Seeing the Milky Way with New Eyes

Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY

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Scheduled to start 4PM CDT/5PM EDT [Image Credit: Alan Dyer © 2013]

New Eyes

The only true voyage of discovery, …, would be not to visit strange lands but to possess other eyes, to behold the universe through the eyes of another, …

[M. Proust, *The Remembrance of Things Past (In Search of Lost Time)*, 1922….]

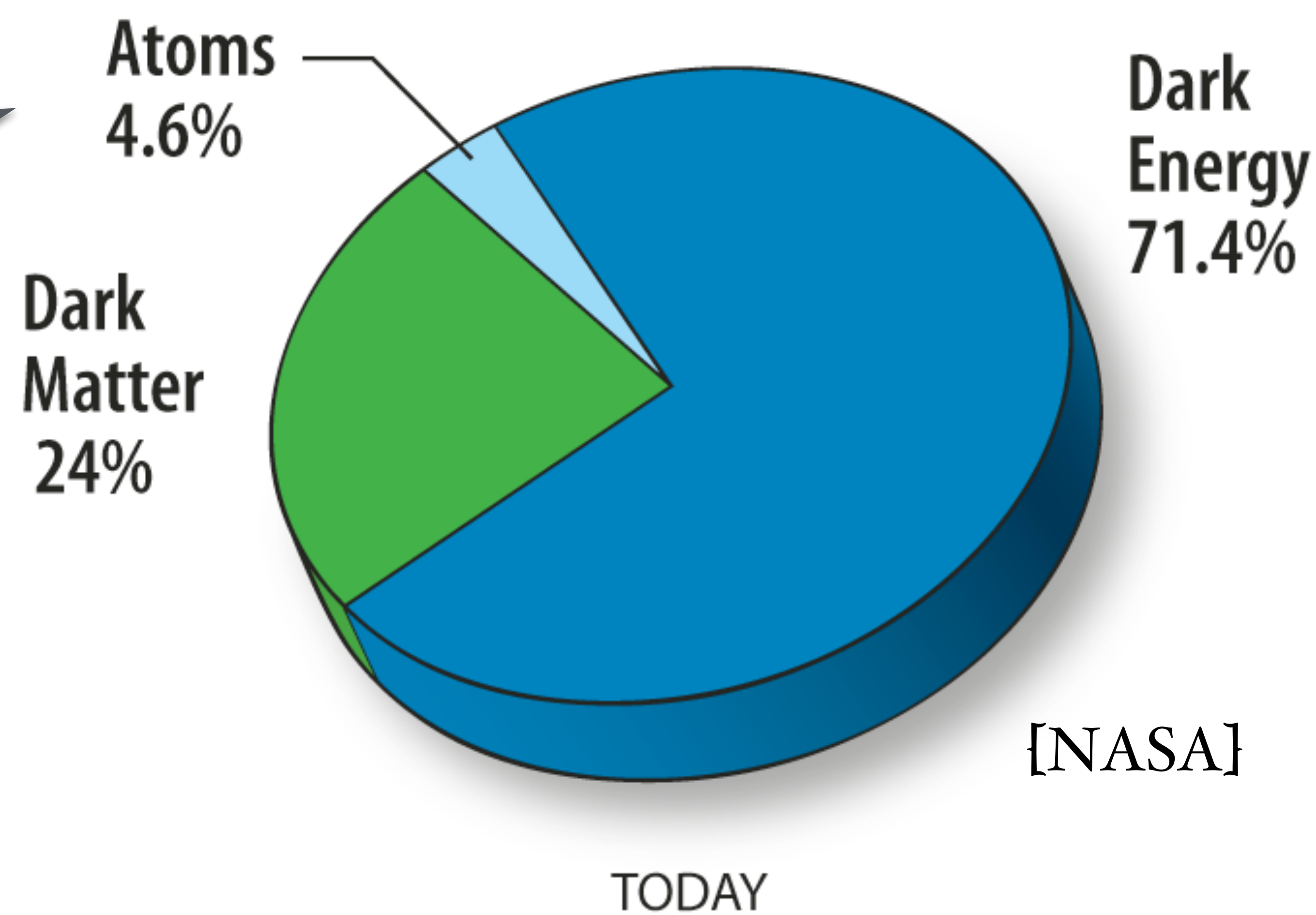
Studies of **complex systems**
— hadrons, nuclei, atoms, molecules —
in terrestrial experiments **reveal "new physics"**
if expected **symmetries**
are discovered to be **broken**

Here we apply that thinking to the Milky Way
using the *Gaia* space telescope to consider not one object
but millions… what patterns do we find?

Two Numbers

Drive new physics searches

Why is the cosmic energy budget in baryons so small? (and what is everything else?!)



And the cosmic baryon asymmetry

$$\eta = n_{\text{baryon}}/n_{\text{photon}} = (5.96 \pm 0.28) \times 10^{-10}$$ [Steigman, 2012]

so large? (And what is the origin of the ν mass?)

A Cosmic Baryon Asymmetry

From particle physics?

The particle physics of the early universe can explain this asymmetry if B (baryon number), C (particle-antiparticle), and CP (matter-antimatter) violation all exist in a non-equilibrium environment. {Sakharov, 1967}

"From S. Okubo's effect [CPV]
At high temperature
A coat is tailored for the Universe
To fit its skewed shape"
[A. Sakharov]

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

НАРУШЕНИЕ CP-ИНВАРИАНТНОСТИ, C-АСИММЕТРИЯ
И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

[http://www.aip.org/history/sakharov/cosmresp.htm]

But what is the mechanism?

The Puzzle of the Missing Antimatter

The baryon asymmetry of the universe (BAU) derives from physics beyond the standard model!

The SM almost has the right ingredients:

B? Yes, at high temperatures

C and CP? Yes, but CP is "special"

Early numerical estimates are much too small. $\eta < 10^{-26}$

[Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.]

Non-equilibrium dynamics? No. (!)

The Higgs particle is too massive to yield a first-order electroweak phase transition

[e.g., Aoki, Csikor, Fodor, Ukawa, 1999]

So that the SM mechanism fails altogether

And we seek new sources of CP violation....

Electric & Magnetic Dipole Moments

A permanent EDM breaks parity (P) & time-reversal (T)

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

Intrinsic property: $\vec{\mu}, \vec{d} \propto \vec{S}$ [spin]

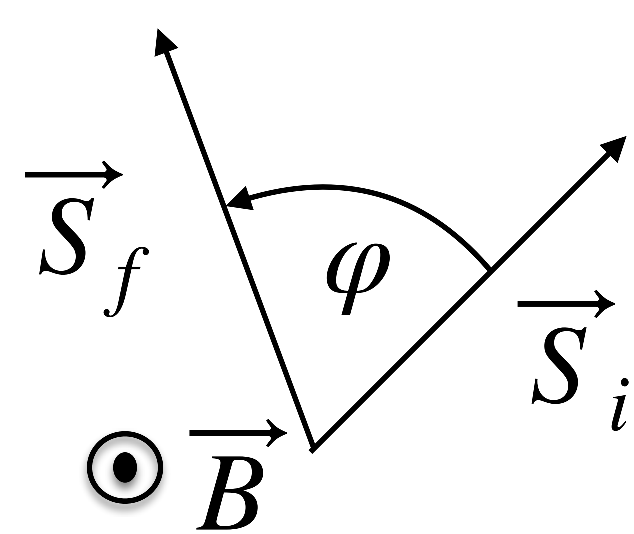
Maxwell Equations… $-\vec{\mu} \cdot \vec{B}$ is P even, T even

$-\vec{d} \cdot \vec{E}$ is P odd, T odd

Note if T is broken so is CP [CPT unbroken]

Classically, the spin precesses if there is a torque:

$$\vec{\tau} = \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}$$



EDM Measurement Principle

Much simplified!

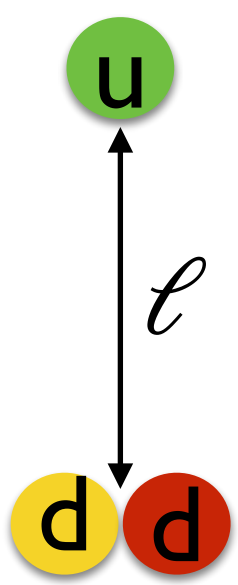
Consider the precession frequency

$$\nu = \frac{1}{2\pi}\frac{d\varphi}{dt} = \frac{2\vec{\mu}\cdot\vec{B} \pm 2\vec{d}\cdot\vec{E}}{h}$$

and its *change* under $\vec{E}$ field reversal

B must be very well determined!

The experimental sensitivity to the energy $\vec{d}\cdot\vec{E}$ is set by



$$\sigma_d \sim \frac{\hbar}{|\vec{E}|\,T_m\sqrt{N}}$$

T_m measurement time

N number of counts

Neutron: $d_n < 1.8 \times 10^{-26}$ e-cm [90 % C.L.]

[Abel et al., 2020]

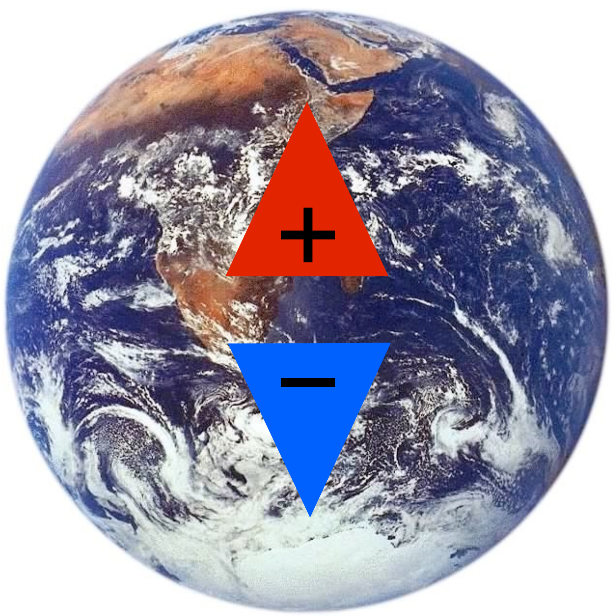
Estimate: $d \sim \frac{2}{3}e\ell \sim 6 \times 10^{-15}$ e-cm if $\ell \sim 0.1 r_p$ (!)

Sensitivity of EDM Measurements

Consider current best limit for the neutron

Neutron: $d_n < 1.8 \times 10^{-26}$ e-cm $[90\,\%$ C.L.$]$ [Abel et al., 2020]

For a sense of scale:



Scaling the n to Earth's size implies a charge separation of < 4μm (cf. human hair width 40 μm)

Experiments under development reach for improvements of 10-100x in sensitivity

Applied electric fields can be enormously enhanced in atoms and molecules [Purcell and Ramsey, 1950]

World's best EDM limit ^{199}Hg , great strides in ^{129}Xe,…

[Graner et al., 2016] [Sachdeva et al., 2020]

New Eyes

Lessons Learned from EDM Studies: Driving Common Features

- A discovery of symmetry breaking (T, P) at the current level of sensitivity reveals new physics, regardless of the complexity of the system.
- Enormous data sets (statistical power) are important to realizing experimental sensitivity [T_m , N]
- Excellent control over unwanted, obscuring effects (systematics) is also required [B….]

The *Gaia* Era: Astrometric Parallaxes+ of ~10^9 Objects [DR2: April, 2018!]

[https://www.cosmos.esa.int/web/gaia/home]

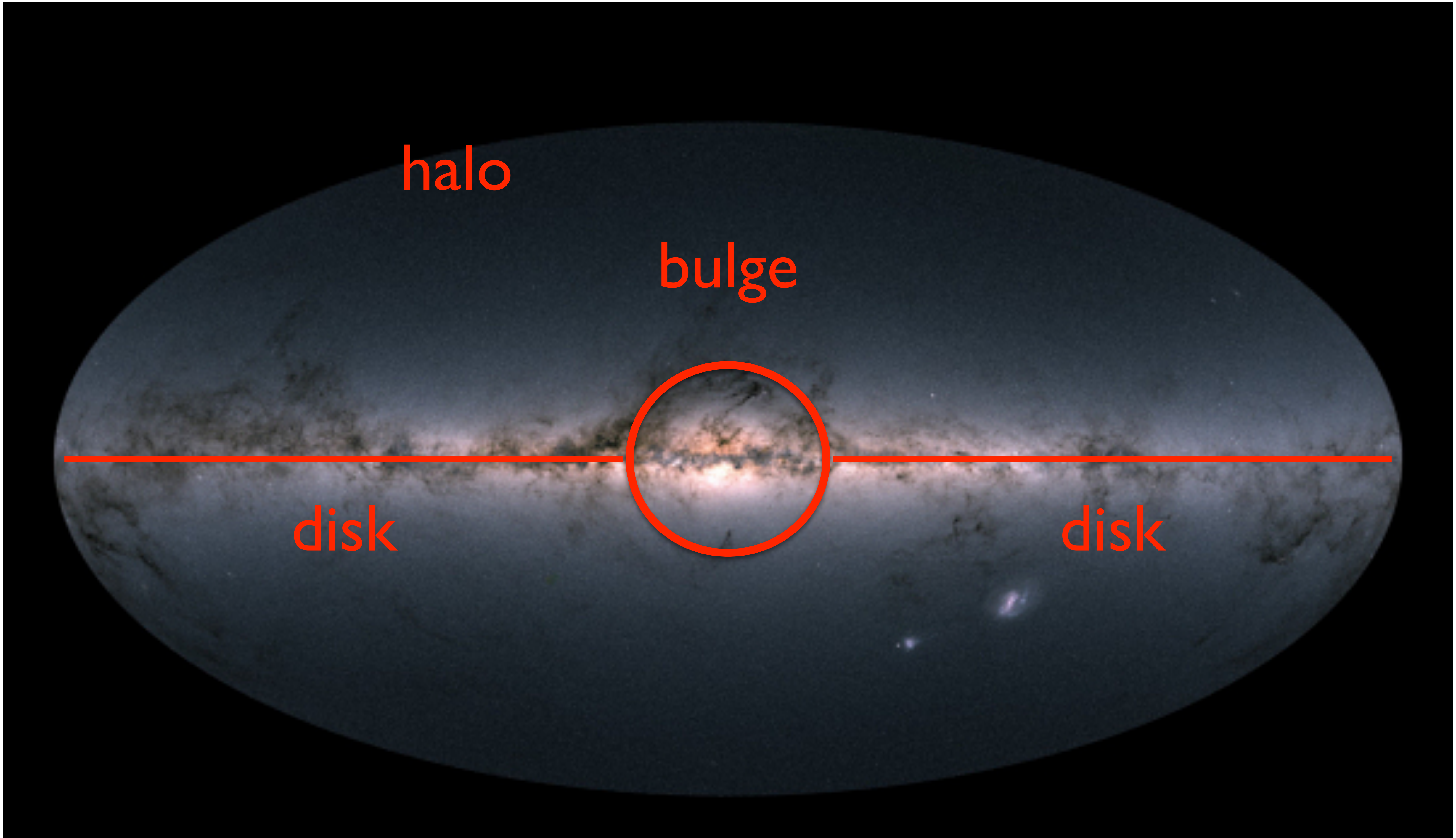
My Collaborators:

Austin Hinkel

Brian Yanny

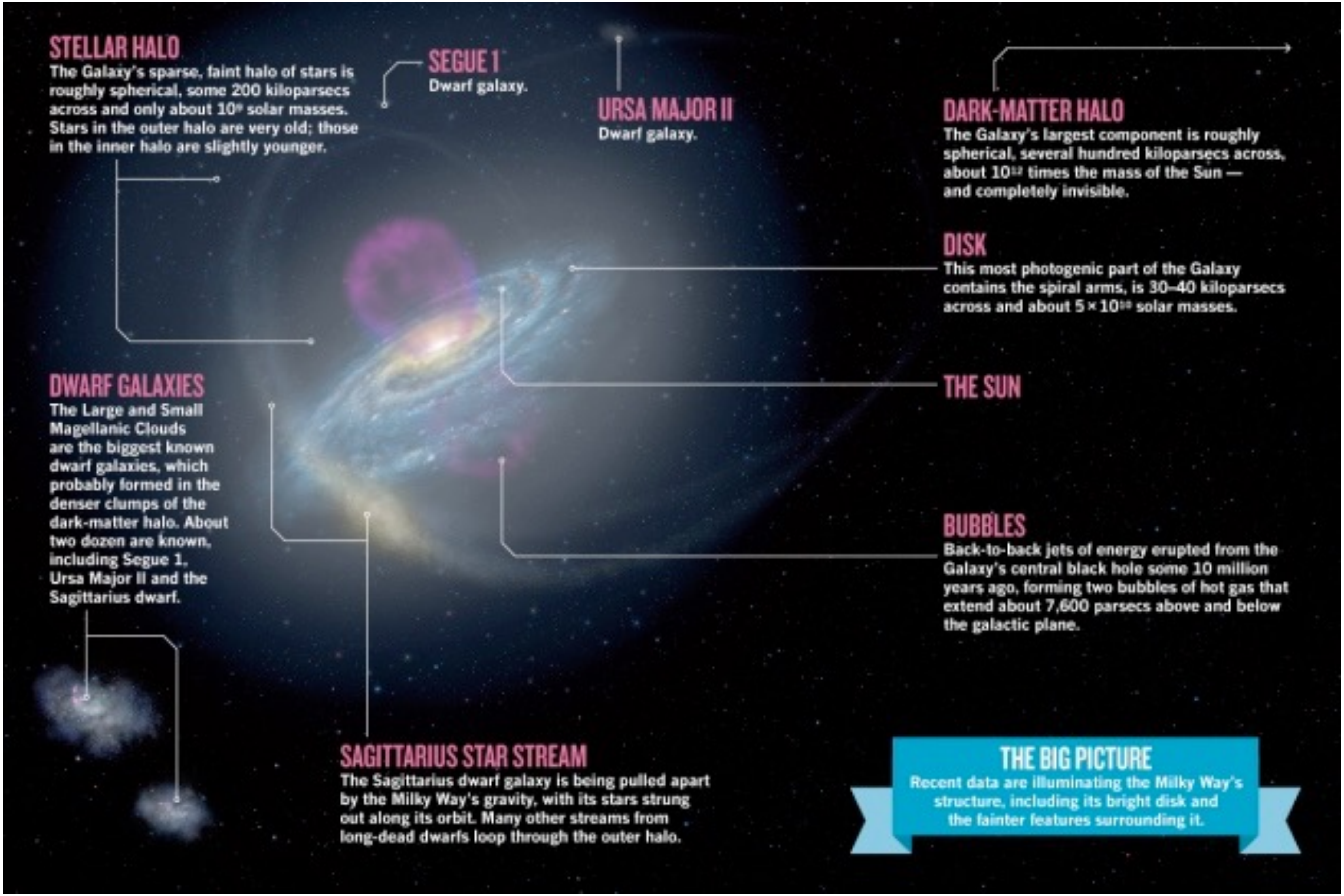
Symmetries of the Milky Way & their breaking?

The Milky Way



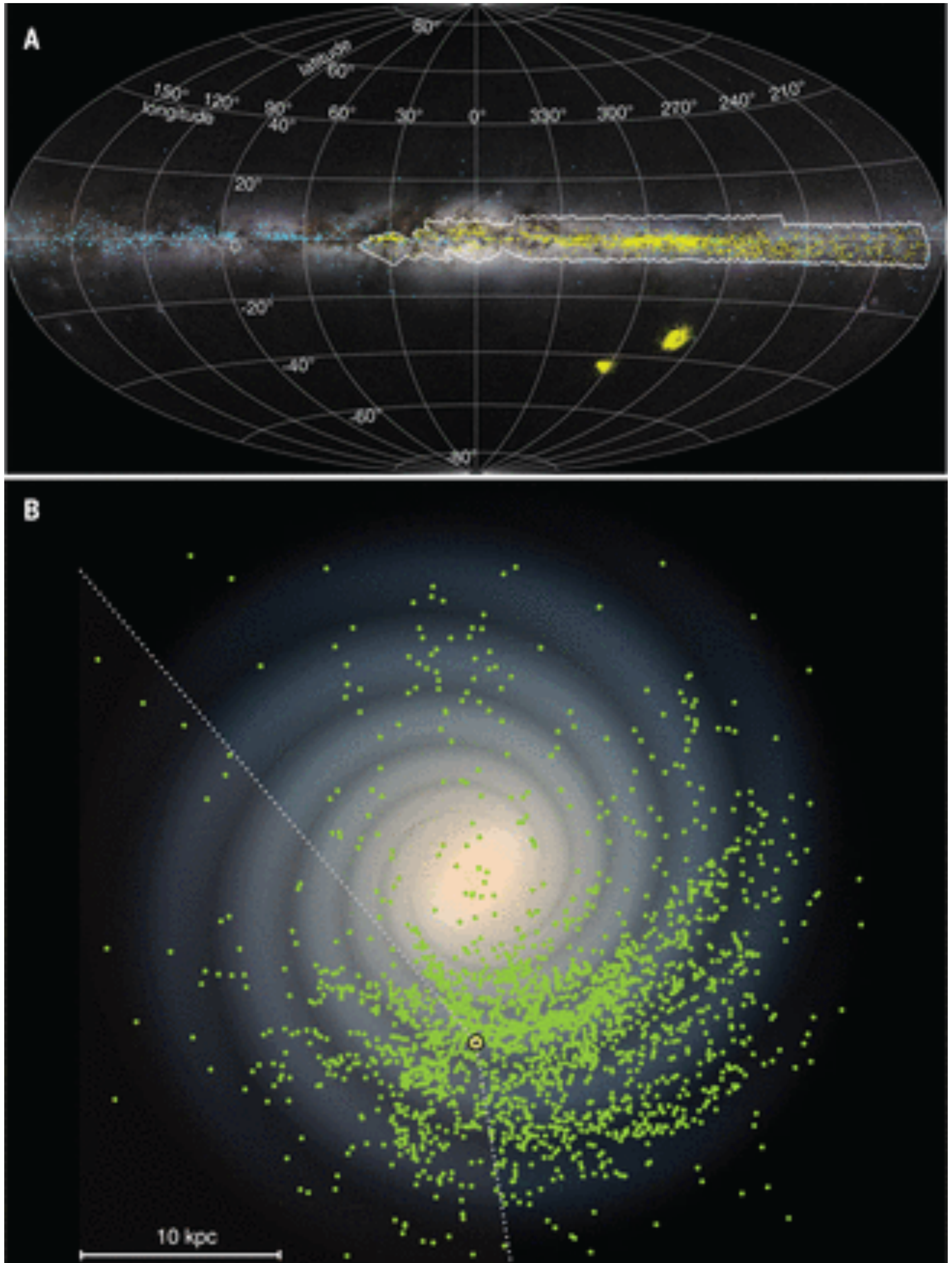
[https://sci.esa.int/web/gaia/-/60169-gaia-s-sky-in-colour (April, 2018)]

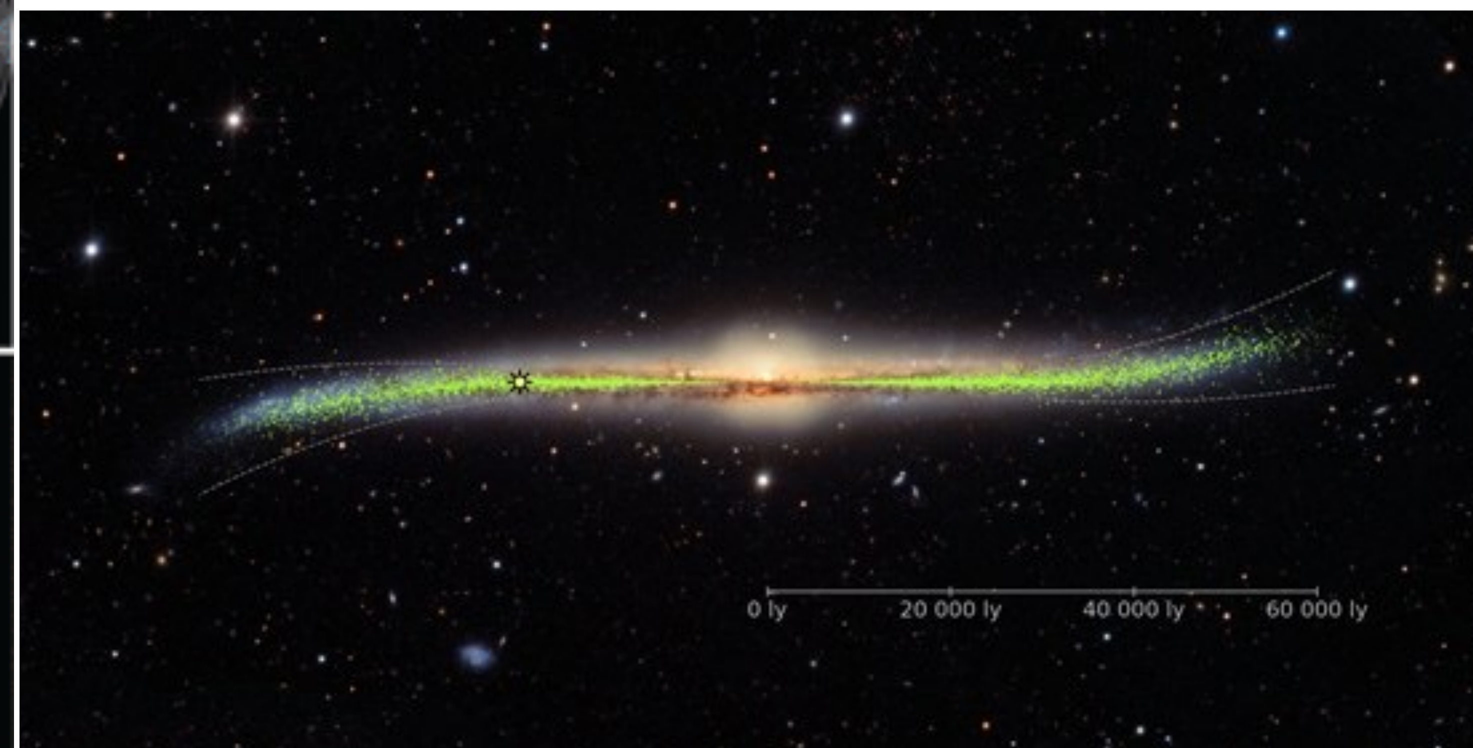
Observations Reveal A "New" Milky Way



[A. Finkbeiner, Nature News 2012]

New Surprises!





OGLE

Skowron, et al., Science 365 (2019) 478

[Also: Chen et al., Nature Astro., 2019]

What has warped the Milky Way?

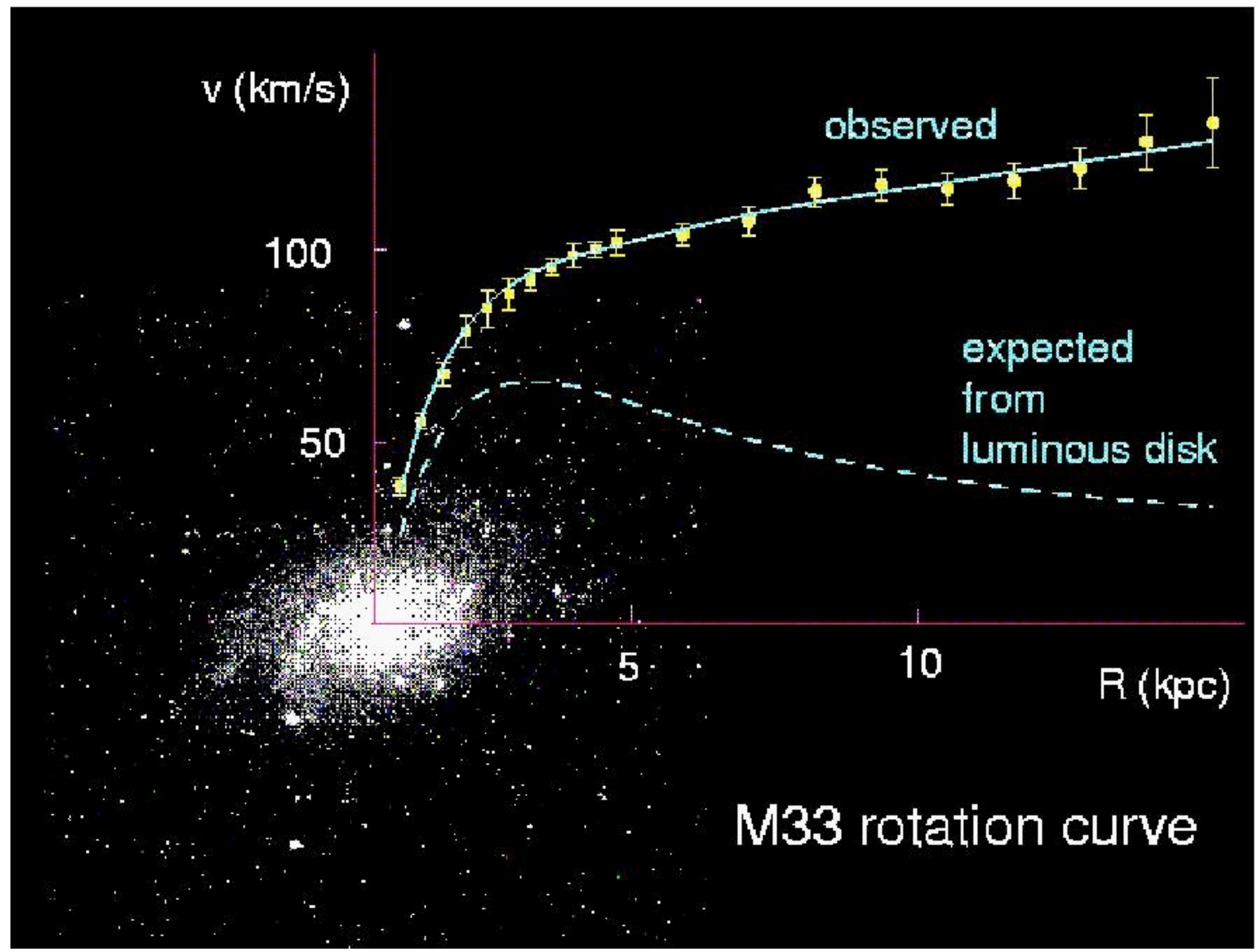
Long-Standing Surprises

Evidence for Missing Matter

Vera Rubin

Measure the rotation velocity from Doppler shift of neutral H (α lines)

Galactic Rotation Curves



Dark Matter: Why Not Seeing is Believing

- “Missing mass” problems have existed – at a variety of length scales – for decades
- Nearly as old is the suggestion (Zwicky, 1933) that “dark” (or non-luminous) matter might exist and solve the puzzle
- Recent, disparate observational results concur!

Gaia's Forecast

Spacecraft sweeps the sky, viewing objects many times

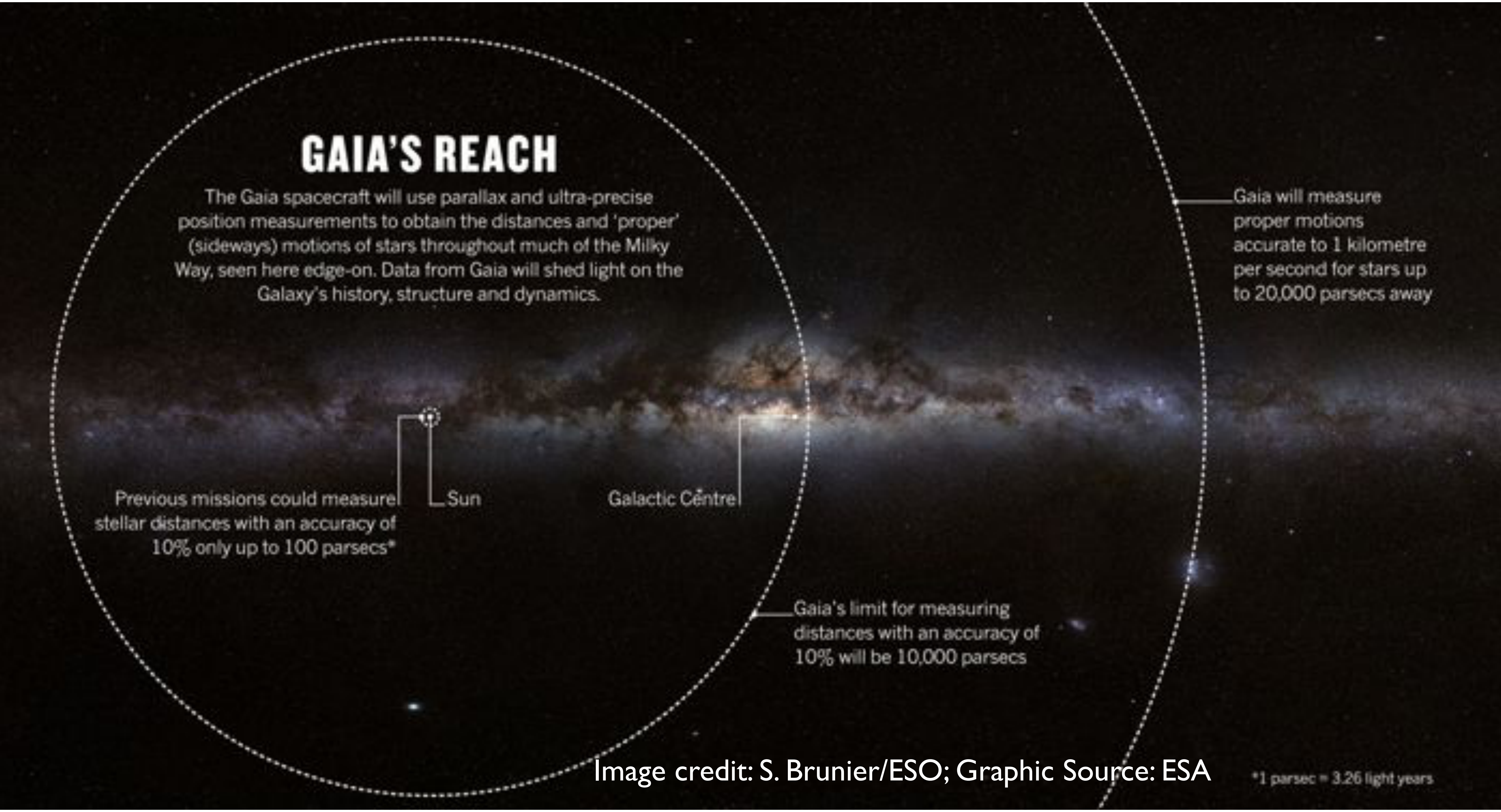
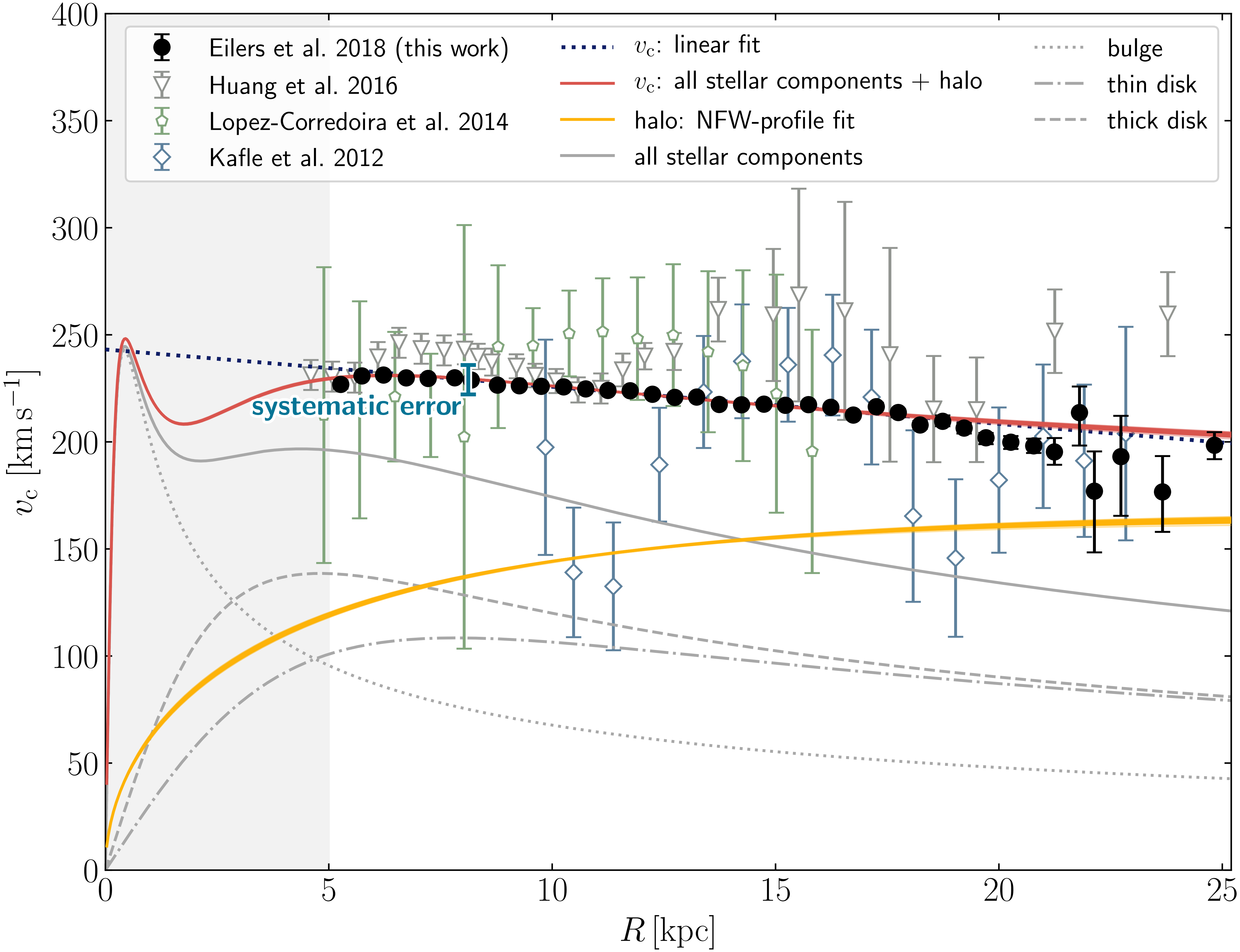


Image credit: S. Brunier/ESO; Graphic Source: ESA

The Galaxy's Rotation Curve with *Gaia*

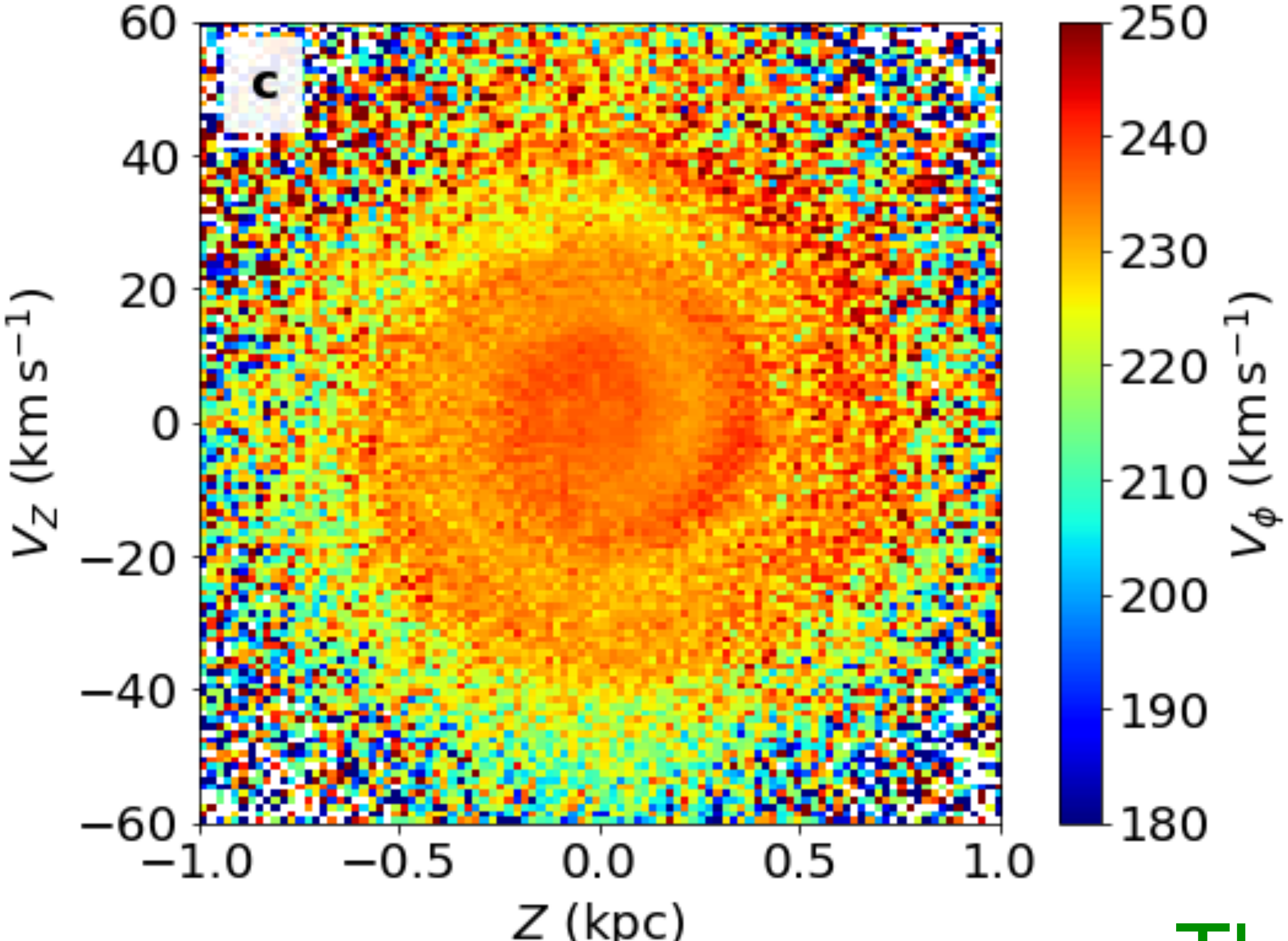


arXiv: 1810.09466

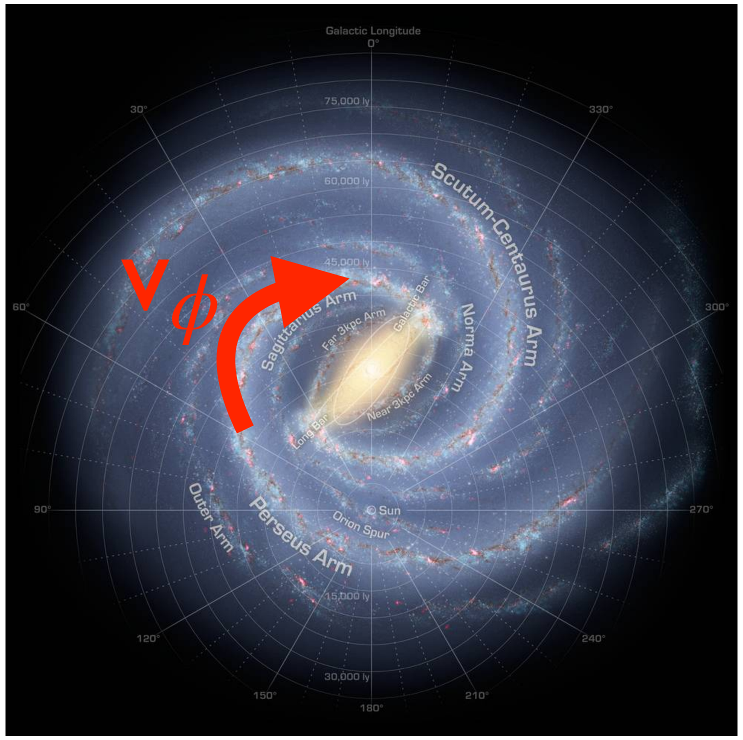
Note very recent improvement in precision!

(Selected) Discoveries with *Gaia*

Gaia "snail" : intricate z-v_z-v_φ correlations (near the Sun) speak to non-steady-state effects



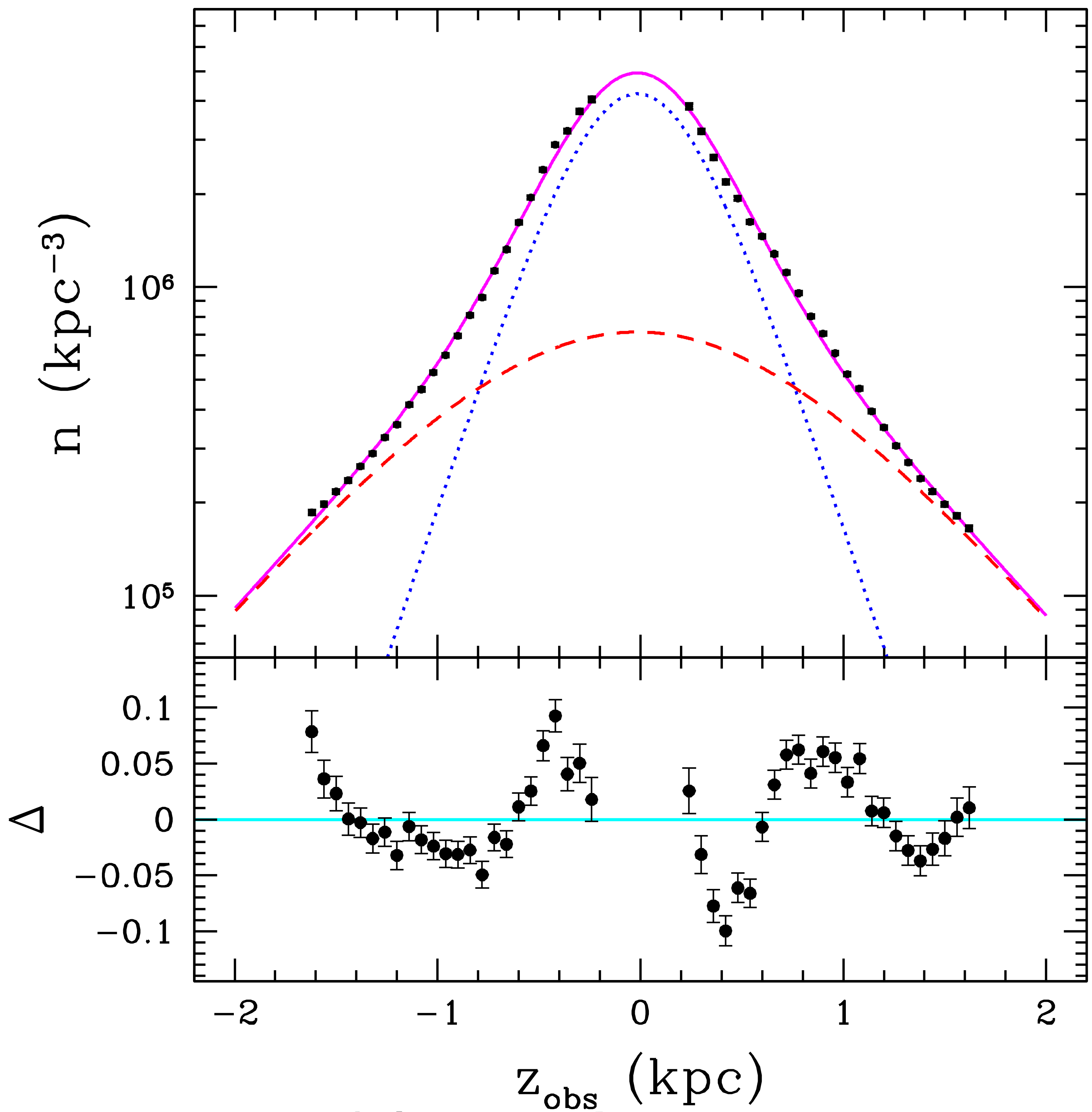
[Antoja et al., Nature, 2018; (also Dehnen, 1998)]



[Image Credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)]

Their origin is unknown.

SDSS Photometry: Discovery of a Vertical Wave in the Galactic Disk



Early Evidence for Non-Steady-State Effects!

sample: 300,000 stars

[Yanny, SG, 2013]

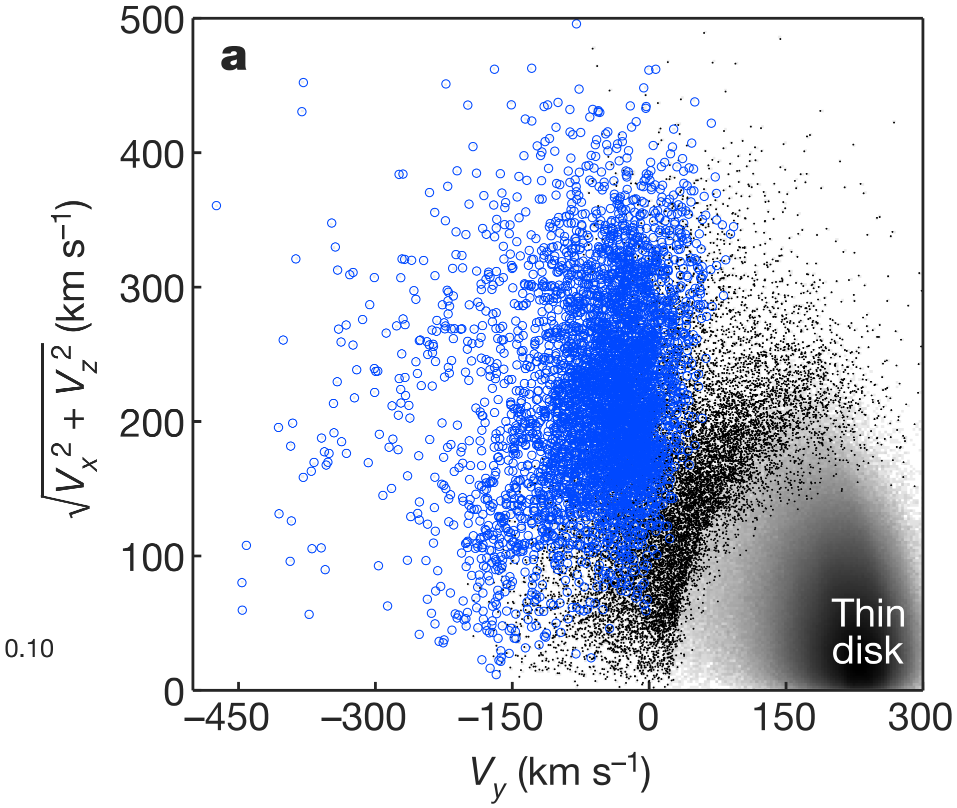
Δ = (data - model)/model

[Widrow, SG, Dodelson, Yanny, Chen, 2012]

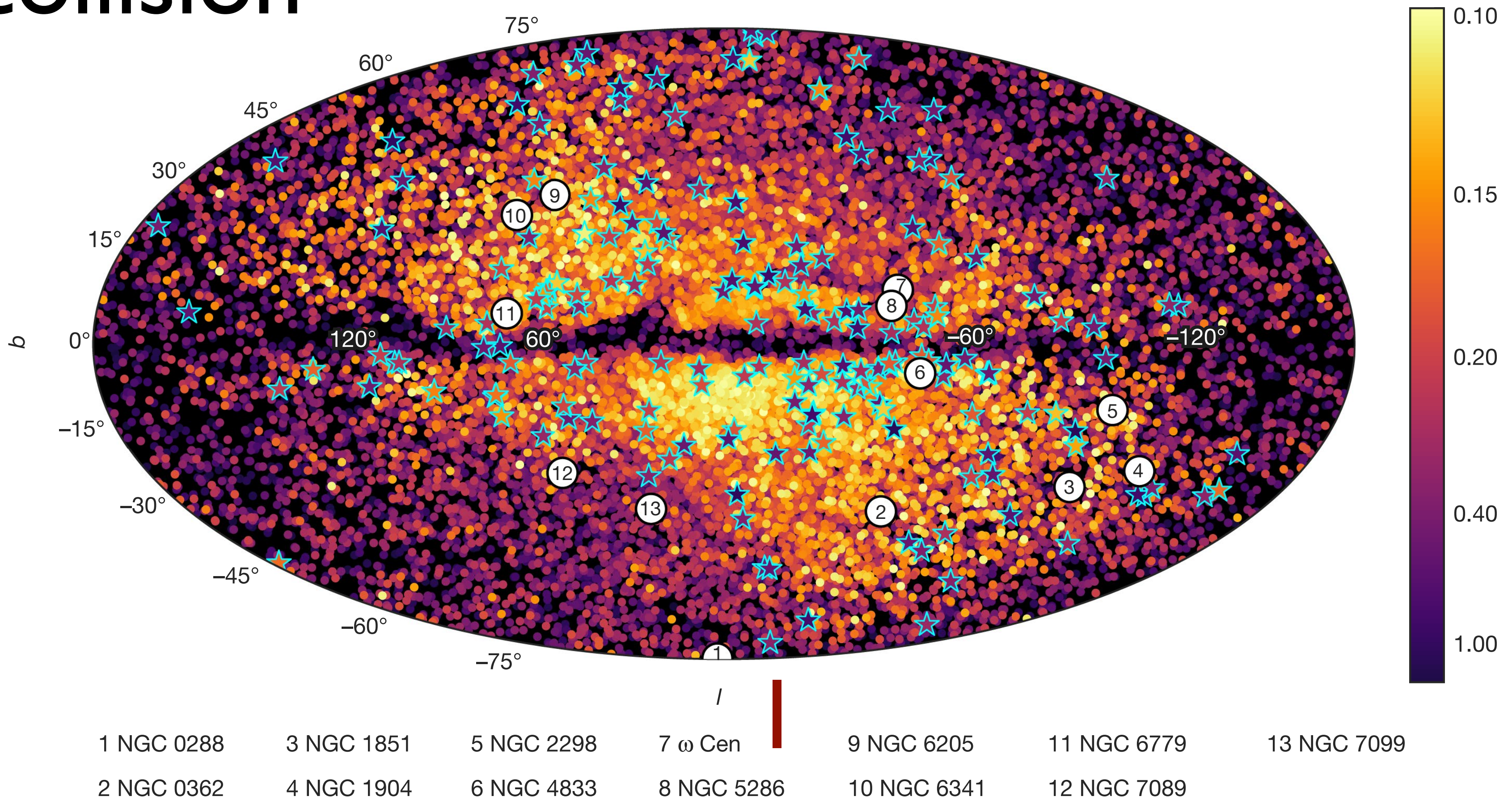
(Selected) Discoveries with *Gaia*

“Intruder” stars that do not rotate with disk; different “chemistry”!

Suggested aftermath of ancient collision



b

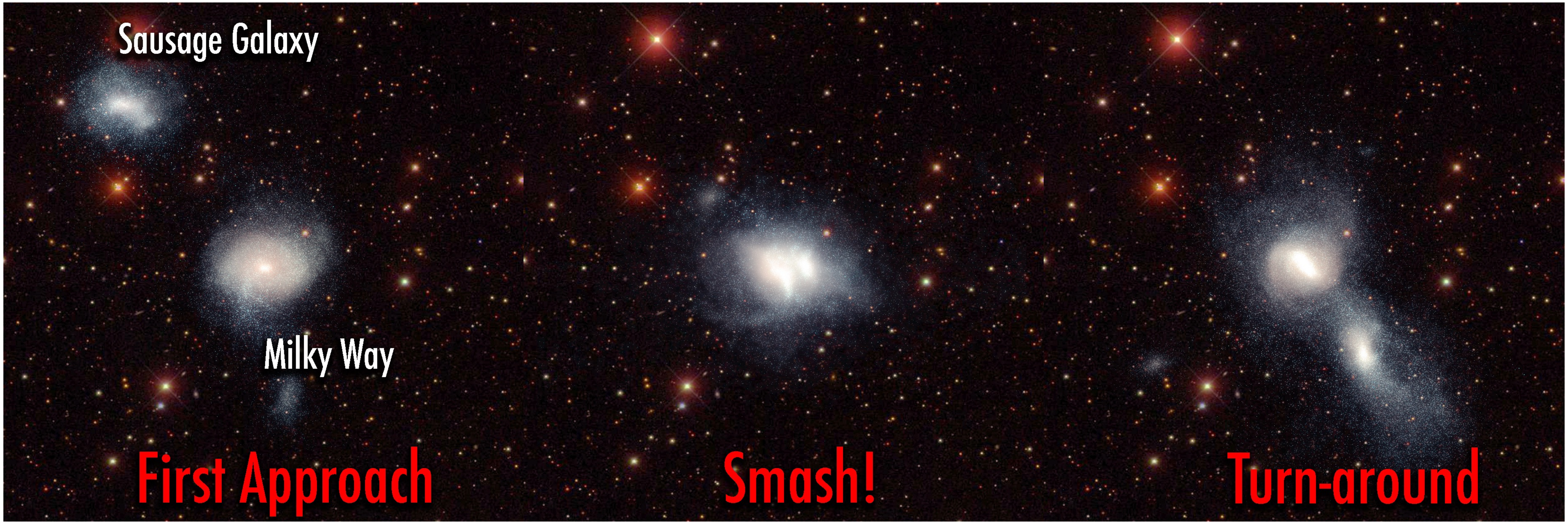


Gaia Enceladus or “Sausage” Galaxy

[Helmi et al., Nature, 2018; note also Belokurov et al., 2018; Deason et al, 2018; Myeong et al., 2018; Koppelman et al., 2018]

(Selected) Discoveries with *Gaia*

Gaia Sausage:
Collision Event
of 10 Gyr ago



[Image Credit: V. Belokurov]

Implications?

Origins and Implications?

We start by testing the assumptions in the usual modeling of the Galaxy.

— in collaboration with —
Austin Hinkel (U. Kentucky), Brian Yanny (Fermilab)

The matter distribution function of an isolated galaxy in steady state has a distribution function $f(\mathbf{x},\mathbf{v})$ controlled by its integrals of motion — in an axially symmetric galaxy the angular momentum L_z should be an integral of motion

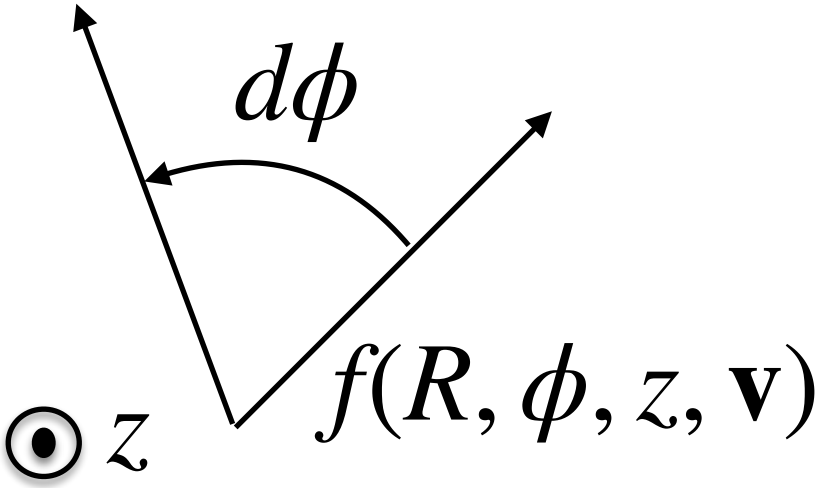
[Jeans, 1915; Binney & Tremaine, 2008]

Symmetries of the Milky Way

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.
[Olver, 1993; Noether, 1918]

Patterns in the symmetry breaking reveals the underlying dynamics!



Analysis 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]

Any 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

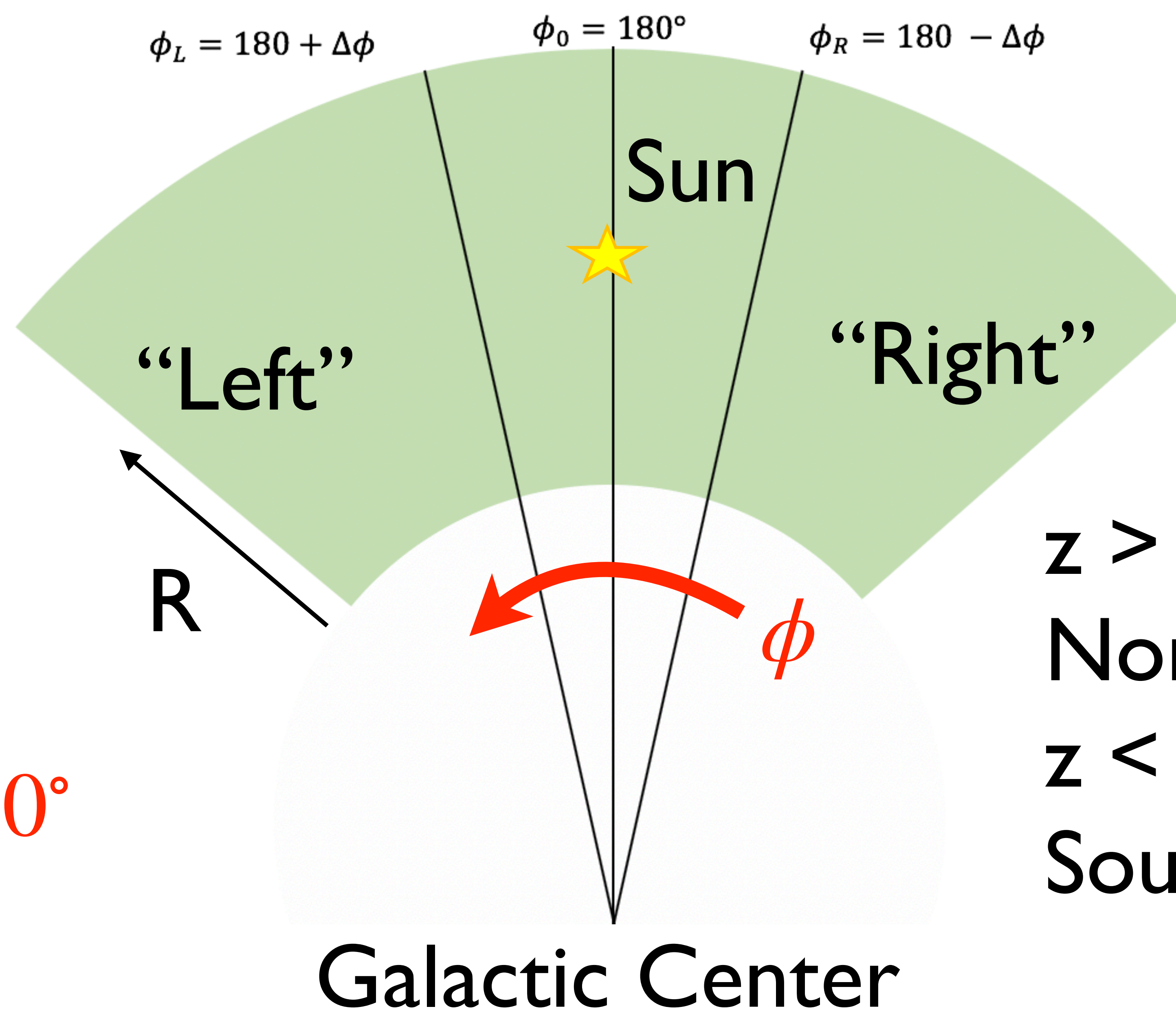
Method

Study Gaia Star Counts, Left/Right, North, South

Form an *asymmetry*:

$$\mathcal{A}(\phi) = \frac{n_L(\phi) - n_R(\phi)}{n_L(\phi) + n_R(\phi)}$$

about the $\phi_0 = 180°$ "fold line"



z > 0 : North
z < 0: South

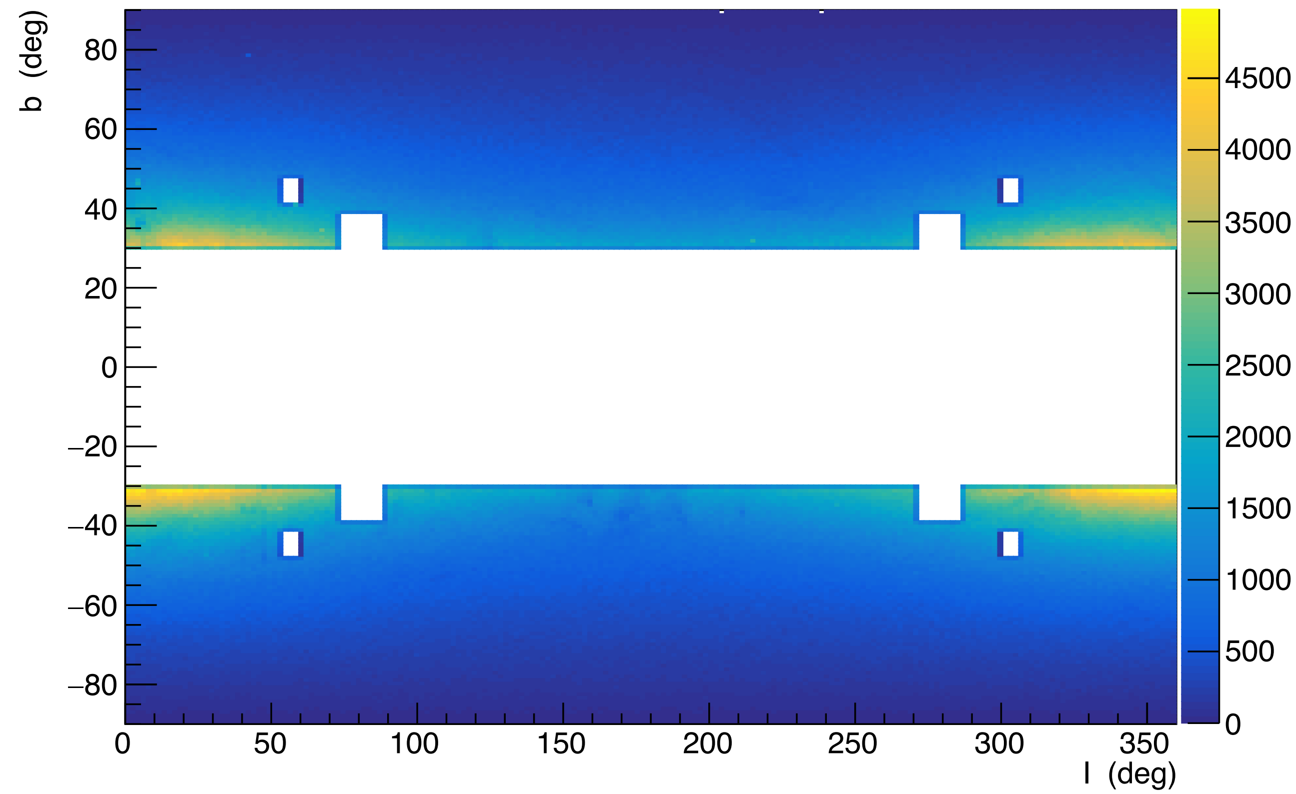
N.B. Spiral arms are an "in-plane" feature

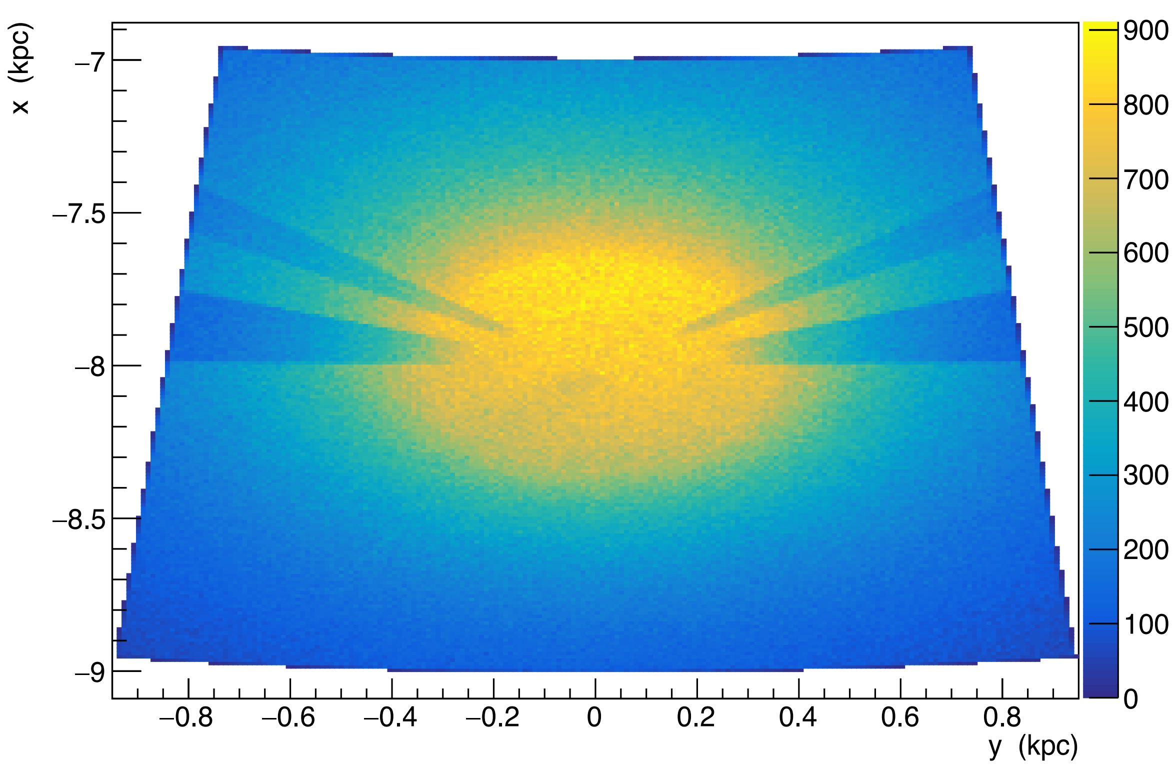
Data Selection

Mask out LMC/SMC regions & their mirrors

- $|b| > 30°$
- $|z| \in [0.2, 3]$ kpc
- $R \in [7, 9]$ kpc
- $G \in [14, 18]$ mag
- $G_{BP} - G_{RP} \in [0.5, 2.5]$ mag

[Hinkel, SG, Yanny, 2020]





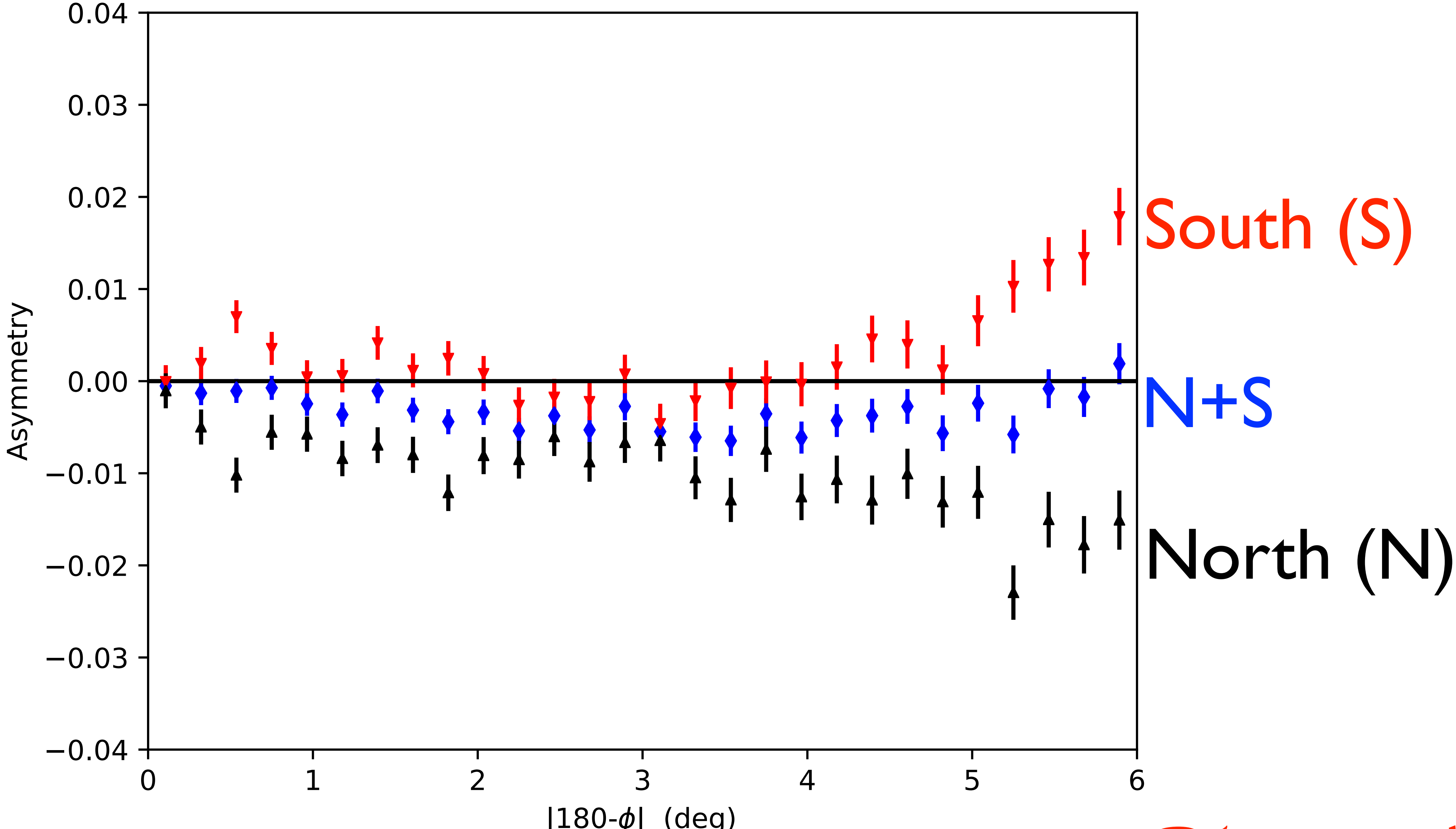
> 11,700,000 stars $[|\phi - 180°| \leq 6°]$

Systematic	$\lvert\mathcal{A}_{\rm sys}\rvert$
Nulls	1.7×10^{-4}
Dense Field Incompleteness	1.3×10^{-5}
Sampling Incompleteness	7.0×10^{-4}
TOTAL:	$\sim 9 \times 10^{-4}$

Left-Right Asymmetry from *Gaia* DR2

Asymmetries implicitly integrate over z and R

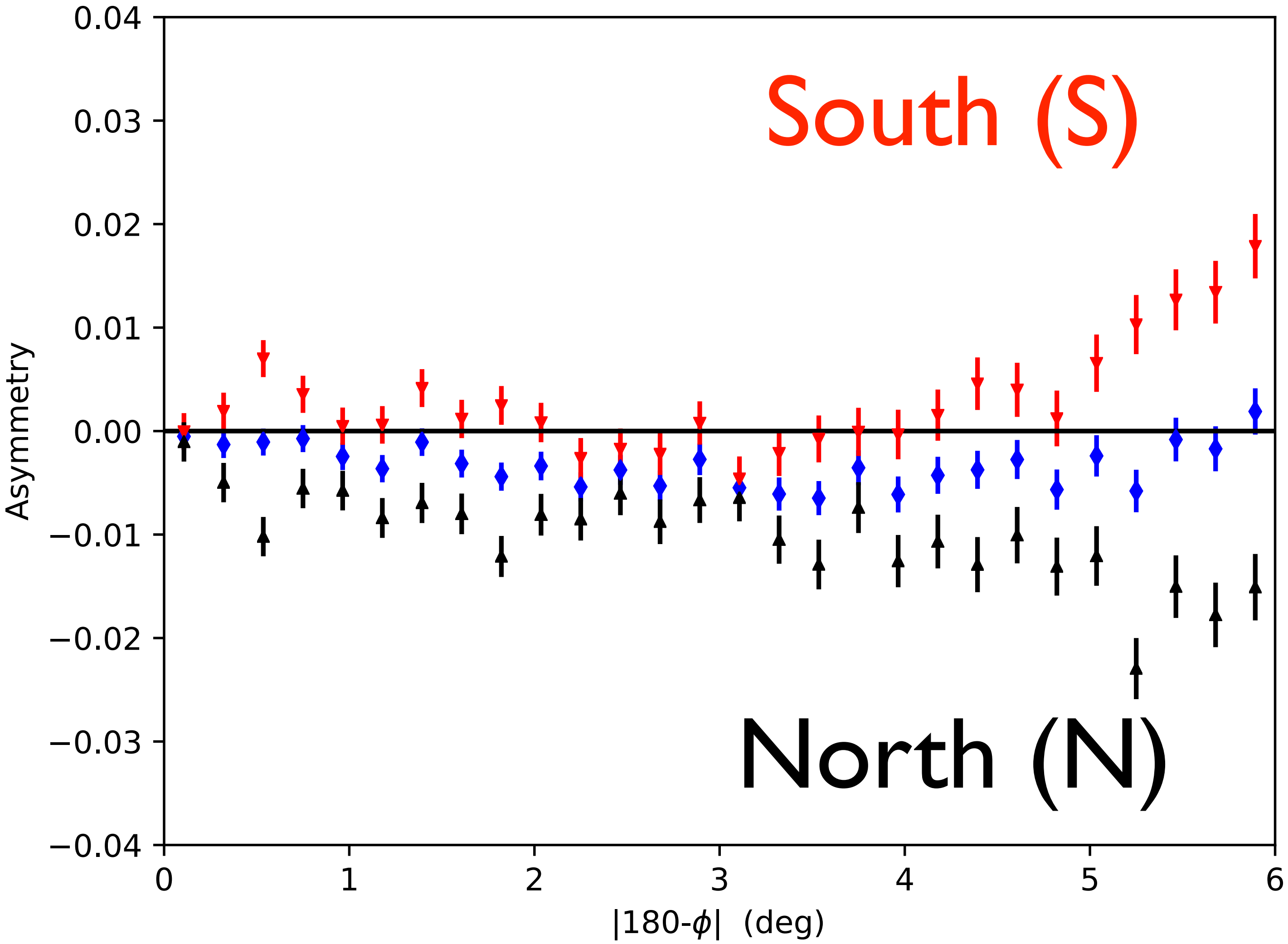
$$\mathcal{A}(\phi) = \frac{n_L(\phi) - n_R(\phi)}{n_L(\phi) + n_R(\phi)}\ ; \quad \text{Note } n_L(\phi)\,[\phi > 180°]\ ,\ n_R(\phi)\,[\phi < 180°]$$



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

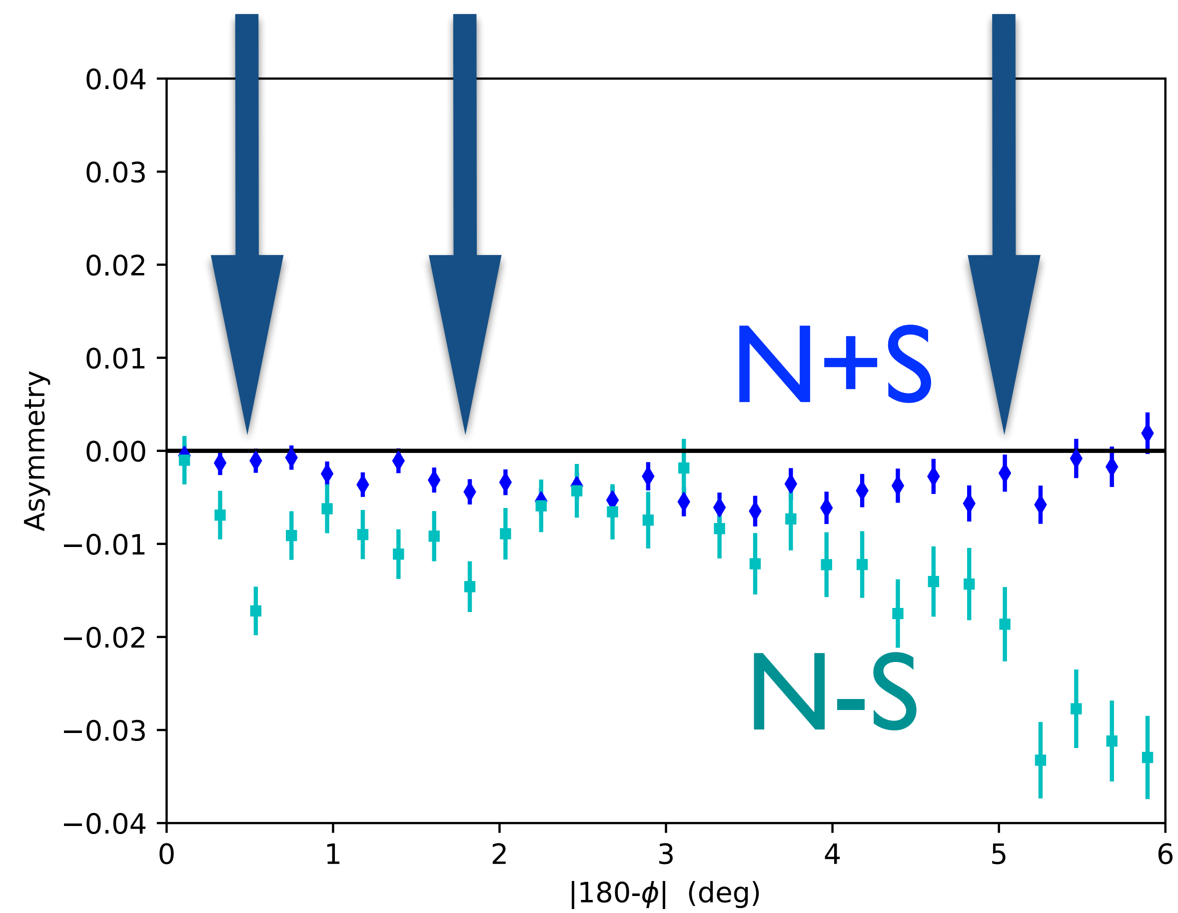
Left-Right Asymmetry from *Gaia* DR2

Asymmetries differ N and S and sometimes markedly so!



N+S

|180°-ϕ| ≈ 0.5°,1.8°, >5°



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

Interpretation

What does it mean if the N+S asymmetry is nonzero?

The Galaxy is not quite axially symmetric

What are the most likely agents?

[Noether, 1918; Olver, 1993]

L_z must not be perfectly conserved

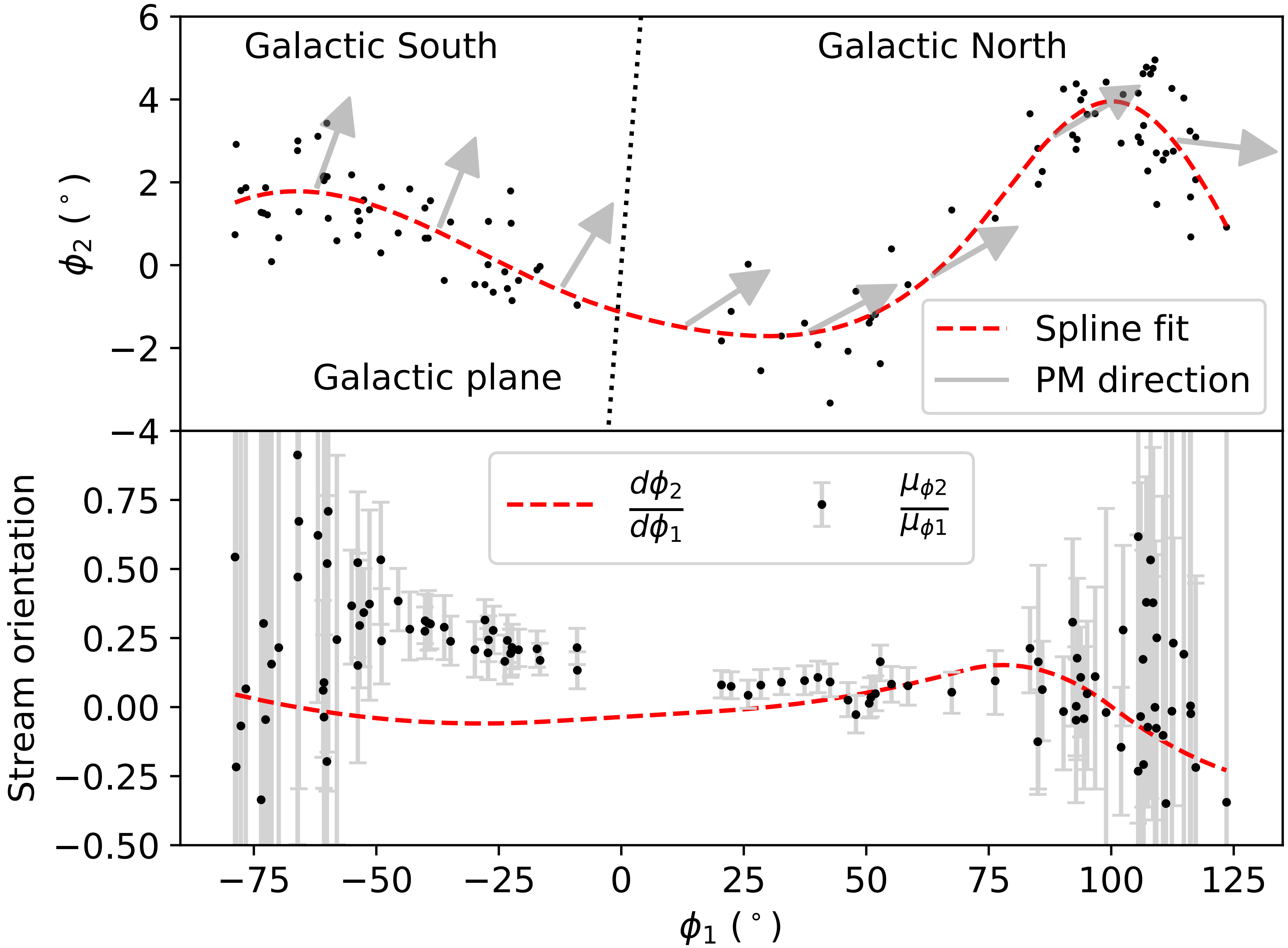
$$\tau_z = \frac{dL_z}{dt}$$

There must be an external torque on our sample.

→ 1) LMC/SMC ; 2) Galactic bar

Evidence for a Massive LMC

Orphan stream stars do not move with the stream velocity

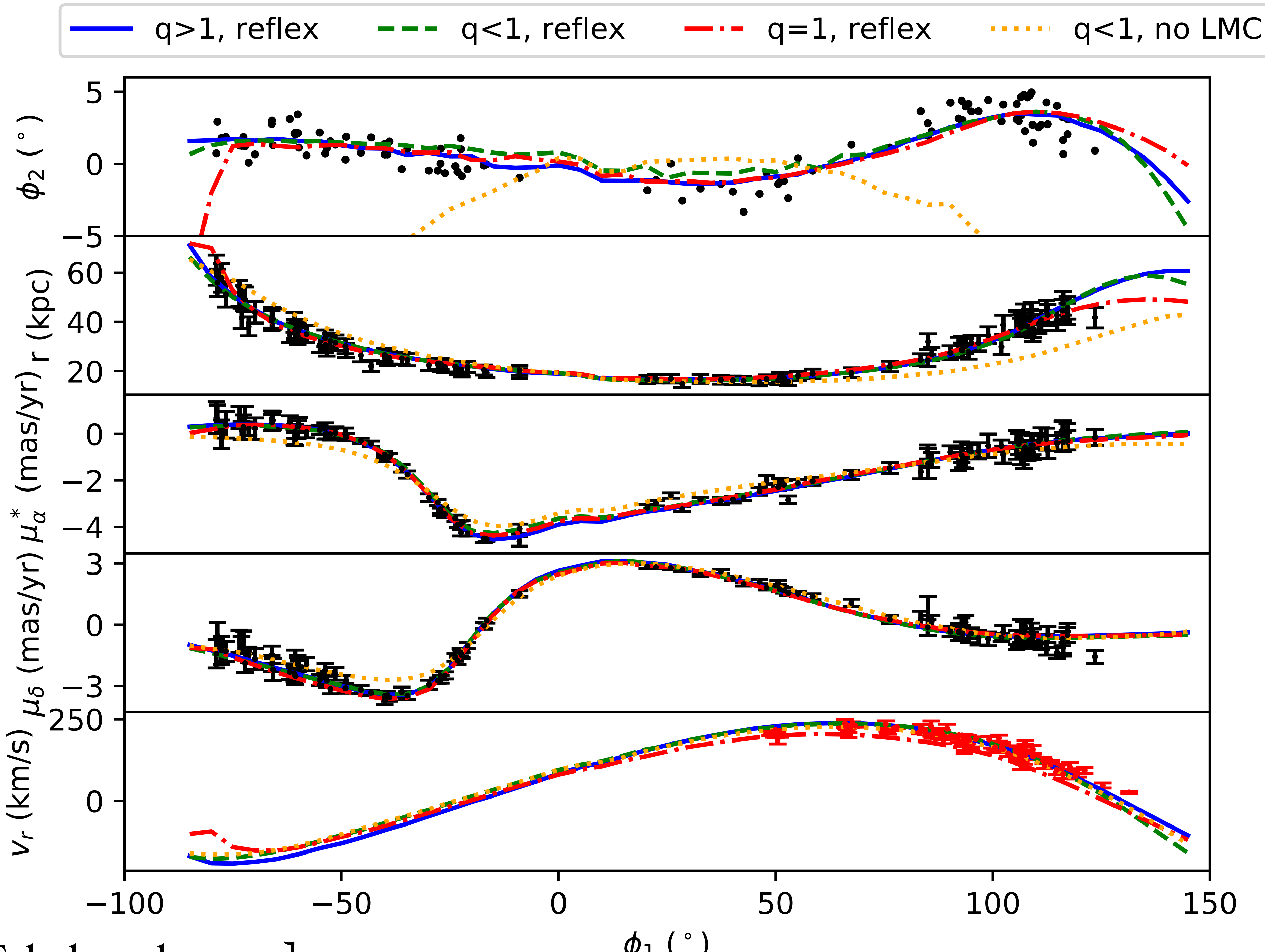


[Erkal et al., 2019]

Orphan Stream Fits: a Massive LMC

Resolve v mismatch with distorted, non-axial DM halo

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

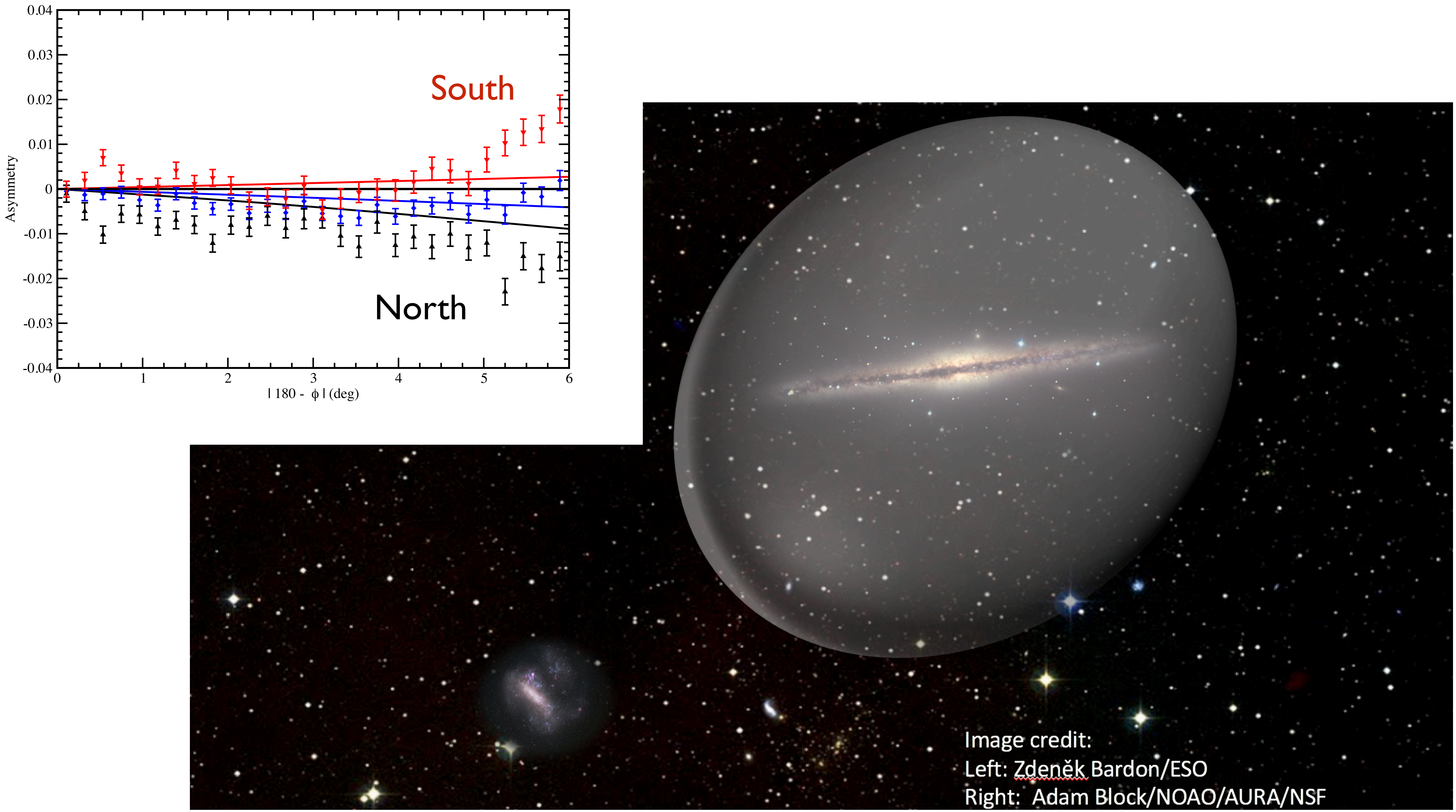


If **n** does not point along **z**, then the potential breaks axial symmetry. Note q >1 prolate, and q<1 oblate

[Erkal et al., 2019]

Evidence for a Massive LMC

Stellar asymmetries favor a prolate DM halo



Summary

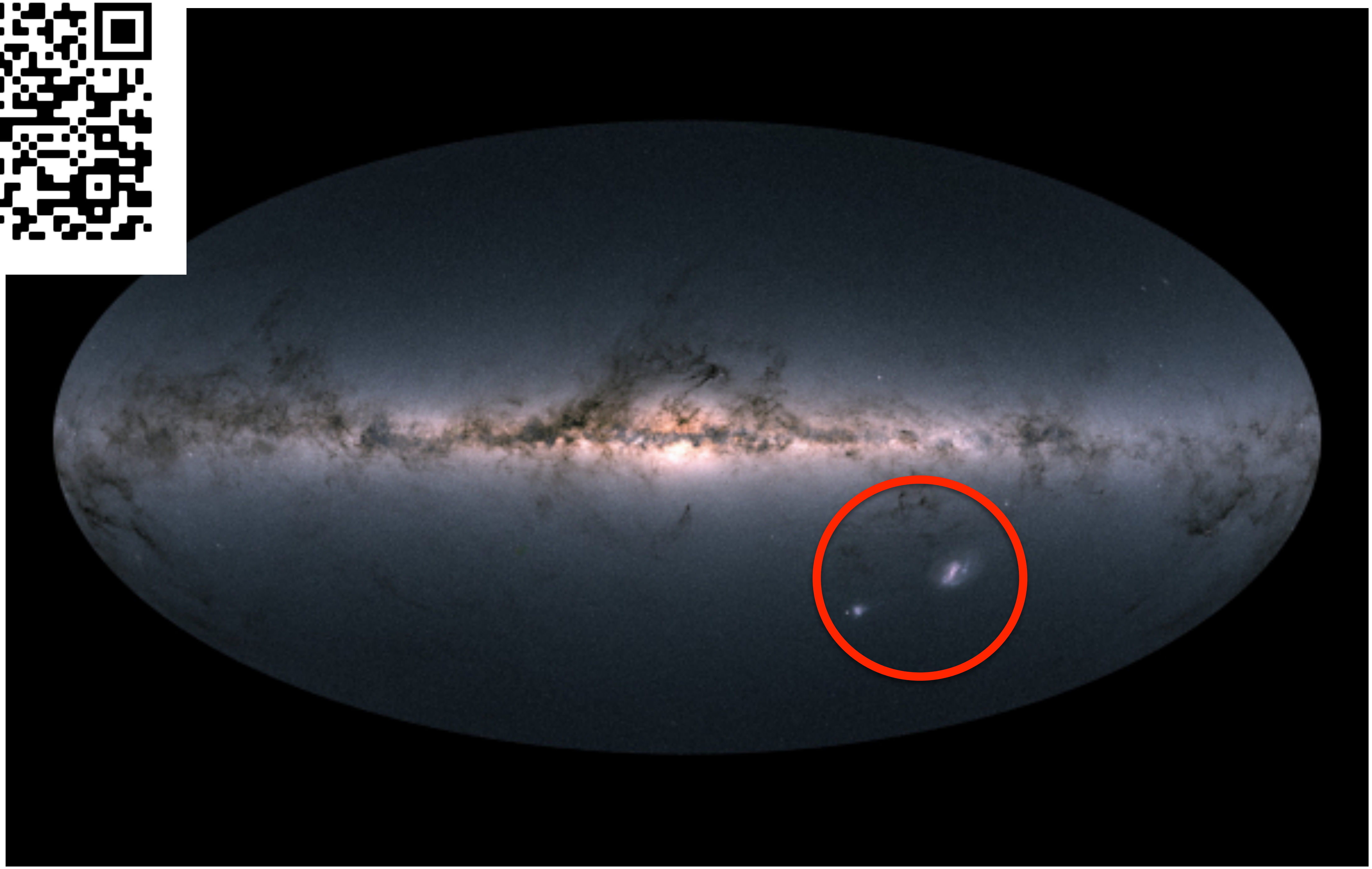
- The Galaxy is axially symmetric to a very good approximation.
- It is not perfectly axisymmetric, implying that it is not isolated.
- Typically, the north/south differences in the asymmetries are larger than their sum, implying that the galaxy is not in steady state.
- The primary perturber appears to be the LMC/SMC system.
- A massive LMC (and distorted DM halo) can explain why the warp in the disk of HI gas is long-lived*, and perhaps the spatial elongation of star counts associated with Gaia Enceladus**
- The observed asymmetries also change at smaller Galactocentric radii, speaking to effects from the Galactic bar.
- As motivated by Noether's theorem (and An et al., 2017), forming asymmetries to probe for failures of axial and north-south symmetry are powerful probes of the influence of satellite torques on the 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

Research supported by the U.S. Dept. of Energy Office of Nuclear Physics under DE-FG02-96ER40989; thanks to the URA & the GAANN Fellowship [AH]!

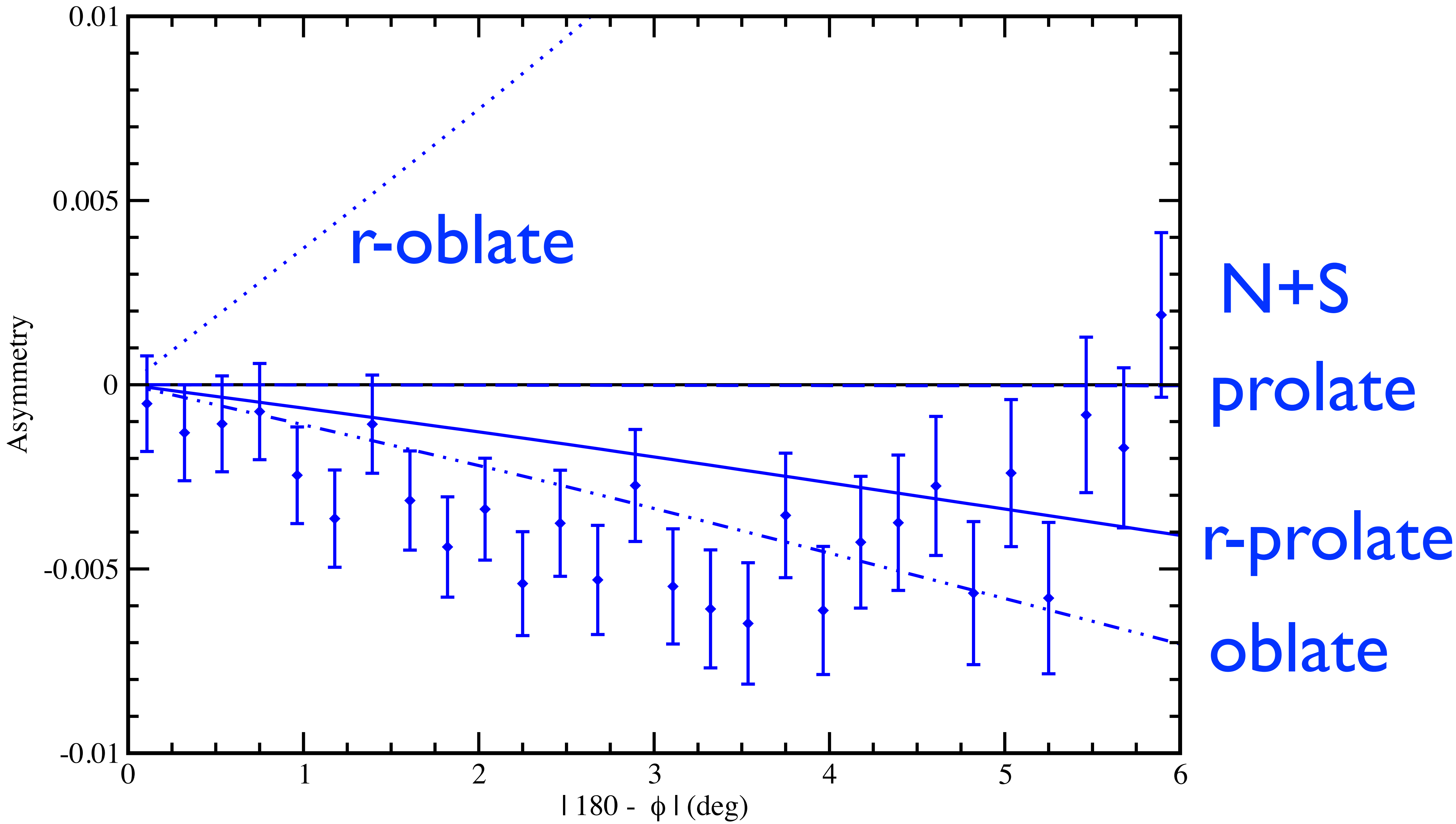


[https://sci.esa.int/web/gaia/-/60169-gaia-s-sky-in-colour (April, 2018)]

Backup Slides

Confronting Distorted DM Halos

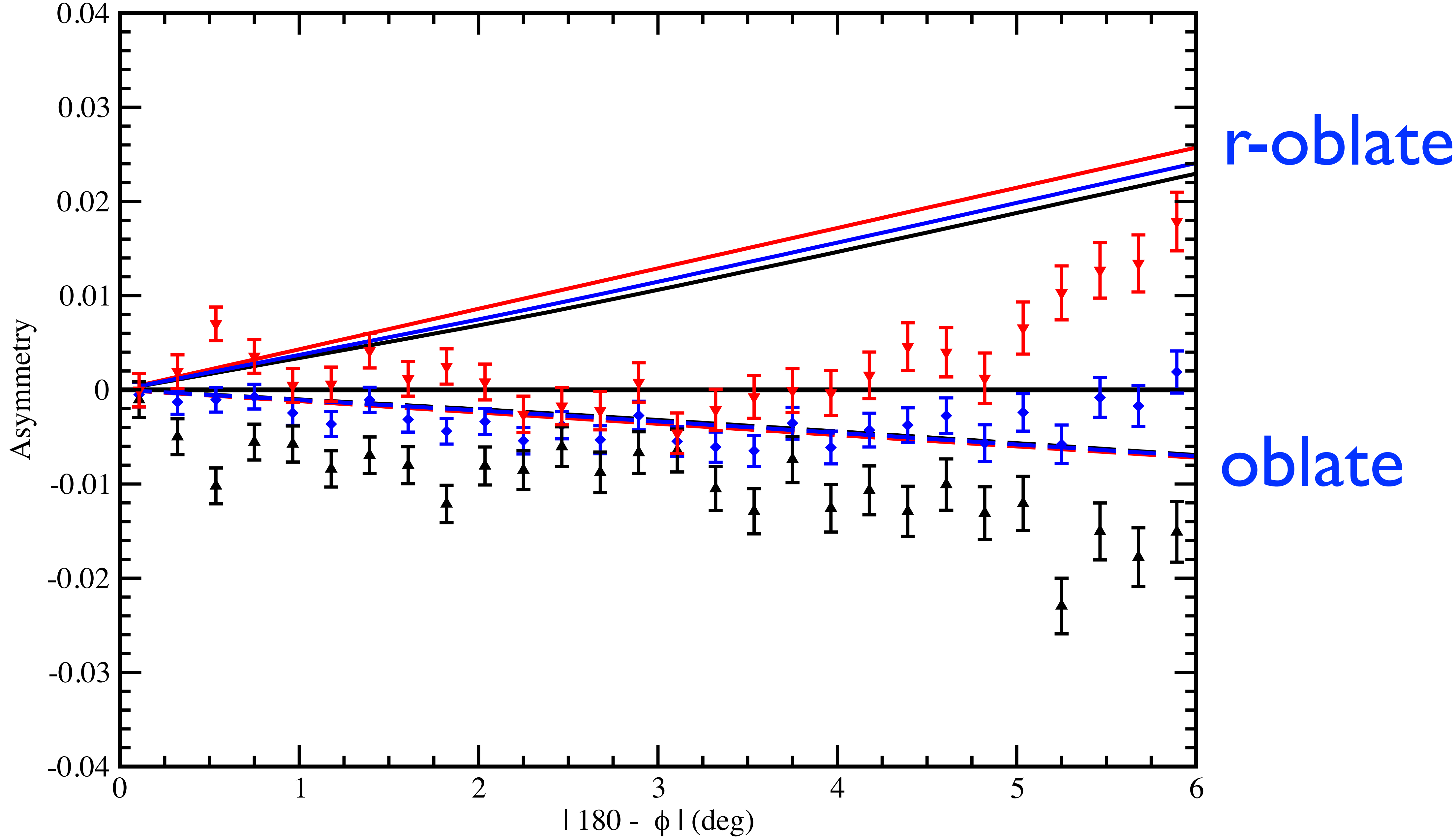
Observed vs. Computed (Orphan Best Fit) Asymmetries



N+S asymmetry only weakly discriminates the possibilities

Confronting Distorted DM Halos

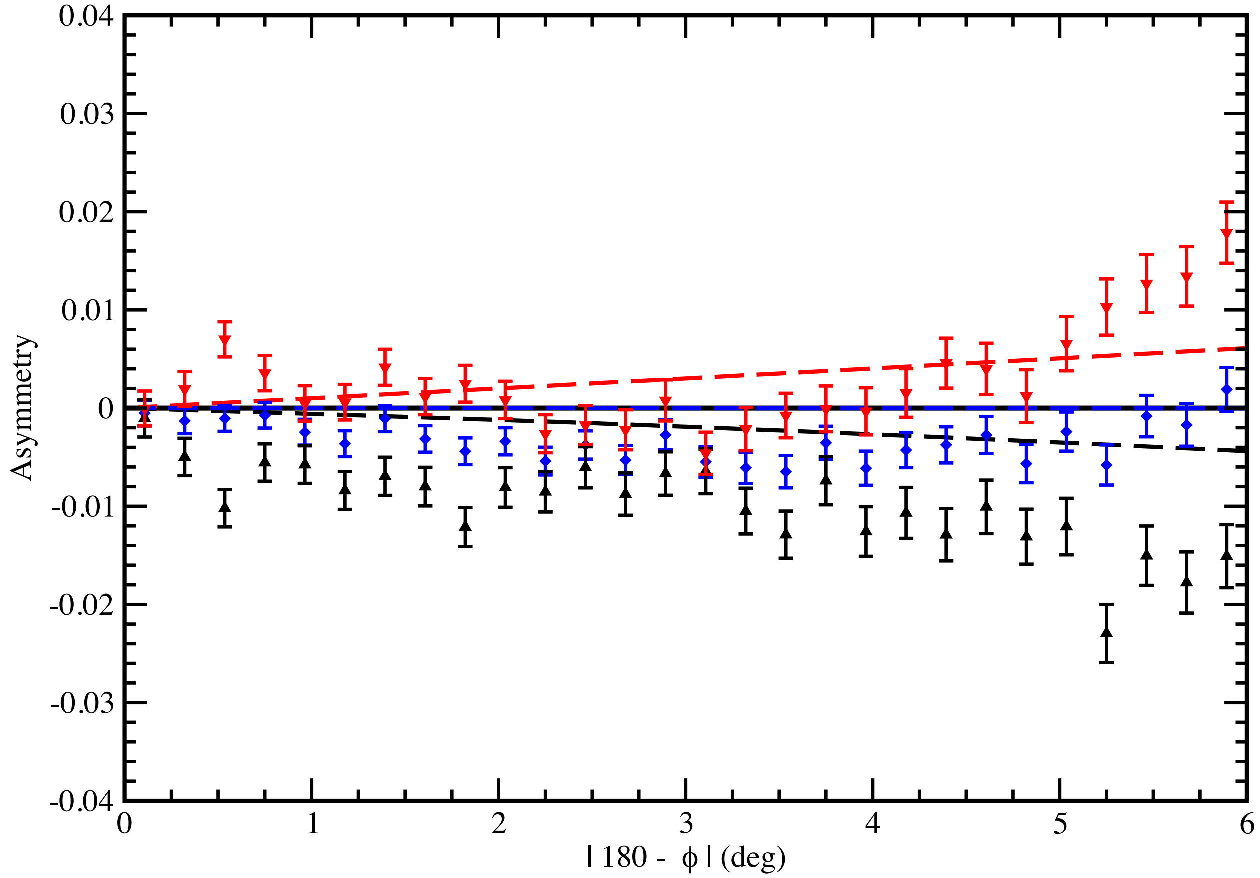
Observed vs. Computed Asymmetries: N, S, & N+S



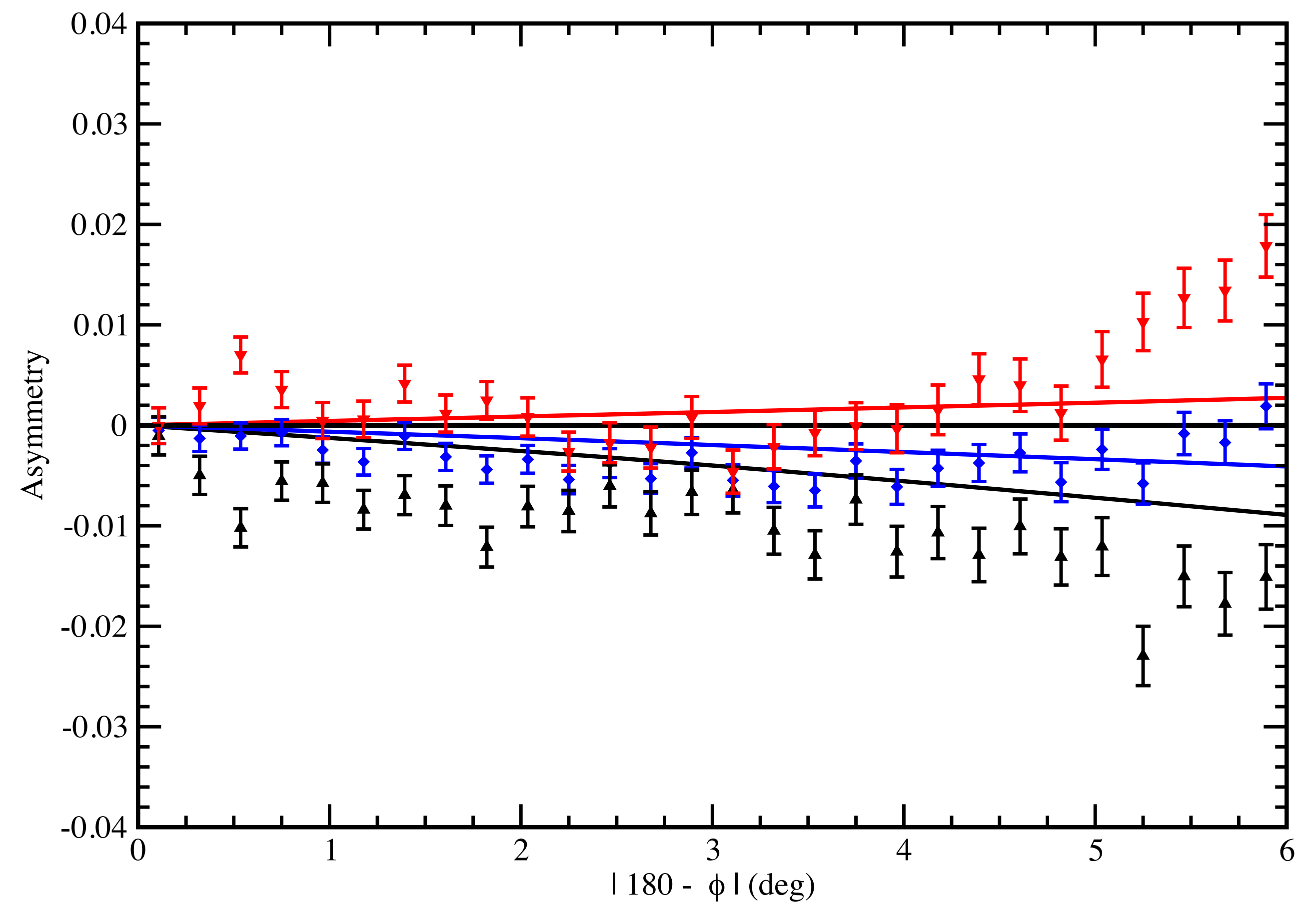
Best-fit oblate forms excluded by N, S, and N+S data

Confronting Distorted DM Halos

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



prolate



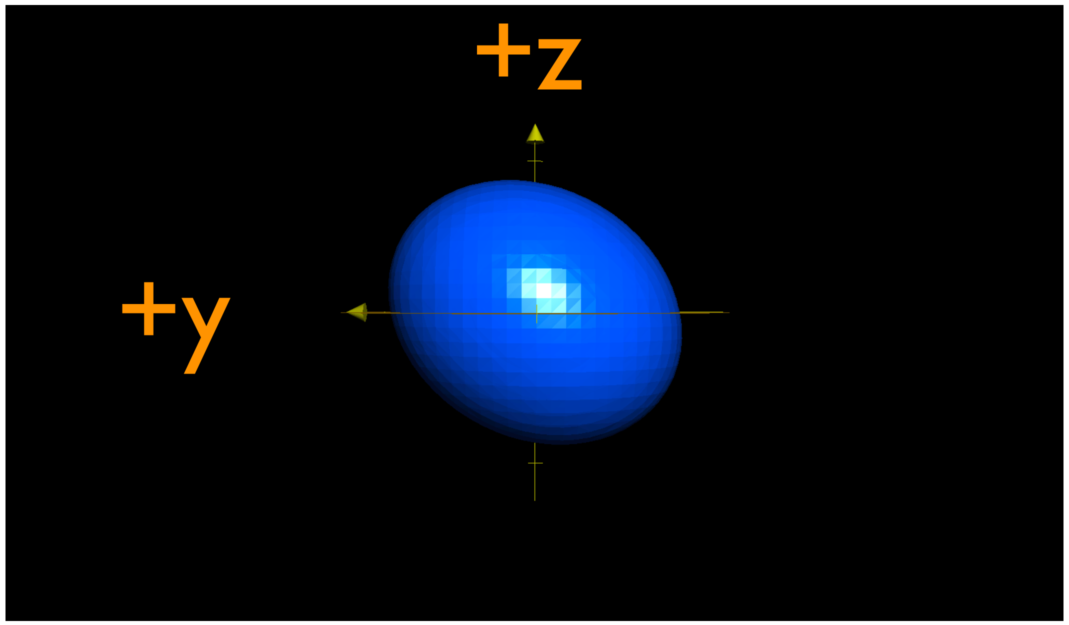
r-prolate

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

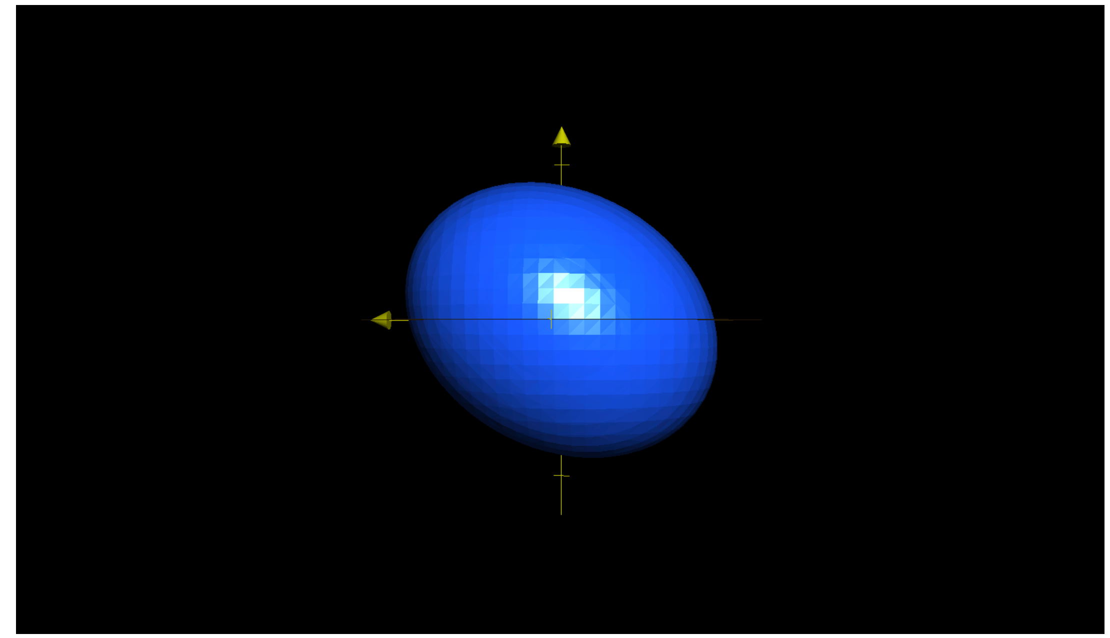
Compare Distorted Halo Potentials

View along anti-center line towards Sun & GC

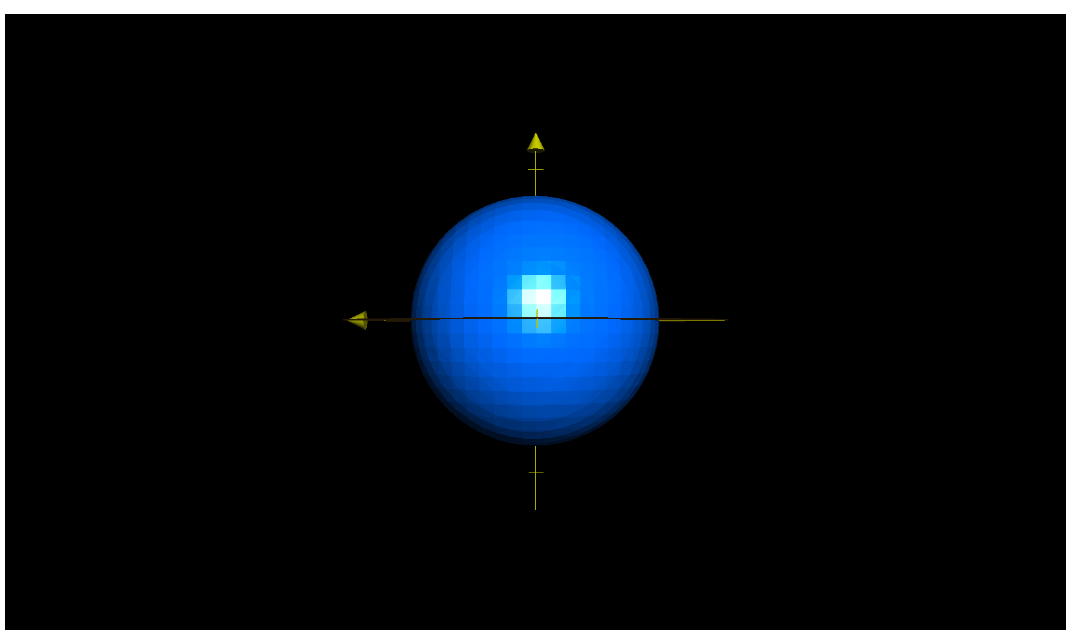
Prolate



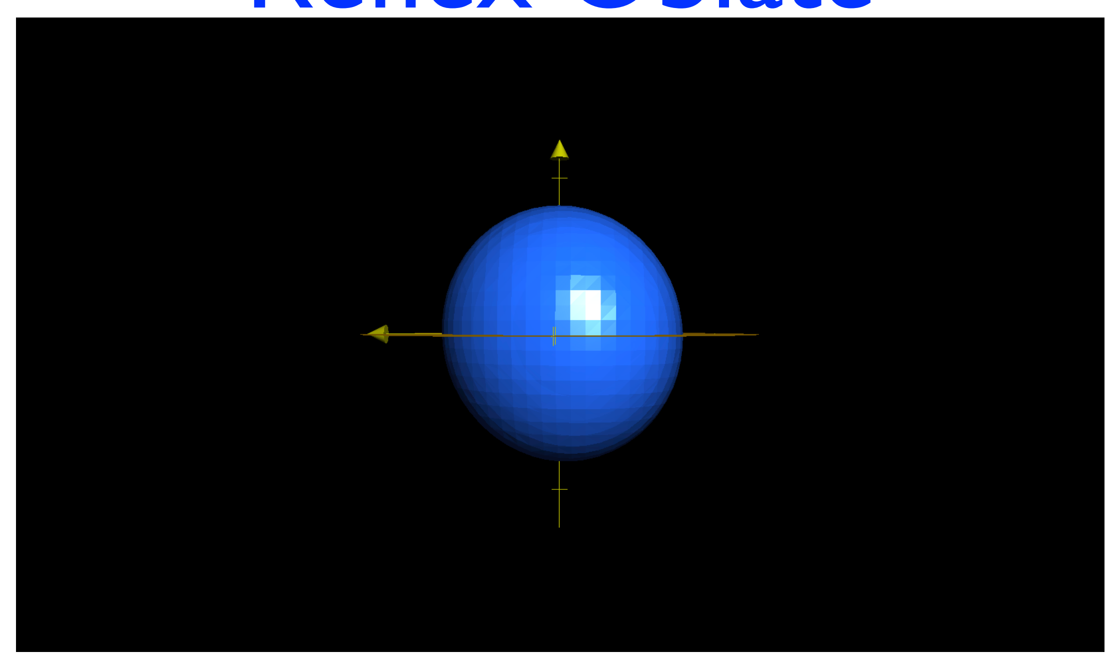
Reflex Prolate



Oblate



Reflex Oblate

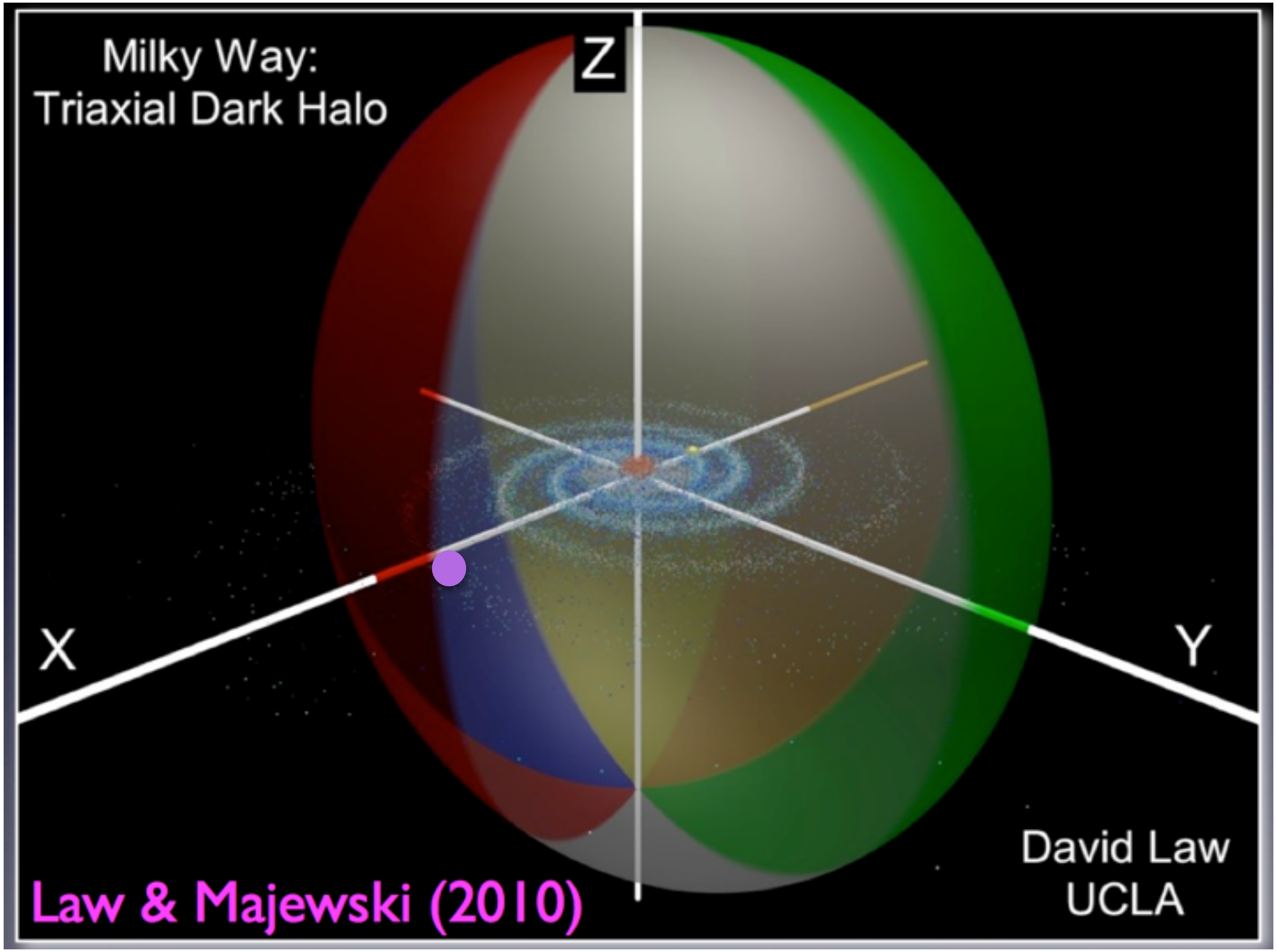


Why Oblate Forms show little N, S sensitivity

A New View of Old Puzzles

Distorted Halo from Sgr stream fits; why its orientation?

LMC!

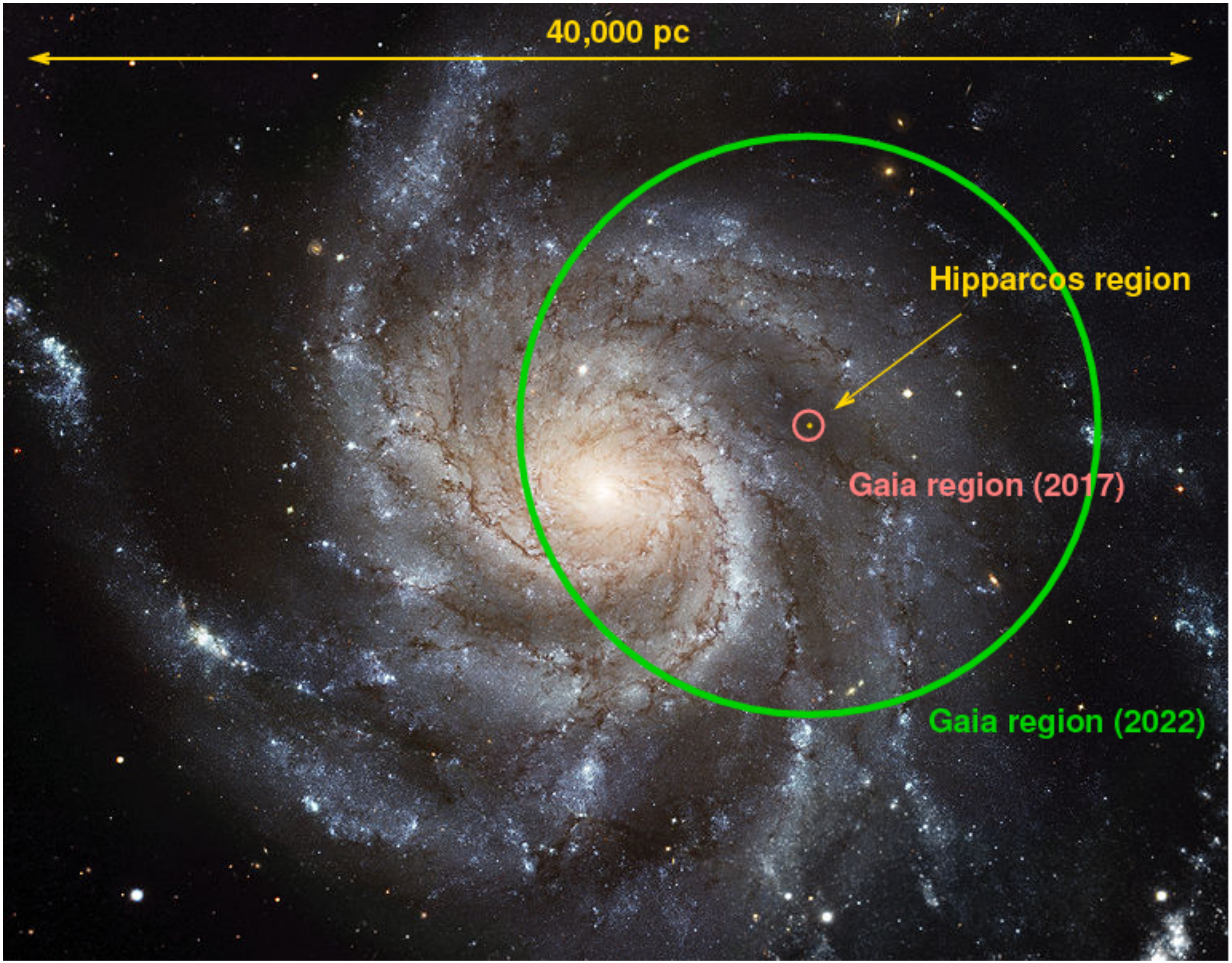


[Figure Credit: Kallivayalil (UVa) [& Law]]

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

Sun: (-8,0,0) kpc

Gaia Observatory Futures



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]	-	-	-

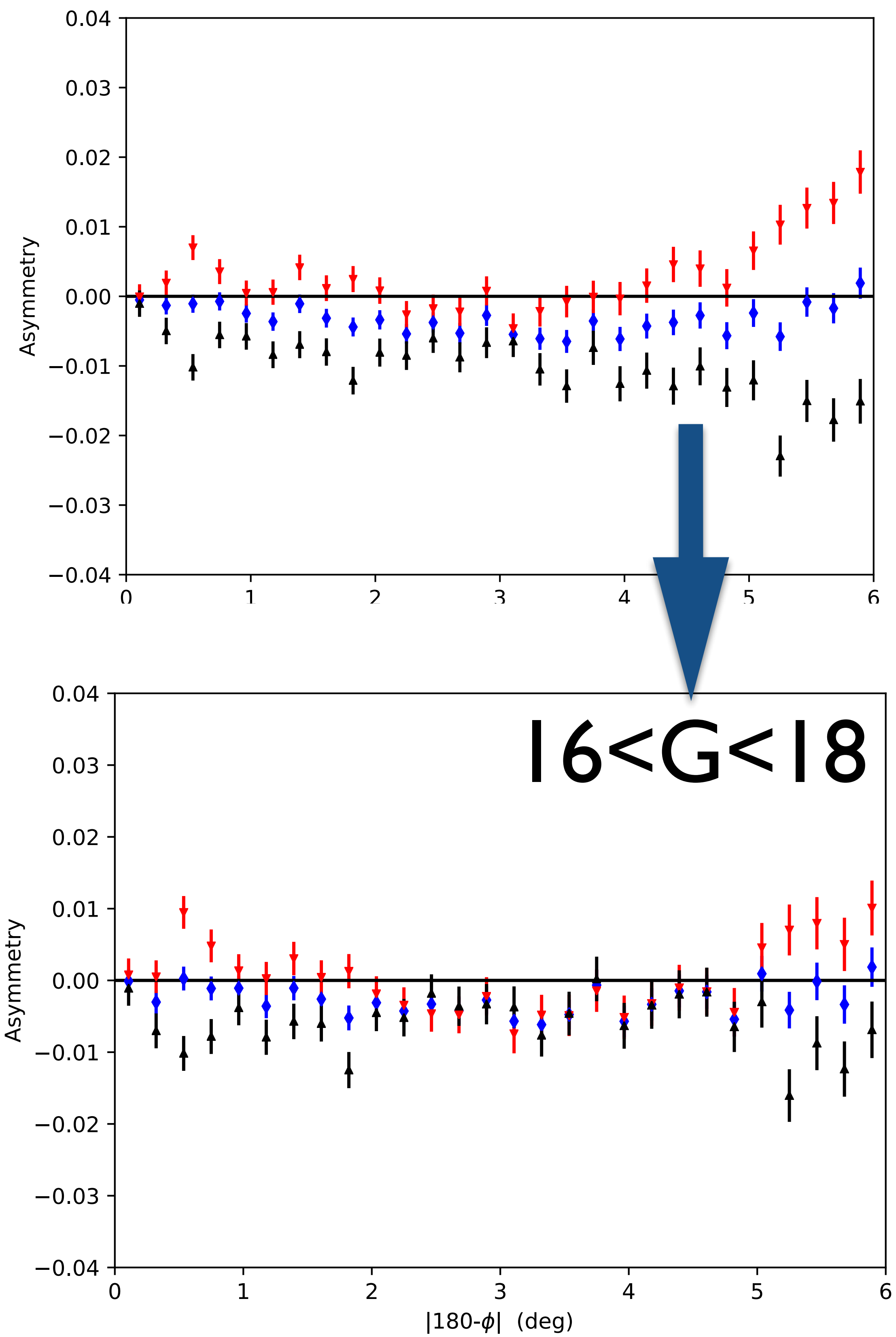
New!

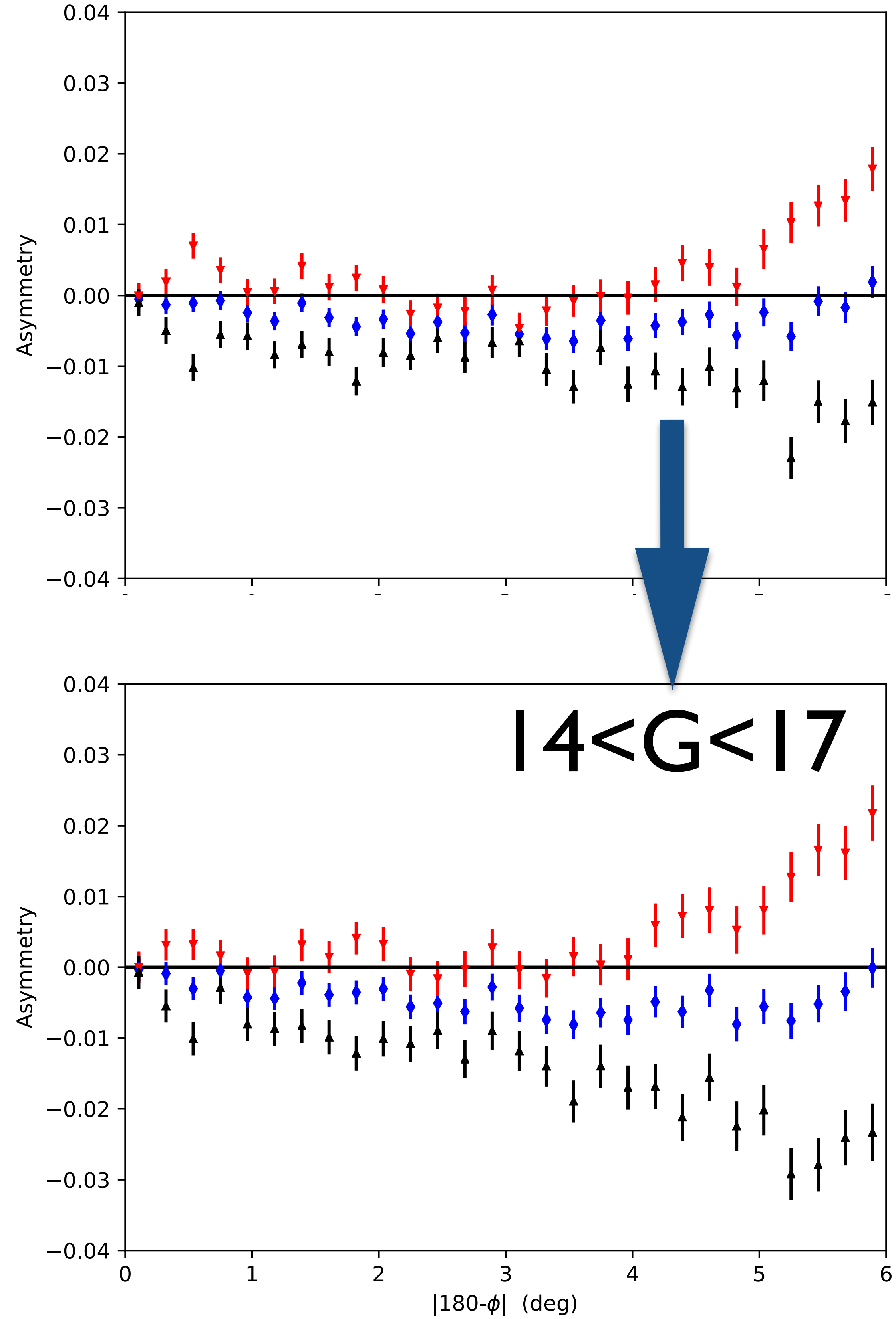
a Erkal et al. (2019)
b Panagia (1999)
c Peñarrubia et al. (2015)
d Ribas et al. (2005)
e Within 17 kpc from center as per Corbelli (2003)
f Gieren et al. (2013)
g Portail et al. (2015)
h Assumed
i Law & Majewski (2010)
j Łokas (2009)
k Helmi et al. (2018); Belokurov et al. (2018)

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

Cross-Checks

Asymmetry insensitive to stellar population chosen





A Cosmic Baryon Asymmetry (BAU)

Assessments in two different epochs agree!

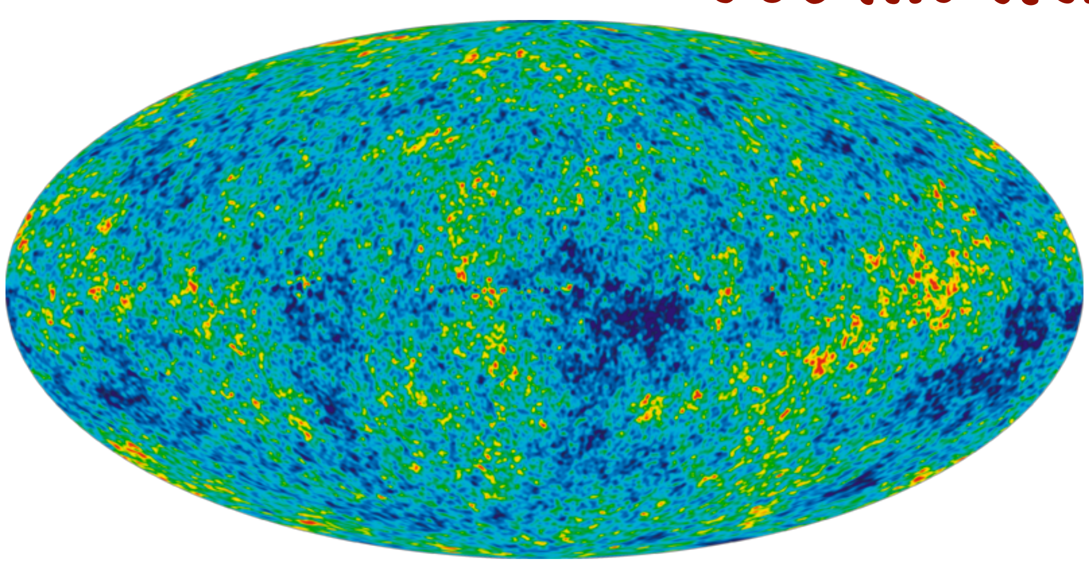
[George Gamow, AIP]

Big-Bang Nucleosynthesis (BBN)

"α, β, γ" Alpher, Bethe, Gamow, "The Origin of the Chemical Elements," 1948

Lightest Elements are made in the Big-Bang, but prediction depends on the BAU

Cosmic Microwave Background (CMB)

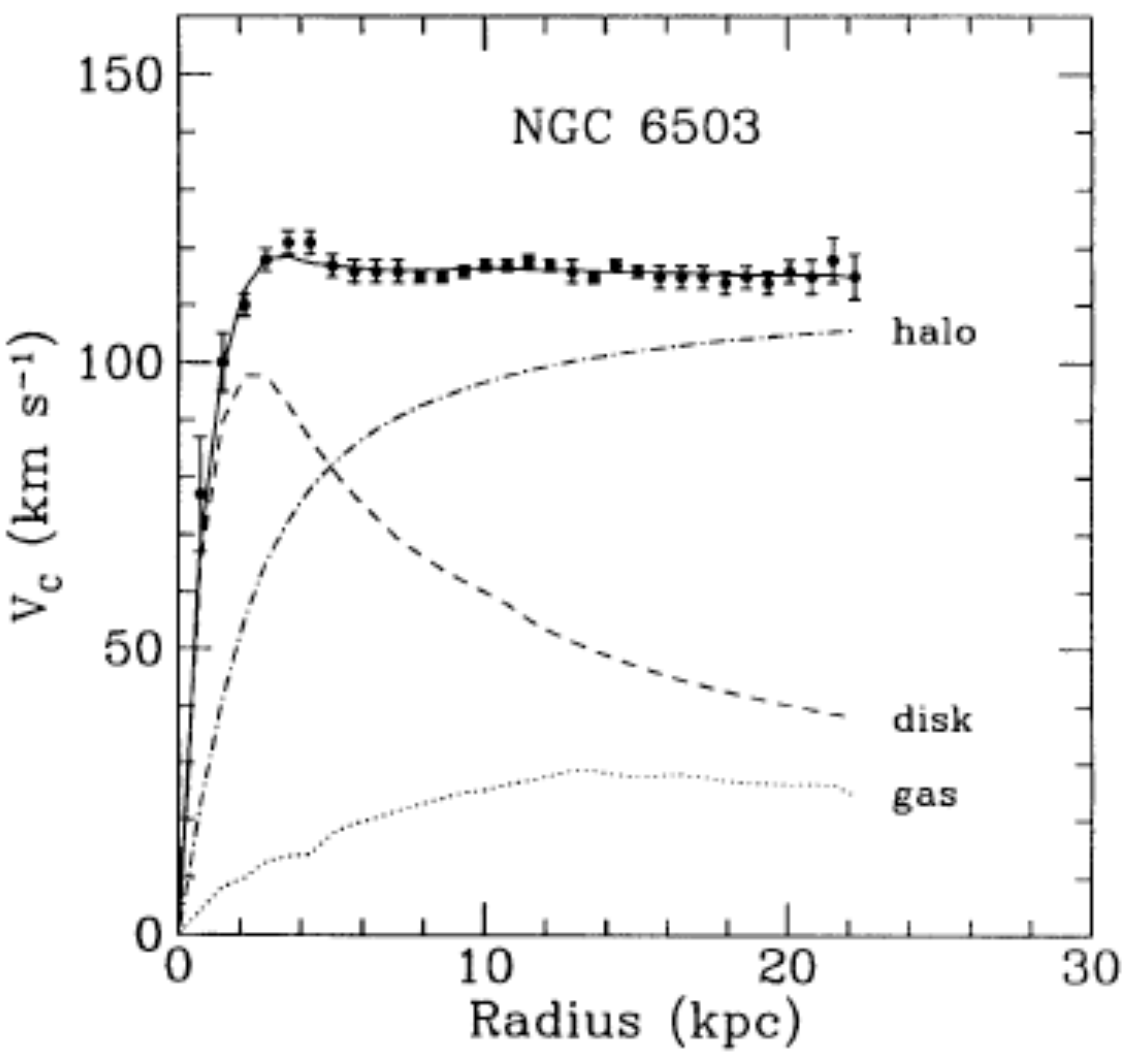


Dicke, Peebles, Roll, & Wilkinson, 1965; Penzias & Wilson, 1965

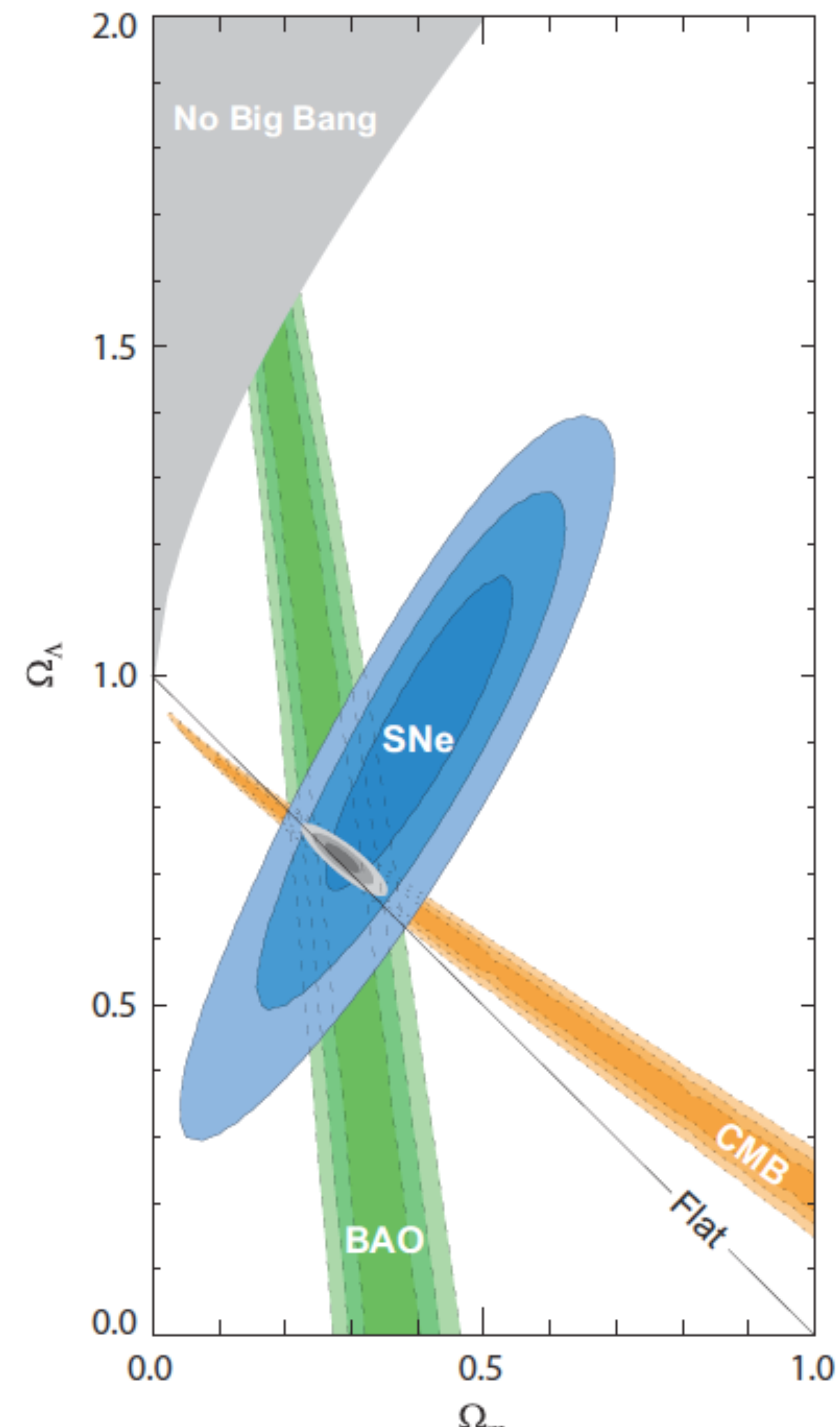
Pattern of Acoustic Peaks reveals baryonic matter

Observational Evidence for Dark Matter ranges from "local" to cosmic scales

Galactic Rotation Curves:
[e.g., from Begeman, Broeils, and Sanders, 1991]



The observed circular speed does not track the luminous mass.



Most of the cosmic energy budget is of an unknown form!

Permanent Electric Dipole Moments

Atomic Scale Effects & Enhancements

Limits on the electron EDM d_e come from paramagnetic and (to a limited extent) diamagnetic atoms — and from molecules

Schiff Theorem (1963):

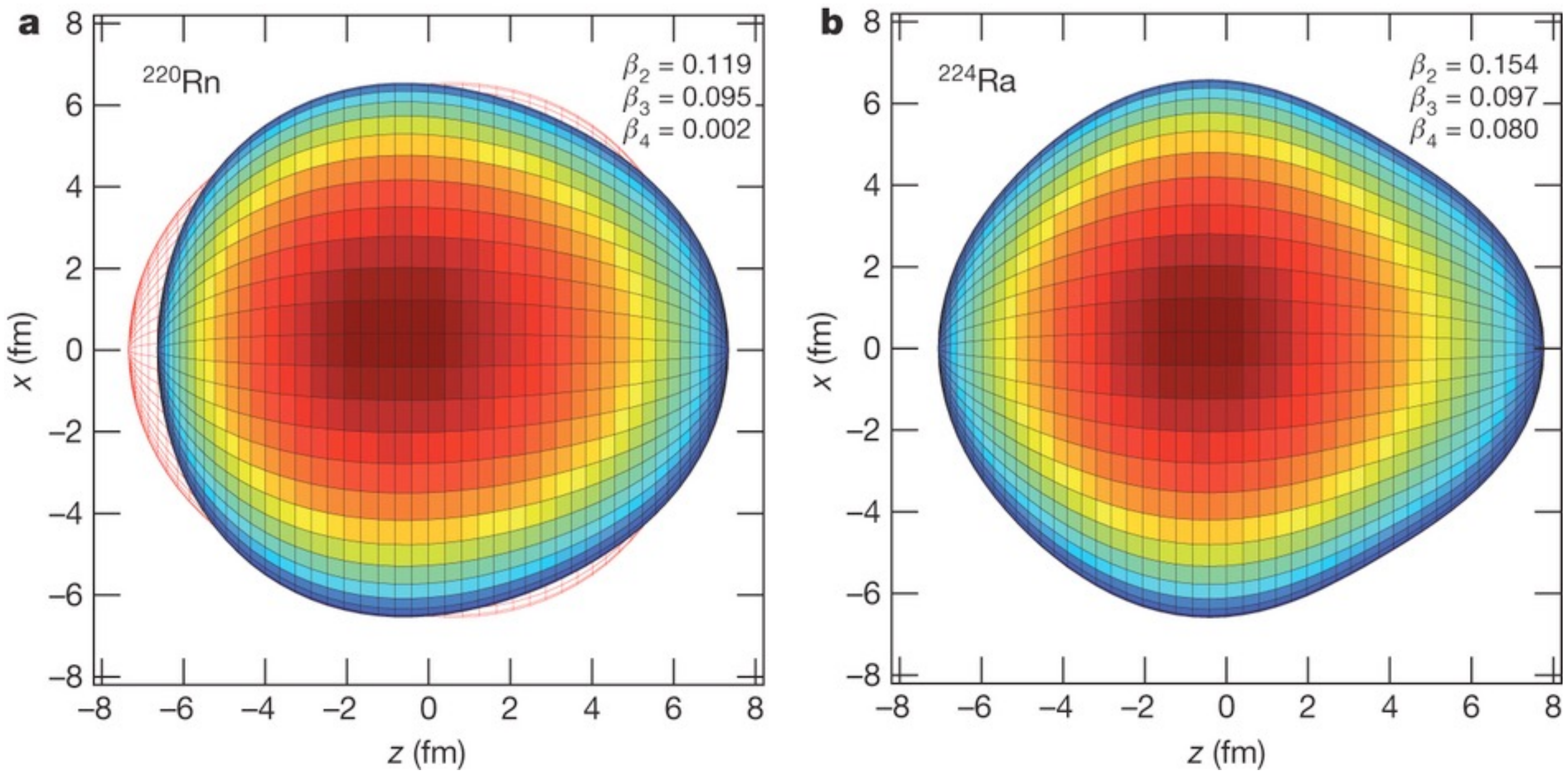
In the non-relativistic limit a neutral, point-like atom will shield an applied electric field, so that there is no atomic EDM even if $d_{nucleus}$ is not zero!

Schiff's theorem can be strongly violated by relativistic and finite-size effects!

In paramagnetic atoms & polar molecules relativistic effects dominate. Note in alkali atoms $d_{atom} \sim Z^3 \alpha^2 d_e$ ($d_{Tl} \sim 585 d_e + \ldots$!) [Sandars, 1965]

Heavy Atom EDMs

evade Schiff's theorem through large Z, finite nuclear size, and permanent (octupole) deformation



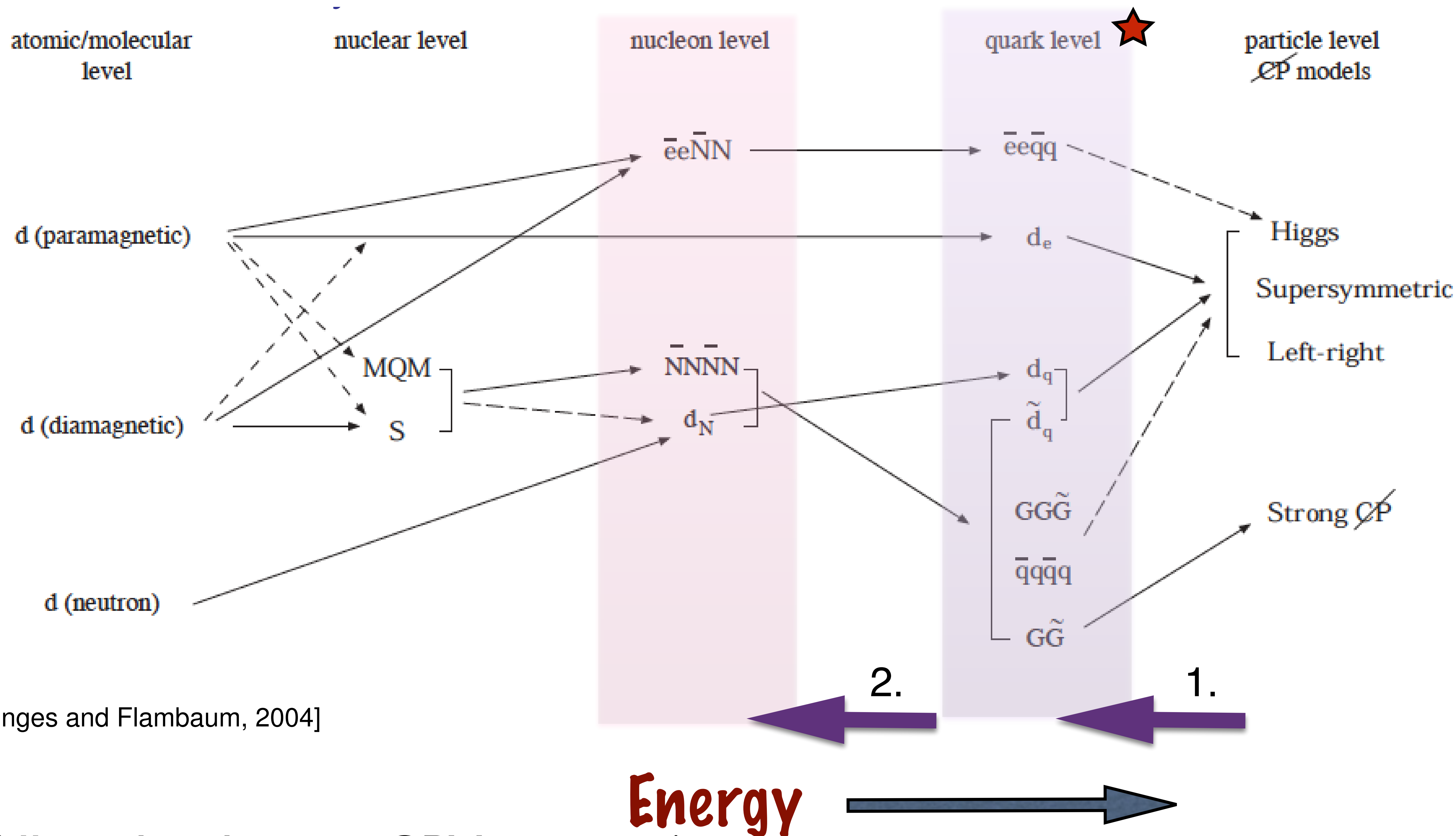
[Gaffney et al., Nature (2013)]

Permanent deformation in Ra-225 makes the nucleus more "rigid" and the Schiff moment computation more robust and 1000x bigger than ^{199}Hg (existing best atomic EDM limit)

This is just one example...

Heavy Atom & Molecular EDMs

Naturally involve multiple energy scales



[Ginges and Flambaum, 2004]

All probe distinct CPV sources!