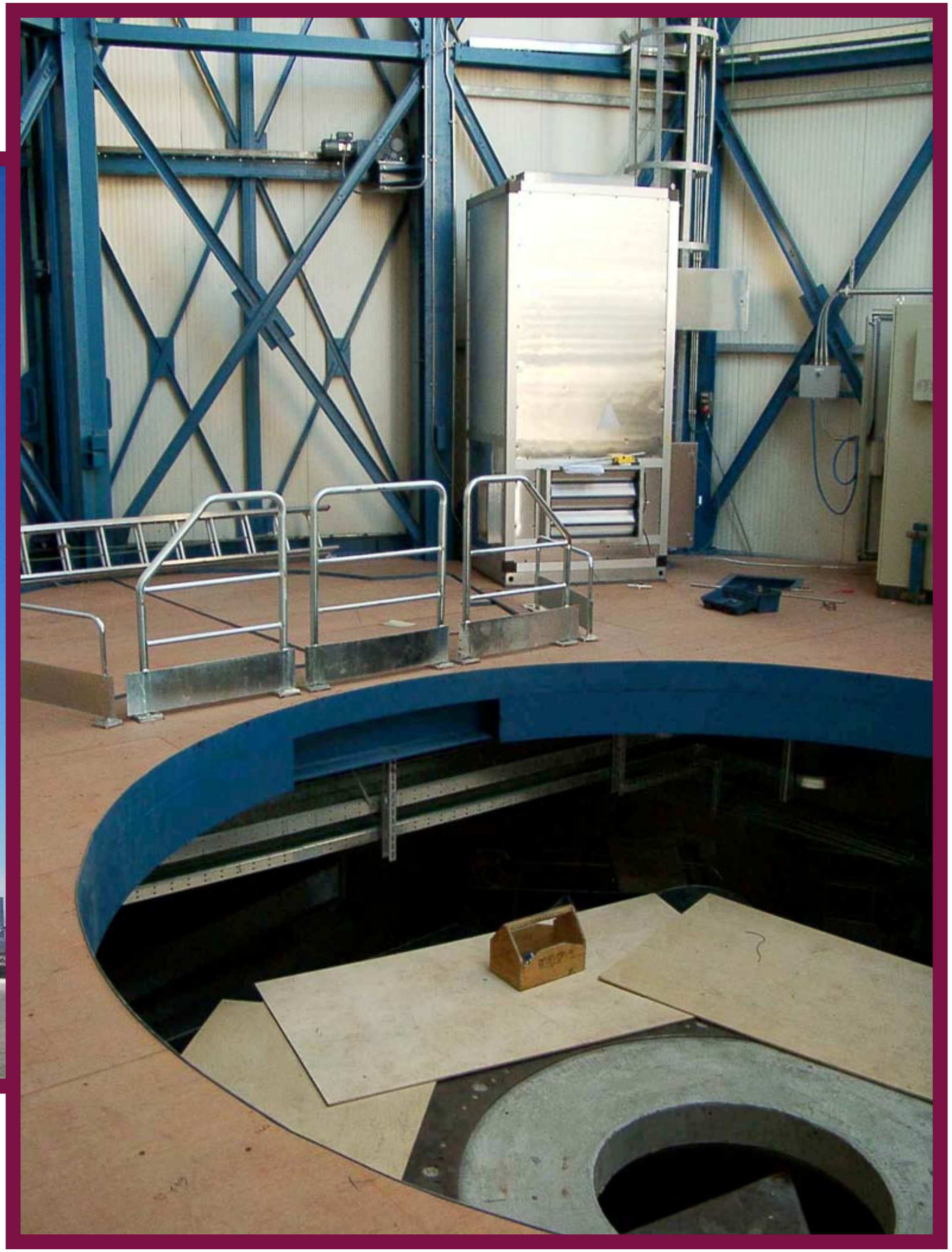
(Naples obs.)

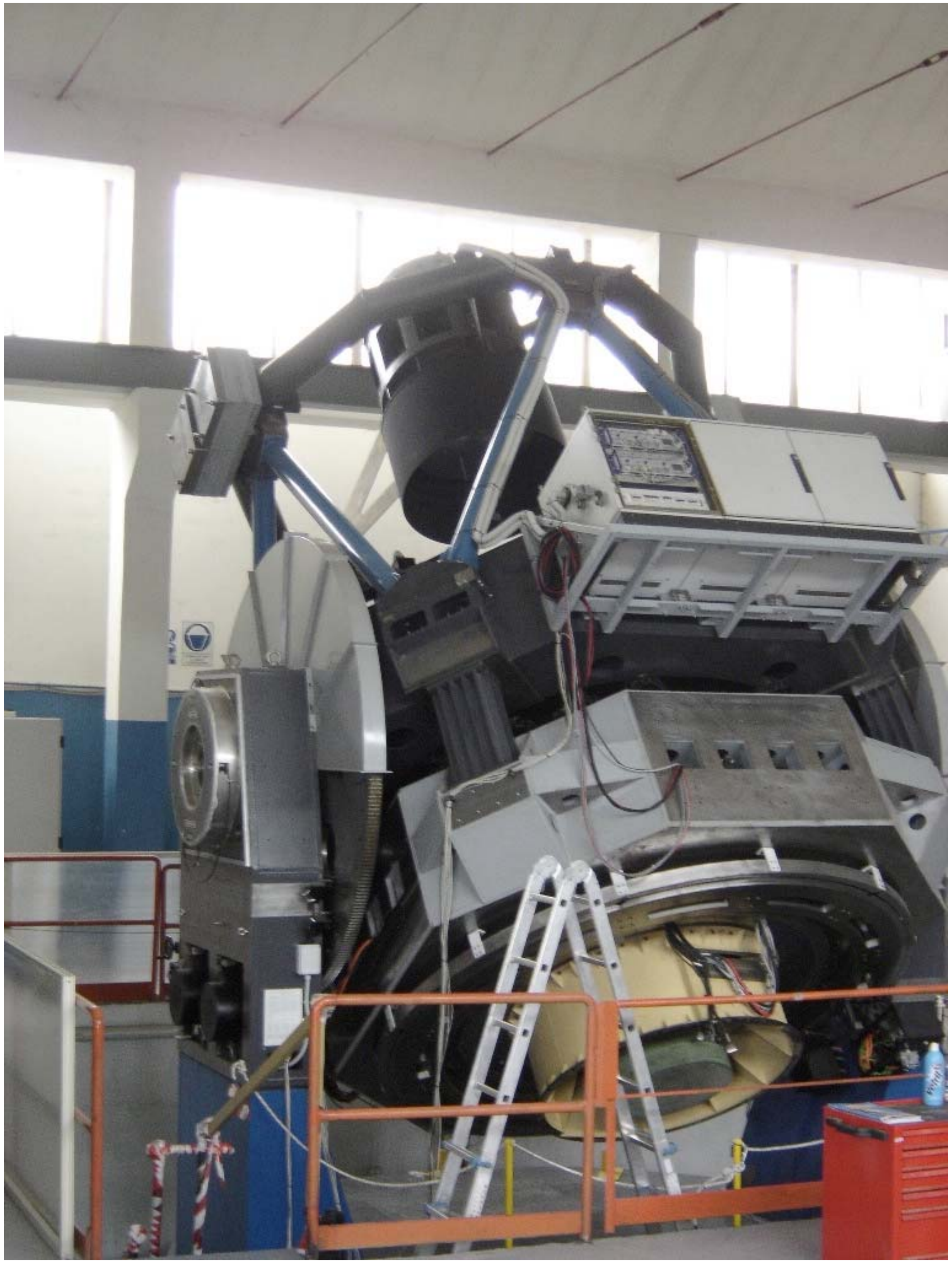


- VST: 2.6m f/5.5, 1.4 deg Φ field, active primary mirror
- Only one instrument: OmegaCAM = 16k x 16k CCD camera

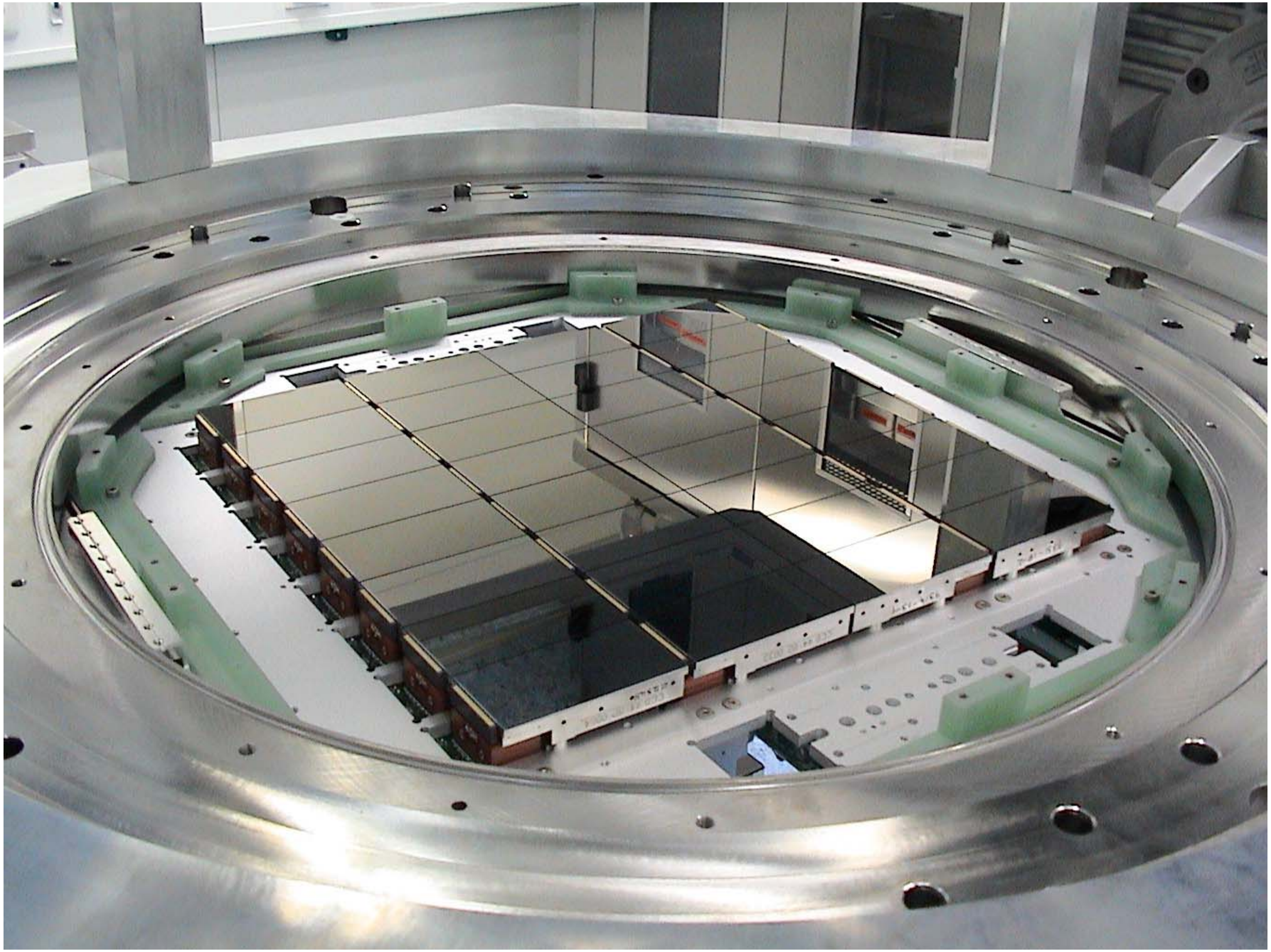


- Operational end 2007
- ~300 nights/year, 30 square deg/night
  =10,000 square deg / year!
  =10 TByte of pixel data / year!

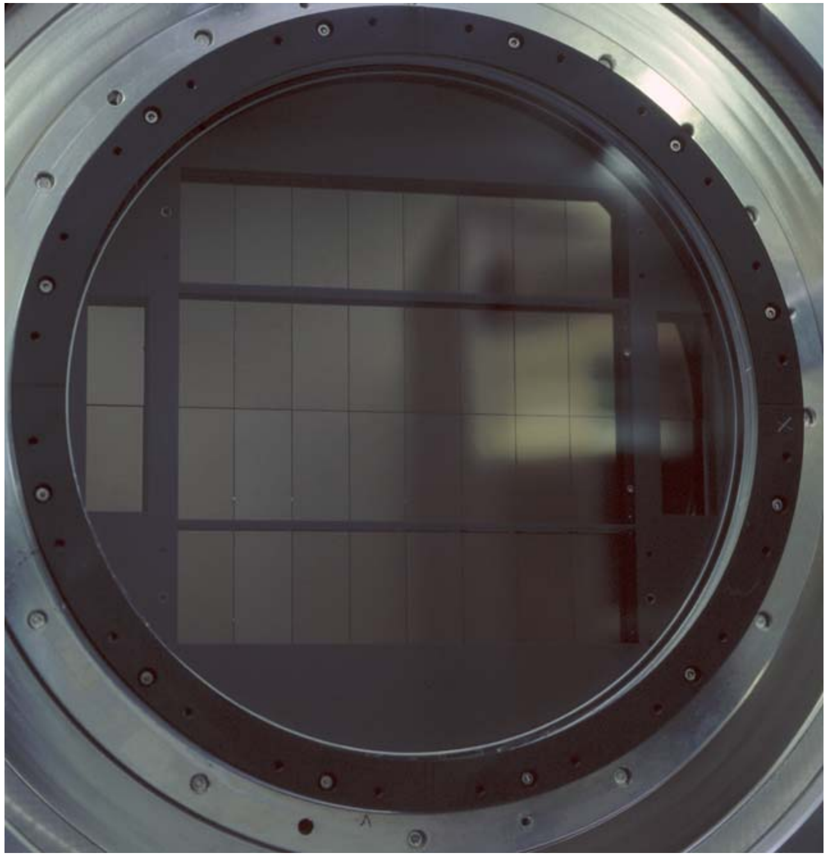




OmegaCAM

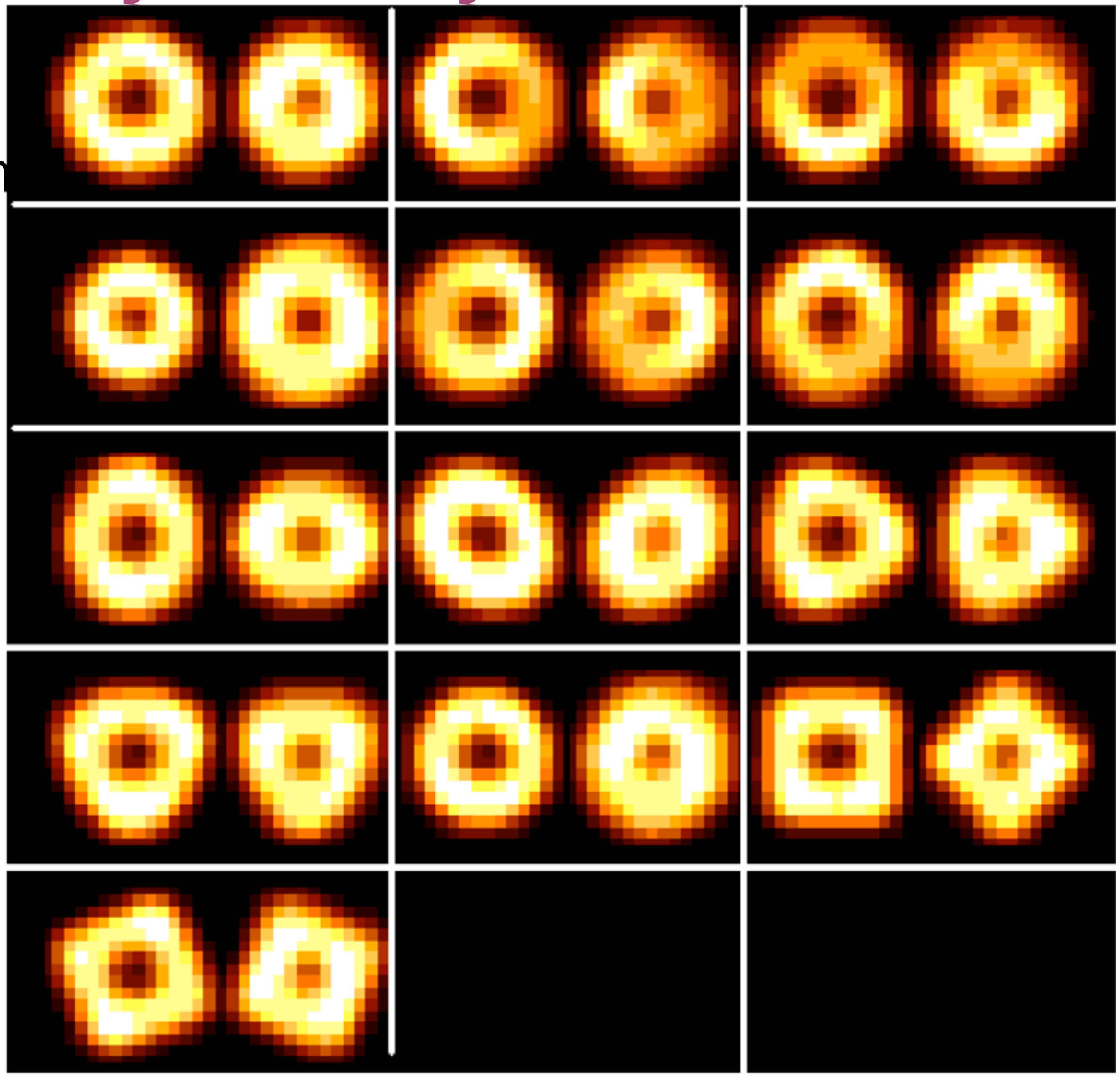


OmegaCAM

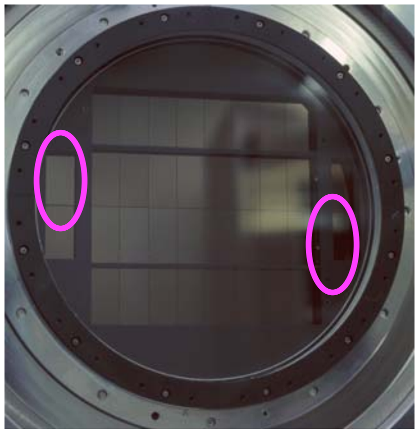


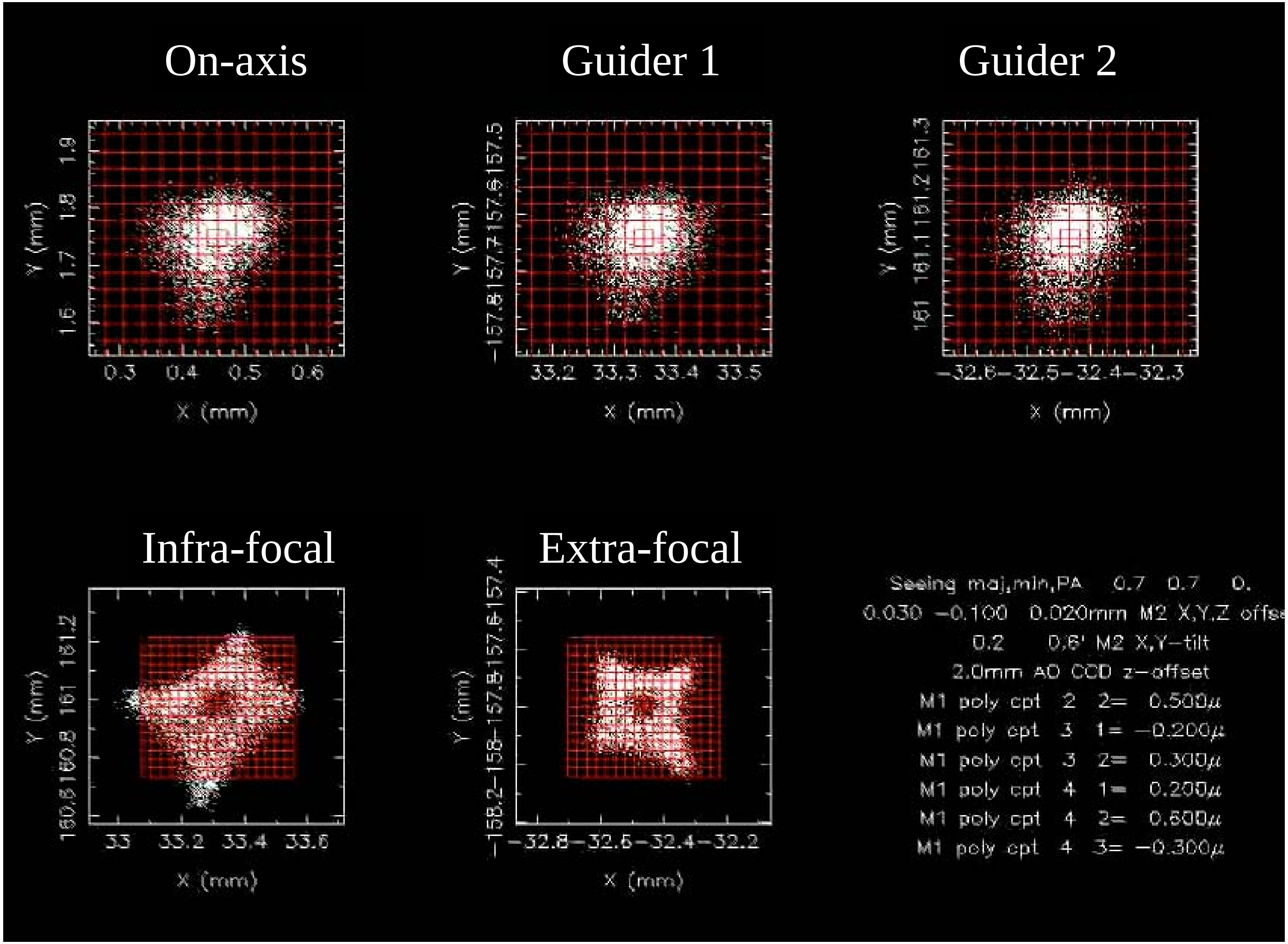
300 million pixels, 36 CCDs

Image Analysis System

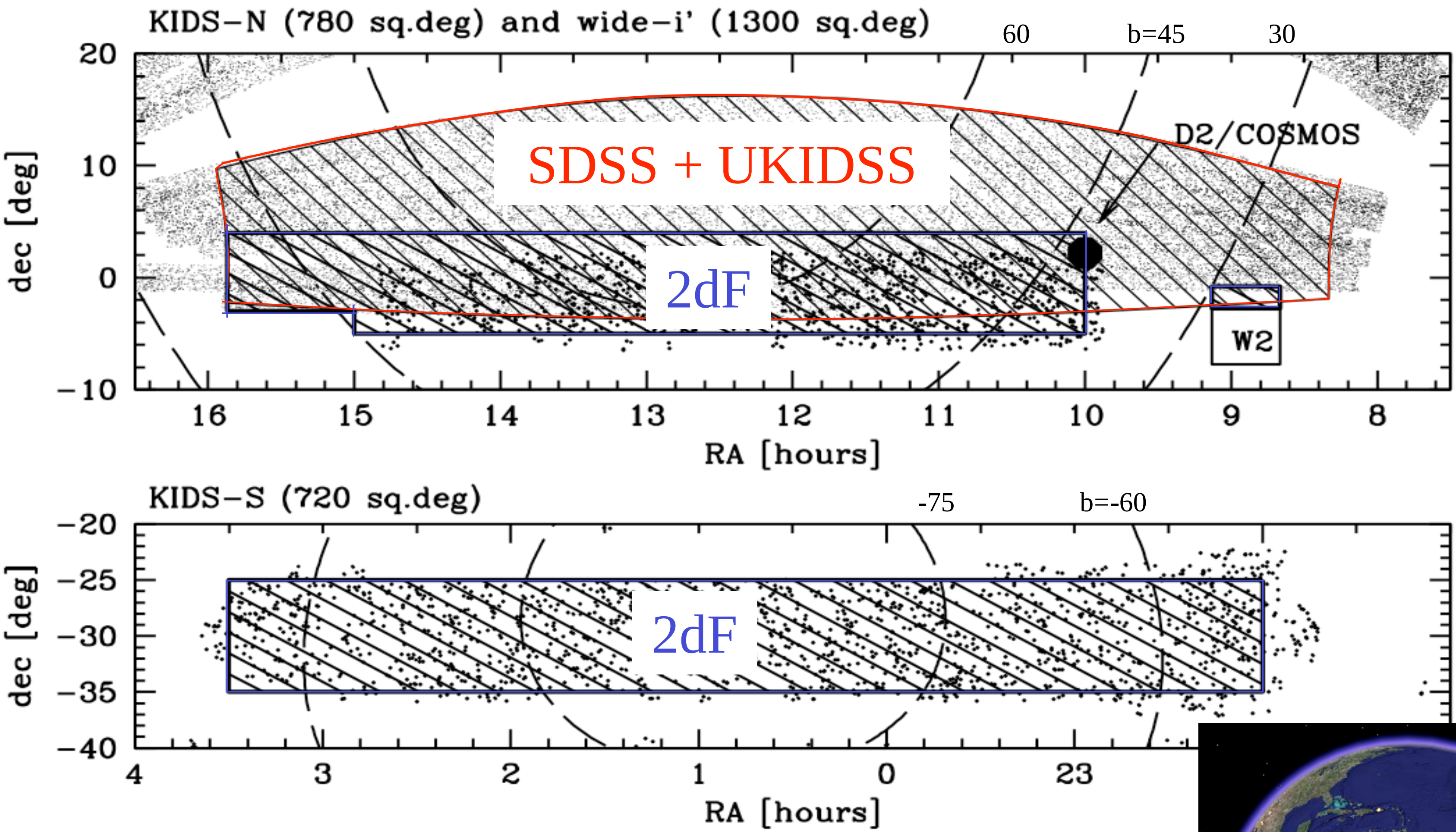


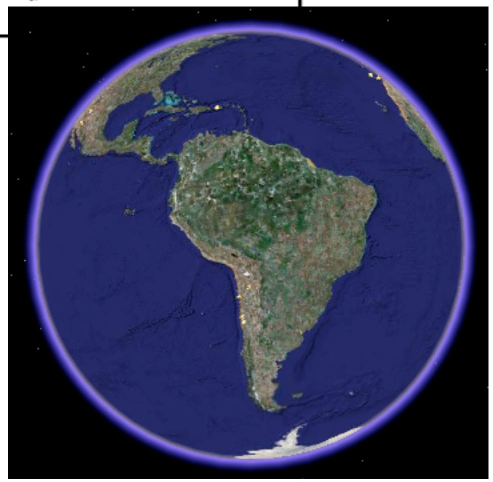
- Roddier-type system
  - Image one star in front of focus, one behind
    - Defocus: one image bigger, one smaller
    - Astigmatism: elongated images
    - Etc etc





On-axis
Guider 1
Guider 2
Infra-focal
Extra-focal
Y (mm)
X (mm)
Seeing maj,min,PA 0.7 0.7 0.
0.030 −0.100 0.020mm M2 X,Y,Z offse
0.2 0.6' M2 X,Y−tilt
2.0mm AO CCD z−offset
M1 poly cpt 2 2= 0.500μ
M1 poly cpt 3 1= −0.200μ
M1 poly cpt 3 2= 0.300μ
M1 poly cpt 4 1= 0.200μ
M1 poly cpt 4 2= 0.500μ
M1 poly cpt 4 3= −0.300μ





1500 sq.deg. in ugriZYJHK

+2000 sq.deg. in i (+UKIDSS YJHK)

KIDS + VIKING

- VST/OmegaCAM: 1 sq deg, 2.6m telescope
- VISTA/VISTACAM: 0.6 sqdeg, 4m telescope
- 1500 sq.deg. of ugri (~400n VST)
  + ZYJHK (~200n VISTA)
- Deeper in r, with good seeing
- VST 2m deeper than SDSS
  (1m shallower than CFHTLS)
- VISTA 1.5m deeper than UKIDSS

filter	Exp (s)	5-σ 2" AB	cf. UKIDSS
Z	500	23.1	-
Y	400	22.4	+1.6
J	400	22.2	+1.8
H	300	21.6	+1.6
K	500	21.3	+1.3

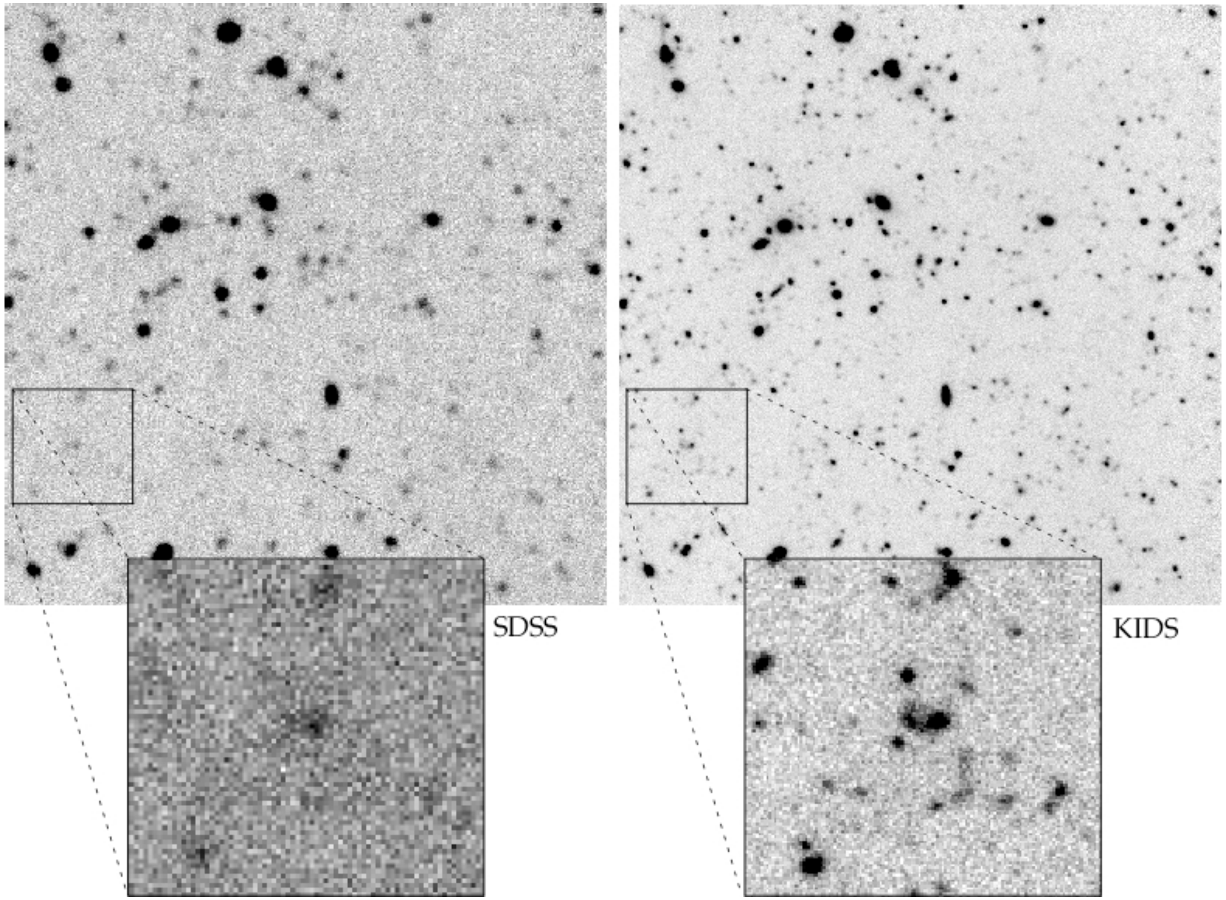
	<0.7" (40%)	0.7-0.85" (20%)	0.85-1.1" (20%)
Dark (50%)	**r'**	**g'**	**u'**
Grey (15%)	**i'**	**i'**	**i'**
Bright (35%)	**z'**	**z'**	**z'**

filter	Exp time (s)	Medn seeing (")	5-σ 2" AB
u'	900	1.0	24.8
g'	900	0.75	25.4
r'	1800	0.6	25.2
i'	1080	0.75	24.2
z'	2520	0.75	23.2

KIDS vs. SDSS, CFHTLS

SDSS	CFHTLS
6 x area	1/9th area
2 mag shallower	1 mag deeper
2x worse seeing	~same

(M.Neeser)

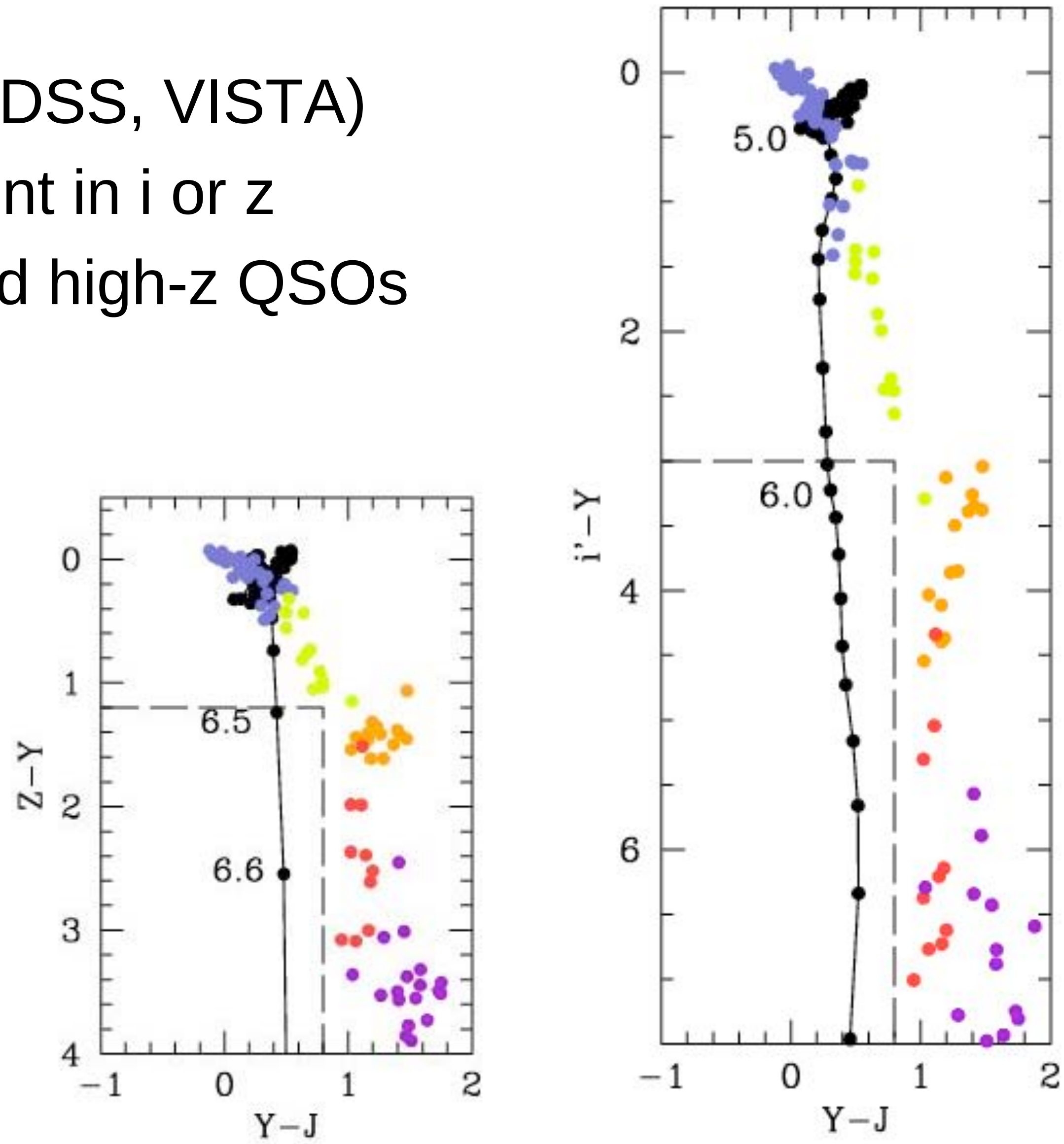


KIDS: Kilo-Degree Survey

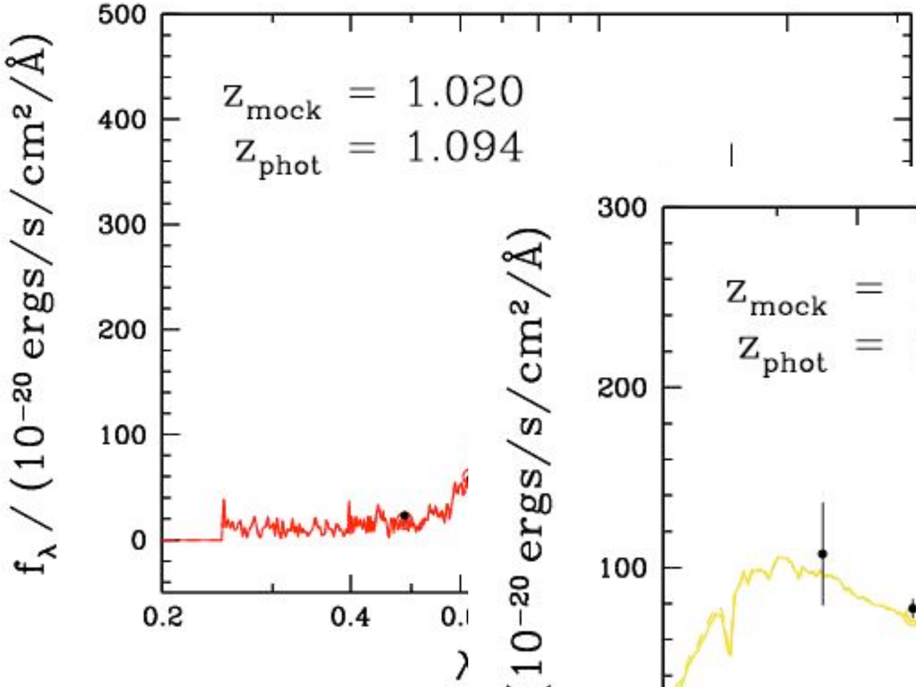
- ESO Public Survey
- Goals:
  - Halo structure (weak lensing)
  - Dark energy (*w* via ang. power spec; wk lensing)
  - Galaxy evolution vs. environment
  - Cluster searches
  - Higher-redshift quasars than SDSS
  - White dwarf searches (2nd pass for `movers & shakers')
  - …

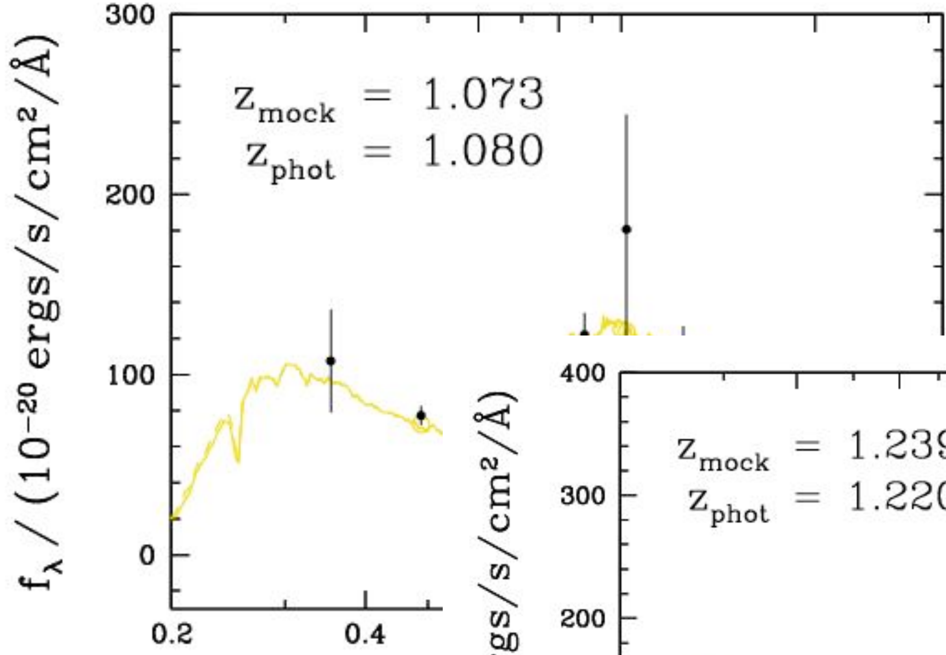
z>6.4 QSOs

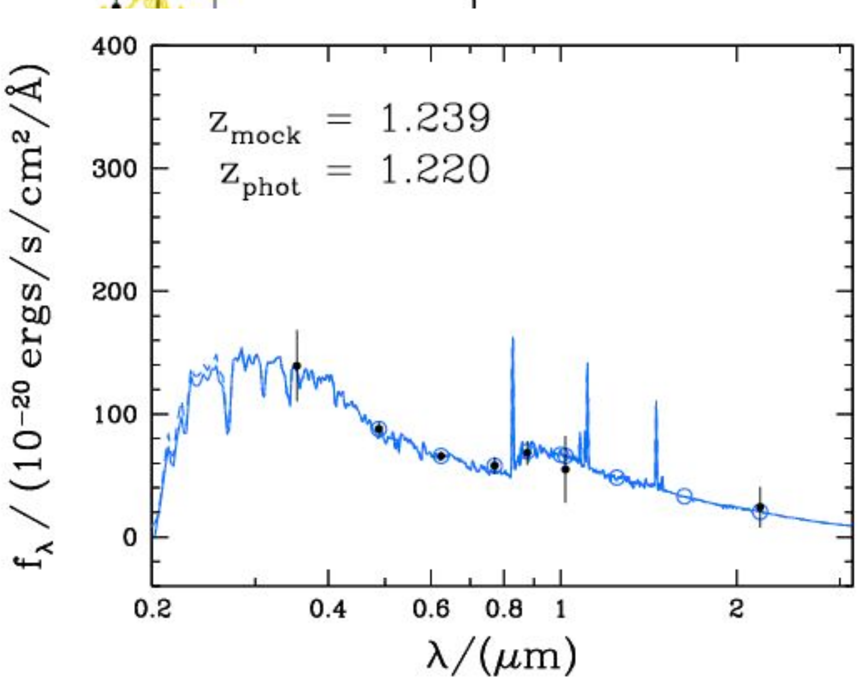
- Combine with IR (UKIDSS, VISTA)
- Look for IR objects faint in i or z
- Find brown dwarfs and high-z QSOs
- Expect ~7 @ z>6.4
- Many fainter z~5-6



Typical SED's (r~24, redshift~1)







- KIDS ugriz
- UKIDS YJHK

Data Flow

(E. Valentijn)

- Spread over 6 data centers in Europe
  - Astro-WISE system = federated database + query-driven pipeline processing
    - Db-wide control of calibration and quality ctl.
  - Mini-VO with a mini-GRID
  - Integration with UKIDSS / VISTA IR data
- Data delivery will be to ESO

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3. Galaxy-galaxy lensing: halo parameters

- Clear predictions on 100kpc-1Mpc scales on dark matter distribution
  - Dark matter dominates the potential
  - Gravity dominates the physics
  - Star formation/feedback etc confined to inner <100kpc

- Barely tested!
  - Rotation curves, satellite dynamics << 50kpc
  - Large-scale structure >>1Mpc

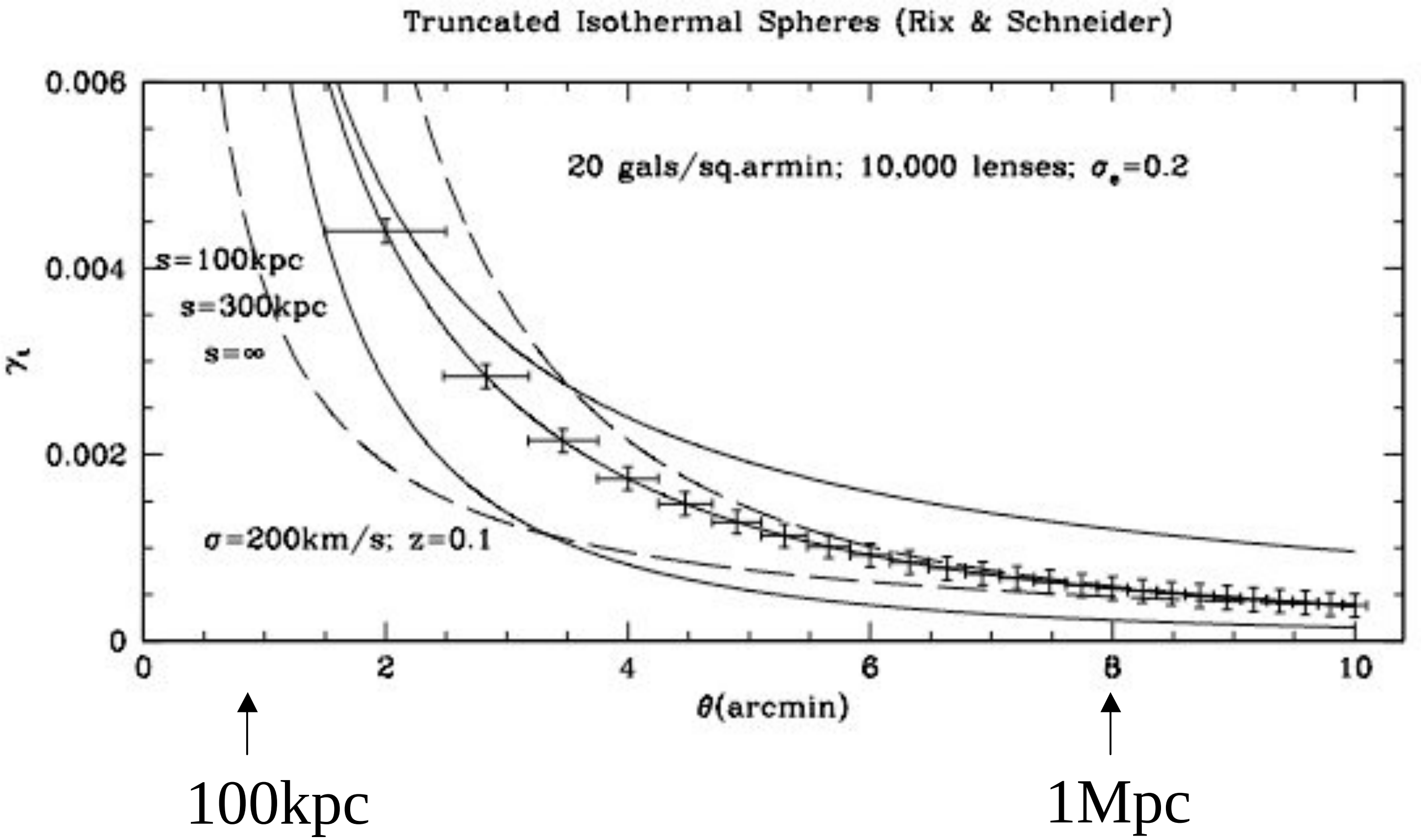
Galaxy-galaxy lensing

- Some crucial tests of galaxy formation:
  - Total baryon / dark matter mass in galaxies
  - Radial profile of dark matter distribution
  - Shape of dark halos
  - …
  - All best probed at several 100kpc scale where dark halo dominates clearly

- Halo ***shapes*** are fundamental test for alternative gravity theories as well

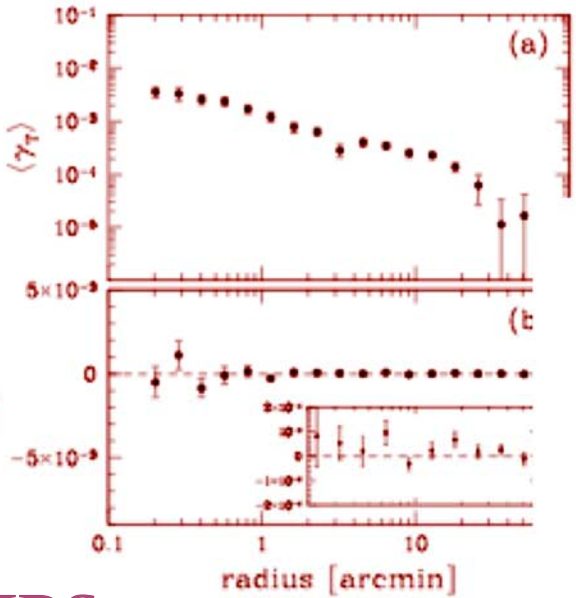
In practice

- Average 10,000 foreground galaxies
    - (1/20th of KIDS foreground galaxies)
- Measure truncation radius

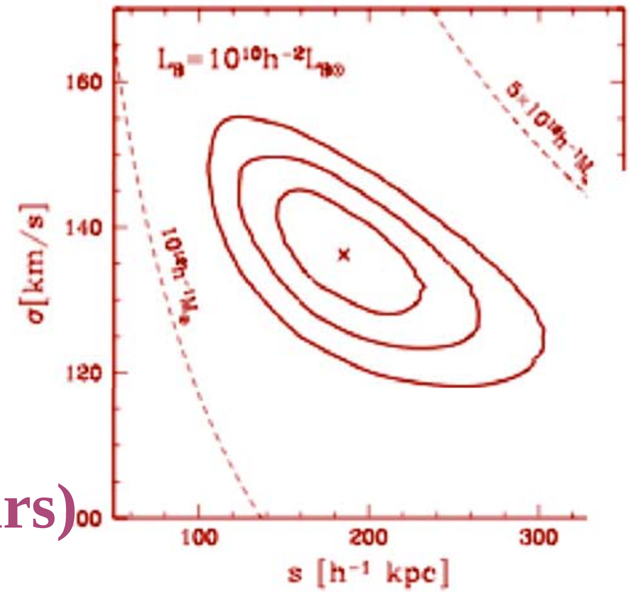


Galaxy-galaxy lensing

45 sq. deg from RCS survey (Hoekstra, Yee, Gladders 2004)

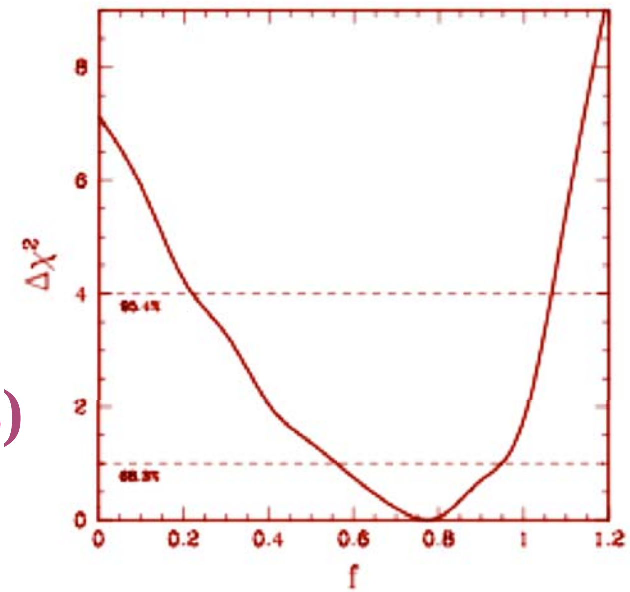


Galaxy-mass correlation



Halo radii

Halo shapes



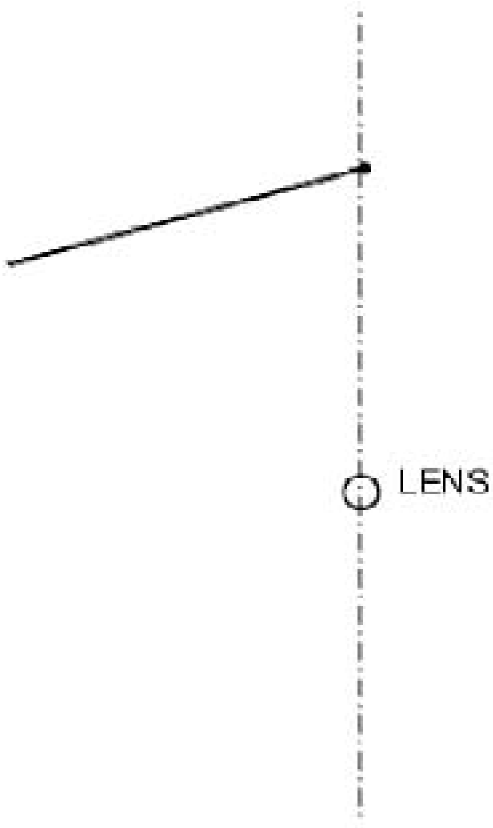
KIDS:

6x smaller errors (#pairs)

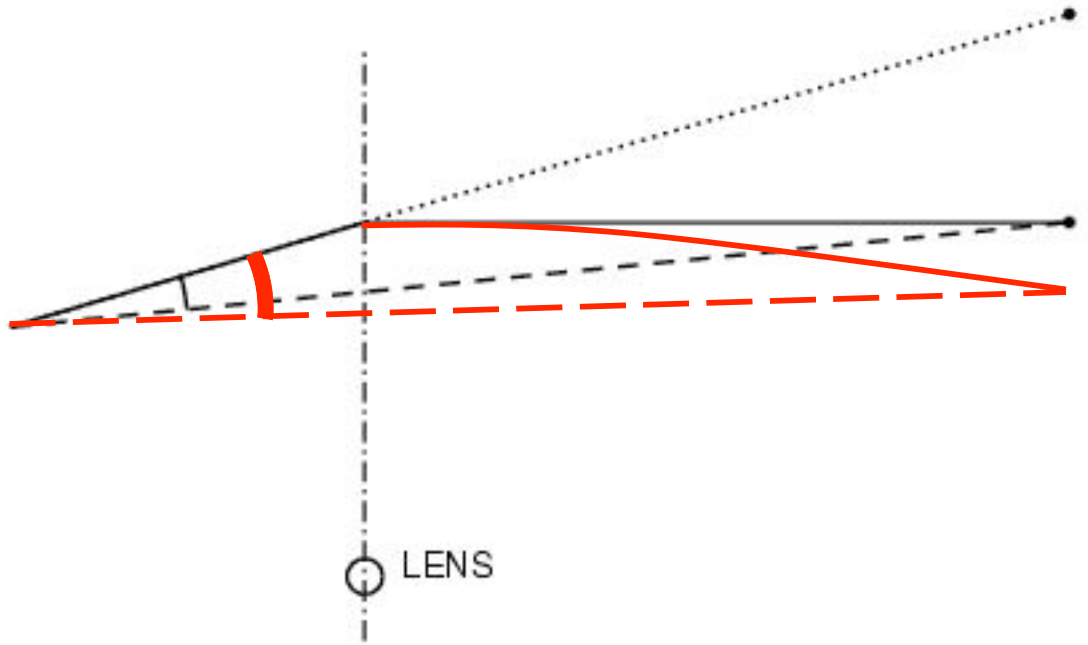
Good photo-z's (b/g), spectroscopic z's (lenses)

Study effect by galaxy type, scaling relations

LENS EFFECT DEPENDS ON DISTANCE TO THE SOURCE



Light bending in an expanding universe



Bending angle depends on expansion history:

Geometric way to deduce expansion history

Learn about evolution of dark energy

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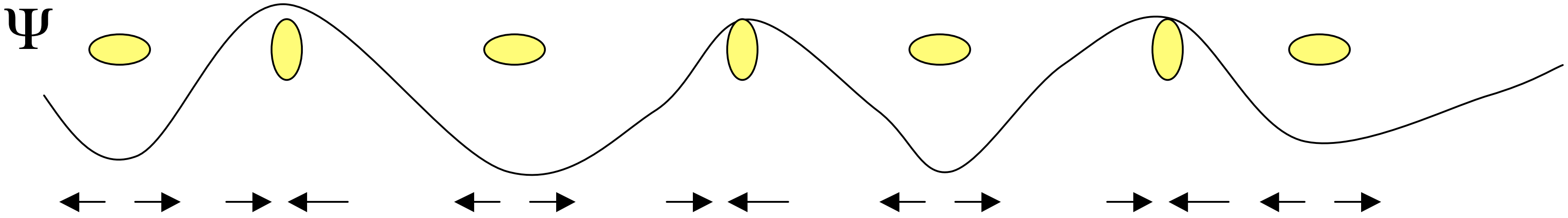
4. Cosmic shear



- ‘Direct’ measure of matter power spectrum

- Evolution of power spectrum amplitude fundamental test of gravitational instability picture

- Detailed growth rate constrains cosmological parameters (Ω, Λ) as well as `w’.
  - CMB gives initial conditions

Cosmic shear maths

- Evolution of scale factor a(t) = $(1+z)^{-1}$:

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\,(\Omega_m + \Omega_\Lambda + \Omega_k)$$

$$\Omega_m \propto (1+z)^3$$

$$\Omega_\Lambda \propto (1+z)^{3(w+1)}$$

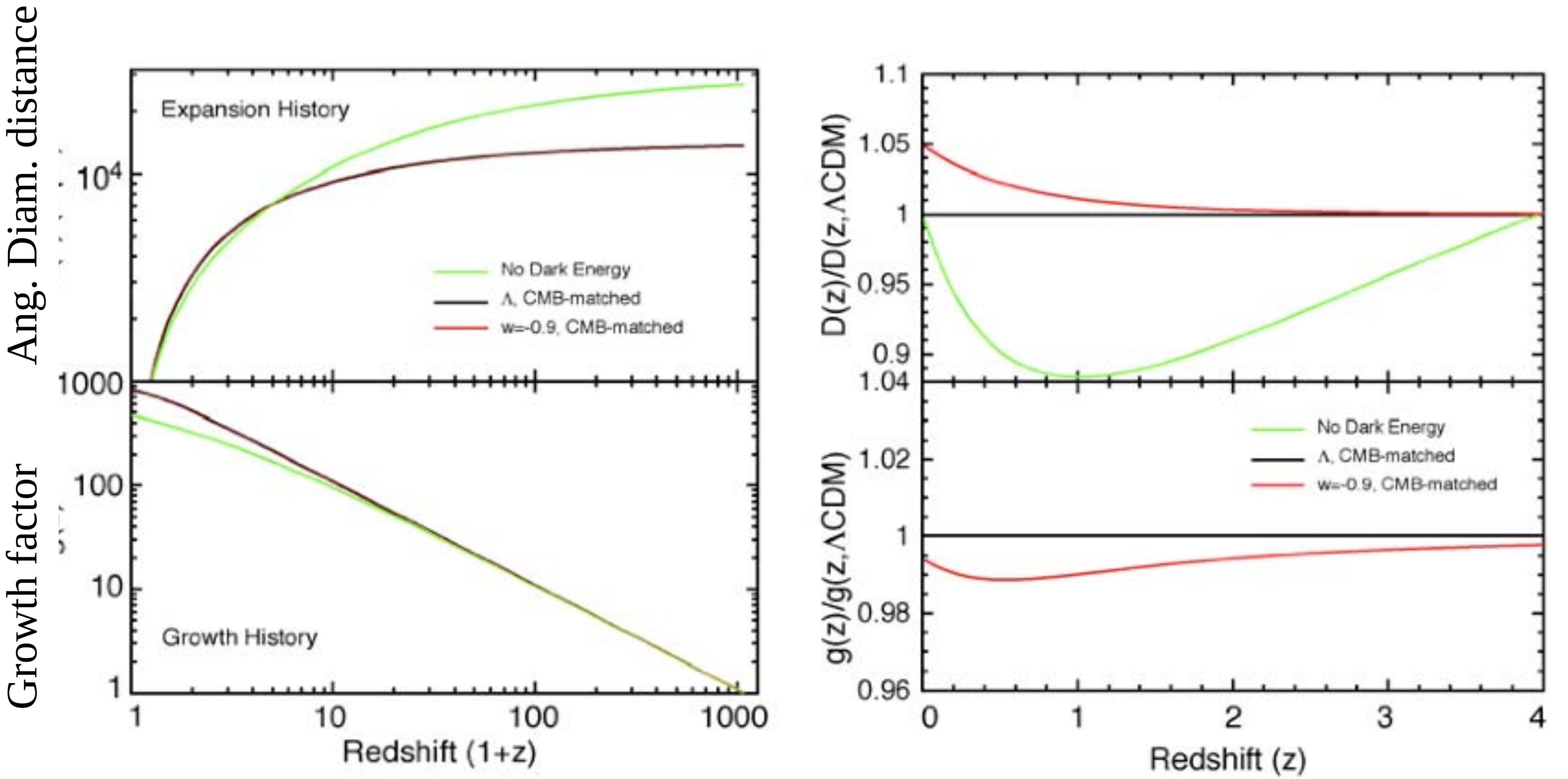
$$\Omega_k \propto (1+z)^2$$

- Growth of structure in expanding universe

$$\ddot{g} + 2\dot{a}\dot{g}/a = 4\pi G\rho g = 3\Omega_m H_0^2 g/2a^3$$

+ non-linear effects on small scales…

Cosmic shear maths



(From 'Dark Energy Task Force' report)

Cosmic shear

- Systematic correlations of galaxy ellipticities $\Leftarrow$ gravitational shear effect $\Leftarrow$ power spectrum of the mass distribution ~ halfway between lens and source

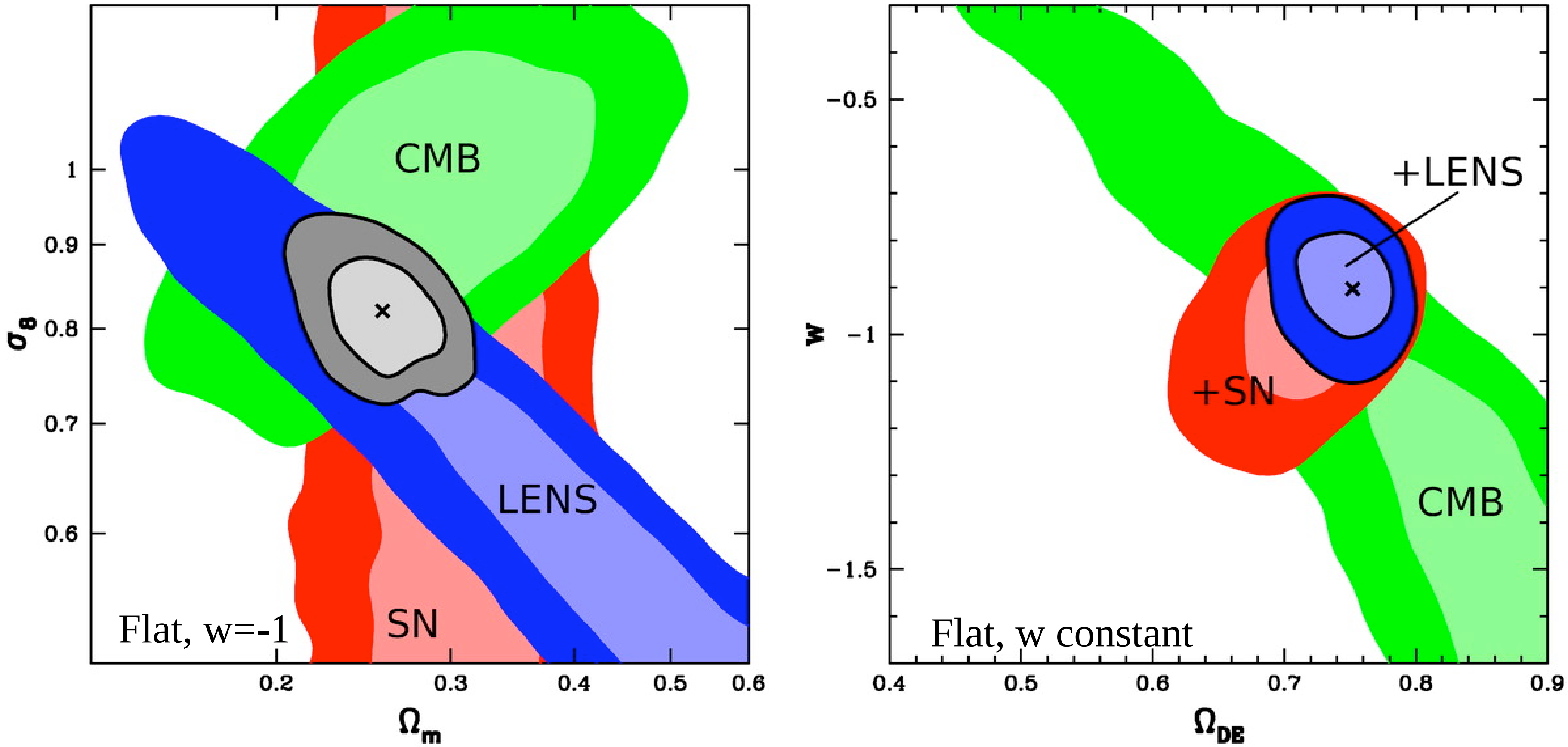
- Many source redshifts $\Rightarrow$ tomography

- Most accurate results thus far: CTIO & CFHTLS
  - Measure result as σ_8: value rather higher than WMAP 3-yr value.

CTIO survey (75sq.deg.)

(Jarvis et al 2006)

- Wk lensing: complimentary info to SNe, CMB
- Constraints on dark energy



CFHTLS vs. WMAP-3yr

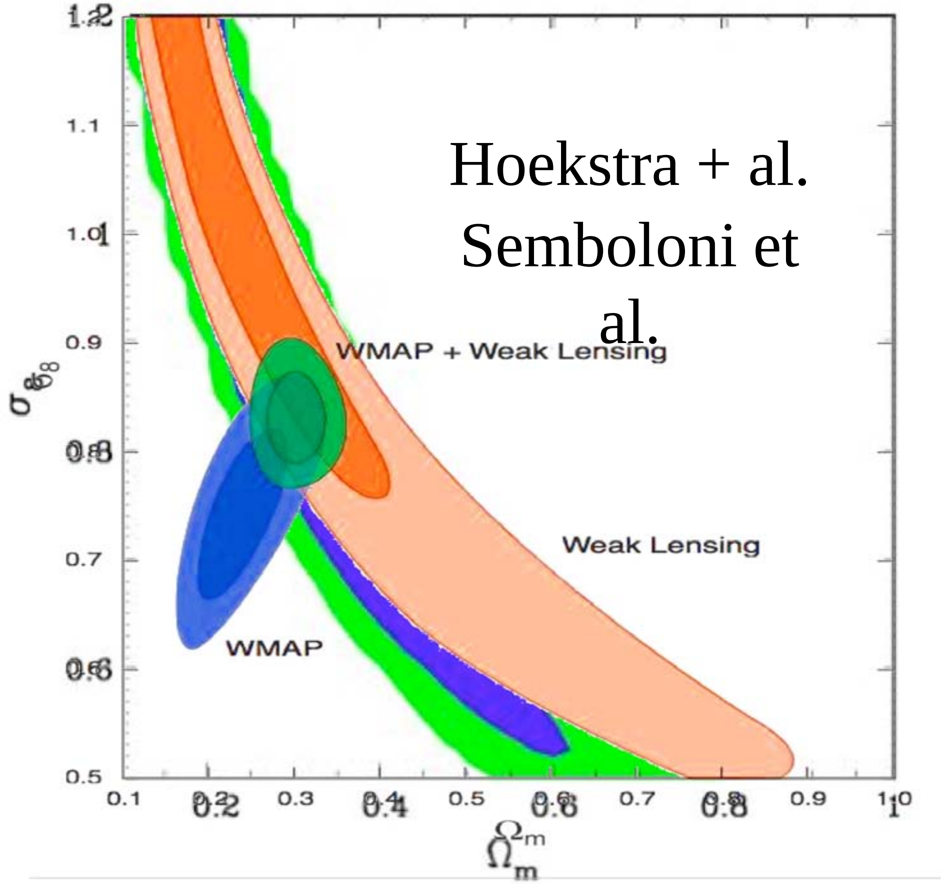
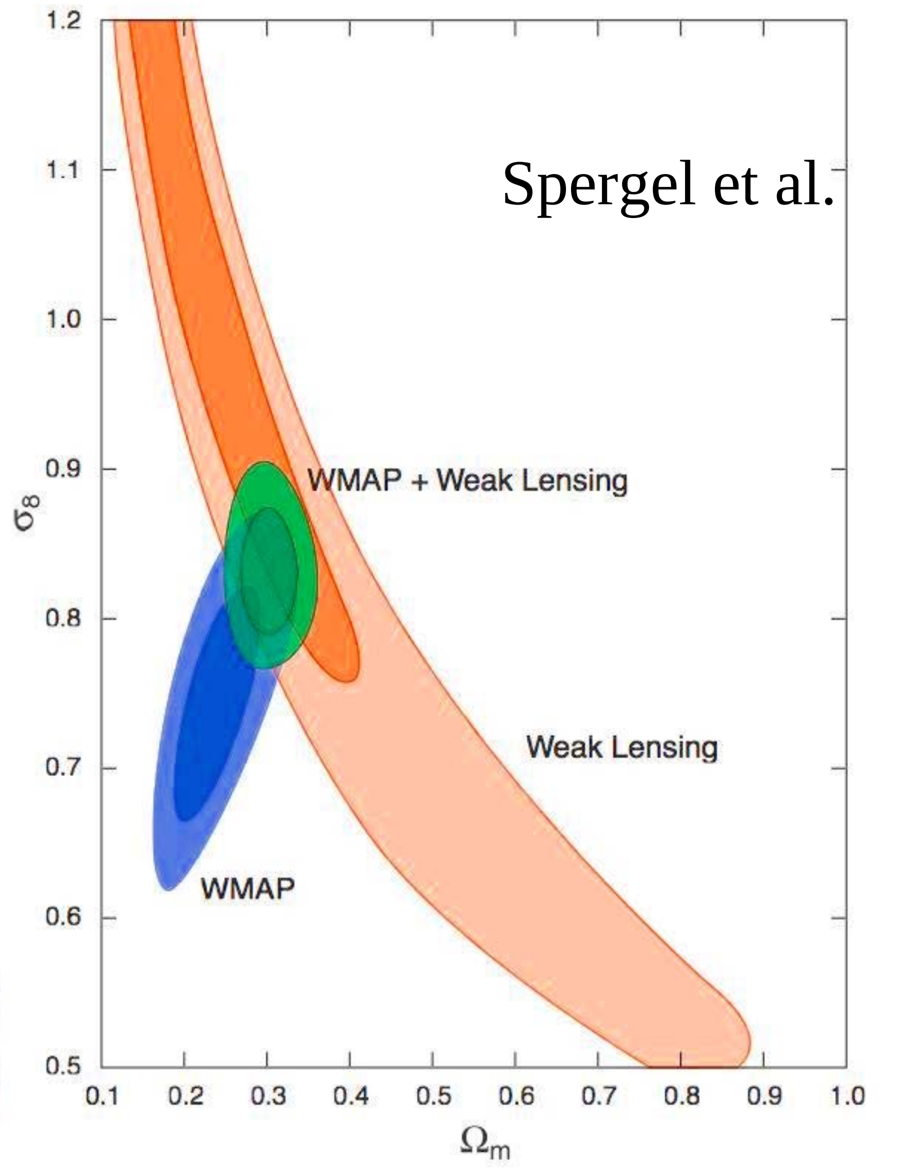
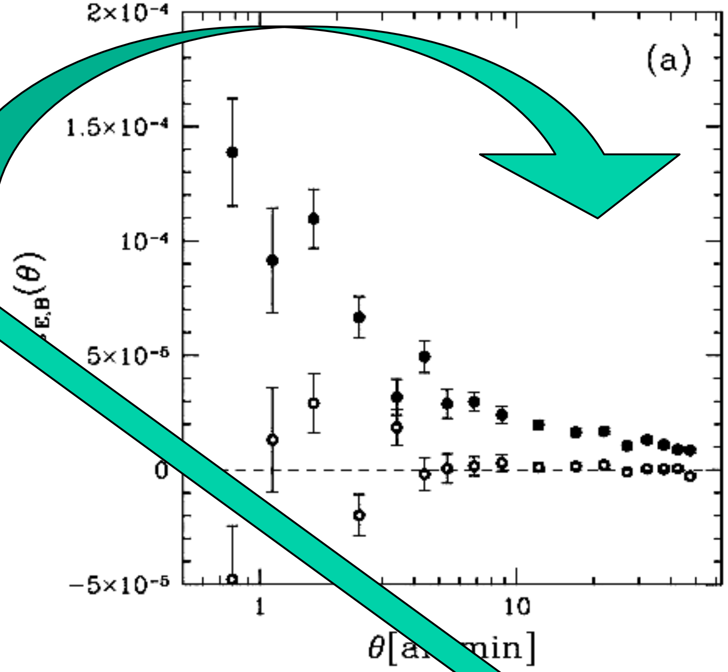


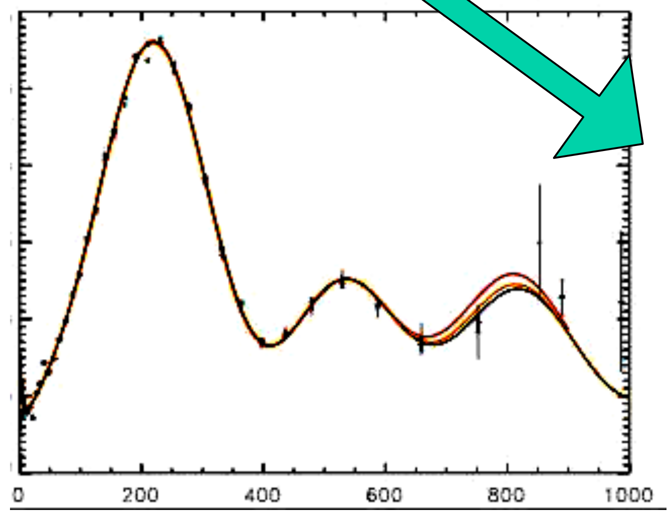
FIG. 11.— Joint constraints on Ω_m and σ_8 constraints from the CFHTLS Wide data using the Smith et al. (2003) model for the non-linear power spectrum. The contours indicate the 68.3%, 95.4%, and 99.7% confidence limits on two paramaters jointly. We marginalised over the Hubble parameter and source redshift distribution as described in the text.



Cosmic shear

- Discrepancy (???) CFHTLS / WMAP
  - Measure different things
    - 8(1+z)Mpc @ z=0.2 subtends ~ 20'
    - 8(1+z)Mpc @ z=1100 subtends ~ 3' (l~2000)
  - Uncertainties in the weak lensing:
    - Source redshift distribution
    - Calibration traditionally delicate
    - Density evol. on 8Mpc scale is non-linear
  - KIDS will provide independent result
    - 14 sq.deg overlap with CFHLS-W to test systematics





Cosmic shear & w

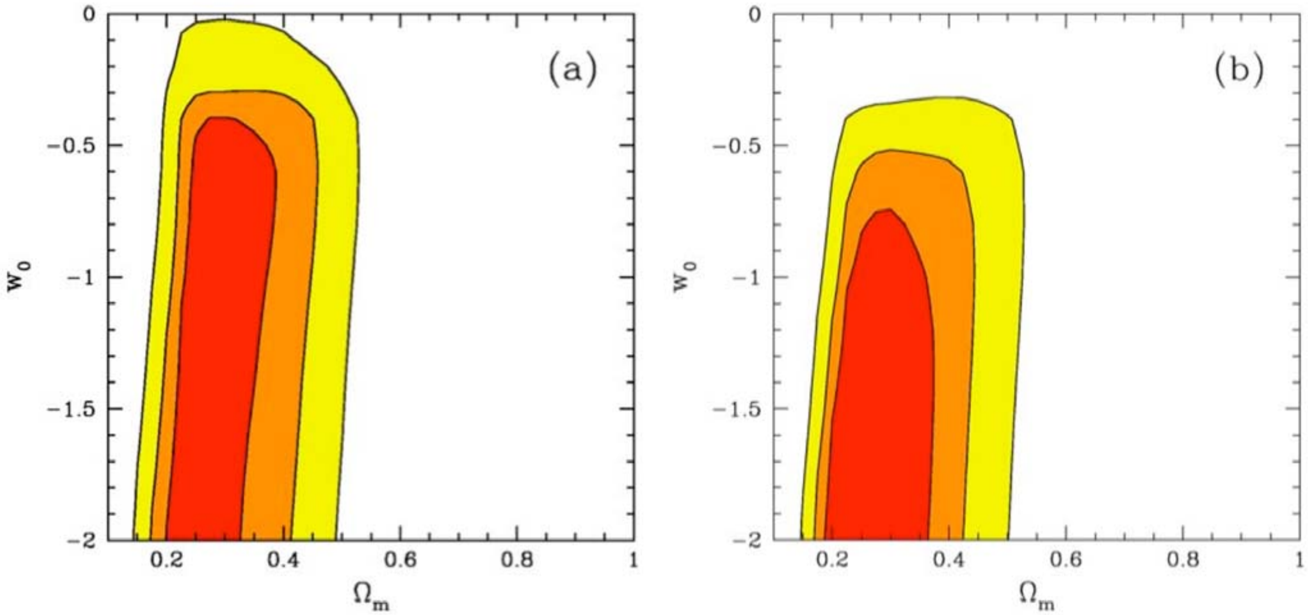
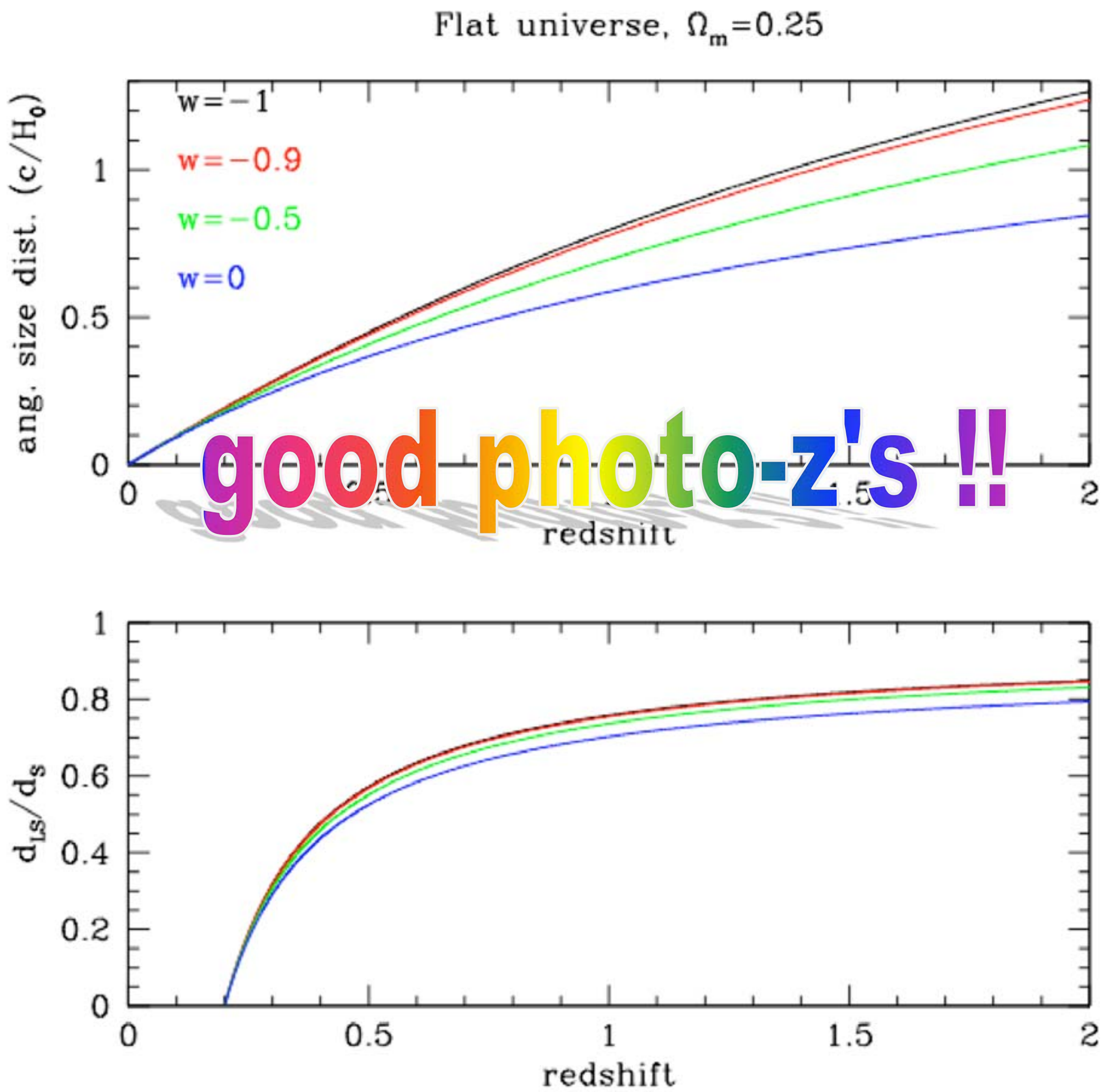


FIG. 12.— *panel a:* Dark energy constraints using the measurements from the W1 and W3 fields. The contours indicate the 68.3%, 95.4%, and 99.7% confidence limits on two paramaters jointly. We marginalised over $\sigma_8 \in [0.7, 1.0]$, $h \in [0.6, 0.8]$ and the source redshift distribution as described in the text. *panel b* Results when the measurements from the Deep component (Semboloni et al. 2005) are included. We used the Peacock & Dodds (1996) prescription for the non-linear power spectrum.

Constraints on w from CFHT wide, wide+deep

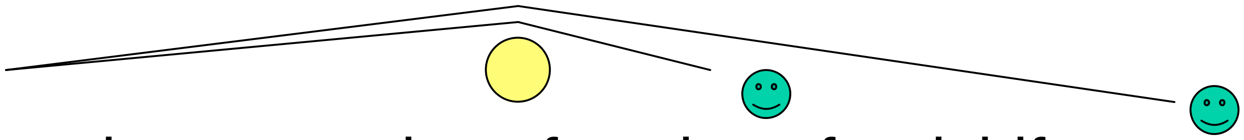
3 handles on w from KIDS

- Cosmic shear: growth of structure
- Baryon oscillation bumps in angular corr. fn. (angular diameter-redshift relation)
- Galaxy-galaxy lensing: shear dependence on source redshift (angular diameter-redshift relation)



‘w’ (weak lensing)

- Weak lensing constraints
  - Lensing effect depends on relative distances of source and lens: $\propto D_{ls}/D_s$



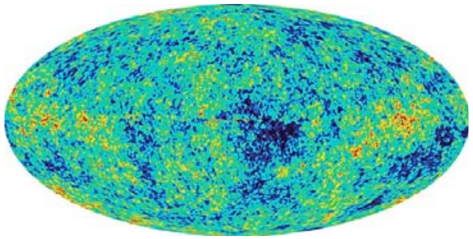
  - Measure lensing strength as function of redshift
  - Deduce distance as function of redshift
  - Geometrical test of expansion history: w (5%)
  - Needs well-controlled photo-z’s!

‘w’ (weak lensing) II

- Weak lensing (cosmic shear) measures power spectrum of ALL matter in front of the lenses

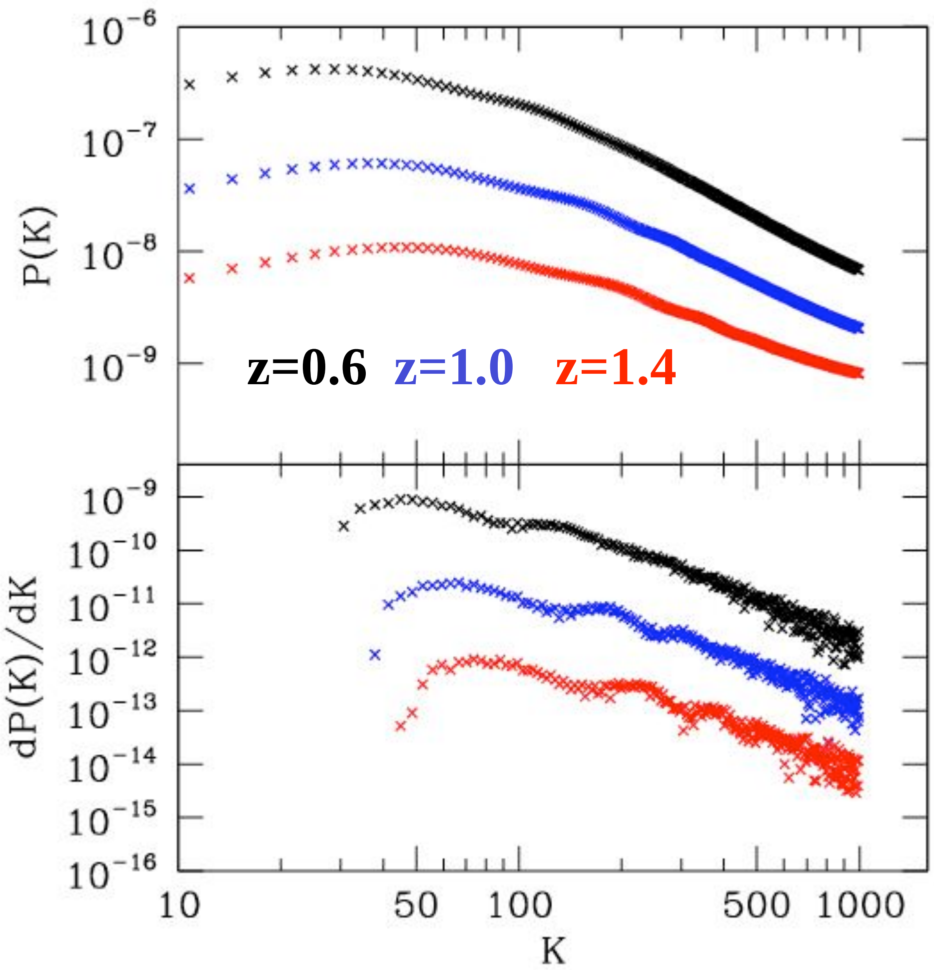
$$P_\kappa(\theta, z_s) = \int dz_l\, W(z_s, z_l)\, P_m[D(z_l)\theta, T(z_l)]$$

  - Tomography $\rightarrow P_m(x,T)$
  - Growth of structure depends on expansion history of the universe, so P_m is a probe



‘w’ (wiggles)

(P. Schuecker)

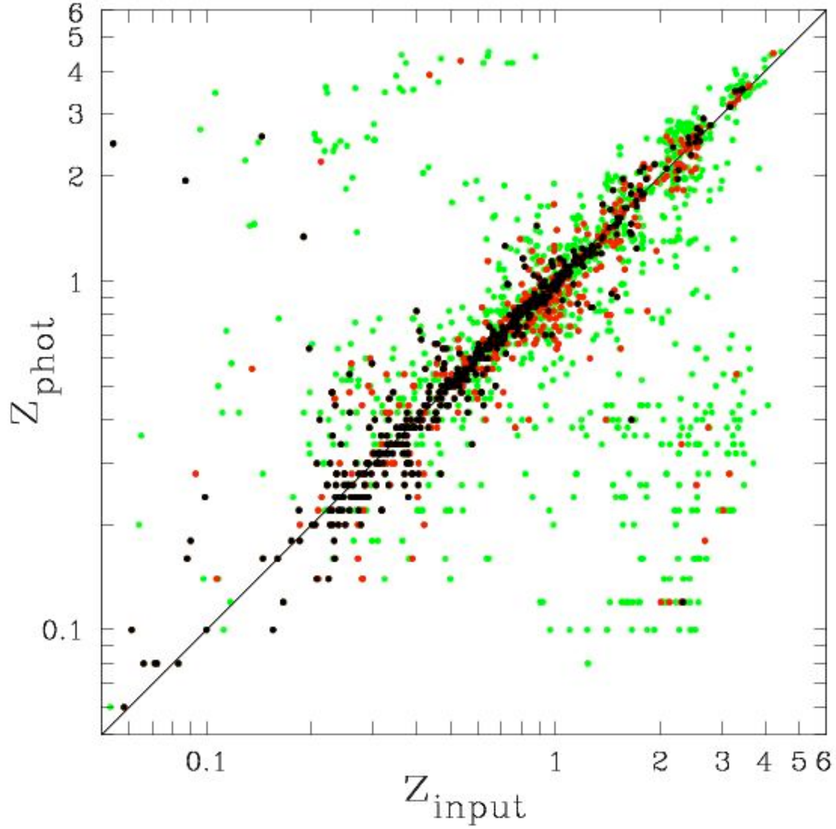


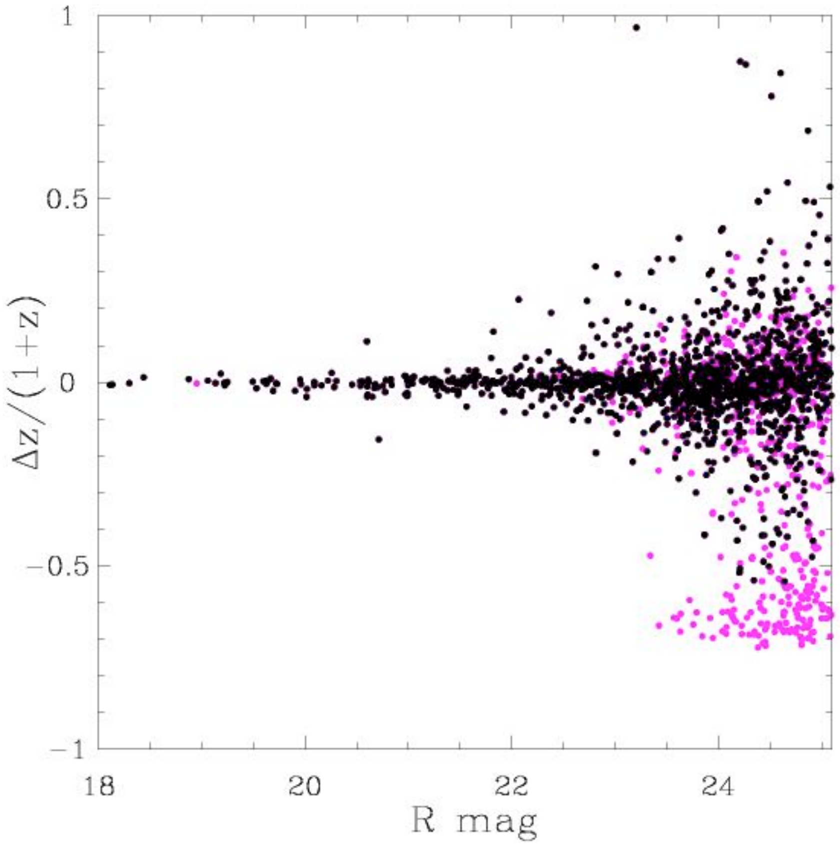
Angular waveno. (deg^{-1})

- Use scale of power spectrum wiggles as standard length
- Spec redshift surveys: need few 100,000 gals for detection
  - Photometric redshift surveys: wash out z information, but many more galaxies!
    - KIDS: 67,000,000 gals with r<23.5 (20-σ fluxes)
    - Photo-z accurate to 0.03(1+z)   (ugrizYJHK)
  - w(z=0) to <15% from KIDS
  - w(z=1) to better accuracy

Photo-z from KIDS/UKIDSS

(Saglia)





r<23.5 **r<24** **r<25**

0<z<6 **0<z<1.5**

Scatter further reduced with deeper IR data

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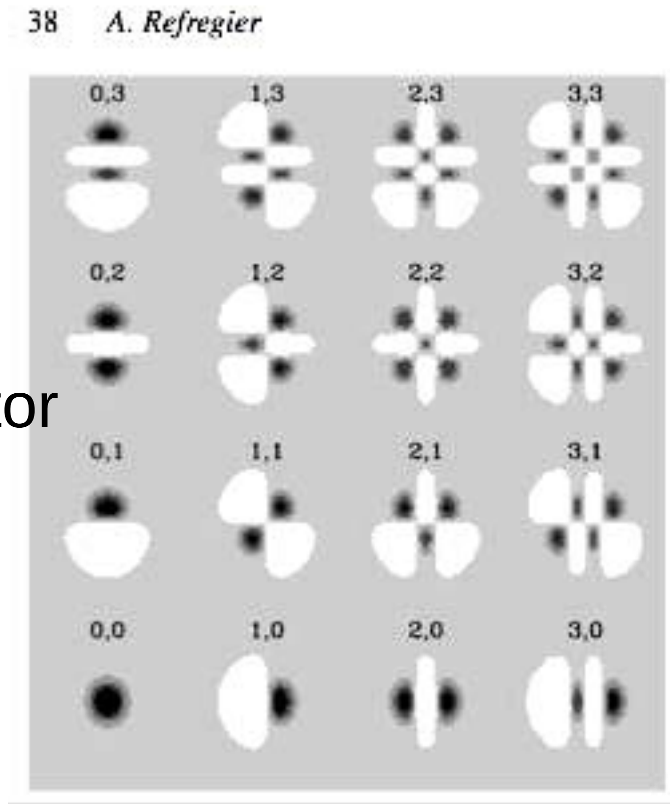
- Development of shapelets-based methods for
  - Weak lensing measurements
  - Aperture and PSF-matched photometry for colours and photo-z's
- Shapelets (Refregier 2003): model sources as

$$e^{-r^2/2\beta^2}[p_{00}+p_{10}x+p_{01}y+p_{20}x^2+p_{11}xy+p_{02}y^2+\dots$$

$$+p_{N0}x^N+p_{N-1,1}x^{N-1}y+\dots+p_{0N}y^N]$$

Shapelets



- Gaussians x Hermite polynomials = Eigenfns of Quantum Harmonic Oscillator
- Complete basis
- Formalism of QM applies:
  - Ladder operators $a_1, a_1^+ : S_{ij} \rightarrow S_{i\pm1,j}$
  - Translation $T_1=(a_1^+ - a_1)/2^{1/2}$
  - Rotation operator $R=a_1 a_2^+ - a_1^+ a_2$
  - Magnification $K=1+(a_1^{+2}+a_2^{+2}-a_1^2-a_2^2)/2$
  - Shear $S_1=(a_1^{+2}-a_2^{+2}-a_1^2+a_2^2)/2$

$\Rightarrow$ easy to compute the effect of operations on a shapelet object *(Refregier 2003)*

Shapelets

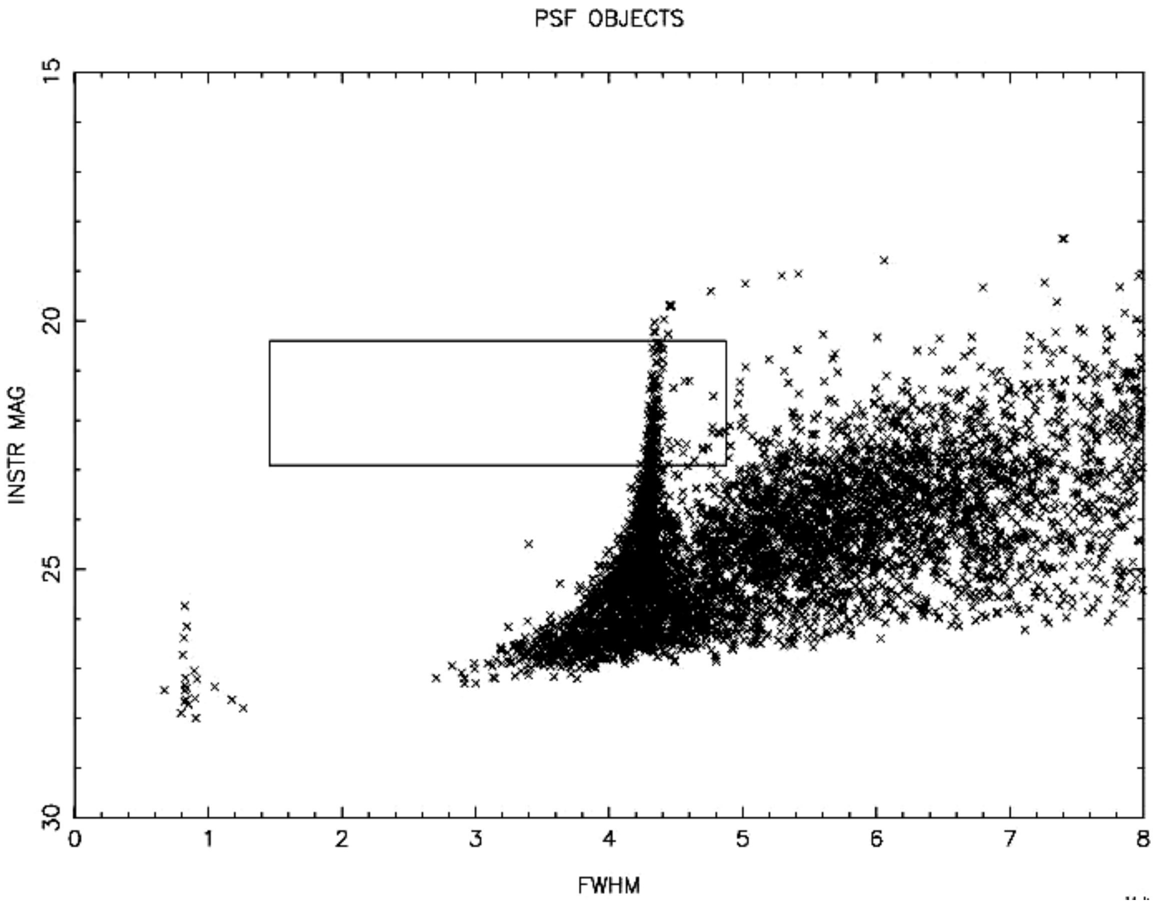
- Convolution (PSF smearing)
  - Component by component:

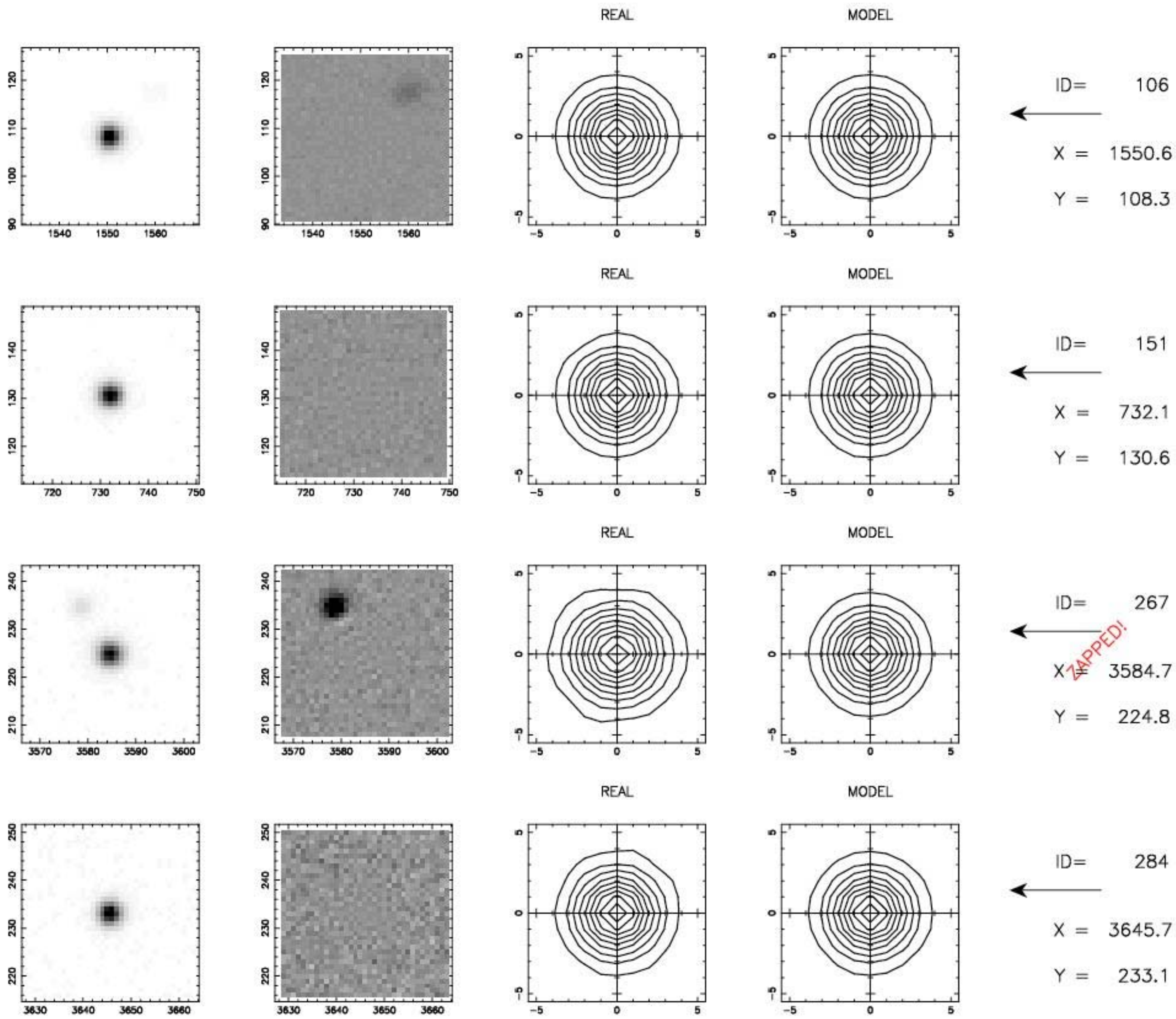
$$S^{\beta_1}_{a_1 b_1} \otimes S^{\beta_2}_{a_2 b_2} = \sum_{a_3 b_3} C^{\beta_3 \beta_1 \beta_2}_{a_3 a_1 a_2} C^{\beta_3 \beta_1 \beta_2}_{b_3 b_1 b_2} S^{\beta_3}_{a_3 b_3}$$

  - i.e. can express convolution of two shapelets objects as a new shapelet object; ‘C’ coefficients can be computed for any shapelet scales β_i.

- Can construct a ‘PSF matrix’ that expresses convolution with PSF on a shapelet object
  - Coefficients of PSF can be interpolated across image

PSF mapping




REAL
MODEL
ID= 106
X = 1550.6
Y = 108.3
REAL
MODEL
ID= 151
X = 732.1
Y = 130.6
REAL
MODEL
ID= 267
ZAPPED!
X = 3584.7
Y = 224.8
REAL
MODEL
ID= 284
X = 3645.7
Y = 233.1

5a. Shears from shapelets

- Model observed sources as

  PSF $\otimes$ sheared circular source

  $$= \mathbf{P} \,.\, (1+e_1\mathbf{S}_1+e_2\mathbf{S}_2).(c_0C_0+c_2C_2+c_4C_4+\ldots)$$

  – Call the best-fit shear the 'ellipticity' e_1,e_2 of the source

- Average ellipticity of sheared set of galaxies:

  $$\langle e_i \rangle = (1-\langle e^2 \rangle/2)\, \gamma_I$$

- Advantage of this formalism is incorporation of PSF effects in modelling

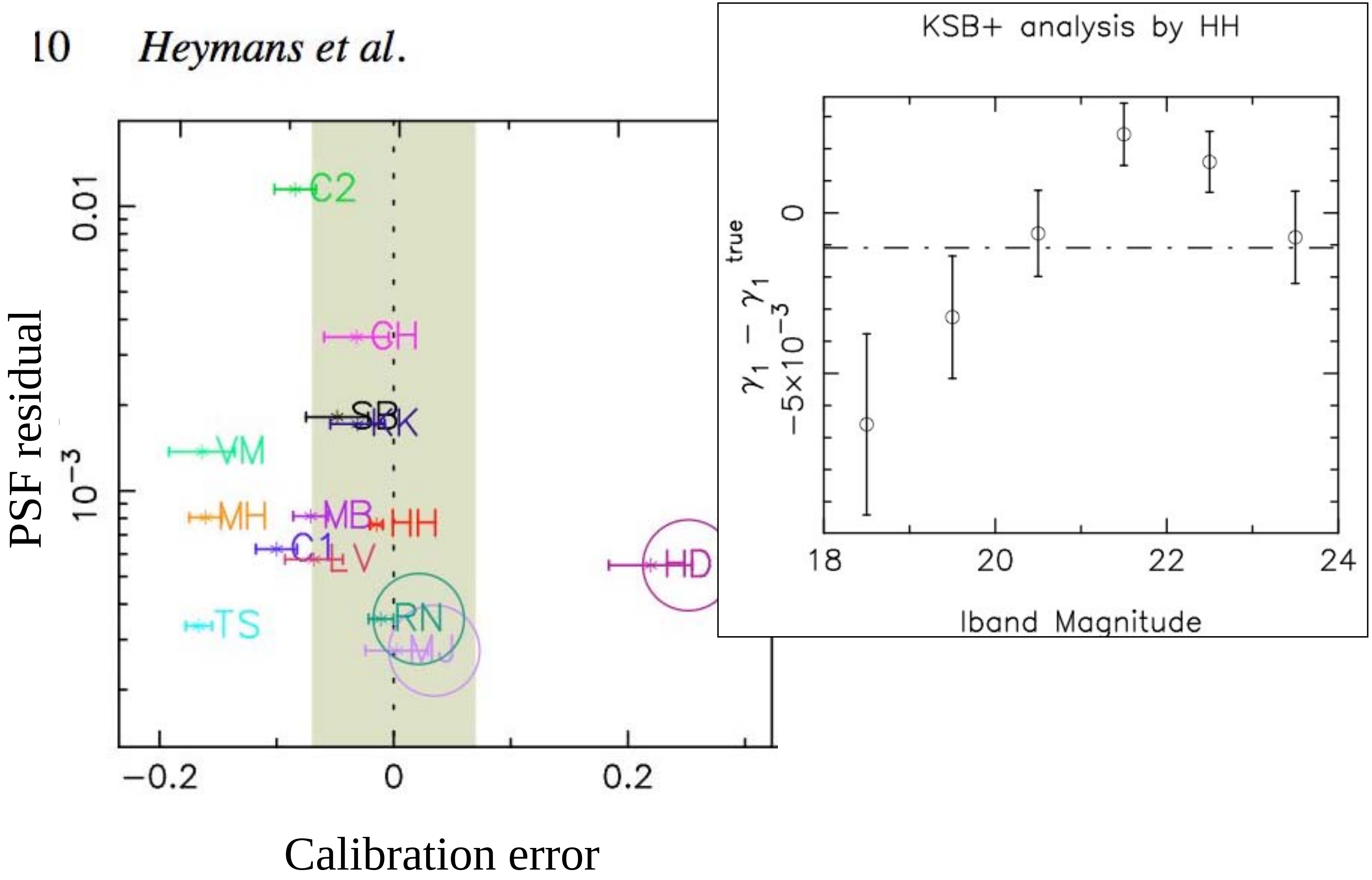
STEP: shear testing prog.

(Heymans + al. 2005, Massey et al. 2006)

- Trick: extract intrinsic ellipticity in spite of blurring by PSF, pixels

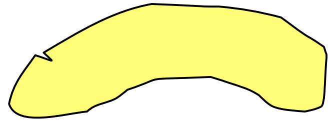
- Blind experiments on simulated sheared images
- Compare methods: (KSB's, shapelets, ellipto, im2shape, …)
- First round: agreement at ~ 5-10% level
  - (idealized galaxies, realistic CFHT PSFs)
- Second round: few percent accuracy
  - (more realistic galaxies and PSFs)
- Space-STEP: ongoing
  - Realistic faint galaxies + SNAP-like PSFs
- Improving further will be hard work!

STEP1 results

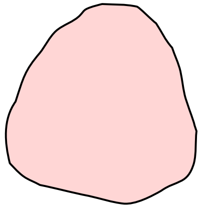


Flexion

- Higher-order term in lensing: gradient of shear (Goldberg & Bacon 2005)
  - Makes bananas and eggs *(mmm!?)*



  - Even weaker effect than shear
  - Decays faster with radius than shear



  - But: intrinsic galaxy shapes have little flexion, so shape noise is lower! Effects roughly balance out.
  - Effect on shapelets can be expressed as 3rd powers of ladder operators

Outline:

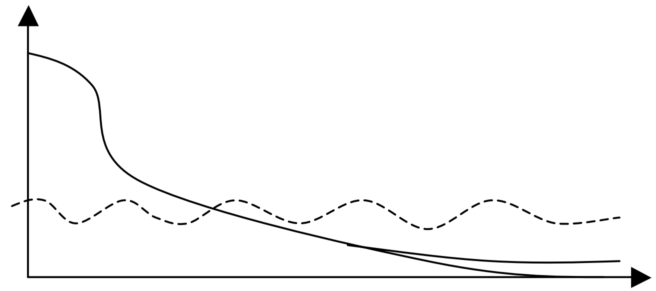
1. Weak lensing introduction
2. The KIDS survey
3. Galaxy-galaxy lensing (halos)
4. Cosmic shear (large scale structure)
5. Methods

5b. Accurate colours

- Photometric redshifts, CMDs, variability, …
  – All require accurate flux comparisons

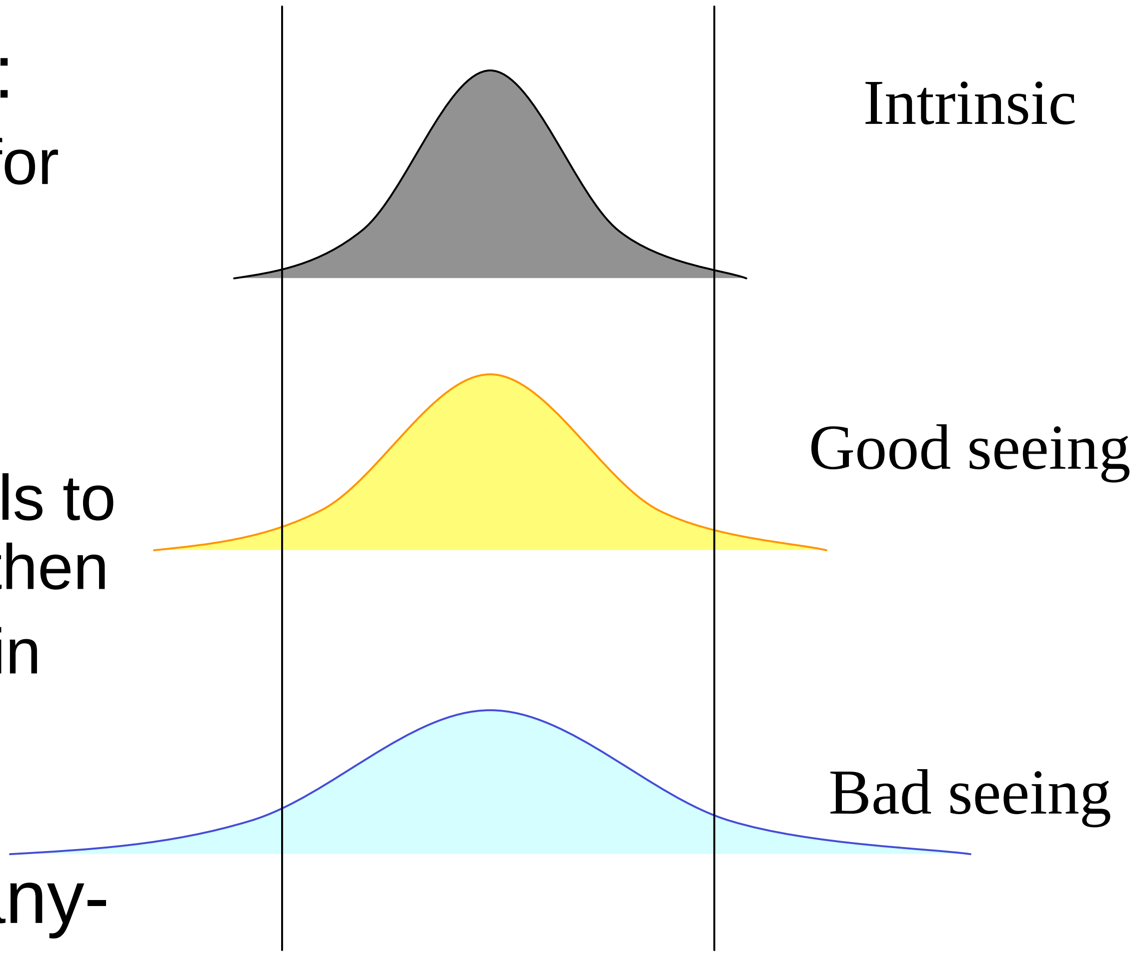
- Point sources
  – Total, PSF-fitted fluxes can be compared directly

- Extended sources
  – Total fluxes ill-defined, noisy
  – Aperture fluxes affected by PSF
  – Colours can be radius-dependent



Extended sources

- Aperture colours:
  - Need to correct for PSF differences
- Usual approach:
  - Reconvolve pixels to poorest seeing, then
  - Compute fluxes in similar apertures
- Laborious for many-band, many-field survey!



GaaP fluxes

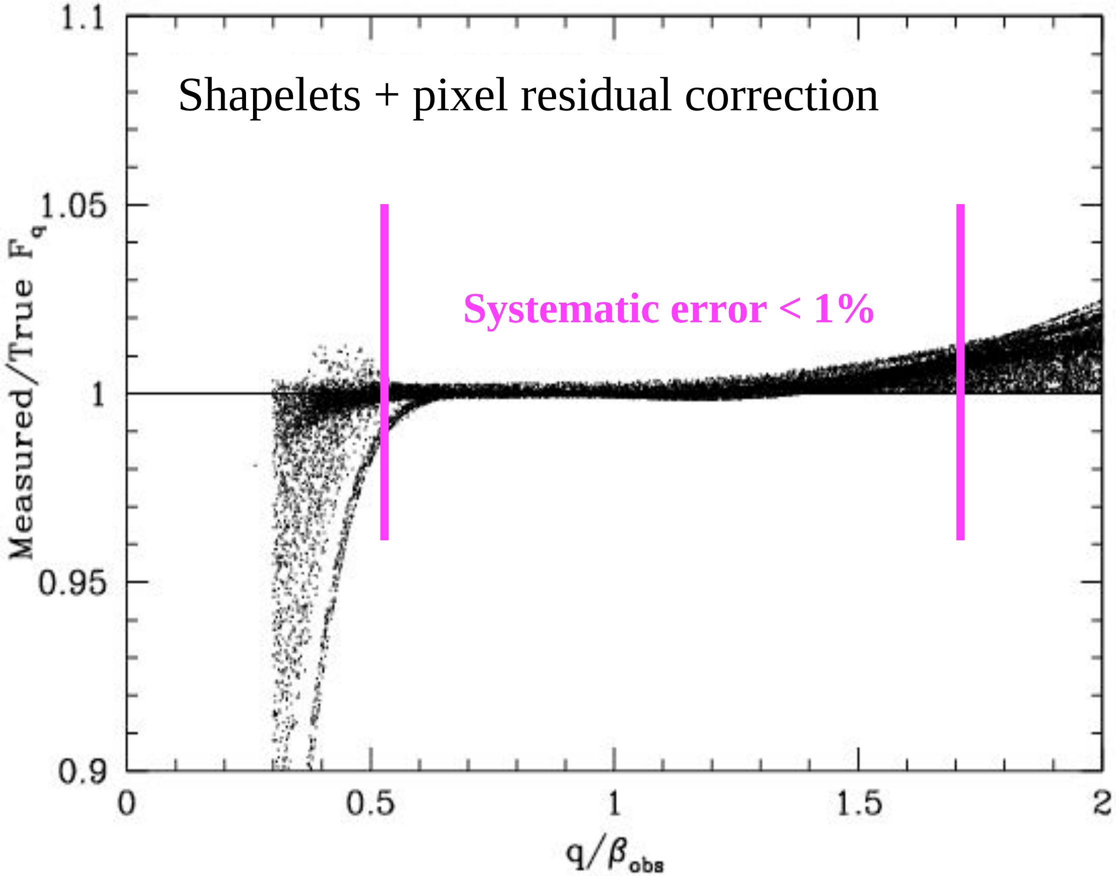
(Kuijken 2006)

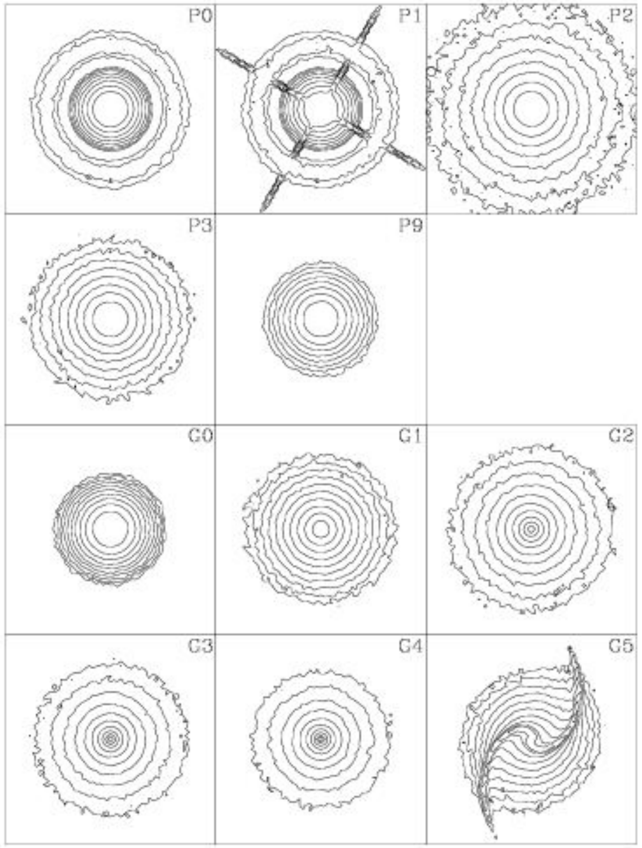
- *Weighted flux that would be observed with a Gaussian aperture and PSF*
  - Can be catalogued (for range of aperture radii)
  - Avoids the need for pixel processing by user
  - Can be implemented as list-driven photometry
    - To check the non-detections !!!

$$F_q \equiv \int d\mathbf{r}\, e^{-r^2/2q^2} \int d\mathbf{r}'\, S(\mathbf{r}') \frac{e^{-(\mathbf{r}-\mathbf{r}')^2/2q^2}}{2\pi q^2}$$
$$= \frac{1}{2} \int d\mathbf{r}\, e^{-r^2/4q^2} S(\mathbf{r})$$

- Algorithm based on shapelets

Many simulations with different PSF & galaxy type & size:





Aperture radius / gaussian radius

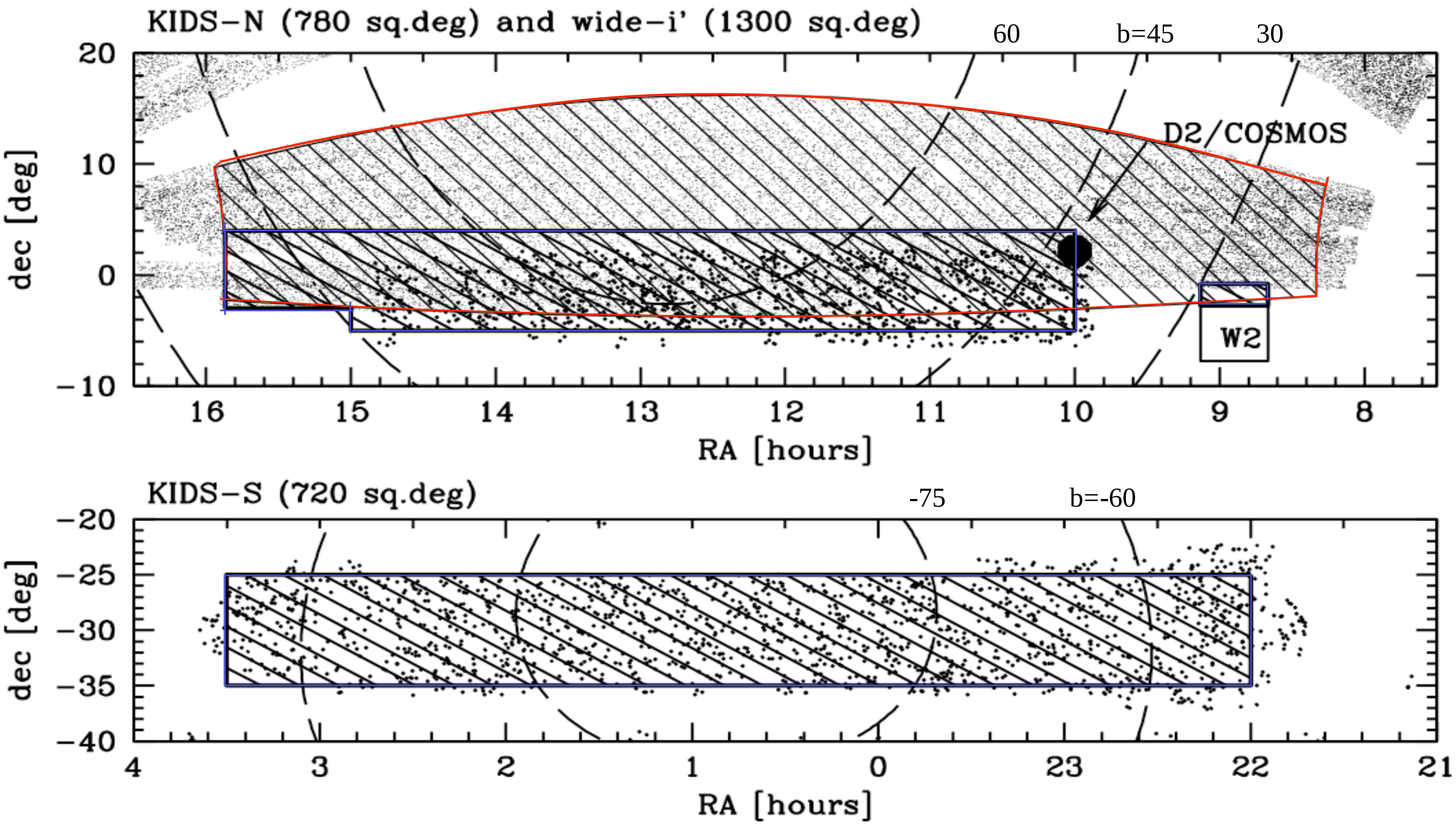
GaaP flux F_q

- PSF-independent photometric quantity
- Ratios give real colours!
- Can be computed accurately over a range of x 2 in PSF size, from image and PSF alone
- Photon statistics propagate straightforwardly
- *No need for PSF matching between exposures to get accurate colours*

Shapelets: summary

- Useful for
  - PSF description
  - Shear estimation (and flexion)
  - Matched-aperture photometry

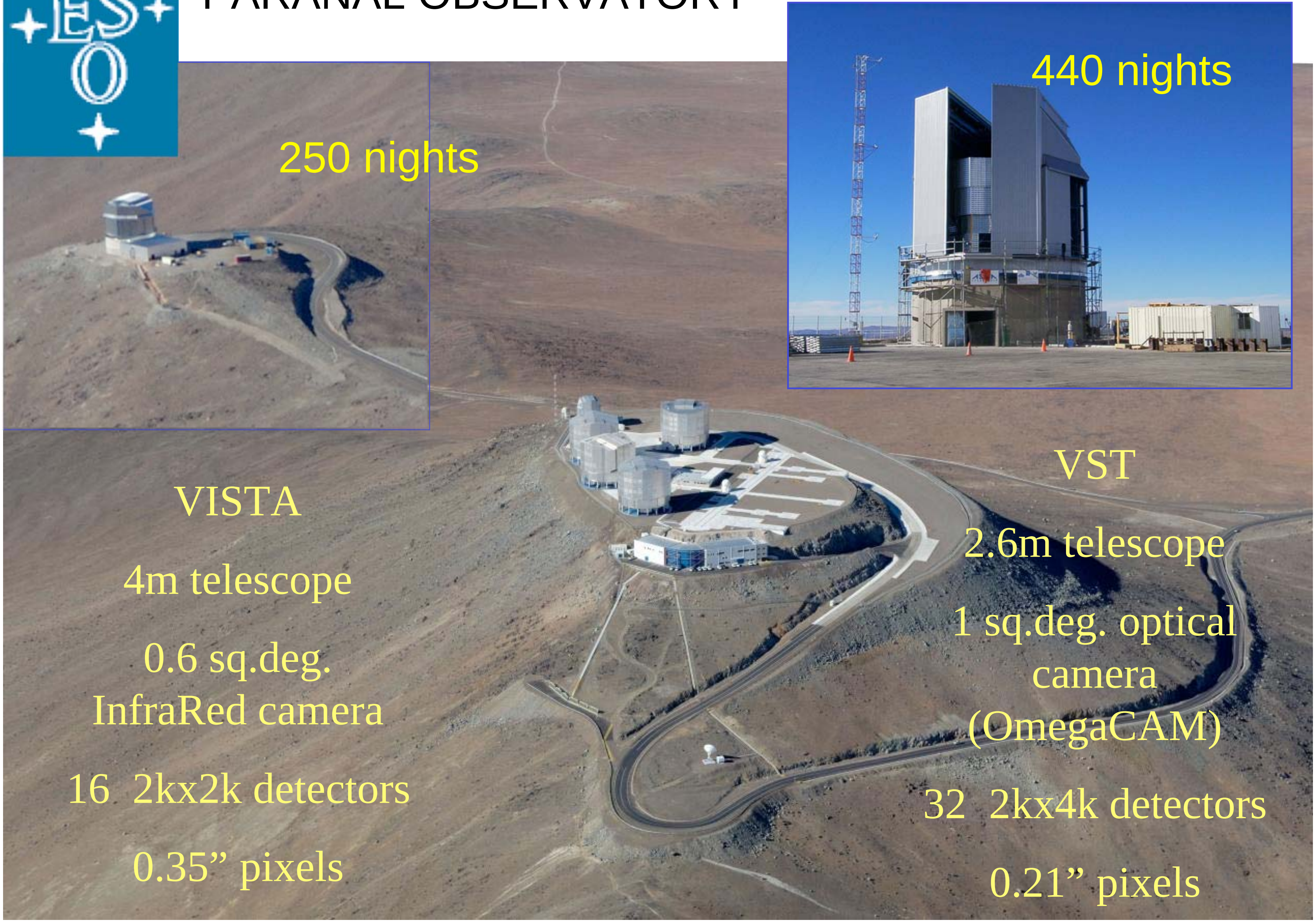
  - Morphological selection:
    - Searching for lensed qso's
    - Filtering out neighbour-affected objects



1500 sq.deg. in ugriZYJHK

+2000 sq.deg. in i (+UKIDSS YJHK)

PARANAL OBSERVATORY



KiDS

LEIDEN GRONINGEN MUNCHEN PARIS NAPLES BONN EDINBURGH CAMBRIDGE IMPERIAL

- Big astronomical survey, starts in 2007;
  - 1500 square degrees map (= area of South America on Earth globe)
  - Many applications incl. studying dark matter and dark energy

- Will use millions of ordinary galaxies as `lenses'
  - Average signal → high accuracy
  - Determine redshifts from colours measured with 9 filters
- Measure ripples from galaxy distribution on sky

- Cf. Sloan Survey:
  - Images 2 x sharper (equiv to map of Earth at 6m resolution!)
  - Will include sources 6 x fainter

- Data volume: 15 terabyte pixel data, +++
  - Astro-WISE data archiving / processing system (with EU funding)
  - Large team!

Future:

- Studies of dark matter:
  - Find the ^#%$*^ particle!
  - (even) better models of predicted growth of structure power spectrum P(k,z)
- Studies of dark energy:
  - Get some real theories to test!
  - DES@CTIO, PANSTARSS, Baryon oscillations
  - LSST / space satellite TBD will improve accuracies dramatically
    - Detect whether $w(z) \equiv -1$ consistent
    - Look for evidence of varying w(z)
  - Weak lensing/photo-z is very (most?) promising technique
- KIDS:
  - Expand survey area to 3000 sq.deg.?
  - Supplement with spectra, Spitzer post-cryo,… ?