Aristotle

Greece, 384 – 322 B.C.

Student of Plato

Tutor to Alexander the Great

The authoritative scientist in Europe for 1800 years

“The speed at which an object falls is directly proportional to its weight”
Simon Stevin
Holland, 1548 – 1620

Experiment shows all objects fall at the same rate

Galileo Galilei
Italy, 1564 – 1642
Authority and the standard model vs discrepant observation; an epistemological controversy over the primacy of “facts”

Galileo using his telescope to show the mountains of the Moon to two cardinals
The Copernican revolution

A controversy over interpretation, not over facts

Nicolaus Copernicus
Poland, 1473 – 1543
Isaac Newton: 1643 – 1727

\[ F = m \ a \]

**Law of Motion**

\[ F_{\text{grav}} = G \ m \ M_\oplus / R_\oplus^2 \]

**Law of Gravity**

\[ a_{\text{grav}} = G \ M_\oplus / R_\oplus^2 \]

**Mathematics** links the motion of the Moon and planets to the falling of objects.

Is mathematical “beauty” relevant for establishing scientific truth?
A controversy over the age of the Earth

Charles Lyell (1797 – 1895)
Erosion arguments lead to time-scales of hundreds of millions of years and an indefinite age.
Imprecise phenomenology

William Thomson (1824 – 1907)
Cooling arguments lead to ages of a few tens of millions of years for the Earth and the Sun.
Rigorous physical calculation
A controversy over the age of the Earth

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Cooling arguments lead to ages of a few tens of millions of years for the Earth and the Sun.
Rigorous physical calculation ✗
The Great Debate: 26 April 1920

Agree that van Maanen's inferred rotational proper motions for M31 and M31 would require them to be galactic, if correct.
This is the first statement of the concept of dark matter as we now understand it.
MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES

S. M. Faber
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

J. S. Gallagher
Department of Astronomy, University of Illinois, Urbana, Illinois 61801

1 INTRODUCTION

Is there more to a galaxy than meets the eye (or can be seen on a photograph)? Many decades ago, Zwicky (1933) and Smith (1936) showed that if the Virgo cluster of galaxies is bound, the total mass must considerably exceed the sum of the masses of the individual member galaxies: i.e. there appeared to be “missing mass” in the cluster.

- Extended dark matter halos became part of the mainstream in the 1970's
- Rotation curves were a small part of the justification (9/54 pages in F&G79)
- The rotation curves used were mostly 21cm, rather than optical
The earliest reliable flat rotation curves (for M31) are usually credited to Rubin & Ford 1970 (optical) and Roberts & Whitehurst 1975 (radio).

- The 21cm goes to larger radius.

- The 1957 Dwingeloo curve is just as good and goes just as far.
The mid-century cosmological controversy

Georges Lemaitre

A primeval atom
An evolving universe with finite age and a singularity

Fred Hoyle

No ugly “Big Bang”, rather a steady state universe with continuous creation
The mid-century cosmological controversy

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Observations decided!
Precise astrophysical evidence for dark matter?

- Results from a single instrument (Planck/HFI)
- **No** local/low-redshift data are used
- Linear perturbation of a homogeneous medium
- No exotic/HE physics needed to set pattern
- No measurable primordial non-gaussianity
- Good fit to minimal 6-parameter ΛCDM

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<td>Age [Gyr]</td>
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<td>$\sigma_8$</td>
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Planck Collaboration 2018
• Peaks in the Planck TT power spectrum are slightly broader than expected
• This can be parametrised as more lensing than expected/measured directly
• No corresponding effect is seen in the TE power spectrum
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- Some “tensions” with other data

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Planck Collaboration 2018

- BBNS dynamics, lensing
- $H_0$ reionization
- $\sigma_8$: clusters, lensing
- inflation
Tensions with low-redshift large-scale structure

Shear measurement sensitive to the redshift distribution of background galaxies

Cluster abundance measurement sensitive to the mass calibration of the clusters
Another $H_0$ controversy

- Low and high redshift estimates of $H_0$ disagree by 10%
Another $H_0$ controversy

- Low and high redshift estimates of $H_0$ disagree by 10%
- Tip of the Red Giant Branch estimate is intermediate (Freedman et al 2019)
Precise astrophysical evidence for dark matter?

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Planck Collaboration 2018
Precise astrophysical evidence for dark matter?

These are precisely measured initial conditions, but they need extrapolation to the scales which form galaxies.

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Planck Collaboration 2018
Lyman α forest spectra compared to ΛCDM predictions

High-resolution Keck and Magellan spectra match ΛCDM up to $z = 5.4$

ΛCDM initial conditions with CMB parameters fit structure in the pre-galactic medium down to dwarf galaxy scales

$m_{\text{WDM}} > 3.3$ keV
Flux ratio anomalies in multiply imaged quasars constrain the mass of thermal relic WDM to be $m_{\text{WDM}} > 3.8$ keV.
Small-scale controversies over $\Lambda$CDM

- The core-cusp problem
- The missing satellite problem
  “Solved” by baryonic processes?
- The Too-Big-To-Fail problem

DM “solutions” have other problems or are insufficiently understood

- **WDM** Abundance of hi-z galaxies? Ly-$\alpha$ forest? flux-ratio anomalies?
- **SIDM** V-dependent X-section needed, complex interaction with G.F.
- **FDM** Not yet explored enough to know
- **Emergent DM** A fully calculable theory has yet to emerge
Many dwarf galaxies have rotation curves that fit ΛCDM predictions well.
Dwarf galaxy rotation curves: cusps vs cores

Many others fail dramatically to fit $\Lambda$CDM predictions. “Cores” from: (i) DM properties? (ii) Baryon effects? (iii) Incorrect modelling?
$V_{\text{circ}}(2 \text{ kpc})$ versus $V_{\text{max}}$ for observed dwarfs

Enormous apparent diversity:
Too large for baryon effects proposed so far?
Too large to reflect DM properties alone?

Oman et al 2015
ΛCDM rules!
ΛCDM rules!

Is dark energy really a cosmological constant? When do we accept that $w = -1$ to astrophysical accuracy?
$\Lambda$CDM rules!

- Is dark energy really a cosmological constant? When do we accept that $w = -1$ to astrophysical accuracy?
- Is the dark matter really cold to astrophysical accuracy? Does it have other measurable interactions?
ΛCDM rules!

Is dark energy really a cosmological constant? When do we accept that $w = -1$ to astrophysical accuracy?

Is the dark matter really cold to astrophysical accuracy? Does it have other measurable interactions?

Is the dark matter really dark? Has decay or annihilation emission been seen?
ΛCDM rules!

Is dark energy really a cosmological constant? When do we accept that $w = -1$ to astrophysical accuracy?

Is the dark matter really cold to astrophysical accuracy? Does it have other measurable interactions?

Is the dark matter really dark? Has decay or annihilation emission been seen?

Does the dark matter phenomenon indicate "funny gravity"?
INNER SPACE OUTER SPACE

The Interface between Cosmology and Particle Physics

Edited by Edward W. Kolb, Michael S. Turner, David Lindley, Keith Olive, and David Seckel
Inner Space

Outer Space

Interface between

and Particle Physics

Three Generations

of Matter (Fermions)

Quarks

Leptons

Bosons (Forces)

Edited by Edward W. Kolb, Michael S. Turner, David Lindley, Keith Olive, and David Seckel
We have validated and apparently complete standard models for both macro- and micro-phenomena.
We have validated and apparently complete standard models for both macro- and micro-phenomena.

But is there more? ...and how/where do we find it?