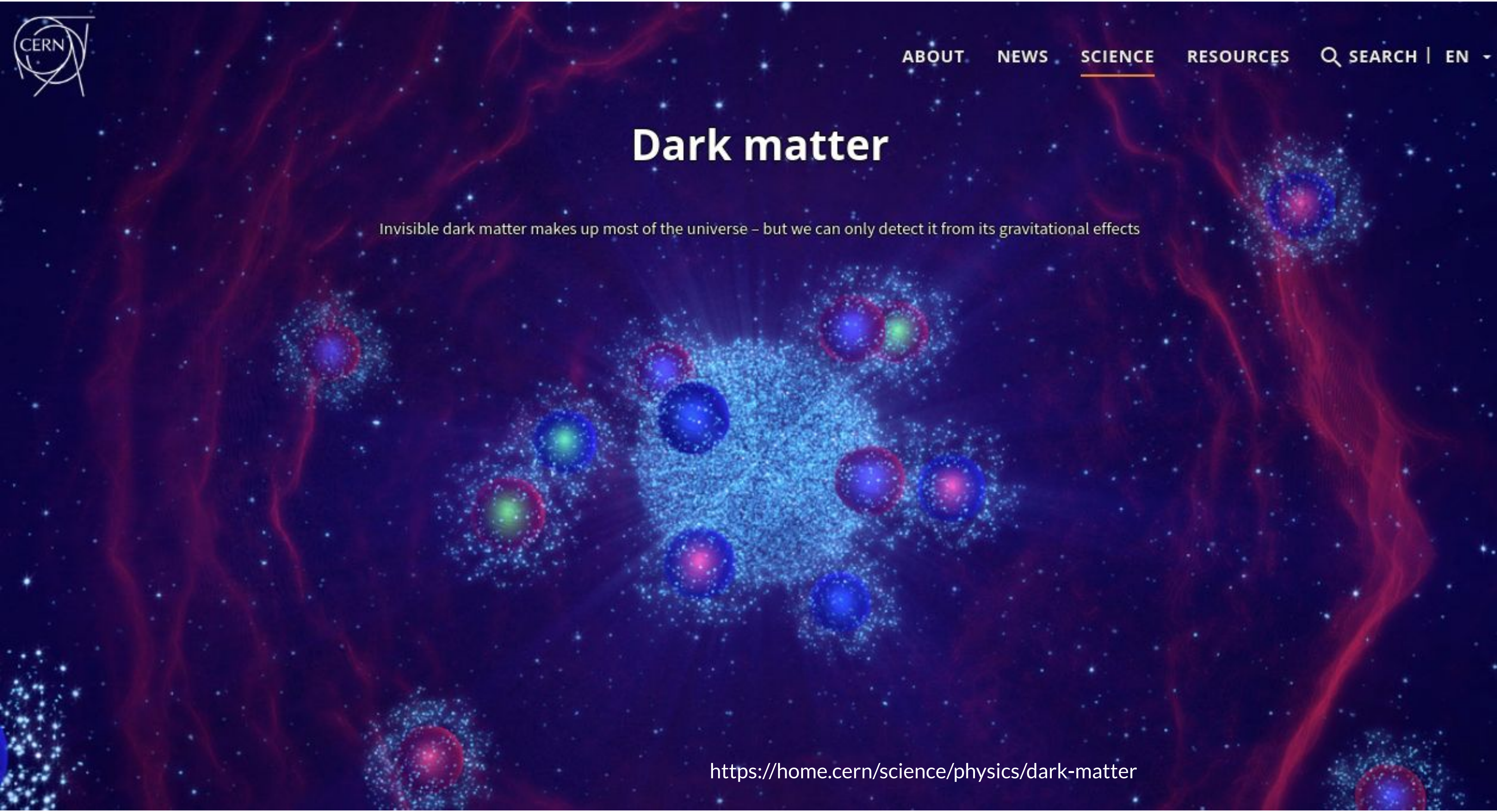
(First) Evidences of Dark Matter

Irina Ene

PH290E, Dec 2, 2020



https://home.cern/science/physics/dark-matter

History of dark matter

Can be divided into 3 main periods:

- 1930’s
  - First hints of dark matter
  - Not yet a concern
- 1970’s
  - More (a lot) evidence from galaxy rotation curves
  - Astronomers can’t ignore the problem anymore
- 1980’s and beyond
  - More astrophysical/cosmological evidence
  - Modern constraints on dark matter in the Universe

1900's: Dark stars, dark planets

New idea/technique in astronomy: Detecting invisible astrophysical objects that influence only through gravitational effects

1844, Friedrich Bessel sent a letter to John Herschel

- Proper motion of Sirius and Procyon imply that they have unobserved, faint companion stars
- "The existence of numberless visible stars can prove nothing against the existence of numberless invisible ones."

XII. Extract from the Translation of a Letter from Professor Bessel, dated Konigsberg, 10th of August, 1844. On the Variations of the Proper Motions of *Procyon* and *Sirius*. Communicated by Sir J. F. W. Herschel.

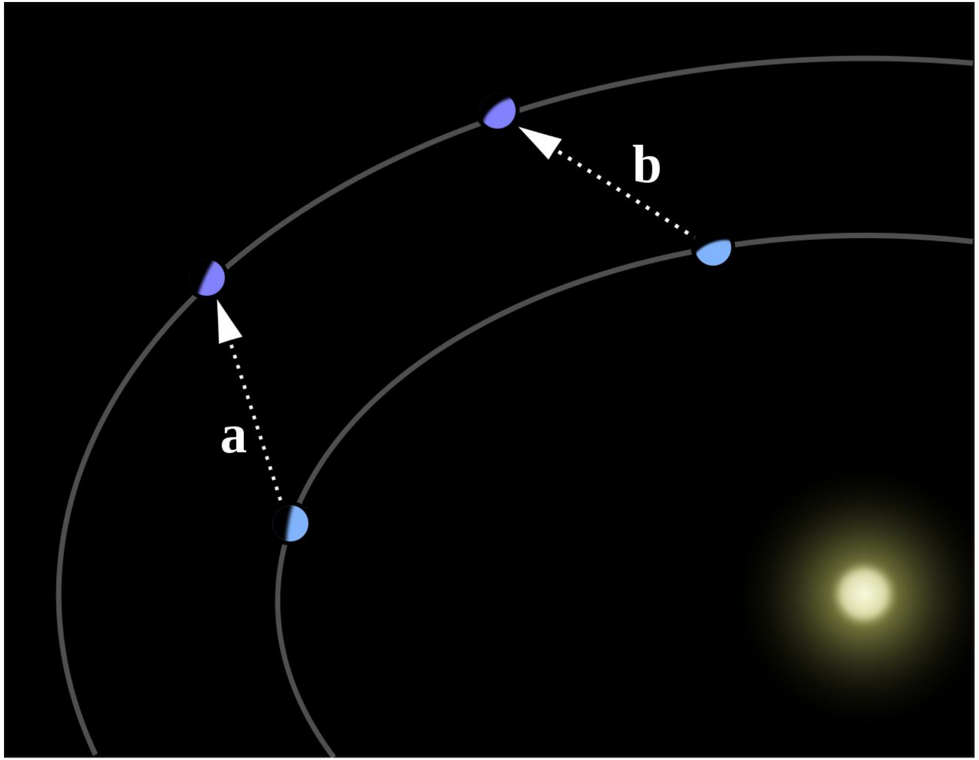
The subject which I wish to communicate to you, seems to me so important for the whole of practical astronomy, that I think it worthy of having your attention directed to it. I find, namely, that existing observations entitle us without hesitation to affirm that the proper motions, of *Procyon* in declination, and of *Sirius* in right ascension, are not constant; but, on the contrary, that they have, since the year 1755, been very sensibly altered. If this be so, the

1900's: Dark stars, dark planets

New idea/technique in astronomy: Detecting invisible astrophysical objects that influence only through gravitational effects

1846, Urbain Le Verrier (and independently by John Couch Adams) propose the existence of a new planet

- Johann Galle and Heinrich D'Arrest observed Neptune (the same night they received Le Verrier's letter, Sep 24)
- Le Verrier also proposed the "dark planet" Vulcan to explain the precession of Mercury's perihelion



1900's: First dynamical estimates

1884, Lord Kelvin was invited to give a series of talks at John Hopkins University

- "Baltimore lectures on molecular dynamics and the wave theory of light"
- Published in 1904 (started writing in 1885)
- Lecture XVI
    - Assumes Milky Way galaxy is a "gas" of stars and estimates how many stars it might contain
    - 10^9 stars

> stars visible in modern telescopes. Young (*General Astronomy*, p. 448) goes beyond this reckoning and estimates at 100 million the total number of stars visible through the Lick telescope. This is only the tenth of our assumed number. It is nevertheless probable that there may be as many as 1000 million stars within the distance r (5); but many of them may be extinct and dark, and nine-tenths of them though not all dark may be not bright enough to be seen by us at their actual distances.

1900’s: First dynamical estimates

1906, Henri Poincare

- “The Milky Way and the theory of gases”
- first explicit mention of “dark matter”
- Since Kelvin estimate agrees with observation → no dark matter

enables us to decide another question. There are the stars which we see because they shine; but might there not be obscure stars which circulate in the interstellar spaces and whose existence might long remain unknown? Very well then, that which Lord Kelvin’s method would give us would be the total number of stars including the dark ones; since his number is comparable

H. Poincaré 481

to that which the telescope gives, then there is no dark matter, or at least not so much as there is of shining matter.

1900’s: First dynamical estimates

1932, Jan Oort

- Studying the numbers and velocities of stars near the Sun
- Finds total matter density near Sun to be 6.3×10^{-24} g/cm^3
- Calculation that density of “nebulous or meteoric matter” is less than 3×10^{-24} g/cm^3

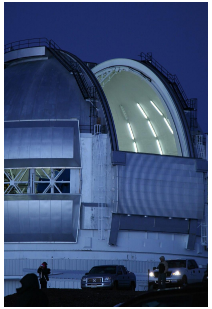
Astronomers of the time thought that dark matter was made of faint stars, nebulous, meteoric matter!

11. *The amount of dark matter.*

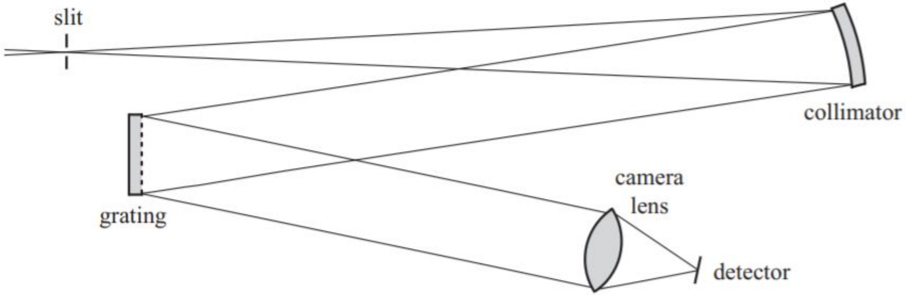
From the results found for the decrease of $K(z)$ with z we may derive an approximate value of the total density of matter, Δ, in the neighbourhood of the sun. Let us suppose that we are situated inside a homogeneous ellipsoid of revolution with semi-axes a and c, and density Δ. For $z = 0$ there will then

We may conclude that the total mass of nebulous or meteoric matter near the sun is less than ·05 suns/ps^3 or 3.10^{-24} g/cm^3; it is probably less than the total mass of visible stars, possibly much less.

Interlude: How do you measure velocity of star/galaxy? Spectroscopy!

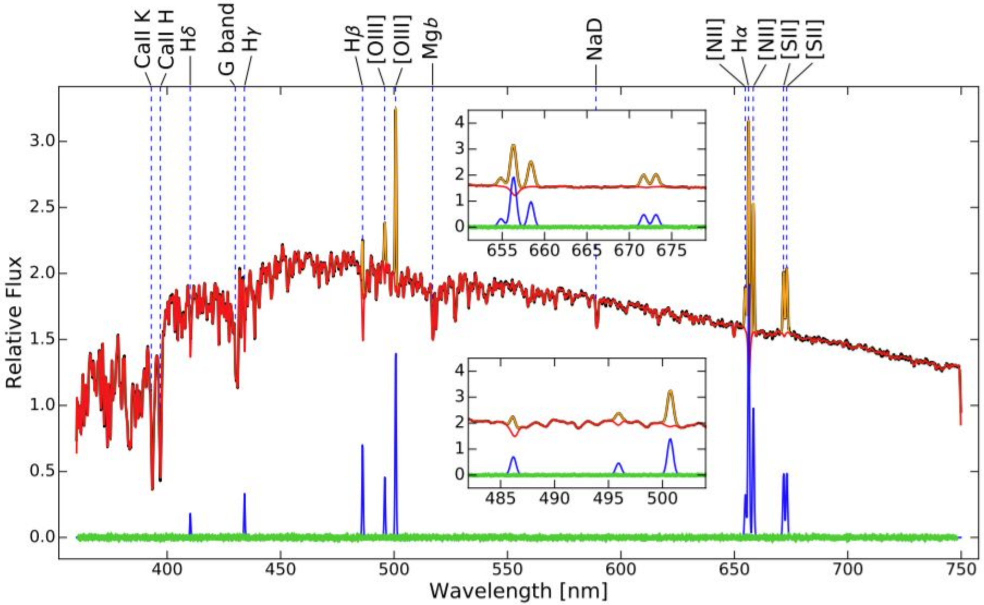


Vadim Kurland, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=10580700



https://home.strw.leidenuniv.nl/~franx/technicalresearchinformation/AstronomicalSpectroscopy.pdf

Spectrum with absorption/emission features



Interlude: How do you measure velocity of star/galaxy?

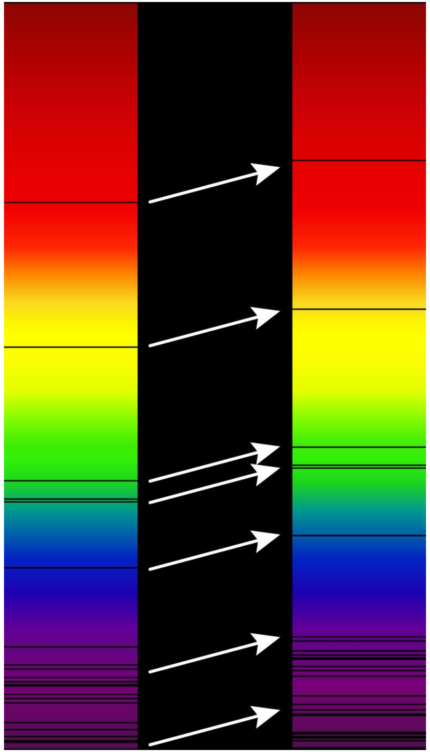
Doppler shift: light from moving objects appears to have different wavelengths depending on the relative motion between the source and the observer

- Source moving away: longer (red) wavelengths
- Source moving towards: shorter (blue) wavelengths

1 + z = wavelength observed / wavelength emitted

z = redshift

For small z, v ~ cz, with c = speed of light



1930’s: Galaxy clusters

1933, Fritz Zwicky

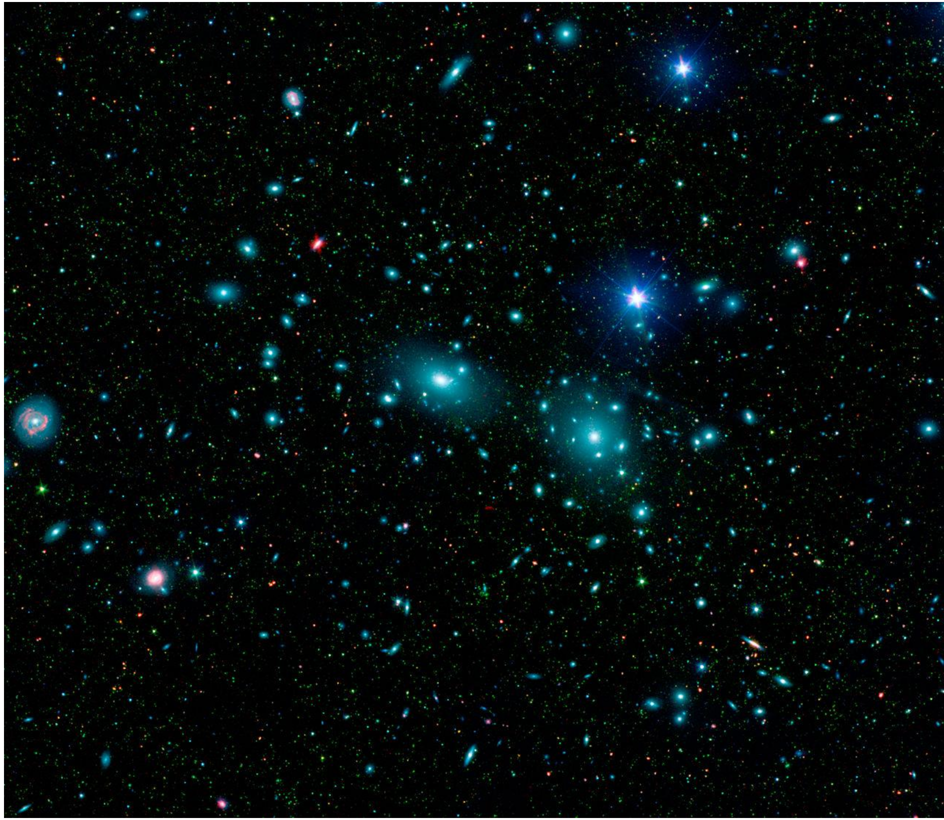
“The redshift of extragalactic nebulae”

- Coma cluster
- Velocity measurements for 8 galaxies
- Large variations from the mean

Rotverschiebung extragalaktischer Nebel. 119

Scheinbare Geschwindigkeiten im Comahaufen.

$v =$ 8500 km/sek	6900 km/sek
7900	6700
7600	6600
7000	5100 (?)



NASA / JPL-Caltech / L. Jenkins (GSFC) - http://www.spitzer.caltech.edu/images/1803-ssc2007-10a1-Dwarf-Galaxies-in-the-Coma-Cluster

1930's: Galaxy clusters

1933, Fritz Zwicky
"The redshift of extragalactic nebulae"

- First use of virial theorem to determine mass of cluster
    - his calculation yielded velocity dispersion of 80 km/s, while the observed value was ~1000 km/s
- More matter than could be seen!
- "If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter."

Virial theorem:

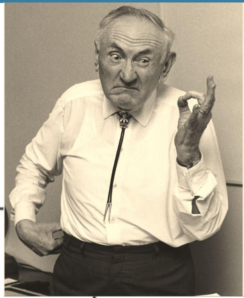
$$\langle KE \rangle = -\frac{1}{2}\langle PE \rangle$$

$$\frac{1}{2}M\langle v^2 \rangle = -\frac{1}{2}\left(-\frac{3}{5}\frac{GM^2}{R}\right)$$

M ~ 800 galaxies x 10^9 solar masses/galaxy
R ~ 10^{24} cm (1 million light years)

Velocity dispersion = root mean square velocity of 80 km/s

1930’s: Galaxy clusters



1937, Zwicky refined calculation, this time wanting to find the mass of galaxies in Coma cluster

- Virial theorem (dispersion → mass)
- R ~ 2 x 10^6 light years
- Dispersion ~ 700 km/s
- 1000 galaxies in the cluster
- 4.5 x 10^{10} solar masses per galaxy
- More mass than could be seen!
- “[...] dark matter is incorporated in nebulae in the form of cool and cold stars, macroscopic and microscopic solid bodies, and gases.”

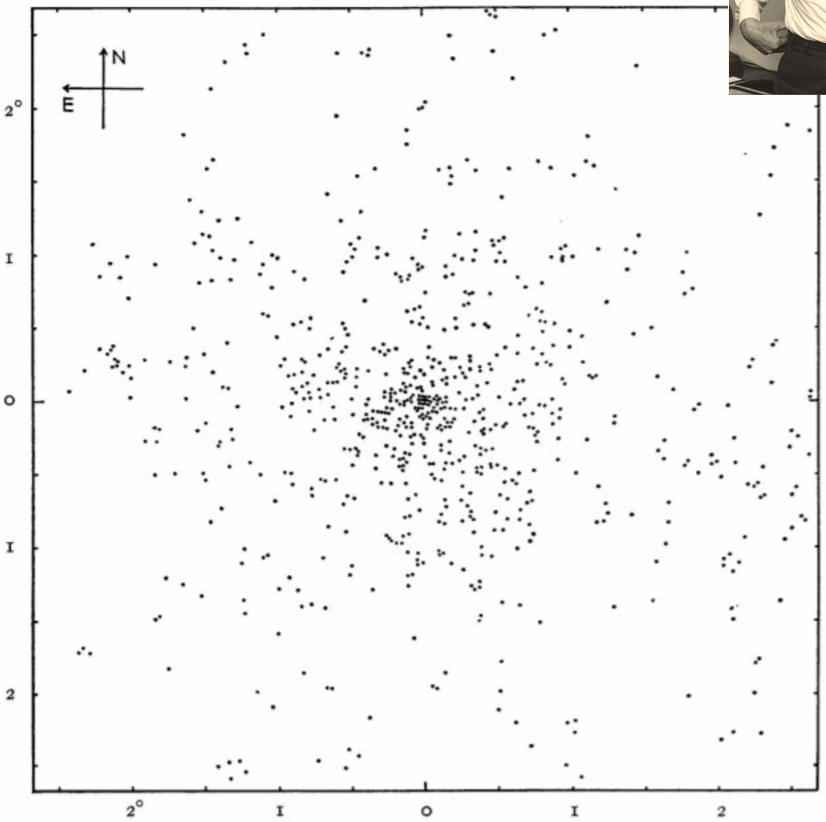


FIG. 3.—The Coma cluster of nebulae

1970's: Galaxy rotation curves

Expectation:
For a rotating disk of stars and gas, the velocity should start decreasing beyond the point where most of the mass is concentrated ("Keplerian")

Simple Newtonian dynamics: $$\frac{GM(r)m}{r^2} = \frac{mv^2}{r} \rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

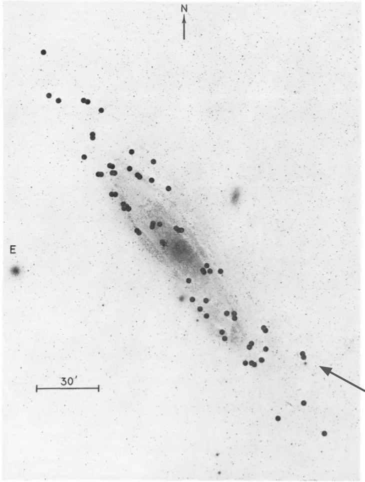
Observation:
The rotational velocity stays the same as the radius increases

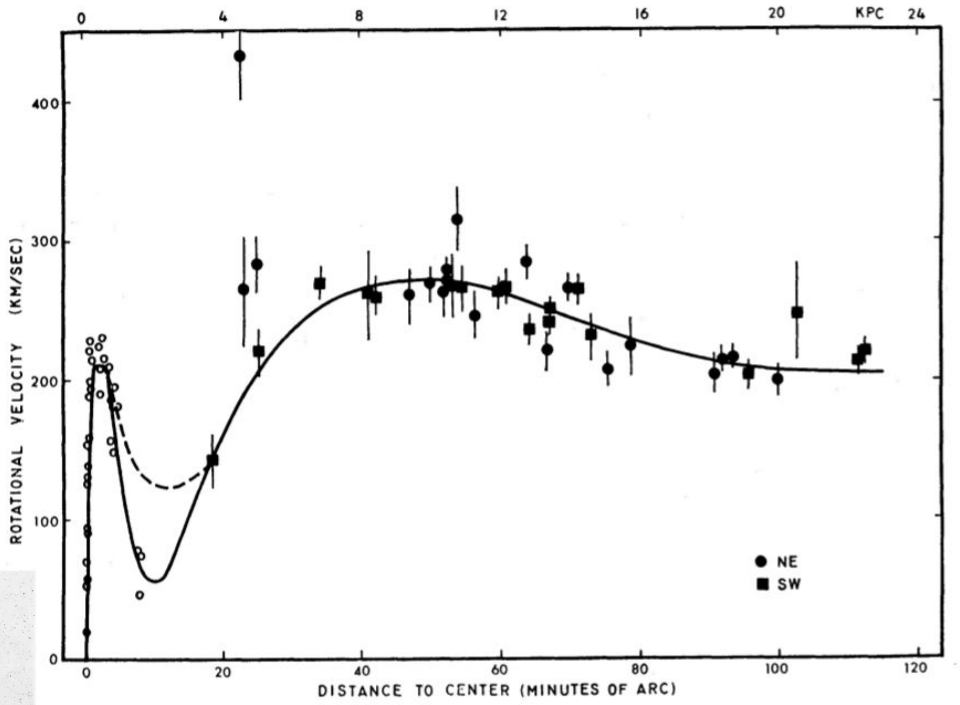
→ There must be more mass in the outer parts of the galaxy.

https://physicstoday.scitation.org/doi/10.1063/1.2435662

1970's

Vera Rubin and Kent Ford, 1970
Studying the rotation curve of M31 (Andromeda galaxy).





Significant rotation at large distance from the center of the galaxy!
No strong claim about extra matter!

One optical spectrum per dot

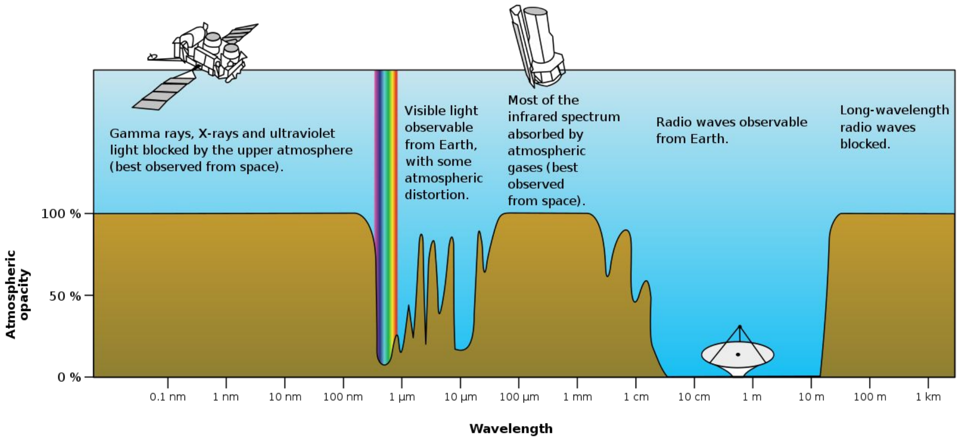
21-cm HI line

1951, Harold Ewen and Edward Purcell detect the 21 cm line.

Due to the spin-flip transition of hydrogen ground state.

Can be used to measure rotation in the outer parts of galaxies, where there are not very many stars.

Earth's atmosphere is transparent in the radio band.



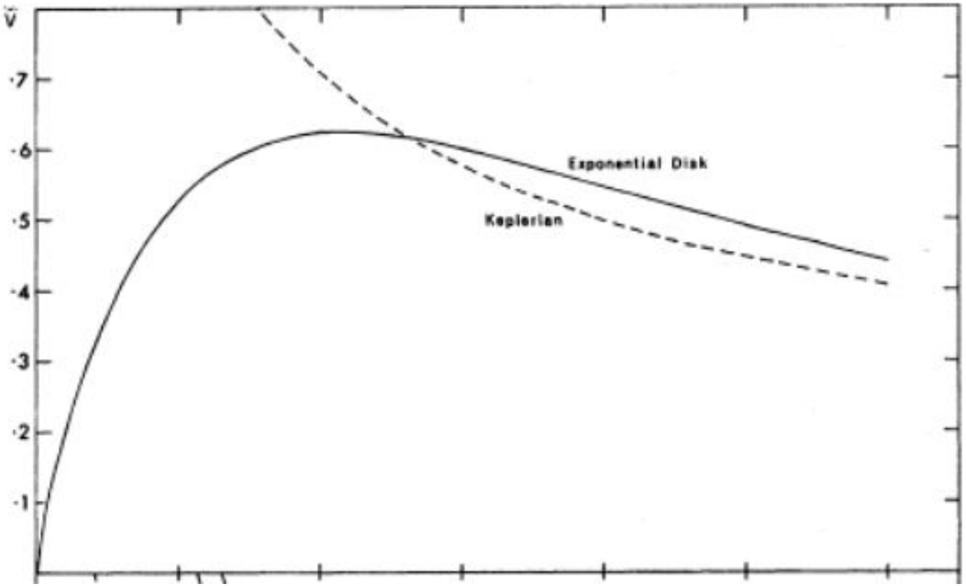
By NASA (original); SVG by Mysid. Public Domain, https://commons.wikimedia.org/w/index.php?curid=5577513

1970's: Galaxy rotation curves

Ken Freeman, 1970
"On the disks of spiral and S0 galaxies"

Appendix:
"For NGC 300 and M33, the 21-cm data give turnover points near the photometric outer edges of these systems. These data have relatively low spatial resolution; if they are correct, then there must be in these galaxies additional matter which is undetected, either optically or at 21 cm. Its mass must be at least as large as the mass of the detected galaxy, and its distribution must be quite different from the exponential distribution which holds for the optical galaxy."

- First convincing (convinced) claim for extra mass in spiral galaxies



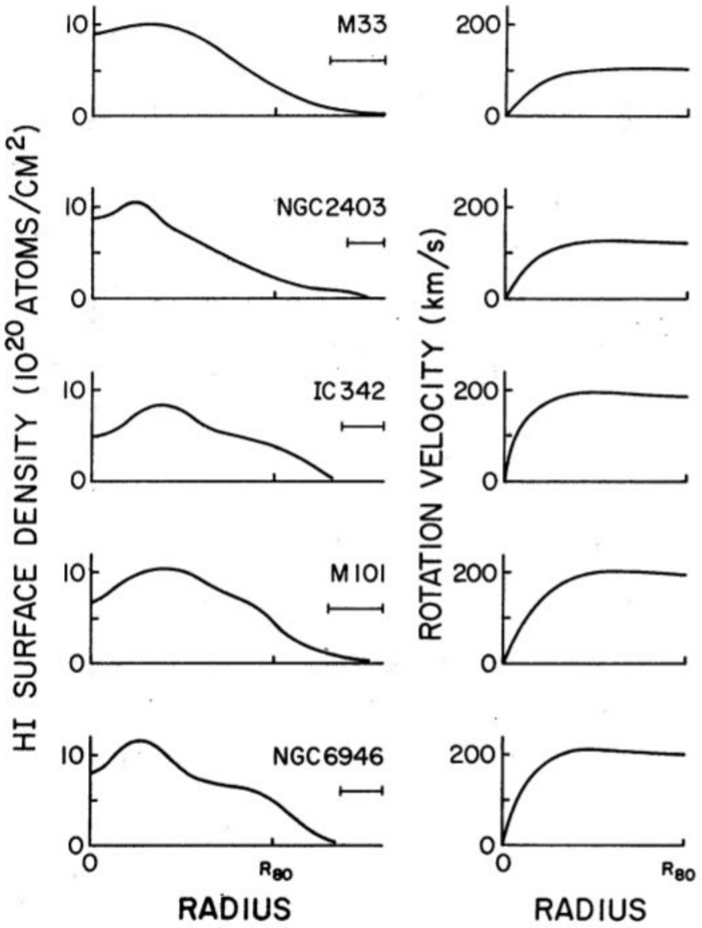
1970’s: Galaxy rotation curves

Rogstad and Shostak, 1972

Rotation curves for 5 spiral galaxies derived from HI emission lines:

Conclusion:

In addition, we confirm here the requirement for low-luminosity material in the outer regions of these galaxies ($M/L \sim 20$), assuming exponentially decreasing surface luminosities (Freeman 1970). The global mass-luminosity ratio M_{80}/L_B for the three unobscured objects is ~ 5. We note that this is considerably higher than the average value for spirals and irregulars observed by Page (1962) in double systems ($\langle M/L \rangle = 1.7$ for a Hubble constant of 60 km s^{-1} Mpc^{-1}).

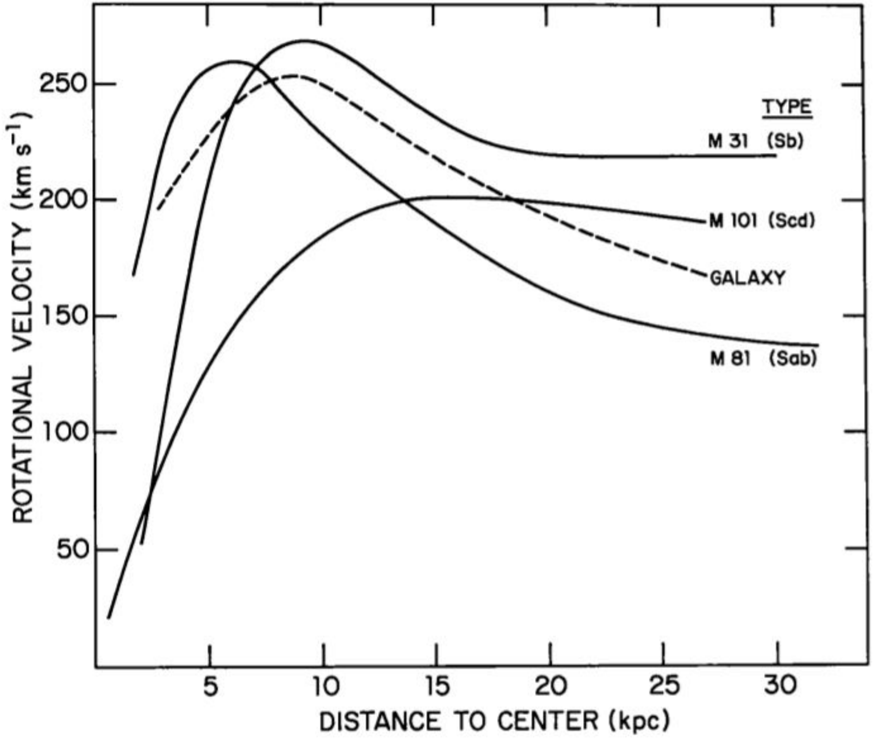


1970’s: Galaxy rotation curves

Roberts and Rots, 1973

Summary. Rotation curves extending to large radial distances are now available for 3 spiral galaxies, each of a different type. Differences in shape of the rotation curves indicate a mass distribution that is related to structural type and is in the same sense as the luminosity distribution for these galaxies. The shapes of the rotation curves at large radii indicate a significant amount of matter at these large distances and imply that spiral galaxies are larger than found from photometric measurements.

Key words: galaxies – rotation curves



People are starting to believe

1973, Ostriker, Peebles - “A numerical study of the stability of flattened galaxies”
They find that galaxies without DM halos are unstable and would fall apart.

1974, Einasto, Kaasik, Saar - “Dynamic evidence on massive coronas of galaxies”
“This discrepancy cannot be the result of expansion or be because of the recent origin of clusters[...]. Therefore it is necessary to adopt an alternative hypothesis: that the clusters of galaxies are stabilised by hidden matter.”

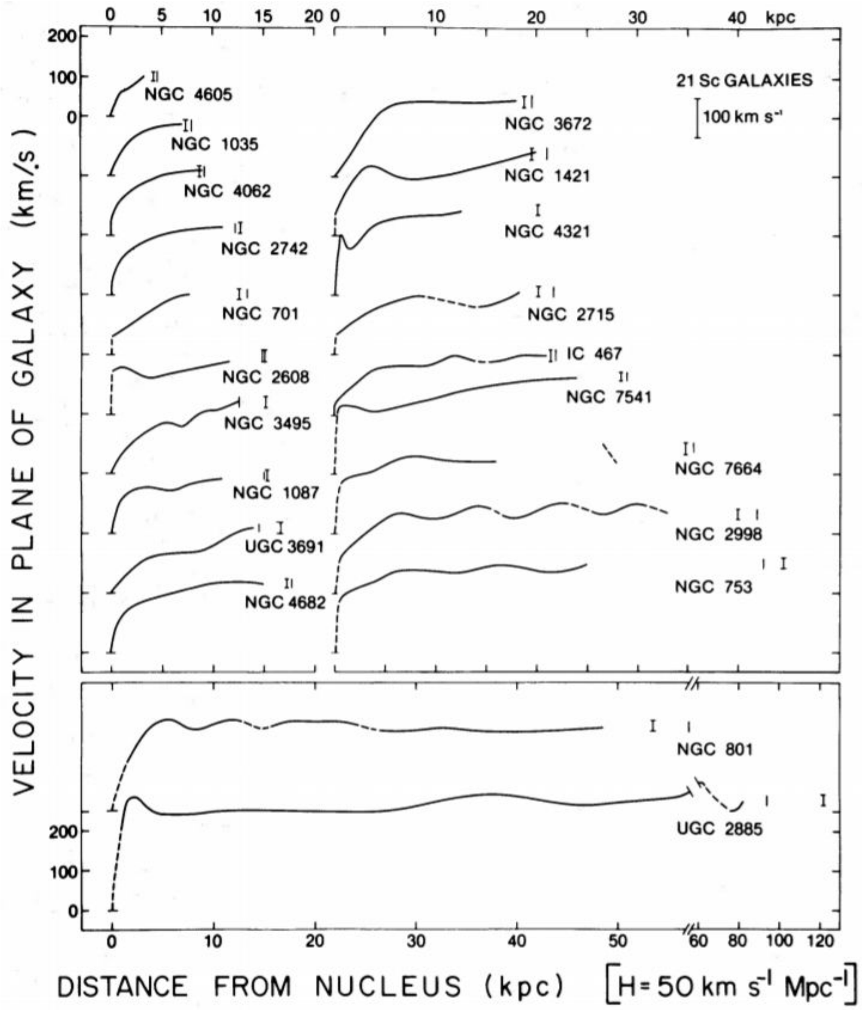
1974, Ostriker, Peebles, Yahil - “The size and mass of galaxies, and the mass of the universe”
“There are reasons, increasing in number and quality, to believe that the masses of ordinary galaxies may have been underestimated by a factor of 10 or more. [...] the mean density of the Universe would have been underestimated by the same factor.”

1970’s: Galaxy rotation

Rubin, Ford, Thonnard, 1980

Rotation curves for 21 spiral galaxies.
All galaxies show flat or rising curves at large radius from the center.
The first point in the conclusions section:

1. Most galaxies exhibit rising rotational velocities at the last measured velocity; only for the very largest galaxies are the rotation curves flat. Thus the smallest Sc’s (i.e., lowest luminosity) exhibit the same lack of a Keplerian velocity decrease at large *R* as do the high-luminosity spirals. This form for the rotation curves implies that the mass is not centrally condensed, but that significant mass is located at large *R*. The integral mass is increasing at least as fast as *R*. The mass is not converging to a limiting mass at the edge of the optical image. The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy.



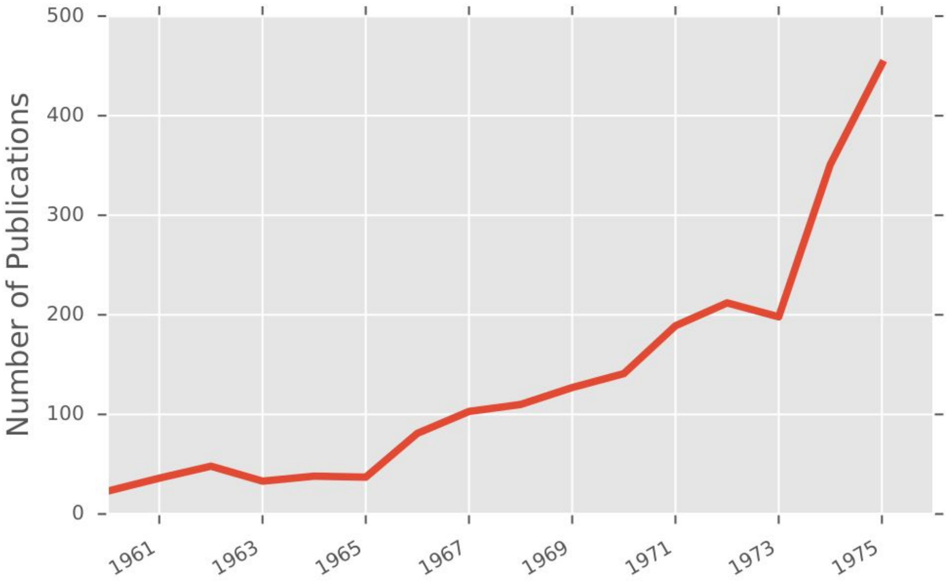
1970’s transition

Between 1960’s and 1970’s the boundary between astronomy and physics was fading.
1966: 26% of astronomy personnel had PhD in physics
1970: up to 45%
→ rise of physical cosmology

1980’s and subsequent:

- More and more evidence for dark matter starts accumulating from cosmological observations

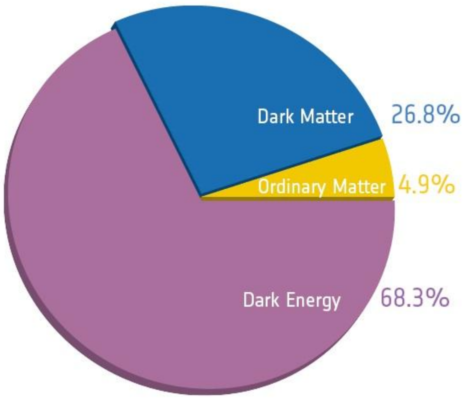
Publications with ‘cosmology’ in abstract or keywords



More recent (cosmological) evidence

Lambda-CDM model of the Universe

- Cosmological constant (dark energy)
- Dark matter
- Ordinary matter



https://www2.physics.ox.ac.uk/sites/default/files/images/Planck_Cosmic%20recipe%20pie%20chart_crop.jpg

Cosmological probes:

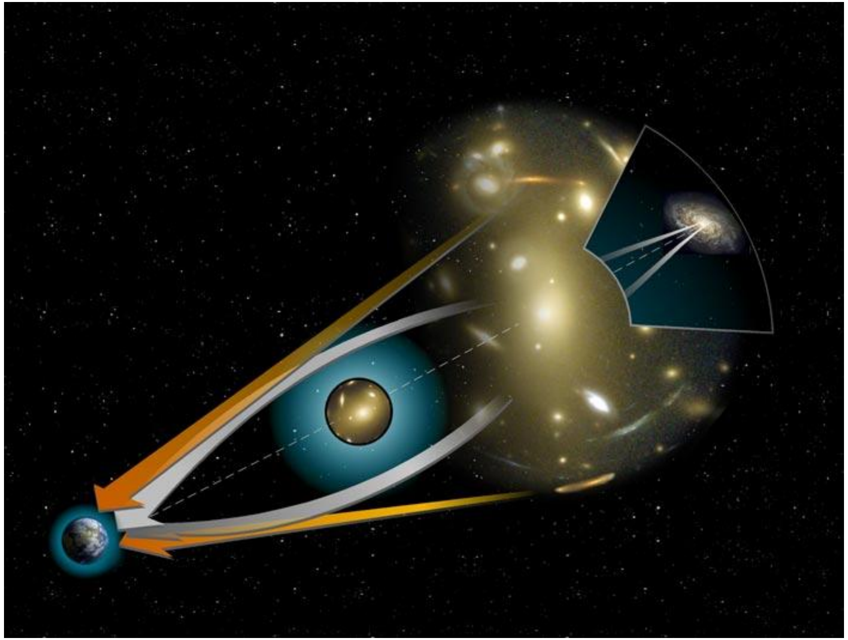
- Gravitational lensing
- Cosmic Microwave Background
- Structure formation
- Big Bang nucleosynthesis
- Hot gas in clusters
- Distant supernovae

Compare observations with predictions from models/simulations → support/constrain parameters of Lambda-CDM model.

Gravitational lensing

Prediction of General Relativity:
A massive astrophysical object bends the spacetime around it.
The light coming from a background source will travel along the curved path → observer sees a distorted image of the source.

Shape of the distortion can be used to compute the total mass of the lens.

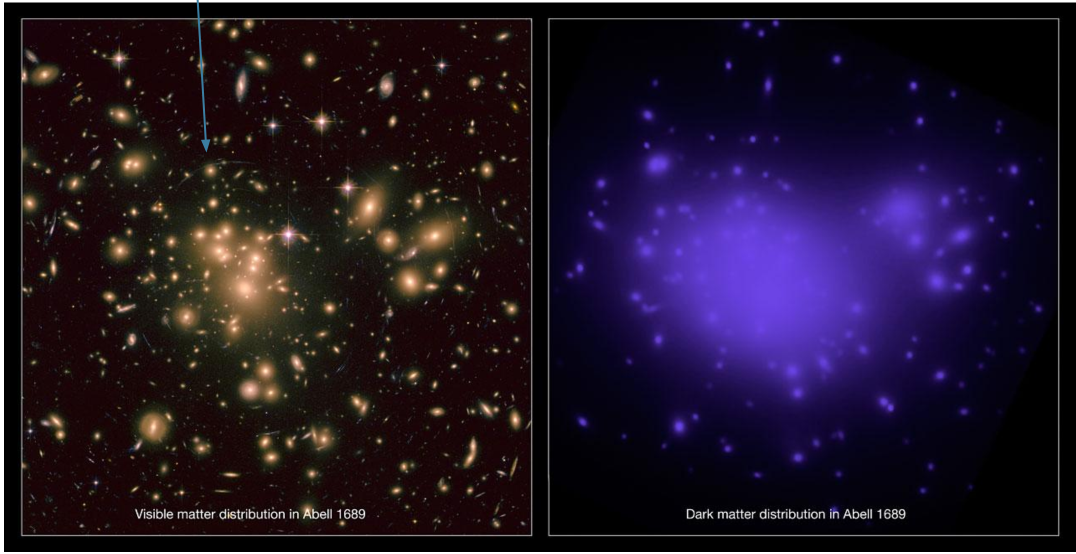


Gravitational lensing

The lens is a massive galaxy cluster.
Observe giant lensed arcs of background sources.

1998, Taylor, Broadhurst, Benitez, Van Kampen
First use of gravitational lensing to measure the mass of the Abell 1689 cluster ~10^{14} solar masses.

Later, studies have produced maps of the dark matter distribution (shown to the right).



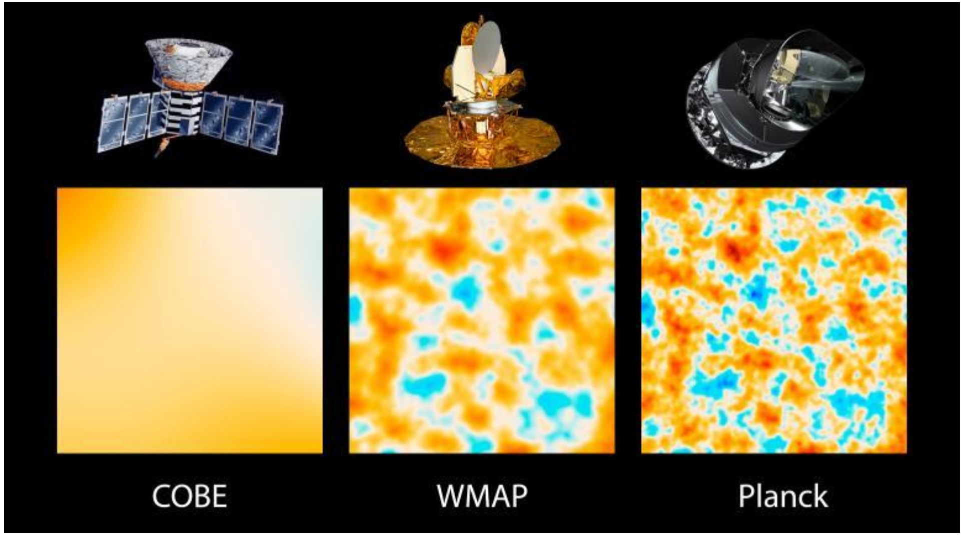
NASA, ESA, E. Jullo (JPL/LAM), P. Natarajan (Yale) and J-P. Kneib (LAM), 2010

Cosmic Microwave Background

Relic EM radiation from the time when the Universe was ~380,000 years old

Spectrum of black body at 2.73 Kelvin with small anisotropies at the level of 10’s micro-Kelvin.

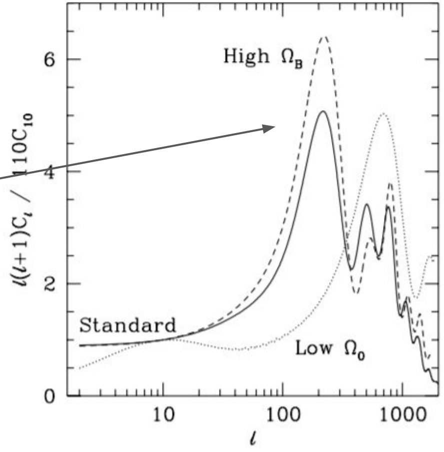
The temperature anisotropies are important to constraining cosmological parameters.

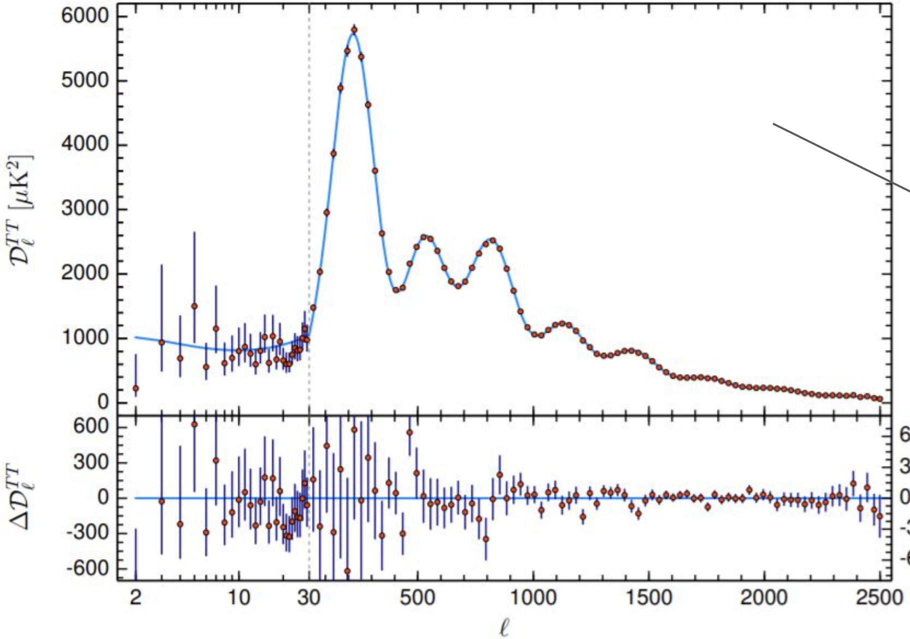


NASA/JPL-Caltech/ESA, 2012

Cosmic Microwave Background

Peaks in CMB power spectrum are sensitive to amount of baryonic matter, dark matter!





Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$

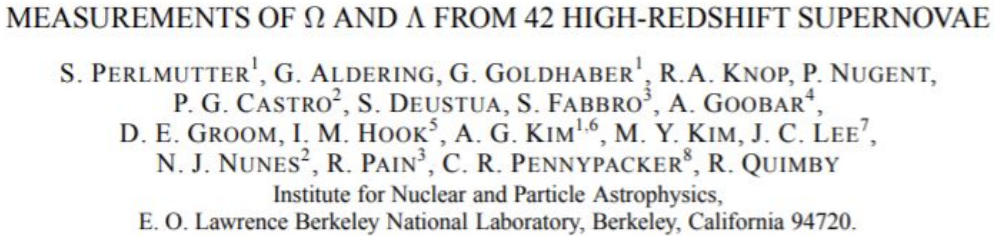
Distant supernovae

Type Ia supernovae are “standard candles” (known intrinsic brightness)

Observed brightness → distance to the supernova

$$d_L(z) = \sqrt{\frac{L}{4\pi S}}$$

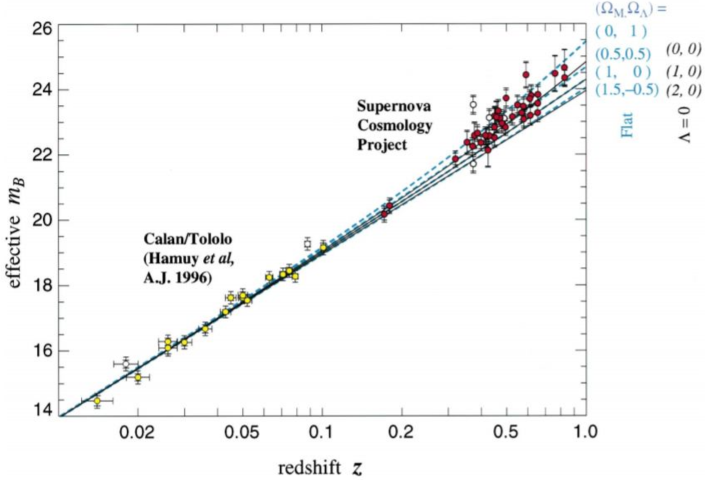
Distance measurement can be related to values of cosmological parameters (matter density, dark energy density)

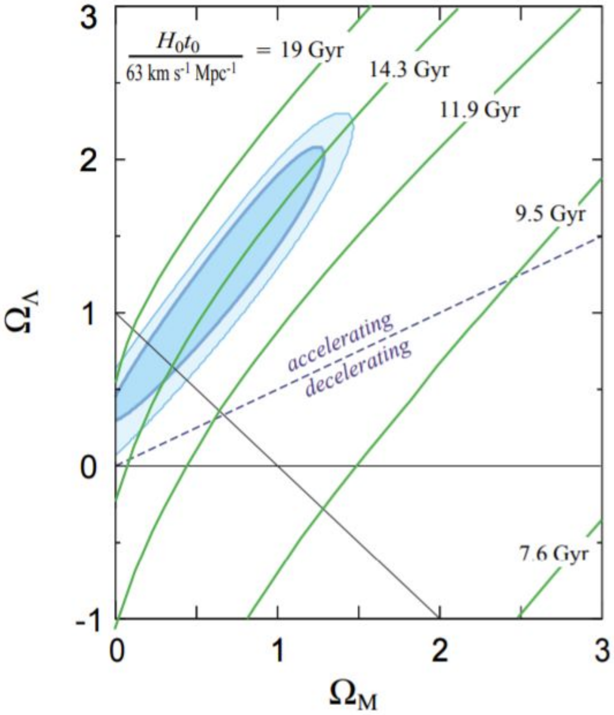


MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER[1], G. ALDERING, G. GOLDHABER[1], R.A. KNOP, P. NUGENT, P. G. CASTRO[2], S. DEUSTUA, S. FABBRO[3], A. GOOBAR[4], D. E. GROOM, I. M. HOOK[5], A. G. KIM[1,6], M. Y. KIM, J. C. LEE[7], N. J. NUNES[2], R. PAIN[3], C. R. PENNYPACKER[8], R. QUIMBY

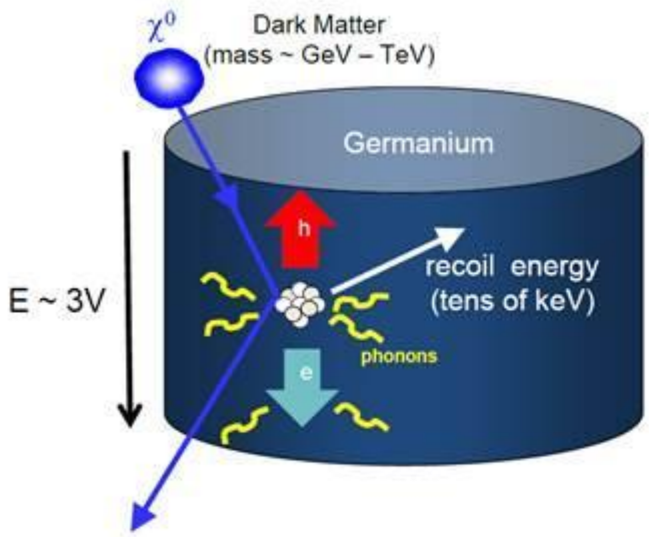
Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720.





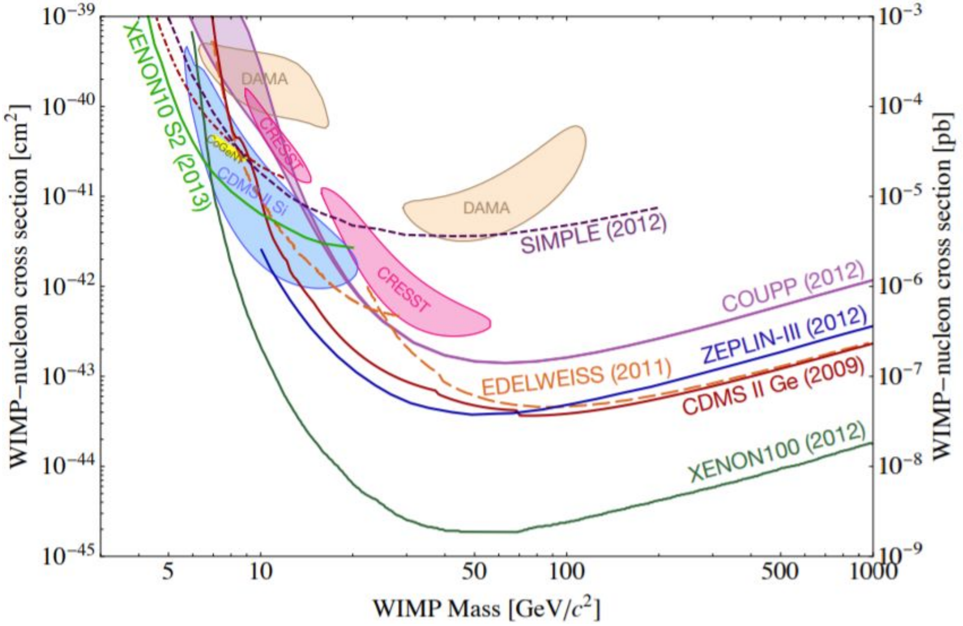
What about direct detection? (it's a hard problem)

Elastic scattering DM particle with nucleon.



https://supercdms.slac.stanford.edu/overview

No direct detections **yet**! The search continues!



Resources

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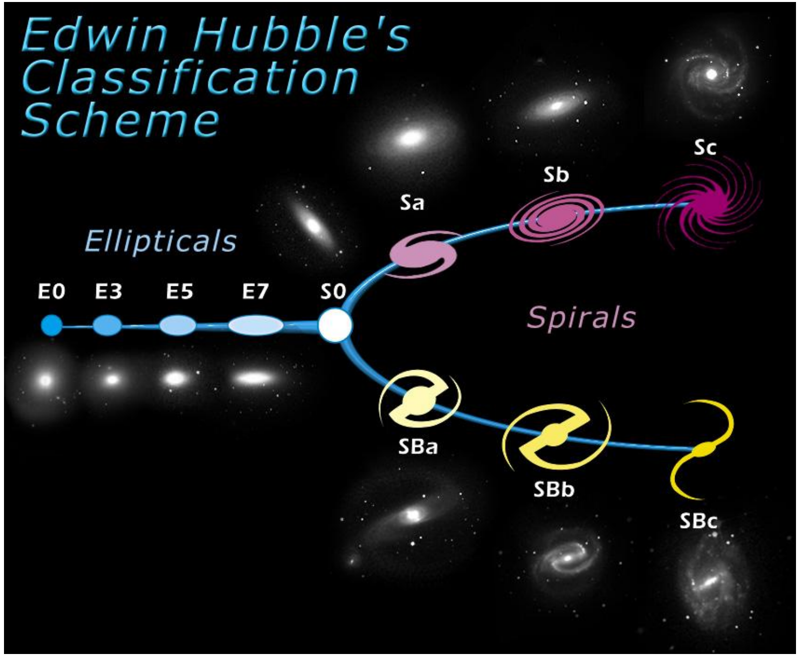
Thank you!

Backup Slides

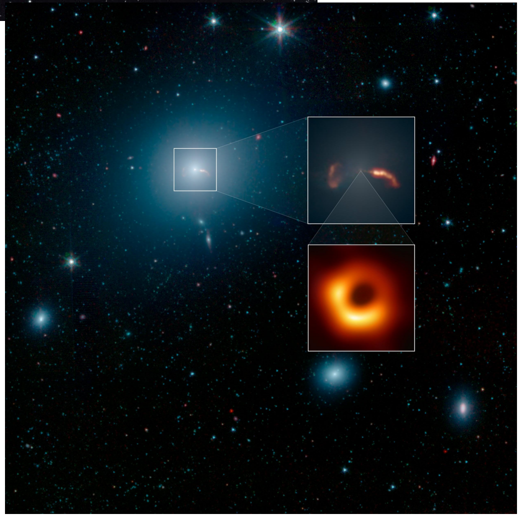
Galaxy classification

Hubble Tuning Fork



http://skyserver.sdss.org/dr1/en/proj/advanced/galaxies/tuningfork.asp

Robert Gendler https://apod.nasa.gov/apod/ap181217.html



NASA/JPL-Caltech/IPAC/Event Horizon Telescope Collaboration

Cosmological equations

$$\frac{H}{H_0} = \sqrt{\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_\Lambda}$$

$$H = \frac{\dot{a}}{a}$$

$$t_L = t_h \int_0^z \frac{dz'}{(1+z')E(z')}$$

$$t_h = \frac{1}{H_0} \text{ with } H_0 = H(z=0) \text{ (Hubble constant)}$$

$$a = \frac{1}{1+z}$$ (scale factor)

$$E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda}$$

$$d_L(z) = (1+z)d_H \int_0^z \frac{dz'}{E(z')} \text{ (spatially flat universe)}$$

Make your own CMB experiment!

https://astro.uni-bonn.de/~kbasu/ObsCosmo/Slides2016/cmb_theory_II.pdf

- Design experiment to measure $\frac{\Delta T}{T}(\theta, \phi)$

- Find component amplitudes $a_{\ell m} = \int_{\Omega} \frac{\Delta T}{T}(\theta, \phi) Y^*_{\ell m}(\theta, \phi) d\Omega$

- Plot $c_\ell = \langle |a_{\ell m}| \rangle^2$ against l (where l is inverse of angular scale, $l \sim \pi / \theta$)