Gravitational Lensing and Observational Cosmology

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ASIAA

Outline

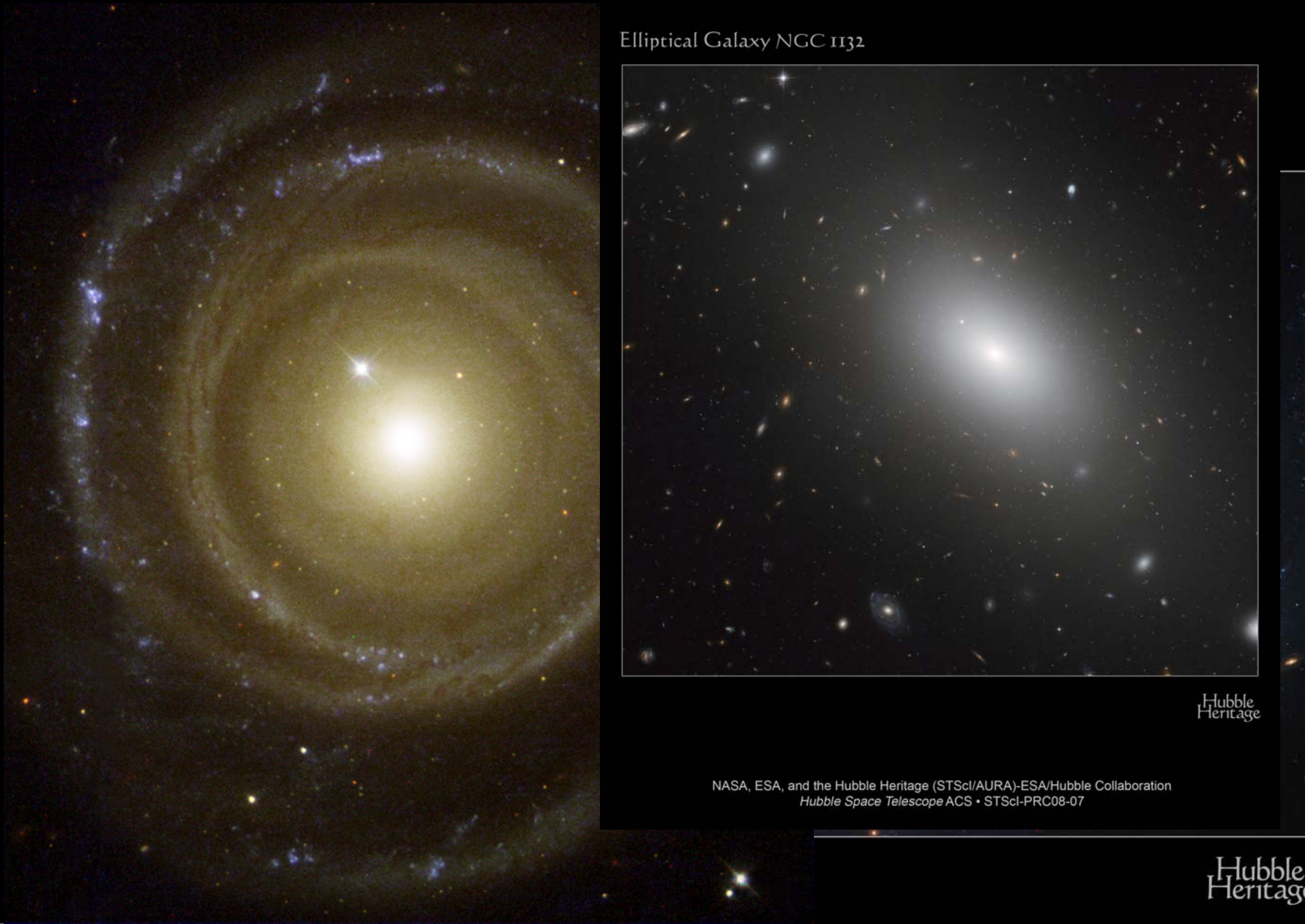
- Lecture Source
  - *Introduction*
    - Structure in the Universe
  - *Observational Cosmology*
    - Evidence for Big Bang: Expanding Universe
    - Initial Seeds of Cosmic Structure
    - Lambda Cold Dark Matter Paradigm – The Dark Side of the Universe
  - *Gravitational Lensing by Clusters of Galaxies and Large Scale Structure*
    - Gravitational Deflection
    - Lens Equation and Image Distortions
    - Strong and Weak Lensing in Clusters
    - Cosmic Weak Gravitational Shear by Large Scale Structure

1. Introduction

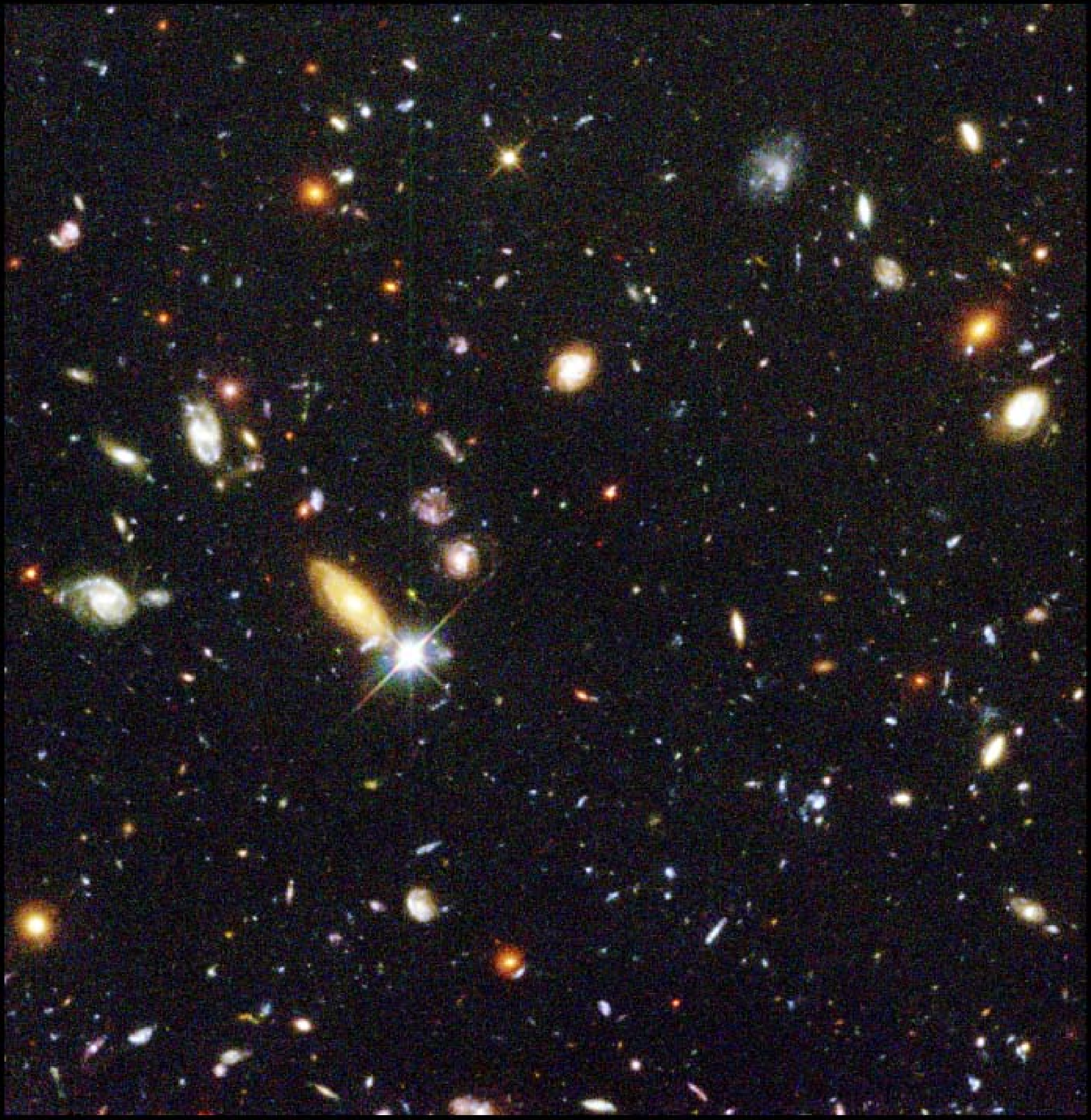
Structure in the Universe

Star Clusters

Galaxies


Elliptical Galaxy NGC 1132
Hubble Heritage
NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration
Hubble Space Telescope ACS • STScI-PRC08-07
Hubble Heritage

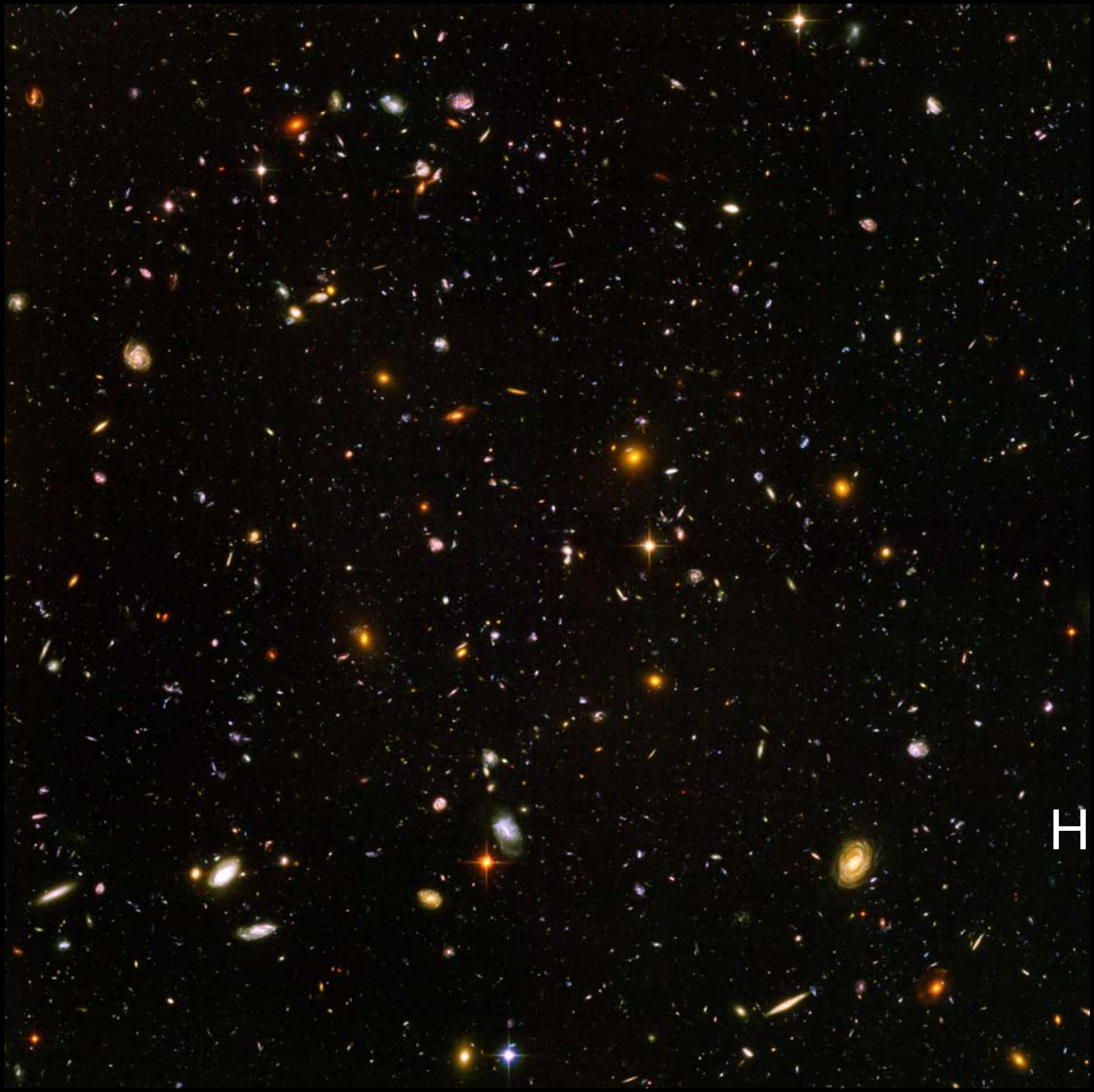
Many² Distant Galaxies…



Hubble Deep Field HST • WFPC2

PRC96-01a • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA

Furthest Galaxies..



Hubble Ultra Deep Field

Group of Galaxies

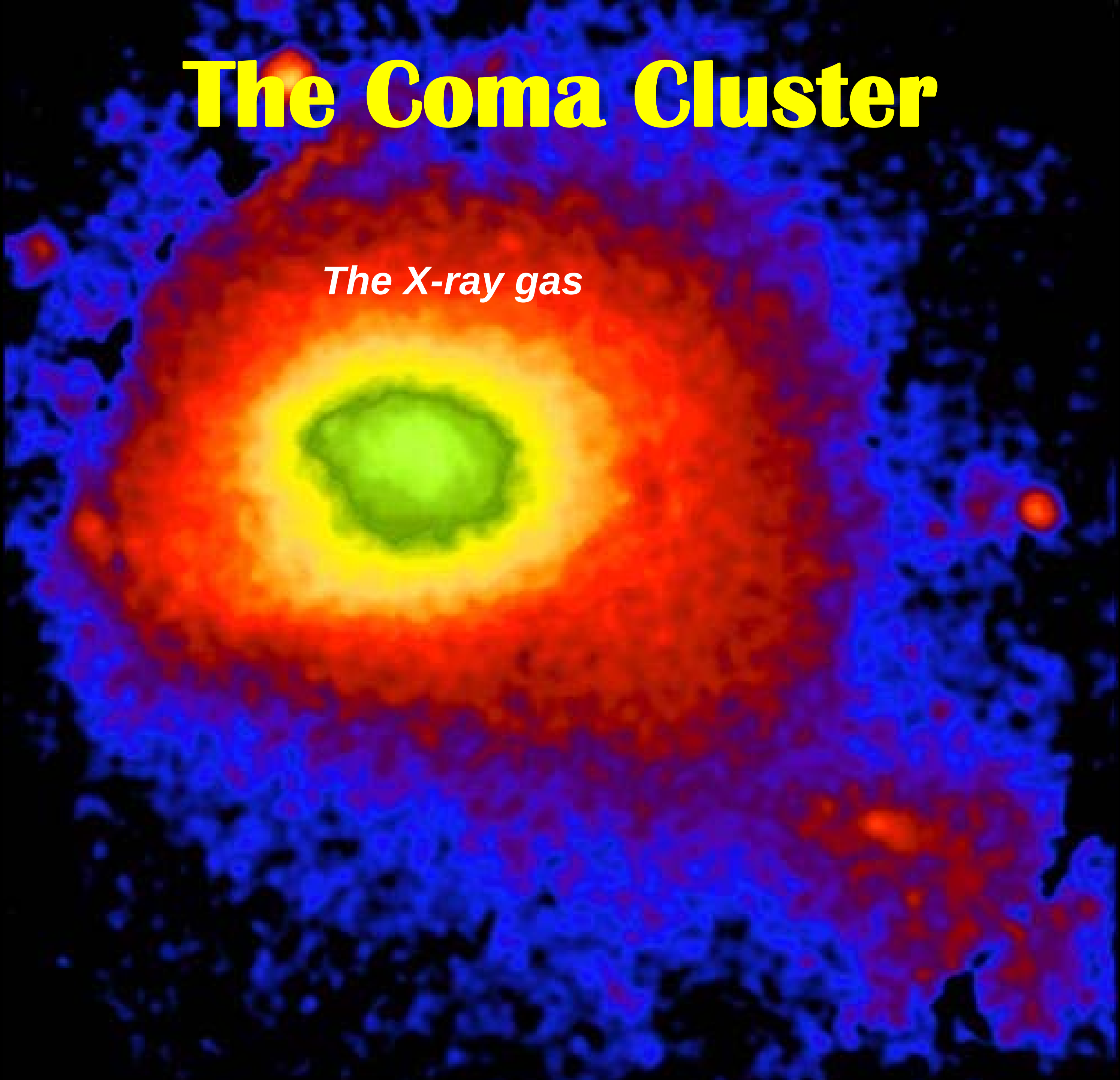
Clusters of Galaxies (I)

A1689: Largest mass concentration in the Universe

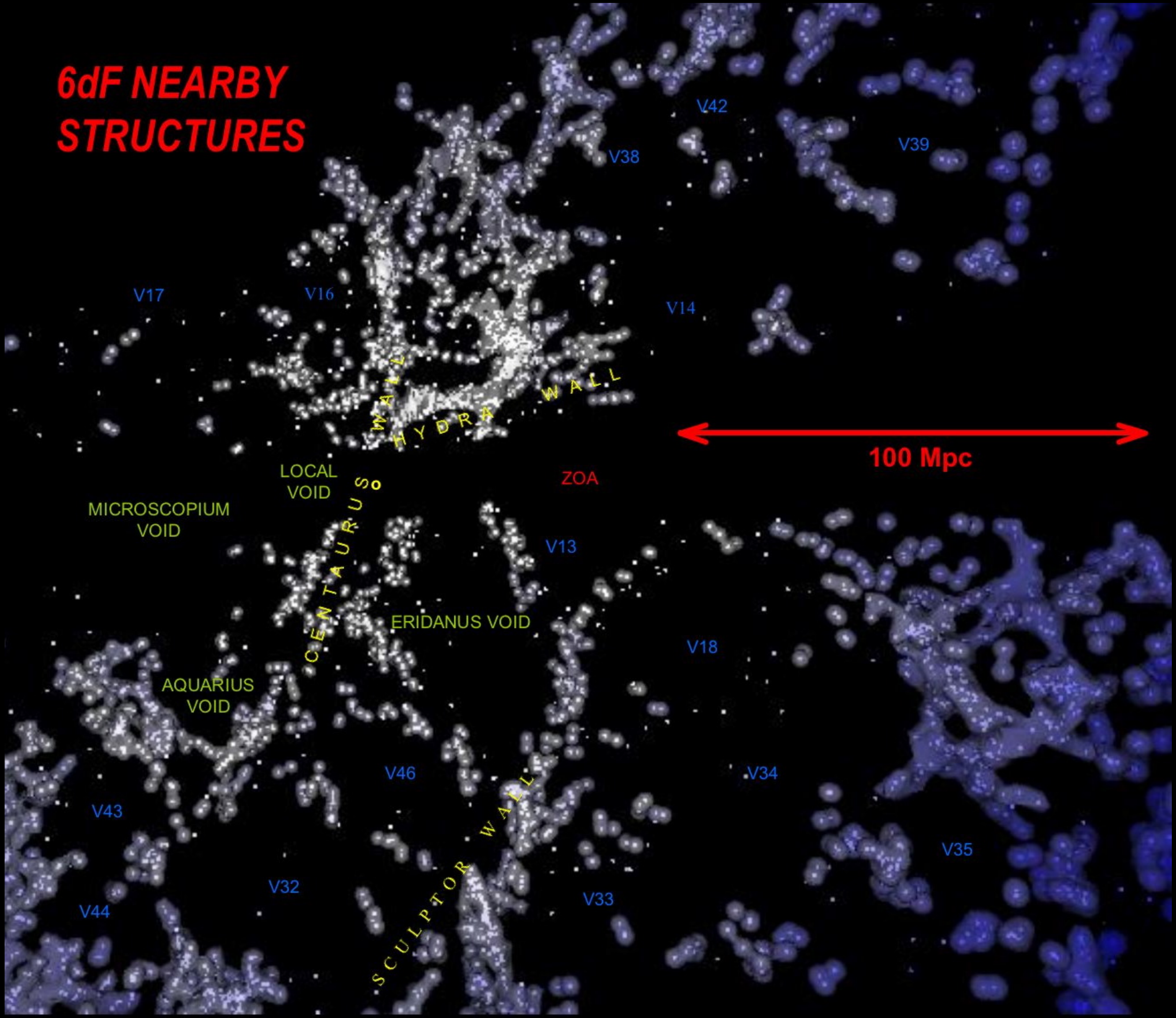
Clusters of Galaxies (II)

Strong Gravitational Lensing Cluster Cl0024+17 at z=0.395

The Coma Cluster



Great Wall, Filaments, Voids



136,304 galaxy redshifts obtained by 2009


Universe
13.7Gyr after the Big-Bang:
Large Variety and Wealth of
Hierarchical Structures:
How are they formed?

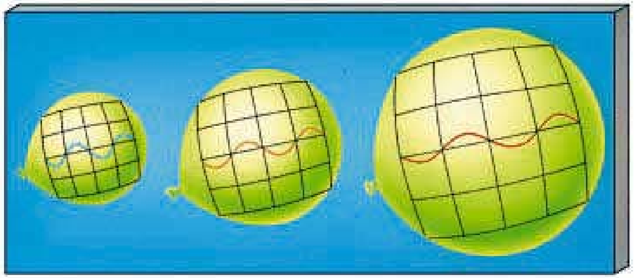
2. Observational Cosmology

Major Pieces of Evidence for Big Bang

"*That the universe is expanding and cooling is the essence of the big bang theory*" by P.J.E. Peebles

Redshift vs. Scale factor

$1+z := \lambda(t_0)/\lambda = a(t_0)/a = 1/a$



- Hubble Expansion
  - *Hubble's law (Edwin Hubble, 1929)*
    - Distant galaxies are receding (redshifting): $V = H_0 r$
  - *The universe (space) is expanding*
    - Separation between 2 points: $r(t) = a(t)\,x$ with no peculiar velocity, $dx/dt=0$
    - Then, $V := dr/dt = (da/dt)/a\, r = Hr$ with the expansion rate, $H := (da/dt)/a$
    - Hubble constant: $H_0 := H(t_0) = 100\,h$ km/s/Mpc with $h=0.71\pm0.025$ (WMAP7)
- Abundances of Light Elements: Big Bang Nucleosynthesis (BBN)
  - *About ¼ of the baryonic mass should be in the form of He^4 ($Y \sim 0.25$)*
- Cosmic Microwave Background Radiation (CMBR)
  - *The universe should be filled with a relic uniform blackbody radiation (with $T_\gamma \sim 2.7K$)*

Now let's look back to the early universe by:

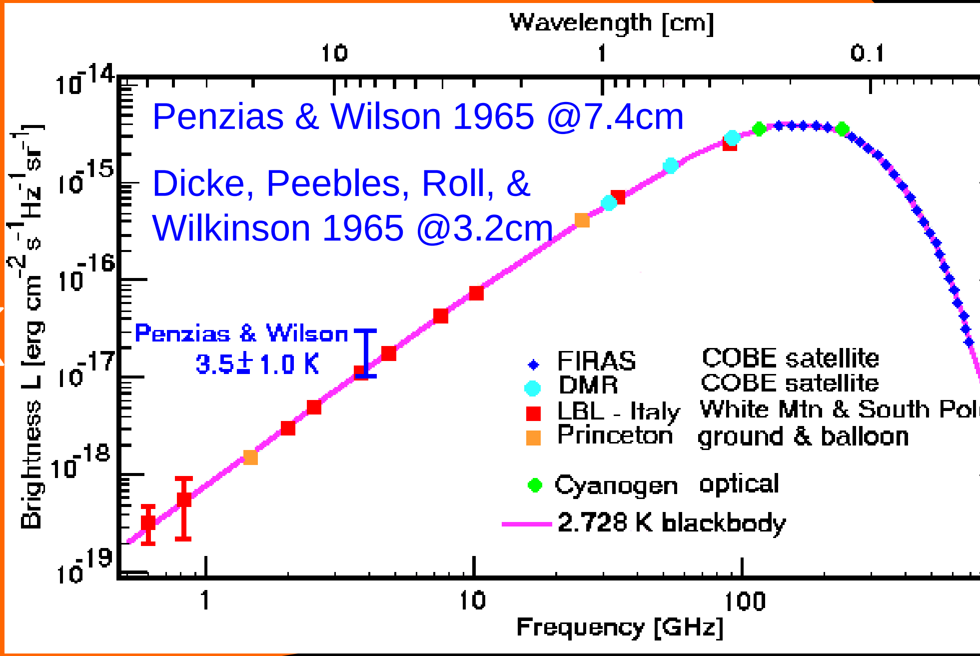
Cosmic Microwave Background radiation (CMB) from its last-scattering surface (z~1100, T~3000 K)– at which CMB photons decouple from matter (electrons) and start freely propagate to us.

Full Sky Microwave Map:
COsmic Background Explore (COBE)

COBE/FIRAS (Far InfraRed Absolute Spectrophotometer)

- Uniform blackbody
- T_{CMB}=2.725±0.002K

(Mather et al. 1999)



Universe 380,000yr after the Big-Bang:

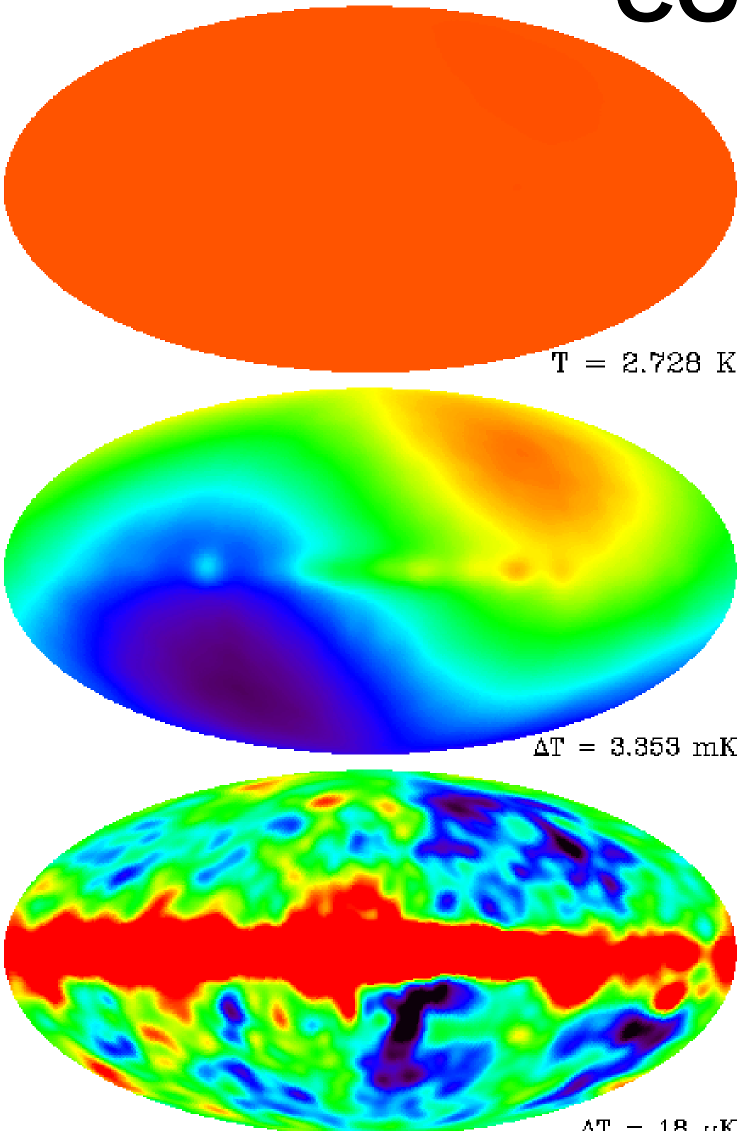
Almost perfectly smooth

The Early Universe:

Almost perfectly uniform and isotropic without any discernible structures..

"How did the present variety and wealth of structures emerge out of the smooth early universe???"

Temperature Anisotropies seen by COBE/DMR



Uniform component

COBE/FIRAS:

$$T_{CMB} = 2.725 \pm 0.002\,[K]$$

determined to 0.1% accuracy

$$T(z) = T_{CMB}(1+z)$$

Dipole component

$$\left(\frac{\delta T}{T_{CMB}}\right)_{180^\circ} \approx 10^{-3}$$

Motion of the solar system w.r.t. CMB: 371 km/s (cf. Galactic rotation: ~220km/s)

Multipole components

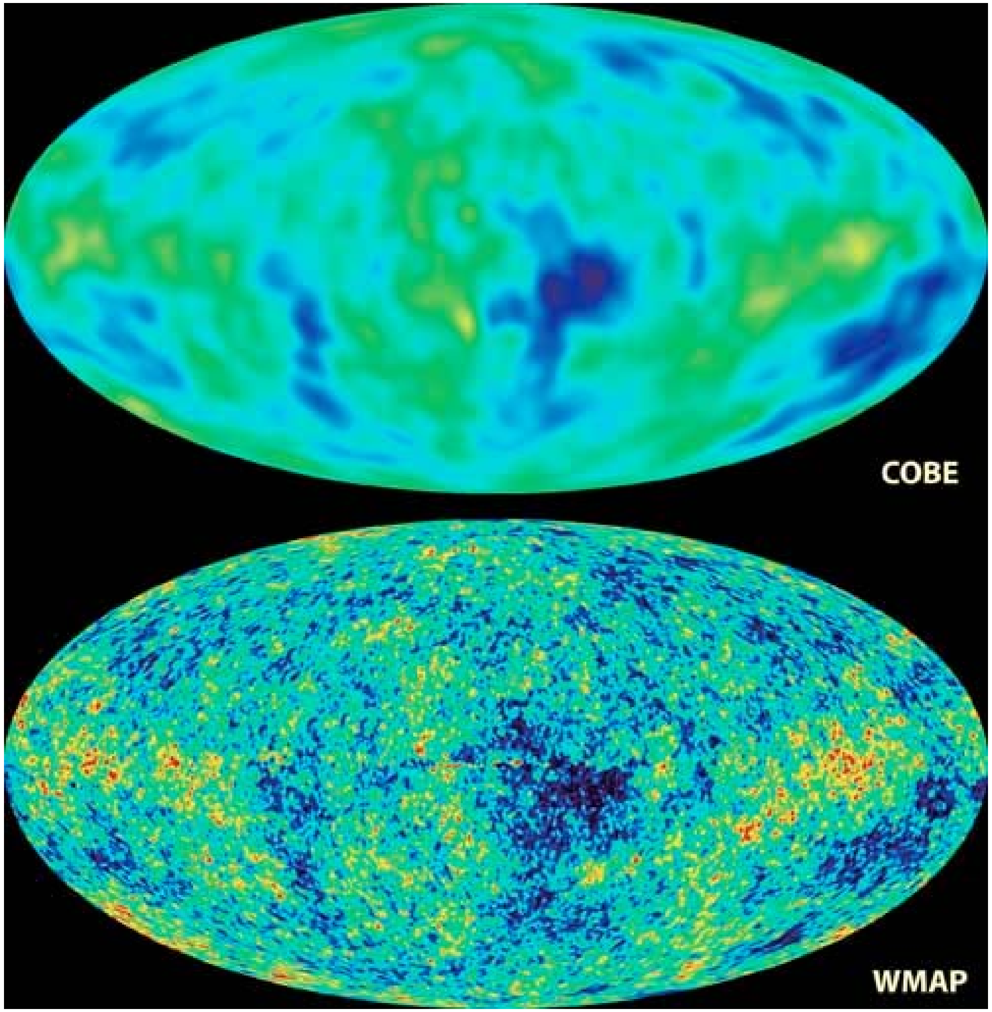
$$\left(\frac{\delta T}{T_{CMB}}\right)_{7^\circ} \approx 10^{-5}$$

Initial seeds of cosmic structure

$$\frac{\Psi}{c^2} \sim \frac{\Delta T}{T} \sim 10^{-5}$$

We Have Seen the Cosmic Seeds!!

Presence of tiny density perturbations in the early universe



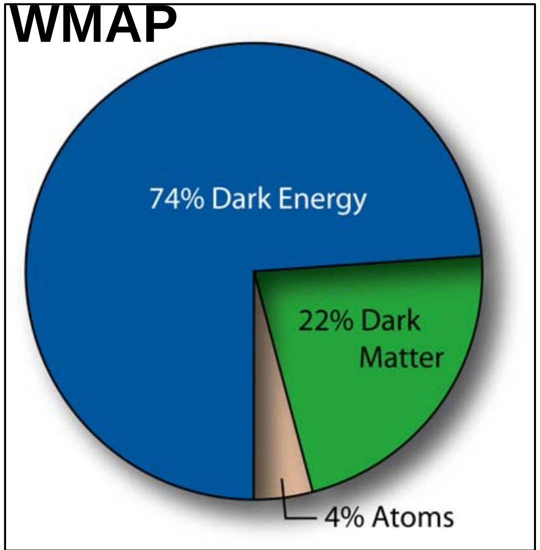
COBE (1989-1993); WMAP (2001-2010)

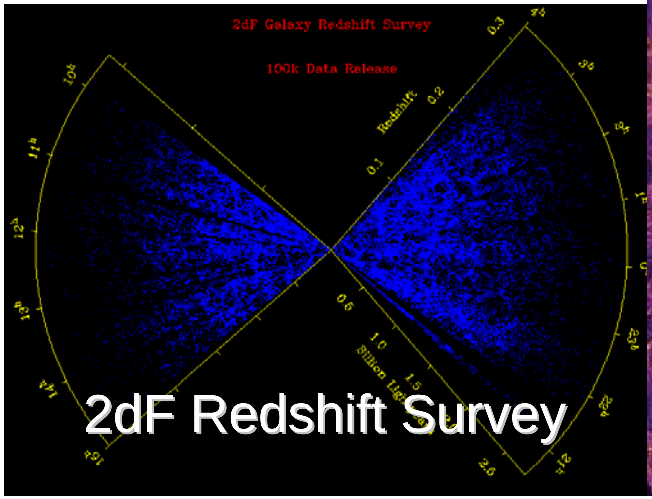
- **Origin**: Quantum fluctuations expanded to super-horizon scales during "*cosmic inflation*"
- **Patterns and strengths** of primordial density and velocity perturbations visible as temperature anisotropy in CMB
- To form structure, an **amplification** by >10^5 needed during the cosmic expansion to the present time → **Dark Matter** (DM) is needed!
- CMB anisotropies observed on sub-degree scales (e.g., WMAP) do indicate the existence of DM!!

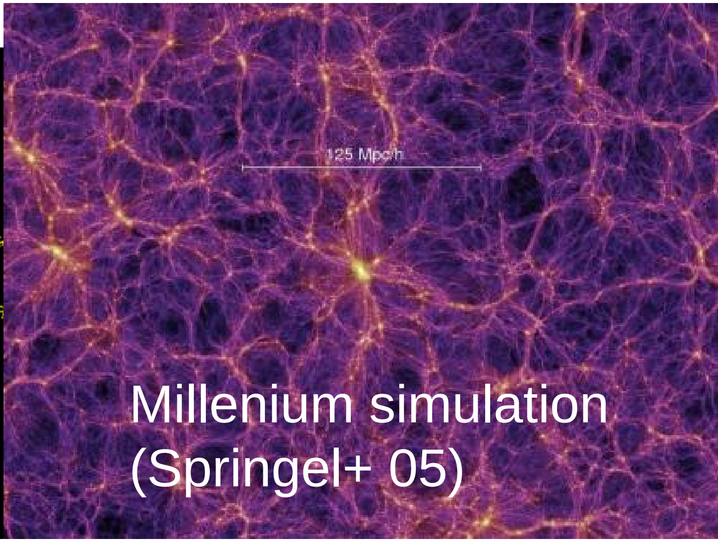
Lambda Cold Dark Matter (ΛCDM) Paradigm

Current paradigm of structure formation: ΛCDM (CDM with a cosmological constant)

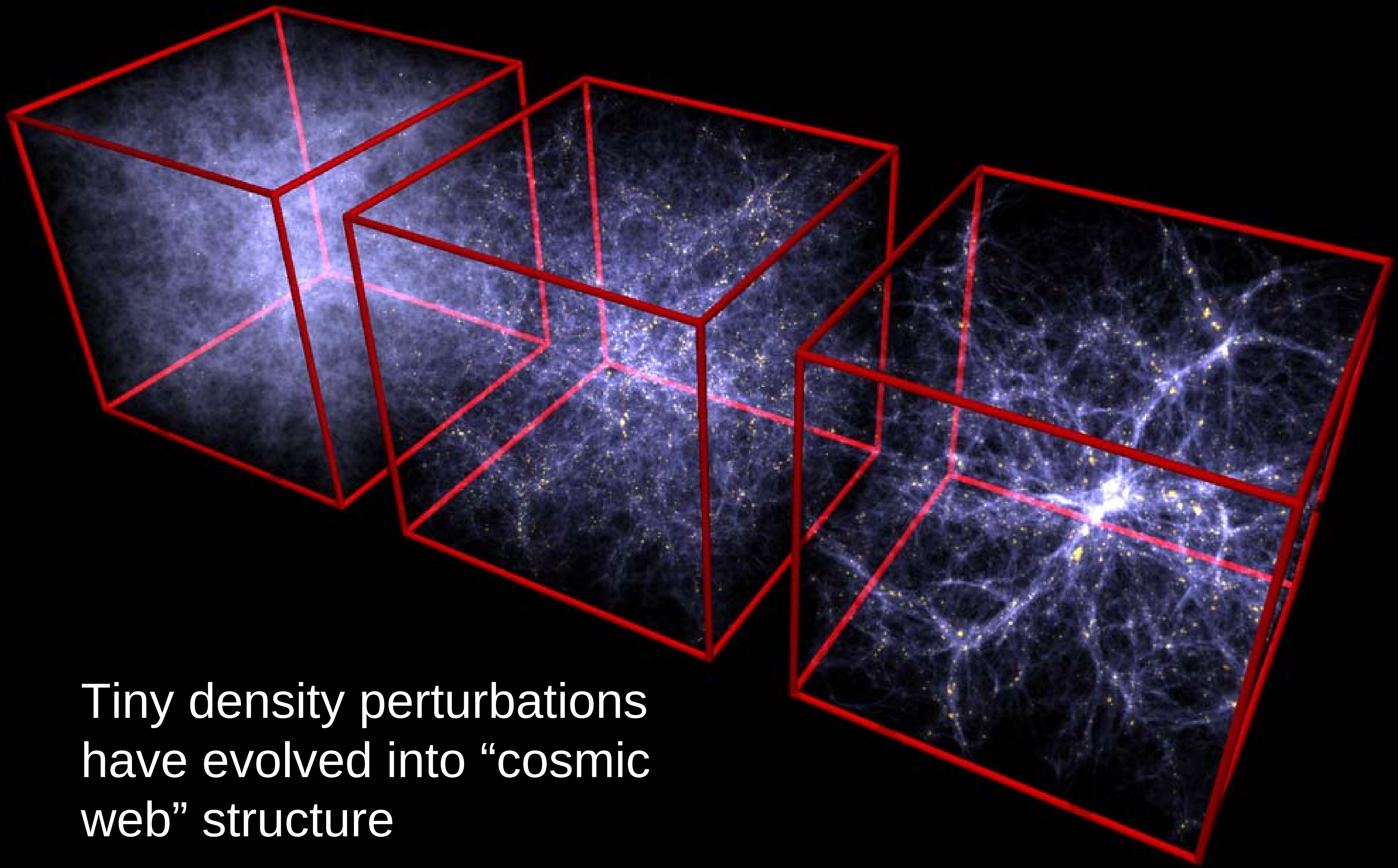
- ***Initial conditions (@ z~1100)****, precisely known from linear theory & CMB+ observations*
- *>70% of the* "present-day" *energy density is in the form of Dark Energy, leading to an accelerated cosmic expansion.*
- *~85% of our* "material universe" *is composed of (non-relativistic, or cold) Dark Matter.*
- *Cosmic structure forms via gravitational instability in an expanding universe*
- *Bottom-up nature: smaller objects first formed, and larger ones form via mergers and mass accretions*





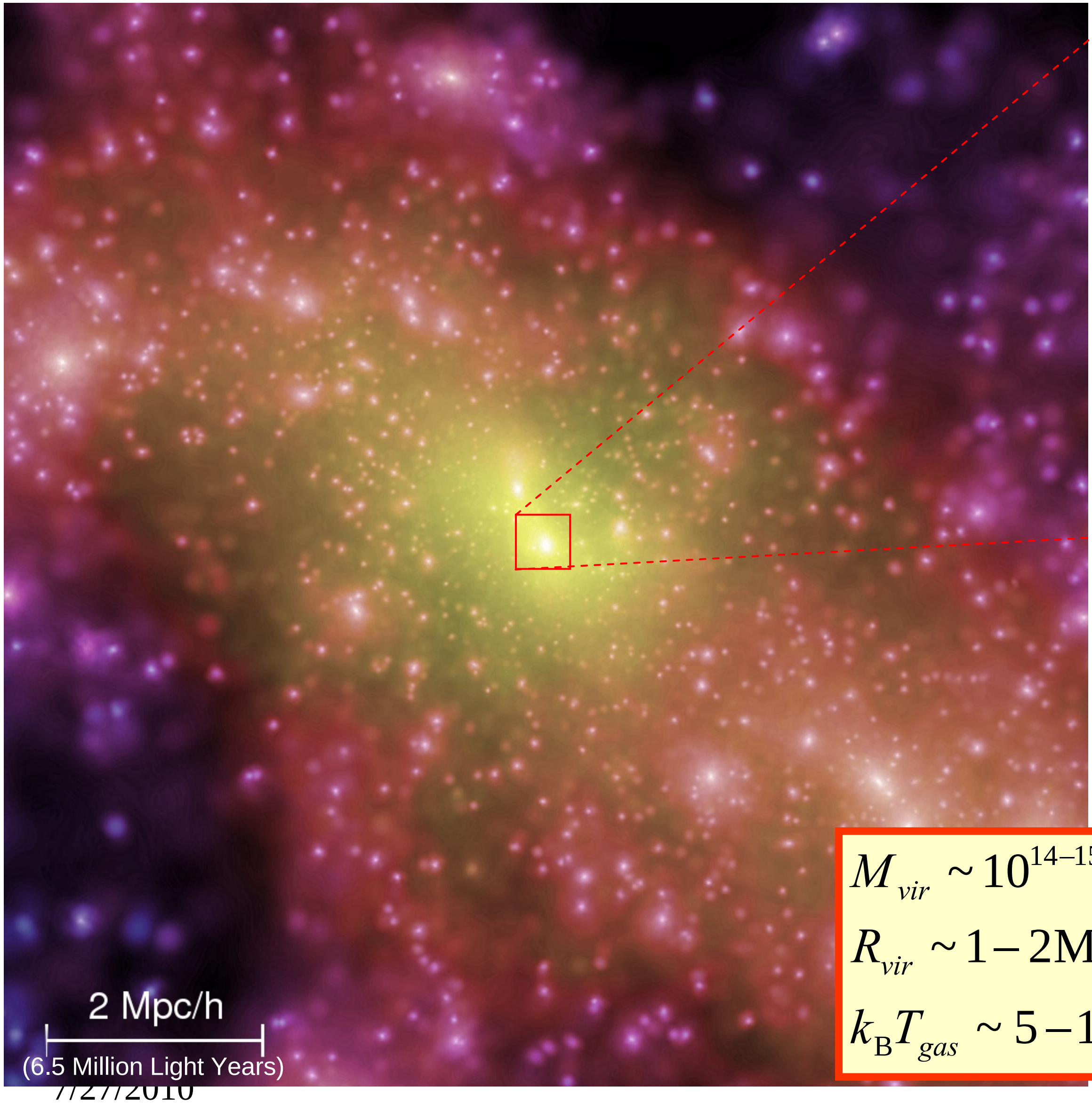


Gravitational Instability



Tiny density perturbations have evolved into “cosmic web” structure

Clusters of Galaxies



Clusters of galaxies: largest self-gravitating systems (aka, DM halos) with $\delta \gg 1$, composed of $10^{2\text{-}3}$ galaxies

$$M_{vir} \sim 10^{14-15} M_{\rm sun} / h$$

$$R_{vir} \sim 1-2\text{Mpc}/h \;\Rightarrow\; t_{dyn} = 3-5\text{Gyr} < \text{t}_{\rm H}$$

$$k_{\rm B} T_{gas} \sim 5-10\text{keV}$$

Simulation of dark matter around a forming cluster (Springel et al. 2005)

Relevant Scales

Distances measured in Mpc/h (Mega per-sec per h)

- 1 Mpc/h = 3.18 x 10^{24} cm = 3.26 x M light-year/h

  ~ typical size of clusters of galaxies
- 5 Mpc/h ~ R_g = typical separation of field galaxies
  - *Galaxy 2-point correlation function: $\xi_{gg}(R_g) := 1$*
- 20 Mpc/h ~ typical separation of clusters of galaxies
  - *Cluster 2-point correlation function: $\xi_{cc}(R_c) := 1$*
- 30 Mpc/h ~ R_{nl} = present-day nonlinear scale
  - *$\delta(R_{nl}, z=0) := 1$ with* $\delta(\mathbf{x},t) \equiv \frac{\rho(\mathbf{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)}$
  - *On large scales $R > R_{nl}$, the universe is homogeneous ($\delta(R) \ll 1$)*
  - *Characteristic scales of large-scale structure: filaments, voids etc.*
- 150 Mpc/h ~ $R_{s.h.}$ = sound horizon at the decoupling epoch (z~1100)
- 3000 Mpc/h ~ c/H_0 ~ Horizon scale of the universe

3. Gravitational Lensing by Clusters of Galaxies and LSS

My lecture note on

“Cluster Weak Gravitational Lensing”

from “Enrico-Fermi Summer School 2008, Italy” found @

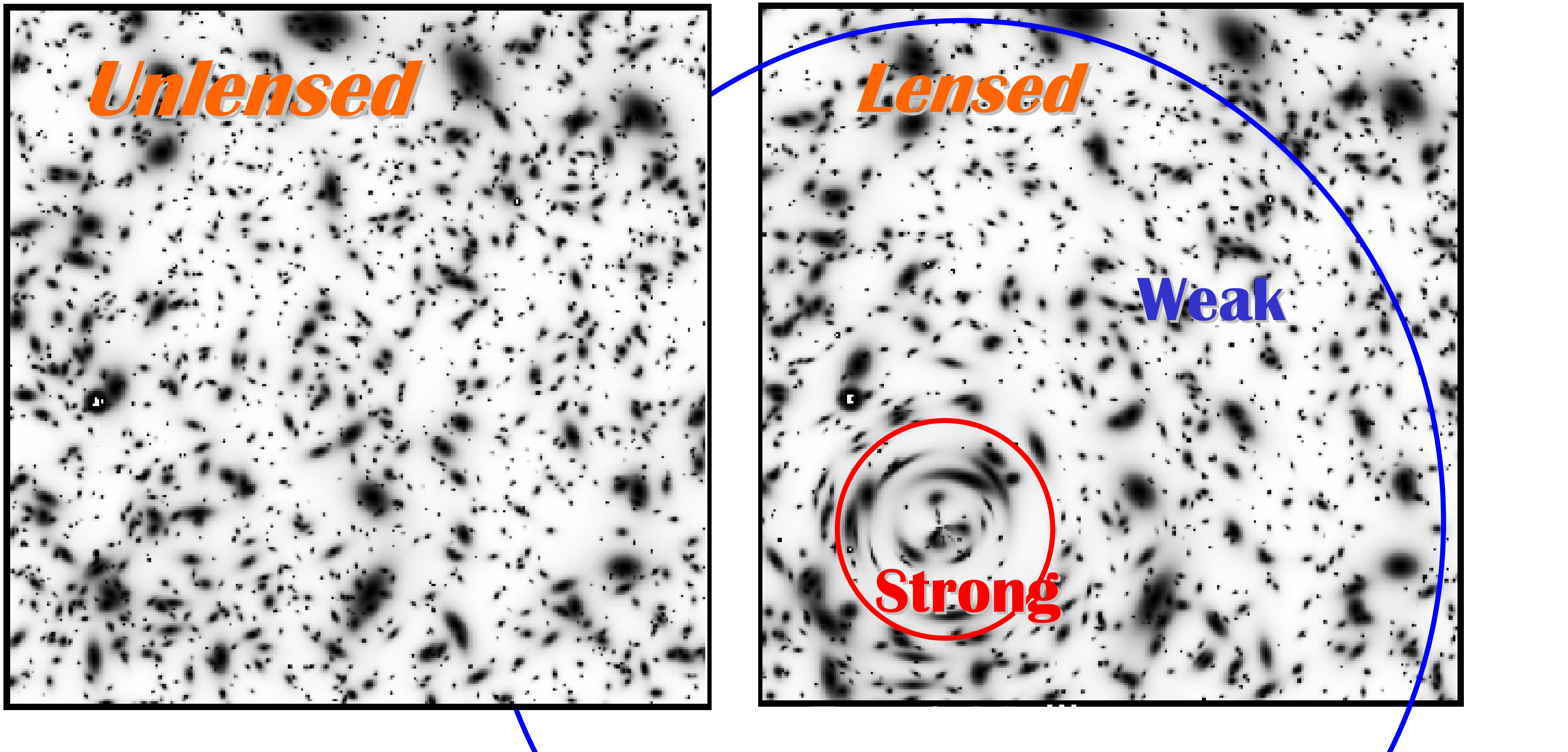
arXiv:1002.3952 (also cited in The Net Advances of Physics)

Theoretical backgrounds and basic concepts on cosmological lensing and observational techniques are summarized in these lecture notes.

Gravitational Lensing

Gravitationally lensed images of background galaxies carry the imprint of $\Phi(x)$ of intervening cosmic structure:

Gravitational Lensing is based only on gravity, so is the most direct method to study the Dark Side of the Universe!



Gravitational Bending of Light Rays

Gravitational deflection angle in the weak-field limit (|Φ|/c^2<<1)

Light rays propagating in an inhomogeneous universe will undergo **small transverse excursions** along the photon path: i.e., **light deflections**

Bending angle

$$\delta\hat{\alpha} \approx \frac{\delta p_{\perp}}{p_{\parallel}} = -\frac{2}{c^2}\nabla_{\perp}\Psi(x_{\parallel}, x_{\perp})\delta x_{\parallel}$$

Small transverse excursion of photon momentum

$$\hat{\alpha}^{\rm GR} = 2\hat{\alpha}^{\rm Newton} \rightarrow \frac{4GM}{c^2 r} = 1.''75\left(\frac{M}{M_{sun}}\right)\left(\frac{r}{R_{sun}}\right)^{-1}$$

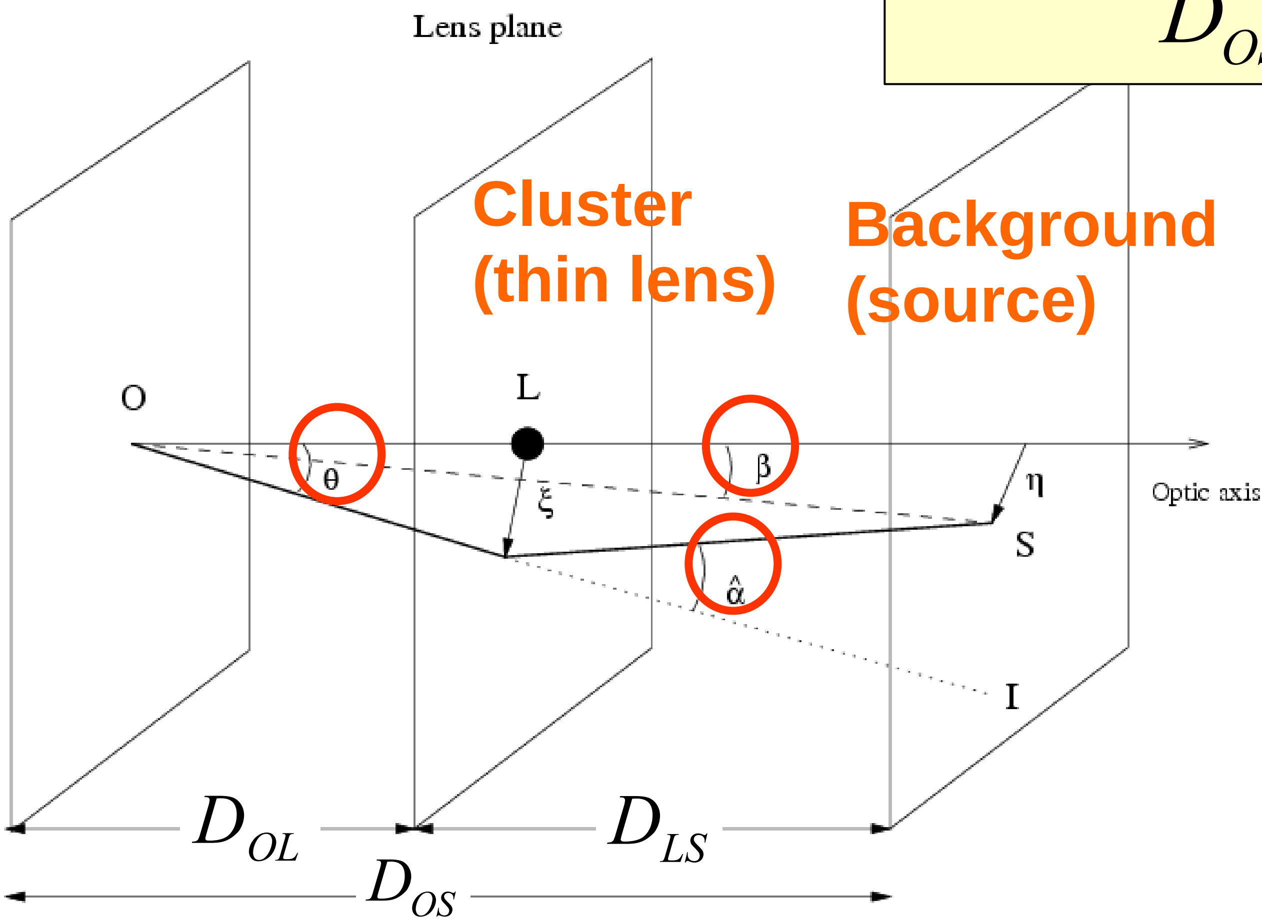
Lens Equation (for galaxy cluster lensing)

Lens equation **(Cosmological lens eq. + single/thin-lens approx.)**

β: true (but unknown) source position

θ: apparent image position

$$\boldsymbol{\beta} - \boldsymbol{\theta} = \frac{D_{LS}}{D_{OS}} \hat{\boldsymbol{\alpha}}(\boldsymbol{\theta}) \equiv -\nabla \psi(\boldsymbol{\theta})$$

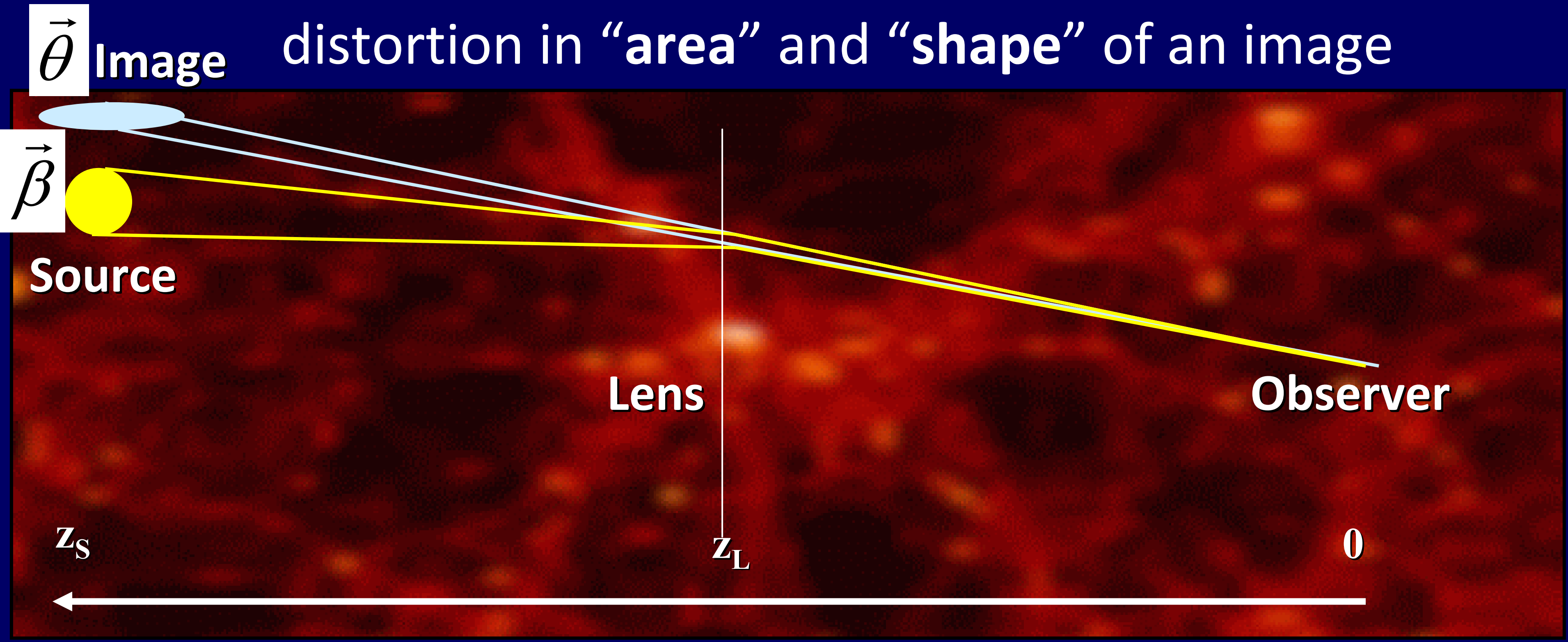


D_{OL}, D_{LS}, D_{OS} ~ $O(c/H_0)$

For a rigid derivation of cosmological lens eq., see, e.g., Futamase 95

Shape and Area Distortions

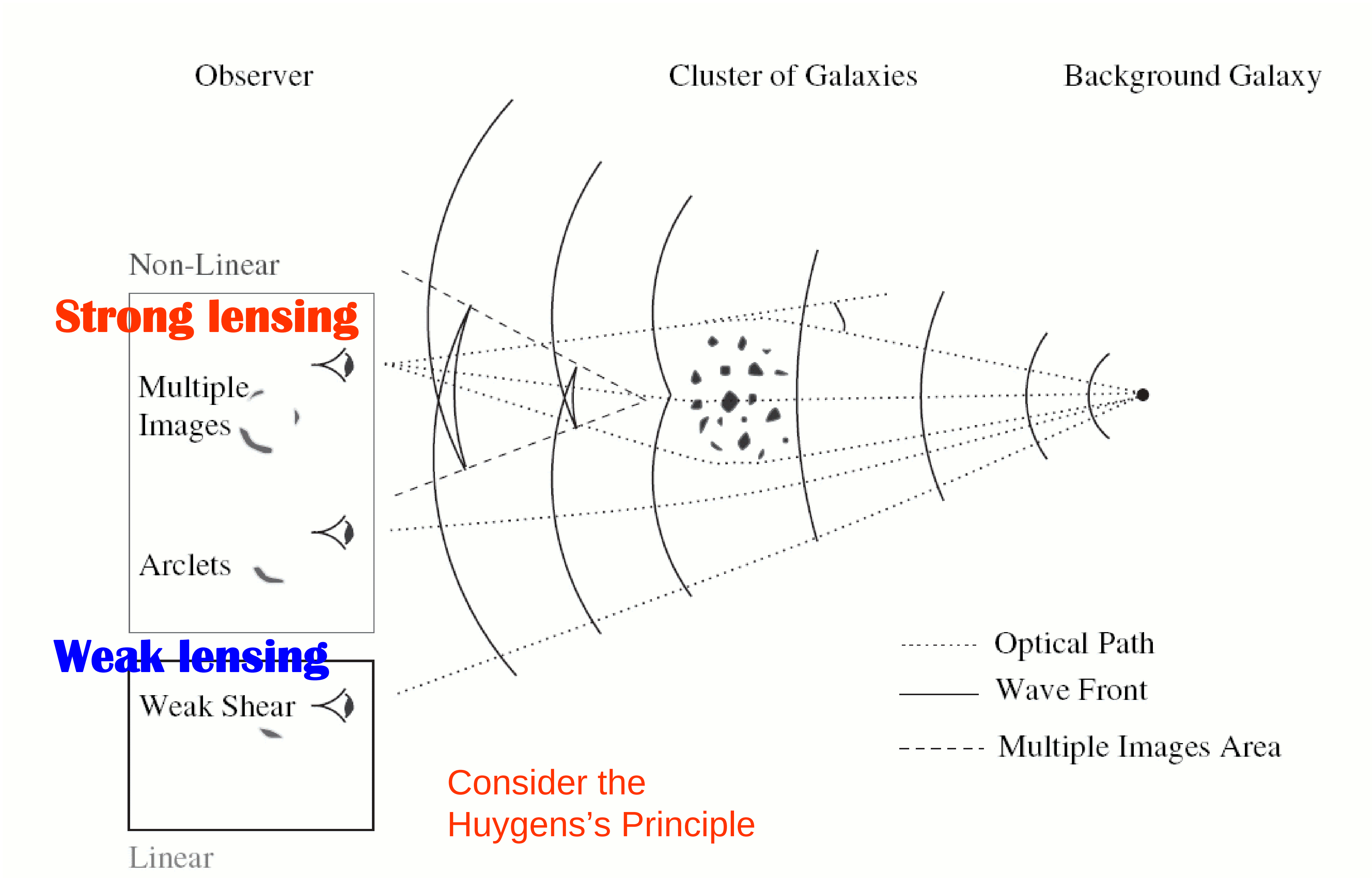
Differential deflection due to tidal force causes a distortion in "**area**" and "**shape**" of an image



Deformation of shape/area of an image

$$\delta\beta_i = (\delta_{ij} - \psi_{,ij})\delta\theta_j + O(\delta\theta^2)$$

Strong and Weak Lensing in Clusters



Consider the
Huygens's Principle

Strong Lensing: Multiple Imaging (I)

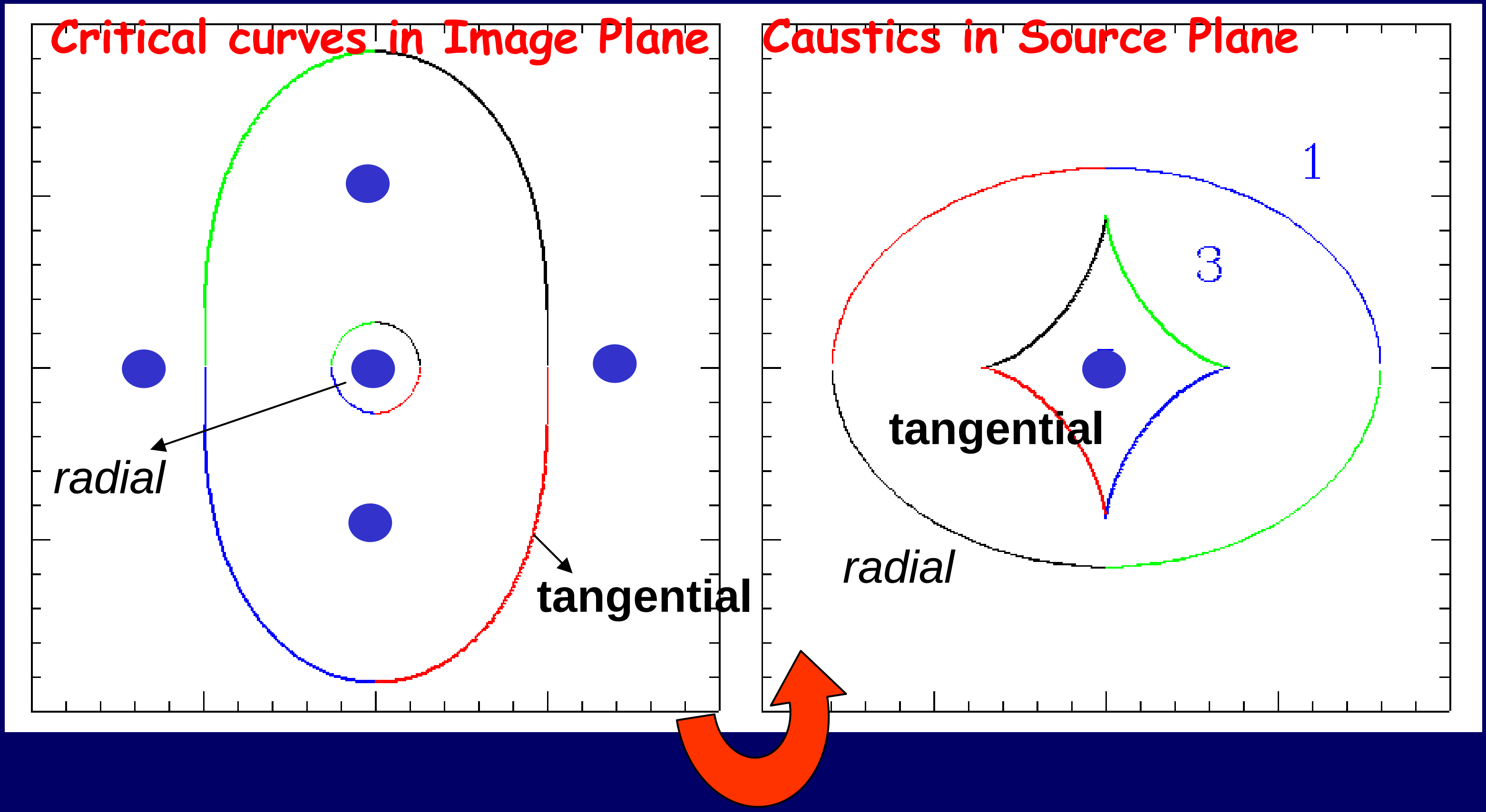
A source galaxy at z=1.675 has been multiply lensed into 5 apparent images

CL0024+1654 (z=0.395)

HST/WFPC2

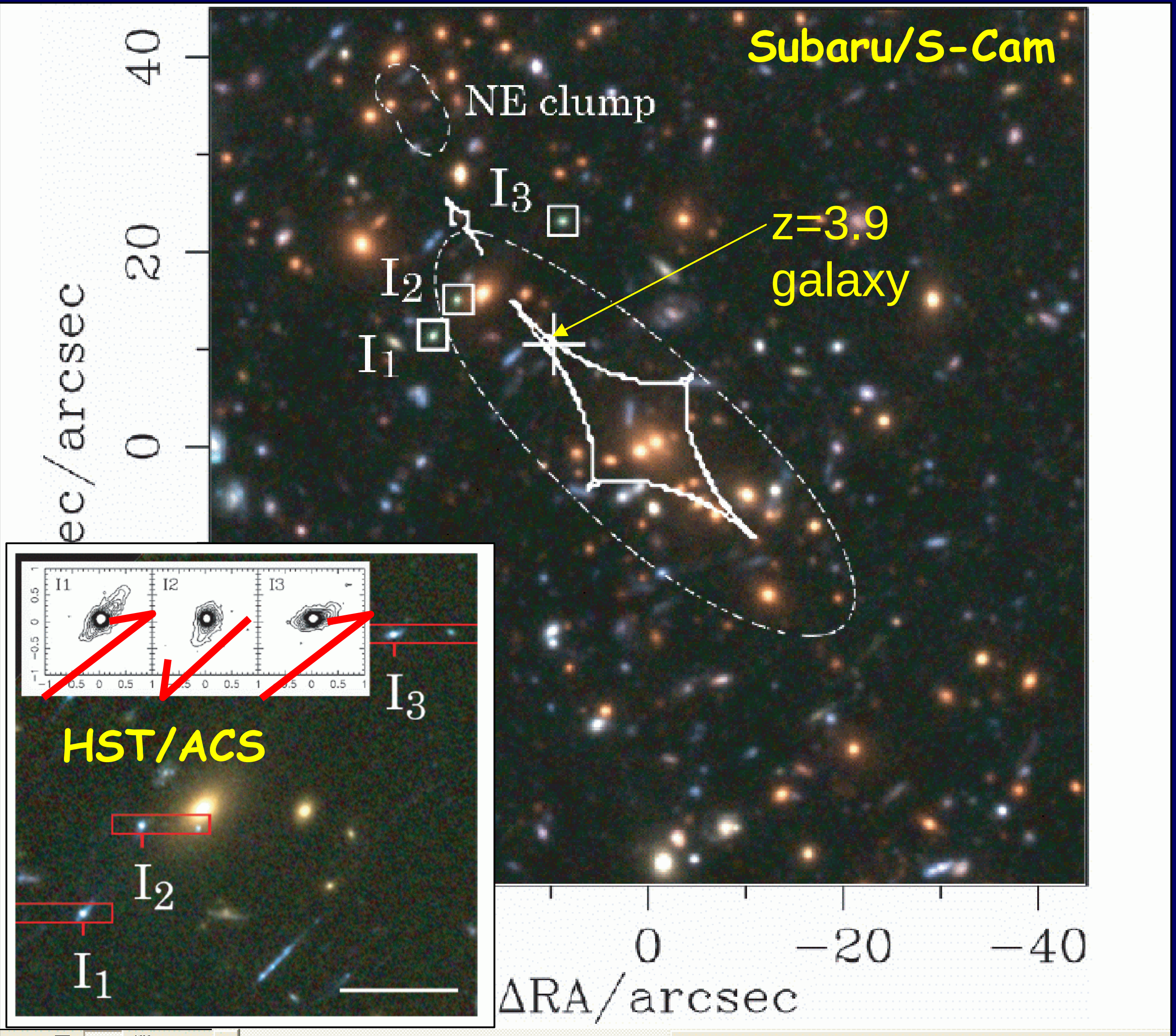
Strong Lensing: Critical Curves and Caustics

Elliptical lens potential **(non-circularly symmetric case)**



$$\boldsymbol{\beta} - \boldsymbol{\theta} = -\nabla \psi(\boldsymbol{\theta})$$

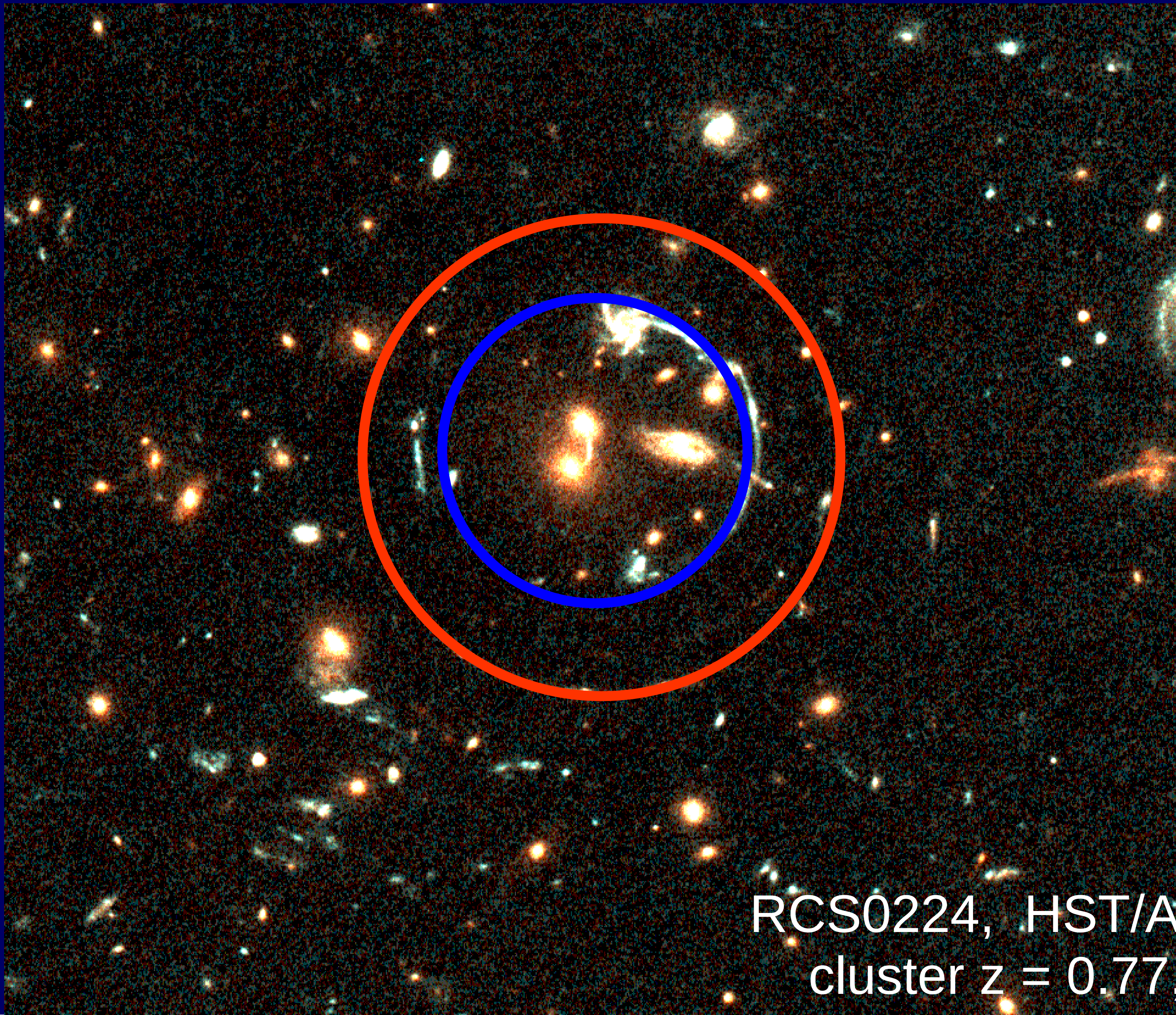
Strong Lensing: Multiple Imaging (II)



- Triple-images (I_1,I_2,I_3) of a z=3.9 source galaxy located in the vicinity of the cusp caustic
- The lens is a z=0.83 chain cluster in the process of formation
- Magnification factor is estimated as ~5
- Clusters serve as Natural Gravitational Lensing Telescopes!

Umetsu et al. 2005

Strong Lensing: Giant Luminous Arcs



RCS0224, HST/ACS
cluster z = 0.77, arc z = 4.89

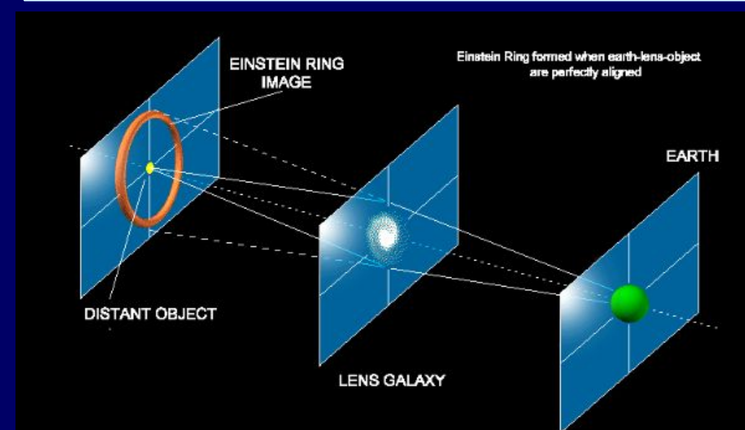
Demonstration of Strong Lensing

"A lens moving across the background galaxies"

Einstein radius

$$\theta_{\mathrm{E}} = \left[\frac{4GM(\theta_{\mathrm{E}})}{c^2 D_d} \frac{D_{ds}}{D_s} \right]^{1/2}$$

$$\approx 2\,\mathrm{arc\,sec} \left[\frac{M(\theta_{\mathrm{E}})}{10^{12} h^{-1} M_{\mathrm{sun}}} \right]^{1/2} \left(\frac{d_{ds}}{d_d d_s} \right)^{1/2}$$



By Frank Summers (STScI)

Spectacular Example of Tangential Arcs

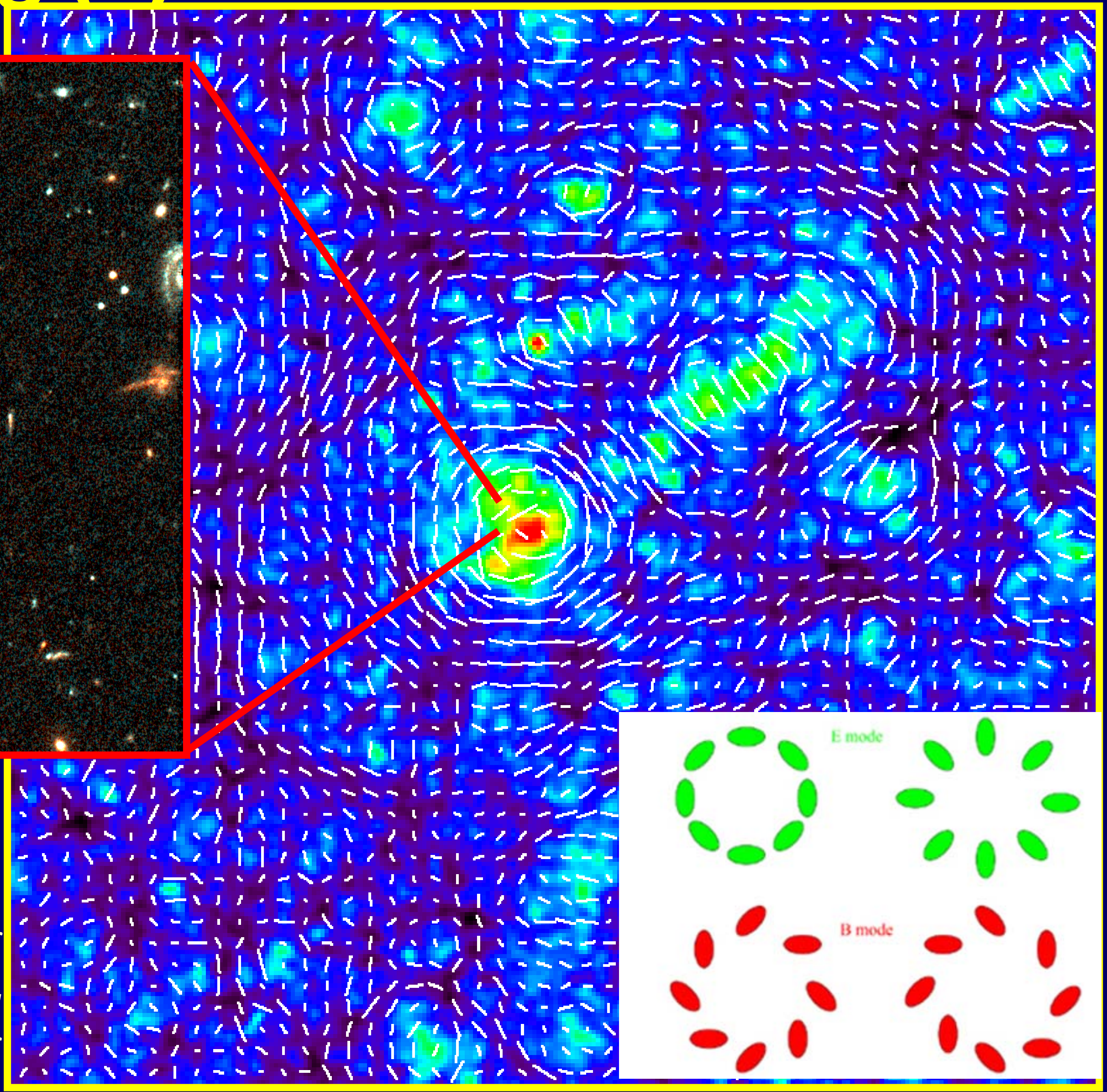
Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Weak Lensing (1): Gravitational Shear

Cluster z = 0.77; Arc z = 4.89:
Photo from H. Yee (HST/ACS)

Observable tangential alignment of background galaxy images, probing the underlying gravitational field of cosmic structure



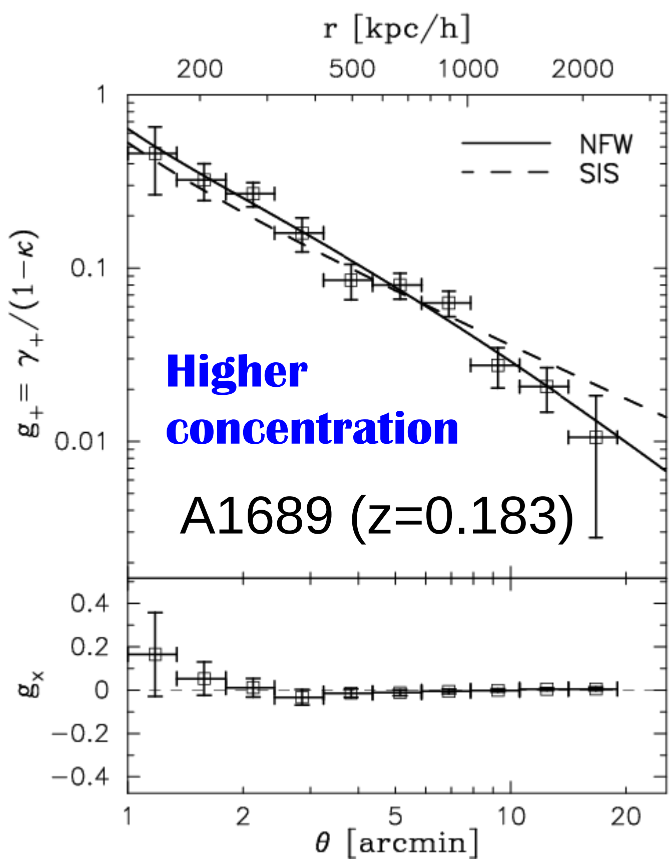
Simulated 3x3 degree field (Hamana 02)

Example of WL Tangential Shear Measurement

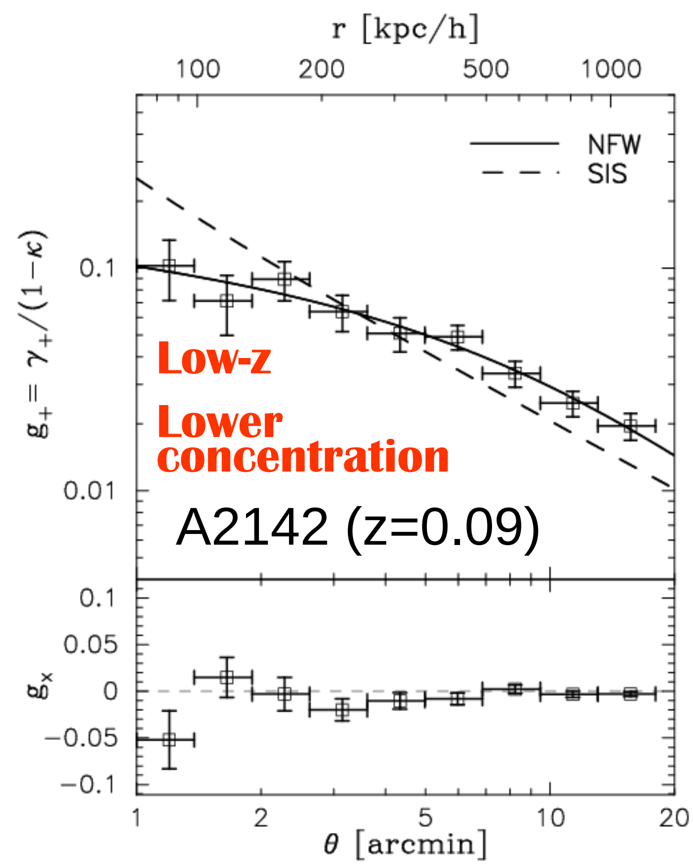
$$\gamma_+(r) \propto \Delta\Sigma_m(r) \equiv \overline{\Sigma}_m(<r) - \Sigma_m(r)$$

Measure of tangential coherence of distortions around the cluster (Tyson & Fisher 1990)

Mean tangential ellipticity of background galaxies (g_+) as a function of cluster radius; uses typically (1-2) x 10^4 background galaxies per cluster, yielding typically S/N=5-15 per cluster.



Umetsu & Broadhurst 2008, ApJ, 684 , 177



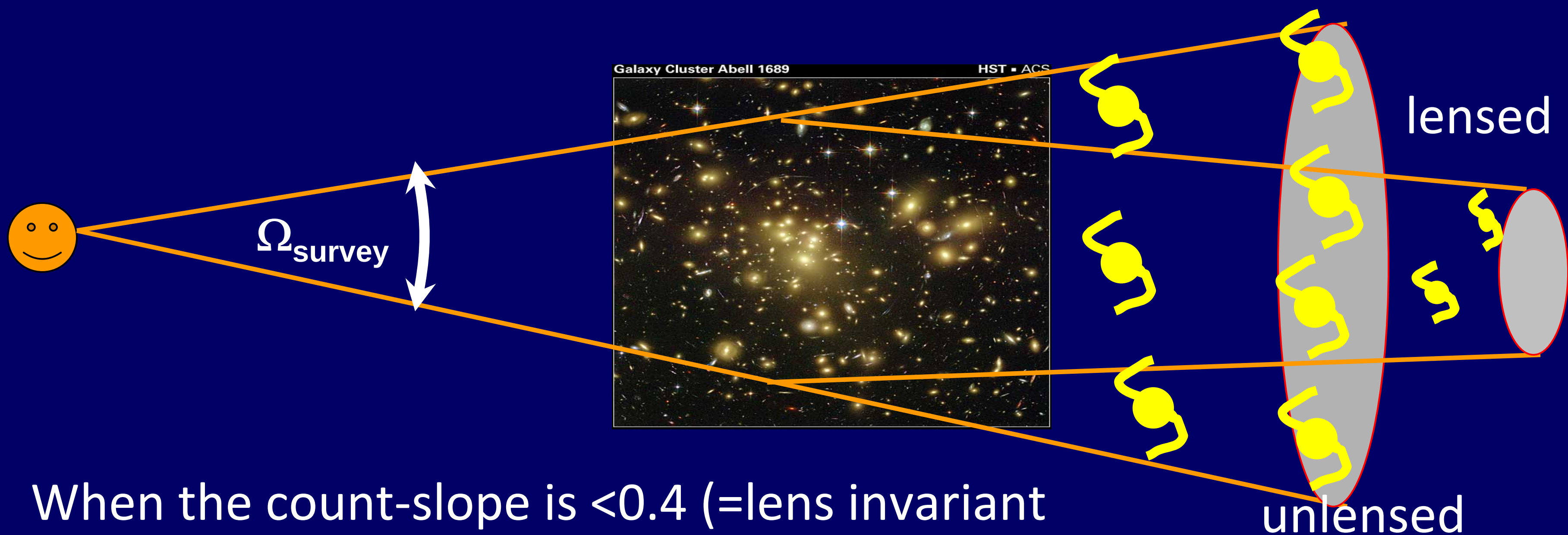
Umetsu et al 2009, ApJ, 694, 1643

Weak Lensing (2): Magnification Bias

Magnification bias: Lensing-induced fluctuations in the background density field (Broadhurst, Taylor, & Peacock 1995)

$$\delta n(\boldsymbol{\theta}) / n_0 \approx -2(1-2.5\alpha)\Sigma_m(\boldsymbol{\theta}) / \Sigma_{\rm crit}$$

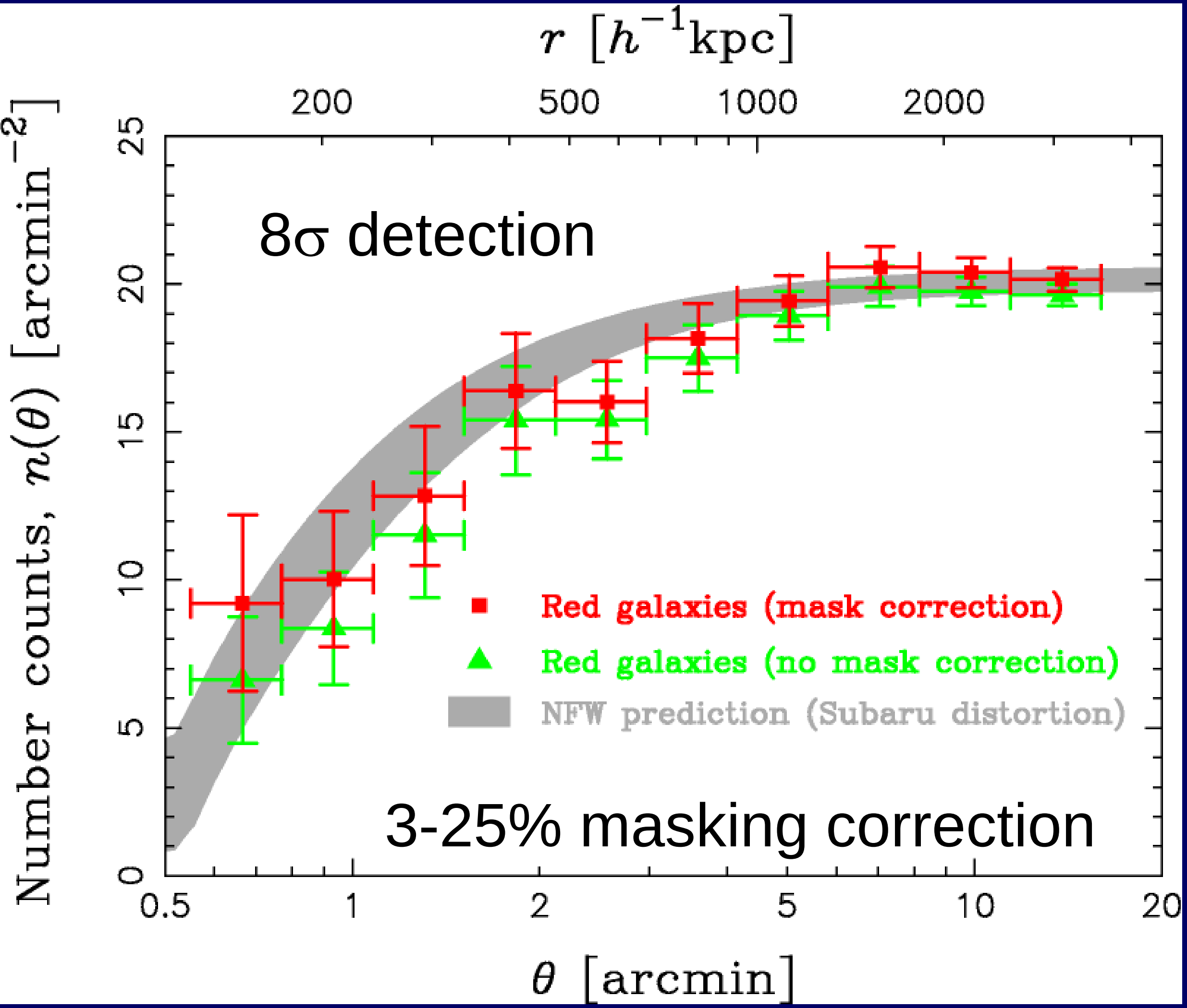
with unlensed counts of background galaxies $n_0(<m) \propto 10^{\alpha m}$



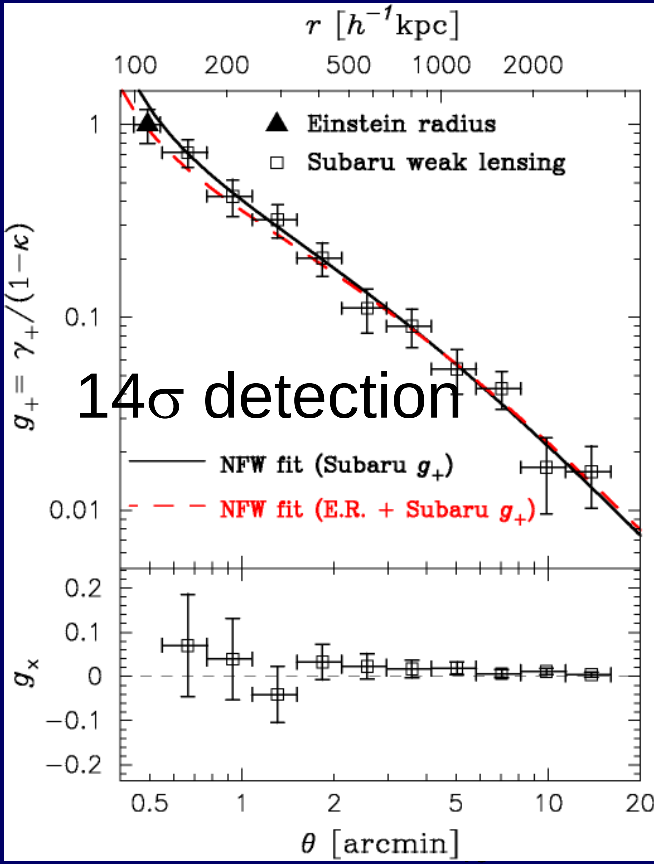
When the count-slope is <0.4 (=lens invariant slope), a net deficit is expected.

Example of Magnification Bias Measurement

Count depletion of "red" galaxies in CL0024+1654 (z=0.395)



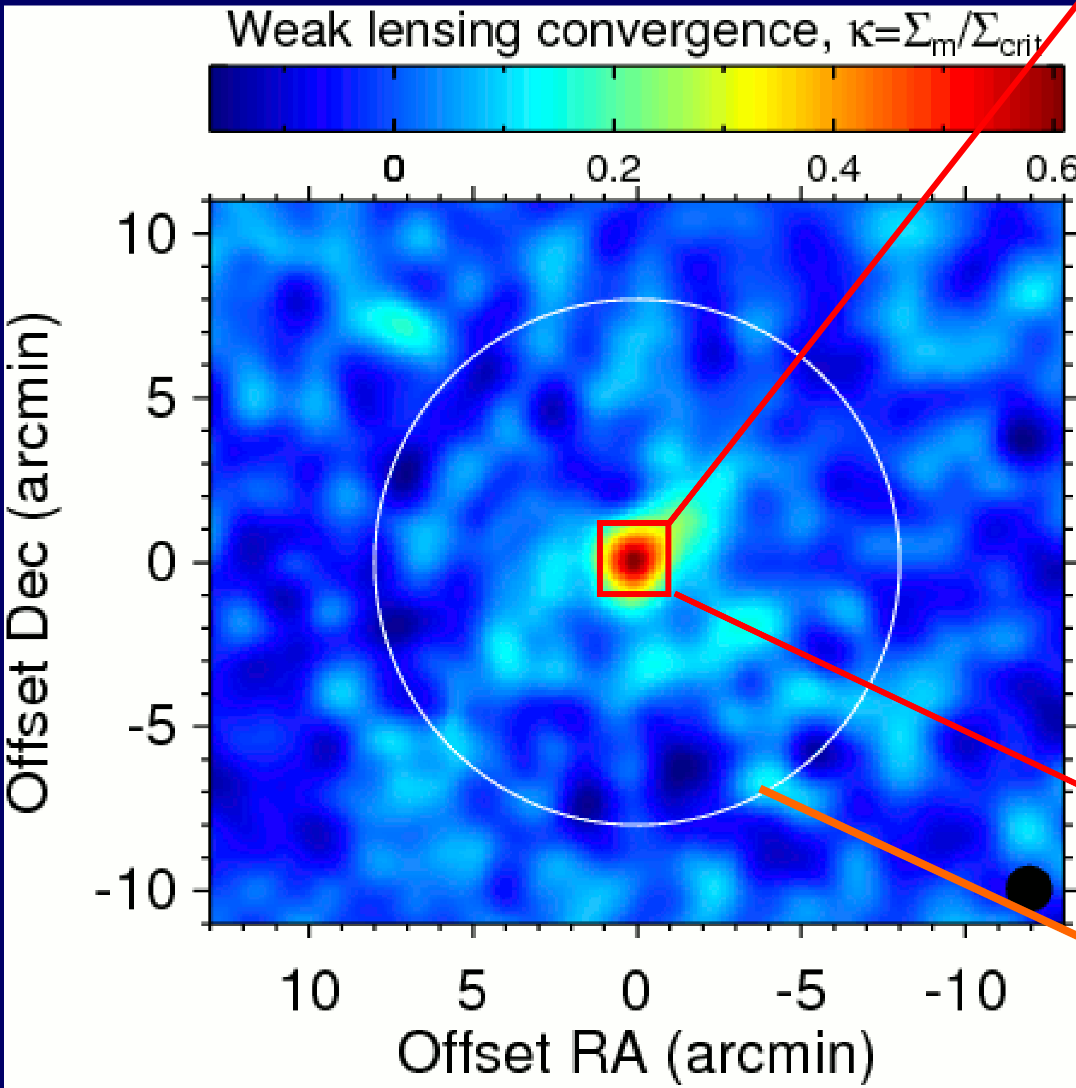
Distortion of "blue+red" sample



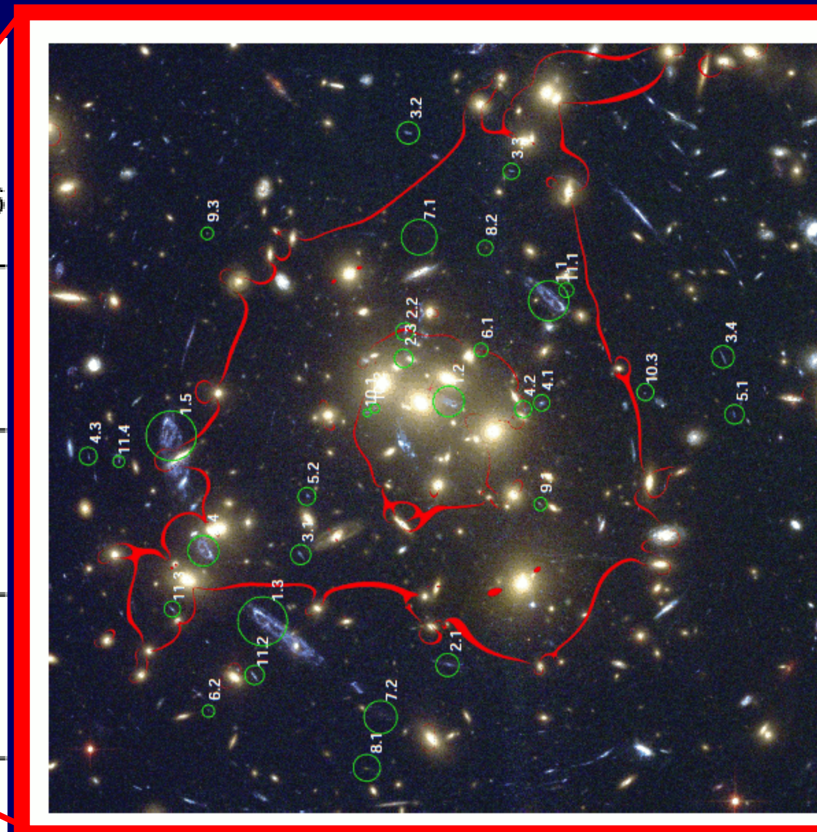
Umetsu et al. 2010, ApJ, 714, 1470

Full Strong + Weak Lensing Analysis

Galaxy cluster: CL0024+1654 (z=0.395)



HST/ACS (2'x2' region)



SUBARU/Suprime-Cam

R_{vir}=~ 1.8Mpc/h (~8 arcmin)

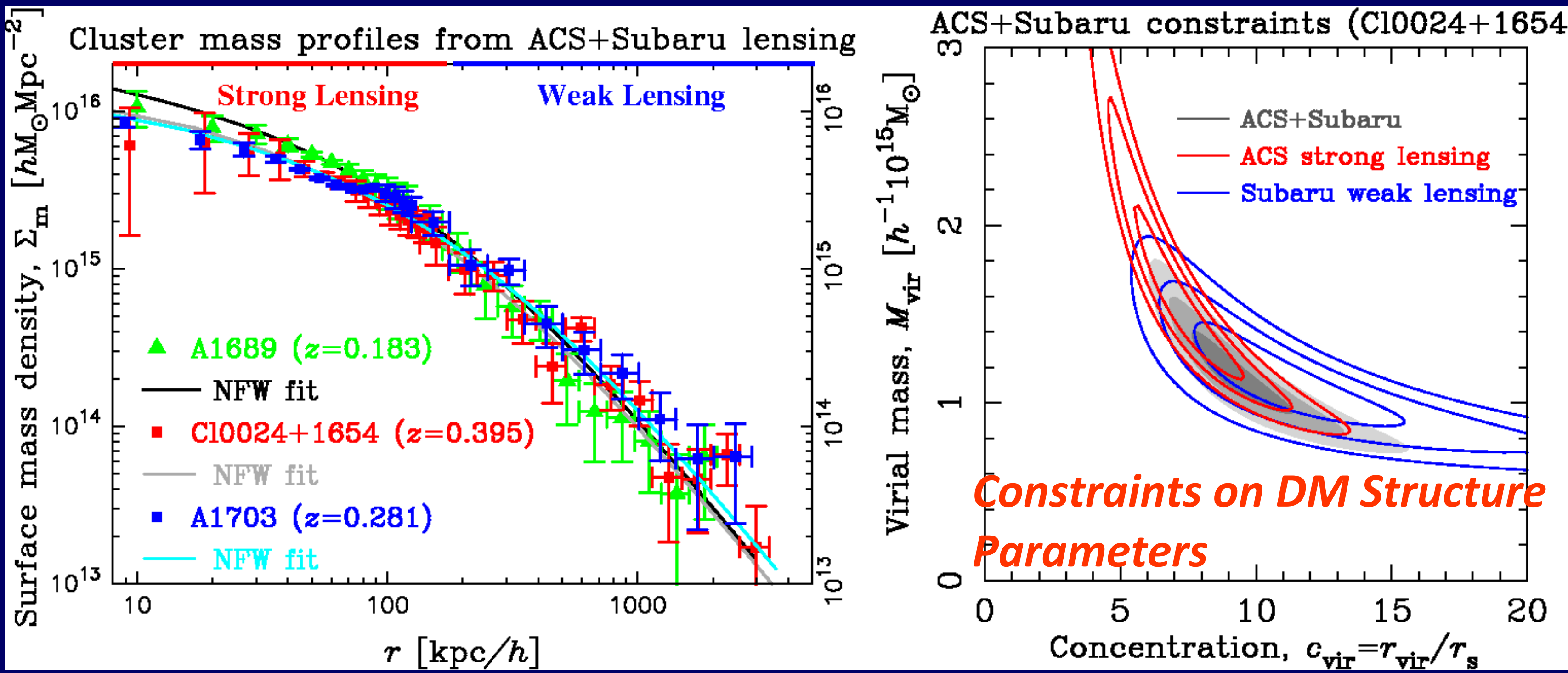
Umetsu et al. 2010

Cluster DM Mass Profiles from Full Lensing

Combining Weak (Subaru) and Strong (HST/ACS) lensing data

→ Probing full cluster mass profiles from 10kpc/h to 3000kpc/h

Results for Abell 1689 (z=0.183), CL0024+1654 (z=0.395), A1703 (z=0.281)



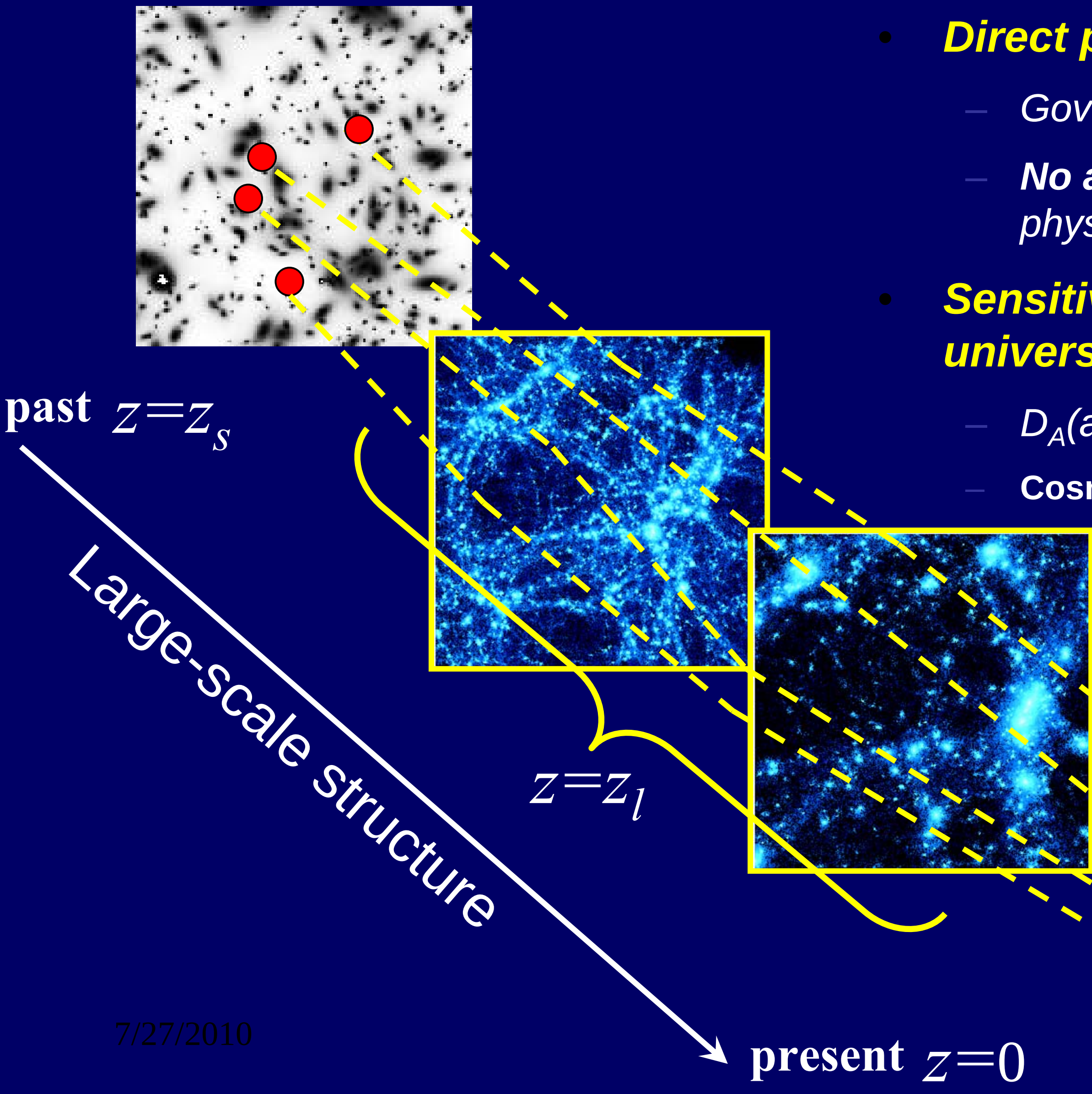
Umetsu+2010b, in prep (Full weak-lensing constraints from distortion + magnification MCMC analysis for 5 massive clusters)

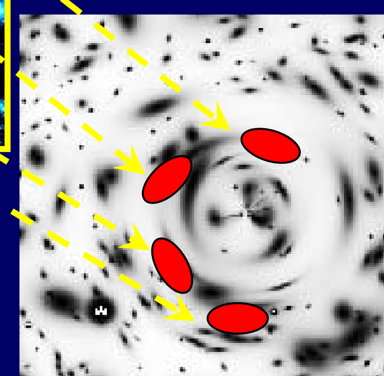
Broadhurst, Takada, Umetsu+2005; Umetsu & Broadhurst 2008 (A1689); Zitrin, Broadhurst, Umetsu+ arXiv.1004.4660: (A1703)

Umetsu+ 2010a (Cl0024+1654)

Weak Lensing by LSS: Cosmic Shear

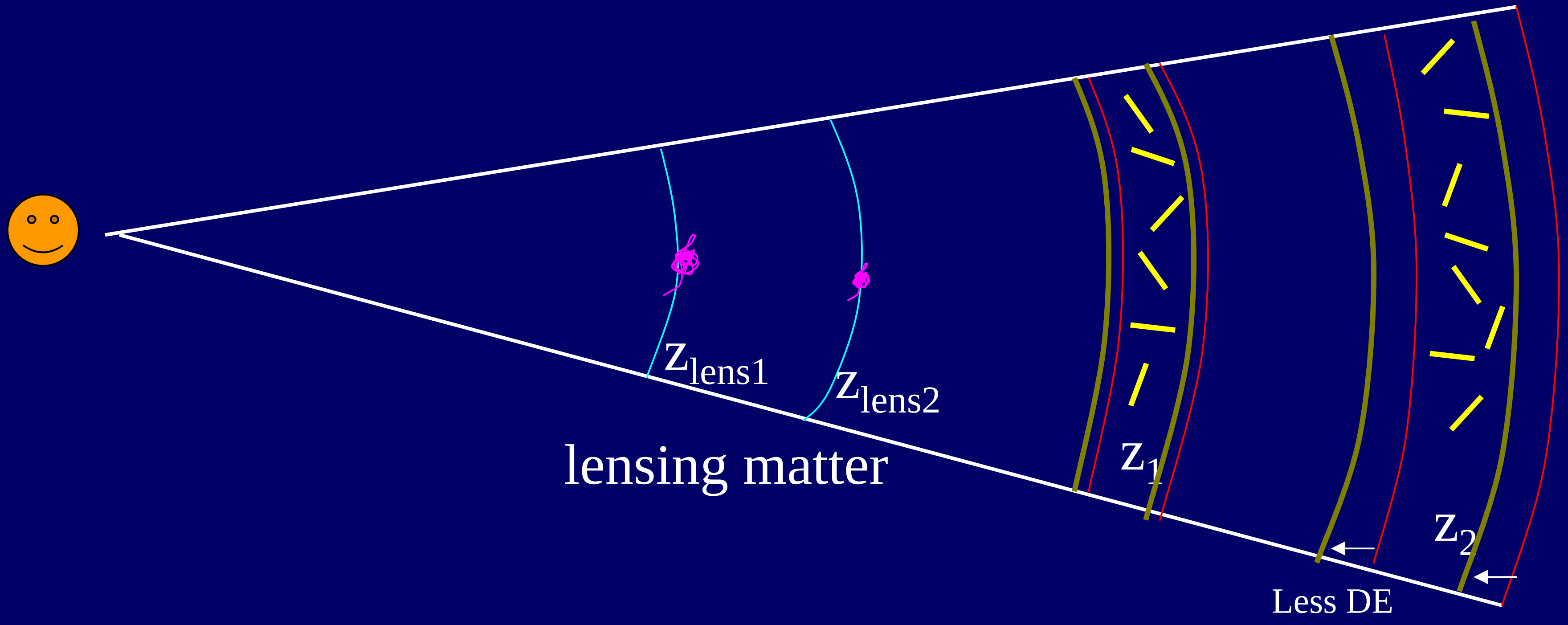
- ***Direct probe of matter distribution***
  - *Governed solely by* ***gravity***
  - ***No assumption*** *about physical/dynamical state of the system*
- ***Sensitive probe of geometry of the universe***
  - *$D_A(a)$, $H(a)$, $dV/da(a)$ vs. DE*
  - **Cosmic structure formation** *imprinted*





Weak Lensing Tomography

Hu 99; Huterer 02; Refregier et al. 03; Takada & Jain 04



Shear @ z=z1 & z2 is given by a LoS-integral of growth function $D_+(a)$ & distances over the matter distribution, $\delta(a)$

Lensing tomography probes "expansion kinematics" H(a) and "growth of structure" $D_+(a)$, thereby sensitive to the background cosmology

Fin