Probing properties of dark matter via stellar kinematics around Sagittarius A*

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(arXiv:2205.04970, arXiv:2303.09284)

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Content

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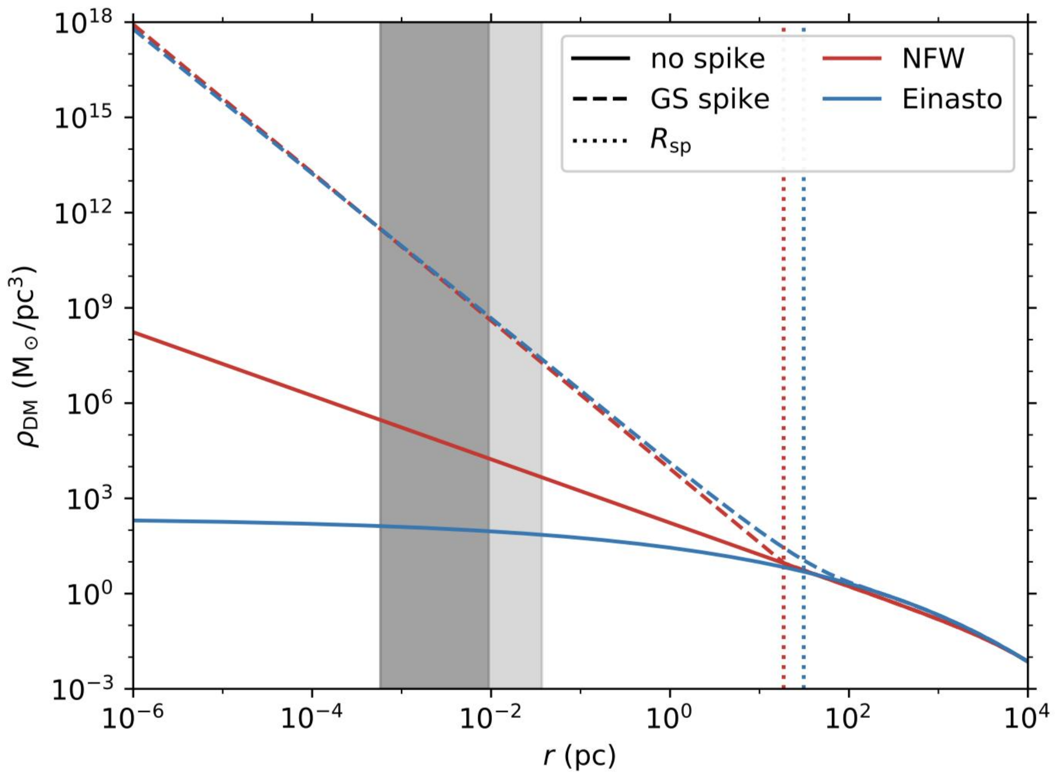
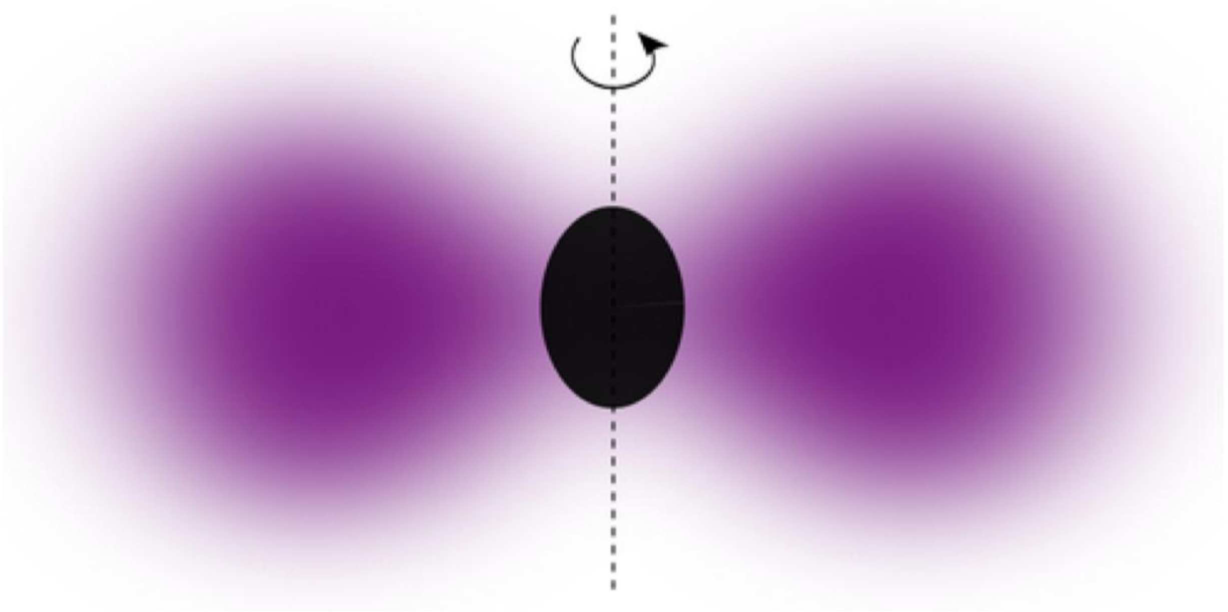
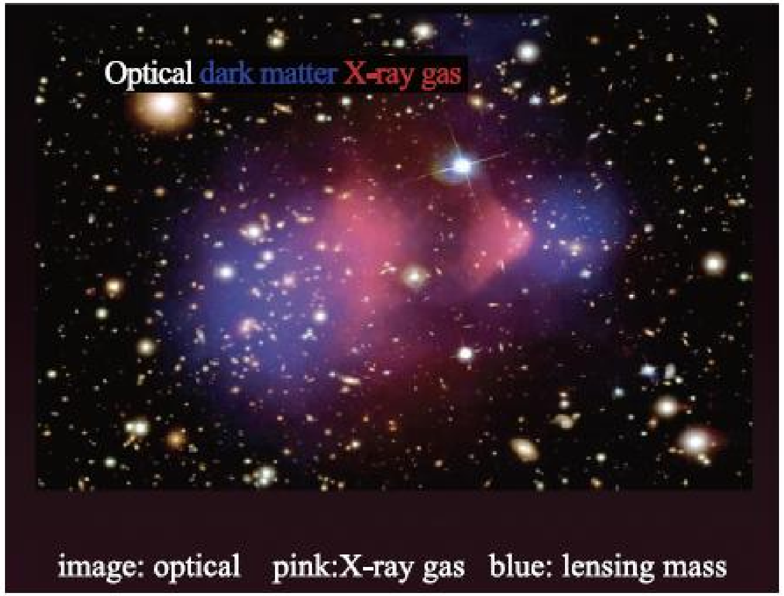
- Probing specific couplings between ultra-light bosonic dark matter and standard model particles

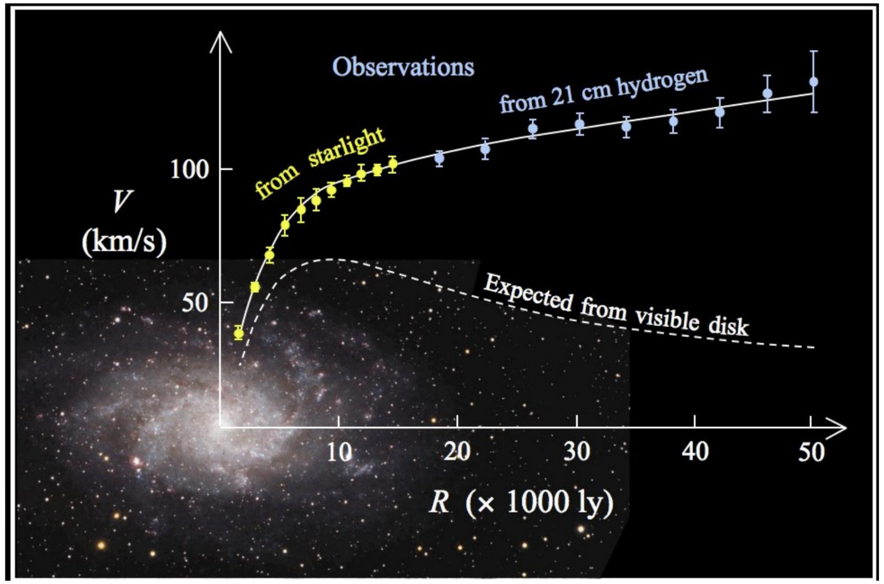




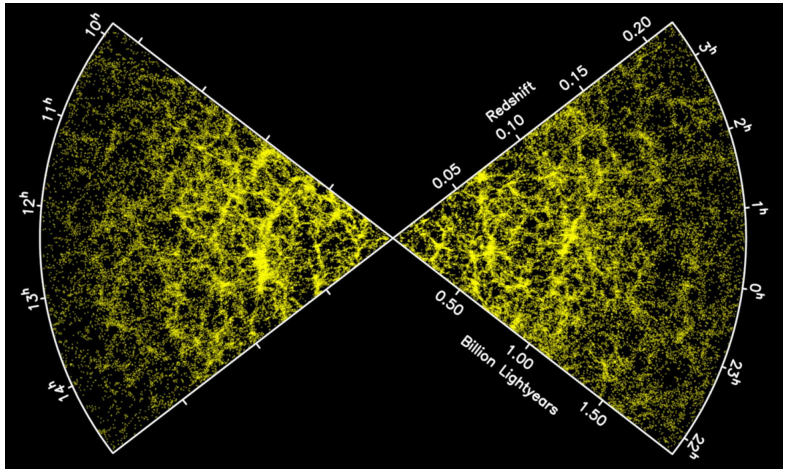
Observational evidence of dark matter



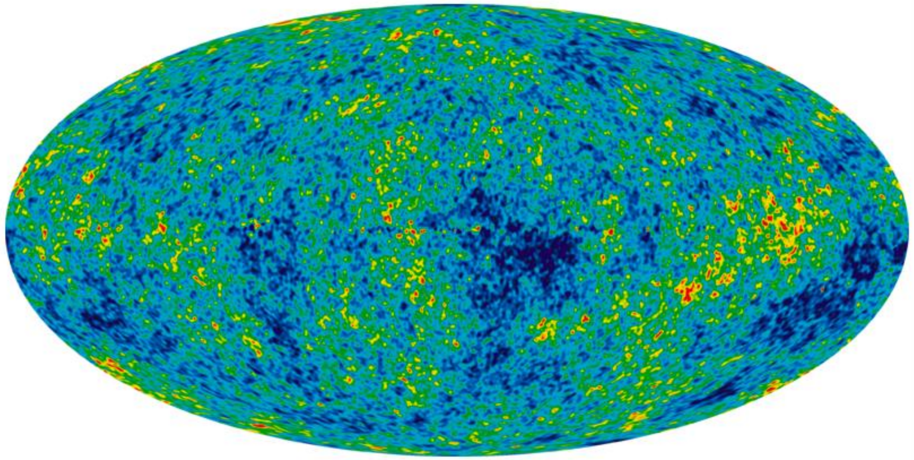
Lensing of Galaxy Clusters



Galactic Rotation Curve

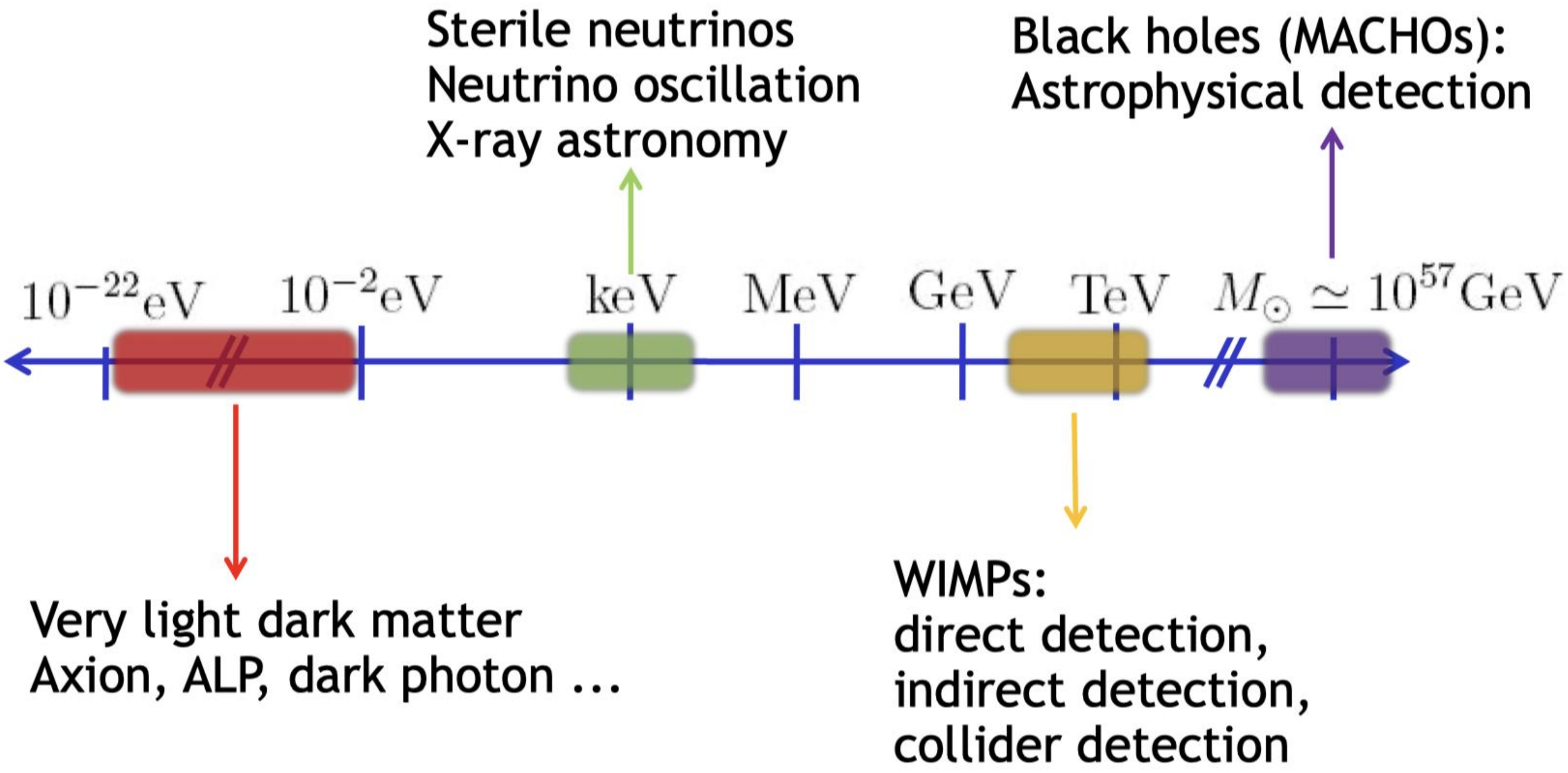


Large Scale Structures

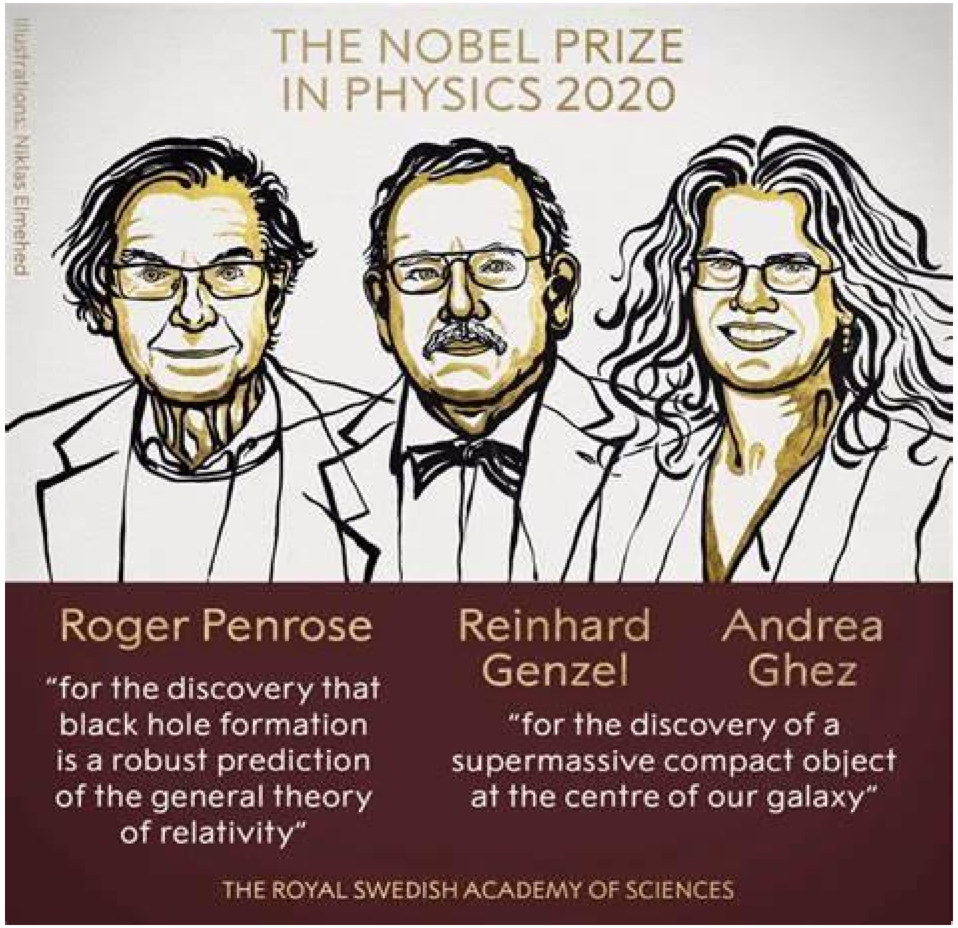


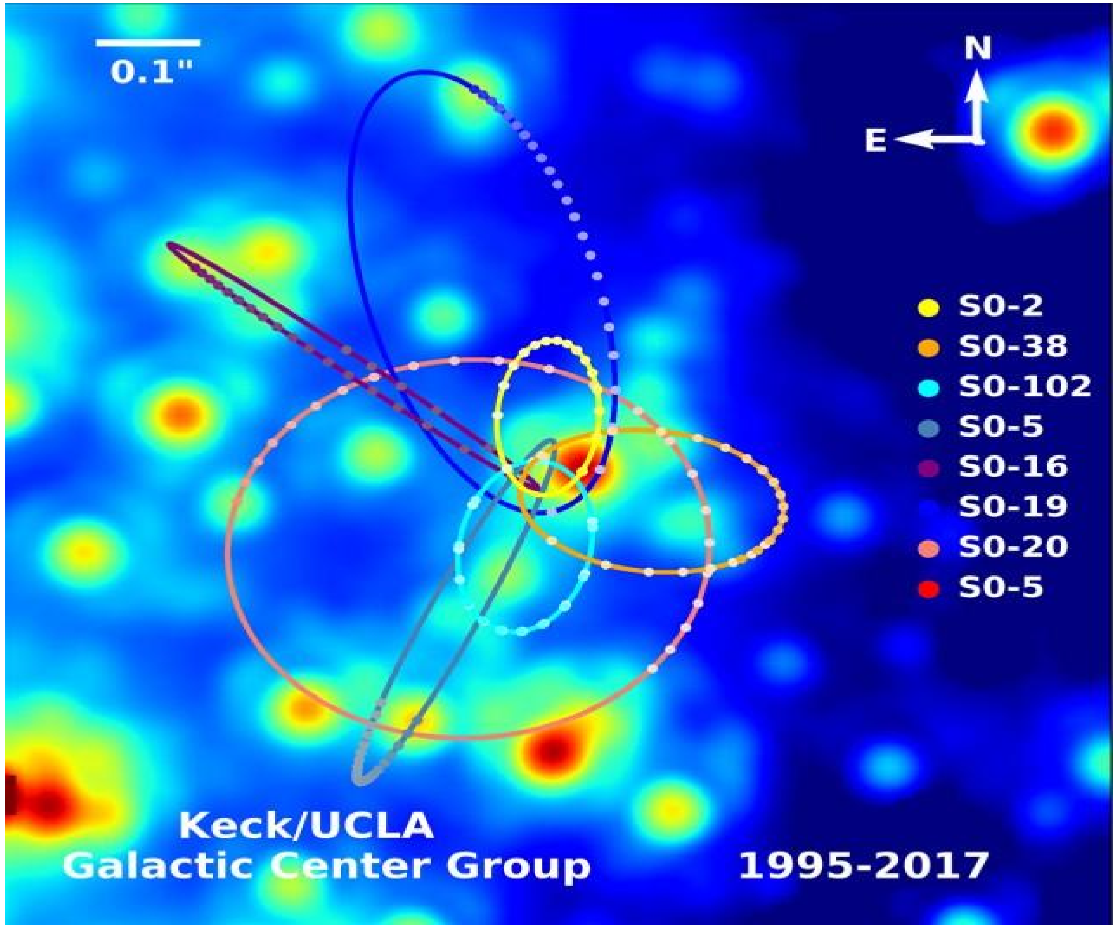
Cosmic Microwave Background

Dark matter candidates



Stellar kinematics around SMBH in the Galactic center





Using the precision measurements of orbits and kinematics of S stars in the Galactic center, a compact object with mass of ~4 million solar mass was revealed, which is consistent with a supermassive black hole.

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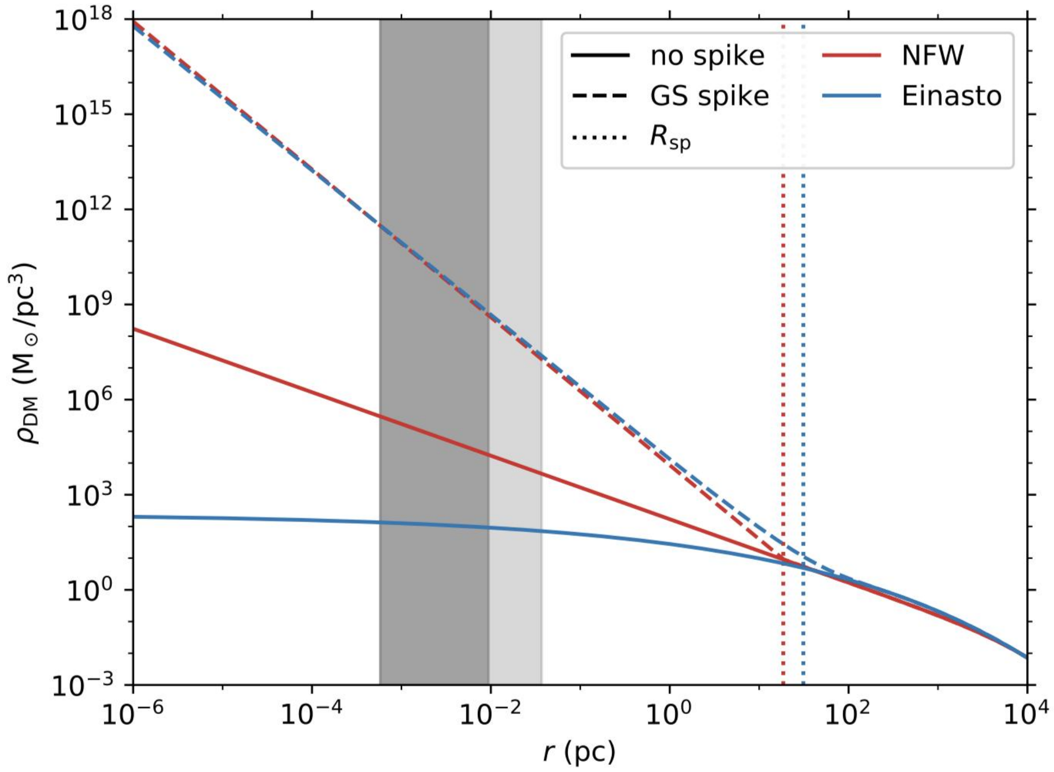
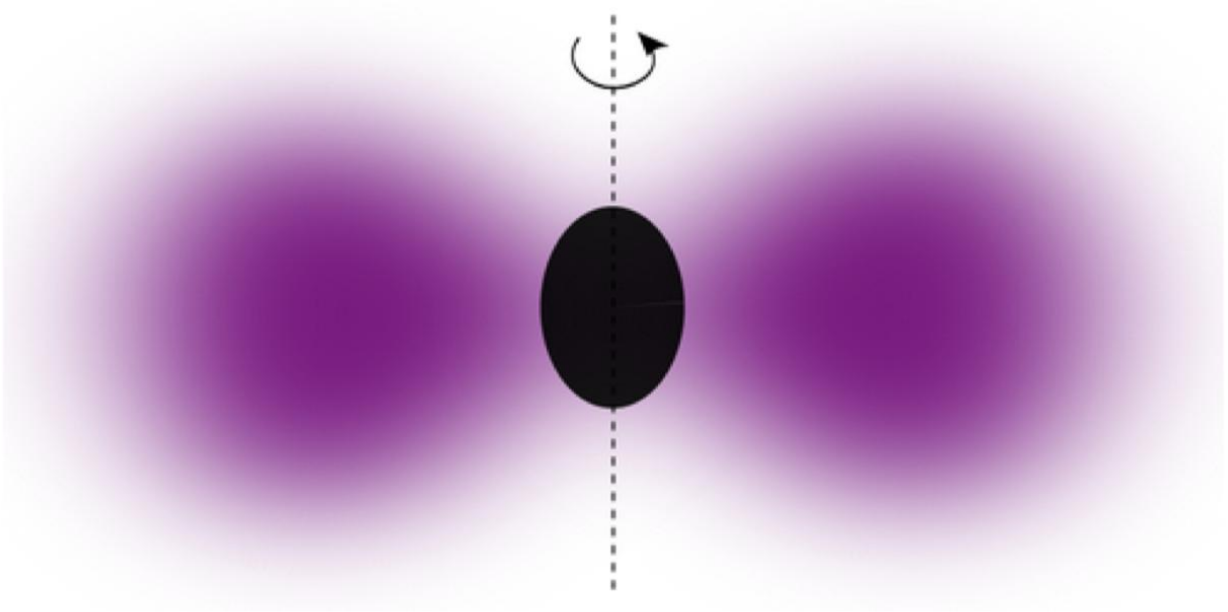
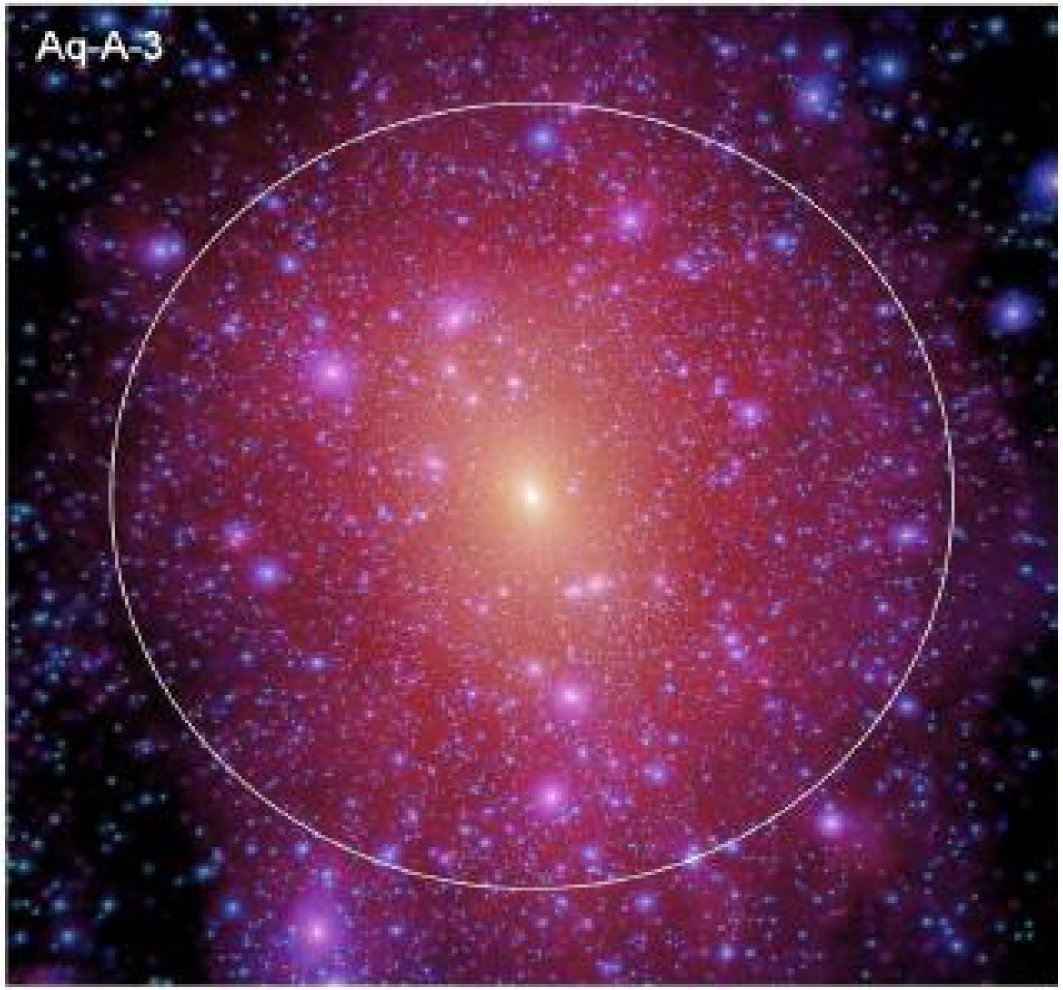
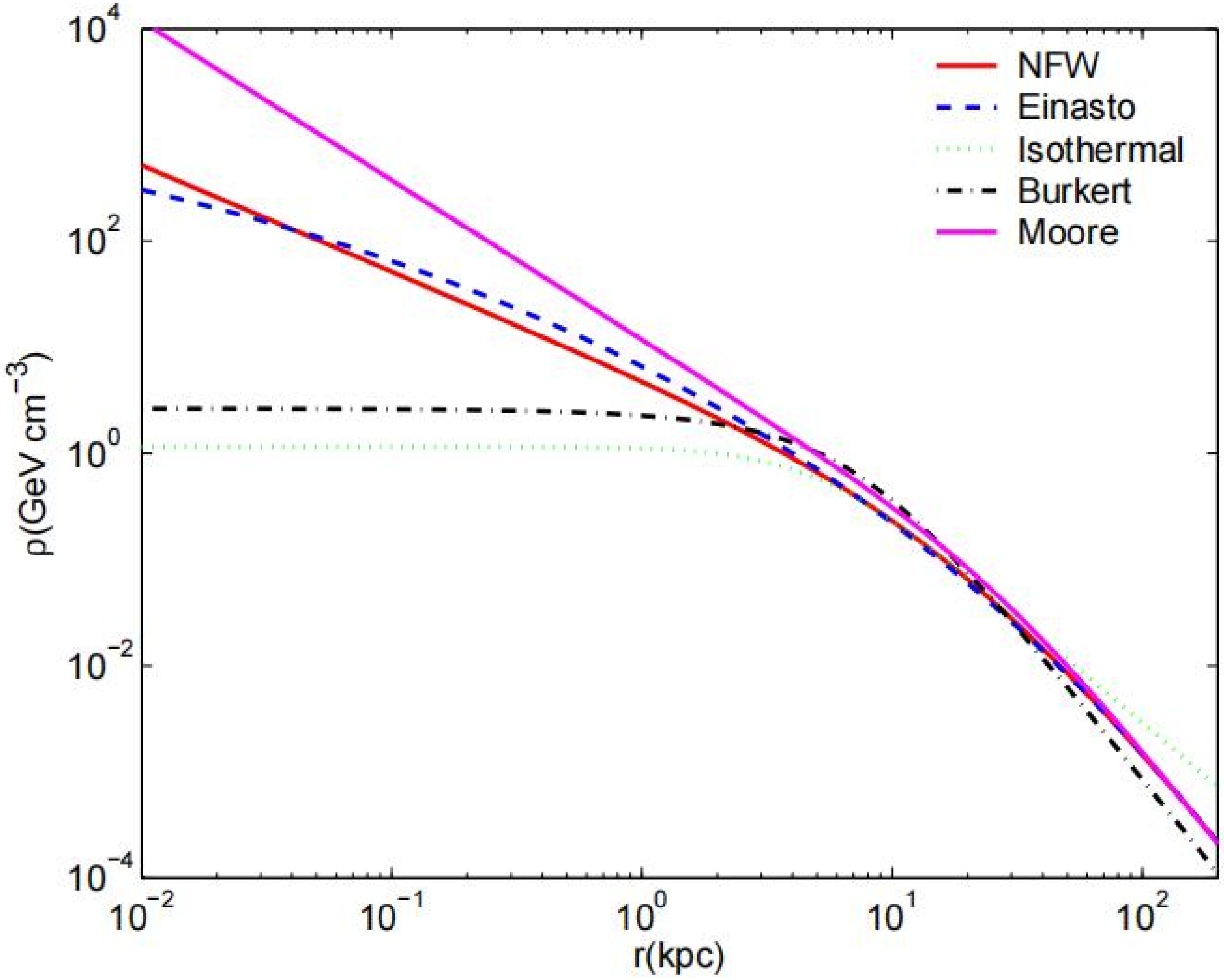




Dark matter distribution in the Milky Way



Aquarius simulation



Density spike due to adiabatic growth of black hole

$$\rho'(r) = \int_{E'_m}^{0} dE' \int_{L'_c}^{L'_m} dL' \, \frac{4\pi L'}{r^2 v_r} f'(E', L')$$

Conservation of phase space distribution, angular momentum, and radial action

$$f'(E', L') = f(E, L), \; L' = L, \; I'(E', L') = I(E, L)$$

Density spike

$$\rho'(r) = \rho_R \, g_\gamma(r) \left(\frac{R_{\rm sp}}{r} \right)^{\gamma_{\rm sp}}$$

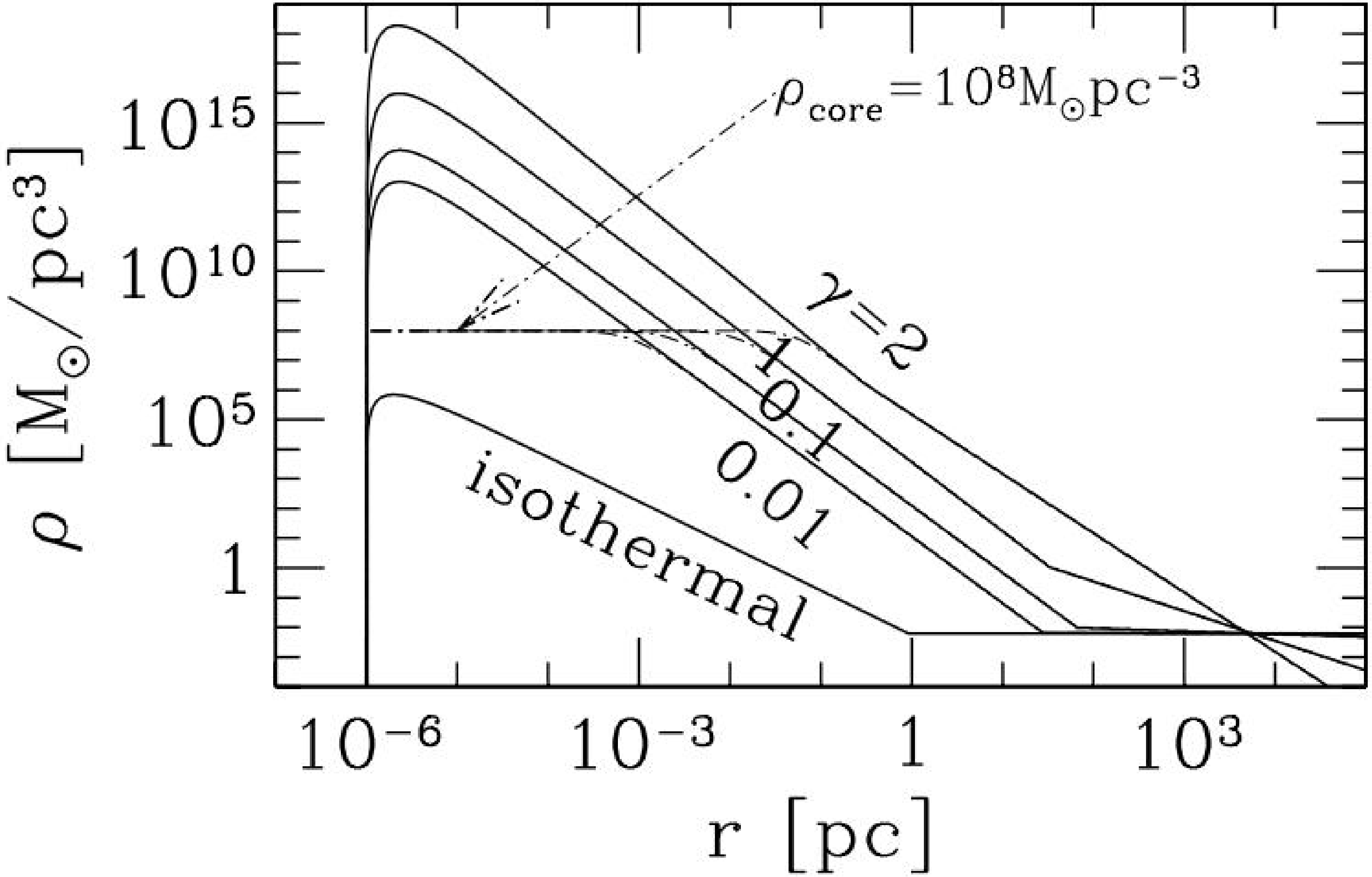
$$\gamma_{\rm sp} = (9 - 2\gamma)/(4 - \gamma)$$

Annihilation suppression

$$\rho_{\rm sp}(r) = \frac{\rho'(r)\rho_{\rm core}}{\rho'(r) + \rho_{\rm core}}$$

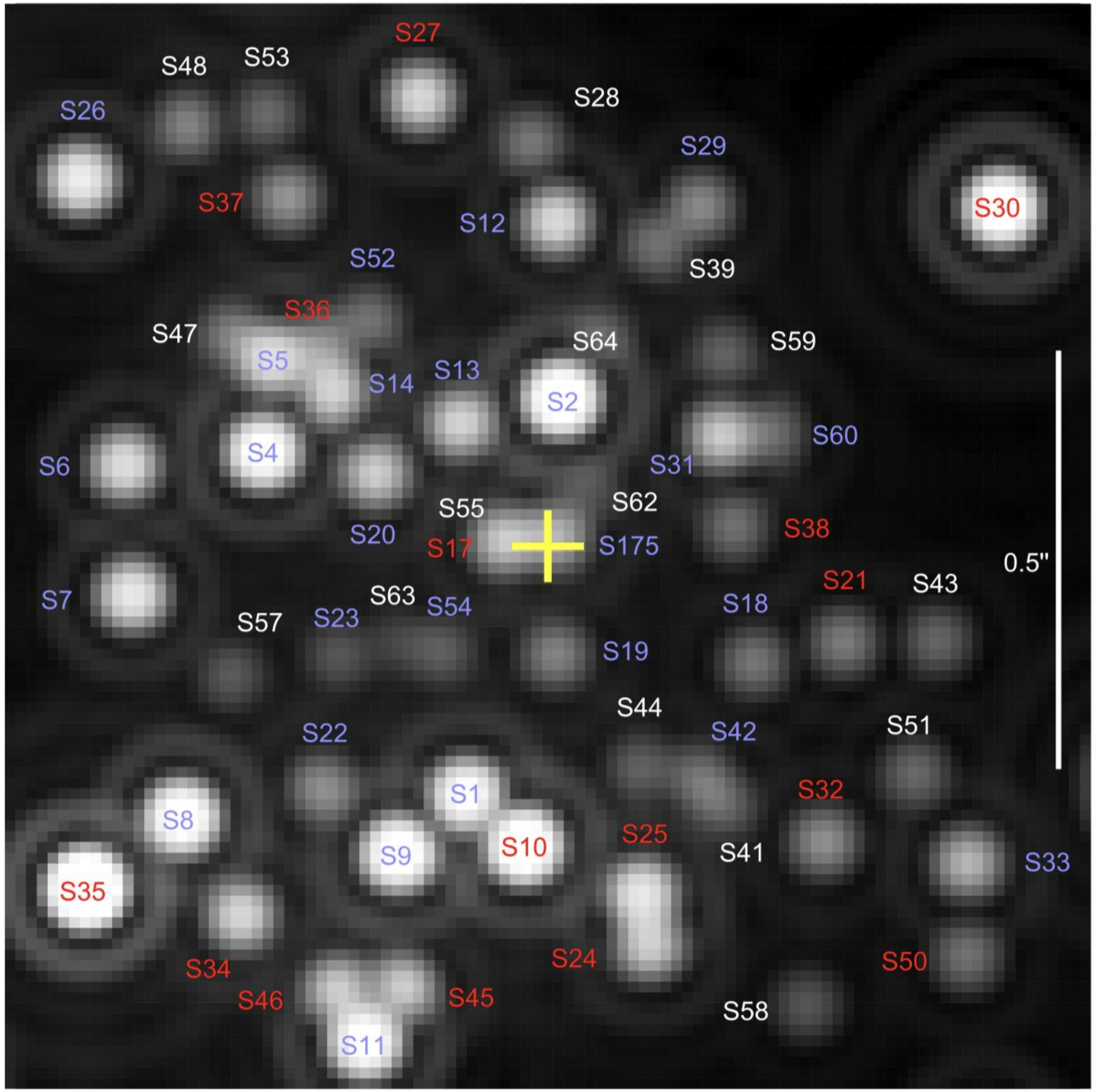
Gondolo and Silk (1999, PRL)

Density spike due to adiabatic growth of black hole



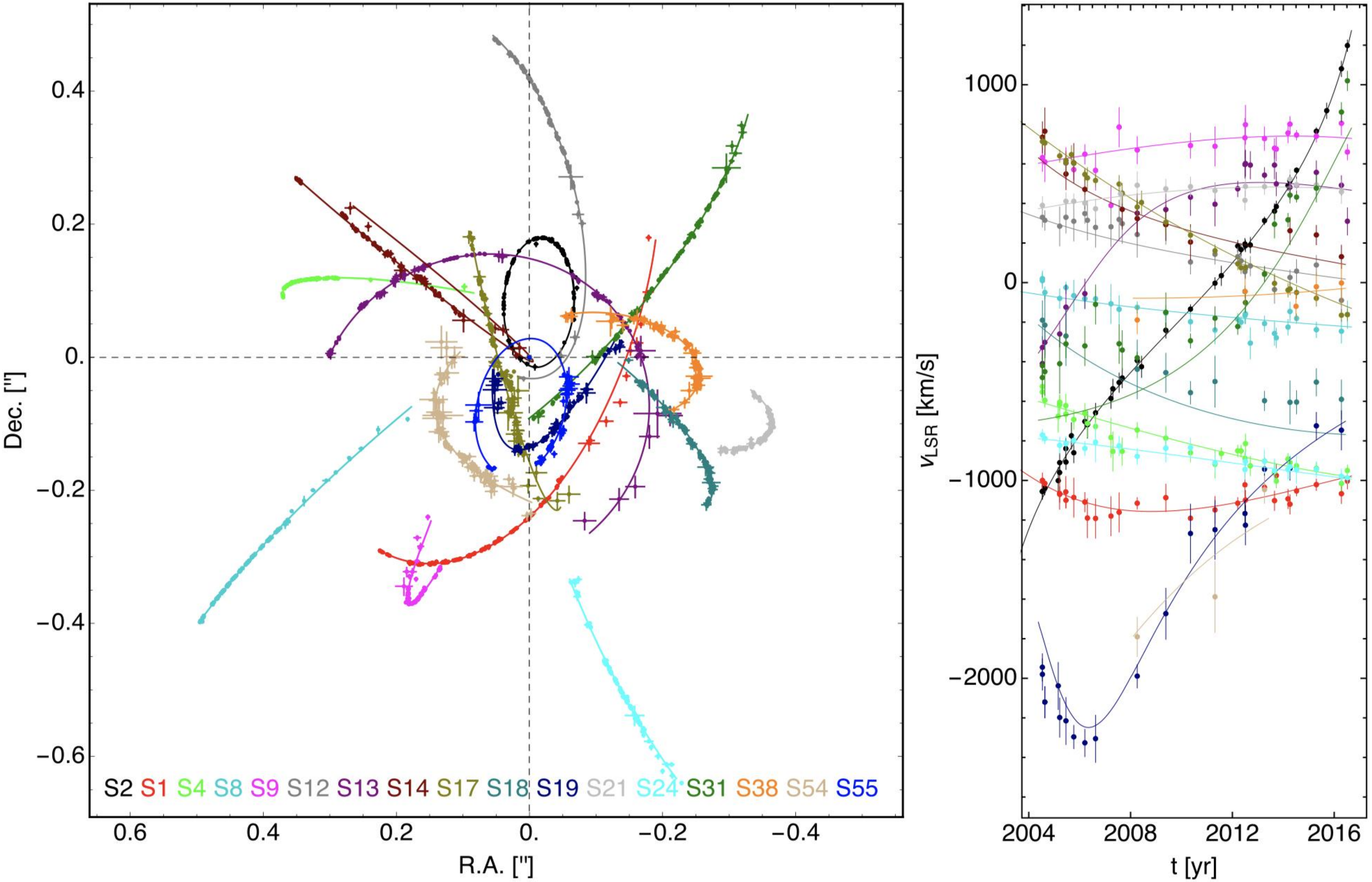
Gondolo and Silk (1999, PRL)

S-stars in the GC observed by VLT/Keck



Very Large Telescope@MPE

Keck Observatory@UCLA



S. Gillessen et al. (2017 ApJ)

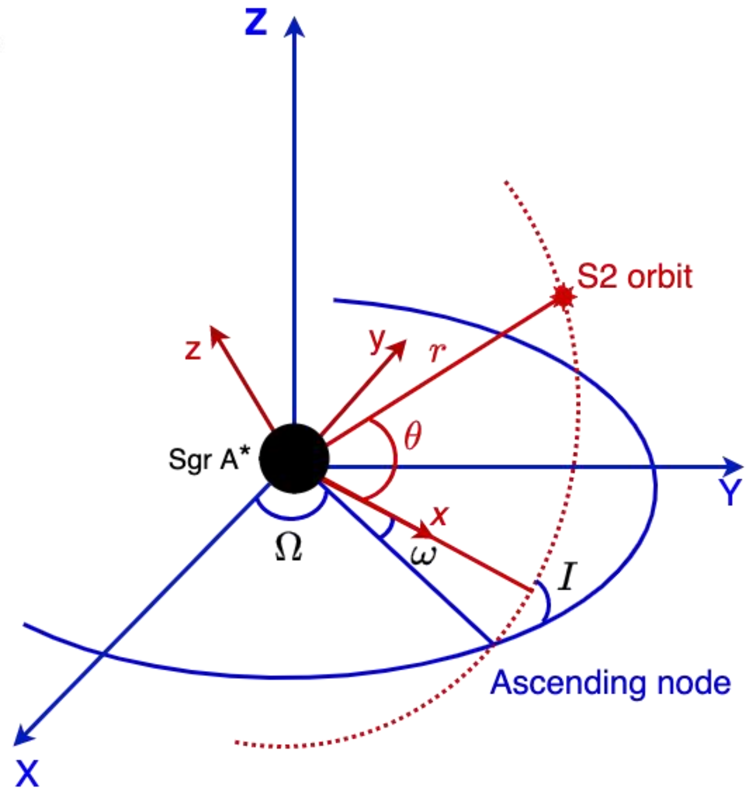
Orbital model

1PN equation of motion

$$\frac{\mathrm{d}^2\boldsymbol{r}}{\mathrm{d}t^2} = -\frac{GM}{r^3}\boldsymbol{r} + \frac{GM}{c^2r^3}\left(4\frac{GM}{r} - v^2\right)\boldsymbol{r} + 4\frac{GM(\boldsymbol{r}\cdot\boldsymbol{v})}{c^2r^3}\boldsymbol{v},$$

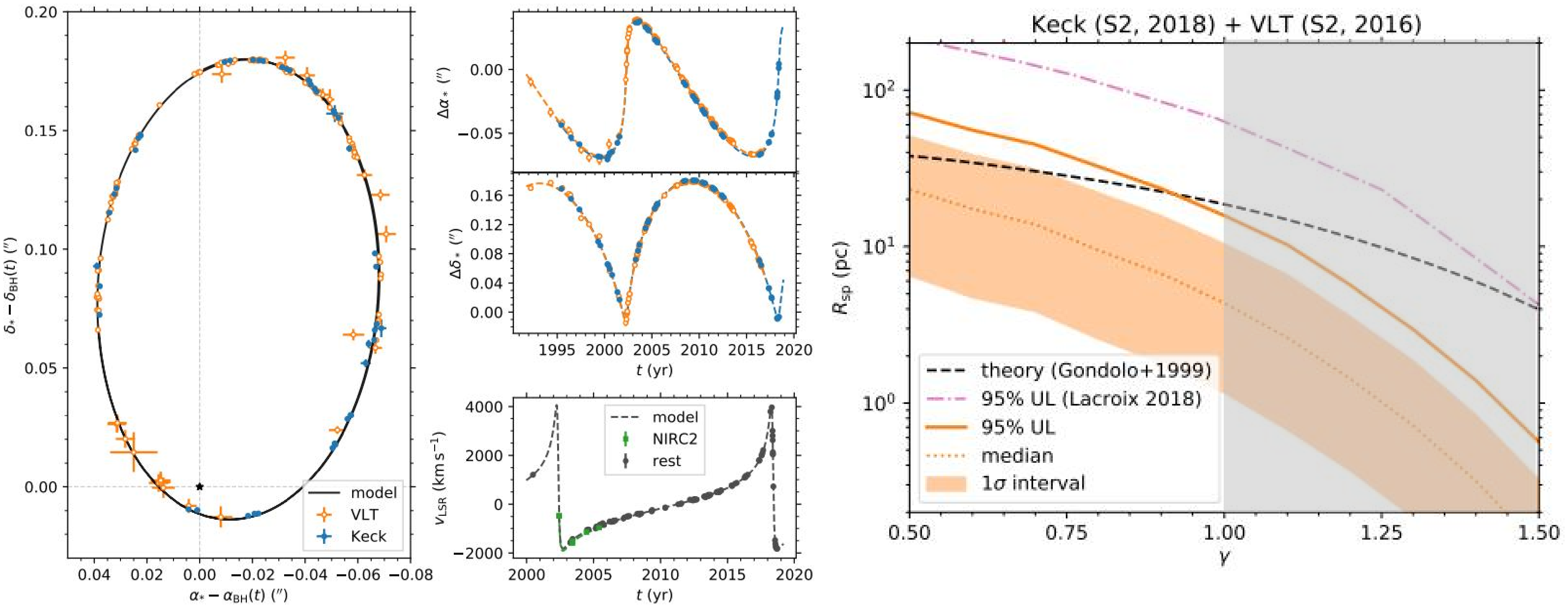
$$M = M_{BH} + M_{DM}(r)$$

$$X(t_p) = -r_p \sin\omega\cos I\sin\Omega + r_p\cos\omega\cos\Omega,$$
$$Y(t_p) = r_p \sin\omega\cos I\cos\Omega + r_p\cos\omega\sin\Omega,$$
$$Z(t_p) = -r_p\sin\omega\sin I,$$
$$V_X(t_p) = -v_p\cos\omega\cos I\sin\Omega - v_p\sin\omega\cos\Omega,$$
$$V_Y(t_p) = v_p\cos\omega\cos I\cos\Omega - v_p\sin\omega\sin\Omega,$$
$$V_Z(t_p) = -v_p\cos\omega\sin I.$$



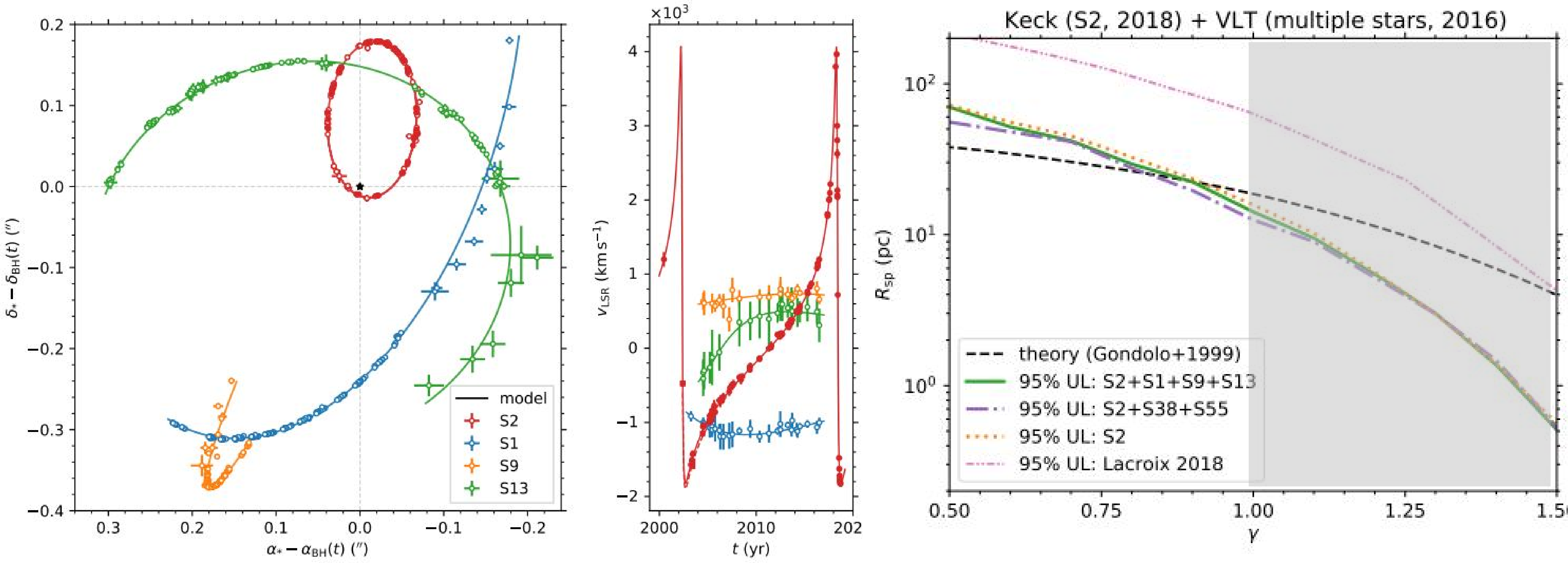
Will and Maitra (2017, PRD)

Results



For NFW or steeper profile, the model prediction by Gondolo & Silk is in conflict with the data at the 95% C.L.

Results



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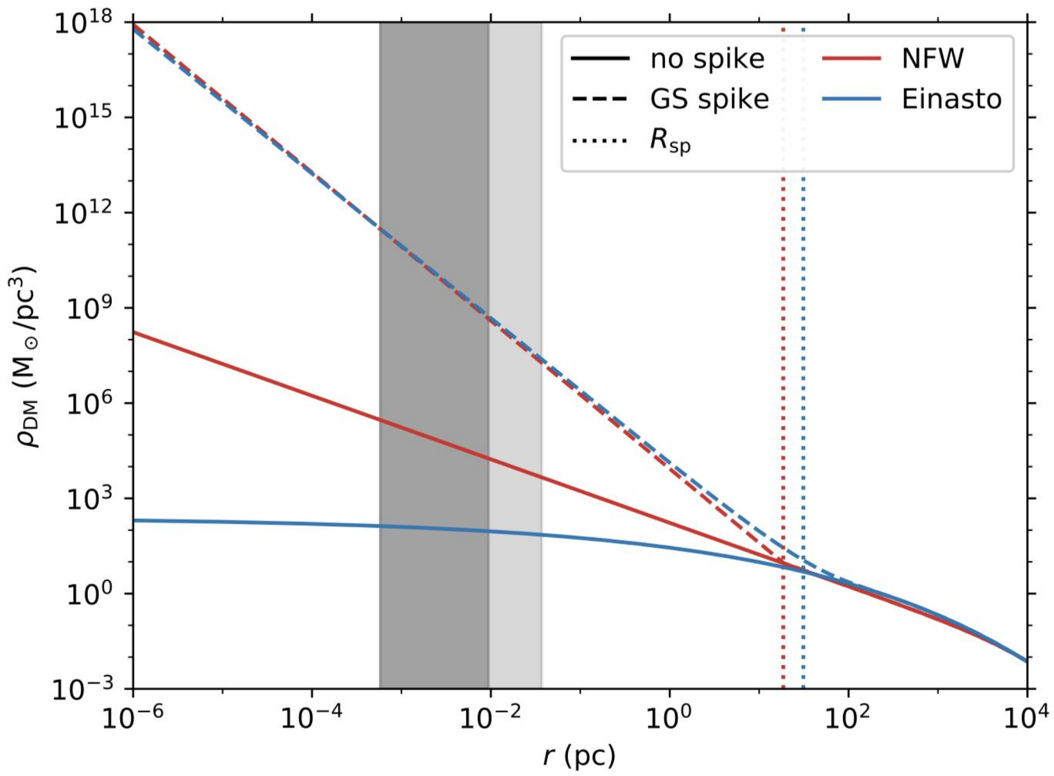
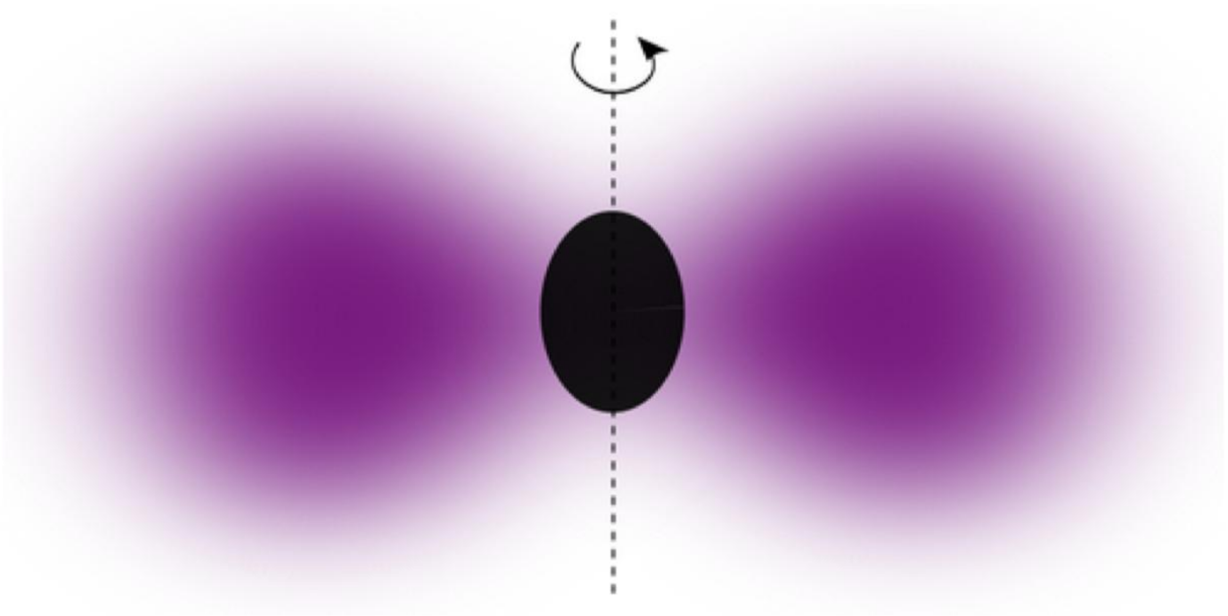




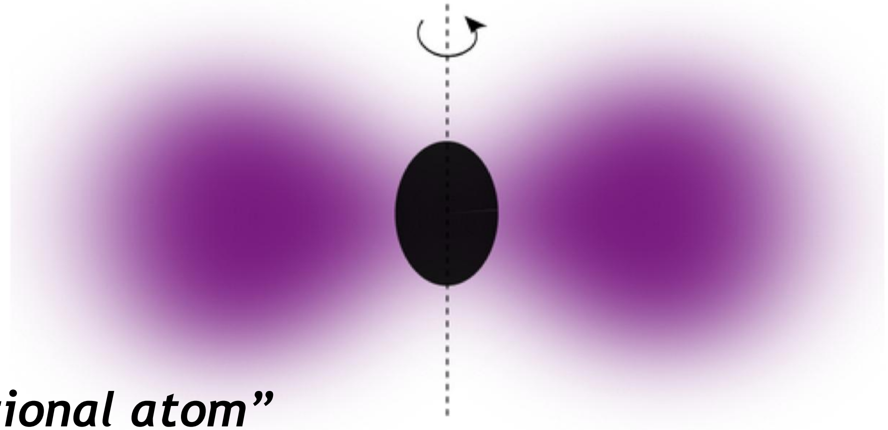
Ultralight scalar dark matter around SMBH

The solution of Klein-Gordon equation in the Kerr metric gives

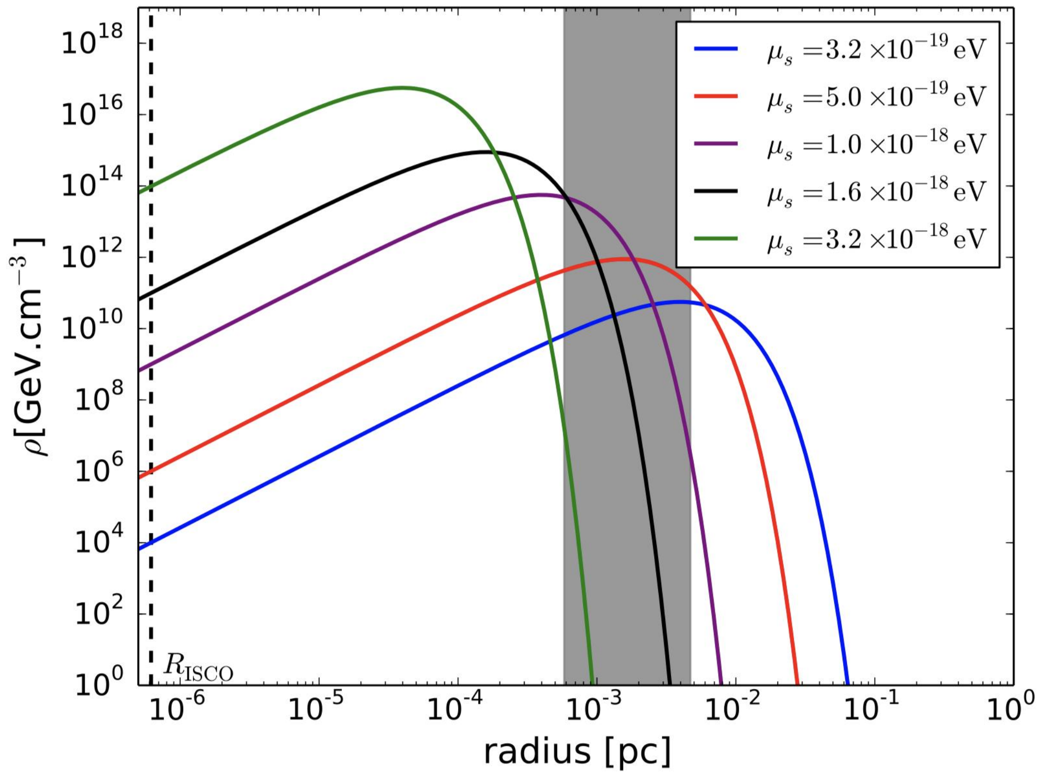
$$\nabla_\alpha \nabla^\alpha \Phi = \mu_s^2 \Phi,$$

$$ds^2 = -\left(1 - \frac{2M_\bullet r}{\Sigma}\right)dt^2 - \frac{4aM_\bullet r}{\Sigma}\sin^2\theta dt d\varphi + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2M \bullet a^2 r}{\Sigma}\sin^2\theta\right)\sin^2\theta d\varphi^2$$

$$\Phi_{\ell m}(t, r, \theta, \varphi) = e^{-i\omega t + im\varphi} S_{\ell m}(\theta) R_{\ell m}(r),$$



"Gravitational atom"



$$n = 0,\ l = m = 1$$

DM-SM coupling

Higgs portal interaction

$$\mathcal{L}_{\Phi H} = \beta|\Phi|^2|H|^2,$$

$$v = v_{\rm ew}\sqrt{1 - \frac{2\beta}{m_H^2}\frac{\rho(r)}{2\mu_s^2}} \approx v_{\rm ew}\left(1 - \frac{\beta}{m_H^2}\frac{\rho(r)}{2\mu_s^2}\right),$$

$$m_e \approx m_e^{\rm bare}\left(1 - \frac{\beta}{m_H^2}\frac{\rho(r)}{2\mu_s^2}\right),$$

Photon portal interaction

$$\mathcal{L}_{\Phi\gamma} = \frac{g}{4}|\Phi|^2 F^2,$$

$$\alpha = \alpha_0\left(\frac{1}{1 - g v_\Phi^2}\right) \approx \alpha_0(1 + g\frac{\rho}{2\mu_s^2}).$$

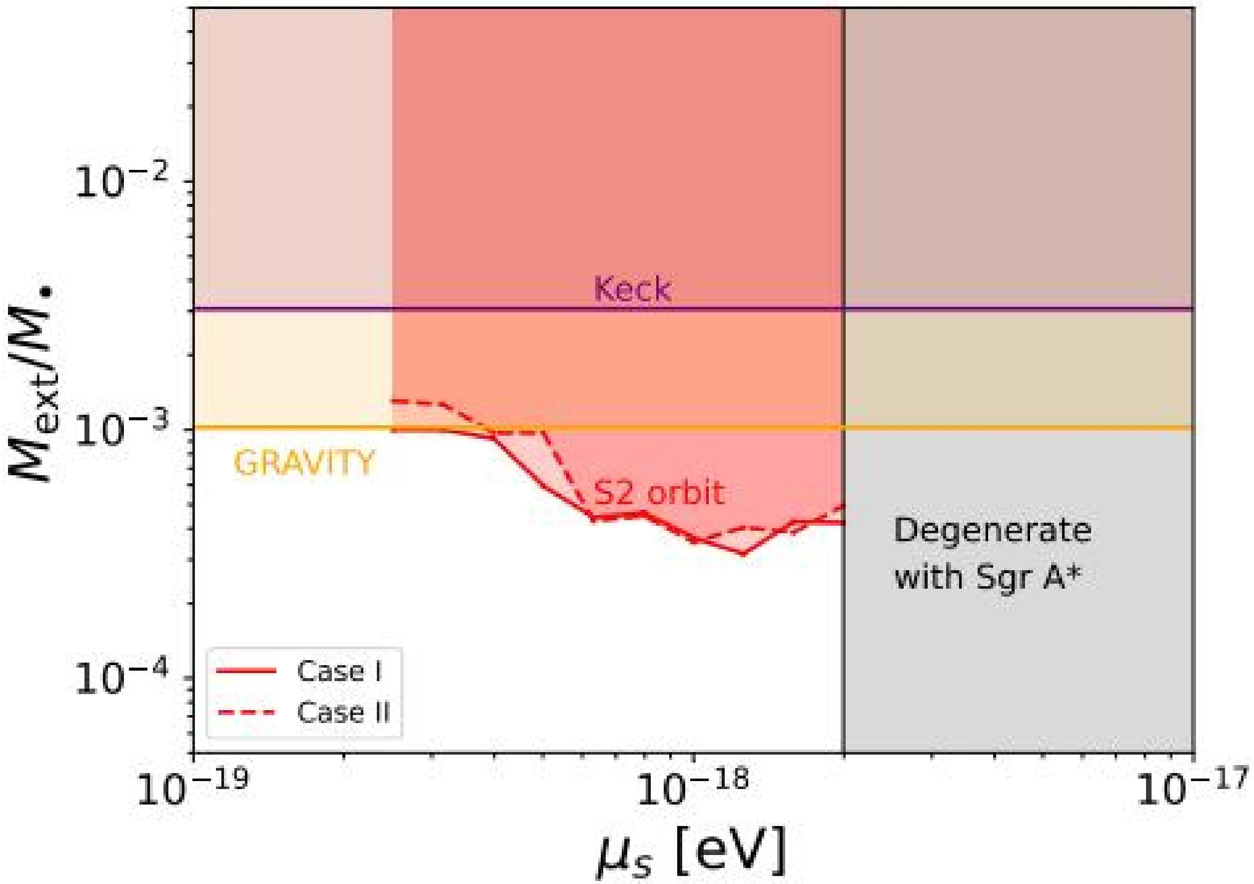
Velocity change

$$\Delta v_{\rm r,higgs} = \frac{\delta f}{f}(r) \approx \frac{\beta}{m_H^2}\frac{\rho(r)}{2\mu_s^2}$$

$$\Delta v_{\rm r,photon} = \frac{\delta f}{f}(r) \approx 2g\frac{\rho(r)}{2\mu_s^2}$$

Both the mass distribution and the velocity perturbation are relevant!

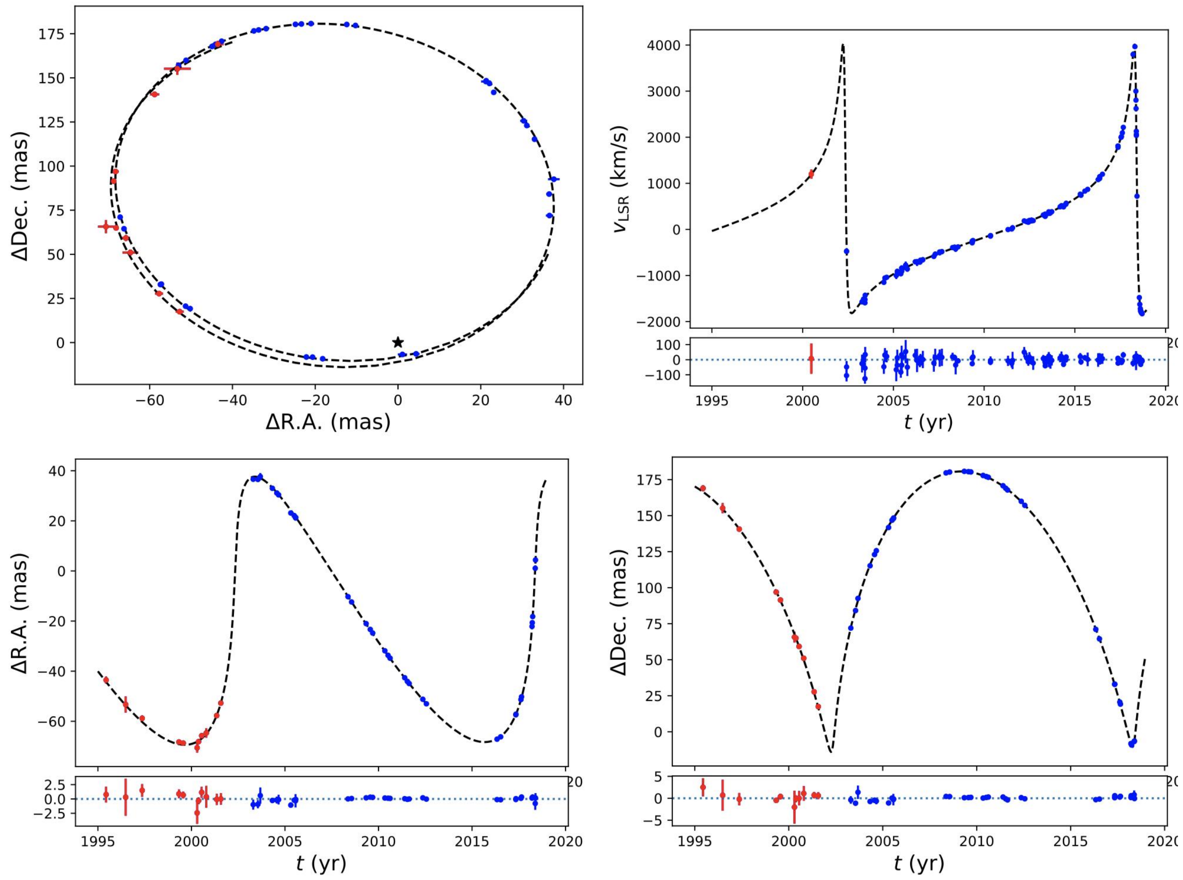
Constraints on the DM mass within S2's orbit

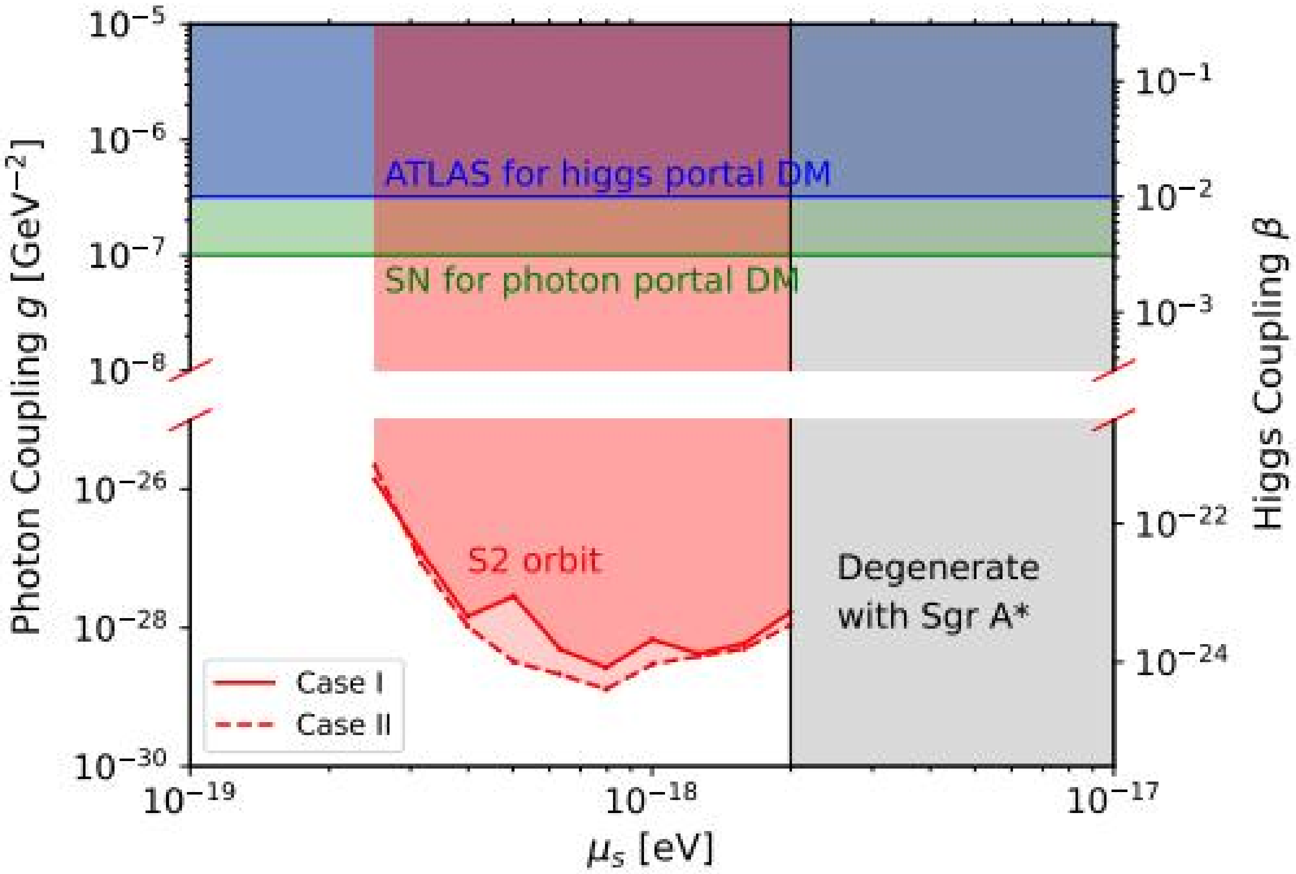


$$M_{\rm ext} = 2\pi \int_{r_{\rm ISCO}}^{r_0} r'^2 {\rm d}r' \int_0^\pi \sin\theta' \, {\rm d}\theta' \, \rho(r', \theta')$$

- The mass of the ultralight scalar dark matter is constrained to be ~1000 - 4000 M_{sun}
- Different from astrophysical extended mass distribution due to the DM-SM coupling

Constraints on the DM-SM coupling





- For small axion mass, the cloud is very extended. Since the extra mass is constrained, the expected frequency shift is small
- For large axion mass, the cloud is concentrated, and becomes degenerate with the SMBH

Summary

- Candidates of dark matter cover a very broad parameter space, which result in big challenges in detecting dark matter

- Precise measurements of stellar orbits and kinematics around the Galactic center SMBH offer a unique probe of specific kinds of dark matter

- Using the VLT and Keck observations of S-stars, we obtain stringent constraints on the density profile of particle dark matter, and the coupling strength of wave dark matter with standard model particle

Thanks for your attention!