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Effects of Black Hole Environments on Gravitational Wave Signals

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Dynamical Friction: Gravitational Drag Force

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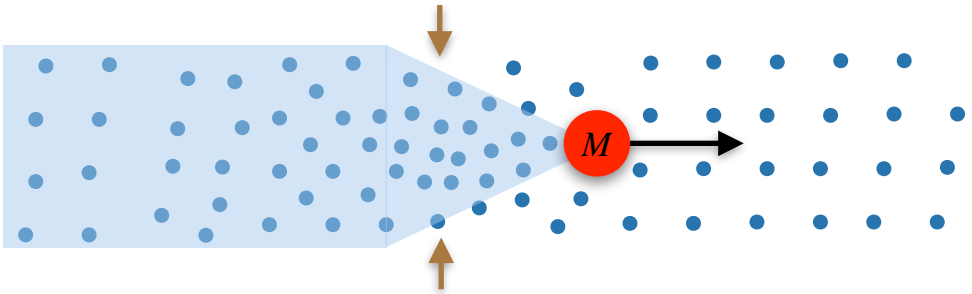
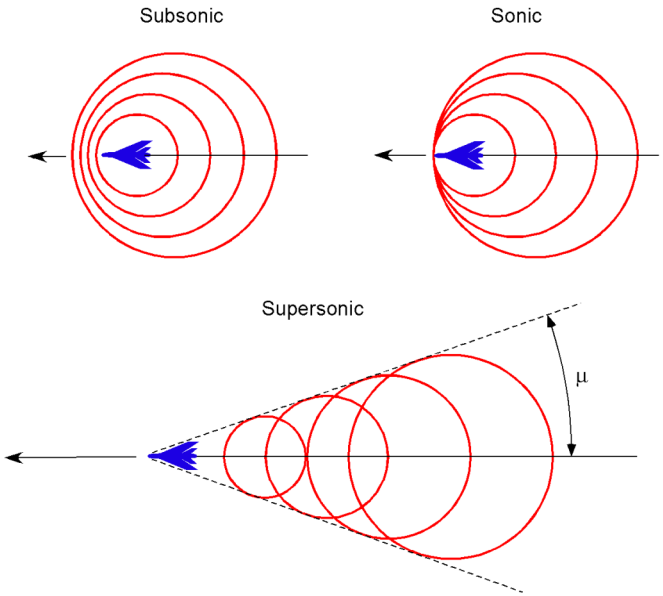
Classical Linear Motion*

- Perturber moving through background medium creates ***wakes***
- **Mach Cone** - Higher density region trailing perturber *pulls back* on it gravitationally
- In steady state, force divergences with medium size at leading order (no backreaction)





$$F_{SS} = \frac{4\pi (G M_p)^2 \rho_0}{V^2} \ln\left(\frac{r_{max}}{r_{min}}\right)$$

*Ostriker 1999 *ApJ*

Motivation

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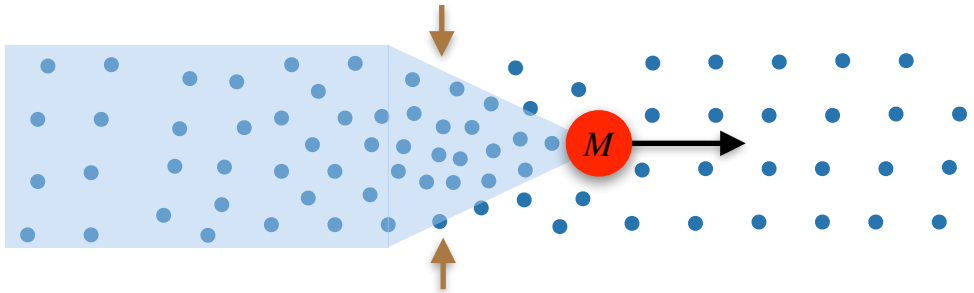
- **Next-generation GW experiments need** $100\times$ **precision**
  - Binary BH mergers in scalar wave dark matter clouds → **GW Dephasing*** (*very sensitive in experiments*)
  - Candidate DM model restrictions
- **Similar processes in QCD** that may be described with *same framework* (more on this later…)
- **Epistemic** - another opportunity to study a "non-conservative" phenomenon with field theory to high precision
- **Novel** - field-theoretic Dynamical Friction in non-trivial geometry (e.g. BH merger)



Studying Dynamical Friction may shed light on how to describe non-conservative forces in varied contexts.

*Cheng 2025 *arXiv:2510.20037 [gr-qc]*

Circular Motion: no divergence

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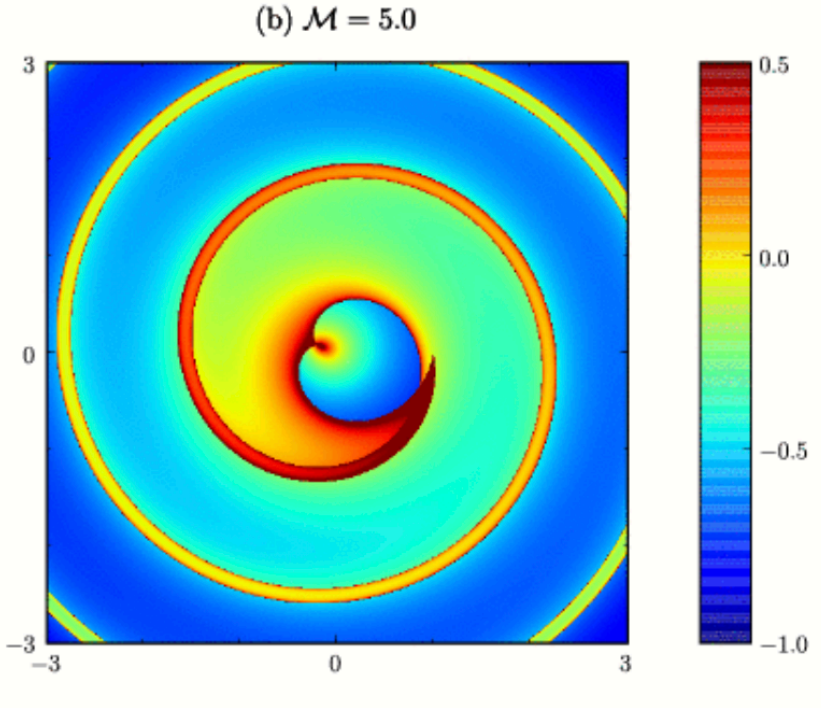
- Apply classical methods to circular orbit in medium*
- Nonzero force when subsonic (wakes bent)
- **No R_{max} divergence** - higher density trailing tail is *approximately cylindrically symmetric* from far away
  - Well-approximated by linear motion with finite medium size

$$F_{\text{circular},\,\hat{\phi}} \approx \underbrace{-\frac{4\pi(GM)^2\rho_0}{V^2}\left[\frac{1}{2}\ln\left(1-\frac{1}{\mathcal{M}^2}\right)+\ln\left(\frac{R_{\text{max}}=\cancel{Vt}}{R_{\text{min}}}\right)\right]}_{F_{\text{linear}}}$$

$2R_{\text{circle}}(t)$



*Kim and Kim 2007 *ApJ*

Promising Approaches

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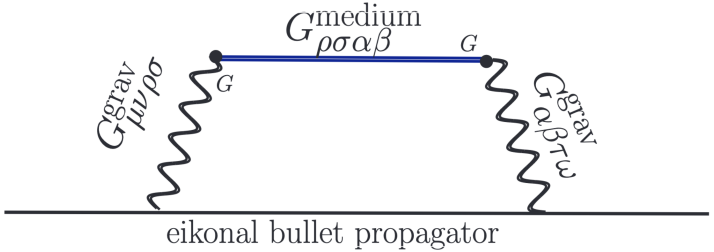
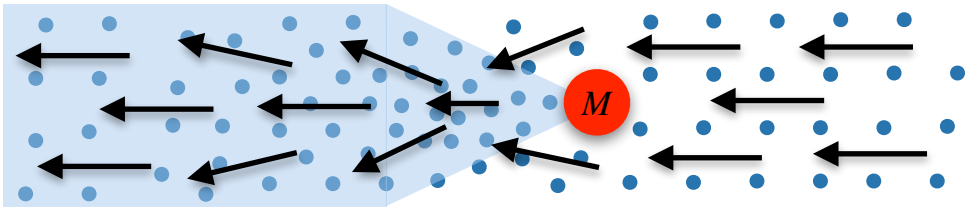
- **Scalar DM wave*** (classical scattering)
  - *Change Perspective* → classical wave scattering off stationary object
- **Worldline Formalism**†
  - nice way to *visualize* Dynamical Friction with particles
  - inconvenient for precision calculations



$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad |h_{\mu\nu}| \ll 1$$



$$h^{\text{bullet}}_{\rho\sigma} = G^{\text{grav}}_{\rho\sigma,\alpha\beta} T^{\alpha\beta}_{\text{bullet}}$$

$$h^{\text{wake}}_{\mu\nu} = \underbrace{G^{\text{grav}}_{\mu\nu,\gamma\delta}\, G^{\gamma\delta,\rho\sigma}_{\text{medium}}\, G^{\text{grav}}_{\rho\sigma,\alpha\beta}}_{G^{\text{dressed}}_{\mu\nu,\alpha\beta}}\, T^{\alpha\beta}_{\text{bullet}}$$

*Vicente and Cardoso 2022 *Phys. Rev. D* †Katz et al. 2019 *JCAP*

Worldline* Intuition: structure of the Mach Cone

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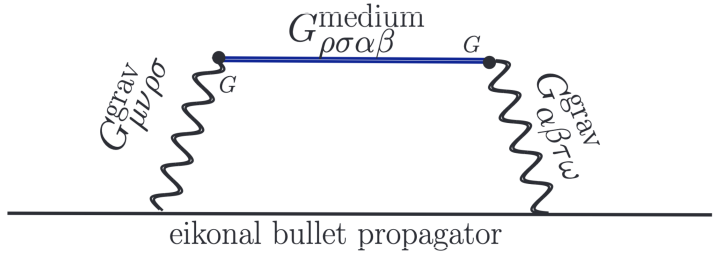
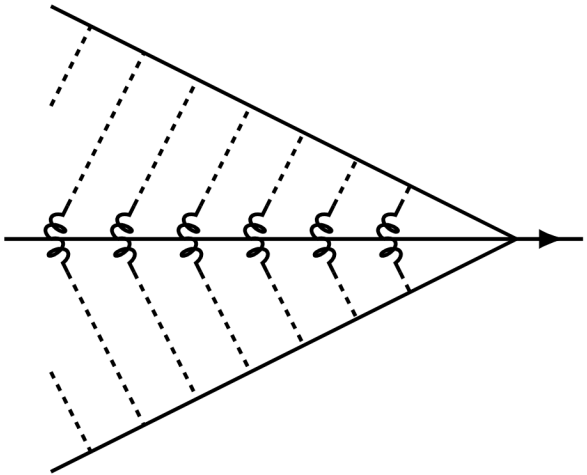
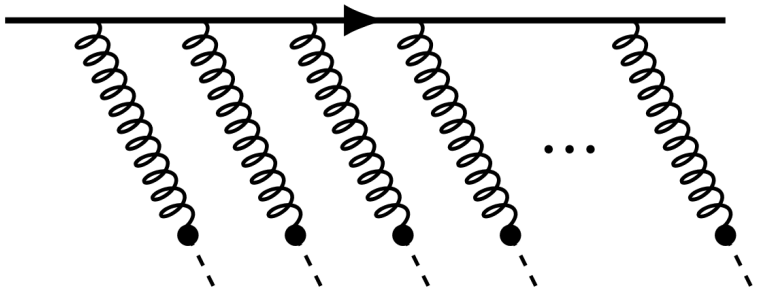
- Couple Gravity to Fluid Dynamics → phonon propagator
  - "dressed graviton" emission
- Long lived modes that carry away energy are **on-shell phonons** emitted at a **specific angle** → *Mach cone structure*





zoom in



*Katz et al. 2019 *JCAP*

Jet Quenching: the same as Dynamical Friction?

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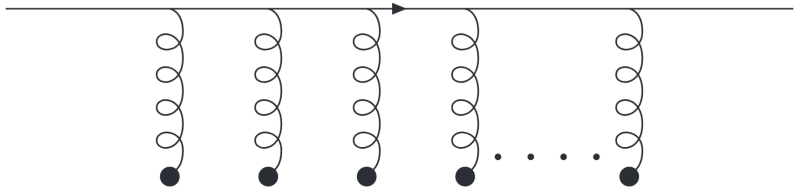
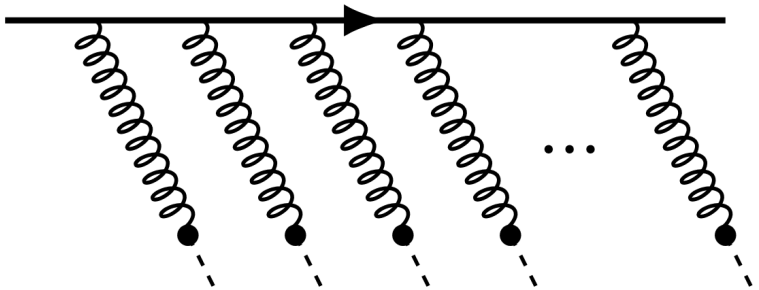
- Suppression of large transverse momentum modes in RHIC
- ***Observable energy loss*** due to multiple scattering of parton with **background QGP**

Would be interesting to sharpen to what extent Dynamical Friction and Jet Quenching can be described within the same framework

Jet Quenching*



Dynamical Friction



*Casalderrey-Solana et al. 2007 *arXiv:0712.3443 [hep-ph]*

Next Steps

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- Translate between ***Wordline*** *formalism* and ***Field Theory***
- Write *higher order diagrams* in the field theory
- Sanity Check - circular motion (expect no divergence)
- Sharpen the connection between ***Dynamical Friction*** (gravity) and ***Jet Quenching*** (QCD)