Dark matter dynamics in Galactic centre

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The evolution of dark matter in central areas of galaxies is considered (Milky Way is taken as an example). It is driven by scattering off of dark matter particles by bulge stars and their absorption by the supermassive black hole, and is described by diffusion equation in phase space of energy and angular momentum. It is shown that by now the density of dark matter inside central parsec is greatly diminished: approximately 10% of initial dark matter mass is captured by black hole, about a half is evaporated. The annihilation of particles may explain observed gamma-ray flux from Galactic center.

Introduction

Dark matter is known to be the dominant component in outer parts of galaxies and in galactic clusters. However, its behavior in central parts of galaxies is also worth investigating.

First of all, in the process of galaxy formation, baryonic matter (gas) cools and settles down in the gravitational potential well created by dark matter, thus increasing the depth of the well and causing adiabatic contraction of dark matter (Blumenthal et al., 1986; Gnedin et al., 2004; Sellwood & McGaugh, 2005; Vasiliev, 2006). Similar effect happens in the very centre of the galaxy, where a supermassive black hole dominates gravitational potential inside so-called region of influence ($r < r_h = GM_{bh}/\sigma^2$), where σ^2 is stellar velocity dispersion outside r_h. (in our Galaxy $r_h = 2$ pc). The adiabatic contraction should lead to very steep dark matter density spike near a black hole (Gondolo & Silk, 1999), which should be decreased by self-annihilation of dark matter particles to form a density plateau or, more likely, a weak cusp (Vasiliev, 2007).

The more important process, however, is the gravitational relaxation of dark matter on stars of galactic nucleus and their capture by the black hole, which is discussed below.

Method

The evolution of dark matter distribution function f is investigated by means of orbit-averaged Fokker-Planck equation:

$$\frac{\partial f}{\partial t} = \mathcal{G}^{-1}\frac{\partial}{\partial \xi_\alpha}\left(\mathcal{G}\left[D_{\alpha\beta}\frac{\partial f}{\partial \xi_\beta} - D_\alpha f\right]\right) - S_{ann}[f] \,. \qquad (1)$$

Here ξ_α are the phase-space variables (e.g. energy E and angular momentum L per unit mass), which are integrals of motion in absence of scattering; $\mathcal{G}$ is the jacobian. The r.h.s consists of collision term, which is determined by gravitational scattering of DM particles by bulge stars, and self-annihilation term. The diffusion coefficients $D_{\alpha\beta}$ are related to the relaxation time, but depend also on ξ_α.

Additionally, the presense of supermassive black hole in the centre of a galaxy imposes a boundary condition at low angular momenta: particles with $L < L_g = 2GM_{bh}/c^2$ are captured by the black hole on passage of orbital pericentre. The form of boundary condition depends on particle energy: low-energy particles with short periods "feel" an absorbing boundary, while high-energy particles can diffuse in and out the area $L < L_g$ during their long orbital period (the "loss cone" is full).

We consider the problem both inside and outside the black hole region of influence consistently. The relaxation time is roughly constant inside r_h, and is less than Hubble time for the case of Milky Way ($r_h = 2$ pc, $T_r \sim 2\cdot 10^9$ yr); outside r_h the relaxation time increases, so that evolution is significant only within roughly 10 pc. The diffusion coefficients $D_{\alpha\beta}$ are different in these two regions.

Unlike previous studies (Ilyin et al., 2004; Merritt, 2004; Bertone & Merritt, 2005), we consider full two-dimensional diffusion equation – for energy and angular momentum. However, even one-dimensional approximations give qualitative predictions, being solvable analytically:

- The diffusion along angular momentum axis L creates flux of DM particles into black hole and drives the distribution function towards characteristic logarithmic profile: $f(L) \propto \ln L + \text{const}$.
- The diffusion along energy E leads to dark matter heating. The system "stars + DM particles" tends towards thermodynamical equilibrium and equipartition of energy, but due to enormous difference in masses this simply causes transfer of energy to DM particles. Therefore, **a stationary solution cannot exist**, contrary to the case of star distribution around a black hole.

So the dark matter distribution is essentially time-dependent, the timescales for diffusion along L and E being similar. Hence, a full two-dimensional equation should be integrated numerically. This was done for a dozen of variants, which differ in initial models of dark matter halo and in inclusion or neglection of some processes (e.g. dark matter annihilation or growth of black hole mass).

Results

The quantitative results essentially depend on the chosen initial model of dark matter halo, but the qualitative picture is the same.

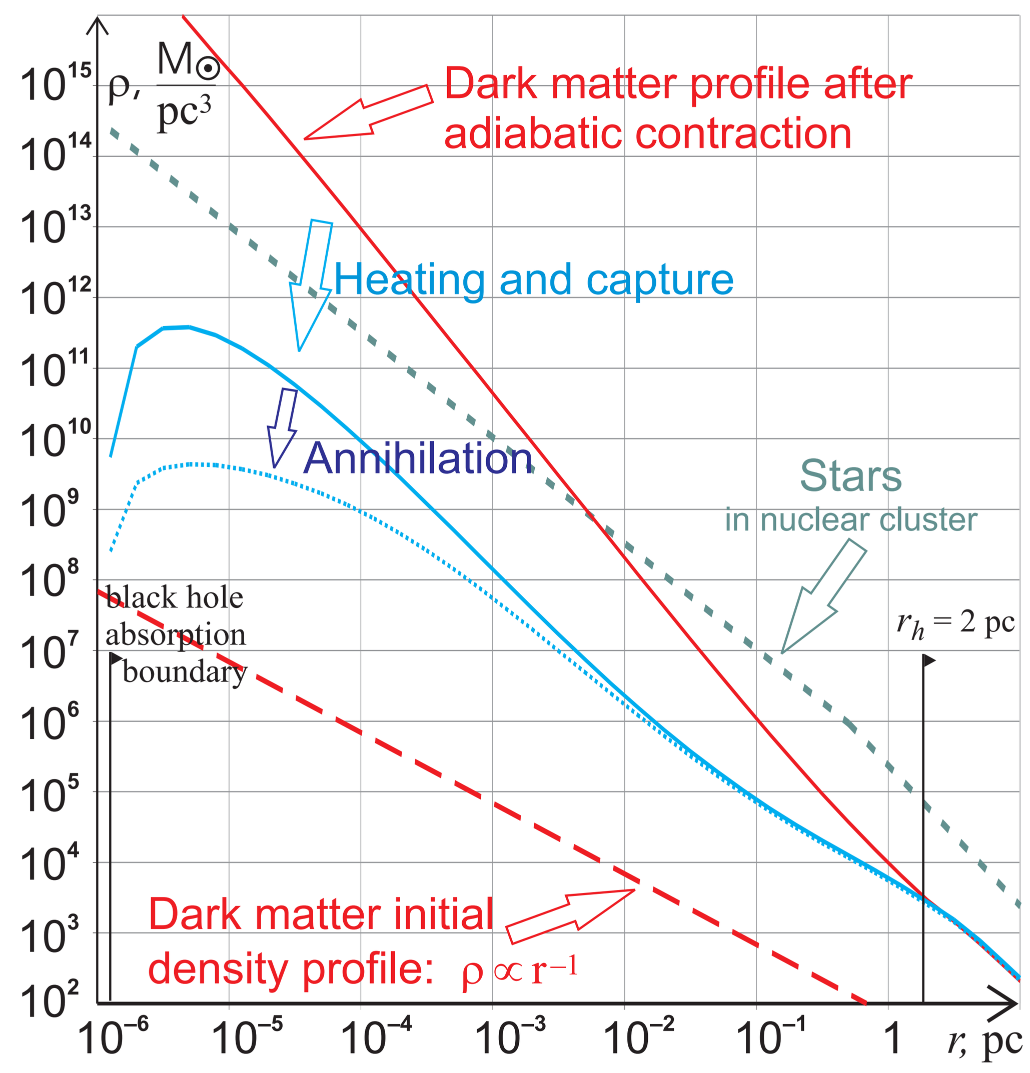

Figure 1: Evolution of dark matter density profile in the galactic centre.
Initial profile is taken in the form $\rho(r) \propto r^{-\gamma}$, $\gamma = 1$ for inner part of NFW profile (red dashed line).
During formation of bulge (green dashed line for star density profile) and black hole in its centre (region $r < r_h \approx 2$ pc is dominated by black hole gravitation) the dark matter is compressed adiabatically (solid red line is DM density after contraction).
Subsequent DM evolution is governed by gravitational scattering on stars which leads to DM heating, and by capture by black hole. The density after 10^{10} years of evolution (solid blue line) is reduced several orders of magnitude inside r_h. Additionally, if the self-annihilation cross-section is large enough, then density in the very centre is depleted even more (dotted blue line).

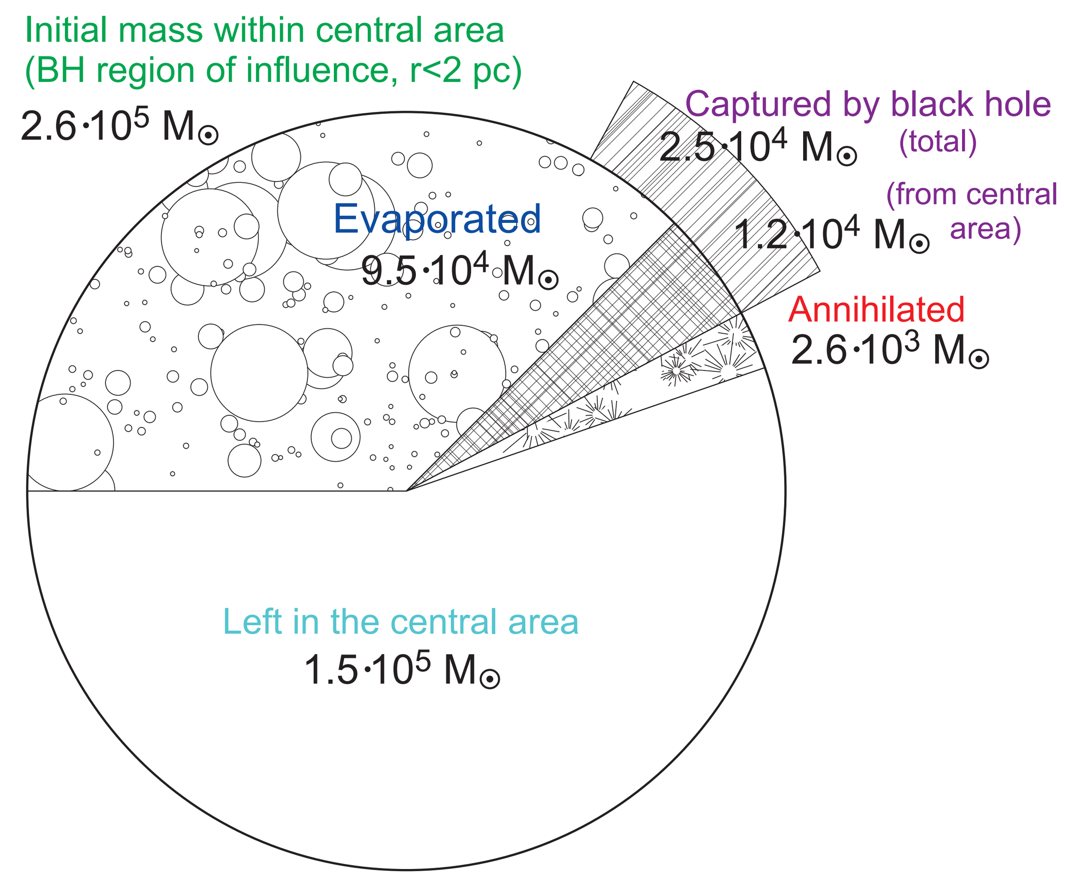

Figure 2: The fate of dark matter inside BH region of influence after 10^{10} yr of evolution (for Milky Way halo, initial DM density profile $\rho(r) = 100M_\odot/\text{pc}^3 \cdot (r/1\ \text{pc})^{-1}$, annihilation cross-section $\langle\sigma v\rangle = 3\cdot 10^{-26}$ cm^3/s, particle mass $M_\chi = 50$ GeV). The numbers are somewhat different for various initial dark matter halo models, but the proportion remains approximately the same: after 10^{10} years almost a half of DM mass is removed from the central region of black hole influence, mostly due to heating by stars. The amount of DM captured by black hole is of order 10% of initial mass, and even less is annihilated.

The difference between initial models is reduced in result of the processes discussed. The knowledge of density profile is crucial for predictions of annihilation flux from Galactic centre. The flux is a product of astrophysical factor, dependent on spatial distribution of dark matter, and a factor dependent on particle mass and cross-section. Recently γ-radiation from Galactic centre was detected by H.E.S.S. Aharonian et al. (2006), which can be attributed to dark matter annihilation. The observed flux is compatible with the results of our calculation for rather typical values of mass and cross-section.

The conclusion is that dark matter distribution in galactic centres significantly changes during the lifetime of the galaxy, mainly because of gravitational interaction with stars of galactic nucleus and supermassive black hole in its centre. Detailed calculation of evolution is needed for making predictions of annihilation flux.

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