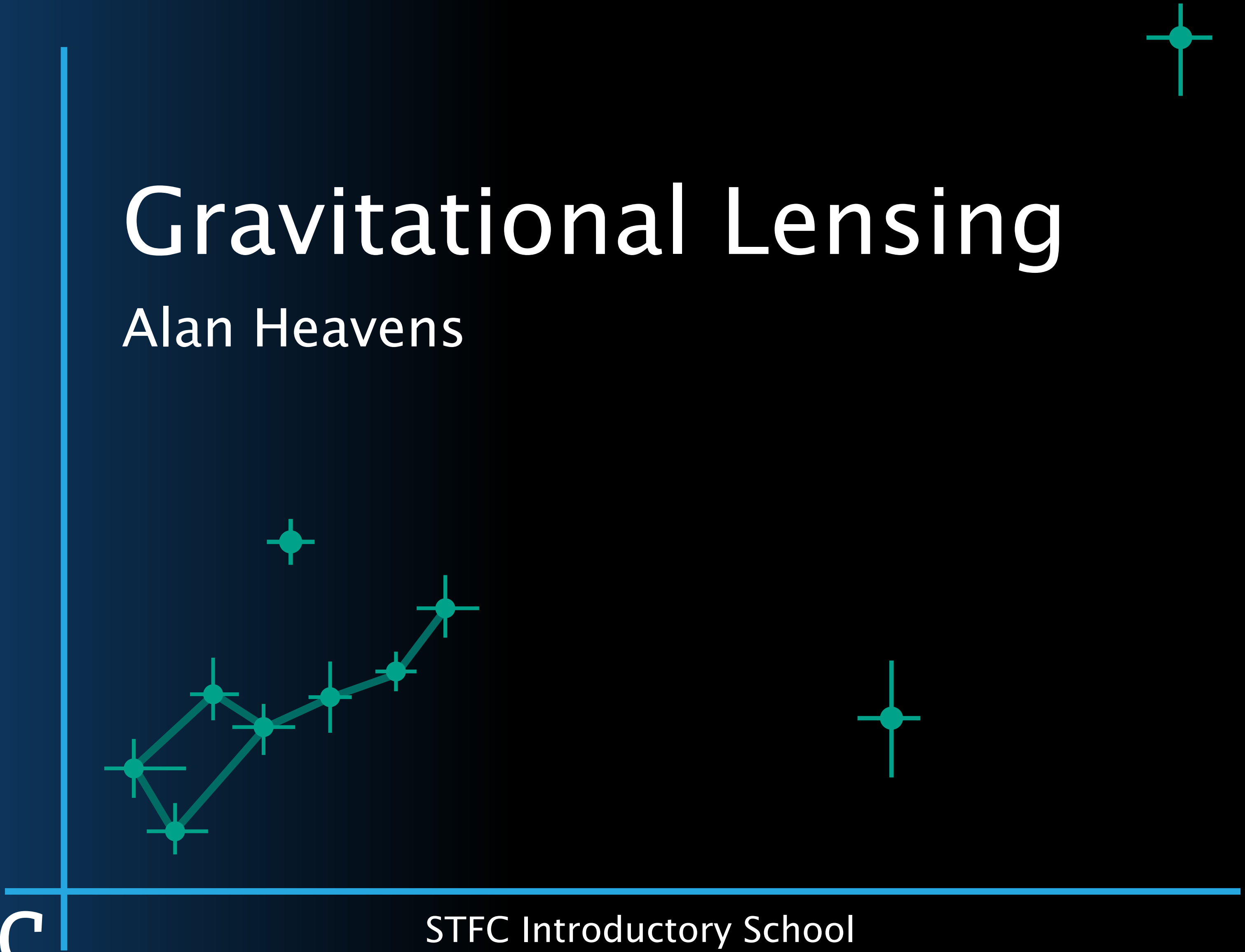
Gravitational Lensing

Alan Heavens



ICIC
Imperial Centre
for Inference & Cosmology

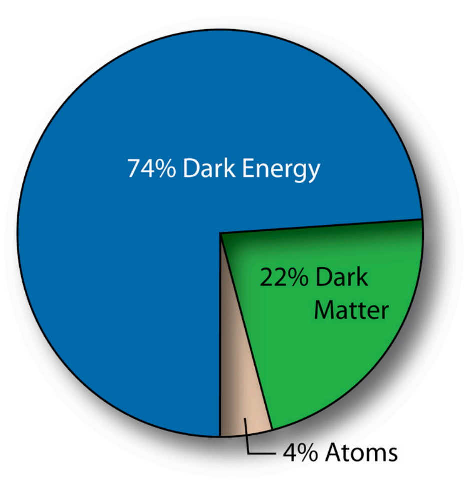
STFC Introductory School
3 September 2012
University of Sussex

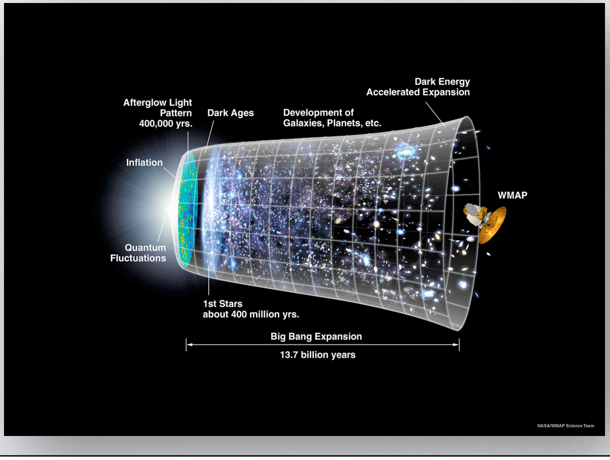
OUTLINE

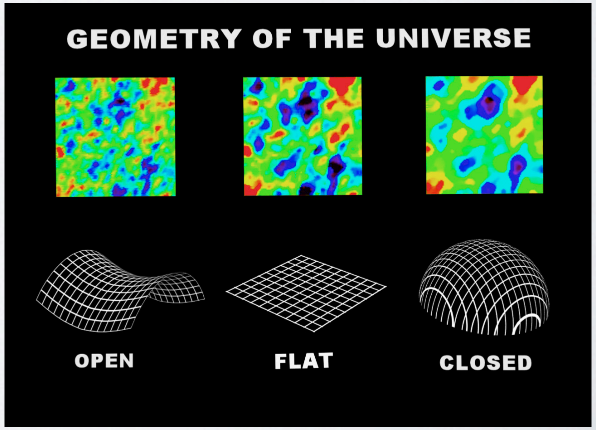
- THE DARK UNIVERSE THROUGH GRAVITATIONAL LENSING:
  - Dark Matter
    - Cross-sections
    - Neutrino masses and hierarchy
  - Dark Energy
  - Dark Gravity
    - Modified Newtonian Dynamics, MOND
    - Braneworlds, f(R) etc

STANDARD COSMOLOGICAL MODEL

- Universe is isotropic and homogeneous, started with Big Bang, is almost flat, governed by Einstein gravity, contains CDM, baryons, photons (++), a Cosmological Constant, and went through a period of rapid inflation, which produced adiabatic, near-gaussian fluctuations.





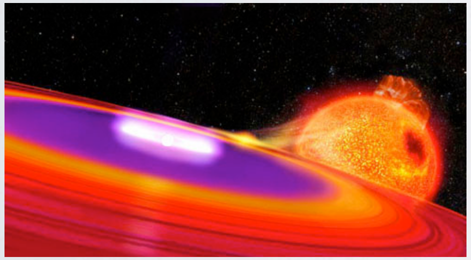


ACCELERATION OF THE UNIVERSE

Saul Perlmutter

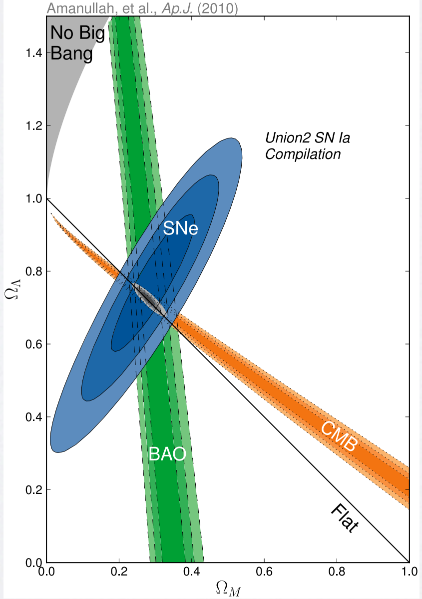
Brian Schmidt

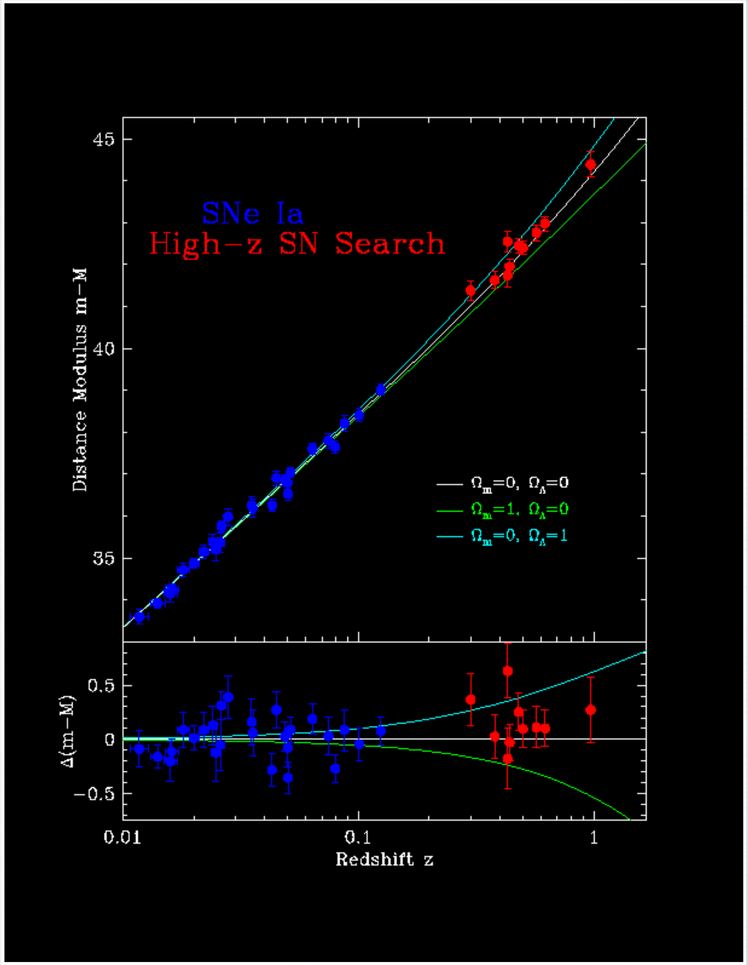
Adam Riess



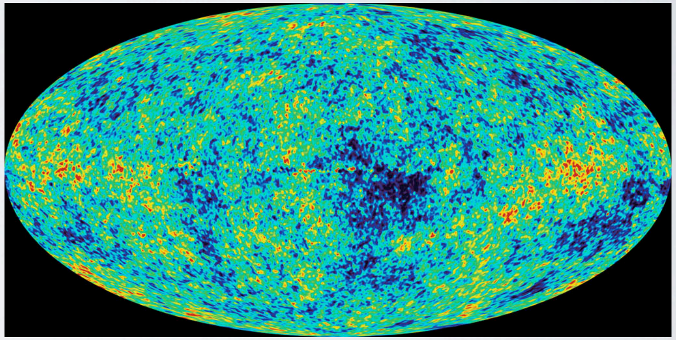
- Cosmological Constant?

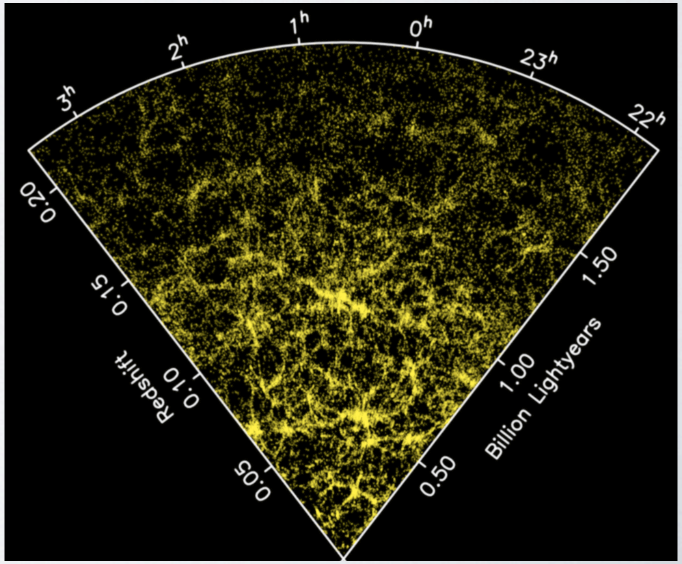
Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)





EXTRACTING INFORMATION FROM COSMOLOGY





- Global measurements (e.g. of geometry) are few
- Fluctuations are also high in information content
- CMB fluctuations - allows robust inference
- Galaxies are easy to measure but their fluctuations may not reflect fluctuations in mass (‘galaxy bias’)

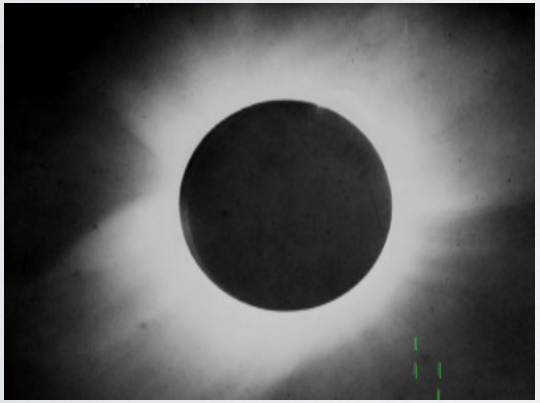
GRAVITATIONAL LENSING

- Coherent distortion of background images by gravity
- Shear, magnification, amplification

Jain & Seljak

- Independent of the *dynamical state* of matter
- Independent of the *nature* of matter   ROBUST INFERENCE

EARLY LENSING



LIGHTS ALL ASKEW IN THE HEAVENS

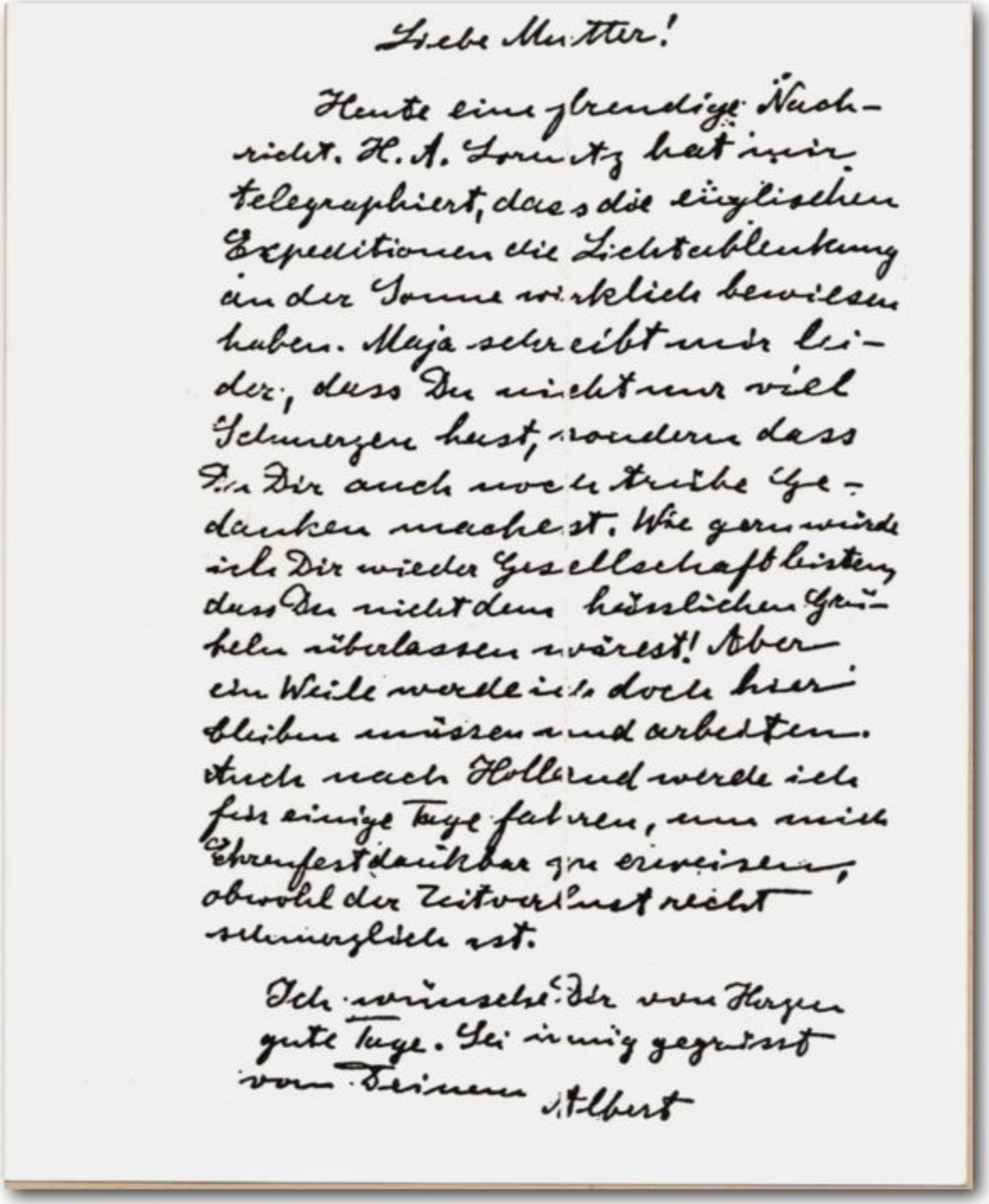
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

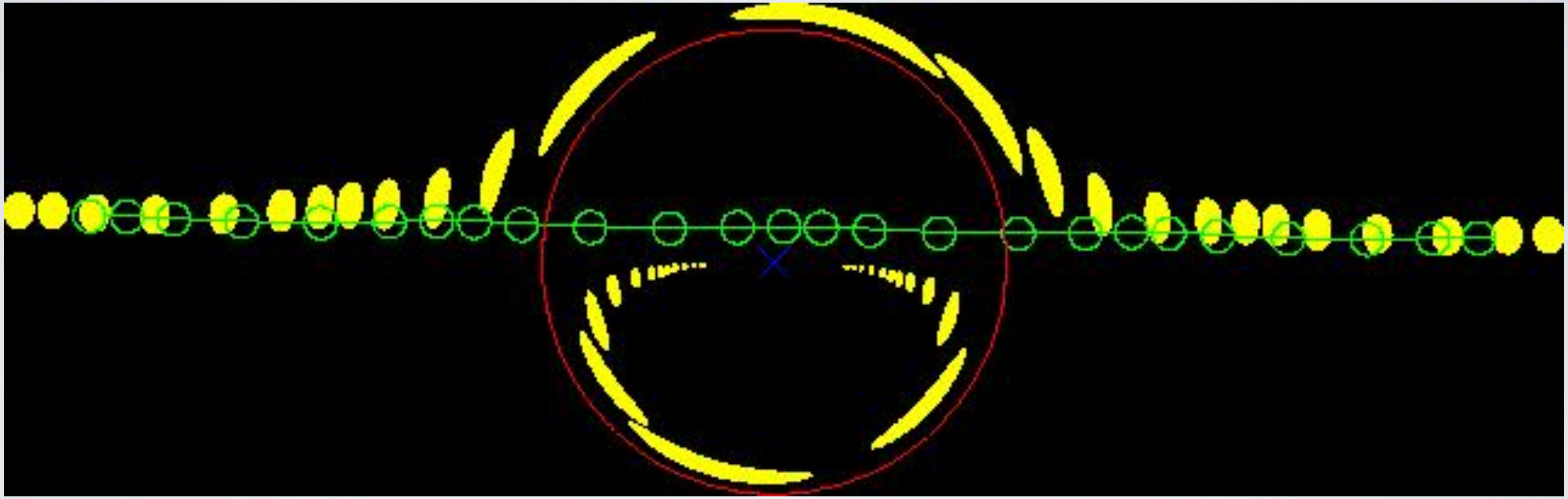


Liebe Mutter!

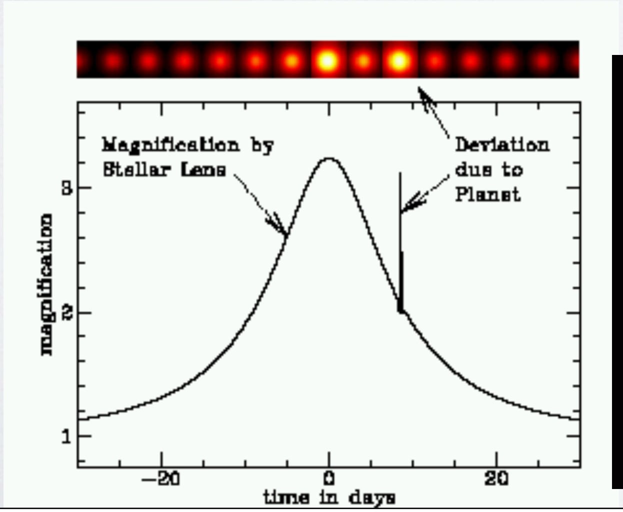
Heute eine freudige Nachricht. H. A. Lorentz hat mir telegraphiert, dass die englischen Expeditionen die Lichtablenkung an der Sonne wirklich bewiesen haben. Maja schreibt mir leider, dass Du nicht nur viel Schmerzen hast, sondern dass Du Dir auch noch trübe Gedanken machst. Wie gern würde ich Dir wieder Gesellschaft leisten, dass Du nicht dem hässlichen Grübeln überlassen wärest! Aber ein Weile werde ich doch hier bleiben müssen und arbeiten. Auch nach Holland werde ich für einige Tage fahren, um mich Ehrenfest dankbar zu erweisen, obwohl der Zeitverlust recht schmerzlich ist.

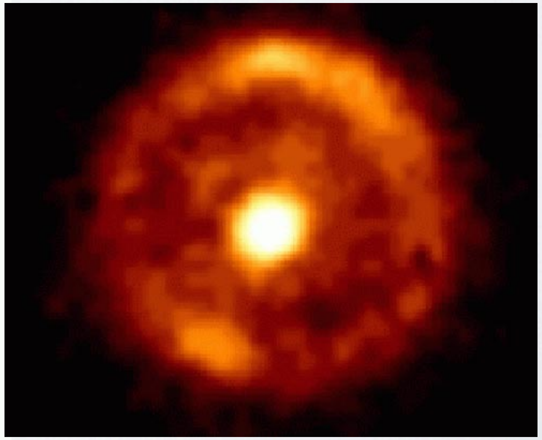
Ich wünsche Dir von Herzen gute Tage. Sei innig gegrüsst von Deinem Albert

STRONG LENSING



Microlensing





Einstein Ring

WEAK LENSING:
THE GEORGE W. BUSH YEARS

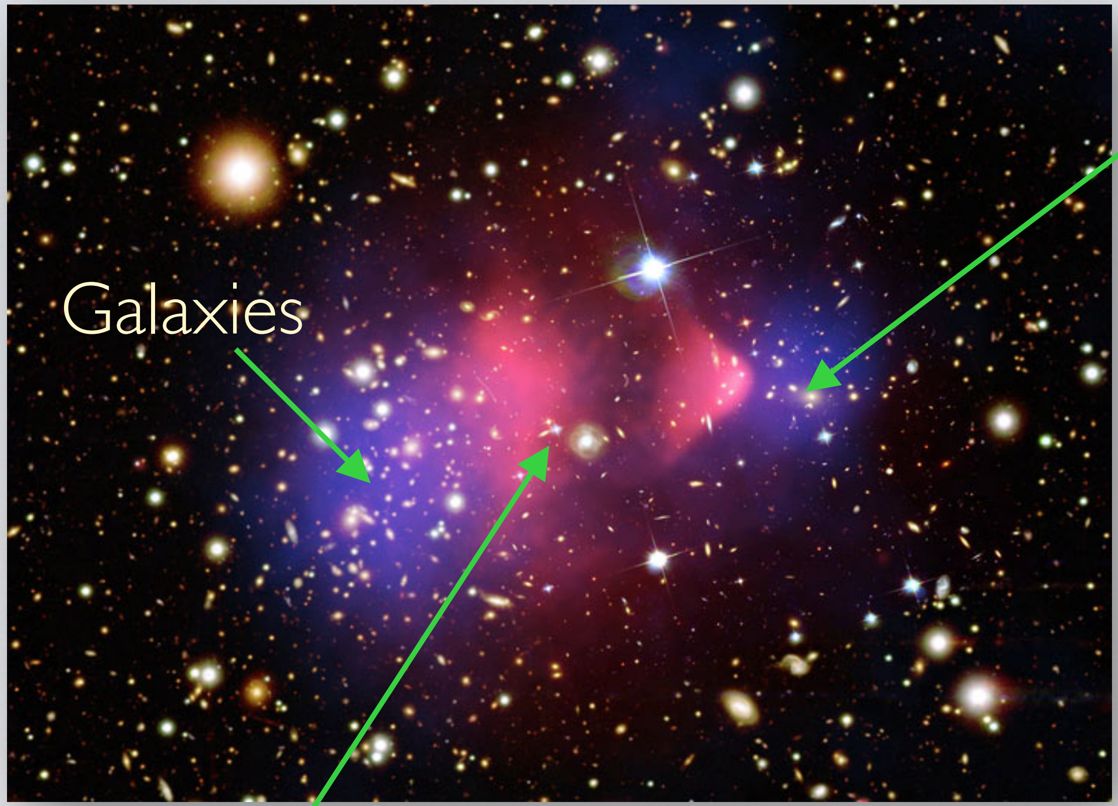
- 2000 First detections (Bacon et al, Kaiser et al, Wittman et al, van Waerbeke et al)
- 2002+ Weak-lensing selected cluster catalogues (e.g. Miyazake et al, Wittman et al)
- 2003+ Non-parametric masses in clusters (Kneib et al, Clowe et al, Jee et al, Gray++)
- 2003+ Matter power spectrum (Brown et al, Heymans et al, Hoekstra et al, Semboloni++)
- 2004 Bullet cluster challenge to MOND (Clowe et al)
- 2004+ 3D potential reconstruction (Taylor et al, Massey et al)
- 2005+ Evolution of structure (Bacon et al)
- 2006+ 3D analyses (Heavens et al, Kitching et al, Taylor et al)
- 2007 100 sq deg surveys, with small error bars (Benjamin et al, Fu et al)

  2010 COSMOS & CFHTLenS + first surveys designed for lensing (Pan-STARRS 1)

  2019+ Euclid, LSST

NO DARK MATTER? ‘BULLET CLUSTER’

- Challenges MOND, TeVeS



Dark Matter

(Lensing)

Hot Gas (X-ray)

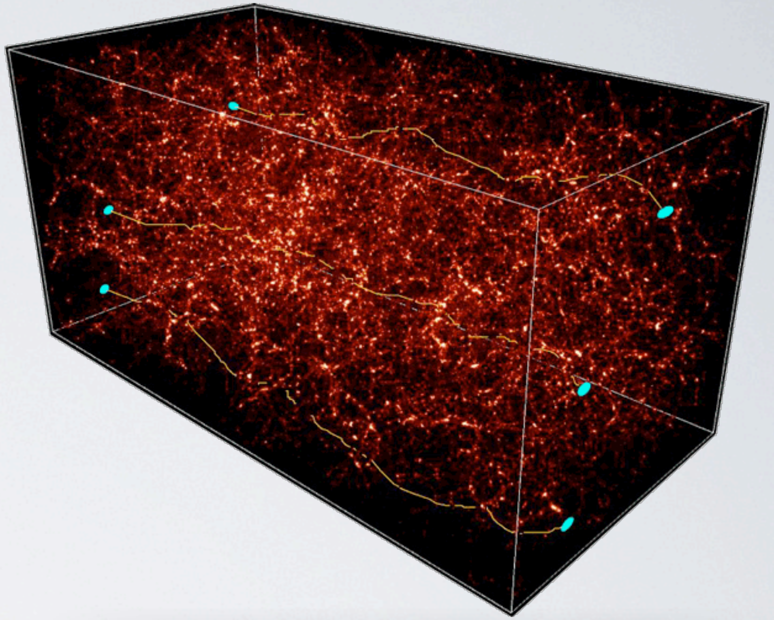
Markevitch et al 2002; Clowe et al 2004

Caveat: lensing measures the *convergence*, **κ**, which is proportional to surface density in GR, but *not* in general modified gravity models.

SELF-INTERACTING DARK MATTER?

- Bullet cluster ⟶ $\sigma/m < 0.12\ m^2/kg$ (Randall et al 2007)
- Limit is about 12 orders of magnitude larger that that of interest for particle physics for typical masses

WEAK GRAVITATIONAL LENSING



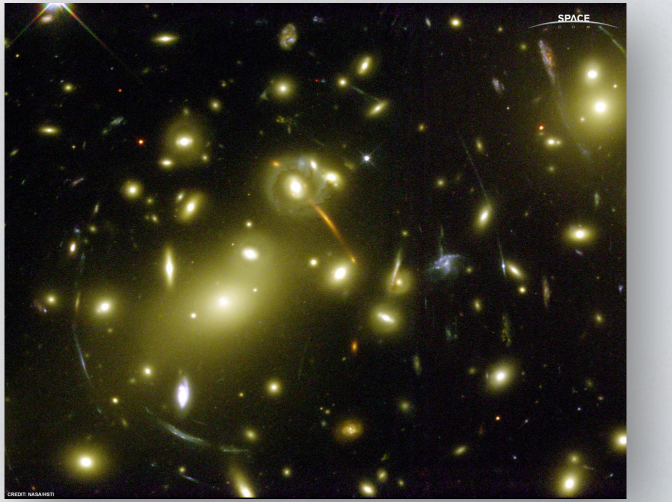
- For small scalar perturbations

$$ds^2 = \left(1+\frac{2\Phi}{c^2}\right)c^2dt^2 - \left(1-\frac{2\Psi}{c^2}\right)R^2(t)\left[dr^2+S_k^2(r)d\psi^2\right]$$

- In terms of conformal time [dη=dt/R(t)]

$$\boxed{\frac{d^2\mathbf{x}}{d\eta^2} = -\frac{1}{c^2}\nabla(\Phi+\Psi)}$$

$[\mathbf{x} = r(\theta_x, \theta_y)]$



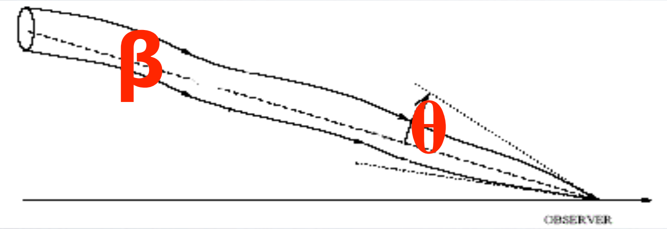
A2218 HST

If no anisotropic stress, and GR,

$\Phi=\Psi$

$$\frac{d^2\mathbf{x}}{d\eta^2} = -\frac{2}{c^2}\nabla\Phi$$

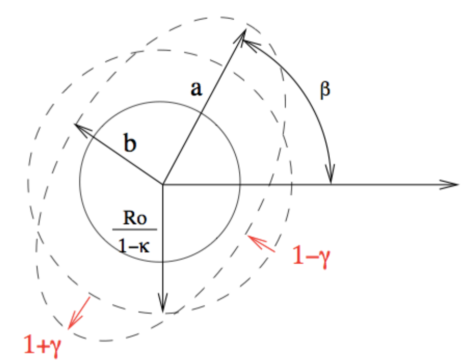
AMPLIFICATION, MAGNIFICATION & SHEAR



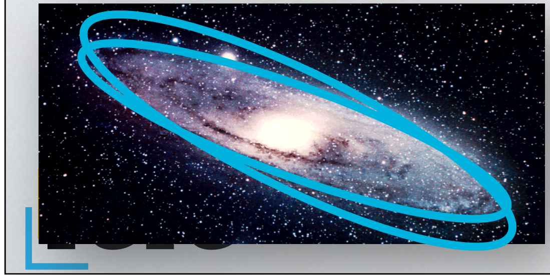
$$\frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \phi_{,ij} = \begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix} + \begin{pmatrix} \gamma_1 & -\gamma_2 \\ -\gamma_1 & -\gamma_1 \end{pmatrix}$$

Cosmological lensing potential (GR assumed):

$$\phi(\mathbf{r}) = \frac{2}{c^2} \int_0^r dr' \, \frac{S_k(r-r')}{S_k(r) S_k(r')} \Phi(\mathbf{r}')$$



Shear, magnification, amplification

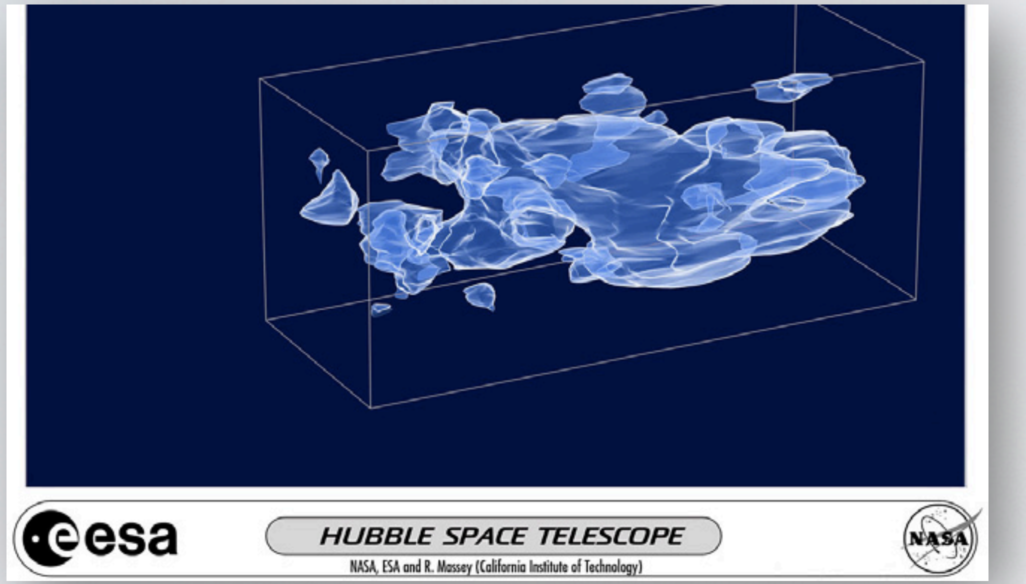


Note: dependence is on gravitational potential: lensing probes the *mass* distribution directly. Galaxy bias is not an issue.

Matter distribution need not be relaxed.

3D RECONSTRUCTION: COSMOS FIELD

- COSMOS data (Massey et al 2007)



Beware! poor resolution in *z* (200 Mpc)

SENSITIVITY TO COSMOLOGY

- Cosmic Shear statistical properties depend on

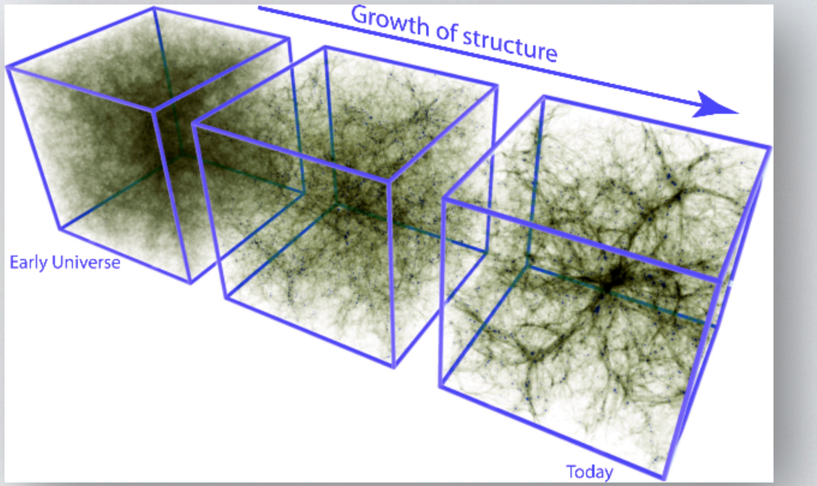
$$\phi(\mathbf{r}) = \frac{2}{c^2}\int_0^r dr' \frac{S_k(r-r')}{S_k(r)S_k(r')}\Phi(\mathbf{r}')$$

a) how clumpy the Universe is, and its *growth rate*, i.e. P(k;t)

b) the source distances, hence the *distance-redshift relation*, r(z)

c) The *gravity law* (e.g. modified Poisson equations)

$$\phi(\vec{r}) = \frac{1}{c^2}\int_0^r \frac{S_k(r-r')}{S_k(r)S_k(r')}\,[\Phi(\vec{r})+\Psi(\vec{r})]$$



Euclid proposal

DARK ENERGY

- Measurable Effects of Dark Energy:
  - Distance-redshift relation

$p_q = w(a)\ \rho_q c^2$
$a(t) = R(t)/R(\mathrm{now})$

$$r = \int_0^z dz' \frac{c}{H(z')} \qquad H(t) = \frac{1}{R}\frac{dR}{dt}$$

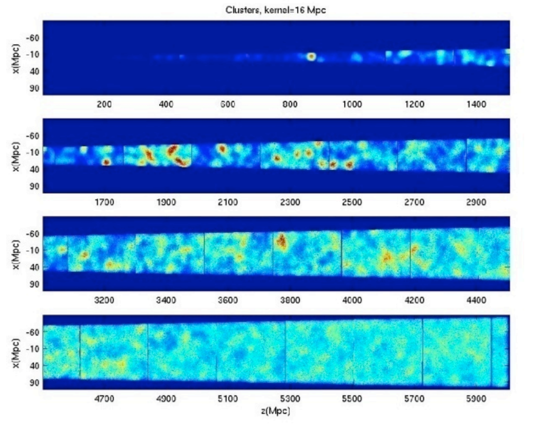
where the Hubble parameter is given by

$$H^2(a) = H_0^2\left[\Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_q \exp\left(3\int_1^a \frac{da'}{a'}\left[1 + w(a')\right]\right)\right]$$

  - Growth rate of perturbations (via H(a))

Assuming DE is smooth,

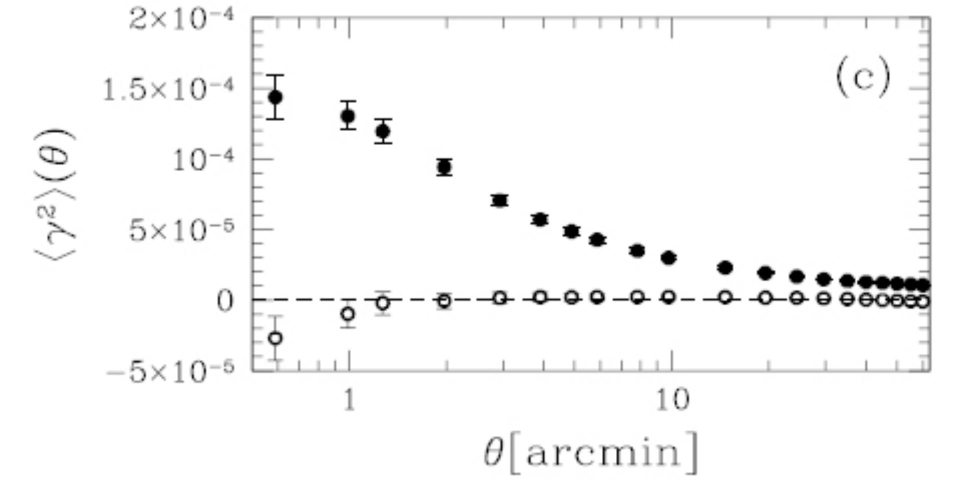
$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_m\delta = 0$$



Assumes GR. δ = fractional mass overdensity

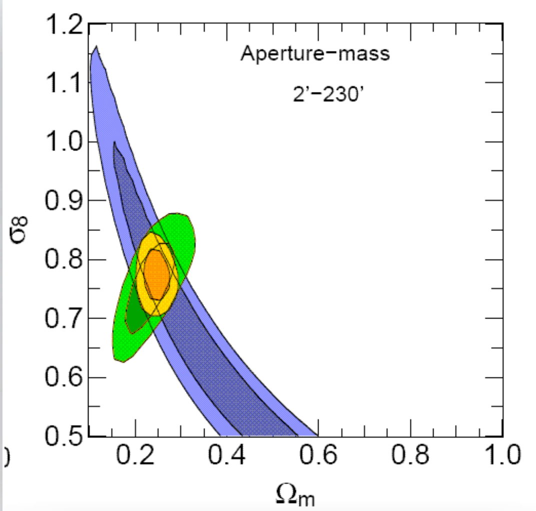
RECENT RESULTS: CFHTLS AND COSMOS

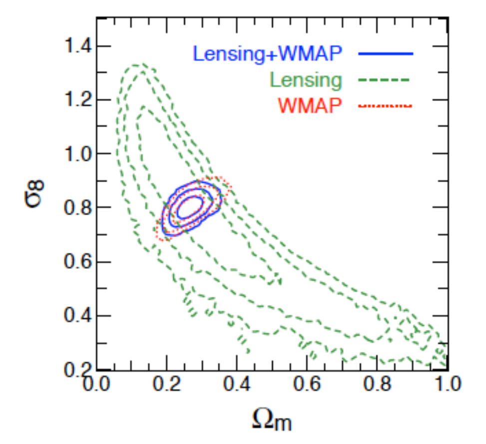
New CFHTLS results soon



100 sq deg; median z=0.8

Hoekstra et al 2005; Benjamin et al. 2007; see also Semboloni et al 2005

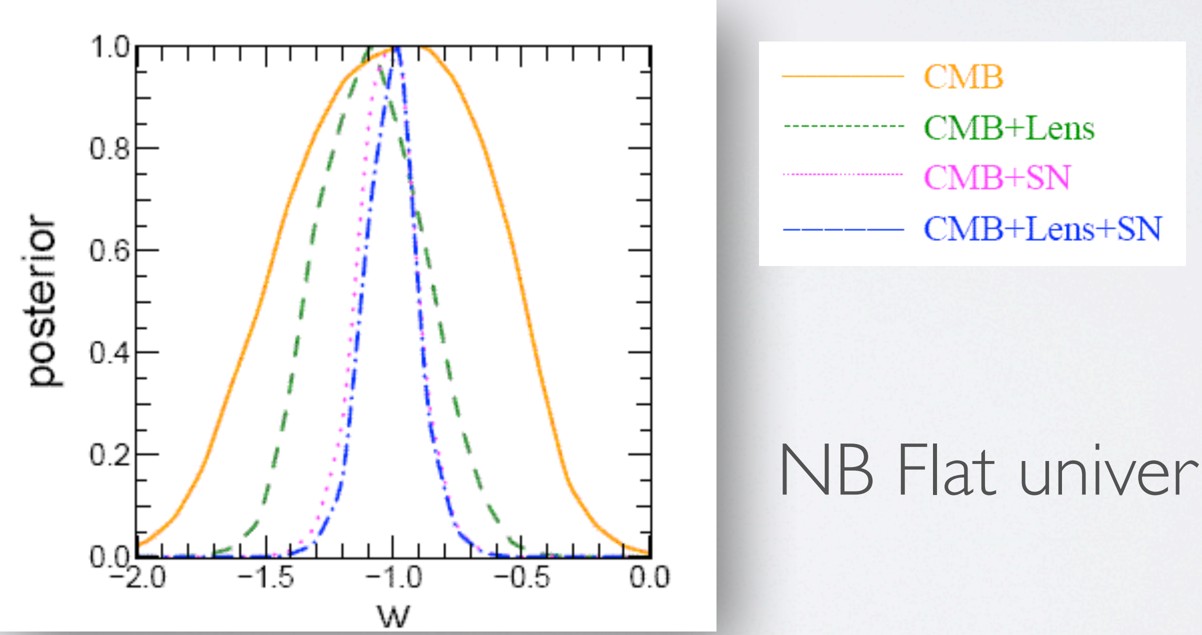




Schrabback et al 2010

DARK ENERGY PROPERTIES: IS W = -1?

- CFHTLS: $-1.18 < w < -0.88$ (95%) $[p=w\rho c^2]$



NB Flat universe assumed

Kilbinger et al (2009)

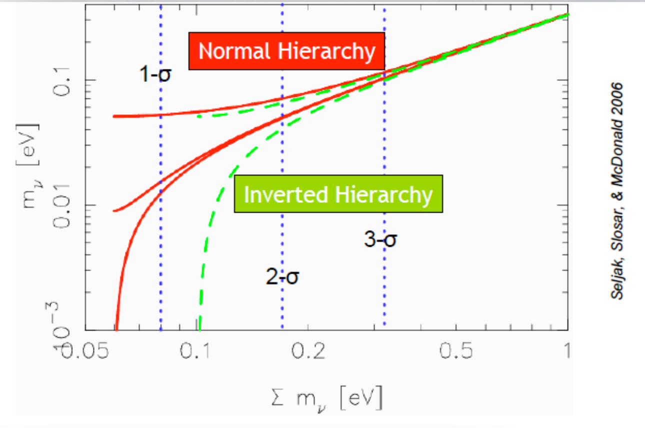
ICIC

DARK MATTER: NEUTRINOS

- Neutrino oscillation experiments give: -

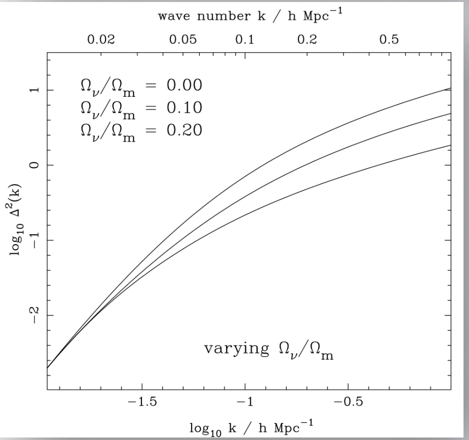
$$\Delta m^2_{12} = 7.9^{+1.0}_{-0.8} \times 10^{-5}\mathrm{eV}^2$$
$$|\Delta m^2_{23}| = 2.2^{+1.1}_{-0.8} \times 10^{-3}\mathrm{eV}^2$$

- Since they interact only weakly/gravitationally, they can exit from small perturbations and partially erase them.



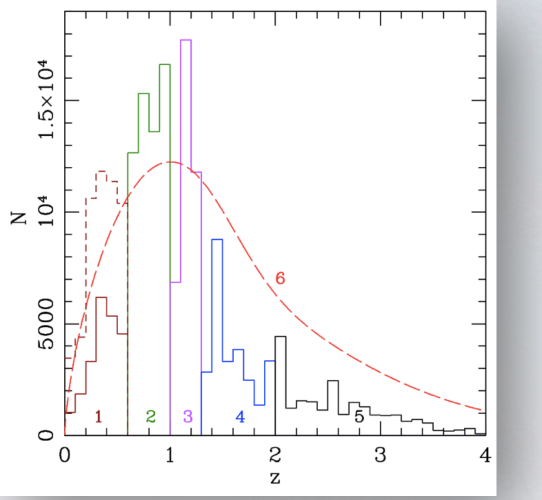
Seljak, Slosar, & McDonald 2006

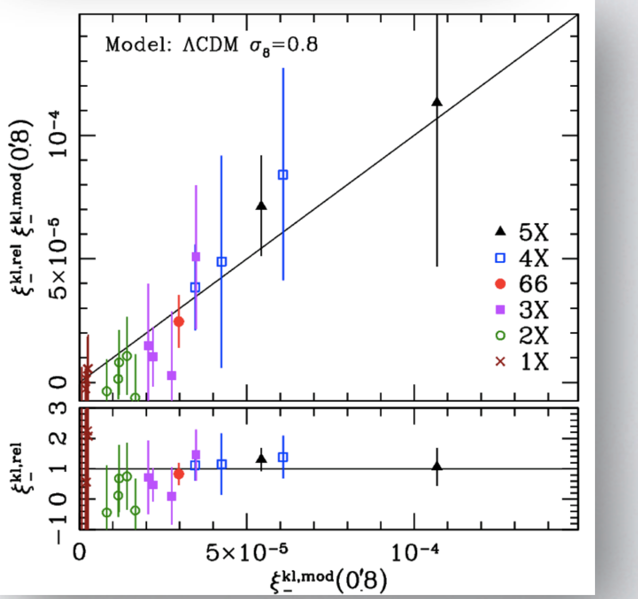
- Free-streaming length is 37 (m_ν/eV)$^{-1}$ Mpc; affects the matter power spectrum – most sensitive to Σ m_ν
- In principle, one can measure *individual* masses (de Bernardis et al 2009, but see Jimenez et al 2010)
- Expected error on sum with Planck and Euclid weak lensing: 0.037eV
- (see also Kitching et al 2008, Hannestad et al 2006; also lensing of CMB)



TOMOGRAPHY

- Use knowledge of source redshifts - better
- Bin galaxies according to their estimated redshift (‘tomography’)
- Powerful check on systematics, and probe for new physics
- COSMOS (Schrabback et al 2010) show expected scaling of lensing signal with redshift:

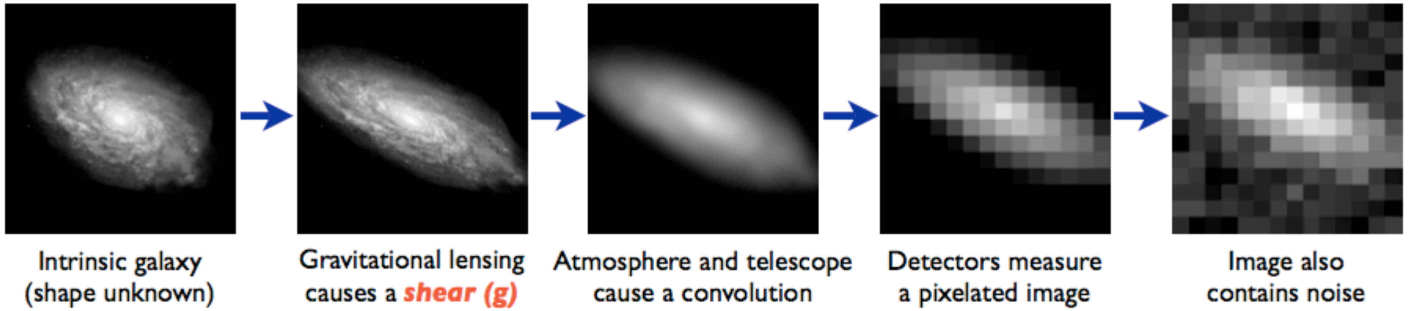




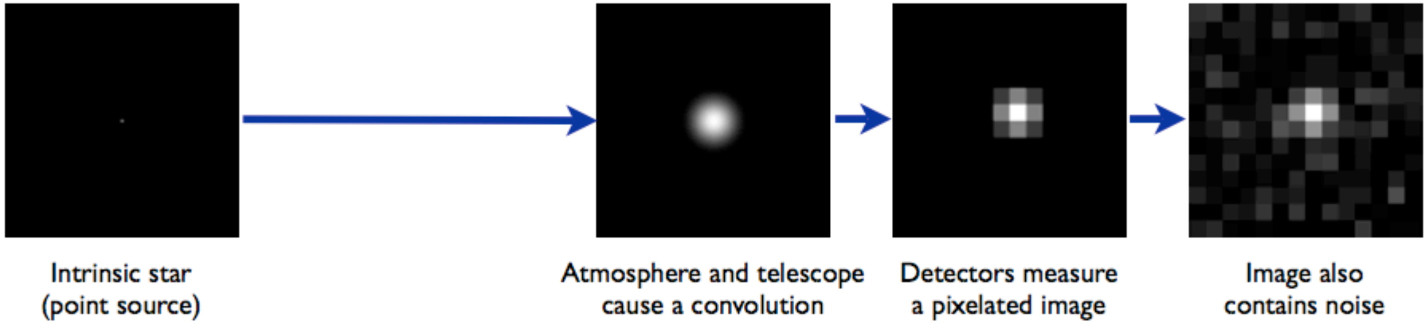
SOME CHALLENGES

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:

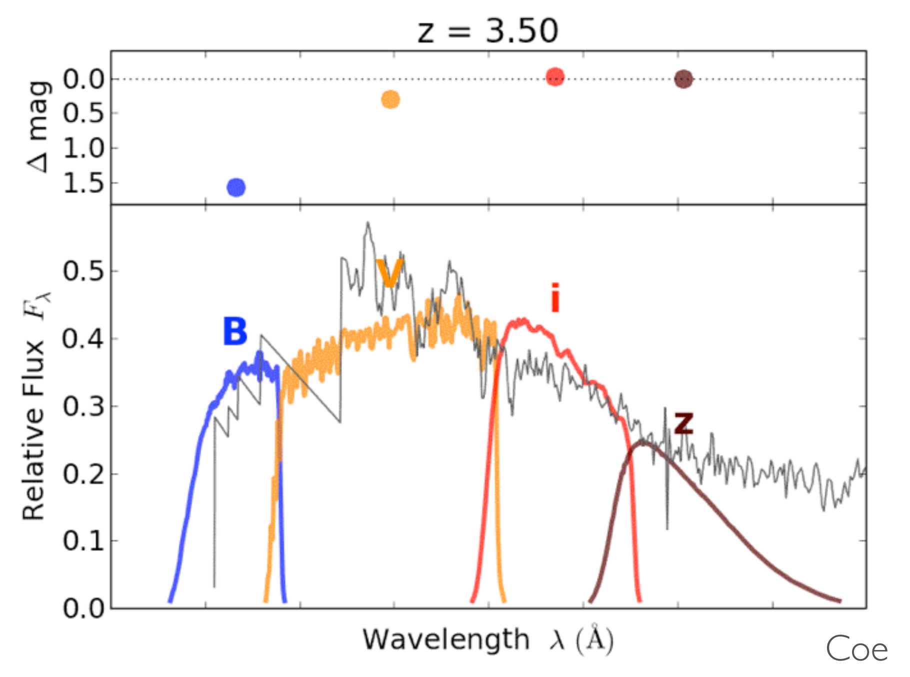


Stars: Point sources to star images:

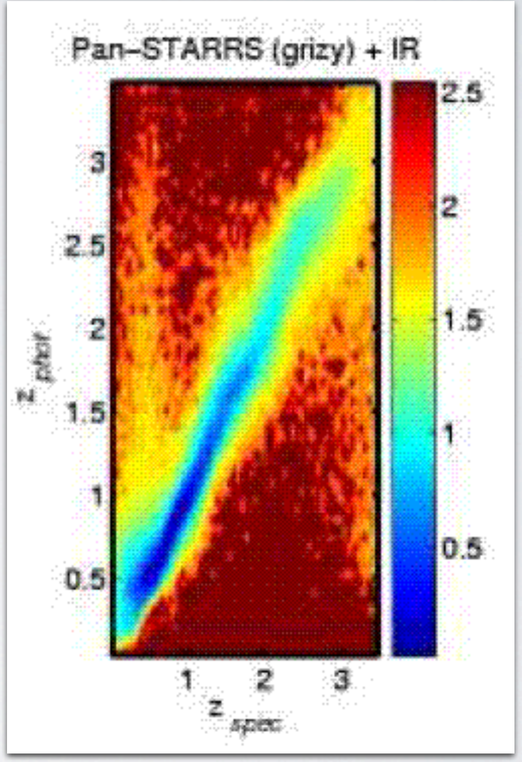


DISTANCES ARE ROUGH

- Photometric redshifts (or 'photozs')
- Rough redshift from broad-band colours



Coe



Abdalla et al 2007

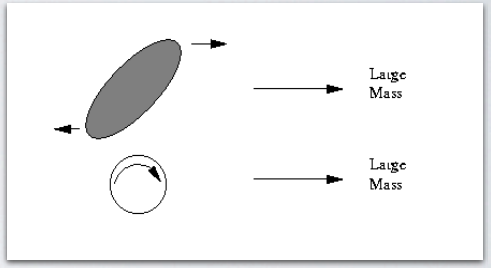
Error in z ~ 0.1

INTRINSIC ALIGNMENTS

- Image Ellipticity = Source Ellipticity + Shear

$$e = \gamma + e_s$$

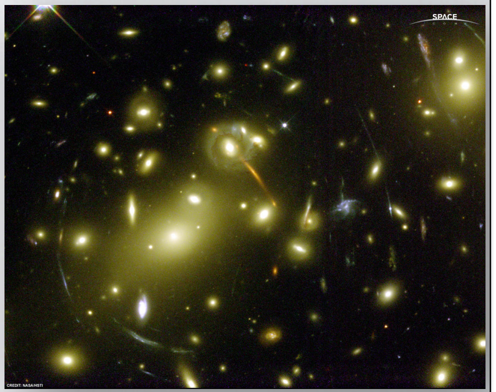
- Dispersion in e_s is ~0.3; shear is ~0.02



- Two-point statistics (1=foreground 2=background):

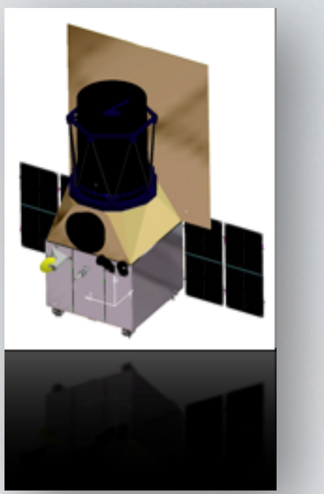
$$\langle e_1 e_2^* \rangle = \langle \gamma_1 \gamma_2^* \rangle + \langle \gamma_1 e_{s2}^* \rangle + \langle e_{s1} \gamma_2^* \rangle + \langle e_{s1} e_{s2}^* \rangle$$

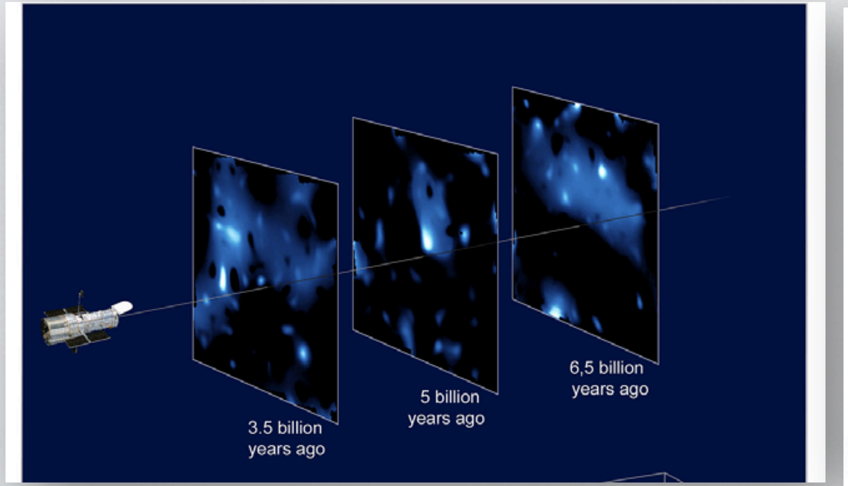
- IG GI II
- Previously: II=GI=IG=0.
- Tidal torques (e.g. Heavens et al 2000, Croft & Metzler 2000,...) II≠0. Easily removed by downweighting close pairs
- GI≠0 (Hirata & Seljak 2004) term is more problematic.
- IG=0? Exercise!

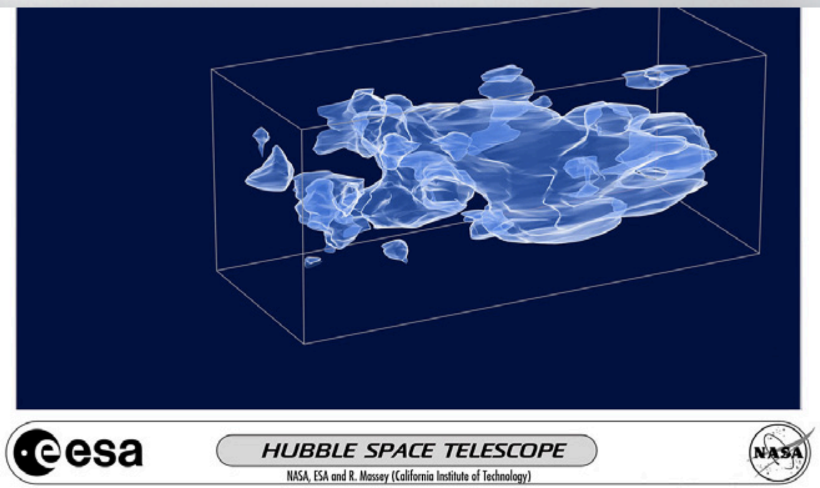


FUTURE EXPERIMENTS

- Euclid (ESA)
  - Selected for Cosmic Vision ~2019
  - Imaging + spectroscopy
  - 15,000 sq deg, median z=0.9, optical+IR
  - Ideal for Cosmic Shear, also BAOs
  - First space-based experiment designed for lensing



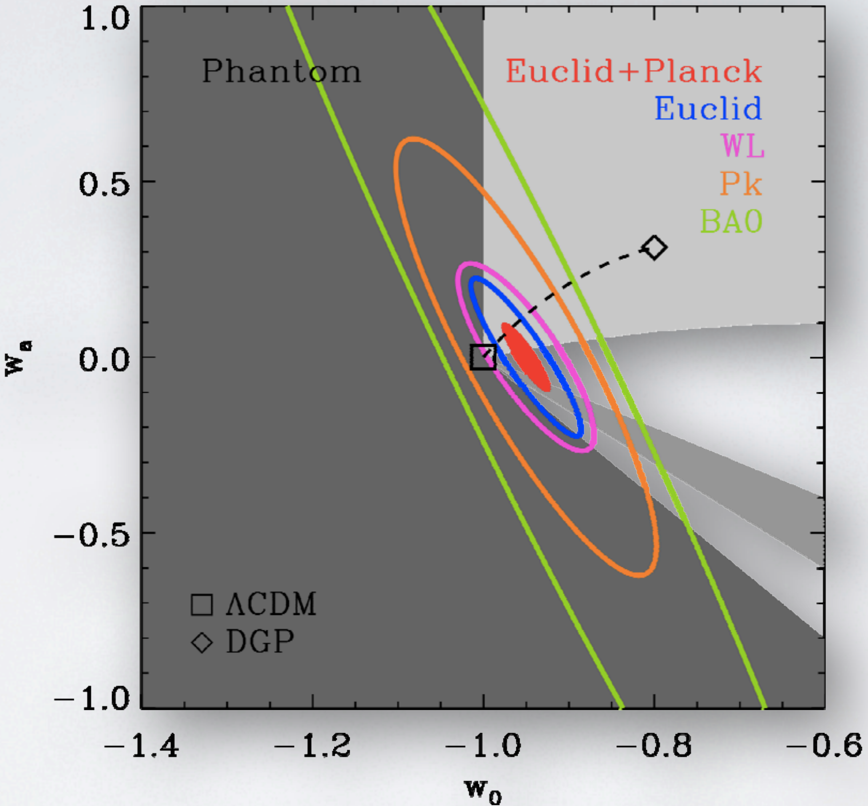




PROSPECTS FOR DARK ENERGY

- Forecasts

$w(a)=w_0+w_a(1\text{-}a)$



Euclid alone: 2% accuracy on w at z=0, 0.2 on w_a

Caveats: nonlinear clustering; DE clustering

MODIFIED GRAVITY

- It is already necessary to modify Einstein's original equations:

$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

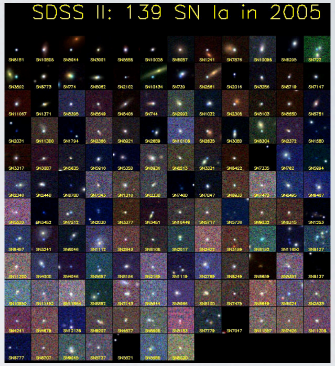
- E.g. by including Dark Energy on right hand side, or including Λ on l.h.s. (equivalent)

$$G^{\mu\nu} - \Lambda g^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

- Modified gravity: more general modifications to l.h.s.
- e.g. Einstein-Hilbert action changed:

$$R - 2\Lambda \rightarrow f(R)$$

MODIFIED GRAVITY OR DARK ENERGY?

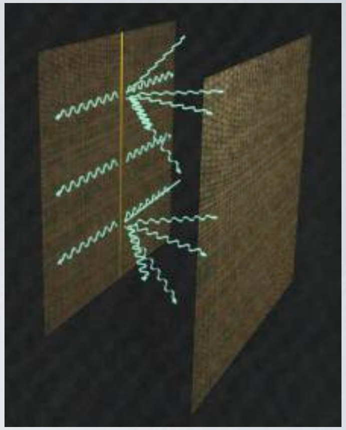


- GEOMETRIC MEASUREMENTS CANNOT TELL.
- Gravity law will give some H(t).
- Friedmann equation plus conservation of energy ⇒ can model any H(t) with GR plus Dark Energy with an equation of state parameter

$$w(t) = -\frac{1}{3}\frac{d}{d\ln R}\ln\left[\frac{1}{\Omega_m(t)} - 1\right]$$

- (Exercise. Flatness assumed)

BRANEWORLD MODELS



- Extra dimensions… broadly motivated by string theory
- E.g. DGP (Dvali, Gabadadze, Porrati 2000) model

$$S = \frac{1}{r_c}\int_{bulk} d^5x^\mu R^{(5)} + \int_{brane} d^4x^\mu R^{(4)}$$

- Leads to a modified Friedmann equation

$$H^2 - \frac{H}{r_c} = \frac{8\pi G\rho}{3}$$

$$r_c^{-1} = H_0(1-\Omega_m)$$

- and modified Poisson equations:

$$\beta = 1 - 2r_cH\left(1+\frac{\dot{H}}{3H^2}\right)$$

$$k^2\Phi_{\mathbf{k}} = -4\pi Ga^2\left(1+\frac{1}{3\beta}\right)\rho_m\delta_{\mathbf{k}} \longleftarrow$$

Growth rate of Newtonian potential is altered

$$k^2\Psi_{\mathbf{k}} = -4\pi Ga^2\left(1-\frac{1}{3\beta}\right)\rho_m\delta_{\mathbf{k}}$$

In this case, **Φ+Ψ** obeys the normal Poisson equation

SUMMARY OF MODIFIED GRAVITY EFFECTS

- Expansion history R(t), [or H(t)] is changed
- Distance-redshift relation r(z) is changed
- Growth rate of matter fluctuations is altered
- Curvature and Newtonian potentials may behave differently
- Different response of photons to density perturbations

- Are these measurable?

PROSPECTS FOR DARK GRAVITY

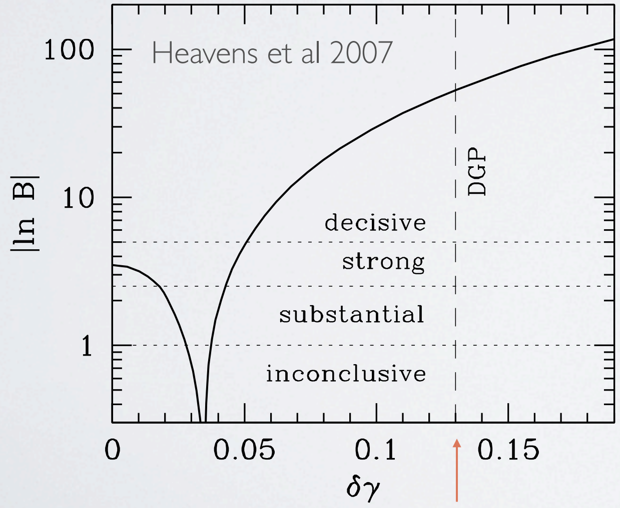
Compare GR with Dark Energy with a modified gravity model *with the same expansion history.*

Compute Expected Bayesian evidence = Probability of model given the data:

~ do the data require a modification to GR?

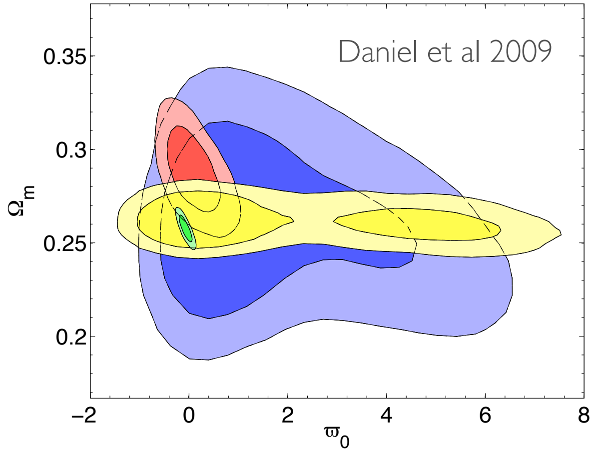
- Euclid + Planck + BAO + SNe: Probability ratio = e^{63} (DGP/GR)

Change in growth rate from GR



DGP

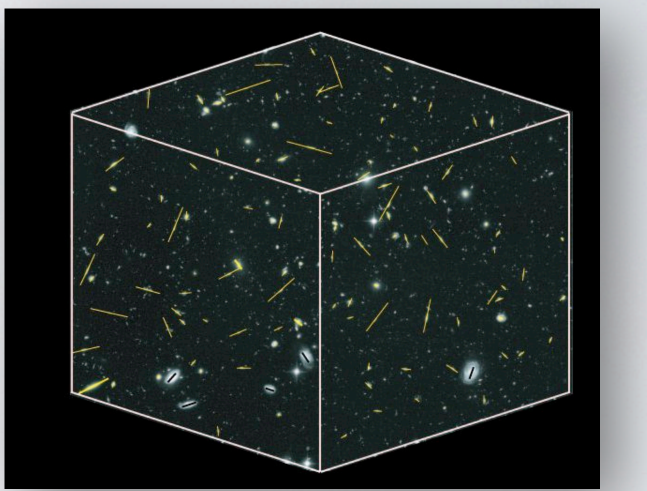
Fractional difference in potentials

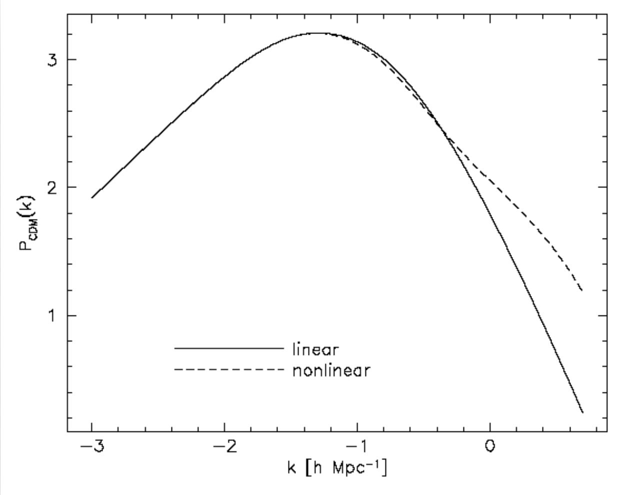


WMAP +WL (now); Planck ; Planck+Euclid

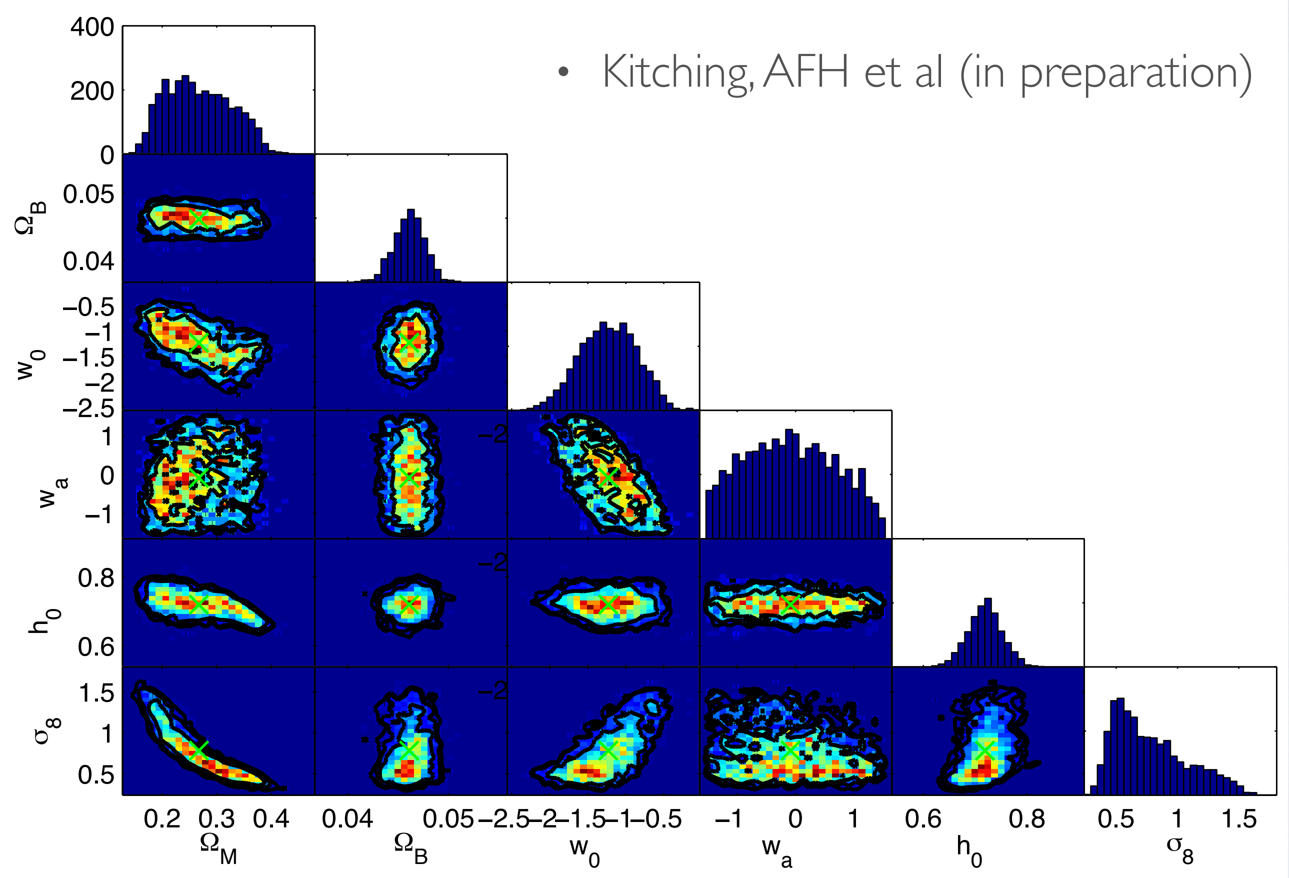
3D LENSING

- Estimated distances for all sources
- Galaxy 'shape' field is a very noisy, radially-smoothed, 3D point process sample of the galaxy shear field. (Heavens 2003)
- Better statistics (Heavens et al 2006; Kitching et al 2007)
- Better control of systematic errors (e.g. Bridle and King 2007)
- Can avoid the highly nonlinear regime where baryon physics is uncertain





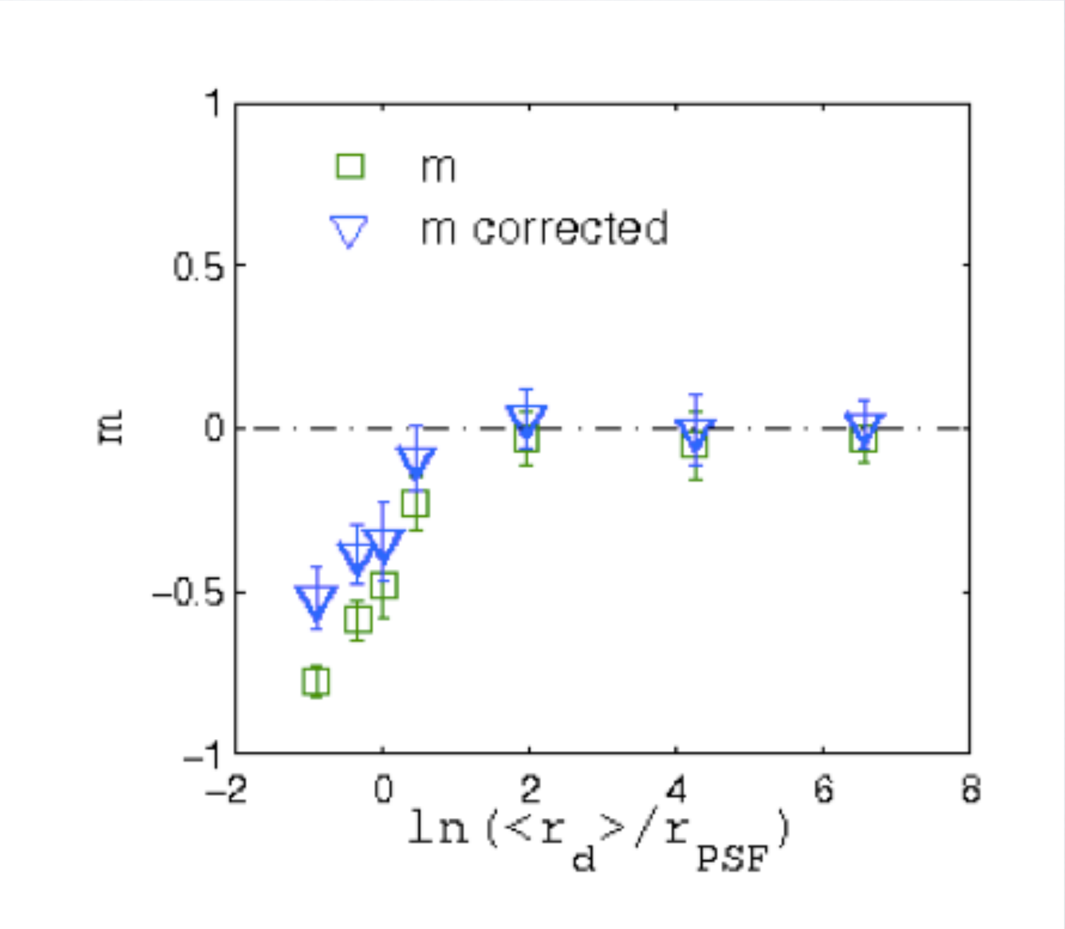
3D WEAK LENSING FROM CFHTLENS



- Kitching, AFH et al (in preparation)

SIZE MAGNIFICATION

Bias in size measurement



Looks very promising for space experiments

- Casaponsa, AFH et al (in preparation)

CONCLUSIONS

Lensing can probe a variety of phenomena of fundamental interest, such as

- Neutrino masses and their hierarchy
- The properties of the dominant Dark Matter component
- The Dark Energy equation-of-state
- Evidence for modifications to Einstein gravity

CMB and 3D lensing are particularly promising probes, as the physics is well-understood, and they have high sensitivity

Euclid + Planck will test this paradigm very thoroughly

Euclid is a Good Bet!