OSSERVATORIO ASTRONOMICO DI CAPODIMONTE

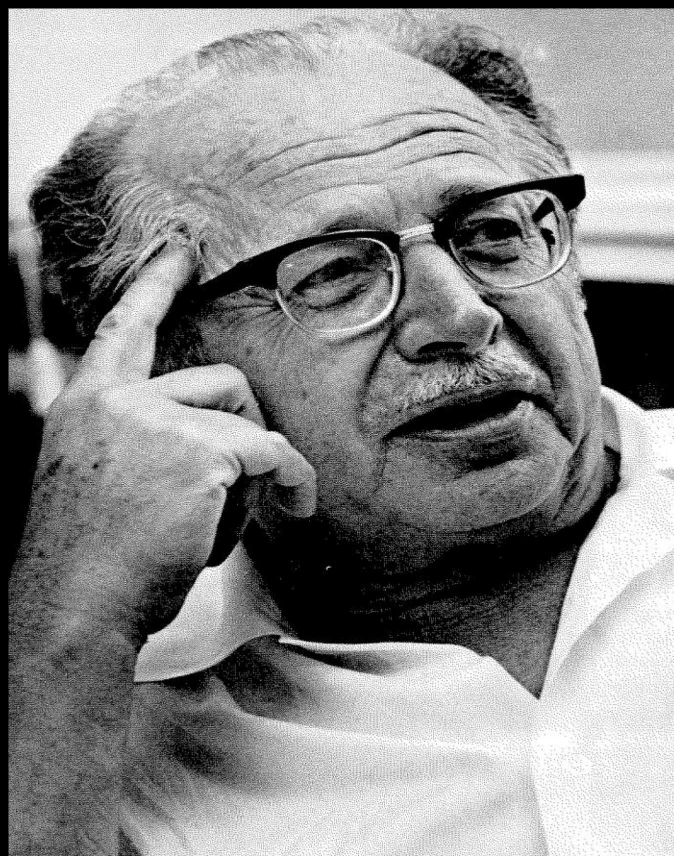
On the Dark Universe

Massimo Capaccioli
Department of Physics, University of Naples *Federico II*

Zolochiv, October 3, 2019

Astronomy and Astrophysics for the 1970's

1972 - Report of the Astronomy Survey Committee of 23 members (+ 100 in the advisory committee), set by the US National Academy of Sciences



Jesse Greenstein: chairman of the committee

The Future of Astronomy

by Jesse Greenstein

After their startling discoveries of the last ten years, astronomers have come to realize that the actual universe is much stranger than science fiction.

As in the age of Galileo, we are suddenly confronted with a new view of the universe. Instead of the sedate cosmos in which we thought we lived, we are in the midst of general cosmic violence—exploding galaxies and quasars, high-energy particles, magnetic fields—violence that suggests energy-releasing events like relativistic collapse, and other effects of the general theory of relativity.

But the discoveries that have given us this new view of the universe have provided few answers—and raised many questions:

- ☐ Where do matter and energy come from?
- ☐ Are there forces and energies at work that we have not yet discovered?
- ☐ How long will the sun shine and the earth survive?
- ☐ How many other "earths" are there, and are any of them habitable or inhabited?
- ☐ What further strange new types of objects does the universe hold?
- ☐ What was it like at the beginning of time, 10 or 15 billion years ago?
- ☐ Does time stretch backward forever, or was there a beginning?

To define the possible ways to answer these questions, an Astronomy Survey Committee was set up in 1969 by the Committee on Science and Public Policy of the National Academy of Sciences. It was directed to formulate for the government, and for scientists, a ten-year plan for the future of astronomy.

The basic questions in 1970's

- ☐ Where do matter and energy come from?
- ☐ Are there forces and energies at work that we have not yet discovered?
- ☐ How long will the sun shine and the earth survive?
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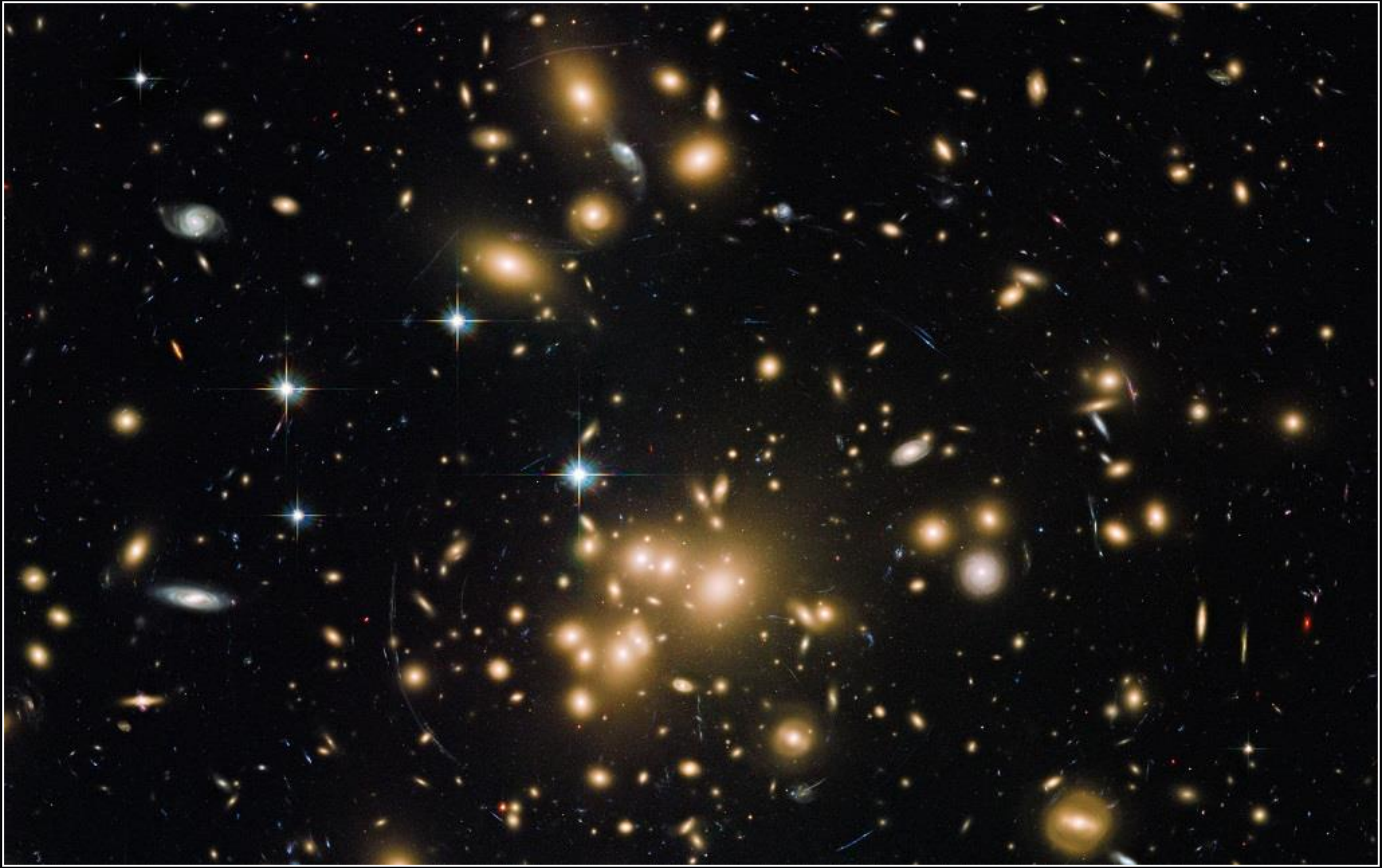
Jesse Greenstein: *The future of Astronomy*

The classical baryonic paradigm

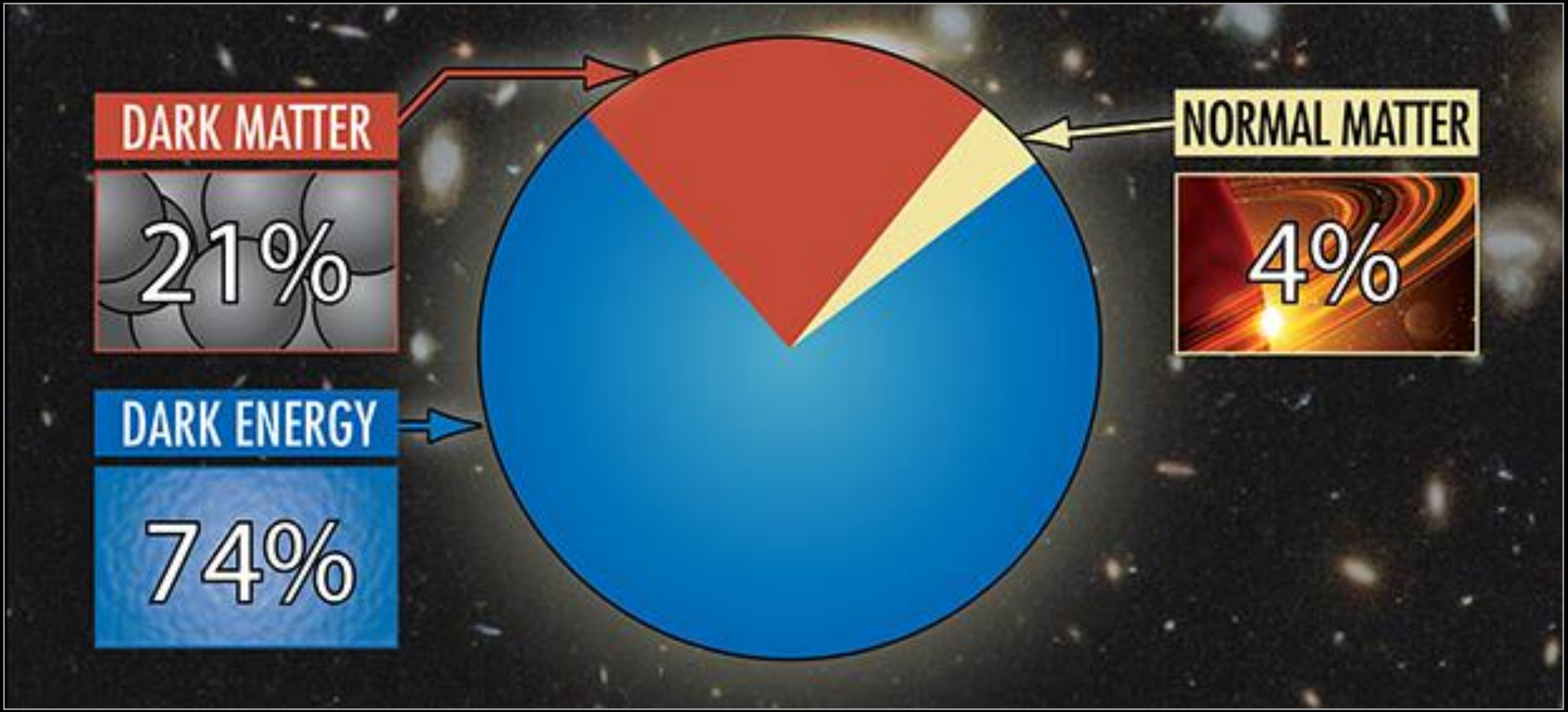
The universe contains some 100 billion galaxies, each with billions of stars, giant gas & dust clouds, and perhaps scads of planets and moons and other little bits of cosmic flotsam.



Galaxy cluster Abell 1689 in Virgo; HST images

New paradigm on stage: the “dark” cosmos

About 95% of cosmic matter/energy
seems to be in some unknown "dark" form



We shell concentrate on the **Dark Matter**

It is not dark matter, sir – you just forgot to remove the cap from the objective

Just the matter which is dark (DM)

About 21% of cosmic matter ($\Omega = 1$) seems to be in some unknown & exotic "dark" form

- (We believe) it is the gravitational glue holding together galaxies & clusters, and that
- it played a key role in the history & fate of the universe.

Yet this matter has not been directly detected

The most popular DM candidates
in terms of detection efforts, are:
MACHOs, WIMPs, axions, sterile neutrinos …

No reason why it shouldn’t exist

Letter of Friederich Bessel (1944) on Procyon and Sirius: “*But light is no real property of mass. The existence of numberless visible stars can prove nothing against the evidence of numberless invisible ones*”

Texas landascape at night

The tricky property: Dark Matter is dark

Undetectable but for the gravitational effects induced on the visible matter.

That means that it must neither emit nor absorb any appreciable electromagnetic radiation in any known waveband.

Thus it is called Dark Matter.

The last-minute numbers

$$
\begin{aligned}
\Omega &= 1.0023^{+.0056}_{-.0054} \\
\text{Dark Energy Density (vacuum energy)} &\simeq 0.73 \\
\text{Dark Matter Density} &\simeq 0.23 \\
\text{Baryon(NormalMatter) Density} &\simeq 0.04 \\
\text{Age of the Universe} &\simeq 1.37 \ \text{billion years}
\end{aligned}
$$

Birth of an idea

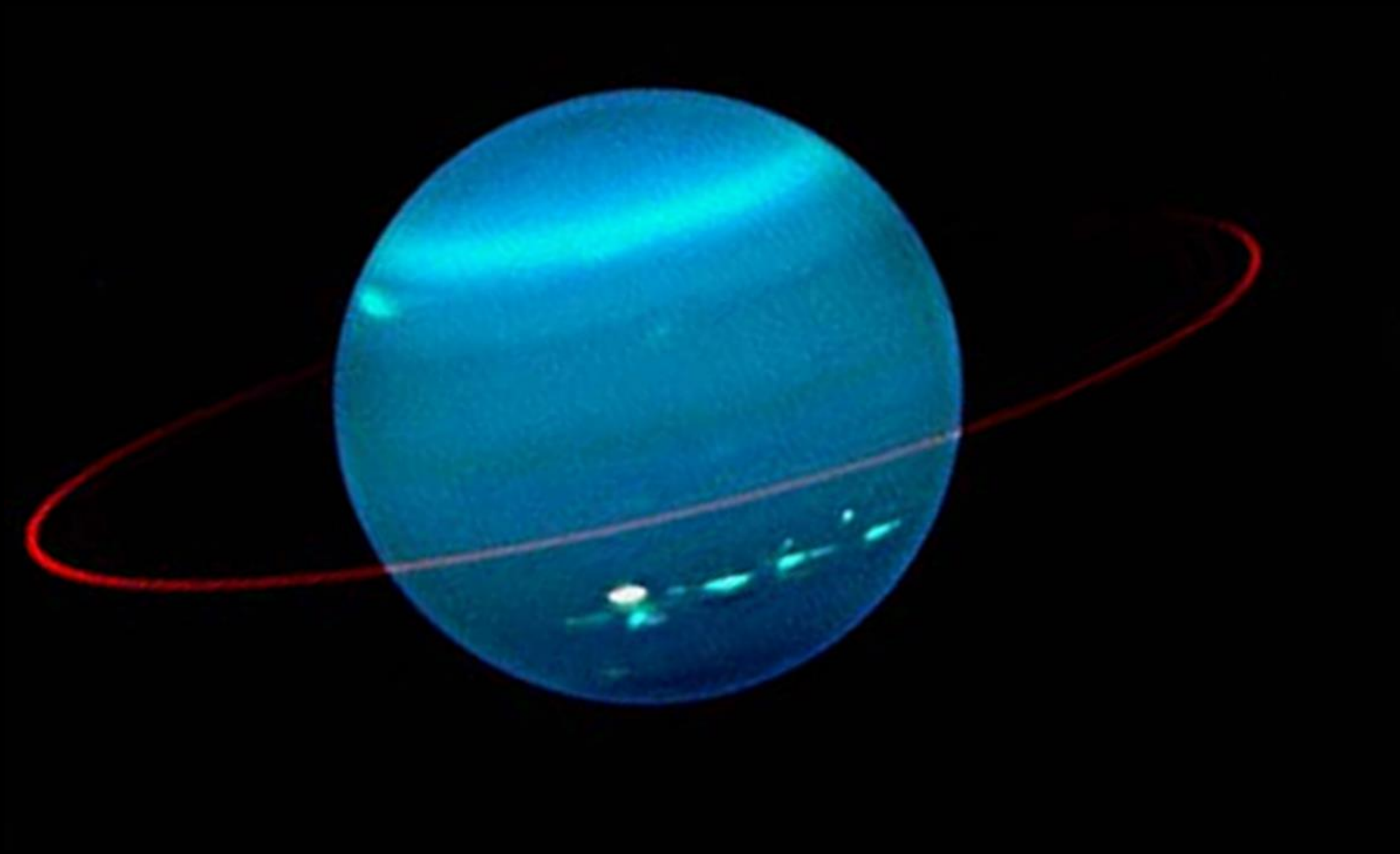
What do you blame
when an observation/experiment
does not match the theoretical expectation?

1. Missing ingredients ?
2. Fault in the physical modelling ?

A lesson learned

The discovery of Uranus

Discovery date:
13 March 1781



Calculation of Uranus' orbital parameters

Solution of a *N*-body problem within Newtonian mechanics:

1) **law of inertia**
2) **law of force**

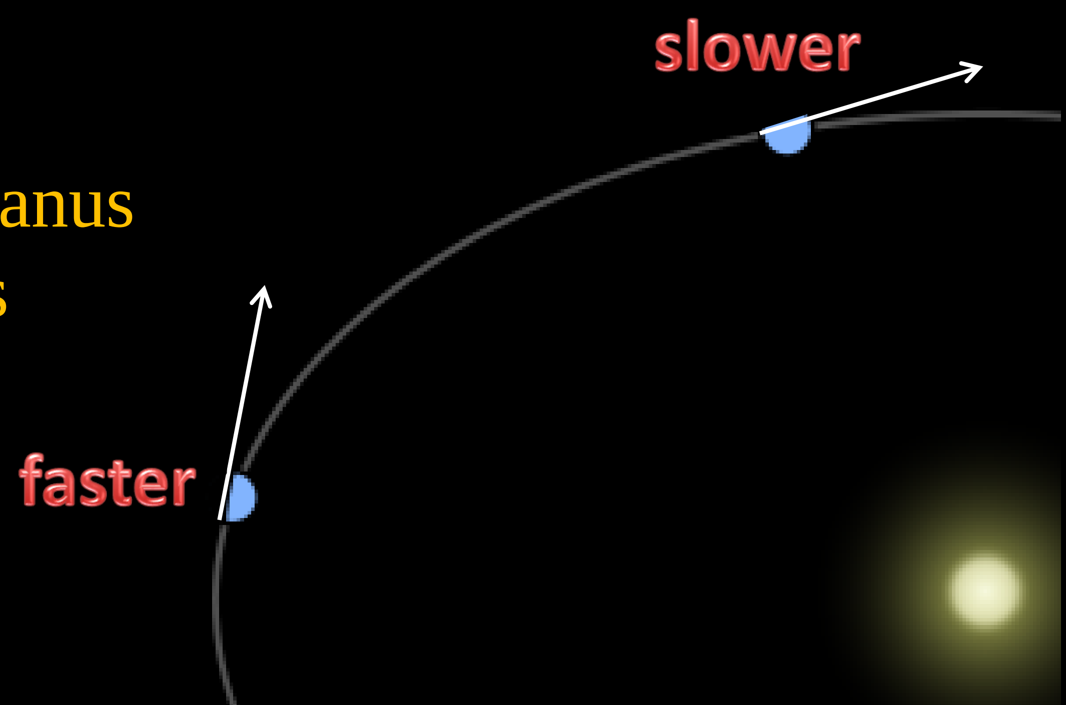
$$\frac{d^2x_i}{dt^2} = -G \sum_{j\neq i=1}^{N} \frac{m_j}{r_{ij}^3}(x_j - x_i)$$

$$\frac{d^2y_i}{dt^2} = -G \sum_{j\neq i=1}^{N} \frac{m_j}{r_{ij}^3}(y_j - y_i) \qquad (i = 1, ..., N),$$

$$\frac{d^2z_i}{dt^2} = -G \sum_{j\neq i=1}^{N} \frac{m_j}{r_{ij}^3}(z_j - z_i)$$

with *N* = number of actors (Sun + known planets).

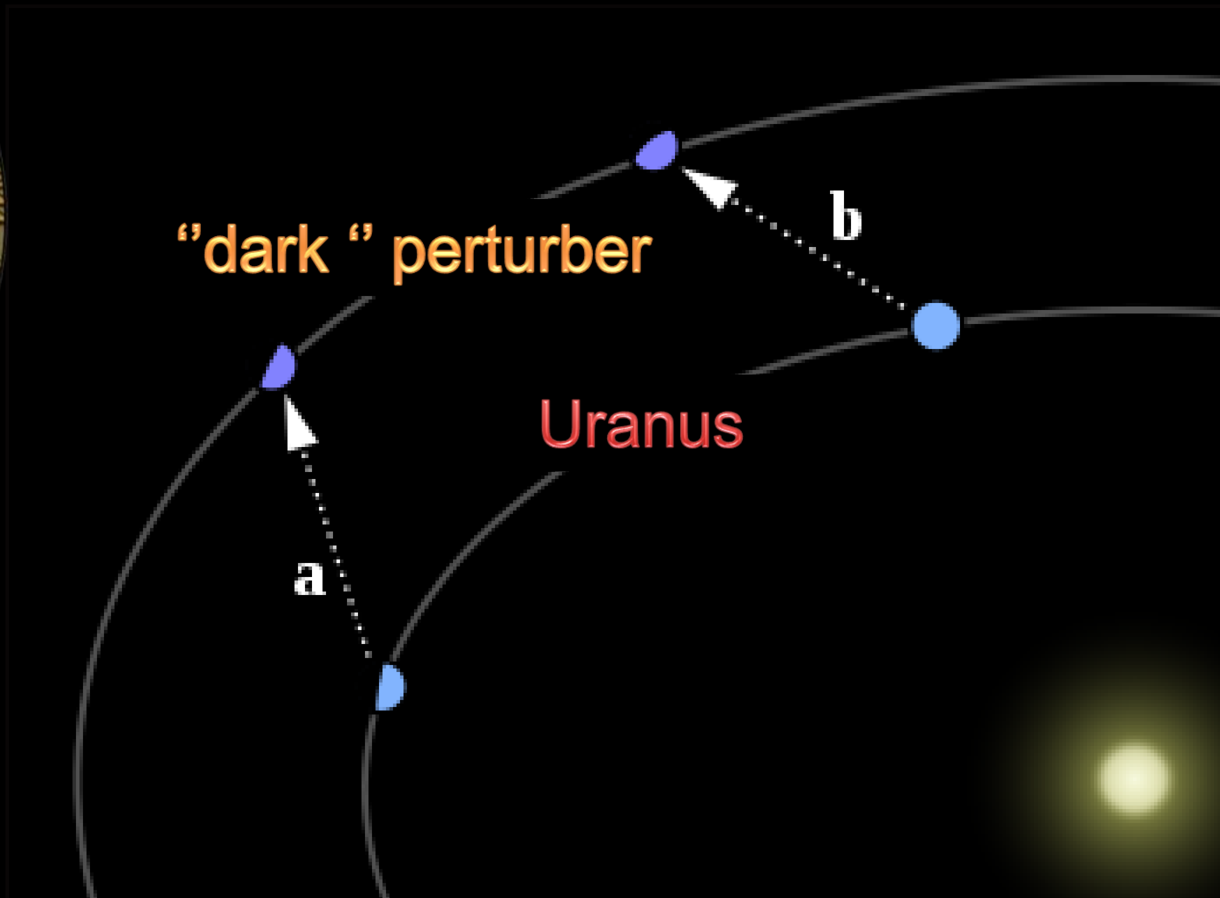
The computed speed of Uranus did not match observations



Way out: an unknown body perturbing Uranus

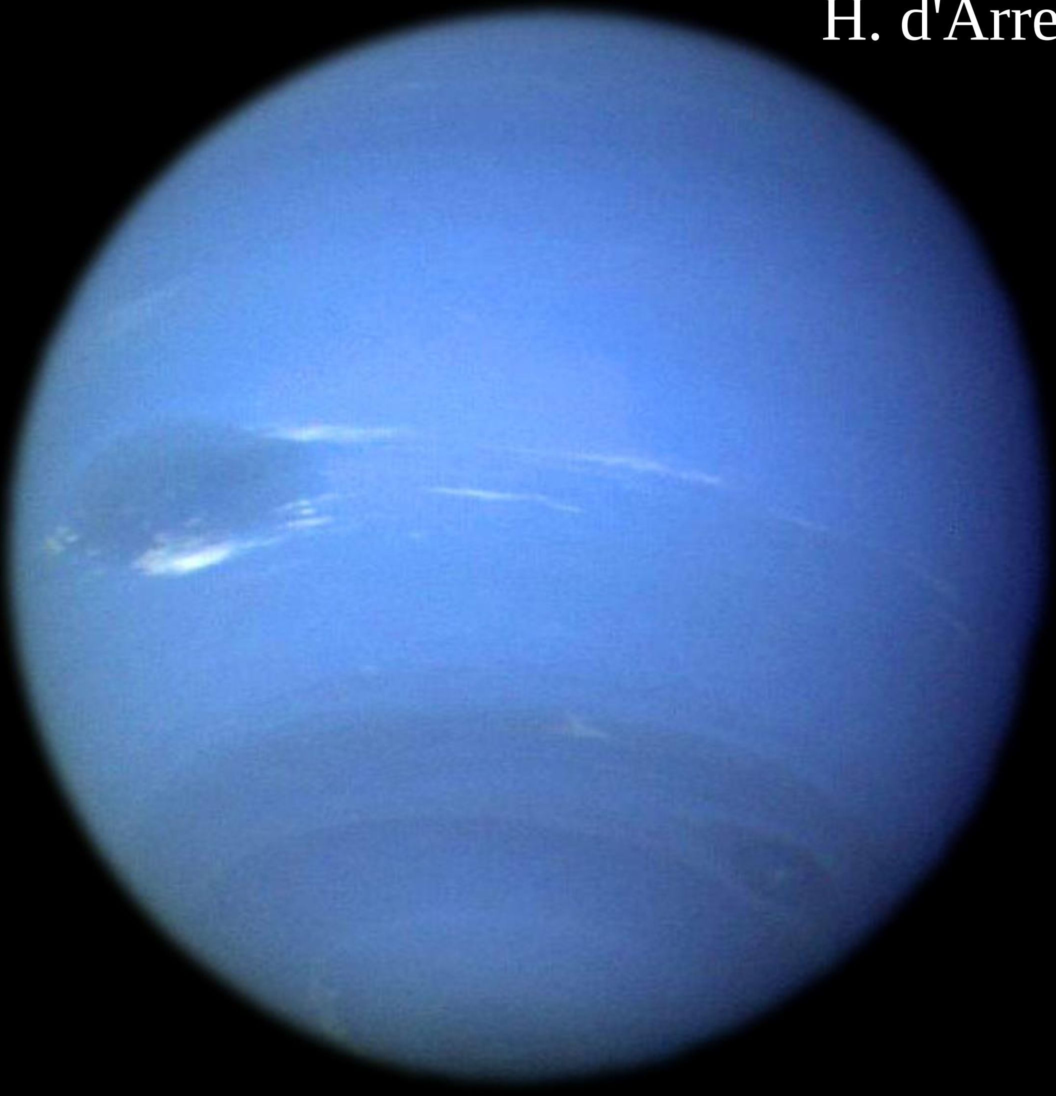
Urbain Le Verrier

J.C. Adams



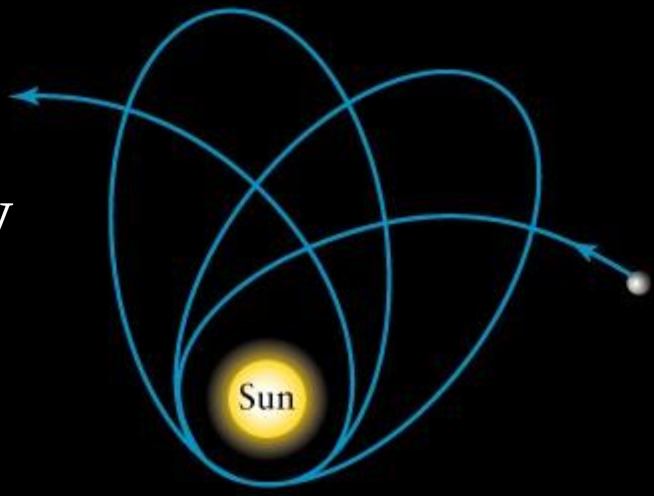
Neptune: the “dark” ingredient is identified

Discovery of Neptune by J. Galle &
H. d'Arrest at the Berlin Observatory



But this is not the rule: a counter-example

Precession of Mercury perihelion



As seen from Earth, the orbit of Mercury precedes by (5000″ + 600″)/century.

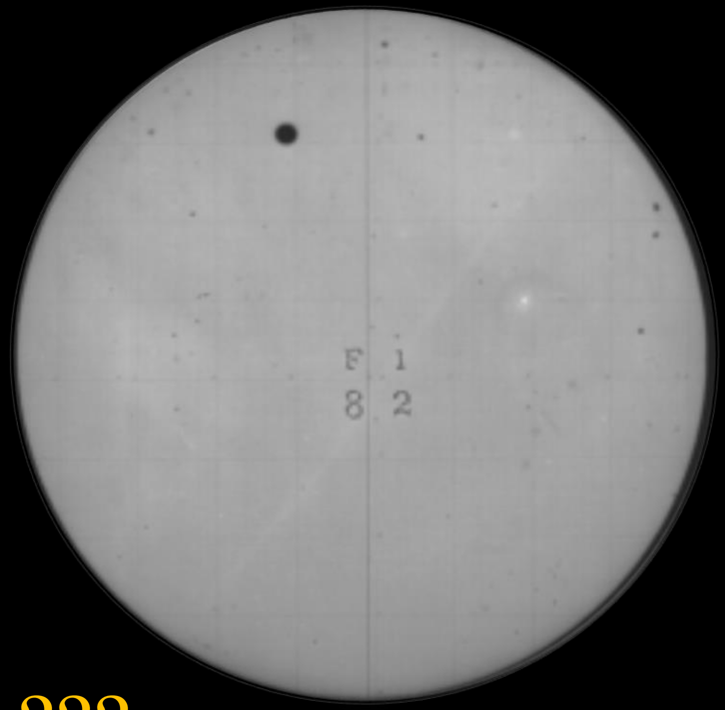
Newton's equations, accounting for
 - all the other planets,
 - the slight rotational flattening of the Sun, and
 - the proper inertial reference frame,

predicts a precession of 557″/century.

There was a discrepancy of 43″/century (7.1%)

The fake planet Vulcan

To account for the precession of Mercury, Urbain Le Verrier postulated the existence of a planet between Mercury and the Sun:
VULCAN

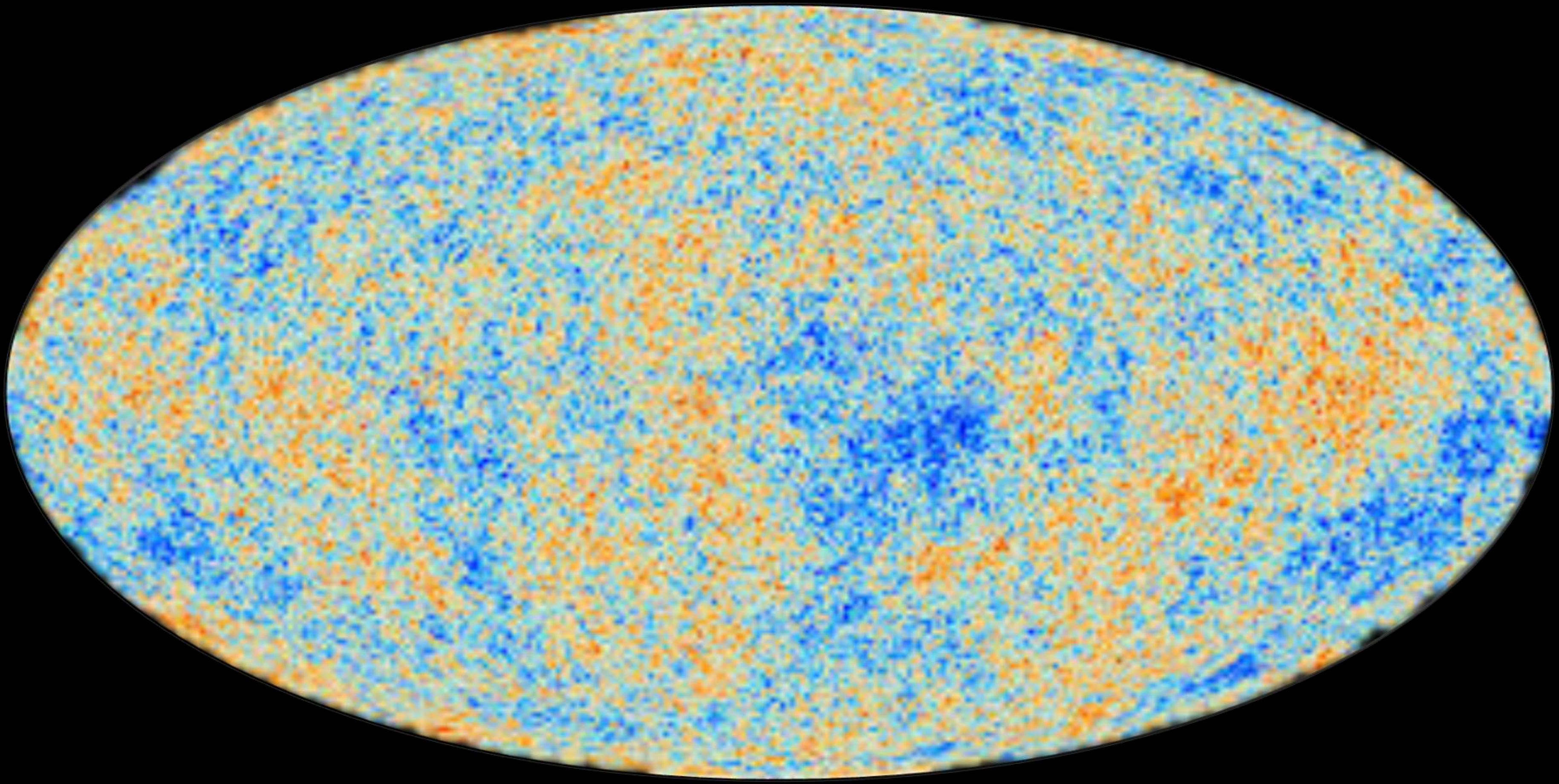


The 1859 "*transit of Vulcan*" may have looked similar to this transit of Venus in a photograph from 1882

Another new ''dark" ingredient ???

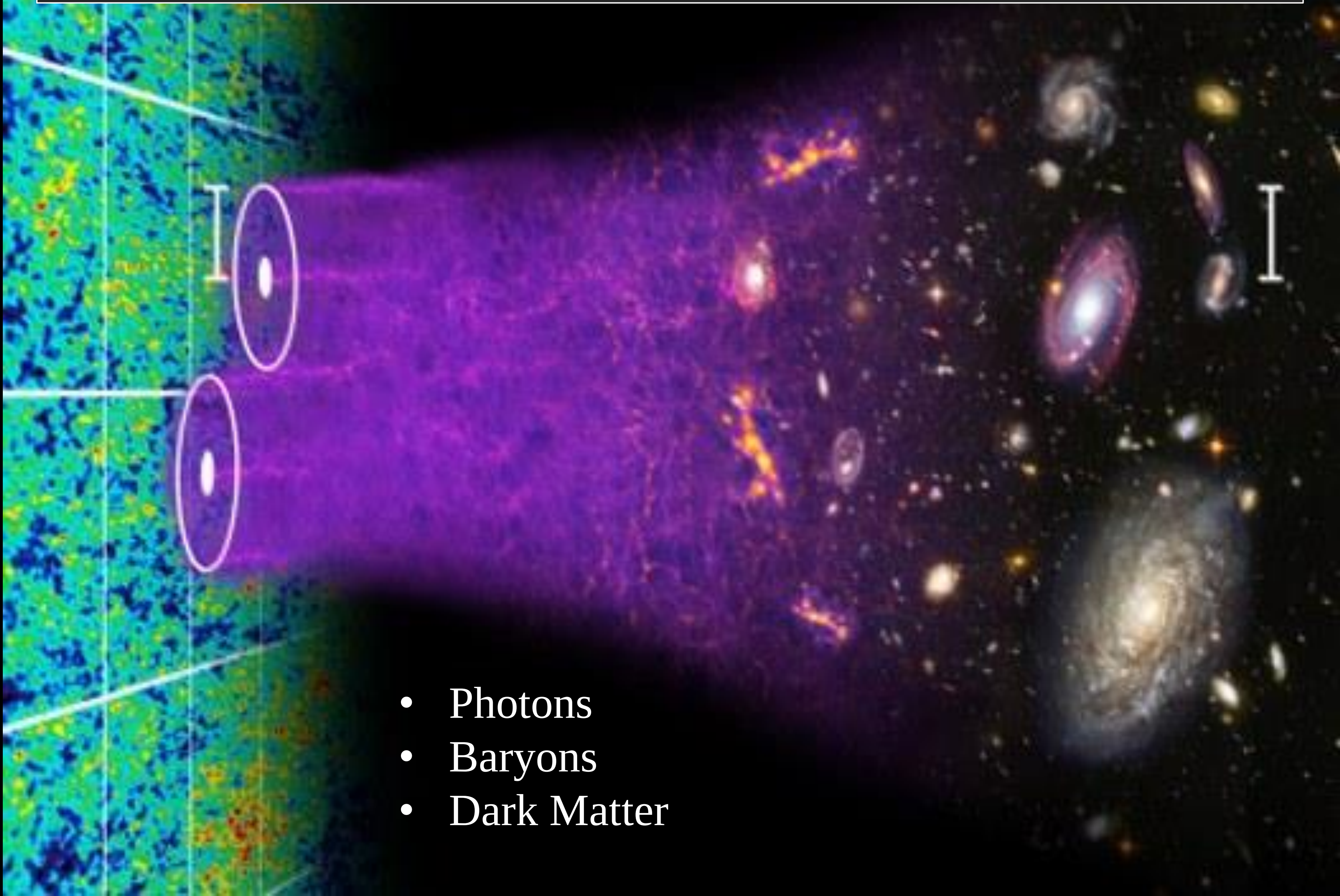
No, a fault in the theory!!!

The cosmological needs



Planck: CMBR temperature map

Baryon acoustic oscillations



- Photons
- Baryons
- Dark Matter

1932: Solar neighborhood density

Jan H.Oort
(1900-1992)

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 | Volume VI. | No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

NOTE ON THE DETERMINATION OF K_z AND ON THE MASS DENSITY NEAR THE SUN [1])

BY J. H. OORT

A force K_z has been determined which is consistent with the observations discussed in the preceding article and which at the same time fulfills the requirement that K_z must be due to the attraction by stars and interstellar matter. Our knowledge of the distribution of this attracting mass, though incomplete, is sufficient to put rather stringent conditions on K_z, so that it can be determined much more reliably than if the requirements of Poisson's law are left out of consideration. On the supposition that the z-distribution of the total stellar density is the same as that of the K giants, the variation of K_z with z was found to be like that indicated by crosses in Figure 3. The total mass density at $z = 0$ was found to be 10.0×10^{-24} g/cm³, or 0.15 solar masses per pc³, with an estimated uncertainty of about 10%. This density agrees well with that derived by HILL without using Poisson's equation. Its precision is considered to be rather greater. A comparison is made with the results of other recent investigations.
The ratio of mass- to light-density, M/L, in solar units, is 2.4. For the total contents of a cylinder perpendicular to the galactic plane $M/L = 4.2$. The curve in Figure 4, marked K giants, is believed to give a fair representation of the variation of the total star density with z.

The strategic idea

The matter density is measured by sampling a uniform population of stars extending above the disk of the galaxy.

Average velocities of the stars and vertical distances they cover above the disk give a measure of the gravitational restoring force keeping these stars in the disk.

The flat disk model

Assuming axisymmetry, the third Jeans equation in cylindrical coordinates is:

$$\frac{\partial\left(\nu\overline{v}_z\right)}{\partial t}+\frac{\partial\left(\nu\overline{v_R v_z}\right)}{\partial R}+\frac{\partial\left(\nu\overline{v_z^2}\right)}{\partial z}+\frac{\nu\overline{v_R v_z}}{R}+\nu\frac{\partial\Phi}{\partial z}=0,$$

which, for a disk in steady state, is:

$$\frac{\partial}{\partial z}\left(\frac{1}{\nu}\frac{\partial\left(\nu\overline{v_z^2}\right)}{\partial z}\right)=-\frac{\partial^2\Phi}{\partial z^2}.$$

Near the plane of a flat system, the Poisson equation writes as:

$$\frac{\partial^2\Phi}{\partial z^2}=4\pi G\rho \qquad (\rho\geq\nu),$$

and:

$$\frac{\partial}{\partial z}\left(\frac{1}{\nu}\frac{\partial\left(\nu\overline{v_z^2}\right)}{\partial z}\right)=-4\pi G\rho.$$

Use to estimate the local density ρ by measuring, as a function of z:

1. the number density ν, and
2. the mean-square vertical velocity $\overline{v_z^2}$ of any population of stars.

“Oort limit”: lack of visible matter

The density of unseen material [illegible] ilky Way disk is ≥ 50% of that of the [illegible] ort limit).

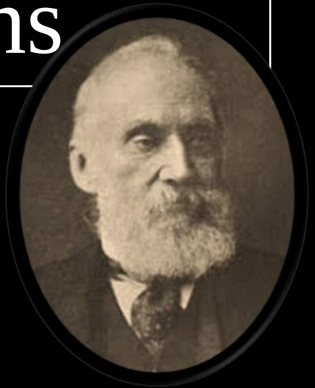
WRONG

This additional compon [illegible] dark, needs to be nothing very exotic.

It might consist [illegible] , such as white and even black dwarfs.

N.B. This result has been eventually questioned as the model ignores the pull by the bulge component of the galaxy.

Pioneers of dynamical investigations



Dark Baryons

Lord Kelvin (Willian ... st to attempt a dynamical estim ... e Milky Way by linking t ... persion:

"It is neverthe ... y be as many as 10^9 stars [within a sphere ... lometres] but many of them may be extinct and ... e-tenths of them though not all dark may be not brig ... gh to be seen by us at their actual distances. [...] Many of our stars, perhaps a great majority of them, may be dark bodies."

Baryons? Some critical milestones

Unthinkable that missing matter in the Solar area would be non-baryonic.

1926: discovery of the nature of the white nebulae by Edwin Hubble

1929: discovery of the expansion of the universe by Edwin Hubble

1932: discovery of the first neutral baryon, the neutron, by James Chadwick

1937: The “missing mass” in the Coma cluster

Fritz Zwicky
(1898-1974)

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF
CLUSTERS OF NEBULAE

F. ZWICKY

Helvetica Physica Acta, Vol. 6, p. 110-127, 1933

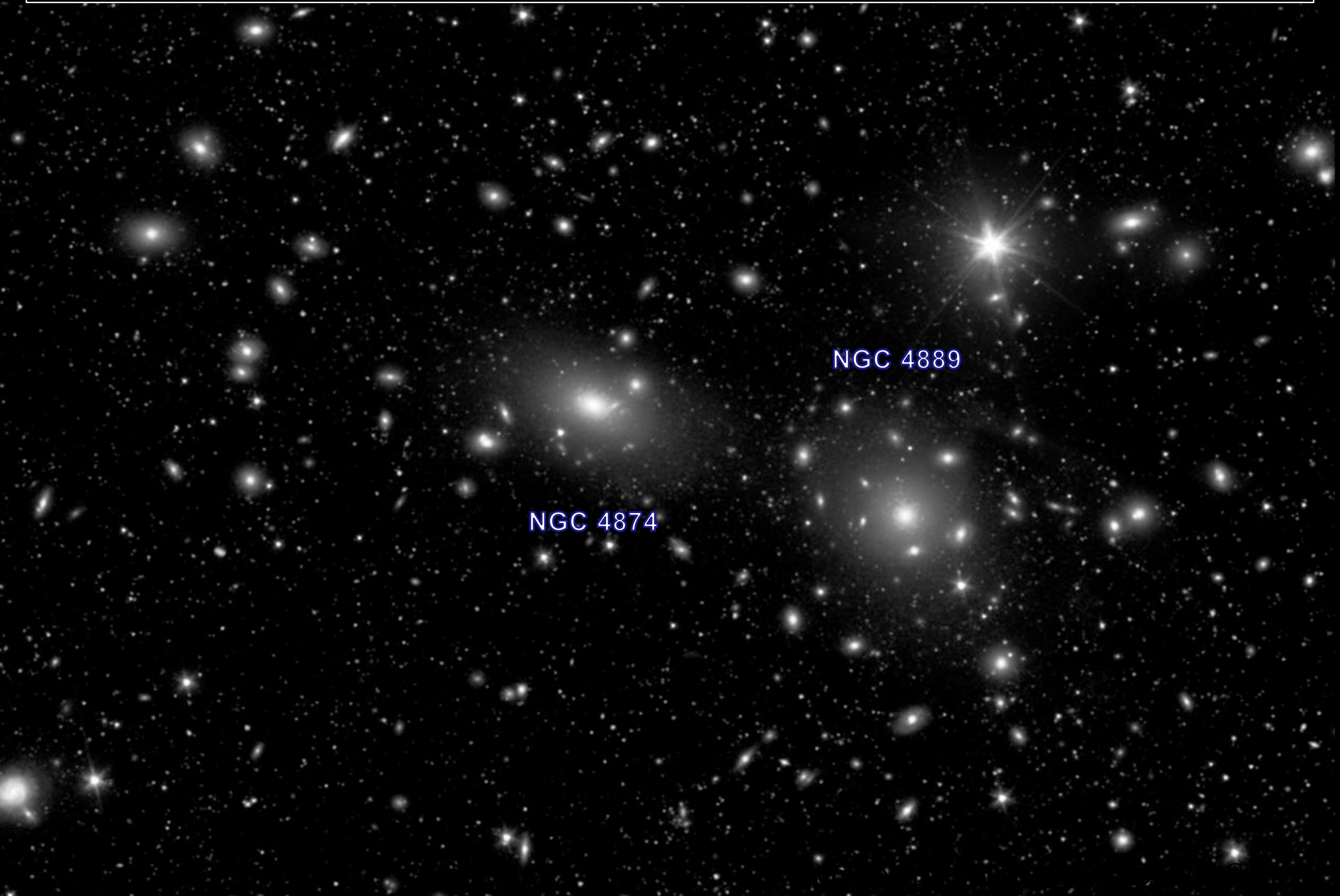
Die R[illegible] Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

The Coma cluster of galaxies



The total virial mass

Using the virial theorem with some acrobatic assumptions to account for the geometry of the system and for the projection effects:

$$M_T = Nm \cong \frac{2R\text{v}^2}{G}$$

borrowed from thermodynamics; already done by Lonr Kelvin

Zwick took: $\sqrt{\text{v}^2} = 700$ km/s,

$R = 2\times10^6$ ly,

$N = 1000$,

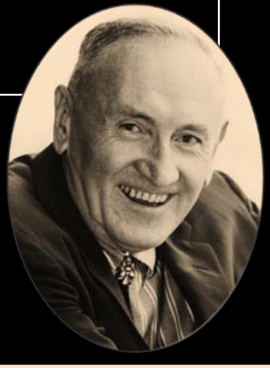
and obtained:

$$M_T > 9\times10^{46} \text{ gr}, \quad \text{or} \quad m > 9\times10^{43} \text{ gr} = 4.5\times10^{10} M_{Sun}.$$

By measuring the luminosity, Zwicky computed mass-to-light ratio γ [$\gamma = 1$ for the Sun].

Plenty of *missing mass*

in the "globular cluster of nebulae"



According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500\,, \tag{37}$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system. This discrepancy is so great that a further analysis of the problem is in order. Parts of the following discussion were published several years ago, when the conclusion expressed in (36) was reached for the first time.[5]

500 vs. 3

Modern value (Lucas & Mamon 2003) is $M/L_B = 351\,h_{70}$

Ignored …; too early

Zwicky's intuitions were not taken seriously by the scientific community.

First of all there were no DM candidates because:

1. gas radiating X-rays and dust radiating in the IR could not yet be observed, and
2. non-baryonic matter was unthinkable.

Zwicky's caustic reputation

Zwicky used to call his colleagues
"*spherical bastards*" as they were bastards
from any direction you would look at them, and

in his *Introduction* to a self-published
Catalogue of compact galaxies in 1971
he described them as
"*scatterbrains, sycophants, and plain thieves … [who]
doctor their observational data to hide their
shortcomings … [and publish] useless trash in the
bulging astronomical journals*".

Zwicky’s popularity gradient

Year	No. citations
1955-59	2
1960-64	6
1965-69	5
1970-74	2
1975-89	63
1990-99	71

Lesson learned

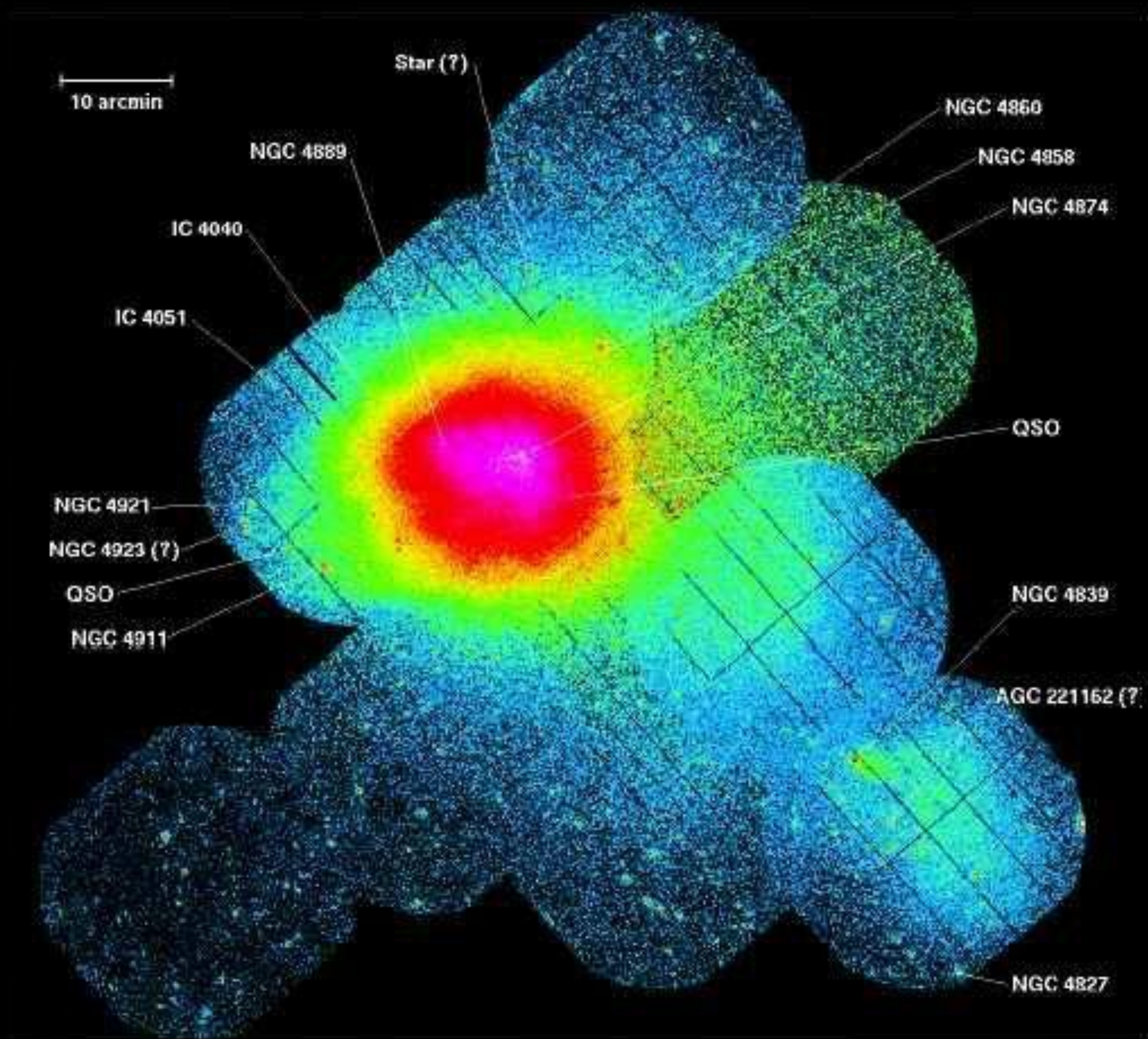
Since then observations have revised
our understanding of the composition of clusters.

- Luminous stars count for a very small fraction of a cluster mass.

- There is also a baryonic, hot intracluster medium (ICM) visible in the X-ray spectrum.

- Rich clusters typically have more mass in hot gas than in stars; in the largest virial systems (e.g. Coma) composition is: 85% DM, 14% ICM, and only 1% stars.

Coma cluster in X-rays

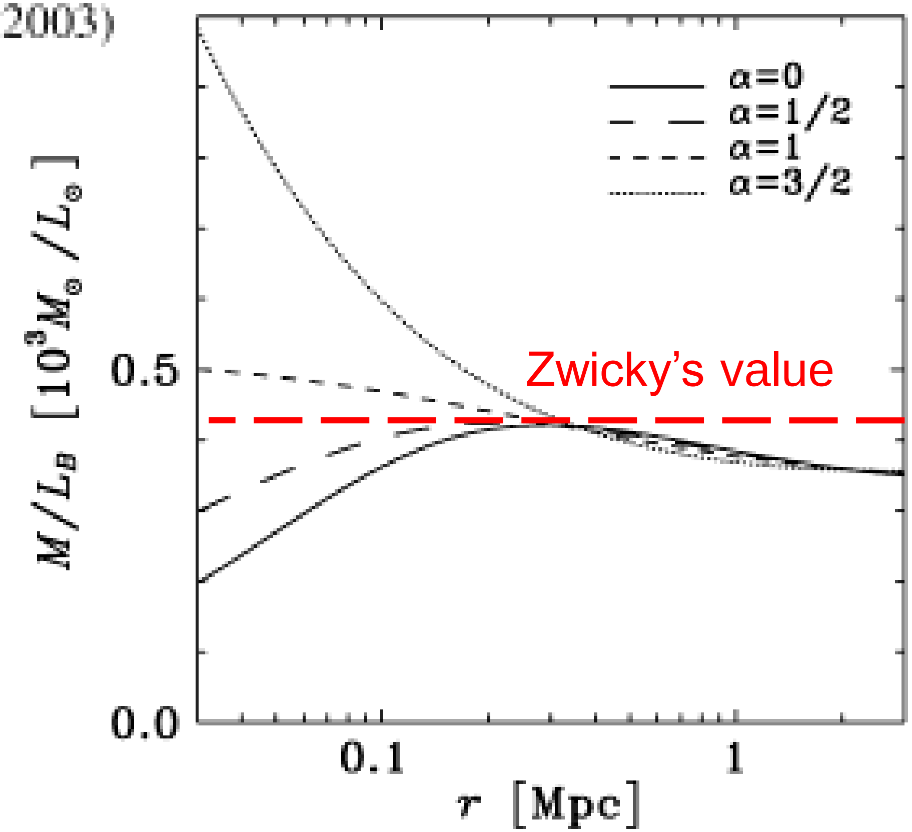


Fritz Zwicky vindicated

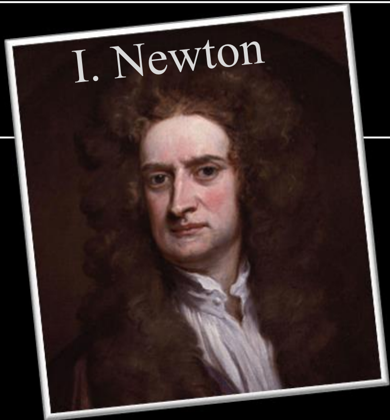
Dark matter distribution in the Coma cluster from galaxy kinematics: breaking the mass–anisotropy degeneracy

Ewa L. Łokas[1★] and Gary A. Mamon[2,3★]

Mon. Not. R. Astron. Soc. **343**, 401–412 (2003)



Zwicky's concern



$$\frac{1}{r^2} \; ???$$

In addition it will be n … methods which allow us to determine the relat … ternebular material in clusters as well as in the general field.

It should also be noticed that the virial theorem as applied to clusters of nebulae provides for a test of the validity of the inverse square law of gravitational forces. This is of fundamental interest because of the enormous distances which separate the gravitating bodies whose motions are investigated. Since clusters of nebulae are the largest known aggregations of matter, the study of their mechanical behavior forms the last stepping-stone before we approach the investigation of the universe as a whole.

He had covered his back ….

On the assumption that Newton's inverse square law accurately describes the gravitational interactions among nebulae,

Zwicky's precaution has eventually evolved into new theories of gravity

Mordehai Milgrom

MOND

Robert Sanders

***f*(*R*)**

Alexei Starobinsky

MOND: Modified Newton Dynamics

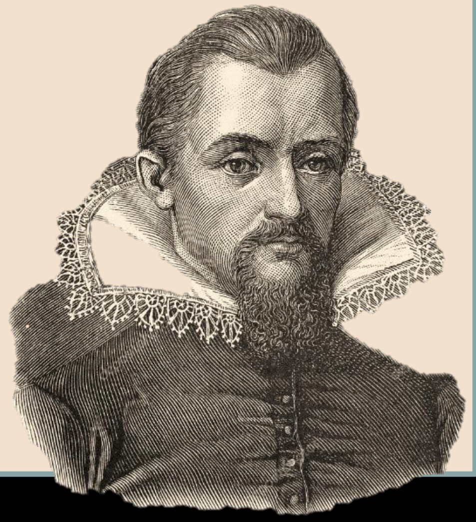
$$a_N = G\frac{M}{r^2} = \frac{\mathrm{v}^2}{r} \quad \text{where } \bar{a}_N = \mu\left(a/a_0 \right)\bar{a}$$

$$\mu\left(a/a_0 \right) = \begin{cases} 1 & \text{for } a >> a_0 \quad \text{classical Newton Dyn: } f = ma \\ a/a_0 & \text{for } a << a_0 \quad \text{modified Newton Dyn: } f = ma^2 \end{cases}$$

with $a_0 = 1.2\times10^{-10}$ m/s^2.

Effect:

- modified inertia: $\mu\left(a/a_0 \right)\bar{a} = G\frac{M}{r^2}$
- modified force: $\bar{a} = G\frac{M}{\mu\left(a/a_0 \right) r^2}$

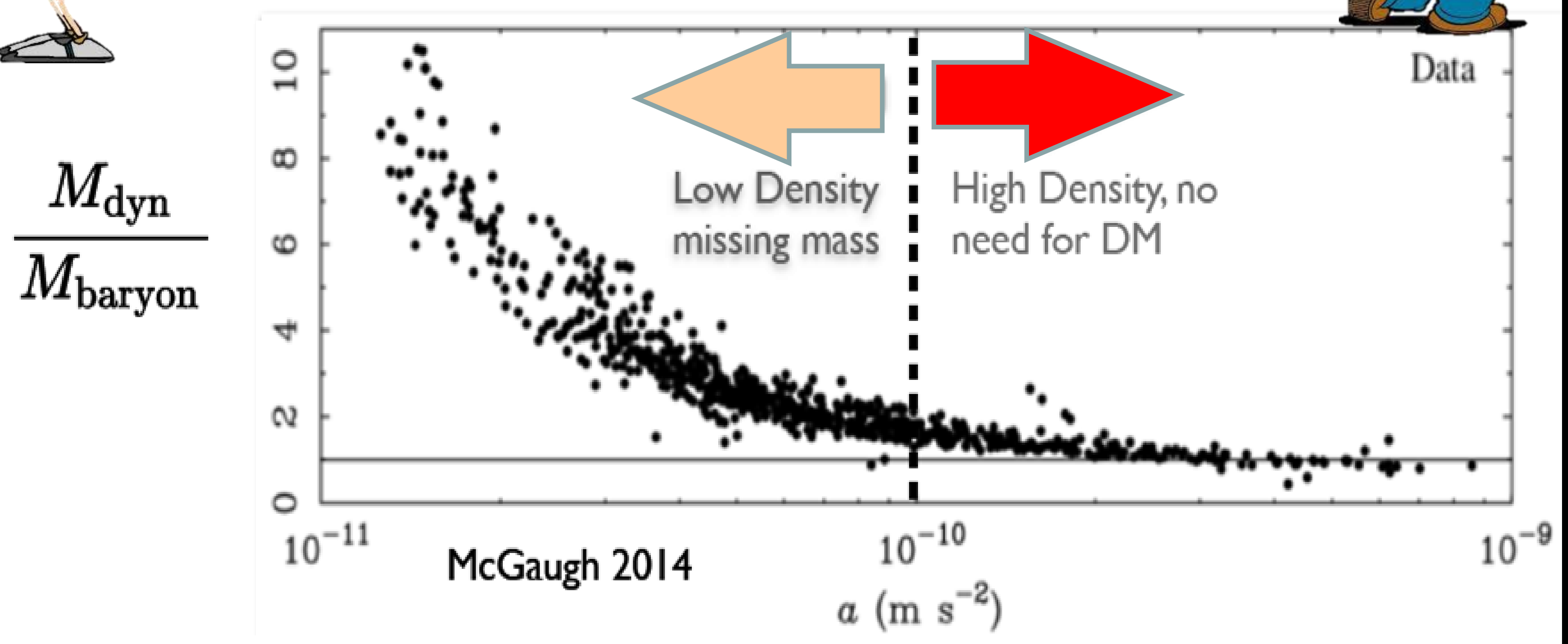


J.Kepler

Phenomenological approach

Weak vs. strong field regimes

Observed characteristic scale for galaxies



$$G\Sigma_c \sim 10^{-10}\,\mathrm{m\,s^{-2}} \rightarrow \Sigma_c \sim 100\,M_\odot\,\mathrm{pc^{-2}}$$

$f(R)$: curvature mimicking gravity

Modified gravity theory geleralizing Einstein's General Relativity.

$f(R)$ gravity is a family of theories defined by a different function of the Ricci scalar R.

$f(R) = R\left(-2\Lambda\right)$ is just General Relativity (and ΛCDM).

Generalized Lagrangian of the Einstein-Hilbert action:

$$S = \int \frac{1}{2\kappa} R\sqrt{g}\ d^4x \quad \rightarrow \quad S = \int \frac{1}{2\kappa} f(R)\sqrt{g}\ d^4x$$

where $\kappa = 8\pi G c^{-4}$ and

$g = \left|g_{\mu\nu}\right|$ is the determinant of the metric tensor.

Focus moved from matter to curvature

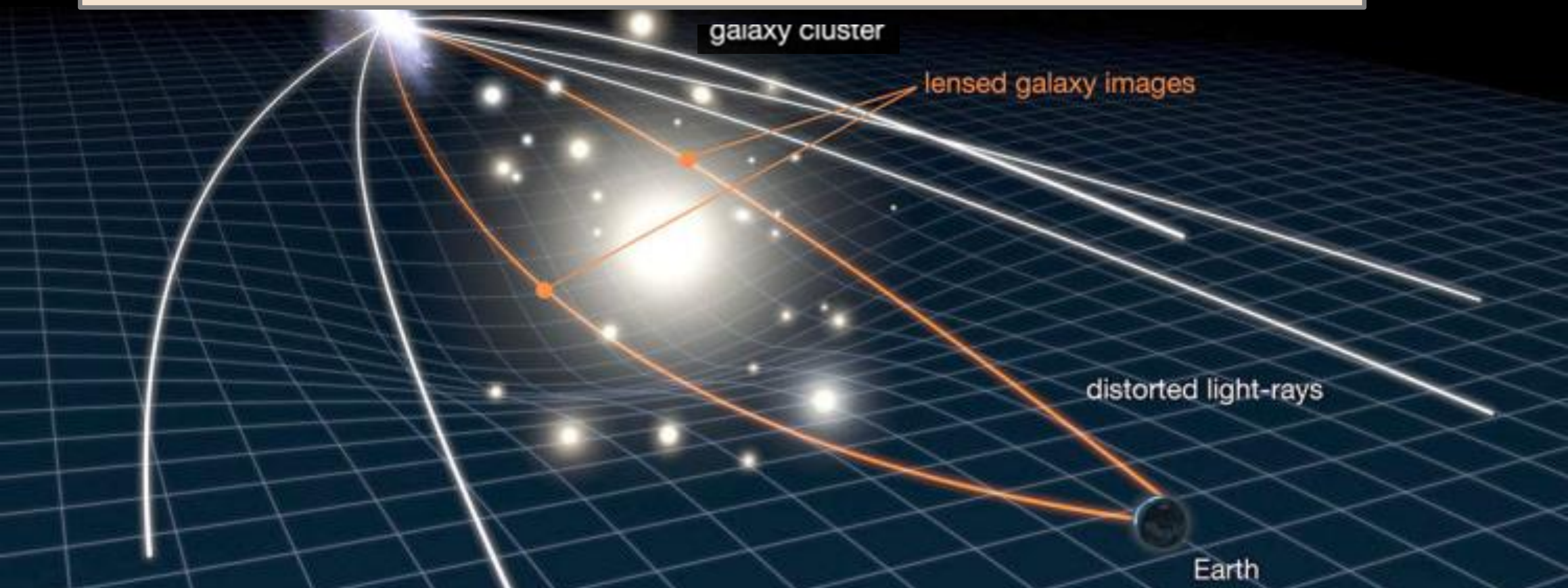
Zwicky's intuitions

- Morphological segregation
- Intracluster light
- Extragalactic surveys

Zwicky’s proposal for gravitational lensing

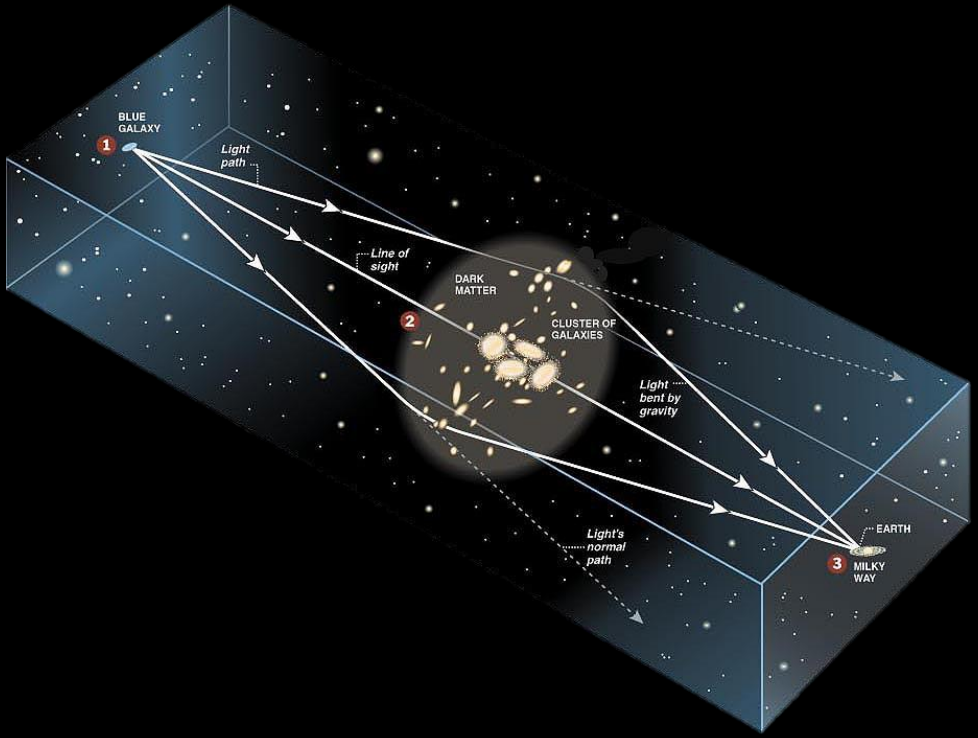
IV. NEBULAE AS GRAVITATIONAL LENSES

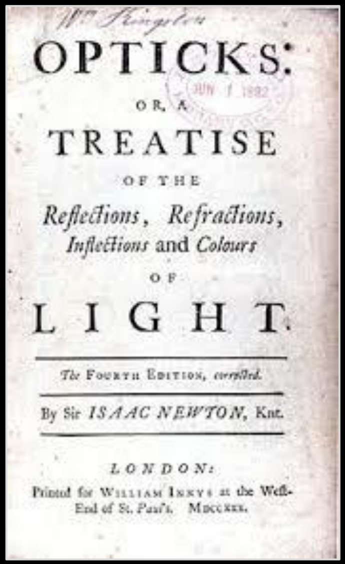
As I have shown previously,[6] the probability of the overlapping of images of nebulae is considerable. The gravitational fields of a number of “foreground” nebulae may therefore be expected to deflect the light coming to us from certain background nebulae. The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses.



Gravitational lensing

Einstein postulated the equivalence principle with Special Relativity to predict that light rays are Bent by a gravitational field.





An idea implicit in Query 1 of Newton's *Opticks*:
"*Do not Bodies act upon Light at a distance, and by their action bend its Rays? And is not this action (ceteris paribus) strongest at the least distance?*"

Gravitational lensing regimes

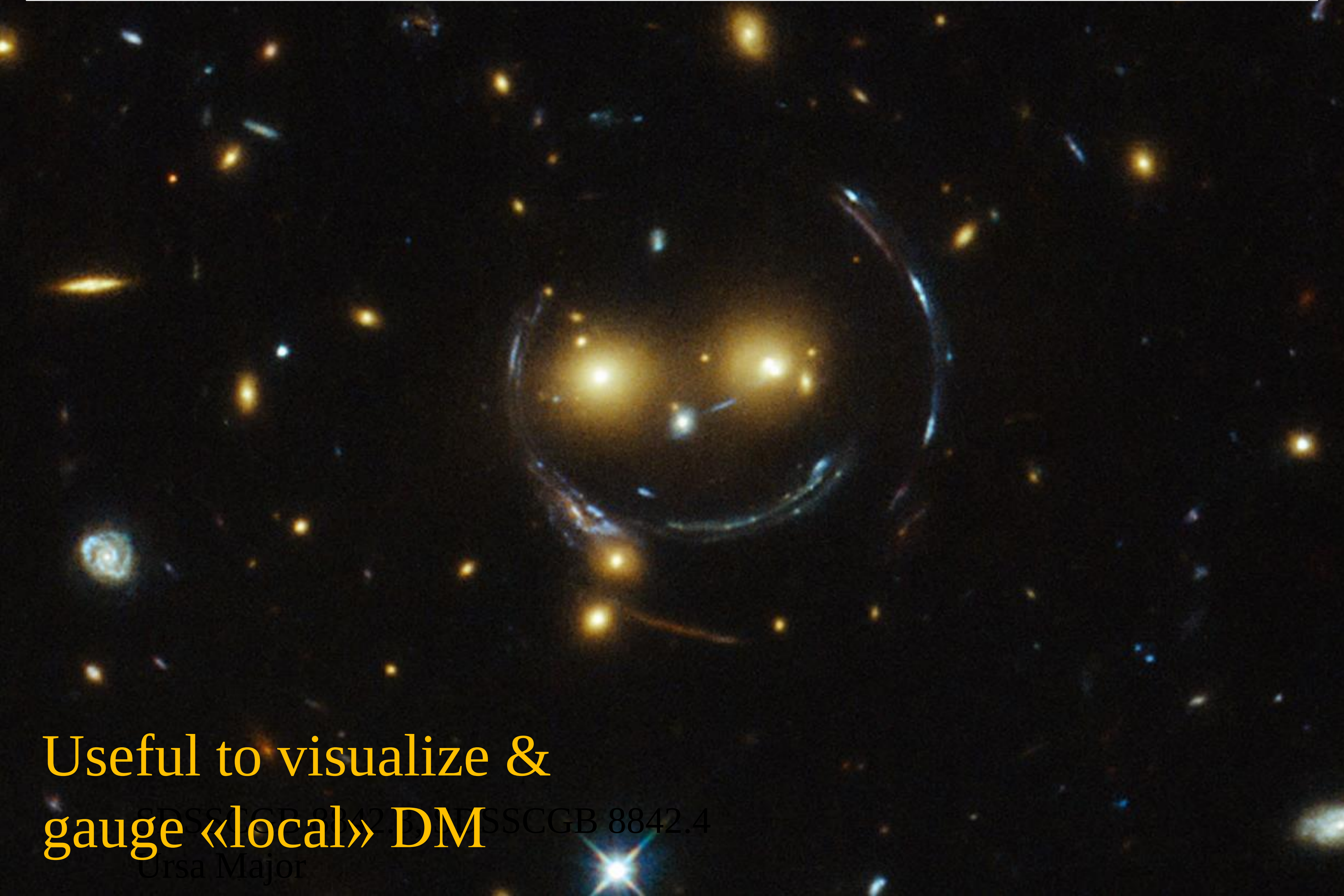
There are three different regimes for gravitational lensing:

1. strong lensing,
2. weak lensing,
3. microlensing.

The distinction between these regimes depends on:

1. the positions of the source, lens, and observer, and
2. the mass and shape of the lens, which controls how much light is deflected and where.

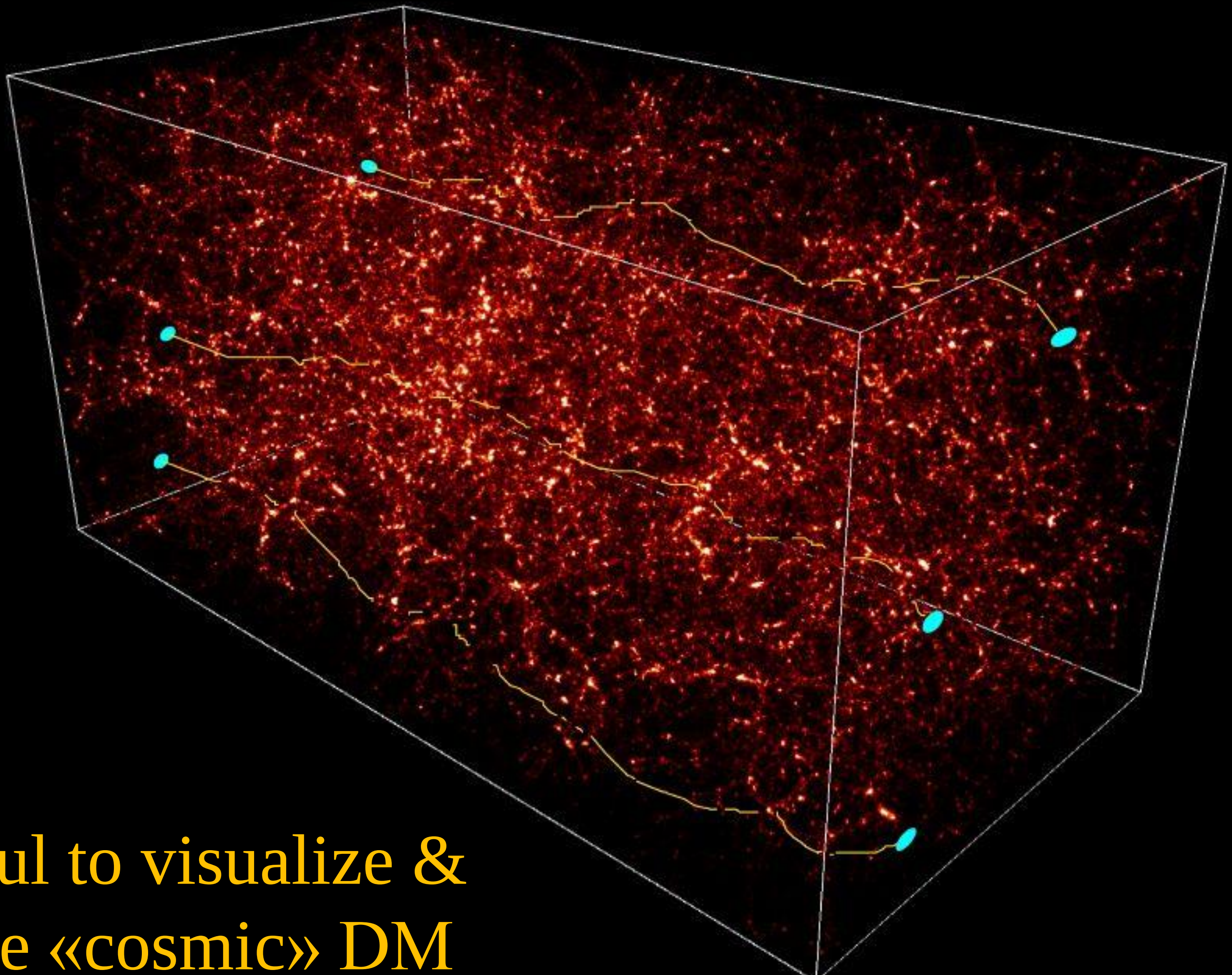
1. Strong lensing



Useful to visualize &
gauge «local» DM

SDSSCGB 8842.3, SDSSCGB 8842.4
Ursa Major

2. Weak lensing



Useful to visualize & gauge «cosmic» DM

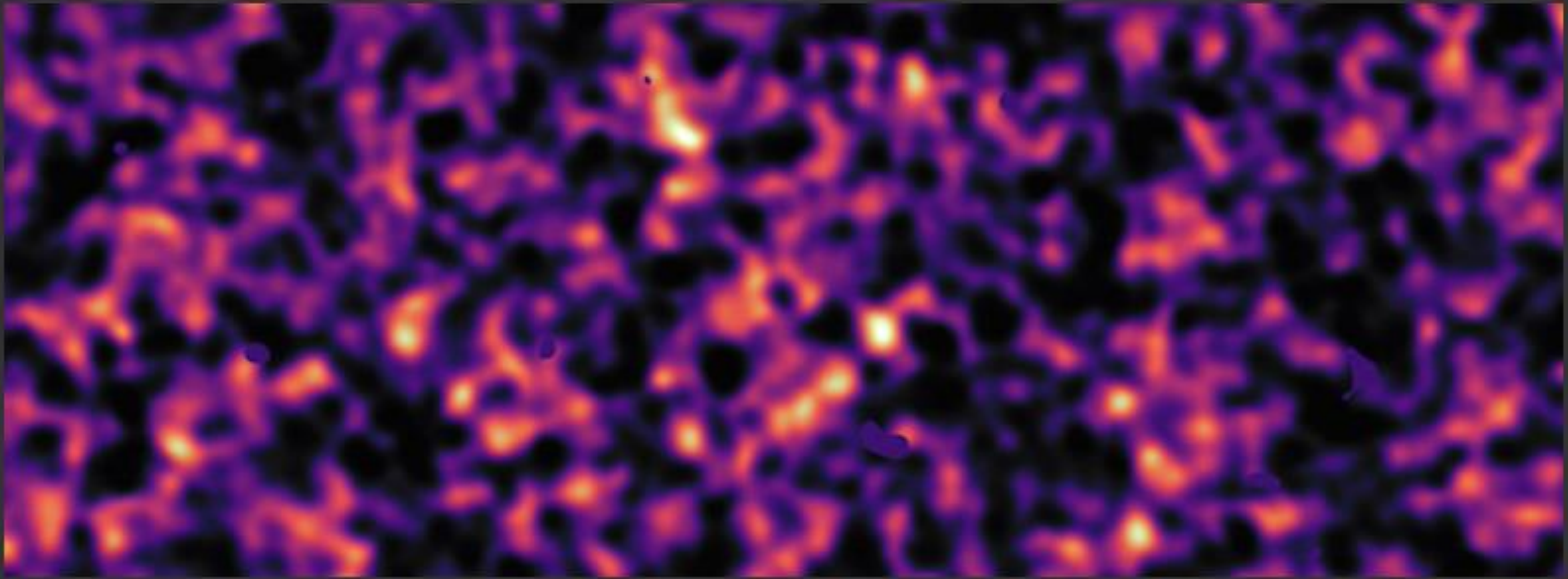
2. Weak lensing analogy

2. Weak lensing

Dark Matter May be Smoother than Expected

Careful study of large area of sky imaged by VST reveals intriguing result

ESO Press release 1642, 7 December 2016



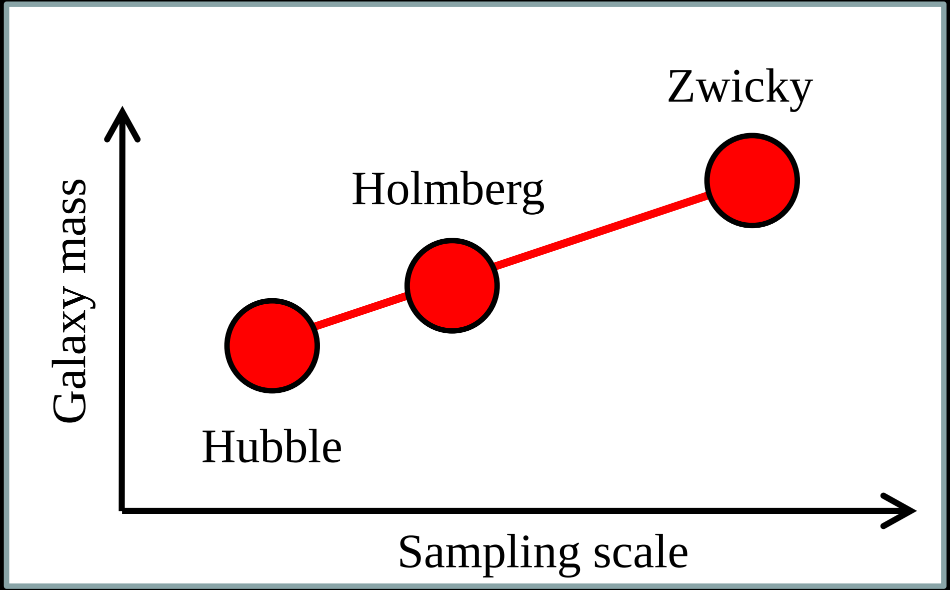
Dark matter map of KiDS survey region (region G12). Credit: Kilo—Degree Survey Collaboration/H. Hildebrandt & B. Giblin/ESO

1937: Holmberg's multiple galaxies

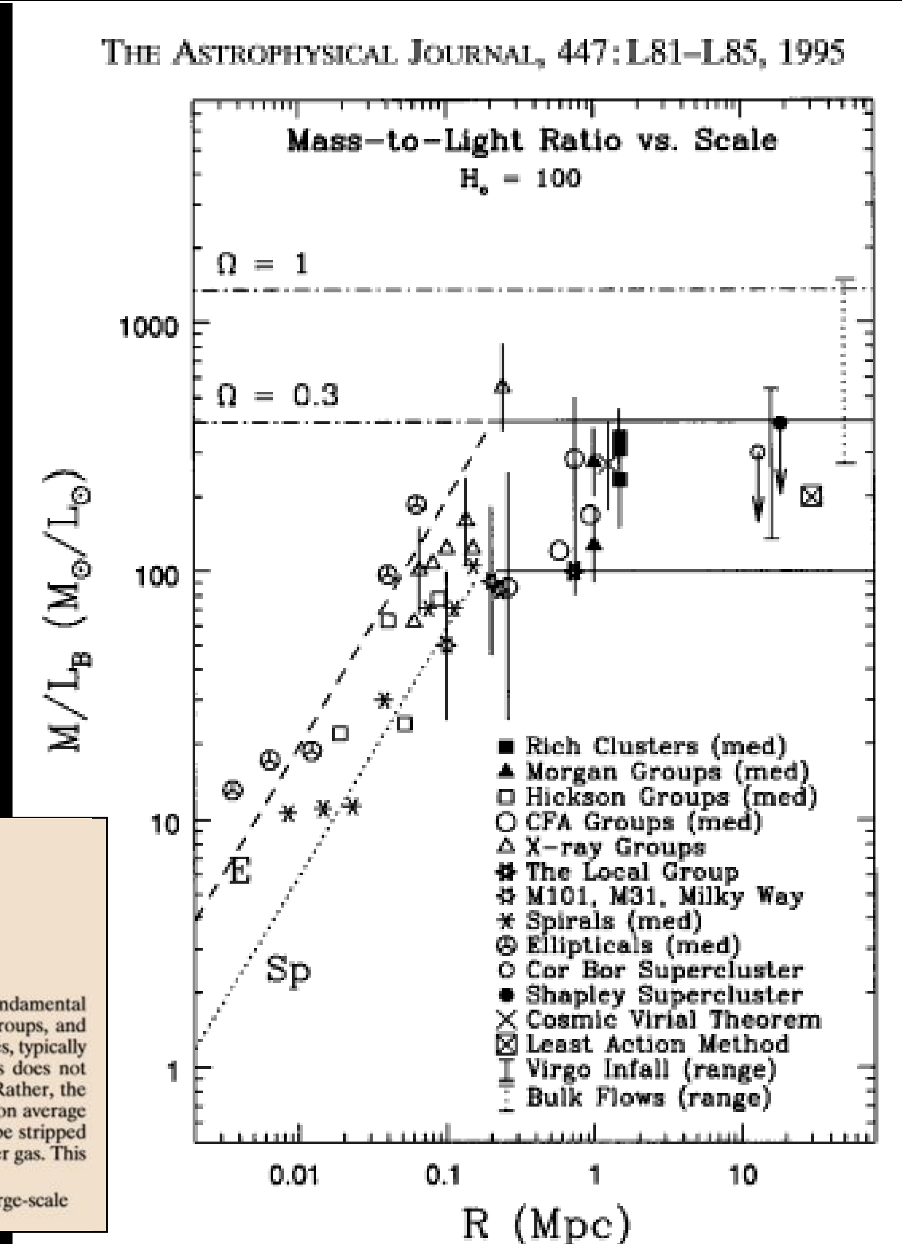
Erik Holmberg was a student of Lundmark at the Lund Observatory. In his dissertation (1937, *Annals of the Observatory of Lund*), he showed that galaxies often appear in groups and pairs, and he realized how it would be possible, using statistics, to determine the masses through the radial velocities of the two components.

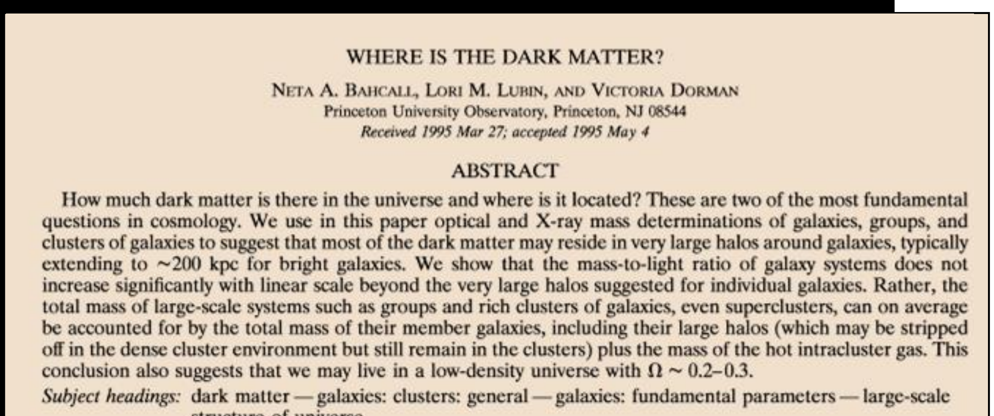
Arp 271

Holmberg's masses of galaxies were just in between Hubble's and Zwicky's.



Modern compilation





WHERE IS THE DARK MATTER?

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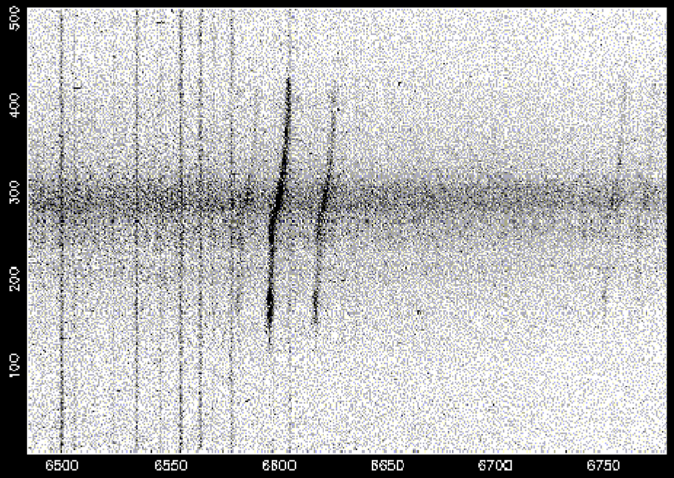
ABSTRACT

How much dark matter is there in the universe and where is it located? These are two of the most fundamental questions in cosmology. We use in this paper optical and X-ray mass determinations of galaxies, groups, and clusters of galaxies to suggest that most of the dark matter may reside in very large halos around galaxies, typically extending to ~200 kpc for bright galaxies. We show that the mass-to-light ratio of galaxy systems does not increase significantly with linear scale beyond the very large halos suggested for individual galaxies. Rather, the total mass of large-scale systems such as groups and rich clusters of galaxies, even superclusters, can on average be accounted for by the total mass of their member galaxies, including their large halos (which may be stripped off in the dense cluster environment but still remain in the clusters) plus the mass of the hot intracluster gas. This conclusion also suggests that we may live in a low-density universe with $\Omega \sim 0.2$–0.3.

Subject headings: dark matter — galaxies: clusters: general — galaxies: fundamental parameters — large-scale structure of universe

The rotation of spiral galaxies

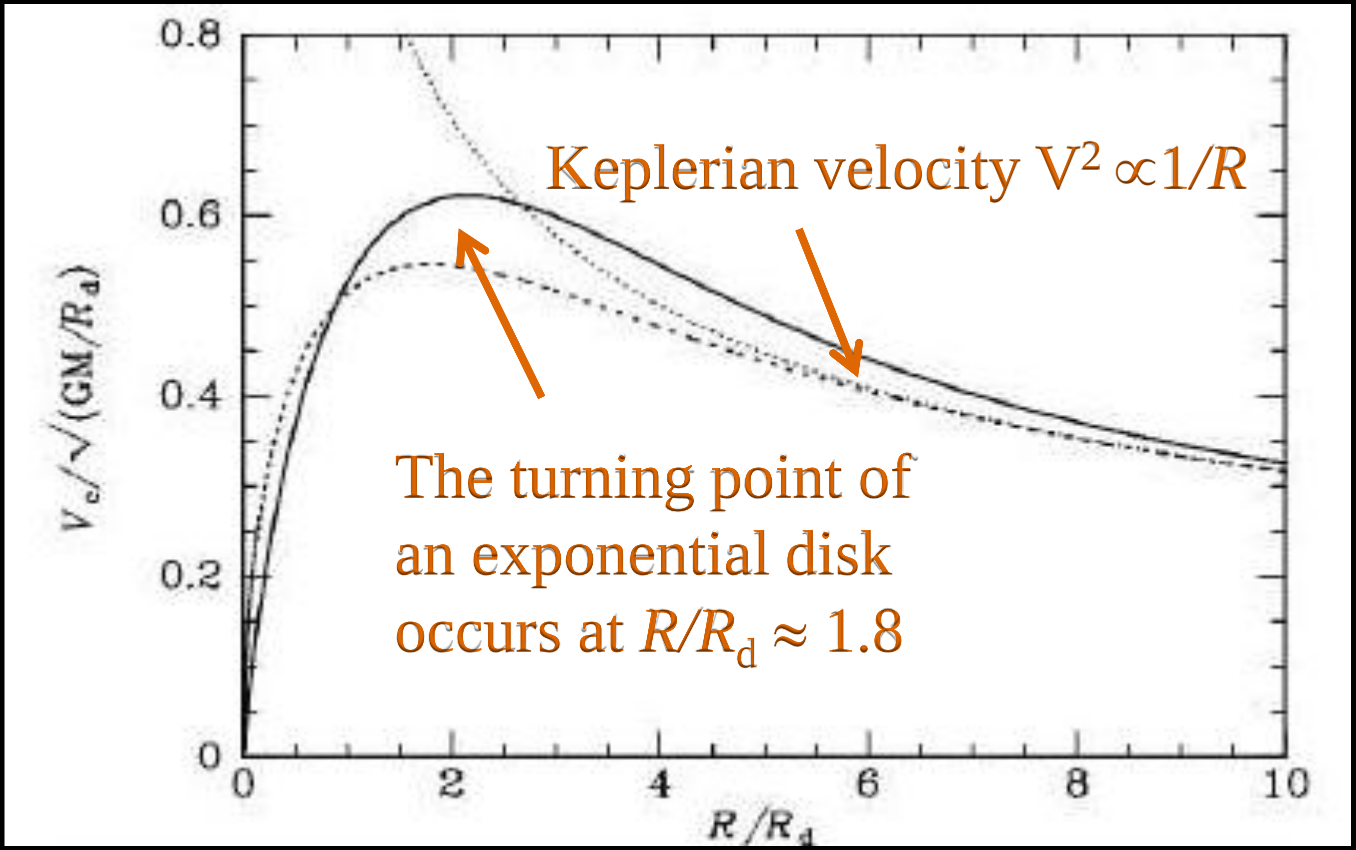


Early pioneers (still unclear nature of the nebulae):

- V. Slipher (1914) detected inclined absorption lines in nuclear spectra of M31 and Sombrero Nebula, and
- M. Wolf (1914) in M81.

- This led G. Pease (1918) to use the Mt. Wilson 60-inch to “investigate the rotation of the great nebula in Andromeda” with exposures of about 80 hours.

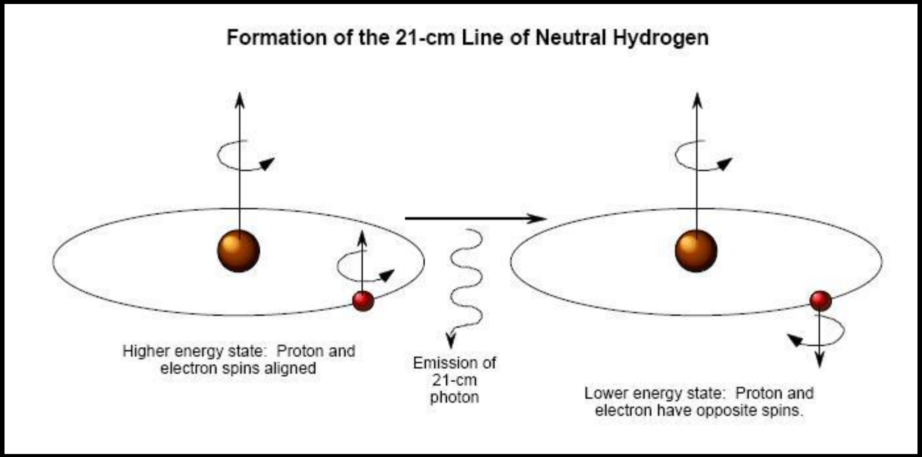
Expected rotation whether *M/L = const*.



Circular velocity V_C (normalized to R_d) for an exponential disk (solid line), compared to that of an exponential sphere (dashed line) and of a point mass (dotted line), all with the same mass

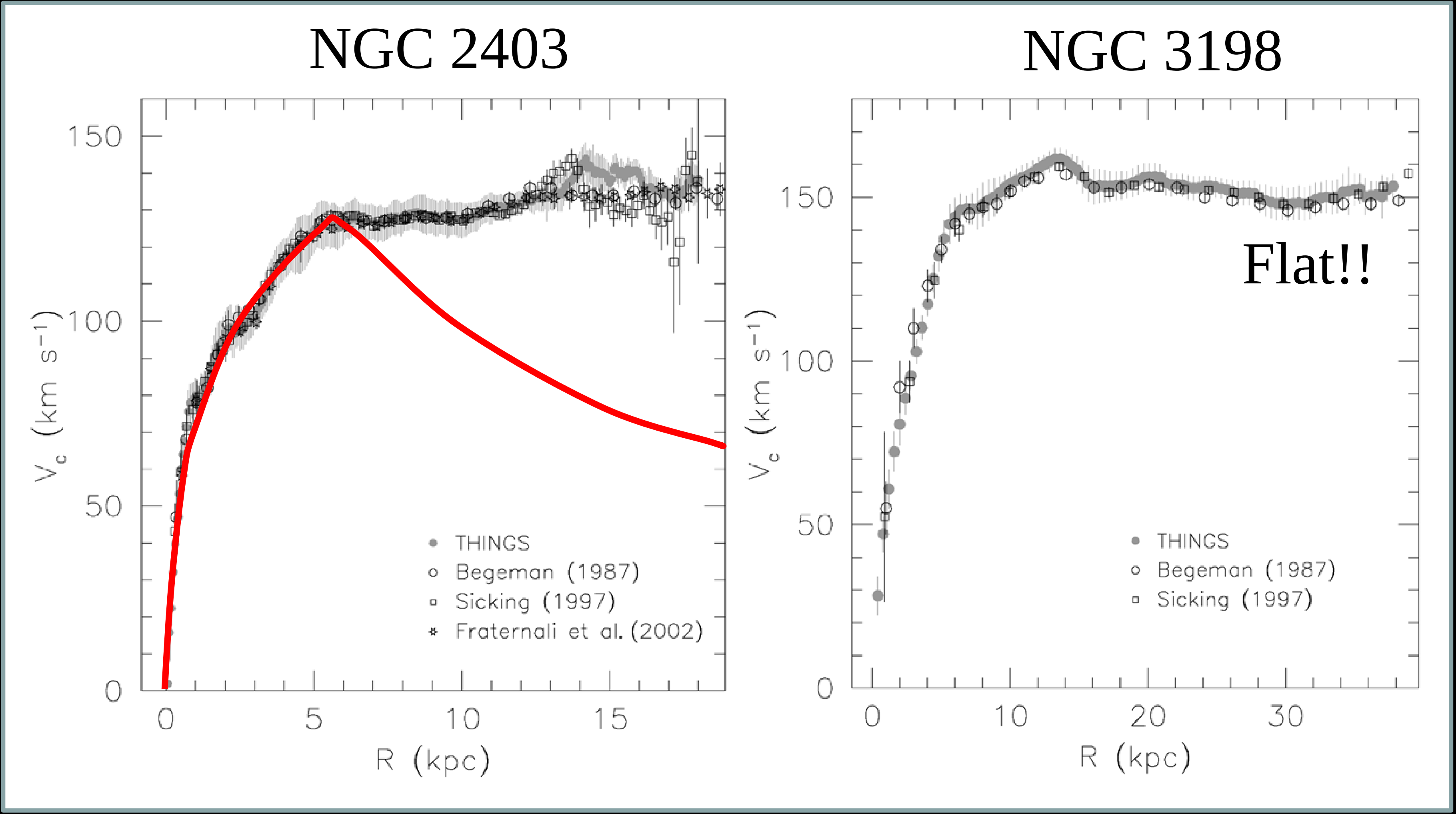
The coming into play of the 21 cm HI line

H. van der Hulst & J. Oort



Westerbork Radio Telescope

The flat rotation curves from HI



from the virial theorem: $M(r) \propto r$

too steep for the light to cope with it

1974: the turning point

The majority of astronomers did not become convinced of the need of any Dark Matter in galaxies until:

- Ostriker & Peebles (1973) speculated on stability of disks;
- Ostriker, Peeeble & Yahil (1974) showed that "the mass of spiral galaxies increases almost linearly with radius to nearly 1 Mpc";
- Einasto et al. (1974) provided the dynamical evidence (from hot gas haloes just discovered) that galaxies ought to be surrounded by "massive coronae";
- Ozernoy (1974-1975) argued that the missing mass has to be dispersed in space, and not constrained within individual galaxies.

1973: at least 30% of all spirals are barred

NGC 1300

NGC 1300

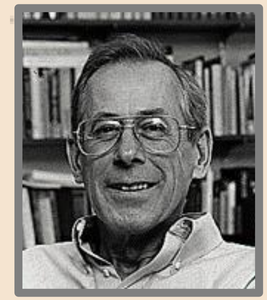
Ostriker & Peebles asked themselves: “why not all?”

A dark halo to stabilize galaxies

THE ASTROPHYSICAL JOURNAL, 186:467–480, 1973 December 1

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

J. P. OSTRIKER
Princeton University Observatory
AND
P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University
Received 1973 May 29



The solution exists
but is not unique (BT pag. 603).
Also, there are many more barred spirals than thought then.

Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

Massive haloes

Letters to Nature

Nature **252**, 111-113 (8 November 1974)

Missing mass around galaxies: morphological evidence

JAAN EINASTO[*], ENN SAAR[*], ANTS KAASIK[*] & ARTHUR D. CHERNIN[†]

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RECENTLY we have obtained convincing empirical indications on the considerable role of hidden matter in the dynamics of single and double galaxies[1]. It seems that this matter is concentrated around massive galaxies, forming their coronas. The total mass of galaxies is about one order of magnitude greater than the mass of their visible parts.

Intergalactic Dark Matter

L. M. Ozernoi, *Where is the 'hidden' mass localized*
Akademiia Nauk SSSR, Fizicheskii Institut, Moscow, USSR
Astronomicheskii Zhurnal, 51, 1108, 1974.
in Russian

Abstract
It is found that the ratio of the virial mass to the observed mass for galaxy systems ranging from pairs up to clusters on the average increases monotonically with the system dimensions.
It is possible to exclude galaxies as the principal source of 'hidden' mass which is needed for the stationarity of galaxy systems.
It is reasoned that if the hidden mass does exist it should be localized in the intergalactic space.

Sudden paradigm change

BARYONS CRISIS

1. Primordial nucleosynthesis, supported by observations, states that the baryonic density is of the order of $0.04\rho_c$, where the critical density is: $\rho_c=3H^2/8\pi G$

2. Primordial baryonic fluctuations seen in the CMBR are largely insufficient to drive galaxy formation.

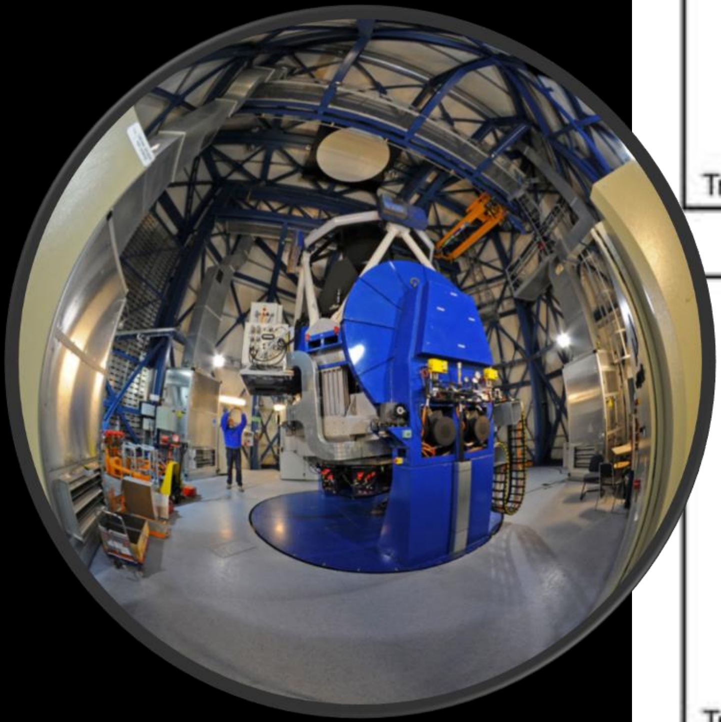
Dark Matter mapped by gravitational lensing

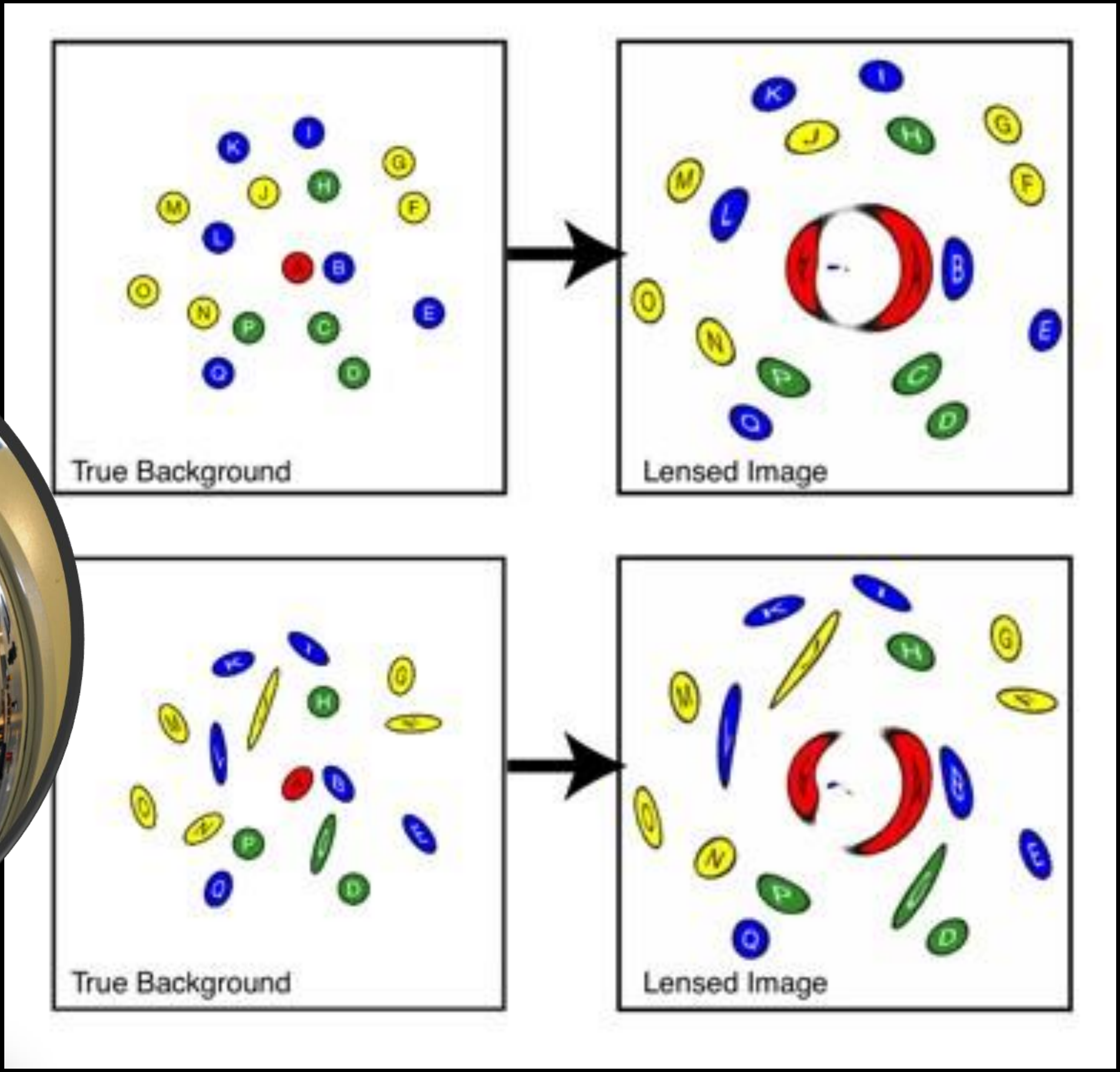
Cosmic shear is the distortion of the shapes of background galaxies due to the bending of light by the potentials associated with large-scale structure.

- For sources at $z_s \sim 1$ and structure at $0.1 < z < 1$, it is a percent level effect which can only be detected statistically.
- Theoretically clean.
- Observationally tractable.

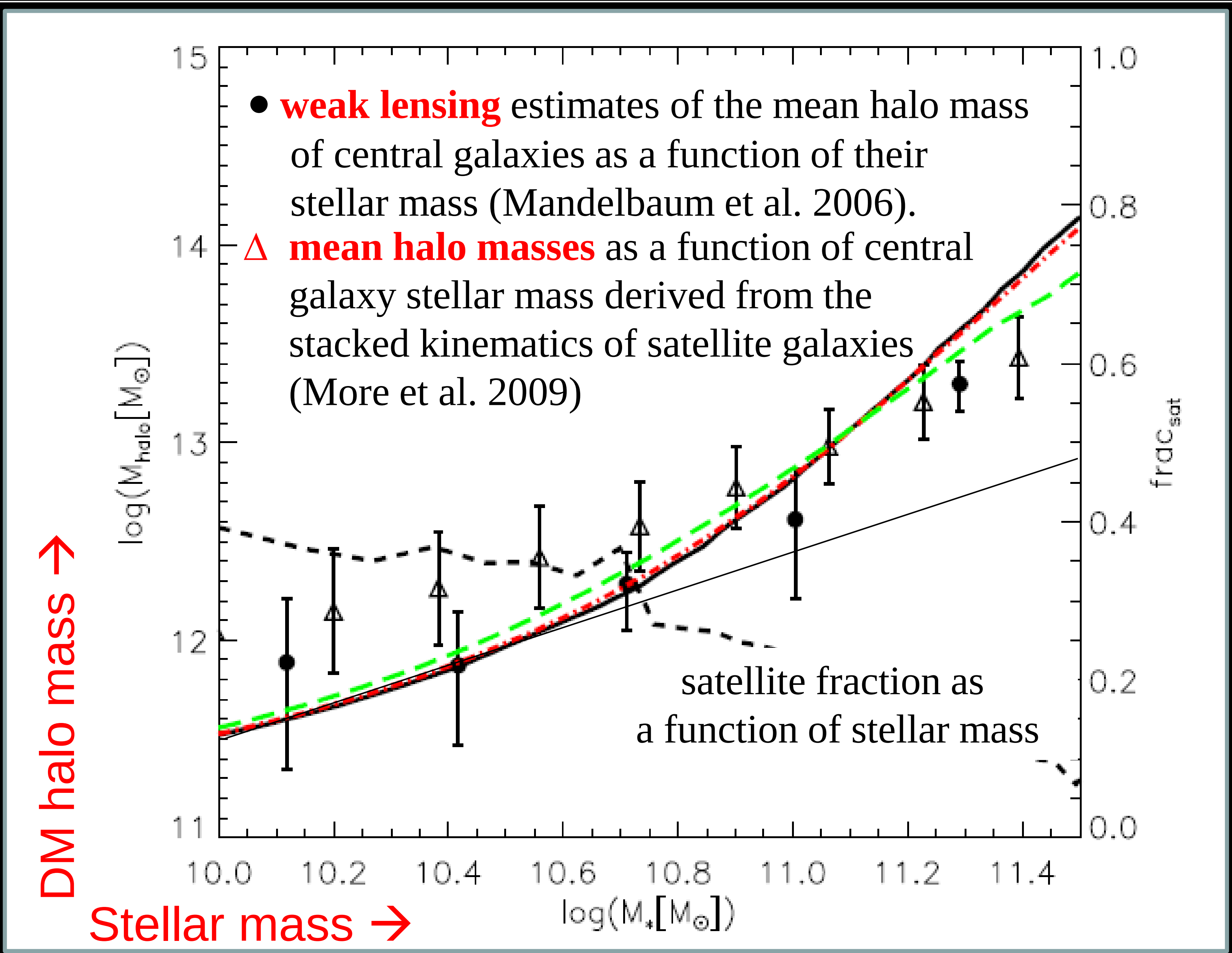
VST KiDs

VST@Paranal





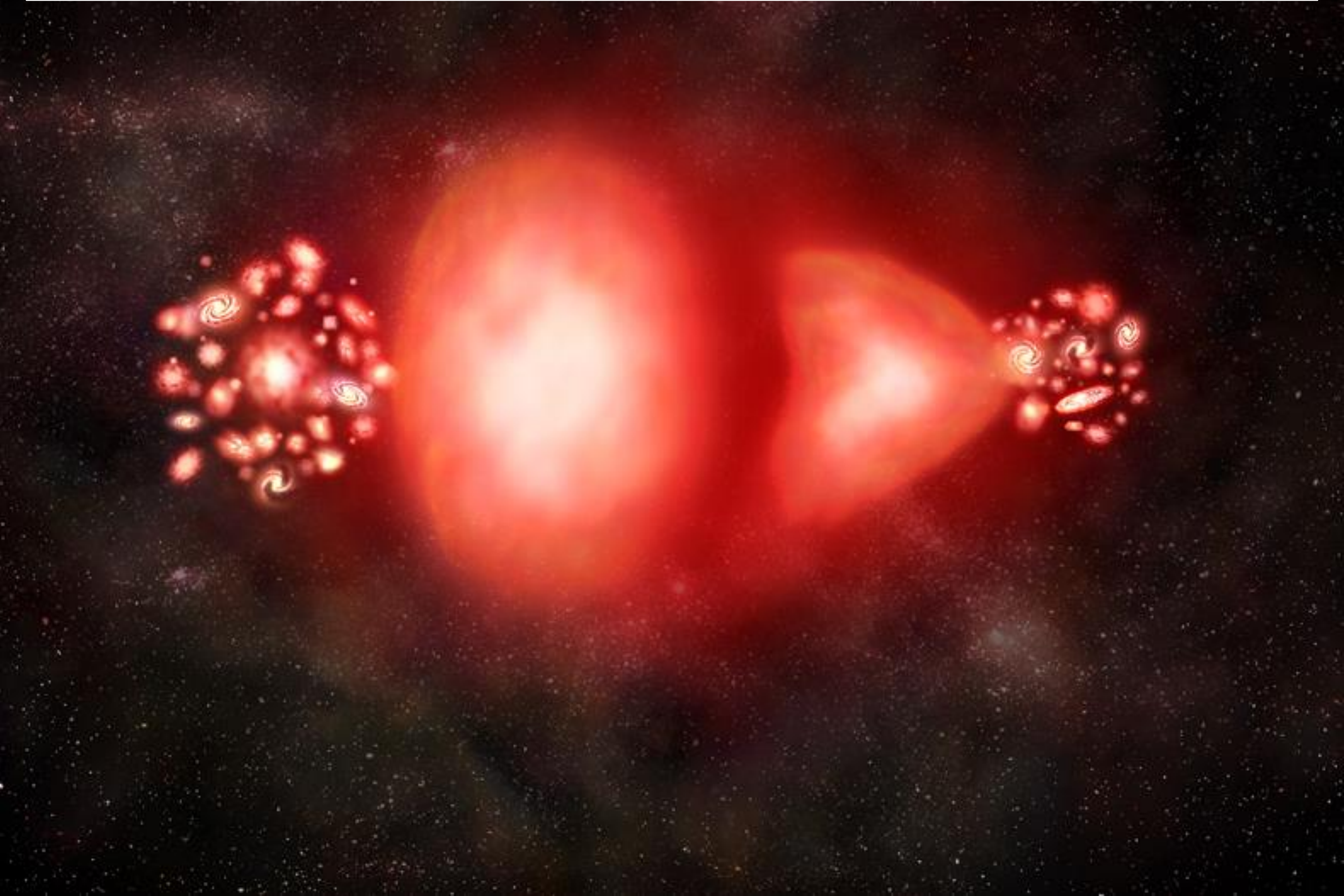
Dark Matter halo mass vs. stellar mass



DM evidence: the smoking gun

“B*ullet cluster*” 1E 0657-56: composite image

DM evidence: dissipation vs. indifference



How dark is the Dark Matter?

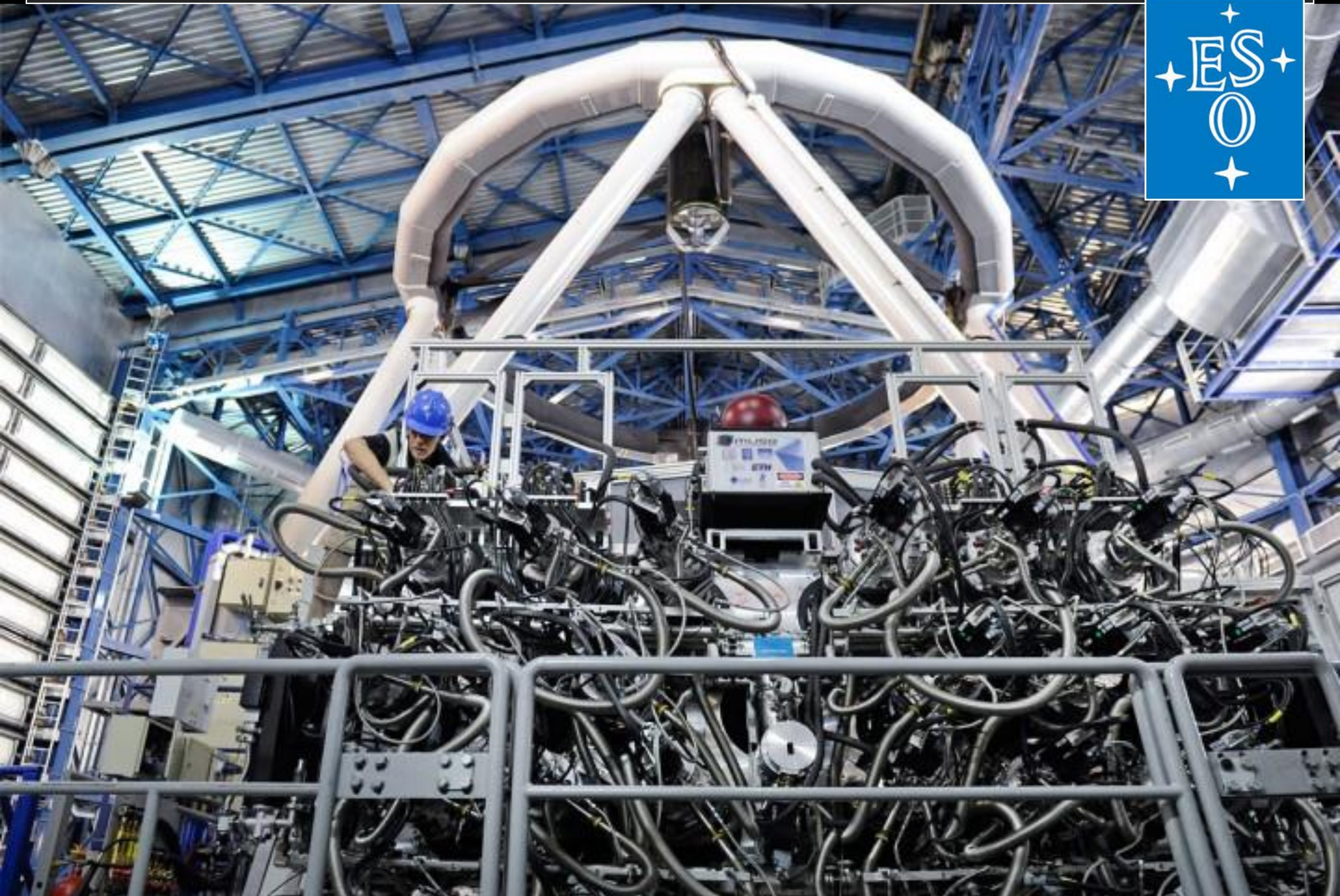
In other words, is the DM self-interacting?

Baryons mapping DM: no self-interaction

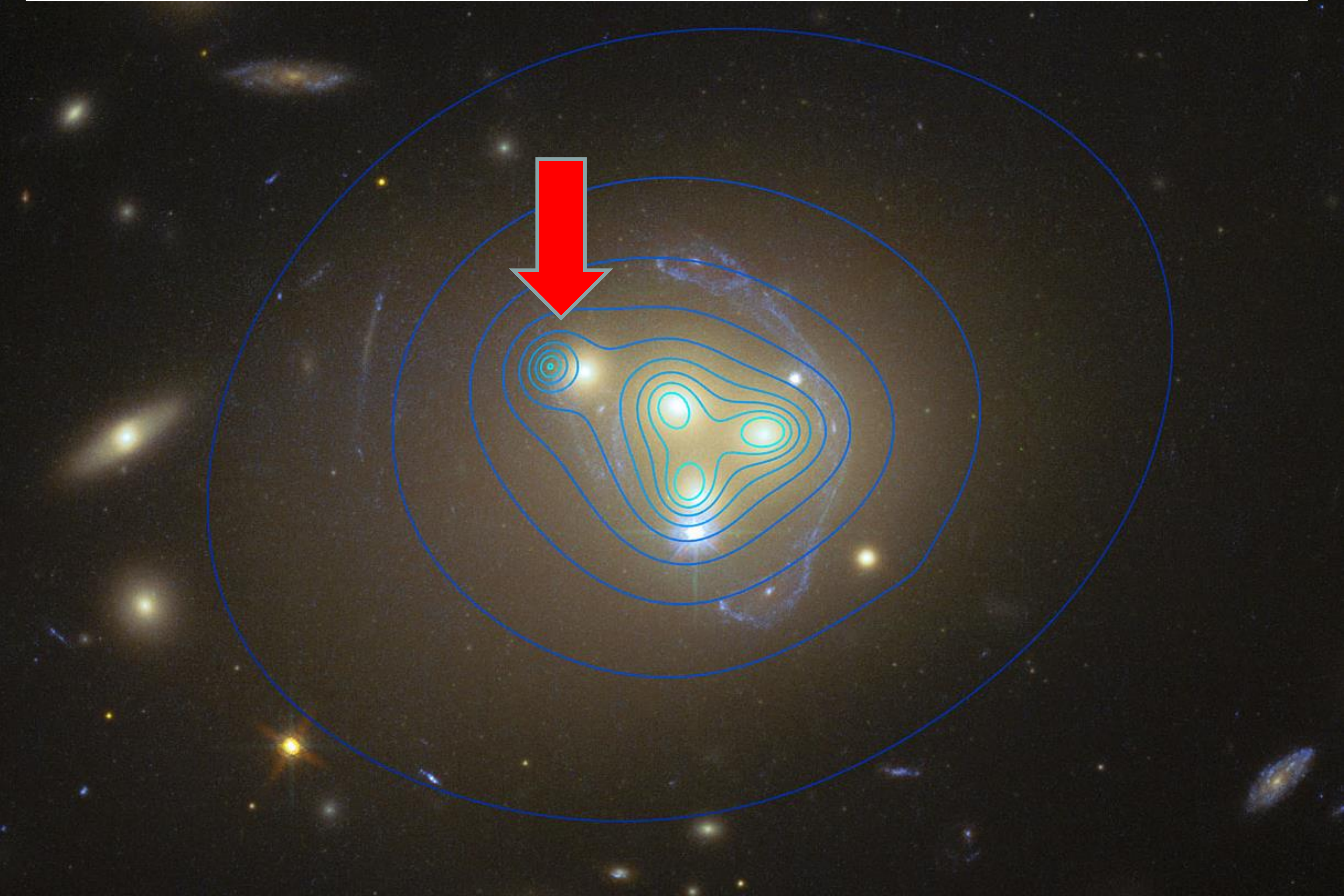
But …

Abell 3827, as taken by Hubble

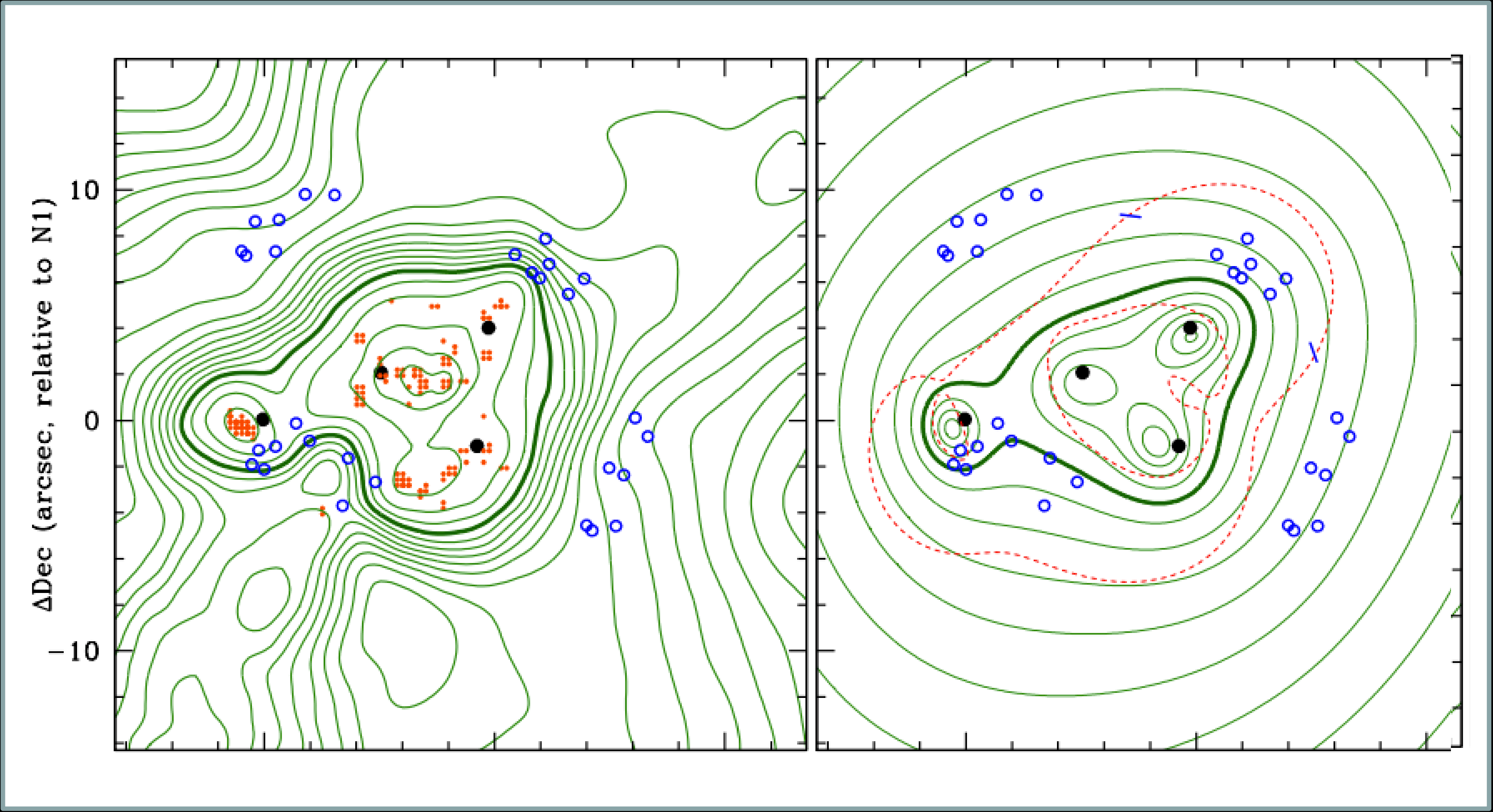
Multi Unit Spectroscopic Explorer (MUSE)



Traces of self-interaction ?



Traces of self-interaction ?



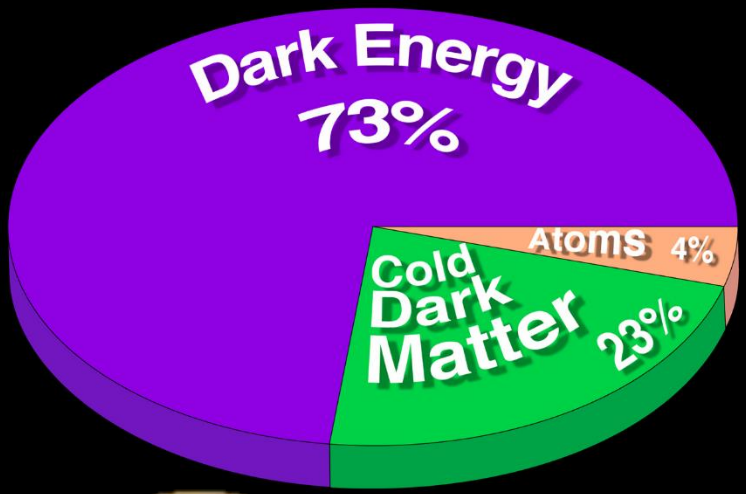
Concluding … with questions

- Does Dark Matter exist ?
- Remember Vulcan.

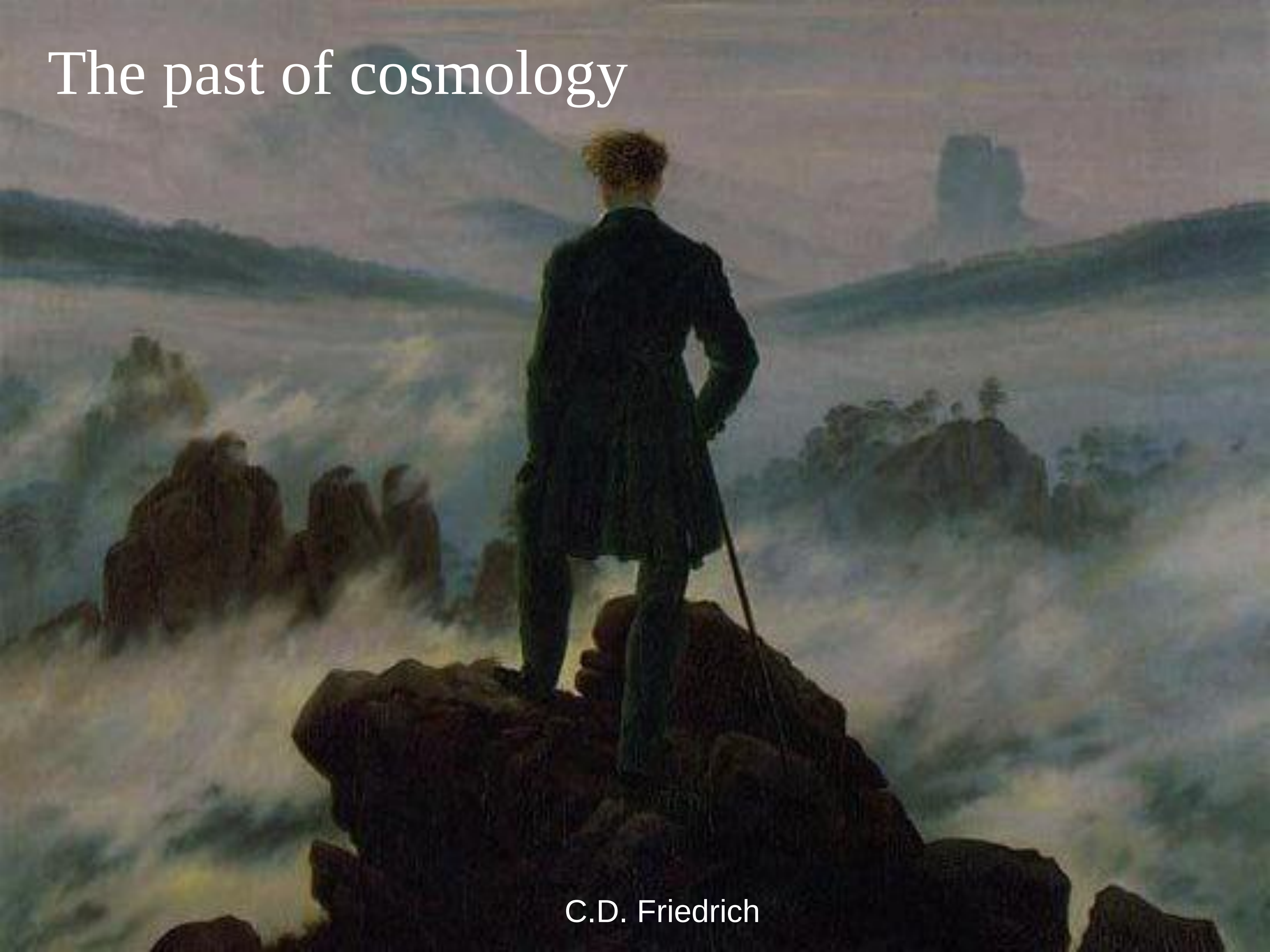
- How much is it ?
- Less than originally thought owing to DE.

- What is it ?
- So far, God knows.

- Is it self-interacting ?
- Possibly….



The past of cosmology



C.D. Friedrich

The present

The future ?

Thank you for your attention