Dark Matter Spikes and Gravitational Waves: Impact of Relativistic Corrections

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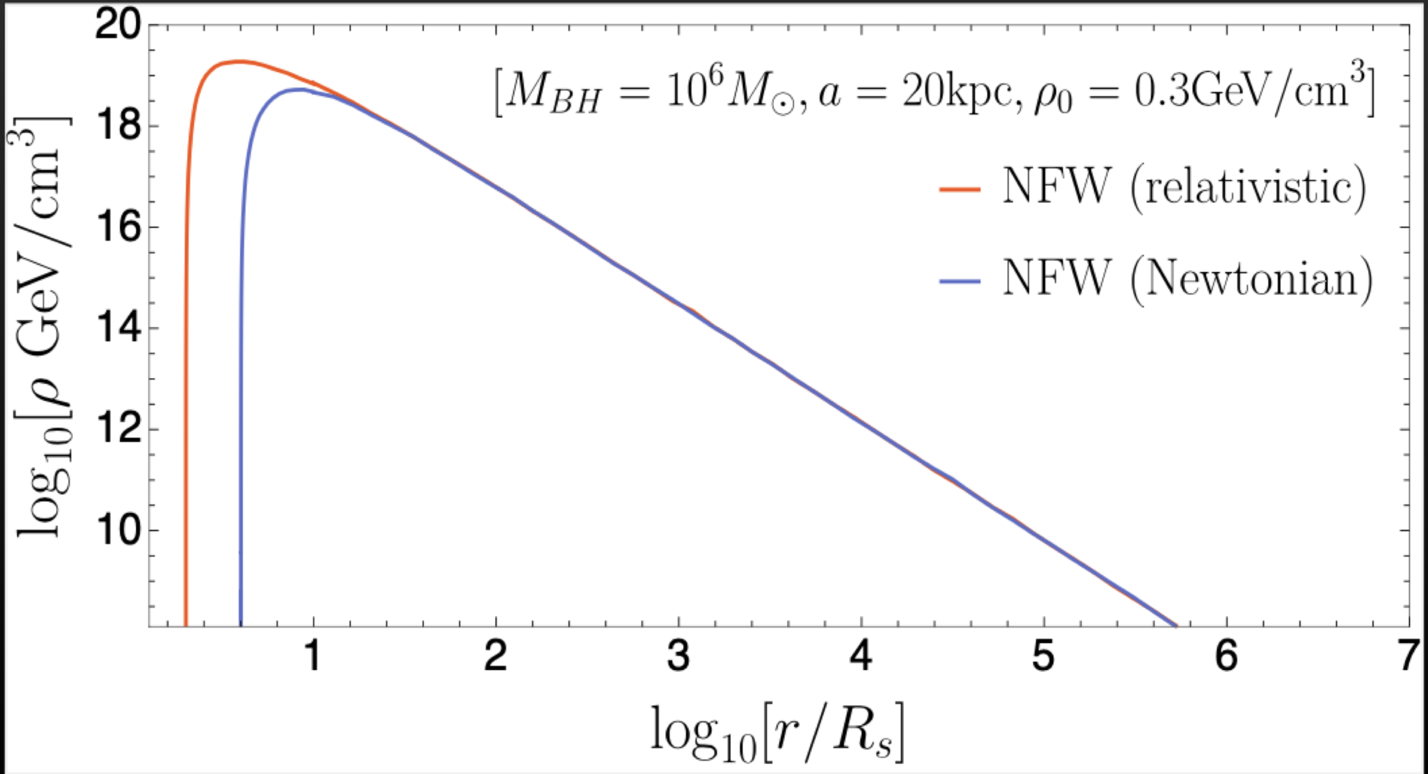
Questions this Work Addresses:

- How important are relativistic corrections to the dark matter (DM) spike and dynamical friction (DF)?
- How do PN terms compare to DM induced effects? Which relativistic corrections are more important to include?
- Can we observe the effects of DM+DF and infer properties of the DM over-densities with EMRIs?

Dark Matter Spikes

- Start with initial distribution of dark matter
- Evolve the distribution adiabatically as central black hole (BH) grows
- Can utilize Newtonian scheme or relativistic scheme

$$\rho(r) = \frac{\rho_0}{(r/a)(1+r/a)^2}$$



Gondolo+ (1999)
Sadeghian+ (2013)

Spike Catalog and "scaling laws"

- Generate many spikes varying DM and BH parameters (ρ_0, a, M_{BH})
- Numerically fit to find effective scaling and model fit for the DM
- Valid for region we care about for LISA band GWs, and for a > 0.005kpc

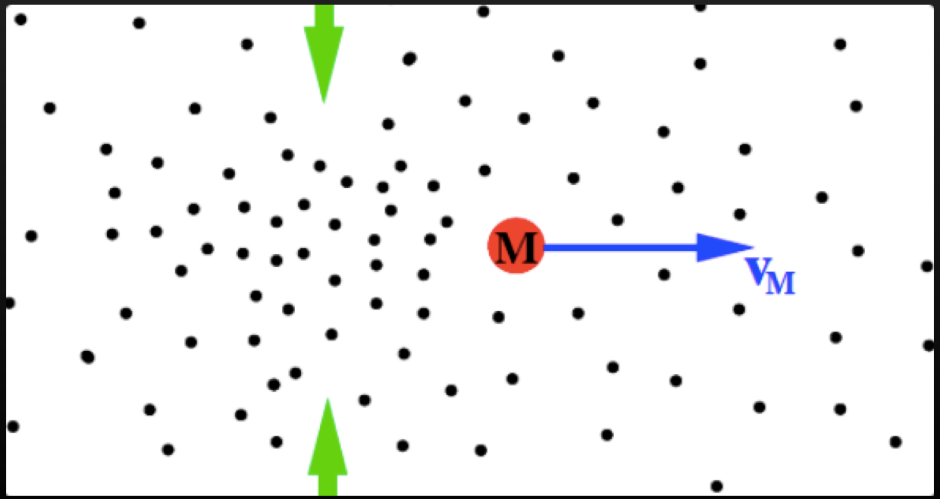
$$\rho = \bar{\rho}\, 10^{\delta} \left(\frac{\rho_0}{0.3\mathrm{GeV}/\mathrm{cm}^3} \right)^{\alpha} \left(\frac{M_{\mathrm{BH}}}{10^6 M_{\odot}} \right)^{\beta} \left(\frac{a}{20\mathrm{kpc}} \right)^{\gamma}$$

$$\bar{\rho} = A \left(1 - \frac{4\eta}{\tilde{x}} \right)^{w} \left(\frac{4.17 \times 10^{11}}{\tilde{x}} \right)^{q}$$

Circular Binary Problem

- Dark Matter induces two major effects:
  - Mass changes gravitational potential
  - Cold DM particles induce dynamical friction force

- Both effects can be treated relativistically
  - DM—use relativistic scheme and treat as a perturbation in the orbit
  - DF—introduce relativistic corrections to the Chandra force



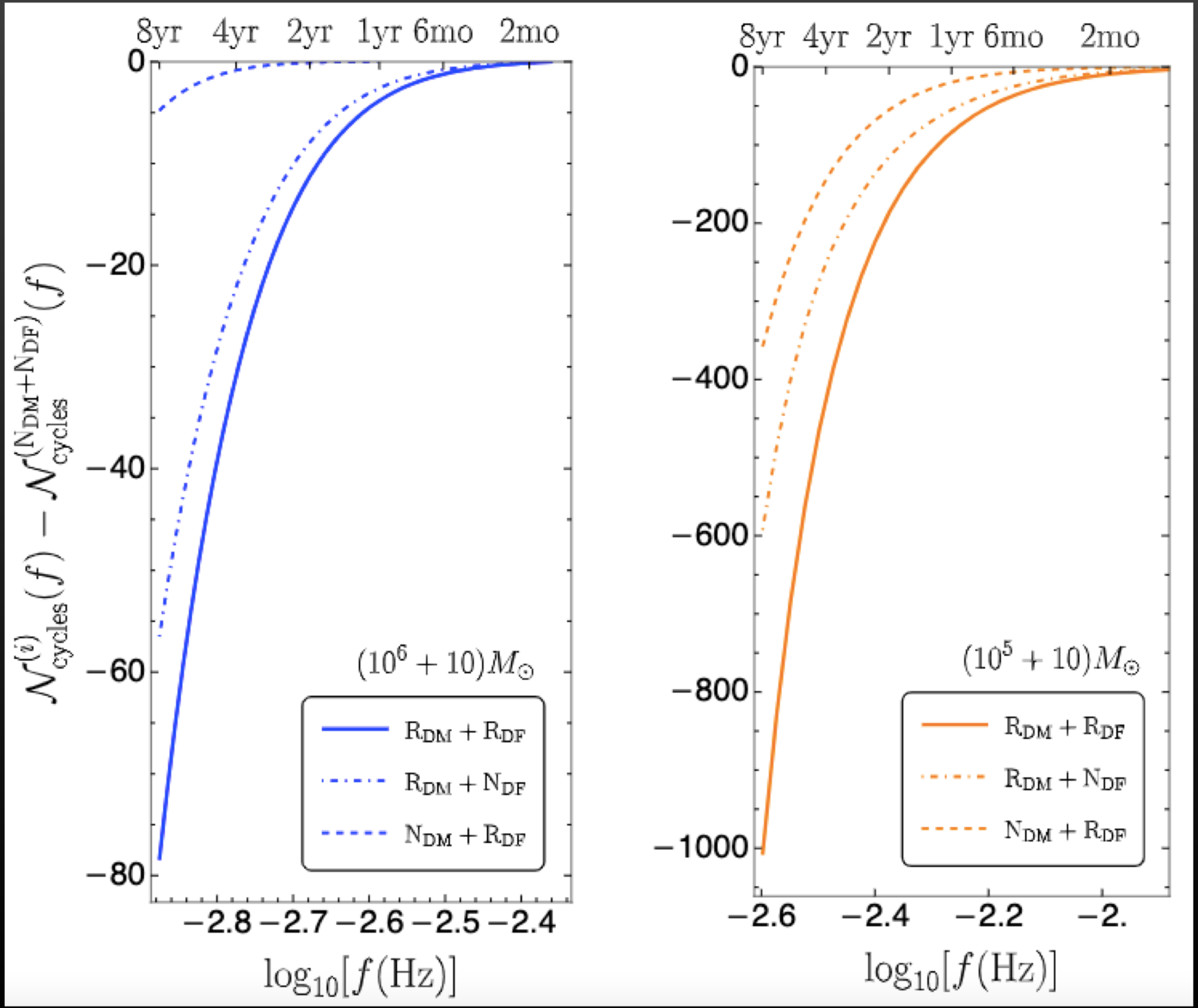
$$\dot{E}_{\rm DF} = \mathbf{v} \cdot \mathbf{F}_{\rm drag} = -4\pi \frac{G^2 \mu^2 \rho(r)}{v} \xi(v) \ln \Lambda$$

$$\xi(v) = \gamma^2 (1 + \zeta v^2/c^2)^2$$

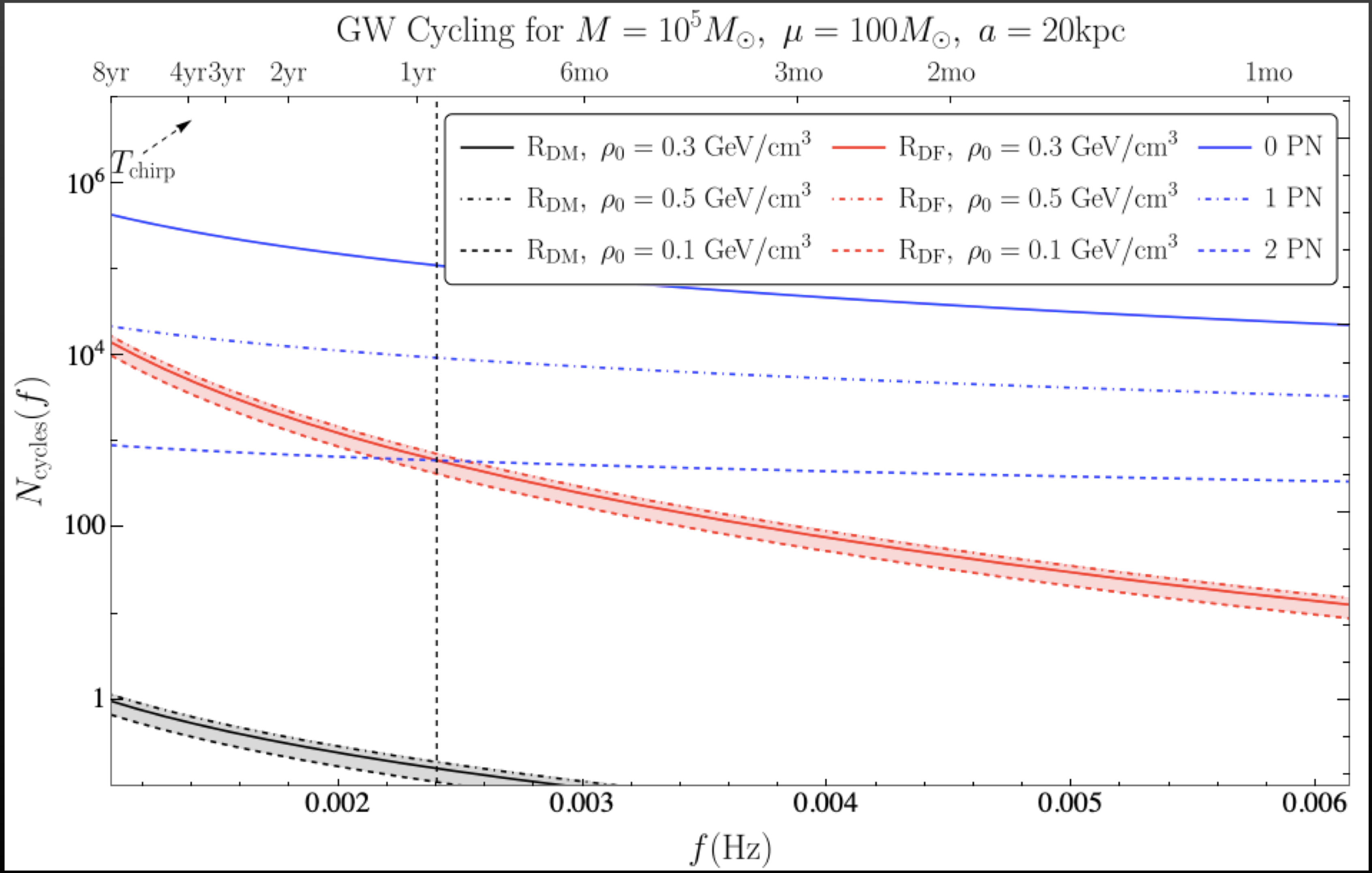
Eda+ (2013, 2015), Traykova+ (2021), Image by Frank Van Den Bosch

How Important are the Relativistic Contributions?

- To get an estimate, we calculate the number of GW cycles
- More important to include the relativistic spike
- Relativistic DF changes the number of cycles appreciably



How does PN Compare to DM Effects?



Detection Scenarios with FEW

- We employ the FastEMRIWaveforms (FEW) package to investigate detectability with LISA, and since EMRIs require more careful treatment

- We introduce the DF as a torque, and utilize our DM spike model fit and scalings within the already existing framework

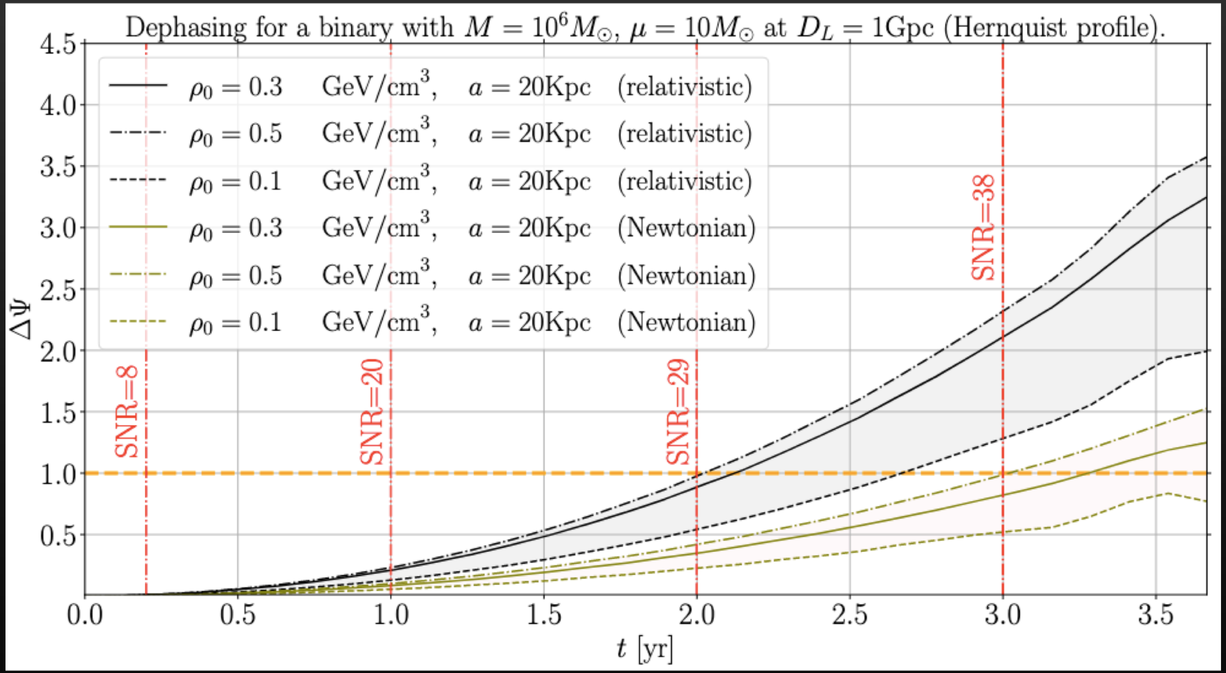
$$\dot{E}_{\rm GW} \rightarrow \left(1 + \frac{\dot{E}_{\rm DF}}{\dot{E}_{\rm GW}}\right) \dot{E}_{\rm GW}$$

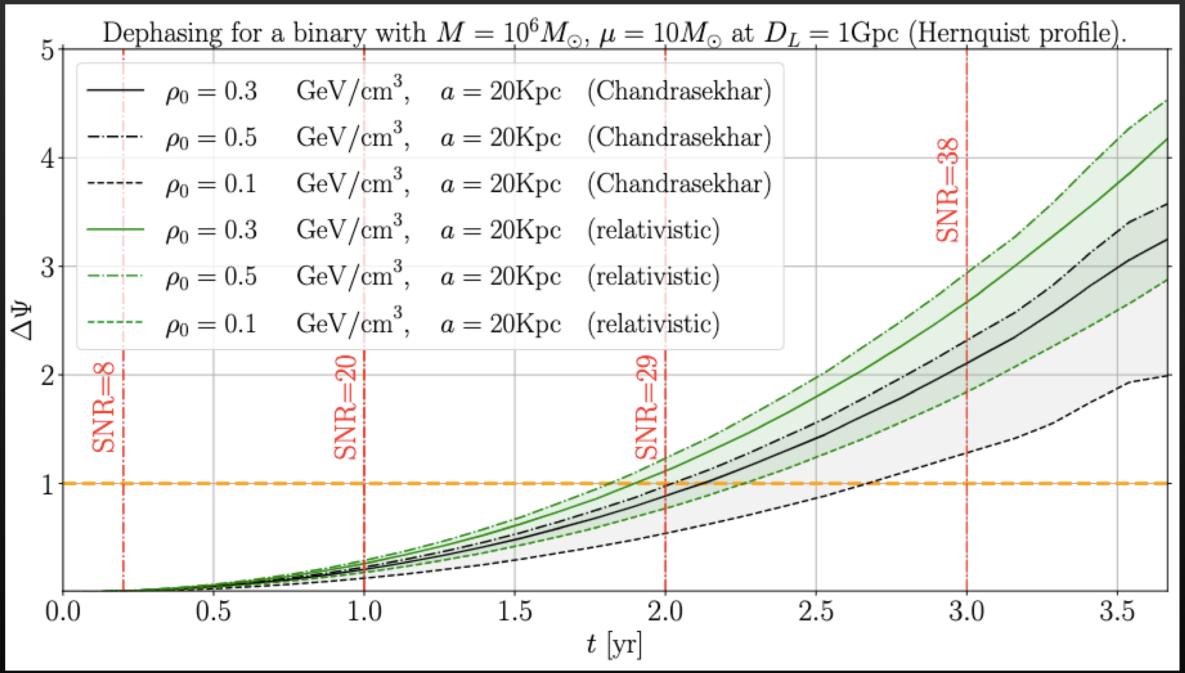
- Major advantage: allows for rapid waveform generation for EMRI systems, which is vital for parameter estimation studies

Fast EMRI Waveforms: bhp-toolkit.org/FastEMRIWaveforms

Detection Scenarios with FEW

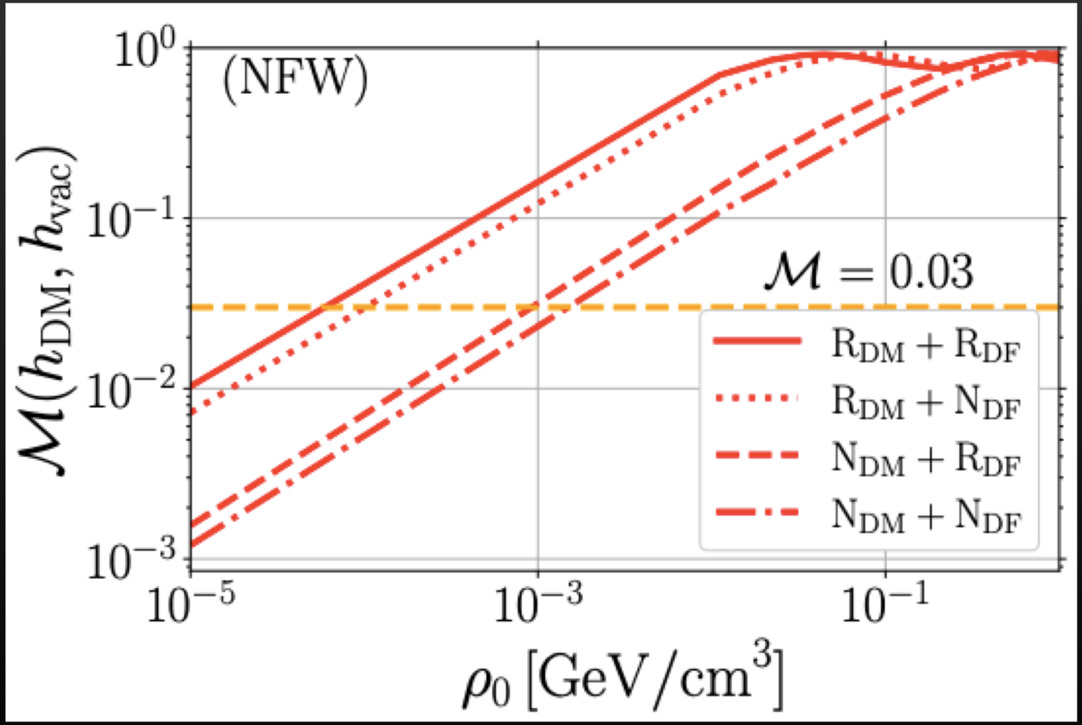
- Dephasings show that relativistic corrections are quite important to include
- Significant dephasings occur on reasonable observation timescales, with high SNR

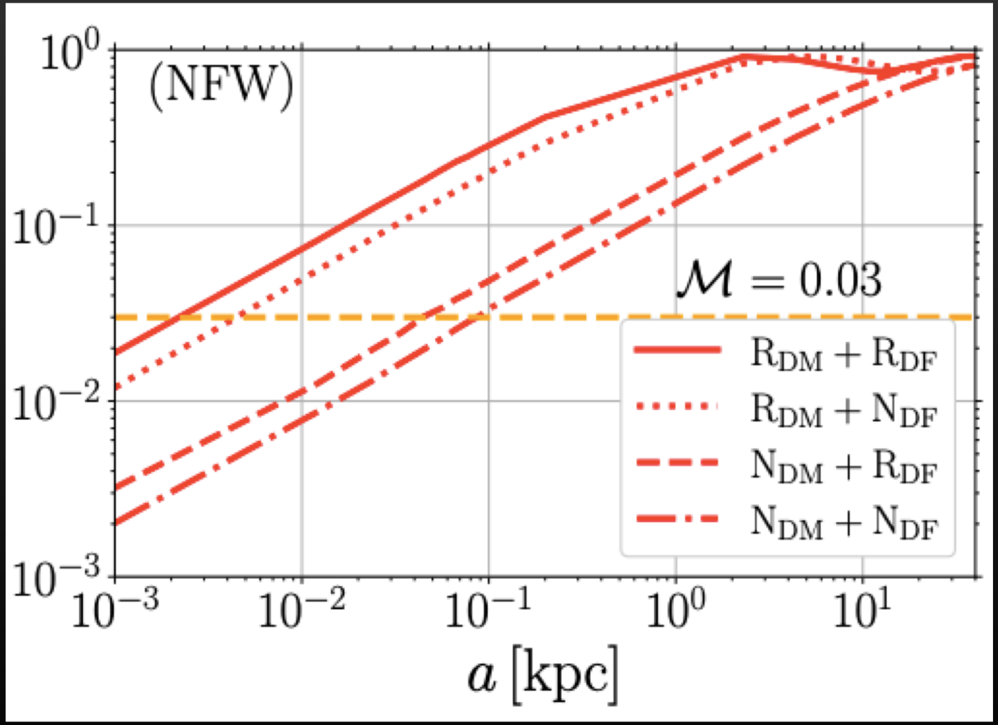




Detection Scenarios with FEW

- We perform a mismatch analysis to investigate LISA detectability
- Mismatch indicates that we have detectable effects of DM for reasonable parameter choices





Limitations

- We use a highly idealized spike density--we expect realistic spikes to have some level of “quenching”, which lessens the density
  - Core scouring, disruption from merger events, feedback mechanisms, etc.

- Limited in the range of central BH masses we can consider, since lower masses require a prescription for Halo feedback (Kavanagh+ 2020)

- Limited currently to cold DM prescriptions, ultralight boson DM could have a different impact on the binary dynamics with a different DF force (Vicente+ 2022)

Current and Future Work

- Consider measurability given some density of DM. How high would the spike need to be to accurately measure the density and slope? Can we select for DM models this way?
  - (Can investigate with similar machinery as Andrea Antonelli talked about yesterday)
  - (update the work of Hannuksela+ 2019)

- Can we distinguish between other effects like accretion and the DM spike effects?
  - (model selection with the slope and amplitude of the energy loss)

$$\frac{\dot{E}_{\rm DF}}{\dot{E}_{\rm GW}} = \frac{c_{\rm DF}}{c_{\rm GW}} \frac{(1+GM_{\rm BH}/r_0c^2)^2}{(1-GM_{\rm BH}/r_0c^2)} r_0^{11/2} \rho(r)$$

?? →

$$Ar^n$$

Summary and Conclusions

- Relativistic corrections to the DM and DF lead to considerable differences in the phasing and number of GW cycles, and should be included in the phenomenological models. Inclusion increases detection prospects

- DM induced effects can become comparable to the 2PN contributions to the number of cycles for BH masses ~10^5 $M_\odot$, and reasonable observation timescales

- FEW models allow for rapid waveform generation and mismatch analyses suggest that the DM and DF effects are measurable for realistic detection scenarios with LISA

References

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