Experimental Search for Dark Matter

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Part 1: Evidence and Characteristics

Introduction

Review of DM evidence and properties

Galaxy Clusters
Galactic Rotation Curves
Gravitational Lensing and X-ray surveys
Structure Formation
DM Candidates

Basic Principles of Direct Detection

Scattering Rates
Corrections
Spin Dependence

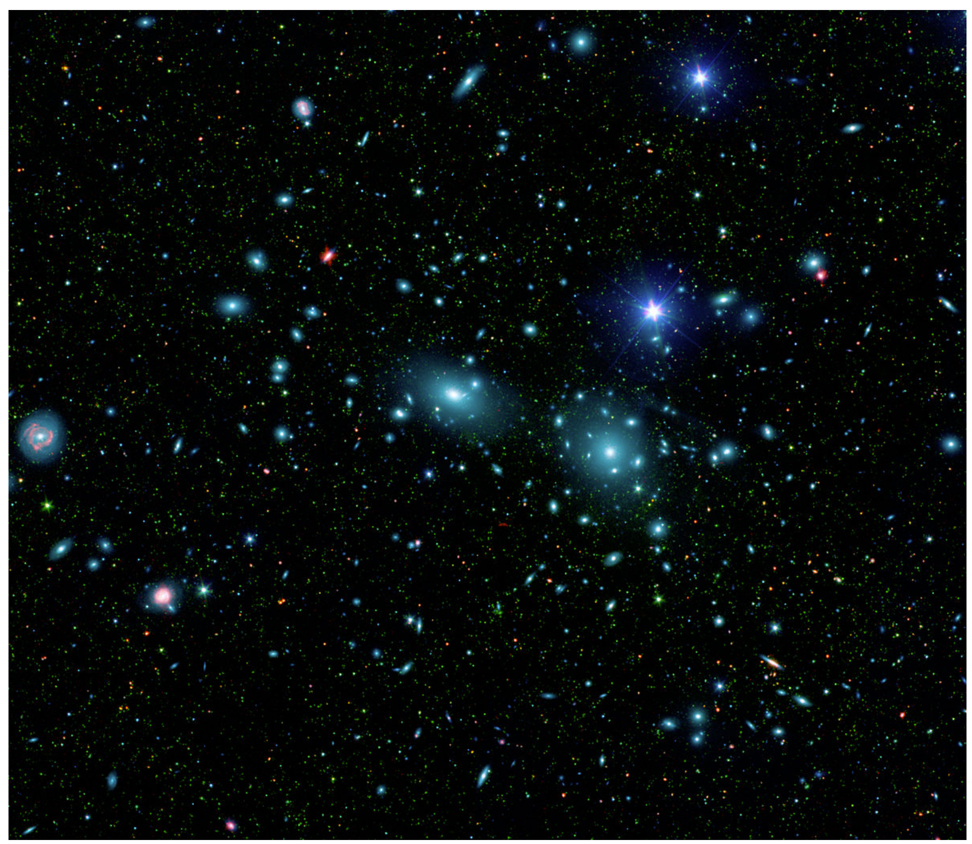
Experimental Techniques

Overview of the detection principles
Current experimental activity
Noble liquids, cryogenic detectors, bubble chambers
Accelerator-based DM production and detection

Evidence for DM: Galaxy Clusters

If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter.

F. Zwicky (1898-1974)



Coma Cluster

Virial Theorem $\langle E_{kin} \rangle = \frac{1}{2} \langle V_g \rangle$

R~1 Mly
M~109 Solar Masses

Estimate $\langle V_g \rangle = (3/5) GM/R$

implies $\sqrt{\langle v^2 \rangle} \approx 80\ \mathrm{km/s}$

To compare with ~1000km/s from Doppler measurements.

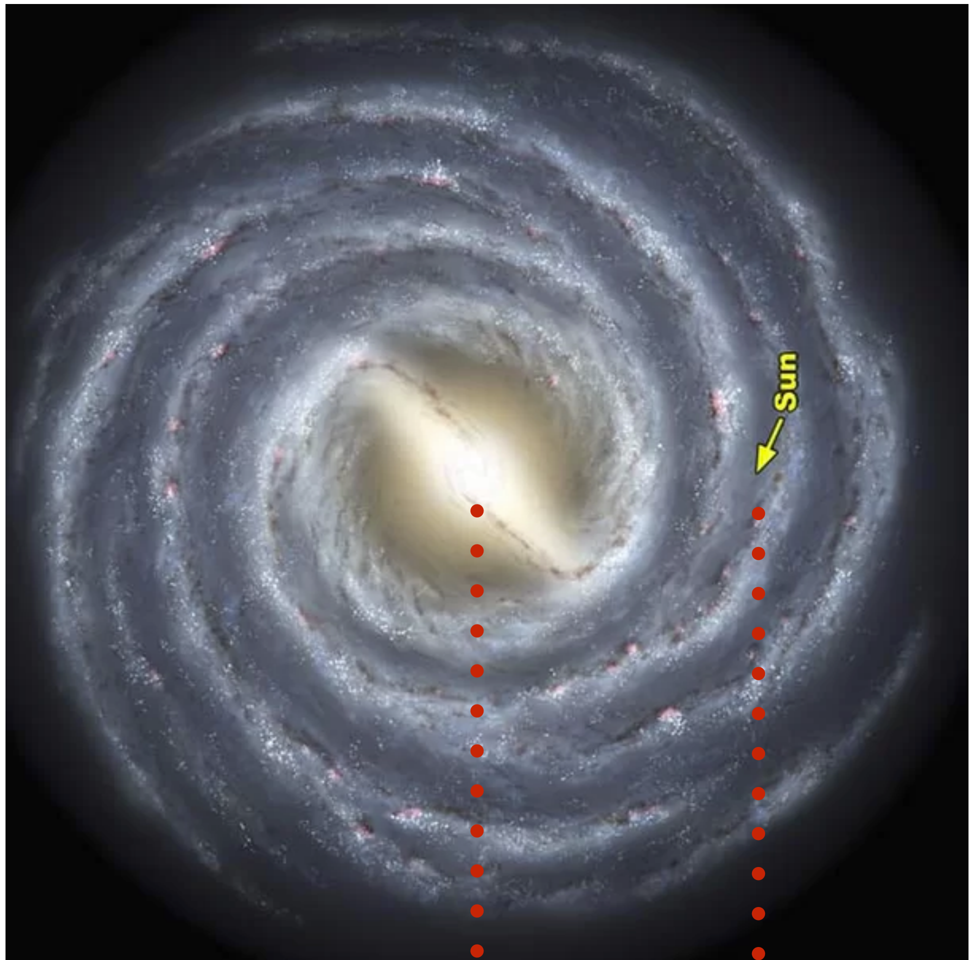
Our Galaxy: The Milky Way

As we see it ...

.. as it might look like from far away

Diameter ~ 50kpc
Distance of the Sun from the centre: ~8kpc
First measurements made by Oort.
Measurements quite difficult: we live on the disk!

The Milky Way and Rotation Velocities



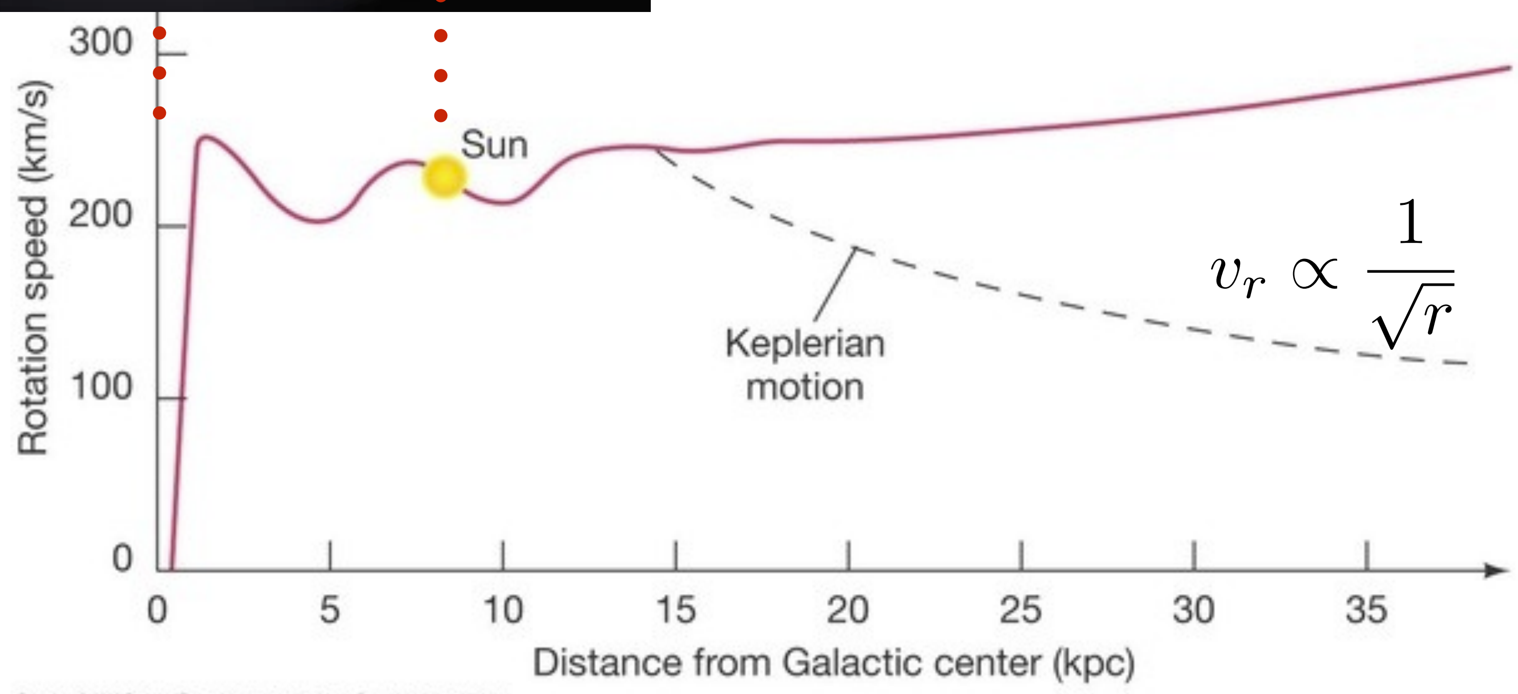
Expectation from Newton's gravity:

$$\frac{mv_r^2}{r} = \frac{GM_r m}{r^2} \Rightarrow v_r = \sqrt{\frac{GM_r}{r}}$$

Experimental evidence: "flattening" of the rotation curves after a certain radius R_0

$$v_r(r > R_0) \sim \text{const.}$$

This would imply $M_r \propto r$
and therefore the presence of additional "dark" mass.



Rotation Velocities and Density Profile

Using Newton's law for a constant rotation velocity V ("flat" rotation curve):

$$M_r = \frac{rV^2}{G} \Rightarrow \frac{dM}{dr} = \frac{V^2}{G}$$

and mass conservation in symmetric systems

$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

we can derive the density profile $\rho(r) = \frac{V^2}{4\pi G r^2}$

which falls off with the inverse squared of the distance.
Density profiles based on visible matter fall off even faster than the inverse cubic distance, pointing again towards the presence of invisible matter interacting gravitationally.

A phenomenological Density Profile

A possible modification of the density profile is

$$\rho(r) = \frac{a}{b^2 + r^2}$$

and a fit of the data yields $a \sim 4.6 \times 10^8 M_\circ \mathrm{kpc}^{-1}$

$$b \sim 2.8 \text{ kpc}$$

This profile will become constant at small radii and decrease “slowly” at large ones. Calculating the total mass with the spherical integral

$$M_{tot} = \int_0^\infty 4\pi r^2 dr \rho(r)$$

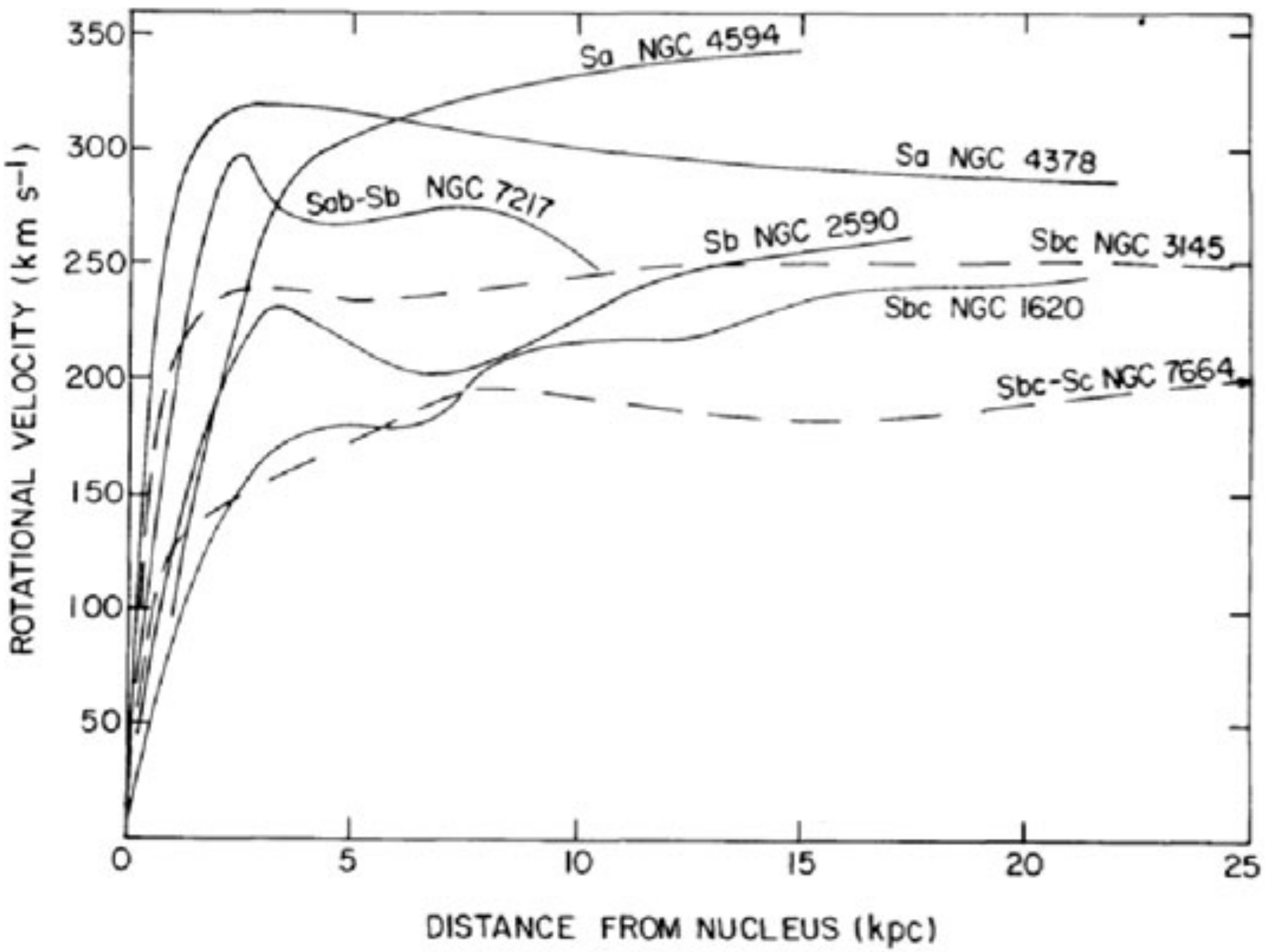
we obtain a divergent result, so we have either to truncate the integral or add a fast fall-off component.

Galactic Rotational Curves

Vera Rubin (1928-2016)

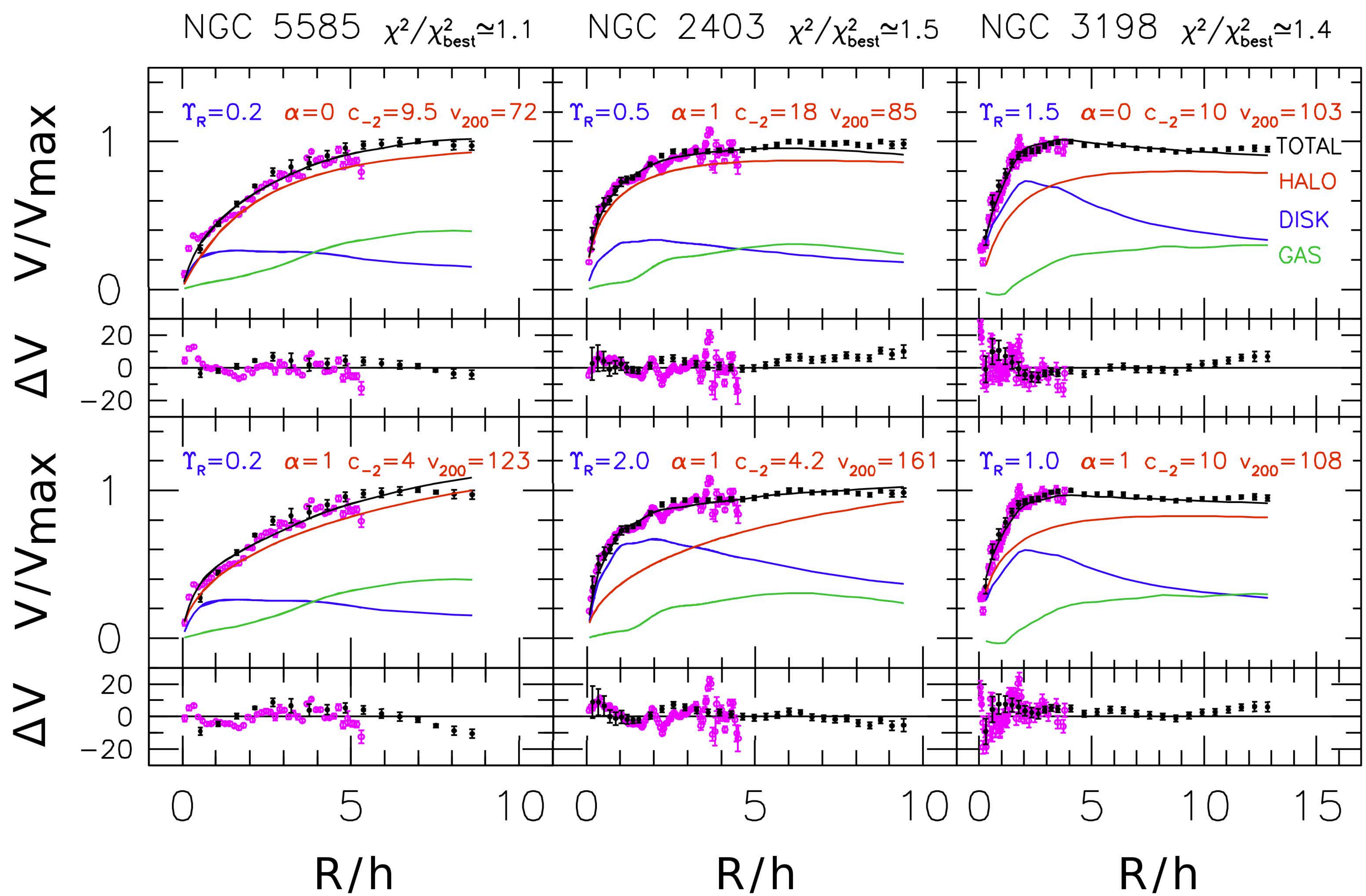
Flat rotational curves are observed in a large class of galaxies.

Nowadays observations comprehend thousands of galaxies.



The first accurate measurements were performed by V. Rubin and collaborators in the 70s. The curves stay flat as fas as astronomers can measure them.

The Dark Matter Halo Model



$$v_{DM}^2(r) = v^2(r) - v_{\rm lum}^2(r) = \frac{GM_{DM}}{r} \quad \Rightarrow \quad M_{DM}(r) = \frac{r}{G}\left[v^2(r) - v_{\rm lum}^2\right]$$

Dark Matter Distribution

Assuming DM as a collisionless gas with an isotropic initial velocity distribution, we have the equation of state

$$P(r) = \rho(r)\langle(v-\bar{v})^2\rangle = \rho\cdot\sigma$$

If pressure P and gravity are in equilibrium $\quad \dfrac{dP(r)}{dr} = -G\dfrac{M(r)\rho(r)}{r^2}$

and combining the two equations $\quad \dfrac{r^2}{\rho}\dfrac{d\rho}{dr} = -\dfrac{GM}{\sigma^2}$

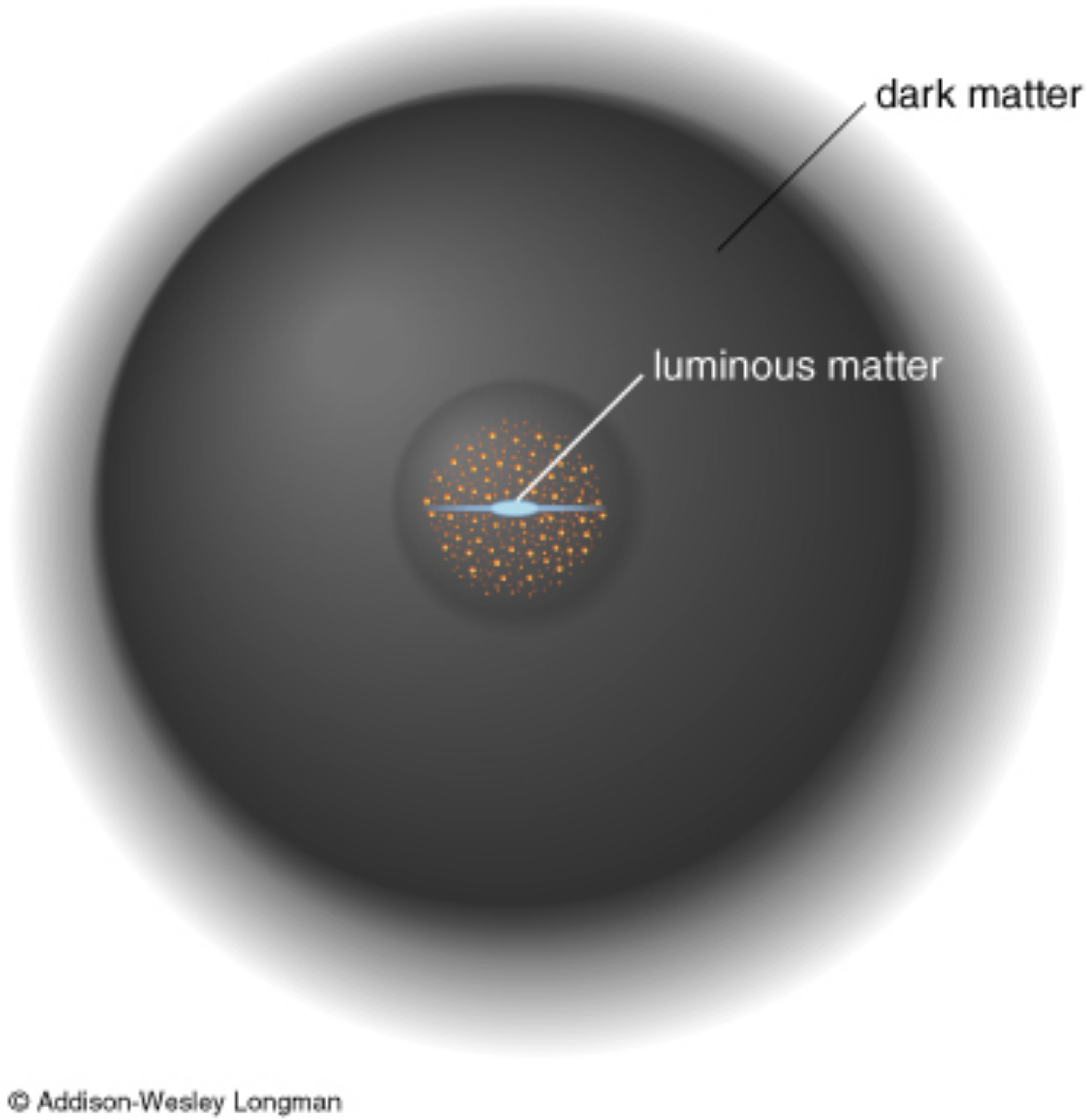
Differentiating wrt the radius

$$\frac{d}{dr}\left(r^2\frac{d\ln\rho}{dr}\right) = -\frac{G}{\sigma^2}\frac{dM}{dr}$$

and using again the mass conservation equation

$$\boxed{\rho(r) = \frac{\sigma^2}{2\pi G r^2}}$$

Dark Matter Distribution



$$\rho(r) = \frac{\sigma^2}{2\pi G r^2}$$

The obtained distribution is a spherical, isothermal distribution of dark matter.
In this model, DM is assumed to be collisionless.

Dark Matter Distribution

The Boltzmann equation without collision term for the distribution function f(x,v,t)

$$\frac{\partial f}{\partial t} + \bar{v}\frac{\partial f}{\partial x} - \frac{\partial \phi}{\partial x}\frac{\partial f}{\partial v} = 0$$

assuming an isotropic isothermal spherical profile $1/r^2$ has solution

$$f(\bar{v}) \propto e^{-\frac{3|\bar{v}|^2}{2\sigma^2}}$$

As an upper limit for the velocities, we take the escape velocity, which for the Milky Way is estimated to be

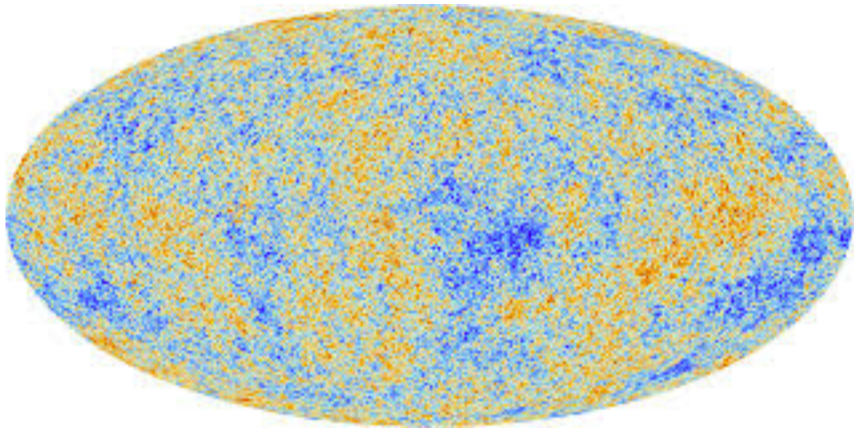
$$v_e(r) = \sqrt{2|\phi(r)|} \approx 498 - 608\mathrm{km}/s$$

The velocity dispersion is connected to the circular speed (the speed at which objects on circular orbits orbit the galaxy's centre)

$$v_c = \sqrt{\frac{2}{3}}\sigma \sim 220\frac{\mathrm{km}}{\mathrm{s}}$$ (local value)

The Structure Formation Argument

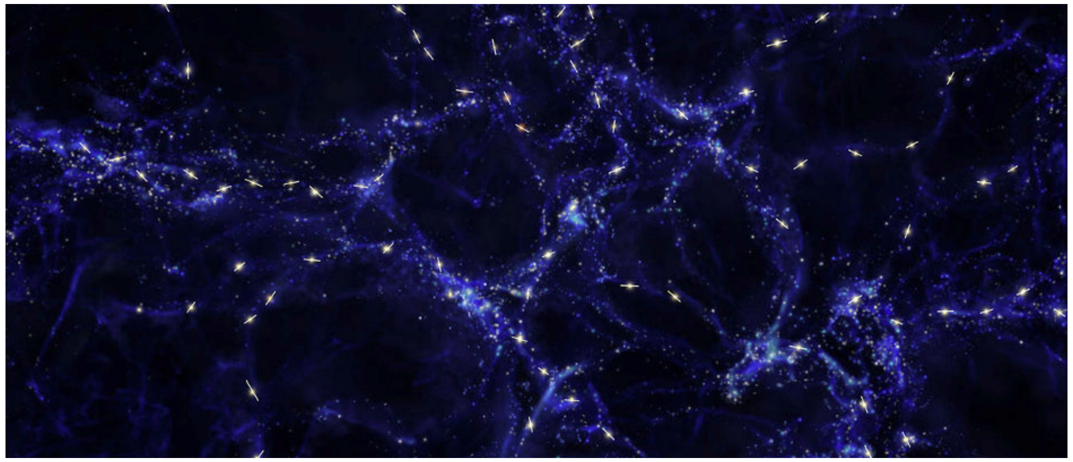
Dark Matter is needed for structure formation



Today we observe CMB density fluctuations at 10^{-4} level

CMB was produced at $z=10^3$

Density perturbations proportional to a (or z).



For structure formation need $\delta\rho/\rho > 1$

Therefore:
Not enough time has passed for observing today's inhomogeneities.

Not easy to explain with MOND

X-ray surveys

Baryonic matter can accelerate charged particles which emit radiation mainly by bremsstrahlung (in the X band).
Measuring the X radiation gives an estimate of the baryonic matter content of the astrophysical object (galaxy cluster usually).

If the cluster is approximated by a spherically symmetric fluid in equilibrium:

$$\cancel{\rho \frac{d\bar{v}}{dt}} = -\nabla P - \rho \nabla \phi \qquad \Rightarrow \qquad \frac{dP}{dr} = -\frac{GM(r)}{r^2}\rho$$

using the law of ideal gases $P = \frac{\rho k_B T}{m}$

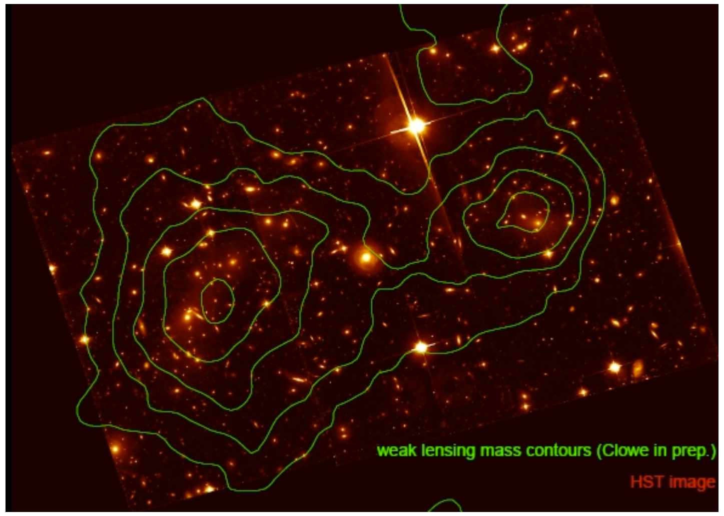
we have (using for m the mass of the proton as an approximation)

$$\boxed{M(r) = \frac{k_B T r}{G m_P}\left(-\frac{d\ln\rho}{d\ln r} - \frac{d\ln T}{d\ln r}\right)}$$

which gives the mass if we measure the density and temperature profiles as function of the radius.
The temperature is derived from the X-ray spectra, while the density from the luminosity density.

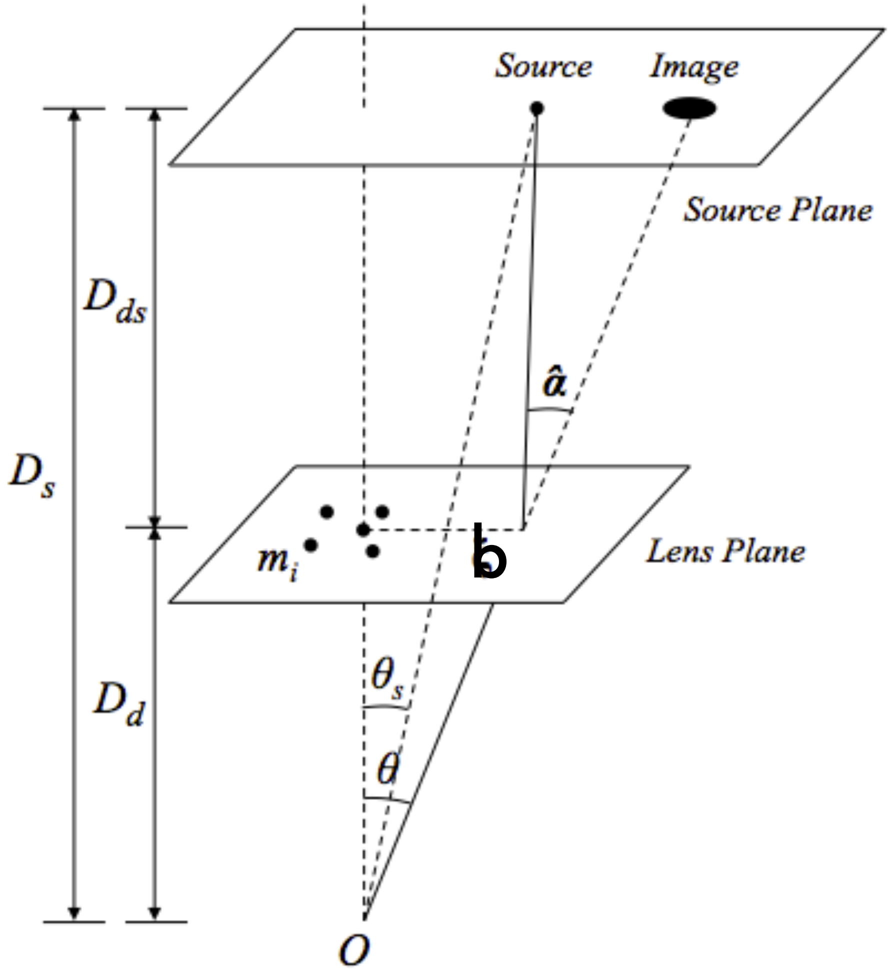
Weak Gravitational Lensing

WGL is the bending of light rays from objects behind another one. Measurements are statistical, in the sense that the lensing of different background objects are needed for reconstructing the mass distribution of the foreground object.



Using the FRW metric the deviation angle is (see notes for the derivation)

$$\alpha = \frac{4GM}{c^2 b} = \frac{2R_S}{b}$$



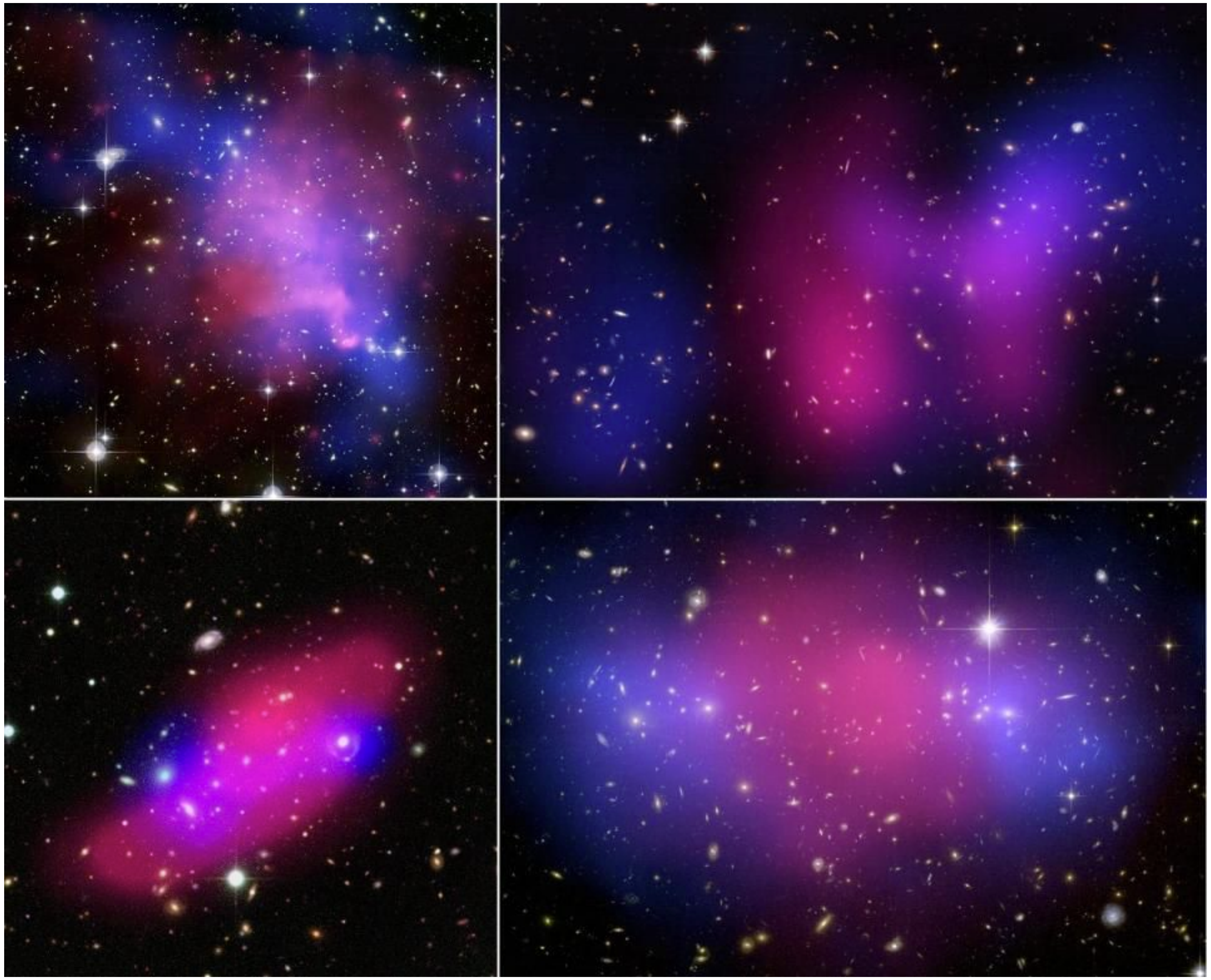
Combining Measurements

This is the famous picture of the Bullet Cluster (1E0657-56).
The regions in blue were reconstructed with WGL while the regions in purple were reconstructed with X-ray data.

WGL is sensitive to the total mass, while X-rays image areas with baryonic matter.
In general, a subtraction of the two contributions indicates the amount of dark matter.

In this case, two clusters are colliding and the image shows that the baryonic part is strongly deformed by the collision, while DM stays almost unperturbed.
This is because DM is concentrated around galaxies which are almost collisionless.

Other Clusters



X-ray: NASA/CXC/UVic./A.Mahdavi et al. Optical/Lensing: CFHT/UVic./A. Mahdavi et al. (top left); X-ray: NASA/CXC/UCDavis/W.Dawson et al.; Optical: NASA/ STScI/UCDavis/ W.Dawson et al. (top right); ESA/XMM-Newton/F. Gastaldello (INAF/ IASF, Milano, Italy)/CFHTLS (bottom left); X-ray: NASA, ESA, CXC, M. Bradac (University of California, Santa Barbara), and S. Allen (Stanford University) (bottom right)

Baryonic Density

The bulk of the matter content in the Universe should be constituted by baryons.
Ways for estimating $\Omega_b^0 = \frac{\rho_b^0}{\rho_c} = \frac{\Omega_b}{a^3}$ are

1) X-ray surveys. They return a value $\Omega_b h^2 \sim 0.02$
2) Light absorption from distant quasars returns same values as 1).
   Light absorption depends from how much matter there is between source and observer.
3) CMB spectrum: Rel. height between odd/even peaks and height of the first peak.
   More baryons enhance the first peak and lower the second.
   Planck observes $\Omega_b h^2 \sim 0.02225 \pm 0.00023$
4) From nuclear physics of BBN: the abundance of Deuterium measurements return $\Omega_b h^2 \sim 0.0205 \pm 0.0.0018$

Consistent results involving many branches of physics: nuclear physics, gravitation, optics, thermodynamics,....

Summary of DM Evidence

Diverse astrophysical measurements point towards the existence of Dark Matter:

Cosmic Microwave background measurements

X-ray and weak gravitational lensing surveys

Dynamics of galaxy clusters

Dynamics of galaxies

Considerations about timely structure formation

Now the question is: what constitutes DM?

Is it a new form of matter (a new particle?)
Is a modification of GR (thus, gravity)?
Or both?
Or something else?

DM Properties

Right now, the most promising candidate for DM is a new particle.
What should be the characteristics of such a particle?

1) Mass: non very well constrained. If one simply estimates the deBroglie wavelenght of a particle confined at galactic scales (~kpc) with typical escape velocities of 100km/s, we can derive a limit $m > 10^{-22}$eV.

2) Interaction: being "dark", it does not interact electromagnetically. This means that i cannot radiate, lowering its tendency to clump or accrete around compact objects. Some DM models (dark sector) postulate a level of interaction with the SM photon or other SM particles (Higgs, neutrino), while other models require DM-DM annihilation into SM particles. This might result in relevant astrophysical signals.

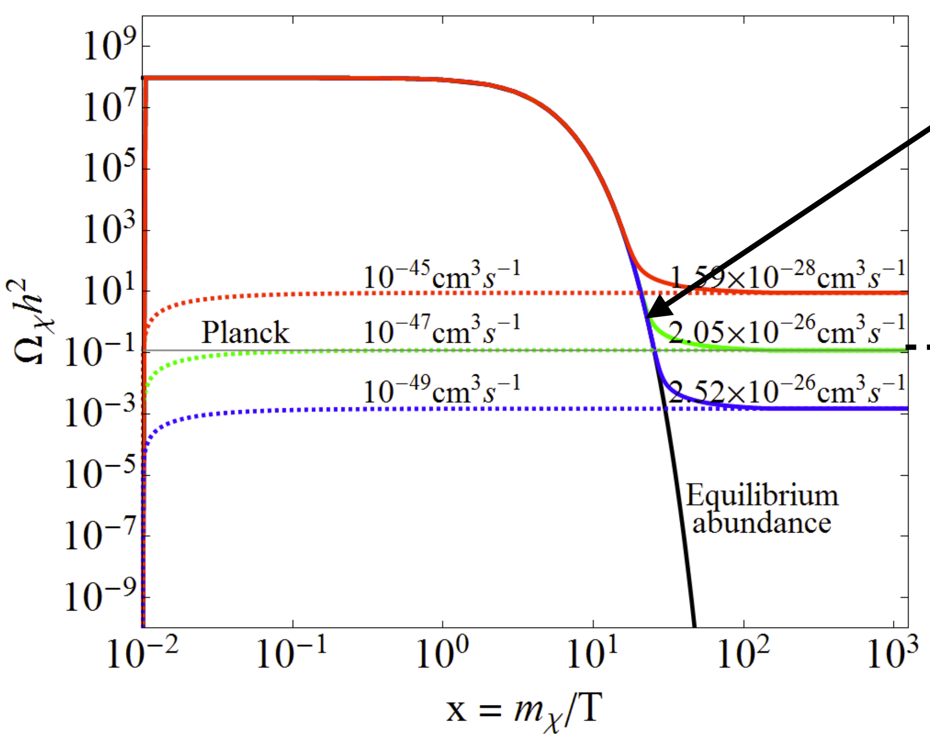
3) Self-Interaction: experimental limits on self-interaction of DM particles allow for cross-sections up to the order of the strong interaction.

The Thermal Relic Paradigm

An appealing idea is considering DM as a thermal relic from the early Universe. This means that DM was at the beginning in thermodynamical equilibrium and later, as the Universe expanded and cooled, it freezed-out to the density we observe today.

Assuming a reaction rate keeping DM in equilibrium $\Gamma = n \cdot \sigma \cdot v$

The freeze-out happened when the expansion rate equated the reaction rate



$$\Gamma(T_{fo}) = H(T_{fo})$$

T_{fo} is the freeze-out temperature.

present DM abundance

The Thermal Relic Paradigm

At decoupling time:

Thermal relic → relativistic → hot DM

Thermal relic → non-relativistic → cold DM

HDM example (e.g. neutrinos)

Equilibrium reaction $\nu + \bar{\nu} \longleftrightarrow f + \bar{f}$

Considering $E \propto T_\nu$

weak cross-section $\sigma \propto G_F^2 T^2$

Friedmann equation $H^2 = \frac{8\pi G}{3}\rho$

relativistic particles $\rho \sim T^4$

the freeze-out condition becomes $n(T_\nu) \cdot \sigma(T_\nu) = H(T_\nu) \Rightarrow T_\nu^3 G_F^2 T_\nu^2 = \frac{T_\nu^2}{M_P}$

and the freeze-out temperature is $T = (G_F^2 M_P)^{-1/3} \approx 1\mathrm{MeV}$

NOTE: the result is compatible with the relativistic condition m<<T

Cold Dark Matter

CDM example (e.g. a heavy SUSY particle)

In the case of non-relativistic particles

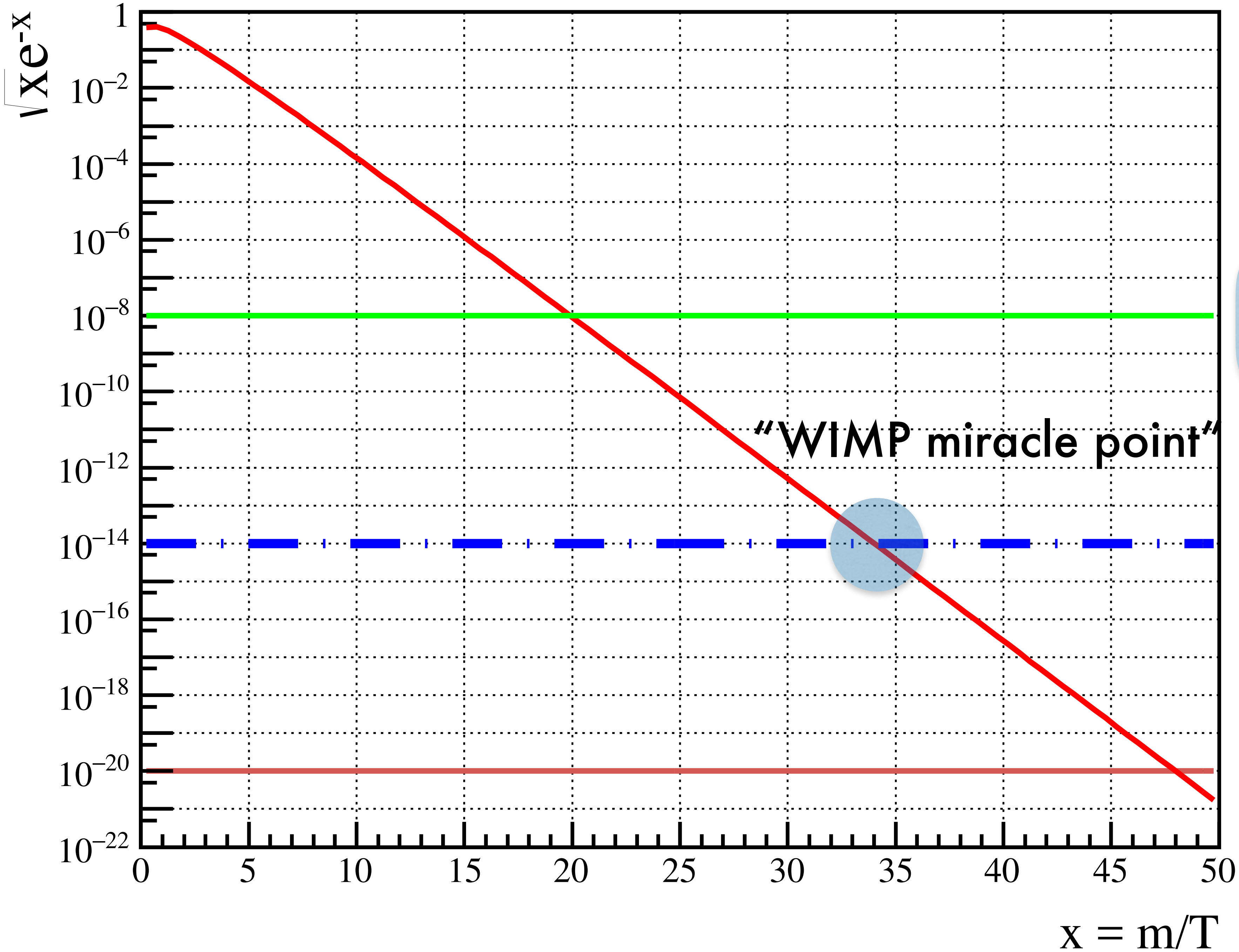
$$n \sim (mT)^{3/2} e^{-\frac{m}{T}} \qquad [1]$$

and in a radiation-dominated Universe (as obtained before with the Friedmann equation), the freeze-out condition $n\sigma \sim H$ (let's keep up to some factor v=c=1) is $n_{fo} = T_{fo}^2/(\sigma M_P)$

and substituting in [1] gives $\sqrt{x}e^{-x} = \dfrac{1}{m \cdot M_P \cdot \sigma}$ [2]

where x = m/T .
Equation [2] has no analytical solutions, but we can plot (see next slide) it and see where the RHS meets the LHS.

Cold Dark Matter



$$m = 100GeV$$

$$\sigma = G_F^2 m^2$$

imply $\frac{1}{m \cdot M_P \cdot \sigma} = 10^{-14}$

$$\frac{1}{m \cdot M_P \cdot \sigma} = 10^{-8}$$

$$\frac{1}{m \cdot M_P \cdot \sigma} = 10^{-14}$$

$$\frac{1}{m \cdot M_P \cdot \sigma} = 10^{-20}$$

The WIMP "miracle"

Consider the DM density parameter $$\Omega_\chi = \frac{m_\chi n_\chi(T_0)}{\rho_c} = \frac{T_0^3}{\rho_c M_P}\frac{x_{fo}}{\sigma}$$

In a FLRW Universe $$\begin{array}{l} T \sim 1/a \\ n \sim 1/a^3 \end{array} \Rightarrow \frac{n_0}{T_0^3} = \frac{n_{fo}}{T_{fo}^3}$$

And rewriting in O(1) terms $$\frac{\Omega_\chi}{0.2} \simeq \frac{x_{fo}}{20}\left(\frac{10^{-8}\mathrm{GeV}^{-2}}{\sigma}\right)$$

The typical EW cross section is $$\sigma_{EW} \sim G_F^2 T_{fo}^2 \sim \left(\frac{E_{EW}}{20}\right)^2 \sim 10^{-8}\mathrm{GeV}^{-2}$$

Since people expected new physics at the EW scale, this looks quite a coincidence (or a "miracle"?)!

Is it a "Miracle"? (No..)

Which ingredients we used to obtain the previous results:

1) Cold relic: x>>1 and therefore $m_\chi \cdot \sigma \cdot M_P >> 1$

2) A cross section of 10^{-8} GeV^{-2}

Using dimensional arguments we can also write $\sigma \propto \frac{g^2}{m_\chi^2}$

And substituting 2) in 1) we have $m_\chi >> 0.1 \quad eV$

This means that we do not really need new particles at the ~100 GeV scale.
As long as the cross section is right, CDM can be as light as 0.1 eV!

Other argument: since $\Omega_\chi \propto \frac{1}{\langle v\sigma \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$ one can play with mass and coupling and obtain the right density parameter.

Mass Range

Constraint from unitarity $\sigma < \dfrac{4\pi}{m_\chi^2}$

with $$\frac{\Omega_\chi}{0.2} \simeq \frac{x_{fo}}{20}\left(\frac{10^{-8}\mathrm{GeV}^{-2}}{\sigma}\right)$$

gives approximately $$\frac{\Omega_\chi}{0.2} > 10^{-8}\mathrm{GeV}^{-2} \times \frac{m_\chi^2}{4\pi}$$

and since $\Omega_\chi < 0.2 \quad \Rightarrow \quad \left(\dfrac{m_\chi}{120\ \mathrm{TeV}}\right)^2 < 1$

Considering weak-type interactions $\sigma \sim G_F^2 m_\chi^2$

we have the Lee-Weinberg limit $\Omega_\chi h^2 \sim 0.1 \dfrac{10^{-8}\mathrm{GeV}^{-2}}{G_F^2 m_\chi^2} \sim 0.1\left(\dfrac{10\ \mathrm{GeV}}{m_\chi}\right)^2$