Gravitational Lensing as a probe of the Dark side of the cosmos

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For very recent reviews on Gravitational Lensing, see:

- Schneider, P.: 2005, "Introduction to Grav. Lensing and Cosmology",
- Kochanek, C.S.: 2005, "Strong Gravitational Lensing",
- Schneider, P.: 2005, "Weak Gravitational Lensing",
- Wambsganss, J.: 2005, "Gravitational Microlensing"

in: Kochanek, C.S., Schneider, P. & Wambsganss, J.: "Gravitational Lensing: Strong, Weak & Micro", Proceedings of the 33rd Saas-Fee Advanced Course, G. Meylan, P. Jetzer & P. North, eds. (Springer-Verlag: Berlin), in press (see `http://www.astro.uni-bonn.de/~peter/SaasFee.html`).

Introduction

Gravitational light deflection is independent of the nature and state of matter producing the gravitational field;

therefore an ideal probe for the (statistical properties of the) mass distribution, dark + luminous, in the Universe;
no reference to relation between dark and luminous matter.

This mass distribution depends on

- geometry of the universe (mainly $\Omega_{\rm m}$, $\Omega_{\rm DE}$)
- evolution of the density field (growth factor, transfer function, i.e. $\Omega_{\rm m}$, $\Omega_{\rm DE}$ and other DE properties, Ω_ν)
- shape and amplitude of density fluctuations ($n_{\rm s}$, σ_8)
- properties of DM – self-interacting, cold or warm.

Furthermore, by relating lensing properties (‘mass’) with observed properties (‘light’) of lenses, one learns about

- relations of galaxies to underlying DM field – biasing
  $\Rightarrow$ calibration of galaxy-redshift surveys vs. dark matter distribution
- mass-to-light ratio of lenses (galaxies, clusters – are there extreme cases?)
- density profile of lenses and their DM halo (universal density profile, NFW?)
- environmental dependence of halo mass properties

This talk

- Basics of lensing, weak and strong
- selected applications, in particular the 'CDM subhalo problem' (the other 'dark matter crisis' $\Rightarrow$ C. Frenk's talk)
- Cosmic Shear: lensing by the Large-Scale Structure
  - Principles
  - Observables
  - Current status
  - Perspectives

Basic principles

- Light bundles are deflected and distorted as they propagate through a gravitational field.
- Deflection causes a shift of the image position; unobservable, unless multiple images are formed.
- Distortion by the tidal gravitational field changes shape of images of distant sources – images of round sources become elliptical;
  effects are 'weak' – not visible in individual images;
  however, sky densely filled with faint galaxies
  $\Rightarrow$ Statistical approach.

- Lensing properties of a deflecting mass distribution are described by the projected surface mass density $\kappa(\boldsymbol{\theta})$;
- Associated with the mass density κ is a deflection potential $\psi(\boldsymbol{\theta})$ which satisfies Poisson equation in 2D,

$$\nabla^2\psi = 2\kappa \; ; \tag{1}$$

- (scaled) deflection angle $\boldsymbol{\alpha}(\boldsymbol{\theta})$ is gradient of the potential,

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \nabla\psi(\boldsymbol{\theta}) \; ; \tag{2}$$

- Lens equation relates true source position $\boldsymbol{\beta}$ to the observed image position $\boldsymbol{\theta}$,

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta}) \; ; \tag{3}$$

multiple images occur when lens equation has multiple solutions,

$$\boldsymbol{\theta}_i - \boldsymbol{\alpha}(\boldsymbol{\theta}_i) = \boldsymbol{\theta}_j - \boldsymbol{\alpha}(\boldsymbol{\theta}_j) \tag{4}$$

- differential light deflection causes image distortions; for 'small' sources, it is given by Jacobian matrix of lens equation

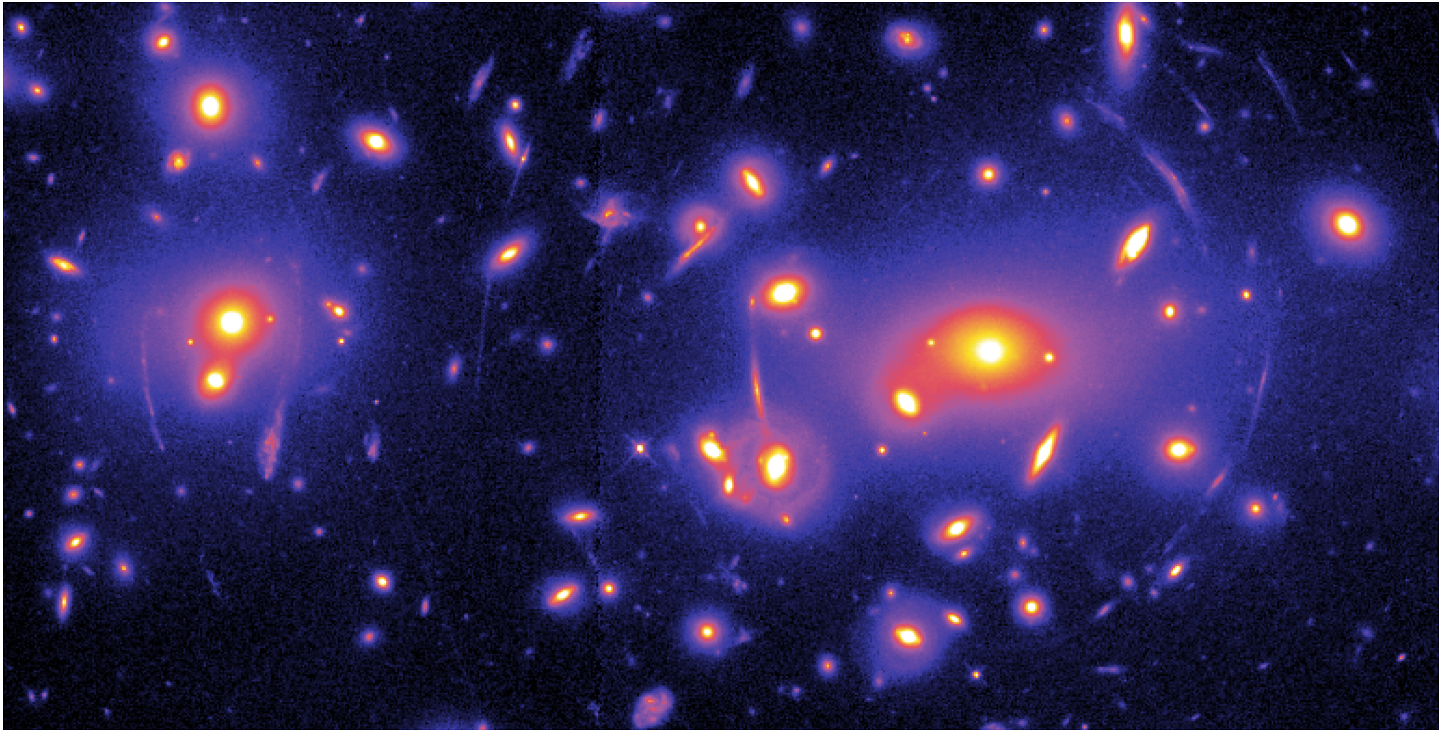
$$\mathcal{A}(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} = \left(\delta_{ij} - \frac{\partial^2 \psi(\boldsymbol{\theta})}{\partial \theta_i \partial \theta_j} \right) = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix} , \tag{5}$$

  where

$$\gamma_1 = \frac{1}{2}(\psi_{,11} - \psi_{,22}) , \quad \gamma_2 = \psi_{,12} \tag{6}$$

  are the two Cartesian components of the shear (or the tidal gravitational force).

- magnification of images is $\mu = 1/\det \mathcal{A}$;
  if $|\det \mathcal{A}| \ll 1$, strong magnification and image distortions
  $\Rightarrow$ giant luminous arcs



- axis ratio of arc $\approx$ eigenvalue ratio of $\mathcal{A}$
- flux ratio of multiple images:

$$S_i/S_j = |\mu_i/\mu_j| \; . \tag{7}$$

- The (complex) ellipticity ϵ of an image (defined in terms of second-order brightness moments) is related to the ellipticity $\epsilon^{\rm s}$ of the source by

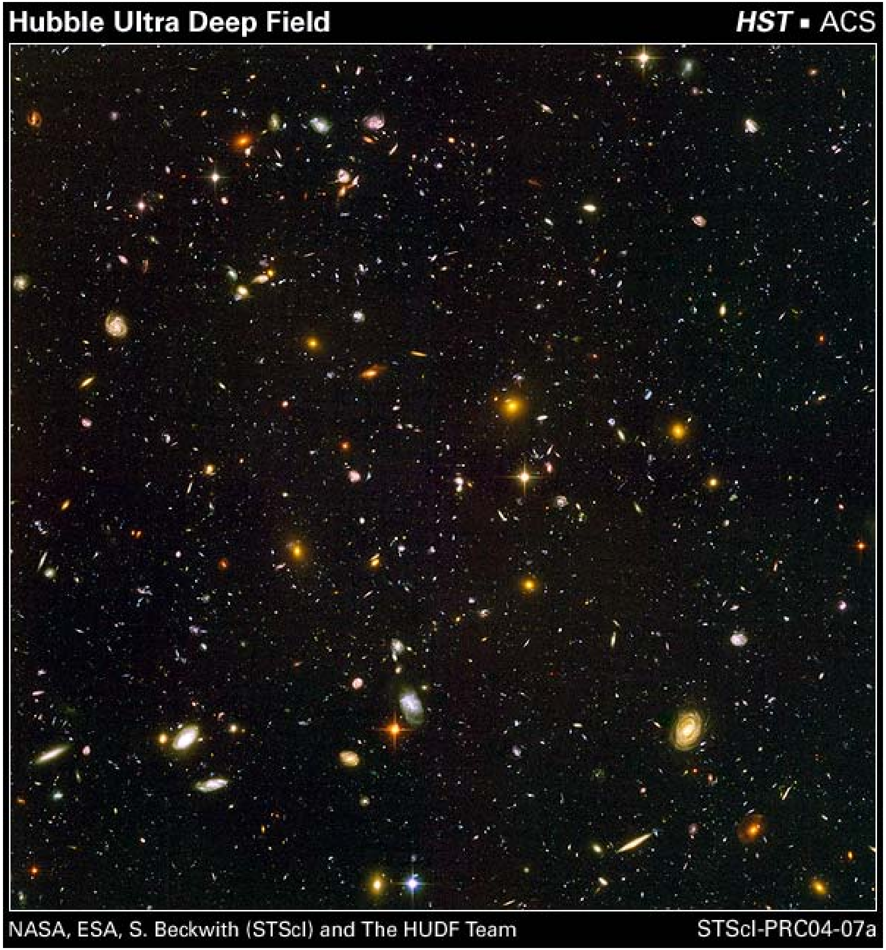
$$\epsilon = \epsilon^{\rm s} + \gamma \tag{8}$$

- No direction in the Universe is singled out $\Rightarrow$ ellipticities of sources are distributed isotropically
- $\Rightarrow$ Expectation value $\langle \epsilon^{\rm s} \rangle = 0$
- Expectation value of image ellipticity is the local shear,

$$\langle \epsilon \rangle = \gamma \; ; \tag{9}$$

Hence, each image ellipticity provides an unbiased estimate of the local shear, though a very noisy one;
noise determined by the intrinsic ellipticity dispersion

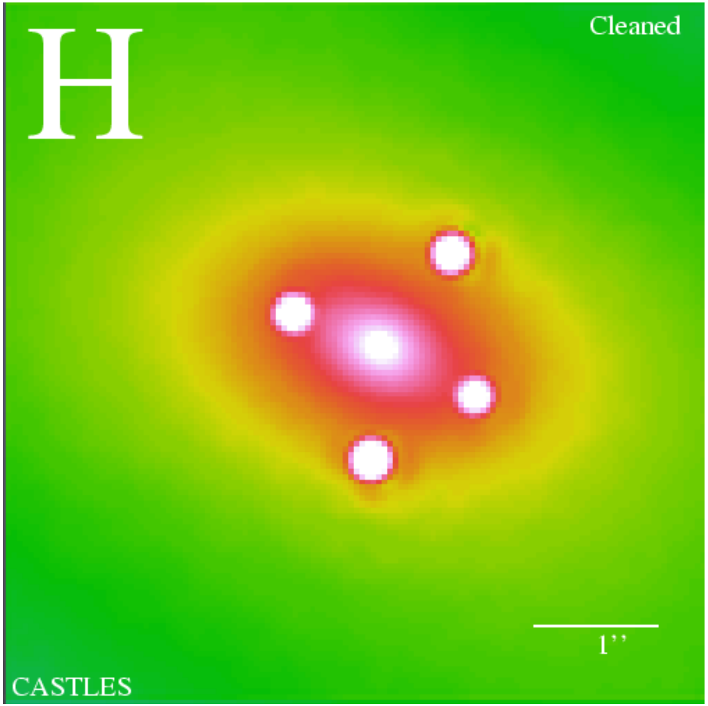
$$\sigma_\epsilon = \sqrt{\left\langle \epsilon^{(\rm s)} \epsilon^{(\rm s)*} \right\rangle} \; .$$

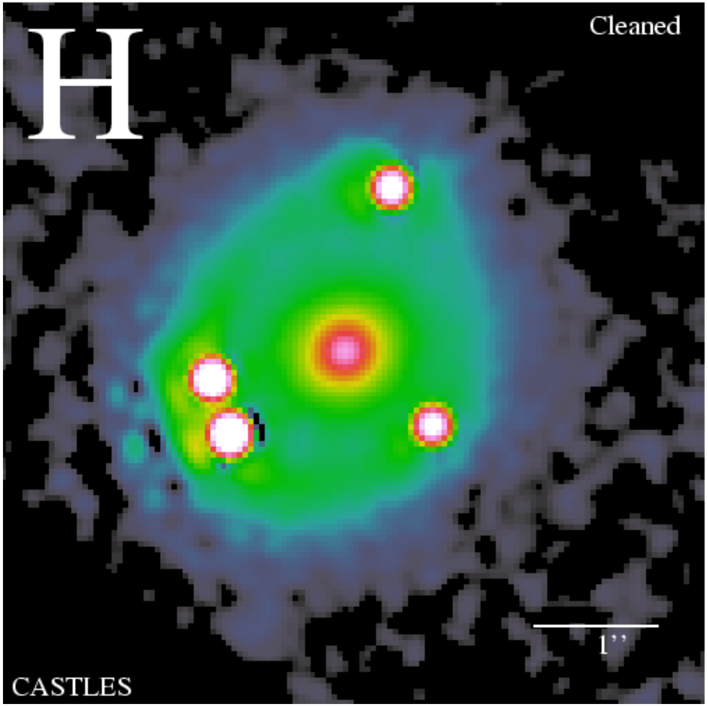


Noise can be beaten down by averaging over many galaxy images;
we live in a Universe where sky is 'full of faint galaxies';
accuracy of shear estimate depends then on local number density of galaxies for which shape can be measured – requires deep imaging observations;
characteristically, on a 3 hour exposure with a 3-meter class telescope, about 30 galaxies per sq. arcmin. can be used for a shape measurement.

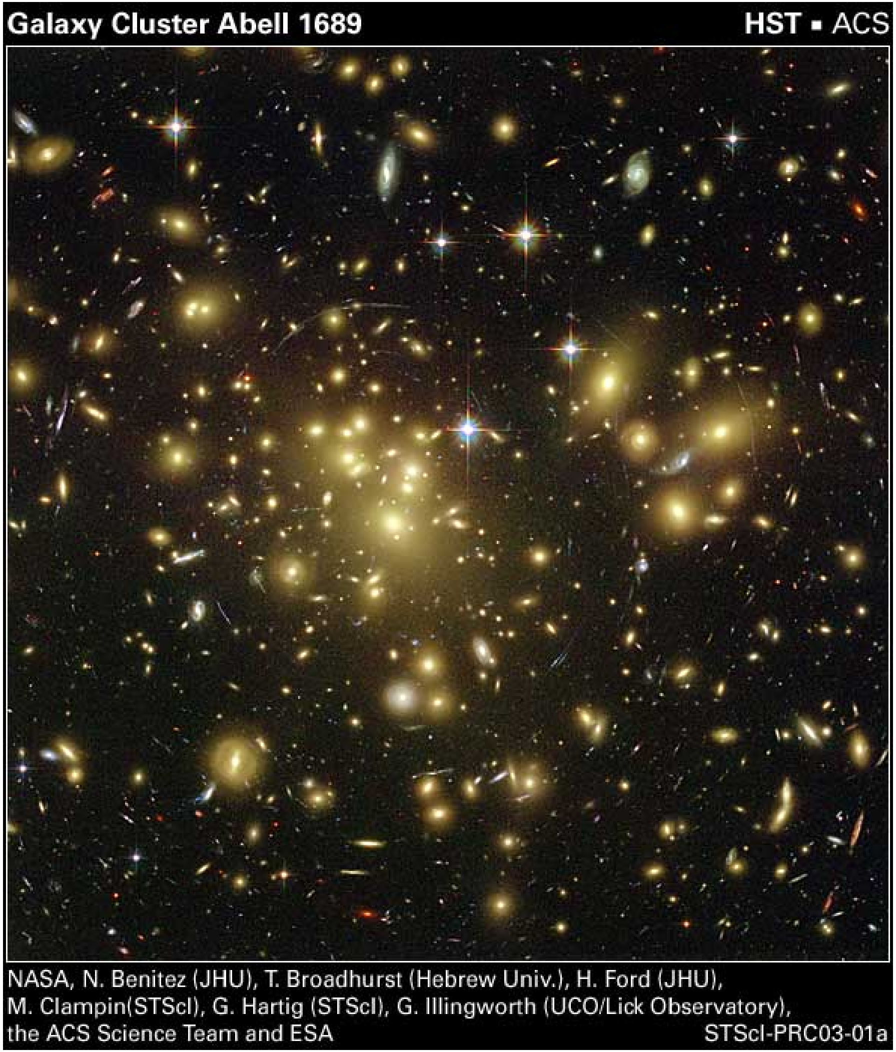
Selected applications

- Mass measurement of galaxies and clusters – often accurate to a few percent





The ‘triple arc’ cluster Cl 0024+17 at $z = 0.39$, with a source at $z_{\mathrm{s}} = 1.67$.



A massive cluster in front of the HUDF-population:
The current star amongst the strong lensing clusters, observed with the ACS onboard HST, which is full of arcs and multiple images, everywhere ....

Galaxy Cluster Abell 1689 Details

Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA ▪ STScI-PRC03-01b

Selected applications

- Mass measurement of galaxies and clusters – often accurate to a few percent
- Existence of giant arcs significantly constrains the dark matter self-interaction cross-section
- arc statistics – does the concordance cosmology yield enough clusters to get observed arc abundance
  (sensitive to early dark energy $\Rightarrow$ M. Doran's talk)
  (more of lensing by clusters $\Rightarrow$ M. Sereno's talk)
- making the dark matter 'visible': direct mapping of the (dark) matter distribution of clusters
- MACHOS, or the nature of DM in our Galaxy ($\Rightarrow$ Ph. Jetzer's talk)
- the substructure problem. Problem?

Substructure, or the flux ratio discrepancy

CDM model predicts that the Milky Way halo contains several hundred subhalos,

BUT

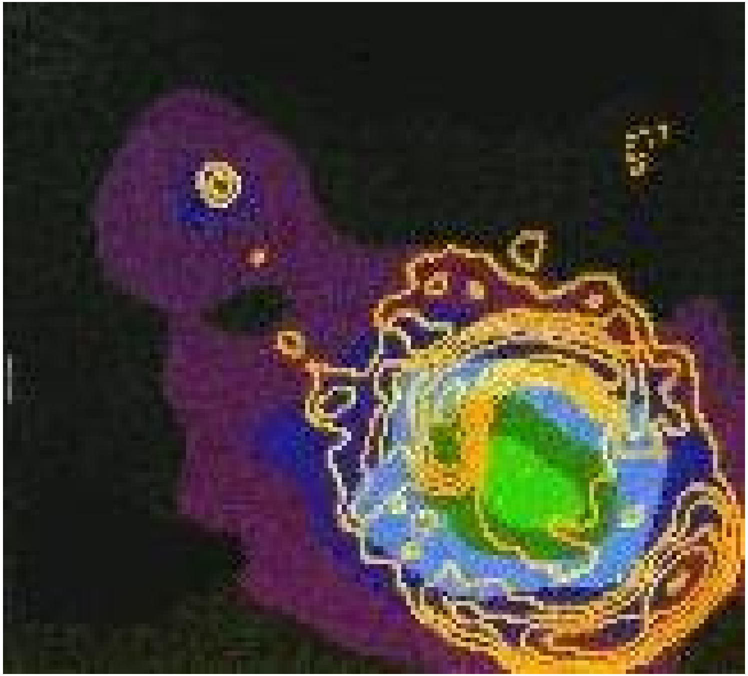
only a dozen satellite galaxies are observed.

The 'SECOND DARK MATTER CRISIS'

Canonical explanation: low-mass halo had suppressed star formation (due to feedback processes), and are therefore mostly dark ($\Rightarrow$ C. Frenk's talk).

But are they really there?

Gravitationally lensed multiple image systems and Einstein rings, with a galaxy acting as (main) deflector, are described by simple mass models;

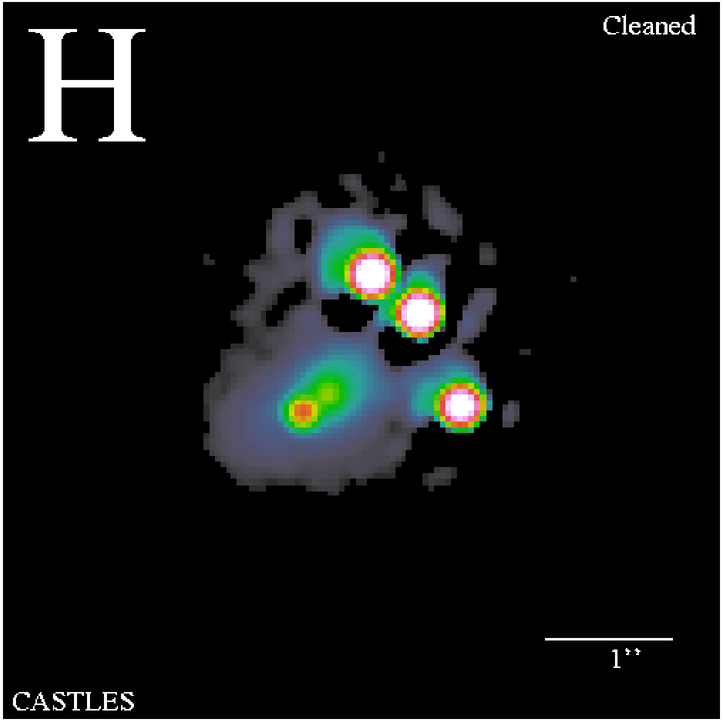


astrometry of images, and detailed brightness distribution of rings, usually very well described by 'simple' mass models;

however, flux ratios in systems with sufficient observational constraints cannot be described by these mass models;

this applies in particular to systems with 4 images.

The first system in which this problem was clearly noted: B1422+231



For example, the quad system B1422+231 has been modeled by several groups in detail;
though observed image positions can be accurately matched (within $\sim 50\,\mu$arcsec), flux ratios cannot!

We are now confident that this is due to substructure in the mass distribution.

N.B.: VLBI images of the four components are extended;
microlensing cannot be a cause for flux mismatch.

Mass substructure can change flux ratios $S_i/S_j = |\mu_i/\mu_j|$,
(nearly) without affecting image positions, unless substructure quite massive.

Effect strongest in highly magnified images.

We can see, it works:

Substructure at work:

the distortion of the ‘triple arc’ by nearby galaxies in the cluster CL0024+17;

the middle arc should have a length being the sum of the two outer ones;

this is strongly violated, owing to the substructure, here visible as the two cluster galaxies near the middle arc.

Mass substructure can change flux ratios (nearly) without affecting image positions, unless substructure quite massive.

Effect strongest in highly magnified images.

Essentially none of the 4-image systems has the 'correct' flux ratios
$\Rightarrow$ substructure is abundant!

Have we disclosed the predicted CDM substructures? Most likely yes!

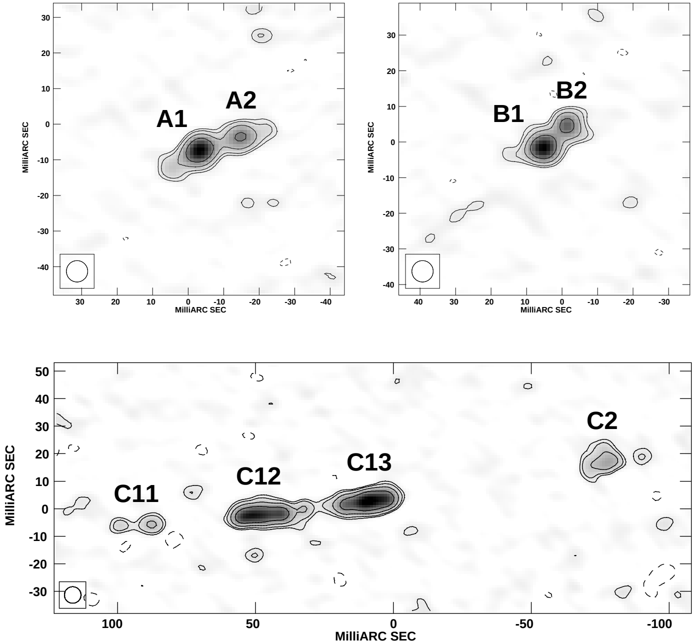
Why CDM sub-halos?

- Predicted by the standard model, i.e. expected to occur
  $\Rightarrow$ Flux mismatches are a prediction of CDM models.

- Lensing properties of CDM-simulated galaxies show very similar flux mismatches – compared to smooth models – as observed quads
  (some controversy about this, though)

- Populating smooth lens galaxies with subhalos according to CDM prediction (mass spectrum $N(M) \propto M^{-1.9}$) yields statistically the same mismatch as observed – again, some controversy about this
- NOTE: could also be low-mass halos somewhere along the line-of-sight; relative importance not yet clear.
- Propagation effects in the ISM (extinction in the optical, scatter broadening, scintillation) can statistically be excluded – since the flux mismatches are correlated with image parities – and the ISM does not know about *that*
- For the upper mass end of sub-halos, i.e. the visible satellites, at least two examples have been optically identified that cause astrometric and photometric perturbations
  $\Rightarrow$ many more with lower mass expected.

Substructure at work:
MG2016+112:



The perturber is in fact identified:

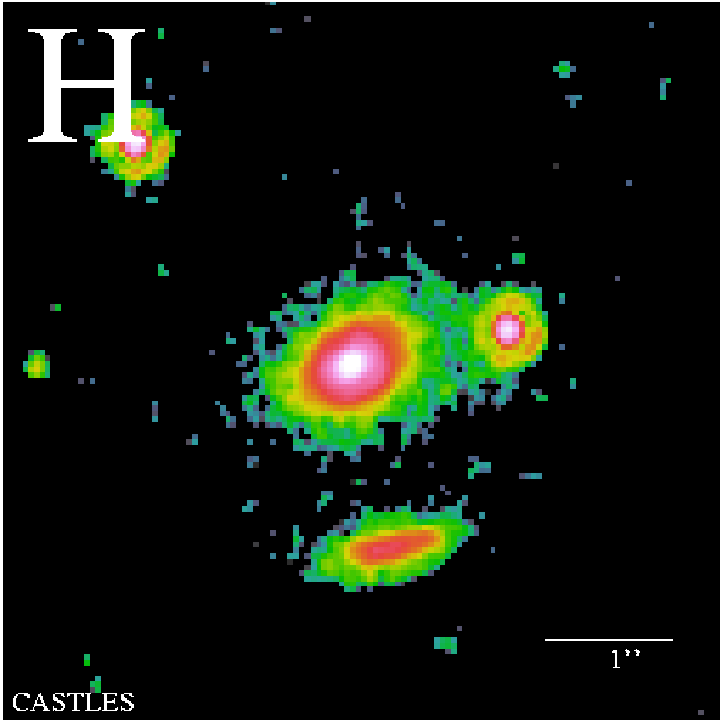


Fig. from Koopmans et al. (2001)

Cosmic shear

Lensing effect of the 3-D matter distribution (the LSS) is described by effective surface mass density $\kappa(\boldsymbol{\theta})$,

$$\kappa(\boldsymbol{\theta}) = \frac{3H_0^2\Omega_\mathrm{m}}{2c^2} \int_0^{w_\mathrm{h}} \mathrm{d}w \; g(w)\, w\, \frac{\delta\left(w\boldsymbol{\theta}, w\right)}{a(w)} \;, \tag{10}$$

with [spatially flat Universe assumed; $a(w) = (1+z)^{-1}$: scale factor]

$$g(w) = \int_w^{w_\mathrm{h}} \mathrm{d}w' \; p_w(w') \frac{w' - w}{w'} \;, \tag{11}$$

depending on the distance distribution $p_w(w)$ of the source galaxies.

Accordingly, power spectrum of κ is

$$P_\kappa(\ell) = \frac{9H_0^4\Omega_\mathrm{m}^2}{4c^4} \int_0^{w_\mathrm{h}} \mathrm{d}w \, \frac{g^2(w)}{a^2(w)} \, P_{\delta\delta}\left(\frac{\ell}{w}, w\right) \;, \tag{12}$$

Where cosmology enters

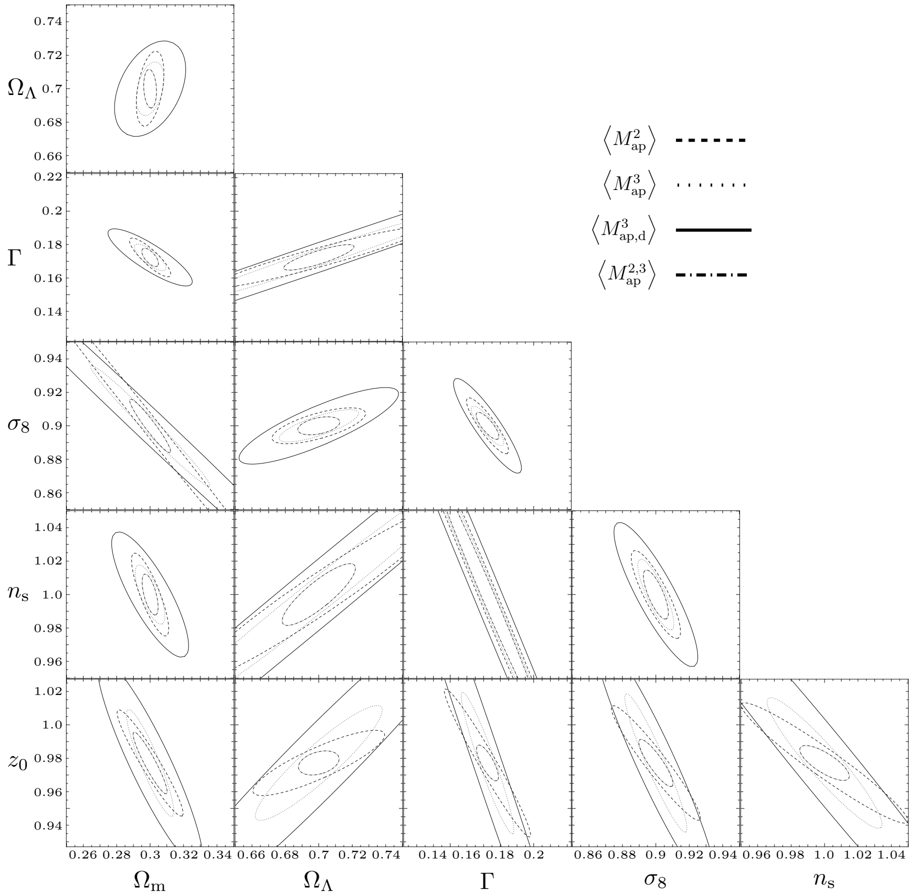
The shear power spectrum depends on cosmology in a number of ways:

- explicitly in the prefactor Ω_{m}^2;
- in the distance-redshift relation – geometrical factors;
- in the 3-D power spectrum P_δ, and its evolution with time.

Hence, measuring second-order shear statistics (such as the shear correlation functions) from wide-field weak lensing surveys, and comparing it to model predictions, allows one to constrain the cosmological parameters.

Also: cosmic magnification statistics (through magnification bias of QSOs or galaxies $\Rightarrow$ R. Scranton's talk)

Higher-order statistics of the shear has different dependence on cosmological quantities – yields very valuable additional information



It is worth to take 3rd-order information into account ....

contours correspond to a $29\,\mathrm{deg}^2$ survey

hidden parameters are kept constant

from a Fisher-matrix consideration; Kilbinger & Schneider (2005)

Power spectrum (and higher-order statistics) is measured from n-point correlation function of galaxy ellipticities
(or weak lensing of the CMB $\Rightarrow$ V. Acquaviva's talk)

pretty straight-forward (well, leaving technicalities aside for a second ...)

Let's see:

- Where are we now?
- Why do we move on?
- Where do we go from here?

Where are we now?

Cosmic shear measured by several independent groups since 2000!
Their results broadly agree.
First cosmological constraints derived, e.g.:

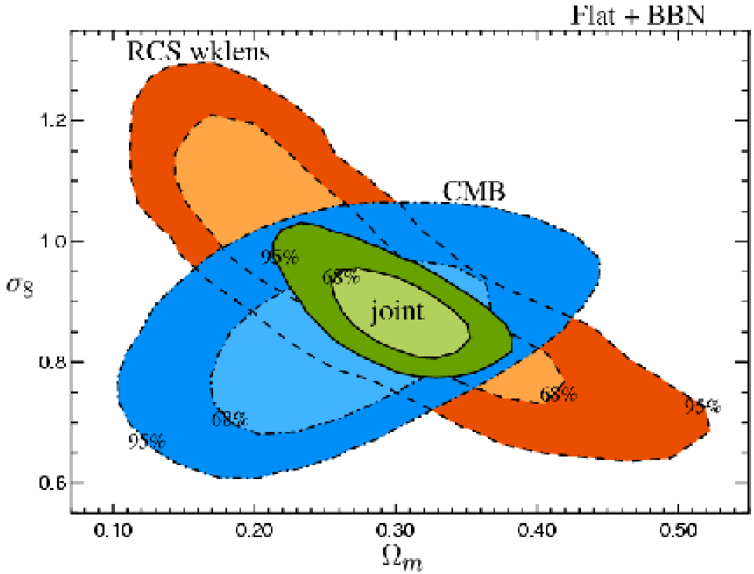
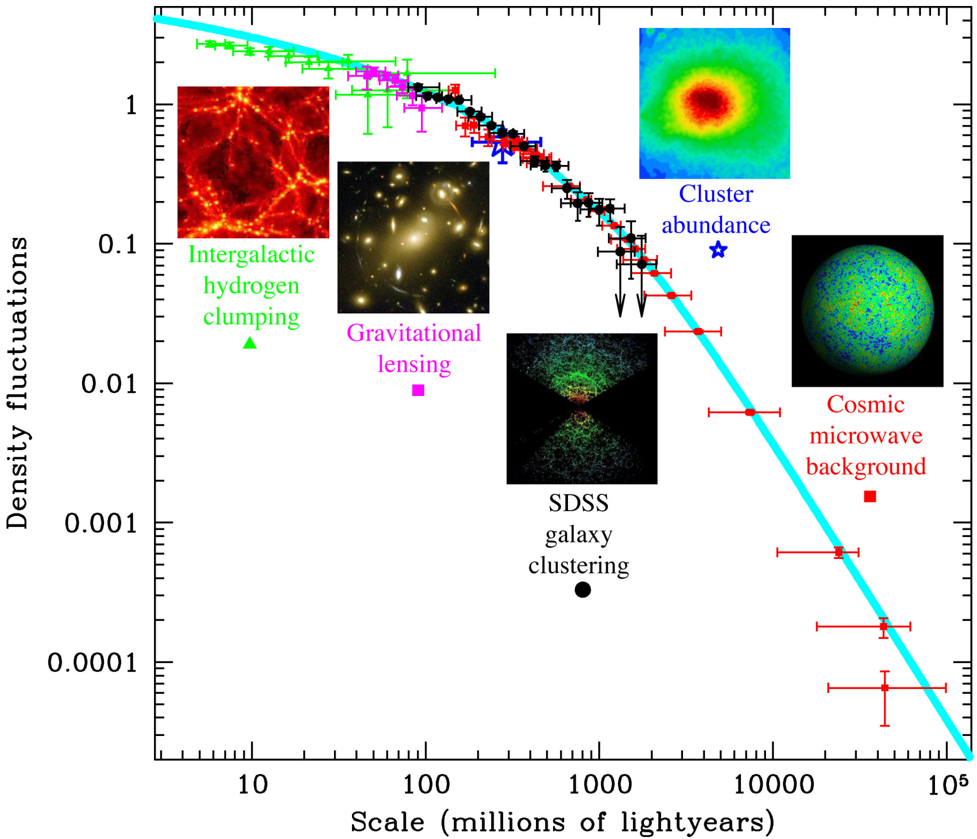


Fig. from Contaldi et al. (2003) shows joint constraints on $\Omega_\mathrm{m} - \sigma_8$ plane from CMB and cosmic shear.

Where are we now?

Cosmic shear measured by several groups since 2000!
State-of-the-art is like this:

- Deep ground-based surveys over $\sim 10\,\mathrm{deg}^2$,
  with $n \sim 25\,\mathrm{arcmin}^{-2}$; $\langle z_{\mathrm{s}} \rangle \sim 0.9$
  soon to be pushed to $\sim 160\,\mathrm{deg}^2$ (CFHTLS);
- Shallow ground-based surveys over $\sim 100\,\mathrm{deg}^2$,
  with $n \sim 12\,\mathrm{arcmin}^{-2}$; $\langle z_{\mathrm{s}} \rangle \sim 0.5$
  soon to be pushed to $\sim 1600\,\mathrm{deg}^2$ (KIDS);
- Space-based surveys over $\lesssim 1\,\mathrm{deg}^2$, with $n \sim 60\,\mathrm{arcmin}^{-2}$; $\langle z_{\mathrm{s}} \rangle \sim 1.2$??



Cosmic shear already now provides important small-scale constraints on power spectrum; arguably, more robust (no gas physics) than Lyα forest

another powerful check on CDM cosmogony!

Why do we move on?

Cosmic shear is seen as equally 'clean probe' of cosmology as is the CMB – because we think we can make very accurate predictions

(gas physics mostly irrelevant, DM-distribution predictable via simulations)

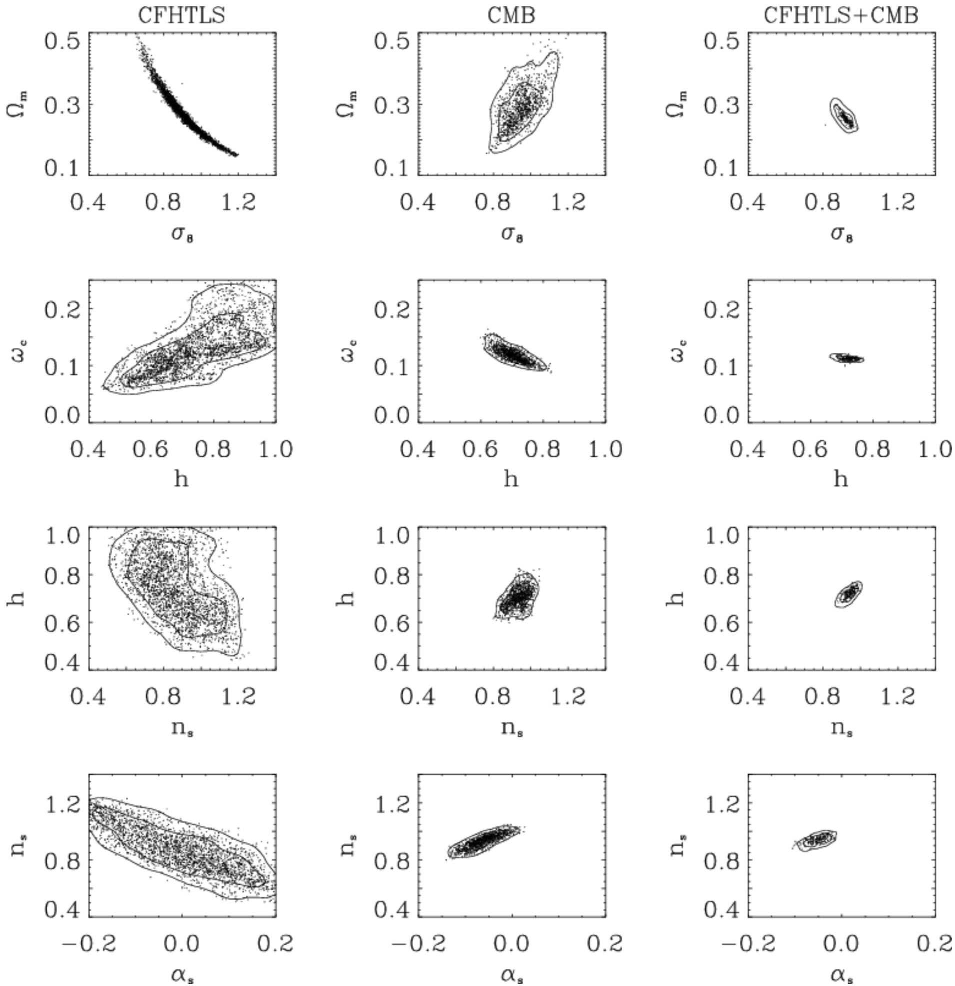
it probes DM-distribution at small redshifts, is sensitive to the structure growth, thus to density and e.o.s. of DE

geometrical effects (distance-redshift relation) can be cleanly separated from structure growth
$\Rightarrow$ internal consistency check; probe of gravity on large scales; also, DE-constraints independent of CDM model – purely geometrically!

cosmic shear complementary to CMB;
also complementary to SN Ia and, arguably, 'cleaner'

Where do we go from here?

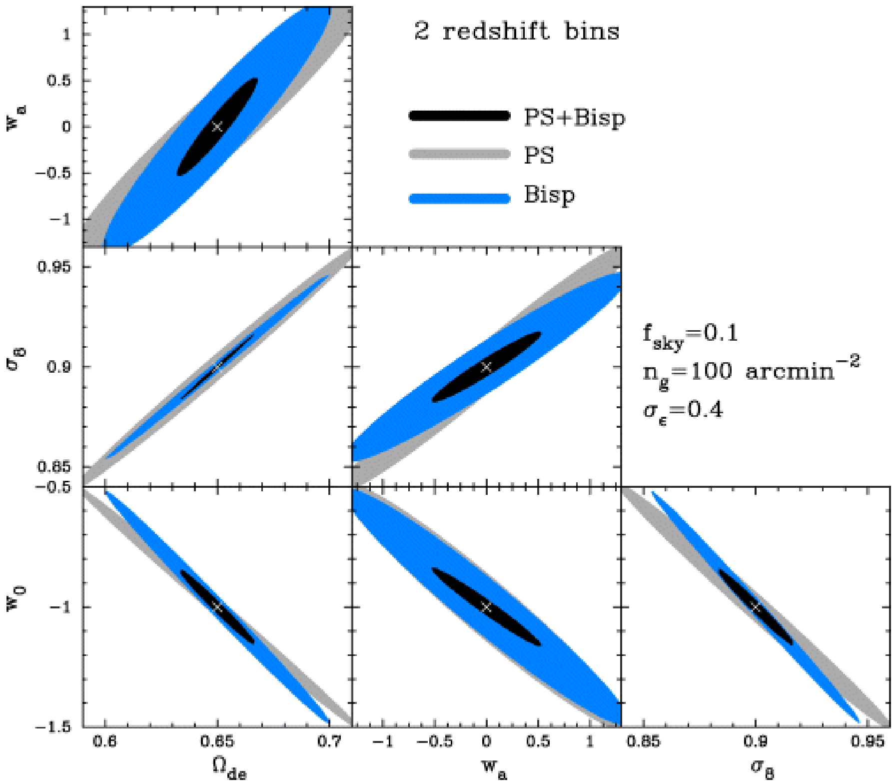
- Second-generation surveys (CFHTLS, KIDS) will tighten parameters substantially;



cosmic shear from CFHTLS plus CMB (WMPA) yields much tighter constraints than CMB alone
from Tereno et al. (2005)

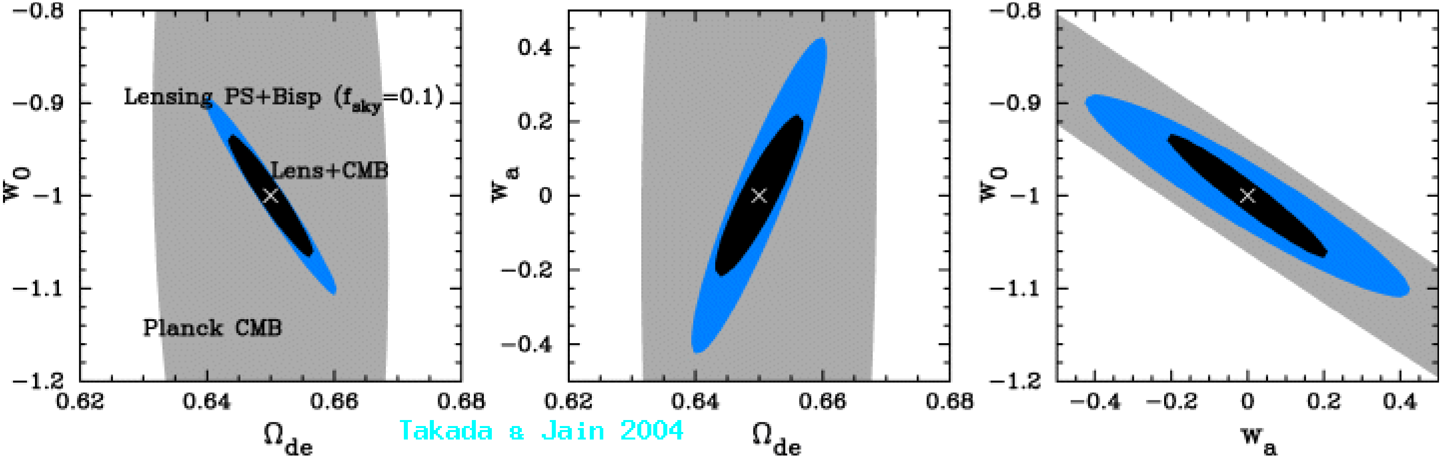
Where do we go from here?

- Second-generation surveys (CFHTLS, KIDS) will tighten parameters substantially;
- together with 2.5-generation surveys (Pan-STARRS, DarkCam@VISTA?), they will consolidate and refine techniques, identify and solve practical problems, to then move to
- third-generation surveys:
  - LSST, the 'ultimate ground-based astronomical imaging machine' ($\sim 20000\,\mathrm{deg}^2$, with $n \sim 30\,\mathrm{arcmin}^{-2}$; $\langle z_\mathrm{s} \rangle \sim 1.0$)
  - A dedicated weak lensing (plus SN Ia) satellite, such as SNAP/JDEM or DUNE ($\sim 5000\,\mathrm{deg}^2$, with $n \sim 100\,\mathrm{arcmin}^{-2}$; $\langle z_\mathrm{s} \rangle \sim 1.5$)



Expectations from a JDEM/SNAP-like survey; including 2nd and 3rd-order shear, redshift information from Takada & Jain (2004)

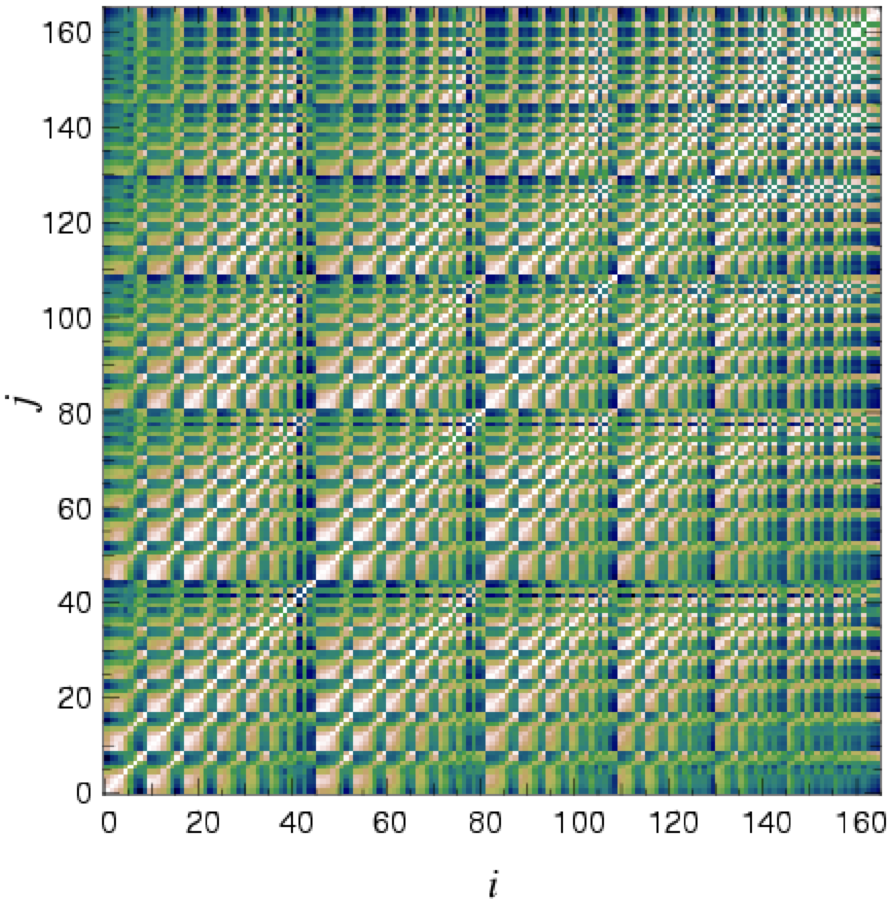
Cosmic shear is one of the few and perhaps most promising methods to constrain the equation-of-state of dark energy.



Combining a JDEM/SNAP-like survey with CMB yields very tight constraints on DE parameter

Obstacles

- Convince funding agencies!
- Unbiased shear estimates from CCD-images of galaxies (PSF, bad pixels, CR, optical distortions, pixelization).
- Data rate and data volume (e.g., KIDS will have $\sim 100\,$TB of raw data)
- Data analysis will pose new challenges, e.g., inverting covariance matrices.



Covariance matrix for a truly modest cosmic shear experiment, including third-order shear statistics;
determined from ray-tracing simulations of T. Hamana, by patch-to-patch variance;
from Kilbinger & Schneider (2005)

Obstacles

- Convince funding agencies!
- Unbiased shear estimates from CCD-images of galaxies (PSF, bad pixels, CR, optical distortions, pixelization).
- Data rate and data volume.
- Data analysis will pose new challenges, e.g., inverting covariance matrices.
- Accurate (photometric) redshift estimates – the bias must be less that $\Delta z \sim 0.003$ to not seriously compromise parameter determination.
- Accuracy of theoretical estimates – soon, sample variance of surveys will be smaller than 'simulation variance'!

Obstacles and salvations

- Convince funding agencies!
  Partly done! DOE seems to be determined to start a Joint Dark Energy Mission (JDEM); a DUNE concept is part of ESA's Cosmic Vision 2015–1025, and first studies have begun in France.

- Unbiased shear estimates from CCD-images of galaxies (PSF, bad pixels, CR, optical distortions, pixelization).
  A worldwide Shear TEsting Program has shown via blind tests that already now, $\sim 2\%$ accuracy is achieved. Directions of further improvements after the first STEP are identified.

- Data rate and data volume.
  Yes, but most likely no serious problem ten years from now.

- Data analysis will pose new challenges, e.g., inverting covariance matrices. CMB community overcame such problems; once the weak lensing community becomes sizeable, they will as well – already now tools from CMB analysis are used – though they are harder (non-Gaussian!).

- Accurate (photometric) redshift estimates – the bias must be less that $\Delta z \sim 0.003$ to not seriously compromise parameter determination. Time to learn – by then, JWST will provide spectroscopic redshifts for small subsets, to train phot-z programs; also self-calibration from n-th order cosmic shear statistics.

- Accuracy of theoretical estimates – soon, sample variance of surveys will be smaller than 'simulation variance'! Apparently a real problem, but how many Millennium Simulations can be done per day in 2015?!? A simulation factory will be set up, most likely.