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

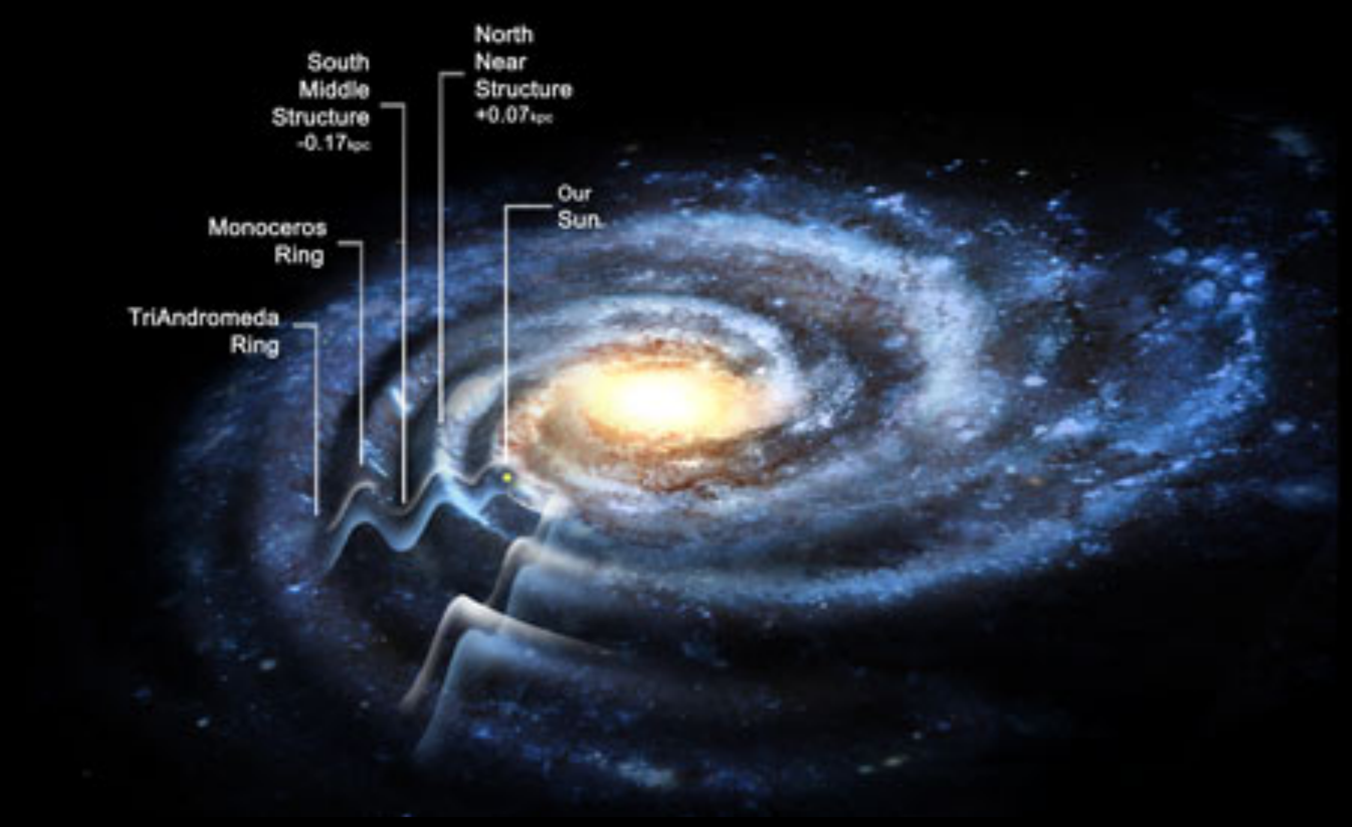
Sukanya Chakrabarti (UAH)

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
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

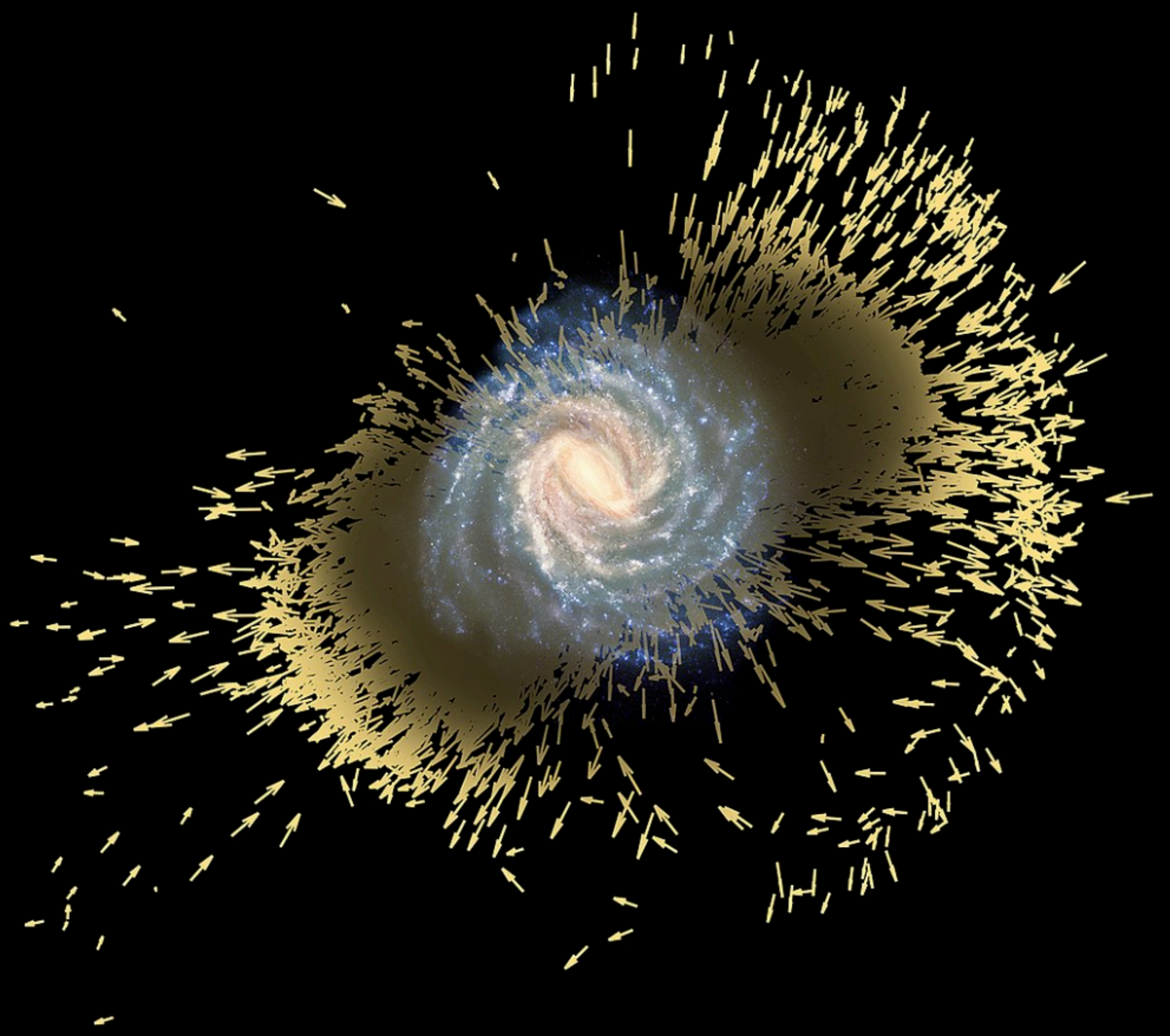
The dynamic Milky Way

Why direct measurements of the Galactic acceleration?

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

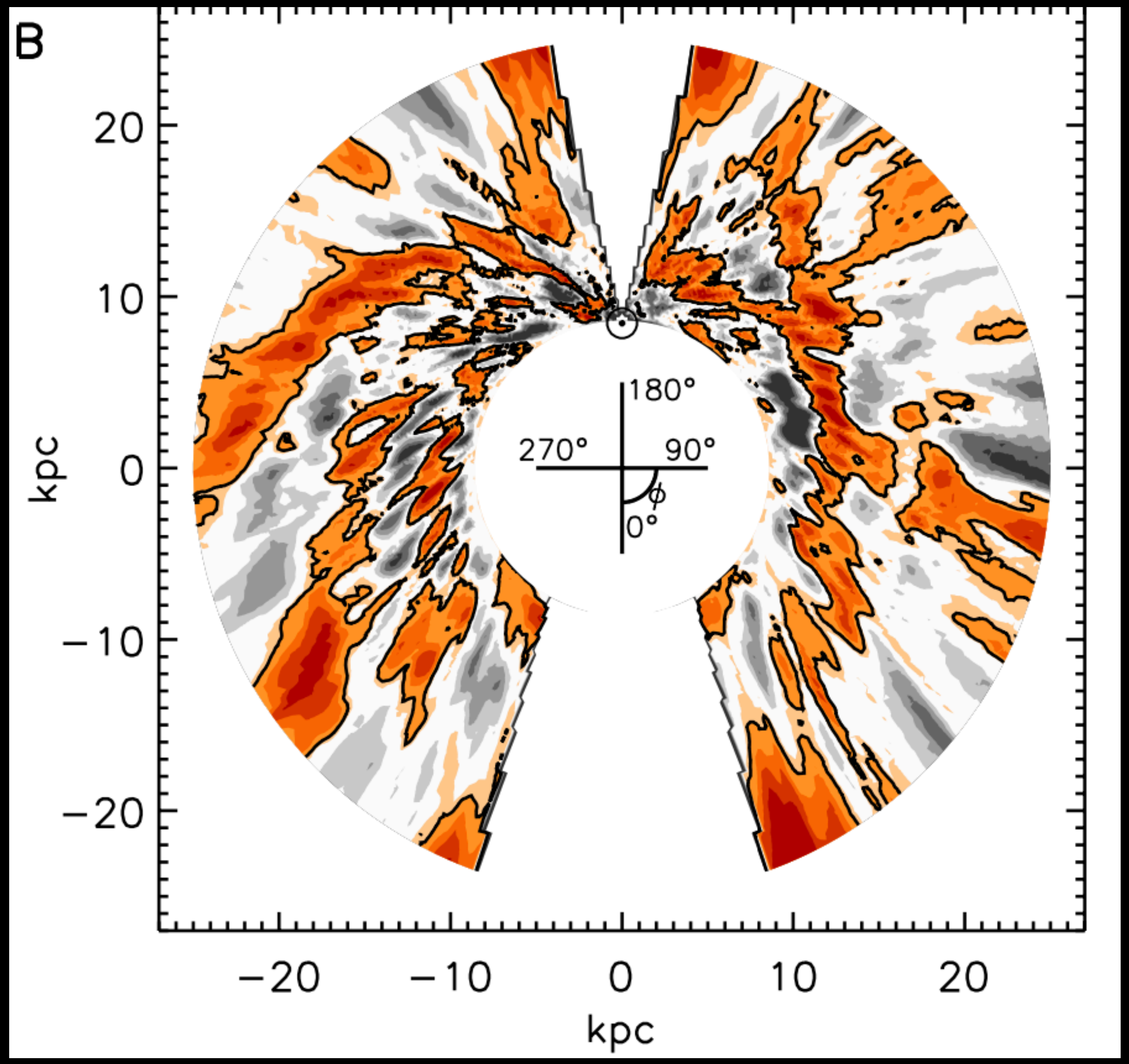


Xu et al. 2015; Widrow et al. 2012

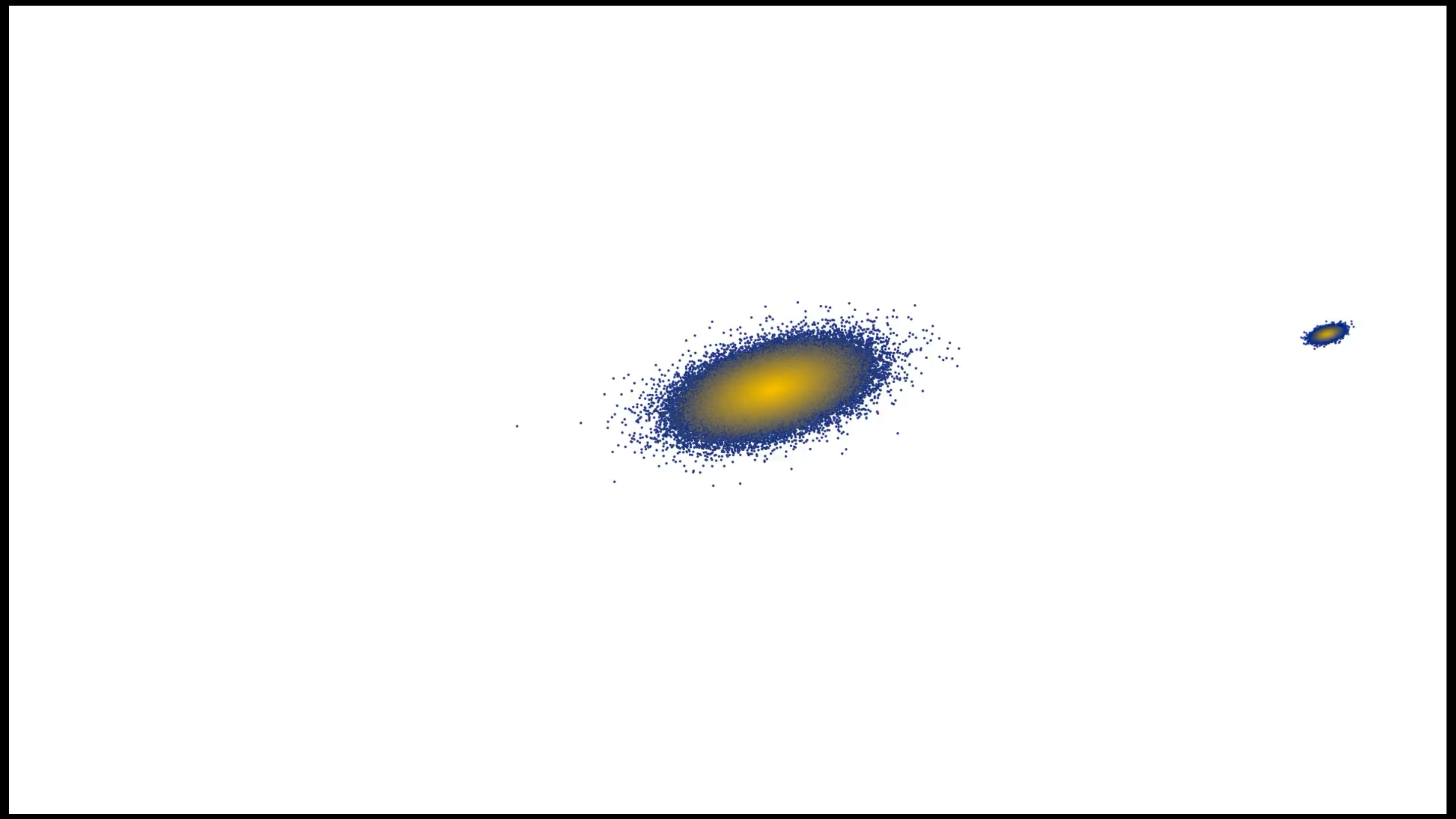


Helmi et al 2018; Belokurov et al 2018

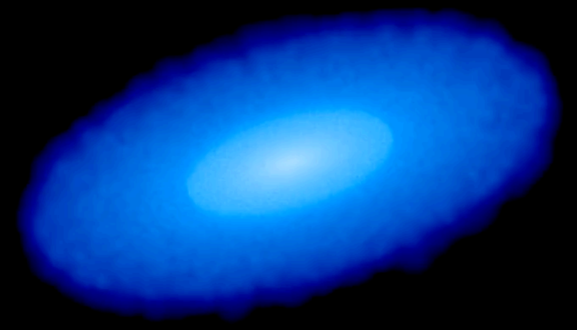
The dynamic Galaxy

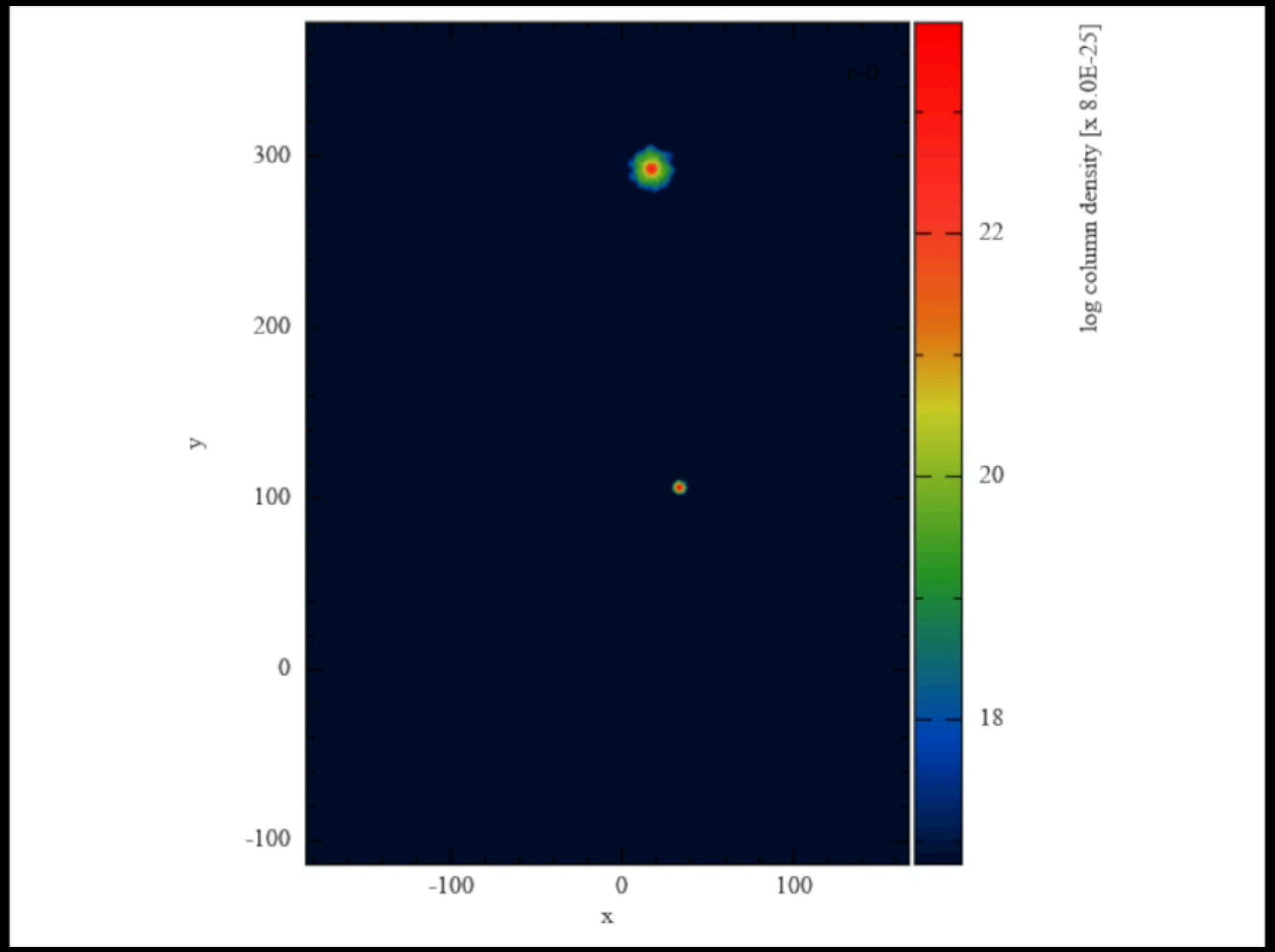


Levine, Blitz & Heiles 2006



Milky Way interaction with Antlia2 : Chakrabarti et al 2019; Chakrabarti & Blitz 2009





Craig, Chakrabarti et al., 2021

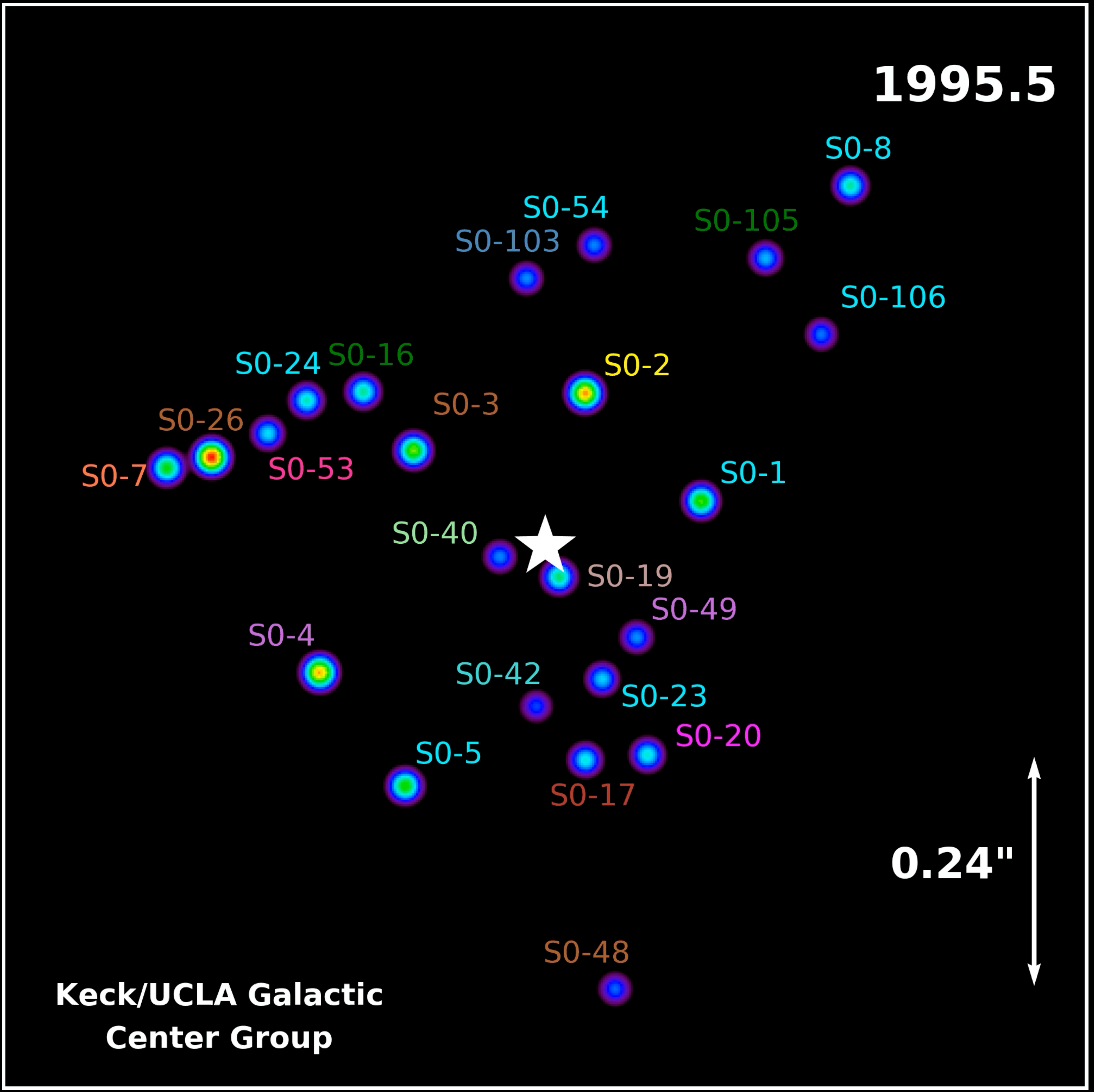
From phase-space (x,v) descriptors to acceleration measurements from extreme-precision time-series observations (x,dv/dt) :

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)

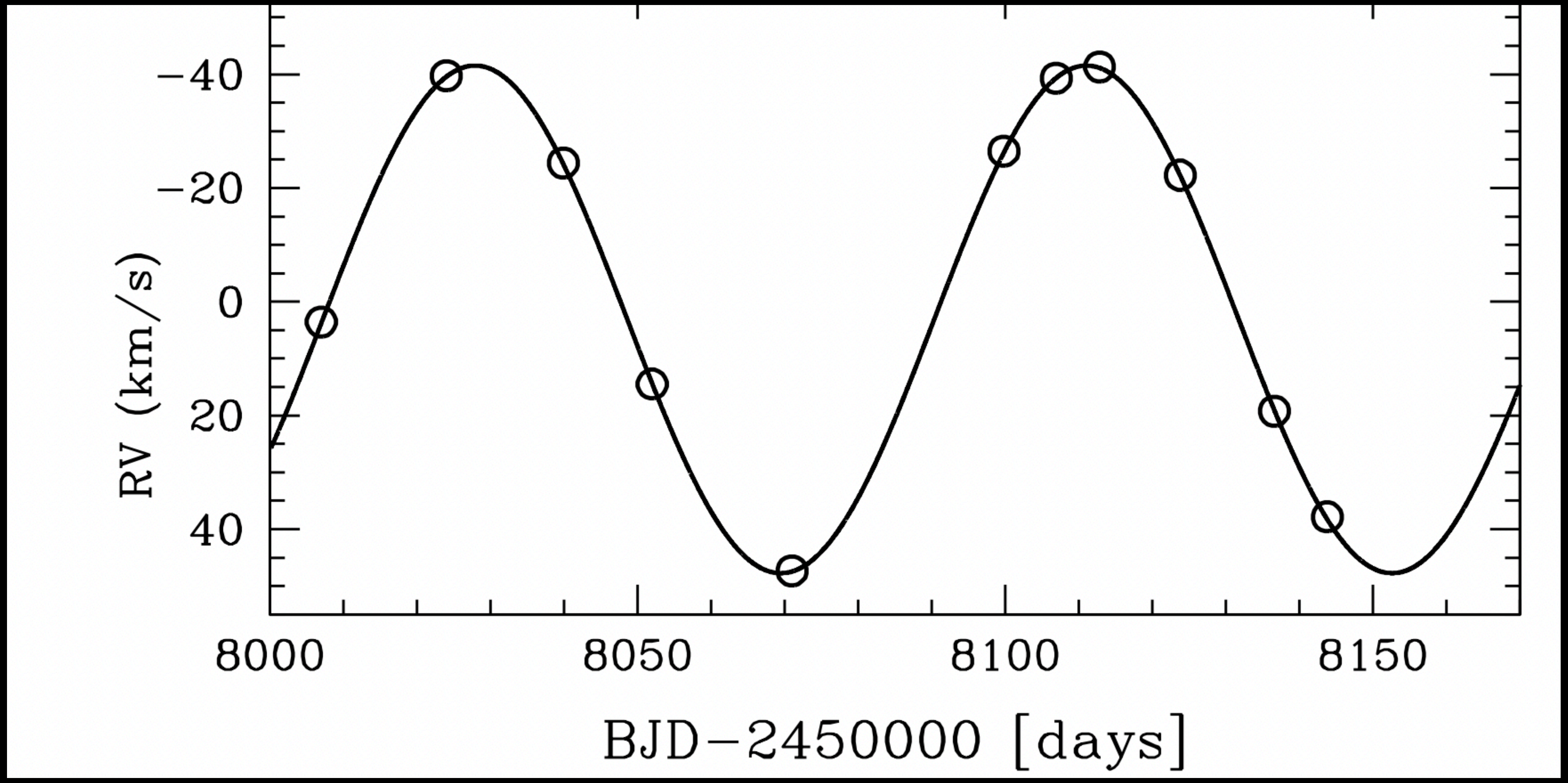

University of Wisconsin-Mil...
Binary White Dwarf
J0923+3028
Visible Star

Measured BIG accelerations

UCLA Galactic center

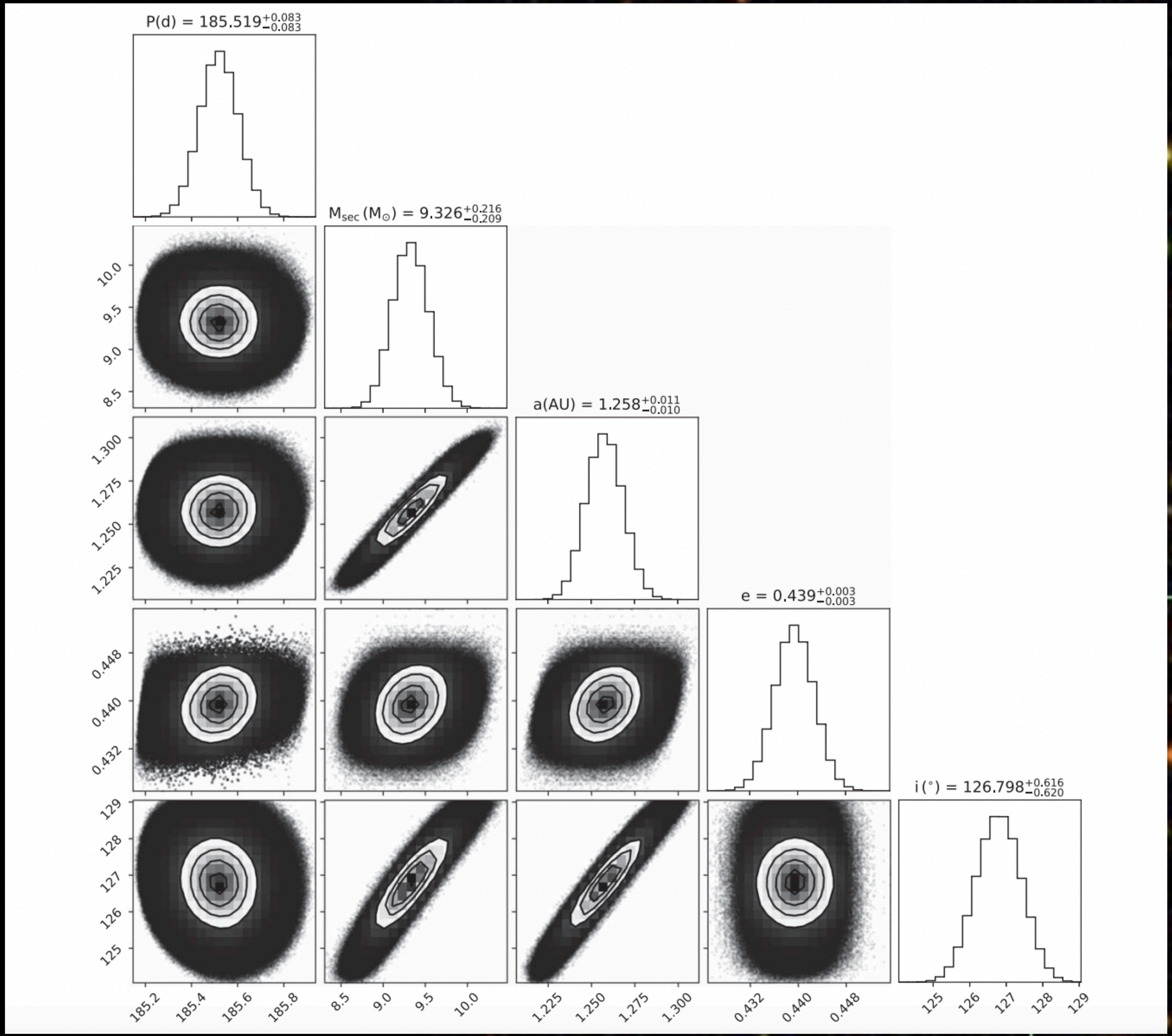


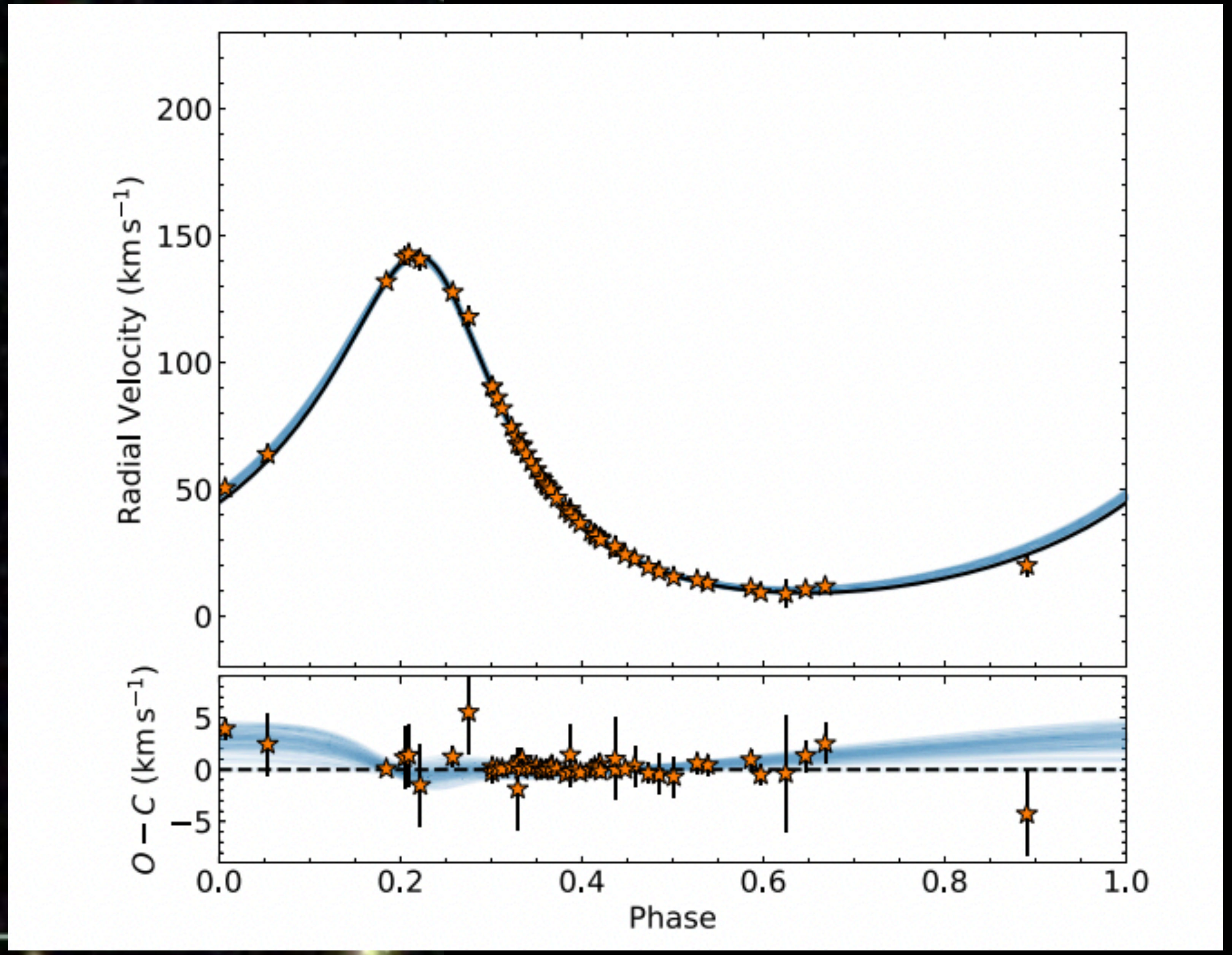
Ghez et al.++,
Genzel et al. ++

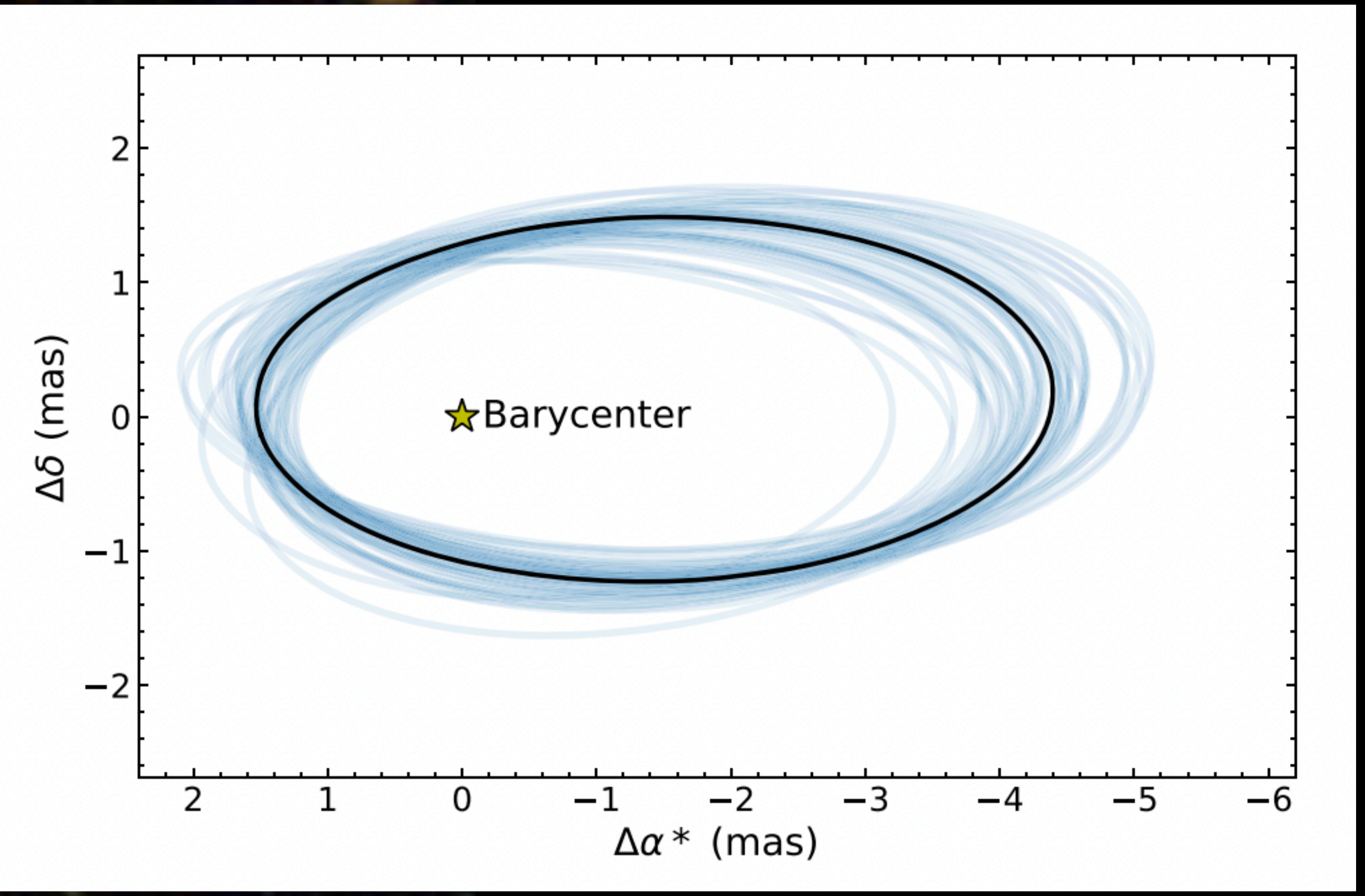


Black holes around luminous companions
(Thompson et al. 2019)

Stellar mass black hole from *Gaia* DR3



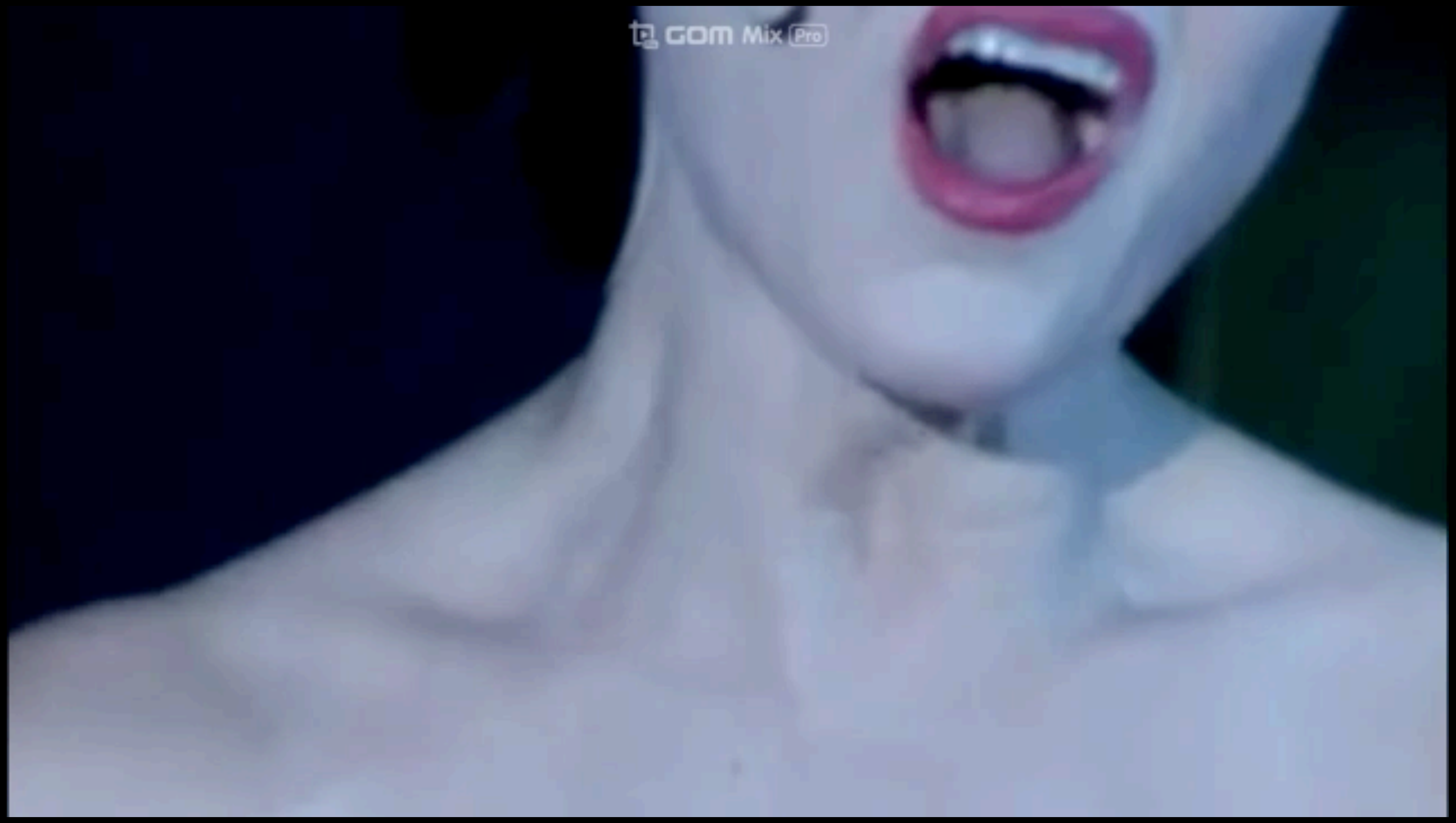




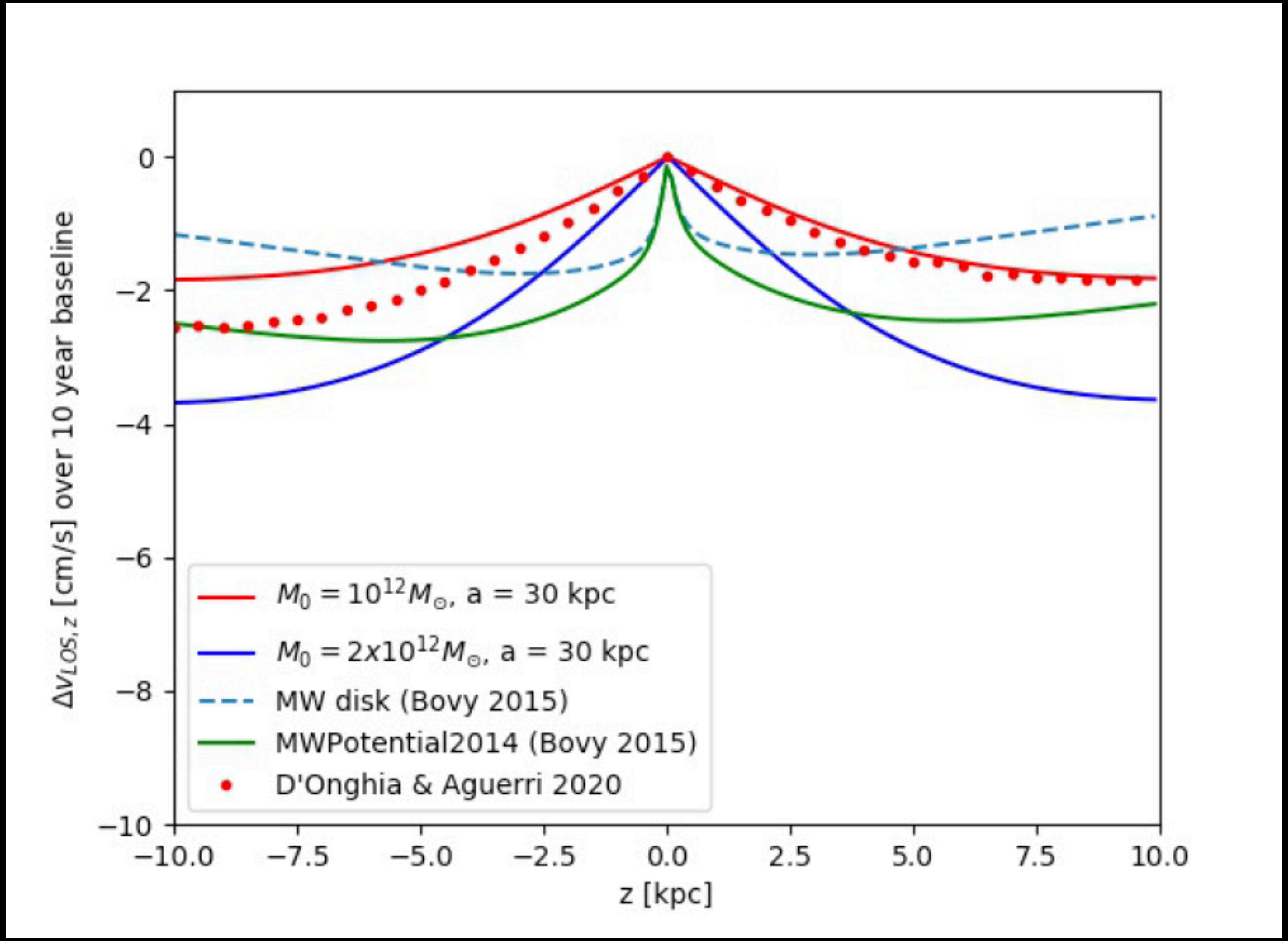
Chakrabarti, Simon, Craig et al. 2023 (see also El-Badry et al. 2023)

Outline: “real-time” Galactic dynamics

- High precision RV observations to measure the Galactic acceleration : requires ~ 10 cm/s precision (these accelerations << Galactic center accelerations)
- Pulsar timing measurements: the Oort limit & the local dark matter density : requires precision on $\dot{P}_b \sim 10^{-13}\ \mathrm{s}^{-1}$
- Eclipse timing measurements: requires precision on eclipse mid-point time of ~ 0.1s over decade baseline
- Angular accelerations - requires ~tens of nanoarcsecond precision (in prep) to constrain Galactic potential

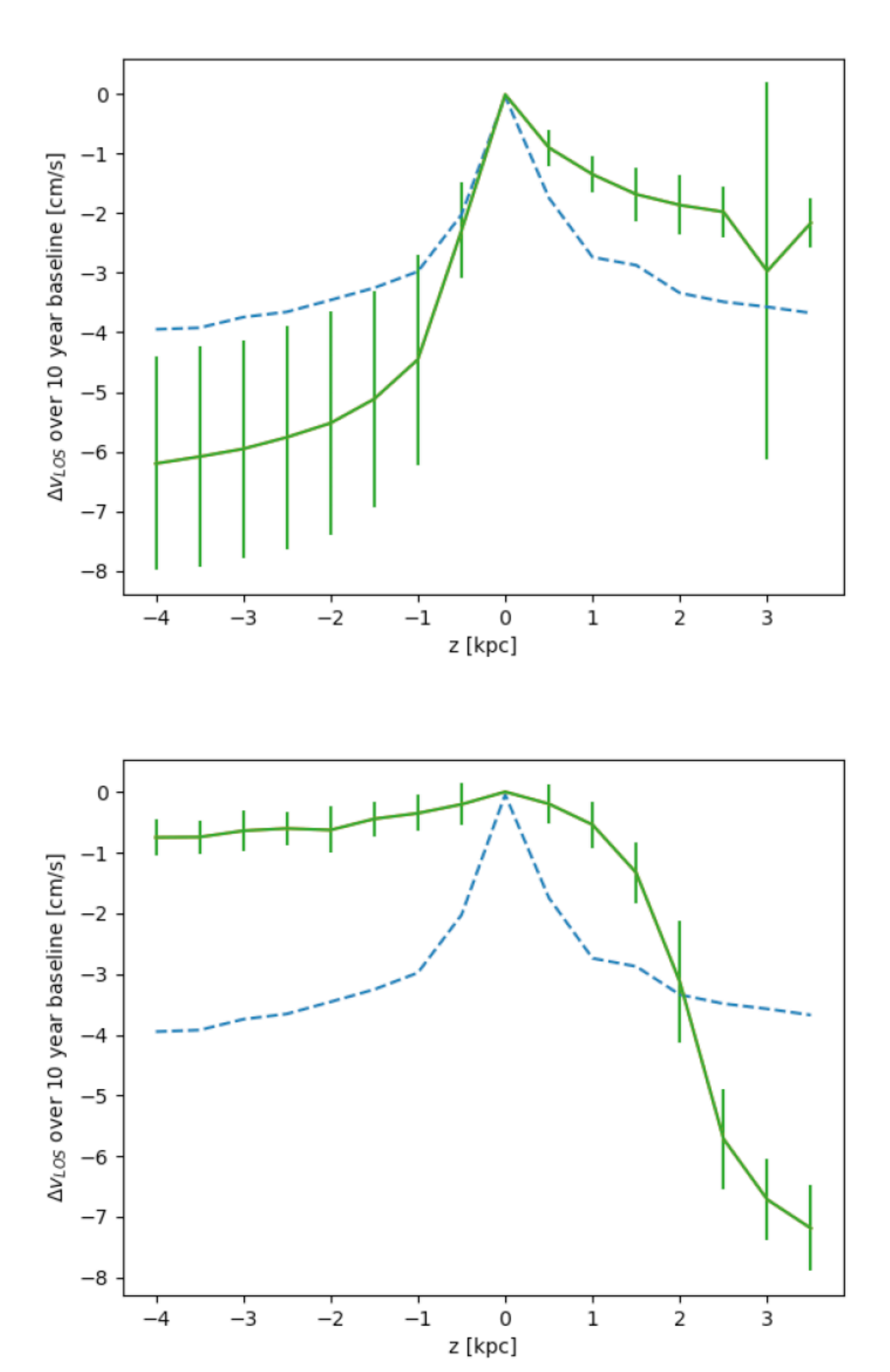


Acceleration profiles in static potentials



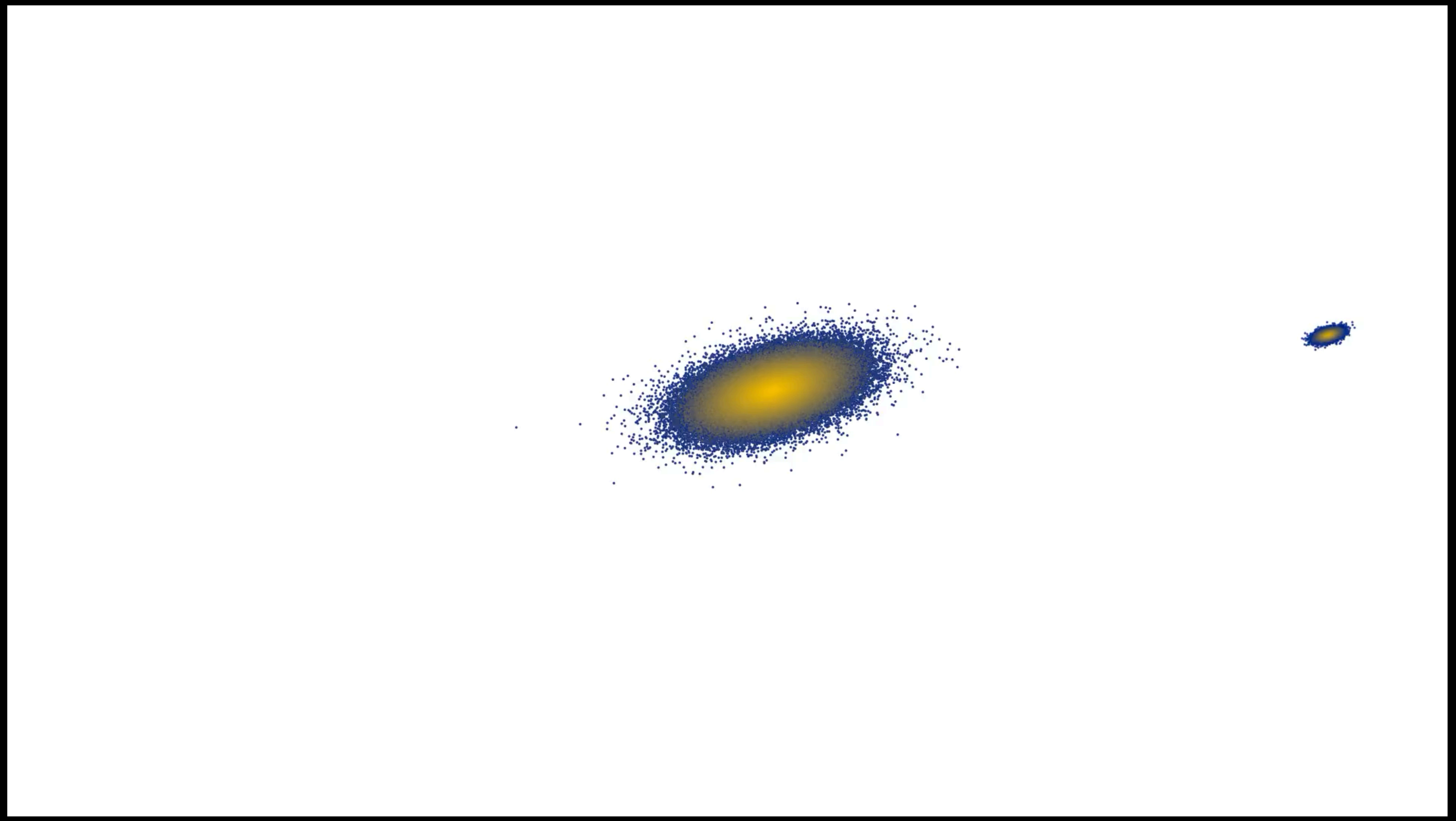
Chakrabarti, Wright, Chang, Quillen, Craig, Territo, D'Onghia, Johnston, de Rosa, Rhode & Nielsen 2020

Acceleration profiles in interacting simulations



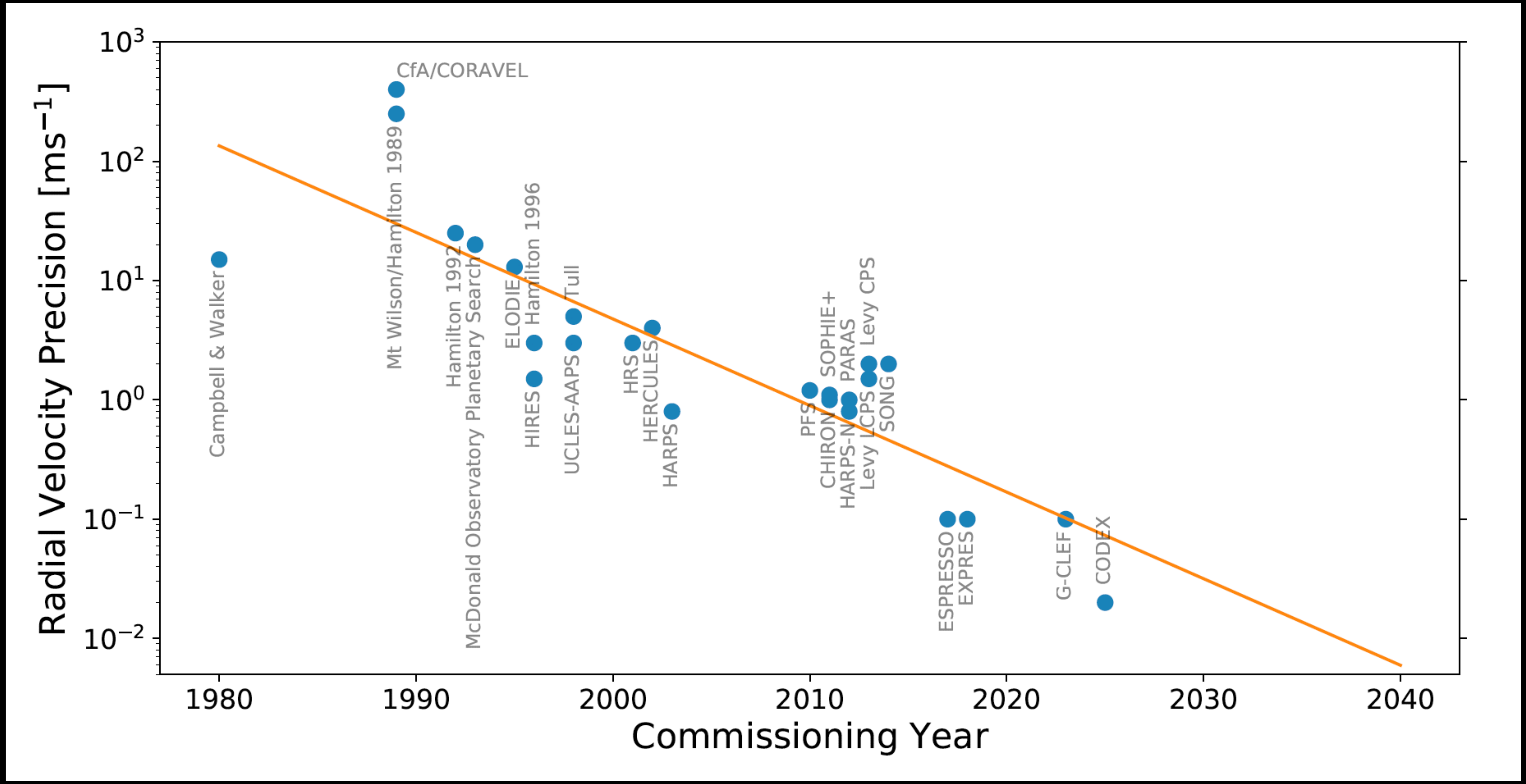
Antlia 2

Sgr dwarf



Chakrabarti et al. (2020) - dwarf galaxy orbits from Gaia proper motions

Extreme-precision radial velocity observations

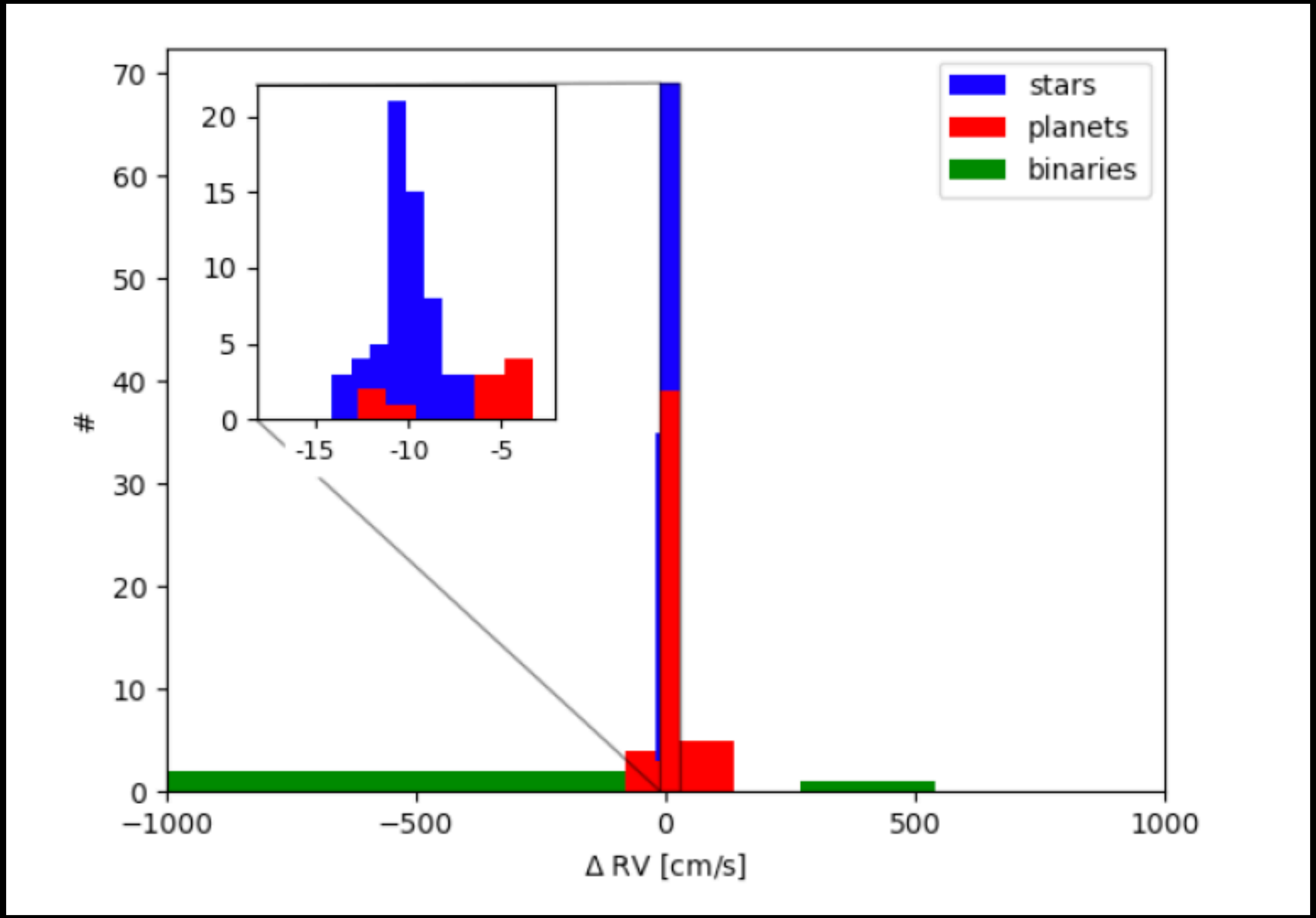


Wright & Robertson 2017; Silverwood & Easther (2019)

Contaminants to the Galactic signal:

- **External** : Stellar binaries & planets
- **Internal** - stellar jitter : sub-giants as compromise between bright stars and fainter, low-jitter dwarfs.

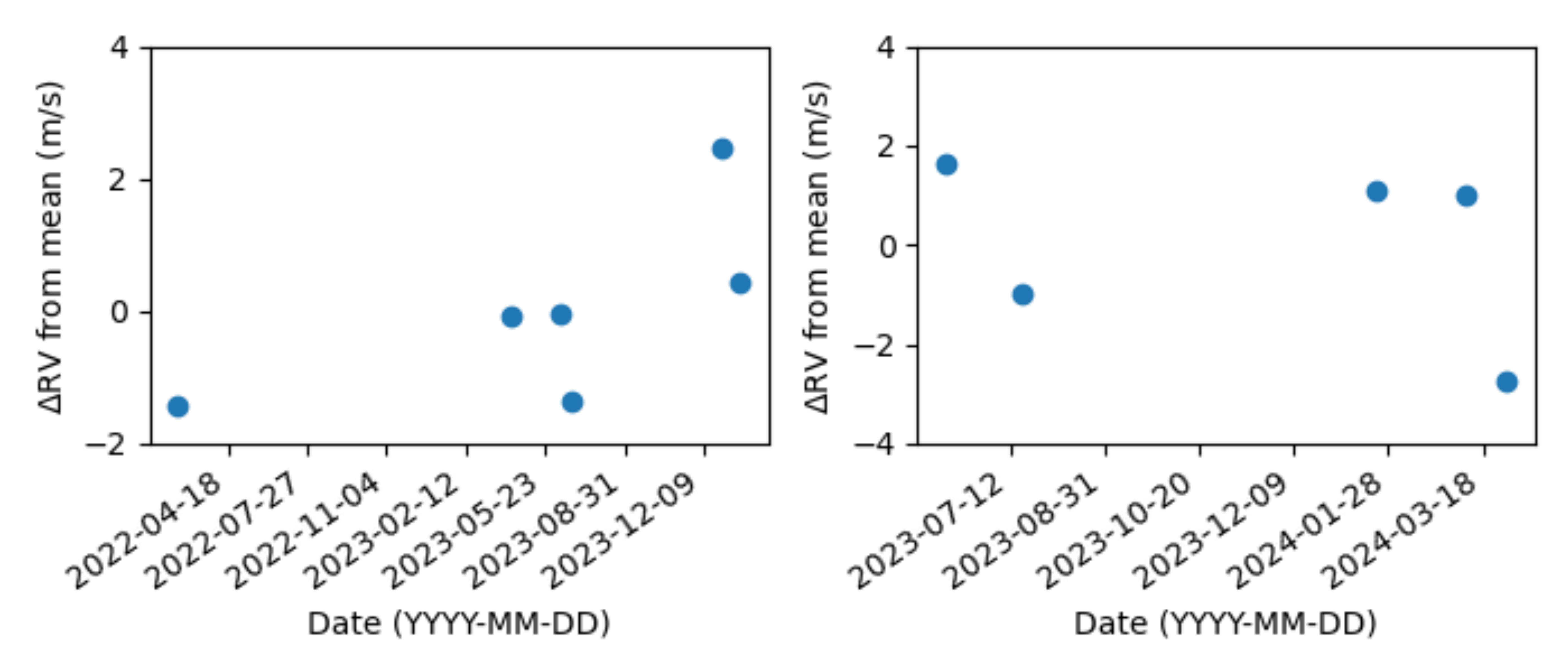
External contaminants - population synthesis model



Chakrabarti et al. 2020 : low-mass, long-period planets are a contaminant but their contribution to the Galactic signal is very small. Can reject null hypothesis that signal is due to stars with planets at high confidence.

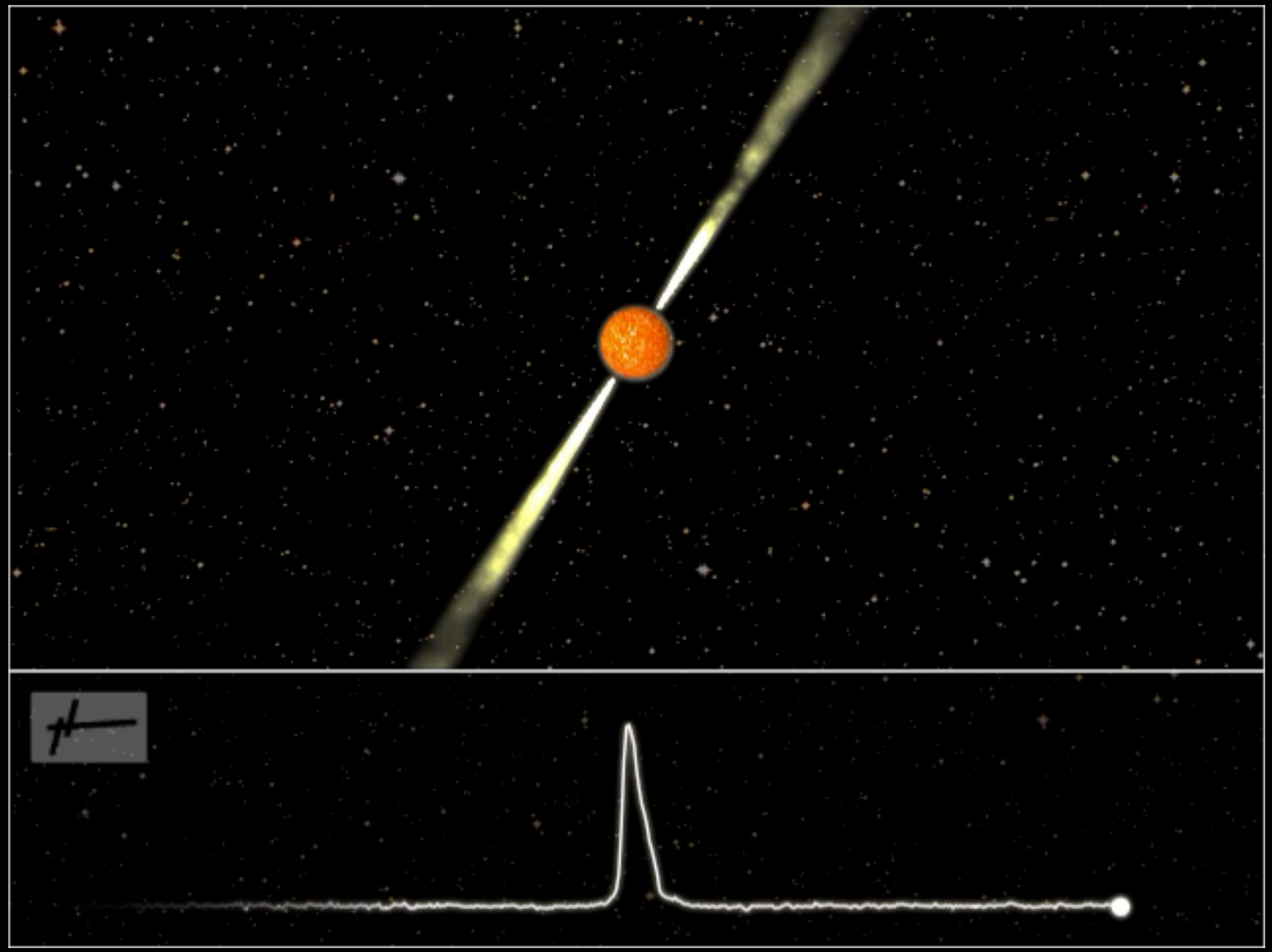
Finding the quietest stars

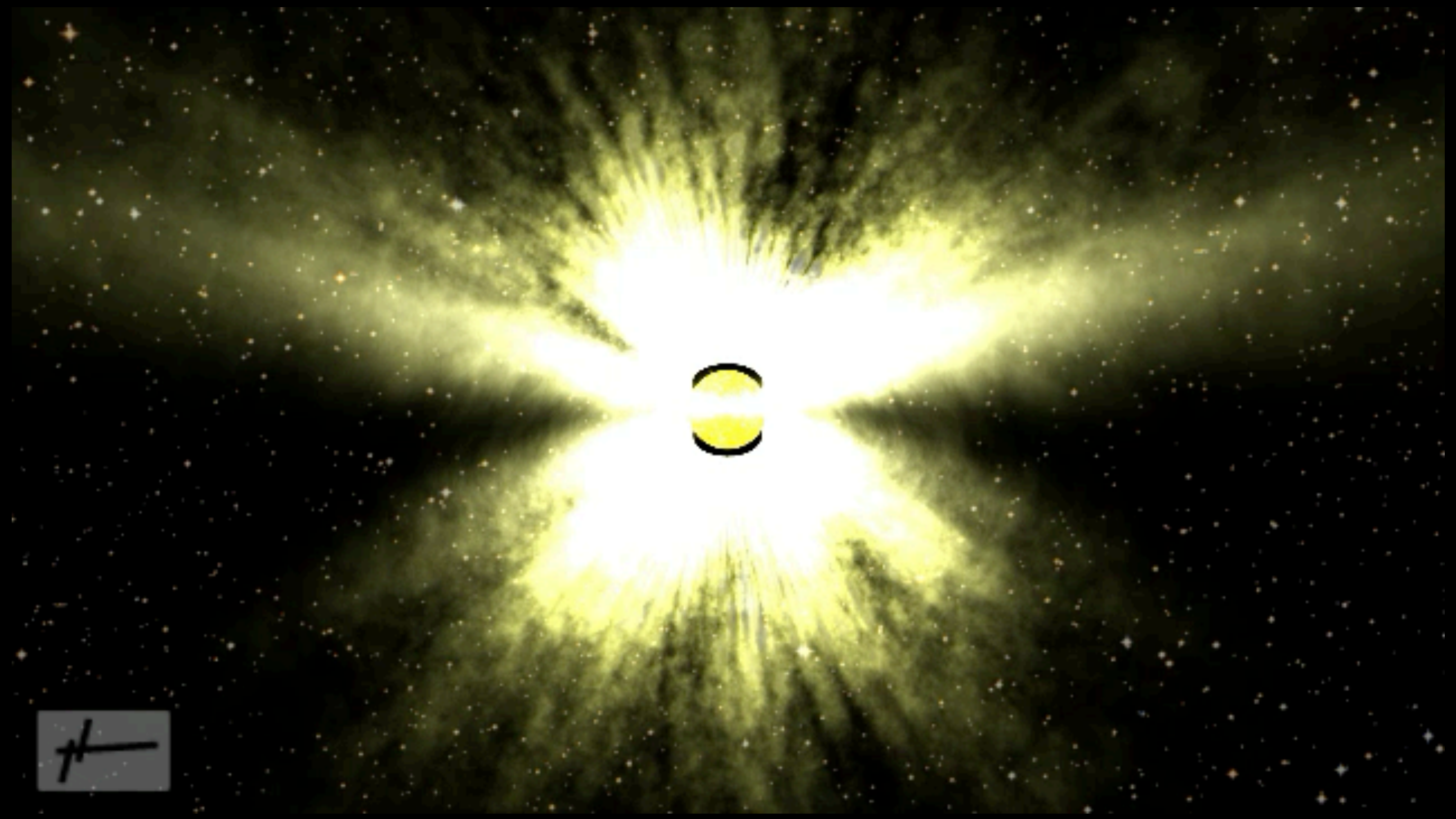
ESPRESSO spectra (PI: Chakrabarti)



Galactic acceleration from pulsar timing

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





Credit: "Joeri van Leeuwen"

Basic setup

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

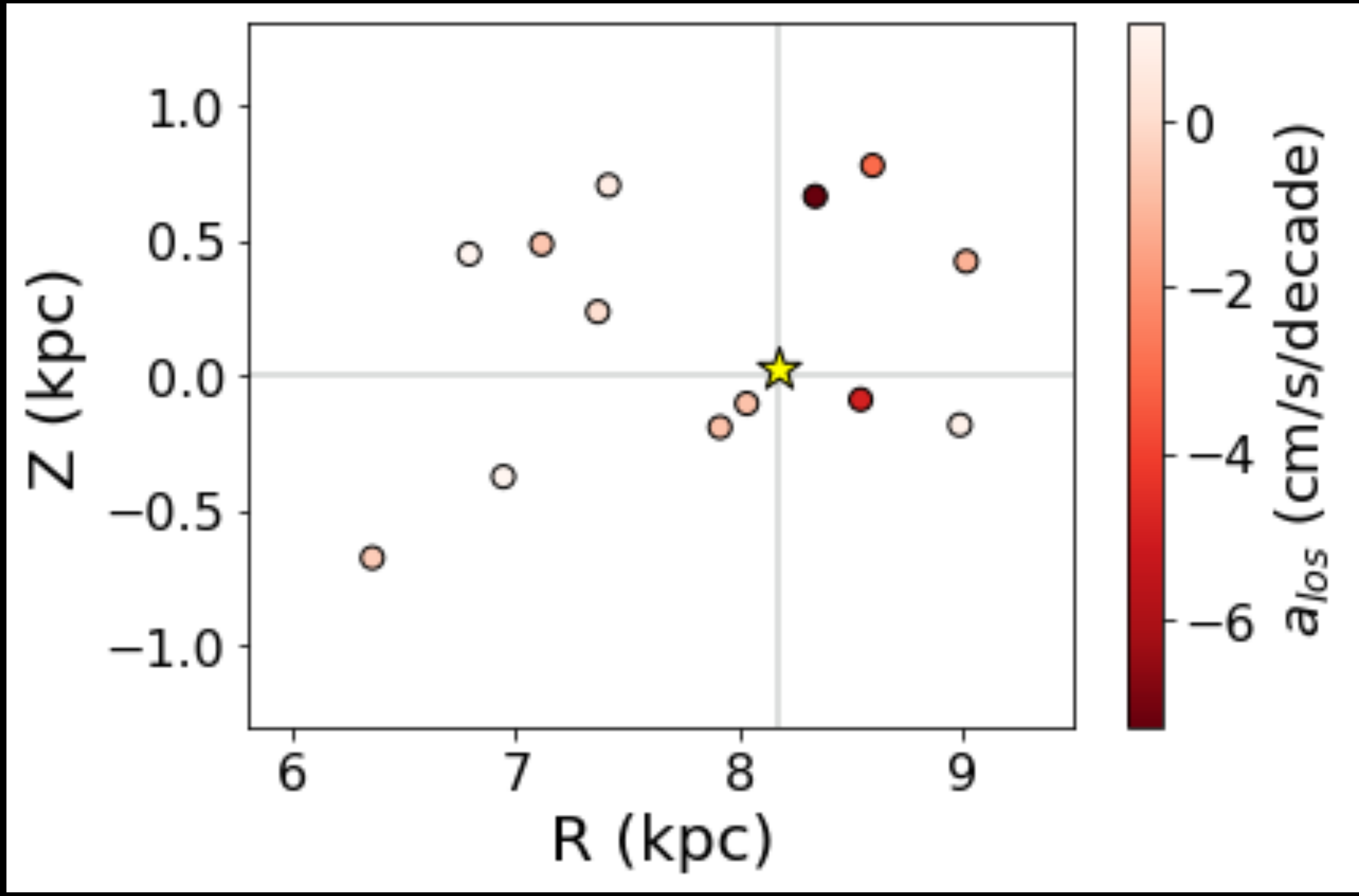
$$\dot{P}_b^{Shk} = \frac{P_b \mu^2 * d}{c^2}$$

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)

A simple example



Chakrabarti et al. 2021

$$\Phi(r, z) = \Phi(r) + \Phi(z)$$

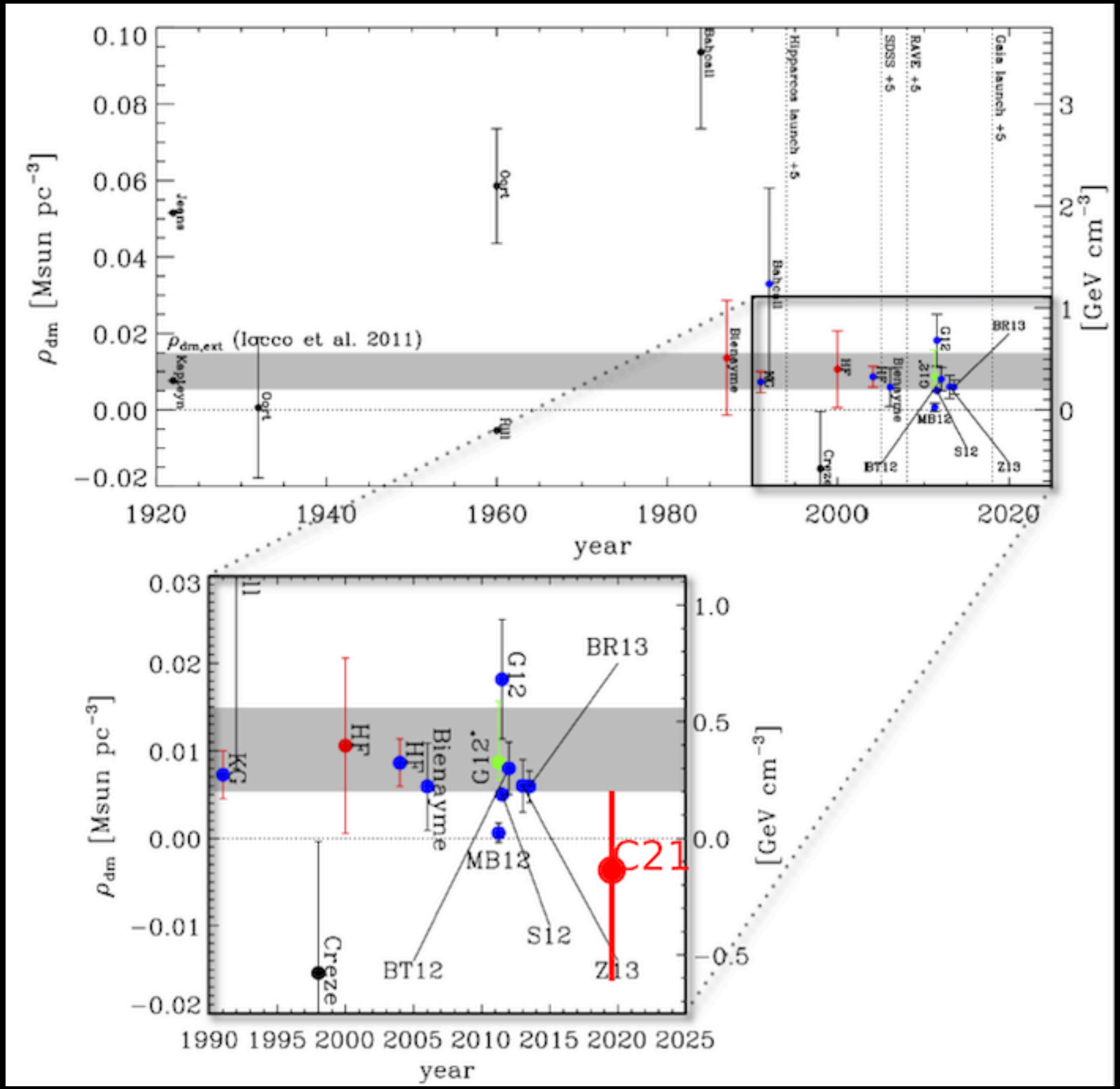
$$\Phi_r = \begin{cases} V_{LSR}^2 \ln\left(\frac{r}{R_\odot}\right) & \text{for} \quad \beta = 0 \\ \frac{V_{LSR}^2}{2\beta}\left(\frac{r}{R_\odot}\right)^{2\beta} & \text{for} \quad \beta \neq 0. \end{cases}$$

$$\Phi(z) = \frac{1}{2}\alpha_1 z_g^2$$

$$\nu^2 = \left.\frac{d^2\Phi_z(z)}{dz^2}\right|_{z=0} = 4\pi G\rho_0 - 2\beta\Omega_\odot^2$$

$$\beta = 0 : \quad \alpha_1 = 4\pi G\rho_0$$

Best-fit parameters & Oort limit from pulsar timing



Oort limit (total mid-plane density)

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

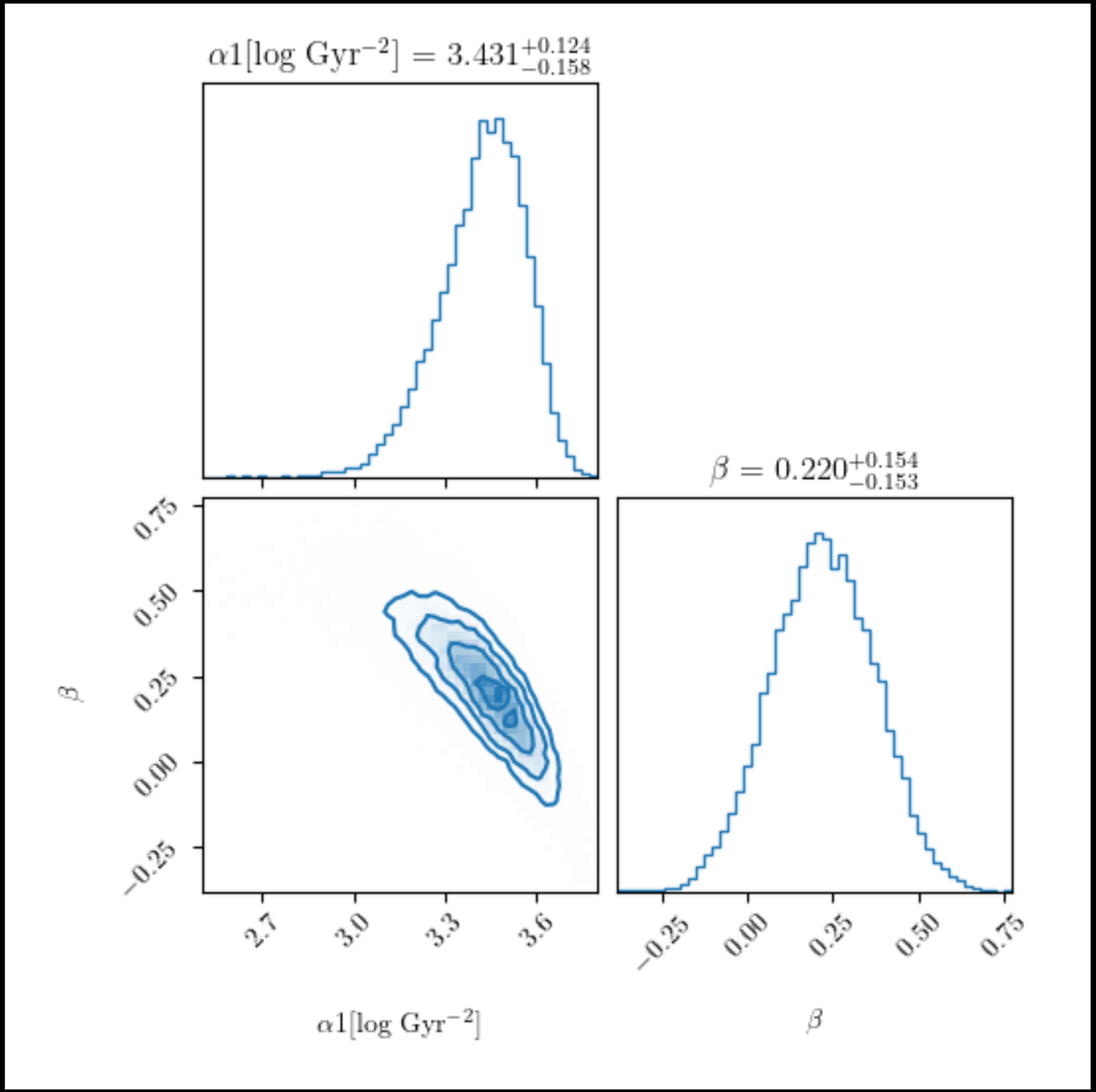
With baryon density from Bienyame et al. 2015:

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

- Oblateness traces disk

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

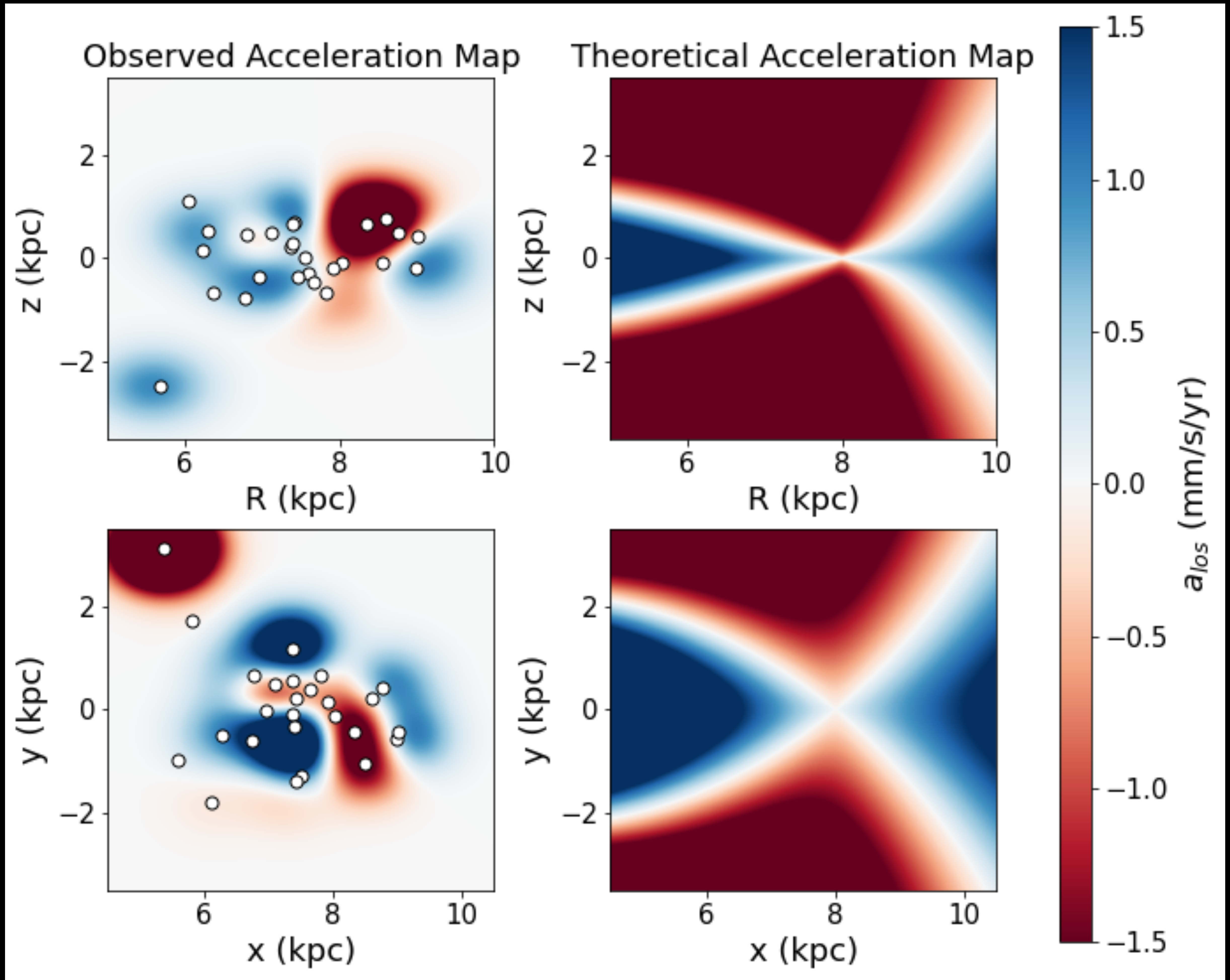
Expanded pulsar timing sample



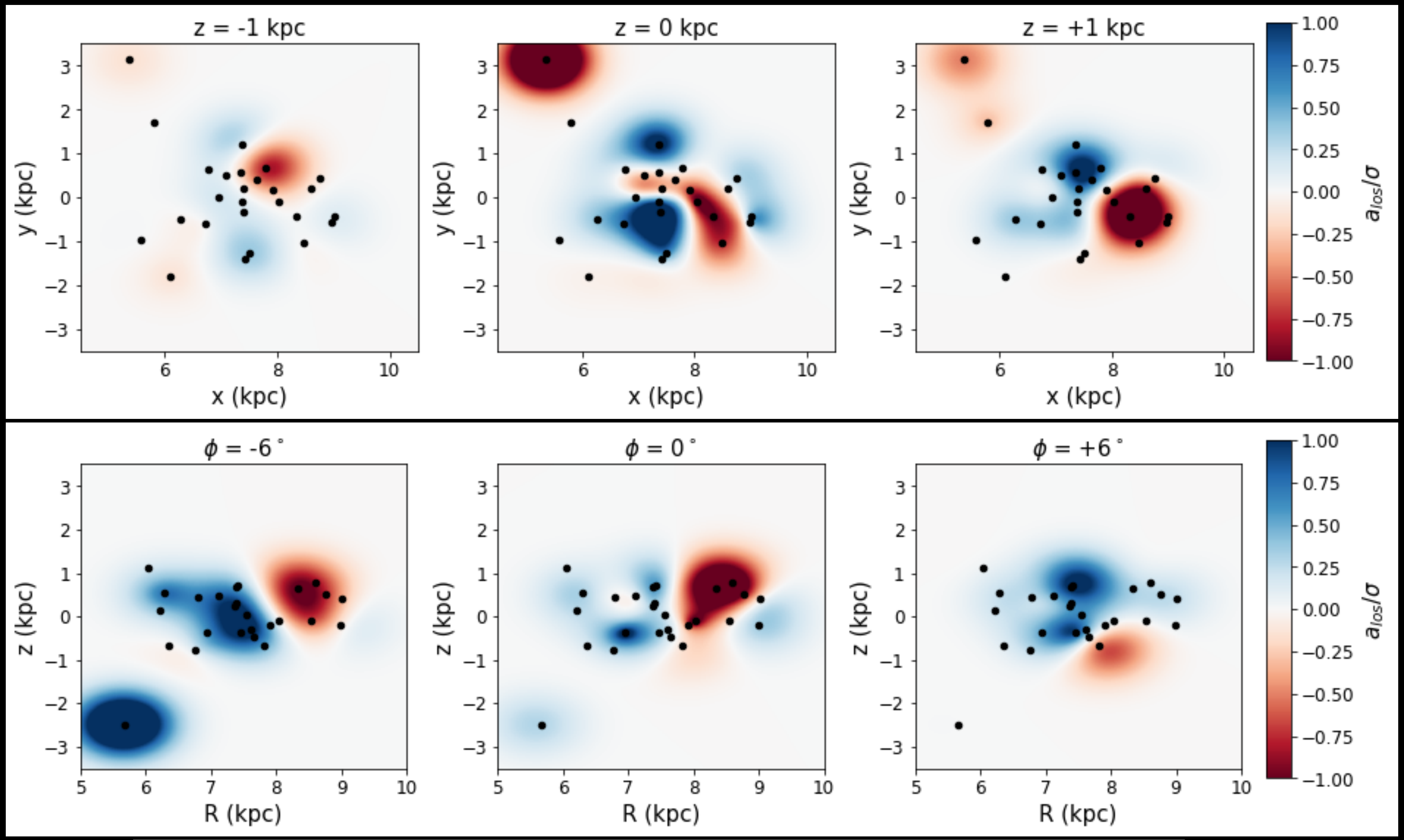
Donlon, Chakrabarti, Widrow, Lam, Chang & Quillen 2024 (total of 26 pulsars, with improved uncertainties).

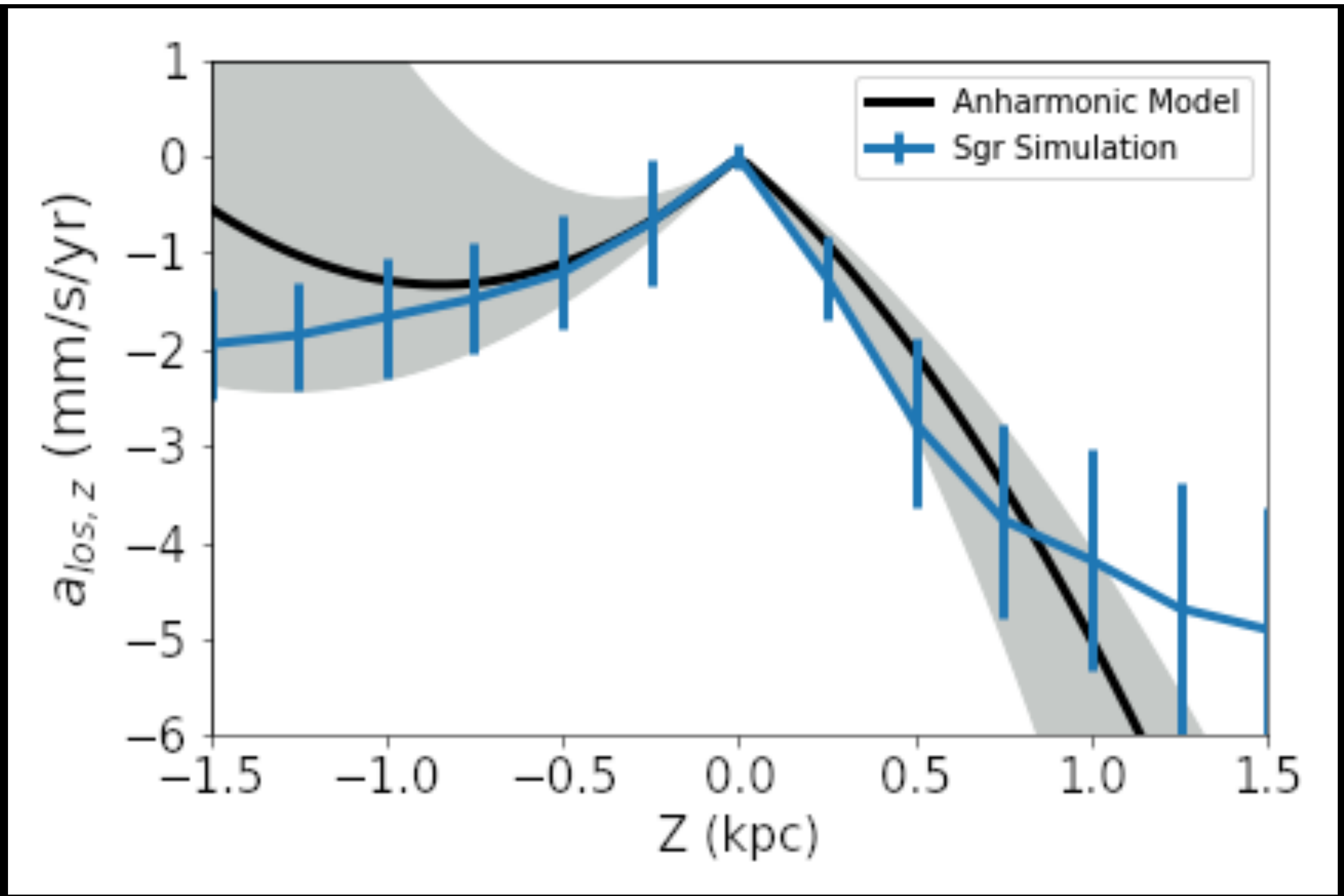
Constraint on rotation curve (-2 +/- 5 km/s/kpc) & Oort constants (A = 15.4 +/- 2.6 km/s/kpc, B = -13.1 +/- 2.6 km/s/kpc), comparable with Gaia values.

Beyond a smooth model



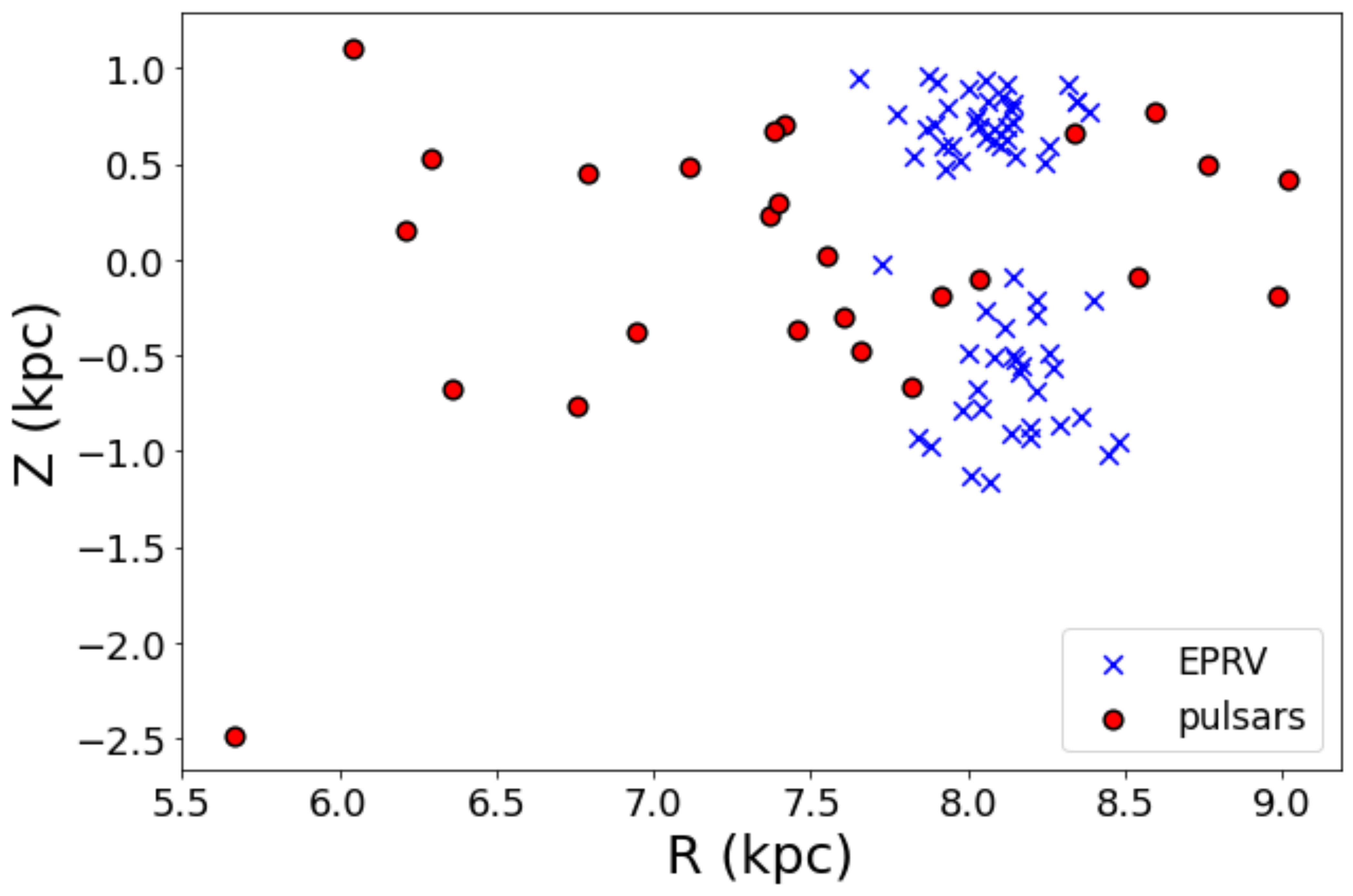
Donlon et al. 2024





Future work — from smooth accelerations to measuring "jerks" in the acceleration

Extreme precision RV sample ESPRESSO (PI: Chakrabarti, with Rob de Rosa, Jack Wagner, Jason Wright et al.).



Bullock & Boylan-Kolchin 2017

Eclipse timing

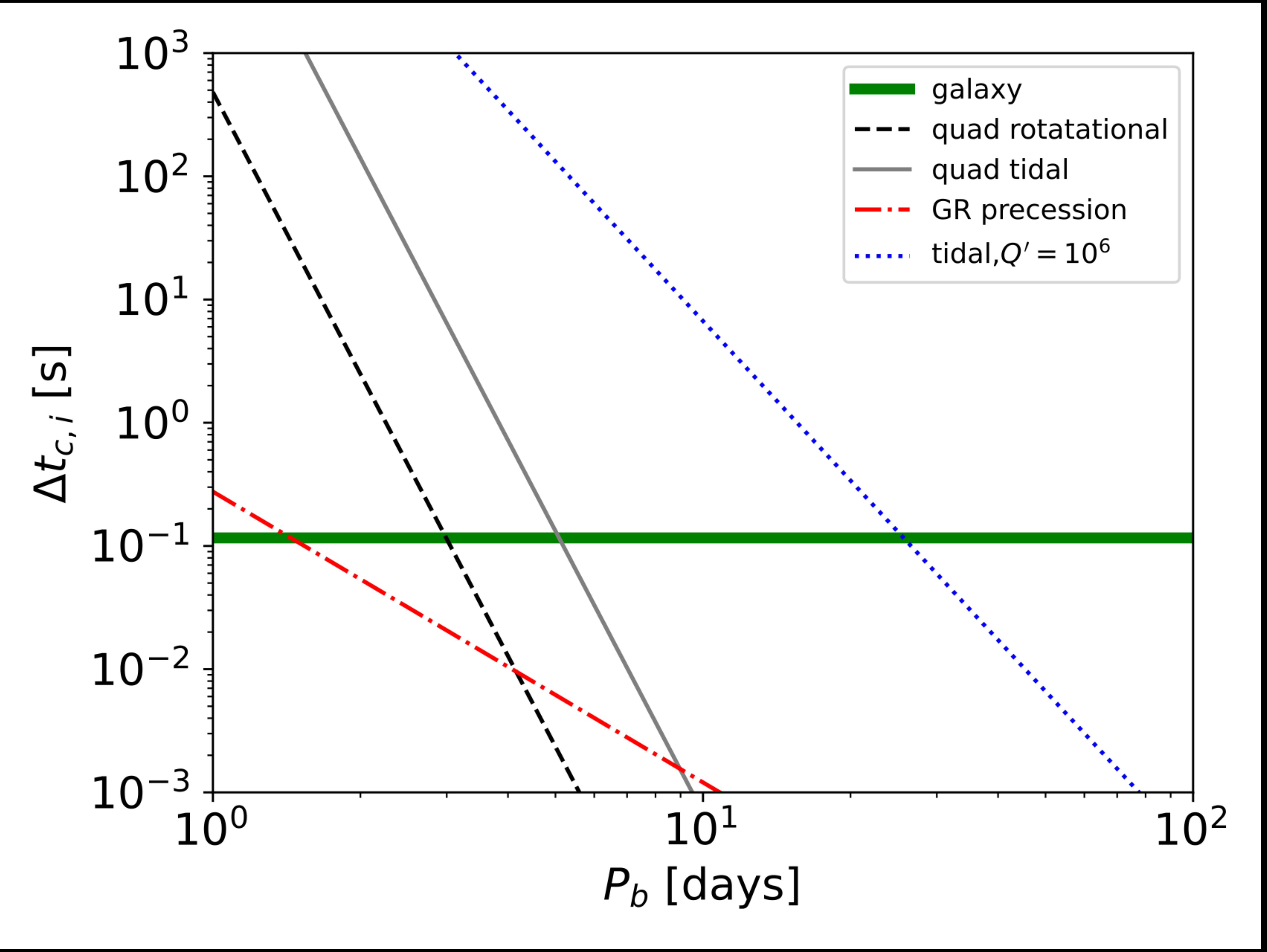
- Measure Galactic acceleration from shift in eclipse mid-point time over decade baseline ~ 0.1s.
- Requires very high (space-based) photometric precision
- It's been about a decade since Kepler!

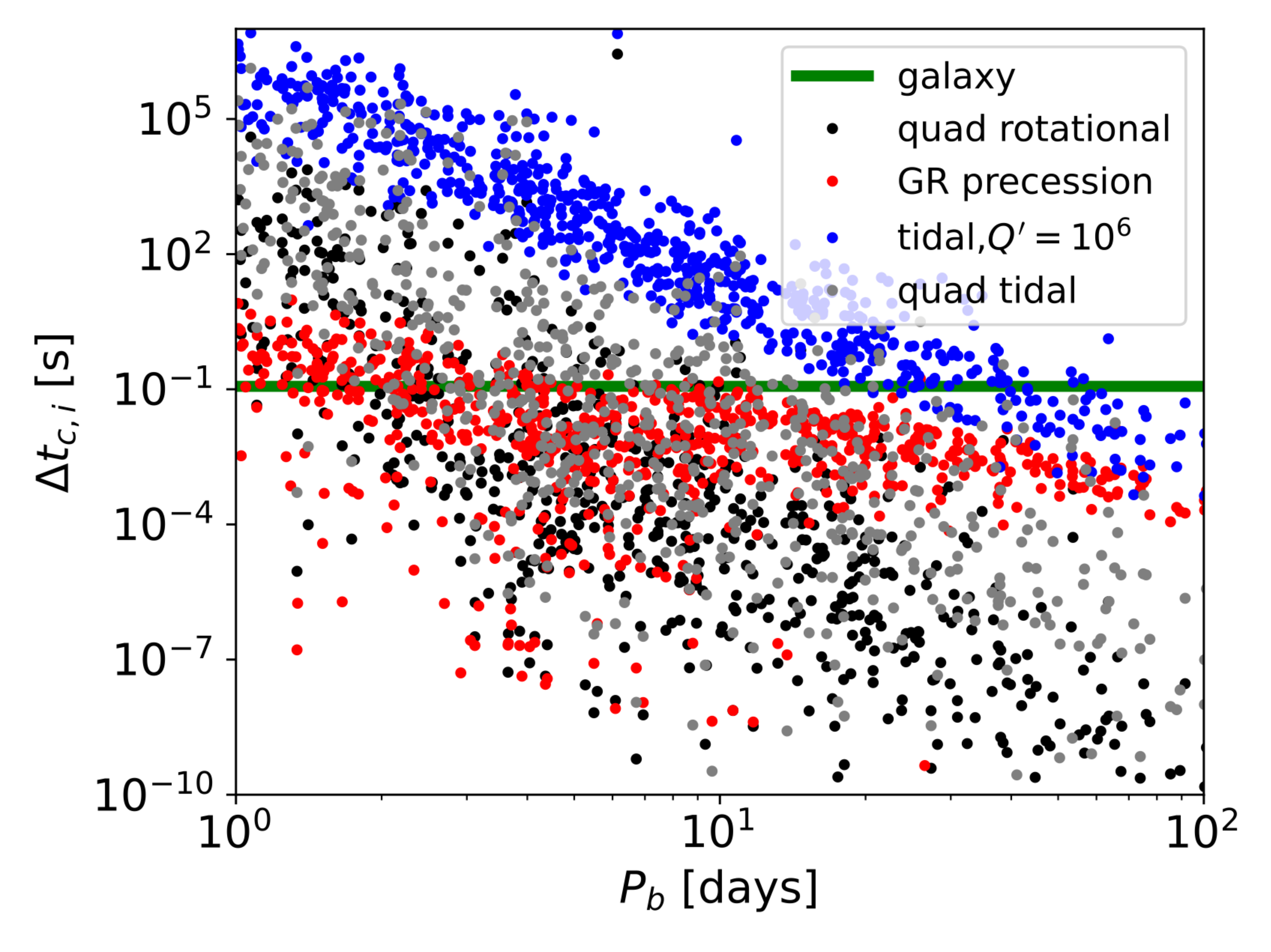
$$\Delta t_{c,Gal} = \frac{\dot{P}_{b,Gal}}{P_b} T^2$$

Contaminants to the Galactic signal

$$\dot{P}_b^{obs} = \dot{P}_b^{Gal} + \dot{P}_b^{Shk} + \dot{P}_b^{GR} + \dot{P}_b^{\mathrm{tidal}} + \dot{P}_b^{\mathrm{quad/rot}} + \dot{P}_b^{\mathrm{quad/tidal}} + \dot{P}_b^{\mathrm{pl}}$$

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

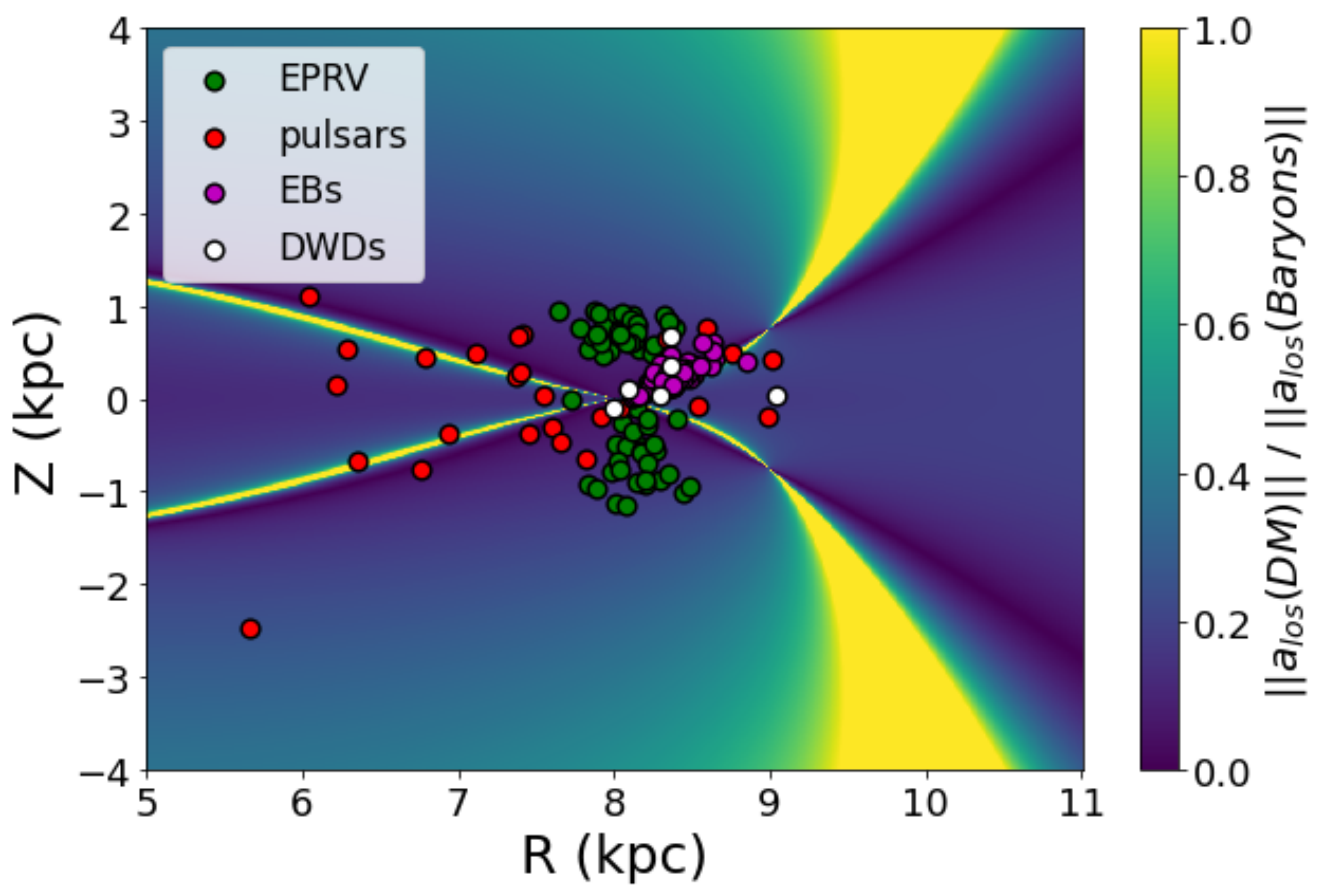




Chakrabarti, Stevens, Wright, Rafikov, Chang, Beatty & Huber 2022 (main-sequence EBs with HST: 2024 onwards)

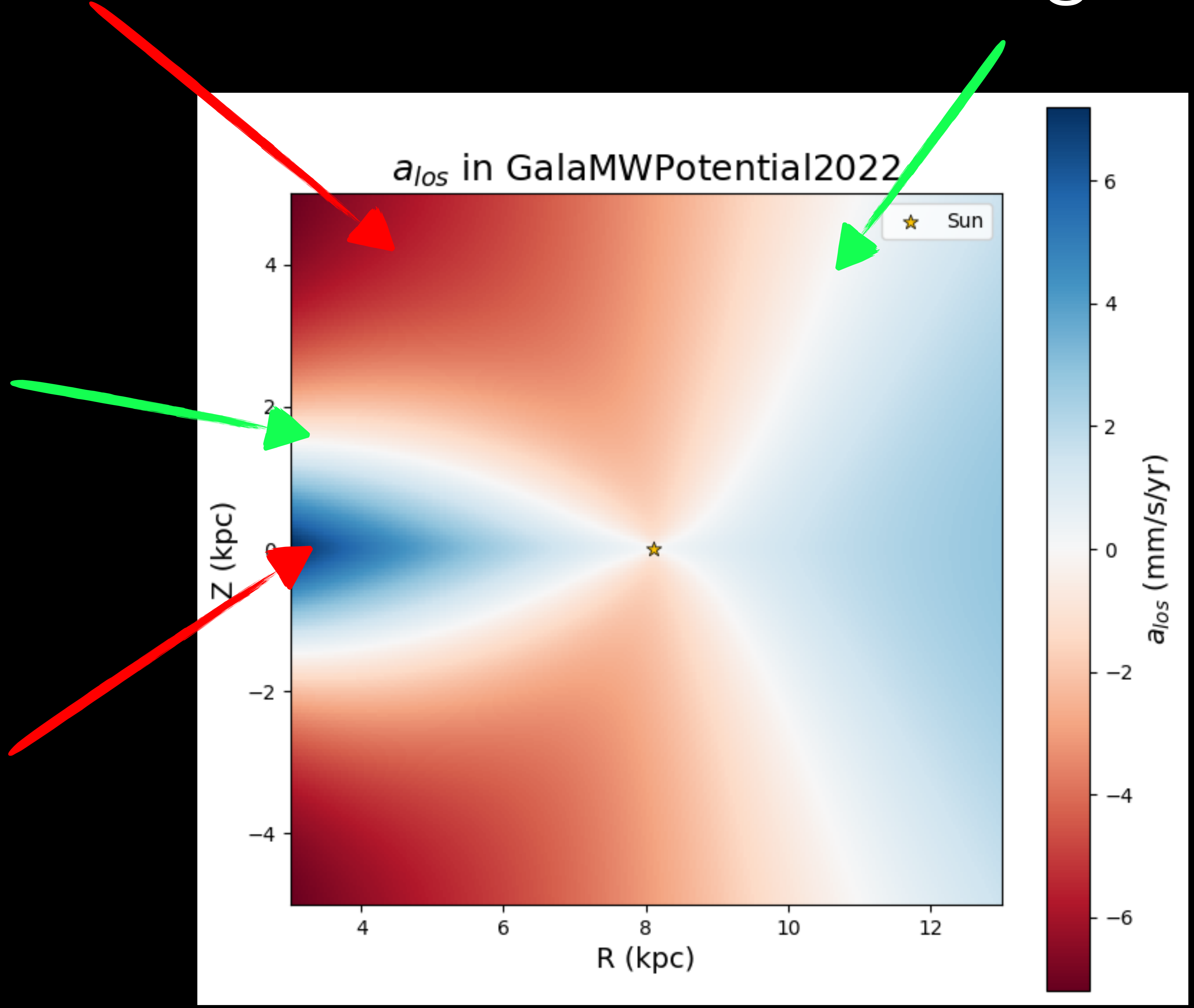
Accelerometers - ongoing observing campaigns

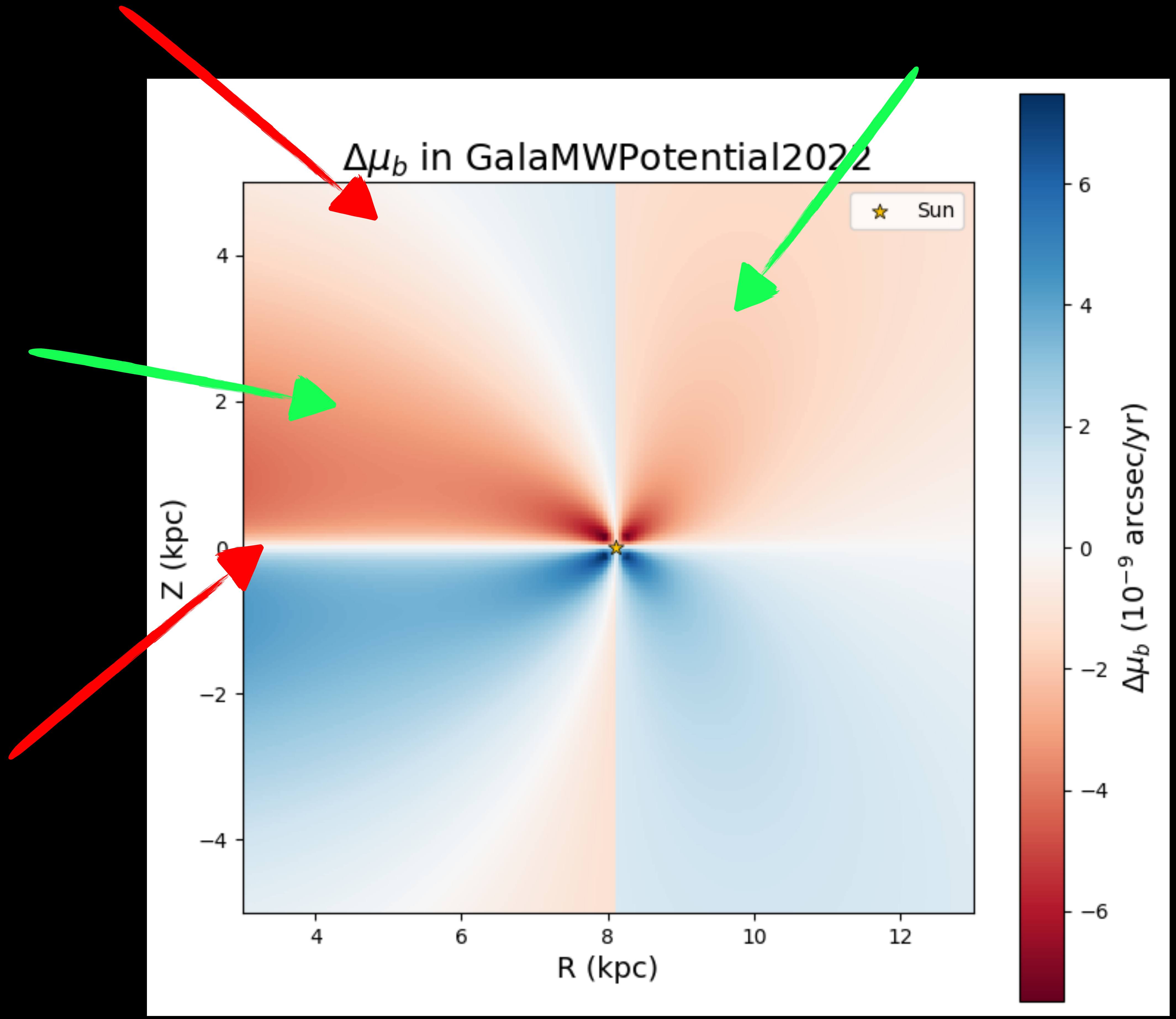
EPRV = extreme precision radial velocity
EBs = eclipsing binaries
DWDs = double white dwarfs



Synergy between precision tests of dark matter & tests of GR - acceleration measurements can help with precision tests of GR: Galactic potential largest uncertainty in tests of GR (PSR B1913+16) (Weisberg & Huang 2016)

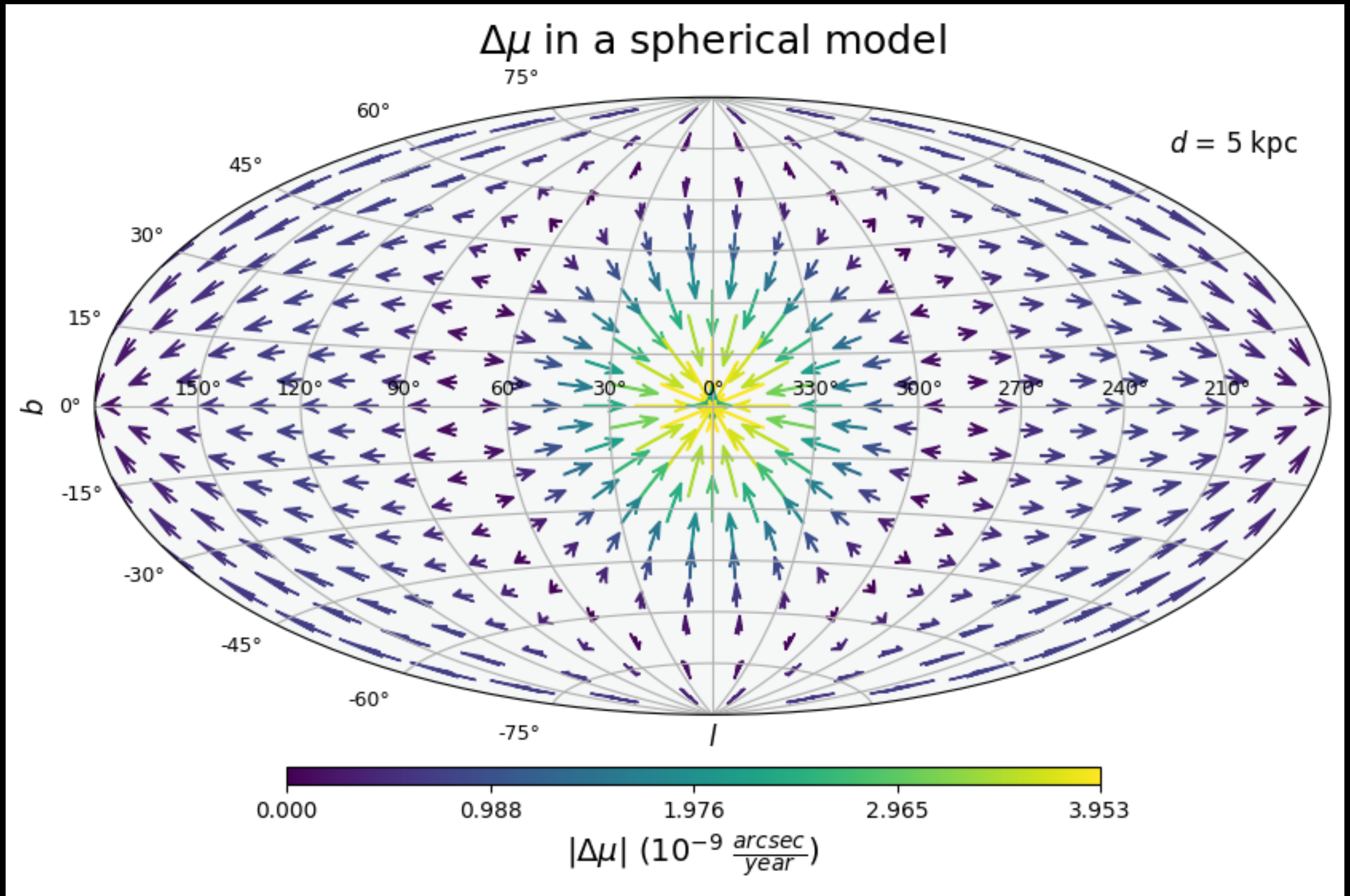
From line-of-sight to angular accelerations

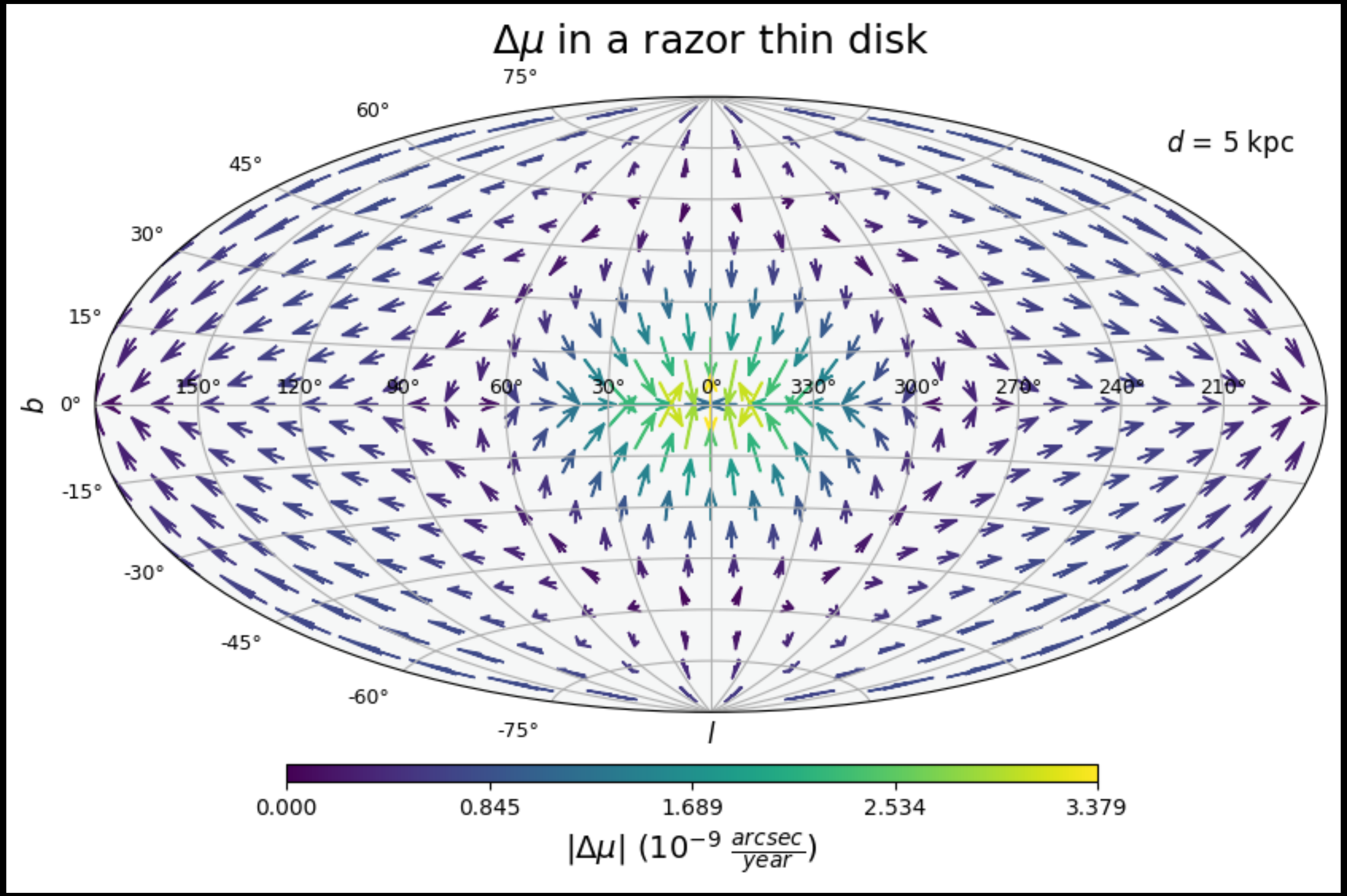




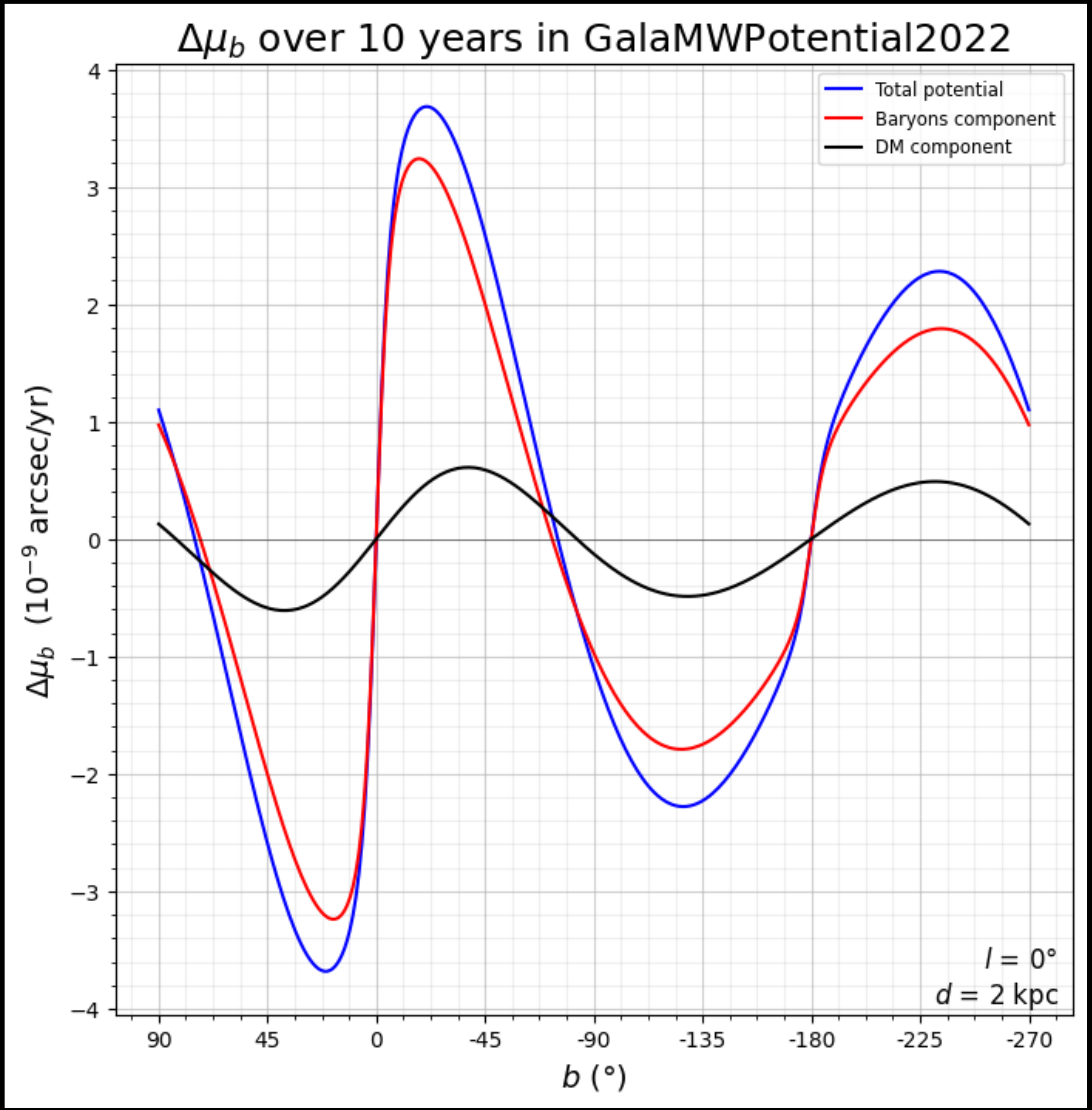
Addy, Chakrabarti, et al., in prep

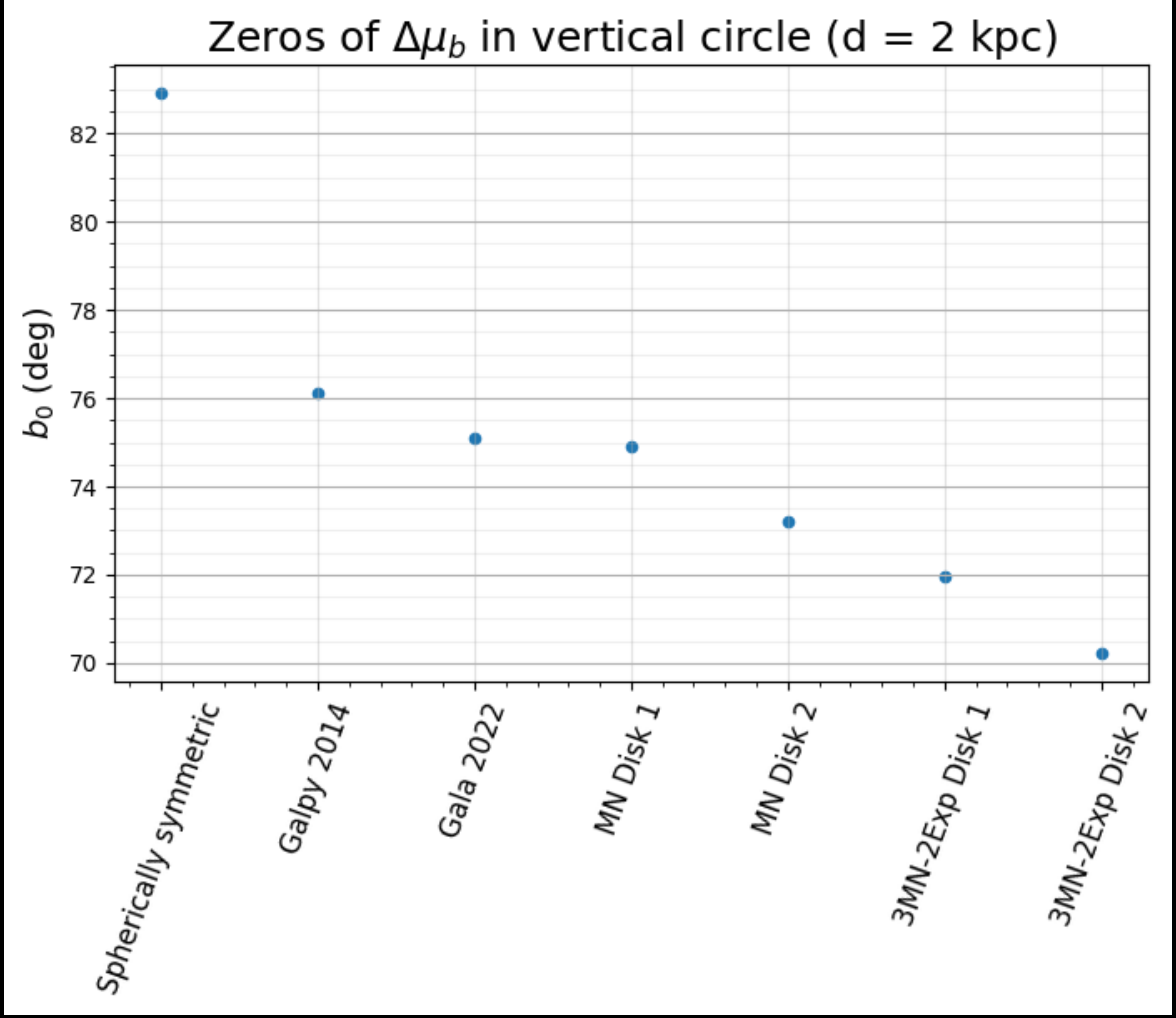
Vector fields in spherically symmetric and razor-thin disks





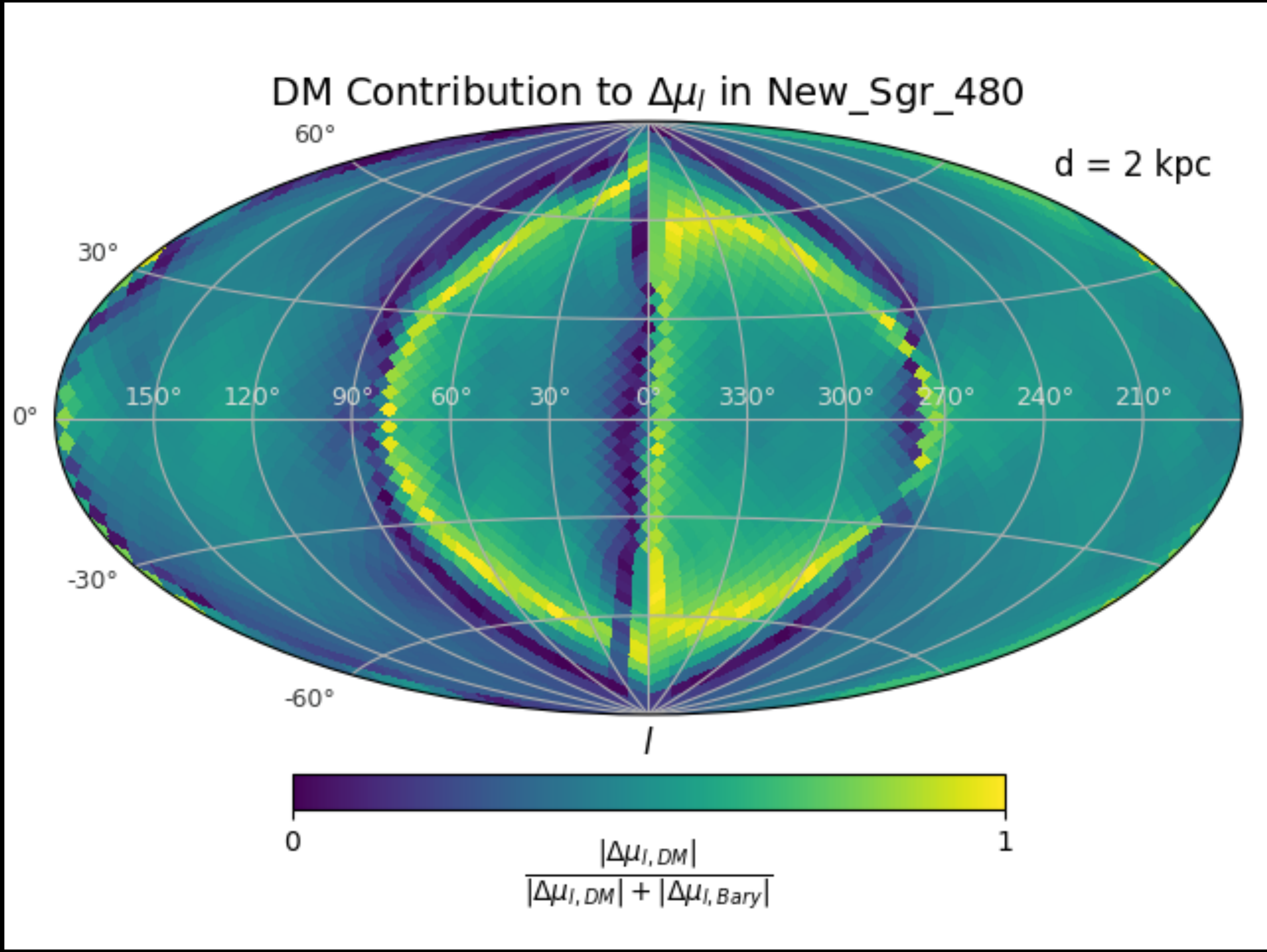
Addy et al., in prep





- Probing the shape of the potential - Addy et al., in prep - note the zero points (in vertical edge on circle)

Probing the misalignment of the baryons and DM



- Addy et al., in prep

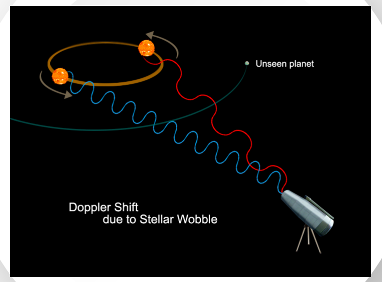
The precision frontier - the next few years

2021

NANOGrav 11 yr data set (2018)

Galactic accelerations measured with 14 binary pulsars

2022-2023



ESPRESSO EPRV survey

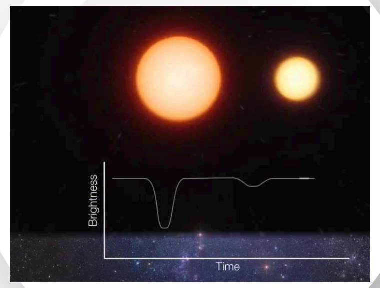
Recon spectra completed. Monitoring phase begun

2024

NANOGrav 15 yr data set

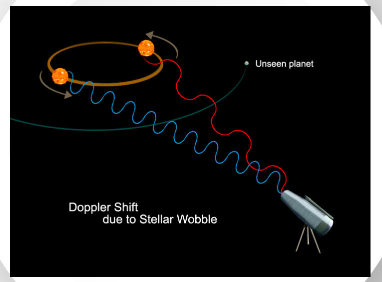
Total of 26 pulsars, evidence for disequilibrium

2024



Eclipse timing of EBs with HST & DWDs with HiPERCAM

~2026



ESPRESSO EPRV survey

Upper limits of the Galactic acceleration for ~ 70 stars

Precision Lab for Dark Matter: Summary

- First determination of Galactic parameters from acceleration measurements, which can inform direct detection experiments for dark matter:

1. Mid-plane density and dark matter density close to but lower than modern estimates
2. Oblateness of Galactic potential constrained by pulsar timing
3. Expanded pulsar timing sample - slope of rotation curve and Oort constants are constrained
4. Larger pulsar timing sample shows clear disequilibrium

EPRV survey (Fall 2021 - onwards) - **pathfinder for ELTs**

Combination of EPRV measurements, pulsar timing and eclipse timing, and precision astrometry : dark matter sub-structure