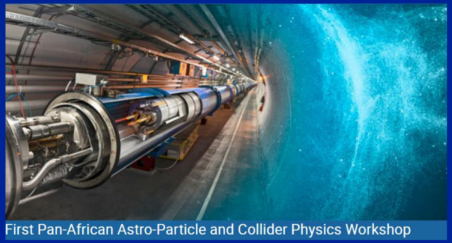

First Pan-African Astro-Particle and Collider Physics Workshop

Université Mohammed V
Faculté des Sciences
Rabat

Mohammed V University of RABAT - Faculty of Sciences

Thermal production of early dark matter from van der Waals fluid

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Presented by Mostafa Bousder
Faculty of Sciences Rabat

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- Introduction

I- Fromalism

II- The van der Waals equation of dark matter

III- Boltzmann equation

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01

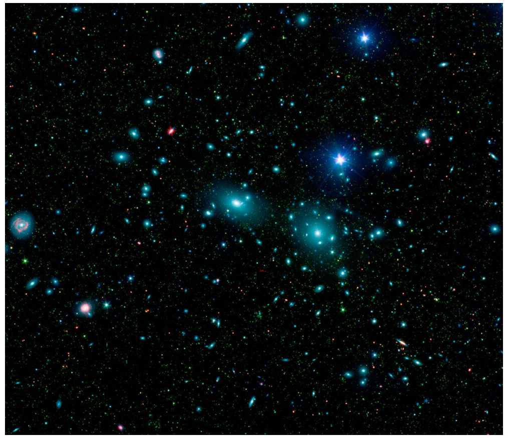
Introduction

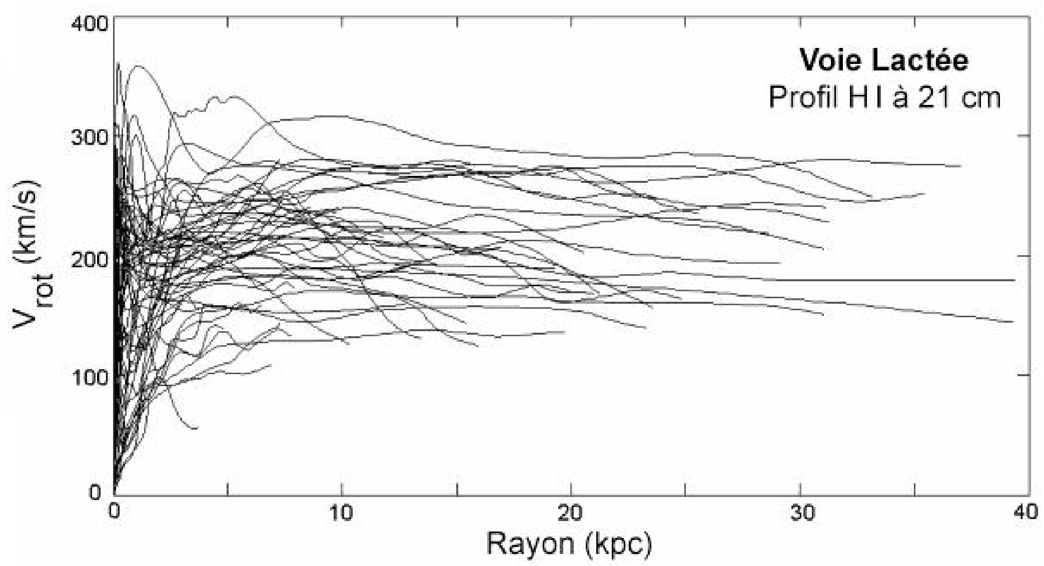
Fritz Zwicky
Swiss-American astrophysicist He discovers several supernovae

the dynamic mass is greater than the luminous mass of clusters...

Vera Rubin
American astronomer
study of stars in spiral galaxies

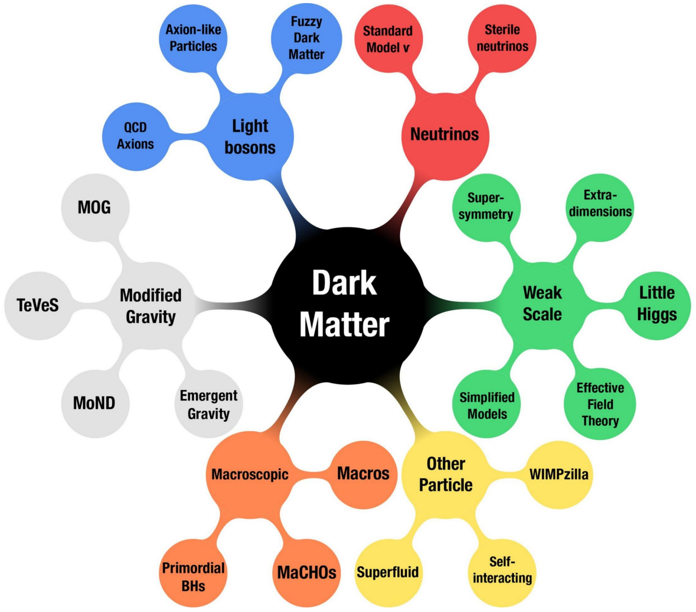
the speed of rotation of the galaxies almost constant...

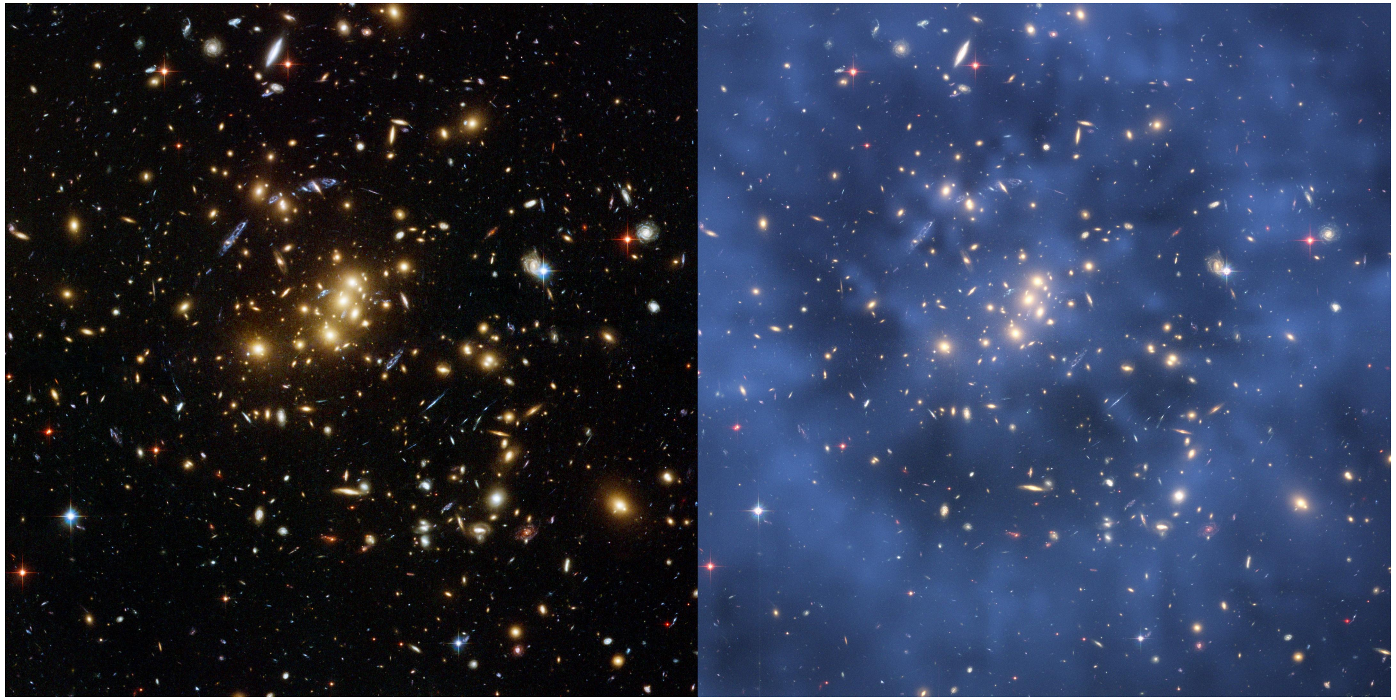


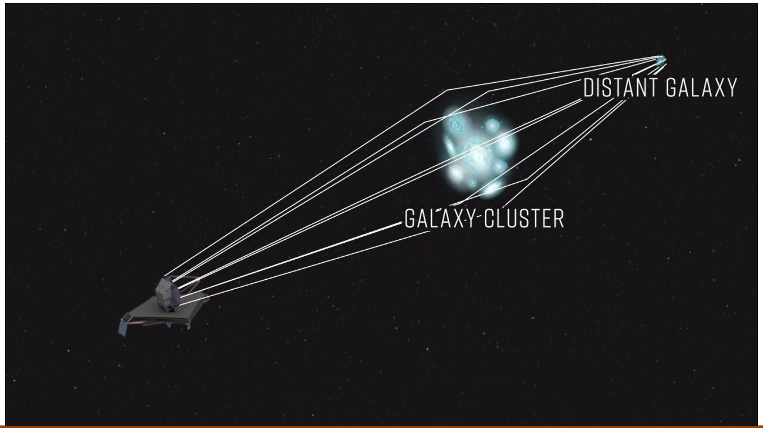


Introduction

Dark matter candidat







Thermal production of early dark matter from van der Waals fluid

03

Fromalism

The simplified model we consider consists of a real scalar dark matter (DM) minimally coupled to gravity and the standard model (SM)

$$\mathcal{S}=\int d^4x\left(\frac{M_p^2}{2}R-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-V(\phi)\right)+\mathcal{S}_m,$$

The metric of a spatially flat homogeneous and isotropic universe in FLRW model is given by:

$$ds^2=-dt^2+a^2(t)\sum_{i=1}^{3}\left(dx^i\right)^2,$$

we introduce the effect of inflaton decay

$$\ddot{\phi}+(3H+\Gamma)\dot{\phi}+V'(\phi)=0.$$

Generally, the Klein Gordon equation in a simple form

$$\ddot{\phi}+\left(3H+\lambda^2\Gamma\right)\dot{\phi}+\partial_\phi V(\phi)=0,$$

Dark matter particle from inflaton field

The Klein Gordon equation is

$$\ddot{\phi} + \left(3H + \lambda^2\Gamma\right)\dot{\phi} + \partial_\phi V\left(\phi\right) = 0,$$

we have

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial}{\partial\phi}V\left(\phi\right) + \frac{\partial}{\phi\Gamma^{-1}\partial t}\left(\frac{1}{2}\lambda^2\phi^2\right) = 0.$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial}{\partial\phi}\left(V\left(\phi\right) + \frac{1}{2}\lambda^2\phi^2\right) = 0.$$

$$\boxed{V_{eff}\left(\phi\right) = V\left(\phi\right) + \frac{1}{2}\lambda^2\phi^2.}$$

the DM decay $\Gamma_{DM}\left(DM \to DM\right) = \frac{1}{\Gamma}.$

$$\boxed{\Gamma = \frac{\phi}{\dot{\phi}} = \frac{1}{\partial_t \ln\phi}.}$$

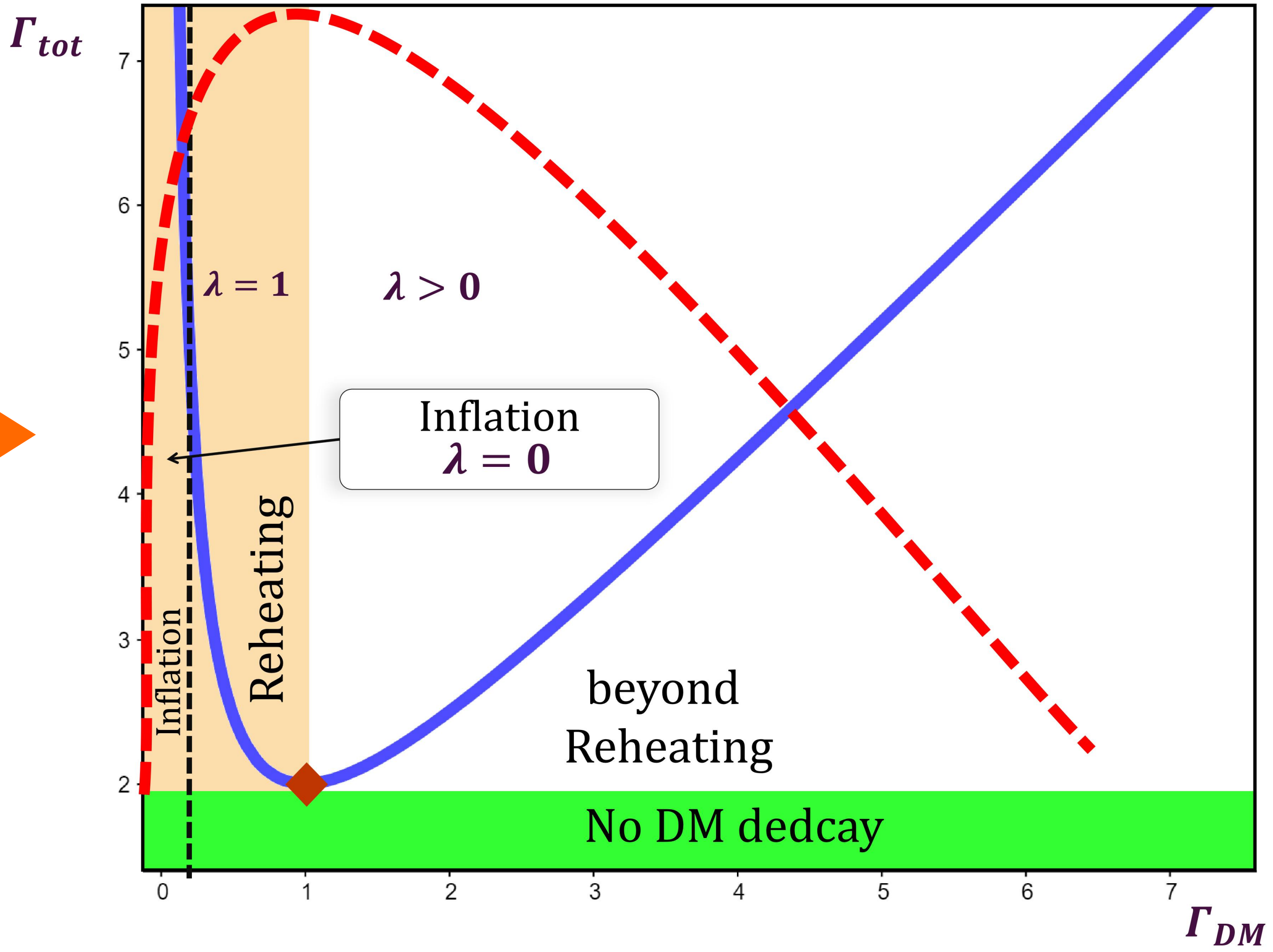
The total decay rate of ϕ-particles is $\Gamma_{tot} = \Gamma + \Gamma^{-1}$

Thermal production of early dark matter from van der Waals fluid

05

Dark matter particle from inflaton field

The blue curve describes the evolution of the total decay decreases during inflation according to Γ_{DM} . The red curve describes the evolution of the Γ_{tot} with respect to Γ. The band (No DM decay) is the domain where there is no production of the field particles, neither the inflaton nor the DM particle. The orange domain is the period of inflation and reheating.



Dark matter particle from inflaton field

the scale factor evolves as

$$\begin{array}{lcl} \text{Inflation} & V_{eff}(\phi) & \approx V(\phi), \\ \text{Reheating and beyond} & V_{eff}(\phi) & \approx \frac{1}{2}\lambda^2\phi^2. \end{array}$$

The mass of small fluctuations around ϕ_{min} give a new scalar field mass as effective mass by

$$m_{eff}^2 = m_\phi^2 + \lambda^2.$$

Let us consider first the decay rate of the particle interaction $\Gamma = \frac{y^2}{8\pi} m_\phi,$

where m_ϕ is the inflaton mass scale and y denotes the effective Yukawa coupling

$$m_{eff}^2 = \frac{16\pi^2}{y^4\dot{\phi}^2}\phi^2 + \lambda^2.$$

Thermal production of early dark matter from van der Waals fluid

The van der Waals gas

we will study the formation of real gas of field ϕ and we give a thermodynamic interpretation of the production of DM particles by the number density and the DM thermodynamic variables.
Notice that the energy density ρ_ϕ and pressure P_ϕ stored in the scalar field are

$$\rho_\phi - V(\phi) = \frac{1}{2}\dot{\phi}^2, \qquad P_\phi + V(\phi) = \frac{1}{2}\dot{\phi}^2.$$

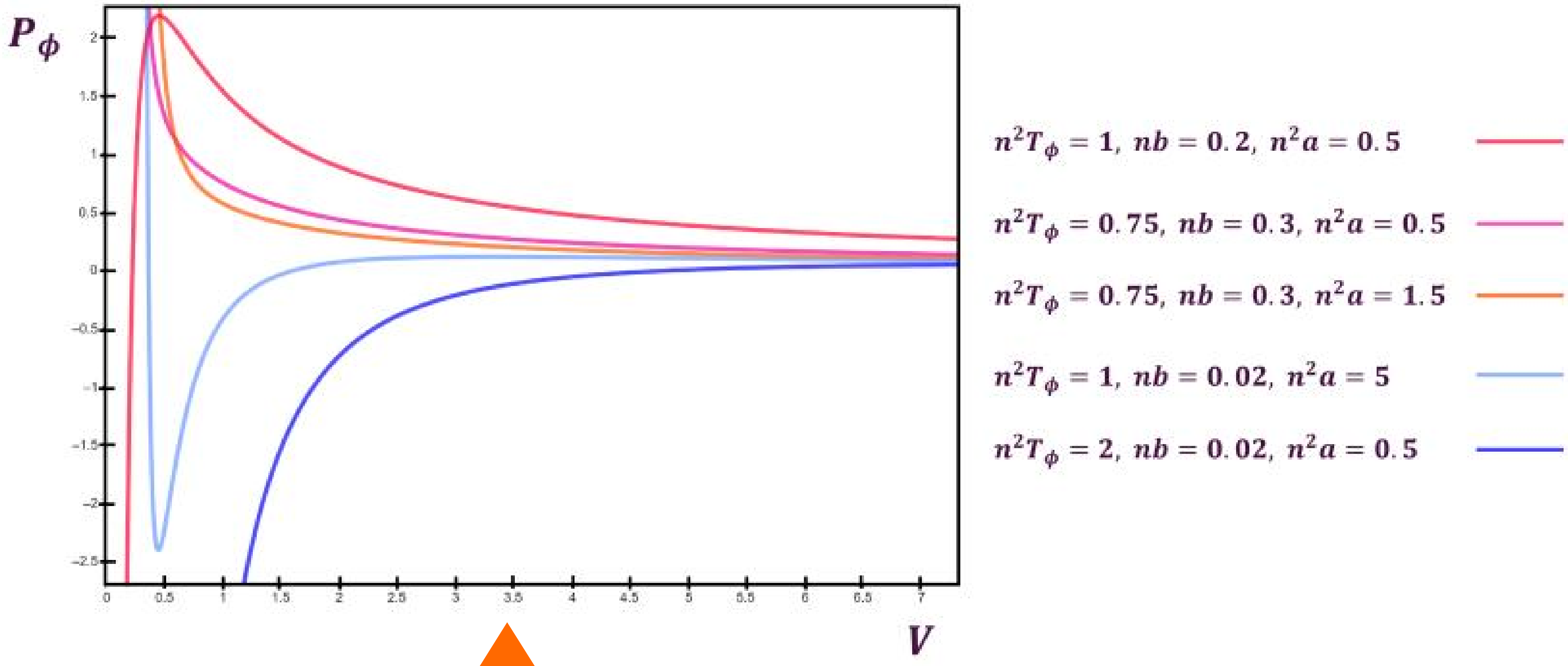
We assume that the scalar field is the inverse of the thermodynamic volume. In this case, the field ϕ becomes very intense if the volume which contains these particles is very small.

$$\left(P_\phi + \frac{m_\phi^2}{2M_p^4\mathcal{V}^2}\right)\left(\mathcal{V} - \frac{\lambda^2\mathcal{V}}{m_{eff}^2}\right) = 8\pi\phi\frac{4\pi}{M_p^2 m_{eff}^2 y^4},$$

We can also deduce the temperature of attraction between the particles of DM gas as

$$T_\phi = \frac{\phi}{2m_{eff}^2\Gamma^2} = \frac{\phi\Gamma_{DM}^2}{2m_{eff}^2}.$$

The van der Waals gas



P_ϕ–V isotherms of the van der Waals equation of state.

Reconstructing Boltzmann equation in inflation

we have studied the possibilities for reconstructing the interaction between the DM particles from the van der Waals equation. In this section, we study the reconstruction of the Boltzmann equation of the inflaton interaction using the same equation of state.

The production of DM particles after the first inflaton oscillation is described by the number density of DM

$$\frac{dn_\phi}{dt} + n_\phi \frac{d}{dt}\left(\int \frac{dt}{\Gamma}\right) = e^{-\int \frac{dt}{\Gamma}} \frac{d}{dt}\left(\frac{2\lambda^2}{b\Gamma_{DM}^2}\frac{T_\phi}{\phi_0}\right).$$

The evolution of the DM number density for scalar DM is given by the Boltzmann equation

$$\frac{dn_\phi}{dt} + 3Hn_\phi = -\langle\sigma v\rangle_{\phi\to\phi=DM}\left(n_\phi^2 - n_{eq}^2\right),$$

$$\boxed{\langle\sigma v\rangle = -\frac{2e^{-3Ht}}{\phi_0 b\left(n_\phi^2 - n_{eq}^2\right)}\frac{d}{dt}\left(\frac{\lambda^2 T_\phi}{\Gamma_{DM}^2}\right).}$$

Reconstructing Boltzmann equation in inflation

for fixed temperature we get

$$\langle \sigma v \rangle_{\phi\to\phi=DM} = -\frac{2e^{-3Ht}T_\phi}{\phi_0 b n_\phi^2}\frac{d}{dt}\left(\frac{\rho_\lambda - P_\lambda}{\rho_\lambda + P_\lambda}\right),$$

where

$$\rho_\lambda - \frac{\lambda^2\phi^2}{2} = \frac{1}{2}\dot{\phi}^2, \qquad P_\lambda + \frac{\lambda^2\phi^2}{2} = \frac{1}{2}\dot{\phi}^2, \qquad P_\lambda = \omega_\lambda \rho_\lambda,$$

then, the cross section reads

$$\langle \sigma v \rangle_{\phi\to\phi=DM} = \left(\frac{4\dot{\omega}_\lambda b T_\phi}{\phi_0}\right)\left(\frac{m_{eff}}{\lambda}\right)^4 \frac{1}{(1+\omega_\lambda)^2}\exp(-3Ht)\,.$$

$$\boxed{\frac{\langle \sigma v \rangle_{\phi\to\phi=DM}}{\langle \sigma v \rangle_0} = \left(\frac{100MeV}{\lambda}\right)^4.}$$

Reconstructing Boltzmann equation after inflation

The DM particle density is described by the Boltzmann equation after inflation

$$n_{DM} = m_{eff}\sqrt{n_\phi b}M_p\phi = 2m_{eff}^3\sqrt{n_\phi b}M_p\frac{T_\phi}{\Gamma_{DM}^2},$$

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = M_p\phi_0\frac{d\lambda}{dt}\exp\left(-3Ht\right),$$

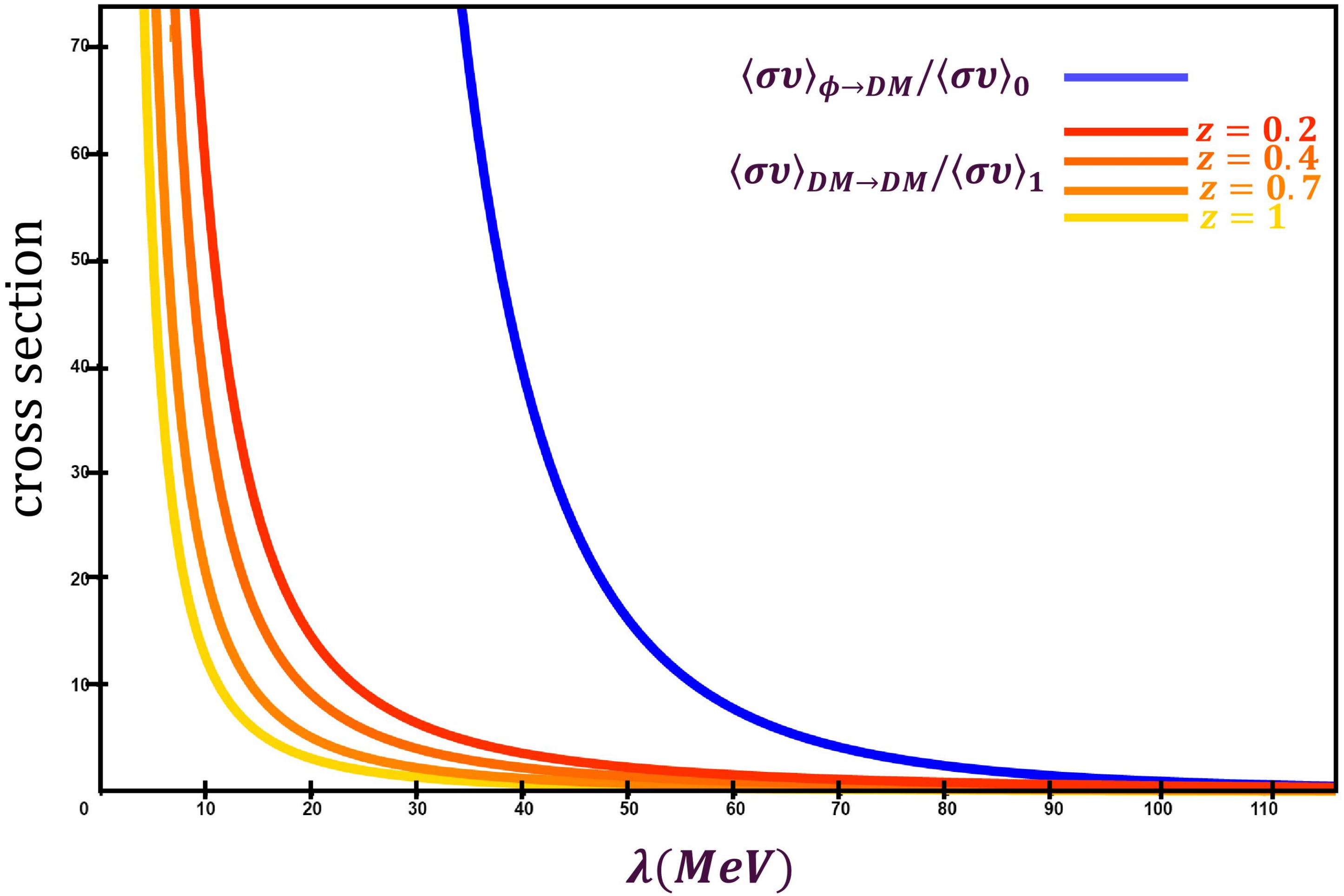
Using $\phi \equiv \phi_{DM} = \phi_0 \exp\left(-3Ht\right).$

then, the cross section reads

$$\langle\sigma v\rangle_{DM\to DM} \sim \frac{-\phi_0 a_0^3 M_p}{n_{DM}^2 - n_{eq}^2}\dot{\lambda}(1+z)^3.$$

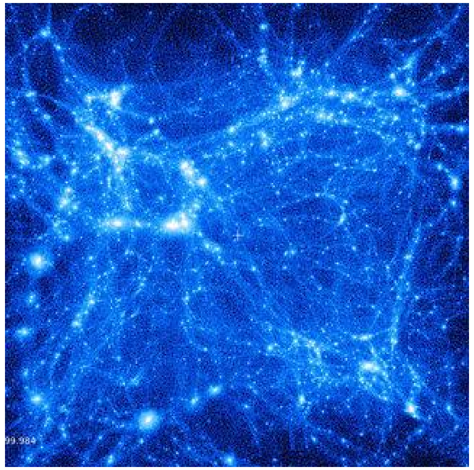
Reconstructing Boltzmann equation after inflation

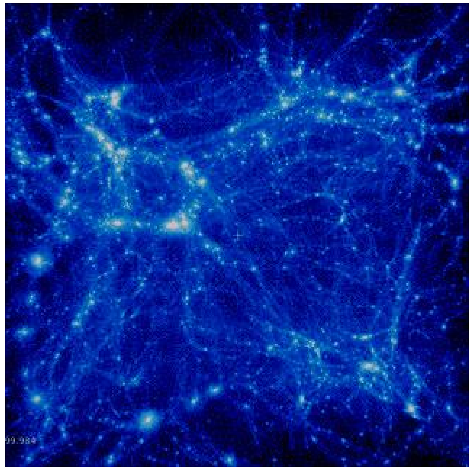
The evolution of DM cross section as a function of λ. The cross section $\langle\sigma\upsilon\rangle_{\phi \to DM}$ represents a barrier of all $\langle\sigma\upsilon\rangle_{DM \to DM}$.

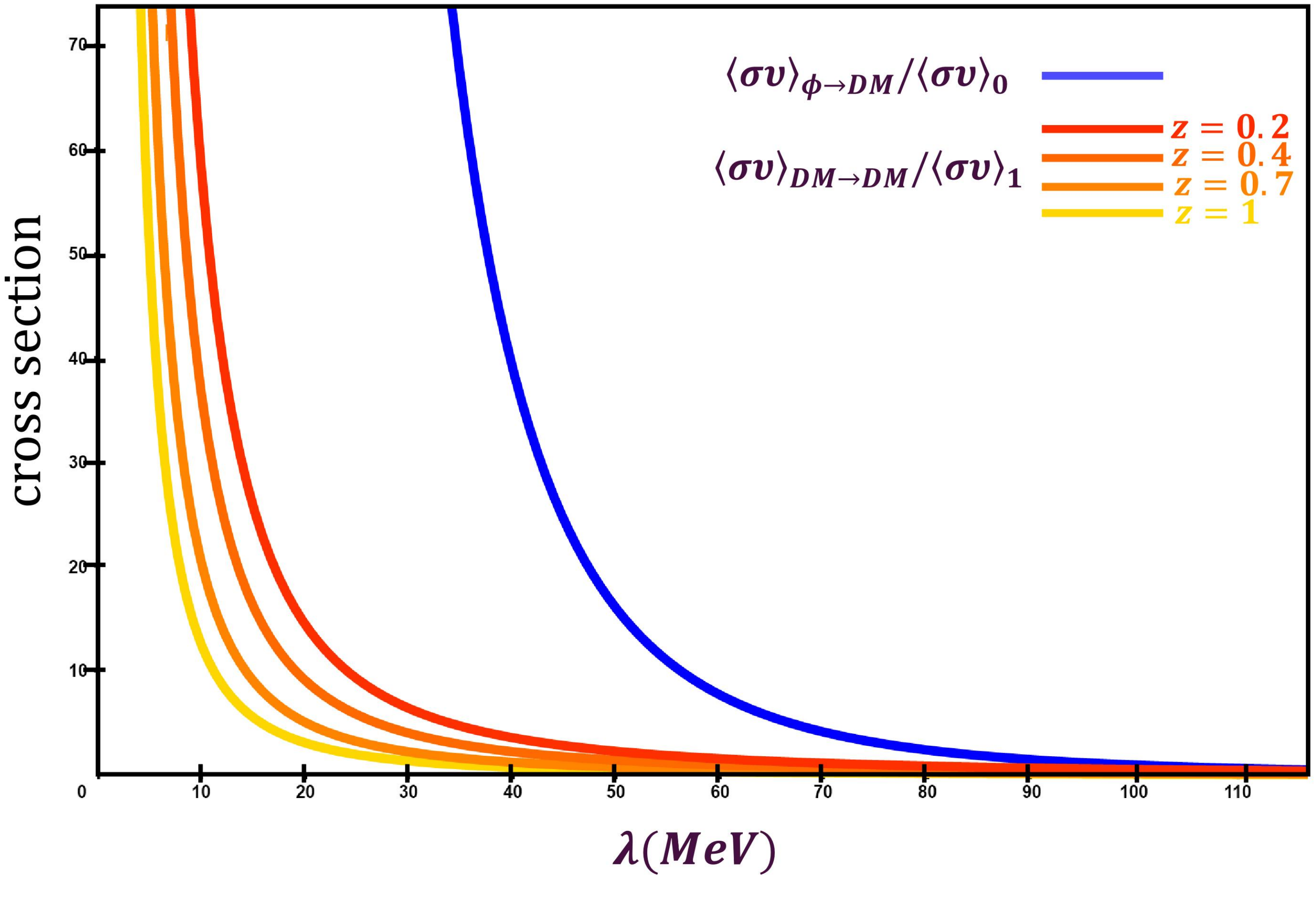


Thermal production of early dark matter from van der Waals fluid

Reconstructing Boltzmann equation after inflation







Conclusion

- We investigated the production of dark matter particles after inflation.

- During reheating, we have considered that the field ϕ (inflaton) stabilizes and becomes a dark matter candidate. During reheating, there is an appearance of the decay rate of the particle interaction in the Klein Gordon equation.

- By a new technique, we have shown a quadratic form of scalar potential after inflation. We have developed an approach to the dark matter evolution, and we have found that λ represents the field ϕ mass after ϕ-stabilization. In this case, the mass λ describes the dark matter after inflation.

- We have studied the thermodynamic properties of dark matter by different mechanisms resulting. We have shown the reconstruction of the interaction between the DM particles from the van der Waals equation

- We have examined the effect of the redshifts during and after reheating on the dark matter cross section. We have studied the thermodynamic interpretation of DM stability.

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A new constant behind the rotational velocity of galaxies

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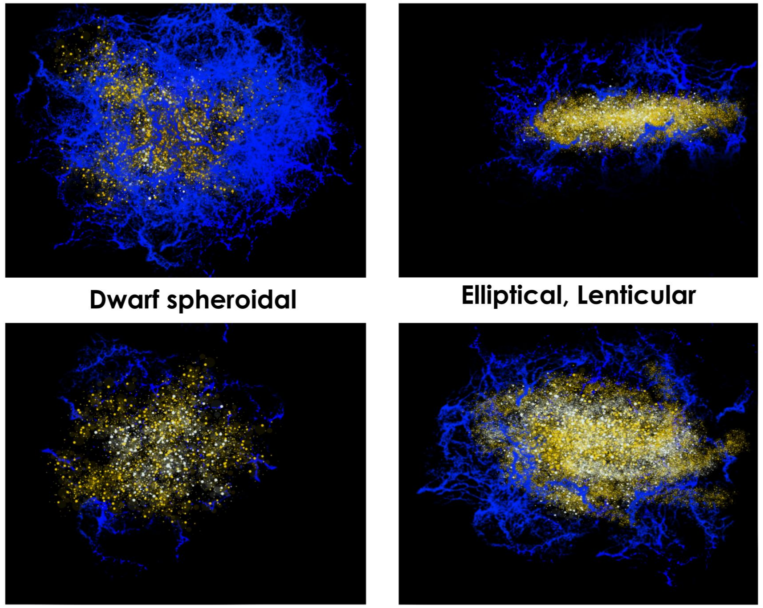
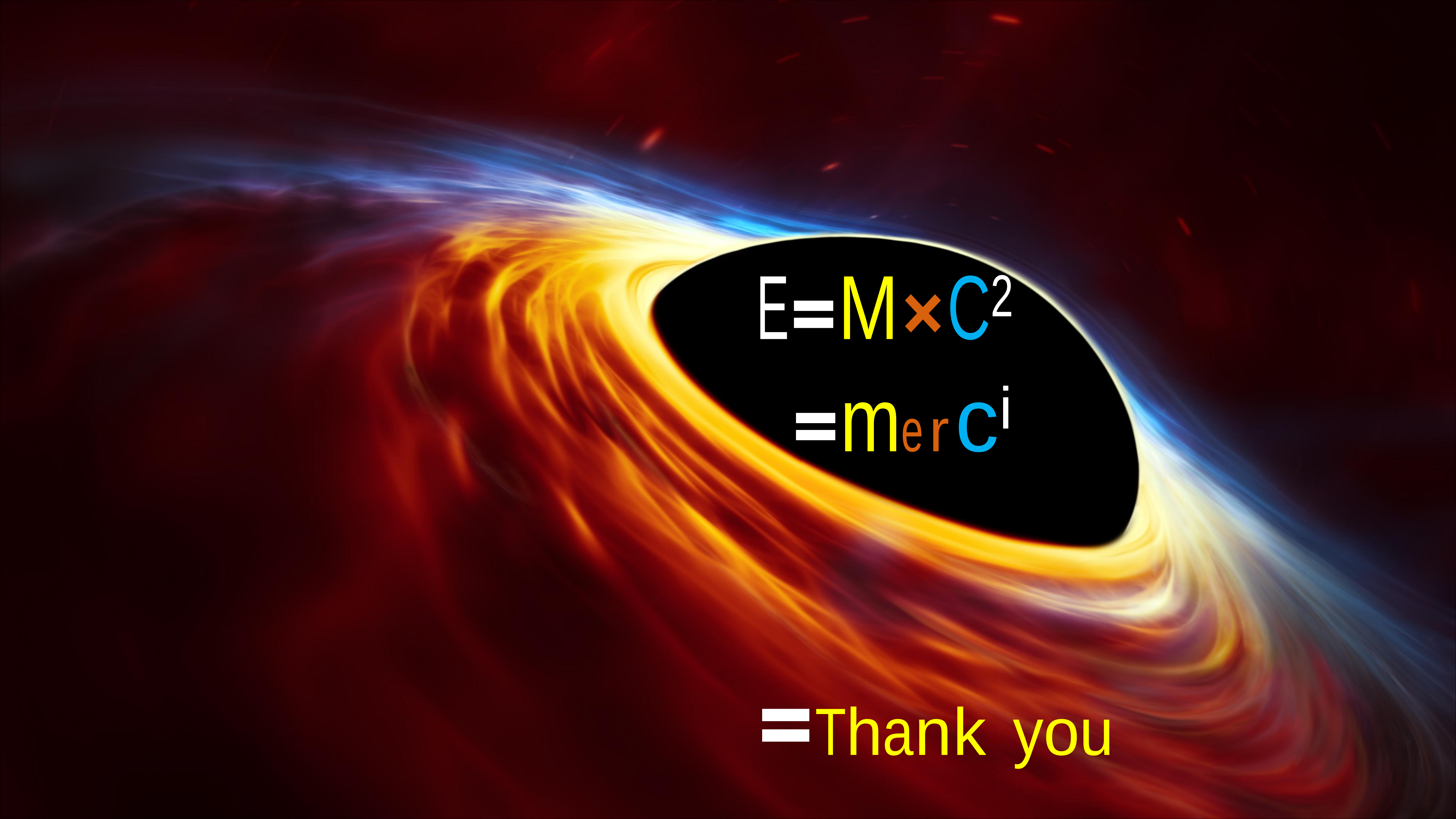


Dwarf spheroidal
Elliptical, Lenticular
Irregular dwarf
Spirals galaxies



$E = M \times C^2$

$= m_{e\,r}\, c^{i}$

= Thank you