The cosmology of X-Fermions

Gregory Vereshchagin and Remo Ruffini

ICRANet

7th Galileo Xu-Guangqui meeting
July 7-11, 2025 (ICRANet, Pescara, Italy)

Outline

- Supermassive black holes
- Black hole in Sgr A*?
- Rotation curves and RAR model
- X-fermion
- Jeans mass
- Conclusions

The talk is based on the paper Remo Ruffini and Gregory Vereshchagin, ”Role of the neutral X-fermion in describing the dark matter of the Universe”, European Physical Journal C (2025), in press.

Supermassive black holes

QSOs were discovered by Schmidt (1963) and interpreted by Salpeter and Zeldovich (1964) as emission from accreting SMBHs of $\sim 10^8 M_\odot$.
Lynden-Bell and Rees (1971) suggested that similar SMBH exists in our Galaxy.
Townes and Genzel initiated long run observations of the Galactic center every decade publishing a review (1987, 1994, 2010, 2024). S-star cluster orbiting Sgr A* was discovered thanks to IR observations.
In the 1980-1990 several possible explanations existed for the mass concentration in the Galactic center: either a BH or a cluster of faint stars, neutron stars, or stellar BHs.
Thanks to speckle imaging and later adaptive optics individual stars were tracked for many years by two groups (Genzel with VLT and Ghez with Keck telescopes), leading determination of the mass $M_{SgrA^*} = 4.3 \times 10^6 \, M_\odot$ and to the Nobel prize in 2020 *"for the discovery of a supermassive compact object at the centre of our galaxy"*.

Black hole in the Glactic center?

- S stars motion, mainly S2 star with pericenter of 17 light hours (2800 GM/c^2) from Sgr A*: the gravitational redshift and orbit precession of 12.1′ per orbit in clockwise direction.
- The near-IR emission from Sgr A* probing 8-9 GM/c^2 from accretion of material supplied by O/WR stars at $1-3''$ from Sgr A (GRAVITY, 2018 and 2022), implying $\dot{M} \sim 10^{-8} M_{\odot} yr^{-1}$.
- The bright ring with a central dip of diameter $51.8 \pm 2.3\mu$as (shadow) of measured 1.3-mm continuum by EHT (2022).
- The issue of spin is controversial: EHT (2022) and outflow method (Daly et al., 2024) give preference for high spin $\chi \sim 0.9$, while Fragione and Loeb (2020) constrain $\chi < 0.1$. No jet is detected.
- Fermi and eRosita bubbles are consistent with episodic AGN activity 5 Myr ago, but may as well be explained by star formation bursts or other mechanisms.
- Emission from molecular cloud Sgr B2 as Compton reflection from AGN activity 300 year ago (Revnivtsev et al., 2004).

Dark matter in galaxies: rotation curves

In the early 1970s, it was noticed that the luminous mass in galaxies cannot provides enough gravitational potential to support the observed rotation velocity in the outer parts (see e.g. Einasto book). Dark matter density profiles are inferred from the measured rotation curves after subtracting luminous component (stars and gas). Density profiles are of different types:

- phenomenological (Einasto, Burkert, Zhao...)
- obtained from numerical simulations (Navarro-Frenk-White)
- theoretical (pseudo-isothermal profile, RAR, ...)

Ruffini-Arguelles-Rueda model

Both central mass concentration and rotation curves can be explained by a neutral self-gravitating fermion at finite temperature. For some specific parameters of the model (particle mass, temperature, chemical potential, cutoff energy) fermions form quantum degenerate core with $R_{core} \sim 10^{-3} - 10^{-6}$ pc and extended halo with $R_{halo} \geq 10$ kpc described by the Boltzmann statistics. The model has been applied to:

- Our Galaxy (Arguelles et al. 2018);
- other galaxies (Arguelles et al. 2019);
- relativistic effects in S cluster of stars and G2 object without invoking the presence of a BH (Becerra-Vergara et al., 2020).

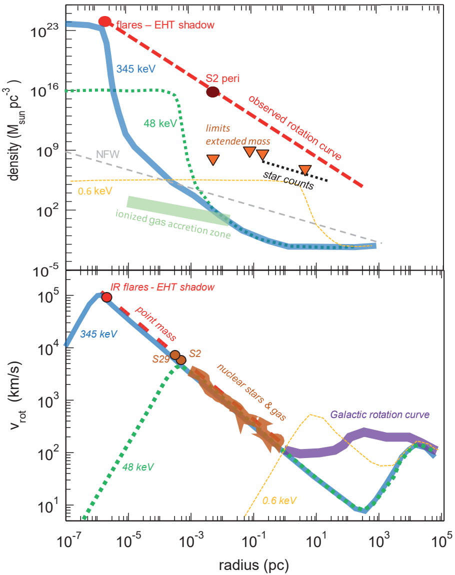


Figure: From Genzel, Eisenhauer and Gillessen (2024)

Critical mass for the gravitational collapse to a BH

Recall the critical mass for fermions

$$M_{cr} \simeq 0.384 \frac{M_P^3}{m_X^2} = 6.95 \times 10^6 \left(\frac{300\,\mathrm{keV}}{m_X} \right)^2 M_\odot .$$

From all the above considerations we infer the absolute lower limit to a cosmological DM SMBH in *any* galaxy

$$M_{\mathrm{SMBH}} > M_{SgrA^*} = 4.3 \times 10^6 \, M_\odot ,$$
$$m_X < 381\,\mathrm{keV}.$$

Dark matter: hot, cold and warm

In the 1980s in cosmology two types of DM particles were introduced: CDM, with mass above GeV, and HDM with mass below 100 eV (Lee-Weinberg bound).

- HDM forms pancakes and follow top-down clustering (Jeans mass $\sim 10^{15} M_{\odot}$). Inconsistent with observations, observed galaxies are older than clusters and superclusters of galaxies.
- CDM structure formation goes through the bottom-up hierarchical clustering (Jeans mass irrelevant). It has its own issues: too big to fail, missing satellites and core-cusp problem.
- WDM was proposed to cure CDM problems, with particle mass in the keV range, but needs non-thermal production mechanism (e.g. active-sterile neutrino oscillations).

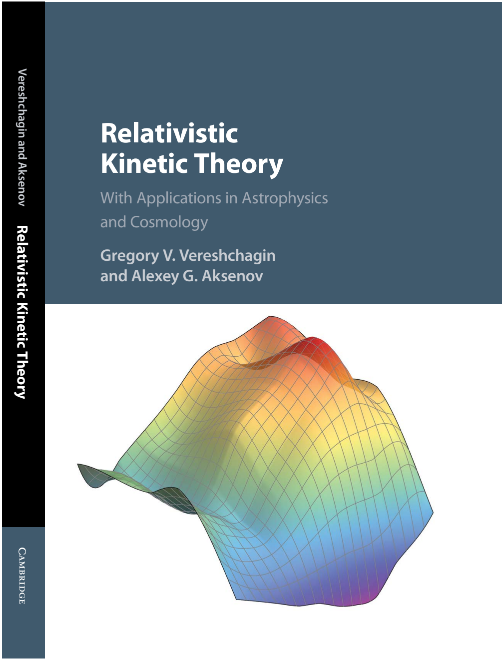
Introducing X-fermion

Consider a neutral fermion following the Fermi-Dirac statistics

$$f(\epsilon) = \frac{1}{\exp\left(\frac{\epsilon-\mu}{kT}\right)+1},$$

with rest mass $m \sim 300$ keV. We adopt the following assumptions:

- At high temperatures $T > MeV$ X-fermions were interacting with the cosmological plasma. Decoupling occurs at a temperature T_D larger than MeV at a cosmological redshift $z_D > 10^9$. At decoupling the X-fermions were ultrarelativistic and in kinetic equilibrium (Vereshchagin and Aksenov, 2017), but not in chemical equilibrium with the primordial plasma.
- Nonequilibrium interactions are necessary to reduce abundance of X-fermions, expressed with a *large* and *negative* chemical potential, for which Fermi-Dirac statistics reduces to the Boltzmann one $f(\epsilon) \propto \exp\left(-\frac{\epsilon-\mu}{kT}\right)$.


Relativistic
Kinetic Theory
With Applications in Astrophysics
and Cosmology
Gregory V. Vereshchagin
and Alexey G. Aksenov
Vereshchagin and Aksenov
Relativistic Kinetic Theory
CAMBRIDGE

Mass density and chemical potential

$$n = \frac{g}{h^3}\int_0^\infty f d^3p = 16\pi \exp\left(\eta\right)\left[\frac{kT_0\left(1+z\right)}{hc}\right]^3 \simeq 124 \exp\left(\eta\right)\ \text{cm}^{-3},$$

where we assume $T_0 = (4/11)^{1/3} T_\gamma = 1.95\text{K}$.
According to Planck measurements (2020) dark matter density parameter is

$$\Omega_m = \frac{m_X n_0}{\rho_c h_0^{-2}} = 0.259.$$

Hence the chemical potential is

$$\eta = \log\left(\frac{22.1}{m_X/\text{eV}}\right).$$

For $m_X = 300$ keV, we find $\eta = -9.51$, and consequently $n = 9.12 \times 10^{-3}\ \text{cm}^{-3}$.

Velocity dispersion

$$\left\langle v^2 \right\rangle = \frac{4\pi g c^2}{\rho h^3} \exp\left(\eta\right) \int_0^\infty \frac{(cp)^2}{\epsilon} \exp\left(-\frac{pc}{kT}\right) p^2 dp,$$

the energy density is

$$\rho = \frac{g}{h^3} \int_0^\infty \epsilon f d^3 p = \frac{8\pi}{h^3} \exp\left(\eta\right) \int_0^\infty \epsilon \exp\left(-\frac{pc}{kT}\right) p^2 dp,$$

Calculation gives c^2 for $z > z_{NR}$ and $\left\langle v^2 \right\rangle = 12 \left[\frac{kT_0(1+z)}{m_X c^2}\right]^2 c^2$ for $z < z_{NR}$, where z_{NR} is defined as

$$1 + z_{NR} = \frac{1}{2\sqrt{3}} \left(\frac{m_X c^2}{kT_0}\right) \simeq 5.16 \times 10^8 \left(\frac{m_X}{300 \text{ keV}}\right).$$

Jeans length and Jeans mass

The Jeans mass is defined as

$$M_J = \frac{4\pi}{3}\frac{\rho}{c^2}\left(\frac{\lambda_J}{2}\right)^3, \qquad \lambda_J^2 = \frac{\pi c^2}{3G\rho}\left\langle v^2\right\rangle.$$

In the UR regime $M_J \propto (1+z)^{-2}$, while in NR regime $M_J \propto (1+z)^{3/2}$ with the peak at

$$M_J(z_{NR}) = \frac{4}{3}\pi^{7/2}e^{-\eta/2}g^{-1/2}\left[\frac{kT_0}{m_X c^2}(1+z_{NR})\right]^{3/2}\frac{m_P^3}{m_X^2}$$
$$\simeq 8e^{-\eta/2}\frac{m_P^3}{m_X^2} \simeq 4.2\times 10^9 M_\odot\left(\frac{m_X}{300\ \mathrm{keV}}\right)^{-3/2}.$$

Clearly this mass corresponds to galactic scale.

Free streaming length

The comoving free-streaming length is calculated by integrating

$$\lambda_{\rm FS} = \int_{t_1}^{t_0} \frac{v(t)}{a(t)} dt = \int_{z}^{z_{max}} \frac{v(z')}{H(z')} dz',$$

where the Hubble function is defined from the Friedmann's equation as $H(z) = H_0\sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda}$.
The corresponding mass at $z = 0$ for $m_X = 300$ keV and $\eta = -9.51$

$$M_{\rm FS} = \frac{4\pi}{3}\rho_{m0}\lambda_{\rm FS}^3 = 2.2 \times 10^5 M_\odot,$$

which corresponds to globular clusters (known to contain no DM).
The horizon mass is comupted by using $v(t) = c$ in the above equations.

Jeans mass as a function of redshift

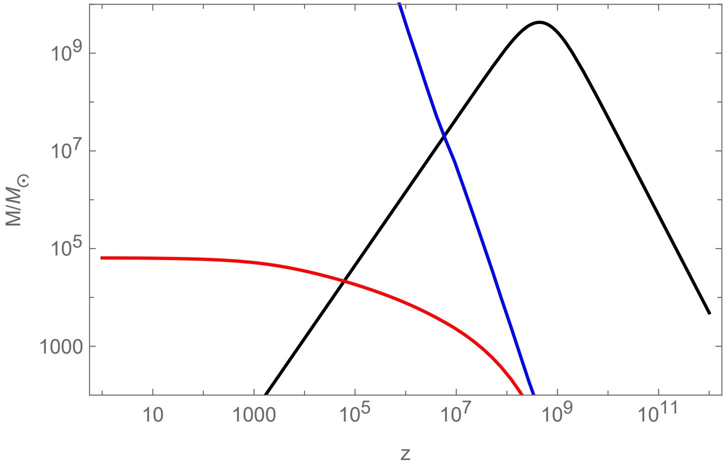


Figure: Jeans mass (black), horizon mass (blue) and free streaming mass (red) as functions of z for $m_X = 300$ keV and $\eta = -9.51$.

Minimum time interval of stability

No matter the value of m_X, our Galactic Center will necessarily evolve, by accretion process, to form a BH. Assuming that the infrared flare motions (GRAVITY, 2018, 2023), represent the Keplerian orbital motion around the object with the mass M_{SgrA^*} having radius $\sim 9GM_c/c^2$ and evaluating the value of the critical mass of fermionic core we obtain $m_X = 355$ keV with the critical mass $M_{cr} = 4.97 \times 10^6\, M_\odot$, which is about 15 per cent larger than M_{SgrA^*}. It is interesting to note that the radius of the degenerate core is indeed just $9.8GM_c/c^2$.
Given the current rate of accretion estimated as $\dot{M} \simeq 10^{-8}\, M_\odot \mathrm{yr}^{-1}$ from observations of GRAVITY and EHT and consistent with the GRMHD simulations of RIAF, the interval of stability is estimated as

$$t = \frac{M}{\dot{M}} \simeq 10^{13}\ \mathrm{yr}.$$

Implications for LRDs and QSOs (Yu Wang's talk!)

The core-halo configuration is at the basis of the structure of LRDs, which we interpret as an isolated primordial object, constituted in a similar amount of DM and baryonic matter of the mass $\sim 10^{10}\,M_{\odot}$.
The initial AGN phase with accretion of baryons in the core is followed by what we call a Quiescent Galactic Nuclei (QGN), observed as LRDs at high redshifts.
It is noteworthy that a lower limit to the BH mass deduced for LRDs coincides with our condition $M_{\rm SMBH} > M_{SgrA^*} = 4.3 \times 10^6\,M_{\odot}$.

SMBHs vs degenerate cores in other galaxies

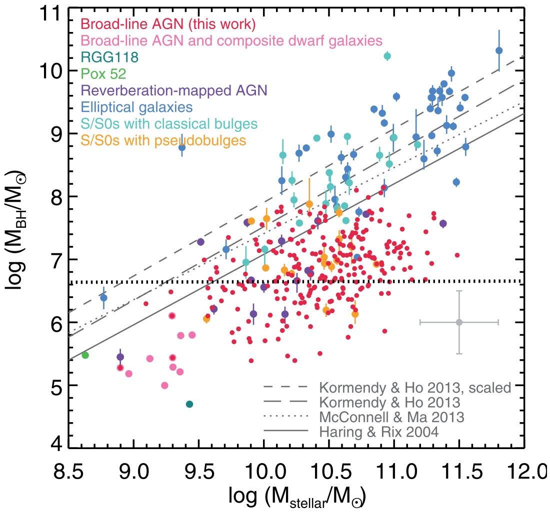


Figure: Reines and Volonteri (2015)

Conclusions

We propose that the compact object with $M_{SgrA^*} = 4.3 \times 10^6\, M_\odot$ in our Galactic Center is not yet a BH, but a quantum degenerate core formed of neutral fermion particles, so it establishes the upper limit on X-fermion mass: $m_X < 381$ keV.

Consistency with the cosmological abundance of DM requires large and negative chemical potential of X-fermions, which in turn determines the mass scale of the DM halo. For particle mass of ~ 300 keV it coincides with the galactic scale of $\sim 10^{10}\, M_\odot$. The free streaming mass is $\sim 10^5\, M_\odot$.

Further, we estimate the "*minimum time interval of stability*" for our Galactic core to accrete sufficient amount of baryons in order to collapse to a BH. With the current accretion rate this time interval is sufficiently large $t \sim 10^{13}$ years.

Additional observations are necessary to narrow down the range of X-fermion mass and the mass accretion rate in the Galactic Center to further improve our estimate.