Implications of Noether's Theorem at Galactic Scales

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Based on
SG, Austin Hinkel (U. Kentucky), Brian Yanny (Fermilab),
``Applying Noether's theorem to matter in the Milky Way: evidence for external perturbations and non-steady-state effects from *Gaia* Data Release 2,"
submitted to ApJ

Research supported by the U.S. Dept. of Energy Office of Nuclear Physics under DE-FG02-96ER40989

``Next Frontiers in the Search for DM"
GGI Institute, Arcetri, Florence
September 23, 2019

Perspective

The matter of a isolated galaxy in steady state has a distribution function (DF) controlled by its integrals of motion — in an axially symmetric galaxy E and L_z should be integrals of motion [Jeans, 2015; Binney & Tremaine, 2008]

In our galaxy, the stellar relaxation time exceeds the age of the Universe — and we can neglect stellar collisions to model the stars as a continuous mass distribution

Thus enters the DF, and its continuous symmetries.

Noether's theorem tells us that for each variational symmetry of an action there is an associated conservation law [Noether, 1918]

Here we test the symmetry to probe the conservation law.

Theory Framework

Here we test axial symmetry of out-of-plane Milky Way stars to probe L_z as an integral of motion

[Noether, 1918; Olver, 1993]

An axially symmetric galaxy in steady-state must also be north-south reflection symmetric

[An et al., 2017; note also Schulz et al., 2013]

If axial symmetry is broken, non-isolating and possibly time-dependent forces must be at work

But a north-south symmetry-breaking pattern speaks to non-steady-state effects, both in and on the Milky Way

Thus studying axial symmetry breaking, north and south, can separate non-isolating from non-steady-state effects

Gaia Data Release (DR2) Data

Select a North/South/Left/Right matched sample

- Choose stars with measured parallaxes [Lindegren et al., 2018]
- Apply +0.07 mas parallax offset to parallax p & then require p > 0 [Zinn et al., 2019; Stassan & Torres, 2018; Lindegren et al., 2018]
- Require |b| > 30°
- Remove LMC/SMC pollution cannot be removed by p error cut; excise via *l*, *b* cut and apply mirrored cuts

Choose [Hinkel, SG, Yanny, in prep.]

$$G_{BP} - G_{RP} \in [0.5, 2.5]\,\mathrm{mag};\, G \in [14, 18]\,\mathrm{mag};\, R \in [7, 9]\,\mathrm{kpc};\, |z| \in [0.2, 3]\,\mathrm{kpc}$$

Table 2. The number of stars found in each quadrant of the analysis, with $|180° - \phi| < 12°$ Totals for the left and right are also shown. The sample is very well matched, left and right, with an aggregate asymmetry of $\mathcal{A} \approx 6 \times 10^{-4}$.

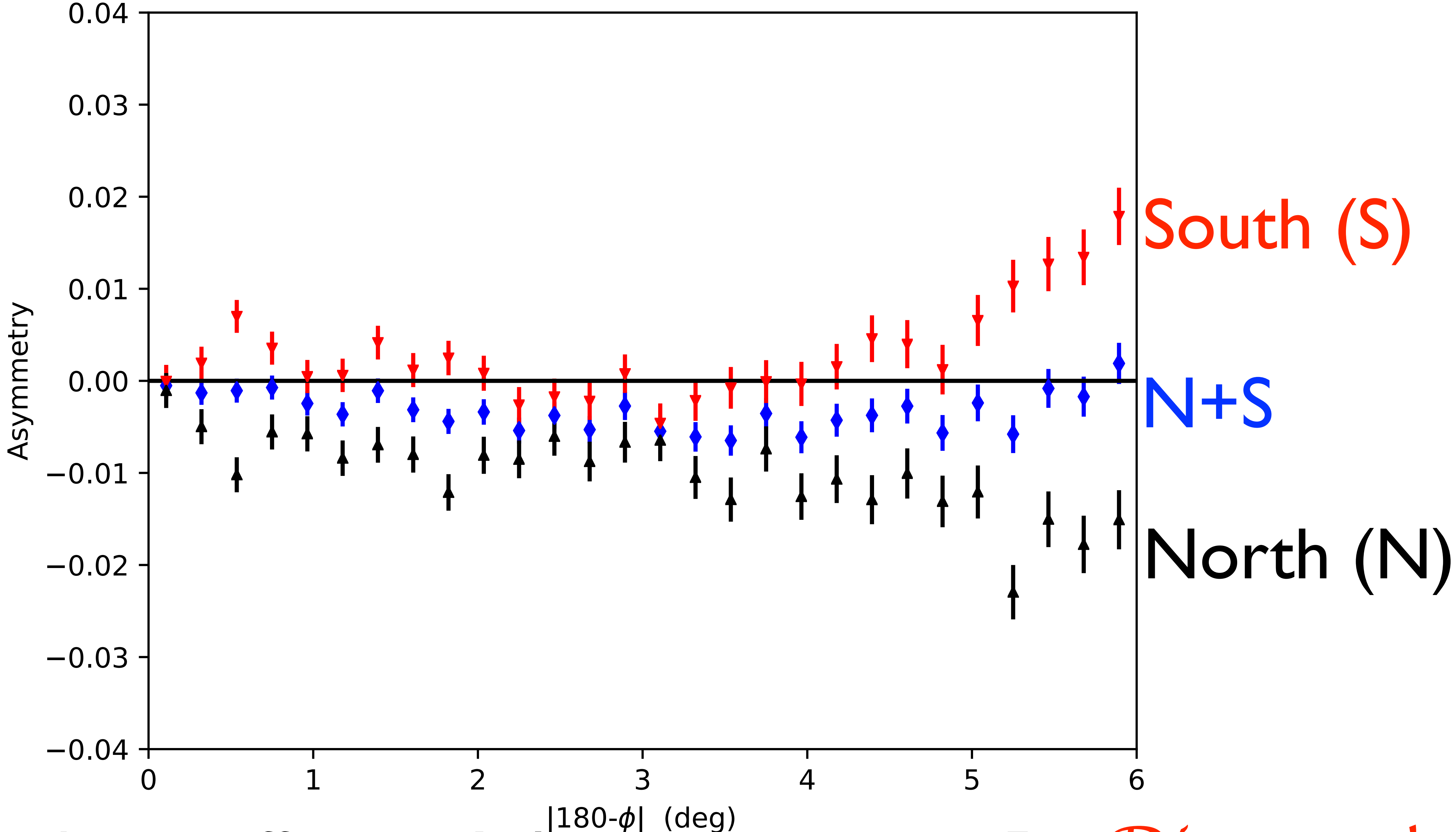
	Left	Right	Asymmetry (%)
North	3,376,969	3,471,980	-1.39
South	3,815,477	3,729,647	1.14
TOTAL:	7,192,446	7,201,627	-0.06

14.4 million stars matched to 0.06%

Left-Right Asymmetry from *Gaia* DR2

Asymmetries implicitly integrate over z and R

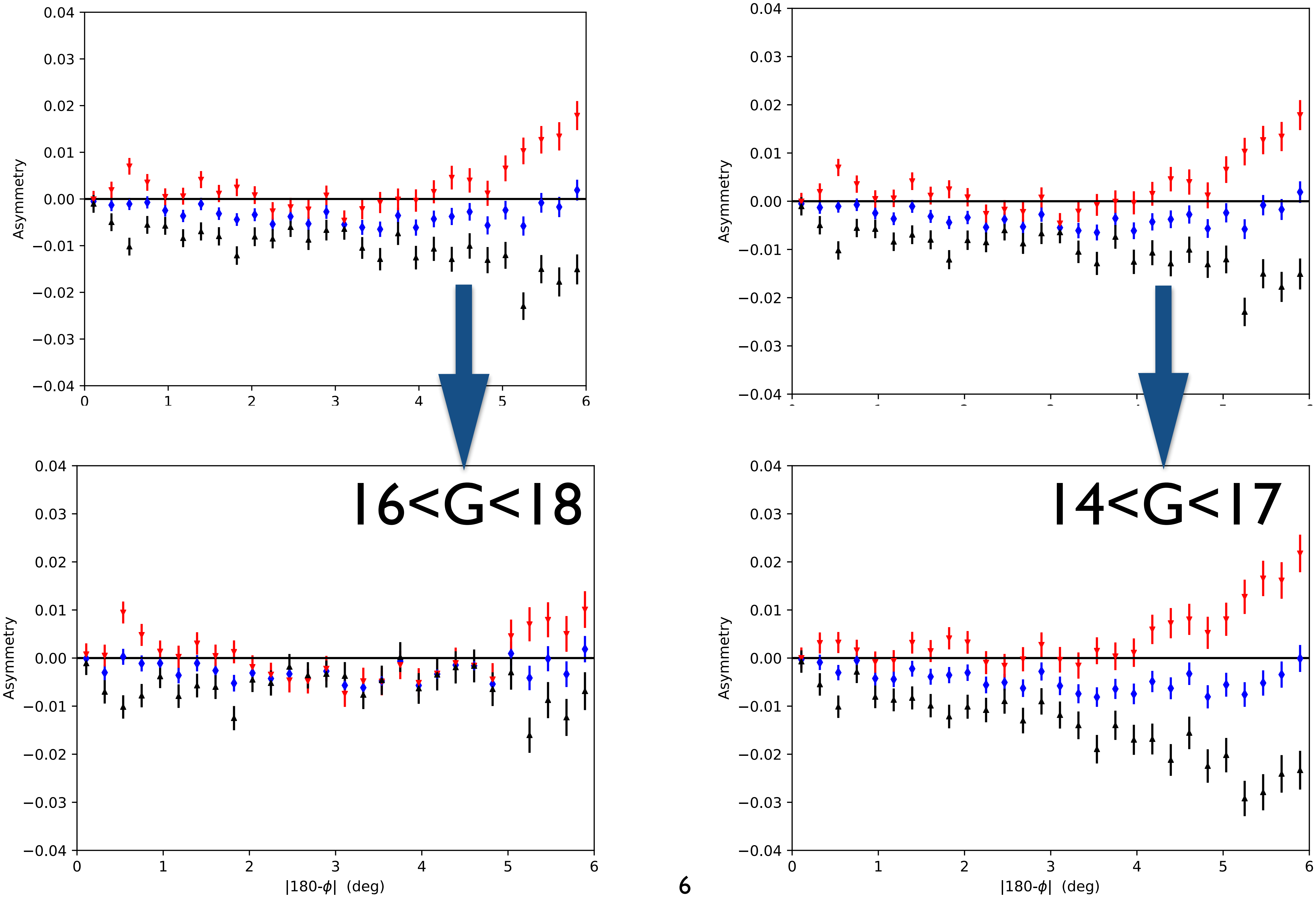
$$\mathcal{A}(\phi) = \frac{n_L(\phi) - n_R(\phi)}{n_L(\phi) + n_R(\phi)}\,; \quad \text{Note } n_L(\phi)\,[\phi > 180°]\,,\; n_R(\phi)\,[\phi < 180°]$$



χ^2 test shows offset and slope nonzero >> 5σ *Discovery!*

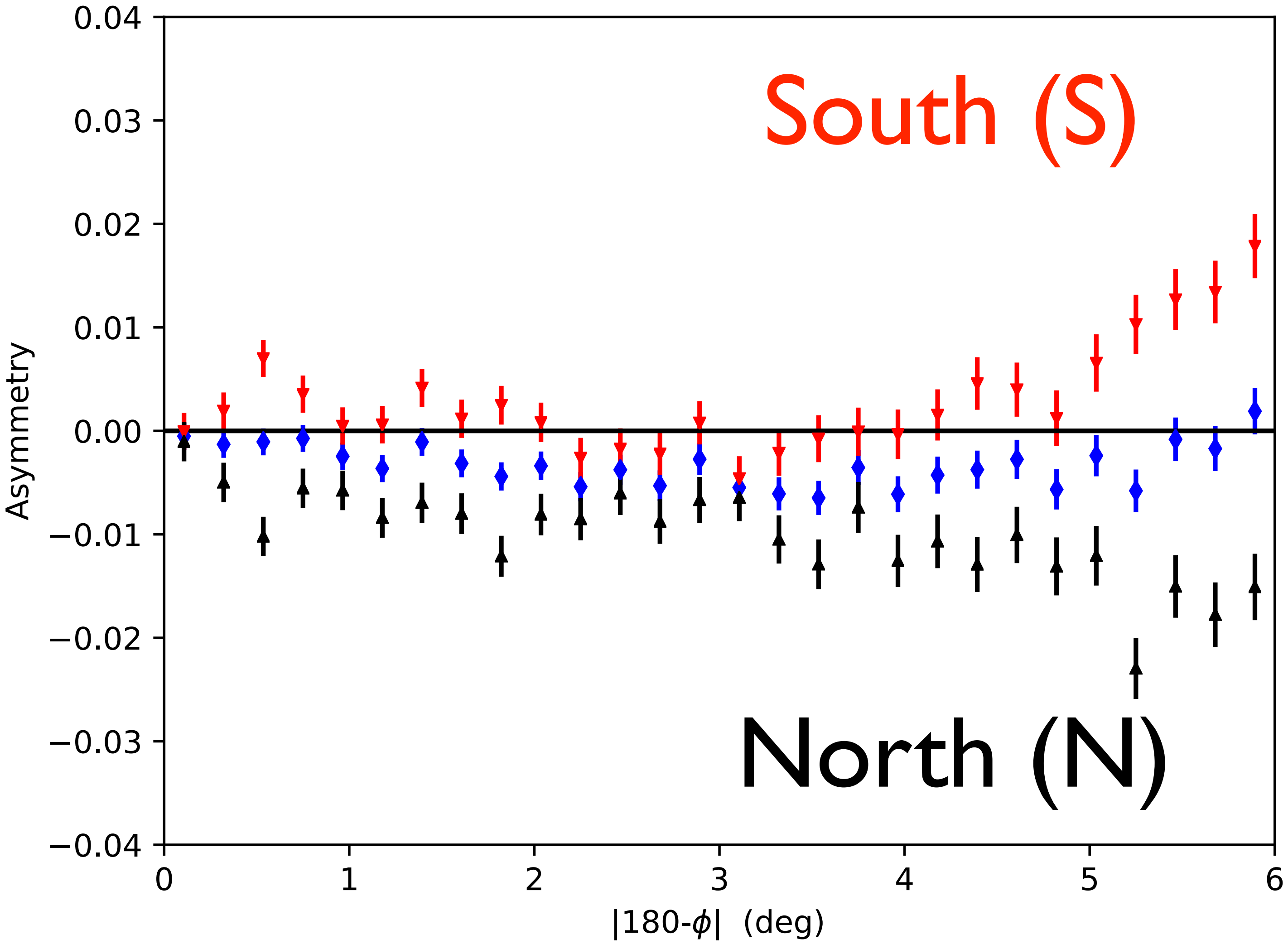
Cross-Checks

Asymmetry insensitive to stellar population chosen



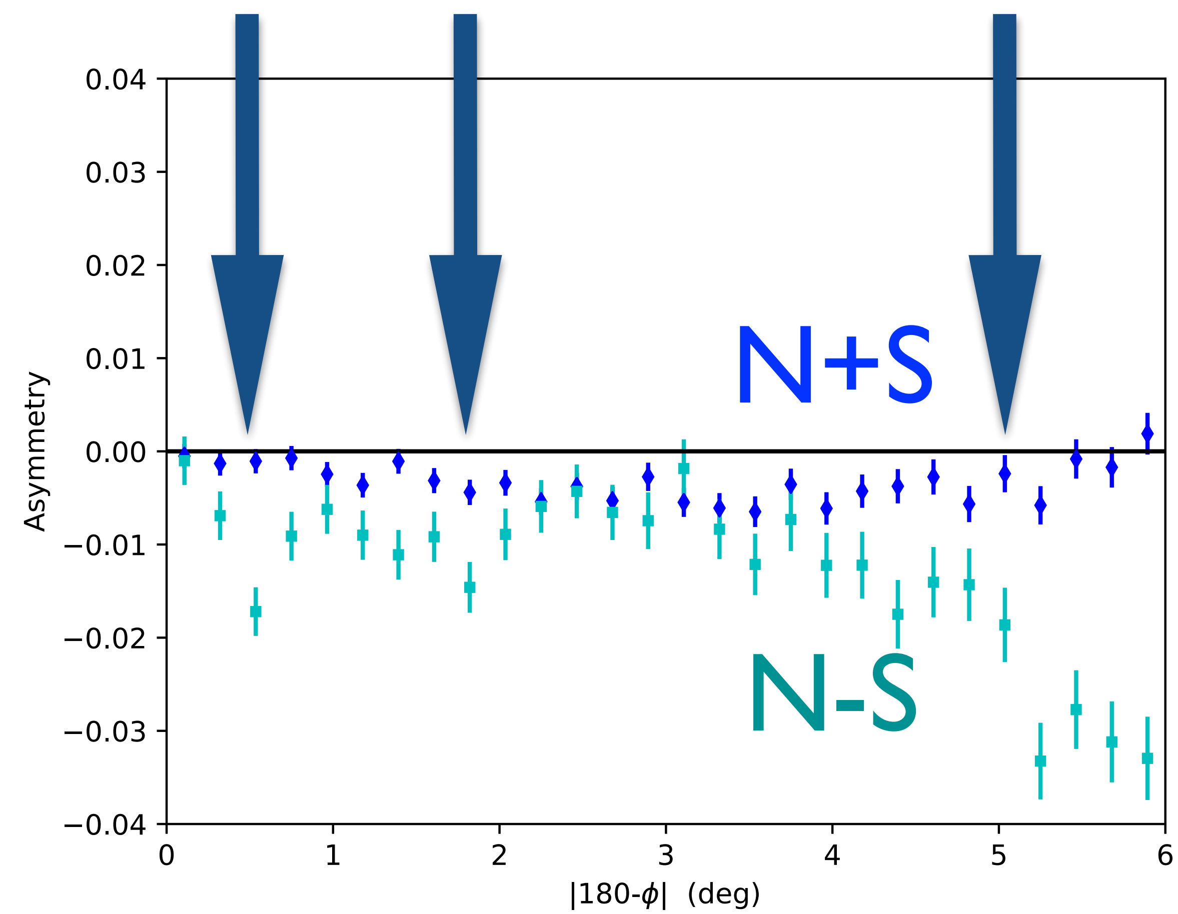
Left-Right Asymmetry from *Gaia* DR2

Asymmetries differ N and S and sometimes marked so!



N+S

$|180° - \phi| \approx 0.5°, 1.8°, >5°$



$A_N - A_S > A_{N+S}$ implies non-steady-state effects exist!

Sources of Left-Right Asymmetry?

Estimate torques (in z) at the Sun's location

Table 1. Nearby objects that torque the stars in our sample, with torque reported in units of $M_\odot^2$/pc. The errors in the inputs are such that the LMC system undoubtedly gives the largest effect.

Object	Mass ($M_\odot$)	distance (kpc)	M/d^2 ($M_\odot$/pc^2)	τ_z ($M_\odot^2$/pc)
LMC (& SMC)	$1.4(3) \times 10^{11}$ [a]	52(2) [b]	51	340,000
M31	$1.3(4) \times 10^{12}$ [c]	772(44) [d]	2	-14,000
Triangulum	6×10^{10} [e]	839(28) [f]	0.1	-420
Galactic Bar/bulge	$1.87(0.4) \times 10^{10}$ [g]	8 [h]	288	-47,000
Sagittarius	$2.5(1.3) \times 10^{8}$ [i]	28 [i]	0.3	-240
Fornax	$1.6(1) \times 10^{8}$ [j]	138(8) [j]	0.01	23
Carina	$2.3(2) \times 10^{7}$ [j]	101(5) [j]	< 0.01	16
Sextans	$4.0(6) \times 10^{7}$ [j]	86(4) [j]	0.01	29
Sculptor	$3.1(2) \times 10^{7}$ [j]	79(4) [j]	0.01	5
Gaia-Enceladus	$\mathcal{O}(10^9)$ [k]	-	-	-

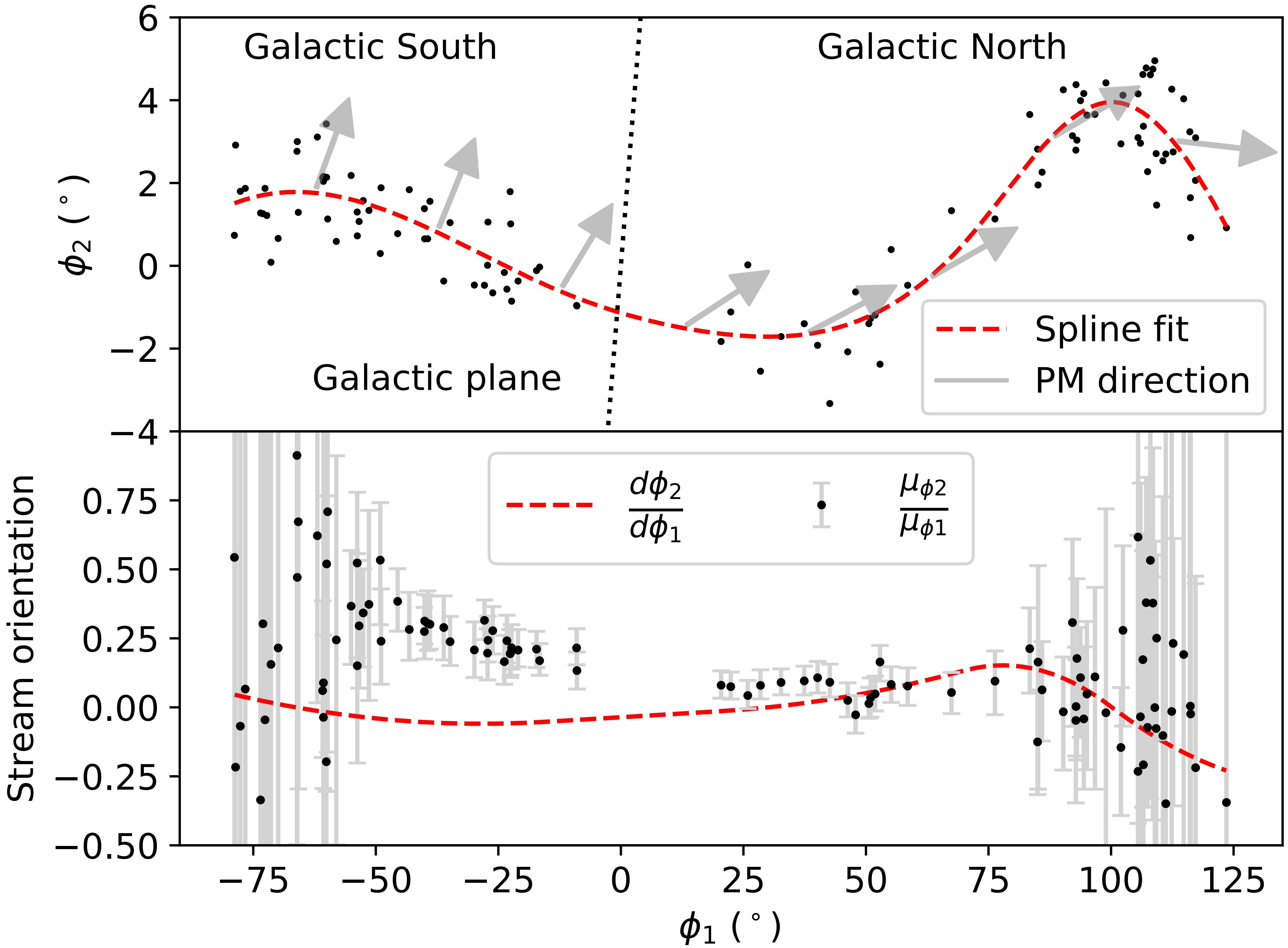
New!

[a] Erkal et al. (2019)
[b] Panagia (1999)
[c] Peñarrubia et al. (2015)
[d] Ribas et al. (2005)
[e] Within 17 kpc from center as per Corbelli (2003)
[f] Gieren et al. (2013)
[g] Portail et al. (2015)
[h] Assumed
[i] Law & Majewski (2010)
[j] Lokas (2009)
[k] Helmi et al. (2018); Belokurov et al. (2018)

the LMC (&SMC),
the Galactic Bar/bulge,
and possibly M31
are the major players

Evidence for a Massive LMC

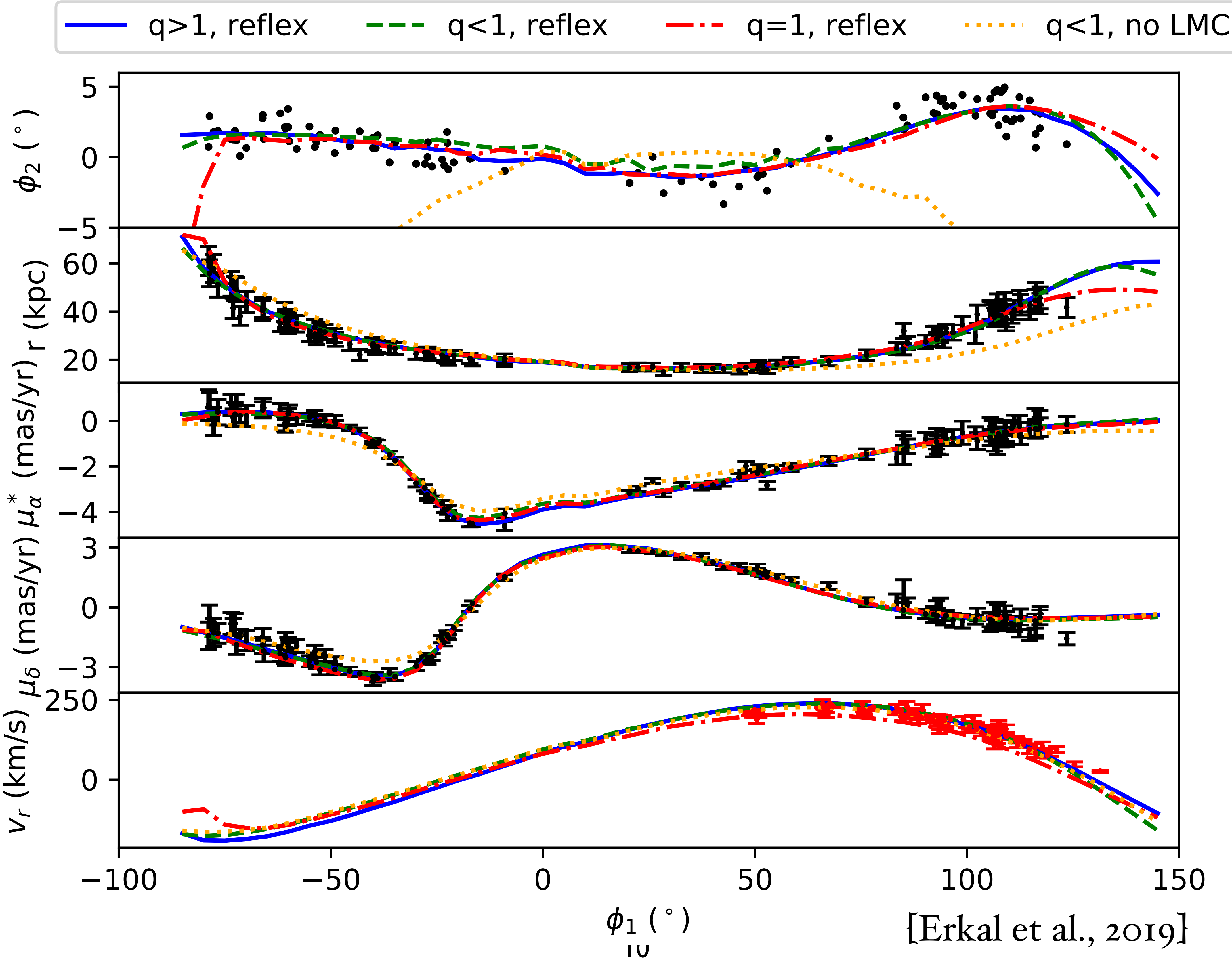
Orphan stream stars do not move with the stream velocity



[Erkal et al., 2019]

Orphan Stream Fits: a Massive LMC

Resolve v mismatch with distorted, non-axial DM halo



[Erkal et al., 2019]

Distorted Dark Matter Halos

From Orphan stream fits [Erkal et al., 2019]

Milky Way model includes disk, bulge, and a DM halo (of NFW form); initially only mass and shape of the halo can change in the fit

$$\phi_{\rm NFW}(x,y,z) = -\frac{GM_{\rm NFW}}{\tilde{r}}\frac{\log(1+\frac{\tilde{r}}{r_s})}{\log(1+c)-\frac{c}{(1+c)}} \quad ;$$

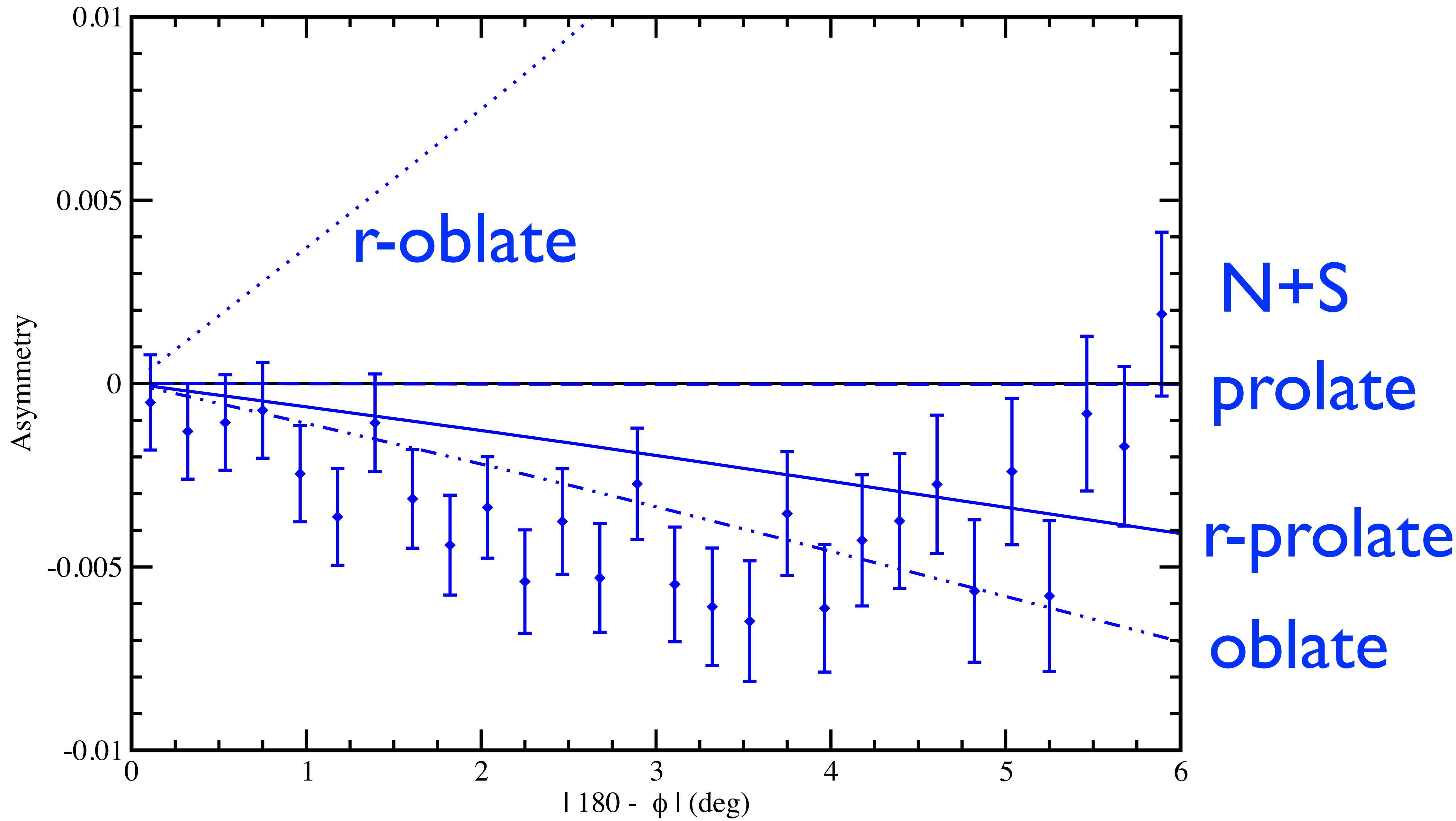
$$\tilde{r}^2 = x^2+y^2+z^2+(\frac{1}{q^2}-1)(\hat{\mathbf{n}}\cdot\mathbf{x})^2$$

If **n** does not point along **z**, then the potential breaks axial symmetry. Note q >0 prolate, and q<0 oblate

Reflex motion of the Milky Way can also modify the halo distortion

Confronting Distorted DM Halos

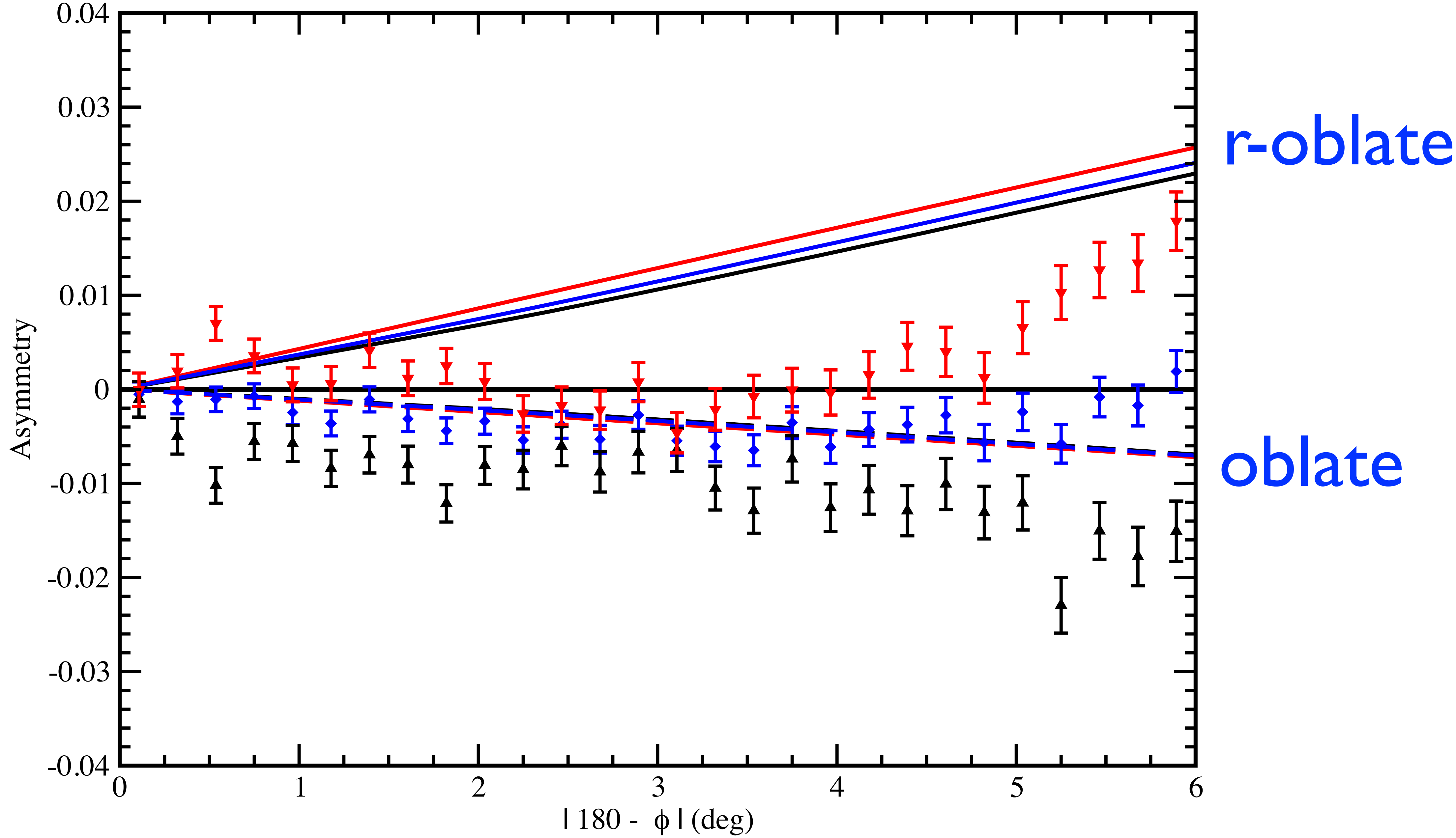
Observed vs. Computed (Orphan Best Fit) Asymmetries



N+S asymmetry only weakly discriminates the possibilities

Confronting Distorted DM Halos

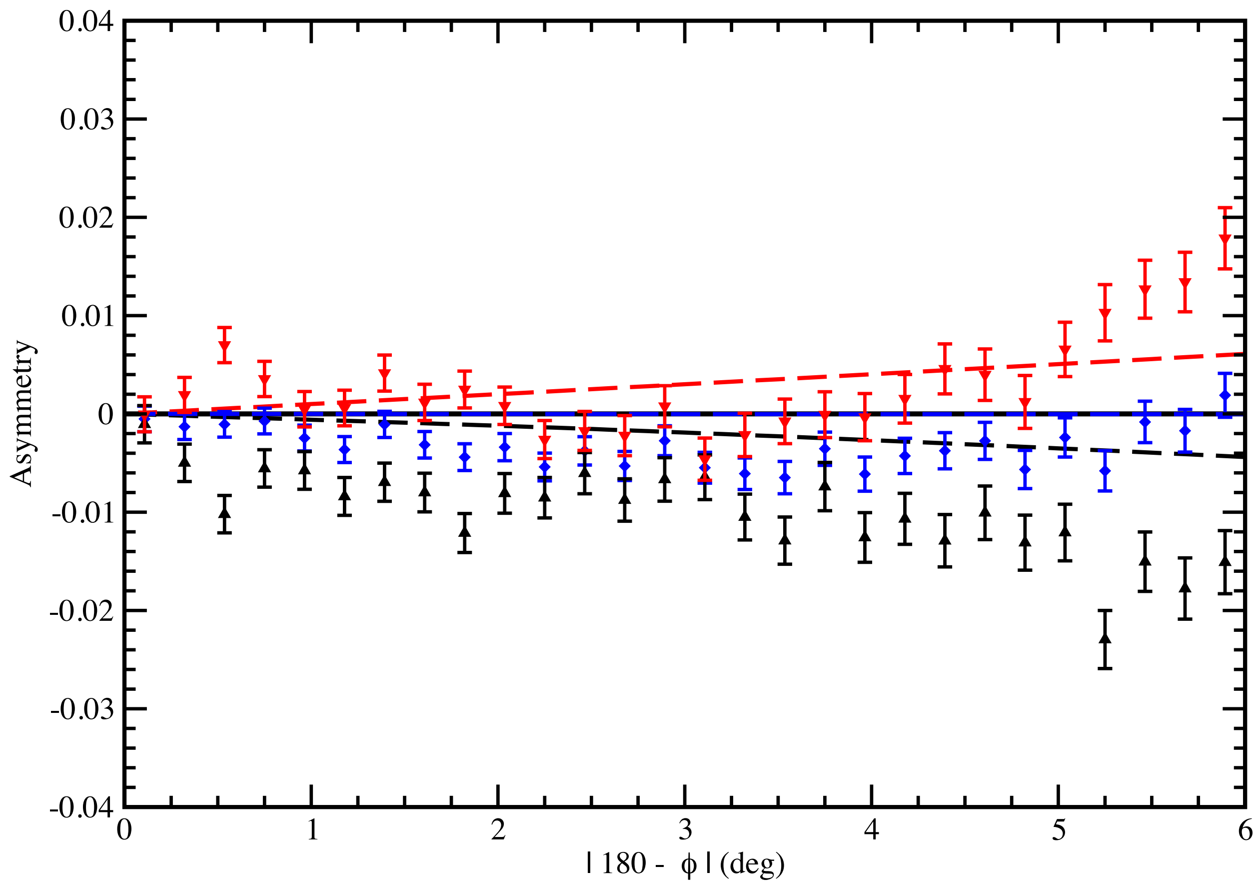
Observed vs. Computed Asymmetries: N, S, & N+S



Best-fit oblate forms excluded by N, S, and N+S data

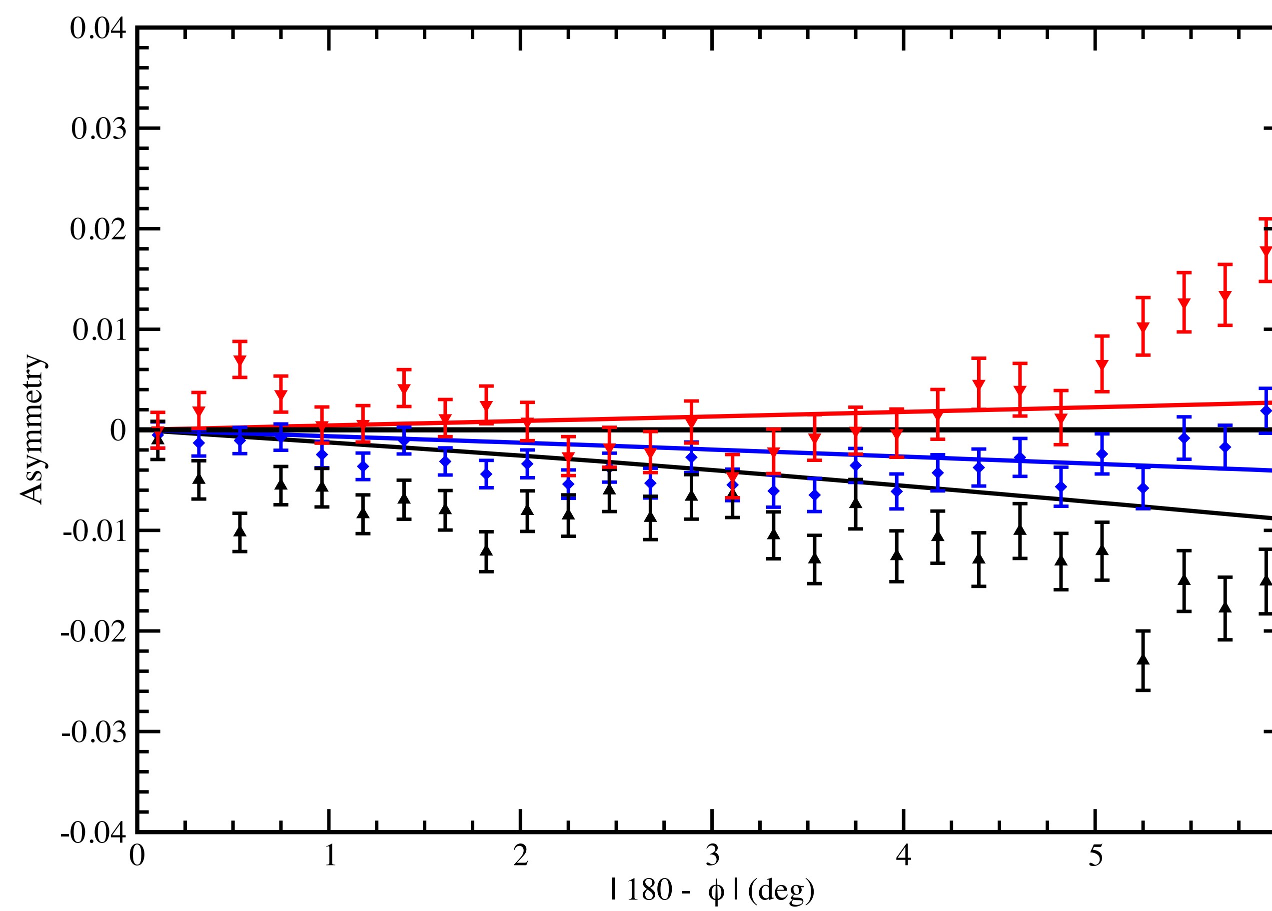
Confronting Distorted DM Halos

Observed vs. Computed Asymmetries: N, S, & N+S



prolate

r-prolate

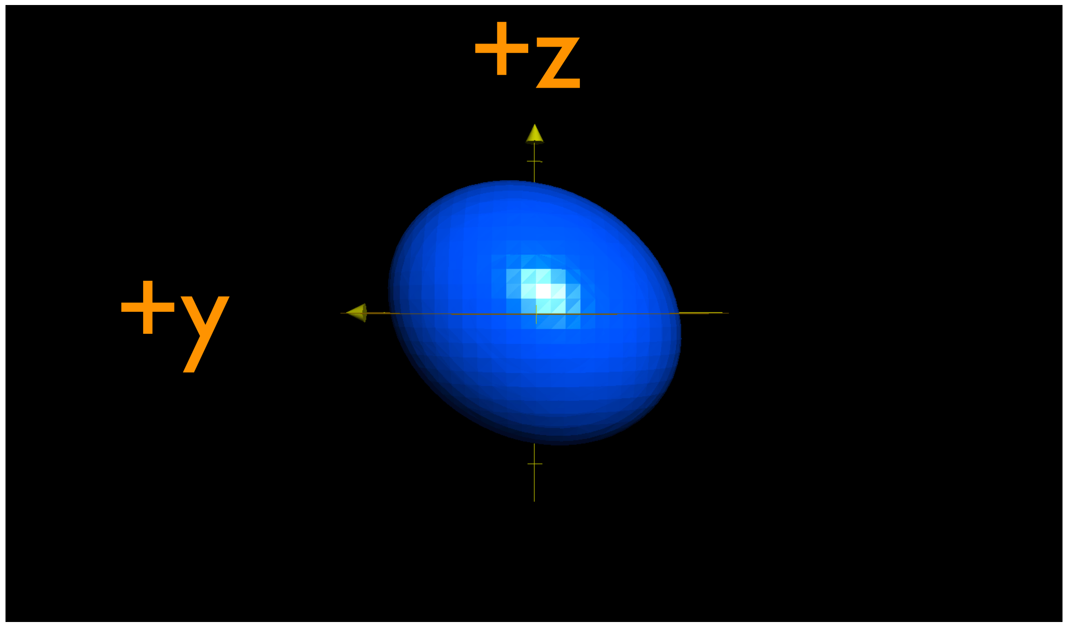


χ^2 test shows r-prolate form to be much preferred!

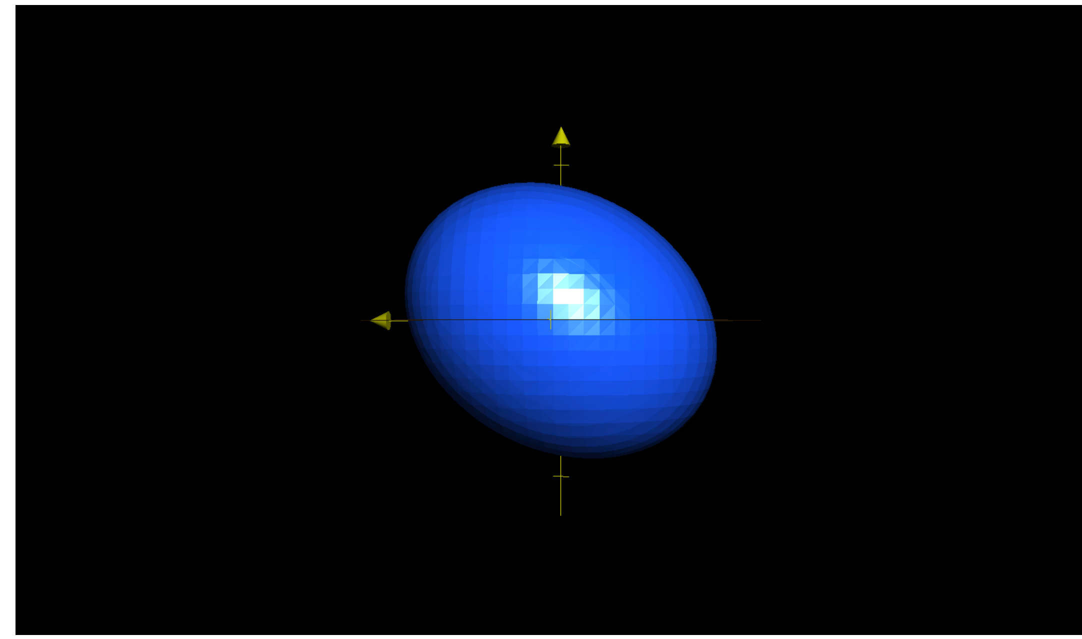
Compare Distorted Halo Potentials

View along anti-center line towards Sun & GC

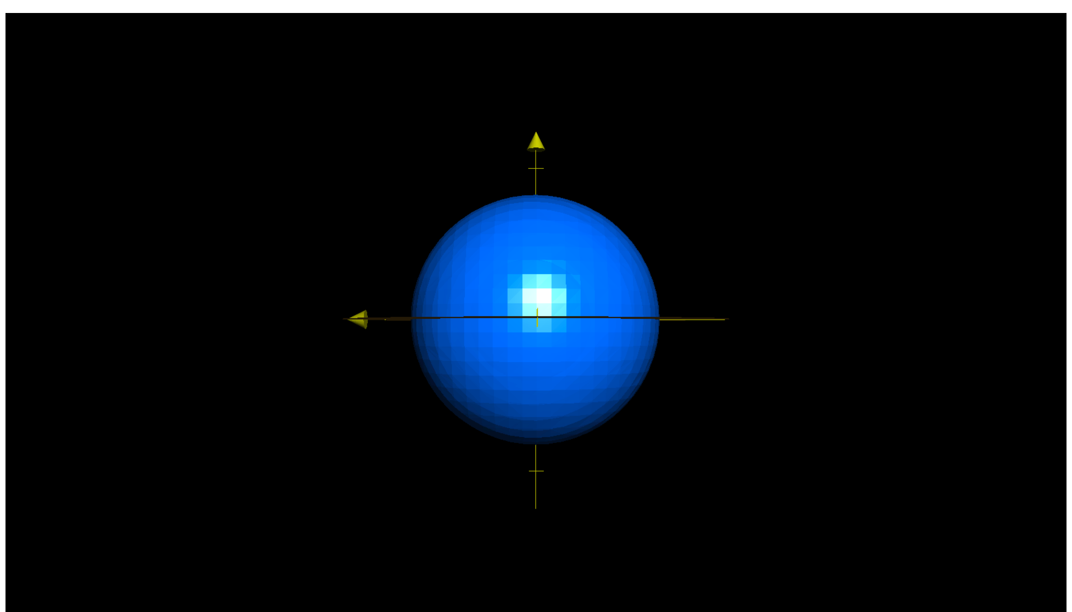
Prolate



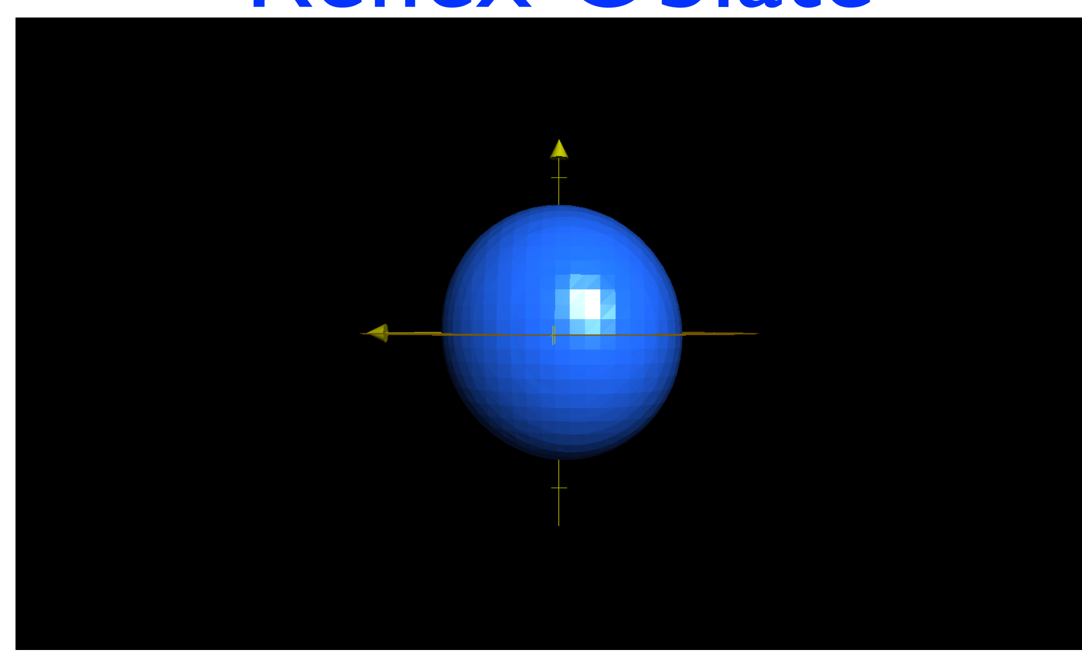
Reflex Prolate



Oblate



Reflex Oblate

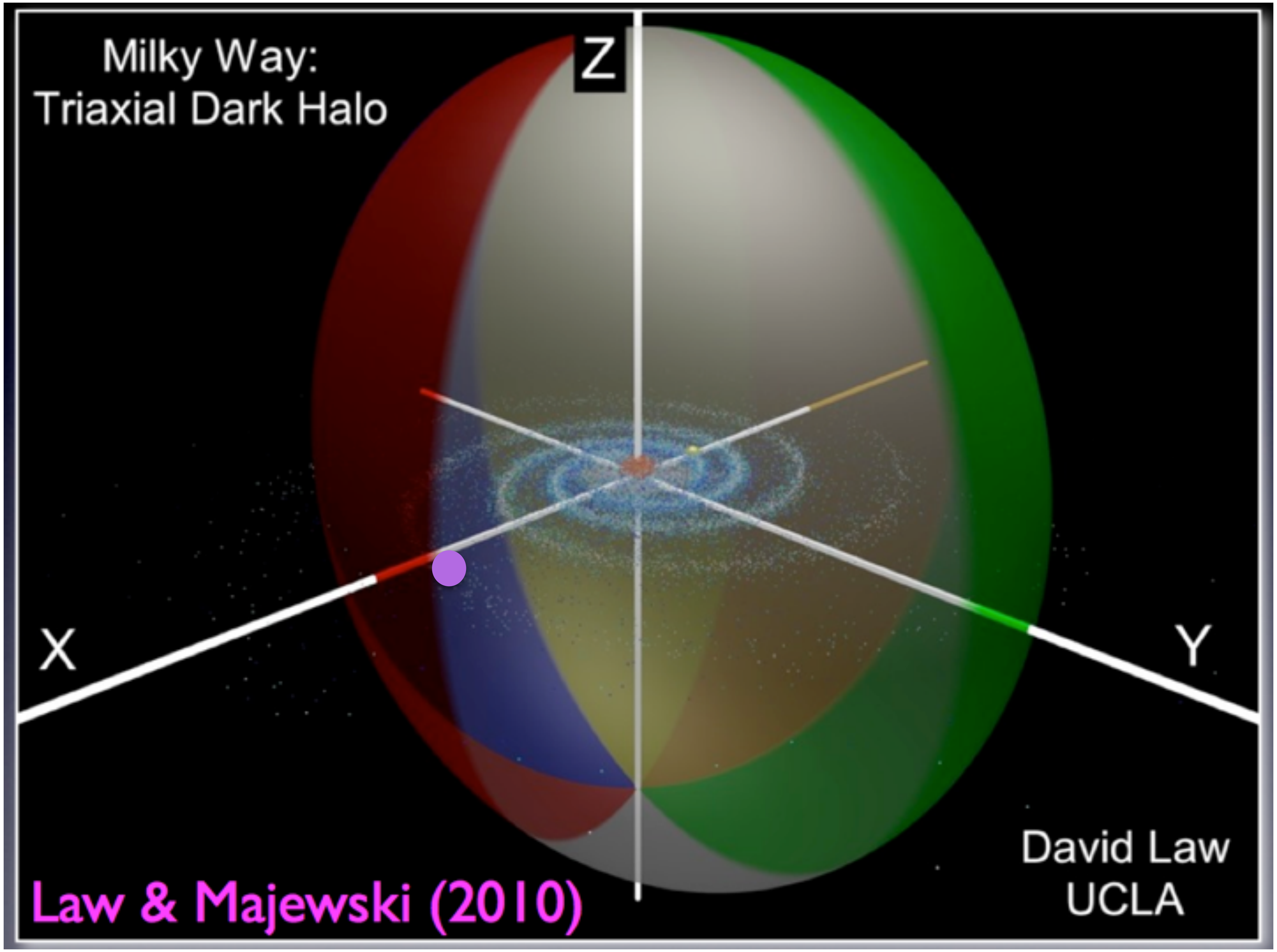


Why Oblate Forms show little N, S sensitivity

A New View of Old Puzzles

Distorted Halo from Sgr stream fits; why its orientation?

LMC!



[Figure Credit: Kallivayalil (UVa) [& Law]]

LMC: (-1,-41,-27) kpc

Sun: (-8,0,0) kpc

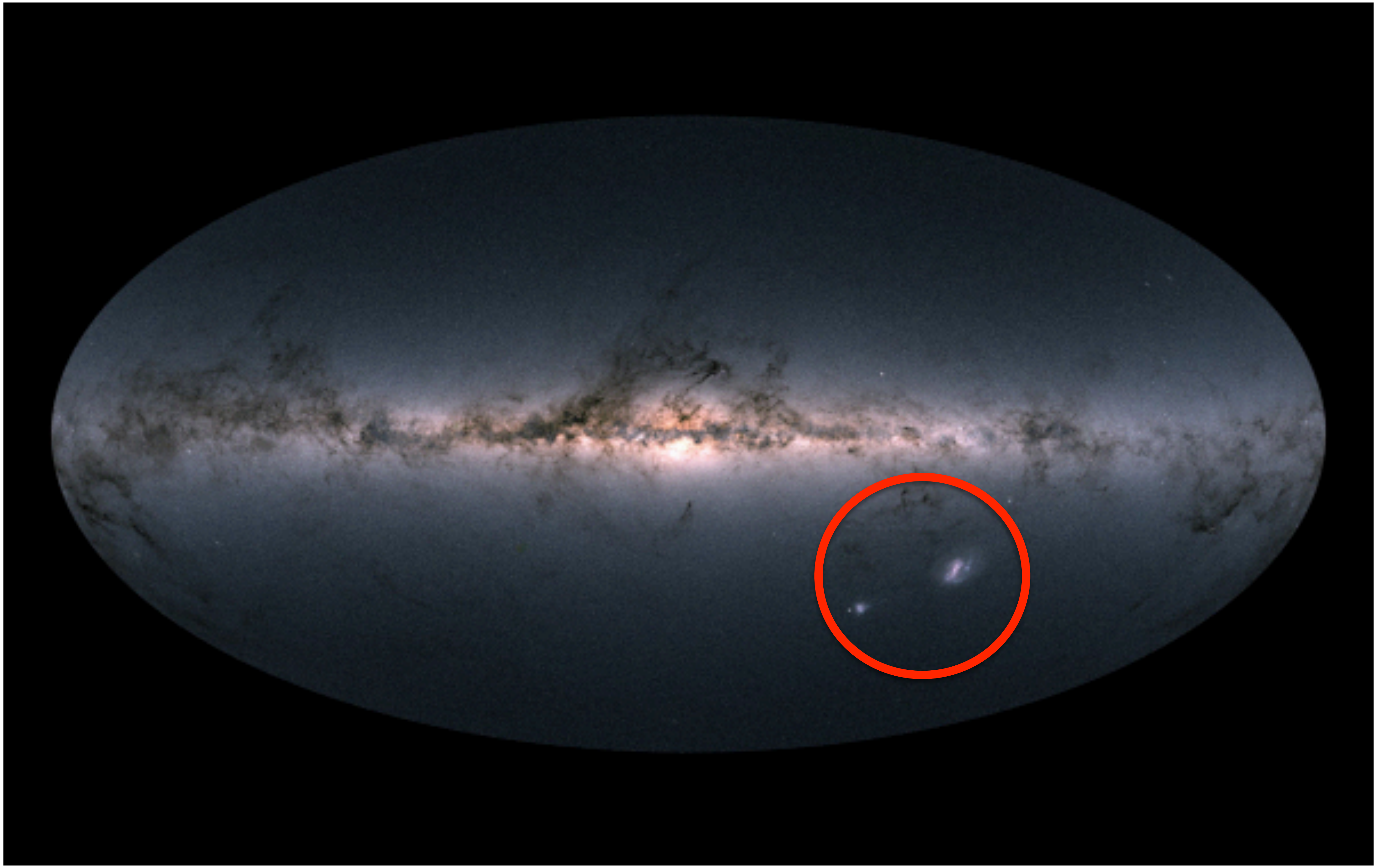
Summary

- We have discovered statistically significant left-right and north-south asymmetries in the out-of-plane star counts — this speaks to **axial symmetry breaking**, with differences in the north and south; the N/S pattern can separate non-isolating from non-steady-state effects!
- The analysis of the Orphan stream data by Erkal et al. points to a more massive (and more accurate) LMC mass; the distorted DM halos that emerge from that analysis can yield both the size and sign of the asymmetries we observe
- A massive LMC (and distorted DM halo) can explain why the warp in the disk of HI gas is long-lived*, and it can explain the spatial elongation of star counts associated with Gaia Enceladus**
- The galactic bar/budge may drive the N-S vs. N+S features we observe close to the plane
- As motivated by Noether's theorem (and An et al., 2017), forming asymmetries to probe for failures of axial and north-south symmetry have been shown to be powerful probes of the influence of satellite torques on the overall distribution of mass in and around the MW.

* Weinberg & Blitz, 2006 **Helmi et al., 2018; Belokurov et al. 2018

Gaia's Sky in Color (DR2)

LMC: architect of warps & asymmetries in the Milky Way



[https://sci.esa.int/web/gaia/-/60169-gaia-s-sky-in-colour (April, 2018)]

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