Probing the Universe with Cosmological Lensing

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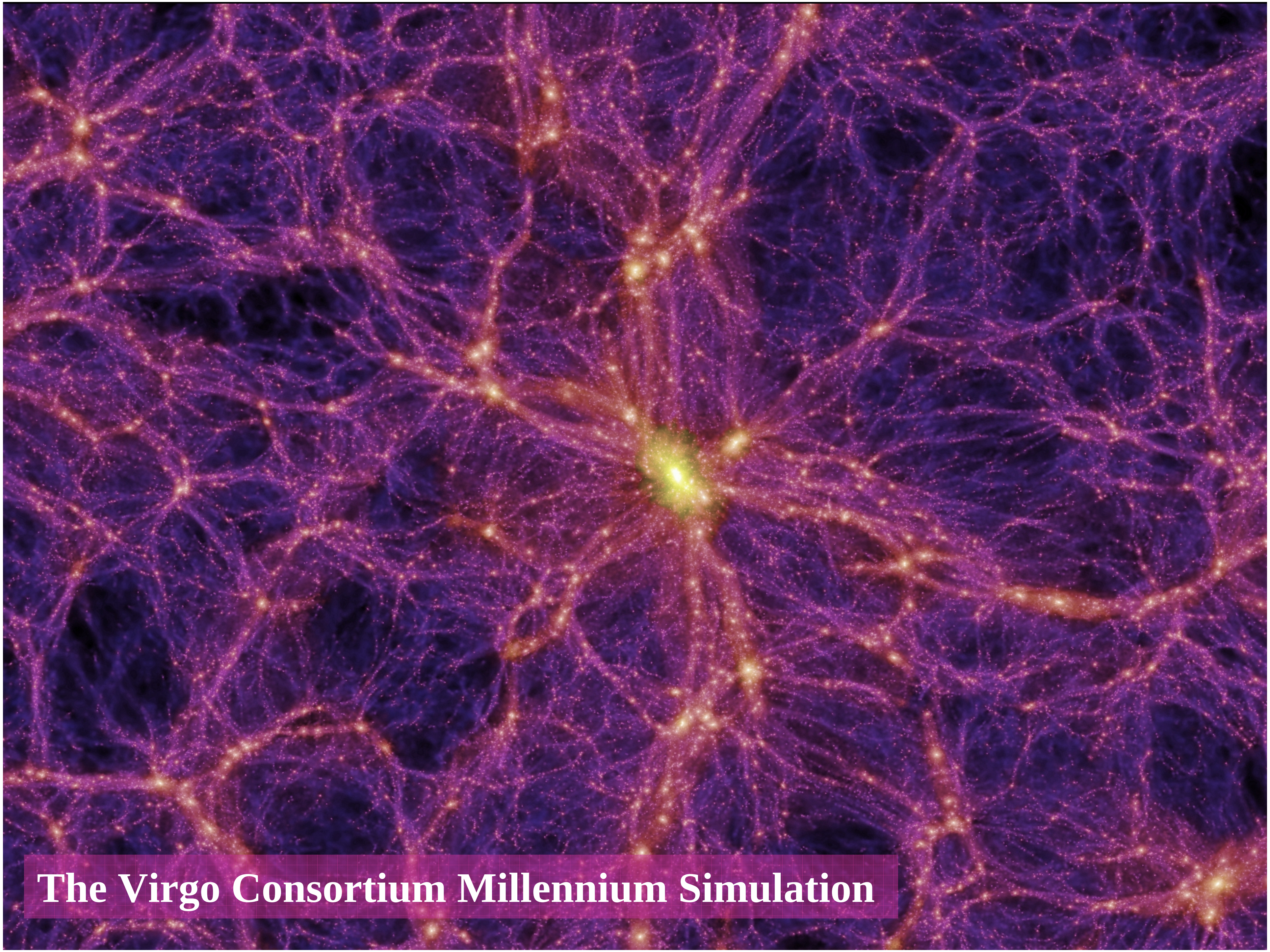
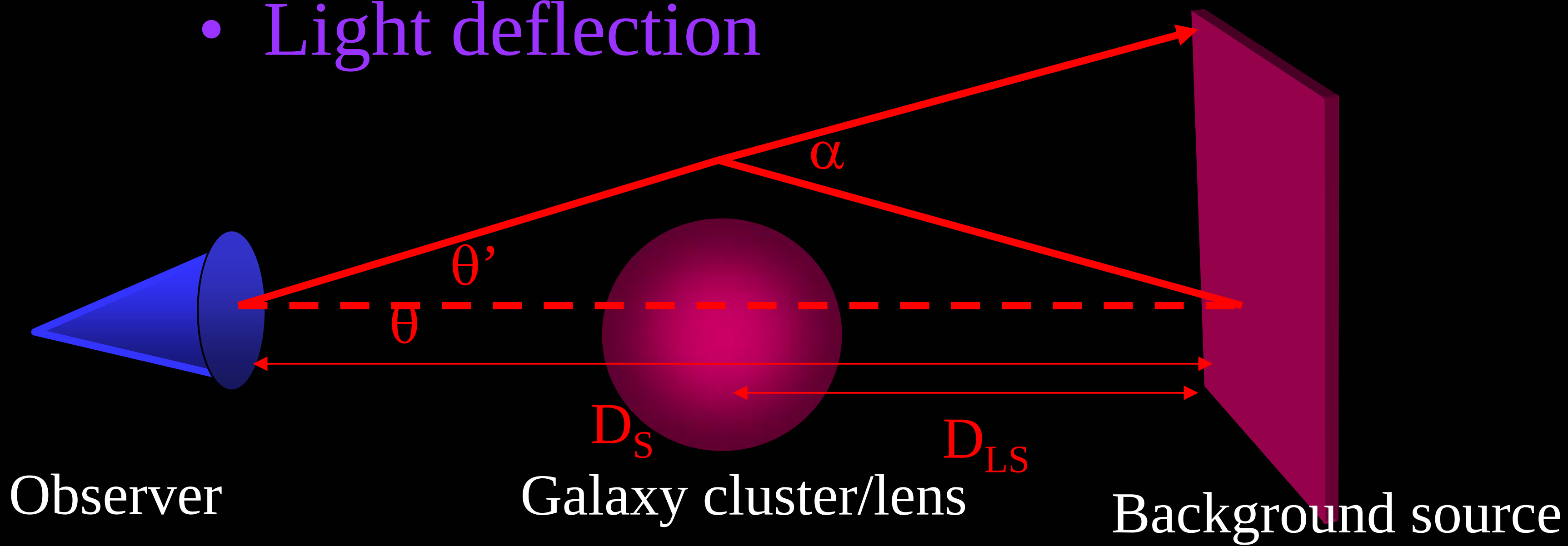

The Virgo Consortium Millennium Simulation

Gravitational Lensing

Basics of Gravitational Lensing

- Light deflection



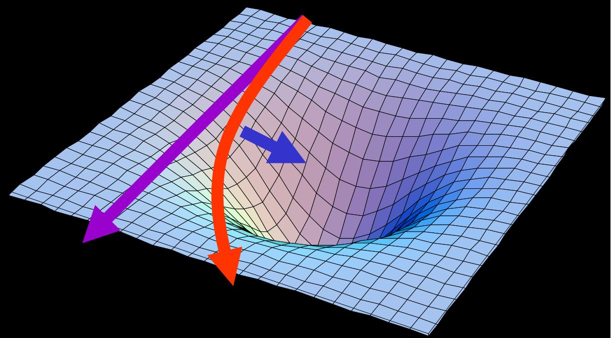
- Lens equation

$$\theta' = \theta + \frac{D_{LS}}{D_S}\alpha(\theta)$$

Basics of Gravitational Lensing

- Relativistic equation of motion

$$\ddot{\underline{\alpha}} = \frac{d}{d\eta} r^2 \frac{d}{d\eta} \underline{\alpha} = -2 \frac{\partial}{\partial \underline{\theta}} \Phi$$



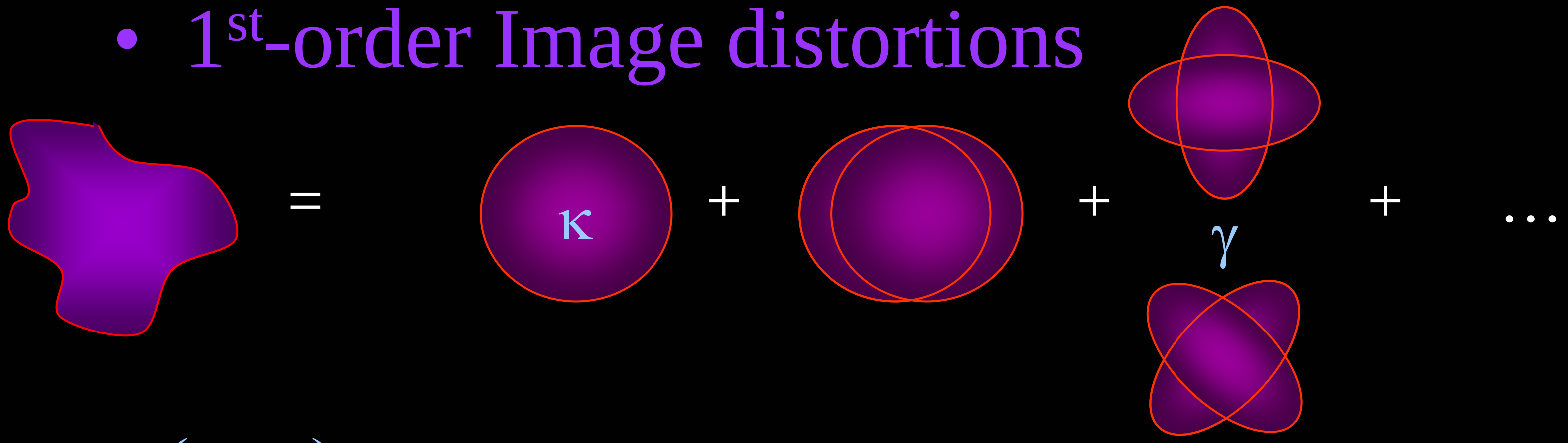
- Solve equation of motion (η=r):

$$\underline{\alpha} = \frac{\partial}{\partial \underline{\theta}} \phi, \qquad \phi = 2 \int_0^r dr' \frac{r - r'}{rr'} \Phi(r', \underline{\theta})$$

Lensing potential

Basics of Gravitational Lensing

- 1st-order Image distortions



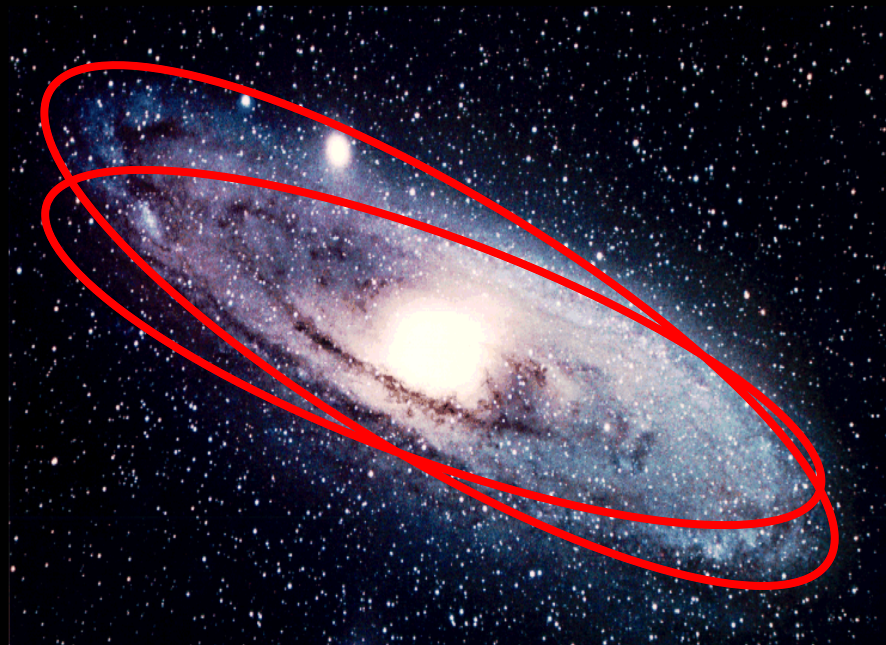
$$\Delta\theta_i' = \left(\frac{\partial\theta_i'}{\partial\theta_j}\right)\Delta\theta_j = \left[\delta_{ij}^K - \partial_i\partial_j\phi\right]\Delta\theta_j = \left[(1-\kappa)\delta_{ij} - \gamma_{ij}\right]\Delta\theta_j$$

Convergence: $\kappa = \frac{1}{2}\partial^2\phi \propto \int_0^r dr'\delta\rho_{\mathrm{m}}(\mathrm{r}')$ Surface mass density

Shear: $\gamma_{ij} = \partial_i\partial_j\phi - \frac{1}{2}\delta_{ij}\partial^2\phi = \begin{pmatrix}\gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1\end{pmatrix}$

Gravitational Lens Distortions

- Galaxy ellipticity, e:



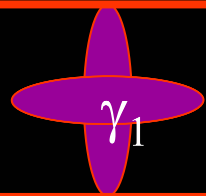
- Lensing effect:

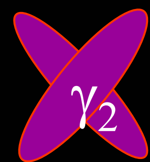
$$e' = e + \gamma$$

- On average $\langle e \rangle = 0$,

  so $\langle e' \rangle = \gamma$.

- Shear matrix:

γ = 

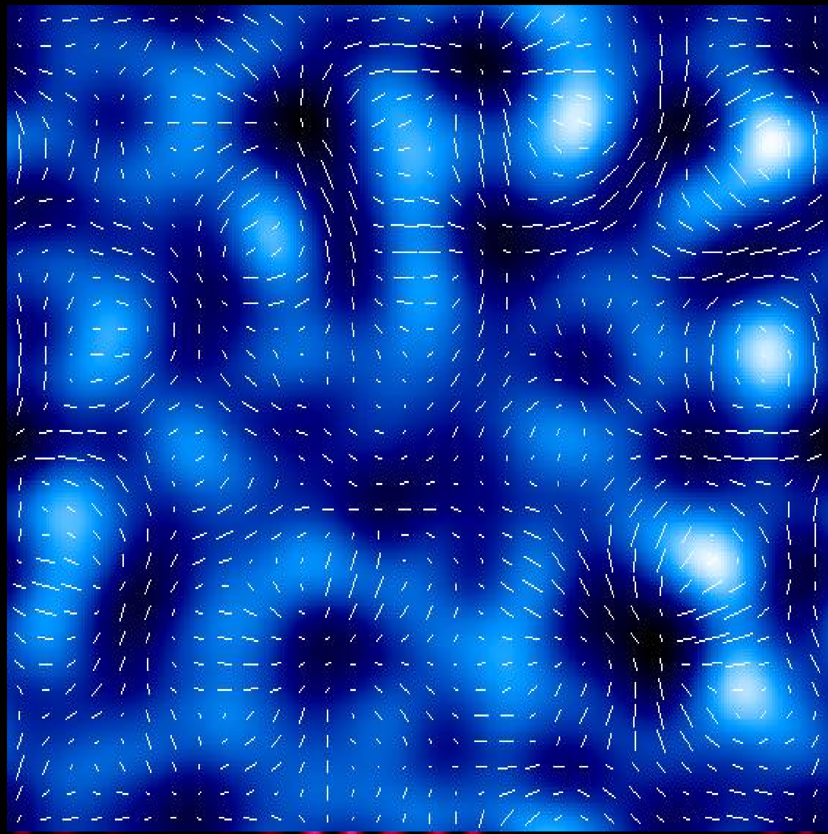
\+ i 

Mapping the Dark Matter

- From shear to surface density:

Kaiser-Squires (1993)

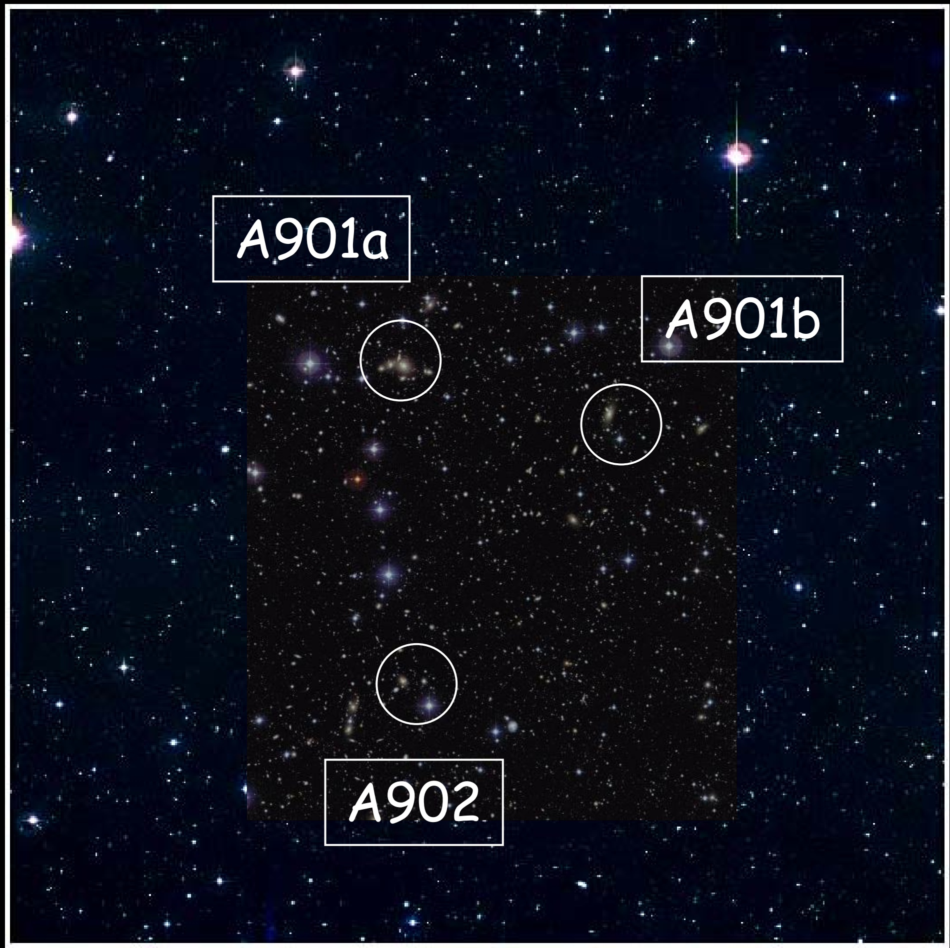
$$\kappa = \partial^{-2}\partial_i\partial_j\gamma_{ij}$$



Supercluster Abell 901/2

1/2 deg

3Mpc/h

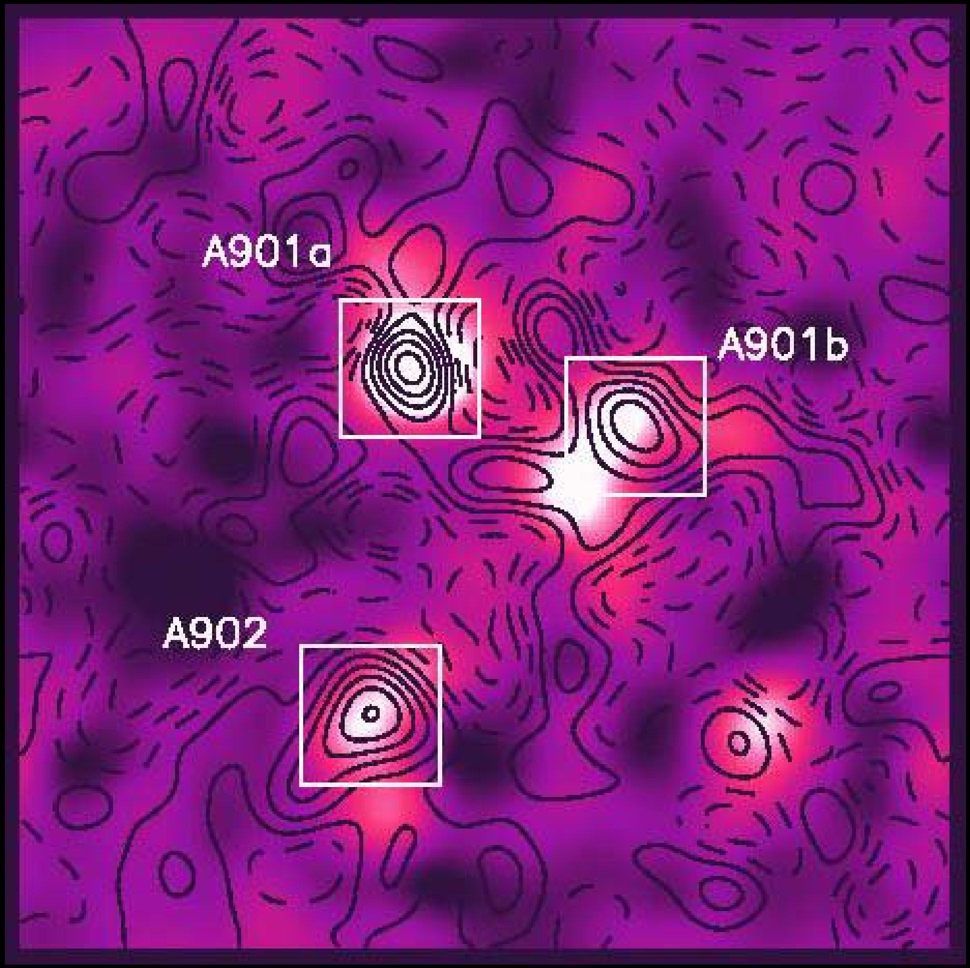


- z=0.16
- Δz=0.01

Mass and light in Supercluster A901/2

Dark Matter contours, κ.

Elliptical galaxy light shading.



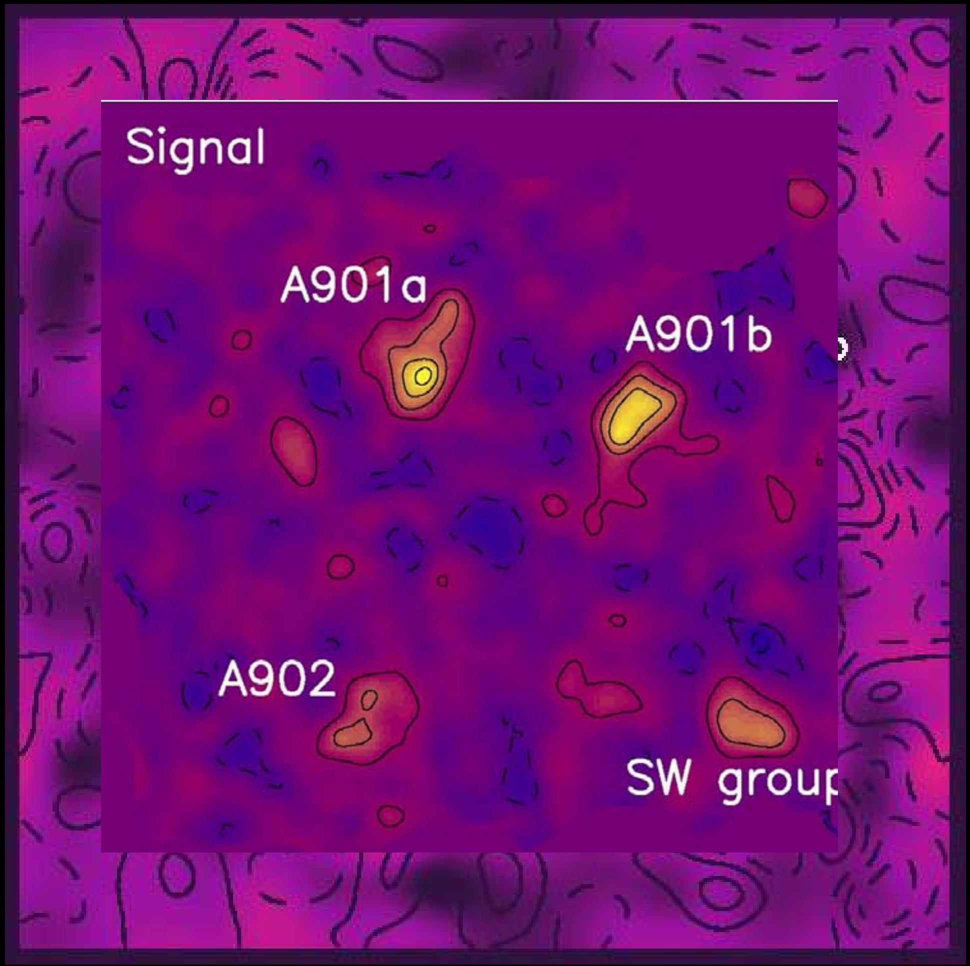
Error: Δκ=0.02 (1–contour)

Ground-based COMBO-17 data (Wolf et al 05)

Mass and light in Supercluster A901/2

Dark Matter contours, κ.

Elliptical galaxy light shading.



Error:
Δκ=0.02
(1−contour)

Space-based HST- STAGES data (Grey et al 07, Heymans et al 2008)

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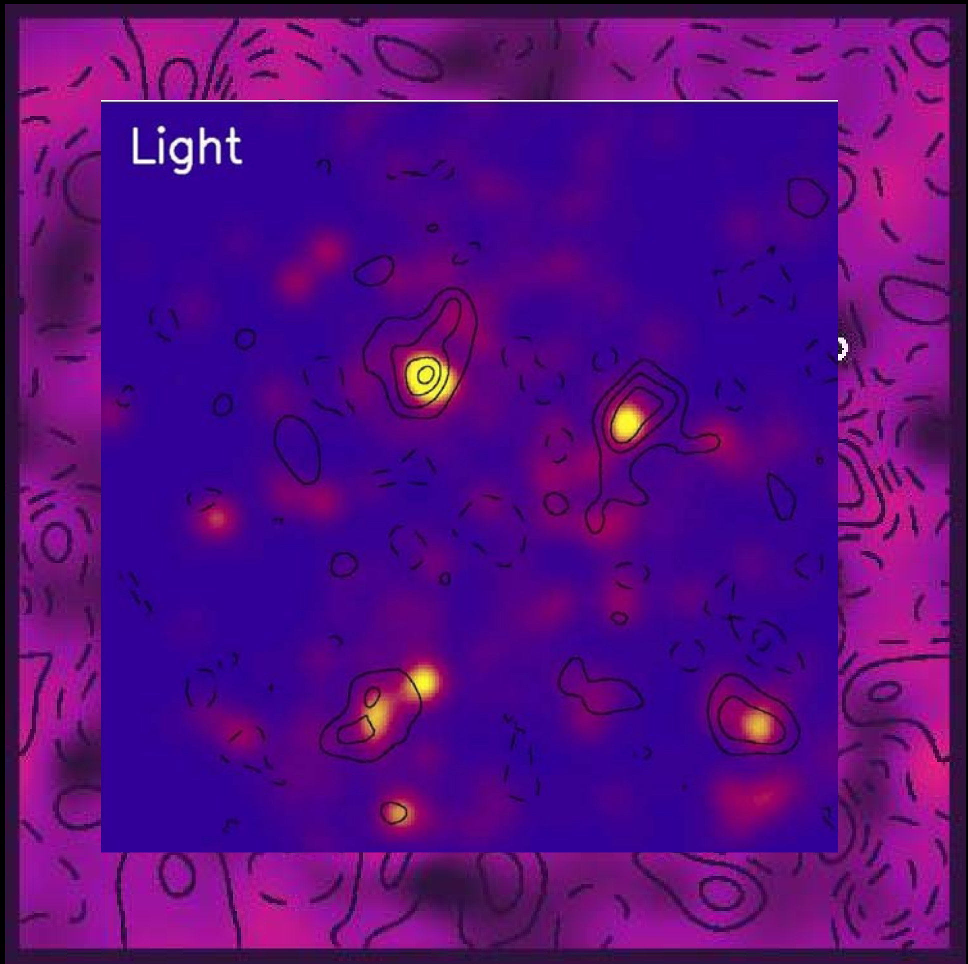
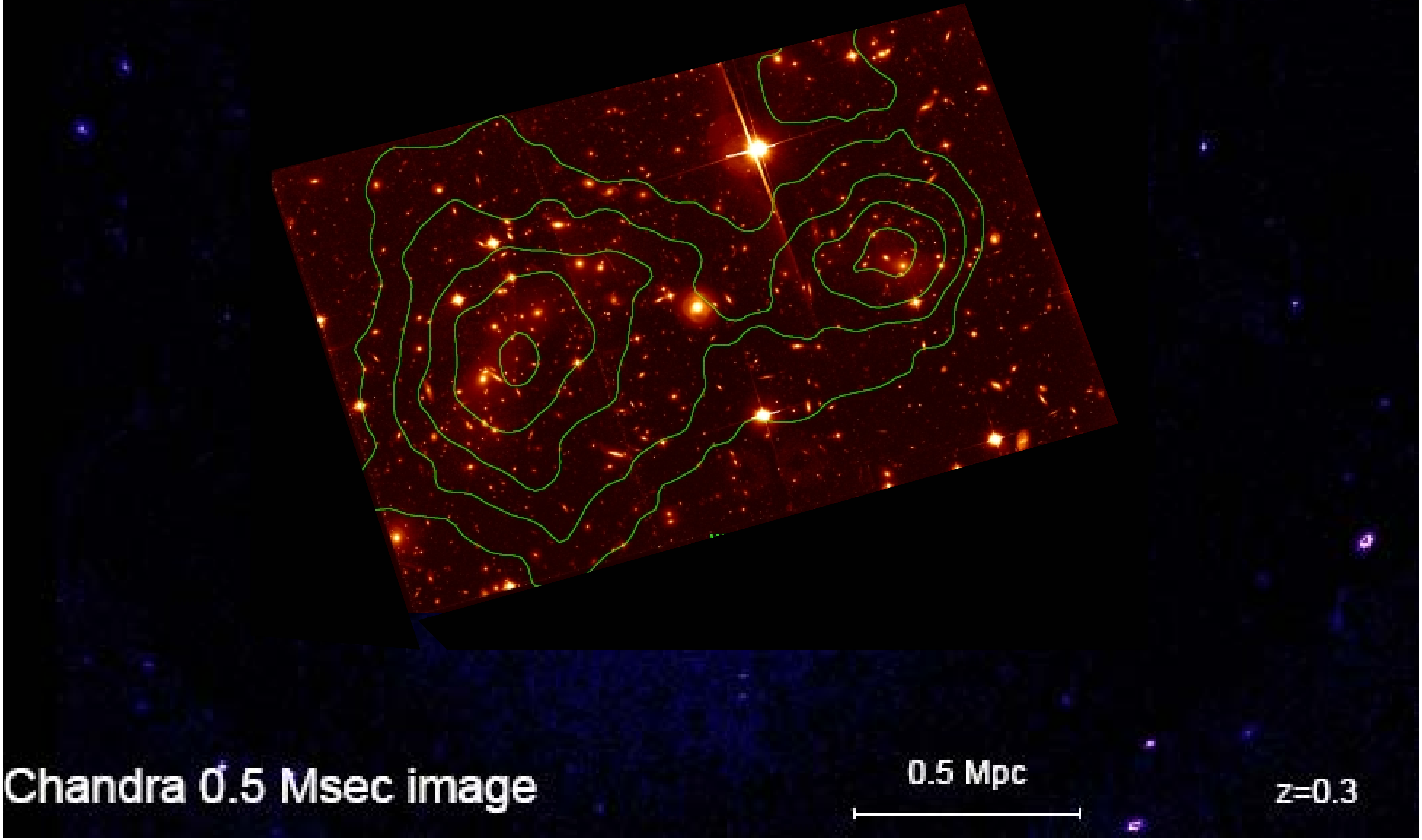


Error:
Δκ=0.02
(1−contour)

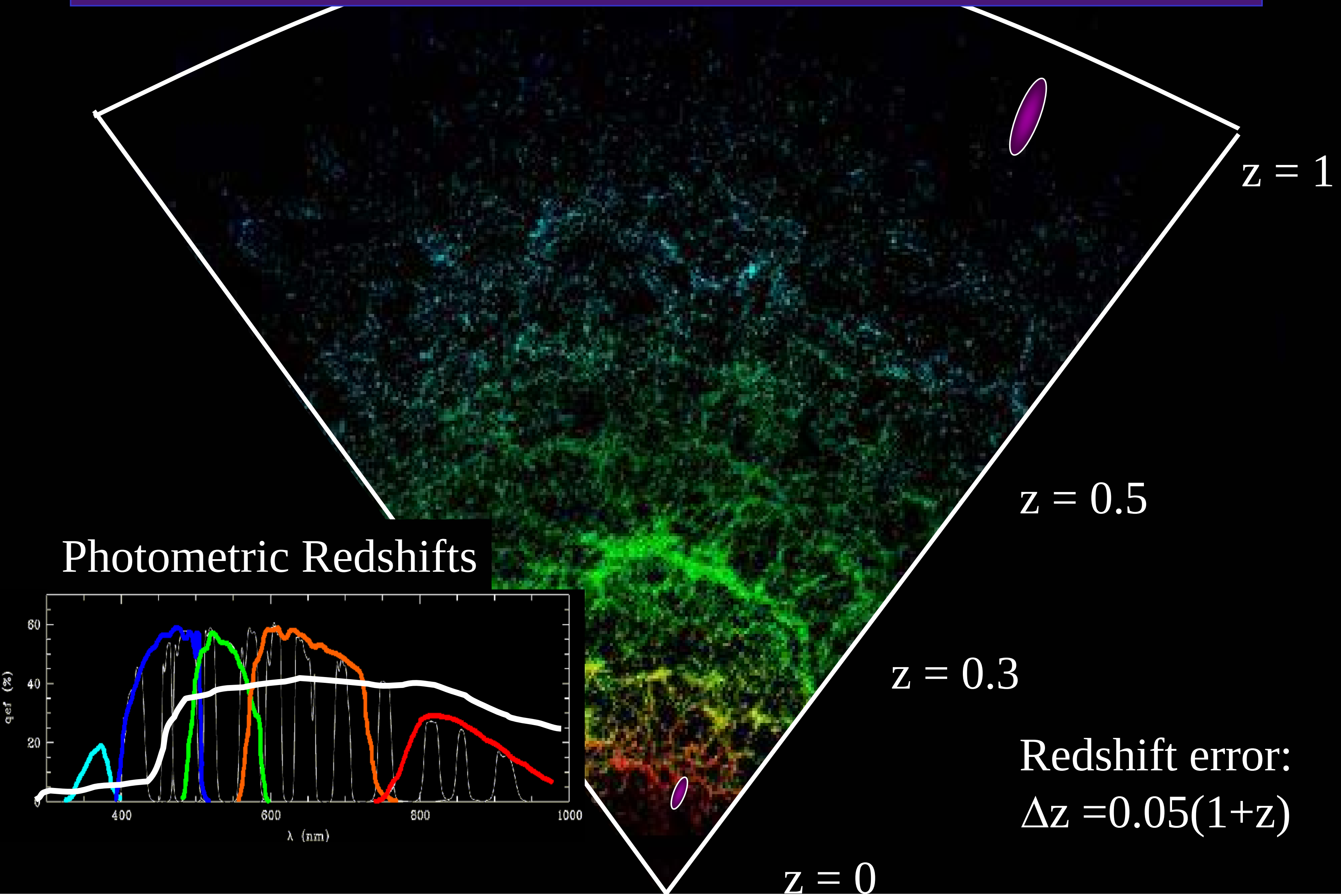
Space-based HST- STAGES data (Grey et al 07, Heymans et al 2008)

The Bullet Cluster: Proof of Dark Matter?

Clowes et al 2006



3D Lensing: Shear + Redshifts

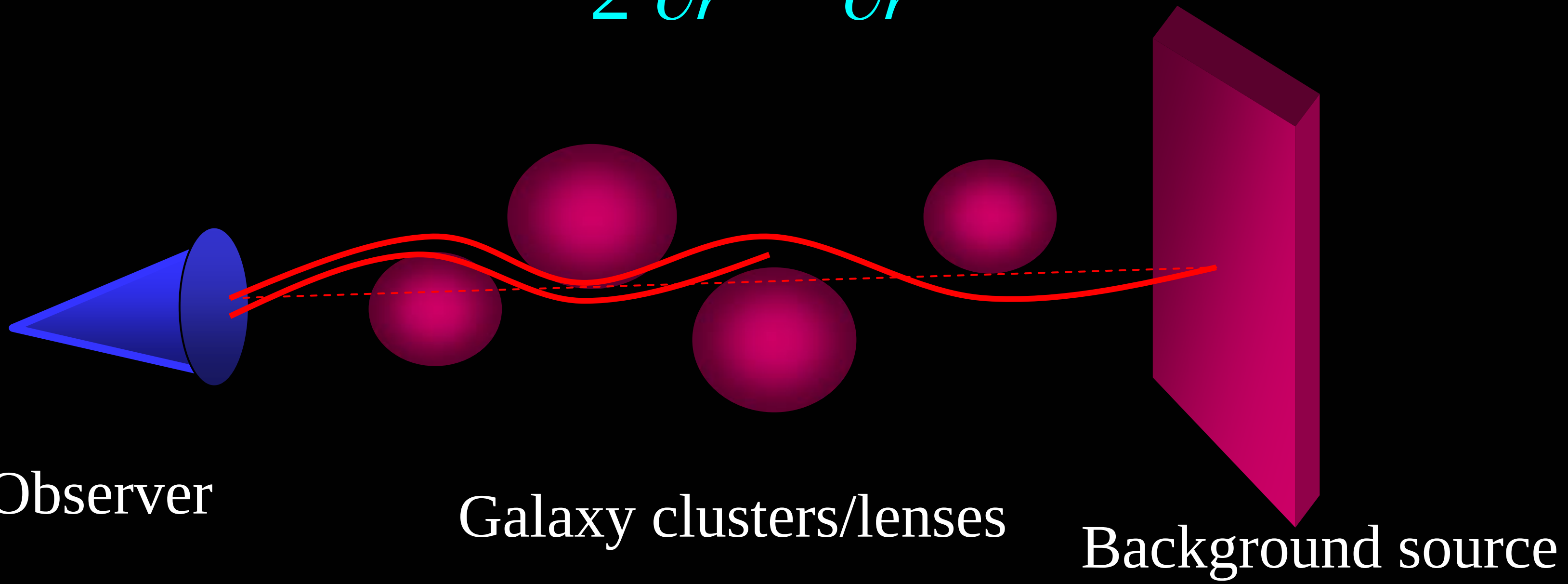


Redshift error:
$\Delta z = 0.05(1+z)$

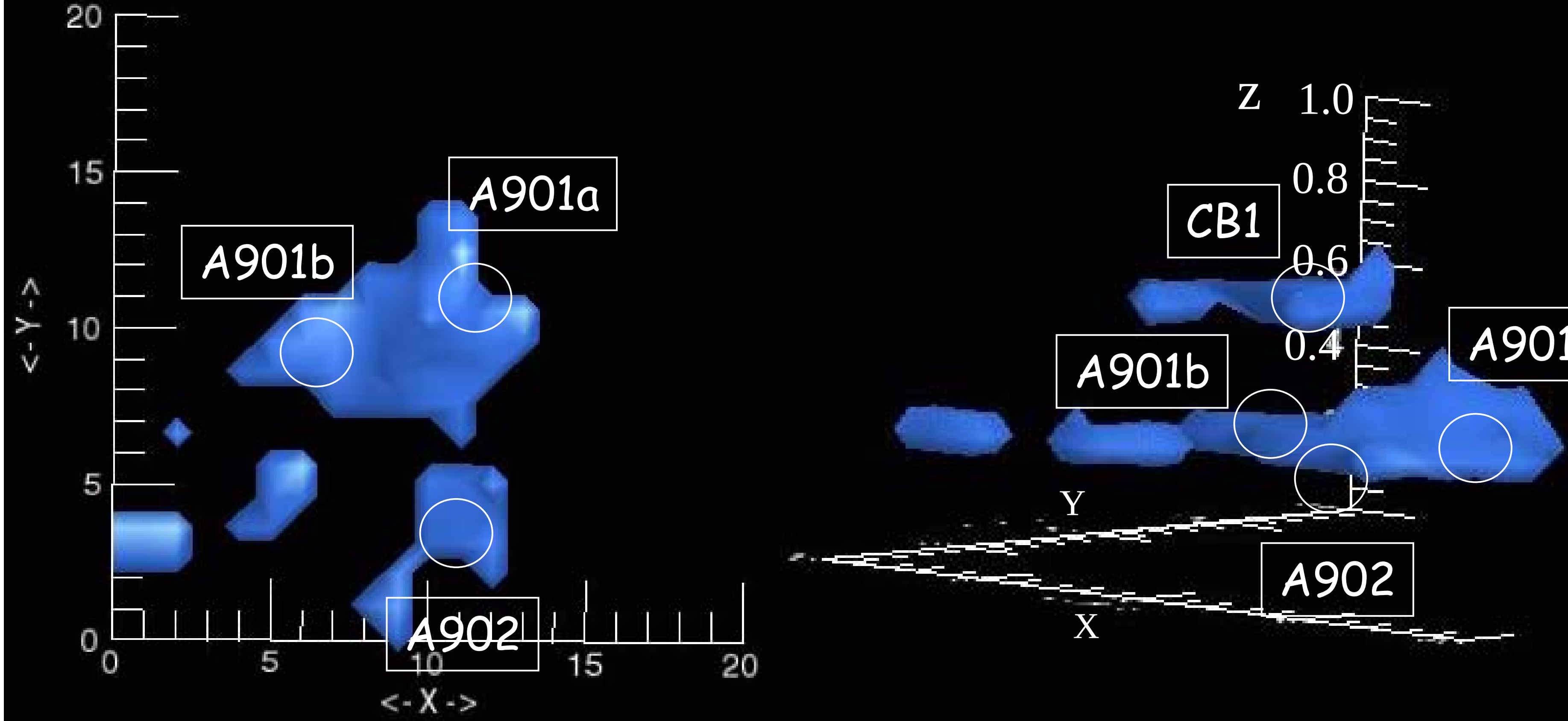
Mapping the Dark Matter in 3-D

- With source redshifts, *z*, solve Φ exactly from the relativistic equation of motion (Taylor, 2001):

$$\Phi(r,\underline{\theta}) = \frac{1}{2}\frac{\partial}{\partial r} r^2 \frac{\partial}{\partial r} \phi(r,\underline{\theta})$$



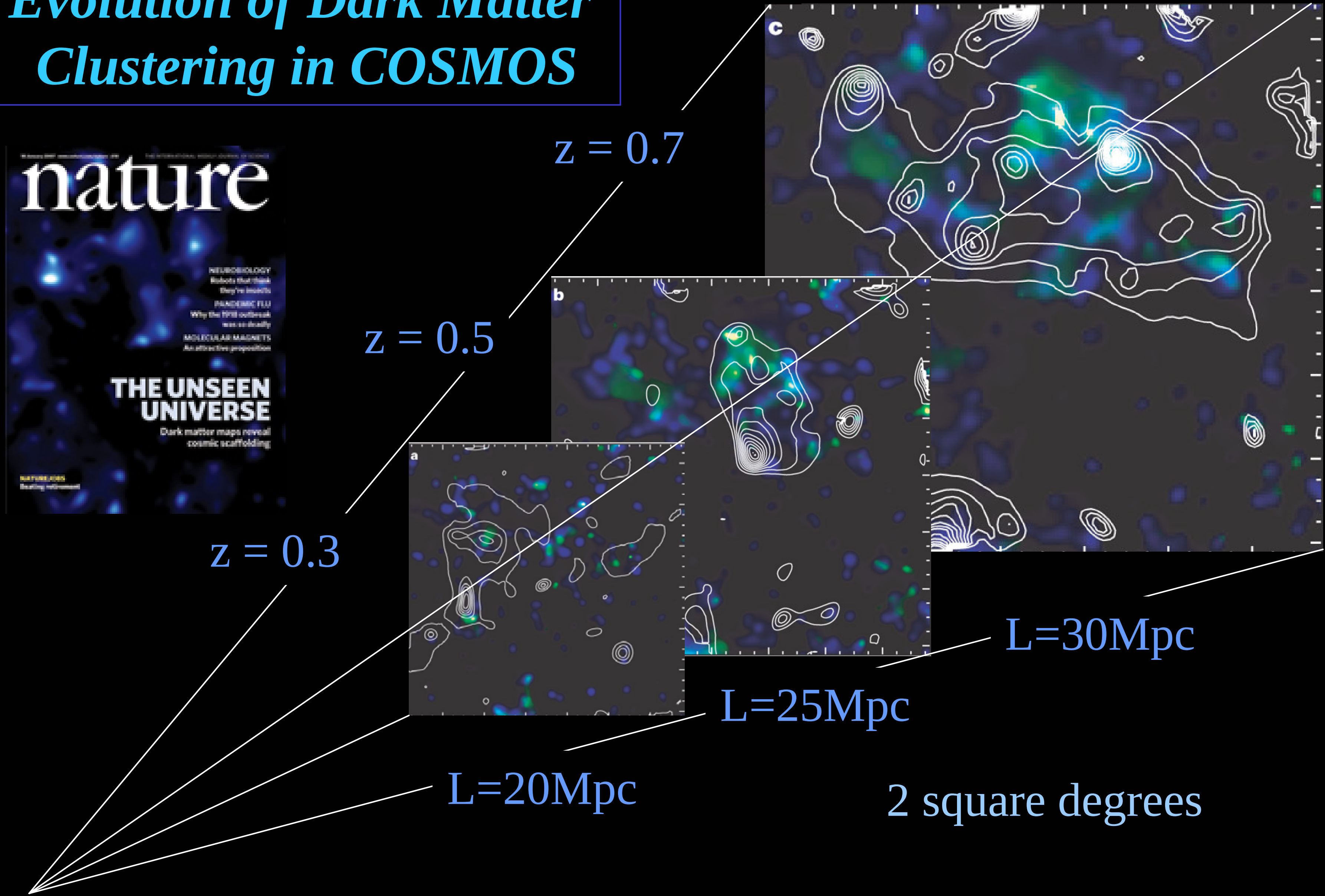
3-D Dark Matter Mapping



(2-σ threshold)

Taylor, et al, 2004 MN

Evolution of Dark Matter Clustering in COSMOS



2 square degrees

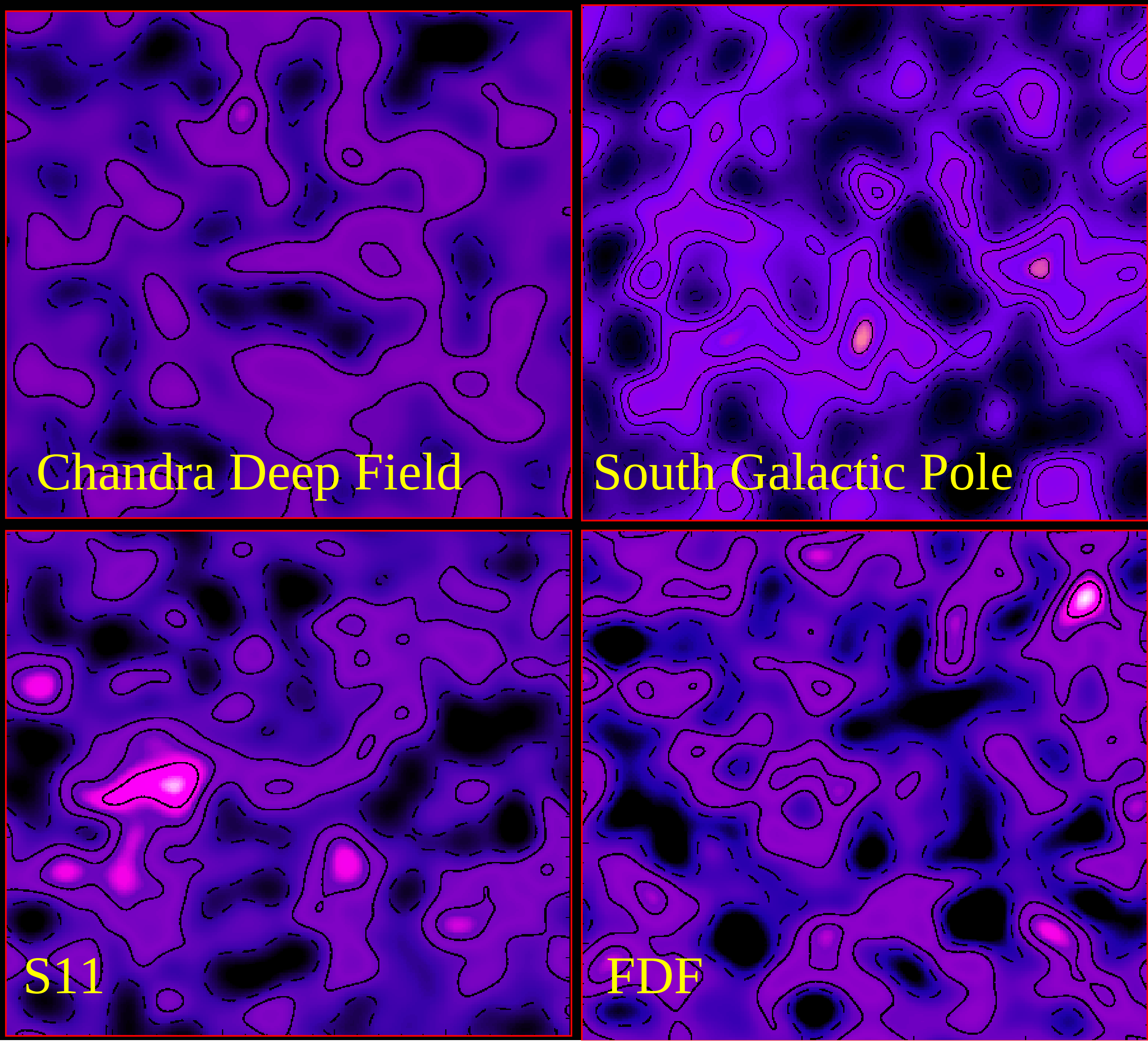
Massey, Taylor et al, Nature, 2007

3-D Dark Matter Mapping with HST-COSMOS

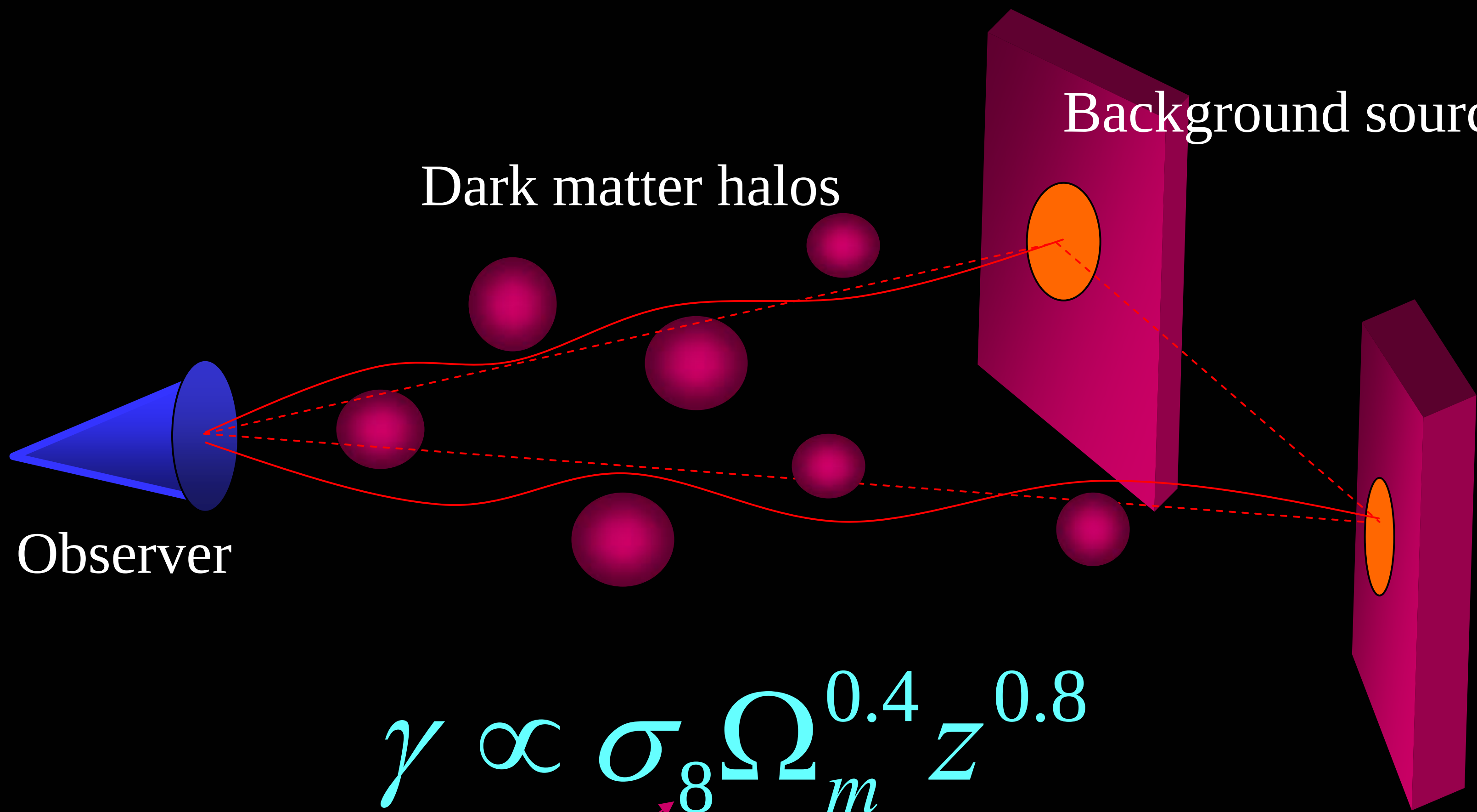
Massey, Taylor et al, Nature (2007)

Random Mass Fields on the Sky

- 1 sq deg.



Geometry & Clustering: Cosmic Shear



$$\gamma \propto \sigma_8 \Omega_m^{0.4} z^{0.8}$$

Variance of matter variations

Matter density parameter

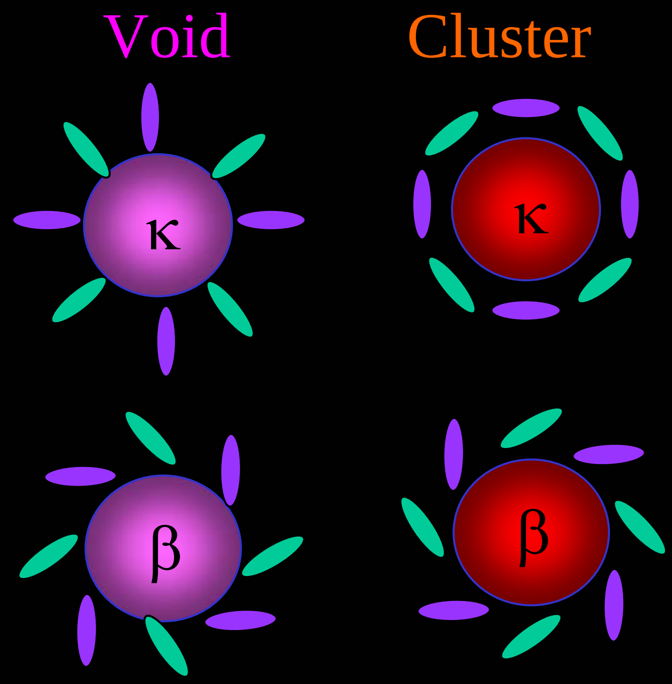
$$\Omega_m \propto \rho_m H_0^2$$

The κ/β (E/B) Decomposition

- Can decompose γ_1,γ_2 into:

  κ-modes (even-parity):
  (or grad)

  β-modes (odd-parity):
  (or curl)



- Gravitational lensing produces only κ-modes.
- Noise & systematics produces both κ & β-modes.

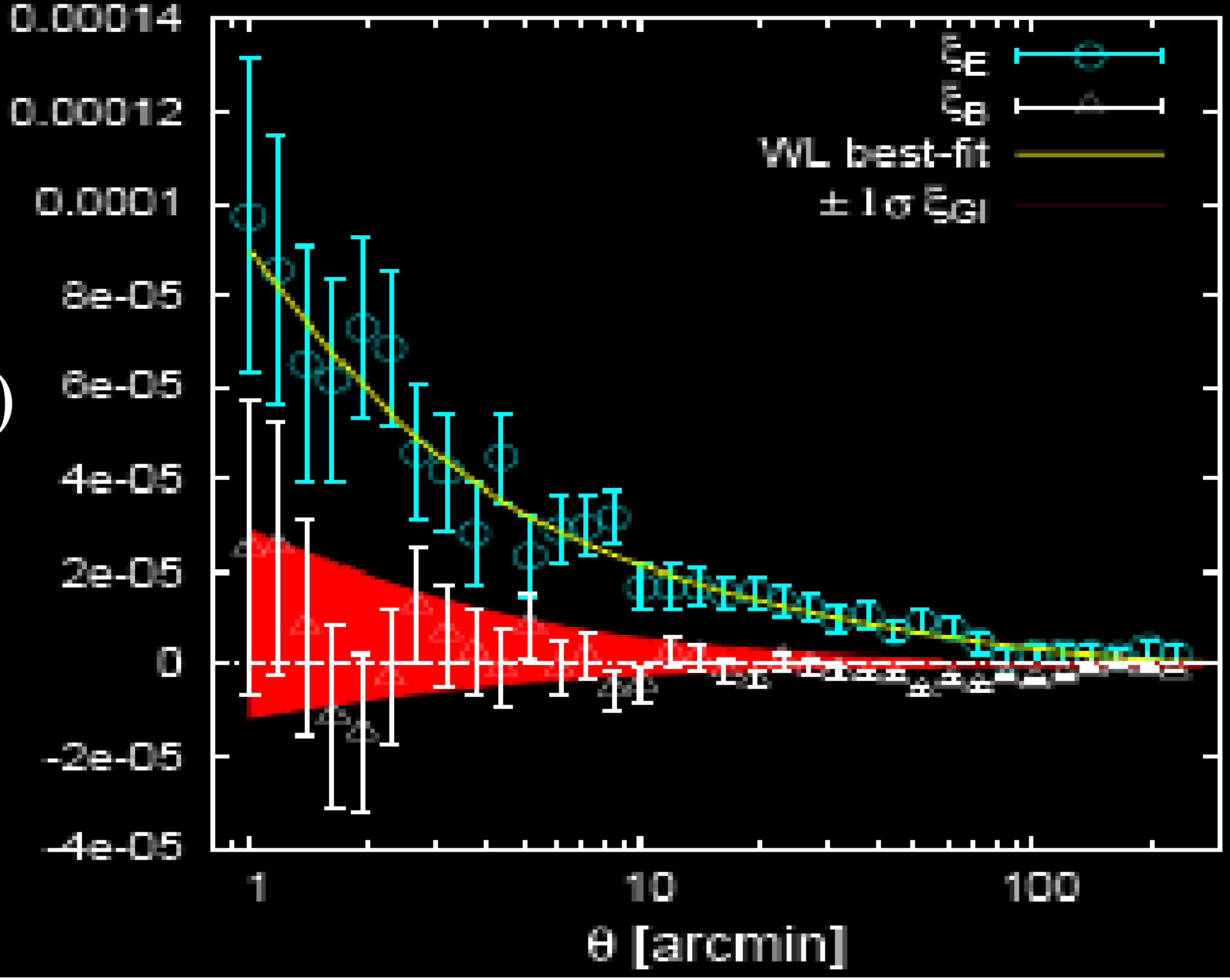
Cosmic Shear Correlations

Fu et al, 2008: Canada-France-Hawaii Legacy Survey 57 sq deg

0.6Mpc/h 6Mpc/h 30Mpc/h

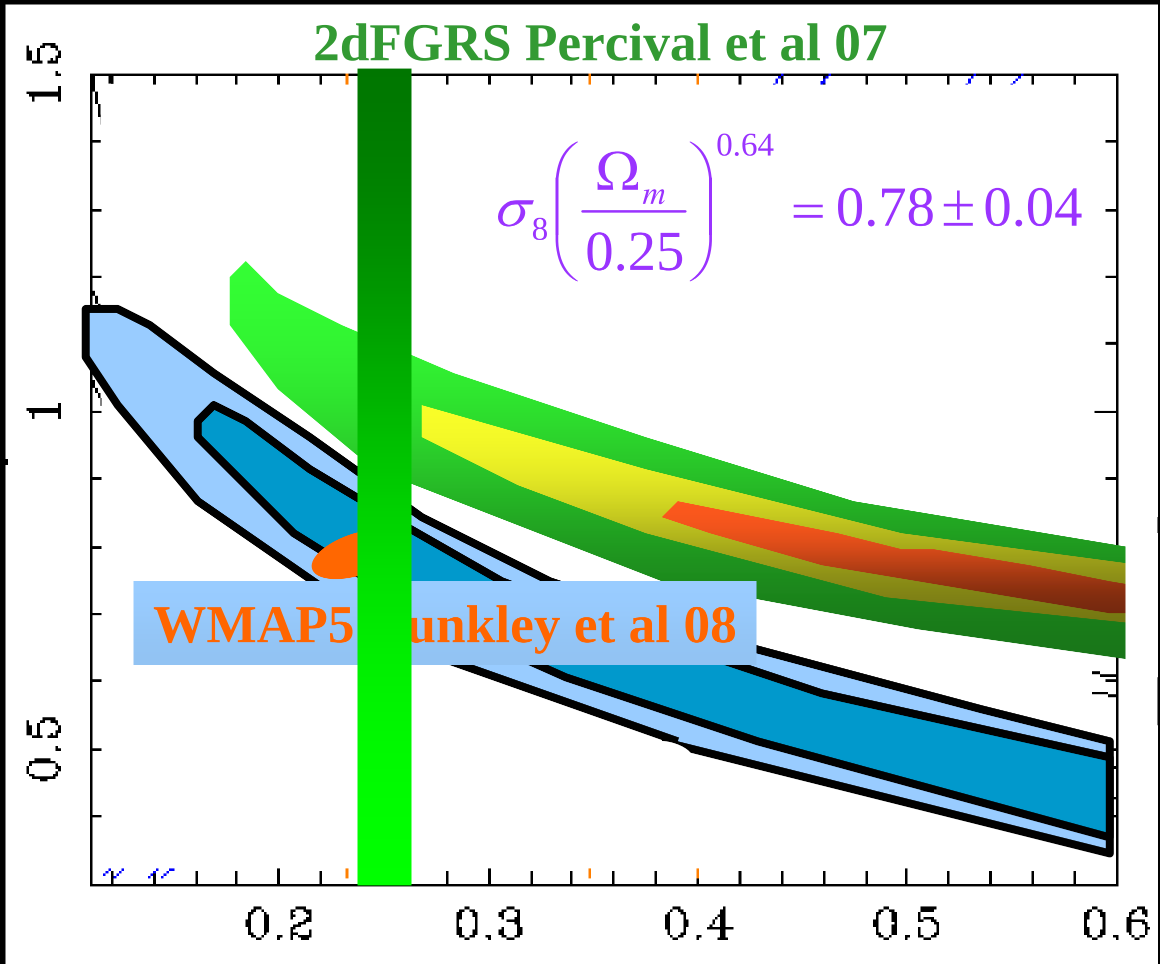
Shear-Shear Correlations

$C_{\gamma\gamma}(\theta)$



Cosmological Parameters from Cosmic Shear

Cosmic Shear from 3yr CFHTLS 57 square degrees (Fu et al '08)



Matter Clustering Amplitude

σ_8

Matter density Ω_m

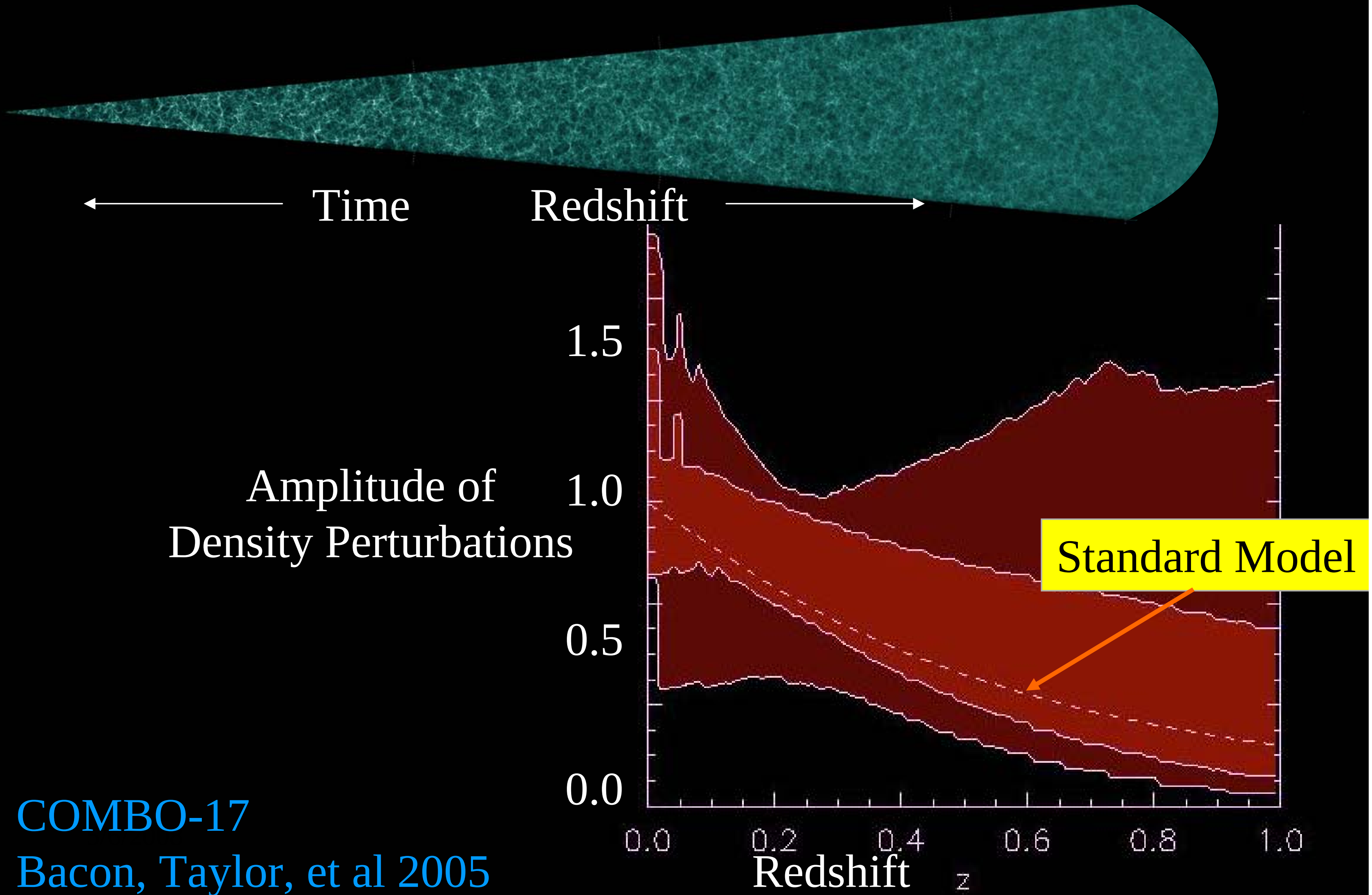
Spatially flat Universe.

$\Omega_m = 0.25 \pm 0.02$

$\sigma_8 = 0.77 \pm 0.03$

Massey et al 07
2 sq deg COSMOS
3-D Analysis

Growth of Density Perturbations from Lensing



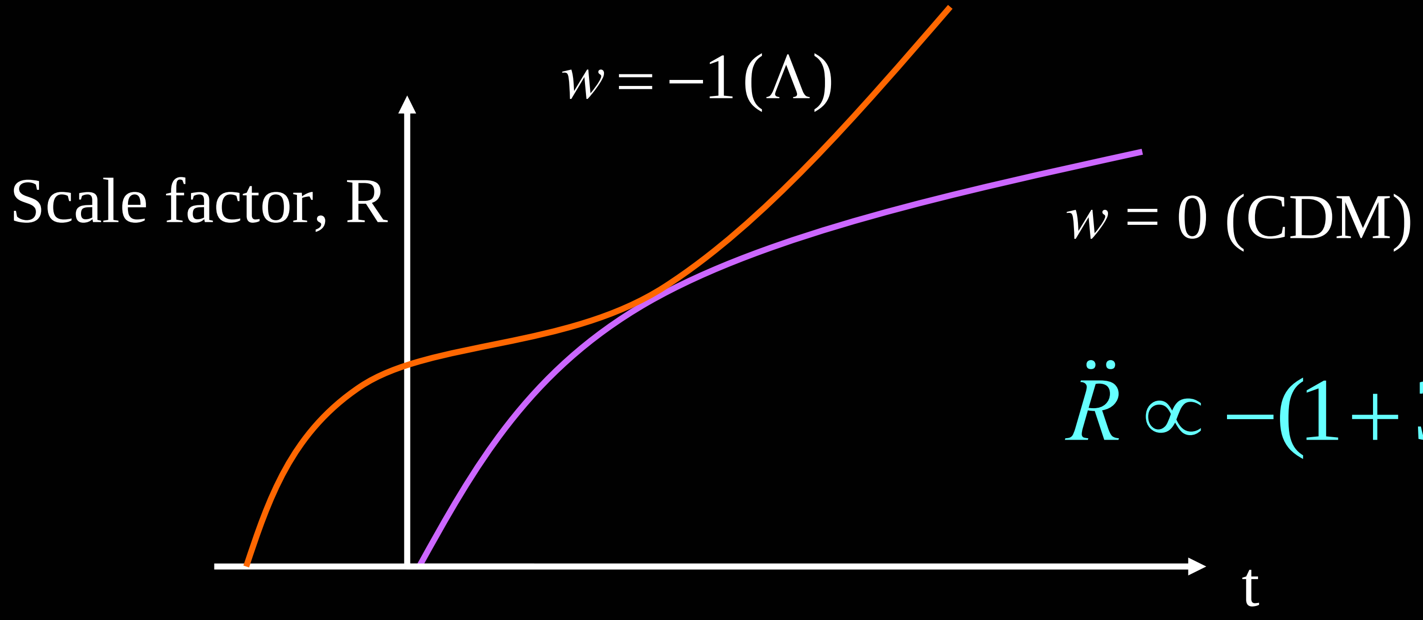
COMBO-17

Bacon, Taylor, et al 2005

Cosmic Acceleration & Dark Energy

Dark Energy characterized by an Equation of State:

$$P = w\rho c^2$$

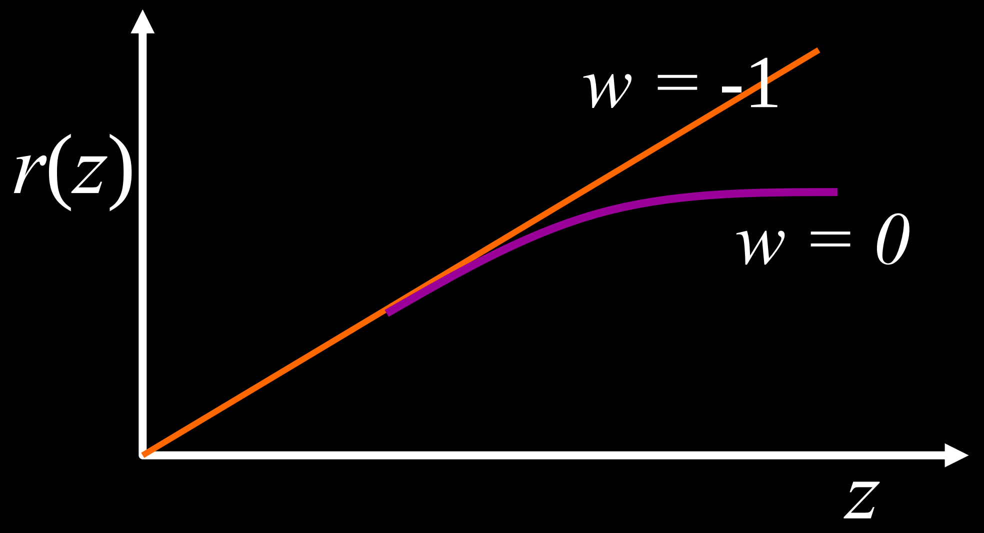


$$\ddot{R} \propto -(1+3w)\rho$$

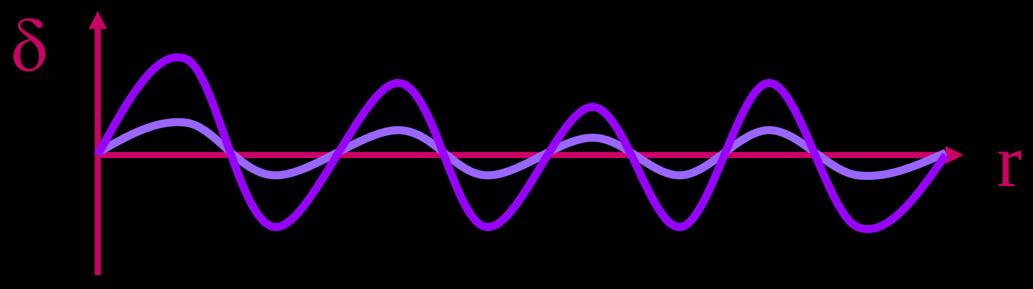
If w = -1 energy-density is Einstein's Cosmological Constant, Λ.

Observable Effects of Dark Energy

- Geometry: DE changes the photon distance-redshift relation: r(z)



- Clustering: Alters the growth of density perturbations, δ(t).



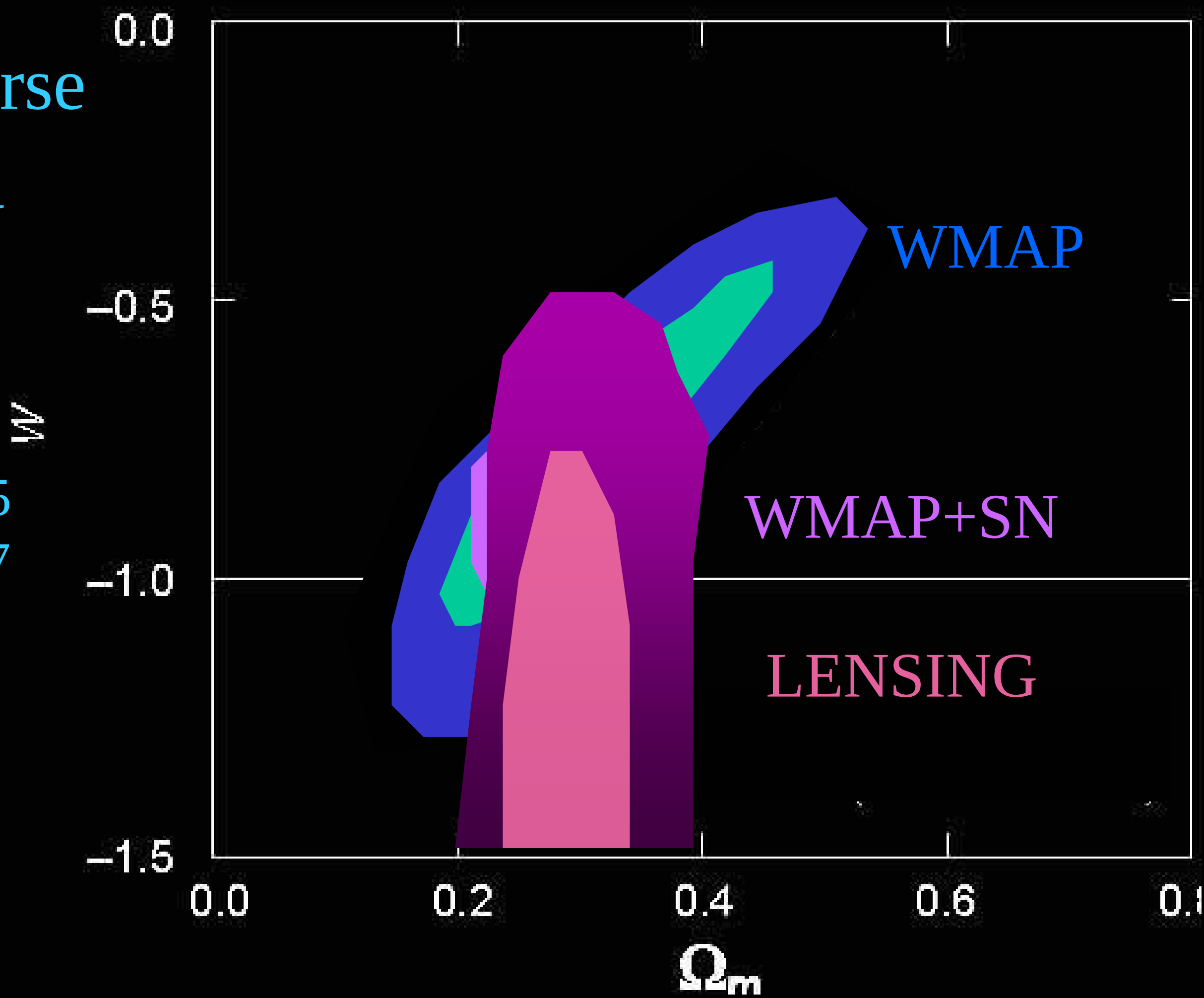
w from the CMB + Supernova + Lensing

Assume flat Universe

WMAP + SN

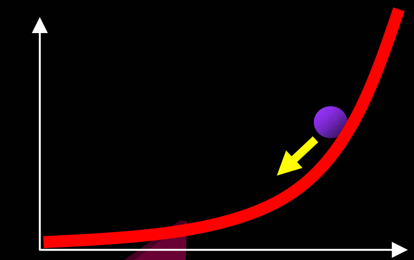
$$P_{DE} = w\rho_{DE}$$

$$w = -0.93^{+0.05}_{-0.07}$$

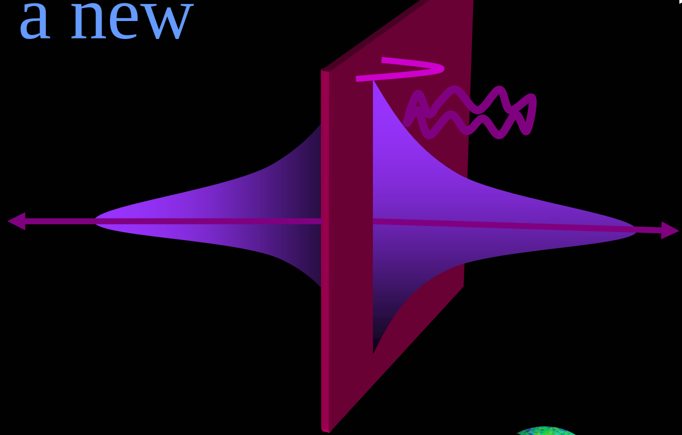


Spergel et al ApJ 2006, Tereno et al 2006

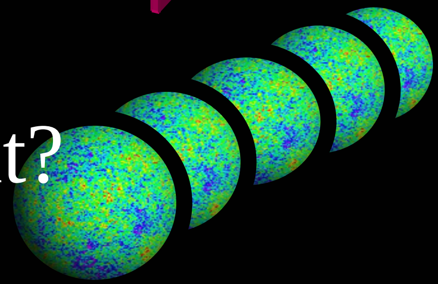
Major Question: What is the Dark Energy?



- Particle physics?
  - Zero-point vacuum energy of a new scalar field.



- Gravitational physics?
  - Extra spatial dimensions.



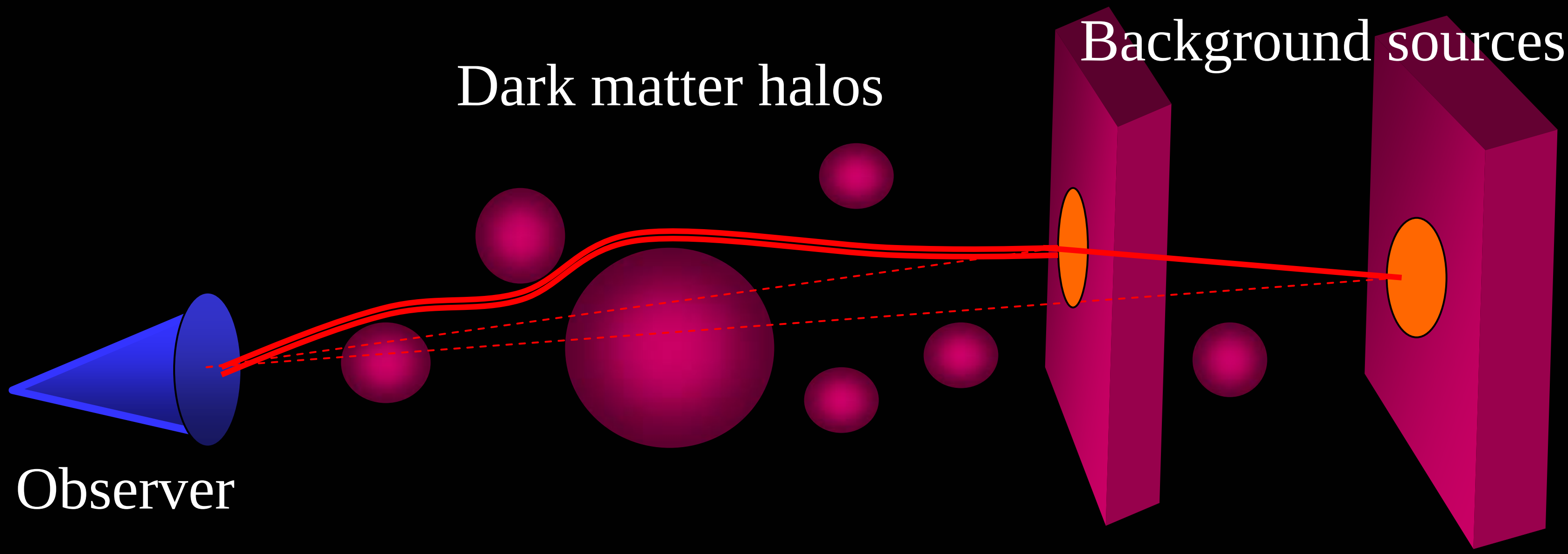
- Einstein's Cosmological Constant?
  - Random variable in a Multiverse?

Dark Energy Equation of State

- The key to Dark Energy lies in its evolution:
  - If it doesn’t its Einstein’s Cosmological Constant.
  - If it does its dynamical field or non-Einstein gravity.
  - Differentiate between dynamical field and non-Einstein gravity by differences in geometry and clustering.

Geometric Test: 3-D Shear Ratios

(Jain & Taylor 2003, Taylor, Kitching, Bacon, Heavens 2005)



$$R_{ij} = \frac{\gamma(z_i)}{\gamma(z_j)} = \frac{S_k[r_j]S_k[r_i - r_L]}{S_k[r_i]S_k[r_j - r_L]} \approx w^{-0.02}\,\Omega_V^{0.01}$$

- Signal depends on (Ω_m, Ω_v, w_0, w_a) and is insensitive to clustering.

Testing Gravity

- Dark energy opens up possibility gravity sector is wrong.
- A number of ways to test gravity with lensing:

  1. Generalize Einstein gravity:
     - $2\Phi \to \Phi+\Psi=(1+\eta)\Phi$.
     - Add vector, tensor perturbations V, E.
  2. Parameterize non-Einstein gravity:
     - Growth index, γ, in DGP, braneworlds.
  3. Compare full non-Einstein gravity models:
     - Scalar/tensor models
     - Braneworld/DGP-like
     - F(R) models
     - TeVeS, vector/tensor
  4. Consistency in *w* from structure and geometry.

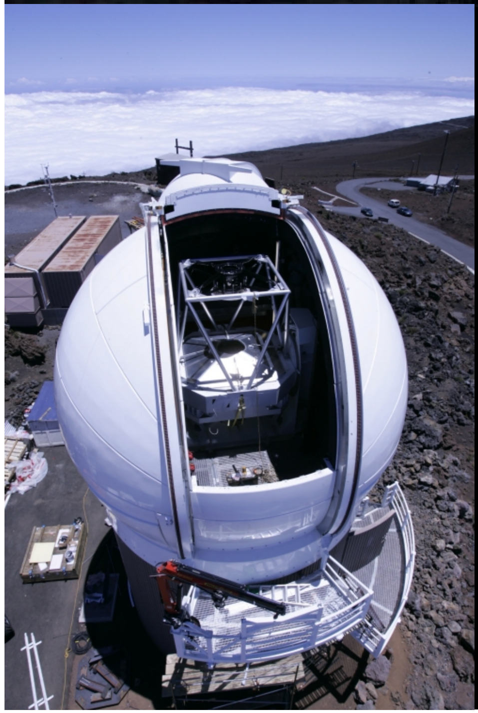
Neutrino dark matter

- Neutrino oscillation experiments show m<2.2eV.
- Limit sum of neutrino masses to >0.06eV.
- Future experiments (eg KATRIN) will reach >0.2eV.
- Planck expects 0.5eV.

- Weak lensing with DUNE (+Planck) from space can measure the damping tail in the matter power spectrum:

$$m > 0.04\text{eV}$$

Pan-STARRS 1



- US led.
- 1.8 meter primary
- 1.4 Gpixel camera.
- 7 square degree field-of-view.
- 3π Survey
- g, r, i, z, y (r=24.5)
- . PS-1 2008-2011 $\mapsto$ PS-4

2008-2013: VST-KIDS

- EU led.
- ESO's Kilo-Degree Survey

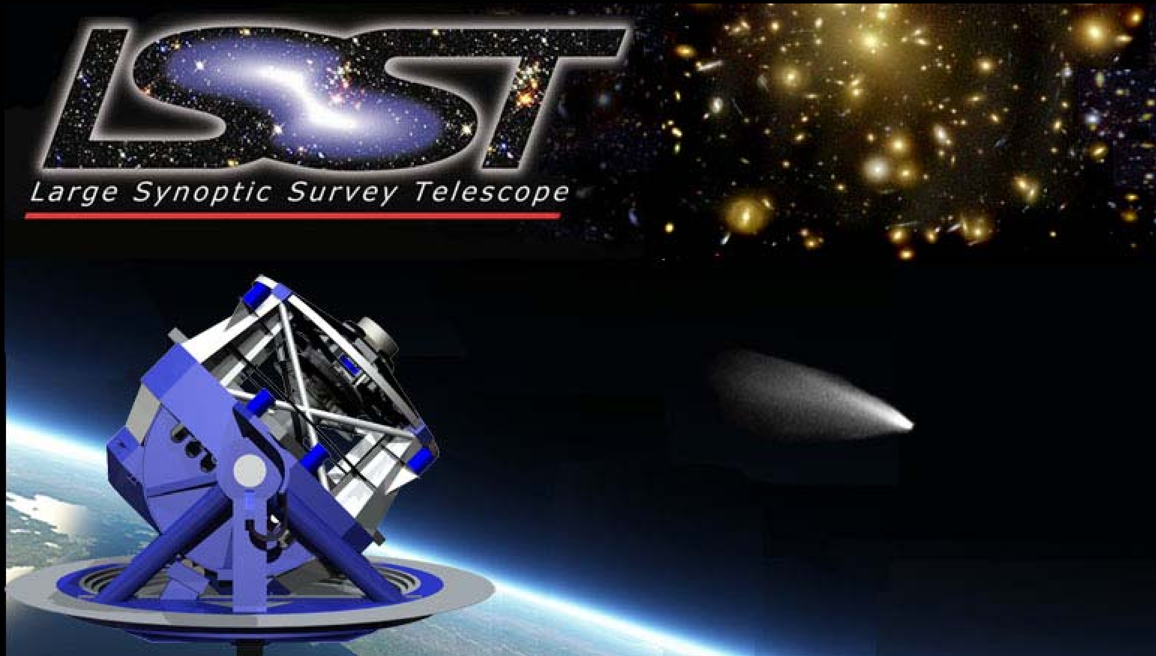
- 2m primary
- 184Mpixels
- 1 square degree field-of-view

- 1,500 sq deg
- u'g'r'i'z'

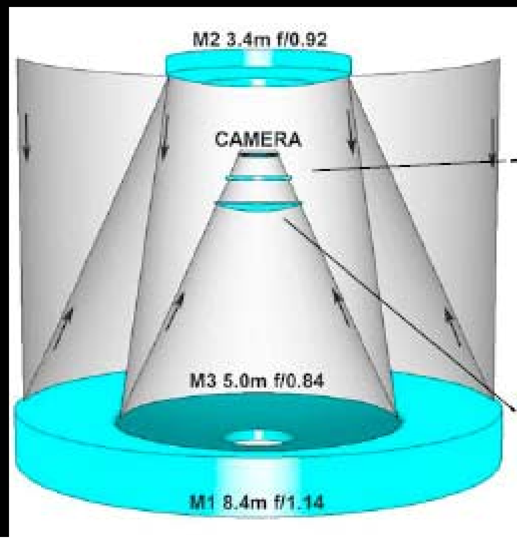
2010-2015: DES

- The Dark Energy Survey.
  - US led.
  - 4-metre primary
  - 500 Megapixel
  - 3 sqdeg fov
  - g,r,i,z
  - 5000 sq deg

2014-2024: LSST

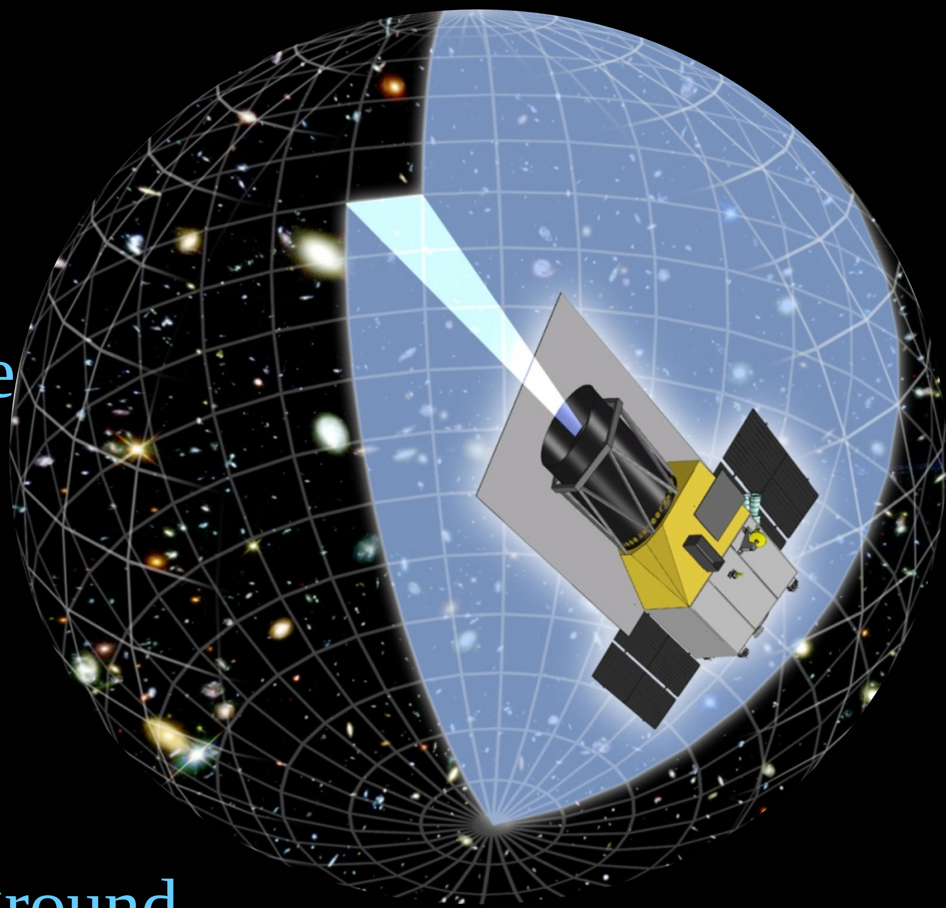


- Large Synoptic Survey Telescope (LSST)
  - US led.
  - 8.4m (effectively 6.5m) Primary
  - 3.2 Gpixels
  - 9.6 sq deg fov
  - ugrizY

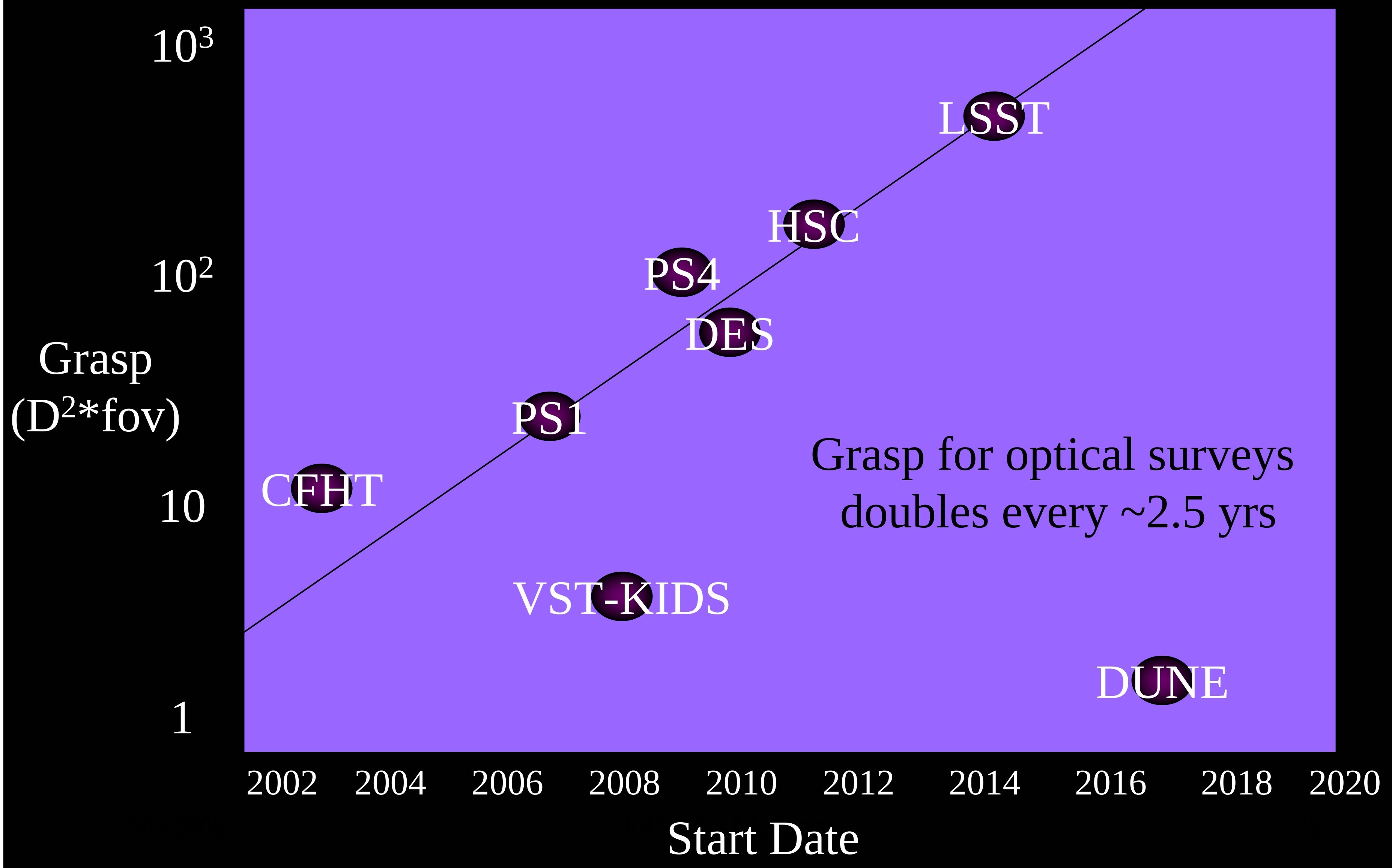


2017-2021: DUNE – Dark UNiverse Explorer

- Cosmic Visions proposal to European Space Agency
  - EU led.
  - 1.2m satellite telescope
  - 0.5 sq deg fov
  - 20,000 sq deg
  - r-i-z + Y,J,H
  - Optical photo-z from ground.
  - Merger with spectroscopic survey SPACE (BAO's).



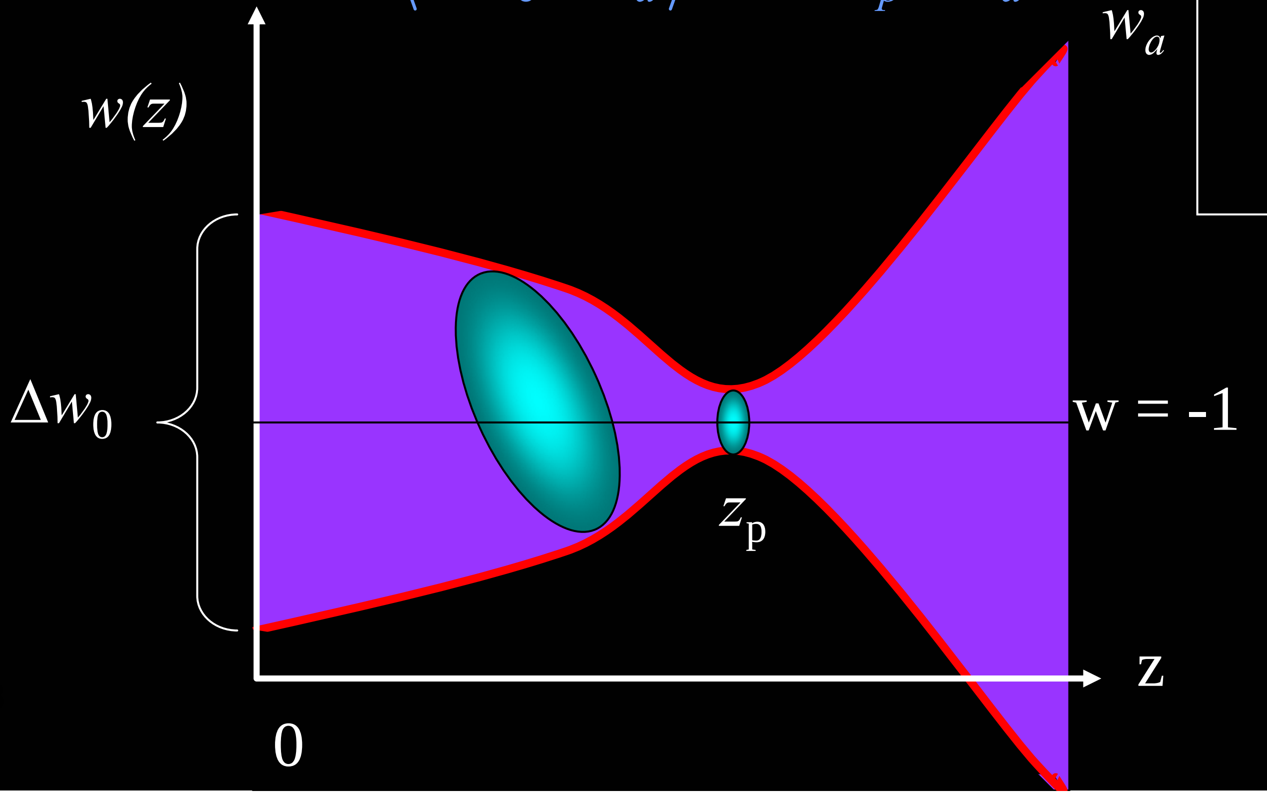
Grasp vs. Start Date

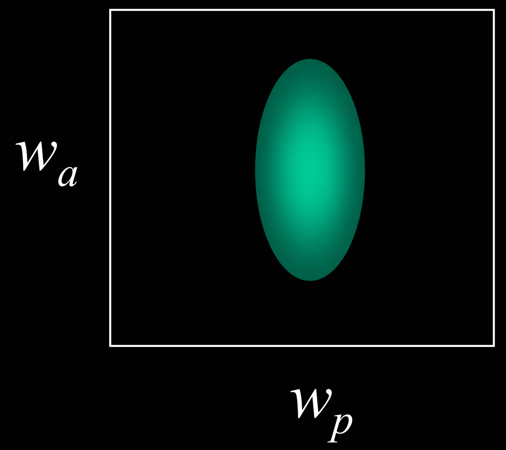


Dark Energy Figure of Merit (FoM)

- Evolving equation of state: $w(z) = w_0 + w_a[1 - a(z)]$
- Define pivot redshift, z_p: $w_p = w_0 + w_a[1 - a_p]$

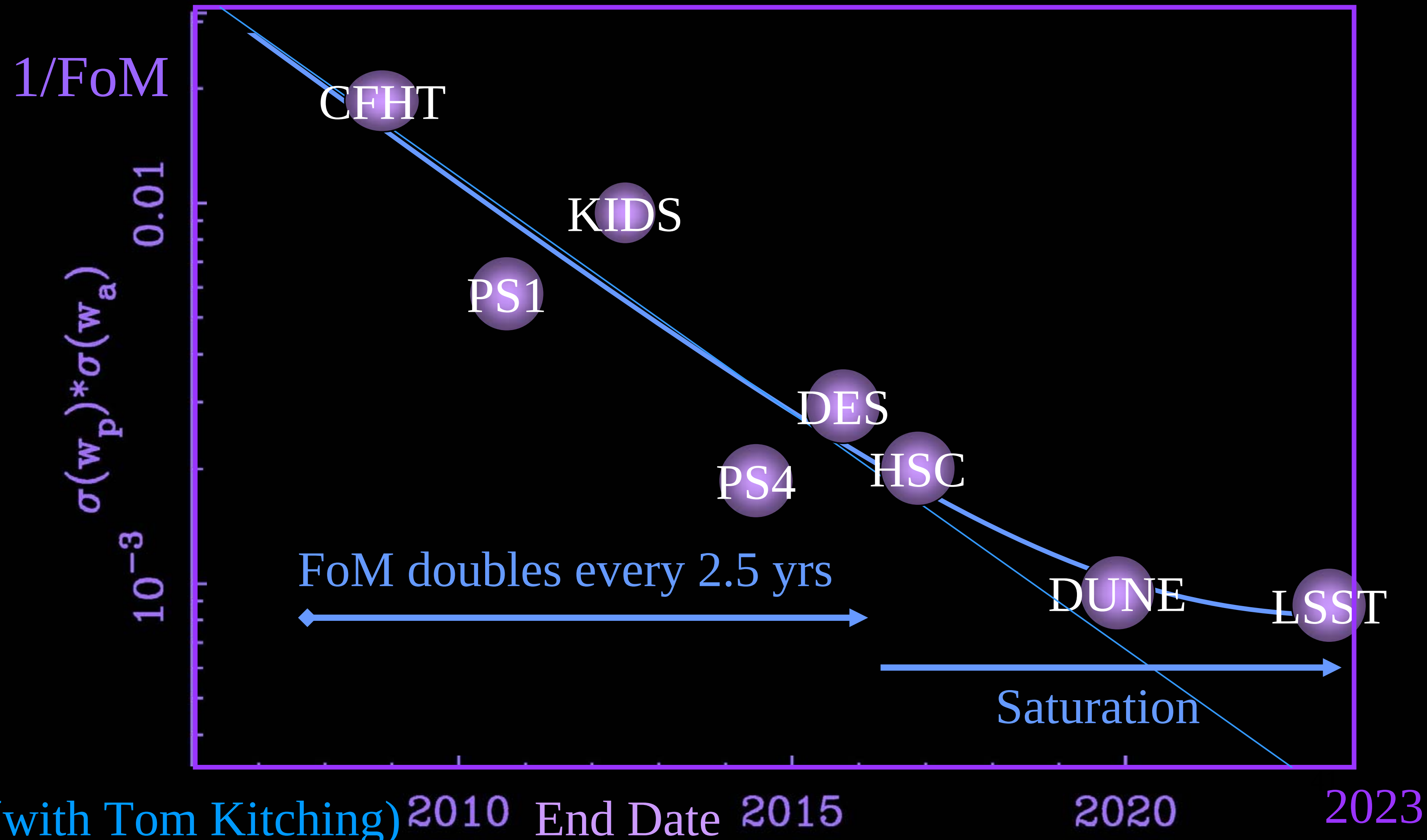
$$FoM = \frac{1}{\langle \Delta w_0 \Delta w_a \rangle} = \frac{1}{\Delta w_p \Delta w_a}$$





FoM for Dark Energy from Lensing

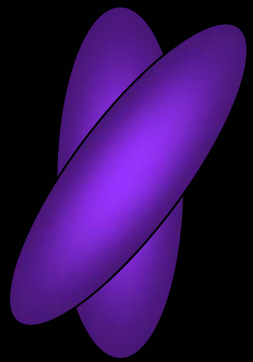
3-D shear power and shear-ratios combined
with Planck Explorer CMB survey (2008)



(with Tom Kitching)

Challenges: Image Distortions

- Image distortions: (Kitching, Taylor & Heavens 2007)

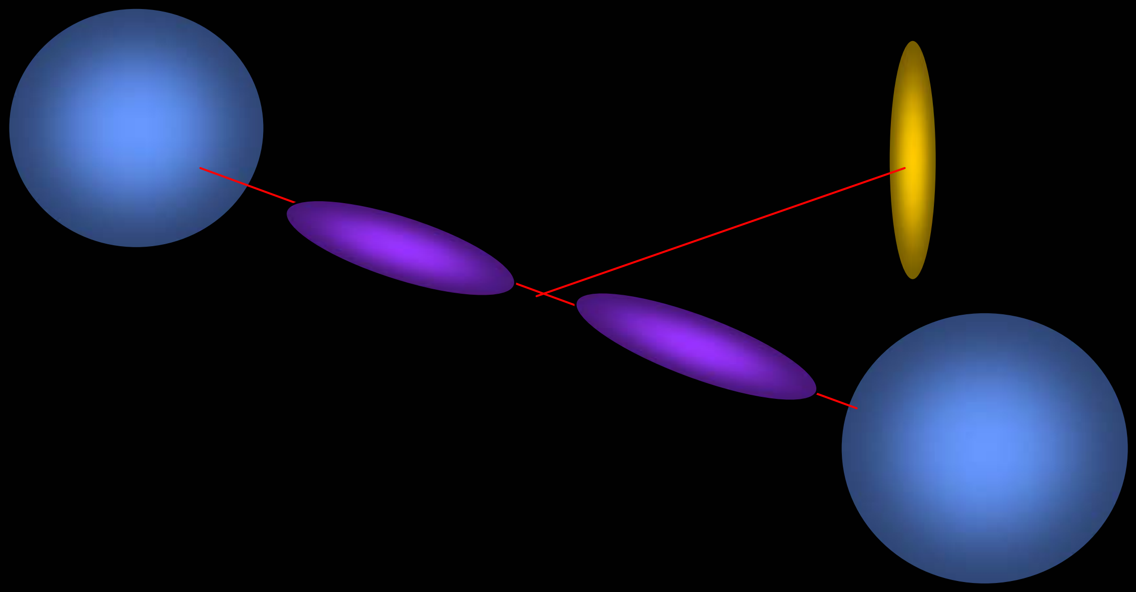


$$\gamma' = A e^{i2\omega}\gamma + \gamma_{bias}$$

calibration rotation bias.

Challenges: Intrinsic Alignment

- Two alignment effects:
  - Intrinsic-Intrinsic alignments
  - Galaxy-Intrinsic alignment

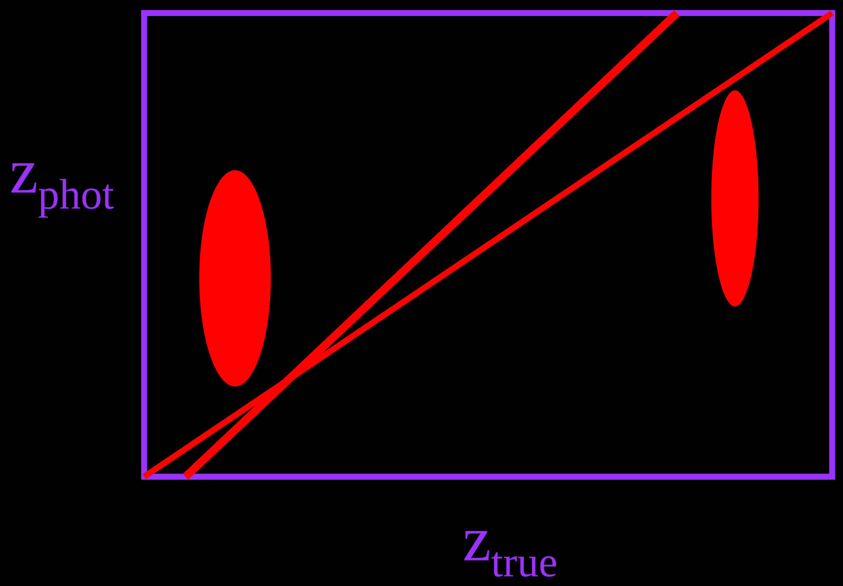


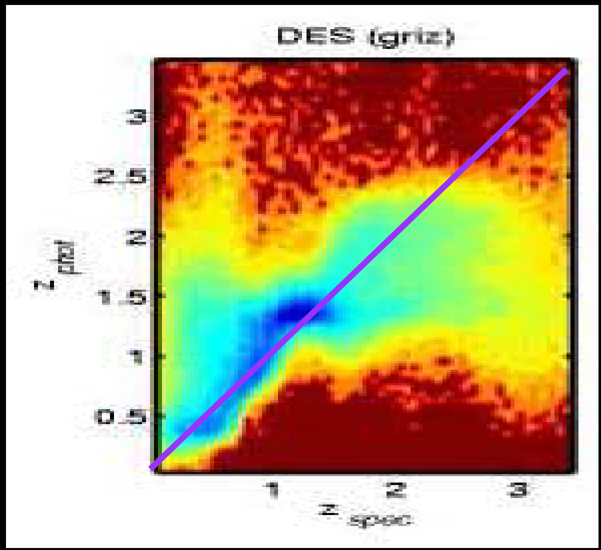
$$C^{\gamma\gamma} = C^{GG} + C^{II} + 2C^{GI}$$

(Bridle & King, 2007; Kitching, Taylor & Heavens 2007)

Challenges: Photometric Redshifts

- Photometric redshifts: calibration, bias, outliers





Abdalla et al (2007)

$$z_{phot} = Cz_{true} + z_{bias}$$

(Abdalla et al, 2007; Kitching, Taylor & Heavens 2007)

Organizational Challenges

MARIE CURIE ACTIONS

- Coordinated effort.
- EU Research-Training Network.
- DUEL (Dark Universe with Extragalactic Lensing)
  - Exploit Cosmological Lensing from CFHTLS, Pan-STARRS, VST-KIDS
  - Plan for future surveys (DUNE…)
  - 8 Network Partners:
    - Edinburgh, Paris, Bonn, Heidelberg, Munich, Leiden, Naples, British Columbia
  - 14 Postdocs & PhD students across network.
  - Training & exchange of methods & data.

Summary

- Currently:
- Accurate 2 & 3D mass maps
- See growth of structure
- Cosmological parameters
- Scaling all of this up for new surveys (Pan-STARRS, VST-KIDS, DES) will be a major challenge.
- European Network (DUEL) to help do this.

- Future Aims (PS4, DUNE, LSST):
- Map Dark Matter over whole sky to z~1.
- Pin down dark energy to ~1%.
- Test gravitational physics.
- Measure neutrino mass to >0.04eV.
- Probe initial conditions (inflation).
- Develop theory and methods.