Measuring Dark Matter and Dark Energy with Gravitational Lensing

Hendrik Hildebrandt, UBC Vancouver

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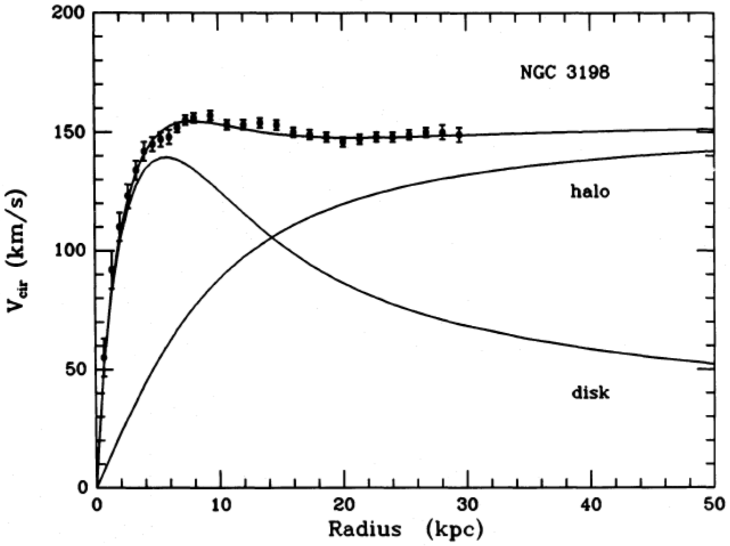
Outline

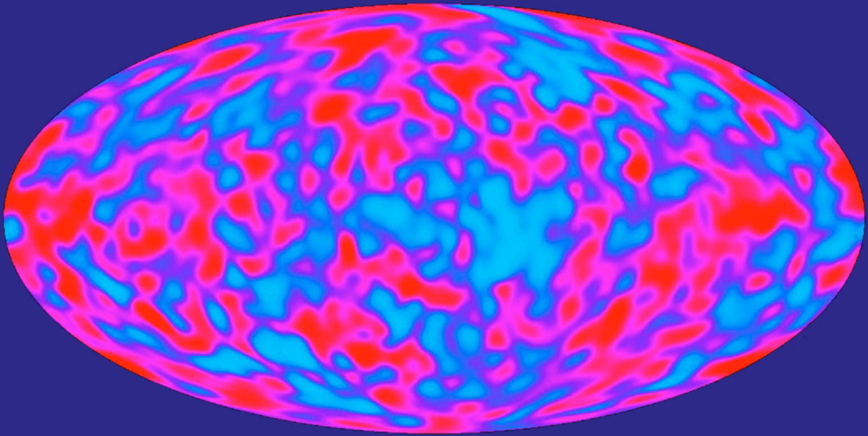
Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA), D. Carter and the Coma HST ACS Treasury Team

Galaxy rotation curves

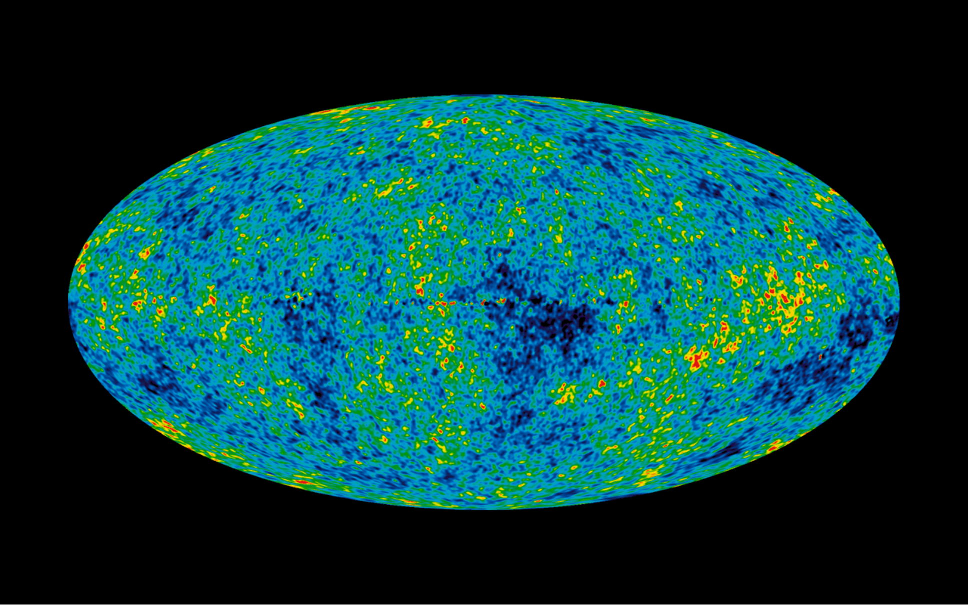


from van Albada et al. (1985)

DMR's Two Year CMB Anisotropy Result

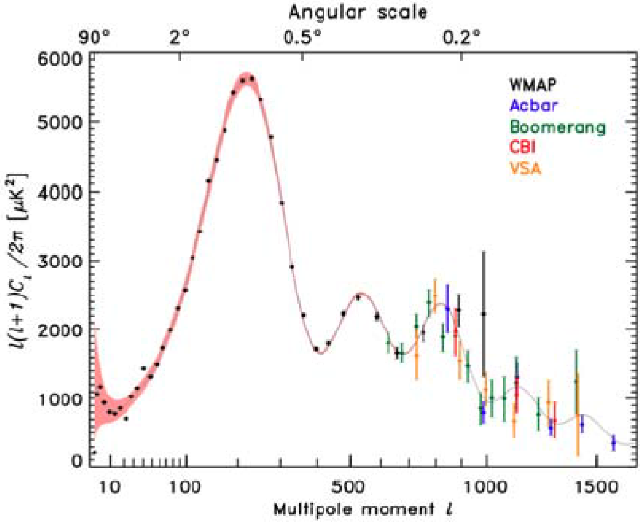


Credit: NASA and the COBE team



Credit: NASA / WMAP Science Team

CMB Power Spectrum



from Hinshaw et al. (2003)

Dark Matter

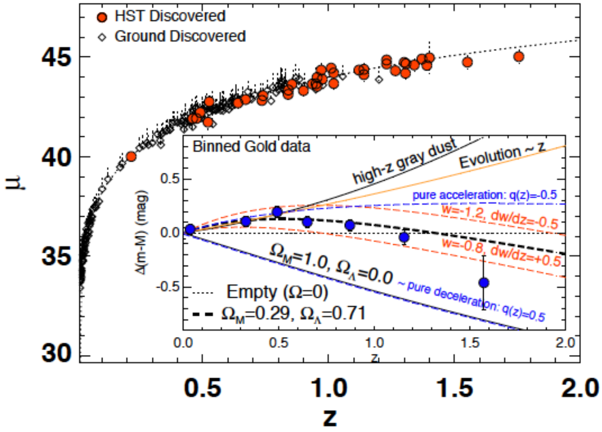
Properties

- Collisionless
- Dissipationless
- Cold (i.e. non-relativistic at matter-radiation equality)
  $\Rightarrow$ No standard-model neutrinos!
- 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

Accelerating expansion (Physics Nobel prize 2011)

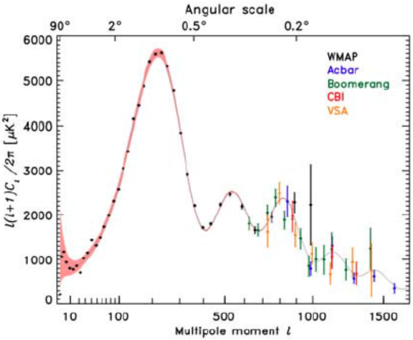


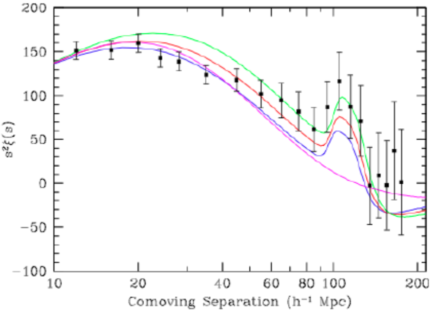
from Riess et al. (2007)

High-redshift supernovae of type Ia are fainter than expected in a decelerating universe.

We want to precisely measure the dark energy equation of state and its time evolution (w & w').

Baryon Acoustic Oscillations





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

Dark Energy

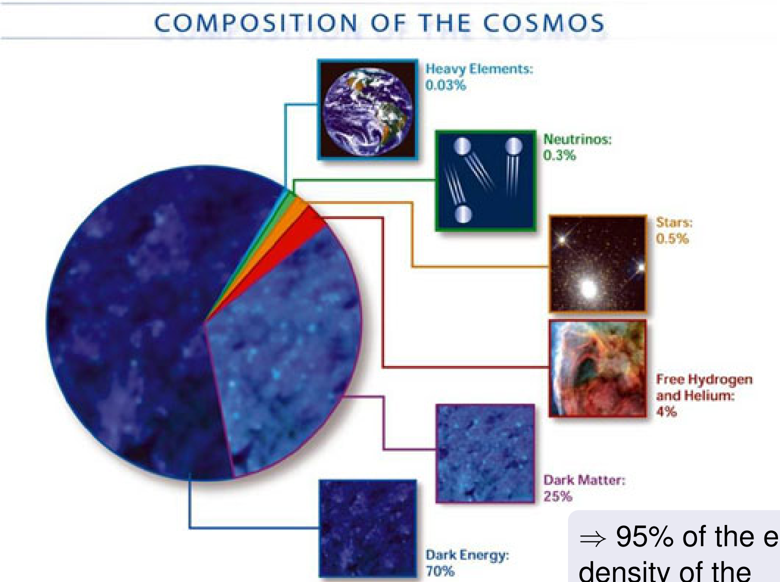
Effects

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

Probes

- Type Ia Supernovae (DR)
- Baryon Acoustic Oscillations (DR)
- Galaxy Cluster Mass Function (DR+GS)
- **Weak Gravitational Lensing (DR+GS)**

Note: CMB alone does **not** constrain dark energy.



from `http://www.lsst.org`

$\Rightarrow$ 95% of the energy density of the Universe is unknown.

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

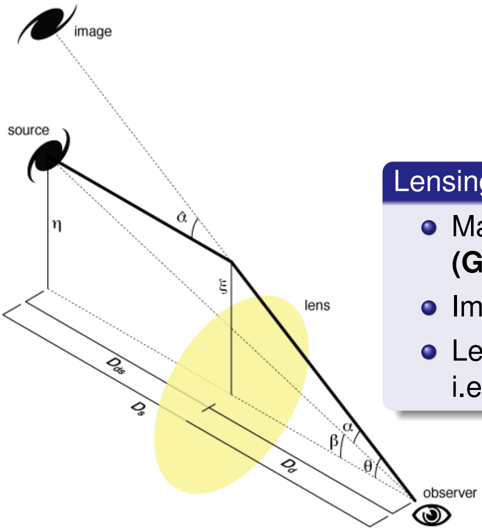


figure created by Michael Sachs

Lensing effect depends on:

- Mass (-distribution) of the lens **(GS)**
- Impact parameter ξ
- Lens-source geometry **(DR)**, i.e. the distances D_d, D_s, D_ds

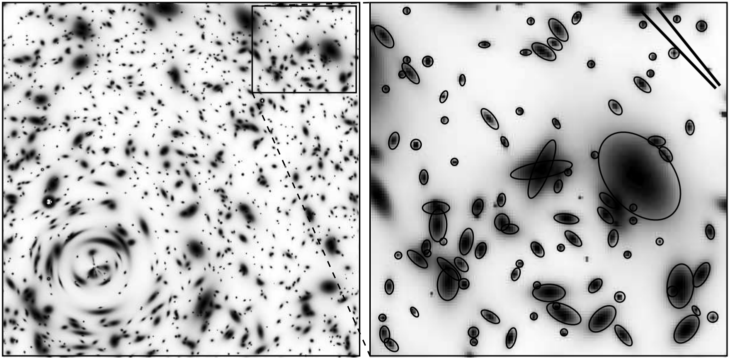
Gravitational Lensing

Characteristics

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

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

Weak Gravitational Lensing



from Mellier (1999)

In WL we measure weak, coherent distortions/magnifications of huge numbers of background galaxies in a statistical way.

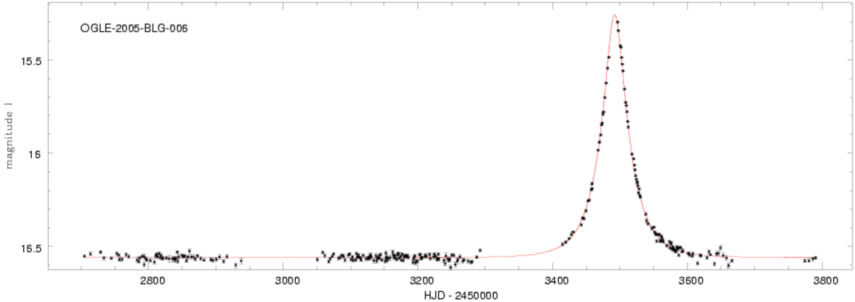
Combined with distances this yields the statistical properties of the DM field over cosmic time (sensitive to DE and GR).

Gravitational Lensing

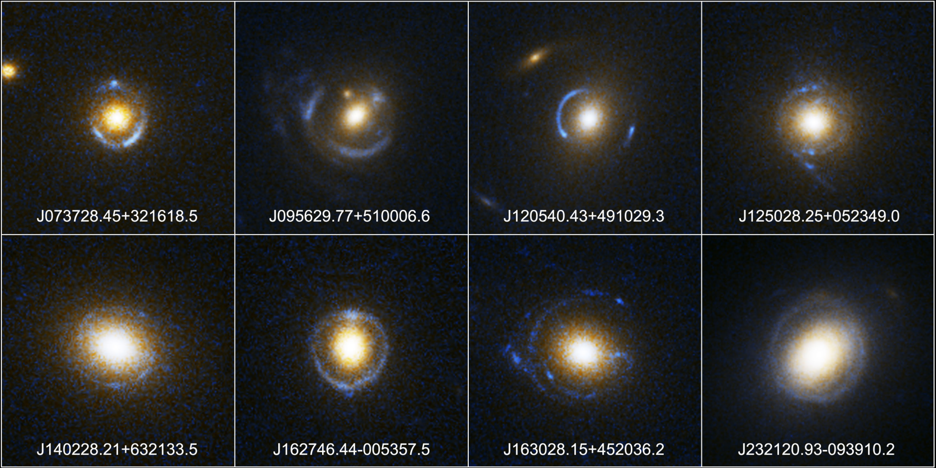
Can be used to study...

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

Microlensing



from OGLE collaboration



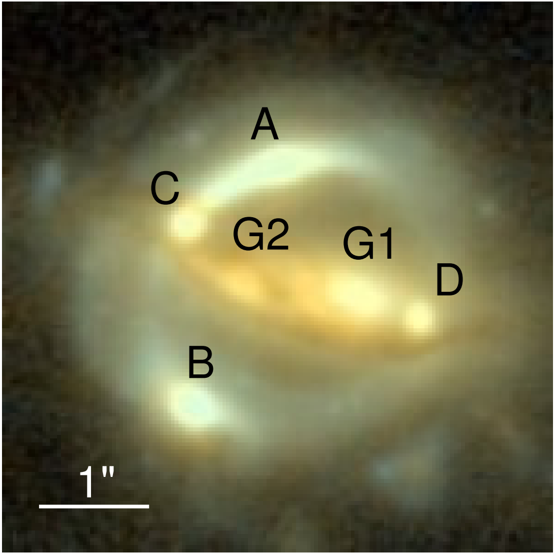
Einstein Ring Gravitational Lenses

Hubble Space Telescope • Advanced Camera for Surveys

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

STScI-PRC05-32

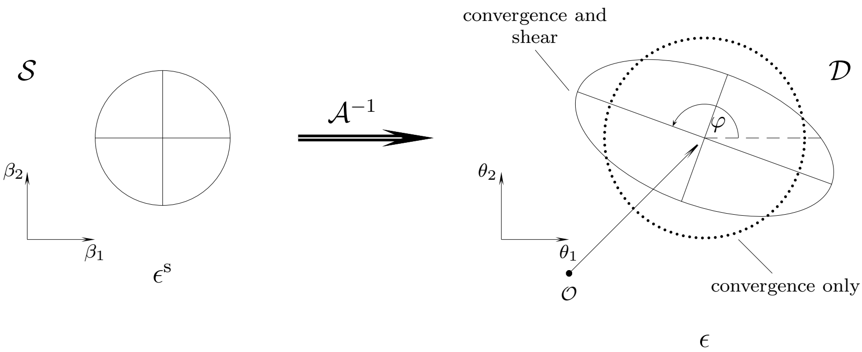
Time delays



from Suyu et al. (2010)

Credit: NASA, ESA, and A. Fruchter

Weak lensing of a circular source

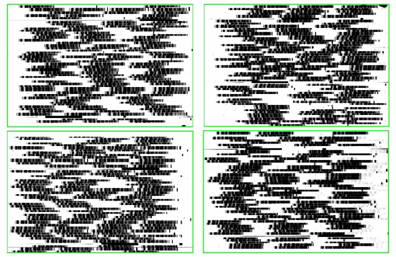


from P. Schneider, Saas Fee lecture on "Weak Gravitational Lensing"

1. Change in shape ⇒ **shear**, the traditional WL observable.
2. Change in size ⇒ **magnification**, largely neglected in the past.

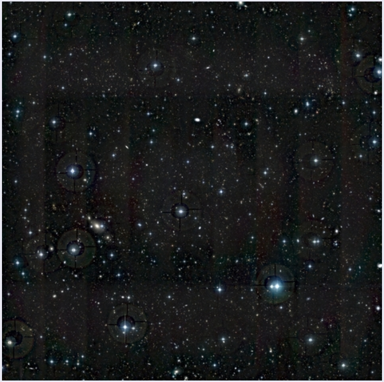
Spectroscopy vs. Photometry

VIMOS@VLT(8m)



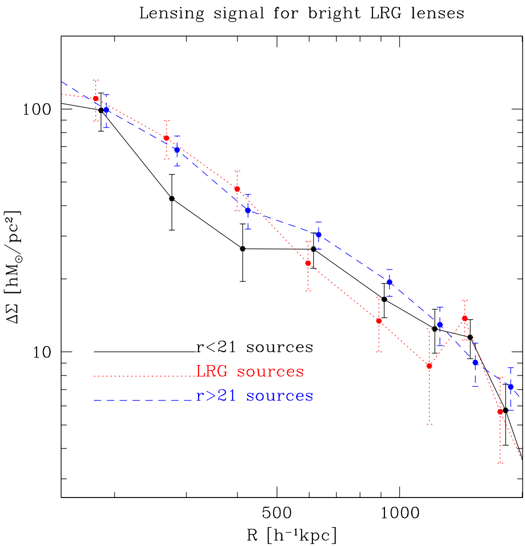
$\sim$ 500 objects in one shot,
$t_{\rm exp} \approx 4{\rm h}$ for $I_{\rm AB} < 24$

MEGACAM@CFHT(4m)



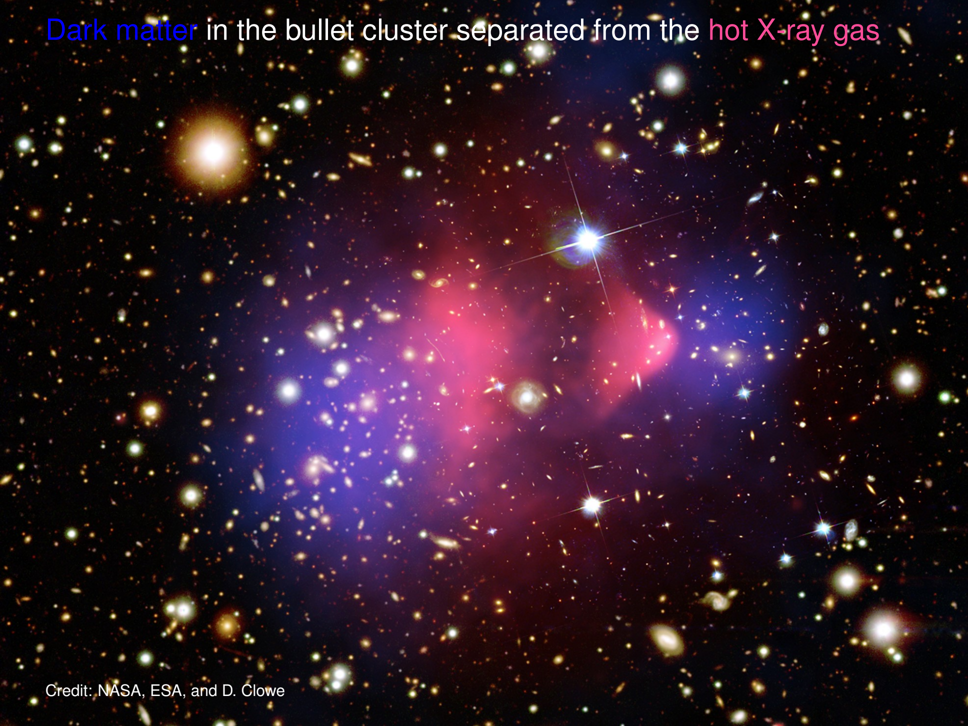
$\sim$ 50 000 objects in one shot,
$t_{\rm exp} \approx 5{\rm h}$ for $I_{\rm AB} < 24$ in *ugriz*

Galaxy-galaxy lensing



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

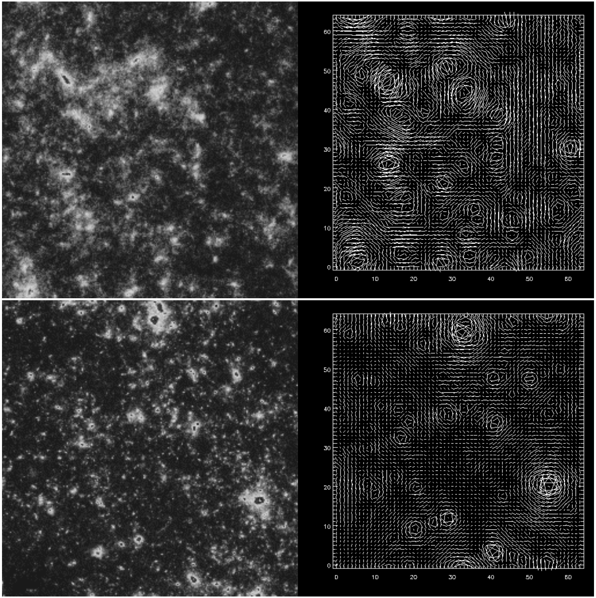
Credit: NASA, ESA, and the STAGES team, and C. Heymans



Credit: NASA, ESA, and D. Clowe

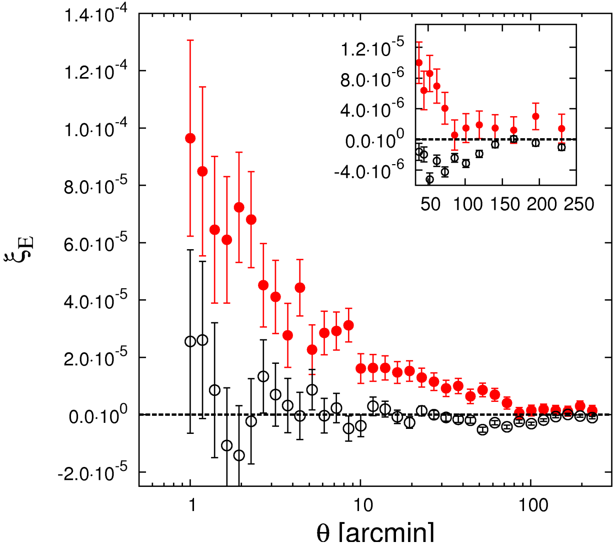
Credit: NASA, ESA, and M. Bradac

Ray-tracing simulations



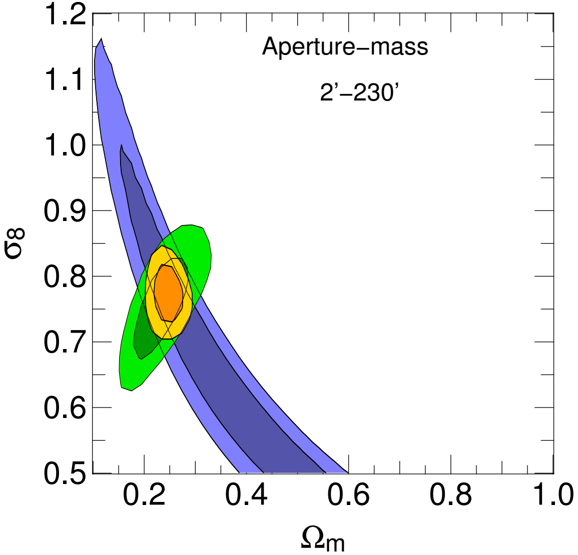
from Jain et al. (2000)

Cosmic shear correlation function



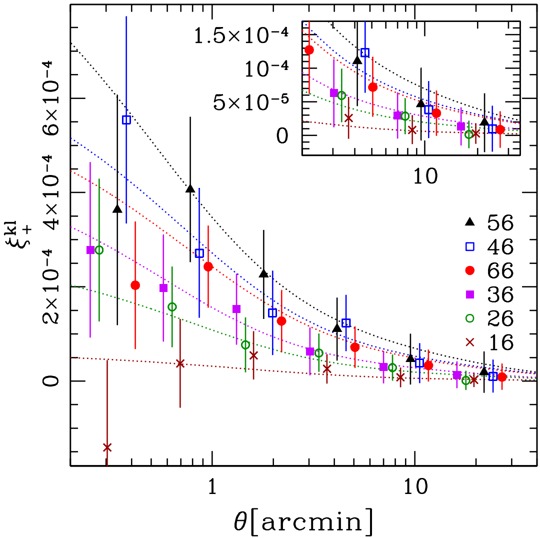
from Fu et al. (2008)

Cosmological constraints



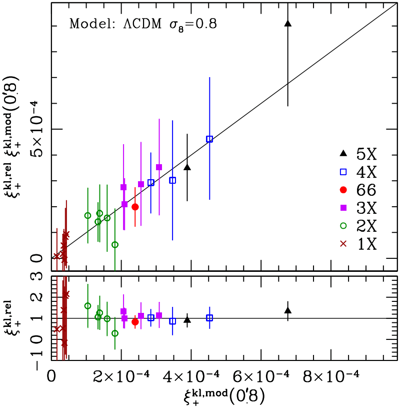
from Fu et al. (2008)

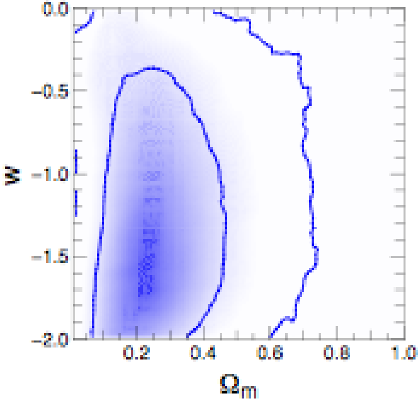
Cosmic shear tomography



from Schrabback et al. (2010)

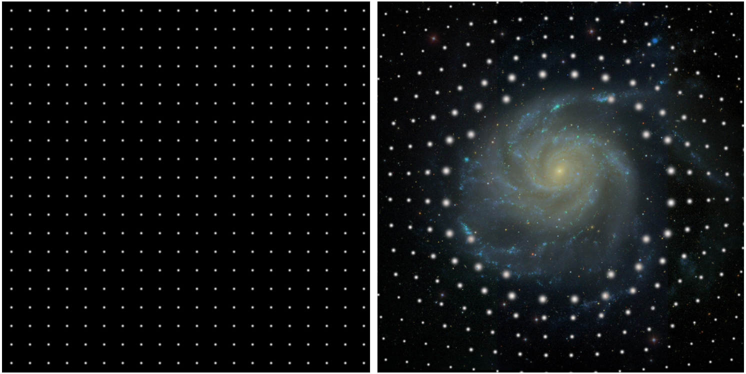
Cosmic shear tomography





from Schrabback et al. (2010)

Weak lensing magnification



from SDSS press release, April 26, 2005

Magnification (lensing galaxy not to scale)

1. Magnifies flux from background sources
2. Angular magnification reduces angular source density
3. Sensitive to dust

Data sets

Existing:

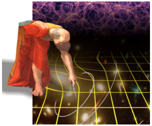
- CFHT Legacy Survey (170 sq. deg., deep)
- RCS2 (800 sq. deg., medium)
- SDSS Stripe 82 (200 sq. deg., deep)

Runnig/Near future:

- KiDS (ESO; 1 500 sq. deg., medium + IR)
- PanSTARRS (3π, shallow)
- DES (5 000 sq. deg., medium)
- Hyper Suprime Cam

Long term:

- **Euclid** (ESA; $\sim$700M€; launch 2019)
- LSST, WFIRST, ...



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.
- WL Magnification has the potential to add more statistical power, check for systematics, and go to higher redshifts.