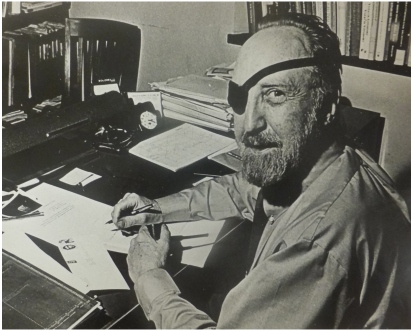
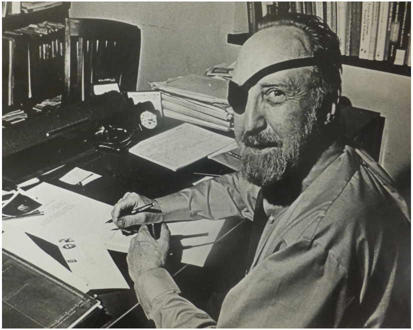

28 APRIL 1900
VERMAARD ASTRONOOM EN ONDERZOEKER
VAN MELKWEGSTELSELS
Emilio Segrè Visual Archives



Vera Rubin in 1991,
Franeker, the Netherlands.

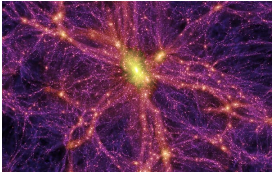


Thornton Page, sitting at his desk writing.

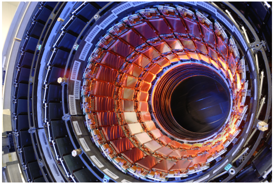
How Dark Matter Came to Matter

Jaco de Swart
University of Amsterdam

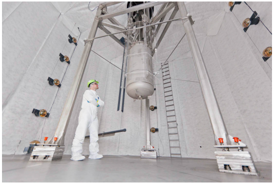
Dr. Gianfranco Bertone (GRAPPA / Astro-Particle Physics)
Prof. Jeroen van Dongen (IoP / History of Physics)
Prof. Erik Verlinde (ITFA / Theoretical Physics)



Millennium Simulation, Max Planck Institute for Astrophysics



CMS detector, at CERN.



LUX detector, in South Dakota.

Erik Verlinde
@erikverlinde

I am a Theoretical Physicist at the University of Amsterdam. I work on string theory, gravity, cosmology and black holes.

Amsterdam
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Joined October 2009

Erik Verlinde @erikverlinde

Following

The emergent gravity formula for rotation curves is based on assumptions that don't hold in the solar system, hence no prediction was made.

> **Gianfranco Bertone** @gfbertone
> A.Hees, @darth_ben and I tested 'emergent gravity' - found it violates solar system constraints by factor 10 million arxiv.org/abs/1702.04358

RETWEETS 5 LIKES 26

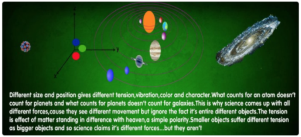
3:43 AM - 16 Feb 2017

4 5 26

Tweet your reply

Matthew Buckley @physicsmatt · Feb 16
Replying to @erikverlinde
could you elaborate on which assumptions don't hold? Doing my best to understand whats going on in your theory.

Fabian Dijk @FabianDijk · Feb 16
Replying to @erikverlinde
Why science sees different forces everywhere:



Aqeel Ahmed @Aqeelhmed · Feb 16
Replying to @erikverlinde
then how to test your proposal if it doesn't hold the solar system tests? Your idea is beautiful but it must pass these tests!

How Dark Matter Came to Matter, 1960 - 1974

de Swart, J.G. Bertone, G., van Dongen, J. (2017). *Nature Astronomy* **1**, 0059

- Dark matter hypothesis dates back to at least the 1930s...

  (Zwicky, 1933; Smith, 1936; Babcock, 1939; Oort, 1940)

- ...but was only widely recognized in the early 1970s.

  (Flat Rotation Curves; Rubin & Ford, 1970)

Understand the *circumstances* in which the missing mass hypothesis started to gain interest *in the first place.*

Not a story of new evidence.

- Two independent and ambiguous issues of mass in the 1960s.
- Cosmology helped synthesizing these in the 1970s.

De Swart, Bertone & van Dongen (2017) “How Dark Matter Came to Matter”, *Nat. Astr.*, **1**:59

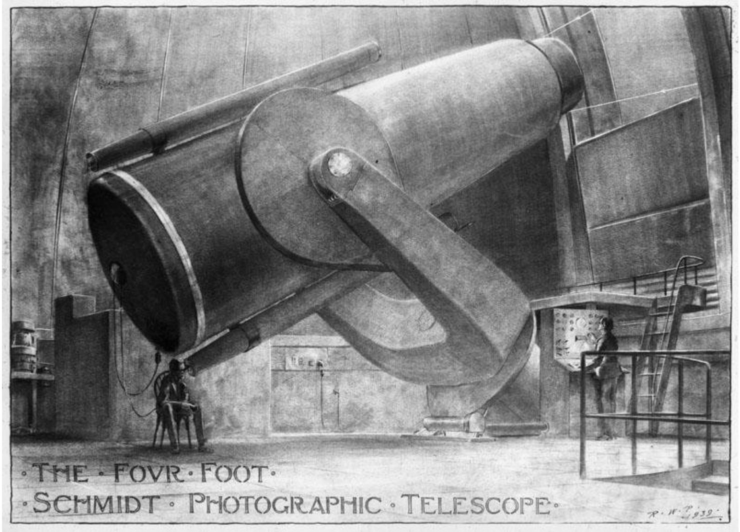
Outline

1. Problem of Mass: Clusters of Galaxies
2. Problem of Mass: Galaxy Rotation Curves
3. Institutional Changes and the Rise of Physical Cosmology
4. Synthesis of Problems in 1974

1. A Mass Discrepancy in Clusters of Galaxies

Fritz Zwicky observing at Palomar 18-inch Schmidt,
circa 1936. (Caltech Archives)

Zwicky, F. (1933). Die Rotverschiebung von extragalaktischen Nebeln. Helvetica Physica Acta, 6, 110-127.



48-inch Schmidt Telescope at Palomar Observatory. By Russel Porter around 1947.

Eleventh Solvay Conference (1958), "The structure and evolution of the universe."

Solution of Mass Discrepancy

1. Excess mass.
2. Excess energy.

- Neyman. J., Page, T., Scott, E. (1961). Foreword. *A.J.*, 66(10):533.

"*For any particular group or cluster, it seems, at the moment, to be very much a matter of taste as to which explanation of the apparent dynamical state of the cluster is assumed to be correct*"

– Geoffrey Burbidge, 1961

IAU Meeting 1961 Berkeley
(Credit: AIP Visual Archives)

“Neither hypothesis – hidden mass or quick disintegration – can be eliminated at present.” *– Field, G. & Saslaw W. (1971)*

- Reddish (1968): Dwarf galaxies.
- Burbidge & Sandage (1969): Undetermined.
- Forman (1970) and Jackson (1970): Different force law.
- Rood, Rothmann, & Turner (1970): Undetermined.
- Cowsik & McClelland (1973): Neutrinos.
- Gott, Wrixon, & Wannier (1973): Field galaxies.
- Abell (1974): No problem after re-examination.
- De Vaucouleurs (1974): Instability.
- Tarter & Silk (1974): Mixture (dwarf stars, and hydrogen).
- Burbidge (1975): Instability.

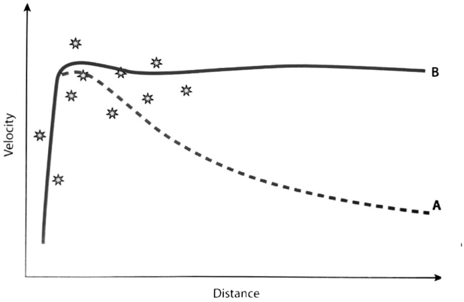
GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

"*This extra density [of collapsed objects] could stabilize clusters of galaxies which, otherwise, appear mostly not to be gravitationally bound.*"

– Hawking, S. (1971), *MNRAS*, **152**, p.76

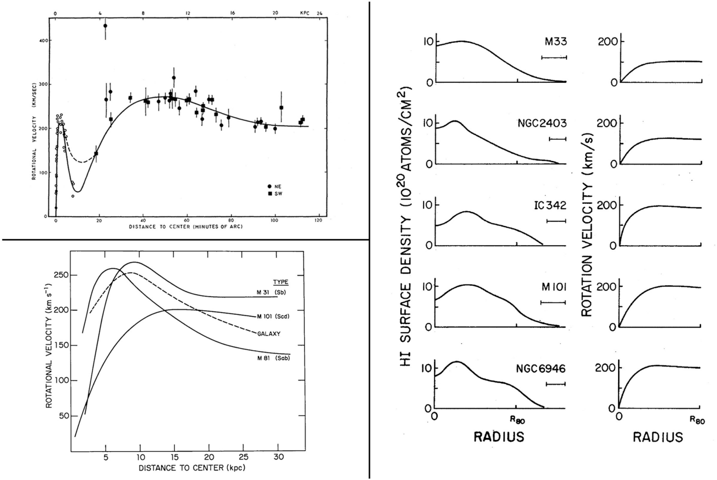
2. Flat Rotation Curves



Ostriker & Mitton (2013)

$$\frac{m v_{rot}^2(r)}{r} = -m\frac{GM_{total}}{r^2};\ \ v_{rot} = \sqrt{\frac{GM_{total}}{r}} \tag{1}$$

Owens Valley Radio Observatory, early 1960s



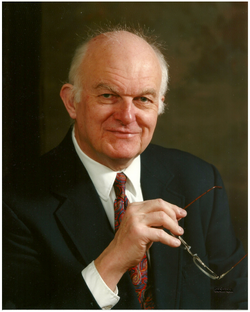
a, Rubin & Ford, 1970; **b**, Rogstad & Shostak, 1972; **c**, Roberts & Rots, 1973

“[Extrapolation] is clearly a matter of taste”

– Rubin, V. C. & Ford, W.K. (1970)

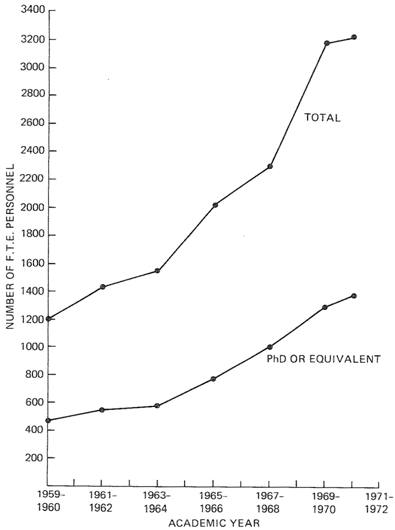
“[A]ny extrapolation of mass is very uncertain”
– Rogstad, D.H., Shostak, G.S. & Rots, A.H. (1973)

"It has long puzzled me why senior folks [...] did not SHOUT about this promptly from the rooftops, as the saying goes, but instead left it to Bosma (1978) to trickle this out in his rich thesis a whole FOUR years later!" – Alar Toomre (MIT), 2015, private communication



The early 1970s: two independent problems of mass, but none used as unambiguous evidence for the existence of unseen mass.

3. Changing Interests and Institutions in the 1960s

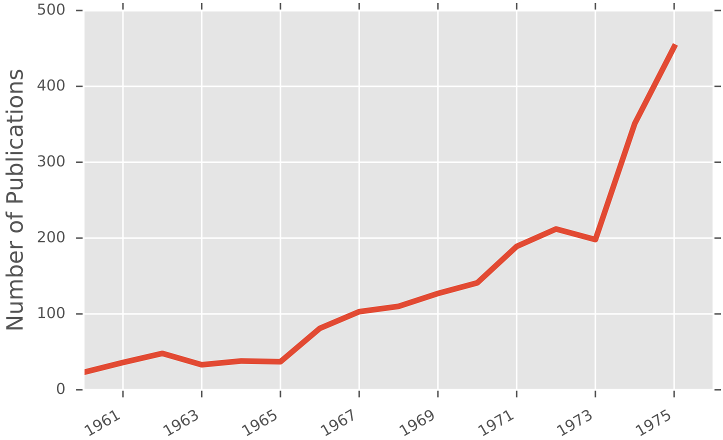


Sandage, A. (1970). Cosmology: a search for two numbers. *Physics Today*, 23:34.

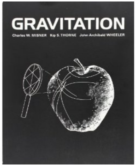
- Astronomy PhD granting institutions:
  Doubled in the 1960s.
- Percentage of Physics Doctorates in Astronomy:
  25% in 1966 to **45%** in 1970.
- ‘Theoretical astrophysics’:
  Most prominent interest in 1970.

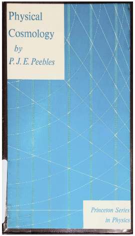
SCHÜCKING opened the scientific meeting by wittily calling it "exotic astrophysics". The first Symposium at Dallas, 1963, he said, considered in great haste quasi-stellar sources (from now on abridged QSS) and models. The suspicion was rising that time was in to bring physicists and astronomers together, for cosmology seemed to necessarily become the field of research.

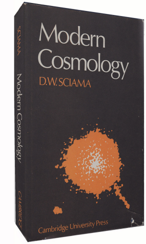
Report on the Second Texas Symposium on Relativistic Astrophysics (1965)

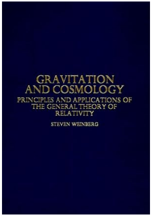


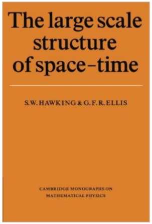
Papers with "Cosmology" in abstract or as keyword, 1960-1975 (SAO/NASA ADS)











Misner, Thorne and Wheeler (1973);Peebles (1971); Sciama (1971); Weinberg (1972); Ellis & Hawking (1973) (Zeldovich (1971); Rees, Ruffini & Wheeler (1974))

COSMOLOGY: A SEARCH FOR TWO NUMBERS

Precision measurements of the rate of expansion
and the deceleration of the universe may soon provide
a major test of cosmological models

ALLAN R. SANDAGE

Sandage, A. (1970). Cosmology: a search for two numbers. *Physics Today*, 23:34.

"Density is destiny."

Curvature	*Density*	*Deceleration*	*Model*	*Evolution*
$k = -1$	$\rho < \rho_c$	$0 \leq q < 1/2$	Open	Ever-expanding
$k = 0$	$\rho = \rho_c$	$q = 1/2$	Flat	Ever-expanding
$k = 1$	$\rho > \rho_c$	$q > 1/2$	Closed	Collapse

(For a 'matter-dominated' universe; $\Lambda = P = 0$).

UPPER LIMIT ON THE MEAN MASS DENSITY DUE TO GALAXIES

P. J. E. PEEBLES AND R. B. PARTRIDGE
Palmer Physical Laboratory, Princeton, New Jersey
Received October 18, 1966; revised December 12, 1966

ABSTRACT

It is shown that present observations of the brightness of the night sky in the visible fix a useful upper limit to the mean mass density due to luminous matter in the Universe. If the material has a mass-to-luminosity ratio of 20 solar units, this upper limit is four times lower than the density needed to close the universe.

A basic parameter for cosmology is the mean mass density in the Universe. One would particularly like to know whether there is enough mass to close the Universe.

(Peebles & Partridge, 1967, p. 713)

"Philosophically, there might be a preferred choice" – Rindler, W. (1967)

- $\rho = \rho_c \ (\Omega = 1)$

$$\rho_{universe} \sim 10^{-31}\ gr.\ cm^{-3}$$

E.g. Oort, 1958; Peebles, 1971; Shapiro, 1971; Noonan, 1971; Weinberg, 1972, p. 478; Burbidge, 1972, p. 493.

$$\Omega = \rho/\rho_c \sim 0.01$$

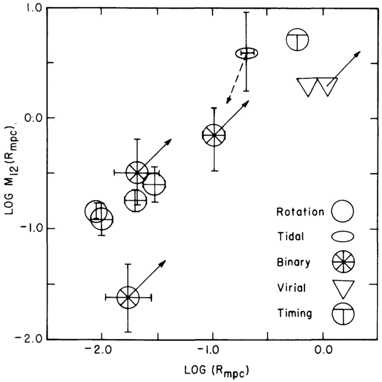
"Where [can] the missing mass be hiding if it is demanded, on theological or other grounds that $\Omega \geq 1$*".*

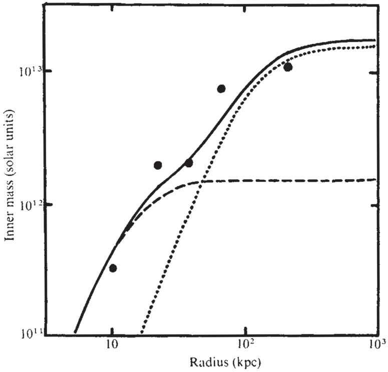
– Gott, J. R., I., Schramm, D. N., Tinsley, B. M., & Gunn, J. E. (1974). An Unbound Universe. *The Astrophysical Journal*, 194:550.

Cosmological turn

- Demand for mass to close the Universe.
- Justification to synthesizing different problems of mass.
- Mass problems turn to *evidence* for missing mass.

4. Missing mass in 1974





Left: Ostriker, Peebles & Yahil (1974) "The Size and Mass of Galaxies, and the Mass of the Universe", *ApJ*, **193**, pp. L1-L4)

Right: Einasto, J., Kaasik, A., & Saar, E. (1974). "Dynamic evidence on massive coronas of galaxies", *Nature*, 250(5464), 309-310.

I. THE ARGUMENT

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. Since the mean density of the Universe is computed by multiplying the observed number density of galaxies by the typical mass per galaxy, the mean mass density of the Universe would have been underestimated by the same factor. Finally, the current estimate (Shapiro 1971) for the ratio of gravitational energy to kinetic energy in the Universe is about $\Omega = 0.01$. If we increase the estimated mass of each galaxy by a factor well in excess of 10, we increase this ratio by the same amount and conclude that observations may be consistent with a Universe which is "just closed" ($\Omega = 1$)—a conclusion believed strongly by some (cf. Wheeler 1973) for essentially nonexperimental reasons.

(Ostriker, Peebles & Yahil, 1974, p. L1)

"Evidence is presented that galaxies are surrounded by massive coronas exceeding the masses of known stars by one order of magnitude. The virial mass discrepancy in clusters of galaxies is considerably reduced, the total density of matter in the galaxies being 20% of the critical cosmological density."

– Einasto, J., Kaasik, A., & Saar, E. (1974). "Dynamic evidence on massive coronas of galaxies", *Nature*, 250(5464), 309-310.

Einasto's Office, April 2017

Conclusion

Dark matter came to matter by virtue of the framework of cosmology, in which two open issues of mass were brought together as one problem of missing mass.