Unified Gas Heating Constraints on Extended Dark Matter Compact Objects

THK, Philip Lu, Volodymyr Takhistov, arXiv:2508.18344 (Accepted to JCAP)

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Abstract

"We obtained a unified gas heating bound on Extended Dark matter Compact Objs. (EDCOs), and analyze the obj. size effect."

- Introduction : EDCOs & Gas heating
- Gas heating bound : General formalism
  - Heating channel 1 : Dynamical friction
  - Heating channel 2 : Accretion
- Resulting EDCO bounds & Conclusion

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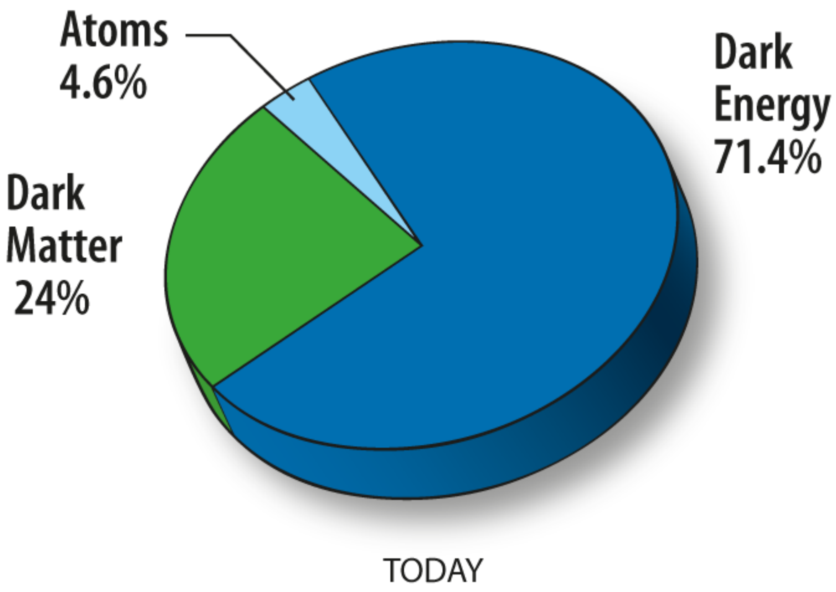
Introduction : EDCOs



https://map.gsfc.nasa.gov/news/index.html

- Dark Matter (DM) : What are they?
  - Particles? Non-particles?
  - Distribution? Substructures?
  - Interactions beyond gravity?
- A class of DM : Extended Dark matter Compact Object (EDCO)
  - Macroscopic self-gravitating configurations composed of dark sector fields

Introduction : EDCOs

- Examples of EDCOs
  - Axion minicluster subhalos, axion stars
  - Q-balls
  - Fermionic dark stars
  - Dressed PBHs (DM halo + PBH; dPBHs)

Case study after obtaining general formalism

- Finite size; internal structure (density profile); transparent to SM particles (for small coupling limit)

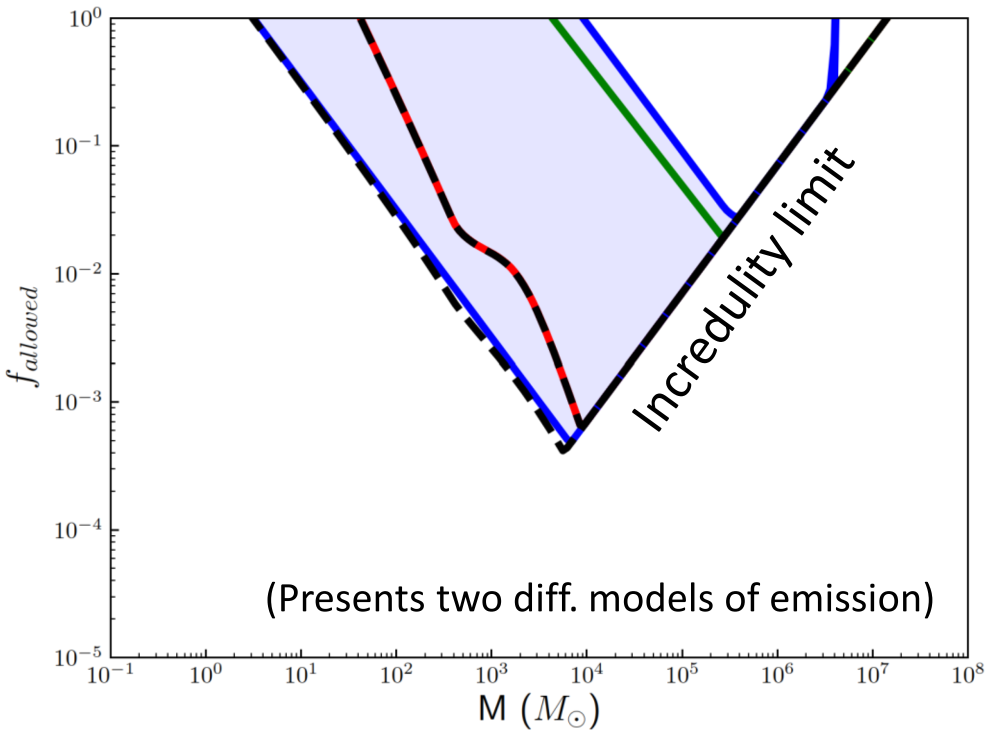
Introduction : Gas heating

- Objective : A general probe of EDCOs based on their interactions with interstellar and galactic gas.
- Focus only on gravitational interaction between DM and SM
  - Serves as a small coupling limit in general case
- Two known gravitational gas heating channels
  - Dynamical friction
  - Accretion (Photon emission & Mass outflow)

Introduction : Gas heating

- Gas heating bounds on PBHs
  - Constrains $10\ M_{\odot} \lesssim M_{PBH} \lesssim 10^{7}\ M_{\odot}$
    - Black : Total
    - Green : Dynamical friction
    - Red (photon) & Blue (mass) : Accretion

Takhistov et. al. (2021)



- We now want to do the same for EDCOs
  - Tactical level question : "How would the finite size of EDCOs alter the bound?"

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Gas heating bound : General formalism

- Basic idea

"DM can heat baryonic gas system. But any stable gas system cannot not be heated beyond the maximum cooling rate."

  - Cooling (by radiation) vs Heating (by DM)
  - Maximum of the former gives bound on the latter

Gas heating bound : General formalism

- Cooling : $\dot{C}$ = (Maximum) Volumetric cooling rate by radiation
  - $[\dot{C}]$ = [Energy / Volume / Time]
  - Baryonic gaseous system predominantly composed of Hydrogen :

    "The radiative cooling rate of neutral Hydrogen gas decreases as the **temperature**, **density**, or **metallicity** of the gas decreases" (Wadekar et. al. (2021))
  - Can be obtained by astrophysical **observations**.

Gas heating bound : General formalism

- Heating : $H(M)/\left(M/\rho_{DM}f(M)\right)$ = Volumetric heating rate by EDCOs
  - $[H(M)\rho_{DM}f(M)/M]$ = [Energy / Volume / Time]
  - $H(M)$ is the heating rate by one EDCO of mass M. **This should be calculated**.
  - Mass fraction $f(M)$.
  - $M/\rho_{DM}f(M)$ is the volume that contains one EDCO of mass M

Gas heating bound : General formalism

- Bound on $f(M)$ is given when $\dot{C} = H(M)/\left(M/\rho_{DM} f(M)\right)$

$$f_{\text{bound}}(M) = \frac{M\dot{C}}{\rho_{\text{DM}} H(M)}$$

  - $\dot{C}$ comes from observation. We now calculate $H(M)$.

Gas heating : General formalism

- $H(M)$ calculation
  - $\mathcal{H}(M, v)$: Heating rate of one EDCO with velocity v.
  - Averaged over the relative speed w.r.t. the gas.

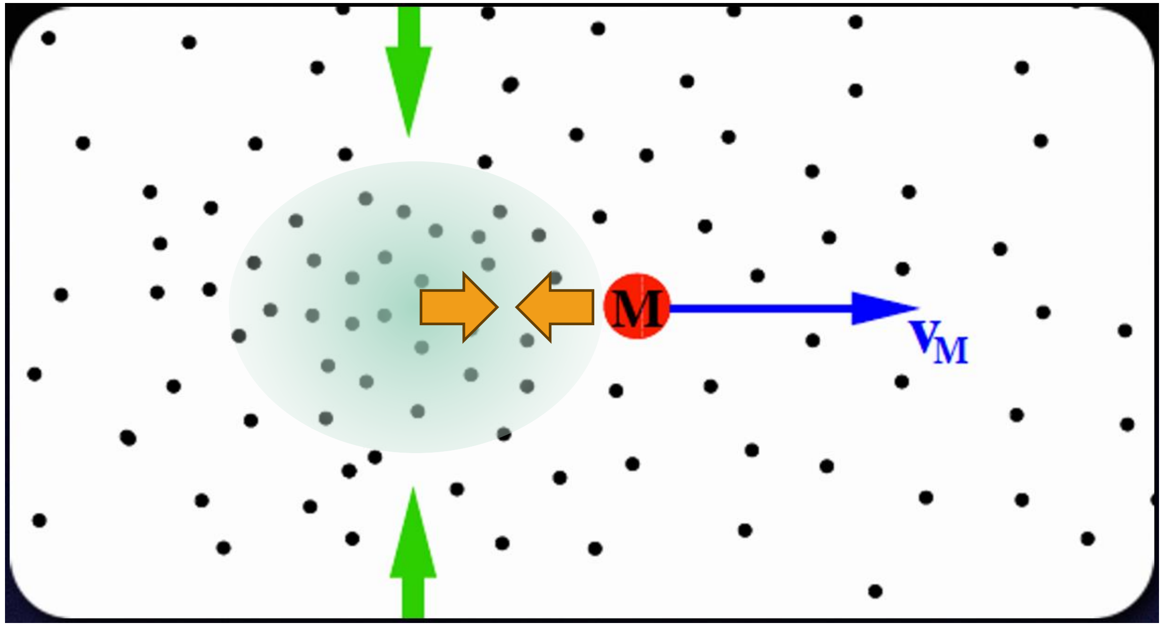
$$H(M) = \int_0^\infty dv \frac{df_v}{dv} \mathcal{H}(M, v)$$

    - Maxwell-Boltzmann distribution f_v
  - Now, everything is on $\mathcal{H}(M, v)$ for each channel.
    - Dynamical friction & Accretion

Gas heating channel 1 : Dynamical friction

- Dynamical friction or gravitational drag
  - “Self-gravity” mediated by medium
- Finite sound speed

  → Backward gravitational force for moving objs. : “Friction”



http://www.astro.yale.edu/vdbosch/astro610_lecture14.pdf

Heating channel 1 : Dynamical friction

- Continuous medium

$$\rho(\vec{x},t) = \bar{\rho} \times \left(1 + \alpha(\vec{x},t)\right)$$

- Linear gravity regime

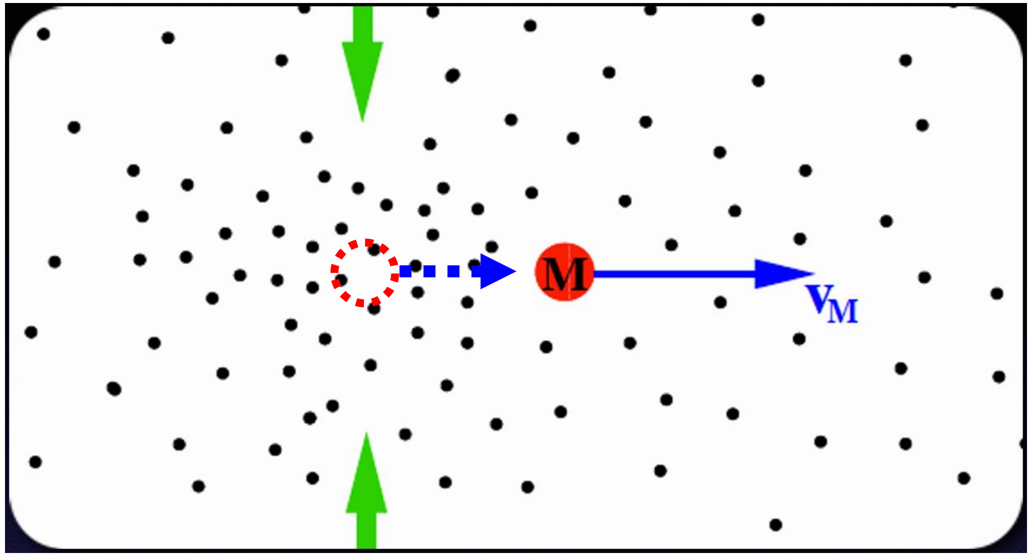
$$\vec{\nabla}^2\alpha - \frac{1}{c_s^2}\frac{\partial^2\alpha}{\partial t^2} = -\frac{1}{c_s^2}\vec{\nabla}^2\Phi_{\mathrm{obj}}, \qquad \vec{\nabla}^2\Phi_{\mathrm{obj}} = 4\pi G\rho_{\mathrm{obj}}$$

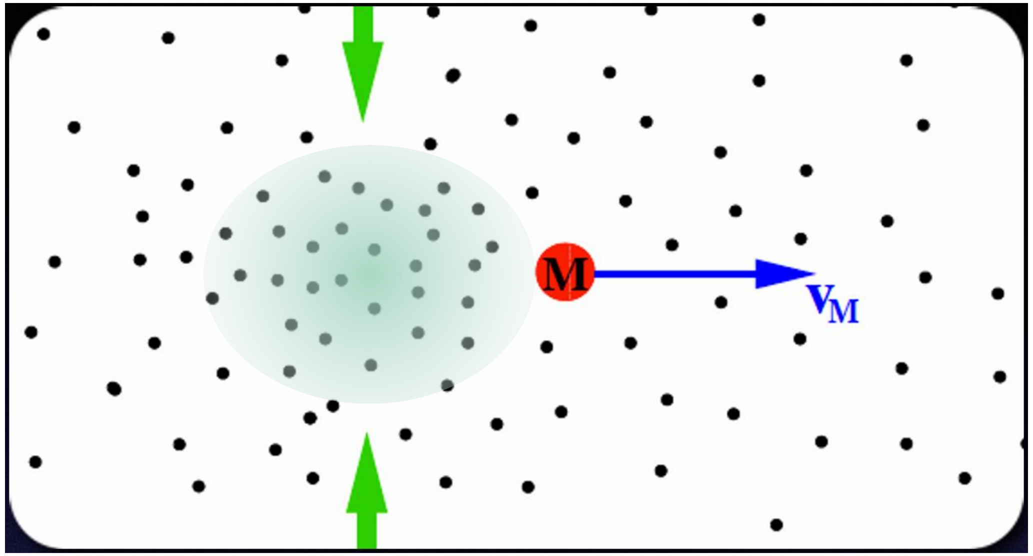
  - Inhom. wave equation with sound speed c_s and sourced by the object's density

Heating channel 1 : Dynamical friction

- Formal solution by retarded Green's function

$$\alpha(\vec{x},t) = \frac{G}{c_s^2}\iint d^3\vec{x}'dt'\,\frac{\delta\big(t' - (t - |\vec{x} - \vec{x}'|/c_s)\big)}{|\vec{x} - \vec{x}'|}\,\rho_{\mathrm{obj}}(\vec{x}',t')$$

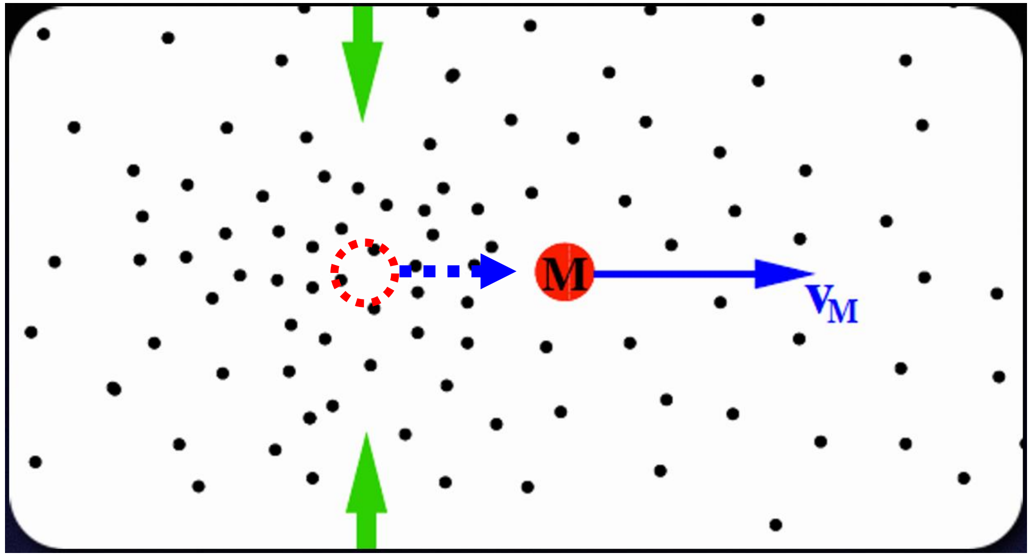


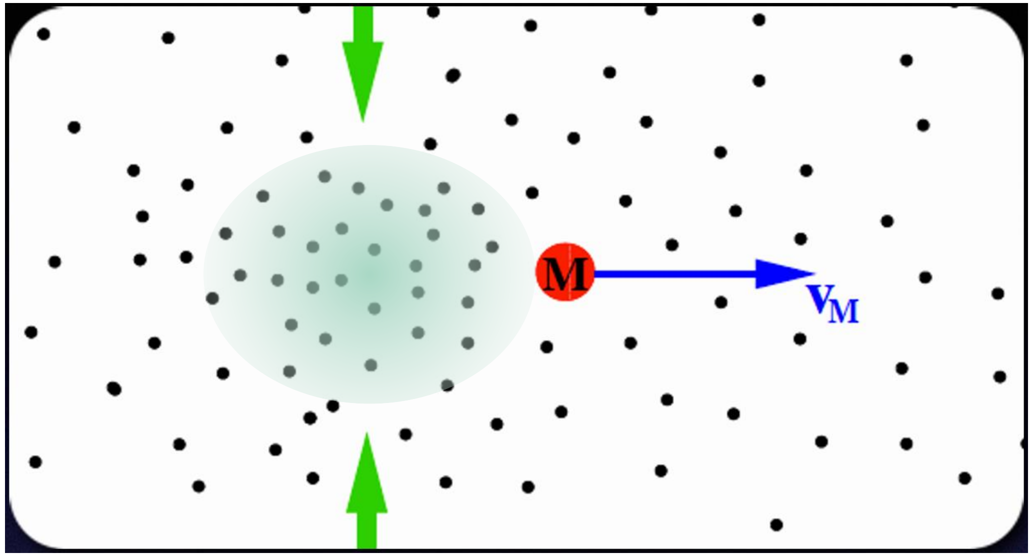


Heating channel 1 : Dynamical friction

- Formal solution by retarded Green's function

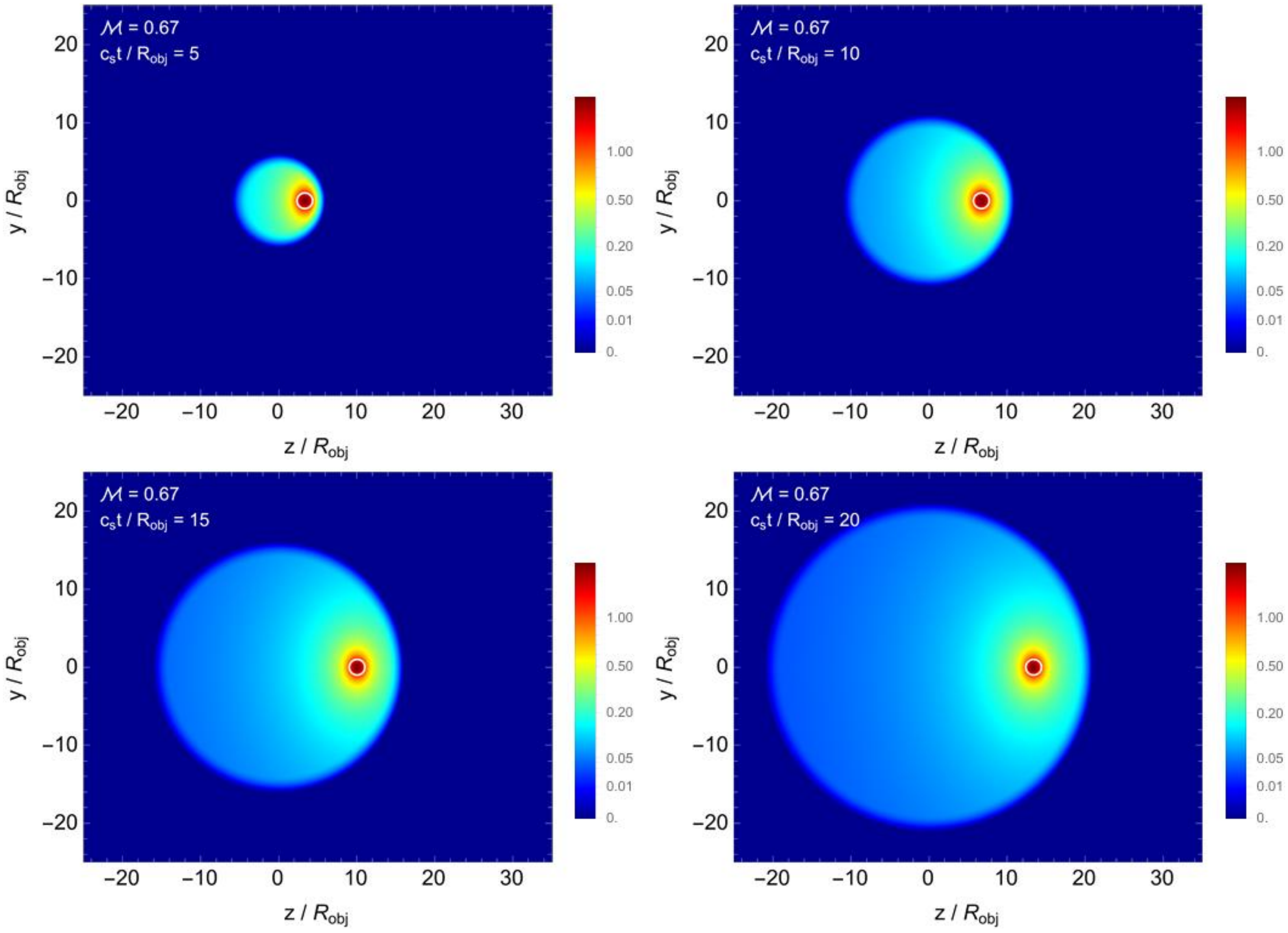
Retarded → Wake forms behind → Attracts backward → "Friction"





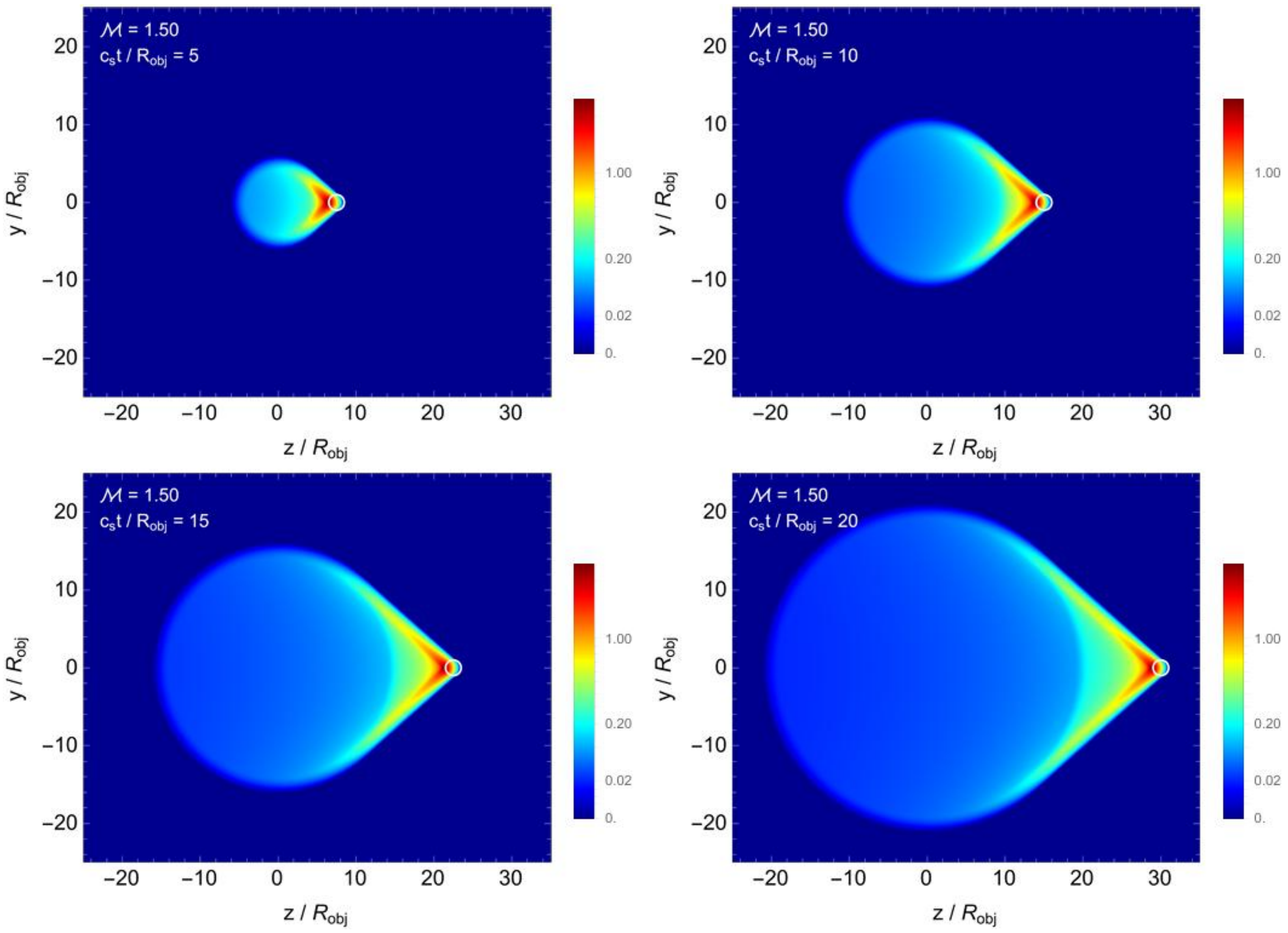
Heating channel 1 : Dynamical friction

- Numerically obtained wake α
- Spherical obj. (white circle)
  - Uniform density
- **Subsonic** velocity rightward
  - Wake inside the sound sphere



Heating channel 1 : Dynamical friction

- Numerically obtained wake α
- Spherical obj. (white circle)
  - Uniform density
- **Supersonic** velocity rightward
  - Sound sphere + **Mach cone**

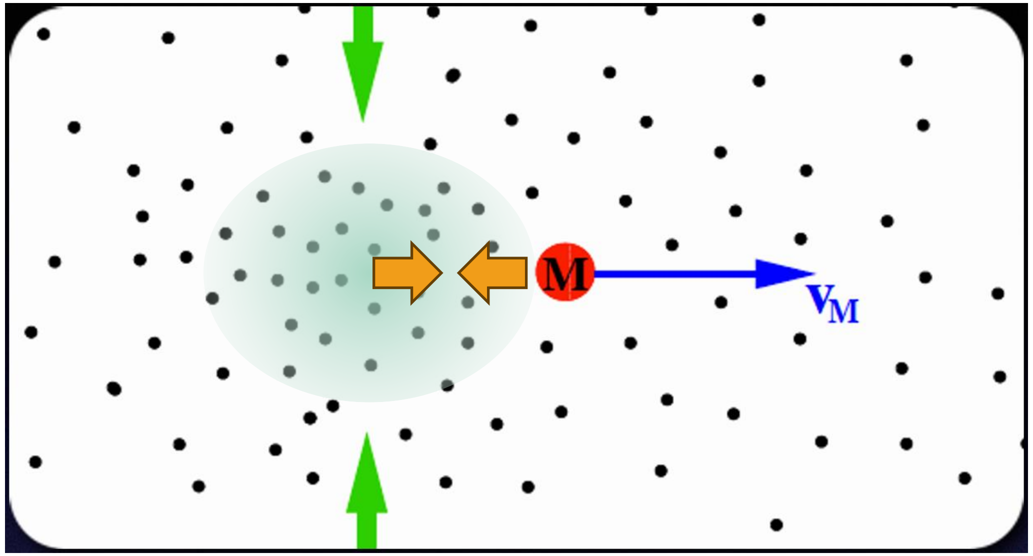


Heating channel 1 : Dynamical friction

- Gravitational interaction between the wake and the obj.

$$F_{DF}(t) = \int d^3x \frac{G\bar{\rho}\,\alpha(\vec{x},t)\,M_{\rm obj}(r)\,r_z}{|\vec{r}|^3}, \qquad M_{\rm obj}(r) = 4\pi\int_0^r dr'\rho_{\rm obj}(r')$$

- $\alpha \propto GM_{\rm obj}$ so $F_{\rm DF} \propto \left(GM_{\rm obj}\right)^2$
  - Gravity sourced by gravitationally induced overdensity
- $\mathcal{H}(M,v) = F_{DF}v$



Heating channel 1 : Dynamical friction

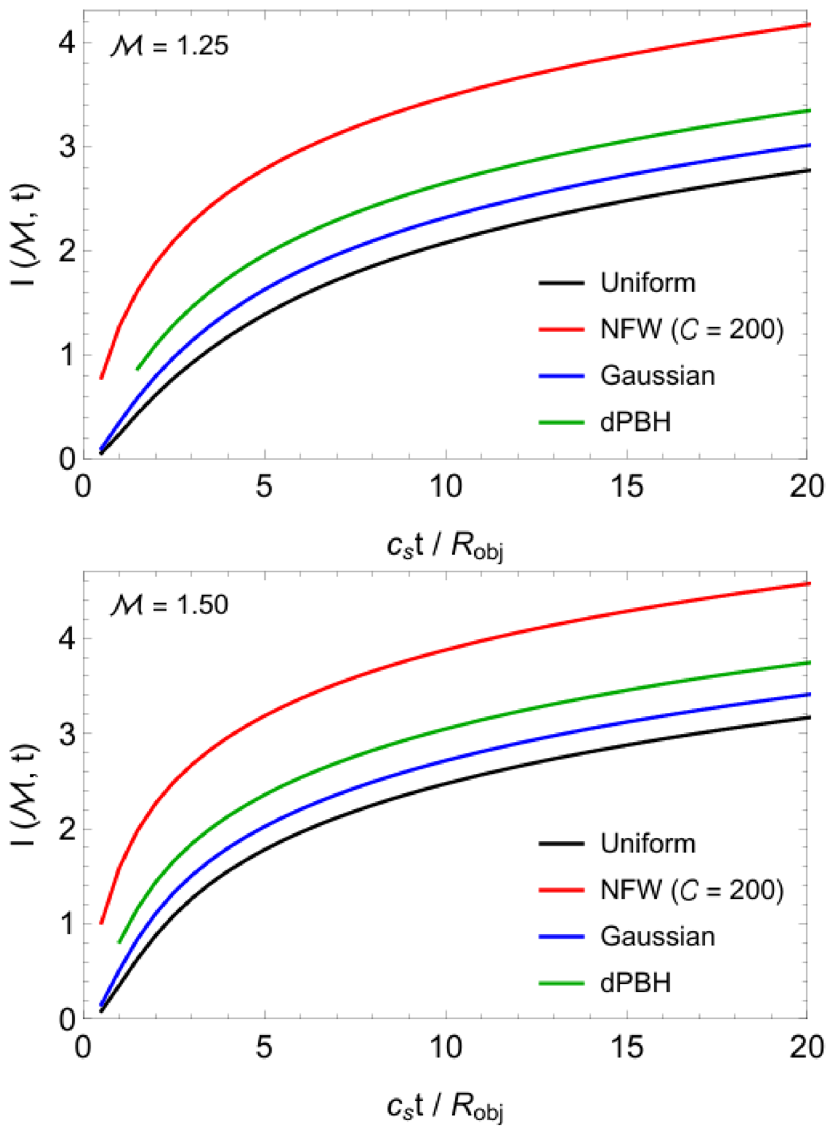
- Ostriker (1999) : Analytical result for **point mass**
  - $\rho_{\mathrm{obj}}(\vec{x},t) = M_{\mathrm{obj}} \times \delta(x)\delta(y)\delta(z-vt)$: Point mass M moving toward +z direction

$$F_{DF} = \frac{4\pi\left(GM_{\mathrm{obj}}\right)^2\bar{\rho}}{(\mathcal{M}c_s)^2} I(\mathcal{M},t), \qquad I(\mathcal{M},t) = \begin{cases} \frac{1}{2}\ln\frac{1+\mathcal{M}}{1-\mathcal{M}} - \mathcal{M}, & \mathcal{M} < 1 \\ \frac{1}{2}\ln\frac{\mathcal{M}^2-1}{\mathcal{M}^2} + \ln\frac{\mathcal{M}c_s t}{r_{\mathrm{min}}}, & \mathcal{M} > 1 \end{cases}$$

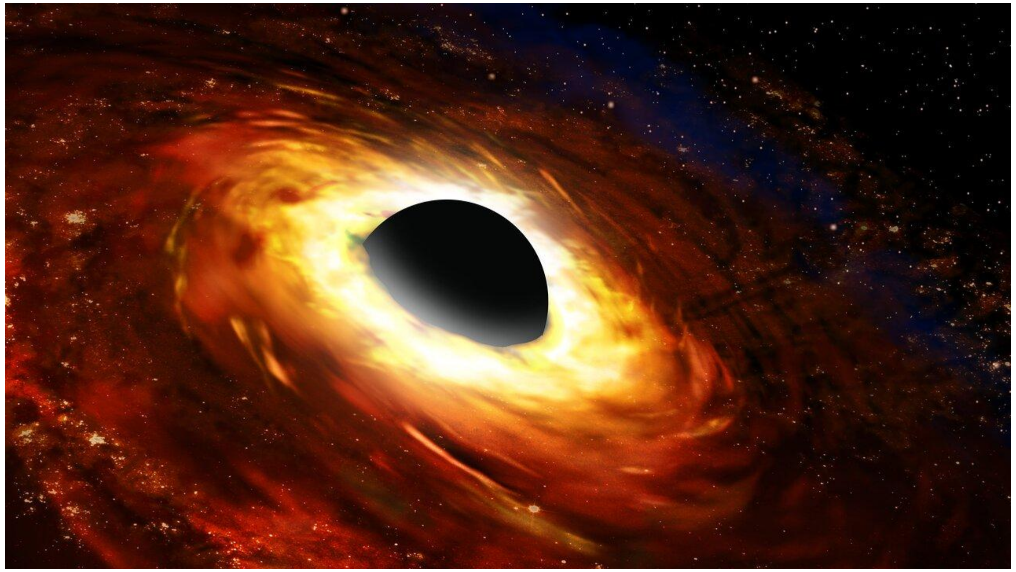
  - t-indep for subsonic, logarithmically increasing with t for supersonic
    - Accounting for the Mach cone, “Coulomb logarithm”

Heating channel 1 : Dynamical friction

- Our numerical results on extended objs.
  - A t-indep. correction term : Result of shell theorem
  - Larger $F_{\rm DF}$ for more concentrated $\rho_{\rm obj}$
    - "**Extendedness hinders dynamical friction**"
  - $\mathcal{O}(10\%)$ of correction
    - **First time (up to our knowledge) to confirm and limit the point mass formula on extended objs.**



Heating channel 2 : Accretion



https://noirlab.edu/public/blog/accretion-disks/

- Gas captured by gravity
  - Accretion disk formed
  - Potential energy of inflow matter is released
    - Photon emission
    - Mass outflow
  - $[\text{Gas heating energy}] = [\text{Total inflow energy}] - [\text{Absorbed energy}]$

    $= \epsilon \times [\text{Total inflow energy}]$
    - ϵ is efficiency

Heating channel 2 : Accretion

- Total inflow rate : Bondi–Hoyle–Lyttleton (BHL) accretion rate

$$\dot{M}_{BHL} = \frac{4\pi G^2 M_{\mathrm{enc}}^2\,\bar{\rho}}{\left(v^2 + c_s^2\right)^{3/2}} \sim \pi R_{\mathrm{Bondi}}^2 \times \bar{\rho} \times \sqrt{v^2 + c_s^2}$$

- Bondi radius

$$R_{\mathrm{Bondi}} = \frac{2GM_{\mathrm{enc}}(R_{\mathrm{Bondi}})}{v^2 + c_s^2}$$

  - M_{enc} : Enclosed mass in the Bondi radius
  - ~ effective cross section for accretion

Heating channel 2 : Accretion

- Efficiency ϵ is determined by the innermost stable circular orbit (ISCO)
  - Determining the absorbed energy
  - E.g. Schwarzshild BH has $\epsilon \simeq 0.057$. But realistically can be much lower.
- For too diffuse EDCOs, $R_{\mathrm{bondi}} \ll R_{\mathrm{obj}}$, nearly no accretion happens
  - Axion miniclusters
  - Axion stars

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Mass-radius relation for selected EDCOs

- Axion

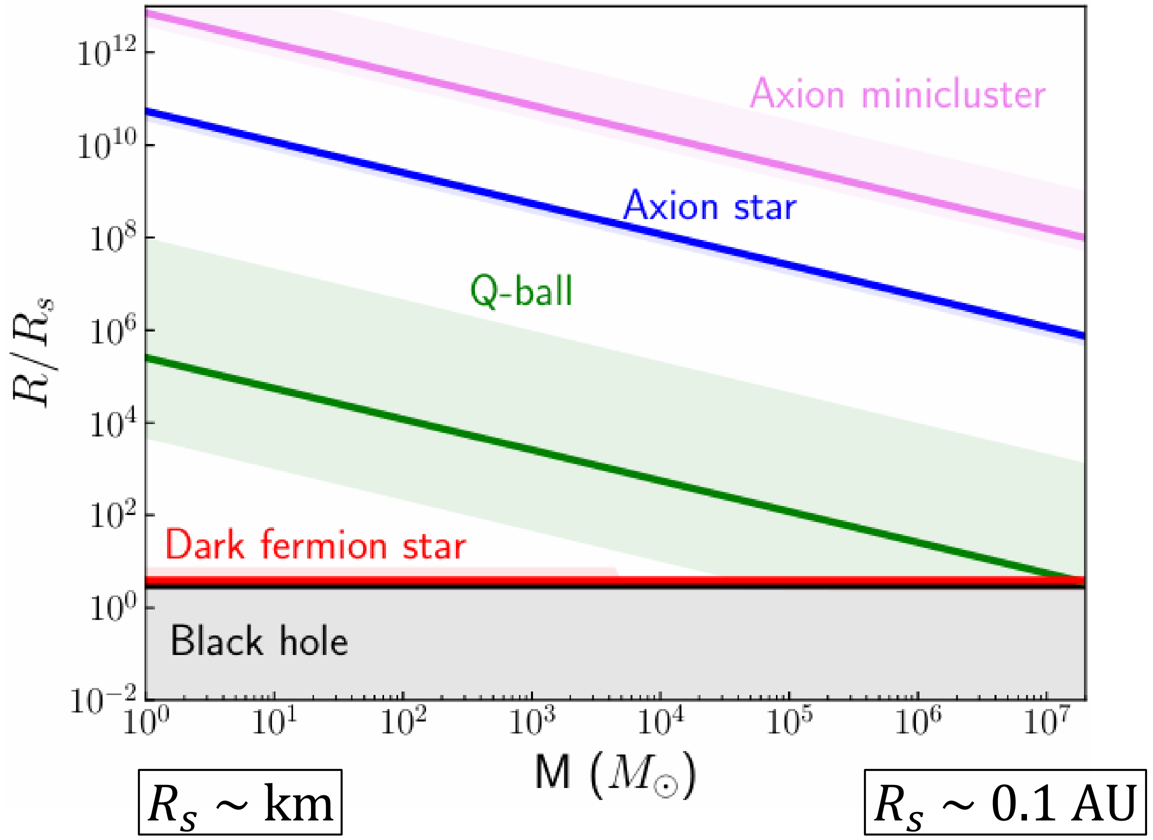
  Chang et. al. (2024)
  Refs. there in

  - Case with negligible self-interaction
    - Minicluster : Virialized clump
    - Star : Gravitationally bounded

- Q-balls

  Ansari et. al. (2024)
  Heeck et. al. (2021)

  - Case of single-field sextic Coleman Q-balls (up to ϕ^6 interaction)



Mass-radius relation for selected EDCOs

- Dark fermion stars

  Narain et. al. (2006)
  Gresham et. al. (2019)

  - ~ Neutron stars but with heavy $(\mathrm{MeV} - \mathrm{GeV})$ DM fermions

- BH

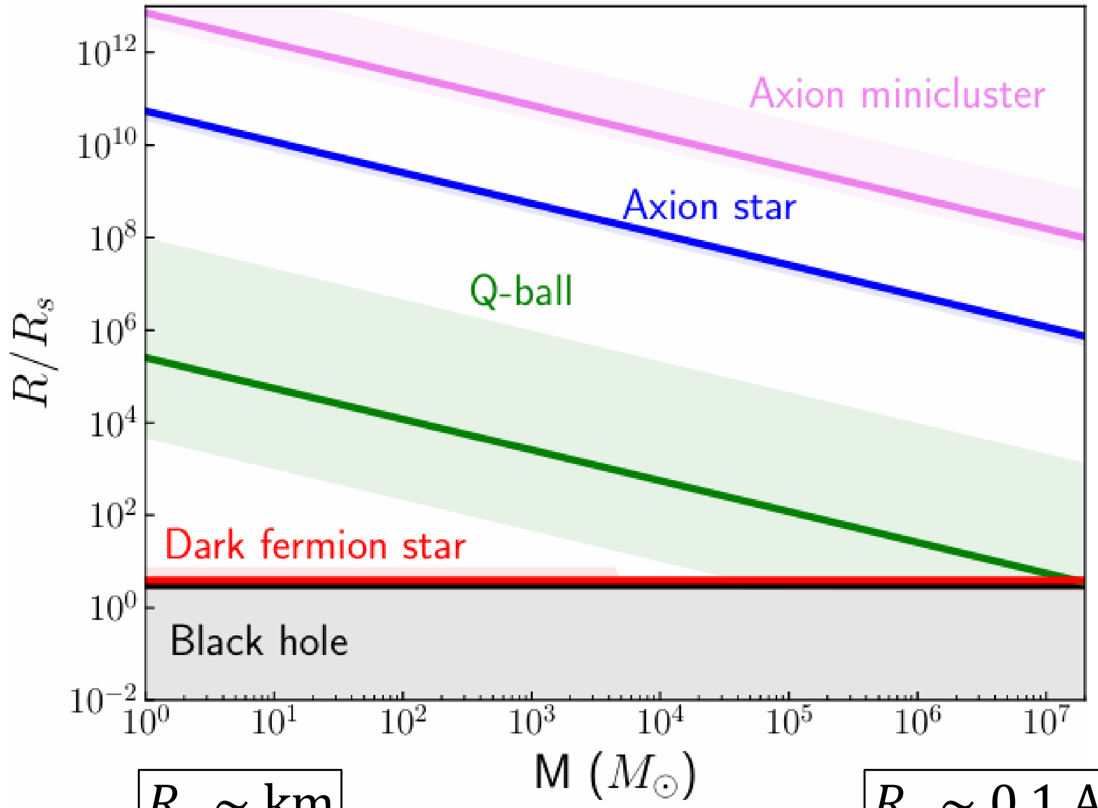
  Schwarzschild (1916)

  - Case of Schwarzschild BH

- dPBH

  Choi et. al. (2024)
  Refs. there in

  - PBH + DM halo ($\mathcal{O}(100) \times$ heavier)



$\boxed{R_s \sim \mathrm{km}}$ $\boxed{R_s \sim 0.1\ \mathrm{AU}}$

Target system Leo T

- Leo T : A dwarf galaxy
  - Located in the Local Group, satellite of Milky Way
  - DM dominated (~96% of total mass of $10^7\ M_\odot$ is DM)
  - Low metallicity (Fe/H number ratio is ~3% of Sun)

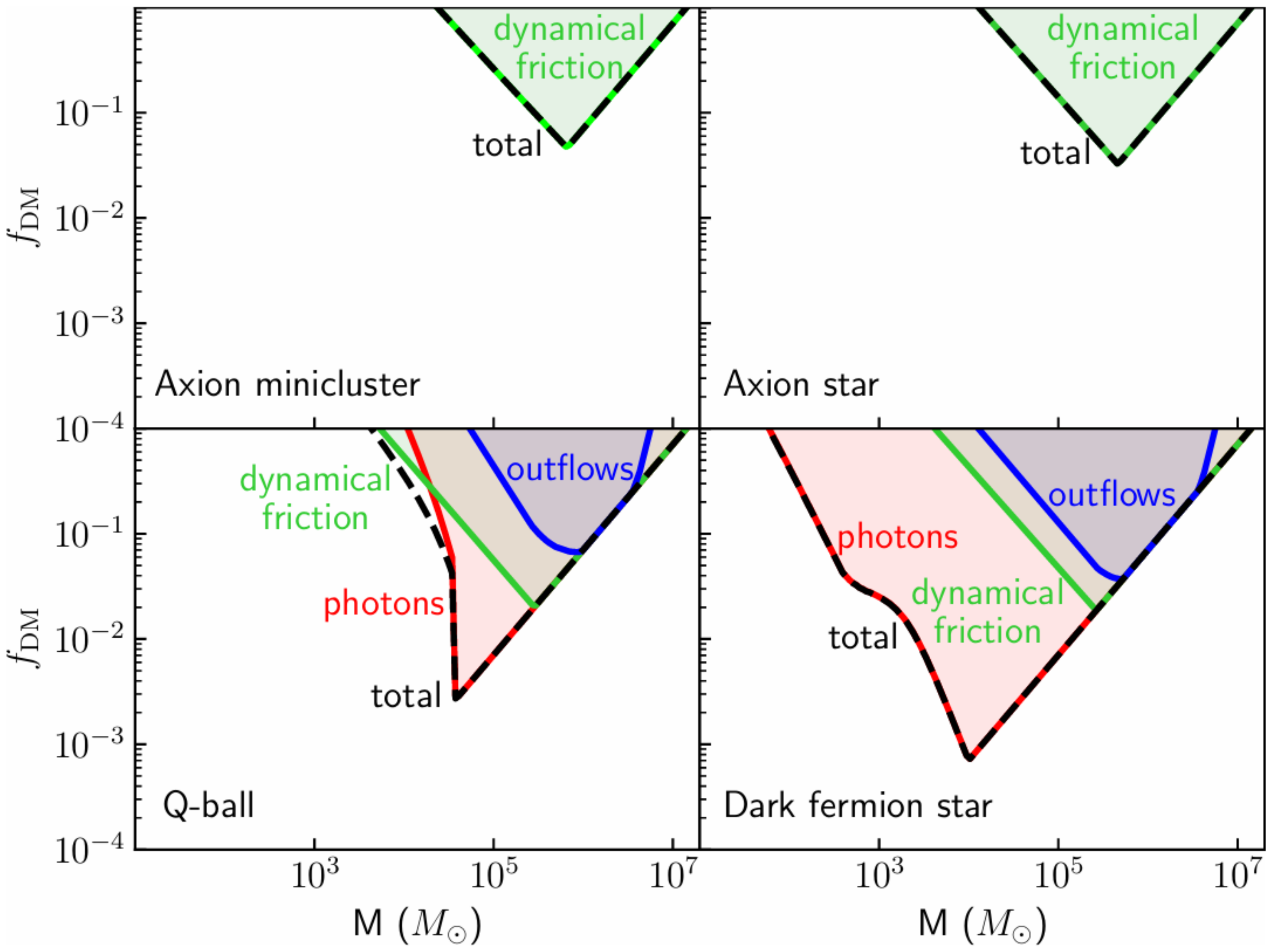
    → Low radiative cooling rate
  - Low DM velocity dispersion ($\sigma_v \sim 7\ \mathrm{km/s}$)

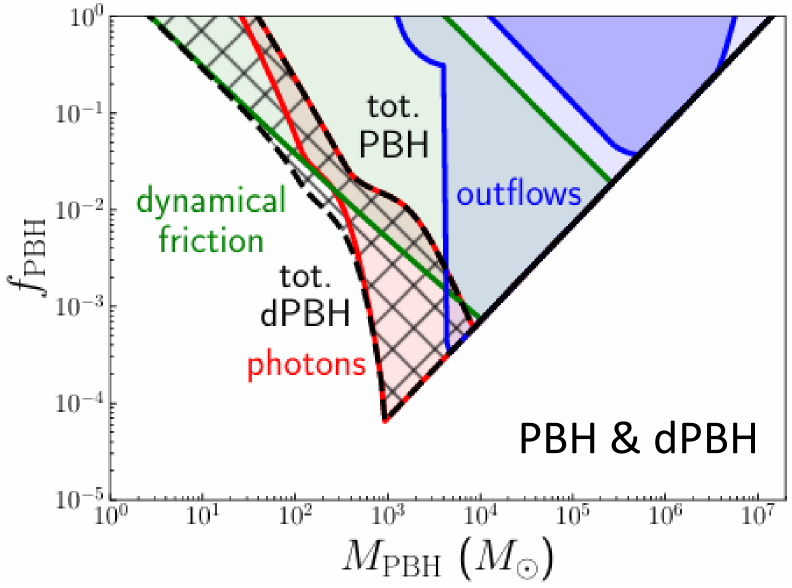
    → Efficient dynamical friction and accretion
  - Favorable candidate to obtain gas heating bound

Irwin et. al. (2007)

$$\downarrow f_{\mathrm{bound}}(M) = \frac{M\dot{C}\downarrow}{\rho_{\mathrm{DM}} H(M)\uparrow}$$

Resultant gas heating bound

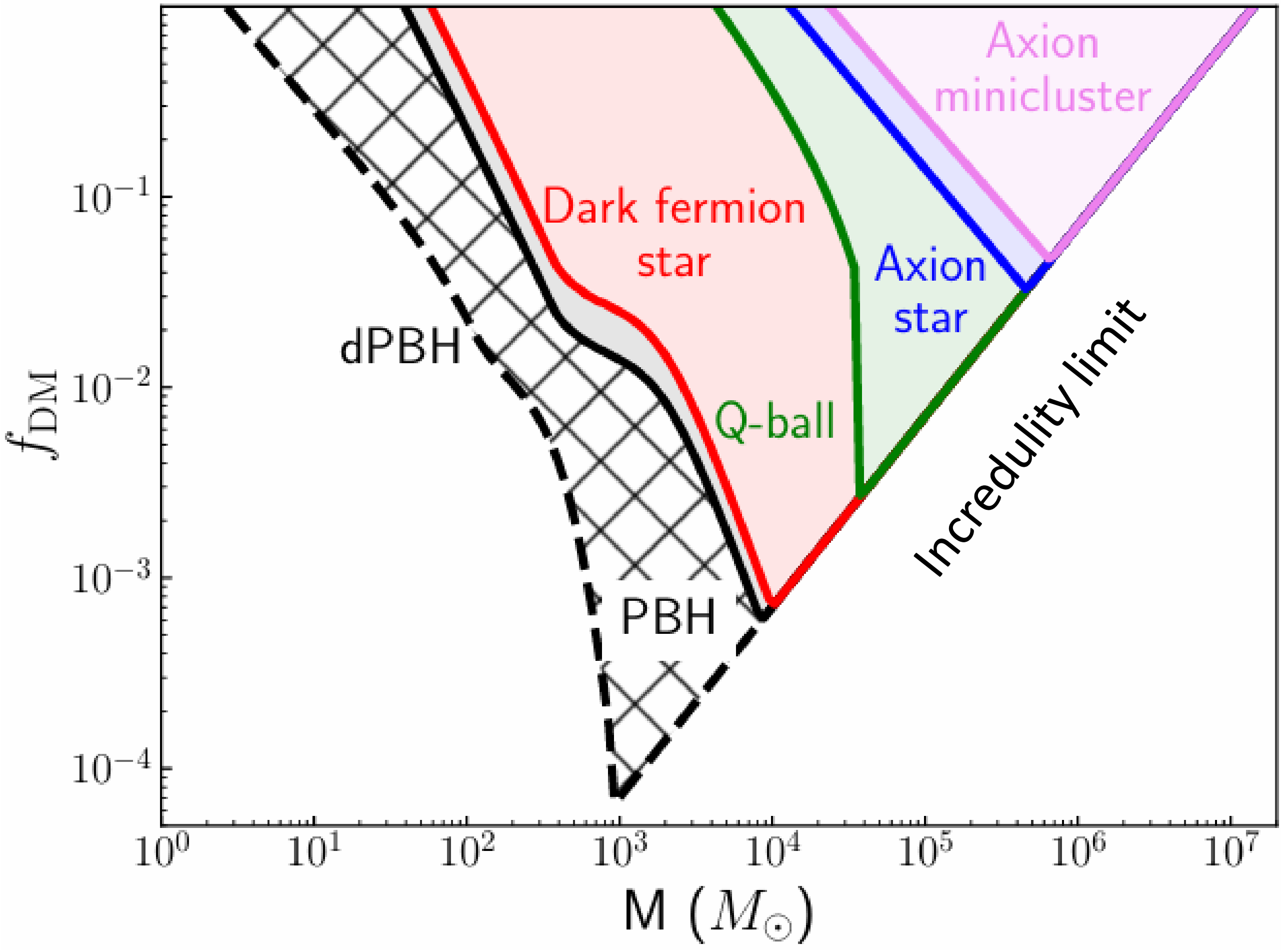


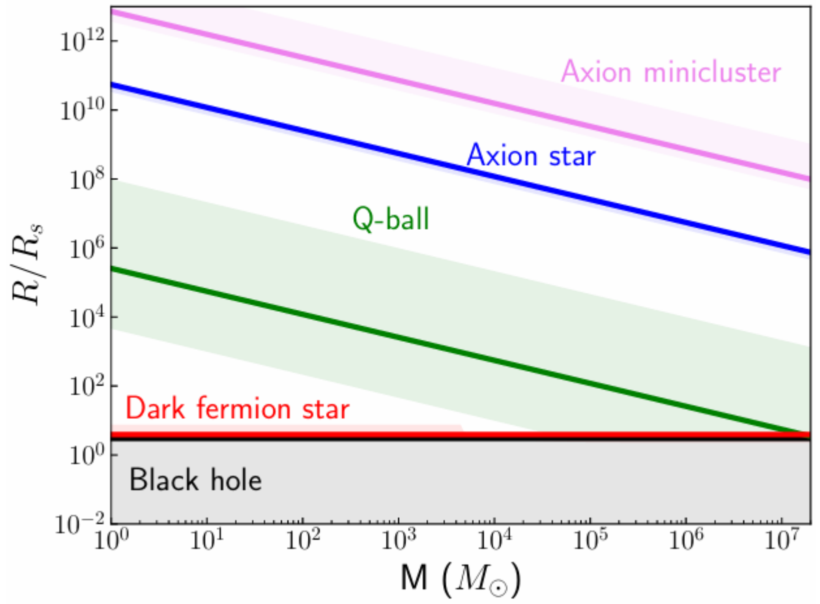


- No accretion for Axion miniclusters and stars – too diffuse
- We parameterize dPBH by central PBH mass, so d. halo is addition

Resultant gas heating bound – Summary

Leo T gas heating bound : $1\ M_\odot - 10^7 M_\odot$





- Ordered : More compact, stronger bound
  - Axion Minicluster → Axion Star → Q-ball → Dark fermion star → PBH
- For dPBH, d. halo is an addition contribution.

Conclusion

- EDCOs can gravitationally heat the surrounding gas
  - Dynamical friction & Accretion
- We derive gas heating bound to EDCOs and check the finite size effect.
  - Dynamical friction : Confirm and limit the point mass formula to EDCOs
  - Accretion : Obj. radius, Bondi radius (accretion on/off), ISCO (luminosity efficiency)
- Obtained a unified bound on different EDCOs using Leo T, aligned in the order of compactness : “**Extendedness hinders gas heating.**”

THE END. Thank you!