The Precision Frontier of Dark Matter Constraints - from Direct Acceleration Measurements

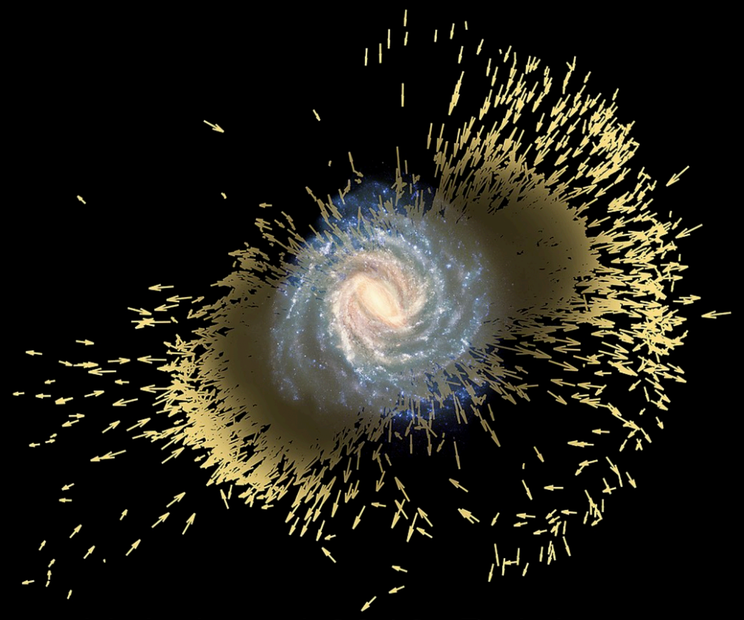
Sukanya Chakrabarti (UAH)

Extreme precision radial velocity (EPRV) : J. Wright, P. Chang, A. Quillen, P. Craig, J.Territo, E. D'Onghia, K. Johnston, R. de Rosa, K. Rhode, D. Huber, E. Nielsen, J. Wagner
Pulsar timing: P. Chang, M. Lam, S. Vigeland, A. Quillen, T. Donlon, L. Widrow, E. Ramirez-Ruiz, B. Shappee + NANOGrav
Eclipse timing: D. Stevens, J. Wright, R. Rafikov, P. Chang, T. Beatty, D. Huber, T. Maccarone, S.Parsons, V. Dhillon + HiPERCAM team
Acceleration ladder: P. Craig, R. Sanderson, F. Nikhatar
SIDM/CDM constraints: A. Arora, R. Sanderson + FIRE team
Angular accelerations: L. Addy

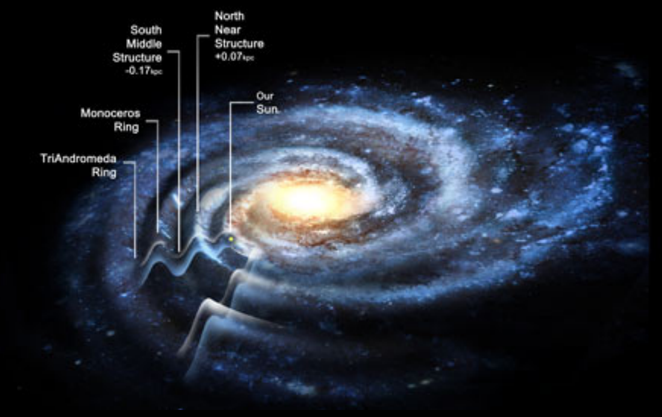
The dynamic Milky Way

Why direct measurements of the Galactic acceleration?

Traditional method: estimate accelerations. True acceleration in interacting Galaxy may be different



Helmi et al 2018; Belokurov et al 2018



Xu et al. 2015; Widrow et al. 2012

From phase-space (x,v) descriptors to acceleration measurements from extreme-precision time-series observations (x,dv/dt) :

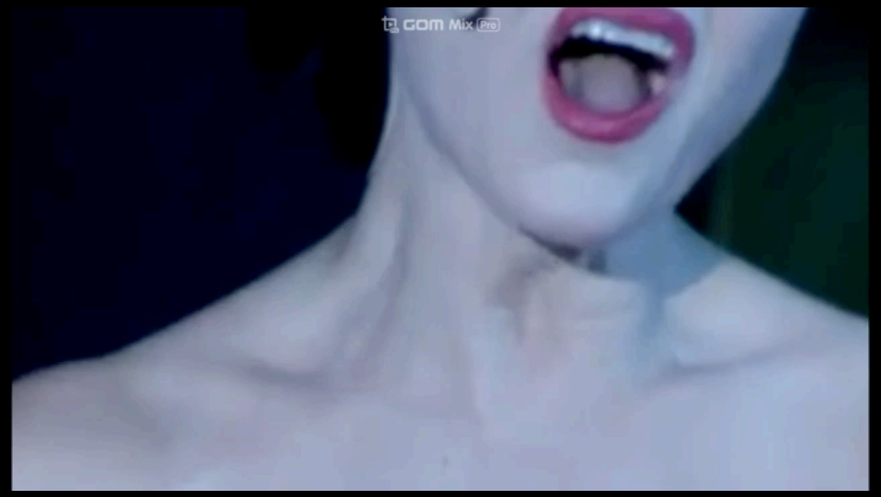
1. Extreme precision radial velocity measurements (Chakrabarti et al. 2020)
2. Pulsar timing (Chakrabarti et al. 2021, Donlon et al., 2024)
3. Eclipse timing (Chakrabarti et al. 2022)

Outline: “real-time” Galactic dynamics

- High precision RV observations to measure the Galactic acceleration : requires ~ 10 cm/s precision (these accelerations << Galactic center accelerations)

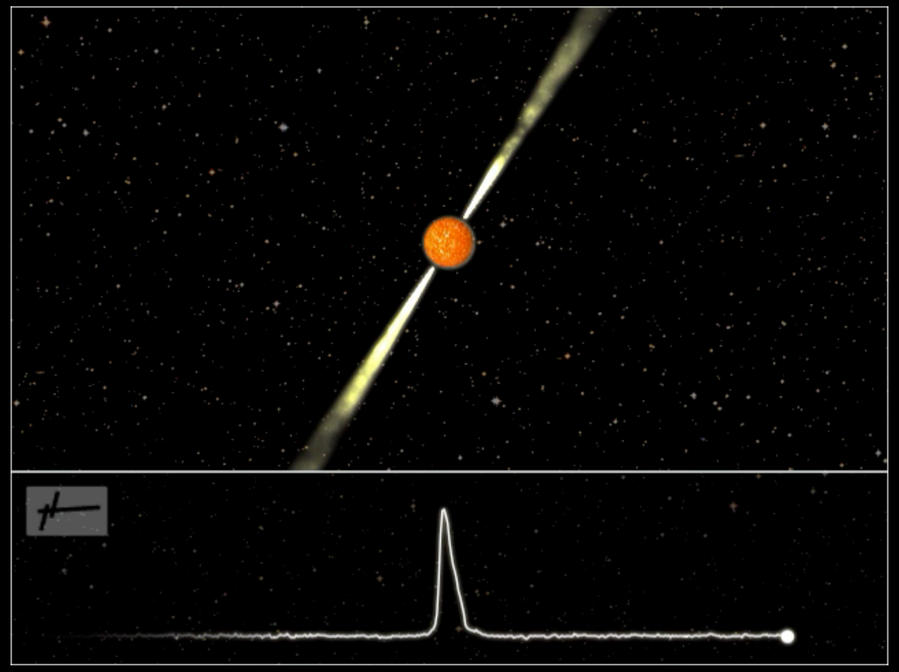
- **<u>Pulsar timing</u>** measurements of the Galactic acceleration, the Oort limit & the local dark matter density : requires precision on $\dot{P}_b$ ~ 10^{-13} s^{-1}

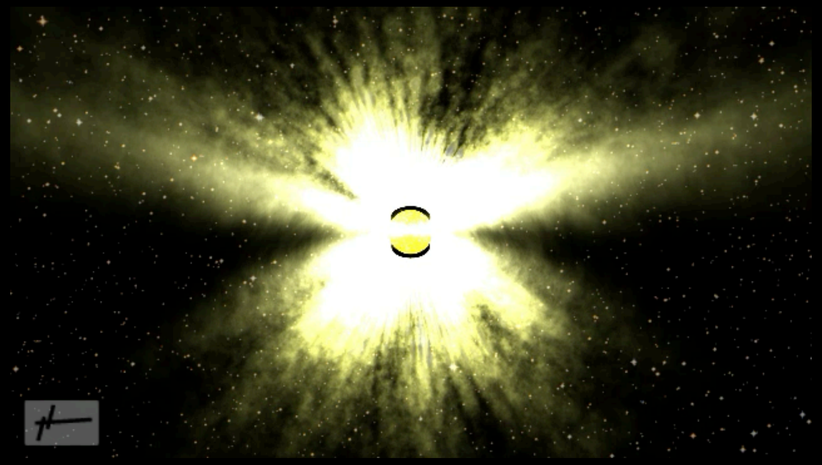
- **<u>Eclipse timing</u>** measurements of the Galactic acceleration: requires precision on eclipse mid-point time of ~ 0.1s over decade baseline



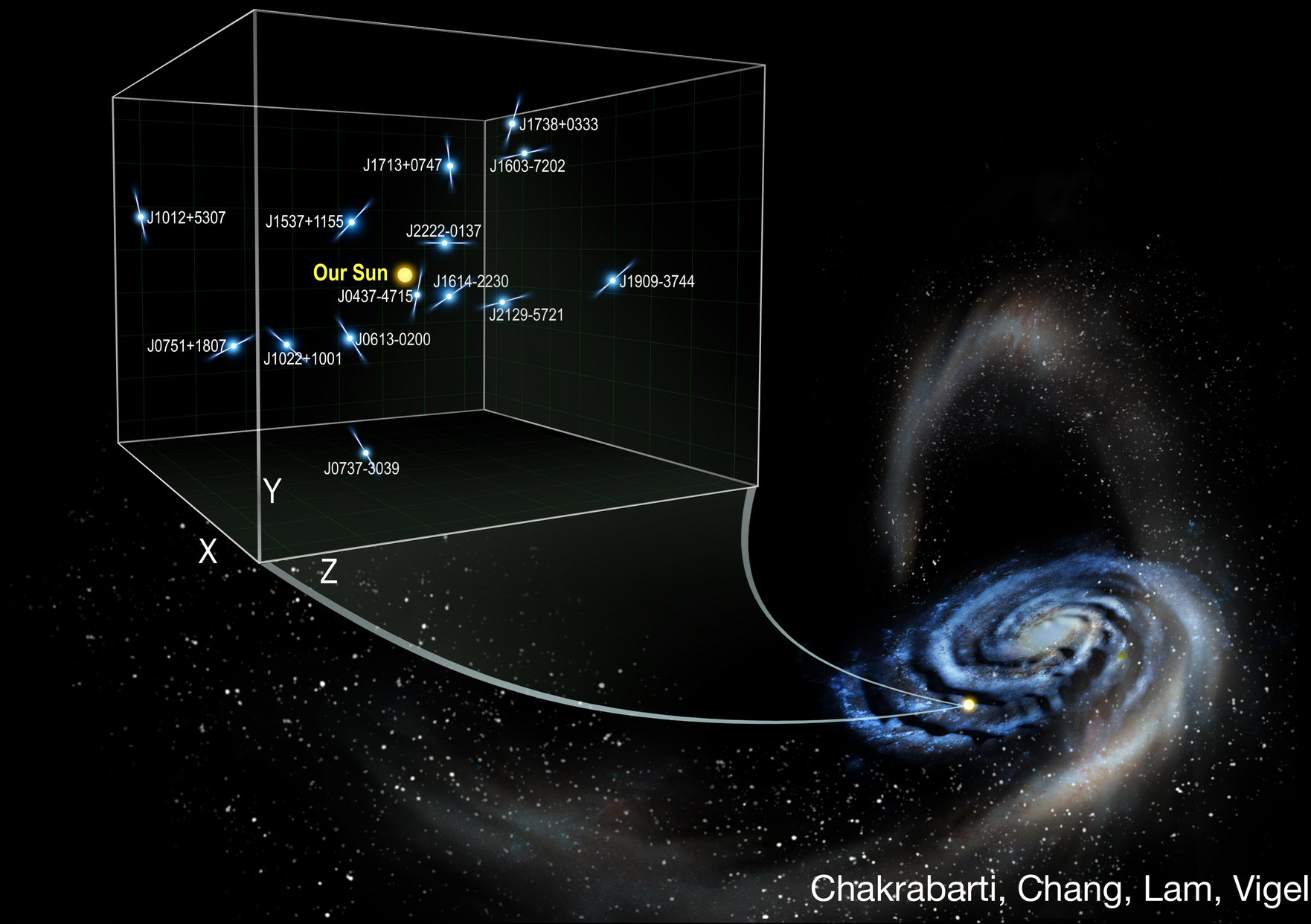
Galactic acceleration from pulsar timing

- Temporal stability of pulsars rivals atomic clocks
- Binary millisecond pulsars & change in *orbital* period: Galactic accelerometers.





Credit: "Joeri van Leeuwen"



Chakrabarti, Chang, Lam, Vigeland & Quillen 2021

Basic setup

$$\dot{P}_b^{obs} = \dot{P}_b^{Gal} + \dot{P}_b^{Shk} + \dot{P}_b^{GR}$$

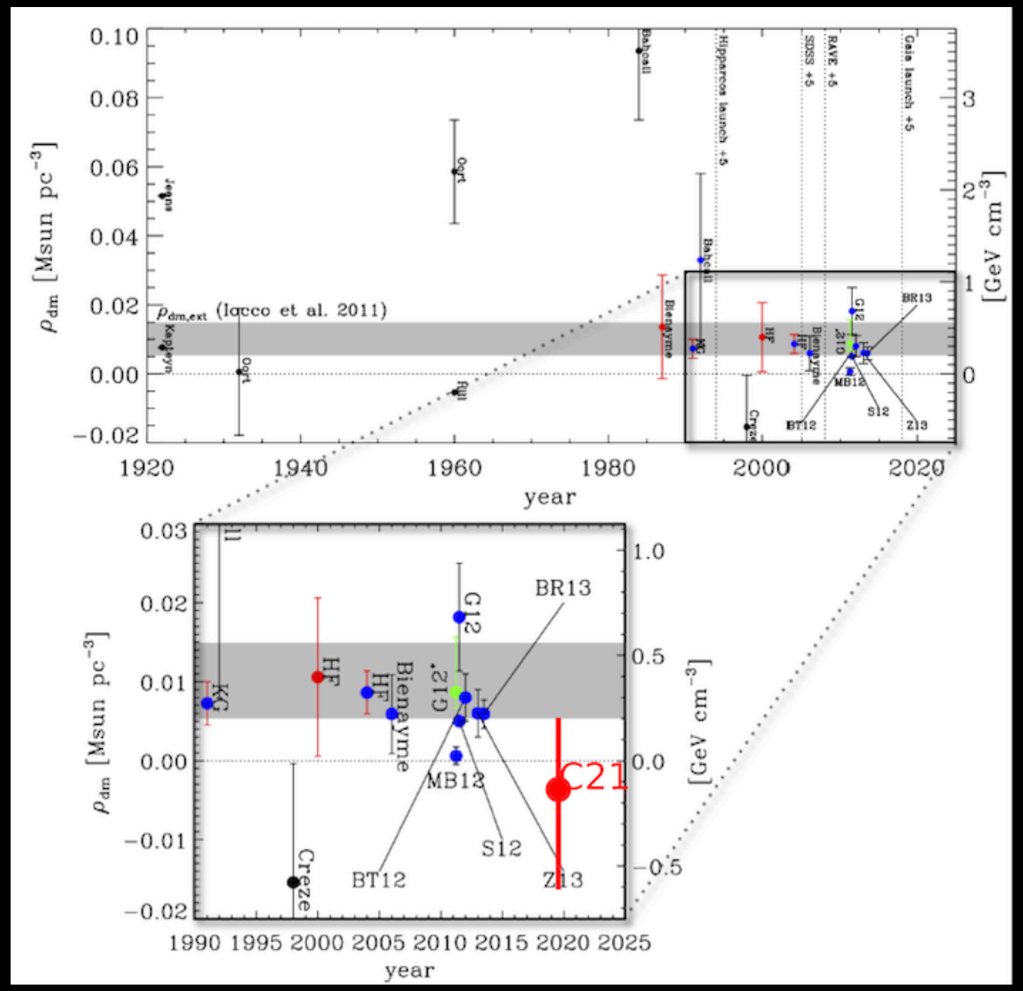
$$\dot{P}_b^{Shk} = \frac{P_b \mu^2 * d}{c^2}$$

Shlovskii effect : apparent orbital change due to pulsar's transverse motion (Damour & Taylor 1991)

$$A_G = c * \frac{\dot{P}_b^{Gal}}{P_b}$$

Exclude sources in globular clusters, use only sources with proper motions and parallaxes (Chakrabarti, Chang, Lam, Vigeland & Quillen 2021)

Fundamental Galactic parameters from pulsar timing



Oort limit (total mid-plane density)

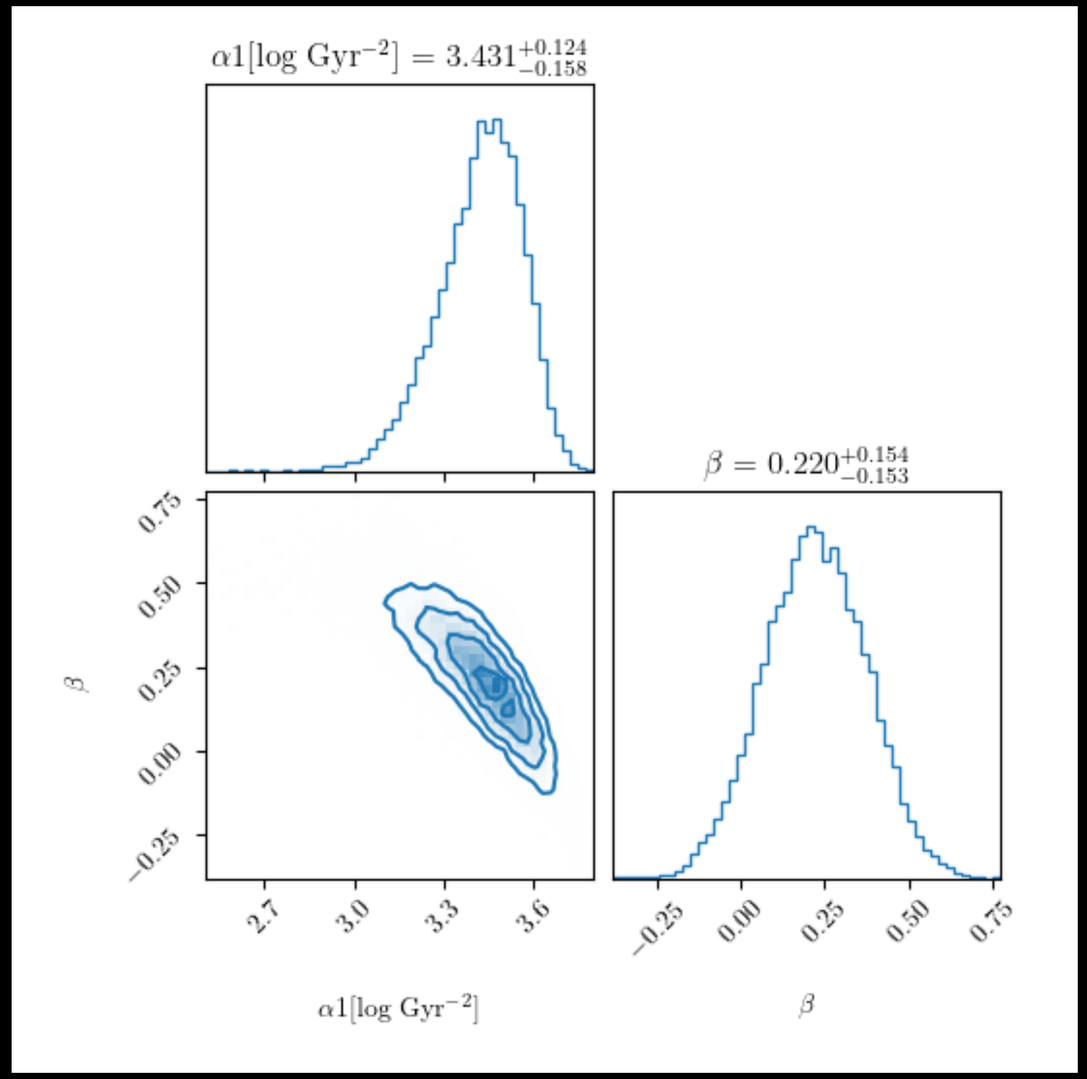
$$0.08^{0.05}_{-0.02} M_\odot/\mathrm{pc}^3$$

With baryon density from Bienyame et al. 2015:

$$\rho_{DM} = 0.0034^{0.05}_{-0.02} M_\odot/\mathrm{pc}^3$$

Chakrabarti et al. 2021 (our local dark matter density superimposed on Reid 2014 figure)

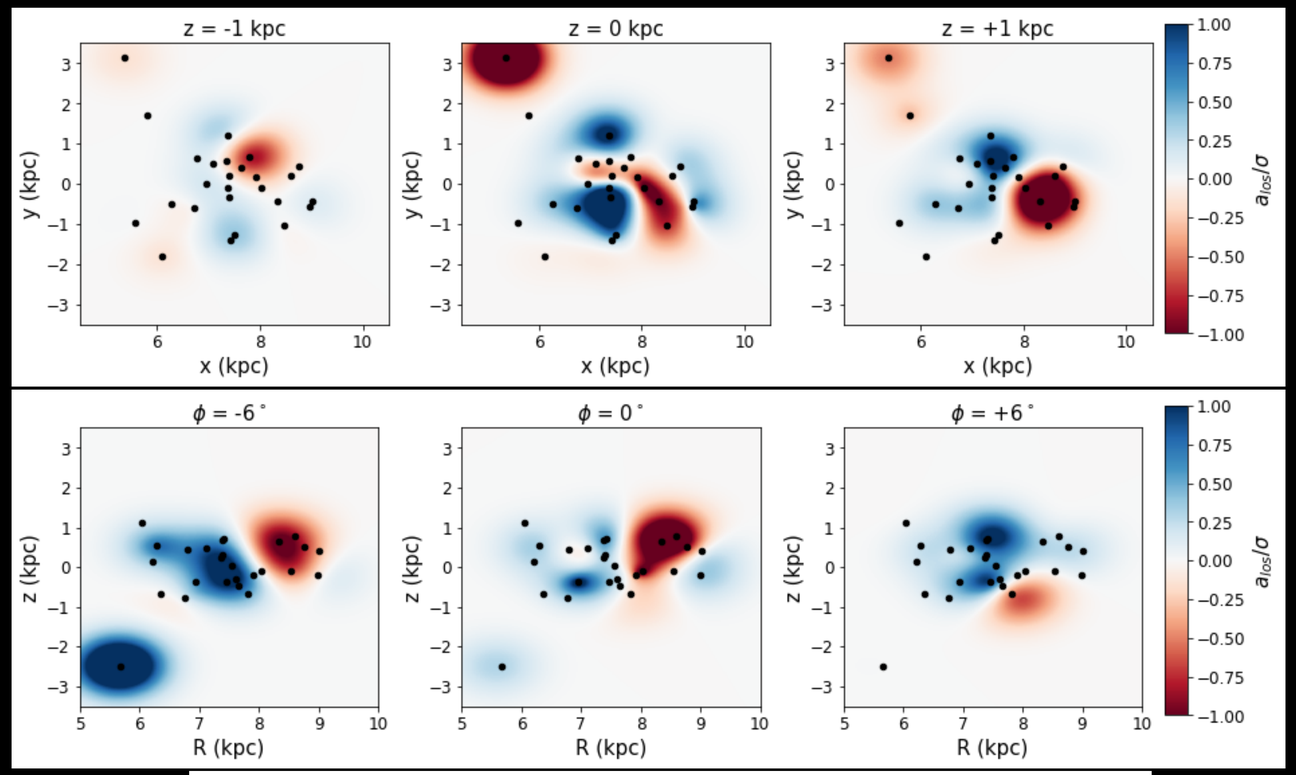
Expanded pulsar timing sample

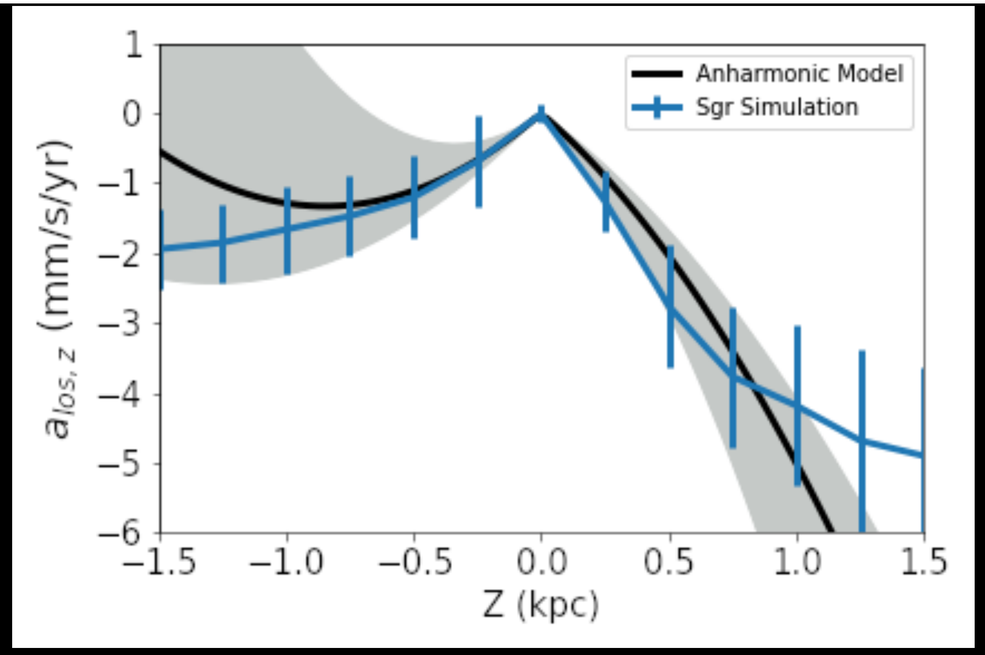


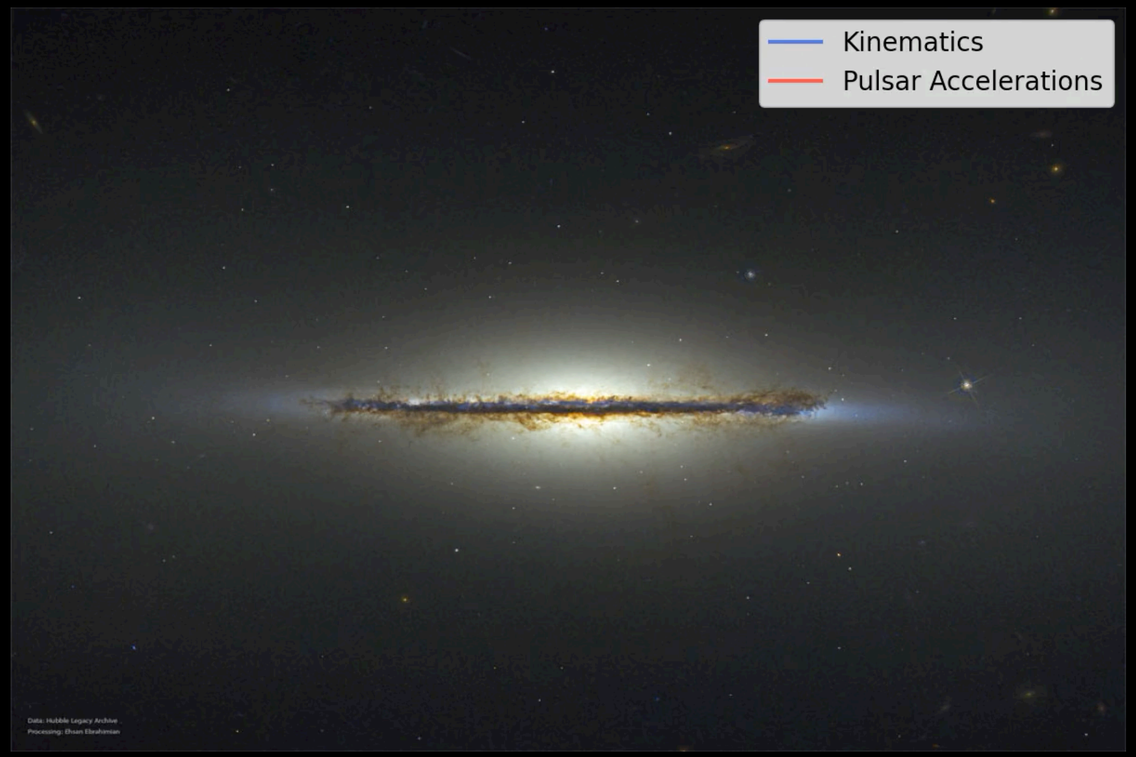
Donlon, Chakrabarti, Widrow, Lam, Chang & Quillen 2024 (total of 26 pulsars, with improved uncertainties).

Constraint on rotation curve (-2 +/- 5 km/s/kpc) & Oort constants (A = 15.4 +/- 2.6 km/s/kpc, B = -13.1 +/- 2.6 km/s/kpc), comparable with Gaia values.

Beyond a smooth model







Donlon, Chakrabarti et al. 2024

Pulsar accelerations from spin periods

$$\dot{P}_b^{\rm Obs} = \dot{P}_b^{\rm Gal} + \dot{P}_b^{\rm Shk} + \dot{P}_b^{\rm GR}$$

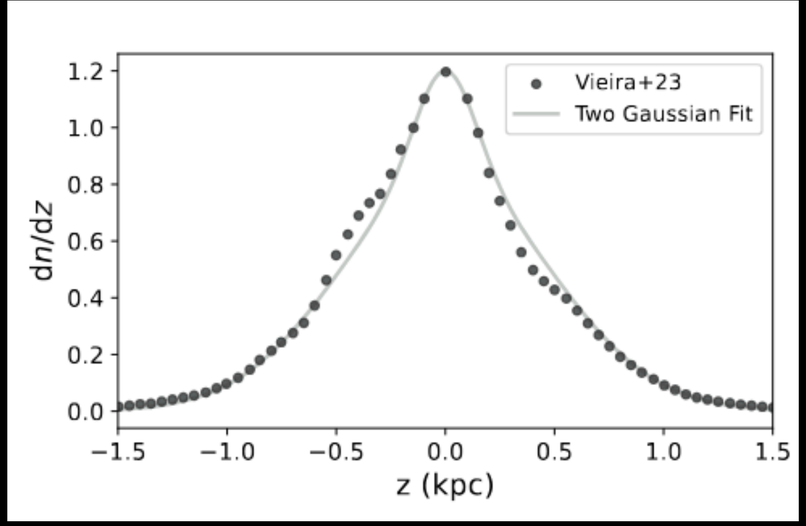
$$\dot{P}_s^{\rm Obs} = \dot{P}_s^{\rm Gal} + \dot{P}_s^{\rm Shk} + \dot{P}_s^{\rm B}$$

How do I get this magnetic braking term?

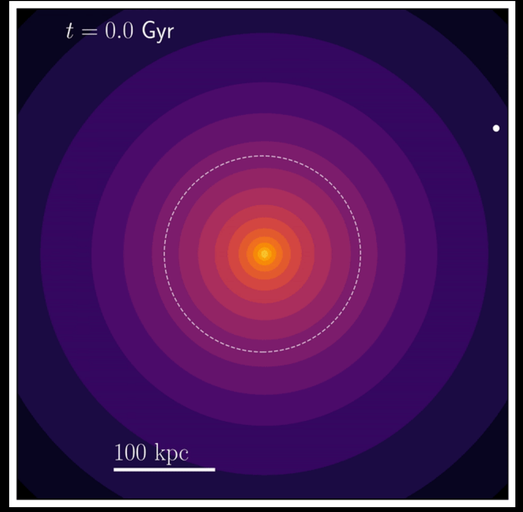
$$\frac{a_{\rm los}}{c} = \frac{\dot{P}_b^{\rm Gal}}{P_b} = \frac{\dot{P}_s^{\rm Gal}}{P_s}$$

$$\dot{P}_s^{B} = \dot{P}_s^{\rm Obs} - \frac{P_s}{P_b}\left(\dot{P}_b^{\rm Obs} - \dot{P}_b^{\rm GR}\right)$$

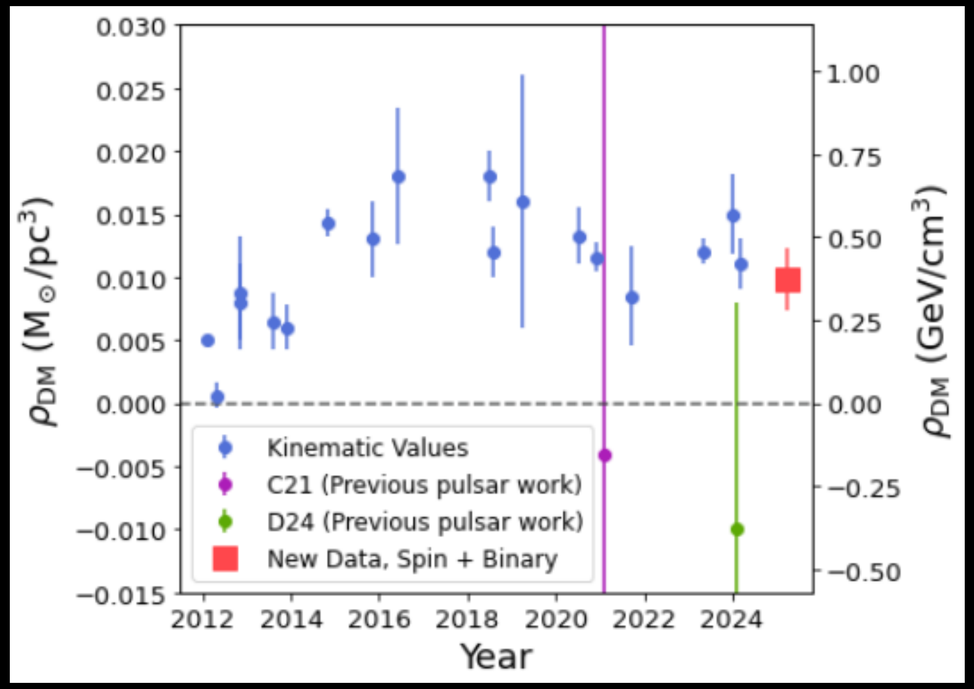
- Donlon, Chakrabarti, Widrow, Vanderwaal, Ransom & Ramirez-Ruiz, 2025 (good agreement with binary pulsar accelerations for small surface magnetic fields, B < 3×10^8 G, and age > 5 Gyr). Expands sample of acceleration measurements from 28 binary pulsars to 54 sources.



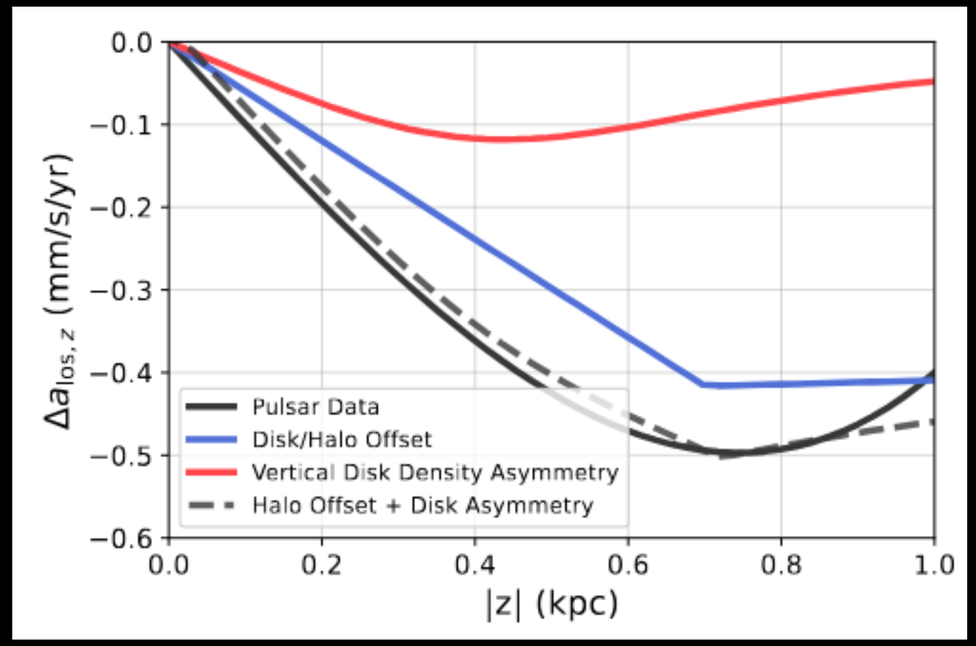
N/S asymmetry



Disk/halo offset/credit: Nico Garavito-Camargo



Updated local dark matter density measurement



Observed accelerations compared to various mechanisms

- Donlon, Chakrabarti et al., 2025 (and the local DM density is not just a single number; in prep)

Astrophysical time standards

- Pulsar timing
- <u>Eclipse timing</u>

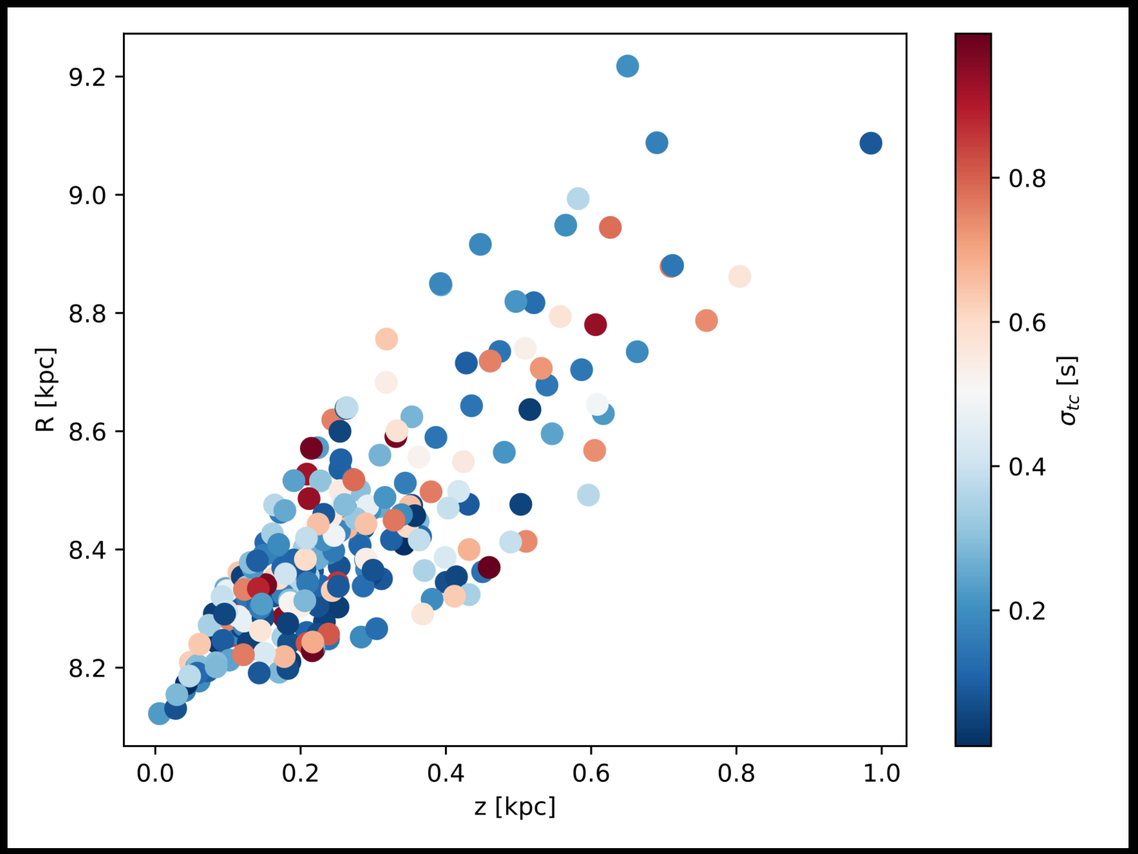
Eclipse timing

www.eso.org

- Measure Galactic acceleration from shift in eclipse mid-point time over decade baseline ~ 0.1s.
- Requires very high (space-based) photometric precision
- It's been about a decade since Kepler!

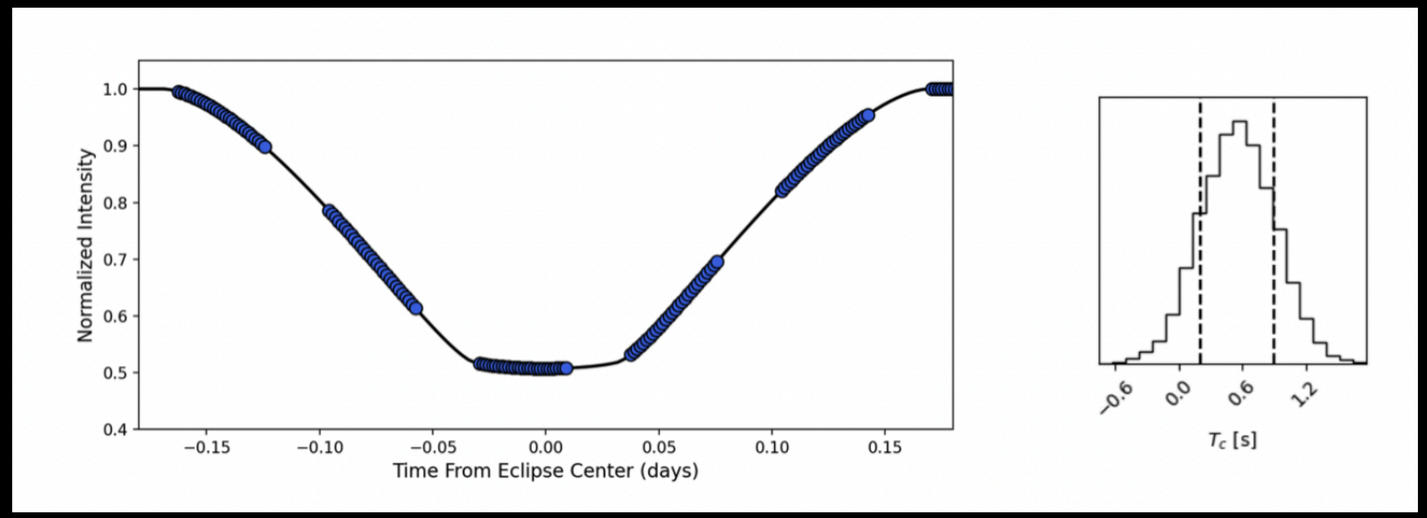
$$\Delta t_{c,Gal} = \frac{\dot{P}_{b,Gal}}{P_b} T^2$$

Expected precisions



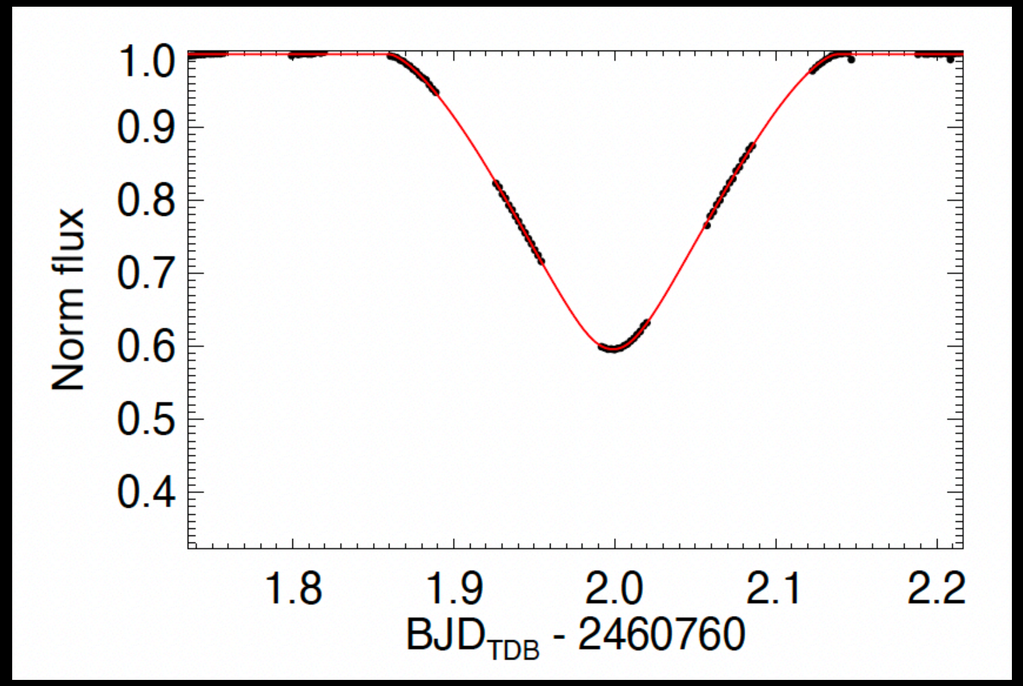
Chakrabarti, Stevens, Wright, Rafikov, Chang, Beatty & Huber 2022

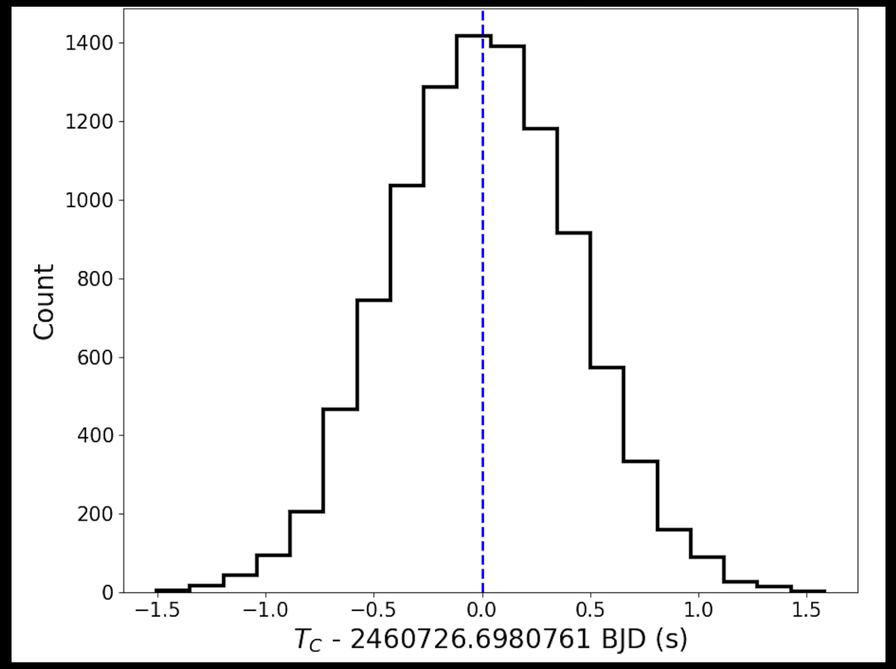
A prototypical eclipsing binary - proof of principle



Need HST level precision (C22); avoid photometric stellar noise from granulation (logg > 3.5)

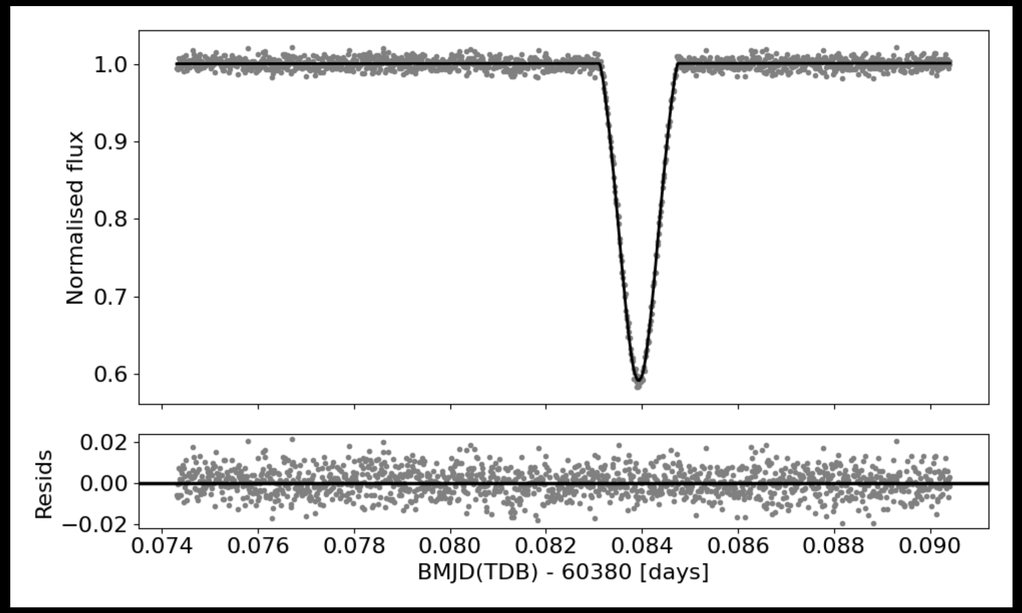
HST results (ongoing) !!



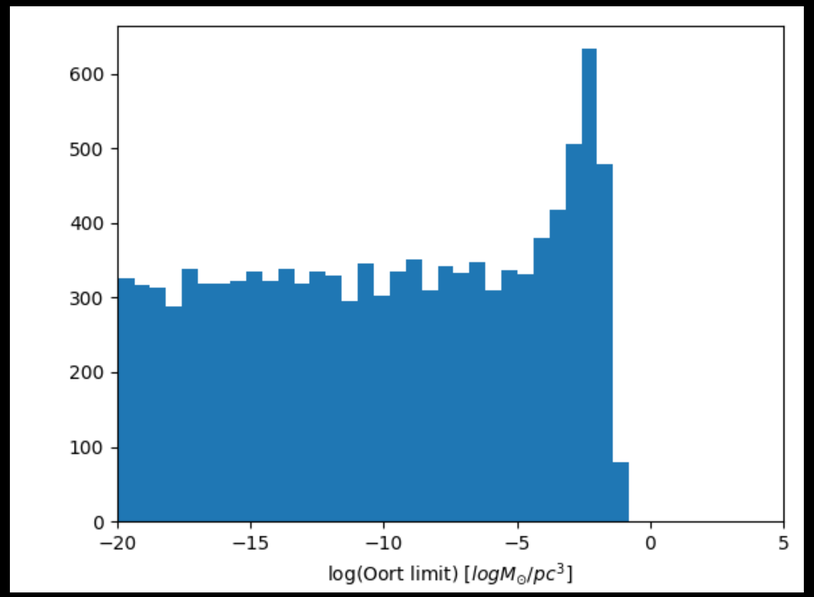


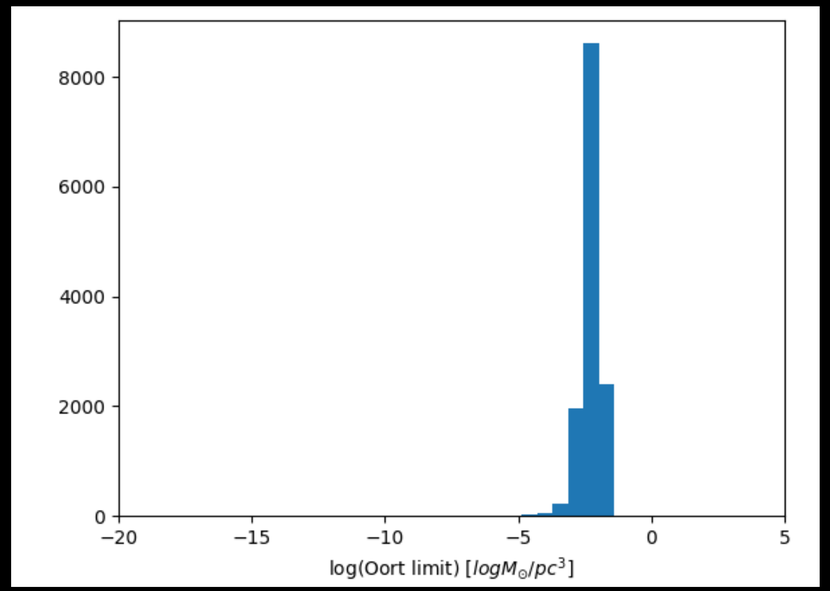
- Chakrabarti et al., in prep

Eclipse timing double white dwarfs

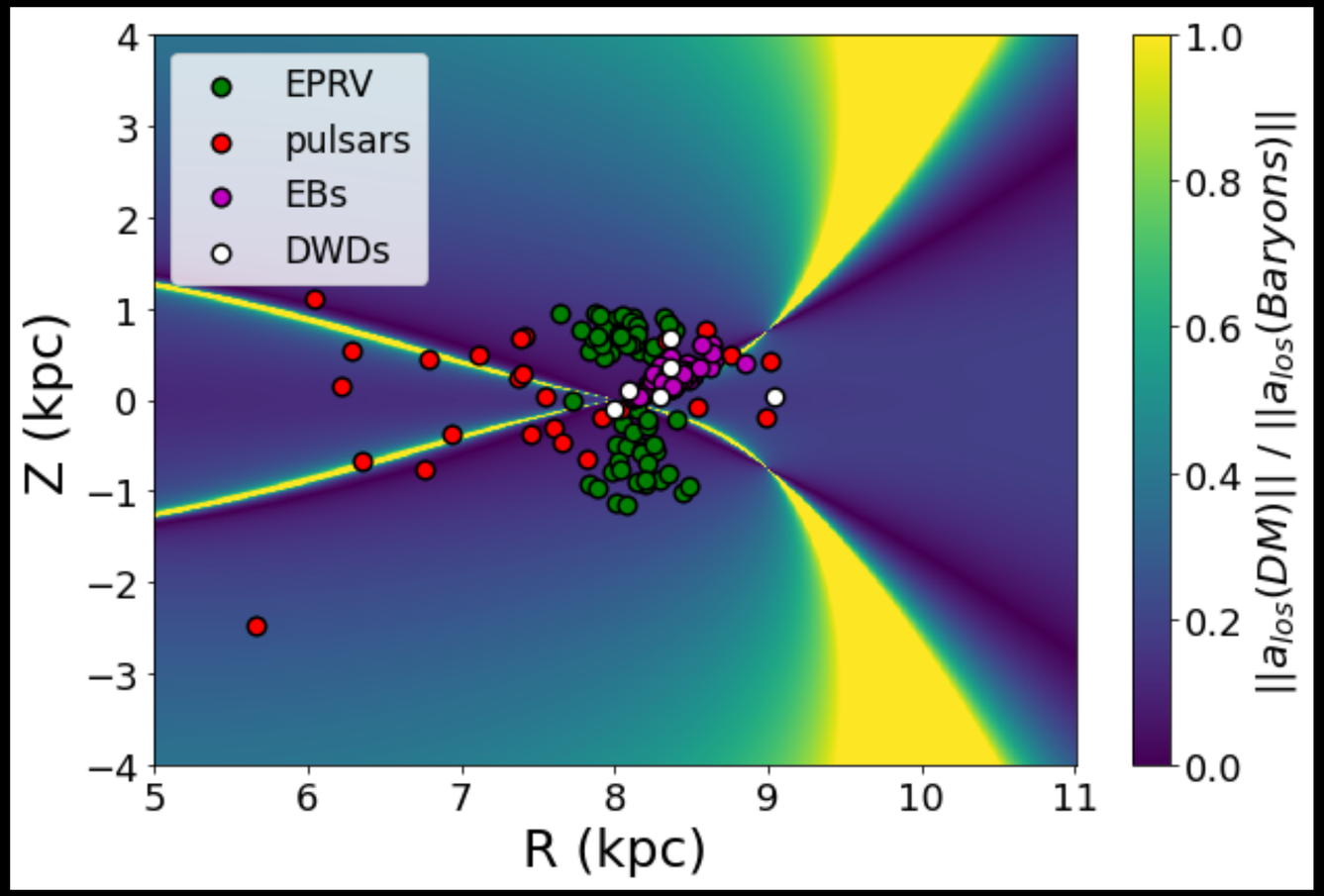


- Chakrabarti + HiPERCAM team, in prep

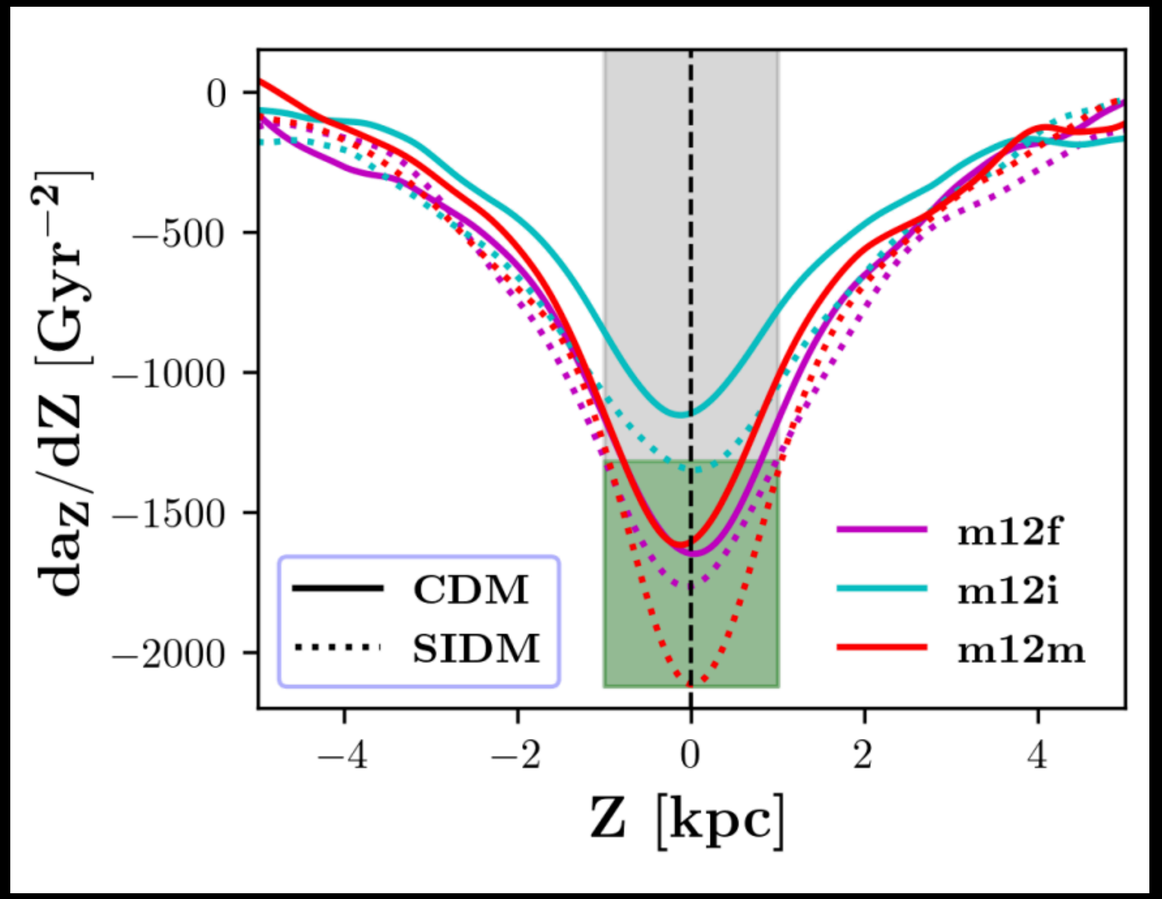




Ongoing work



Our accelerometers



Arora, Sanderson, Chakrabarti et al. 2024