SELF-INTERACTING DARK MATTER
AND
FINAL PARSEC PROBLEM:
CONSTRAINTS FROM
GRAVITATIONAL WAVE DATA

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OUTLINE

- Final parsec problem
- Dark matter (DM)
- Self-interacting dark matter
- SIDM strain spectrum
- Statistical analysis
- Results

FINAL PARSEC PROBLEM

- Mechanisms (dynamical friction, 3-body gravitational slingshot) can bring supermassive black hole binaries (SMBHBs) from kpc to ~1pc separation.
- If binary gets as close as 0.01 pc, only GW emission is sufficient to make them merge within the age of the universe
- We don't know a clear mechanism yet that can bring binary from ~ 1 pc to ~0.01 pc
- Self-interacting dark matter model provides a potential solution.

DARK MATTER

- Dark matter has been proposed to account for the missing mass that is needed to explain some astrophysical and cosmological observations
- The following are some of the observational evidence of dark matter
  - Mass of galaxy clusters (using, for example, X rays, strong lensing) (Zwicky 1930s)
  - Galaxy rotation curves (Vera Rubin, 1970s)
  - Large scale structures and anisotropies in CMB- matter content of universe (~30%)
  - Measurements of BBN and anisotropies in CMB- baryonic matter (~5%)
  - Structure formation

SELF-INTERACTING DARK MATTER

- 3 regions in SIDM halo- Density profiles in these regions are
- NFW- outermost

$$\rho(r) = \frac{\rho_s r_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

- Isothermal core- middle

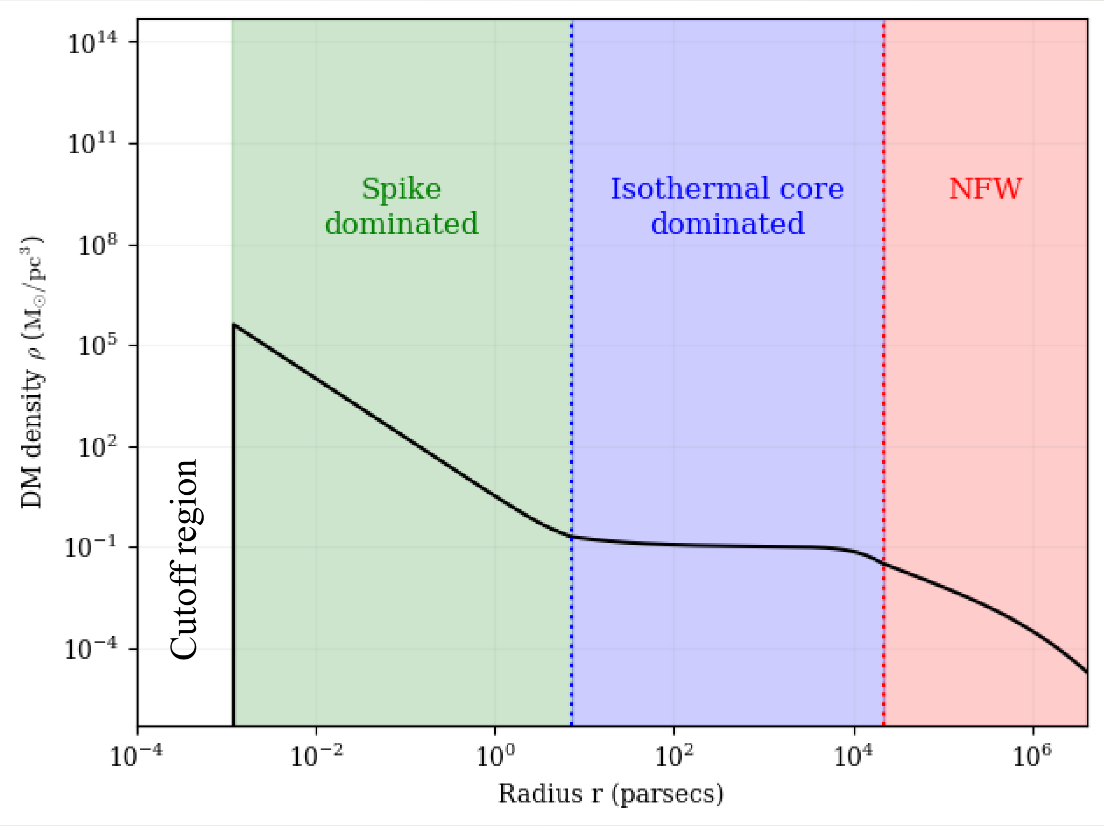
$$v_0^2\, \nabla^2 \ln \rho(r) = -4\pi G \rho(r)$$

(v_0 is SIDM velocity dispersion in the core)

- Spike- innermost

$$\rho(r) = \rho_{sp} \left(\frac{r_{sp}}{r}\right)^{\gamma}$$

(γ is the spike slope (log scale))

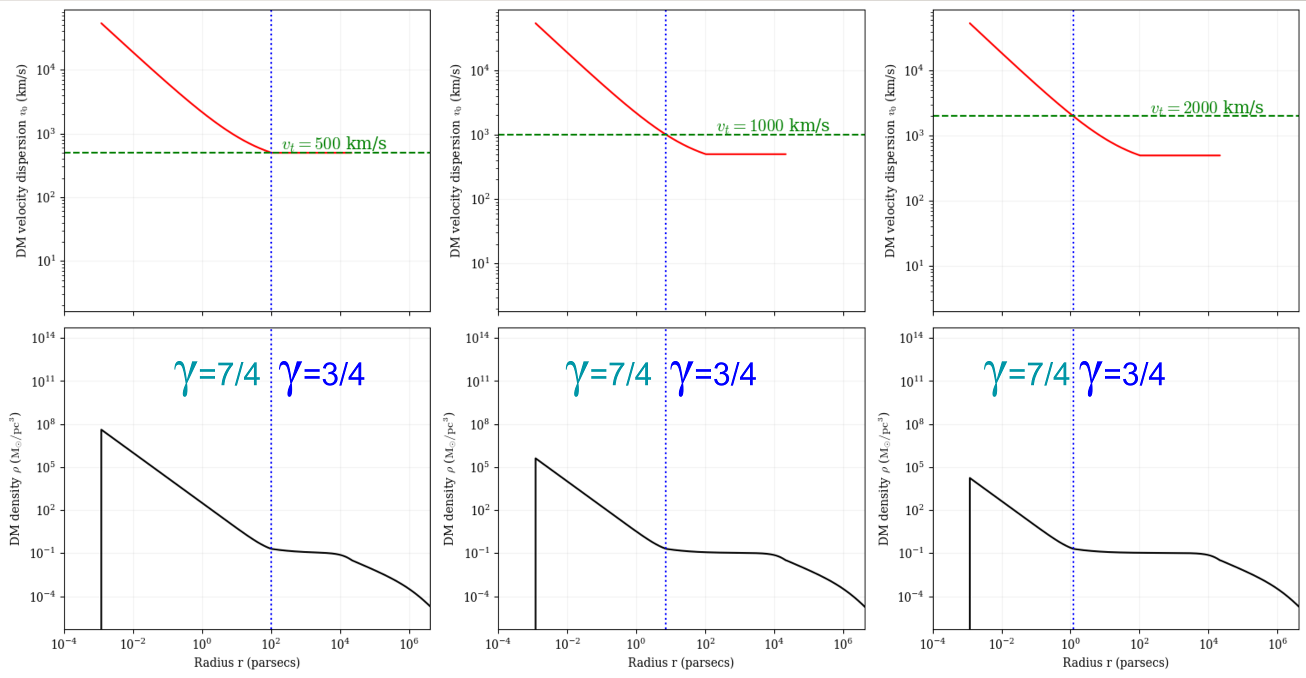


SELF-INTERACTING DARK MATTER

- Interaction types-
  - Contact interaction

    Spike slope γ = 3/4
  - Coulomb interaction

    Spike slope γ = 7/4
- Transition velocity-
  - SIDM velocity constant in core, but increases in spike.
  - When DM velocity = transition velocity, interaction type changes (spike slope changes)



DM SPIKE- STRAIN SPECTRUM

- The gravitational strain spectrum is calculated as-

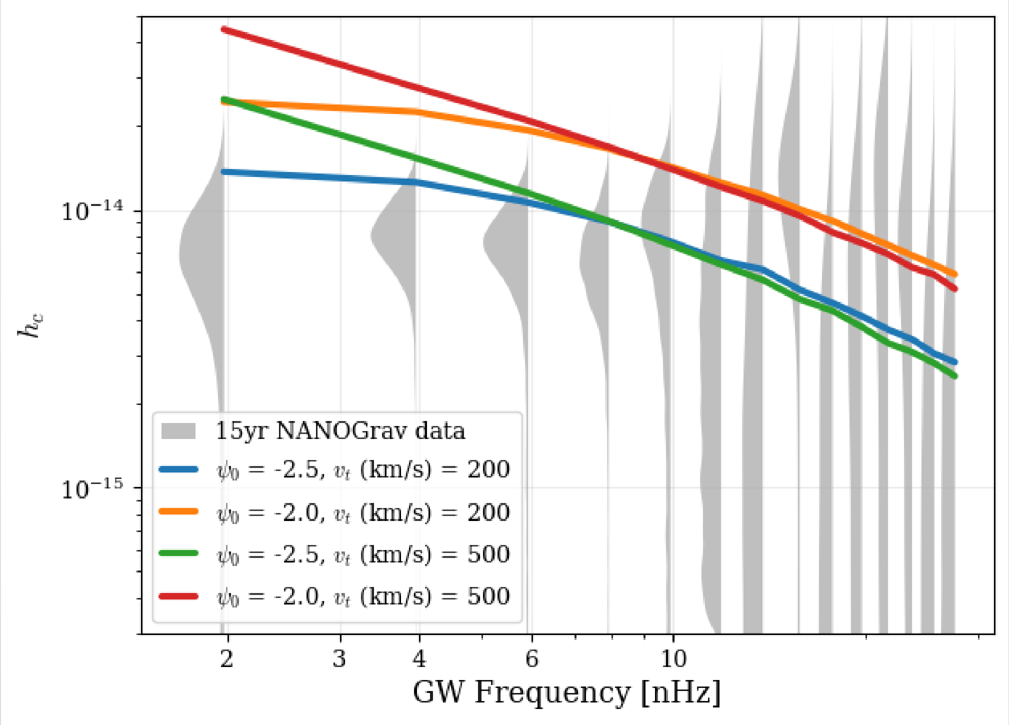
$$h_c^2(f) = \frac{4G}{\pi c^2 f} \iiint dz\, dM\, dq \, \frac{d^3 n}{dz\, dM\, dq} \frac{dE_{GW}}{df_s}$$

z is the redshift, M is the total mass of the black hole binary, q is the mass ratio (lighter/heavier)

- $\frac{dE_{GW}}{df_s}$ depends on $\frac{P_{GW}}{P_{GW} + P_{DF}}$
- P_{GW} - Power loss due to gravitational waves radiation
- P_{DF} - Power loss due to dynamical friction (depends on SIDM density profile)
- Limits of integration- *z: 0-10, M:* 10^4*-*10^{12} $M_\odot$*, q: 0-1*

STATISTICAL ANALYSIS

- Vary the parameters of your model
- Different parameter values will give different strain spectra
- Check which parameter values give the strain closest to the data
- We used ***holodeck*** ***** – a package developed by NANOGrav to perform this analysis



***** I had to make changes and fix some errors to use it for my analysis.

STATISTICAL ANALYSIS

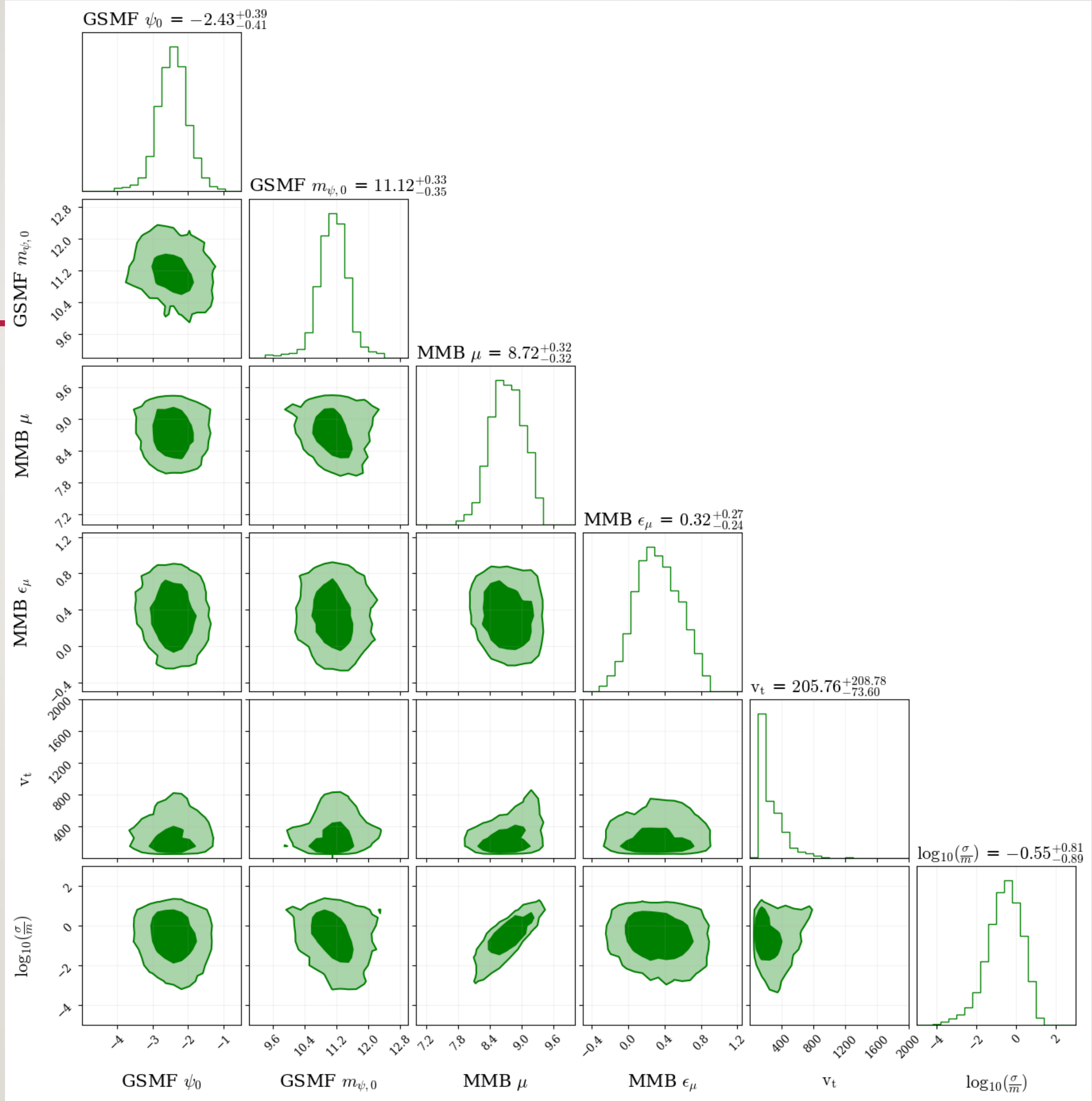
- For 8000 param. value combinations calculate corresponding strain spectra -“library”
- Use Gaussian process to interpolate between param values, strain values
- Use MCMC to generate posterior distributions of these model parameters

8000

ψ_0	v_t	σ/m	hc(f)
-2.5	500	0.3	**[1e-14, 9e-15,….]**
-2.7	800	1.2	**[7e-15, 4e-16,….]**
…	…	…	**…**
…	…	…	**…**
…	…	…	**…**
…	…	…	**…**
-3.5	1500	30	**[3e-15, 9e-16,….]**

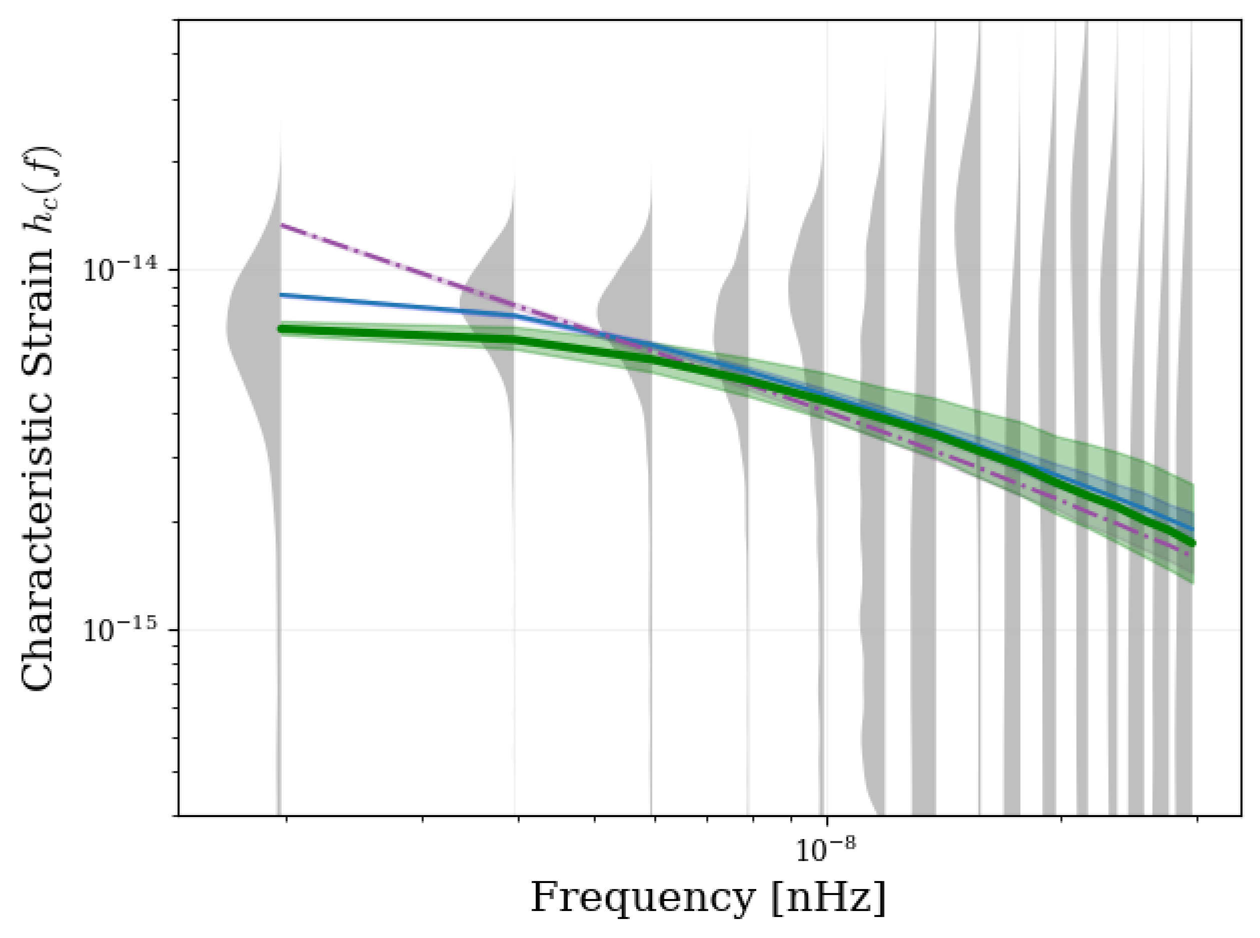
RESULTS

- First 2 parameters- SMBH Binary population
- Next 2 parameters- Black hole mass - halo mass relation
- Last 2 parameters-SIDM model related-
  - Transition velocity
  - Cross section (of self-interaction) over mass of the SIDM particle



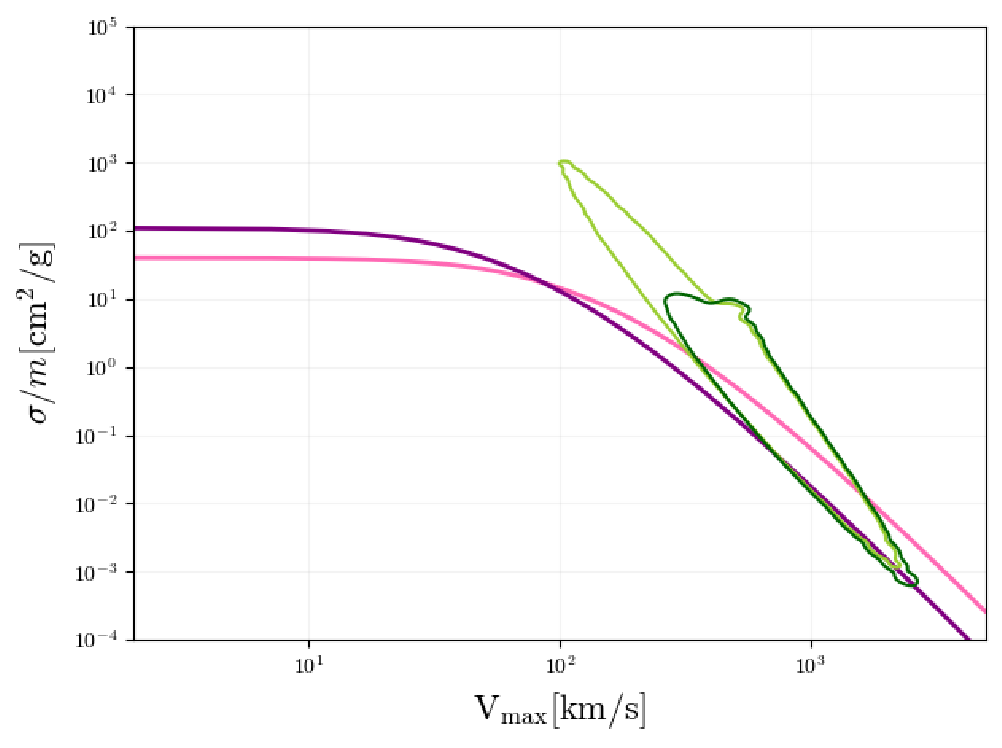
RESULTS

- Strain spectra using best fit params
- Green- Our results for SIDM model
- Blue- NANOGrav's phenomenological model
- Purple- Grav. wave-only model



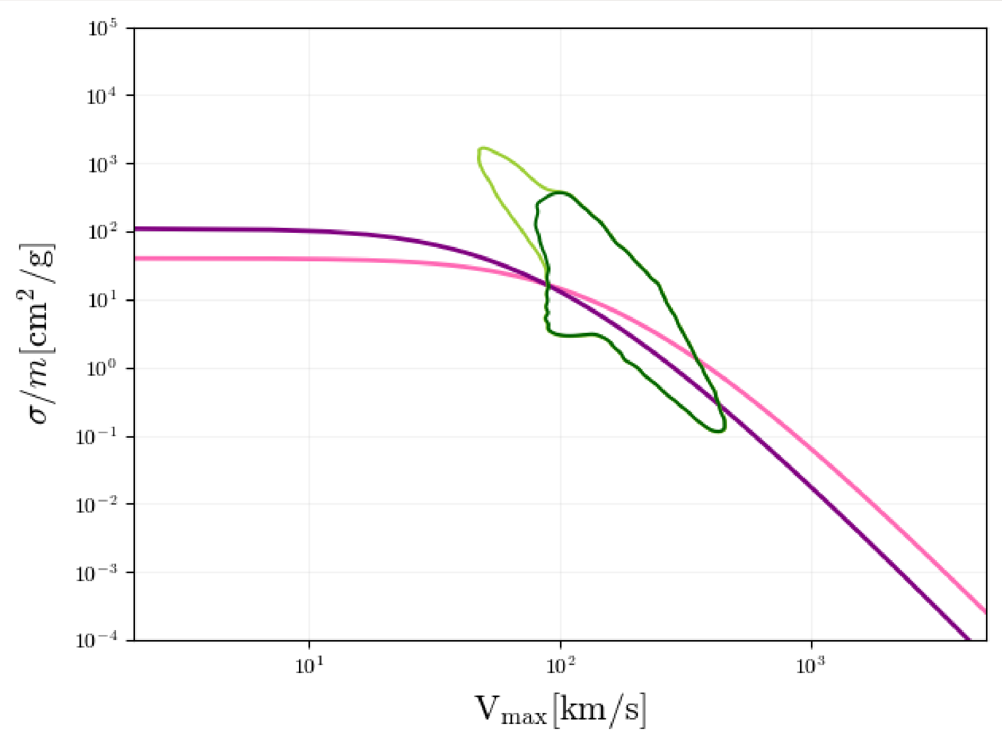
RESULTS

- Comparison with standard SIDM literature- background image from (Roberts et.al 2025) (for two different DM masses)
- Green contours- Our result: 95% region (for SMBHB mass of $10^{10}\, M_{\odot}$)
- σ/m = $0.28^{+1.81}_{-0.04}\ \mathrm{cm}^2/\mathrm{g}$



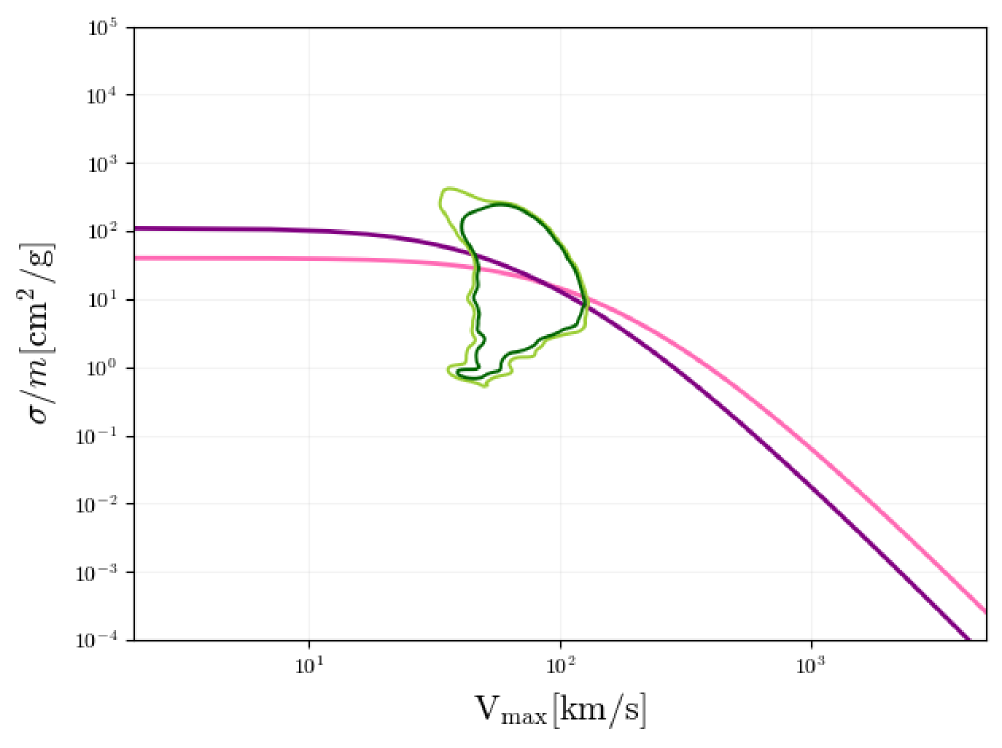
RESULTS

- Green contours- Our result: 95% region (for SMBHB mass of $10^9\, M_\odot$)



RESULTS

- Green contours- Our result: 95% region (for SMBHB mass of $10^8 M_\odot$)



CONCLUSION

- SIDM model with a density spike can solve the final parsec problem.
- The model with SIDM can be probed using PTA data.
- MCMC method gives constraints on transition velocity and cross section over mass.
- When compared with the existing literature, our results seem consistent.

THANK YOU!

BIBLIOGRAPHY

1. *G. Alonso- ´Alvarez, J. M. Cline, and C. Dewar, Self-interacting dark matter solves the final parsec problem of supermassive black hole mergers, Phys. Rev. Lett. 133,021401 (2024).*
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Hopefully up by tomorrow