Darkness in the Universe

1

Review Symbols

- $a(t)$: __________
- P: __________
- ρ: __________
- G: __________
- c: __________
- Λ: __________

2

Early Indications of Missing Matter

- 1844: Motion of the star Sirius suggested mutual orbital motion with an invisible companion of comparable mass (Bessel). In 1862, companion identified as a faint whir dwarf (Clark).
- 1930s: Velocities of stars near the sun (Oort), and velocities of stars in other galaxies (Zwicky) greater than explainable by the total visible mass.

3

- 1940s, 50s and 60s: Other evidence accumulated that the behavior of astronomical systems (motions, etc.) was not consistent with the amount of matter that was visible.
- 1970s: The scope of the problem was finally established by the careful observations of Rubin and Ford (underrecognized at the time) , and the theoretical work of Ostriker, Peebles, and others.

4

Dark Matter

Modern evidence suggests that ____________________
____
____

What is the evidence? Among others,

- ____________________
- ________________________.

5

Galactic Rotation and Dark Matter

All the stars of a galaxy rotate around the galactic center.

But there's a puzzle in how they rotate. This was known since the 1930s, but was firmly established by the work of Rubin and Ford from the late 1960s to the late 1970s.

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They first studied Andromeda . . .

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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Received 1969 July 7; revised 1969 August 21

. . . and found curves such as these:

7

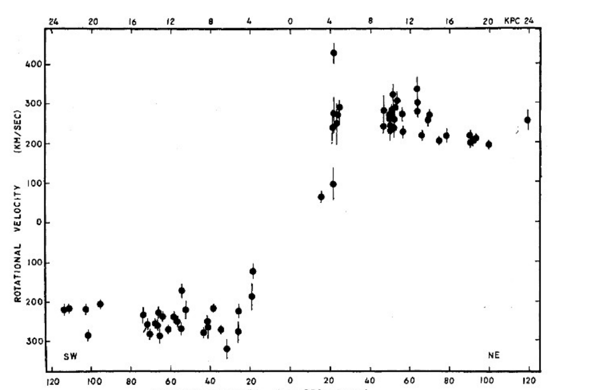

Fig. 3.—Rotational velocities for sixty-seven emission regions in M31, as a function of distance from the center. Error bars indicate average error of rotational velocities.

8

(1) What does the graph on the previous page show about rotational velocities as you go out from the center of Andromeda?

9

Over the next decade they carefully studied another 21 galaxies . . .

ROTATIONAL PROPERTIES OF 21 Sc GALAXIES WITH A LARGE RANGE OF LUMINOSITIES AND RADII, FROM NGC 4605 ($R = 4$ kpc) TO UGC 2885 ($R = 122$ kpc)

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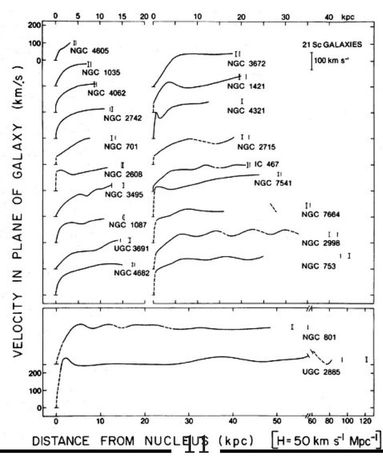
Received 1979 October 11; accepted 1979 November 29

. . . and found similar behavior:

10



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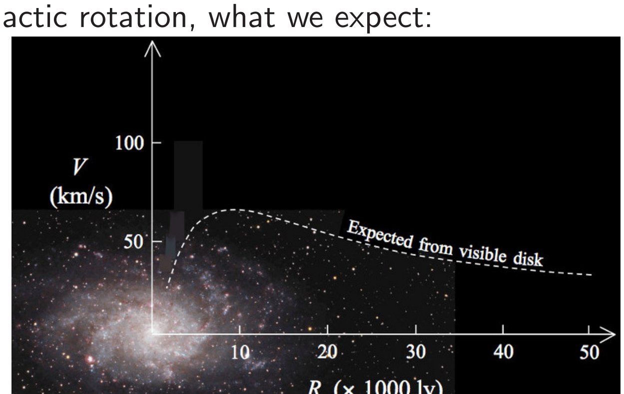
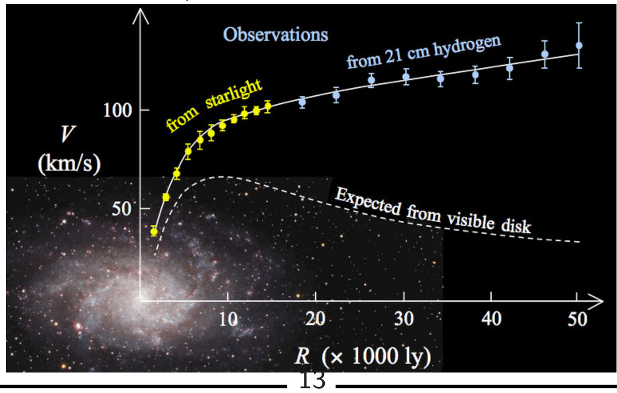
Galactic rotation, what we expect:



12

Galactic rotation, what we observe:



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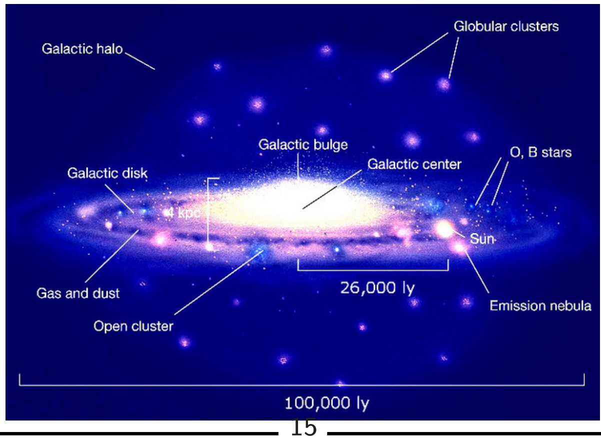
The rotations of stars around the centers of galaxies are more rapid than we expect from the visible matter in them.

14



15

(2) Why, based on the rotation curve, do we expect the dark matter to be scattered throughout the halo, not just concentrated in the black hole at the center of a galaxy?

16

From the New York Times, December 27, 2016:

Vera Rubin, 88, Dies; Opened Doors in Astronomy, and for Women

Vera Rubin, who transformed modern physics and astronomy with her observations showing that galaxies and stars are immersed in the gravitational grip of vast clouds of dark matter, died on Sunday in Princeton, N.J. She was 88.

Her work helped usher in . . . the realization that what astronomers always saw and thought was the universe is just the visible tip of a lumbering iceberg of mystery.

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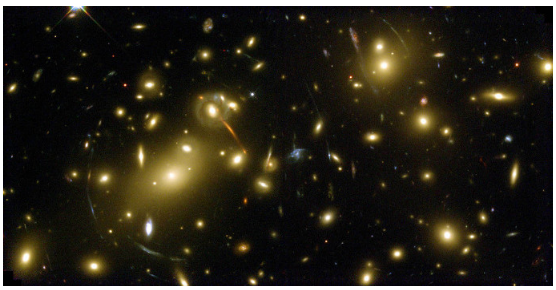
Gravitational Lensing and Dark Matter



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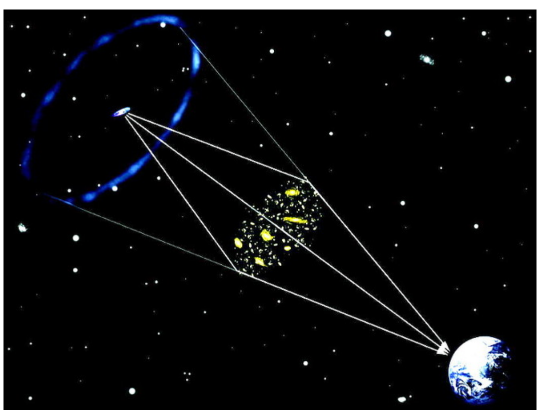

19

There appears to be invisible – or "dark" – matter causing the extra bending.

20

What is dark matter not?

We're more certain of this than what it is...

- ______________________________
- ______________
- ______________________________

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What might dark matter be?

Various proposals:

- ______________________________
- ______________________________
- ______________

Still an open question ...

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The Search for Dark Matter

- The Alpha Magnetic Spectrometer (AMS-02) on the International Space Station is analyzing cosmic rays for evidence of unusual particles.
- The China Dark Matter Experiment (CDEX), a search for dark matter WIMP particles, at the China Jinping Underground Laboratory, $7{,}900$ ft deep.

... plus IceCube at the S.P. and others.

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Dark Energy

Evidence suggests that ______________________________

(3) So, you HICOPS , how much of the Universe is visible? ____

24

What is the evidence for dark energy?

We need to review the expansion of the Universe:

- ○ ____
- ○ ____
- ○ ______________________________________

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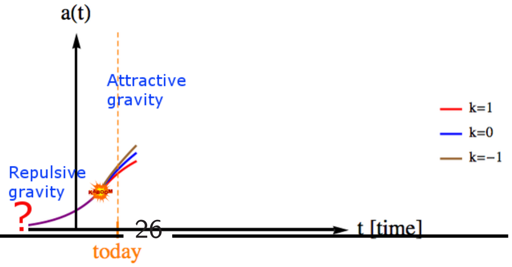
- ○ ________________________________
- ○ ___________________________________
- ○ ____



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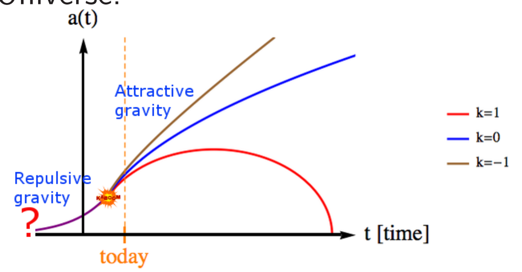
▷ If the expansion is decelerating, this is the future of the Universe:



Measuring the deceleration rate is important.

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The Supernova Cosmology Project (SCP) was started in 1988 by Saul Perlmutter with the aim of measuring the deceleration of the Universe - using ________ __________ (SNe Ia) as standard candles.

SNe Ia: Supernova from the explosion of an accreting white dwarf or white dwarf merger.

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SNe Ia are rare – only a couple of times per millennium in a galaxy. To get a statistically significant result a large observational sample is needed.

Perlmutter's group observed thousands of galaxies over two to three nights then imaged the same patches of the sky about three weeks later.

They found batches of about a dozen or so new SNe at a time.

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From the success of this strategy Brian Schmidt in Australia and others founded in 1994 a competing collaboration – the High-z Supernova Search Team (HZT).

Over the following years, the HZT led by Schmidt and the SCP led by Perlmutter independently searched for supernovae, often but not always at the same telescopes.

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The two teams published breakthrough papers in 1998 announcing that they had found that the expansion of the Universe does not decelerate, but actually accelerates.

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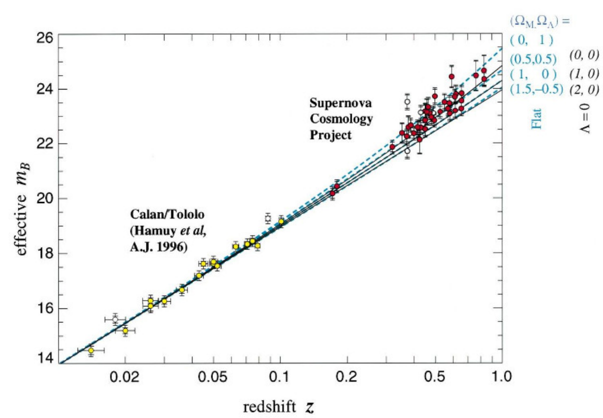

Perlmutter

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We do not see the energy that drives this acceleration.

To what do we attribute this dark energy?

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MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fitted jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia light-curve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximated by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{\text{flat}} = 0.28^{+0.09}_{-0.08}$ (1 σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is nonzero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including the identified systematic uncertainties. The best-fit age of the universe relative to the Hubble time is $t_0^{\text{flat}} = 14.9^{+1.4}_{-1.1}(0.63/h)$ Gyr for a flat cosmology. The size of our sample allows us to perform a variety of statistical tests to check for possible systematic errors and biases. We find no significant differences in either the host reddening distribution or Malmquist bias between the low-redshift Calán/Tololo sample and our high-redshift sample. Excluding those few supernovae that are outliers in color excess or fit residual does not significantly change the results. The conclusions are also robust whether or not a width-luminosity relation is used to standardize the supernova peak magnitudes. We discuss and constrain, where possible, hypothetical alternatives to a cosmological constant.

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OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior

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(4) How might the cosmological constant accelerate expansion?

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The observational work led to Nobel prizes for some team members in 2011.

Over the last seventeen years other observations of the CMBR, large scale structure of galaxies, etc., have confirmed that around 68% of the content of the Universe is in the form of dark energy.

We do not have a good understanding of what this energy is that underlies a possible cosmological constant.

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So here we are...

... on a planet going around a star, that's one in at least 200 billion stars in...

... a galaxy that's one of at least 200 billion others.

40

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Are there other "intelligent" beings out there with different biology, different ways of living, different language – but the same mathematical thoughts, and the same understanding of the Universe?

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On our part:

We feel we understand parts of the Universe . . . but 95% of what it contains remains unknown.

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