Making Counter-Orbiting Tidal Debris. The Origin of the MW Satellites?

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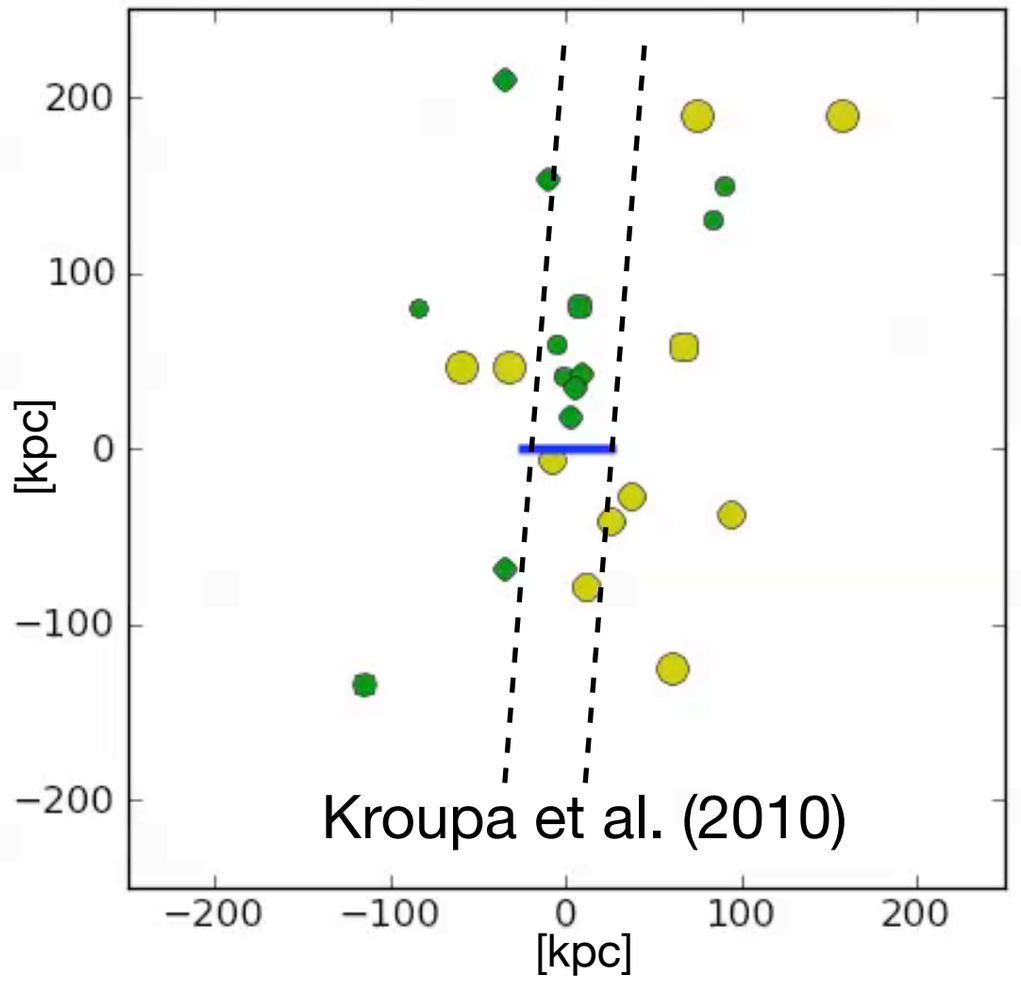
Milky Way satellites

Missing Satellites:

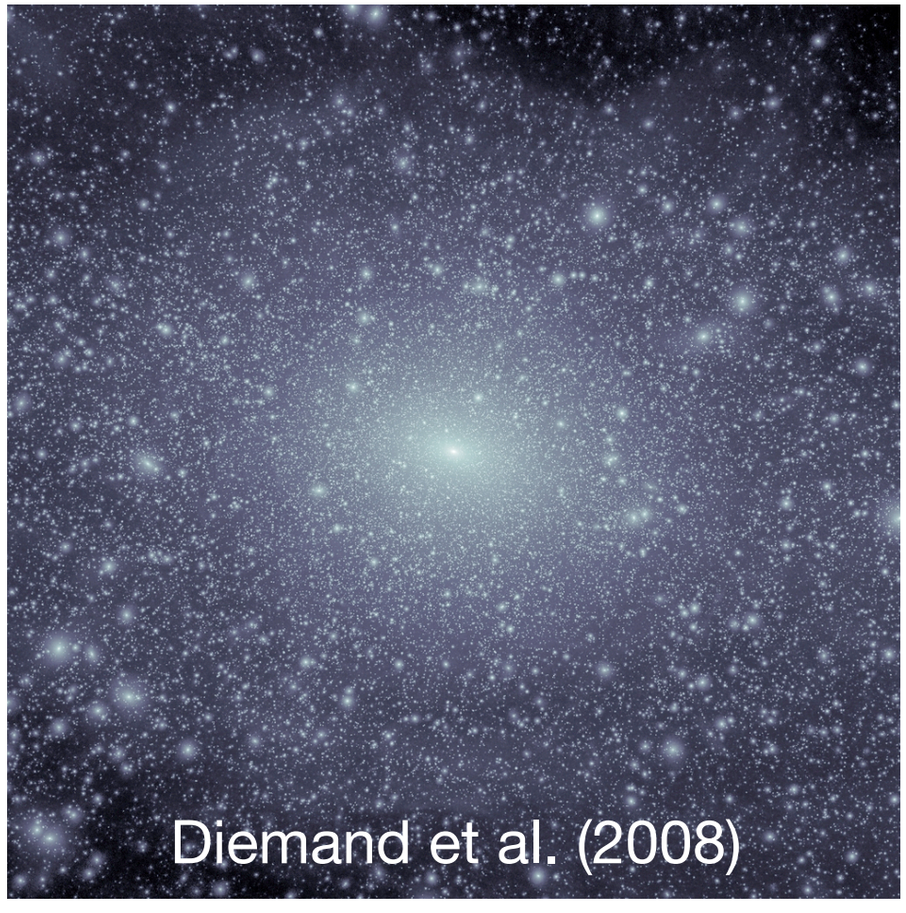
- MW-Observation:
  ~ 24 satellite galaxies
- ΛCDM-prediction:
  ~1000 DM subhalos

Distribution:

- Disc of Satellites (DoS)

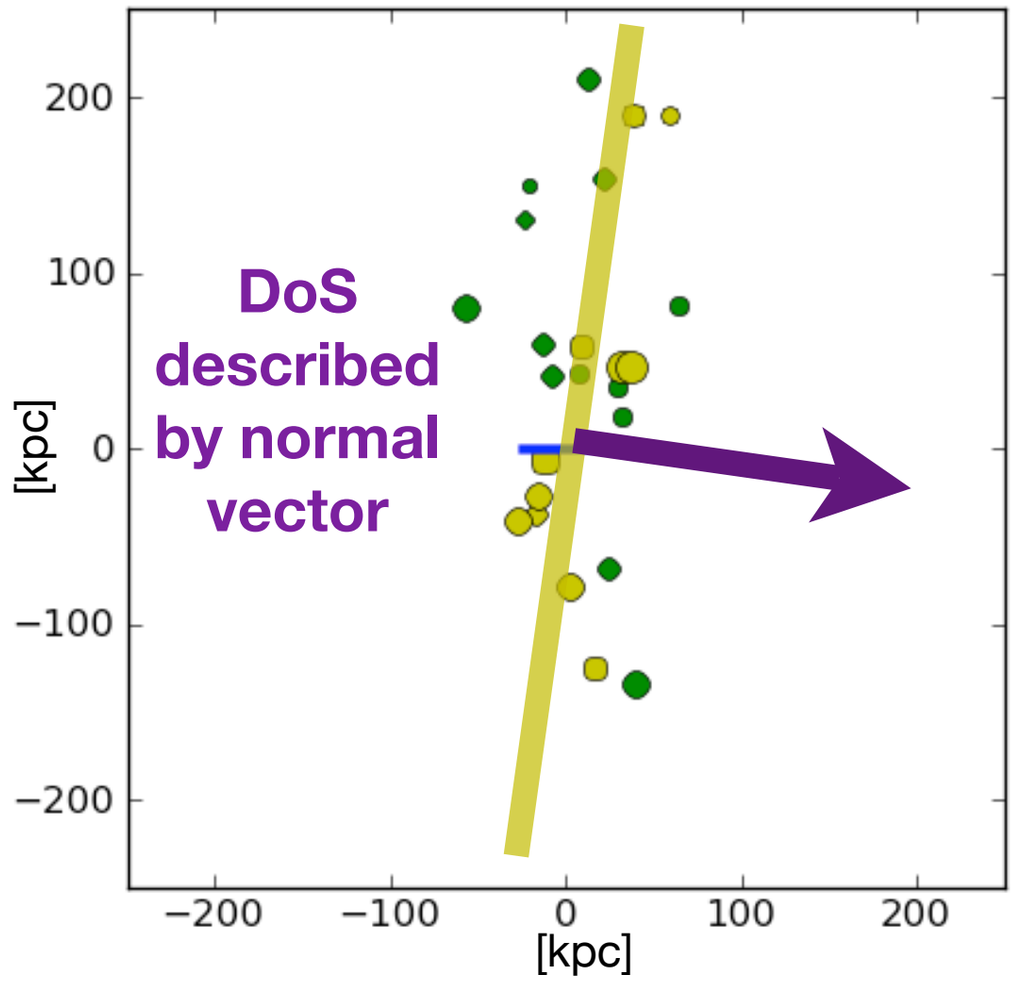


Kroupa et al. (2010)


Diemand et al. (2008)

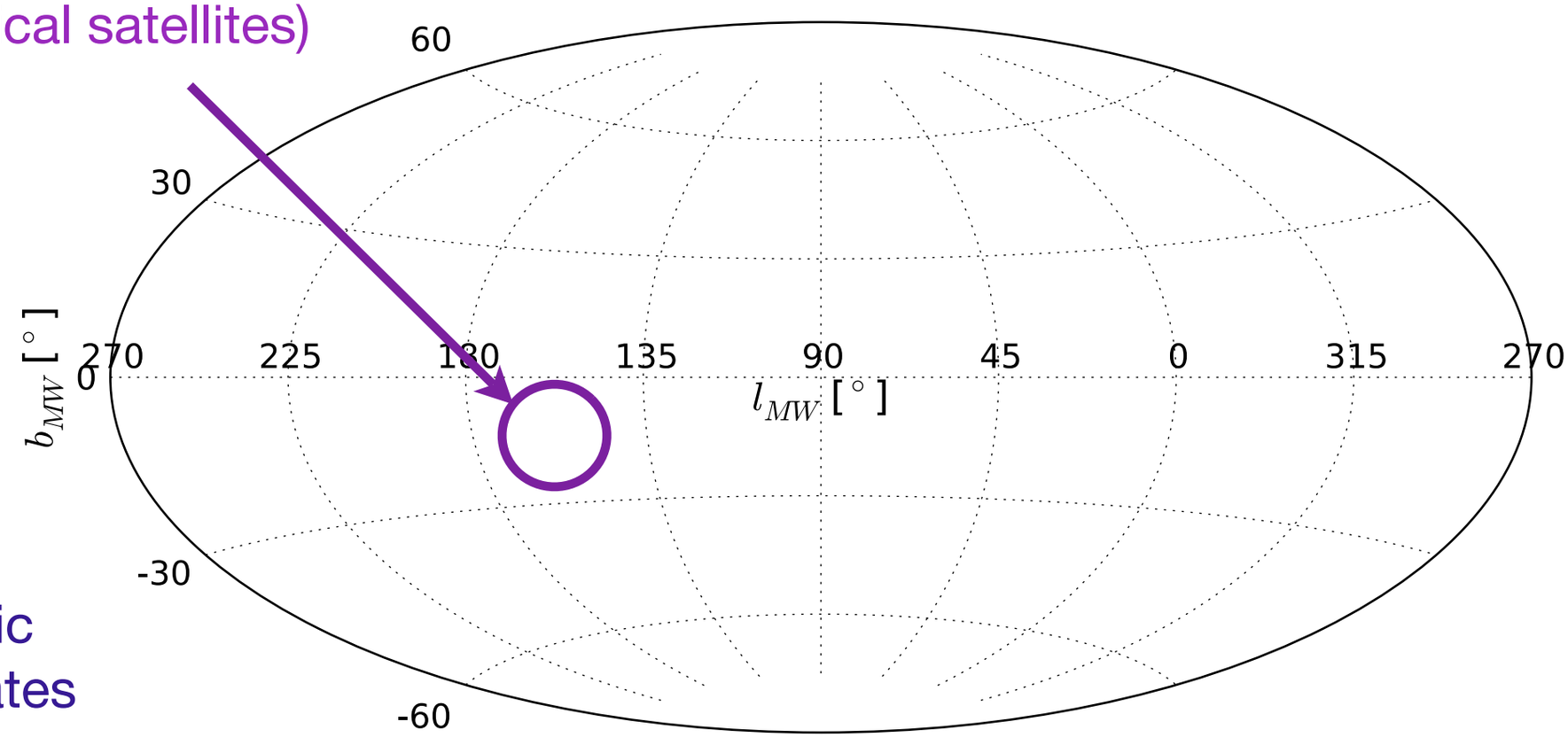
Disc of Satellites (DoS)

- 11 ‘classical’ bright satellites (Metz et al. 2007)



DoS
(11 classical satellites)

MW North Pole

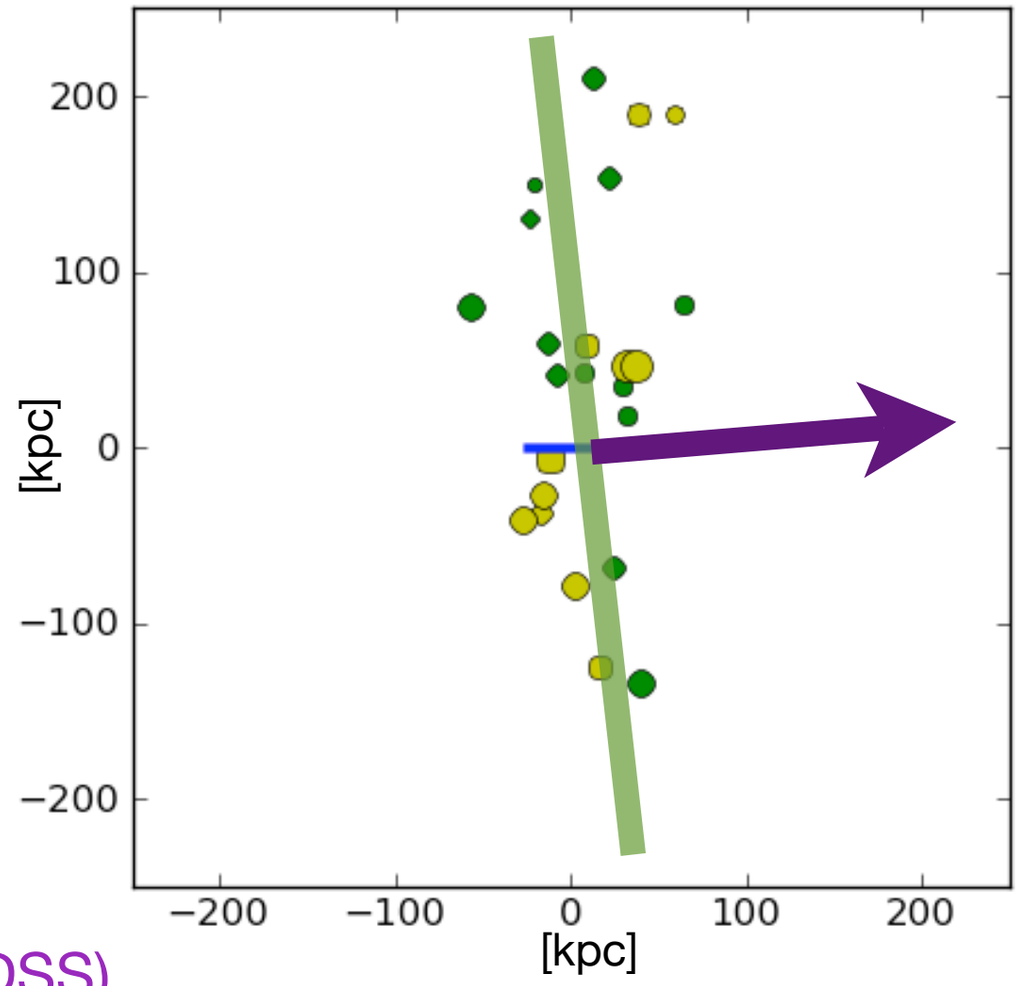


MW equator
= disc plane

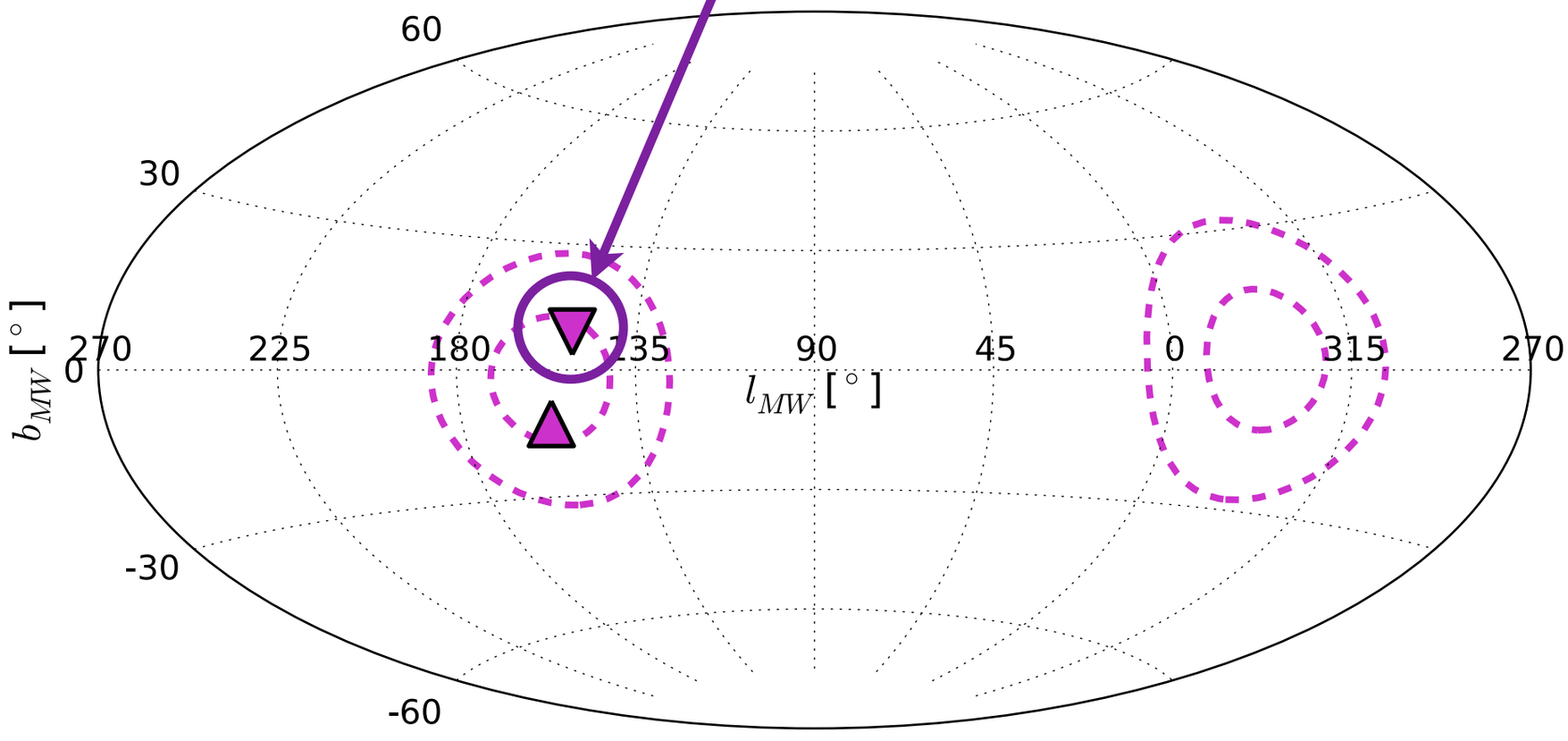
Galactic
coordinates

Disc of Satellites (DoS)

- 11 ‘classical’ bright satellites (Metz et al. 2007)
- 13 faint satellites (mostly discovered in SDSS) (Kroupa et al. 2010)

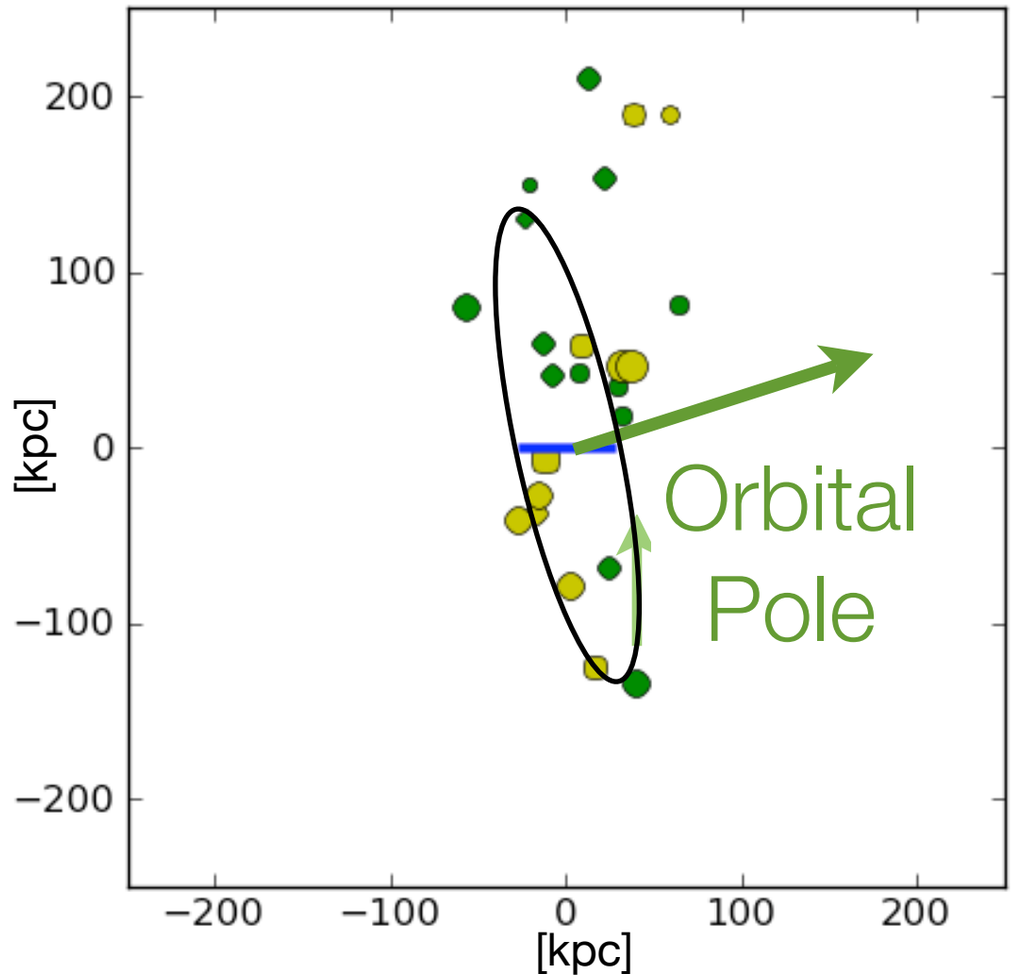


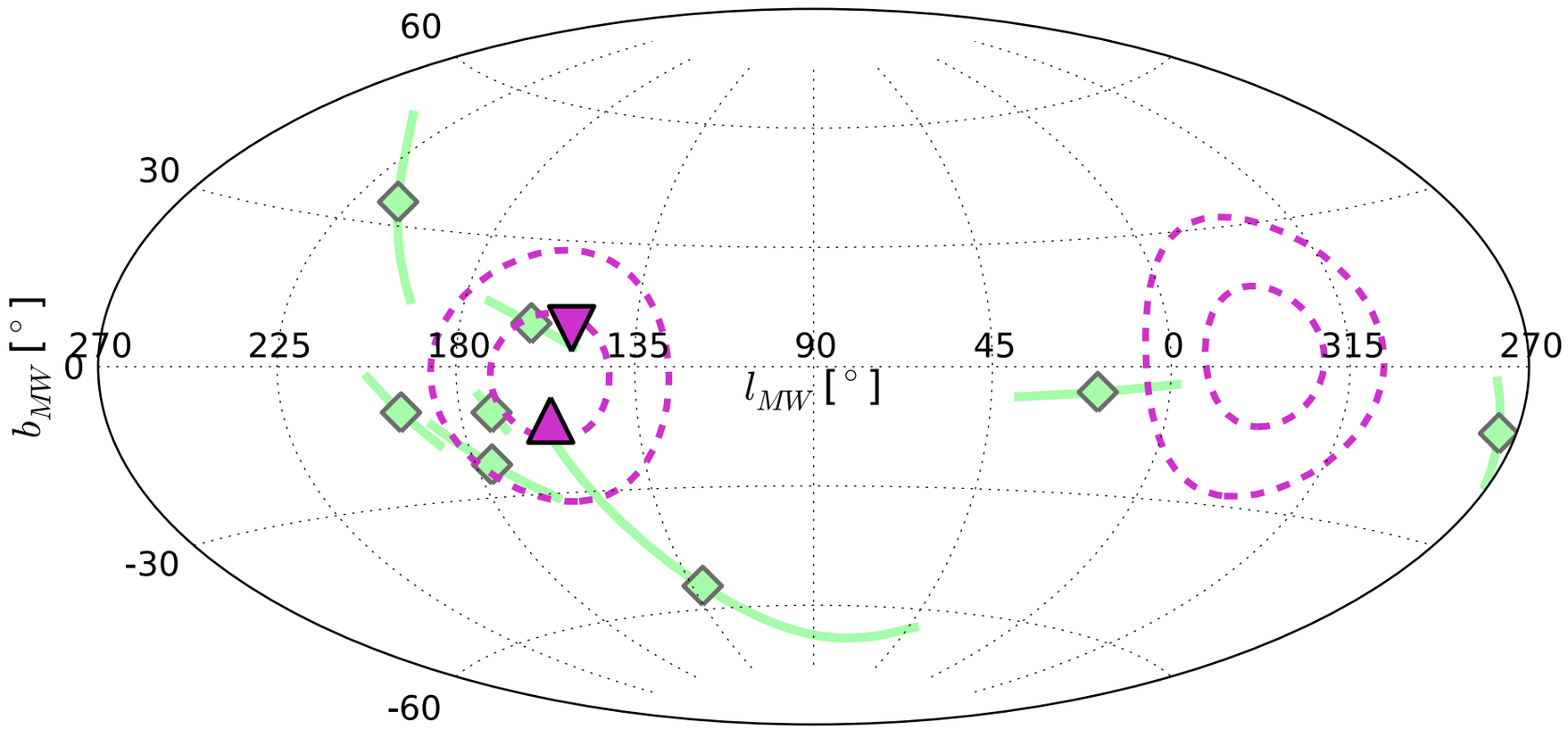
DoS
(13 faint satellites, SDSS)



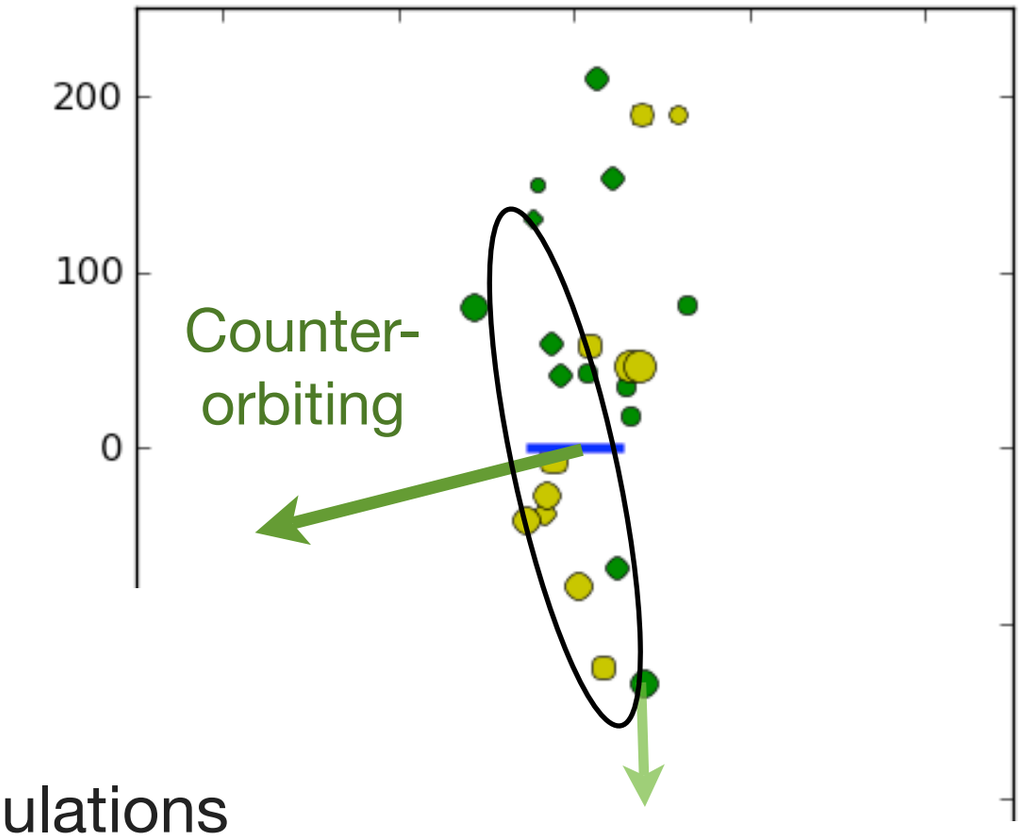
Disc of Satellites (DoS) + Orbital Poles

- Proper motions measures for 8 satellites
  - ➡ Orbital poles ($\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{v}$) Metz et al. (2008)





Disc of Satellites (DoS) + Orbital Poles

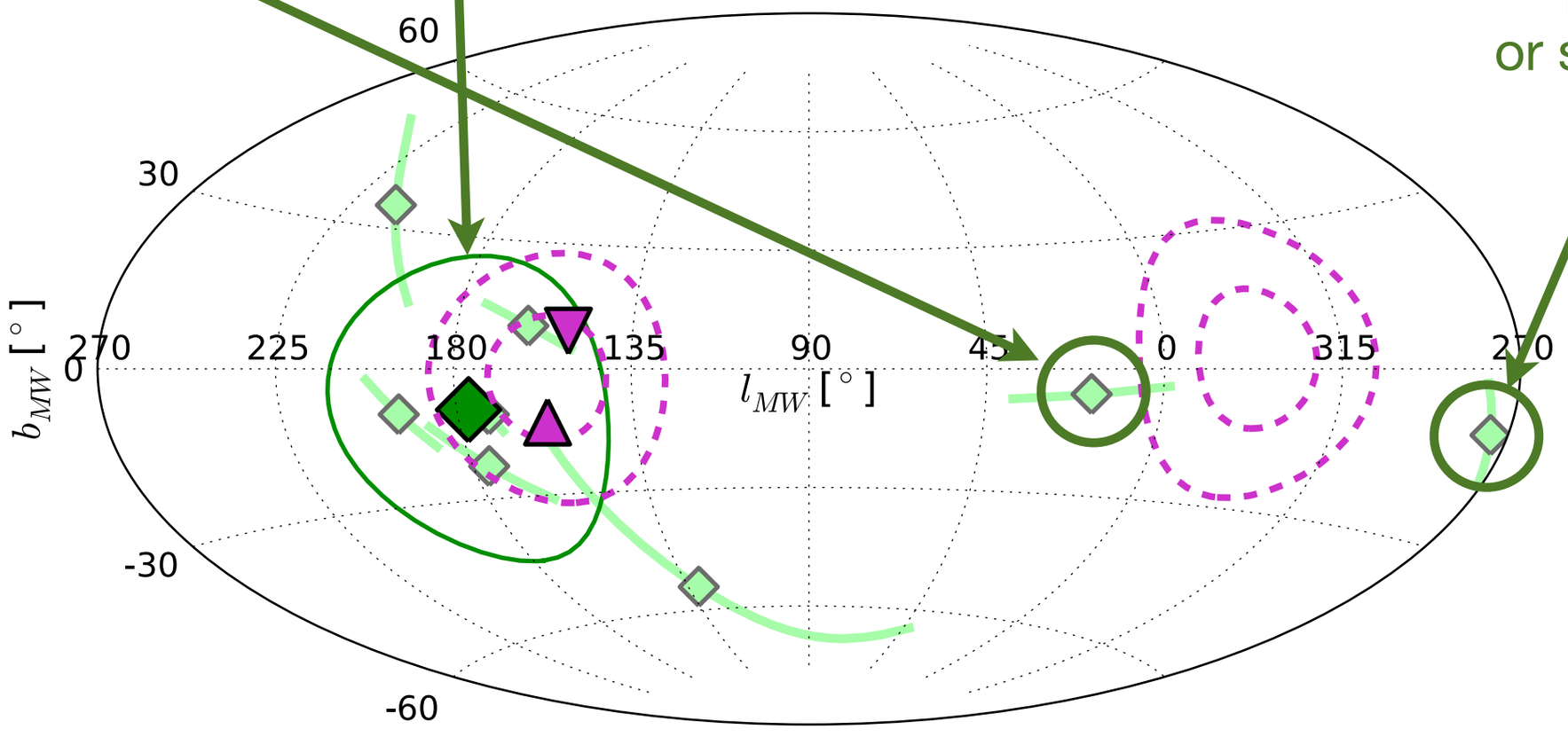


- Proper motions measures for 8 satellites
  - ➡ Orbital poles (***L*** = ***r*** x ***v***) Metz et al. (2008)

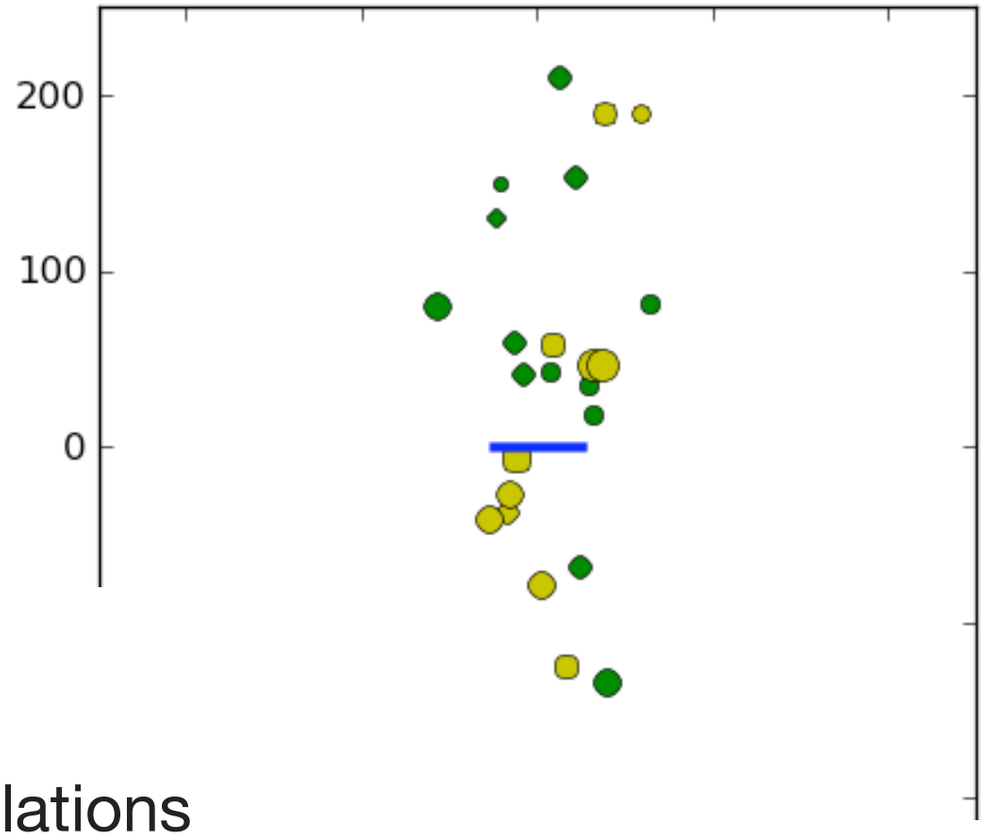
- 6 satellites co-orbit *in the DoS*
  - ➡ Extremely unlikely if drawn from CDM simulations

- Sculptor: counter-orbiting (***L*** offset by ~ 180º) *in the DoS*

Sagittarius:
close to MW
➡ precession
or scattered



Disc of Satellites (DoS) + Orbital Poles + Disc of GCs



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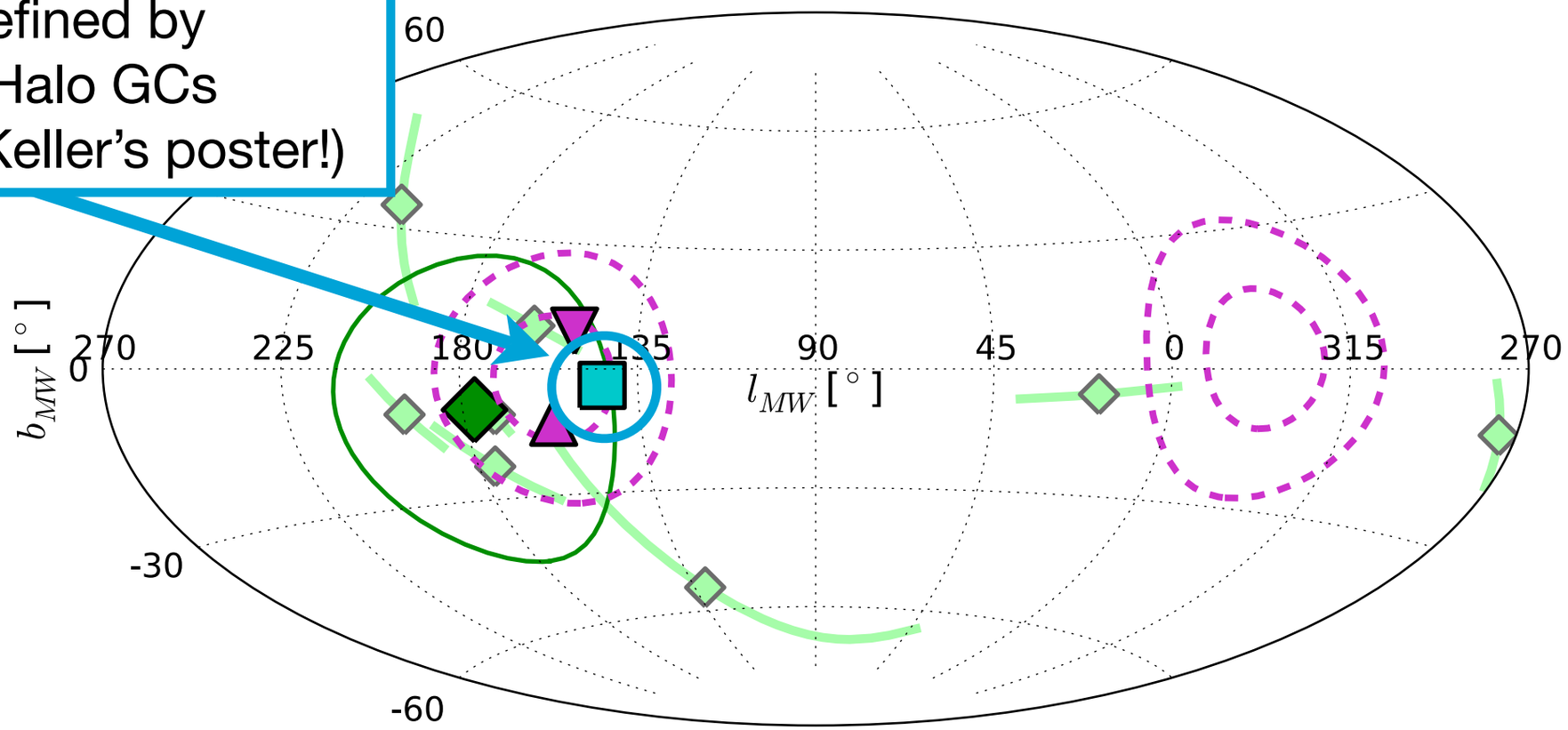
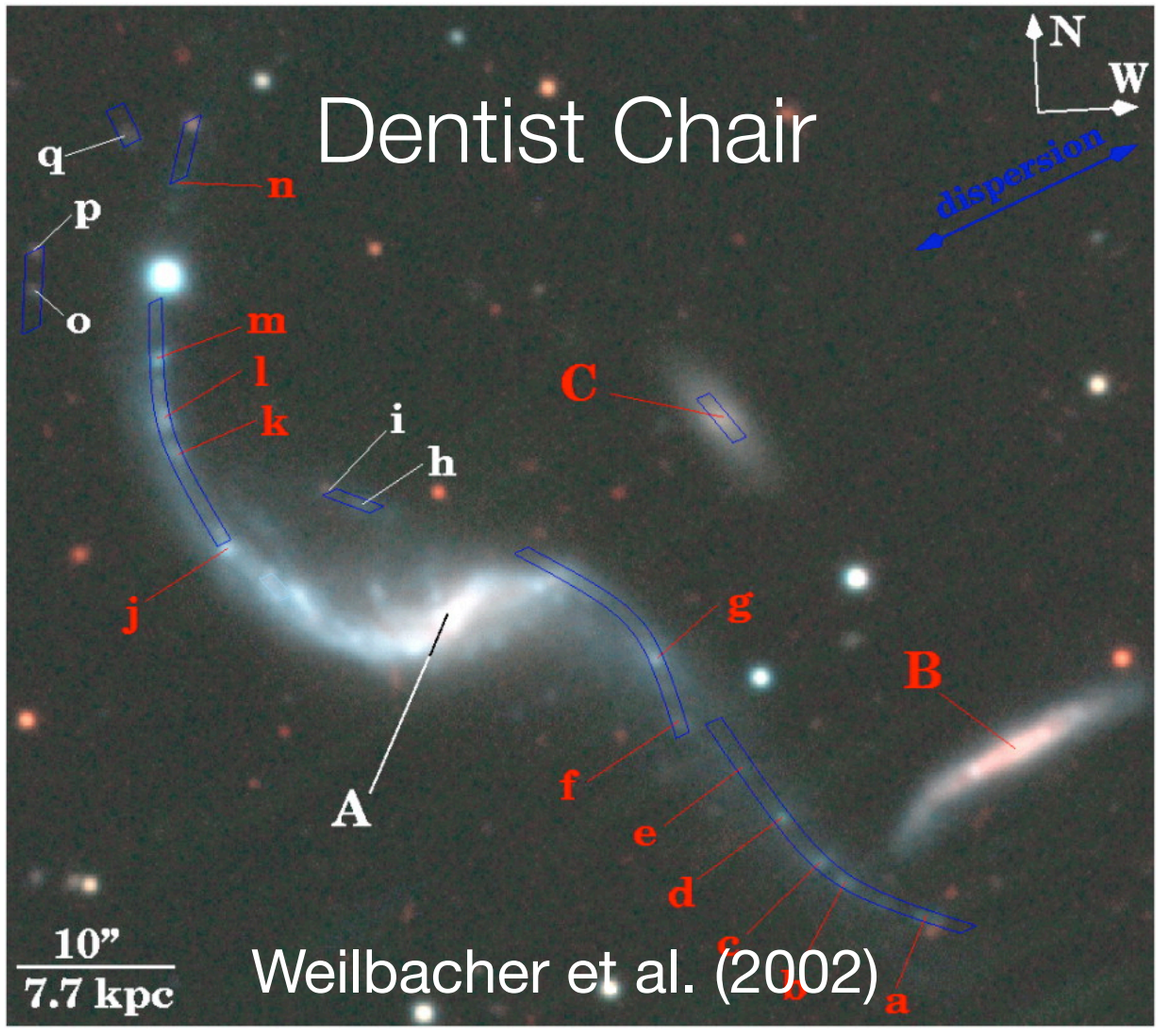
Disc defined by
Young Halo GCs
(see Stefan Keller's poster!)

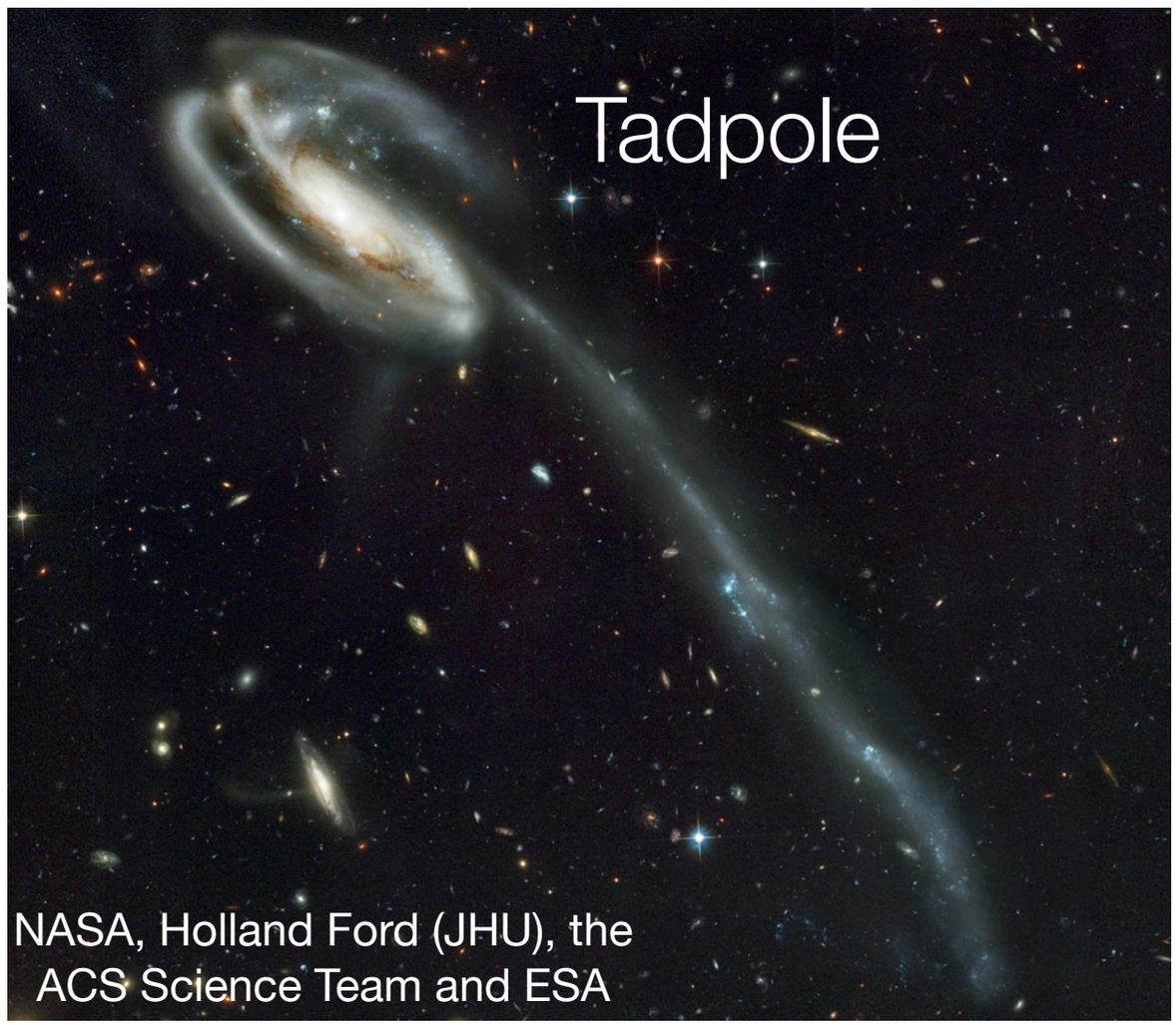


Another possible origin

Common positions and velocities hint at common origin.

Tidal Dwarf Galaxies (TDGs)?





Another possible origin

Common positions and velocities hint at common origin.

Tidal Dwarf Galaxies (TDGs)?

Tidal debris form in the plane of a galaxy interaction

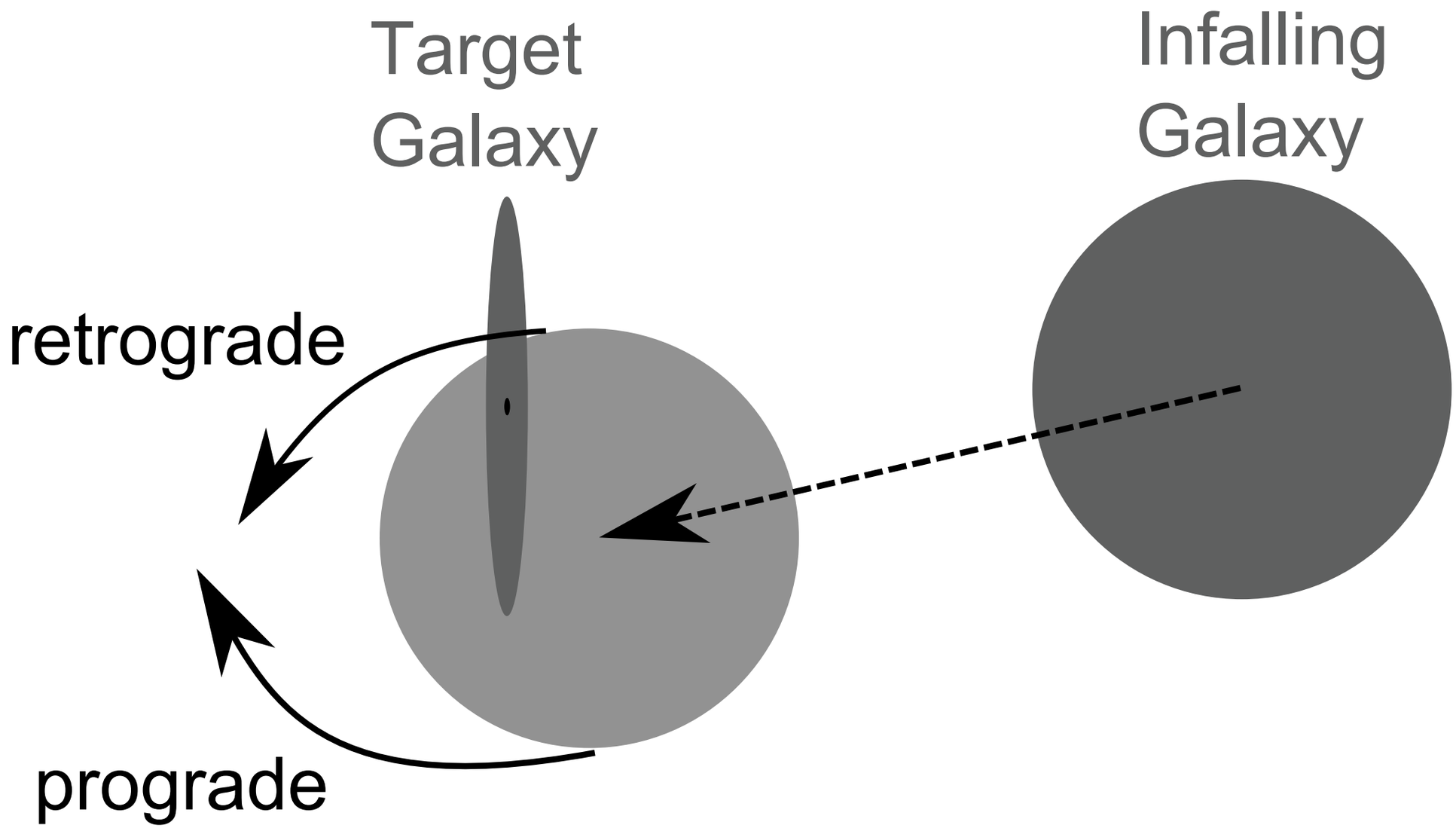
➡ TDGs distributed in a disc

Can *counter-orbiting* tidal debris form in a galaxy collision?

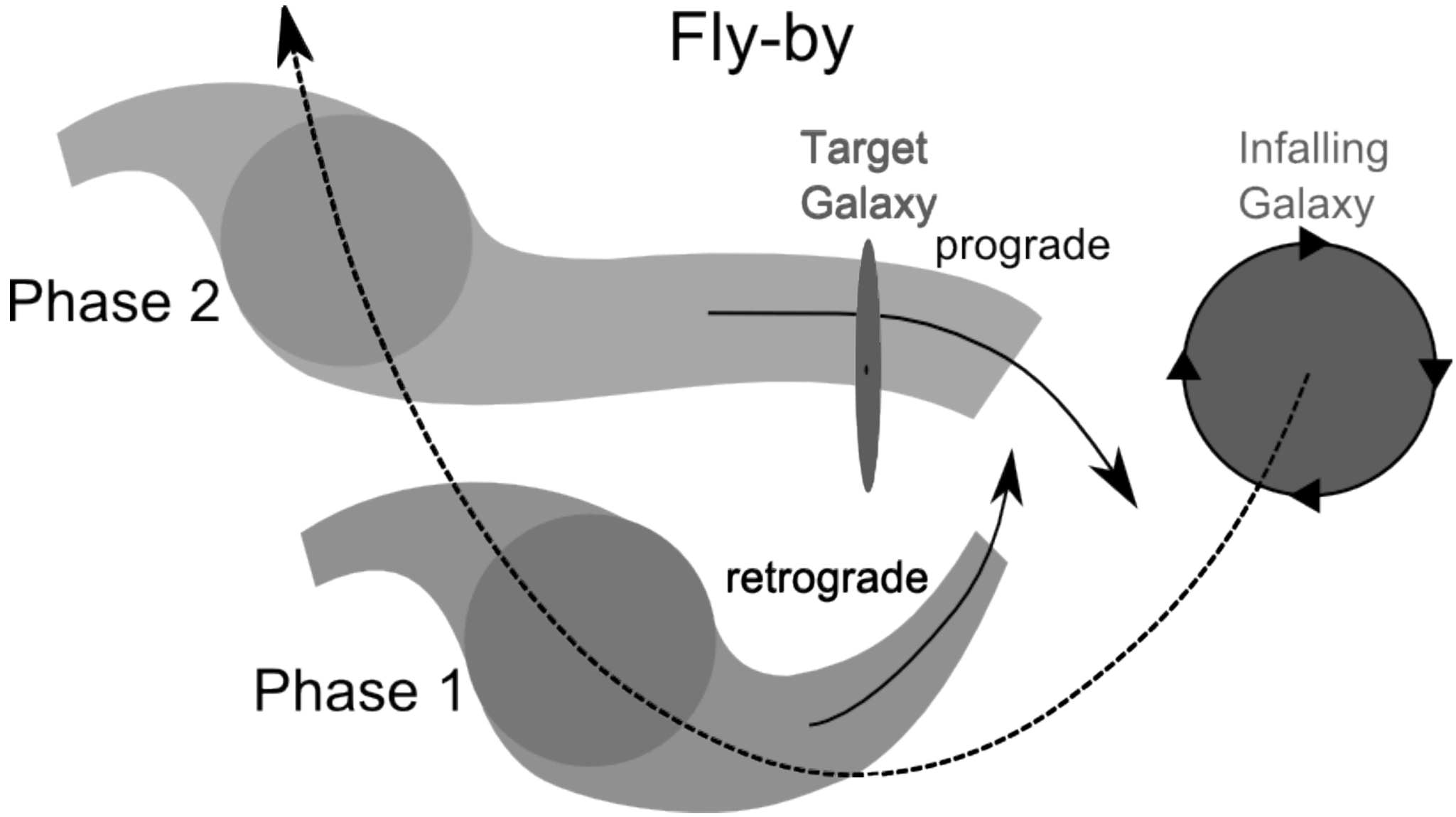
Method: numerical calculations

The Idea

Merger



The Idea


Fly-by
Target
Galaxy
Infalling
Galaxy
prograde
Phase 2
retrograde
Phase 1

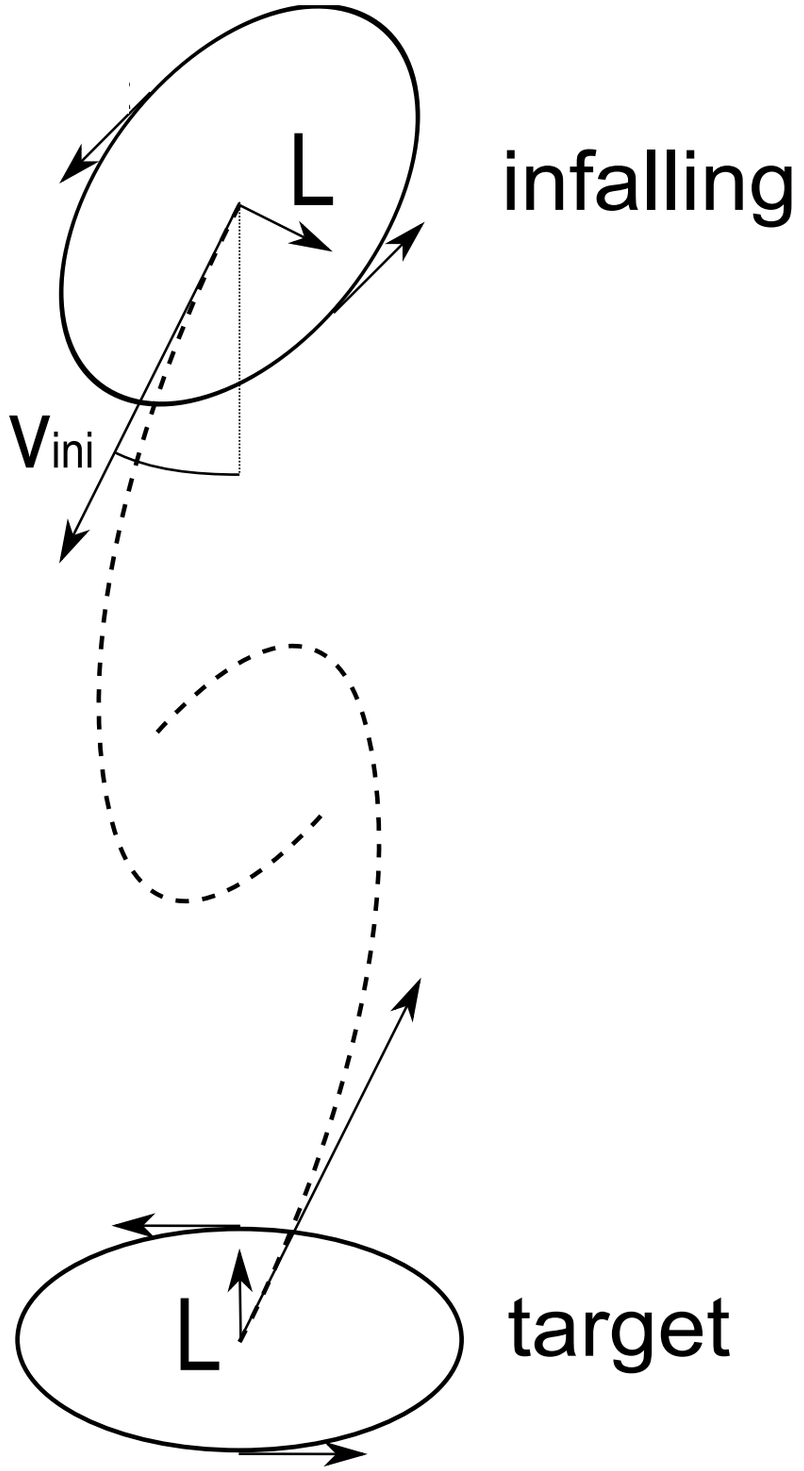
The Setup

- Nbody models with SUPERBOX++

- Scaled MW (10 Gyr ago)
  - exponential disc
  - M_{disc} = 8 x 10^9 M_{sun}
  - R_{scale} = 1.6 kpc
  - v_{rot} = 125 $^{km}/_{s}$
  - N = 5 x 10^5 particles
  - Hernquist halo, 10 x M_{disc}

- Similar to M33 today

- Parameter study
  - Mass ratios Target to Infalling
    1:1 and 4:1
  - 74 models (>200 CPU-days)

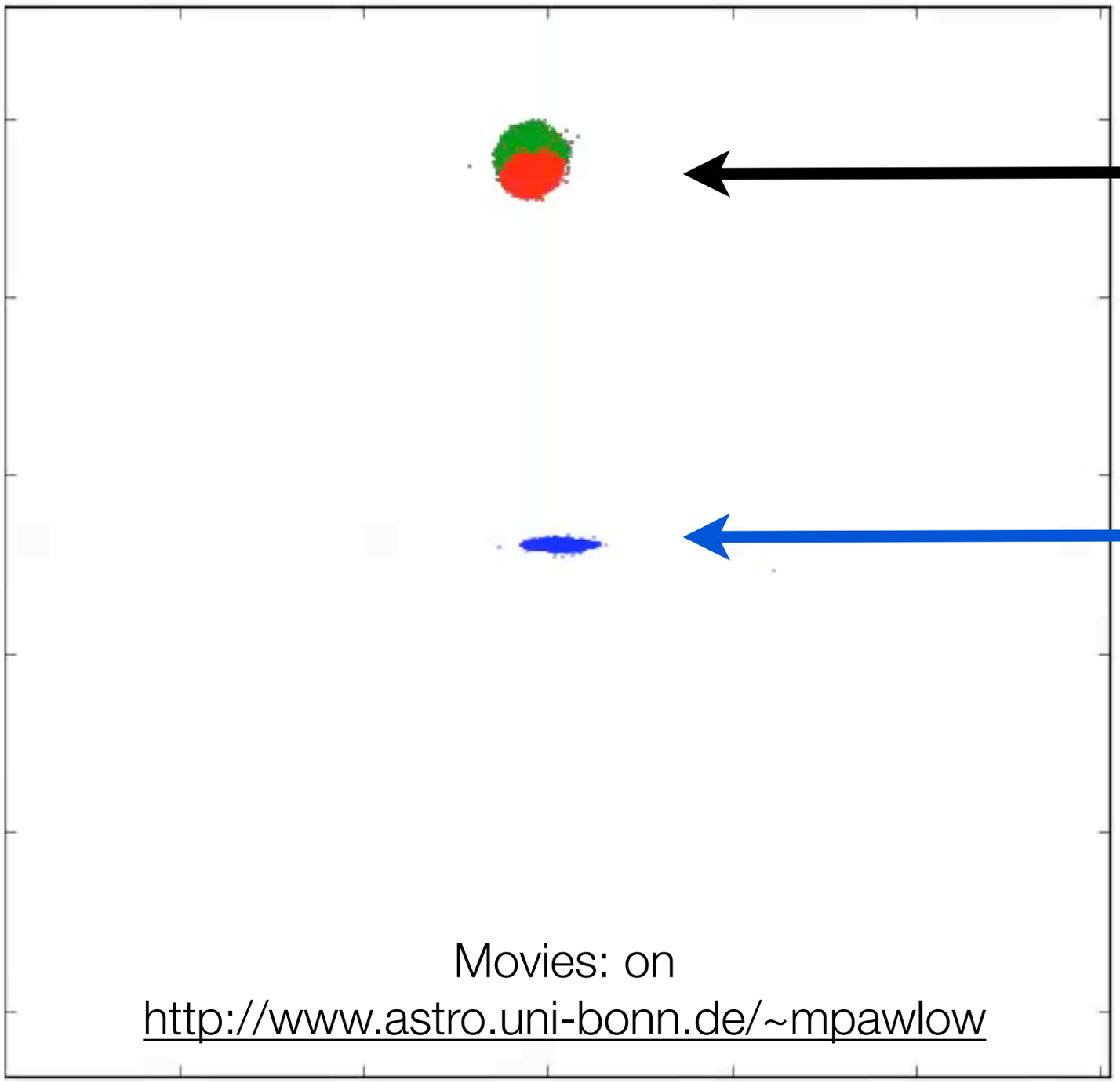


Do counter-orbiting tidal debris form?

Fly-by example

Fly-By Movie

Projection into the plane of the interaction
= disc of tidal debris seen face-on



Movies: on
http://www.astro.uni-bonn.de/~mpawlow

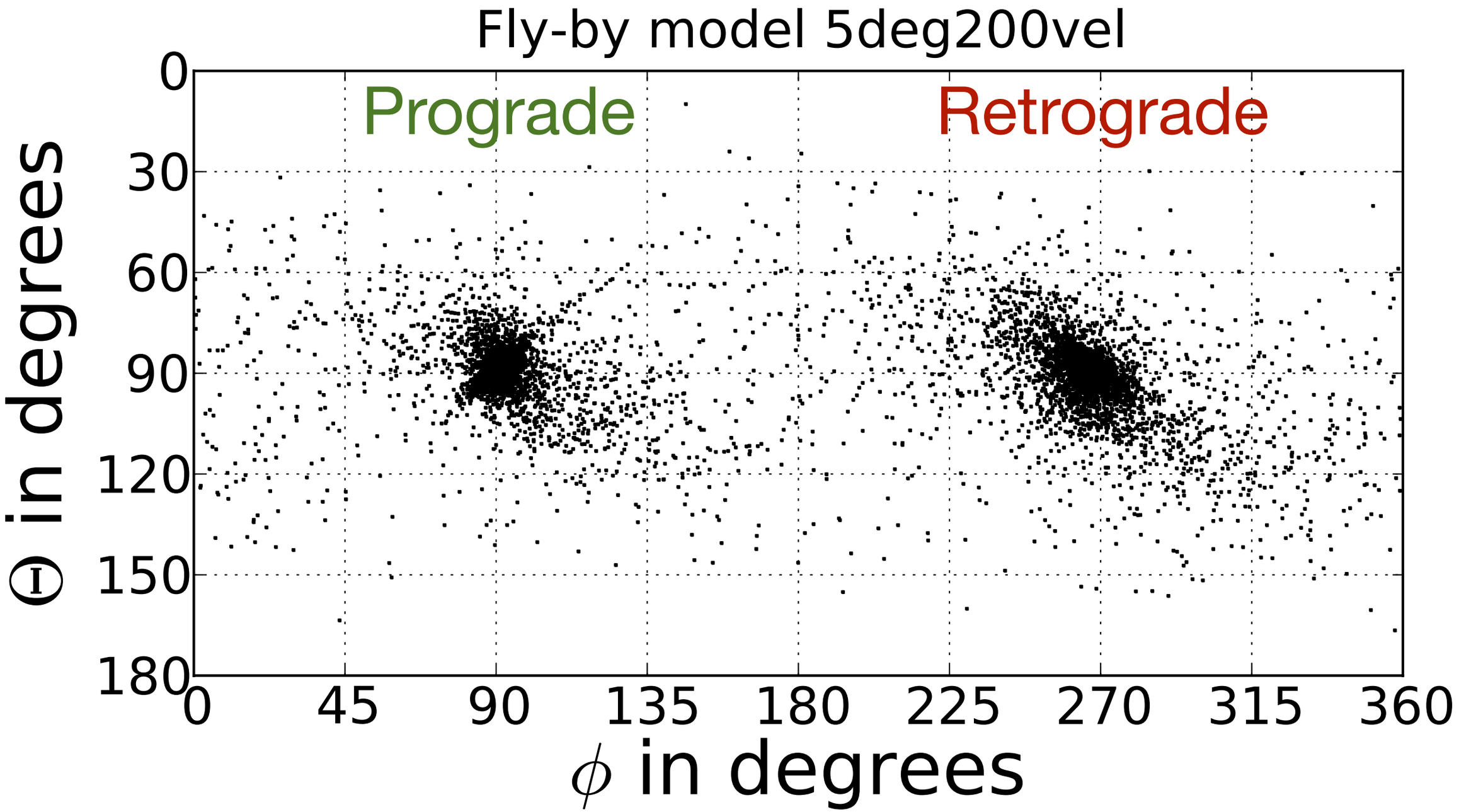
2 Phases:
retrograde first
tail sweeps over target
then prograde

Target Galaxy
(edge-on)

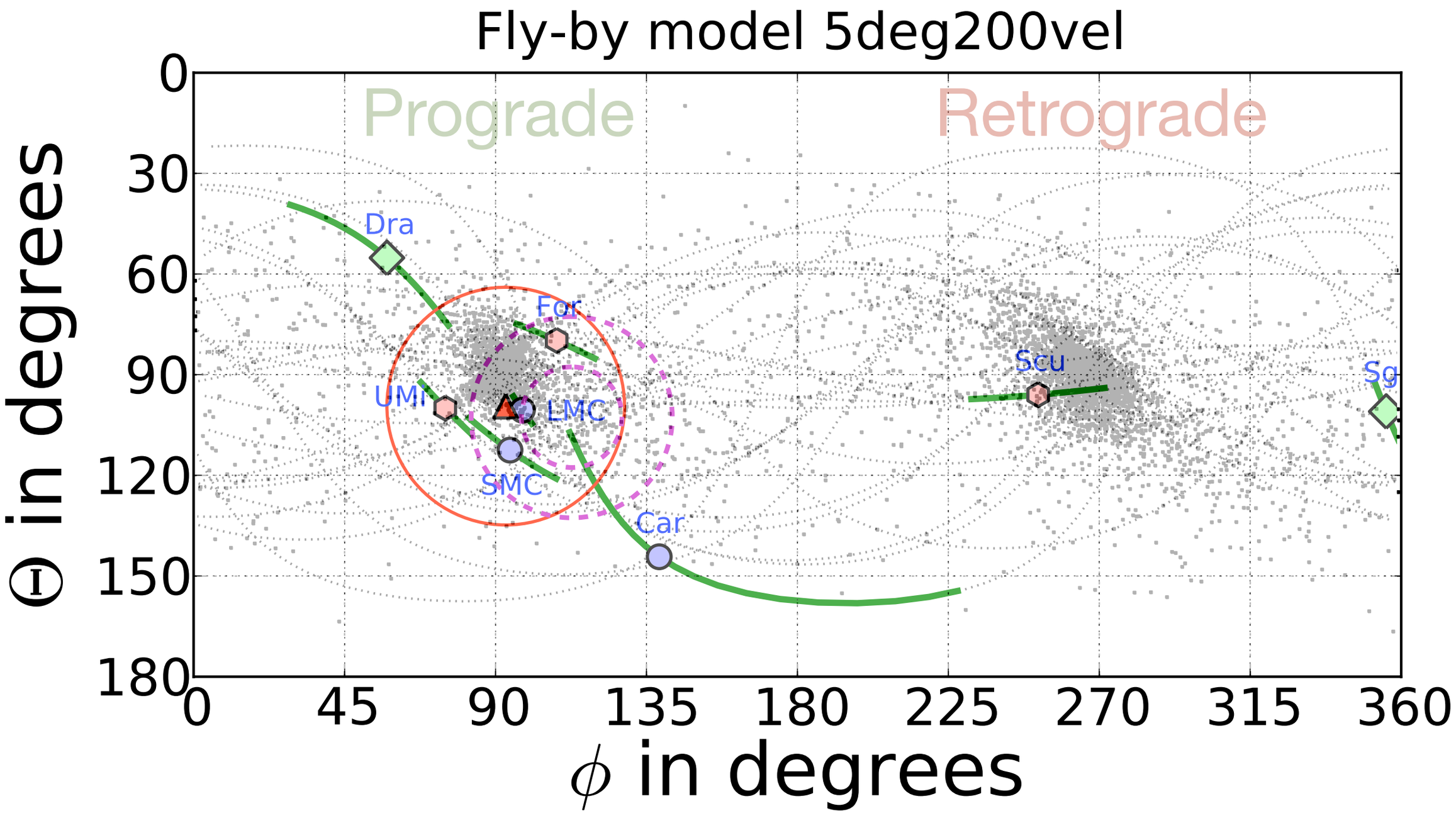
Prograde Particles

Retrograde Particles

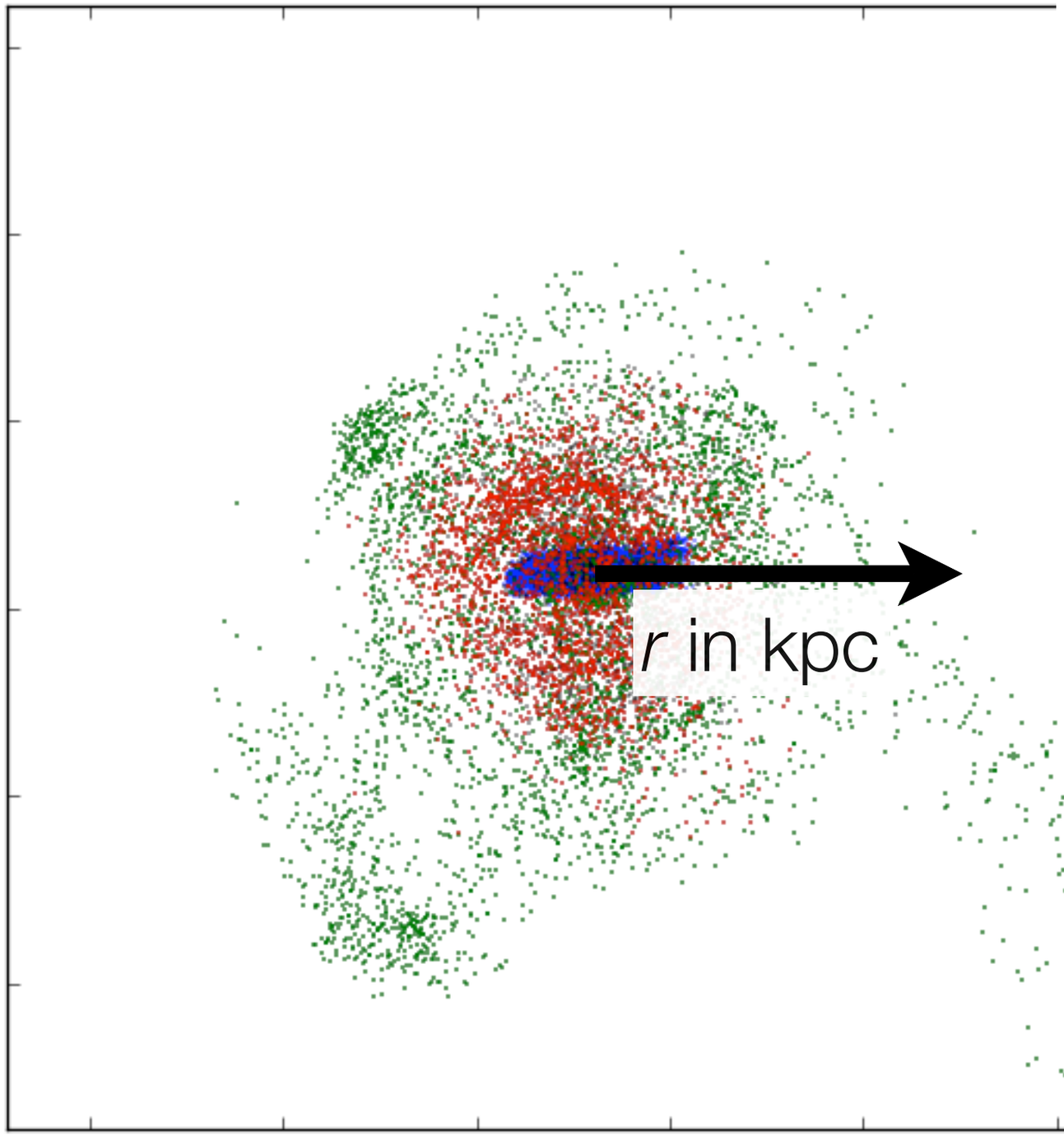
Fly-By
Orbital Poles

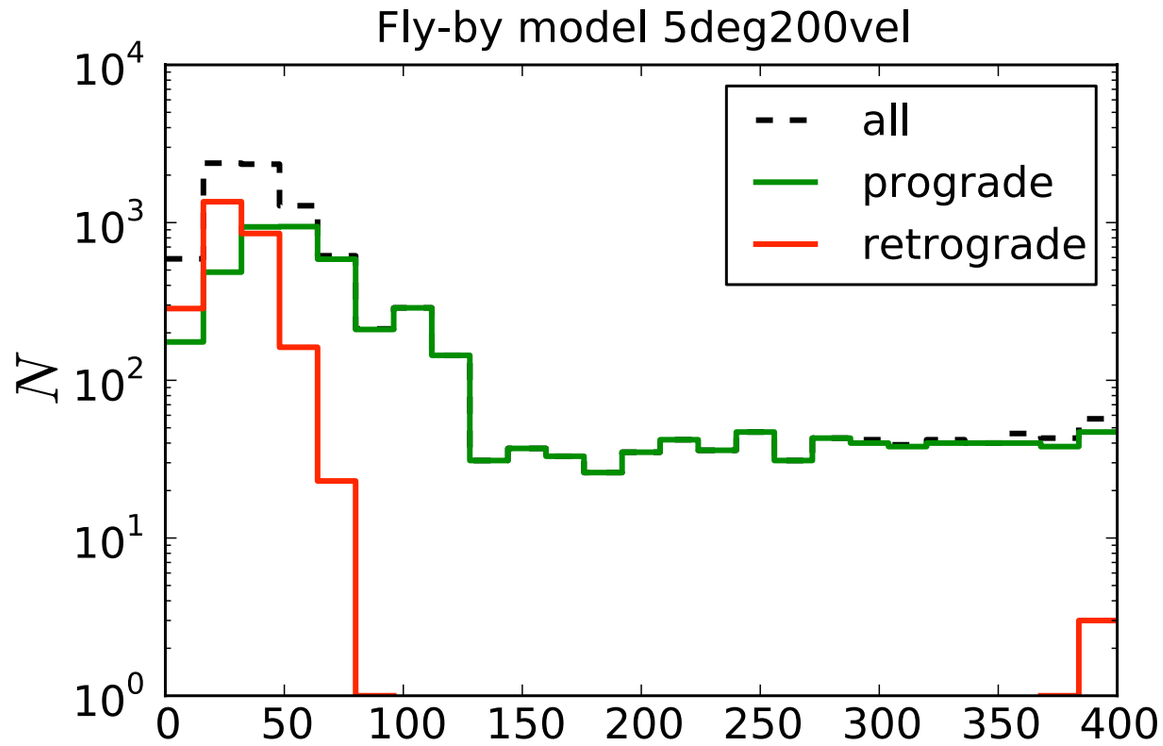


Fly-By
Orbital Poles



Fly-by
Radial Distribution

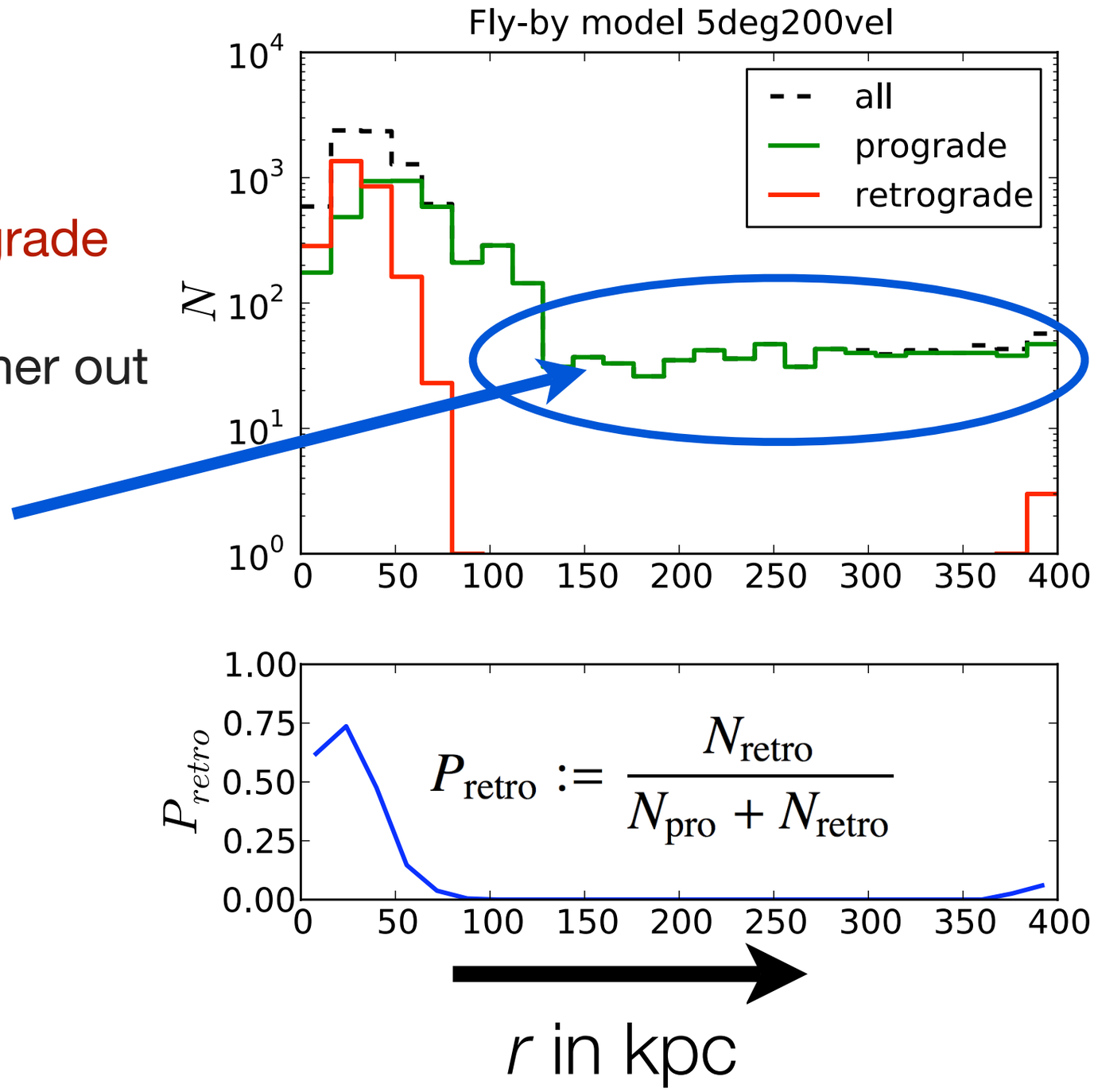




Fly-By
Radial Distribution

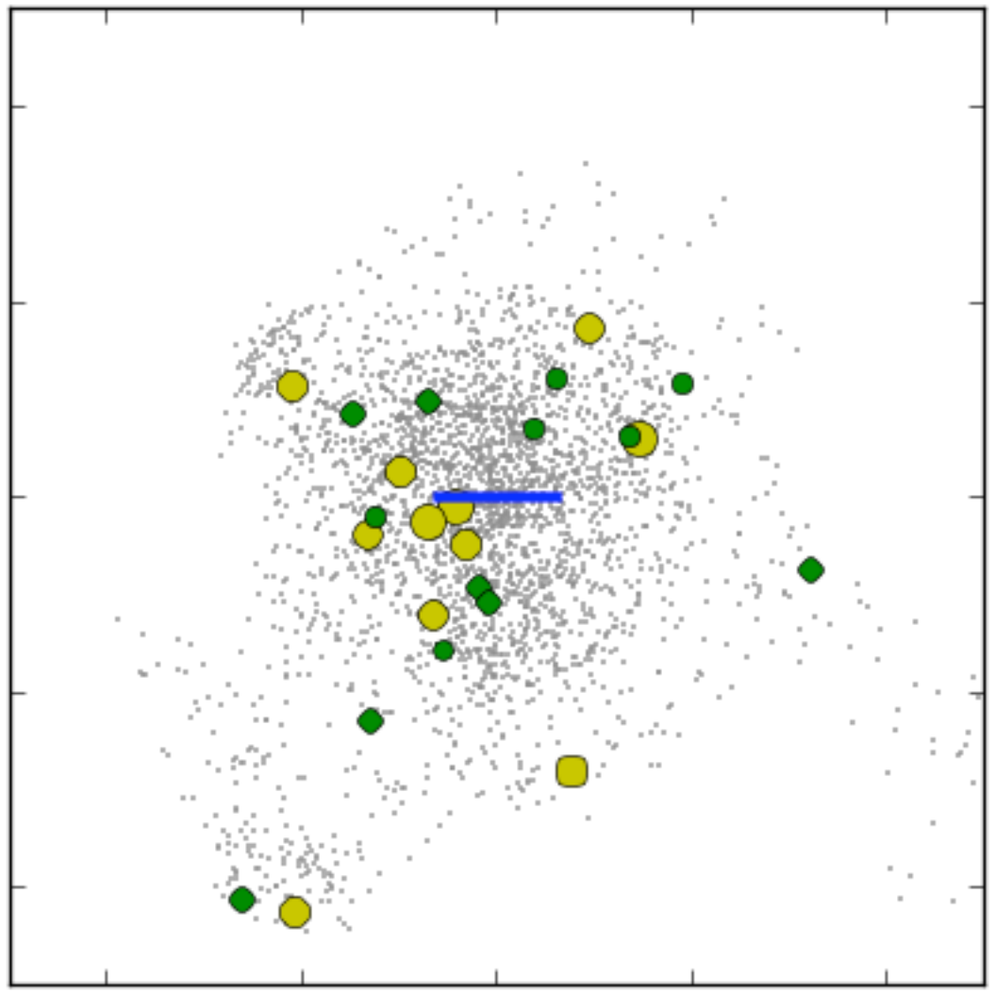
- Two phases:
  - ➡ Retrograde material more concentrated
  - ➡ Maximum distance for retrograde material
  - ➡ P_{retro} high in center, zero further out

- Prograde material along tidal tail connecting the galaxies

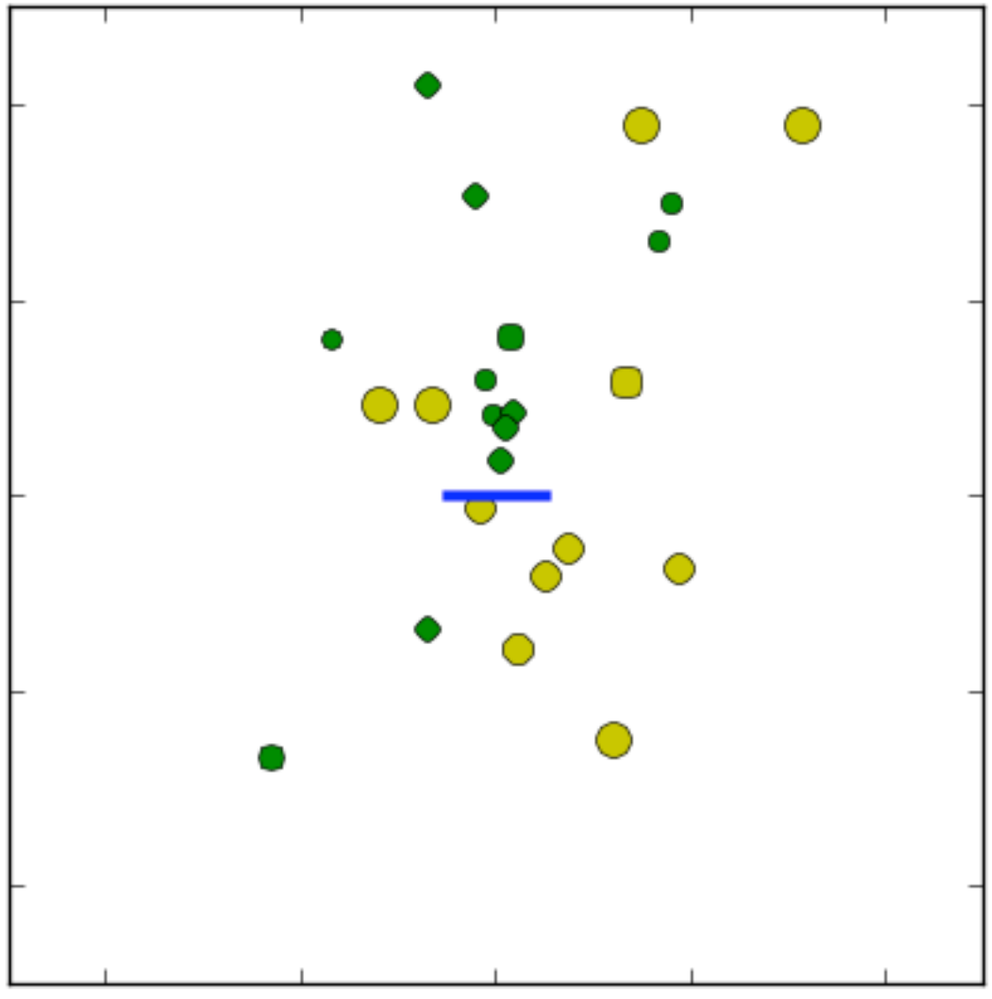


Fly-By
Comparison to MW satellite system

Model



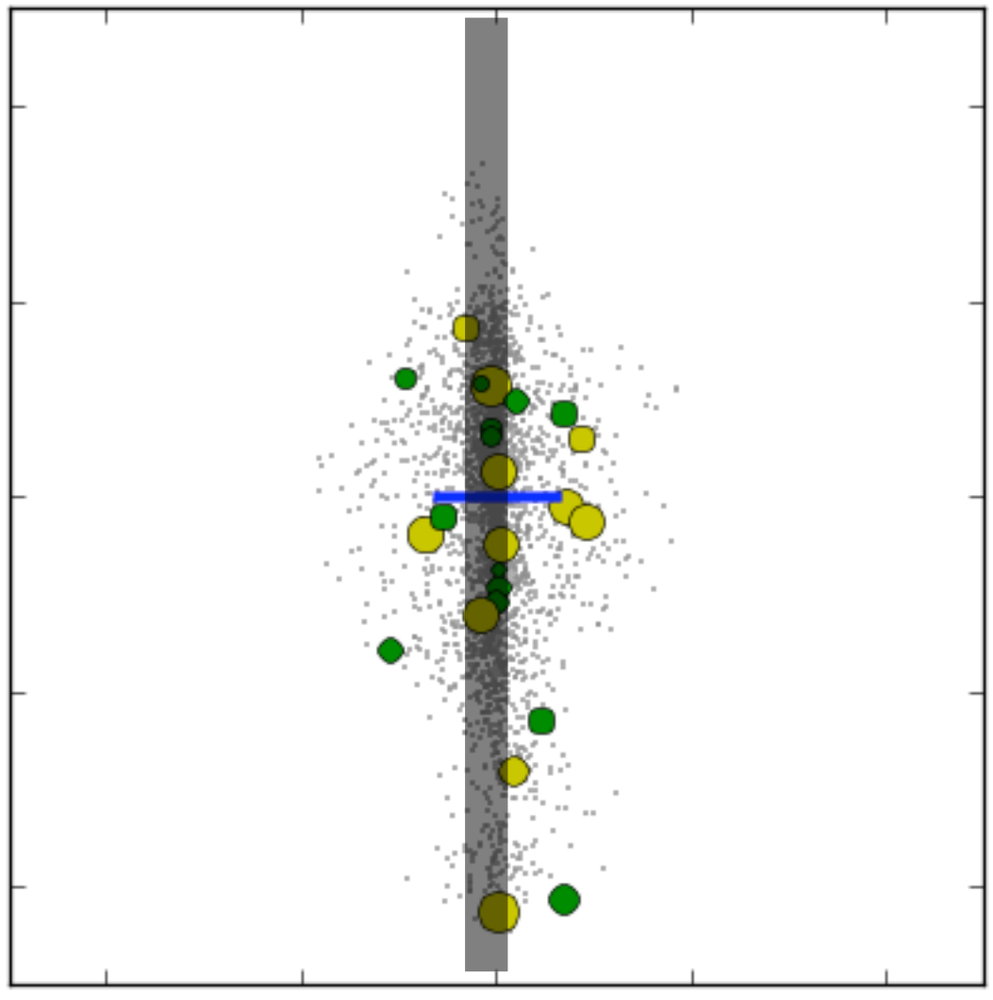
MW Satellites



Arbitrarily picked particles

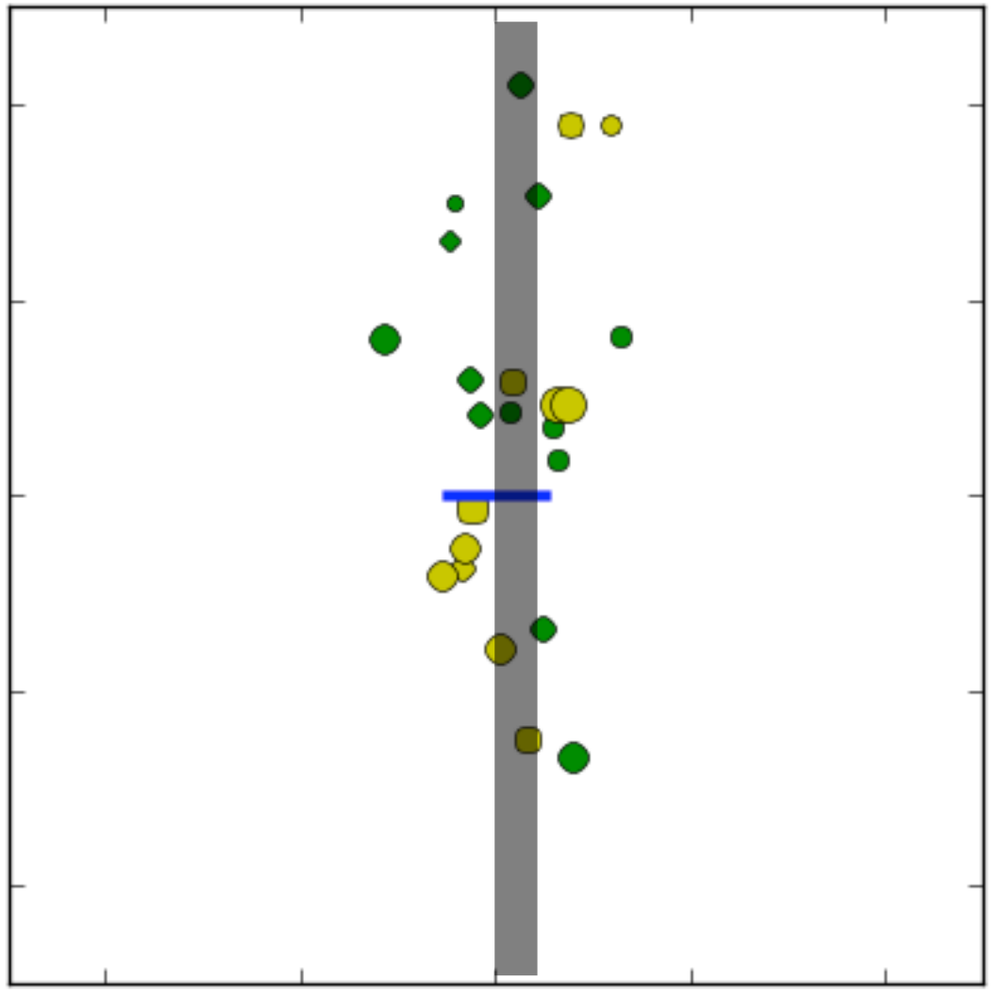
Fly-By
Comparison to MW satellite system

Model



Arbitrarily picked particles

MW Satellites



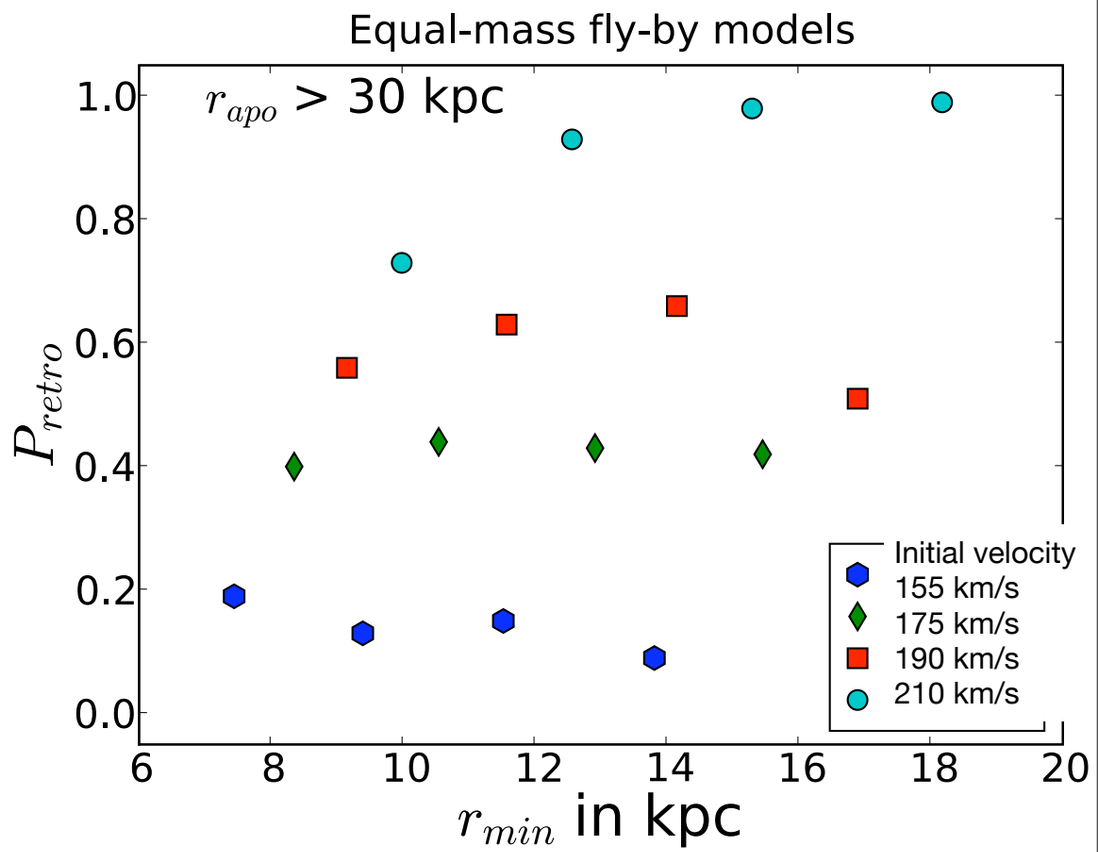
Rotated by 90 degrees

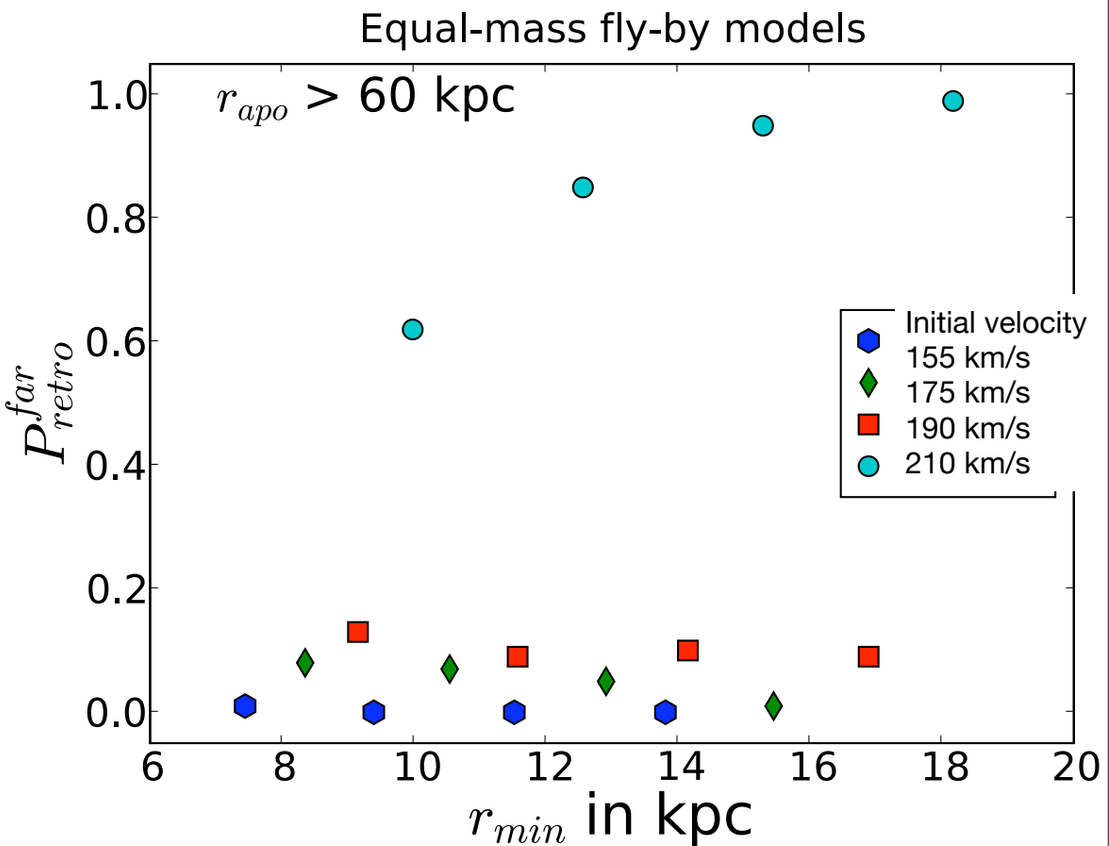
Is it possible to reconstruct the early MW-encounter?

Fly-by parameter scan

- Same 2-phase origin in all models.
- Maximum velocities ~ 300-350 $^{km}/_{s}$
- P_{retro} depends on *initial* velocity, almost independent of perigalacticon r_{min}
  - ➡ Useful for reconstructions of galaxy interactions.
- P_{retro} drops for particle-subset of higher apogalactica r_{apo}
  - ➡ 2-phase origin, retrograde more concentrated.

$$P_{\text{retro}} := \frac{N_{\text{retro}}}{N_{\text{pro}} + N_{\text{retro}}}$$





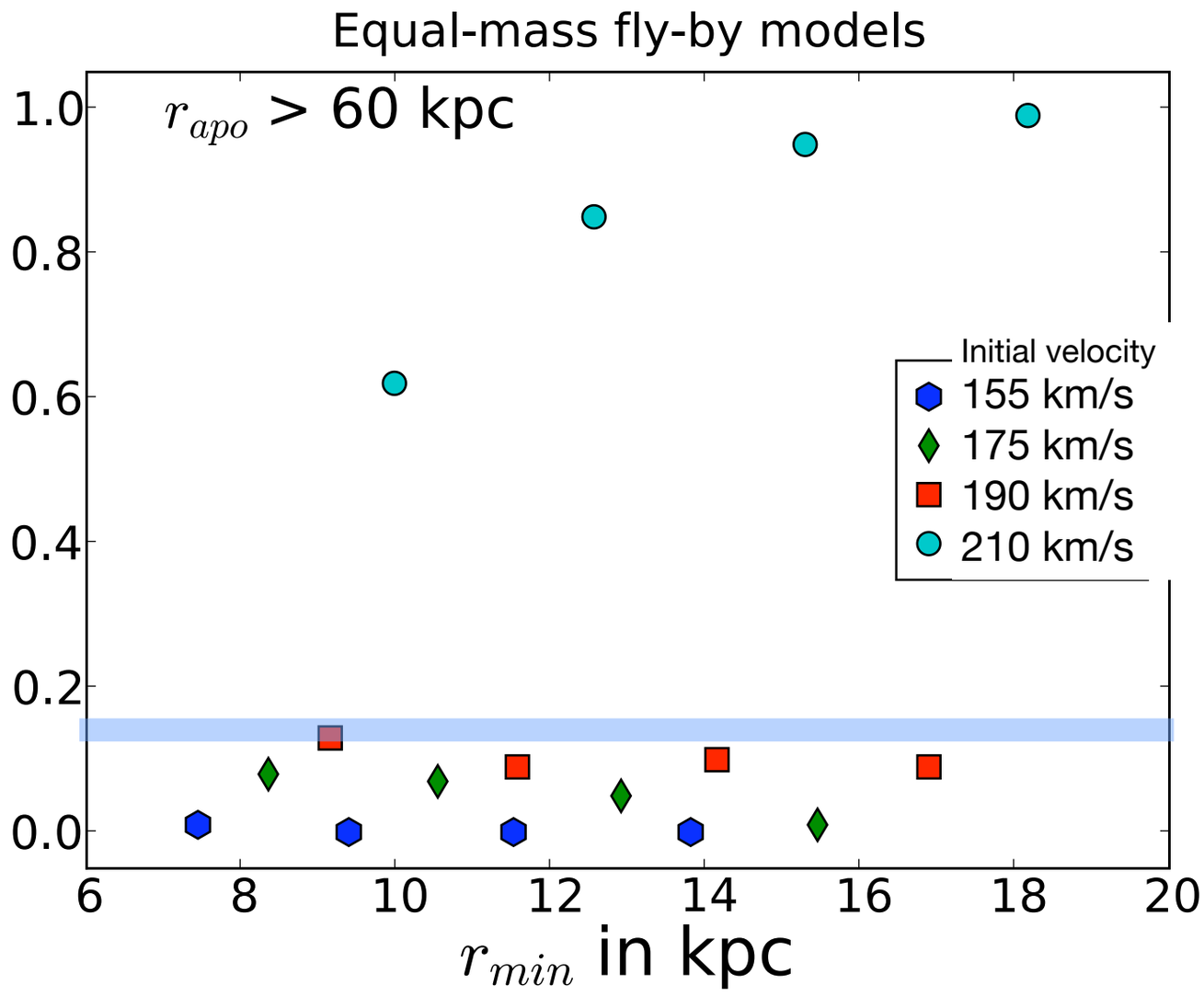
LMC as origin of the DoS?

(c) Wei-Hao Wang (IfA, U. Hawaii)

- Suggested by Lynden-Bell (1976).
- LMC lies and orbits within the DoS, v_{LMC} ~380 $^{km}/_{s}$ (Kallivayalil et al. 2006) comparable to infalling galaxies.

Compare to fly-by parameter scan:

- LMC co-orbiting
  - ➡ low P_{retro} (1:7)
  - ➡ in agreement with most models (*no fine-tuning*)
- Sculptor counter-orbiting, thus retrograde
  - rather low apogalacticon (~120 kpc, Piatek et al. 2006)
  - ➡ like retrograde particles



What did we learn?

Conclusions

- Creation of pro- and retrograde tidal debris is a natural outcome of galaxy interactions!

- True for both mergers and fly-by interactions of different mass-ratios.

- Here: Fly-Bys
  - number/mass-ratios: in general low P_{retro}
  - radial distribution: retrograde tidal debris more concentrated

- Tidal material resembles Disc of Satellites around the MW.

- TDGs will occupy phase-space region of tidal debris
  - ➡ Reconstruction of early MW interaction that shaped MW-interaction
  - ➡ Interesting agreements with LMC progenitor