Dwarf satellite galaxies in the MW after Gaia EDR3 : are they at first infall?

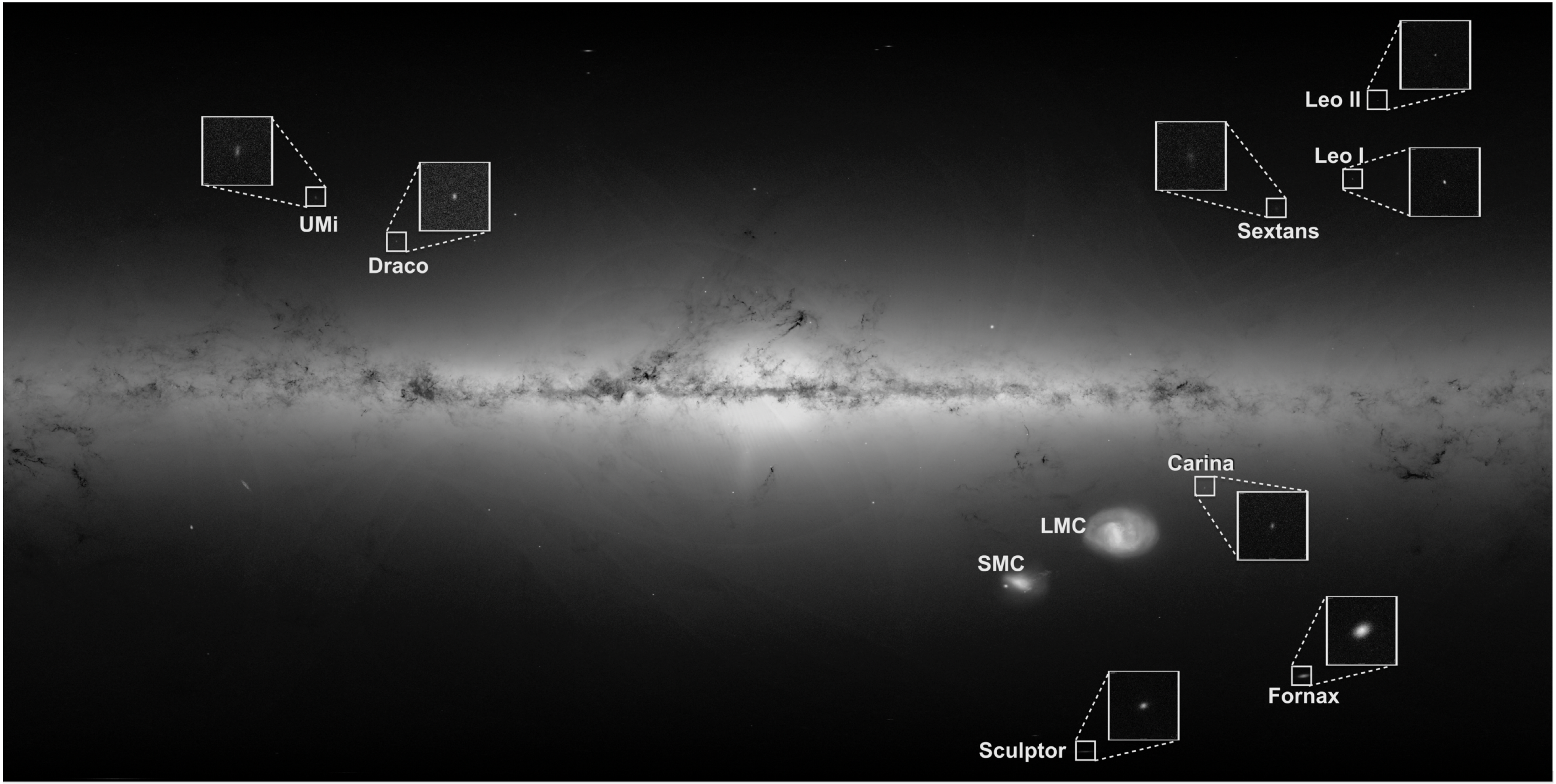
Presented par François Hammer

With: Jianling Wang, Marcel Pawlowski, Yanbin Yang, Piercarlo Bonifacio, Hefan Li, Fréderic Arenou, Carine Babusiaux, and Yongjun Jiao

2 Papers (2021):

I. Gaia EDR3 Proper Motions of Milky Way Dwarfs. I. 3D Motions and Orbits **Li et al.** (2021, ApJ, 916, 8)

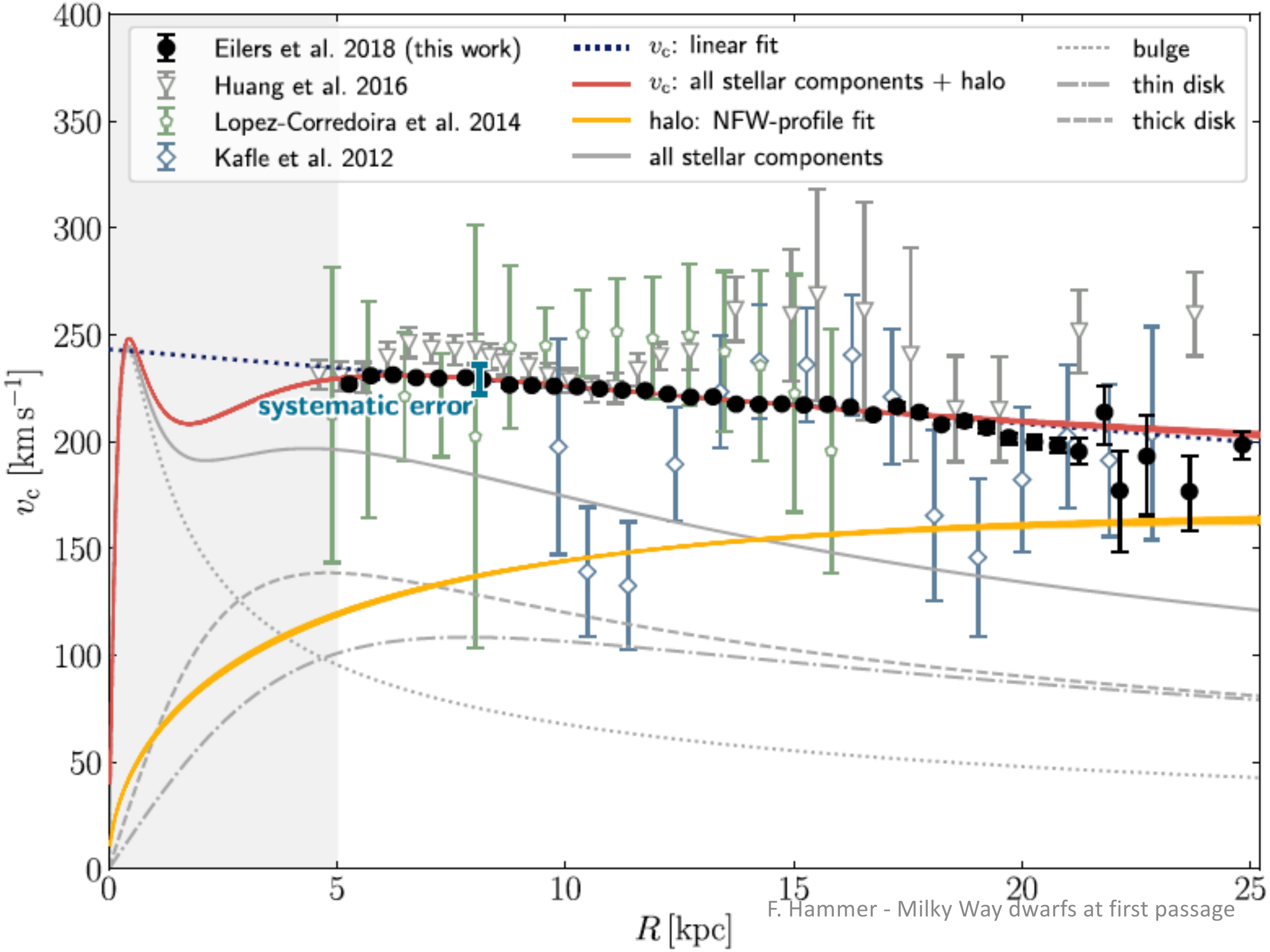
II. Gaia EDR3 proper motions of Milky Way dwarfs. II: Velocities, Total Energy and Angular Momentum **Hammer et al.** (2021, ApJ, 922, 93)


Leo II
UMi
Draco
Sextans
Leo I
Carina
LMC
SMC
Fornax
Sculptor

Gaia DR2 revolution

- Provide the first rotation curve of the Milky Way
- First proper motions and orbits for Milky Way dwarfs

Eilers et al 2019, GAIA DR2, slightly declining rotation curve



6D phase space coordinates of 23,000 red giant stars in the MW disk

Confirmed by Mroz et al. 2019, using 773 Classical Cepheids with precise distances

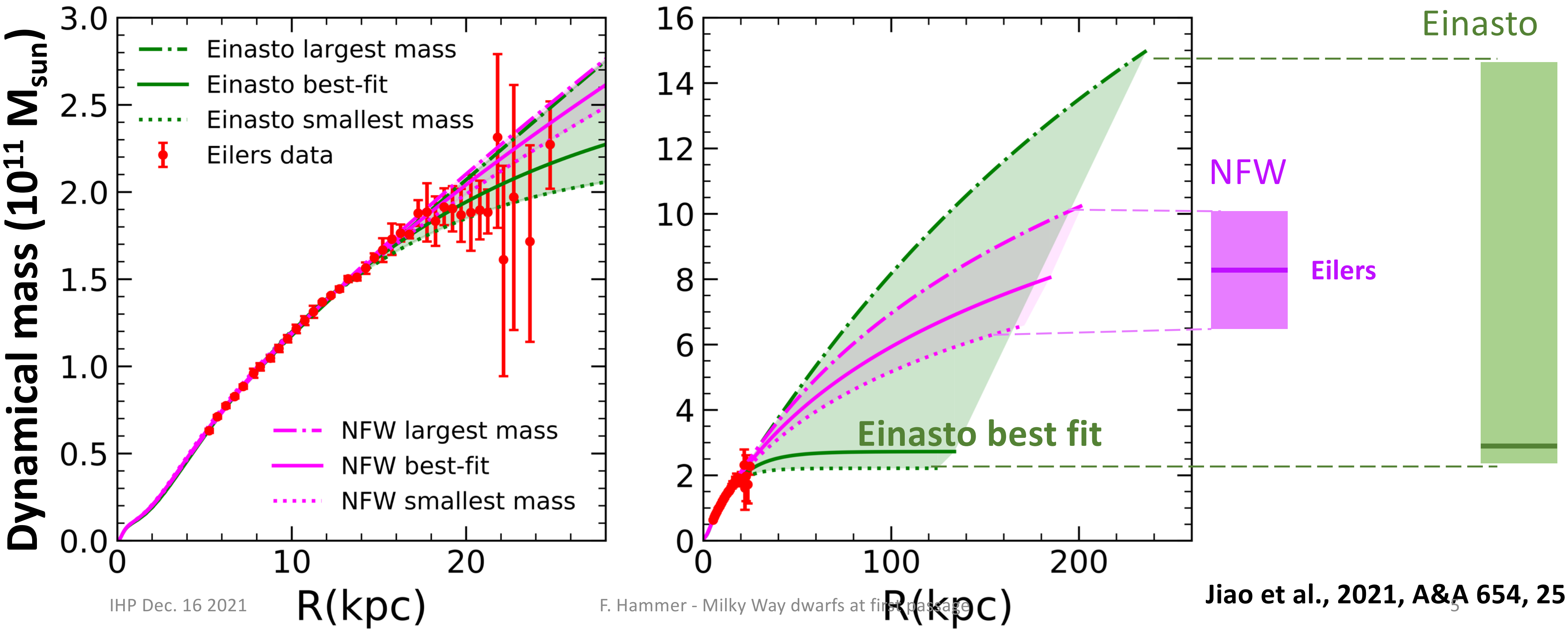
Errors and systematics reduced by more than an order of magnitude

Eilers et al. modelled the MW mass distribution with:

- M_{DM}= 7.25 10^{11} M_O
- $M_{baryons}$= 0.895 10^{11} M_O

-Using NFW model biases the total mass values;

-Using Einasto model RC is best fitted by small total masses, though allowing a large mass range



Jiao et al., 2021, A&A 654, 25

Gaia EDR3: a revolution for Milky Way dwarf orbits

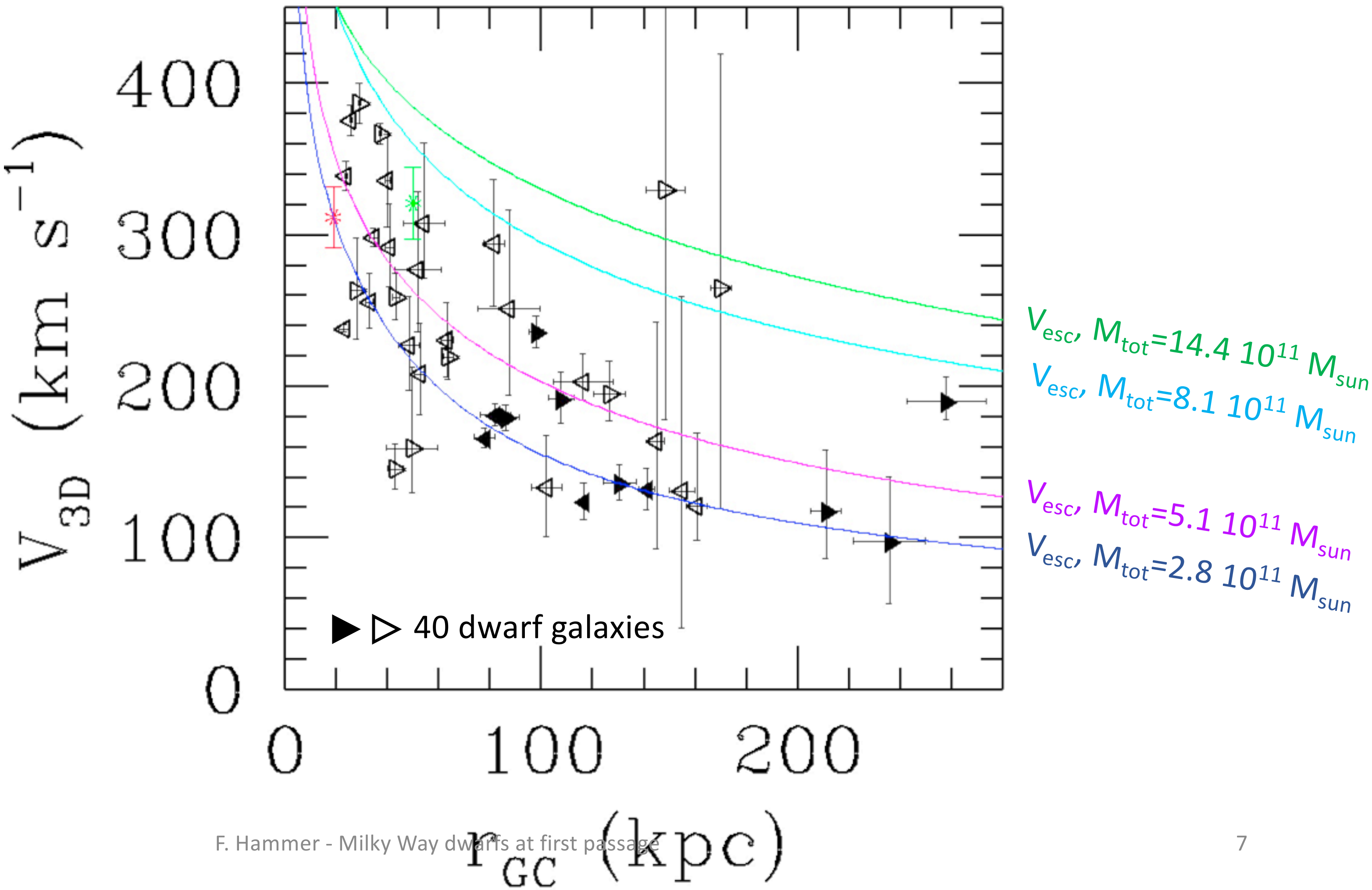
- Error on proper motions divided by a factor 2.5

- 3D velocities, total energies & angular momenta for 30 Milky Way dwarfs instead of 12 !

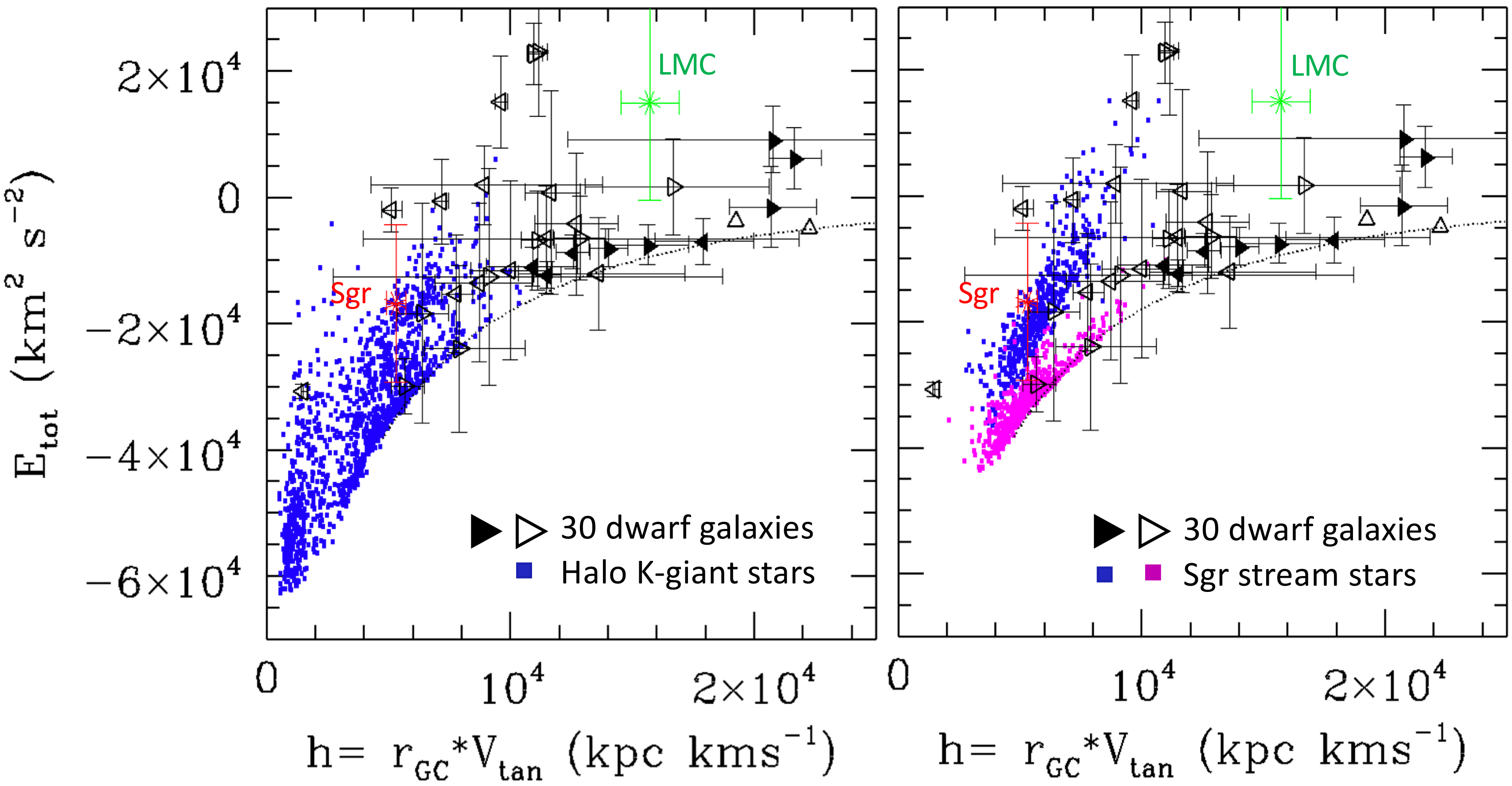
Gaia EDR3: a revolution for Milky Way dwarf orbits

Do we know if Milky Way dwarfs are bound or not? It depends on the adopted mass for the Milky Way

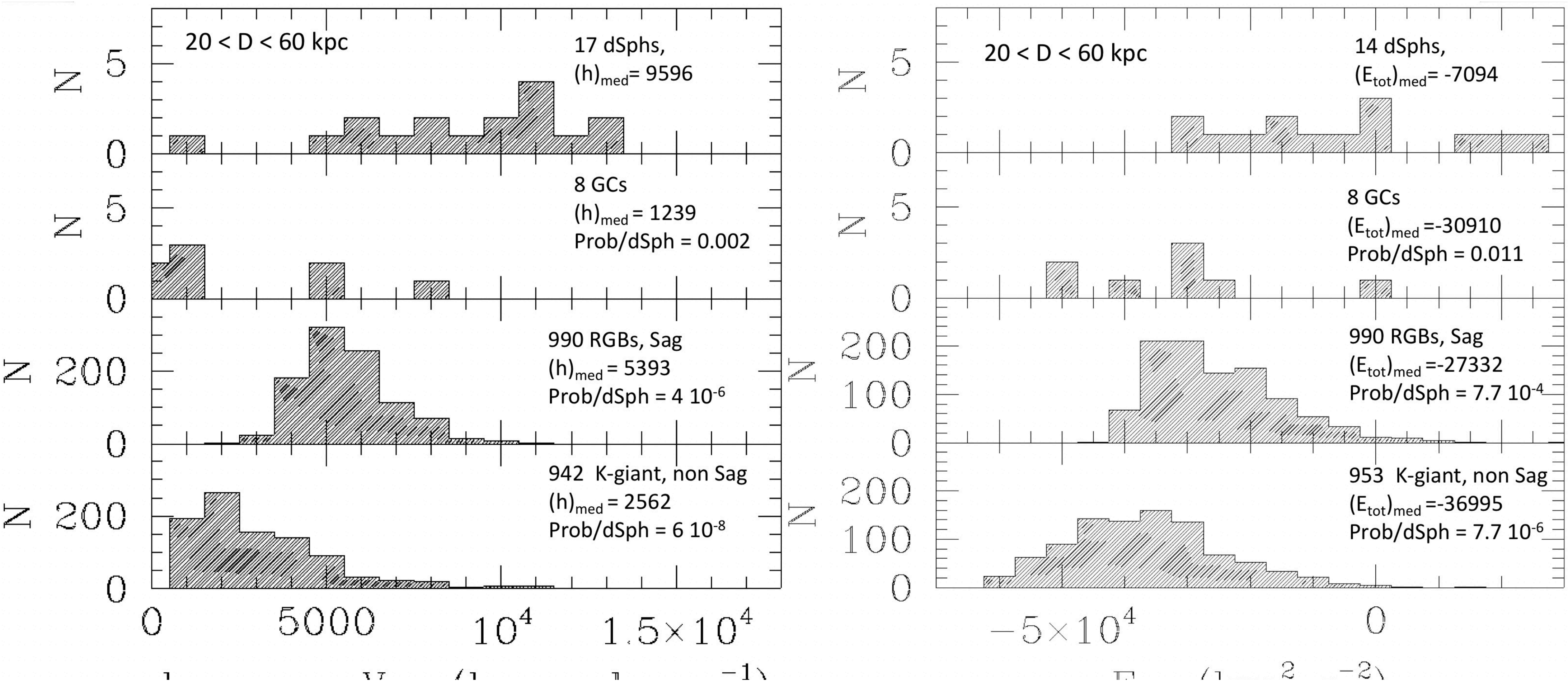
Here we only consider Milky Way masses and profiles consistent with the Milky Way rotation curve



Total energy versus angular momentum: comparison with K-giant stars & Sgr stream stars



Total energy versus angular momentum at ≤ 60 kpc: comparison with K-giant stars & Sgr stream stars



GAIA EDR3 : energies and angular momenta of MW dwarfs are significantly larger than K-giant stars & Sgr stream stars

Very robust comparison: valid for all Milky Way masses
at ≤ 60 kpc sample of dwarfs is complete

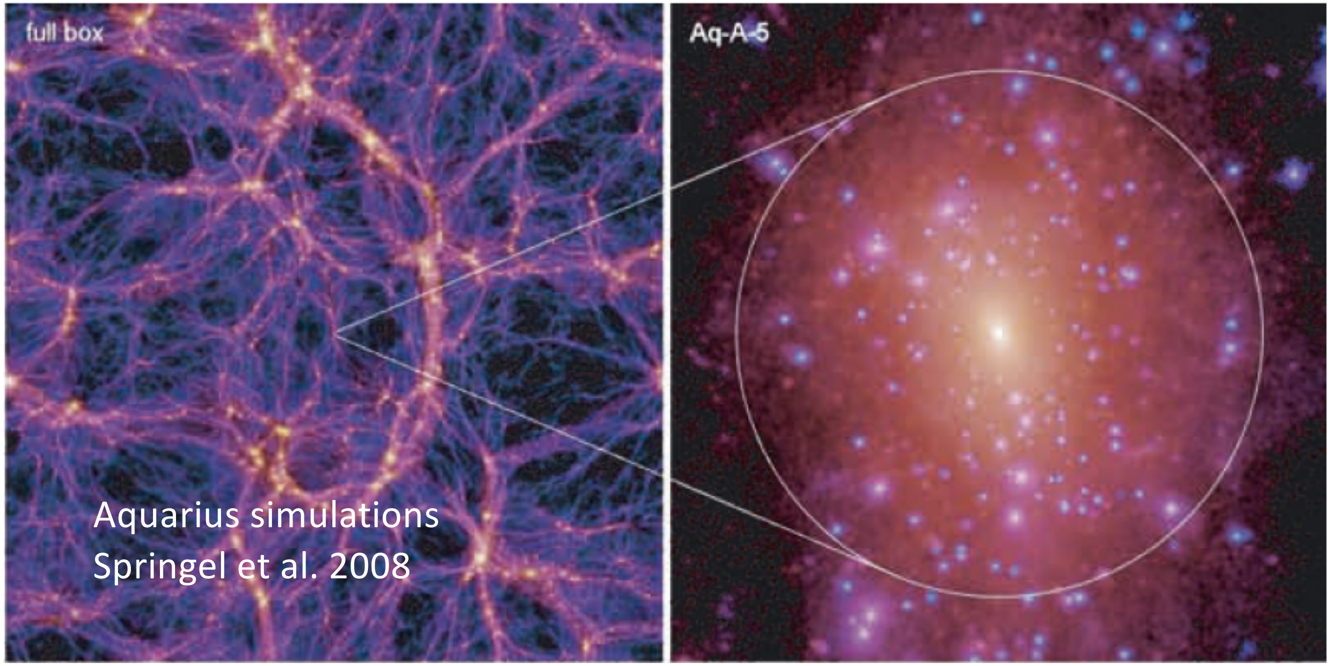
K-giant stars: from the primordial Milky Way or from Gaia-Enceladus (8-10 Gyr ago)

Sgr stream stars: infall 4-5 Gyr ago

Last comers have highest energies & angular momenta (Boylan-Kolchin et al. 2013)

➔ Milky Way dwarfs are coming since ≤ 2 Gyr ago, just the time to make one orbit, i.e., **most Milky Way dwarfs are new comers to the halo!**

Milky Way dwarfs are no more long-lived satellites



Are they consistent with ΛCDM subhalos?

Are Milky Way dwarfs consistent with subhalos?

- Tangential/radial velocities
- Spatial location
- Locations versus pericenters

Are Milky Way dwarfs consistent with subhalos?

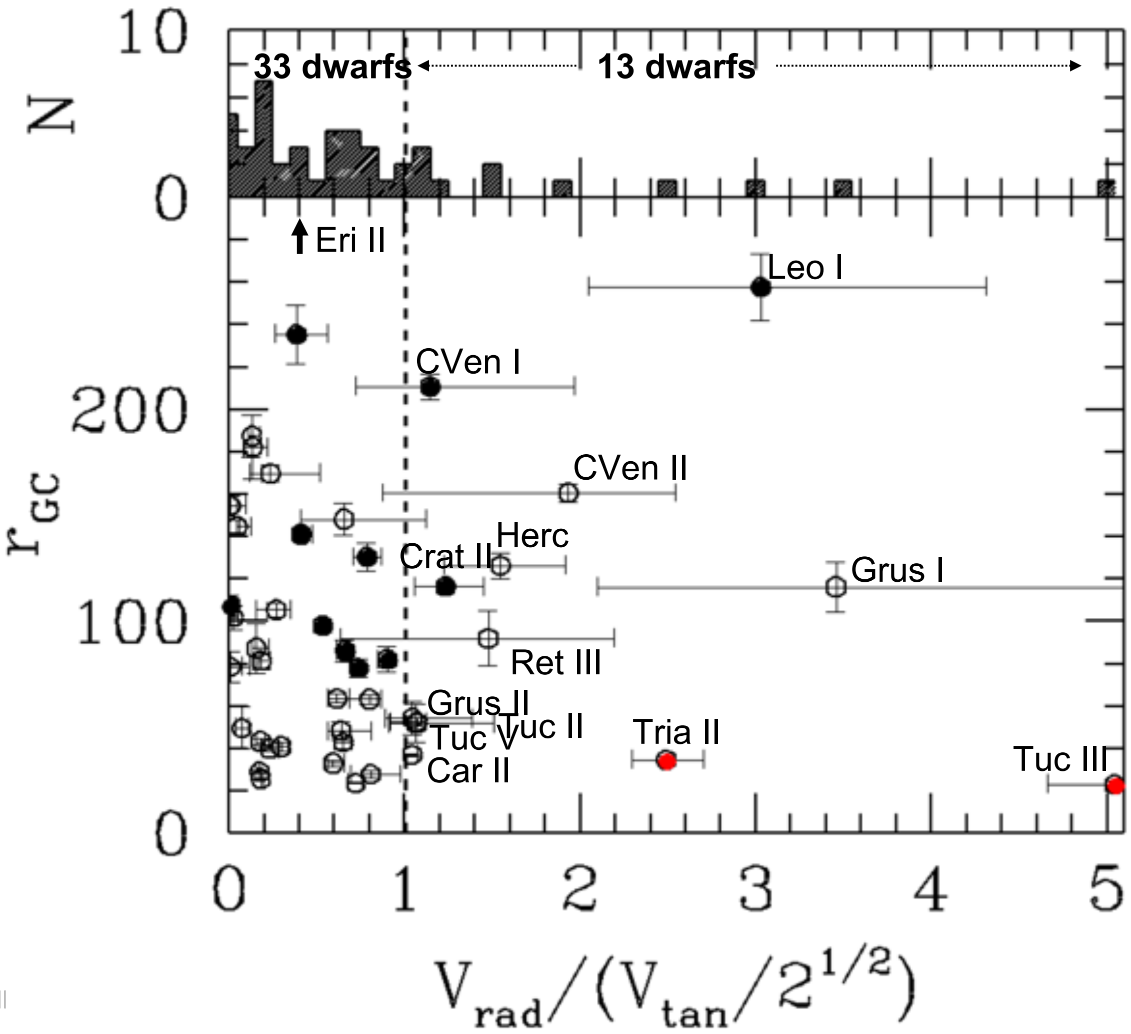
- **Tangential/radial velocities**
- Spatial location
- Locations versus pericenters

Are Milky Way dwarfs consistent with subhalos?

- **Tangential/radial velocities**

As already found by Cautun & Frenk (2017), dwarfs have excessive tangential velocities when compared to subhalos (see also Riley et al. 2019), they estimate to 2-3% the fraction of halos consistent with the observations.

Gaia EDR3: 33/46 dwarfs have excessively large V_{tan}



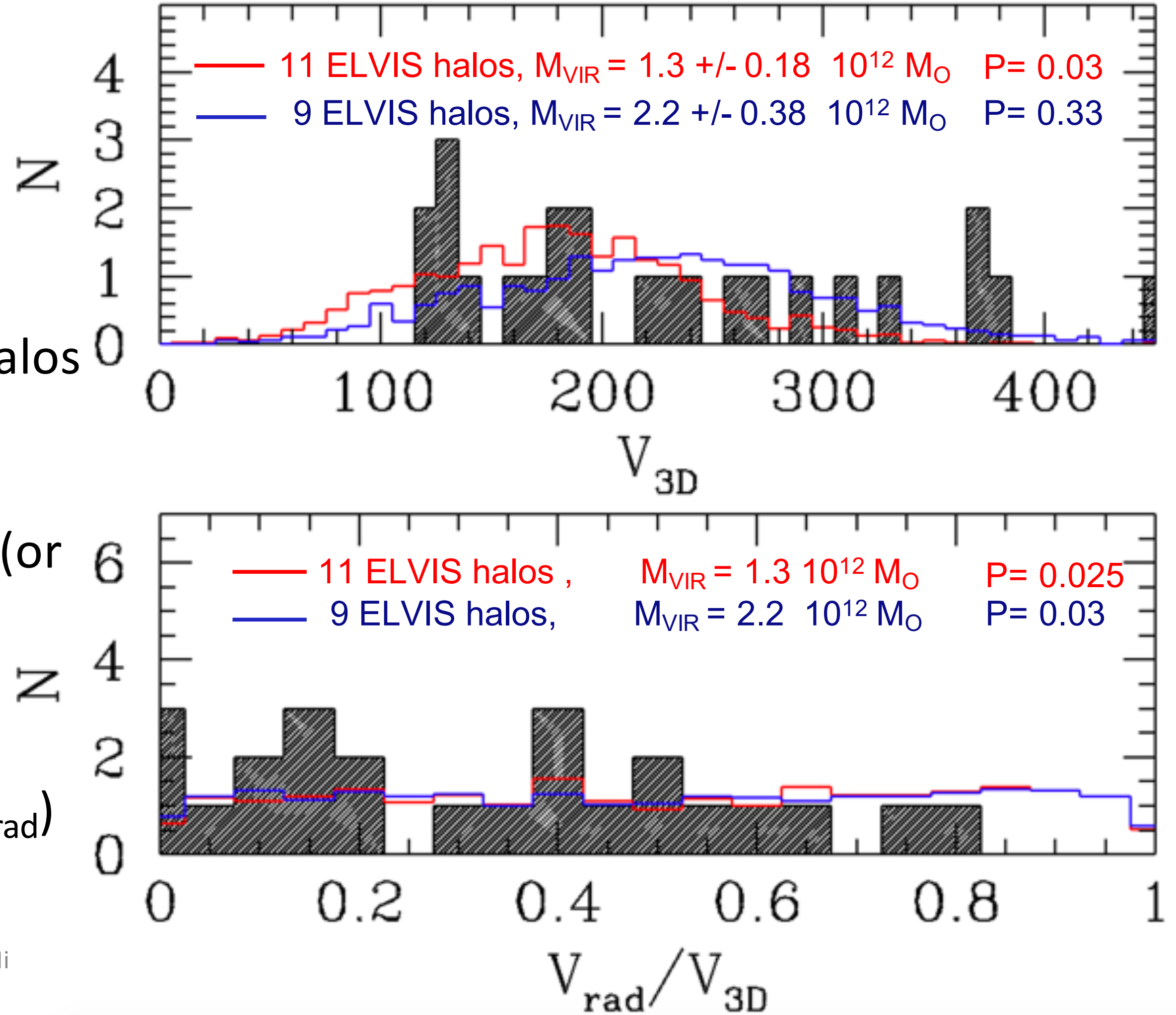
Are Milky Way dwarfs consistent with subhalos?

- **Tangential/radial velocities**

Comparison with ELVIS -host halos and subhalos from Garrison-Kimmel et al. 2014

Only massive host halos fit the 3D velocities (or kinetic energies), but not the rotation curve

Only 3% of host halos have subhalos with tangential velocity excess (or deficiency of V_{rad})



Are Milky Way dwarfs consistent with subhalos?

- **Tangential/radial velocities: 0.03 of occurrence**
- Spatial location
- Locations versus pericenters

Are Milky Way dwarfs consistent with subhalos?

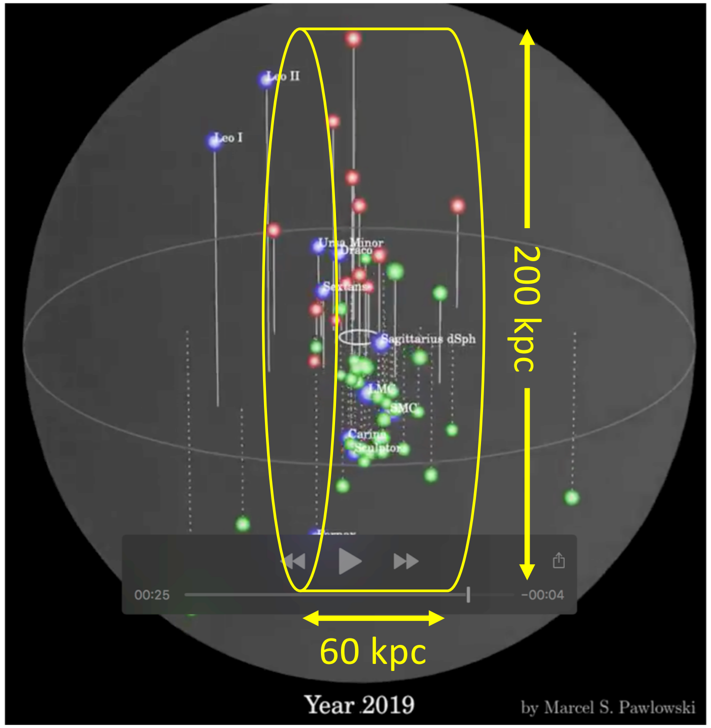
- Tangential/radial velocities: 0.03 of occurrence
- **Spatial location**
- Locations versus pericenters

Are Milky Way dwarfs consistent with subhalos?

- **Spatial location**

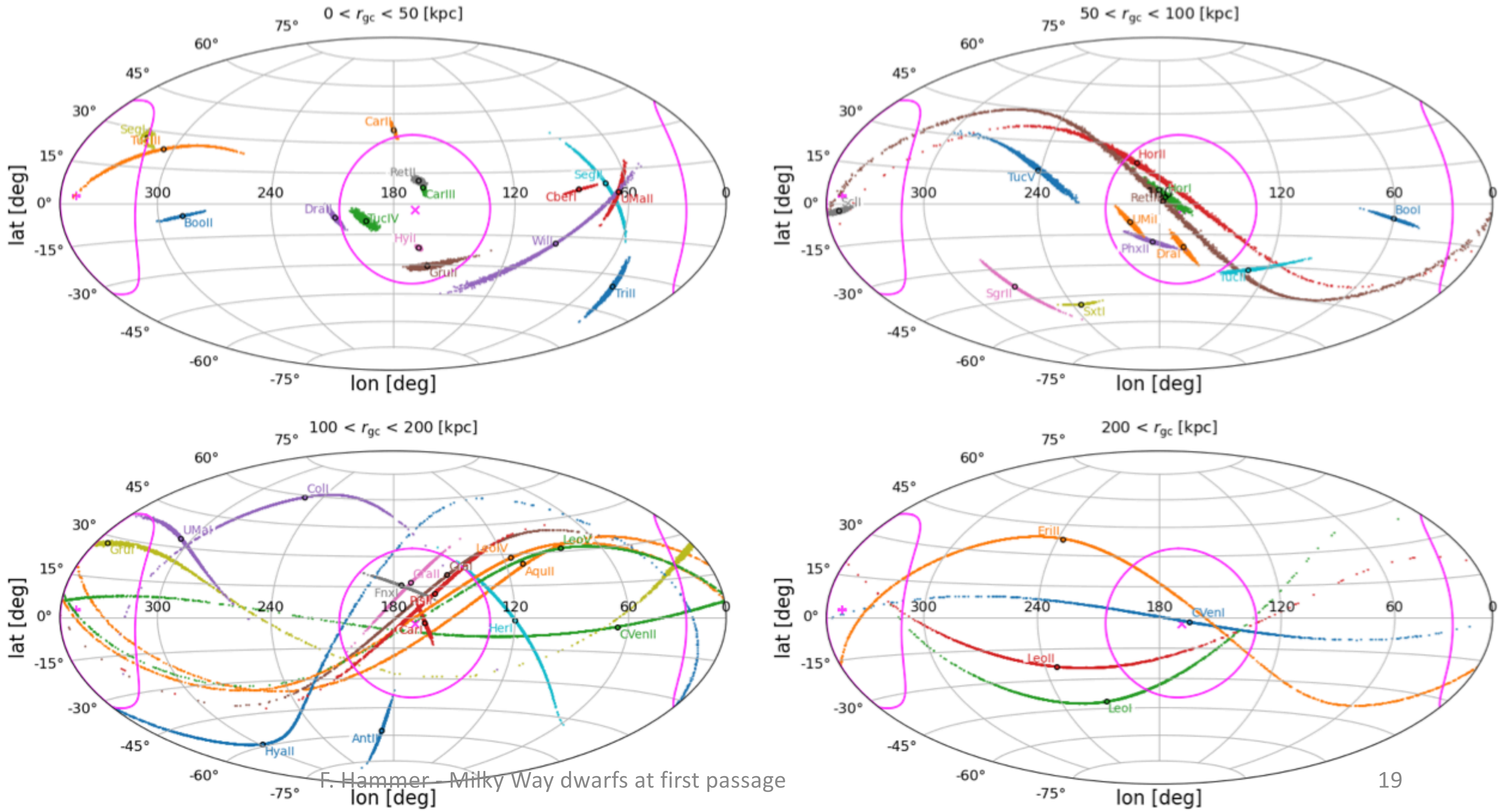
Many Milky Way dwarfs lie and move into the Vast Polar Structure (200x60 kpc^2), still not consistent with LCDM halo/subhalos (Pawlowski et al. 2014-2021)

Comparison with simulated subhaloes: P < 0.005 (Pawlowski 2018, and others)



Are Milky Way dwarfs consistent with subhalos?

- **Spatial location: Gaia EDR3 confirms that 50 to 66% of dwarfs lie and move in the VPOS**



Li et al. (2021)

Are Milky Way dwarfs consistent with subhalos?

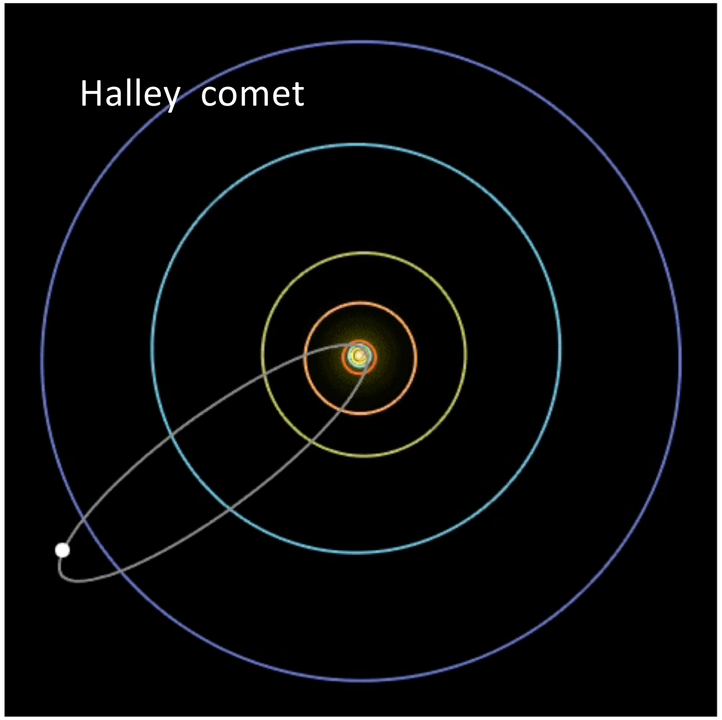
- Tangential/radial velocities: 0.03 of occurrence
- **Spatial location: < 0.005 of occurrence**
- Locations versus pericenters

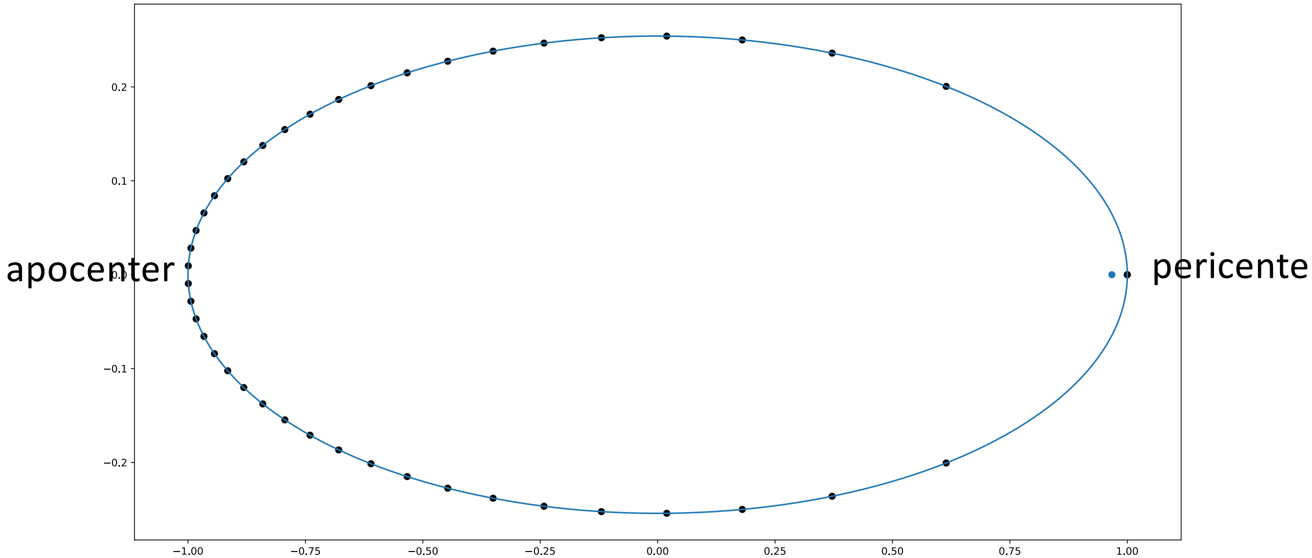
Are Milky Way dwarfs consistent with subhalos?

- Tangential/radial velocities: 0.03 of occurrence
- Spatial location: < 0.005 of occurrence
- **Locations versus pericenters**

Are Milky Way dwarfs consistent with subhalos?

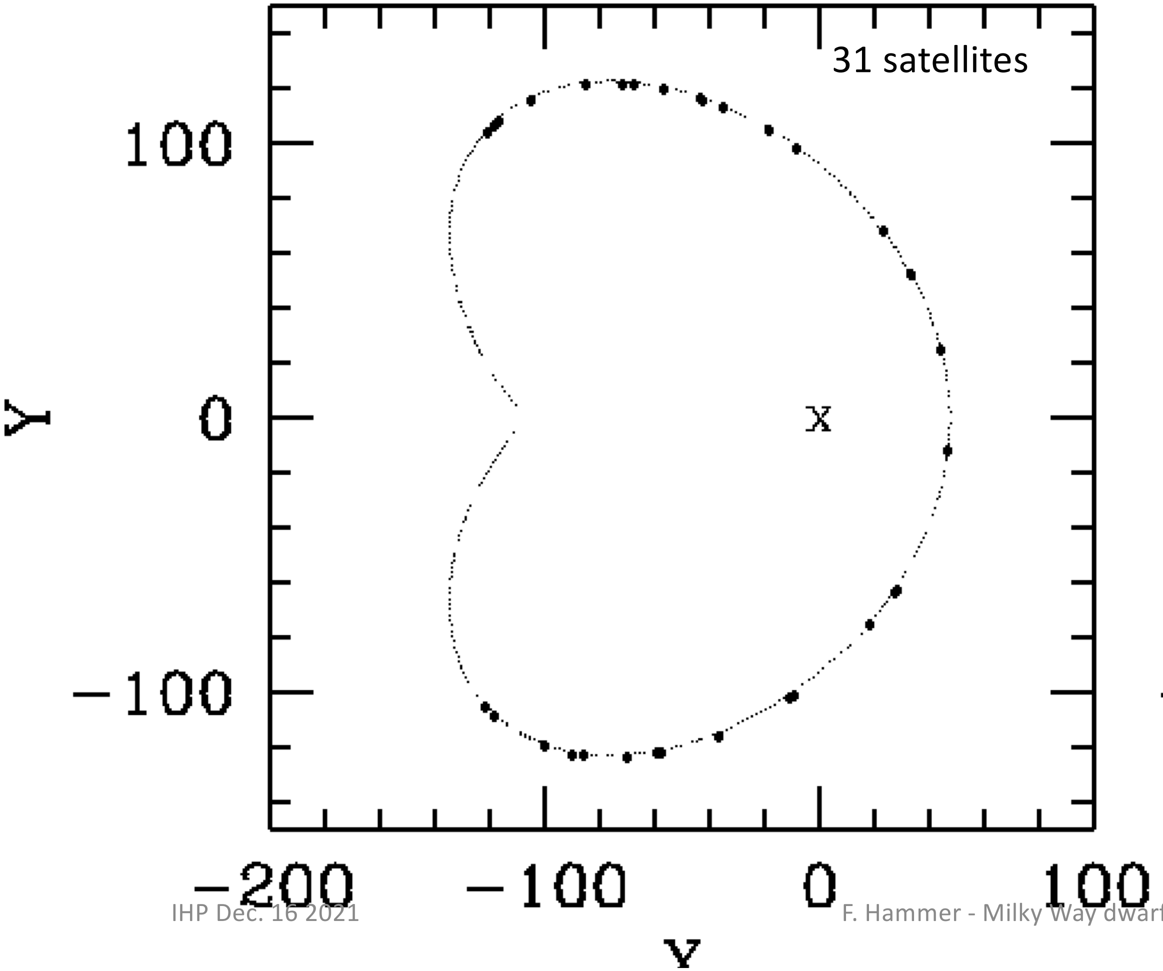
- **Locations versus pericenters: expectations for satellite orbits**

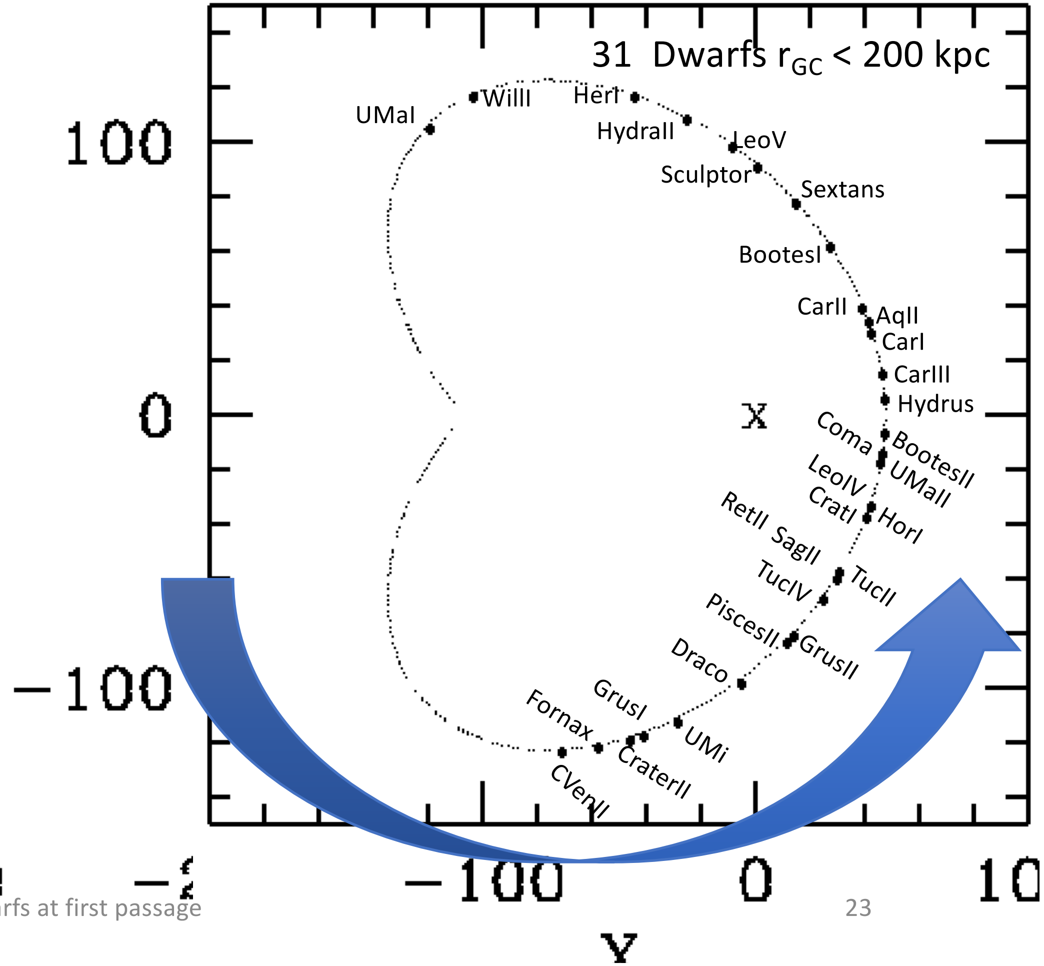




Are Milky Way dwarfs consistent with subhalos?

- **Locations versus pericenters: expectations for satellite orbits**



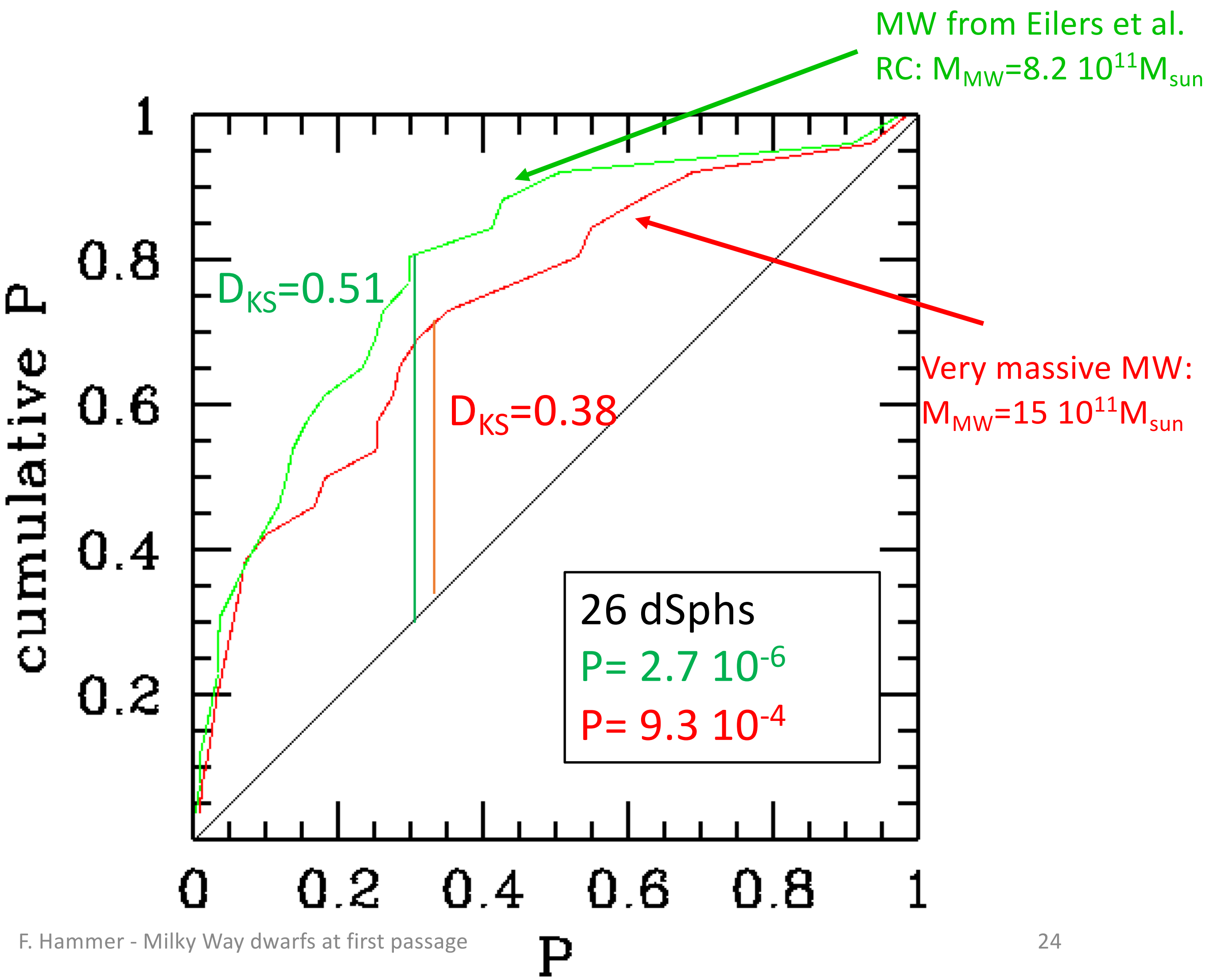


- **Locations versus pericenters: expectations for satellite orbits**

There could be incompleteness in the dwarf inventory affecting especially those at r_{GC} > 100-200 kpc (Drlica-Wagner et al. 2020).

That is why here (Li et al. 2021) we have selected a complete sample of **26 dSphs kept in a complete sample at 90 kpc.**

Dwarfs are too close to their pericenters even if the Milky Way is very massive!!



Are Milky Way dwarfs consistent with subhalos?

- Tangential/radial velocities: 0.03 of occurrence
- Spatial location: < 0.005 of occurrence
- **Locations versus pericenters: < 0.001 of occurrence**

Are Milky Way dwarfs consistent with subhalos?

- Tangential/radial velocities: 0.03 of occurrence
- Spatial location: < 0.005 of occurrence
- **Locations versus pericenters: < 0.001 of occurrence**
- **AND MILKY WAY DWARFS ARE MOSTLY AT FIRST PASSAGE**

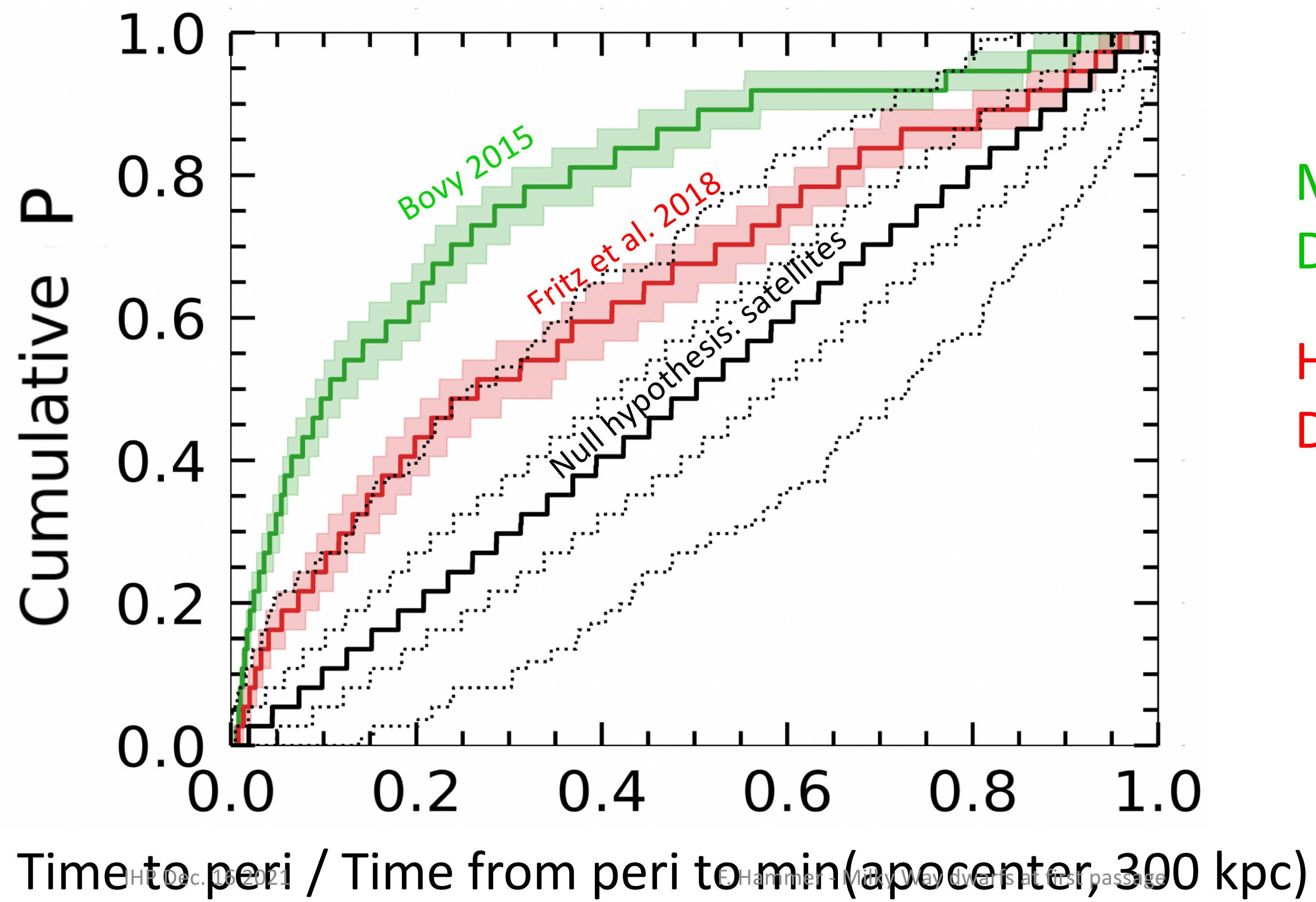
Conclusion: Milky Way dwarfs NOT consistent with subhalos

- Combined rate of occurrence for Milky Way dwarfs to behave as subhalos is exceptionally low **($P << 10^{-6}$),** if you account for their velocities, position in the sky and on their orbit: they do not behave as ΛCDM subhalos.

- **FROM THEIR ENERGIES AND ANGULAR MOMENTA, MOST MILKY WAY DWARFS ARE AT FIRST PASSAGE ➔ MISSING SATELLITES!**

➔ One has to study how they arrived, how they loose their gas, why their velocity dispersions are large, and what is their matter content

Gaia DR2: Fritz et al 2018 sample (except Eridanus II & Phoenix)



MW mass, Bovy 2015:

D= 0.486, P= 2 10^{-7}

High MW mass, Fritz 2018:

D=0.270, P=0.0045