The no-hair theorems at work in M87*

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universe

time and space

Outline

1. Motivations
2. The spin and orbital configuration
3. The Lense-Thirring and quadrupolar orbital precessions
4. Confrontation with the observations
5. Conclusions

The observed jet precession in M87*

- Recently, VLBI allowed to *measure* the precession of the jet from the supermassive black hole–or *megapyknon* [Iorio 2025a]–M87* [Cui et al. 2023, Cui and Lin. 2025] at a rate

$$\left|\Omega_{\mathrm{p}}^{\mathrm{exp}}\right| = 0.56 \pm 0.02\,\mathrm{rad\,yr}^{-1} = 32 \pm 1.1^{\circ}\,\mathrm{yr}^{-1}. \quad (1)$$

- The jet and the orbital angular momentum $\hat{\boldsymbol{h}}$ of the accretion disk existing around M87* are assumed *tightly coupled* [Cui and Lin. 2025].
- The *measured* features of the jet precession can be reproduced, both *qualitatively* and *quantitatively*, by a simple analytical model of the 1pN Lense-Thirring and quadrupolar orbital precessions of a fictitious test particle mimicking the accretion disk assumed circular [Iorio 2025b, Iorio 2025c].

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The spin-orbit geometry of M87*

- The SMBH's spin axis is [Cui et al. 2023]

$$\hat{\boldsymbol{k}} = \{\sin\theta \sin\eta_{\rm p}, -\sin\theta\cos\eta_{\rm p}, \cos\theta\}, \quad (2)$$

$$\theta = 17.21^\circ,\ \eta_{\rm p} = 288.47^\circ. \quad (3)$$

- The particle/disk's orbital angular momentum is [Cui et al. 2023]

$$\hat{\boldsymbol{h}} = \{\sin\phi\cos\eta, \sin\phi\sin\eta, \cos\phi\}, \quad (4)$$

$$\phi_0 = 17.85^\circ,\ \eta_0 = 291.7^\circ. \quad (5)$$

The angles η and ϕ are called position angle and viewing angle, respectively [Cui et al. 2023].

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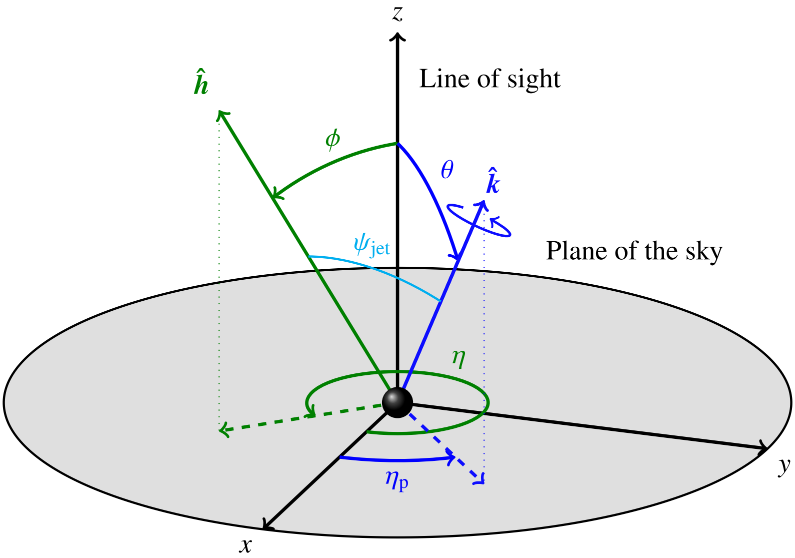
z
Line of sight
ĥ
φ
θ
k̂
ψjet
Plane of the sky
η
ηp
y
x

The no-hair orbital precession

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- $$\frac{d\hat{\boldsymbol{h}}}{dt} = \boldsymbol{\Omega}^{\mathrm{LT}} \times \hat{\boldsymbol{h}}, \tag{7}$$

  $$\boldsymbol{\Omega}^{\mathrm{LT}} = \frac{2GJ}{c^2 r_0^3}\hat{\boldsymbol{k}}. \tag{8}$$

- $$\frac{d\hat{\boldsymbol{h}}}{dt} = \boldsymbol{\Omega}^{Q_2} \times \hat{\boldsymbol{h}}, \tag{9}$$

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- In eq. (8) and eq. (10), G is the Newtonian constant of gravitation, c is the speed of light, r_0 is the radius of the effective circular orbit representing the accretion disk, M is the mass of the black hole–or *pyknon* [Iorio 2025a], $n_{\mathrm{K}} := \sqrt{GM/r_0^3}$ is the Keplerian mean motion, and J and Q_2 are the spin angular momentum and the quadrupole mass moment of the SMBH, respectively.
- According to the no-hair theorems, the spin angular momentum and the quadrupole mass moment of a Kerr black hole are given by

$$J = a^* \frac{M^2 G}{c}, \ |a^*| \leq 1, \tag{11}$$

$$Q_2 = -\frac{J^2}{c^2 M} = -{a^*}^2 \frac{M^3 G^2}{c^4}. \tag{12}$$

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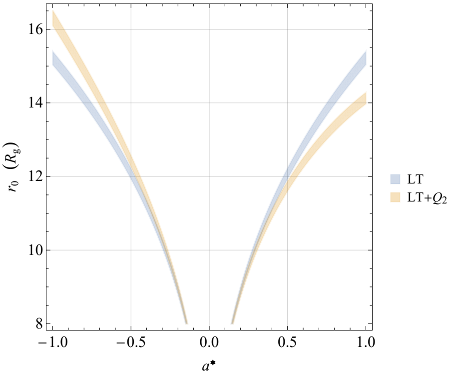
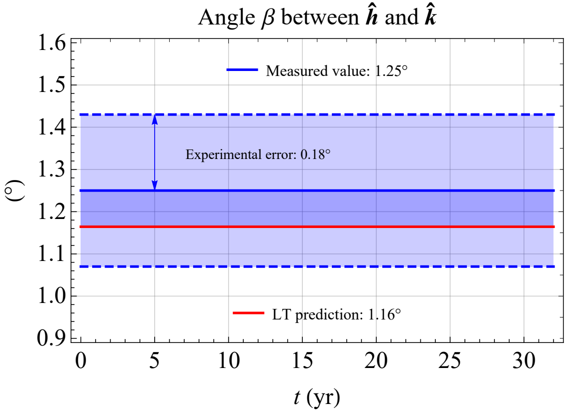
Constraints on the hole's spin and the disk radius

By imposing that the *theoretically* predicted no-hair jet precessions Ω^{LT} or $\Omega^{\mathrm{LT}} + \Omega^{Q_2}$ lie within the *measured* bounds set by eq. (1), one gets the following allowed regions in the $\{a^*, r_0\}$ plane, where $R_{\mathrm{g}} = GM/c^2$ is the hole's gravitational radius.



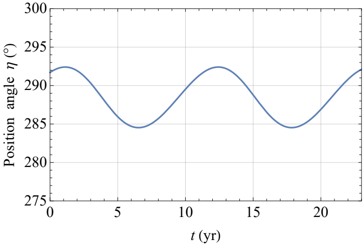
The spin-orbit angle

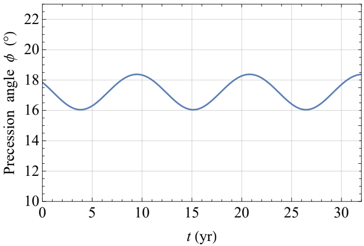
The angle β between $\hat{\boldsymbol{k}}$ and $\hat{\boldsymbol{h}}$, *theoretically* calculated from the Lense-Thirring precession for $a^* = 0.9375$, $r_0 = 14.9\,R_\mathrm{g}$, agrees well with the *measured* value of eq. (6)



The precession of the jet's axis

The *theoretically* produced Lense-Thirring time series for η and ϕ, calculated by simultaneously integrating eqs. (7)–(8) with the initial conditions of eq. (5) and $a^* = 0.9375$, $r_0 = 14.9\,R_\mathrm{g}$, agree both *qualitatively* and *quantitatively* with the corresponding *measured* signals in [Cui et al. 2023]





Summary and overview (I)

- By assuming a *tight disk-jet coupling* in M87*, a simple 1pN analytical model of the orbital precessions of a fictitious test particle due to the black hole's Lense-Thirring and quadrupole fields is able to reproduce the recently *measured* features of the jet precession.
- By considering the spin parameter a^* and the effective disk radius r_0 as independent variables of the *theoretical* disk precession rate Ω^{theo}, allowed regions in the $\{a^*, r_0\}$ plane can be obtained by imposing that Ω^{theo} is constrained by its *measured* counterpart $\Omega_{\mathrm{p}}^{\mathrm{exp}}$.

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Summary and overview (II)

- The inclusion of the hole's quadrupole Q_2 removes the degeneration of the two allowed branches in the $\{a^*, r_0\}$ plane occurring for the negative and positive values of a^* when only the Lense-Thirring effect is considered. The resulting allowed regions tend to become indistinguishable from the purely gravitomagnetic ones for $|a^*| \lesssim 0.5$.
- The spin-orbit angle, *calculated* only with the Lense-Thirring effect, agrees with the *measured* angle between the jet and the hole's spin.
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References

- Y. Cui et al.,
  Nature, **621**, 711, 2023
- Y. Cui and W. Lin,
  Nature Astron., **9**, 1218, 2025
- L. Iorio,
  Universe, **11**, 251, 2025a
- L. Iorio,
  Phys. Rev. D, **111**, 044035, 2025b
- L. Iorio,
  Mon. Not. Roy. Astron. Soc., **537**, 1470, 2025c