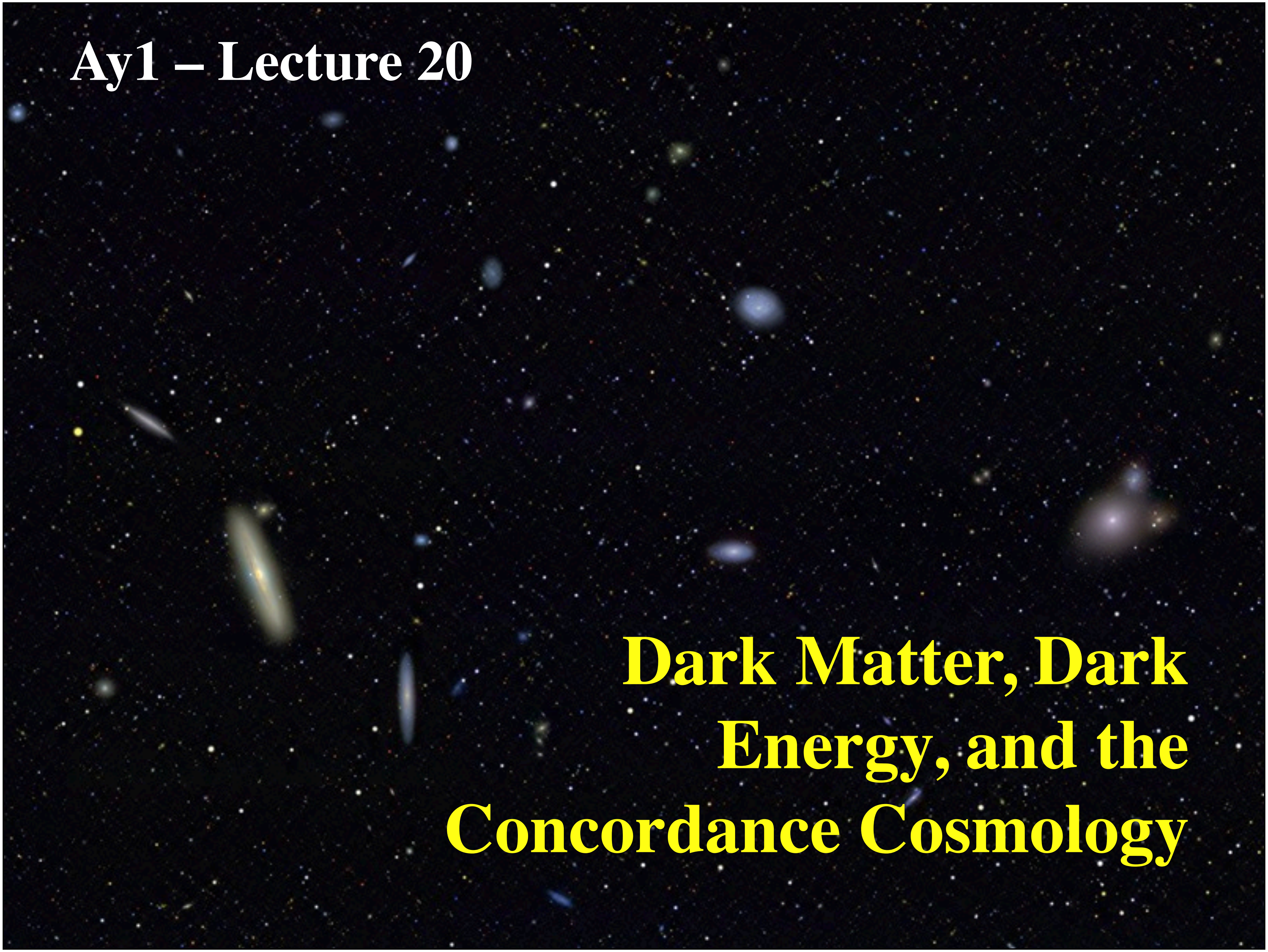


Ay1 – Lecture 20

Dark Matter, Dark Energy, and the Concordance Cosmology

20.1 Matter and Energy Contents of the Universe

All Matter and Energy in the Universe

There are several components:

- Luminous matter in galaxies: stars and gas ("luminous baryons")
- All normal matter not accounted by the luminous component ("dark baryons")

} "baryons"

} "matter"

- Non-baryonic dark matter (DM)
- "Dark energy" (recall that $\rho_{energy} = \rho_{matter}\, c^2$)
- Radiation (all photons, mostly CMB)

Each has a mean density ρ_i and density parameter $\Omega_i = \rho_i / \rho_{crit}$

where $\rho_{crit} = 3H^2 / (8\pi G) = 0.921 \times 10^{-29}\, h_{70}^2$ g cm^{-3}

The total density parameter is their sum: $\Omega_{total} = \Sigma\ \Omega_i$

Luminous Mass Density

Add up all of the starlight in galaxies to get the mean luminosity density:

$$\rho_{light} \approx (1.6 \pm 0.2) \times 10^8\, h_{70}\, L_\odot/\text{Mpc}^3$$

Convert to mass density using a mean mass to light ratio of stellar populations, $\langle M/L \rangle \approx 5$, and correct for the fraction of the gas in the ISM, $f_{\text{gas}} \approx 10\%$

$$\rho_{lum} = \rho_{light} \times \langle M/L \rangle \times \langle 1 + f_{\text{gas}} \rangle \approx (7 \pm 2) \times 10^8\, h_{70}\, M_\odot/\text{Mpc}^3$$

$$\rho_{\text{lum}} \approx (4.7 \pm 1.3) \times 10^{-32}\, h_{70}\ \text{g cm}^{-3}$$

$$\text{Thus, } \Omega_{0,lum} \approx (0.0051 \pm 0.0015)\, h_{70}^{-1}$$

All of the visible matter amounts to only half a percent of the total mass/energy content of the universe!

The Total Baryon Density

It is measured in two independent ways:

1. The cosmic nucleosynthesis:

✧ Reaction rates are ~ ρ_{baryon}^2, so the abundances of D, He, and Li are very sensitive to ρ_{baryon} (especially for D)

✧ Measured in spectra of distant QSOs (actually Lyα forest clouds), star forming dwarf galaxies, halo stars, etc.

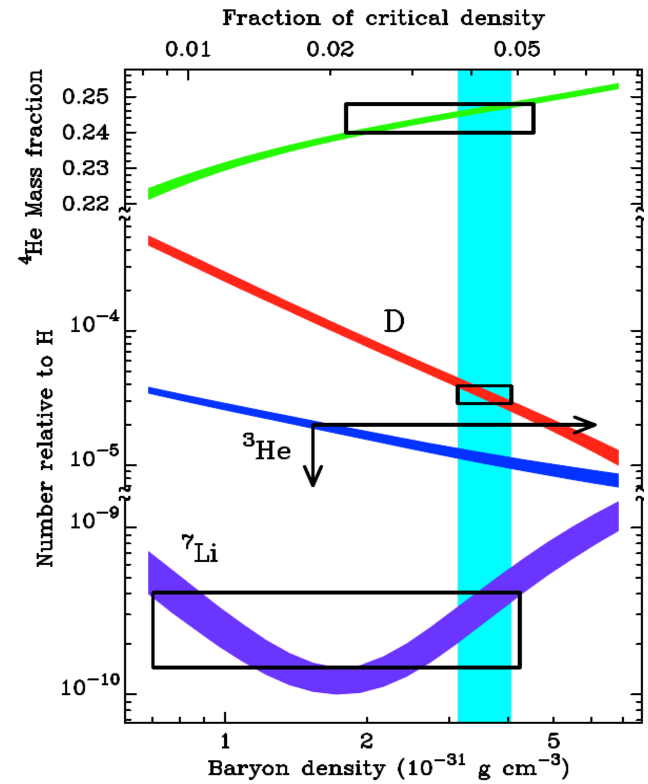
Result: $\Omega_{baryons} h^2 = 0.021 \rightarrow 0.025$

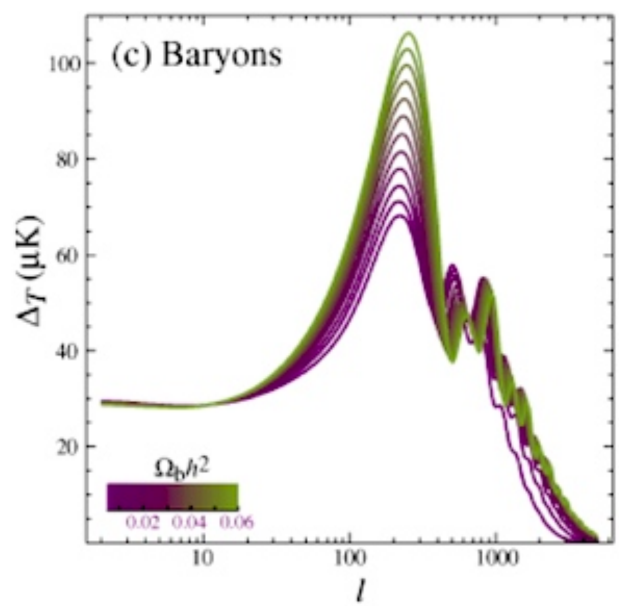
2. Acoustic peaks in the CMB

✧ Amplitude is sensitive to ρ_{baryon}

Result: $\Omega_{baryons} h^2 = 0.0221 \pm 0.0003$

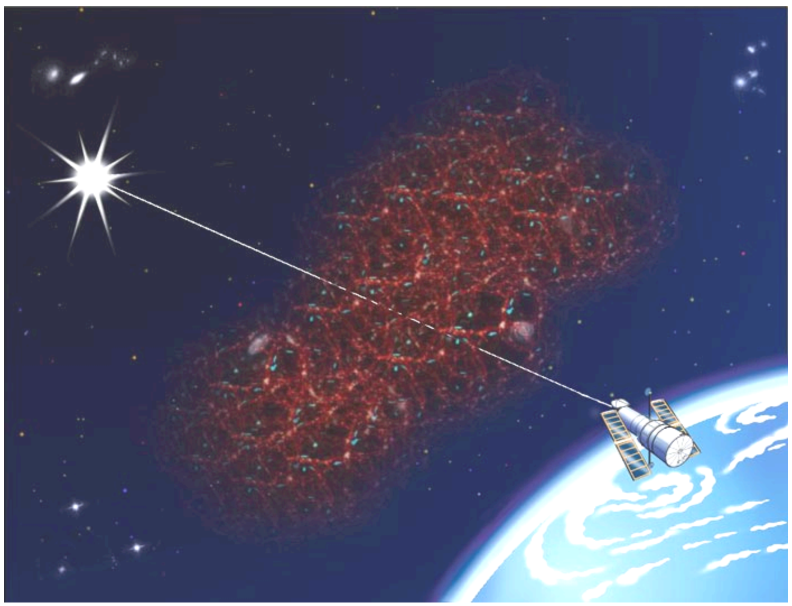
Thus, $\Omega_{0,lum} \approx (0.048 \pm 0.005)\ h_{70}^{-1}$

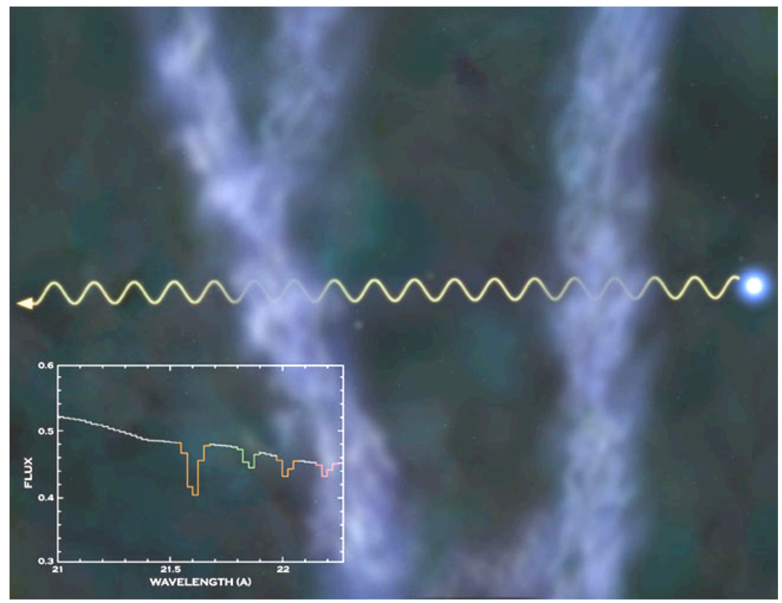




Missing Baryons in Warm/Hot IGM?

This hypothetical Baryon reservoir would have Virial temps. of ~ 10^5 - 10^6 K, where the peak emission is in FUV/soft-X, which is effectively absorbed by the ISM in our Galaxy, and is thus essentially impossible to detect in emission …

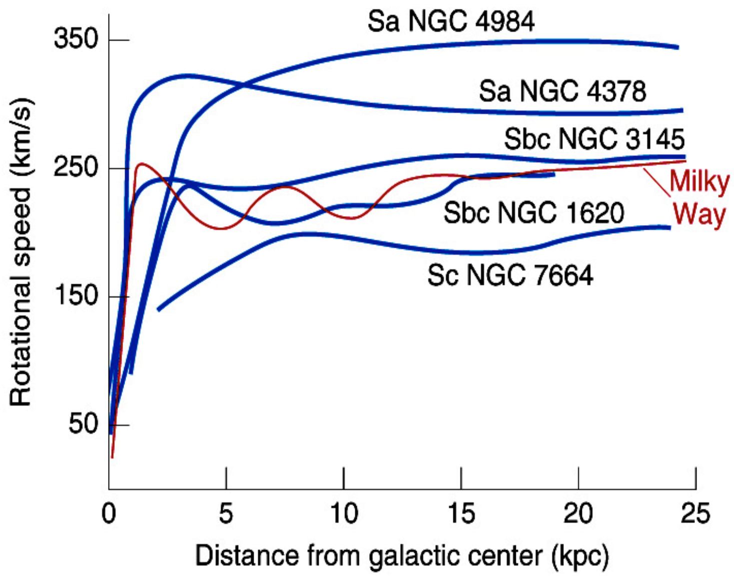




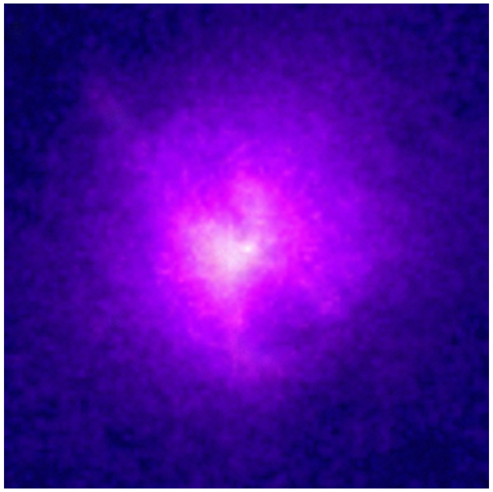
However, it might have been ***detected in absorption*** in the UV (HST and FUSE) and X-Rays (Chandra), using O VI, O VII, and O VIII lines

The Total Matter Density

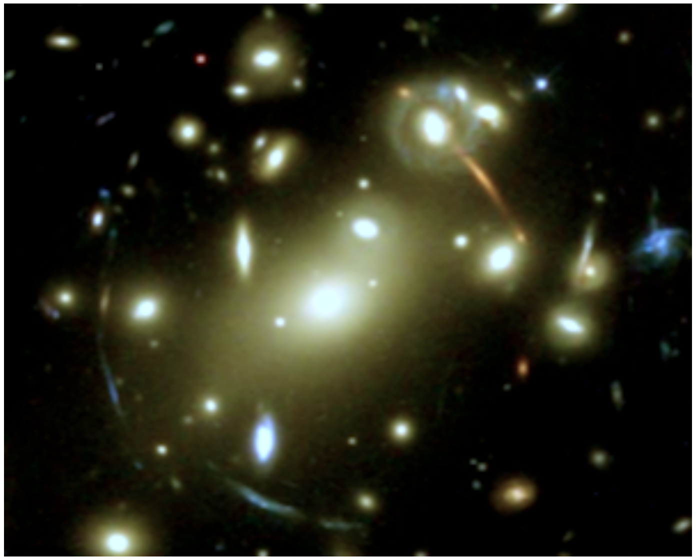
It is measured in in several ***independent*** ways:



< Galaxy dynamics:
rotation curves,
velocity dispersions…

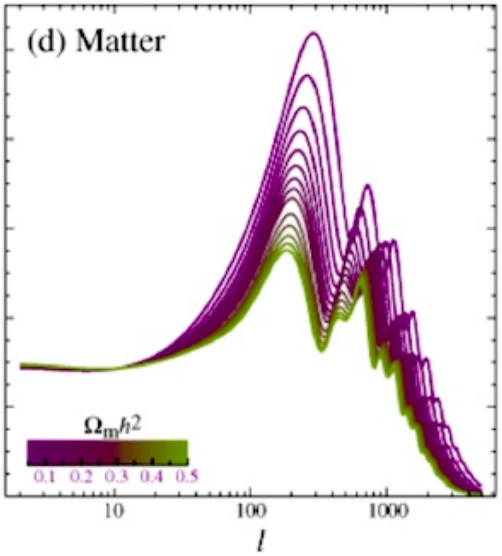


Cluster masses >
from the X-ray gas



< Cluster masses from
gravitational lensing

CMB fluctuations >



\+ Large-scale structure…

The Component Densities

at z ~ 0, in critical density units, assuming $h \approx 0.7$

Total matter/energy density: $\Omega_{0,tot} \approx 1.00$ From CMB, and consistent with SNe, LSS

Matter density: $\Omega_{0,m} \approx 0.31$ From local dynamics and LSS, and consistent with SNe, CMB

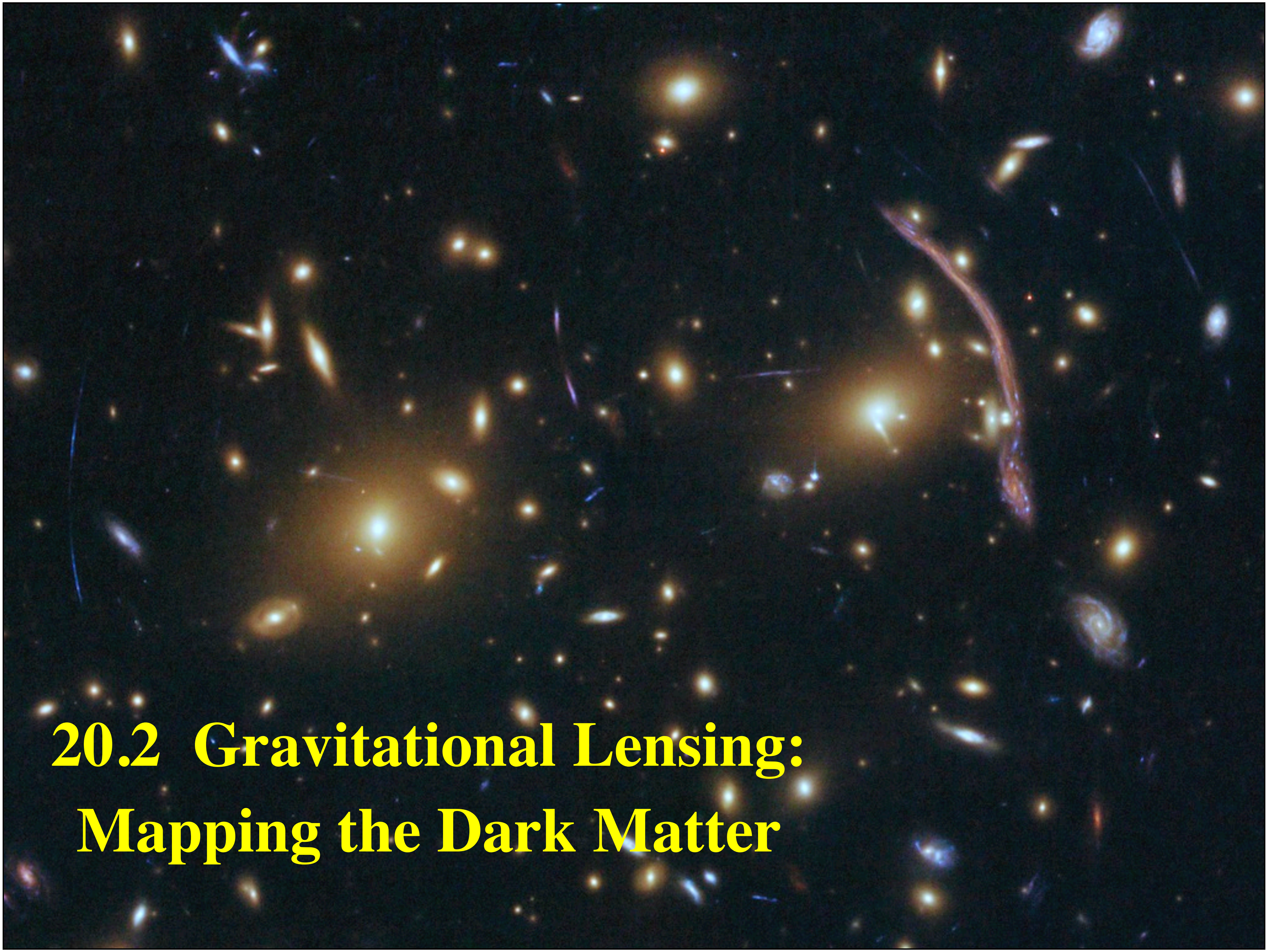
Baryon density: $\Omega_{0,b} \approx 0.045$ From cosmic nucleosynthesis, and independently from CMB

Luminous baryon density: $\Omega_{0,lum} \approx 0.005$ From the census of luminous matter (stars, gas)

Since: $\Omega_{0,tot} > \Omega_{0,m} > \Omega_{0,b} > \Omega_{0,lum}$

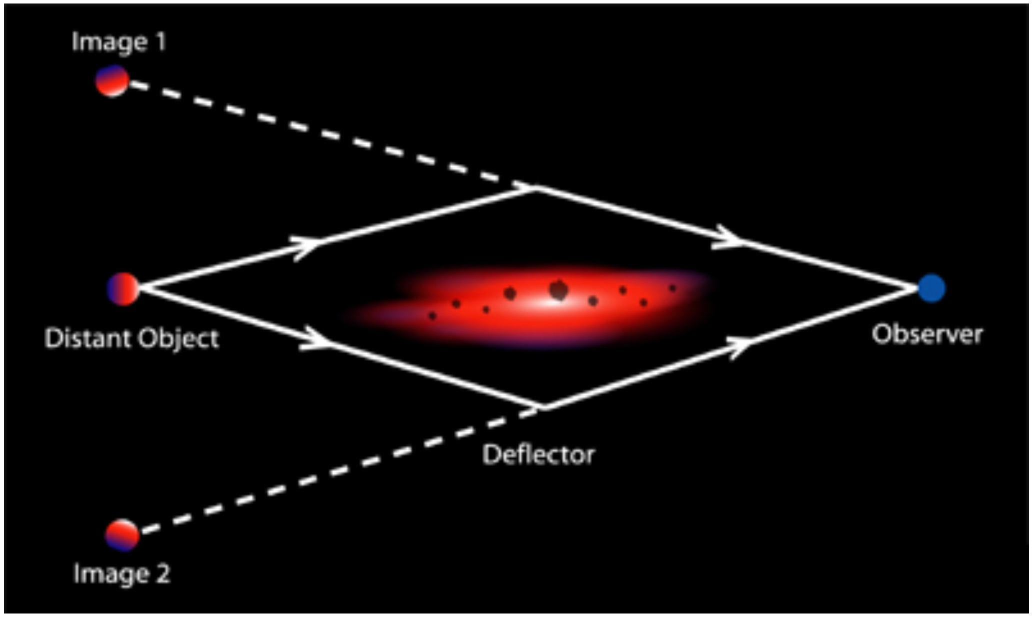
- $\Omega_{0,b} > \Omega_{0,lum}$ → There is baryonic dark matter
- $\Omega_{0,m} > \Omega_{0,b}$ → There is non-baryonic dark matter
- $\Omega_{0,tot} > \Omega_{0,m}$ → There is dark energy

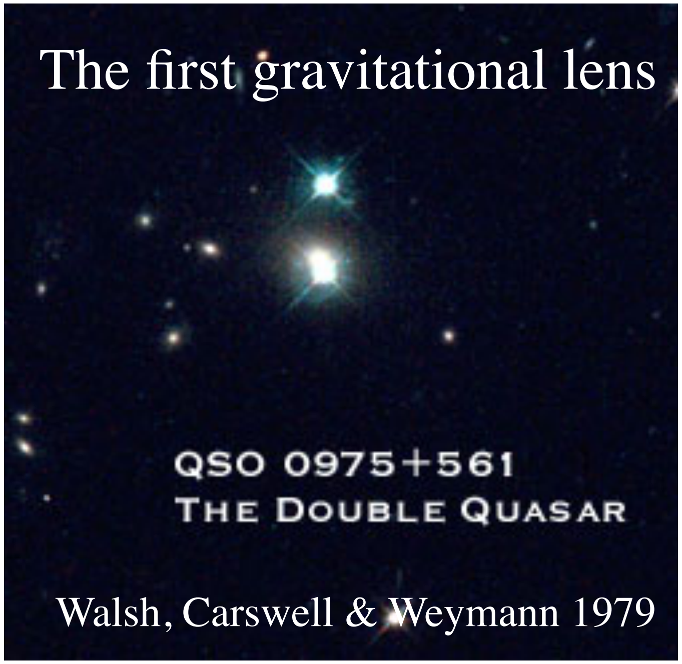
20.2 Gravitational Lensing: Mapping the Dark Matter



Gravitational Lensing:
Mapping the Distribution of the Dark Matter

- We know from general relativity that mass - whether it is visible or not - bends light. This opens a possibility of "seeing" the distribution of dark matter
- Chowlson (1924) and Einstein (1936) predicted that if a background object is directly aligned with a point source mass, the light rays will be deflected into an "Einstein Ring"





Gravitational Lensing

Photons are deflected by gravitational fields - hence images of background objects are distorted if there is a massive foreground object along the line of sight.

Bending of light is similar to deflection of massive particles, except that GR predicts that for **photons** the bending is exactly twice the Newtonian value:

$$\alpha = \frac{4GM}{bc^2} = \frac{2R_s}{b}$$

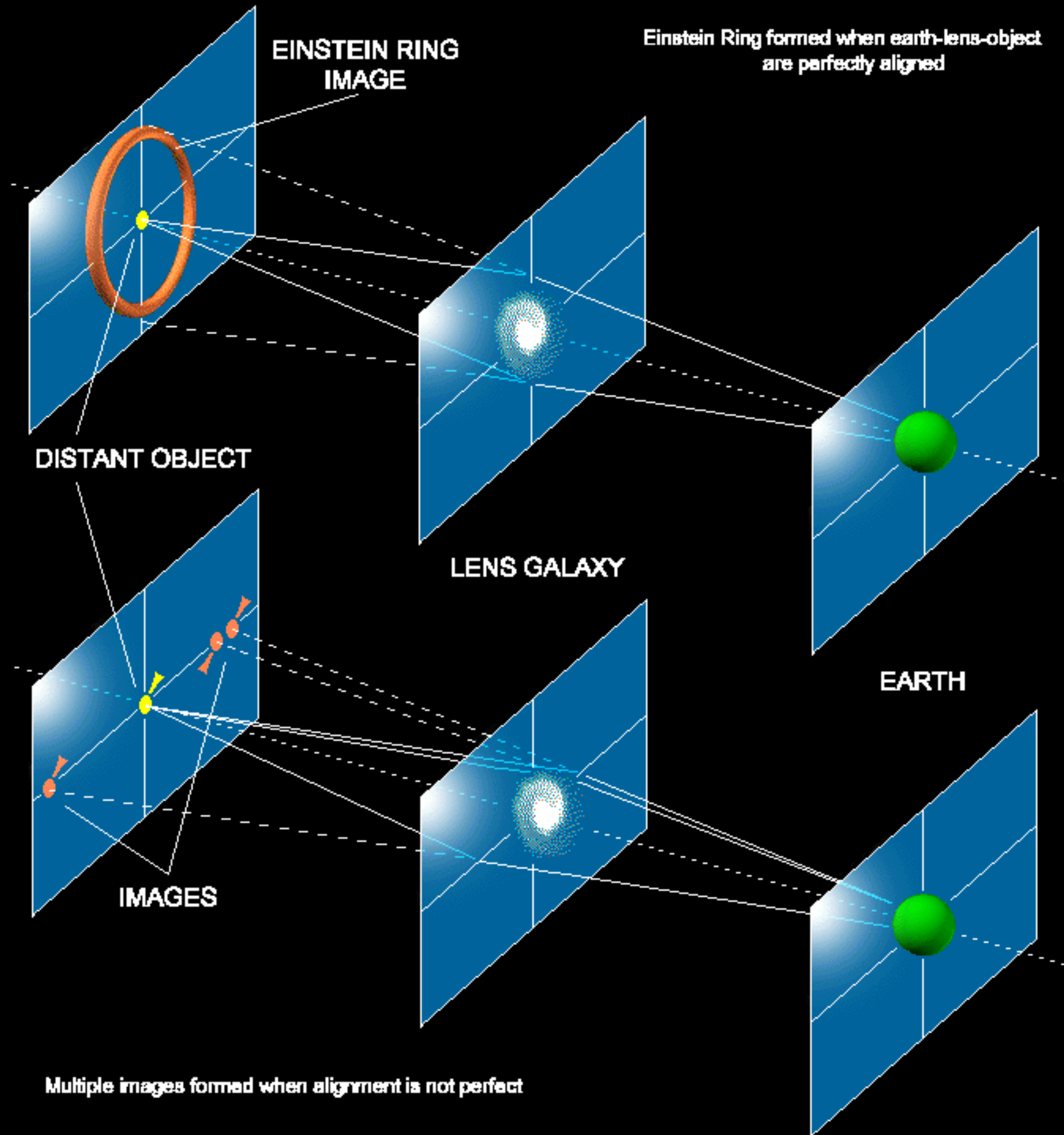
…where R_s is the Schwarzschild radius of a body of mass M, and b is the impact parameter. This formula is valid if $b \gg R_s$:

- Not valid very close to a black hole or neutron star
- Valid everywhere else
- Implies that deflection angle a will be small

  e.g., for the stars near the Solar limb, ~ 2 arcsec

Gravitational lensing in the strong regime

Misalignment of the line of sight and the center of the lensing mass splits the Einstein ring into multiple images



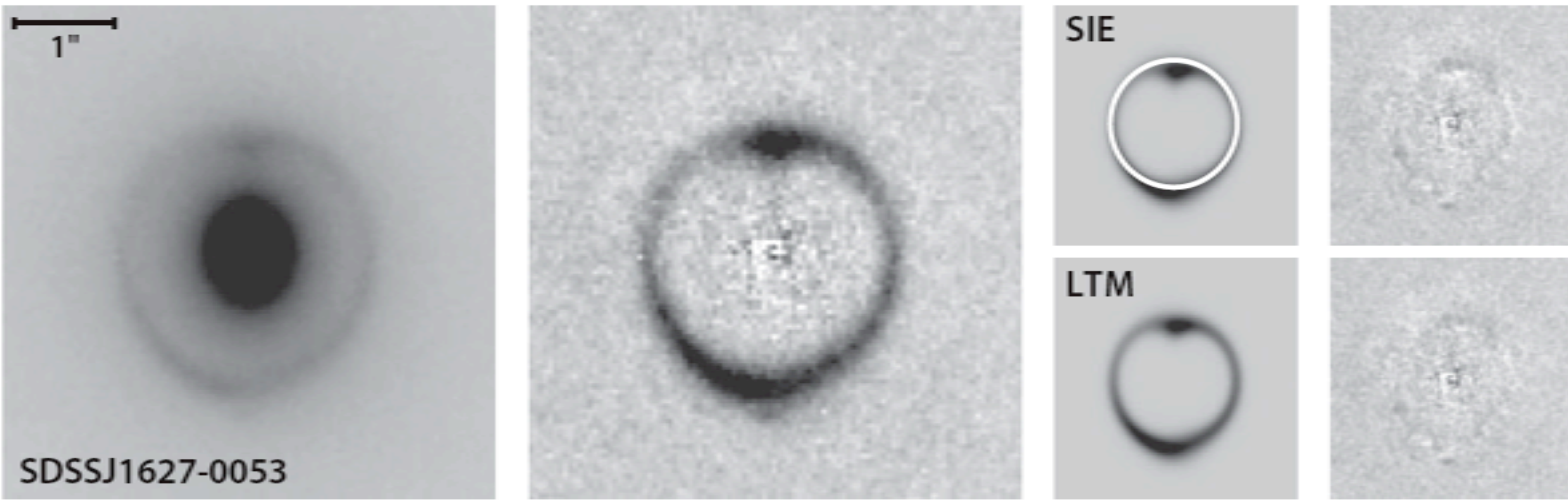
Gravitationally Lensed Galaxies - "Arcs"

In 1937, Zwicky predicted that one could study the mass distribution (dark matter) in clusters by studying background galaxies that are lensed by the dark matter in the cluster. This was not observationally feasible until the mid-1990's

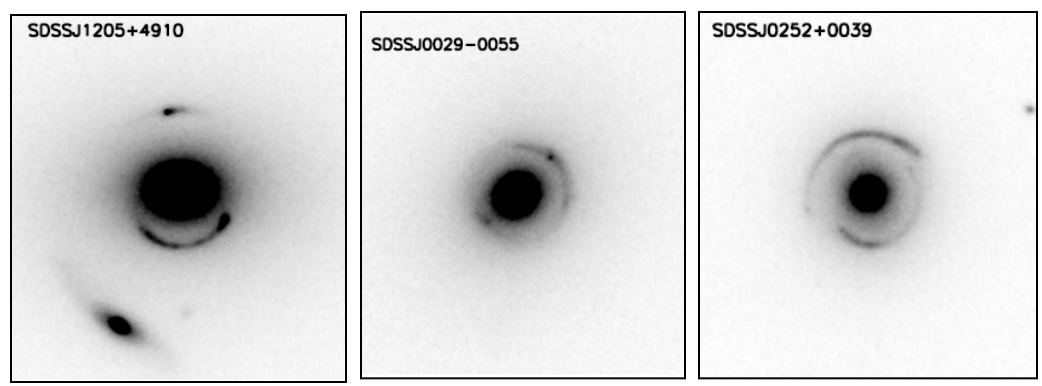
Galaxy Masses From Gravitational Lensing

Treu et al. (the SLACS collaboration)

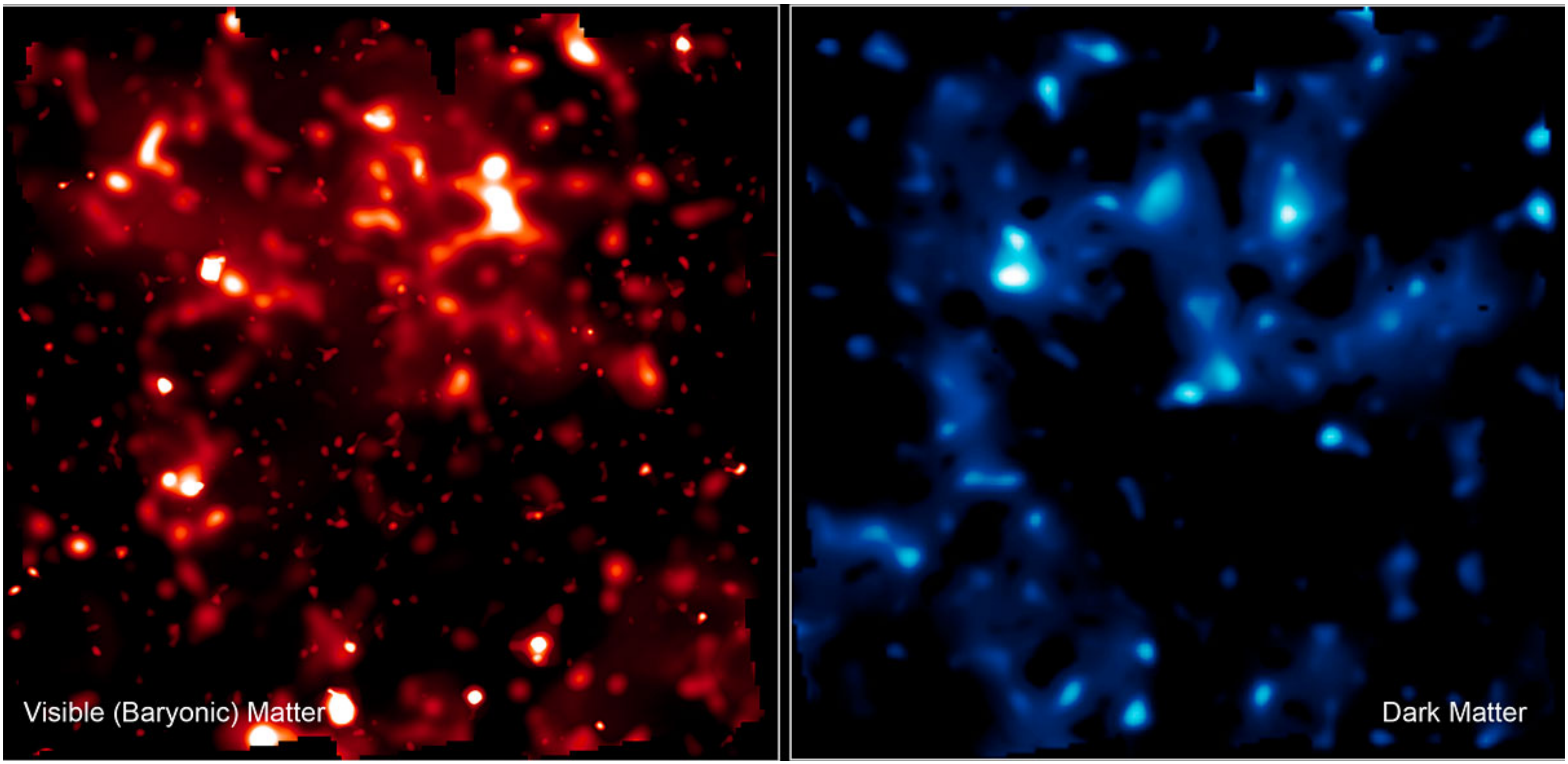
Original | Lens galaxy subtracted | Lens models | Residuals



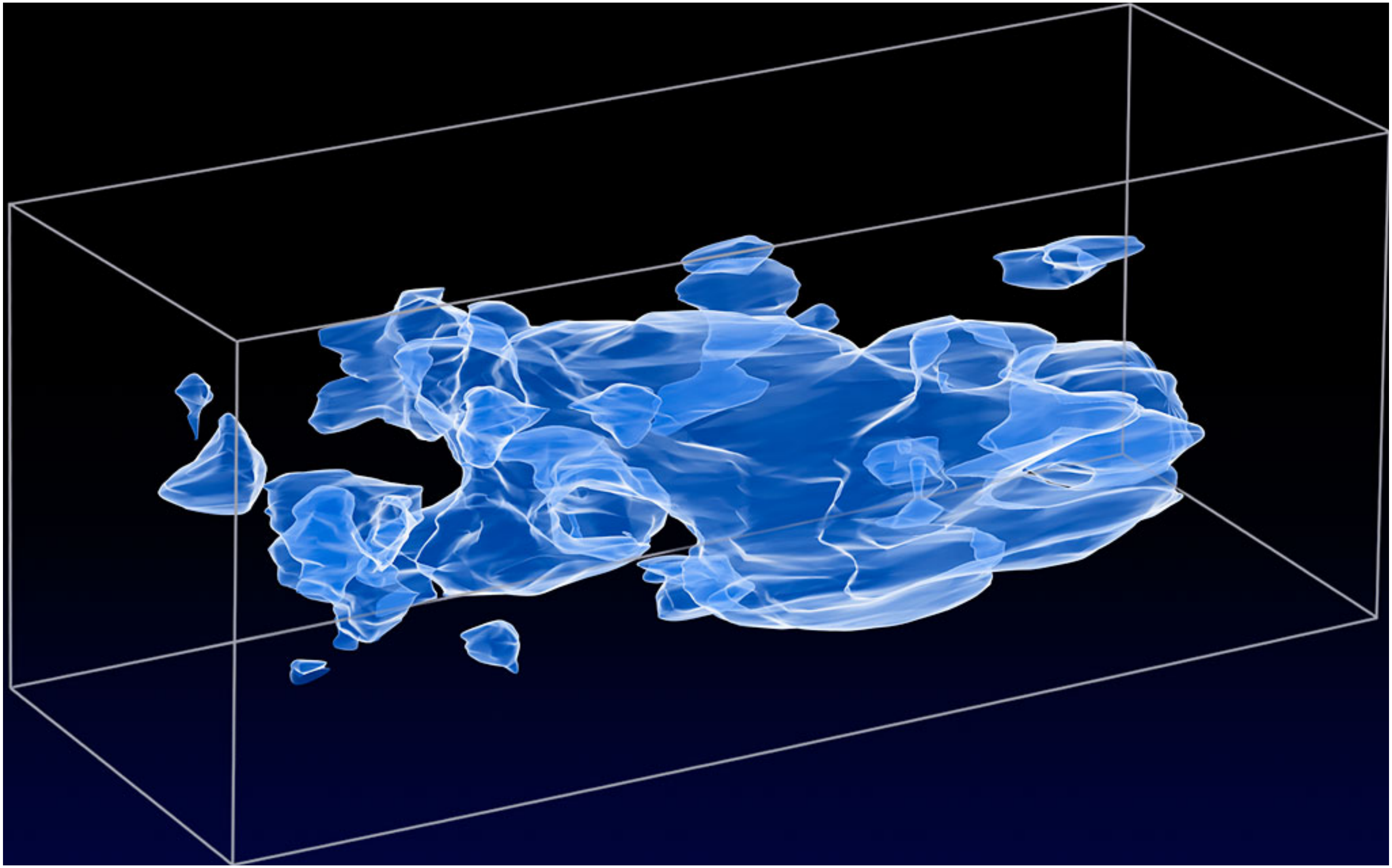
Typically using a Singular Isothermal Ellipsoid (SIE) as a lens mass model



Visible and DM Distribution From the COSMOS Survey (Scoville, Massey et al. 2007)



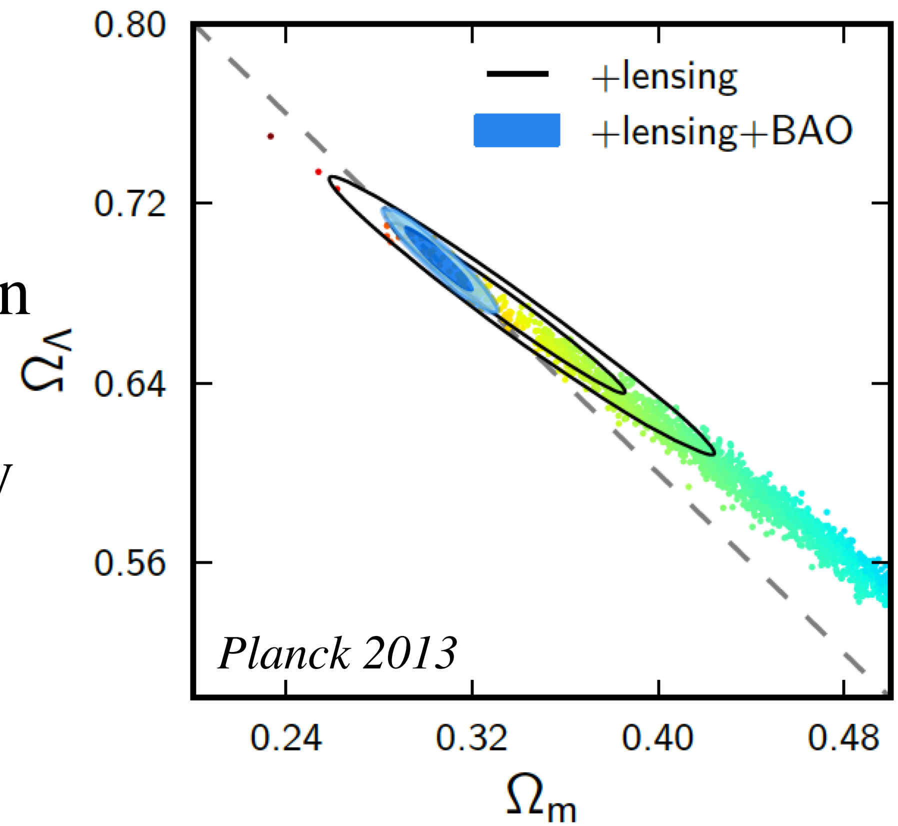
3-D DM Distribution From the COSMOS Survey (Massey et al. 2007)



20.3 The Dark Energy

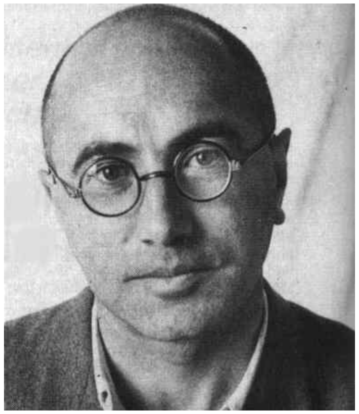
The Dark Energy

- The **dominant component** of the observed matter/energy density: $\Omega_{0,DE} \approx 0.7$
- Causes the accelerated expansion of the universe
- May affect the growth of density perturbations
- Effective only at cosmological distances

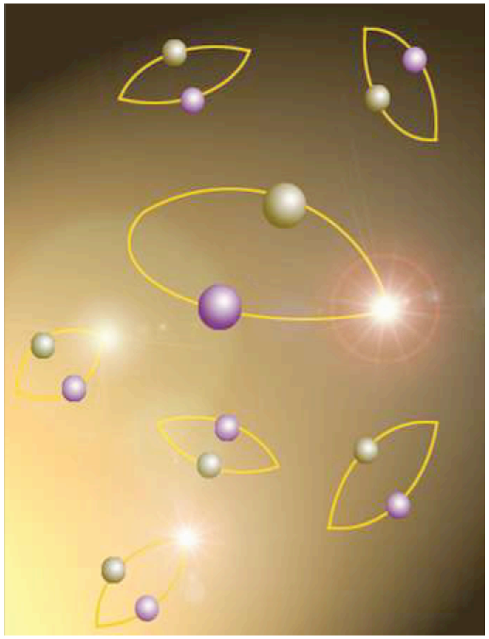


- Its physical nature is as yet ***unknown***; this may be the biggest outstanding problem in physics today
- ***Cosmological constant*** is just one special case; a more general possibility is called ***quintessence***

Cosmological Constant as a Quantum Field Phenomenon



- Proposed by Yakov Zeldovich (1967)
- A modern view of the physical vacuum is that it is not really empty - it is filled with virtual particle-antiparticle pairs, which annihilate within $\Delta t < \hbar/mc^2$, and their fluctuations give rise to a net energy density - a ground(?) state of the physical vacuum



- This is essentially the same mechanism proposed as the origin of the inflation
- But to really estimate the value of this vacuum energy density, we need a quantum theory of gravity, which we don't have yet
- Nevertheless, eager minds do try …

The Worst Scientific Prediction Ever

- A "natural" Planck system of units expresses everything as combination of fundamental physical constants; the Planck density is:

$$\rho_{Planck} = c^{5} / (\hbar G^{2}) = 5.15 \times 10^{+93} \text{ g cm}^{-3}$$

- The observed value is:

$$\rho_{vac} = \Omega_{\text{vac}} \rho_{crit} \approx 6.5 \times 10^{-30} \text{ g cm}^{-3}$$

Ooops! Off by 123 orders of magnitude …

- This is modestly called "the fine-tuning problem" (because it requires a cancellation to 1 part in 10^{123})
- The other "natural" value is zero
- So, lacking a proper theory, physicists just declared the cosmological constant to be zero, and went on…

Physical Origins of the Dark Energy

… are completely unknown at this time, and not for the lack of trying: there are literally thousands of papers about it, and more being published every day

- Many of the proposed models are based on one of the following:
  - Decay of some scalar field, similar to the inflation mechanism
  - Modified theories of gravity
  - Holographic models, connecting the vacuum energy density to the area of the event horizon and thermodynamics
  - Landscape or multiverse models that postulate the existence of $\sim 10^{500}$ separate universes, with different (random) values of the physical constants, Λ included
  - Models connecting DM and DE … ***etc., etc.***
- One measurement that might help eliminate some possibilities is a possible deviation (evolution) of the EOS parameter w

Cosmological Constant or Quintessence?

- **Cosmological constant:** energy density constant in time and spatially uniform
  - Corresponds to the energy density of the physical vacuum
  - A coincidence problem: why is $\Omega_\Lambda \sim \Omega_m$ just now?
- **Quintessence:** time dependent and possibly spatially inhomogeneous; e.g. scalar field rolling down a potential
- Both can be described in the equation of state formalism:

$$P = w\,\rho$$

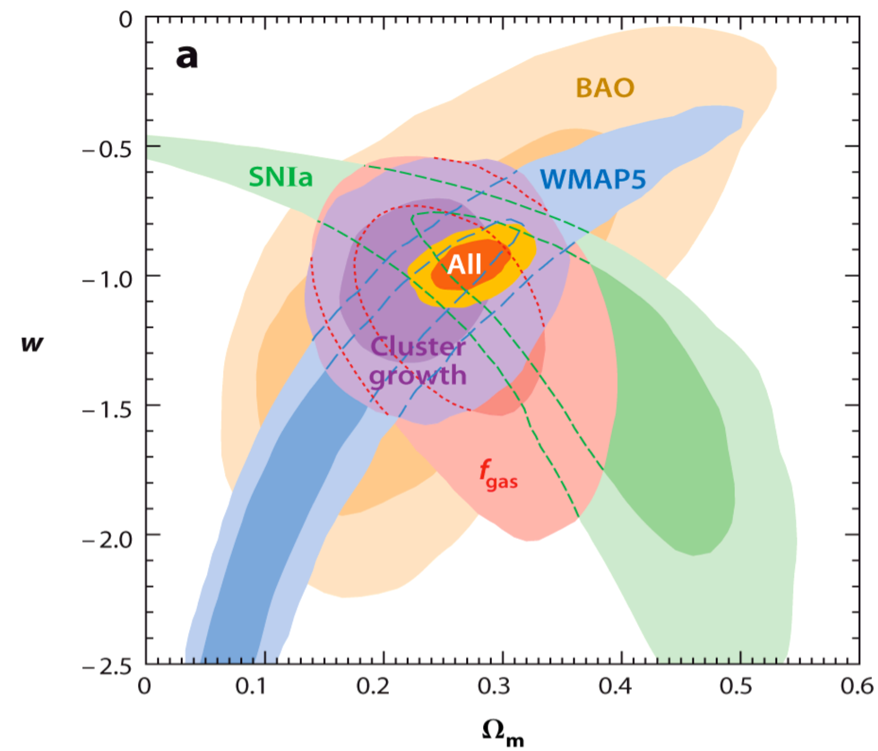
$$\rho \sim R^{-3(w+1)}$$

Cosmological constant: $w = const. = -1,\ \rho = const.$

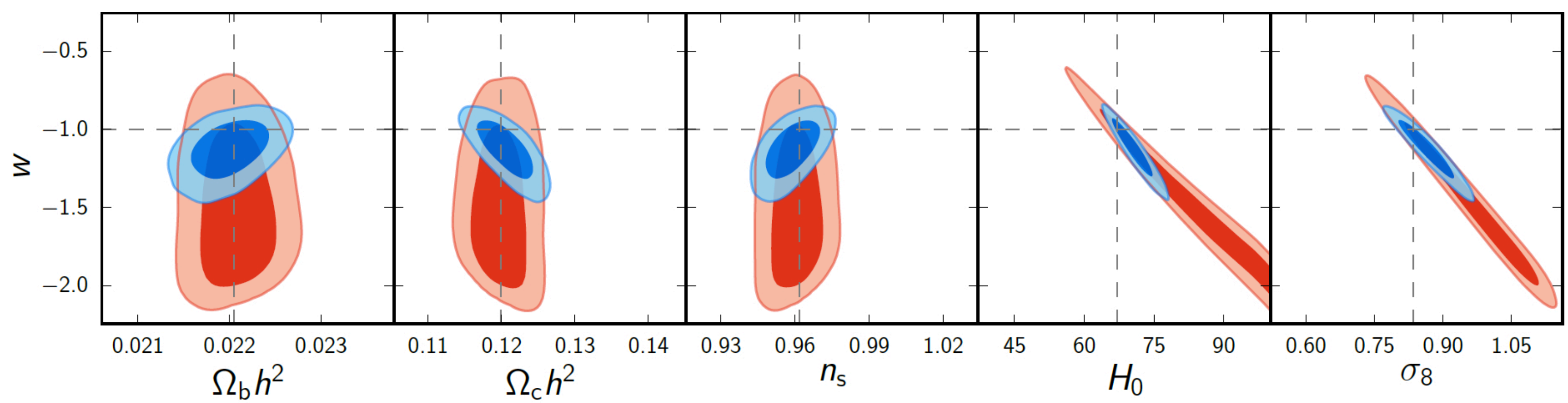
Quintessence: w can have other values and change in time

Observational Constraints on *w*

Strongly favor values of $w \sim -1$, i.e., cosmological constant. Some models can be excluded, but there is still room for $\rho_{vac} \neq const.$ models

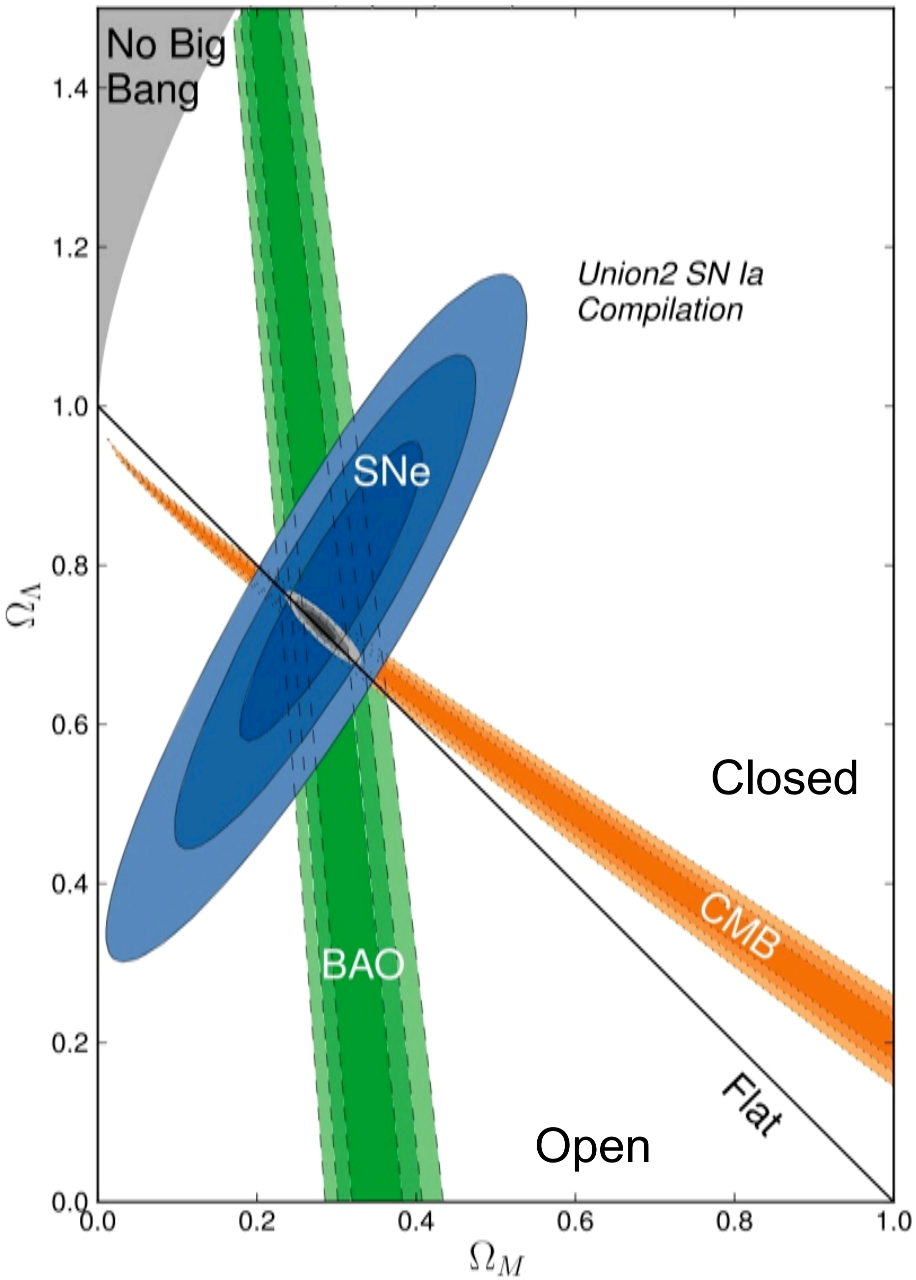


Planck + WMAP (red) + BAO (blue)



20.4 The Cosmic Concordance

The Cosmic Concordance



Supernovae alone

⇒ **Accelerating expansion**

⇒ **$\Lambda > 0$**

CMB alone

⇒ **Flat universe**

⇒ **$\Lambda > 0$**

Any two of SN, CMB, LSS

⇒ **Dark energy ~70%**

Also in agreement with the age estimates (globular clusters, nucleocosmochronology, white dwarfs)

Today's Best Estimates of the Cosmological Parameters

Age:

$t_0 = 13.82 \pm 0.05$ Gyr

Best fit CMB model - consistent with ages of oldest stars

Hubble constant:

$H_0 = 69$ km s^{-1} Mpc^{-1}

CMB + HST Key Project to measure Cepheid distances

Density of ordinary matter:

$\Omega_{baryon} = 0.045$

CMB + nucleosynthesis

Density of all forms of matter:

$\Omega_{matter} = 0.31$

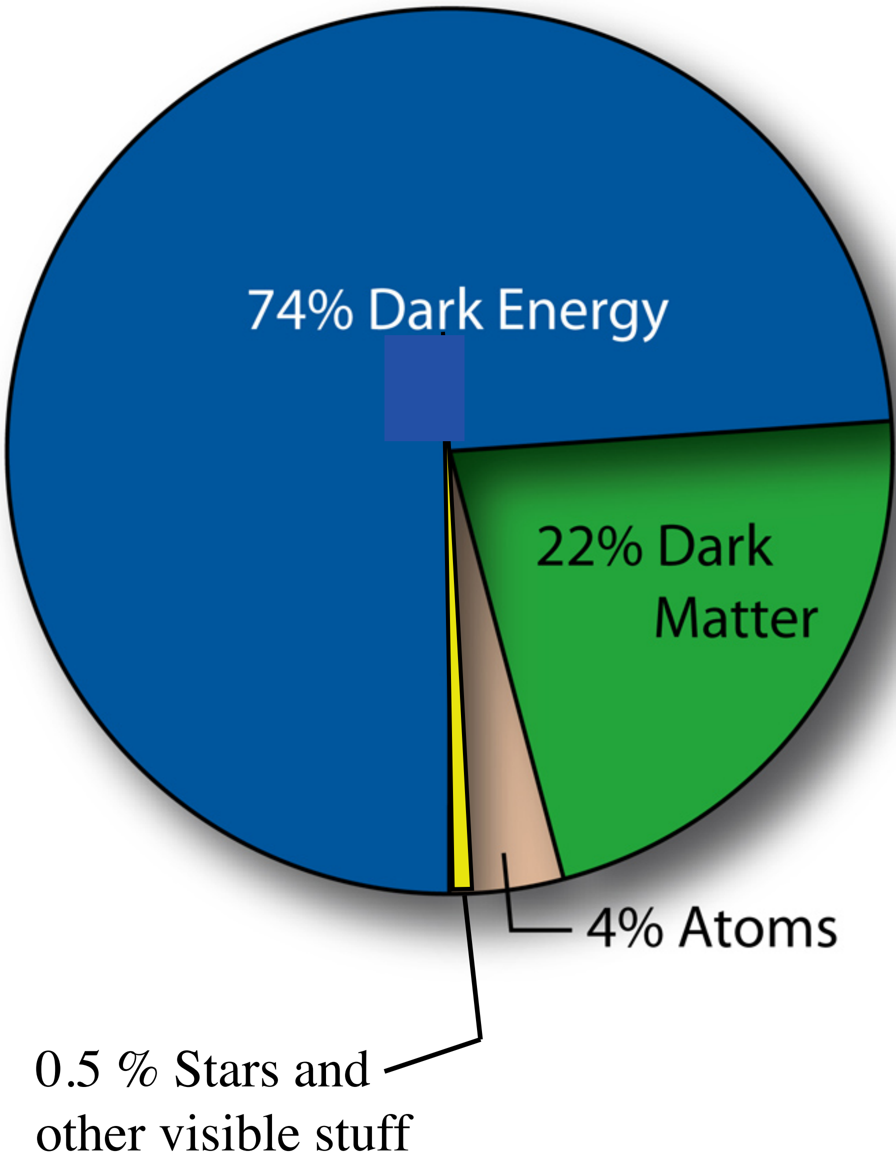
Cluster dark matter estimate
CMB power spectrum

Cosmological constant:

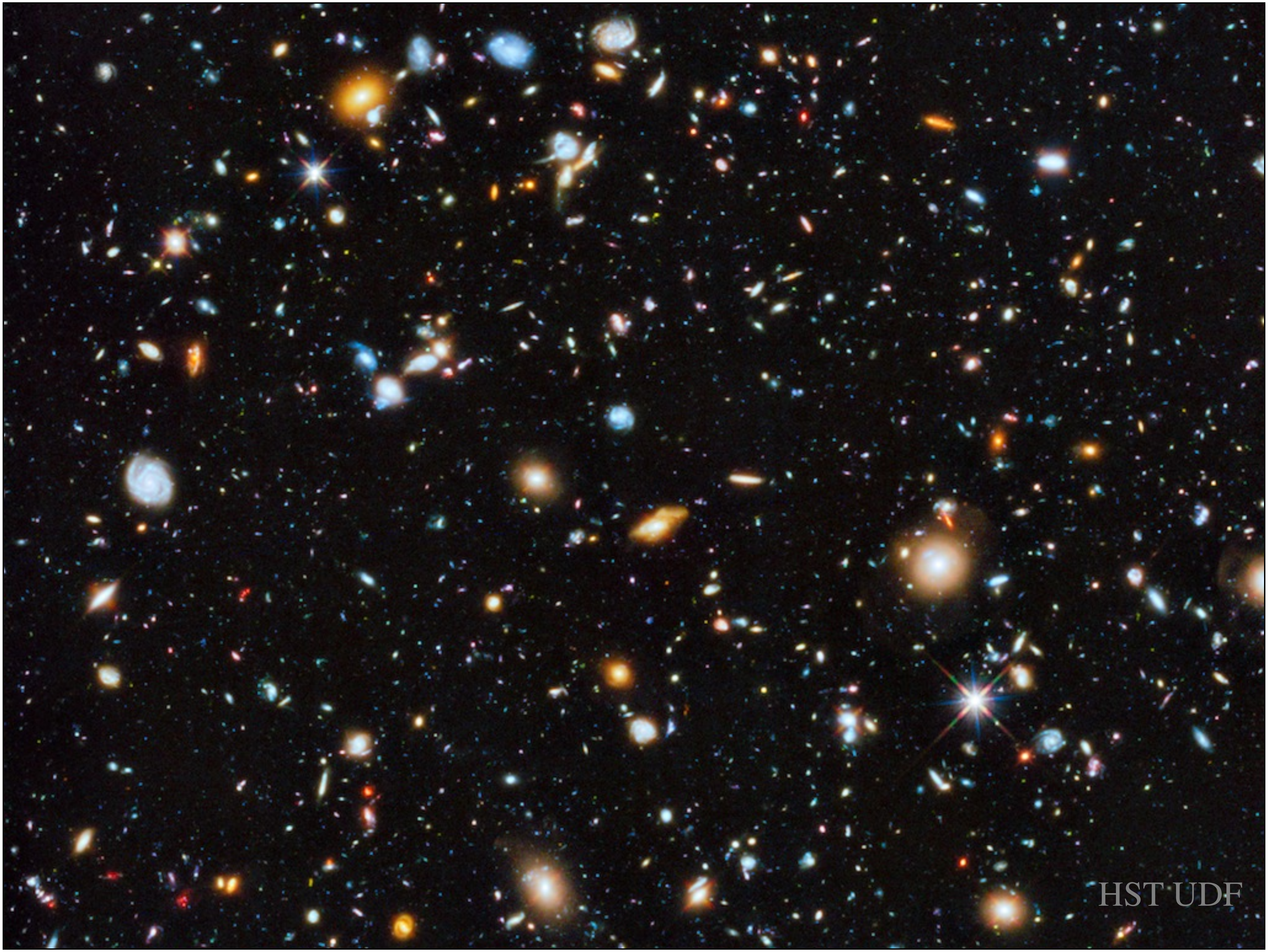
$\Omega_{\Lambda} = 0.69$

Supernova data, CMB evidence for a flat universe plus a low matter density

Contents of the Universe: Summary



- $\Omega_0 = 1.00 \pm 0.02$
- $\Omega_m \approx 0.27 \pm 20\%$
  - $\Omega_b \approx 0.045 \pm 10\%$
    - Includes $\Omega_{visible} \approx 0.005$
  - $\Omega_{non\text{-}b} \approx 0.22$
    - Includes $\Omega_\nu < 0.005$
  - $\Omega_{CMBR} \approx 0.0001$
- $\Omega_{de} \approx 0.73 \pm 10\%$
- The physical nature of the DE is currently completely unknown


HST UDF