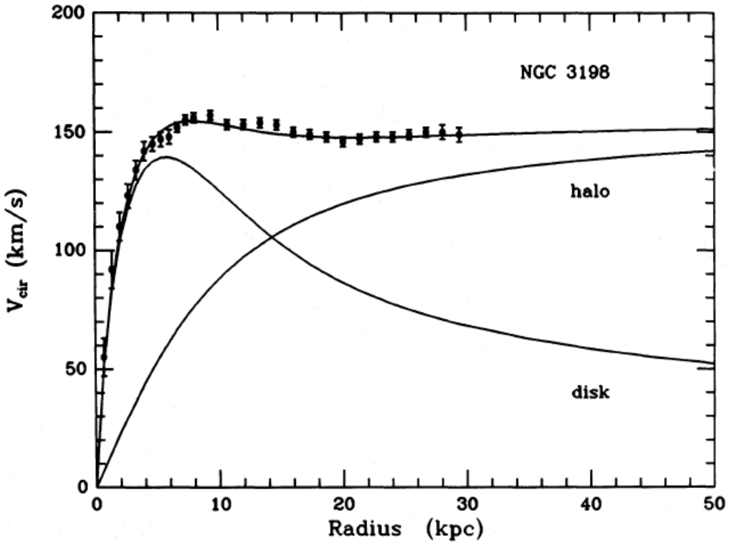
Lensing and dark matter/energy

Hendrik Hildebrandt, UBC Vancouver

September 1st, 2011

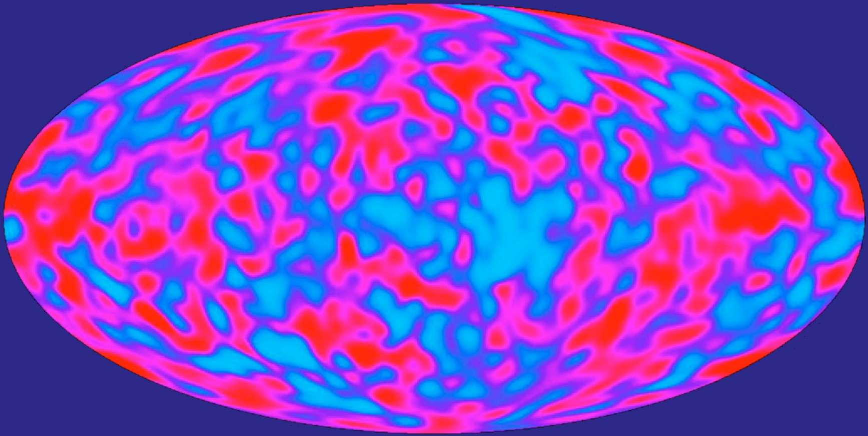
Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA), D. Carter and the Coma HST ACS Treasury Team

Galaxy rotation curves

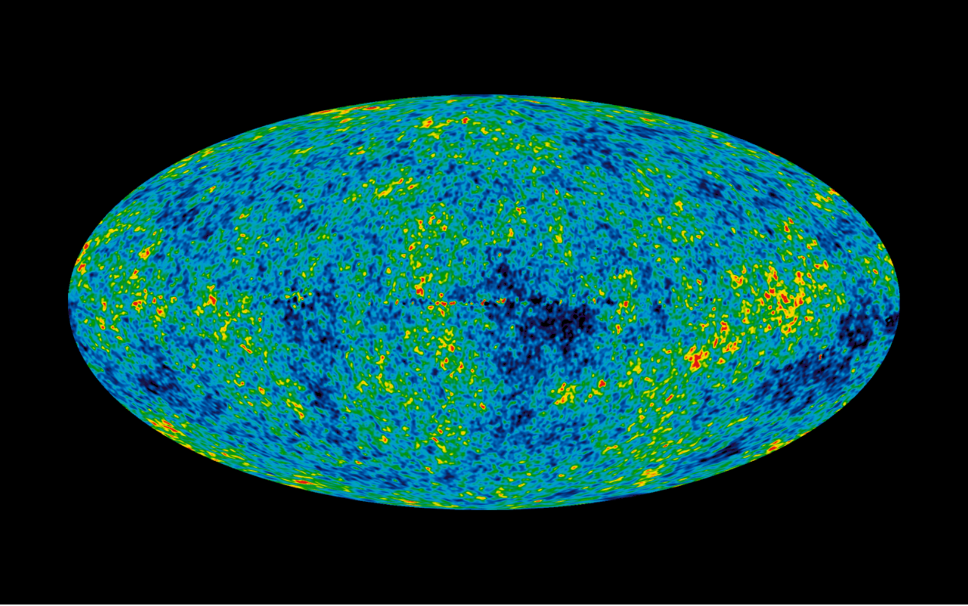


from van Albada et al. (1985)

DMR's Two Year CMB Anisotropy Result



Credit: NASA and the COBE team



Credit: NASA / WMAP Science Team

Dark Matter

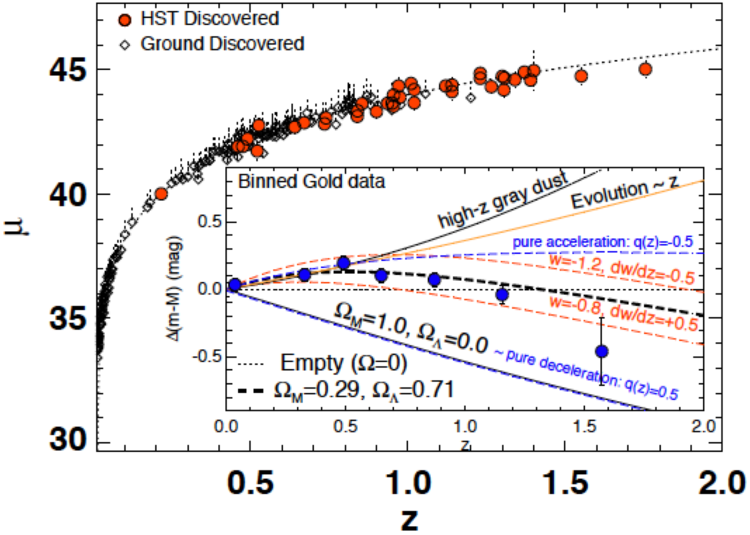
Properties

- Cold (i.e. non-relativistic at matter-radiation equality)
- Collisionless
- Dissipationless
- Most probably WIMPs (Weakly Interacting Massive Particles)

Predictions (relevant for lensing)

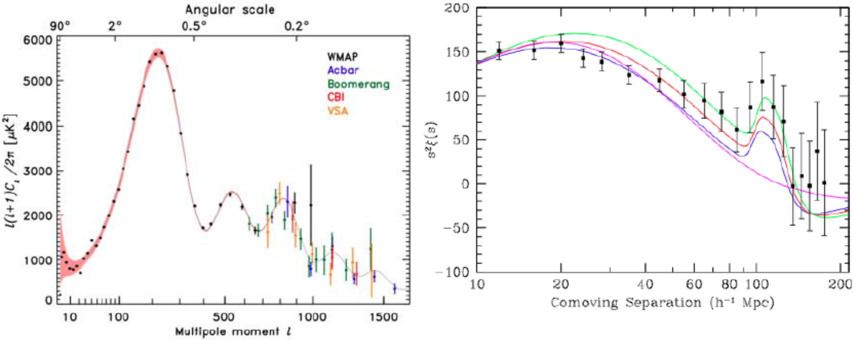
- Hierarchical structure formation
- Universal dark matter halo profile
- Triaxial dark matter halos
- Stripping of sub-halos

Type Ia Supernovae



from Riess et al. (2007)

Baryon Acoustic Oscillations



from Hinshaw et al. (2003) and Eisenstein et al. (2005)

Dark Energy

Effects

- Distance-redshift relation (DR)
- Growth of cosmic structures (GS)

Probes

- Type Ia Supernovae (DR)
- Baryon Acoustic Oscillations (DR)
- Galaxy Cluster Mass Function (DR+GS)
- **Cosmic Shear (DR+GS)**

Modified Gravity

Paradigm

- This all assumes that General Relativity (GR) is the correct theory of gravity.
- But GR has not been tested in the low acceleration regime.
- It was proposed (Milgrom 1983) that the gravitational acceleration, a, could drop below the Newtonian prediction for values of $a < a_0 \approx 10^{-10} m/s^2$.
- This would explain the flat galaxy rotation curves without the need for dark matter.
- More complicated theories of modified gravity try to explain dark energy as well.
- Measuring DR and GS simultaneously one can distinguish between different gravity models.

Gravitational Lensing

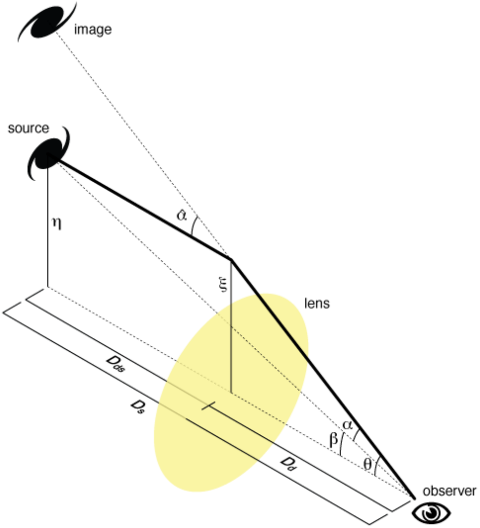


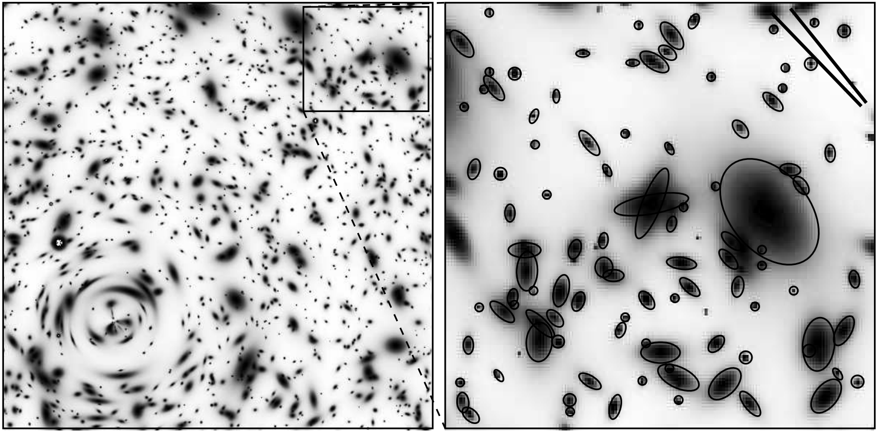
figure created by Michael Sachs

Gravitational Lensing

Characteristics

- Weak gravitational fields ($\Phi/c^2 \ll 1$)
- Purely geometric effect
- Achromatic
- Conserves surface brightness
- **Sensitive to any kind of matter**
- Independent of dynamical state (as long as non-relativistic)
- **Theoretically well-understood**
- Tow regimes:
  - Strong lensing (SL)
  - Weak lensing (WL)

Gravitational Lensing



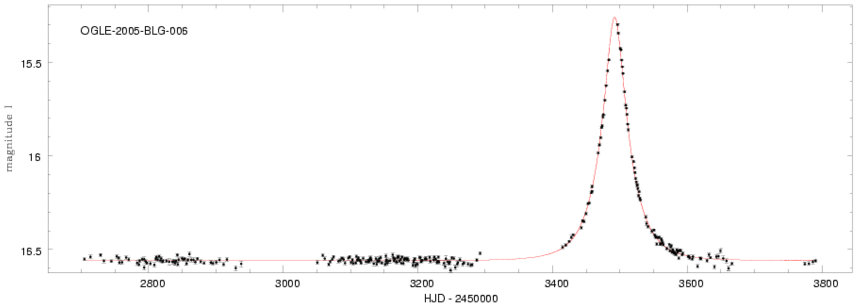
from Mellier (1999)

Gravitational Lensing

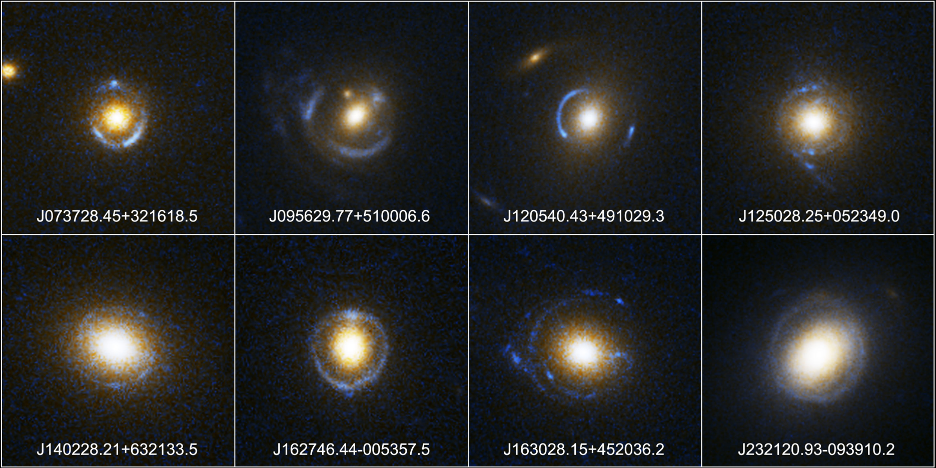
Can be used to study...

- Stars and substellar objects (SL also called micro-lensing)
- Galaxies (SL & WL)
- Galaxy clusters (SL & WL)
- Large-scale structure (WL)

Microlensing



from OGLE collaboration



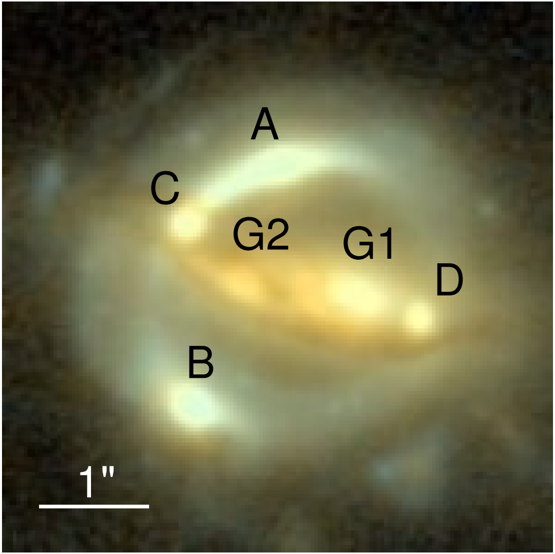
Einstein Ring Gravitational Lenses

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32

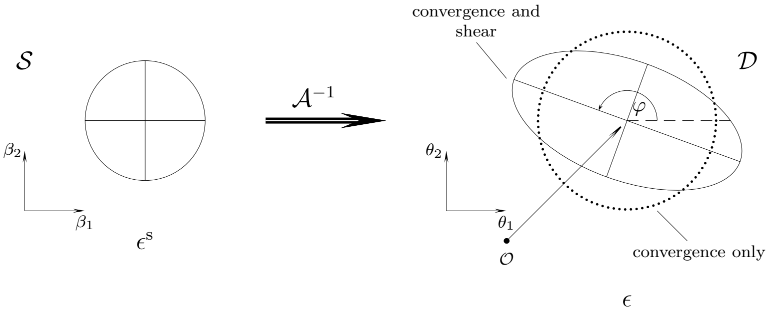
Time delays



from Suyu et al. (2010)

Credit: NASA, ESA, and A. Fruchter

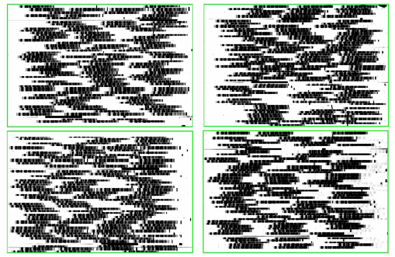
Weak lensing of a circular source



from P. Schneider, Saas Fee lecture on "Weak Gravitational Lensing"

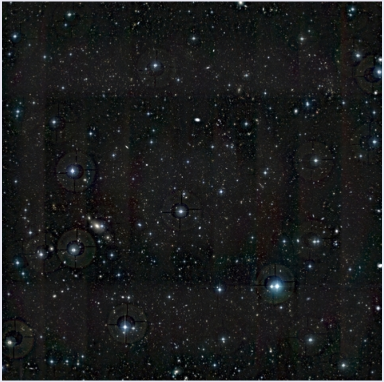
Spectroscopy vs. Photometry

VIMOS@VLT(8m)



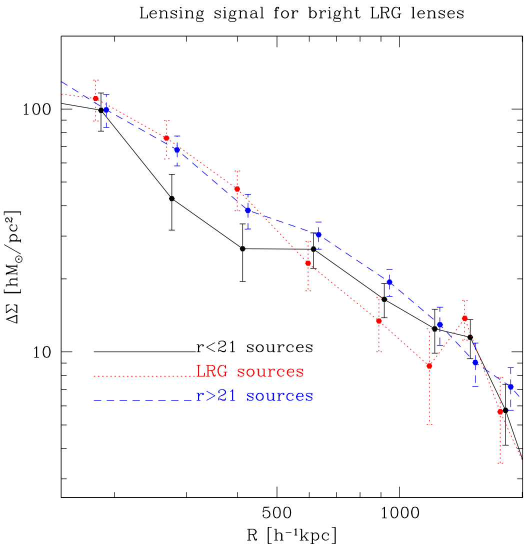
$\sim$ 500 objects in one shot,
$t_{\rm exp} \approx 4{\rm h}$ for $I_{\rm AB} < 24$

MEGACAM@CFHT(4m)



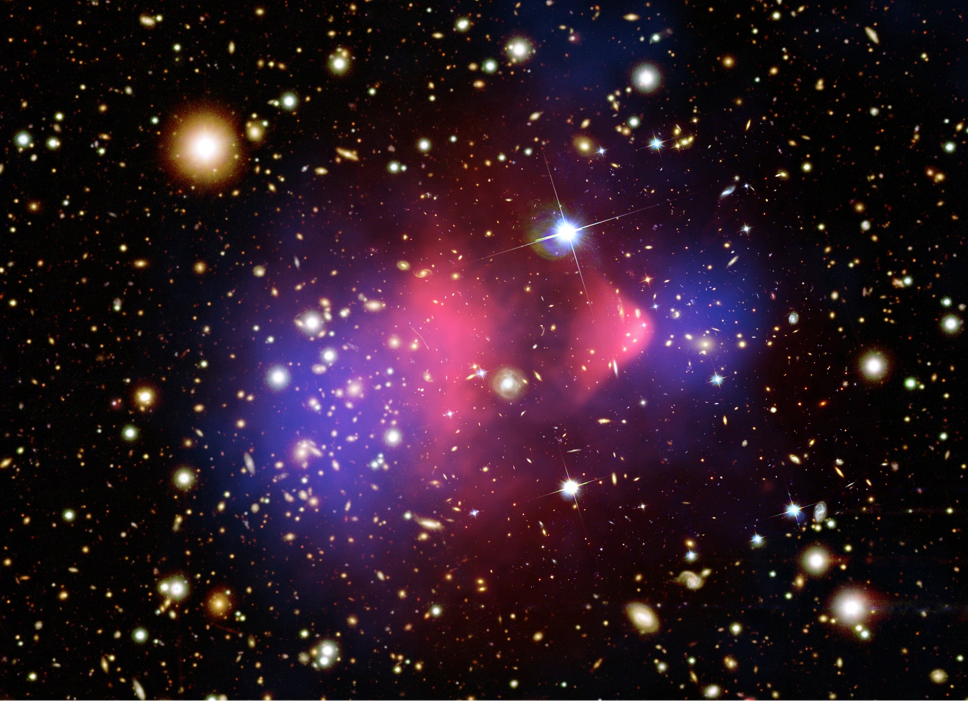
$\sim$ 50 000 objects in one shot,
$t_{\rm exp} \approx 5{\rm h}$ for $I_{\rm AB} < 24$ in *ugriz*

Galaxy-galaxy lensing



from Mandelbaum et al. (2006) using **15 635** lenses

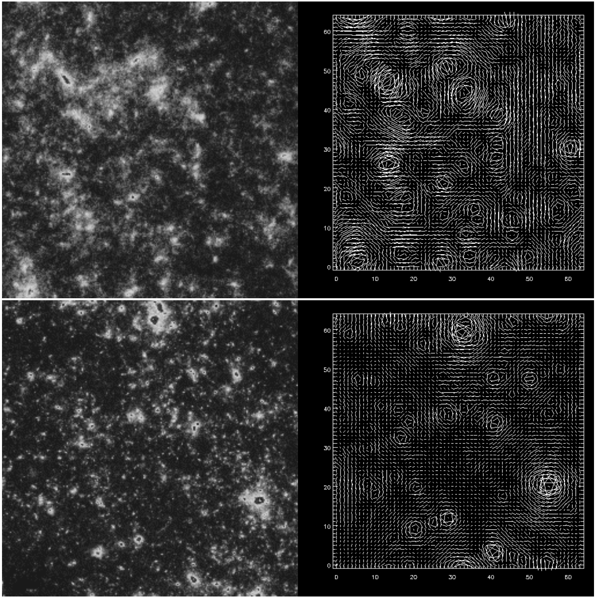
Credit: NASA, ESA, and the STAGES team, and C. Heymans



Credit: NASA, ESA, and D. Clowe

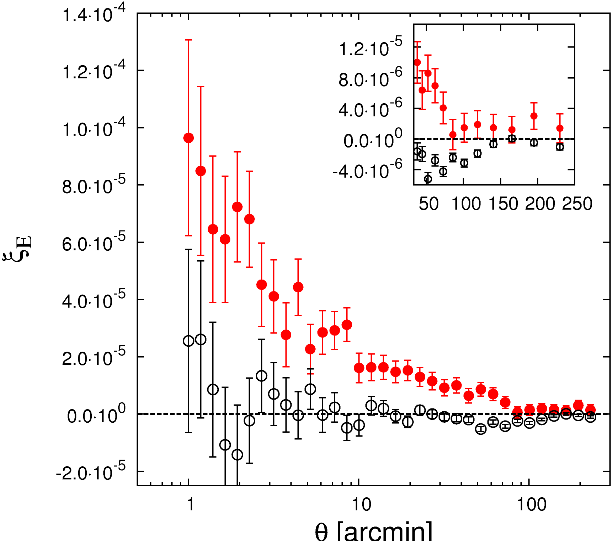
Credit: NASA, ESA, and M. Bradac

Ray-tracing simulations



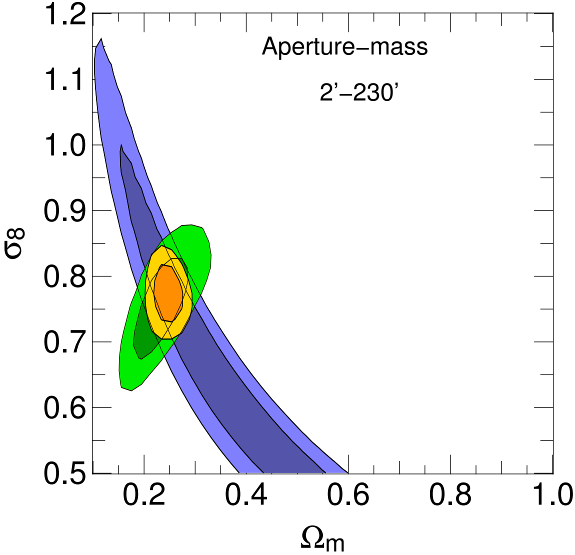
from Jain et al. (2000)

Cosmic shear correlation function



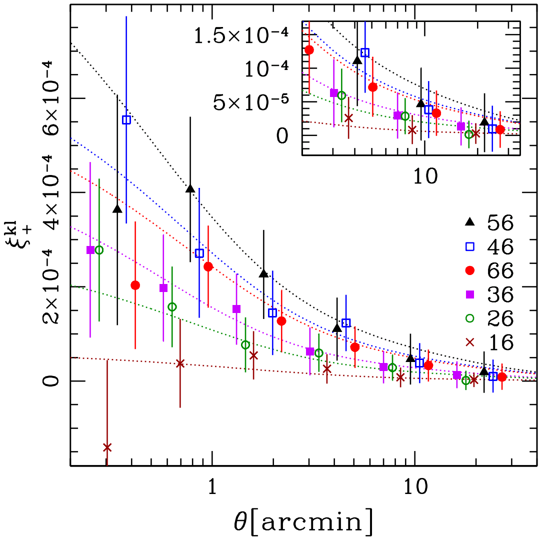
from Fu et al. (2008)

Cosmological constraints



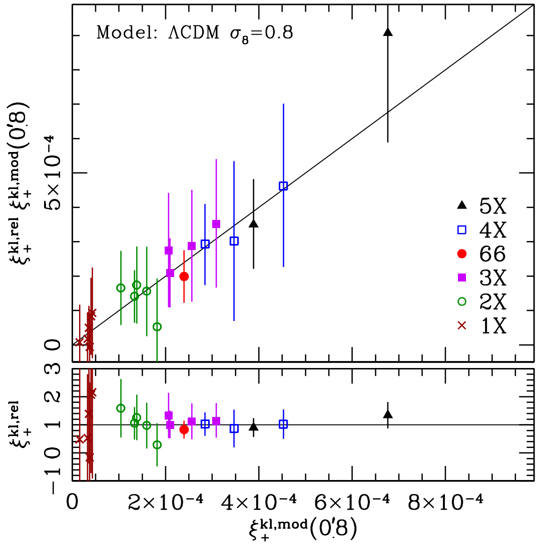
from Fu et al. (2008)

Cosmic shear tomography



from Schrabback et al. (2010)

Cosmic shear tomography



from Schrabback et al. (2010)

Summary

- Gravitational lensing is a unique tool to study the dark sector of the Universe.
- Evidence for dark matter through lensing in:
    - MACHOS in our galaxy (only small fraction of total DM)
    - Other galaxies (seen through SL and WL)
    - Galaxy clusters
    - Bullet cluster where it's separate from the hot gas
    - Large-scale structure
- Cosmic shear (weak lensing effect of the large-scale structure) is the most promising probe of dark energy.
- Cosmic shear can constrain modified gravity models by itself.