Intermediate Mass Ratio Inspirals in Dark Matter Spikes

[2112.09586]

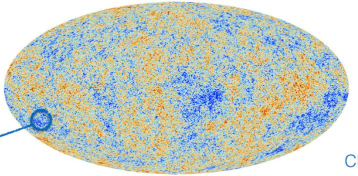
Niklas Becker, Laura Sagunski, Saeed Rastgoo, Lukas Prinz

DMGW @ ITP, Goethe University Frankfurt

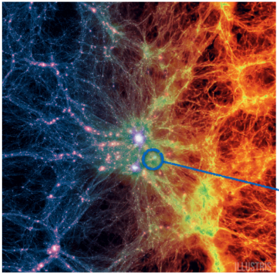
June 8, 2022

Introduction

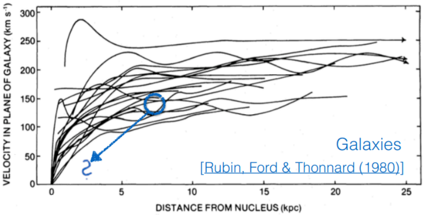
Dark Matter at all scales



CMB
[Planck, 1502.01589]



Galaxy clusters
[Illustris, 1405.2921]
[astro-ph/0006397]



Galaxies
[Rubin, Ford & Thonnard (1980)]

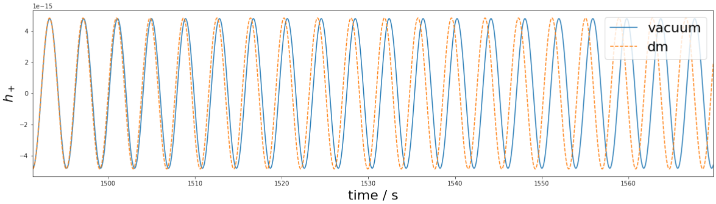
Credit: B. Kavanagh

Motivation

- Can we detect dark matter on smaller scales through Gravitational Wave observations?
- There might be dark matter *spikes* around Intermediate Mass Black Holes

→ Test inspiral of small objects inside dark matter

- This could be observable with the Laser Interferometer Space Antenna (LISA) over several years!



Intermediate Mass Black Holes

Intermediate Mass Black Holes

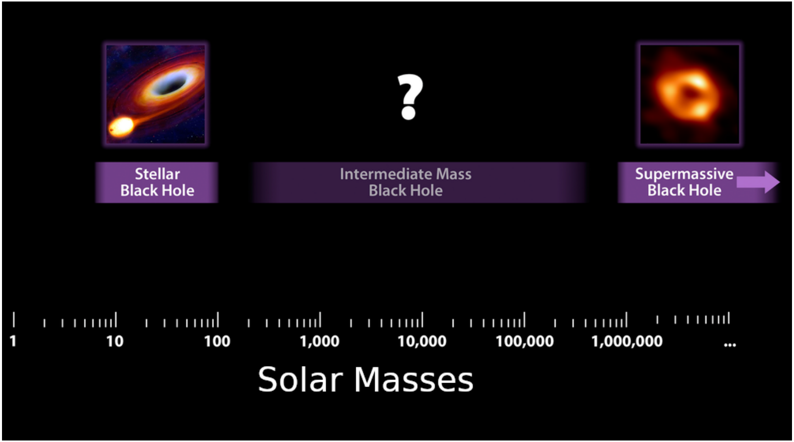
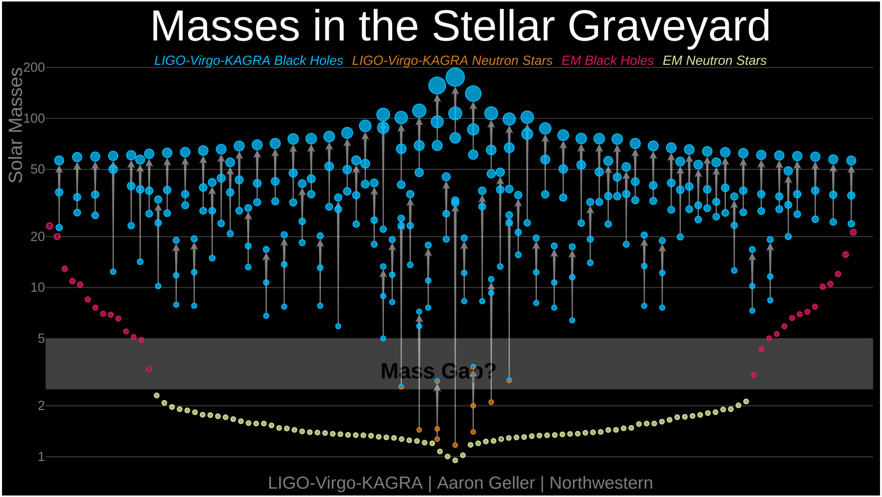


Image Credit: NASA/JPL-Caltech(edited), EHT collaboration

Intermediate Mass Black Holes

Dark Matter
Modified Gravity
Gravitational Waves

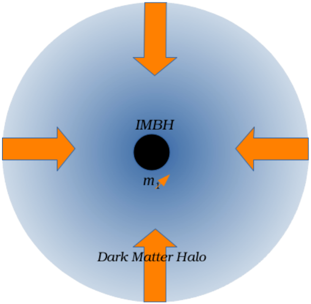


IMBH Population

- We know they are produced through binary mergers
- There are candidate objects from X-ray observations and kinematic considerations
- Possible alternative origins
  - Pop III stars,
  - direct gas cloud collapse
  - Primoridial Black Holes
- We need SMBH seeds
- James Webb Space Telescope might reveal population(s)

Adiabatic Growth

- Slow Accretion $\longrightarrow$ slow potential change
- Adiabatic Approximation $\longrightarrow$ Conserved Quantities
- Concentrates Dark Matter
- Assumes "calm" neighborhood and no mergers
  - → Not expected around SMBH in AGN
  - → Maybe around IMBH



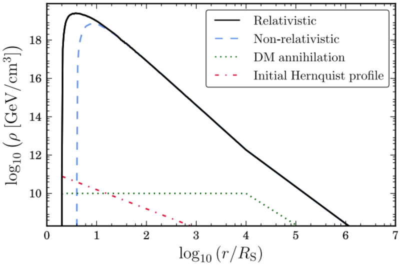
Dark Matter Spike

DMGW Dark Matter Modified Gravity Gravitational Waves

- Assume simple power law [1]

$$\rho_{\rm dm}(r) = \rho_6 \left(\frac{r_6}{r}\right)^{\alpha_{\rm spike}}$$

- Different dark matter models/history can give different power laws
  - NFW→Spike: $\alpha_{\rm spike} = 7/3$
  - PBH→Spike: $\alpha_{\rm spike} = 9/4$
  - SIDM→Spike: $\alpha_{\rm spike} = 7/4$



Spike for an initially Hernquist profile[2]

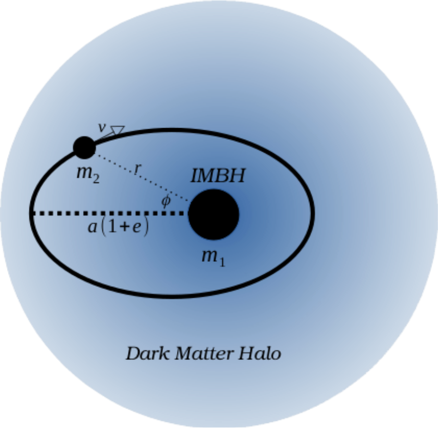
[1] A. Coogan, G. Bertone, D. Gaggero, B. J. Kavanagh and D. A. Nichols, *Measuring the dark matter environments of black hole binaries with gravitational waves*, 2108.04154

[2] L. Sadeghian, F. Ferrer and C. M. Will, *Dark matter distributions around massive black holes: A general relativistic analysis*, *Phys. Rev. D* **88** (2013) 063522, [1305.2619]

Intermediate Mass Ratio Inspirals

Intermediate Mass Ratio Inspiral

DMGW Dark Matter Modified Gravity Gravitational Waves



Keplerian orbit

Parameters:

Semimajor axis a, Eccentricity e

$$m_2 \sim M_\odot \ll m_1 \sim 10^2 - 10^5 M_\odot$$

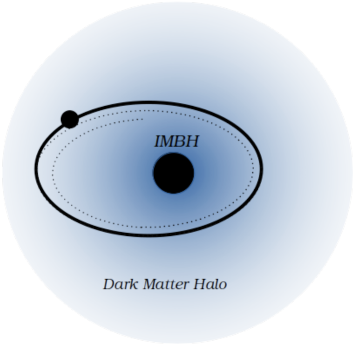
$\rightarrow$ Energy & angular momentum:

$$E_{orb} = \frac{m_1 m_2}{2a}$$
$$L^2_{orb} = m\mu^2 a(1 - e^2)$$

Inspiral

- Quasiadiabatic Inspiral
- Two timescales:
  orbital and secular
- Dissipative forces cause inspiral
- Allows simple modeling

$$-\dot{E}_{\mathrm{orb}} = \dot{E}_{\mathrm{gw}} + \dot{E}_{\mathrm{df}} + \dot{E}_{\mathrm{acc}}$$
$$-\dot{L}_{orb} = \dot{L}_{gw} + \dot{L}_{df} + \dot{L}_{acc}$$



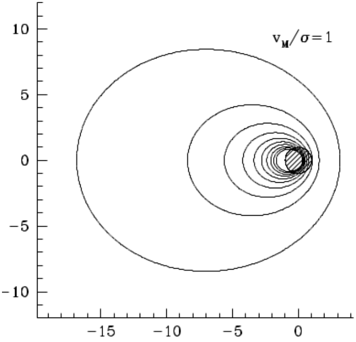
Dynamical Friction

DMGW Dark Matter Modified Gravity Gravitational Waves

- Energy loss through dynamical friction[3]

$$F_{df}(r,v) = \frac{4\pi m_2^2 \rho_{\rm dm}(r)\xi(v)\ln\Lambda}{v^2}$$

- $\xi(v)$ accounts for DM particles moving slower than the secondary object
- The halo is assumed to be static
- Can be modified for different DM models



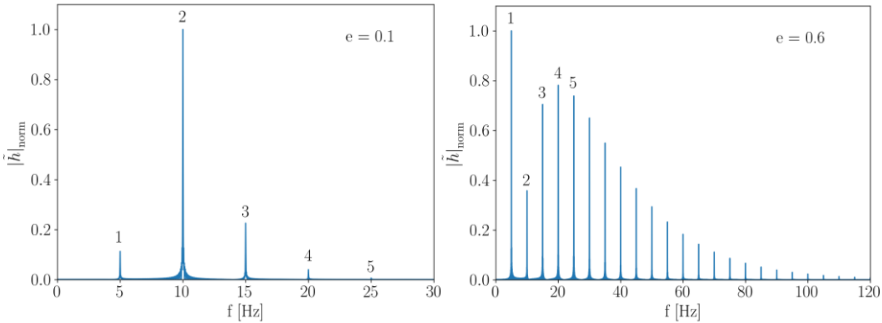
Density wake induced by moving object [4]

[3] B. J. Kavanagh, D. A. Nichols, G. Bertone and D. Gaggero, *Detecting dark matter around black holes with gravitational waves: Effects of dark-matter dynamics on the gravitational waveform*, *Phys. Rev. D* **102** (2020) 083006, [2002.12811]

[4] J. Binney and S. Tremaine, *Galactic dynamics*. 1987

Gravitational Wave Signal

- Eccentric system emits at harmonics n of orbital frequency $f = \sqrt{\frac{m}{a^3}}$
- Most prominent for $e \ll 1$ is $n = 2$, changes for higher e



Harmonics of the Gravitational Wave Signal for different eccentricities[5]

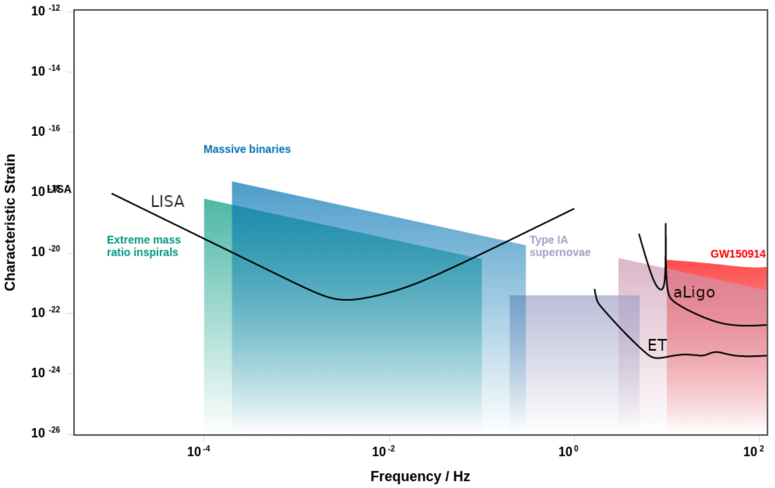
---

[5] B. Moore, T. Robson, N. Loutrel and N. Yunes, *Towards a Fourier domain waveform for non-spinning binaries with arbitrary eccentricity*, *Class. Quant. Grav.* **35** (2018) 235006, [1807.07163]

LISA Sensitivity

Gravitational Wave Detectors and Sources

By Christopher Moore, Robert Cole and Christopher Berry, formerly of the Gravitational Wave Group at the Institute of Astronomy, University of Cambridge



Credit: gwplotter.com

Observable Effects

Dephasing

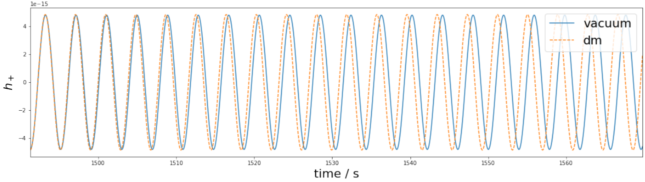
D | M | G | W Dark Matter Modified Gravity Gravitational Waves

- The inclusion of DM effects changes the inspiral
- Observed number of cycles is given by

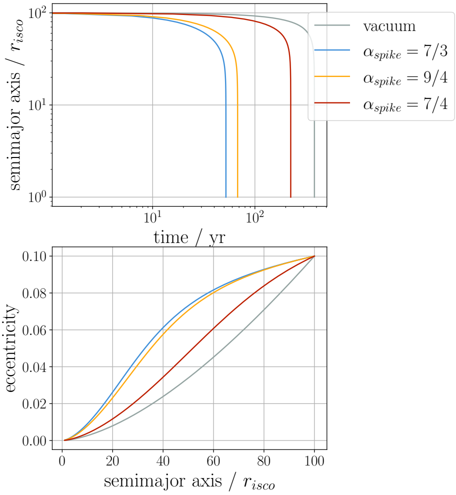
$$N^{(n)}(t_f, t_i) = n \int_{t_i}^{t_f} f(t) dt.$$

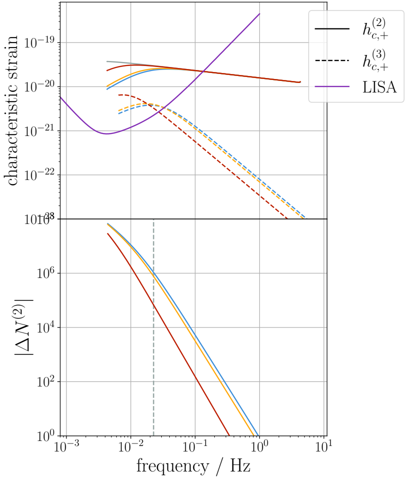
- The difference with the DM is

$$\Delta N^{(n)}(t) = N^{(n)}_{\text{vacuum}}(t_c, t) - N^{(n)}_{\text{DM}}(t_c, t)$$



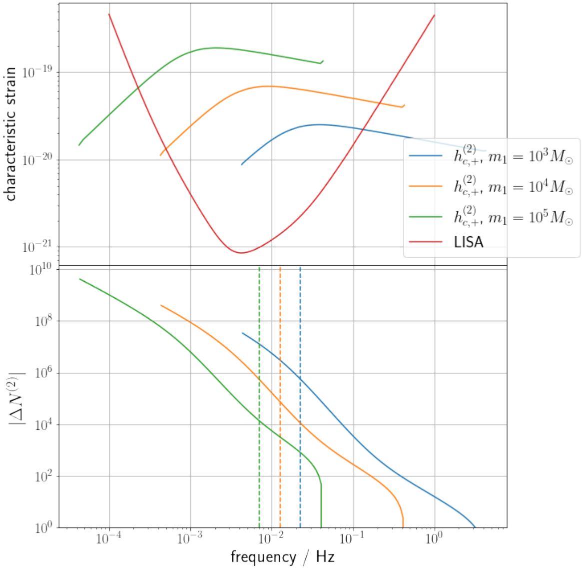
Dephasing





[6] N. Becker, L. Sagunski, L. Prinz and S. Rastgoo [2112.09586]

Mass Ratio

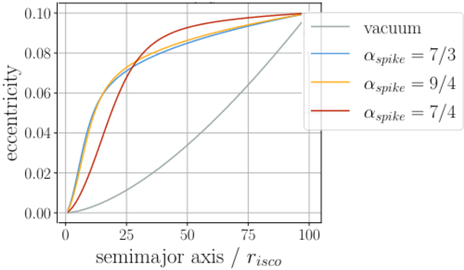


[6] N. Becker, L. Sagunski, L. Prinz and S. Rastgoo [2112.09586]

Circularization

- Dynamical Friction circularizes the orbit [6]
- depends on the power law index

$$\frac{\mathrm{d}e}{\mathrm{d}a} \approx \frac{e}{2a}\alpha_{\text{spike}}$$



[6] N. Becker, L. Sagunski, L. Prinz and S. Rastgoo [2112.09586]

Conclusions

- If these spikes exist, we should see their effect with LISA
- Dephasing & circularization can tease out DM distribution
  - → Reveal the particle nature of DM
  - → Reveal history of DM & IMBH population

Thank you for your attention!
Questions?

nbecker@itp.uni-frankfurt.de

See also [6]

[6] N. Becker, L. Sagunski, L. Prinz and S. Rastgoo, *Circularization versus eccentrification in intermediate mass ratio inspirals inside dark matter spikes*, *Phys. Rev. D* **105** (2022) 063029, [2112.09586]

References

A. Coogan, G. Bertone, D. Gaggero, B. J. Kavanagh and D. A. Nichols, *Measuring the dark matter environments of black hole binaries with gravitational waves*, 2108.04154.

L. Sadeghian, F. Ferrer and C. M. Will, *Dark matter distributions around massive black holes: A general relativistic analysis*, *Phys. Rev. D* **88** (2013) 063522, [1305.2619].

B. J. Kavanagh, D. A. Nichols, G. Bertone and D. Gaggero, *Detecting dark matter around black holes with gravitational waves: Effects of dark-matter dynamics on the gravitational waveform*, *Phys. Rev. D* **102** (2020) 083006, [2002.12811].

J. Binney and S. Tremaine, *Galactic dynamics*. 1987.

B. Moore, T. Robson, N. Loutrel and N. Yunes, *Towards a Fourier domain waveform for non-spinning binaries with arbitrary eccentricity*, *Class. Quant. Grav.* **35** (2018) 235006, [1807.07163].

N. Becker, L. Sagunski, L. Prinz and S. Rastgoo, *Circularization versus eccentrification in intermediate mass ratio inspirals inside dark matter spikes*, *Phys. Rev. D* **105** (2022) 063029, [2112.09586].

M. Maggiore, *Gravitational Waves. Vol. 1: Theory and Experiments*. Oxford Master Series in Physics. Oxford University Press, 2007.

G. Fragione, I. Ginsburg and B. Kocsis, *Gravitational Waves and Intermediate-mass Black Hole Retention in Globular Clusters*, *Astrophys. J.* **856** (2018) 92, [1711.00483].

P. D. Serpico, V. Poulin, D. Inman and K. Kohri, *Cosmic microwave background bounds on primordial black holes including dark matter halo accretion*, *Phys. Rev. Res.* **2** (2020) 023204, [2002.10771].

X.-J. Yue and Z. Cao, *Dark matter minispike: A significant enhancement of eccentricity for intermediate-mass-ratio inspirals*, *Phys. Rev. D* **100** (2019) 043013, [1908.10241].

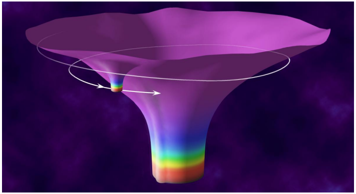
Gravitational Waves

D | M | G | W Dark Matter Modified Gravity Gravitational Waves

- Energy & angular momentum loss on Keplerian orbit [7]

$$\left\langle \frac{\mathrm{d}E_{\mathrm{gw}}}{\mathrm{d}t} \right\rangle = -\frac{32}{5}\frac{\mu^2 m^3}{a^5}\frac{1+\frac{73}{24}e^2+\frac{37}{96}e^4}{(1-e^2)^{7/2}}$$

$$\left\langle \frac{\mathrm{d}L_{\mathrm{gw}}}{\mathrm{d}t} \right\rangle = -\frac{32}{5}\frac{\mu^2 m^{5/2}}{a^{7/2}}\frac{1+\frac{7}{8}e^2}{(1-e^2)^2}$$



Credit: NASA

[7] M. Maggiore, *Gravitational Waves. Vol. 1: Theory and Experiments*. Oxford Master Series in Physics. Oxford University Press, 2007

Event Rate

DMGW Dark Matter Modified Gravity Gravitational Waves

- IMBH population and origin not well understood

$\longrightarrow$ IMRI rate very difficult to estimate!

- For IMBH in Globular Clusters the event rate is estimated to be $> 1 - 10\text{Gpc}^{-3}\text{yr}^{-1}$ at $z = 0$ [8]
- For IMBH from PBH we can expect 10^6 of mass $10^3 M_\odot$ [9]

$\longrightarrow$ Merger formation unknown

- JWST will shed light on SMBH formation and IMBH history

---

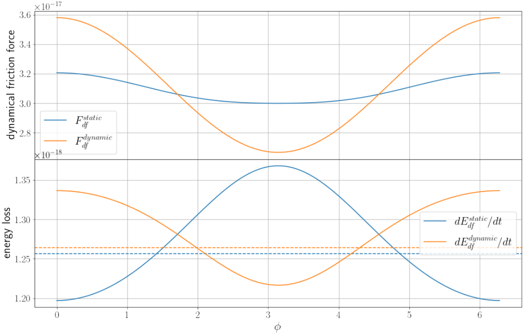
[8] G. Fragione, I. Ginsburg and B. Kocsis, *Gravitational Waves and Intermediate-mass Black Hole Retention in Globular Clusters*, *Astrophys. J.* **856** (2018) 92, [1711.00483]

[9] P. D. Serpico, V. Poulin, D. Inman and K. Kohri, *Cosmic microwave background bounds on primordial black holes including dark matter halo accretion*, *Phys. Rev. Res.* **2** (2020) 023204, [2002.10771]

Inclusion of $\xi(v)$

$$\rho(r)\xi(v) = 4\pi \int_0^v v'^2 f(\Psi(r) - \frac{1}{2}v'^2)dv' \text{ with } \Psi(r) = \frac{m_1}{r}$$

Dynamical friction force and energy loss over one eccentric orbit

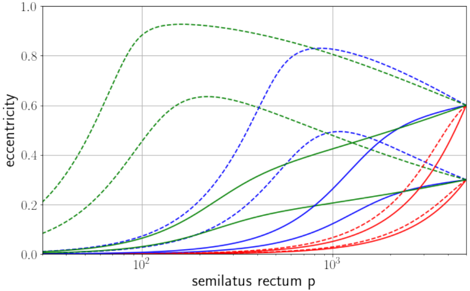


Inclusion of $\xi(v)$

Equations

- [10] predicted eccentrification through dynamical friction
- The inclusion of $\xi(v)$ completely eliminates that

$\rightarrow$ Eccentricity not a good marker for DM spikes



The evolution of the eccentricity e as a function of semilatus rectum p. The red, blue, green lines correspond to a spike power law index of $\alpha_{\text{spike}} = \{1.5, 2, 7/3\}$.

[10] X.-J. Yue and Z. Cao, *Dark matter minispike: A significant enhancement of eccentricity for intermediate-mass-ratio inspirals*, *Phys. Rev. D* **100** (2019) 043013, [1908.10241]

Eccentrification Conditions

- Why does the inclusion of $\xi(v)$ result in circularization?
- Consider the equation for e

$$\frac{\mathrm{d}e}{\mathrm{d}t} = -\frac{1-e^2}{2e}\left(\underbrace{\frac{\mathrm{d}E_{orb}}{\mathrm{d}t}/E_{orb} + 2\frac{\mathrm{d}L_{orb}}{\mathrm{d}t}/L_{orb}}_{X}\right)$$

- Look at X for a single force $F(r,v)$

$$X = \frac{2(1-e^2)}{\mu}\int_0^{2\pi}\frac{d\phi}{2\pi}(1+e\cos\phi)^{-2}F(r,v)\left(\frac{av}{m}-\frac{1}{v}\right)$$

Eccentrification Conditions

- Assume simple form for $F(r, v) \propto r^\alpha v^\beta$

$$\mathrm{sgn}(X) \approx \frac{e}{2}(-1 + \beta - \alpha)$$

- For $\alpha < \beta - 1$, $X > 0$ and the force circularizes the orbit
- For $\alpha > \beta - 1$ the force eccentrifies the orbit

→ Thus we have for our forces

$$\begin{aligned}
F_{gw} &\propto r^{-4} v^{-1}(11r^{-2} + v^2) &&\longrightarrow \text{circularization} \\
F_{df}\big|_{\xi(v)\equiv 1} &\propto r^{-\alpha_{spike}} v^{-2} &&\longrightarrow \text{eccentrification if } \alpha_{spike} < 3 \\
F_{df}\big|_{\xi(v)\propto v^3} &\propto r^{-\alpha_{spike}} v^{1} &&\longrightarrow \text{circularization} \\
F_{acc} &\propto r^{-\alpha_{spike}}(1 + v^2) &&\longrightarrow \text{circularization.}
\end{aligned}$$

D | M | G | W Dark Matter Modified Gravity Gravitational Waves

Questions?

Thank you for your attention!

Niklas Becker, Laura Sagunski, Saeed Rastgoo, Lukas Prinz

nbecker@itp.uni-frankfurt.de

dmgw.space