# Dark, Spiky Primordial Black Holes

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

| | A0620-00 | XTE J1118+480 |
|---|---|---|
| $M_{\mathrm{BH}}\ (M_\odot)$ | $5.86 \pm 0.24$ | $7.46^{+0.34}_{-0.69}$ |
| $q = M_*/M_{\mathrm{BH}}$ | $0.060 \pm 0.004$ | $0.024 \pm 0.009$ |
| $P$ (day) | $0.32301415(7)$ | $0.16993404(5)$ |
| $\dot{P}$ (ms/yr) | $-0.60 \pm 0.08$ | $-1.90 \pm 0.57$ |

[1112.1839], [1311.5412], [1609.02961]

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    - Magnetic braking
    - Mass transfer from donor star
    - Gravitational wave emission

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

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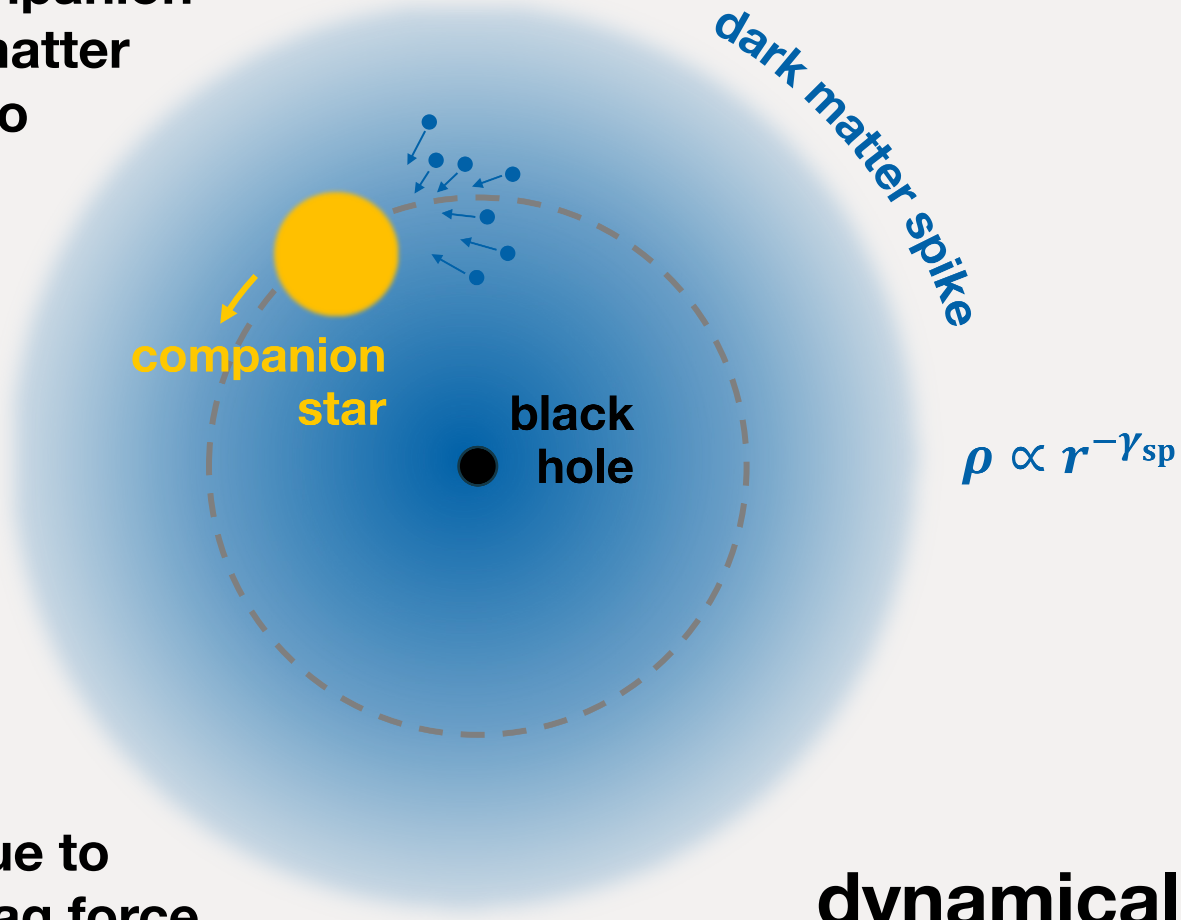
  - Interactions with the circumbinary disk?

    ⇒ 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**

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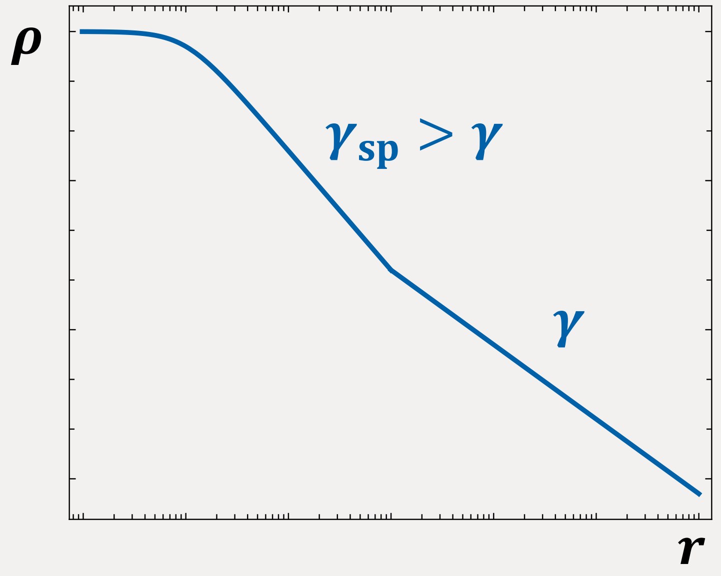
- **Issue:** Assumed DM profile appropriate for a supermassive BH in the galactic center, **not** a stellar-mass black hole in a LMXB
- DM spikes
  - Arise for intermediate-mass and supermassive BHs growing *adiabatically* in cold, collisionless DM halos
  - $\rho \propto r^{-\gamma} \rightarrow \rho \propto r^{-\gamma_{\rm sp}}$ with $\gamma_{\rm sp} = \dfrac{9 - 2\gamma}{4 - \gamma}$



# Motivations

- DM density spikes are **not** expected around stellar-mass BHs
  - Weaker gravitational influence
  - Locations in baryon-dense, DM-sparse regions
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Q. Can a primordial origin for these black holes account for the DM density implied by the dynamical friction interpretation?

# 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: $r_{\rm ta} \simeq 1.0\, r_{\rm s}^{1/3}\, t_{\rm ta}^{2/3}$ [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:

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

# Mini-Spike Formation

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

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

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

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

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

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

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

  - $\Gamma_{\mathrm{ann}} \propto \rho^2$ ⇒ Enhanced $\gamma$-ray emission ⇒ Relevant parameter space excluded

# Mini-Spike Growth

- Following $t_{\mathrm{eq}}$, 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 $\sim 100$ between $z_{\mathrm{eq}}$ 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
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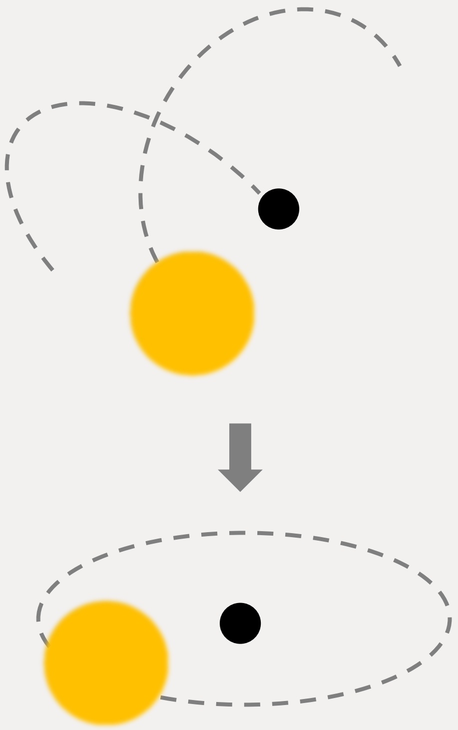
  - Incorporation in binaries ⇒ **BH-LMXB formation event**
- Dynamical friction & gravitational scattering with companion star
  - Particles with $v < v_*$ gain energy
  - Energy lost by star heats DM halo
  - Increases velocity dispersion, decreases local DM density

# Mini-Spike Disruption

- BH-LMXB formation channel: **Dynamical capture**
  - Energy dissipation due to dynamical friction
- Likelihood highest
  - In dense stellar environments
  - For $M_{\mathrm{BH}} \gg M_*$



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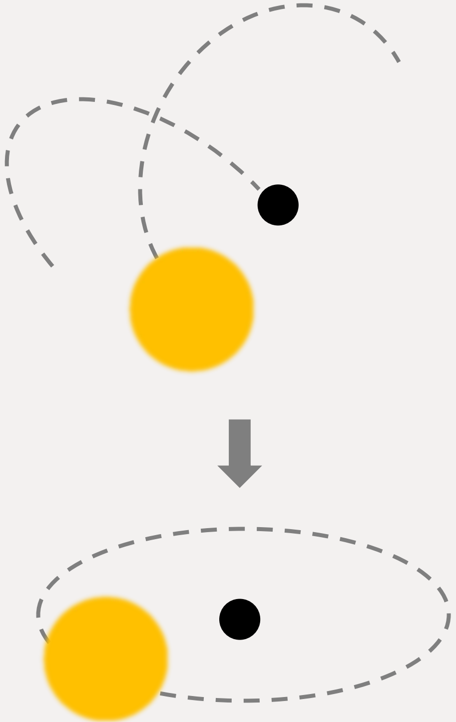

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- Estimate: $N_{\mathrm{bin}} = N_{\mathrm{enc}}\ P_{\mathrm{form}} \simeq N_{\mathrm{enc}}(b \lesssim b_{\max})$
  - Encounter rate: $\Gamma_{\mathrm{enc}} = n_{\mathrm{PBH}}\, n_*\, \sigma\, v_{\mathrm{rel}} \quad \Rightarrow \quad N_{\mathrm{enc}} = \Gamma_{\mathrm{enc}}\, \mathcal{V}\, \mathcal{T}$ ← time since reionization
  - Interaction cross section: $\sigma \simeq \pi b_{\max}^2$

($\mathcal{V}$: volume of Milky Way)

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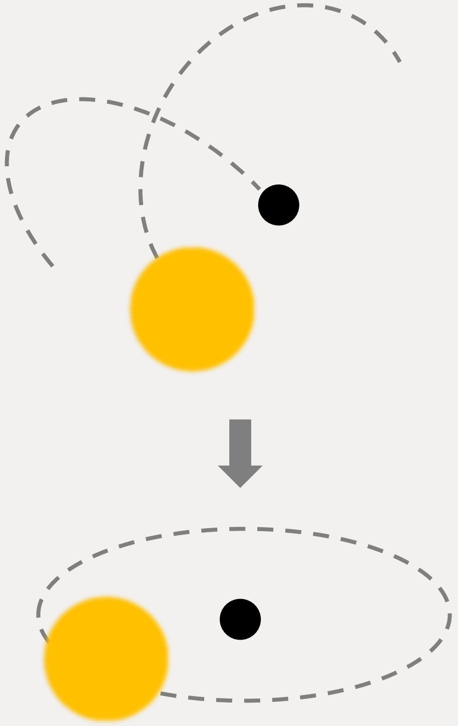

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  - Encounter rate: $\Gamma_{\rm enc} = n_{\rm PBH}\, n_*\, \sigma\, v_{\rm rel}$ $\Rightarrow$ $N_{\rm enc} = \Gamma_{\rm enc}\, \mathcal{V}\, \mathcal{T}$ ← time since reionization; ↖ volume of Milky Way
  - Interaction cross section: $\sigma \simeq \pi b_{\rm max}^2$

$$N_{\rm bin} \sim 10^6 \left(\frac{f_{\rm PBH}}{10^{-5}}\right)\left(\frac{M_{\rm BH}}{5\, M_\odot}\right)$$

# Mini-Spike Disruption

- 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]
    $\Rightarrow$ BH can be **primordial**!

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    ⇒ BH can be **primordial**!
- Concern: Tidal stripping of DM halo?
  - Expect to be mild for $q \ll 1$, $\epsilon \ll 1$
  - To check, compare mini-spike binding energy to energy lost to dynamical friction
  - Can show $W_{\rm df}/|\Delta U| \ll 1$ across parameter space of interest
    ⇒ spike intact

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

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

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

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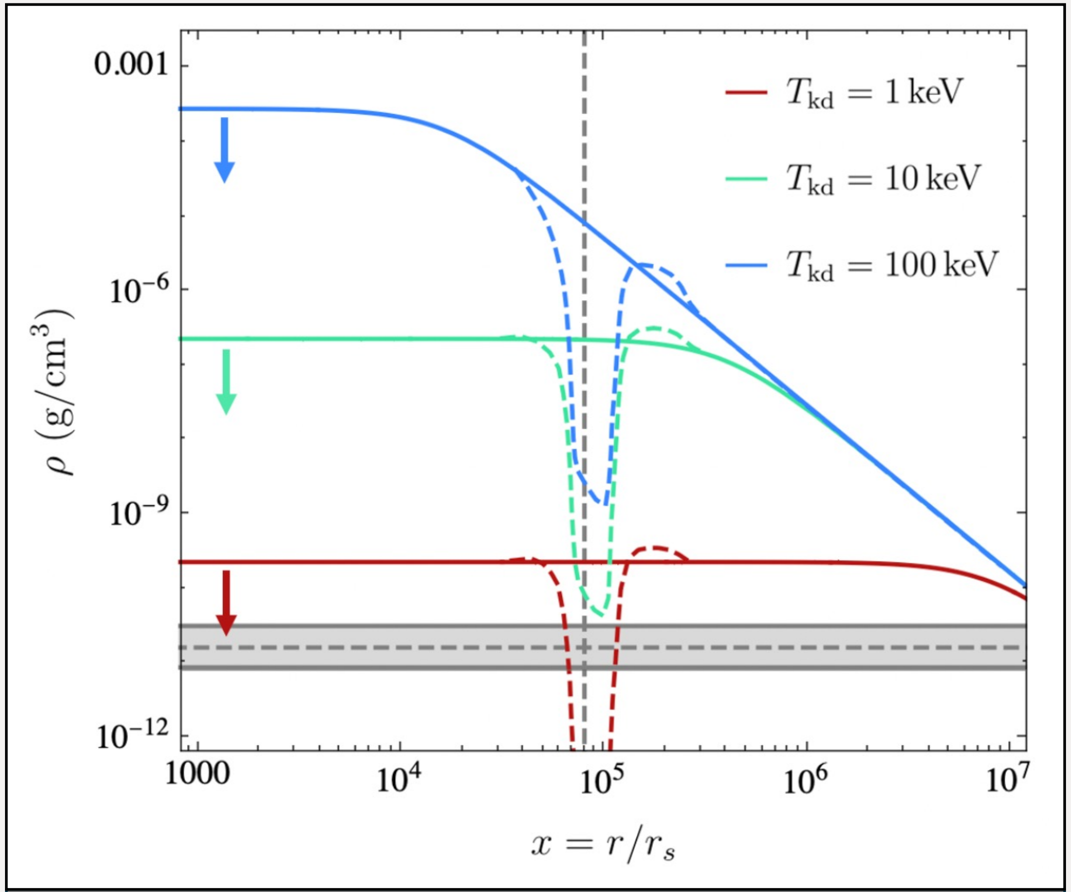


Sample mini-spike profiles for a $7.46\ \mathrm{M}_\odot$ PBH, as in XTE J1118+480

Halo feedback from dynamical friction [2002.12811]

# Summary

- Two nearby BH-LMXBs suggest evidence of DM density spikes
  - Light BHs formed from stellar collapse don't form density spikes
  - Light primordial BHs do
  - Could the $\mathcal{O}(1-10)\ M_{\odot}$ BHs in these LMXBs be primordial?
- In this work
  - Derive mini-spike profile for generic DM
  - Scenario plausible for heavy DM with late kinematic decoupling
- Future work
  - Numerical simulations to better model disruption due to astrophysical effects
  - Refined measurements