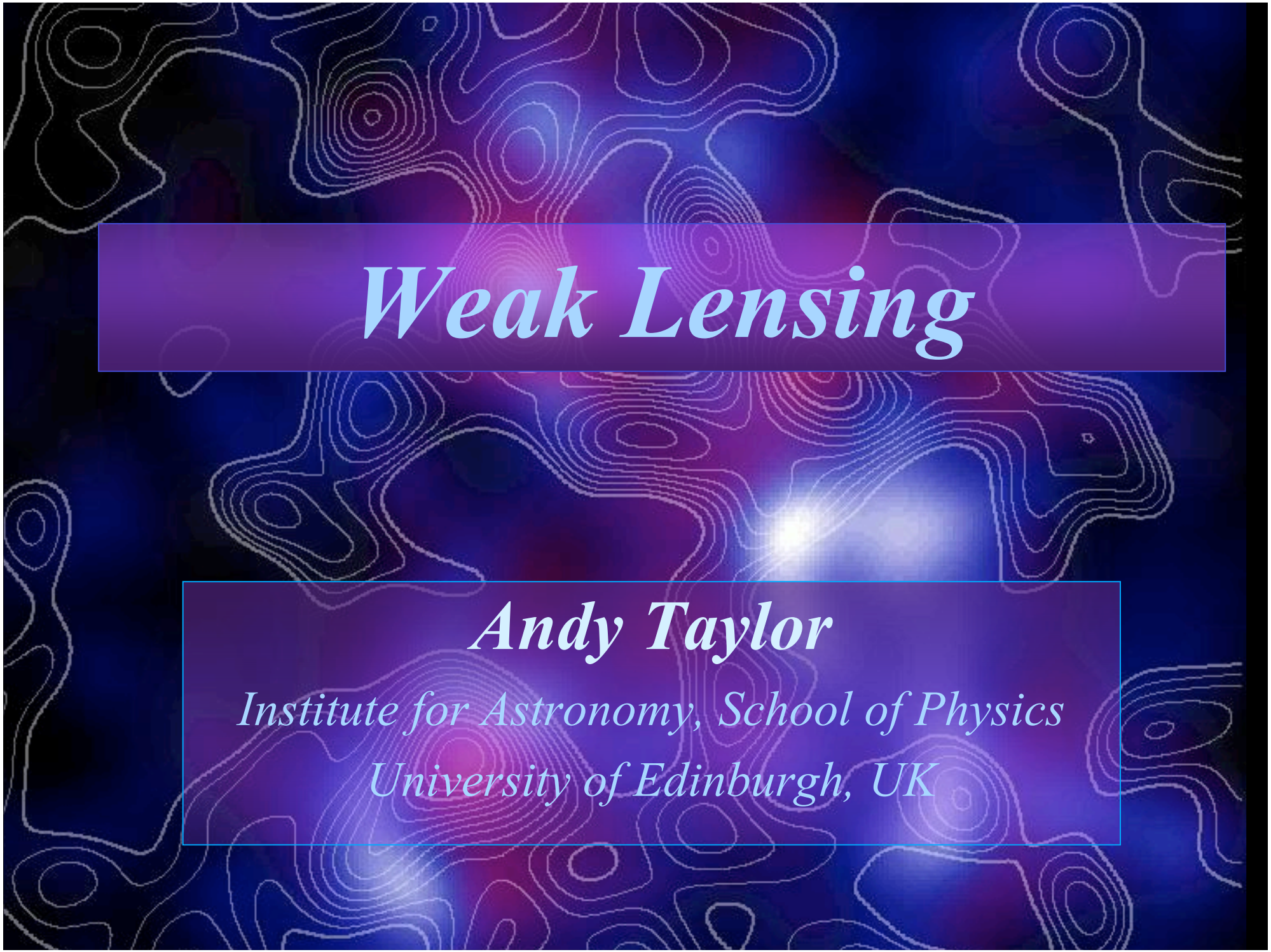
Weak Lensing
Andy Taylor
Institute for Astronomy, School of Physics
University of Edinburgh, UK

Gravitational Lensing

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Gravitational Lensing

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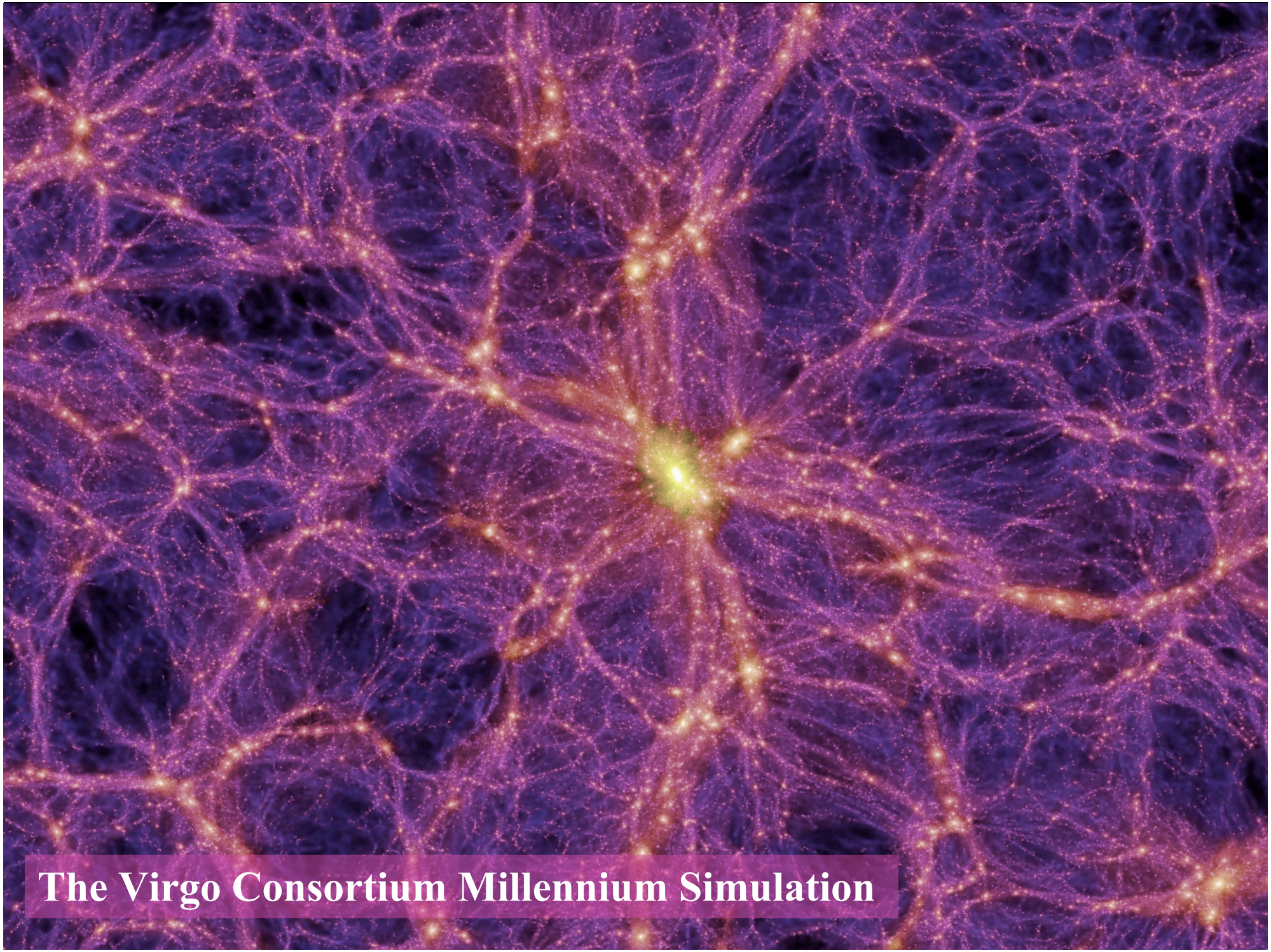
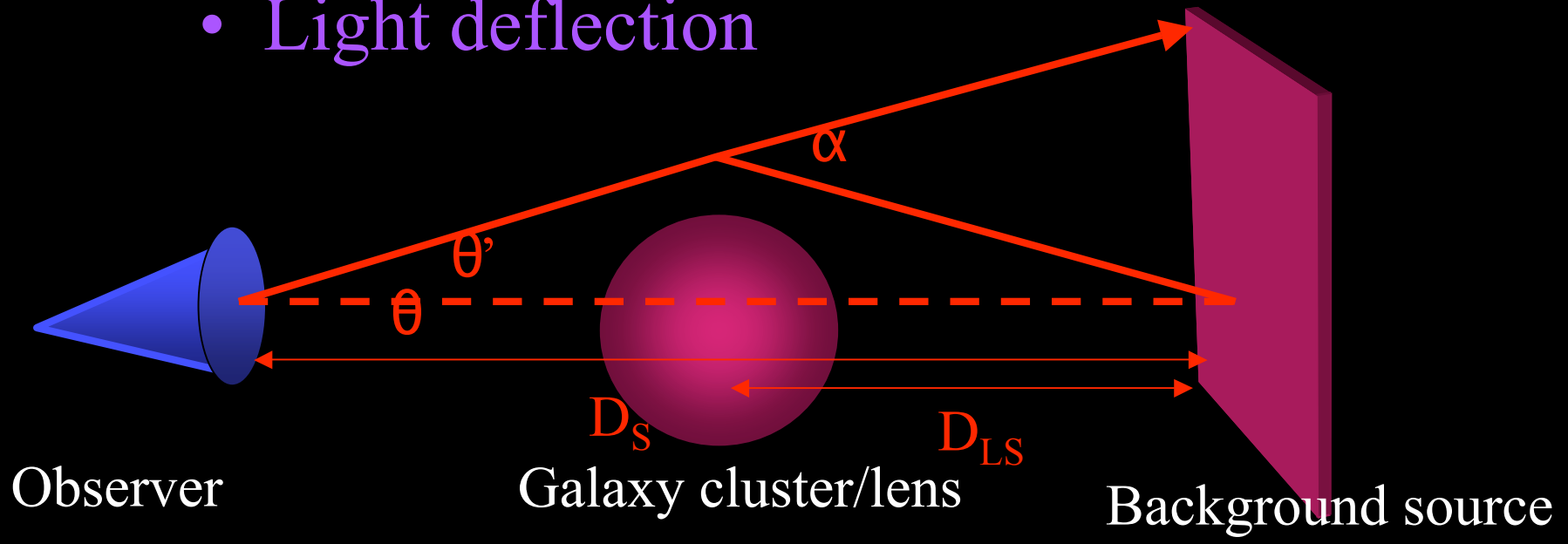

The Virgo Consortium Millennium Simulation

Gravitational Lensing

Basics of Gravitational Lensing

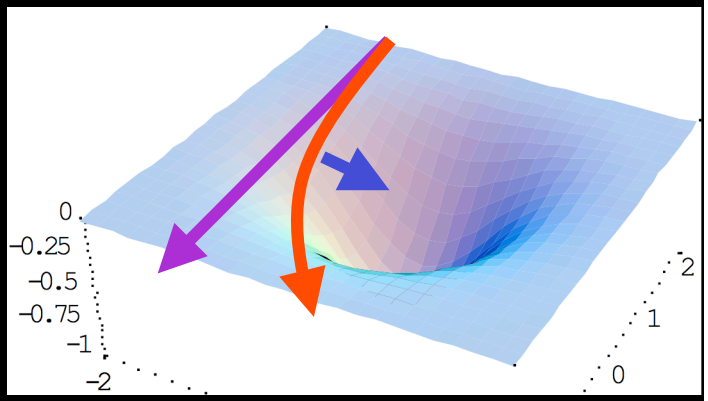
- Light deflection



- Lens equation

Basics of Gravitational Lensing

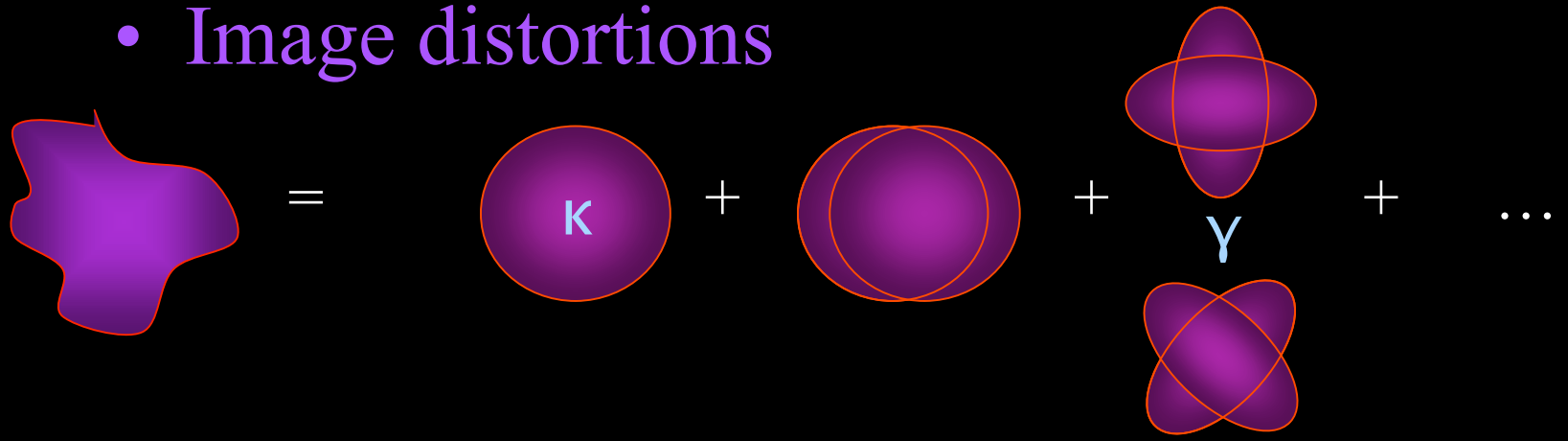
- Relativistic equation of motion



- Solve equation of motion ($\eta = r$):

Basics of Gravitational Lensing

- Image distortions



Gravitational Lens Distortions

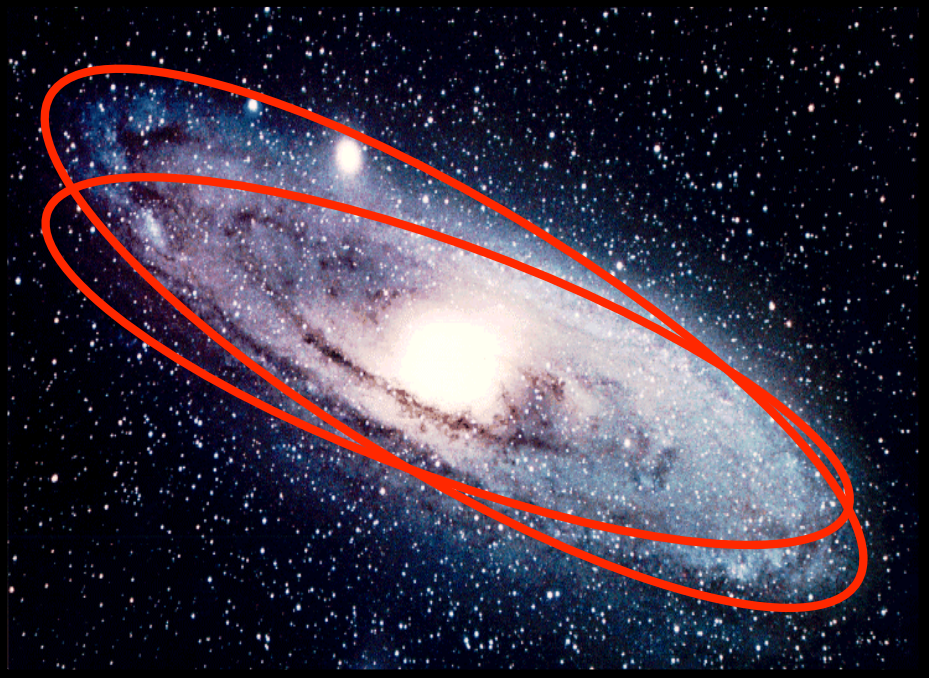
- Galaxy ellipticity, *e*:
- Lensing effect:

$$e' = e + \gamma$$

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

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

- Shear matrix:



$$\gamma = \begin{pmatrix} \gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{pmatrix}$$

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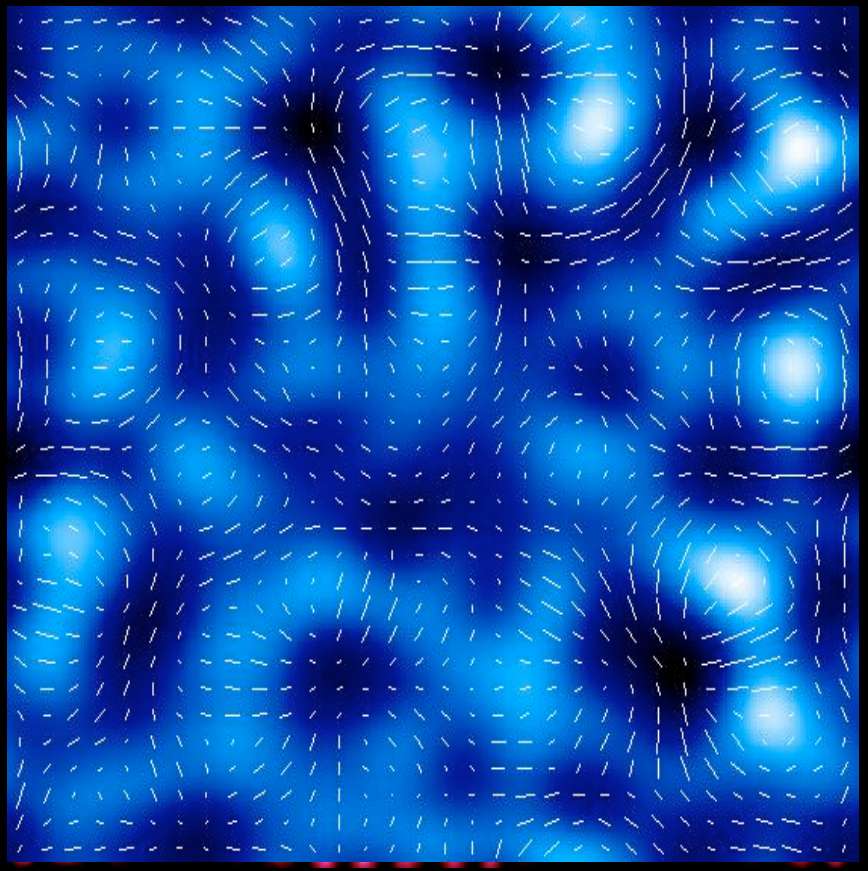
Mapping the Dark Matter

- From shear to surface density:

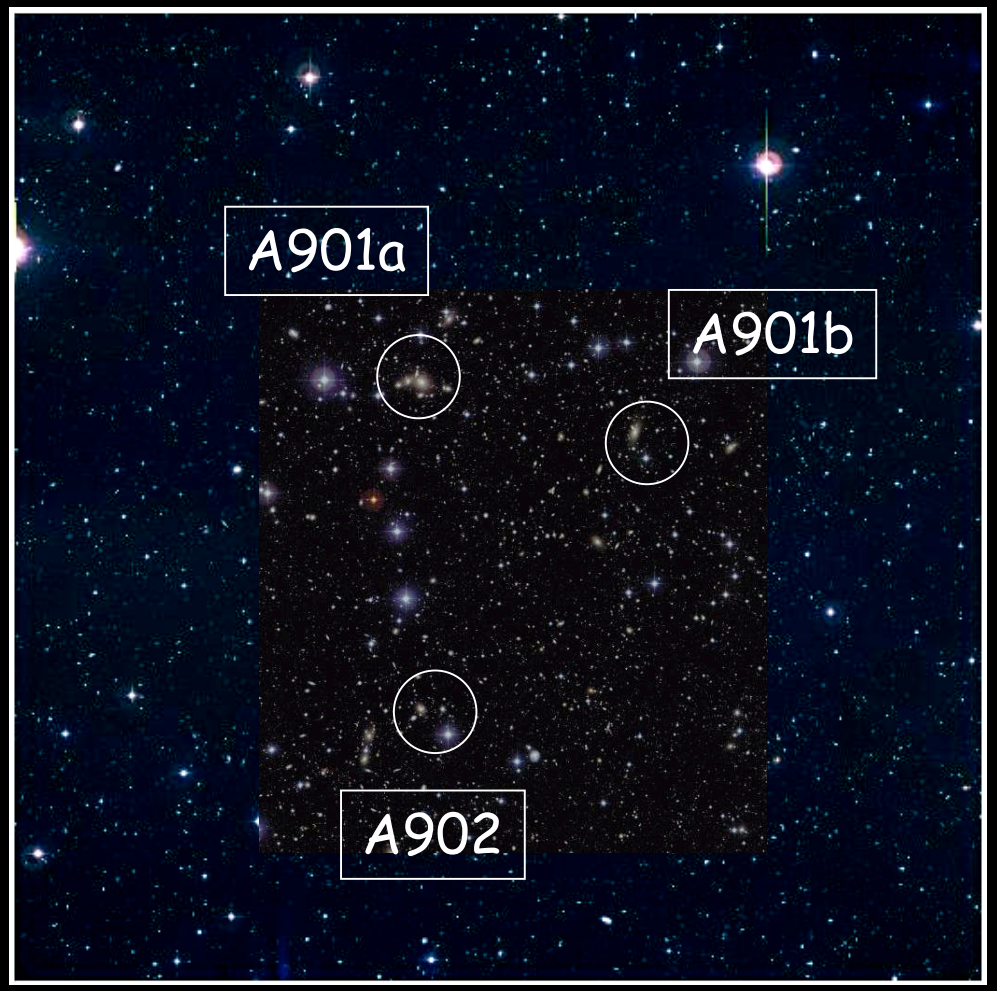
  Kaiser-Squires (1993)



Supercluster Abell 901/2

1/2 deg

3Mpc/h

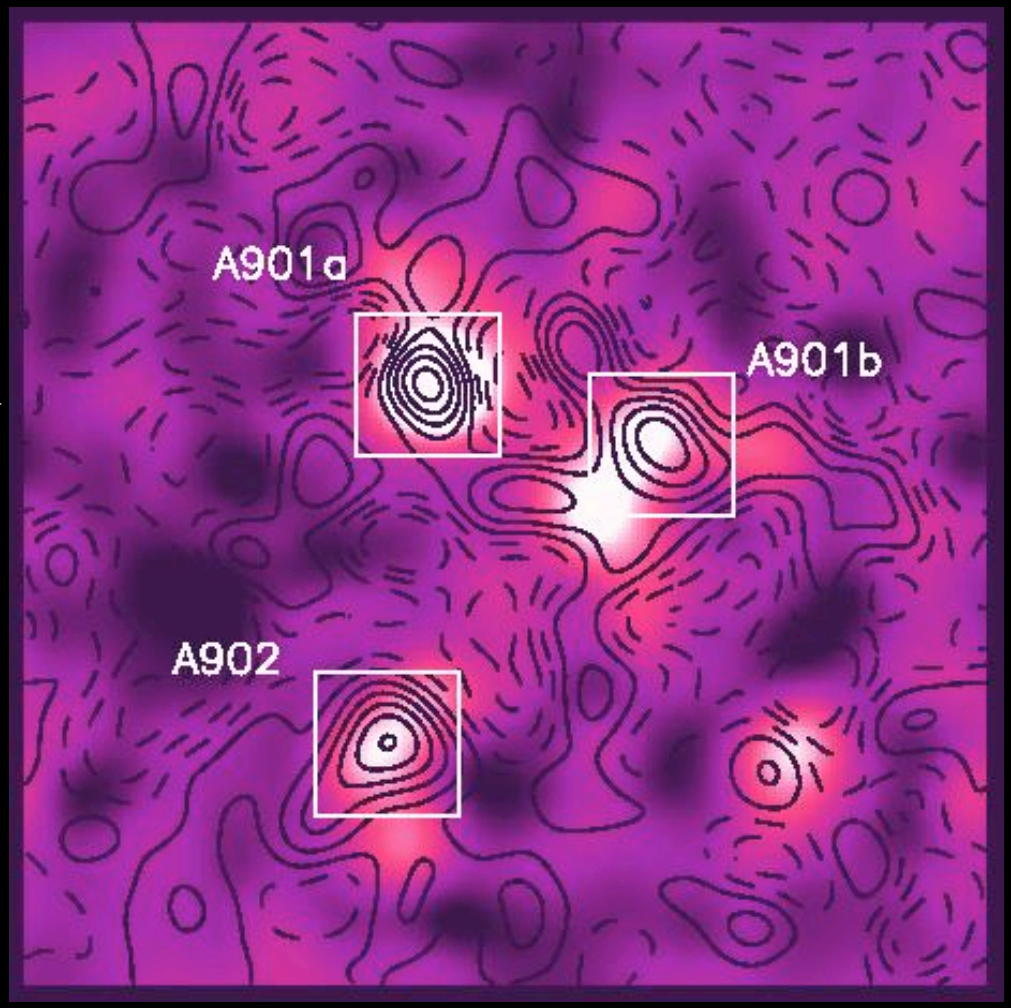


- z=0.16
- Δz=0.01

Mass and light in Supercluster A901/2

Dark Matter contours, κ.

Elliptical galaxy light shading.



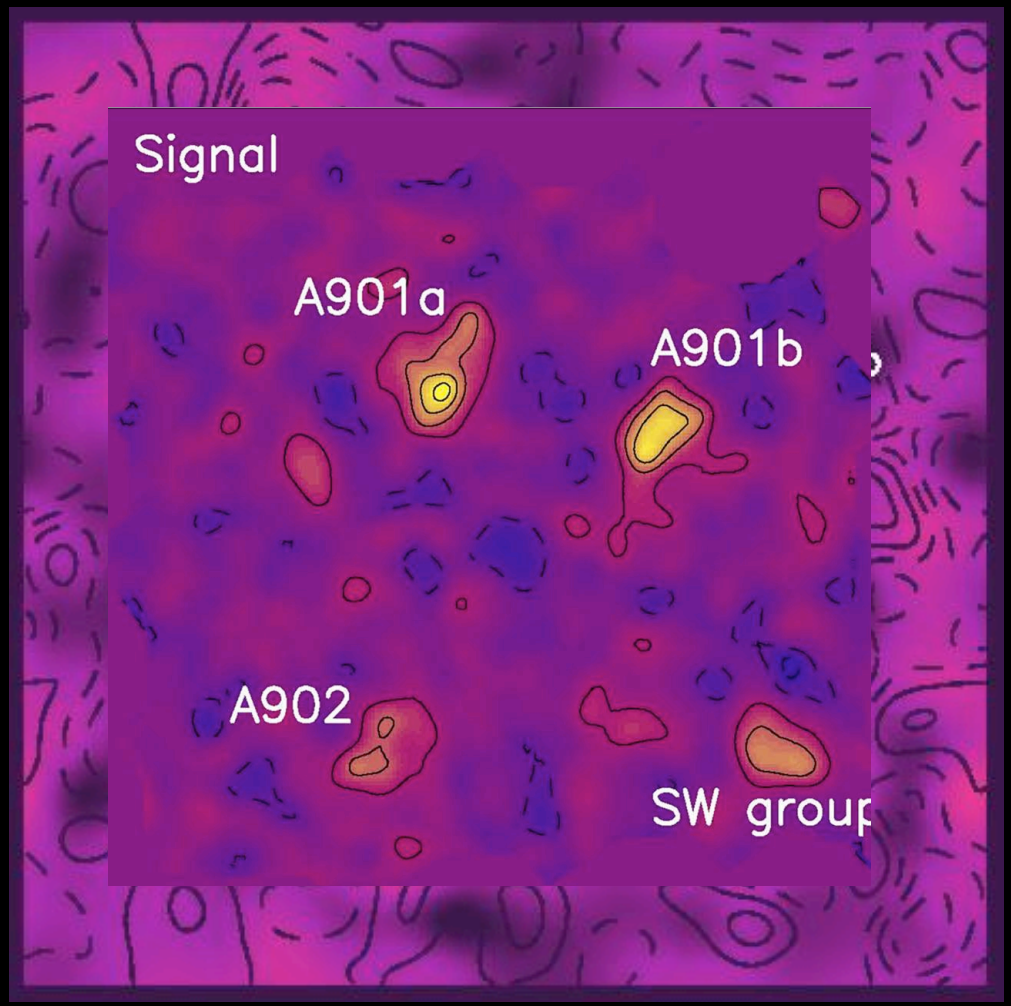
Error:
$\Delta\kappa = 0.02$
(1–contour)

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

Mass and light in Supercluster A901/2

Dark Matter contours, κ.

Dark Matter shading.



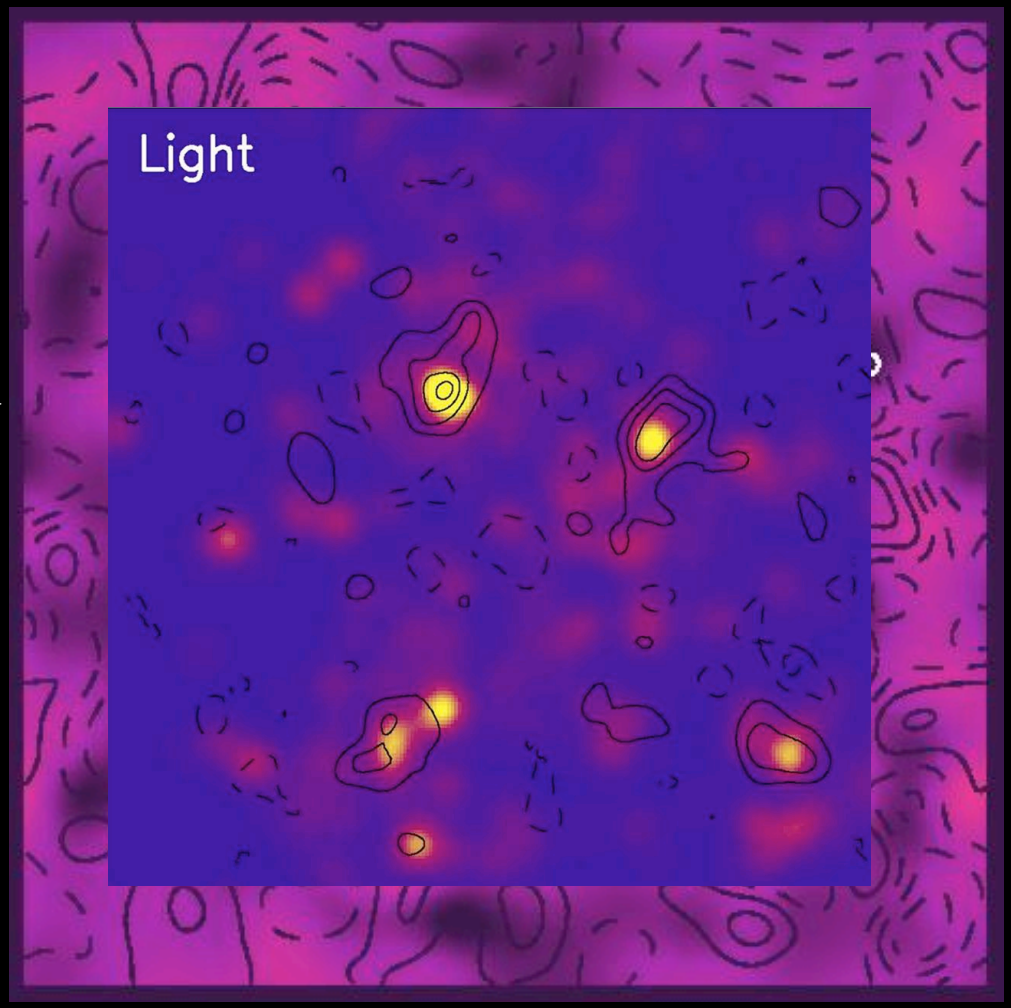
Solid contours: 2,4,6,8 sigma

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

Mass and light in Supercluster A901/2

Dark Matter contours, κ.

Elliptical galaxy light shading.



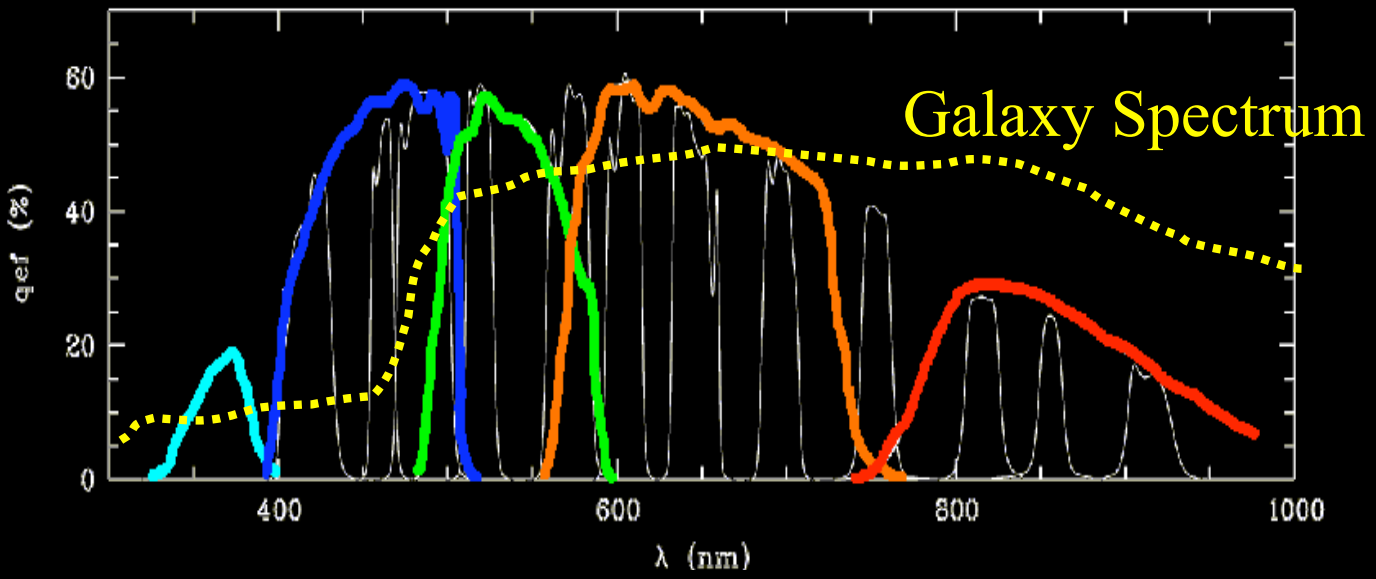
Solid contours: 2,4,6,8 sigma

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

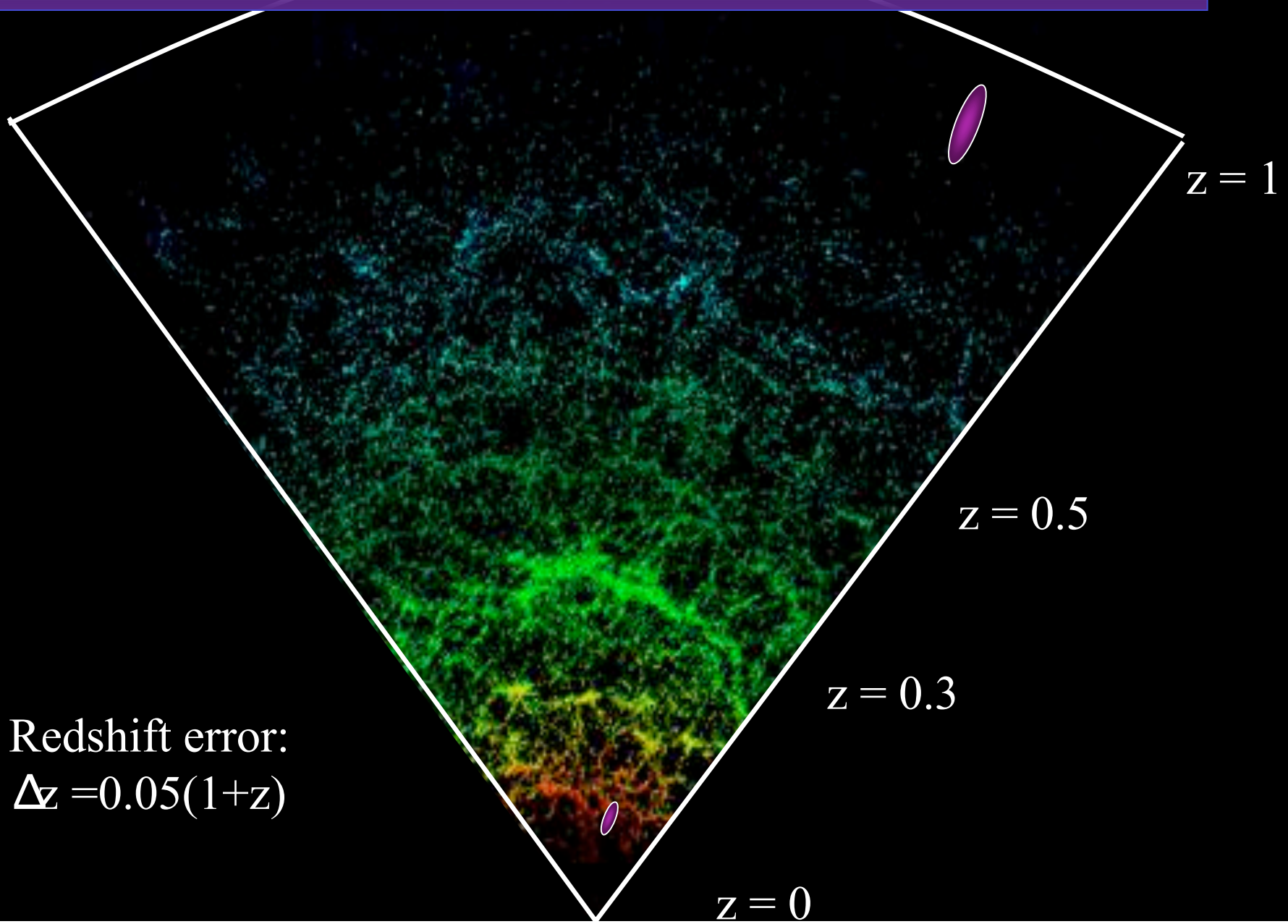
3-D Gravitational Lensing

- Combine galaxy ellipticities with redshift information, $\gamma_i(\theta_x, \theta_y, z)$ to get 3D lensing.
- For large samples, use multiband photometric redshifts

$$\frac{\Delta z}{1+z} = 0.05\left(\frac{5}{N_{bands}}\right)$$

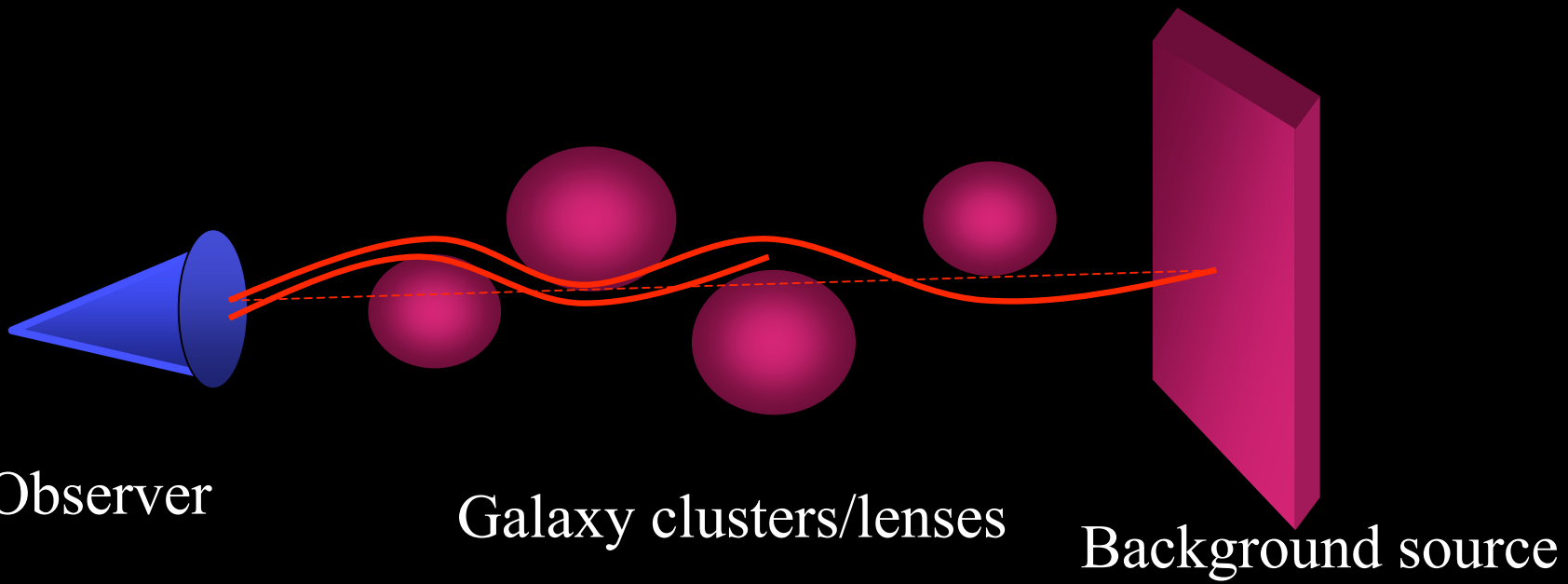


Photometric Galaxy Redshift Survey

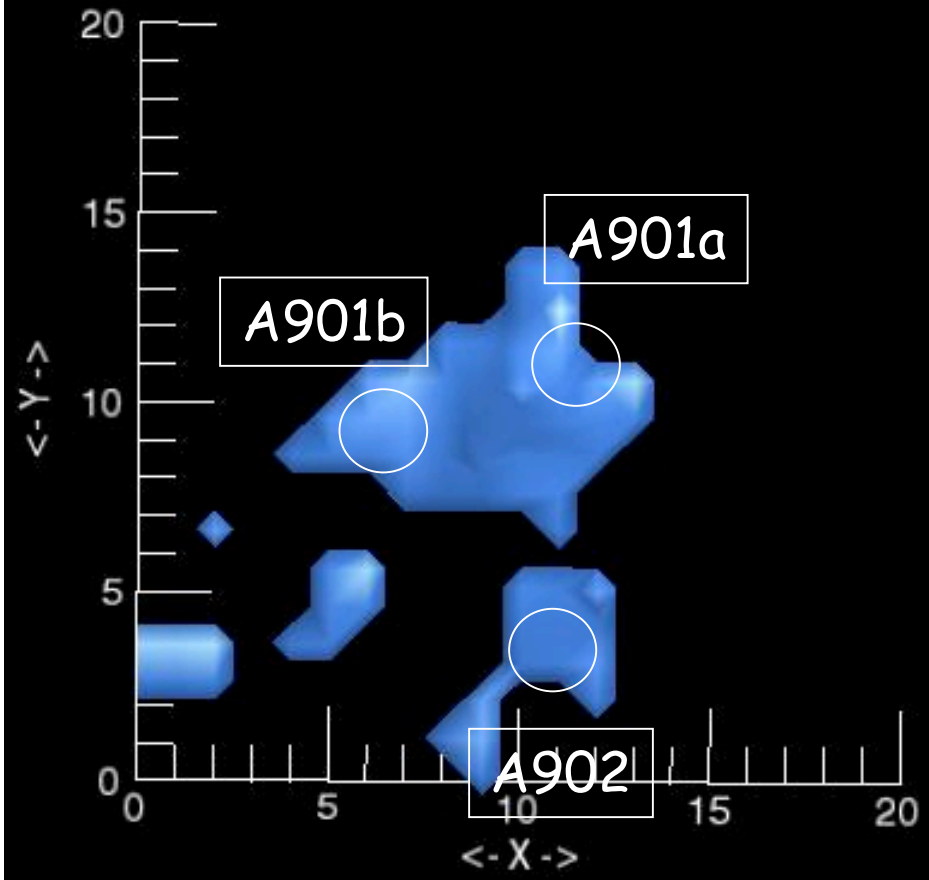


Mapping the Dark Matter in 3-D

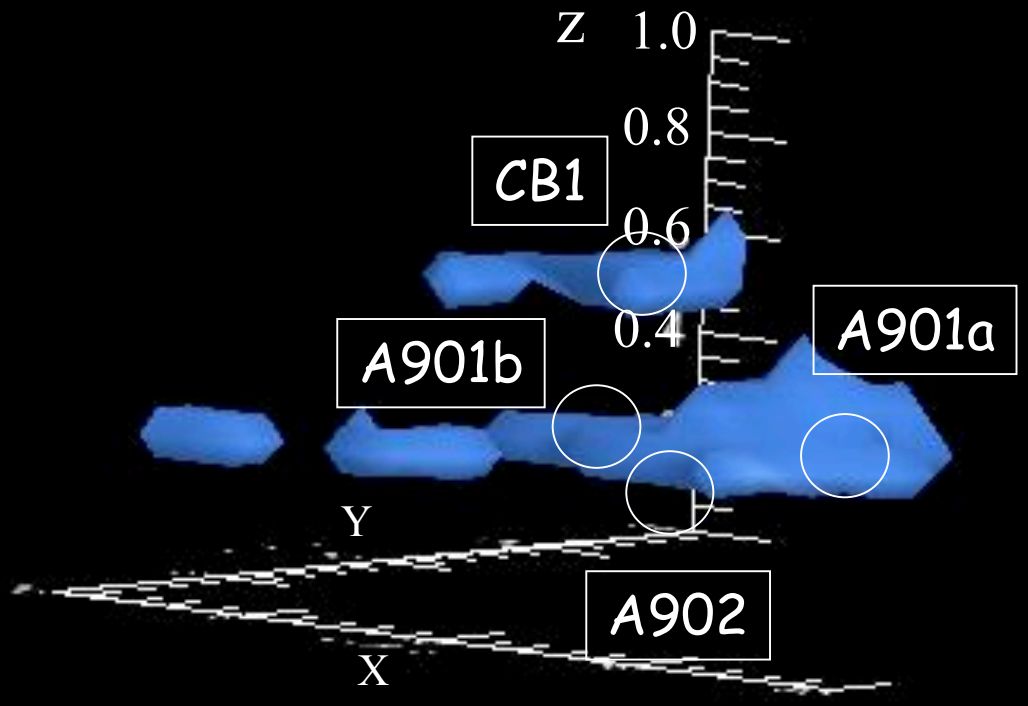
- With source redshifts, z, solved exactly by the relativistic equation of motion ($r = \eta$):



3-D Dark Matter Mapping

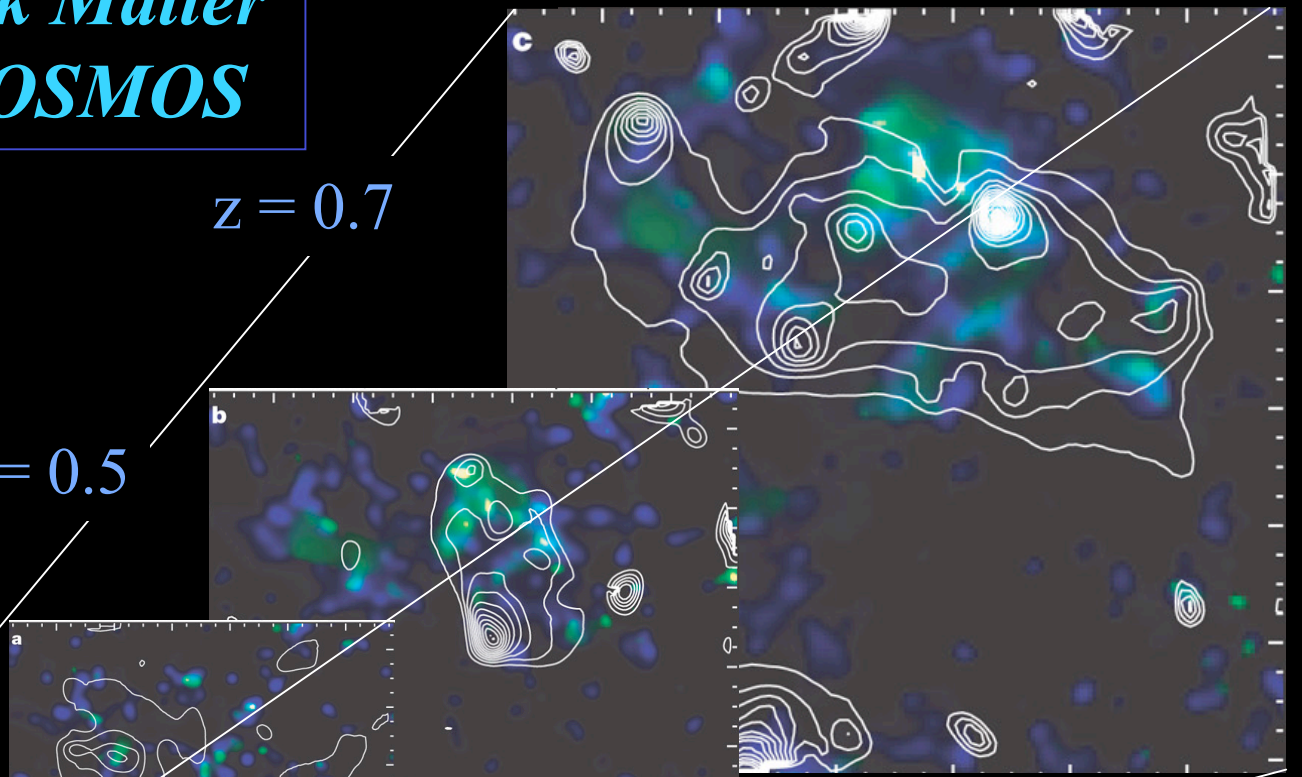


(2-σthreshold)



Taylor, et al, 2004 MN

Evolution of Dark Matter Clustering in COSMOS



z = 0.7

z = 0.5

z = 0.3

L=30Mpc

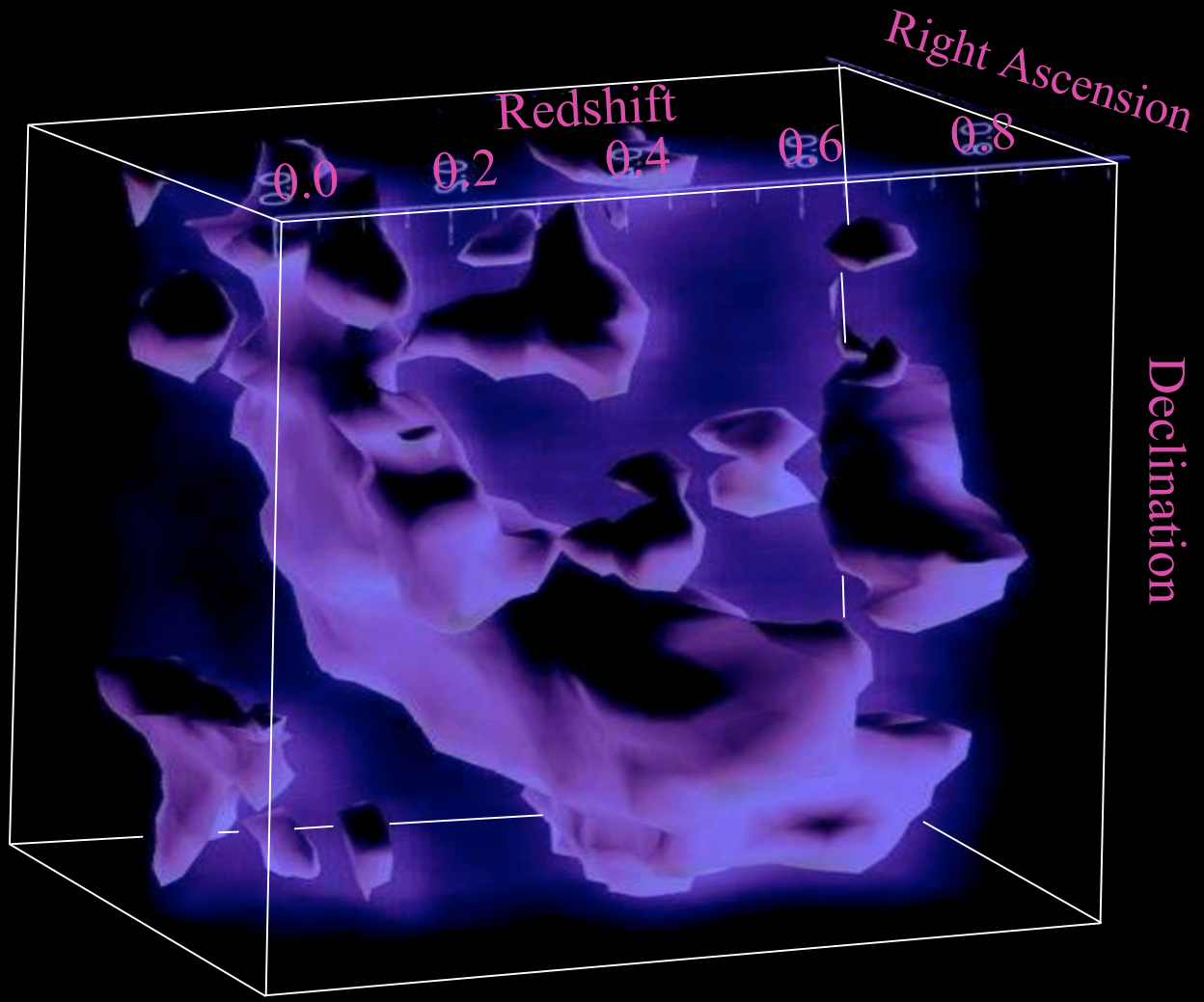
L=25Mpc

L=20Mpc

Massey, Taylor et al, Nature, 2007

COSMOS 3-D Dark Matter Maps

Relativistic equation of motion:

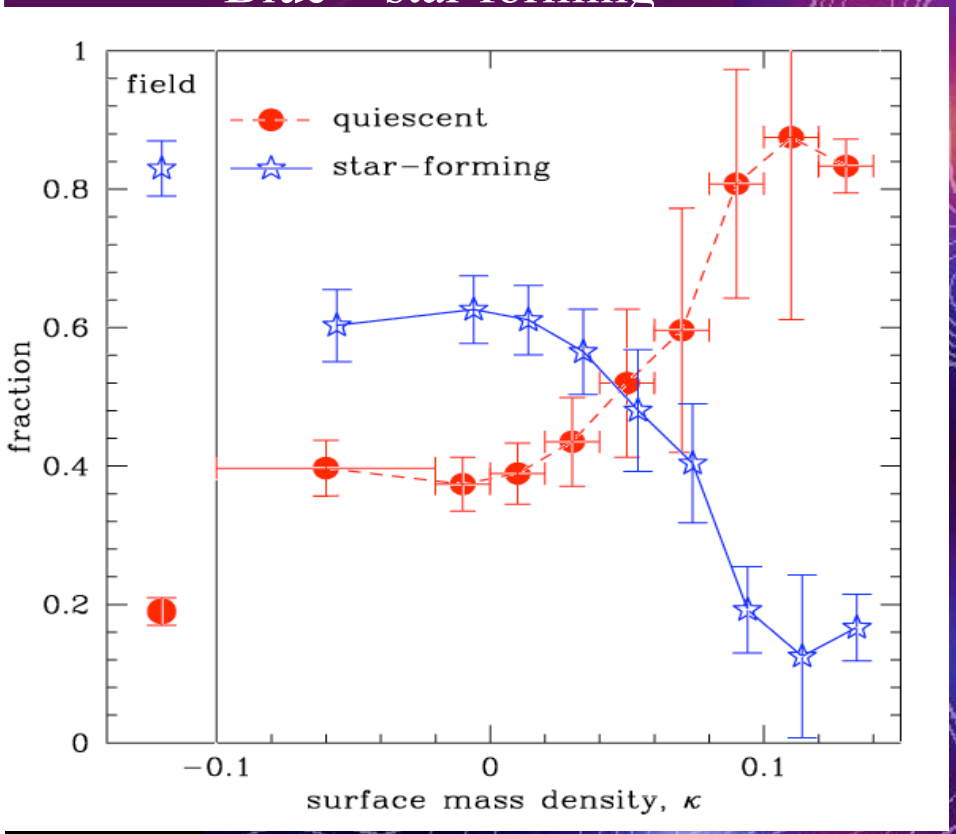


Massey, Taylor et al, Nature (2007)

Galaxy Formation & Environment

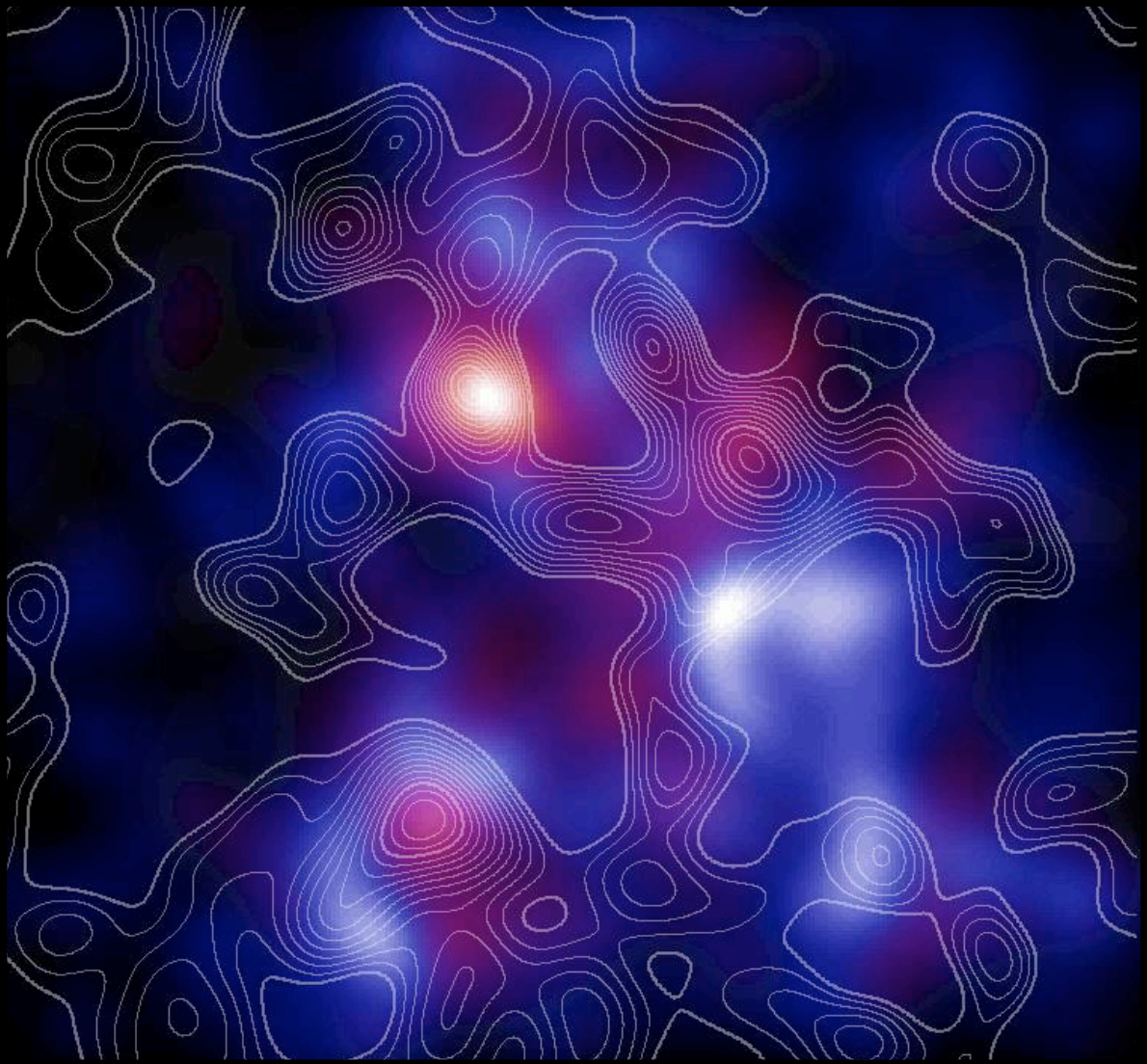
Photo-z: select cluster galaxies

SEDs: Red – quiescent
Blue – star forming



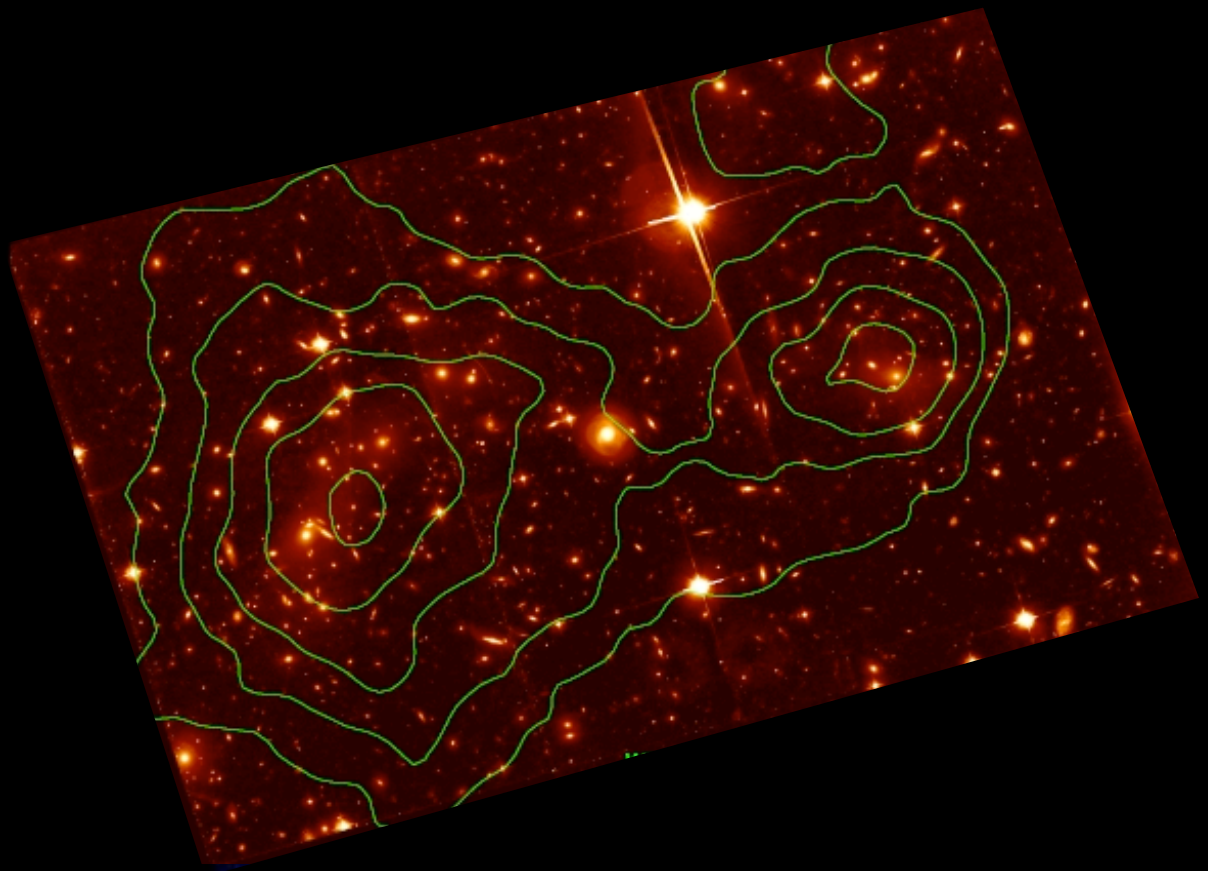
Gray et al 2004

Dark Matter, Galaxies and Hot Gas



The Bullet Cluster: Proof of Dark Matter?

Clowes et al 2006



Chandra 0.5 Msec image

0.5 Mpc

z=0.3

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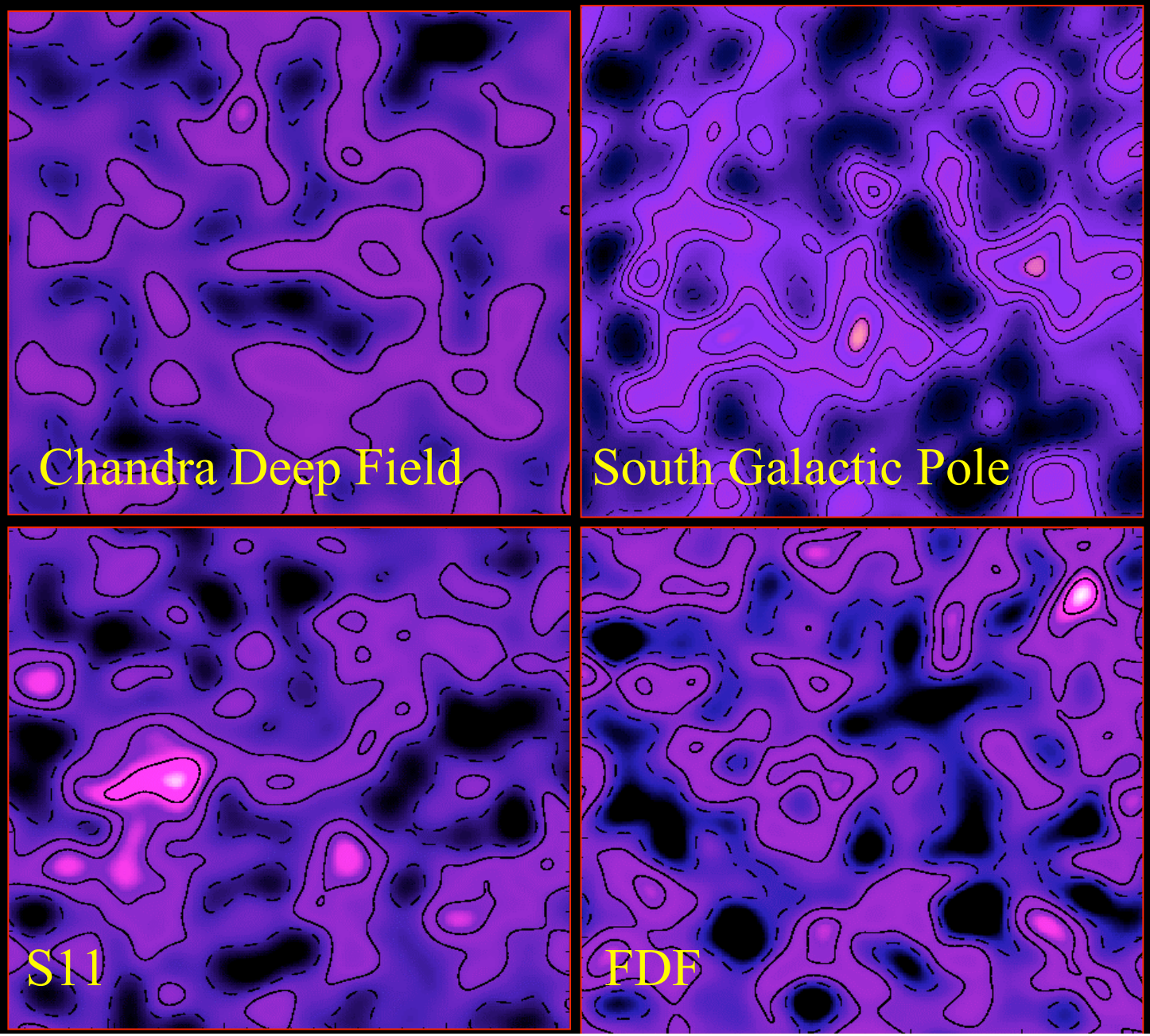
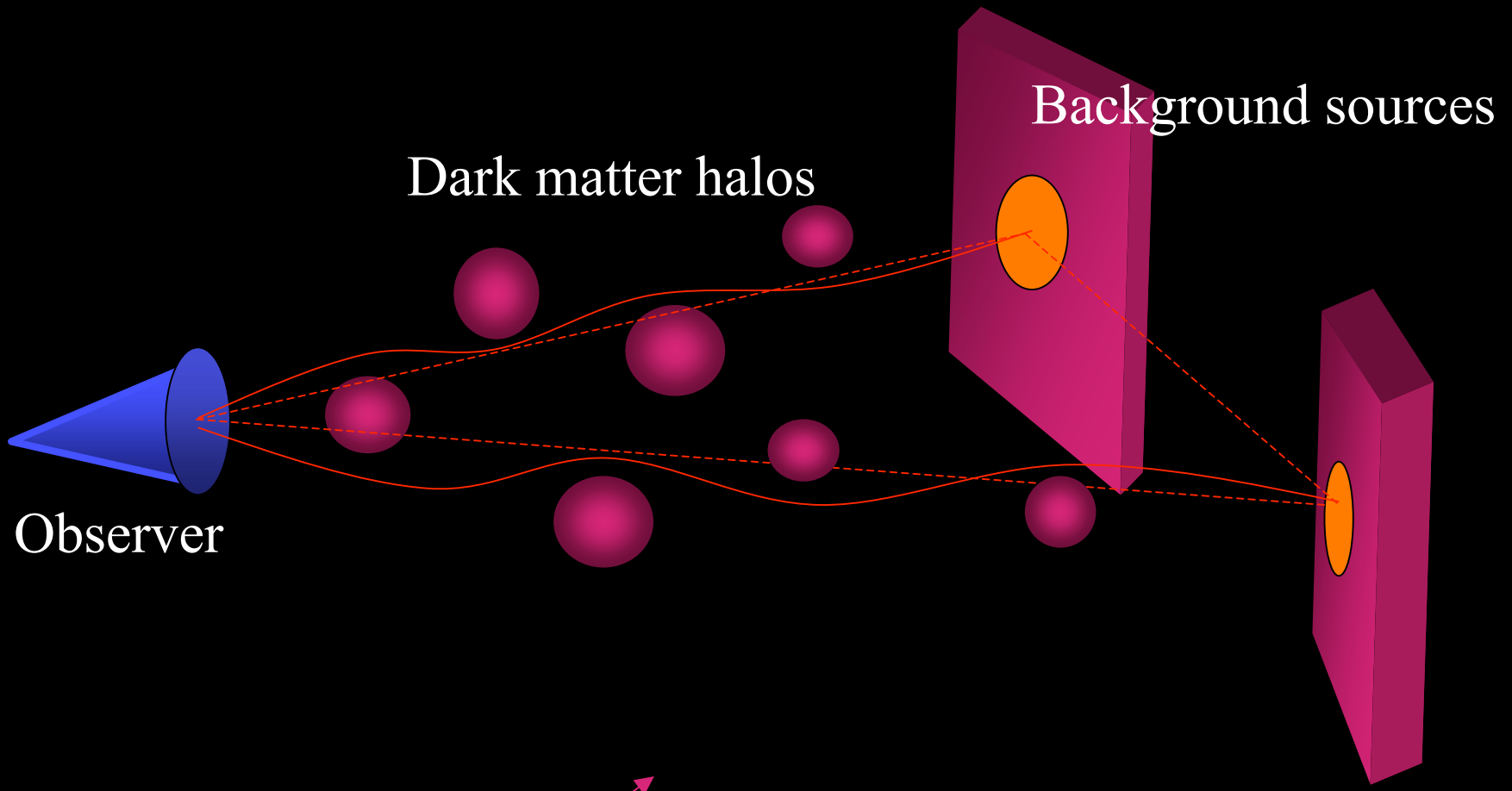
Random Mass Fields on the Sky

- 1 sq deg.



Cosmic Shear

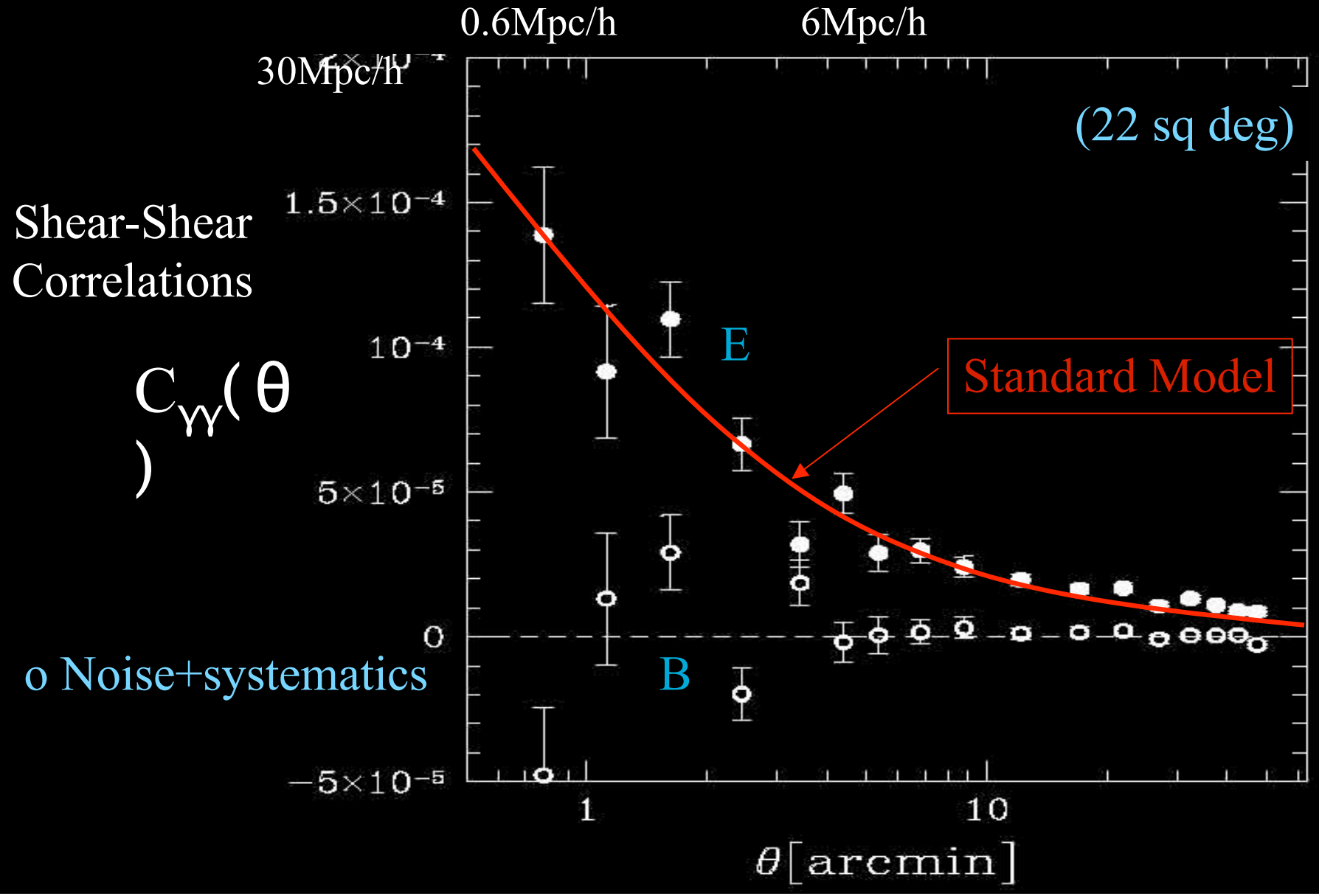


Variance of matter variations

Matter density parameter

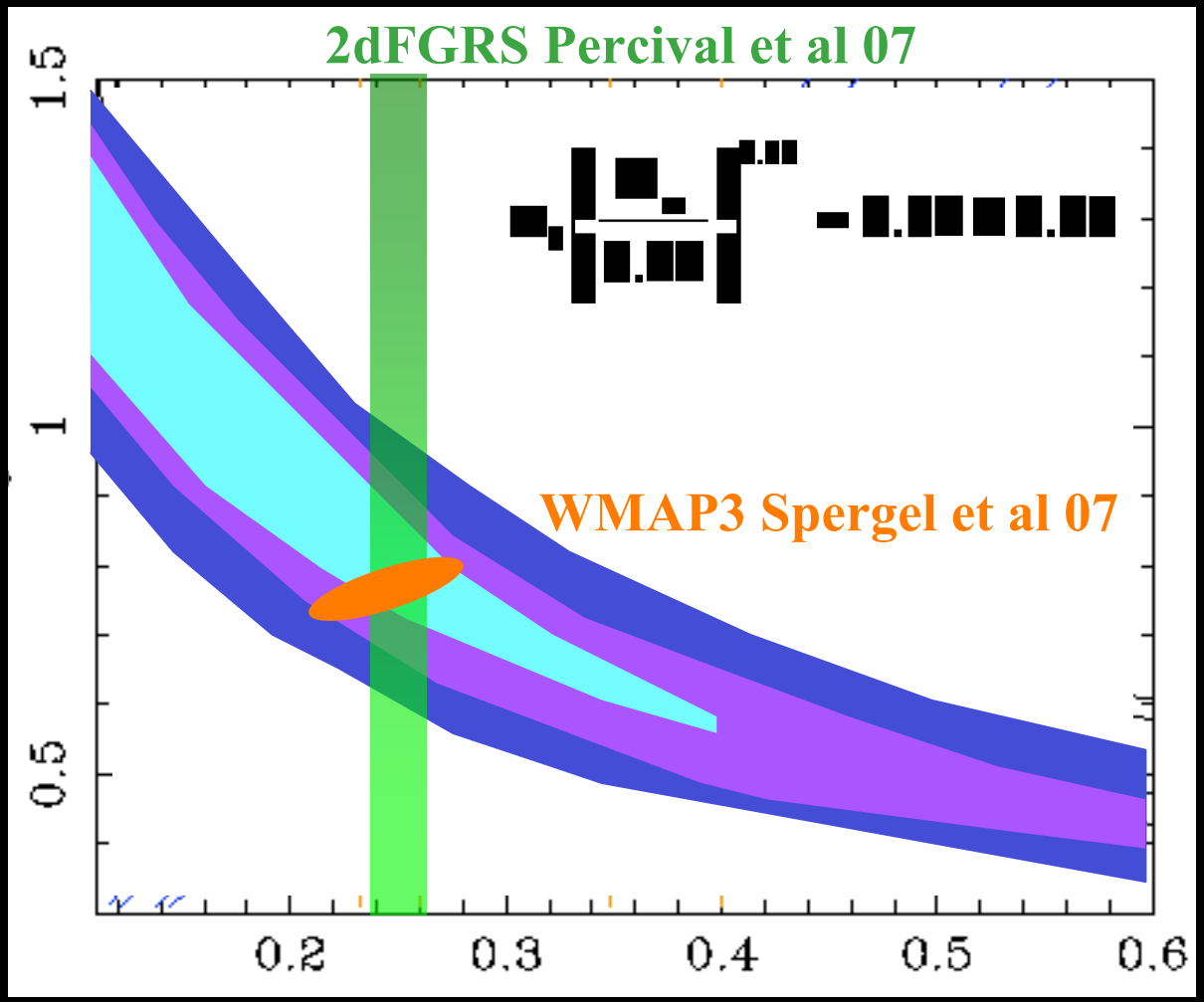
Cosmic Shear Correlations

Hoekstra et al, 2006: Canada-France-Hawaii Legacy Survey



Cosmological Parameters from Cosmic Shear

Cosmic Shear from 100 square degrees (Benjamin et al '07)



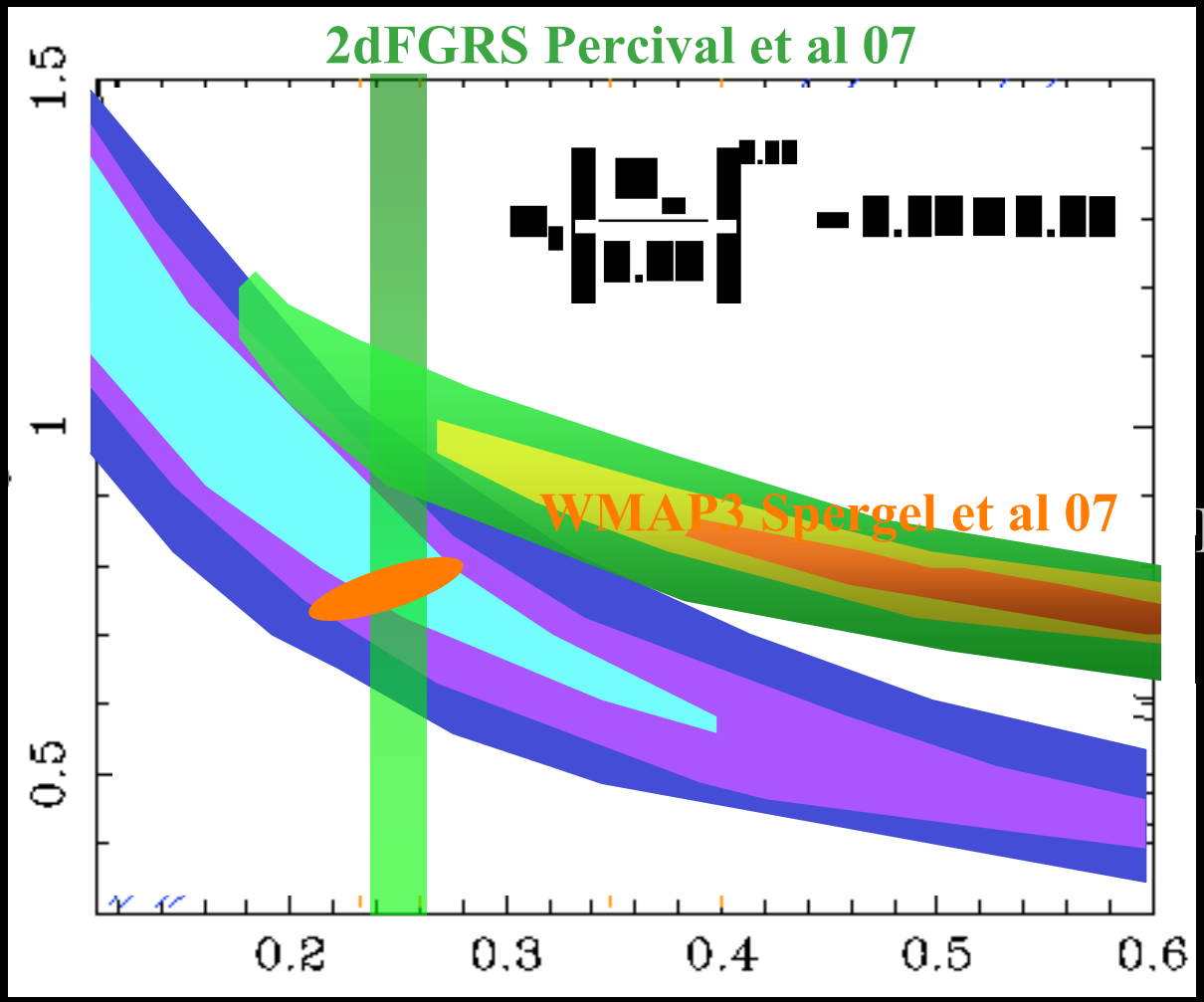
Spatially flat Universe.

Matter Clustering amplitude σ_8

Matter density Ω_m

Cosmological Parameters from Cosmic Shear

Cosmic Shear from 100 square degrees (Benjamin et al '07)



Spatially flat Universe.

Matter Clustering amplitude σ_8

Massey et al 07 COSMOS 3-D Analysis

Matter density Ω_m

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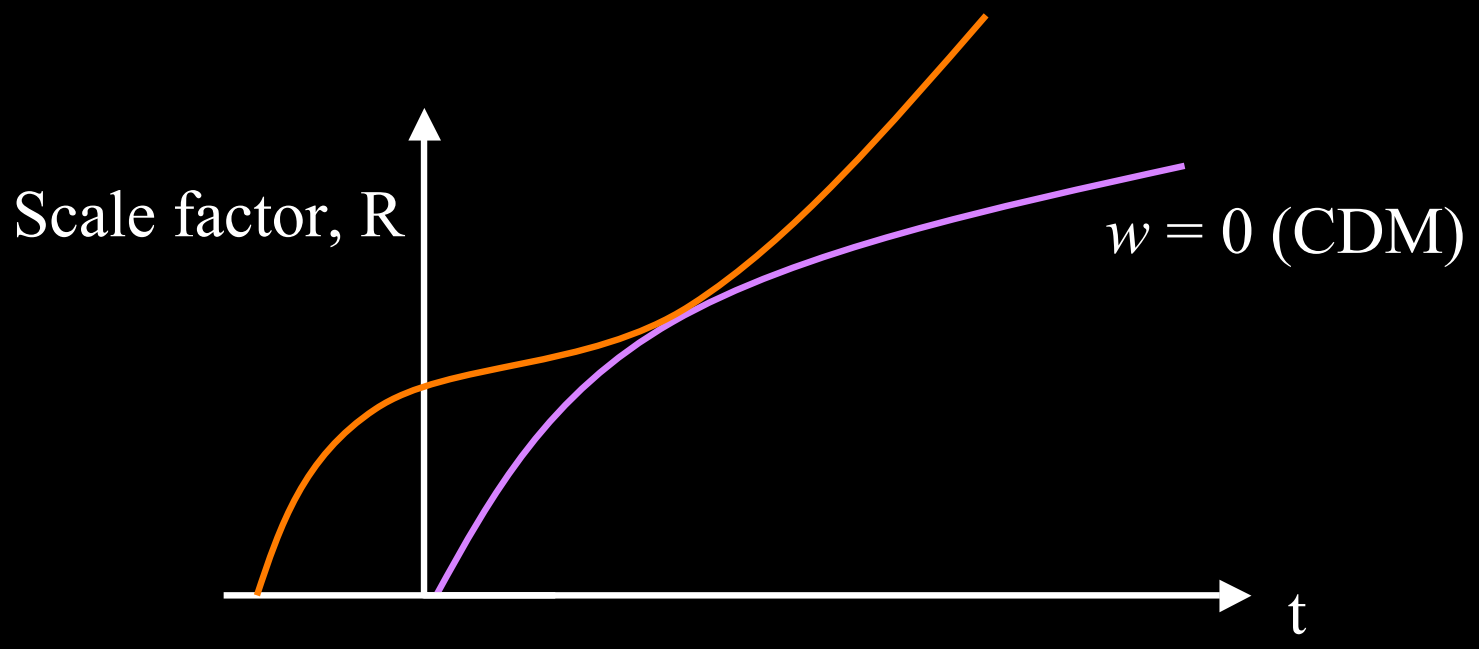
Cosmic Acceleration & Dark Energy

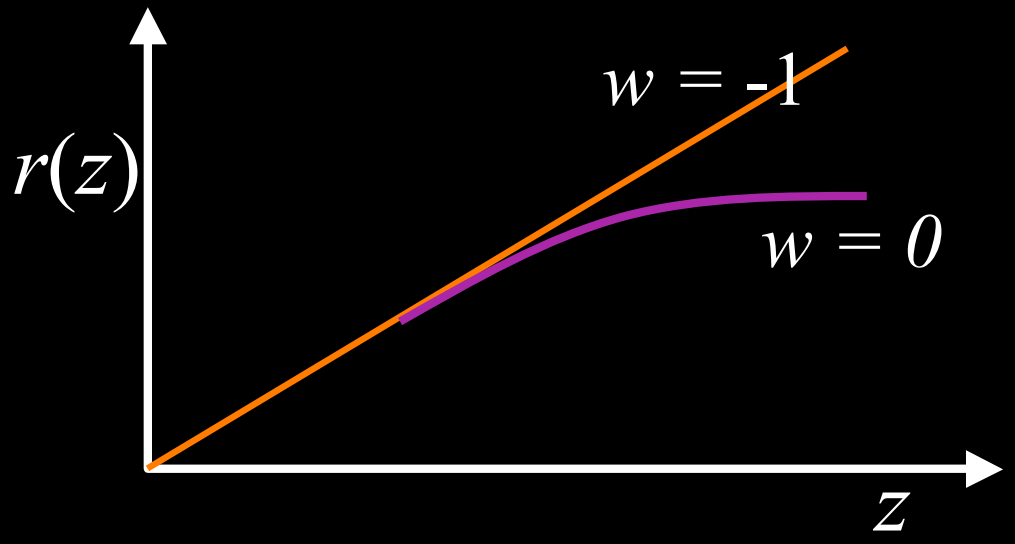
Dark Energy characterized by an Equation of State:



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

Observable Effects of Dark Energy

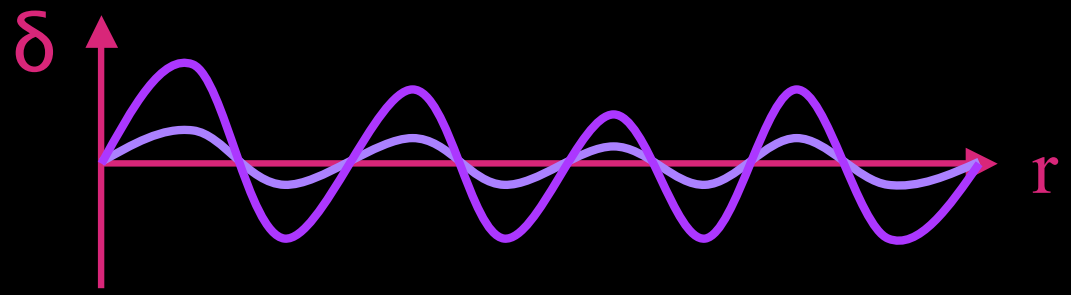
- Geometry: DE changes the photon distance-redshift relation: r(z)



Angular diameter distance D_A

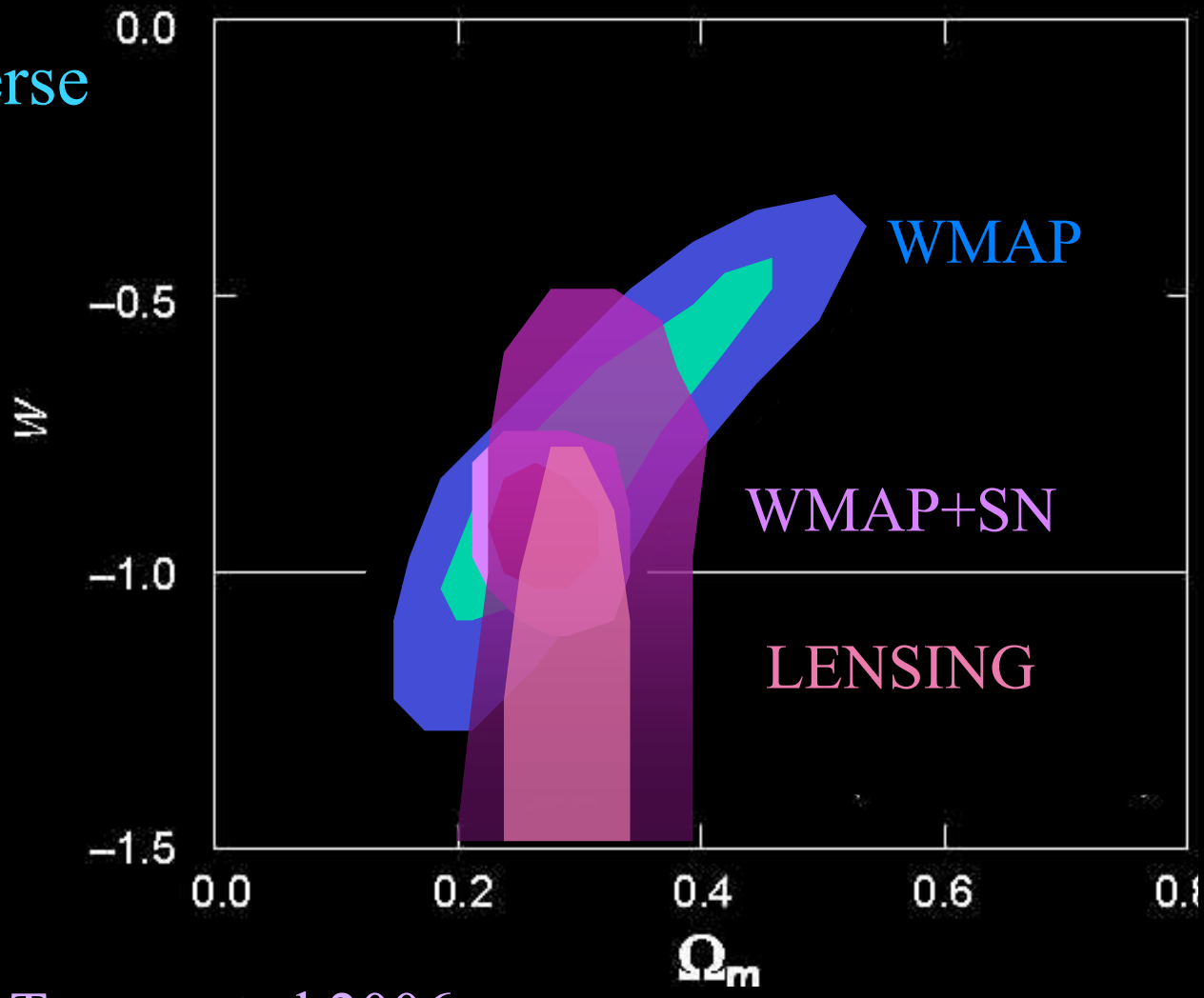
Luminosity Distance D_L

- Dynamics: Alters the growth of density perturbations, $\delta(t)$.



w from the CMB + Supernova + Lensing

Assume flat Universe



Spergel et al ApJ 2006, Tereno et al 2006

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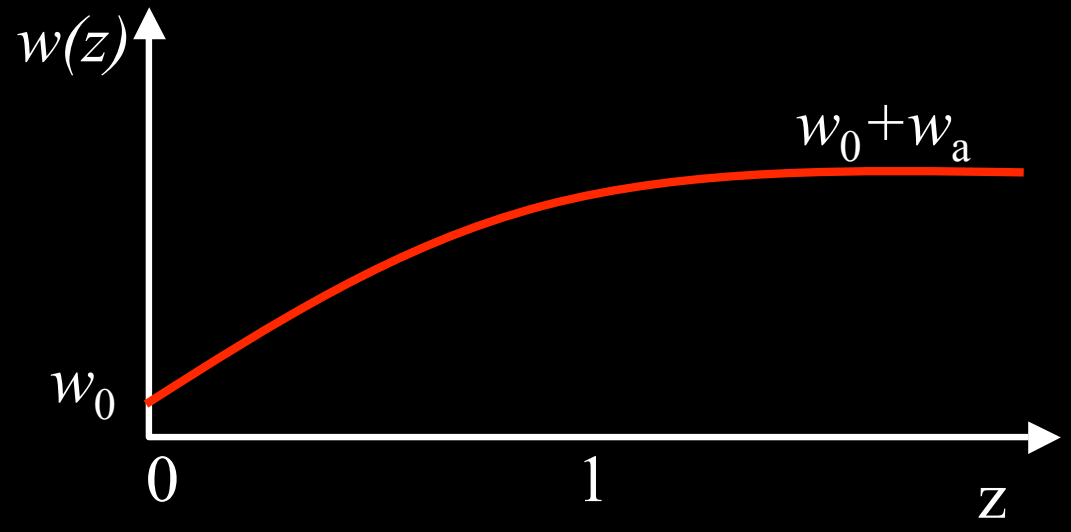
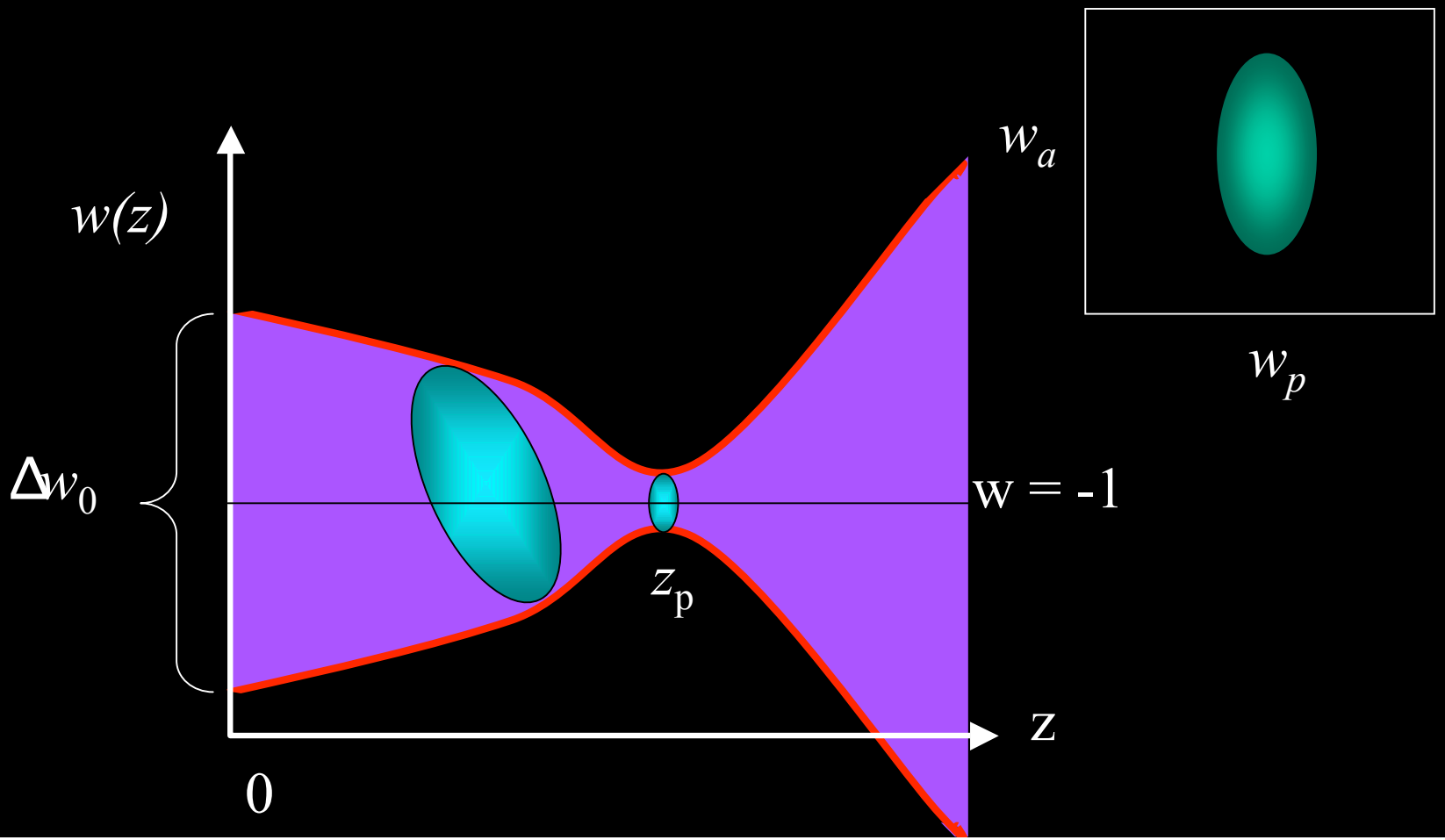
Dark Energy Equation of State

- 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 dynamics (lensing).
- Evolving equation of state:
- Measure w_0 and w_a



Dark Energy Figure of Merit (FoM)

- Evolving equation of state:
- Define pivot redshift, z_p:



2007-2010: Pan-STARRS-1

- Panoramic Survey Telescope and Rapid Response System (Pan-STARRS).

- 1.8 meter primary
- 1.4Gpixel camera.
- 7 square degree field-of-view.

- 3πSurvey
- g, r, i, z, y (r=24.5)

2008-2013: VST-KIDS

- ESO's Kilo-Degree Survey

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

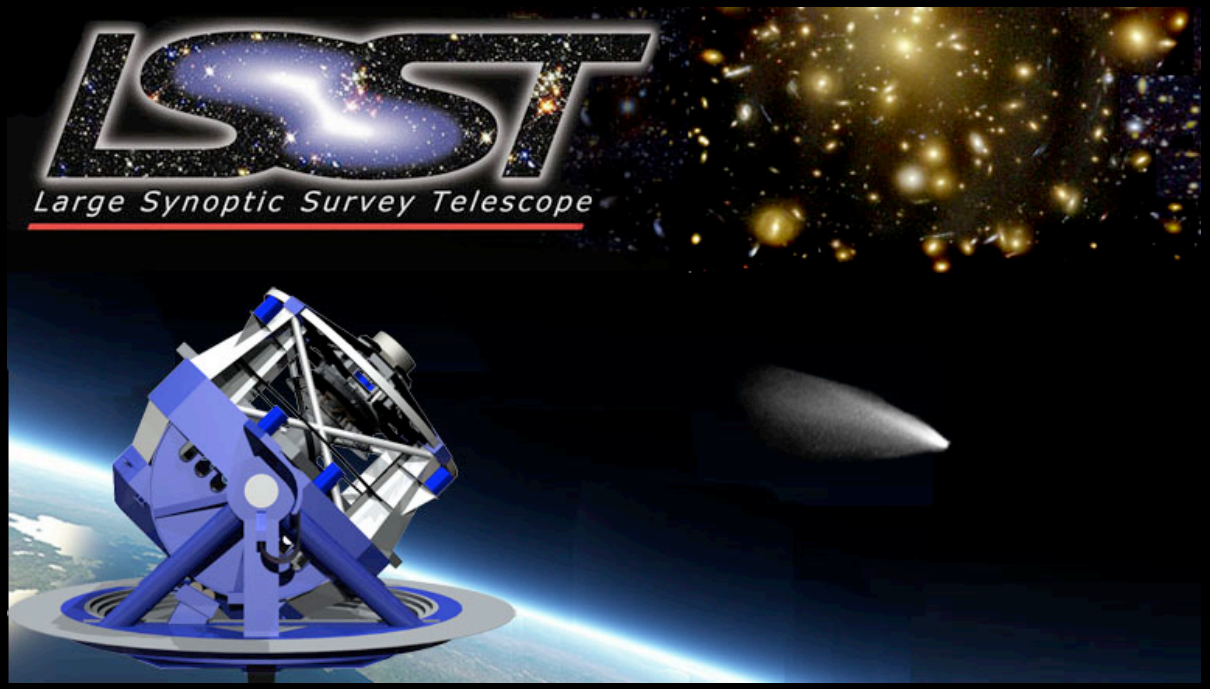
- 1,500 sq deg
- u'g'r'i'z'

2010-2015: DES

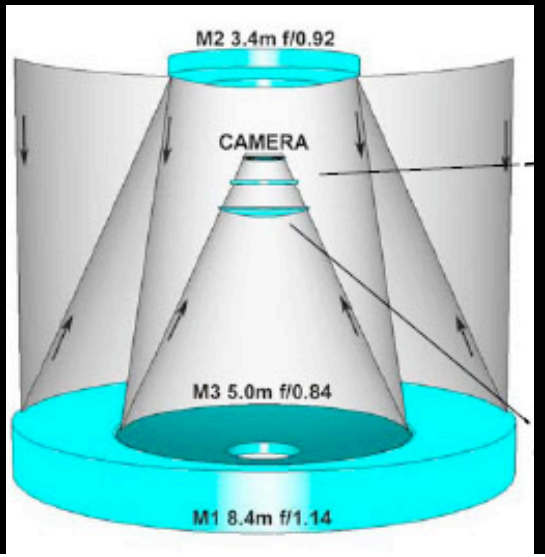
- The Dark Energy Survey.
  - 4-metre primary
  - 500 Megapixel
  - 3 sqdeg fov
  - g,r,i,z
  - 5000 sq deg

DARK ENERGY
Survey

2014-2024: LSST

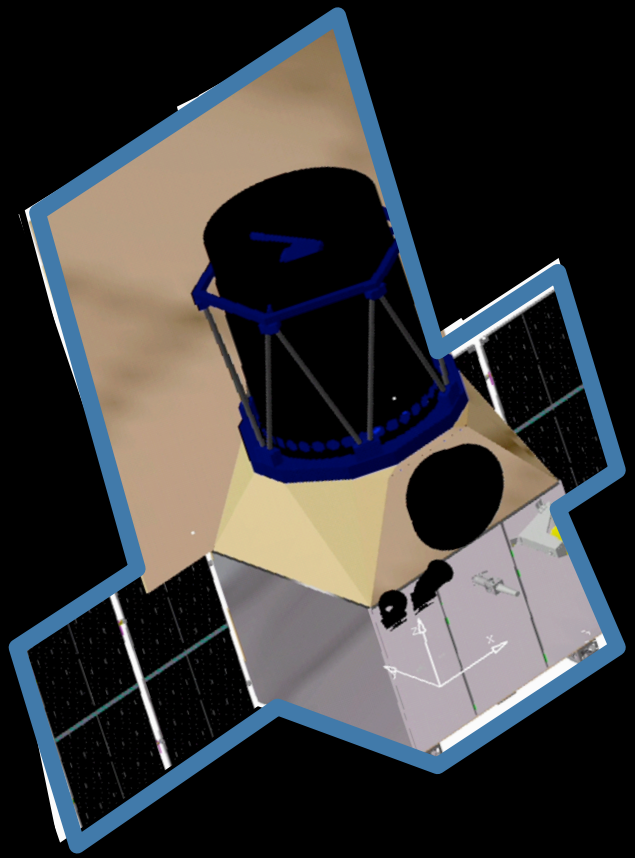


- Large Synoptic Survey Telescope (LSST)
  - 8.4m (effectively 6.5m) Primary
  - 3.2 Gpixels
  - 9.6 sq deg fov
  - ugrizY

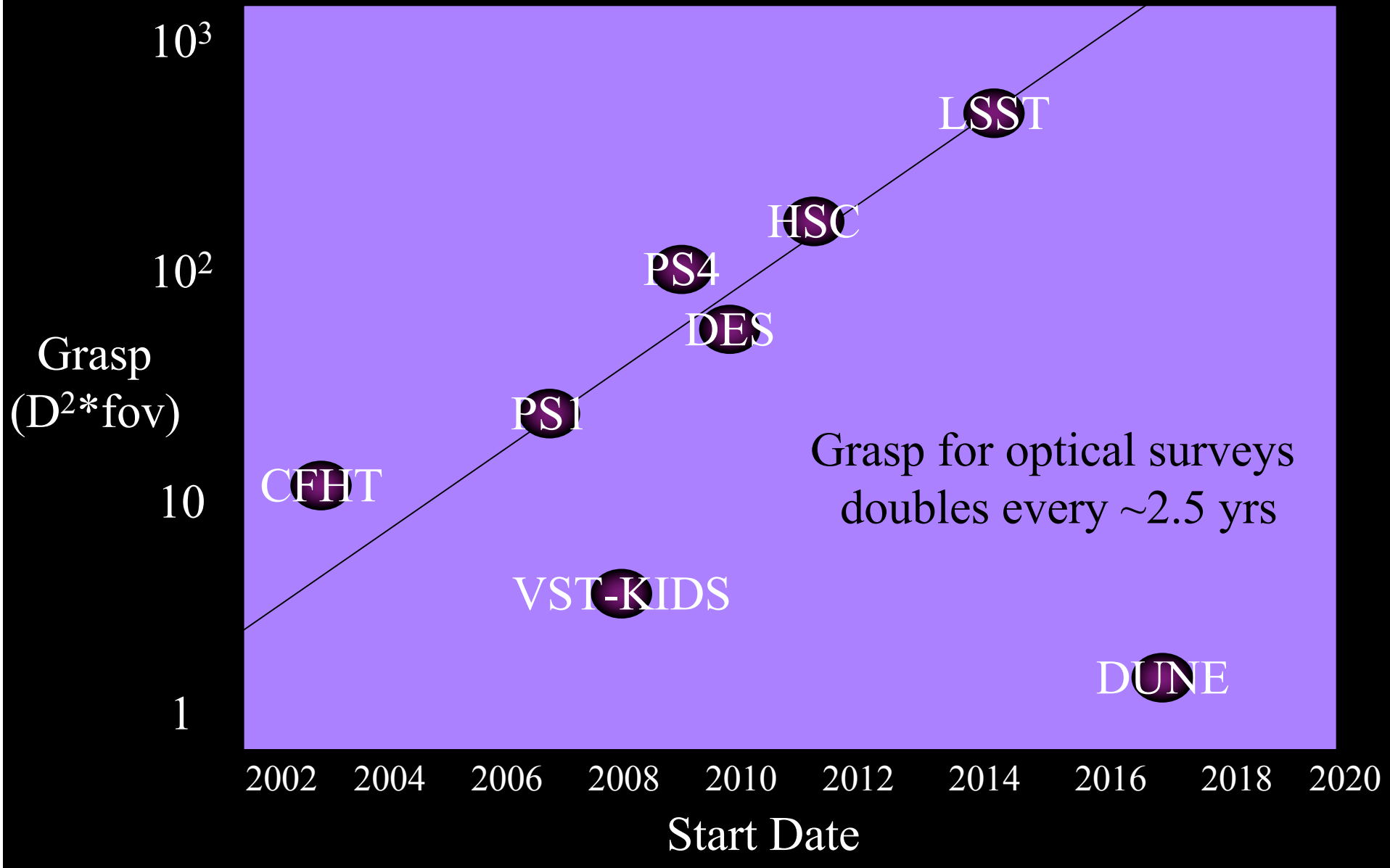


2017-2021: DUNE – Dark UNiverse Explorer

- Proposal to European Space Agency
  - 1.2m satellite telescope
  - 0.5 sq deg fov
  - 20,000 sq deg
  - r-i-z + Y,J,H

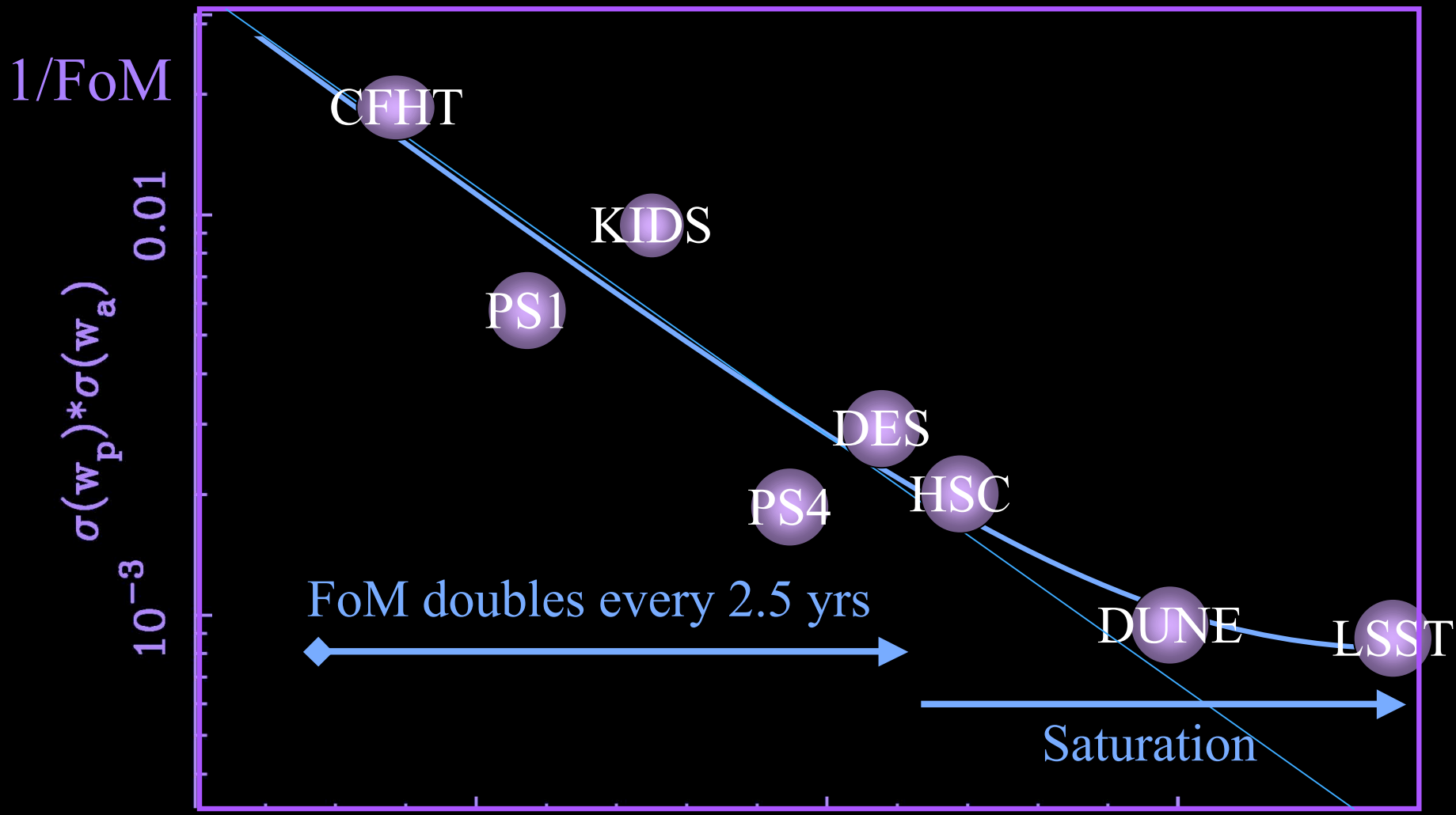


Grasp vs. Start Date



FoM for Dark Energy from Lensing

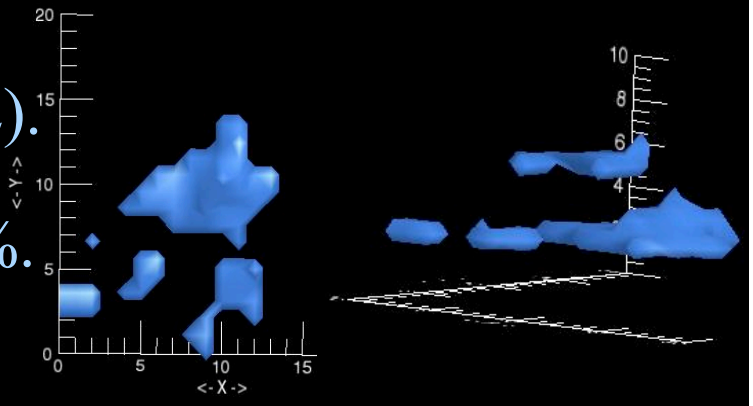
3-D shear power and shear-ratios combined
with Planck Explorer CMB survey (2008)



(with Tom Kitching)

Conclusions

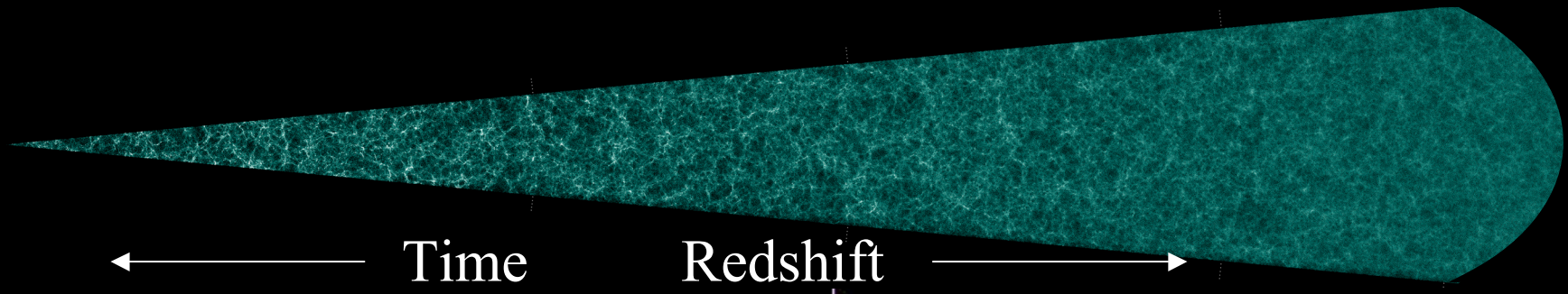
- Accurate 2 & 3D mass maps
- See growth of structure
- Cosmological parameters (systematics?)
- Scaling all of this up for new surveys (Pan-STARRS, VST-KIDS, DES) will be a major challenge.
- Set up European Network (DUEL) to help do this.
- Map Dark Matter over whole sky to z~1.
- Measure neutrino mass to 0.04eV (DUNE).
- Pin down evolution of dark energy to ~1%.
- Test gravitational physics.



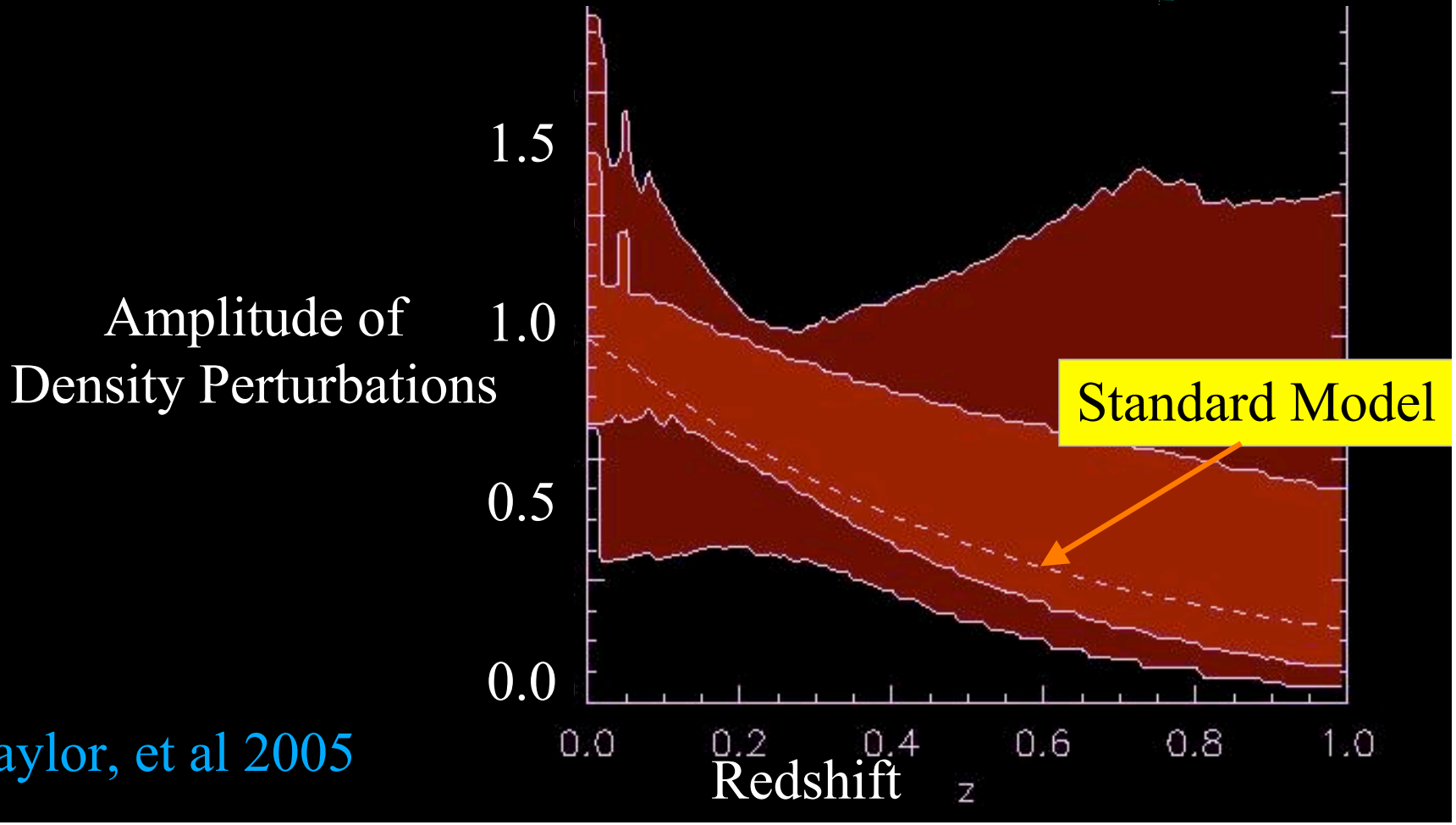
END

Gravitational Lensing

Growth of Density Perturbations from Lensing



Time ← → Redshift



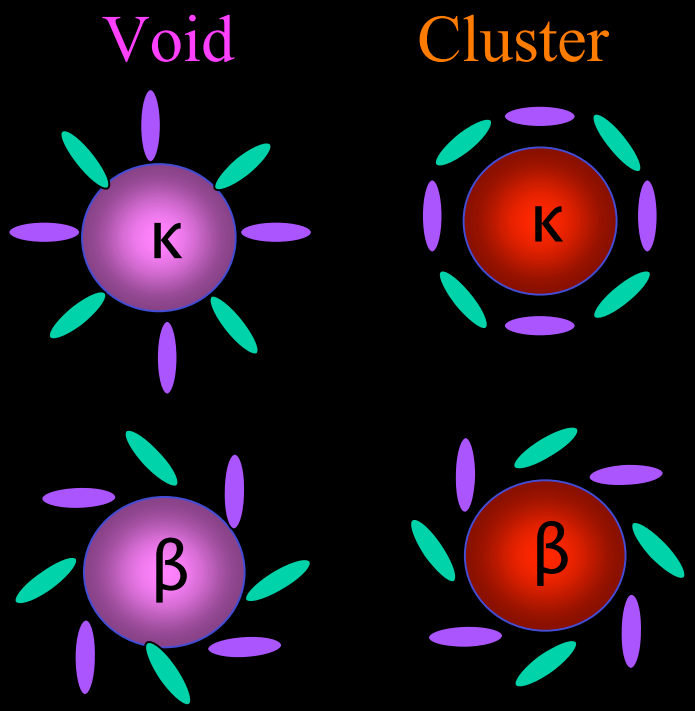
Bacon, Taylor, et al 2005

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.

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?