New Constraints on the Central Mass Contents of Omega Centauri from Combined Stellar Kinematics and Pulsar Timing

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Why is ω Cen interesting?

- Believed to be the nucleus of a disrupted dwarf galaxy
- Ideal candidate for dark matter annihilation signals (only ~ 5 kpc away + high DM concentrations)
- Argued to host a ~ $\mathbf{10^4}$ $M_\odot$ intermediate-mass black hole (IMBH)
- … and also a cluster of stellar-mass black holes
- Has an abundant population of recently discovered pulsars

Mass contents from stellar kinematics

- Stellar velocity dispersions trace mass contents from the Jeans equations:

$$\frac{1}{\nu_\star}\frac{\partial \nu_\star \sigma_r^2}{\partial r} + \frac{2\beta\sigma_r^2}{r} = -\frac{GM}{r^2},$$

where: $$\sigma^2_{r/t} = \langle \mathrm{v}^2_{r/t}\rangle - \langle \mathrm{v}_{r/t}\rangle^2, \qquad \beta \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

- Solve for the radial velocity dispersion for a given mass profile:

$$\sigma_r^2(r) = \frac{1}{\nu_\star(r)g(r)}\int_r^\infty \frac{GM(r')\nu_\star(r')}{r'^2}g(r')dr', \qquad g(r) \equiv \exp\left(2\int \frac{\beta(r)}{r}dr\right)$$

IMBH discovered in ω Cen?

- IMBH can produce a steep rise in central velocity dispersions
- However, studies claiming IMBHs have been susceptible to degeneracies and biases from limited data / modeling
- Concentrated cluster of remnants can produce degenerate effects

GEMINI AND *HUBBLE SPACE TELESCOPE* EVIDENCE FOR AN INTERMEDIATE-MASS BLACK HOLE IN ω CENTAURI

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Black hole found in Omega Centauri

ESA / Science & Exploration / Space Science

Constraining mass models with pulsar timing

- Doppler-induced changes in apparent period derivatives trace LOS acceleration due to GC potential

$$a_{\rm LOS}(r, l) = -G\left(\frac{l}{r}\right)\frac{M(r)}{r^2}$$

$$\dot{P}_{\rm obs} = \frac{(a_{\rm LOS} + a_{\rm S} + a_{\rm g})P}{c} + \dot{P}_{\rm int}$$

- Intrinsic spin-down can be modeled as magnetic dipole emission:

$$a_{\rm int} \equiv c\left(\frac{\dot{P}}{P}\right)_{\rm int} = 7.96 \times 10^{-10}\left(\frac{B}{2\times 10^8\ {\rm G}}\right)^2\left(\frac{2{\rm ms}}{P}\right)^2\ {\rm m\,s^{-2}}$$

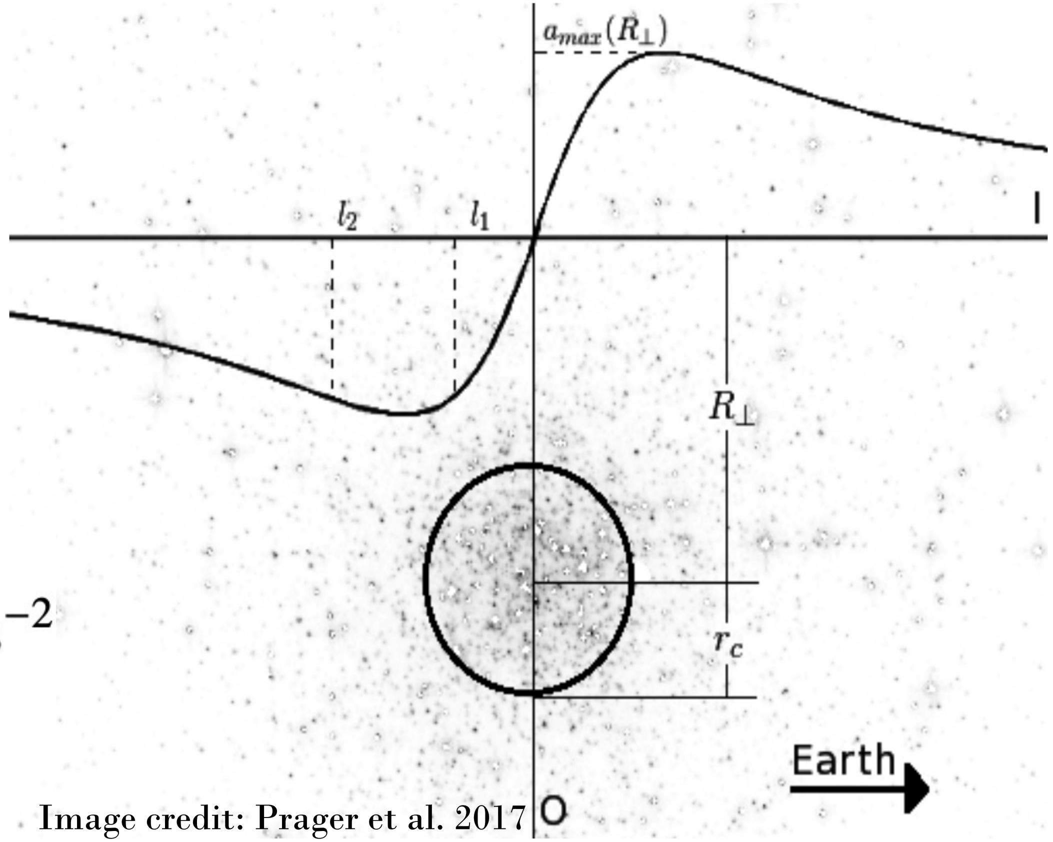


Image credit: Prager et al. 2017

Generalized multi-component mass modeling

- Fully explore mass degeneracies by including both an IMBH and extended remnant and stellar distributions:

$$M(r) = M_\star(r) + M_{\rm cen}(r) + M_{\rm BH} + M_p(r)$$

- IMBH modeled as a point mass
- Central cluster of remnants as a Plummer component:

$$M_{\rm cen}(r) = M_{\rm cen}\frac{r^3}{r_{\rm cen}^3}\left(1 + \frac{r^2}{r_{\rm cen}^2}\right)^{-3/2}$$

- Stellar profile set by photometry
- Included a mass component traced by the pulsars

Implementation

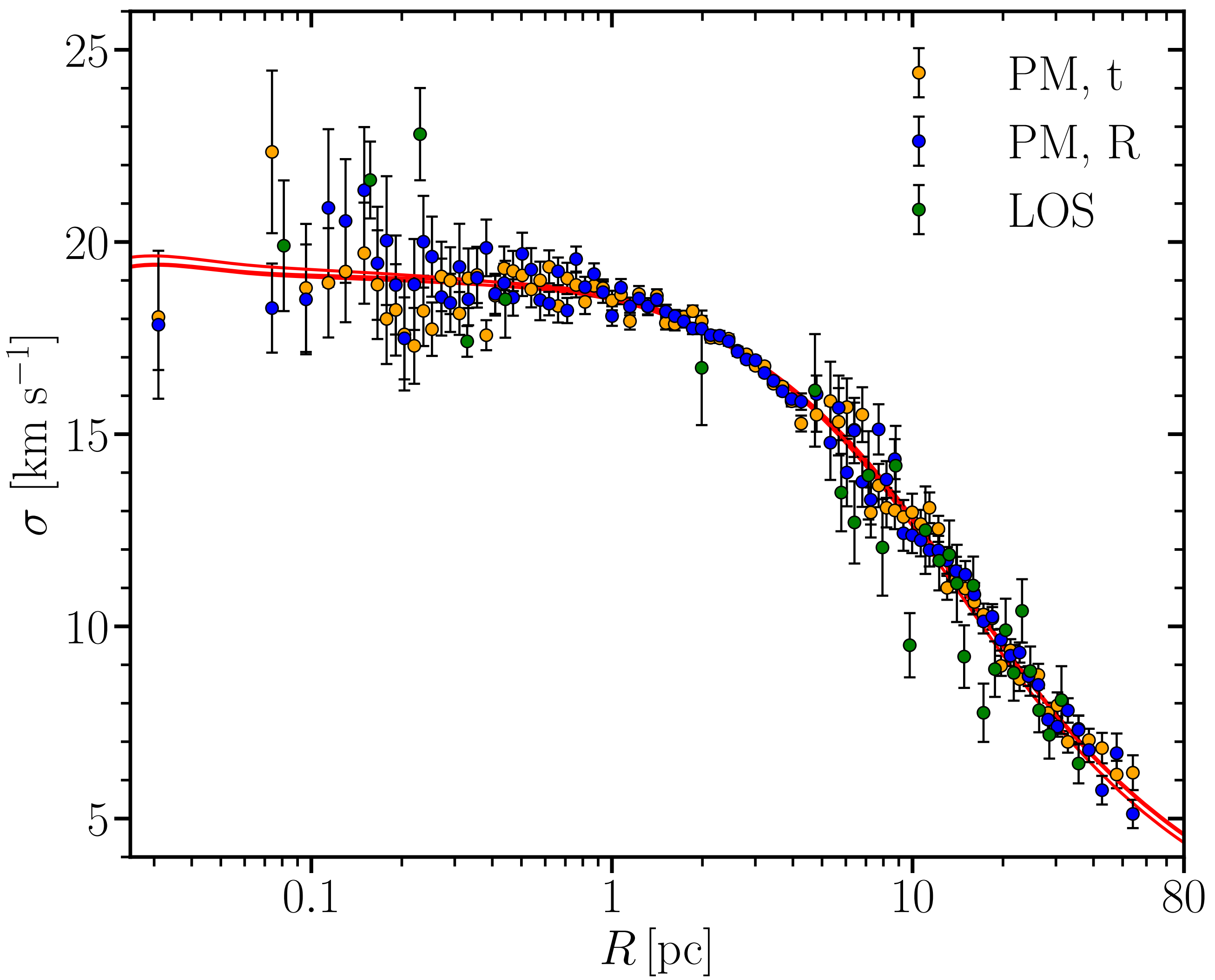
- Employed **GravSphere** (Read & Steger 2017) as a Jeans equations solver for stellar kinematics with full anisotropic modeling

- Extended GravSphere to include pulsar timing data and robust posterior sampling with **dynesty**

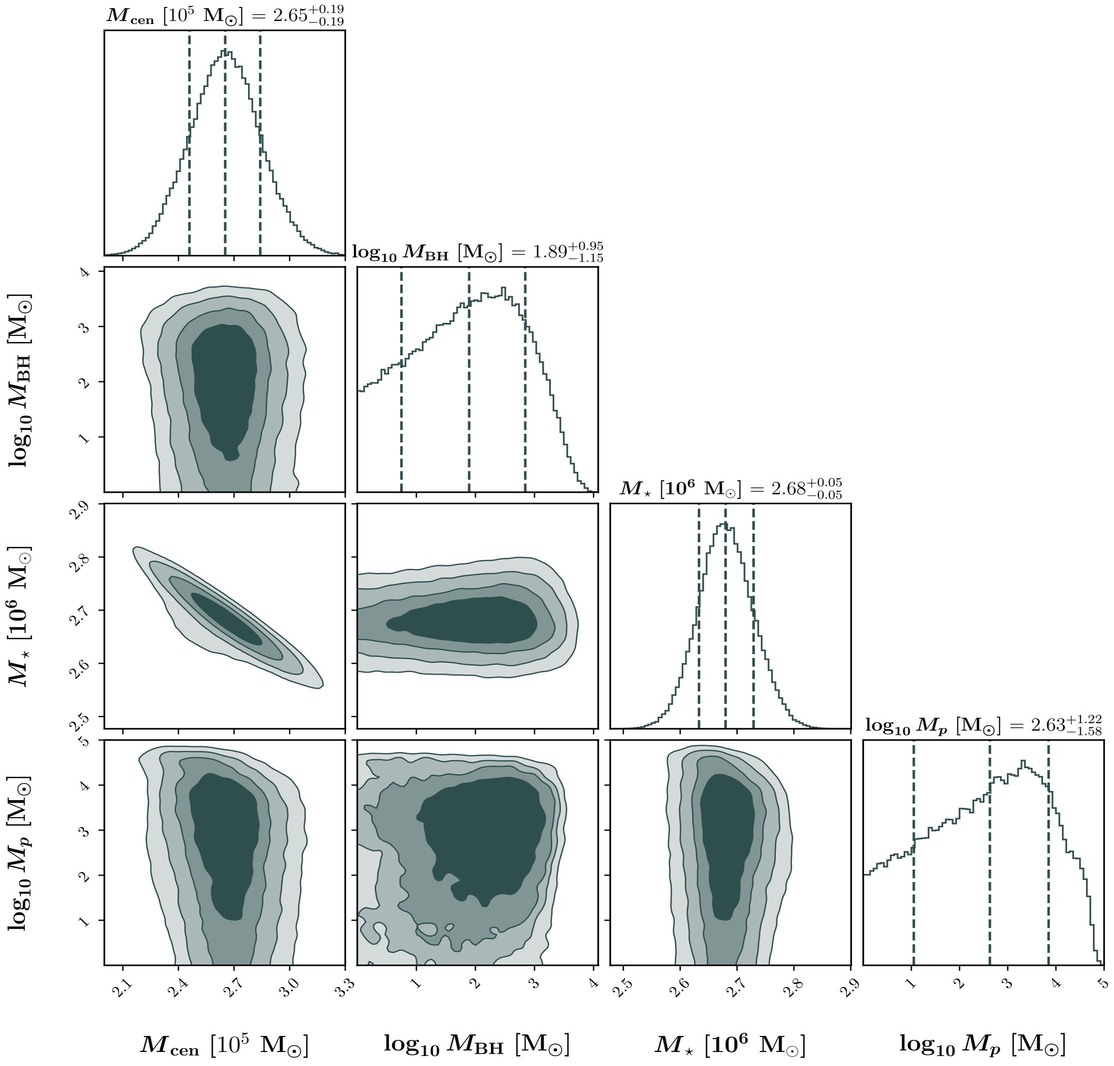
- Self-consistently binned, high-resolution data from HST + Gaia (PMs) and multiple ground-based observations (LOS)

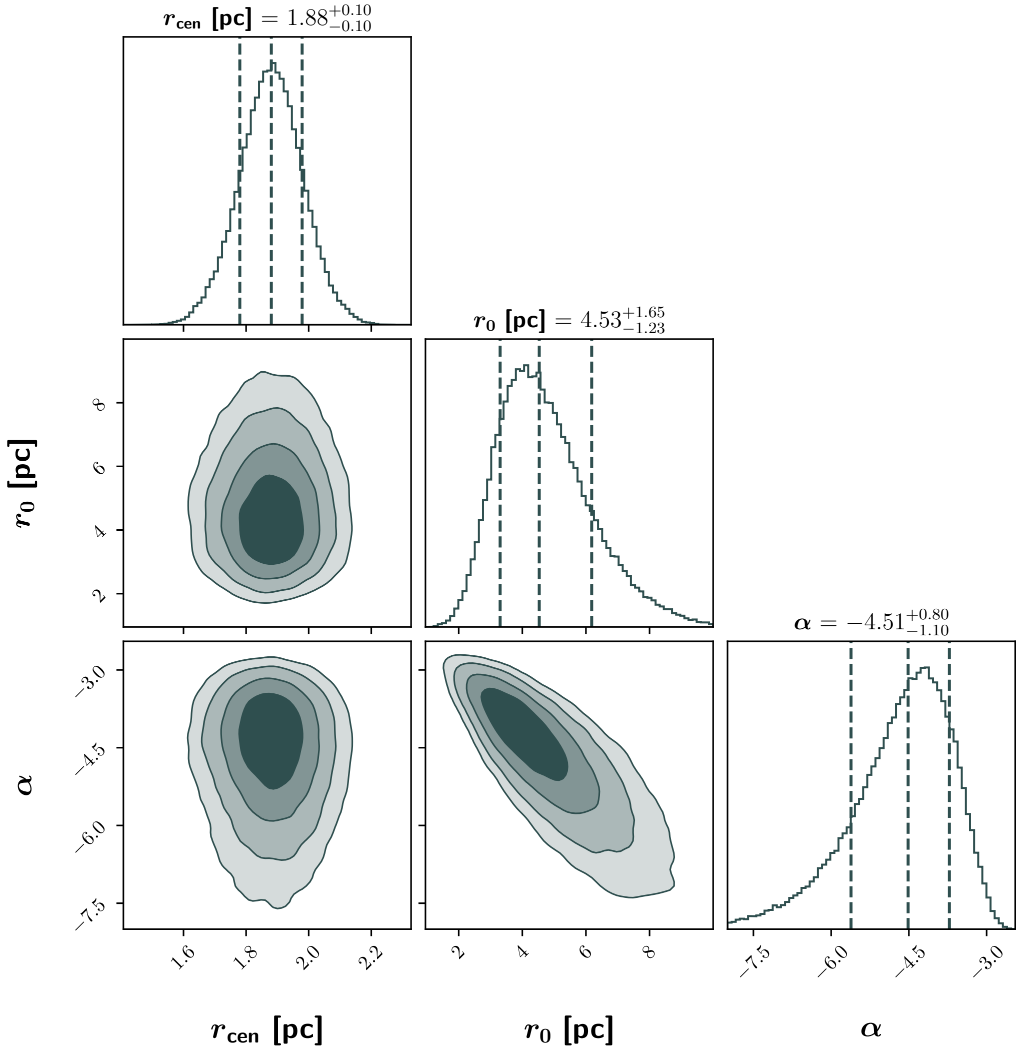
Results: Velocity dispersions

- **Fit can reproduce the profile well**
- **Somewhat elevated, but flat at the centre (important)**
- **LOS ~ PM,t ~ PM,R (isotropy)**



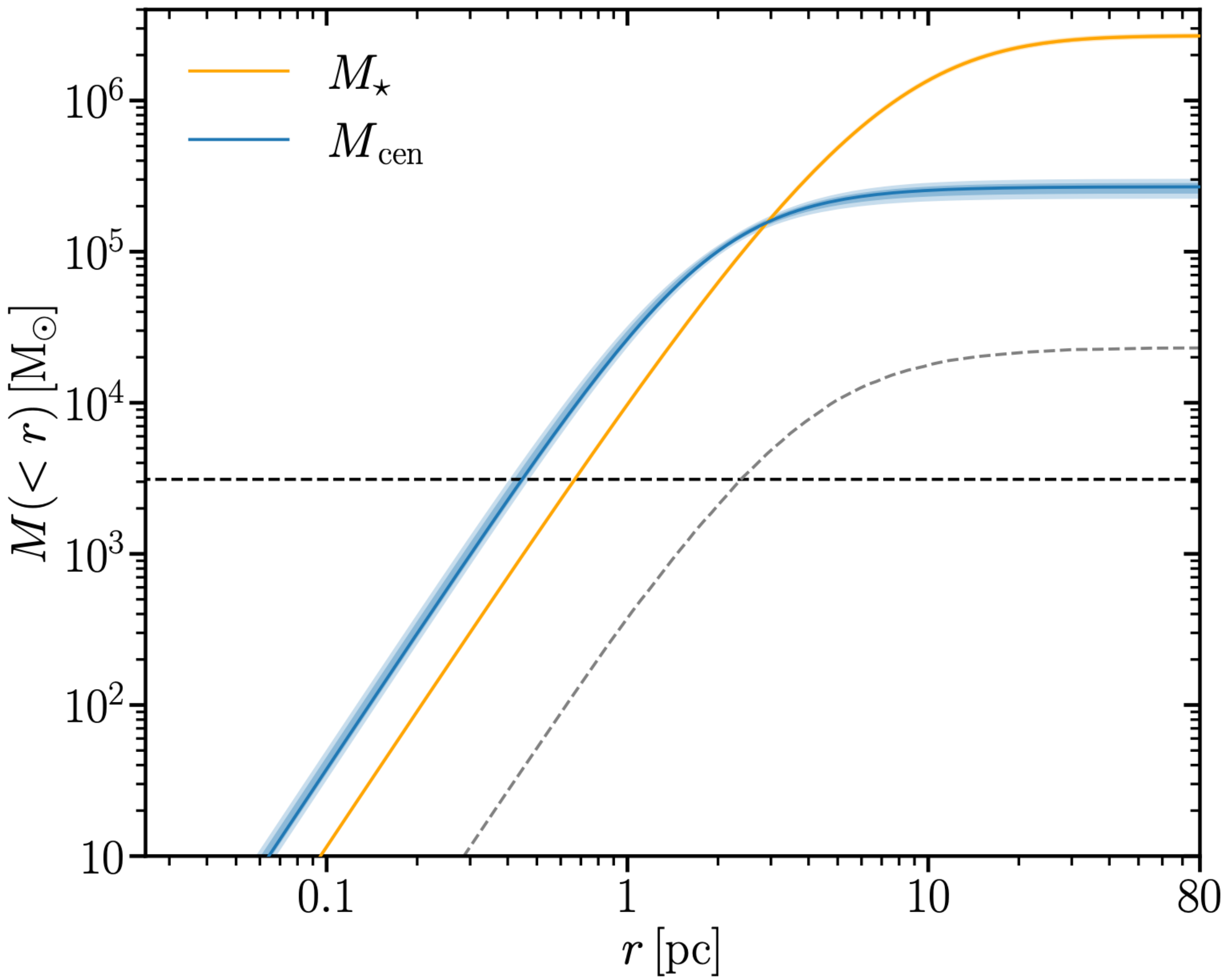
Mass model parameter results





Stellar-mass black holes over an IMBH

- Fit shows strong preference for two-component model with extended central mass
- IMBHs greater than 6,000 $M_\odot$ excluded at 3σ, limiting their kinematic relevance
- Pulsar profile has intermediate concentration and also has limited kinematic relevance

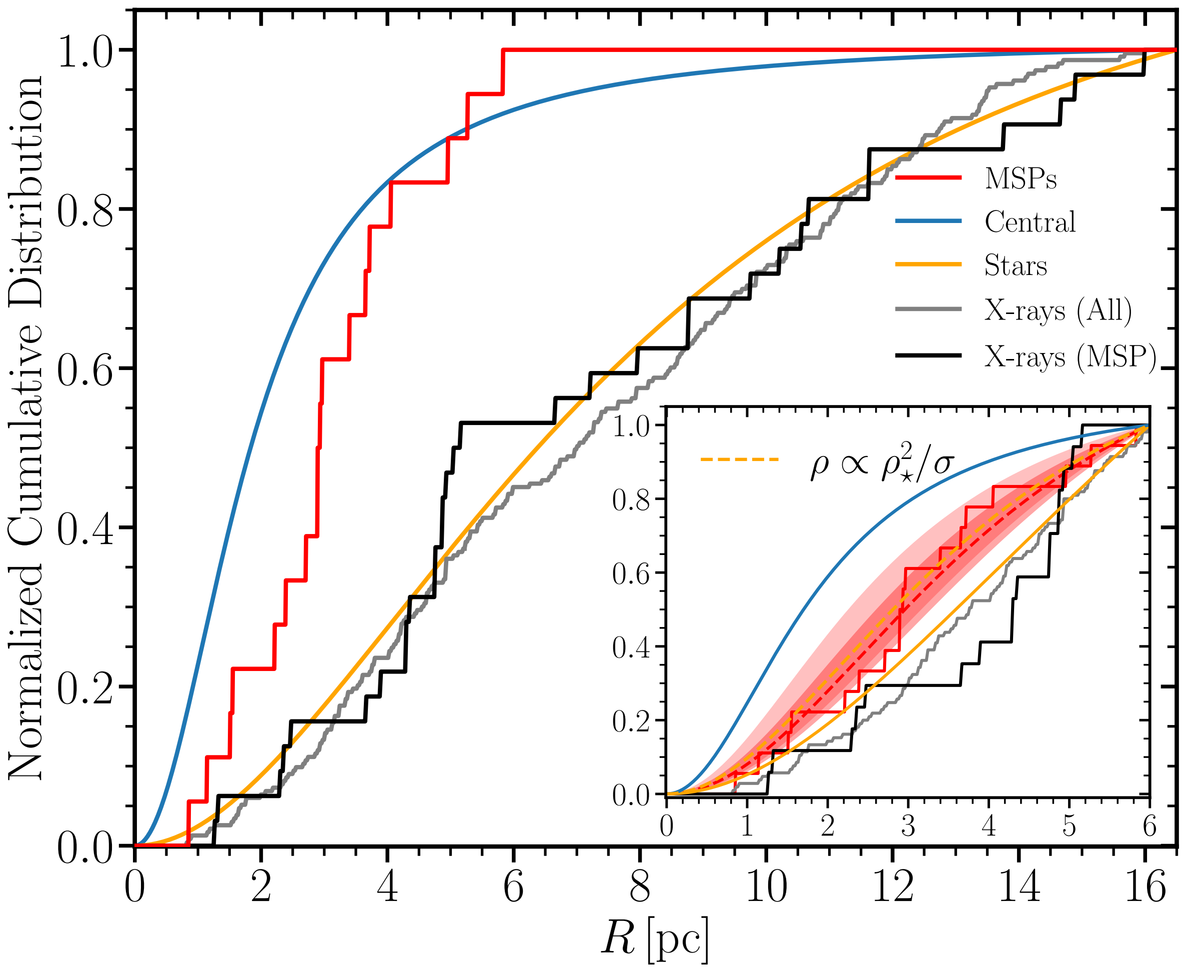


Probing models of pulsar formation in ω Cen

- Milli-second pulsars (MSPs) are believed progeny of X-ray binaries
- Encounter models predict MSP abundances scale with stellar encounter rates:

$$\Gamma \propto \int dr\, r^2 \rho_\star(r)^2 / \sigma(r)$$

- We extend this for densities to describe the intra-cluster MSP distribution, showing excellent agreement (inset)



Conclusions

- Introduced promising methodology combining stellar kinematics and pulsar timing, providing additional constraints on mass models
- Simultaneously considered the presence of IMBH and central cluster of remnants, favoring remnants and setting a stringent 3σ upper limit of 6,000 $M_\odot$ on IMBH
- Analyzed MSP distribution, exploring stellar encounter formation scenario. Extended previous validation analyses to derive a profile for the intra-cluster distribution, showing excellent agreement

Comments & future directions

- Our methodology shows promise with the advent of rapidly growing and upcoming observations (e.g. SKA)

- Will address the presence of a DM halo and its comparison to simulations in a future publication (in prep.)

- Following realistic DM halo modeling, J-factors and escape velocities for ω Cen should be revisited (in prep.)

- Followup analysis with new MUSE + HST data (~ 600,000 PMs)

Image credit: ESO (CC BY 4.0)

IMBH discovered in ω Cen: a comeback?

- 3σ lower bound of 8,200 $M_\odot$ from high-velocity stars, in apparent tension with ours
- Sensitive to the assumed escape velocity of the cluster
- Remnants already increase this by ~ 10 %, while kinematics allow an extended DM halo to ~ double it!

NASA's Hubble Finds Strong Evidence for Intermediate-Mass Black Hole in Omega Centauri

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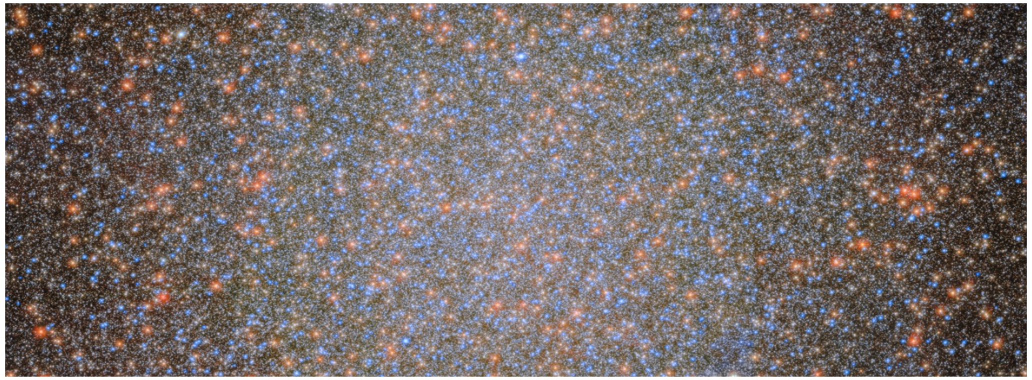

Article

Fast-moving stars around an intermediate-mass black hole in ω Centauri

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Combining stellar kinematics + pulsar timing

- Included all data self-consistently into the likelihood:

$$\ln \mathcal{L}_{\rm tot}(\boldsymbol{\theta}) = \ln \mathcal{L}_{\rm LOS} + \ln \mathcal{L}_{\rm PM,t} + \ln \mathcal{L}_{\rm PM,R} + \ln \mathcal{L}_{\rm VSP1} + \ln \mathcal{L}_{\rm VSP2} + \ln \mathcal{L}_{p,\,\rm LOS} + \ln \mathcal{L}_{\rm pos} + \ln \mathcal{L}_{\rm pos,\,R}$$

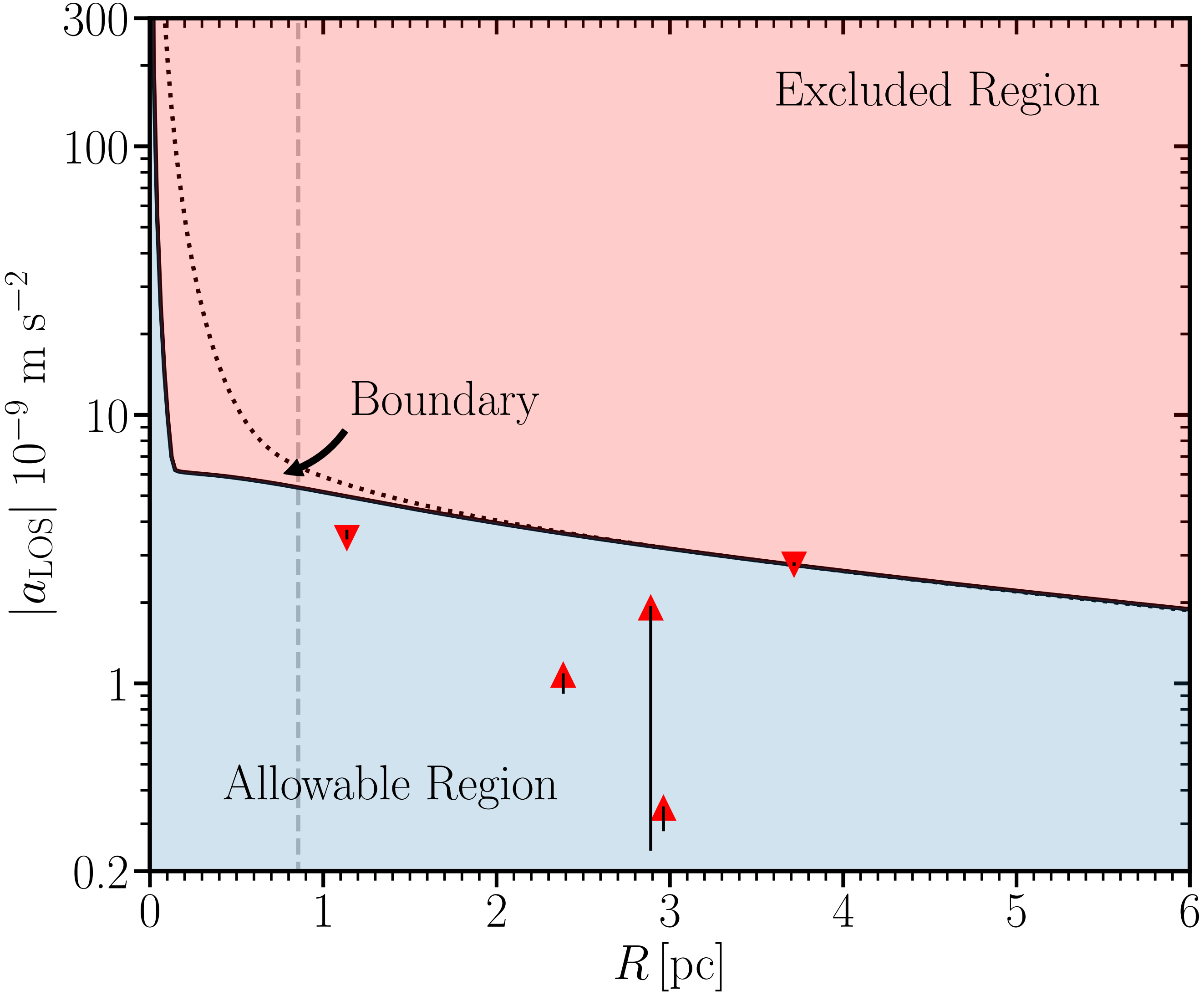
- For stellar kinematics and LOS accelerations:

$$\ln \mathcal{L}(\boldsymbol{\theta}) = -\frac{1}{2}\sum_y \chi_y^2, \qquad \chi_y^2 \equiv \sum_i \frac{\left[y_{i,\,\rm obs} - y_i(\boldsymbol{\theta})\right]^2}{\delta y_i^2}$$

- For positional likelihoods of pulsars: $n(r) = f(\alpha,\ r_0,\ n_0)\left[1 + \left(\frac{r}{r_0}\right)^2\right]^{(\alpha-1)/2}$

Pulsar accelerations

- Favor ~ 20 % more massive and extended central mass than stellar kinematics alone
- Extremal central pulsar accelerations are IMBH 'smoking gun' signatures
- These are not favored by our analysis (except for a small IMBH very close to the center)



Stellar kinematics observables (LOS + PMs)

- Can't measure $\sigma_r(r)$ and $\beta(r)$ directly, but can constrain them with projected quantities (line-of-sight + proper motions):

$$\sigma^2_{\rm LOS}(R) = \frac{2}{\Sigma_\star(R)} \int_R^\infty \left(1 - \frac{R^2}{r^2}\beta(r)\right) \frac{\nu_\star(r)\sigma_r^2(r)r}{\sqrt{r^2 - R^2}} dr,$$

$$\sigma^2_{\rm PM,\,t}(R) = \frac{2}{\Sigma_\star(R)} \int_R^\infty \left(1 - \beta(r)\right) \frac{\nu_\star(r)\sigma_r^2(r)r}{\sqrt{r^2 - R^2}} dr.$$

$$\sigma^2_{\rm PM,\,R}(R) = \frac{2}{\Sigma_\star(R)} \int_R^\infty \left(1 - \beta(r) + \frac{R^2}{r^2}\beta(r)\right) \frac{\nu_\star(r)\sigma_r^2(r)r}{\sqrt{r^2 - R^2}} dr$$

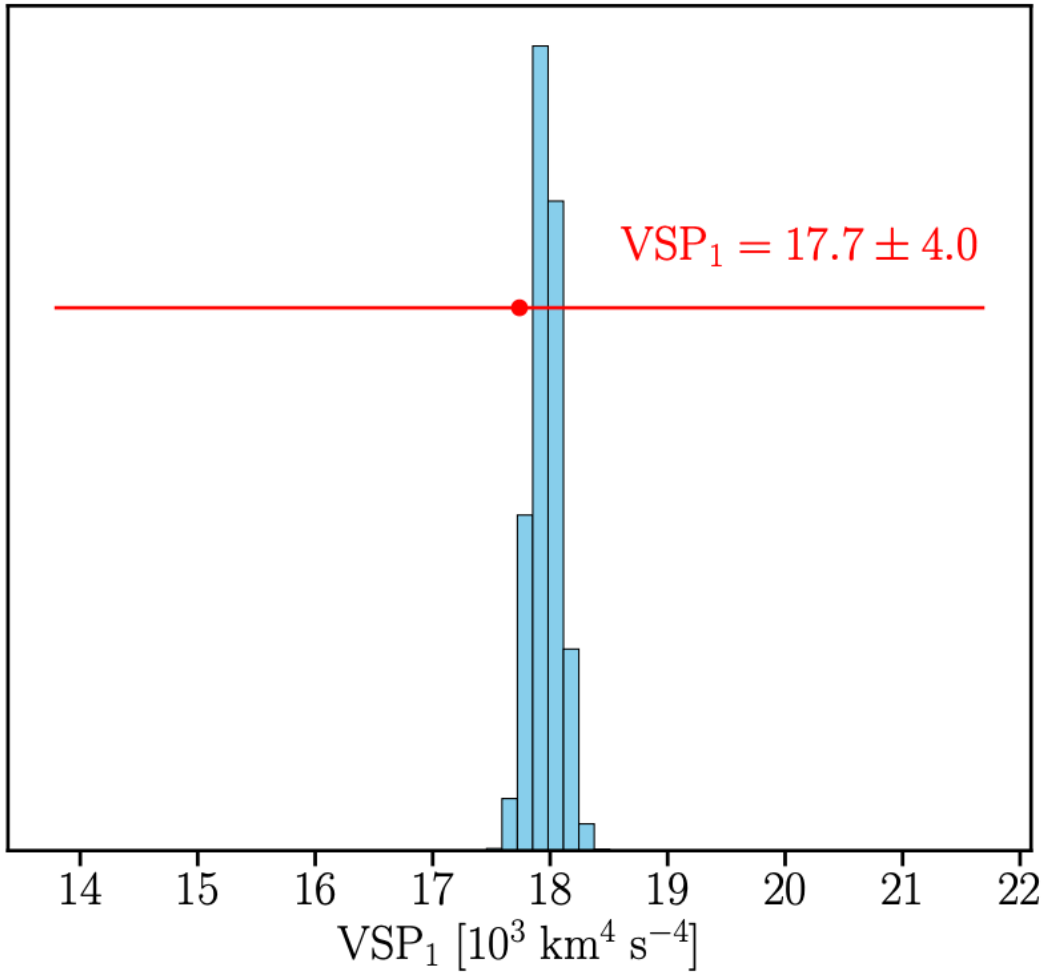
Stellar kinematics observables (VSPs)

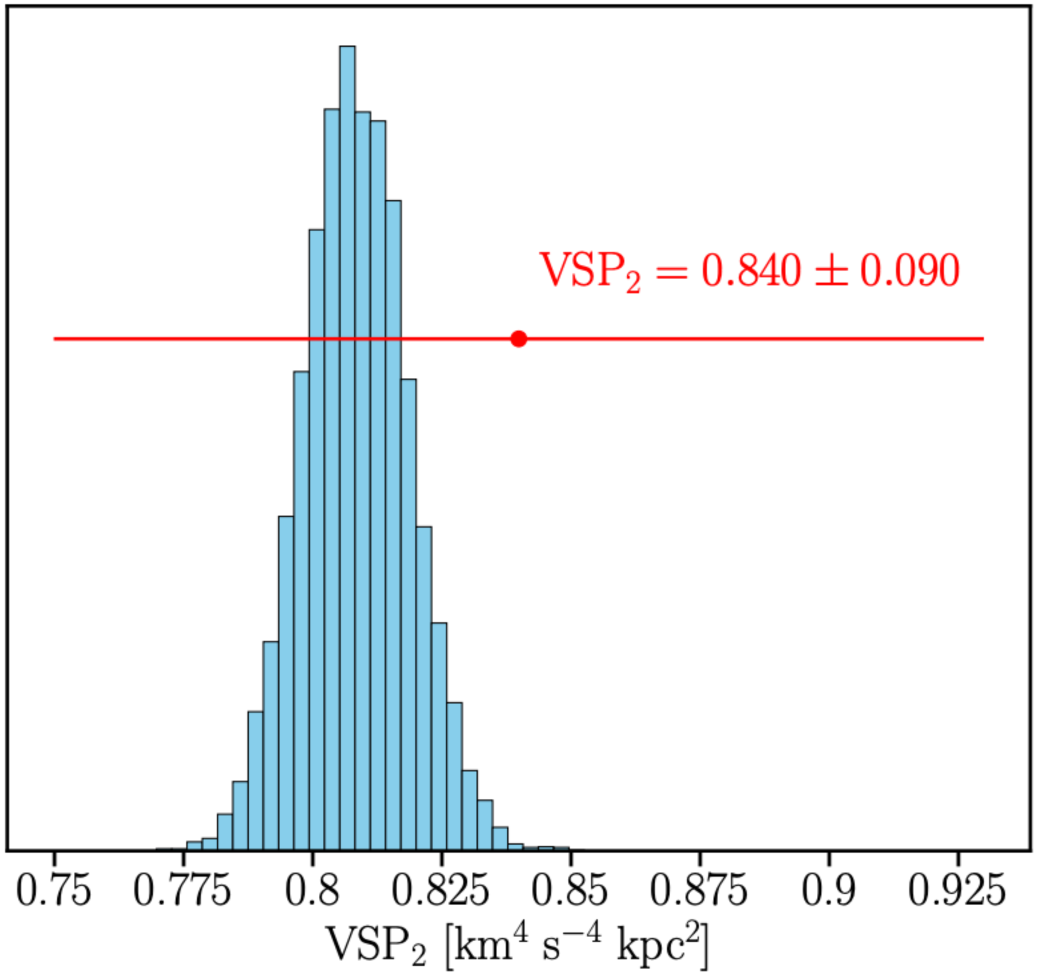
- Can also measure higher velocity moments (virial shape paremeters) as an additional constraint:

$$\mathrm{VSP1} = \frac{2}{5}\int_0^\infty GM\nu_\star(5-2\beta)\sigma_r^2 r\,dr = \int_0^\infty \Sigma_\star \langle \mathrm{v}_{\mathrm{LOS}}^4 \rangle R\,dR$$

$$\mathrm{VSP2} = \frac{4}{35}\int_0^\infty GM\nu_\star(7-6\beta)\sigma_r^2 r^3\,dr = \int_0^\infty \Sigma_\star \langle \mathrm{v}_{\mathrm{LOS}}^4 \rangle R^3\,dR$$

Results: VSPs





The mass/density - anisotropy degeneracy

- Full consideration of these observables is important to avoid degeneracies with mass models

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How to break the density-anisotropy degeneracy in spherical stellar systems

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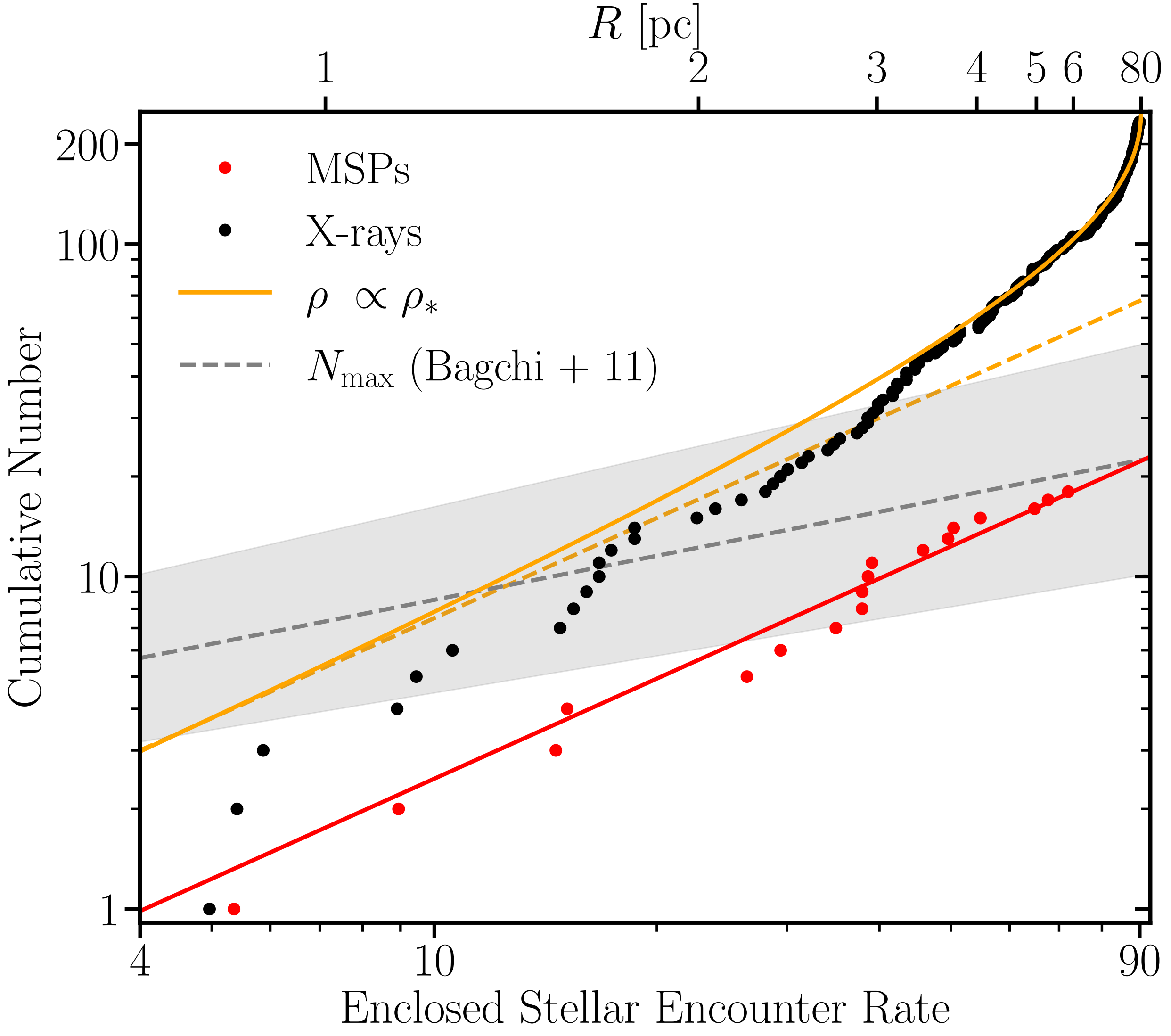
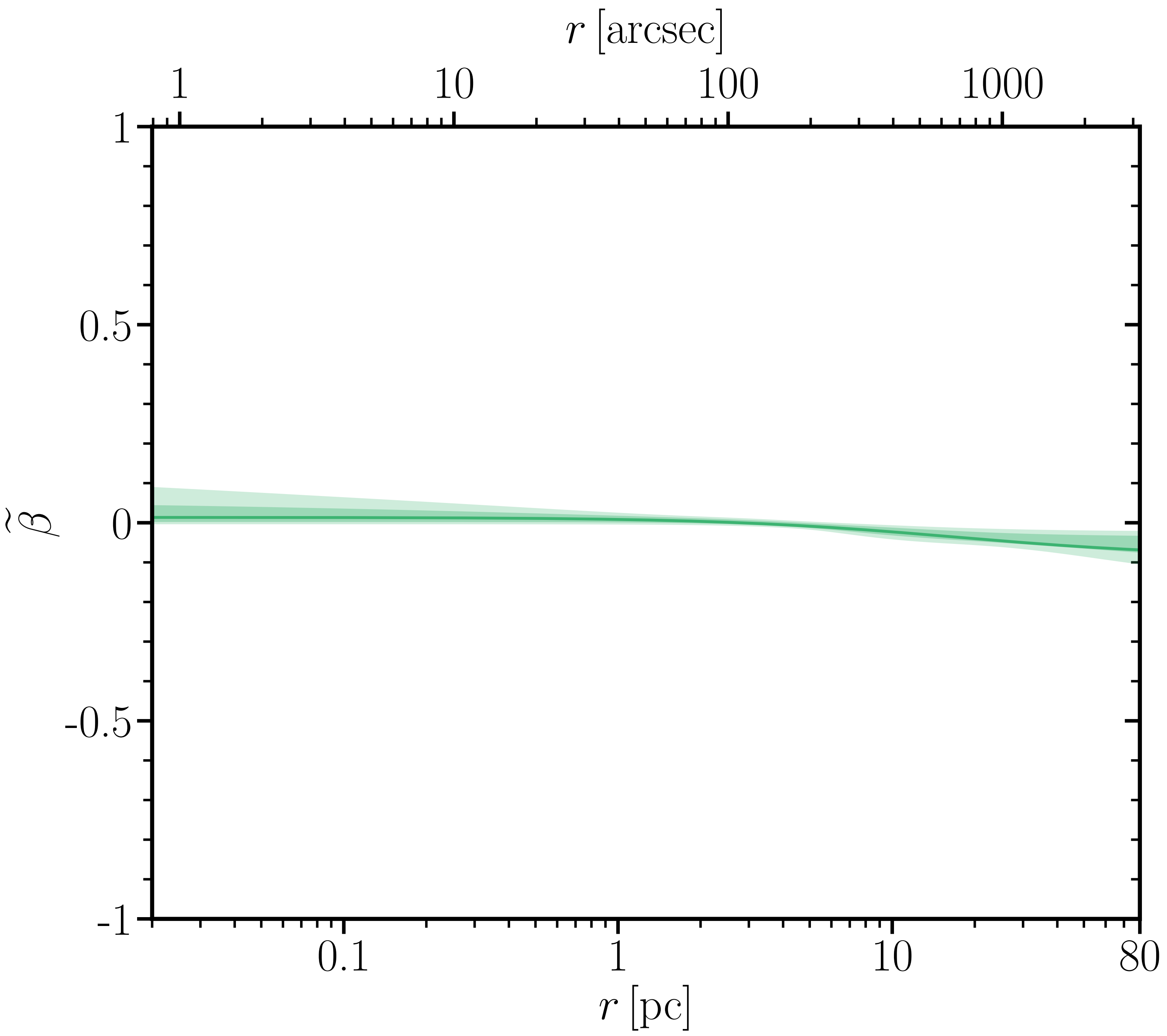
Dependence with enclosed encounter rates

- We define the enclosed encounter rate:

$$\Gamma(R) \propto \int_{-\infty}^{\infty} dl \int_0^R dR' R' \rho_\star(r)^2/\sigma(r),$$

- MSPs show a clear linear scaling, the other components don't
- Similar to the relation for total encounter rates of GCs (gray dots)
- X-ray sources are traced by stellar profile, not the encounter rate





r [arcsec]
1
10
100
1000
1
0.5
0
-0.5
-1
$\tilde{\beta}$
0.1
1
10
80
r [pc]