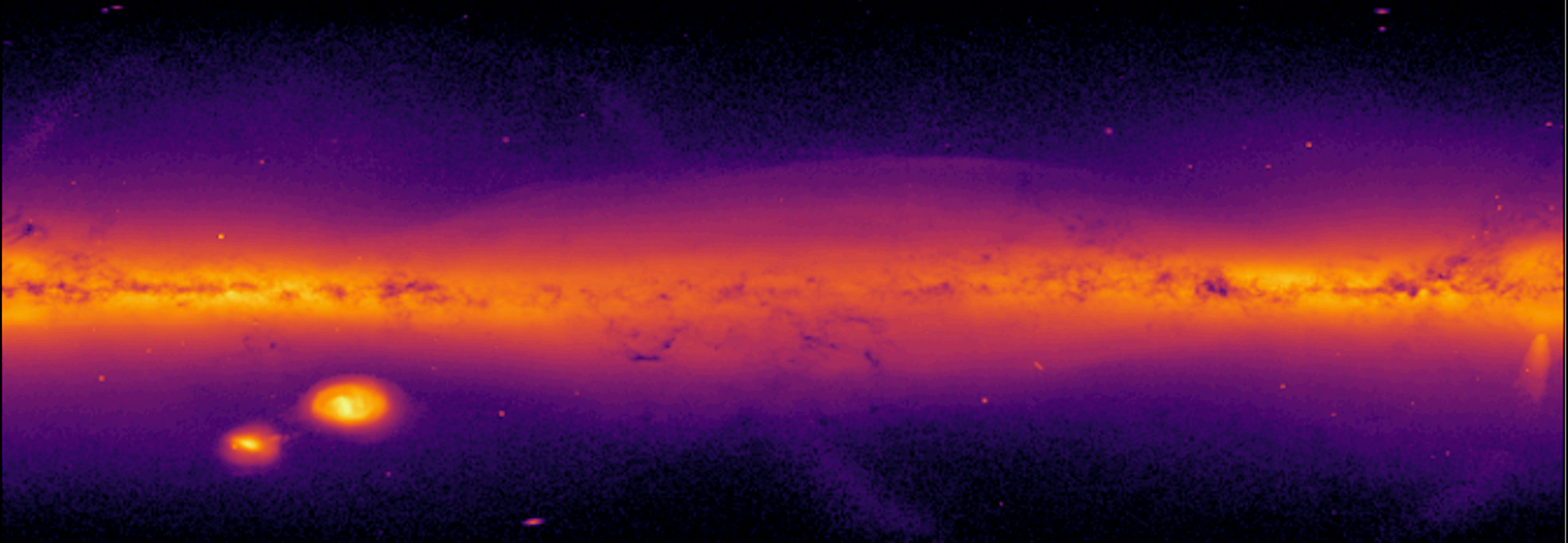
Kavli IPMU - APEC Seminar 3rd June 2021

Using the perturbed Milky Way as a time machine and dark matter detector



Chervin Laporte

(IPMU -> Institute of Cosmos Sciences University of Barcelona)

XSEDE Extreme Science and Engineering Discovery Environment

erc European Research Council Established by the European Commission

Life when things were good (2 months in 2020):

Quarantine life (March 2020 - now)

March

May

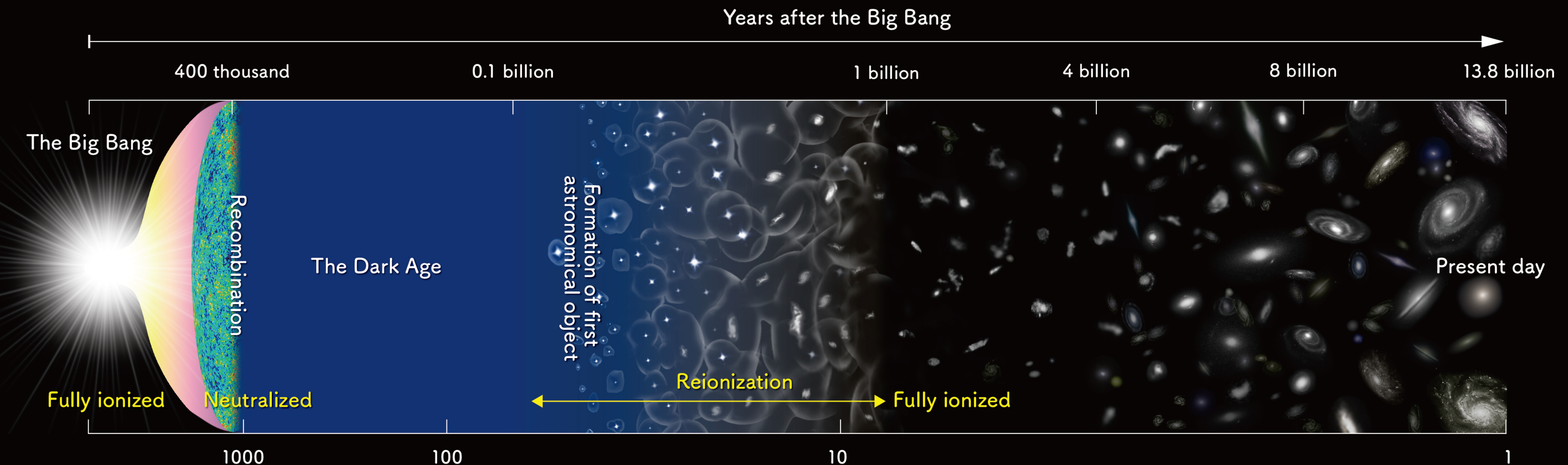
June

November

Fundamental questions in Galaxy Formation/Galactic Archaeology:

- How did the Milky Way (an L* galaxy) form?
- What can galaxies (e.g. Milky Way) teach us about what dark matter could be or is not?

Dark matter seeding galaxy formation

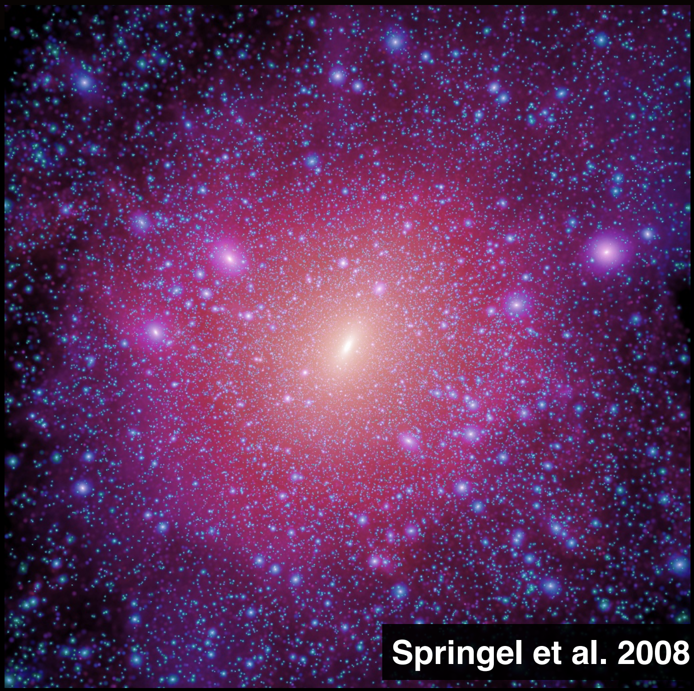


Credit: NAOJ

Computers simulations of structure formation predict:

1. **Density** profile for dark matter (NFW 1996)
2. **Shape** (triaxial)
3. **Abundance of DM substructure** (hierarchy) dependent on the particle nature of DM: over 20 orders of magnitude in mass (down to Earth mass for GeV DM candidate)
4. **Phase-space structure** -> indirect/direct detection

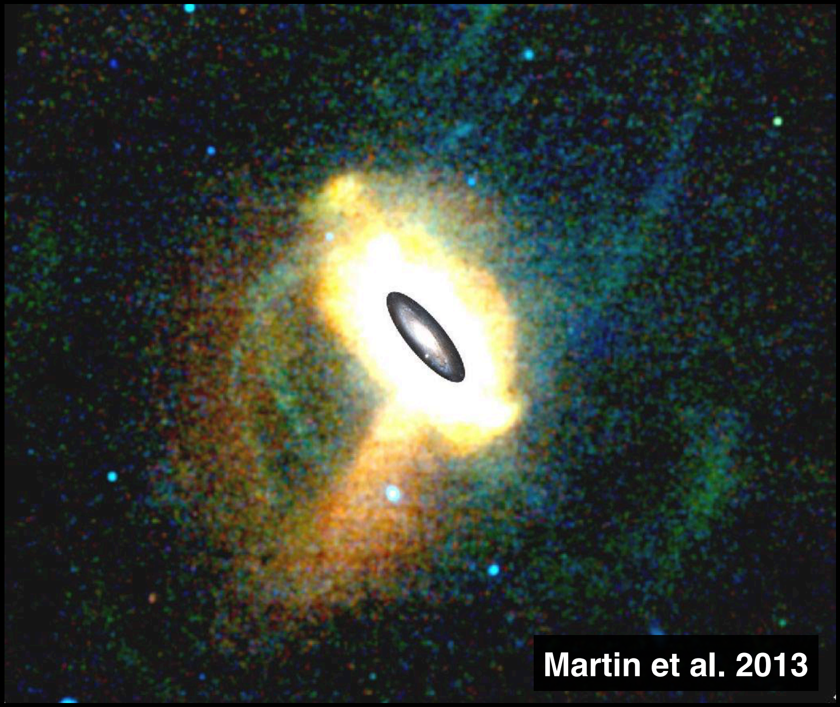
On Galactic scales, these are **prone to modifications due to baryonic physics**



Springel et al. 2008

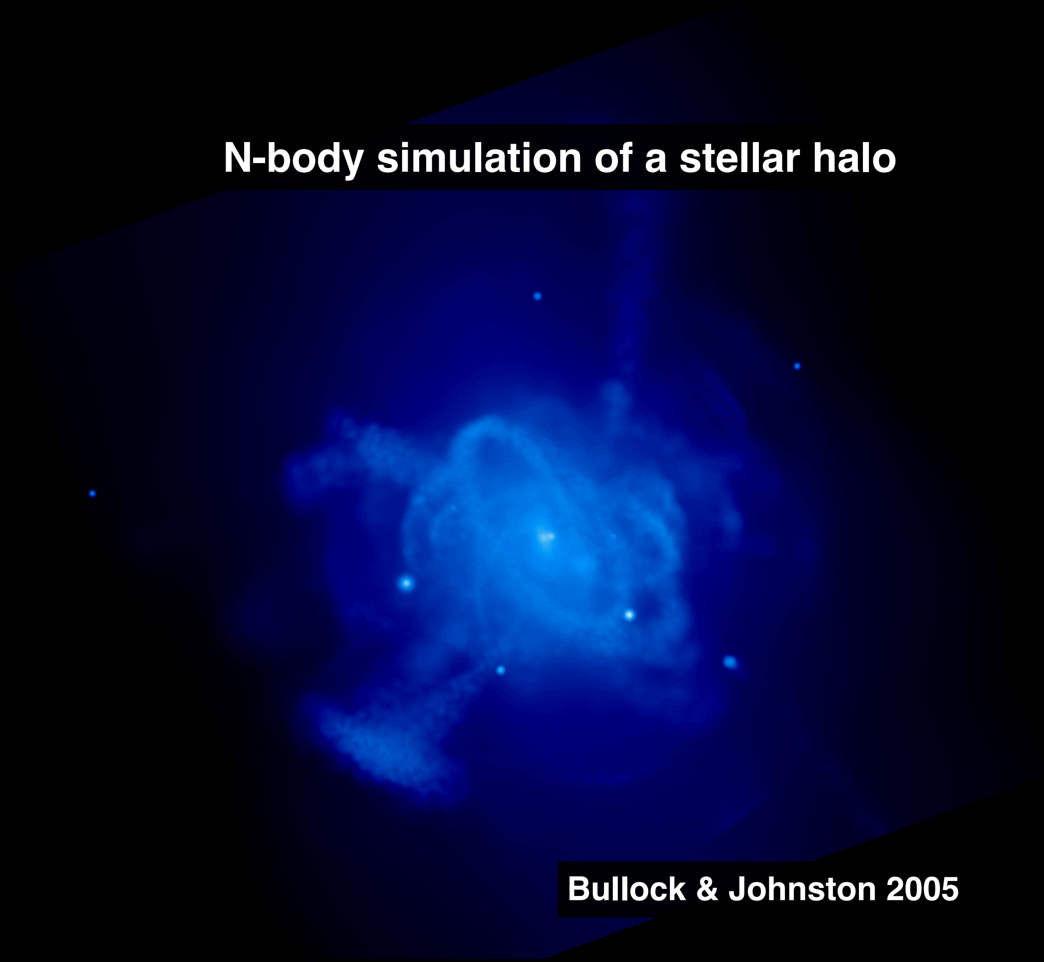
Stellar halos as a testament for the hierarchical growth of galaxies

Andromeda Galaxy PandAS survey



Surface Brigthness map through star count colour-coded by metallicity

N-body simulation of a stellar halo



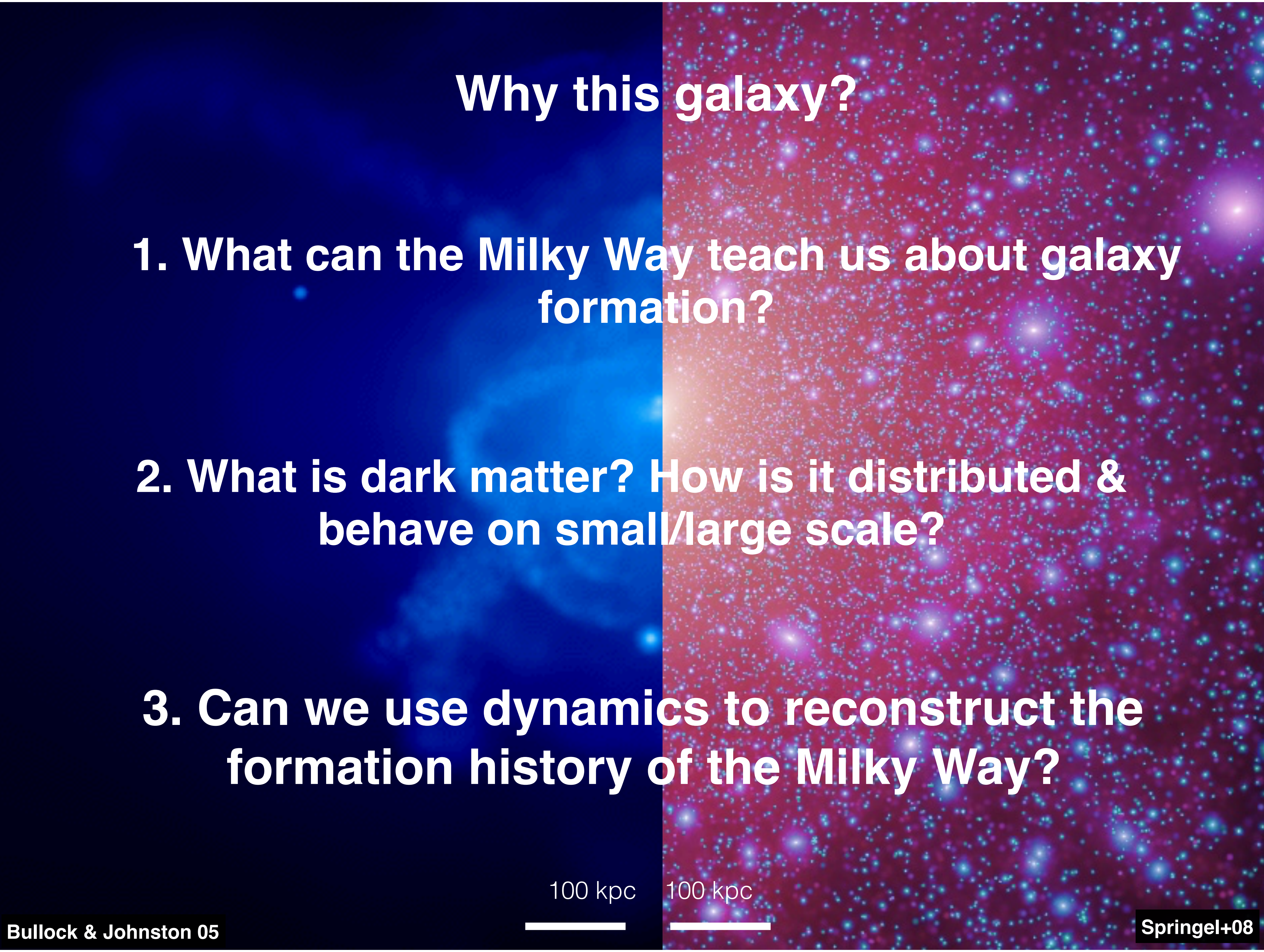
Simulated surface brightness map

Why this galaxy?

1. What can the Milky Way teach us about galaxy formation?

2. What is dark matter? How is it distributed & behave on small/large scale?

3. Can we use dynamics to reconstruct the formation history of the Milky Way?



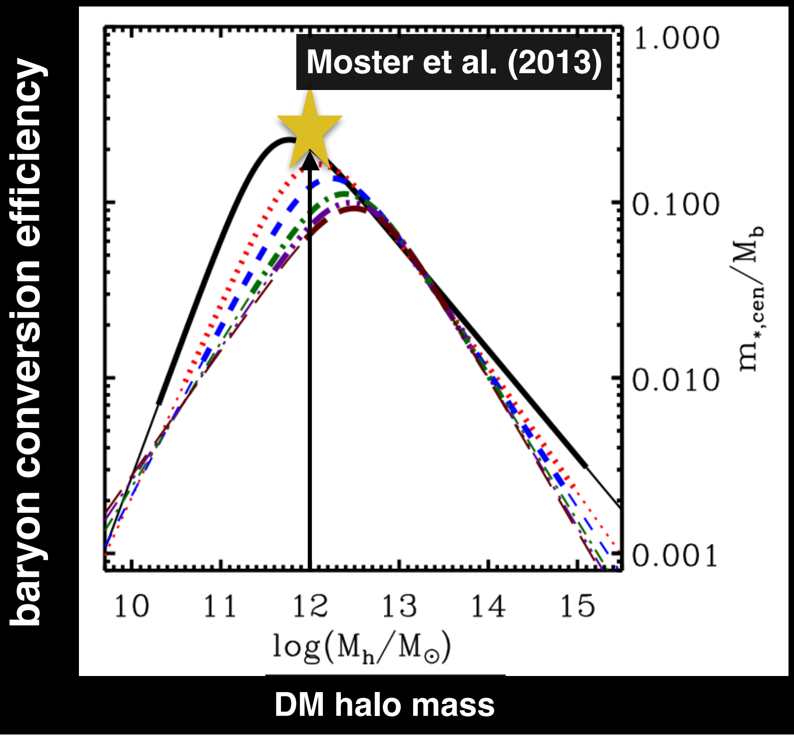
Bullock & Johnston 05

Springel+08

1. What can the Milky Way teach us about galaxy formation in a cosmological context?

Ancient shredded and surviving dwarfs in MW: **a resolved window into re-ionization** in our cosmic backyard

Test bed for galaxy formation at the **smallest mass scales** but also for a **L* galaxy**.

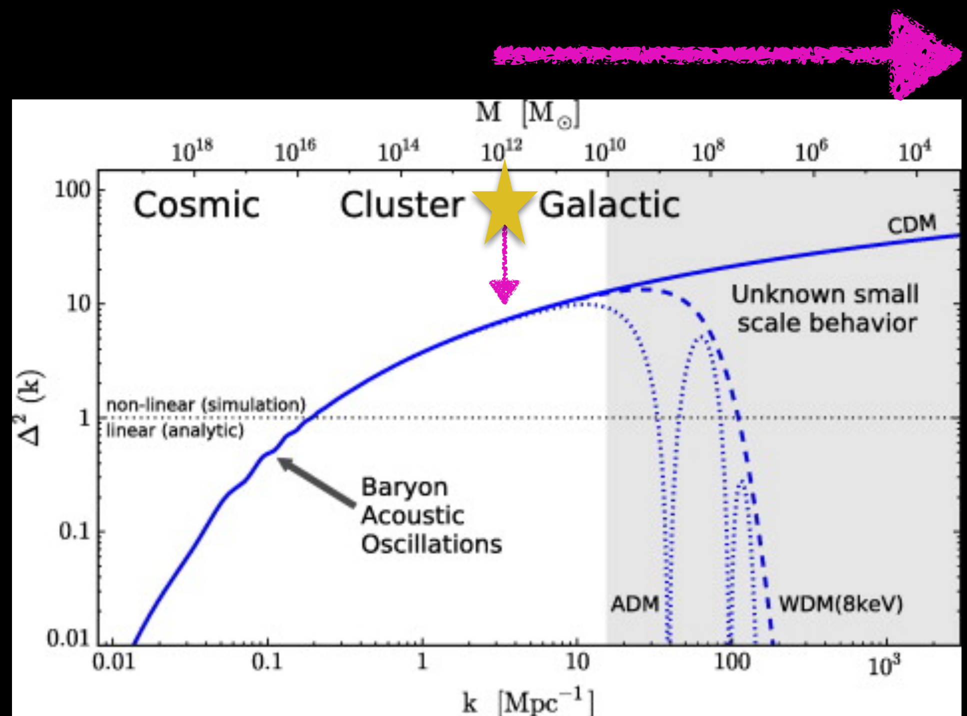


2. What/Where is dark matter? Astrophysics / Particle physics link

DM clustering on smallest scales

regime most sensitivite to particle nature of DM

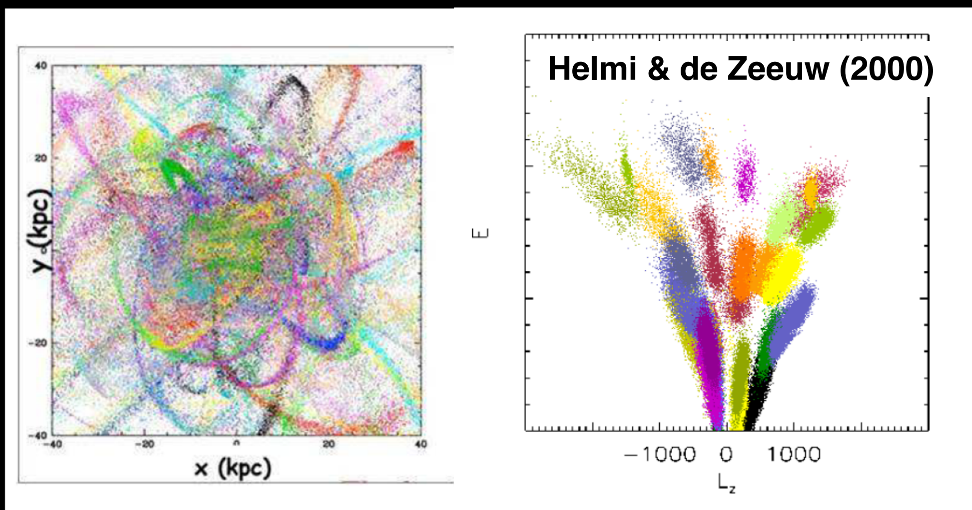
how does it "behave" on large scales (~100 kpc)?



Linear matter power spectrum at z=0

Dark matter will be detected on **Earth**

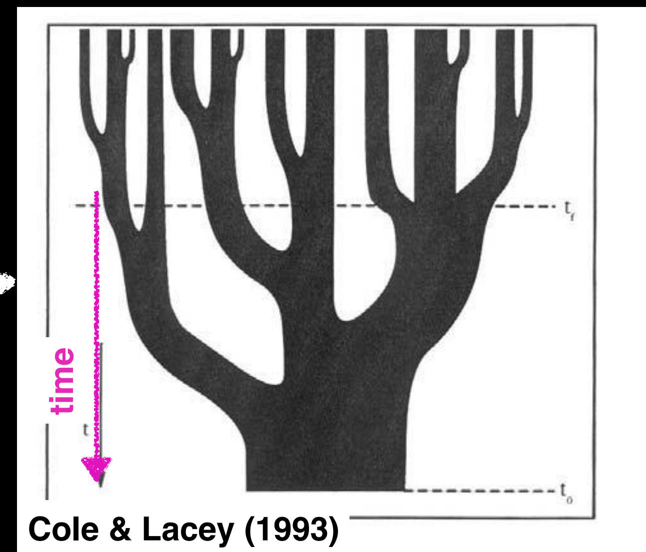
3. Can we use dynamics to reconstruct the formation history of the Milky Way?



physical space

integral of motion -
Energy-Angular momentum

?



merger tree

How did the Galaxy grow and evolve?

What were the important events in the lifetime of the Galaxy?

Quantify imprints of internal vs externally driven processes?

Seriously, what does the Milky Way even look like?

90s: Milky Way has a **bar** (COBE DIRBE)

late 90s: **Sagittarius** dwarf galaxy (3rd most luminous MW companion)

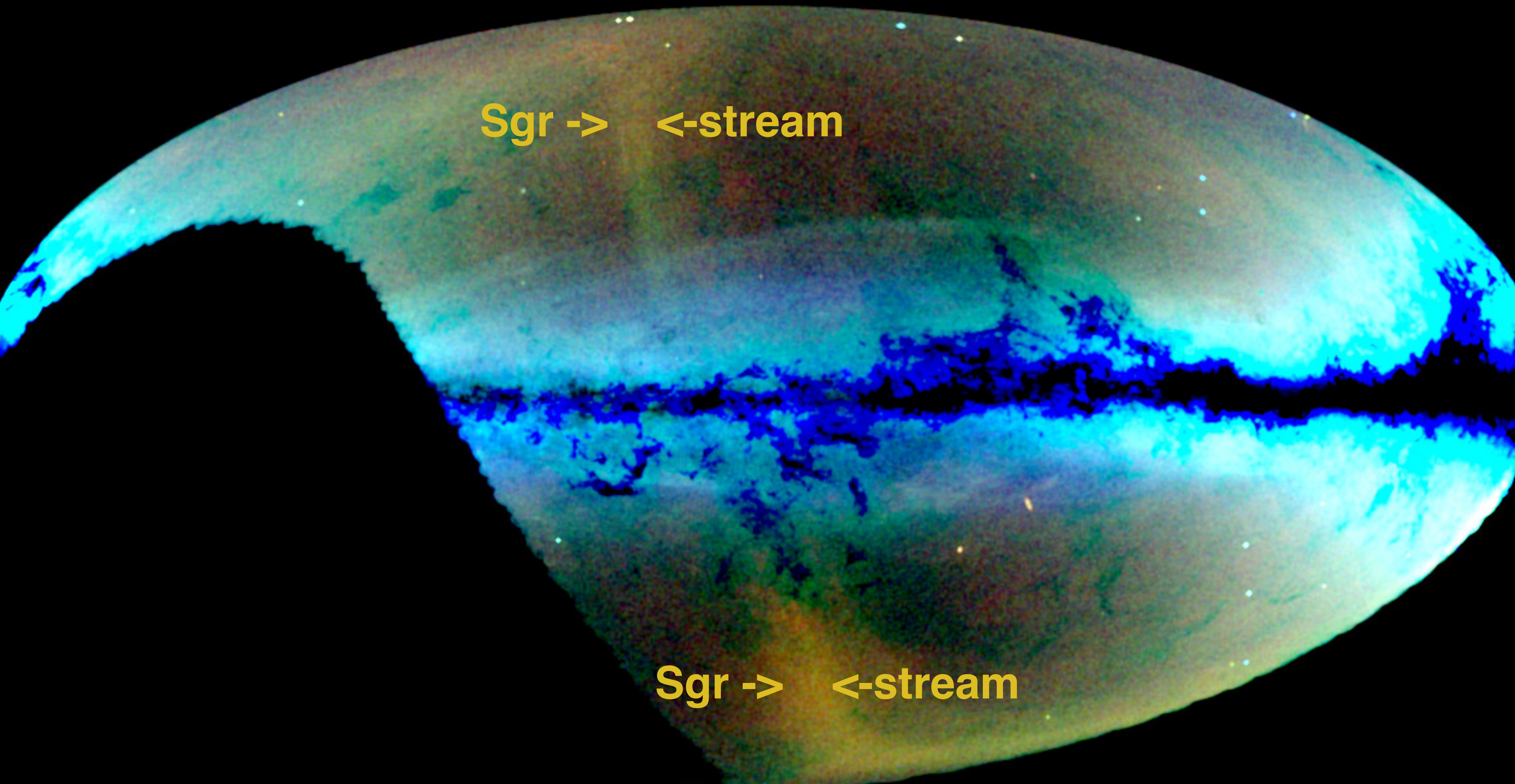
2000s: 2MASS, SDSS - **dwarf streams, GC streams, faint satellites, streams with no progenitors**

2010s: deeper surveys (DES, HSC): **MORE of the above + FAINTER!**

2018 & 2020s: **Gaia**, **age of large spectroscopic surveys & Vera Rubin Obs**

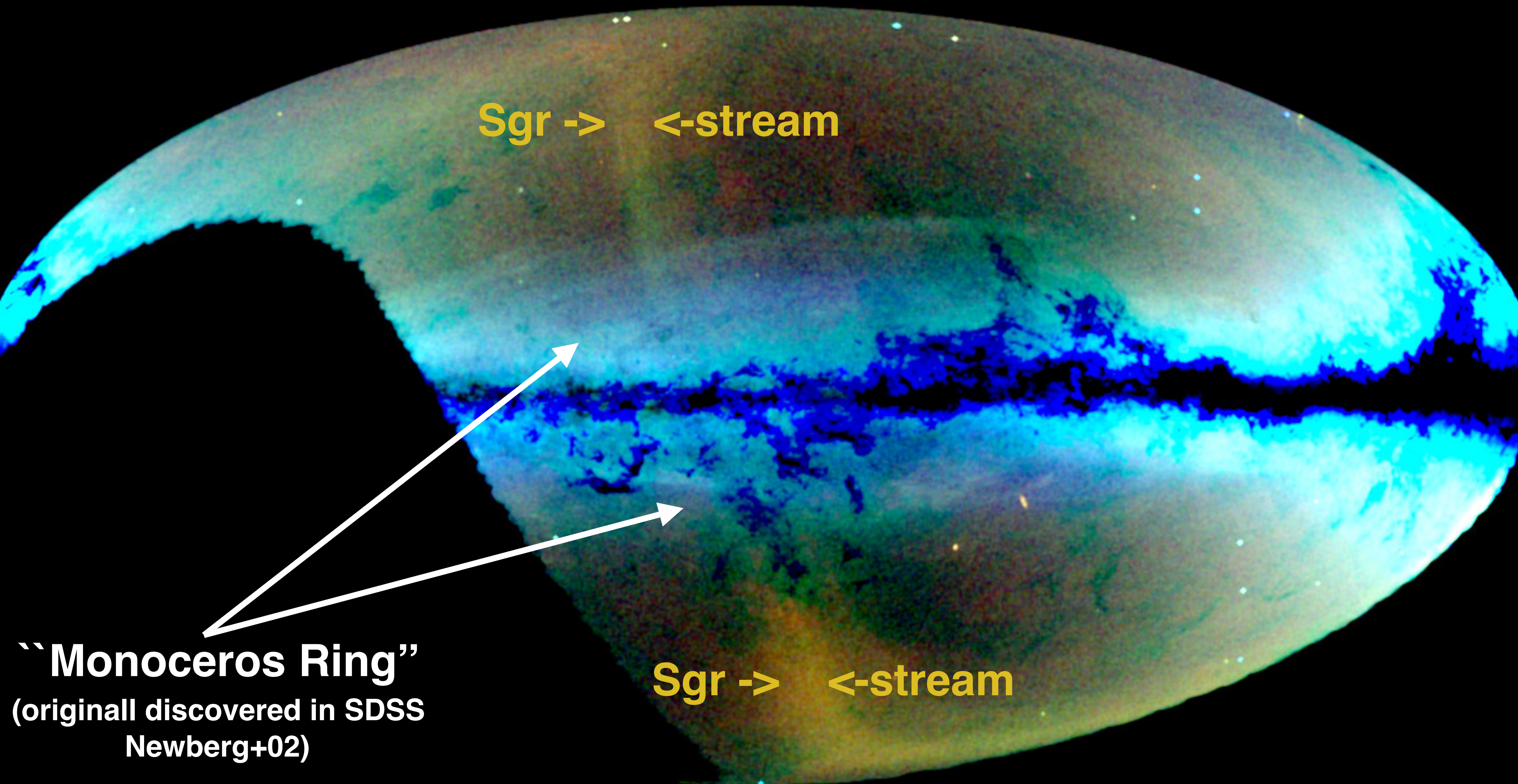
2030: Now that we know what the MW looks like, let's go ahead and age date every star in it!!!

The Anticenter viewed by Pan-STARRS in MSTOs



Bernard+16

The Anticenter viewed by Pan-STARRS in MSTOs



Bernard+16

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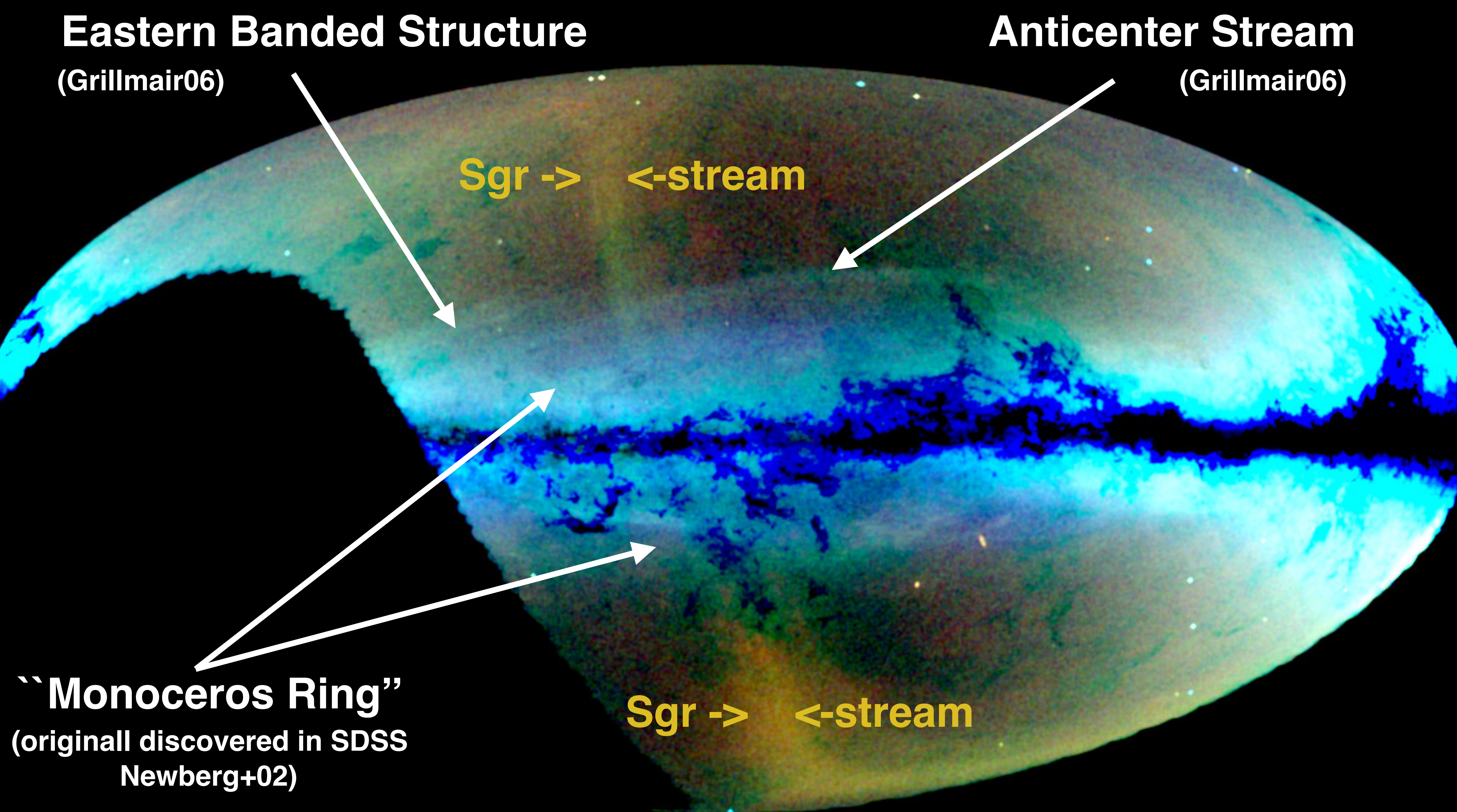


Structures @ d~10 kpc

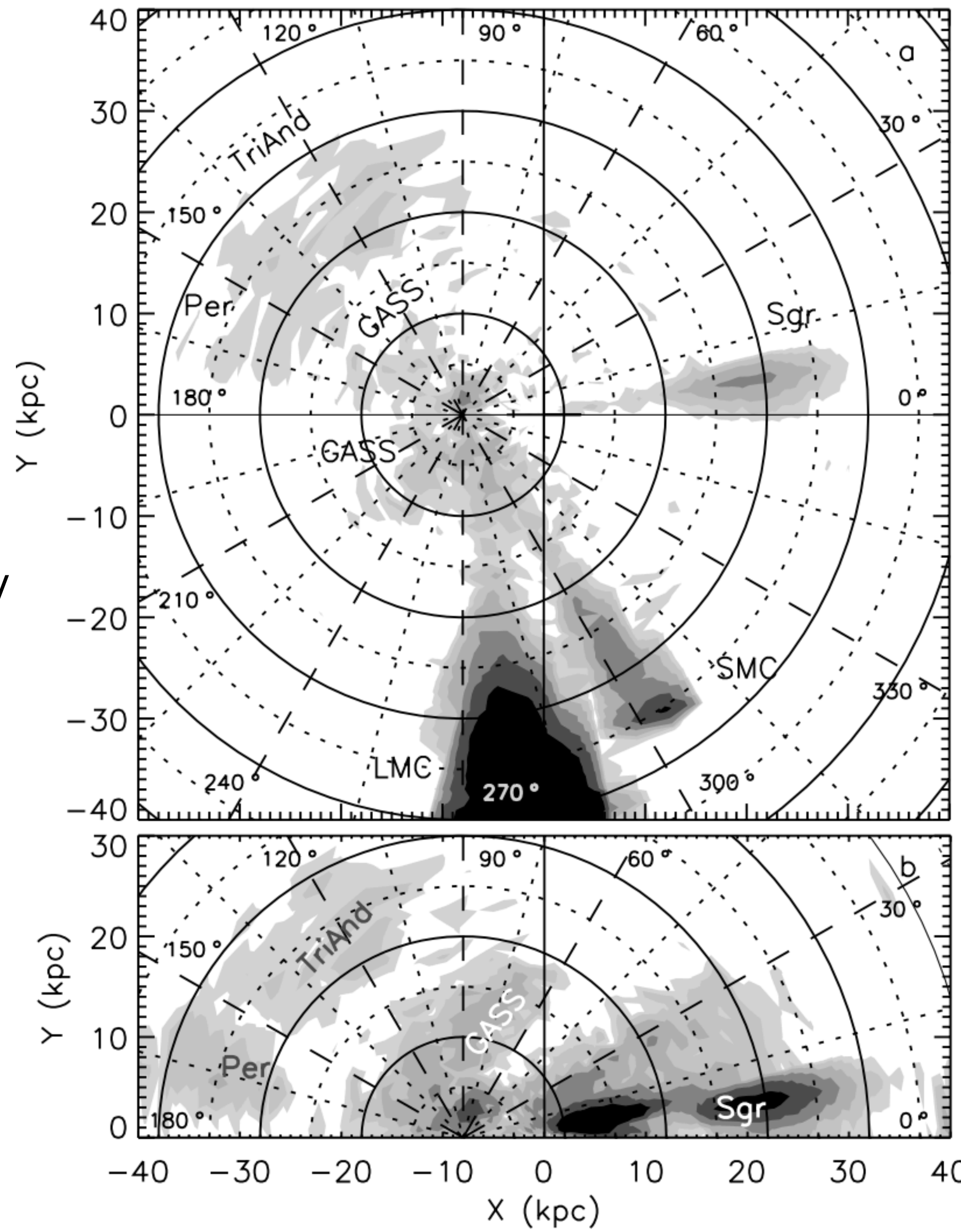
Bernard+16

Beyond the Monoceros Complex (d~10 kpc)

Beyond ~20 kpc:

- **Triangulum Andromeda** overdensity
- **Perseus** overdensity

Originally detected with 2MASS (Majewski+03, Rocha Pinto+04)



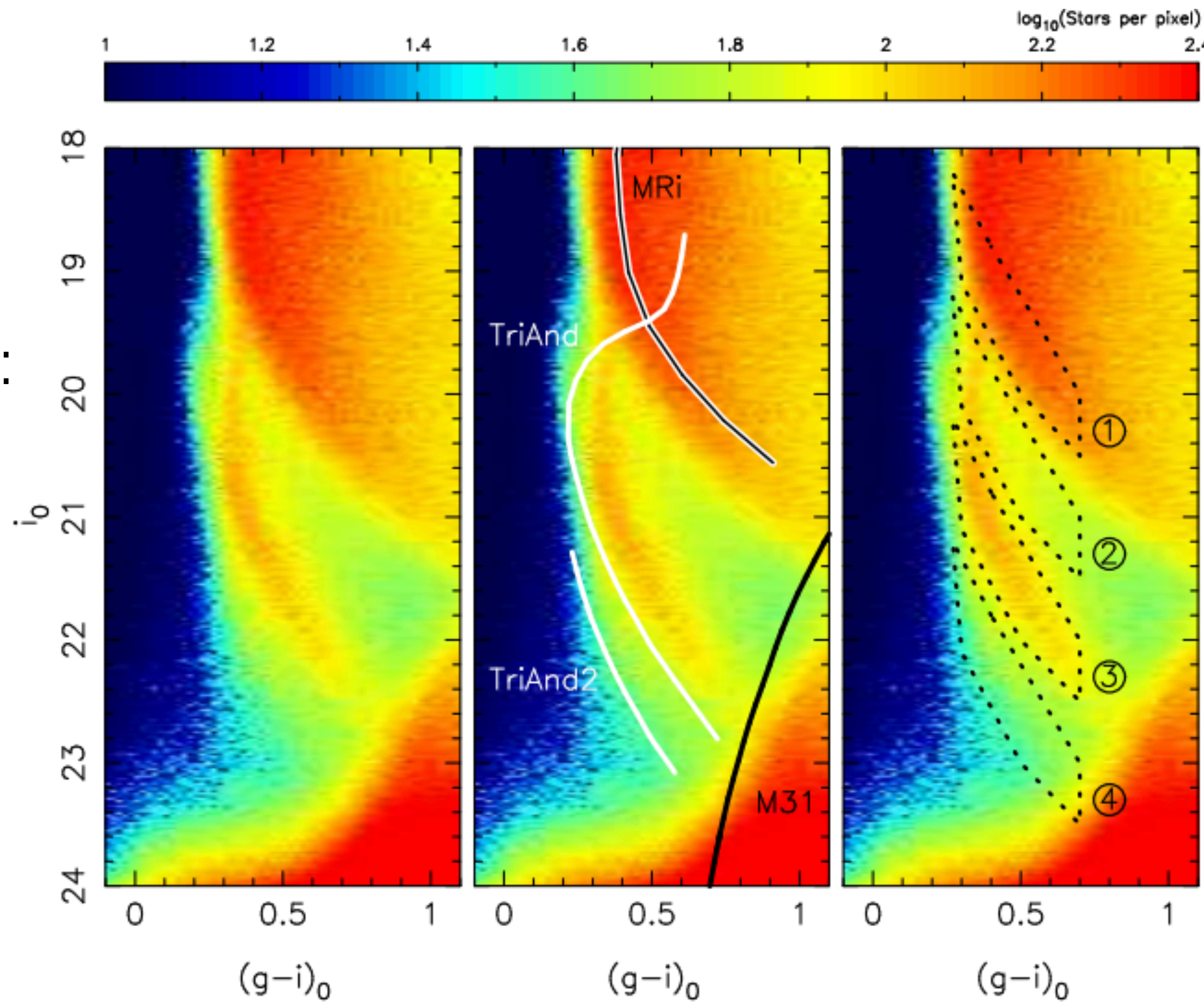
Rocha-Pinto+04

TriAnd / PAndAS field of Streams

Substructure within substructure

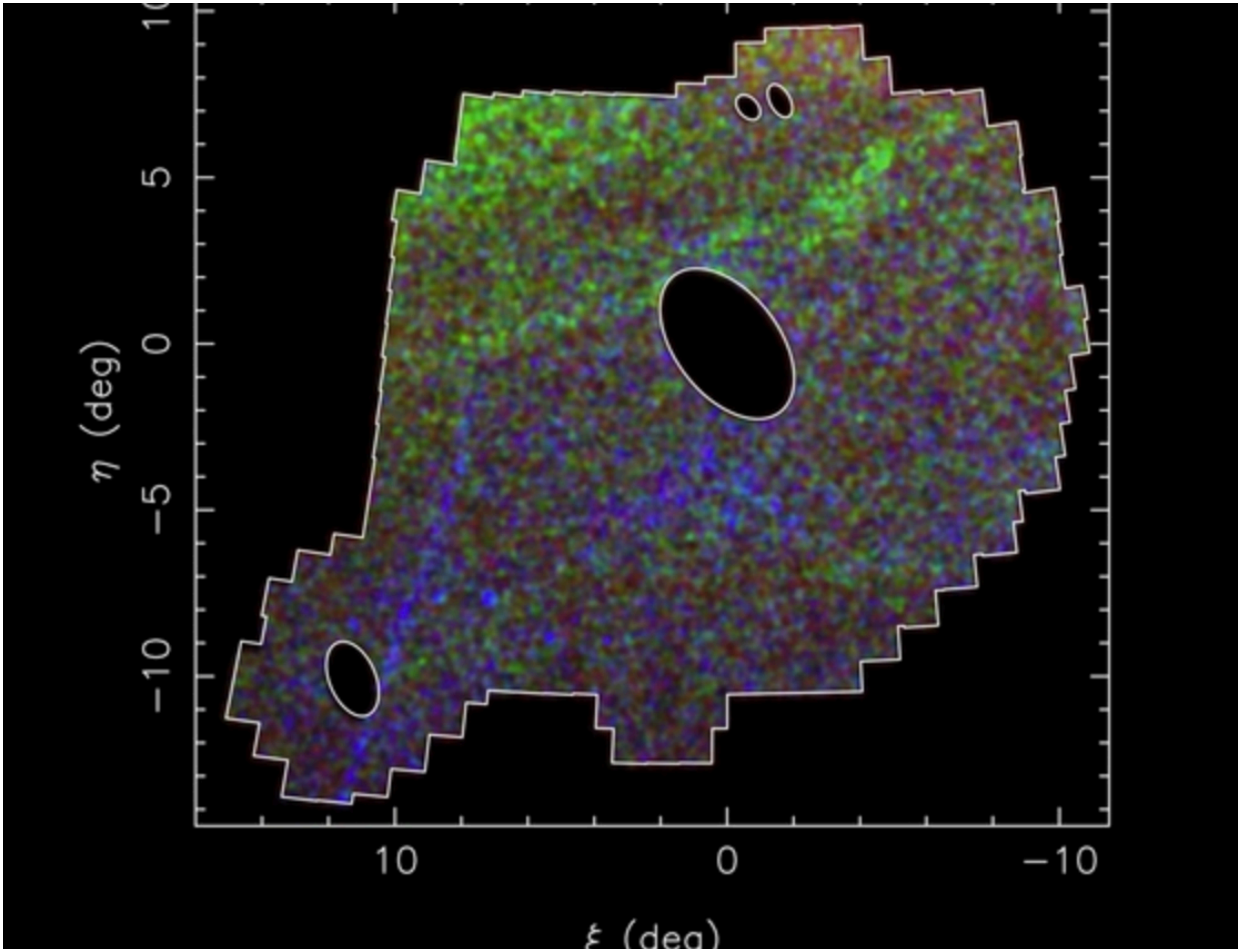
Same game as before:

exploration using MS/MSTO sequences



Martin+14

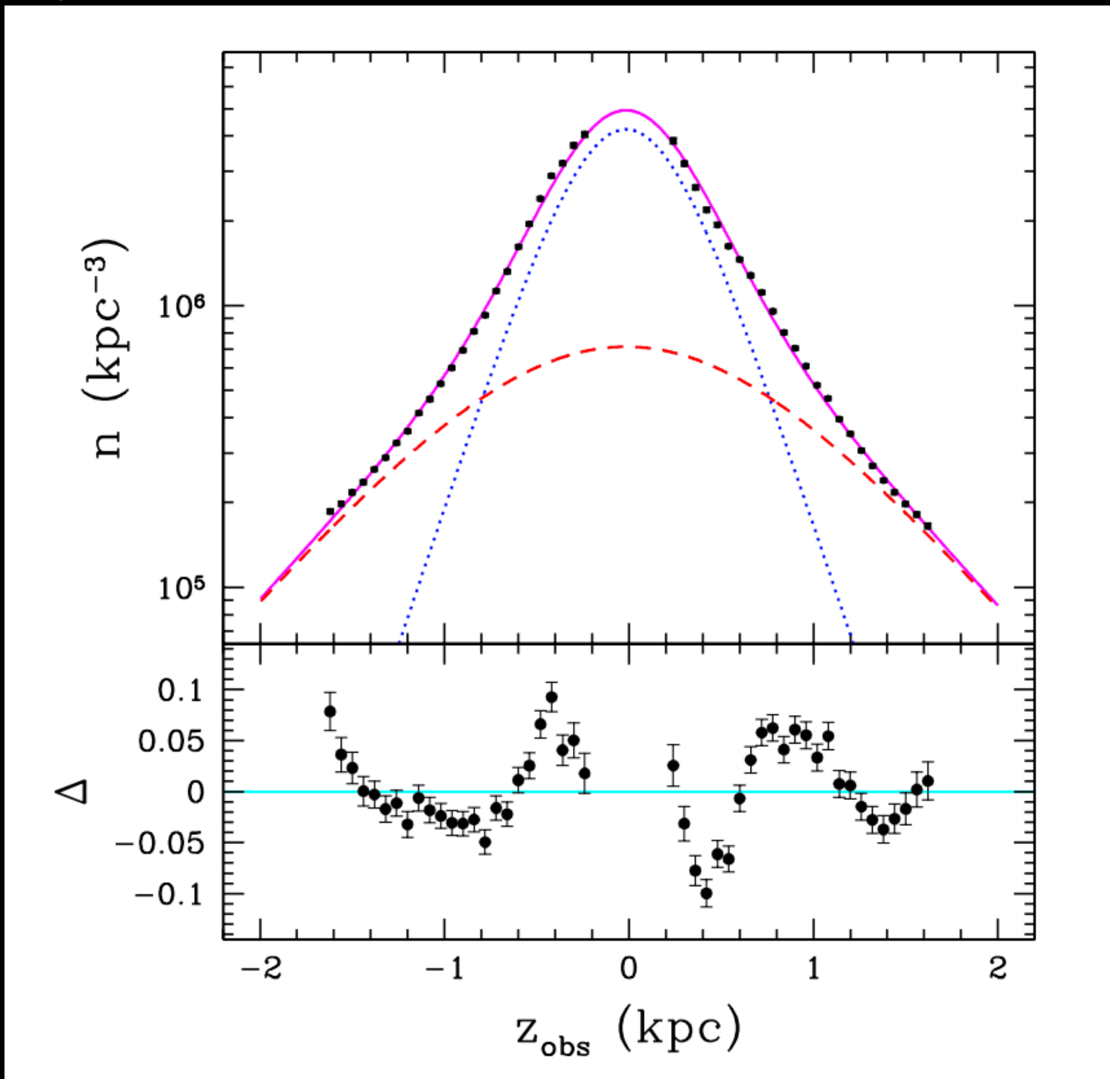
TriAnd / PAndAS field of Streams



Martin+14

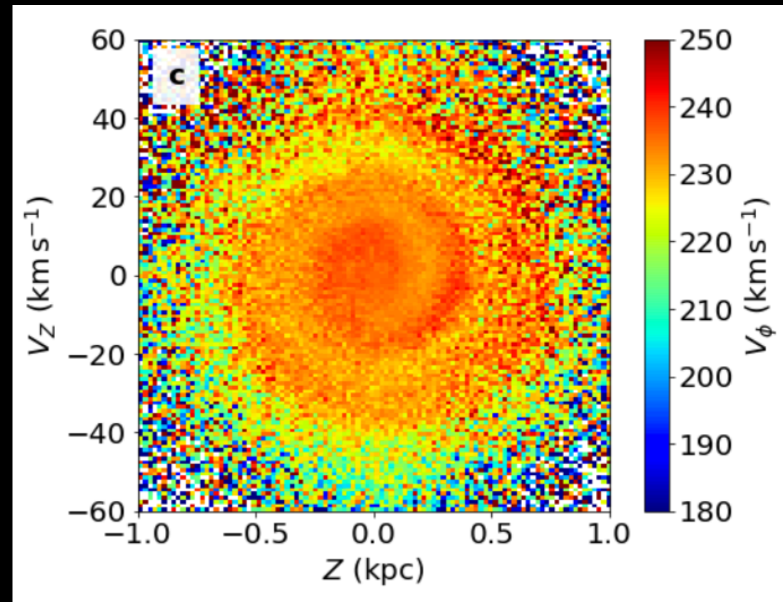
Local oscillations of the disc

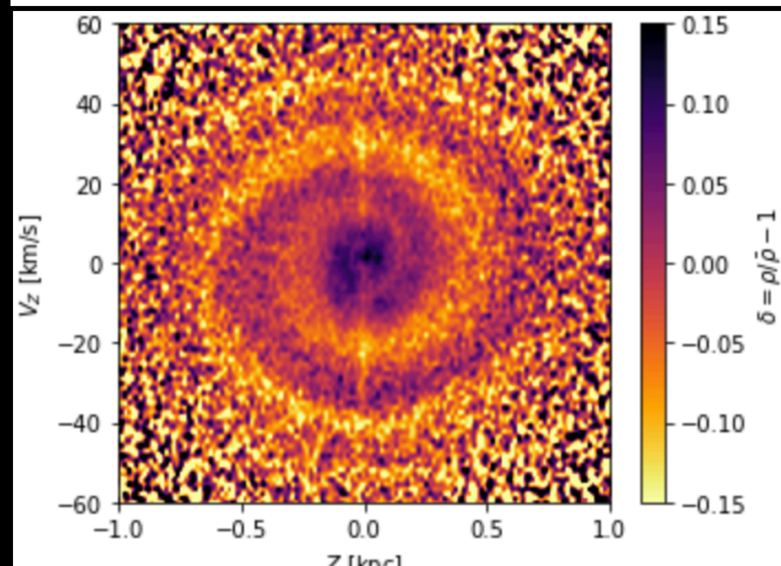
pre-Gaia



Widrow+12 (discovery)

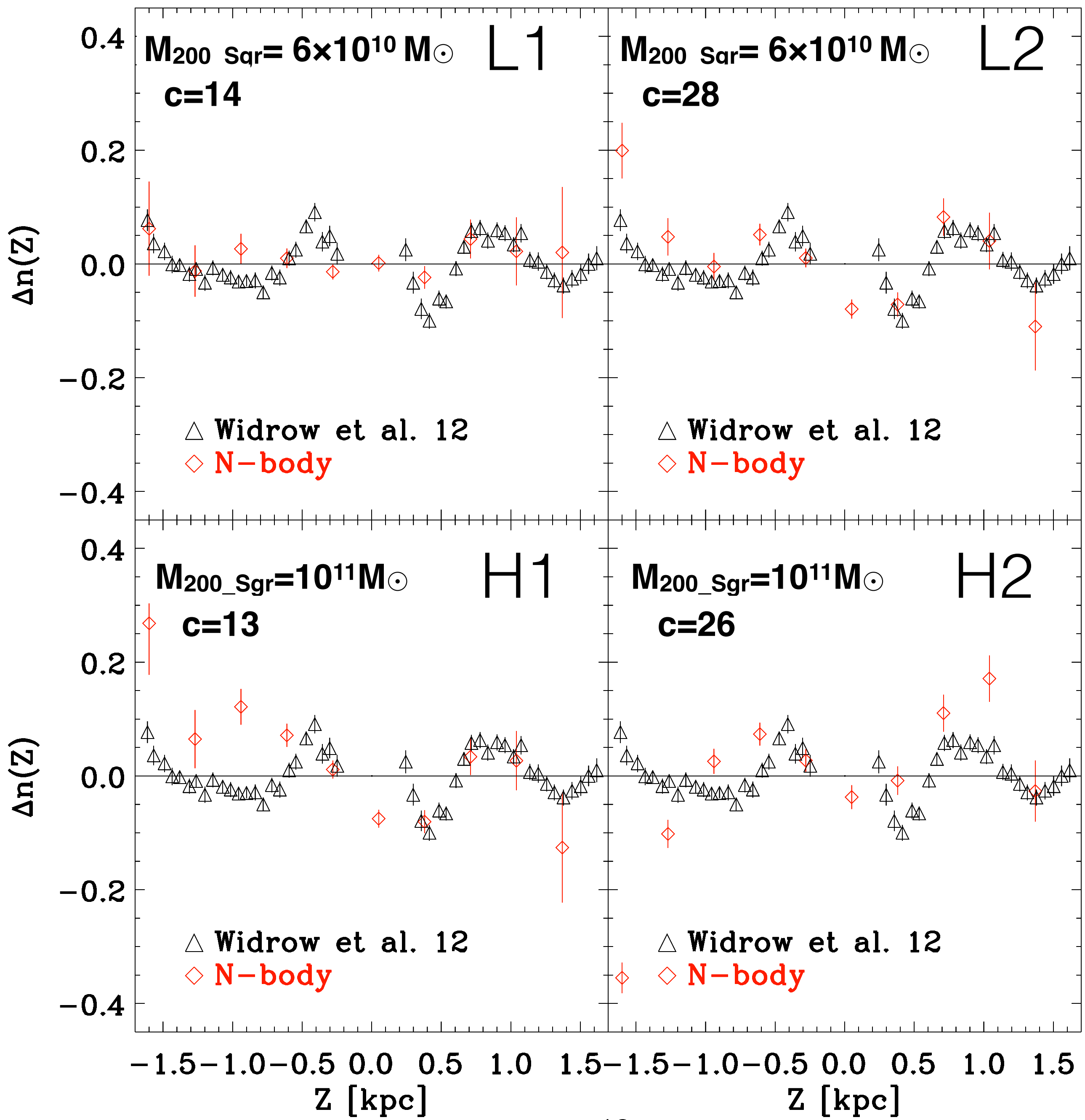
Antoja+18 (discovery) Gaia DR2





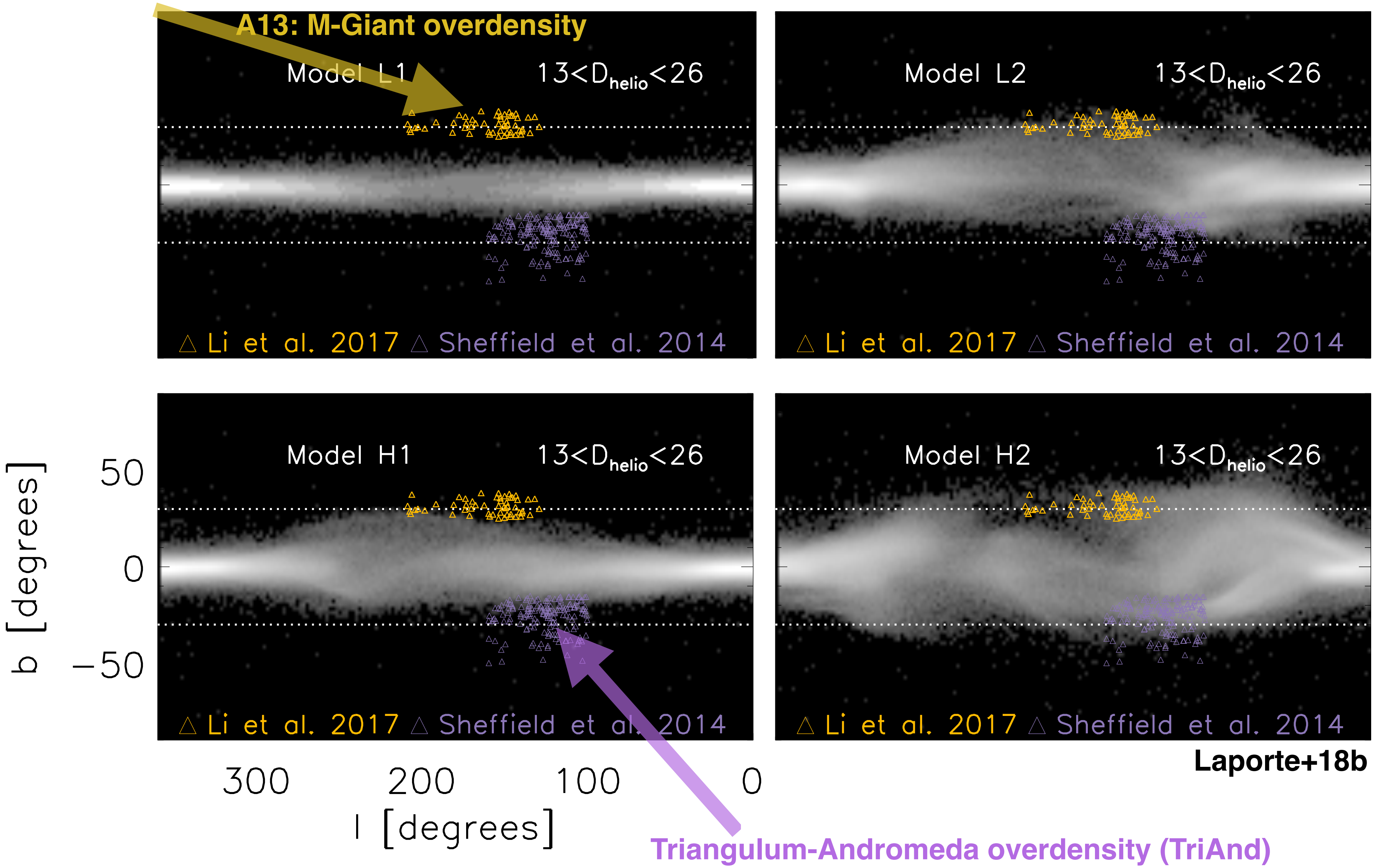
Laporte+19c

Sgr induces vertical oscillations in the Solar neighbourhood



Laporte+18b

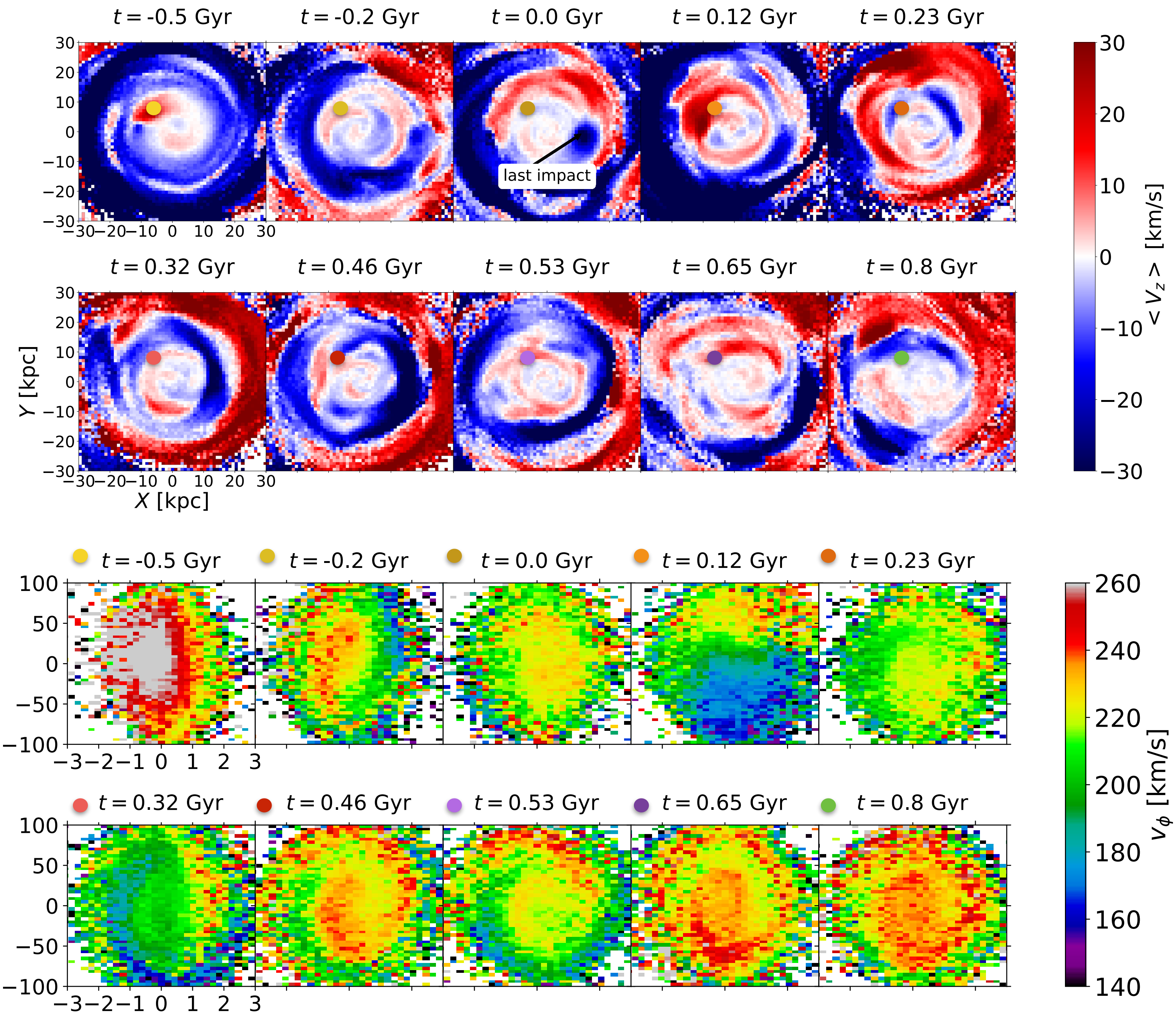
…and outer disc structures



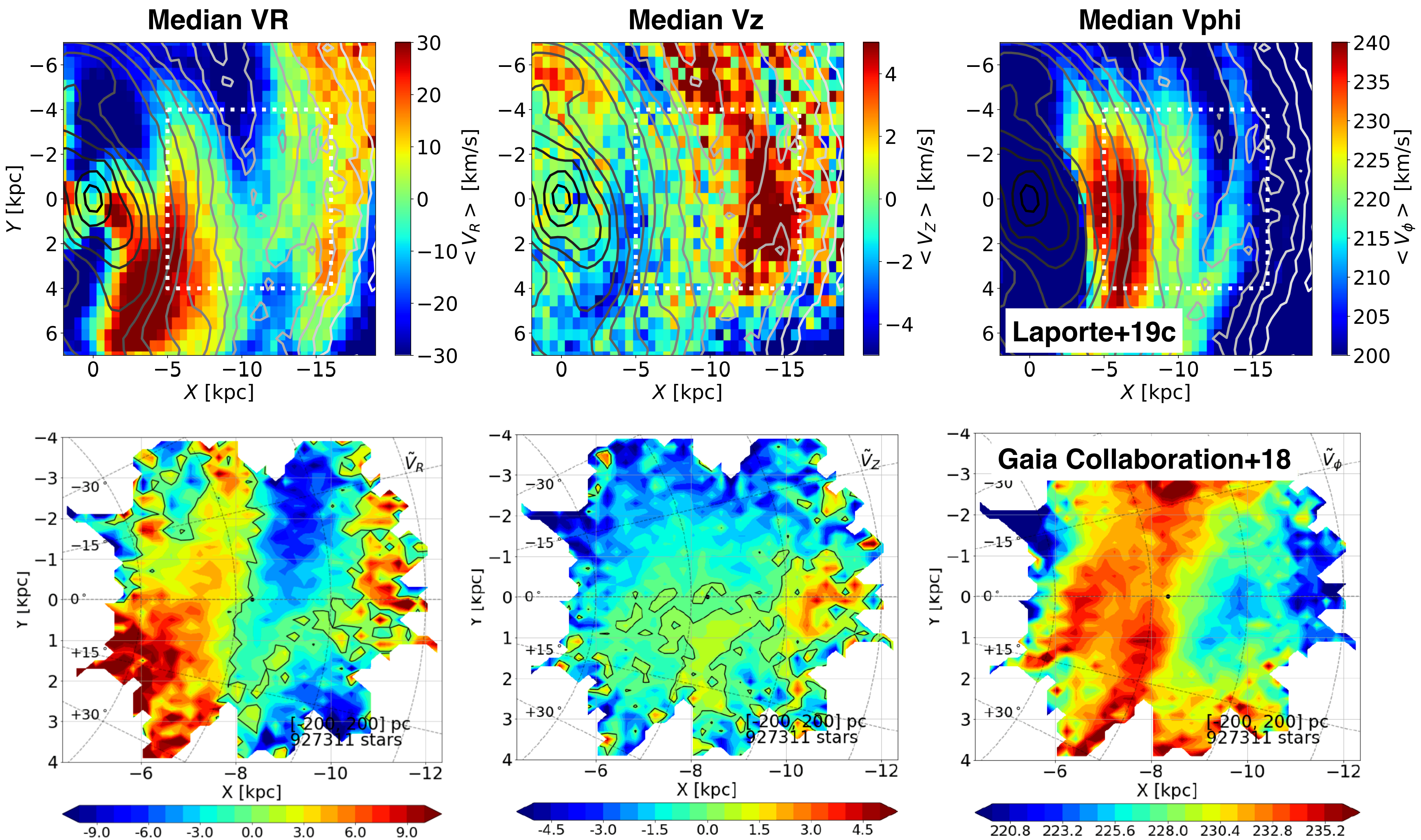
Phase-space spiral due to disc response during last stages of Sgr's orbit

Global

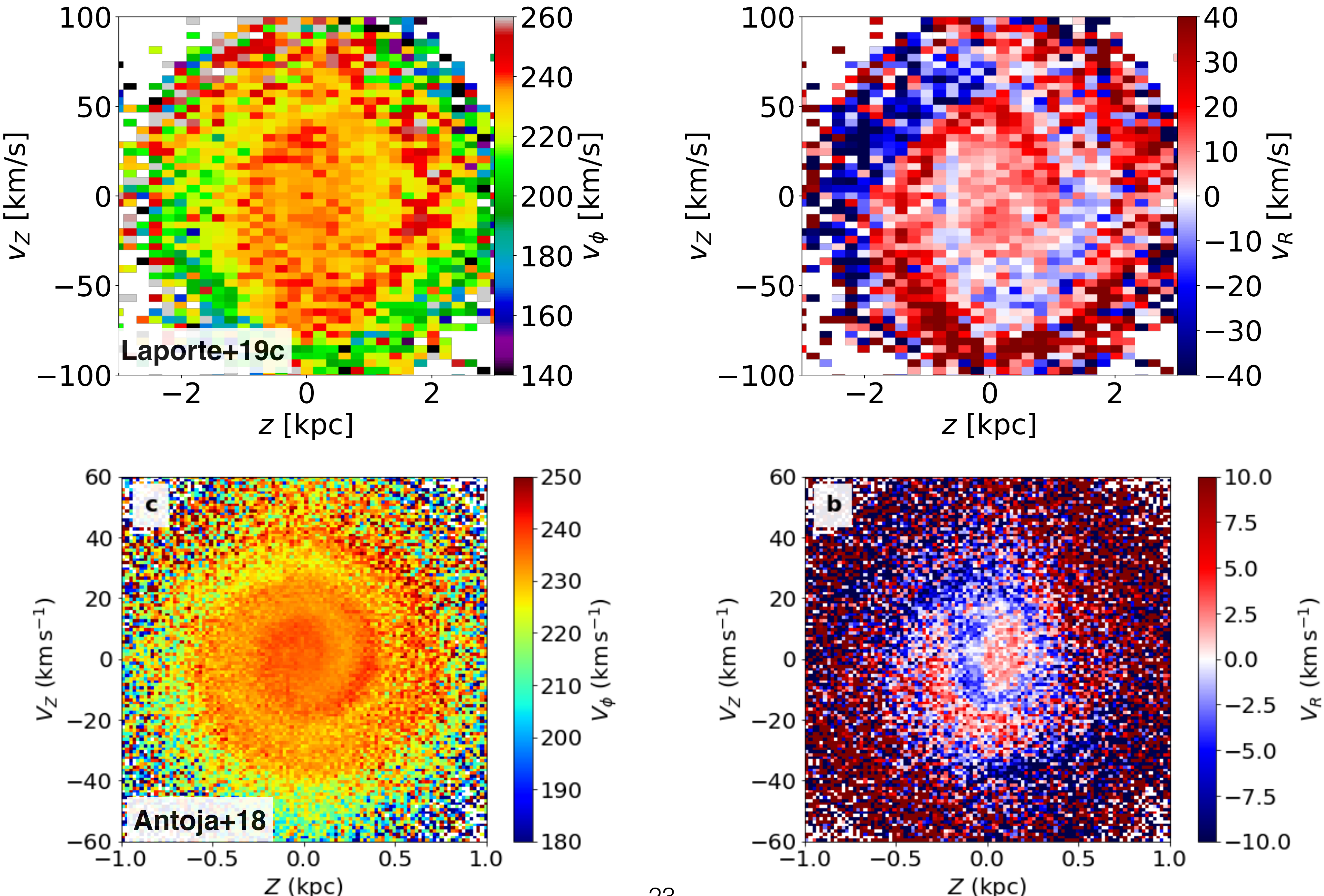
Solar Neighbourhood



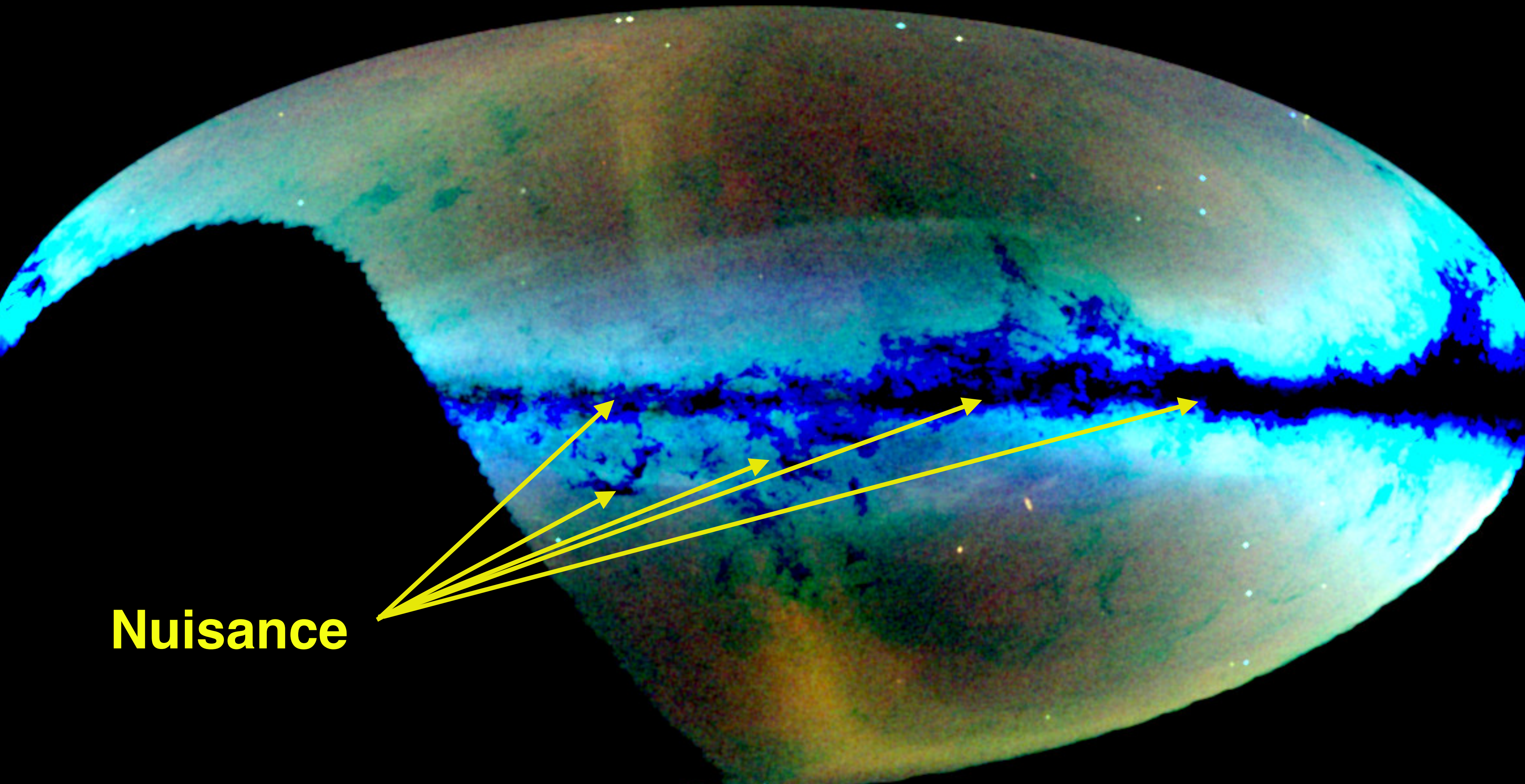
Simulated velocity fields



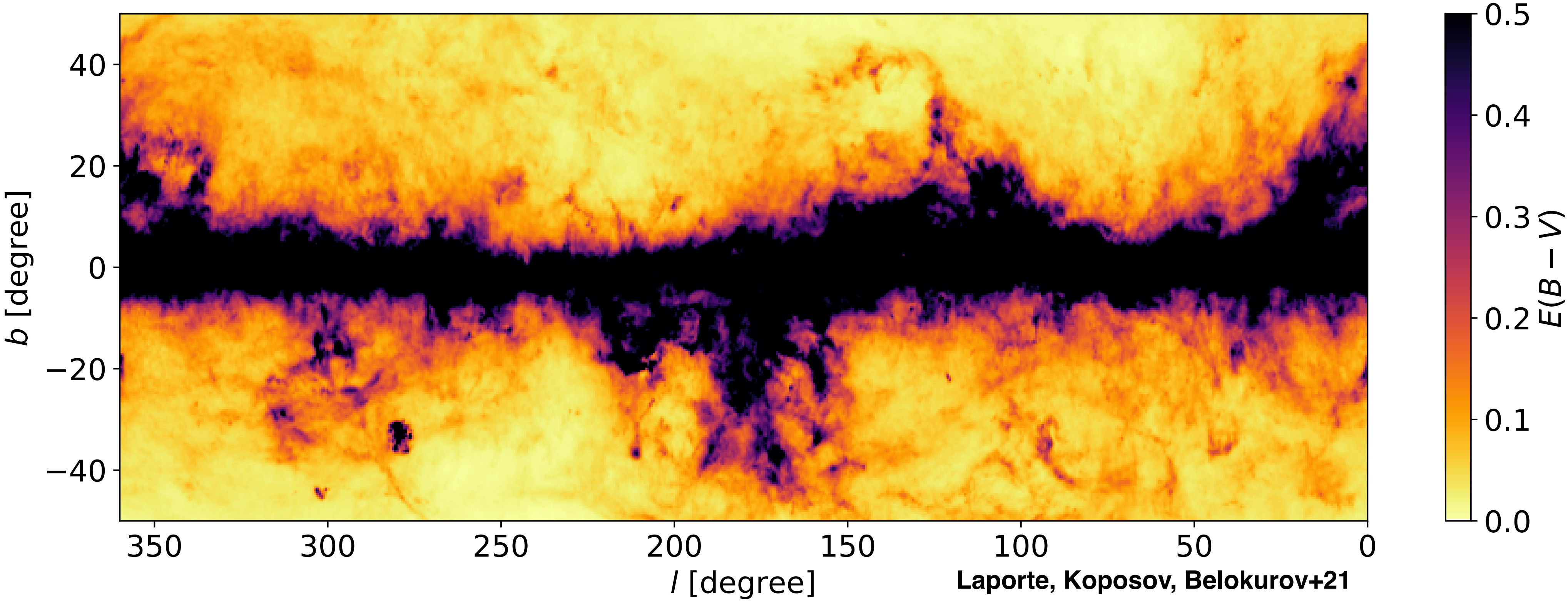
Local effect of Sgr in the Solar Neighbourhood



The Anticenter viewed by Pan-STARRS

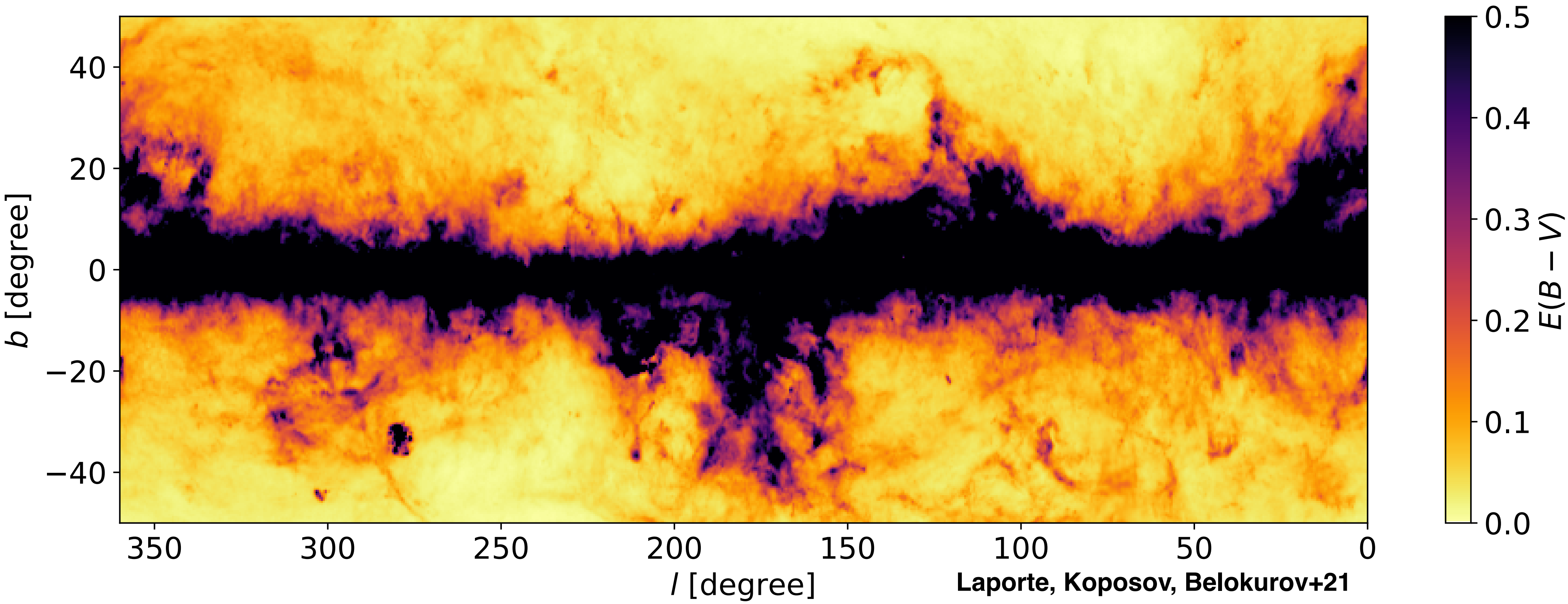


Schlegel et al. 1998 dust map in the midplane



Dust affects **luminosity** of your stars, **difficult for imaging**, total nuisance for exploring Galactic structure in the midplane

Schlegel et al. 1998 dust map in the midplane



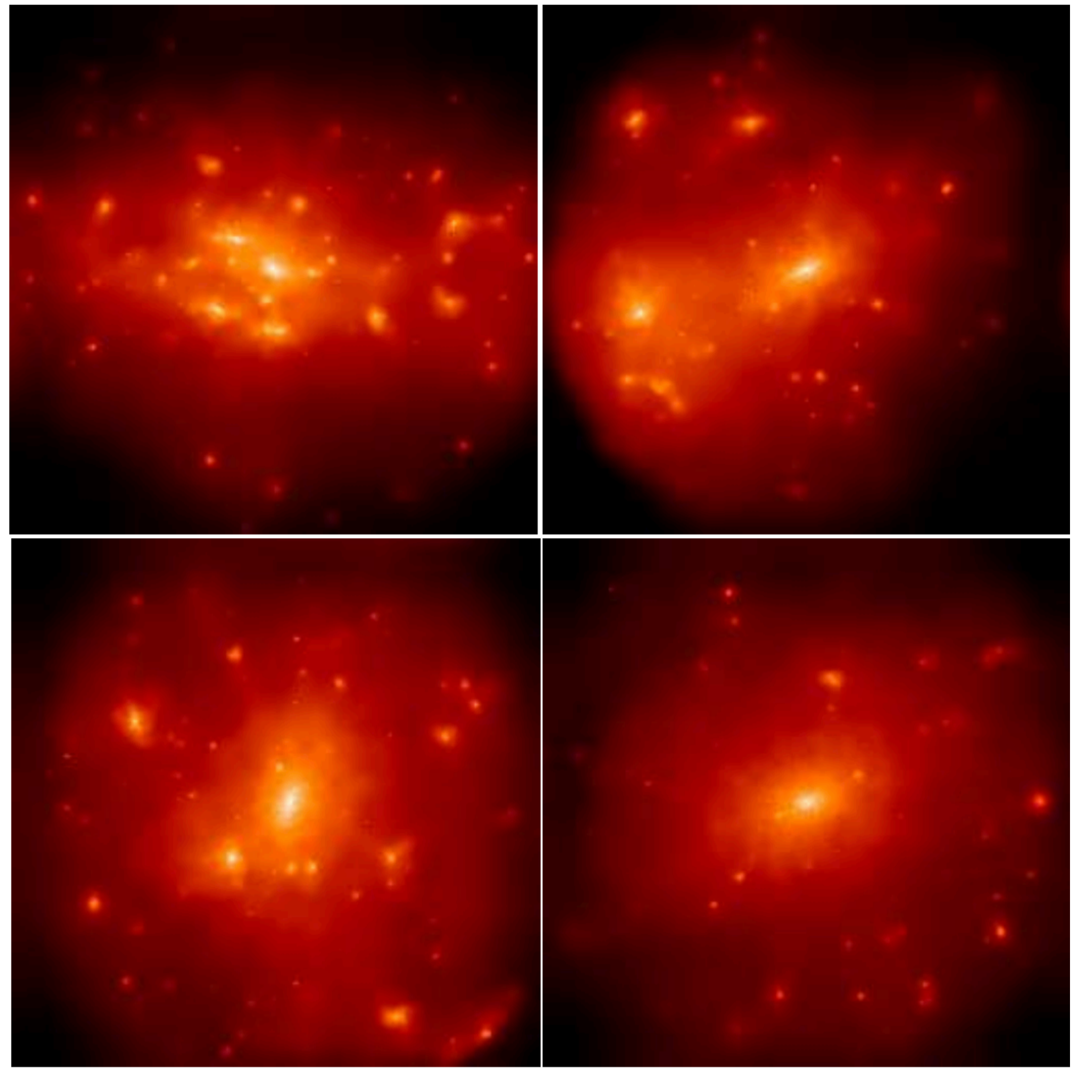
Laporte, Koposov, Belokurov+21

Stellar motions ***trace*** Galactic structure and do not care about dust*.

*Only affects the luminosities down to which you can detect the proper motions spatially.

Finding halo centers in cosmological simulations

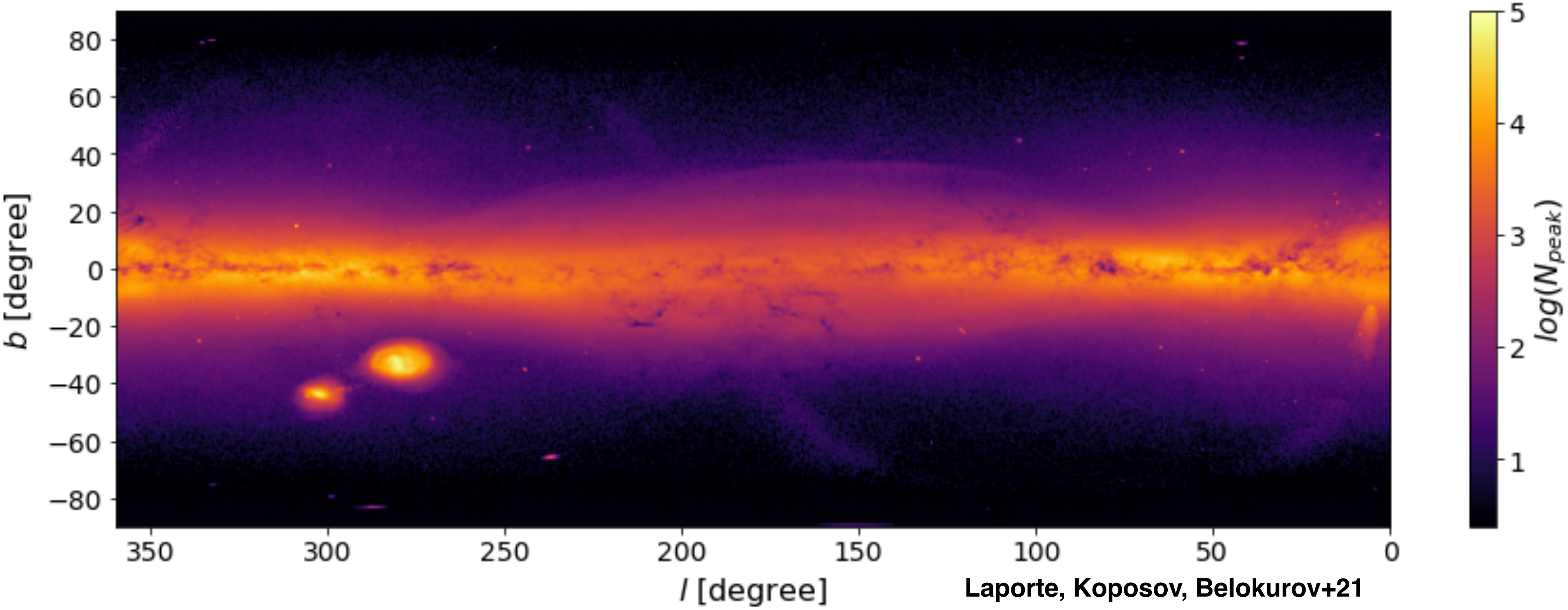
- Minimum of potential (**right way**)
- Shrinking sphere (**cheap/fast way**) - great for identifying first subhalos*



Netto+07

*can struggle in merger situations when two subhalos spatially overlap and converge on second subhalo

Apply a shrinking sphere algorithm to 2D proper motion data to the full Gaia catalog for stars d>10 kpc.



Laporte, Koposov, Belokurov+21

GCs, classical dSphs, Andromeda, M33, Sgr stream + body **even Magellanic Bridges (young & old**) correctly picked up

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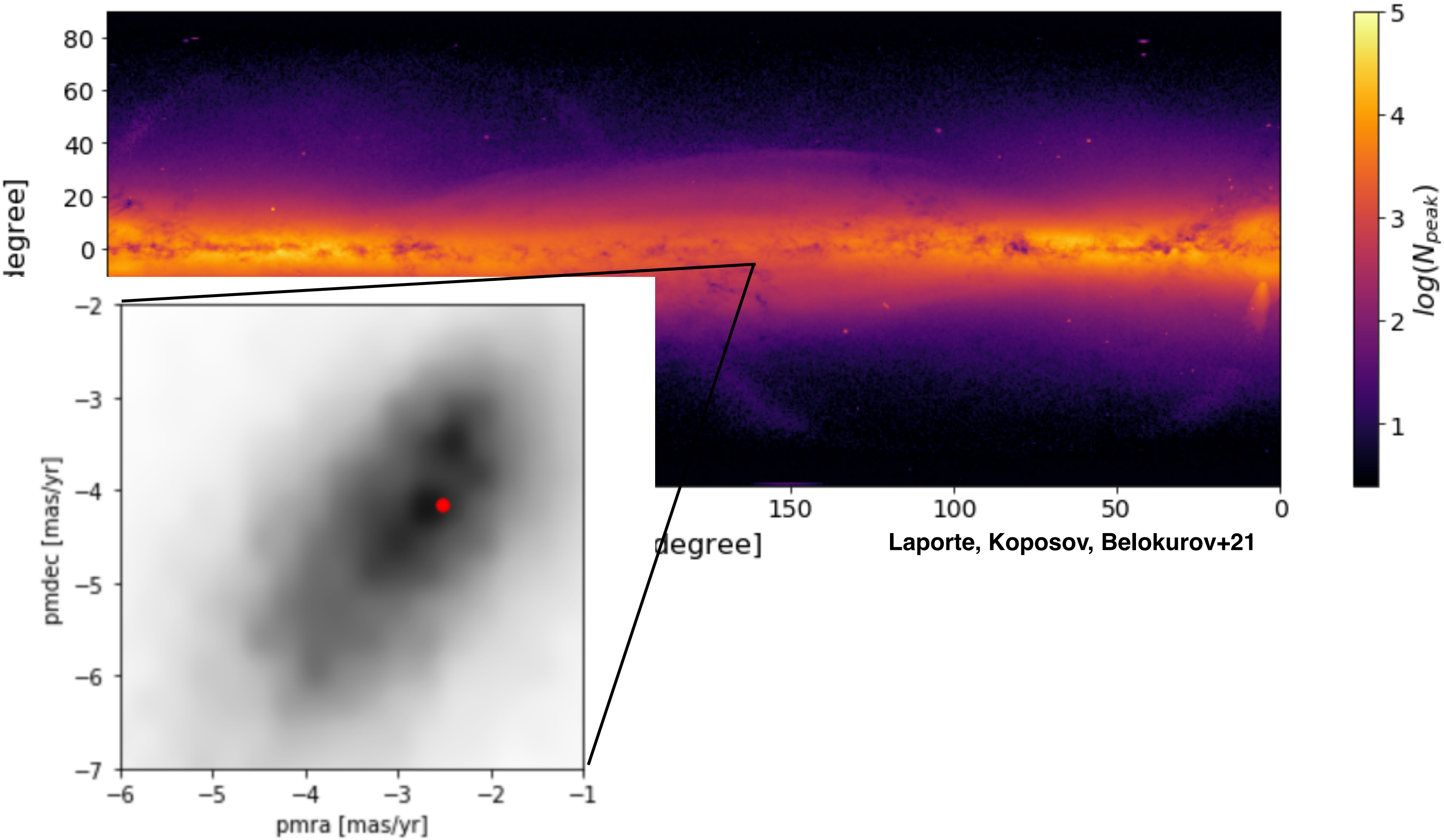

Laporte, Koposov, Belokurov+21

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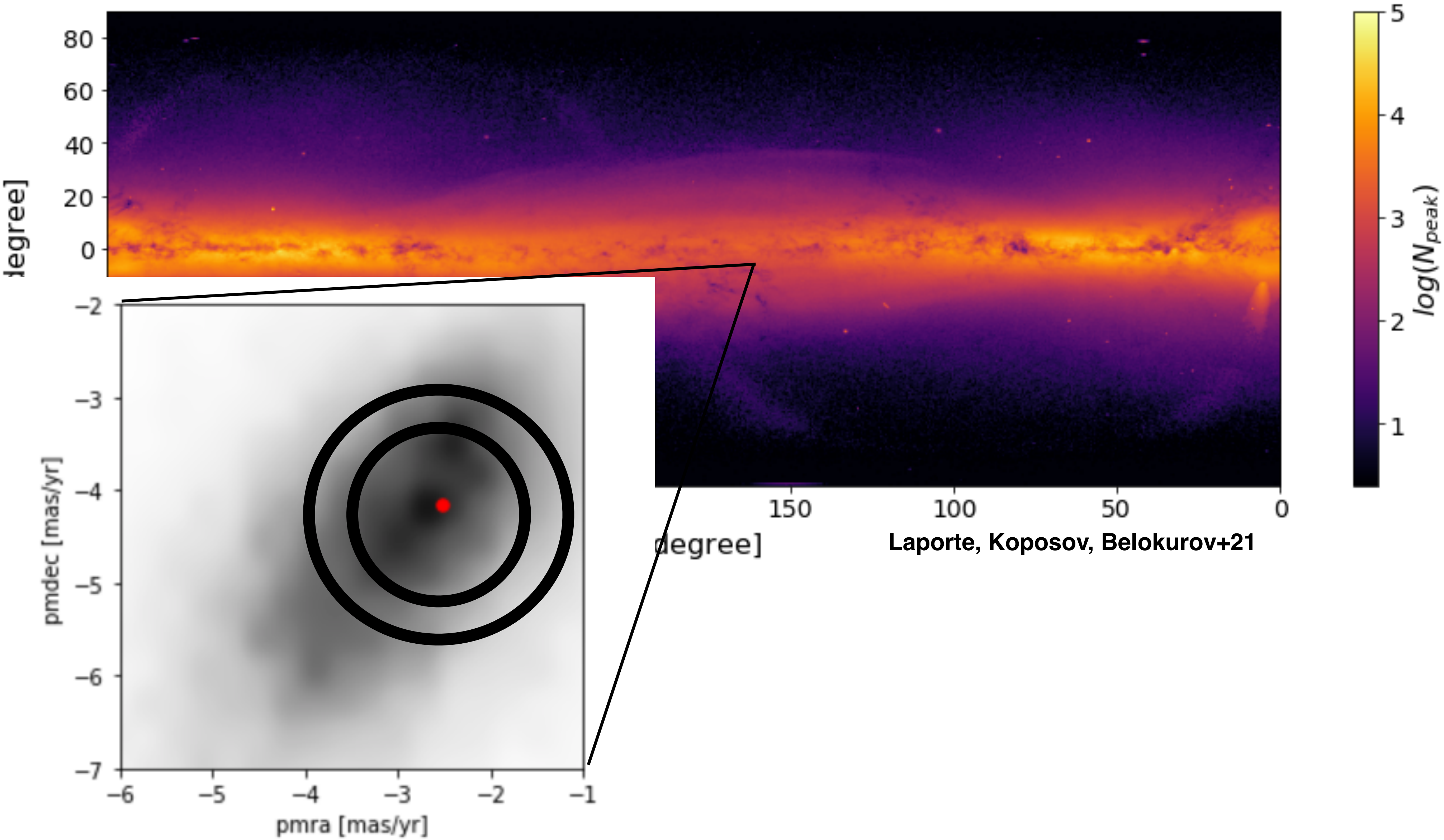
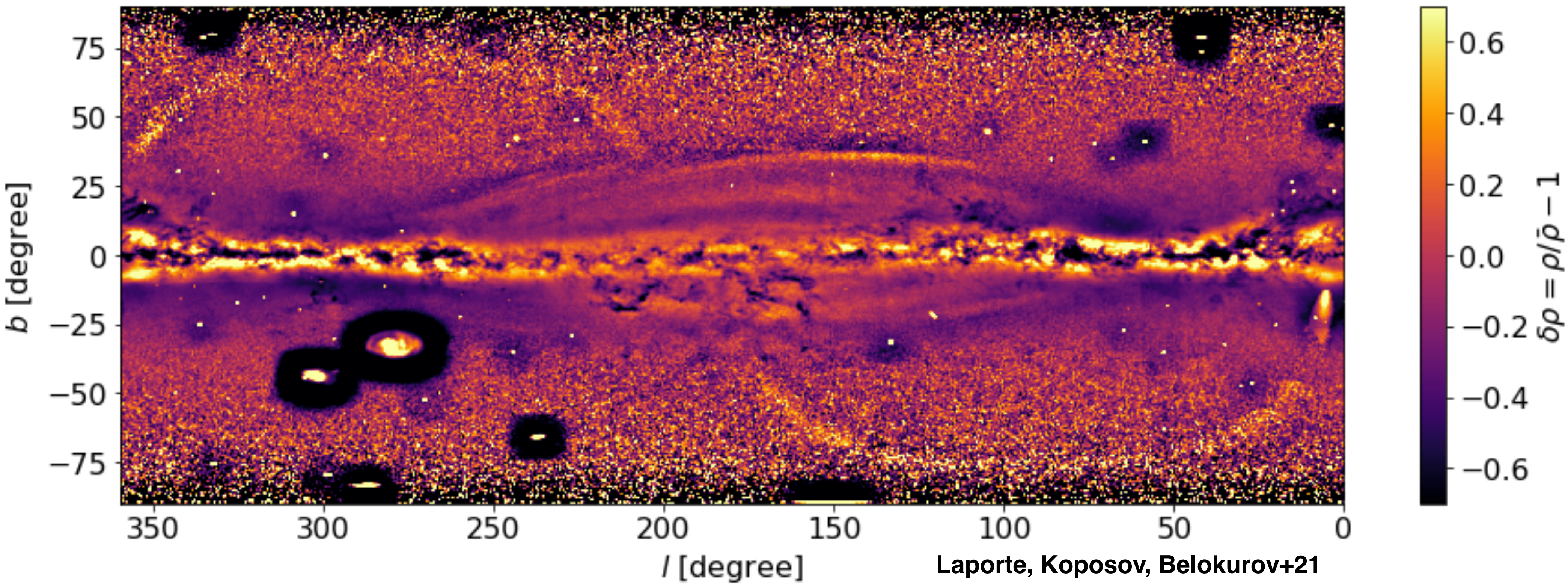


Laporte, Koposov, Belokurov+21

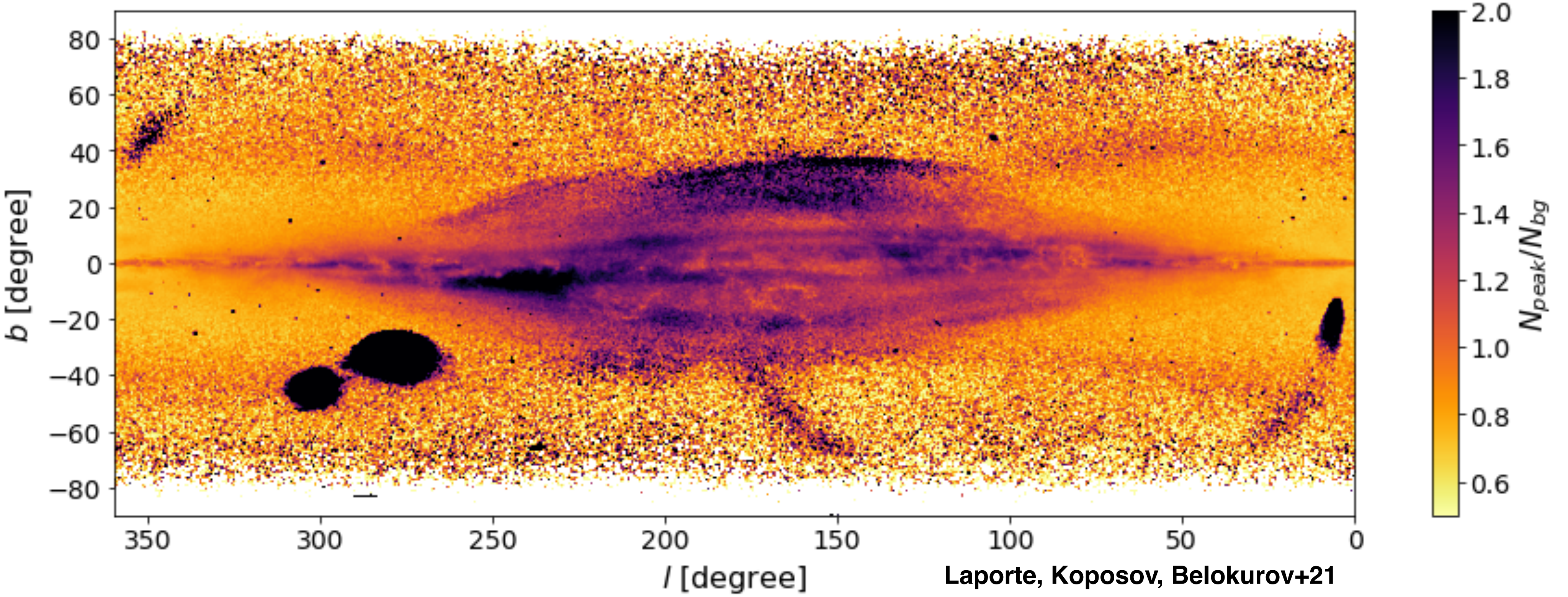
Unsharp masked image



Laporte, Koposov, Belokurov+21

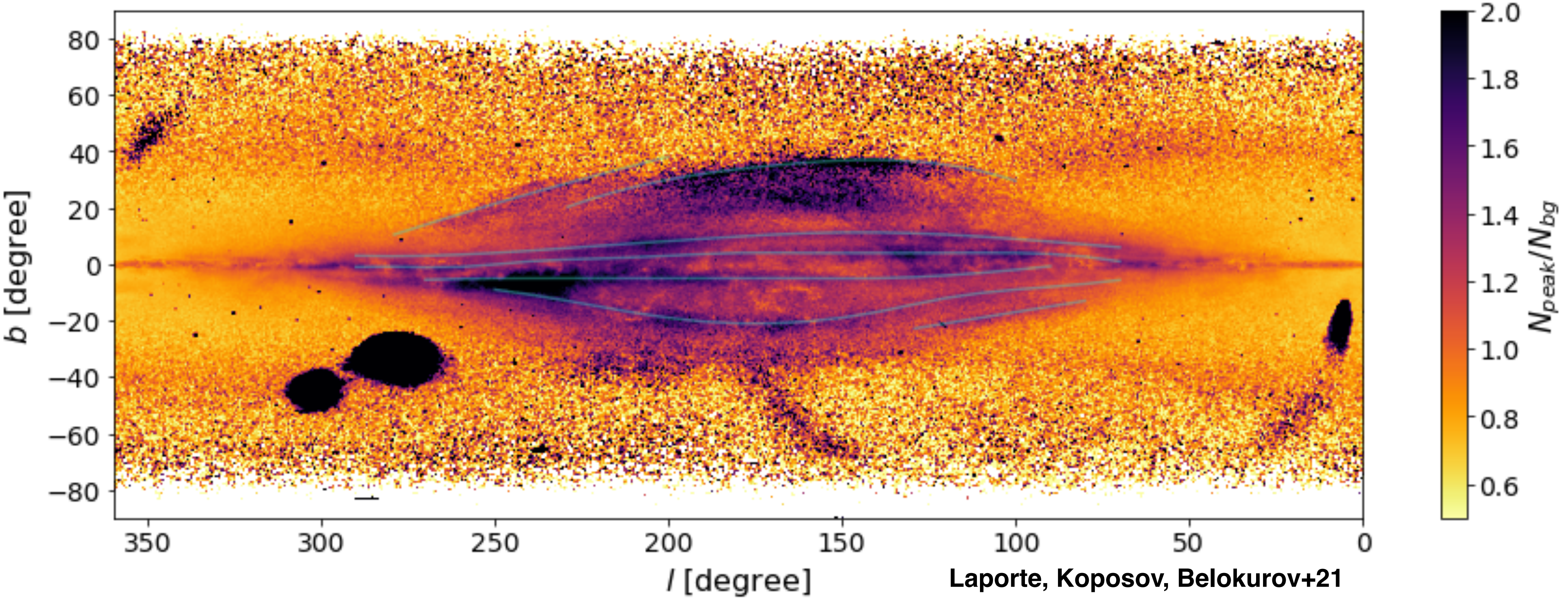
Good for revealing strong constrast… but still get a slight residual from dust

A background map to the rescue



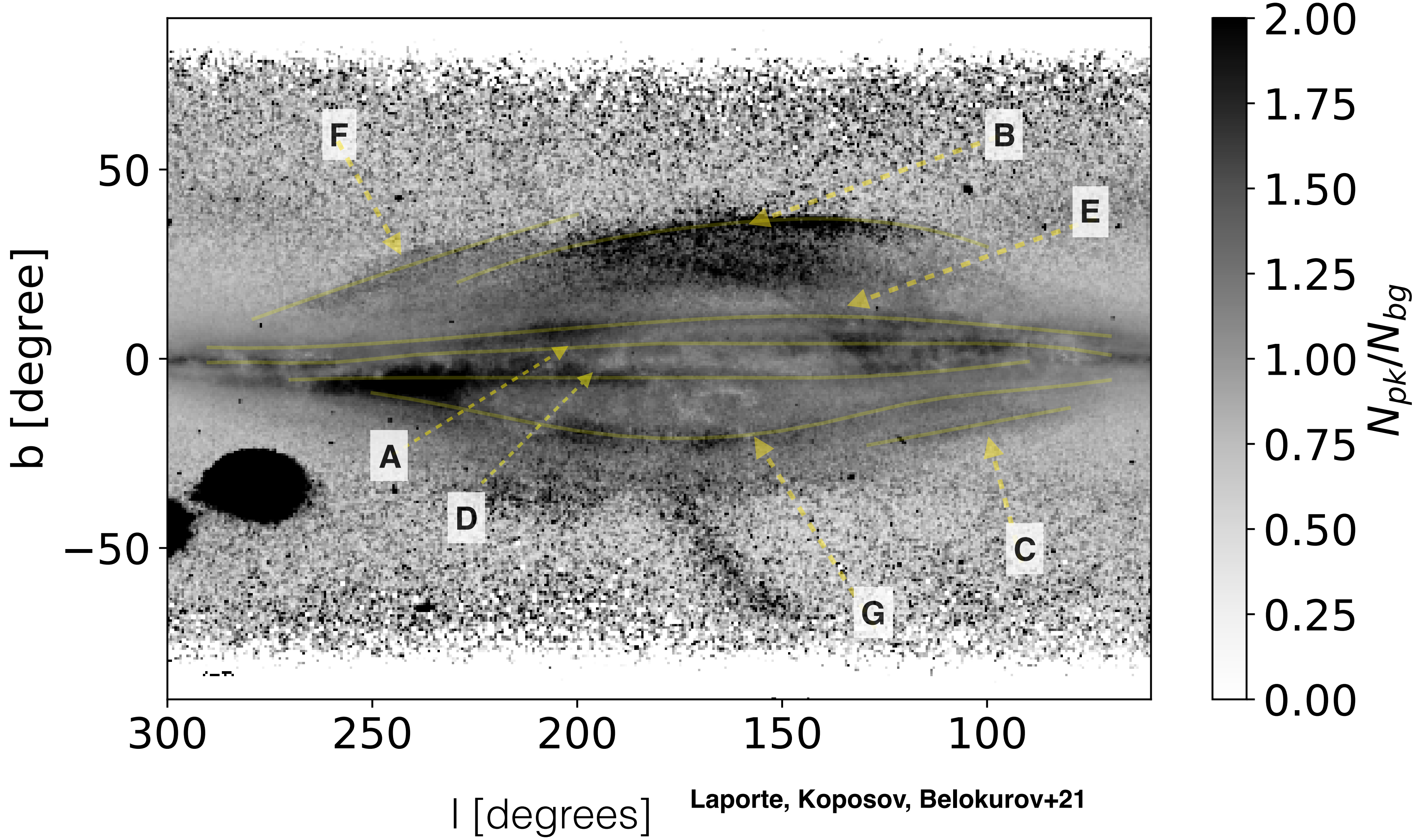
Laporte, Koposov, Belokurov+21

Variable stars in structures - give extra info on distance

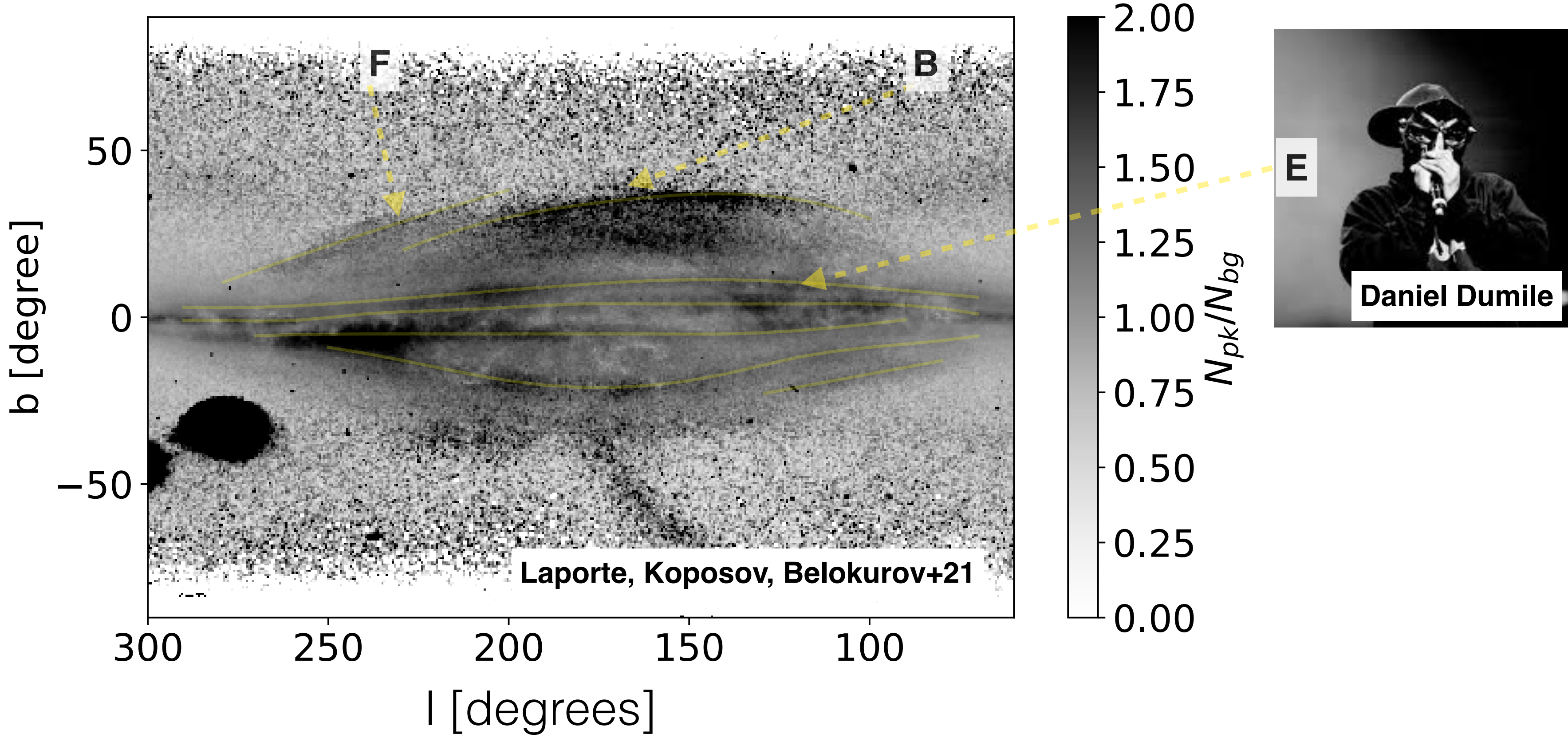


Laporte, Koposov, Belokurov+21

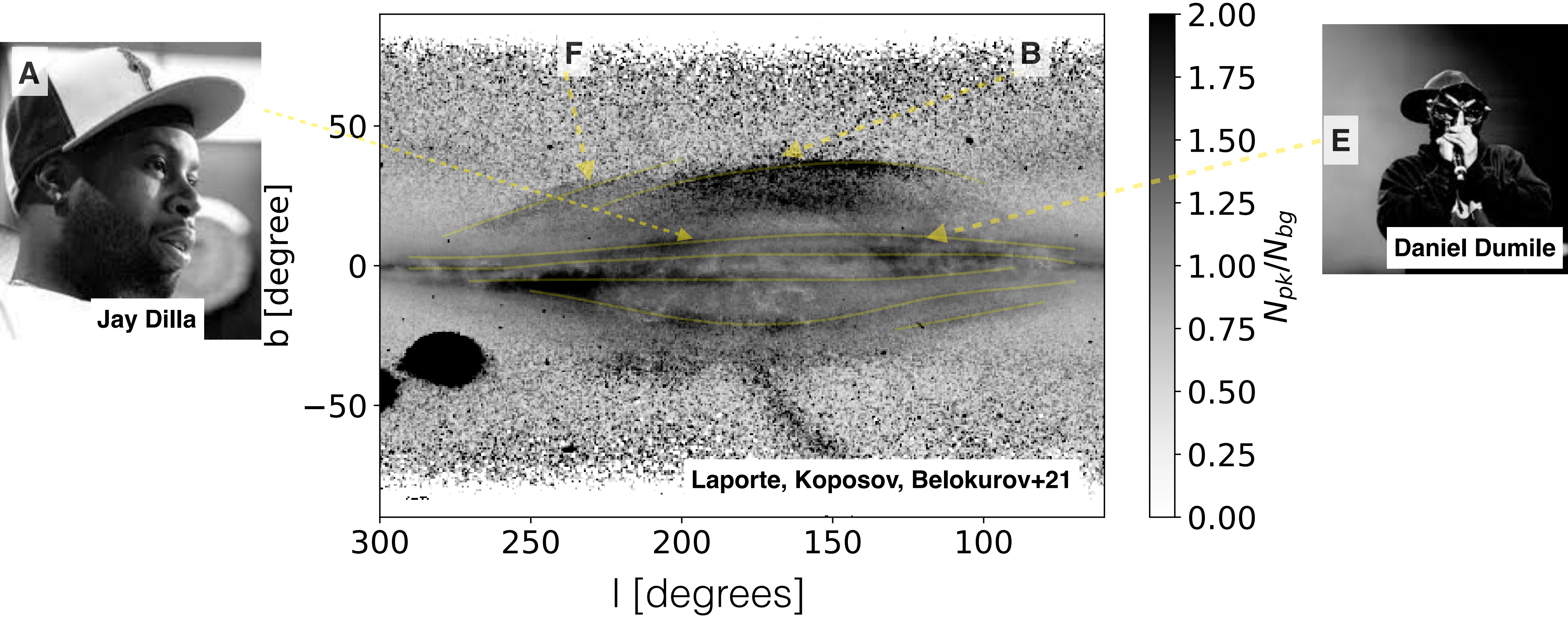
New structures detected towards the midplane at |b|<10 and two below at b~20-30.



F = Eastern Banded Structure (Grillmair06), **B**= Anticenter Stream (Grillmair06)
*__E, A, D, G, C__ = LKB-01,LKB-02,LKB-03,LKB-04,LKB-05



***E, A, D, G, C** = LKB-01,LKB-02,LKB-03,LKB-04,LKB-05, also known as "Dumile", "Dilla", "Shakur", "Ndegeocello", "Latifah"



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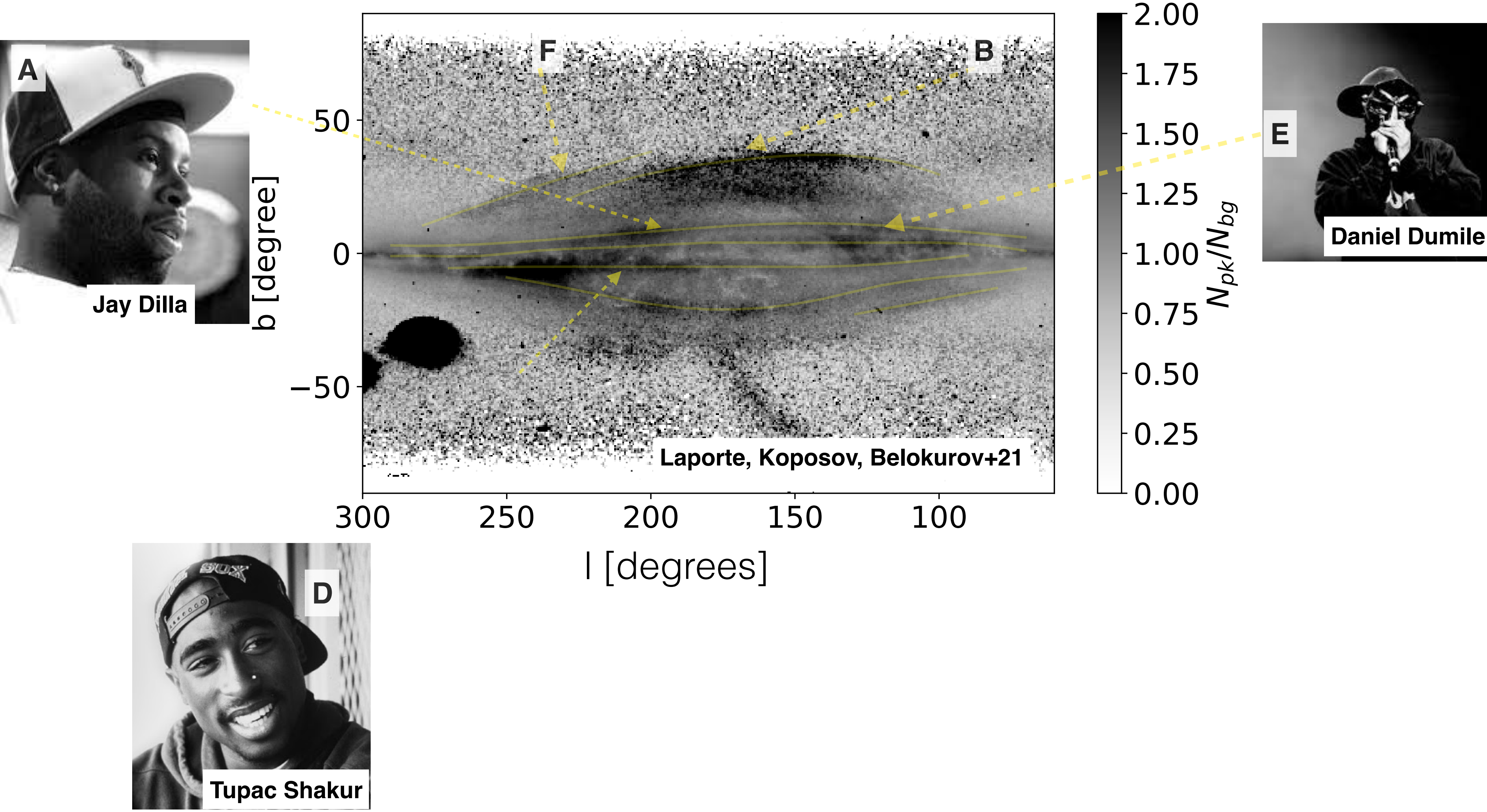

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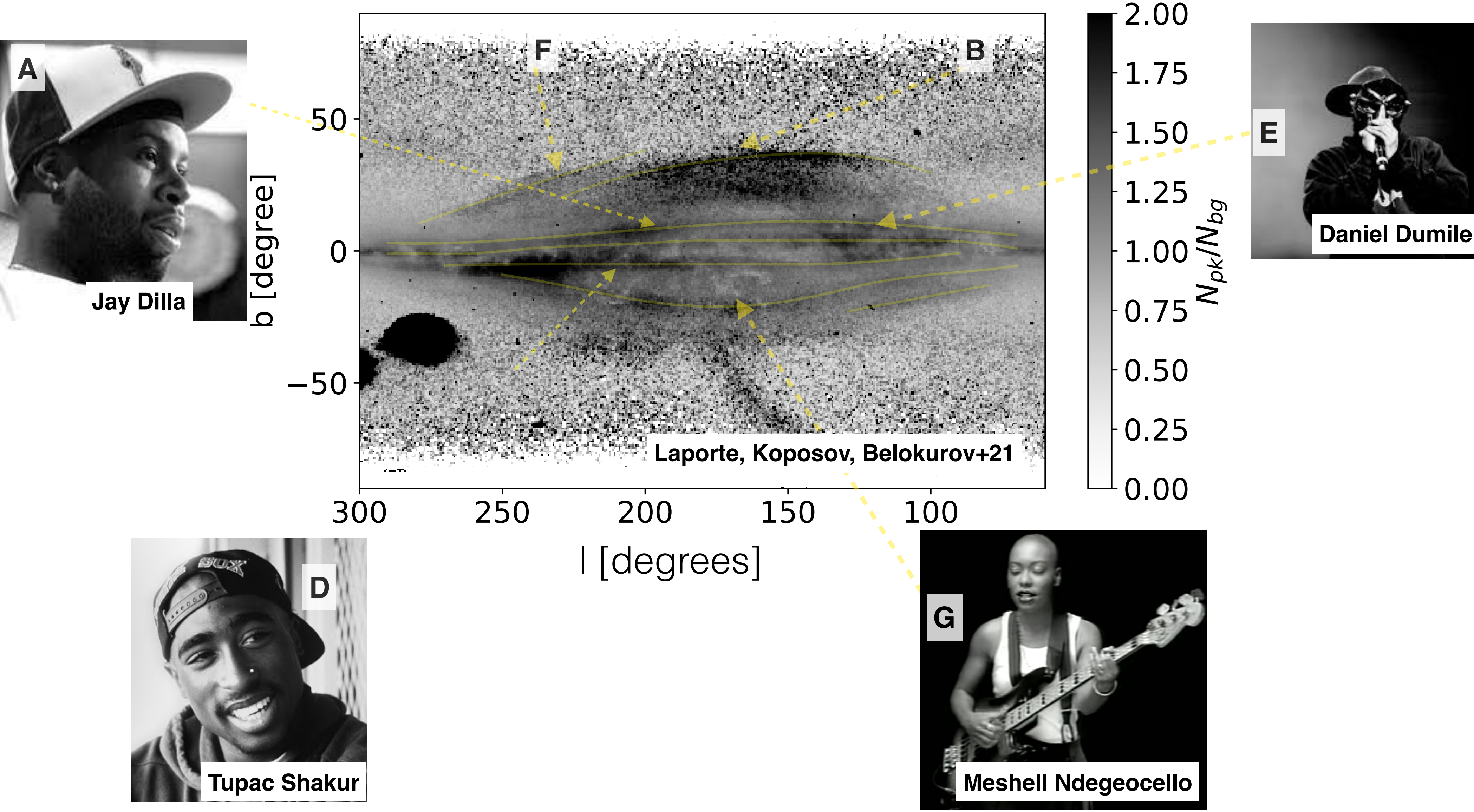

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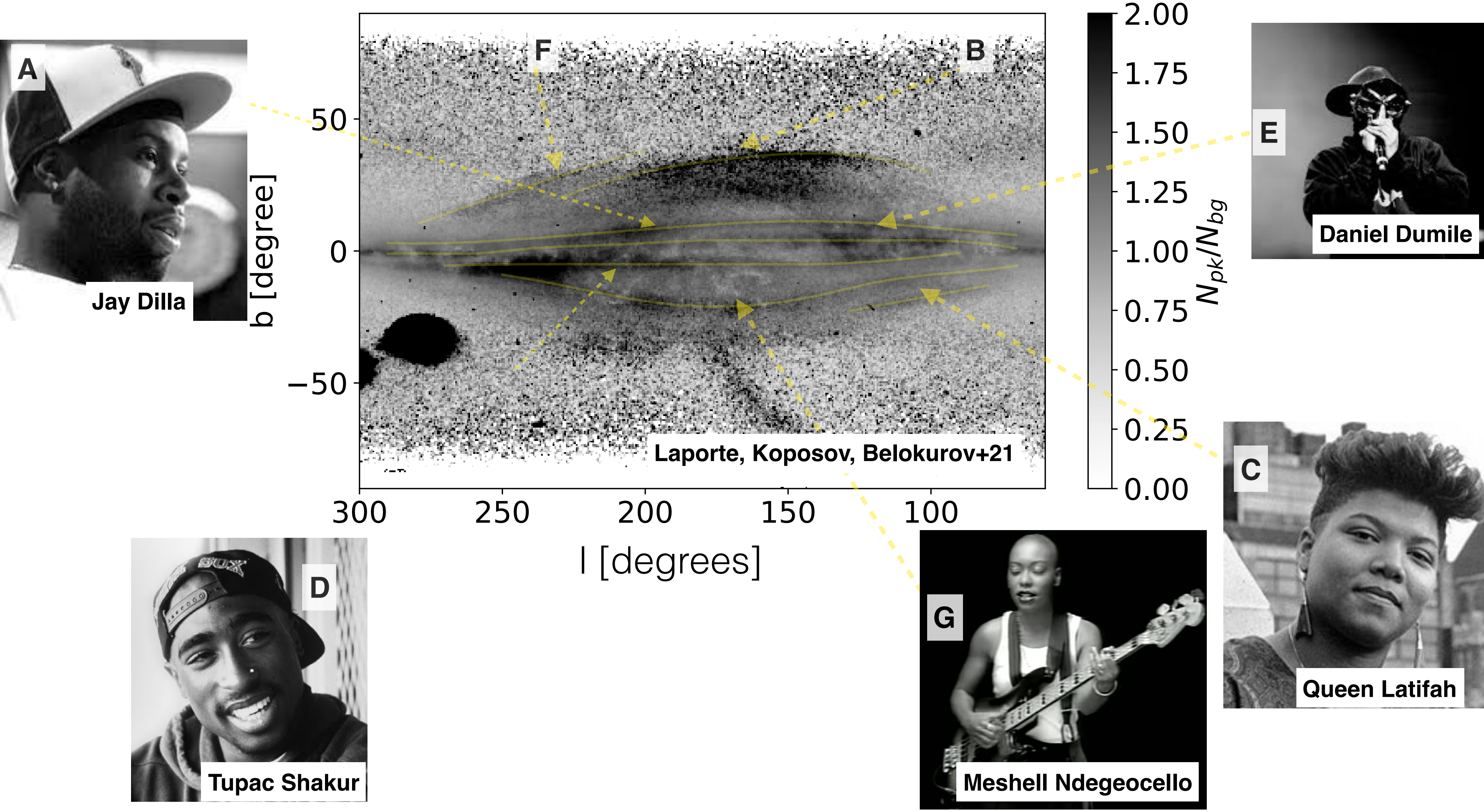

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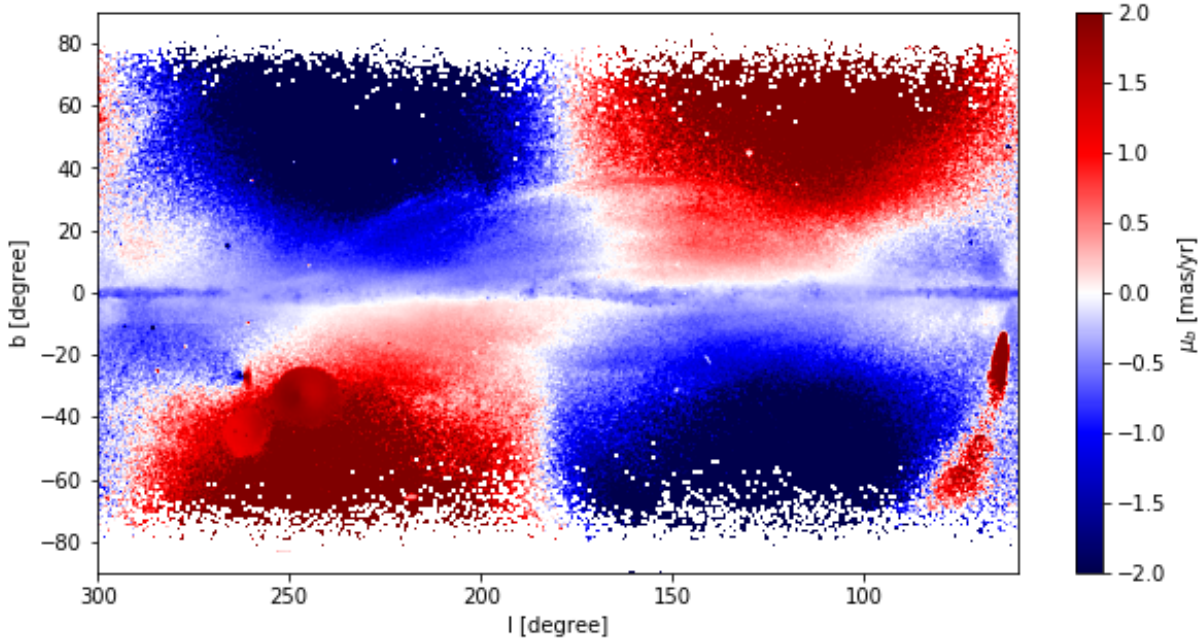
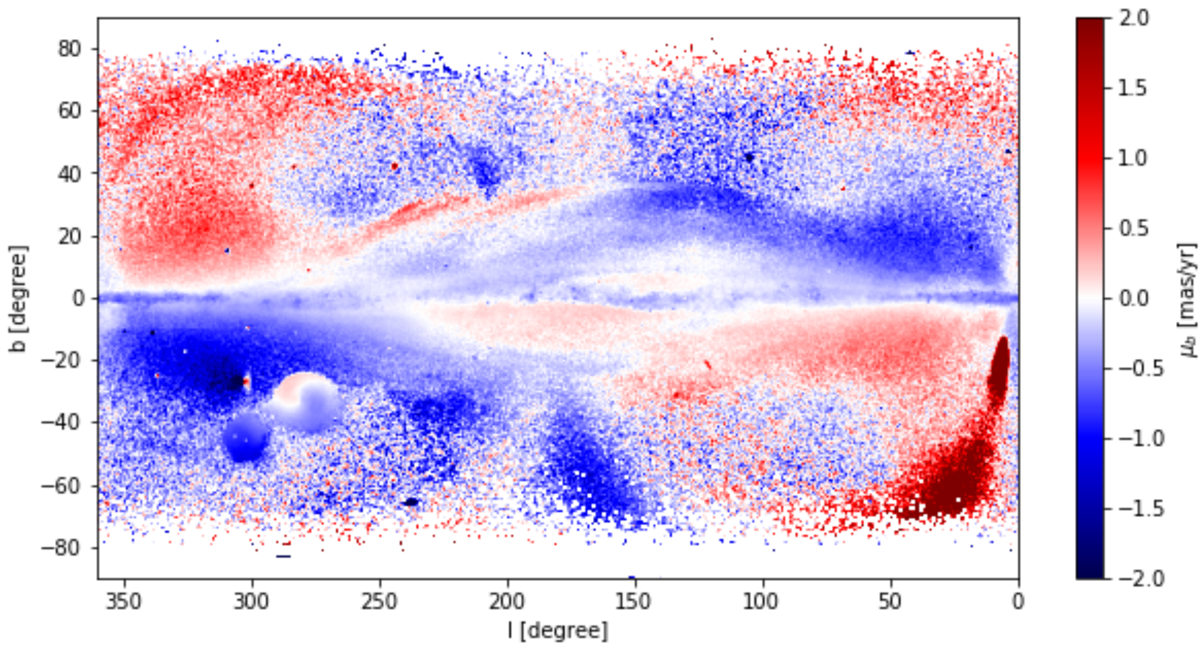


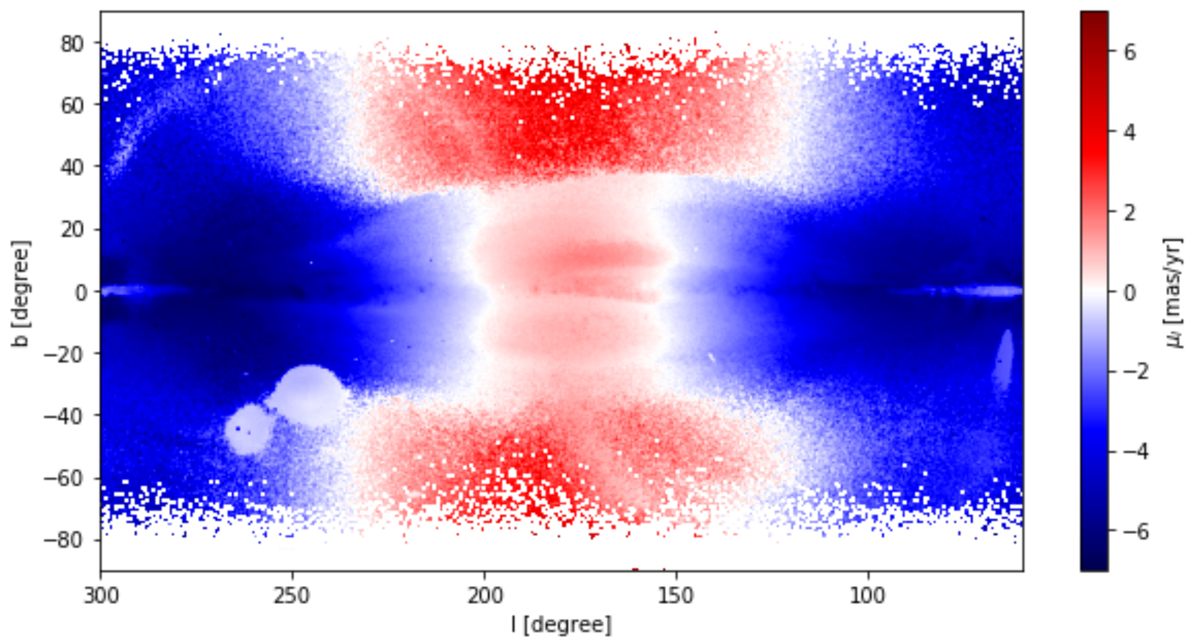
mu_b(l,b)

solar reflex corrected (applying uniform d~13kpc)



mu_l(l,b)

uncorrected for solar reflex motion



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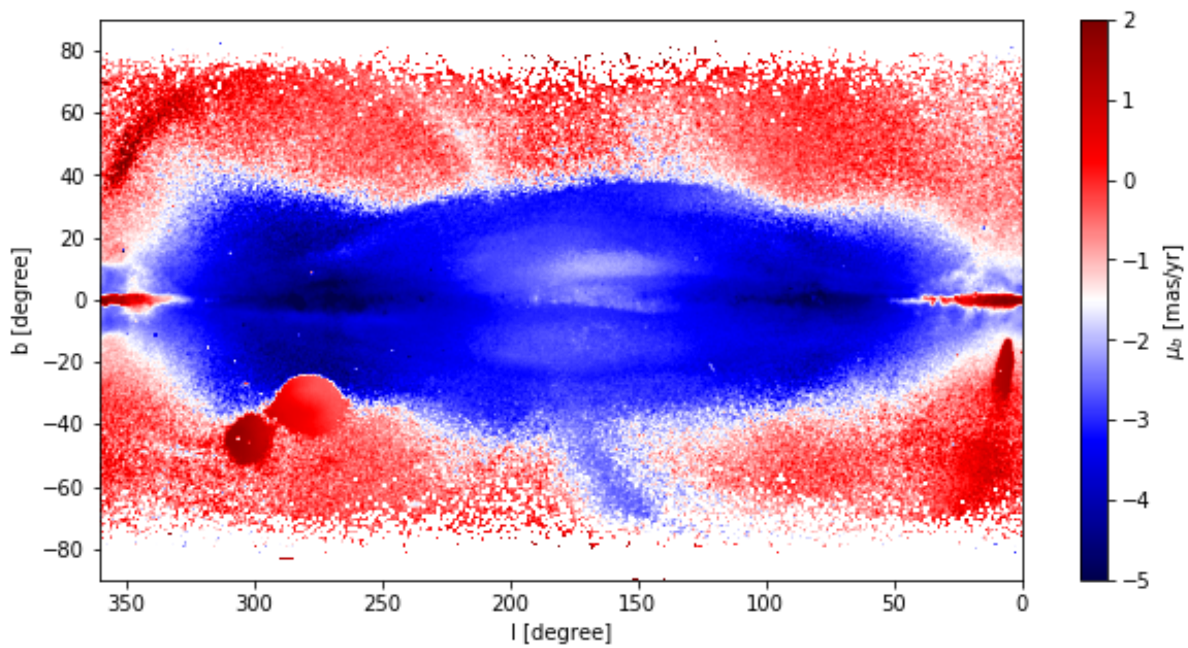
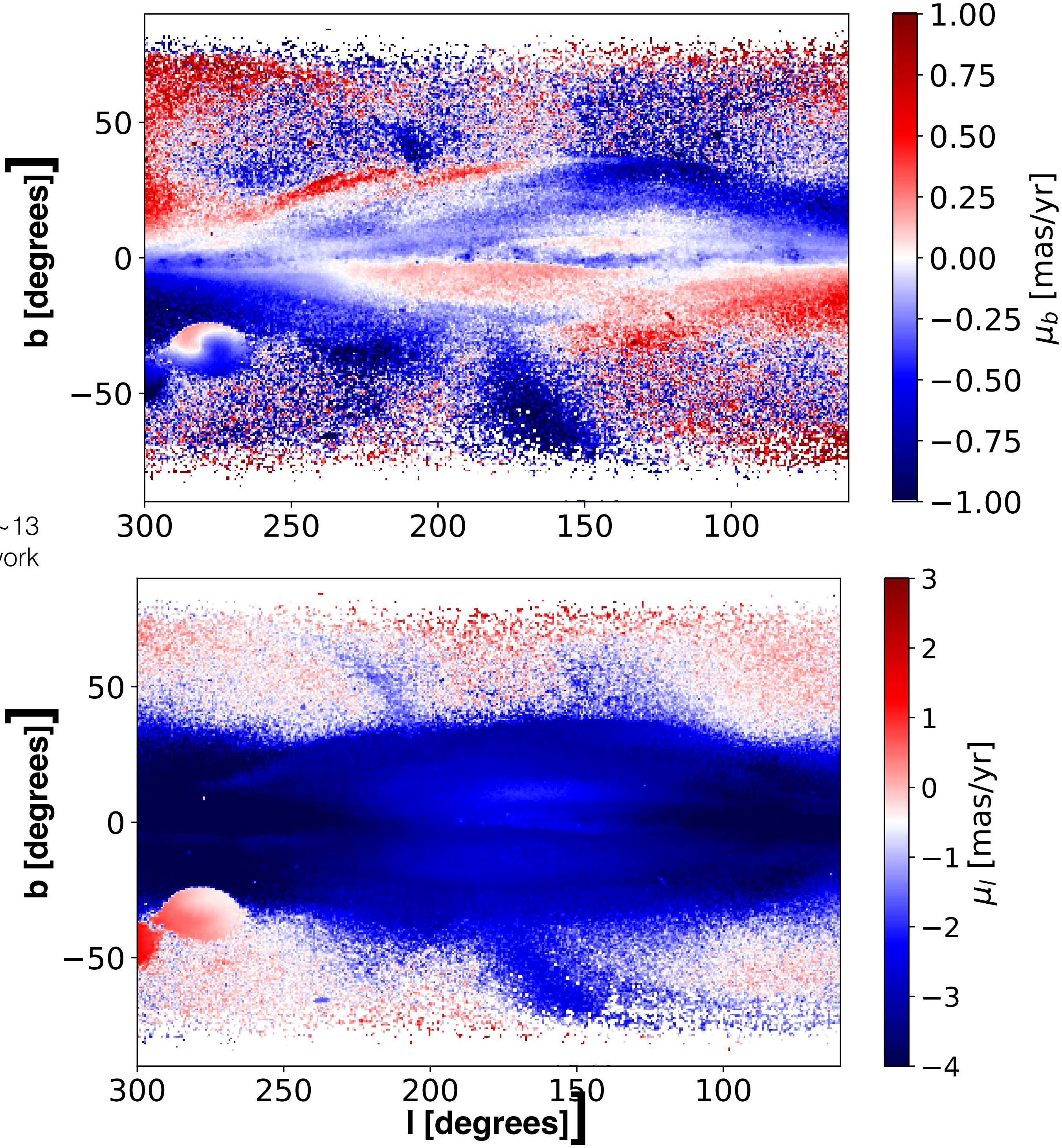
solar reflex corrected (applying uniform d~13kpc)



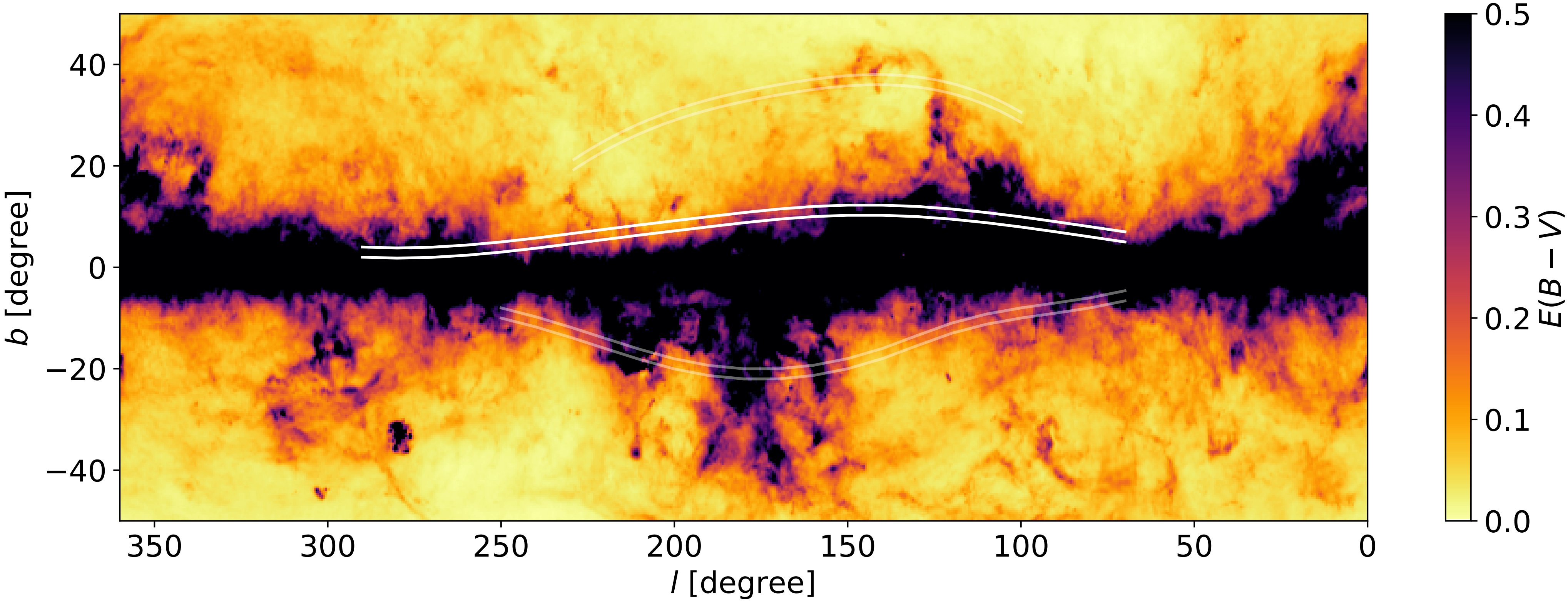
mu_l(l,b)

Proper motion maps (solar reflex motion corrected*)



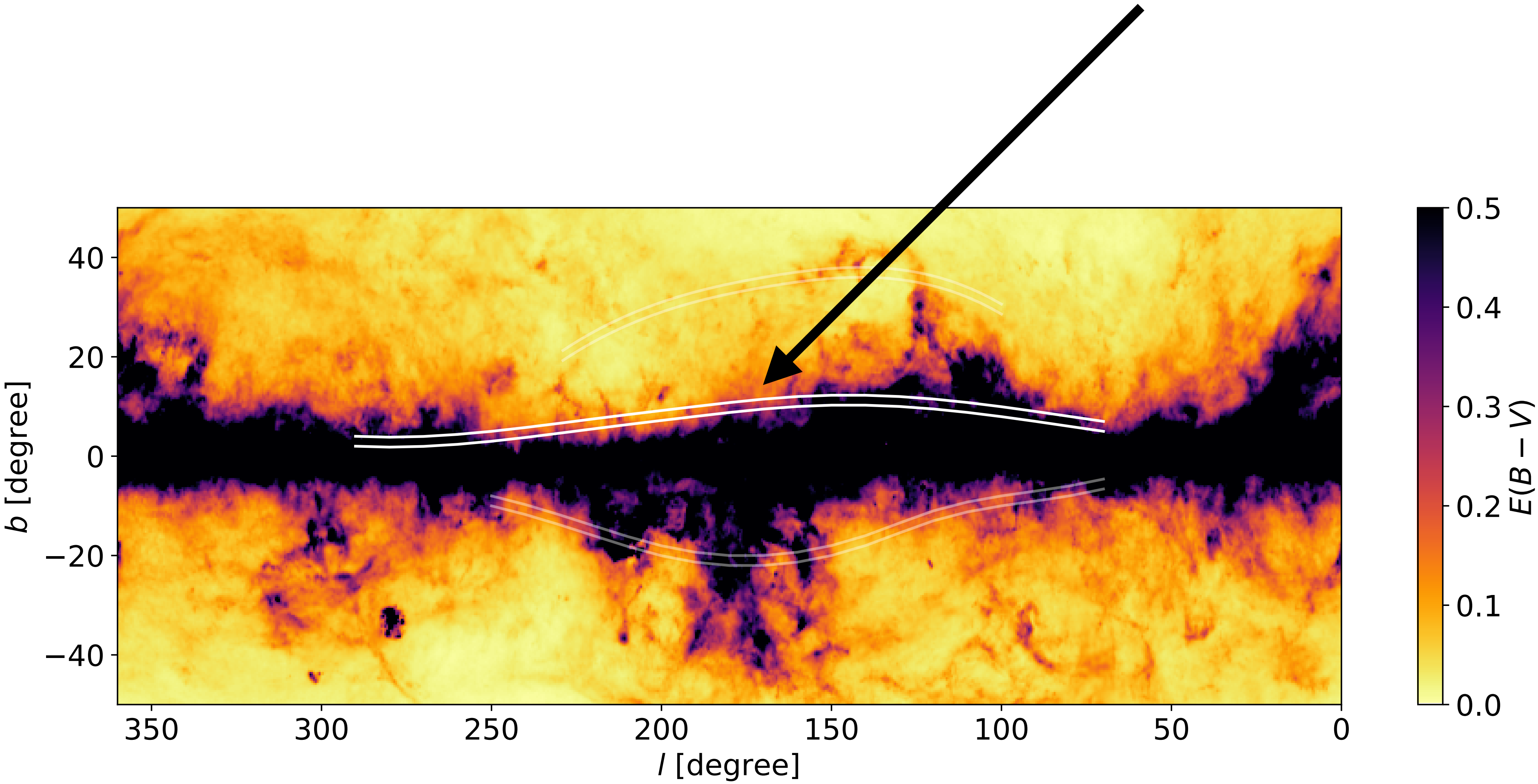
*Correction assumes d~13 kpc overall - does not work on high lat edges

Did we *really* miss them just because of dust???



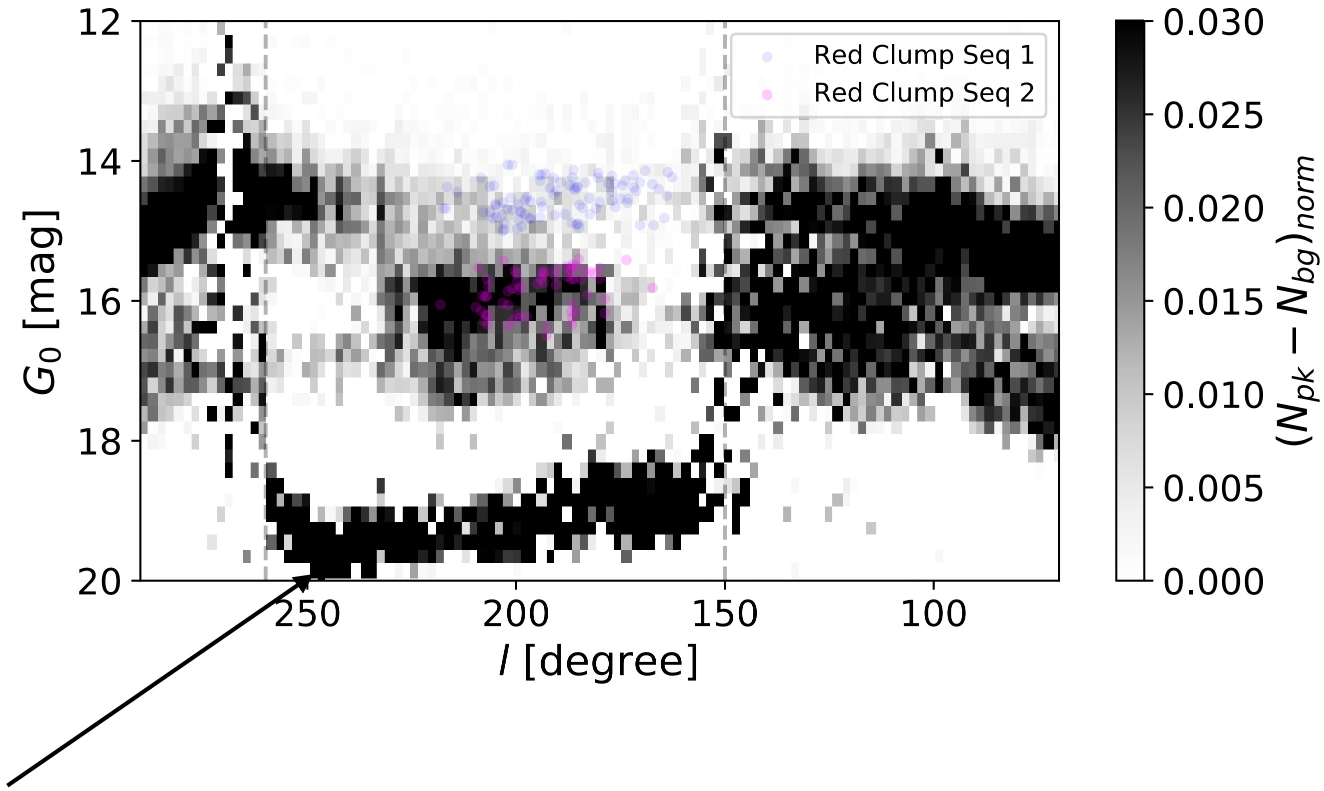
…yes

A closer look on one substructure



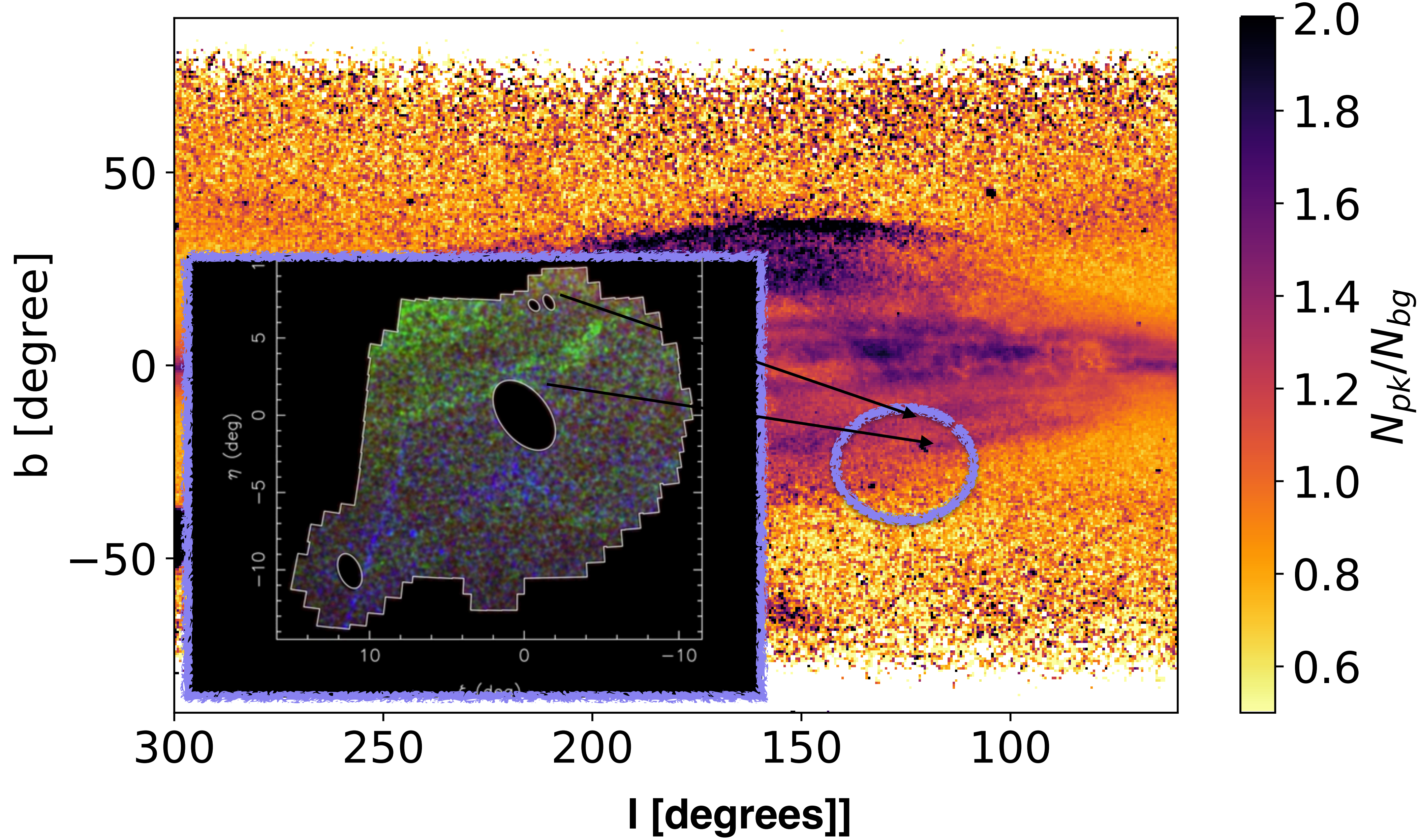
Magnitude (distance) variation for Red Clump candidates (0.9<BP-RP<1.2)

LKB-03 (Dumile)

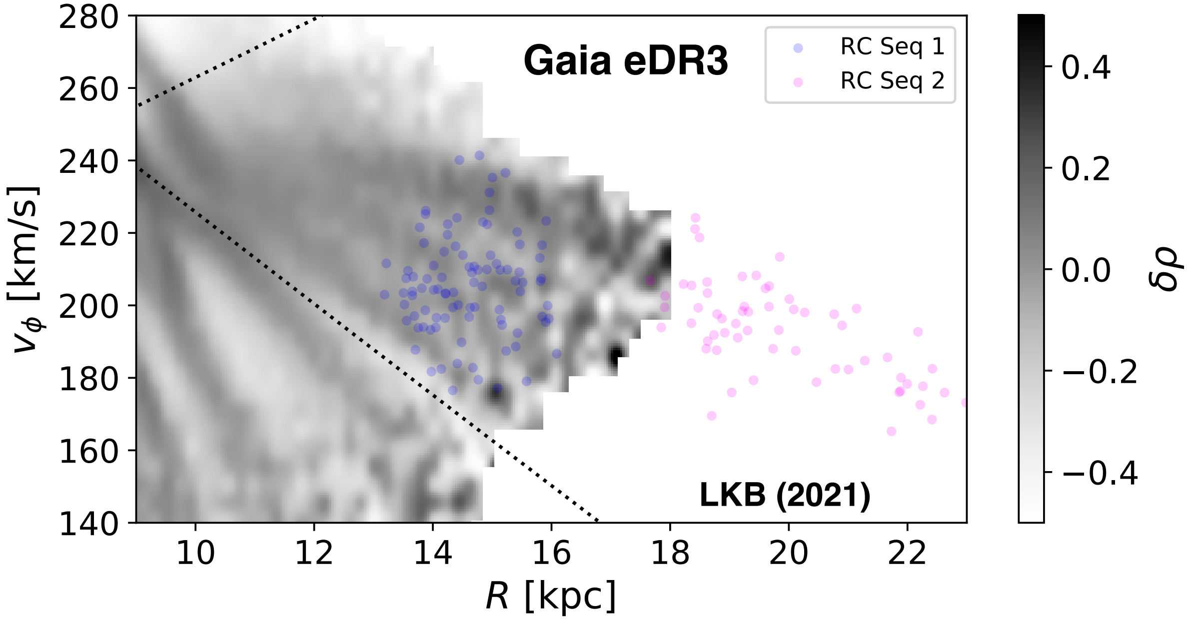


subgiant - expected at 2.5-3 magnitudes below (see also Belokurov+06)

Relation to Triangulum Andromeda overdensity & PandAs field of Streams?



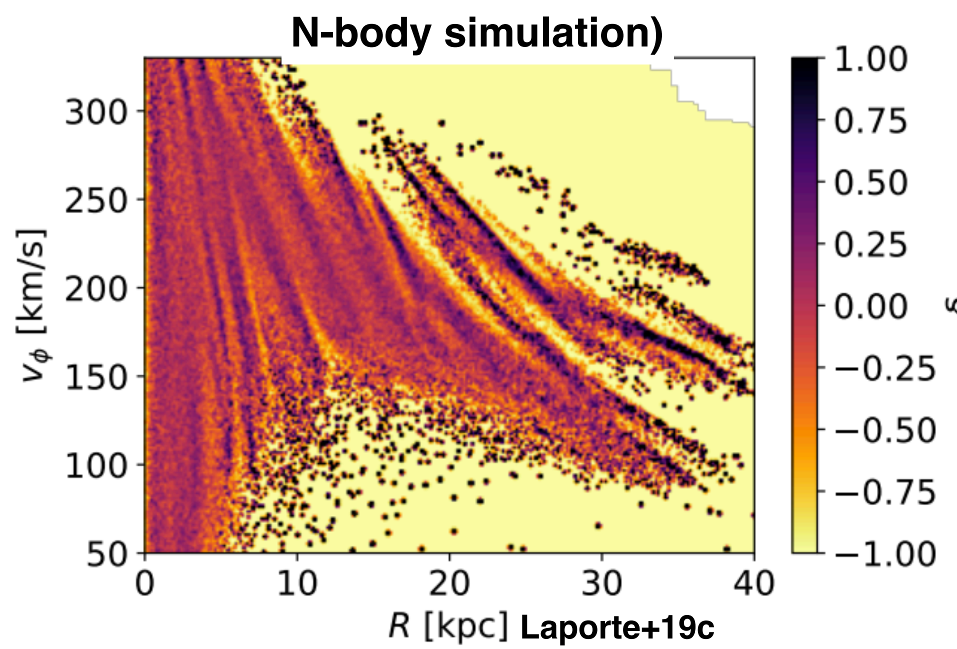
Kinematics & Metallicity



<[Fe/H]>_LKB-03~-0.6
(similar to ACS Laporte+20a)

Disc-like kinematics vphi~230-180 km/s
Wider spread in energy Seq 1 (large-scale background)
Smaller Energy spread in Seq 2 (substructure)

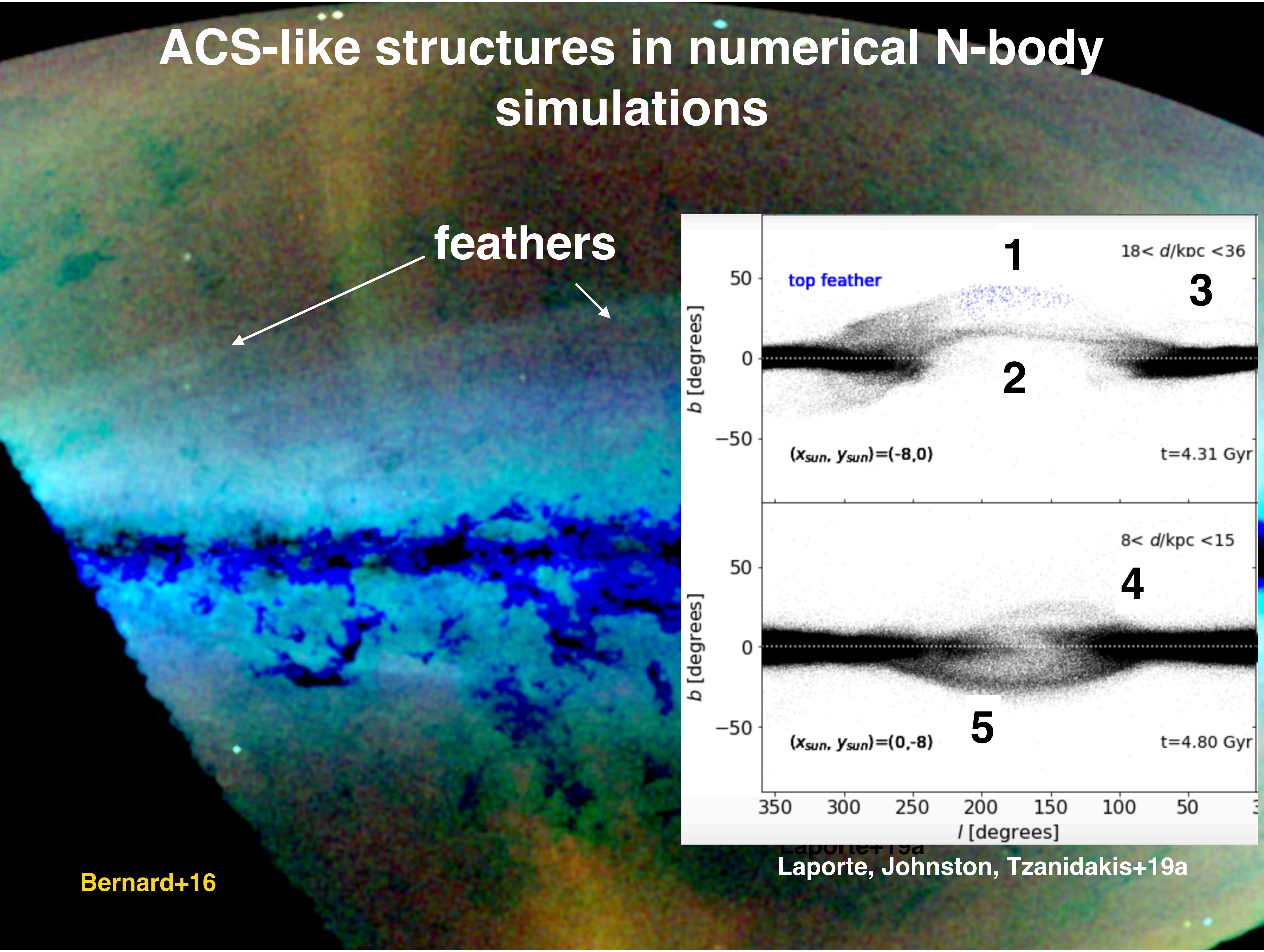
predicted kinematics of outer disc from pre-Gaia DR2 Sgr impact model (Laporte+18b)



OK, chemistry says this is disc material but do we have an interpretation as to what these streamy structure could be?

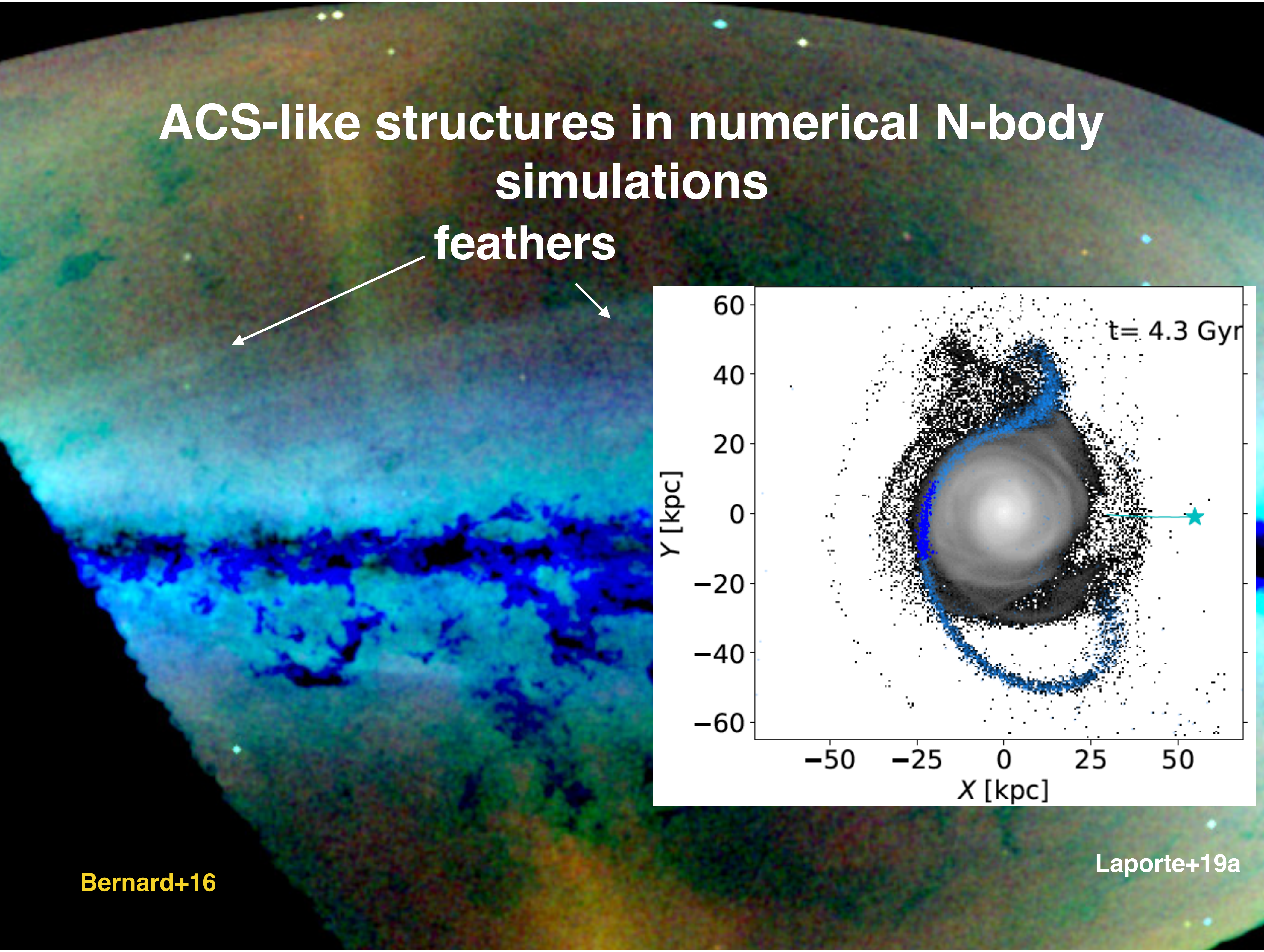
Two possibilities, would need to follow-up to be certain

ACS-like structures in numerical N-body simulations

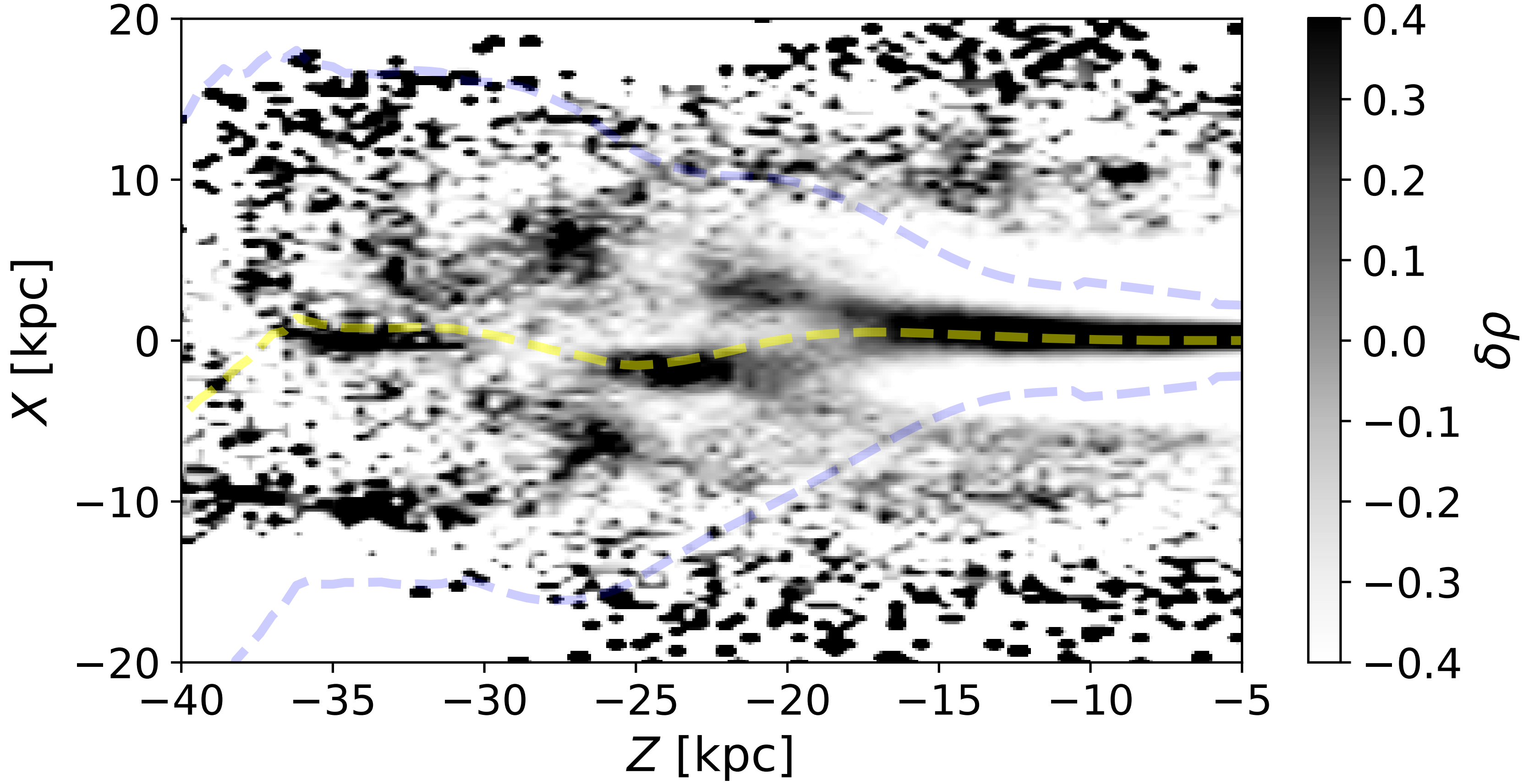


Laporte, Johnston, Tzanidakis+19a

ACS-like structures in numerical N-body simulations

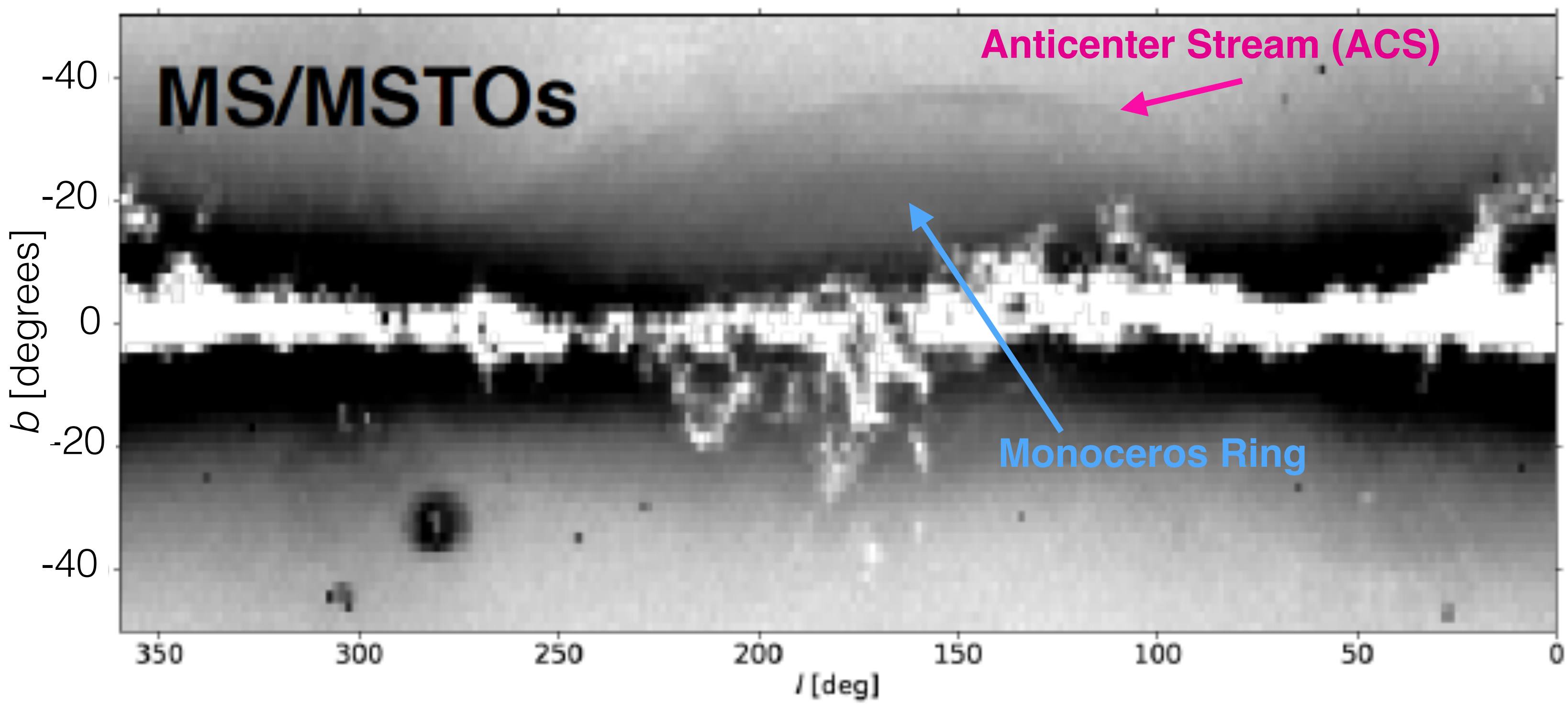


Folds from a corrugated disc



The two can certainly co-exist within the disc… need to find a way to tell

Anticenter structures: spatial/kinematic selection

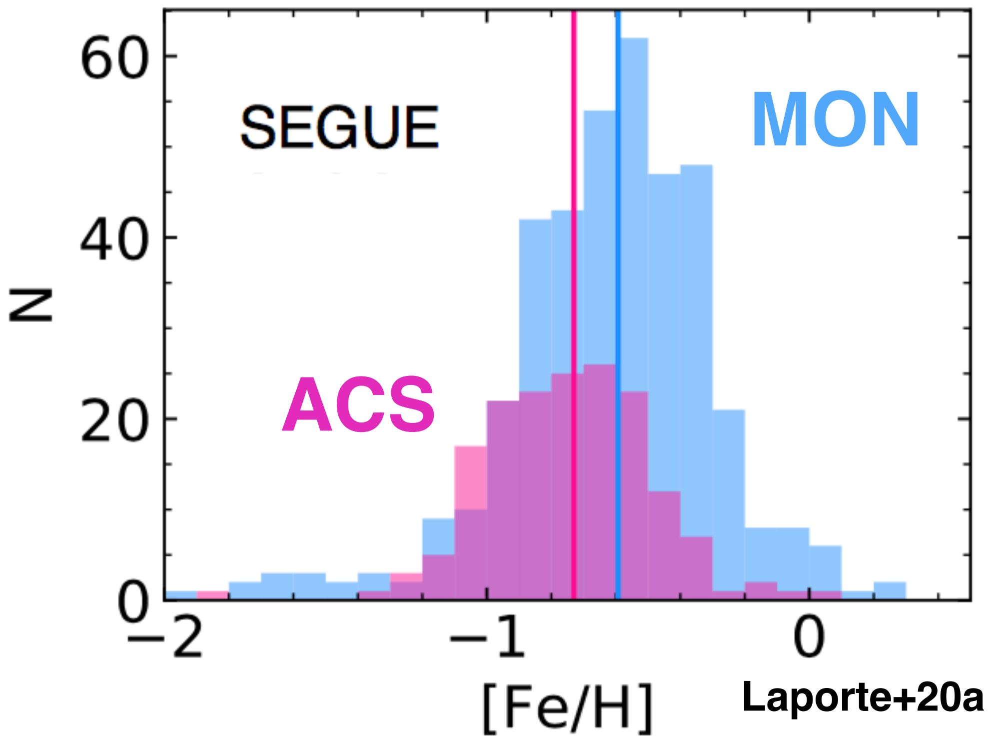


Adapted from Laporte+20a

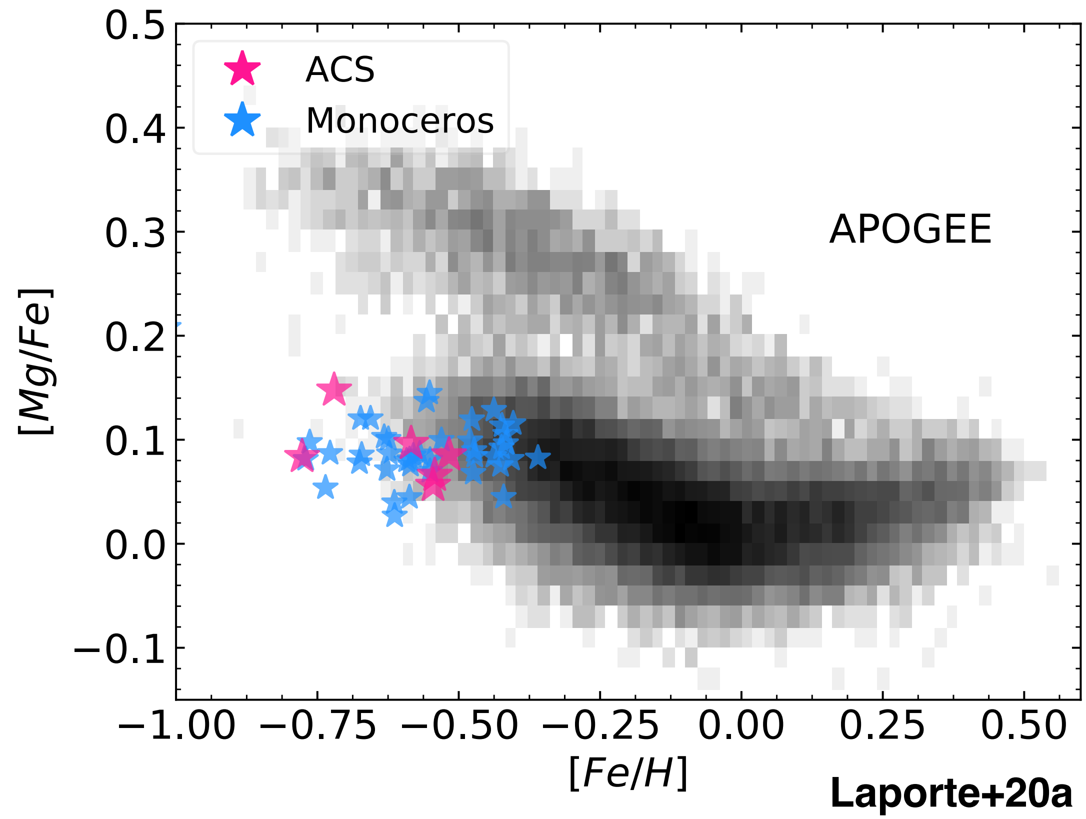
Gaia DR2

Other Anticenter structures (Monoceros, ACS)
Chemistry

Metallicity



Mg-abundances



<[Fe/H]>~ -0.6

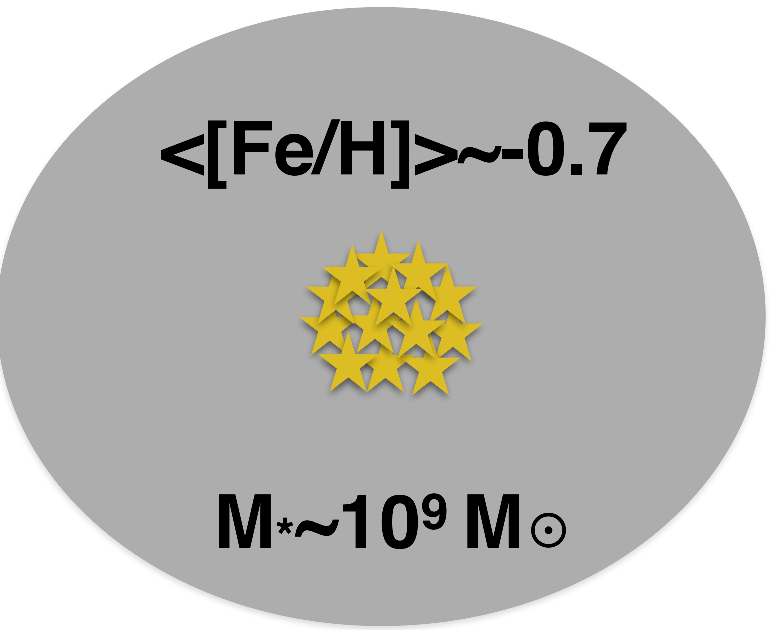
<[Fe/H]>~ -0.7

Flat [Mg/Fe]: no alpha-knee

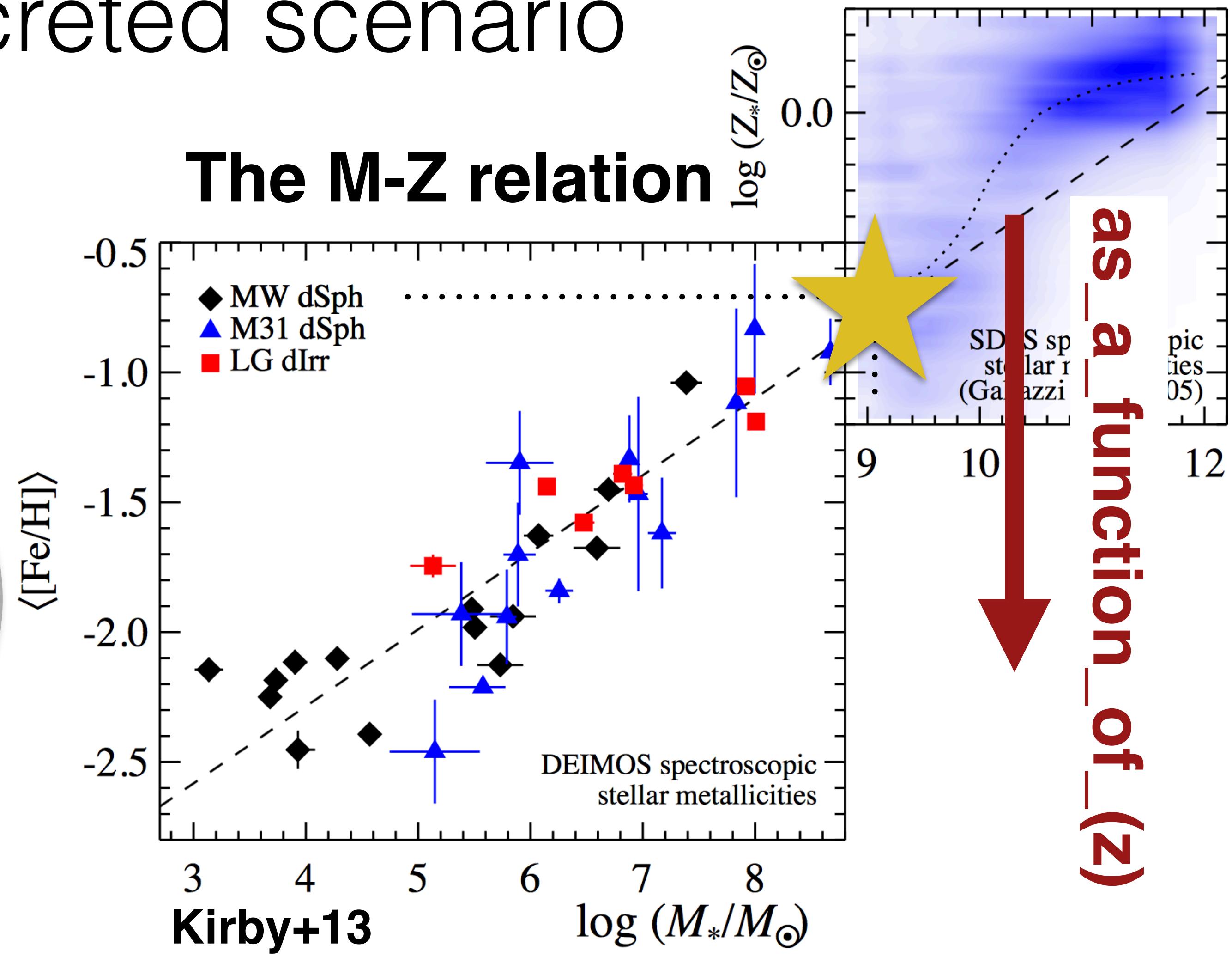
→ metal poor end chemical thin disc

Accreted scenario

Monoceros/ACS galaxy



The M-Z relation

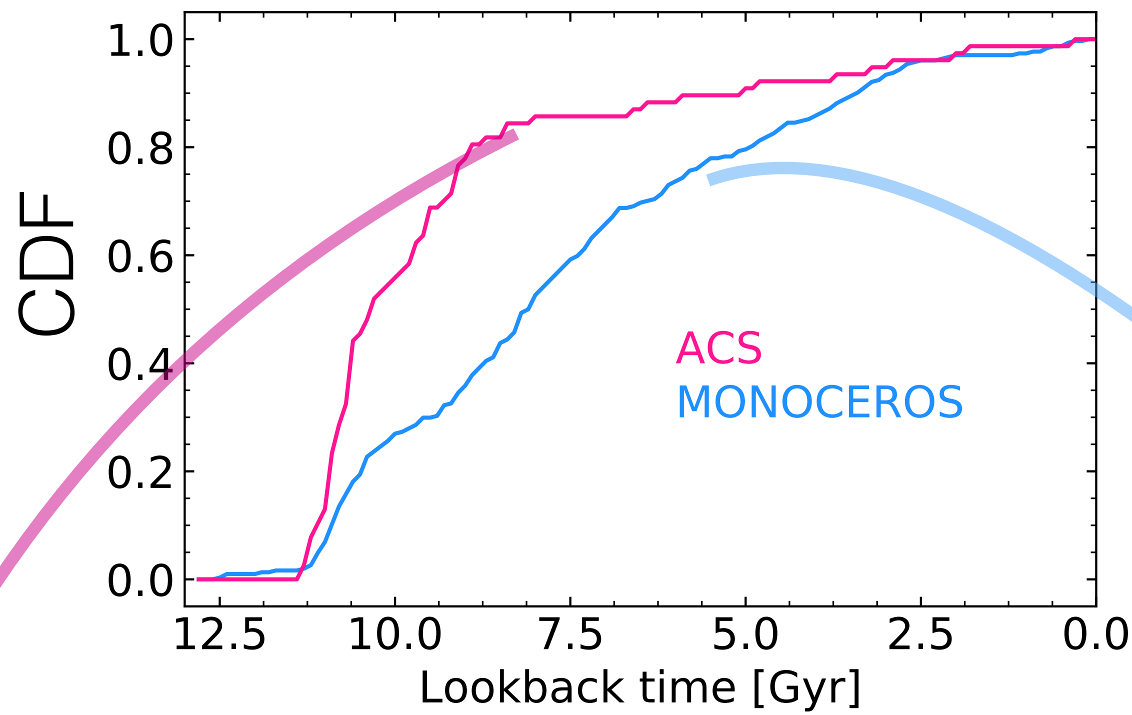


$M^*_{monceros}$~ few10^7 M⊙ → 2 orders of magnitude violation

$M^*_{MW\ stellar\ halo}$~ 10^9 M⊙ → account for all MW stellar halo

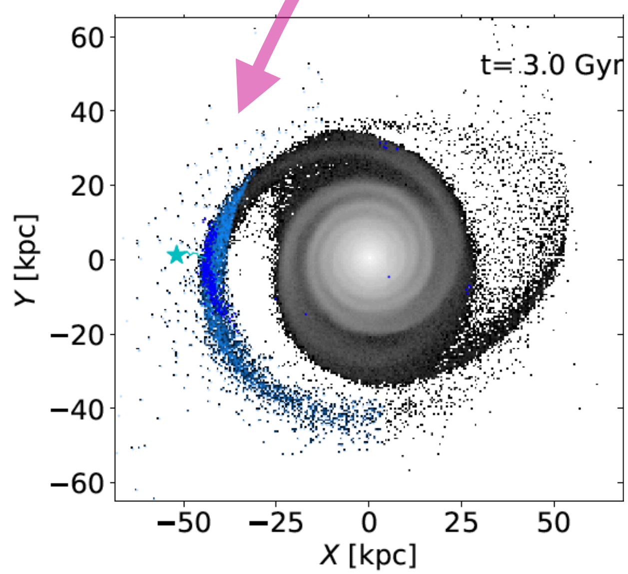
Morganson+16, Deason+19

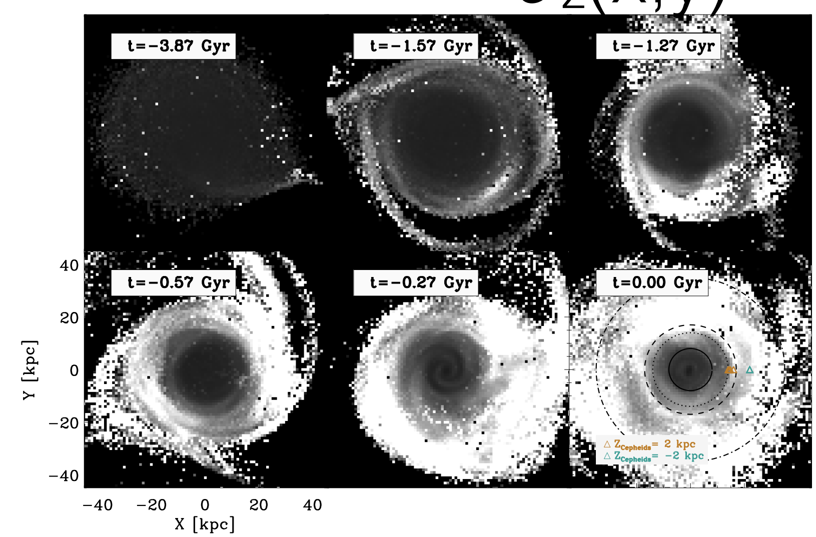
Confirmation of the disc nature of feathers
ages distributions and evidence for modulation in SFH in outer disc



continuous formation

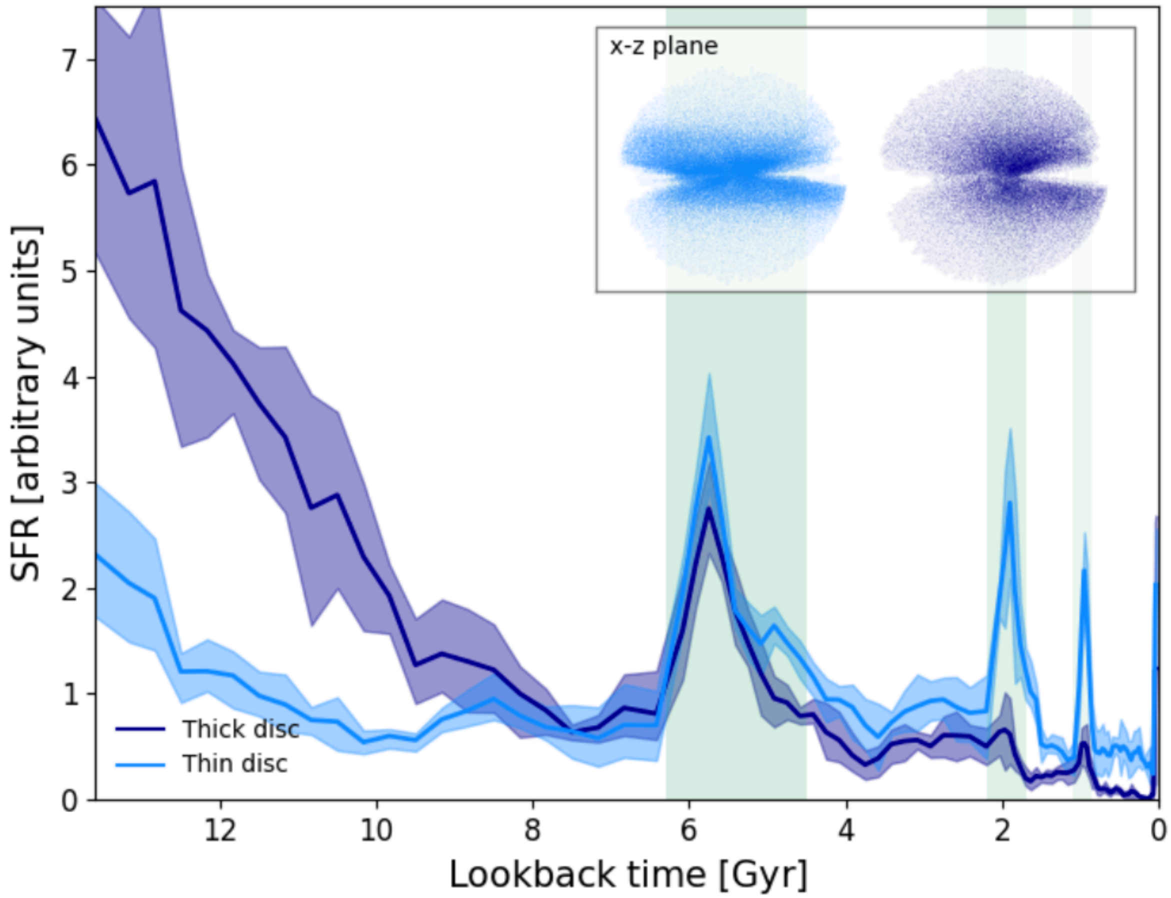
$\boldsymbol{\sigma}_Z(x,y)$

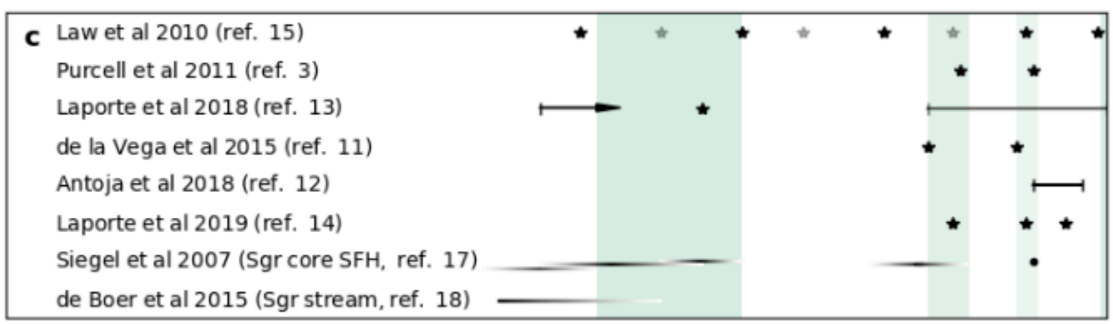




early decoupling

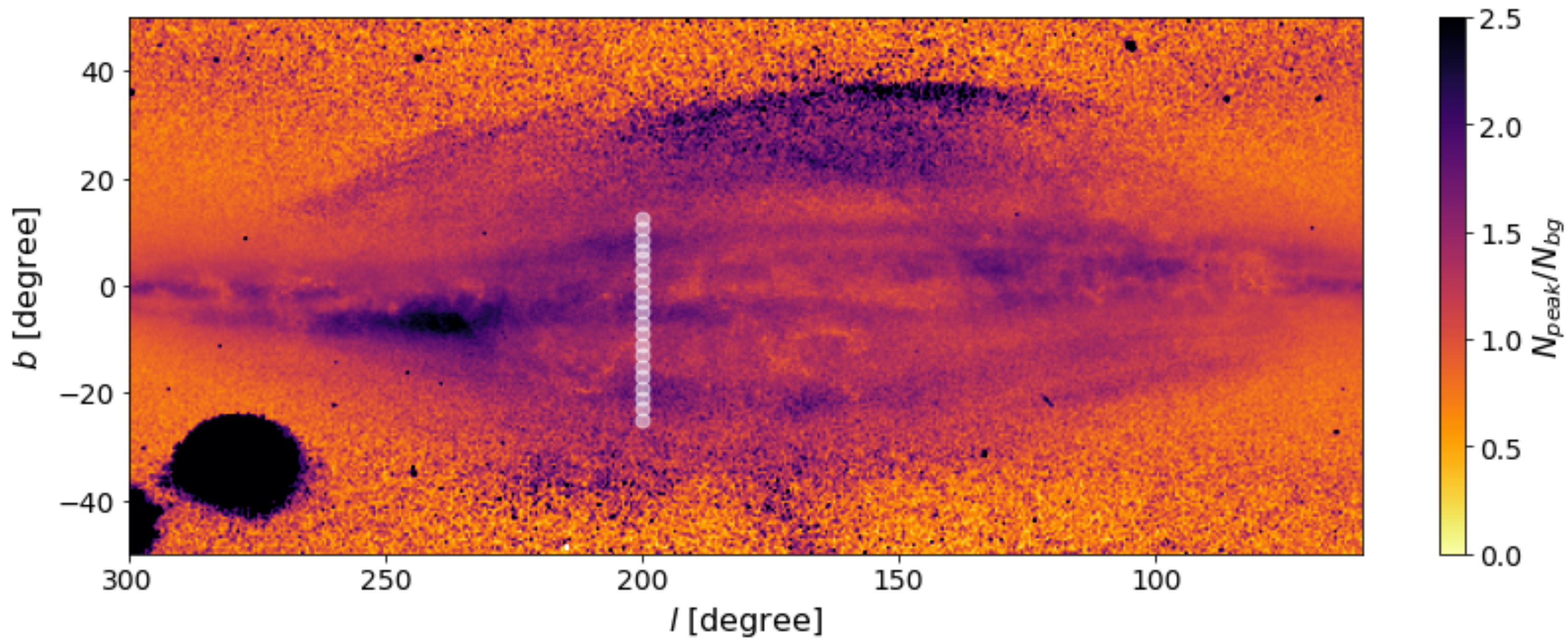
Using the disc to constrain the orbital mass loss history of Sgr





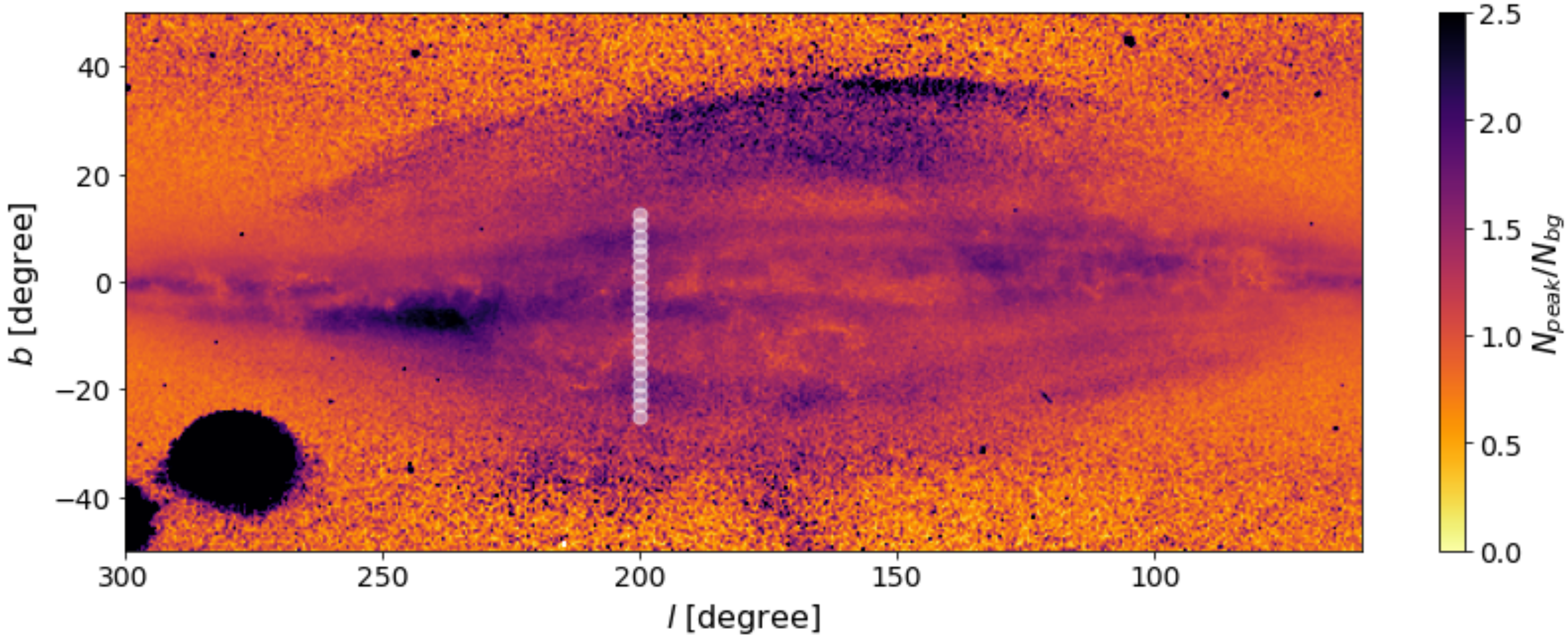
Ruiz-Lara et al. 2020

Spectroscopic follow-up with WEAVE (PI: Laporte)



20 pointings, ~16,000 spectra for **MSTOs (not covered by WEAVE GA survey)** down to G~20 to get photo-spectroscopic ages in substructure/background

Spectroscopic follow-up with WEAVE (PI: Laporte)



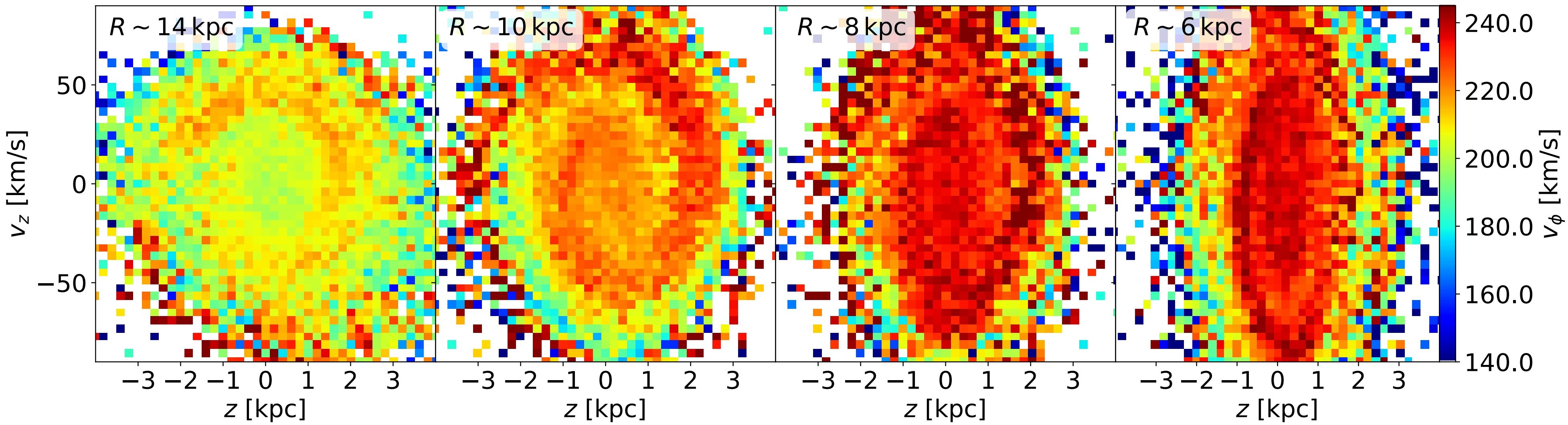
20 pointings, ~16,000 spectra for **MSTOs (not covered by WEAVE GA survey)** down to G~20 to get photo-spectroscopic ages in substructure/background

Science questions:

- Modulation in SFHs? (see also Ruiz-Lara+20)
- Timing impacts of perturber(s)?
- Which structures are genuine "feathers" which ones are folds?

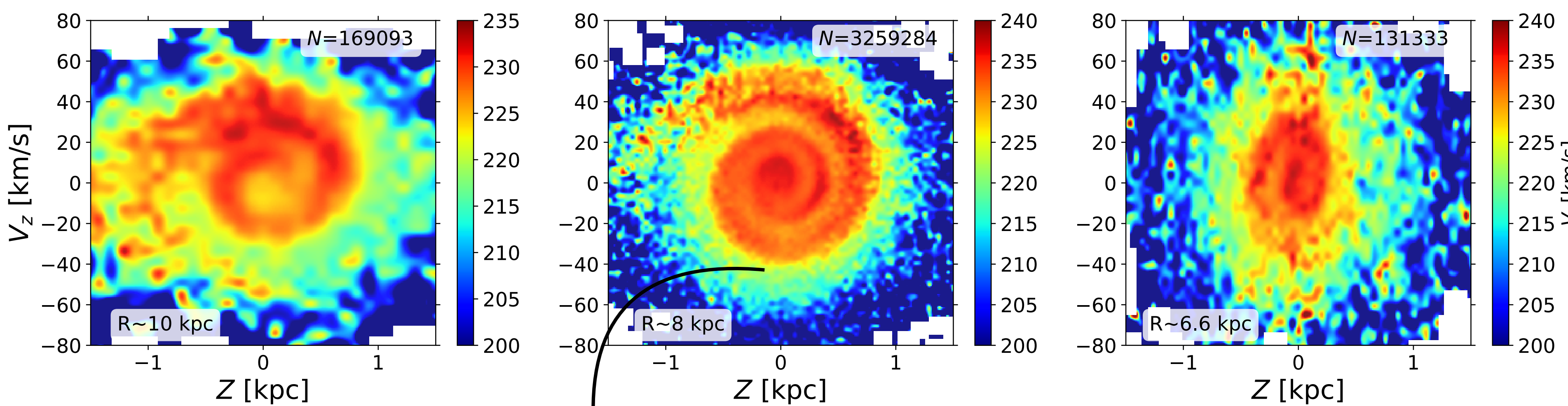
phase-space spiral behaviour in a **Galactic** potential perturbed by a recent satellite encounter

pre-Gaia DR2 N-body simulations



Laporte+19c

Gaia DR2 observations



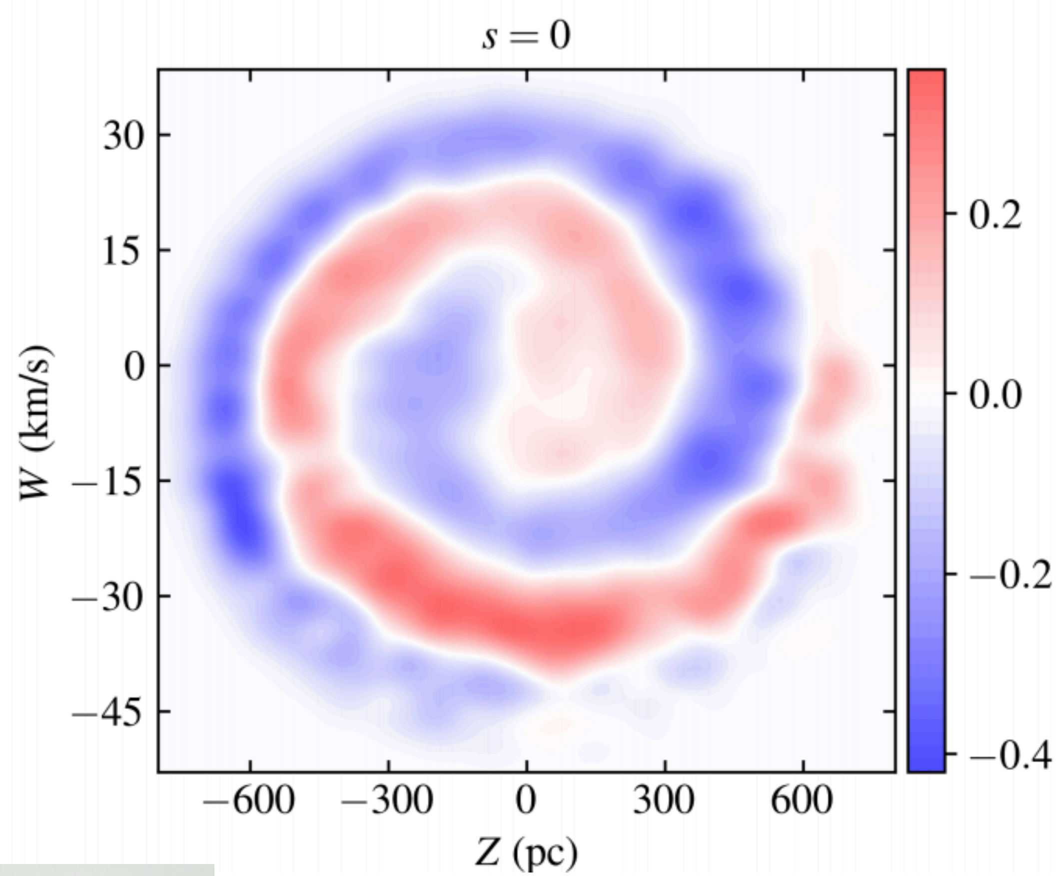
(original) Antoja+18 @8kpc

Laporte+19c

First measurement of the dark matter density using **non-equilibrium dynamics** rules out thin dark disc

Model background phase-space
distribution modelled as GMM

What’s left is the phase-space spiral -> potential



Widmark, Laporte, de Salas (2021)
Widmark, Laporte, de Salas, Monari (2021)

Applied to eleven different volumes around the Sun

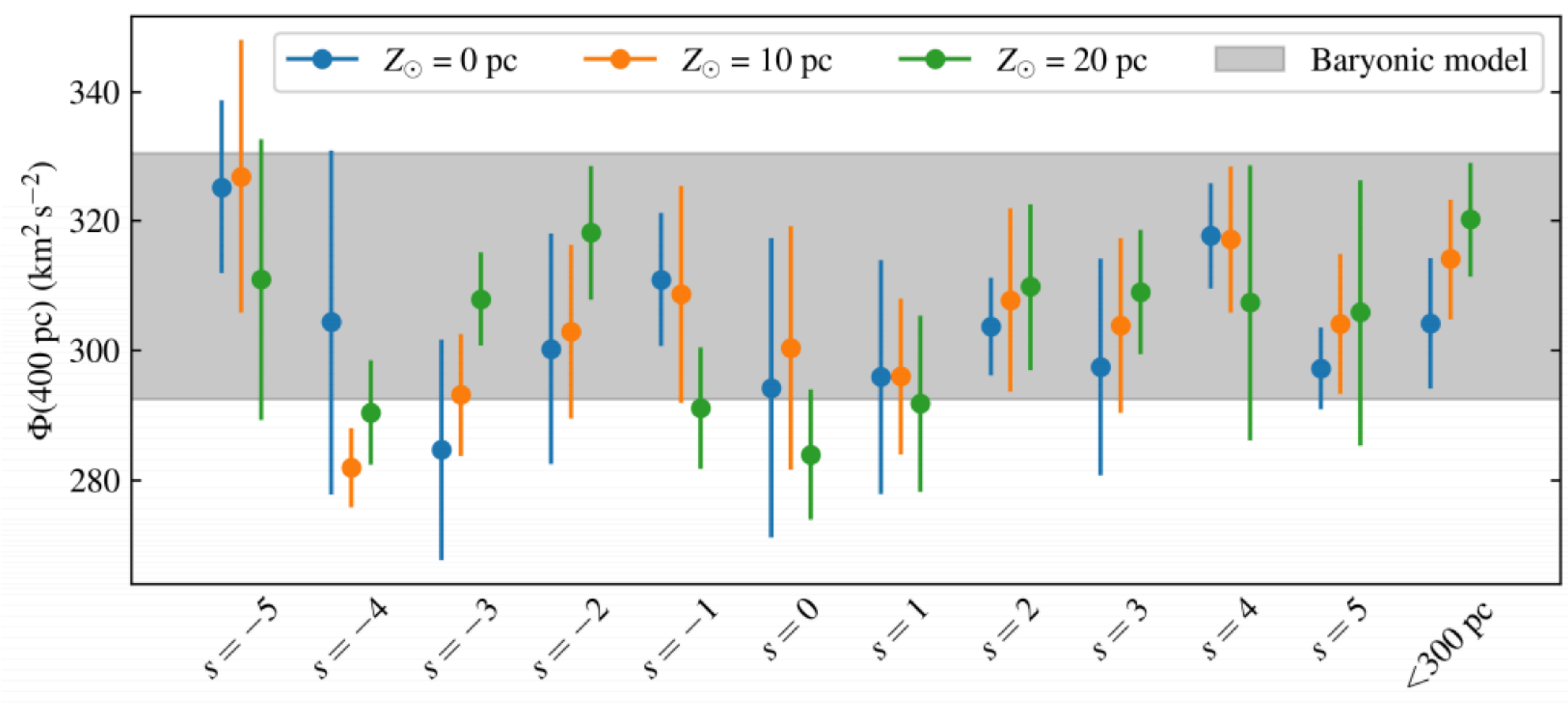


Fig. 6: Inferred gravitational potential at height z = 400 pc for all data samples (s from -5 to 5 and $\sqrt{X^2+Y^2}$ < 300 pc). The markers and vertical lines show the mean and standard deviations as derived from jackknifing, where the colours represent the three fixed values for the height of the Sun ($Z_\odot = \{0, 10, 20\}$ pc). The grey band represents the baryonic model, including a dark matter density of $0.011 \pm 0.003\ M_\odot pc^{-3}$.

Local DM_density = 0.0085 ± 0.0039 Mpc^–3 = 0.32 ± 0.15 GeV cm^–3

Conclusions

- Proper motions can be used to probe Galactic structure - cheap new efficient method to explore substructure in the disc based (to be extended to treat multiple peaks)

- Many newly uncovered substructures towards the midplane historically heavily obscured by dust (Laporte, Koposov & Belokurov 2021)

- Could be groups of stars coherently excited during satellite encounters or folds of bending waves seen in projection. Confirmation for a few structures already from legacy surveys (Laporte+20)

- Spectroscopic follow up possible to get reliable ages potentially probe sequence of events that shaped SFH of outer disc (more on that in the future)

- Non-equilibrium dynamics can be used constrain DM density locally (but also prospects to apply it across the disc are good) - Widmark+21

THANK YOU IPMU

Hope to see you all again in the near future…

… hopefully IPMU GA workshop 2022