Fermionic Dark Matter Distribution as a Lens Model of Galaxy: Inquiring the GL Properties Around the Galactic Center

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university of ferrara
600 YEARS OF LOOKING FORWARD.

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Outline:

- ✧ DM properties
- ✧ DM at small scales
- ✧ The sterile neutrinos
- ✧ The Inos fermionic profile as a lens model of galaxy
  - Halo Part
  - Galactic Center

Dark Particle Candidates

- **Axions**: very well mortivated for particle physics as well as the Neutralino. Axino (fermionic partner, E-WIMPs): Can be produced in both TP and NTP and depending on conditions, the may comprise hot, cold or warm. The mass is model dependent.

- **WIMPs:** Introduced by Lee and Weinberg in the form of stable, left hander. Their mass can lie in the range between a few GeV

- **Sterile Neutrinos:** Right -handed neutrinos in the range of KeV. Help to explain data on neutrino oscillations and are never in thermal equilibrium. They are produced via oscillations from active neutrinos.

The Dark Particle Candidates

We expect DM particle today to be:

- ✧ Non relativistic
- ✧ Non barionic
- ✧ Stable

DM thermal (and non thermal) relics are considered to be produced in the early Universe.

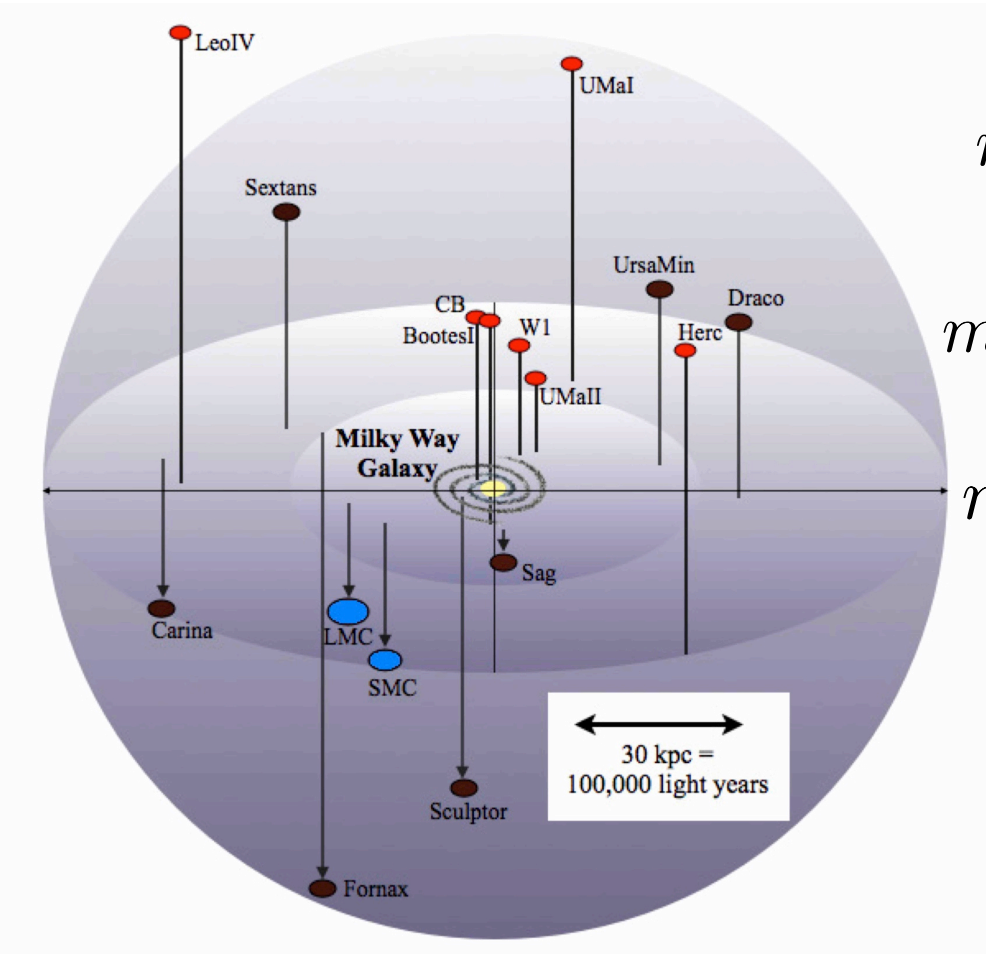
The Theory of structure formation

It happened aproximately 0.1 - 13.7 Gyr, Tiny fluctuation in the distribution of matter strart to grow under the action of gravity. A crucial point is that DM fluctuations can efficiently strart to grow as the Universe become matter dominated, unlike barionic matter which interact with radiation.

Usually the effect of the free streaming is quantized by the length a particle travels before the primordial perturbations start to grow

$$\lambda_{fs} = \int_0^{t_{NR}} \frac{cdt}{a(t)} + \int_{t_{NR}}^{t_{EQ}} \frac{v(t)dt}{a(t)} \simeq r_H(t_{NR}) \left[1 + \frac{1}{2} log \frac{t_{EQ}}{t_{NR}}\right].$$

The Theory of structure formation



$$m_{DM} \sim eV, \quad \lambda_{fs}^{HDM} \sim 10Mpc,$$

$$m_{DM} \sim GeV, \ \lambda_{fs}^{CDM} \sim 0.1pc,$$

$$m_{DM} \sim keV, \lambda_{fs}^{WDM} \sim 60kpc,$$

$$\lambda_{fs} = 57.2kpc\frac{keV}{m}\left(\frac{100}{g_d}\right)^{1/3}.$$

The Linear Power Spectrum

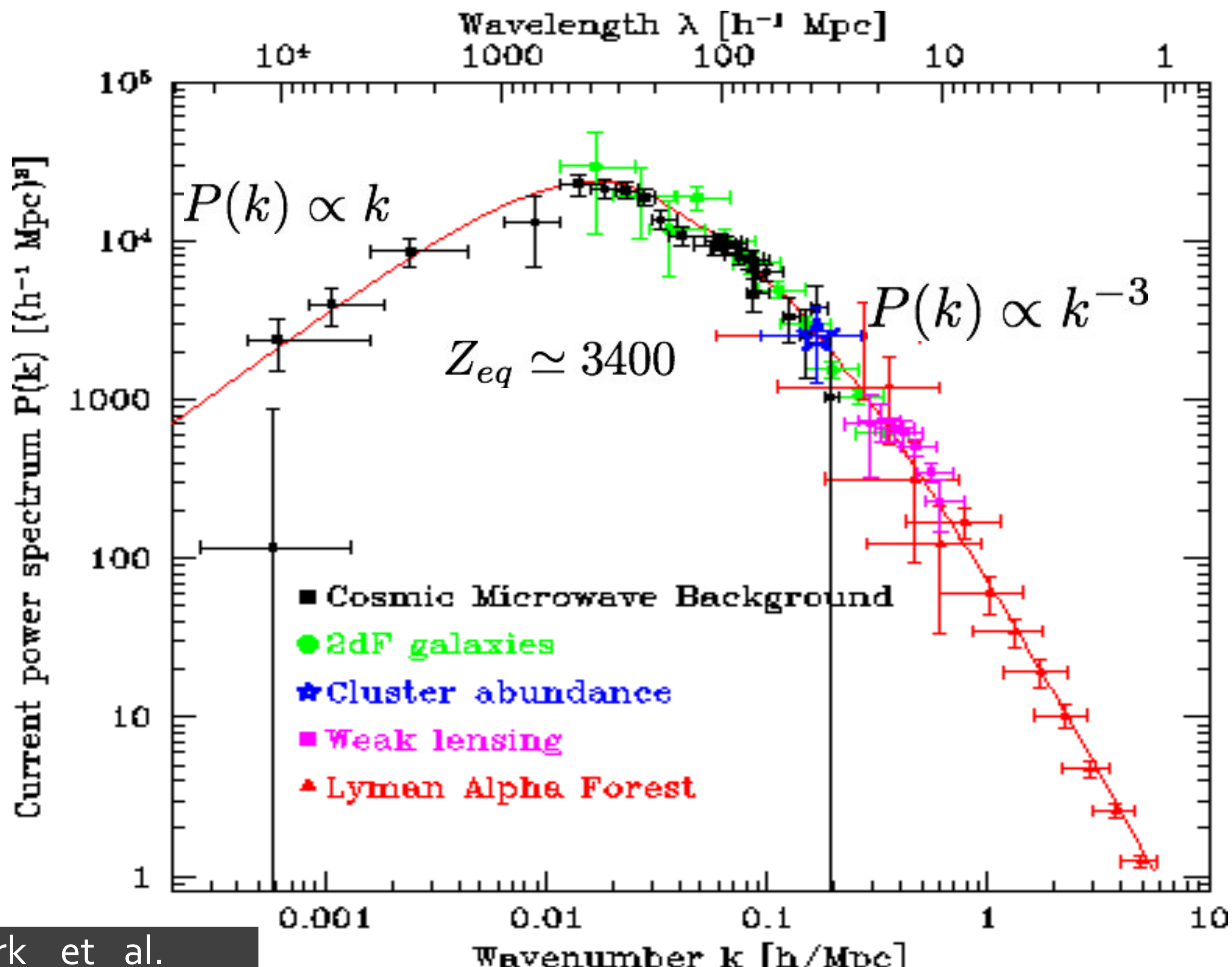


FIGURE SOURCE: Tegmark et al. (2002).

Conflicts of CDM at small Scales

Numerical simulations of CDM predict overabundance of (several hundred) dwarf galaxy halo satellites within the Local Group compared to observations. (B. Moore et al 2009).

Simulations of CDM also predict cuspy profile whereas the density profile inferred from galaxy rotation curves are shallower. (B. Moore et al. 1999.)

Explanations of such problems can be treated by invoking the barionic physics , galaxy formation and dark halos.

One of the most accepted proposals is to modify the properties of dark matter particles. Other alternatives: f(R) , MOND, SIDM.

Astrophysical Constraints: Indirect Detection

Rotation curves of galaxies: Dark matter component is required in order to reproduce data coming from HI.

Distribution of dark matter in galaxies: One of the best observational test of DM is likely to be in the dark matter distribution of faint dwarf galaxies

Galaxy satellites around the MW: Missing problem and too big to fail

Gamma-ray excess: there is an exciting hint of an annihilation spectrum from our Galactic Center which has been seen in Fermi Gamma-Ray Space Telescope data that is not attributable to any known or understood source

***Gravitational lensing*:** helps to constraint the outer and inner part of the halo

The sterile Neutrinos as Warm dark matter

- The formation epoch for small WDM halos is dalayed compared to the formation epoch of their CDM counterpart.

- Suppression of halos due to thermal velocities under the free-streaming mass scale. This thermal velocity also affect the concentration of halos producing core-liked profiles in contrast to the cusp-liked profiles for CDM.

- At later times the particles cool with the expansion and at the present times essencially behave like CDM.

- The lighter the WDM particle the longer it remains relativistic and hence the larger the free-streaming scale.

Non Linear Power Spectrum from Simulations

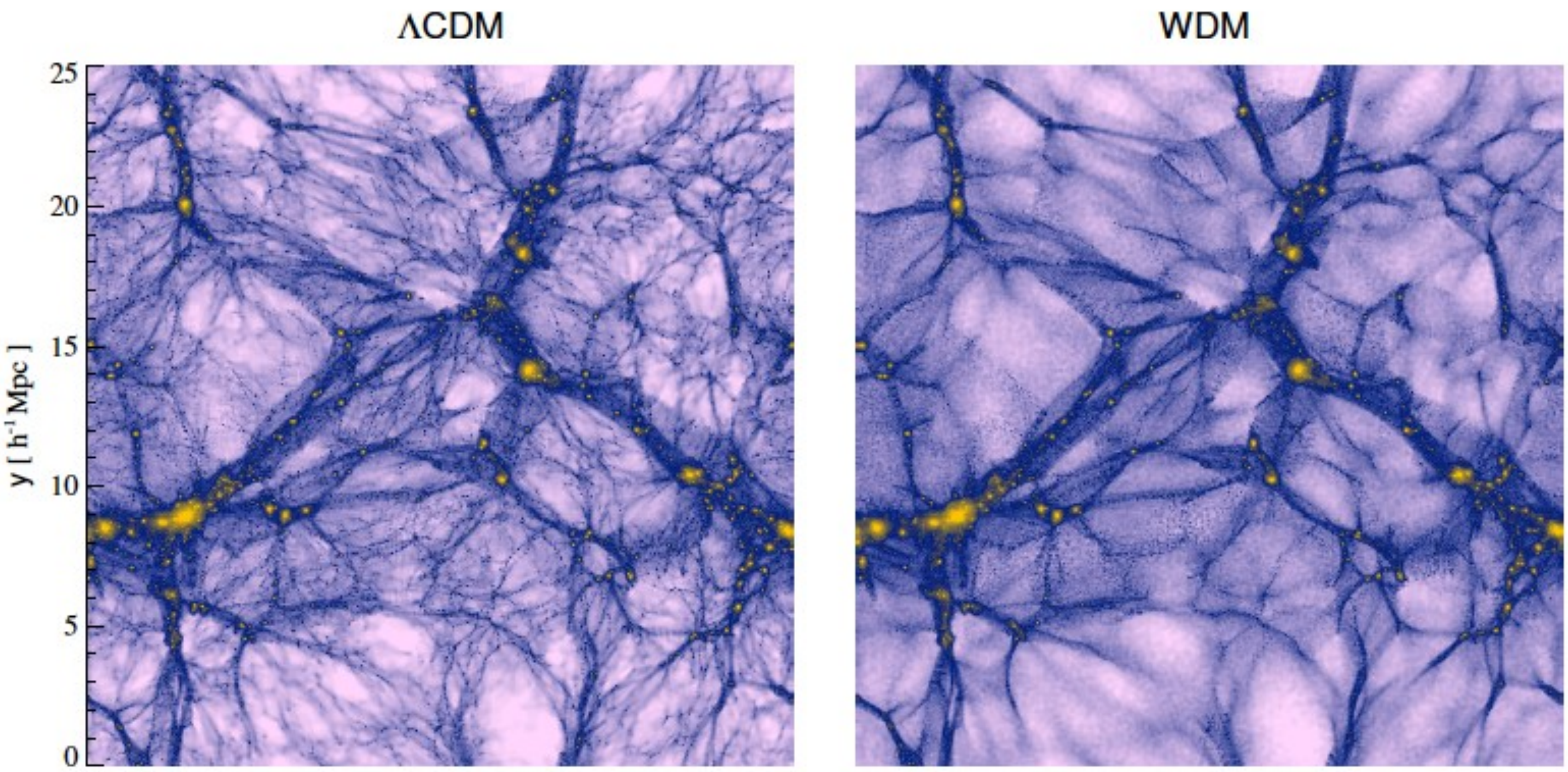


FIGURE SOURCE: Viel et al.

"Standard" Densities profiles

The NFW profile fits results from N-body numerical simulation

$$\rho(r) = \frac{\rho_c}{(r/r_s)(1 + r/r_s)^2},$$

Halos can also be represented in the form of softened isothermal (NSIS)

$$\rho(r) = \frac{\rho_0}{1 + r/r_0},$$

$$\frac{v_c^2}{c^2} = r\Phi\prime(r),$$

$$\Phi = -GM/r.$$

The Fermionic RAR model

The Einstein equations for the spherically symmetric metric

$g_{\mu\nu} = diag(e^{\nu}, -e^{\lambda}, -r^2, -r^2 sin^2\phi)$, are

$$\frac{d\hat{M}}{d\hat{r}} = 4\pi\hat{r}^2\hat{\rho},$$

$$\frac{d\theta}{d\hat{r}} = -\frac{1-\beta_0(\theta-\theta_0)}{\beta_0}\frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})},$$

$$\frac{d\nu}{d\hat{r}} = 2\frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})},$$

Equation of state

$$\rho = \frac{g}{h^3} m \int_0^{\epsilon_c} f_c(p) \left(1 + \frac{\epsilon(p)}{mc^2}\right) d^3p,$$

$$p = \frac{2}{3} \frac{g}{h^3} \int_0^{\epsilon_c} f_c(p) \frac{1 + \epsilon(p)/2mc^2}{1 + \epsilon(p)/mc^2} d^3p,$$

$$f_c(p) = \begin{cases} \frac{1 - e^{(\epsilon - \epsilon_c)/kT}}{e^{(\epsilon - \mu)/kT} + 1} & \epsilon \leqslant \epsilon_c, \\ 0 & \epsilon > \epsilon_c, \end{cases}$$

$$\epsilon = \sqrt{c^2p^2 + m^2c^4} - mc^2.$$

Parameters of the model

$$\beta(r) = \beta_0 e^{\frac{\nu_0 - \nu(r)}{2}},$$

$$W(r) = W_0 + \theta(r) - \theta_0,$$

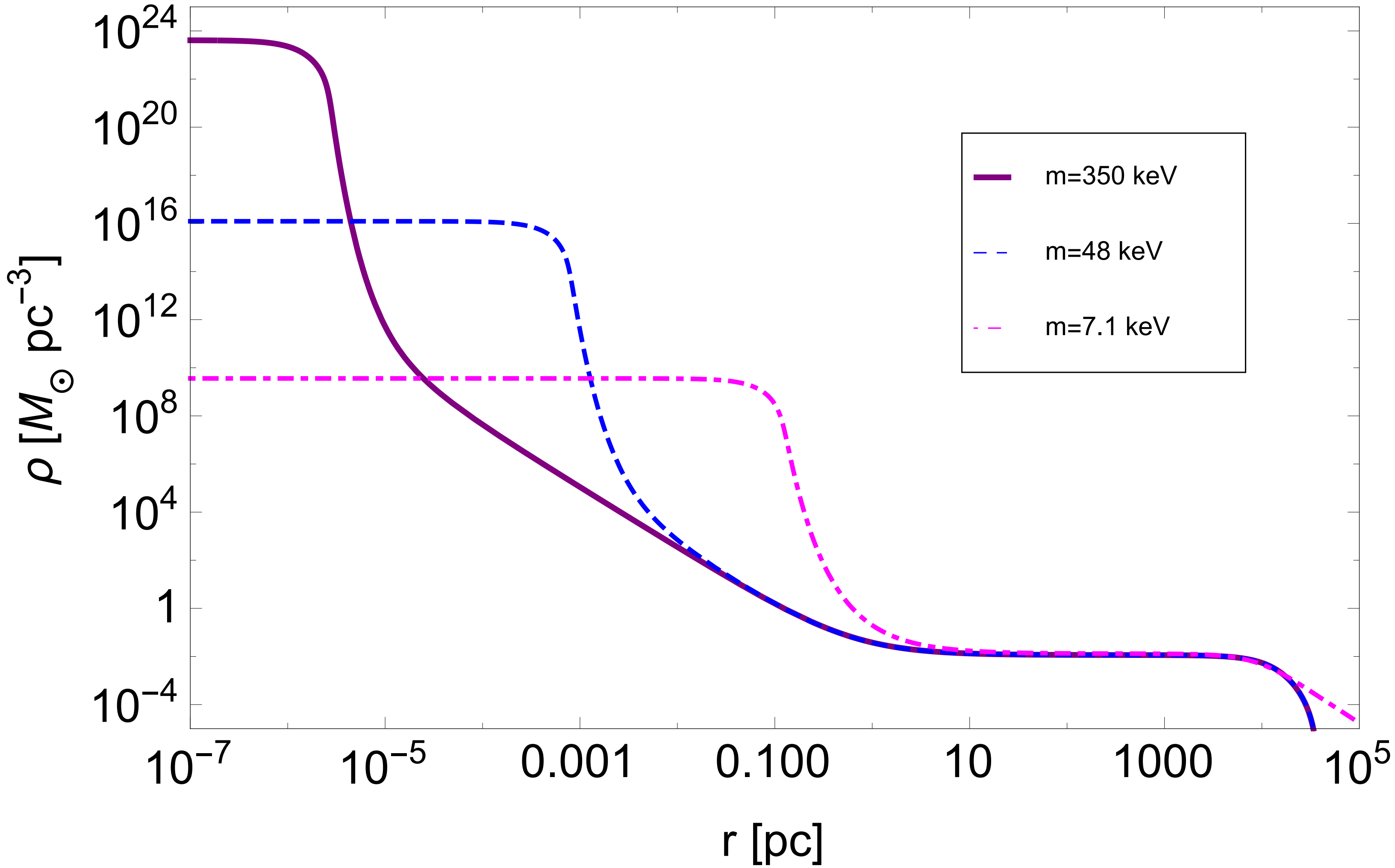
Where the parameters of the model have been defined as

$$\beta = kT/mc^2,$$

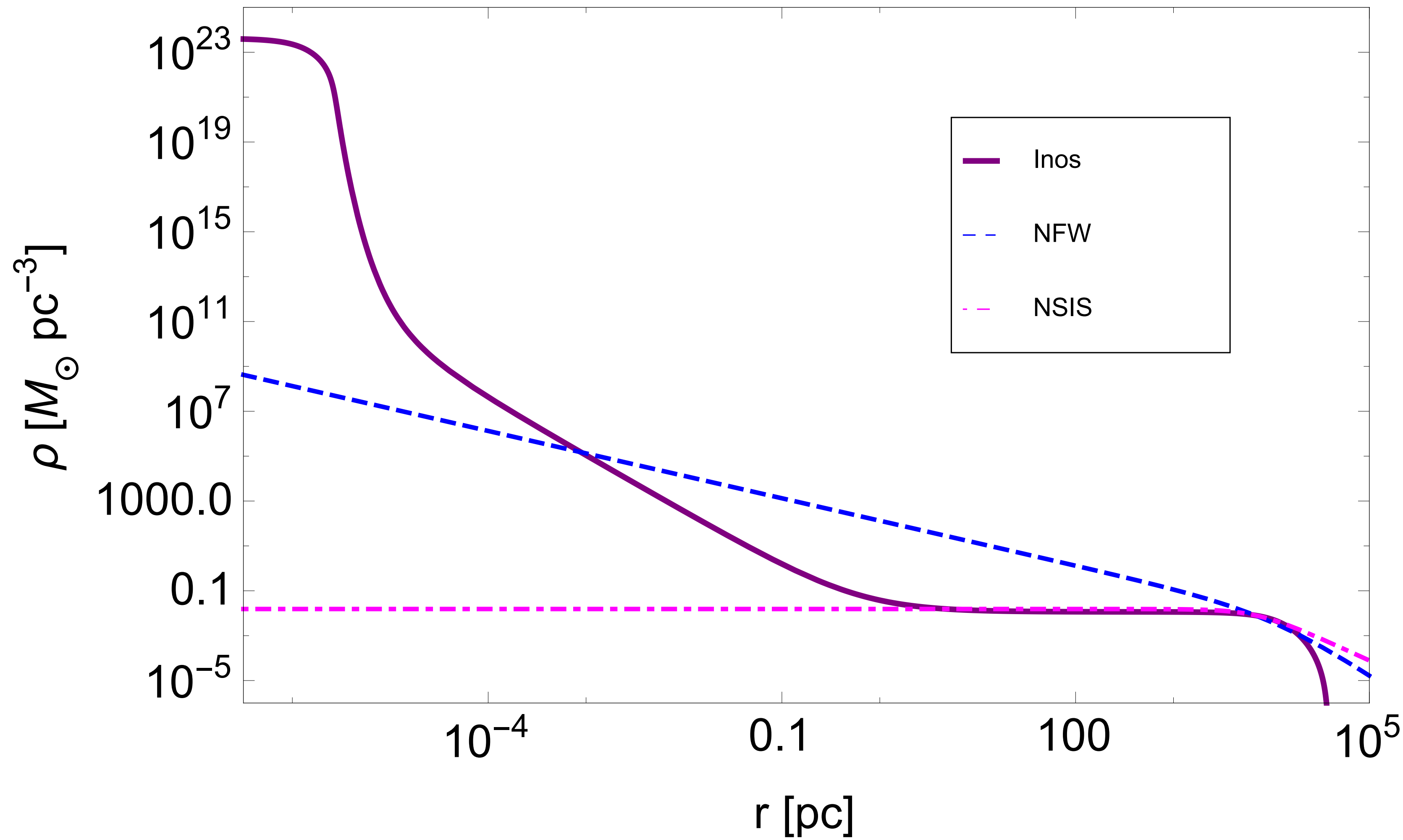
$$\theta = \mu/kT,$$

$$W = \epsilon_c/kT.$$

The density Profile for the MW



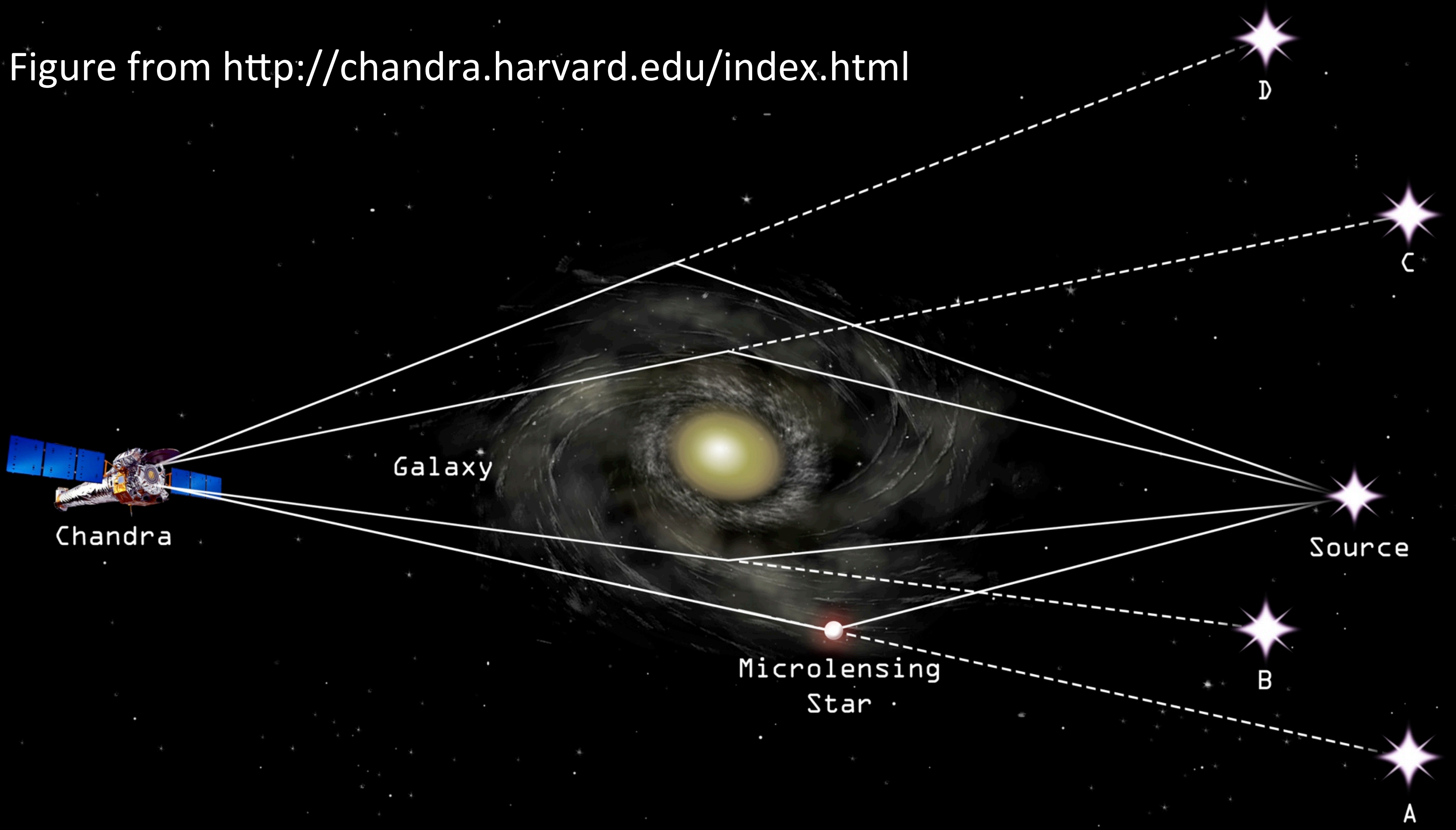
Dark Matter Density Profiles



Could this fermionic density profile act as a lens model of galaxy?

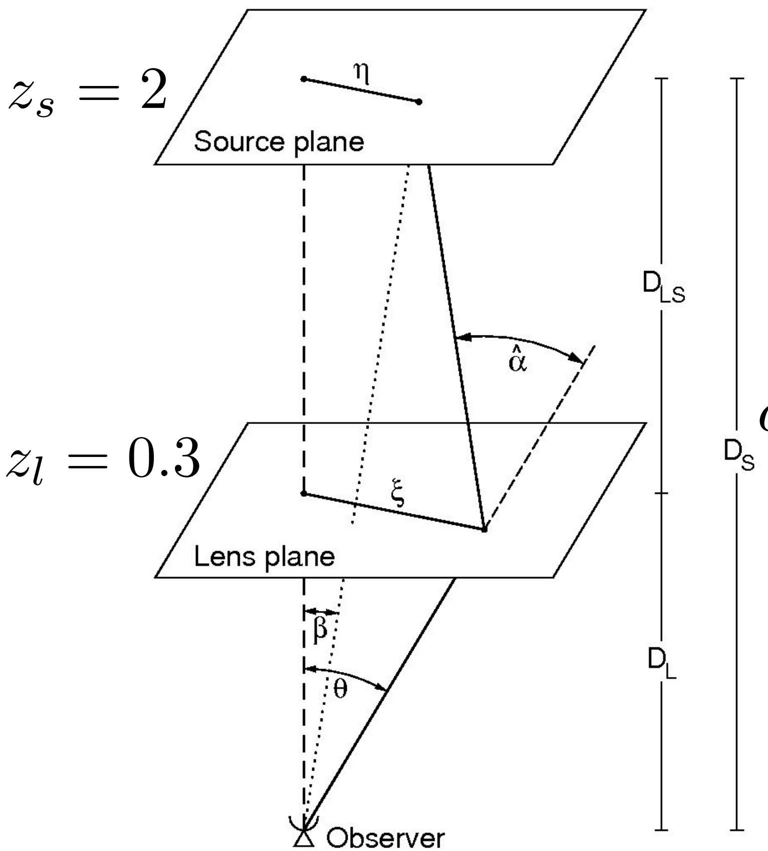
Let's see…

Figure from http://chandra.harvard.edu/index.html



Theory predicts that there should be an odd number of images produced by the lens, but almost all lensed objects have two or four images. The missing 'central' images, which should be faint and appear near the centre of the lensing galaxy.

Sketch of a typical gravitational lensing system



$$D(z) = \frac{c}{H}\frac{1}{(1+z)}\int_0^z \frac{1}{\sqrt{\Omega_\Lambda(z)+\Omega_c(z)}}.$$

$$\Sigma(\xi) = 2\int_0^\infty \rho(\xi, z)dz,$$

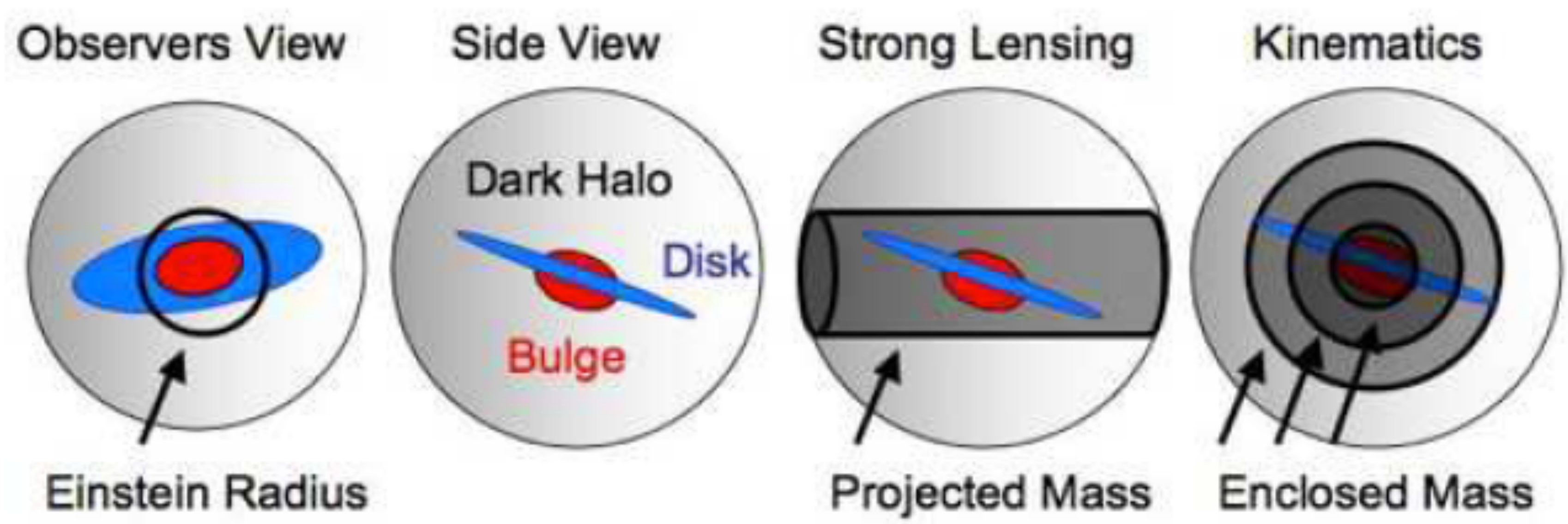
$$\hat{\alpha}(\xi) = \frac{4G}{c^2}\frac{2\pi\int_0^\xi \Sigma(\xi')\xi' d\xi'}{\xi} = \frac{4GM(\leq \xi)}{c^2\xi}.$$

$$k(\xi) = \frac{\Sigma(\xi)}{\Sigma_{cr}},$$

$$\Sigma_{cr} = \frac{c^2}{4\pi G}\frac{D_s}{D_l D_{ls}}.$$

Figure from Bartelmann & Schneider, 2001

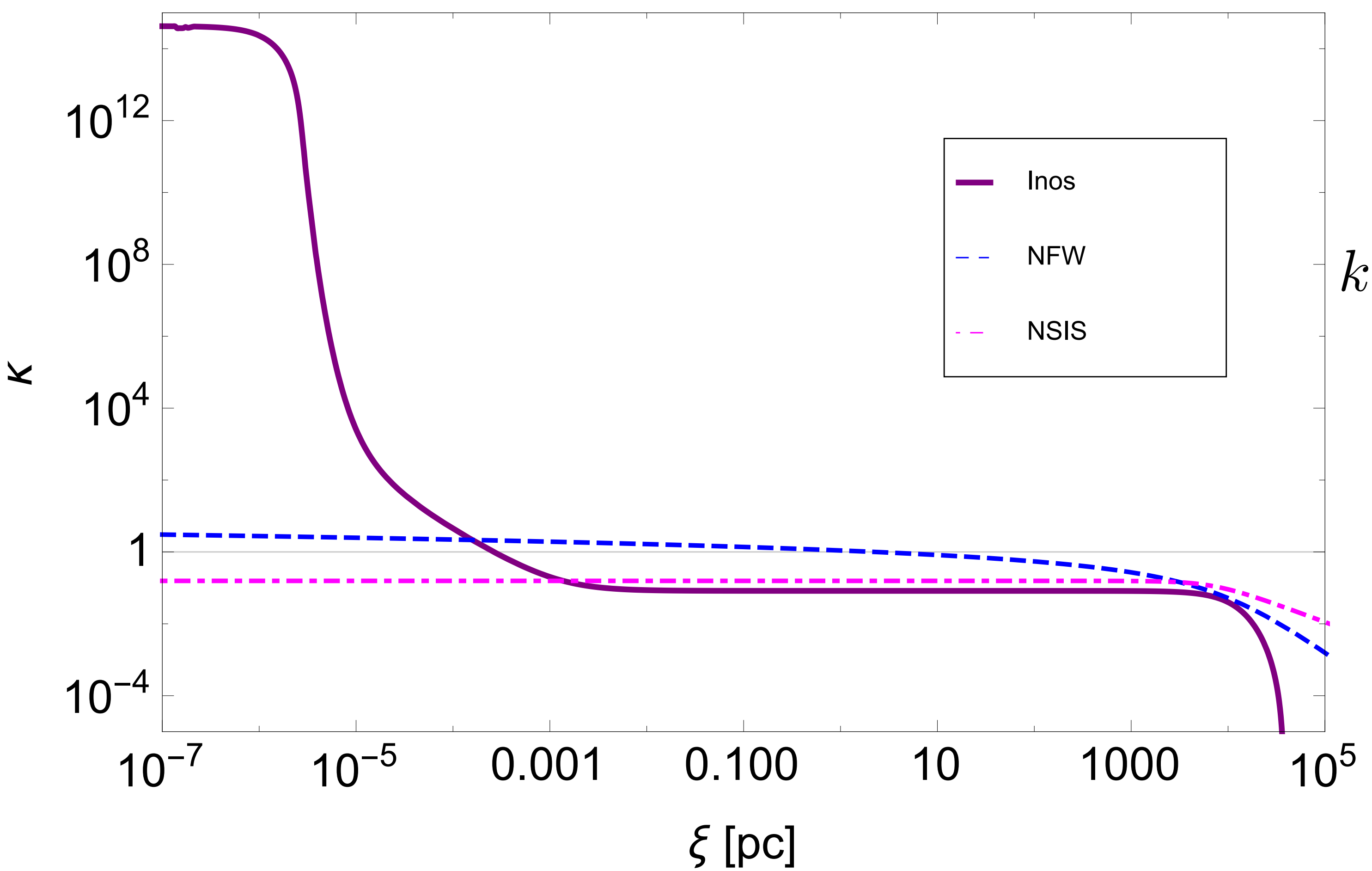
Strong lensing + Kinematic: the disc-halo degeneracy (SWELLS survey) Mass models fit equally well RC and halo is poorly constrained



$$\theta_E = \left(\frac{4GM(\theta)D_{ls}}{c^2 D_l D_s}\right)^2 \approx 1'' \left(\frac{M}{10^{12} M_\odot}\right)^{1/2} \left(\frac{D}{Gpc}\right)^{-1/2}; \; D = \frac{D_l D_s}{D_{ls}}.$$

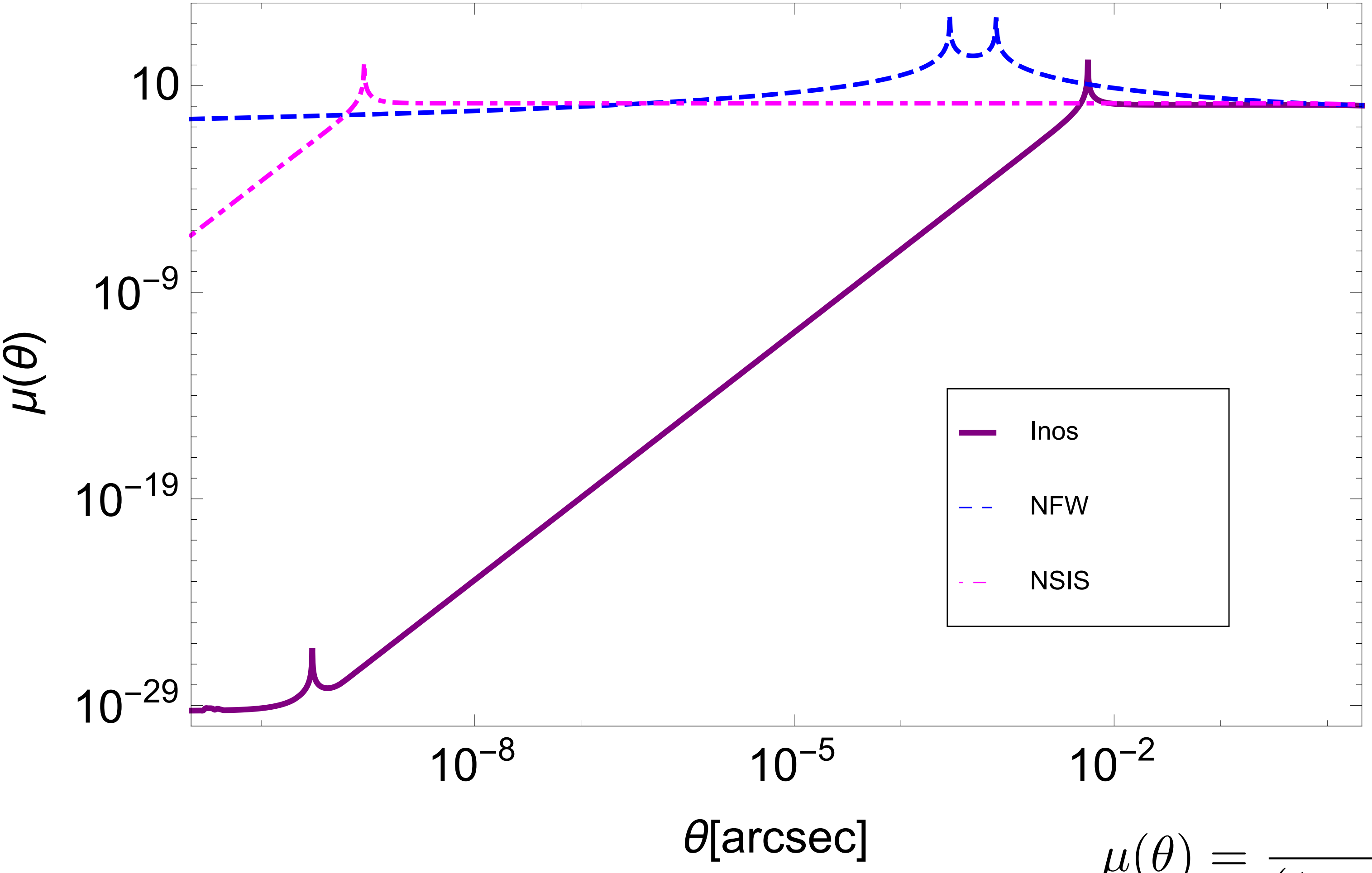
A. A. Dutton et al. 2011

The convergence: the central image flux depends inversely on the square of the surface density, the concentrated density profiles should cause central images to be very faint (or even to have zero flux, if the density is singular)



$$k(\xi) = \frac{\Sigma(\xi)}{\Sigma_{cr}},$$

The magnification factor



$$\mu(\theta) = \frac{1}{(1-k(\theta))^2 - \gamma(\theta)^2}.$$

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The influence of central black holes on gravitational lenses

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ABSTRACT

Recent observations indicate that many if not all galaxies host massive central black holes. In this paper we explore the influence of black holes on the lensing properties. We model the lens as an isothermal ellipsoid with a finite core radius plus a central black hole. We show that the presence of the black hole substantially changes the critical curves and caustics. If the black hole mass is above a critical value, then it will completely suppress the central images for all source positions. Realistic central black holes are likely to have masses below this critical value. Even in such subcritical cases, the black hole can suppress the central image when the source is inside a zone of influence, which depends on the core radius and black hole mass. In the subcritical cases, an additional image may be created by the black hole in some regions, which for some radio lenses may be detectable with high-resolution and large dynamic range VLBI maps. The presence of central black holes should also be taken into account when one constrains the core radius from the lack of central images in gravitational lenses.

Key words: gravitational lensing – galaxies: nuclei – galaxies: structure – cosmology: theory – dark matter.

The central image of a gravitationally lensed quasar

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A galaxy can act as a gravitational lens, producing multiple images of a background object. Theory predicts that there should be an odd number of images produced by the lens[1,2], but hitherto almost all lensed objects have two or four images. The missing 'central' images, which should be faint and appear near the centre of the lensing galaxy, have long been sought as probes of galactic cores too distant to resolve with ordinary observations[3–7]. There are five candidates for central images, but in one case the third image is not necessarily the central one[8–10], and in the others the putative central images might be foreground sources[11–15]. Here we report a secure identification of a central image, based on radio observations of one of the candidates[14]. Lens models using the central image reveal that the massive black hole at the centre of the lensing galaxy has a mass of $<2 \times 10^8$ solar masses ($M_\odot$), and the galaxy's surface density at the location of the central image is $> 20{,}000 M_\odot\,\mathrm{pc}^{-2}$, which is in agreement with expectations based on observations of galaxies that are much closer to the Earth.

Because lensing preserves the frequency of photons, lensed images have the same spectrum (in the absence of differential propagation effects) whereas there is no reason why a foreground active galactic nucleus would have the same spectrum as a background source.

Previously, we attempted this comparison at frequencies from 1.7 to 15 GHz, finding that C was fainter at low frequency than expected for a third image[15]. However, the discrepancy was limited to a single measurement at the lowest frequency, where radio propagation effects are strongest. A central image might be affected more than other images by scintillation or absorption, owing to its passage through the dense galactic centre. Thus we could not come to a firm conclusion before obtaining data at higher frequencies, where propagation effects (scaling characteristically as ν^{-2}) are negligible.

We have now extended our measurements to 22 and 43 GHz, and obtained additional data at 8 and 15 GHz, using the Very Large Array. The high-frequency spectrum of the central component agrees well with those of the bright quasar images (Fig. 2). For $\nu > 1.7$ GHz, the logarithmic slopes of flux density ratio versus frequency (which should be zero for lensed images) are 0.00 ± 0.04 for B/A and -0.02 ± 0.07 for C/A. This is powerful evidence that C is a third quasar image.

The evidence that C is not only a third image, but also a long-sought central image, is its proximity to the centre of the lens galaxy ($\lesssim 30$ milli-arcsec, mas) and its faintness (0.41% the flux density of A). This sets PMN J1632–0033 apart from the only other three-image system known, Automatic Plate Measuring Survey (APM) 08279+5255, in which the lens galaxy has not been detected, and the fluxes of all three images are of the same order of magnitude. (Similar fluxes suggest that the third image in that system may not be a central image, but rather a 'naked-cusp' image due to a highly flattened mass distribution[8,9].)

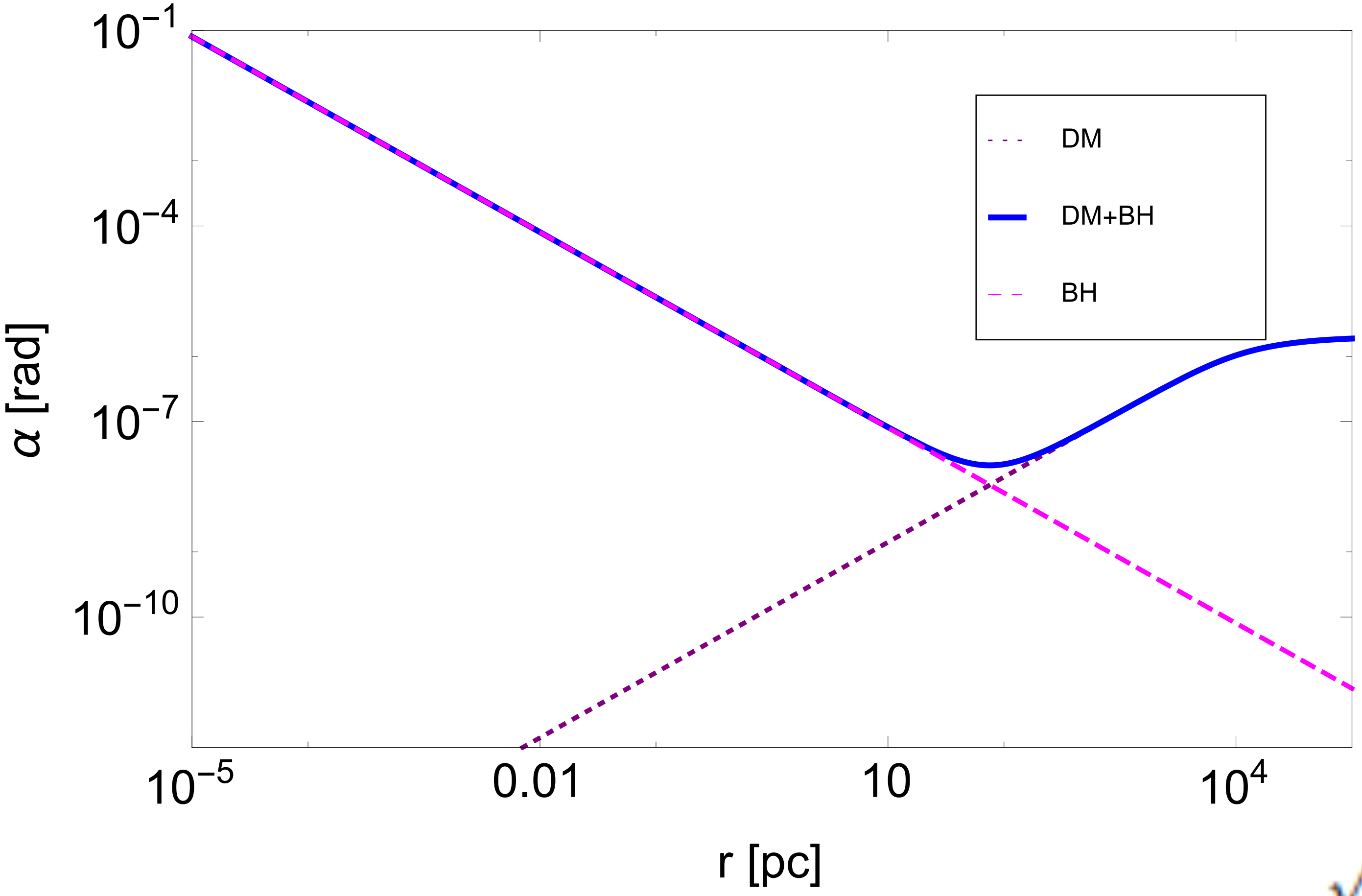
The bending angle

$$\hat{\alpha}(r_0) = 2\int_{r_0}^{\infty} \frac{e^{\lambda/2}dr}{\sqrt{(r^4/b^2)e^{-\nu} - r^2}} - \pi,$$

$$\hat{\alpha}(r_0) = \frac{4M}{r_0} + \mathcal{O}\left(\frac{M^2}{r_0^2}\right).$$

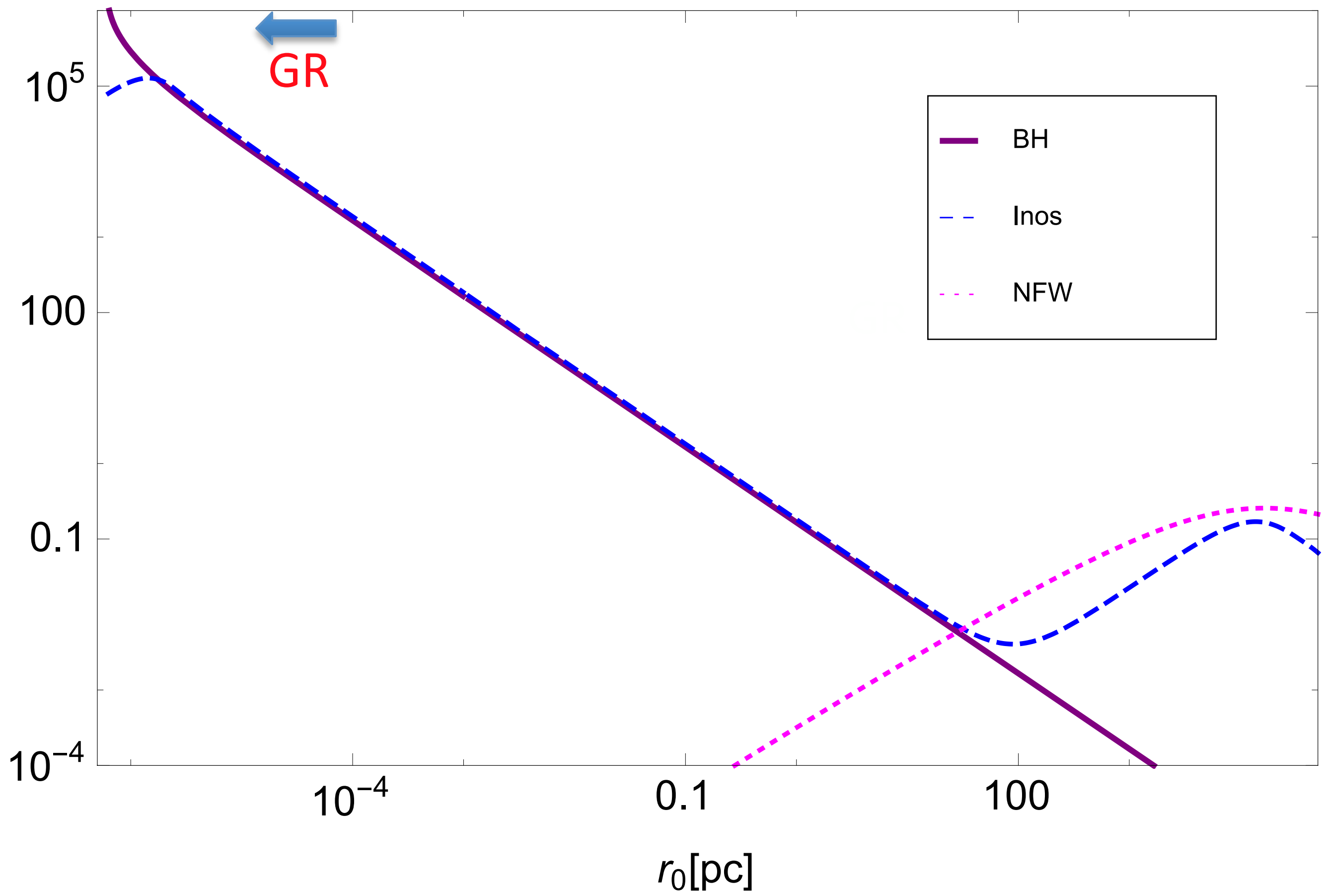
$$\hat{\alpha}(\xi) = \frac{4G}{c^2}\frac{2\pi\int_0^{\xi}\Sigma(\xi')\xi' d\xi'}{\xi} = \frac{4GM(\leq\xi)}{c^2\xi}.$$

The bending angle along the entire galaxy



$$\alpha(r) = \frac{\sqrt{r^2 + r_c^2} - r_c}{r} + \frac{m}{r},$$

The bending angle along the entire galaxy

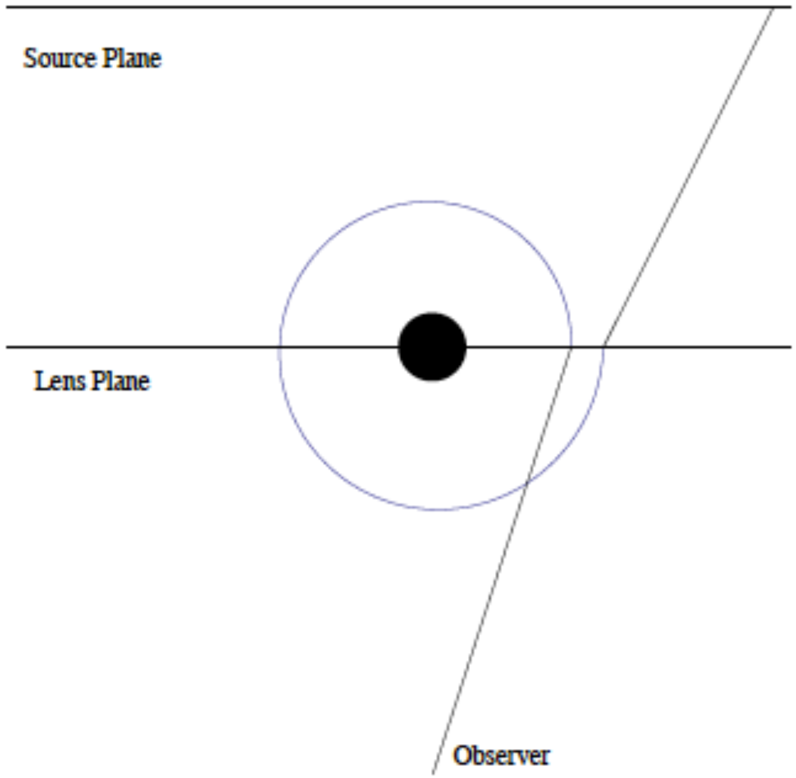


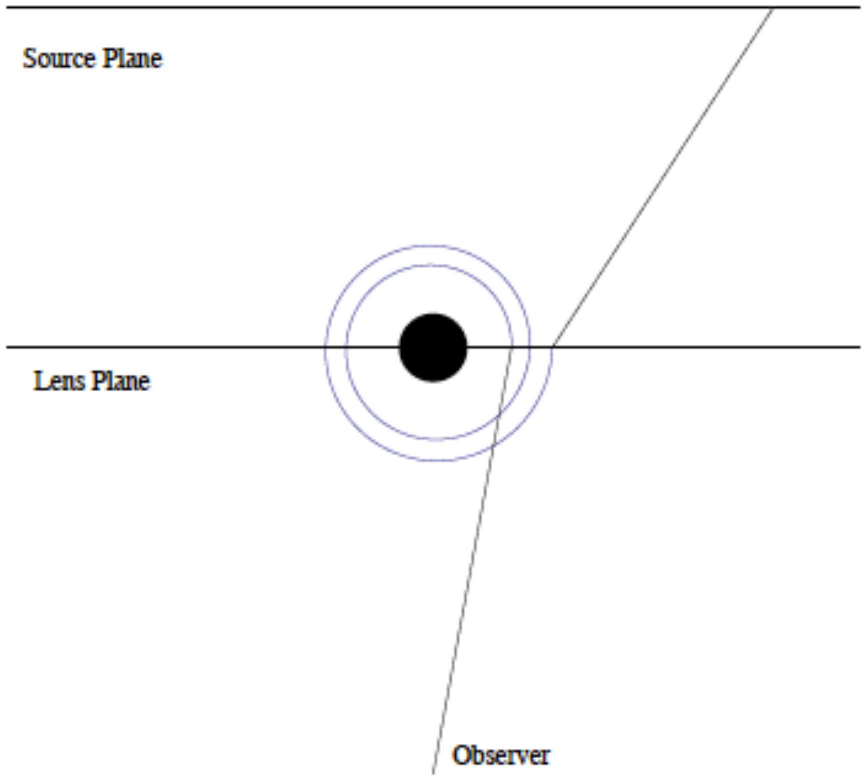
$$\hat{\alpha}^{NFW}(R^{GC}) \approx 0.24'',$$

$$\hat{\alpha}^{NSIS}(R^{GC}) \approx 0.59'',$$

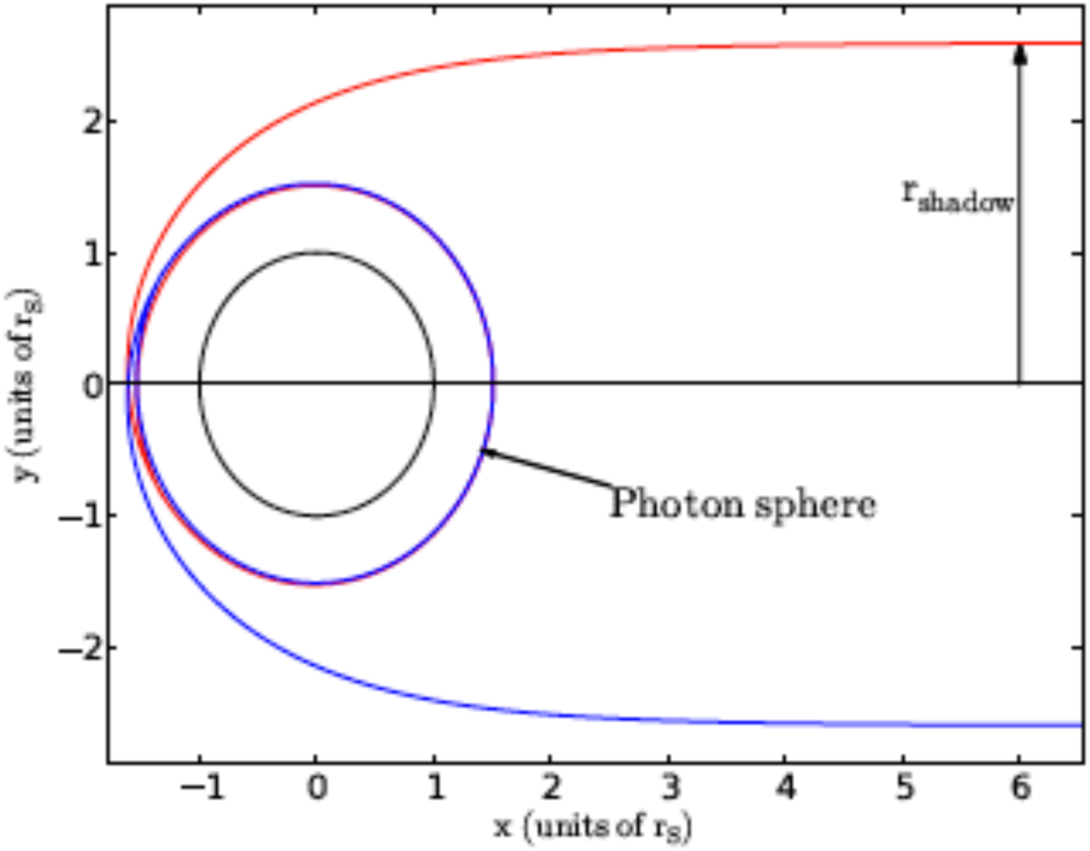
$$\hat{\alpha}^{Inos}(R^{GC}) \approx 0.15''.$$

Black Hole lensing prediction

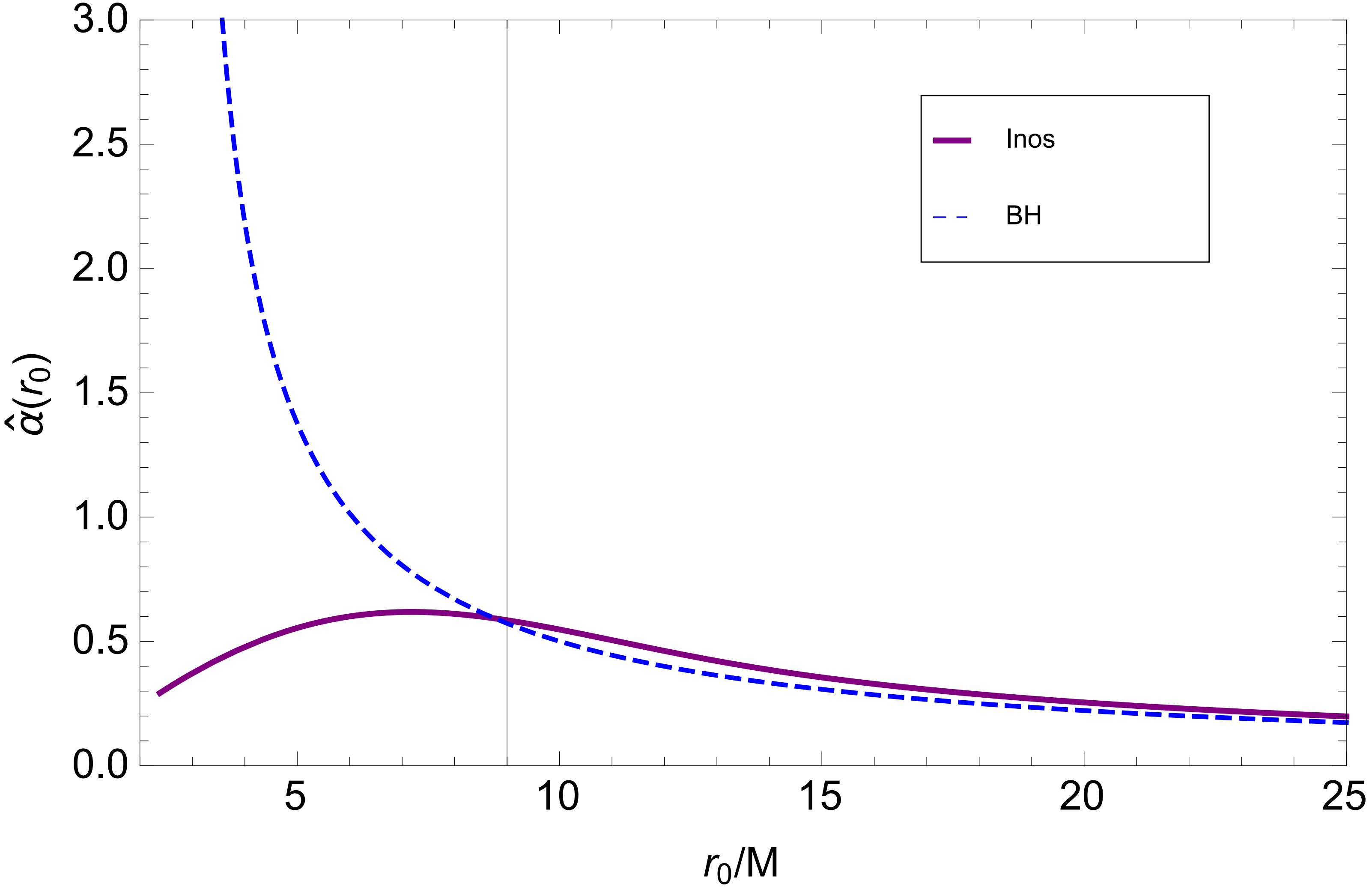




Black Hole lensing in GR



The bending angle at the GC



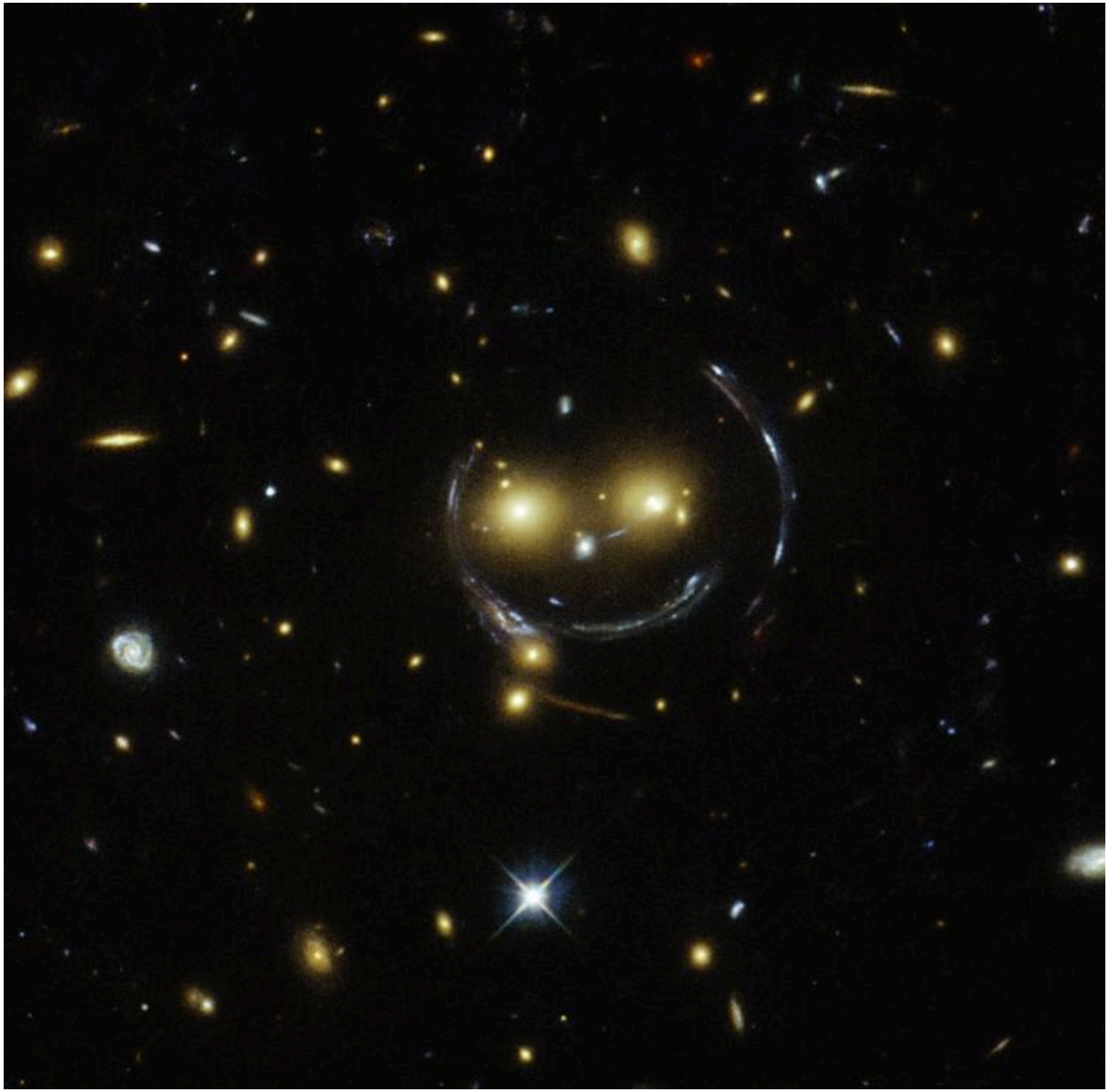
Conclusions

- We study the gravitational lensing properties of DM fermions as a lens model of galaxies.

- Density profile which fit RC's data and can simultaneously act as a lens model.

- DM central core can produce a demagnified image (Einstein rig) at the center of galaxies as in the case of BH.

- The RAR model can mimic dynamically the central compact object in Sgr A* but is unable to account for the formation of the photon sphere (multiple images).



Thank you