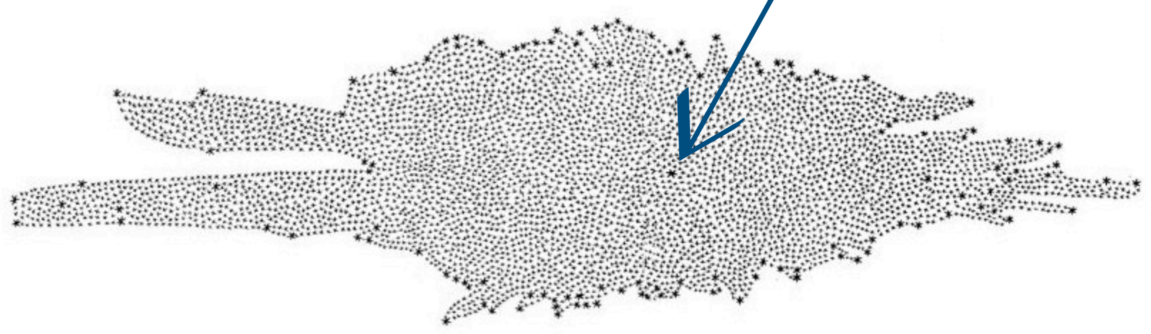
Dark Matter in the Milky Way

Shortcomings & Dynamical Tests

María Benito - 1st General Meeting of COST Action COSMIC WISPers (CA21106)

Hyper-brief (biased) history

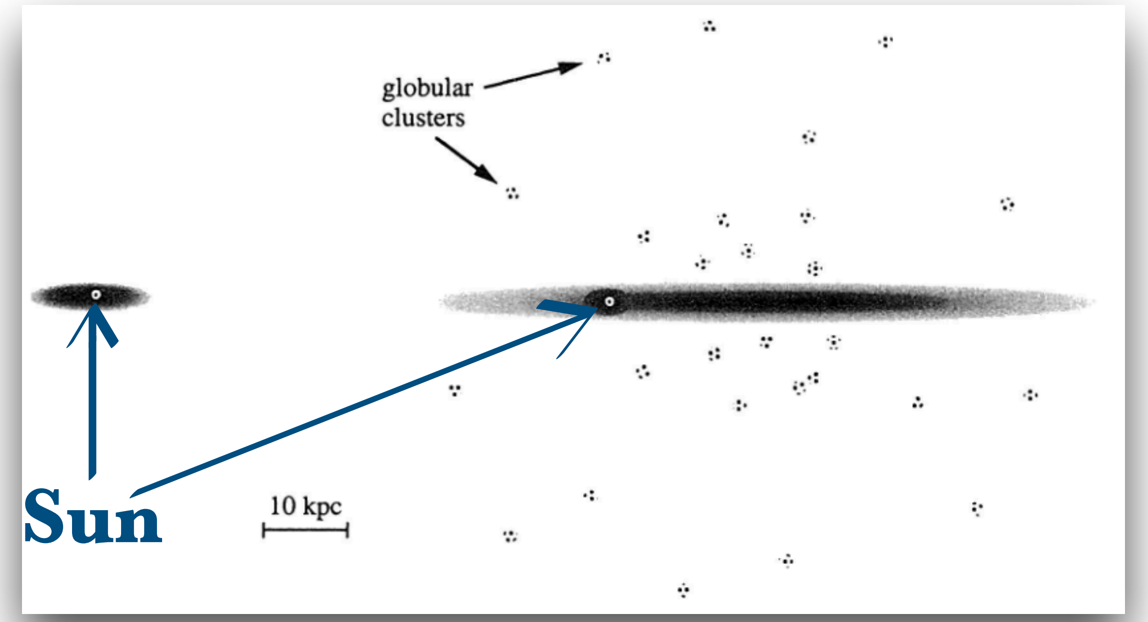
Sun



1785

Herschels MW model
- Sun lies close to the middle
- Distribution is flattened extending ~5x further in plane that in the perpendicular direction

1920



Kapteyn & van Rhijn/ Shapley MW models

Dust obscures our view of the MW
1930

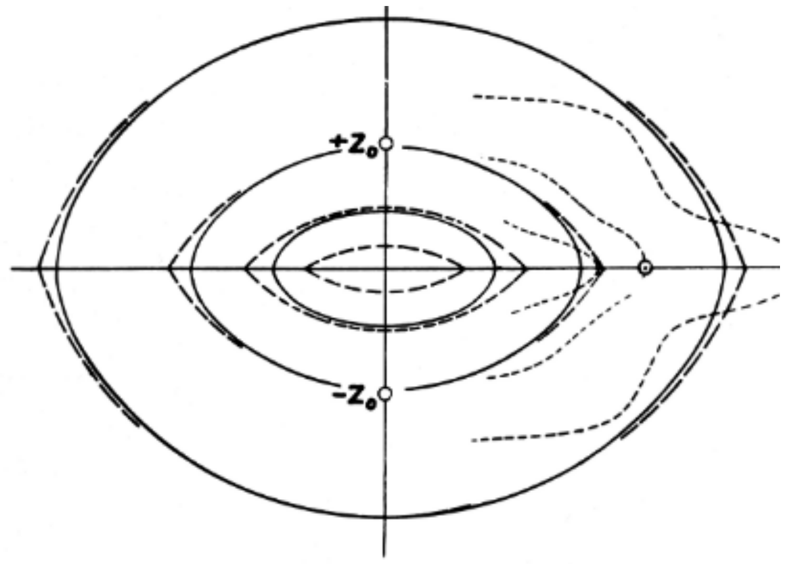
1944
21-cm line discovery

Schmidt 1956
Kuzmin 1956
Perek 1959
Idlis 1961
Einasto 1965
Innanen 1966
Takase 1967
Einasto 1970
Miyamoto & Nagai 1975

MW models

1960

1970

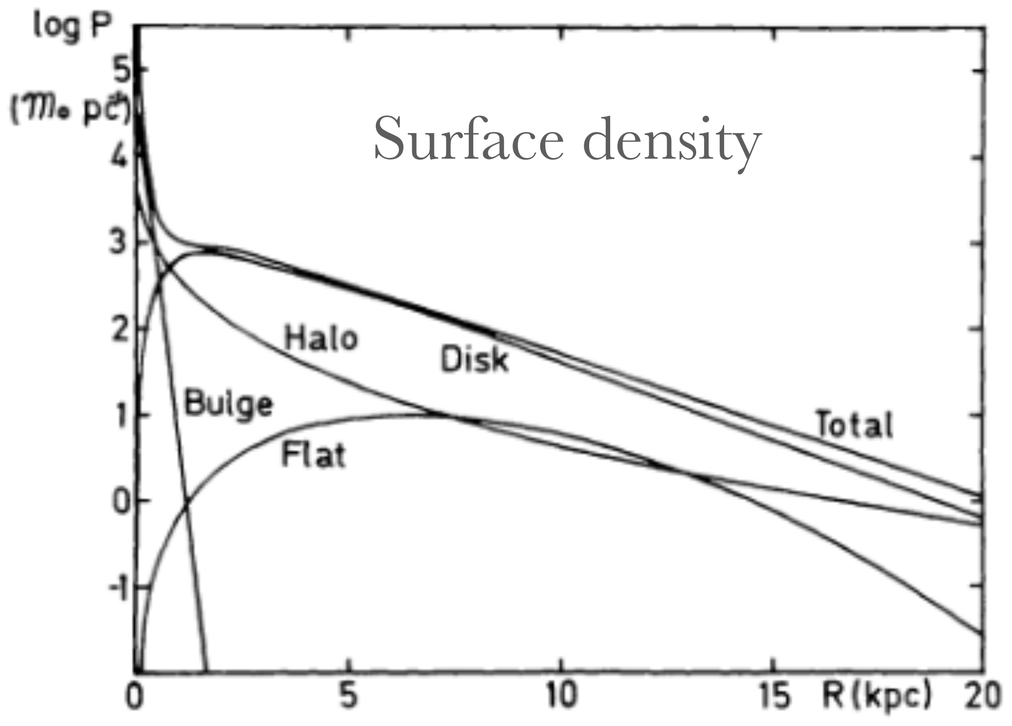


Isodensity contours

1974
Einasto et al &
Ostriker et al:
Galaxies are surrounded by an extended halo

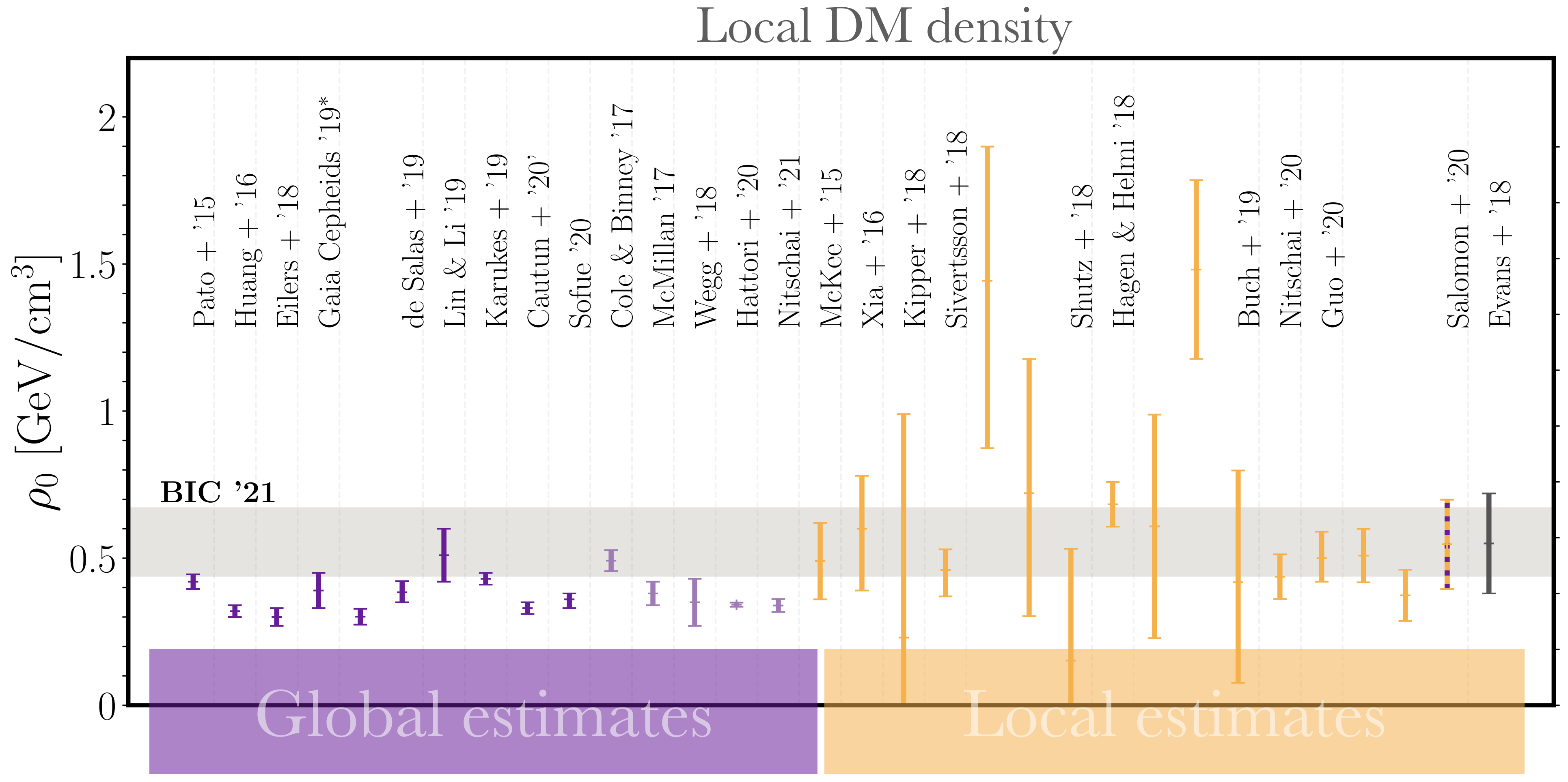
Classical paradigm with no DM VS. new one with DM @ 3rd European Astronomy meeting in Tbilisi (Georgia)
1975

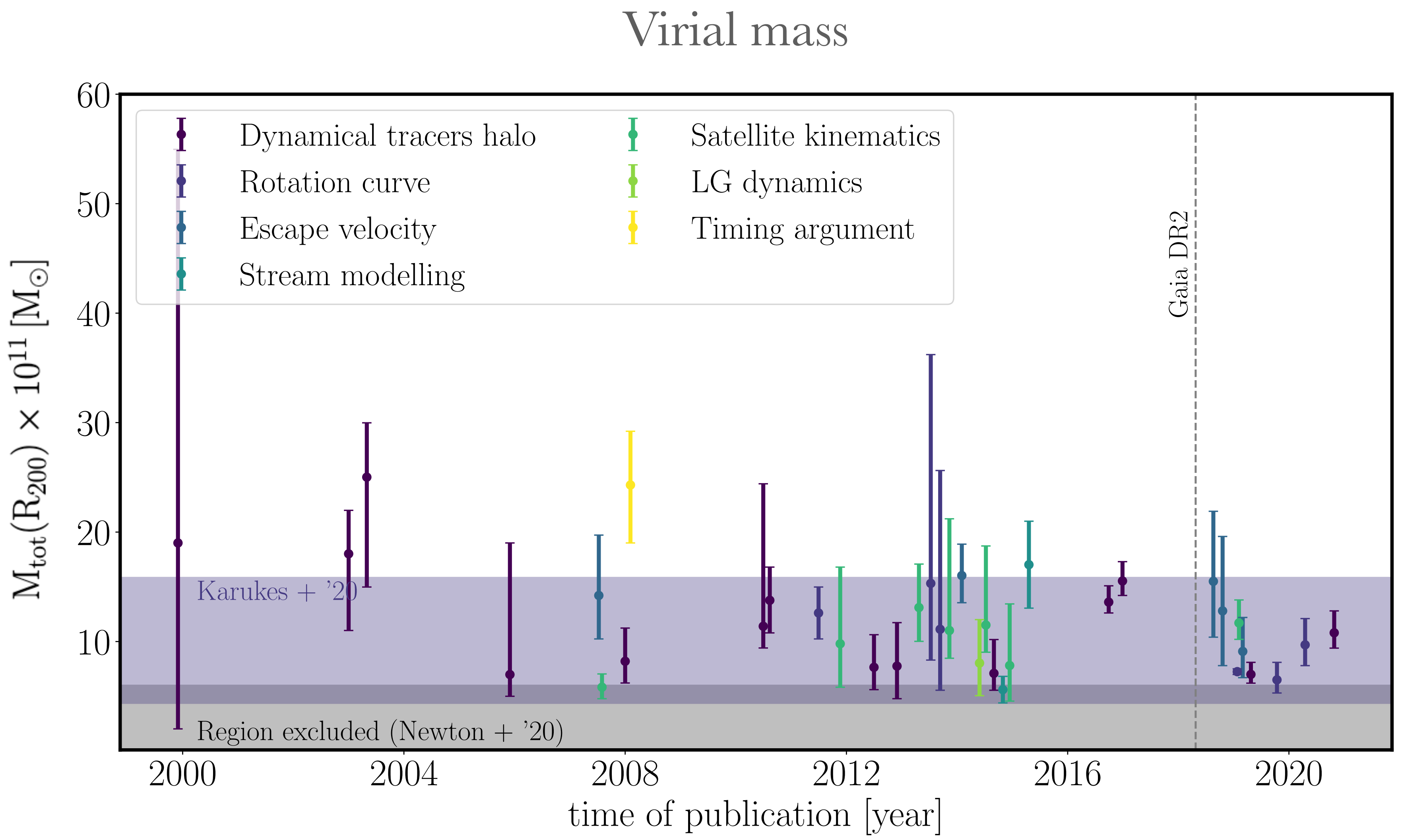
Galactic models w/ a DM halo

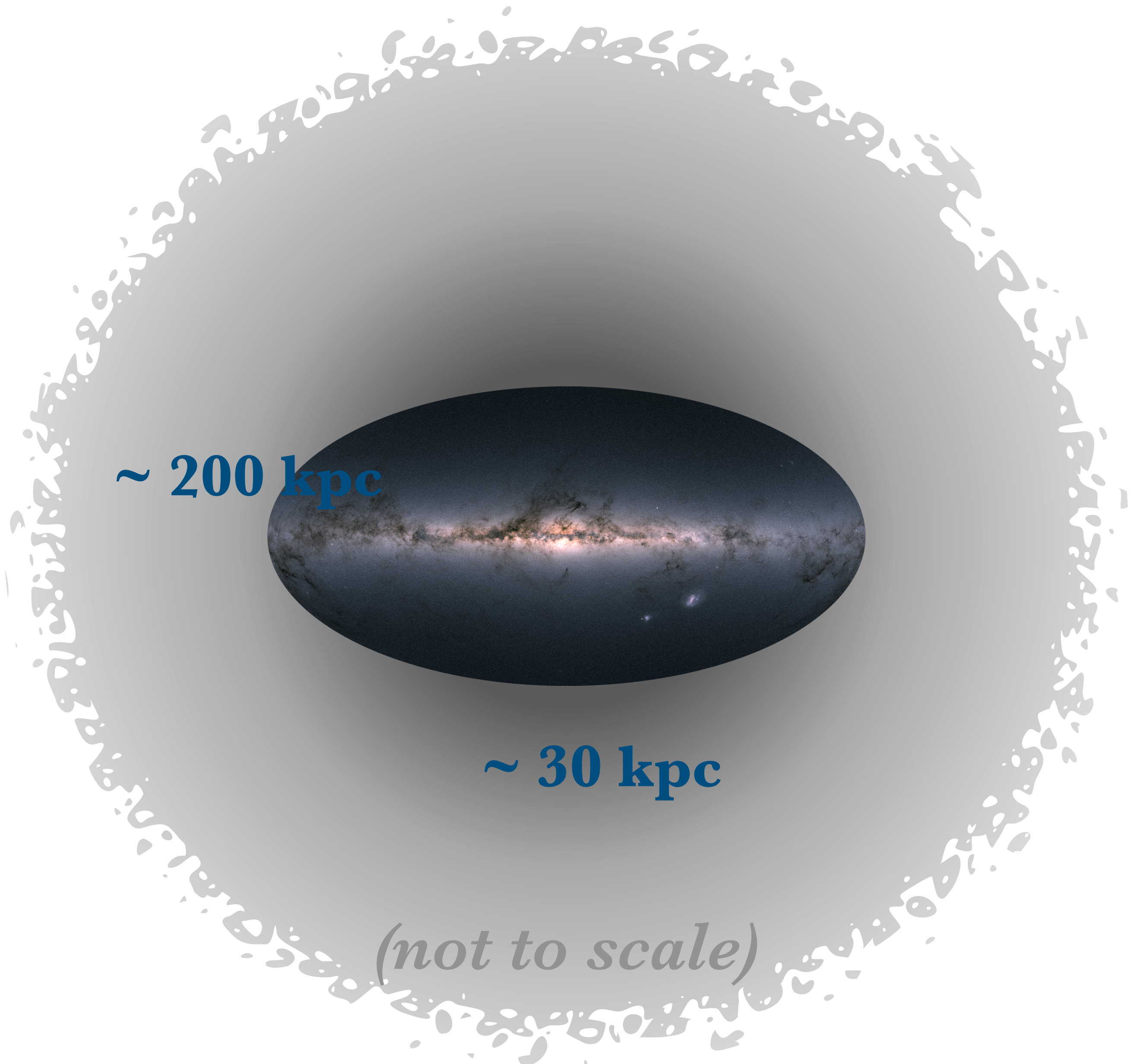


Einasto 1979

Hyper-brief (biased) history



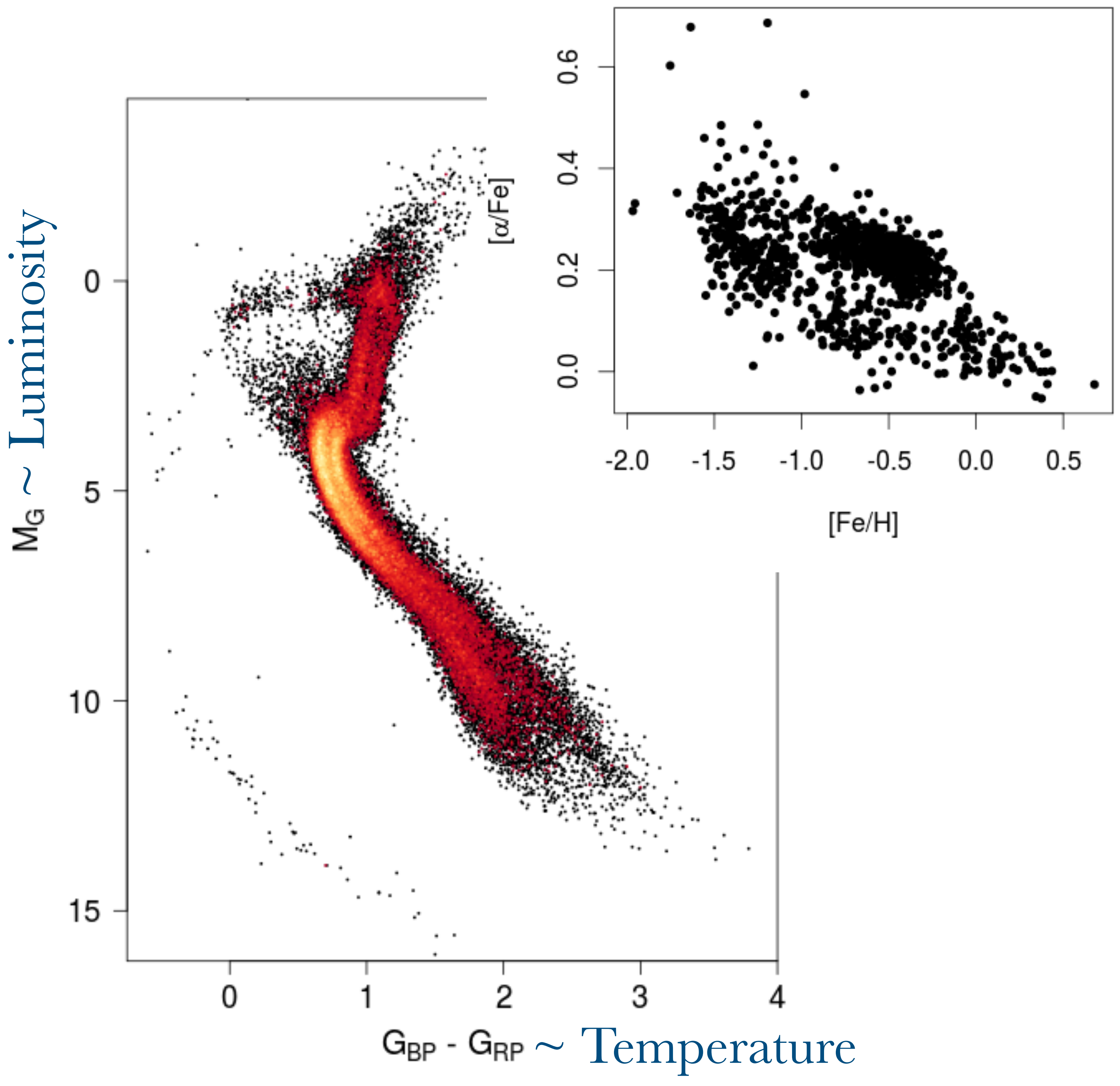




See also e.g. Helmi + [1806.06038], Gallart + [1901.02900]

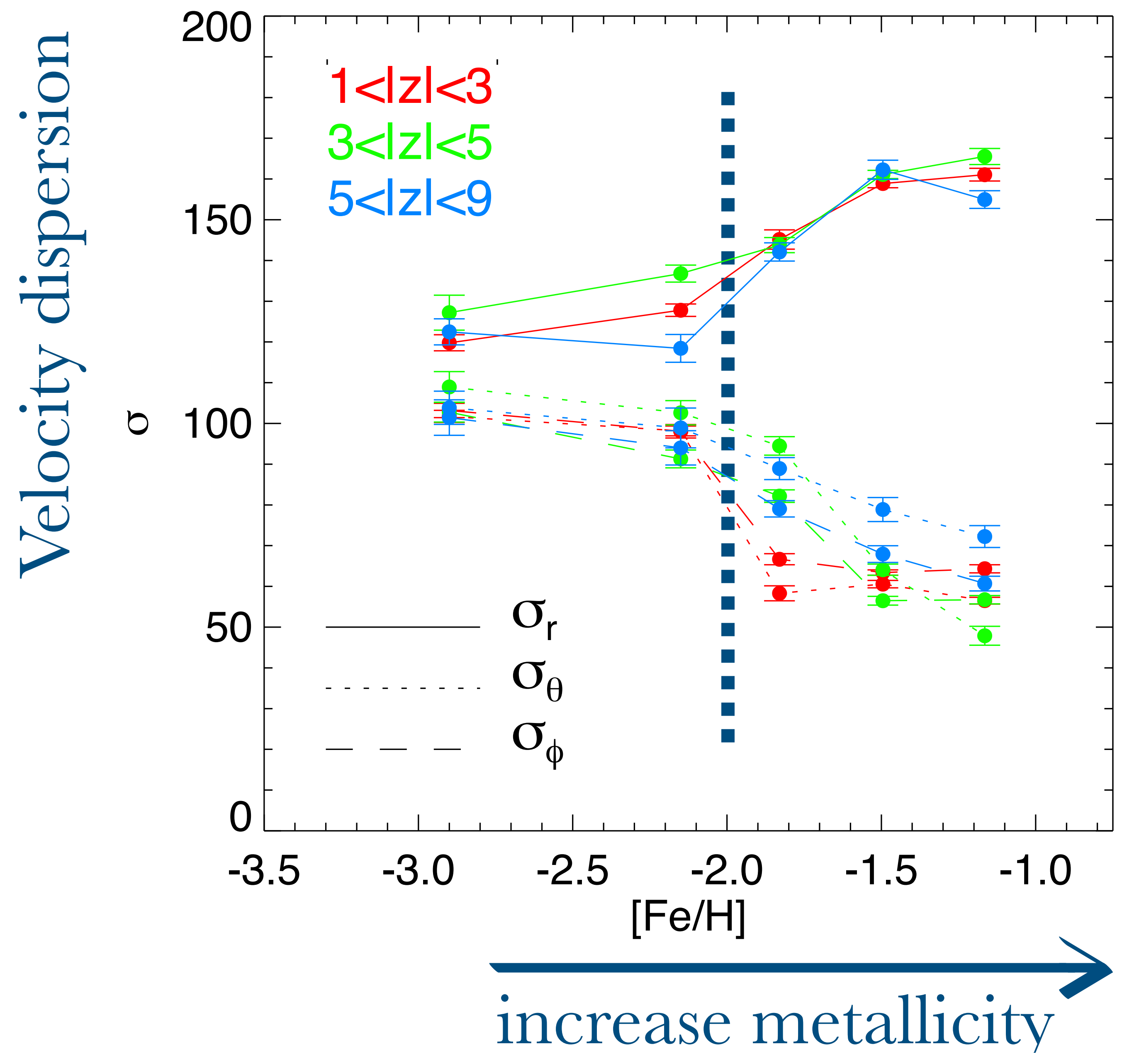
Gaia-Sausage-Enceladus merger 7-11 Gyr ago

Bimodal chemical composition



Babusiaux + (Gaia collab.) [1804.09378]

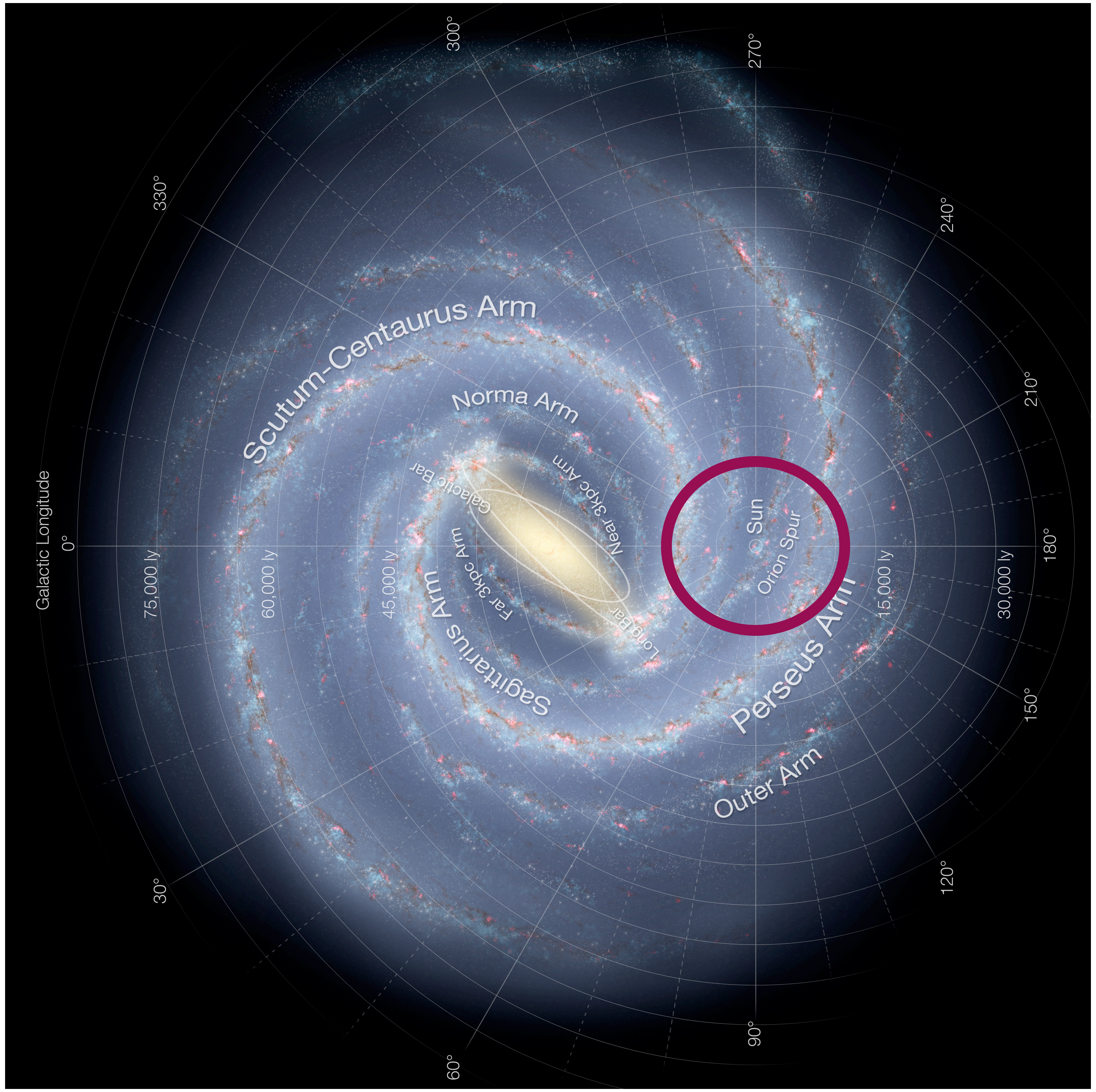
Bimodal kinematics

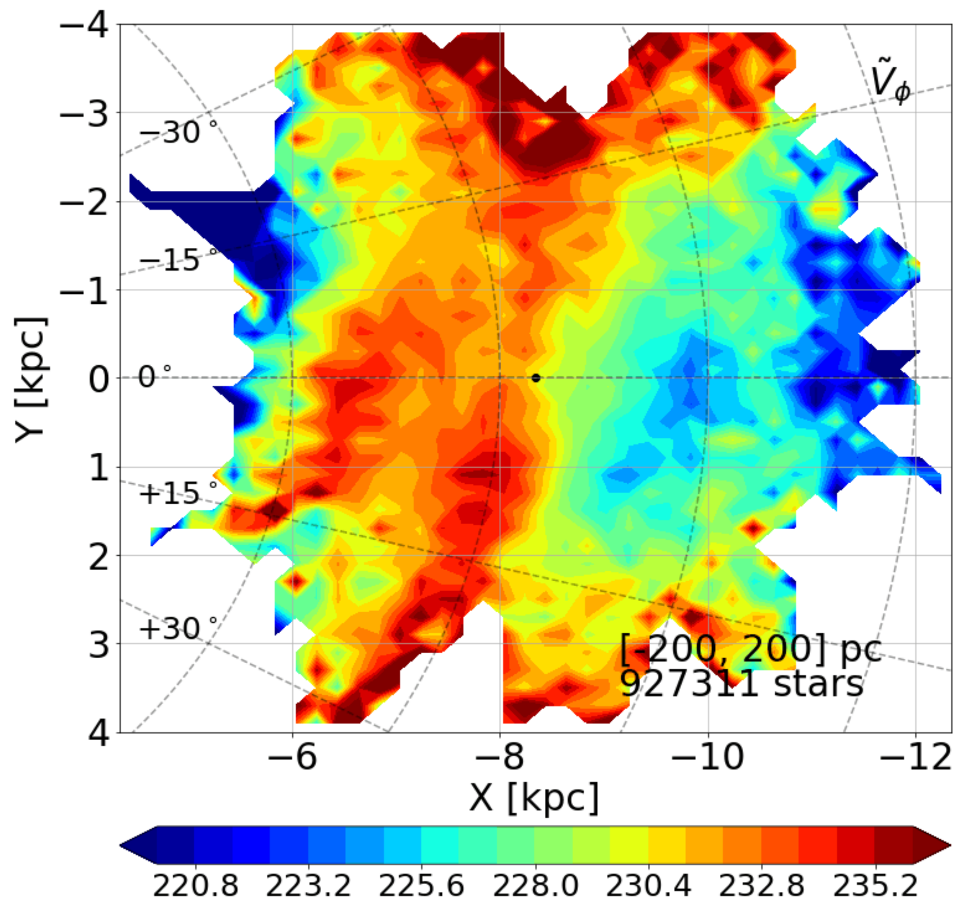


Belokurov +[1802.03414]

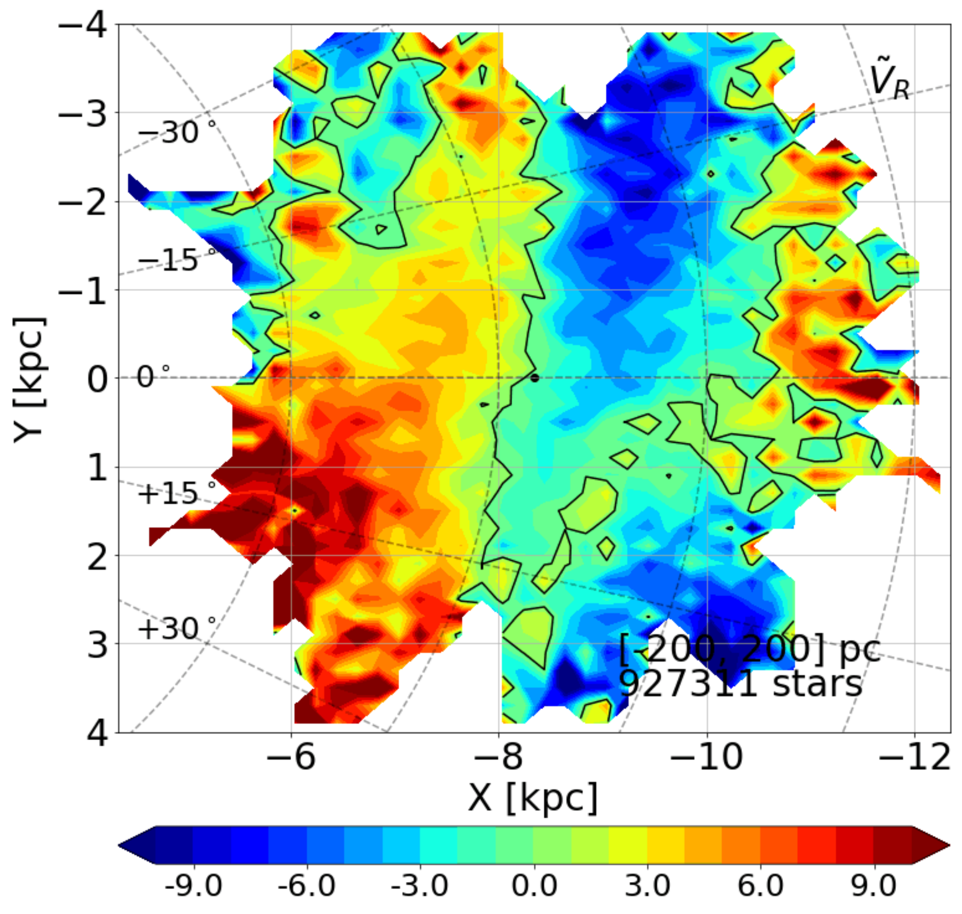
Galaxy as a complex evolving system

Katz + (Gaia collab.) [1804.09380]

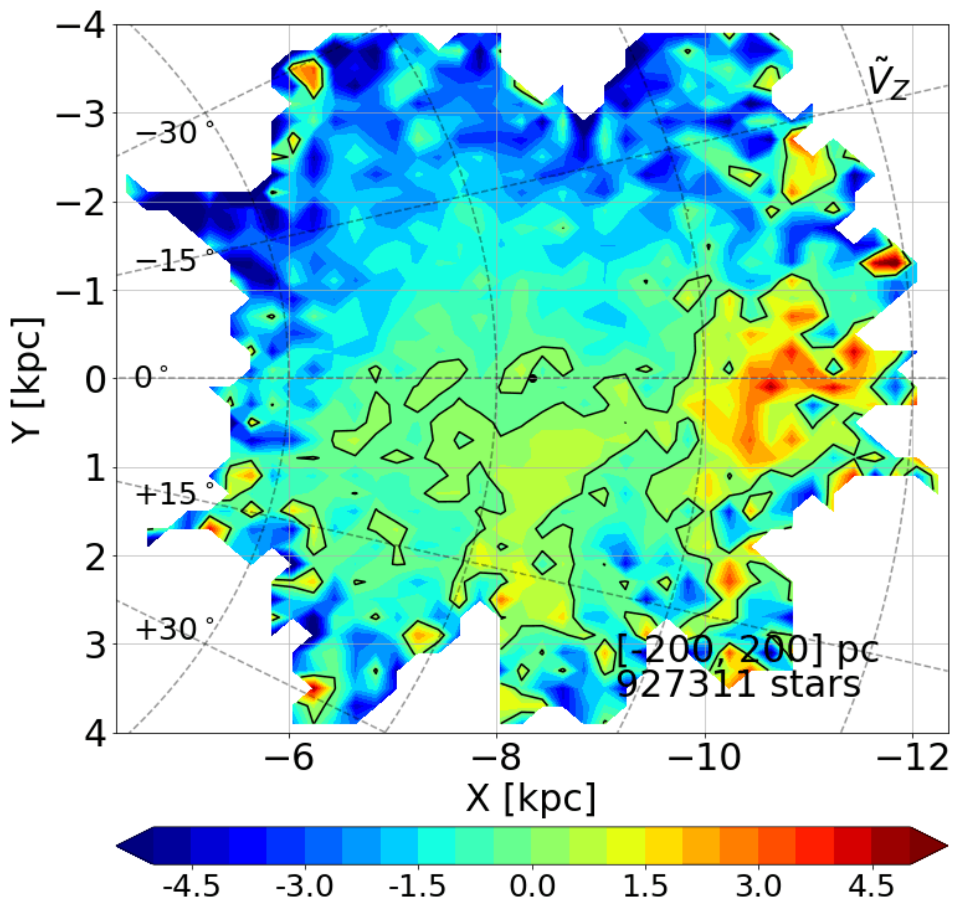




Rotational velocity [km/s]



Radial velocity [km/s]

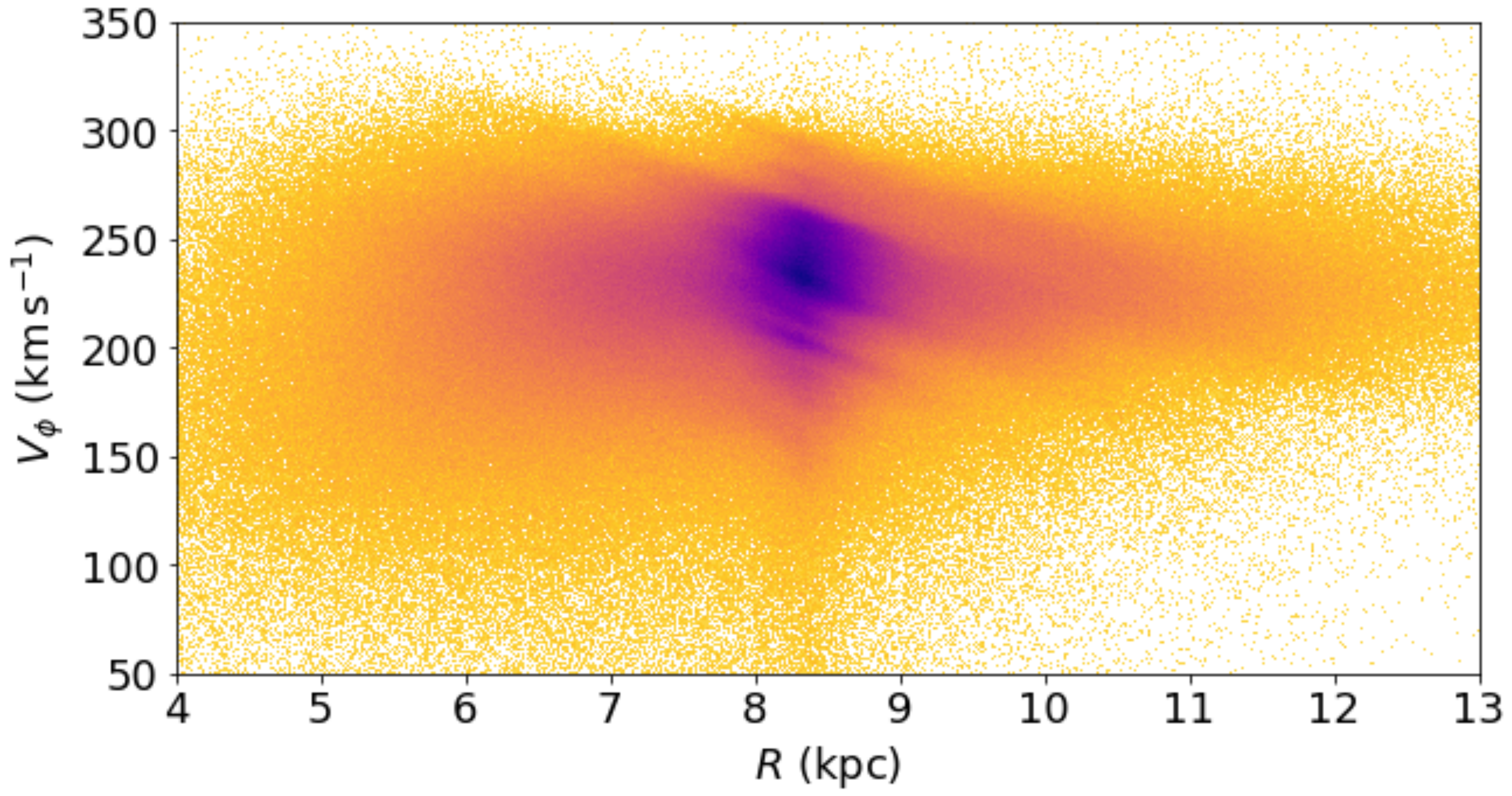


Vertical velocity [km/s]

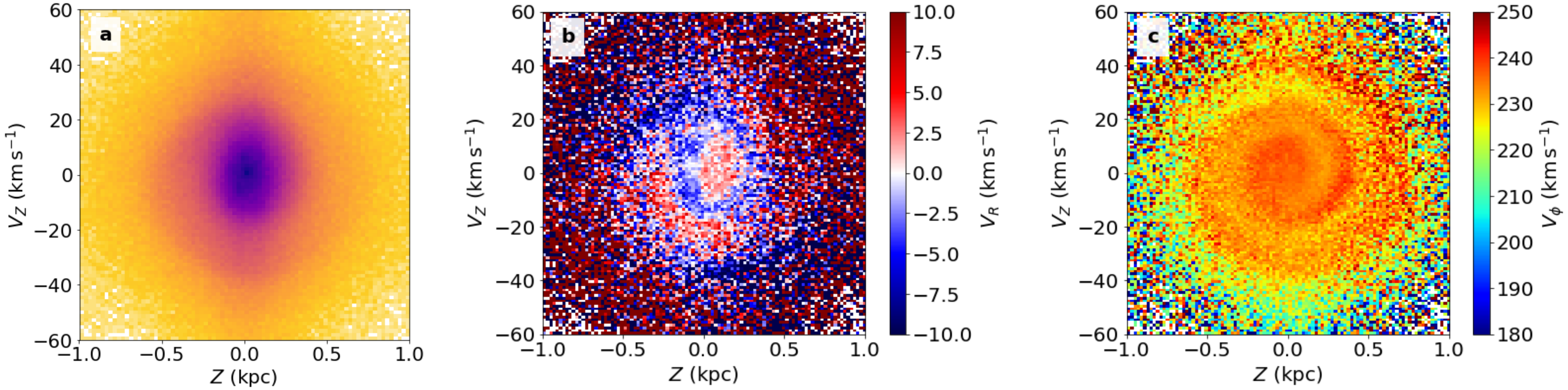
Galaxy as a complex evolving system

Large-scale dynamical features: ripples, ridges and spirals

Rotational velocity vs. Galactocentric radius



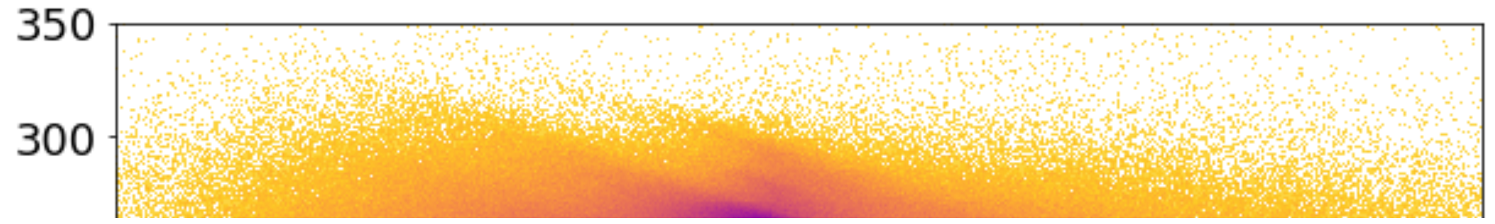
Vertical phase-space (z, v_z)



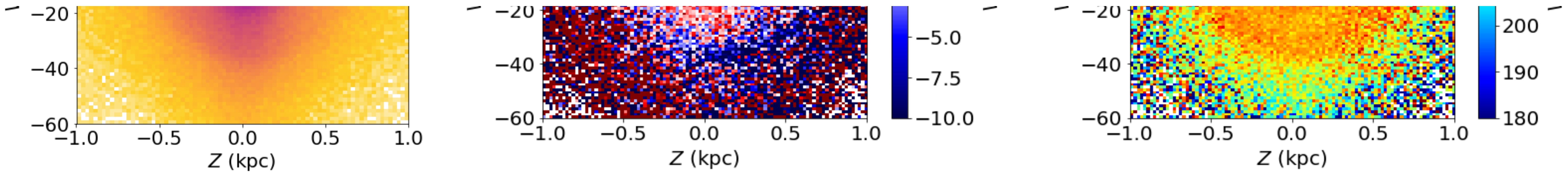
Antoja + [1804.10196]

Large-scale dynamical features: ripples, ridges and spirals

Rotational velocity vs. Galactocentric radius



Astrophysical Observables → Dynamical model → ¿? DM Distribution → Astrophysical/ Laboratory DM searches → Particle Physics



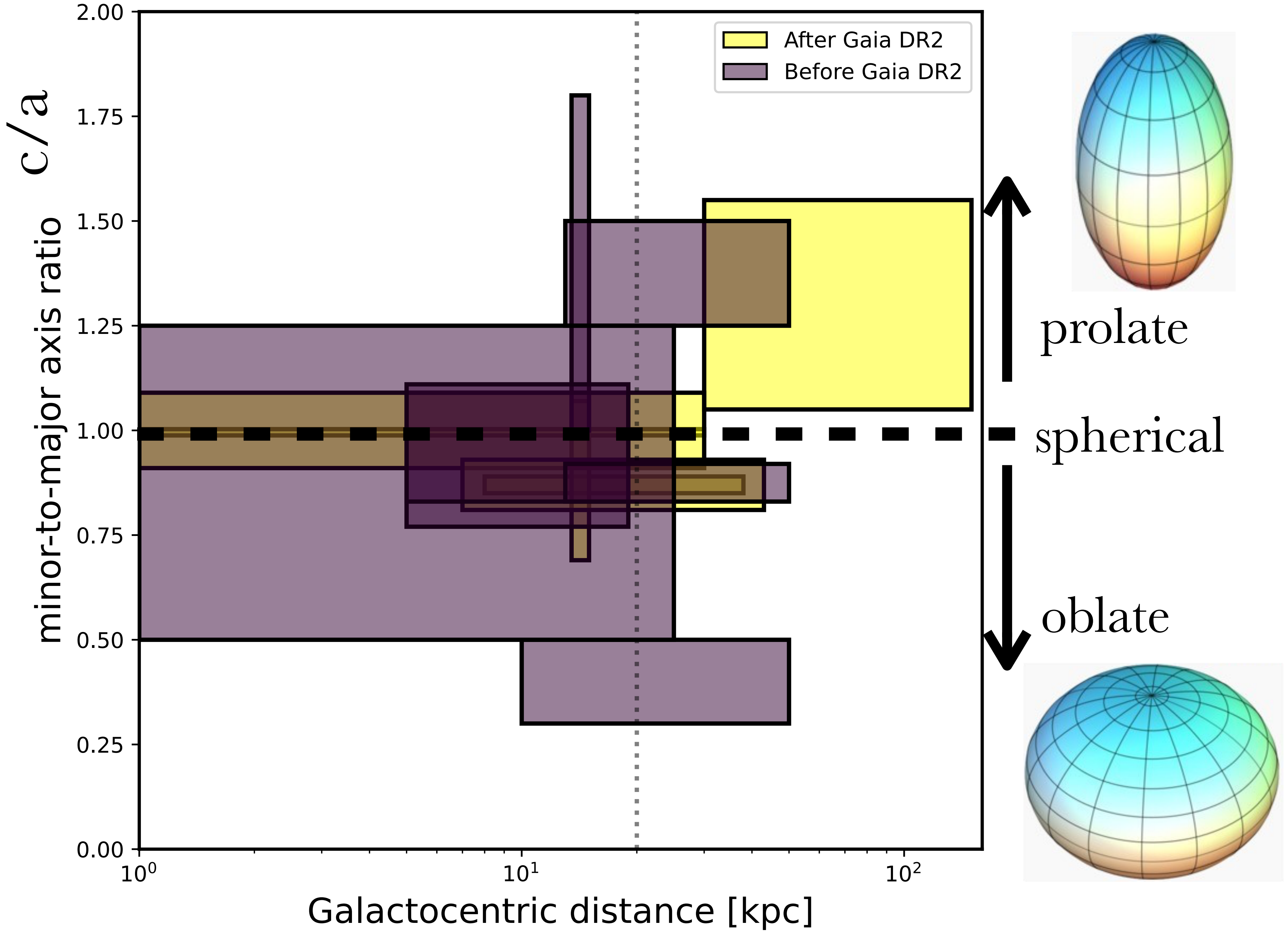
Antoja + [1804.10196]

¿ DM halo shape ?

The shape of the MW's DM halo likely changes as a function of radius, as expected in cosmological simulations Vera-Ciro & Helmi 2013 [1304.4646]

$q_\rho = c/a = 0.93 \pm 0.16$

$q_\rho = c/a = 1.00 \pm 0.09$



See Vargya + [2104.14069] for references

- Radii smaller than ~ 20 kpc: spherical

Using Pal-5: $q_\rho = c/a = 0.93 \pm 0.16$ Bovy + [1609.01298]

Using halo stars: $q_\rho = c/a = 1.00 \pm 0.09$ Wegg + [1806.09635]

See also Koposov + '10, Bowden + ' 15, Küpper + '15

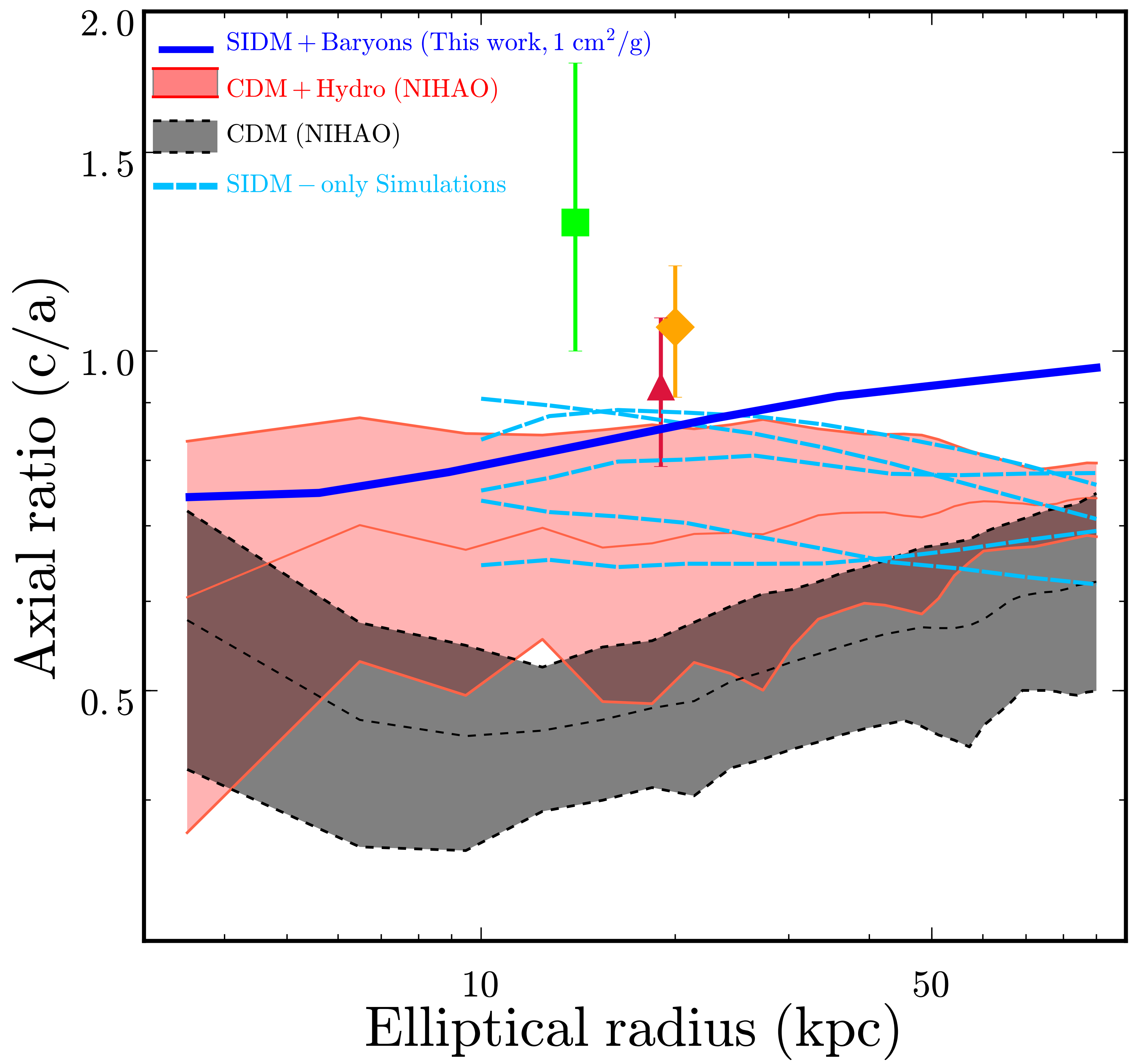
- Radii larger than ~ 20 kpc: oblate w/ minor axis ~ aligned to the LMC orbital pole?

Erkal + ' 19, Cunningham + '20, Vasiliev + '21

But see e.g. Vera-Ciro & Helmi '13

DM halo shape

Information about DM self-interactions?



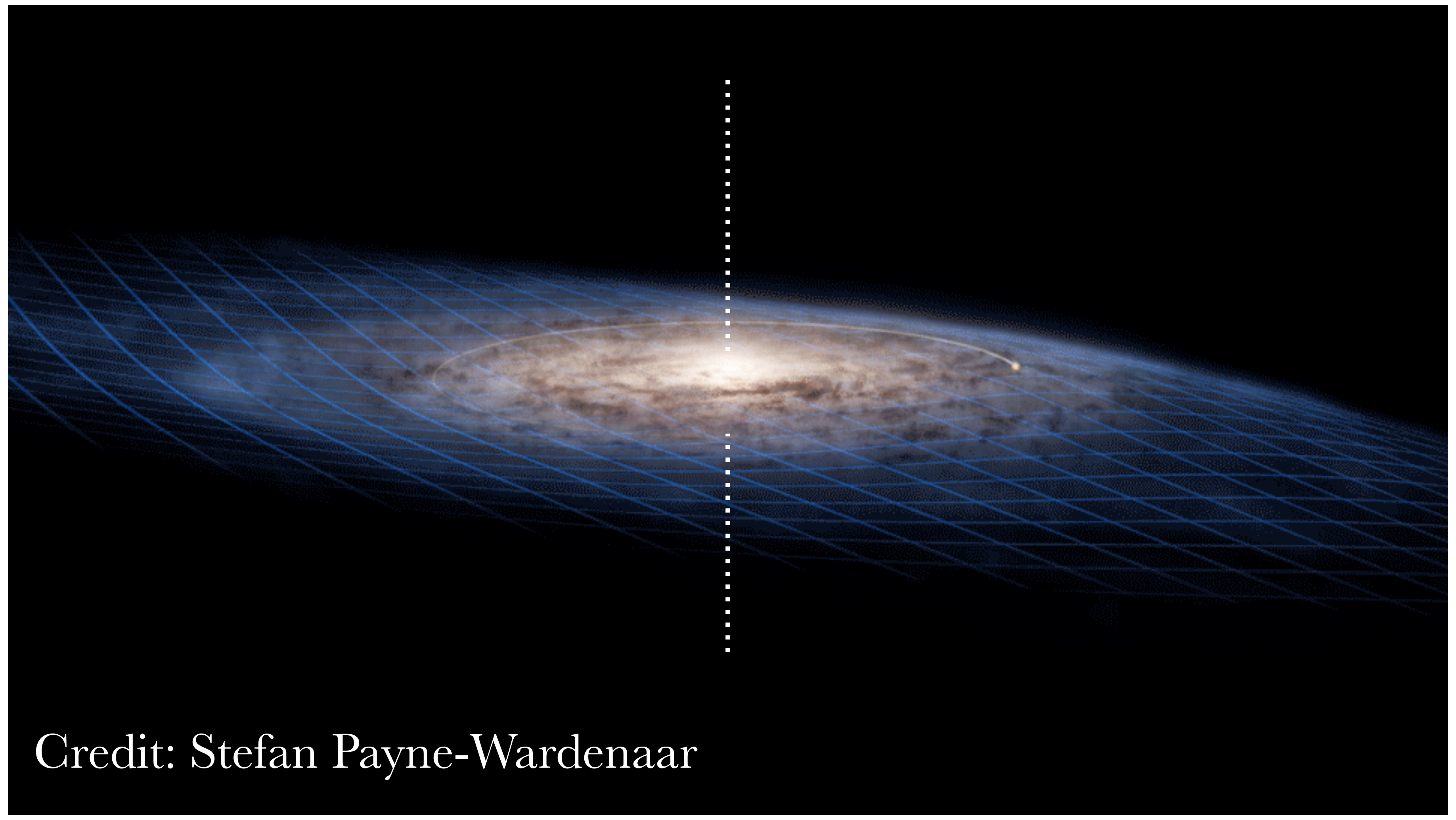
Sameie +[1801.09682]

See also Yoshida + '00, Peter + '13, Bose + '16, Vargya + '22

Dark Matter distribution (under steady-state and axial symmetry)

accounting for uncertainties on:

1. *Rotation curve measurements*
2. *Morphology (3D shape) baryons*
3. *Normalisation (mass) baryons*
4. *Galactic parameters: Sun's velocity & Galactocentric distance*

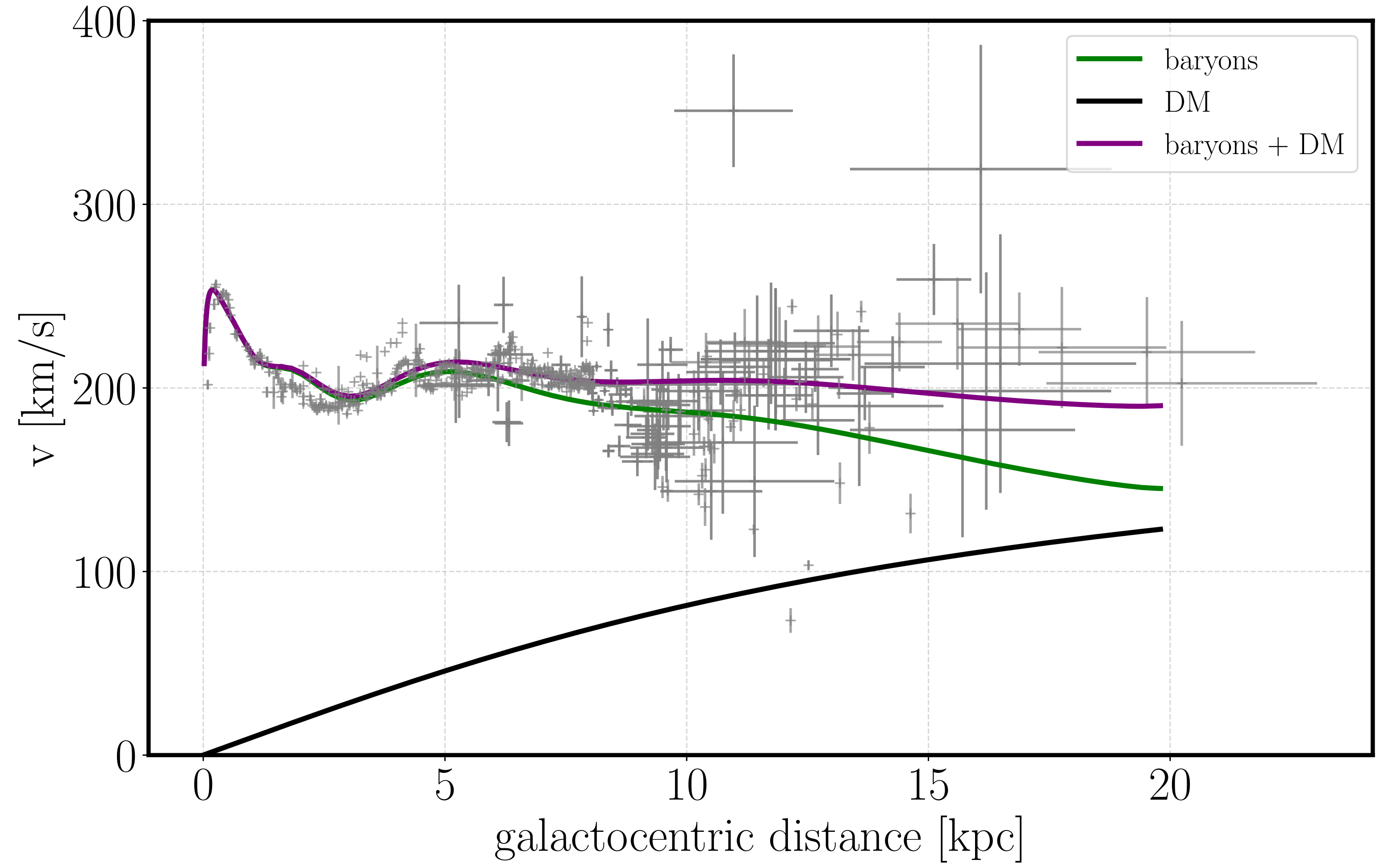


$$\chi^2_{\mathrm{RC,prof}}(V_0, R_s, \rho_0, \gamma)$$

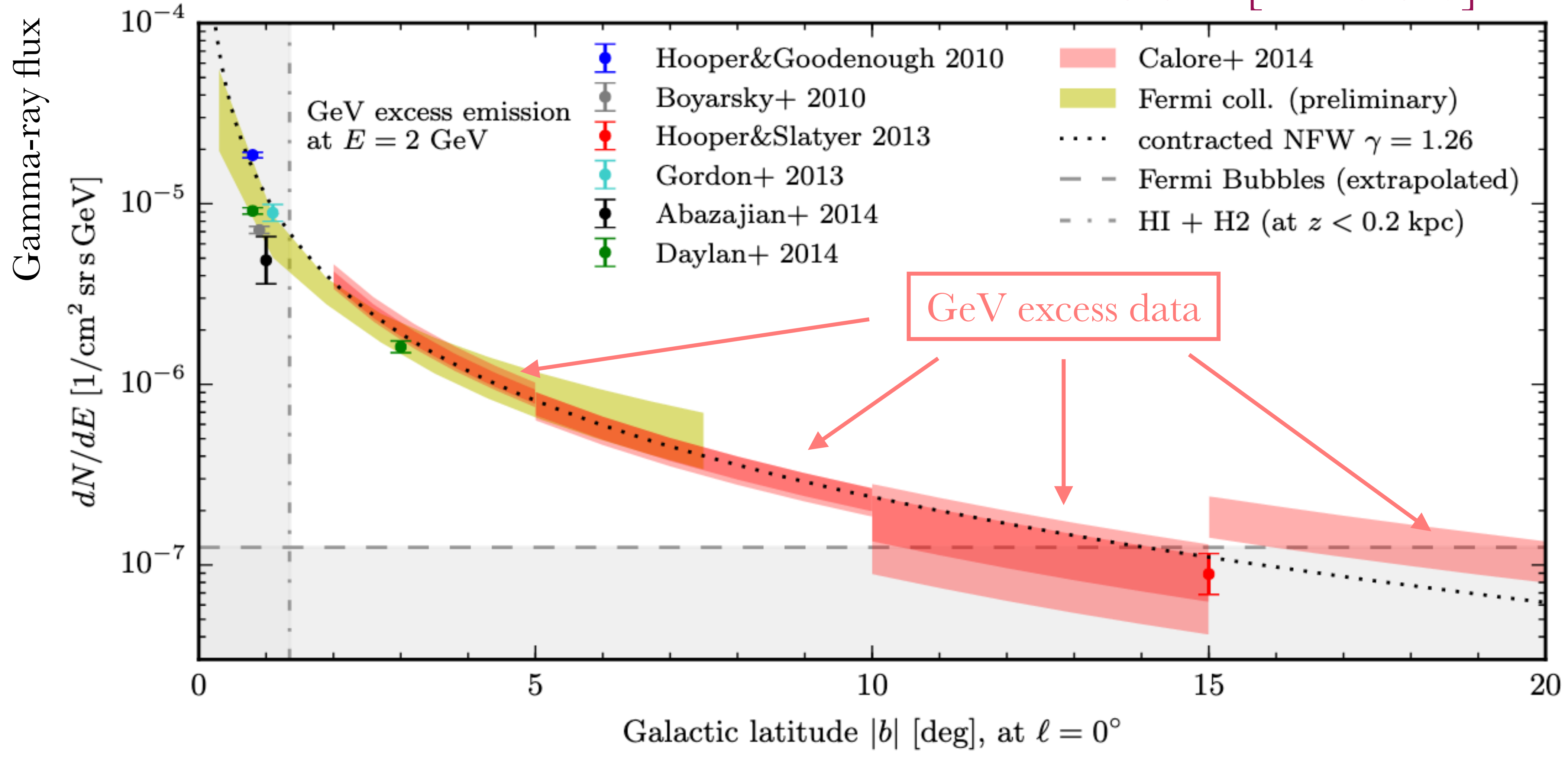
Likelihood accounts for astro uncertainties & its available @ https://github.com/mariabenitocst/UncertaintiesDMinTheMW

MB + [1901.02460] / MB + [2009.13523] / Põder, MB + '23 (accepted in A&A)

Sofue + [0811.0859]

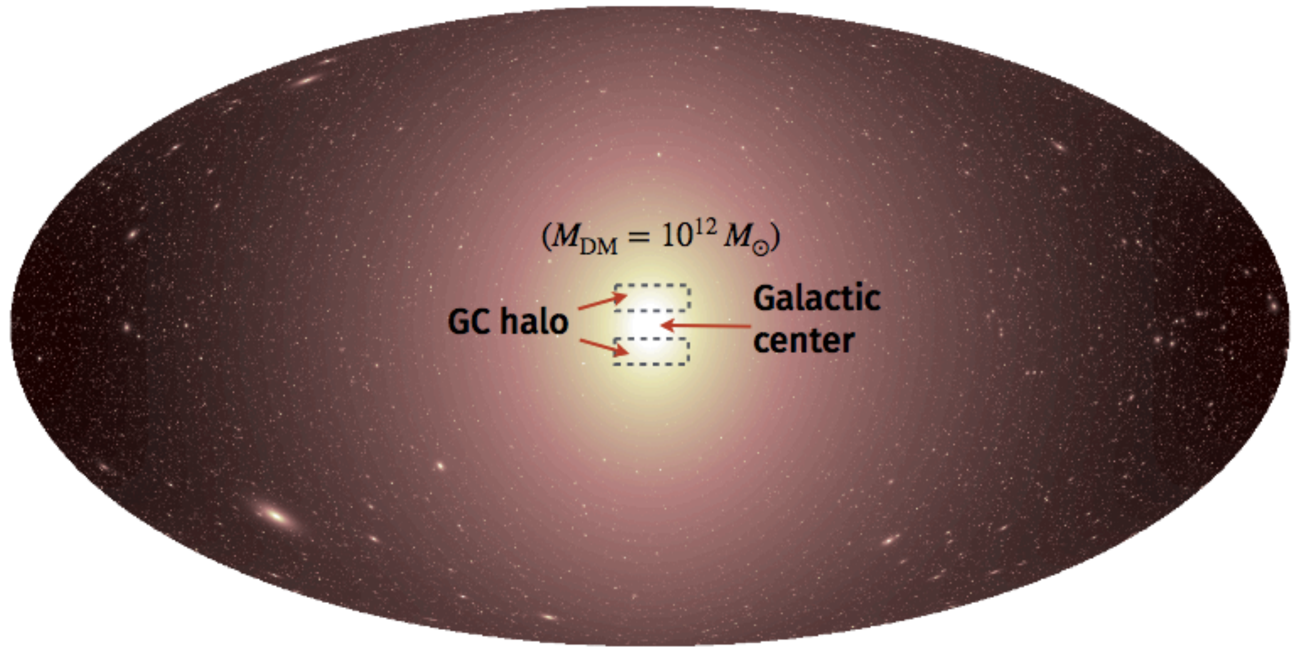


Calore + [1411.4647]

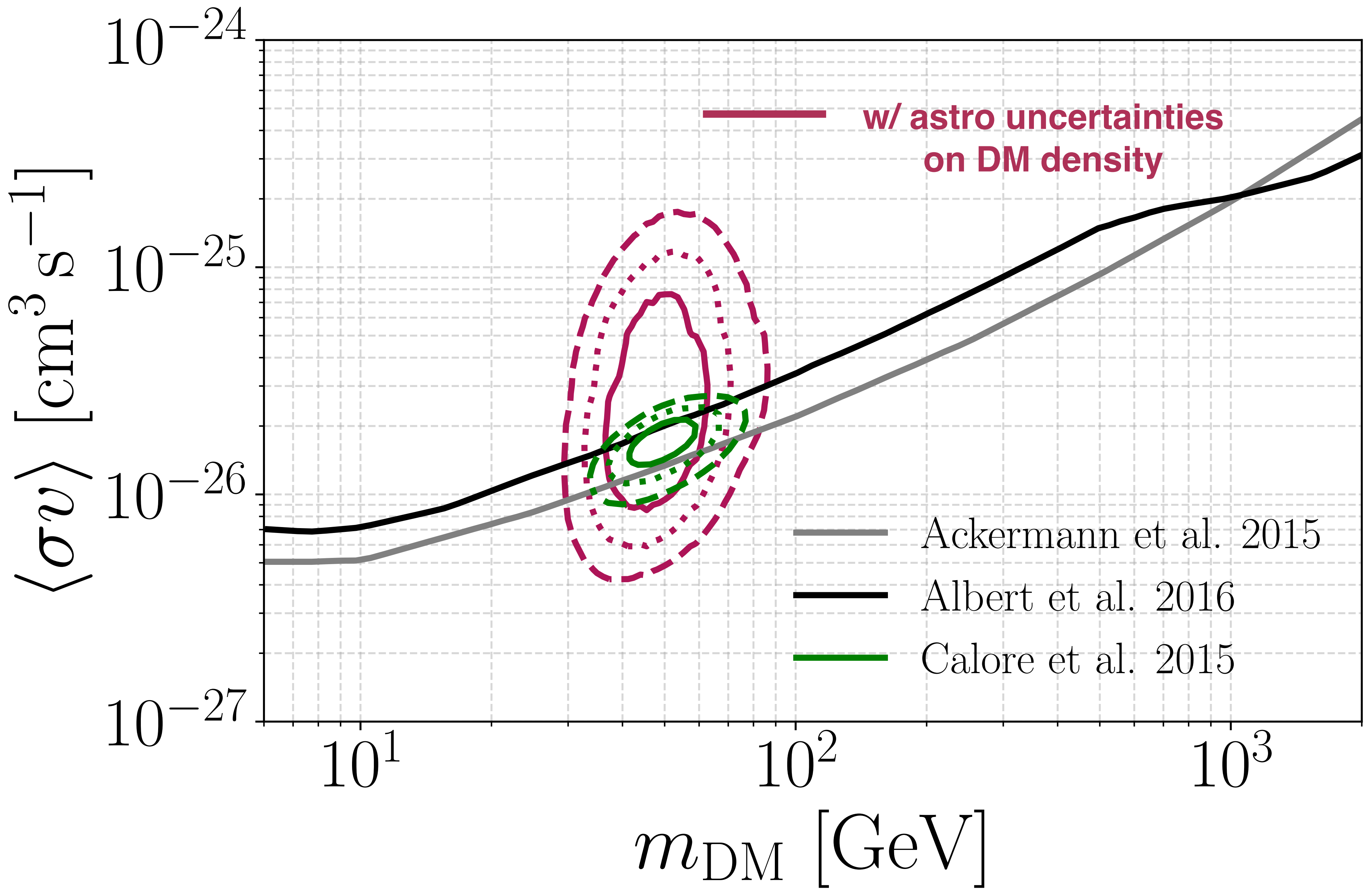


Angular distance from GC [°]

Synthetic γ-ray intensity map from WIMP annihilation (created with CLUMPY)



Credit: M. Hütten



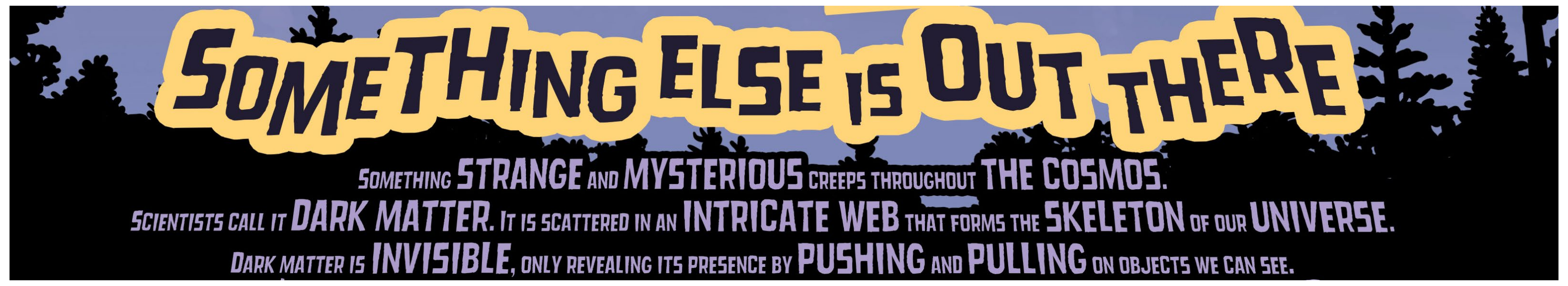
MB + [1901.02460]

Constraints are set by comparing observed and predicted number of photon counts via

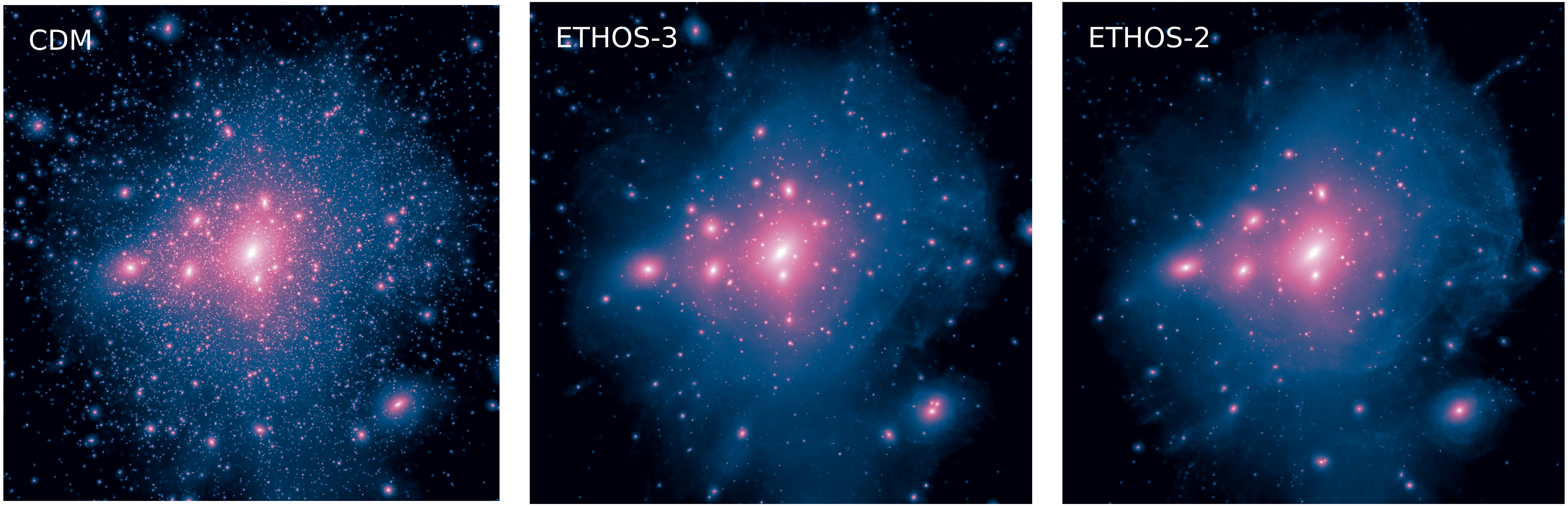
$$\chi^2_{\rm total} = \chi^2_{\rm GCE}(\langle \sigma v \rangle, m_{\rm DM}, \mathcal{J})$$

GCE analysis

Dark satellites



Including:
(1) dark matter - dark energy interaction, and
(2) Velocity-dependent dark matter self-interactions

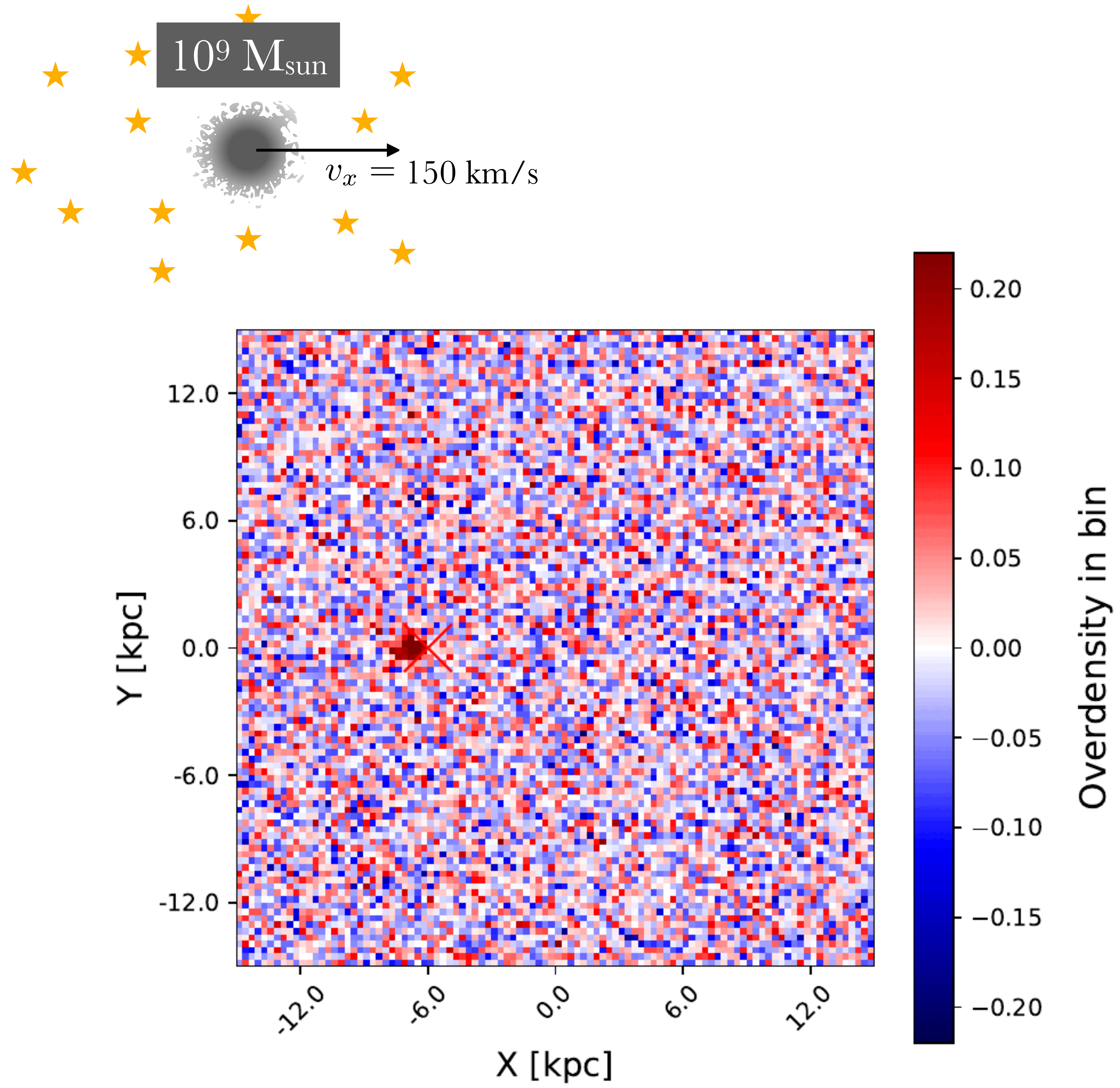


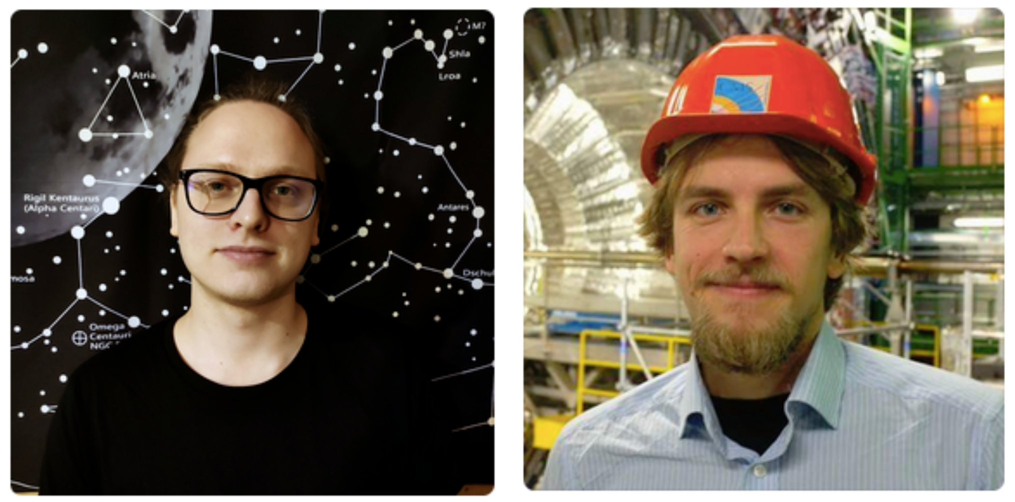
Vogelsberger + [1512.05349]

Searching for dark subhalos in the Milky Way using …

- γ-ray instruments (may detect DM(WIMP) signals emitted therein)
- Stellar streams
- Pulsar timing arrays
- Stellar phase-space signatures:
    - Apparent perturbations due to (weak) lensing by subhalos
    - Real perturbations due to passing subhalos

Stellar wakes driven by dark subhalos





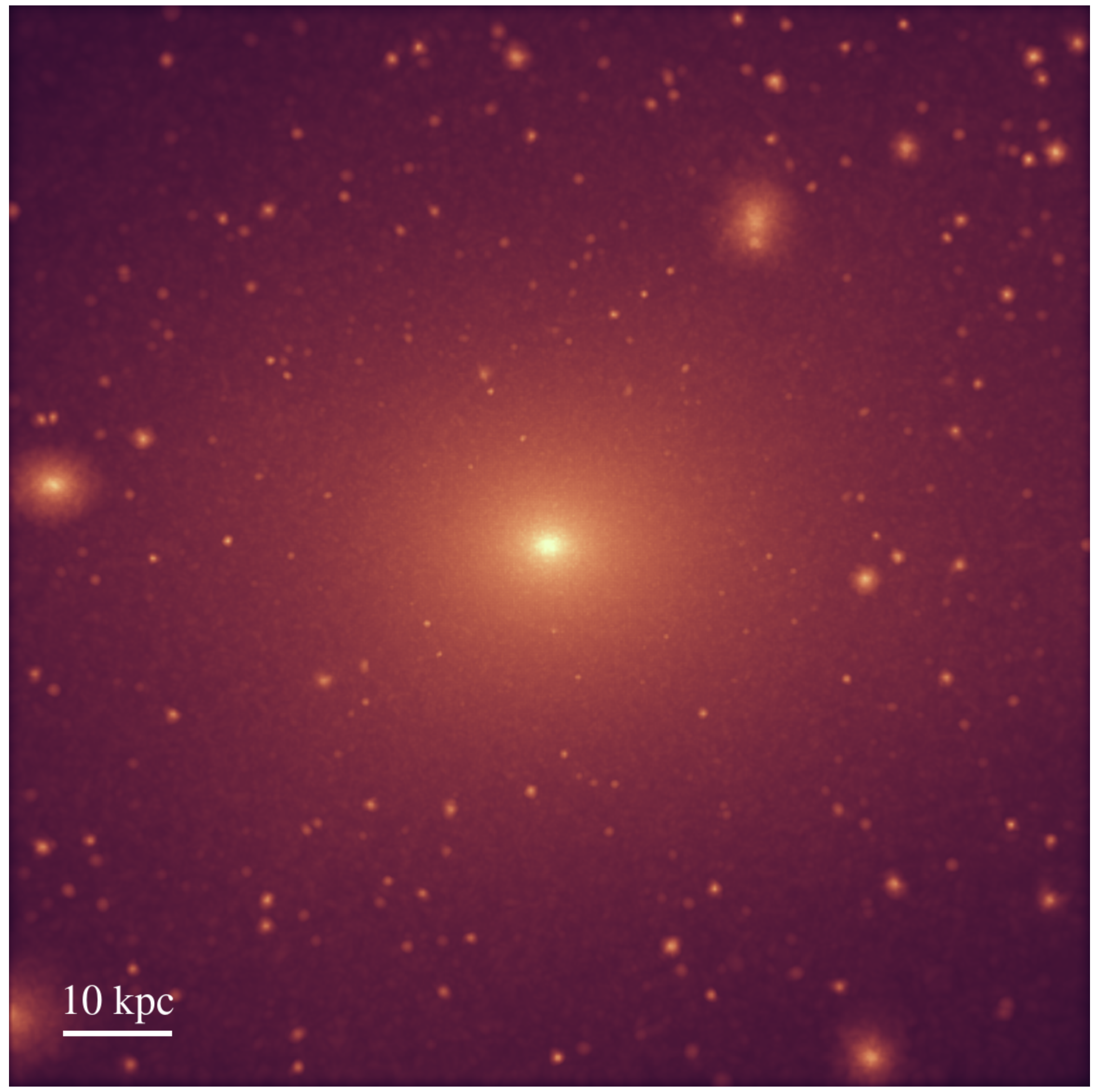
Bazarov + [2203.08161]

See also Buschmann + [1711.03554]

MW-like galaxies

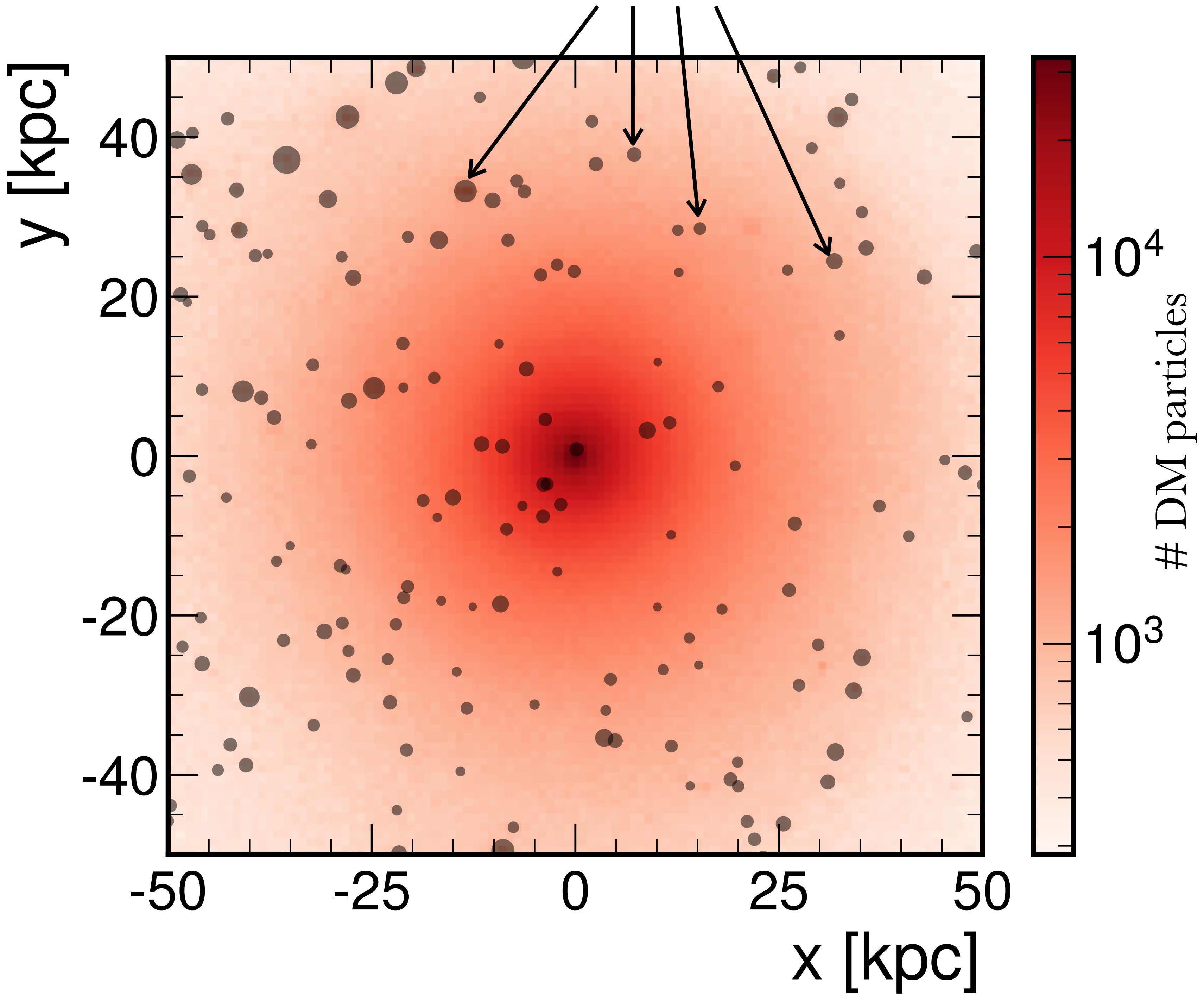
From Latte suite of FIRE-2 simulations

m12i galaxy

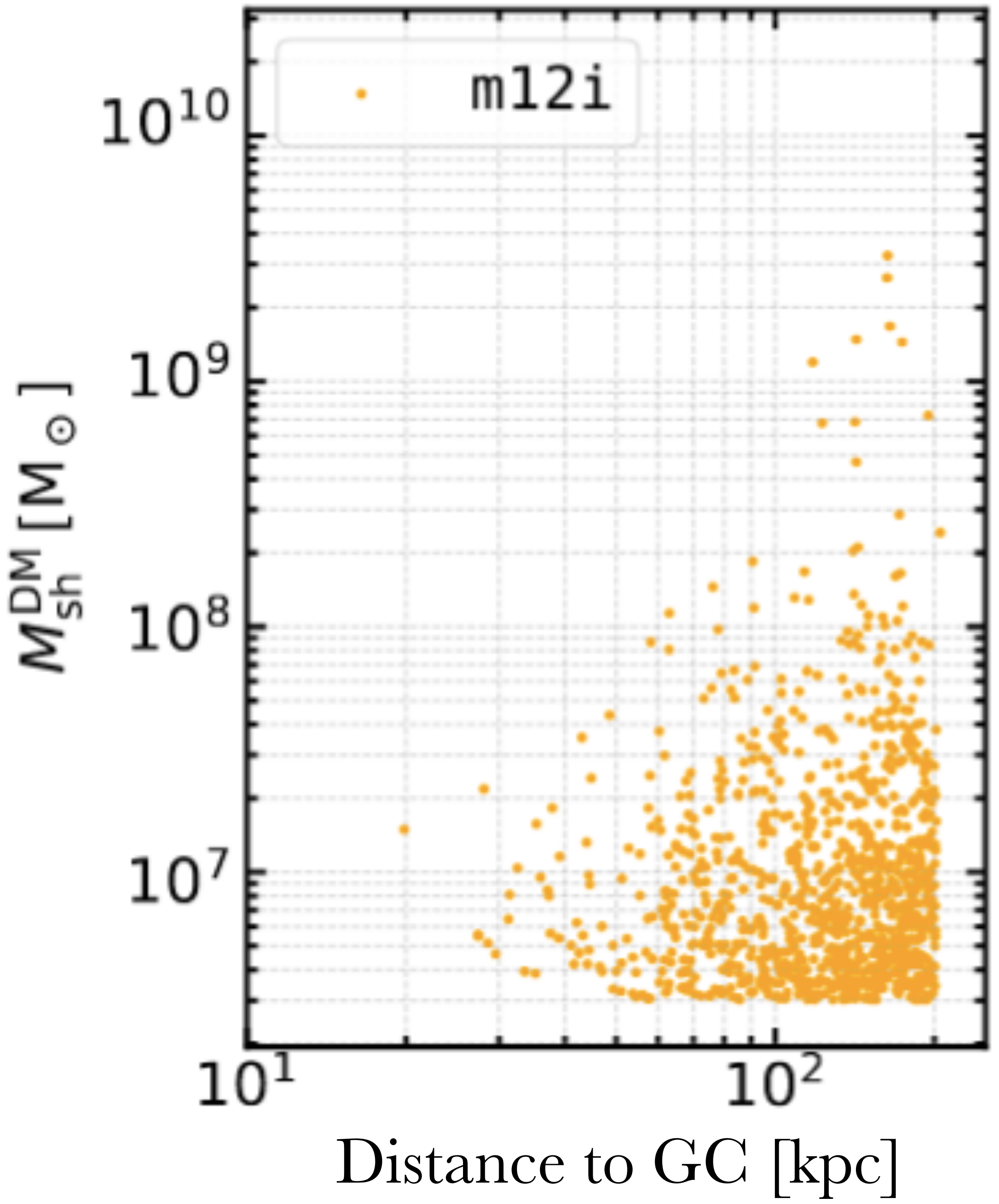


Garrison-Kimmel + [1701.03792]

AHF subhalos



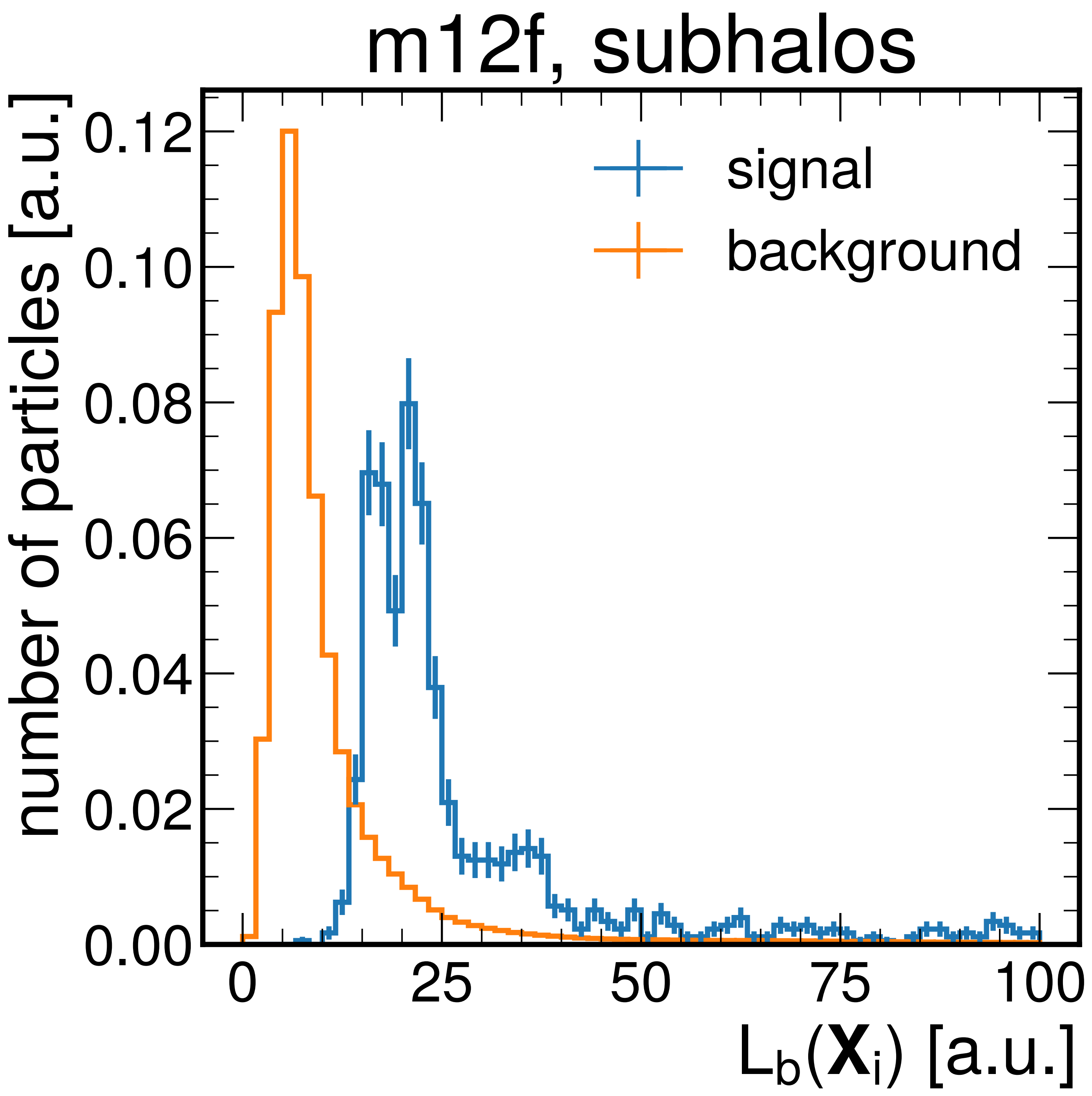
Distribution of subhalos

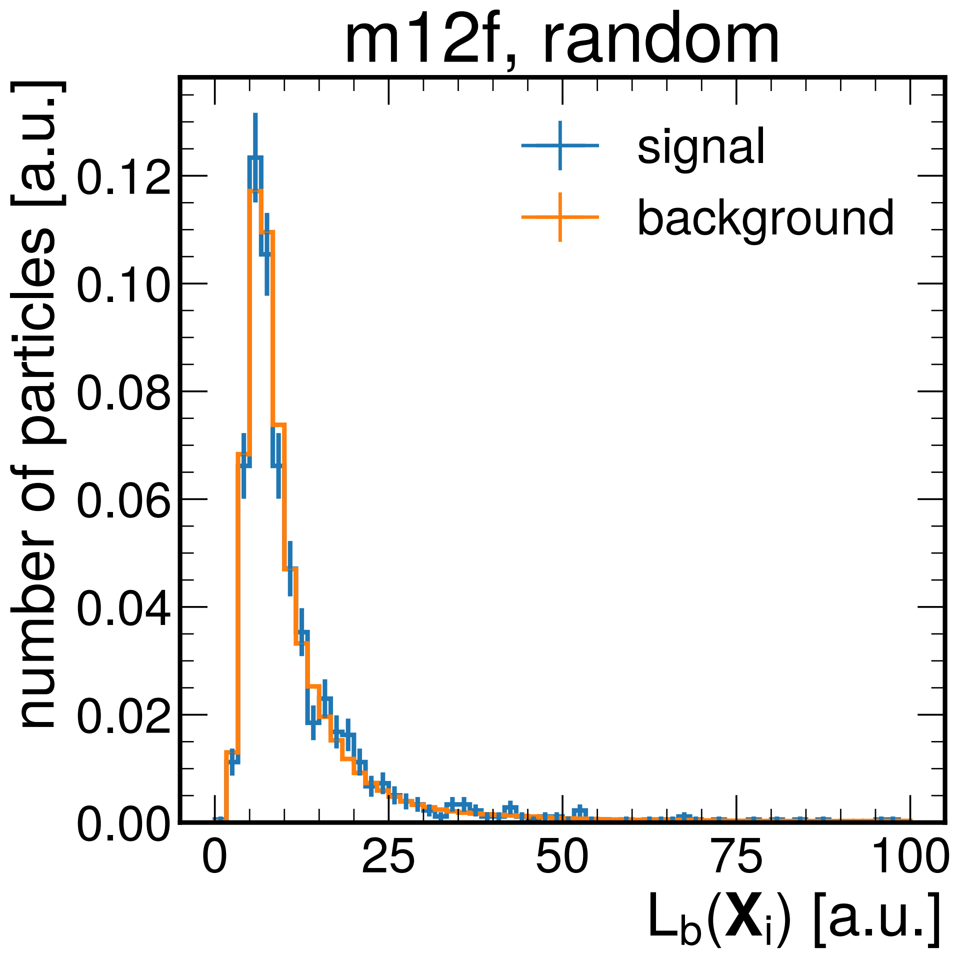


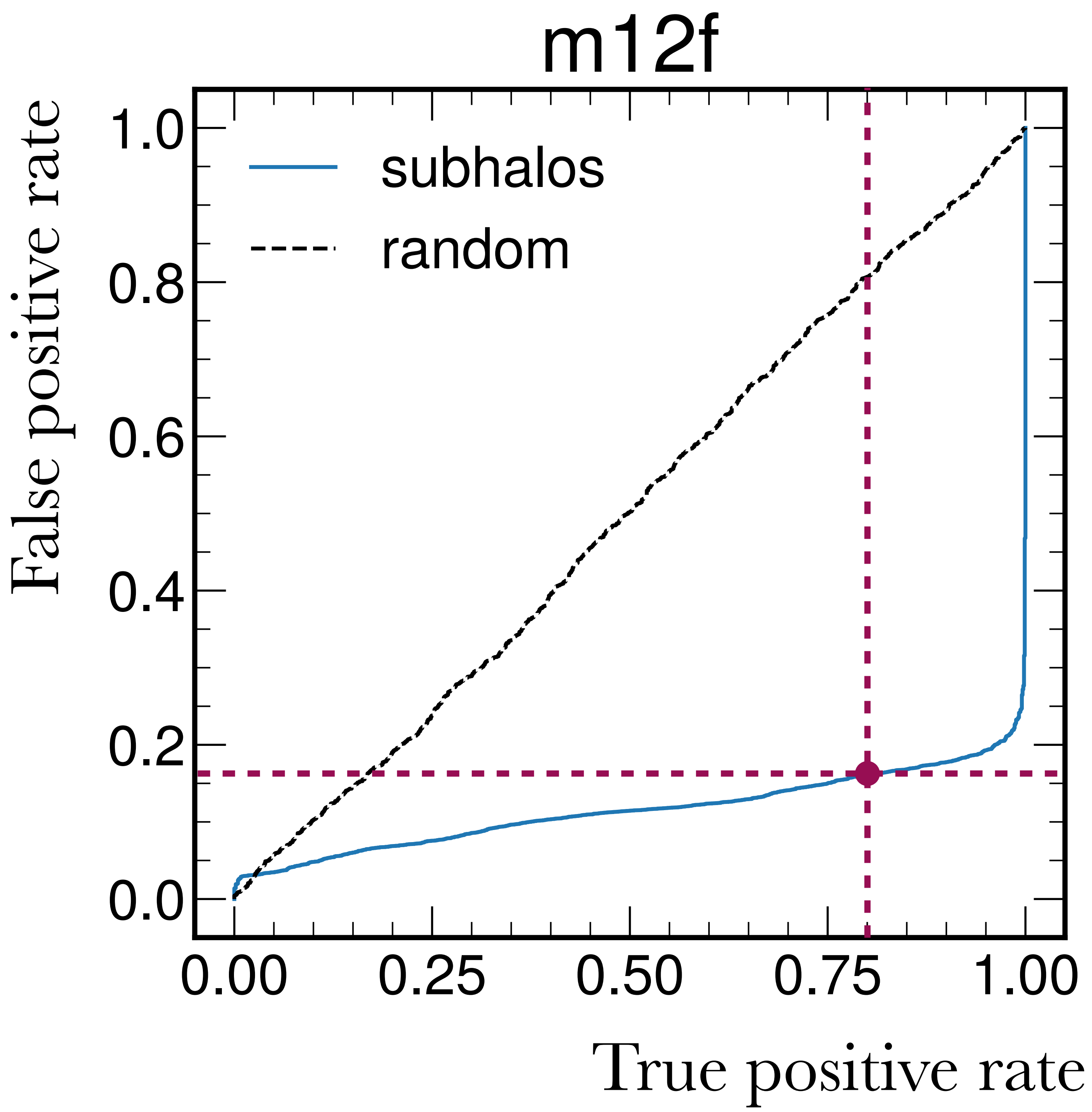
Stellar wakes driven by dark subhalos

In MW-like (simulated) galaxies

Detectable!







$$L_b(\mathbf{X}) = \|\mathbf{X} - D(E(\mathbf{X}))\|$$

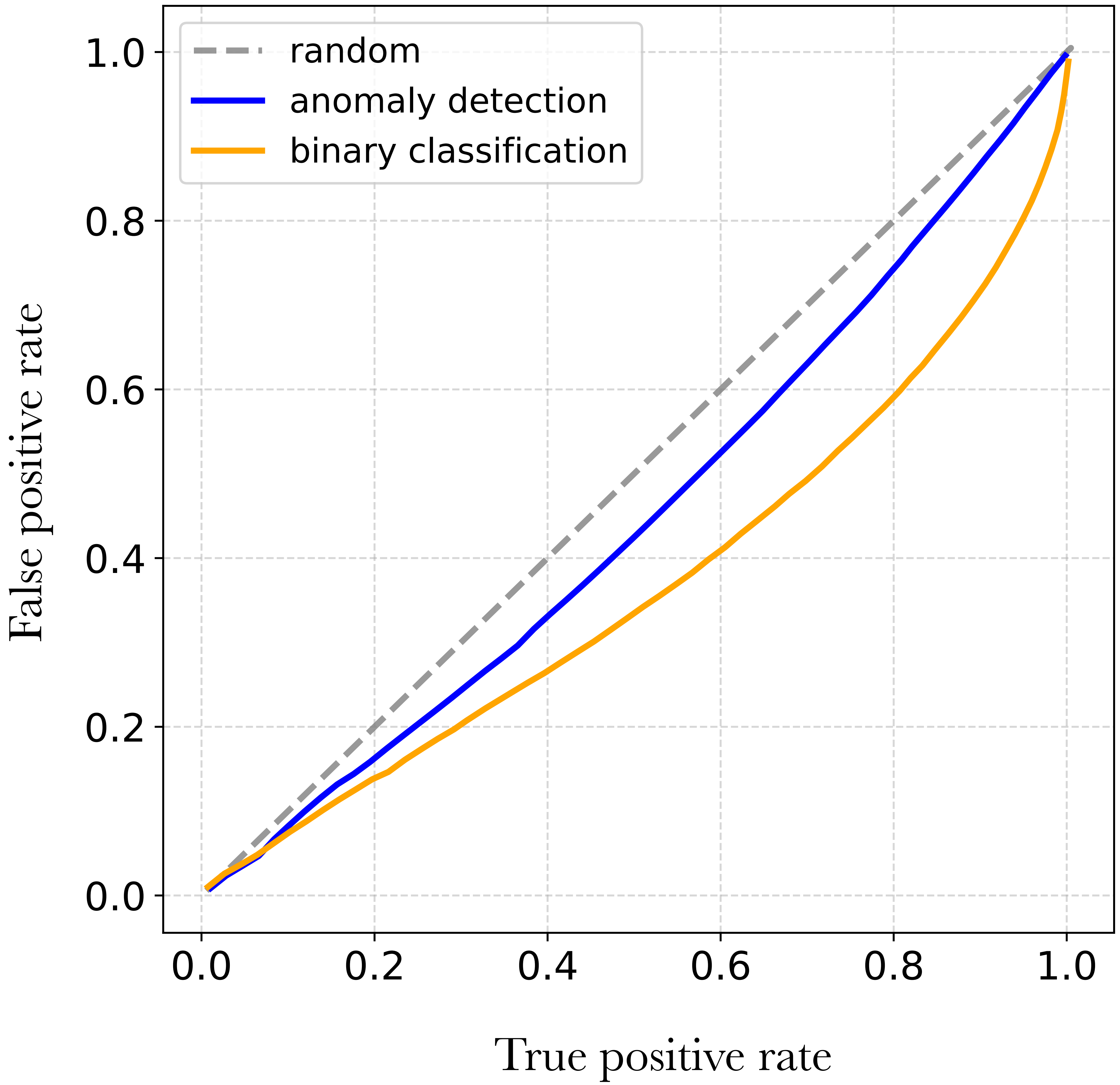
True 3D position & 3D velocity

Reconstructed 3D position & 3D velocity

80% of signal stars are correctly identified while we misclassify ~15% of the background stars as signal

Stellar wakes driven by dark subhalos

In Gaia-like mock catalogs



Binary classification distinguishes between the halo-associated and background stars at a non-negligible level: FPR of ~35% at a TPR of ~50%

Anomaly detection does not differ significantly from purely random selection

Work in progress … Stay tuned!

DM particle landscape

Exoplanets & Brown Dwarfs are new, excited and powerful detectors of WISPs

Brown Dwarf temperature

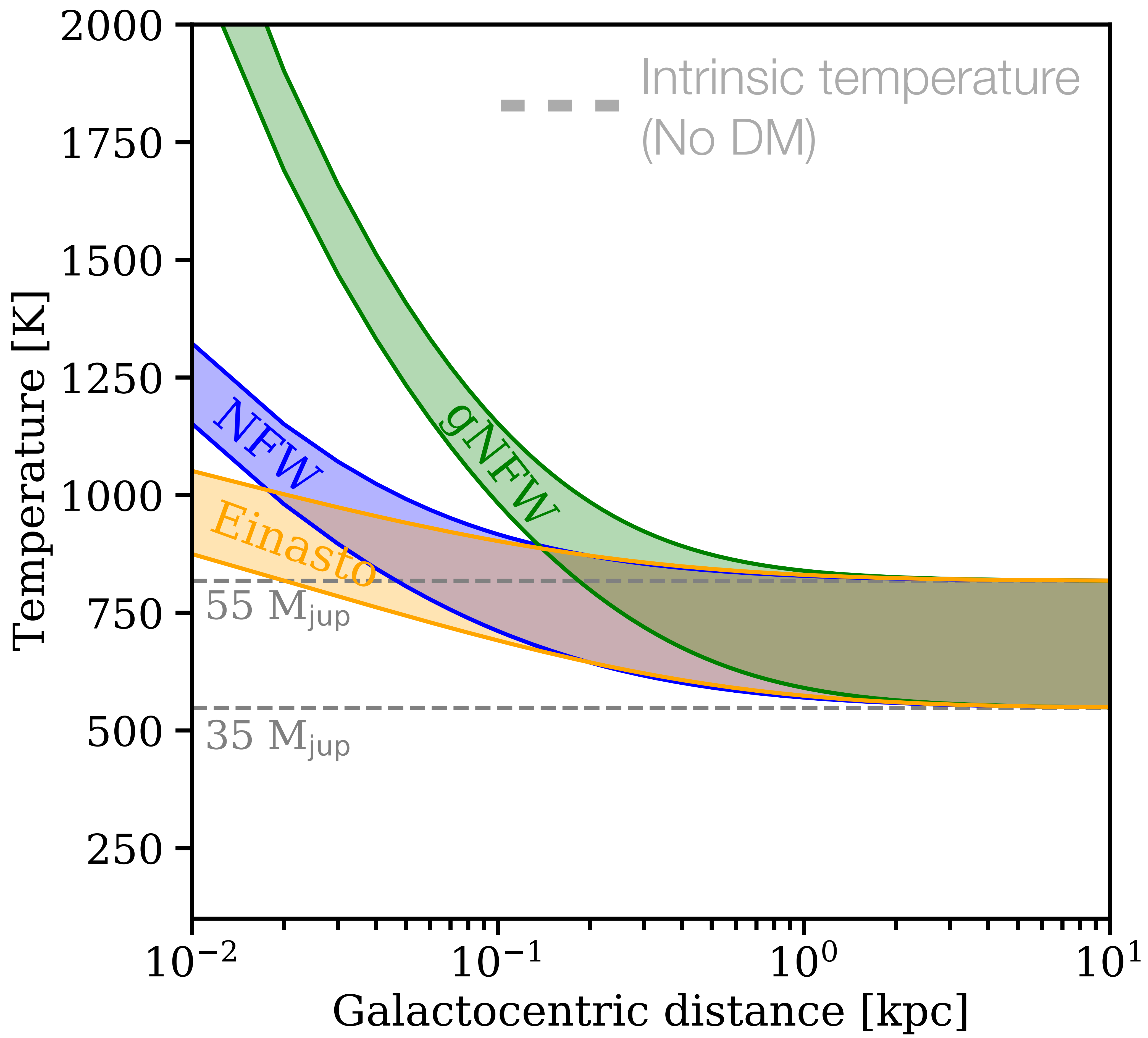
$$\Gamma_{\rm heat}^{\rm tot} = \Gamma_{\rm heat}^{\rm ext} + \Gamma_{\rm heat}^{\rm int} + \Gamma_{\rm heat}^{\rm DM} = 4\pi R^2 \sigma_{\rm SB} T_{\rm eff}^4 \epsilon$$

DM heat:

$$\Gamma_{\rm heat}^{\rm DM} = f\pi R^2 \rho_{\rm DM}(r) \bar{v}_{\rm DM}(r) \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2(R,M)}{\sigma_{\rm DM}^2(r)}\right)$$

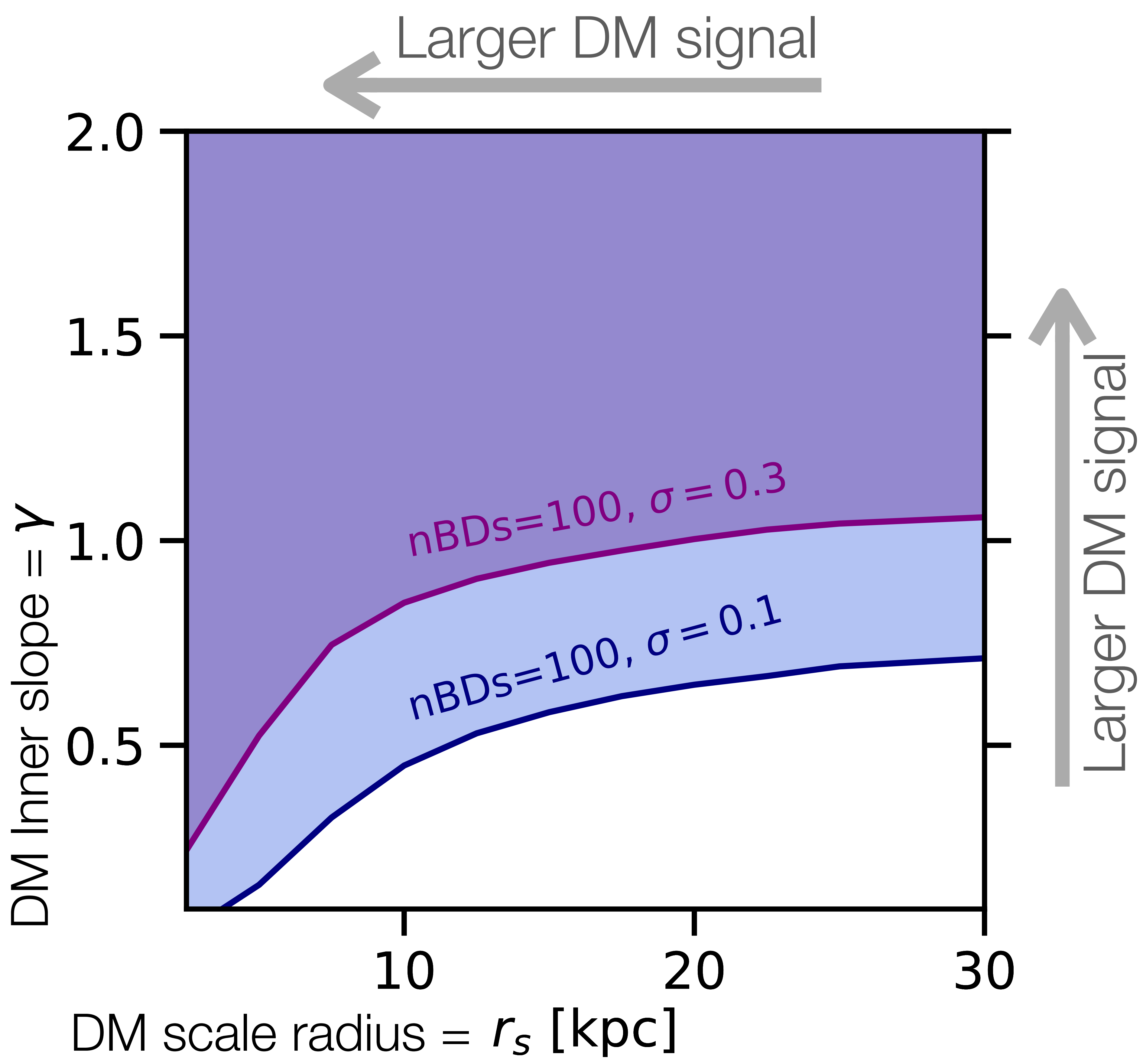
$$\Gamma_{\rm heat}^{\rm DM} \propto \rho_{\rm DM}(r)$$

Increase of Brown Dwarf temperature with decreasing Galactocentric distance

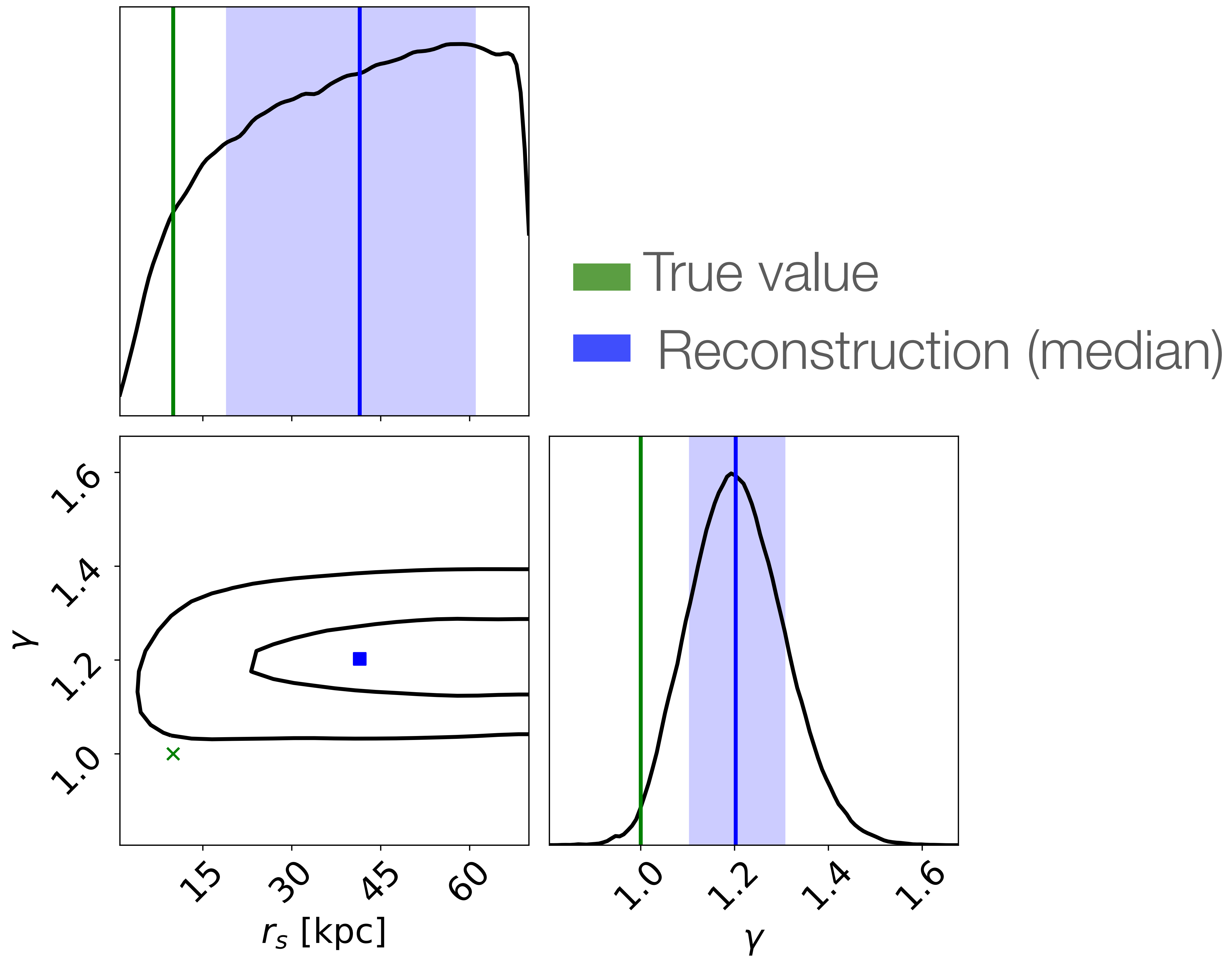


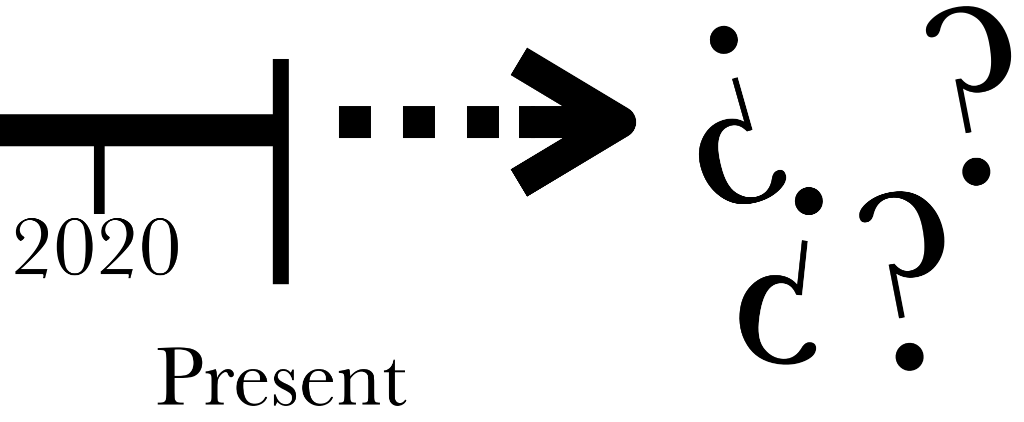
Preliminary

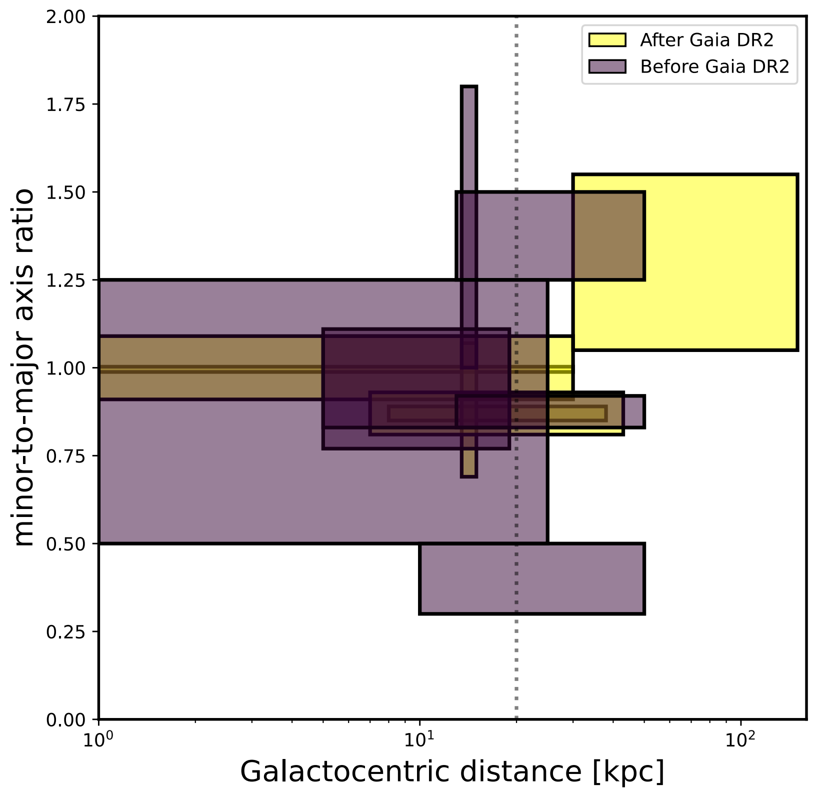
Sensitivity to overheated BDs

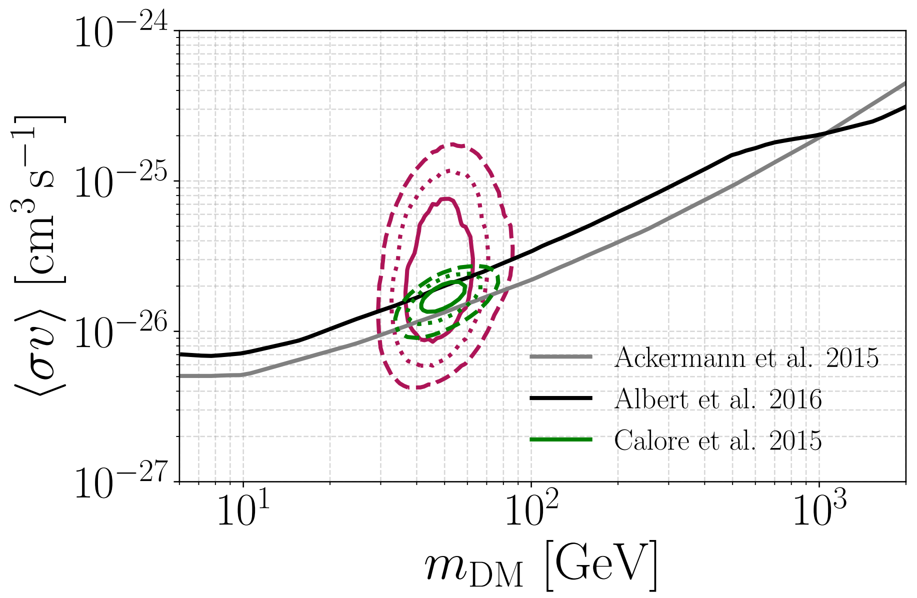


Performance in DM reconstruction

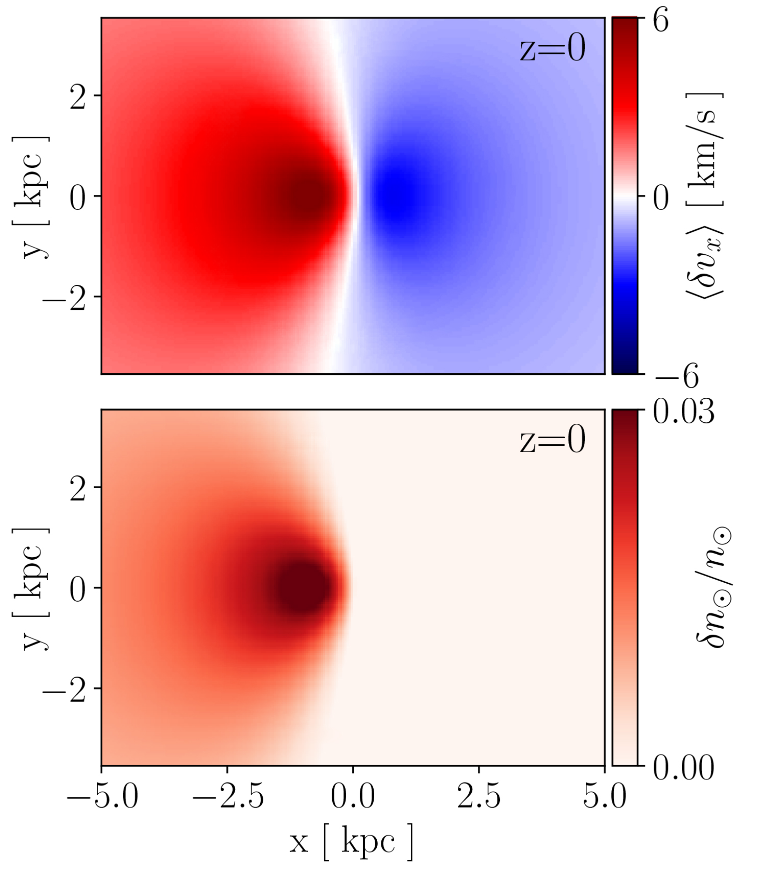






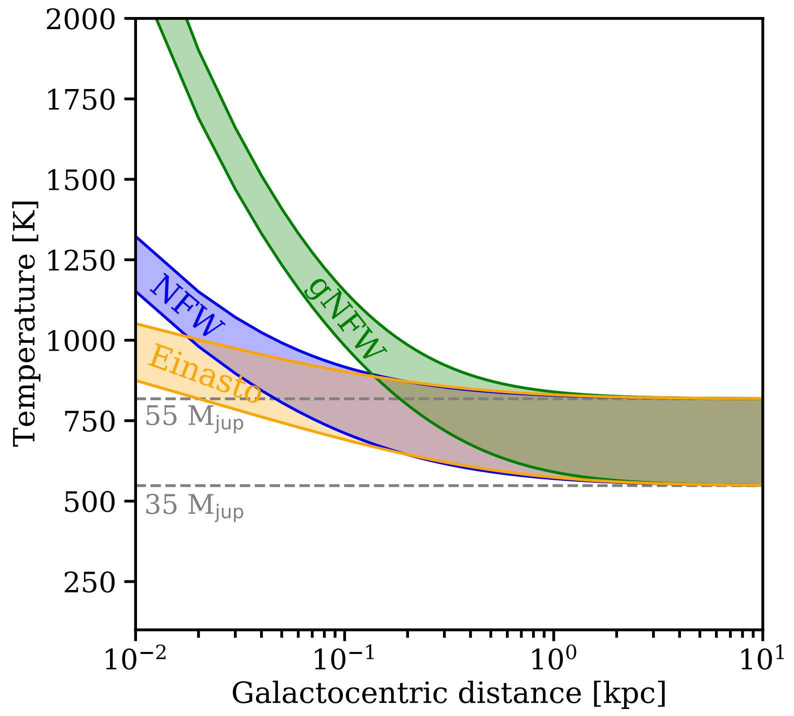


- Essential for interpreting results from particle DM searches:
  - Are classical modelling assumptions (steady-state & axial symmetry) still valid for reconstructing of the distribution of DM in the Milky Way? We need to understand to what extent the presence of the stellar bar and the assembly history of our Galaxy affect the DM distribution
  - What is the 3D shape of the DM halo? What is the impact of the LMC?



- Dark subhalos can be key to understand properties of dark matter @ microscopic scales, there are more than just stellar streams to find (constrain) *invisible* subhalos orbiting the Milky Way

- WISPs are more than axions! Exoplanets/brown dwarfs are promising detectors.



“If you look historically, almost all of the models at any given time that people have are wrong. So there's no particular reason why they shouldn't be at this time, and why should scientists be so stupid as to not realise this?”

Ostriker (Oral History Interviews)