Stellar-Mass Black Holes with Dark Matter Mini-Spikes: Indication of a Primordial Origin?

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Based on [2406.07624]

Overview

- Motivations
- Mini-spike profile
  - Formation
  - Growth
  - Astrophysical effects
- Confronting the data
- Summary

Motivations

Recent observations of three nearby black hole low-mass X-ray binaries (BH-LMXBs) reveal companion stars with anomalously fast orbital decay rates

	A0620-00	XTE J1118+480	Nova Muscae 1991
$M_{\mathrm{BH}}\ (M_\odot)$	5.86 ± 0.24	$7.46^{+0.34}_{-0.69}$	$11.0^{+2.1}_{-1.4}$
$q = M_*/M_{\mathrm{BH}}$	0.060 ± 0.004	0.024 ± 0.009	0.079 ± 0.007
P (day)	0.32301415(7)	0.16993404(5)	0.432605(1)
$\dot{P}$ (ms/yr)	-0.60 ± 0.08	-1.90 ± 0.57	-20.7 ± 12.7

[1112.1839], [1311.5412], [1609.02961]

Motivations

- Dominant sources of angular momentum loss
  - Magnetic braking
  - Mass transfer from donor star
  - Gravitational wave emission

  $\Big\}\ |\dot{P}| \lesssim 0.03\ \mathrm{ms/yr}$

- Other explanations?
  - Extremely strong stellar magnetic field?
  - Interactions with the circumbinary disk?
  - Dynamical friction due to dark matter density spike [2212.05664]

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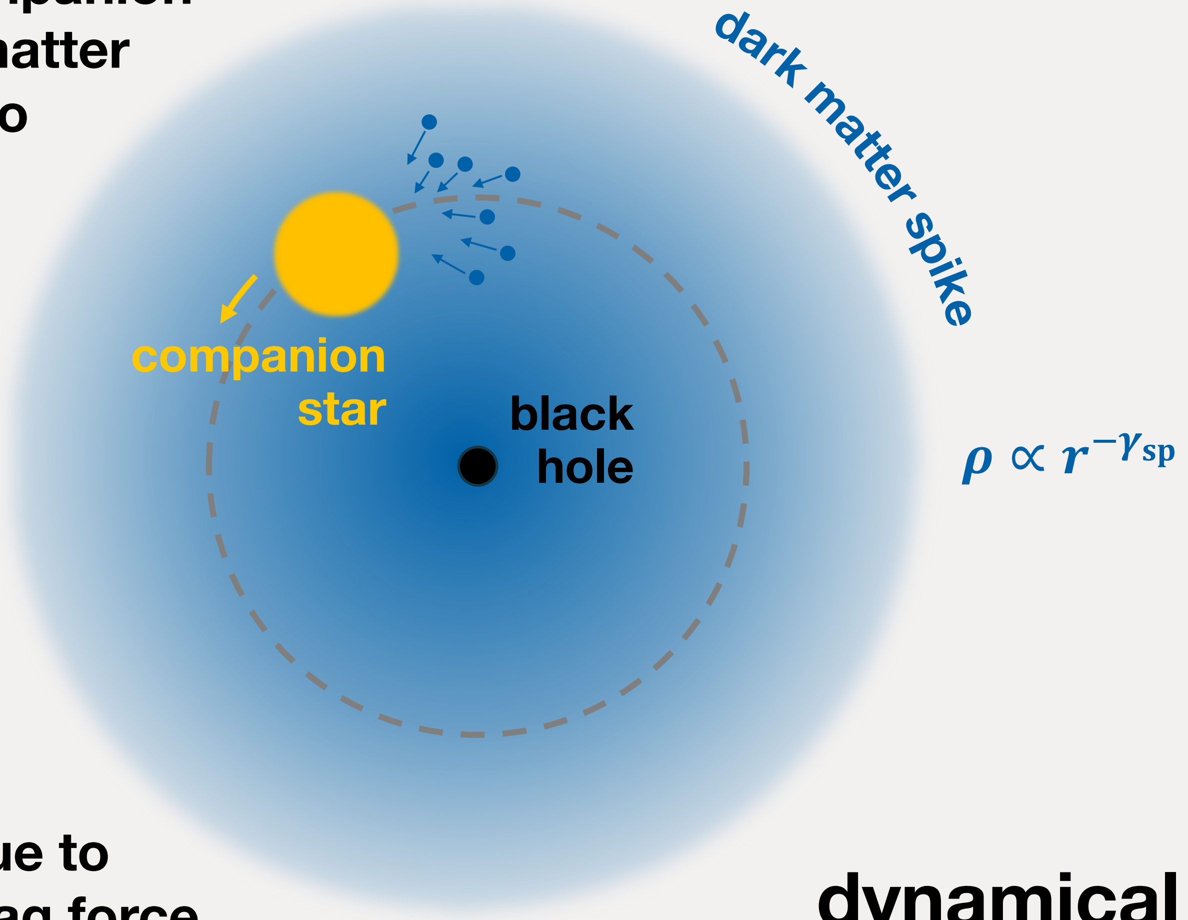
    ⇒ Insufficient mass transfer rate with inner binary [1511.00534]
  - Dynamical friction due to dark matter density spike [2212.05664]

Motivations

orbiting companion
pulls dark matter
particles into
its wake



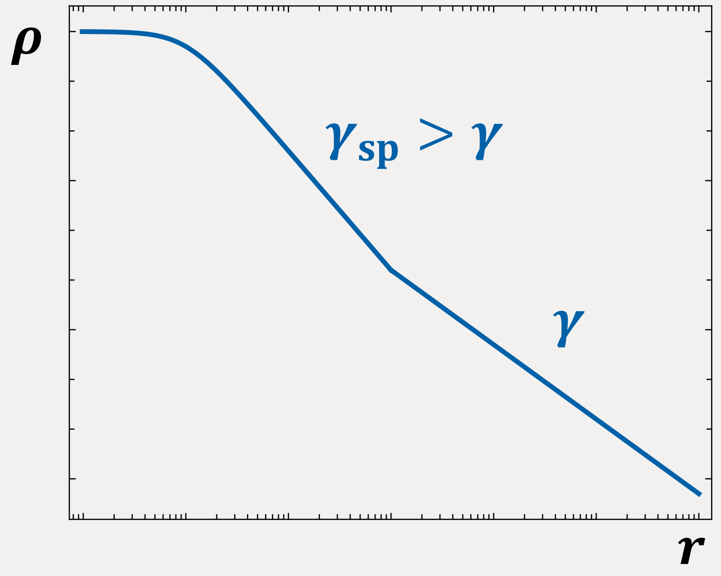
energy loss
& inspiral due to
resultant drag force

dynamical friction

Motivations

[2212.05664]

- Chan & Lee, 2022
  - $\gamma_{\rm sp} \sim 1.7 - 1.9$ consistent with observed decay
  - Indirect evidence of DM density spike
- **Issue:** Assumed DM profile appropriate for a supermassive BH in the galactic center, **not** a stellar-mass black hole in a LMXB
- DM spikes
  - Arise for intermediate-mass and supermassive BHs growing *adiabatically* in cold, collisionless DM halos
  - $\rho \propto r^{-\gamma} \rightarrow \rho \propto r^{-\gamma_{\rm sp}}$ with $\gamma_{\rm sp} = \dfrac{9-2\gamma}{4-\gamma}$



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- DM density spikes are **not** expected around stellar-mass BHs
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  - Assembly begins soon after PBH formation
  - After matter-radiation equality, growth through secondary-infall
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Q. Can the mini-spikes about primordial black holes account for the DM density inferred by the dynamical friction hypothesis?

Mini-Spike Formation

- Mini-spike assembly begins during radiation domination
- Cold DM particles with small v
  - Decouple from Hubble flow
  - Fall into orbit about PBH
- Turn-around radius: $r_{\mathrm{ta}} \simeq 1.0\, r_{\mathrm{s}}^{1/3}\, t_{\mathrm{ta}}^{2/3}$ [1901.08528]
  ⇒ defines PBH sphere of influence
- Initial DM profile $\rho_i(r)$ depends on whether PBH forms before or after kinetic decoupling
- Formation at:

$$T_{\mathrm{form}} = 141\ \mathrm{MeV}\left(\frac{\gamma_{\mathrm{eff}}}{0.2}\right)^{1/2}\left(\frac{24.0}{g_\star(T)}\right)^{1/4}\left(\frac{M_\odot}{M_{\mathrm{BH}}}\right)^{1/2}$$

Mini-Spike Formation

- $T_{\text{form}} > T_{\text{kd}}$
  - DM too tightly coupled to appreciably accrete
    ⇒ Constant ρ_{kd} out to $r_{\text{ta}}(t_{\text{kd}})$
  - After kinetic decoupling, halo radius grows, diluting as $\rho \propto a^{-3} \propto t^{-3/2}$
    ⇒ Mini-spike $\rho_{\text{sp}}(r)$ for $r > r_{\text{ta}}(t_{\text{kd}})$

$$\rho_{\text{kd}} = \frac{\rho_{\text{eq}}}{2} f_{\text{DM}} \left(\frac{r_{\text{ta}}(t_{\text{eq}})}{r_{\text{ta}}(t_{\text{kd}})} \right)^{9/4}$$

$$\rho_i(r) = \begin{cases} \rho_{\text{kd}} & r < r_{\text{ta}}(t_{\text{kd}}) \\ \rho_{\text{sp}}(r) & r_{\text{ta}}(t_{\text{kd}}) < r < r_{\text{ta}}(t_{\text{eq}}) \end{cases}$$

$$\rho_{\text{sp}}(r) = \rho_{\text{kd}} \left(\frac{r_{\text{ta}}(t_{\text{kd}})}{\text{r}} \right)^{9/4}$$

- $T_{\text{form}} < T_{\text{kd}}$:
  - No constant density core, $\rho_i(r) = \rho_{\text{sp}}(r)$

Mini-Spike Formation

- Disruption by large thermal kinetic energy?
  - Demand $E_K/E_P < 1 \Rightarrow$ Can be satisfied for our $\mathcal{O}(1-10)\,M_\odot$ BHs
- Modification by finite DM velocity?

$$\rho(r) = \frac{2}{r^2}\int d^3v_i\, f_B(v_i)\int dr_i\, r_i^2\,\frac{\rho_i(r_i)}{\tau_{\rm orb}}\left|\frac{dt}{dr}\right| \quad \Rightarrow \quad \boxed{\rho(r) \simeq 1.526\,\rho_{\rm kd}\left(\frac{r_{\rm ta}(t_{\rm kd})}{r}\right)^{9/4}}$$

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- Modification by DM annihilations?
  - Impose upper limit on DM density

$$\rho_{\rm max} \simeq (1.3\times10^{-16}{\rm g/cm^3})\ f_{\rm DM}\left(\frac{m_{\rm DM}}{\rm GeV}\right)\left(\frac{3\times10^{-26}{\rm cm^3/s}}{\langle\sigma v\rangle}\right)$$

  - $\Gamma_{\rm ann} \propto \rho^2 \Rightarrow$ Enhanced γ-ray emission $\Rightarrow$ Relevant parameter space excluded

Mini-Spike Growth

- Following t_{eq}, accretion becomes efficient
- Bound shells of DM added at successively larger radii
- Density profile
  - PBH+halo constitute overdensity $\Delta = \delta M/\bar{M}$
  - Density perturbations grow as $\Delta \propto a \propto t^{2/3}$
  - Gravitationally bound mass: $M_{\mathrm{bound}}(t) = M_{\mathrm{bound}}(t_{\mathrm{eq}})(t/t_{\mathrm{eq}})^{2/3}$
  - Turn-around radius:

$$r \propto \left(\frac{M_{\mathrm{bound}}(t)}{\rho(t)}\right)^{1/3} \propto t^{8/9} \propto \rho^{-4/9} \quad \Rightarrow \quad \boxed{\rho \propto r^{-9/4}}$$

growth by factor ~ 100 between z_{eq} and $z \sim 30$

same power law scaling as before

Mini-Spike Disruption

- Various astrophysical processes can disrupt the DM spike
  - Tidal stripping
  - Gravitational scattering/other interactions with stars
  - Dynamical friction
  - Mergers with other PBHs
  - Incorporation in binaries

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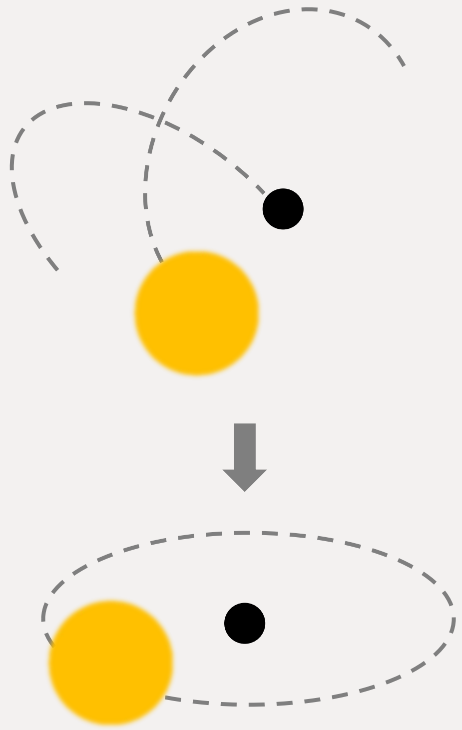
  - Incorporation in binaries ⇒ BH-LMXB formation event
- Dynamical friction & gravitational scattering
  - Particles with $v < v_*$ gain energy
  - Energy lost by star heats DM halo
  - Increases velocity dispersion, decreases local DM density

Mini-Spike Disruption

- LMXB formation via dynamical capture
- Likelihood highest
  - In dense stellar environments
  - For $M_{\mathrm{BH}} \gg M_*$



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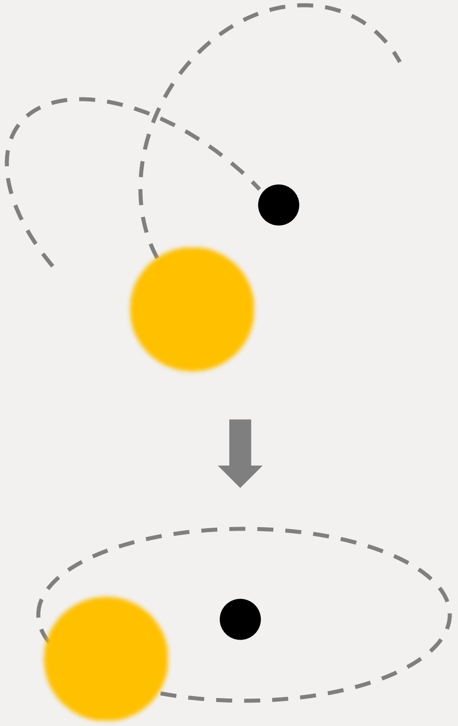

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- Likelihood highest
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  - For $M_{\mathrm{BH}} \gg M_*$
- XTE J1118+480 likely formed through this channel!
  - High metallicity stellar component (pollution from supernova event)
  - Constituents of binary likely **not** born together [astro-ph/0605107], [0801.4936]
    ⇒ BH can be primordial!
  - If so, extra gravitational influence, energy dissipation aid in capture
  - Tidal stripping? Mild for $q \ll 1$

Confronting the Data

- Energy loss due to dynamical friction:

$$\dot{E}_* \simeq -4\pi\mu^2 G^2 \rho_{\rm orb} \frac{\xi(v_*)}{v_*} \ln\sqrt{1/q}$$

- From $\left|\dot{P}/P\right| = \frac{3}{2}\left|\dot{E}_*/E_*\right|$:

$$\boxed{\rho_{\rm orb} \simeq \frac{1}{6\pi} \frac{M_{\rm Pl}^{8/3}}{M_{\rm BH}^{1/3}} \frac{(1+q)^{5/3}}{q\ln(1/q)} \frac{v_*}{\xi(v_*)} \left|\frac{\dot{P}}{P}\right| \left(\frac{2\pi}{P}\right)^{2/3}}$$

	A0620-00	XTE J1118+480	Nova Muscae 1991
$\boldsymbol{x_{\rm orb} = r_{\rm orb}/r_s}$	$(1.46 \pm 0.04)\times 10^5$	$8.01^{+0.56}_{-0.26} \times 10^4$	$1.17^{+0.11}_{-0.13} \times 10^5$
$\boldsymbol{\rho_{\rm orb}\ ({\rm g/cm^3})}$	$7.62^{+1.62}_{-1.42} \times 10^{-13}$	$1.59^{+1.51}_{-0.74} \times 10^{-11}$	$1.26^{+1.10}_{-0.84} \times 10^{-11}$

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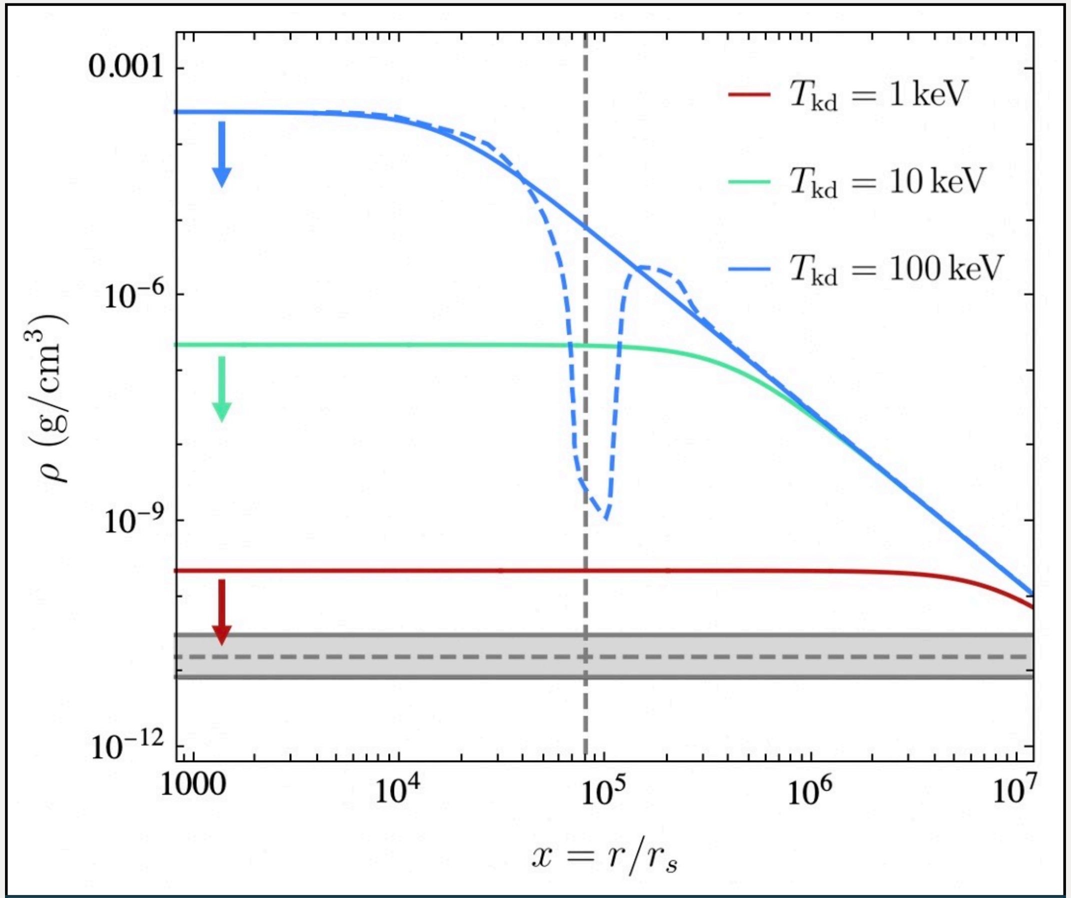

Sample mini-spike profiles for a $7.46\ M_\odot$ PBH, as in XTE J1118+480

Halo feedback from dynamical friction [2002.12811]

Summary

- Three nearby BH-LMXBs suggest evidence of dark matter density spikes
  - Stellar-mass BHs formed from stellar collapse don't form density spikes
  - Stellar-mass primordial BHs do
  - Could the $\mathcal{O}(1-10)\ M_\odot$ BHs in these LMXBs be primordial?
- In this work
  - Compute mini-spike profile under variety of assumptions
  - Scenario plausible for heavy DM with late kinematic decoupling
- Future work
  - Quantify extent of halo disruption during binary formation
  - Numerical simulations