PROBING THE DARK UNIVERSE WITH CURRENT AND FUTURE SURVEYS

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DARK MATTER, DARK ENERGY

Observations of cosmological probes give evidence of:

- an expansion history, and
- a history of growth of structure

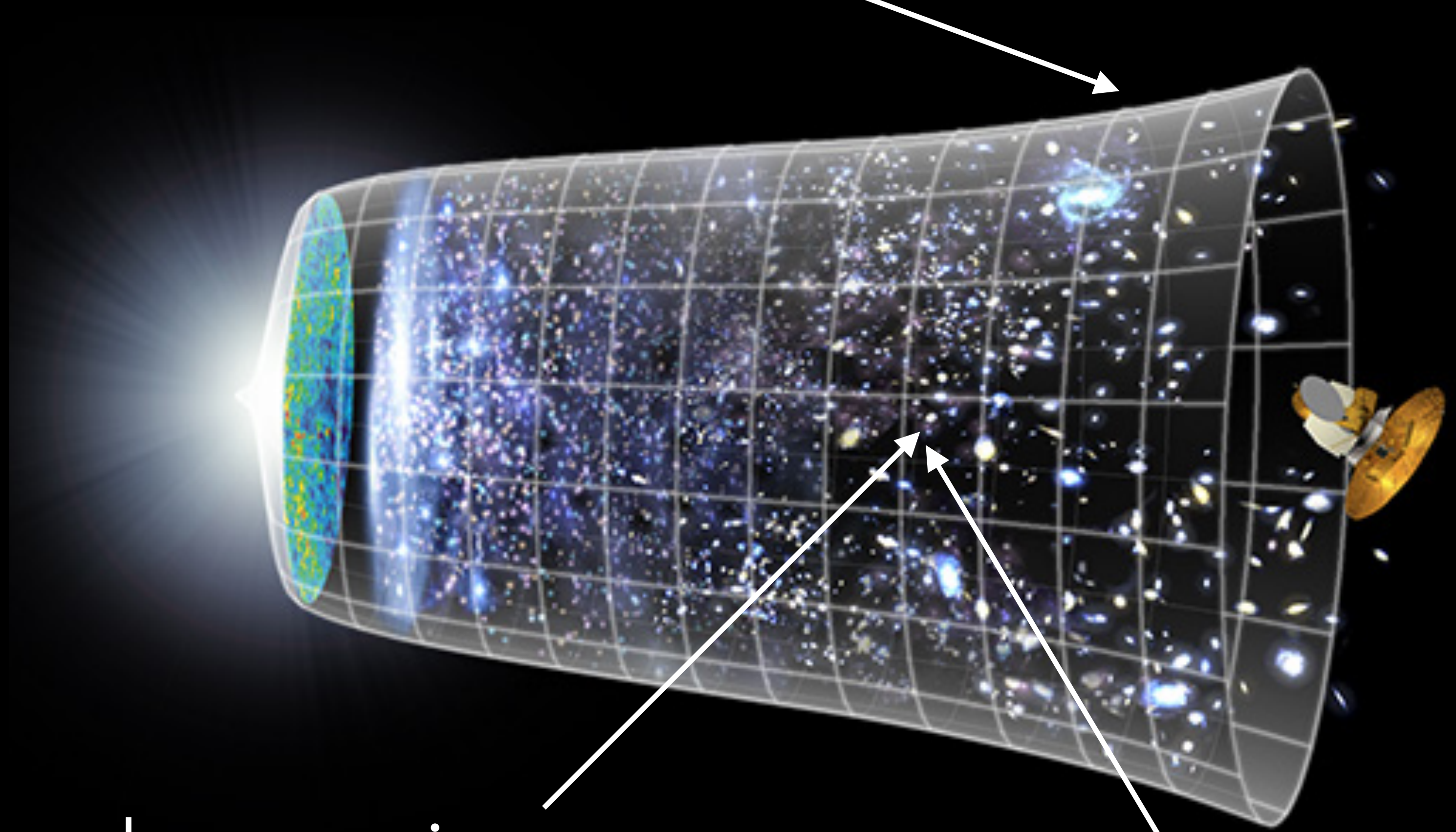
which are consistent with an accelerating expansion of the Universe;

and a matter density dominated by a dust-like material which does not (usually) radiate.

OBSERVATIONAL PROBES: INITIAL VIEW

Some observations constrain expansion history

$$H^2(z) = H_0^2 \left(\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{de} \exp\left(3\int_0^z \frac{1+w(z')}{1+z'}dz'\right)\right)$$

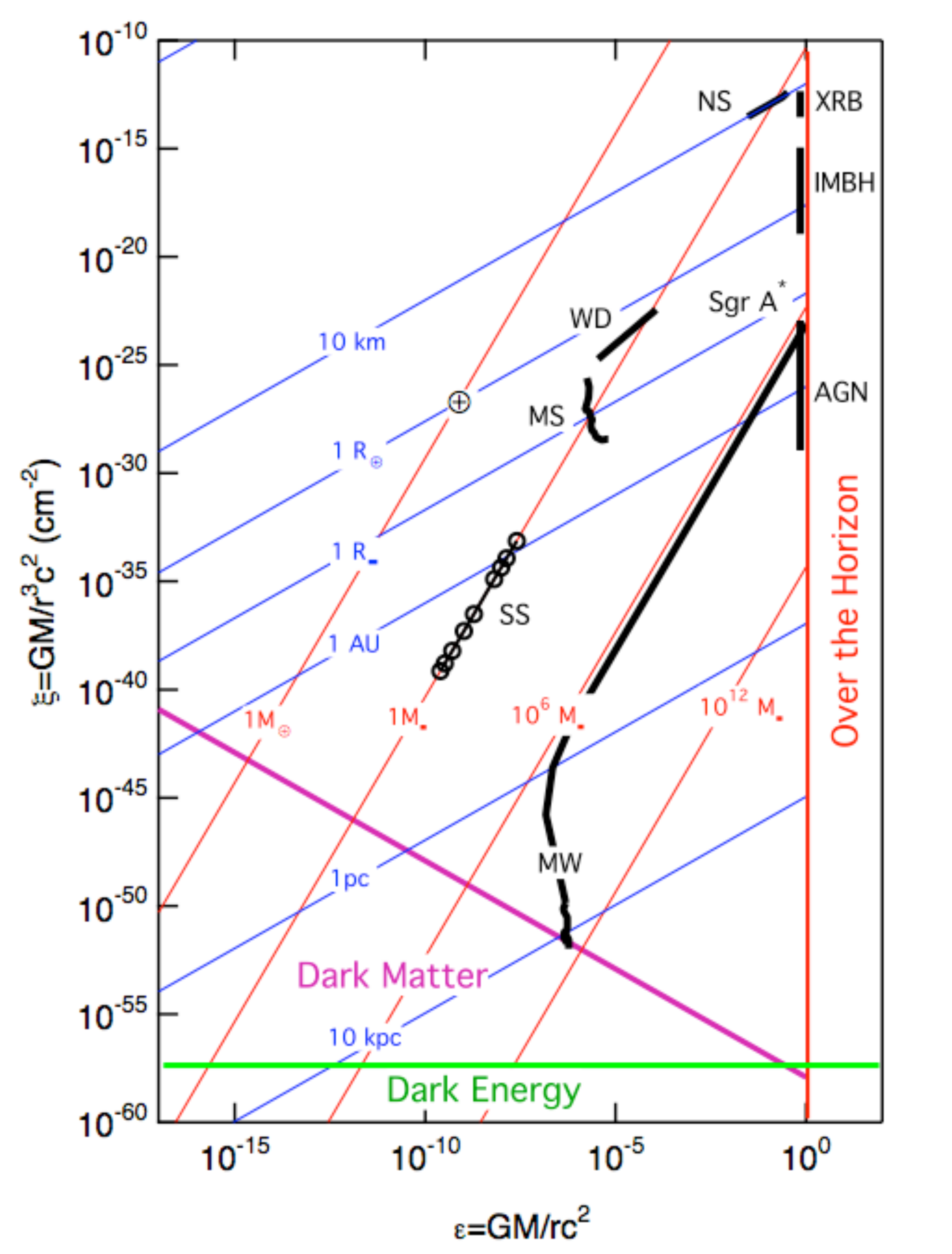


Some observations constrain growth history

$$\ddot{\delta} + 2H\dot{\delta} - \frac{v_s^2}{a^2}\nabla^2\delta = 4\pi G\rho_b\delta$$

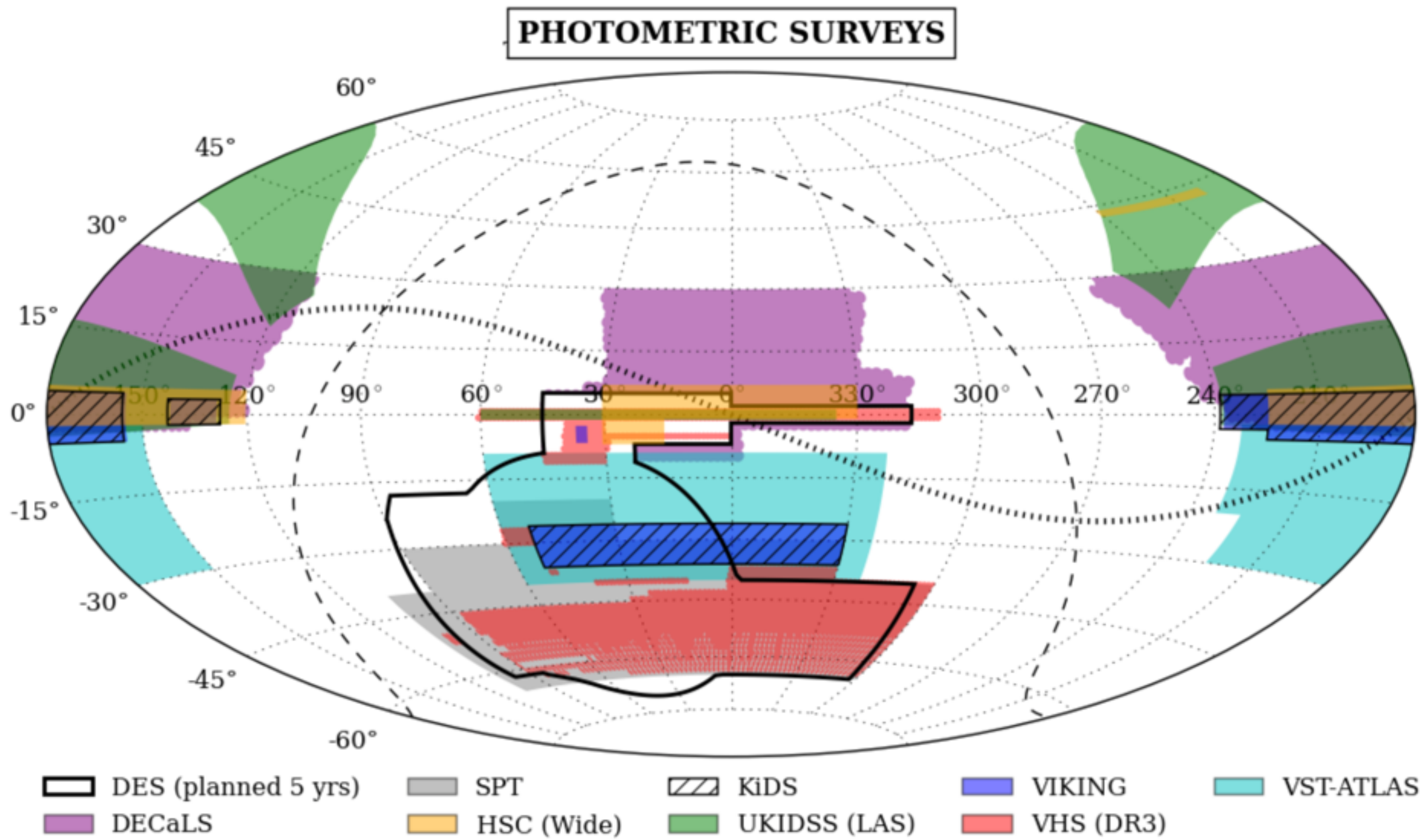
Some care about time part, some +space part of metric

TESTS OF GRAVITY

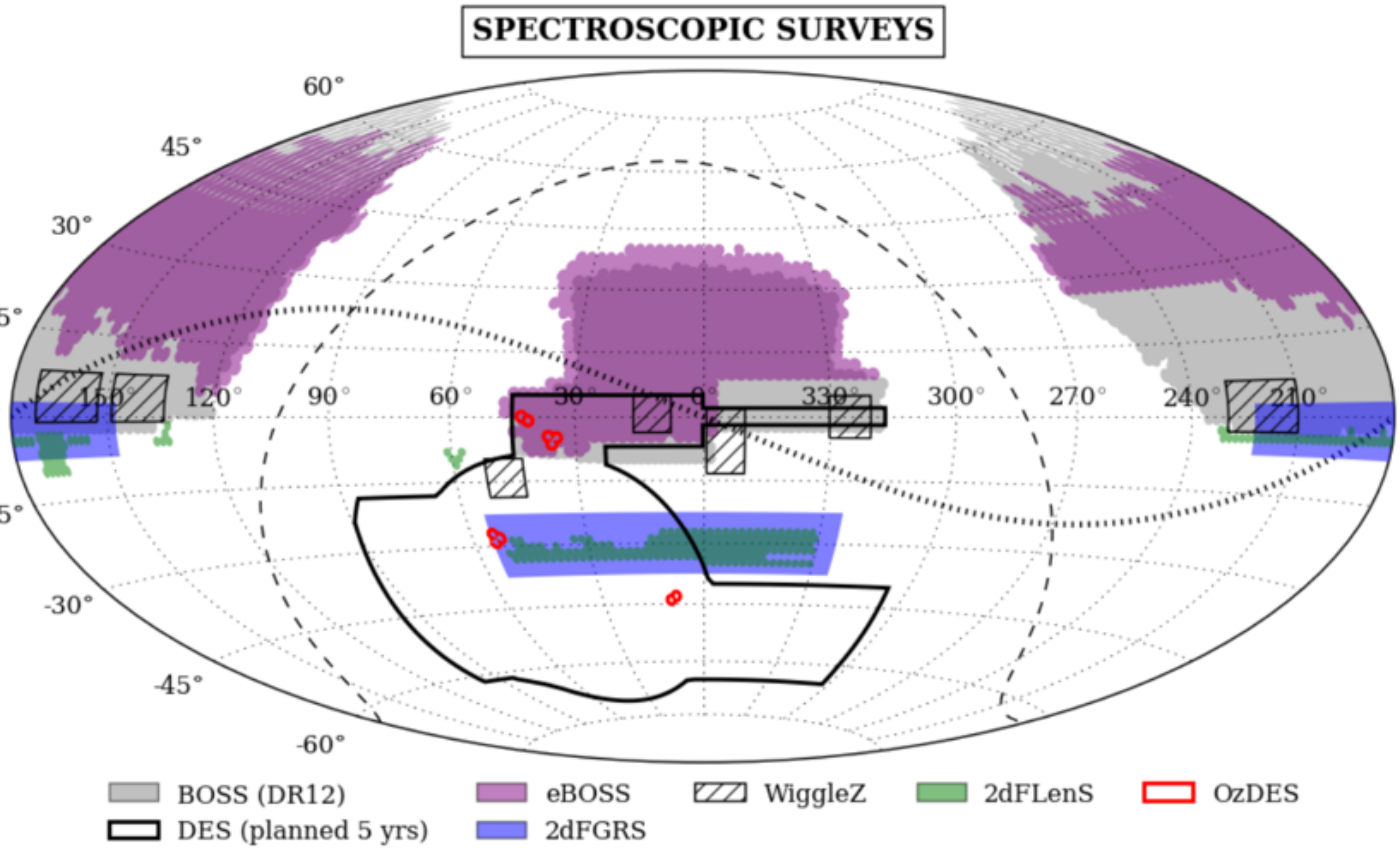


Psaltis 2008

OBSERVATIONAL SURVEYS

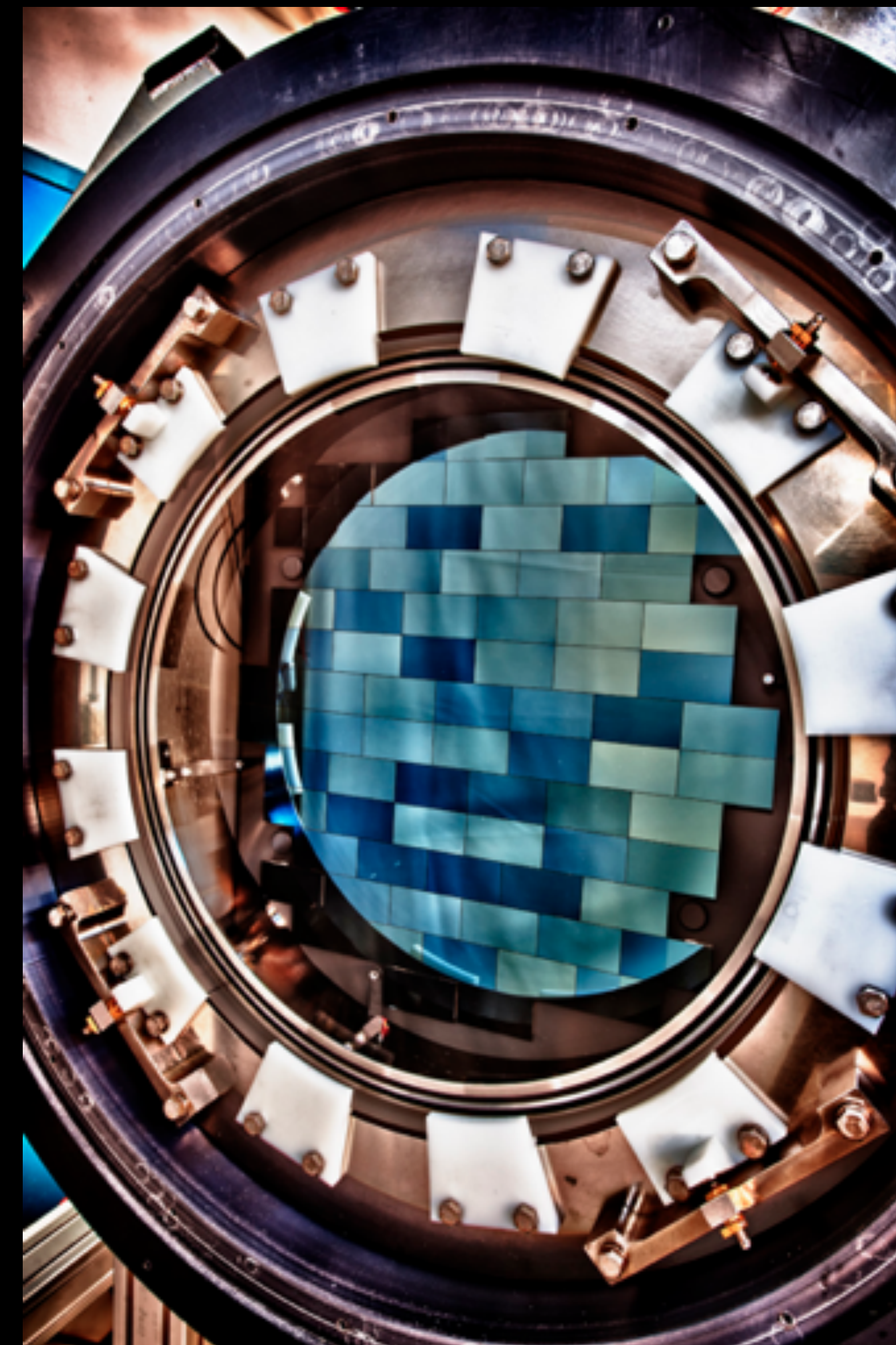


OBSERVATIONAL SURVEYS



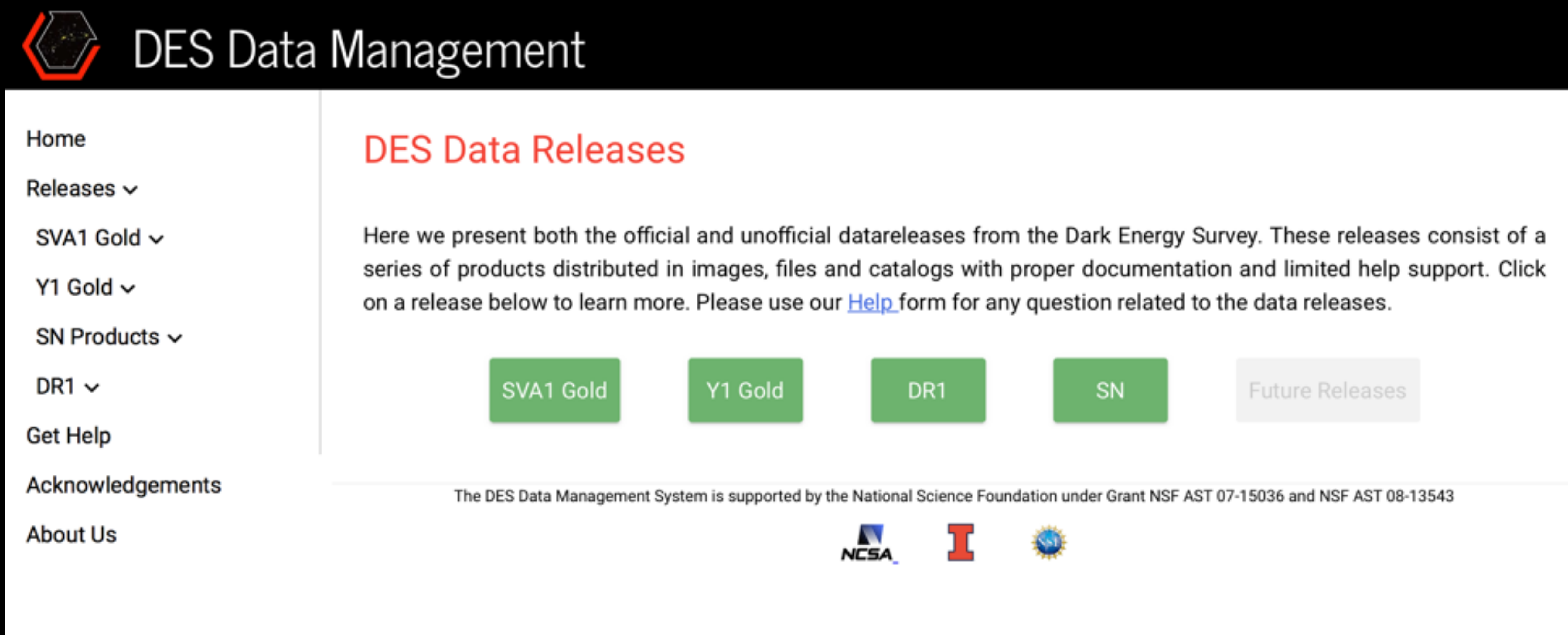
DARK ENERGY SURVEY

CTIO, Chile
5000 sq degree map, 8 billion ly deep, i~24, 5 filter bands (grizY)



570Megapixels, 3 sq deg field
0.26'' per pixel

DARK ENERGY SURVEY DATA AVAILABLE


DES Data Management

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DES Data Releases

Here we present both the official and unofficial datareleases from the Dark Energy Survey. These releases consist of a series of products distributed in images, files and catalogs with proper documentation and limited help support. Click on a release below to learn more. Please use our Help form for any question related to the data releases.

SVA1 Gold | Y1 Gold | DR1 | SN | Future Releases

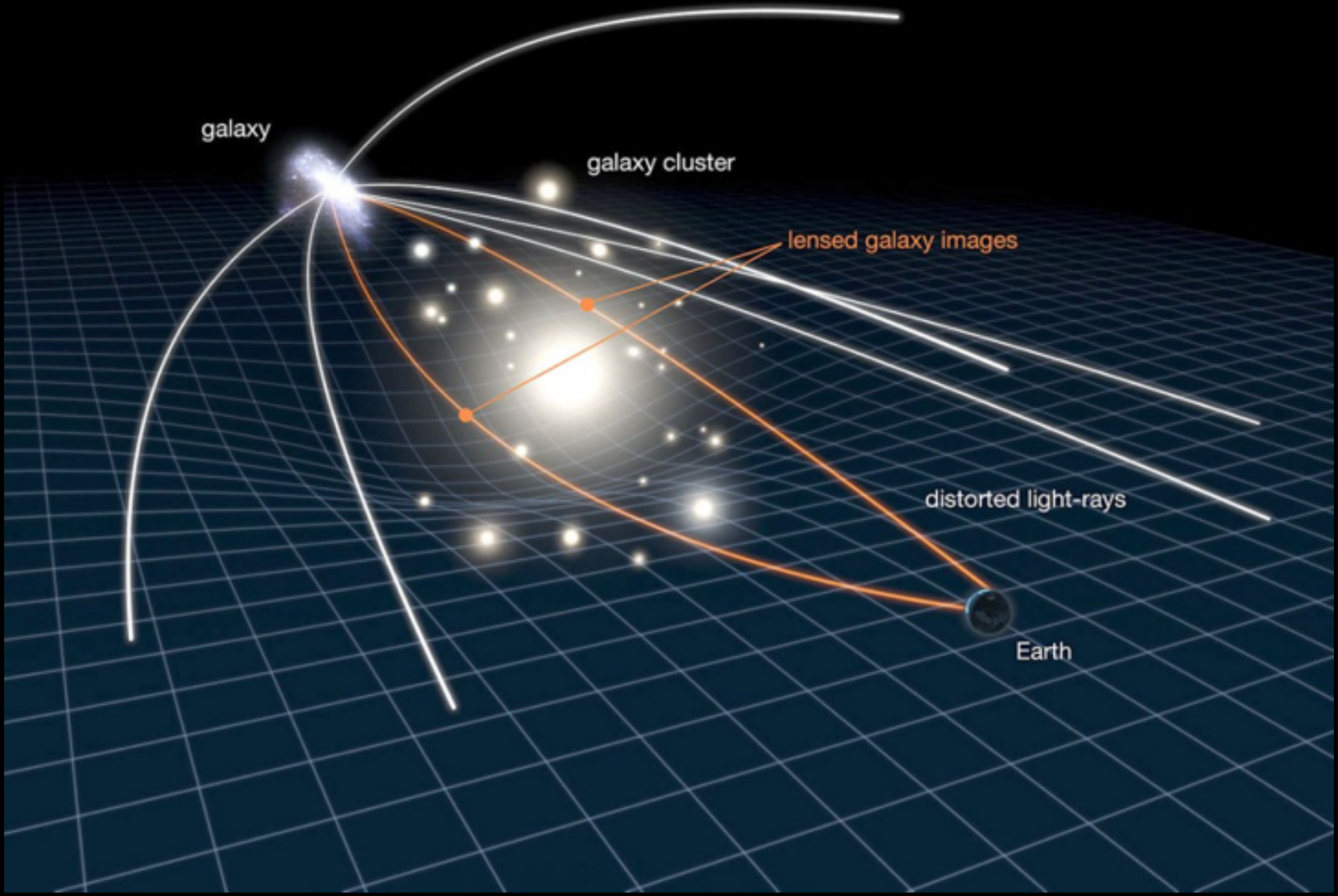
The DES Data Management System is supported by the National Science Foundation under Grant NSF AST 07-15036 and NSF AST 08-13543

NCSA

https://des.ncsa.illinois.edu/releases

GROWTH/EXPANSION PROBE: GRAVITATIONAL LENSING

ESA/NASA



Allows detailed 'view' of inhomogeneities

GEODESIC EQUATION

Ray:

Basis vectors $\mathbf{e}_a$

Tangent vector

$$\mathbf{t} = \frac{dx^a}{dl}\mathbf{e}_a$$

This is parallel transported along ray, so

$$\frac{dt_a}{dl} - \Gamma^b_{ac} t_b \frac{dx^c}{dl} = 0$$

We can rewrite this as

$$\boxed{\frac{dt_a}{dl} = \frac{1}{2} g_{cd,a} t^c t^d}$$

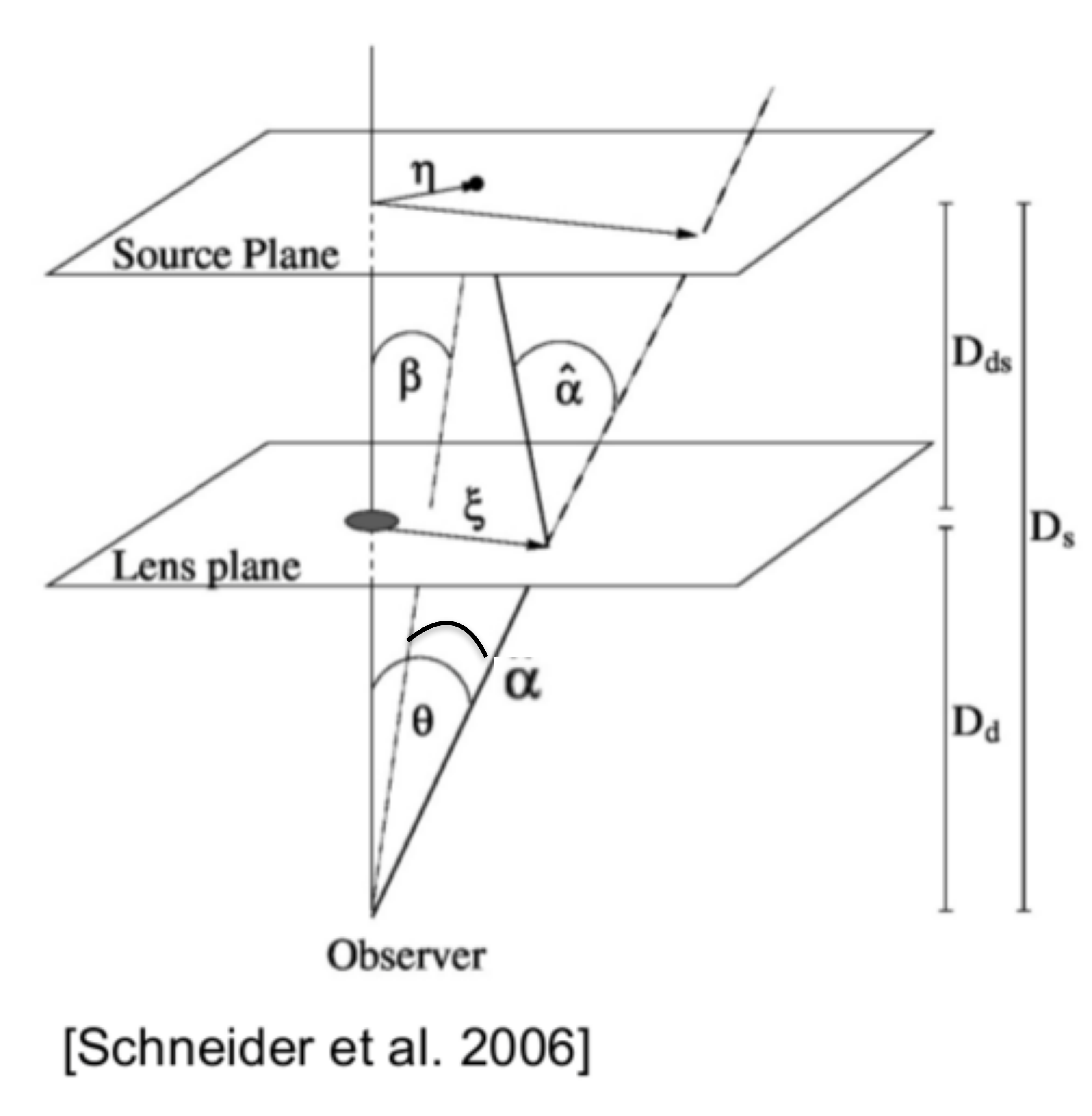
c.f. geometrical optics:

$$\frac{d\mathbf{t}}{dl} = \frac{\nabla_\perp n}{n}$$

Perturbed FRW: $\boxed{n = 1 - \frac{2\Phi}{c^2}}$

or Ψ+Φ

LENS GEOMETRY



With some approximations,

$$\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi}) = \frac{4G}{c^2} \int \mathrm{d}^2\xi' \underbrace{\int \mathrm{d}r_3' \, \rho(\xi_1', \xi_2', r_3')}_{\Sigma(\boldsymbol{\xi}')} \frac{\boldsymbol{\xi} - \boldsymbol{\xi}'}{|\boldsymbol{\xi} - \boldsymbol{\xi}'|^2}$$

$$\boxed{\vec{\theta} = \vec{\beta} + \vec{\alpha}}$$

Lens equation

STRONG LENSING

$$\vec{\theta} = \vec{\beta} + \vec{\alpha}$$

Jacobian matrix:

$$\mathcal{A}_{ij} = \frac{\partial \beta_i}{\partial \theta_j}$$

Source plane

Image plane

Magnification factor:

$$\mu(\boldsymbol{\theta}) = \frac{1}{\det \mathcal{A}(\boldsymbol{\theta})}$$

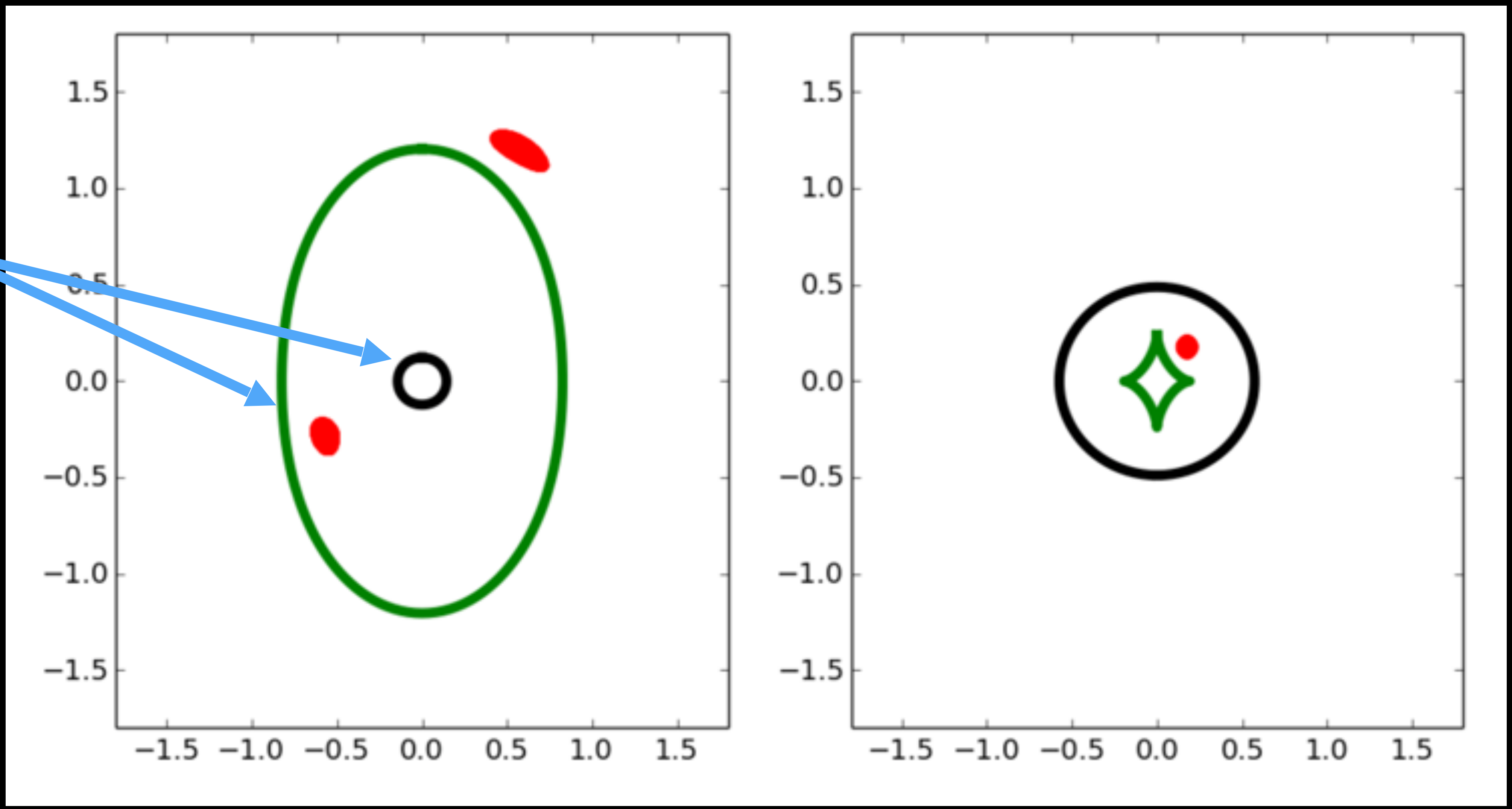
So det A = 0 gives critical curves of high magnification

MULTIPLE IMAGES

e.g. Isothermal ellipsoid:

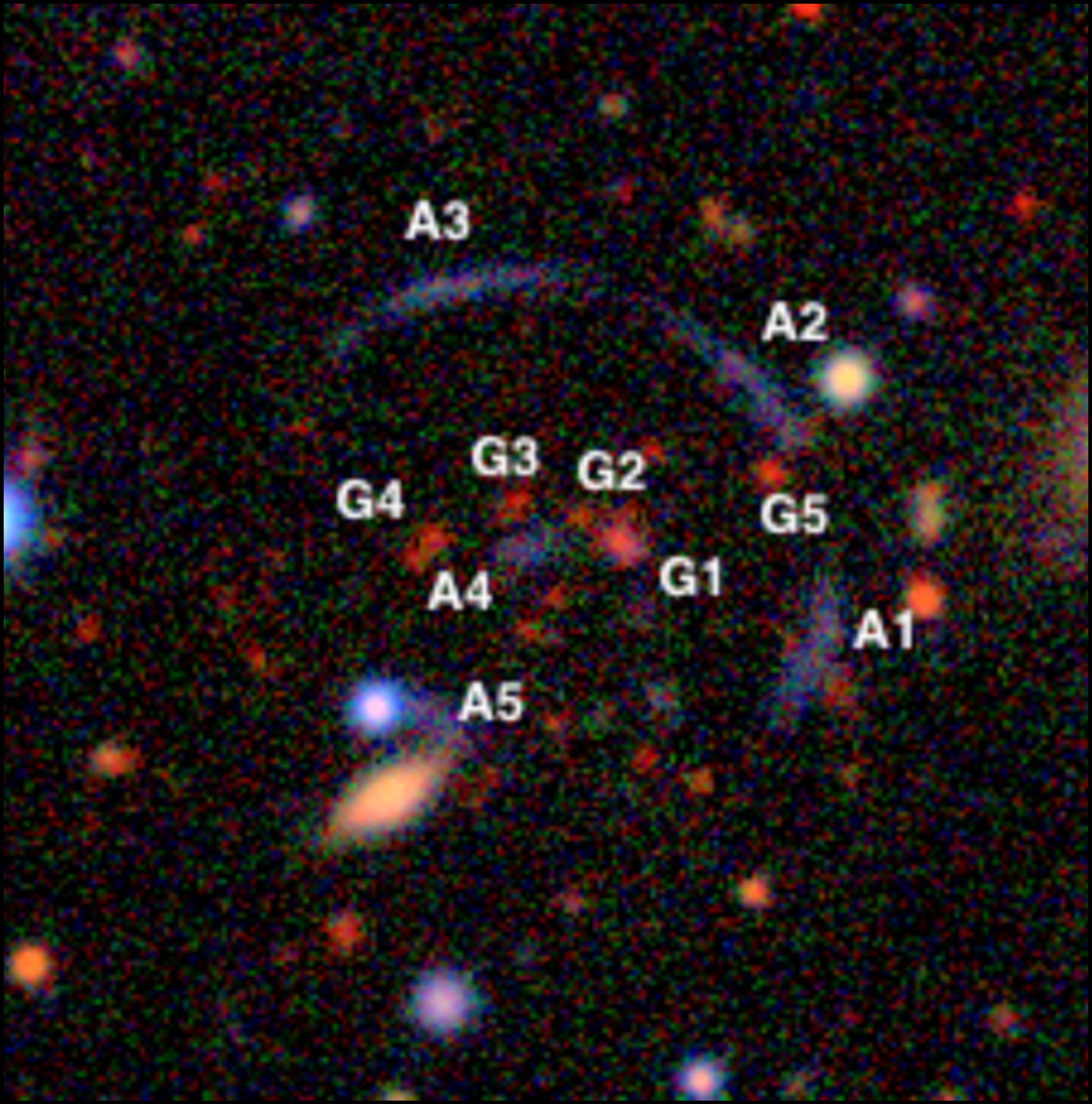
$$\kappa_{\mathrm{lens}}(\boldsymbol{x}) = \frac{2-\eta}{2}\left(\frac{\theta_E}{q x_1^2 + x_2^2/q}\right)^{\eta}$$

det A = 0



Tom Collett

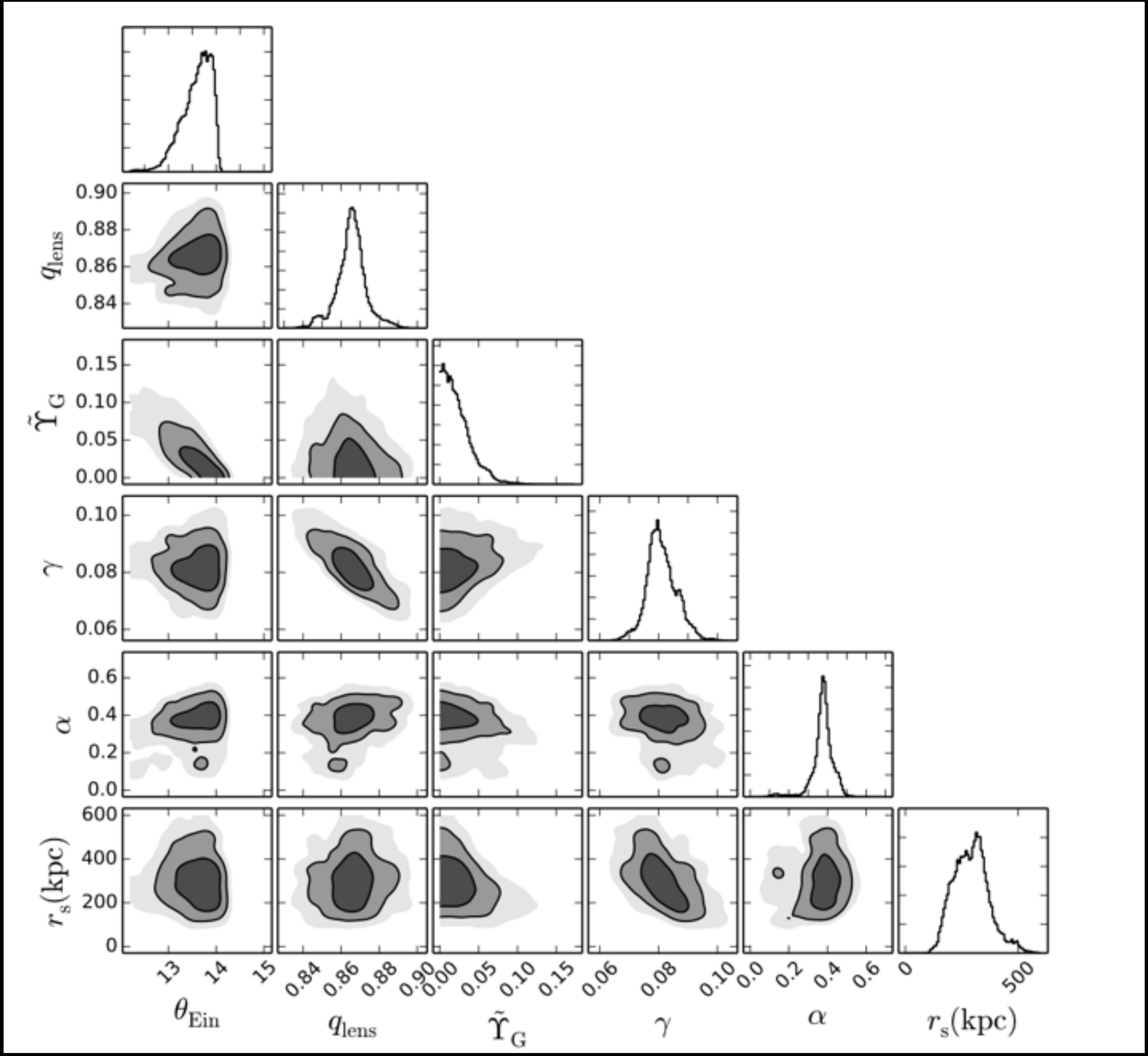
STRONG GRAVITATIONAL LENSING



$z_l = 1.06$
$z_s = 2.39$

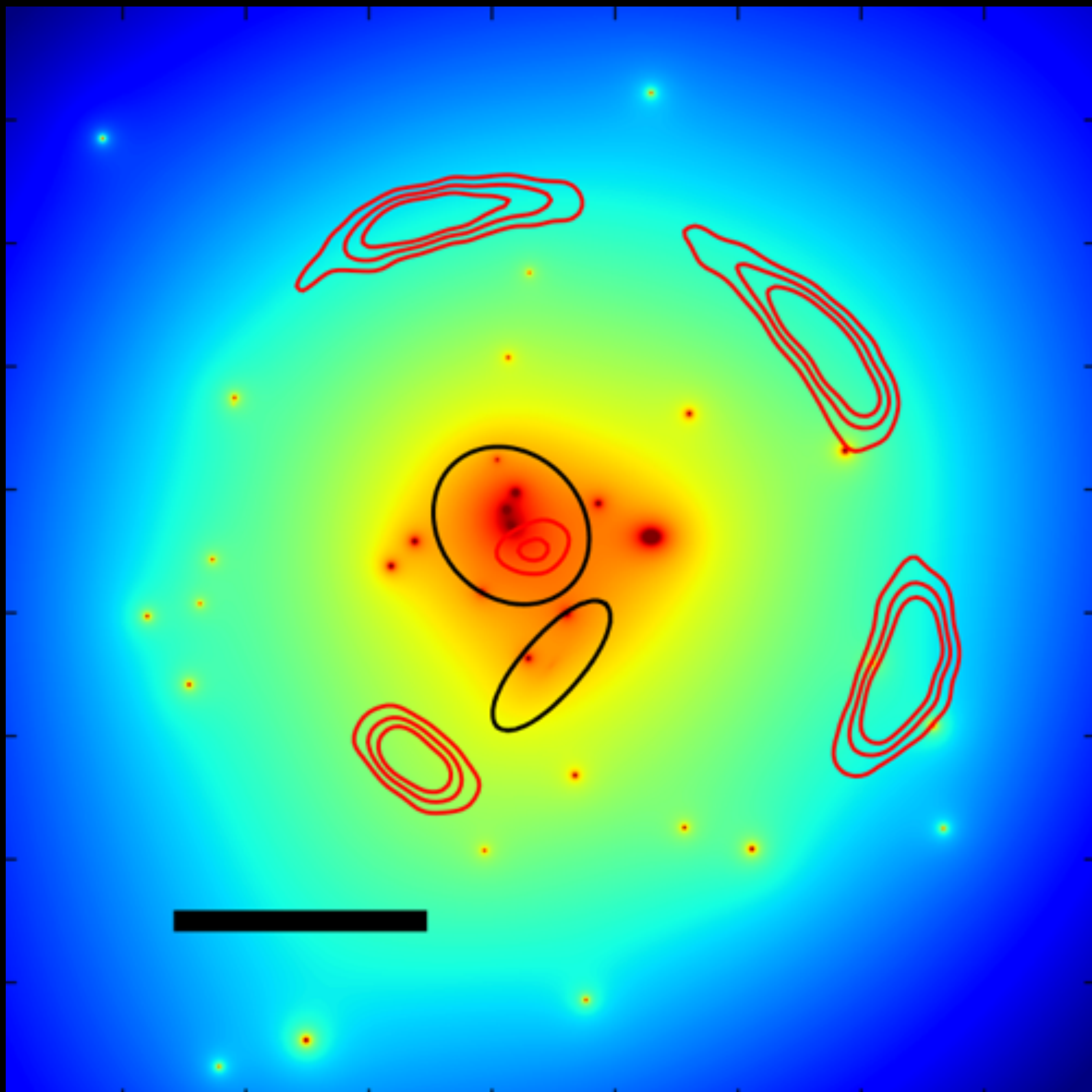
Collett et al 17

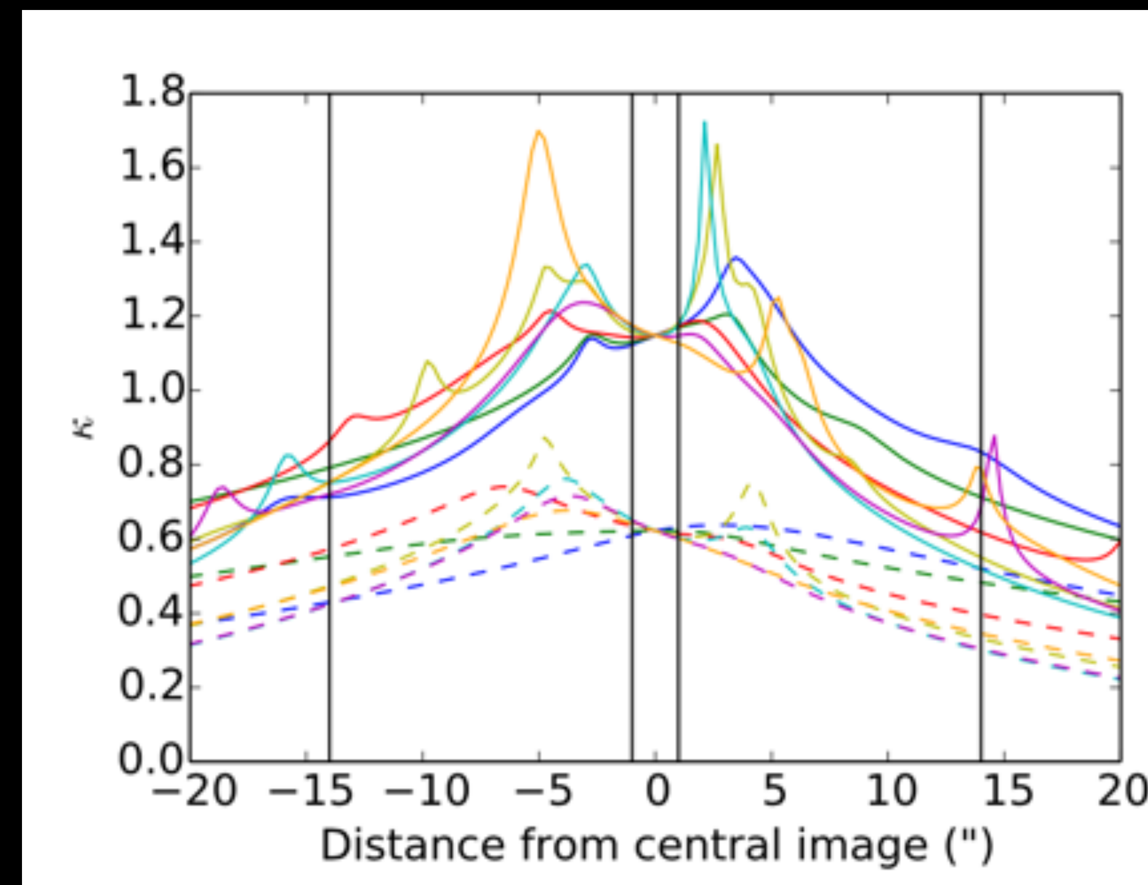
MODEL PARAMETERS



Collett et al 17

2 CLUMP MODEL

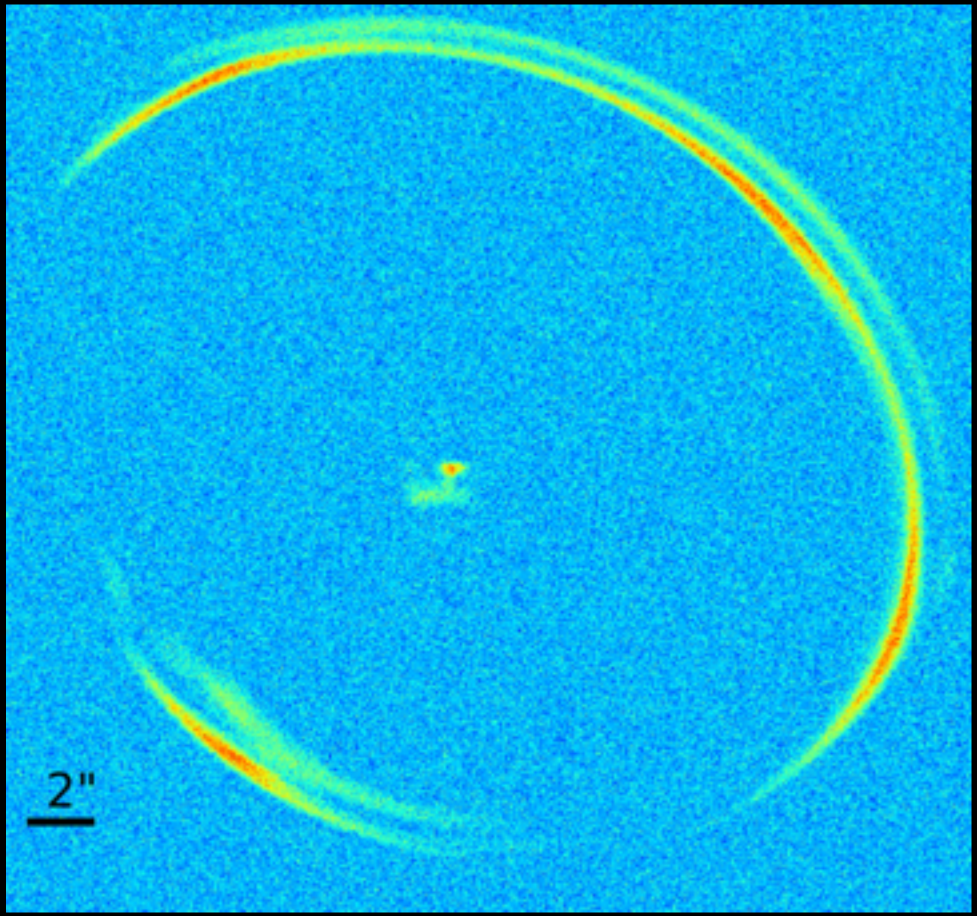




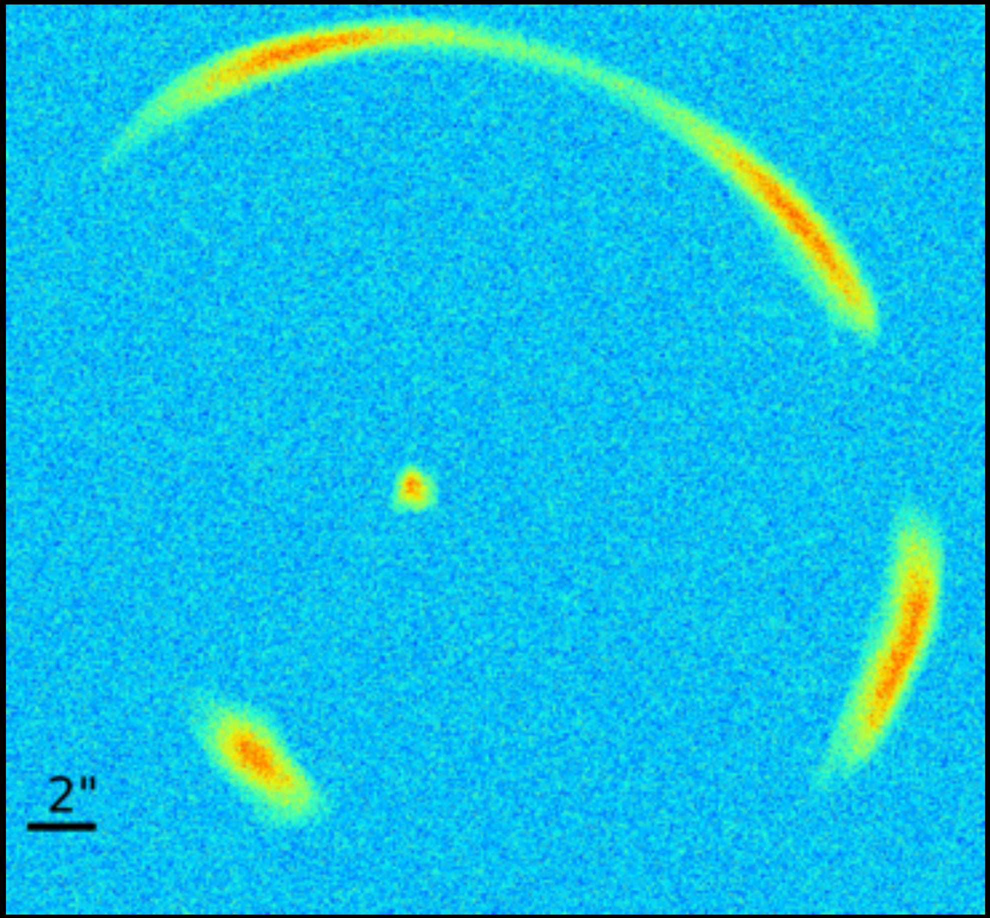
Need to be very careful about lens modelling

Collett et al 17

PREDICTIONS



1 halo



2 halo

Collett et al 17

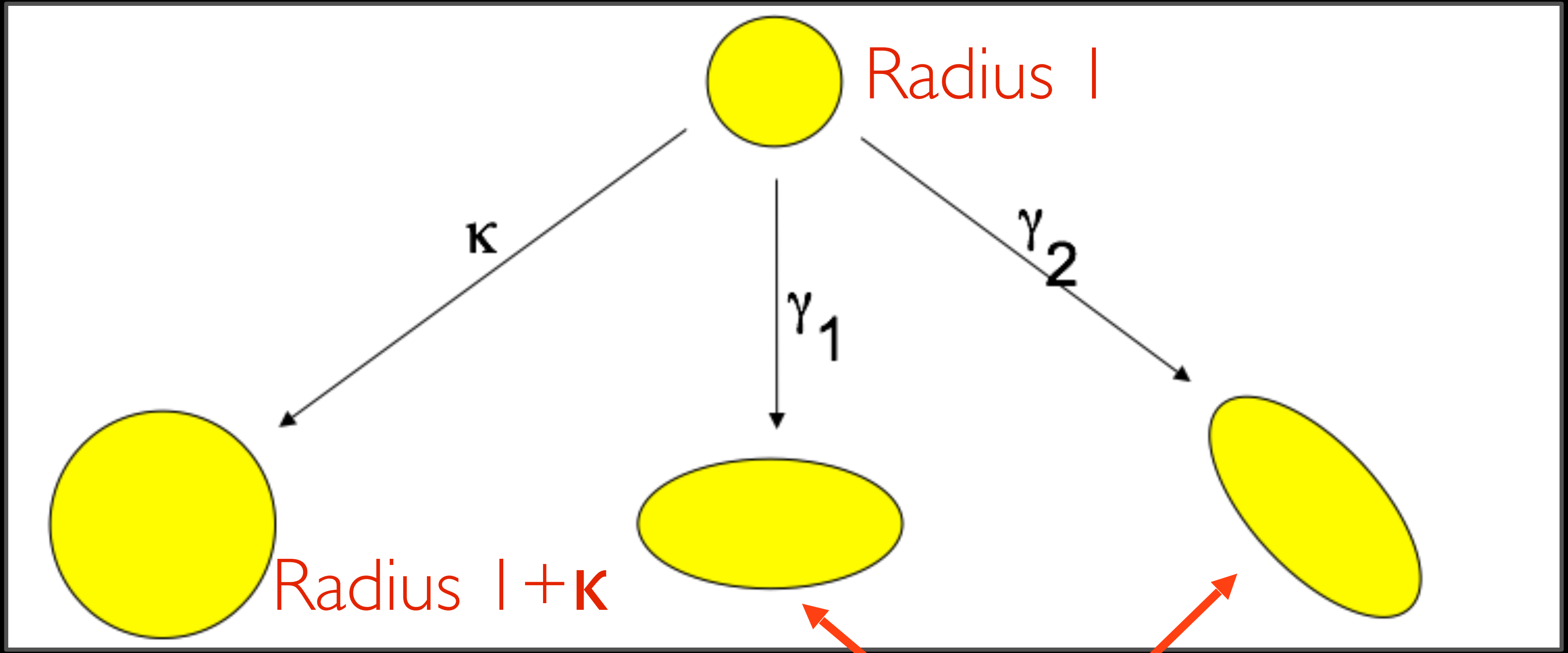
WEAK DISTORTIONS

$$\beta_i = A_{ij}\theta_j$$

Source plane

Image plane

$$A = \begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix} + \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & \gamma_1 \end{pmatrix}$$



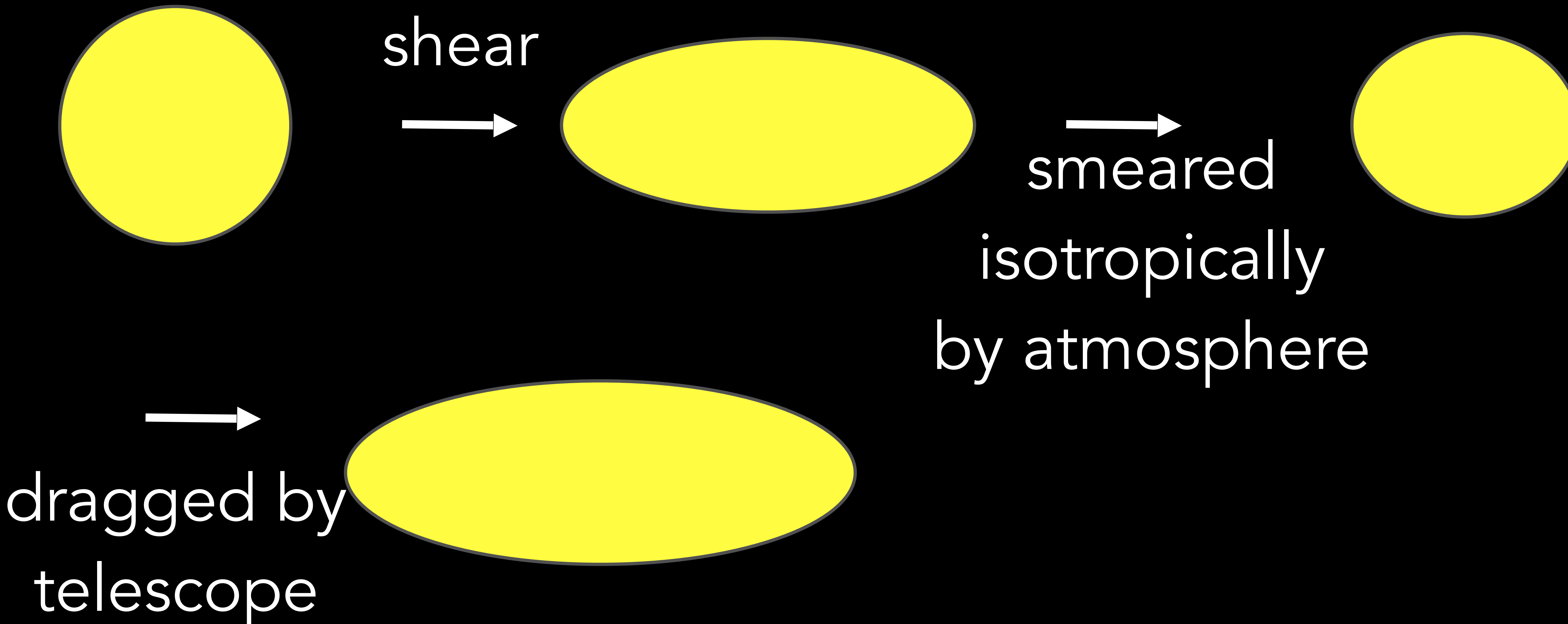
Convergence

Shear

$$\kappa \sim \partial^2\psi$$

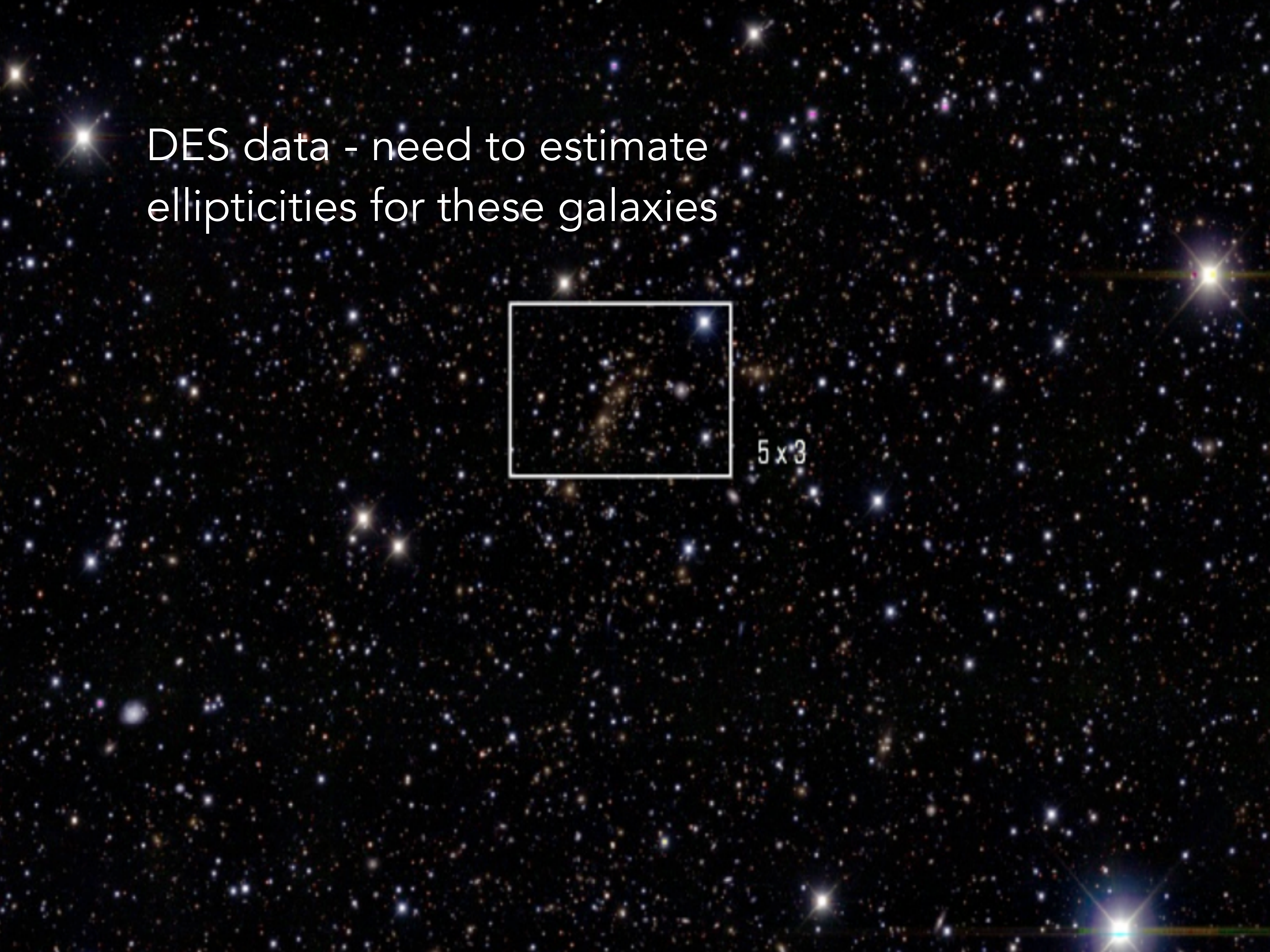
$$\gamma \sim \partial^2\psi$$

THE MEASUREMENT PROBLEM

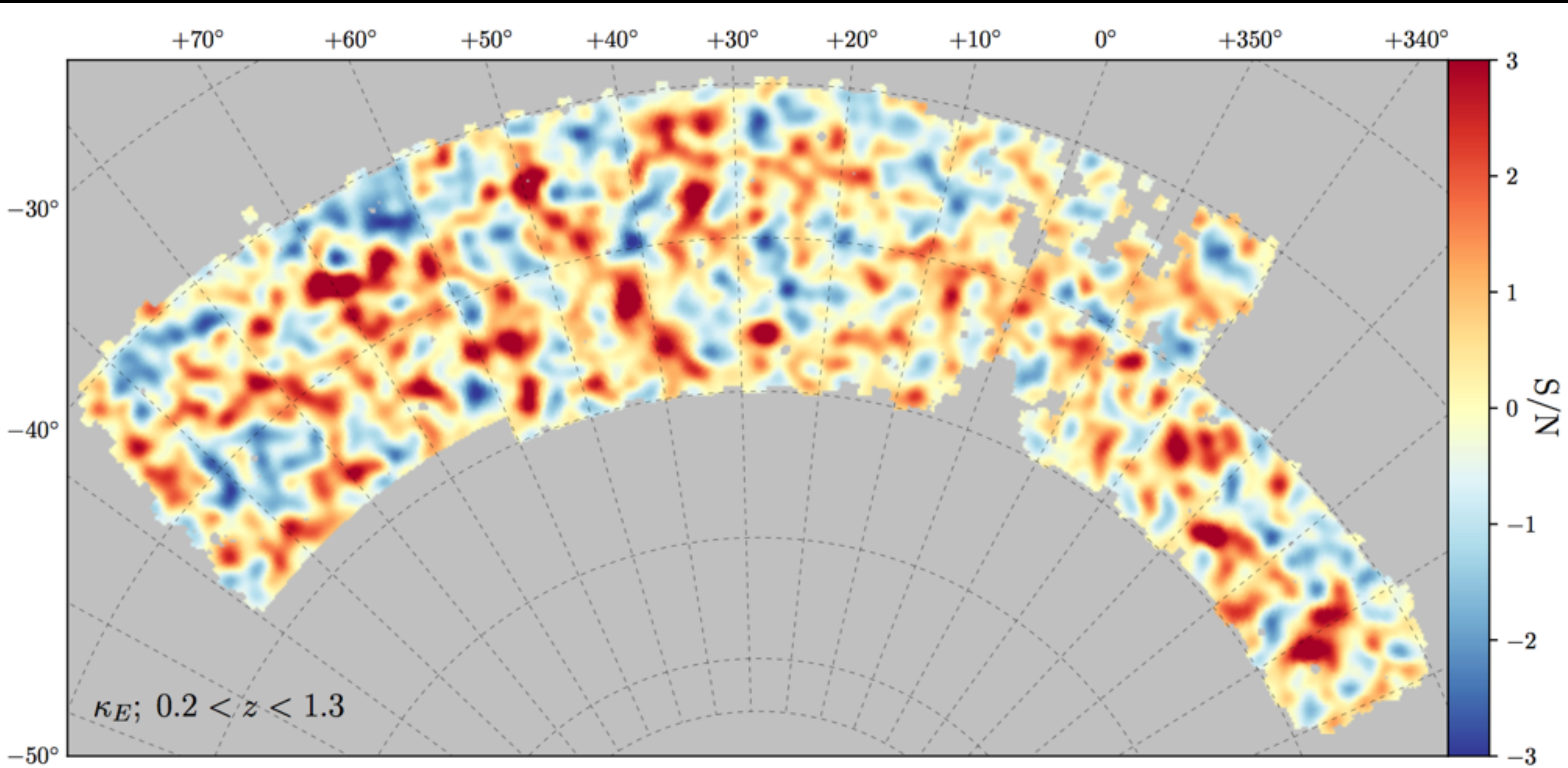


Measure PSF smearing from stars; fit for shape in presence of PSF

DES data - need to estimate ellipticities for these galaxies



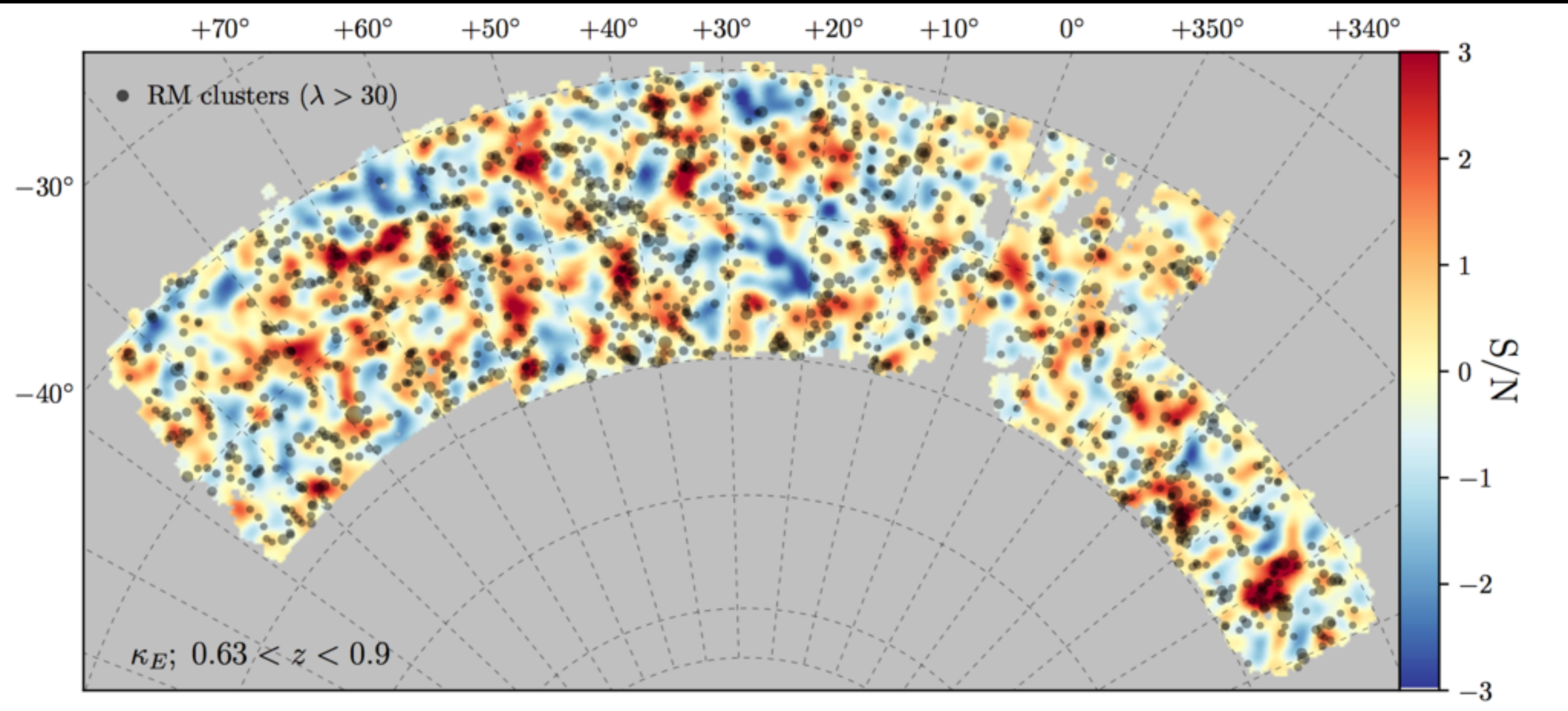
DARK MATTER MAP



Dark matter distribution inferred from 30M galaxies

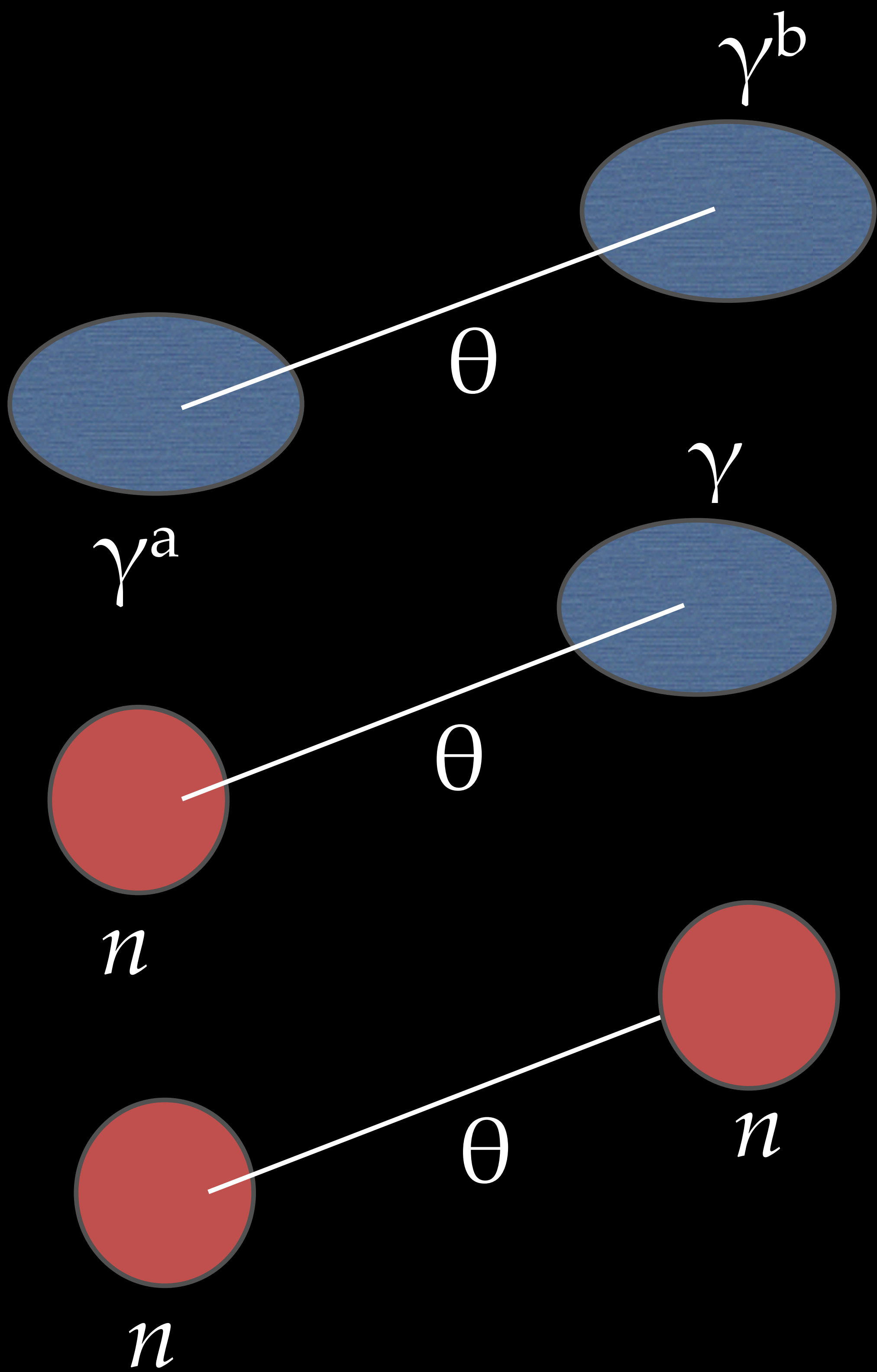
Chang et al 17

THE NEW DARK MATTER MAP



Chang et al 17

LENSING AND CLUSTERING STATISTICS

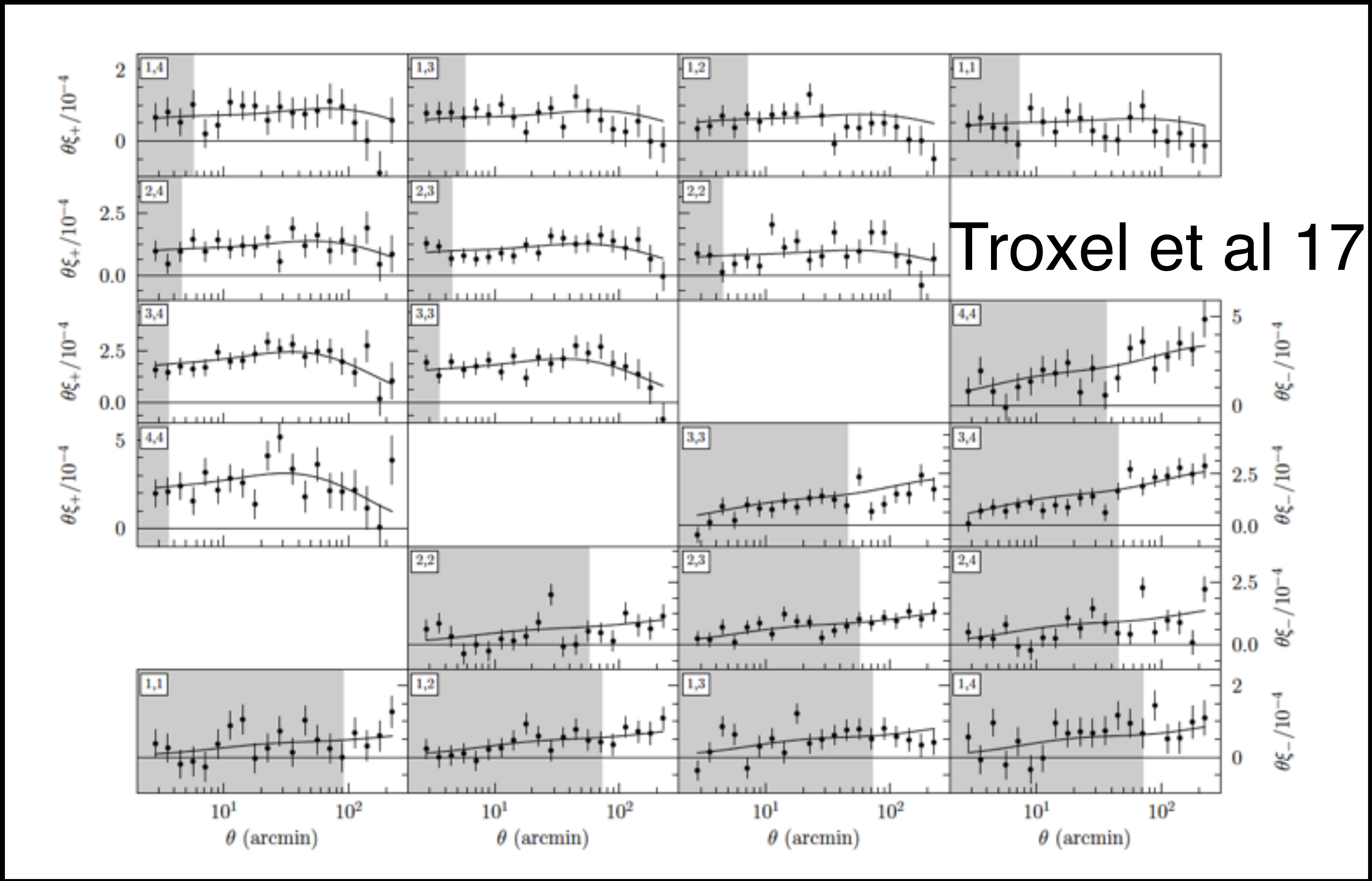


Sensitive to matter power spectrum, geometry

Sensitive to matter power spectrum, geometry, bias

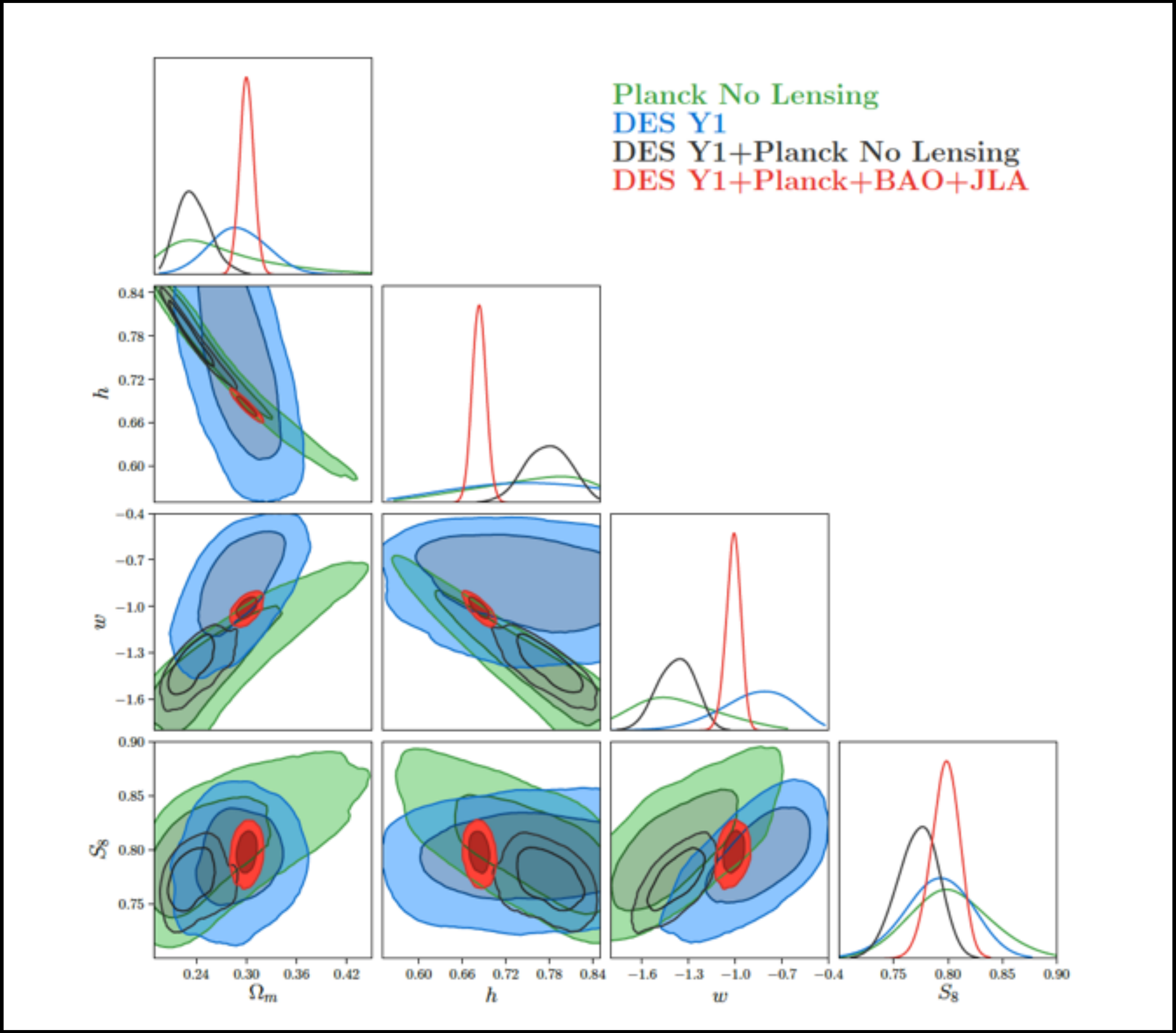
Sensitive to matter power spectrum, bias

COSMIC SHEAR RESULTS



Troxel et al 17

COMBINED RESULTS



Expansion rate

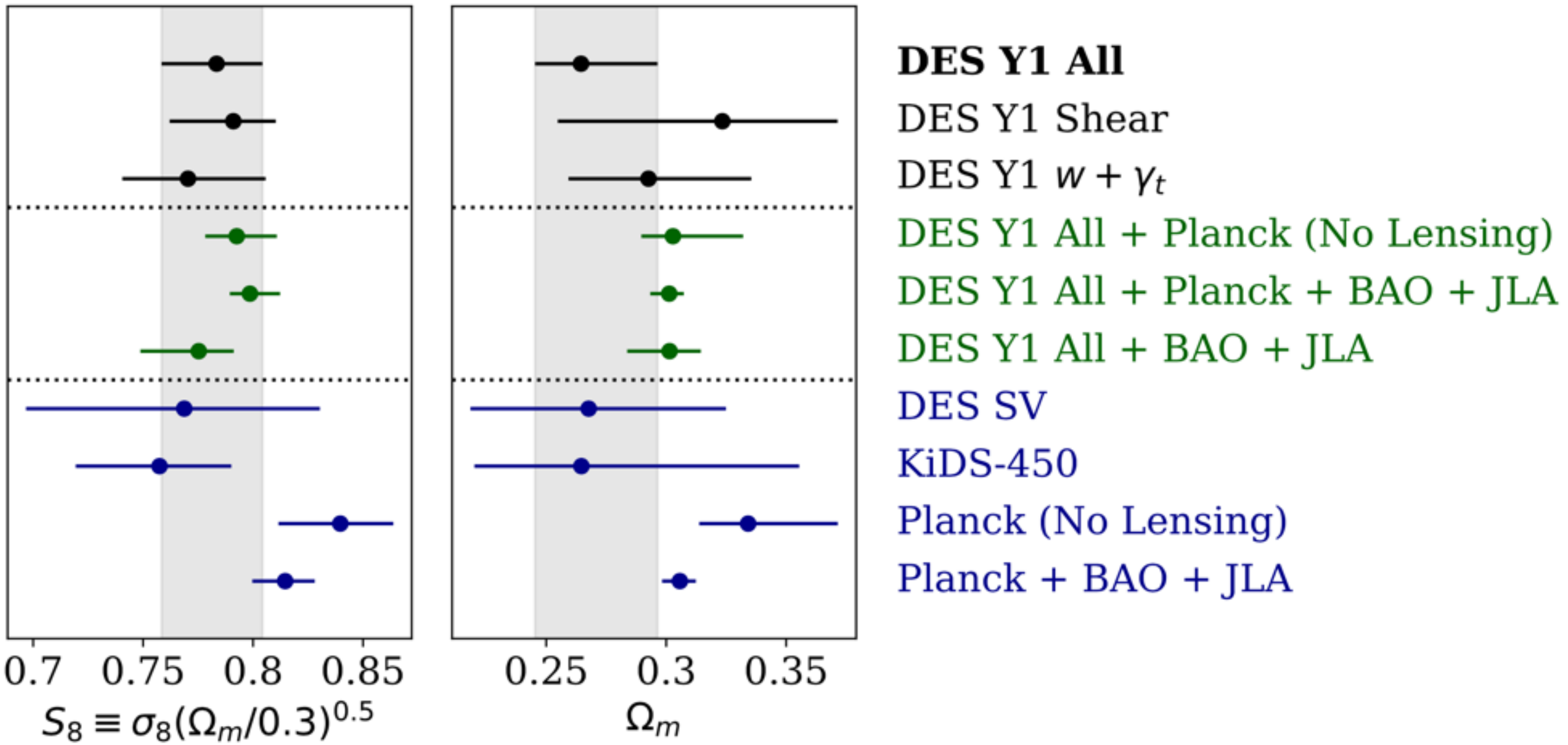
Dark energy pressure/ density

Matter clustering

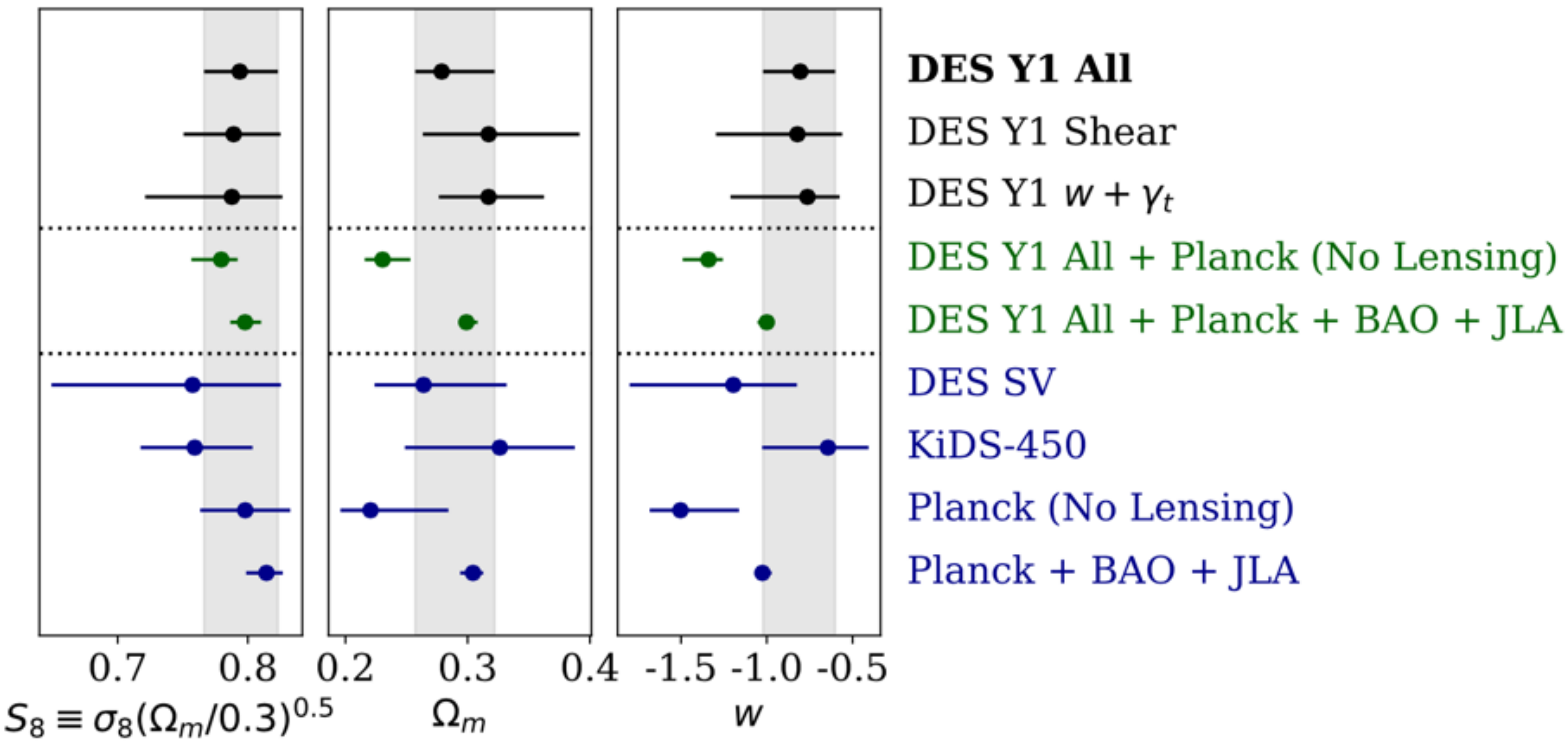
Matter density | Expansion rate | Dark energy pressure/ density | Matter clustering

DES 17

COMBINED RESULTS

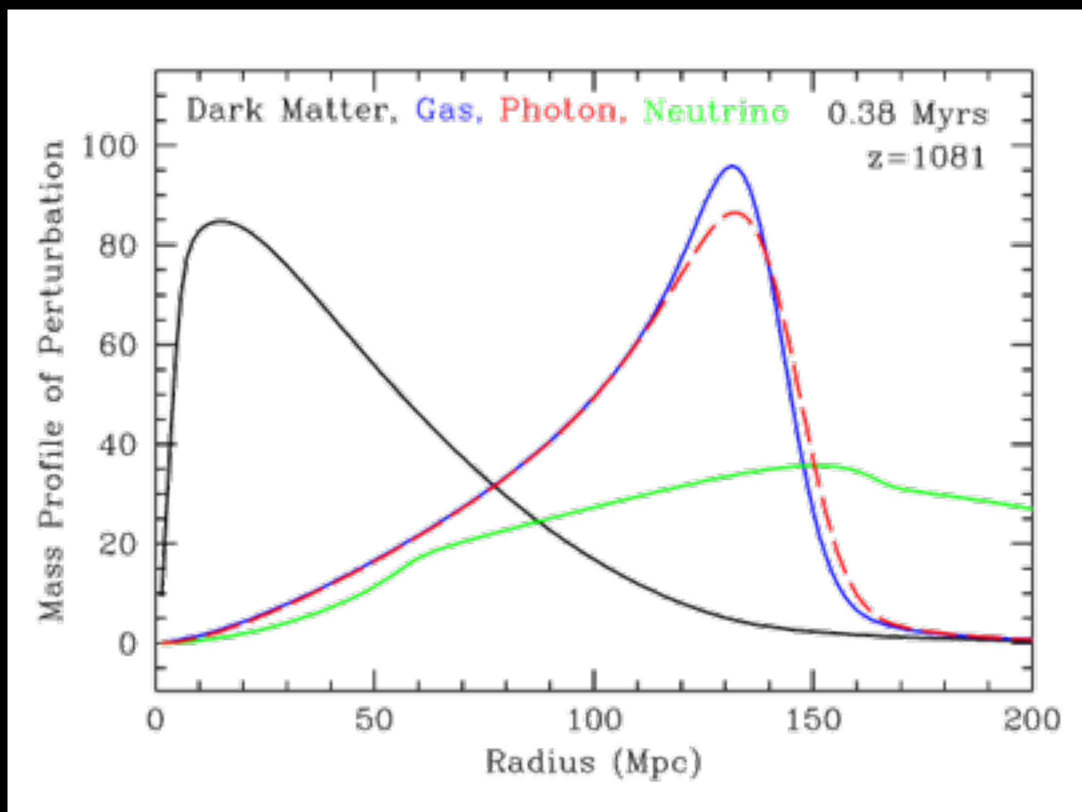


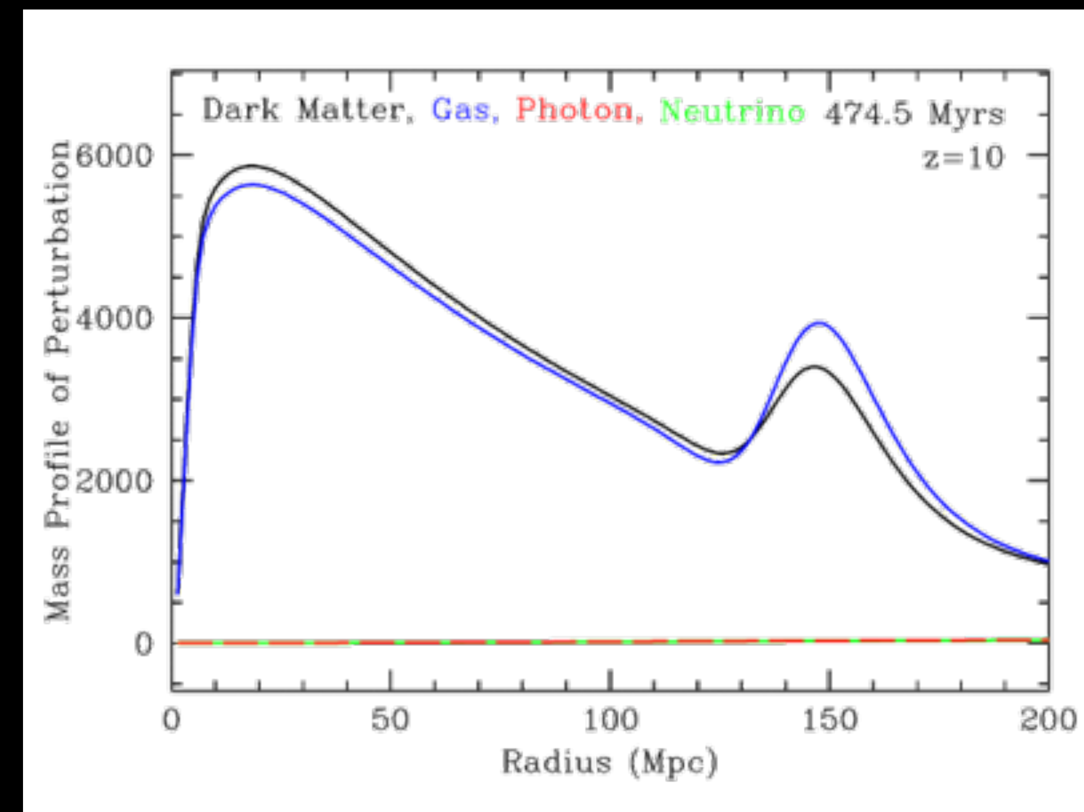
DES 17


DES Y1 All
DES Y1 Shear
DES Y1 $w + \gamma_t$
DES Y1 All + Planck (No Lensing)
DES Y1 All + Planck + BAO + JLA
DES SV
KiDS-450
Planck (No Lensing)
Planck + BAO + JLA
0.7 0.8 0.2 0.3 0.4 -1.5 -1.0 -0.5
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$
Ω_m
w

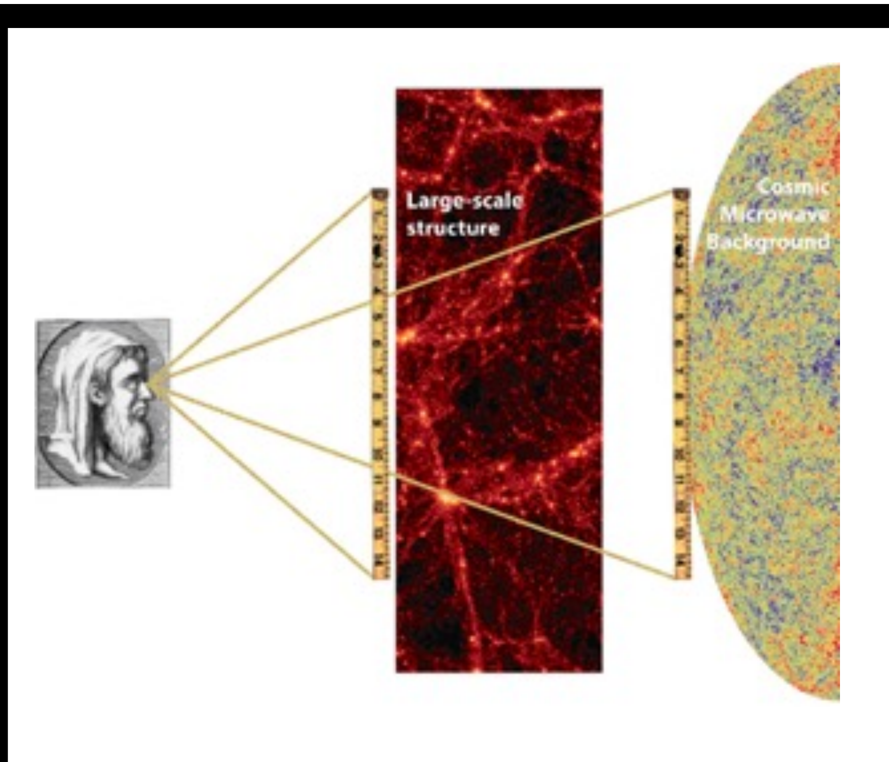
DES 17

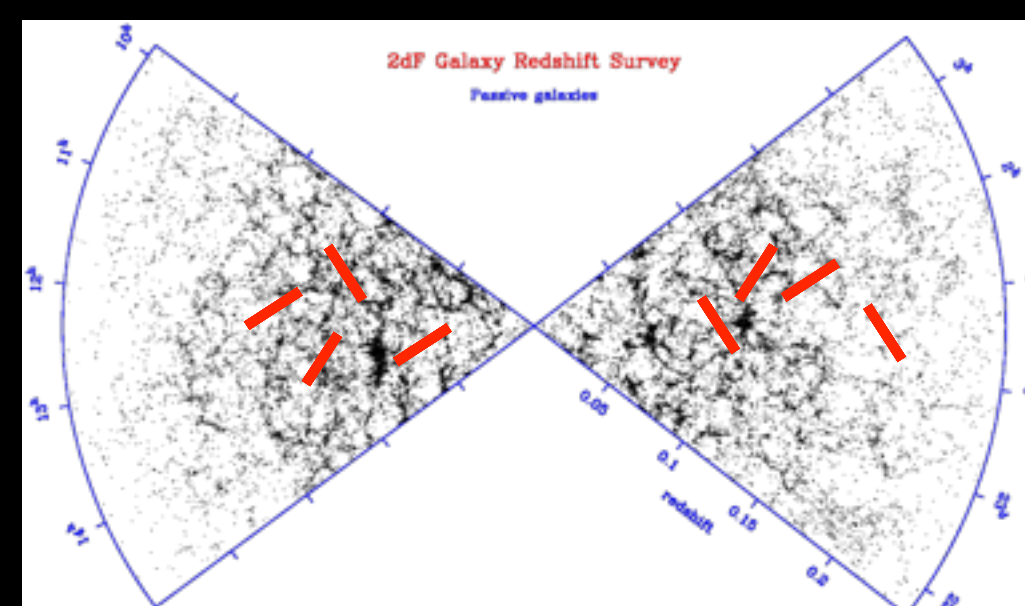
EXPANSION PROBE - BARYON ACOUSTIC OSCILLATIONS



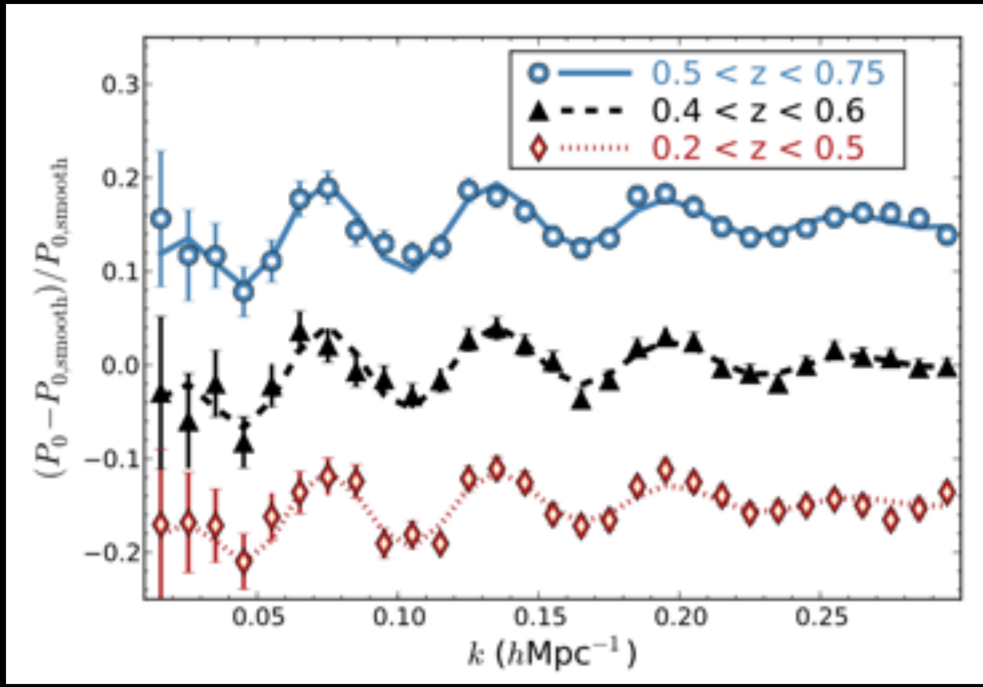


Eisenstein



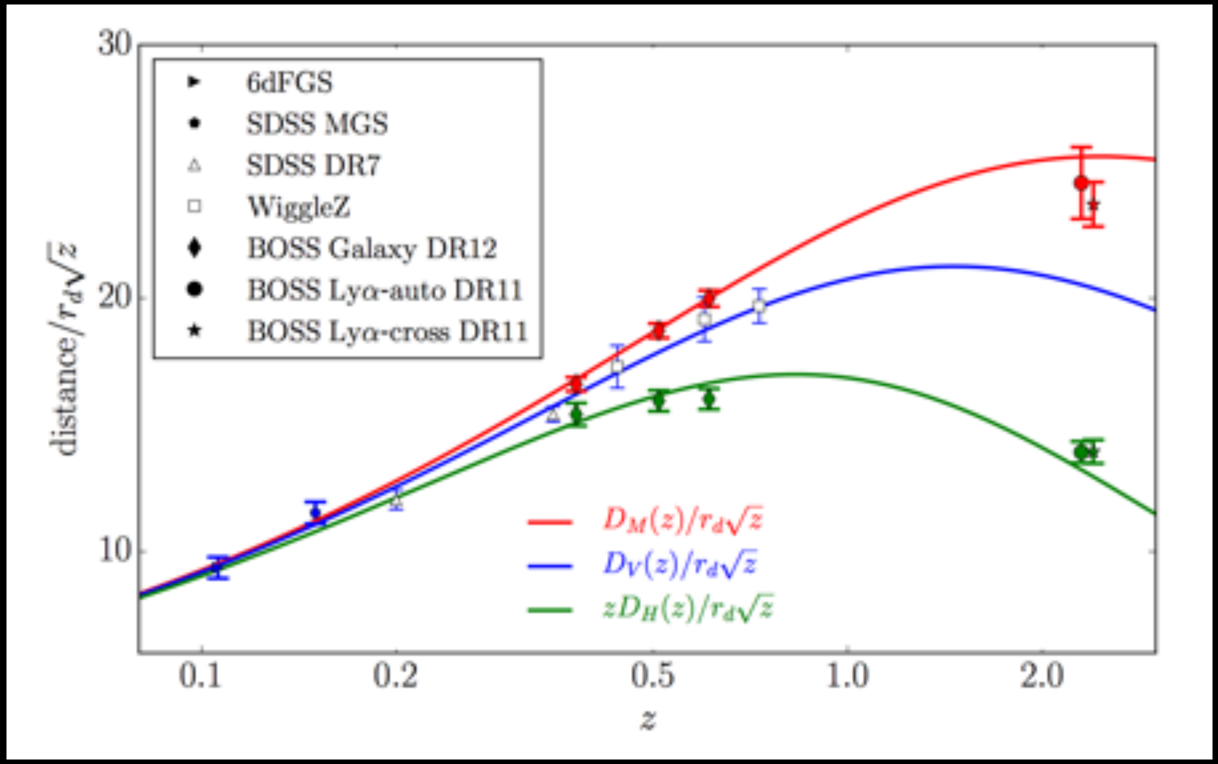


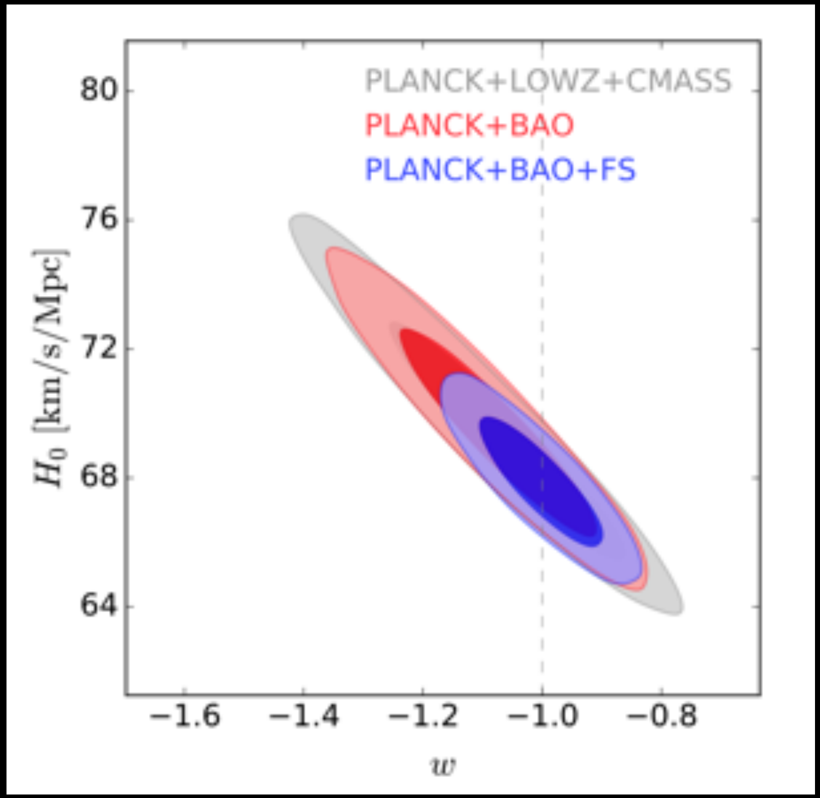
EXPANSION PROBES - BARYON ACOUSTIC OSCILLATIONS



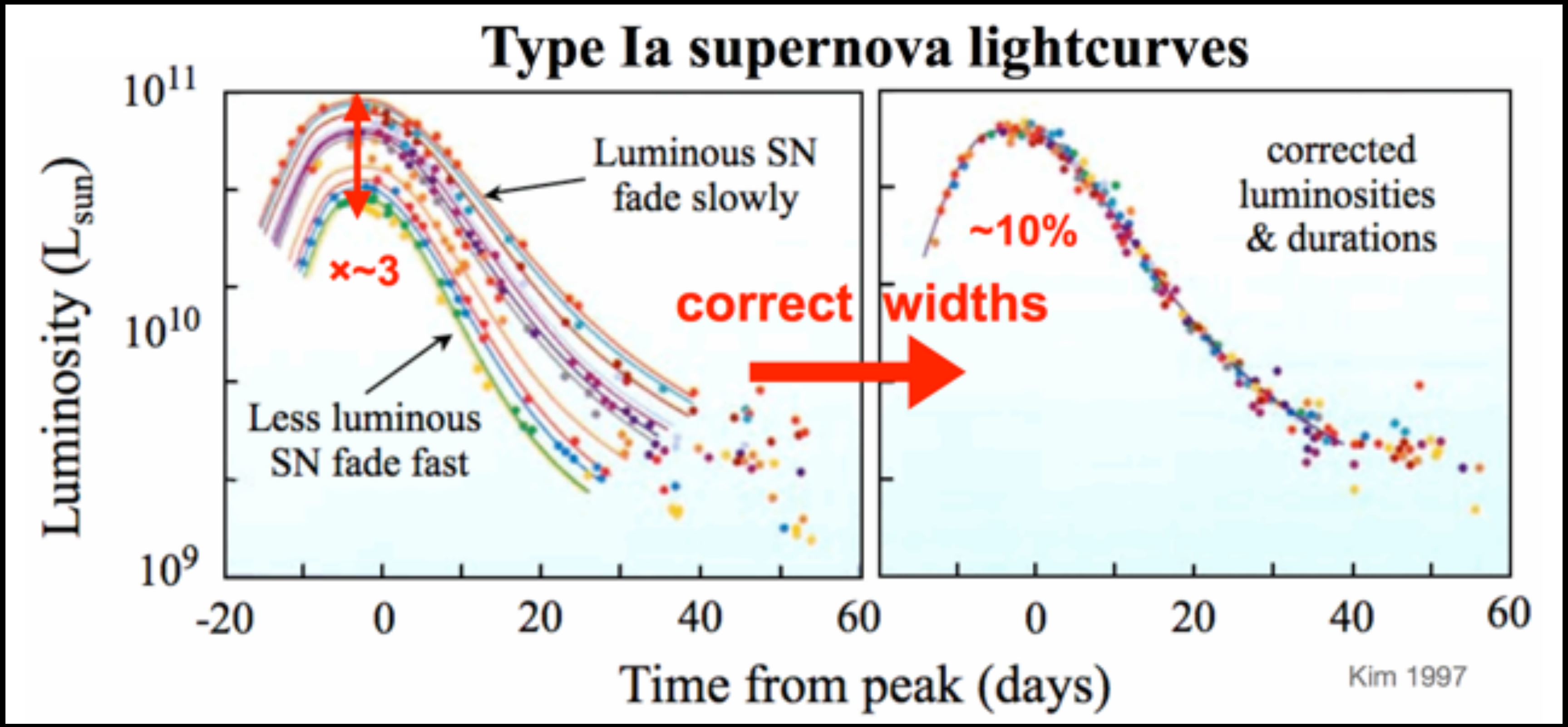
SDSS-III
BOSS

Alam et al 16

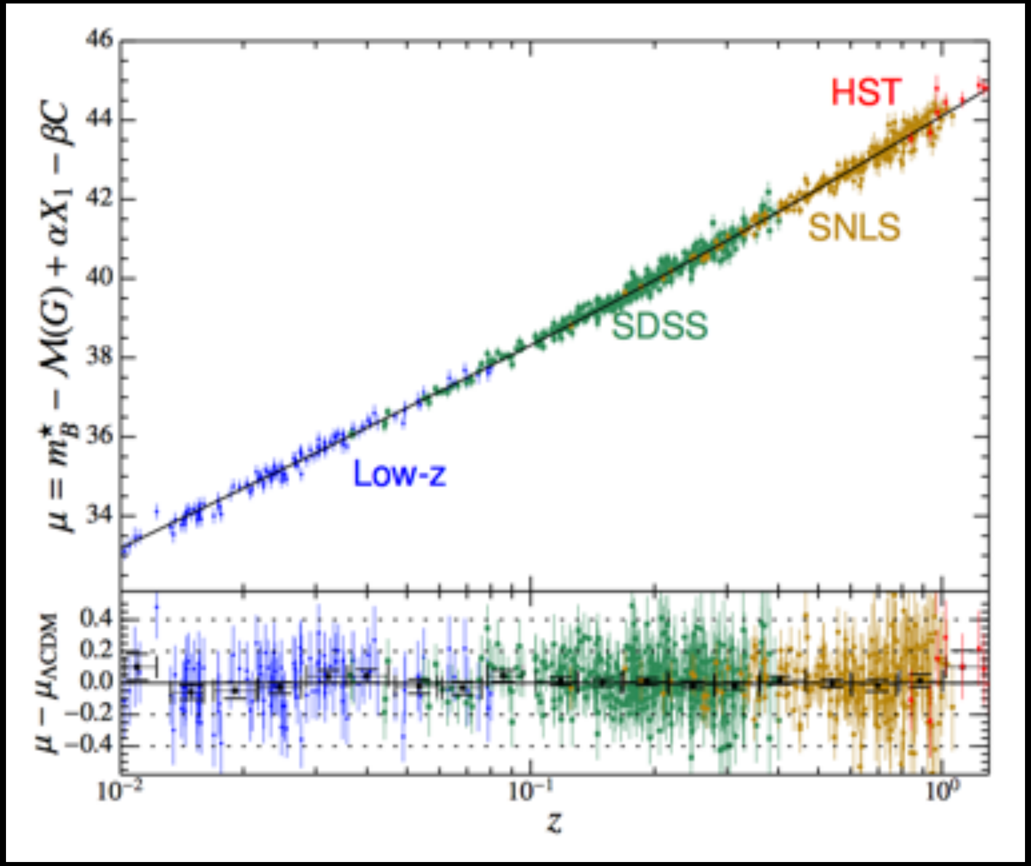


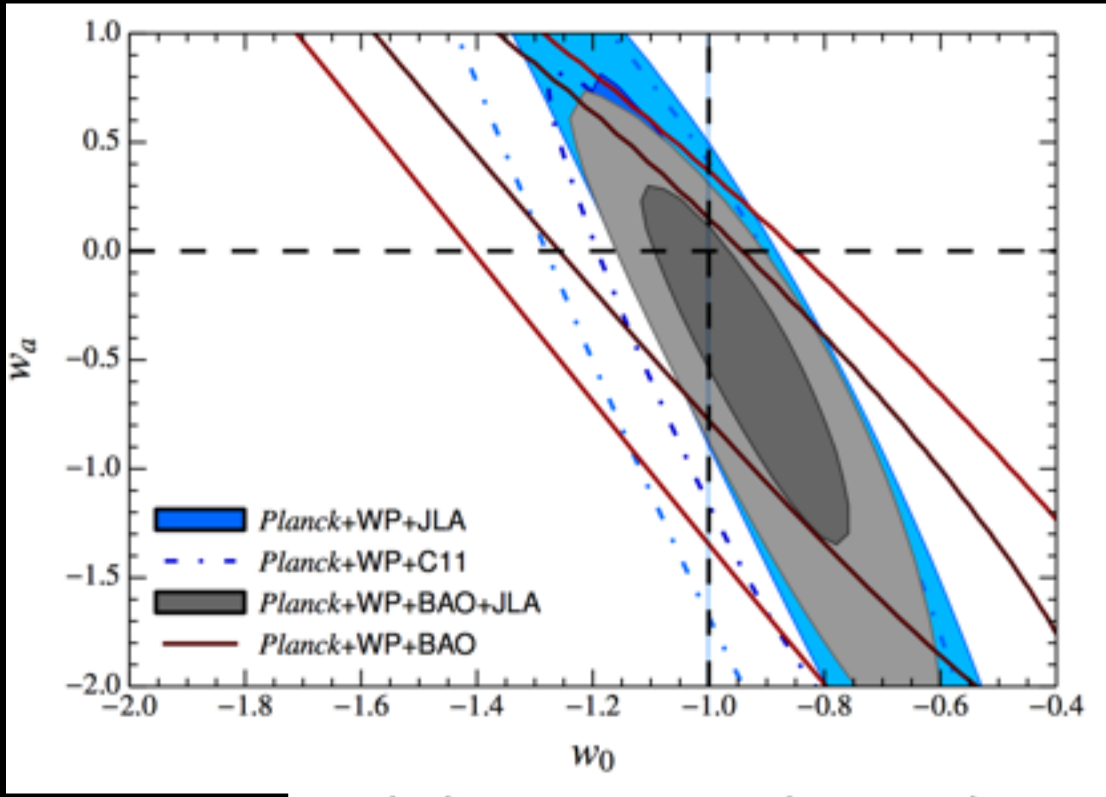


EXPANSION PROBES - SUPERNOVAE IA



Betoule et al 14





$$w(a) = w_0 + (1-a)w_a$$

DEGENERACY FOR EXPANSION RATE

Supernova H_0 - M_B Degeneracy

$$\mu = 25 + 5\log_{10}(D_{\rm L})$$

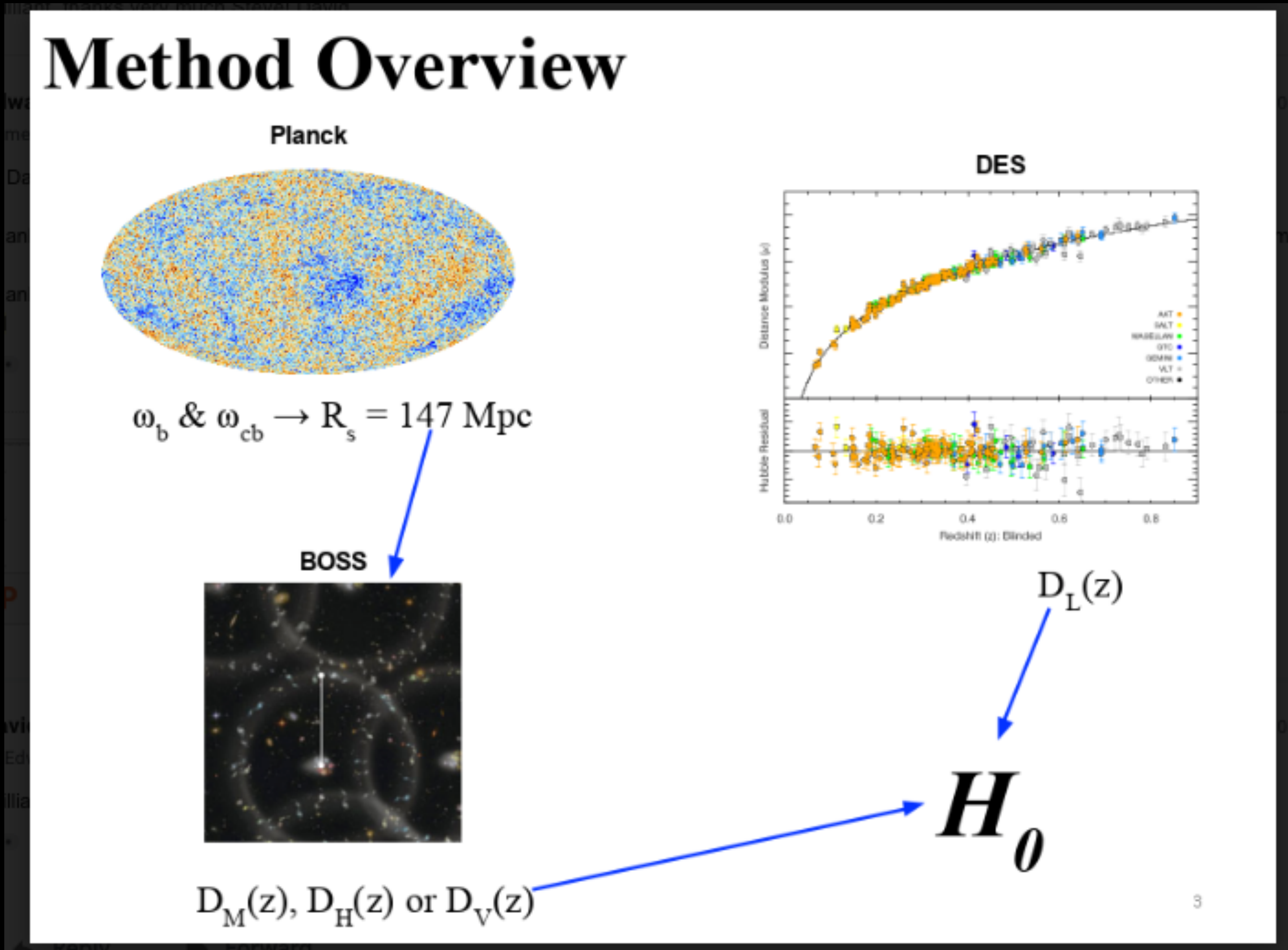
$$D_{\rm L} = (1 + z_{\rm obs}) \int dz \frac{c}{H(z)}$$

Degenerate

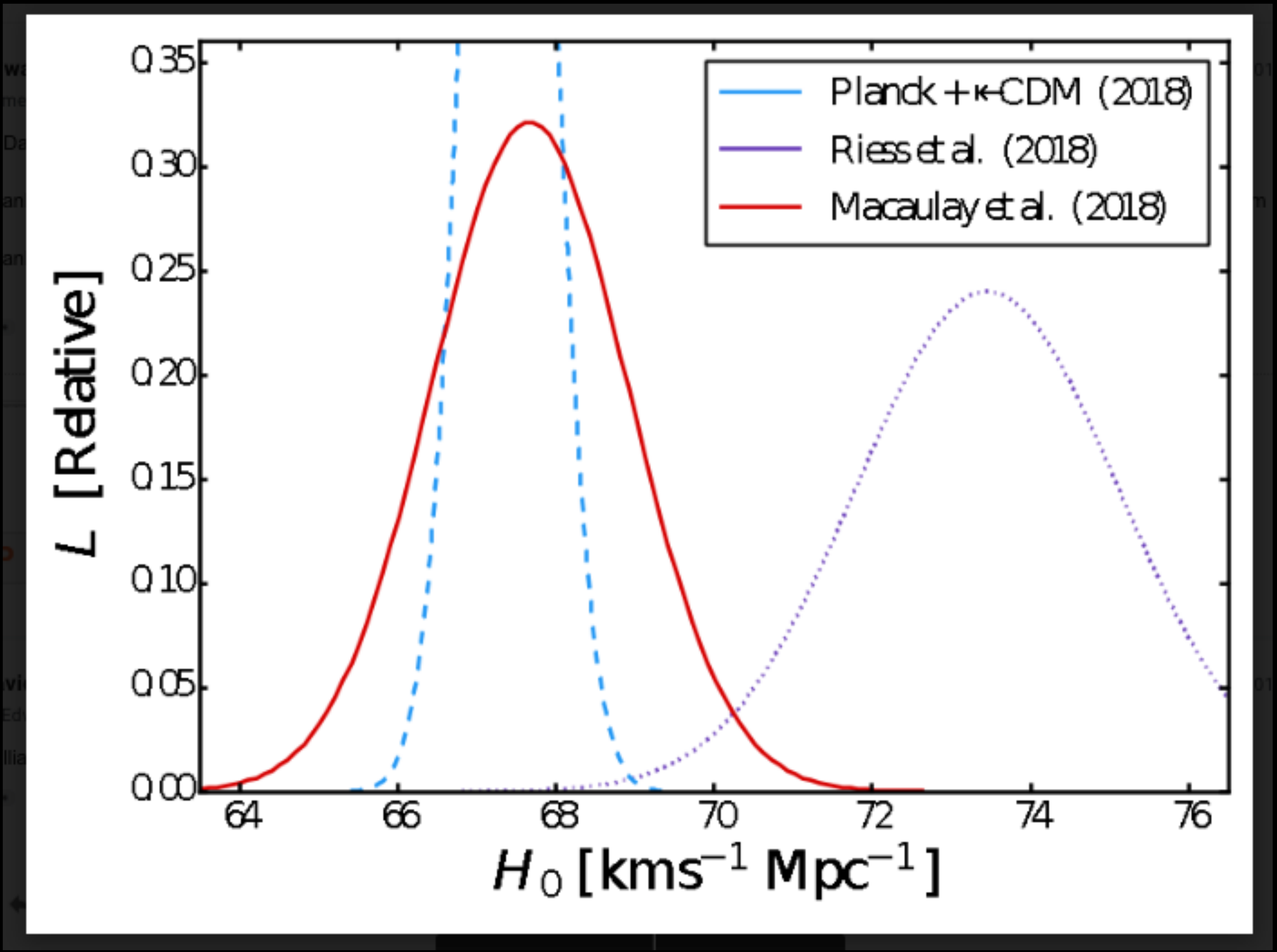
$$\mu = m_B^\star - (M_B - \alpha X_1 + \beta C)$$

2

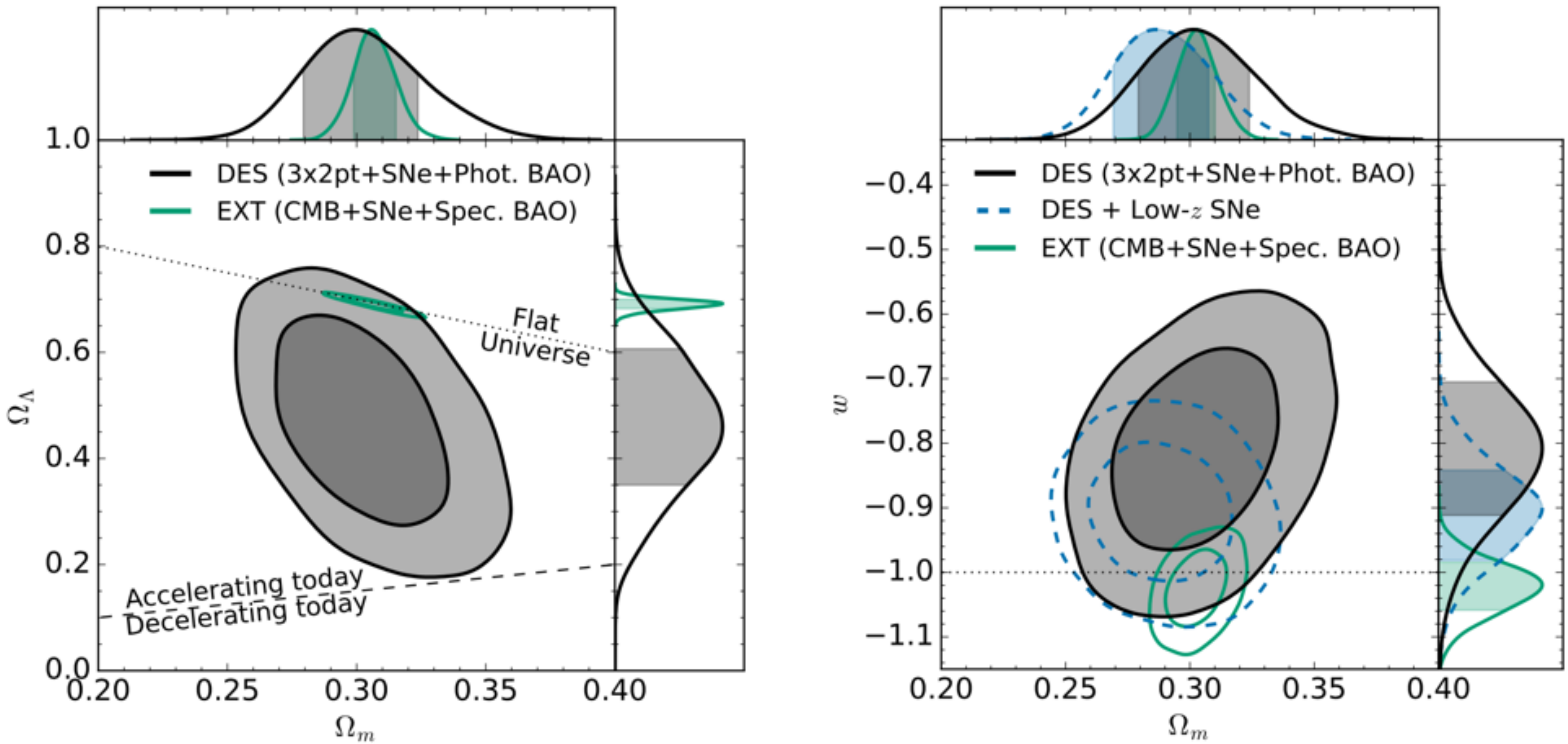
Macaulay, Nichol, Bacon et al 18



Macaulay, Nichol, Bacon et al 18



Macaulay, Nichol, Bacon et al 18



Abbott et al 18

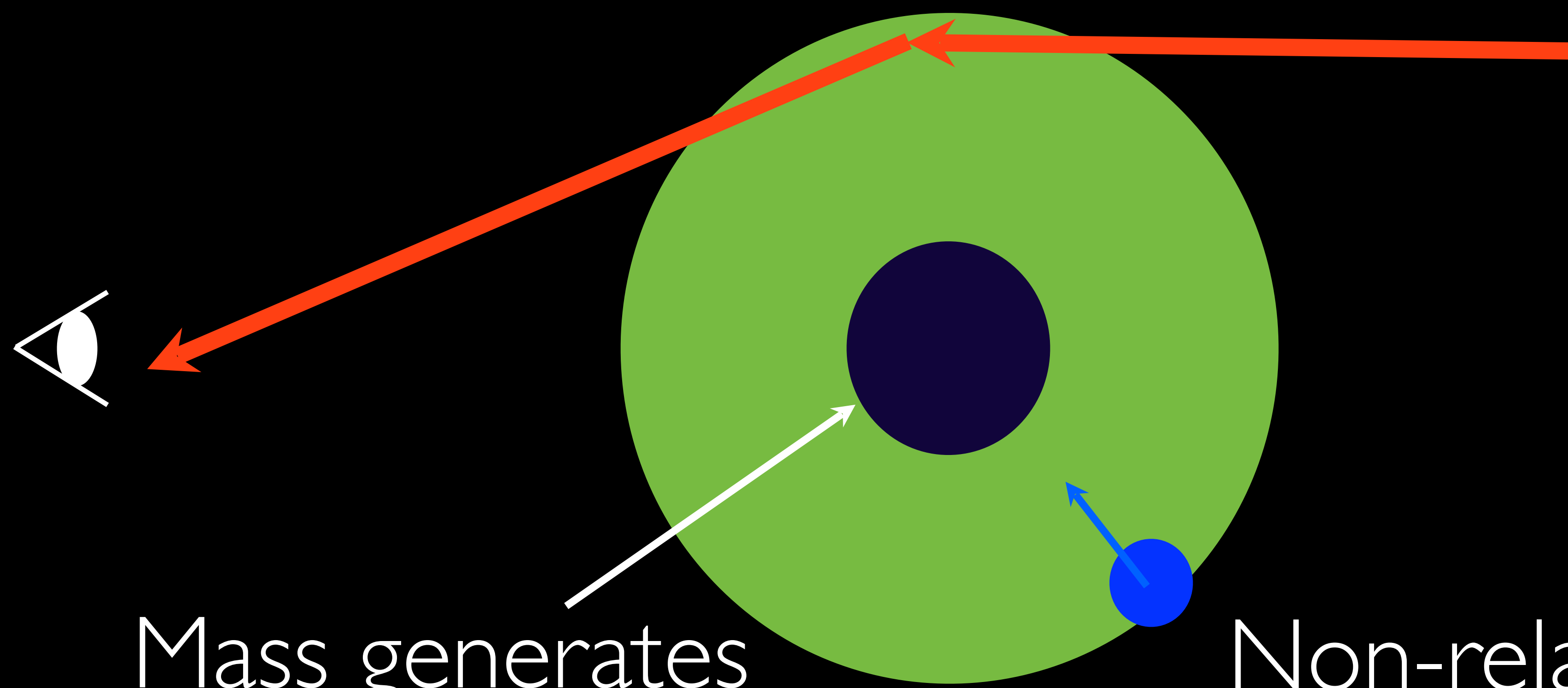
GRAVITY TESTS

$$ds^2 = -(1+2\Psi)dt^2 + (1+2\Phi)a^2\delta_{ij}dx^i dx^j$$

Newtonian guage

Simpler approach:

Lensing feels $\Psi+\Phi$
Modification η

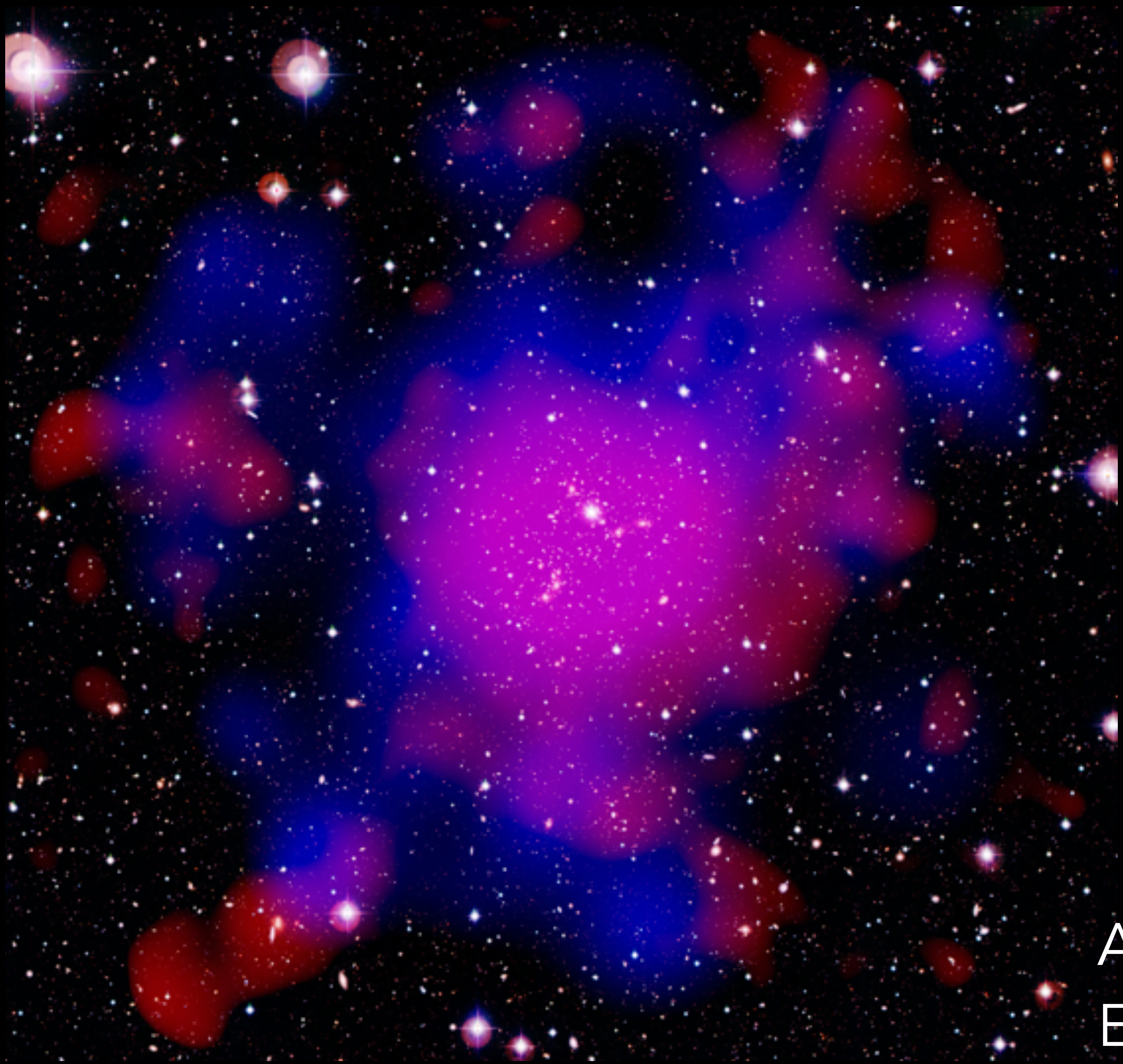


Mass generates potential Ψ (Poisson)
Modification μ

Non-relativistic objects respond to Ψ

Or: can find parameters for general action, e.g. Lagos et al 16

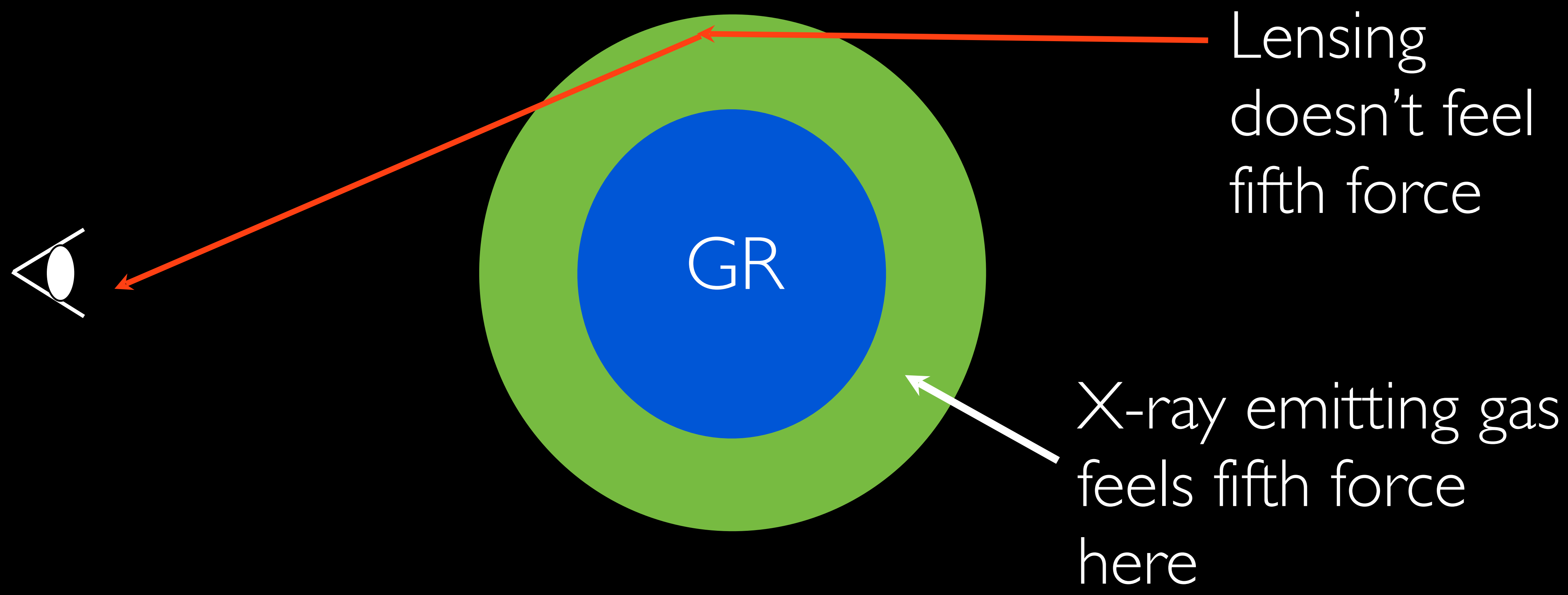
TESTING GRAVITY THEORIES WITH CLUSTERS OF GALAXIES



Abell 2744
Eckert et al 15

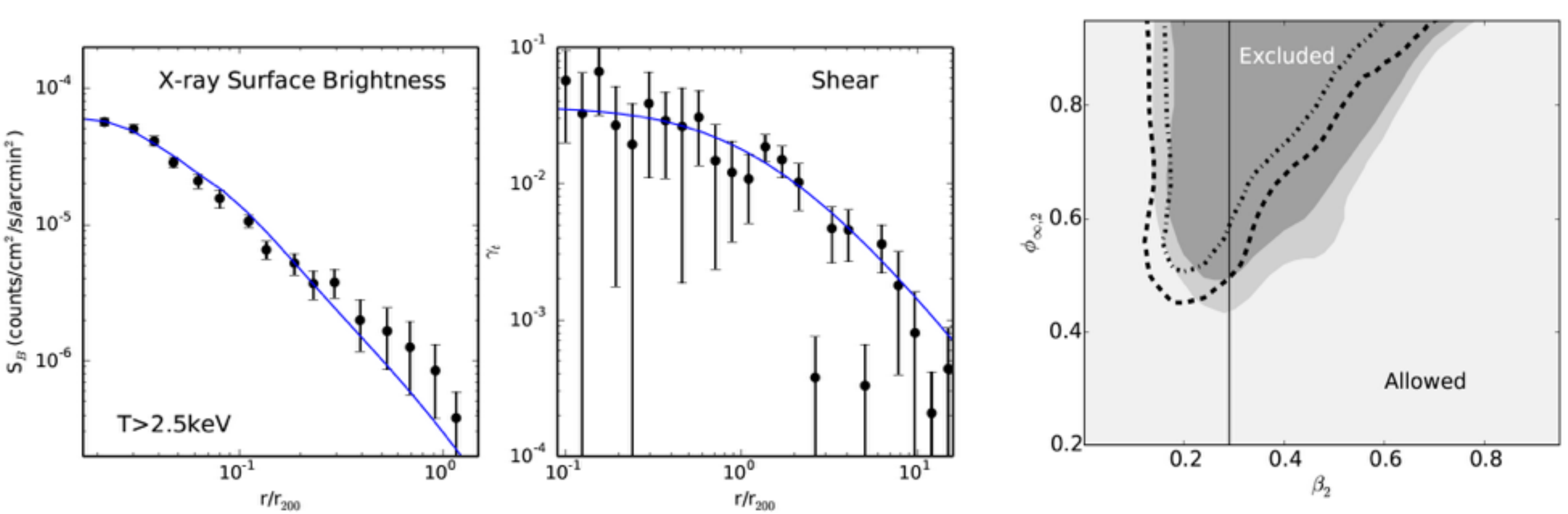
GRAVITY TESTS

e.g. Chameleon mechanism:



GRAVITY TESTS

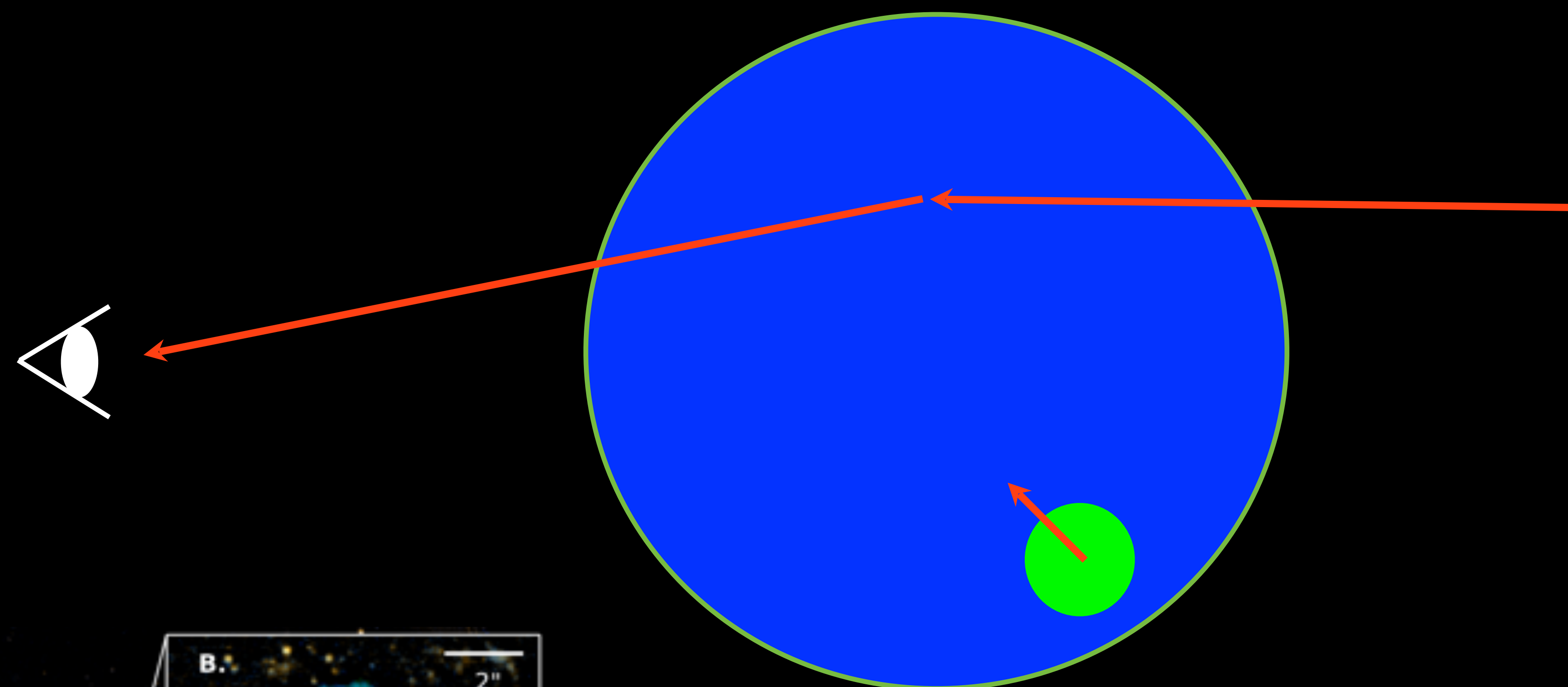
Wilcox et al 2015

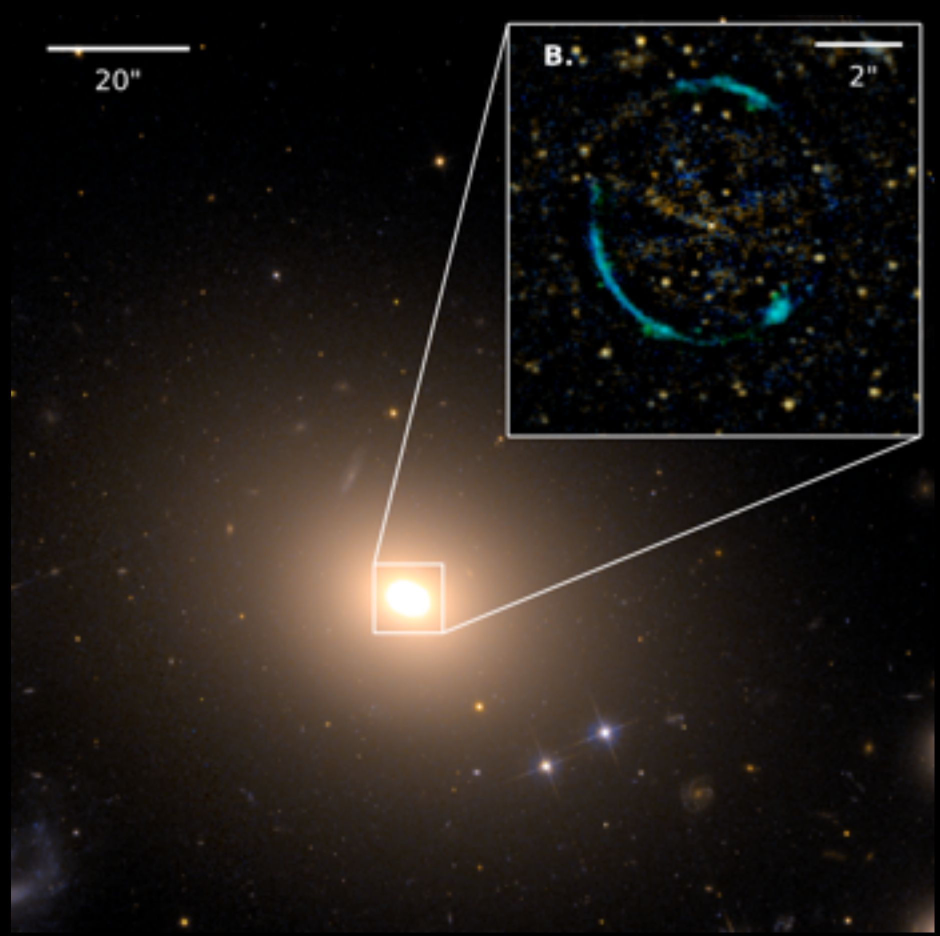


CFHTLens + XMM,
52 clusters

β is 5th force strength
ϕ_∞ is screening efficiency

STRONG LENSING TEST OF GRAVITY





Collett et al 18
Space and time parts of metric within 10% of each other
(Ratio is 0.97±0.09)

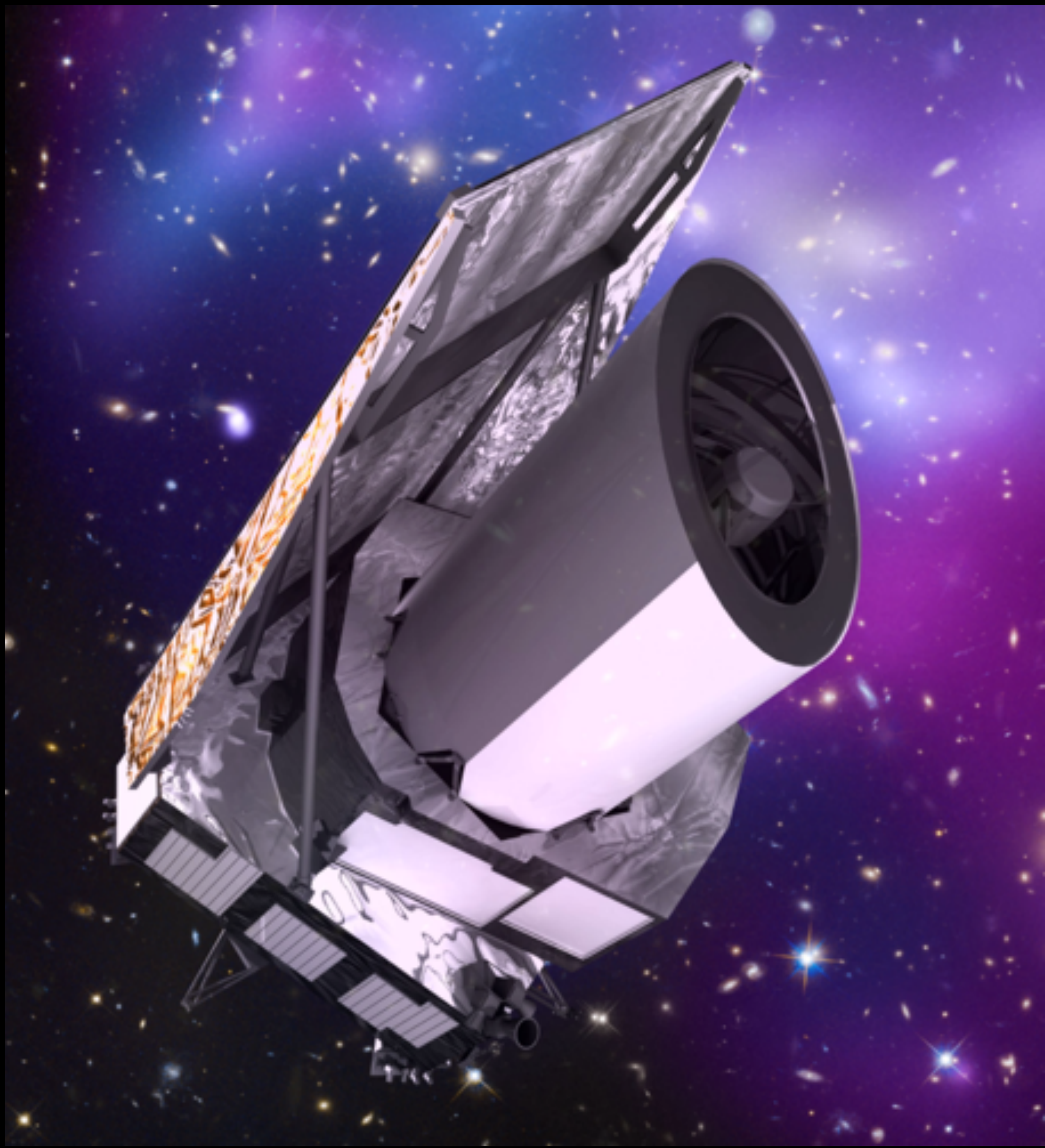
HST + VLT MUSE

NEXT STEPS: EUCLID

15000 sq deg wide survey
40 sq deg deep survey

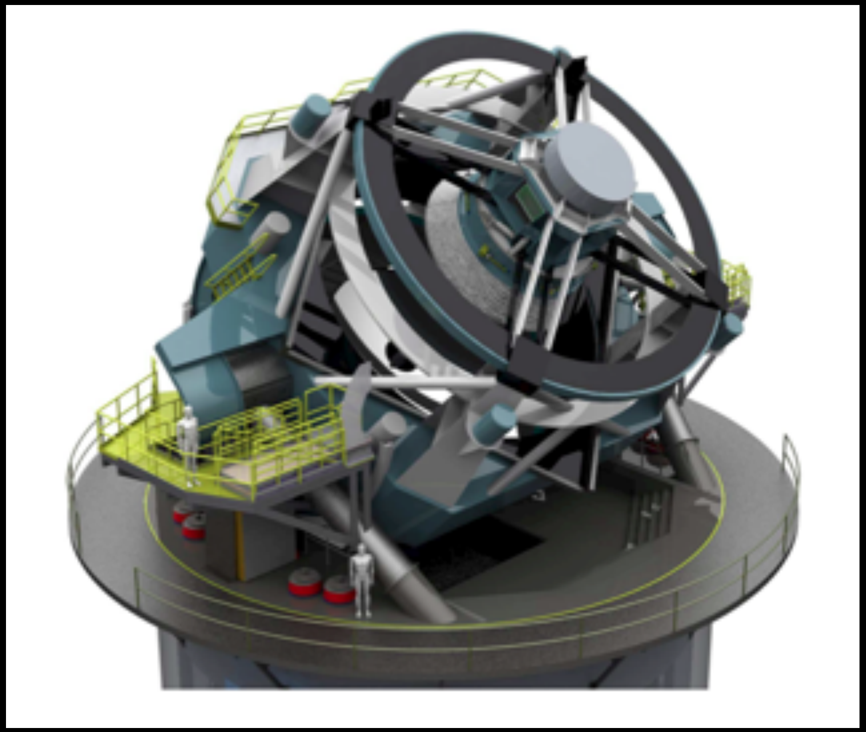
1.2m mirror; FOV 0.53 sq deg

Visible (0.1", R+I+Z)
1.6G galaxies (mag<24.5)
+NIR (Y,J,H) imaging
NIR spectroscopy - 45M galaxies



Launch 2022

THE LARGE SYNOPTIC SURVEY TELESCOPE



Cerro Pachón in northern Chile

Effective diameter of 6.5m

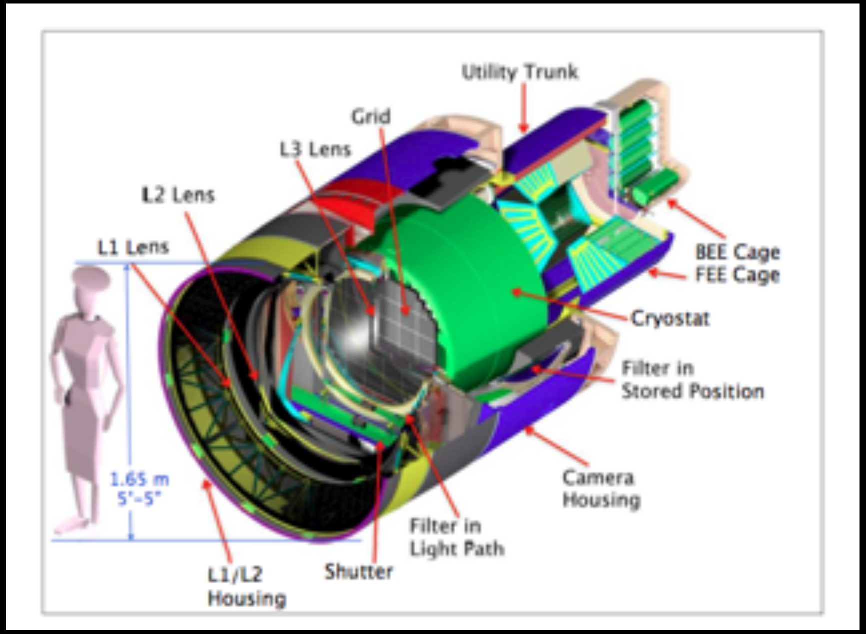
0.2×0.2 arcsec^2 pixels

6 bands (ugrizy, 320–1050 nm)

First light around 2021

30,000 deg^2

20 billion galaxies and a similar number of stars

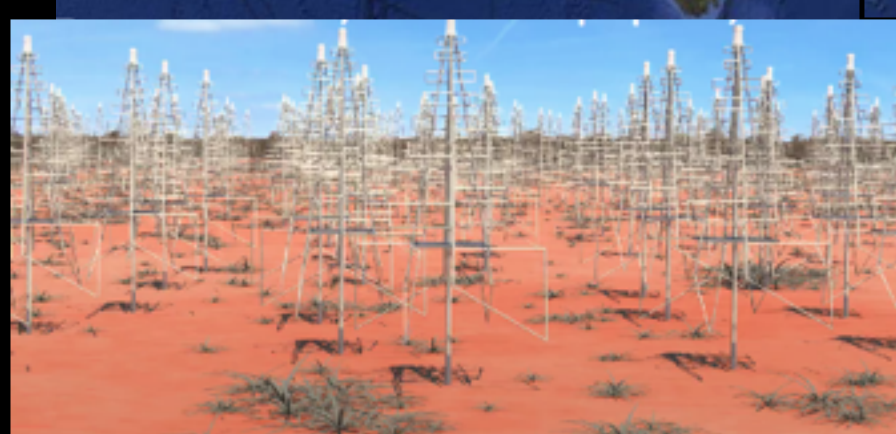


SQUARE KILOMETRE ARRAY

SKA Phase 1 baseline design:

Frequency range: 50MHz -14GHz

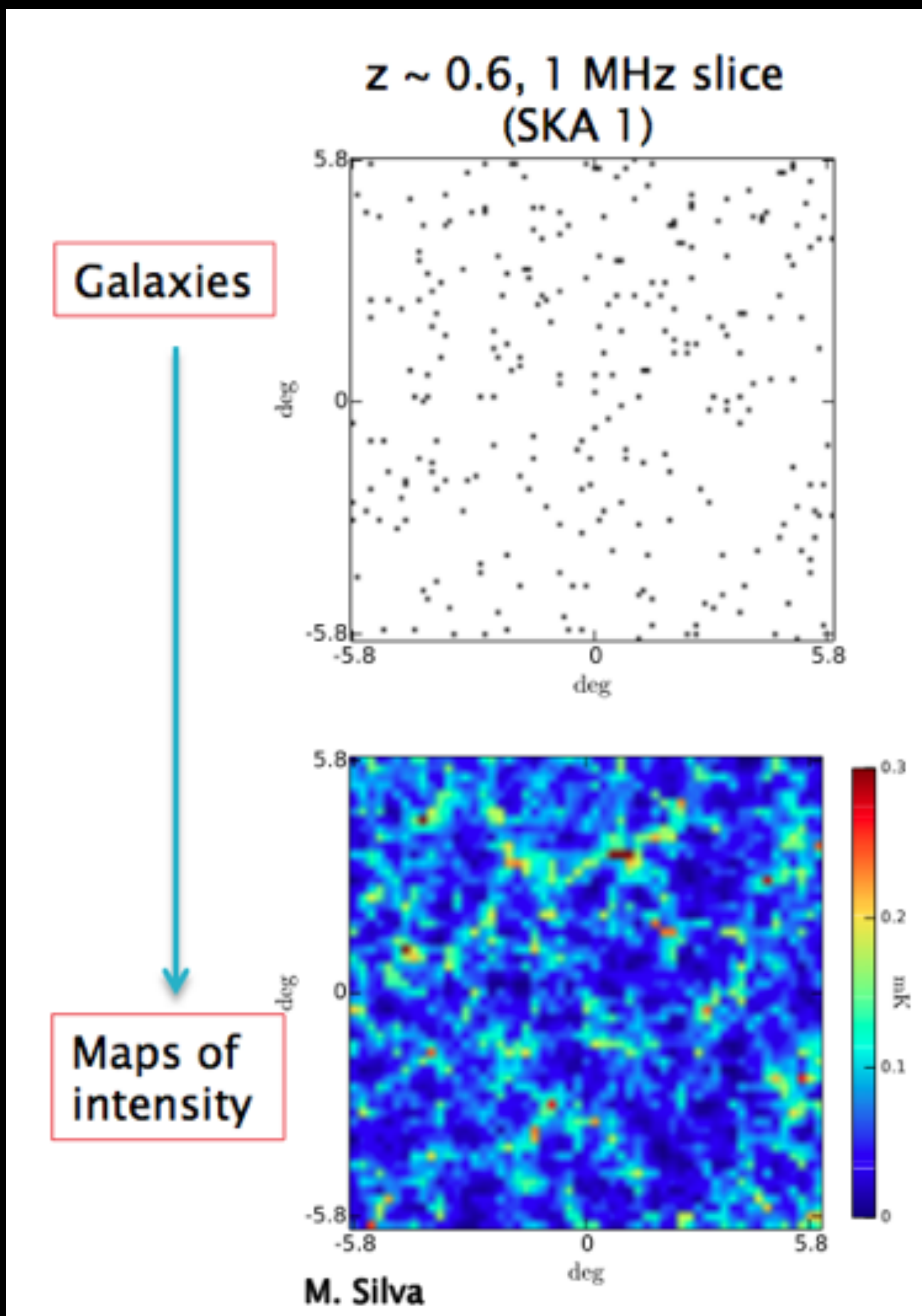
SKA-Low ~130,000 low frequency dipoles

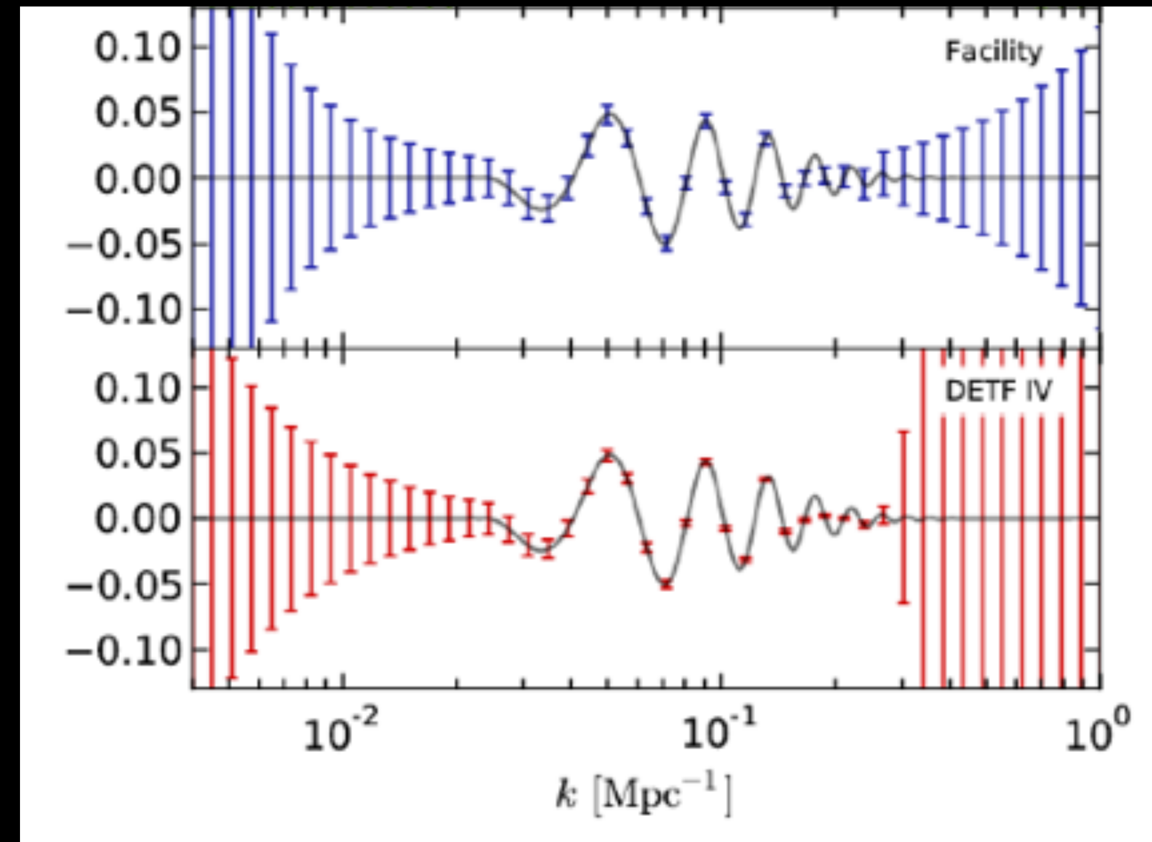


SKA-Mid ~130 15m dishes + 64 MeerKAT

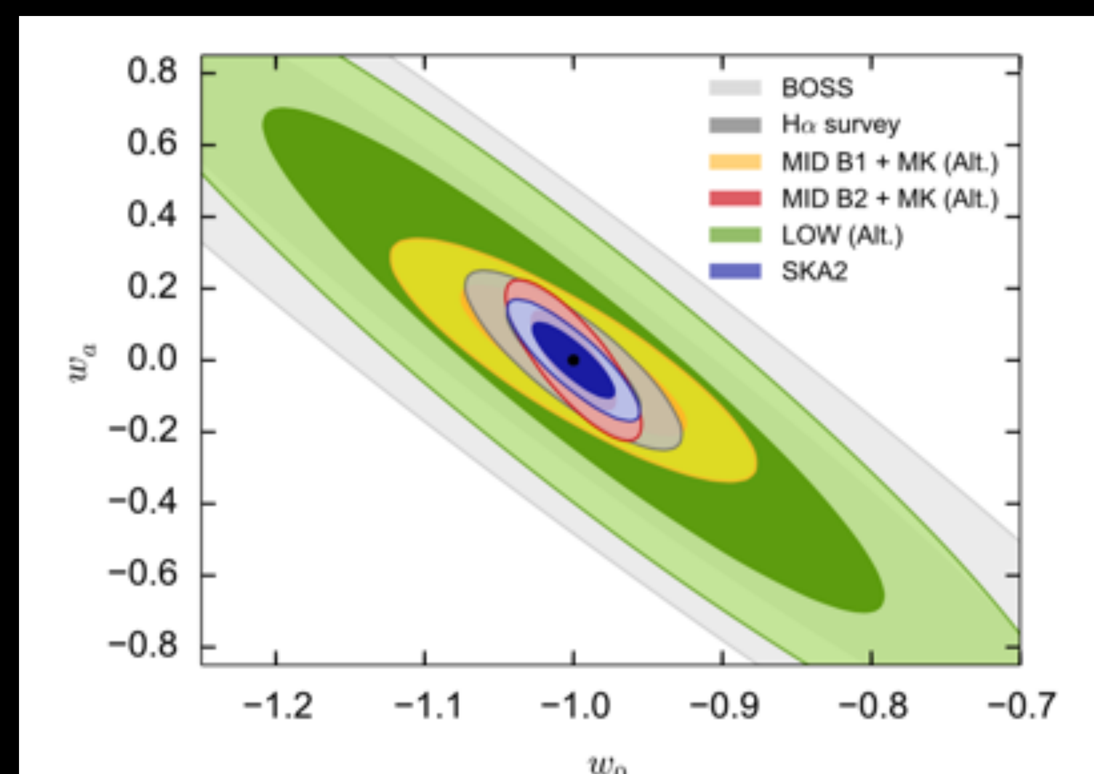
COMPARABLY POWERFUL SURVEYS

Intensity mapping (SKA1):



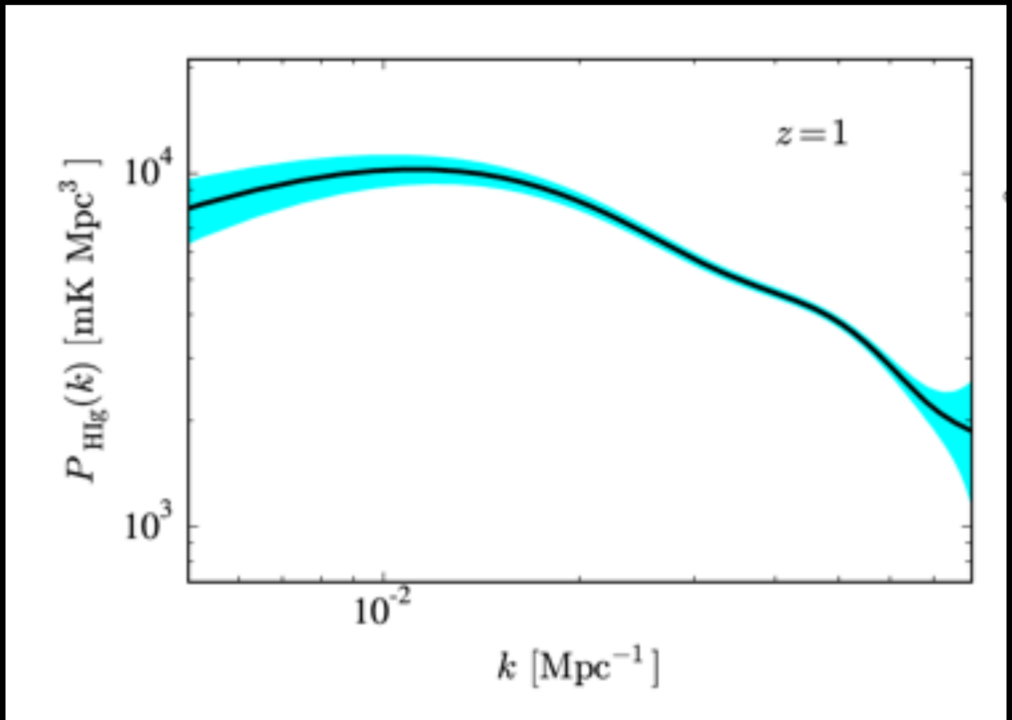


Bull et al 15

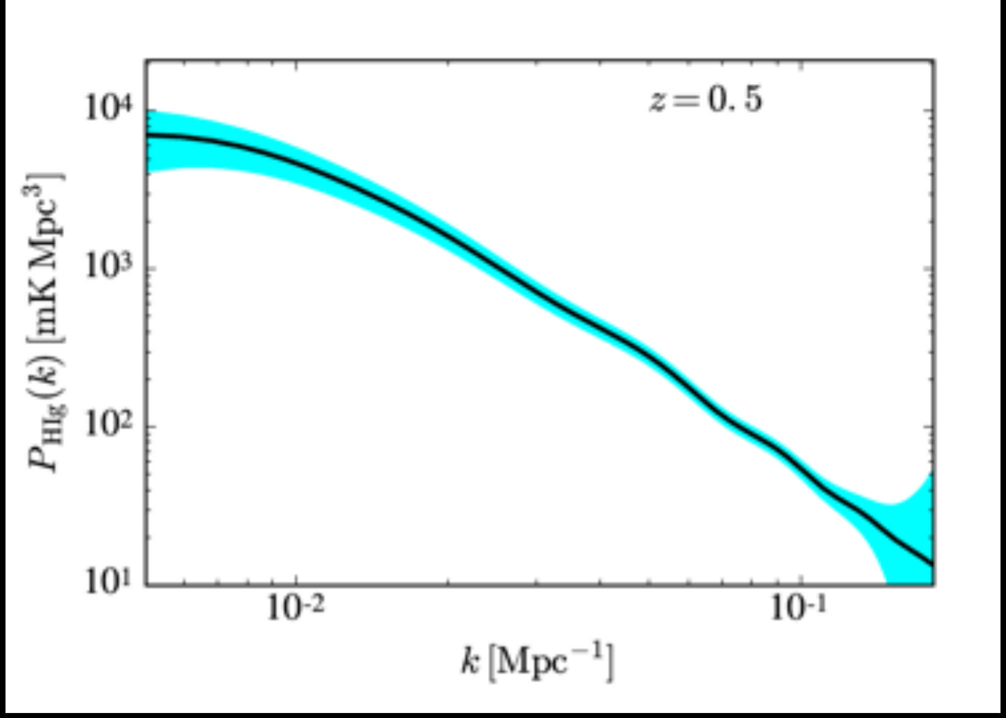


Bull 2016

INTENSITY MAPPING



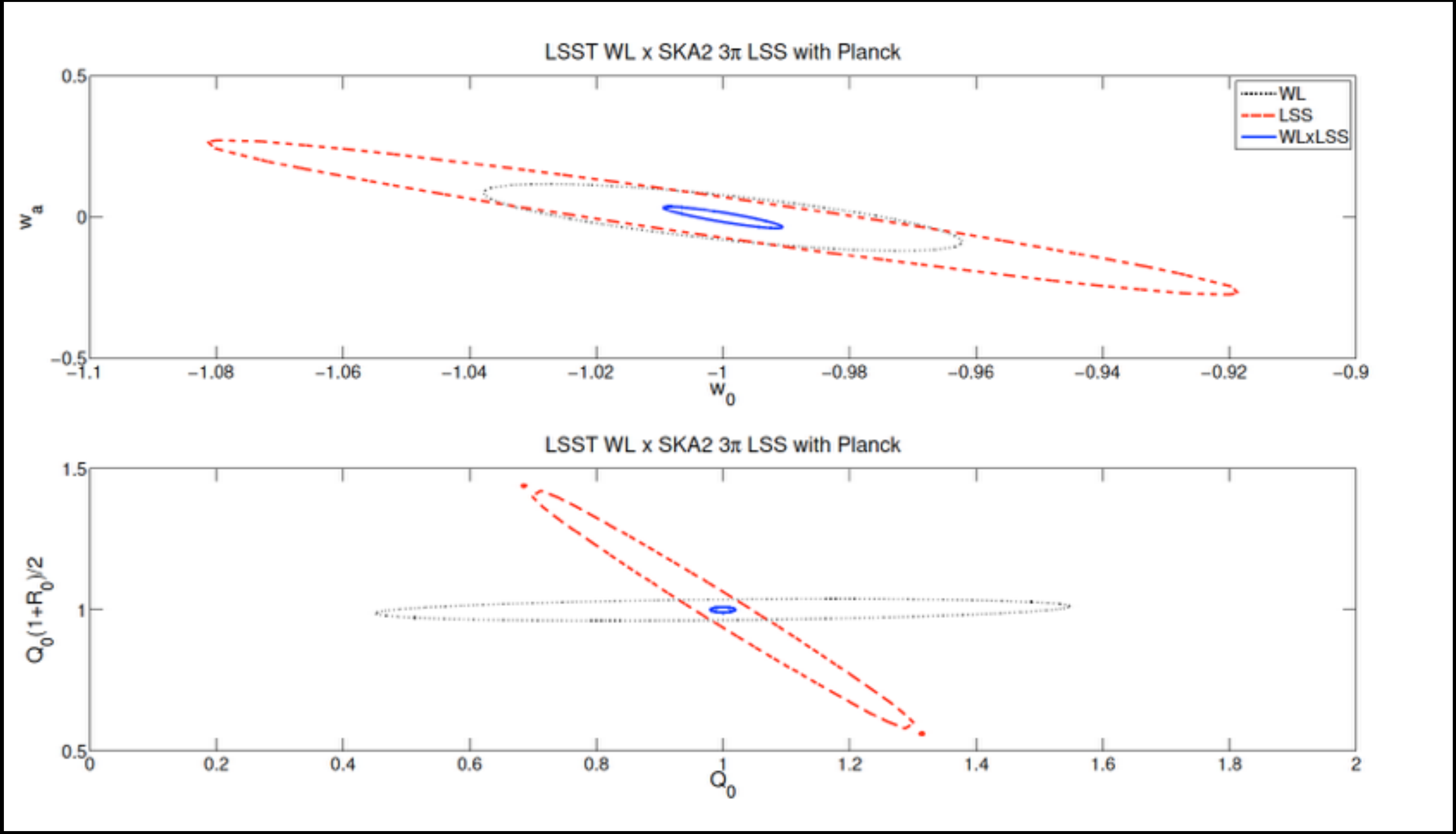
MeerKAT cross-correlations with Euclid and DES (SKA Red Book 18)



SO WHAT CAN BE DONE IN COMBINATION?

COMBINING SURVEYS - 1) AT THE END

e.g. Combining constraints from LSST lensing+SKA2 HI galaxy clustering (including RSD):

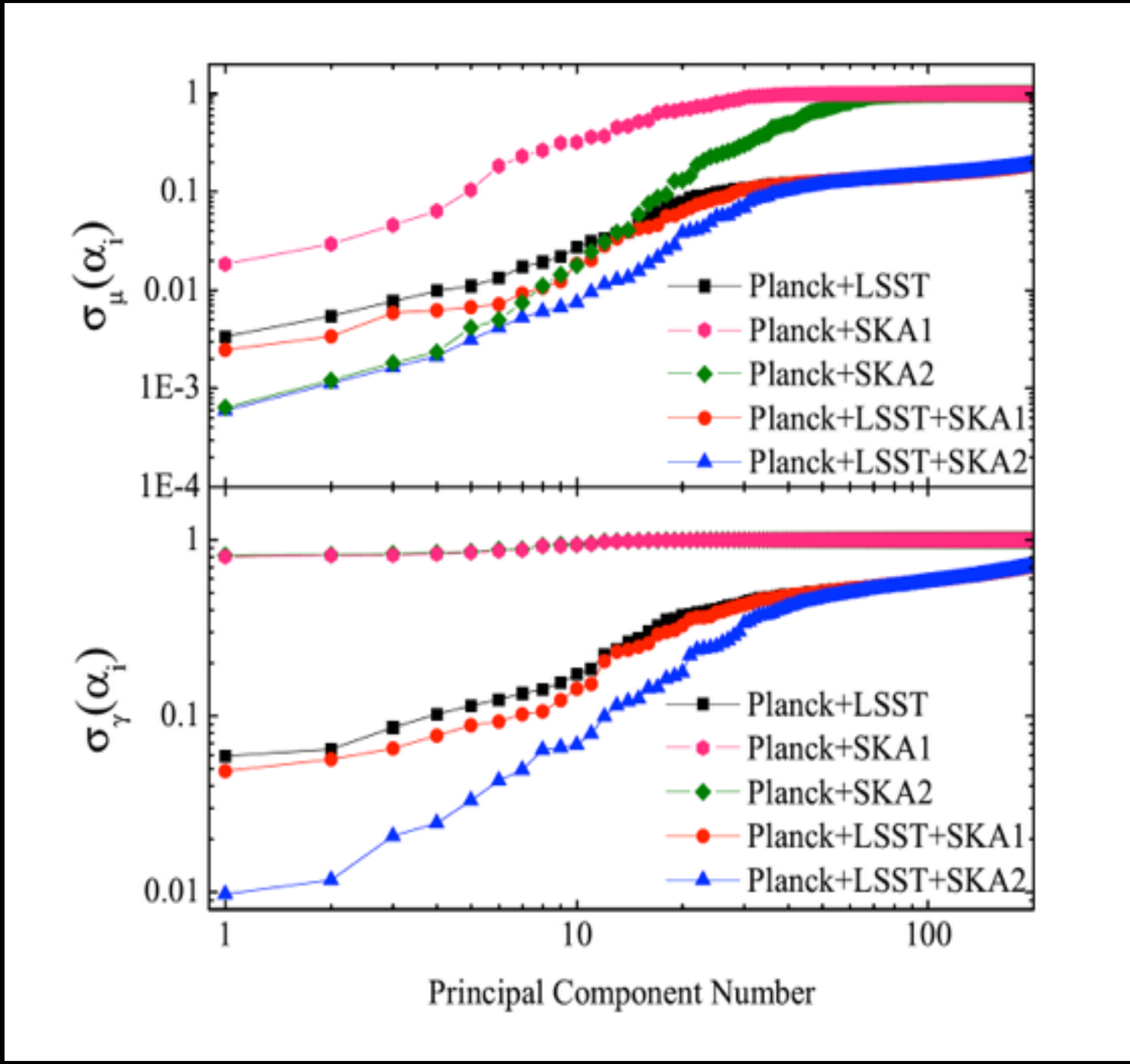


Bacon et al 15

c.f. DES/Planck tension issue

COMBINING SURVEYS - 2) IN COMBINED STATISTICS

e.g. PCA approach: LSST lensing + SKA HI clustering

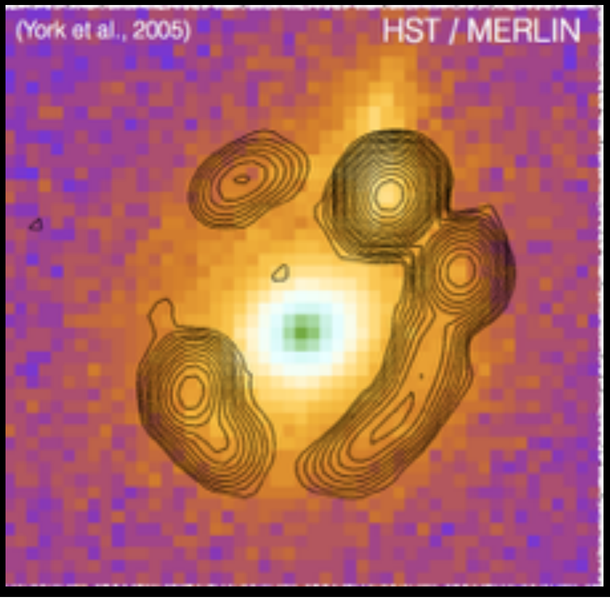


Allow gravity/DE parameters to be scale and z-dependent functions:

$$g(z)+1 = \sum \alpha_i \, e_i(z)$$

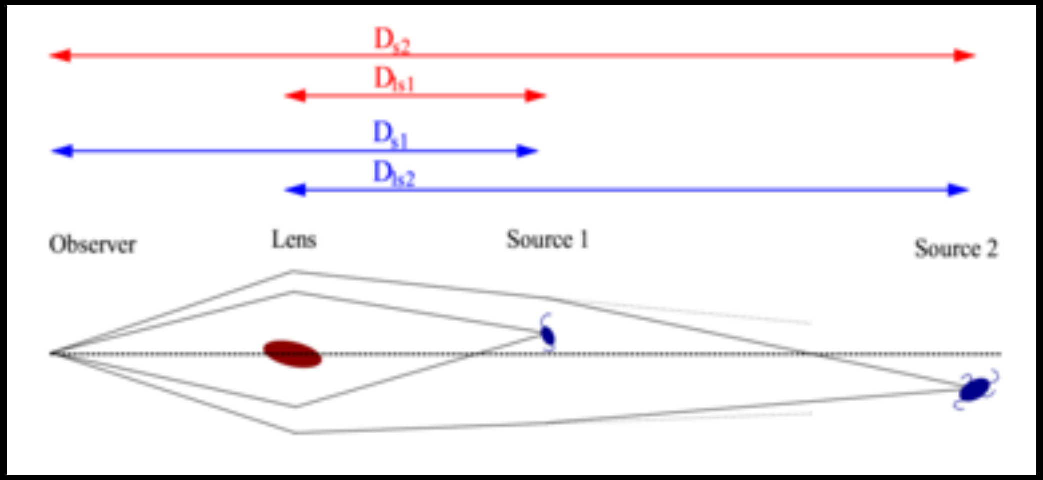
Bacon et al 15, Zhao et al 15

RADIO + OPTICAL PRESENT DIFFERENT FEATURES

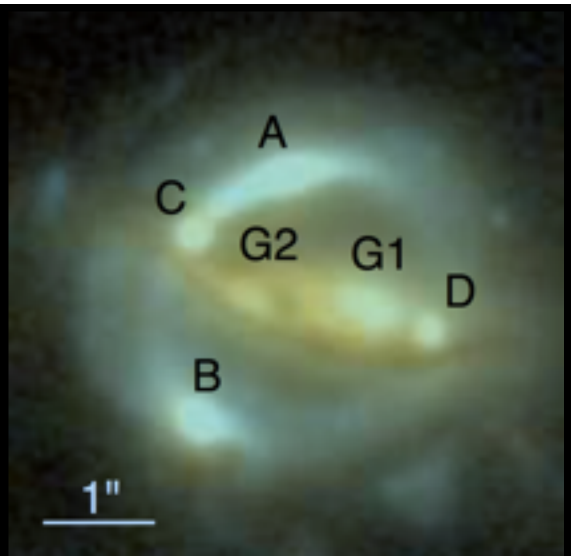


Joint selection of strong lensing systems (e.g. optical ellipticals + radio b/g sources)

10^4-10^5 lenses - examine sources at high magnification (McKean et al 15)
+ spectroscopy can constrain η (Collett et al 18)

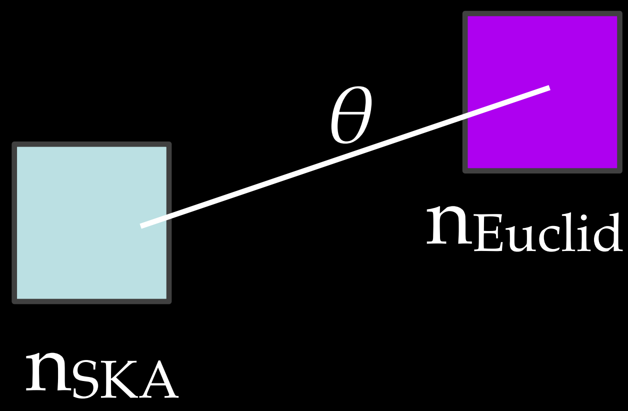


SL Cosmography (e.g. Collett & Auger 15, Collett & Bacon 16) - may find multiple arcs in optical + radio. ~150 compound lenses, 2% constraint on w

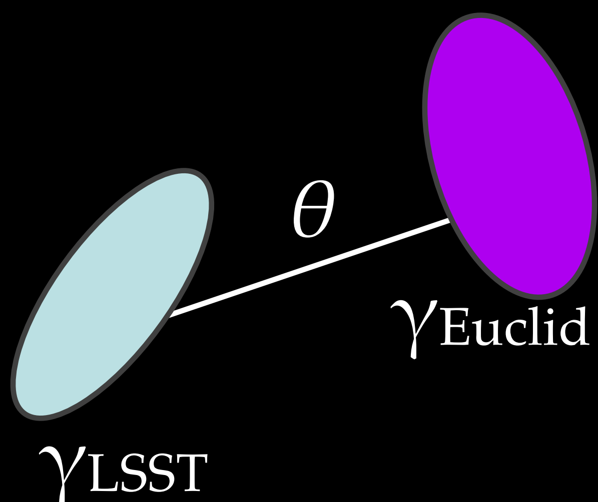


Time delays: radio quasars + optical extended arcs for mass model. (e.g. Suyu et al 2010) H_0 to fraction of %

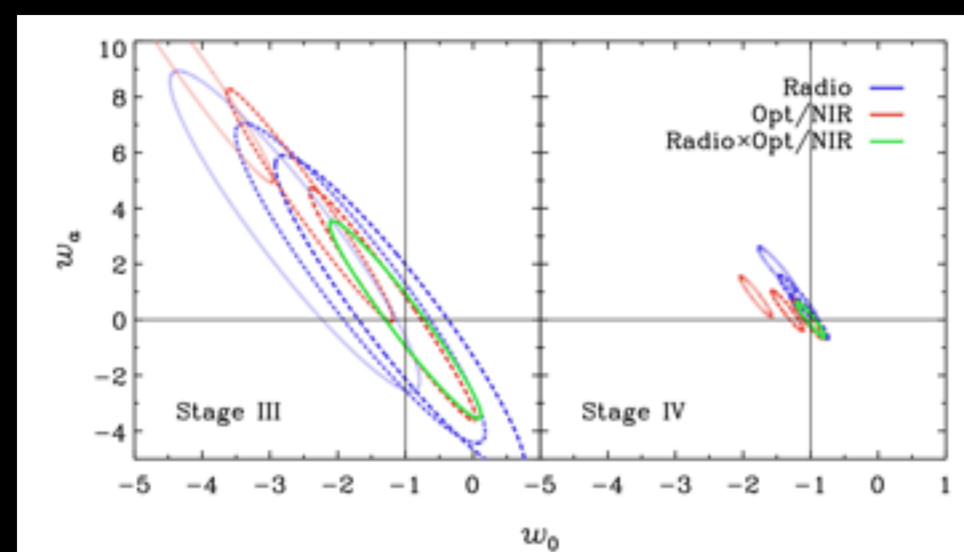
COMBINING SURVEYS - 3) OVERCOMING SYSTEMATIC ERRORS



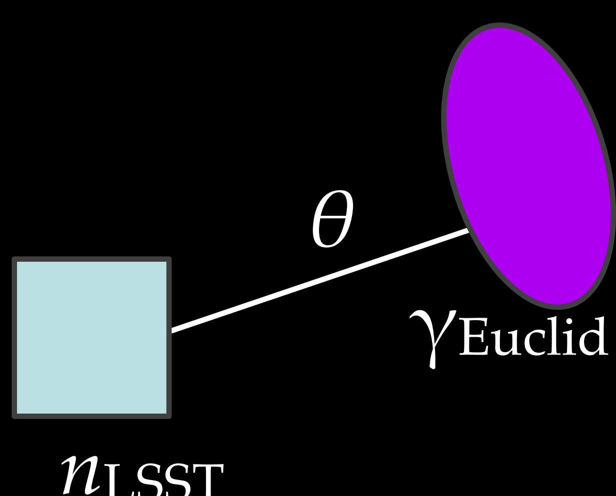
Cross correlation of clustering picks out fluctuations which are not due to instrumental effects or e.g. stars.



Cross correlation of lensing shear picks out signal which is not due to telescope systematics.



Camera et al 17

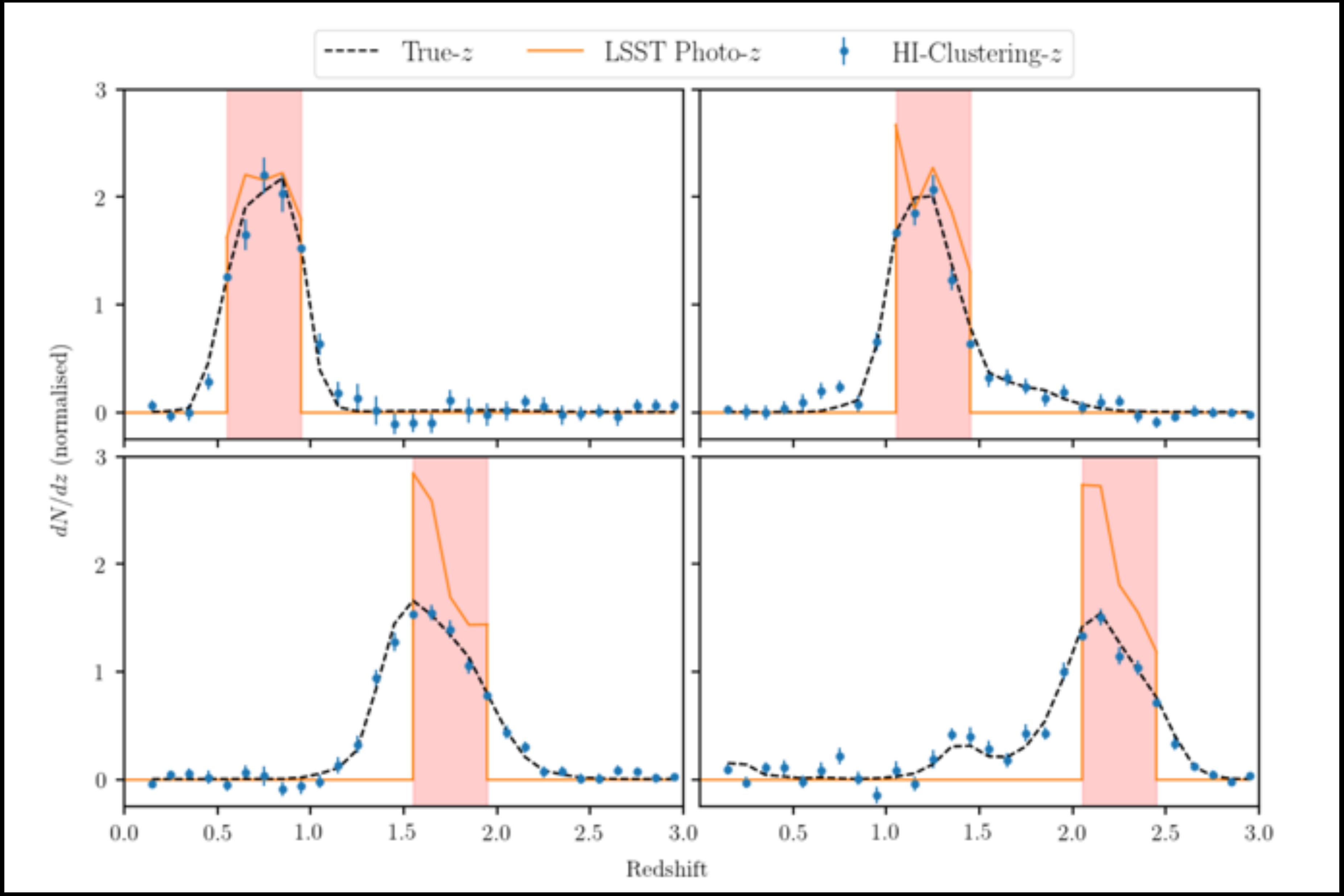


Cross correlation of clustering and lensing picks out signal with different combination of systematics, and measures galaxy bias.

MUTUAL HELP WITH REDSHIFTS

LSST is able to provide photometric redshifts for SKA continuum (SKA1 1 per sq arcmin, SKA2 10 per sq arcmin, Harrison et al 16);

SKA HI redshifts can calibrate optical photo-zs, using cross-correlation of clustering (Newman 08).



Cunnington et al 18

COMMON/JOINT EFFORTS

The surveys share large computational challenges; e.g. need $10^{9??}$ simulations for covariance matrices.

Can attempt joint shape fitting at the raw data level

Eventually joint catalogues

Measure many cross-power spectra between the surveys, to constrain systematics and cosmology.

SUMMARY

We can learn about the dark energy with:

- Probes of the expansion history, e.g. SNe, baryon acoustic oscillations;
- Probes of the growth history, e.g. lensing

A simple model with $w=-1$ is currently ~OK

But some very interesting tensions in both expansion rate and growth

Future surveys allow many dark energy functions to be constrained,

and many cross-correlations for information about systematics and physics.