Towards precision measurements of dark matter

Sukanya Chakrabarti (UAH)

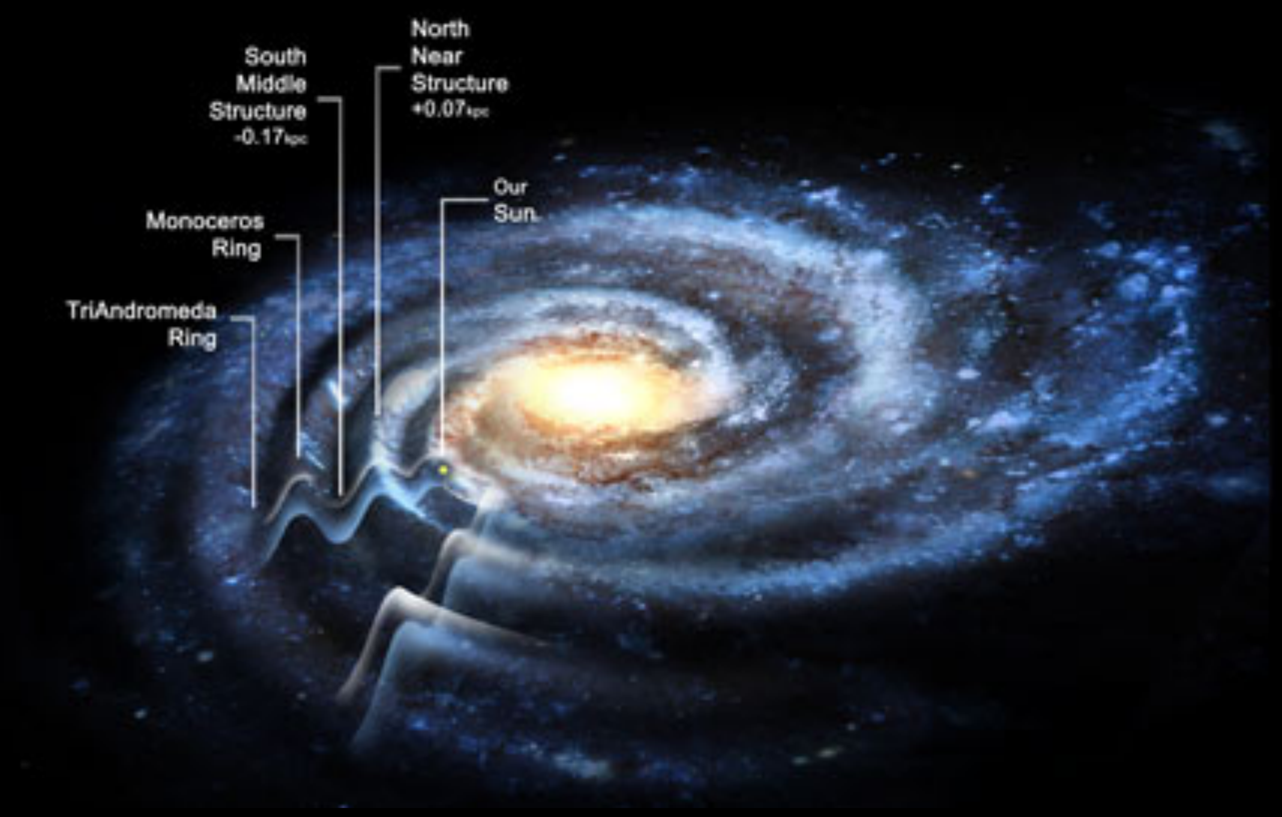
EPRV : J. Wright, P. Chang, A. Quillen, P. Craig*, J.Territo*, E. D'Onghia, K. Johnston, R. de Rosa, K. Rhode, D. Huber & E. Nielsen
Pulsar timing: P. Chang, M. Lam, S. Vigeland & A. Quillen
Eclipse timing: D. Stevens, J. Wright, R. Rafikov, P. Chang, T. Beatty & D. Huber
Acceleration ladder: P. Craig*, R. Sanderson, F. Nikhatar

Motivations: the dynamic Milky Way

Why direct measurements of the Galactic acceleration?

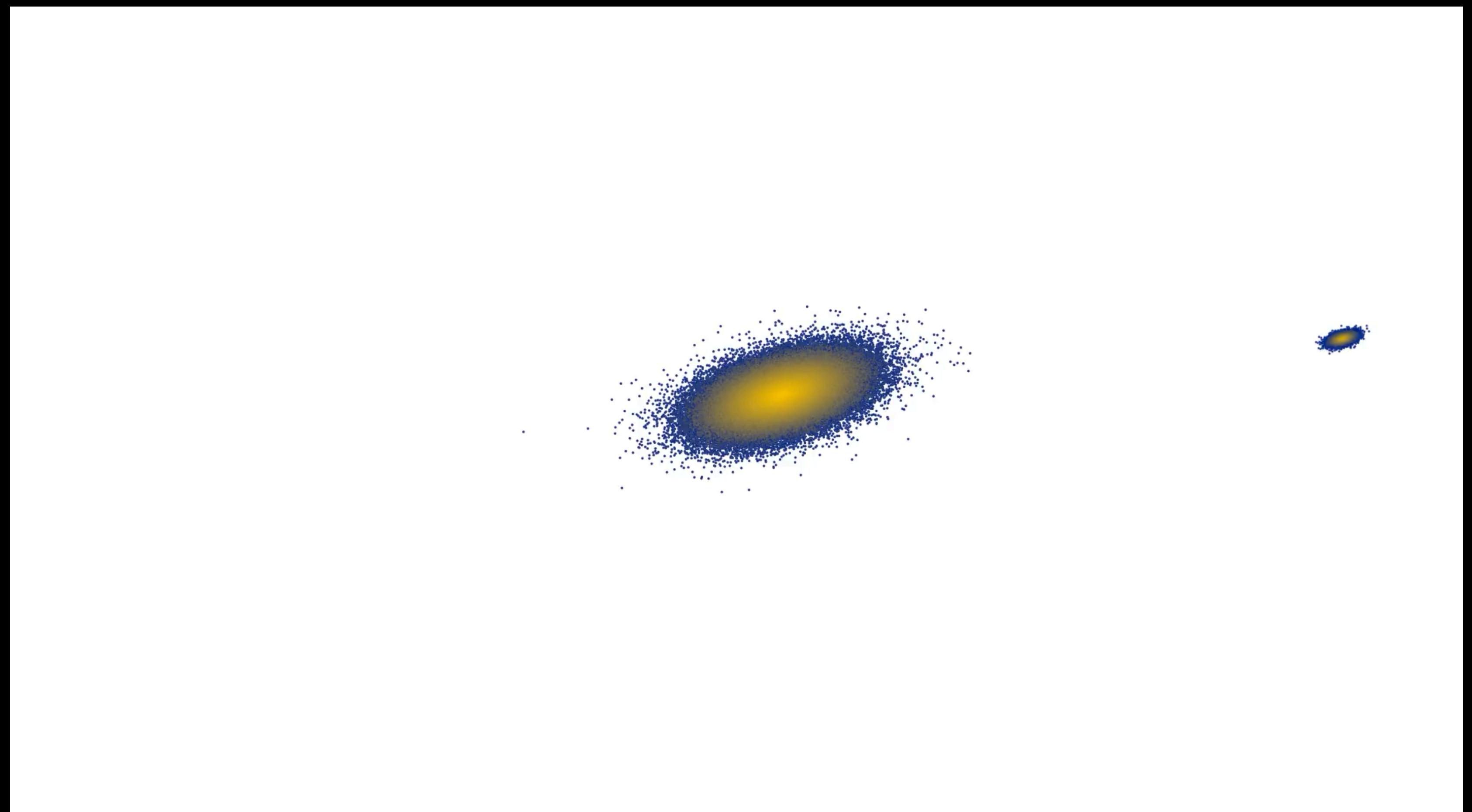
Traditional method: *estimate* accelerations. True acceleration in interacting Galaxy may be different

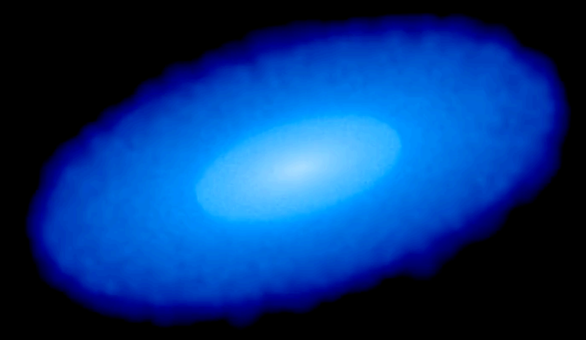
1. Extreme precision radial velocity measurements (Chakrabarti et al. 2020)
2. Pulsar timing (Chakrabarti et al. 2021)
3. Eclipse timing (Chakrabarti et al. 2022)



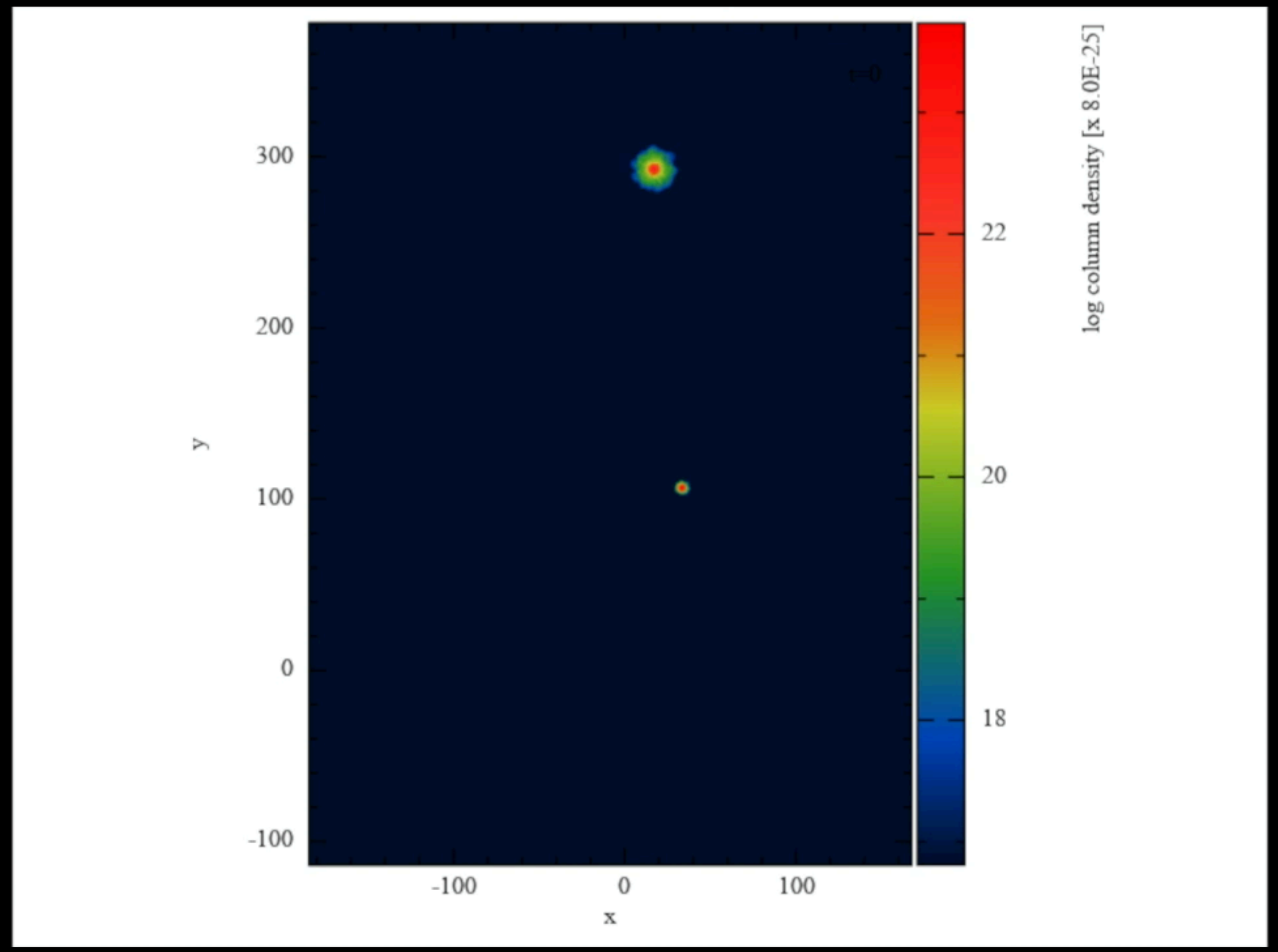
Xu et al. 2015

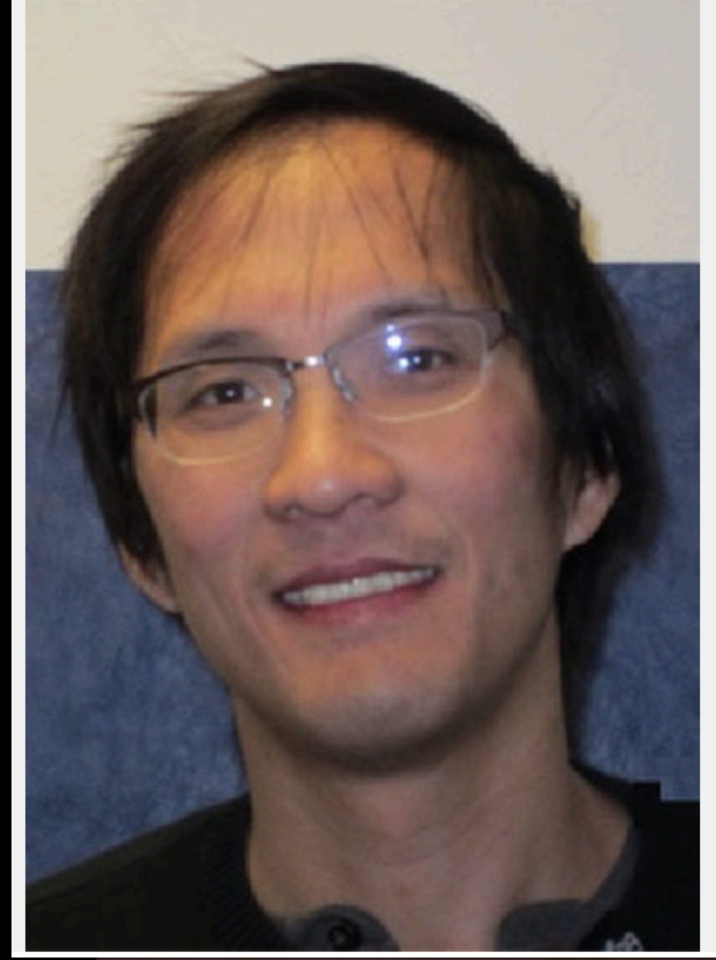
Milky Way interaction with Antlia2 : Chakrabarti et al 2019

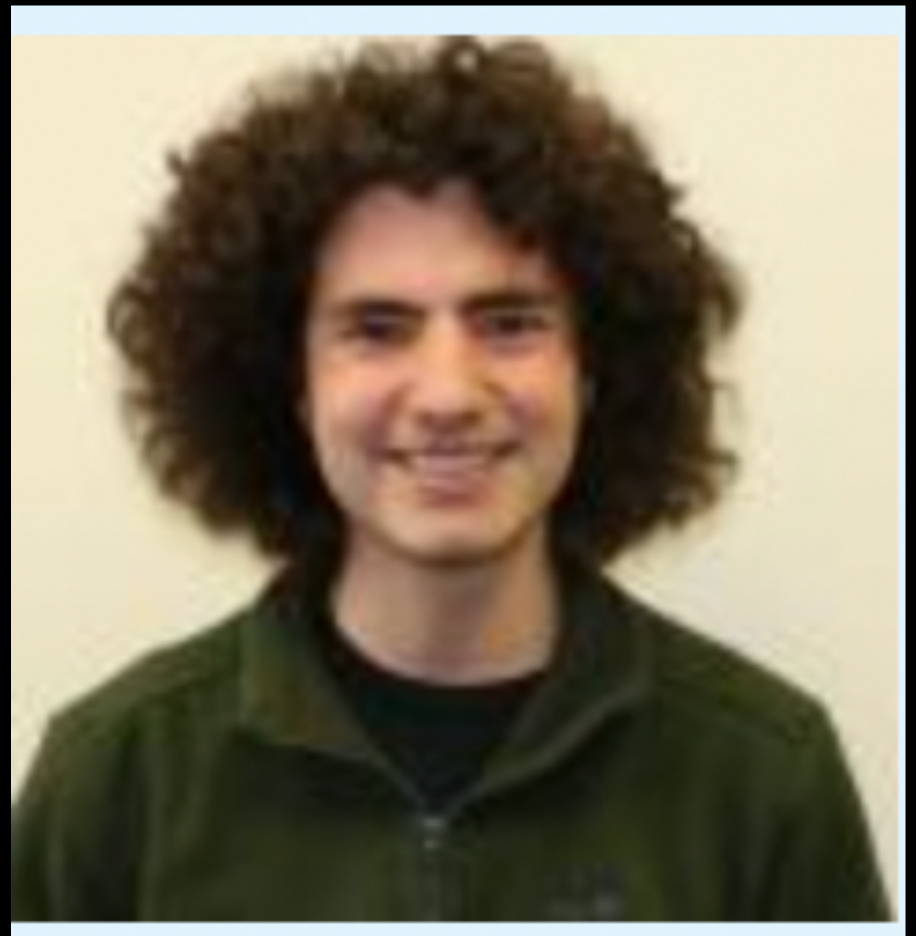




Craig*, Chakrabarti et al., 2021











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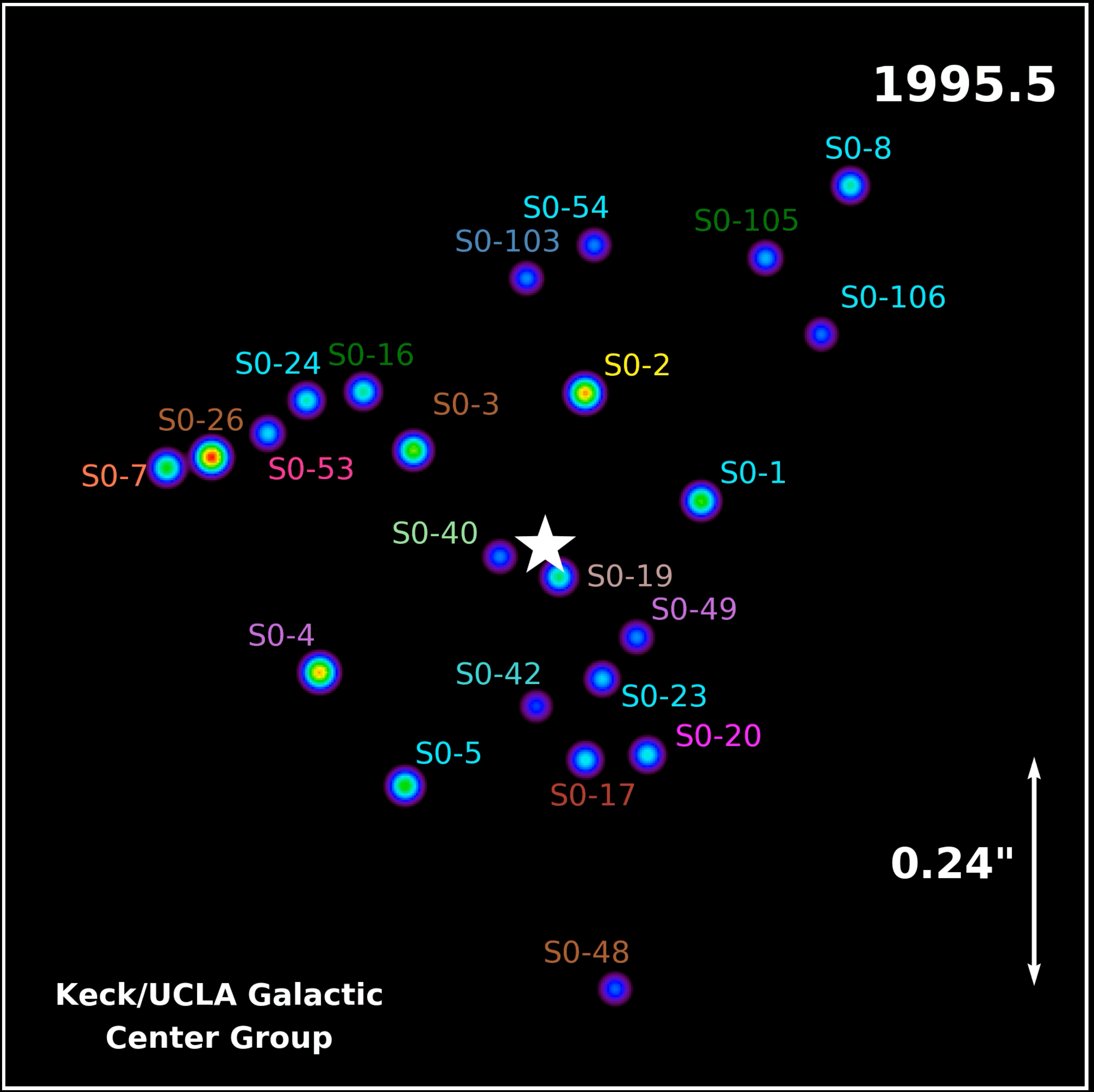
Binary White Dwarf
J0923+3028
Unseen Companion
Visible Star

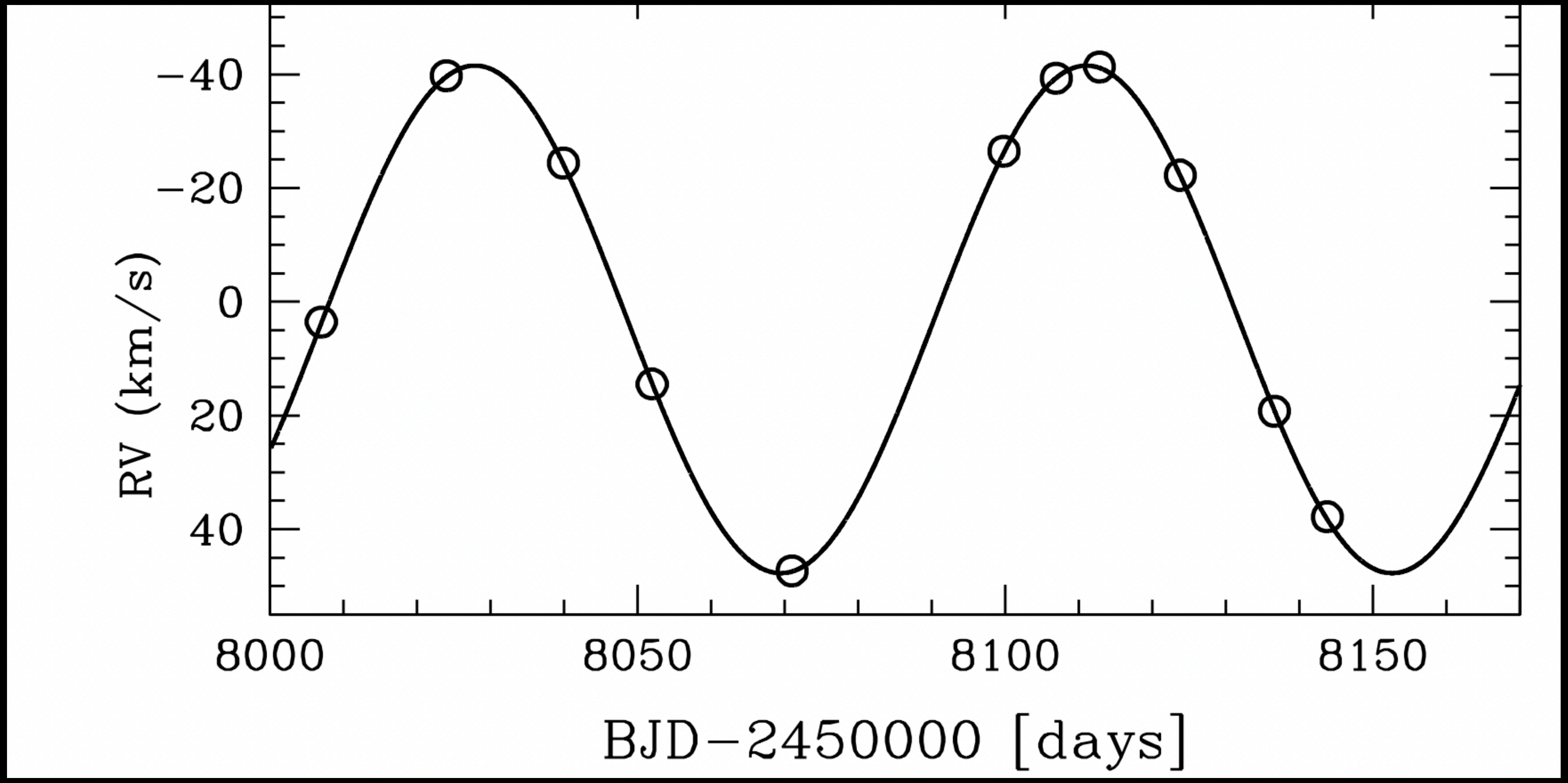


Measured BIG accelerations

UCLA Galactic center

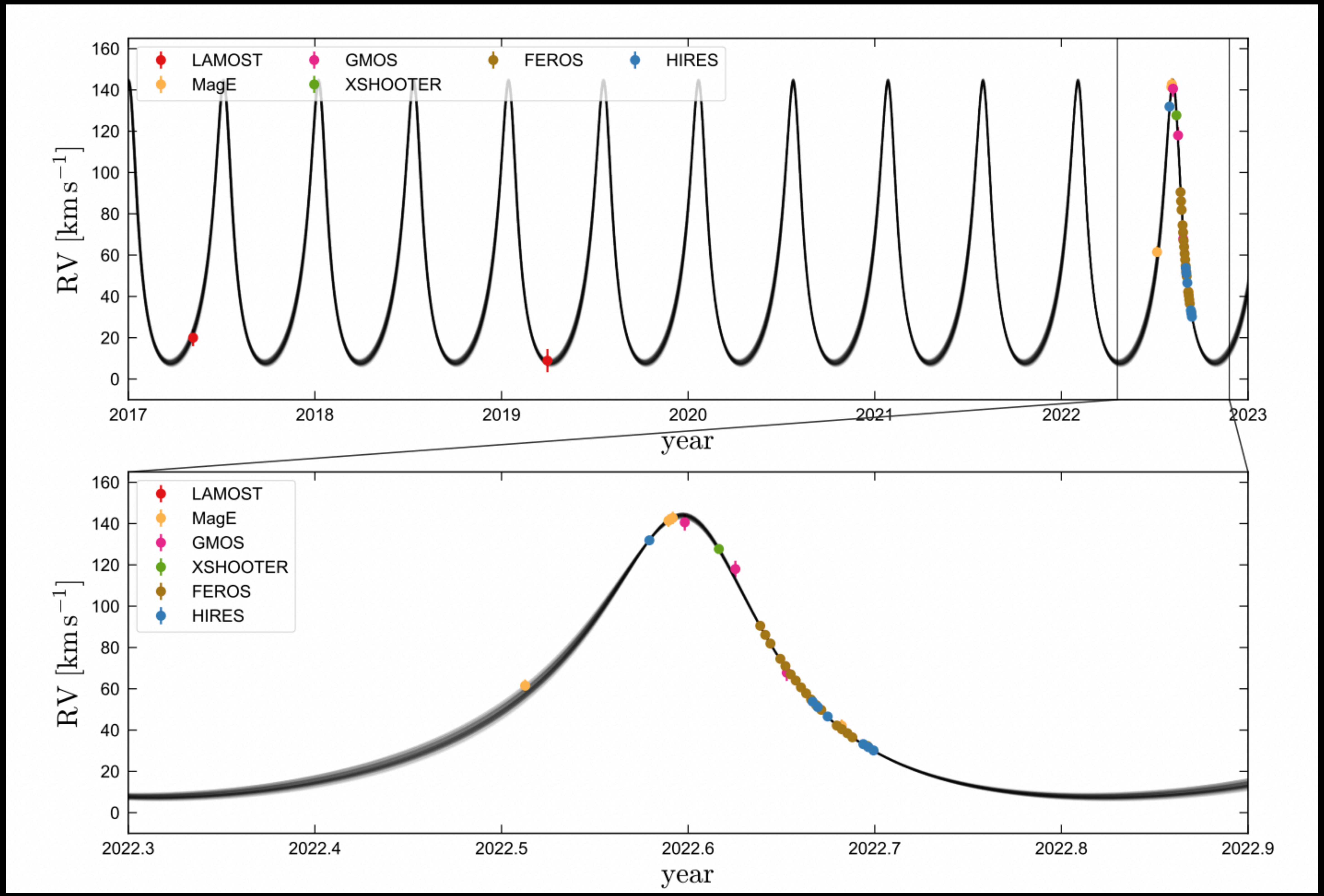
Ghez et al. 1998++



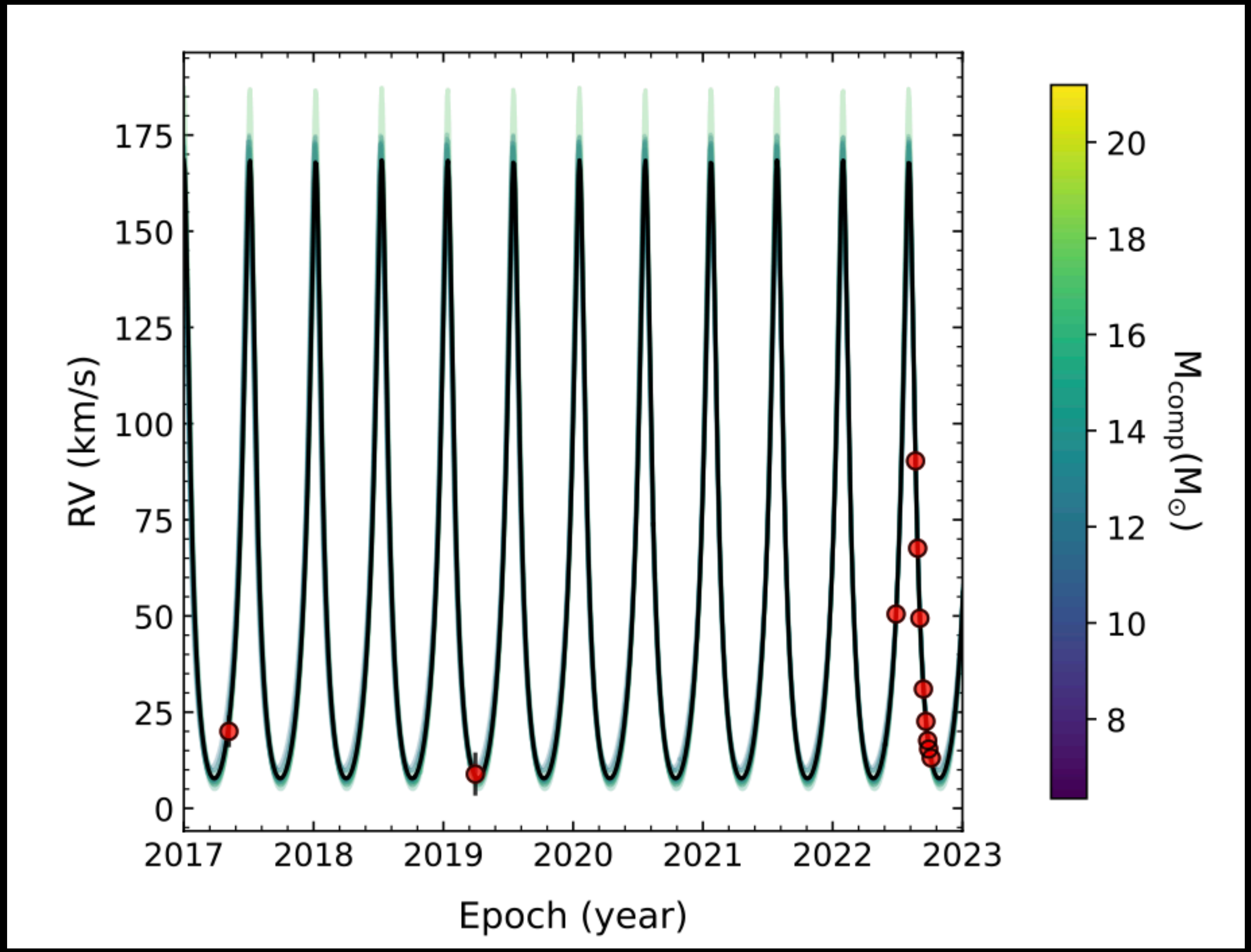


Black holes around luminous companions (Thompson et al. 2019)

Non-interacting black holes from Gaia DR3



El-Badry et al. 2023



Chakrabarti et al. 2023

Outline: “real-time” Galactic dynamics

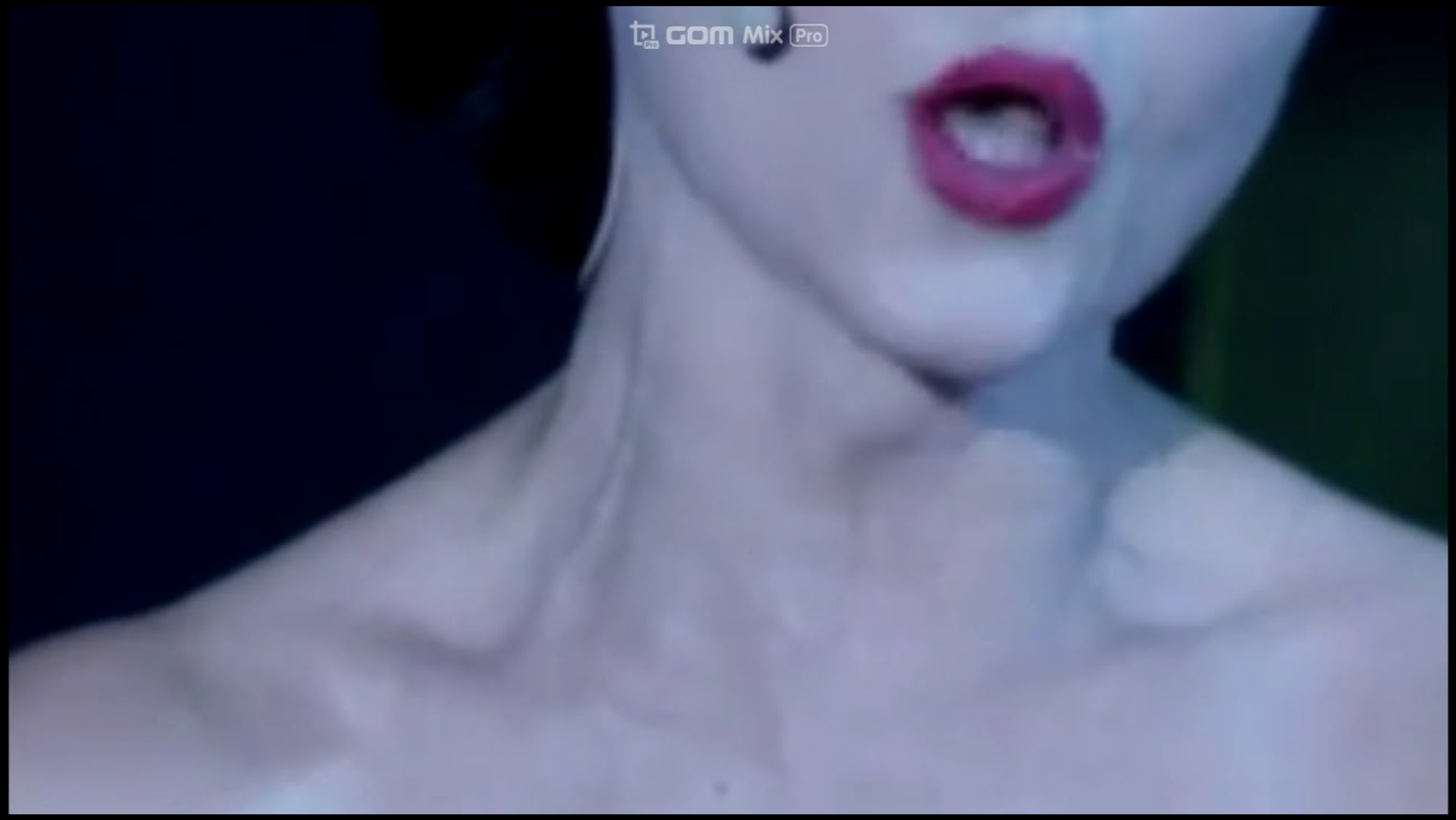
- High precision RV observations to measure the Galactic acceleration : requires ~ 10 cm/s precision (these accelerations << Galactic center accelerations)

- Milky Way simulations

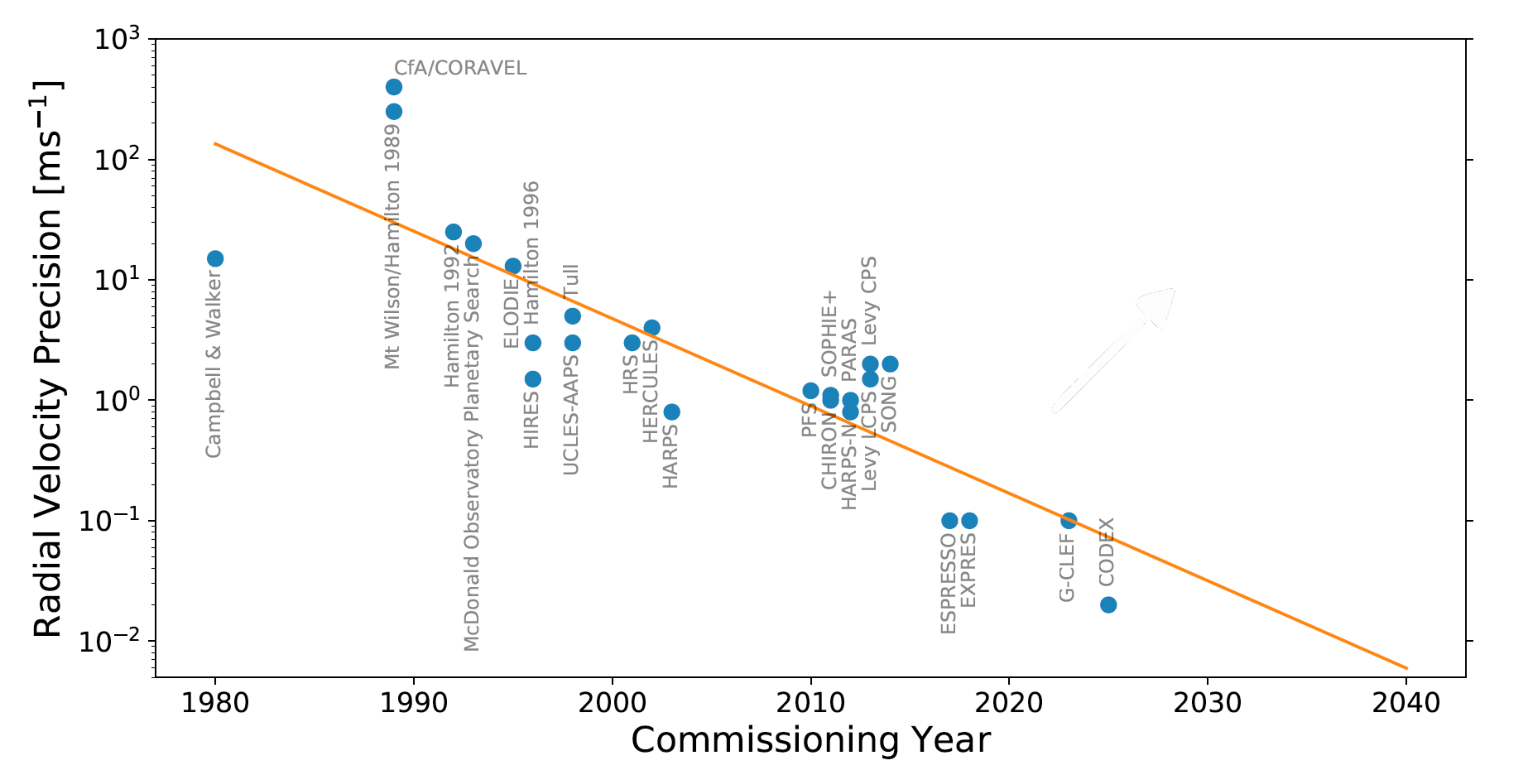
- Pulsar timing measurements of the Galactic acceleration, the Oort limit & the local dark matter density : requires precision on $\dot{P}_b \sim 10^{-13}\ s^{-1}$

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

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



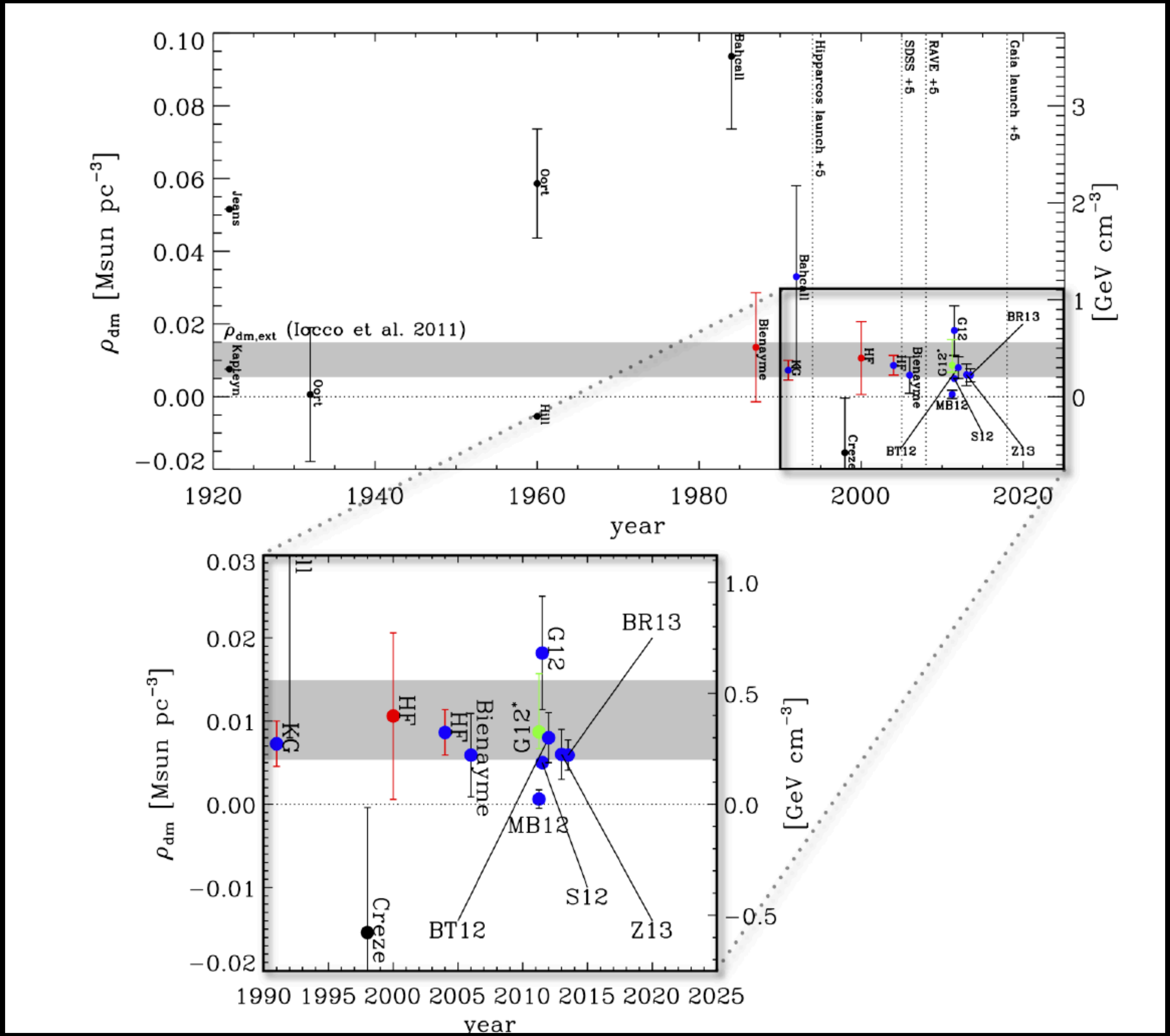
Towards extreme precision RV measurements



www.eso.org

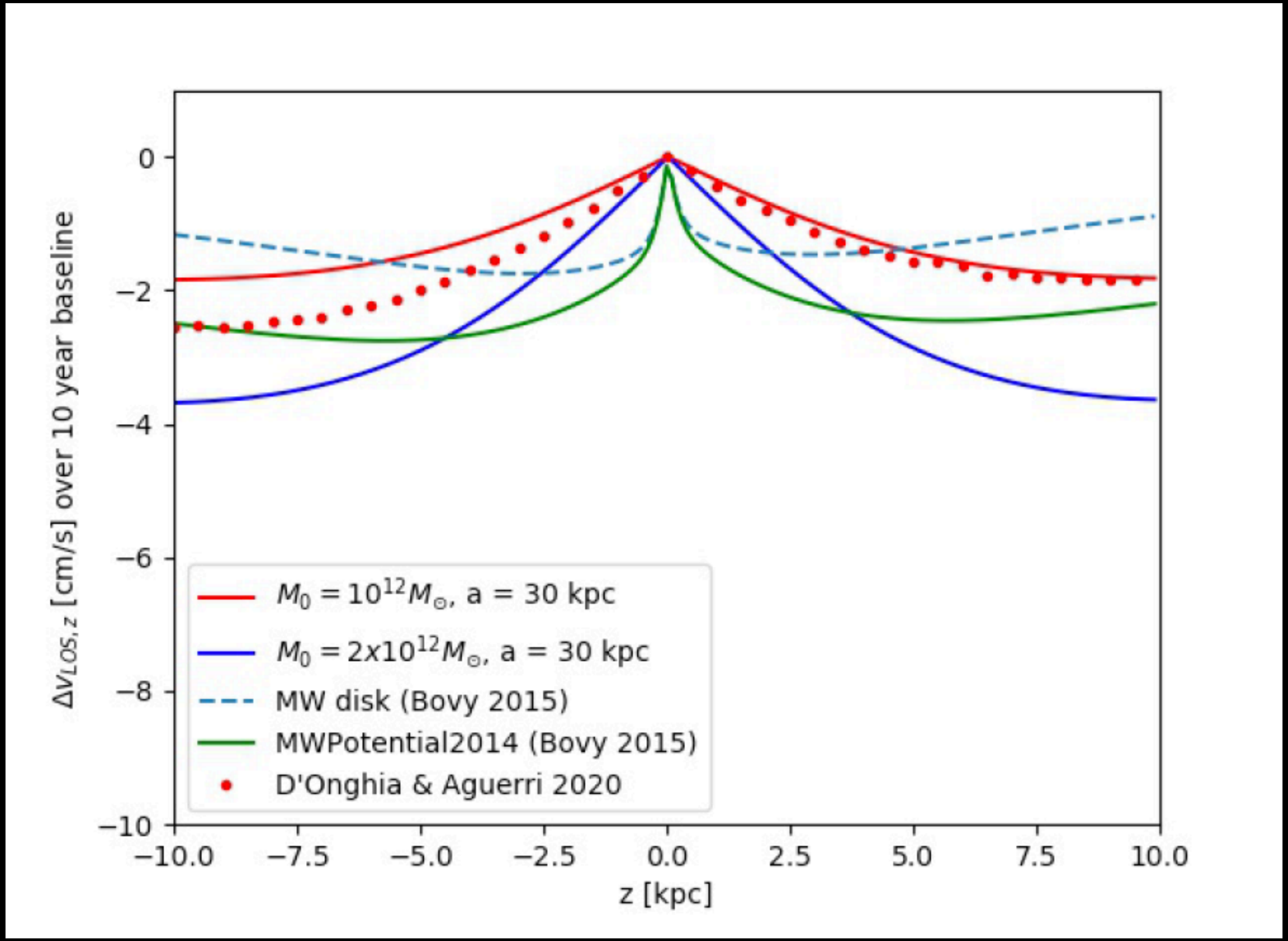
Wright & Robertson 2017; Silverwood & Easther (2019)

The Oort limit & the local dark matter density



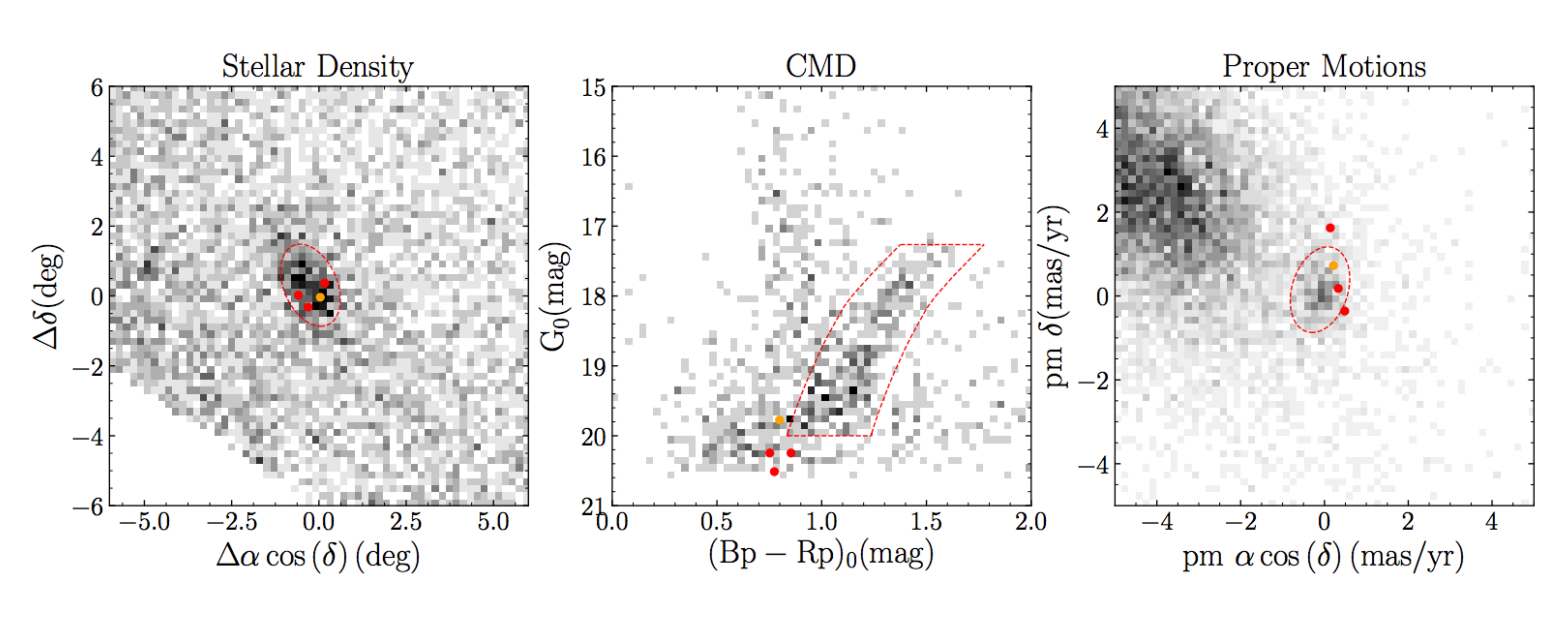
Read (2014) (recoil rate ~ local DM density)

Baseline expectations



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

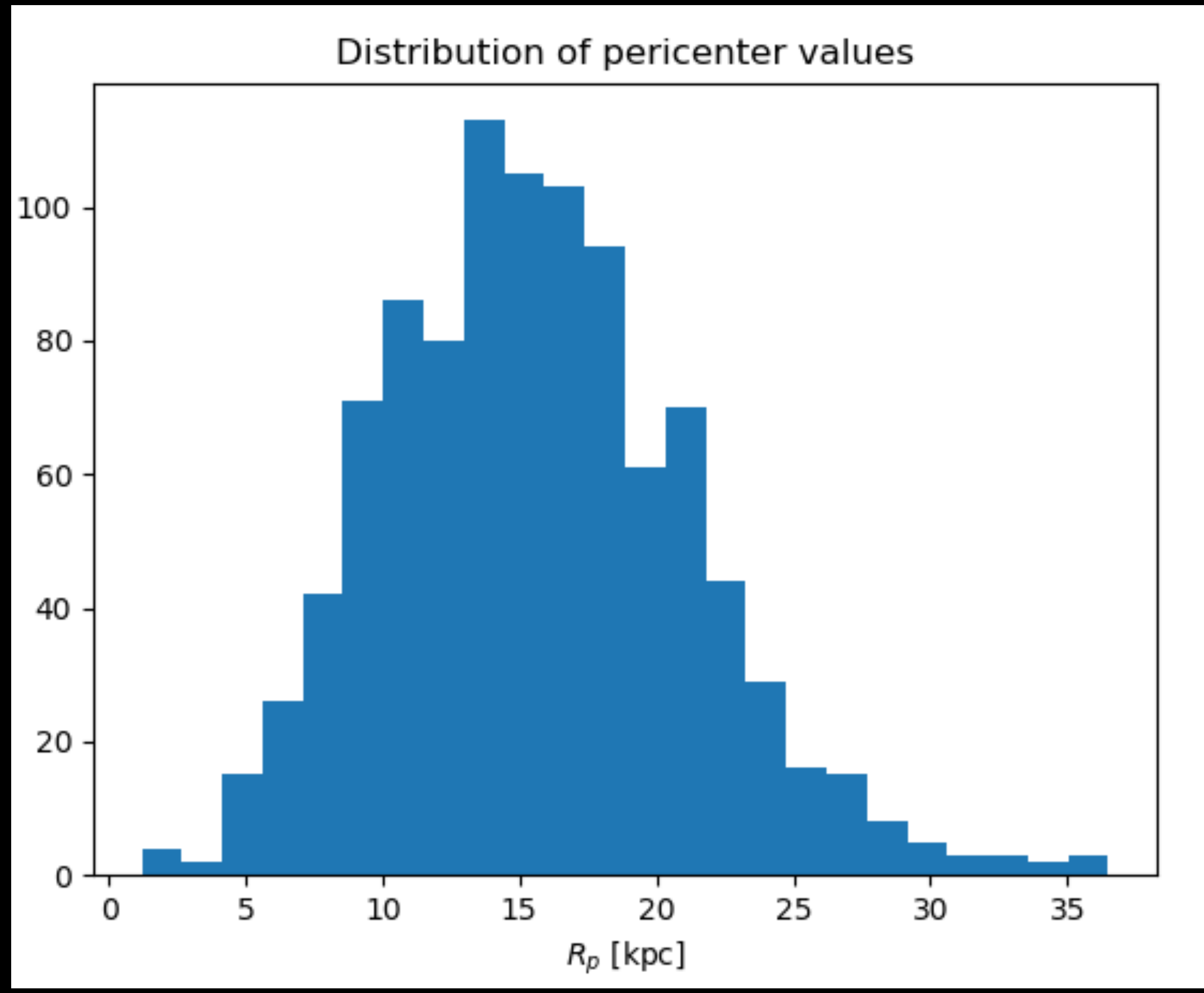
The hidden giant : Gaia observations of Antlia 2

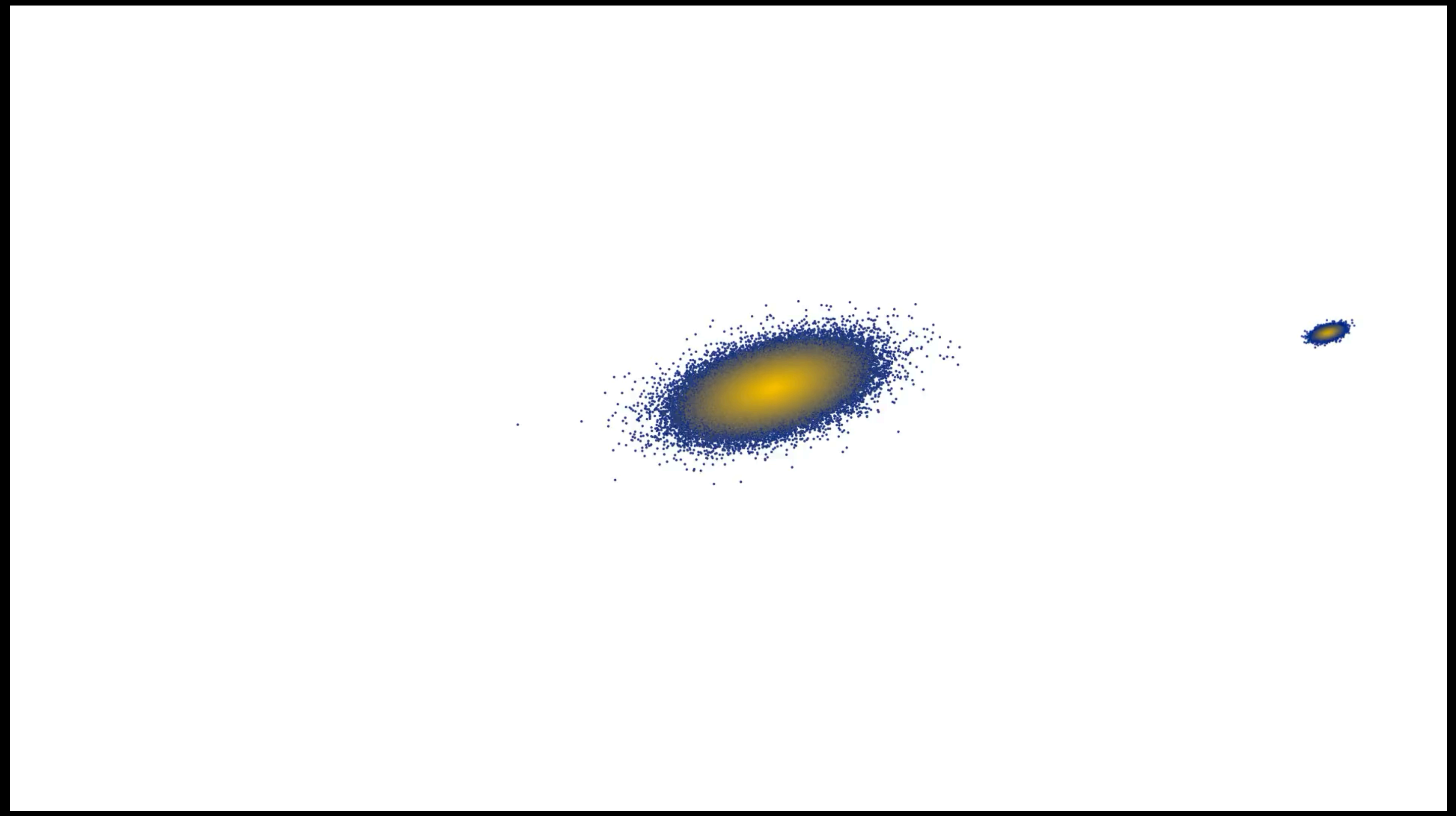


Torrealba et al. (2019)

- The least dense galaxy known — similar in extent to Large Magellanic Cloud, but 4000 times fainter
- 11 degrees from the plane of the Galaxy
- ~ 130 kpc away

Antila 2's orbit distribution & stream from Gaia observations

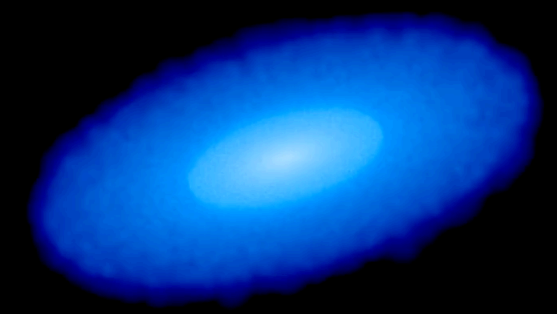




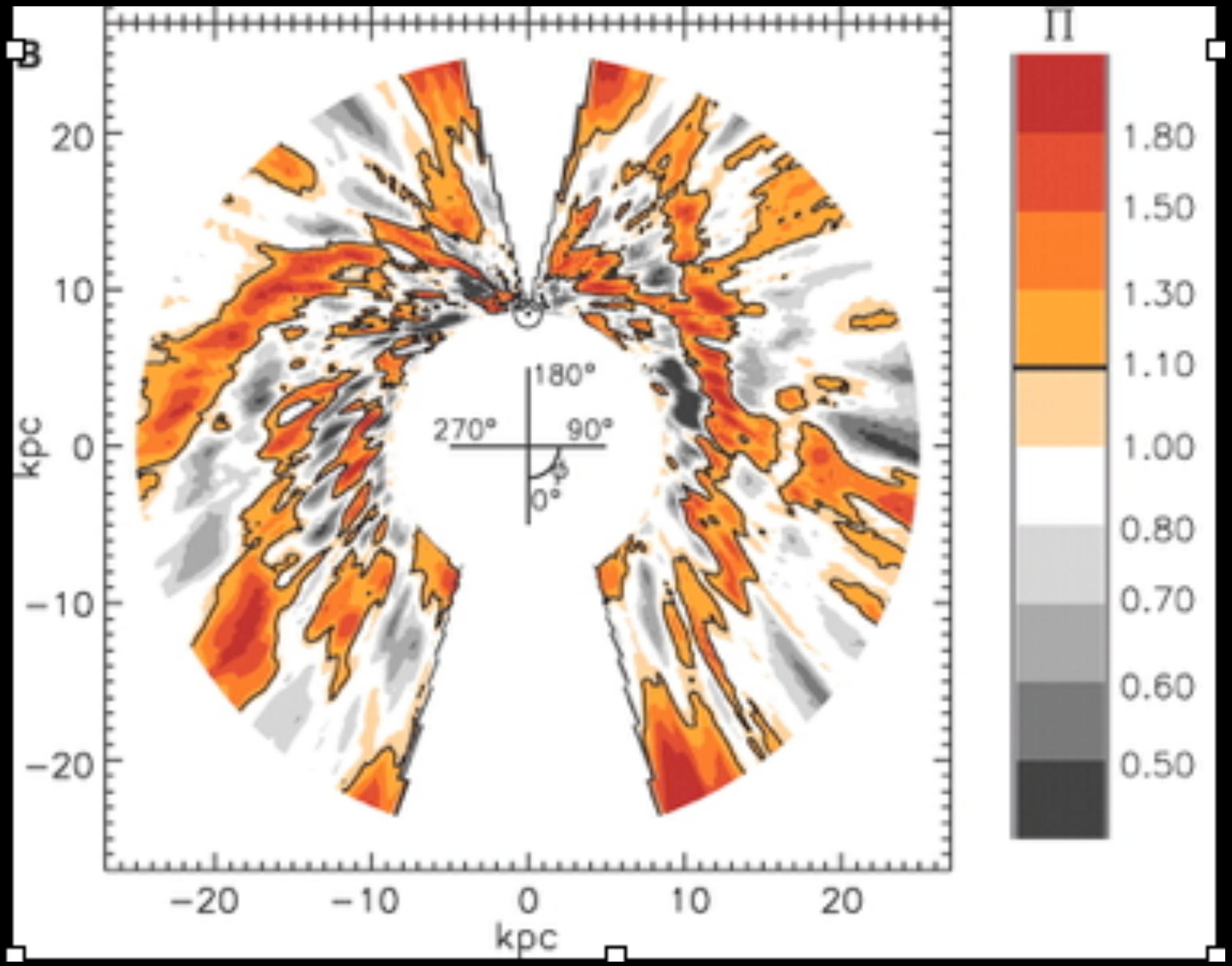
$<R_p>$ = 15 kpc

Near co-planar orbit

Chakrabarti et al. 2019



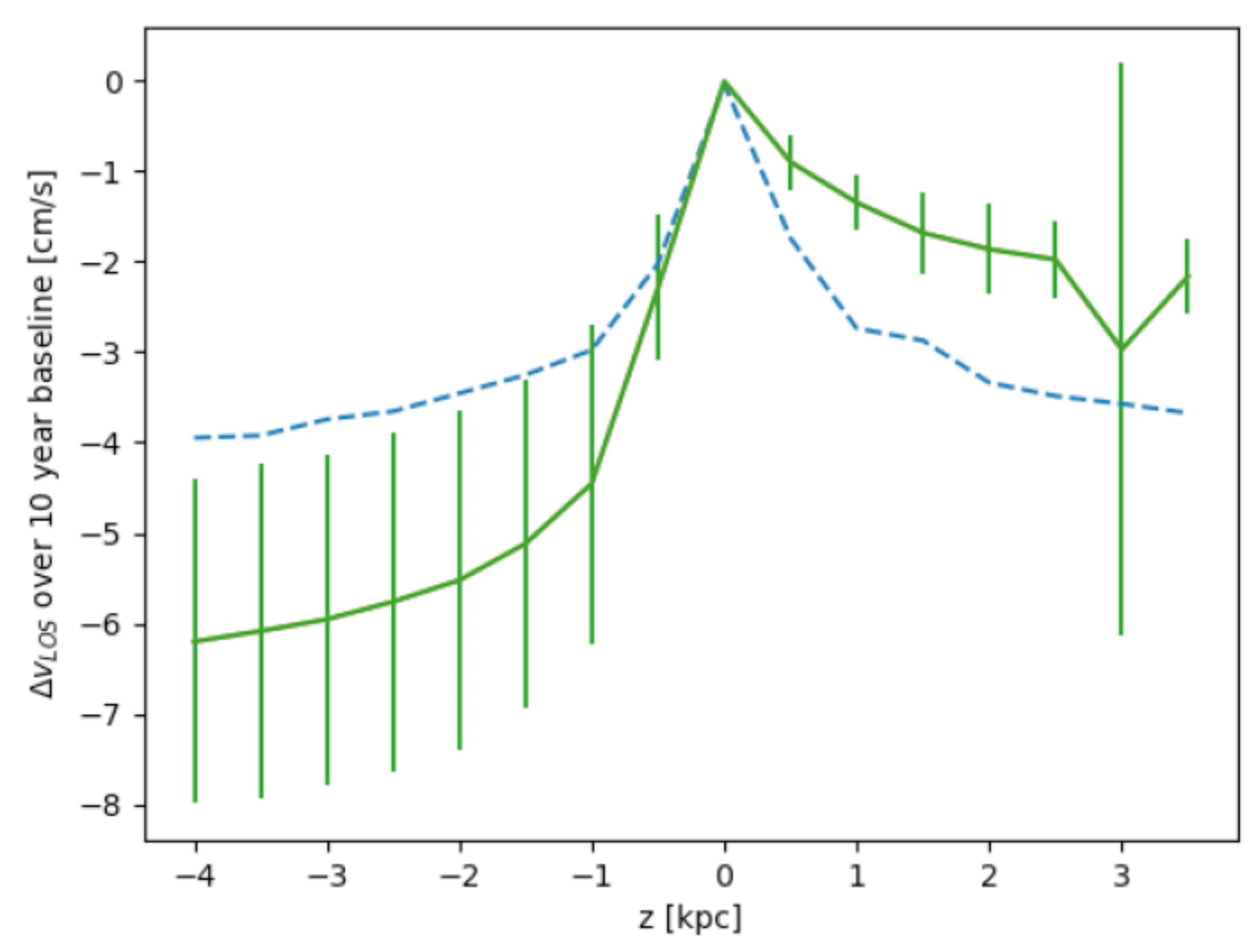
Levine, Blitz & Heiles 2006



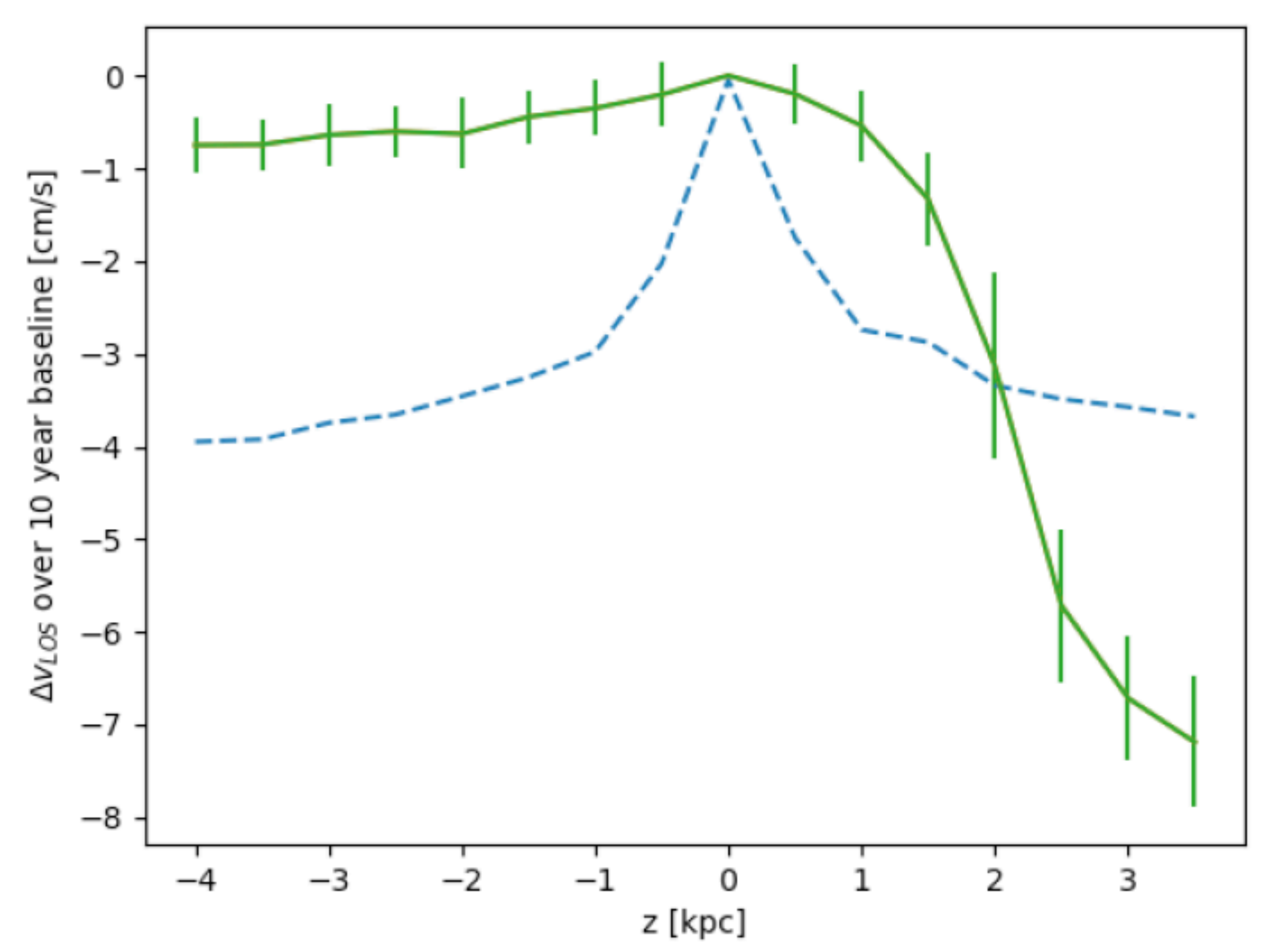
Chakrabarti & Blitz 2009:

- radial location
- near co-planar orbit
- dwarf galaxy mass

Vertical acceleration profile in interacting simulations



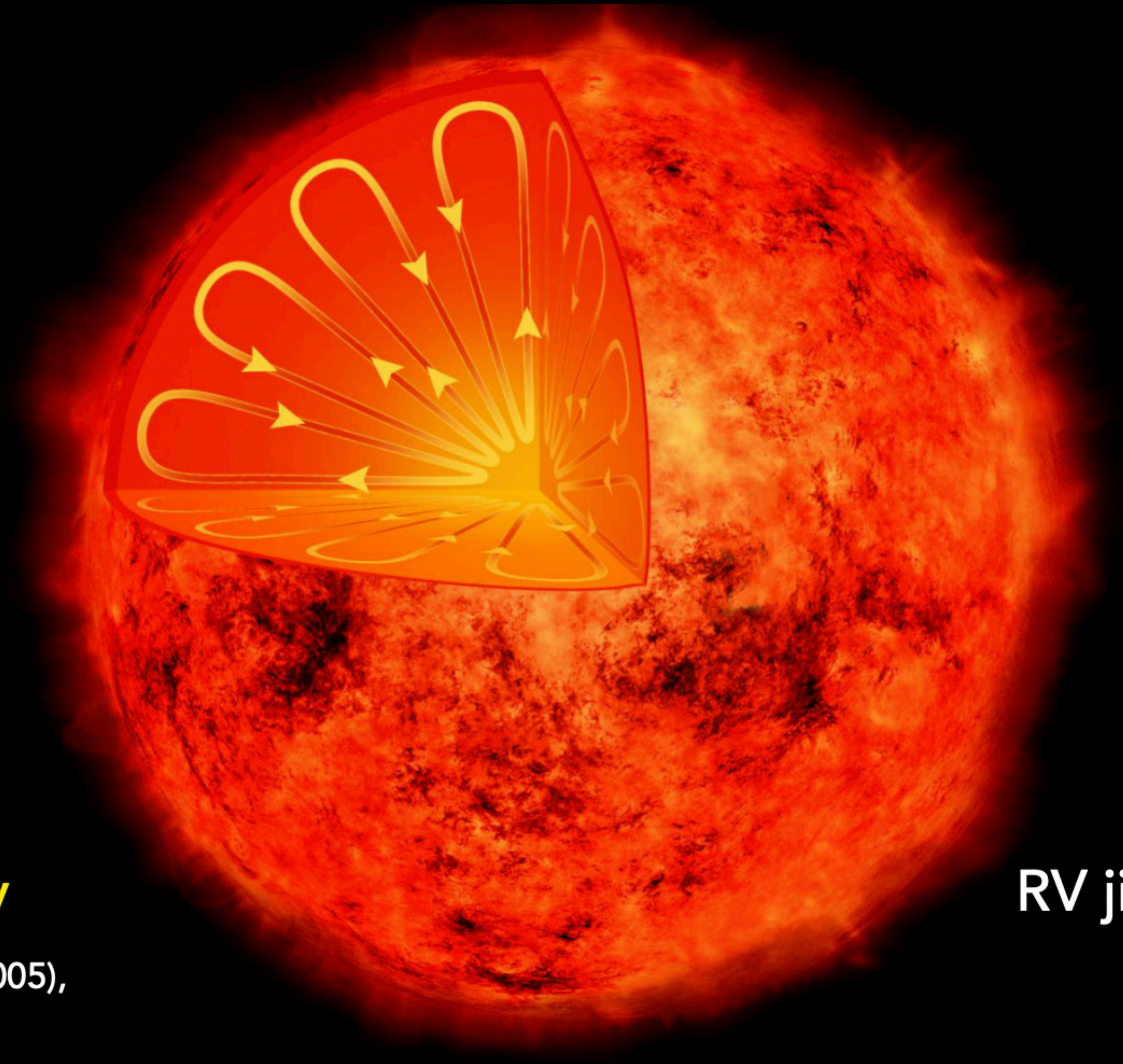
Antlia 2



Sgr dwarf

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

Contaminants to the Galactic signal



Credit: Jacob Luhn

Magnetically driven

star spots/faculae

flares

…

RV jitter increases with activity

Saar et al. (1998), Santos et al. (2000), Wright (2005), Isaacson & Fischer (2010)…among others

Convection driven

granulation

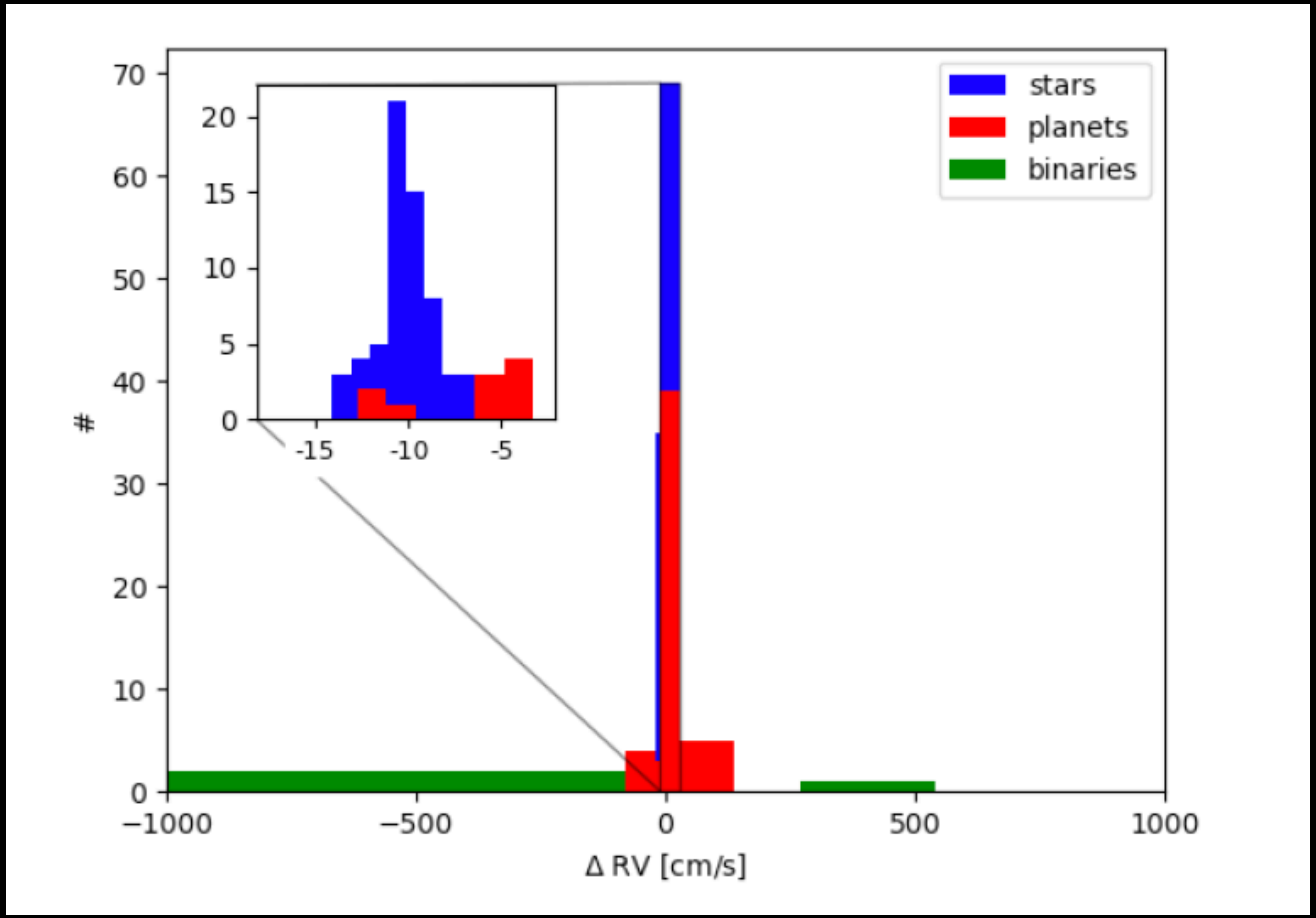
oscillations

RV jitter increases with convection

Wright et al. (2005), Dumusque et al. (2011), Bastien et al. (2014)

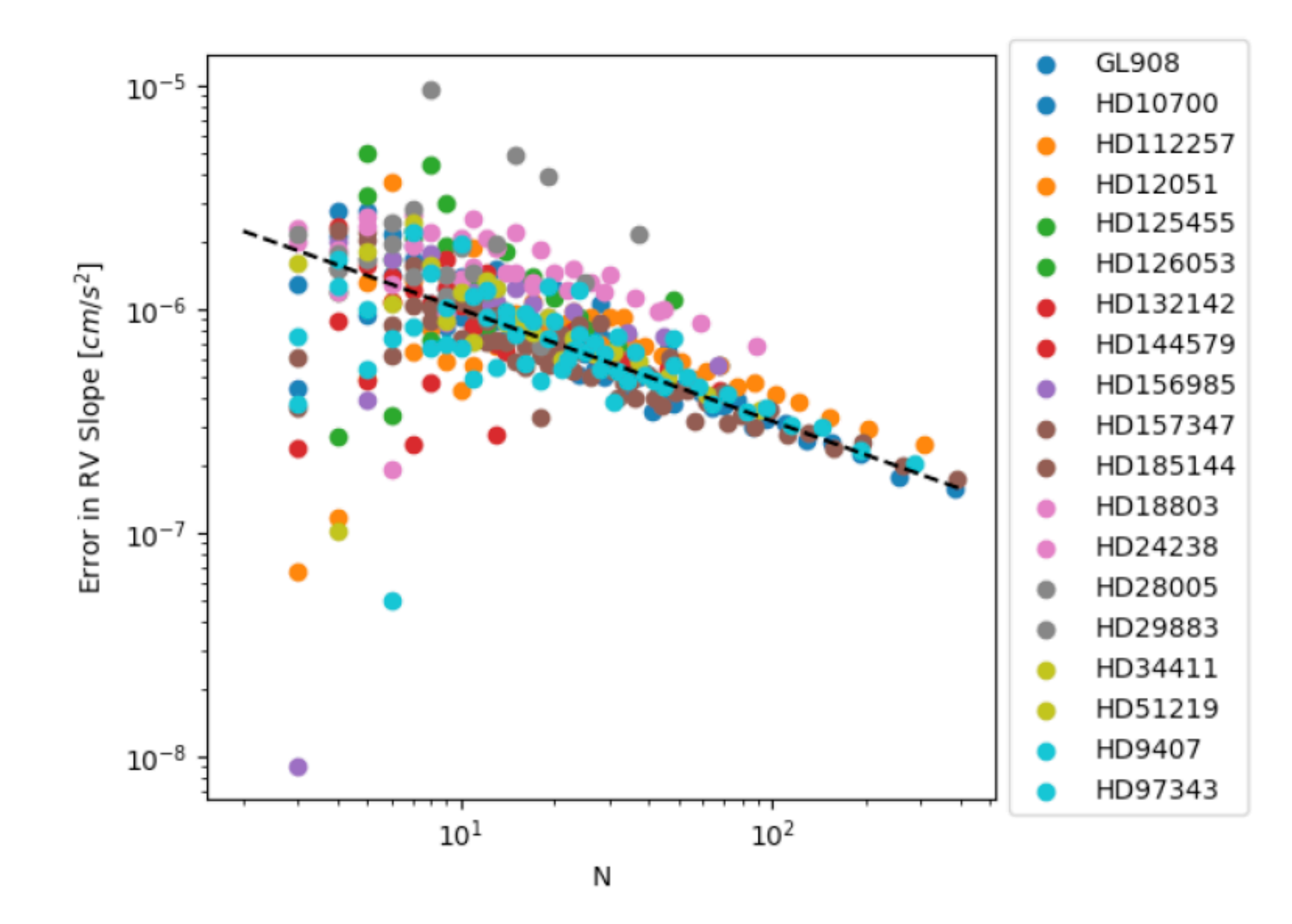
- Stellar jitter : choose <u>sub-giants as compromise</u> between bright stars and fainter, low-jitter dwarfs. Relations between Gaia color & RV jitter (Luhn et al. 2020)
- Stellar binaries
- Planets

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.

Expectation for error in RV slope



- Chakrabarti et al. 2020: analysis of RV data of standard RV stars from 10 year LCES/HIRES survey (Butler et al. 2017); error in RV slope ~ $N^{-1/2}$

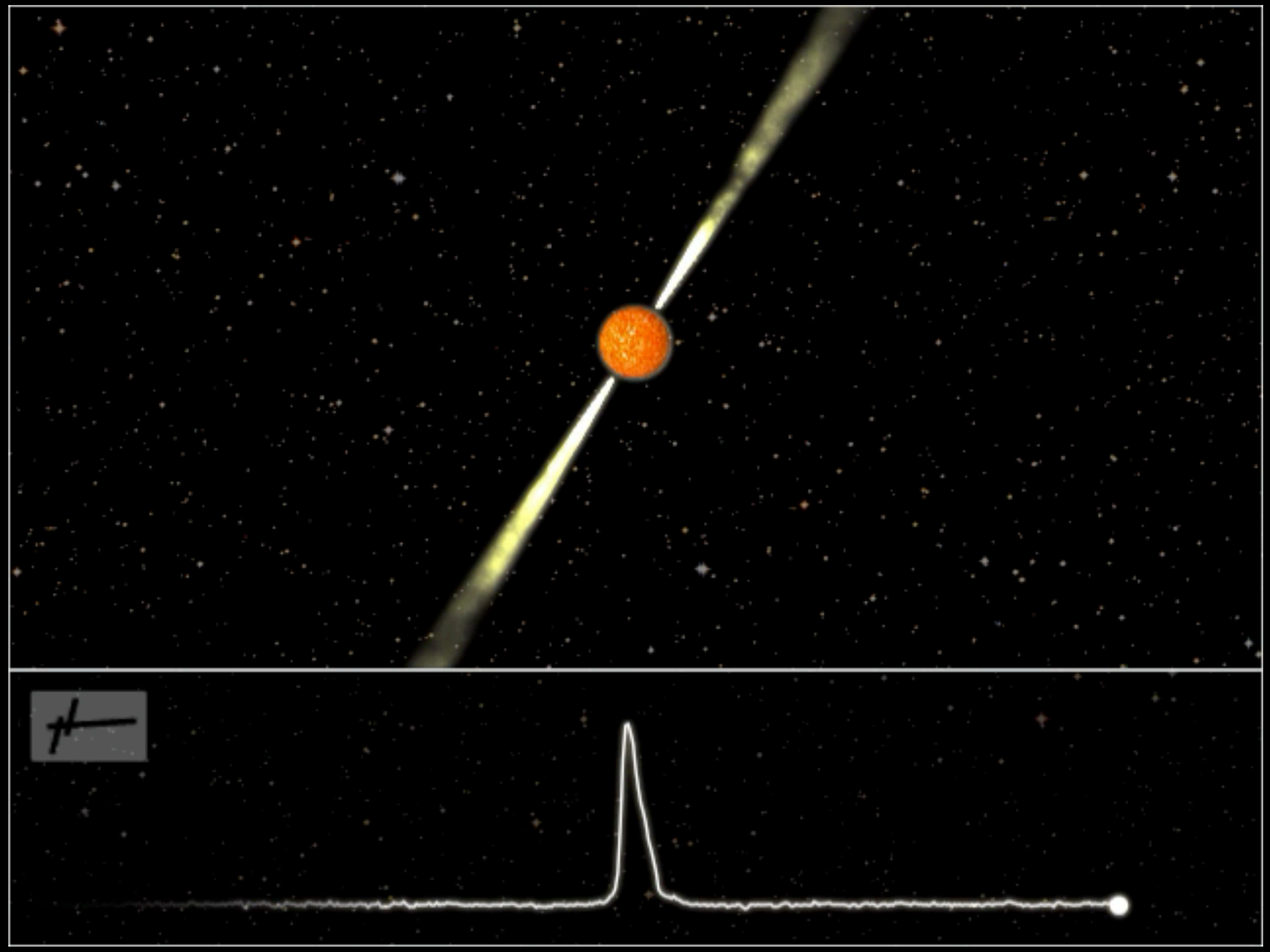
The good, the bad, and the ugly

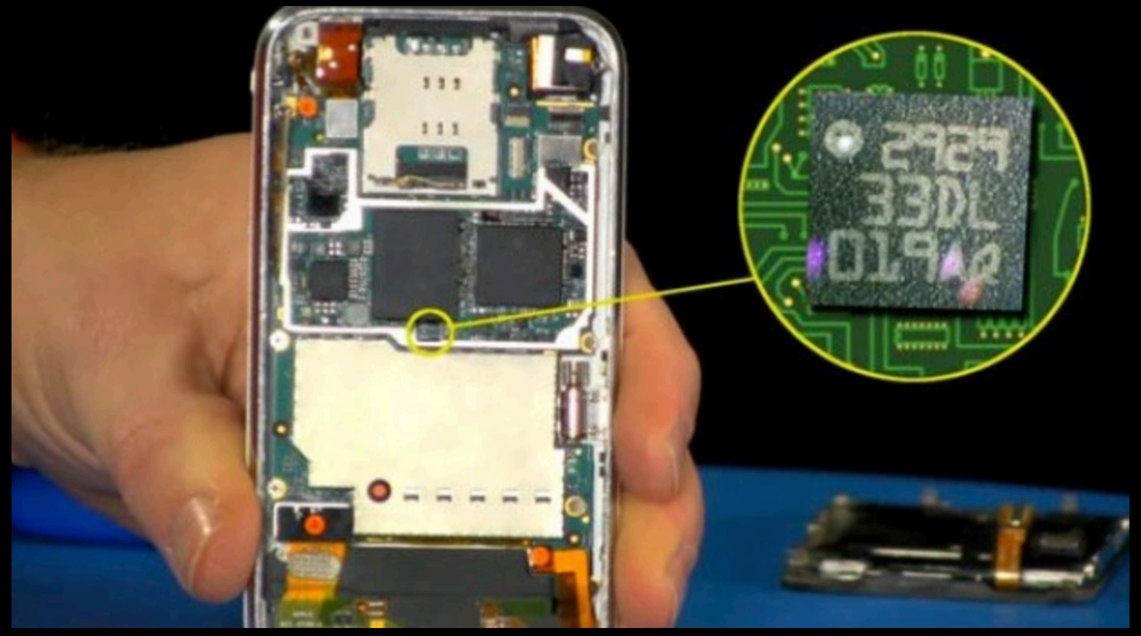
ESPRESSO spectra (PI: Chakrabarti)

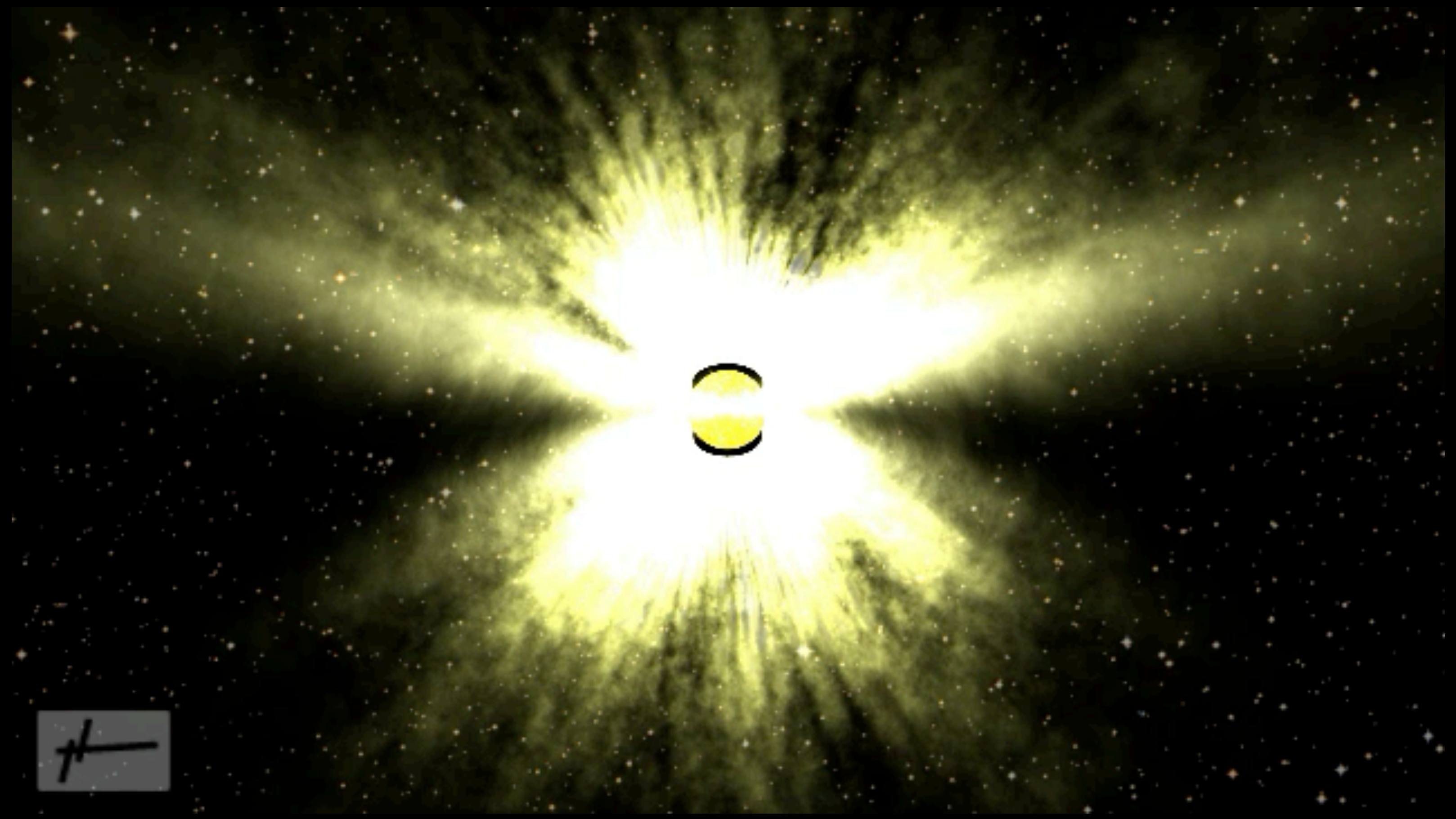
The quietest stars are dead stars

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.

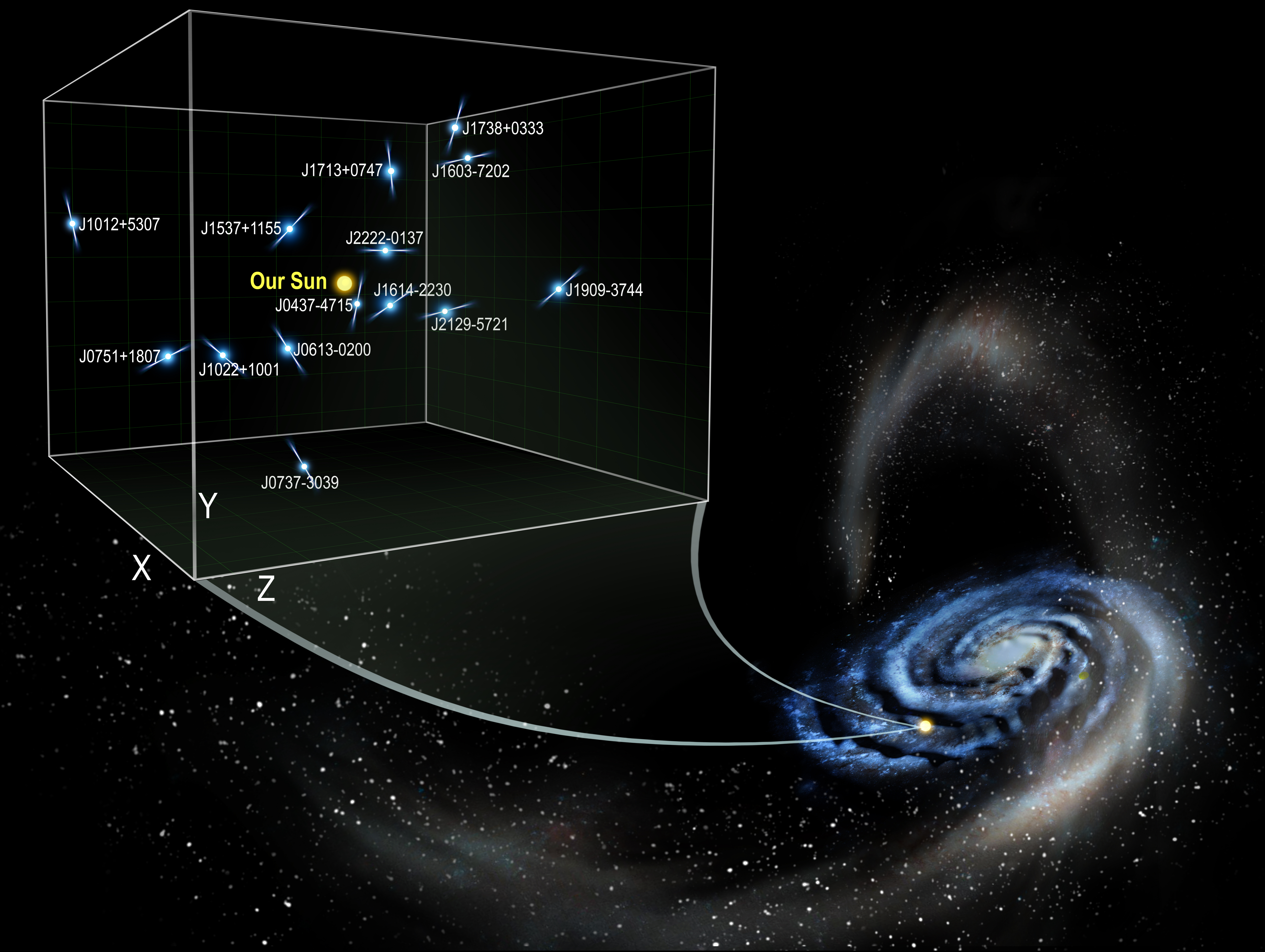






Credit: "Joeri van Leeuwen"

Using binary millisecond pulsars to measure Galactic accelerations



Basic setup

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

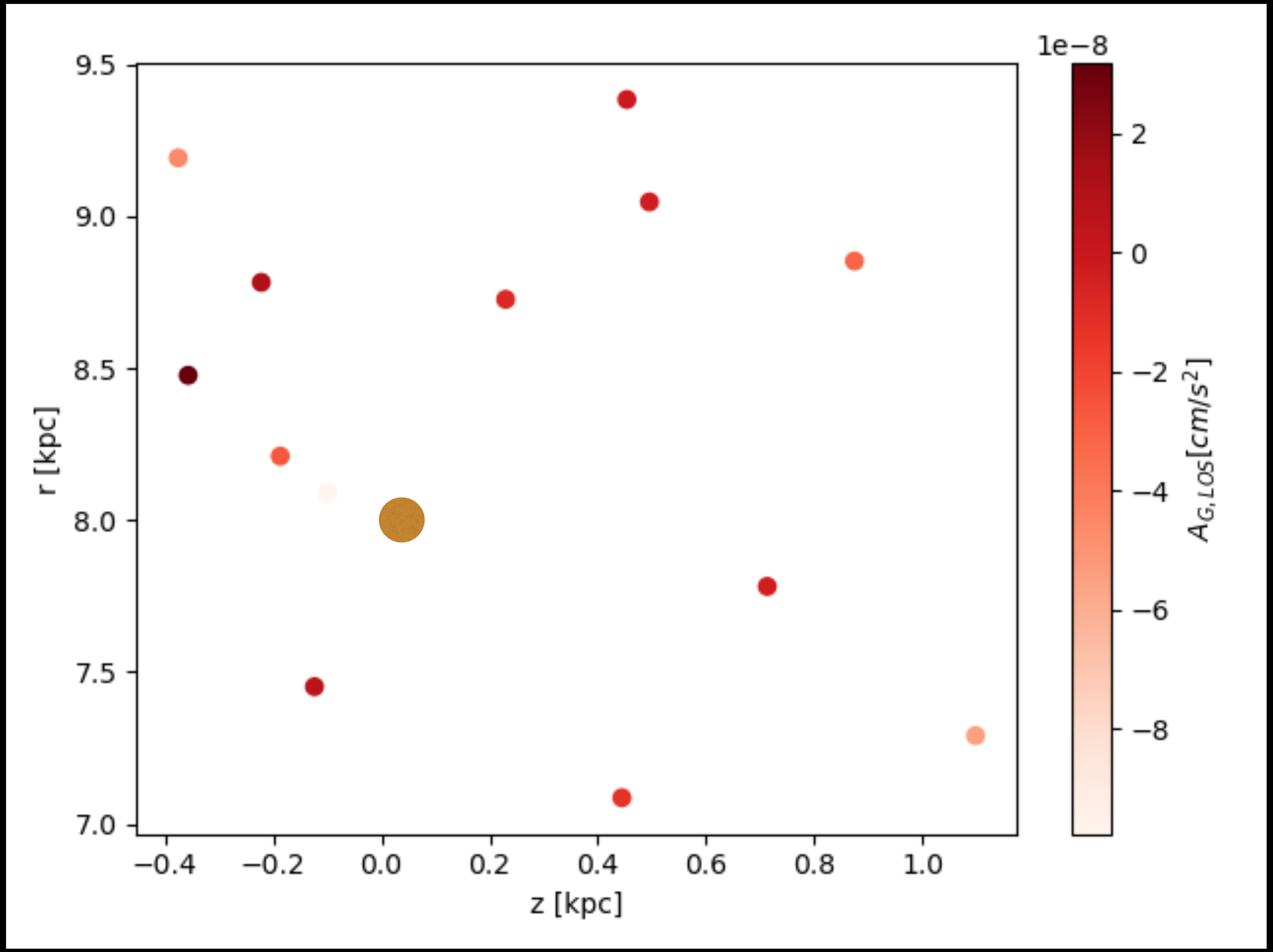
$$\dot{P}_b^{Shk} = \frac{P_b \mu^2 * d}{c^2}$$

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

Models vs observations



An example

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

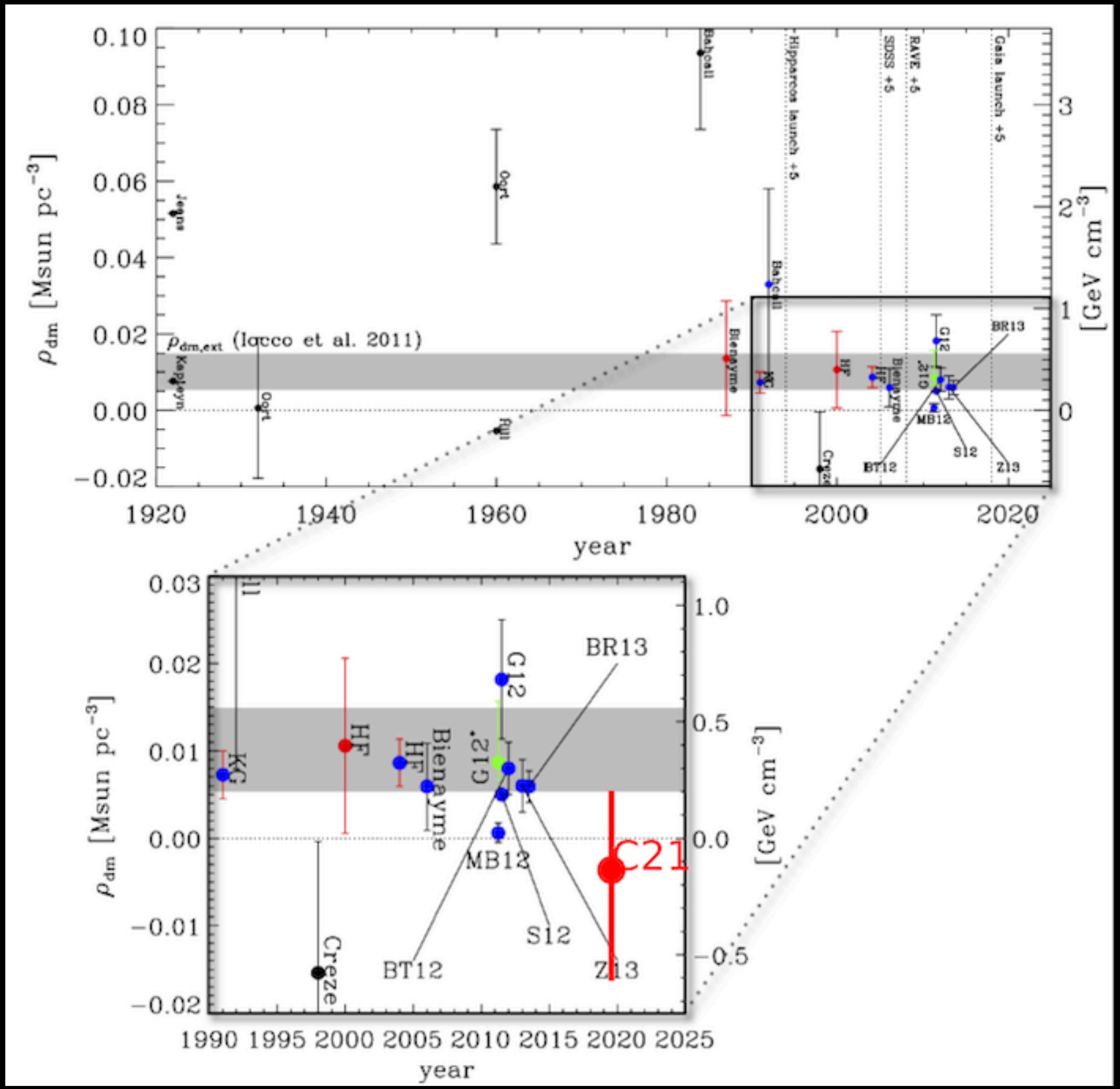
$$\Phi_r = \begin{cases} V_{LSR}^2 \ln\left(\frac{r}{R_\odot}\right) & \text{for} \quad \beta = 0 \\ \frac{V_{LSR}^2}{2\beta}\left(\frac{r}{R_\odot}\right)^{2\beta} & \text{for} \quad \beta \neq 0. \end{cases}$$

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

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

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

Best-fit parameters & Oort limit from pulsar timing



Chakrabarti, Chang, Lam, Vigeland & Quillen, 2021

Oort limit

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

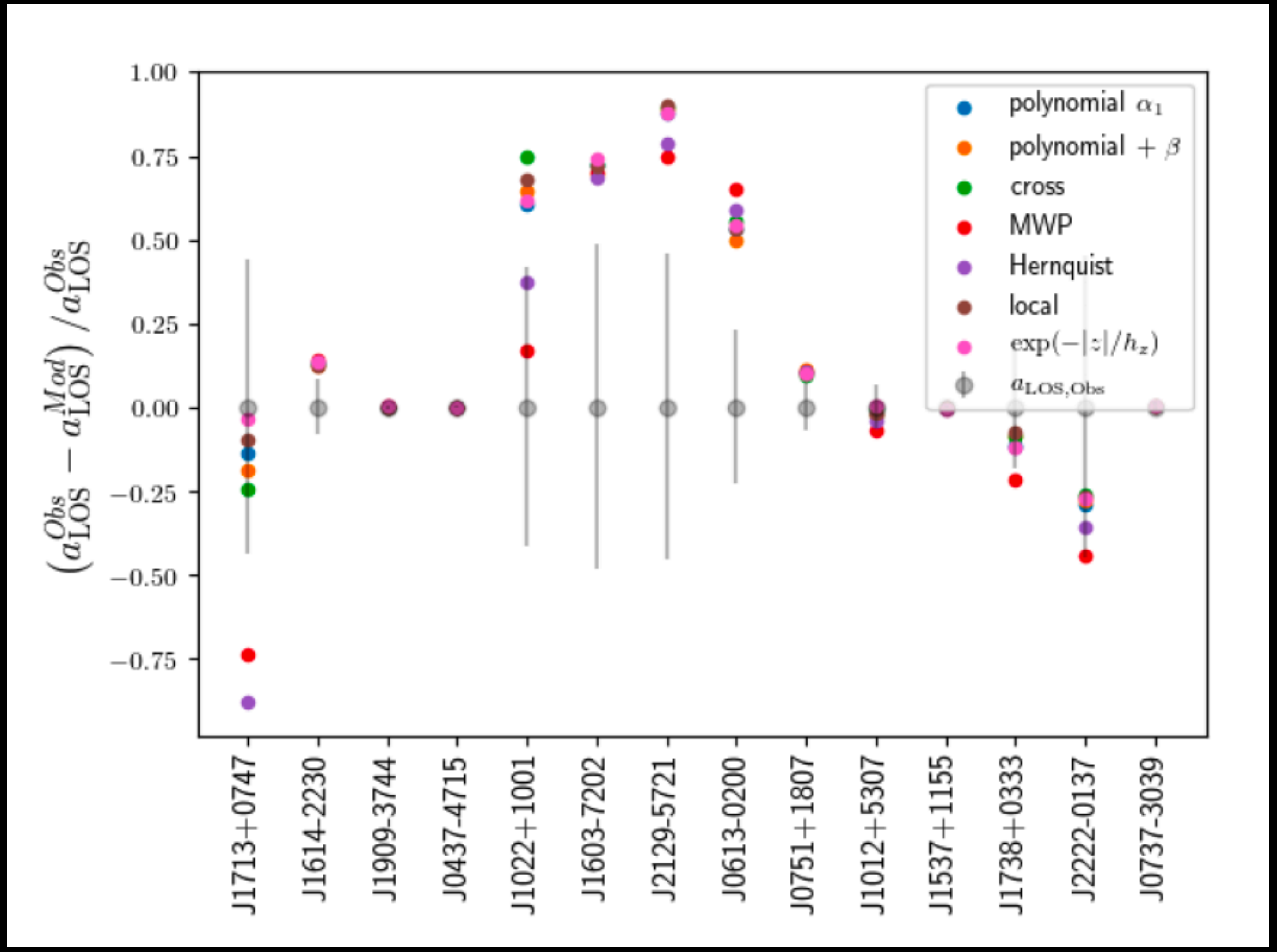
With baryon density from McKee et al. 2015:

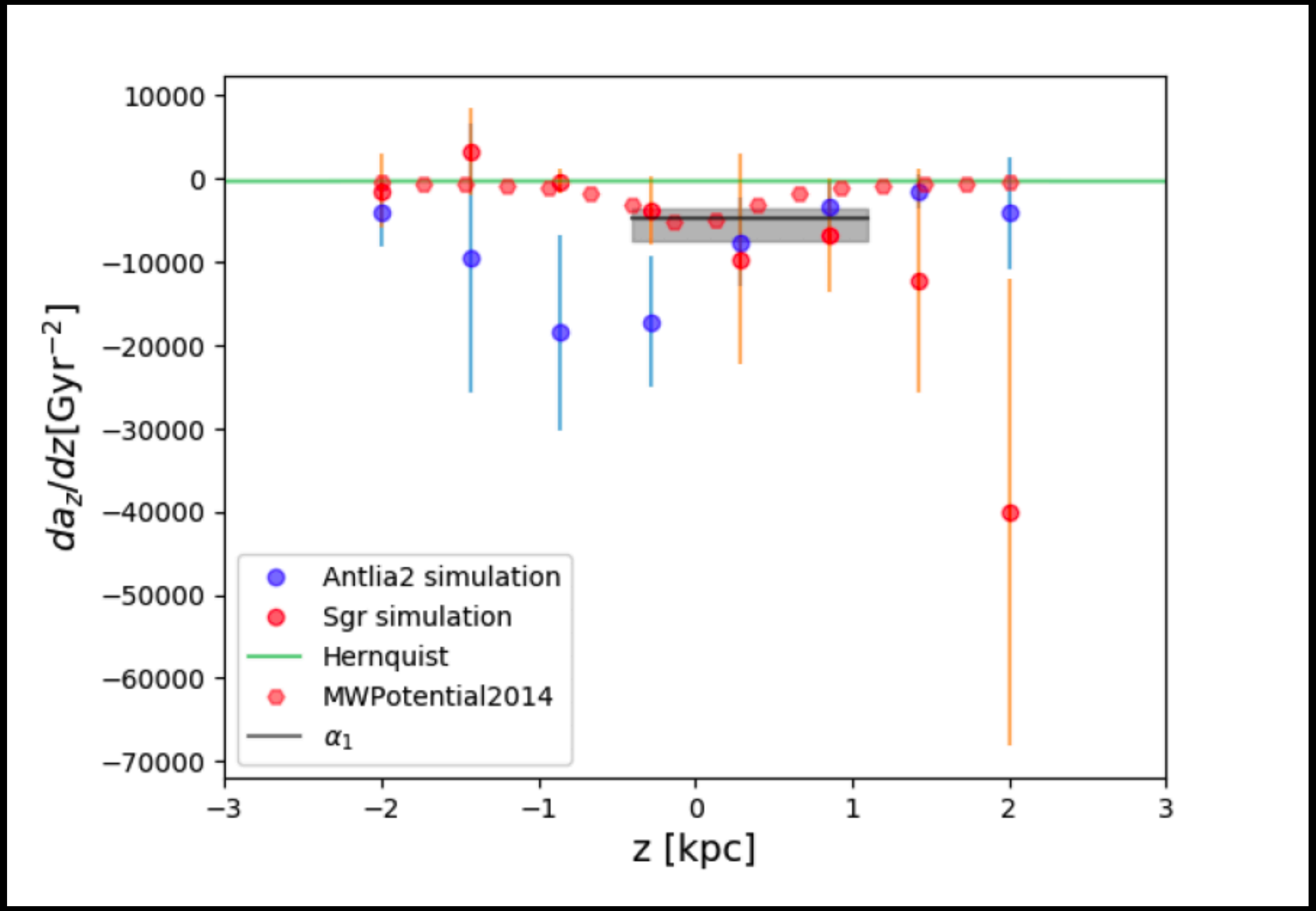
$$\rho_{DM} = -0.004^{0.05}_{-0.02} M_{\odot}/\mathrm{pc}^3$$

With baryon density from Bienyame et al. 2015:

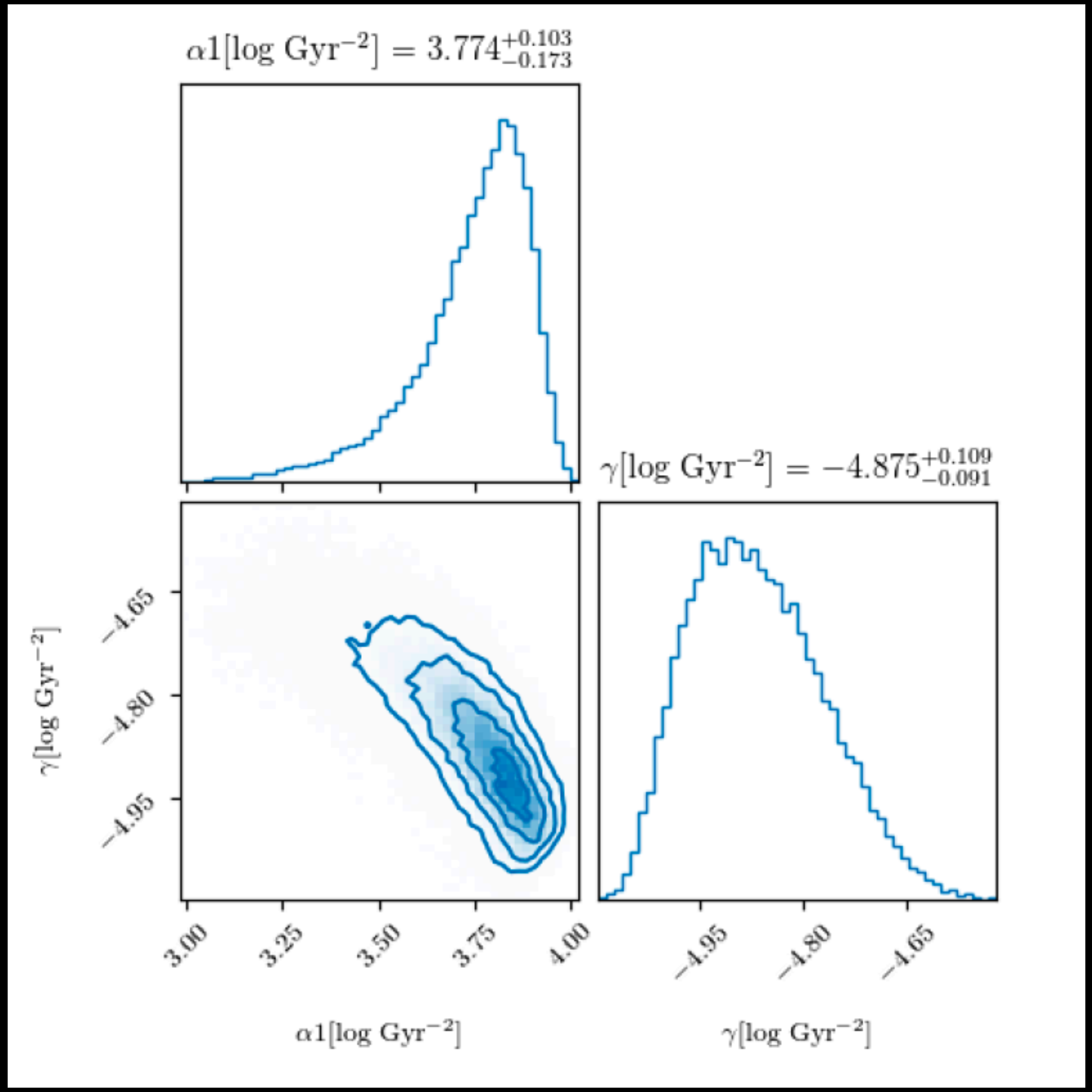
$$\rho_{DM} = 0.0034^{0.05}_{-0.02} M_{\odot}/\mathrm{pc}^3$$

Comparison to models





Constraint on oblateness of potential

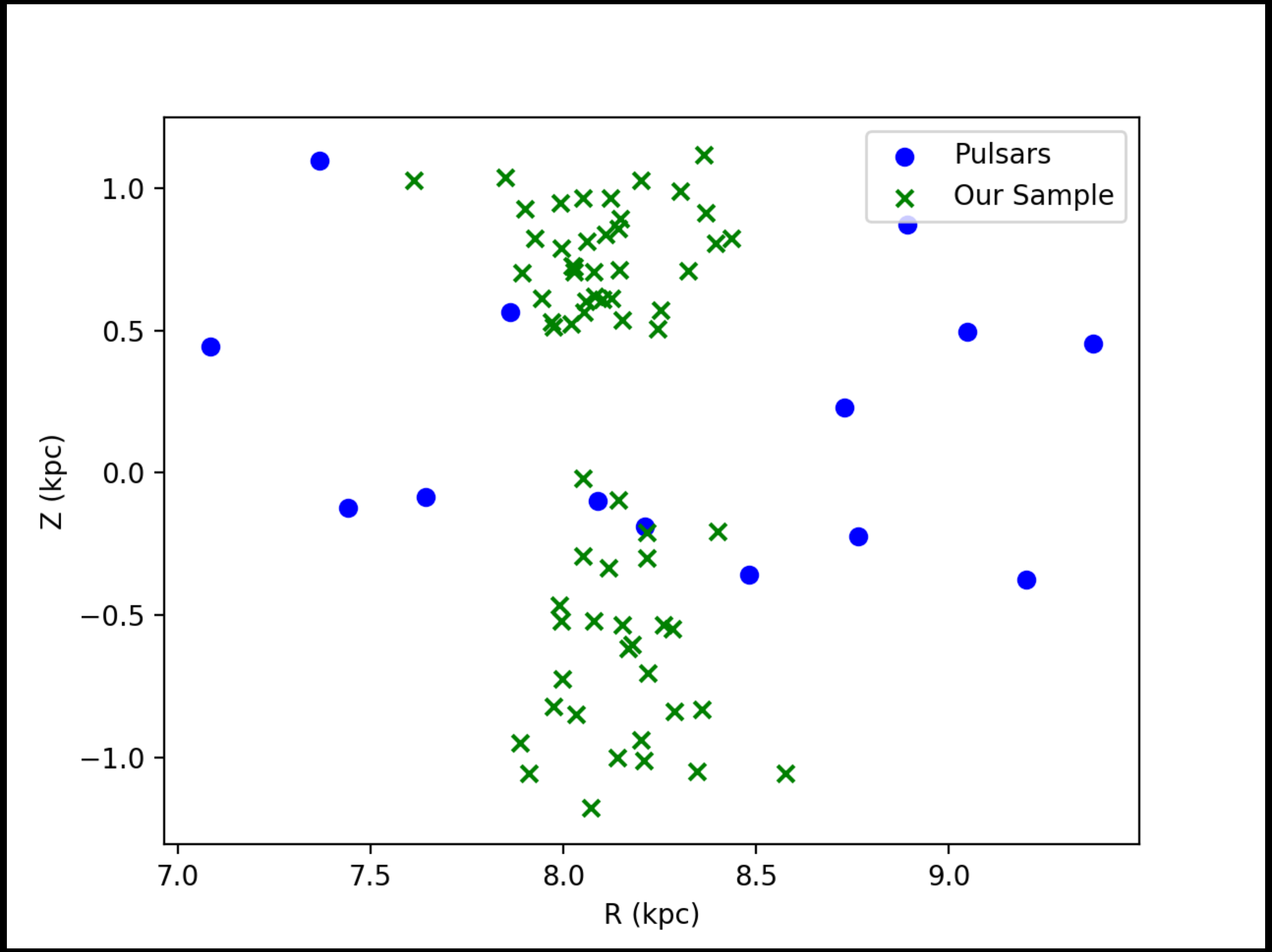


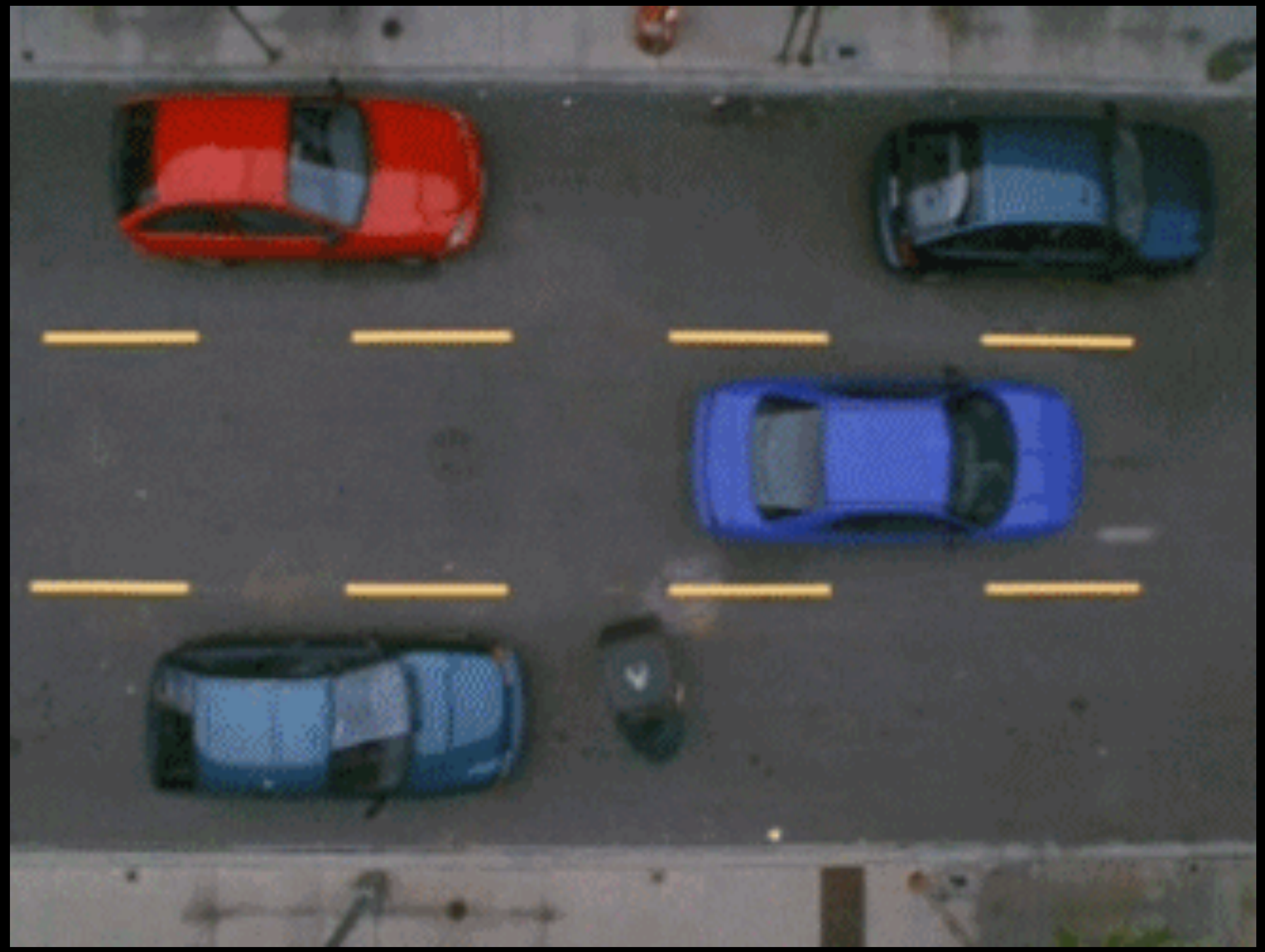
- Oblateness traces disk

Effect of interactions, dark matter sub-structure

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

Extreme precision RV sample ESPRESSO (PI: Chakrabarti)

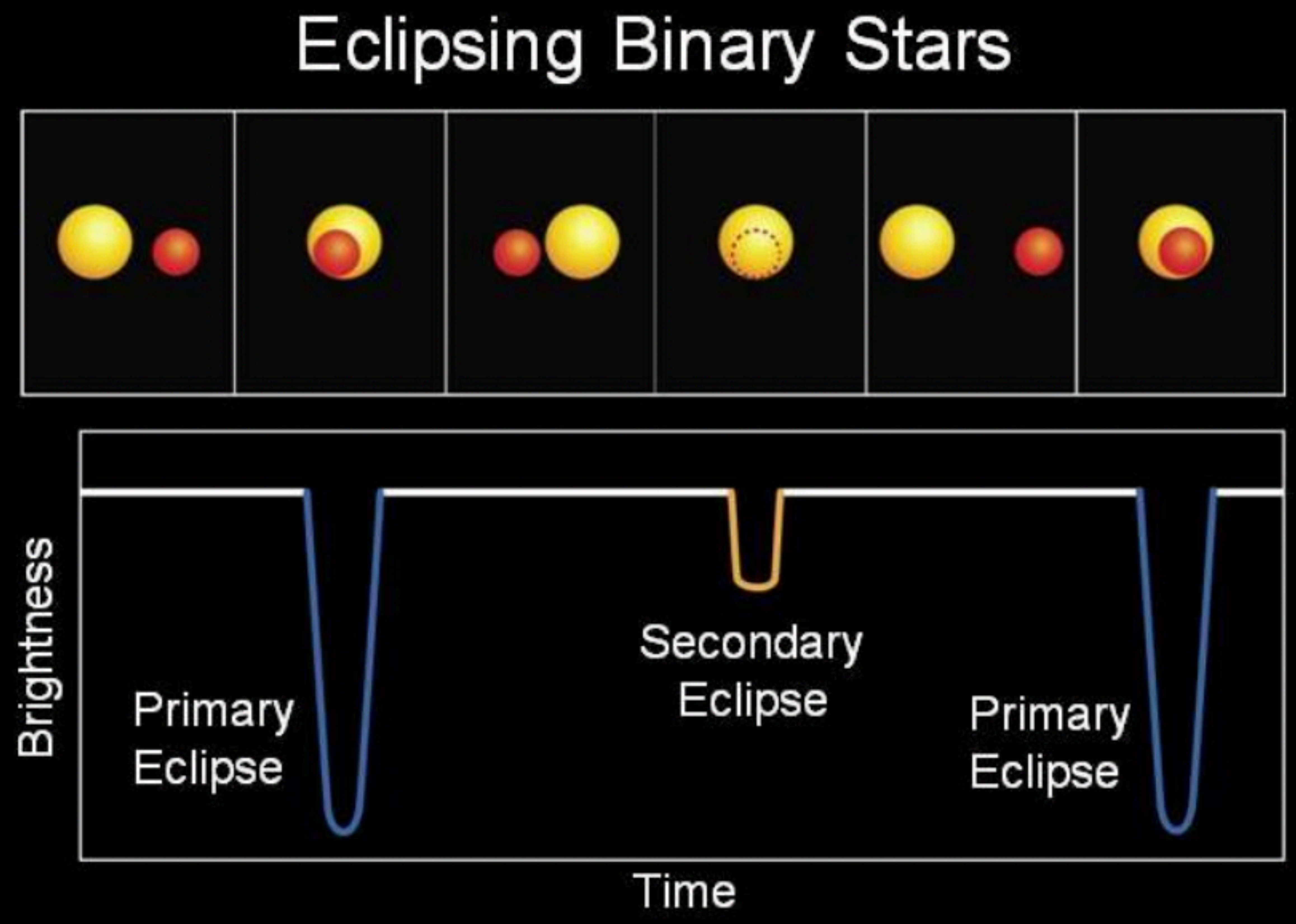


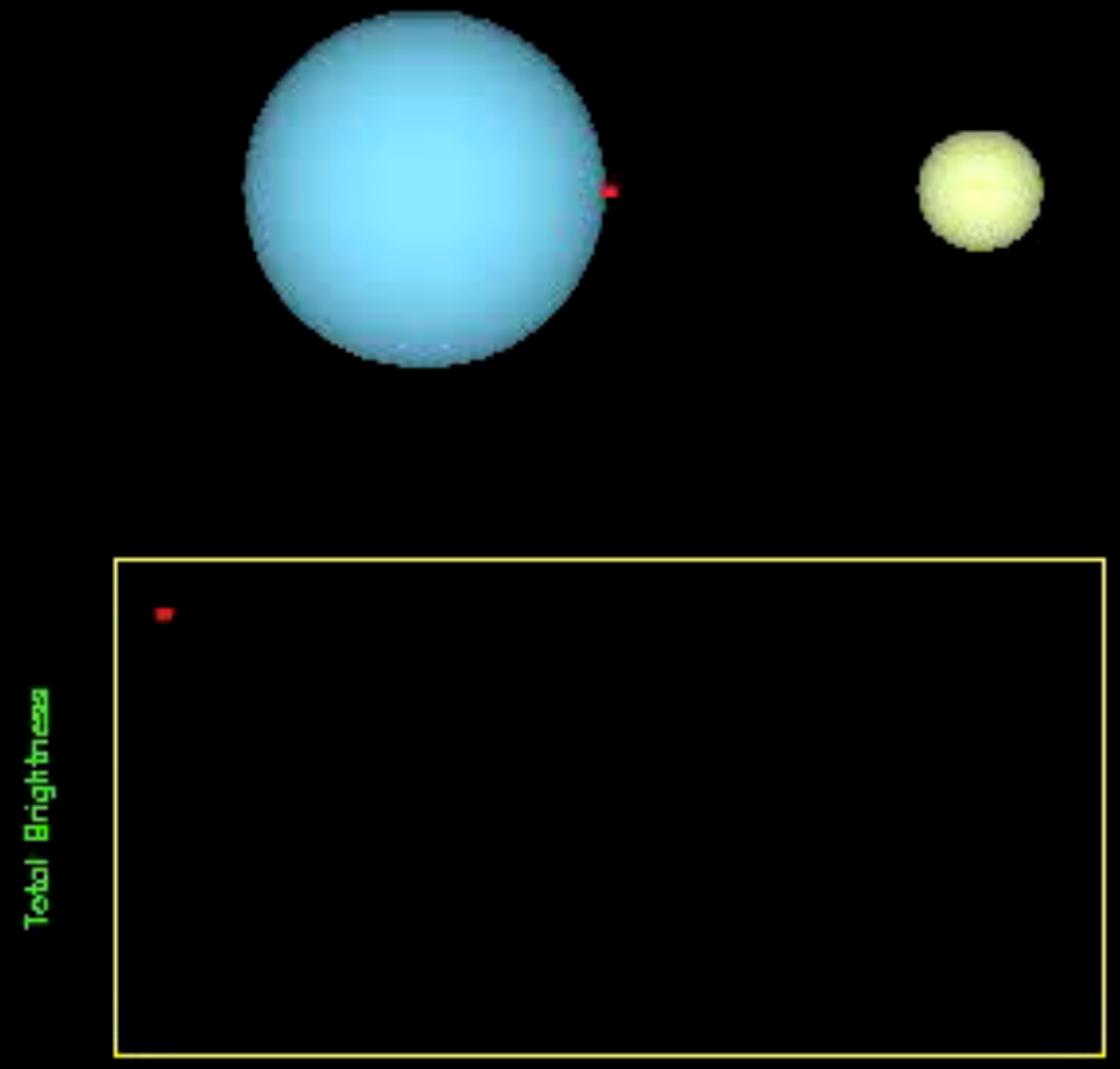


Non-smooth acceleration

Bullock & Boylan-Kolchin 2017

Eclipse timing





- Measure Galactic acceleration from shift in eclipse mid-point time over decade baseline ~ 0.1s.

- Requires v high (space-based) photometric precision

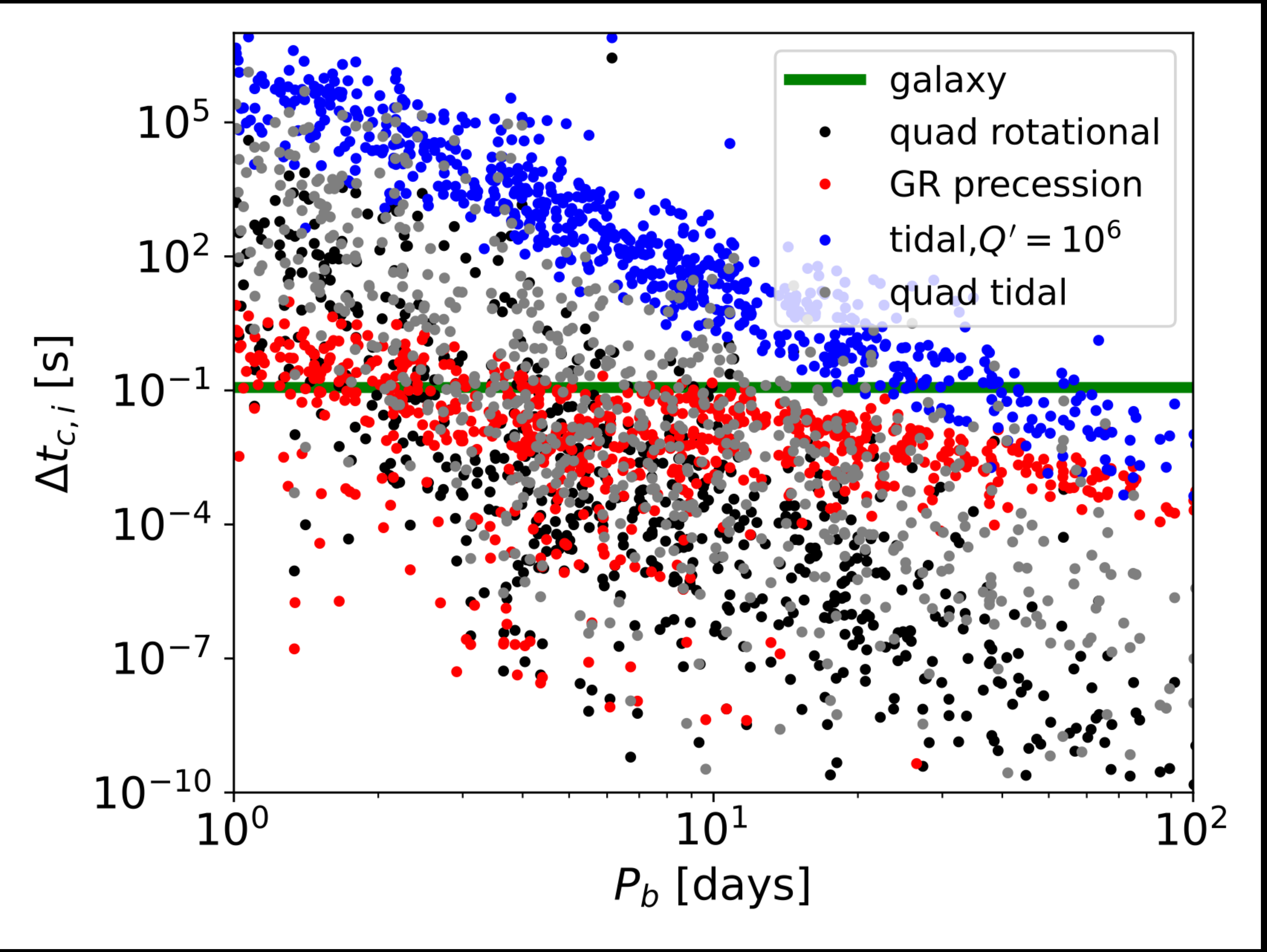
- It's been about a decade since Kepler!

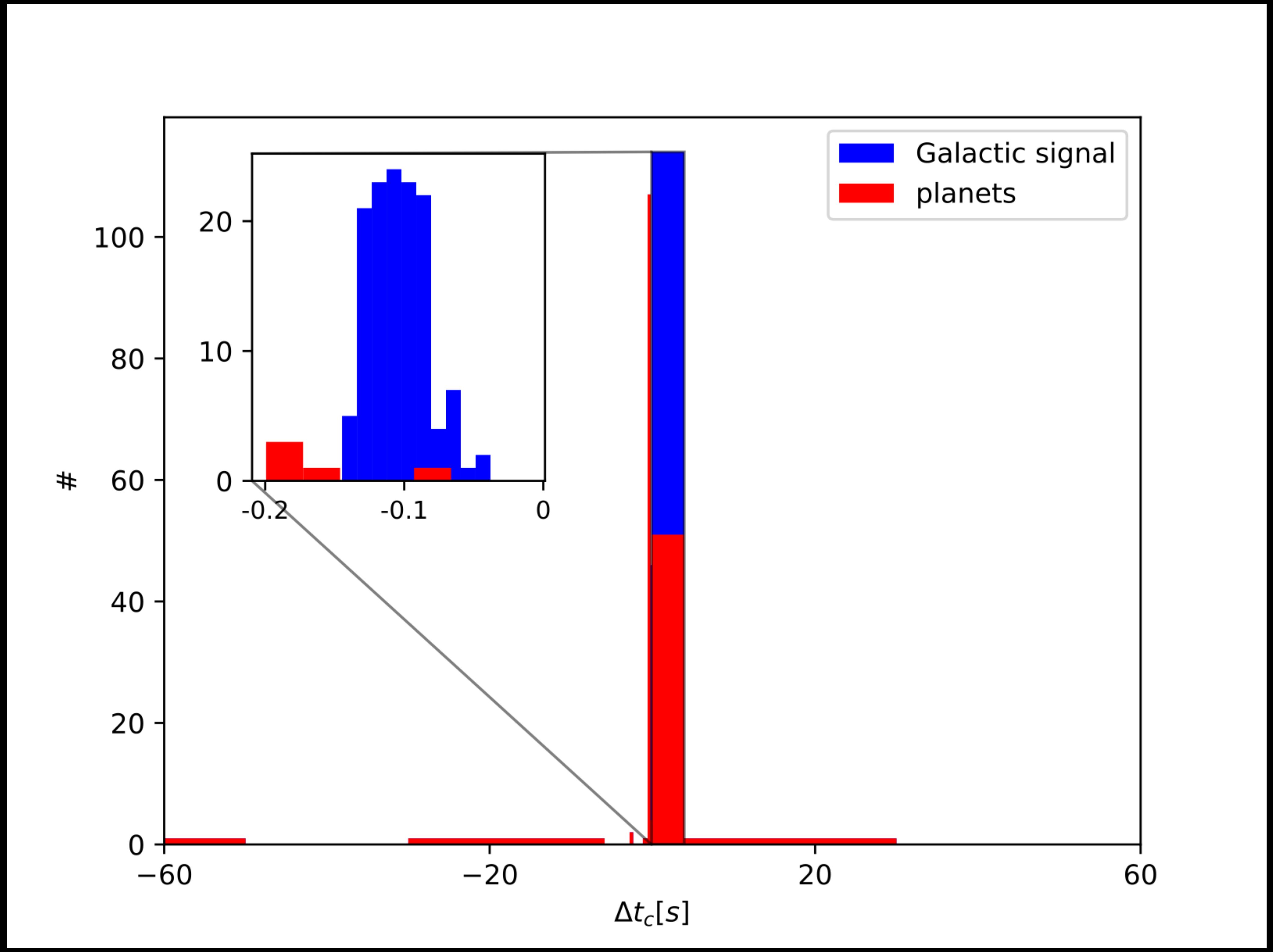
$$\Delta t_{c,Gal} = \frac{\dot{P}_{b,Gal}}{P_b} T^2$$

Contaminants to the Galactic signal

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

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

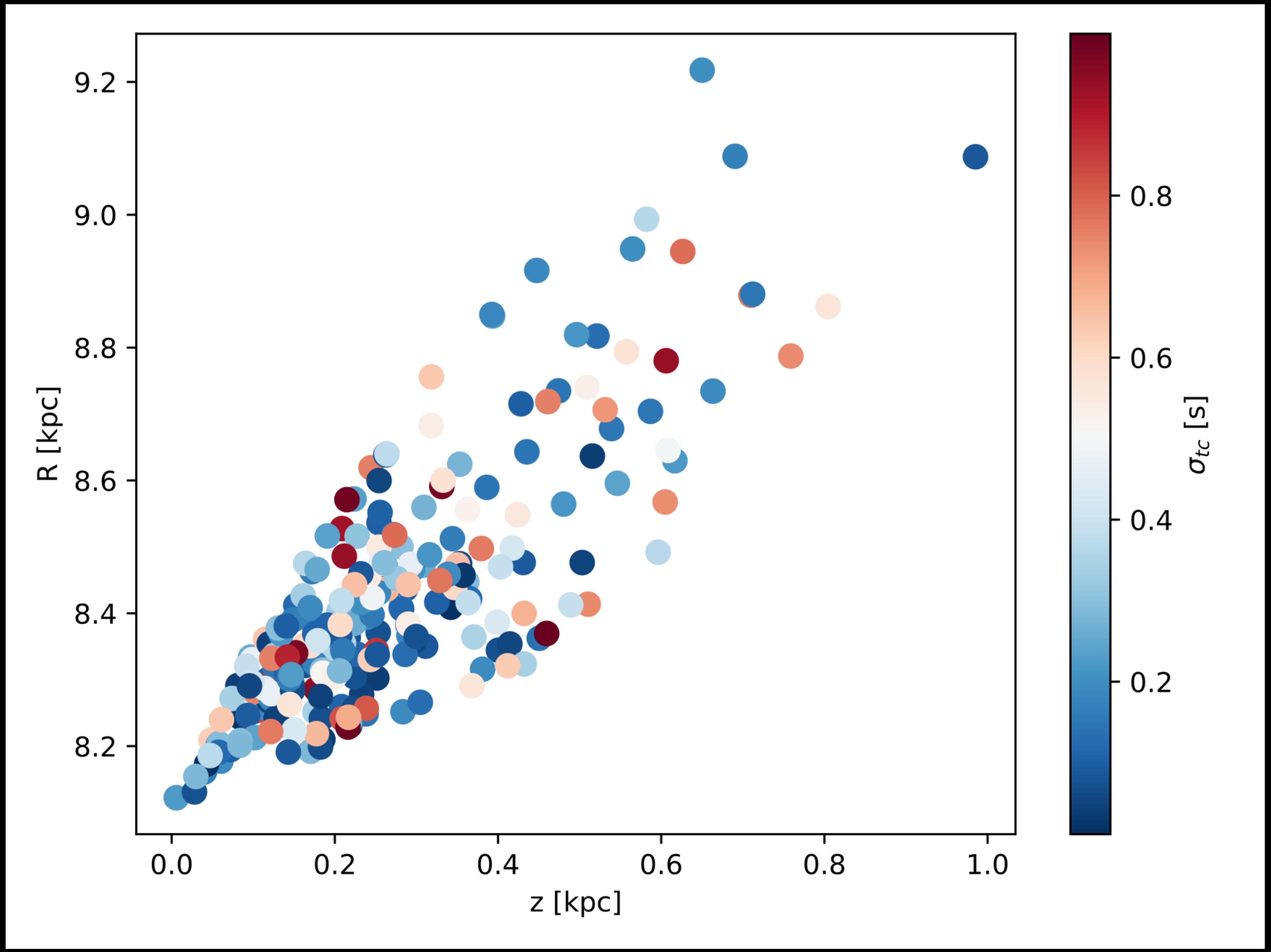




Circumbinary planets

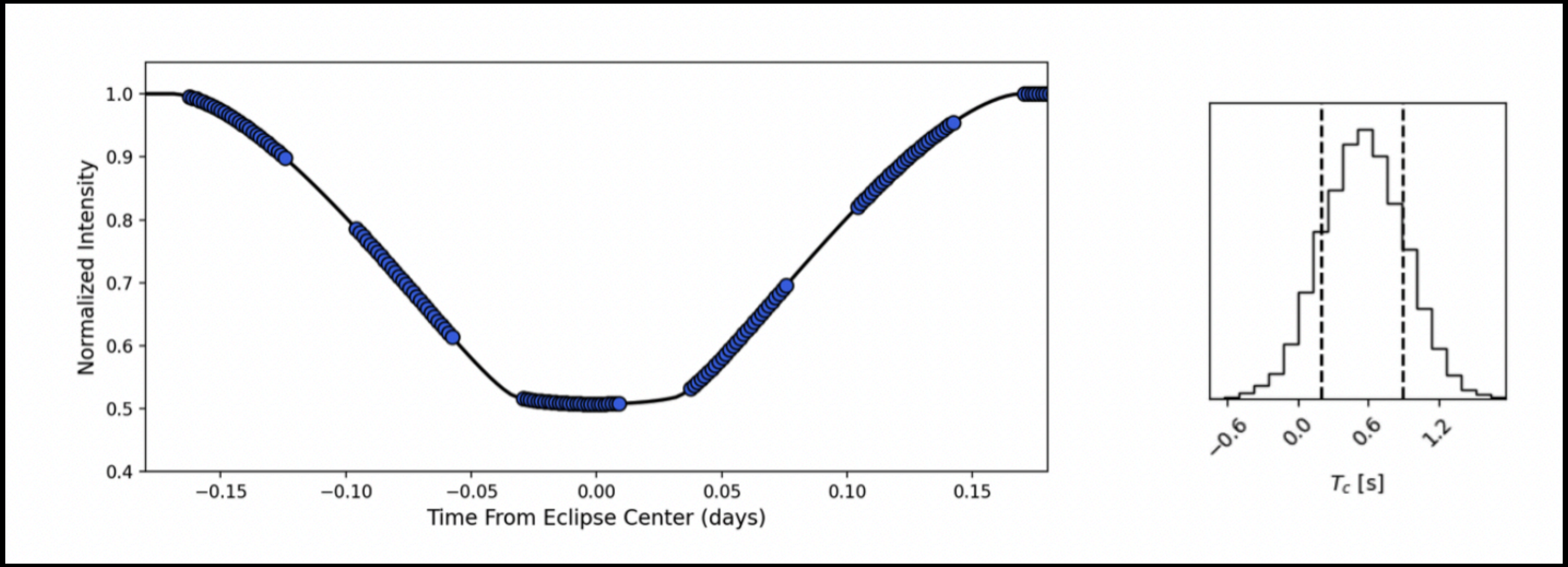
Chakrabarti, Stevens, Wright, Rafikov, Chang, Beatty & Huber 2022

Expected precisions



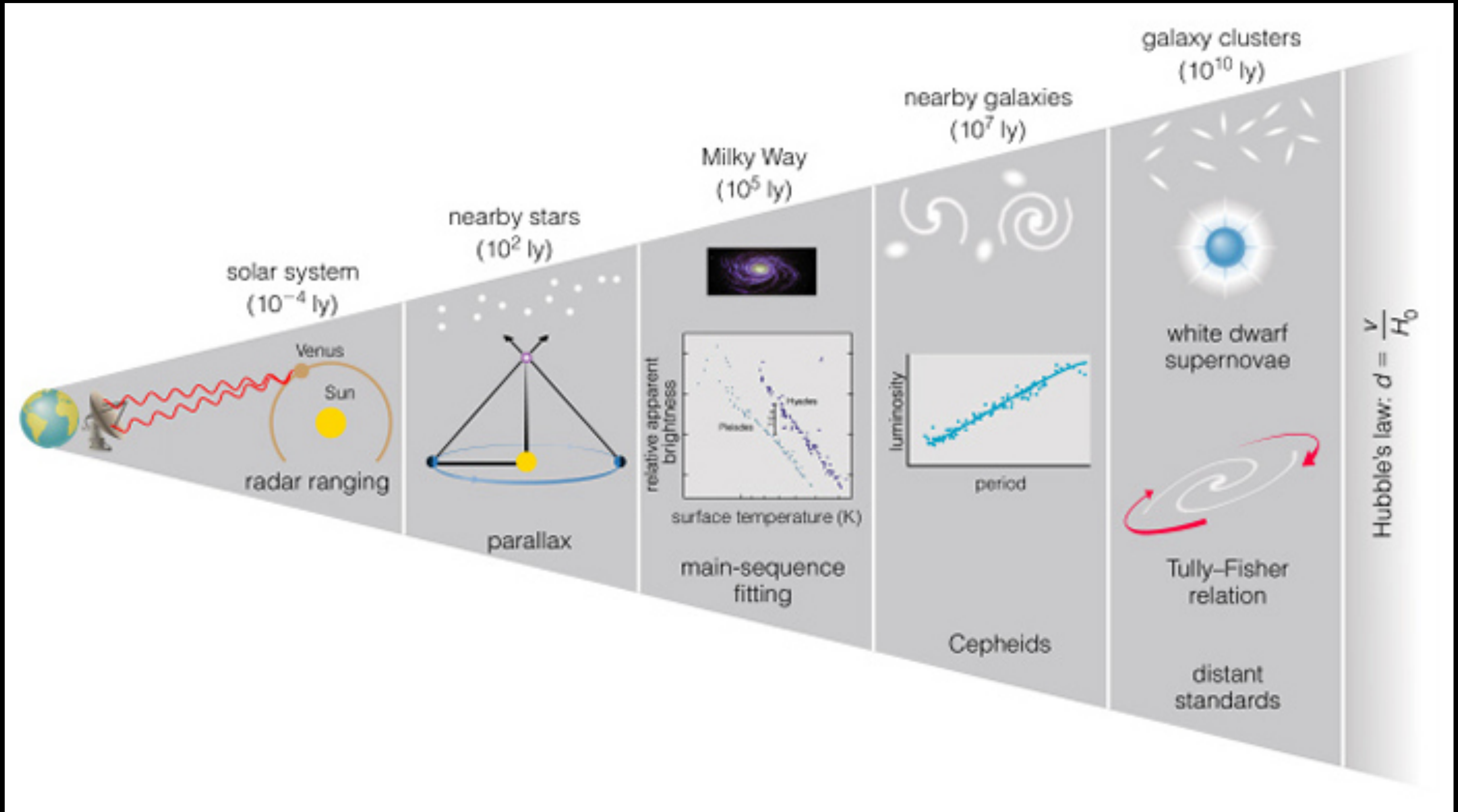
C22

A prototypical eclipsing binary - proof of principle



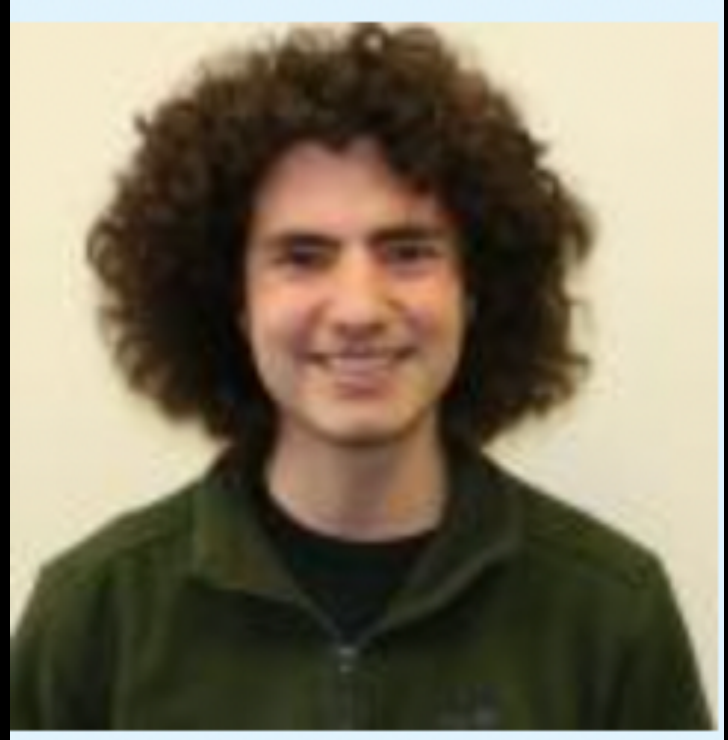
Need HST level precision (C22)

Acceleration measurements ***across*** the Galaxy



The distance ladder

Towards an acceleration ladder

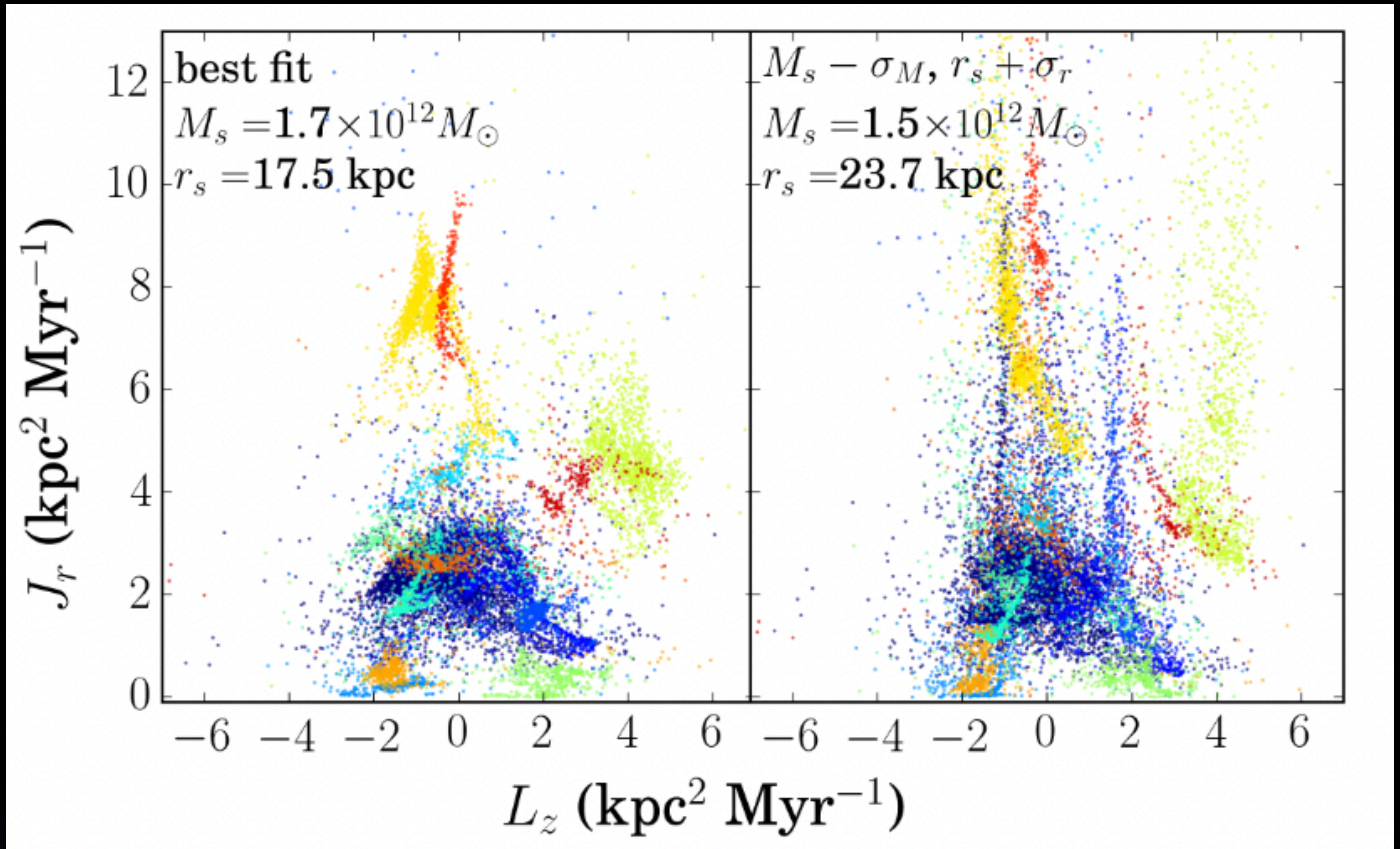


Peter Craig

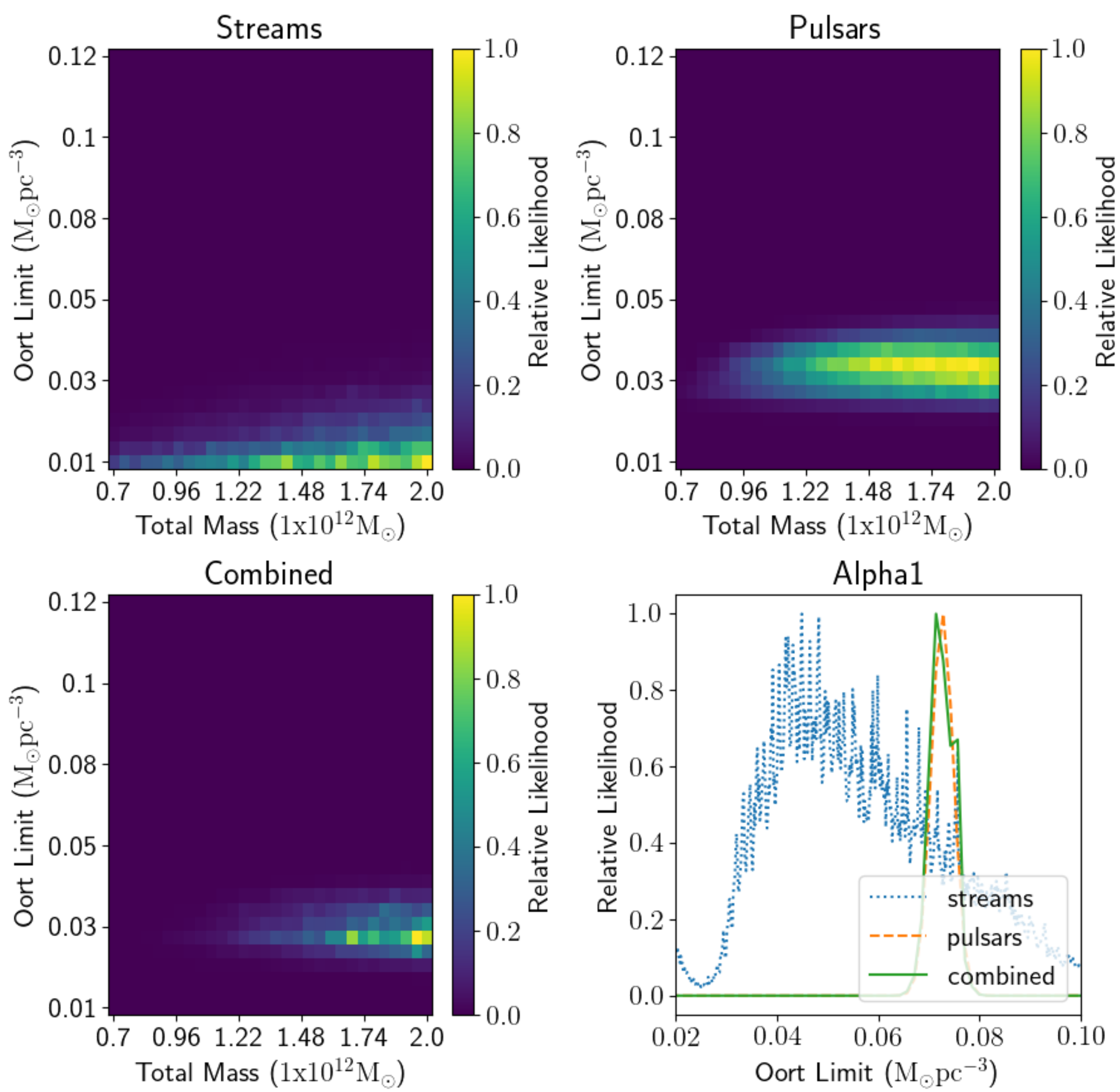
- Stellar streams to constrain the Galactic potential. We can expect to discover many stellar streams in the Galaxy and beyond with Rubin & Roman!

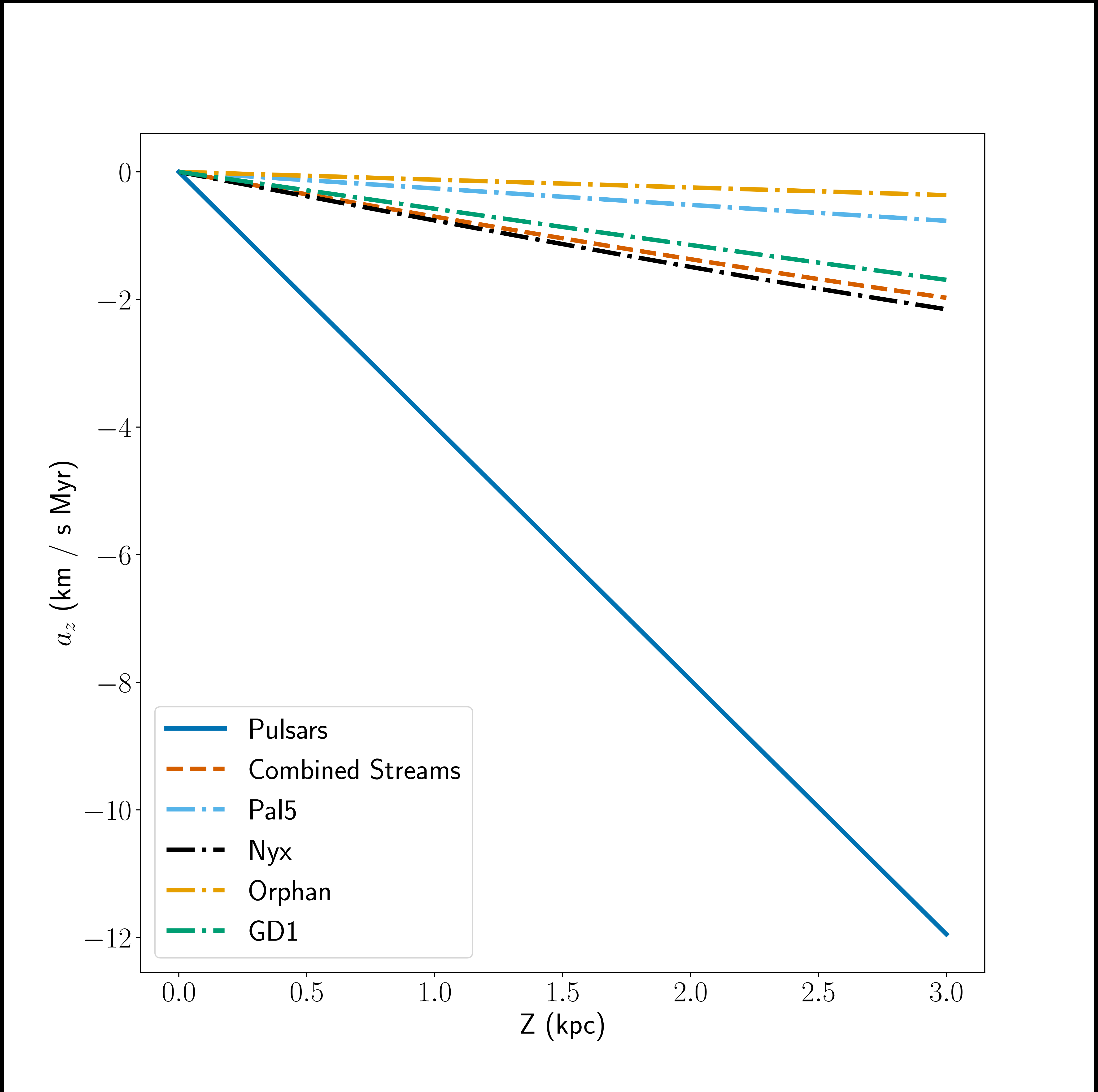
- Direct acceleration measurements can at present only access a small volume

- Calibrate stellar stream accelerations to pulsar accelerations (Craig, Chakrabarti, Sanderson et al., 2023)



Sanderson et al. 2017





Stream accelerations vs pulsar accelerations

Joint constraints from streams and pulsar timing

Craig et al., 2023

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 traced by pulsars similar to disk (rather than halo)
3. Large uncertainties in slope of rotation curve (but consistent with being flat)

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

Extending pulsar sample (15-year Nanograv dataset), EPRV surveys (ESPRESSO - Fall 2021 - onwards); **pathfinder for ELTs**

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