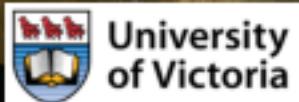


News from the dark - Montpellier

Footprints of the Sagittarius dwarf galaxy in the Milky Way: from outer disc to the Gaia volume

Chervin F. P. Laporte

CITA National Fellow - University of Victoria



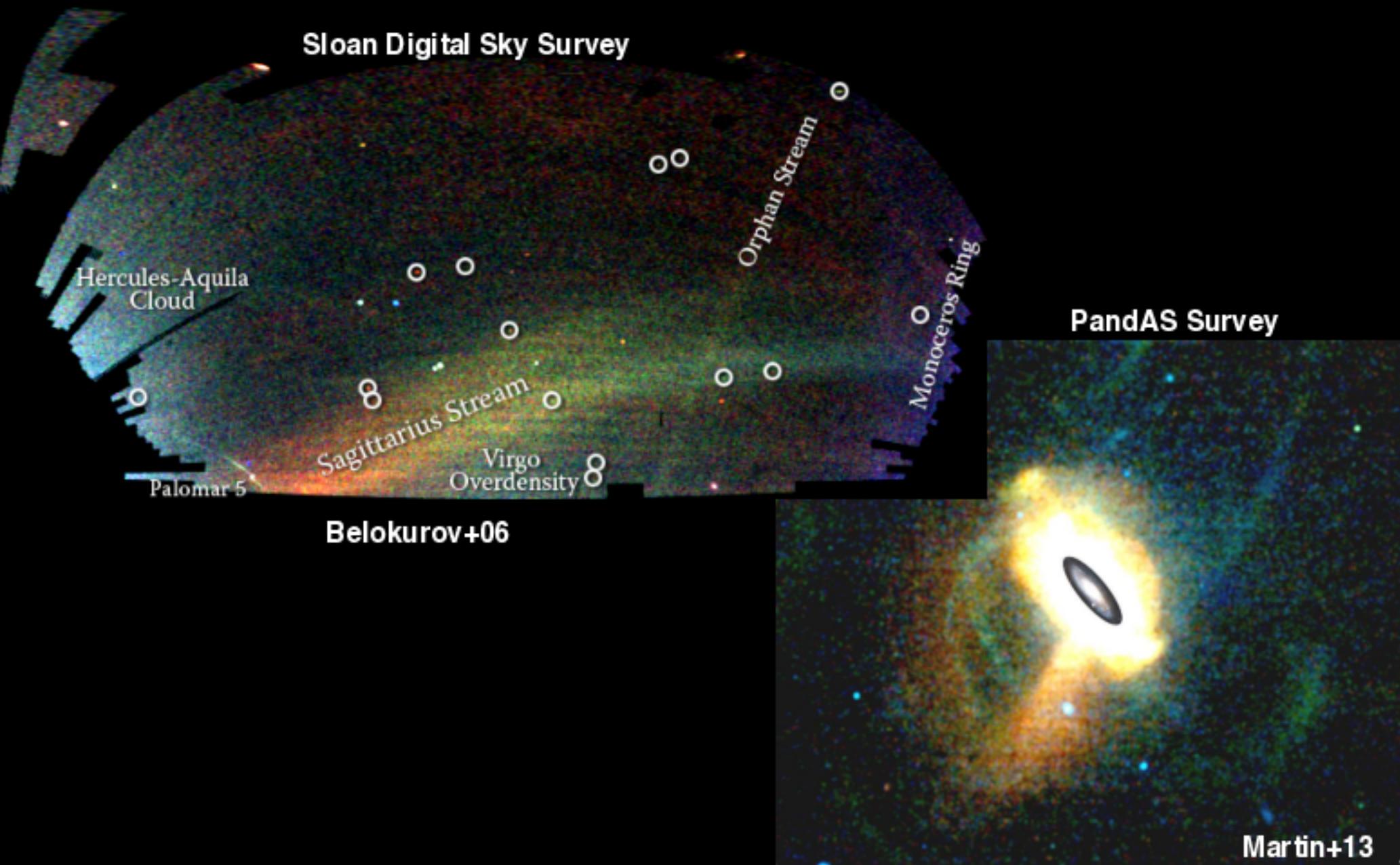
University
of Victoria

XSEDE

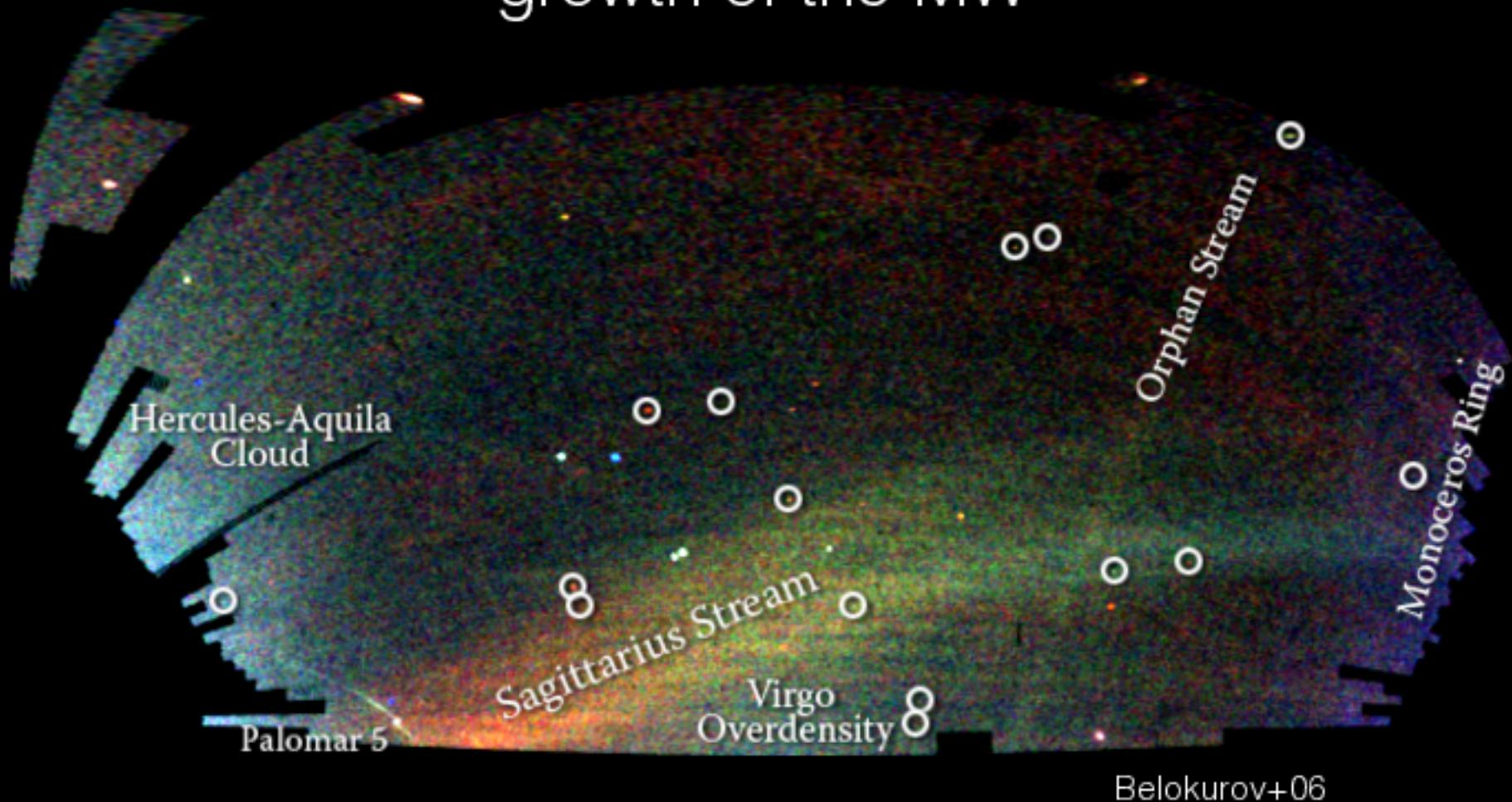
Extreme Science and Engineering
Discovery Environment



Stellar halos: testaments of the hierarchical growth of galaxies

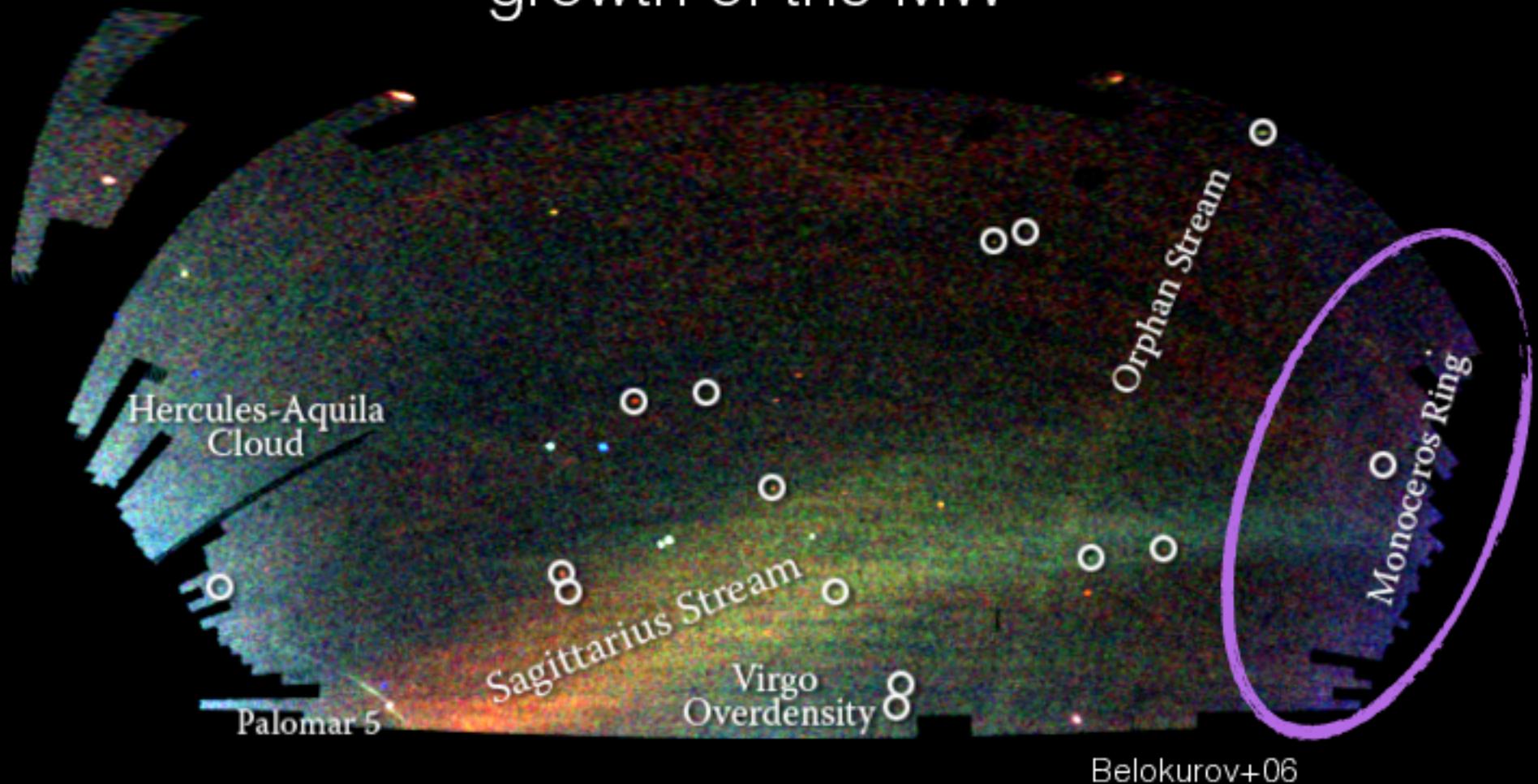


The Field of Streams - a testament of the hierarchical growth of the MW



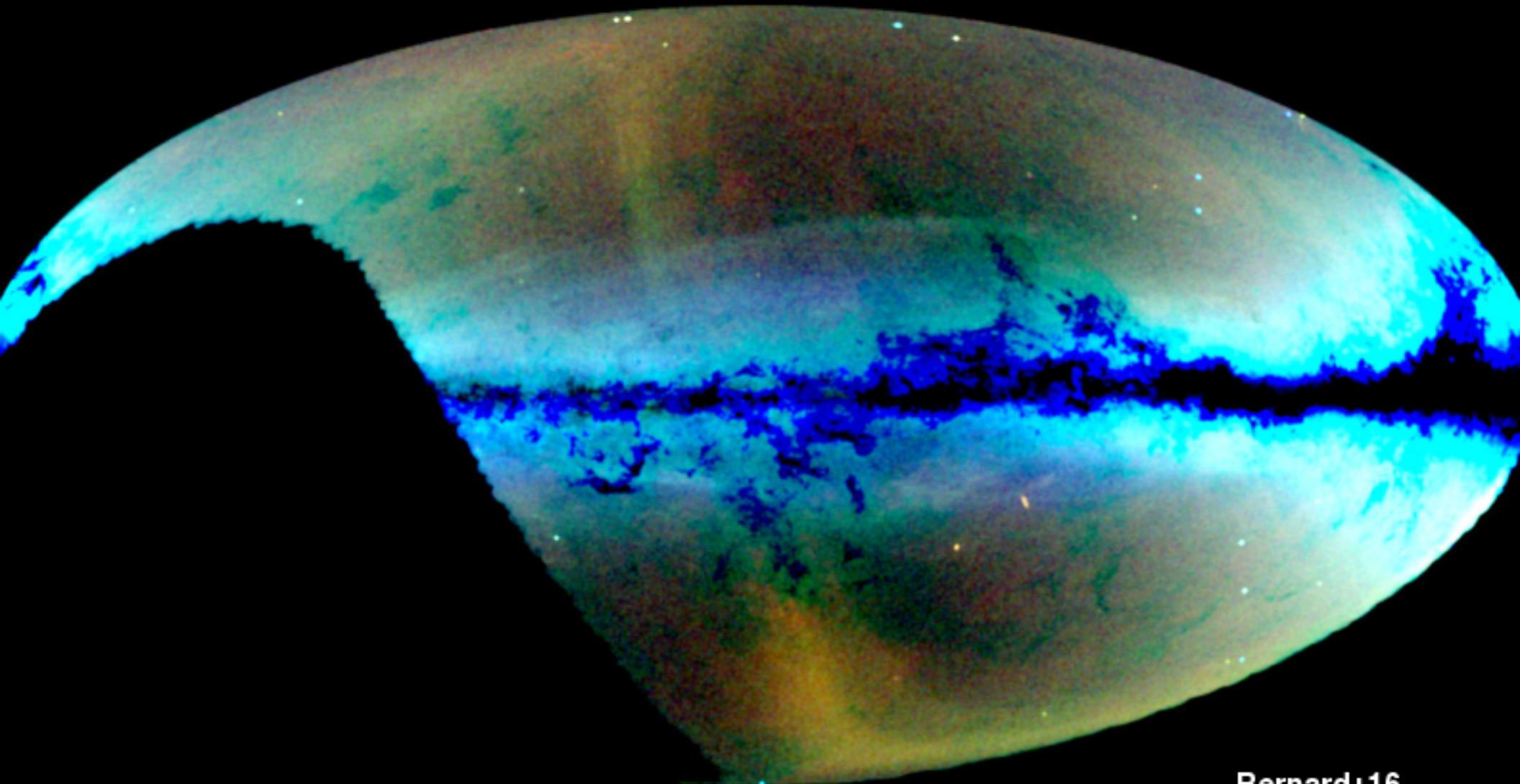
But are all streams on the sky necessarily accreted?

The Field of Streams - a testament of the hierarchical growth of the MW



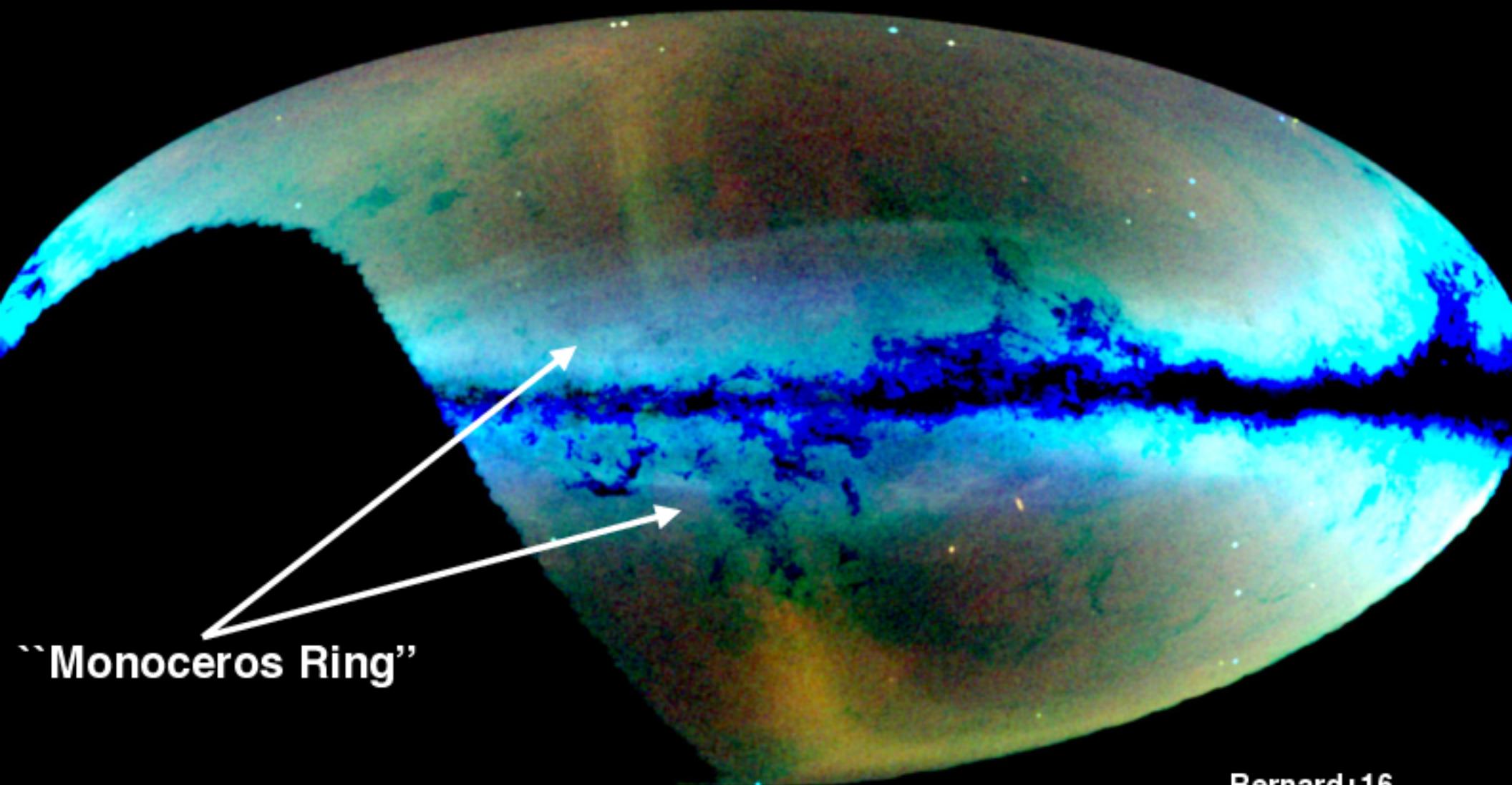
But are all streams on the sky necessarily accreted?

The Anticenter viewed by Pan-STARRS



Bernard+16

The Anticenter viewed by Pan-STARRS



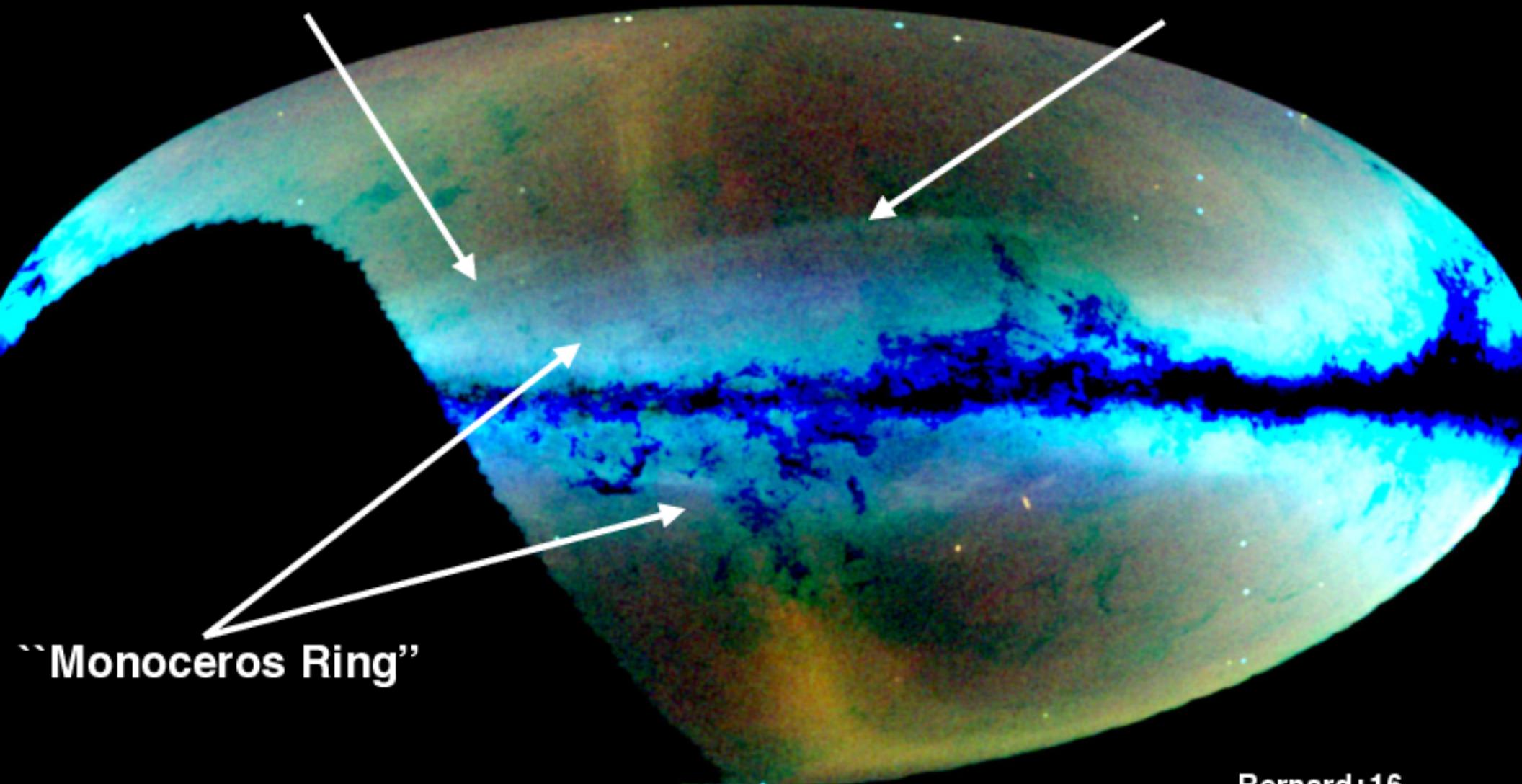
"Monoceros Ring"

Bernard+16

The Anticenter viewed by Pan-STARRS

Eastern Banded Structure

Anticenter Stream

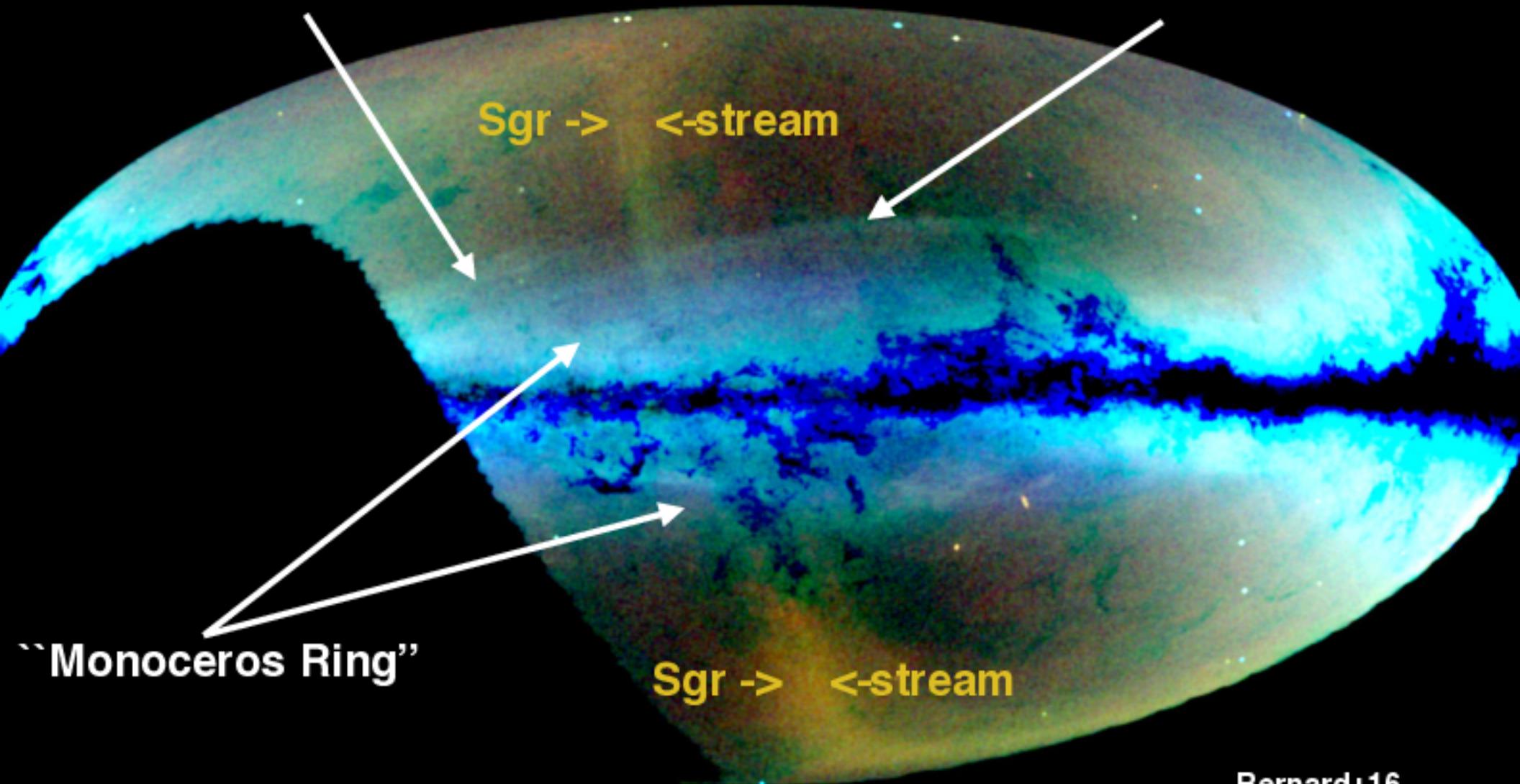


Bernard+16

The Anticenter viewed by Pan-STARRS

Eastern Banded Structure

Anticenter Stream

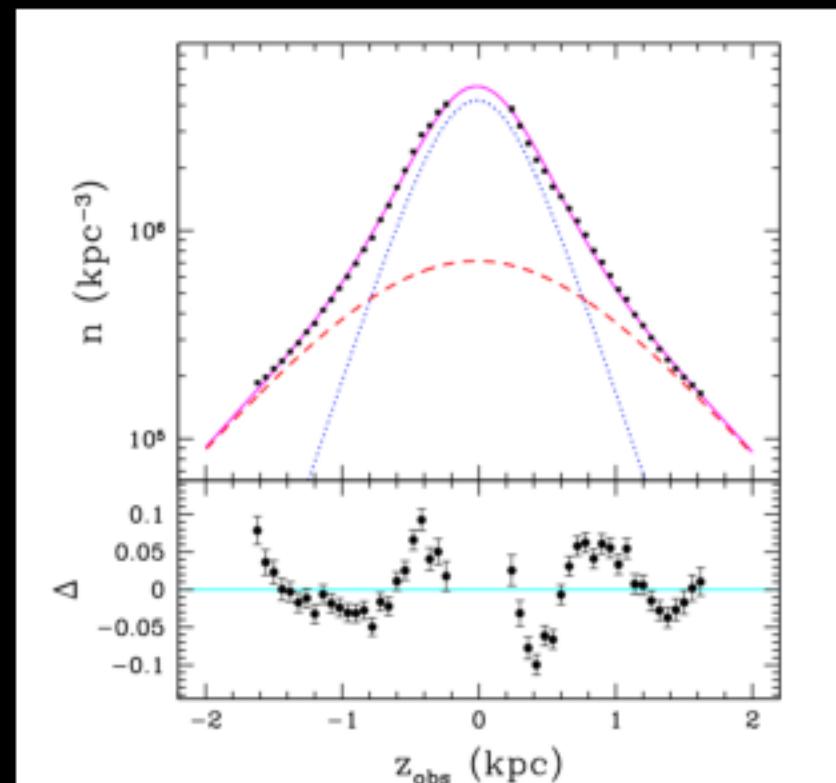


Bernard+16

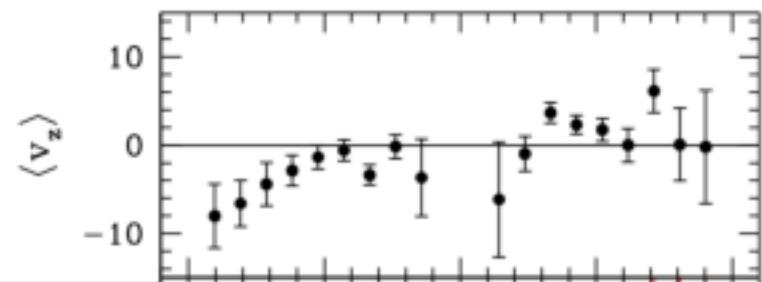
Local oscillations of the disc

pre-Gaia

Widrow+12



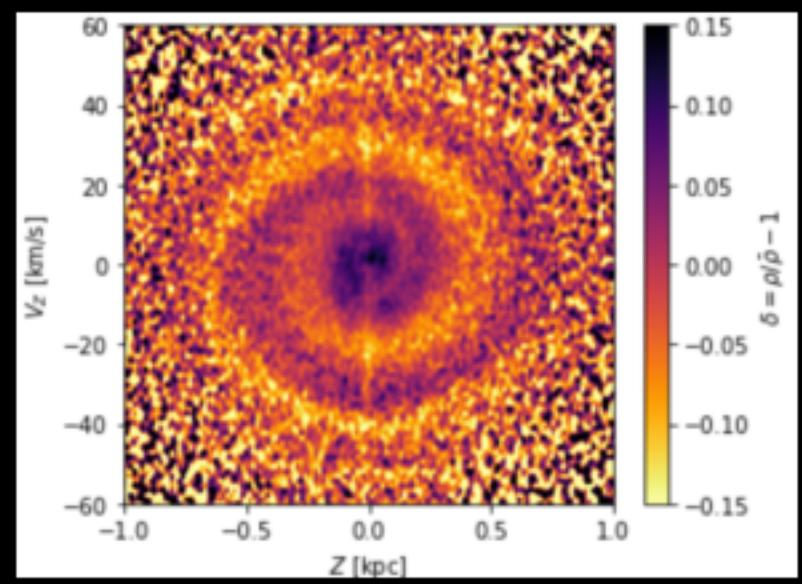
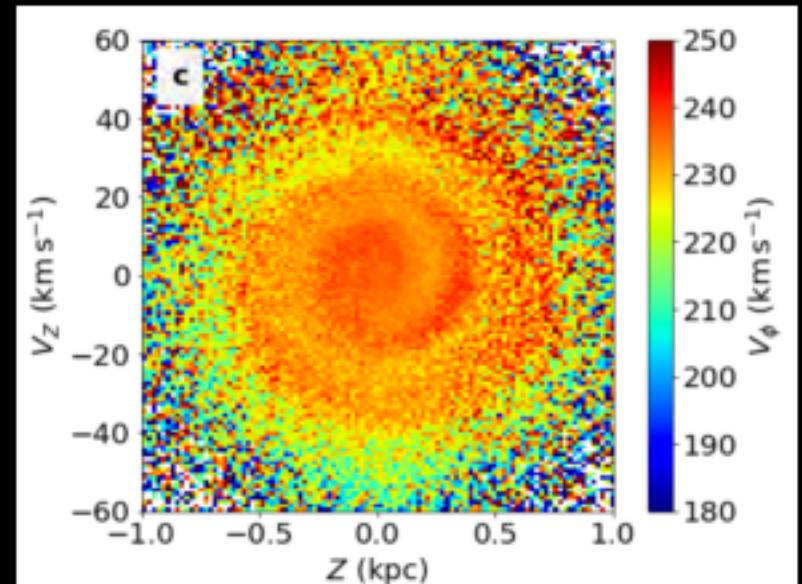
N/S vertical velocity asymmetry



see also results with RAVE, LAMOST in v_z

Gaia DR2

Antoja+18

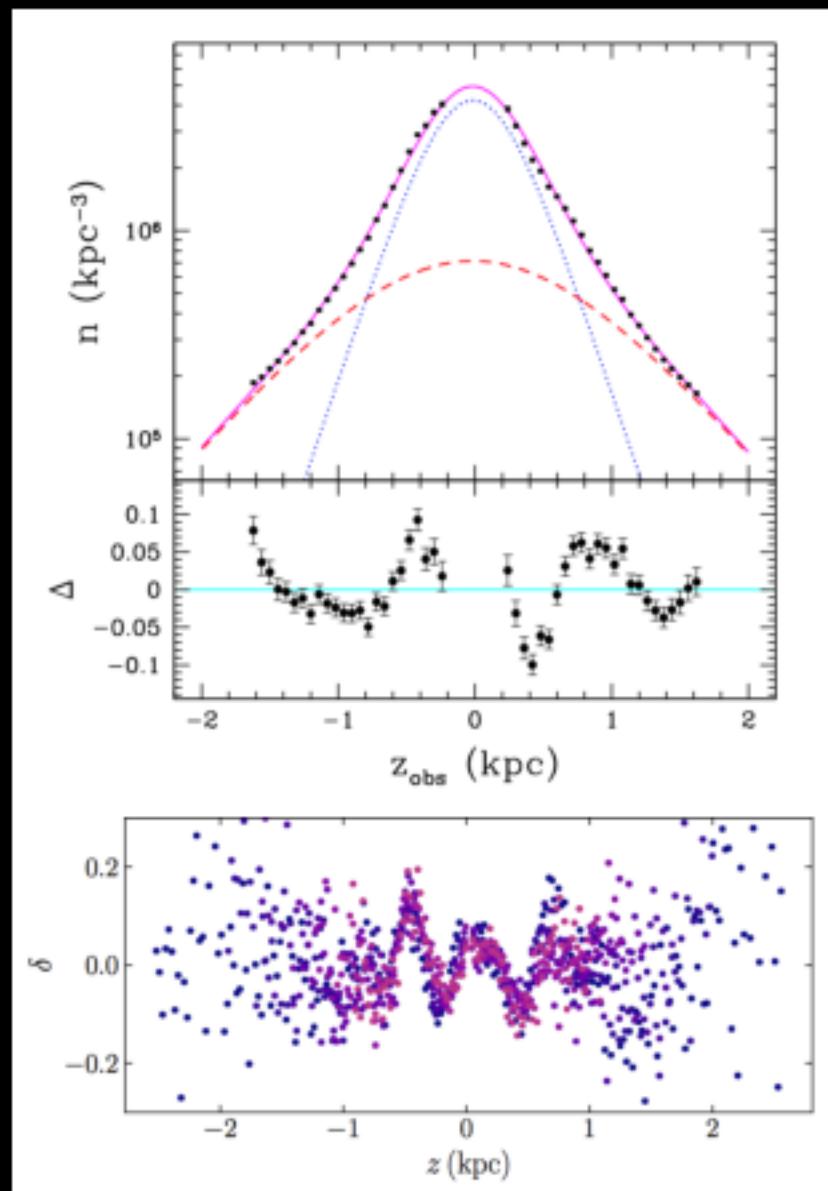


Laporte+19c

Local oscillations of the disc - revisiting SEGUE in 2D

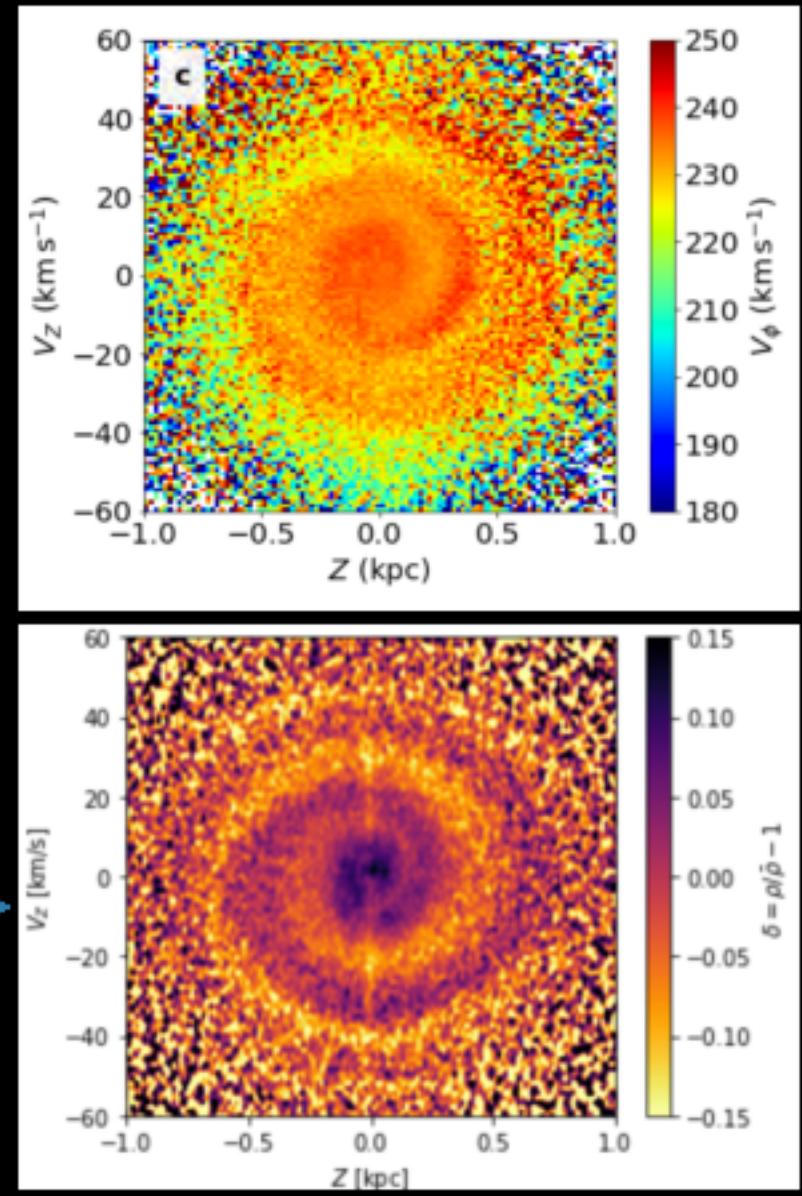
pre-Gaia

Widrow+12



Gaia DR2

Antoja+18

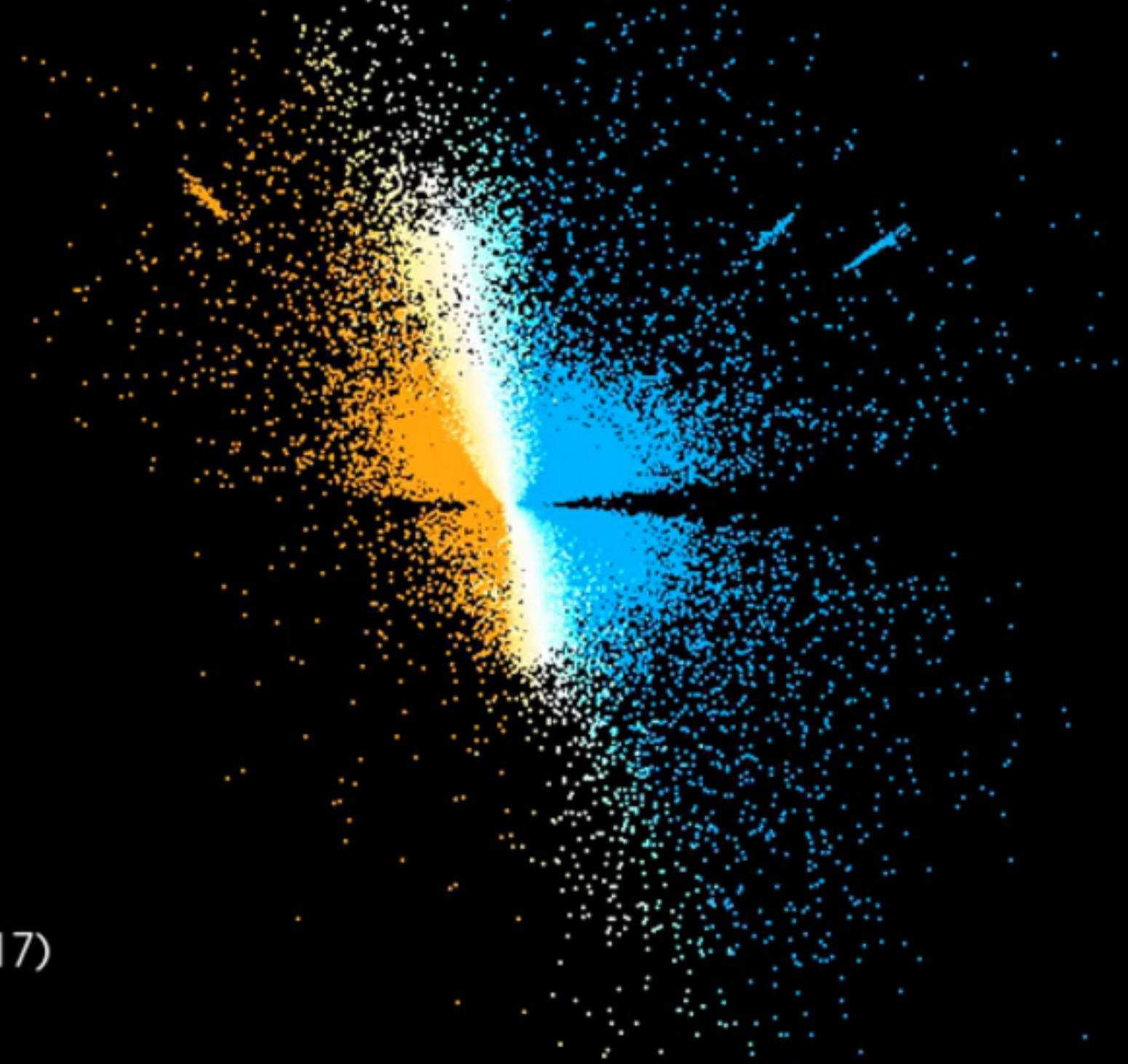


Bennett+Bovy+19, DR2 re-analysis of Widrow+12

Laporte+19c

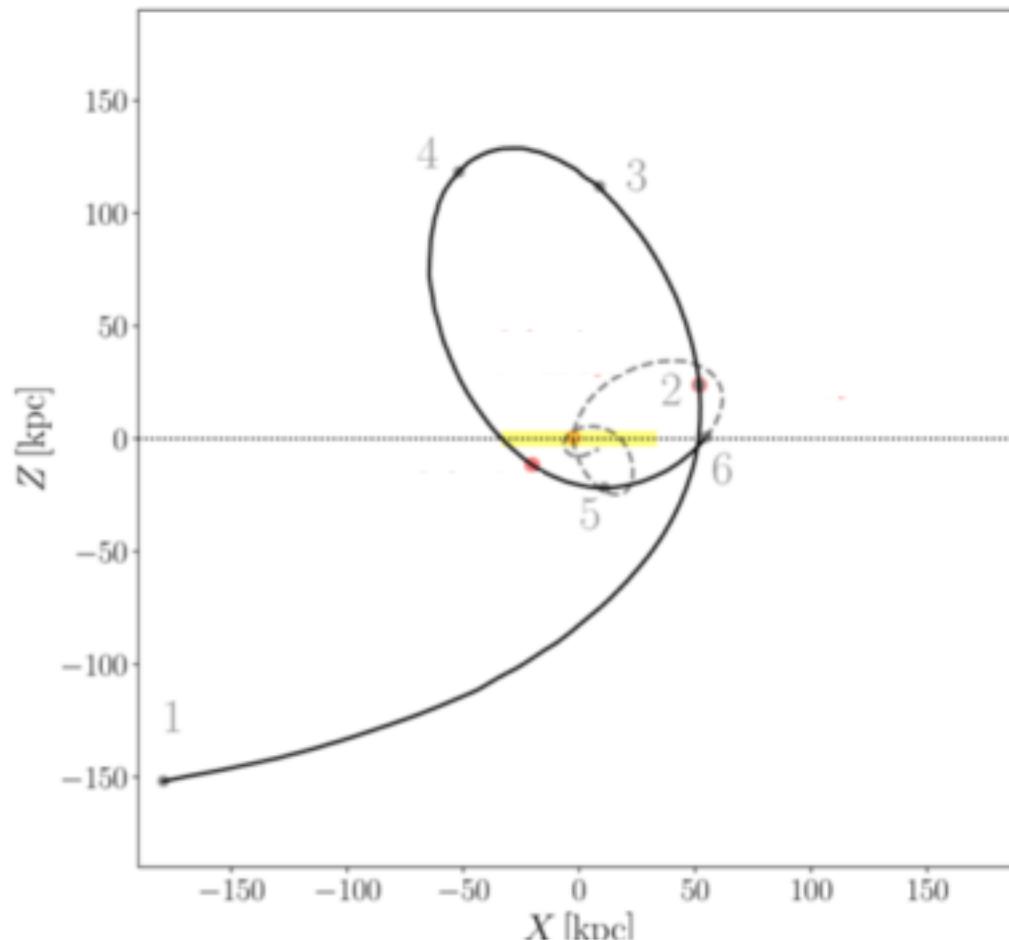
The Sgr dwarf in RR Lyrae

Sgr latitude (deg)

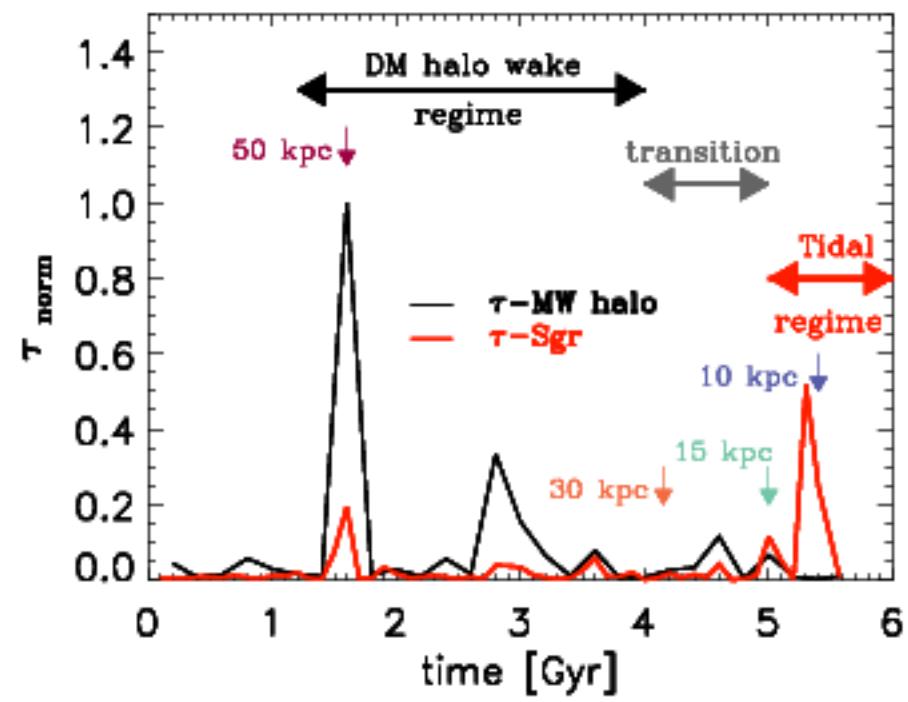
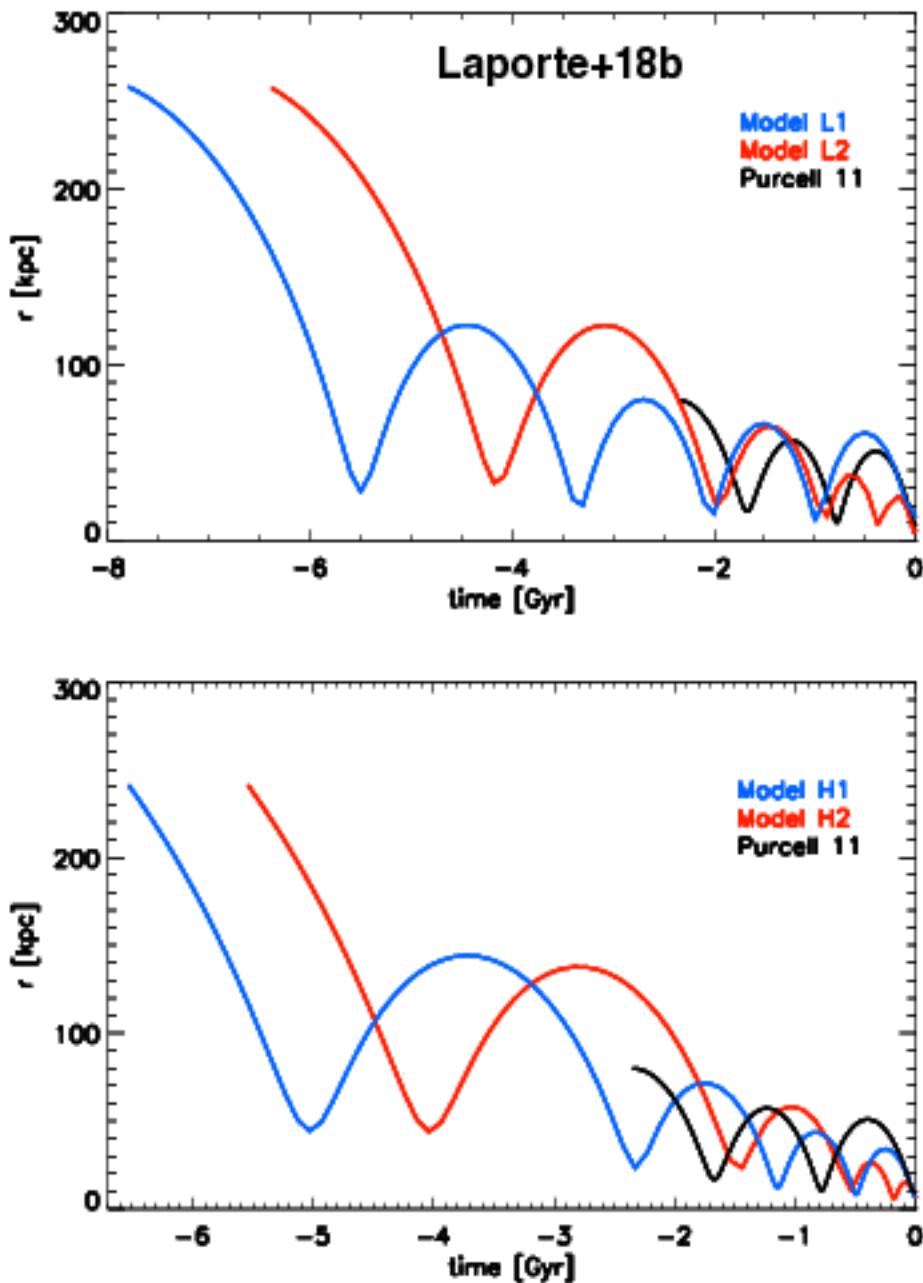


Sesar et al. (2017)

Prelude pre-Gaia DR2 models

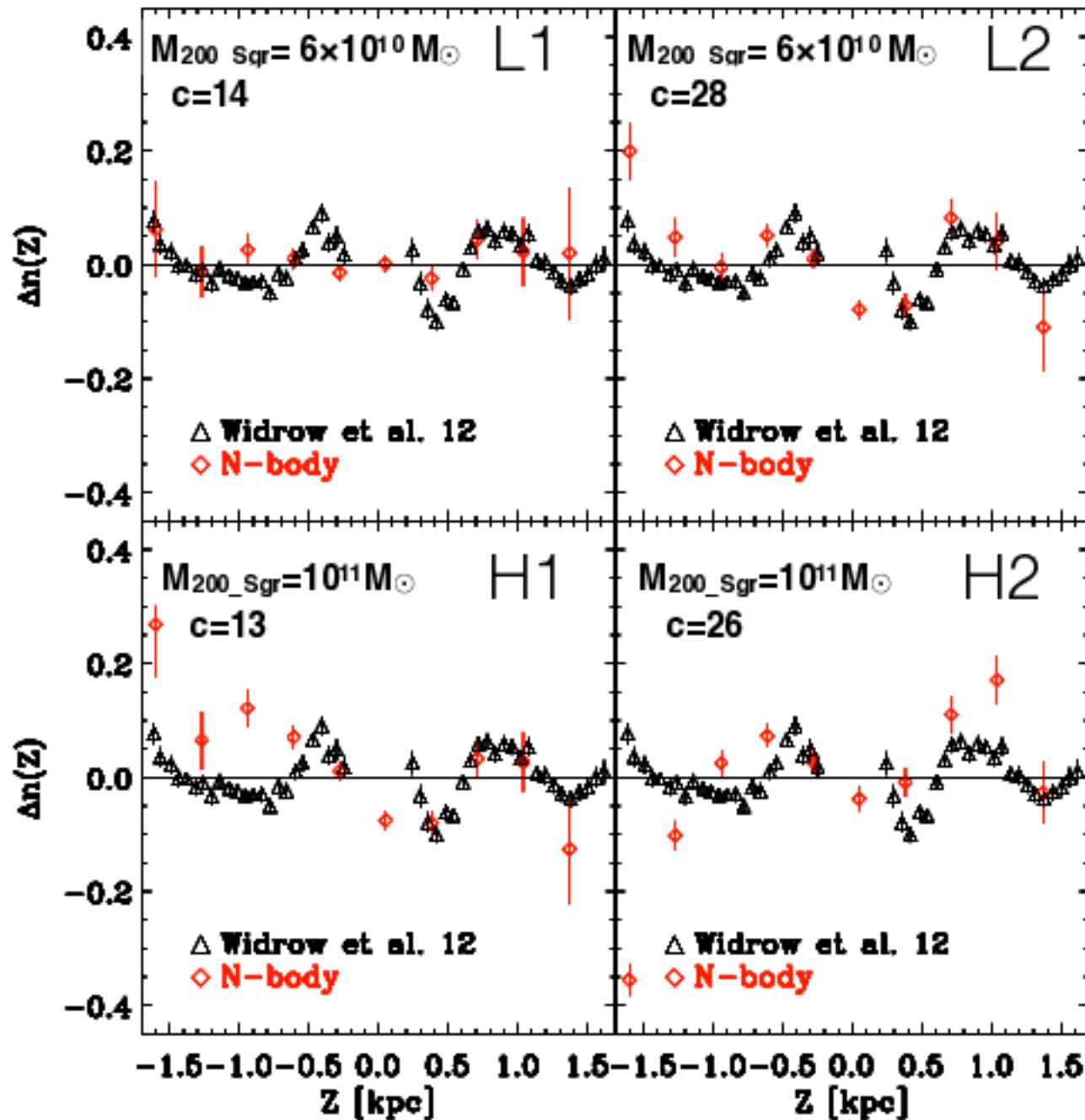


Live N-body simulations of massive* Sgr dwarf interaction with MW disc

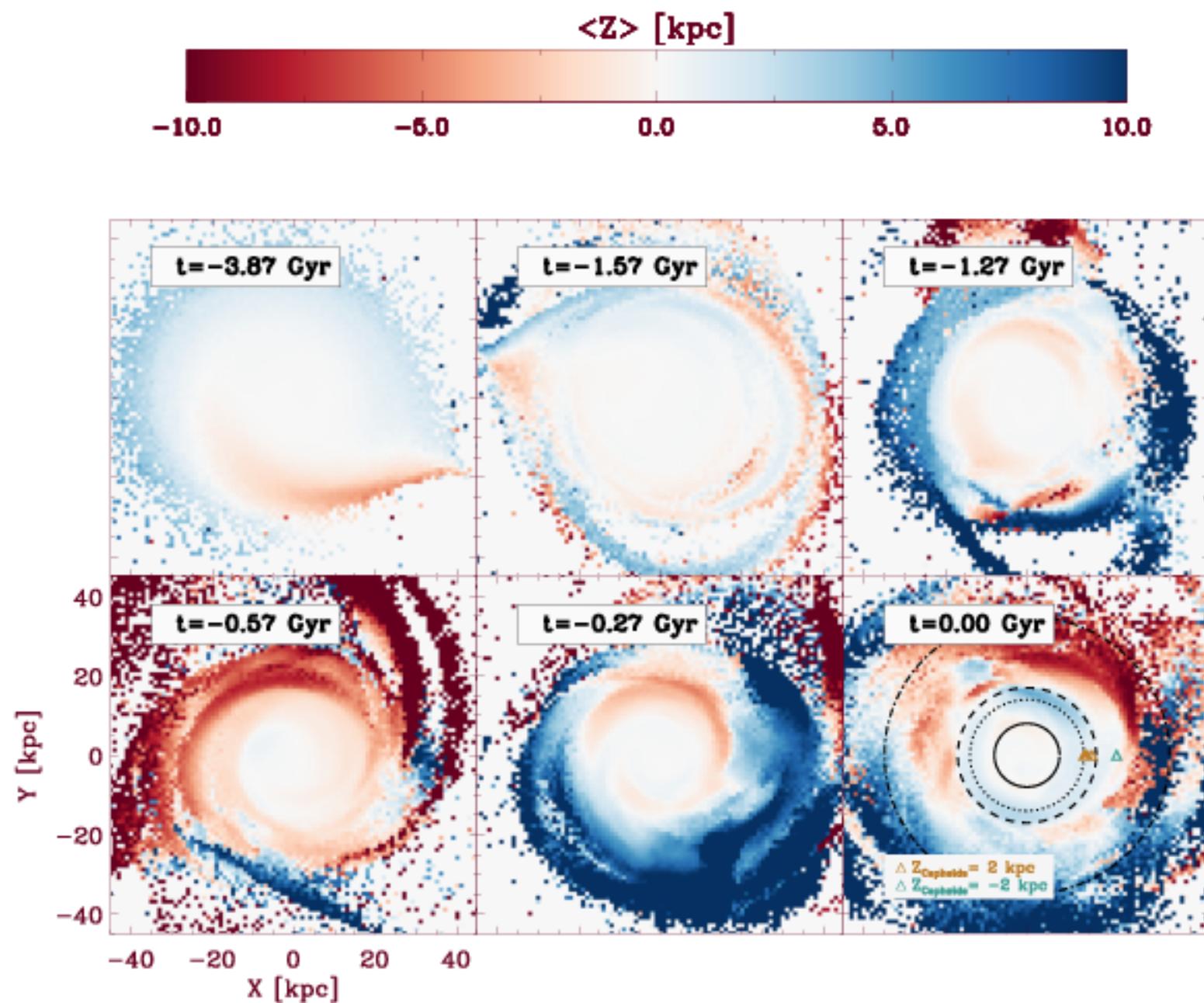


*see Jiang&Binney00, de Boer+14, Gibbons+16

Sgr induces vertical oscillations in the Solar neighbourhood

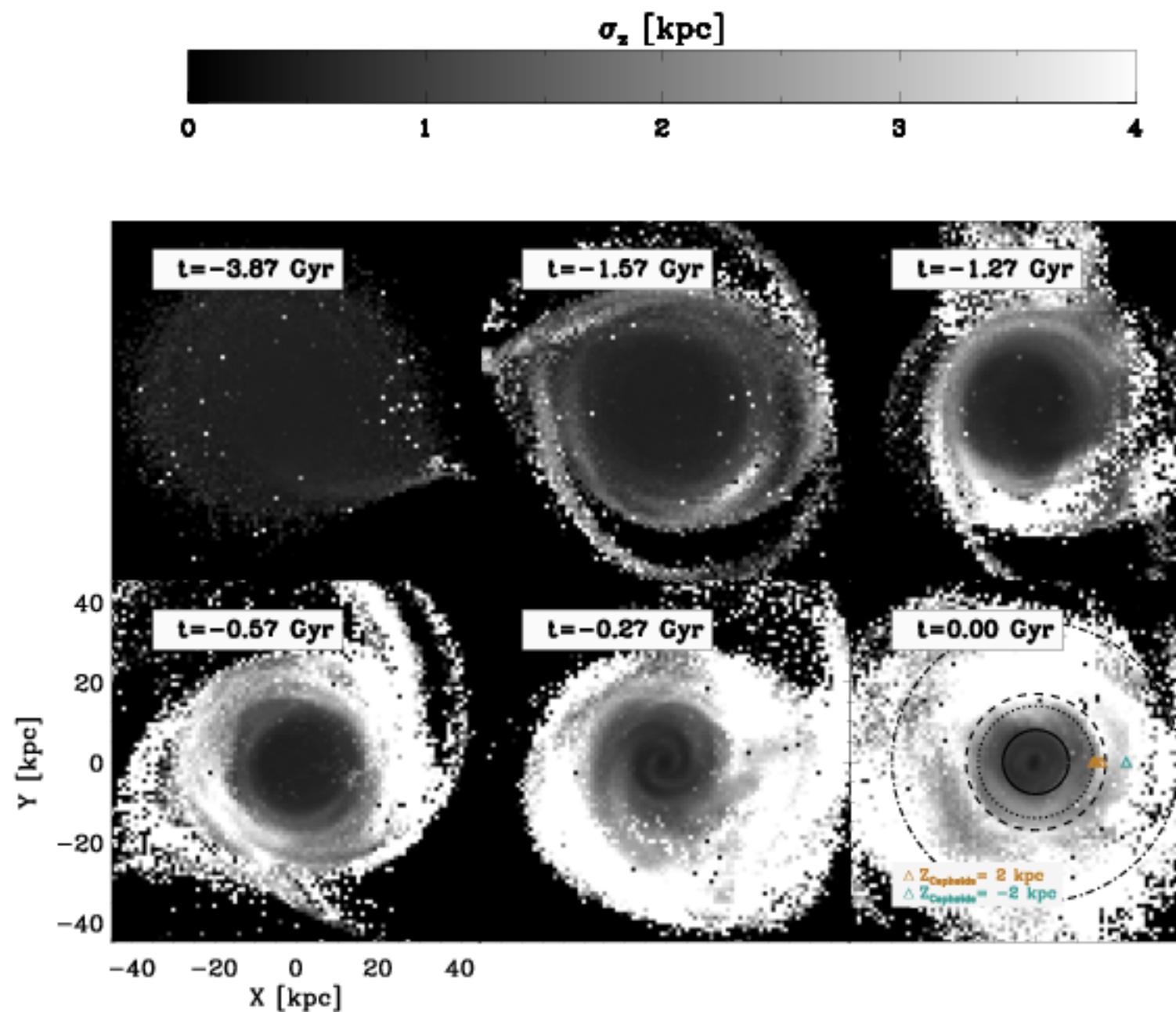


vertical displacements about the midplane of the disc



Laporte+18b

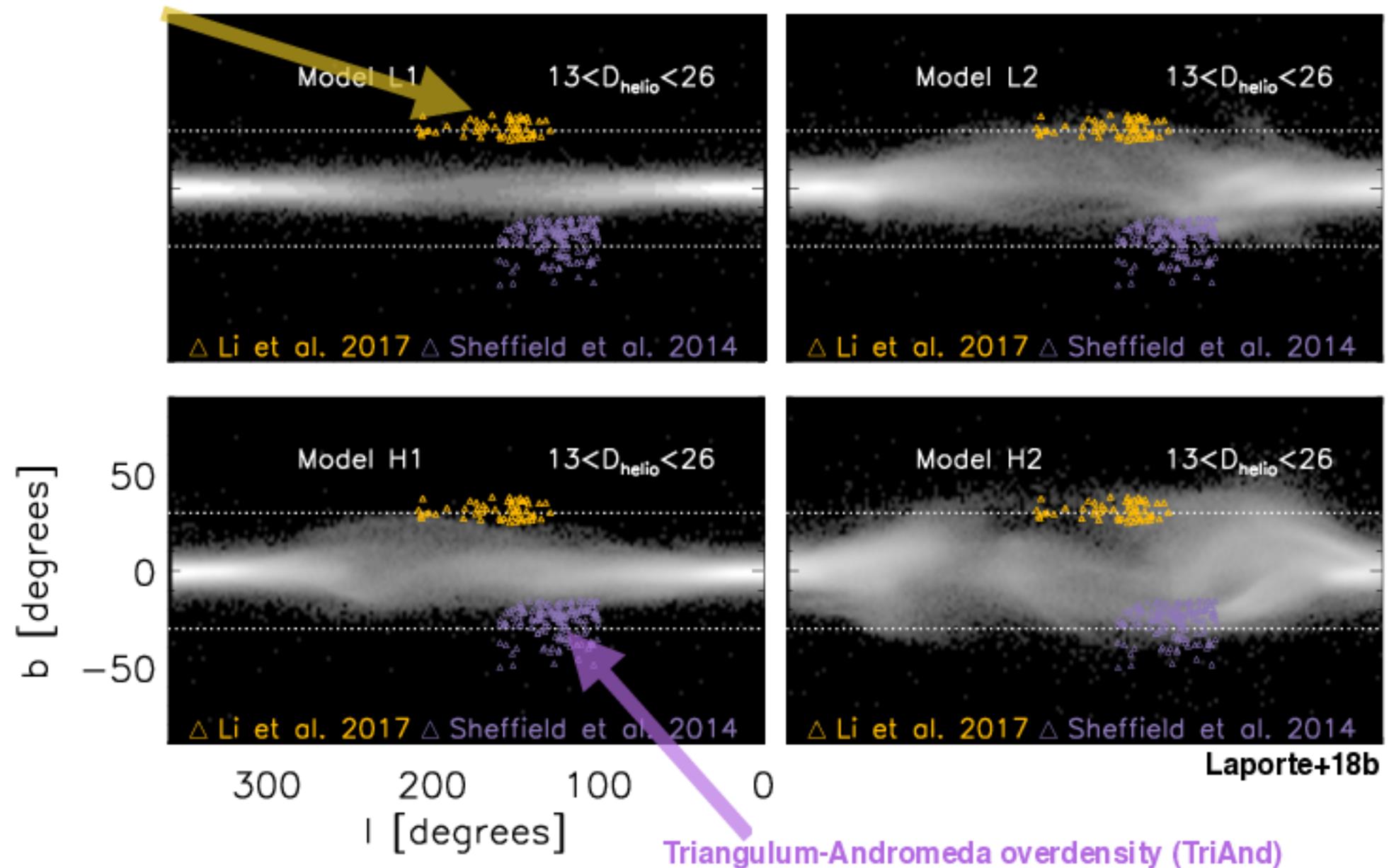
vertical heating (flaring) about the midplane of the disc



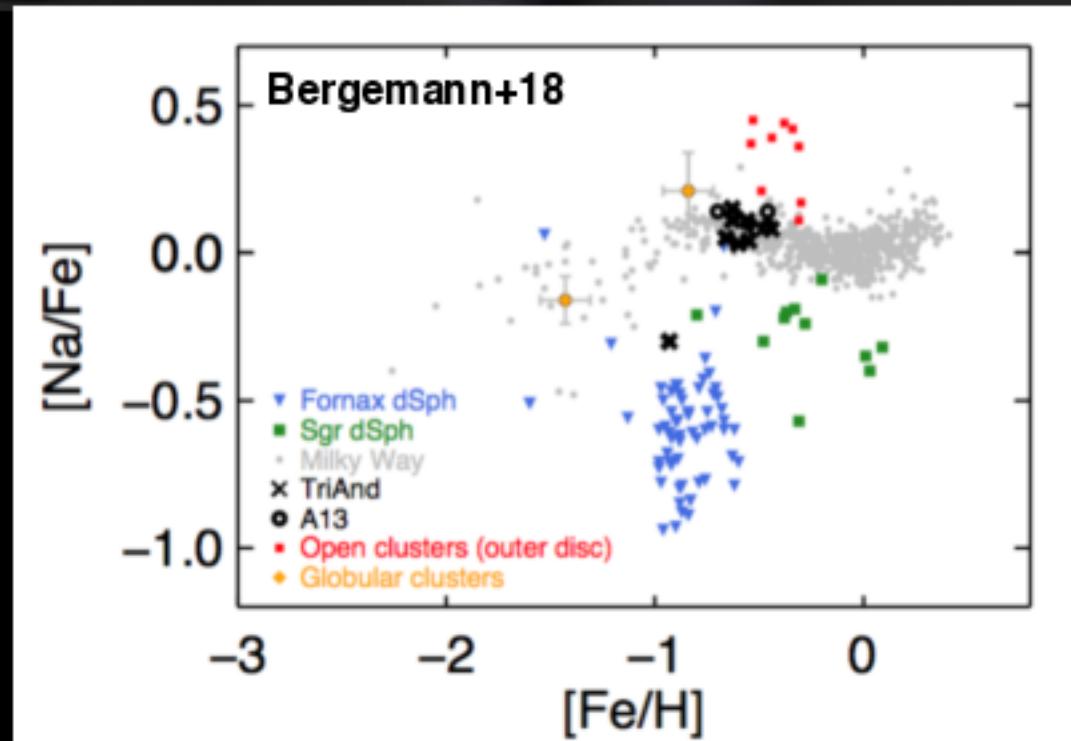
Laporte+18b

...and outer disc structures

A13: M-Giant overdensity

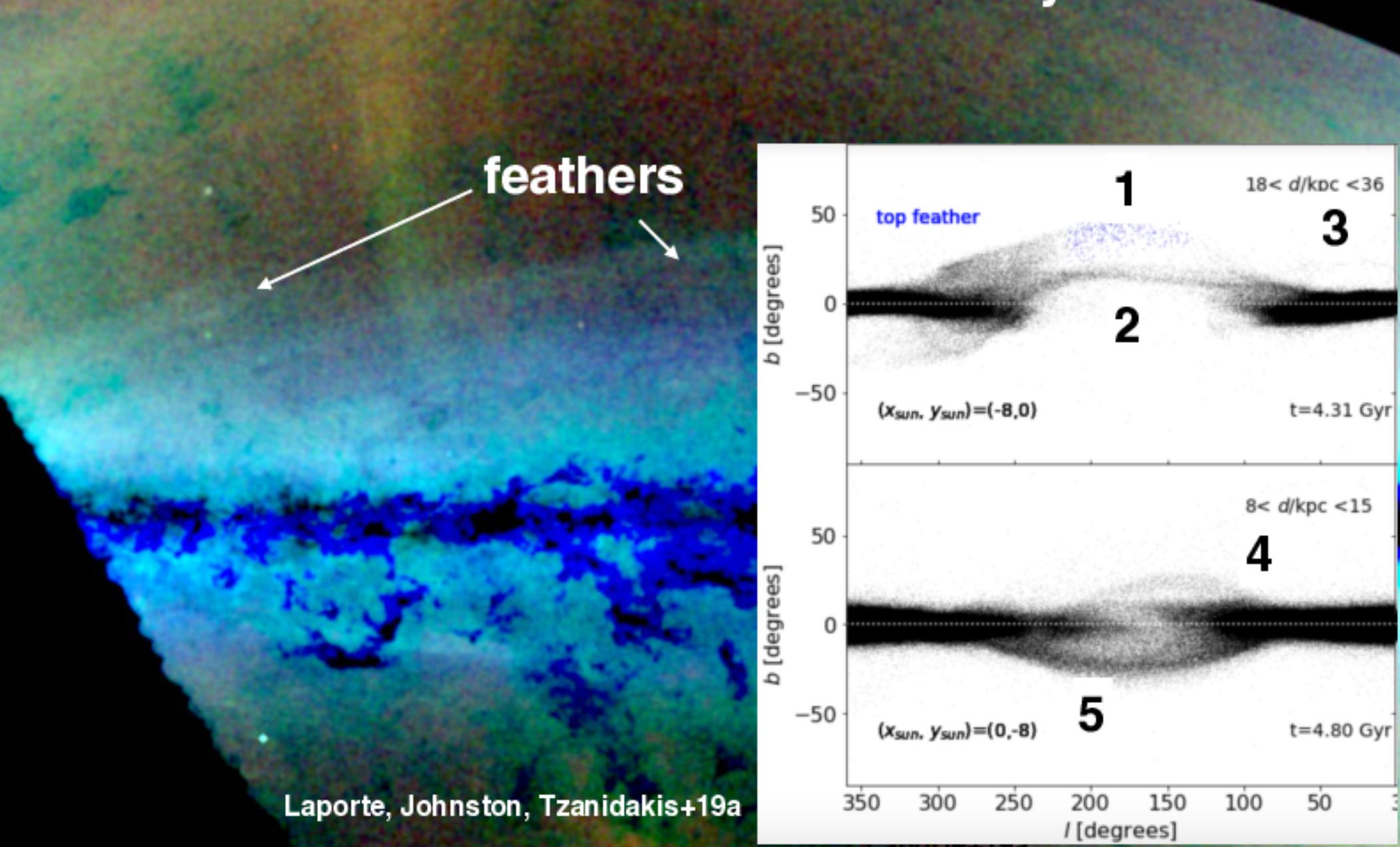


The tour de force: Chemical abundance measurements



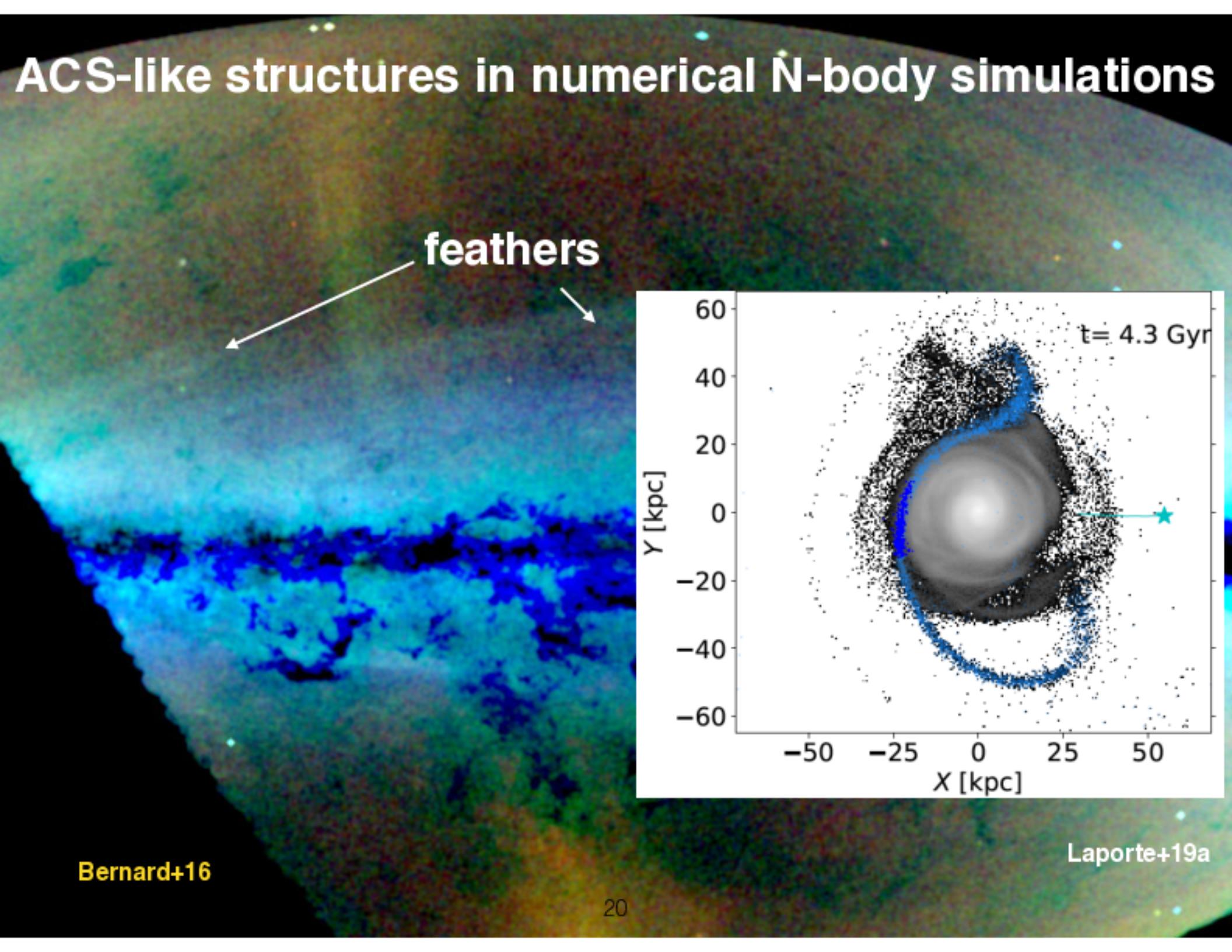
Bergemann+18 (incl CFPL), see also Price-Whelan+15, Sheffield+18 on stellar RRL/M-giant ratios, see also de Boer+18, Deason+18

ACS-like structures in numerical N-body simulations



Bernard+16

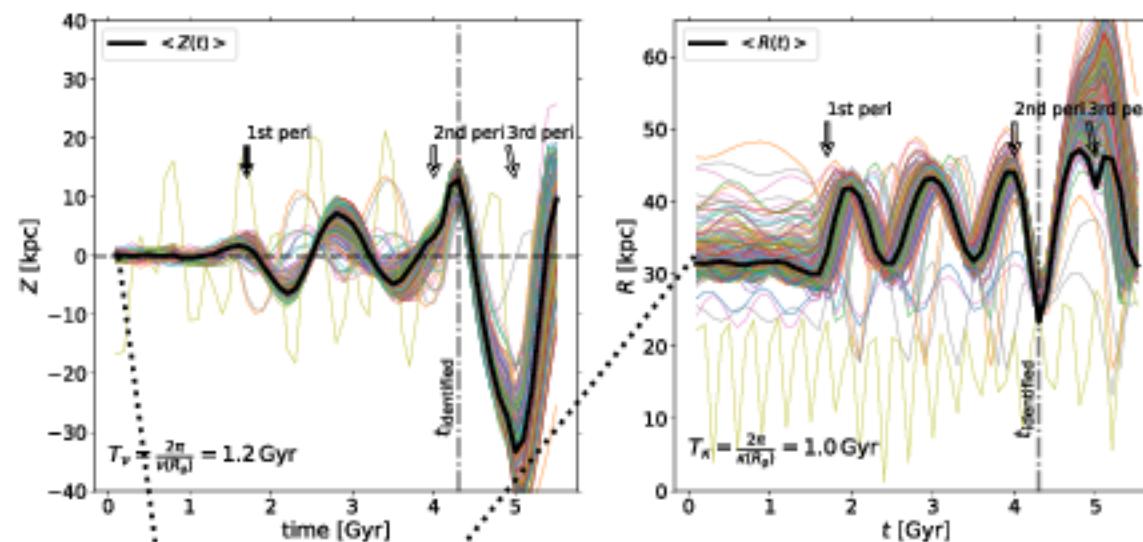
ACS-like structures in numerical N-body simulations



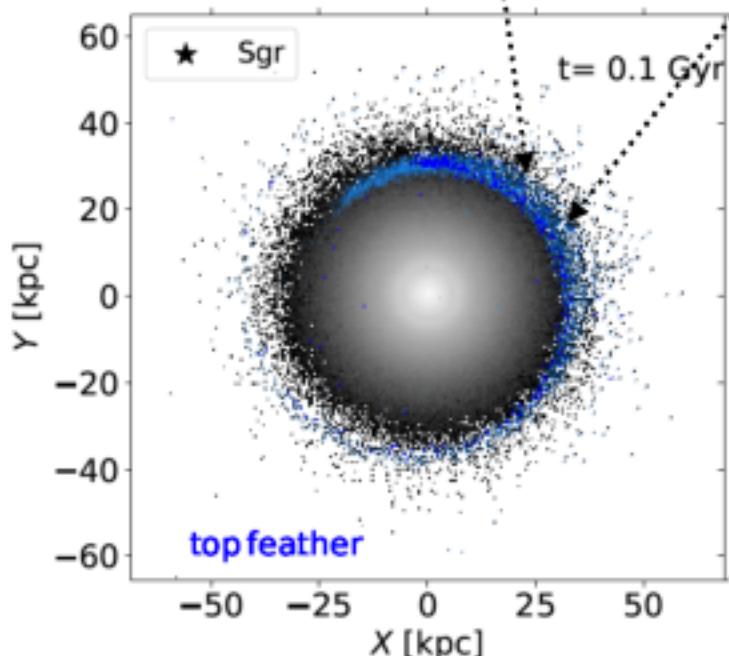
Bernard+16

Laporte+19a

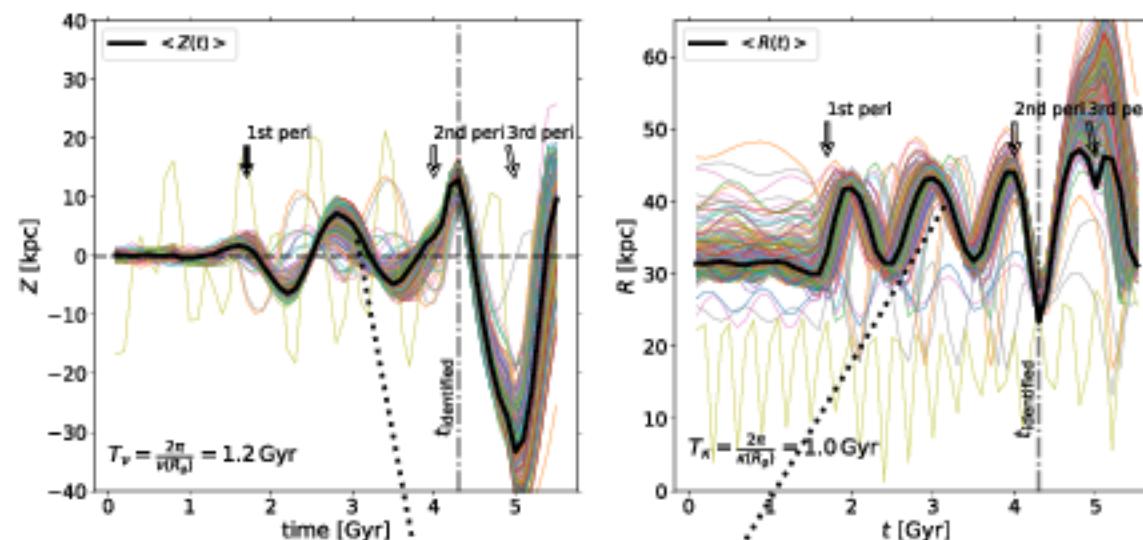
A closer look at an **individual** ``feather'' mean motion about epicyclic/vertical frequencies.



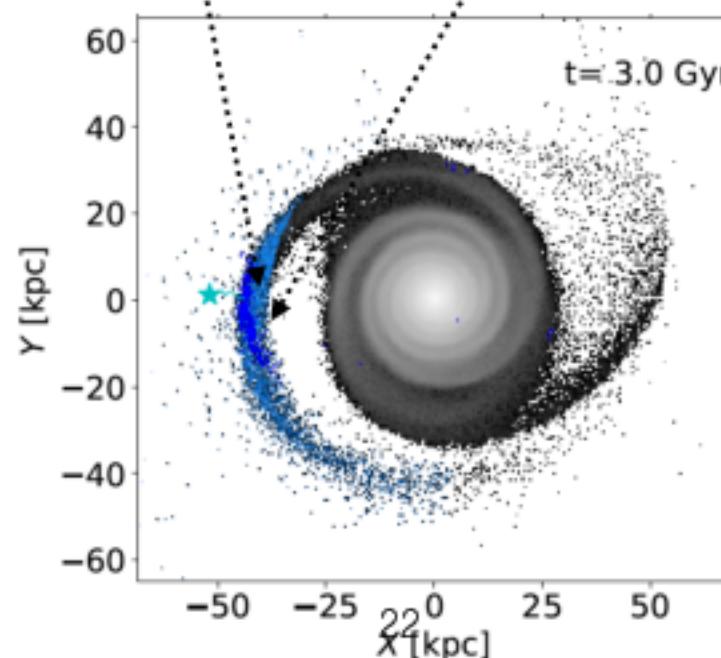
Laporte+19a



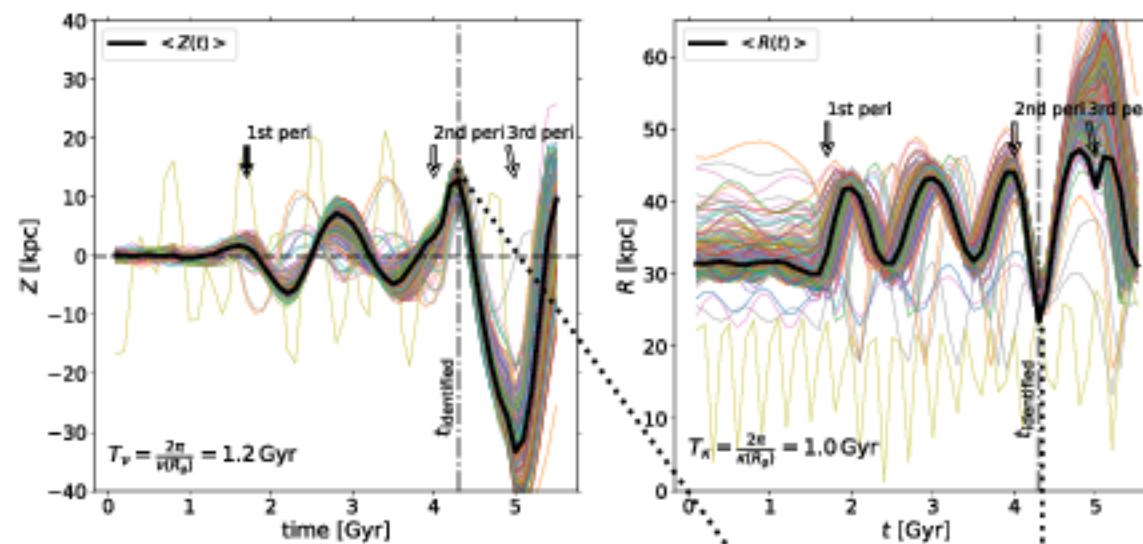
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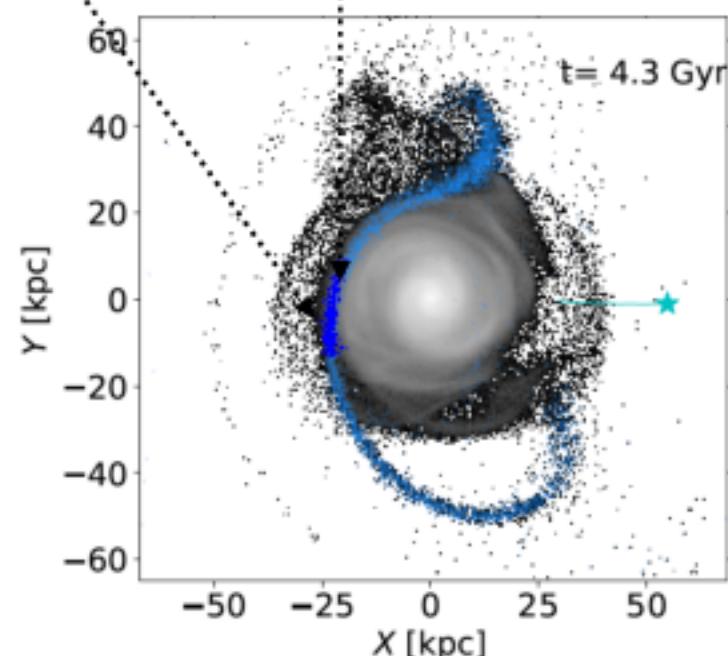
Laporte+19a



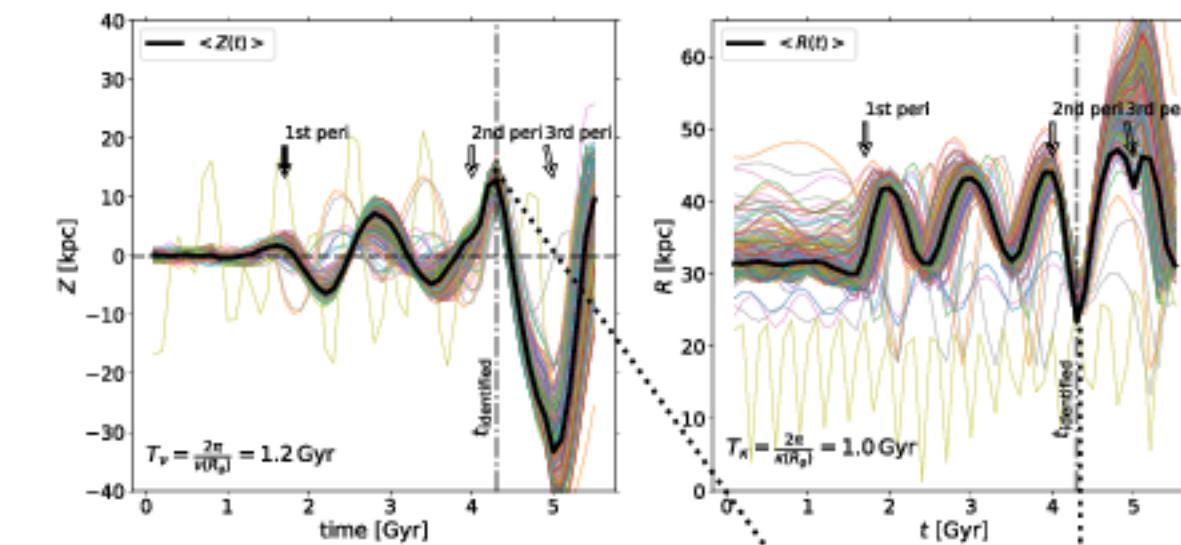
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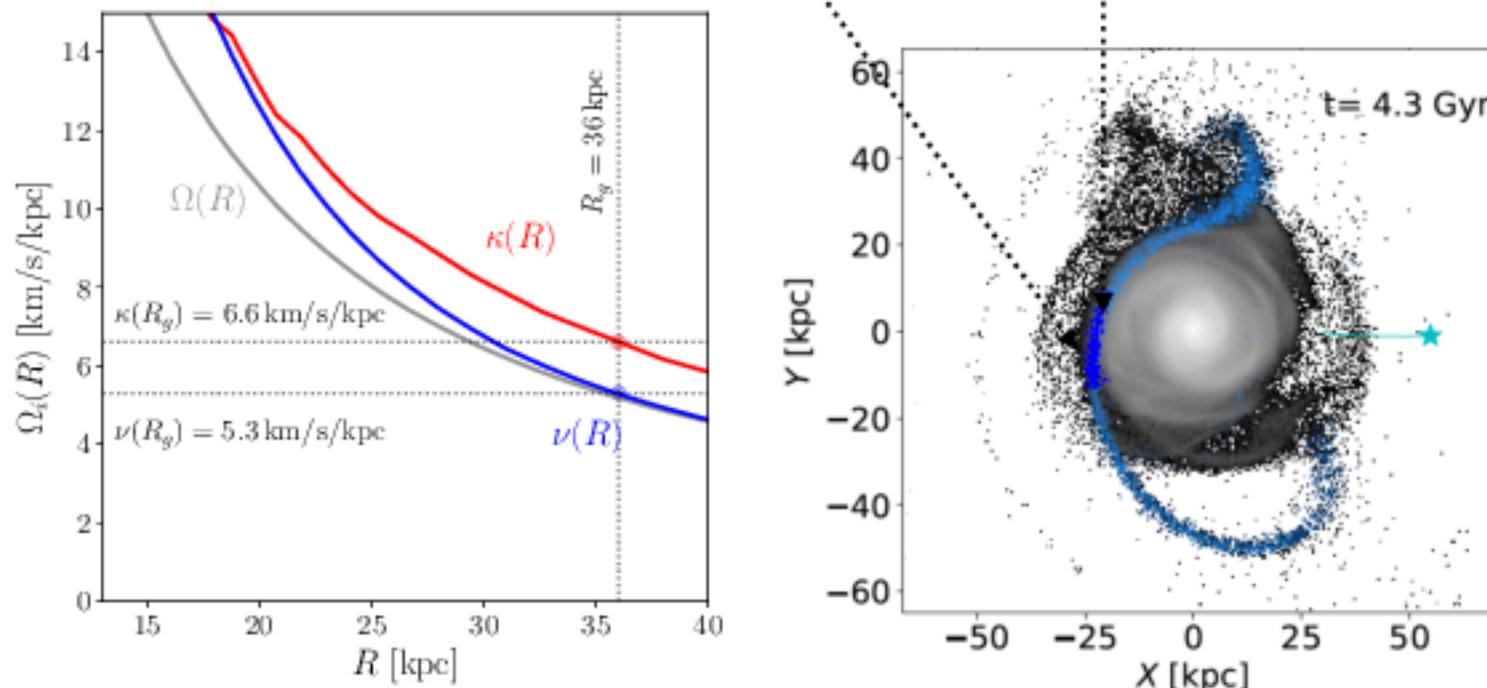
Laporte+19a



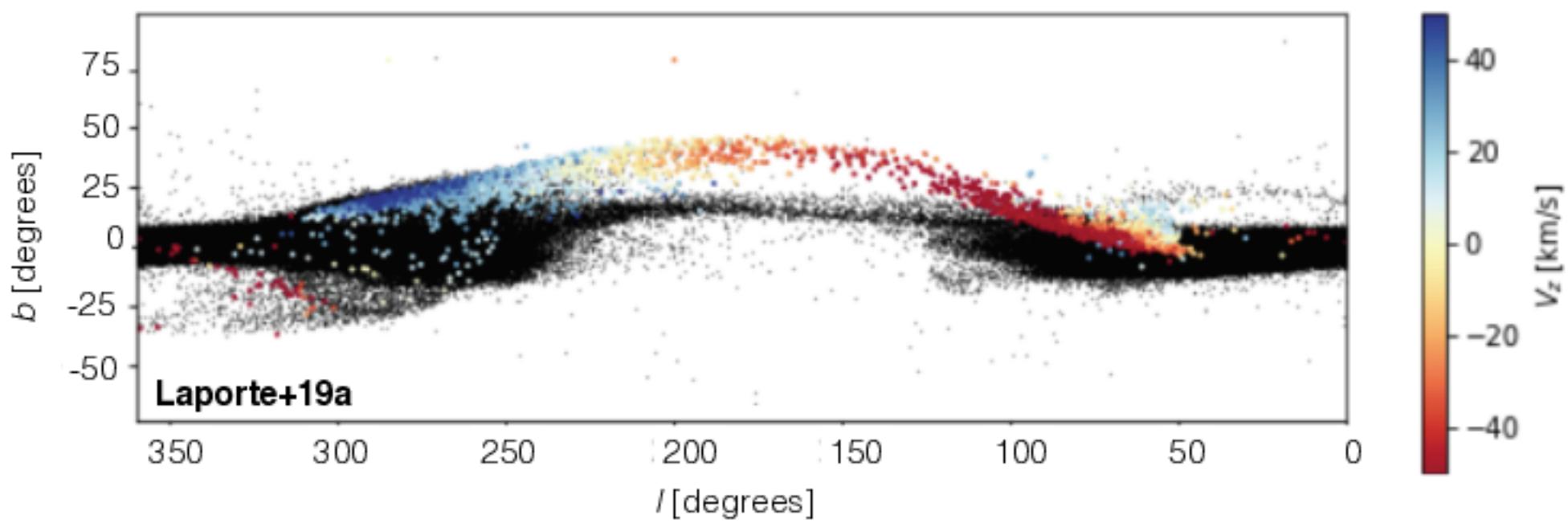
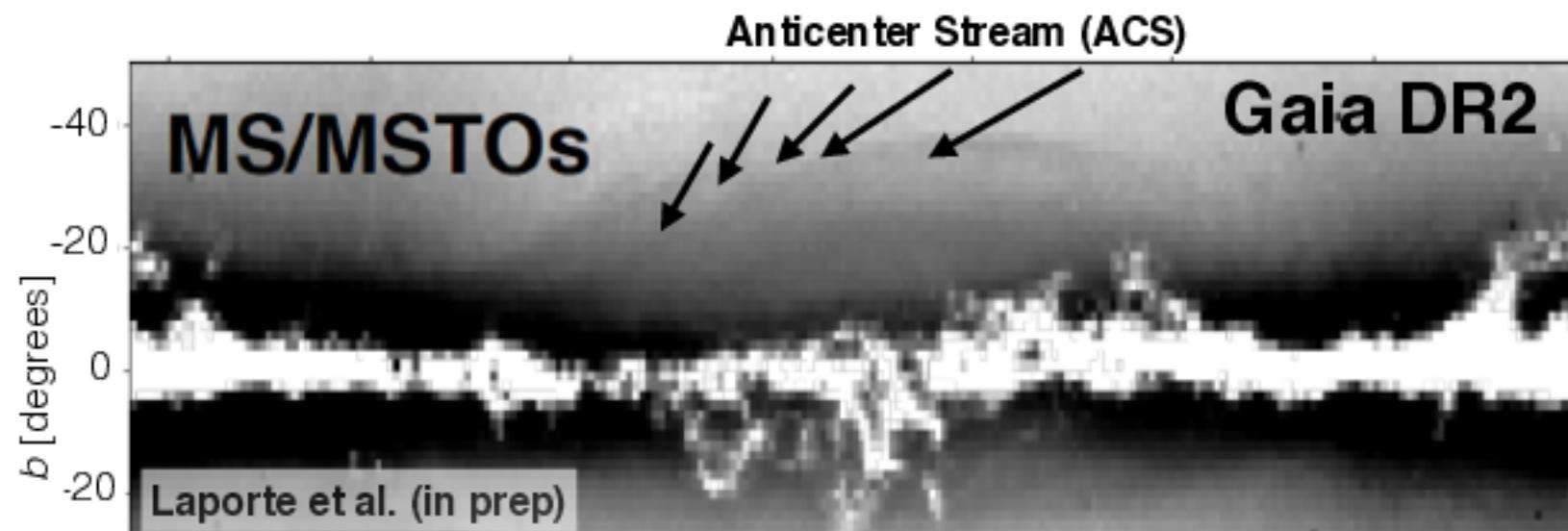
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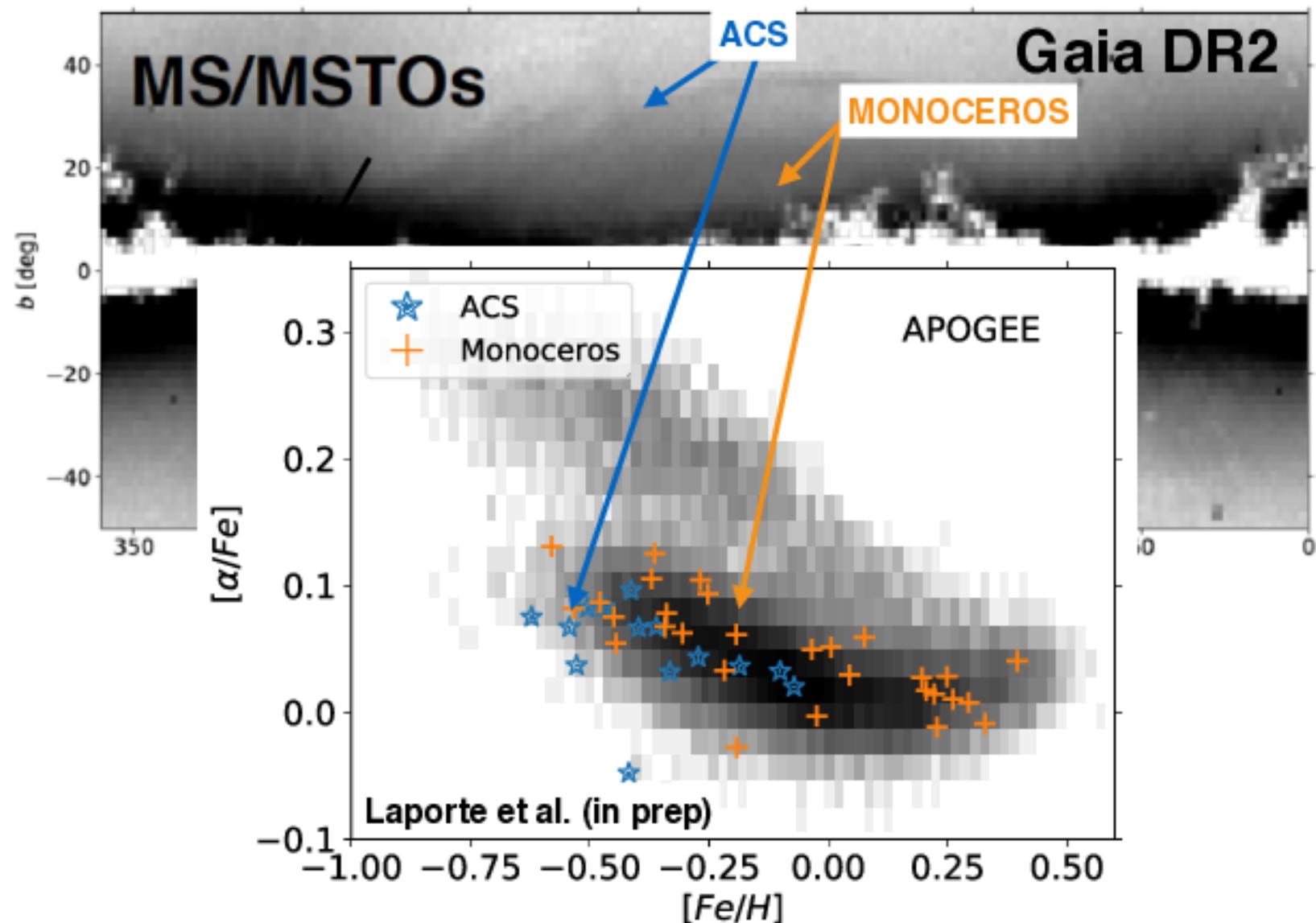
Laporte+19a



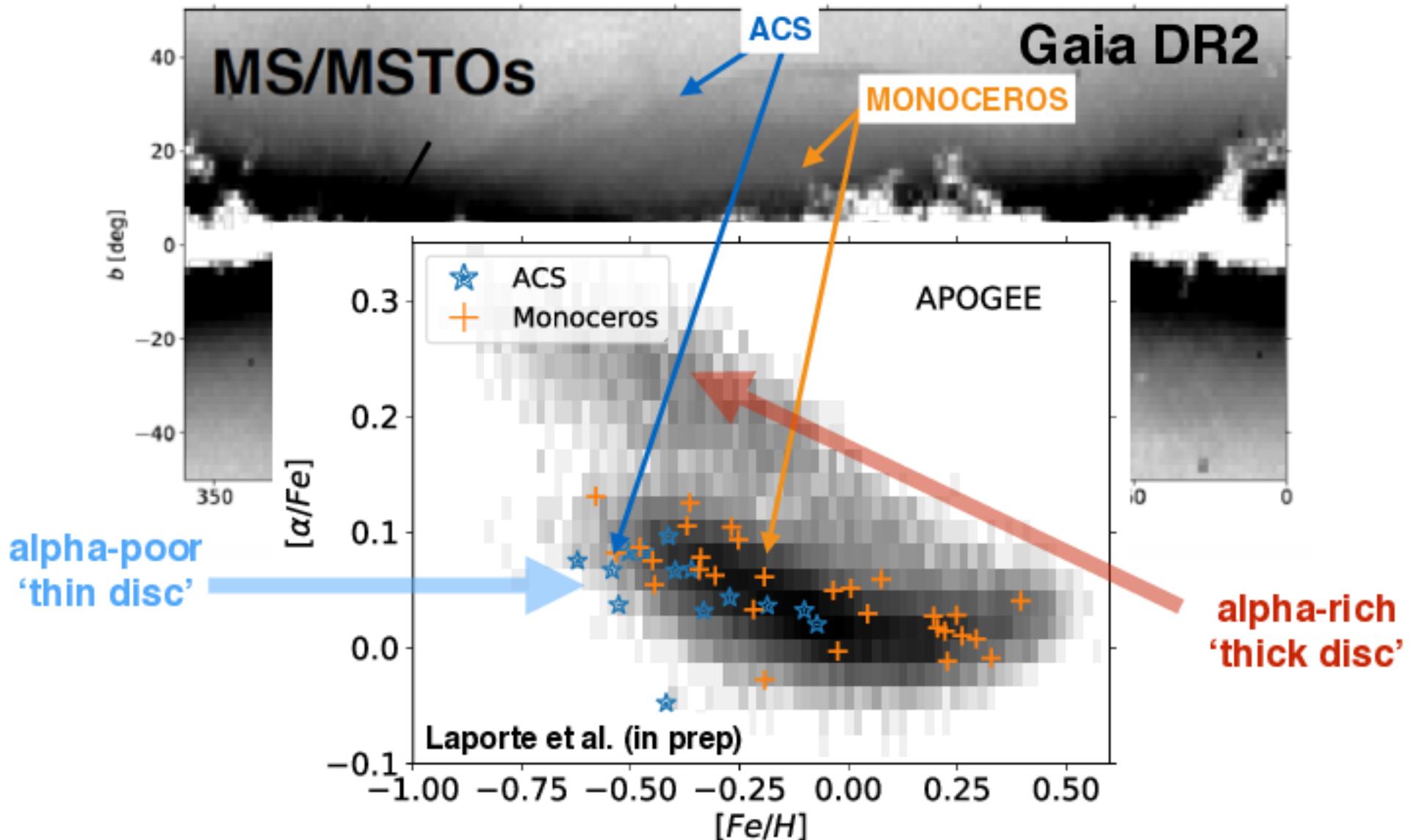
Confirmation of the disc nature of feathers



Confirmation of the disc nature of feathers



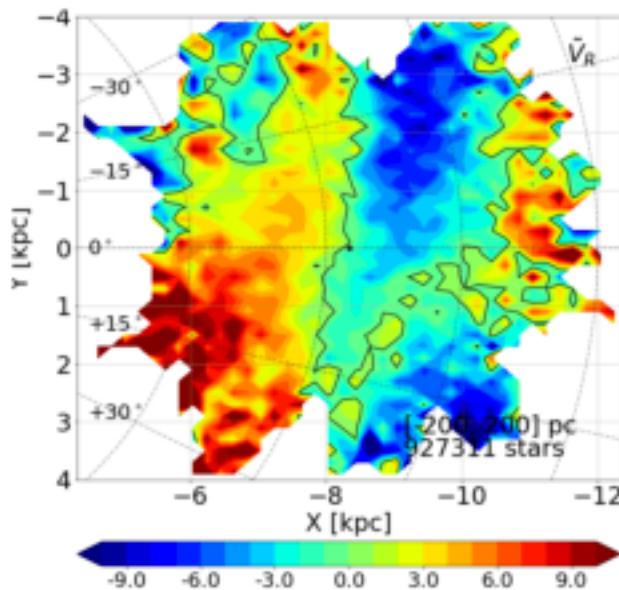
Confirmation of the disc nature of feathers



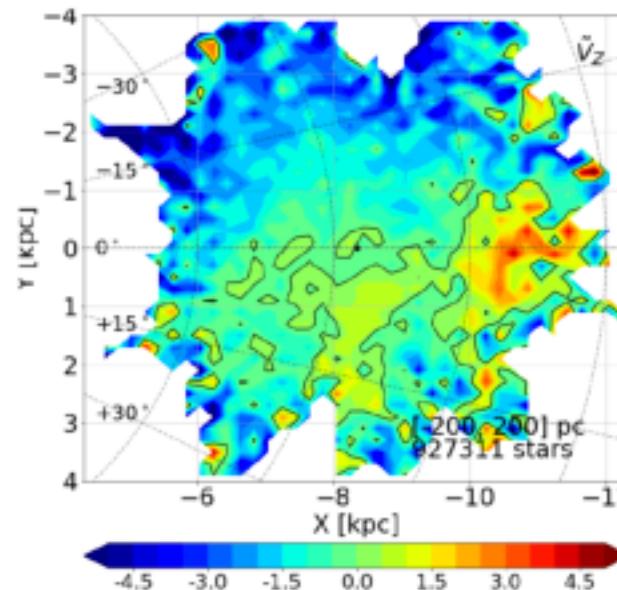
Pre-Gaia DR2 models in light of the Gaia DR2 era

Bulk motions in the disc

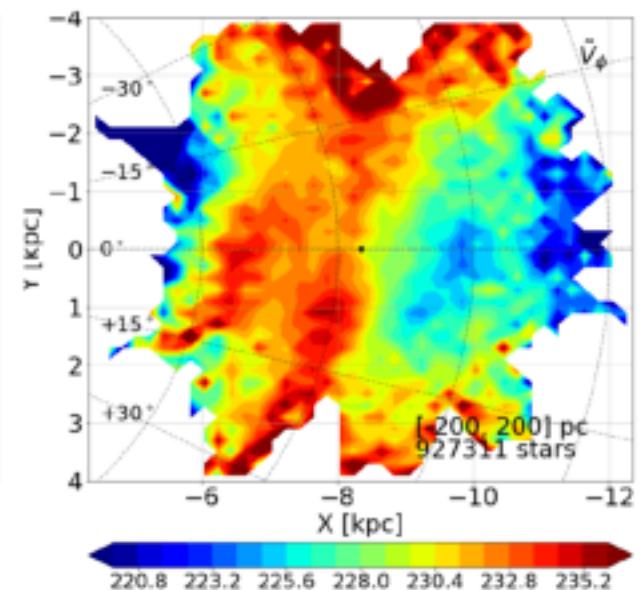
kinematic spiral arms



kinematic warp



kinematic spiral arms

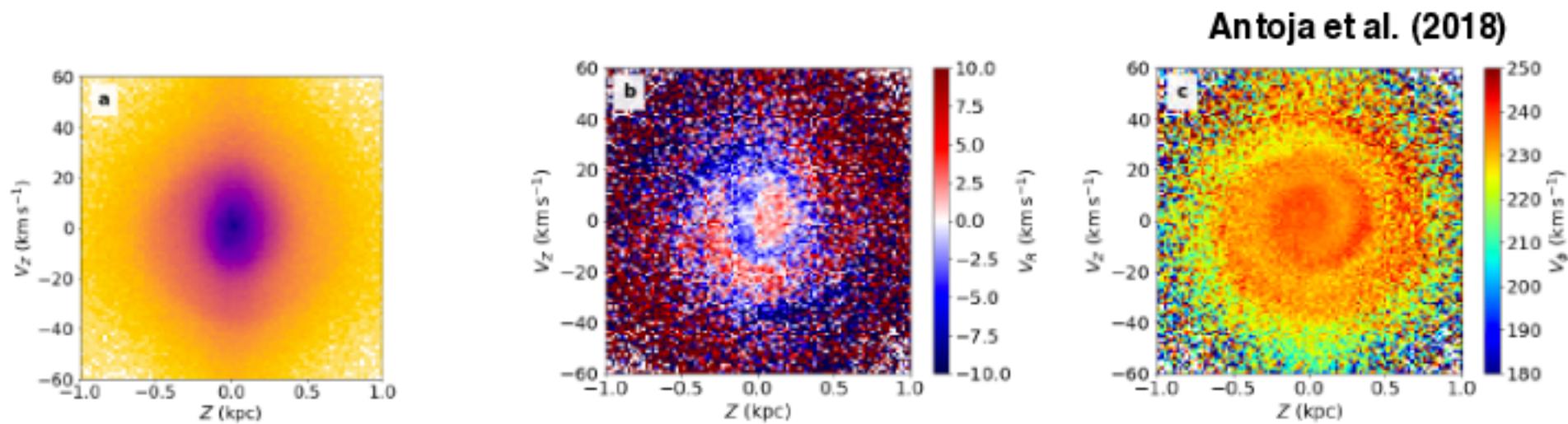


Gaia Collaboration: Katz et al. (2018)

Complex velocity field revealed by DR2

see also Monari+16 for LPT $\langle V_R \rangle$ maps, Poggio+18 for warp

Ongoing phase-mixing in the disc



Using a toy-model for phase-mixing Antoja+18 find $t_{\text{perturb}} \sim 300\text{-}900$ Myr

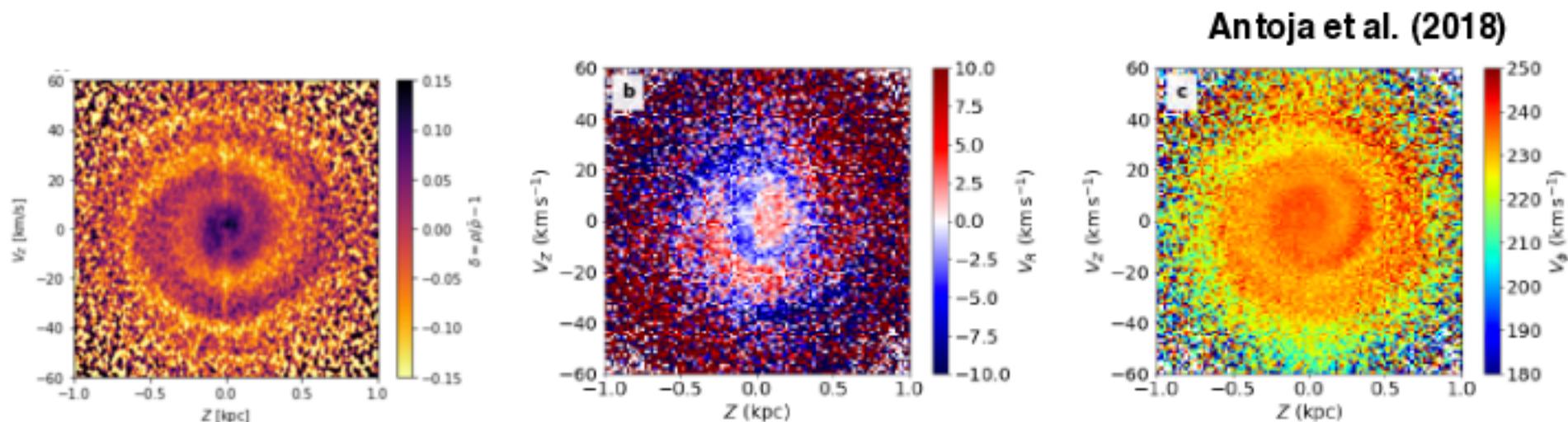
deduce that Sgr could have been the culprit

T_{orb}~0.8-1.2 Gyr from stream fitting (Johnston+05, Law+10, Penarrubia+10)

see also earlier works by Minchev+09 and Gomez+12 on UV-plane, and also Coma Berenices RAVE/DR2 work by Monari et al. 2018

See also another toy model by Binney & Schoenrich+18

Ongoing phase-mixing in the disc



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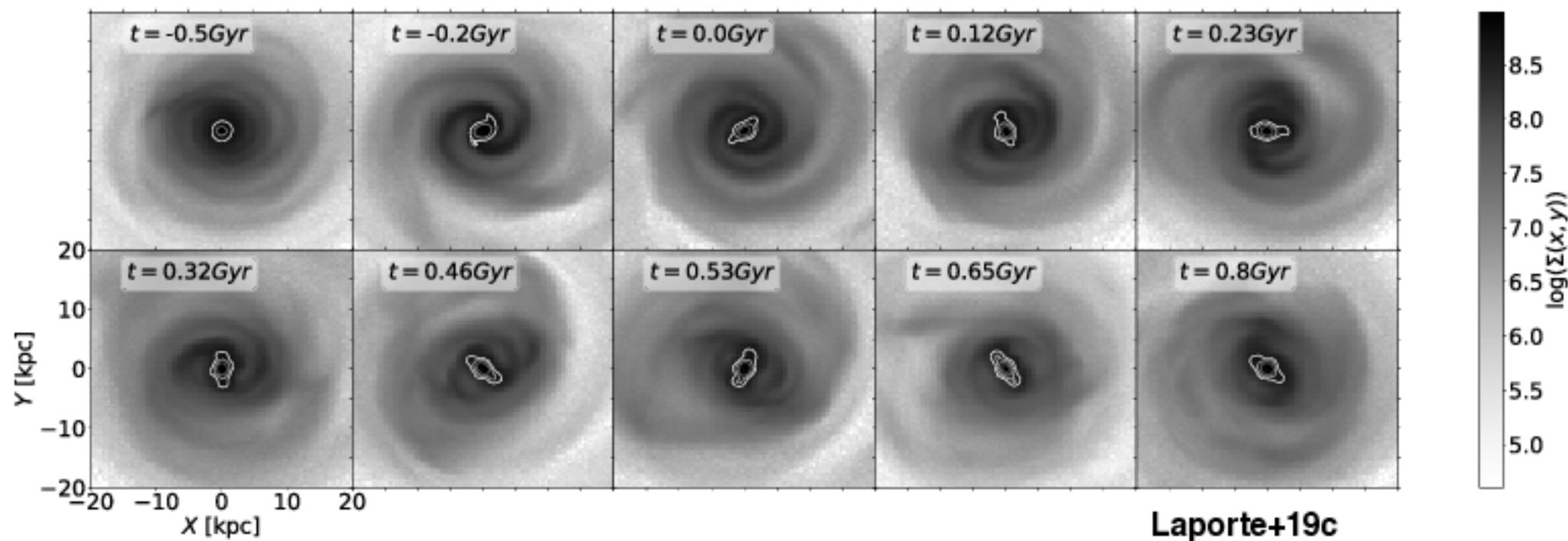
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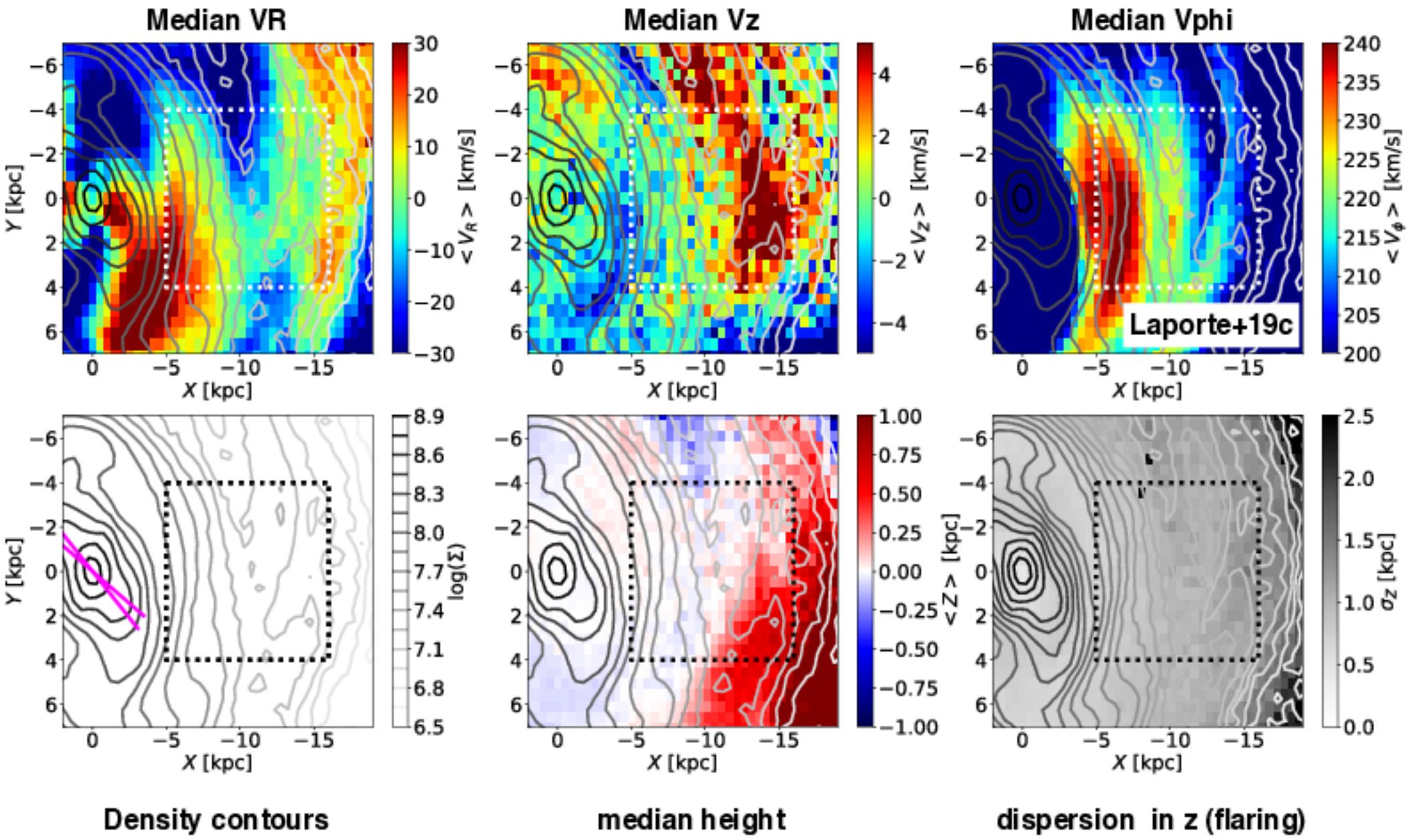
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See also another toy model by Binney & Schoenrich+18

Evolution of Galactic disc during very last stages of Sgr's orbit



Simulated velocity fields

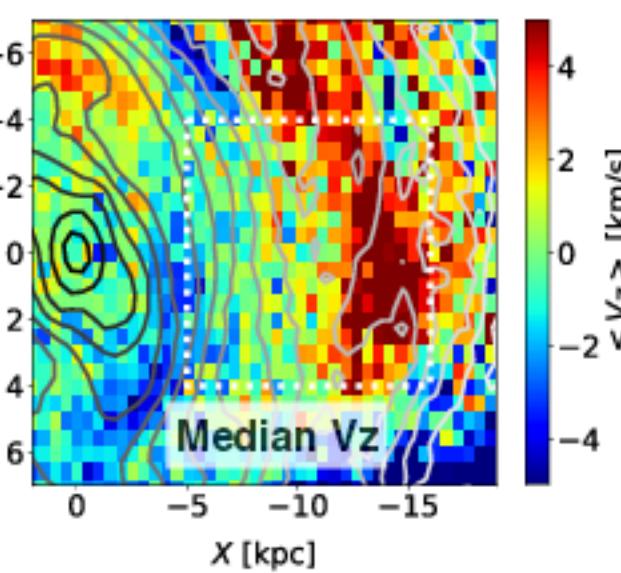
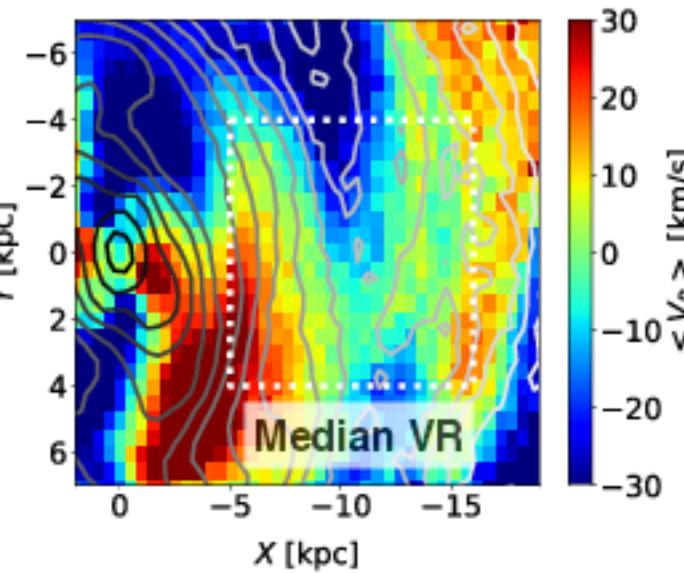


Density contours

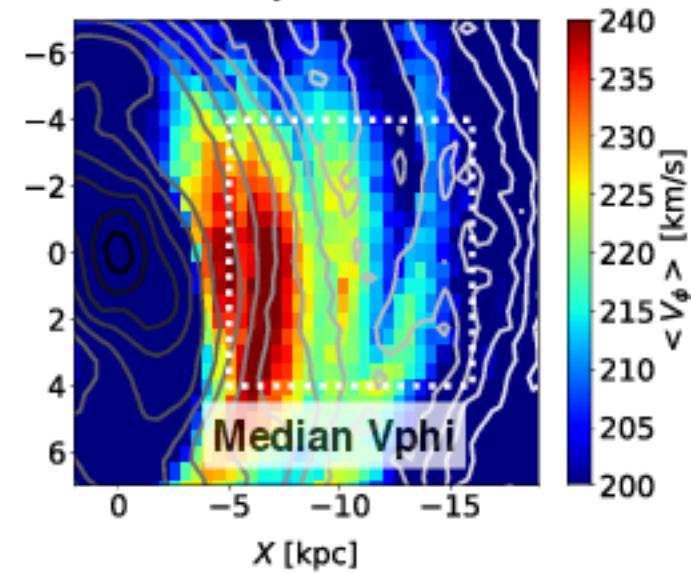
median height

dispersion in Z (flaring)

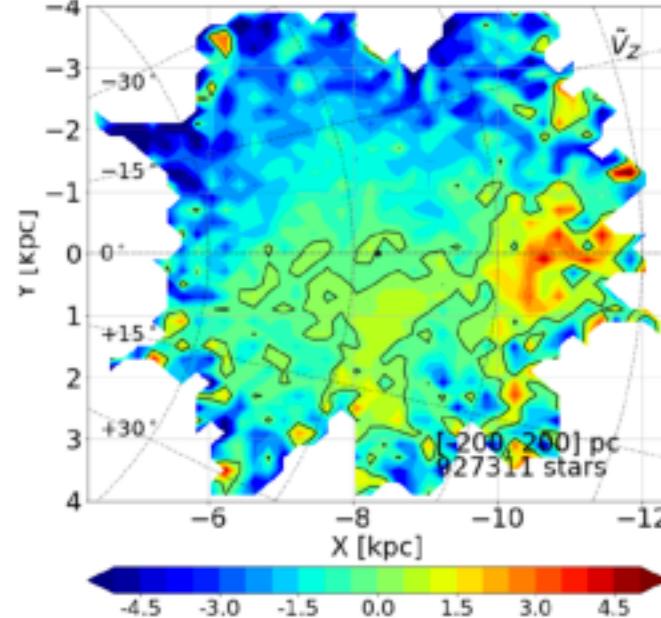
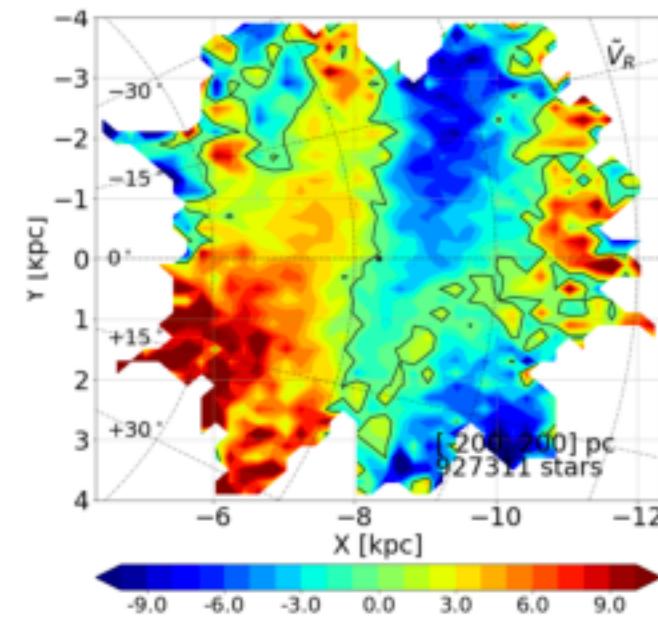
pre-Gaia Simulations



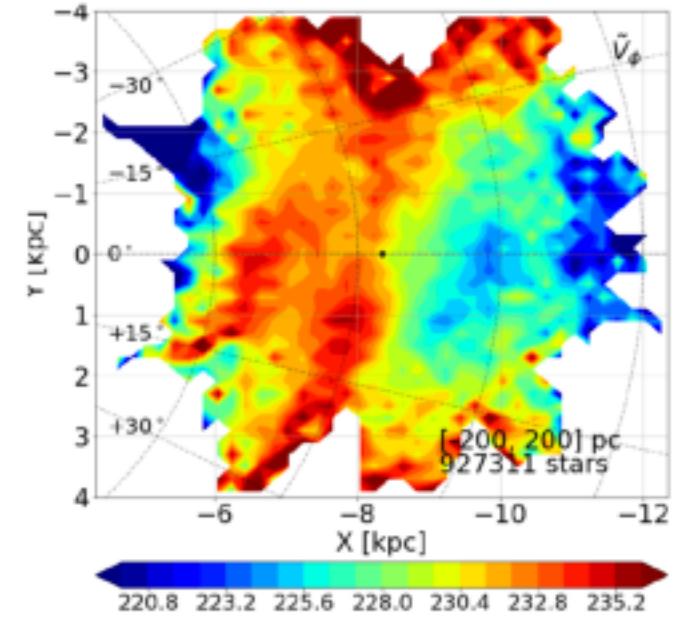
Laporte+19

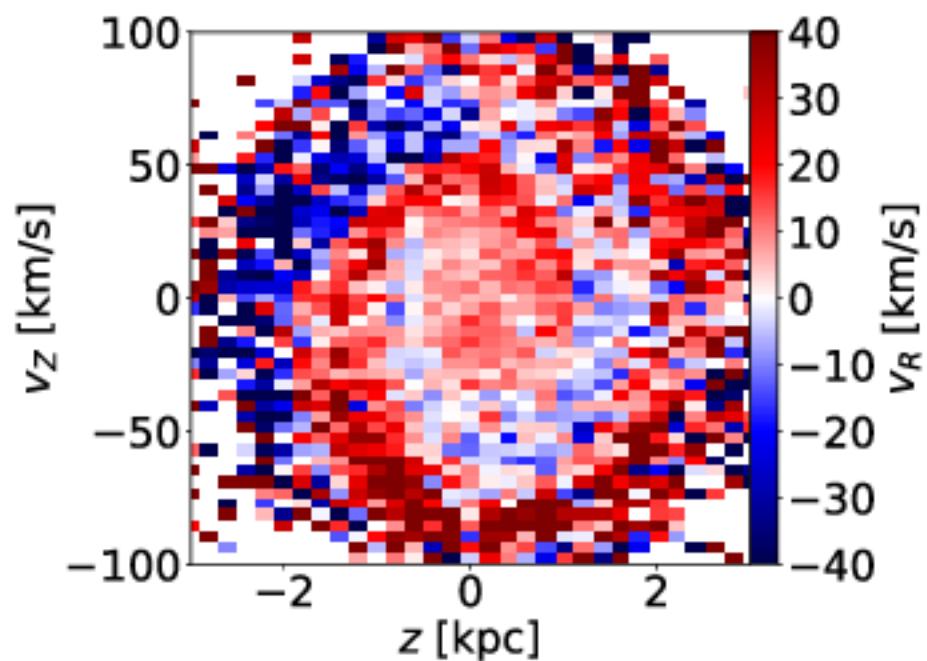
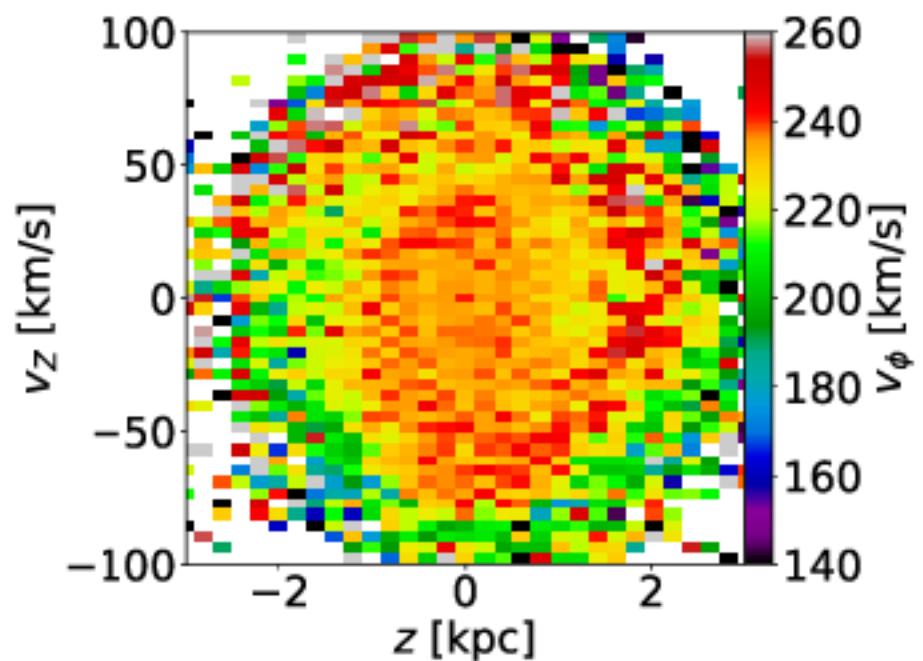
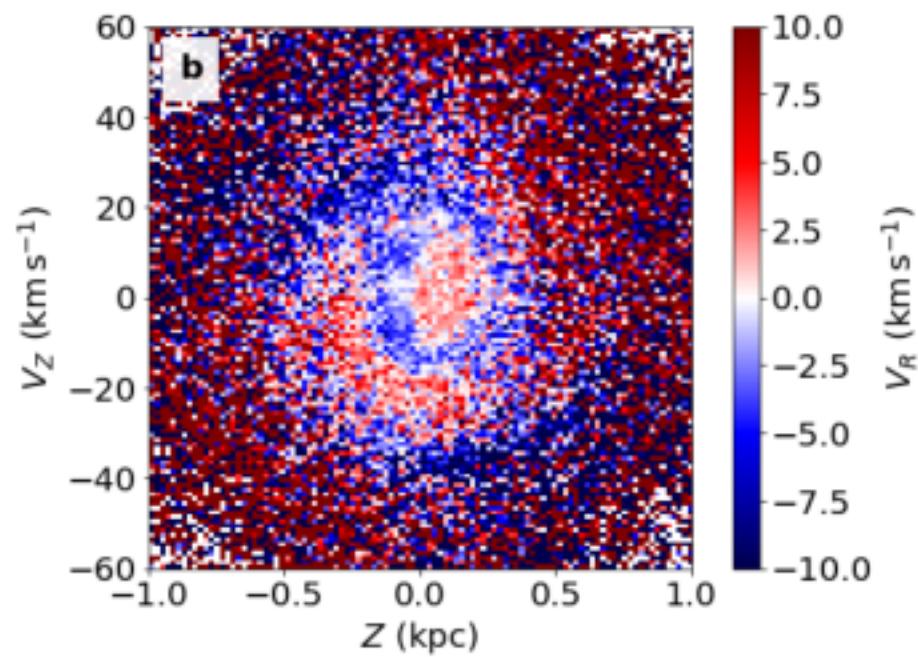
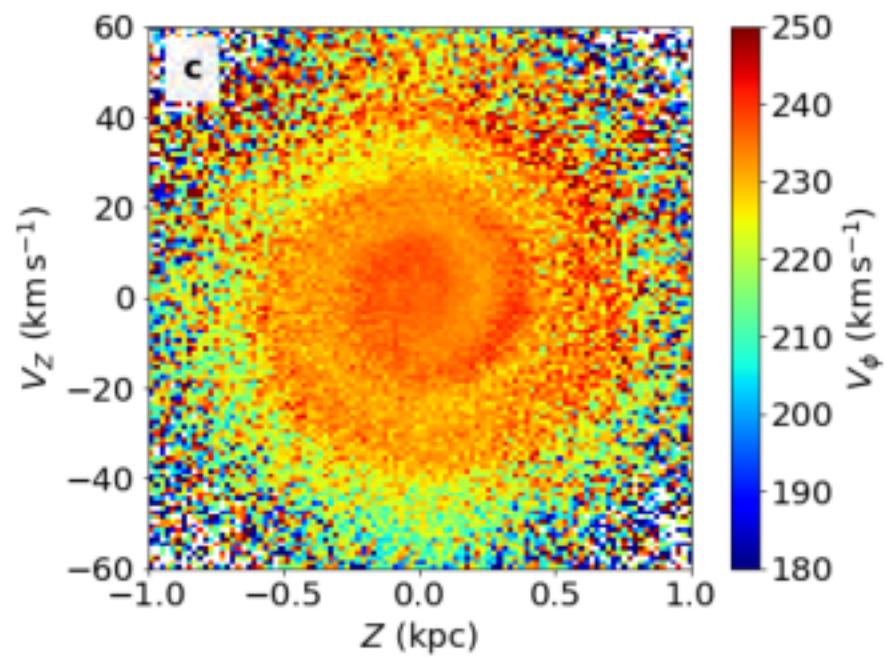


Gaia DR2



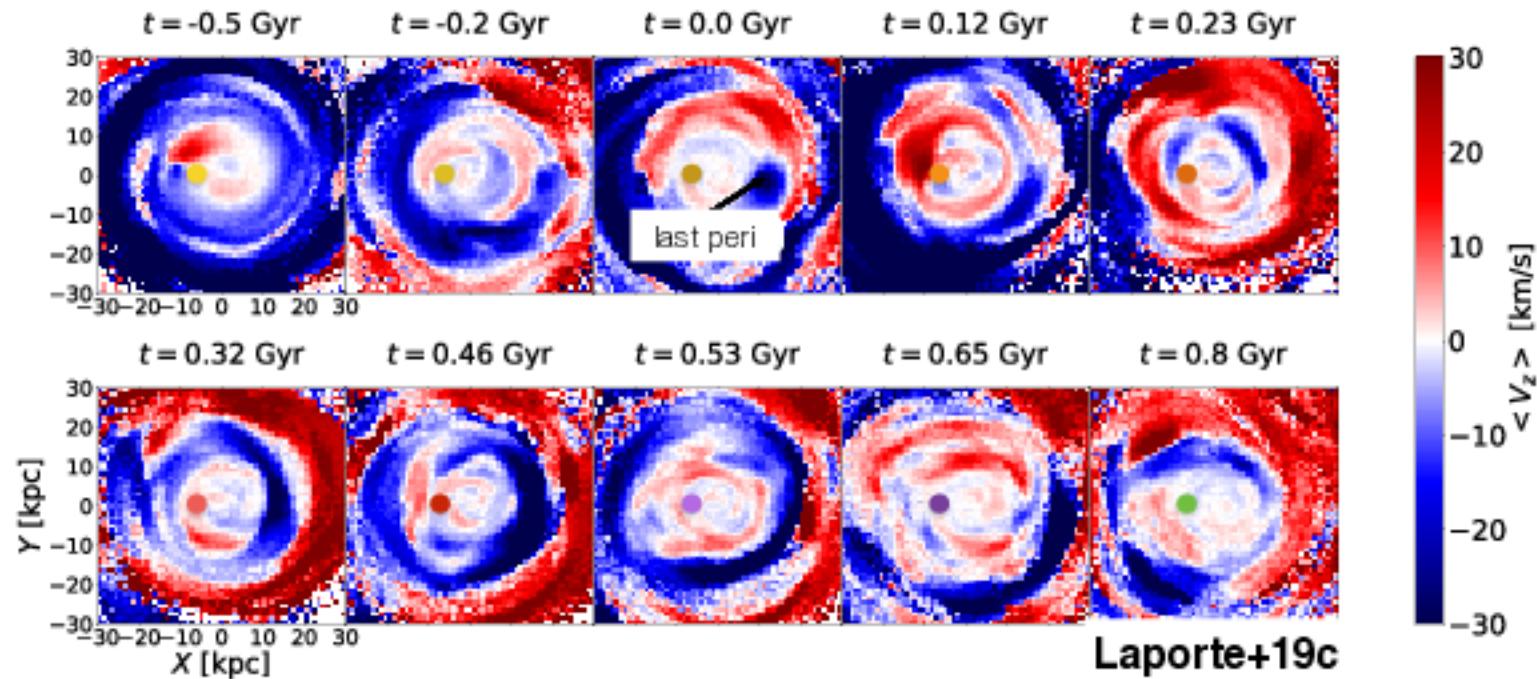
Gaia Collab+18





Disc response during last stages of Sgr's orbit

Global

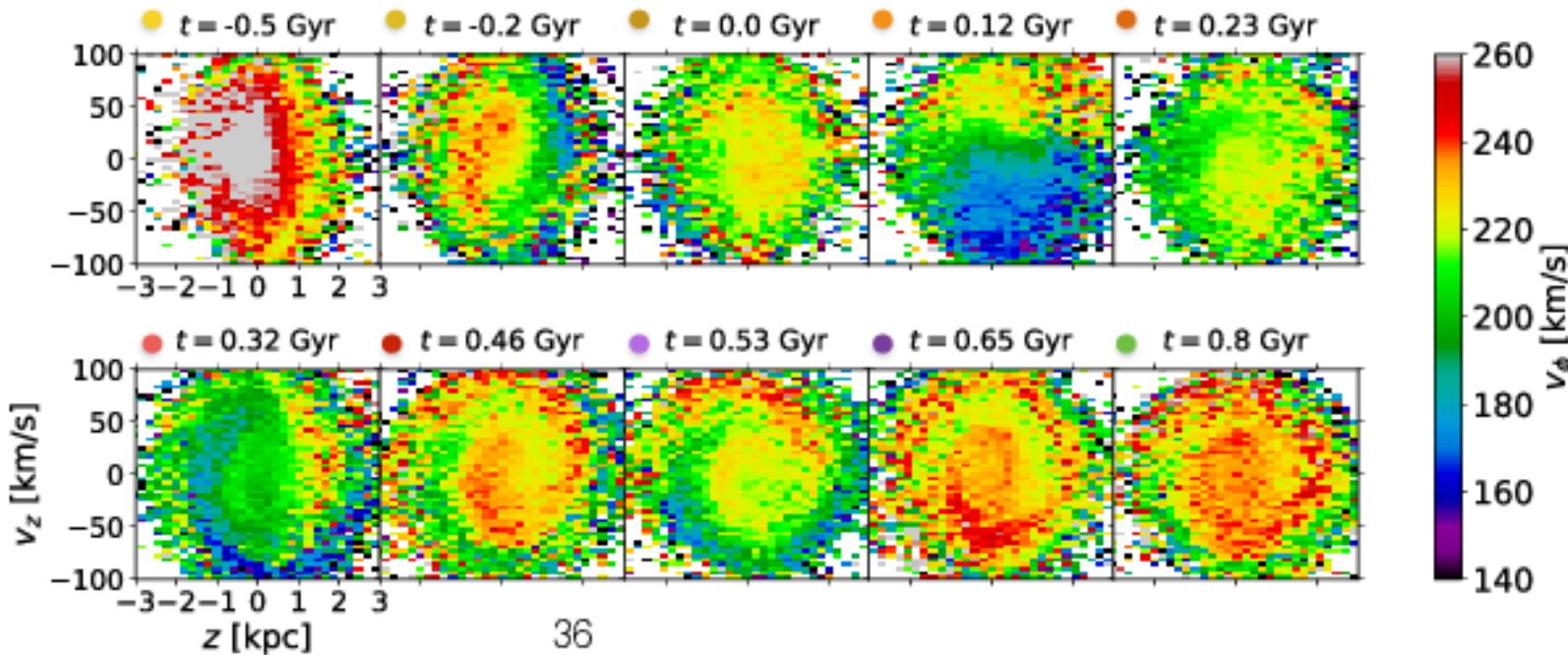


Laporte+19c

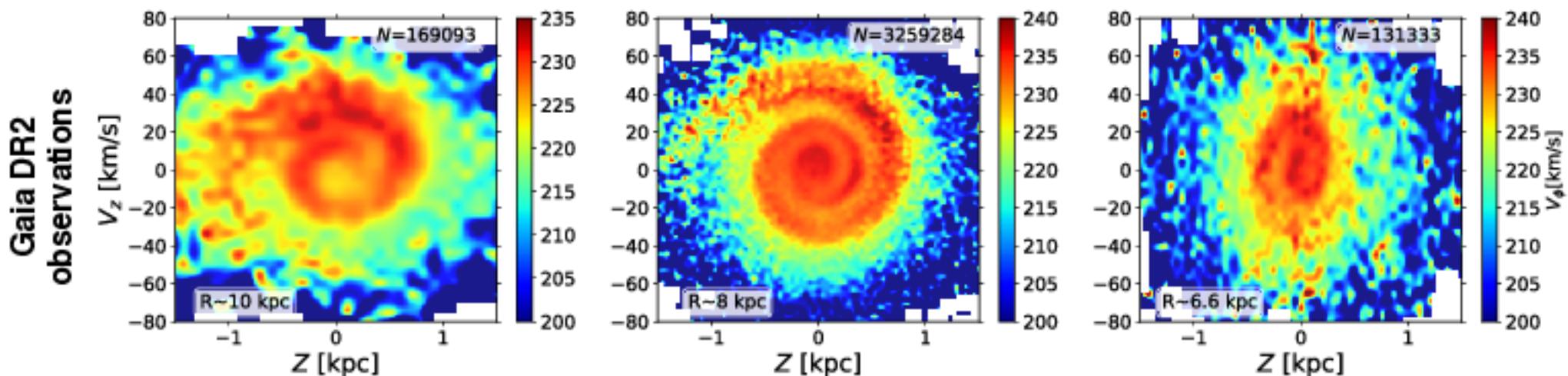
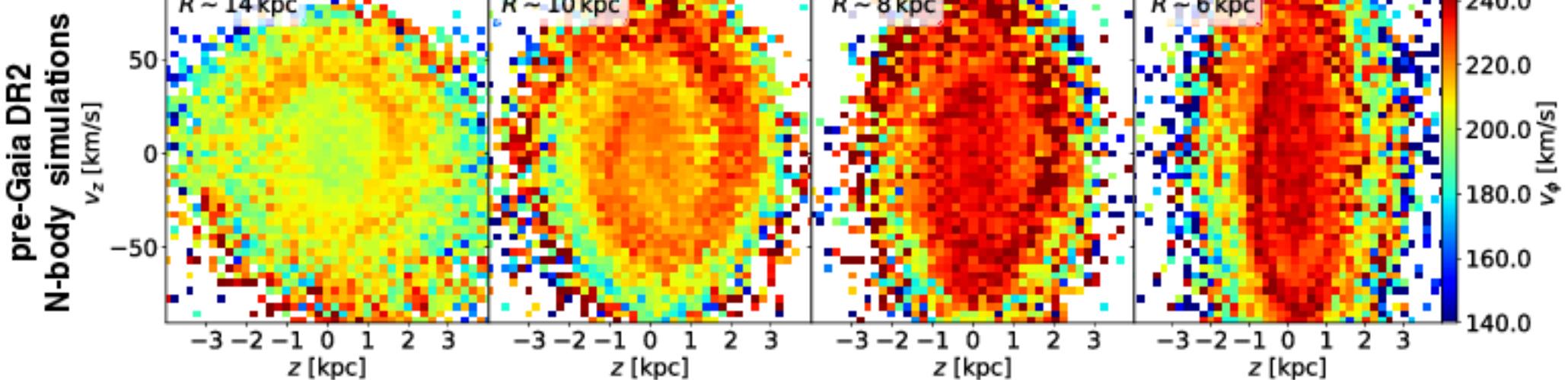
Solar
Neighbourhood

Last peri
resets
PS-spiral

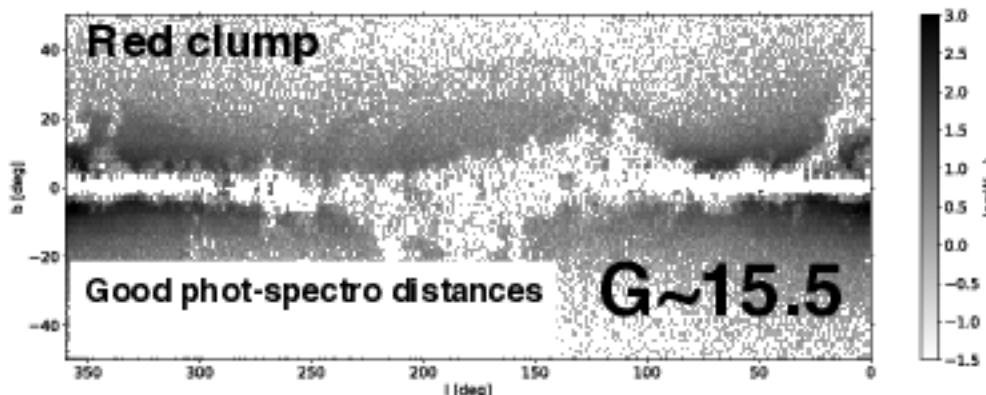
Laporte+19c



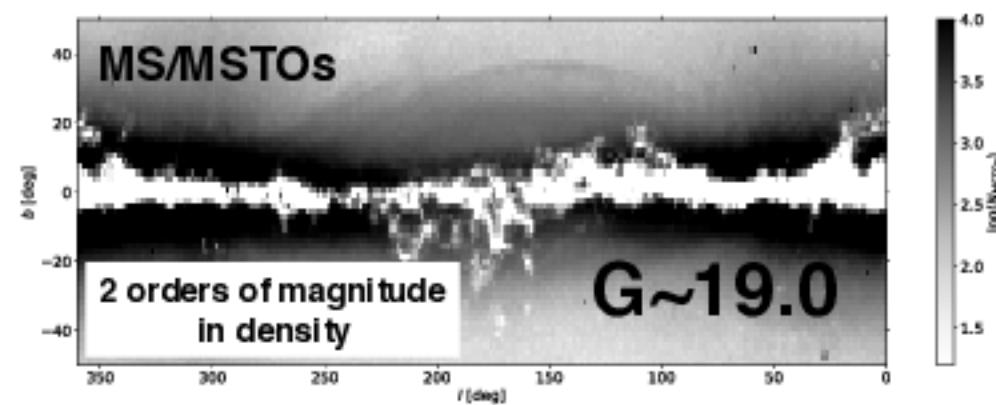
phase-space spiral behaviour in a **Galactic** potential perturbed by a recent satellite encounter



Probing *prior perturbation events* with SDSS V, 4MOST, LSST, MSE **constraining the orbital mass loss of Sgr**

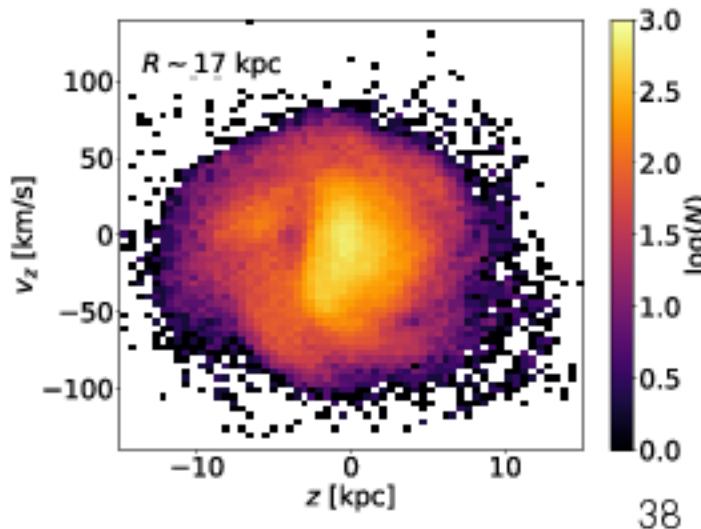


Gaia DR2

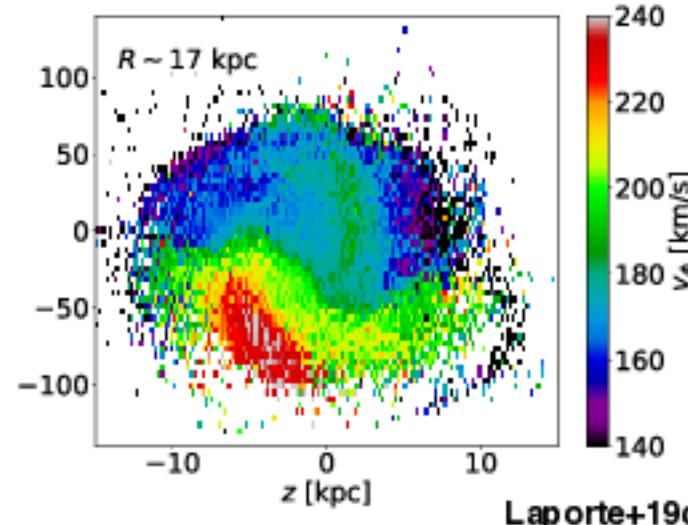


Laporte et al. (in prep.)

N-body simulations

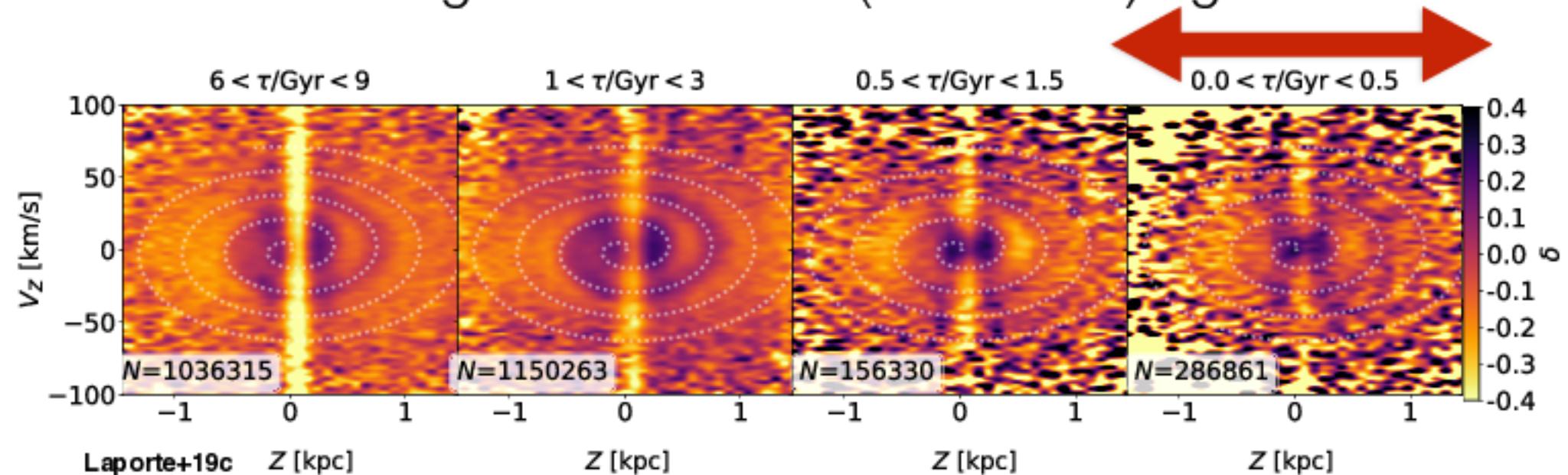


38



Laporte+19c

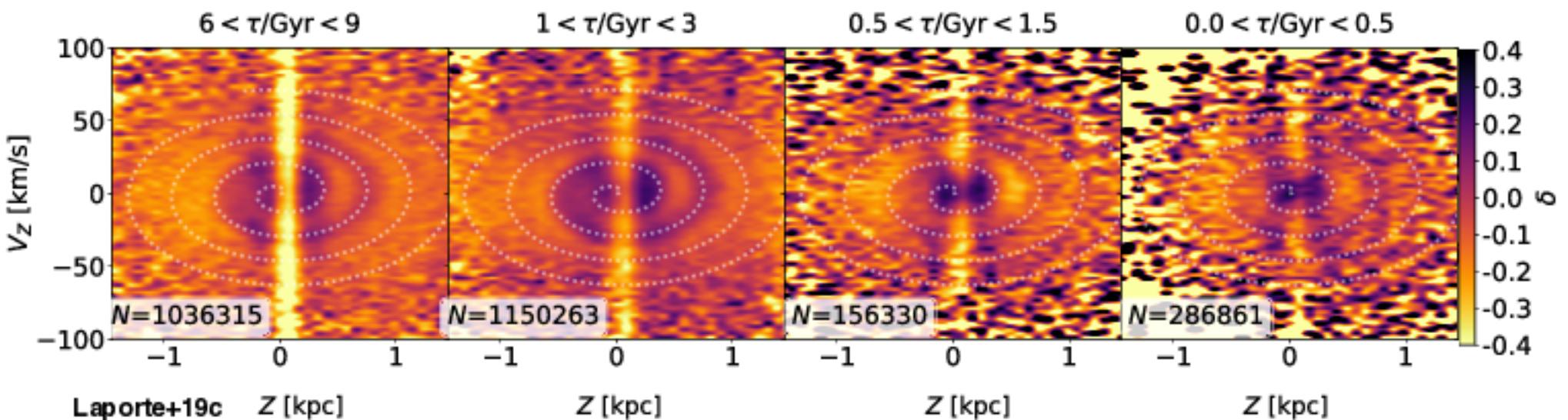
Timing the event with (isochrone) ages



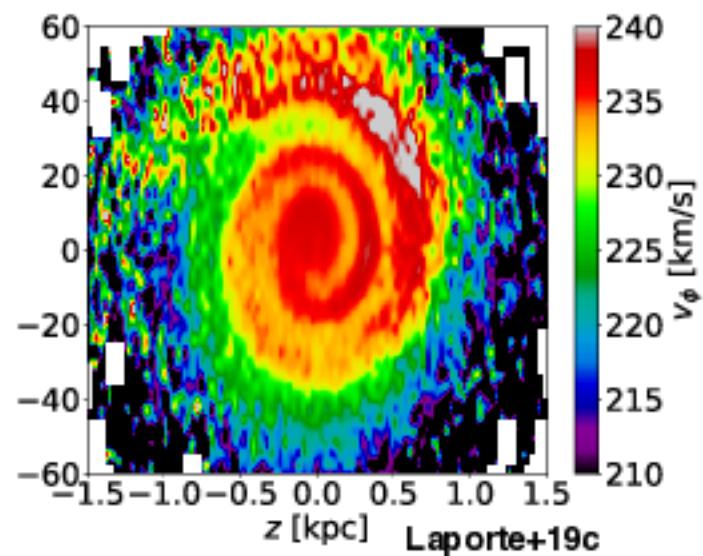
See also Tian+18 for exploration in vR , $v\phi$

Perturbation must have been recent
shape similar at all ages down to youngest age bin

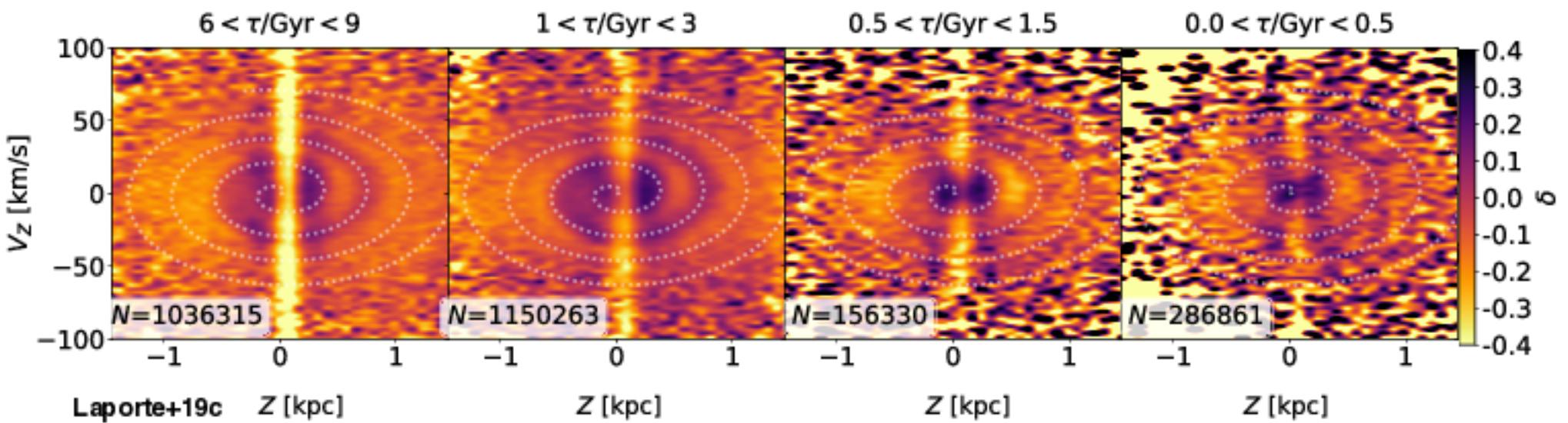
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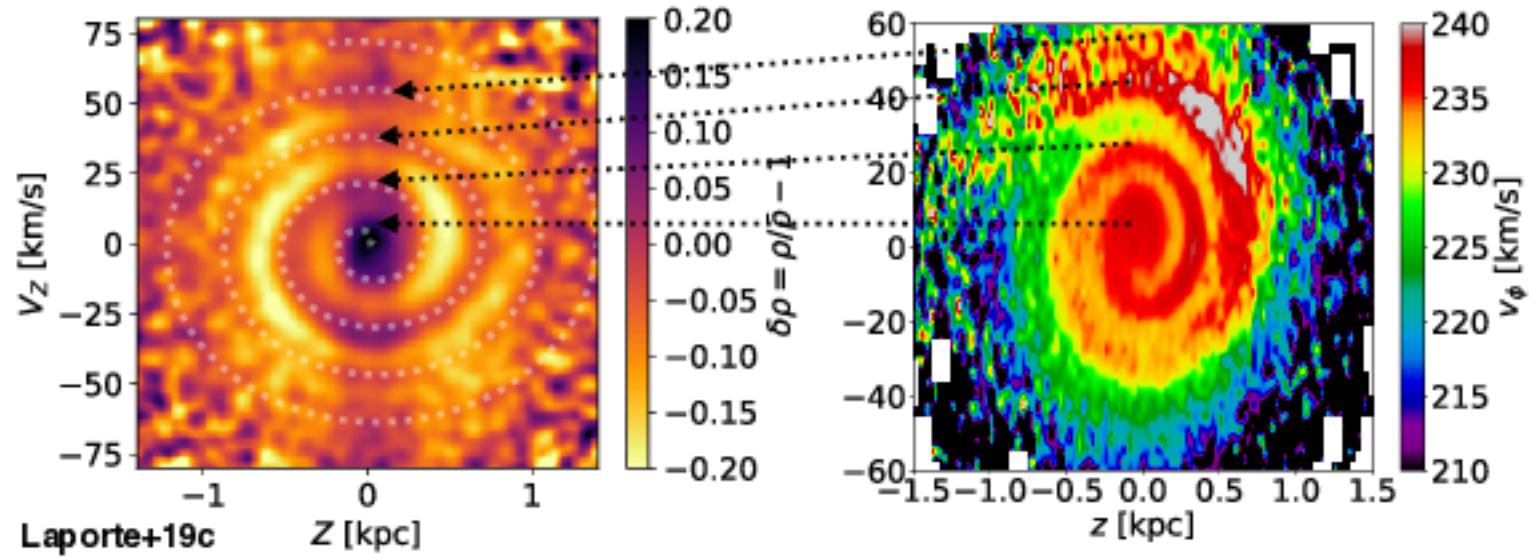
and stellar dynamics (Binney & Schoenrich 2018)



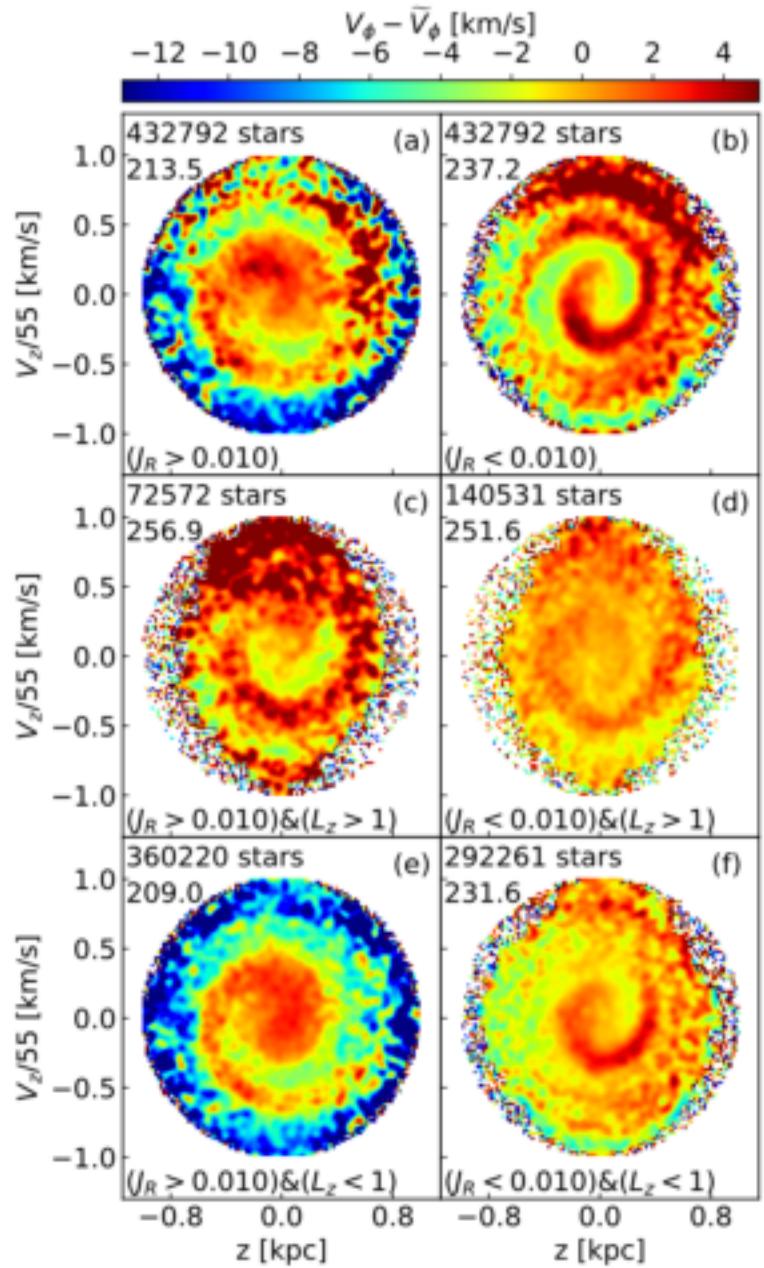
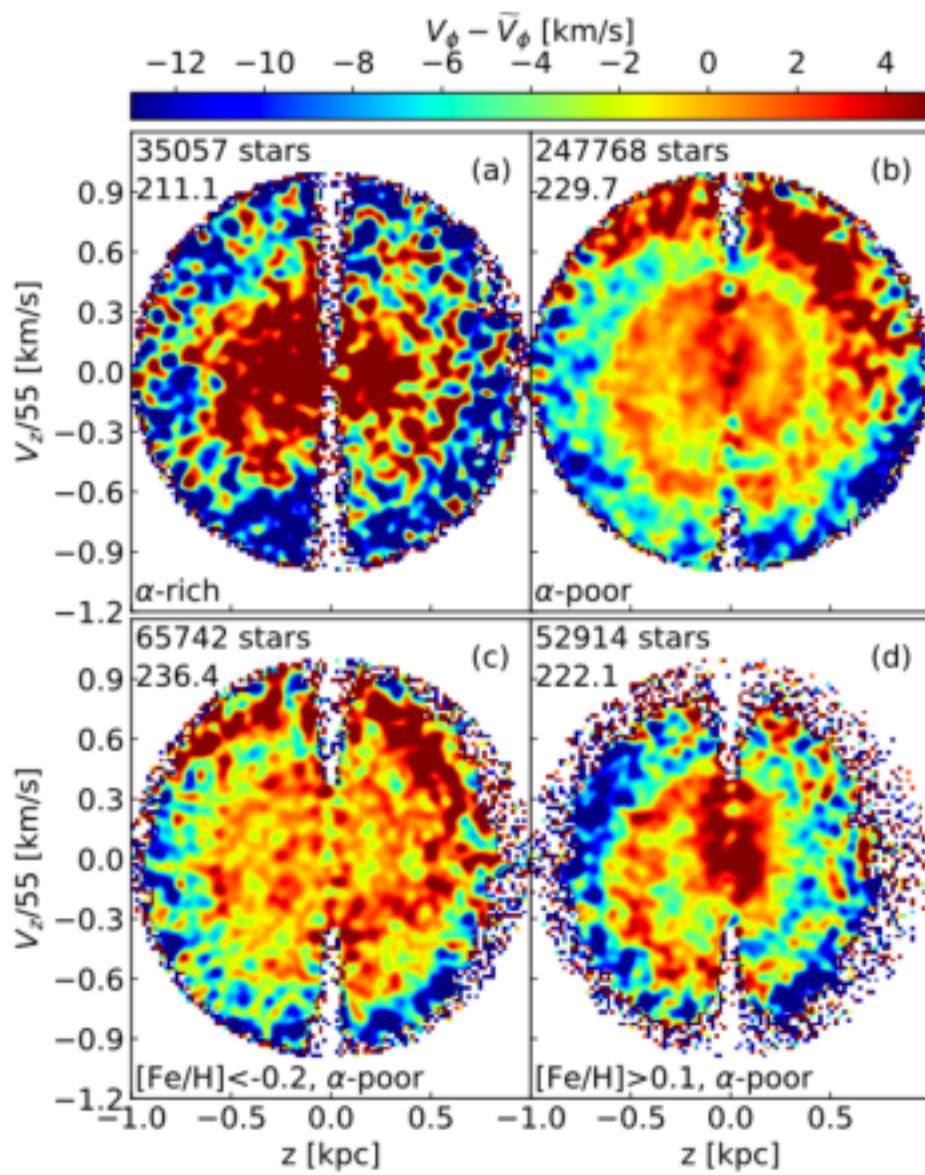
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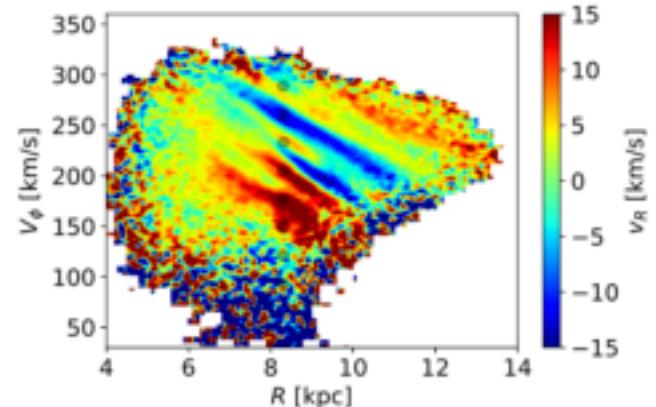
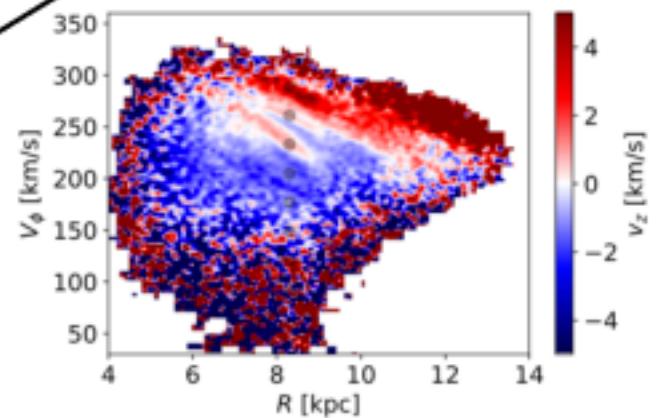
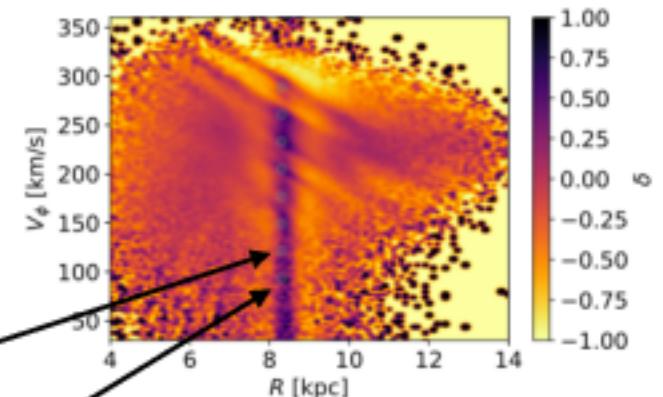
Other dissections of the PS-spiral



Other DR2 Curiosities

New ridges below Arcturus (originally predicted by Minchev+09): "Snoop", "Herbie"

Snoop Dogg



Laporte+19c

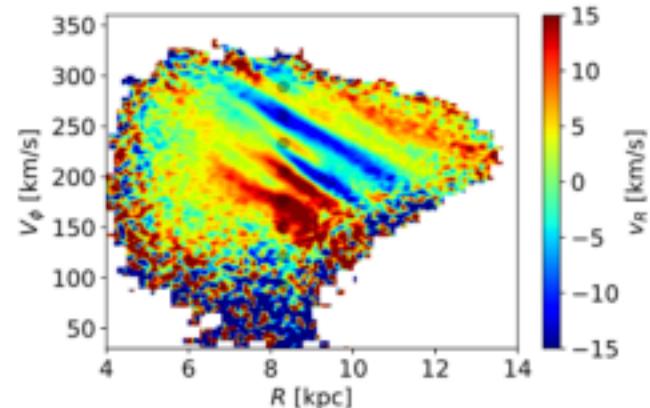
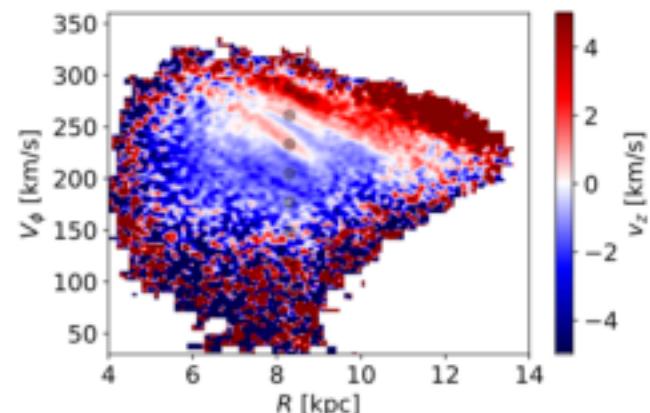
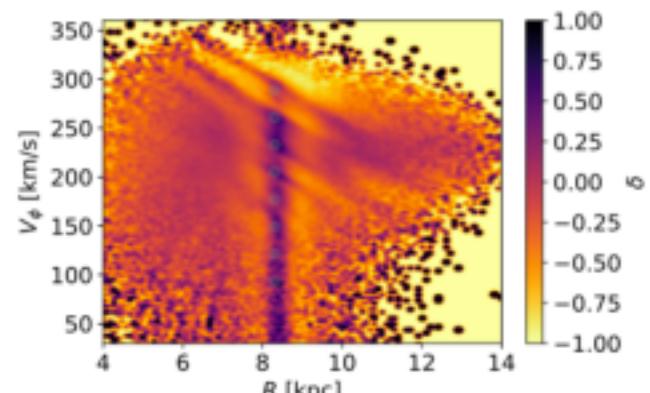
Other DR2 Curiosities

New ridges below Arcturus (originally predicted by Minchev+09): "Snoop", "Herbie"

see also Minchev09 (arches), Kawata18, Ramos+18+Wilma's talk for the classical ridges

Some ridges have systematic bulk vertical streaming motions. (also re-confirmed later by GALAH Khanna+19)

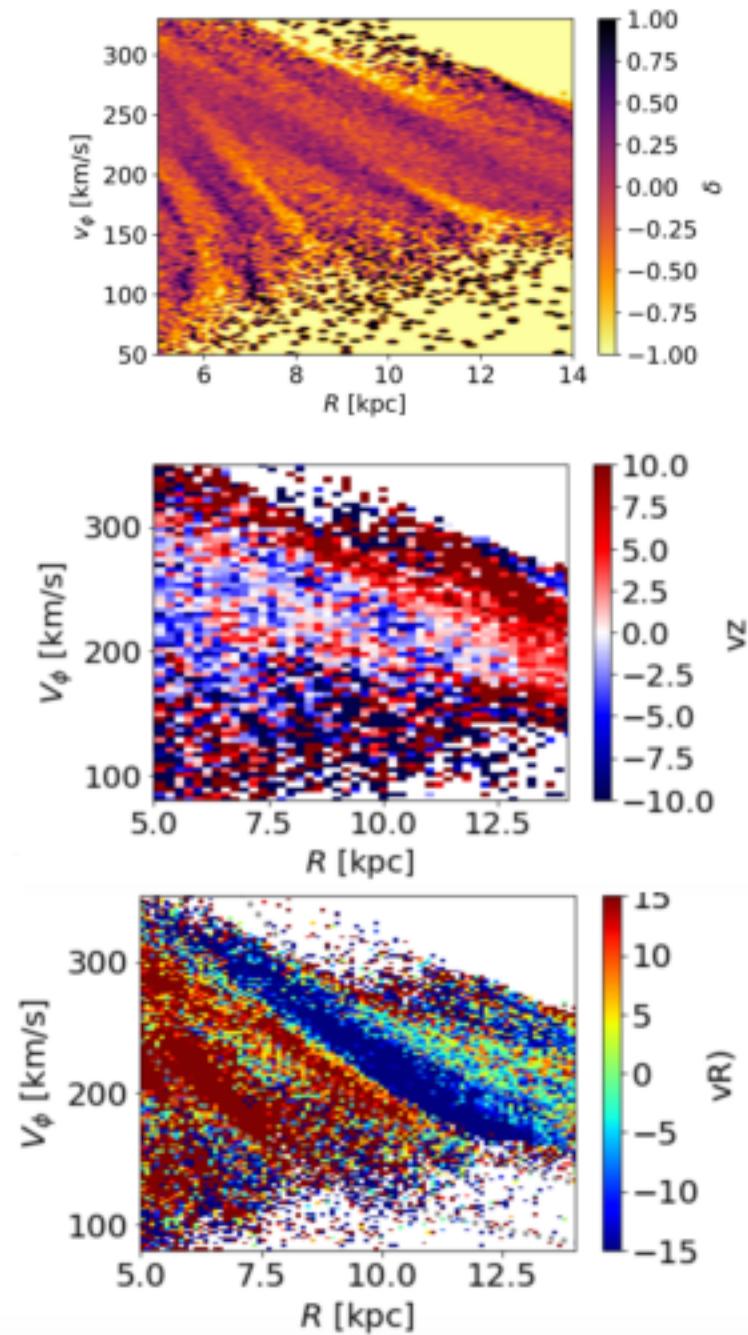
Undulations in vR (shown in Ramos+18) see also Fragkoudi+19 and Jason's Talk



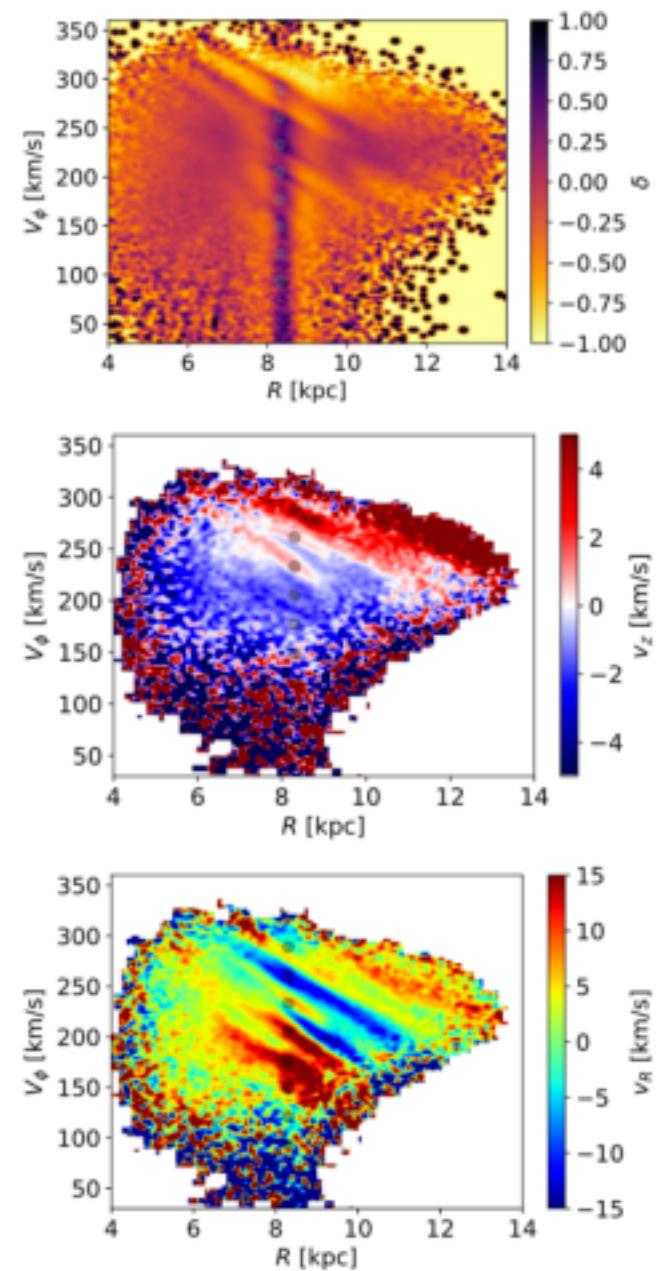
Laporte+19c

Other DR2 Curiosities

pre-Gaia model

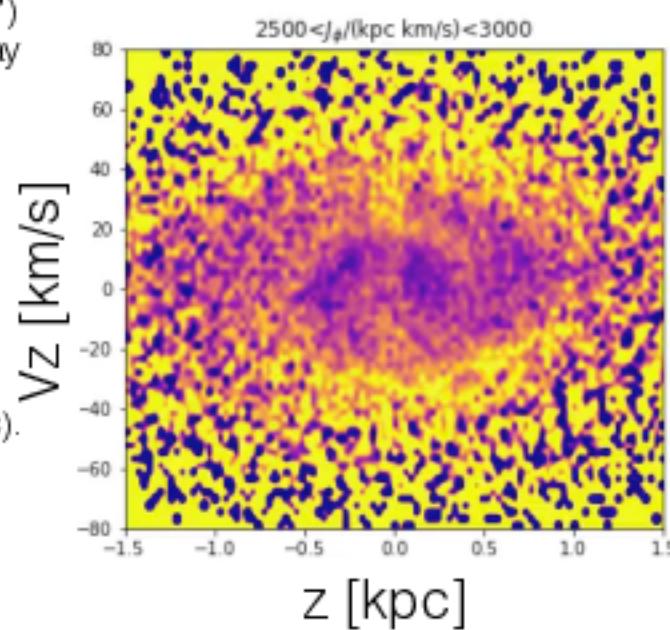


Gaia DR2



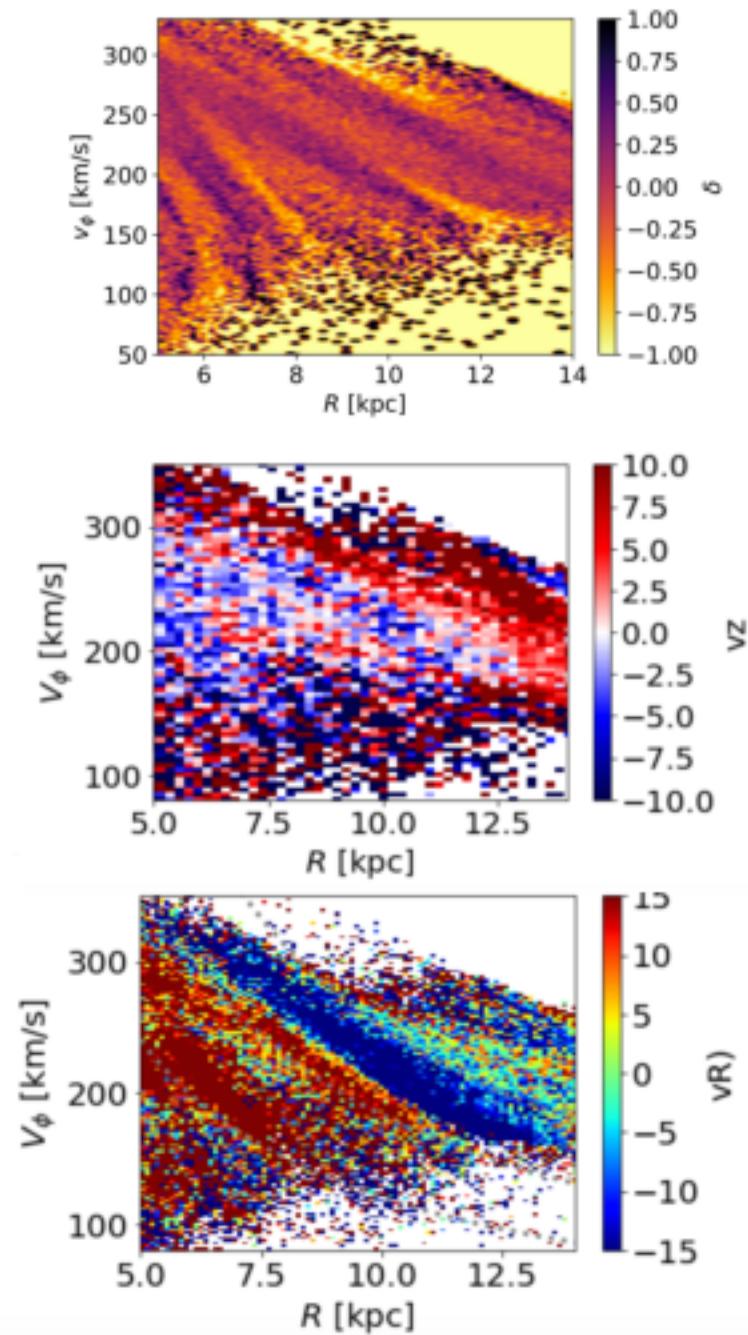
Conclusions

- **The Sgr dSph is likely responsible for many asymmetries in the disc (outer - inner):** first N-body models to show qualitative+quantitative predictions **pre-Gaia** and **post-Gaia DR2**.
- Detailed live N-body model of Sgr interaction with disc: can simultaneously account for **local perturbations** and **global perturbations** of the disc (L18b).
- **Re-interpretation** of thin streams towards the Anticenter (EBS, ACS, “**feathers**”) as tidal tails of the MW seen in projection (L19 a). Confirmed observationally (stay tuned).
- Gaia PS-spiral is the manifestation of **phase-mixing in the Snbhd** to a **global perturbation** of the disc by Sgr exciting bending waves (L18b, L19 c).
- **Last pericentric passage of Sgr resets PS-spiral in the Snbhd** with $t_{\text{form}} \sim 500\text{-}800 \text{ Myr}$ (L19c).
- **Outer disc should hold signs of prior perturbations** due to longer T_{orb} (L19 c).
- **Bar buckling echo model is ruled out by DR2 data:** amplitude of PS-spiral, ages, shape of spiral follows expectations from Sgr impact model (L19 c). See Carrillo+19 too.
- PS-spiral has **more than 2 wraps. Variation in PS-spiral in radius over 2 scale lengths using DR2**, matches behaviour expected from recent impact model (L19 c).
- **Gaia DR2 reveals new ridges in vphi-R below Arcturus:** Snoop, Herbie (L19 c, predicted by Minchev+09).

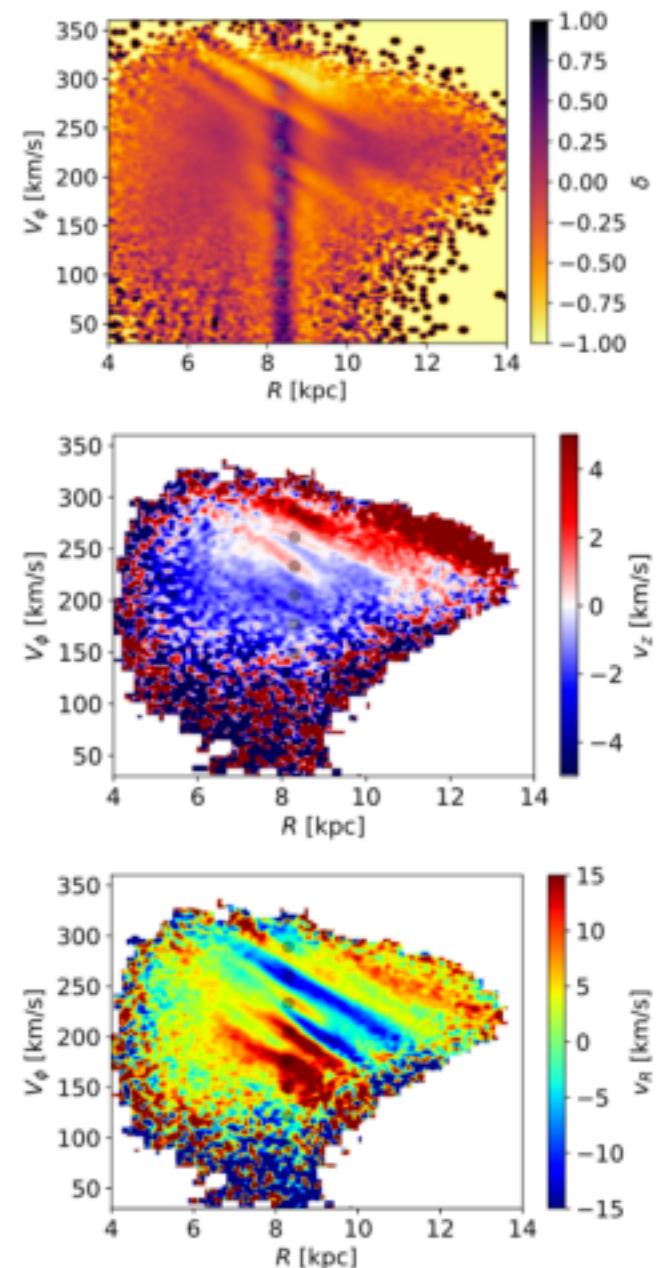


Other DR2 Curiosities

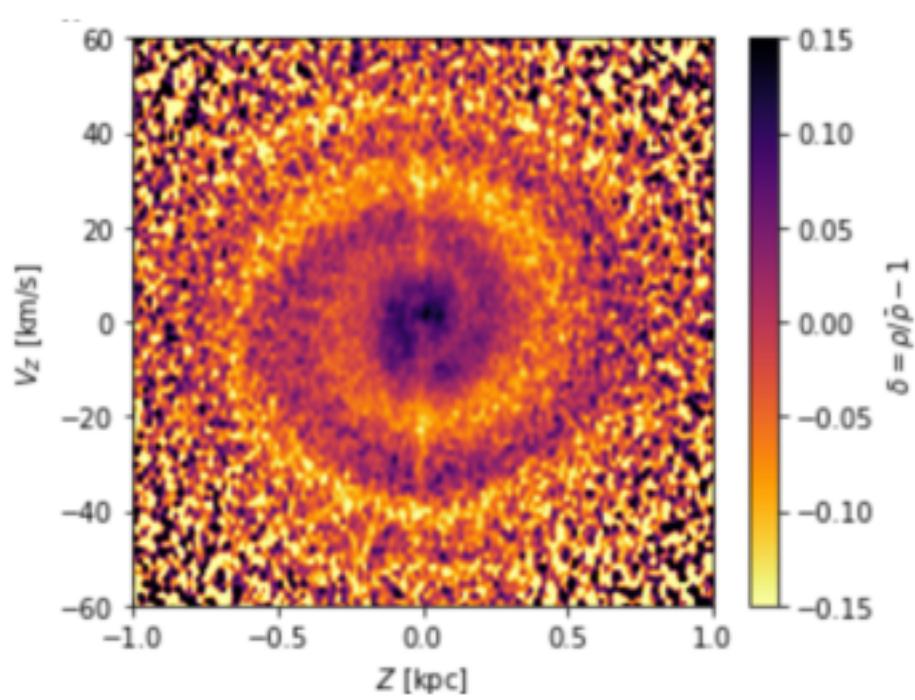
pre-Gaia model



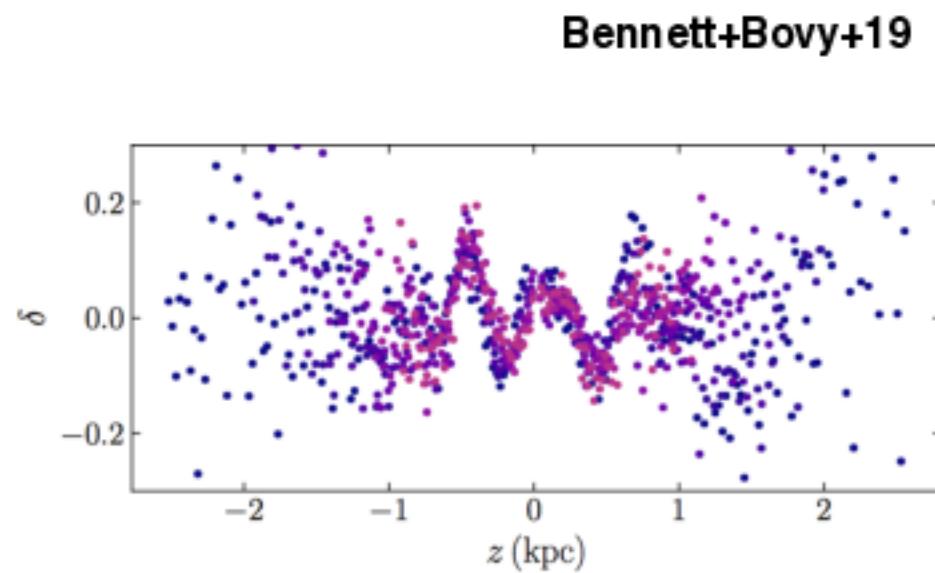
Gaia DR2



Gaia Phase-Space Spiral is just the 2D version of SNbhd disc oscillations



Laporte+19c



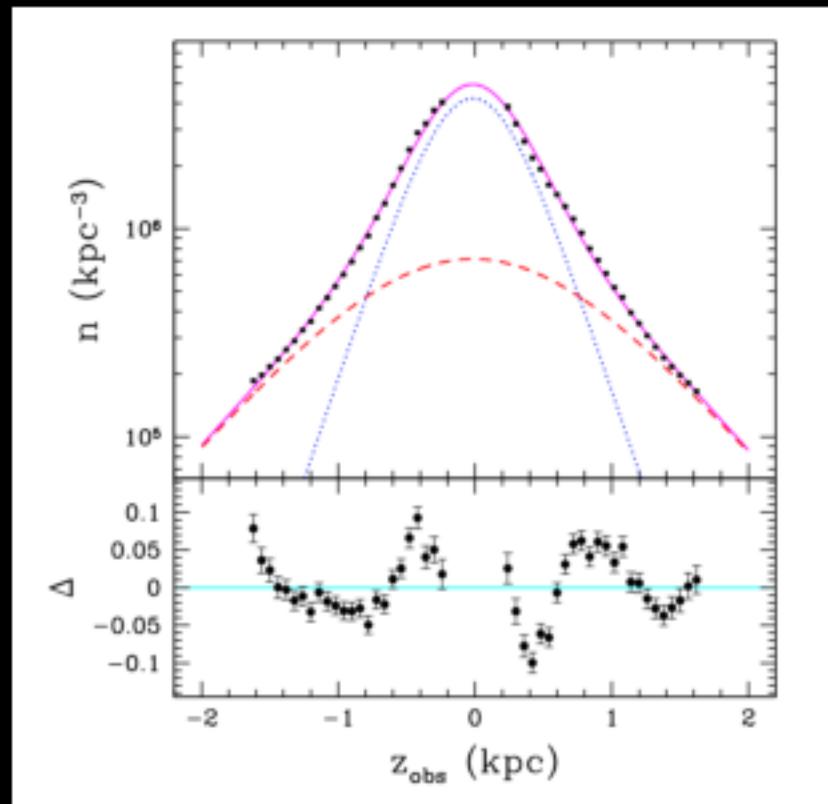
Bennett+Bovy+19

see also earlier works by Minchev+09 and Gomez+12 on UV-plane, and also Coma Berenices RAVE/DR2 work by Monari et al. 2018

See also another toy model by Binney & Schoenrich+18

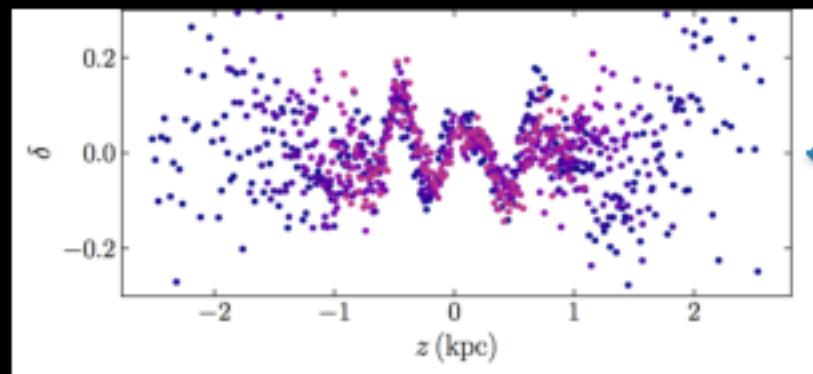
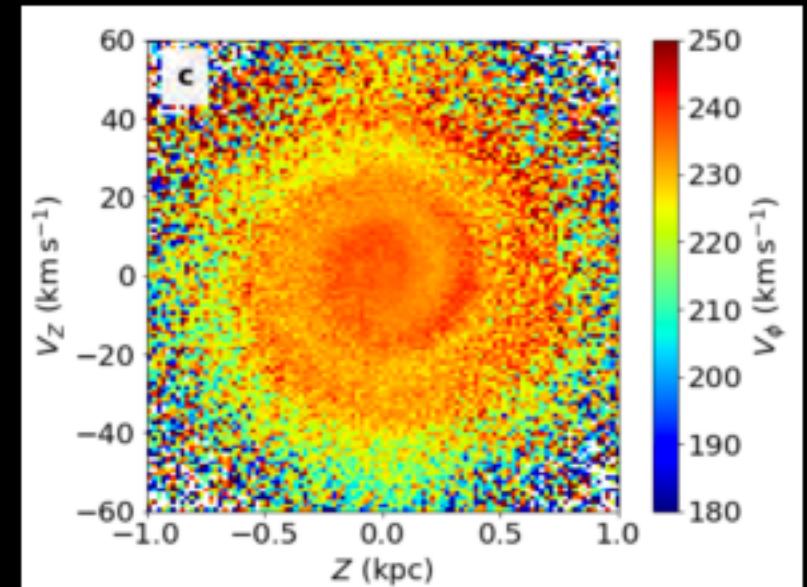
Local oscillations of the disc

pre-Gaia

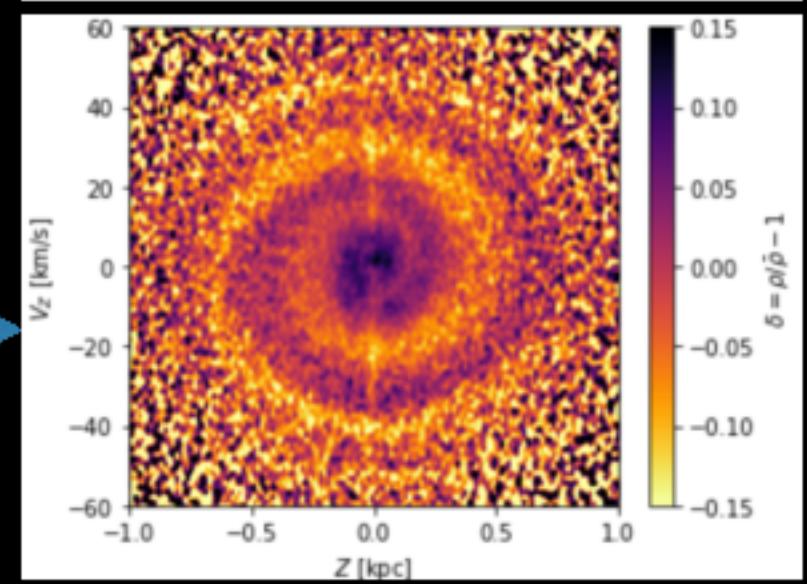


Gaia DR2

Antoja+18



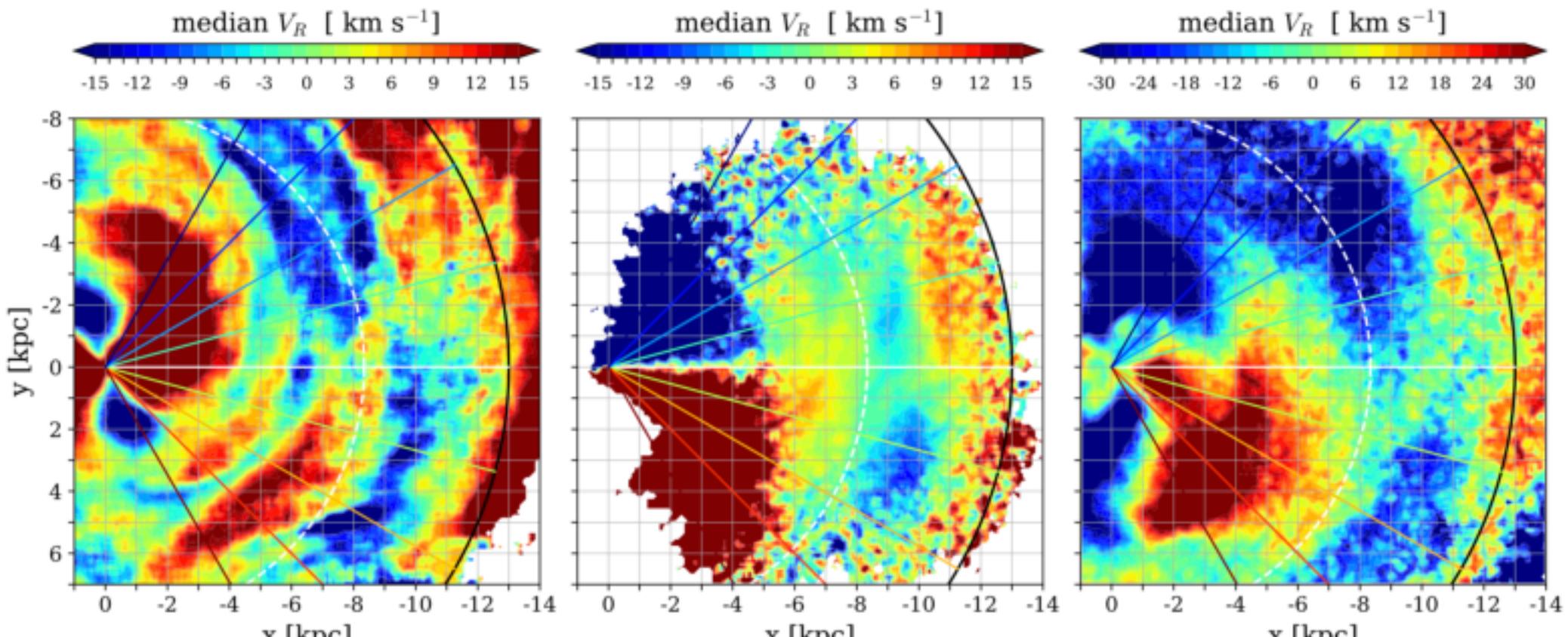
Bennett+Bovy19



Laporte+19c

Food for thought for this workshop

- The Milky Way communicates *on all scales* from DM halo to disc (Weinberg98) - **Gaia** should make us think “**global**” and **NOT “local”** anymore.
- Models presented here **pre-date DR2**, yet **predict** many recently uncovered DR2 features **over 10 scale lengths**.

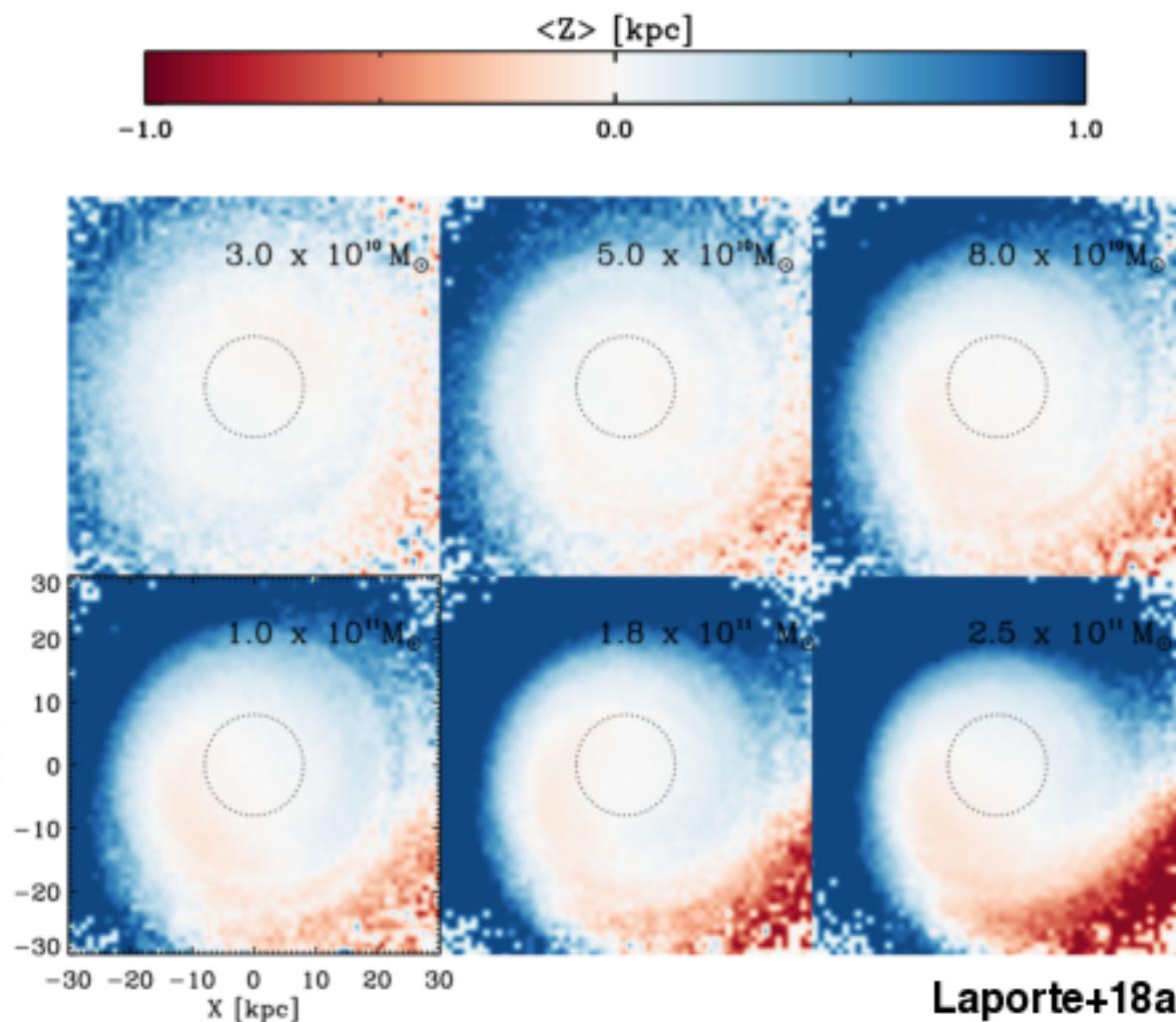


Secular bar model

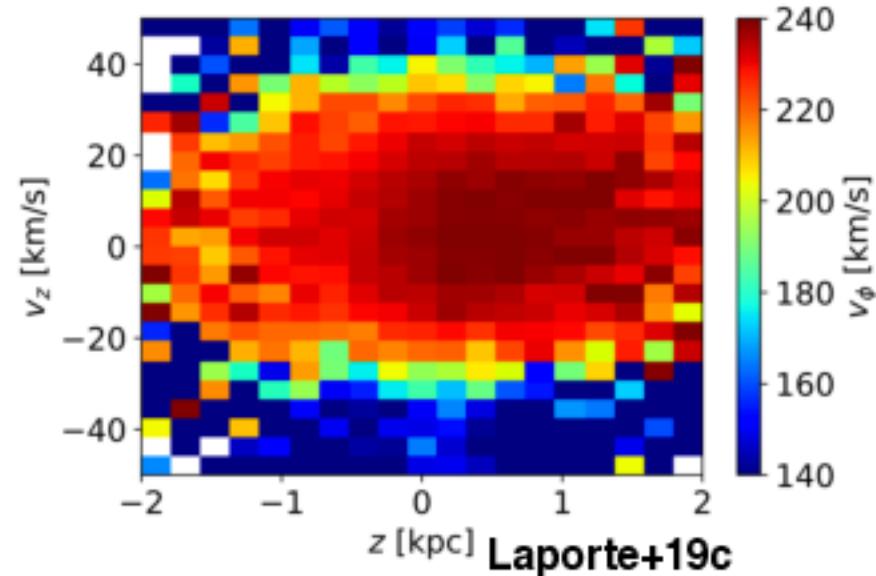
Gaia DR2

impact model

But what about the LMC?

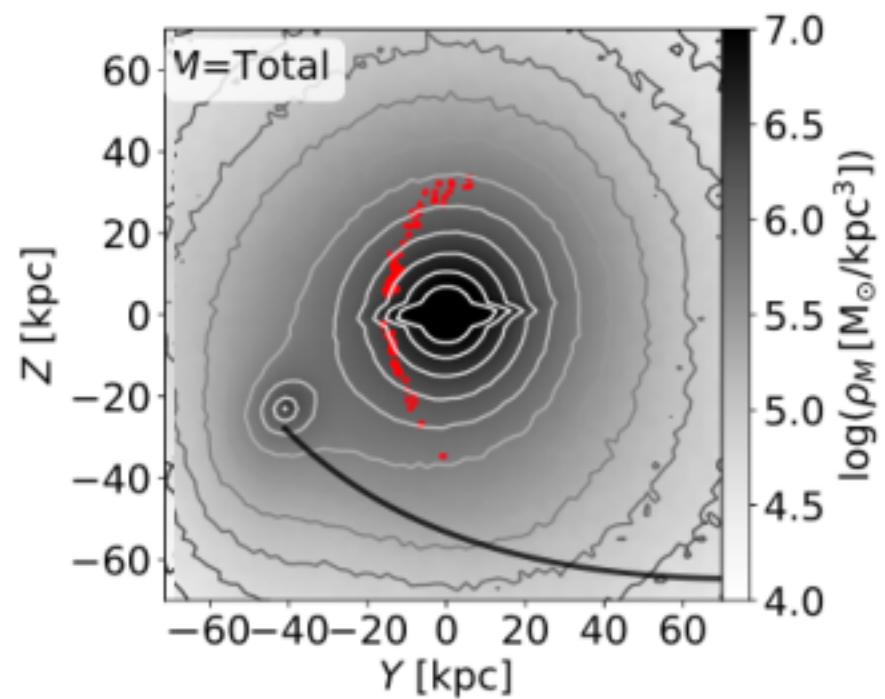
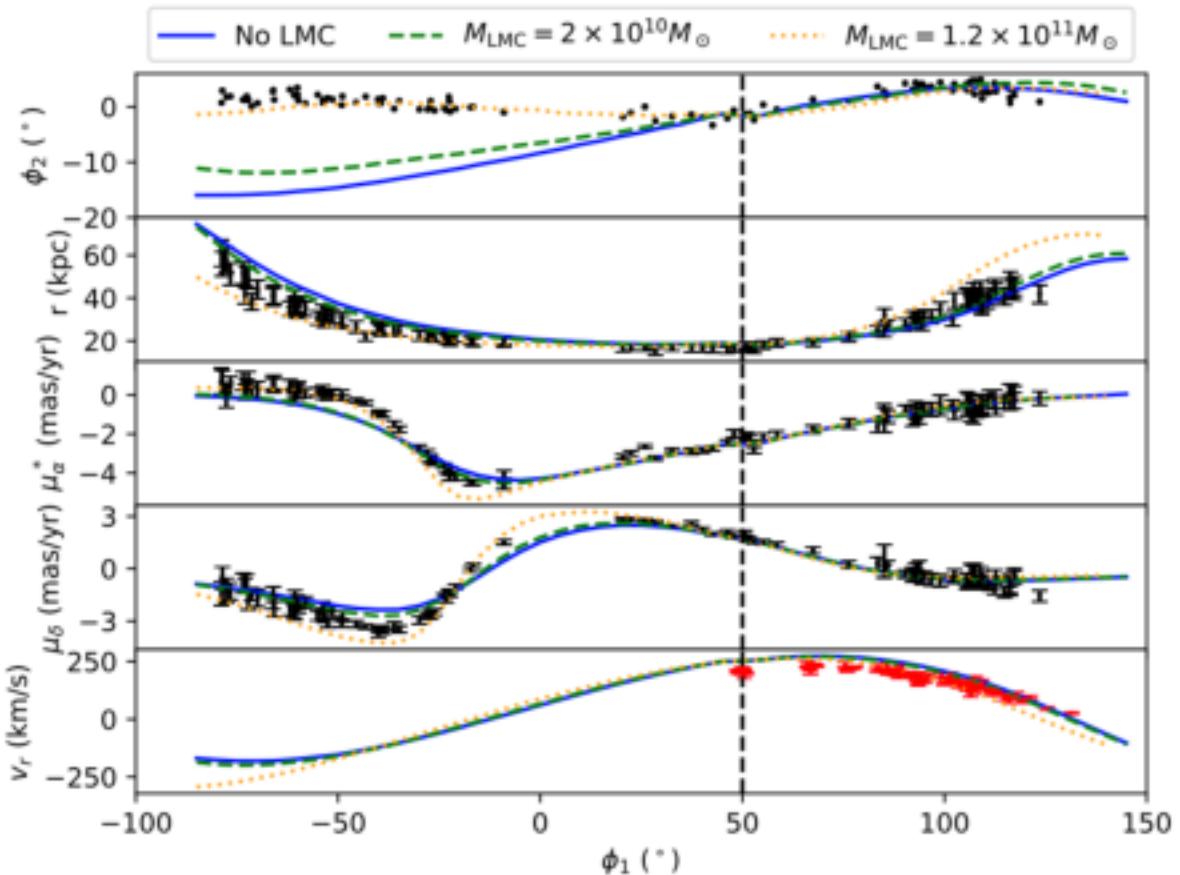


LMC warps the disc



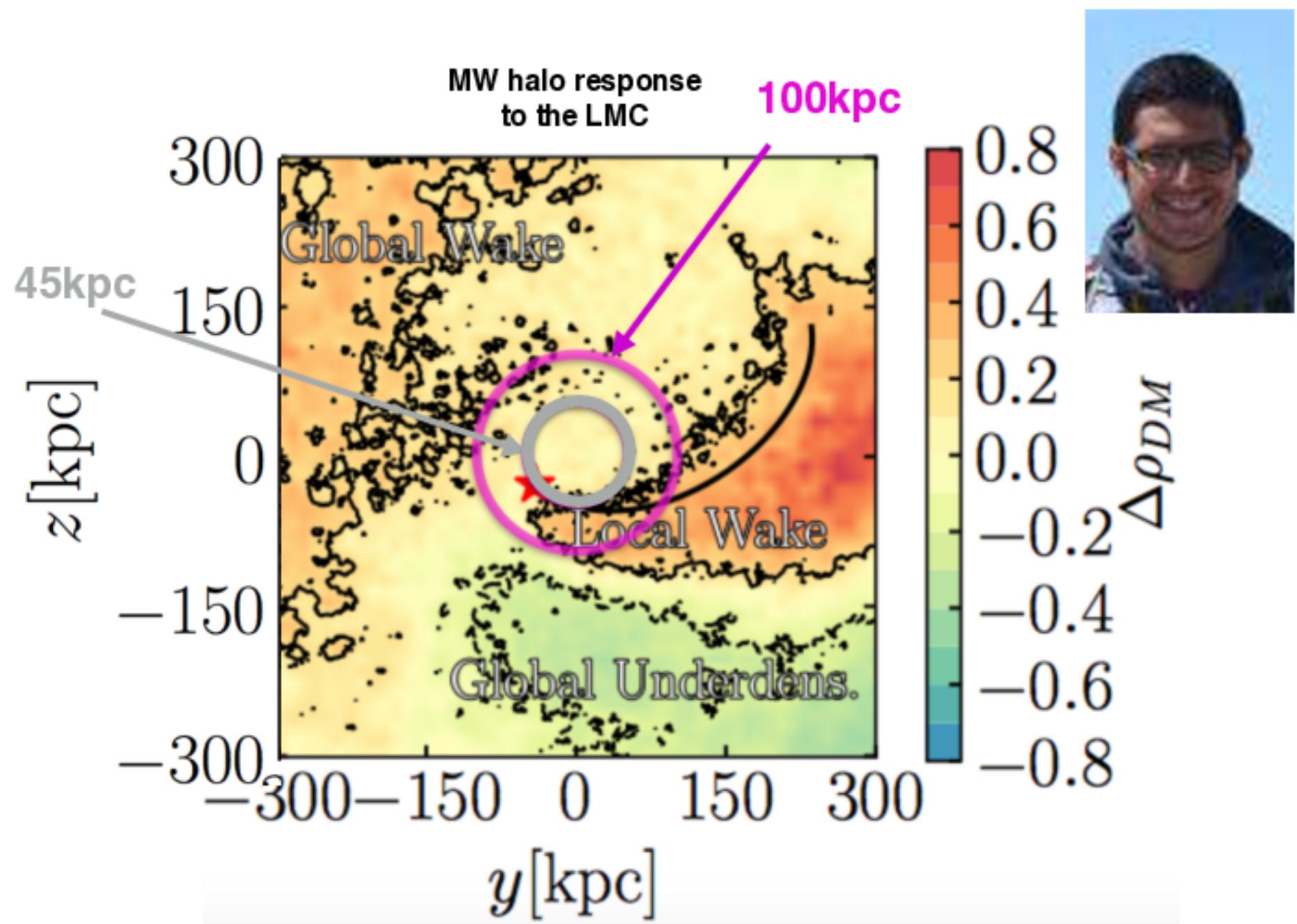
No time to form
(v_z, z) spiral

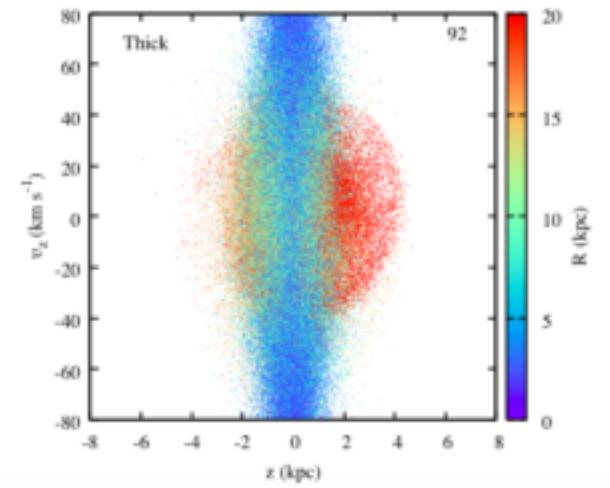
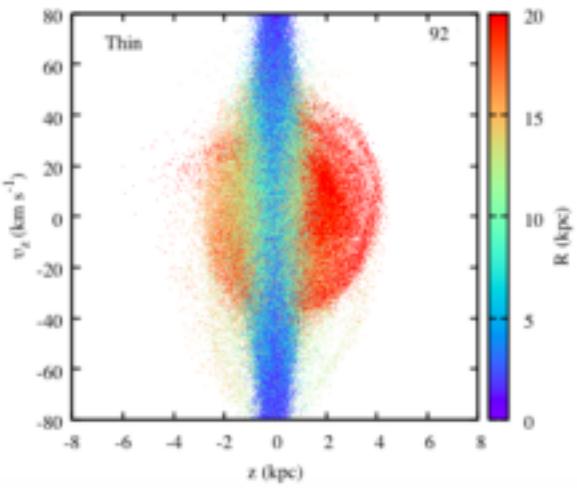
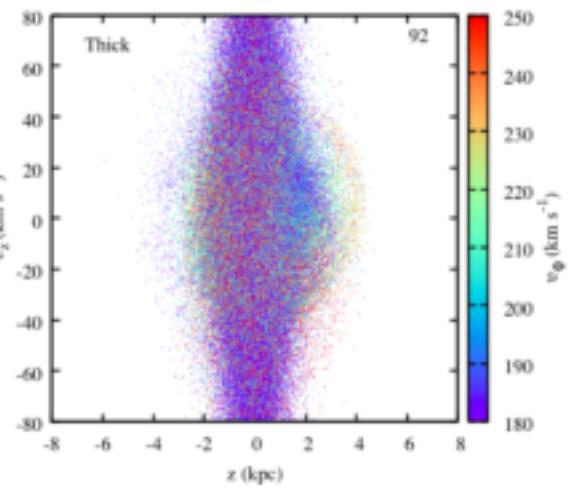
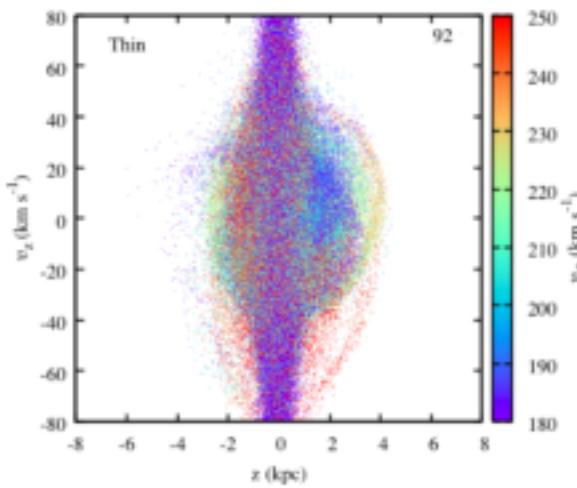
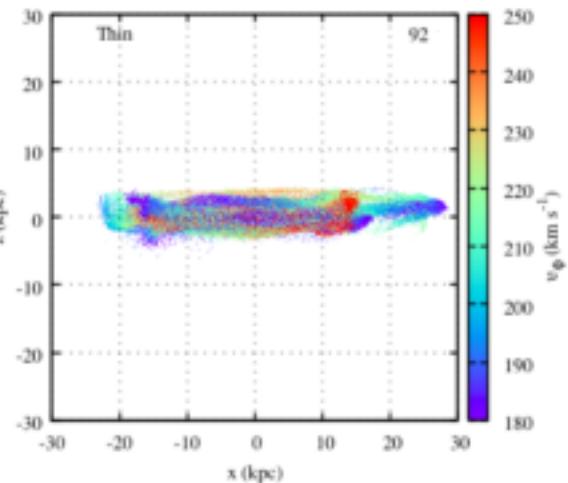
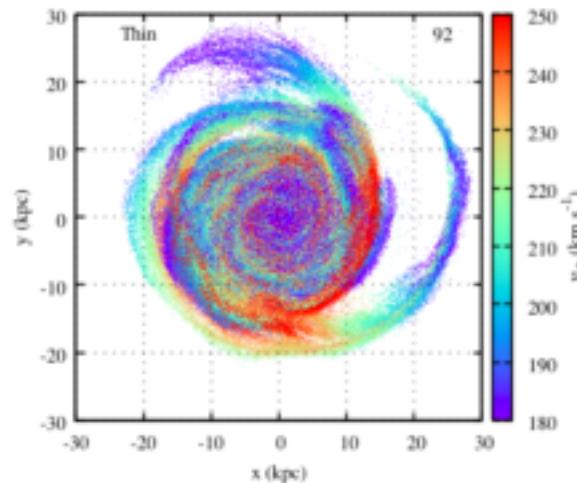
But it affects streams like Orphan



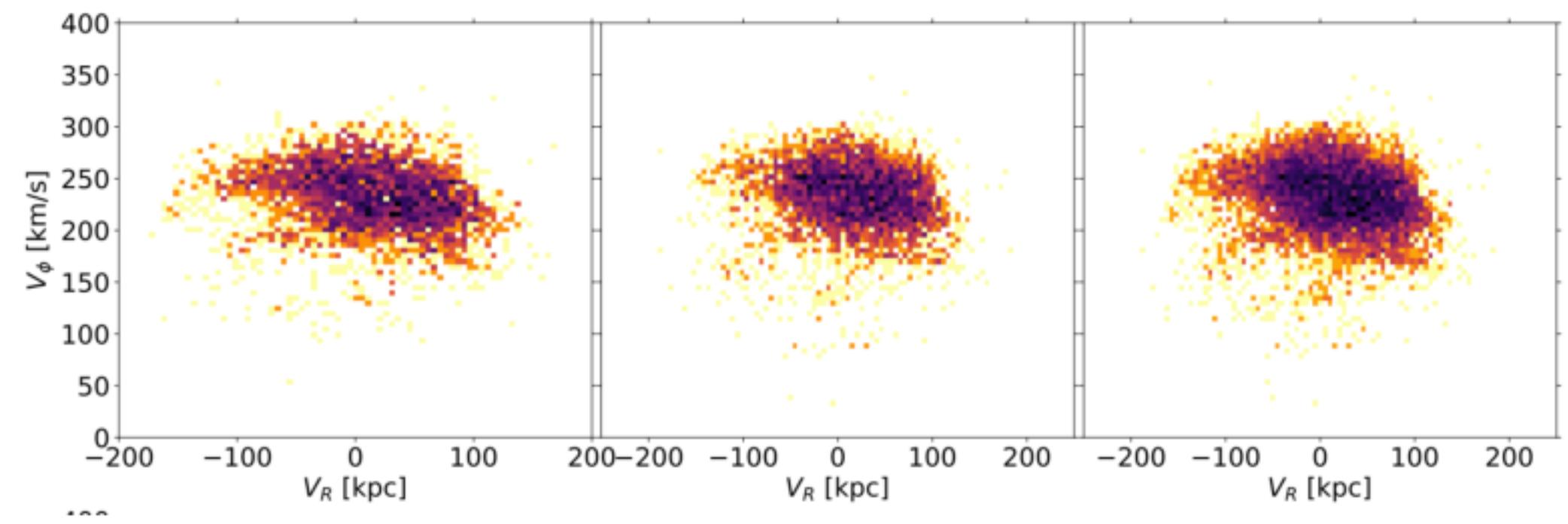
Erkal, Belokurov, Laporte+19

Response of MW halo to LMC

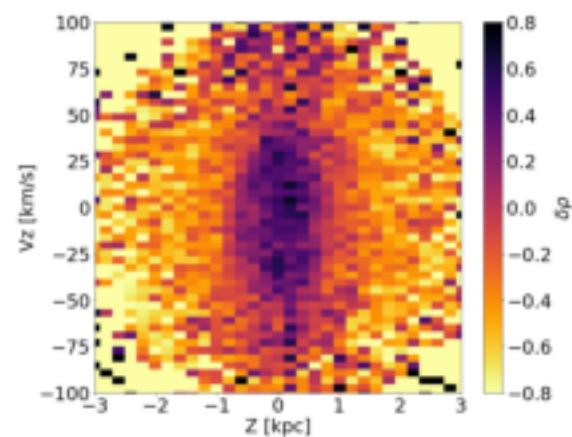
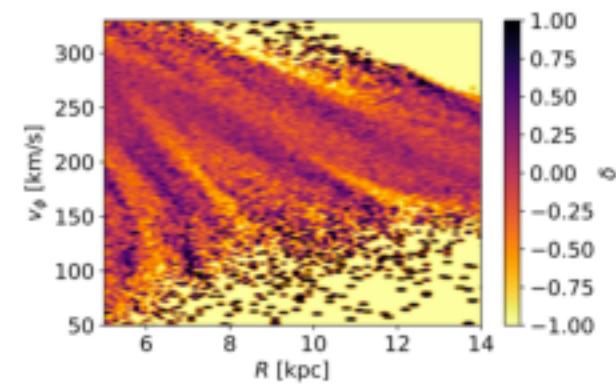
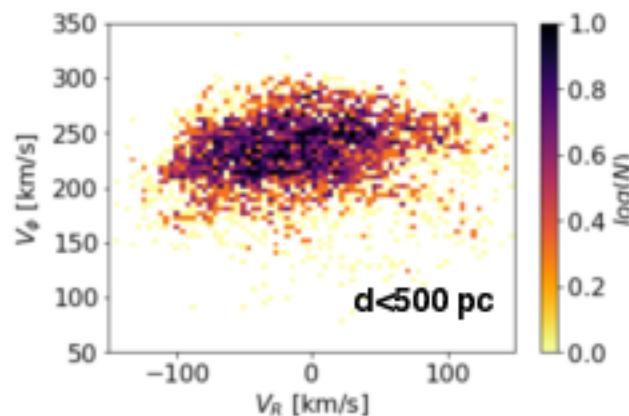




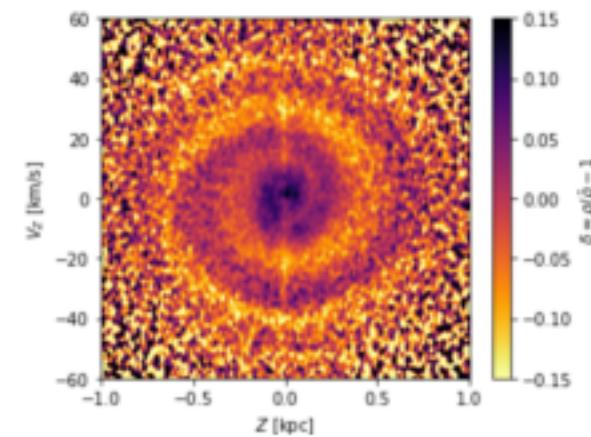
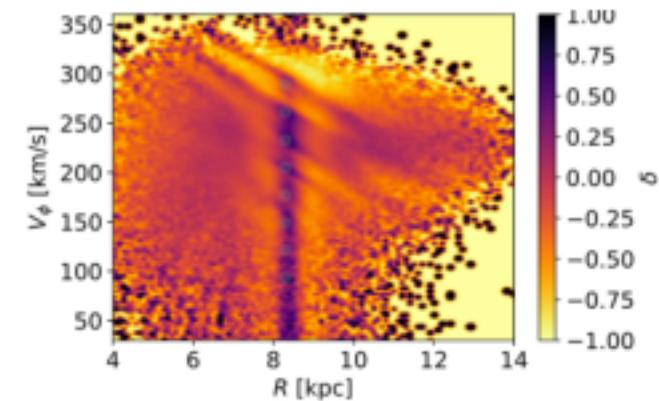
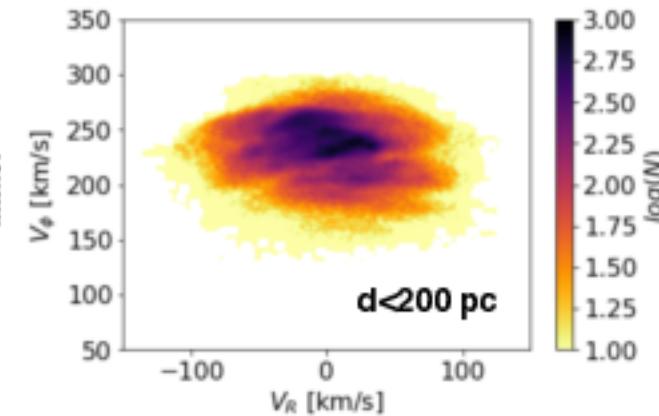
feature at 20 kpc
is just a feather
not a PS-spiral



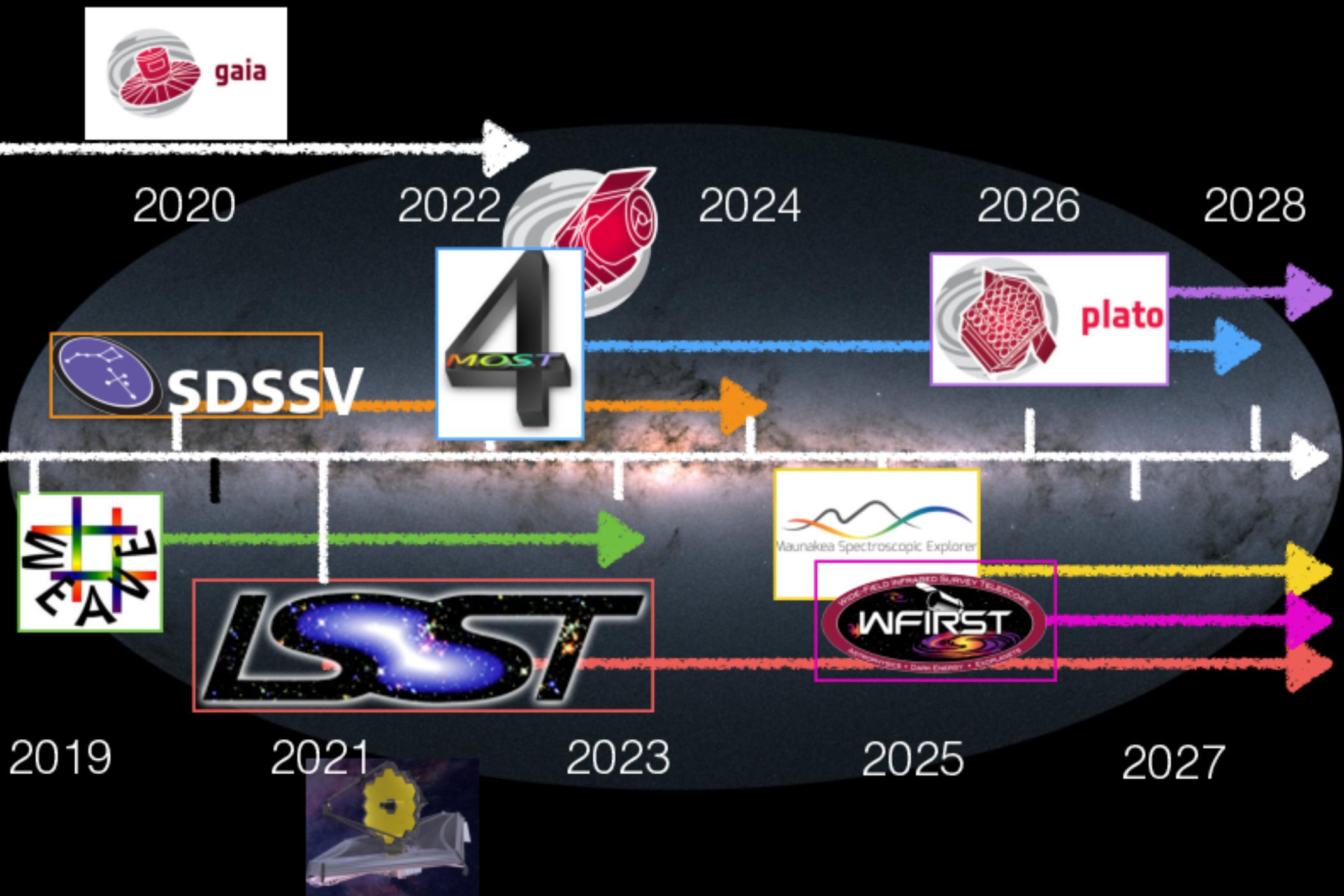
Laporte et al. (2018b)
N-body sims



Gaia DR2

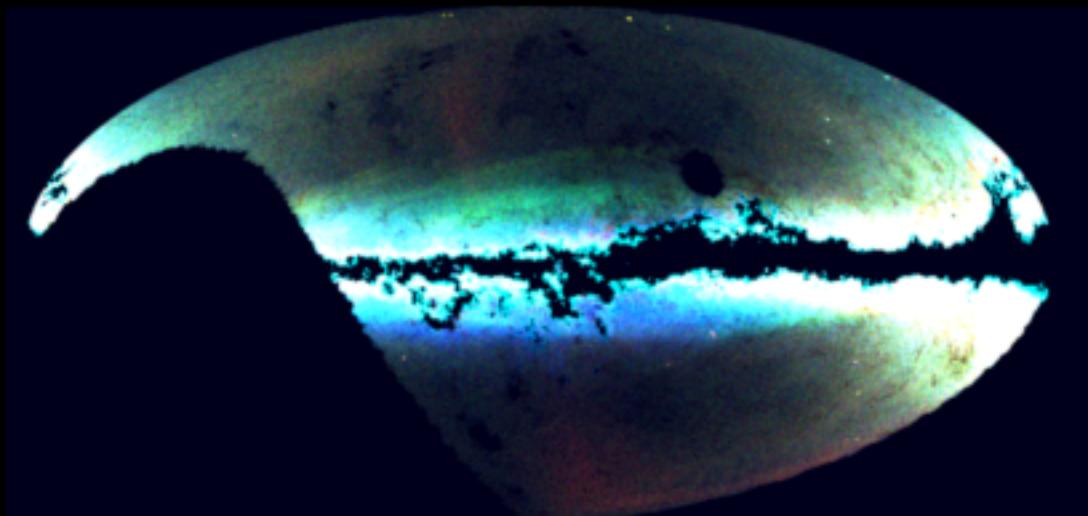


A programme for the landscape of ongoing/upcoming missions



Proposed formation mechanisms for Monoceros Ring and outer disc structures

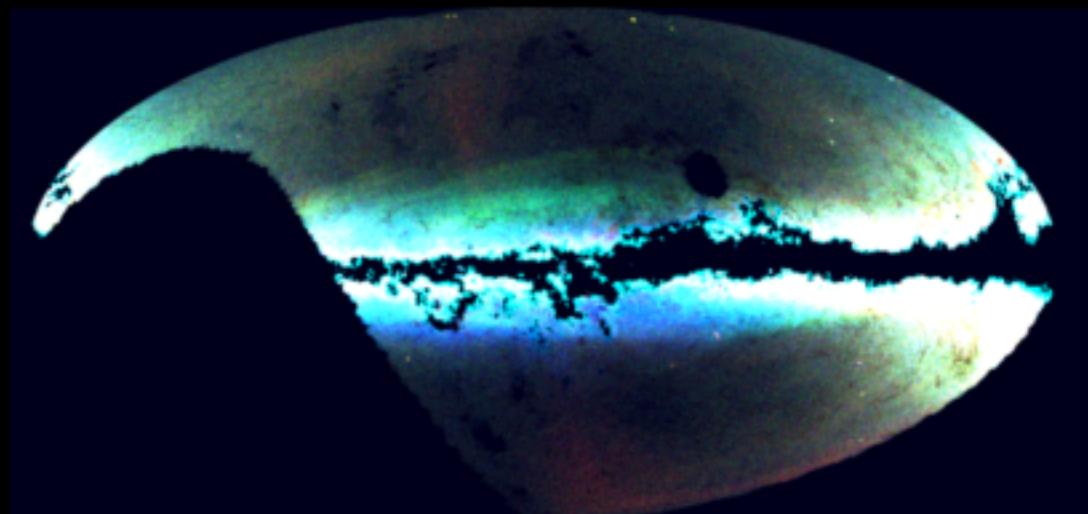
- Accretion of a satellite on planar orbit (Penarrubia et al. 05, Sheffield et al. 14)
- Tidal interactions with multiple ($6 \sim 10^{10} M_{\text{sun}}$ satellites) - Kazantzidis et al. 08
- Massive low-velocity fly-by - Gomez et al. 2016
- Collective effect from subhalo mass function



Proposed formation mechanisms for Monoceros Ring and outer disc structures

ruled out from stellar populations & chemical abundances

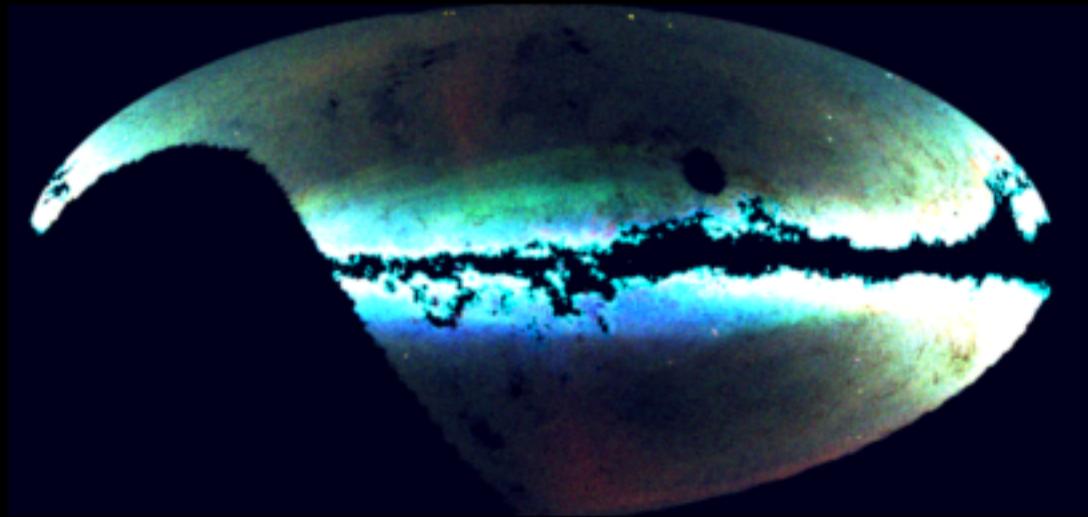
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ruled out from structure of stellar halo

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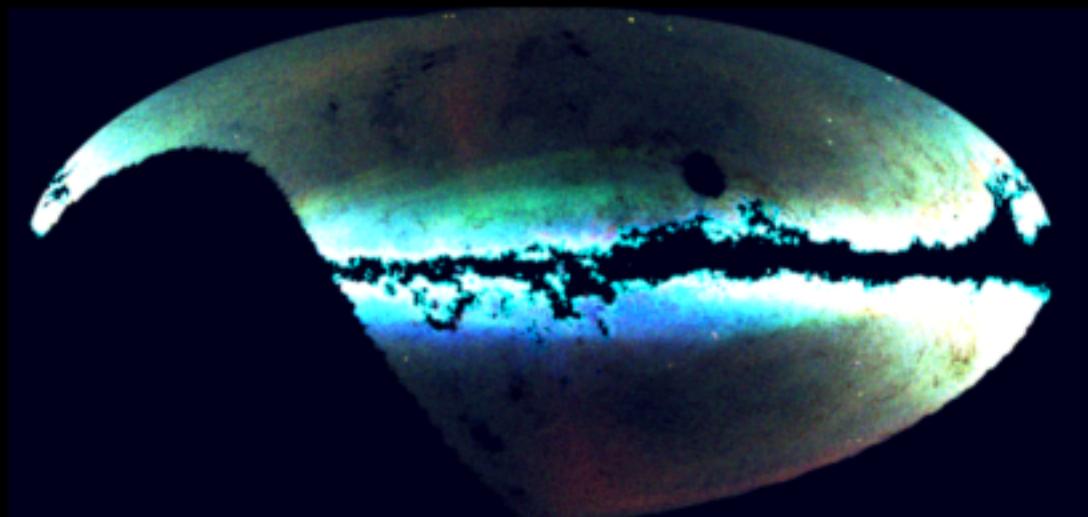
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- Collective effect from subhalo mass function

Gauthier08, Chequers18



interesting possibility, does well for $m=1$ distortion

ruled out from structure of stellar halo

ICs used inconsistent with LCDM $f_{\text{sub}}(x,v)$

very few subhalos get close to the disc

low mass objects -> no dyn friction -> no halo response

The Milky Way as a Rosetta stone for **galaxy formation** and **dark matter**

