Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Weak Lensing

Adam Amara

Outline

1. General Introduction
2. Gravitational Lensing Basics
3. Overview of Euclid
4. Technical Challenges

Concordance Cosmology

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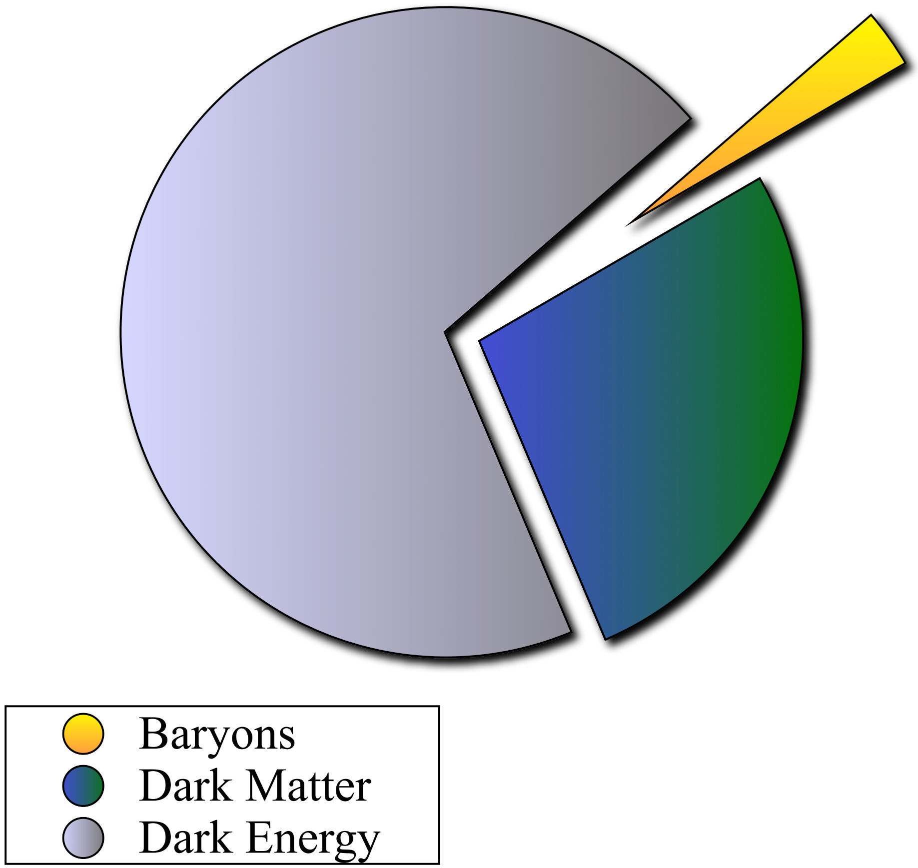

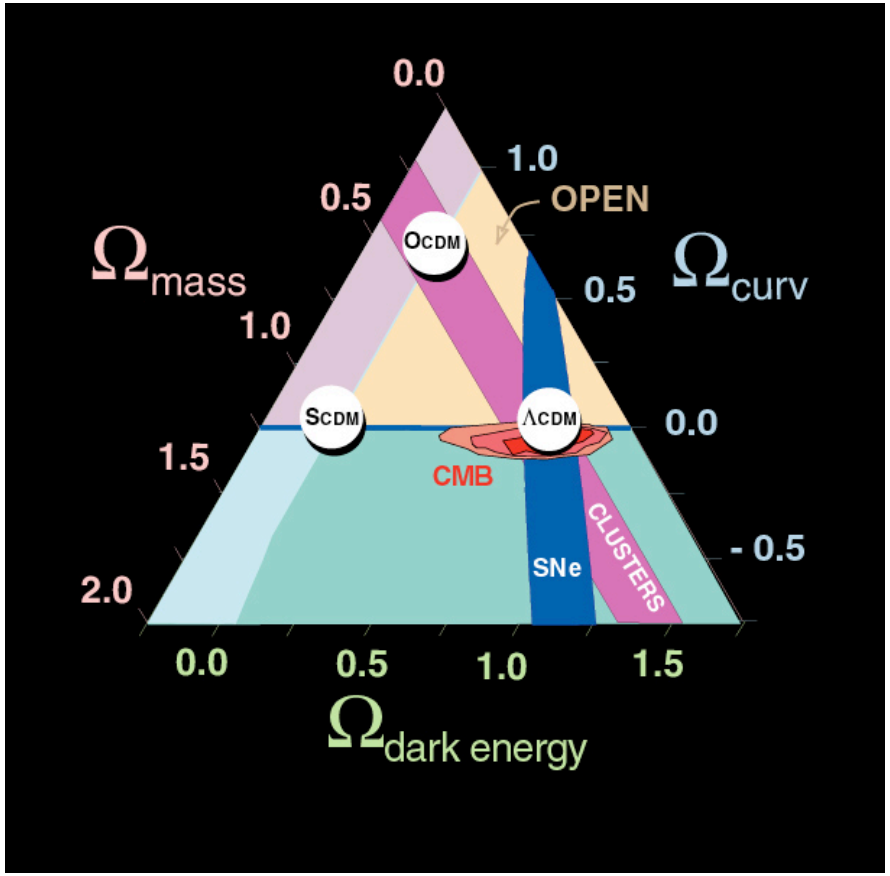

Sectors of Concordance Model:

(i) Dark Energy, (ii) Dark Matter, (iii) Gravity and (iv) Initial Conditions

Dark Energy Sector

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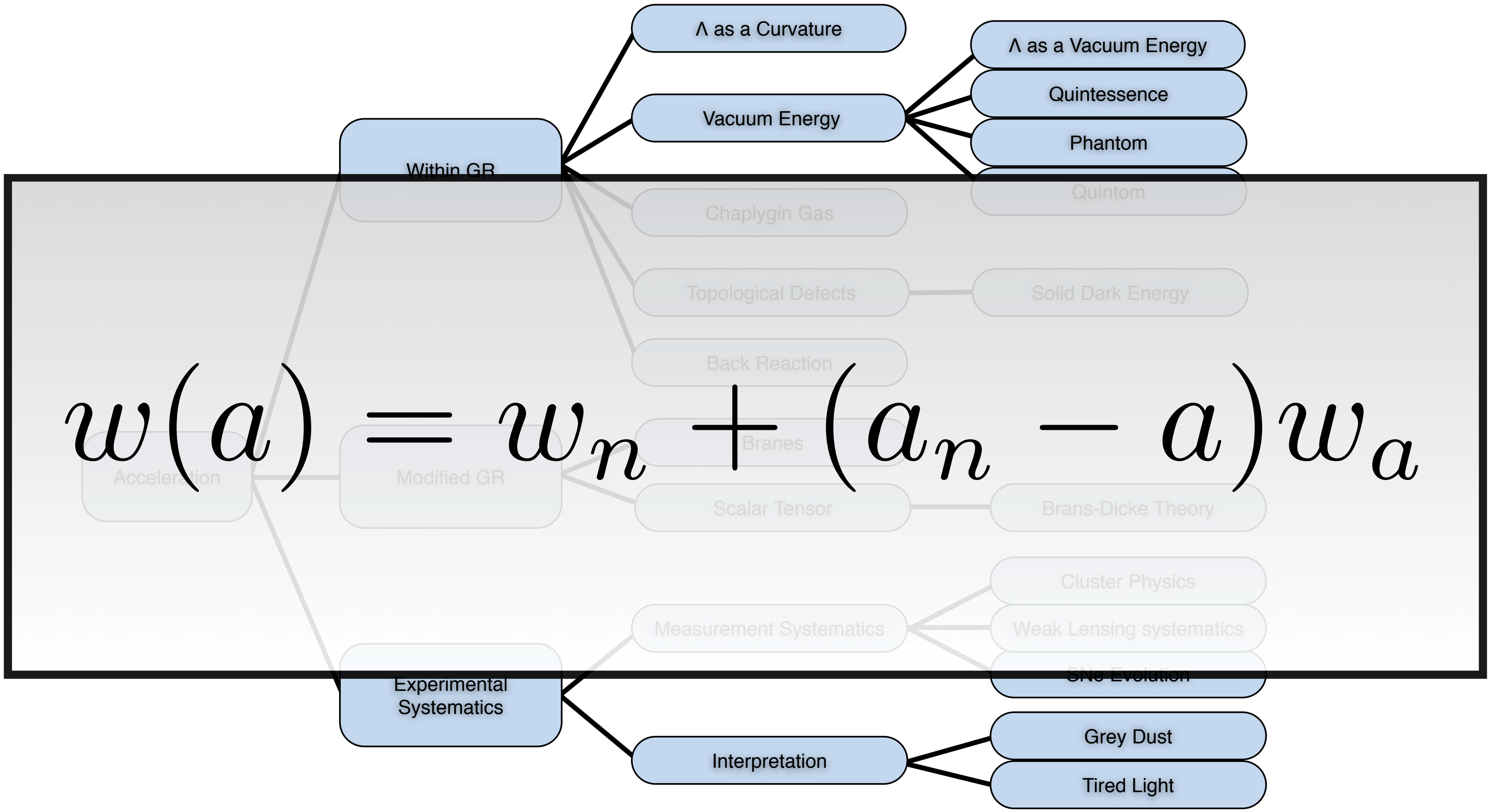

$$w(a) = w_n + (a_n - a)w_a$$

Two effects: Background and structure growth

Relevant Equation for DE

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Dark Energy
Equation of State

$$w \equiv P/\rho c^2$$

Geometry:

$$H^2(a) = H_0^2 \left[\Omega_{\rm v} e^{\int -3[w(a)+1]\, {\rm d}\ln a} + \Omega_{\rm m} a^{-3} + \Omega_r a^{-4} - (\Omega_{\rm total} - 1) a^{-2}\right]$$

$$D(z) = \int_0^z \frac{c}{H(z')} {\rm d}z'$$

Growth of
Structure:

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = \delta\left(4\pi G \rho_{\rm m} - c_s^2 k^2 / a^2\right)$$

ESA/ESO WGFC: astro-ph-0610906

Modified Gravity

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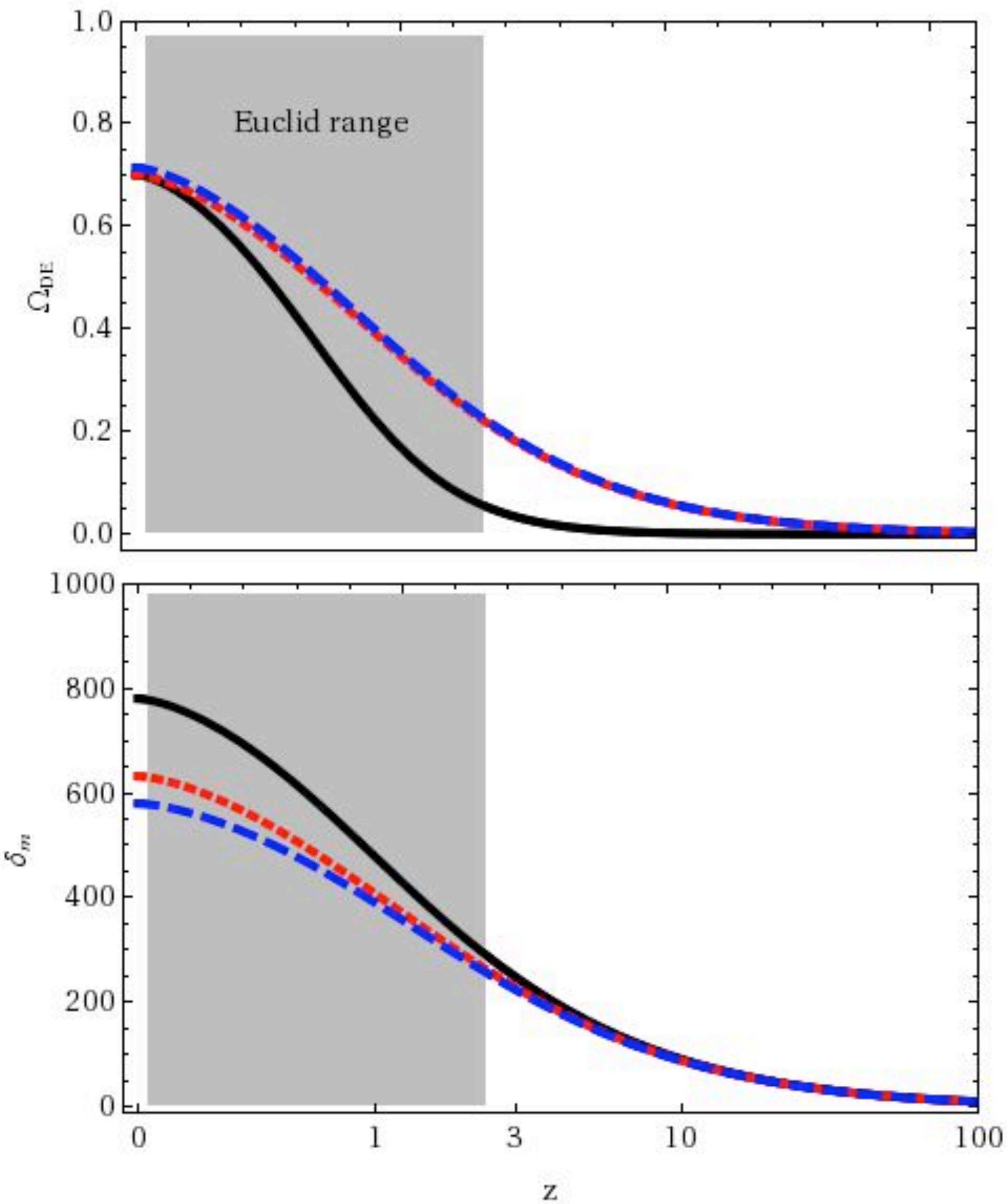
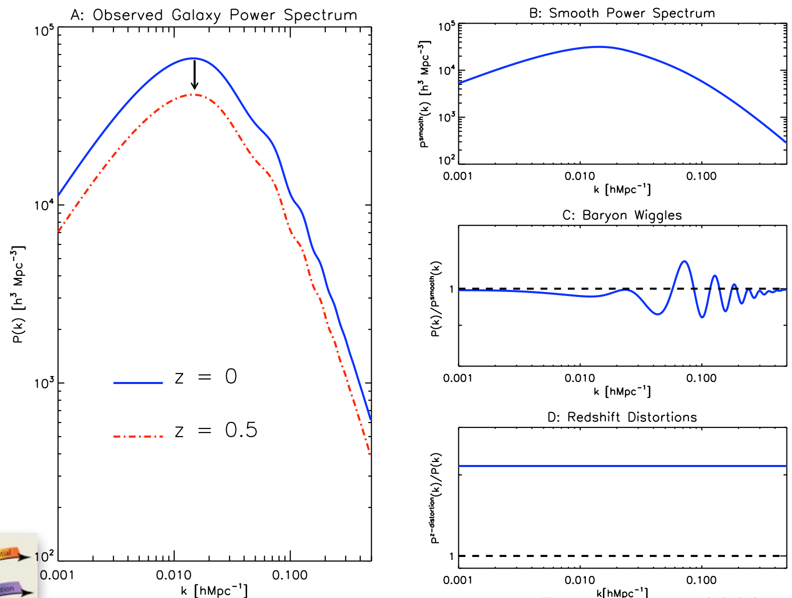
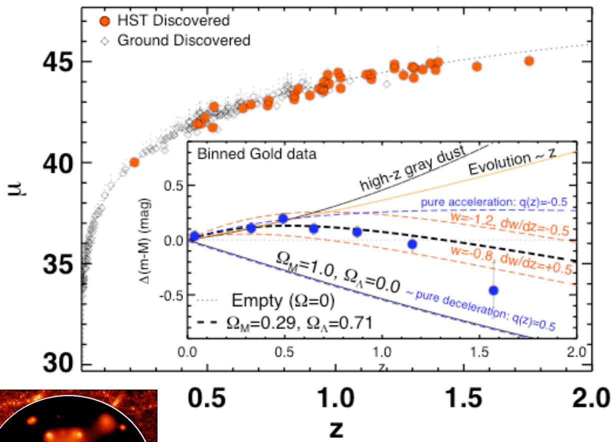


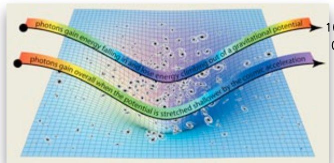
Dark Energy Probes

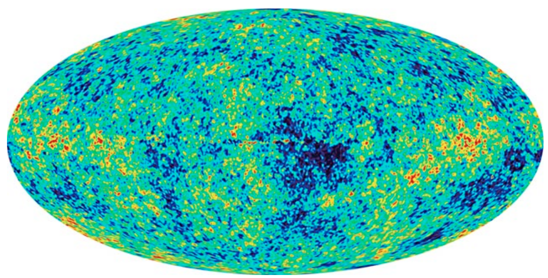
- Measurements of Dark Energy:
  - Weak Lensing
  - Galaxy correlations (inc BAOs)
  - Supernovae
  - Galaxy Clusters
  - ISW
- Each probe suffers from different systematics

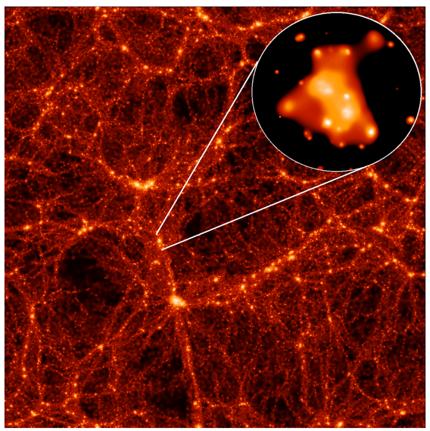


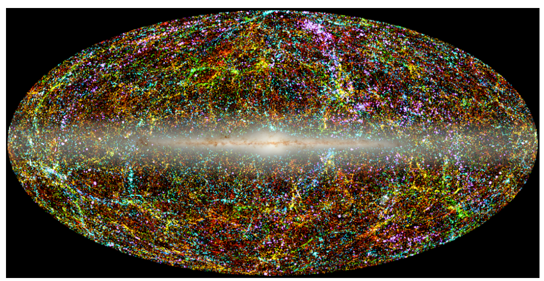
Rassat et al, 2008

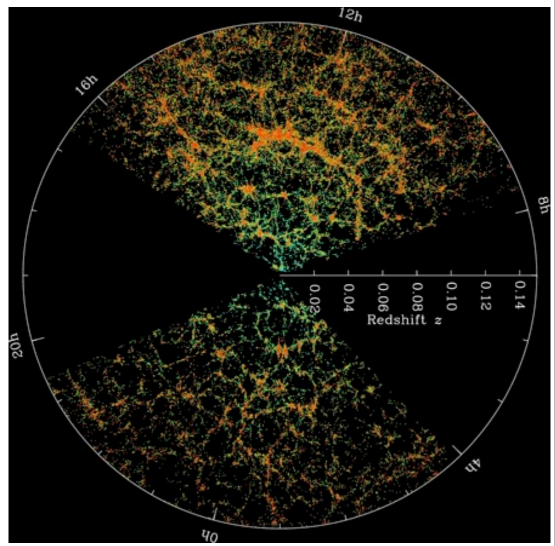












iCosmo:
cosmology for every level

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- Repository of web-based resources for cosmology:
  - www.icosmo.org
- Background material on several topics in cosmology
  - (wikipages so still growing)
- Web based cosmology calculations
  - (very easy to use)
- Publicly available source code
  - (transparent box - i.e. opposite of black box)

Gravitational Lensing

Weak Lensing

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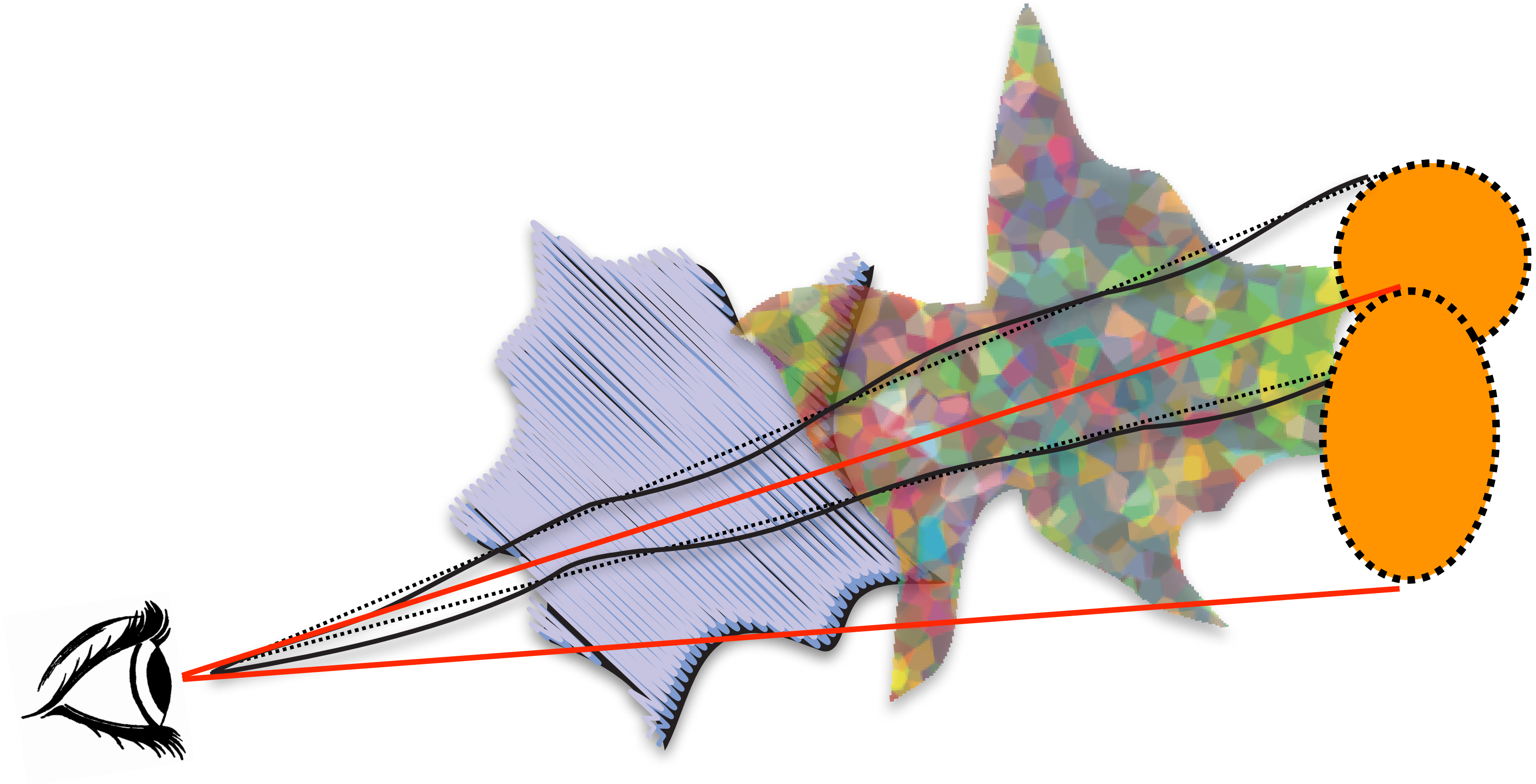

http://icosmo.org

Ray Shooting in Lensing

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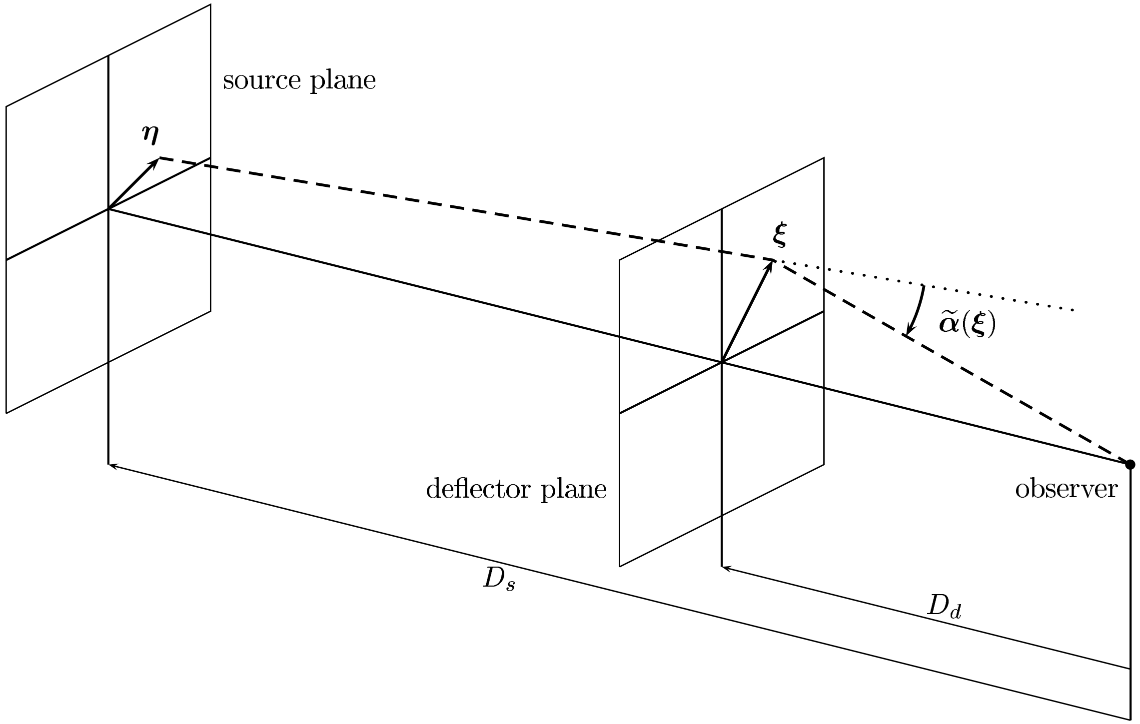
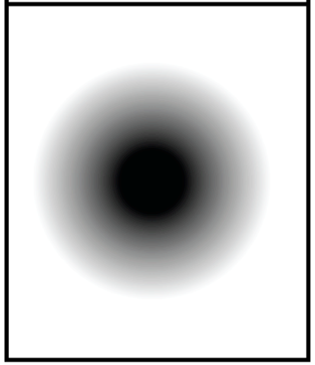
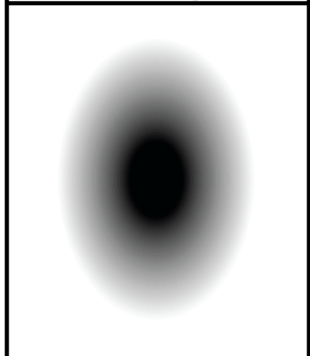
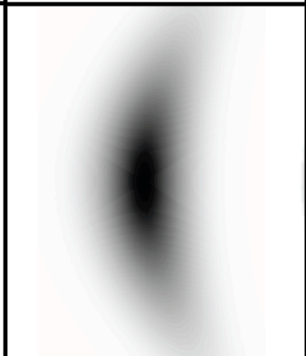
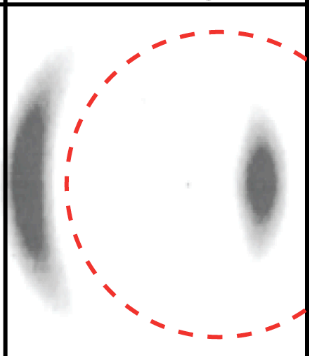
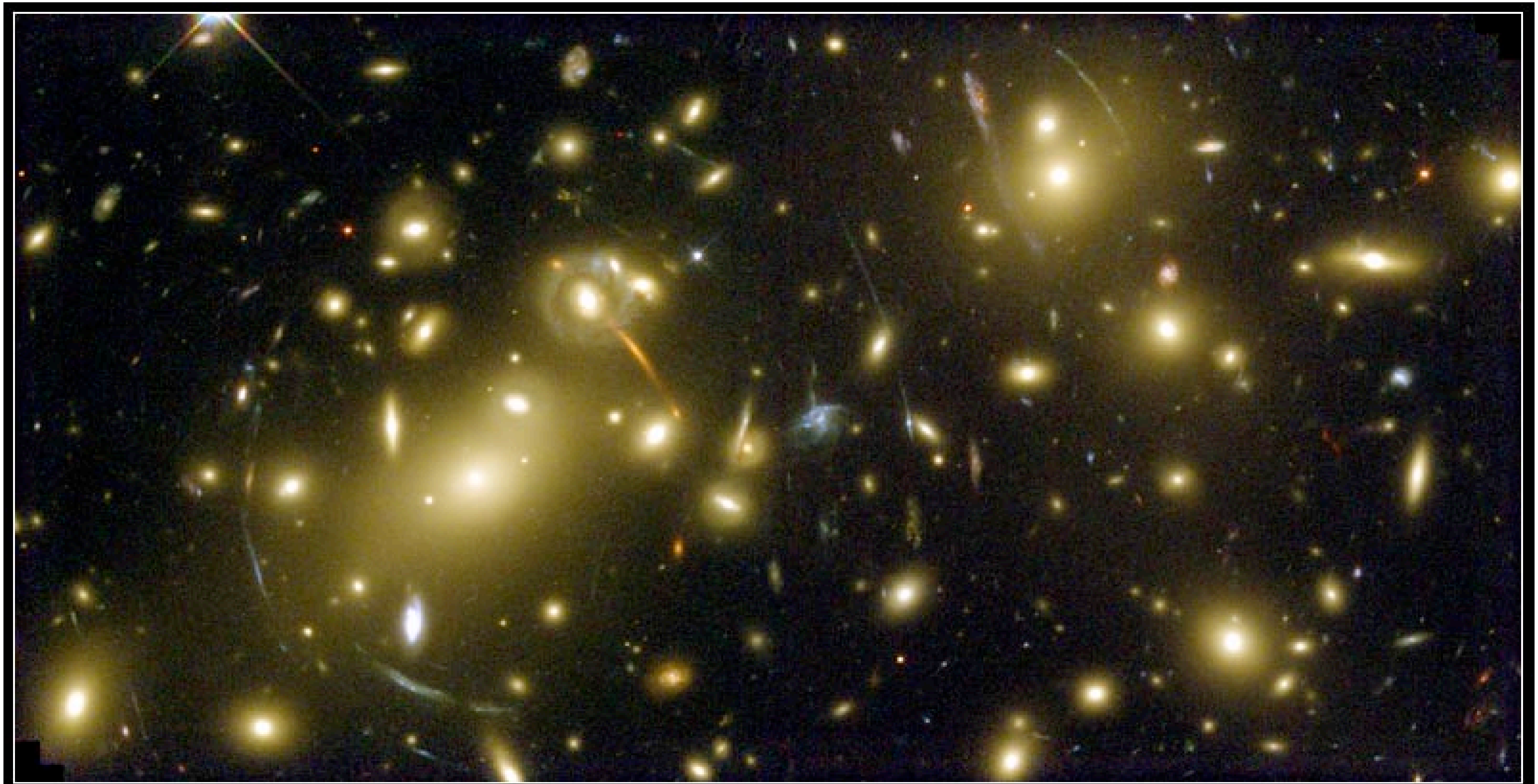


No lensing	Weak lensing	Flexion	Strong lensing
			
	Large-scale structure	Substructure, outskirts of halos	Cluster and galaxy cores

Lensing examples: Giant Arcs



Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Lensing examples: Einstein Rings

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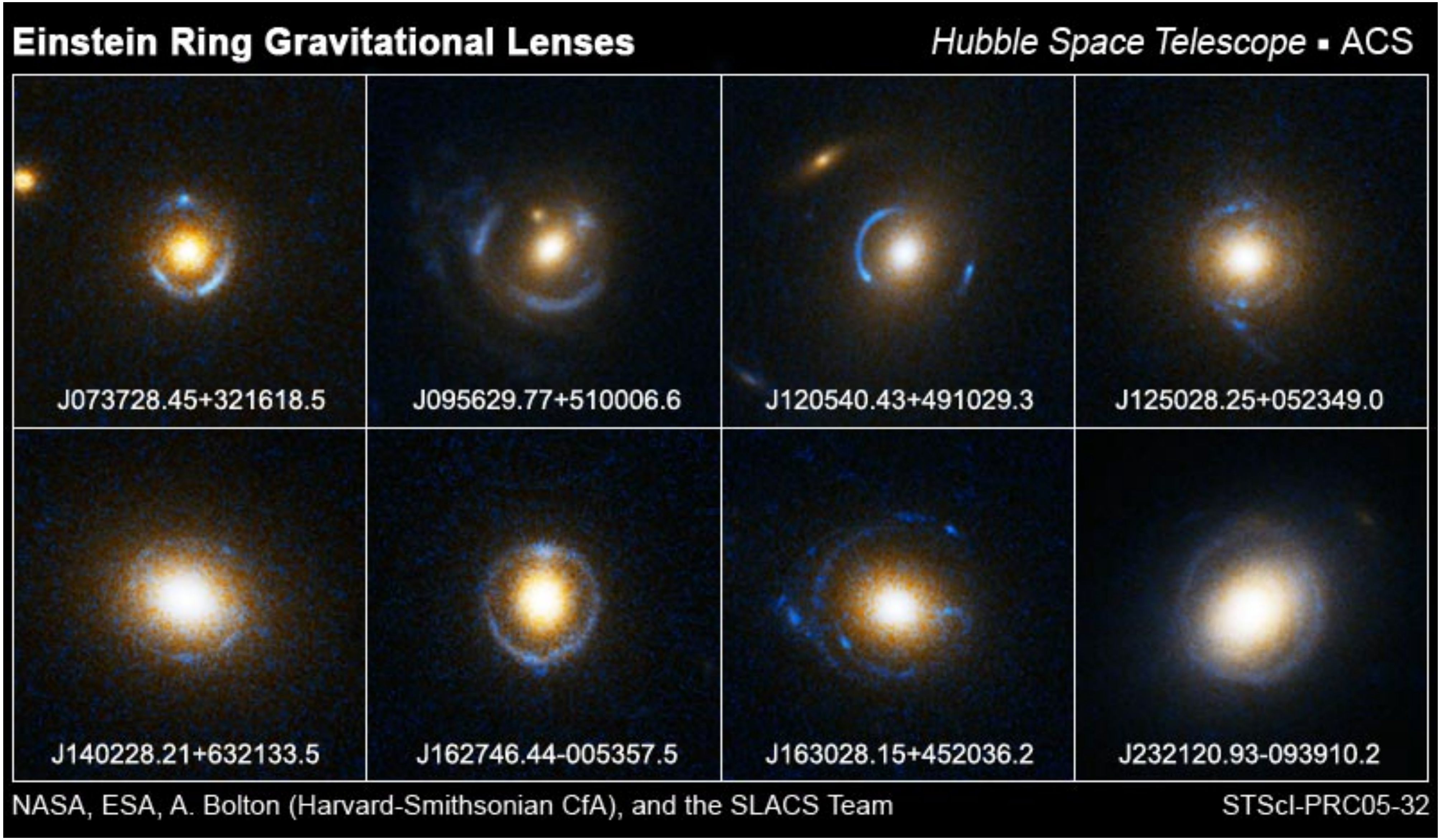

Lensing Geometry

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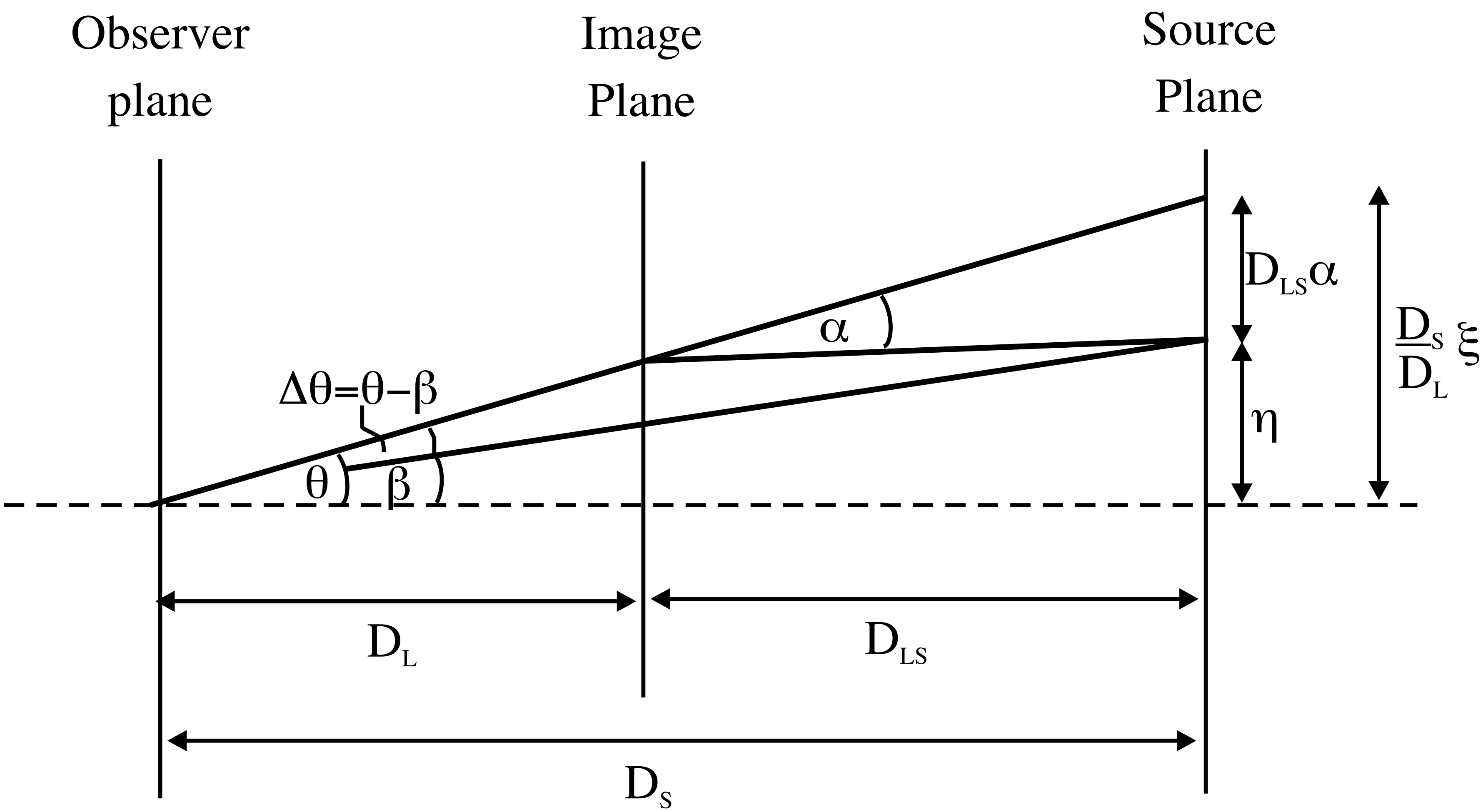

Equations in Lensing

Time Delay	$t(\vec{\theta}) \propto \left[\frac{(\Delta\theta(\vec{\theta}))^2}{2} - \psi(\vec{\theta})\right]$
Deflection Angle	$\overrightarrow{\Delta\theta}(\vec{\theta}) = \nabla\psi(\vec{\theta})$
Convergence	$\kappa(\vec{\theta}) = \frac{1}{2}\left(\frac{\partial^2\psi}{\partial\theta_i^2} + \frac{\partial^2\psi}{\partial\theta_j^2}\right)$
Components of Shear ($\gamma = \gamma_1 + i\gamma_2$)	$\gamma_1(\vec{\theta}) = \frac{1}{2}\left(\frac{\partial^2\psi}{\partial\theta_i^2} - \frac{\partial^2\psi}{\partial\theta_j^2}\right)$
	$\gamma_2(\vec{\theta}) = \left(\frac{\partial^2\psi}{\partial\theta_i\partial\theta_j}\right)$
Magnification	$\mu = \frac{1}{(1-\kappa)^2 - \lvert\gamma\rvert^2}$

Weak Lensing Correlations and Mass Reconstruction

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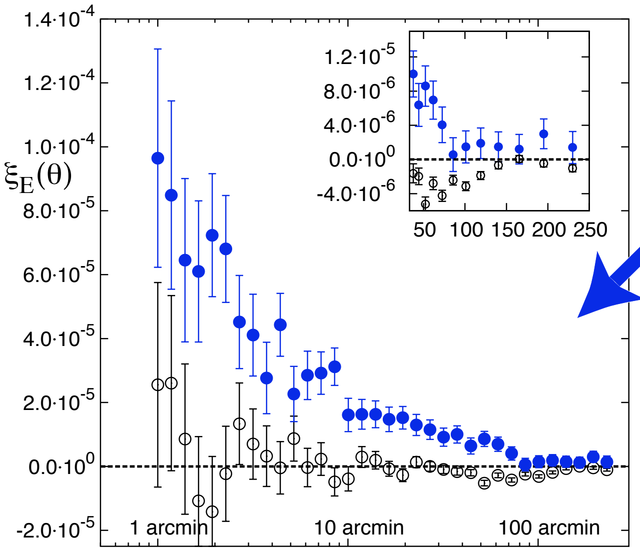
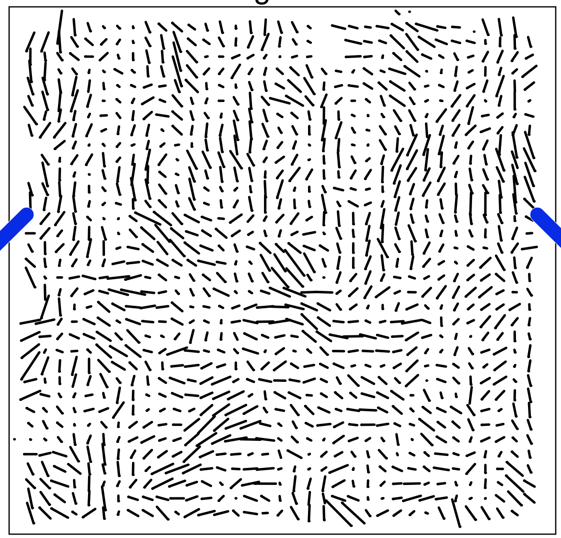
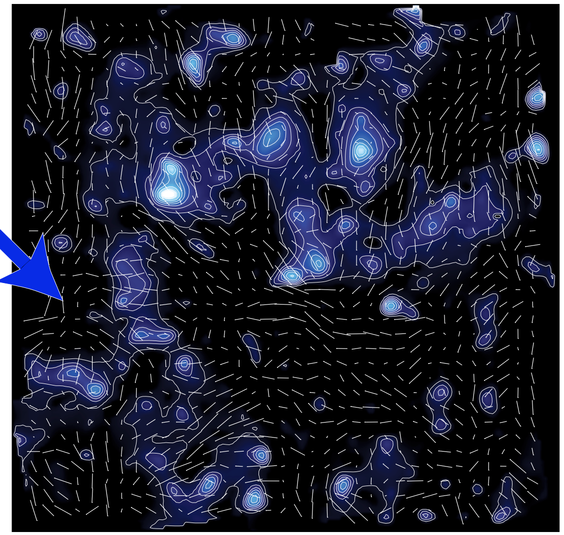


Correlation function

Raw lensing measurement





Dark matter distribution

Fu et al 2005

Massey et al 2007

Dark Matter

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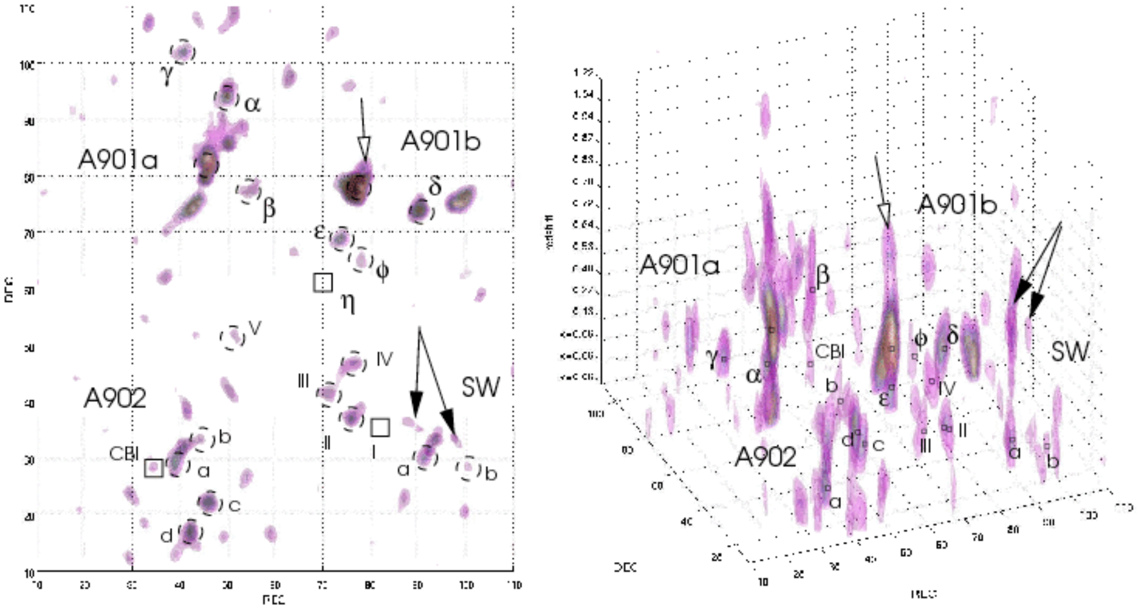
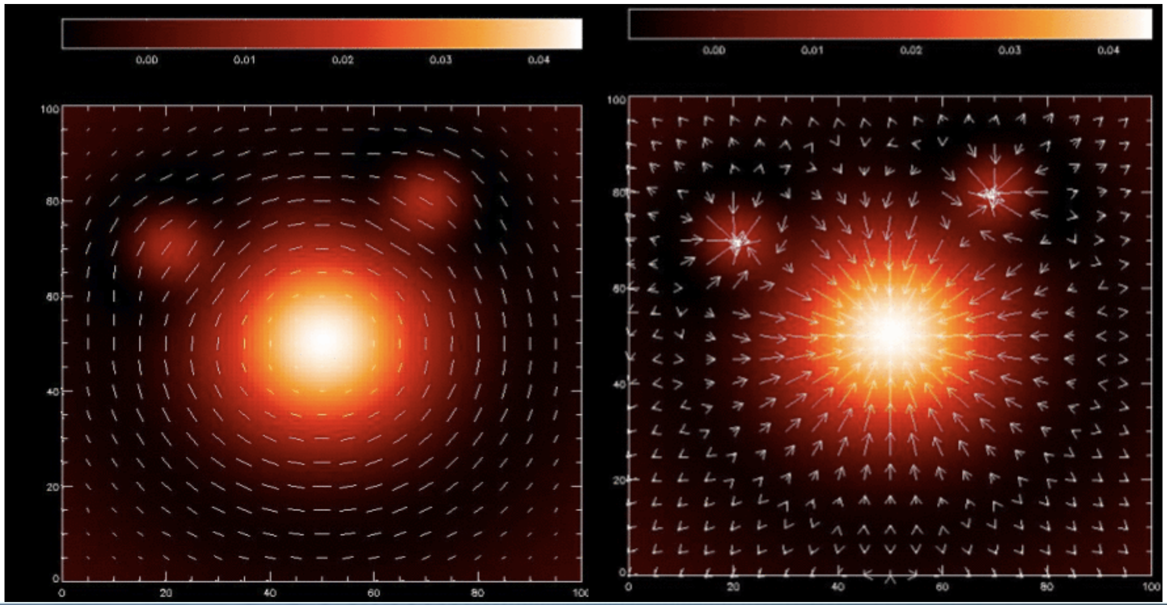
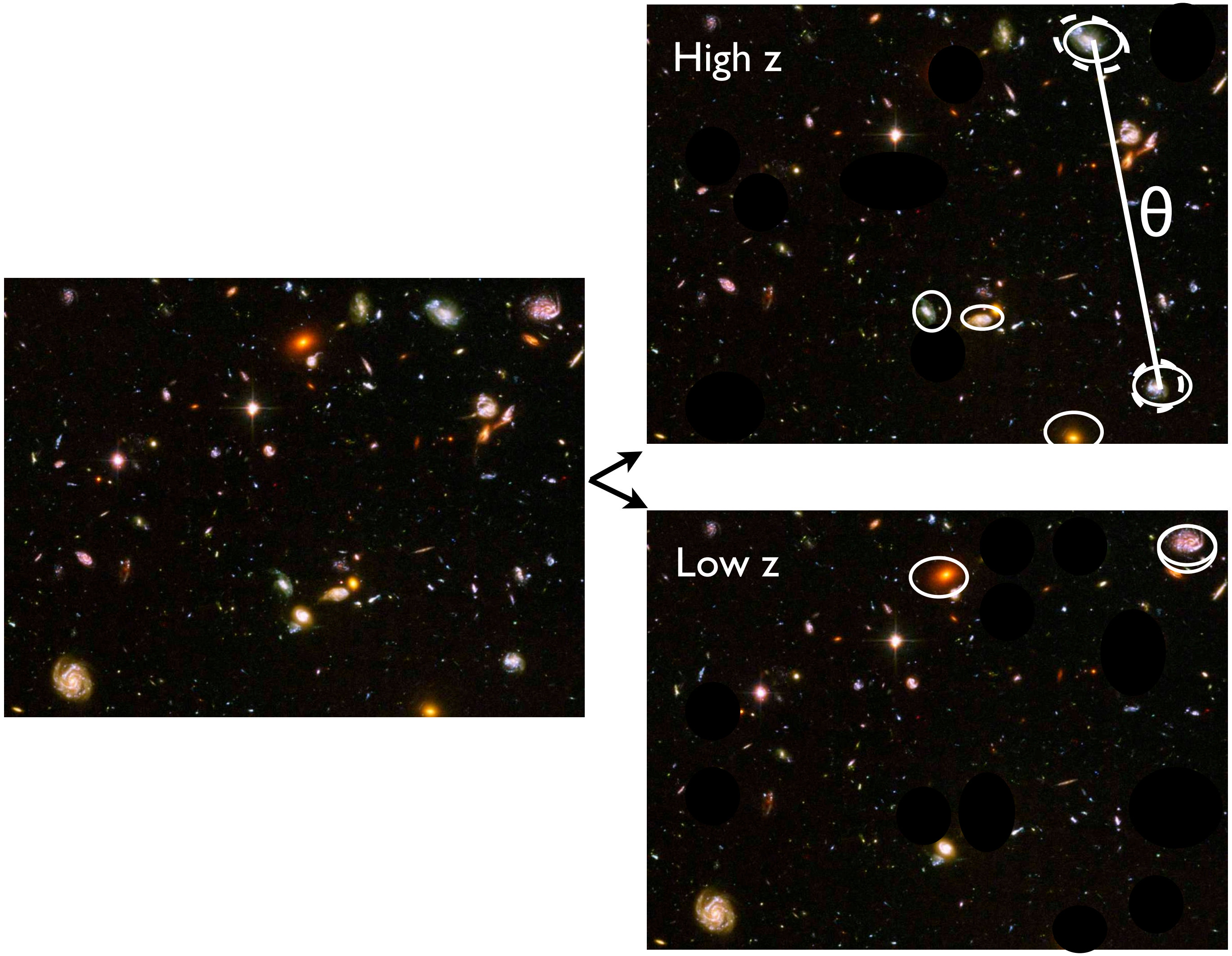


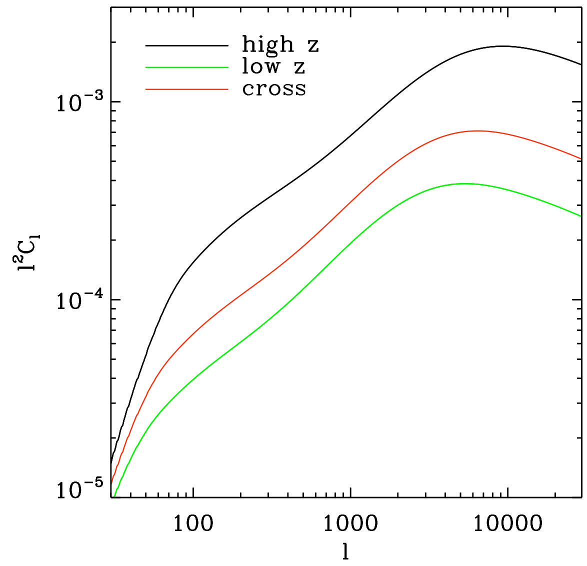
Simon et al 2009



Bacon et al 2005

Lensing Tomography





$l \sim 1/\theta$

Lensing Equations

Lensing Correlation Function:

$$C_{\ell(ij)}^{GG} = \int_0^\infty \frac{q_i(\chi) q_j(\chi)}{\chi^2} P_\delta(k; \chi) d\chi$$

Lensing Weight Function:

$$q_i(\chi_d) = \frac{3}{2} \Omega_m \frac{H_0^2}{c^2} (1 + z_d) \int_0^\infty n_i(\chi_s) \frac{(\chi_s - \chi_d)\chi_d}{\chi_s} d\chi_s$$

Bridle and King: arXiv:0705.0166

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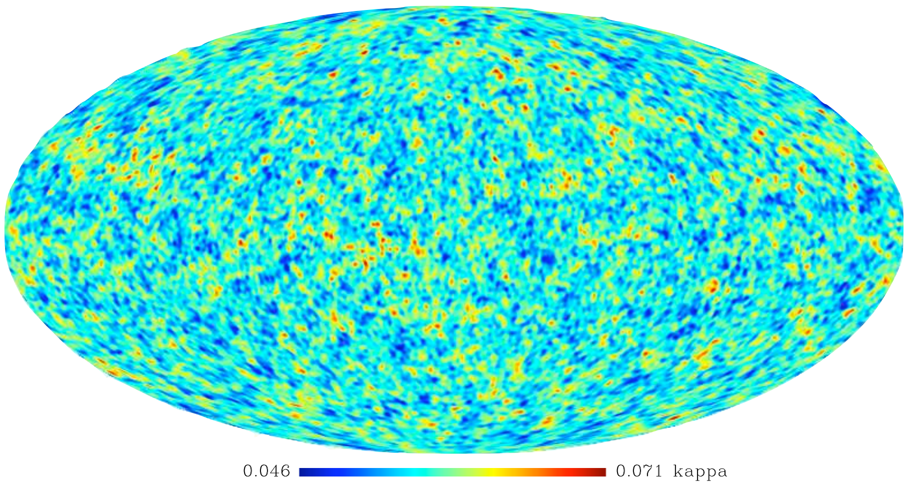
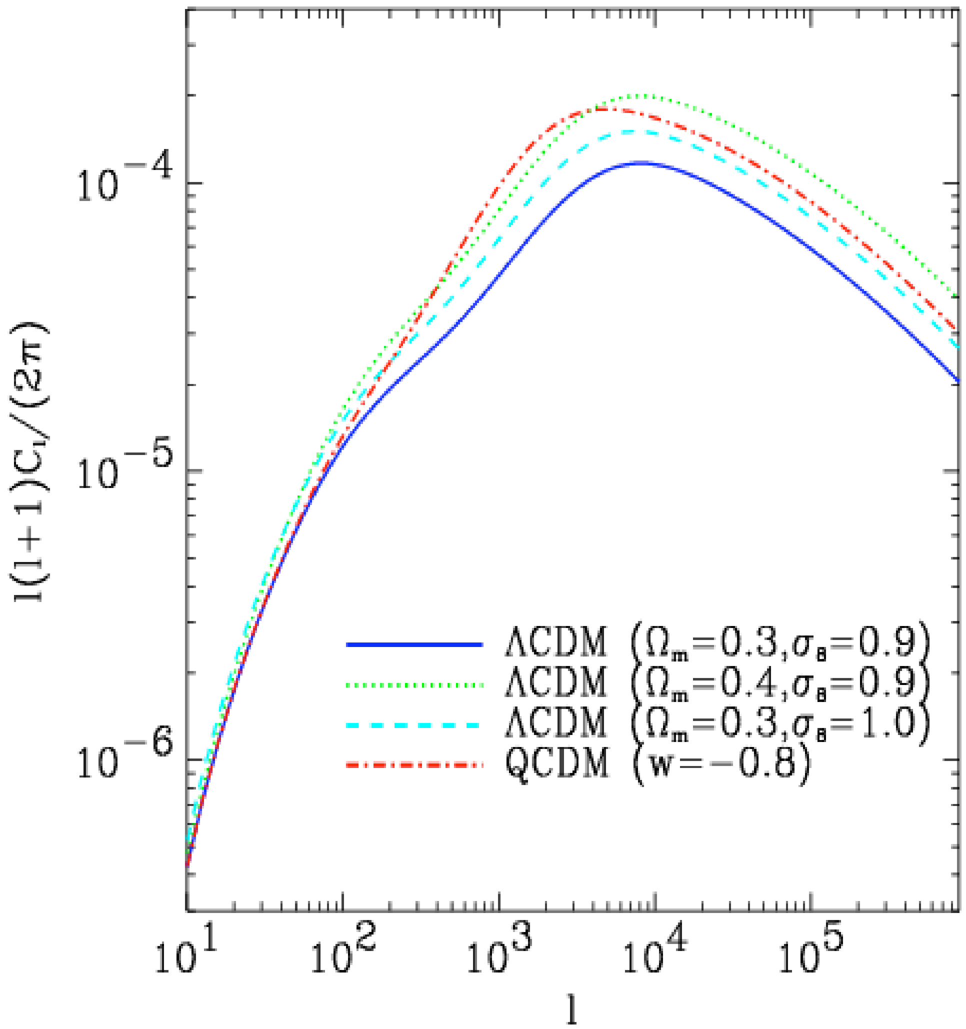
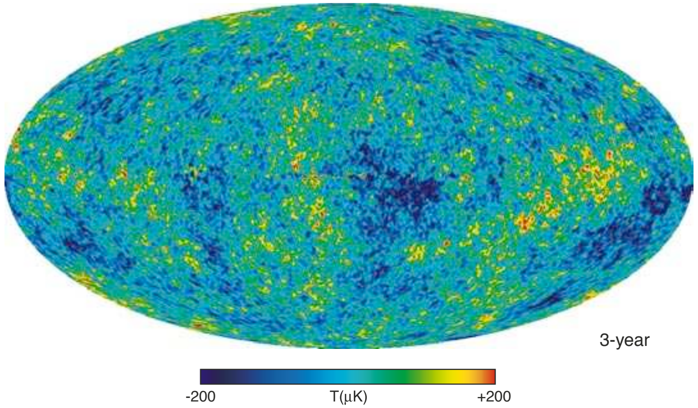


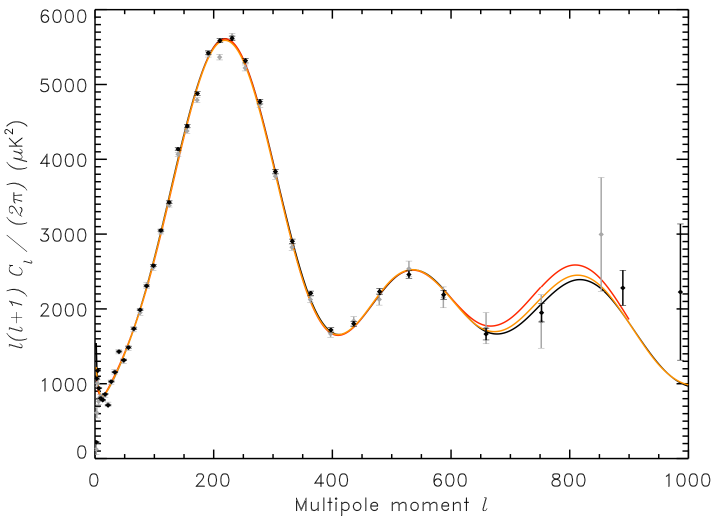


http://icosmo.org

CMB

Temperature map WMAP 3 year data





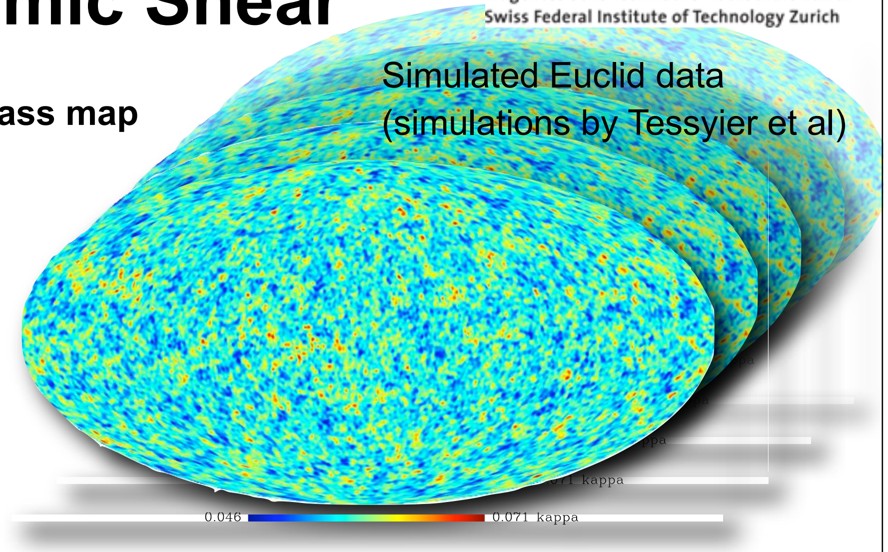
Spergel et al (2007)

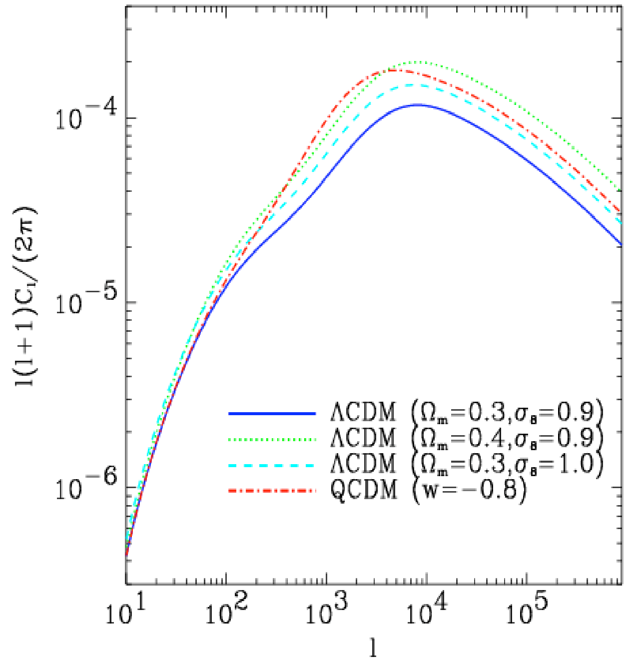
Page et al (2007)

Cosmic Shear

Mass map

Simulated Euclid data
(simulations by Tessyier et al)





$$F_{ij} = \sum_{\ell} \Delta C_l^{-2} \frac{dC_\ell^{\text{lens}}}{dp_i} \frac{dC_\ell^{\text{lens}}}{dp_j}.$$

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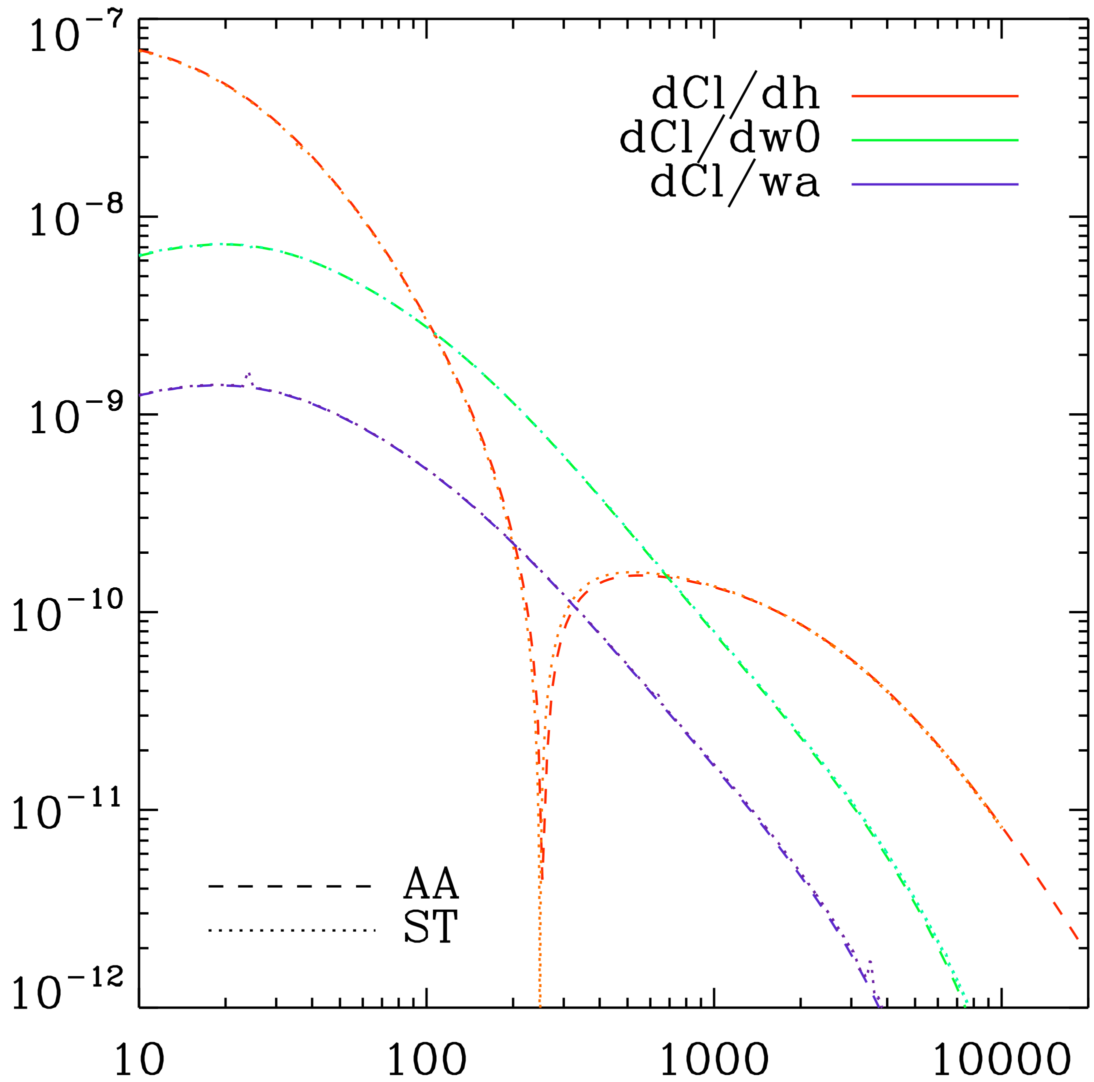

Survey Geometry

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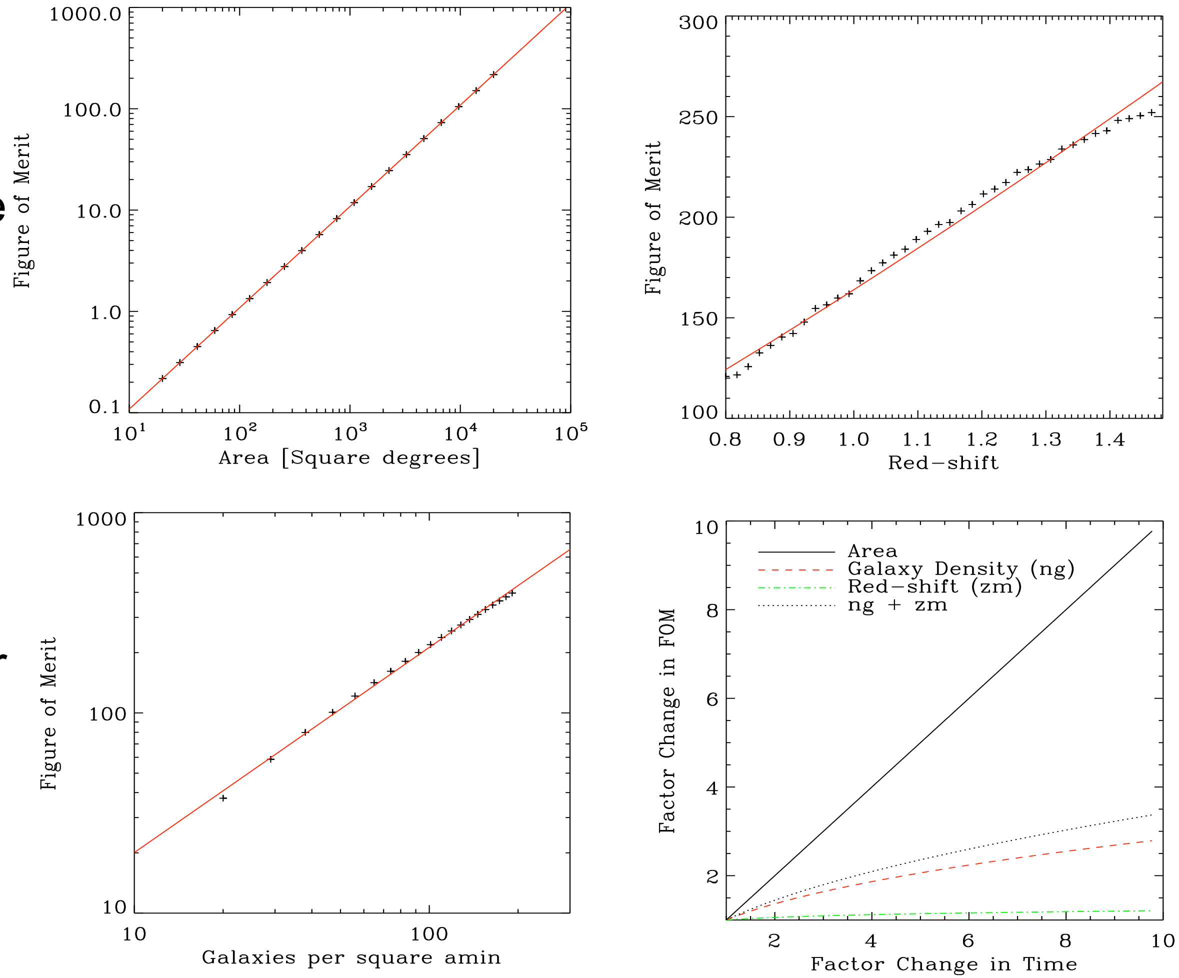
- Dark Energy Figure of Merit:
  - $FOM=1/(\delta w_n \delta w_a)$
- Wide field imaging survey has three basic properties:
  - Area (A_s)
  - Median redshift (z_m)
  - Number of galaxies (n_g)
- Choice between wide and deep
- When the median redshift is greater than 0.8 it is always better to go wide
- Constructed a simple scaling relation for survey designers



Amara and Refregier (2007)

Impact of Systematics

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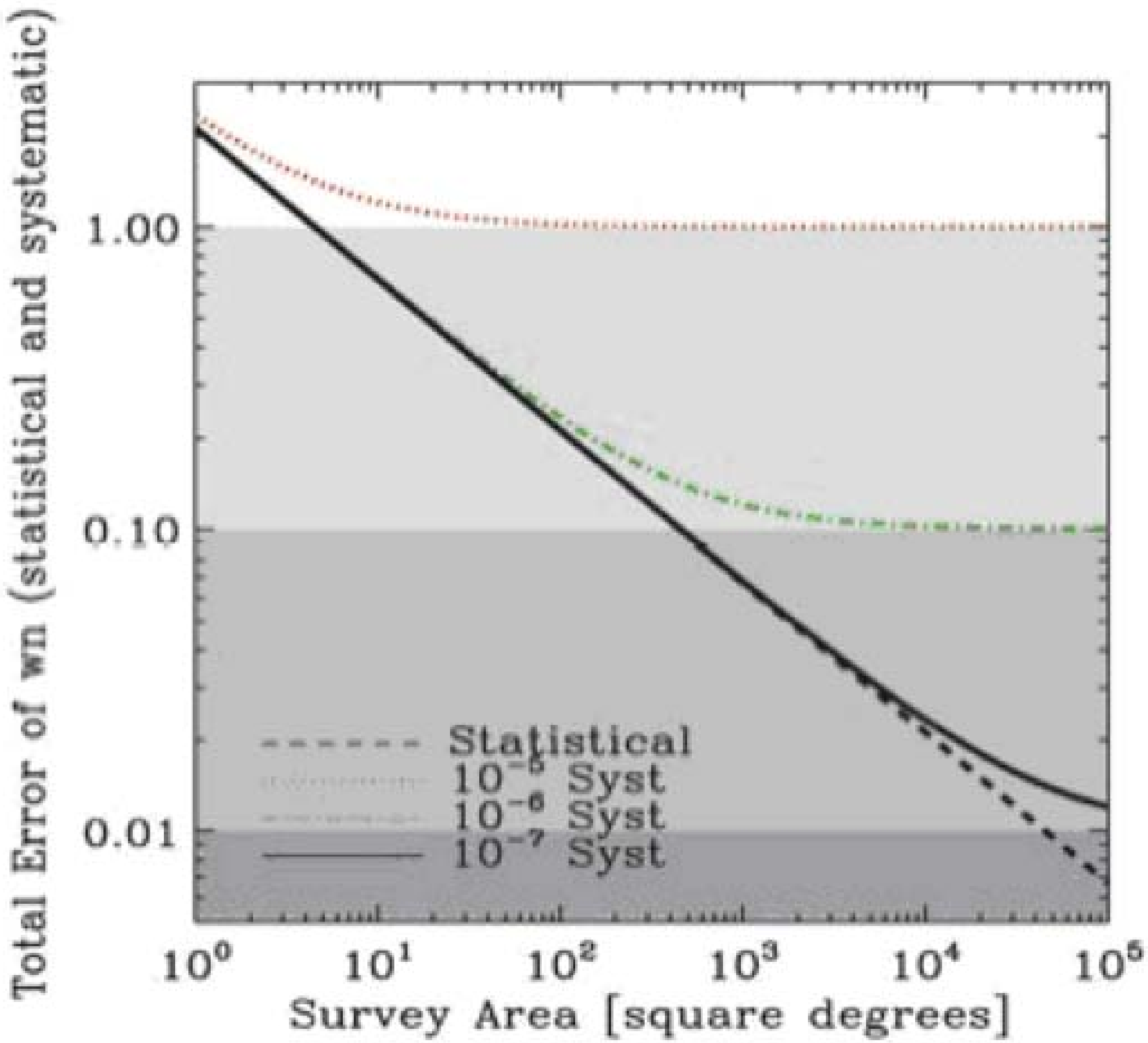
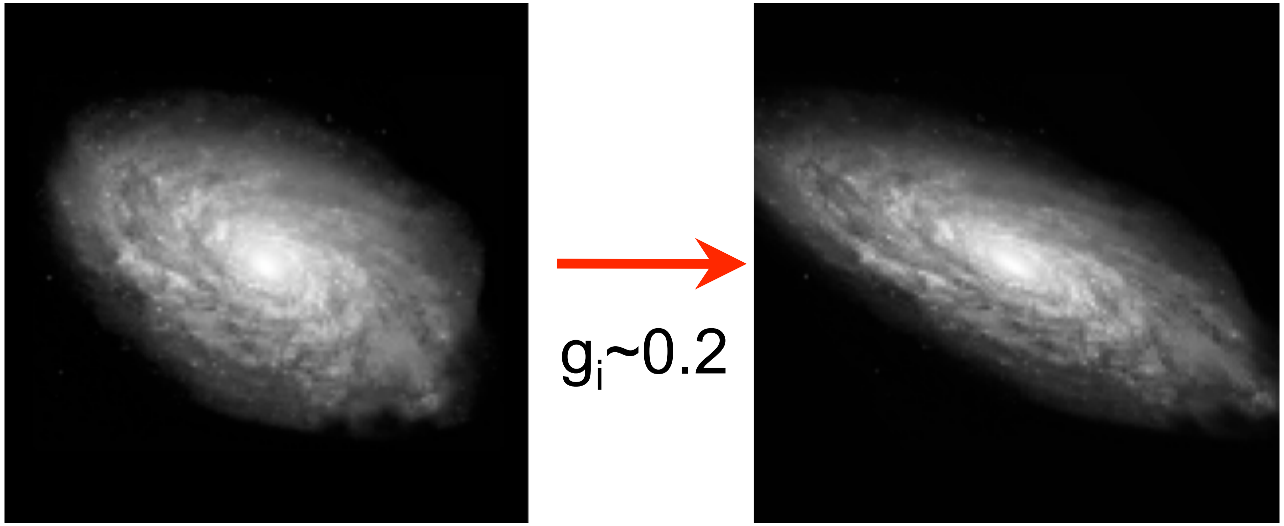


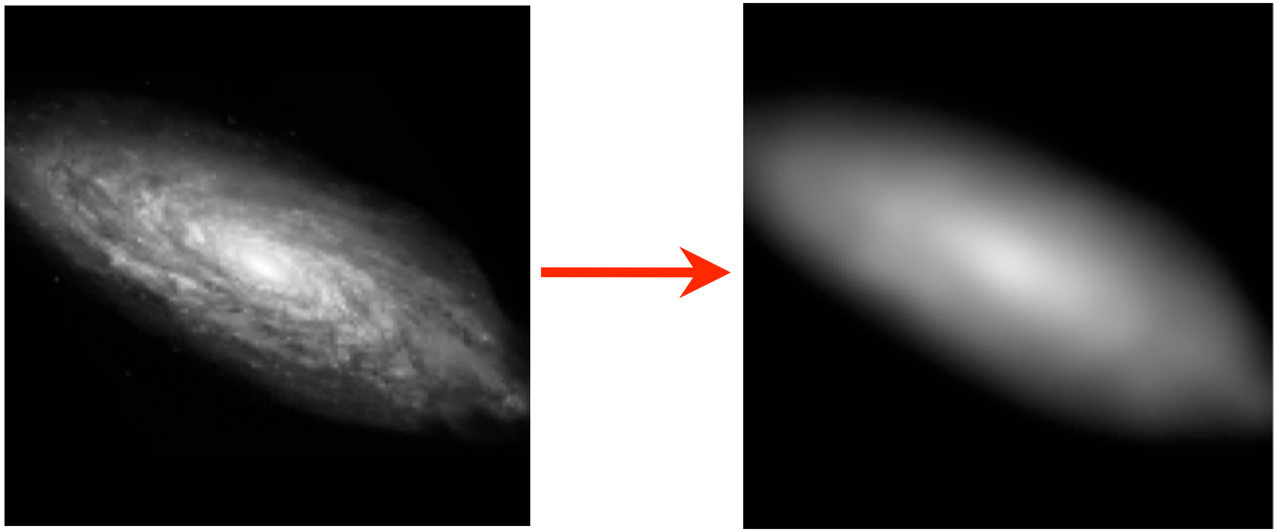
Cosmic Lensing



$$\begin{pmatrix} x_u \\ y_u \end{pmatrix} = \begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix} \begin{pmatrix} x_l \\ y_l \end{pmatrix}$$

Real data:
g_i~0.03

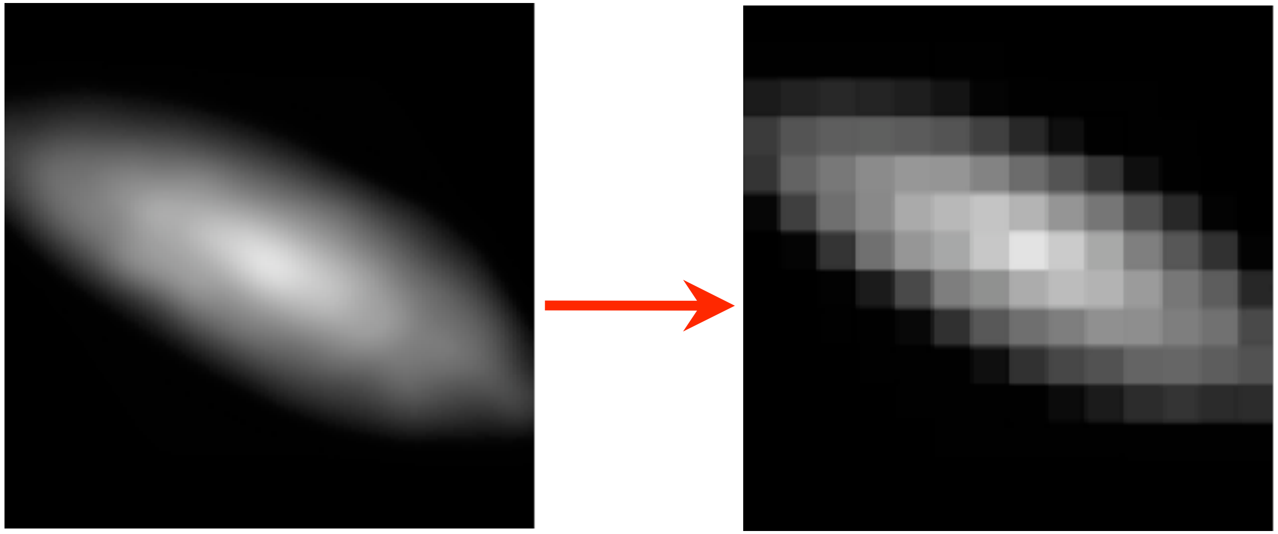
Atmosphere and Telescope



Convolution with kernel

Real data: Kernel size ~ Galaxy size

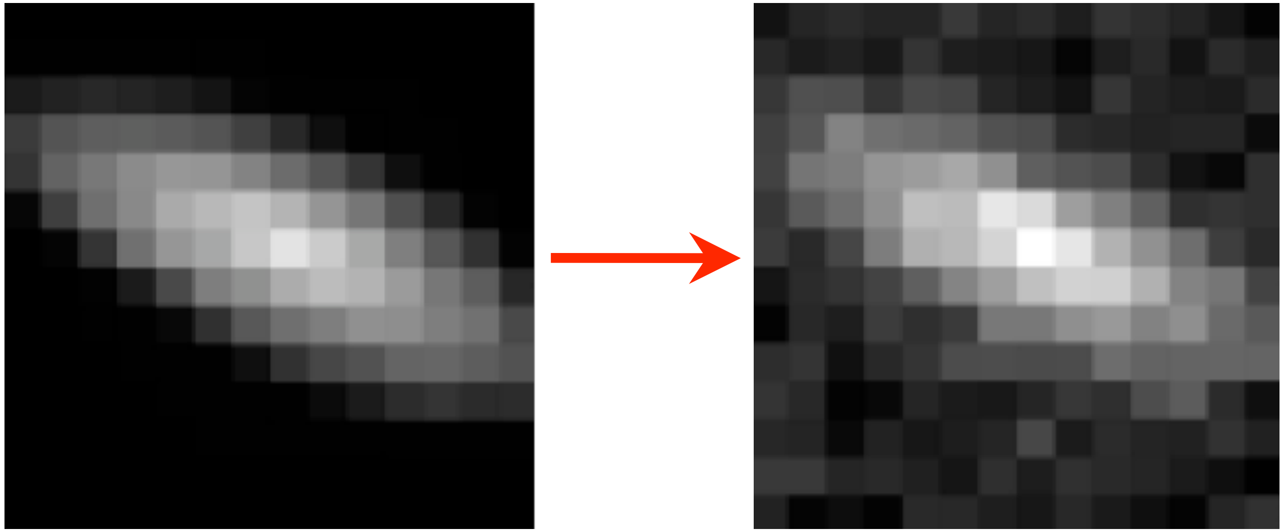
Pixelisation



Sum light in each square

Real data: Pixel size ~ Kernel size /2

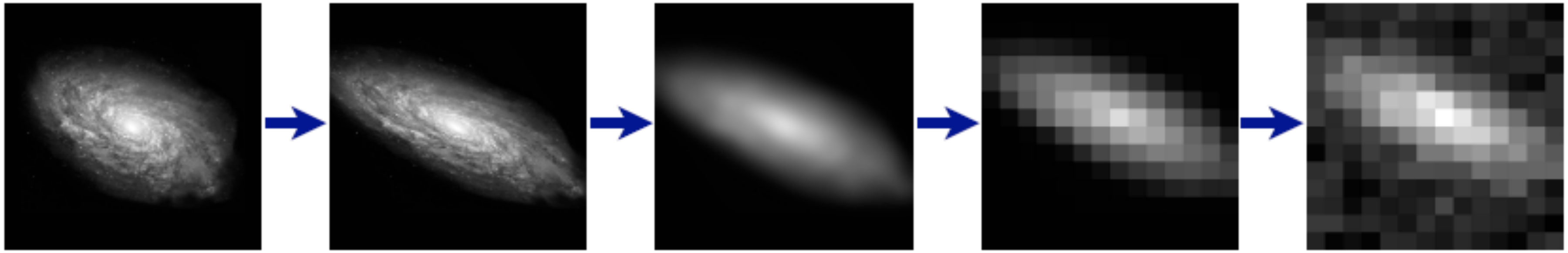
Noise



Mostly Poisson. Some Gaussian and bad pixels.
Uncertainty on total light ~ 5 per cent

The Forward Process.

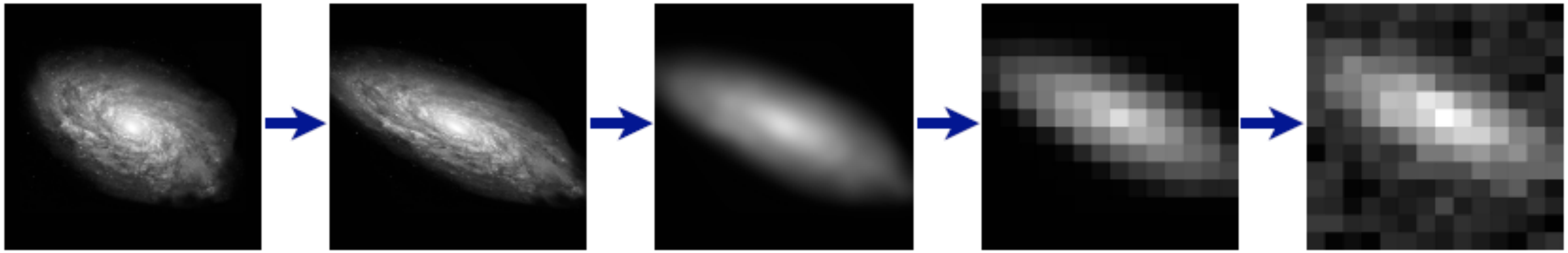
Galaxies: Intrinsic galaxy shapes to measured image:



Intrinsic galaxy (shape unknown) → Gravitational lensing causes a ***shear (g)*** → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:



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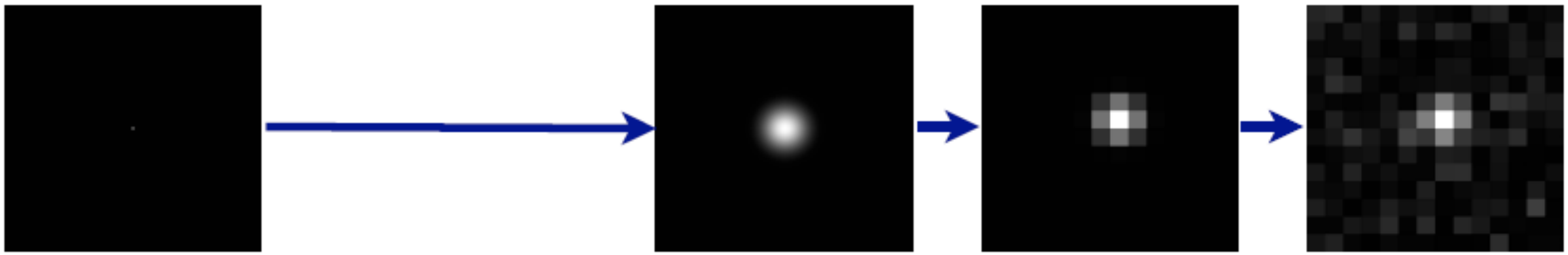
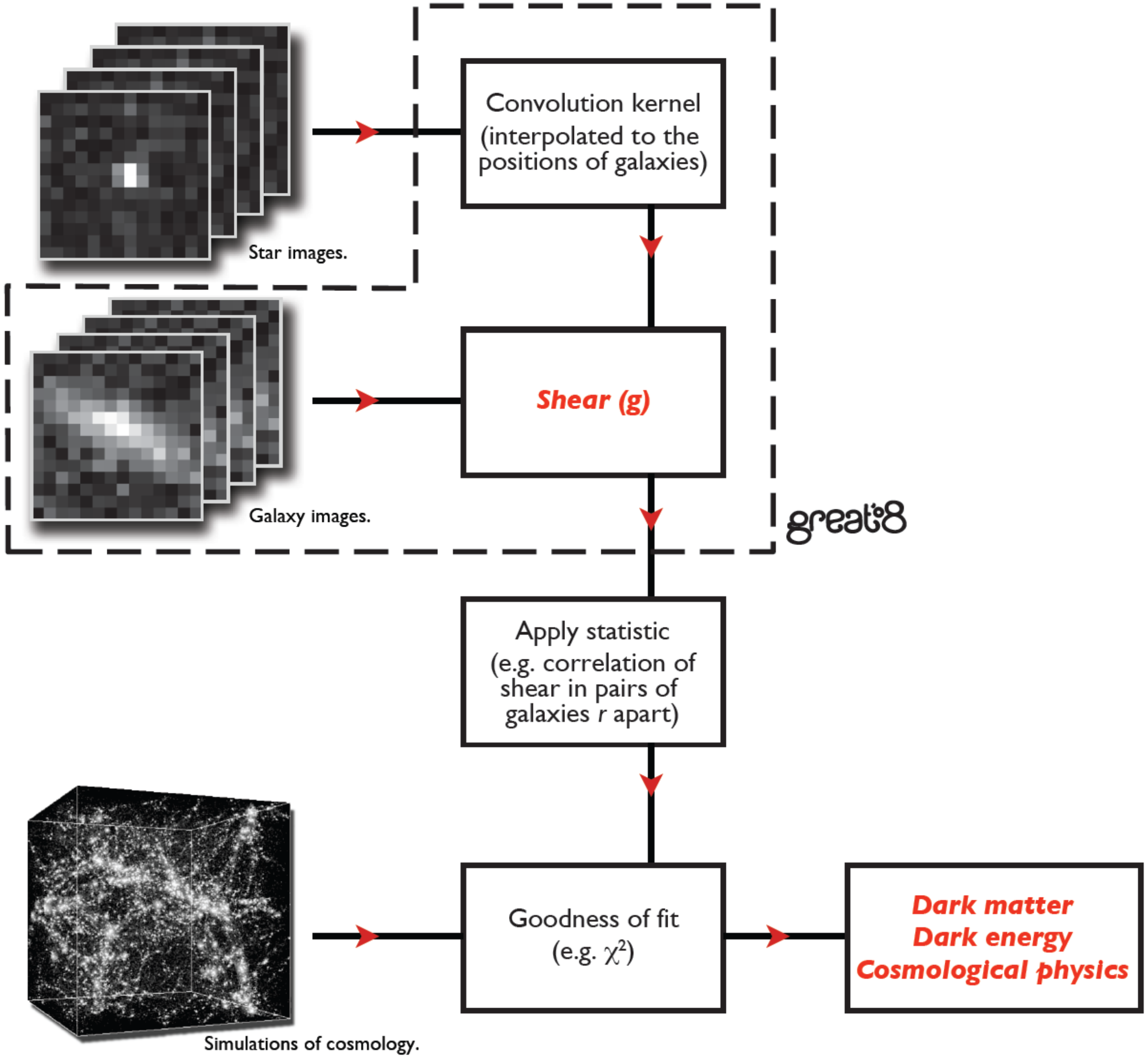
Stars: Point sources to star images:



Intrinsic star (point source) → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise

A full weak lensing pipeline:

The broader context typical for cosmological measurements



Current and Planned Lensing Surveys

Survey	Diameter (m)	FOV (deg2)	Lensing Area (deg2)	Start (out of date)
DLS	2 x 4	2 x 0.3	28	1999
CFHTLS	3.6	1	172	2003
DES	4	2.2	5,000	2008
Pan-STARRS	4 x 1.8	4 x 4	20,000	2008
LSST	8.4	7	20,000	2012
Euclid	1.2	0.5	20,000	2017
JDEM?	1.5	0.5	10,000 ?	2017

Euclid - Project Status

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2004	Wide-field Dark Universe Mission proposed as a Theme to ESA's Cosmic Vision programme
2005	DUNE Phase 0 (pre-study) phase by CNES
2006	Recommendation of ESO/ESA Working Group on Fundamental Cosmology
June 2007	DUNE and SPACE proposed to ESA's Cosmic Vision (M-class missions)
Oct 2007	DUNE and SPACE jointly selected for an ESA Assessment Phase
Jan-May 2008	Concept Advisory Team (CAT) to define a common mission concept
May 2008	Validation of the merged concept Euclid by the ESA AWG
May 2008	Formation of the Euclid Science Study team (ESST) to replace CAT
May - June 2008	Technical study by ESA's Concurrent Design Facility (CDF)
May 2008	Call for Interest for instrument consortia and Industrial ITT
Sept 2008	Recommendation from Astronet Infrastructure Roadmap report
Sept 2008 - Sept 2009	Assessment study phase
Jan - Apr 2009	Euclid JDEM interaction - IDECS
2010-2011	Definition phase (if selected)
2012-2017	Implementation phase (if selected)
2017	ESA launch of the first M-class mission

P.I. - A. Refregier

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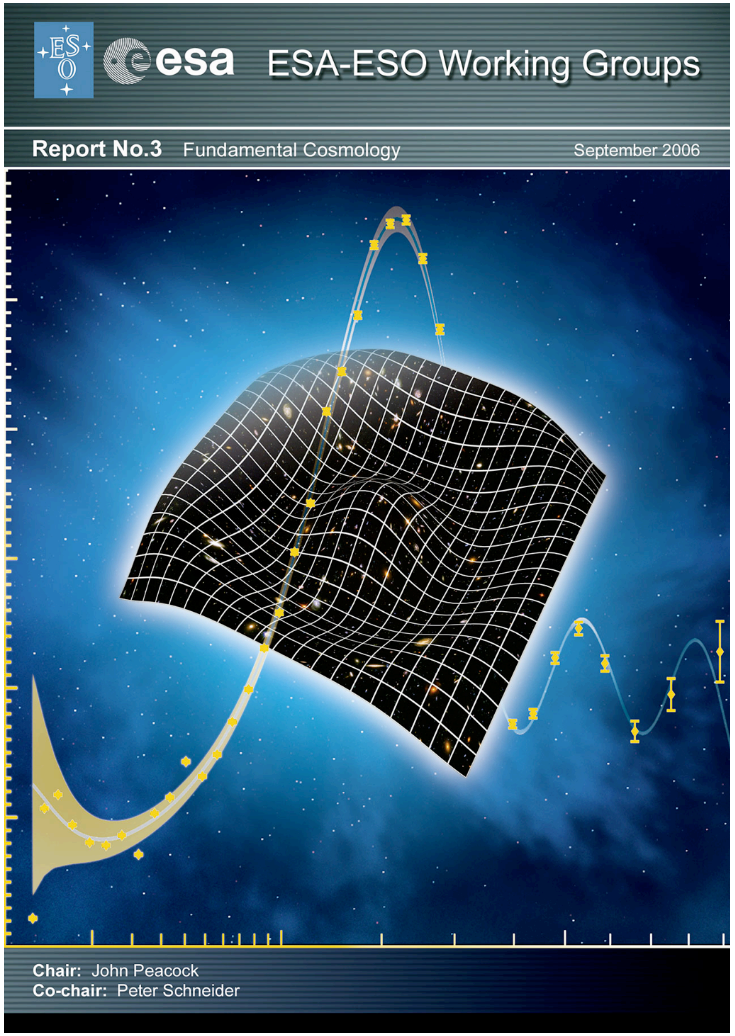

arXiv:astro-ph/0610906

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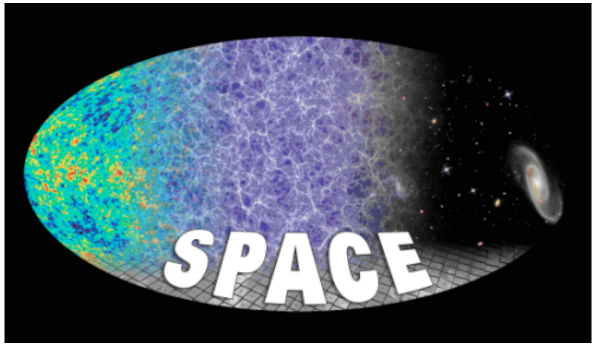
P.I. A. Cimatti



DUNE

P.I. A. Refregier

Euclid

esa

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Euclid - Project Status

2004	Wide-field Dark Universe Mission proposed as a Theme to ESA's Cosmic Vision programme
2005	DUNE Phase 0 (pre-study) phase by CNES
2006	Recommendation of ESO/ESA Working Group on Fundamental Cosmology
June 2007	DUNE and SPACE proposed to ESA's Cosmic Vision (M-class missions)
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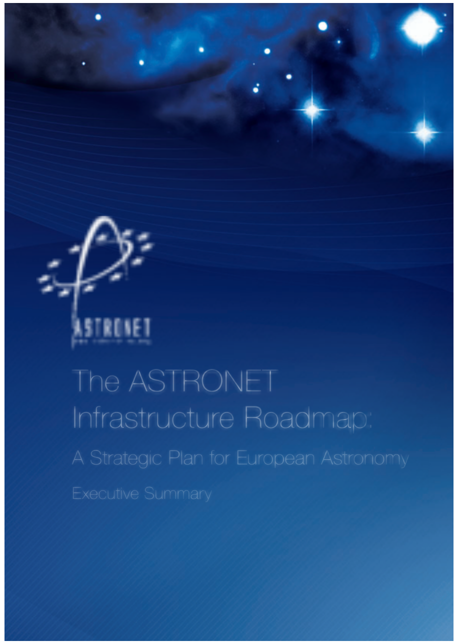
May 2008	Call for Interest for instrument consortia and Industrial ITT
Sept 2008	Recommendation from Astronet Infrastructure Roadmap report
Sept 2008 - Sept 2009	Assessment study phase
Jan - Apr 2009	Euclid JDEM interaction - IDECS
2010-2011	Definition phase (if selected)
2012-2017	Implementation phase (if selected)
2017	ESA launch of the first M-class mission



'ASTRONET aims to prepare long-term scientific and investment plans for European astronomy for the next 10–20 years.'

'Among proposed new projects in [the M Class] category, the dark energy mission EUCLID and then Solar Orbiter were ranked highest.'

http://www.astronet-eu.org/IMG/pdf/Astronet-Brochure_light.pdf

Euclid - Project Status

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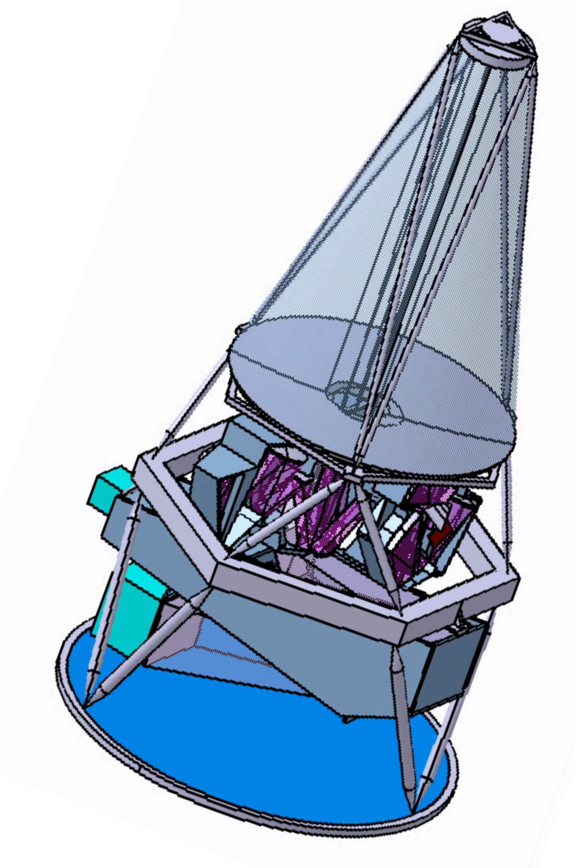

Cosmic Vision - M Class

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Partnerships: ESA-NASA
To map the geometry of the dark Universe

Partnerships: To be confirmed
Discover and characterise a large number of close-by exoplanetary systems, with a precision in the determination of mass and radius of 1%

Partnerships: ESA-JAXA
Return to Earth multiple unaltered samples from a NEO

Partnerships: JAXA-ESA
Understanding how galaxies, stars and planets form and evolve as well as the interaction between the astrophysical processes that have led to the formation of our own Solar System

Partnerships: ESA-JAXA-NASA
Quantifying the coupling in plasmas between different physical scales in order to address fundamental questions such as: how shocks accelerate and heat particles; how reconnection converts magnetic energy and how turbulence transports energy from source to dissipation.

Partnerships: ESA-NASA
To produce images of the Sun at an unprecedented resolution and perform closest ever in-situ measurements

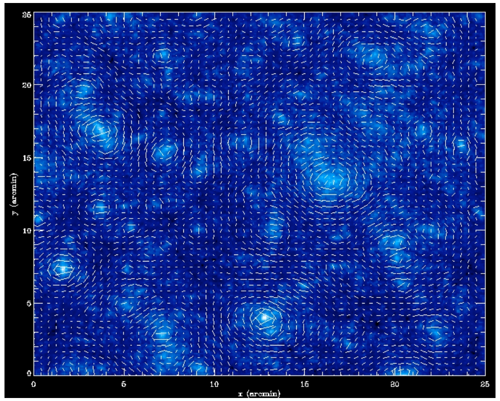
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42437

Euclid - Primary Science Goals

Issue	Our Targets
Dark Energy	Measure the DE equation of state parameters w0 and wa to a precision of 2% and 10%, respectively, using both expansion history and structure growth.
Test of General Relativity	Distinguish General Relativity from the simplest modified-gravity theories, by measuring the growth factor exponent γ with a precision of 2%
Dark Matter	Test the Cold Dark Matter paradigm for structure formation, and measure the sum of the neutrino masses to a precision better than 0.04eV when combined with Planck.
The seeds of cosmic structures	Improve by a factor of 20 the determination of the initial condition parameters compared to Planck alone.

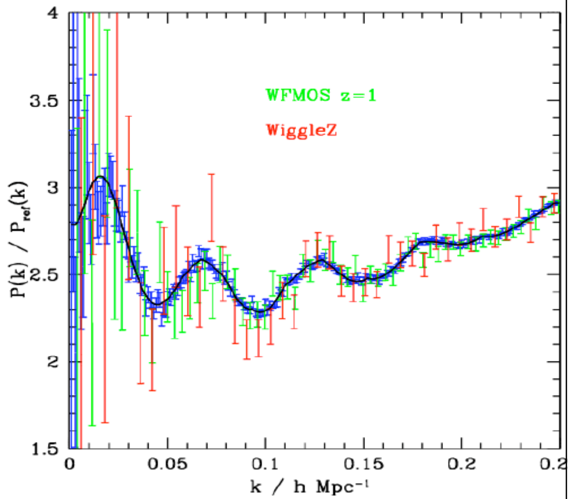
Euclid Measurement Methods

- **Mission Drives:** used for (i) instrument design, (ii) survey design, (iii) maximising performance within cost envelope
  - Gravitational Lensing (Galaxy Shapes)
  - Galaxy Clustering (Galaxy Distribution)



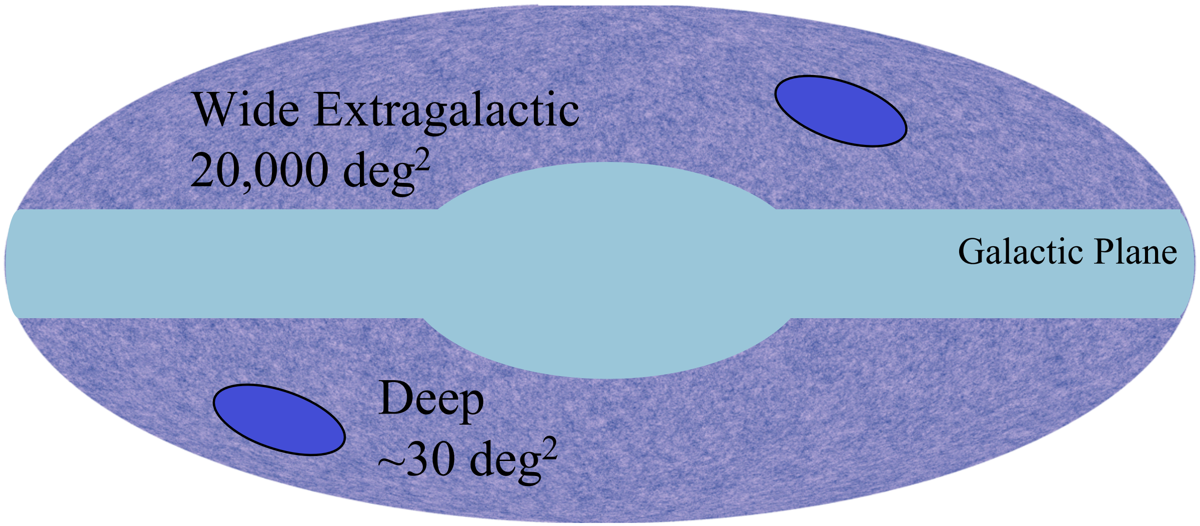
- **Additional Science:** (i) **cannot** impact instrument design (ii) may modify survey - when not in conflict with mission drives and (iii) should not increase cost
  - Cluster Counts
  - Integrated Sachs Wolfe
  - Supernovae
  - Legacy Science

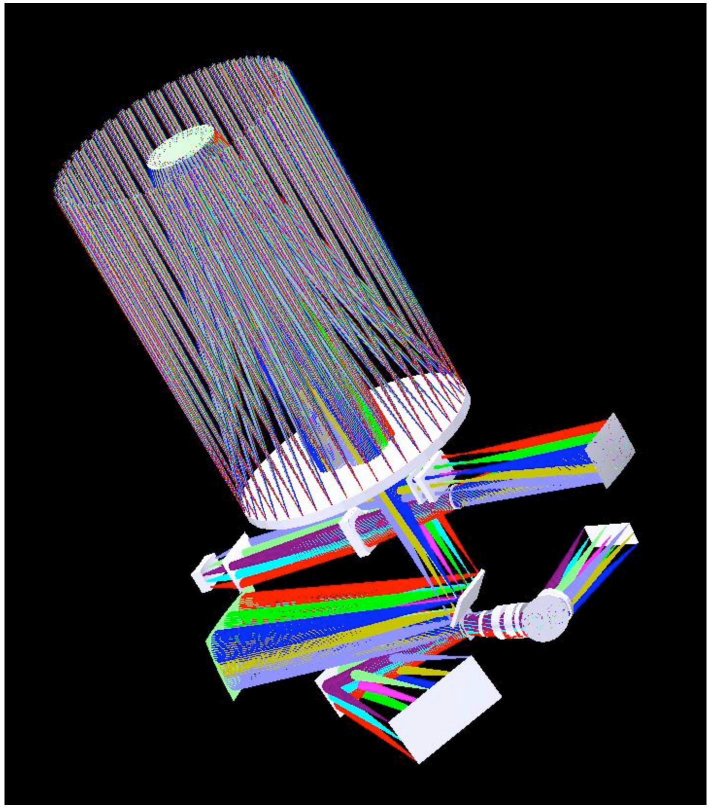
BAO



Euclid Surveys

- Wide Survey:
  - Simultaneous (i) visible imaging (ii) NIR photometry (iii) NIR spectroscopy
  - 20,000 square degrees
  - Median redshift z = 1
  - PSF FWHM ~0.18''





Euclid Parameter Constraints

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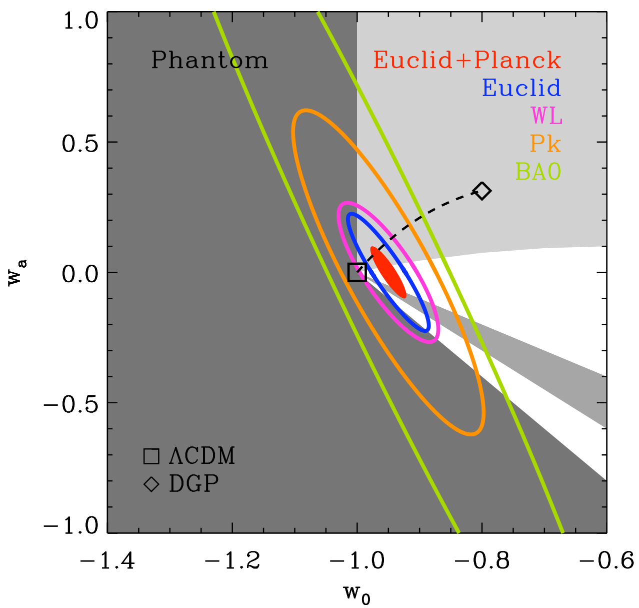
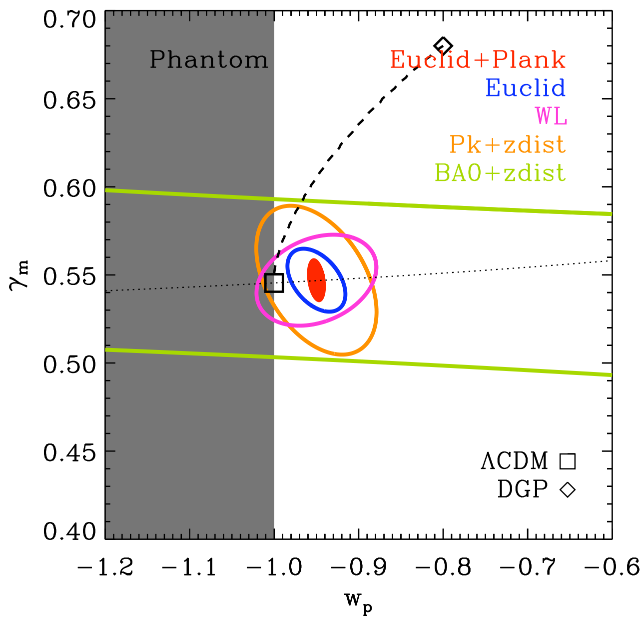
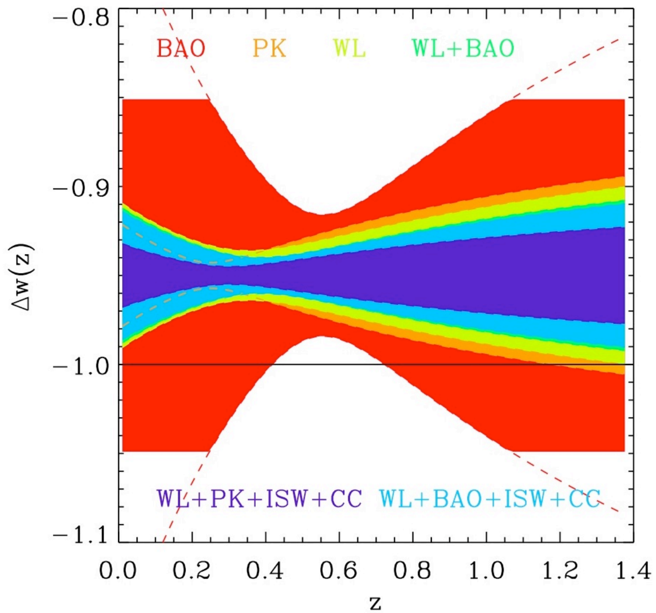
	Dark Energy		Densities			Initial Conditions		Hubble	DE FoM[2]
	Δw_p	Δw_a	$\Delta\Omega_m$	$\Delta\Omega_\Lambda$	$\Delta\Omega_b$	$\Delta\sigma_8$	Δn_s	Δh	
Current +WMAP[3]	0.13	-	0.01	0.015	0.0015	0.026	0.013	0.013	**~10**
Planck	-	-	0.008	-	0.0007	0.05	0.005	0.007	**-**
Euclid Req.	0.018	0.15	0.004	0.012	0.006	0.004	0.007	0.022	**400**
Euclid Goal	0.016	0.13	0.003	0.012	0.005	0.003	0.006	0.020	**500**
Euclid +Planck	0.010	0.066	0.0008	0.003	0.0004	0.0015	0.003	0.002	**1500**
Factor gain on Current	**13**	**> 15**	**13**	**5**	**4**	**17**	**4**	**7**	**150**







By Euclid Cosmology Working Group

Technical Details and Control of Systematics

Stable and well behaved PSF

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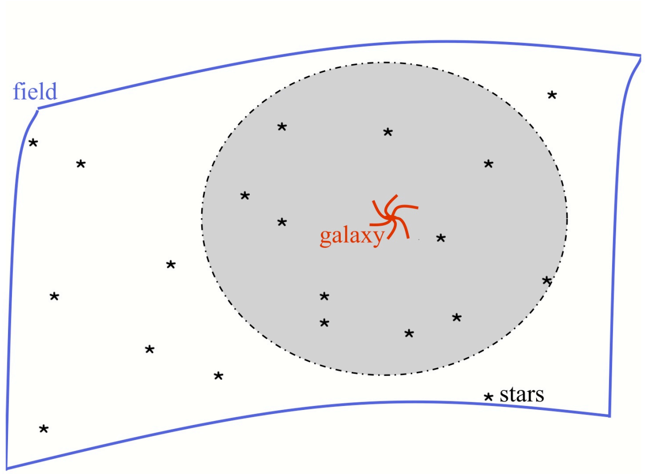
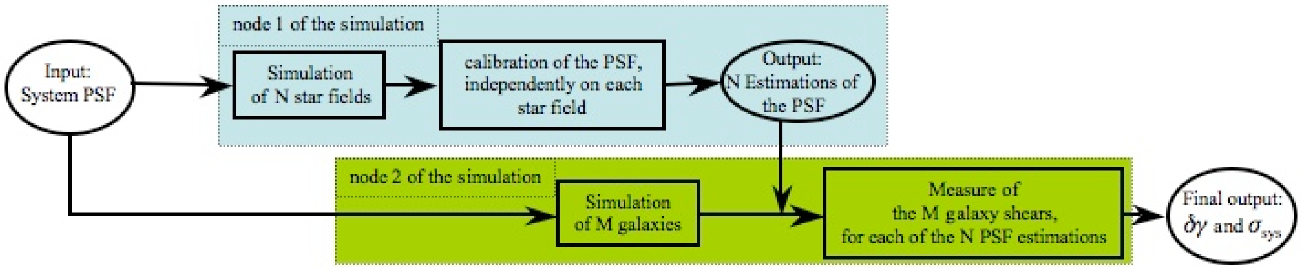
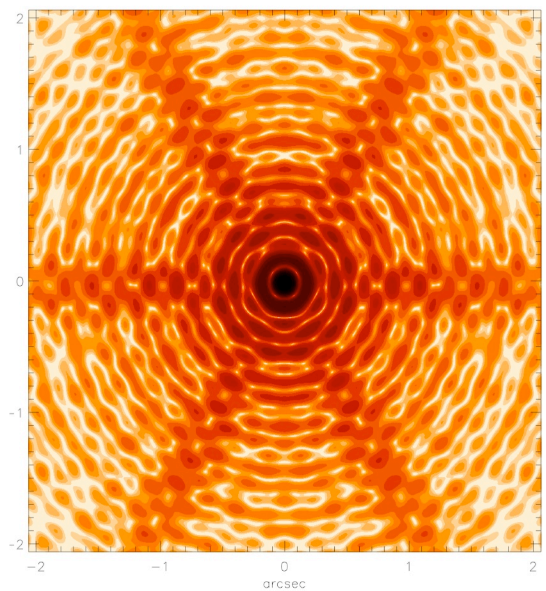
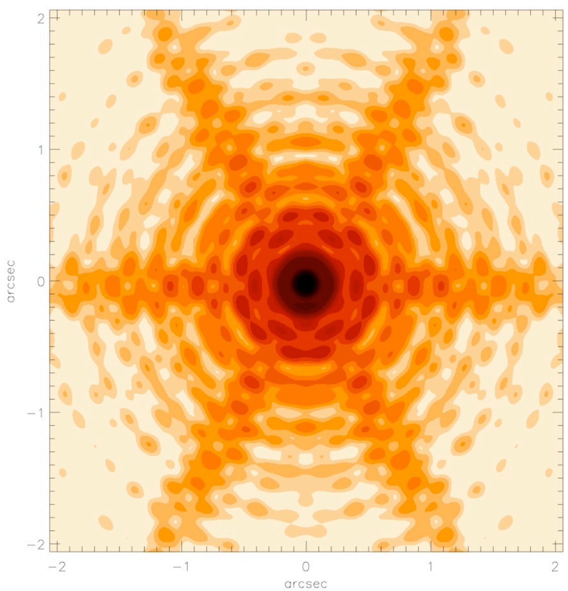
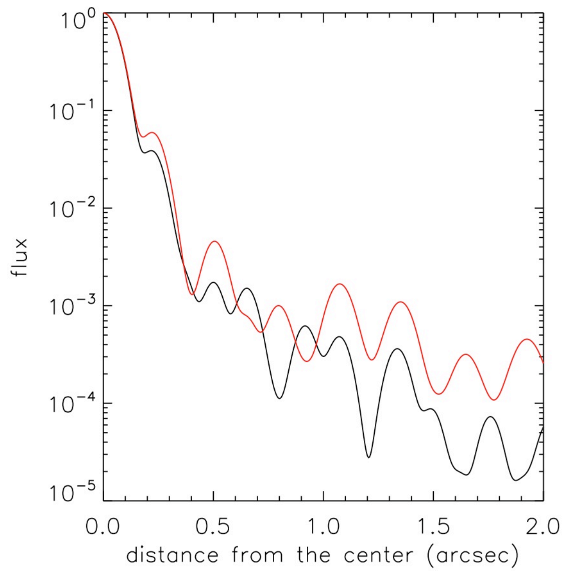
Paulin-Henriksson et al, 2007, 2008











Wavelength dependent PSF

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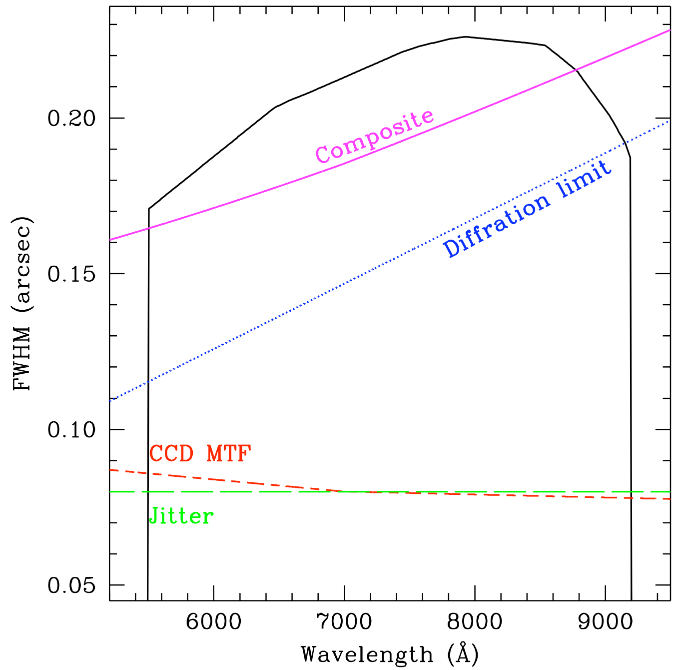
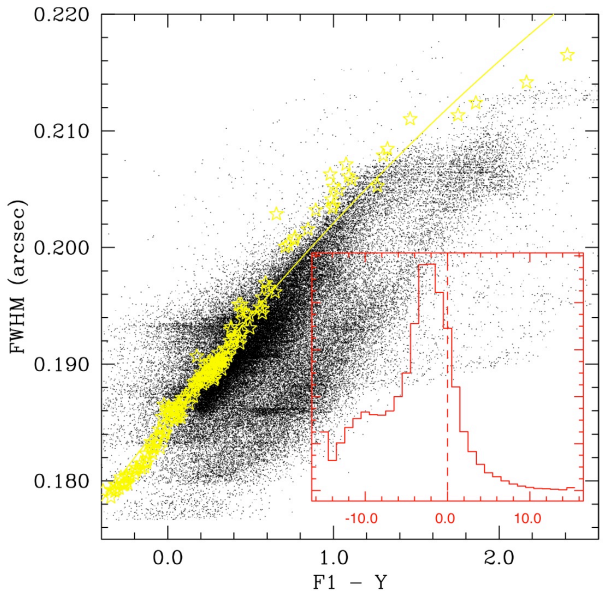
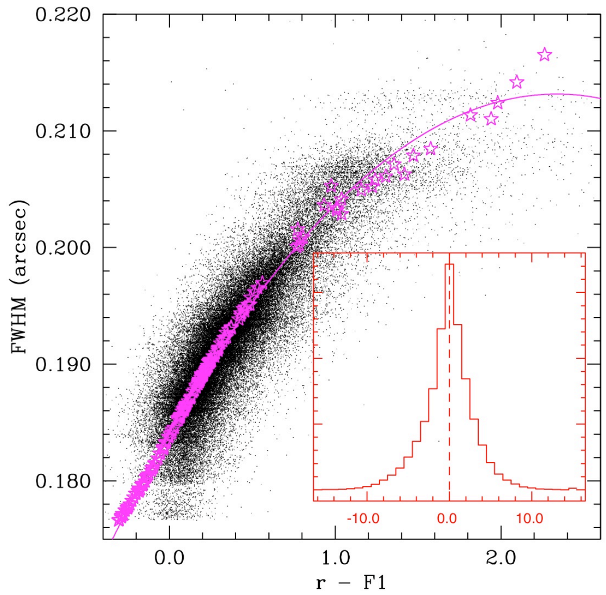
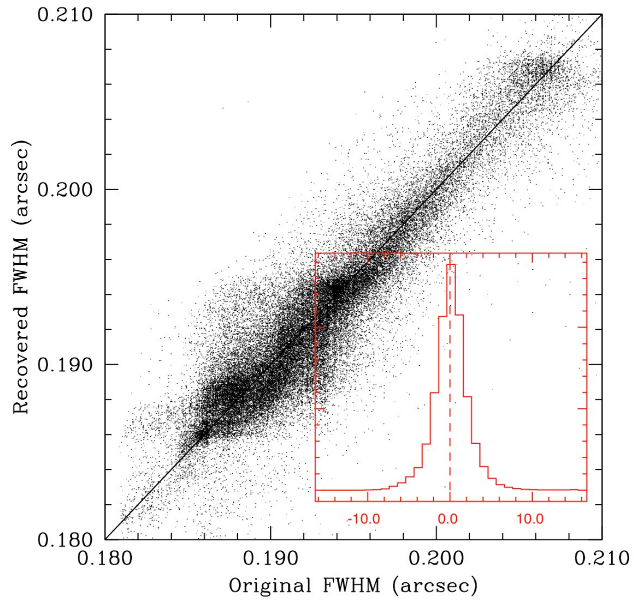
- Measure the PSF as a function of wavelength using stars
- Considered three contributions to the PSF
  - Diffraction limit
  - CCD MTF
  - Jitter
- We can correct the global effect by measuring the SED galaxies using photoz (Cypriano et al in prep)
- Work on Colour gradients is still on going









CCD Effects - CTI

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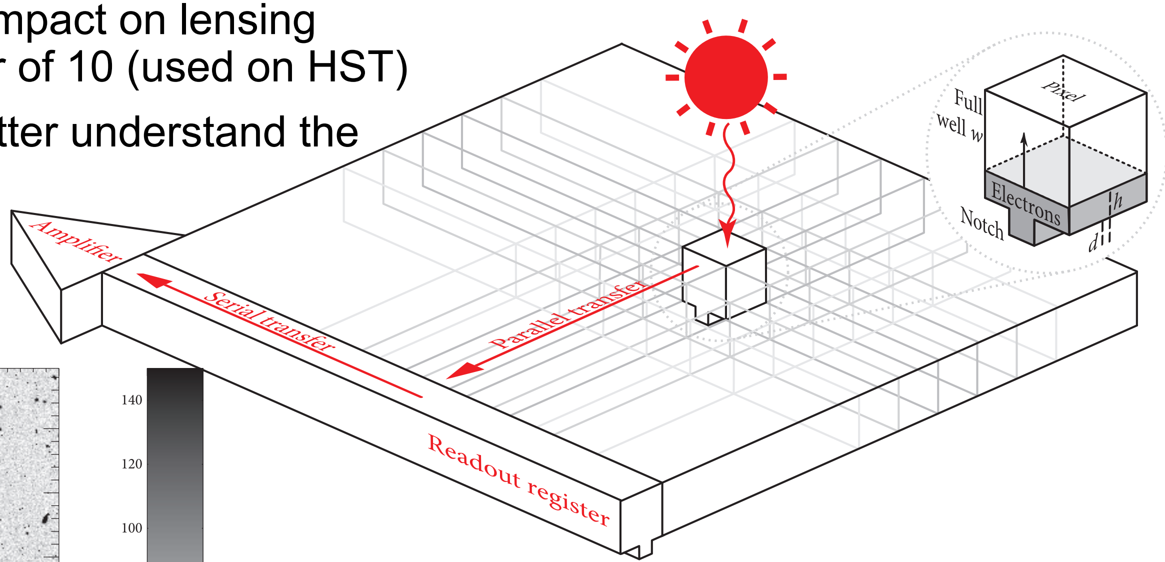
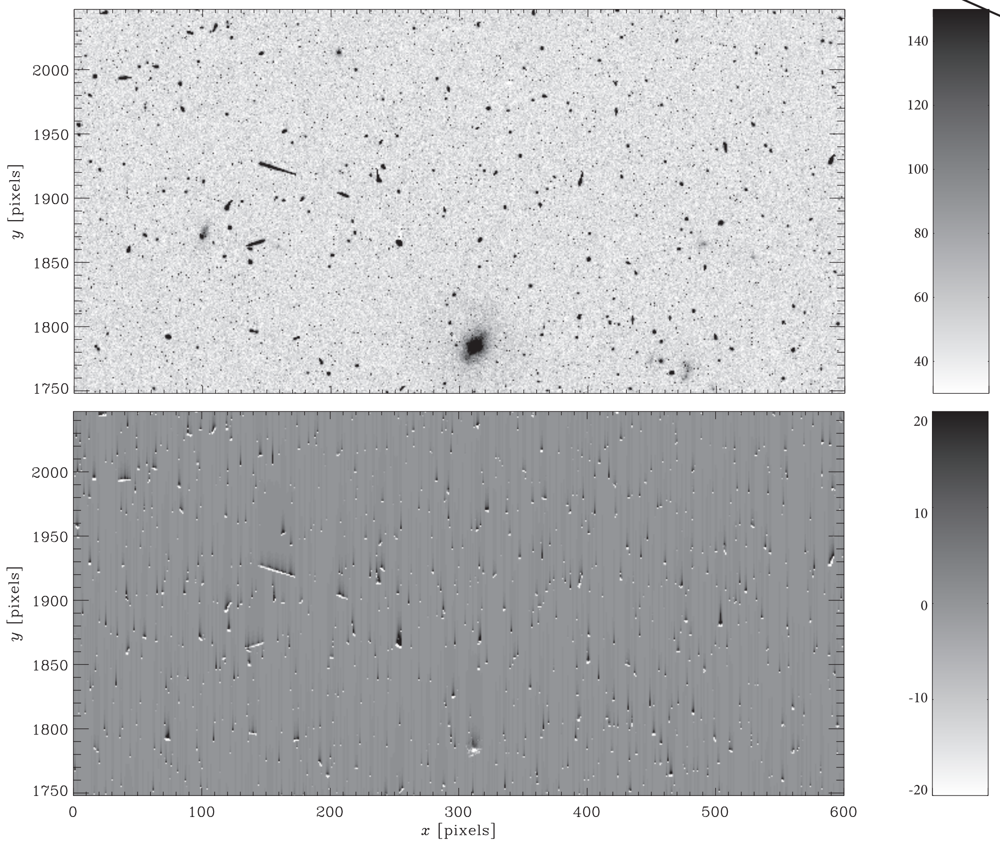
- Radiation damage leads to traps in the CCD
- Through modeling of these traps their impact on lensing observables can be reduced by a factor of 10 (used on HST)
- We have initiated hardware tests to better understand the performance of the CCD's



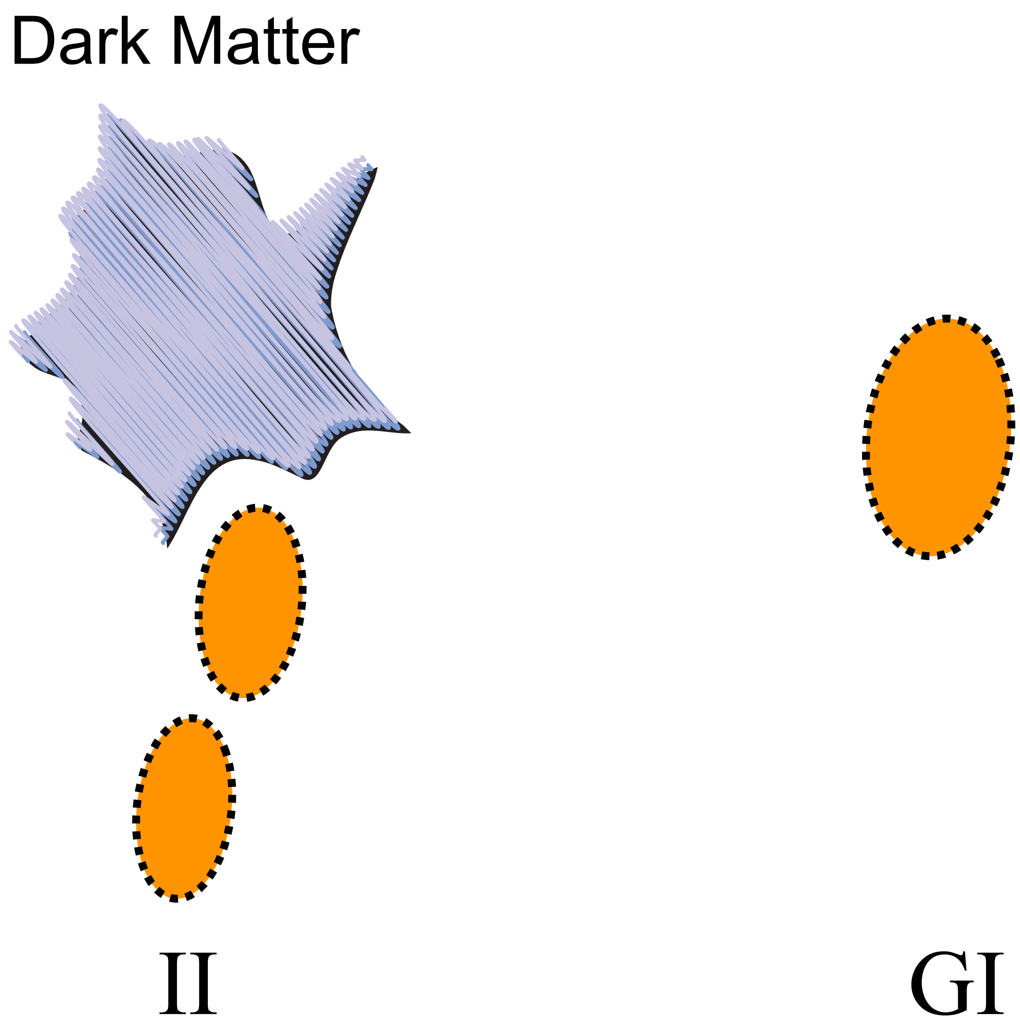


Massey et al 2009

Intrinsic Alignment

Treatment:

- Nulling
- Modeling
- Simulations



For examples see
Bridle & King 2007,
Joachimi & P. Schneider 2008
M. Schneider & Bridle 2009
Joachimi & Bridle 2009 ...

Photo-z

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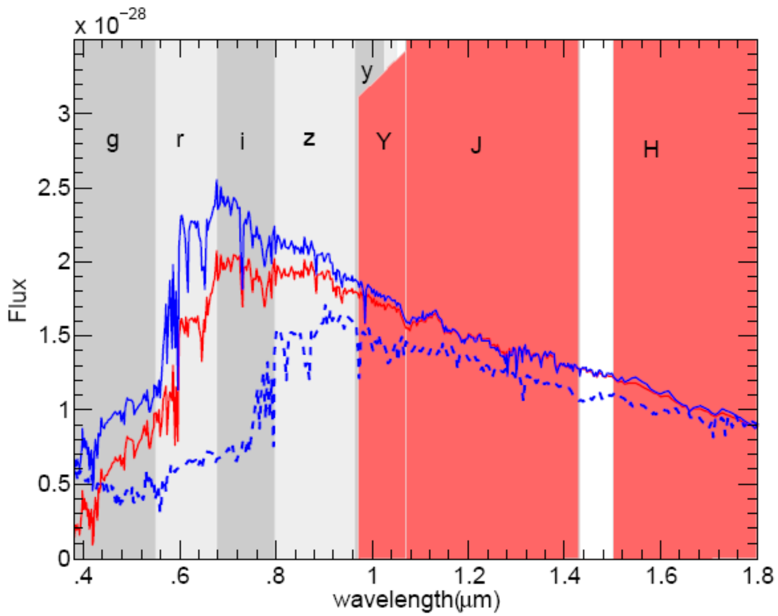
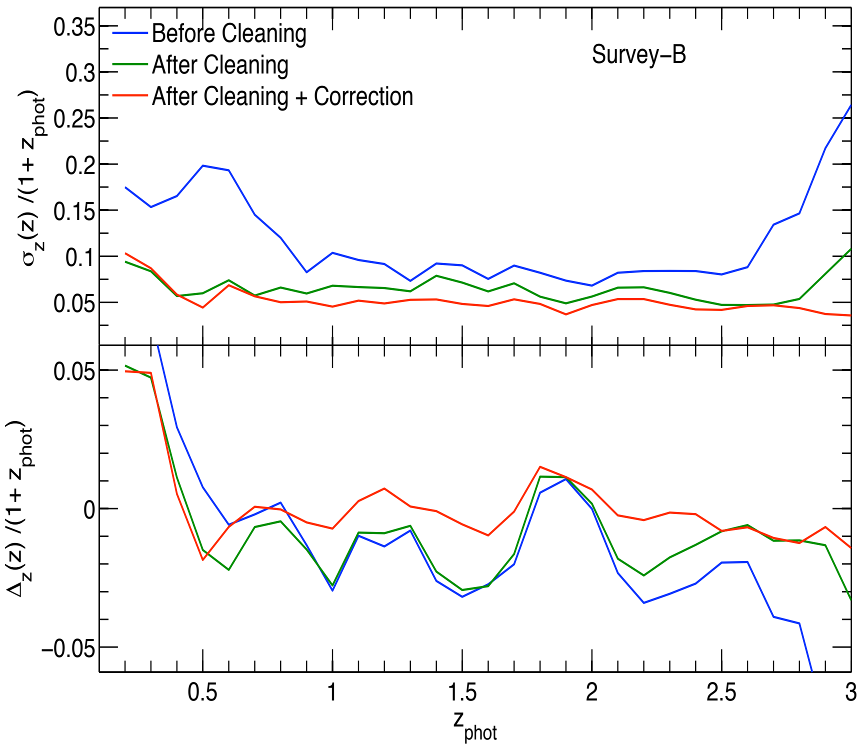
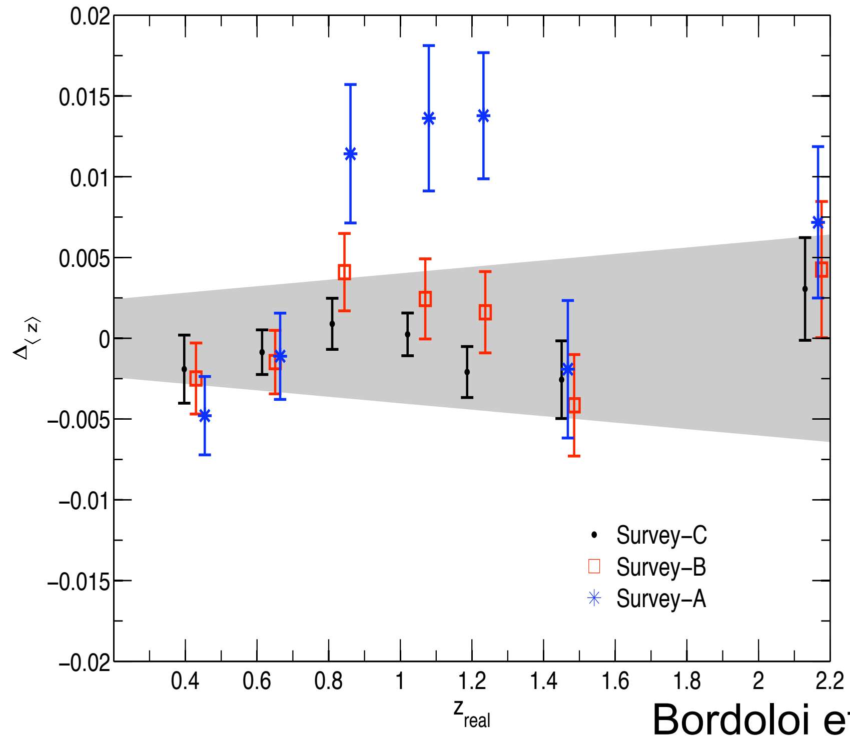
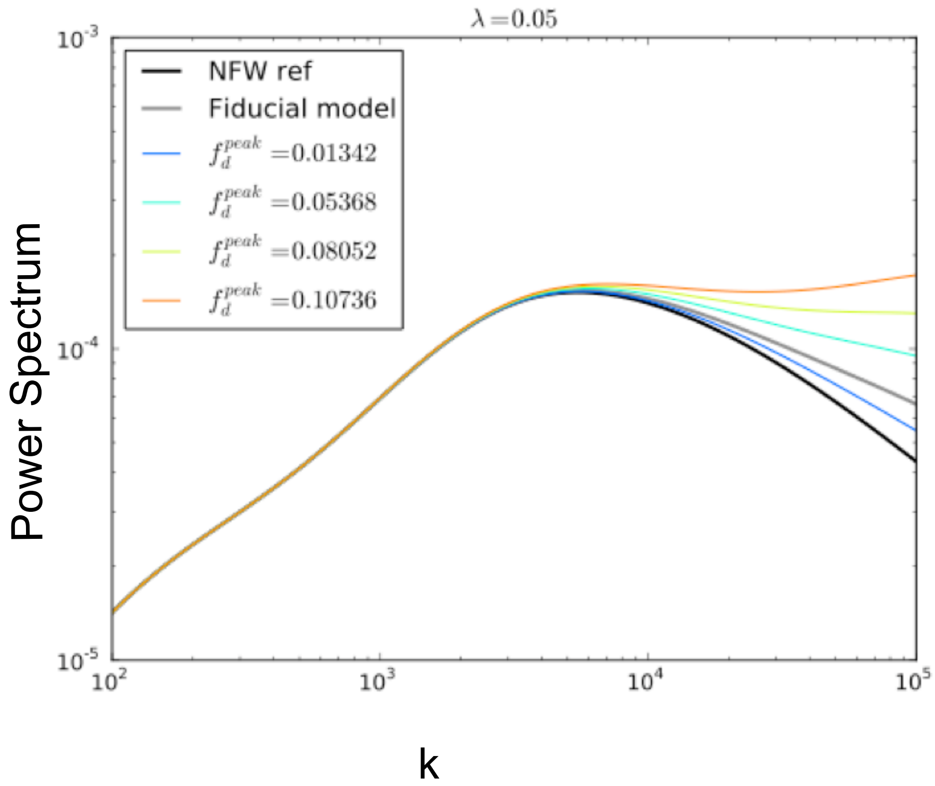




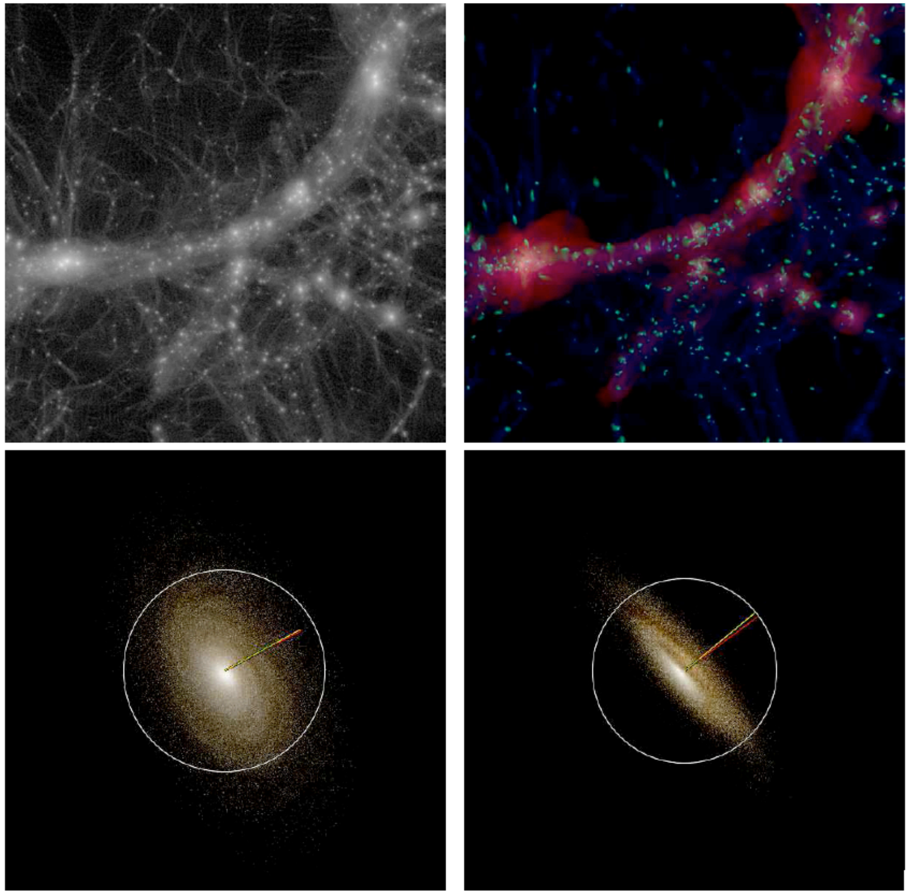


Bordoloi et al 2009

Physics of the Baryons



Guilllet et al 2009



Hahn et al 2009

End