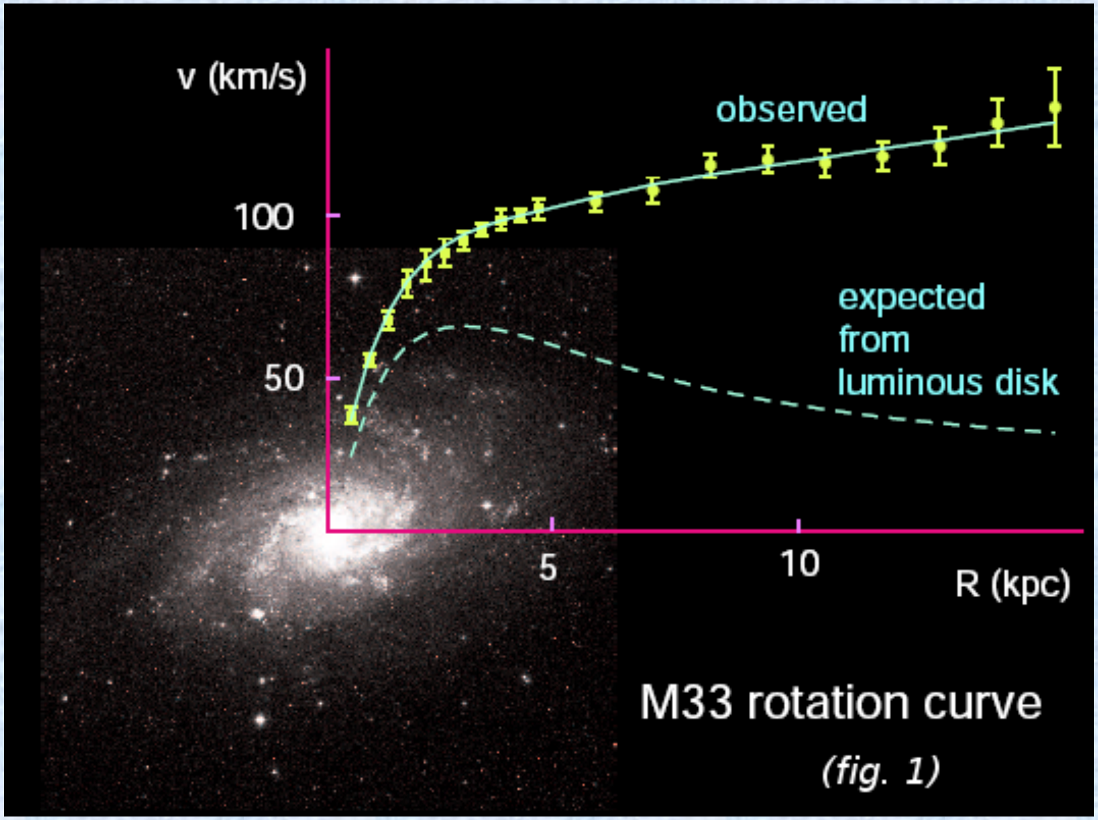
Physics 133: Extragalactic Astronomy and Cosmology

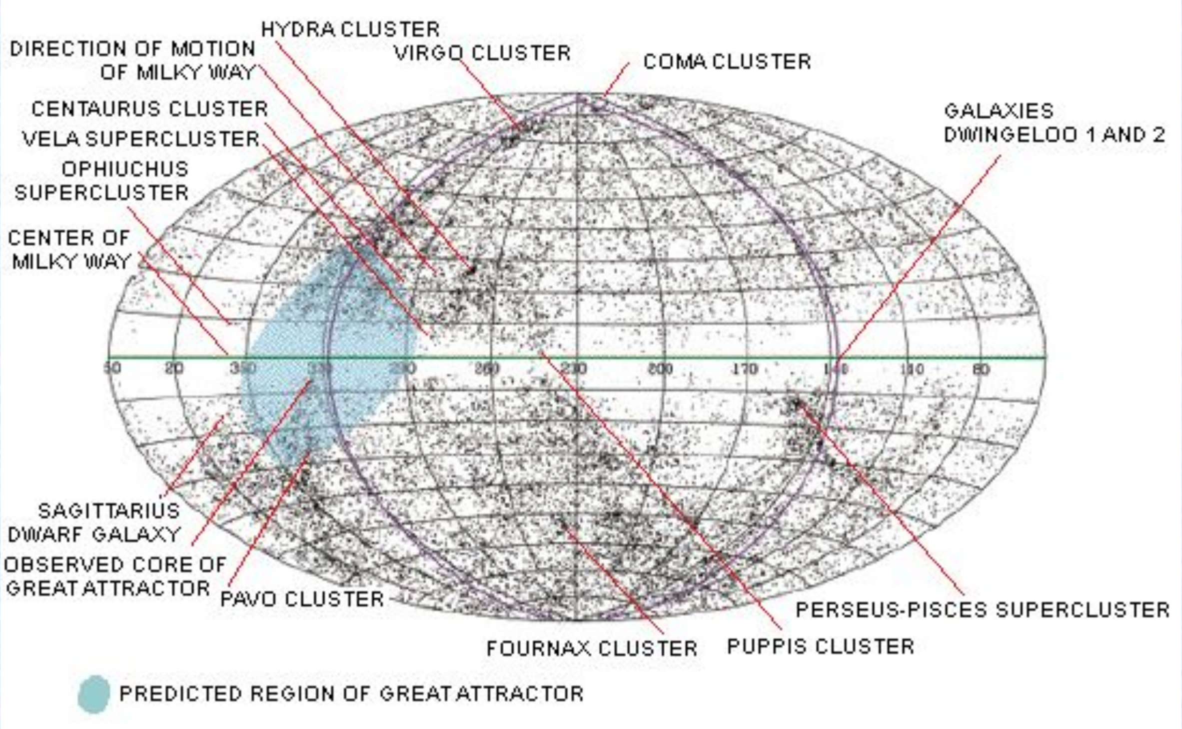


Week 6

Outline for Week 6

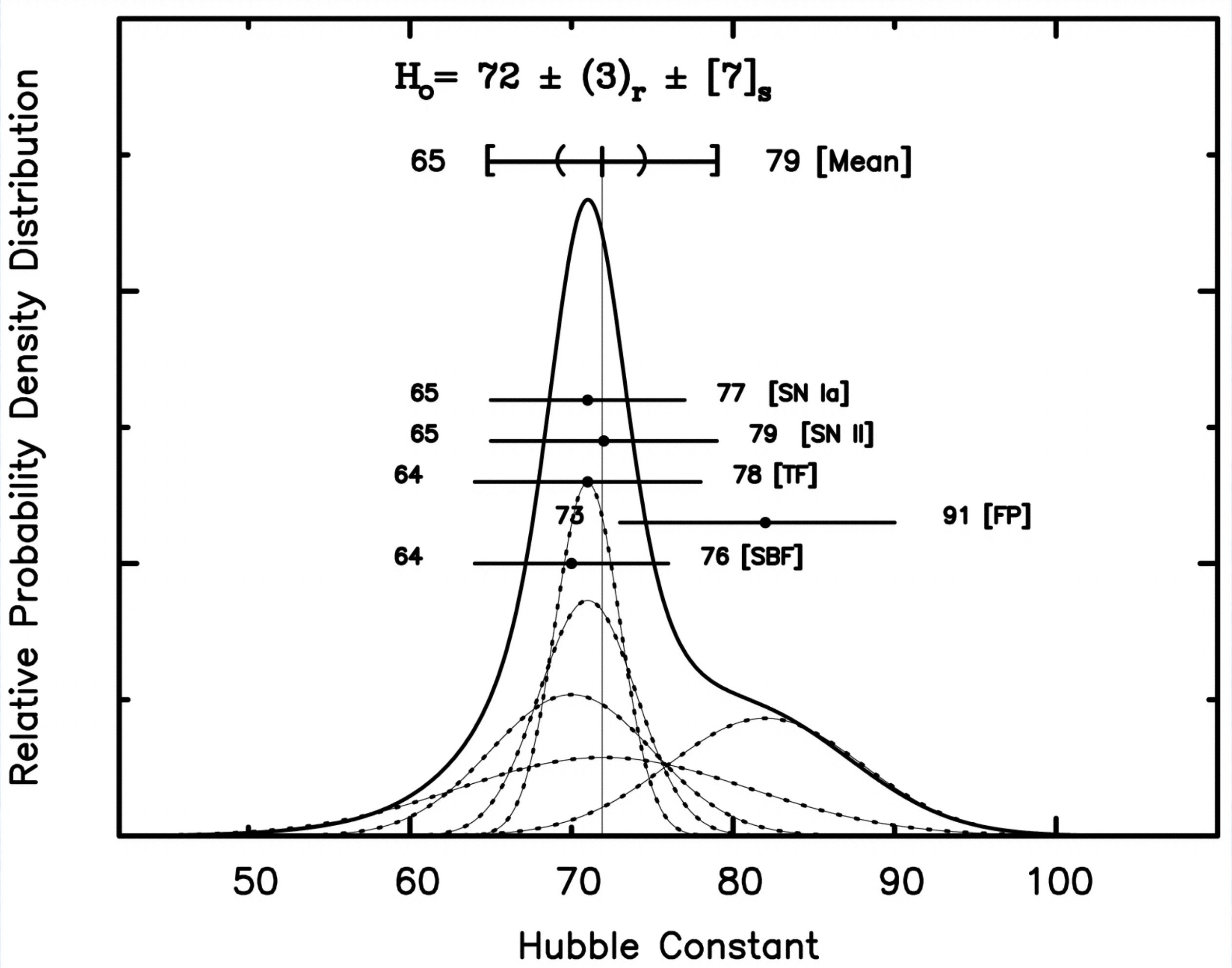
- **Controversy over the Hubble Constant**
  - We learned how to measure H_0 and q_0:
    - $z = H_0 / c \ \ d \, (1 + \ldots.)$
    - What distance is this?
  - New astrophysics or new cosmology?
- **Dynamical Mass Measurements**
  - Galaxy Rotation Curves
  - Virial Theorem
  - Gravitational Lensing
- **Non-baryonic matter**
  - Dark Matter in Galaxies
  - Dark Matter in Clusters of Galaxies
  - What is the Dark Matter?

Cosmic Expansion vs. Motion Through Space



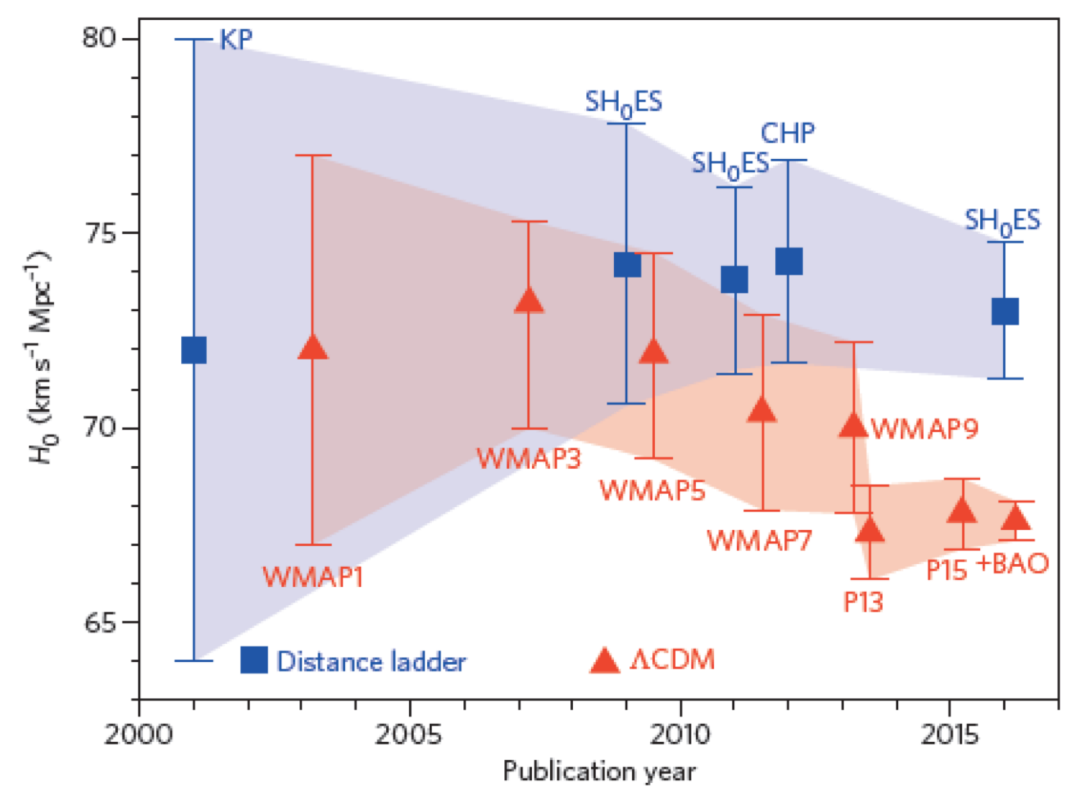
- $v = zc + v_{pec}$
  - ➢ First term represents the cosmic expansion (Hubble Flow) to first order.
  - ➢ The peculiar velocity describes motion through space.
  - ➢ Example: Virgo Cluster infall ~250 km/s.
  - ➢ At large enough redshift, we see pure Hubble Flow.
    - ➢ H_0 (100Mpc) = 7000 km/s requires $z \sim v / c \sim 0.023$

The Hubble constant.
HST Key project results



Freedman et al. 2001

Cosmology at a Crossroads



Red: Derived values of H0 based on adopted cosmological model

Blue: Values of H0 determined from measurements based on Cepheid distance calibration.

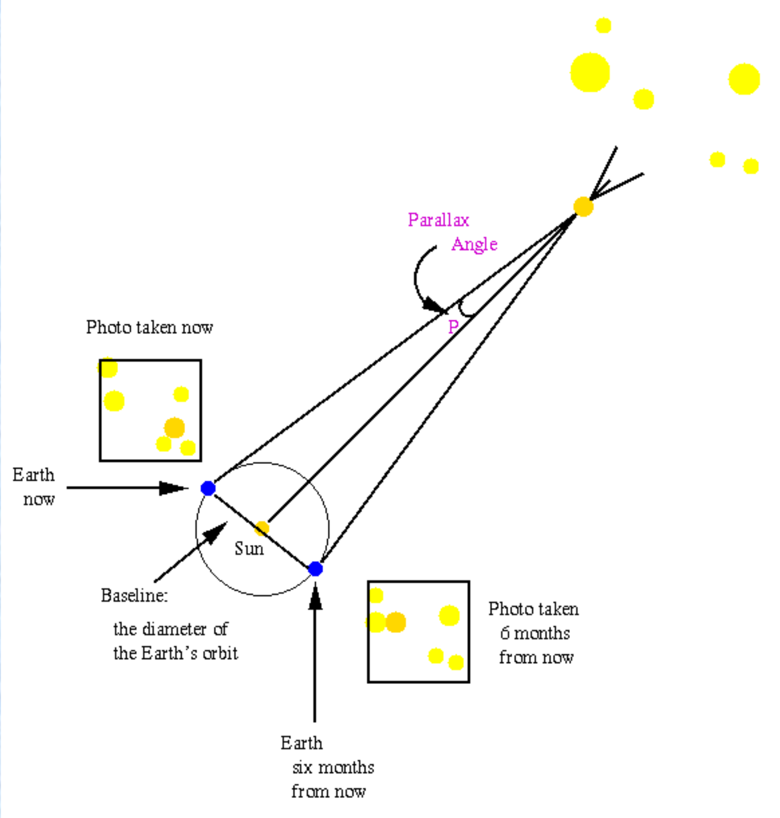
Calibration of Standard Candles

- Need to know the luminosity of the standard candle, and that requires a direct distance measurement.

- Parallax works within the Milky Way Galaxy; see GAIA results!

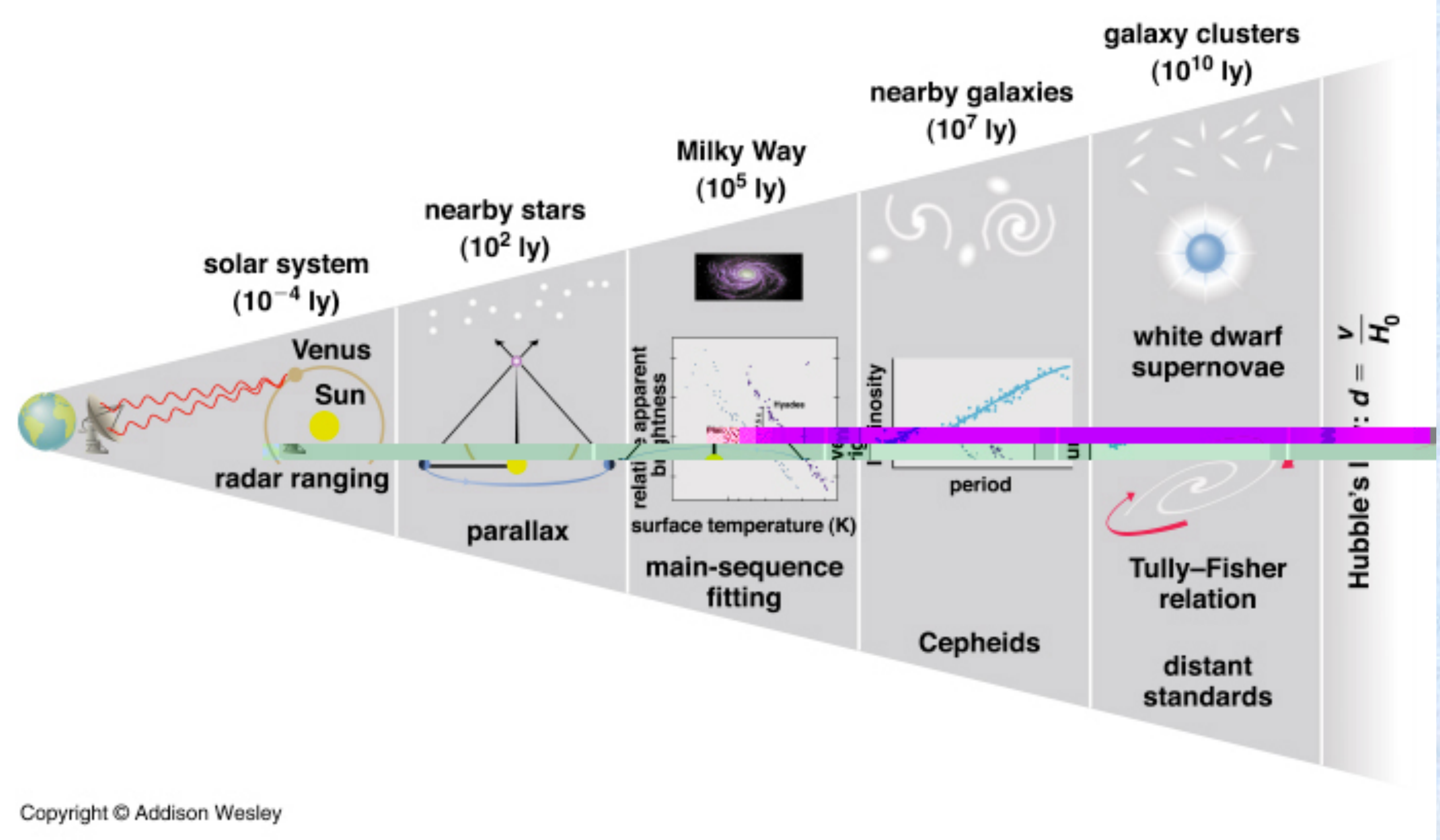
- Calibrate pulsational variables including (e.g., Cepheid variables, RR Lyraes) in the Milky Way and its Satellites (LMC/SMC).

- Possible problems:
    - Distance to LMC
    - Chemical composition



The cosmic distance ladder

“Secondary” distance indicators calibrated with Cepheid Period -- Luminosity relation reach into the Hubble Flow.



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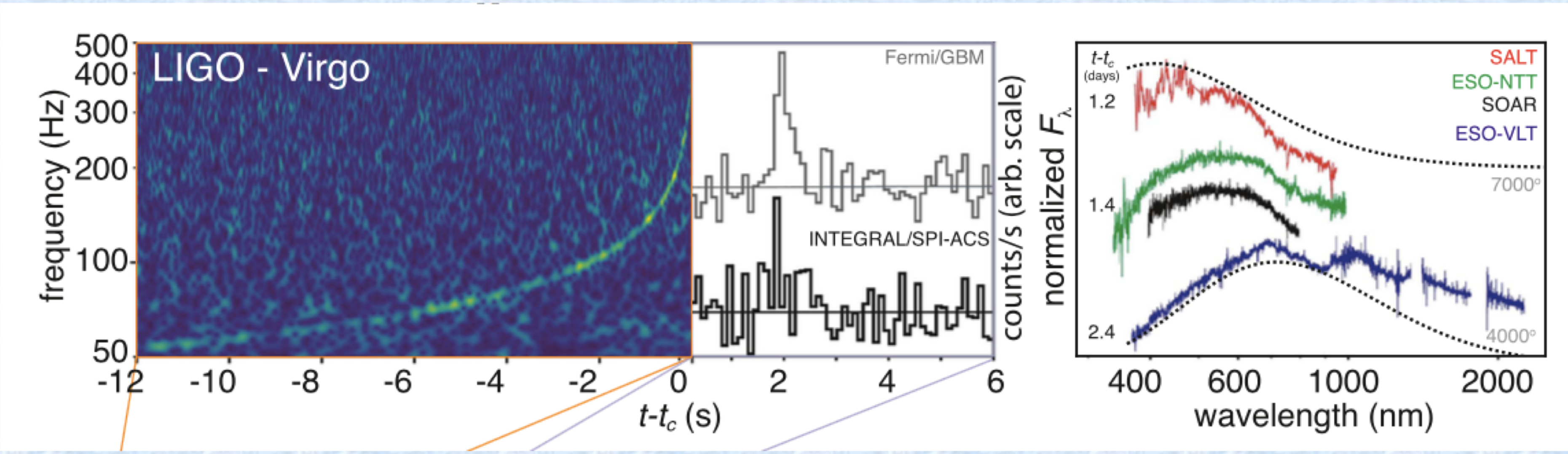
Future: Measuring H_0 without using the distance ladder!

Standard Sirens

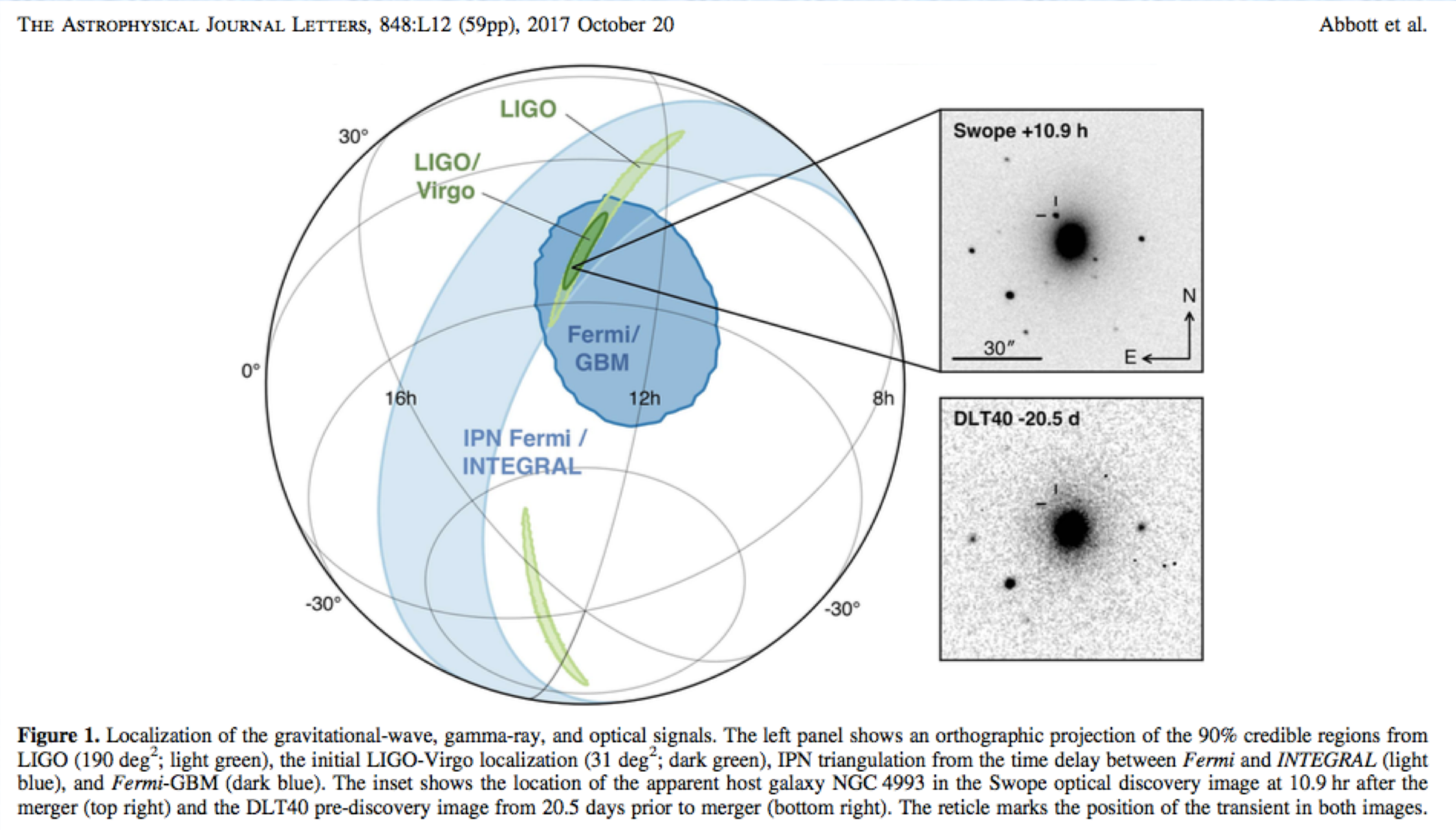
- Neutron star – neutron star mergers do not give a standard candle, but the luminosity can be worked out from the characteristic chirp of the gravitational waveform, which is determined by how rapidly the 2 stars spiral together.

Observations of a Binary NS Merger



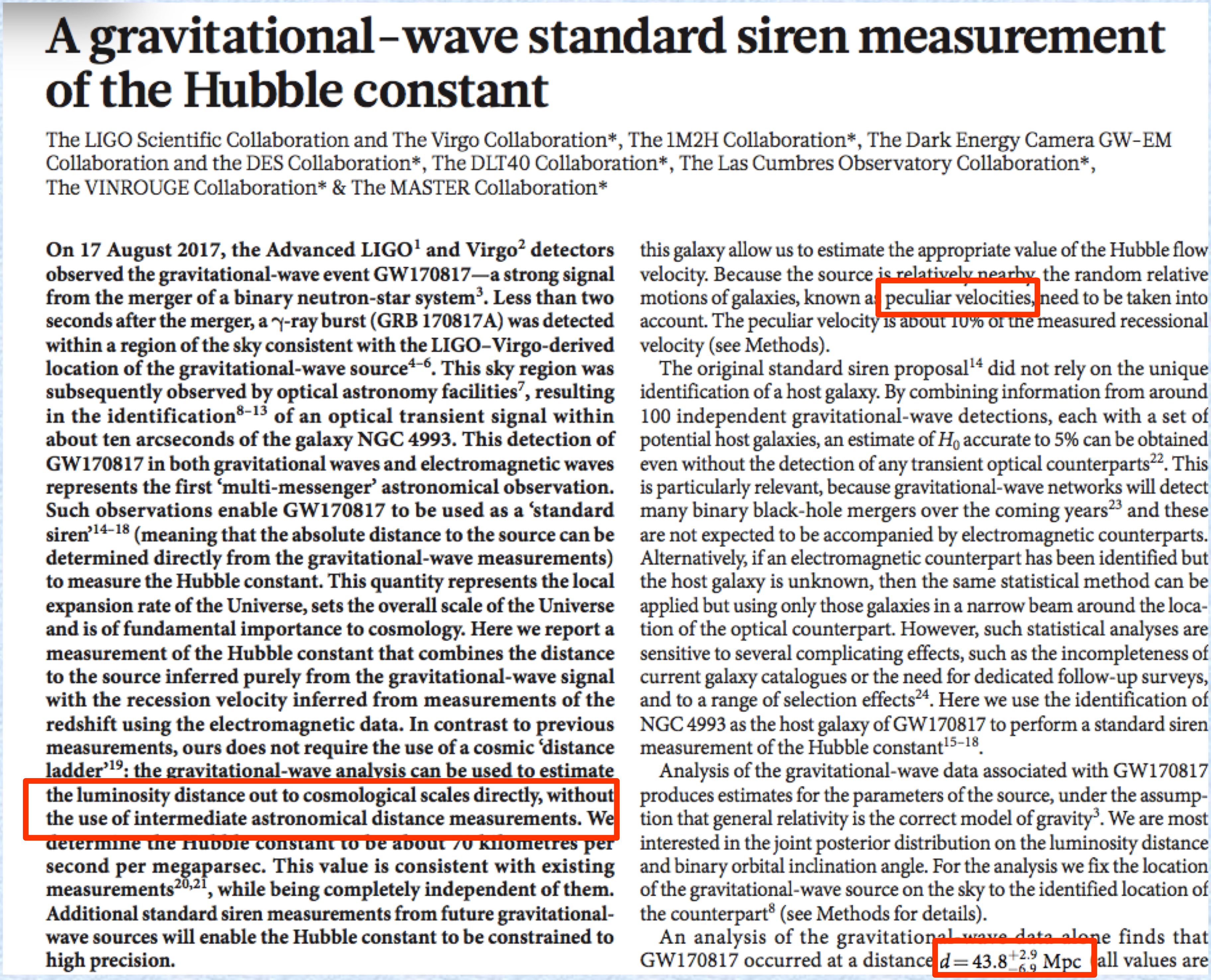
Standard Sirens

- The tricky part is to get the redshift. There’s not enough structure in the gravitational waves to measure redshift.
- That’s why it is such a big deal to detect the host galaxy of the NS-NS merger. The galaxy redshift can be easily measured spectroscopically.



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 Abbott et al.

Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2; light green), the initial LIGO-Virgo localization (31 deg^2; dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi*-GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.



A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

On 17 August 2017, the Advanced LIGO[1] and Virgo[2] detectors observed the gravitational-wave event GW170817—a strong signal from the merger of a binary neutron-star system[3]. Less than two seconds after the merger, a γ-ray burst (GRB 170817A) was detected within a region of the sky consistent with the LIGO–Virgo-derived location of the gravitational-wave source[4–6]. This sky region was subsequently observed by optical astronomy facilities[7], resulting in the identification[8–13] of an optical transient signal within about ten arcseconds of the galaxy NGC 4993. This detection of GW170817 in both gravitational waves and electromagnetic waves represents the first 'multi-messenger' astronomical observation. Such observations enable GW170817 to be used as a 'standard siren'[14–18] (meaning that the absolute distance to the source can be determined directly from the gravitational-wave measurements) to measure the Hubble constant. This quantity represents the local expansion rate of the Universe, sets the overall scale of the Universe and is of fundamental importance to cosmology. Here we report a measurement of the Hubble constant that combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using the electromagnetic data. In contrast to previous measurements, ours does not require the use of a cosmic 'distance ladder'[19]: the gravitational-wave analysis can be used to estimate the luminosity distance out to cosmological scales directly, without the use of intermediate astronomical distance measurements. We determine the Hubble constant to be about 70 kilometres per second per megaparsec. This value is consistent with existing measurements[20,21], while being completely independent of them. Additional standard siren measurements from future gravitational-wave sources will enable the Hubble constant to be constrained to high precision.

this galaxy allow us to estimate the appropriate value of the Hubble flow velocity. Because the source is relatively nearby, the random relative motions of galaxies, known as peculiar velocities, need to be taken into account. The peculiar velocity is about 10% of the measured recessional velocity (see Methods).

The original standard siren proposal[14] did not rely on the unique identification of a host galaxy. By combining information from around 100 independent gravitational-wave detections, each with a set of potential host galaxies, an estimate of H_0 accurate to 5% can be obtained even without the detection of any transient optical counterparts[22]. This is particularly relevant, because gravitational-wave networks will detect many binary black-hole mergers over the coming years[23] and these are not expected to be accompanied by electromagnetic counterparts. Alternatively, if an electromagnetic counterpart has been identified but the host galaxy is unknown, then the same statistical method can be applied but using only those galaxies in a narrow beam around the location of the optical counterpart. However, such statistical analyses are sensitive to several complicating effects, such as the incompleteness of current galaxy catalogues or the need for dedicated follow-up surveys, and to a range of selection effects[24]. Here we use the identification of NGC 4993 as the host galaxy of GW170817 to perform a standard siren measurement of the Hubble constant[15–18].

Analysis of the gravitational-wave data associated with GW170817 produces estimates for the parameters of the source, under the assumption that general relativity is the correct model of gravity[3]. We are most interested in the joint posterior distribution on the luminosity distance and binary orbital inclination angle. For the analysis we fix the location of the gravitational-wave source on the sky to the identified location of the counterpart[8] (see Methods for details).

An analysis of the gravitational-wave data alone finds that GW170817 occurred at a distance $d = 43.8^{+2.9}_{-6.9}$ Mpc (all values are

Controversy Over the Hubble Constant!

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

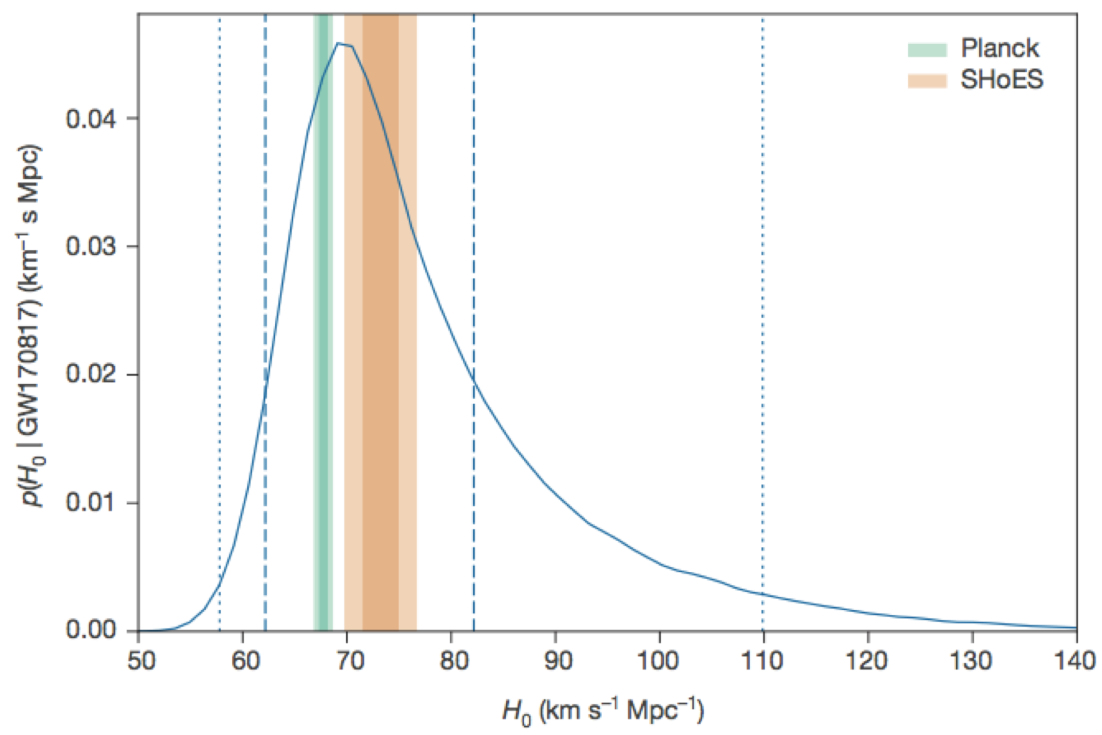
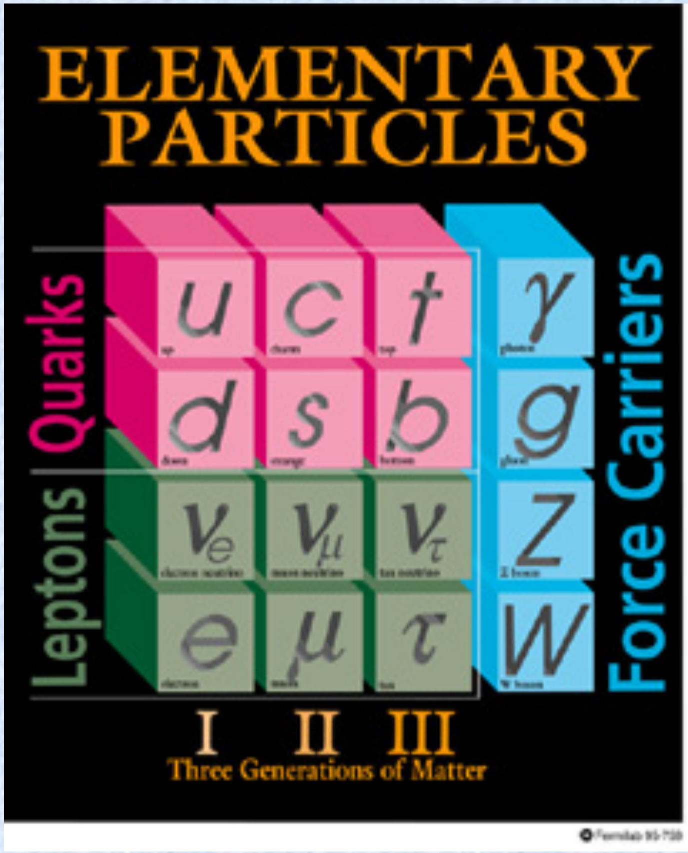


Figure 1 | GW170817 measurement of H_0. The marginalized posterior density for H_0, $p(H_0 \mid \mathrm{GW170817})$, is shown by the blue curve. Constraints at 1σ (darker shading) and 2σ (lighter shading) from Planck[20] and SHoES[21] are shown in green and orange, respectively. The maximum a posteriori value and minimal 68.3% credible interval from this posterior density function is $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}. The 68.3% (1σ) and 95.4% (2σ) minimal credible intervals are indicated by dashed and dotted lines, respectively.

What is “Baryonic” Matter?

- Ordinary matter is made of protons and neutrons, i.e. quarks up and down.
- Ordinary matter is baryonic matter



Density Parameter in Stars. I.

- Milky Way Galaxy as $L_B \sim 2.3e10\ L_{0,B}$.
- Find 0.005 galaxies of similar luminosity per Mpc^3
- So the luminous stellar matter in galaxies is $\rho_* \sim 5 \times 10^8\ M_0/Mpc^3$.

QUIZ #10

- What is the critical density in units of M_0/Mpc^3? [Use H_0 = 68 km/s/Mpc.]
- Then, in the chat box, enter the density parameter in stars.

Density Parameter in Stars. II.

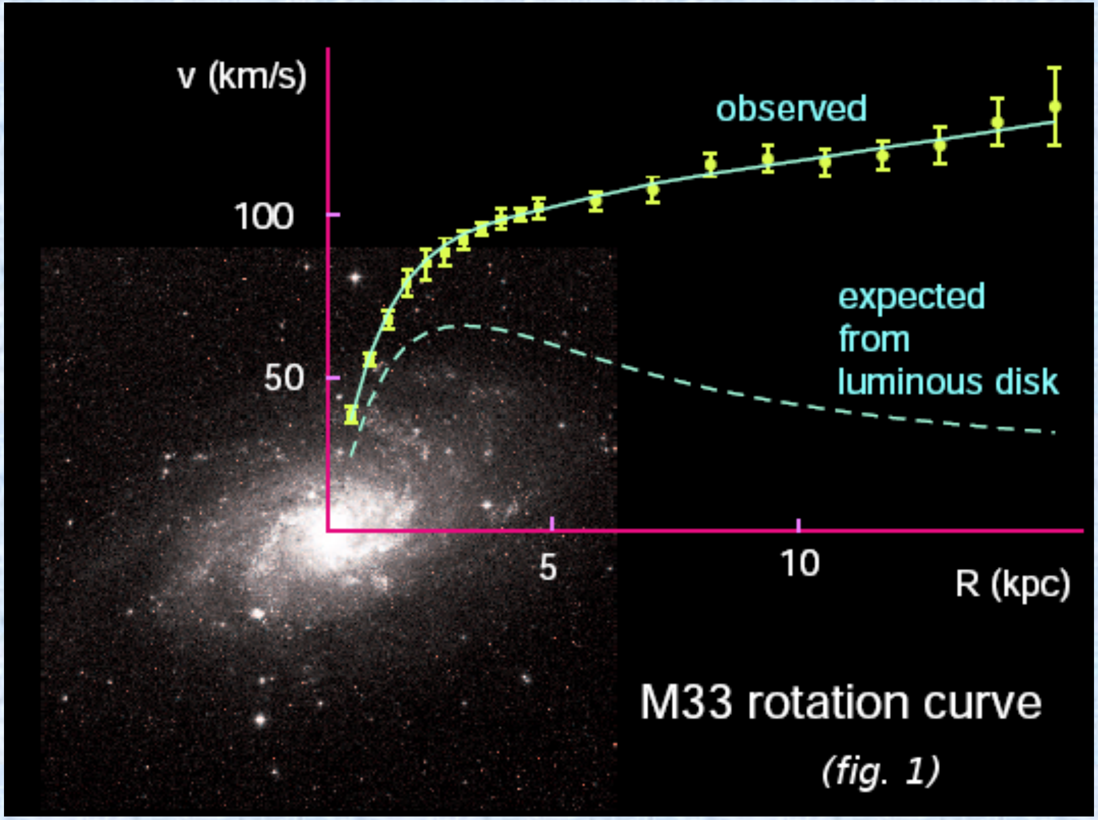
- Milky Way Galaxy as $L_B \sim 2.3e10\ L_{0,B}$.
- Find 0.005 galaxies of similar luminosity per Mpc^3
- So the luminous stellar matter in galaxies is $\rho_* \sim 5 \times 10^8\ M_0/\mathrm{Mpc}^3$.

- Comparison to critical density yields $\Omega_* \sim 0.004$.

- We've been saying the Ω_m is roughly 0.3 in the Benchmark model and that Ω_b is 0.04.
- Let's use gravity to find all the matter. Then we will return to the missing baryons in [R 9].
- *Let's starting on relatively small scales and work our way out to larger scales.*

Rotation Curves Measure Galaxy Masses

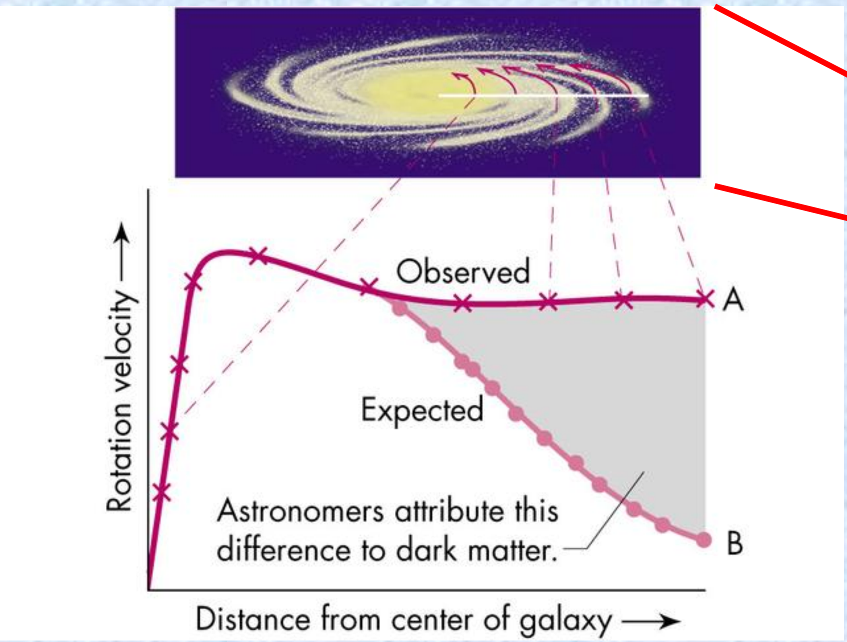
- Circular Orbits [blackboard]
- The rotation speed of a galaxy measures total mass, i.e. dynamical mass.
- Vera Rubin found V(R) is constant across many scale lengths in surface brightness.
- This was a big surprise because the light falls off exponentially with radius.
- *Galaxies rotate too fast to be held together by the visible matter.*

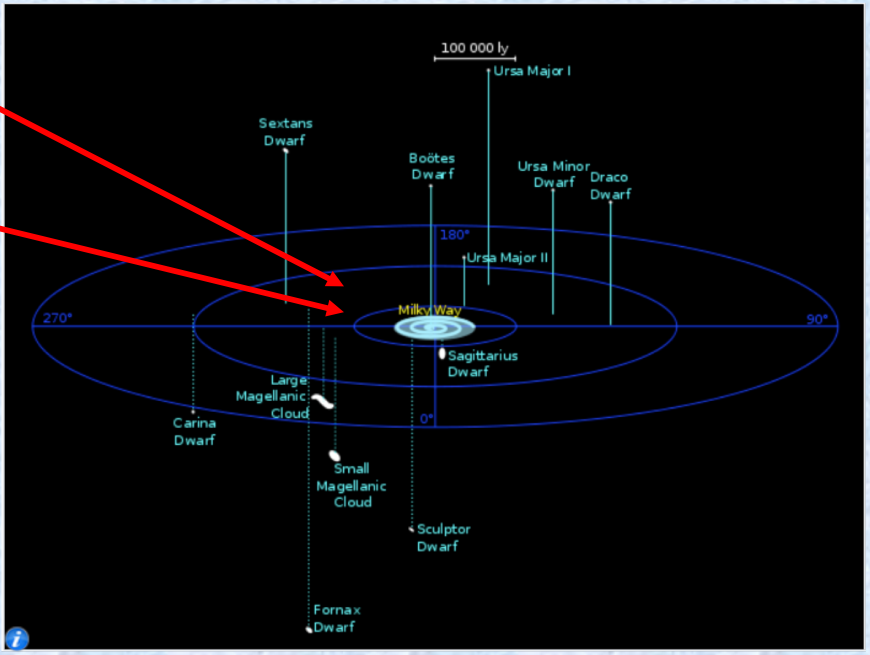


M33 rotation curve

(fig. 1)

How Much Matter?





- How massive is the Milky Way Galaxy?
  - The Milky Way rotates at about 220 km/s.
  - Distance from the Sun to the center of the MW is 8.5 kpc.
  - Dark halo extends to 75 (300) kpc
  - [blackboard] – Dynamical mass vs. radius.
- *Could this matter be stars?* [Let's work it out and check.]

Luminous Matter in Galaxies: I. Stars

- The light in galaxies is centrally concentrated; it falls off exponentially with radius.
- The density of stars is largest near the center.
- Integration yields total luminosity of Milky Way Galaxy as **$L_B \sim 2.3e10\ L_{0,B}$.**

Within R = 8.5 kpc, we have $<M/L_B> = 9.6e10 / 2.3e10 = 4.3\ M_0 /L_{0,B.}$

Within R = 20 kpc, we have $<M/L_B> = 2.3e11 / 2.3e10 = 10\ M_0 /L_{0,B.}$

Within R = 75 kpc, we have $<M/L_B> = 40\ M_0 /L_{0,B.}$

Within R = 300 kpc, we have $<M/L_B> = 150\ M_0 /L_{0,B.}$

Could stars contribute all the light?

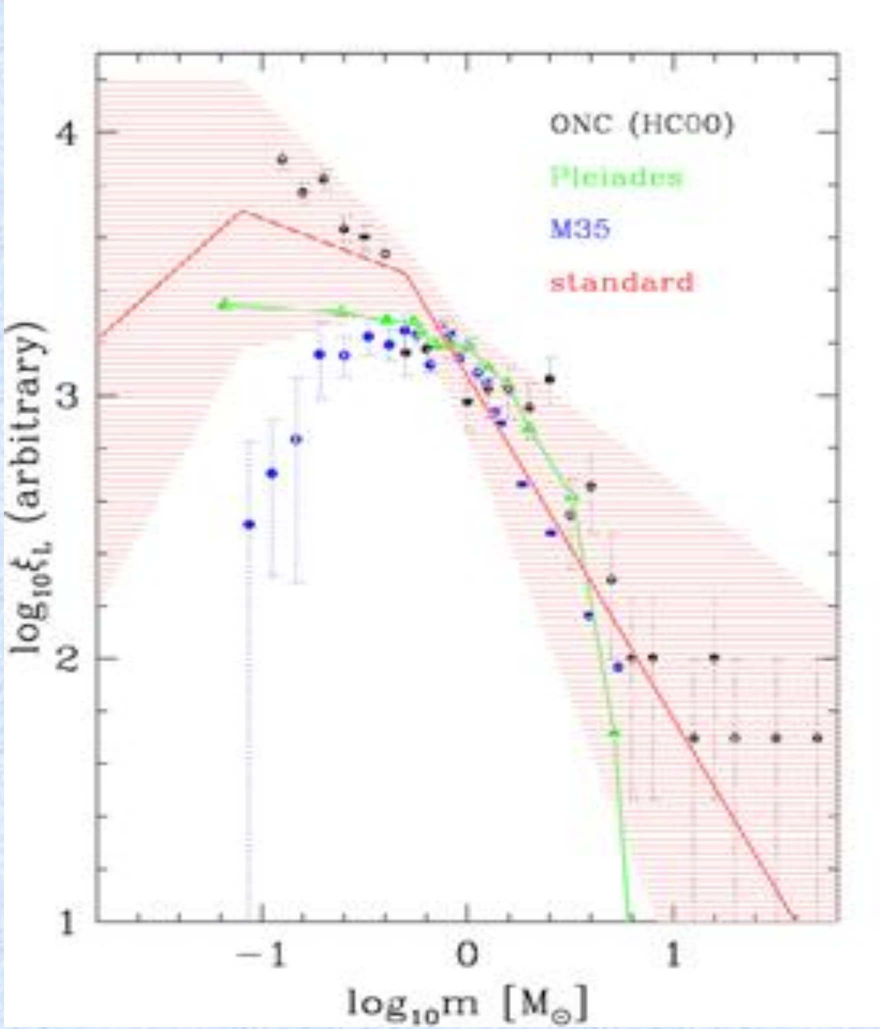
Mass-to-Light Ratio for Stars

- Sun: Easy, 1 M_0/L_0
- What about massive stars?
- What about low mass stars?

- Measured distribution of stellar masses [figure].

- Stellar Mass Function gives mean M/L around 4 M_0/L_0 (in solar units).

Number of stars per unit stellar mass



Luminous Matter in Galaxies: II. Gas

The gas in galaxies extends to larger radii than the stars.

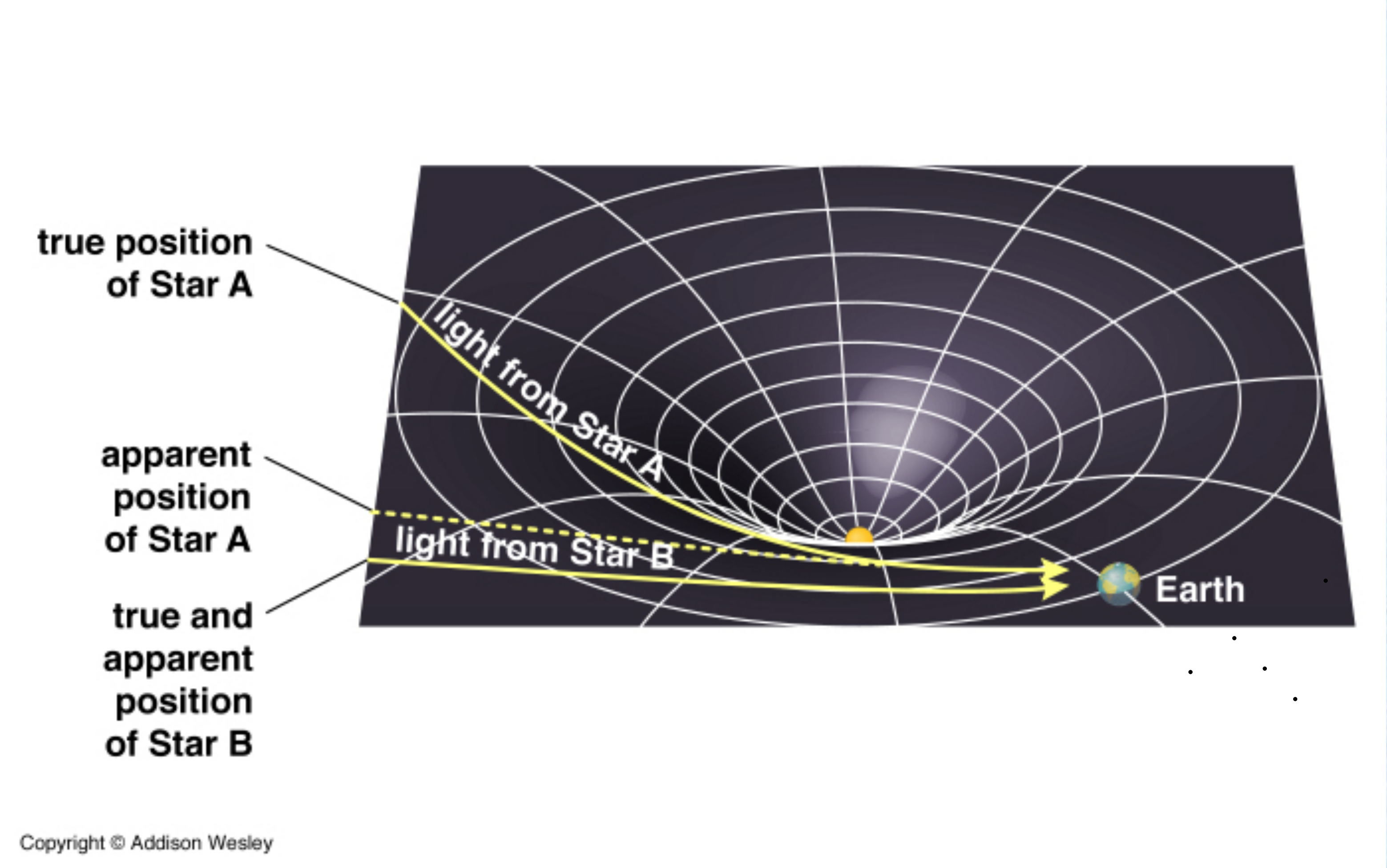
We add the stars and gas to get the total baryonic mass.

- Observe the gas in galaxies with radio telescopes.
- Measured gas mass is similar to the mass in stars.
  - So gas doesn't account for the missing mass.

- *What about 'rocks' or the remnant cores of dead stars?*

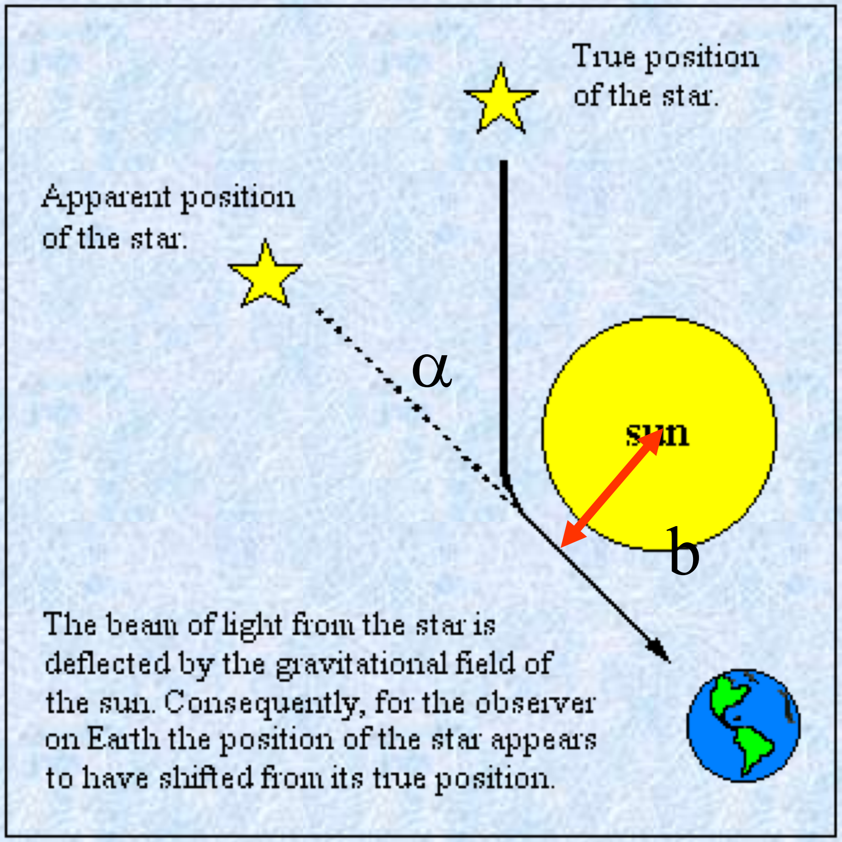
Gravitational Lensing

The strong gravitational field near the surface of a compact object (white dwarf, neutron star, or any massive compact halo object) bends space, so light rays are deflected.



Gravitational Lenses Reveal Concentrations of Matter (Dark or Luminous)

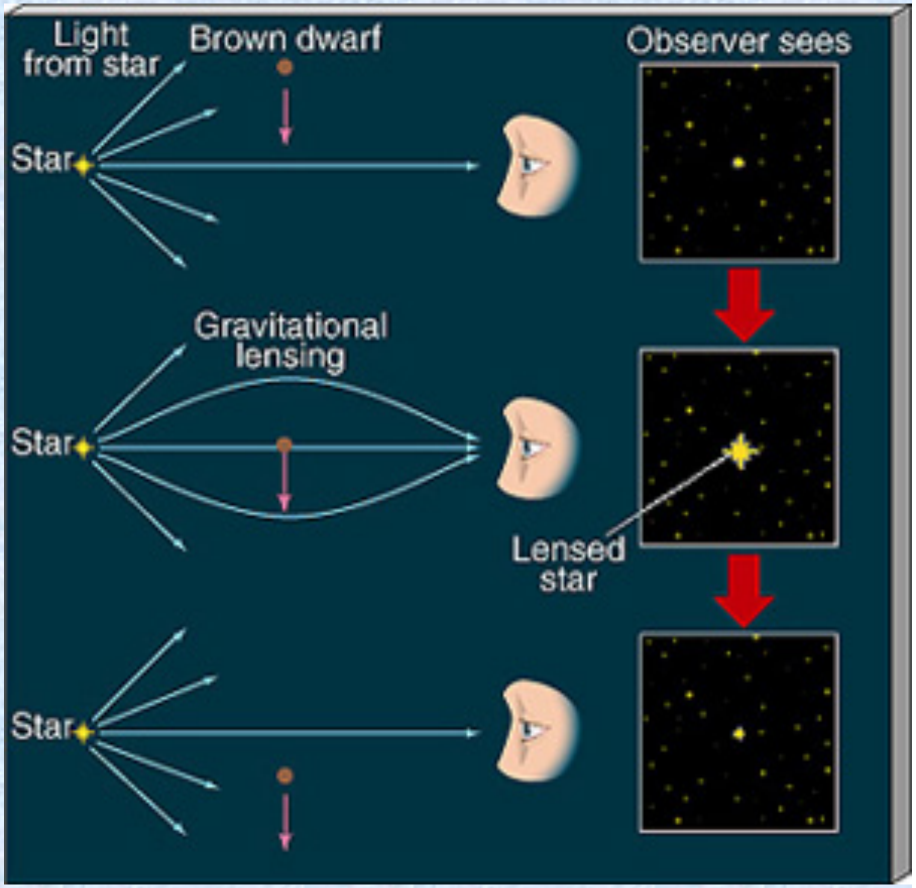
- Einstein said that matter curves space-time
- He predicted the amount by which the light from a star would be deflected when grazing the Sun
- **$\alpha = 4GM / c^2b \sim 1.7'' (M/M_O)(R_0/R)$**
- Confirmed GR on eclipse expedition in 1919
- The physics is very similar to that of common lenses



The beam of light from the star is deflected by the gravitational field of the sun. Consequently, for the observer on Earth the position of the star appears to have shifted from its true position.

Detecting MACHOS via Microlensing

- The deflection of light near the surface of a compact object (white dwarf, neutron star) is large. See HW problem [R 7.3].
- At the distances of halo stars, the deflection is too small to produce multiple images, but it does amplify the luminosity for a time.
- The brightening lasts longer the more massive the compact object.
- The duration of the typical lensing events is ~ a month, so typical masses of compact objects in the halo are > 0.15 Msun. Not planets. White dwarfs?
- **The rate of lensing events indicates < 20% of the halo mass of the Milky Way could be in compact stellar remnants**



Summary

Luminous Matter in Galaxies ($\Omega_* \sim 0.004$, $\Omega_{gas} \sim 0.004$) is a small fraction of the total baryonic matter in the universe ($\Omega_{Baryons} \sim 0.04$)

- Most of the baryons associated with galaxies are in a very dilute gas called the *circumgalactic medium*.

- Dark Matter in Galaxies
  - Either there is dark matter, making up 40 times the stellar component: $\Omega = 0.004 * 40 = 0.16$, which is not baryonic
  - Or, gravitational theory is wrong at small accelerations (modified Newtonian dynamics - MOND)

The Virial Theorem

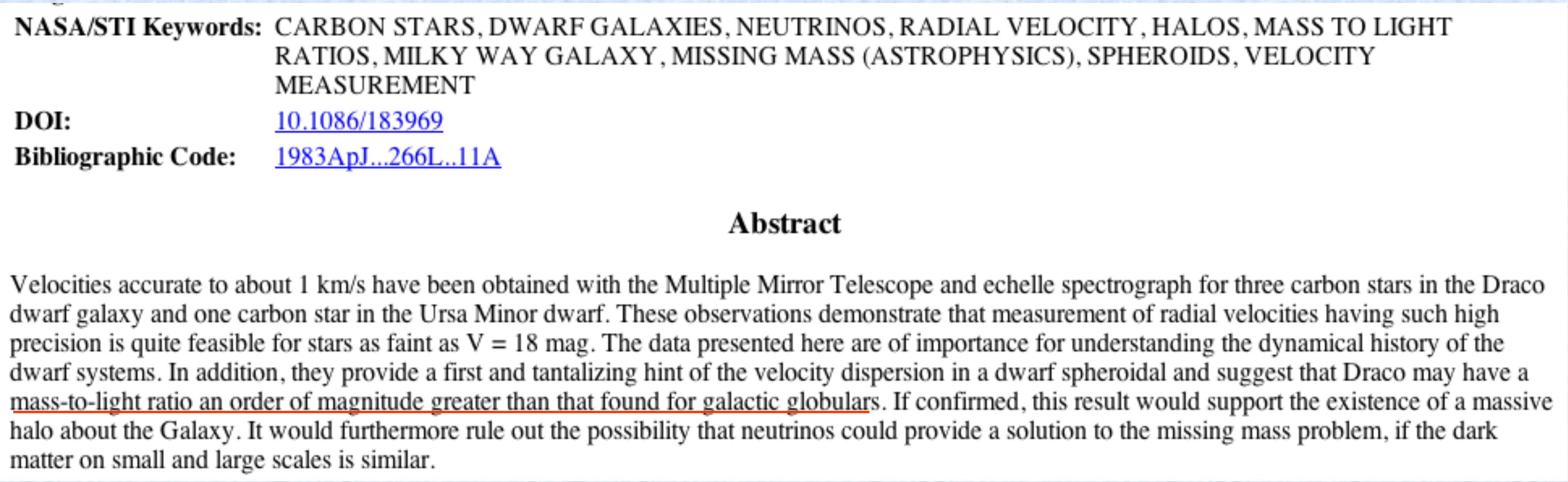
Draco

HW - problem [7.2]

$L = 1.8\text{e}5\ L_0$
$R_h = 120$ pc
$\sigma_r = 10.5$ km/s

- What is the mass of the Draco galaxy?
- What is the M/L ratio?
- Propagate errors.

A History Lesson… The Draco Dwarf



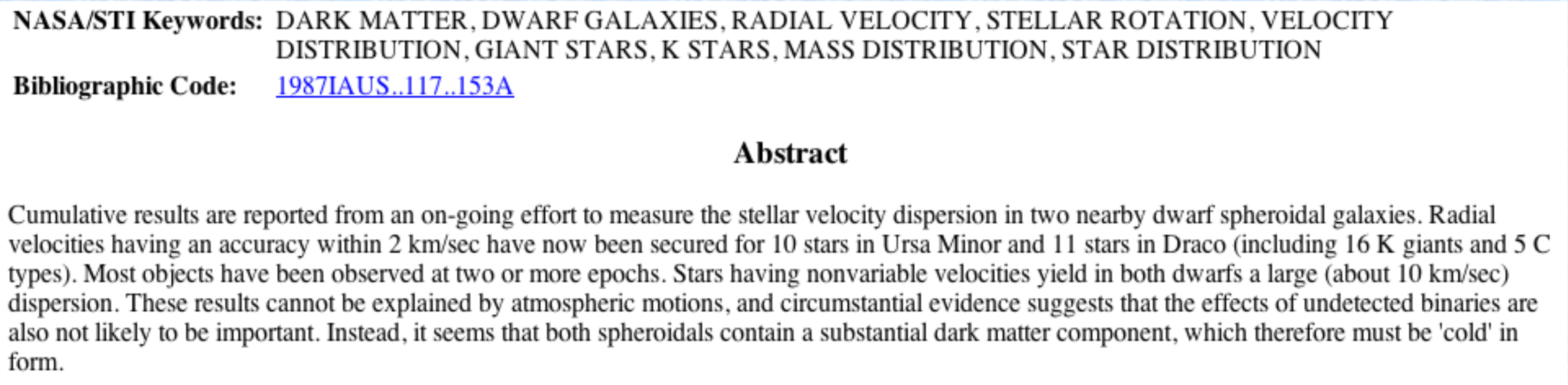
NASA/STI Keywords: CARBON STARS, DWARF GALAXIES, NEUTRINOS, RADIAL VELOCITY, HALOS, MASS TO LIGHT RATIOS, MILKY WAY GALAXY, MISSING MASS (ASTROPHYSICS), SPHEROIDS, VELOCITY MEASUREMENT

DOI: 10.1086/183969

Bibliographic Code: 1983ApJ...266L..11A

Abstract

Velocities accurate to about 1 km/s have been obtained with the Multiple Mirror Telescope and echelle spectrograph for three carbon stars in the Draco dwarf galaxy and one carbon star in the Ursa Minor dwarf. These observations demonstrate that measurement of radial velocities having such high precision is quite feasible for stars as faint as V = 18 mag. The data presented here are of importance for understanding the dynamical history of the dwarf systems. In addition, they provide a first and tantalizing hint of the velocity dispersion in a dwarf spheroidal and suggest that Draco may have a mass-to-light ratio an order of magnitude greater than that found for galactic globulars. If confirmed, this result would support the existence of a massive halo about the Galaxy. It would furthermore rule out the possibility that neutrinos could provide a solution to the missing mass problem, if the dark matter on small and large scales is similar.



NASA/STI Keywords: DARK MATTER, DWARF GALAXIES, RADIAL VELOCITY, STELLAR ROTATION, VELOCITY DISTRIBUTION, GIANT STARS, K STARS, MASS DISTRIBUTION, STAR DISTRIBUTION

Bibliographic Code: 1987IAUS..117..153A

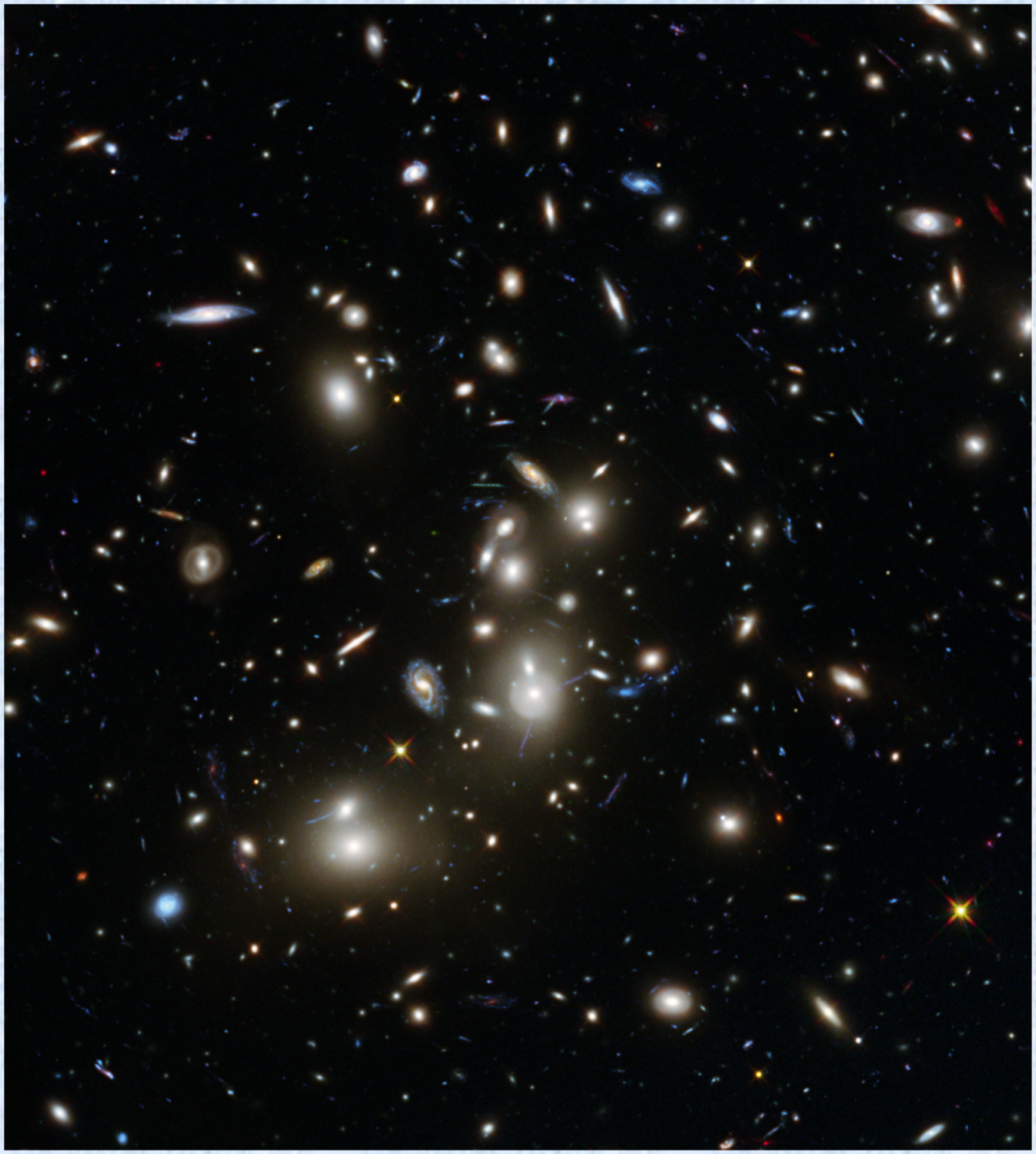
Abstract

Cumulative results are reported from an on-going effort to measure the stellar velocity dispersion in two nearby dwarf spheroidal galaxies. Radial velocities having an accuracy within 2 km/sec have now been secured for 10 stars in Ursa Minor and 11 stars in Draco (including 16 K giants and 5 C types). Most objects have been observed at two or more epochs. Stars having nonvariable velocities yield in both dwarfs a large (about 10 km/sec) dispersion. These results cannot be explained by atmospheric motions, and circumstantial evidence suggests that the effects of undetected binaries are also not likely to be important. Instead, it seems that both spheroidals contain a substantial dark matter component, which therefore must be 'cold' in form.

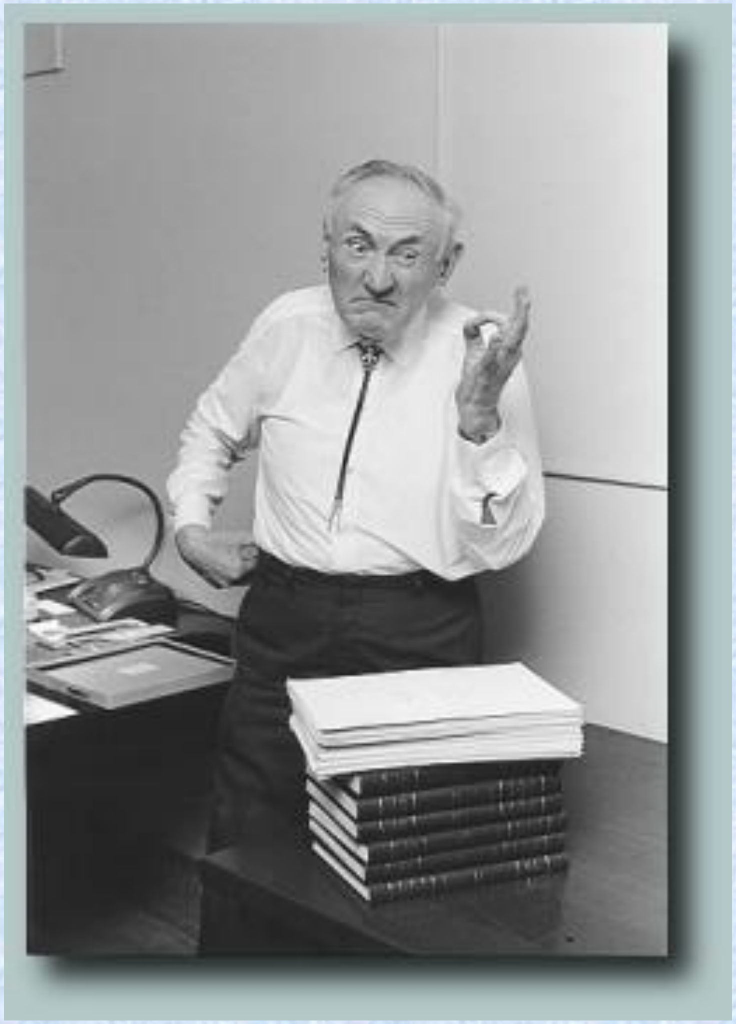
Coma Cluster of Galaxies

- HW [R] 7.5 -- You will estimate the density of galaxies, the mean free path between collisions, and the time between galaxy – galaxy collisions. *[Hint: Galaxy mergers are in fact quite common.]*

- The virial theorem tells us how much mass is required to form a bound galaxy cluster.



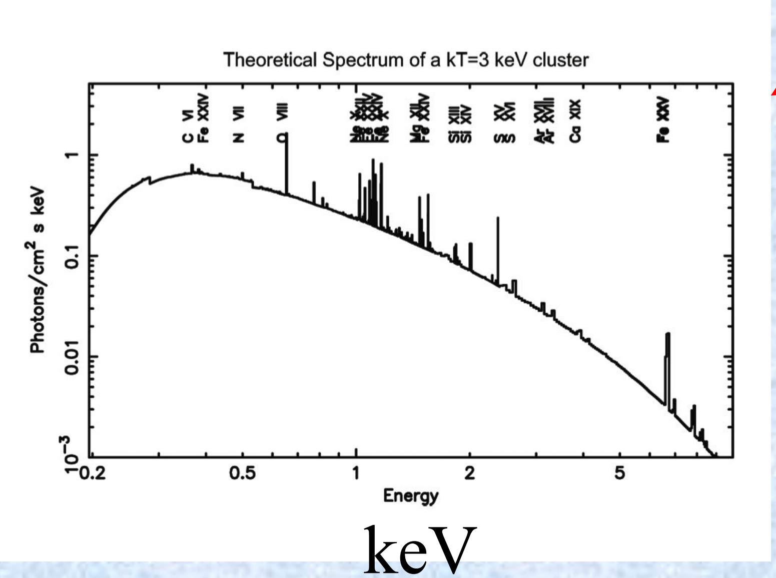
Dark matter in clusters. Virial Theorem



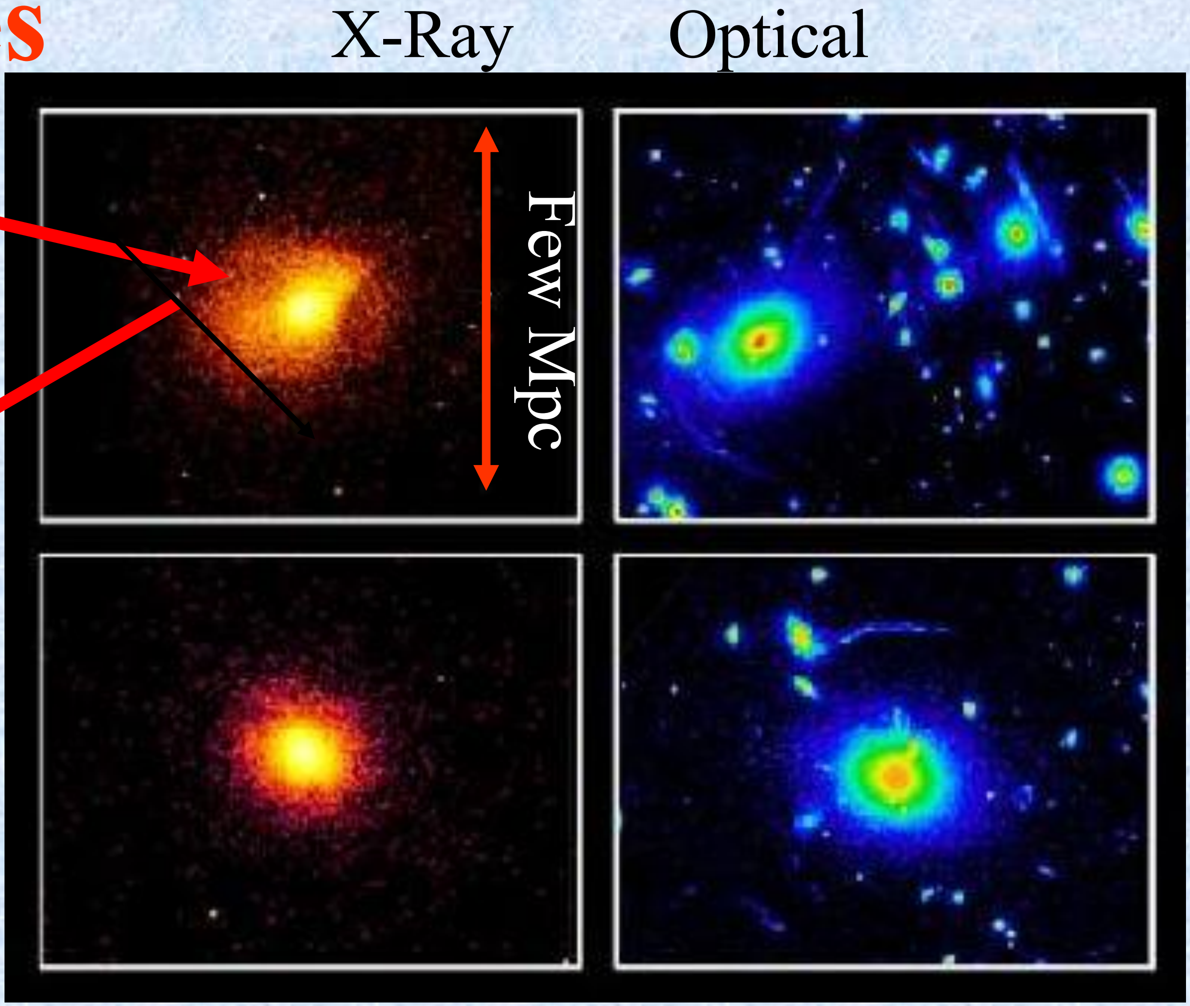
- In the 1930s Zwicky used the virial theorem to derive the mass of the Coma cluster.
- Recall M*=3e13 Msun and Mgas=2e14 Msun
- Coma Cluster: $<\sigma_r>$=880 km/s, r_h=1.5 Mpc implies M=2e15 Msun,
- What assumptions are inherent to this mass estimate?
- The dynamical mass is much higher than that of stars (Zwicky didn't know about ICM)

Intracluster Medium: Very Hot Gas Between Galaxies

X-ray (plasma at T~10^8K)
Brehmsstrahlung Emission



keV



- L_B ~ 8e12 Lsun
- Mstar ~ 3e13 Msun
- Mgas ~ 2e14 Msun
- Mstars~15% Mgas

Hydrostatic equilibrium gives an independent estimate of M(r).

Can the unseen matter in galaxy clusters be gas (rather than non-baryonic matter)?

- A second method to determine cluster mass treats the X-ray emitting plasma as a fluid in **hydrostatic equilibrium.**
- Measure temperature and density gradients to estimate M_{tot}(R). Integrate density profile to get M_{gas} (R).
- Gas mass in Coma (2e14 M_0) ~5 times larger than the stellar mass (4e13 M_0)

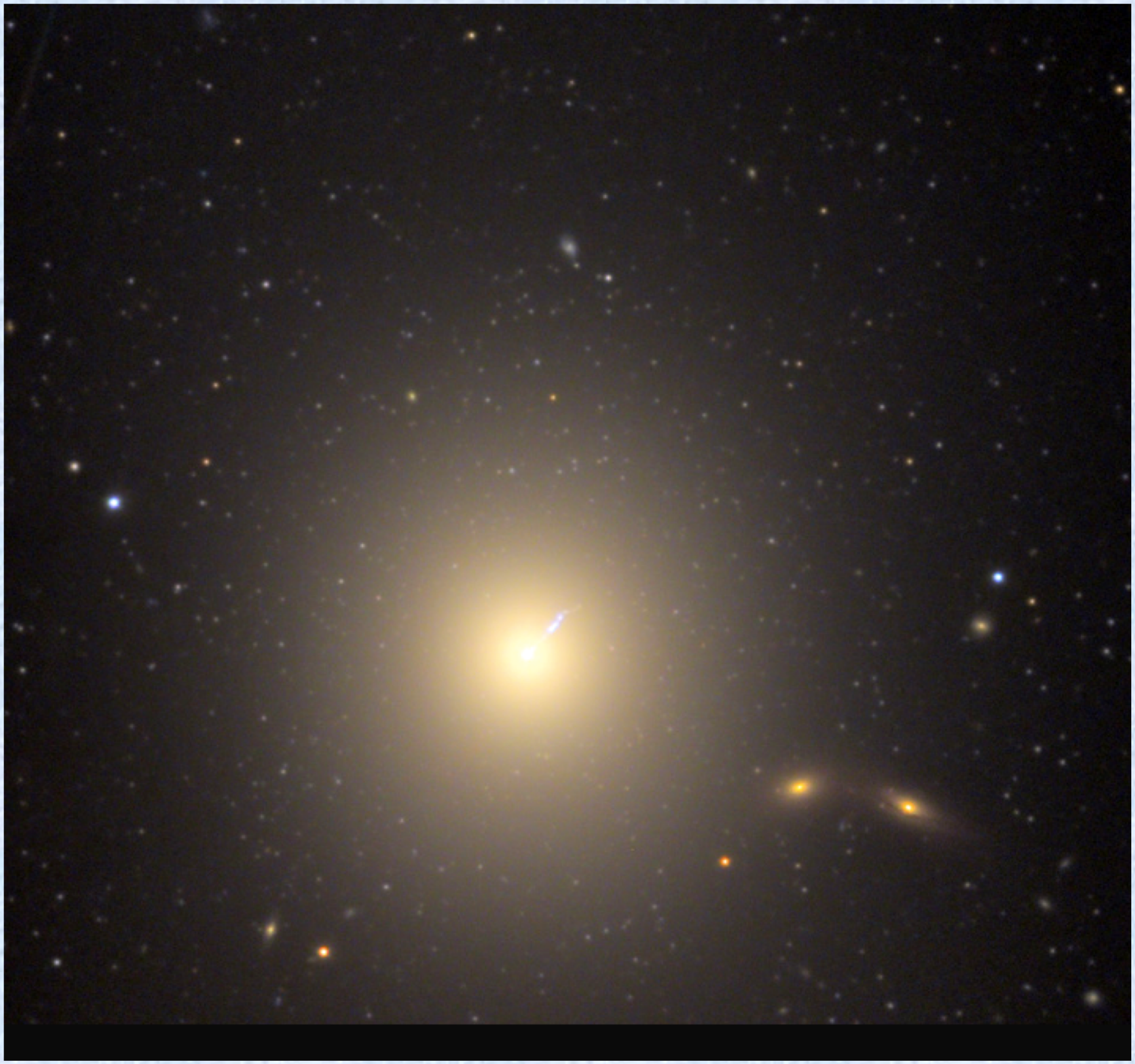
Compare to the total mas of the Coma Cluster 1-2e15 M_0 (R=3.6 Mpc) from the virial theorem:

- $<M/L_B> \sim 200 - 300\ M_0/L_0$
- Adding all the visible matter in clusters together is between 10-30% of the total gravitating mass.
- Clusters are fair samples of the Universe, m(baryons)/m(total)= $\Omega_b/\Omega_m = 0.04 / (0.23 + 0.04) = 0.15$

Virial Theorem.
Example: Mass of a Black Hole

- Movie! How stars move around the Galactic Center
- http://www.galacticcenter.astro.ucla.edu/animations.html
- Provides evidence for M_{BH}=3.6e6 M_O object within a small region (radius < 0.7 AU).
  - A black hole with this mass has a Schwarzchild radius of 0.07 AU.
  - This object is likely a black hole because that's the simplest explanation.
- Star SO-2 has a period of 15.56 years.
  - Kepler's 3^{rd} Law says the semi-major axis of the orbit is 0.32 pc.
  - How much does the star move on the sky?
- We can apply the virial theorem to the orbit of SO-2 about the massive central object ($m_* << M_{BH}$).
  - Find an average velocity of 220 km/s.

The Most Massive Galaxies Contain the Most Massive Black Holes & Live in Galaxy Clusters



- The galaxy M87 lies near the center of the Virgo Cluster, which is the nearest galaxy cluster (d = 16.5 Mpc)
- $M_{BH}= (6.5 \pm 0.7) \times 10^9 \, M_\odot$
- R_S= 130 AU

Why are the image distortions called *lensing*?

- Many of the features of gravitational lensing can be reproduced by common optical devices.

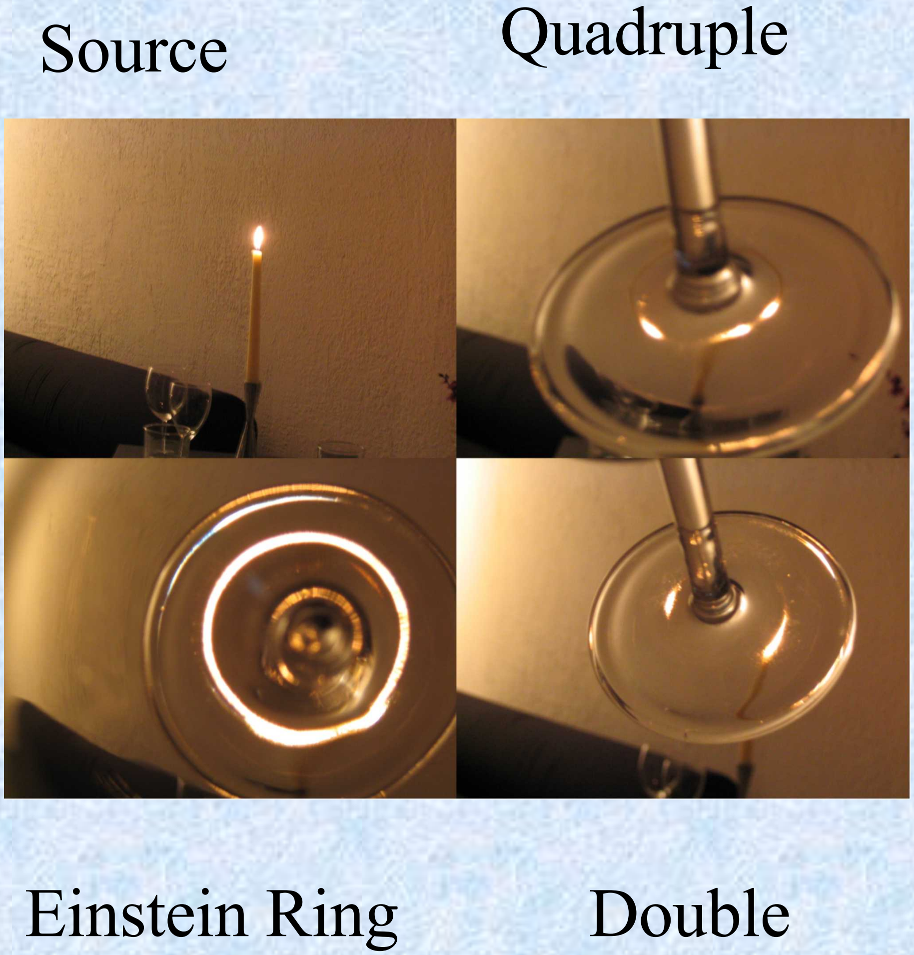
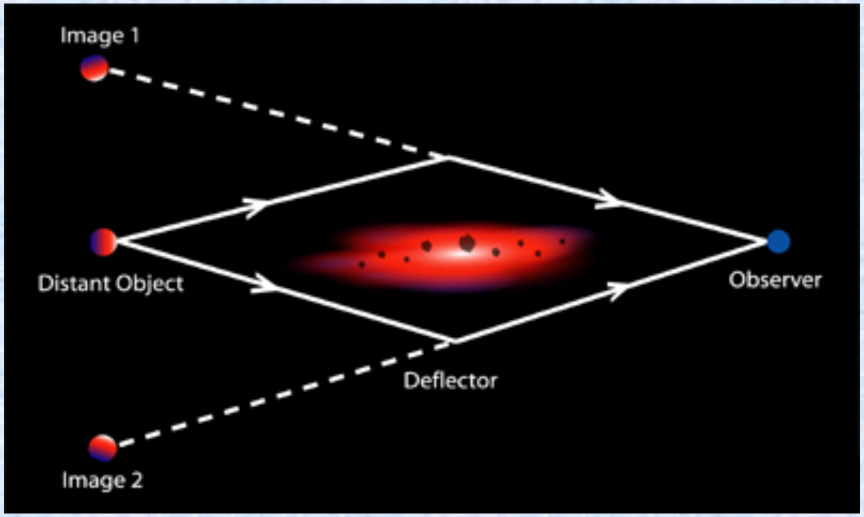


Figure courtesy of Phil Marshall

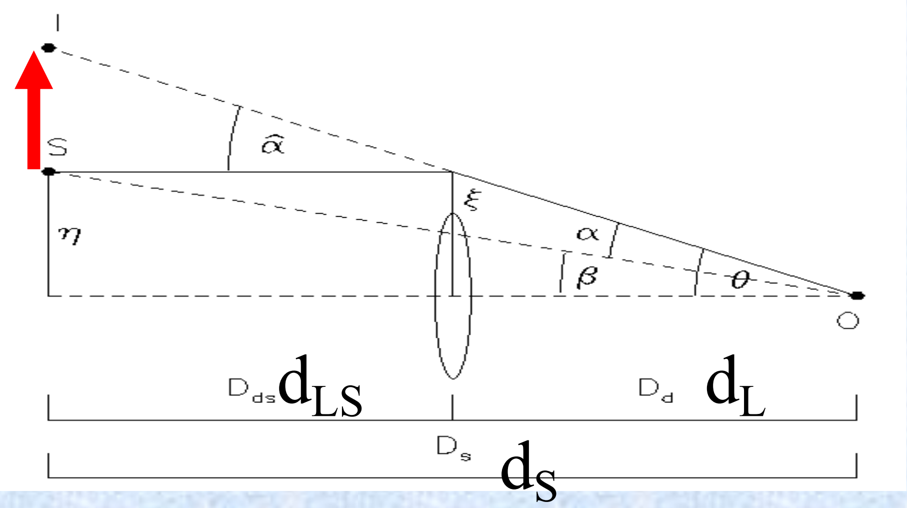
Detecting dark matter.
I. Strong Lensing

- Under special circumstances the distortion is so strong that it creates multiple images of a background object. This is called **strong lensing**



Detecting dark matter with Lenses

- The image separation gives us a direct measurement of the mass enclosed by the images.
- When the lens is directly between the observer and the source the image is a ring - a.ka. Einstein Ring.
- [blackboard]
- What d_L/d_S ratio gives the largest ring?
- How does the size of the ring depend on the mass of the lens?



$$\theta - \beta \underset{\wedge}{=} \alpha(\theta)\frac{d_{LS}}{d_S} = \frac{4GM(<b)}{c^2}\frac{1}{\theta}\frac{d_{LS}}{d_L d_S}$$

$$\theta_E^2 = \frac{4GM(<b)}{c^2}\frac{d_{LS}}{d_L d_S}$$

Galaxies and Galaxy Clusters are Strong Lenses

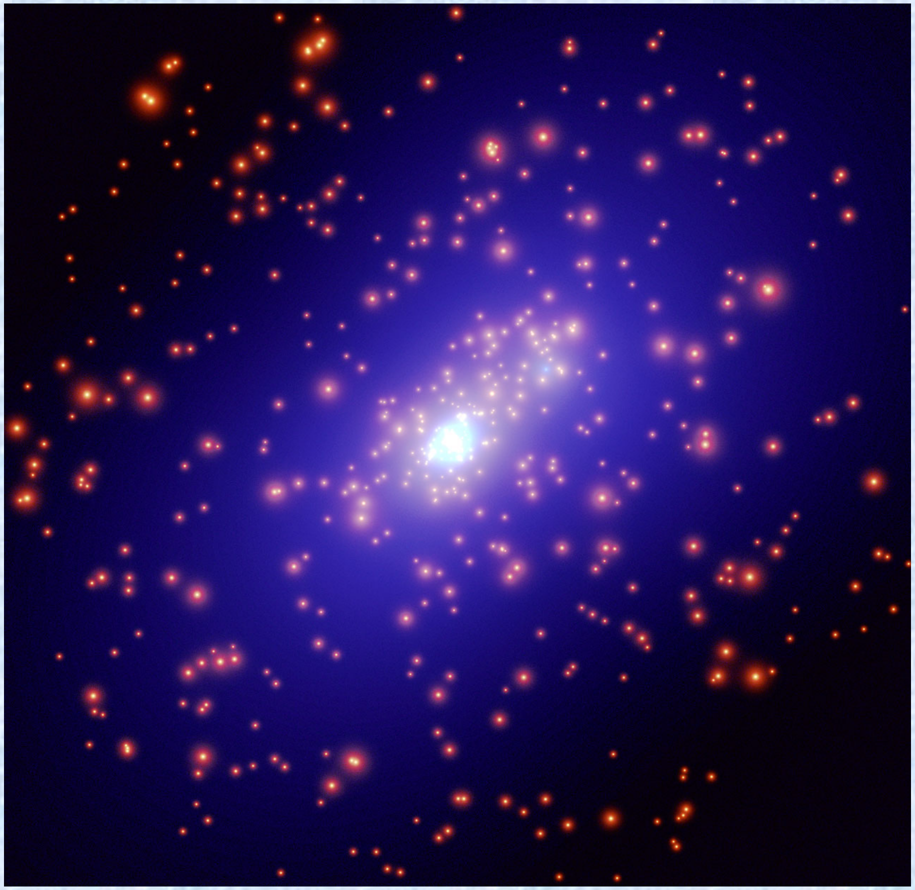
Galaxy cluster mass measurements from lensing agree with those obtained from the virial theorem.

Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

PRC96-10 • ST ScI OPO • April 24, 1996 • W. Colley (Princeton Univ.), NASA

Detecting dark matter.
Weak lensing mass maps

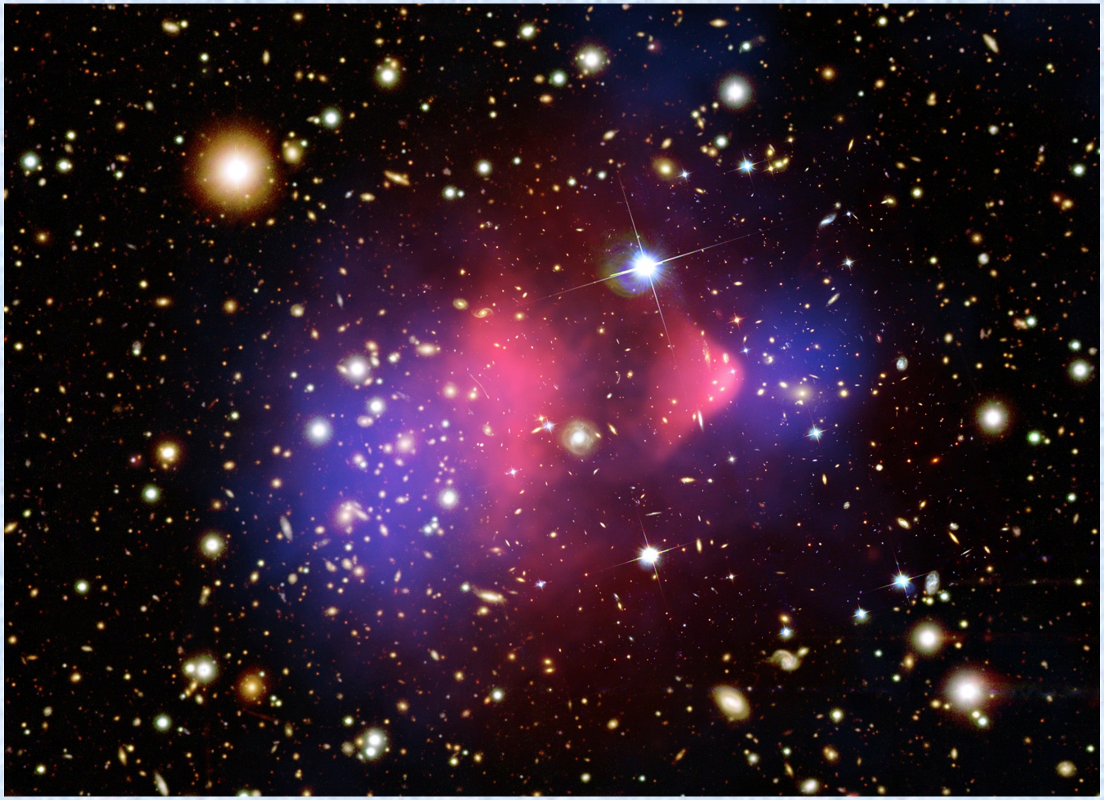
Optical image



Dark matter mass

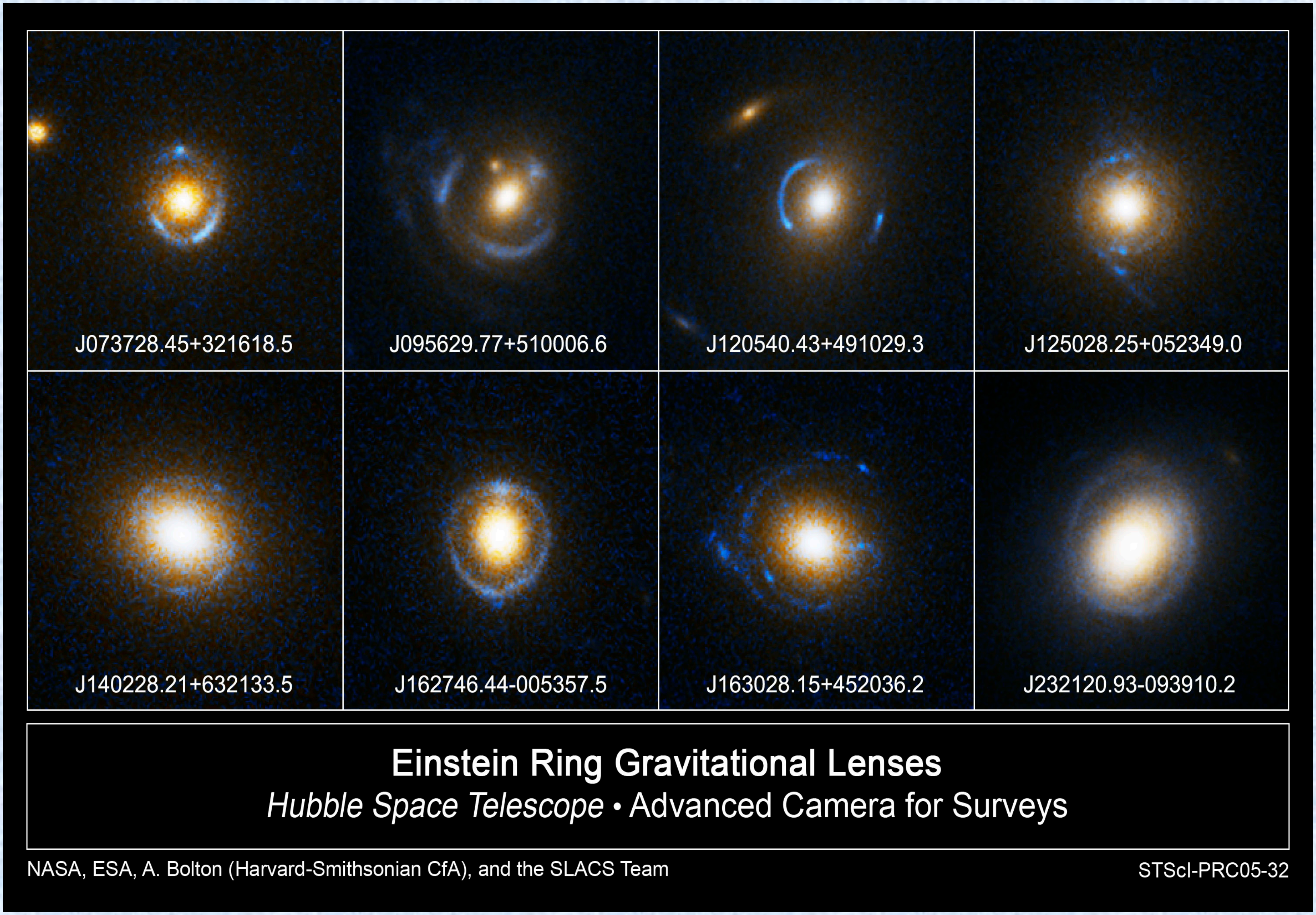
Mass Maps of Colliding Clusters Test the Nature of Dark Matter

- There is mass where there are no baryons
  - –Non baryonic dark matter
  - –MOND is wrong
- Dark matter is collisionless
  - –Limits on self interaction cross section $<0.7 \text{cm}^2/\text{g}$



Clowe et al. 2006; Bradac et al. 2006

Einstein Rings from Strong Lenses



Einstein Ring Gravitational Lenses

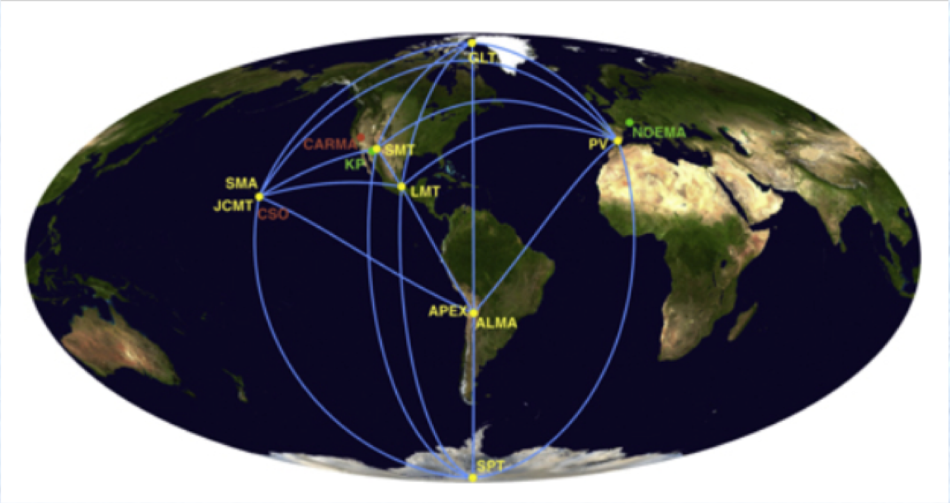
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

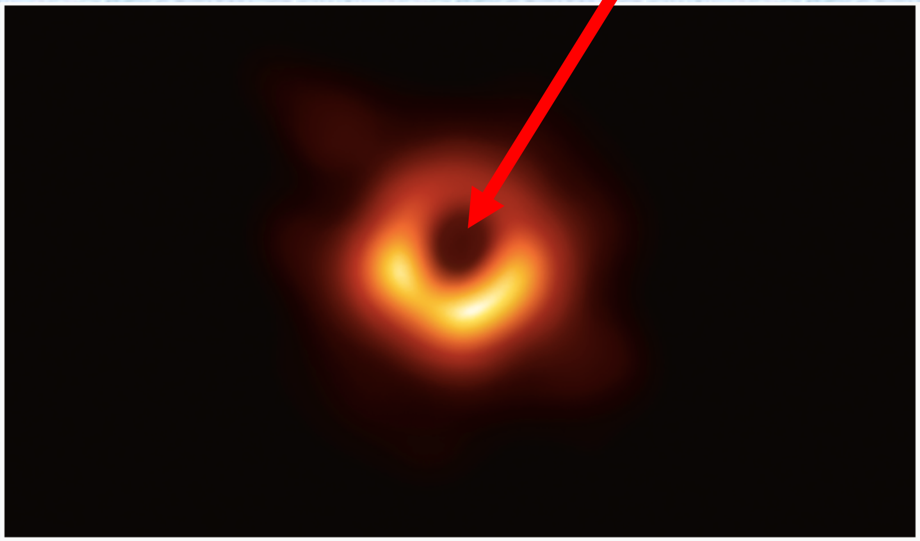
STScI-PRC05-32

Supermassive Black Holes are Strong Lenses

Event Horizon Telescope
April 2019



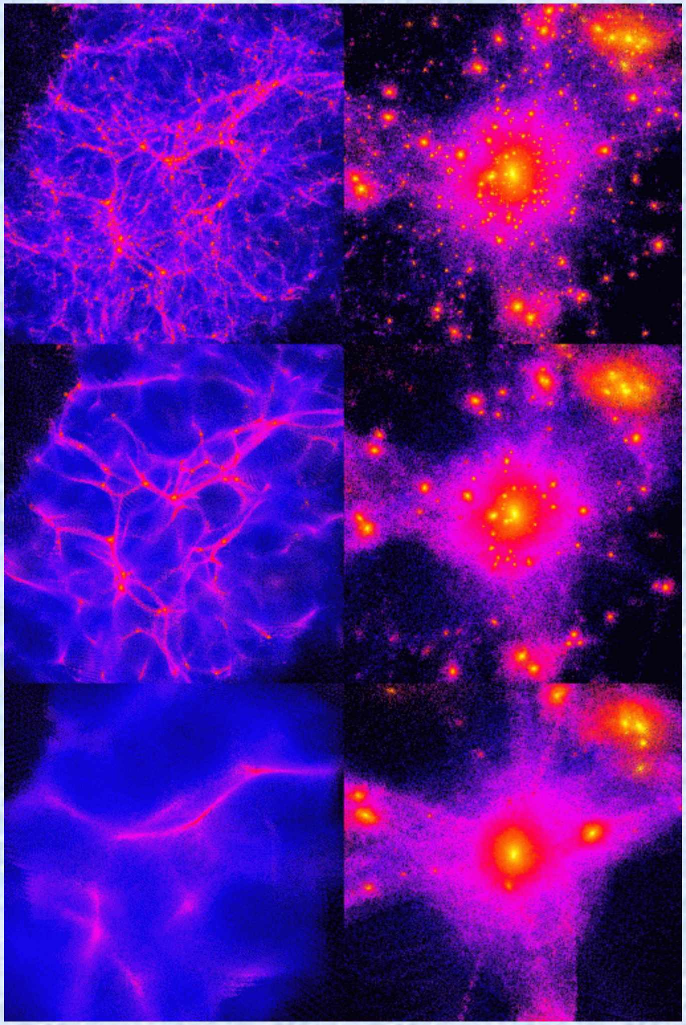
When surrounded by a transparent emission region, black holes are expected to reveal a dark shadow caused by gravitational light bending and photon capture at the event horizon.



The asymmetry in brightness in the ring can be explained in terms of relativistic beaming of the emission from a plasma rotating close to the speed of light around a black hole

What is dark matter?

- We don't know.
- Various extensions of the Standard Model in particle physics known as Supersymmetry predict the existence of massive nonbaryonic particles with energies ~ 10 GeV
- Many people thought that finding the Higgs would determine the nature of dark matter. It hasn't.
- Hot dark matter escapes easily from overdensities, smoothing out large scale structure. This would not match the observed large scale structure



COLD

WARM

HOT

Summary for Week 5

- Galaxies rotate too fast to be held together by their visible matter
  - MACHOS can account for no more than 20% of the Milky Way halo mass
- Dark Matter Holds Clusters of Galaxies together!
  - Weak lensing observations of colliding clusters shows that the dark matter is not dissipational and test theories of gravity.
- Nature of the non-baryonic dark matter is not known.