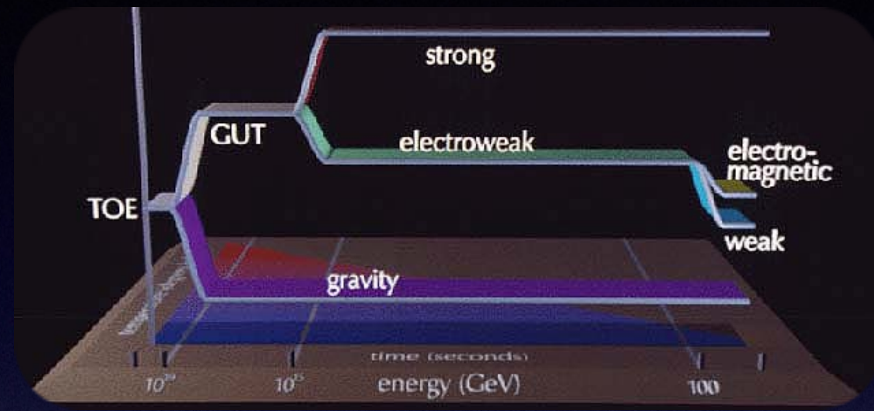
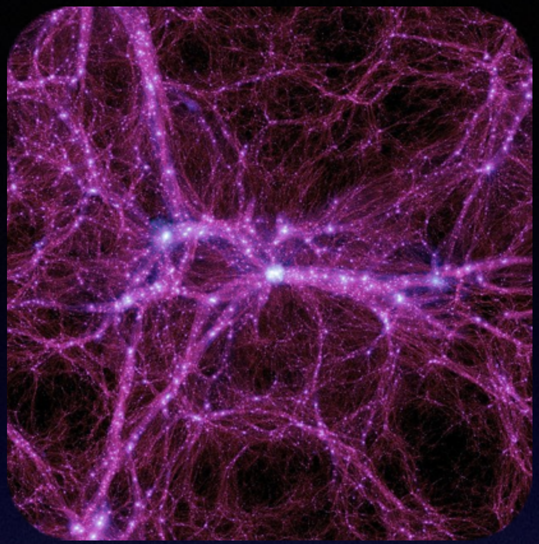
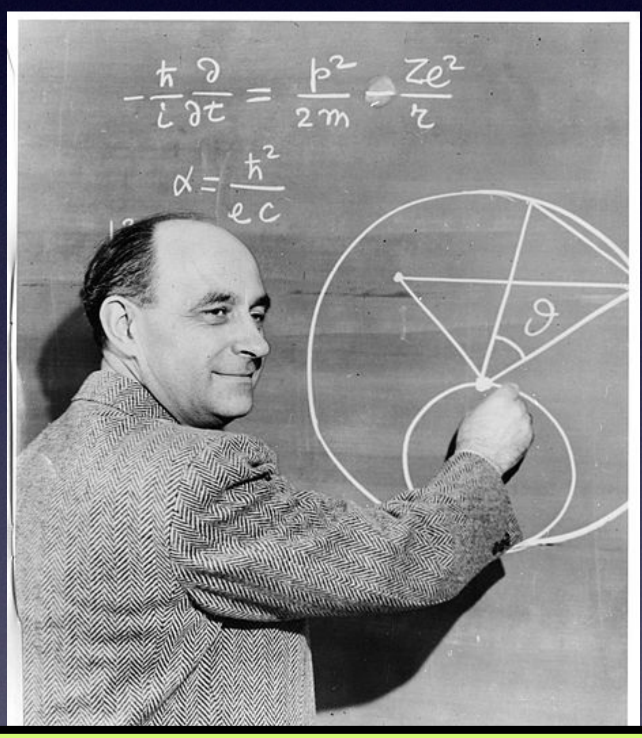
Modeling the dark matter

1) An historical perspective







« Never underestimate the joy people derive from hearing something they already know.»
E. Fermi

ERC Higgs@LHC

MultiDark
Multimessenger Approach for Dark Matter Detection

« So I am just sitting and waiting, listening, and if something exciting comes, I just jump in»
G. Gamow

Yann Mambrini, University of Paris-Saclay

http://www.ymambrini.com/My_World/Physics.html

Seminar at Frascati, 8th of November 2016

« What is the first Dark Matter paper? »

Coffee discussion with K. Olive and L. Bergstrom
in June 2016 at the Bethe Forum (Bonn)

Histories of dark matter

historical perspective

Book, chapter 17

Evolution of the Universe
Ralph A. Alpher
Robert Herman
Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland. Oct. 25.

THE EVOLUTION OF THE UNIVERSE
By Dr. G. Gamow

NUMERICAL EXPERIMENTS WITH A DISK OF STARS
Frank Hohl

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY
S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

PRIMEVAL HELIUM ABUNDANCE AND THE PRIMEVAL FIREBALL*
P. J. E. Peebles

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*
Vera C. Rubin† and W. Kent Ford, Jr.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡
Received 1969 July 7; revised 1969 August 21

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

Die Rotverschiebung von extragalaktischen 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.

Radio Waves from Outside the Solar System
Karl G. Jansky.

VOLUME 59 — 1954 September ~ No. 1220

MASS DISTRIBUTION AND MASS-LUMINOSITY RATIO IN GALAXIES
By M. Schwarzschild

COSMIC BLACK-BODY RADIATION*
R. H. Dicke, P. J. E. Peebles, P. G. Roll, D. T. Wilkinson

THE ROTATION OF THE ANDROMEDA NEBULA*
by
Horace W. Babcock

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.*

The Origin of Chemical Elements
R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
and
H. Bethe
Cornell University, Ithaca, New York
and
G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

The Origin of Elements and the Separation of Galaxies
G. Gamow

ROTATION AND DENSITY DISTRIBUTION OF THE ANDROMEDA NEBULA DERIVED FROM OBSERVATIONS OF THE 21-cm LINE
by H. C. van de Hulst, E. Raimond and H. van Woerden

université PARIS-SACLAY

cnrs

LPT Orsay

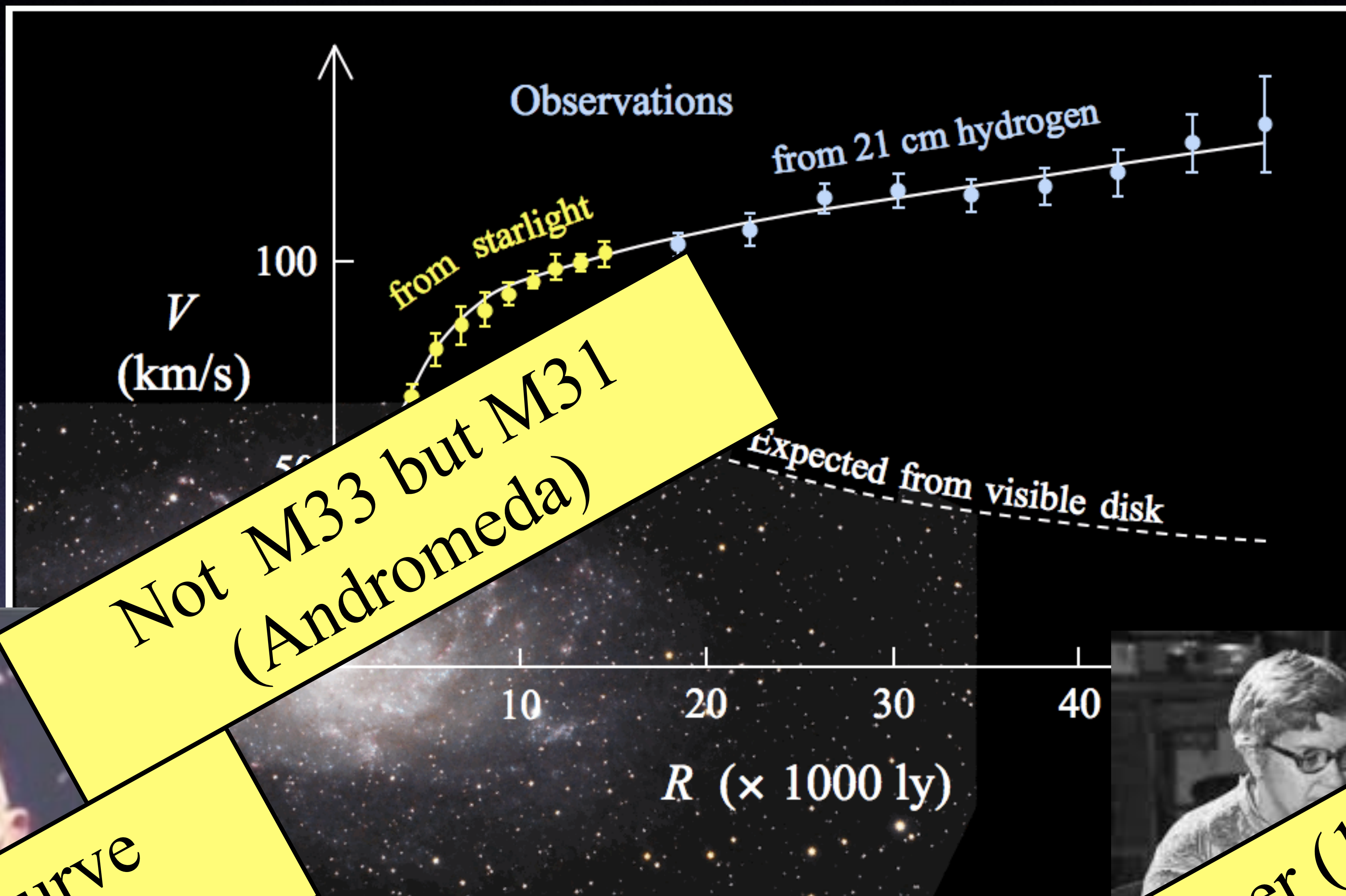
http://www.ymambrini.com/My_World/Physics.html

Yann Mambrini

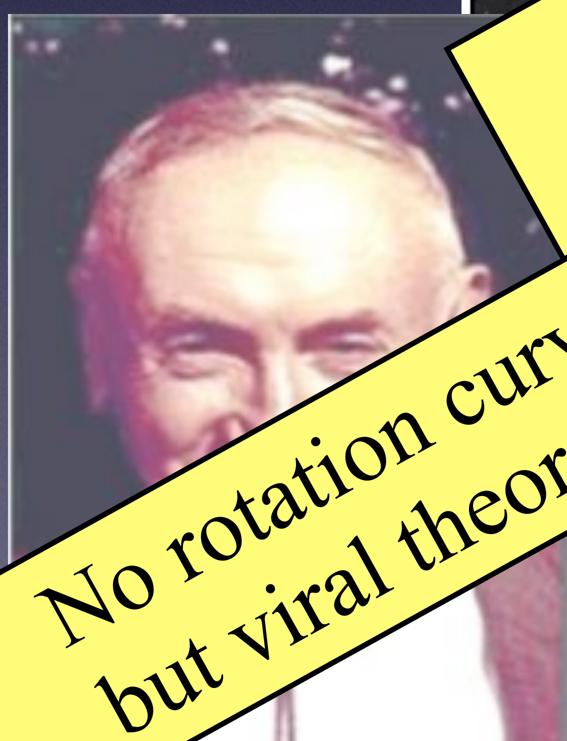
Classical introduction on DM

In atrophysics

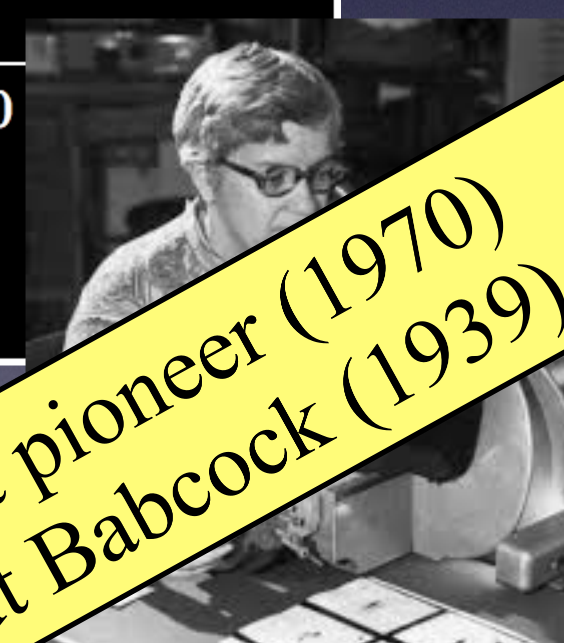
Rotation curve, Zwicky, Vera Rubin..



Not M33 but M31
(Andromeda)



No rotation curve
but viral theorem



Not pioneer (1970)
but Babcock (1939)

Global Warning

In this historical section, I will retrace the scientific dark matter history. In other words, I will reconstruct step by step how the hypothesis of the existence of a dark structure in the clusters of galaxies, then in the galaxies and finally in the imprints of the Cosmological Microwave Background. It means that several numbers, observations, conclusions will be falsified during the lecture. The distances for instance are twice smaller in the early time due do the Hubble parameter which has been divided by two between its first evaluation in 1930 and now. Same for the age of the Universe, or temperature of the CMB. The aim of the lecture is indeed to make you understand the process of model building from hypothesis that can change with time due to new observations.

All reasonings will be based on the original articles, the complete list of references being given at the end of the lecture.

All the original historical articles discussed in this section can be found on the page:

http://www.ymambrini.com/My_World/History.html

THE MILKY WAY AND THE THEORY OF GASES.*

H. POINCARÉ.†

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

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FRANK HOHL

NASA, Langley Research Center, Hampton, Virginia

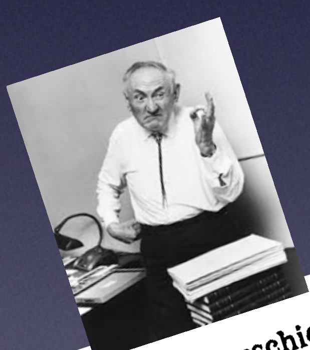
Received 1971 March 10; revised 1971 April 28

Radio Waves from Outside the Solar System

KARL G. JANSKY.

Observing the present sky

From the clusters to the galaxies



Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

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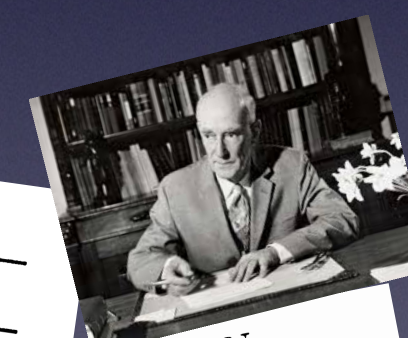
Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung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

VOLUME 59 — 1954 September ~ No. 1220 — *NUMBER 8*

MASS DISTRIBUTION AND MASS–LUMINOSITY RATIO IN GALAXIES

BY M. SCHWARZSCHILD



COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

...by the stellar system in the direction perpendicular to the galactic ...d some related problems, by *J. H. Oort.*

The forc...

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THE ROTATION OF THE ANDROMEDA NEBULA*

BY

HORACE W. BABCOCK

Henri Poincaré

The pre-history

Book, chapter 17

Contrarily to the common belief, the first time the word « dark matter » is proposed in a scientific paper is not Oort in 1932 but Poincaré in 1906. Indeed, Lord Kelvin in 1904 had the genius to apply the kinetic theory of gas recently elaborated, to the galactic structures in his Baltimore lecture (*molecular dynamics and the wave theory of light*). Poincaré was impressed by this idea and computed the amount of stars in the Milky way necessary to explain the velocity of our sun one observes nowadays.

THE MILKY WAY AND THE THEORY OF GASES.*

H. POINCARÉ.†

equation of living forces. We thus find that this velocity is proportional to the radius of the sphere and to the square root of its density. If the mass of this sphere were that of the Sun and its radius that of the terrestrial orbit, it is easy to see that this velocity would be that of the Earth in its orbit. In the case that we have supposed, the mass of the Sun should be distributed in a sphere with a radius one million times larger, this radius being the distance of the nearest stars; the density is then 10^{18} times less; now the velocities are of the same order, hence it must be that the radius is 10^9 times greater, that is one thousand times the distance of the nearest stars, which would make about one thousand millions of stars in the Milky Way.

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

Using the viral theorem, Poincaré computed first the density of stars around the sun, then supposing it constant, the radius of the sun to the galactic center, and then the number of stars in the Milky Way (~10^9) corresponding to the observations, thus discrediting the existence of dark matter, or dark stars.

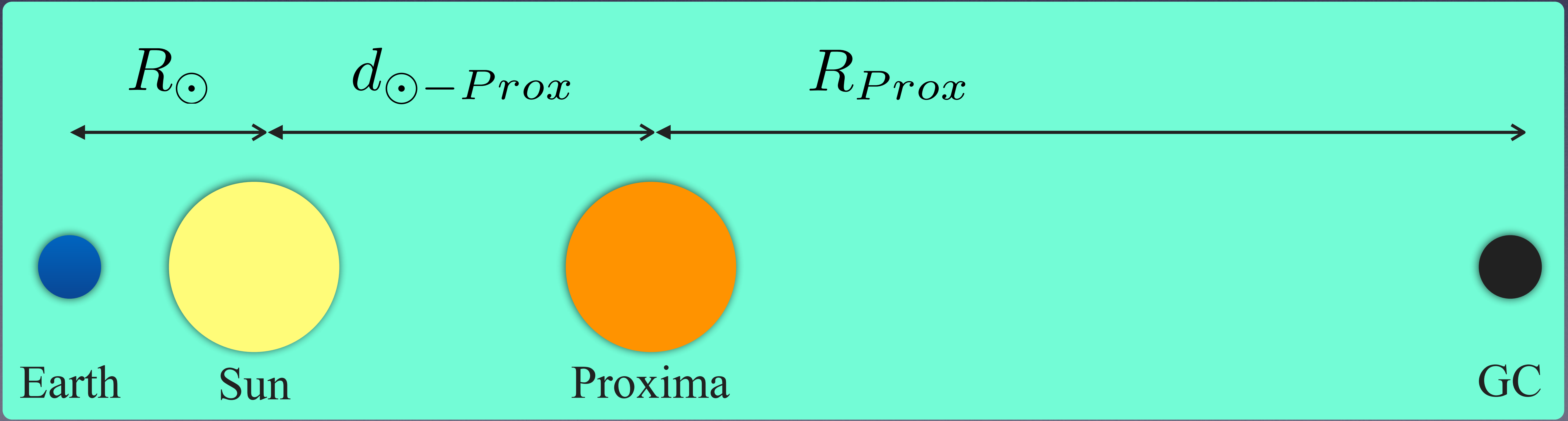
$$v(R) \propto R\sqrt{\rho}$$

$$\frac{v_{earth}(R_\odot)}{v_{sun}(R_{Prox})} = \frac{R_\odot}{R_{Prox}} \frac{\sqrt{\rho_\odot}}{\sqrt{\rho_{Prox}}}$$

$$d_{Prox-\odot} = 10^6 R_\odot \quad \Rightarrow \quad \rho_{Prox} = 10^{-18} \rho_\odot$$

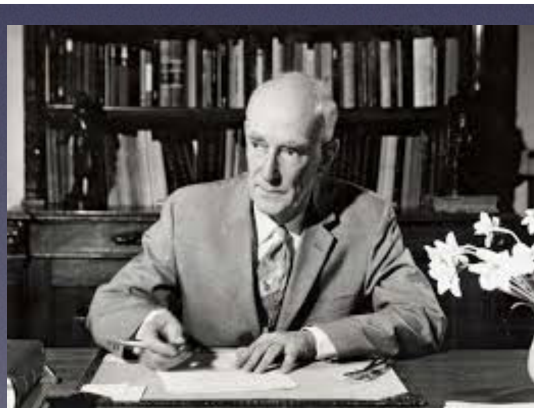
$$v_{earth} \simeq v_{sun} \quad \Rightarrow R_{Prox} = 10^9 R_\odot$$

$$\Rightarrow N_{stars} = \rho_{Prox} \times R^3_{Prox} \simeq 10^9$$



The early times (1930-1960)

The second appearance of the word « dark matter » in the literature is in a paper of the physicist Jan Oort from Netherland in 1932. While he was analyzing the radial velocities, he notice a discrepancy with Newton law. He computed that only one third of the dynamically inferred mass was present in bright visible stars. It is clear from the context that, as characterizing the remainder as « dark » («Dunkle Materie »), Oort was describing all matter not in the form of visible stars with luminosity comparable or larger than that of the Sun. Gas and dusts between the stars was his « invisible mass » that should be found (for him) soon. The main reason evoked at this time was the presence of low luminosity objects (dead stars) or large absorbing gas. Imagining a new dark component took a very long time to physicists, who even preferred to modified the law of gravity at large scale before invoking a new particle.



Jan Oort

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.*

Jan Oort, Bulletin of the Astronomical Institutes of the Netherlands, Vol. 6, p.249

(the original articles can be found there: http://www.ymambrini.com/My_World/History.html)

In this sense, the first real work underlining that the missing mass could be problematic is Fritz Zwicky in 1933

« The Redshift of Extragalactic Nebulae »

Fritz Zwicky, Helv. Phys. Acta 6, 110-127 (1933)

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

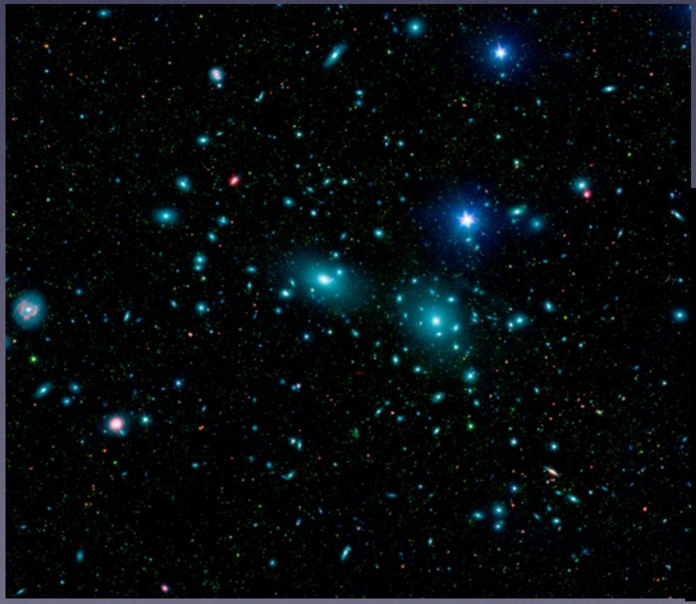
Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung 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 Redshift of Extragalactic Nebulae

by F. Zwicky.

(16.II.33.)

Contents. This paper gives a representation of the main characteristics of extragalactic nebulae and of the methods which served their exploration. In particular, the so called redshift of extragalactic nebulae is discussed in detail. Different theories which have been worked out in order to explain this important phenomenon will be discussed briefly. Finally it will be indicated to what degree the redshift promises to be important for the study of penetrating radiation.



The Coma Cluster of Galaxies. This is a highly regular gravitationally bound system of thousands of galaxies at a distance of about **100 Mpc** (NASA, SDSS)

§5. Remarks concerning the dispersion of velociti nebular cluster.

As the data in §3 show, there are in the Coma clust velocity of at least 1500 to 2000 km/sec. In the context variation of velocities the following considerations can be m

1. Under the supposition that the Coma system has re cally, a stationary state, the Virial Theorem implies

$$\bar{\epsilon}_k = -\tfrac{1}{2}\bar{\epsilon}_p, \qquad (4)$$

where $\bar{\epsilon}_k$ and $\bar{\epsilon}_p$ denote average kinetic and potential energies, e.g. of the unit of mass in the system. For the purpose of estimation we assume that the matter in the cluster is distributed uniformly in space. The cluster has a radius R of about one million light-years (equal to 10^{24} cm) and contains 800 individual nebulae with a mass of each corresponding to 10^9 solar masses. The mass M of the whole system is therefore

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45} \text{ g}. \qquad (5)$$

This implies for the total potential energy Ω:

$$\Omega = -\frac{3}{5}\Gamma\frac{M^2}{R} \qquad (6)$$

Γ = Gravitational constant

or

$$\bar{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12} \text{ cm}^2\text{s}^{-2} \qquad (7)$$

and then

$$\bar{\varepsilon}_k = \overline{v^2}/2 \sim -\bar{\varepsilon}_p/2 = 32 \times 10^{12} \text{ cm}^2\text{s}^{-2}$$

$$\left(\overline{v^2}\right)^{1/2} = 80 \text{ km/s}. \qquad (8)$$

In order to obtain the observed value of an average Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter.[8] If this would be confirmed we would get the surprising result that dark matter is present in much greater amount than luminous matter.

The calculation

Book, chapter 17

Statement of the virial theorem:

For the n point particles, bound together into a system, the *time average* of the kinetic energy of the particles, $\sum \frac{1}{2} m_i v_i^2$, plus one half of the *time average* of $\sum \vec{F}_i . \vec{r}_i$ is equal to zero.

$$H = \sum \vec{p}_i . \vec{r}_i$$

The average of the derivative of a finite function cancels for large time or periodic H

$$\frac{dH}{dt} = \sum \vec{F}_i . \vec{r}_i + 2K \qquad \overline{\left(\frac{dH}{dt}\right)} = \sum \overline{\vec{F}_i . \vec{r}_i} + 2\overline{K}.$$

$$\overline{K} + \frac{1}{2} \sum \overline{\vec{F}_i . \vec{r}_i} = 0 \qquad \vec{F}_i = -\partial V / \partial r_i$$

$$V = -\alpha \frac{GM^2}{R} \qquad \frac{M}{2} \underline{v^2} = \frac{1}{2} \alpha \frac{GM^2}{R}$$

α depends on the shape of the halo (3/5 for an homogenous sphere)

$$\underline{v^2} = \frac{3}{5} \frac{GM}{R} = \frac{3}{5} \times \frac{6.67 \times 10^{-11} \times 1.6 \times 10^{42}}{10^{22}} \Rightarrow \sqrt{\underline{v^2}} \simeq 80 \text{ km/s}.$$

One observed velocity spread of 1000 km/s whereas one should oversee 80 km/s. Mass of the Coma should then be larger by a factor **few thousands**.

Zwicky took 7500 km/s as a mean velocity to obtain D=50 Mpc (v=H x D)

Table II.[3]

Nebular cluster	Number of nebulae in the cluster	Apparent diameter	Distance in 10^6 light-years	Average velocity km/s
Virgo	(500)	12°	6	890
Pegasus	100	1°	23.6	3810
Pisces	20	0.5	22.8	4630
Cancer	150	1.5	29.3	4820
Perseus.	500	2.0	36	5230
Coma	800	1.7	45	7500
Ursa Major I	300	0.7	72	11800
Leo	400	0.6	104	19600
Gemini	(300)	—	135	23500

These results are shown graphically in Fig. 2.

From the apparent diameter d, Zwicky deduced the radius of the cluster, R= d x D = 1Mpc

And 800 galaxies of 10^9 solar mass in the cluster

He considered that the spread in velocities (~1000km/s) correspond to a mean velocity of the galaxies inside the cluster

Apparent velocities in the Coma cluster

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

Conclusion of the Zwicky article

« In order to obtain the observed value of an average Doppler effect of 1000 km/s or more, the average density in the Coma system **would have to be at least 400 times larger** than that derived on the grounds of observations of luminous matter. If this would be confirmed we would get the surprising result that **dark matter is present in much greater amount than luminous matter** »

This result was completely forgotten and nobody took really seriously this comment of Zwicky. Indeed, the large scale astrophysics was at its beginning after the Hubble discovery and a lot of physicists believed that the « missing mass » problem will be solved once we will understand better the mechanism of absorption of light in the interstellar/internebulae medium. In fact, the « missing mass » problem was a this time considered as a « missing luminosity » problem: why we do not see the astrophysics bodies that should be responsible of the Newtonian dynamics. On the other hand, several scientists tried to modify (already in the 30's) the $1/r^2$ attraction law. Then began the galaxies analysis.

At the Galactic scale

THE ROTATION OF THE ANDROMEDA NEBULA*

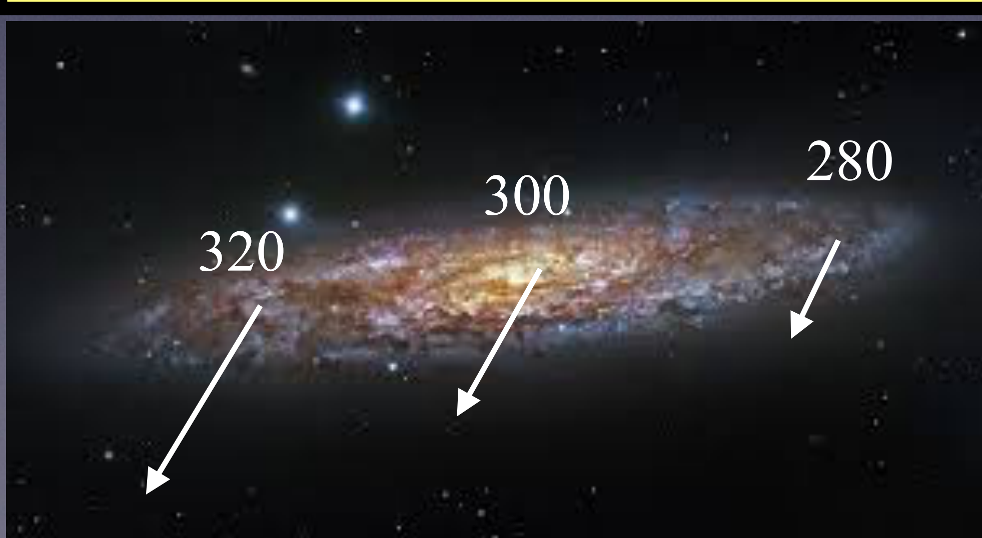
BY

HORACE W. BABCOCK

In **1939**, **Horace Babcock** presents his PhD thesis on the subject of rotation curves of galaxies. He compute the rotation curve in Andromeda and measured a **constant angular velocity** and concluded :

core of the nebula, and the approach to constant angular velocity discovered for the outer spiral arms is hardly to be anticipated from current theories of galactic rotation.

The history of the measurements of rotation curves dates **back to 1914** (!!) where **Slipher** at the Lowell laboratory observed that the velocities measured on the **left of the bulge** of the nearby galaxy (nebula) **Andromeda** (the nearest galaxy ~800 kpc from us, but believed to be 210 kpc at this time due to the Hubble parameter determination were approaching us at **higher velocities** (~**320 km/s**) than the ones on the **right part of the central bulge** (~**280 km/s**). This is what is expected in a disk turn in front of us.

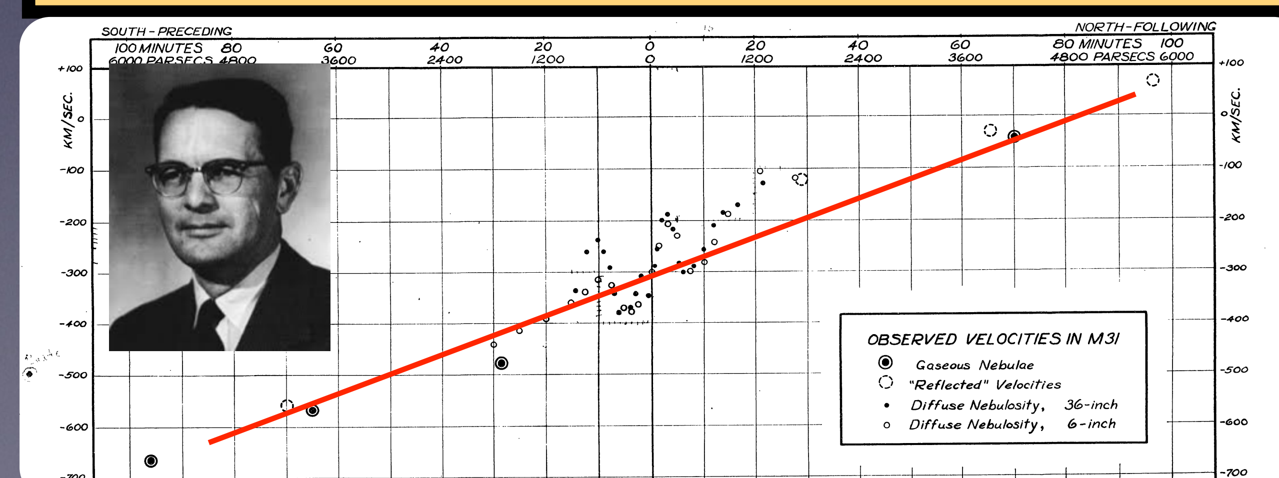


In **1918**, **Pease** at the Mount Wilson Observatory measured the rotation out to a radius of **600 pc** (central part of **Andromeda**). His result were expressed by the formula

$$V_c = -0.48\, r - 316$$

where V_c is the circular velocity measured (in km/s) at a distance **r** from the central bulge of **Andromeda**, showing that this central portion appears to rotate with constant angular velocity.

Babcock in **1939** extend the study to larger scale, up to **24 kpc** from the center.



The work of Babcock

Babcock measured the rotation curve much more far away from the central bulge of Andromeda, and **plotted** the circular velocity and the angular velocity as **function of the distance r** from the center of Andromeda.

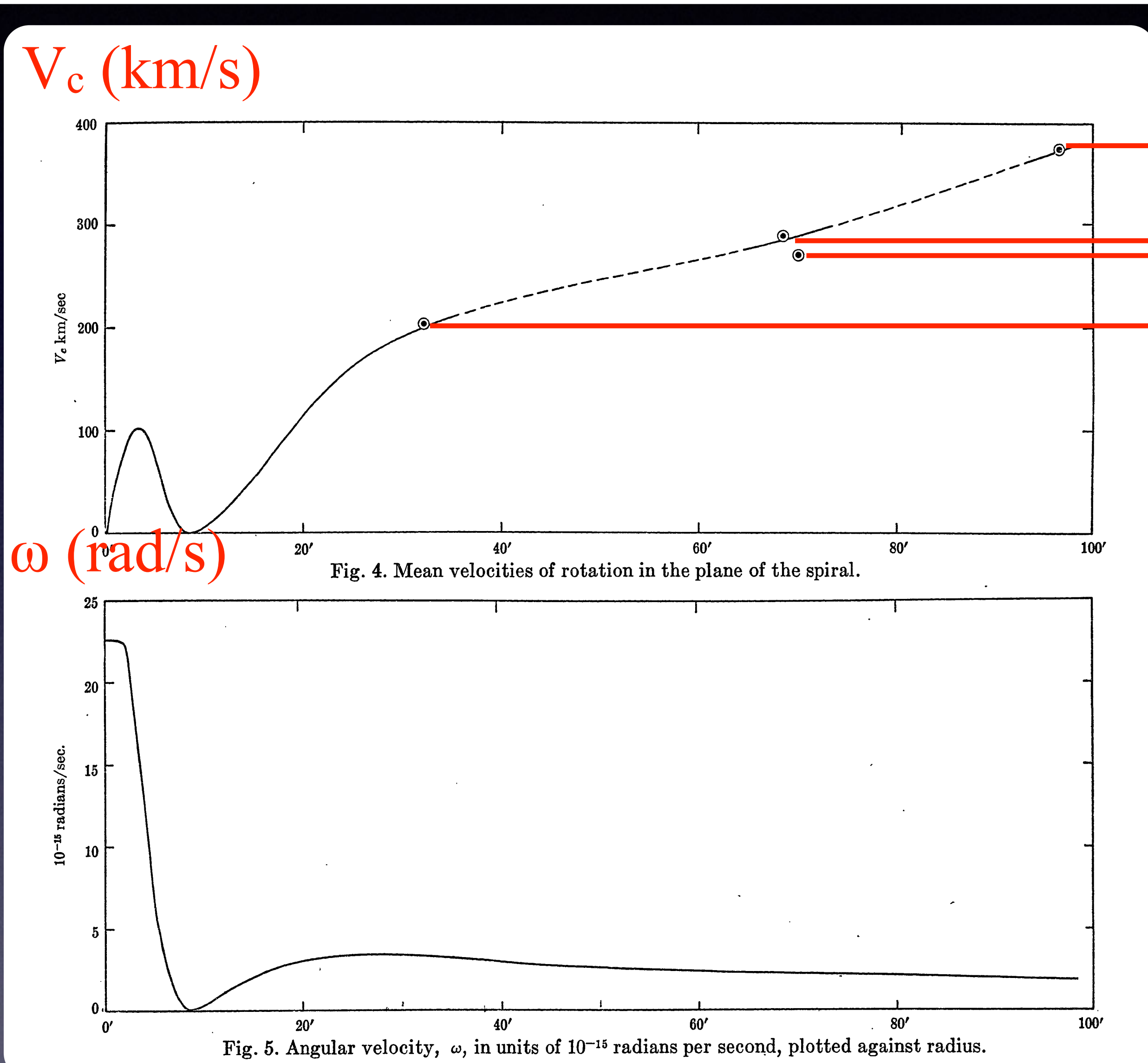
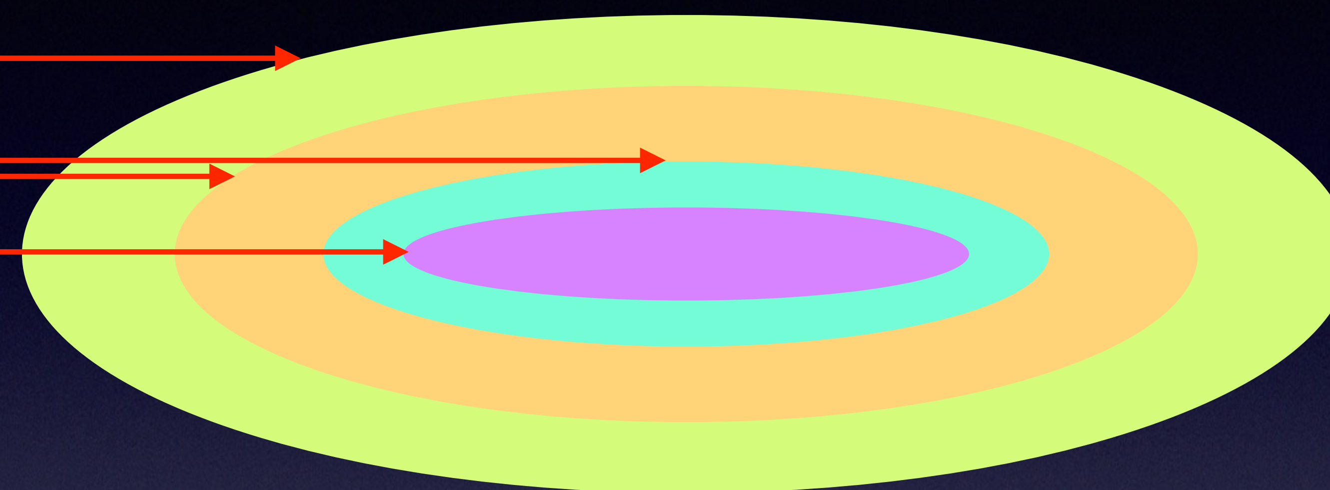
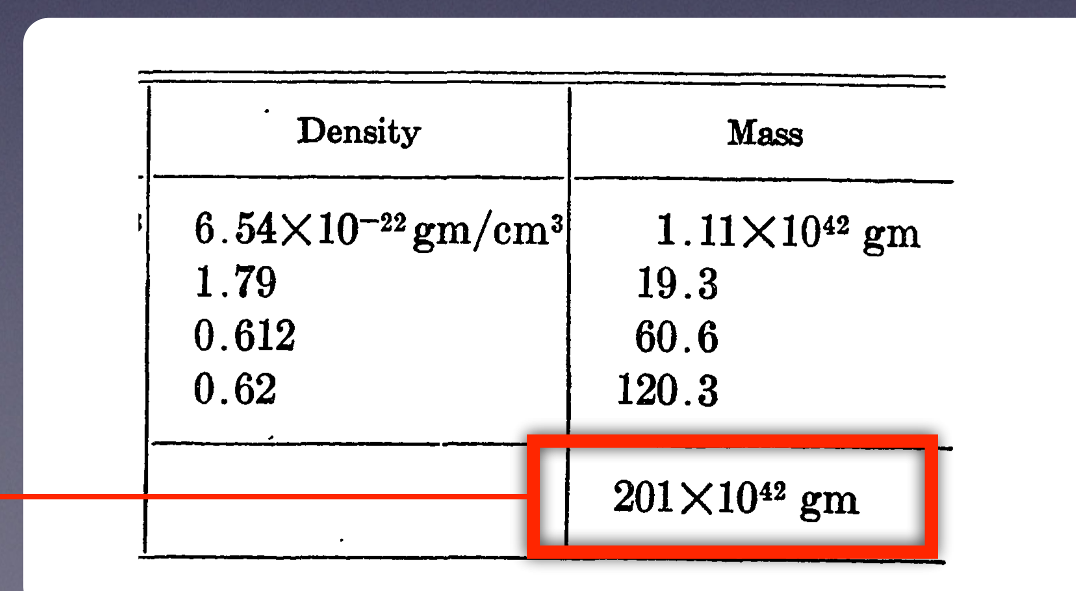


Fig. 4. Mean velocities of rotation in the plane of the spiral.

Fig. 5. Angular velocity, ω, in units of 10^{-15} radians per second, plotted against radius.

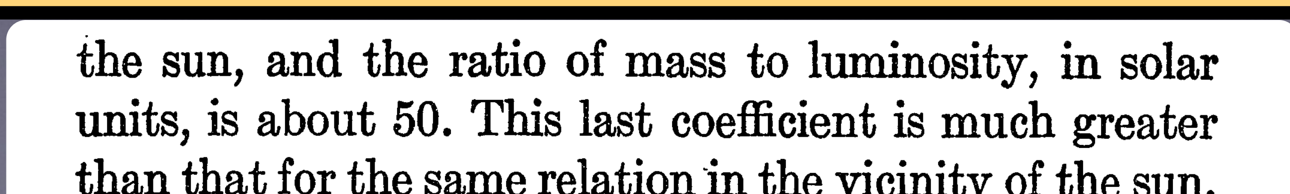


Babcock supposed a concentration of spheroids of densities σ_1, σ_2, σ_3, and σ_4. He then computed the 4 densities to respect the velocities measured on the left. He obtained



Density	Mass
6.54×10^{-22} gm/cm^3	1.11×10^{42} gm
1.79	19.3
0.612	60.6
0.62	120.3
	201×10^{42} gm

From the computation of the density, he deduced the total mass of Andromeda of **10^{11} solar mass**, equivalent to a mass to light ratio **M/L=50.** He then concludes:



the sun, and the ratio of mass to luminosity, in solar units, is about 50. This last coefficient is much greater than that for the same relation in the vicinity of the sun.

Jansky sees the invisible (1932)

Karl Jansky

Radio Waves from Outside the Solar System

In a recent paper[1] on the direction of arrival of high-frequency atmospherics, curves were given showing the horizontal component of the direction of arrival of an electromagnetic disturbance, which I termed hiss type atmospherics, plotted against time of day. These curves showed that the horizontal component of the direction of arrival changed nearly 360° in 24 hours and, at the time the paper was written, this component was approximately the same as the azimuth of the sun, leading to the assumption that the source of this disturbance was somehow associated with the sun.

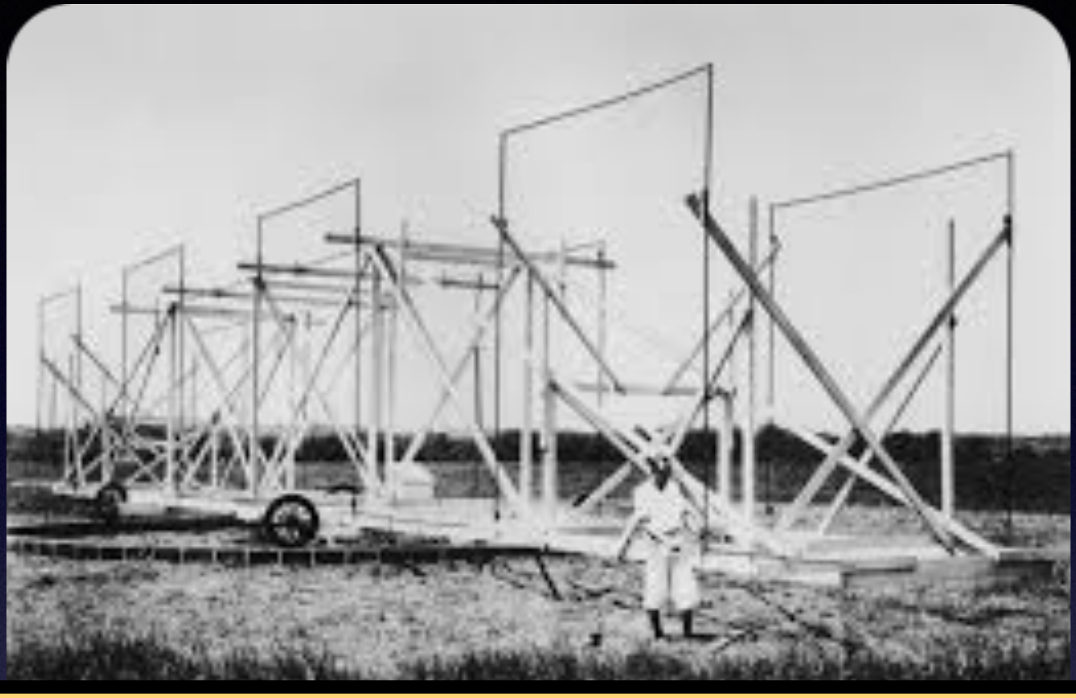
Records have now been taken of this phenomenon for more than a year, but the data obtained from them are not consistent with the assumptions made in the above paper. The curves of the horizontal component of the direction of arrival plotted against time of day for the different months show a uniformly progressive shift with respect to the time of day, which at the end of one sidereal year brings the curve back to its initial position. Consideration of this shift and the shape of the individual curves leads to the conclusion that the direction of arrival of this disturbance remains fixed in space, that is to say, the source of this noise is located in some region that is stationary with respect to the stars. Although the right ascension of this region can be determined from the data with considerable accuracy, the error not being greater than ± 30 minutes of right ascension, the limitations of the apparatus and the errors that might be caused by the ionised layers of the earth's atmosphere and by attenuation of the waves in passing over the surface of the earth are such that the declination of the region can be determined only very approximately. Thus the value obtained from the data might be in error by as much as ± 30°.

The data give for the co-ordinates of the region from which the disturbance comes, a right ascension of 18 hours and declination of − 10°.

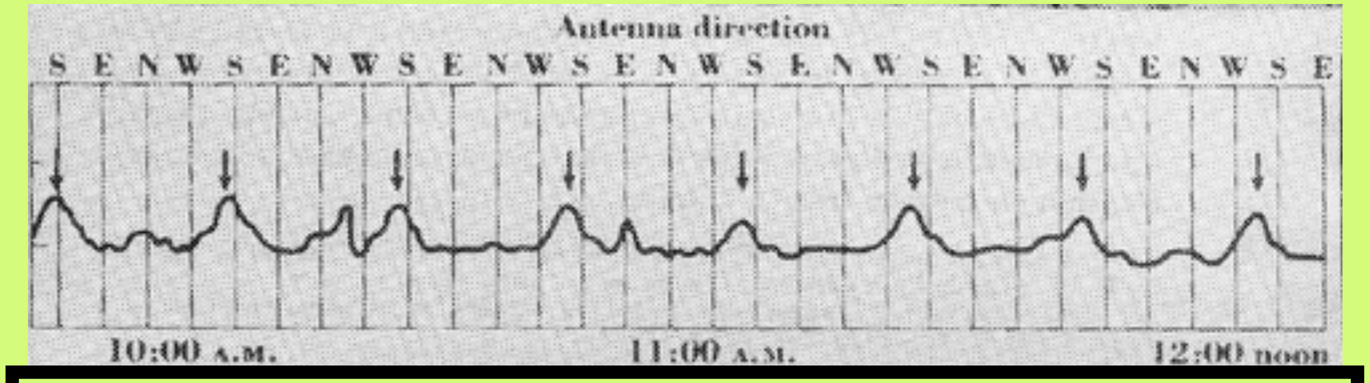
A more detailed description of the experiments and the results will be given later.

KARL G. JANSKY.

Bell Telephone Laboratories, Inc.,
New York, N. Y.
May 8.



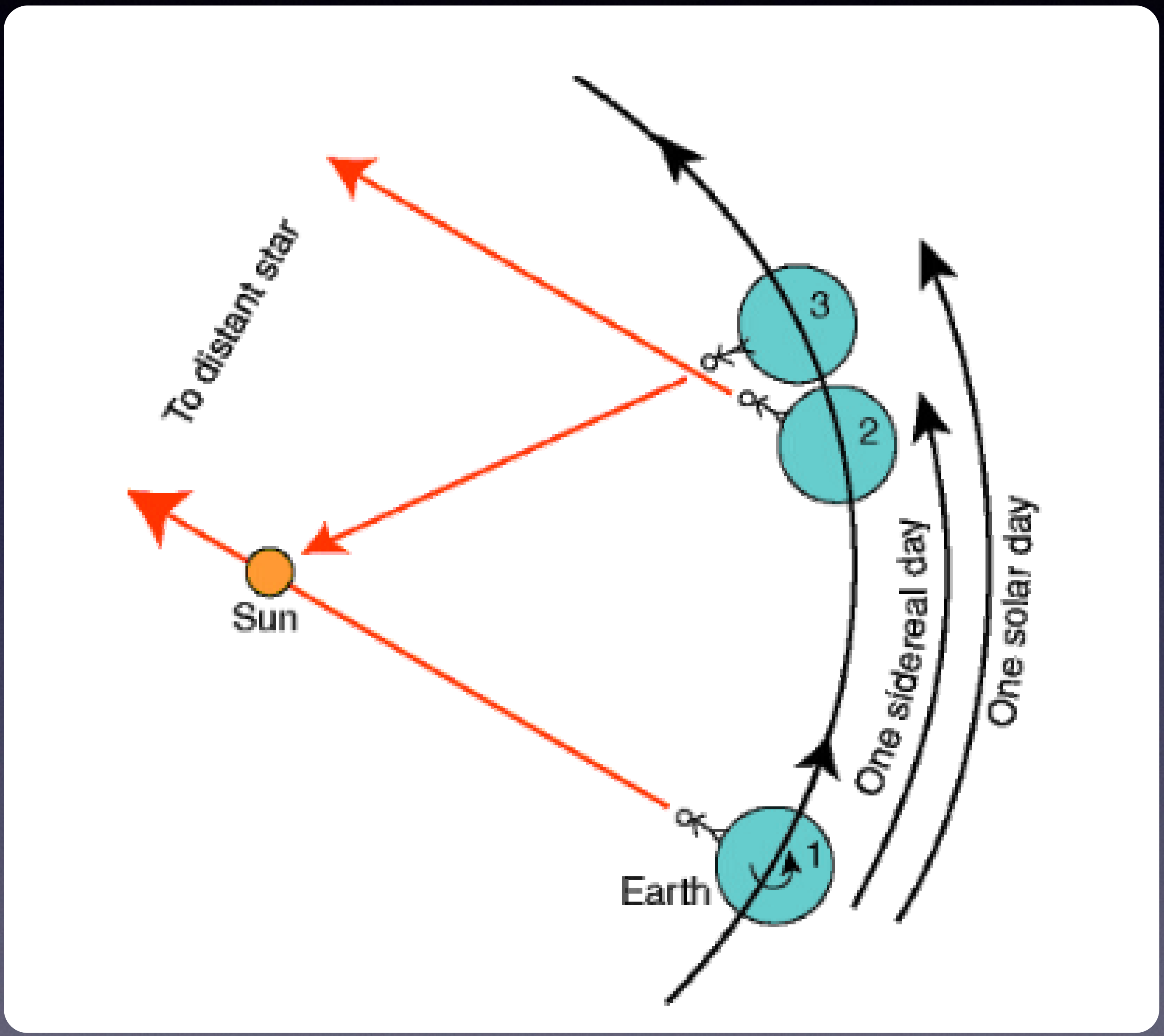
« An airplane wing rotating on automobile (Ford Model T) wheels in potato field »
Was built to investigate and eliminate the **crackling thunderstorm** noise (« **static** ») which interfered with **radio-telephone conversations** over trans-Atlantic short-wave links of the **Bell system**.

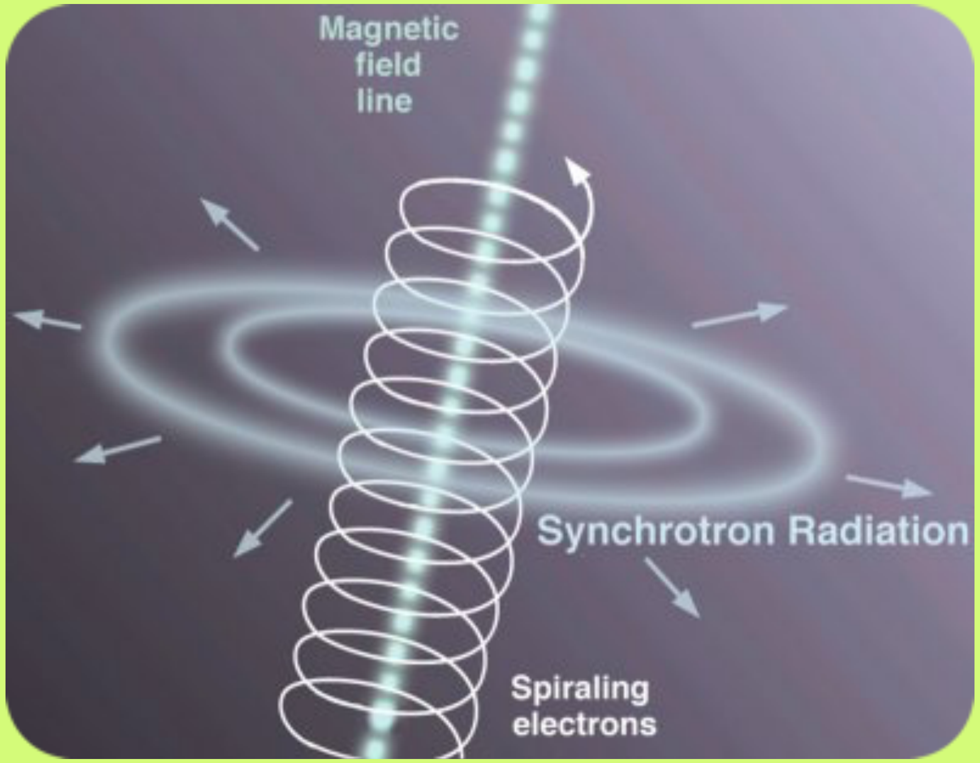


Small « bumps » observed by **Karl Jansky**, one for each revolution of the antenna every **20 minutes** (rotation time)

Jansky sees the invisible (1932)

However, after making an analysis on a complete year, **Jansky** noticed that the periodicity of the larger signal was **not 24 hours, but 23h56**, which corresponds to a **sidereal day and not a solar day**: the signal was coming from the center of the galaxy and not from the sun (« stationary with respect to the stars »).





What observed **Jansky** was in fact the **synchrotron radiation** of ultra high energy electrons produced in the Galactic Center. A GeV electron emit synchrotron photons at radio-wave (**1 MHz=300m, 1GHz=30cm**, frequencies measured by **WMAP** and **PLANCK**)

Jansky died in **1950** (at 44) without knowing the revolution he initiated.
p.s.: he was lucky to look at a wavelength of 14 meters, which was the range **not absorbed by the ionosphere** while still emitted by galactic center.

The 21cm tracer (1944-1951)

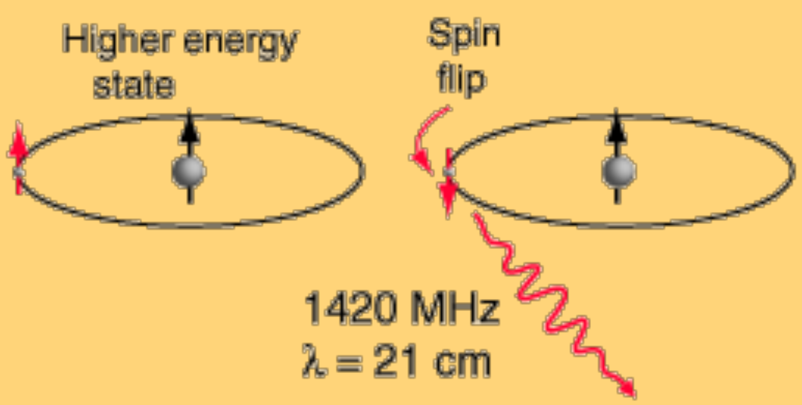
Hendrick van de Hulst

Jan Oort

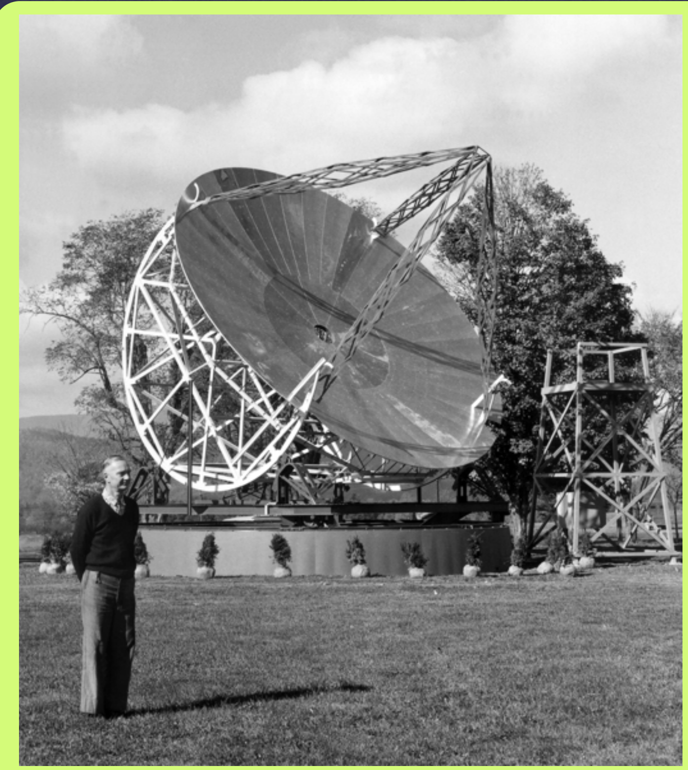
In **1944**, **Jan Oort** in **Leiden** realised that should any of the atoms or molecules in space give rise to a **spectral line** in the radio spectrum, it would enable much information about the **interstellar medium**.

***Ewen** on his horn telescope*

Unfortunately, **van de Hulst** is scooped in **1951** for **6 weeks** by **Ewen and Purcell** at **Harvard** (who heard about the line in a talk by van de Hulst they assisted in 1949) for which they received the **Nobel prize** of Physics in **1952** (never van de Hulst).



In a **magnetic field**, there is a slight difference in energy of the ground state depending wether the spin of the proton and electron are in the same or opposite sense (**Casimir**, friend of **Oort**). This transition between them gives rise to a **line close to 1420 MHz-21 cm in wavelength**



***Van de Hulst** at Dwingeloo*

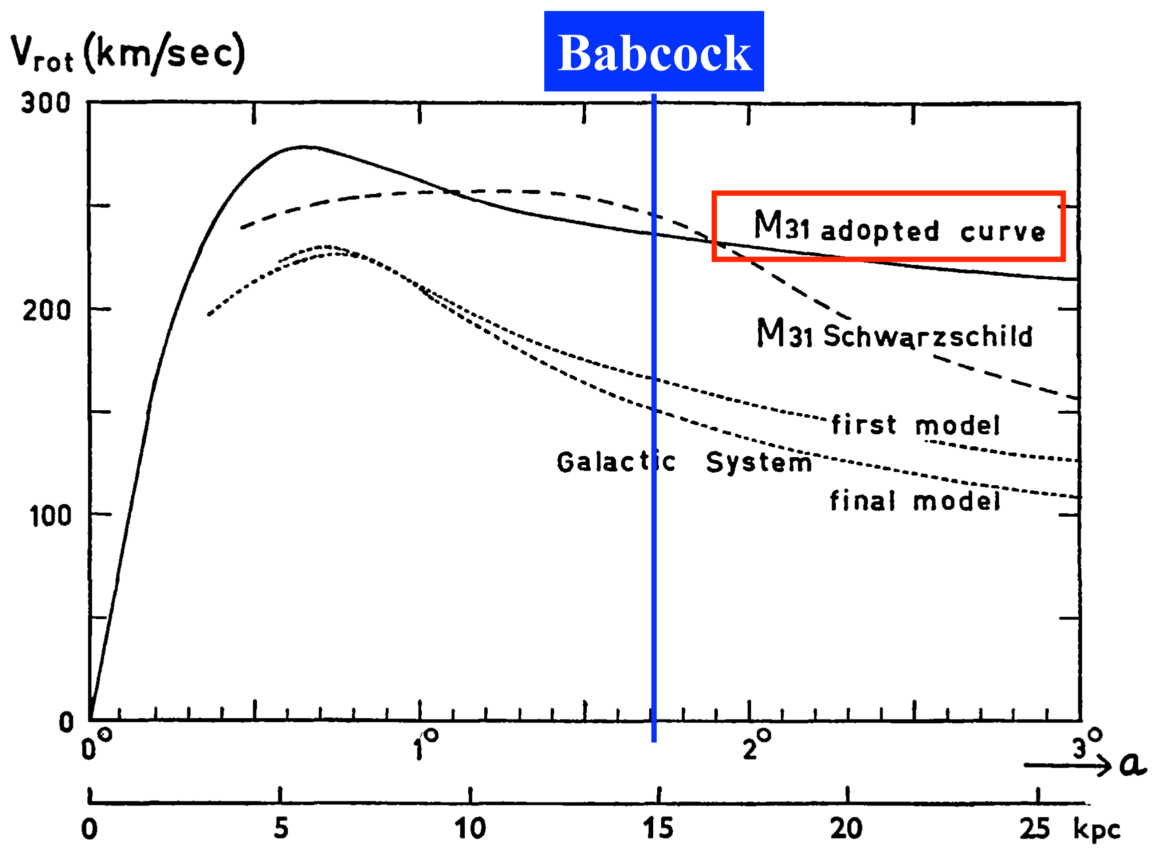
However, **van de Hulst** never stopped and gave the first 21cm map of Andromeda in 1957, showing that the velocities stays constant **much far away from the visible region** with the **Dwingeloo telescope**

ROTATION AND DENSITY DISTRIBUTION OF THE ANDROMEDA NEBULA DERIVED FROM OBSERVATIONS OF THE 21-cm LINE

BY H. C. VAN DE HULST, E. RAIMOND AND H. VAN WOERDEN

The atomic hydrogen emission from the Andromeda nebula (M31) was observed with the 25-metre telescope at Dwingeloo; the beamwidth was 0°.6. Line profiles were measured at 20 points of the major axis (Figure 5). The mean error of the brightness temperature measured at one frequency in one direction was 0.2 to 0.3°K except in the frequency range contaminated by galactic foreground radiation. The line was observable to 2°.5 at either side of the centre. The central velocity with respect to the local standard of rest is − 296 km/sec. The velocity of rotation slowly falls from 278 km/sec at 0°.6 from the centre to 221 km/sec at 2°.5 (Table 7). The accuracy is well within 10 km/sec. The density distributions determined from the integrated profiles in the SW and NE halves of the system separately show pronounced peaks at 1° from the centre in each half (Table 6). Model line profiles were computed with the average density distribution of the two halves on the assumption of circular symmetry, taking full account of the antenna pattern. They fit the observed profiles quite well if a broadening effect is introduced corresponding to random cloud motions with a root mean square velocity of 8 km/sec. The total mass of atomic hydrogen in the system is $0.25 \times 10^{10}\, c^2$ solar masses if the distance of M31 is 500 c kpc; it is 0.01 c times the total mass of M31 determined by SCHMIDT in the succeeding paper. Both the hydrogen mass and the total mass exceed those of the Galactic System. A local excess of radiation found at $v = -224$ km/sec in the NE part of the system has been investigated by more complete measurements but no satisfactory explanation has been found.

FIGURE 11



Rotation laws of M31 and the Galactic System.

In view of the observations on M31 it might be conjectured that the rotational velocity falls less sharply with increasing distance from the centre than has been assumed. This would lead to a higher mass,

Van de Hulst do not insist so much in his paper about the flatness of the rotation curve. But, computing the mass of M31 he conclude that is is much larger than the Milky way. The « dark matter » hypothesis does not (yet) strikes the Galactic scale.

The problem of instability at a galactic scale

In the 70's, **the Moore law** of **exponential** development describing the time evolution of computing power reached astrophysics studies: **the computing power doubling every two years**, it was possible in the late 60's to apply electronic computing machines in the numerical solution of complex problems (technically, it was the replacement of **vacuum tubes** by **transistors** which gives a large leap in the field).

Franck Hohl in **1971** made one of the very first « N-body » simulation (100 000 stars !!) to test the stability of the galactic structures with a disk of particles supported in equilibrium almost entirely by rotation.

He noticed that a spiral-elongated shape is formed after 2 revolutions, but rapidly the kinetic energy diffuse the particles toward a pressure dominated gas with large elongated axi-symmetric ellipses

Miller, **Pendergast** and **Quirk** tried to stabilized the model by adding energy lost, but still, reheating of the gas destroys the structures some revolutions after. This is when a **dark halo** came to the rescue and is first mentioned in a paper.

NUMERICAL EXPERIMENTS WITH A DISK OF STARS

Frank Hohl
NASA, Langley Research Center, Hampton, Virginia
Received 1971 March 10; revised 1971 April 28

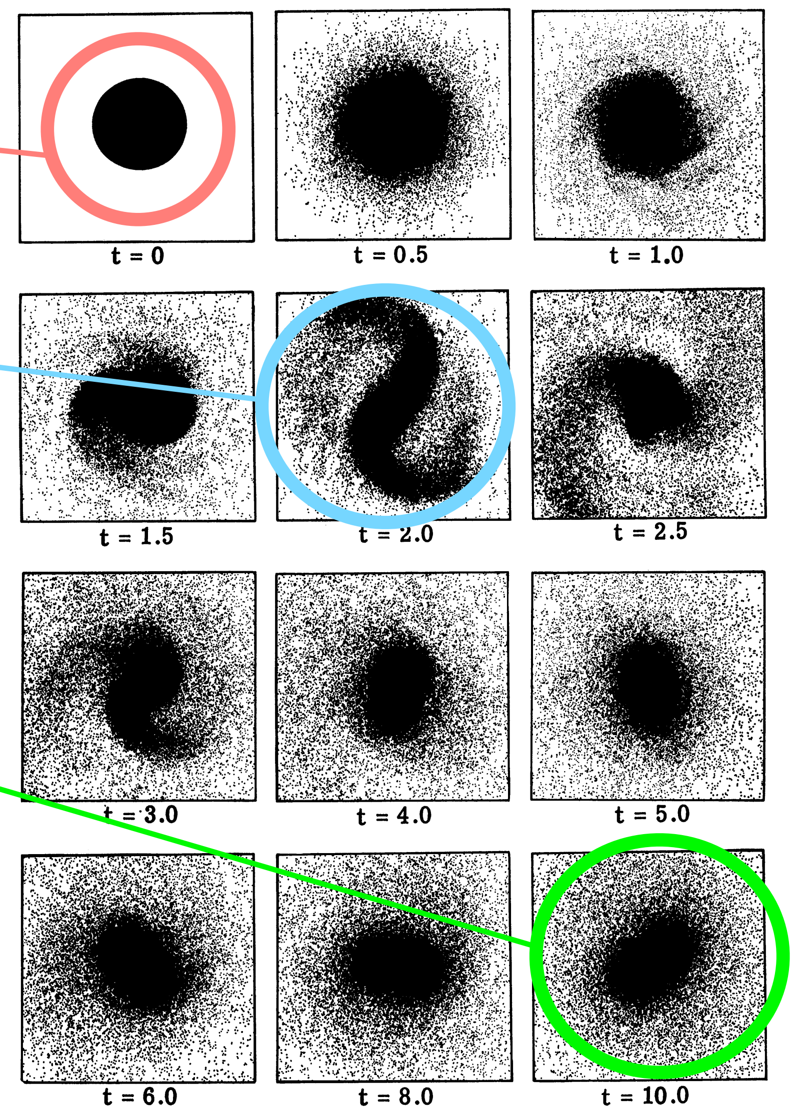


Fig. 4.—Unconstrained evolution of the initially balanced uniformly rotating disk of 100000 stars. The stars have an initial velocity dispersion given by Toomre's criterion.

First hypothesis of dark halo

The idea

Peebles and **Ostriker** noticed that the **random velocities** in our galaxies (around **30-40 km/s**) are much smaller than the **systematic circular motion** (around **200 km/s**). Thus, not only the system is unstable as remarked by **Hohl et al.**, but it shows that galaxies seems to be dominated by a **cold gravitational** system and **not a kinetic** pressure dominated one.

Indeed, the **virial theorem** can be decomposed as:

$$2T + U = 0, \text{ or } 2T_{rot} + 2T_{ran} = U, \text{ which can be written } t + r = 1/2$$

with $t = T_{rot}/(-U)$ and $r = T_{ran}/(-U)$. So, if **t=1/2** (r=0) the system is completely supported against gravity by **rotation**, but if **r=1/2** (t=0) the system is completely supported by **random motion**.

Peebles and **Ostriker** noticed that **if t > 0.14** (28% of the kinetic energy is rotational), **the system is unstable** and becomes elongated very quickly. However, we just saw that in our Milky Way, the rotation velocity is around **200 km/s** whereas the random one approaches **40 km/s**, which gives **t ~ 0.49**, **far in excess of the stability limit!!**

The clever idea of **Peebles** and **Ostriker** is then to add an **additional component** to the galaxy, a **dark halo** which contributes at least **50% of the mass** inside the position of the Sun

$$U \rightarrow U + U_{dark}$$

Then this spheroidal system would **add to the gravitational potential** energy, but add **nothing to the rotational energy**; **t would be decreased** and perhaps stability restored.

The article

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

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Princeton University Observatory
AND
P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University

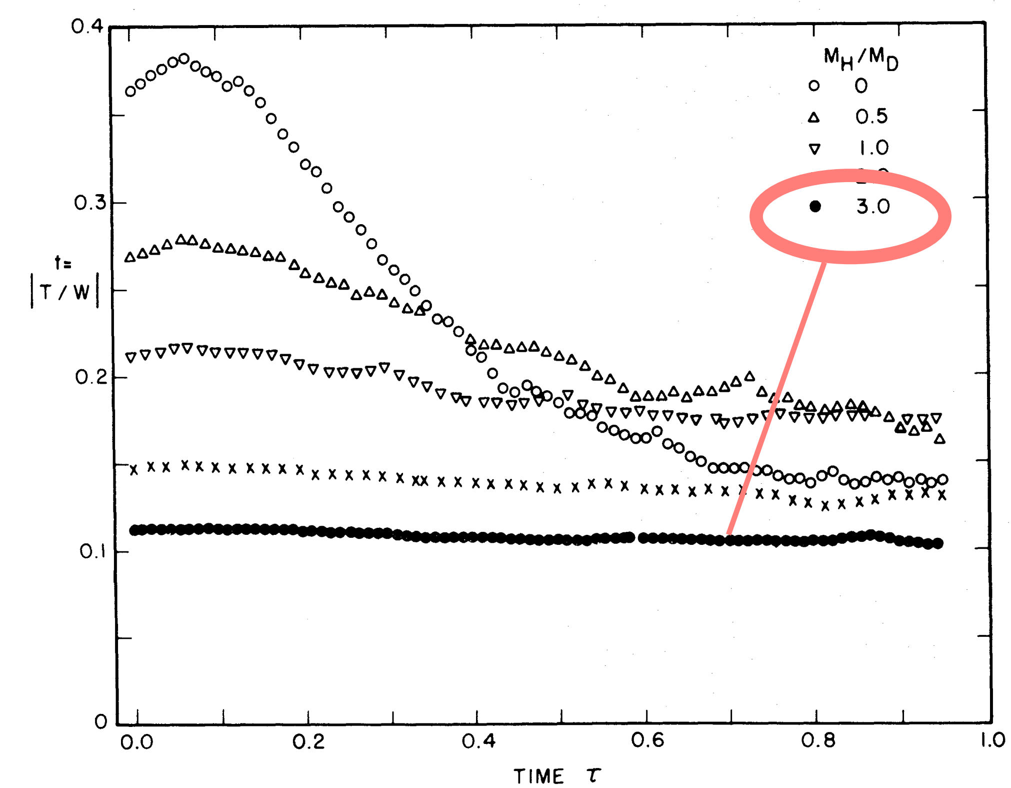
Received 1973 May 29

ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \sim 0.14$ has been found by a variety of methods. Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to 2½, and an initial value of $t \cong 0.14 \pm 0.03$, are required for stability. If our 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.

Subject headings: galactic structure — stellar dynamics

P.J. Peebles J.P. Ostriker



Finally, one can add another hot component and thus stabilize the total system. Adding a hot disk component reduces to alternative (1) and would require an unseen disk component with large mass and largely radial orbits. Adding an extended component corresponding to the "halo" described in § II apparently will stabilize the system if the halo mass is equal to or somewhat greater than the disk mass. A similar conclusion was reached by Kalnajs (1972) from an independent consideration of possible stabilizing influences.

Of these three alternatives, the last—the massive halo—seems the most likely solution for our own Galaxy. Though we have not exhausted the possibilities of constructing ingenious models having hot components interior to the Sun but most of the total mass in a flat cold component (a variant of alternative [1]), we have not found a way to produce a stable model by this means that does not do violence to the observed rotation curve. Further work assessing this alternative would be quite useful.

Combining 21cm observations with Peebles idea

Vera Rubin

After the work of **Van de Hulst**, a lot of instrumental developments allowed to have a better understanding of the rotation curves of galaxies much above the optical limit.

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

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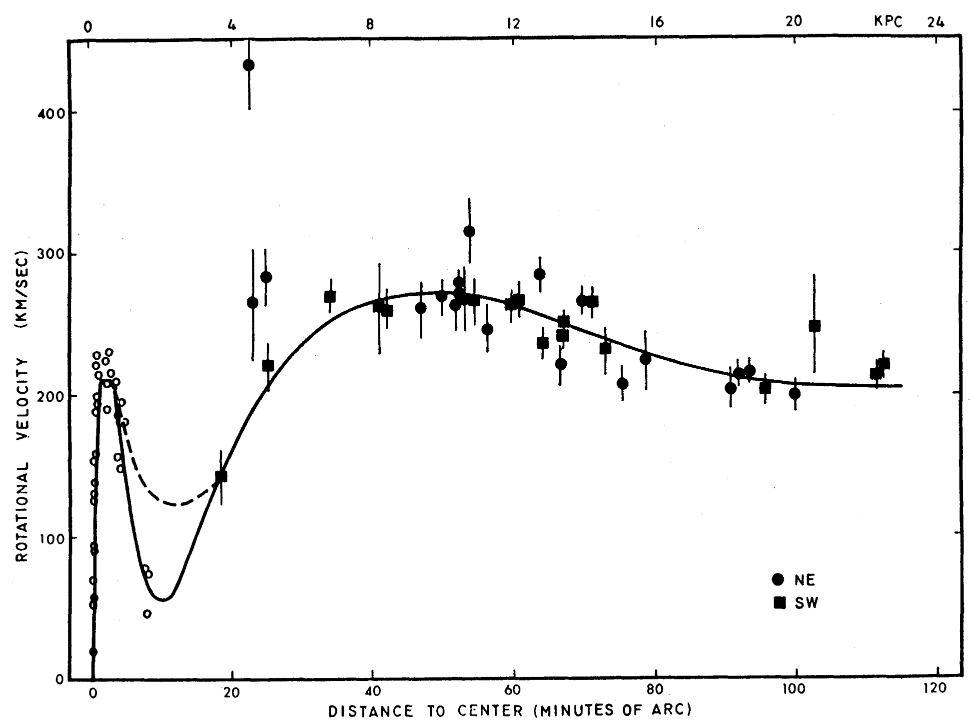
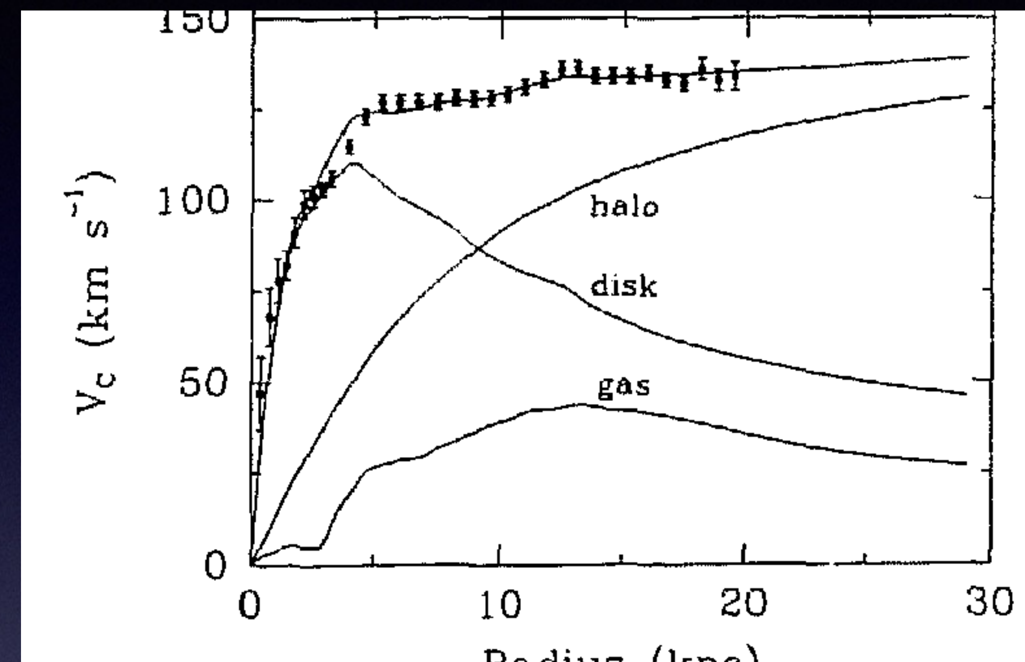
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21



Andromeda, M31

which will establish the amount of neutral hydrogen. For the present, we prefer to adopt as the mass of M31 that mass contained within the outermost observed point; extrapolation beyond that distance is clearly a matter of taste.



K.G. Begeman thesis

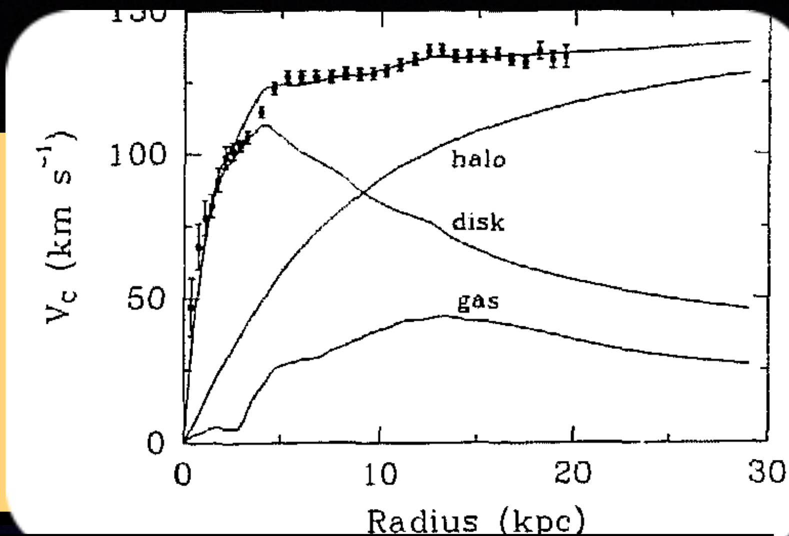
Which profiles?

The rotation curve is given by

$v^2(r) = GM(r)/r$

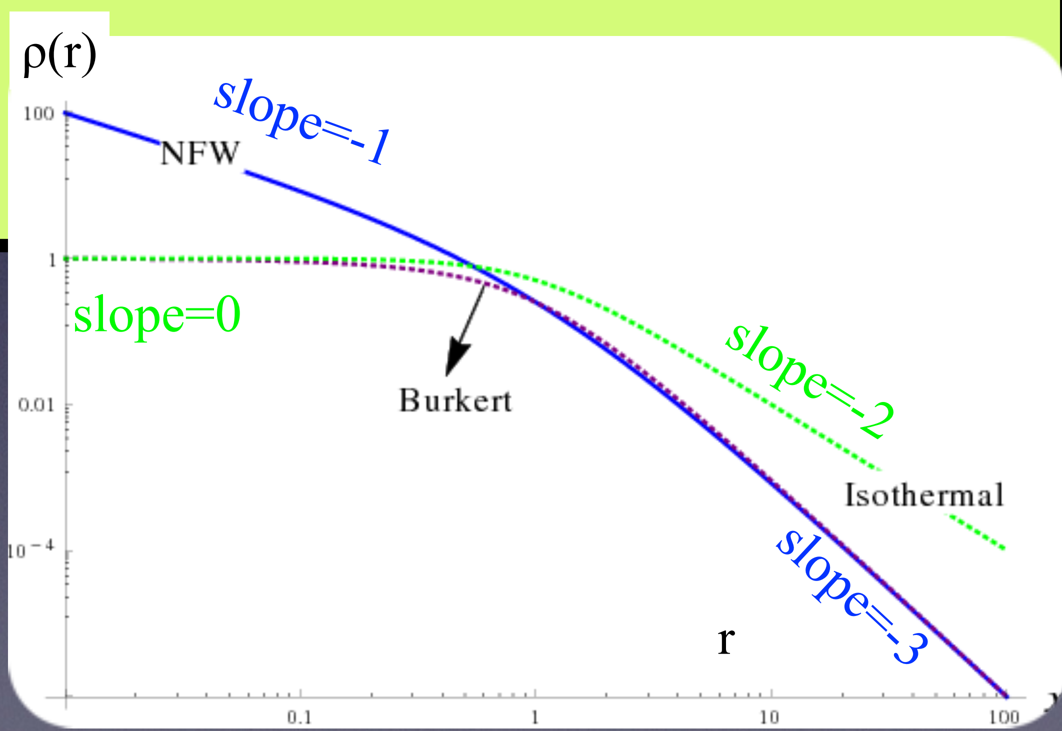
A constant velocity at large radius means

$$M(r) = \int 4\pi r^2 \rho(r) dr \ \propto r \Rightarrow \rho(r) = \frac{\rho_0}{r^2}$$



In **1907**, **R. Emden** (brother in law of **K. Schwarzschild**) in a book called « **Gaskugeln** » demonstrates by thermodynamics argument that a gaz of **constant temperature** is equilibrate with a density following **$\rho(r) = \rho_0/r^2$**. One then call these types of profile, **isothermal**. However, for low radius, rotation curves clearly indicates that the density of dark matter is dominated by the gaz, and does not diverge. One then add a constant term toward the center which gives

$$\rho^{iso}(r) = \frac{\rho_0}{1 + \left(\frac{r}{r_c}\right)^2}$$



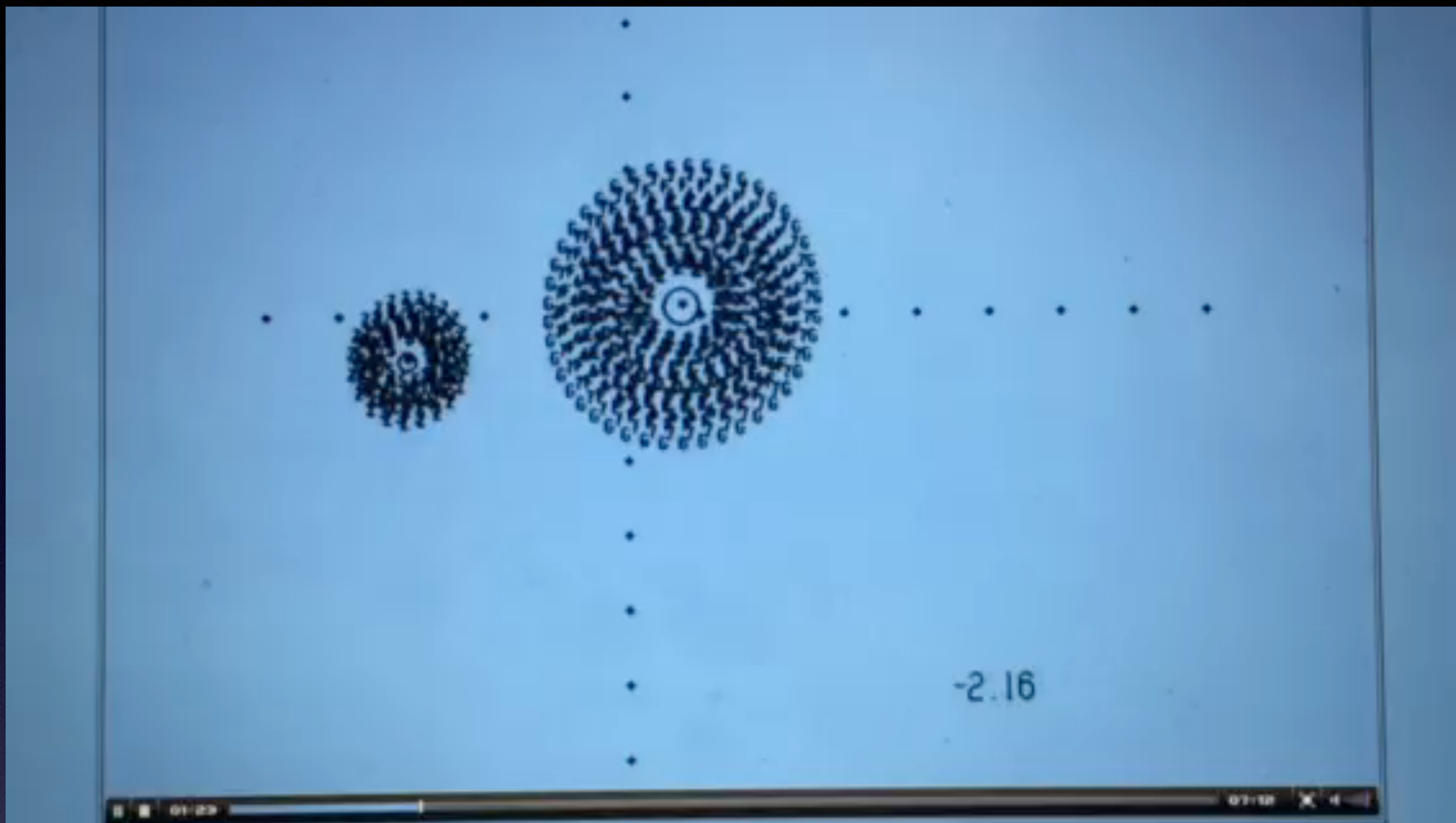
Navarro (Arizona), **Frenk** (Durham) and **White** (Munchen), in a series of papers between **1995** and **1997** extracted from precise N-body simulation that the dark matter profile observes a cusp feature near the center proportional to **1/r** and then evolves toward a **$1/r^3$** shape in the outskirt regions. This profile is called **NFW**

$$\rho^{NFW}(r) = \frac{\rho_0}{\frac{r}{r_c}\left(1 + \frac{r}{r_c}\right)^2}$$

A Universal Density Profile from Hierarchical Clustering

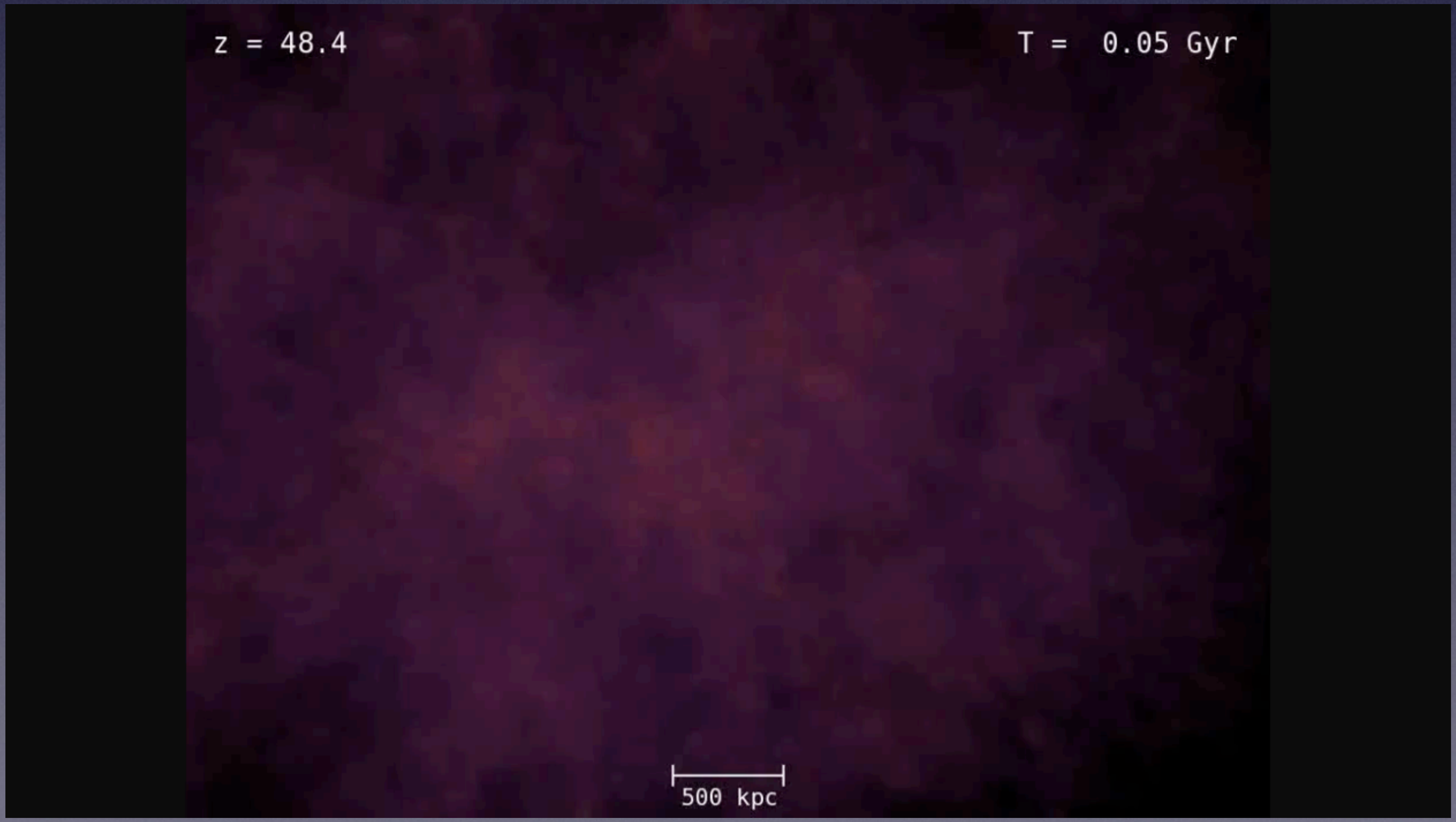
Navaro, Frenk and White 1995

Two examples

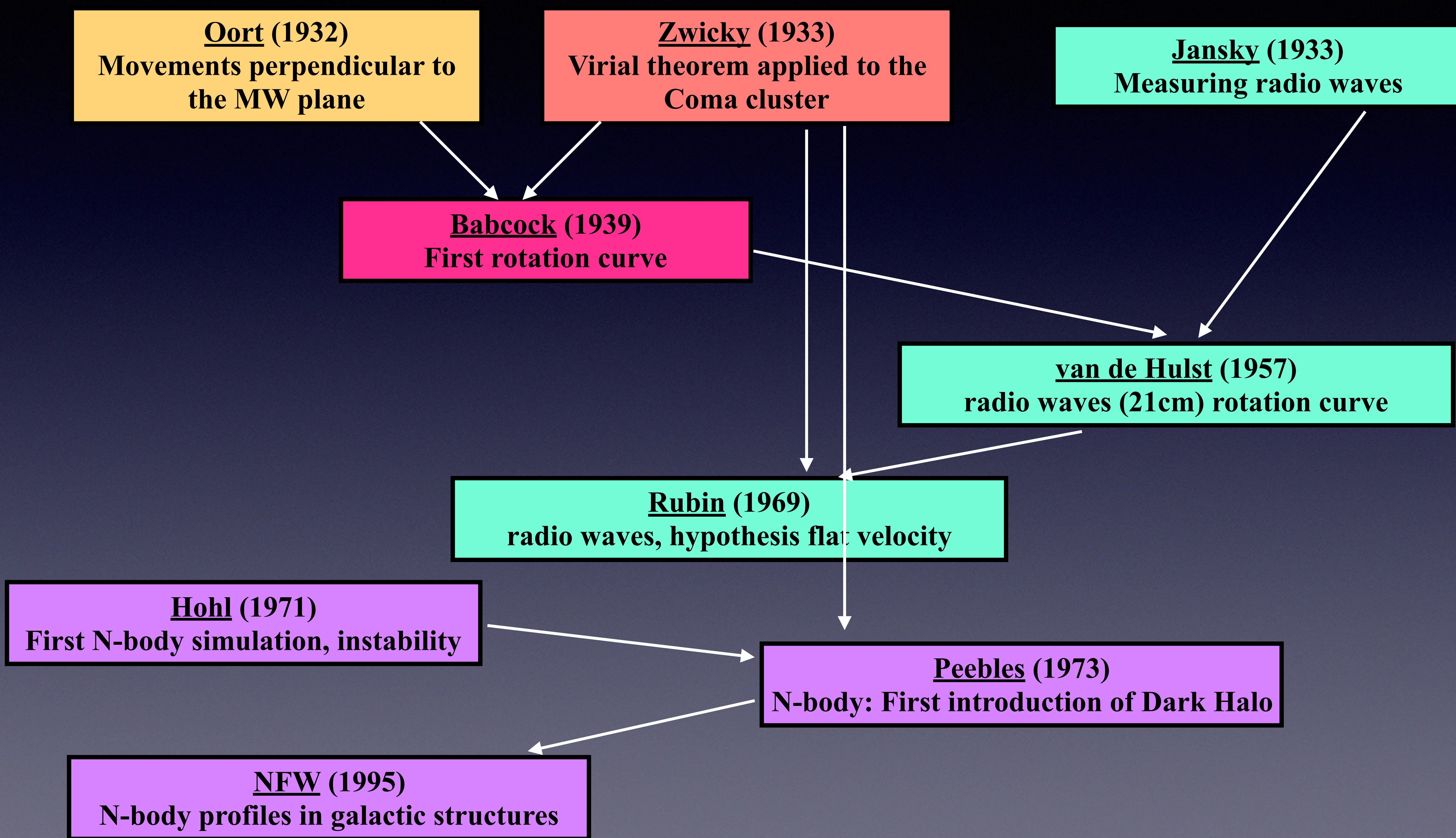


The first N-body simulation was made by the **Toomre brothers (Alar and Juri)** in 1972 (!!!) with 200 points.

Aquarius simulation (2009) with 10^9 points



Summary (present sky)



pre-conclusion

We have seen in this first part that it was a long way from the first papers of Oort and Zwicky in the 30's to the latest N-Body simulation in the 90's to picture a coherent framework in the analysis of dark matter in the structures and substructures of the Universe. However, in the 60's the discovery of the CMB will shed a completely new light on the content of the Universe and will reinforce the notion of dark matter. This is the subject of the next lecture.

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Filling the Universe with neutrino

The Zeldovich-Cowsik-McClelland bound, or the birth of cosmological astroparticle

Once the **CMB** has been discovered, and measured, a lot of particle physicists jumped on it to test their predictions through interactions on it (**GZK cutoff** and cosmic ray) to astrophysical consequences.

Zeldovich and **Ghershtein in June 1966** (!!) were the first to obtain limits on a heavy neutrino (the muonic neutrino $\boldsymbol{\nu_\mu}$ has been discovered by **Lederman** in **1962**) from cosmological consideration, asking for a Universe respecting the deceleration parameter, obtaining $m_{\nu\mu} < 400$ eV.

Cowsik and **Mac Clelland in 1972** (!!) recomputed it (without citing Zeldovich) with more accurate values of the Hubble parameter and obtained $m_{\nu\mu} < 8$ eV (the now called « Cowsik Mac Clelland » bound).

The idea of Zeldovich

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Y. Zeldovich

Suppose a gas of electrons, neutrinos and photons in equilibrium.

$$n_{e^-} + n_{e^+} = n_\nu + n_{\bar{\nu}} = \frac{3}{2} n_\gamma$$

where 3/2 = 3/4 (fermi gas versus boson gas)
*2 (2+2 degrees of freedom for fermions vs 2 degrees of freedom for photons)
whereas after decoupling of the $e^+ e^-$:

$$n_{e^-} + n_{e^+} = 0 \; ; \quad n_\nu + n_{\bar{\nu}} = \frac{1}{2} n_\gamma$$

where 1/2 ~ 3/2 * 4/11 [(2 + 7/8*4)/2 = 11/4] corresponds to the degrees of freedom of the $e^+ e^-$ absorbed by the photons (and not the neutrino that already decoupled)

Then, from the measurements of the **CMB** temperature T_γ, **Zeldovich** deduced
$\mathbf{n_\gamma = 550\ cm^{-3}}$ implying $\mathbf{n_\nu = 300\ cm^{-3}}$.
Knowing from astrophysics a limit on the mass density of the Universe
$\boldsymbol{\rho_m < 1.25\ x10^{-28}\ g\ cm^{-3}}$,
they inferred
n_ν x $m_\nu < \rho_m$ => $\mathbf{m_\nu < 7\ x10^{-31}\ g = 400\ eV}$

of the e^+e^- increases the number of quanta without changing the number of neutrinos per unit of co-moving volume [5]. At the present time we can expect

$$[e^+] + [e^-] = 0, \quad [\nu_\mu] + [\bar{\nu}_\mu] = [\nu_e] + [\bar{\nu}_e] = 0.5[\gamma].$$

At 3°K we have $[\gamma] = 550$ g/cm^3, from which we obtain for the neutrino at the present time

$$[\nu_\mu] + [\bar{\nu}_\mu] = [\nu_e] + [\bar{\nu}_e] = 300 \text{ cm}^{-3}.$$

Comparing with the density limit given above, we obtain

$$m_0(\nu_\mu) < 7 \times 10^{-31} \text{ g} = 400 \text{ eV}/c^2$$

1) We use the asymptotic formula

$$T = \pi/2H\sqrt{\rho/\rho_c} \; ; \quad \rho_c = 3H^2/8\pi\sigma \; ; \quad \rho = 3\pi/32\sigma T^2.$$

Other more complicated estimates based on an investigation of remote objects give a similar result:

$$q_0 = \rho/2\rho_c < 2.5; \quad H \leq 120 \text{ km/sec.Mparsec},$$

$$\rho_c \leq 2.5 \times 10^{-29} \text{ g/cm}^3, \quad \rho < 1.25 \times 10^{-28} \text{ g/cm}^3.$$

The Cowsik-Mac Clelland bound (1972)

The rediscovering of Zeldovich bound

Enrico Fermi

"Tentativo di una teoria dei raggi β".

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720
(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

The Zeldovich-Hut-Lee-Weinberg bound (1977)

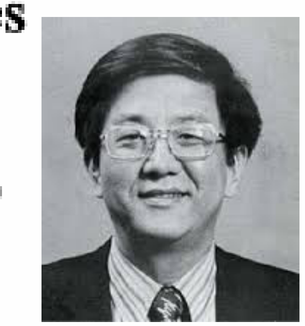
LIMITS ON MASSES AND NUMBER OF NEUTRAL WEAKLY INTERACTING PARTICLES

P. HUT
Institute for Theoretical Physics, University of Utrecht, Utrecht, Netherlands

Received 25 April 1977

VOLUME 39 | 25 JULY 1977 | NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses



Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] Batavia, Illinois 60510

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

The Lee-Weinberg way (1977)

The recipe

1) Compute the temperature of freeze out T_f of χ (mass m) from the thermal bath :

$$n(T_f)\langle\sigma v\rangle = H(T_f) \quad \Rightarrow \quad (T_f m)^{3/2}\, e^{-m/T_f}\langle\sigma v\rangle < \frac{T_f^2}{M_{Pl}} \quad \Rightarrow \quad T_f = \frac{m}{\ln M_{Pl}} = \frac{m}{26}$$

2) Solve the Boltzmann equation for the Yields $Y=(n_\chi / n_\gamma)$ from the thermal equilibrium $\chi\,\chi \longleftrightarrow \gamma\,\gamma$

$$\frac{dY}{dT} = \frac{T^2}{H(T)}\langle\sigma v\rangle Y^2 \quad \Rightarrow \quad Y(T_{now}) = \frac{1}{M_{Pl} T_f \langle\sigma v\rangle} = \frac{26}{M_{Pl} m \langle\sigma v\rangle}$$

3) Compute the relic abundance and compare with the experimental limits

$$\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26 \times 400\ \mathrm{cm}^{-3}}{\rho_c M_{Pl}\langle\sigma v\rangle} < 1 \qquad \Rightarrow \langle\sigma v\rangle > 10^{-9} h^{-2}\ \mathrm{GeV}^{-2}$$

4) Conclude

$$\langle\sigma v\rangle \simeq G_F^2 m^2 > 10^{-9}\ \mathrm{GeV}^{-2} \quad \Rightarrow \quad m > 2\ \mathrm{GeV}$$

5) Wait for applauses for that **first lower bound** on a massive non-baryonic matter filling the Universe.

SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

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California Institute of Technology; and Institute of Astronomy, Cambridge, England
B. W. LEE†
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I. LERCHE
Enrico Fermi Institute and Department of Physics, University of Chicago
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AND
G. STEIGMAN
Astronomy Department, Yale University
Received 1977 December 1; accepted 1978 February 14

ABSTRACT

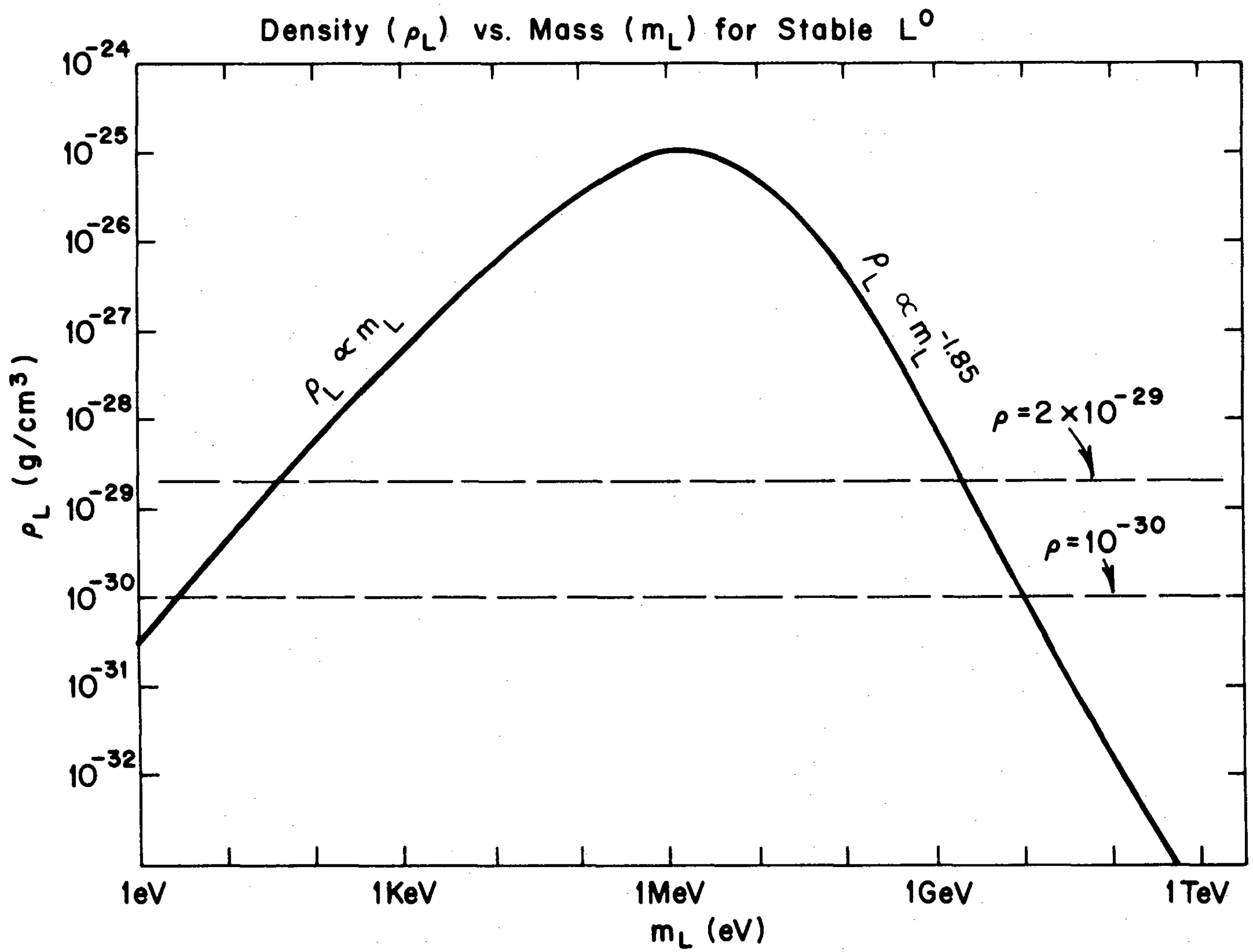
Recently, high-energy particle theorists have constructed new extended gauge theories which may fit experiment somewhat better than previous already very successful theories. One of the predictions which is often discussed is the possible existence of a stable neutral lepton, probably with a mass of a few GeV/c^2. Following this motivation we here investigate some cosmological consequences of the existence of *any* stable, massive, neutral lepton, and show that it could well dominate the present mass density in the universe. The contribution to the mass density depends on the mass of the lepton, which should eventually be determined with high-energy accelerators. It is interesting that the more massive the lepton, the smaller its contribution to the present mass density. It is unlikely that these leptons affect big bang nucleosynthesis or condense into stellar size objects. However, such a lepton is an excellent candidate for the material in galactic halos and for the mass required to bind the great clusters of galaxies. Annihilation radiation from these structures should be detectable. At the end of the paper a brief mention is made of the astrophysical constraints on the mass-lifetime relationship if the neutral lepton is unstable.

Subject headings: cosmology — elementary particles

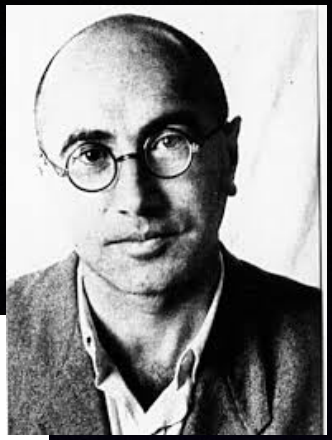
The difference with the « neutrino » dark matter paradigm of **Zeldovich** is that they were not limited in the ranges of masses, **could be above the GeV scale**.

SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

J. E. Gunn*



Zeldovich paper



Cosmological limits on the masses of neutral leptons

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Institute of Theoretical and Experimental Physics

Ya. B. Zel'dovich

Institute of Applied Mathematics, USSR Academy of Sciences

(Submitted June 30, 1977)

Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 3 200–202 (5 August 1977)

Cosmological arguments are presented which forbid the existence of stable weakly interacting particles in the mass interval 30 eV $< m <$ 2.5 GeV. Limits are also imposed on the masses of new neutral leptons if the latter are unstable.

Cowsik-McClelland bound

Lee-Weinberg bound

Historical references

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Pré-Conclusion

We have then seen that 4 main periods have seen a fast developments of new ideas and concepts around the dark matter hypothesis :

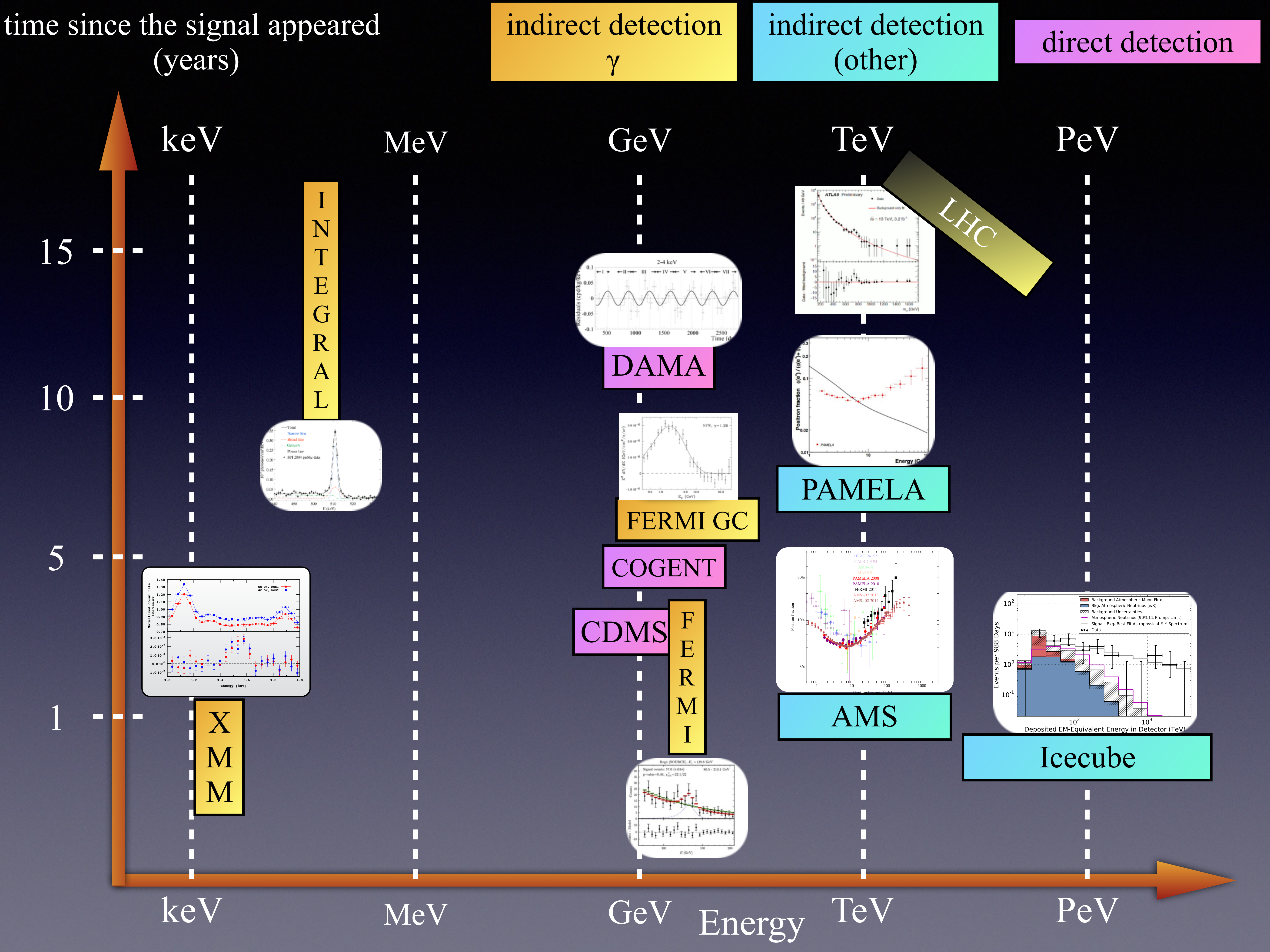
1) In the 40's during the development of the observations of the sky at the radio-waves, following the developments of the radar especially during the WWII

2) In the 50's once the nuclear physics fused with the model of expansion of Universe

3) In the 60's following the outbreaking discovery of the cosmic microwave background

4) And finally in the 70's once computing progress made possible the first simulations of our Universe by solving Einstein's equation from the CMB till present day.

Where are we now?



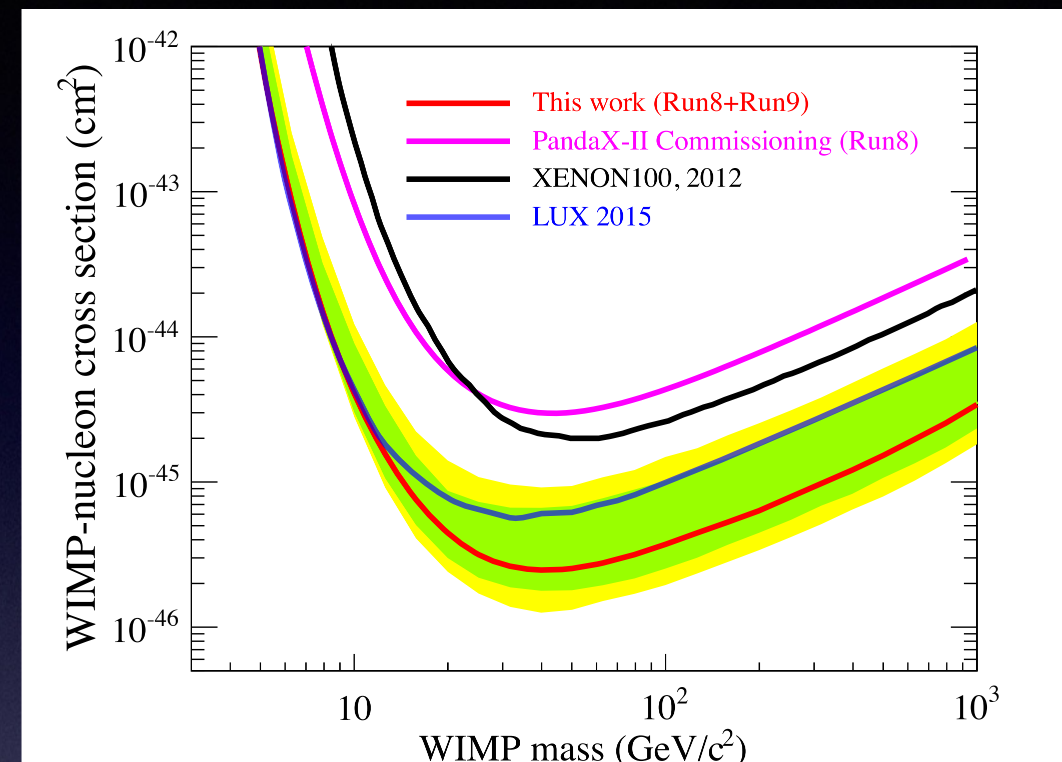
time since the signal appeared (years)
indirect detection γ
indirect detection (other)
direct detection
keV
MeV
GeV
TeV
PeV
15
10
5
1
INTEGRAL
XMM
DAMA
FERMI GC
COGENT
CDMS
FERMI
LHC
PAMELA
AMS
Icecube
keV
MeV
GeV
Energy
TeV
PeV

1

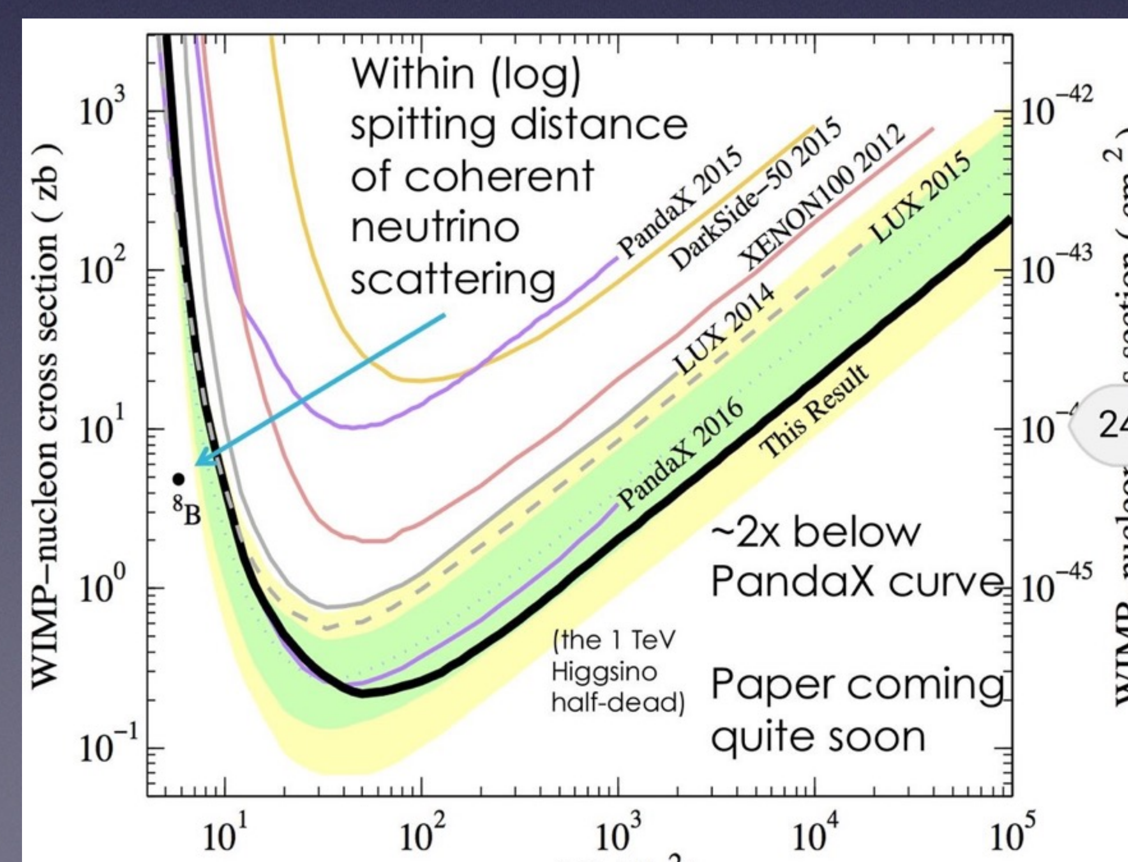
The direct detection race

December 2015, the **LUX** collaboration released the best limit on direct detection cross section : **6 x 10^{-46} cm^2** for a WIMP mass of 40 GeV

July 2016, **PANDAX-II**, after having eliminated the Krypton background early 2016 (by distillation) reached **2.5 x 10^{-46} cm^2** for a WIMP mass of 40 GeV (March to June 2016 campaign, run 9). One order (!!) of magnitude better than in 2015.

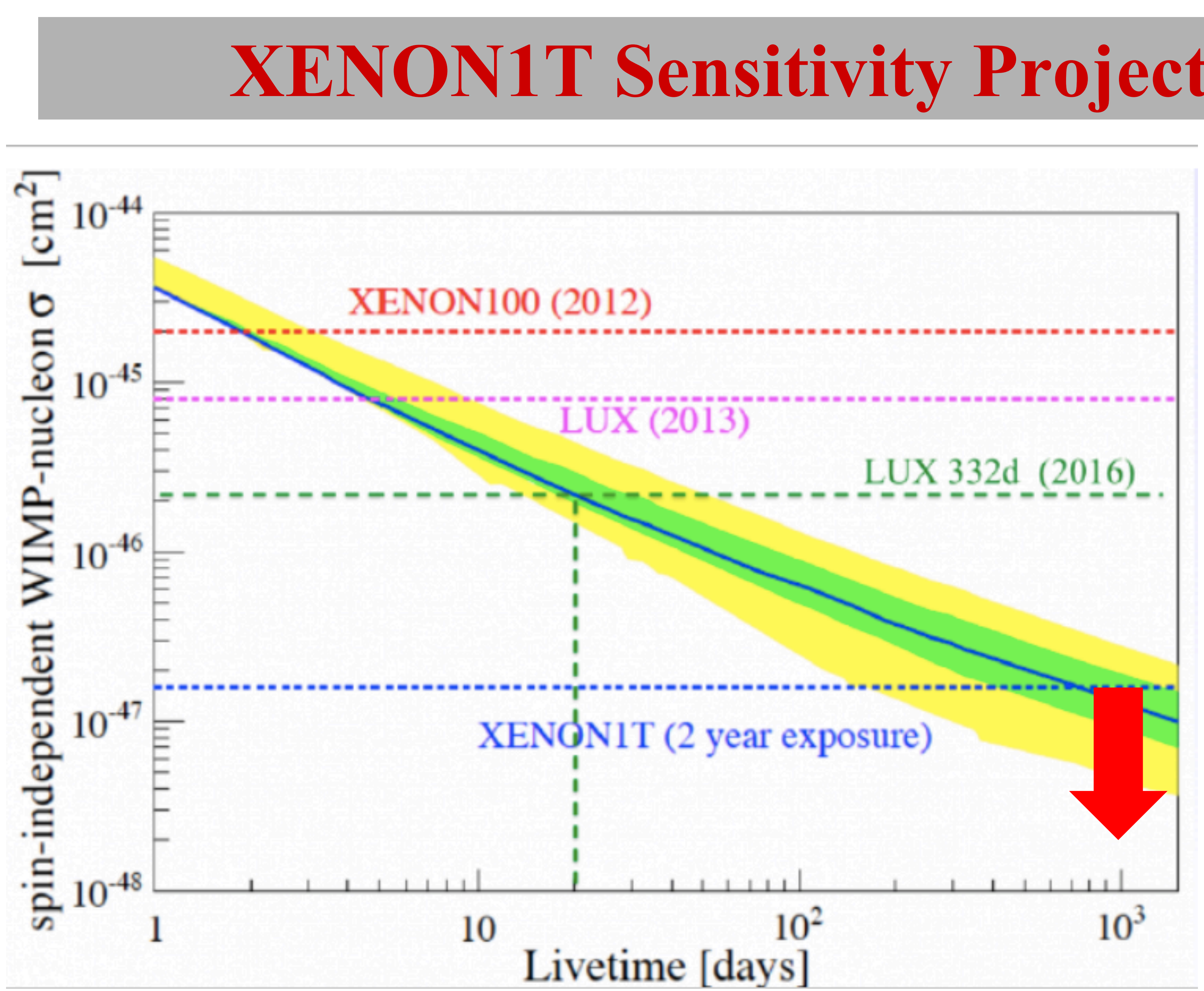


August 2016, **LUX** released a new analysis, giving slightly better limit than **PANDAX-II**:



• • •

August 2016, the **XENON** collaboration claimed (by a tweet..) that the latest 332 days LUX limit will be reached by XENON 1T by the end of the year, in less than 20 days!!

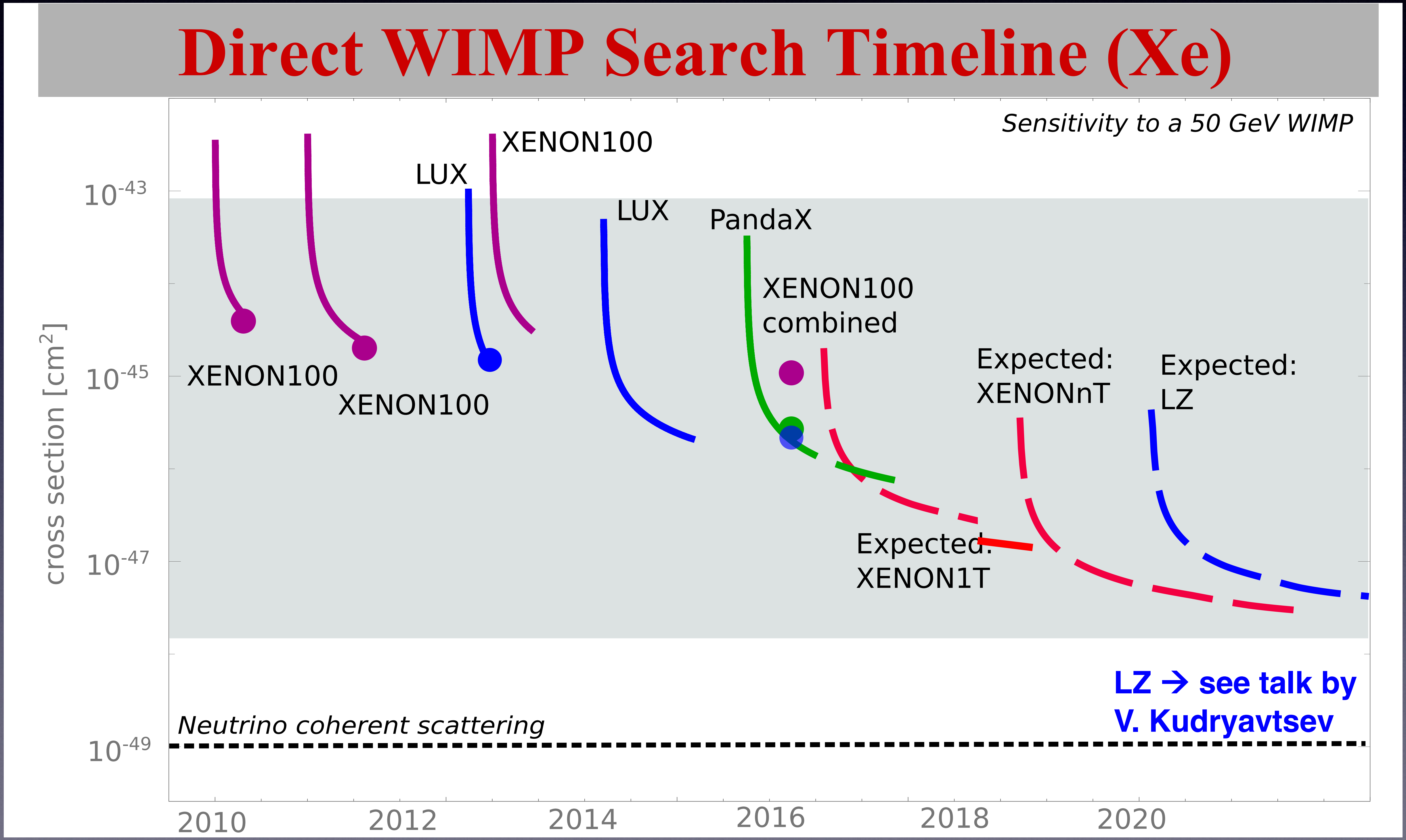


and then XENONnT → 20ty → x10

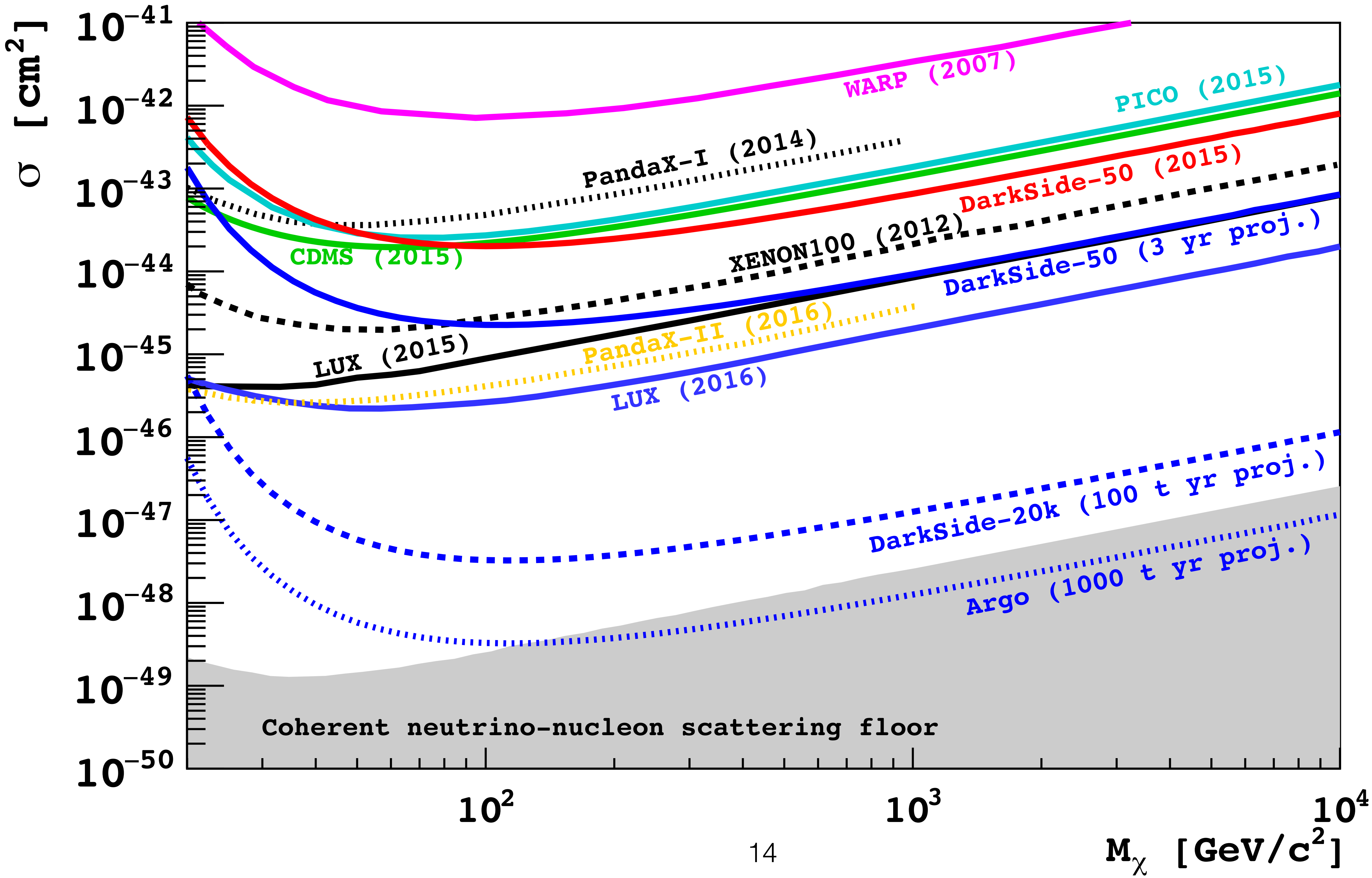
is built while XENON1T is running; reuses most parts → faster

• • •

September 2016, **LZ (LUX + ZEPLIN)** collaboration confirmed that they obtained the DoE approval, beginning the hunt in 2020. LZ consist of 10 tons detector. The entire supply of XENON is already under contract and will be supply under the help of the South Dakota sate.



What next? Sensitivity

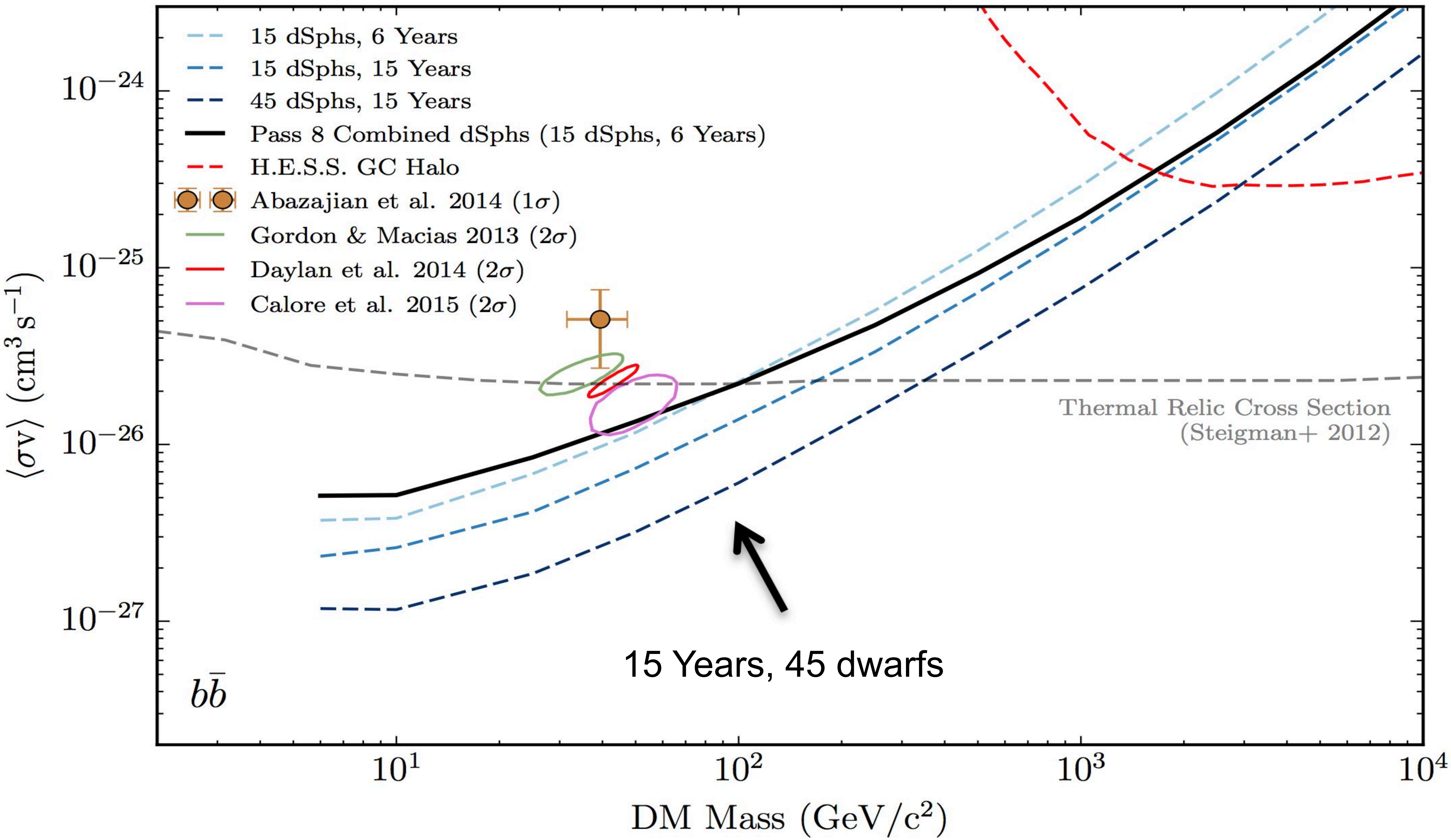


Darkside : maybe, but I won’t see it

2

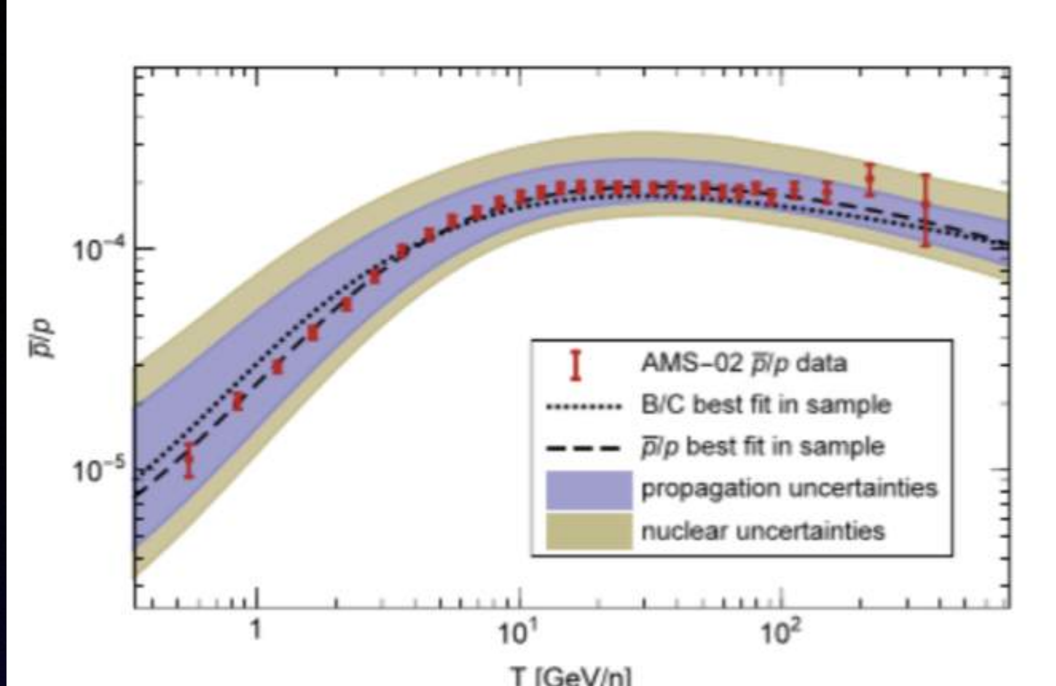
The indirect detection status

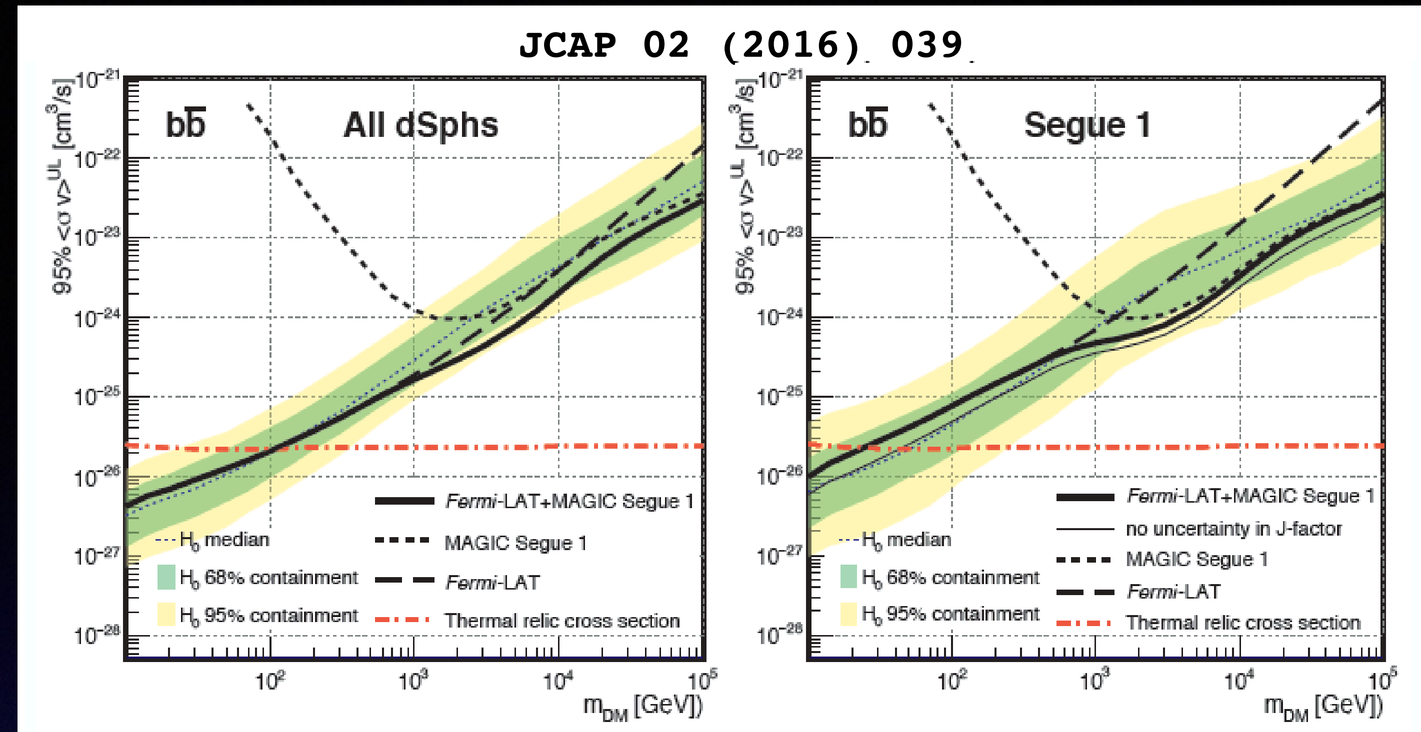
DM limit improvement estimate in 15 years with the composite likelihood approach (2008- 2023)



E. Charles et.al, Phy Rep. 636 2016, arXiv:1605.02016

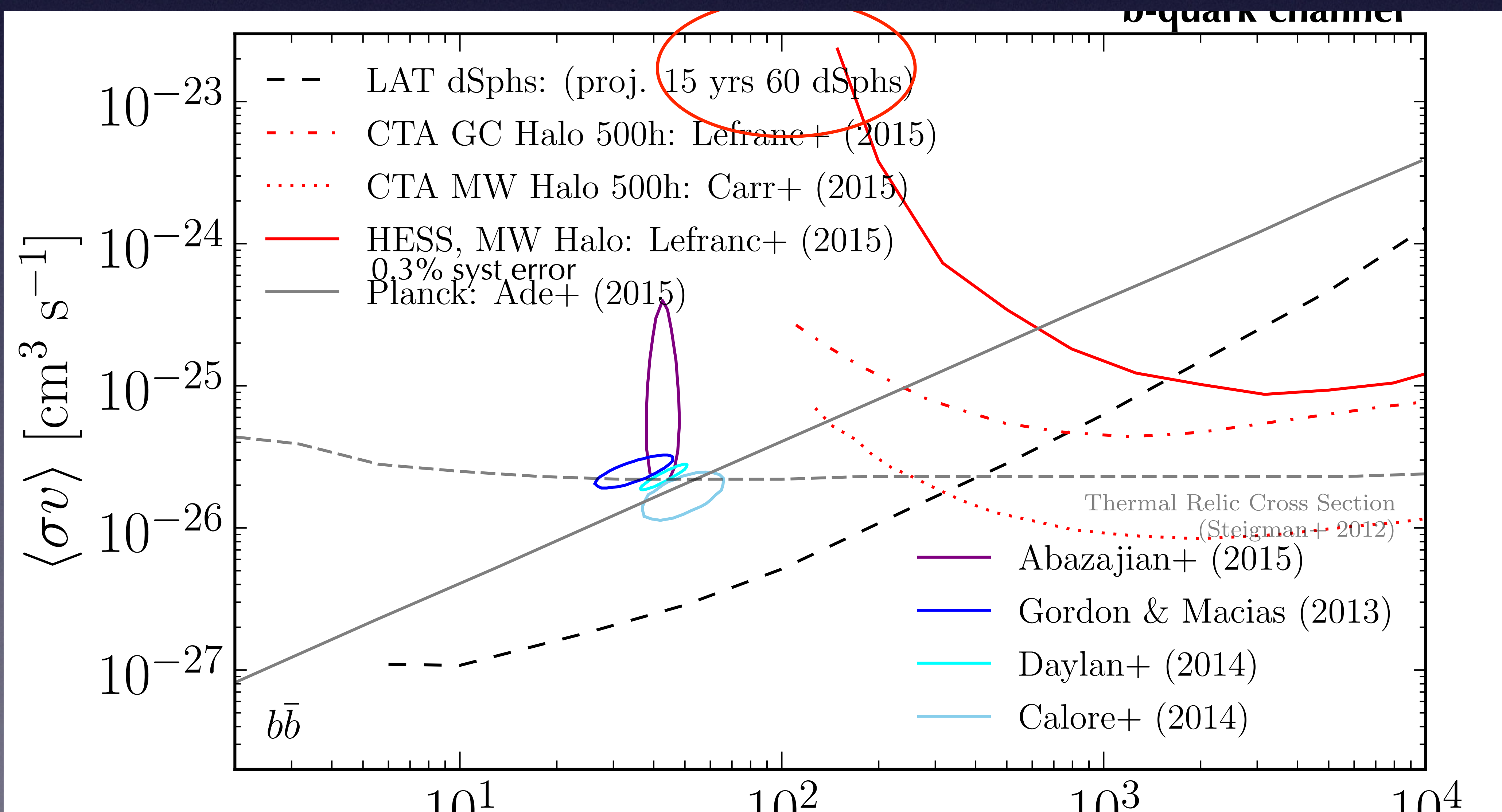
Latest result by FERMI in May: nothing





AMS : nothing

MAGIC : nothing



HESS : nothing

CTA : ??

3

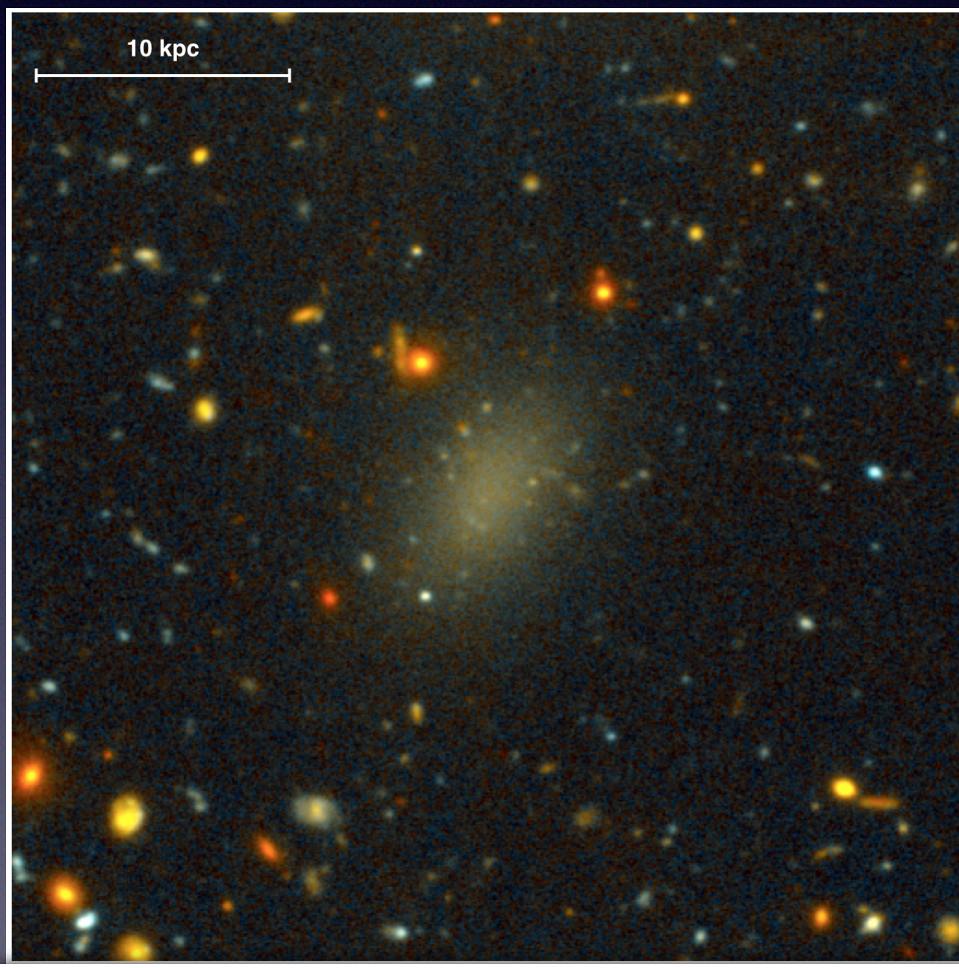
Some positive news

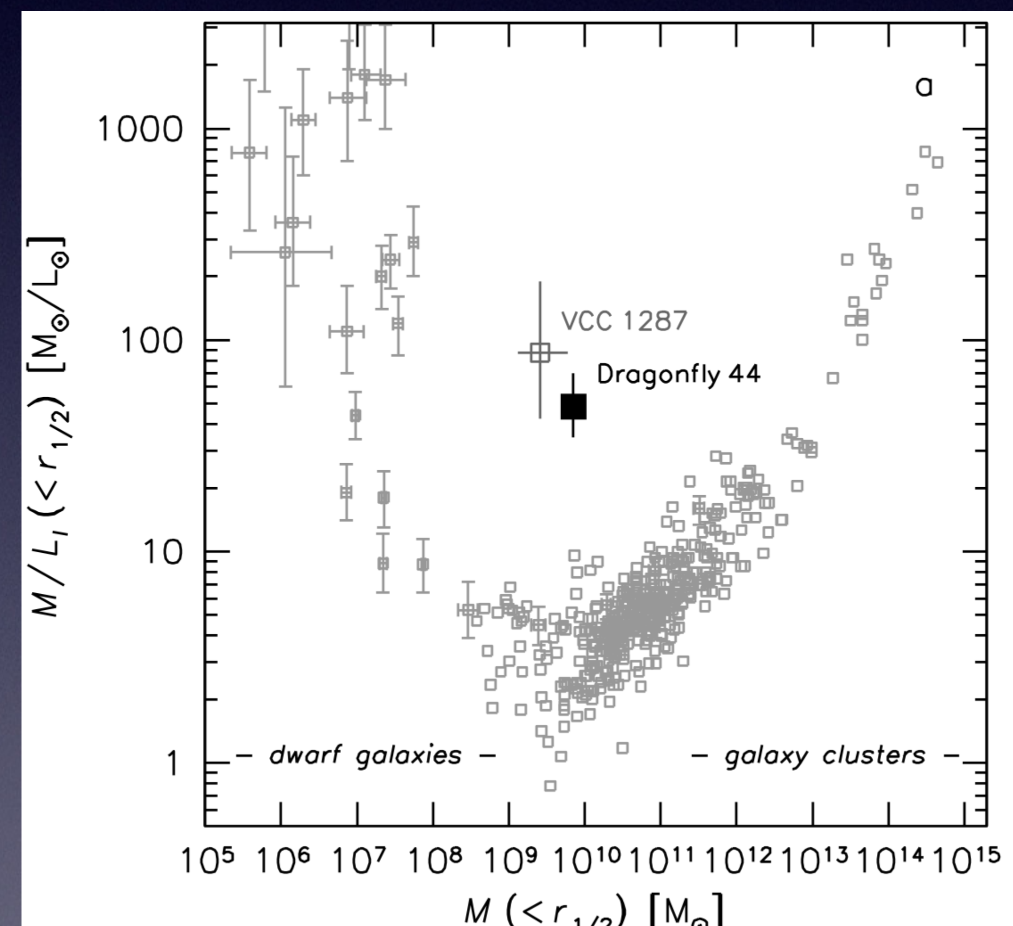
Dragonfly 44, discovery of a milky-way sized dark galaxy

1606.06291

A HIGH STELLAR VELOCITY DISPERSION AND ~ 100 GLOBULAR CLUSTERS FOR THE ULTRA DIFFUSE GALAXY DRAGONFLY 44

PIETER VAN DOKKUM[1], ROBERTO ABRAHAM[2], JEAN BRODIE[3], CHARLIE CONROY[4], SHANY DANIELI[1], ALLISON MERRITT[1], LAMIYA MOWLA[1], AARON ROMANOWSKY[3,5], JIELAI ZHANG[2]



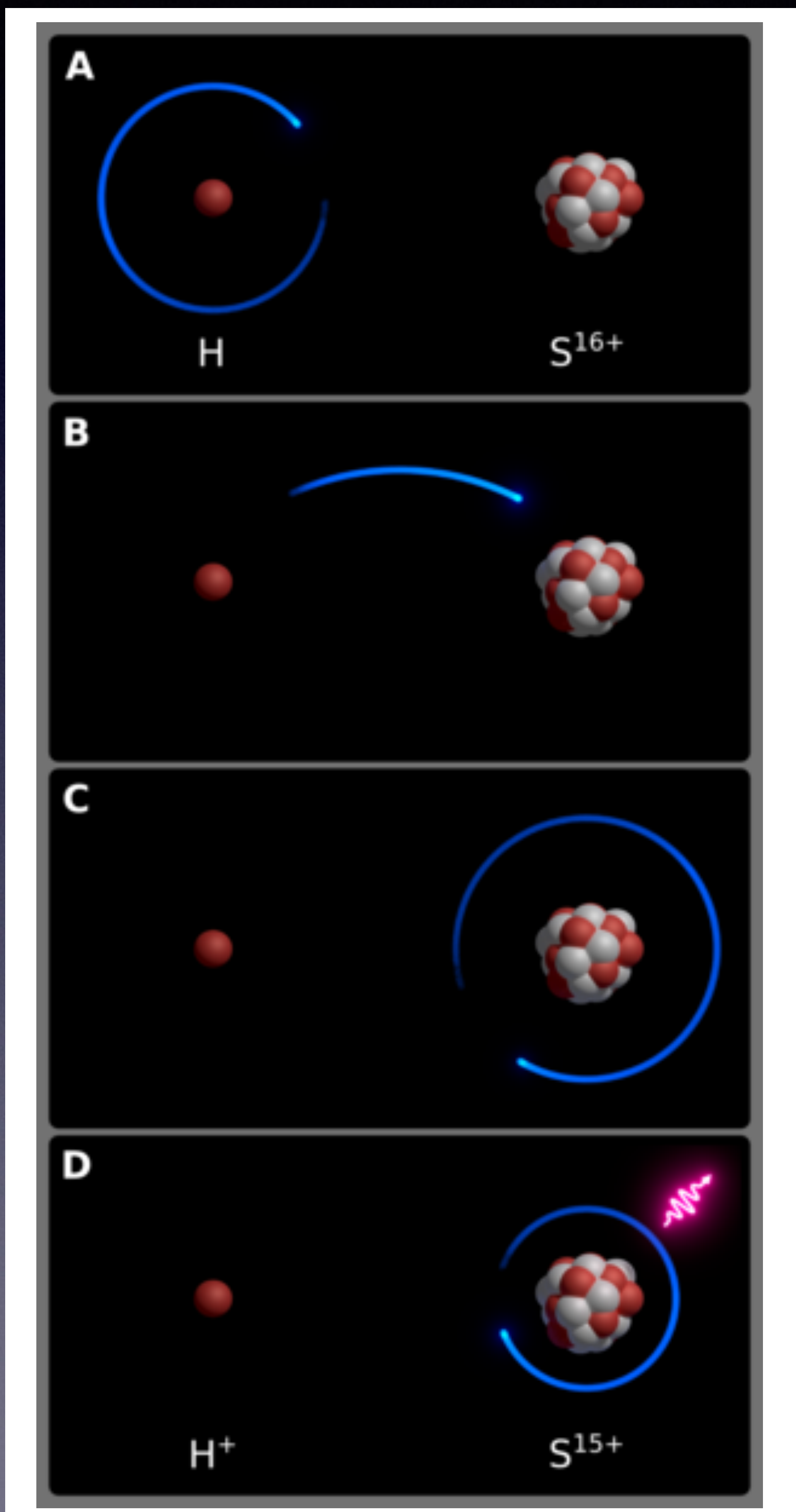


cracy between concentration and derived halo mass (see, e.g., Taylor et al. 2015). The observed enclosed mass of Dragonfly 44 suggests a halo mass of $M_{\rm halo}(<r_{200}) \approx 8\times10^{11}\,{\rm M}_\odot$, if the halo has an average concentration and no truncation (see,

be considered "failed" LMCs or M33s, the more massive Dragonfly 44 can be viewed as a failed Milky Way. This distinction is potentially important: it is the accepted view that

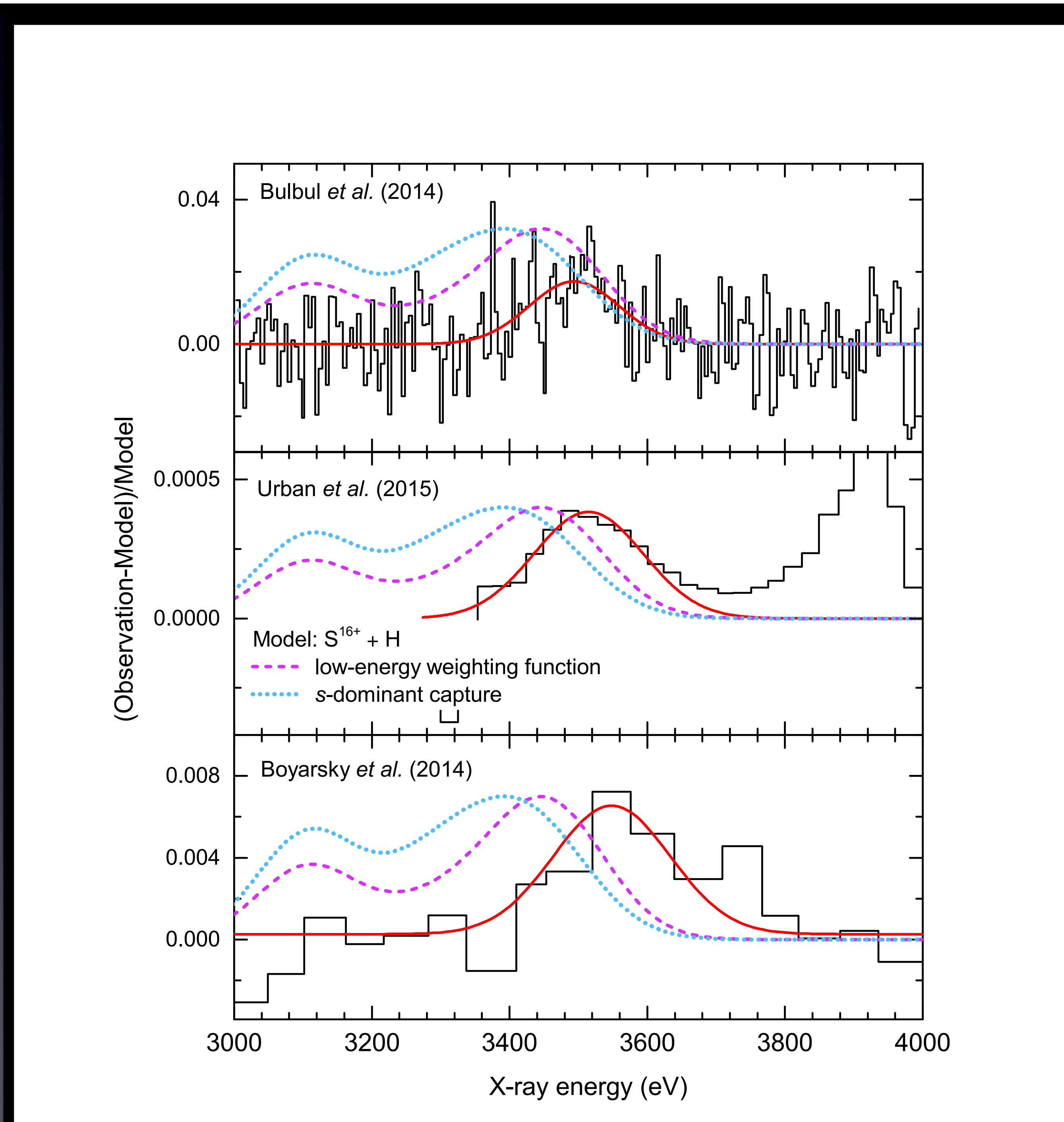
Charge exchange explains the 3.5 keV line mystery

1609.04751



LABORATORY MEASUREMENTS COMPELLINGLY SUPPORT CHARGE-EXCHANGE MECHANISM FOR THE 'DARK MATTER' ~3.5 keV X-RAY LINE

Chintan Shah[1,*], Stepan Dobrodey[1], Sven Bernitt[1,2], René Steinbrügge[1,†], José R. Crespo López-Urrutia[1], Liyi Gu[3], Jelle Kaastra[3,4]



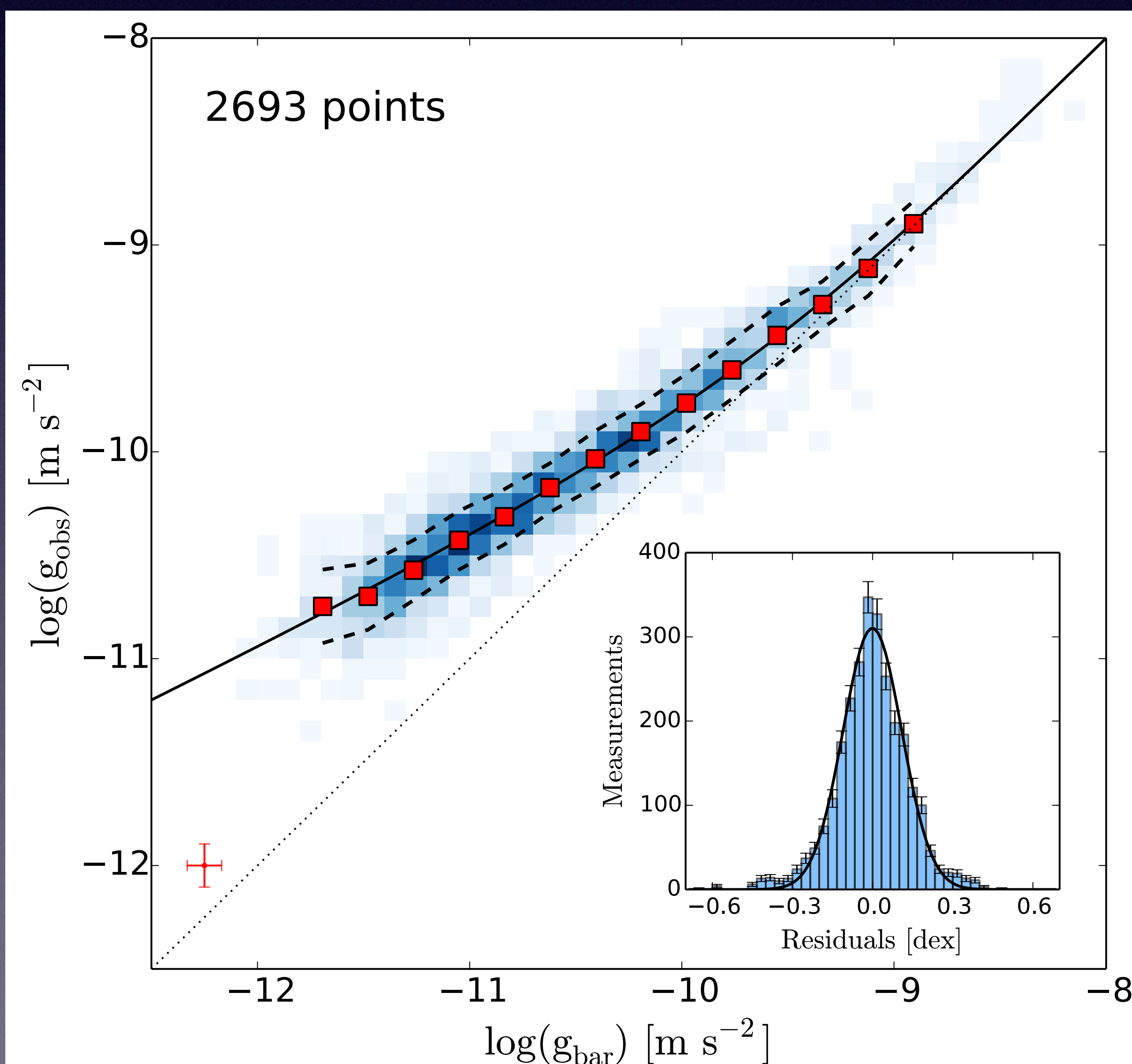
Baryonic-dark matter interaction?

1609.05917

The Radial Acceleration Relation in Rotationally Supported Galaxies

Stacy S. McGaugh and Federico Lelli
Department of Astronomy, Case Western Reserve University,
10900 Euclid Avenue, Cleveland, OH 44106, USA

The analysis of rotation curves of 153 (!) galaxies shows a strong correlation between the baryonic acceleration and the dark component



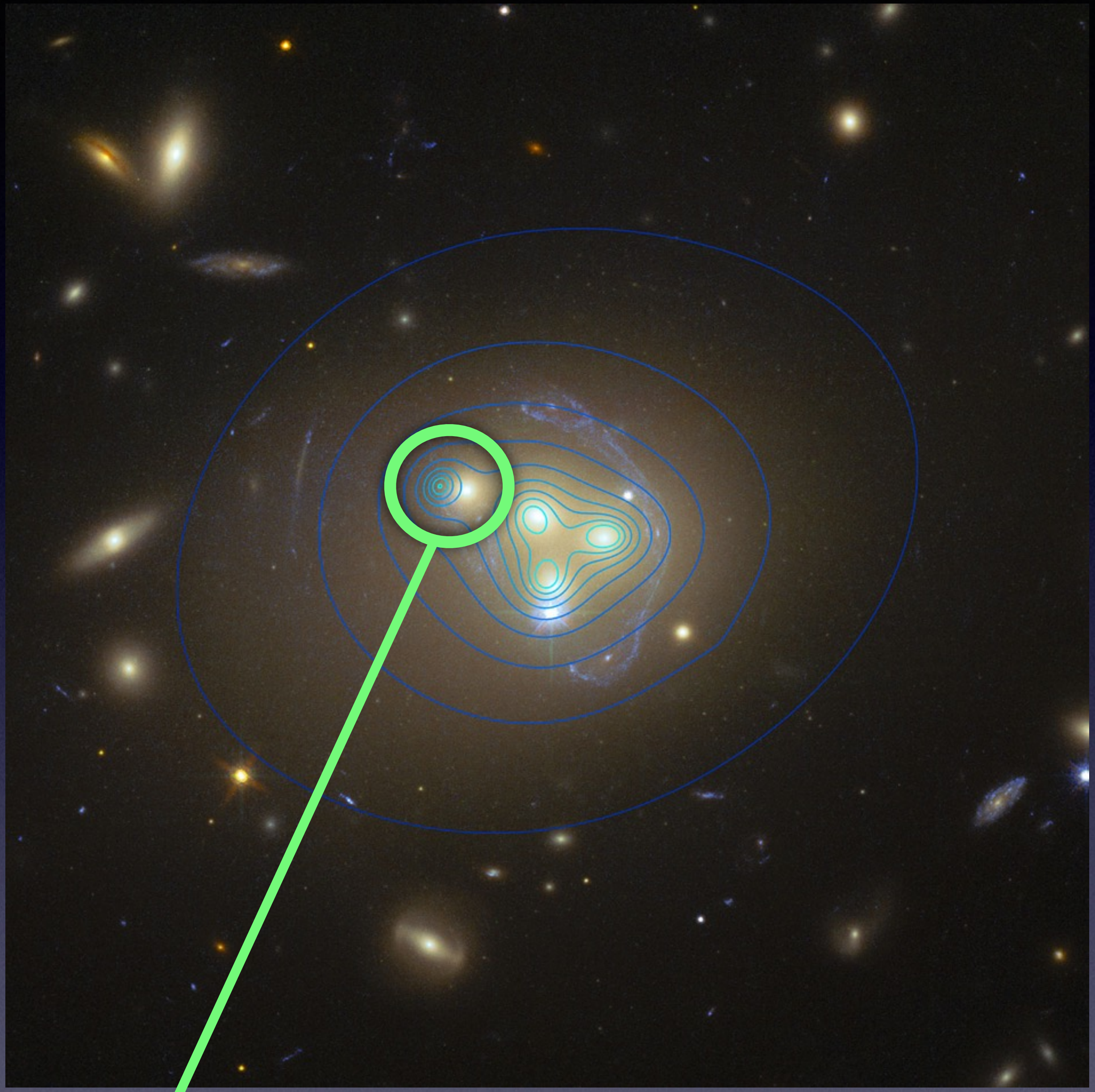
$$\nabla^2 \Phi_{\rm bar} = 4\pi G \rho_{\rm bar}$$

$$g_{\rm bar} = \left| \frac{\partial \Phi_{\rm bar}}{\partial R} \right| .$$

$$g_{\rm obs} = \mathcal{F}(g_{\rm bar}) = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_\dagger}}}$$

$$g_{\rm DM} = g_{\rm obs} - g_{\rm bar} = \frac{g_{\rm bar}}{e^{\sqrt{g_{\rm bar}/g_\dagger}} - 1} .$$

Self-interacting dark matter?



ESO 146-5 (ESO 146-IG 005) is the designation given to a group of interacting giant elliptical galaxies in the center of the Abell 3827 cluster. The group is well noted due to their strong gravitational lensing effect.

This group of interacting galaxies was found 1.4 billion light years away in the center of Abell 3827. A huge halo of stars is surrounding their interacting nuclei.

In 2015, Massey *et al.* [1504.03388] found an offset of 1.67 kpc between the center of the halo and its stars. Interpreting as self interacting DM they obtained:

$$\sigma/m \sim (1.7 \pm 0.7) \times 10^{-4} \left(\frac{t_{\rm infall}}{10^9 \text{ yrs}}\right)^{-2} \text{cm}^2/\text{g}.$$

Massey *et al.* obtained a *lower limit* because the clusters have interacted

Building a model of self-interaction

The difficulties to build a microscopical model of self-interacting dark matter is coming from the order of magnitude of the cross section measurable in this context:

$$\sigma/m \simeq (10^{-5} - 2)\ \mathrm{cm^2 g^{-1}} \simeq (0.05 - 9000)\ \mathrm{GeV^{-3}}$$

For a WIMP, one expects:

$$\sigma_{wimp}/m_{wimp} \simeq 10^{-11}\mathrm{GeV^{-3}}$$

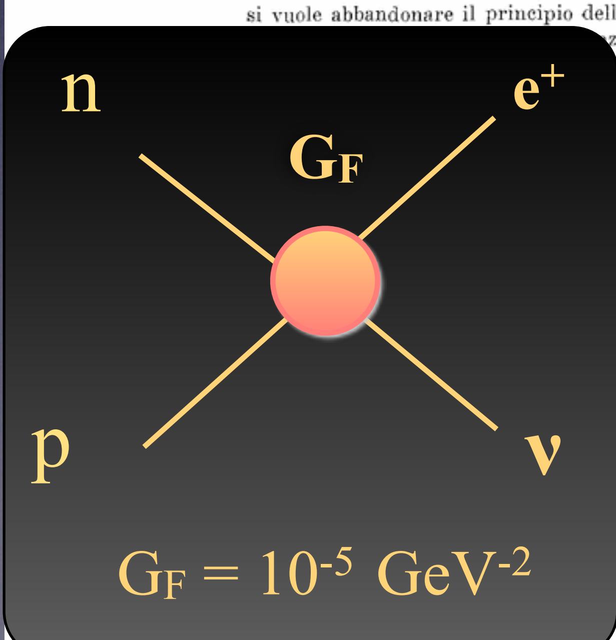
We understand then the need to go « beyond » the WIMP paradigm. One needs a strongly coupled dark matter (a « dark colored » sector ») or one can invoke velocity enhancement « à la » Sommerfeld. There exist a third way, which is to look for mightier dark matter candidates.

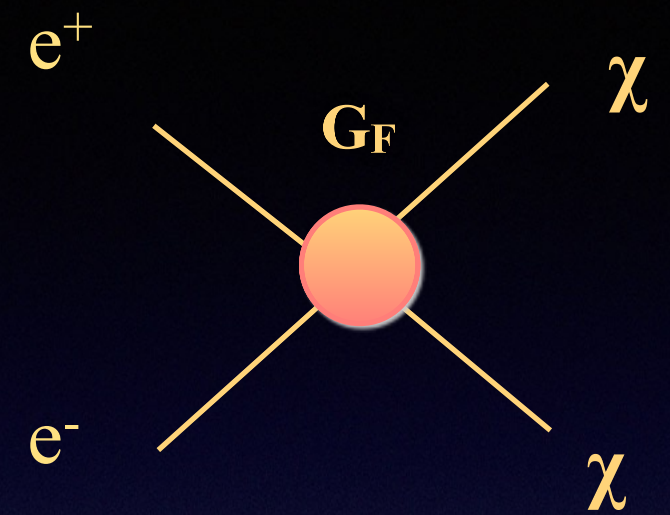
4

Model building consequences

The pure effective approach « a la Fermi »

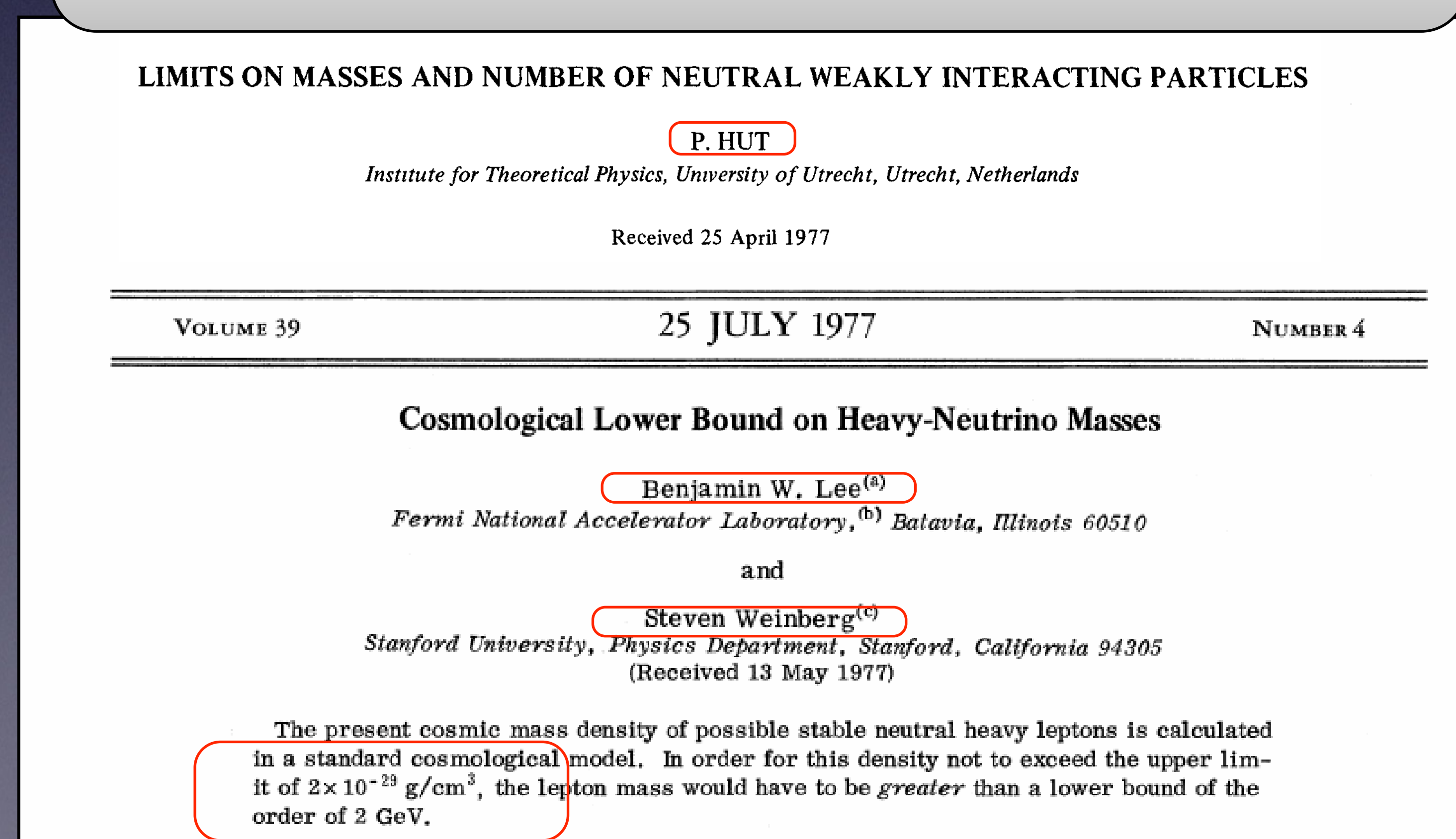
Application: the Zeldovich-Hut-Lee-Weinberg bound





The (Hut-)Lee-Weinberg bound (1977)

$$\langle\sigma v\rangle = G_F^2 m_\chi^2 > 10^{-9}\ \mathrm{GeV}^{-2} \quad \Rightarrow \quad m_\chi > 2\ \mathrm{GeV}$$



LIMITS ON MASSES AND NUMBER OF NEUTRAL WEAKLY INTERACTING PARTICLES

P. HUT

Institute for Theoretical Physics, University of Utrecht, Utrecht, Netherlands

Received 25 April 1977

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Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]

Fermi National Accelerator Laboratory,[b] Batavia, Illinois 60510

and

Steven Weinberg[c]

Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

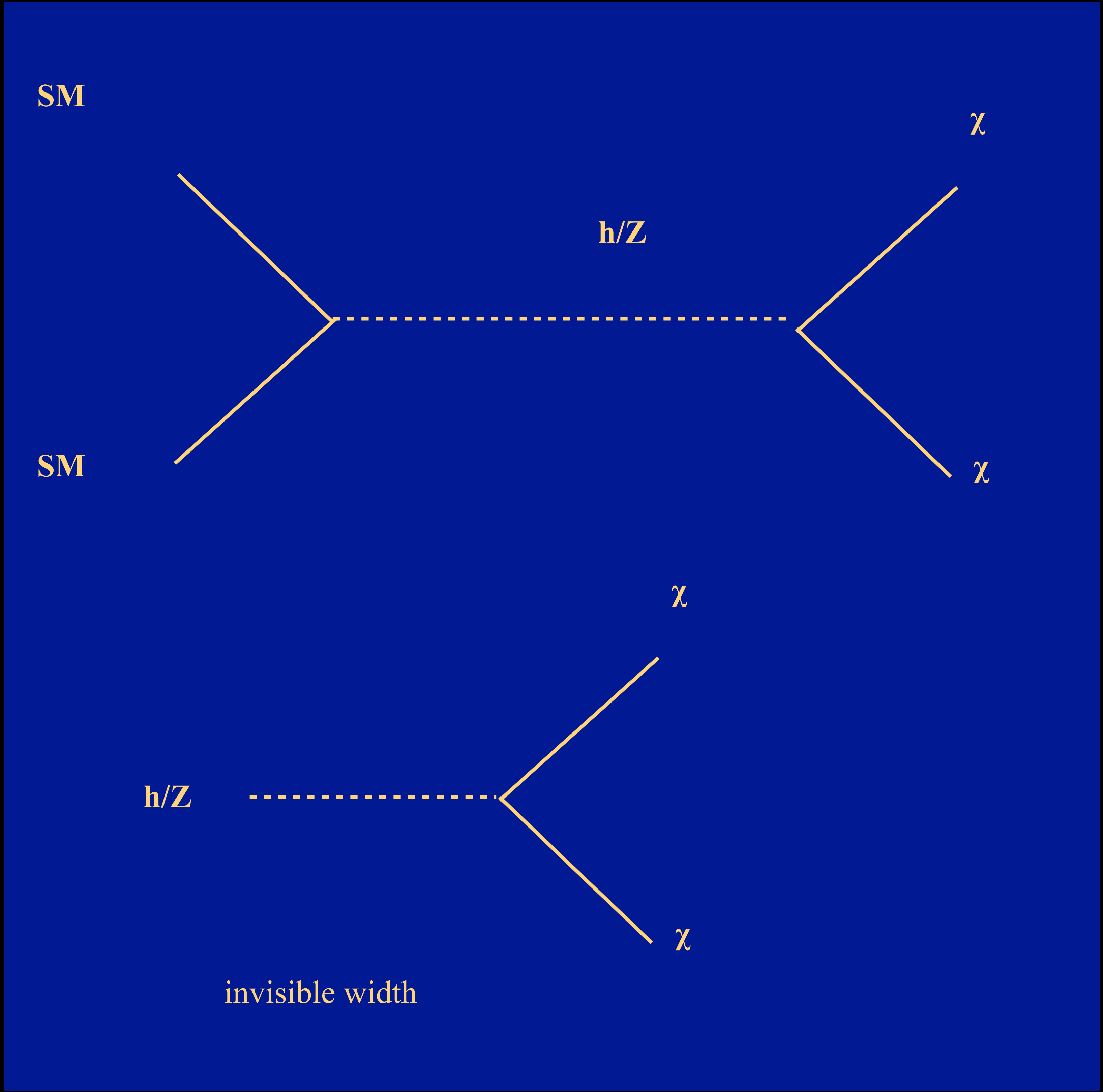
Developing a microscopical approach

On which principle should we extend the microscopic interaction?

Ockham, in Cambridge
13th century

Ockham's razor (*lex parsimoniae*) principle :
« Pluralitas non est ponenda sine necessitate »
Among competing hypotheses, the one with the fewest assumptions should be selected
(everything should be made as simple as possible..)

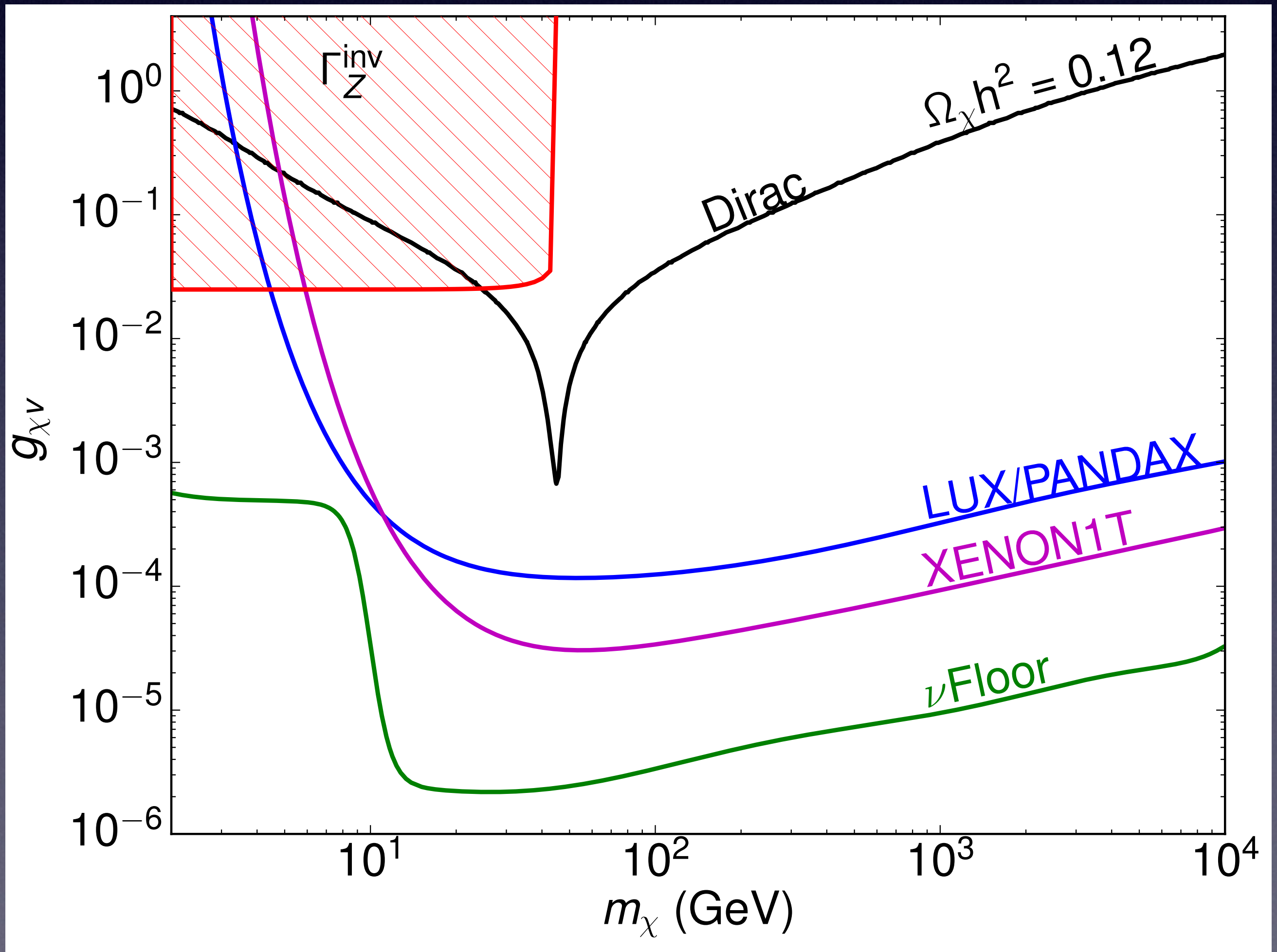
Dark matter couple only with the Standard Model (SM) particles : Higgs-portal, Z-portal, sterile neutrino. Consequences on observables are strong:
Invisible width of the Higgs/Z, LHC/LEP production in the case of portal models, instability and production of monochromatic photons in the case of sterile neutrino.


SM
χ
h/Z
SM
χ
χ
h/Z
χ
invisible width

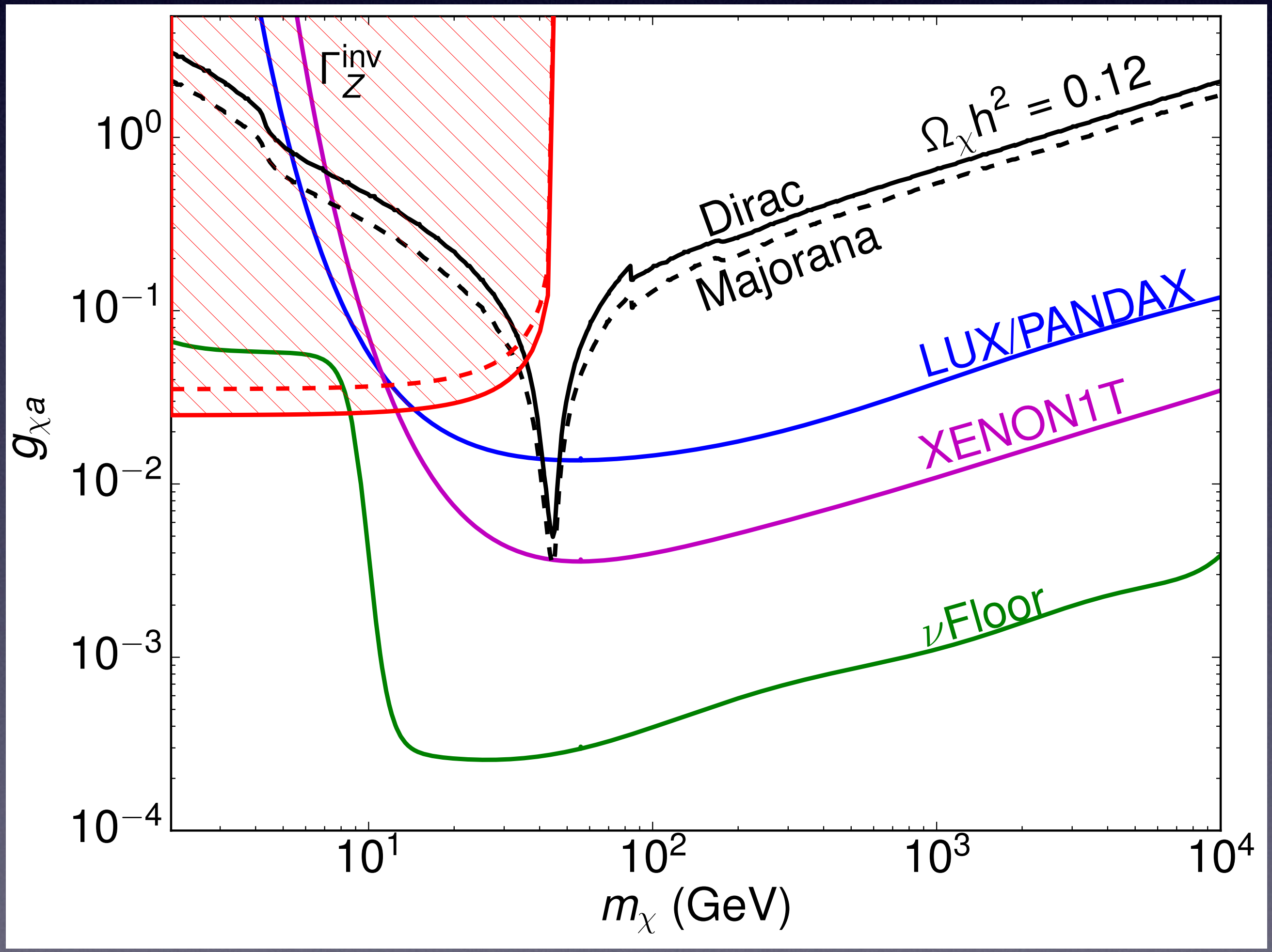
Z-portal : fermionic DM

$$\mathcal{L} \supset \left[a\bar{\chi}\gamma^{\mu}(g_{\chi v} + g_{\chi a}\gamma^5)\chi\right] Z_{\mu},$$

Vectorial coupling



Axial coupling

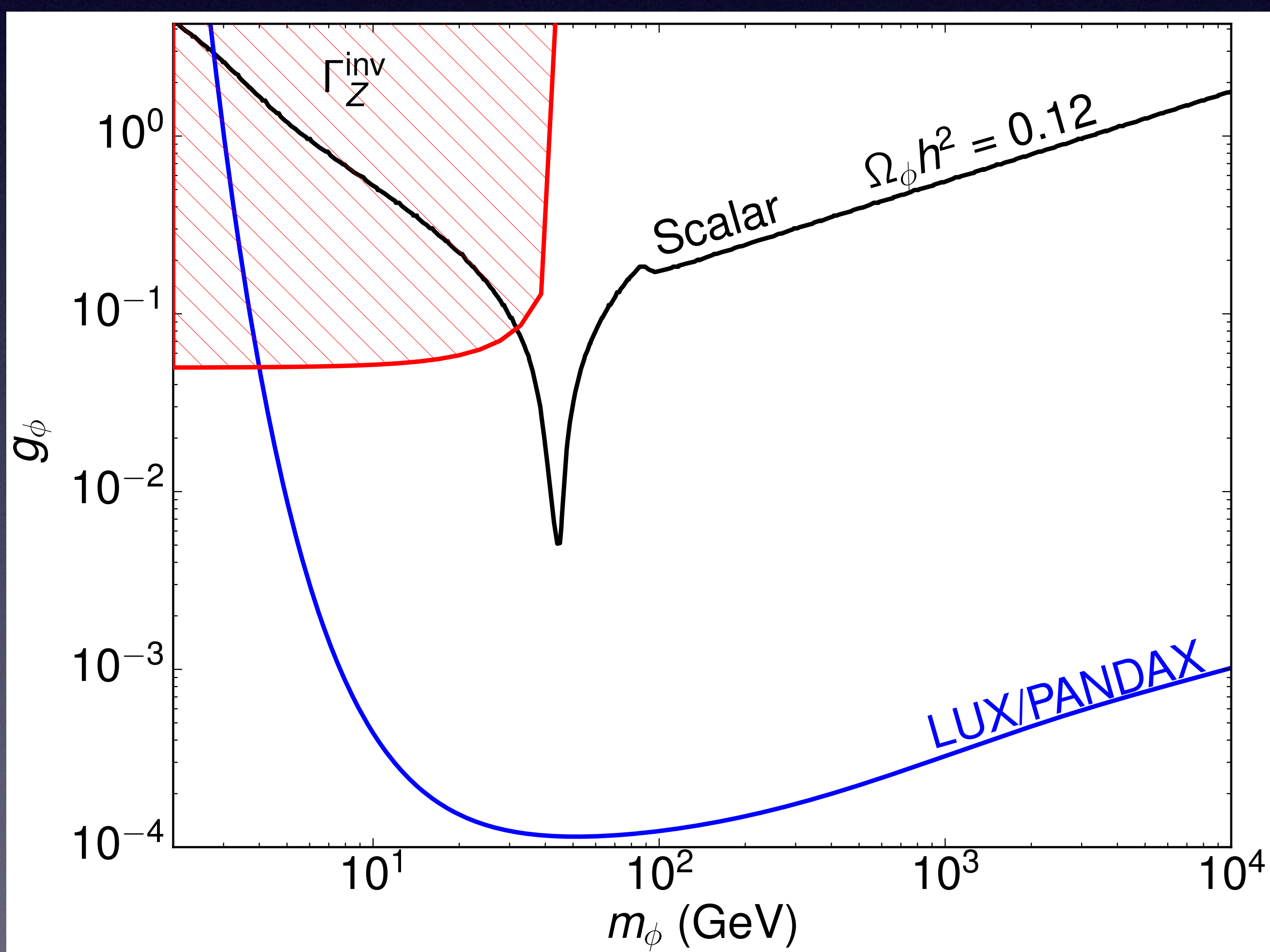


Esudero et al. 1609.09079

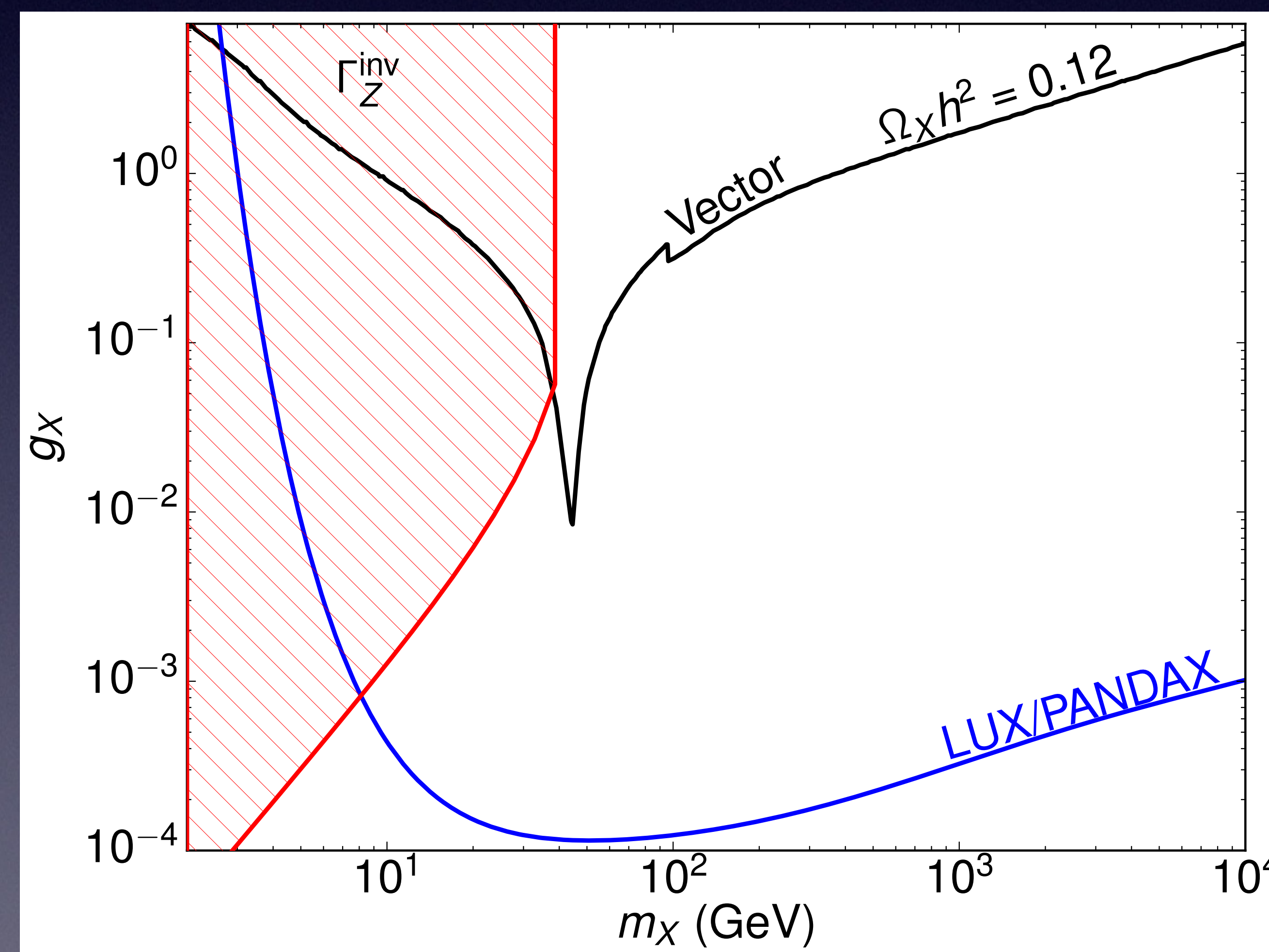
Z-portal : scalar/vectorial DM

$$\mathcal{L} \supset i\, g_\phi \phi^\dagger \overleftrightarrow{\partial}_\mu \phi Z^\mu + g_\phi^2 \phi^2 Z^\mu Z_\mu.$$

Scalar DM



Vectorial DM

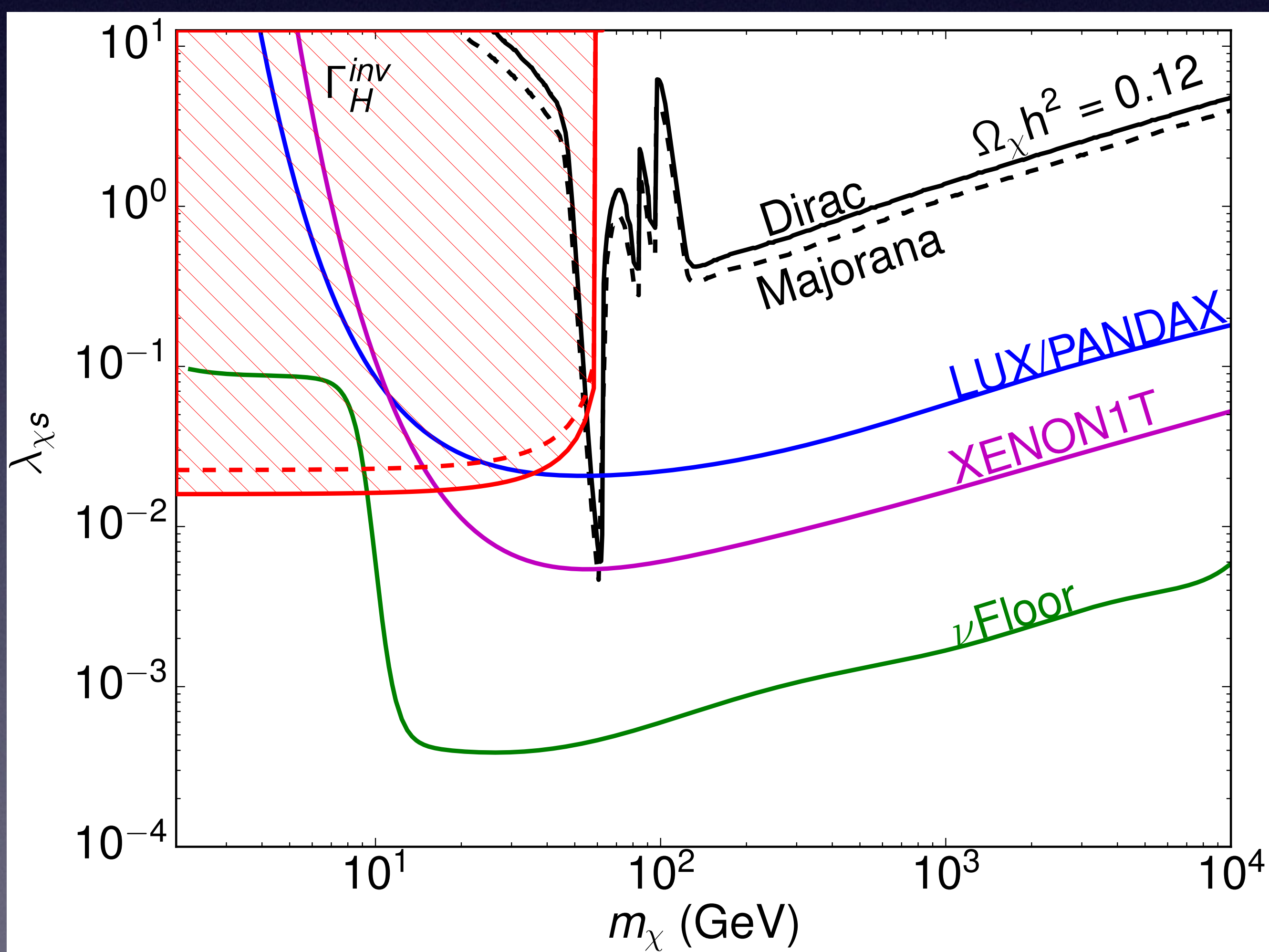


Esudero et al. 1609.09079

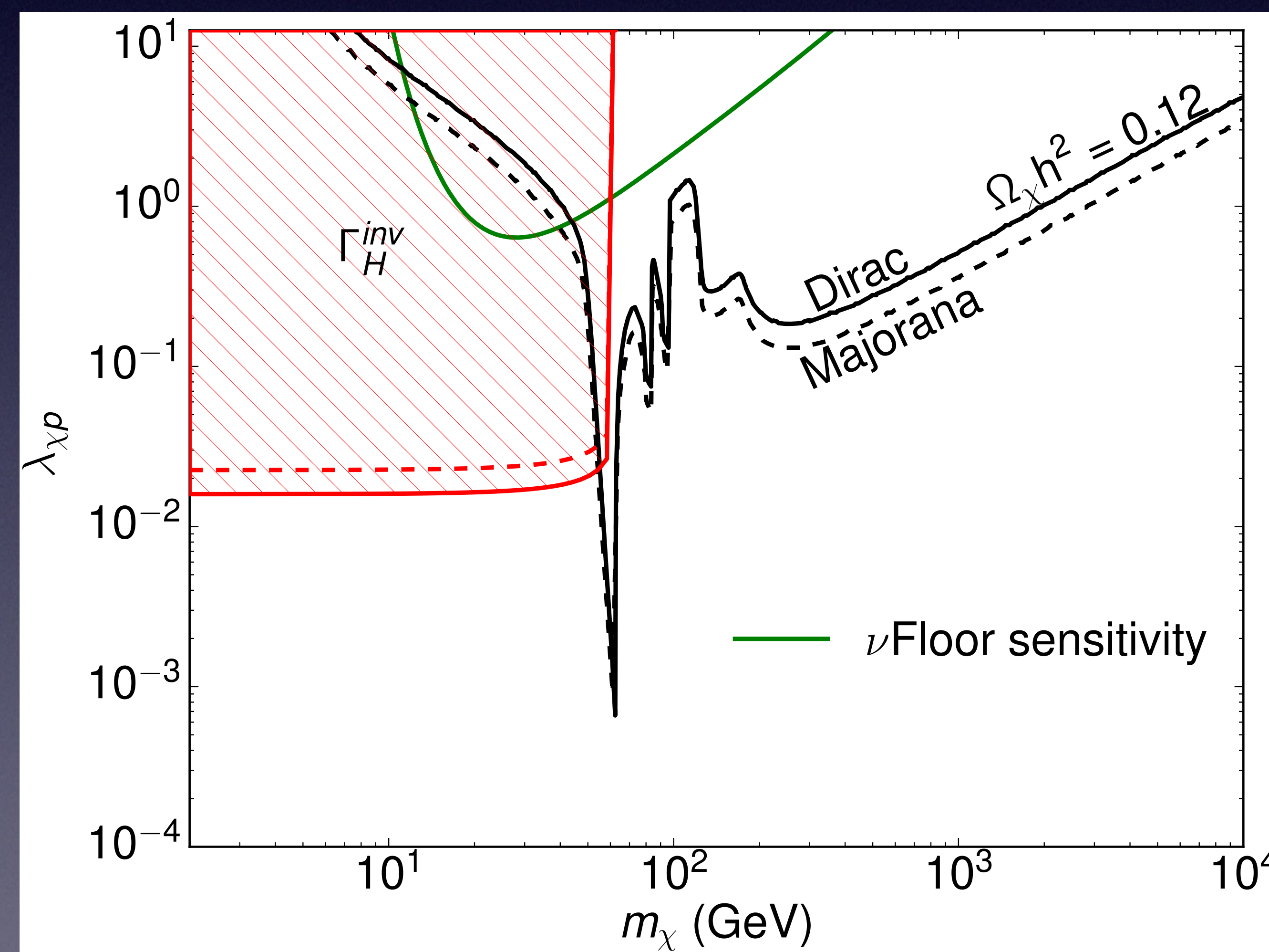
Higgs-portal : fermionic DM

$$\mathcal{L} \supset \left[a\bar{\chi}(\lambda_{\chi s} + \lambda_{\chi p} i\gamma^5)\chi\right] H,$$

Scalar coupling



pseudoscalar coupling



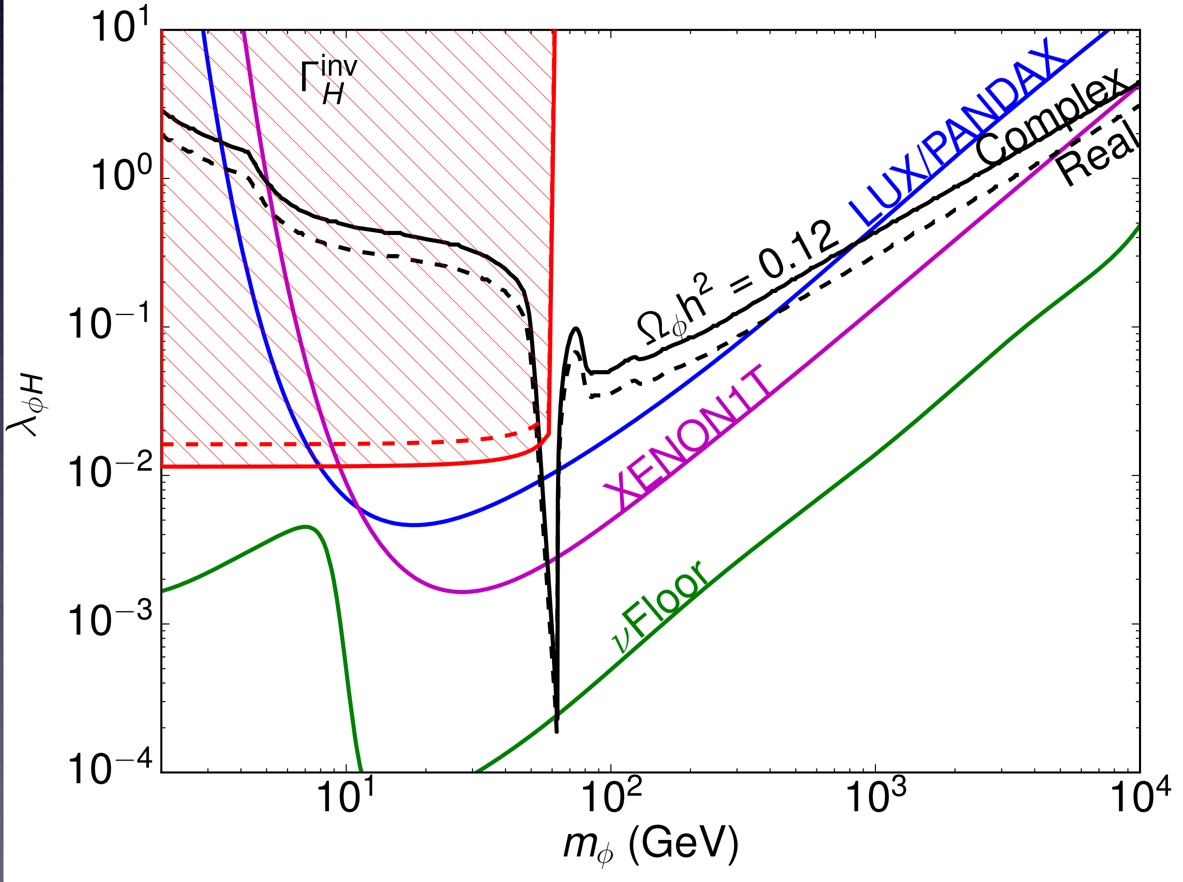
Esudero et al. 1609.09079

Higgs-portal : scalar/vectorial DM

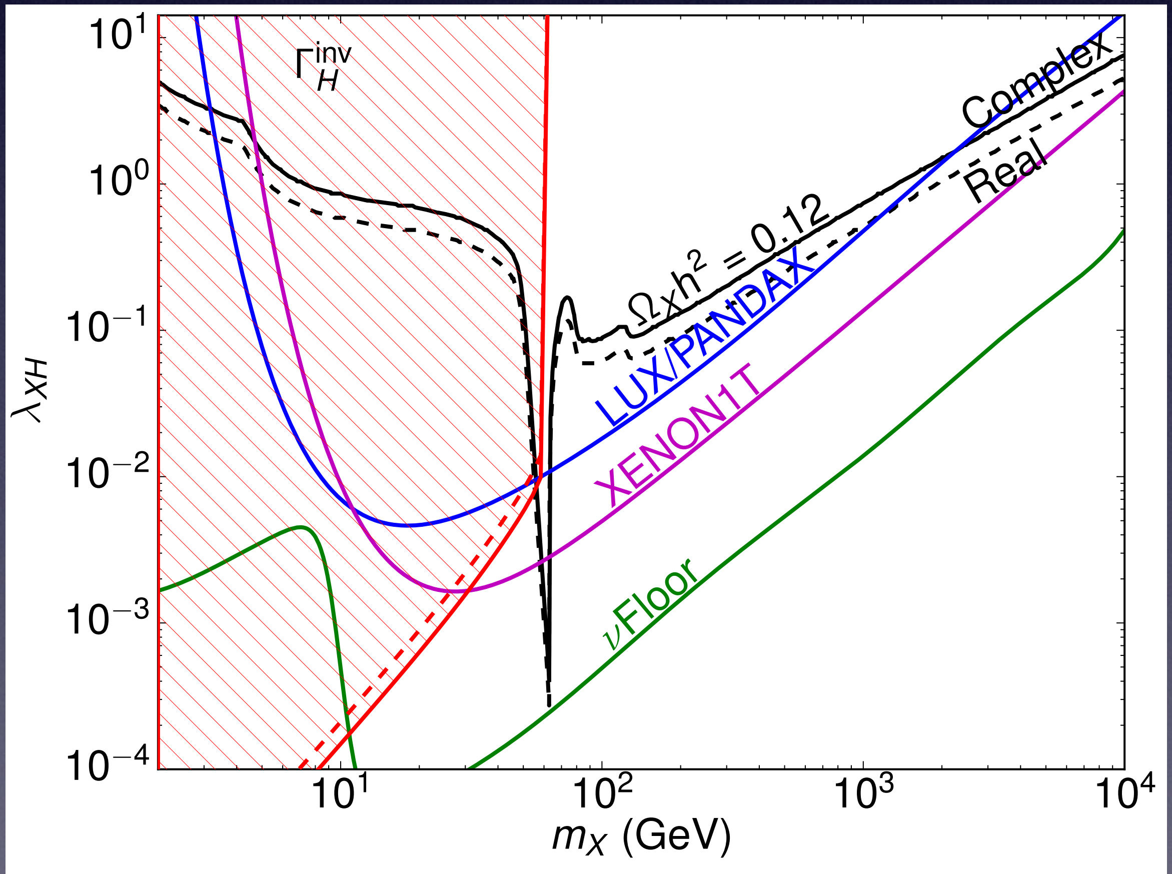
$$\mathcal{L} \supset a\,\lambda_{\phi H}\left[vH\phi^2 + \frac{1}{2}H^2\phi^2\right],$$

$$\mathcal{L} \supset a\lambda_{XH}\left[vHX^\mu X^\dagger_\mu + \frac{1}{2}H^2X^\mu X^\dagger_\mu\right]$$

Scalar DM



Vectorial DM



Esudero et al. 1609.09079

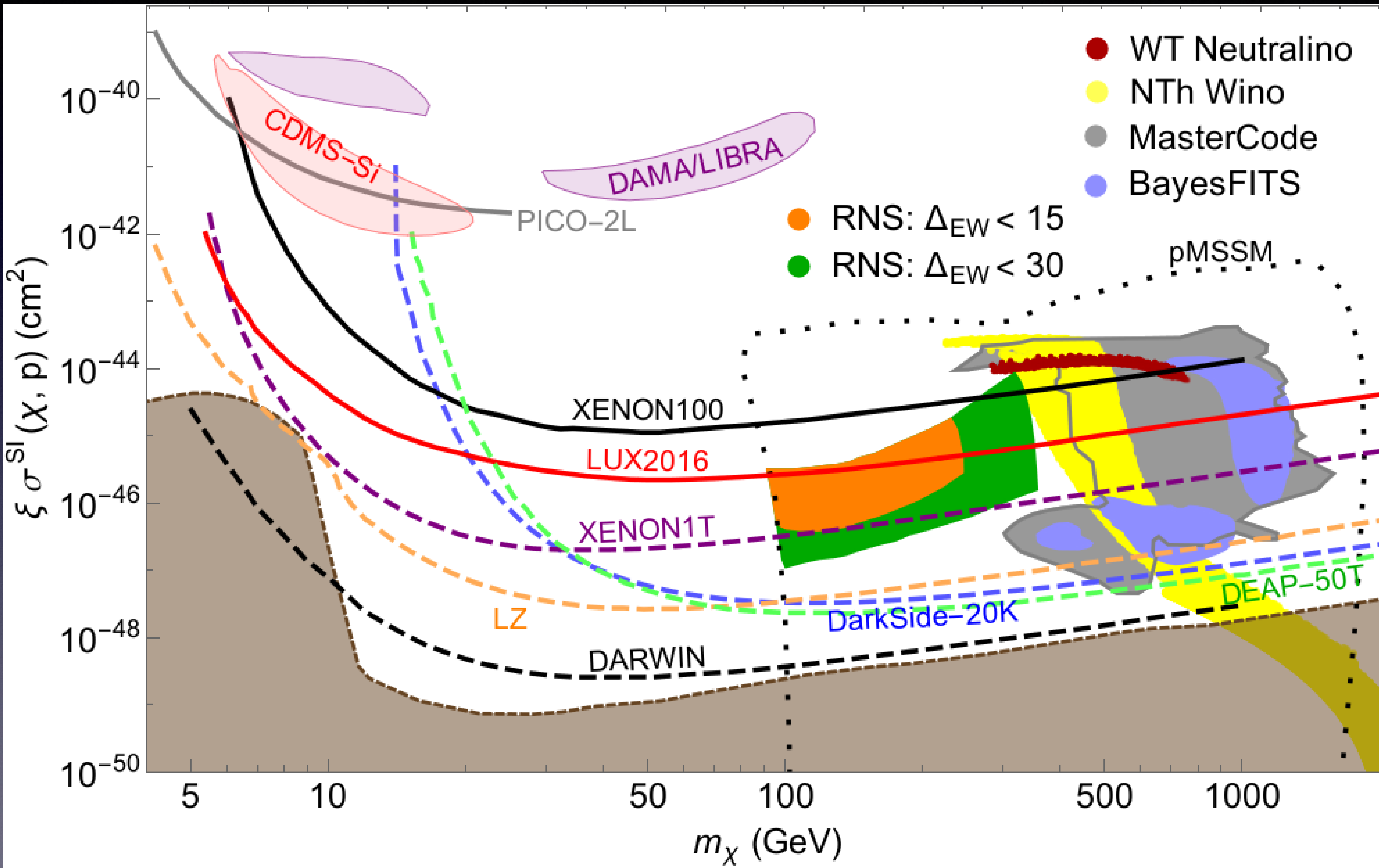
Summary

The only scenarios that are **not excluded** are those in which the dark matter is a **scalar** (**vector**) **heavier than 400 GeV** (**1160 GeV**) with a **Higgs portal** coupling, or a **fermion** with a **pseudoscalar** (CP violating) **coupling** to the Standard Model Higgs boson. **With the exception of dark matter with a purely pseudoscalar coupling** to the Higgs, it is anticipated that planned direct detection experiments **will probe the entire range of models**

And SUSY?

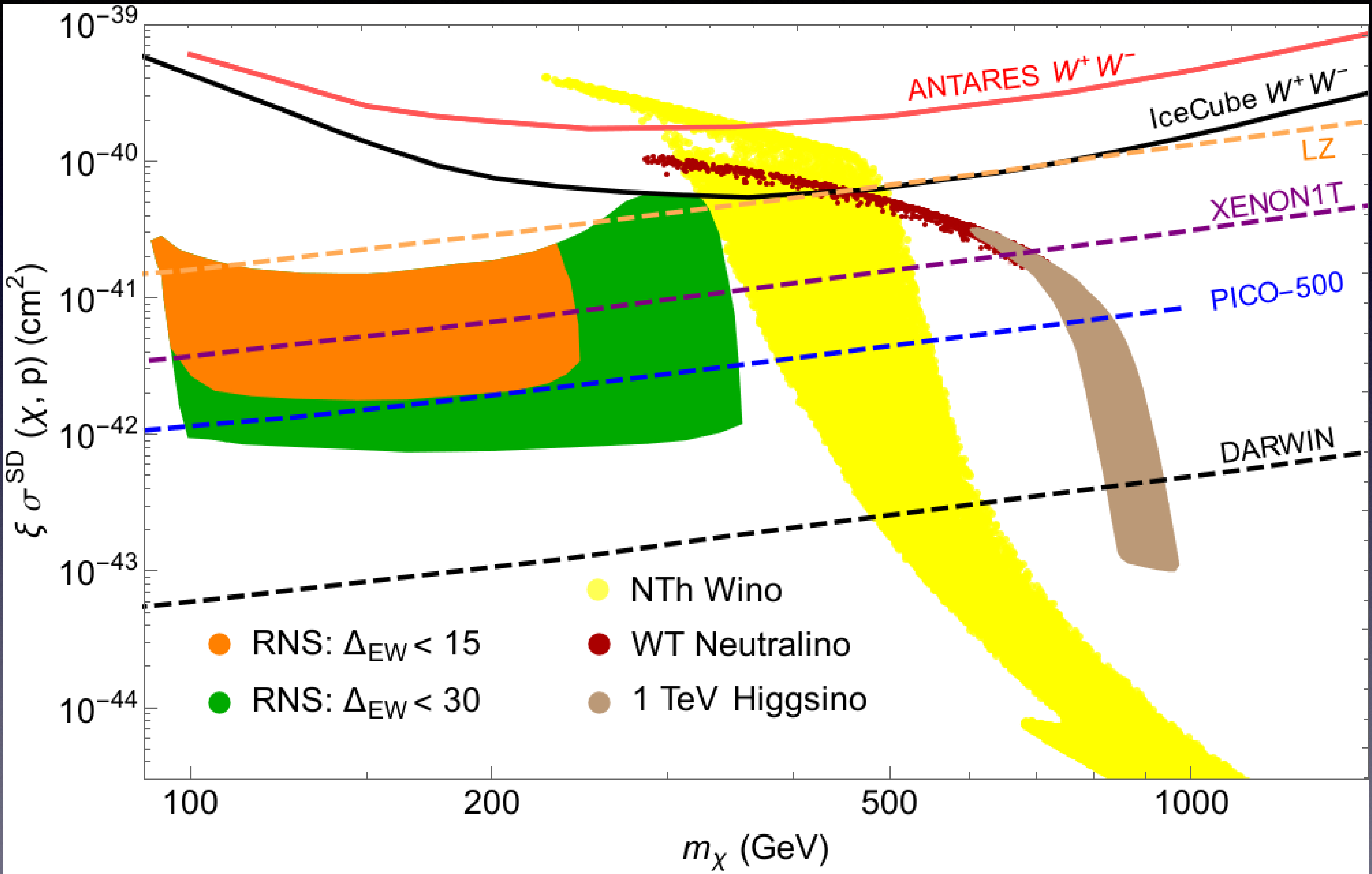
$$\chi_1^0 = c_B\ \tilde{B} + c_W\ \tilde{W} + c_1\ \tilde{H}_1 + c_2\ \tilde{H}_2$$

Spin Independant Direct Detetction



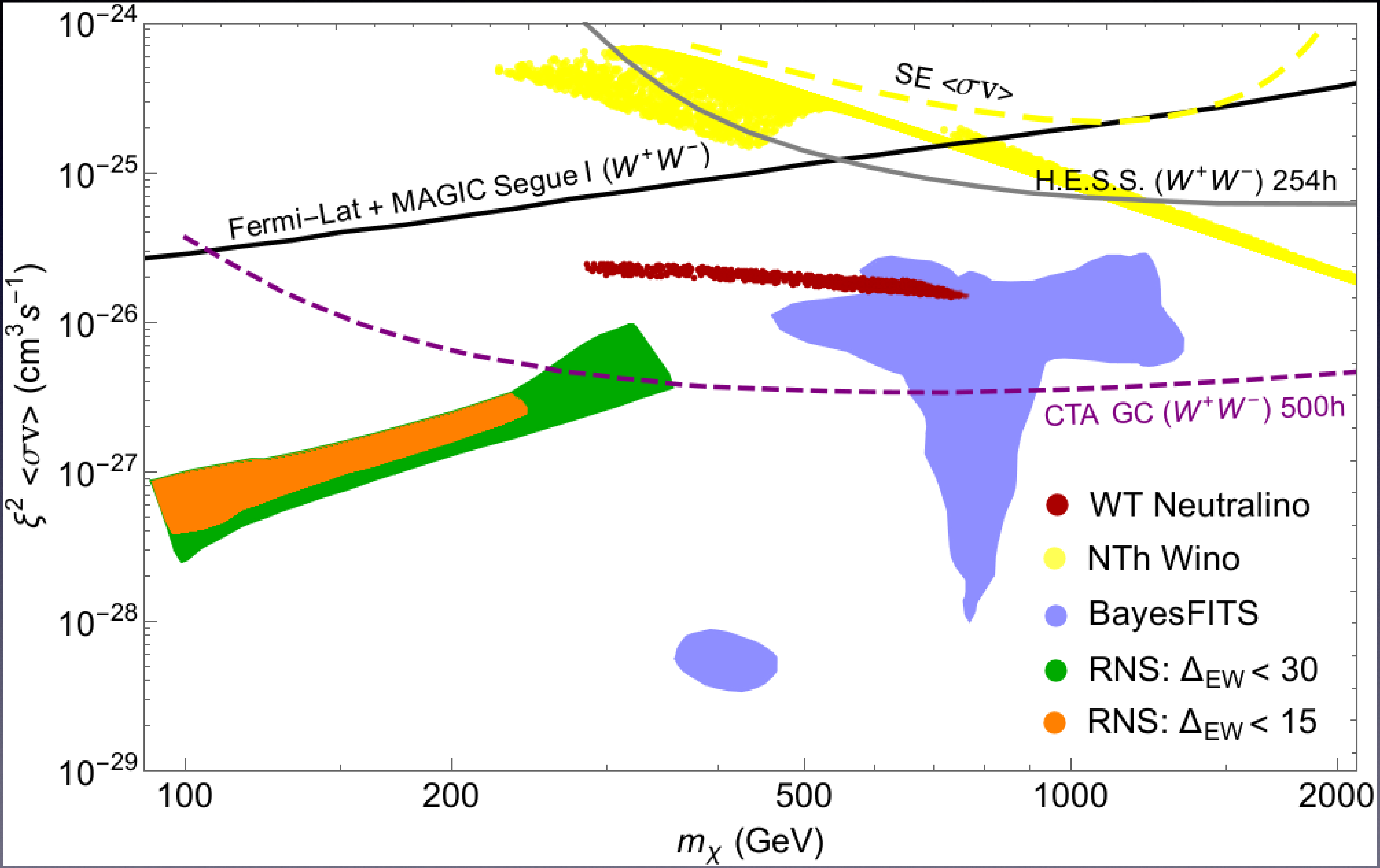
Baer et al. 1609.06735

Spin Dependant



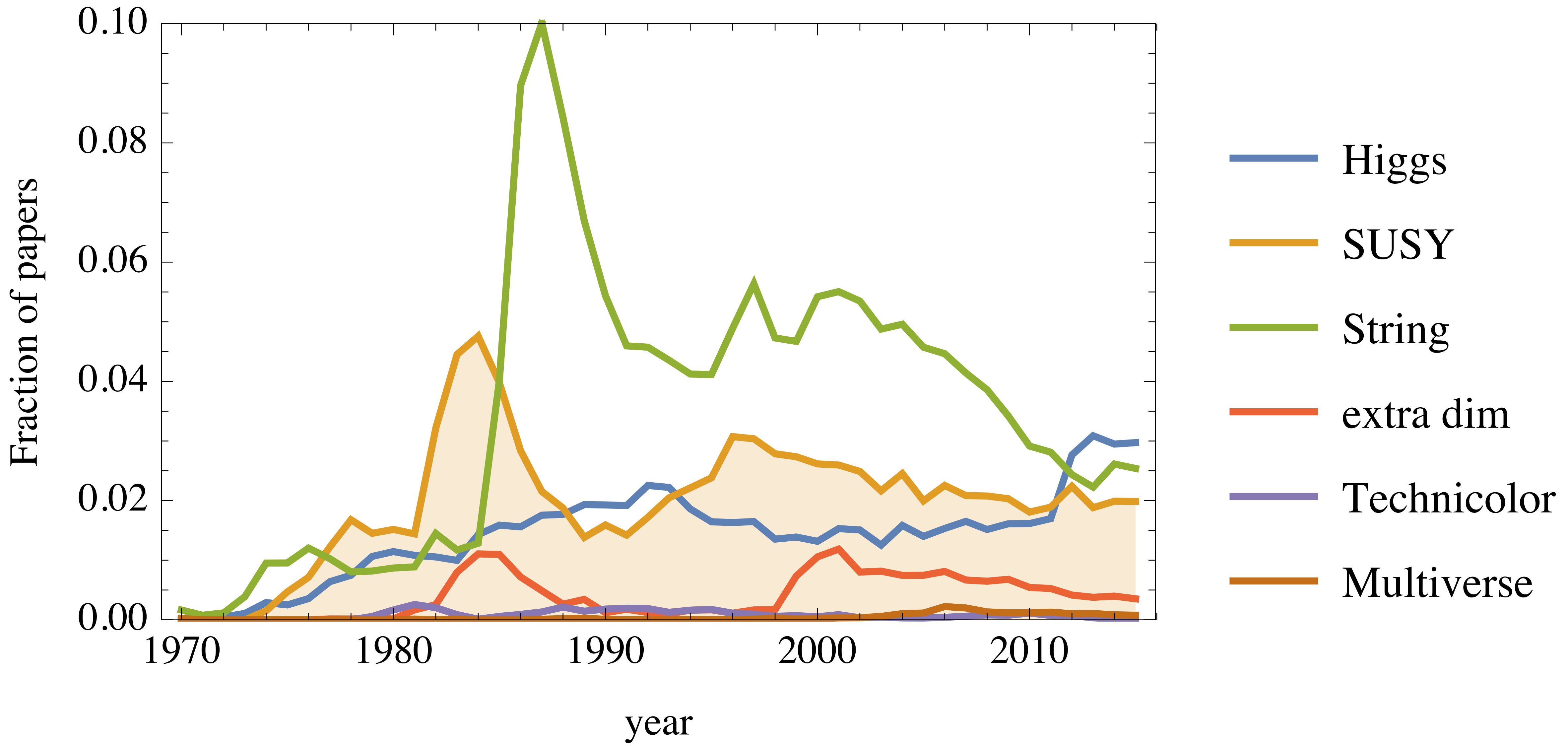
Baer et al. 1609.06735

Indirect Detection



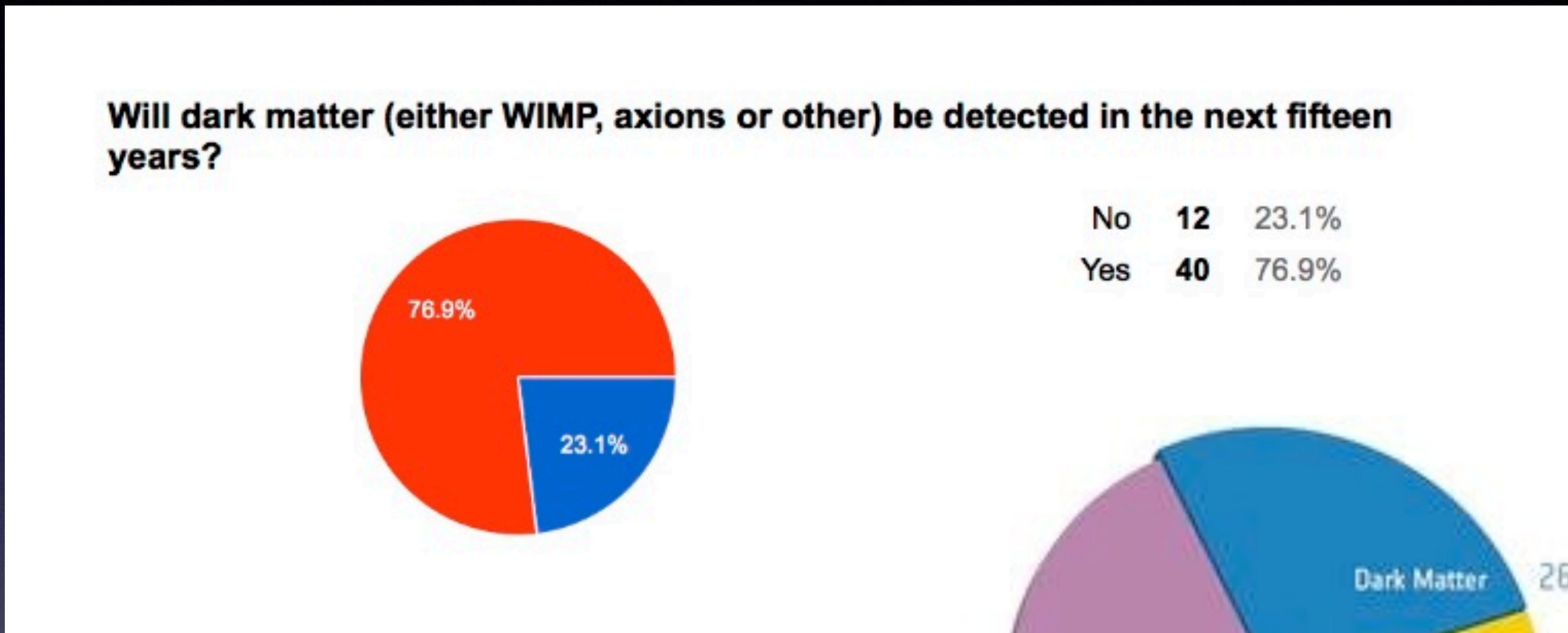
Baer et al. 1609.06735

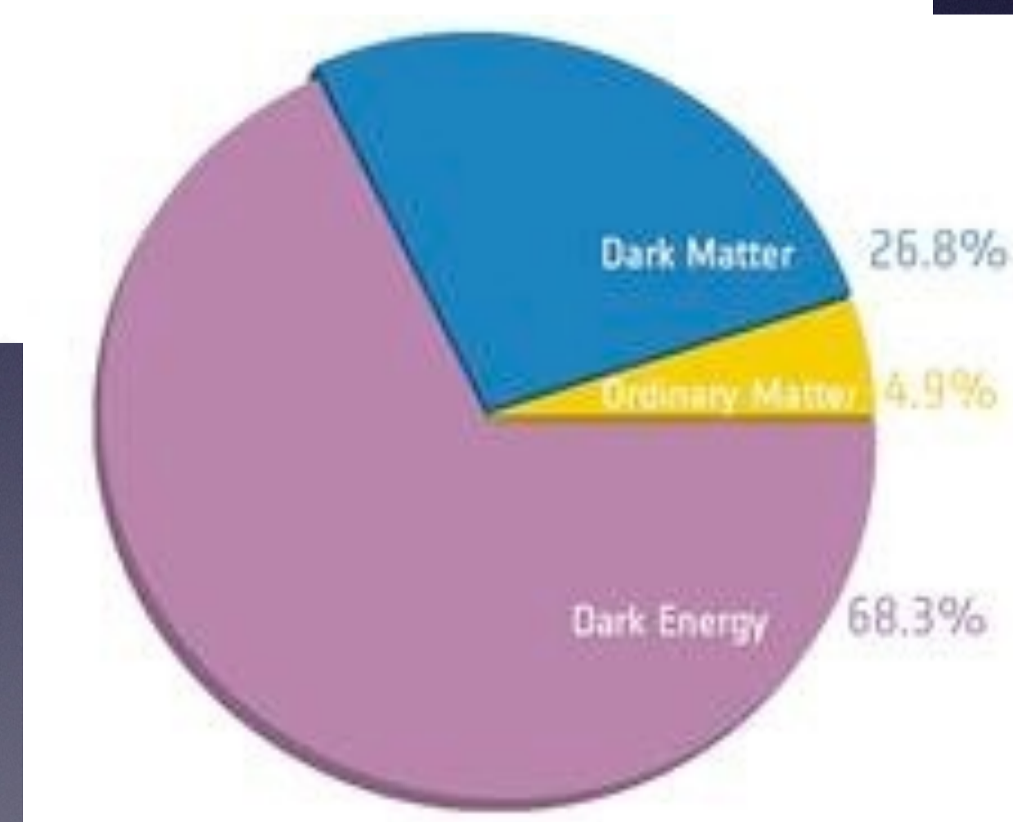
Is SUSY alive?
Not so well, but at least still popular..



Strumia talk, Madrid, September 2016

Pool at IFT workshop, September 2016





At least optimism…

Conclusion

« Prediction is very difficult, especially if it's about the future »

Niels Bohr

```
n_{e^-} + n_{e^+} = 0 ~ ; ~~ n_{\nu} + n_{\bar \nu} = \frac{1}{2} n_{\gamma}


\frac{\ddot a}{a} = - \frac{4 \pi G}{3}  \rho ~\Rightarrow ~ q(t) = - \frac{1}{H^2} \frac{\ddot a}{a} = \frac{4 \pi
G}{3 H^2} \rho
\\
= \frac{1}{2} \frac{\rho}{\rho_c}= \frac{1}{2} \Omega,
 ~~~~~~ \mathrm{with} ~ H^2 = \frac{8 \pi G}{3} \rho_c


n(T_f) \langle \sigma v \rangle = H(T_f) ~~ \Rightarrow ~~\left(T_f m \right)^{3/2} e^{-m/T_f} \langle \sigma v
\rangle < \frac{T_f^2}{M_{Pl}} ~~\Rightarrow ~~ T_f=\frac{m}{\ln{M_{Pl}}} = \frac{m}{26}


\frac{dY}{dT} = \frac{T^2}{H(T)} \langle \sigma v \rangle Y^2 ~~\Rightarrow ~~ Y(T_{now}) = \frac{1}{M_{Pl} T_f
\langle \sigma v \rangle } = \frac{26}{M_{Pl} m \langle \sigma v \rangle }



\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26
\times 400~\mathrm{cm^{-3}}}{\rho_c M_{Pl} \langle \sigma v \rangle} < 1
~~~~~~~~
\Rightarrow \langle \sigma v \rangle > 10^{-9} h^{-2} ~\mathrm{GeV^{-2}}


\langle \sigma v \rangle \simeq G_F^2 m^2 > 10^{-9} ~\mathrm{GeV^{-2}} ~~\Rightarrow ~~ m > 2 ~\mathrm{GeV}
```

This **LIA** is a unique opportunity to strengthens our links and develop new directions of research in this future very (!!) exciting and bright future for our discipline..