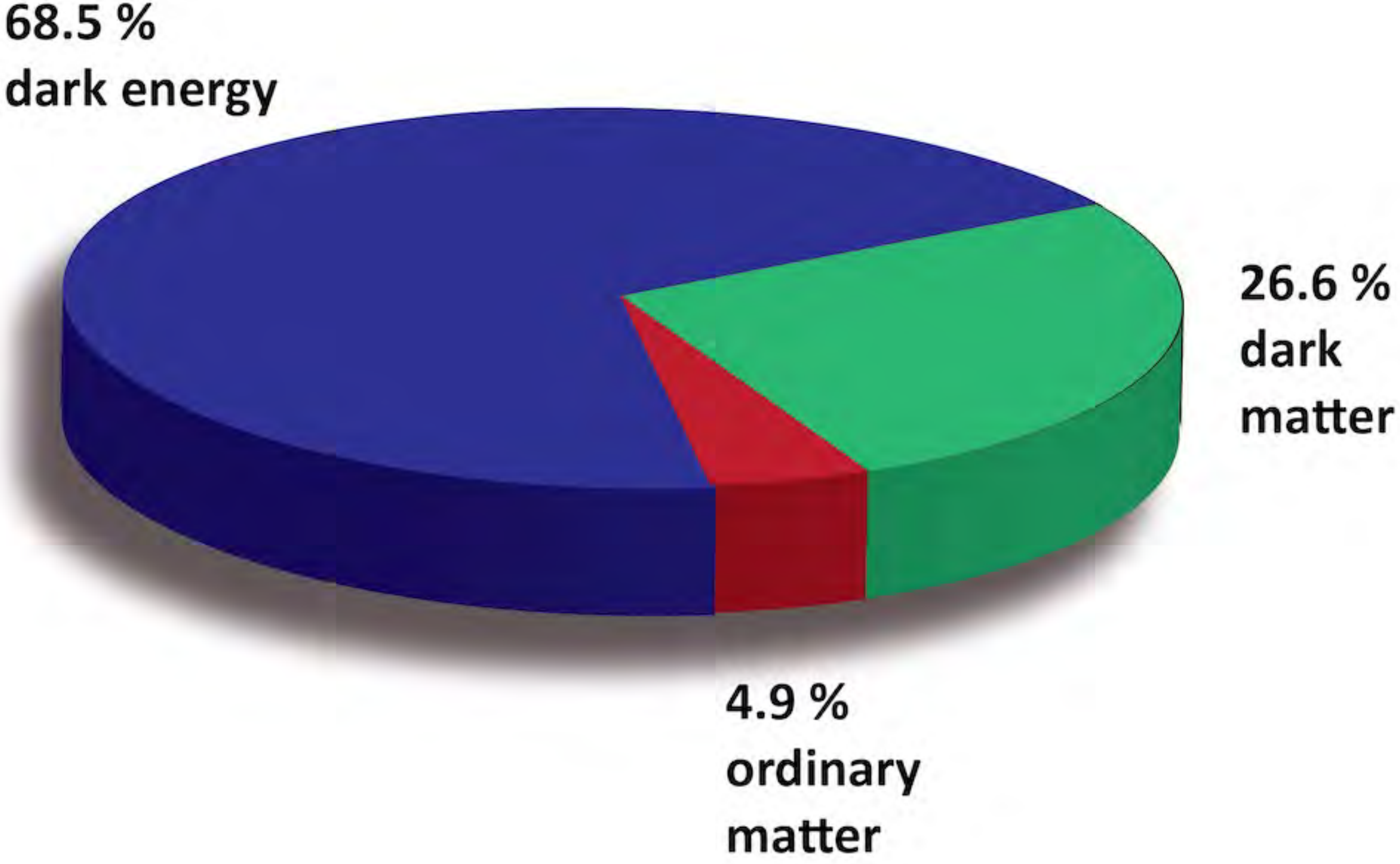
Ay 21

The Contents of the Universe



The Component Densities

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

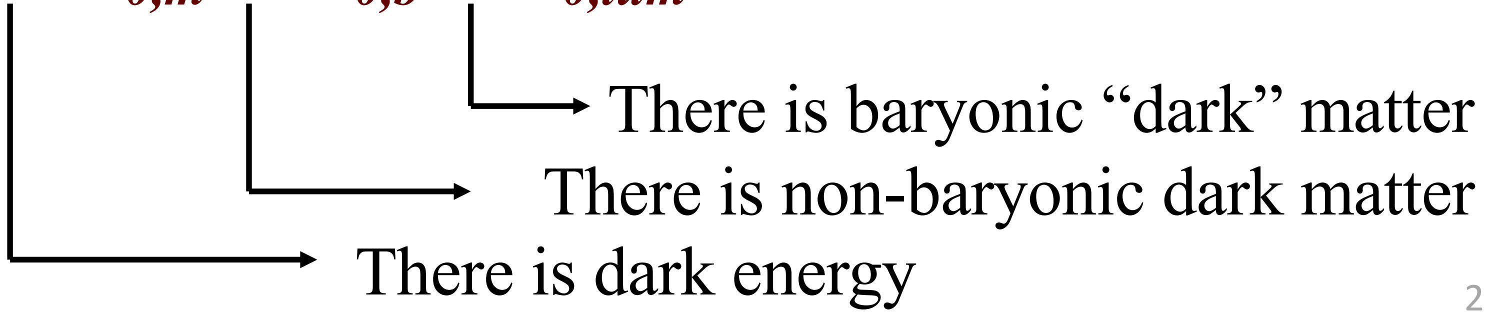
Total matter/energy density: $\Omega_{0,tot} \approx 1.00$ From CMB, and consistent with SNe, LSS

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



There is baryonic “dark” matter

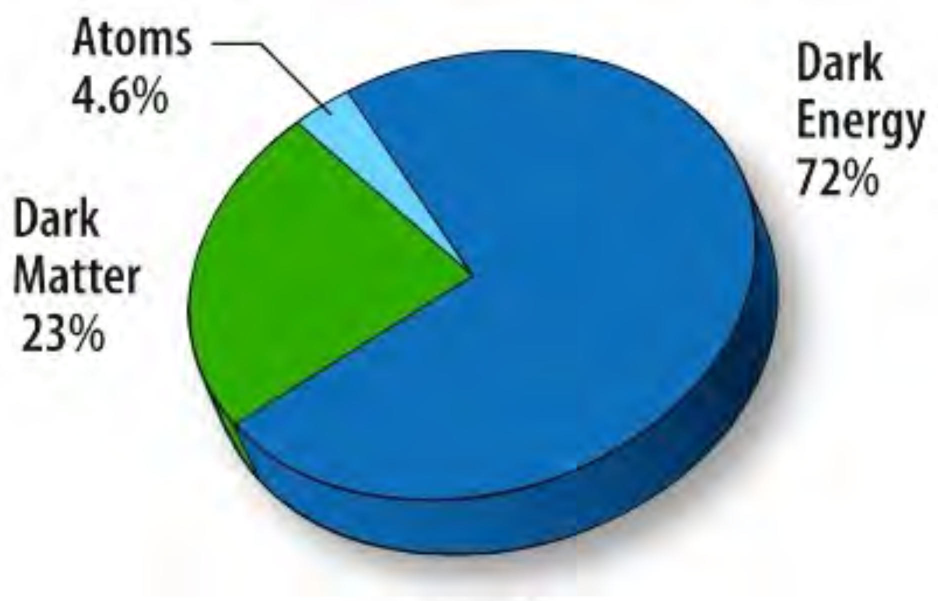
There is non-baryonic dark matter

There is dark energy

The Contents of the Universe Evolve

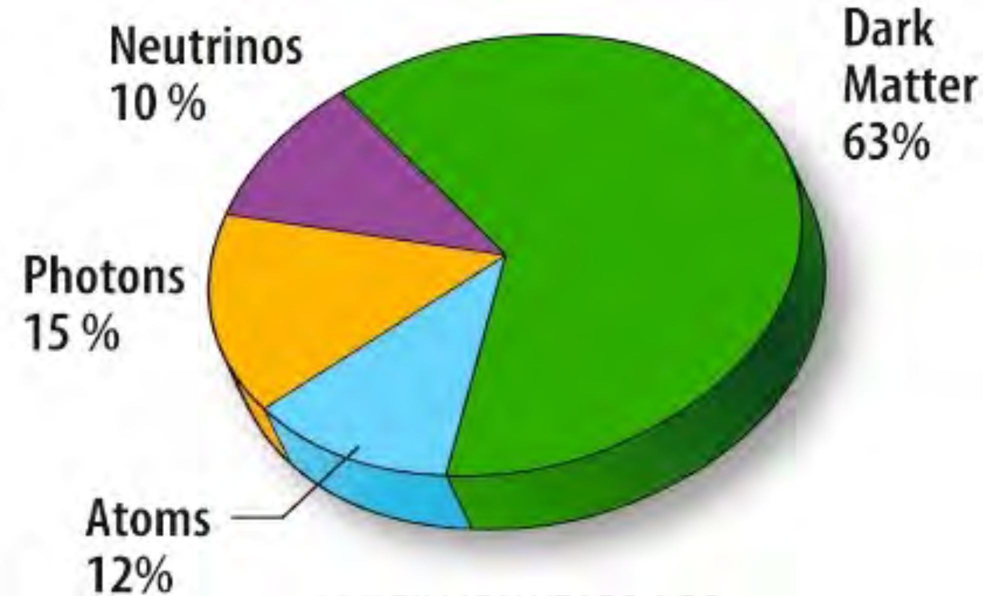
The relative abundances of different components change in time, due to their different EOS behavior:

Now



TODAY

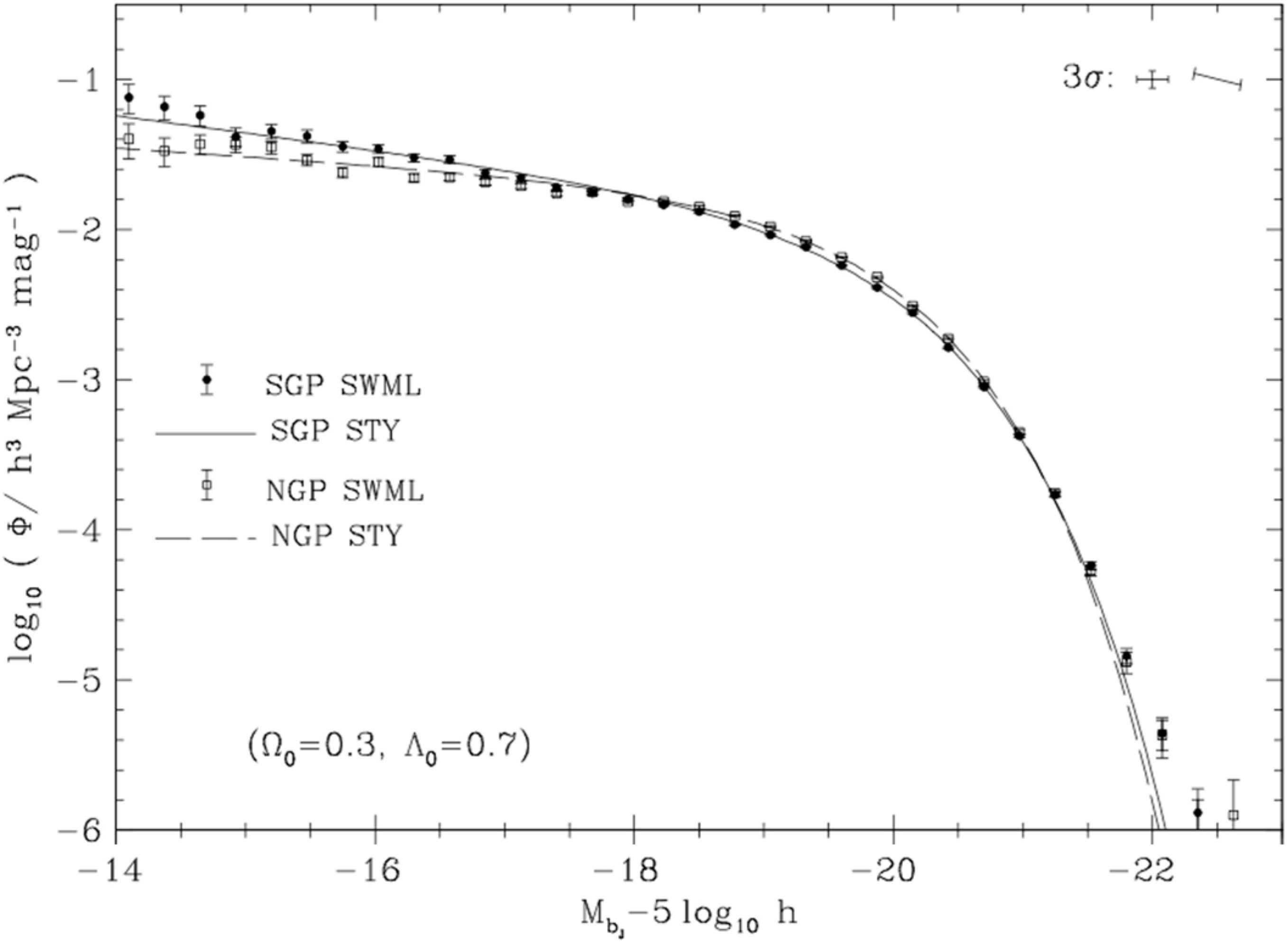
Recombination era



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Baryons also move gas <—> stars, DM particles may decay, DE may be in the form of a quintessence

The Luminosity Density



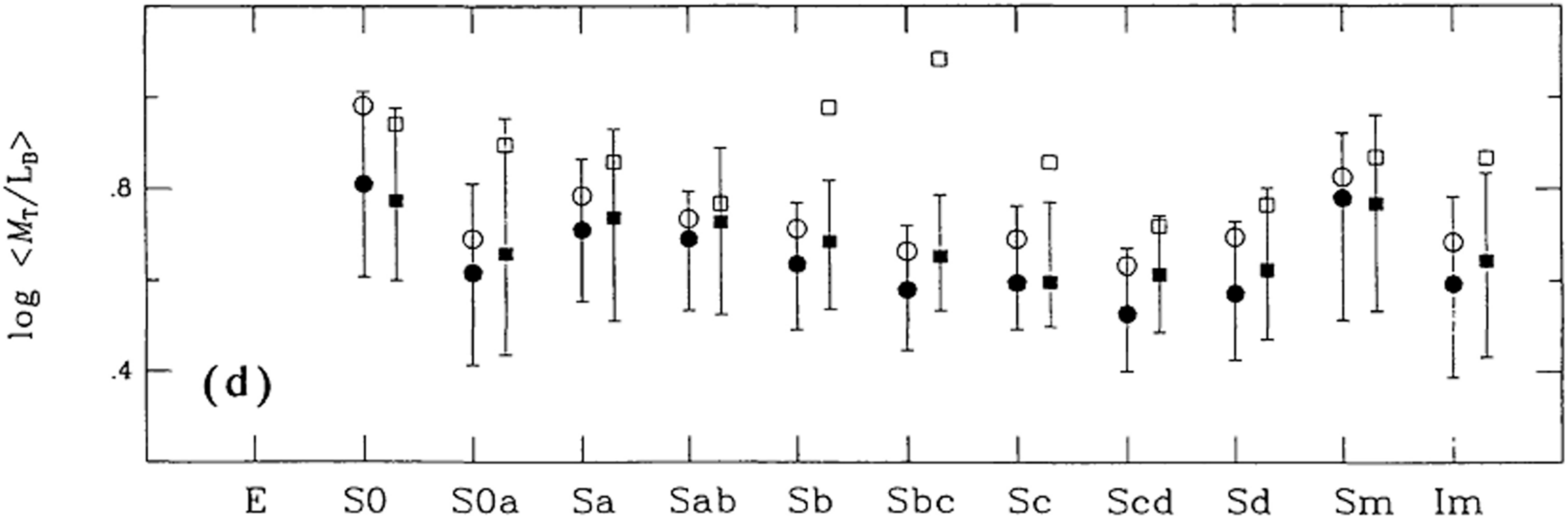
Integrate galaxy luminosity function (obtained from large redshift surveys) to obtain the mean luminosity density at $z \sim 0$

SDSS, *r* band: $\rho_L = (1.8 \pm 0.2) \times 10^8\ h_{70}\ L_\odot/\mathrm{Mpc}^3$

2dFGRS, *b* band: $\rho_L = (1.4 \pm 0.2) \times 10^8\ h_{70}\ L_\odot/\mathrm{Mpc}^3$

Luminosity To Stellar Mass

Typical (*M/L*) ratios in the *B* band along the Hubble sequence, within the luminous portions of galaxies, are $\sim$ 4 - 5 $M_\odot/L_\odot$



This includes some dark matter - for pure stellar populations, (*M/L*) ratios should be slightly lower.

Note that in the *B* band, they are very sensitive to any recent star formation, and to dust extinction.

The Local Mass Density of the Luminous Matter in Galaxies

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

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

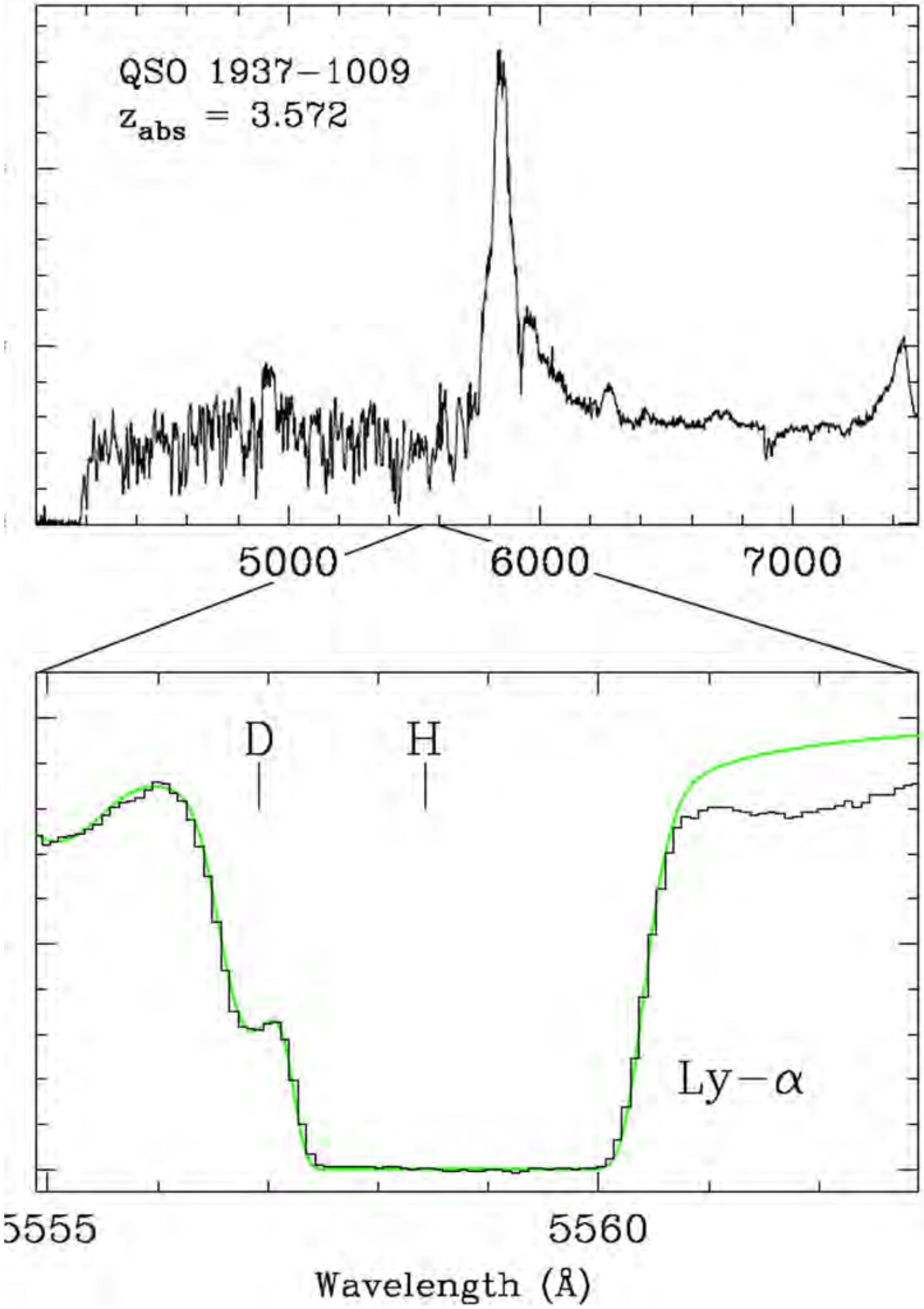
Recall that $\rho_{0,\mathrm{crit}} = 3H_0^2/(8\pi G) = 0.921 \times 10^{-29}\, h_{70}^2\ \mathrm{g\ cm}^{-3}$

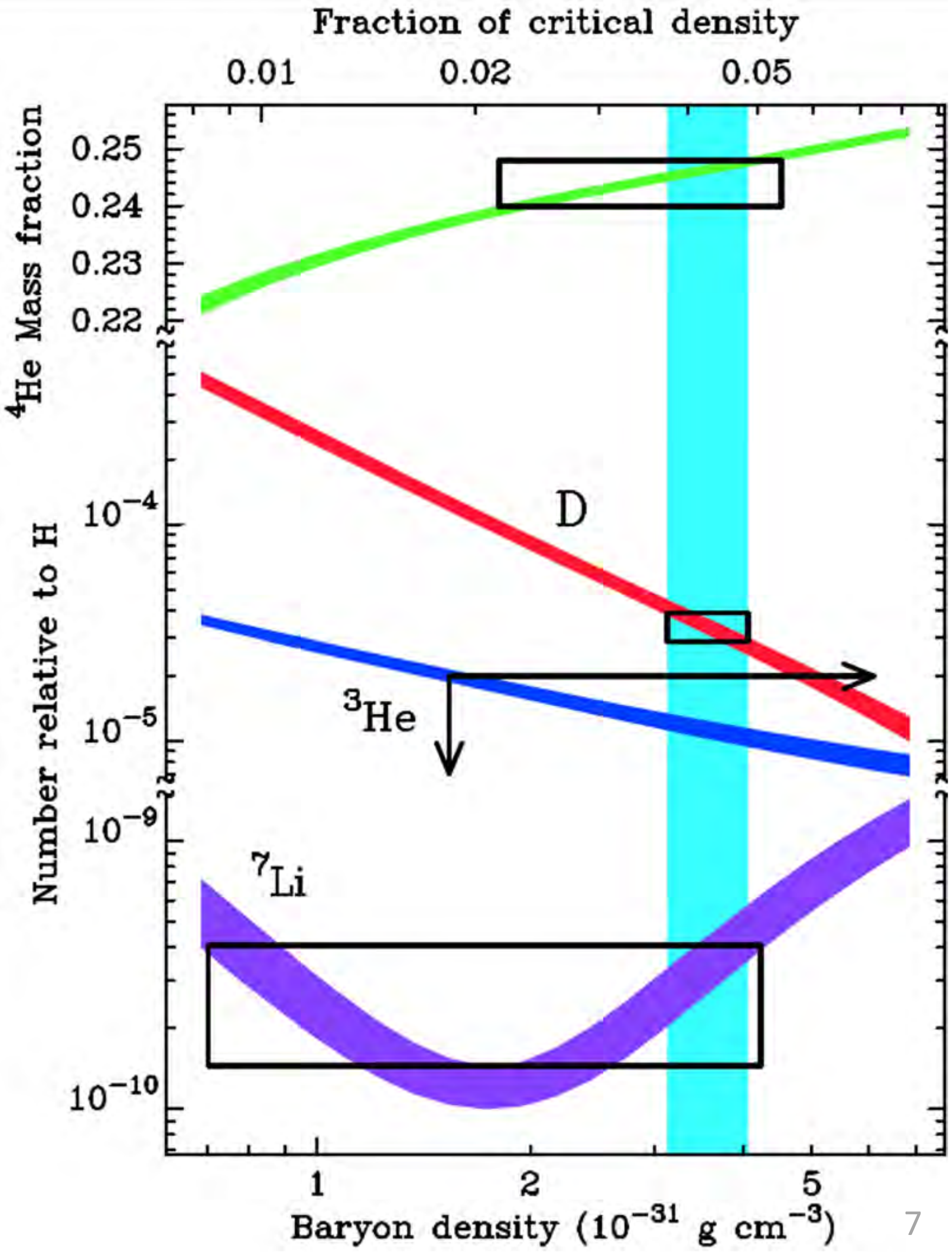
Thus, $\underline{\Omega_{0,lum} \approx (0.0051 \pm 0.0015)\, h_{70}^{-1}}$

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

(Interestingly, this may be about the same as the contribution from the massive cosmological neutrinos…)

Baryon Density From Cosmic Nucleosynthesis





The Total Baryon Density

It is measured in *two completely independent ways*:

1. The cosmic nucleosynthesis:

- It occurs in the first few minutes after the Big Bang
- Reaction rates are ~ ρ_{baryon}^2, so the residual 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), low metallicity starforming dwarfs, halo stars, etc.

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

2. Analysis of CMB fluctuations:

Results give: $\Omega_{baryons} h^2 = 0.024 \pm 0.001$

Thus, $\boldsymbol{\Omega_{0,b}} \approx (0.045 \pm 0.002)\ h_{70}^{-2}$

The “Missing” Baryons

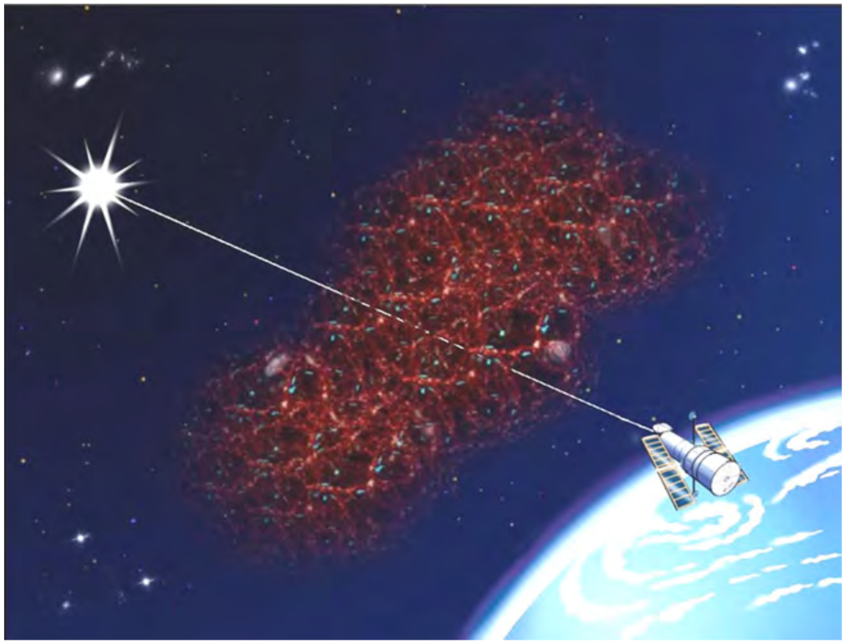
So, where are 90% of baryons hiding? Some possibilities:

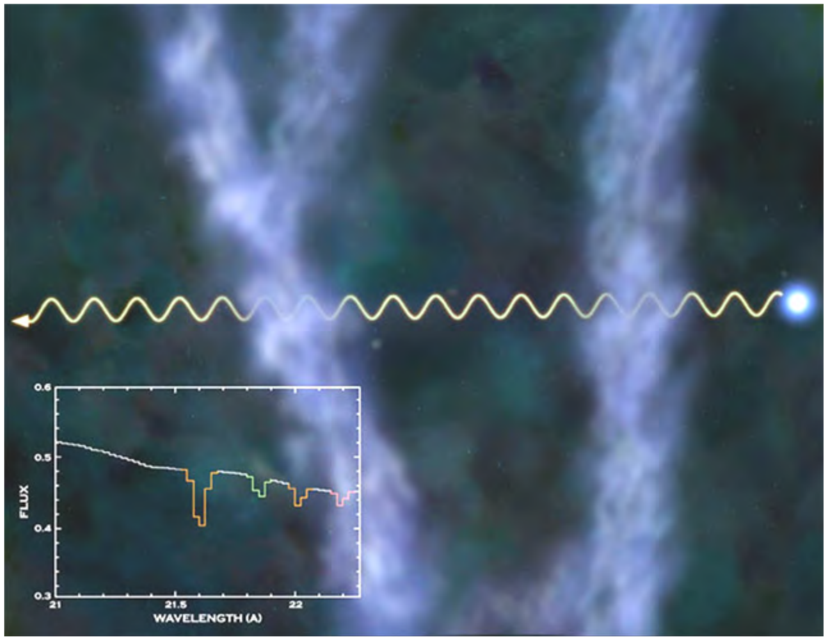
- **MAssive Compact Halo Objects (MACHOs)**
  - Very low mass stars, white dwarfs, neutron stars, black holes, brown dwarfs, interstellar comets, slushballs…
- **Cold molecular (H_2) gas clouds**
  - Would have to be compact, dense, low volume fill factor
  - Very hard to detect!
- **Warm/hot gas**, bound to galaxy groups

  The right answer
  - Leftover gas from IGM, never collapsed to galaxies
  - Virial temperatures ~ 10^5 - 10^6 K, corresponding to the velocity dispersions ~ 300 km/s
  - Very hard to detect! (ISM opaque to FUV/soft-X)
  - But it can be detected ***in absorption***

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 Non-Baryonic Dark Matter

Discovered by Zwicky in 1937, by comparing the visible mass in galaxies in the Coma cluster (estimated $M_* \sim 10^{13}$ $M_\odot$), with the virial mass estimates ($M_{vir} \sim 5 \times 10^{14}$ $M_\odot$)

Confirmed by the modern measurements of galaxy dynamics, X-ray gas analysis, and masses derived from gravitational lensing

Virial Masses of Clusters:

Virial Theorem for a test particle (a galaxy, or a proton), moving in a cluster potential well:

$$E_k = E_p / 2 \quad \rightarrow \quad m_g \sigma^2 / 2 = G\, m_g\, M_{cl} / (2\, R_{cl})$$

where σ is the velocity dispersion

Thus the cluster mass is: $M_{cl} = \sigma^2 R_{cl} / G$

Typical values for clusters:

$\sigma \sim 500 - 1500$ km/s

$R_{cl} \sim 3 - 5$ Mpc

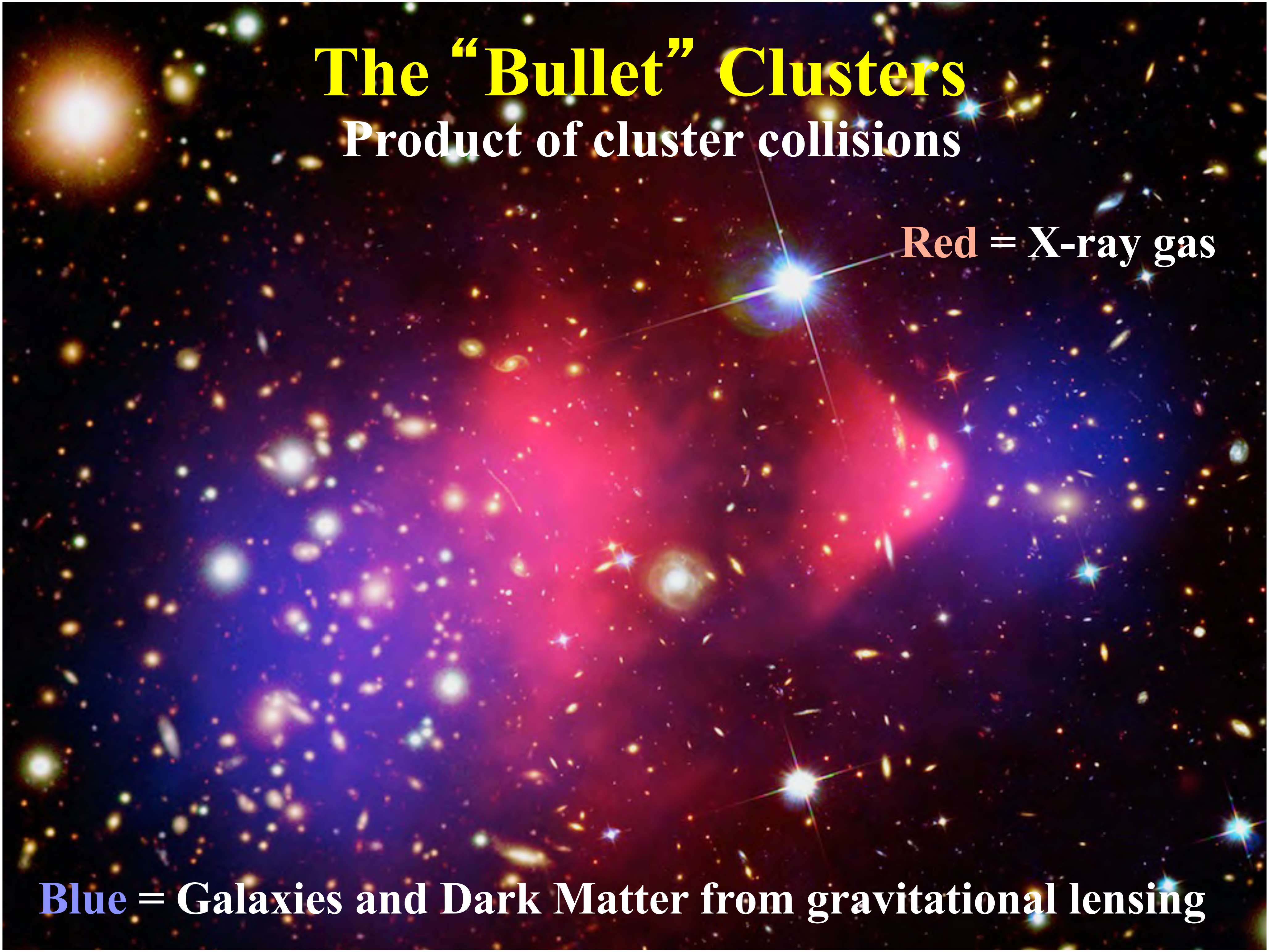
Thus, typical cluster masses are $\boldsymbol{M_{cl} \sim 10^{14} - 10^{15}\, M_\odot}$

The typical cluster luminosities (~ 100 - 1000 galaxies) are $L_{cl} \sim 10^{12}\, L_\odot$, and thus $(M/L) \sim 200 - 500$ in solar units

➞ ***Lots of dark matter!***

The “Bullet” Clusters

Product of cluster collisions

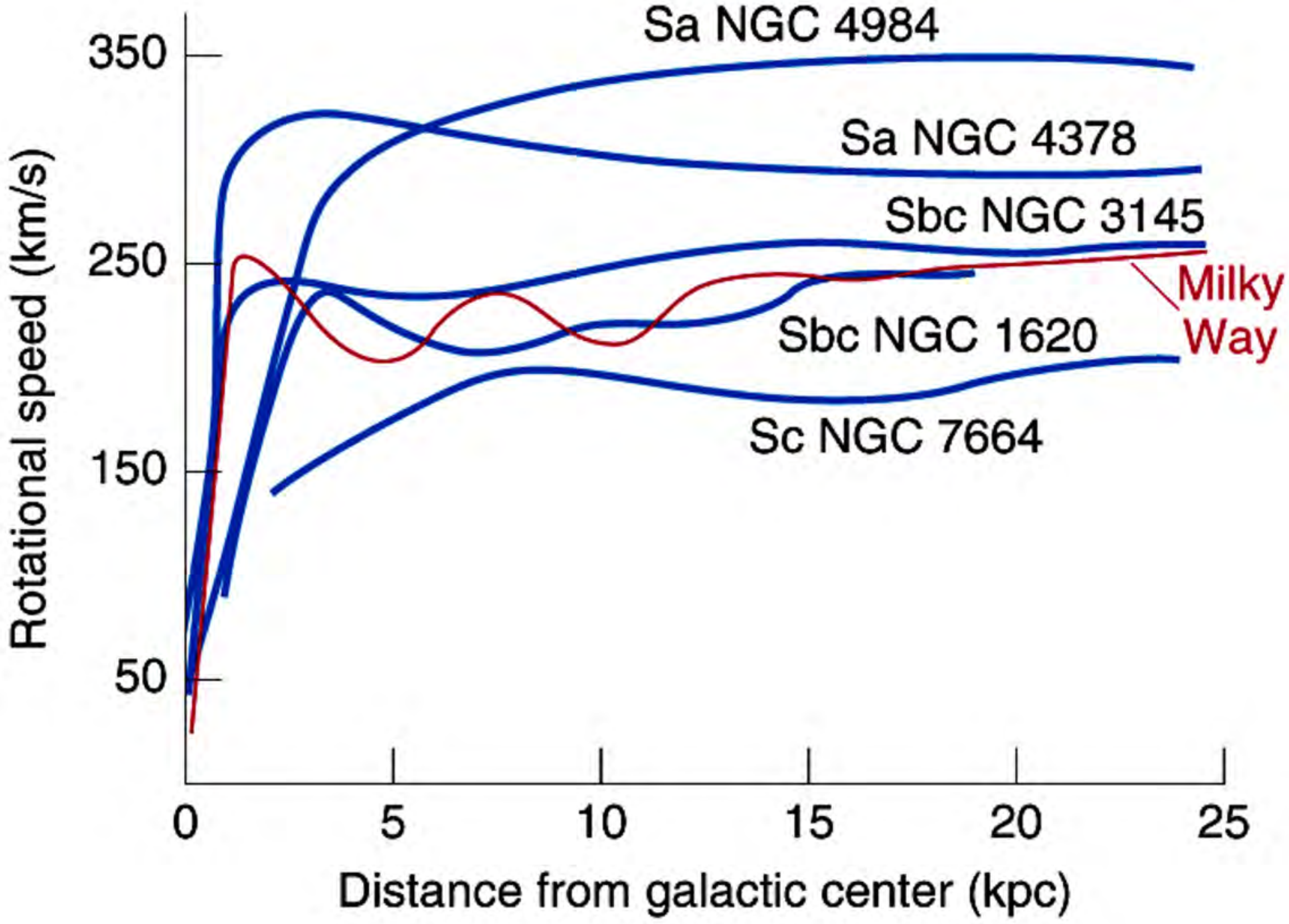


Red = X-ray gas

Blue = Galaxies and Dark Matter from gravitational lensing

Flat Rotation Curves of Disk Galaxies:

The Other Key Piece of Evidence for the Existence of Dark Matter



Noted early by Jan Oort and others, but really got attention in the 1970’s, due to the work by Vera Rubin, Kenneth Ford, Ken Freeman, Mort Roberts, and others

Interpreting the Rotation Curve

Motions of the stars and gas in the disk of a spiral galaxy are approximately circular (V_R and $V_Z << V_R$).

Define the circular velocity at radius r in the galaxy as $V(r)$. Acceleration of the star moving in a circular orbit must be balanced by the gravitational force:

$$\frac{V^2(r)}{r} = -F_r(r)$$

To calculate $F_r(r)$, must in principle sum up gravitational force from bulge, disk and halo. If the mass enclosed within radius r is $M(r)$, gravitational force is:

$$F_r = -\frac{GM(r)}{r^2}$$

Thus, from observed $V(r)$, we can infer $M(r)$

Mass Distribution and Rotation Curve

If the average density ρ within the radius r, then the enclosed mass is:

$$M(r) = \frac{4}{3}\pi r^3 \rho$$

The implied rotation curve is:

$$V(r) = \sqrt{\frac{4\pi G\rho}{3}r}$$

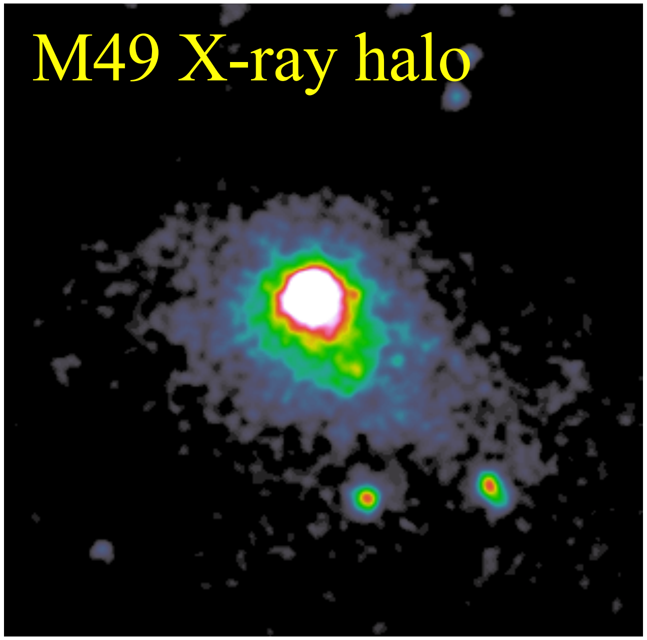
Since $V(r) \sim \rho^{-1/2}$, a flat rotation curve $V(r) = const.$ then implies $\boldsymbol{\rho(r) \sim r^{-2}}$

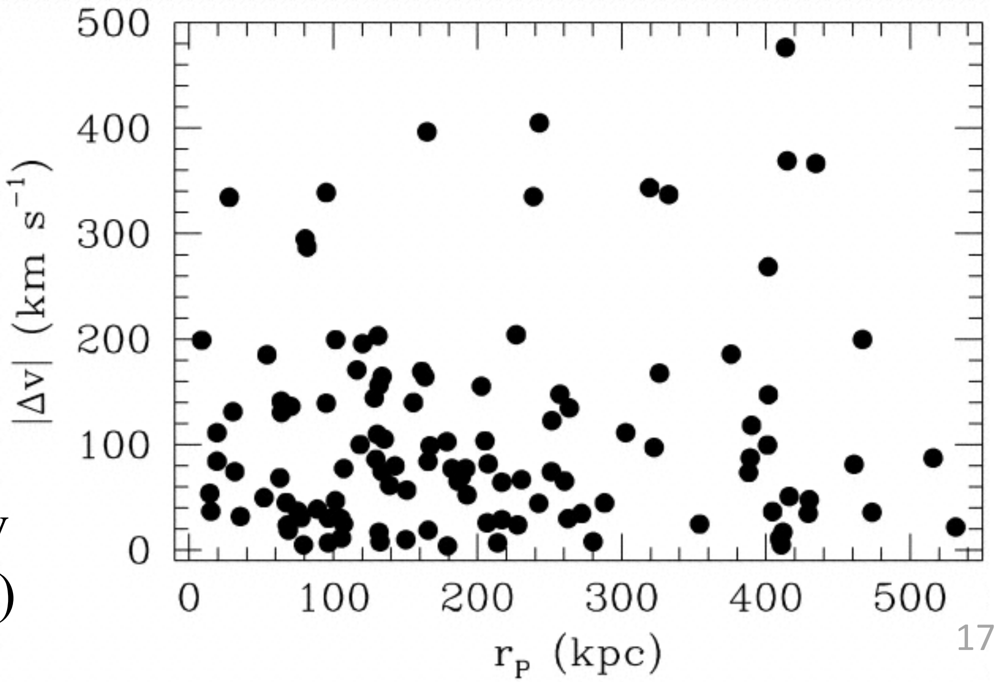
This density profile is called a ***singular isothermal sphere***, since it predicts an infinite density at $r = 0$. But the density in the central parts of galaxies is finite, and the rotation curves drops in value.

Note that the *enclosed mass increases linearly with radius*, $M(r) \sim r$! (Where does it stop?)

Dark Matter in Elliptical Galaxies

- Similar to spirals, but using X-ray gas, planetary nebulae, globular clusters, or companion galaxies as test particles to map the velocity field at large radii
- X-ray gas gives the strongest evidence for DM in ellipticals, but mass density in the visible parts is dominated by baryons
- Most of the motions are random rather than circular, so one can speak of a *flat velocity dispersion curve*



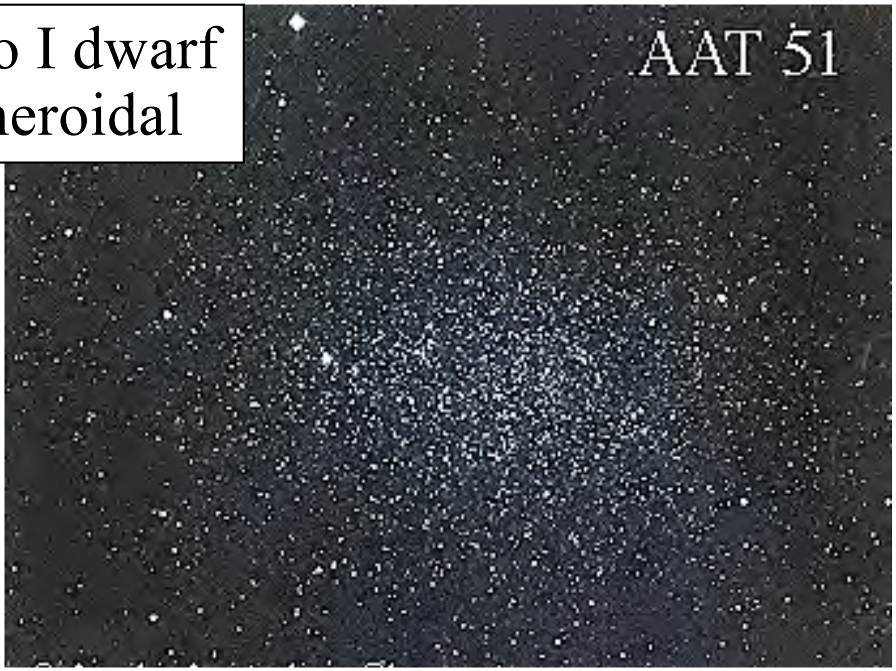


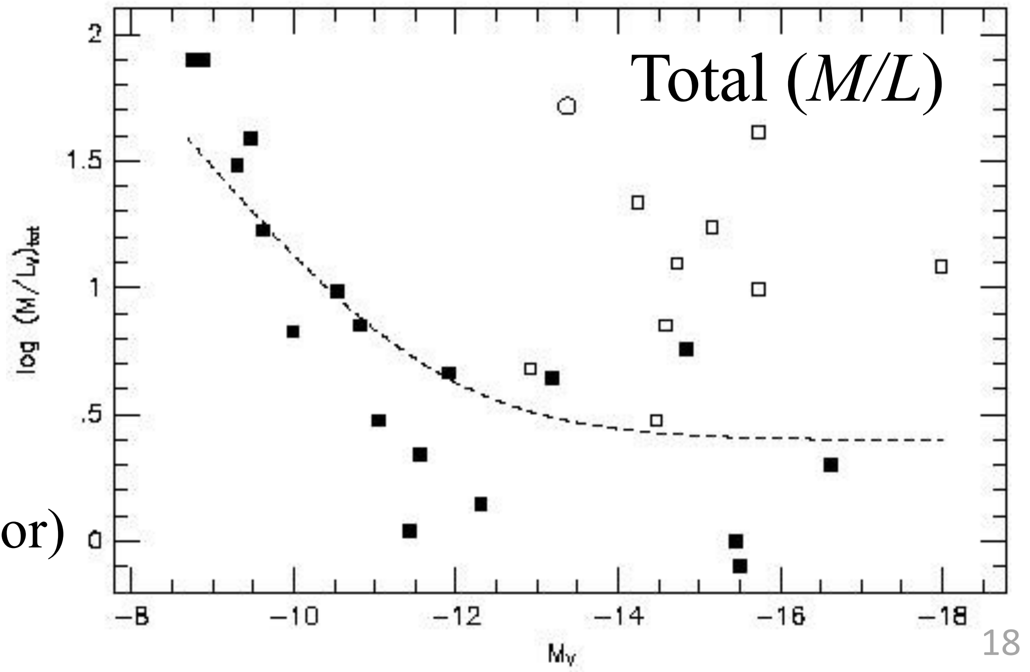
Relative velocities of dwarf galaxy companions of E’s (Zaritsky et al.)

Dark Matter in Dwarf Galaxies

- Kinematics of dwarf galaxies suggests copious amounts of DM, especially in the lowest luminosity systems (the smallest systems are the darkest), with (*M/L*) ratios reaching ~ 100!
- One theory is that baryons have been expelled by galactic winds in their early star forming stages, while the DM remained

Leo I dwarf spheroidal



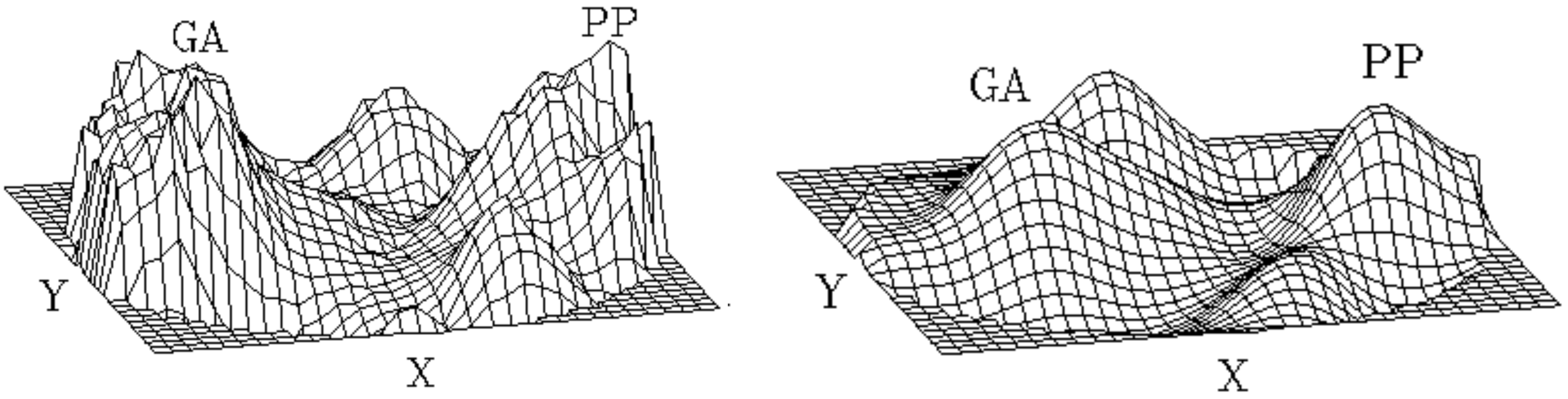


Filled squares = dSph (gas poor)
Open squares= dIrr (gas rich)

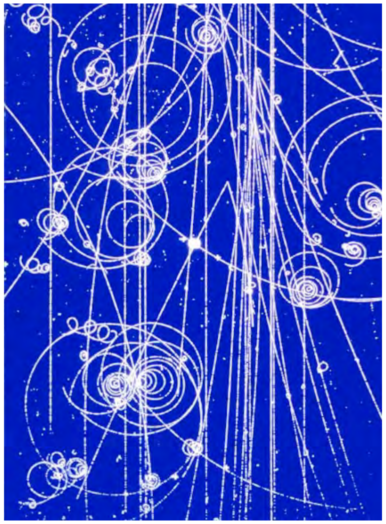
Mass Density From Peculiar Velocities

- Assume that the measured galaxy peculiar velocities are generated from nearby large mass concentrations; derive the implied gravitational potential, which implies the mass distribution
- Compare the observed velocity field to a density field (derived from a galaxy redshift survey) and derive the matter density distribution
- Most results favor $\Omega_m < 0.3$

Density contours from POTENT (peculiar velocity analysis) and IRAS redshift survey



The Physical Nature of the DM



We know that ***some of it*** is regular matter, H and He atoms and ions, just hidden; and some is in massive cosmological neutrinos

But we also know that ***most of it*** is composed of some as yet unknown type of particles, or represents some new physics

The proposed possible constituents range from unknown ultra-light particles, to massive black holes and cosmic strings, but the favorite DM particles are WIMPs or axions

These particles could be detected in laboratory experiments, or with accelerators like the LHC

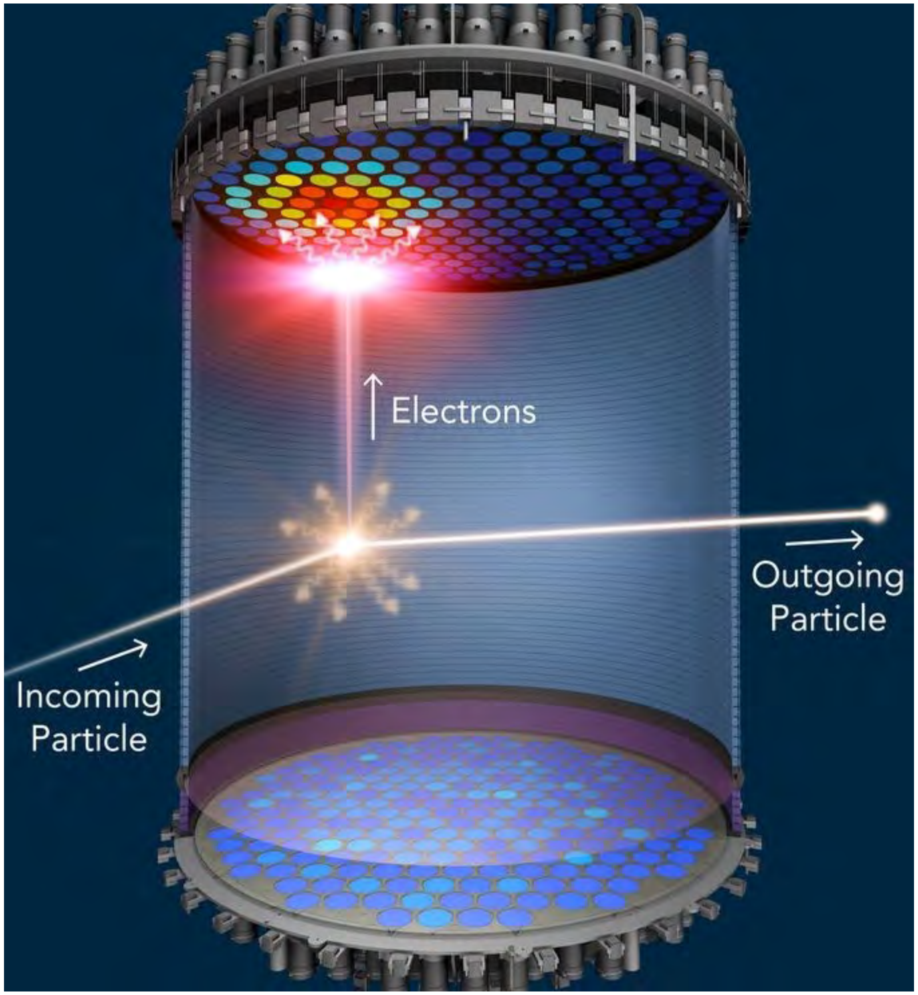
Non-Baryonic DM Candidates

- **Massive neutrinos**

  The *only* DM constituent actually known to exist!

  - Known to exist and to have mass, but how much?
- **Weakly Interacting Massive Particles (WIMPs)**
  - Not known to exist, but possible
  - A generic category, e.g., the neutralino = the least massive SUSY particle; also inlcude gravitinos, photinos, and higgsino …
  - Thermal relics from the Big Bang
  - Possible masses > 10 GeV
  - WIMPzillas: 10^{10} × mass of WIMPS, would have been created just after the Big Bang, and might explain ultra-high-energy cosmic rays
- **Axions**
  - Predicted in some versions of quantum chromodynamics
  - Originate in non-thermal processes
  - Could interact electromagnetically
  - Possible masses 10^{-12} eV to 1 MeV, maybe higher
- **Many (many!) other speculative possibilities …**

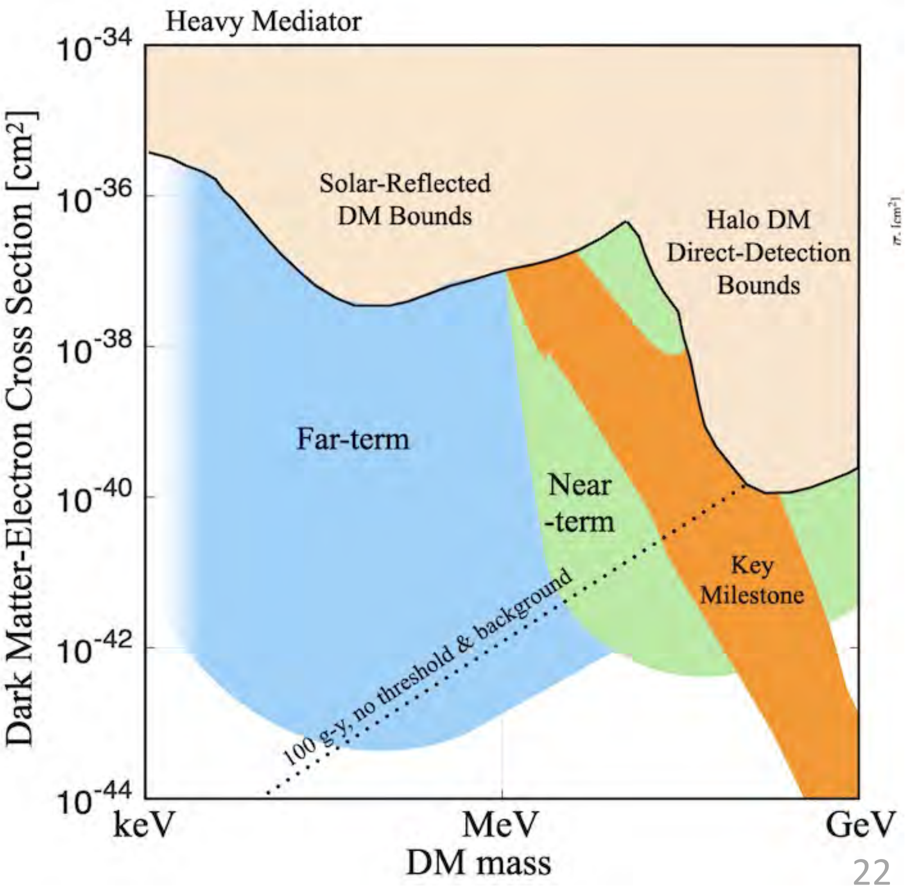
Laboratory Detection of DM Particles?



Now pursued by many groups. Usually involves inelastic scattering of a DM particle in an ultracold crystal or liquid, and measurement of the deposited kinetic energy

The detectors are in deep underground mines, to shield from the cosmic rays

An example of upper limits →



The Types of Non-Baryonic Dark Matter

- DM dominates the density field and thus *governs the structure formation* in the universe
- **Hot (HDM):** matter is relativistic, so low-mass particles such as neutrinos
  - *Their streaming erases the small-scale density fluctuations*, so big structures form first, then later fragment. This is "top-down" structure formation
- **Cold (CDM):** matter moves more slowly; includes exotic as yet unknown particles such as axions, WIMPs, etc.
  - *Density fluctuations at all scales survive*. Small fluctuations collapse first, then larger ones (pulling in the littler ones along the way). This is "bottom-up" structure formation and this is the best match to what we observe
- There is probably a little bit of HDM and a lot of CDM

Is There Really a Dark Matter …
… Or is Newtonian Gravity Wrong?

- Milgrom (1983) proposed a modification to Newtonian gravity, Modified Newtonian Dynamics (MOND), in which

$$F = m\,\mu\,(a/a_0)\,a$$

where $\mu\,(x \gg 1) = 1$ (normal gravity), and $\mu\,(x \ll 1) \sim x$, so MOND would only kick in at low accelerations (what we generally see in galaxy dynamics) $a_0 \sim 10^{-8}$ cm/s^2

- For $a \ll a_0$, $a = (a_0\, g_N)^{1/2}$ there is more acceleration than expected from Newtonian gravity at slow acceleration scales
- MOND *may* explain flat rotation curves and the Tully-Fisher relation, but can't explain extra mass in the cores of big clusters (acceleration scales too big); probably not dwarf galaxies
- It is an *ad hoc* model - no clear physical motivation other than to get rid of the DM - and no other testable predictions
- It could be made consistent with GR, but it is contrived

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:

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

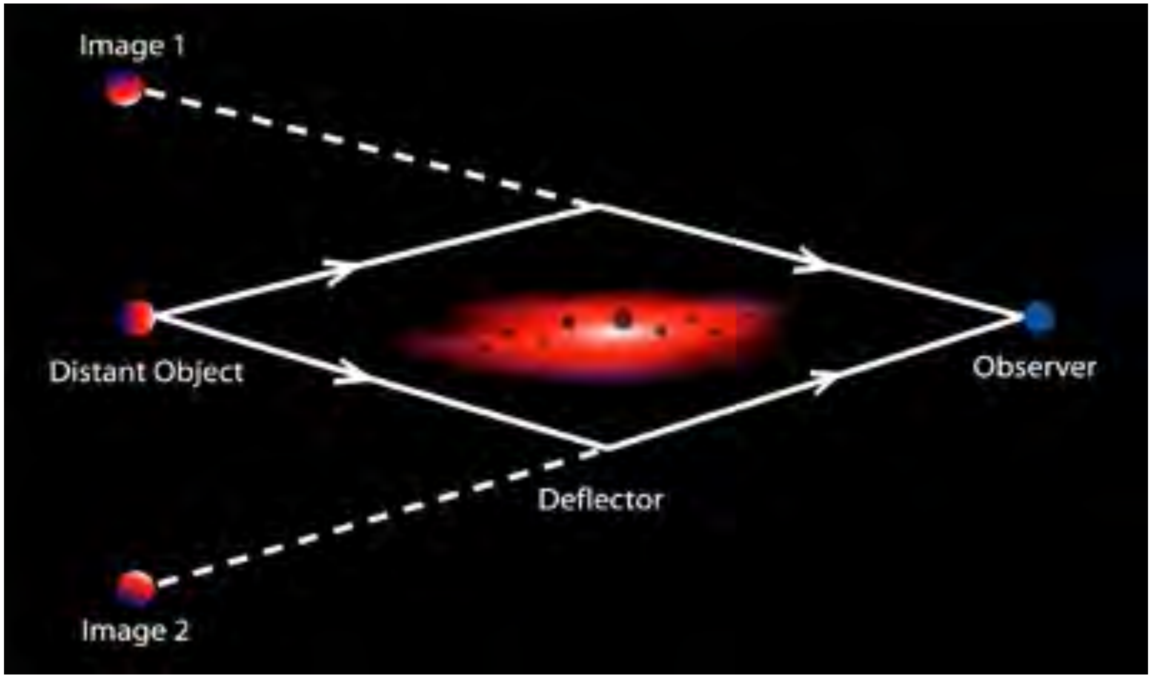
…where R_s is the Schwarzschild radius of a body of mass M, and b is the impact parameter. This formula is valid if $b >> R_s$:

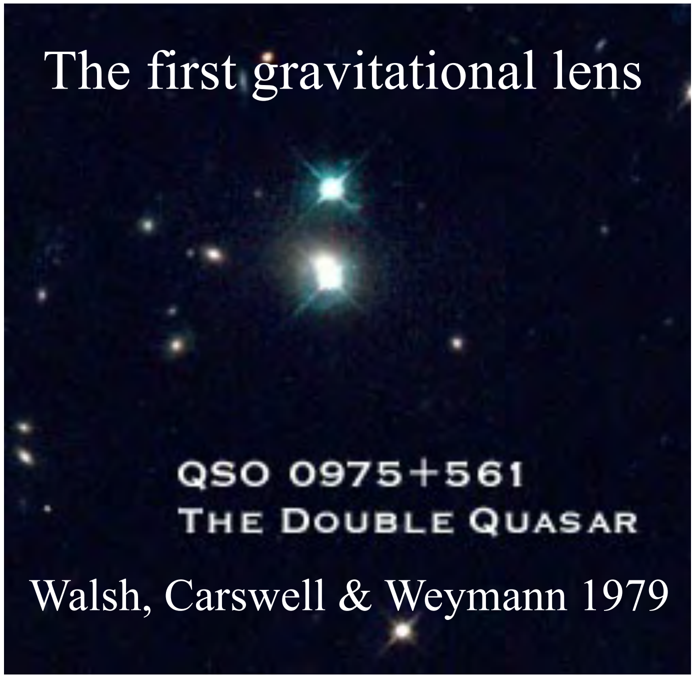
- Not valid very close to a black hole or neutron star
- Valid everywhere else
- Implies that deflection angle a will be small
  e.g., for the stars near the Solar limb, ~ 2 arcsec

Gravitational Lensing:

Mapping the Distribution of the Dark Matter

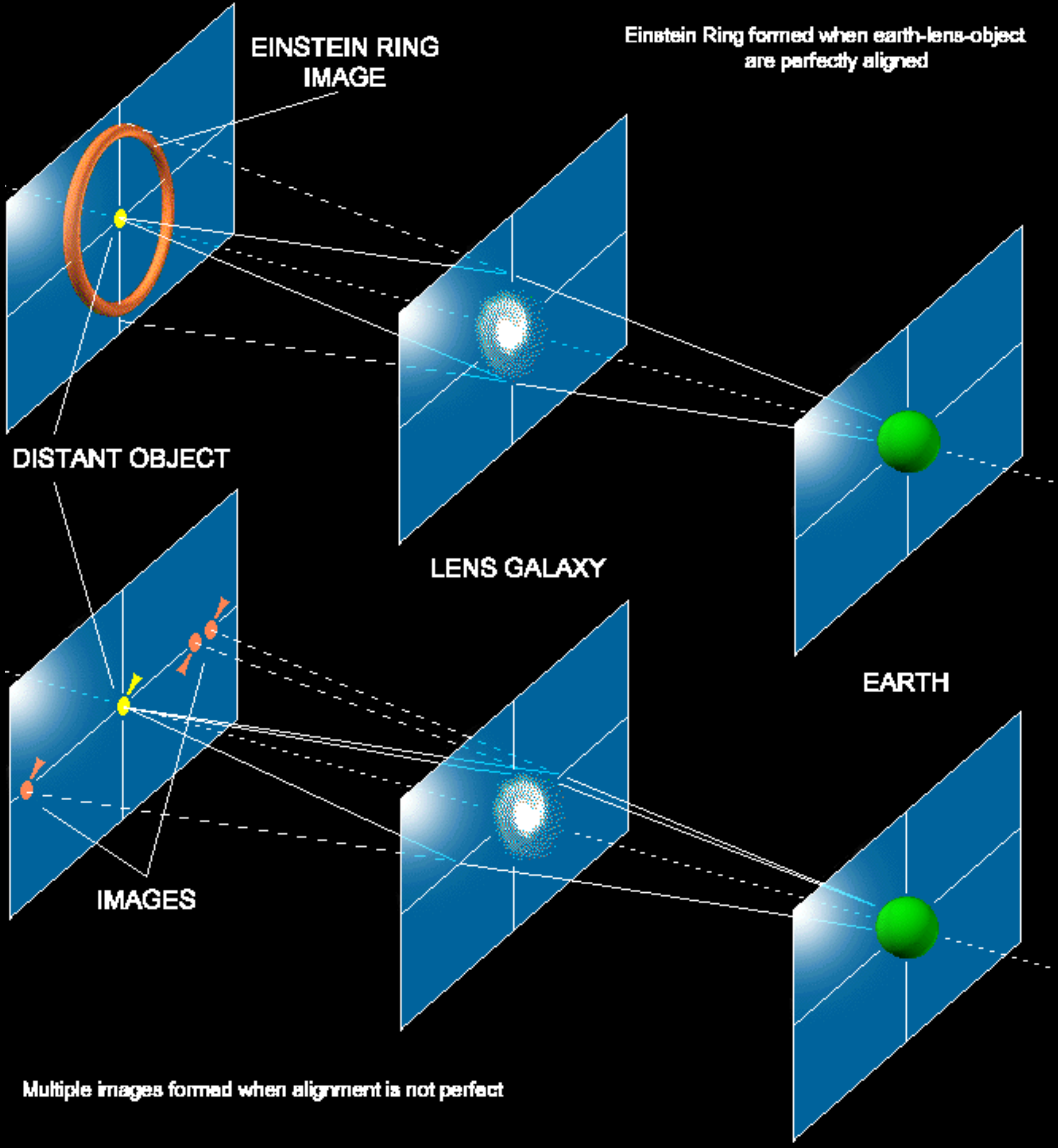
- We know from general relativity that mass - whether it is visible or not - bends light. This opens a possibility of "seeing" the distribution of dark matter
- Chowlson (1924) and Einstein (1936) predicted that if a background object is directly aligned with a point source mass, the light rays will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





Gravitational lensing in the strong regime

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



Einstein Ring formed when earth-lens-object are perfectly aligned

Multiple images formed when alignment is not perfect

Gravitational Lensing by Single Galaxies

Derived masses are in an excellent agreement with those measured using the kinematical tracers

Gravitationally Lensed Galaxies - “Arcs”

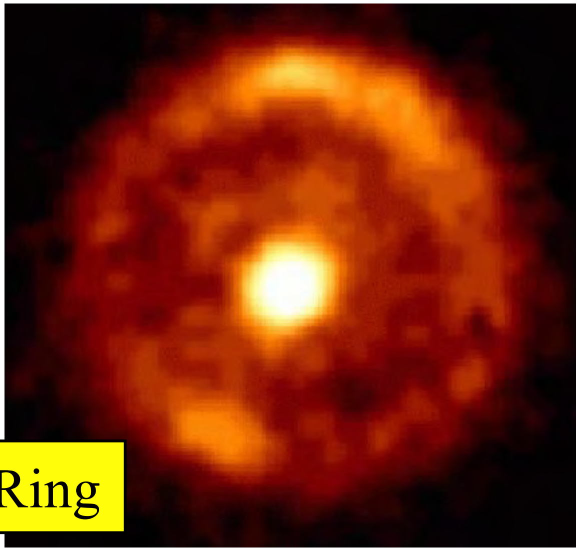
In 1937, Zwicky predicted that one could study the mass distribution (dark matter) in clusters by studying background galaxies that are lensed by the dark matter in the cluster. This was not observationally feasible until the mid-1990’s

JWST first light image

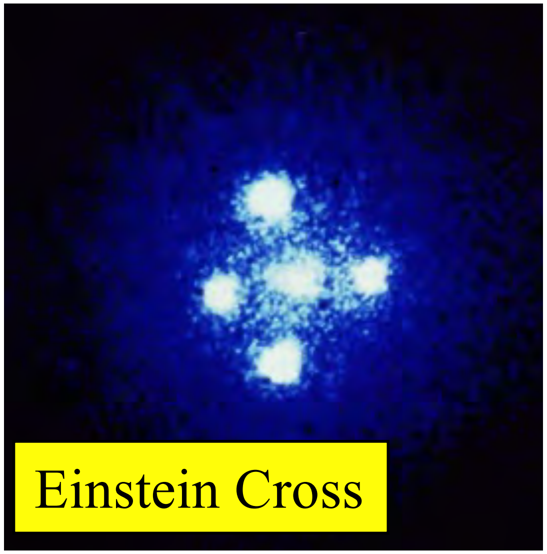
Different Lensing Regimes

Conceptually simplest situation for gravitational lensing is when the lens is massive enough to produce a large angle of deflection.

Case where we can resolve multiple images of the background source is called **strong lensing**



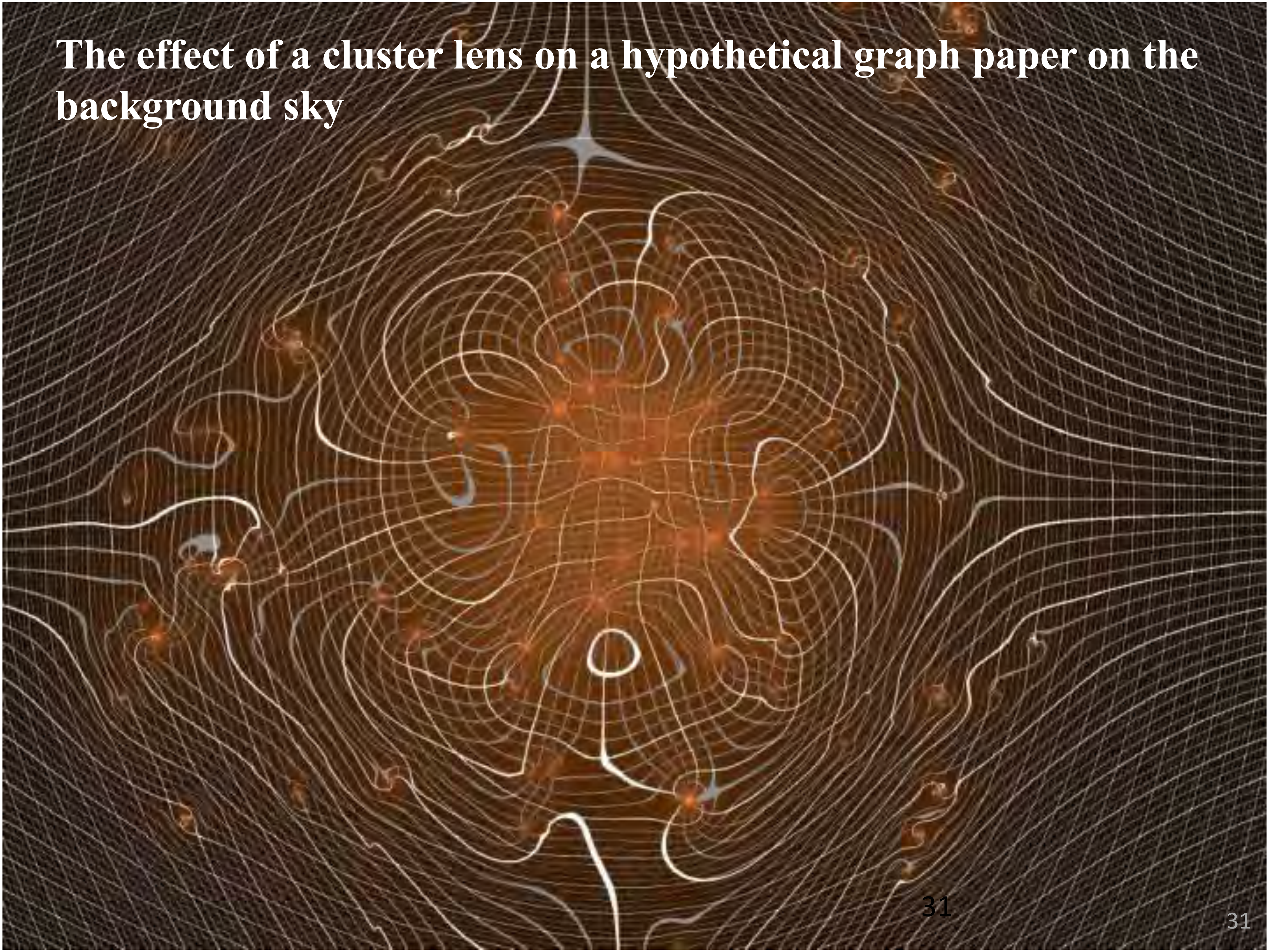
Einstein Ring



Einstein Cross

If the lensing is not strong enough to split the images, but it does magnify and distort them, it is **weak lensing.** This is the effect of the large-scale structure or the outskirts of clusters of galaxies on the background sources (galaxies). ***These image distortions can then be inverted to map the mass distribution***

The effect of a cluster lens on a hypothetical graph paper on the background sky



Cluster Masses From Gravitational Lensing

Strong lensing constraints:

A370	$M \sim 5\text{x}10^{13} h^{-1} M_\odot$	$M/L \sim 270h$
A2390	$M \sim 8\text{x}10^{13} h^{-1} M_\odot$	$M/L \sim 240h$
MS2137	$M \sim 3\text{x}10^{13} h^{-1} M_\odot$	$M/L \sim 500h$
A2218	$M \sim 1.4\text{x}10^{14} h^{-1} M_\odot$	$M/L \sim 360h$

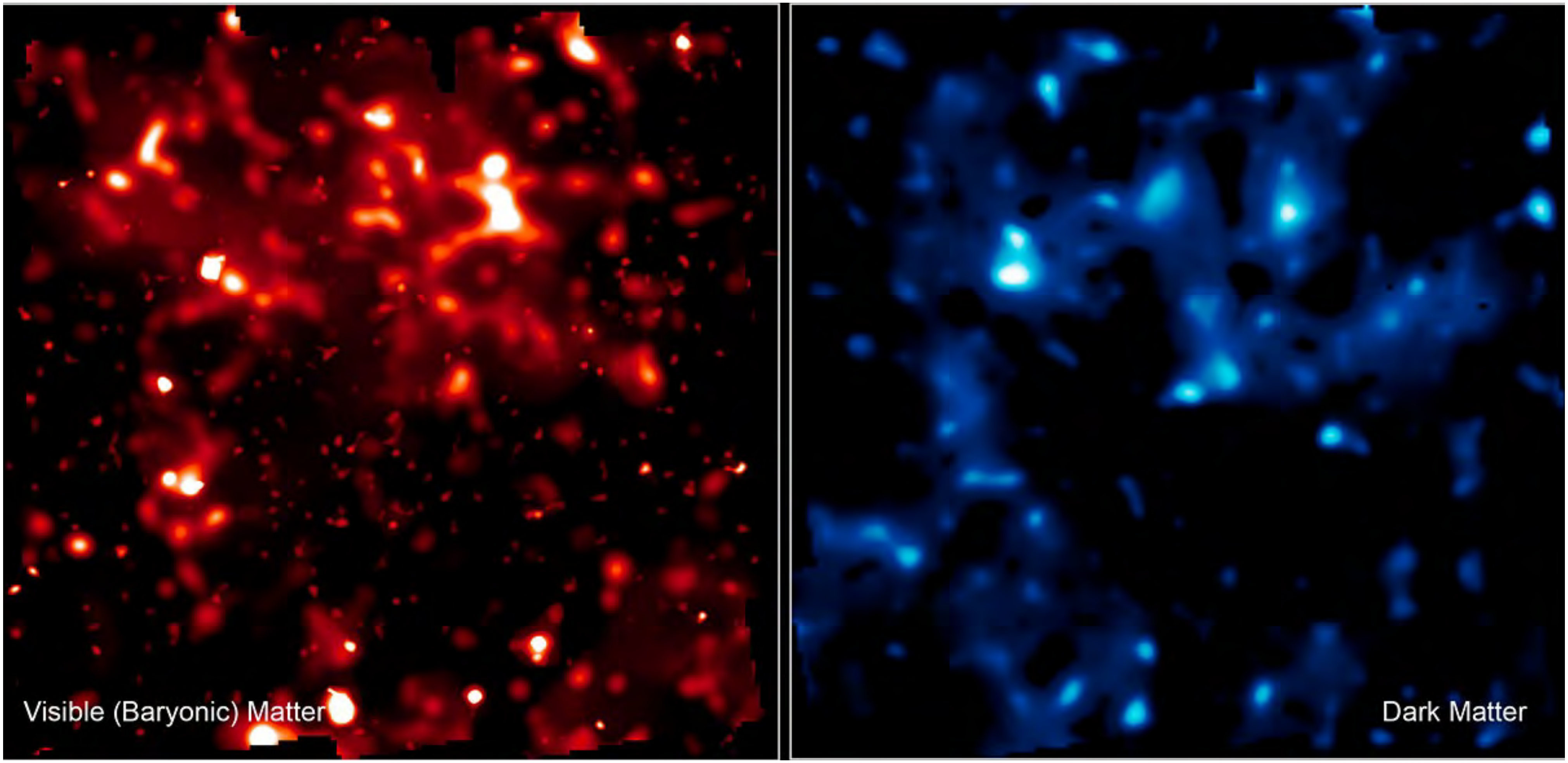
Weak lensing constraints (a subset):

MS1224	$M/L \sim 800h$
A1689	$M/L \sim 400h$
CL1455	$M/L \sim 520h$
A2218	$M/L \sim 310h$
CL0016	$M/L \sim 180h$
A851	$M/L \sim 200h$
A2163	$M/L \sim 300h$

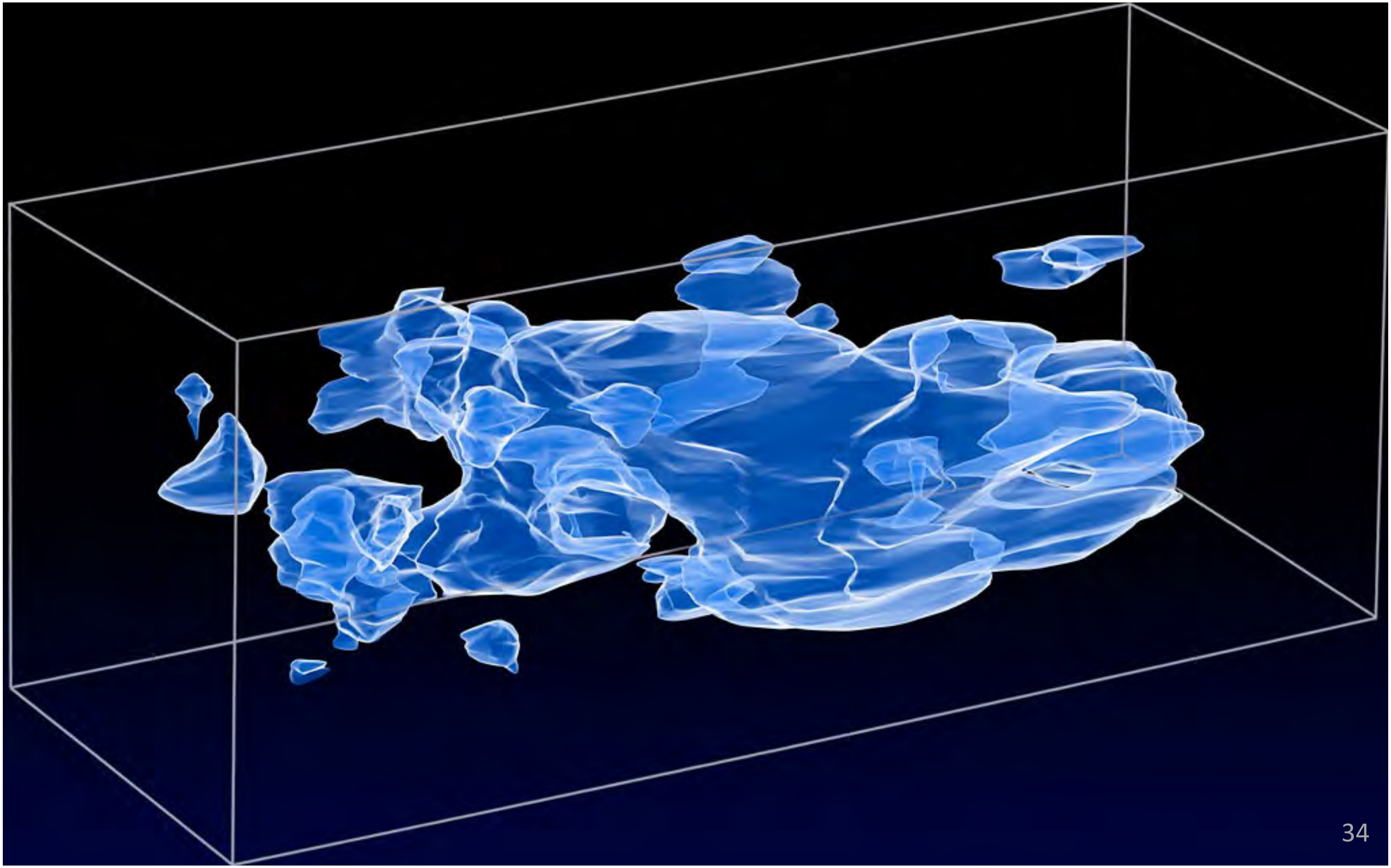
Lots of dark matter in clusters, in a good agreement with the virial mass estimates

Clusters of galaxies imply $\Omega_{dm} \sim 0.2 - 0.3$

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



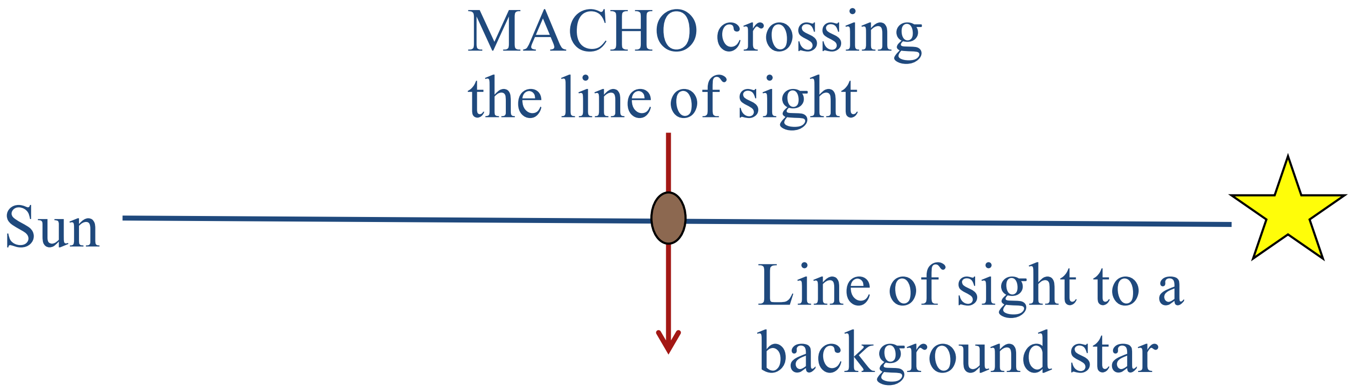
3-D DM Distribution From the COSMOS Survey (Massey et al. 2007)



Gravitational Microlensing

Lensing event occurs as a MAssive Compact (Halo) Object, MACHO (could be a main sequence star, white or brown dwarf, neutron star or black hole, or … ?), passes within an angular distance $\boldsymbol{q_E}$ of a background star:

- background star initially brightens
- eventually fades as the alignment is lost



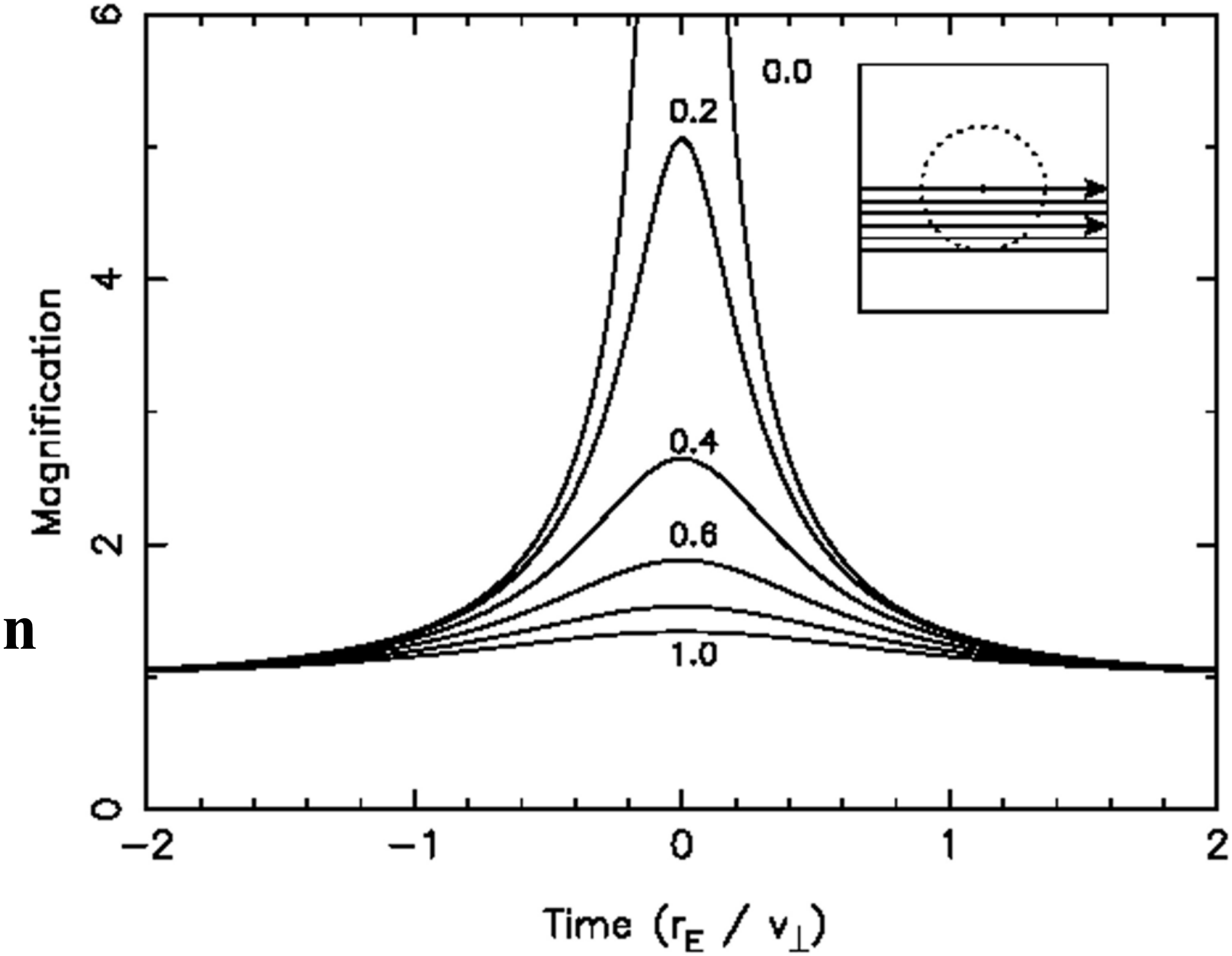
MACHO crossing
the line of sight

Sun

Line of sight to a
background star

Since the cross section for a strong lensing is small compared to interstellar separations, such events must be exceedingly rare

Expected Gravitational Microlensing Lightcurves

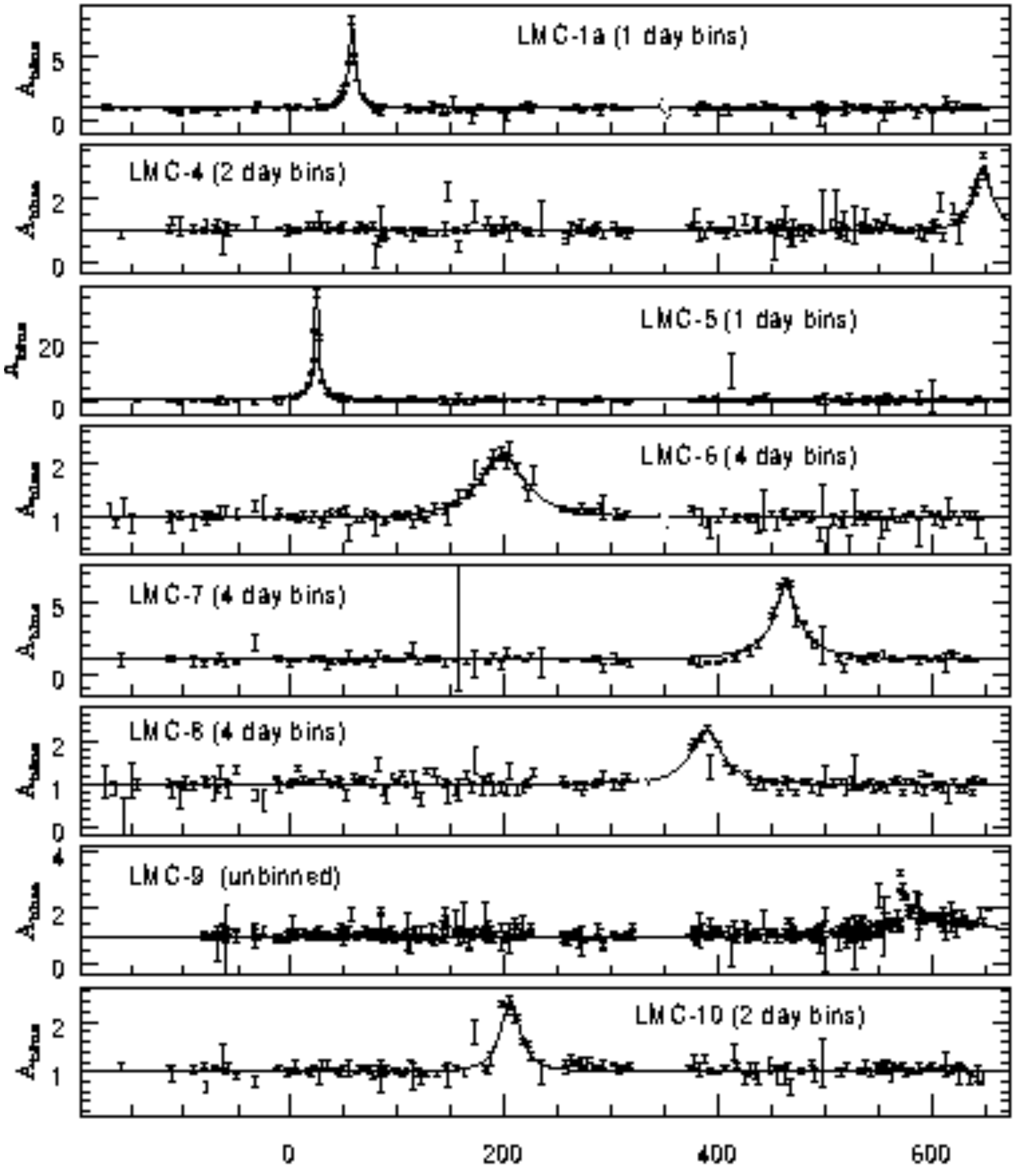


The **peak magnification** depends on the lens alignment (impact parameter)

The **event duration** depends on the lens velocity

- A probability of a distant star being lensed is ~ 10^{-7}/year
- Need to monitor > 10^7 stars simultaneously, typically in the LMC (MACHO) or the Galactic Bulge (OGLE), and many others

The First MACHO Event Seen in the LMC Experiment →



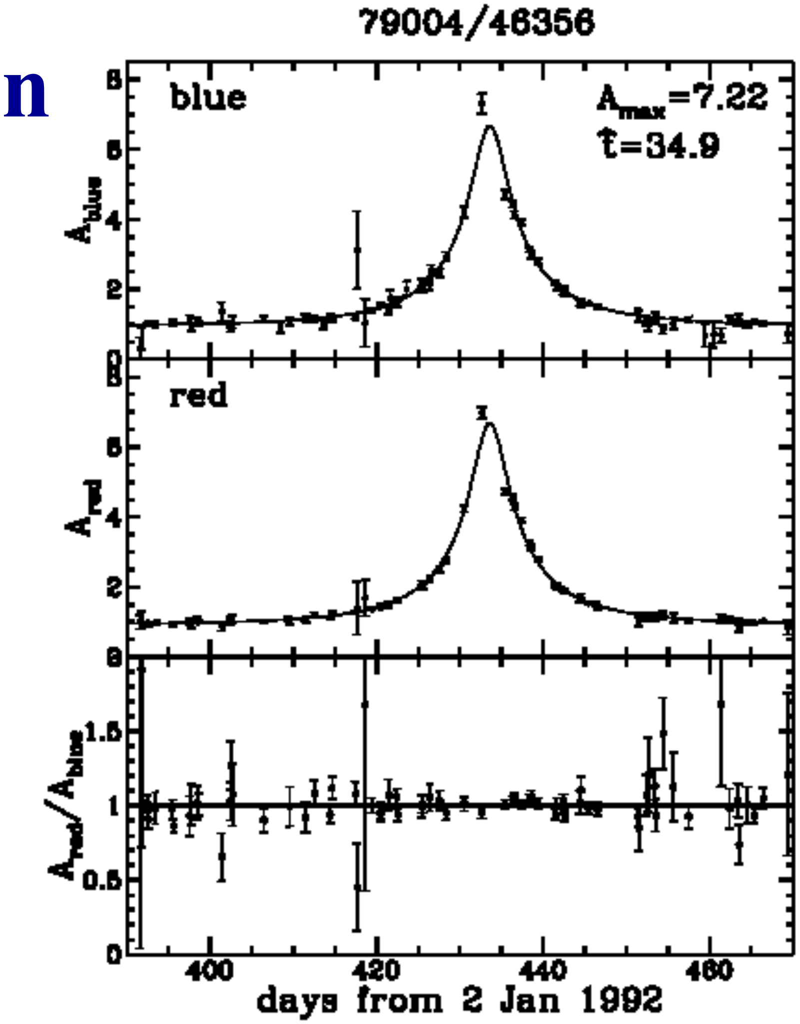


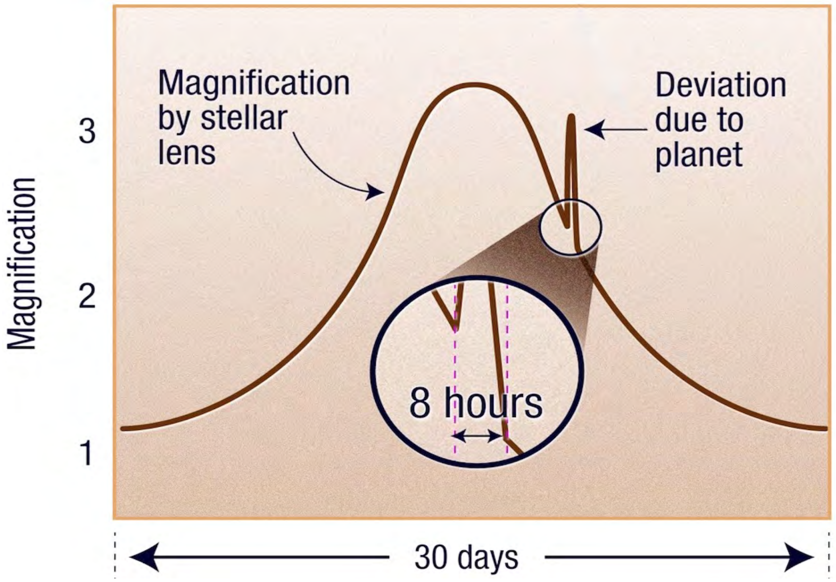
Figure 3. The first LMC microlensing candidate from the MACHO project. (Expanded view: 6 yr of constant data are

To date, thousands of microlensing events have been detected by various groups

Microlensing Results

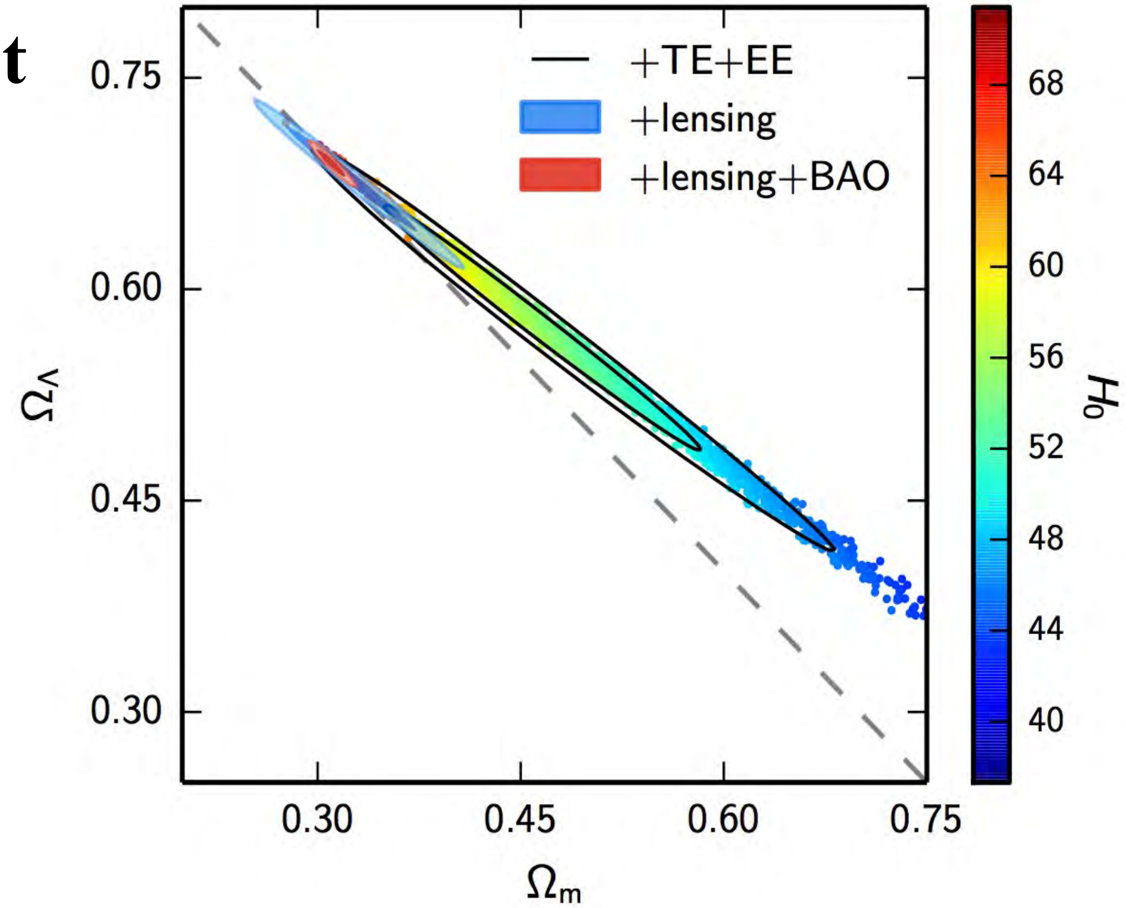
Based on the number and duration of MACHO events, ***if the lenses are objects in the Galactic Halo:***

- At most 20% of the mass of the Galactic halo is in the form of MACHOs; the idea that ***all*** the mass in the halo is MACHOs is ***definitely ruled out***
- Typical lens mass is between 0.15 $M_\odot$ and 0.9 $M_\odot$: too massive to be brown dwarfs or smaller objects, not massive enough to be neutron stars or black holes → normal stars, probably in the Galactic disk
- Modern microlensing experiments can even detect lensing by planets orbiting the lensing stars:



The Dark Energy

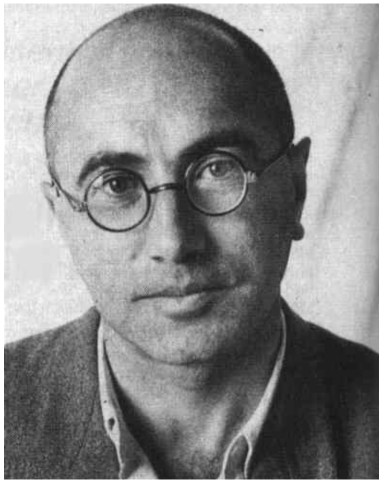
- The **dominant component** of the observed matter/energy density: $\Omega_{0,DE} \approx 0.69$
- Causes the accelerated expansion of the universe
- May affect the growth of density perturbations
- Effective only at cosmological distances

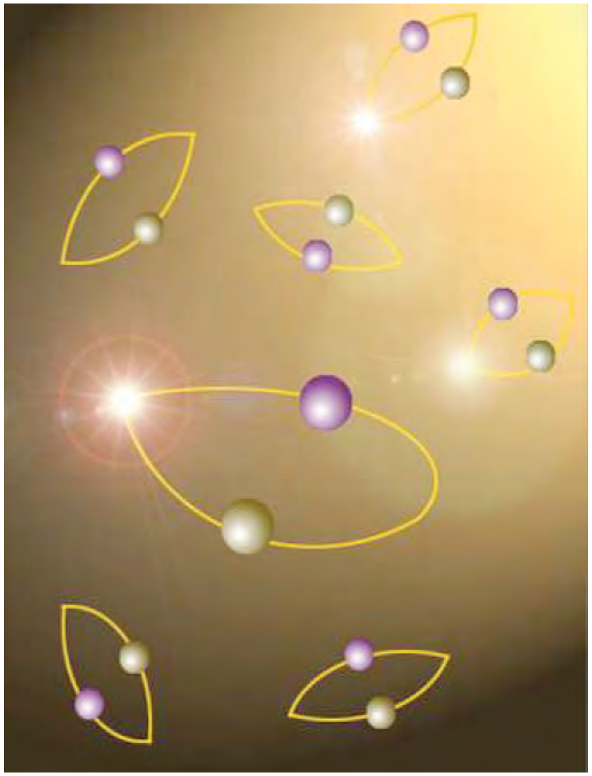


- Its physical nature is as yet ***unknown***; this may be the biggest outstanding problem in physics today
- ***Cosmological constant*** is just one special case; a more general possibility is called ***quintessence***

The Weight of the Vacuum

A key idea was due to Yakov Zel’dovich (1968)





A modern, quantum view of the physical vacuum is that it is not really empty - it is filled with virtual particle-antiparticle pairs. Their fluctuations give rise to a net energy density - a ground(?) state of the physical vacuum.

That would manifest itself as a **cosmological constant**

Unfortunately, we do not yet have a theory which would enable us to calculate this. But 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:

$$\rho_{Planck} = c^{5} / (hG^{2}) = 5.15 \times 10^{93}\ \mathrm{g\ cm^{-3}}$$

- The observed value is:

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

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 pseudo-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:

$$P = w\,\rho$$

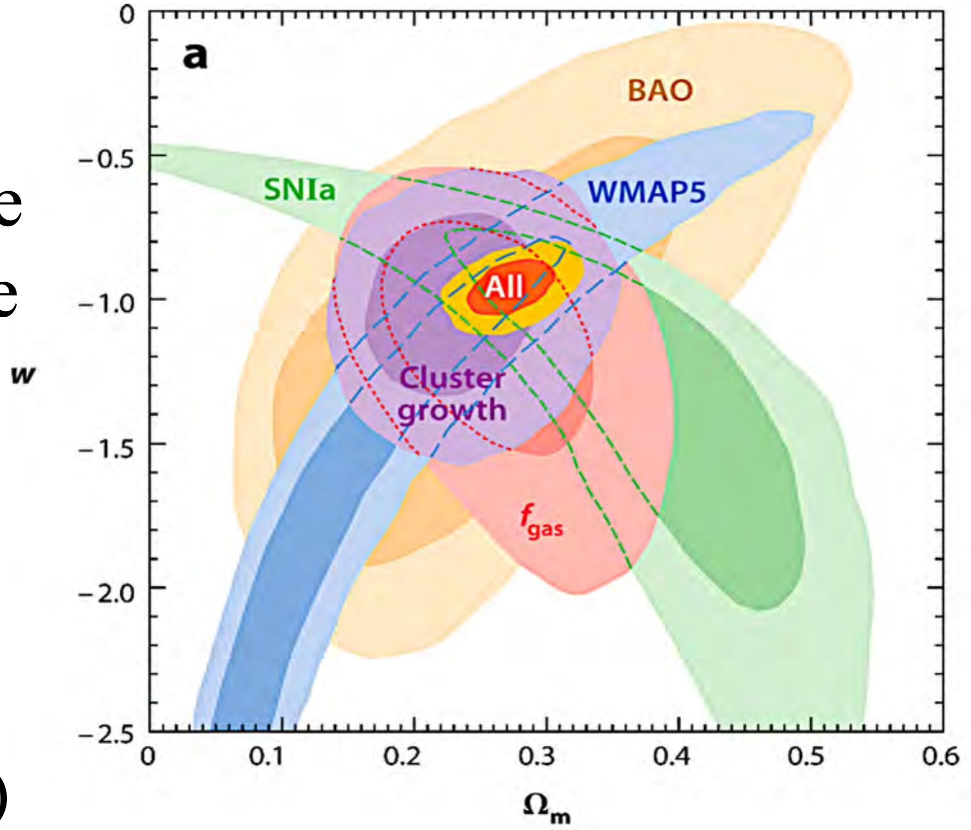
$$\rho \sim R^{-3(w+1)}$$

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

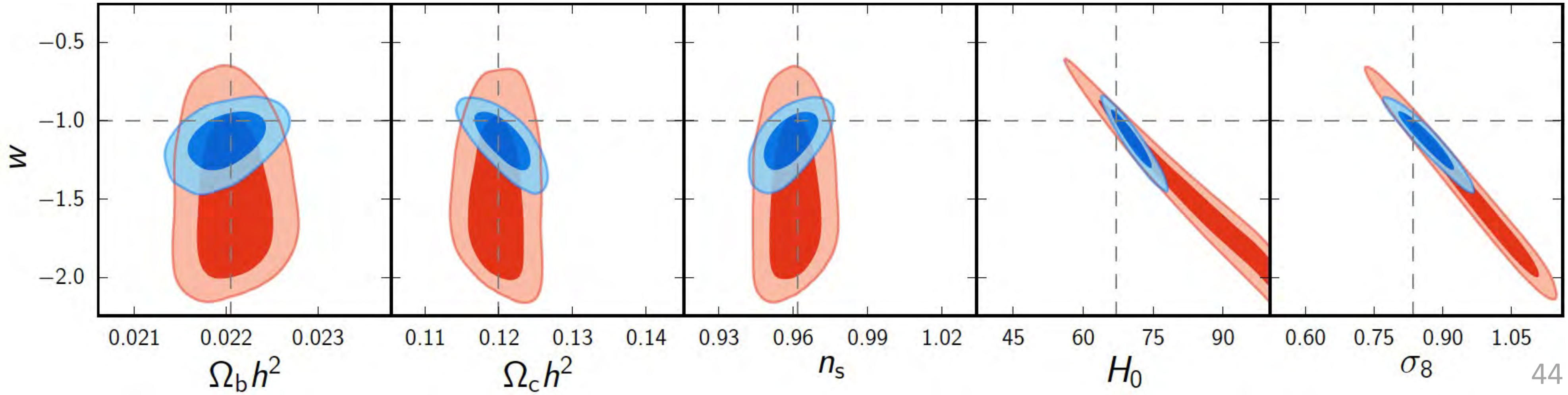
Quintessence: w can have other values and change in time

Observational Constraints on *w*

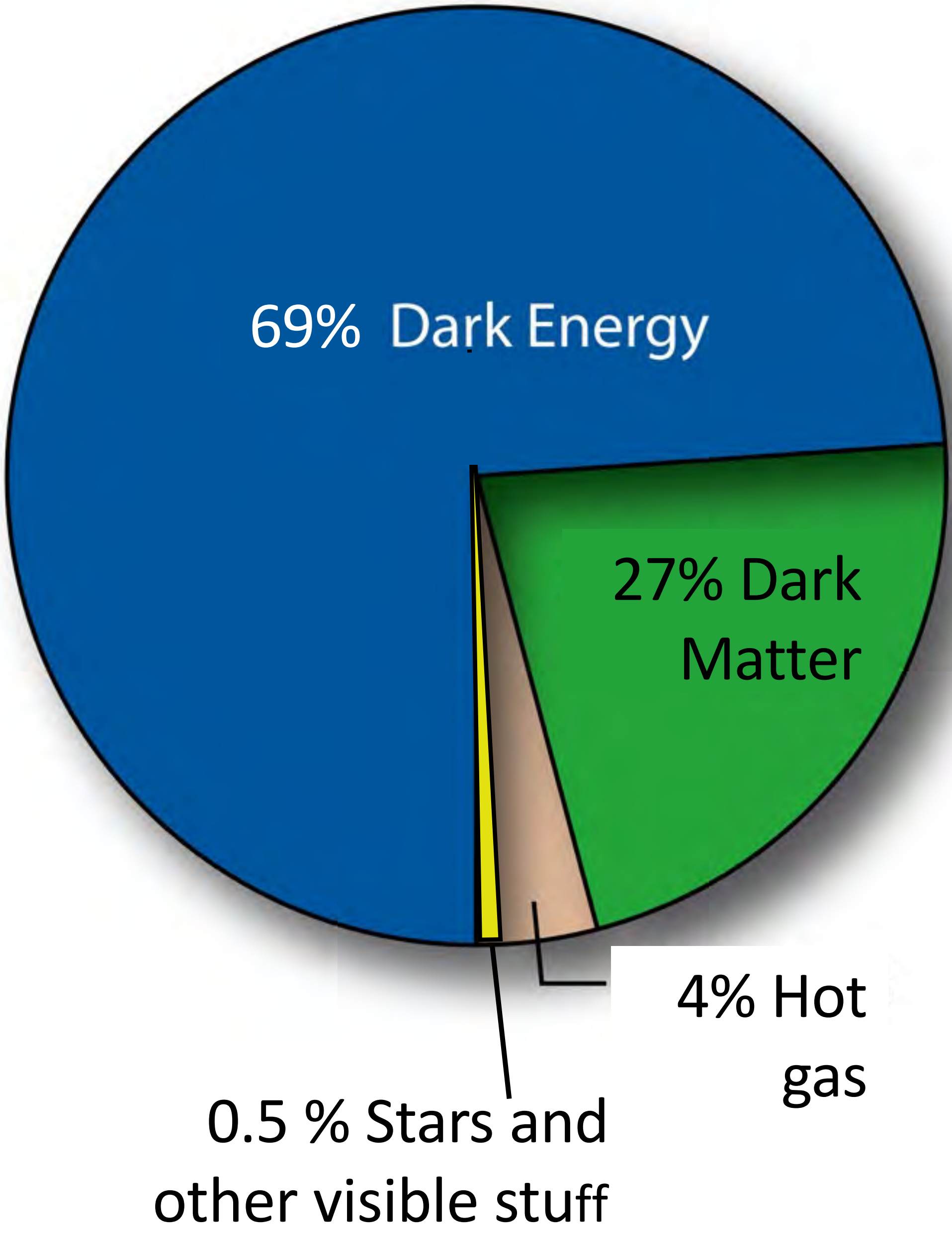
Strongly favor values of $w \sim -1$, i.e., cosmological constant. Some models can be excluded, but there is still room for $\rho_{vac} \neq const.$ models



Planck + WMAP (red) + BAO (blue)



Contents of the Universe: Summary



- $\Omega_0 = 1.000 \pm 0.002$
- $\Omega_m \approx 0.315 \pm 0.007$
  - $\Omega_b \approx 0.0457 \pm 0.0002$
    - Includes $\Omega_{visible} \approx 0.005$
  - $\Omega_{non\text{-}b} \approx 0.269 \pm 0.008$
    - Includes $\Omega_\nu < 0.005$
  - $\Omega_{CMBR} \approx 0.00005$
- $\Omega_{de} \approx 0.685 \pm 0.009$
- The physical nature of the DE is currently completely unknown