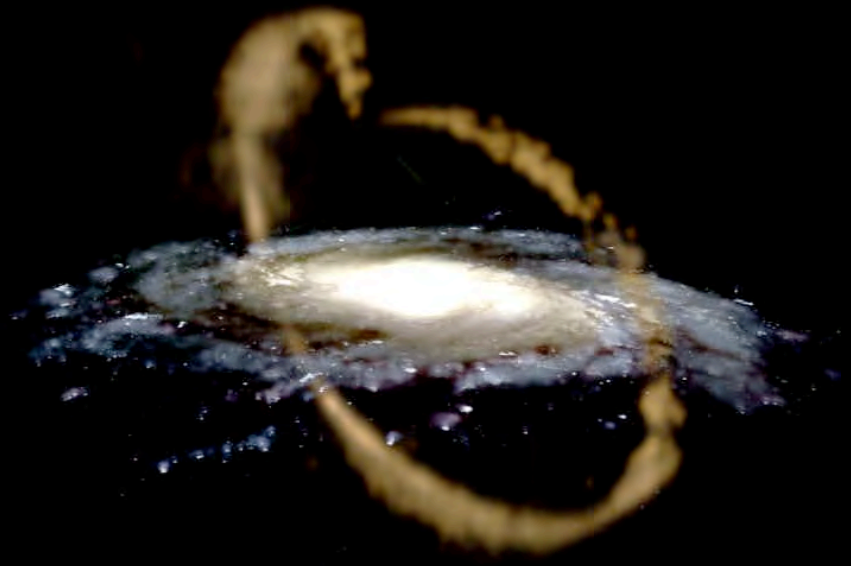
Kavli Institute
for Cosmological Physics
at The University of Chicago

Evidence of dark matter substructure in tidal debris



Jennifer Siegal-Gaskins

in collaboration with Monica Valluri

arXiv:0710.0385

Image credit: Martinez-Delgado & Perez

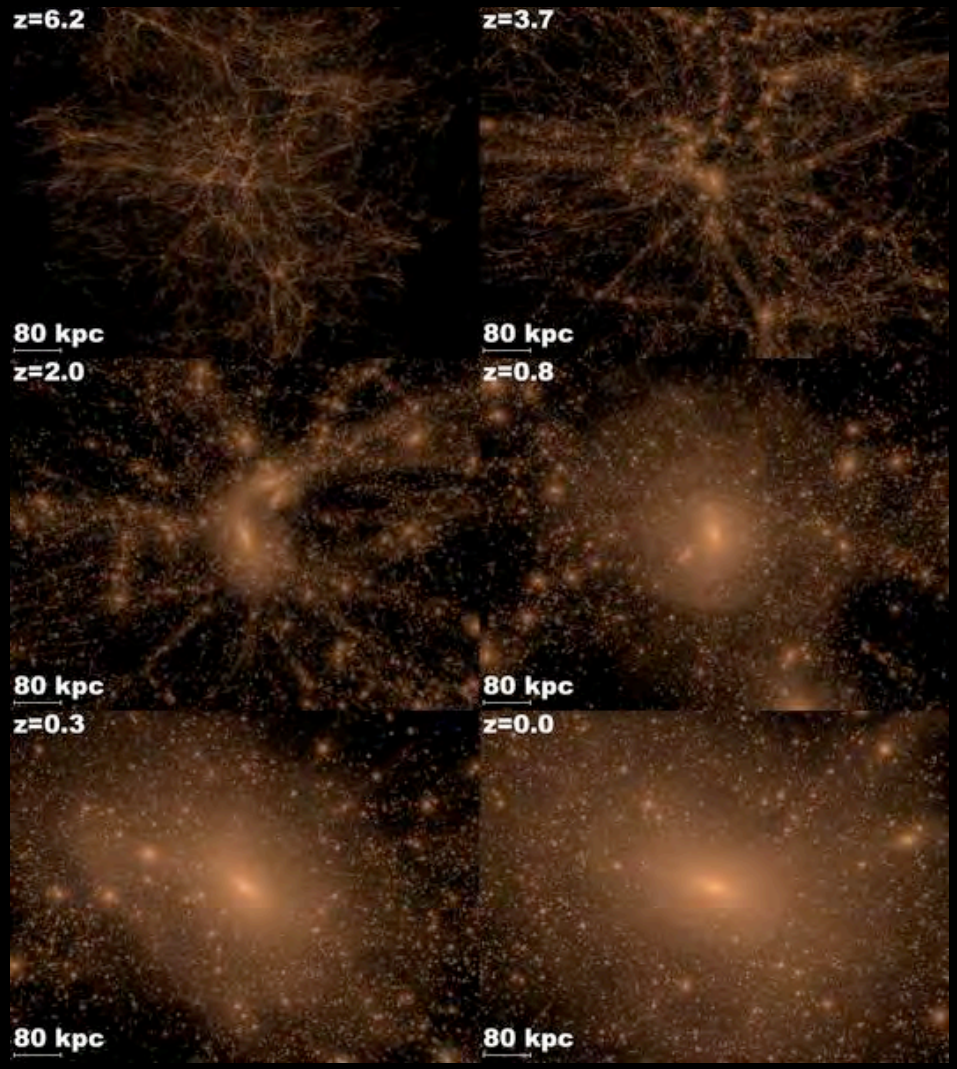
Overview

- Motivation: to test cold dark matter on small scales
- Tidal disruption: theory, observations, possibilities
- Results: tidal debris in CDM models

A universe with cold dark matter

N-body simulations of structure formation:

- In CDM models, an abundance of substructure should be present in a Galaxy-sized halo
- CDM halos generally triaxial



Credit: J. Diemand, M. Kuhlen and P. Madau

Missing satellites?

Known

Credit: Roen Kelly / Astronomy

Predicted

Credit: J. Diemand, M. Kuhlen and P. Madau

Are they really missing? e.g., Hogan & Dalcanton 2000 (WDM); Spergel & Steinhardt 2000 (SIDM)

Or just dark? e.g., Bullock et al. 2001; Kravtsov et al. 2004

Formation of tidal streams

Tidal forces elongate the object

Image credit: European Space Agency

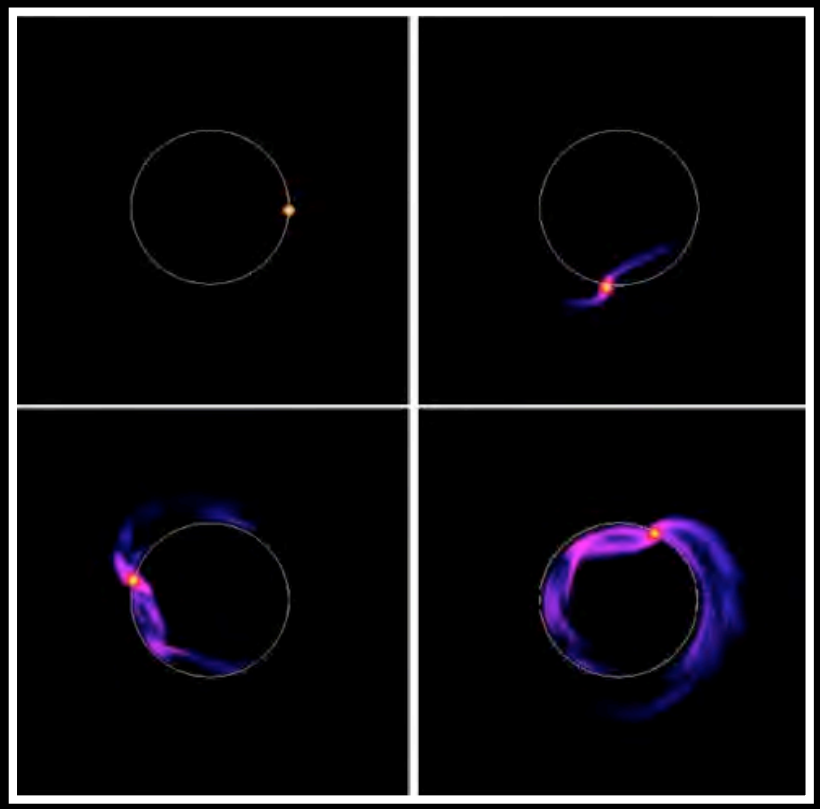
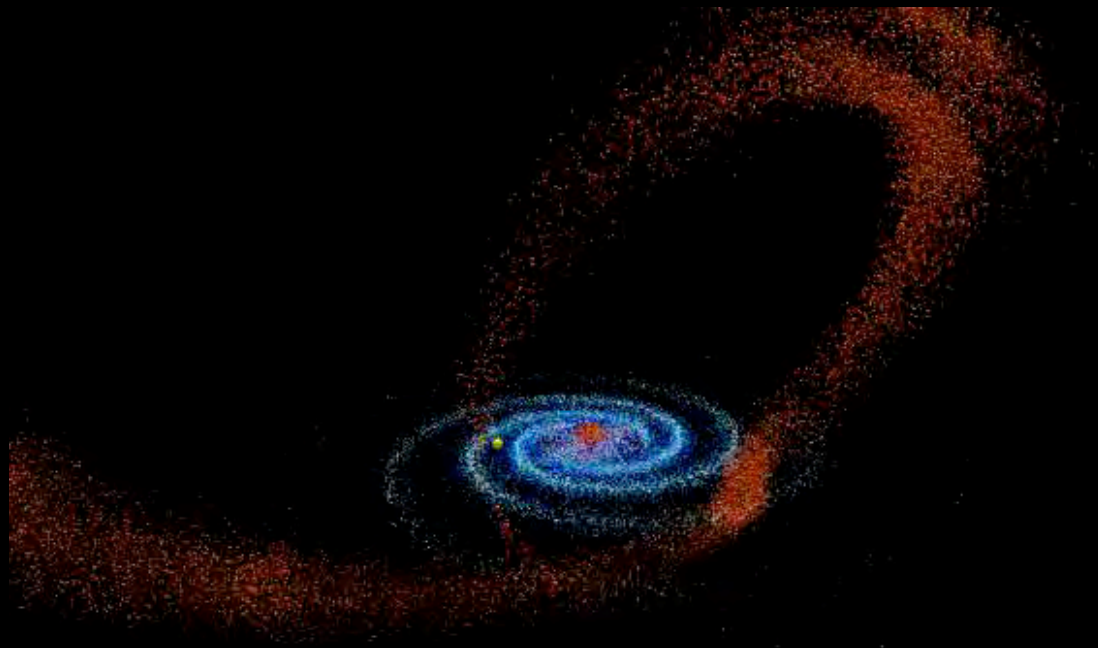


Image credit: Choi, Weinberg, & Katz 2007

Particles become unbound and form leading and trailing streams of debris

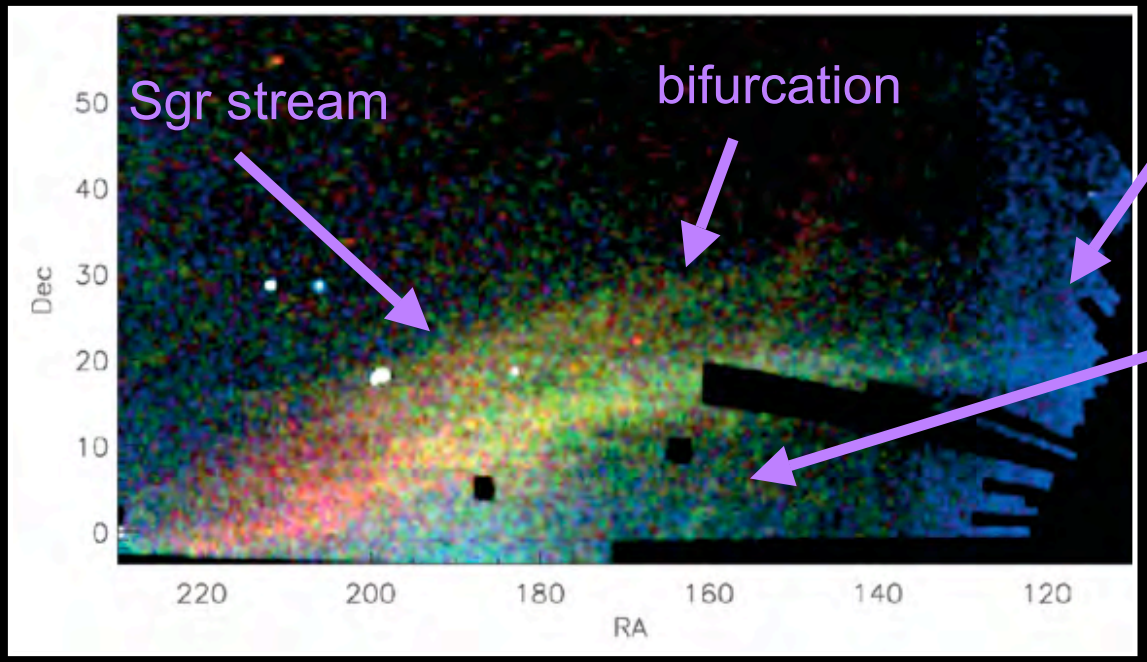
Tidal streams as probes of the Galaxy's mass distribution

- Tidal tails trace out orbital path of progenitor
- Sensitive to gravitational potential over large scales
- Could show evidence of interactions with substructure



Credit: David Law/University of Virginia

Observed tidal streams

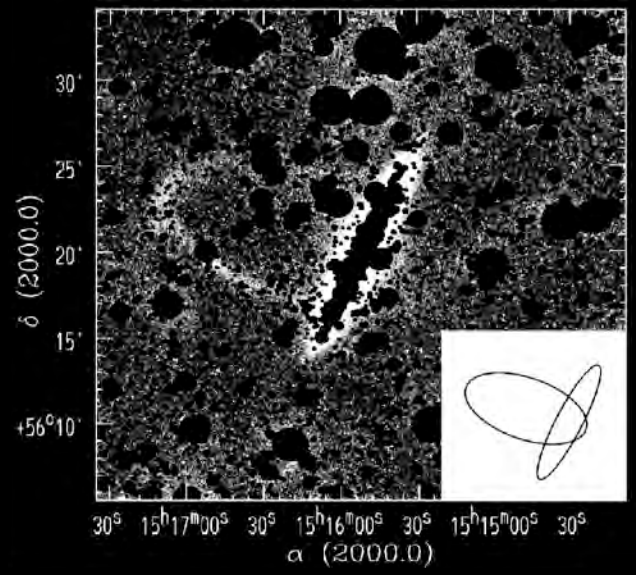


`Field of Streams', Belokurov et al. 2006 (SDSS)

Also: globular cluster streams (Pal 5, NGC 5466)

More data on the way:
e.g., SDSS-SEGUE, GAIA, RAVE,
SIM-Planetquest

NGC 5907, Shang et al. 1998

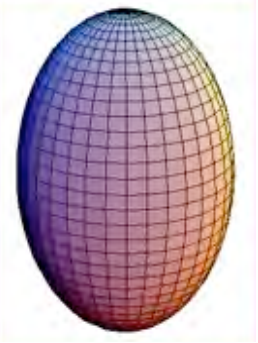


Tidal streams in CDM halos

Part I: non-spherical halos

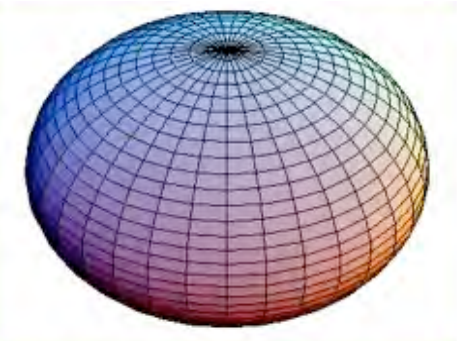
- In a spherical potential, orbits are confined to a plane
  - ➔ Tidal debris localized to a single plane
- In a non-spherical potential, orbits not confined to a plane
  - ➔ Tidal debris fills a 3-D volume
  - ➔ Precession leads to dispersion of streams

Prolate



$q > 1$

Oblate



$q < 1$

Orbits at large radii particularly sensitive to halo shape

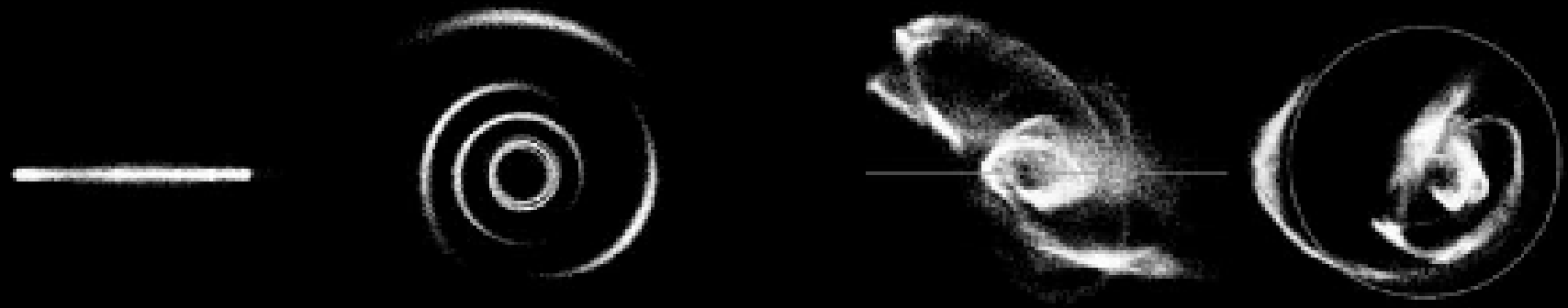
Tidal streams in CDM halos

Part II: substructure

Could coherent streams survive in a halo with substructure?

e.g., Ibata et al. 2002; Johnston et al. 2002; Mayer et al. 2002; Peñarrubia et al. 2006

Massless test particles on circular orbits



Credit: Mayer et al. 2002

Smooth spherical potential

Triaxial CDM halo with substructure

Constraints on substructure from tidal streams?

- Is it possible to robustly detect substructure?
  - Substructure could lead to heating of the streams -- is this a smoking gun?
- Is it possible to robustly rule out substructure?
  - Would a detection of a SINGLE COHERENT STREAM provide strong evidence against substructure?
  - Can we expect coherent streams to survive in ANY scenario with substructure?

Testing a wide range of scenarios

1. Selected variety of orbits for progenitor satellite
2. Looked at host models with different halo shapes
3. Simulated tidal disruption of satellite on these orbits both with and without subhalos

Simulations

Using N-body tree code GADGET-2 (V. Springel 2005)

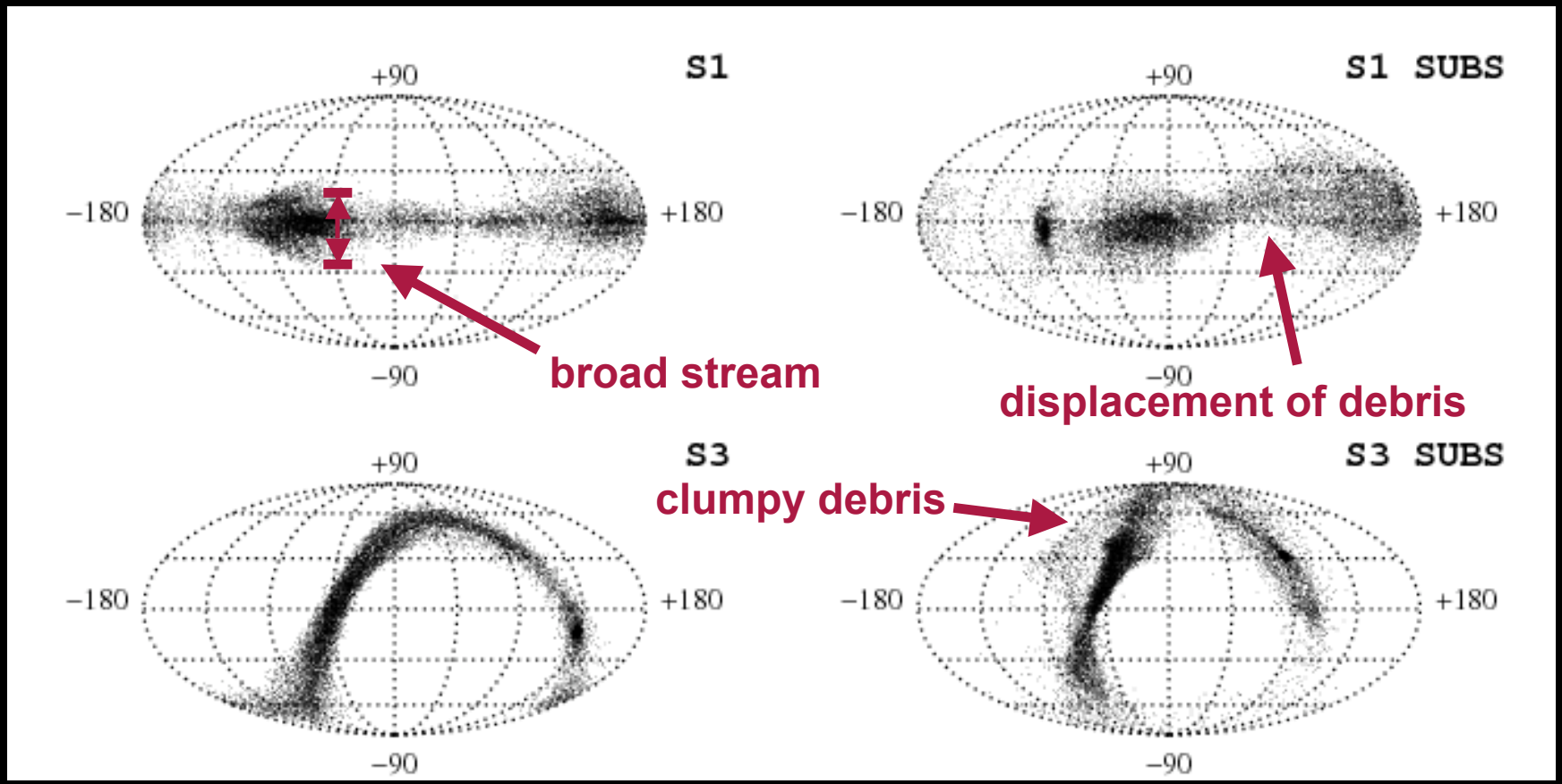
- Static Milky Way potential:
  - halo, disk, and bulge
  - total mass ~ 10^{12} M_{solar}
- Progenitor satellite:
  - NFW profile
  - initially 500k particles, 10^{10} M_{solar}, tidally stripped to produce 'remnant' in quasi-equilibrium with host potential, ~ 150k particles
  - `star particles' marked
  - integrated for ~ 5 Gyr
- Dark matter substructure:
  - softened point masses from cosmological N-body simulation (Kravtsov et al., 2004)
  - mass range ~ 10^{7} - 10^{10} M_{solar}

Sky distribution: spherical halo

(star particles)

without substructure

with substructure

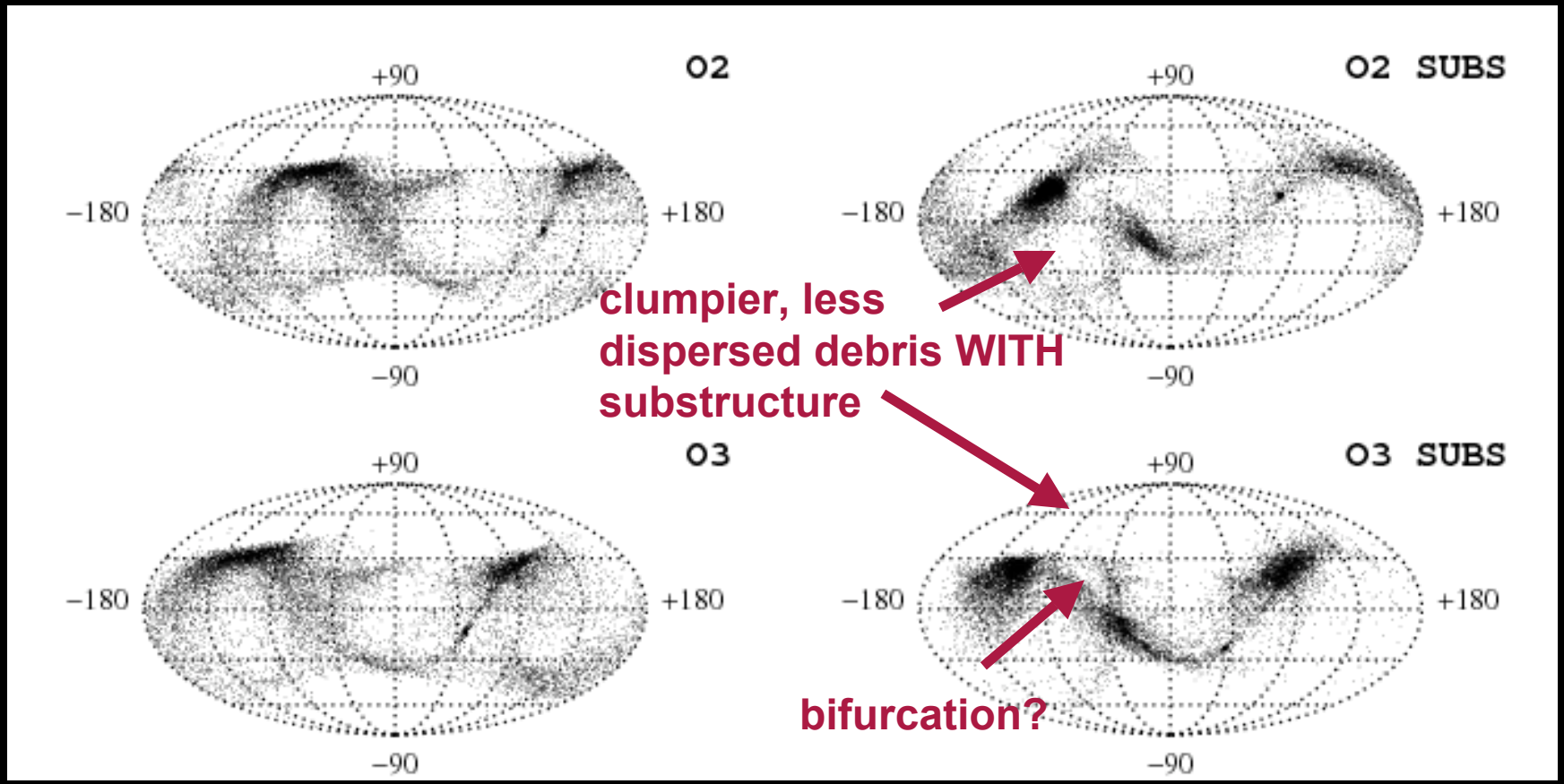


Sky distribution: oblate halo

(star particles)

without substructure

with substructure

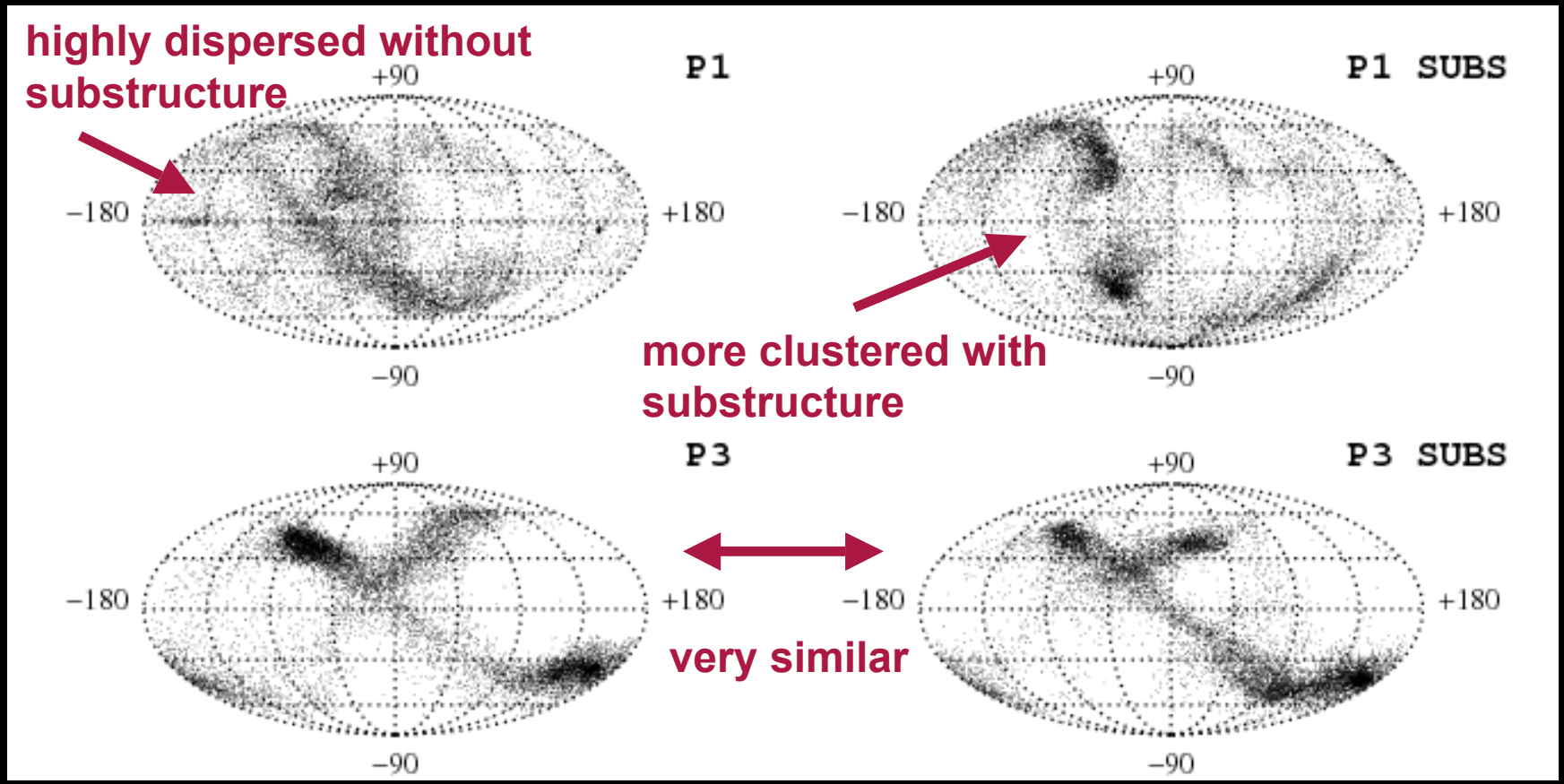


Sky distribution: prolate halo

(star particles)

without substructure

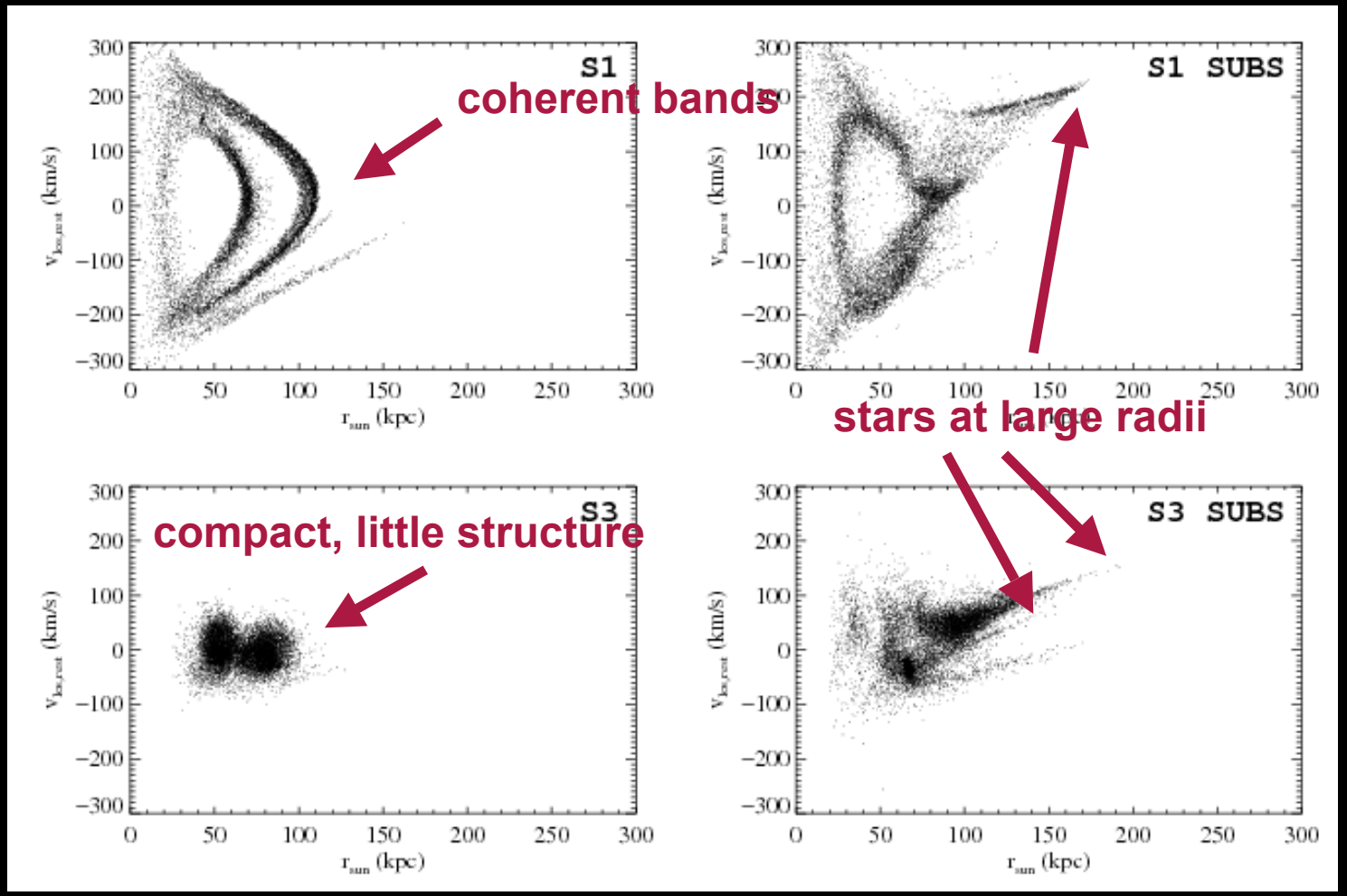
with substructure



Phase space structure: spherical halo

(star particles)

without substructure with substructure



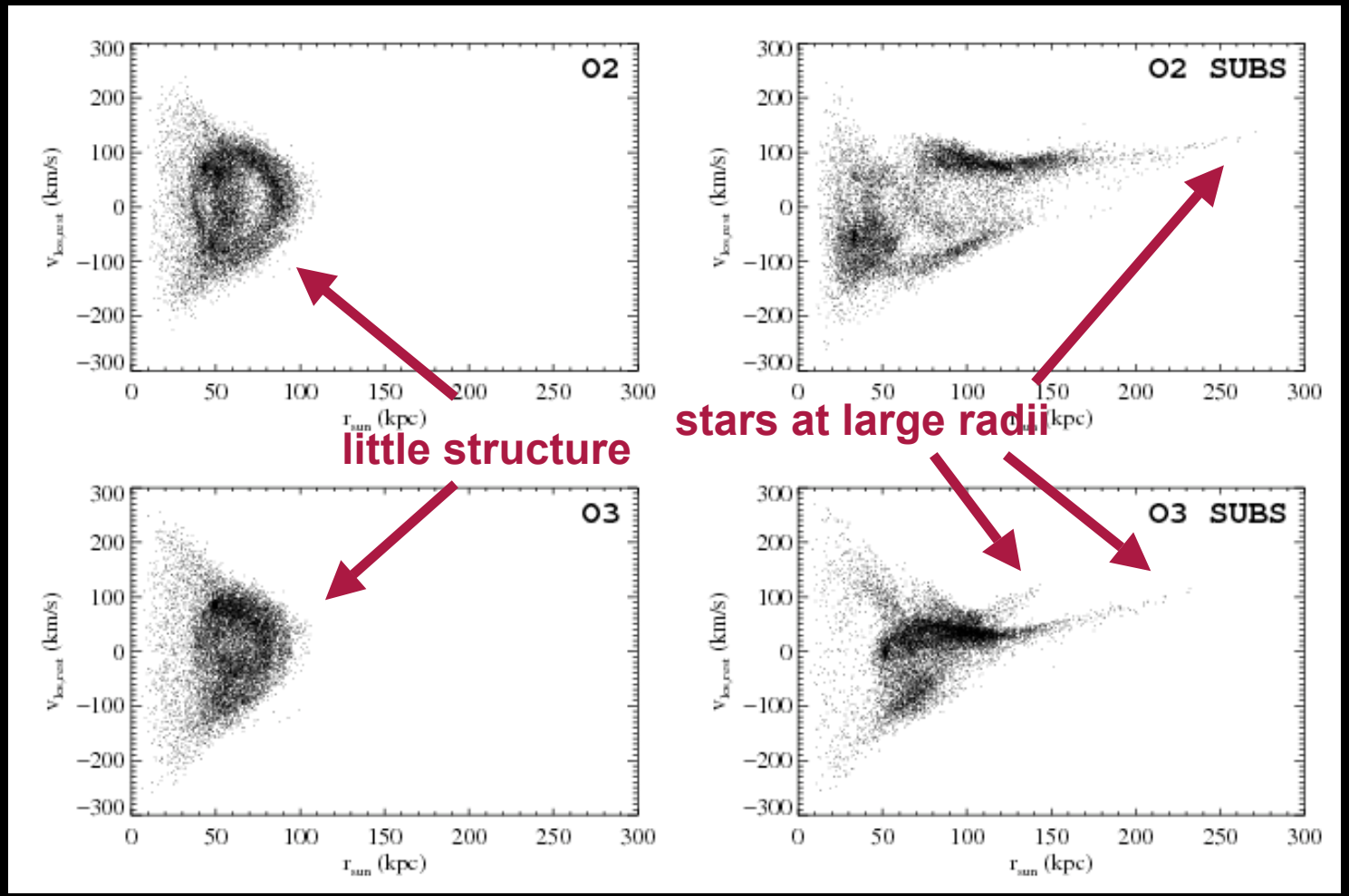
$v_{los,rest}$ (km/s)

r_{sun} (kpc)

Phase space structure: oblate halo

(star particles)

without substructure with substructure



$v_{los,rest}$ (km/s)

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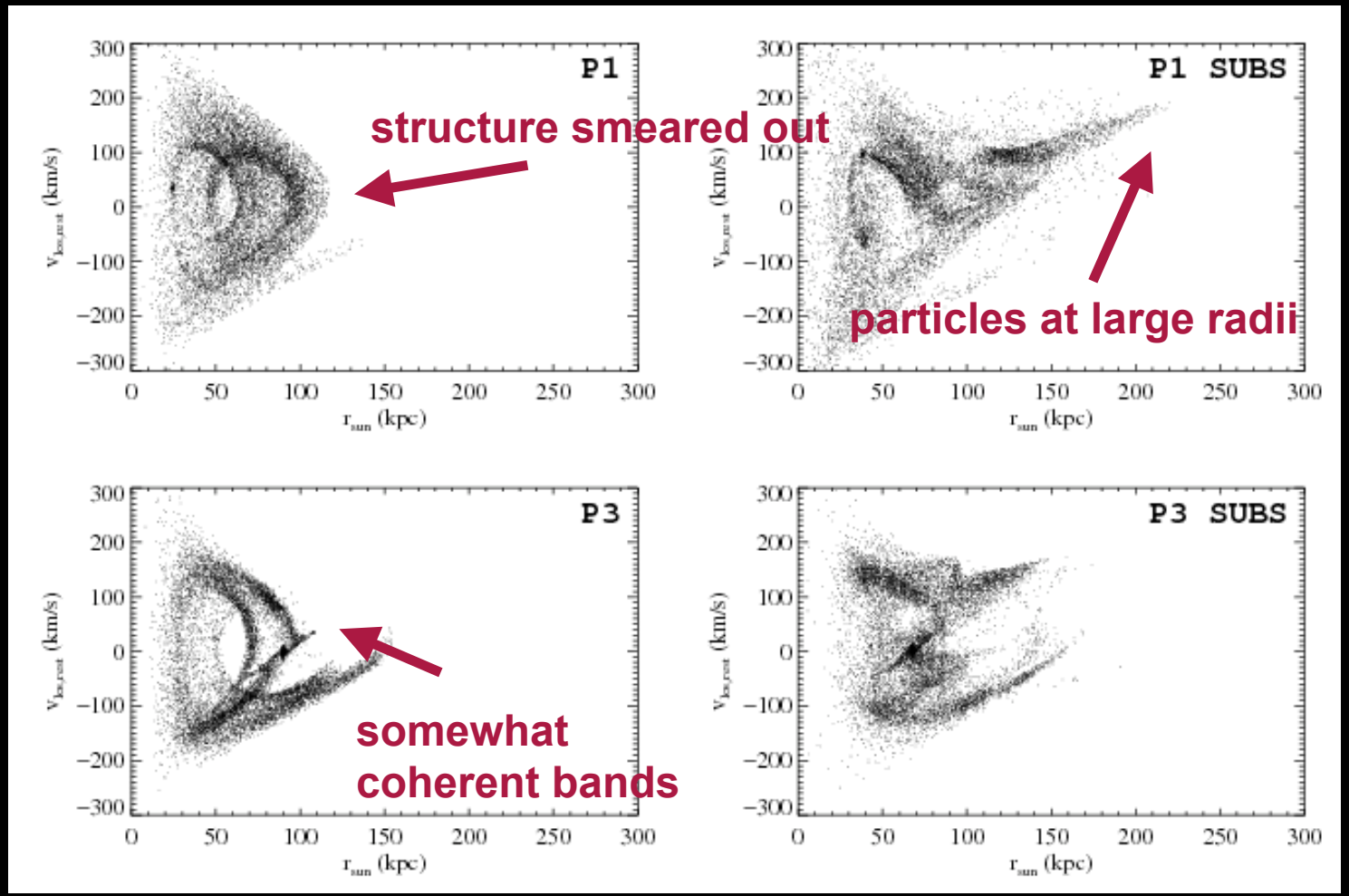
Phase space structure: prolate halo

(star particles)

without substructure with substructure



$v_{los,rest}$ (km/s)

r_{sun} (kpc)

Summary of results so far…

- Wide range in properties of debris in a given smooth halo shape for different orbits
- Variations between debris from orbits simulated without substructure larger than changes induced by addition of substructure
- Effects of substructure relative to smooth halo models:
  - clustering in sky projection
  - debris displaced relative to smooth halo simulation
  - smearing of structure in phase space coordinates
  - particles present at large distances with coherent velocities

Heating from substructure?

(star particles)

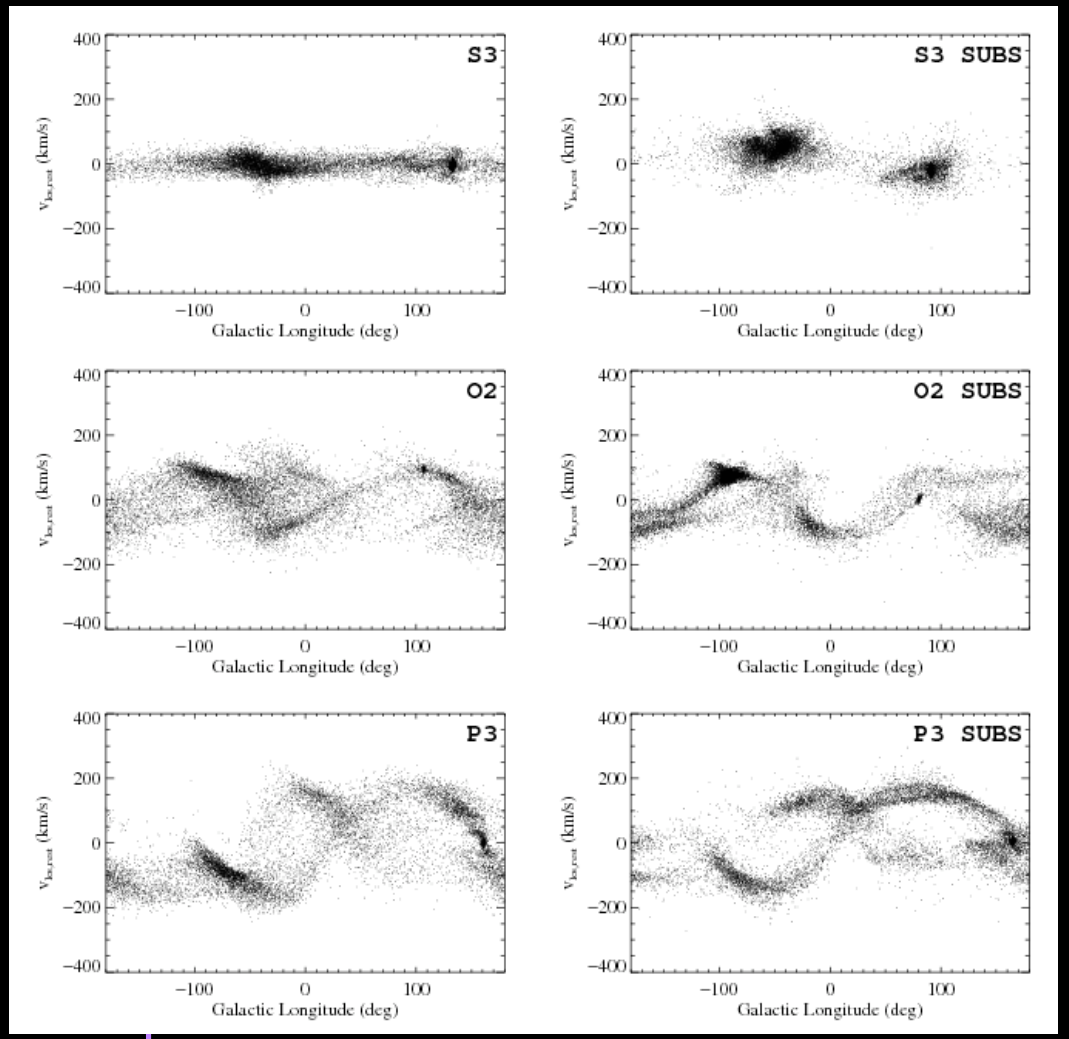
without substructure

with substructure

Spherical halo

Oblate halo

Prolate halo



$v_{los,rest}$ (km/s)

Galactic longitude

Summary of results so far…

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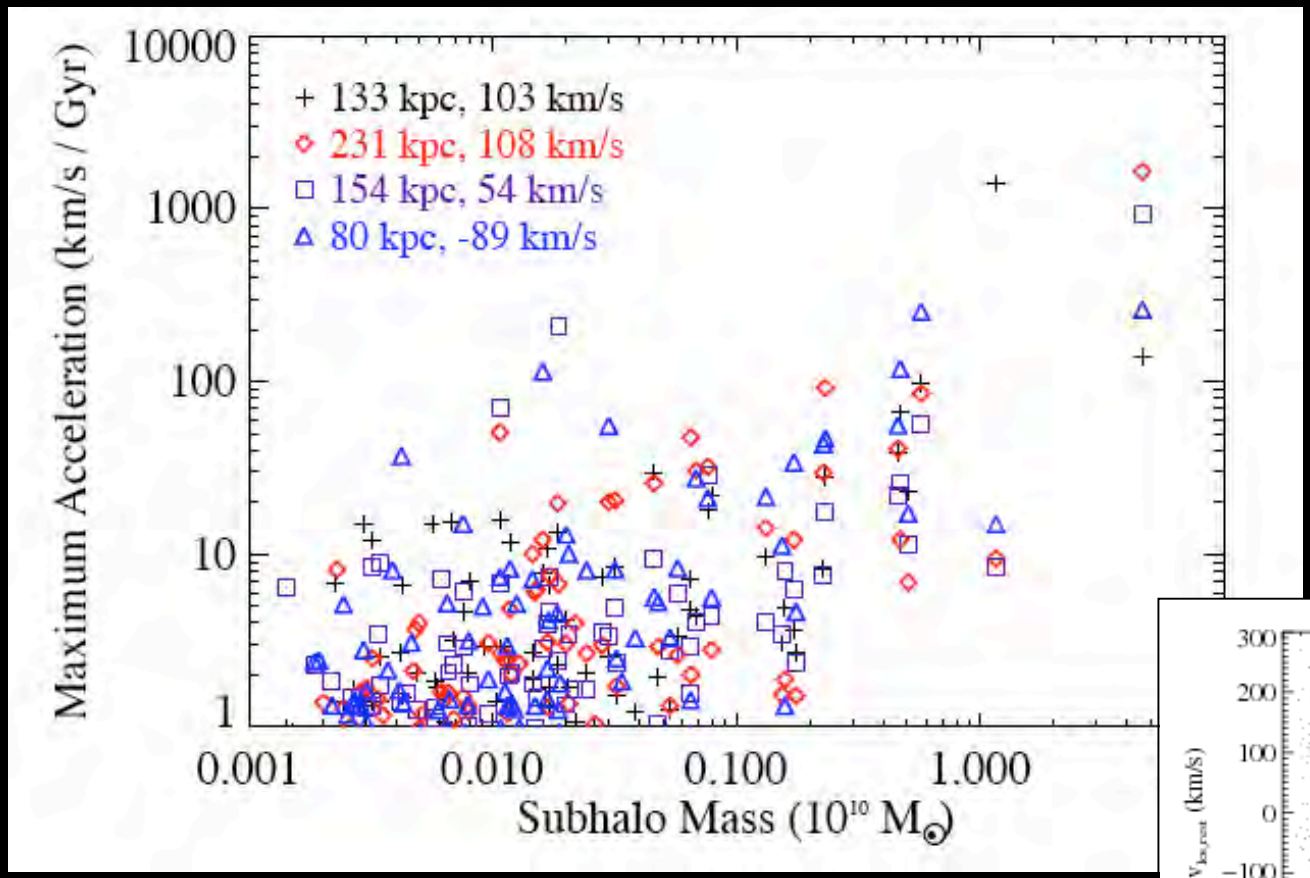
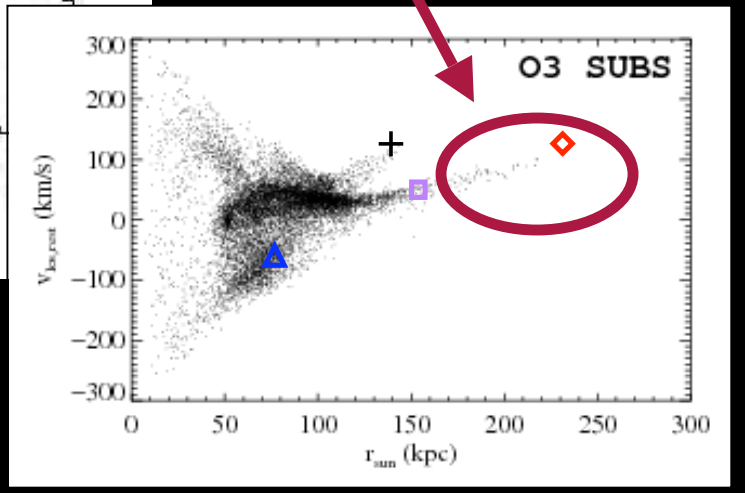
Strength of subhalo interactions

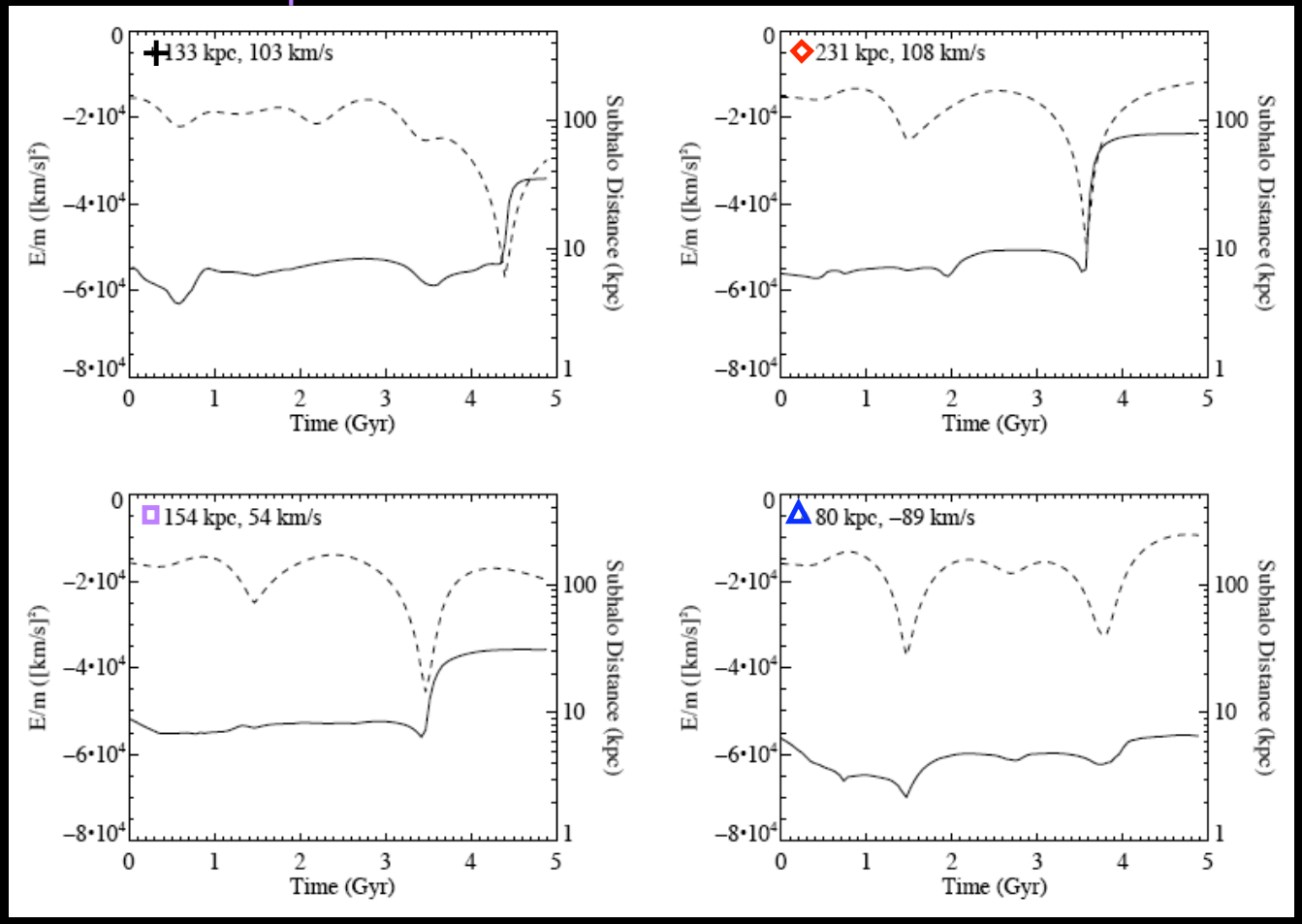


All star particles in this feature experienced max acceleration > 600 km/s /Gyr



Single encounter or cumulative effect?

particle E/m - - - subhalo distance



Particle E/m

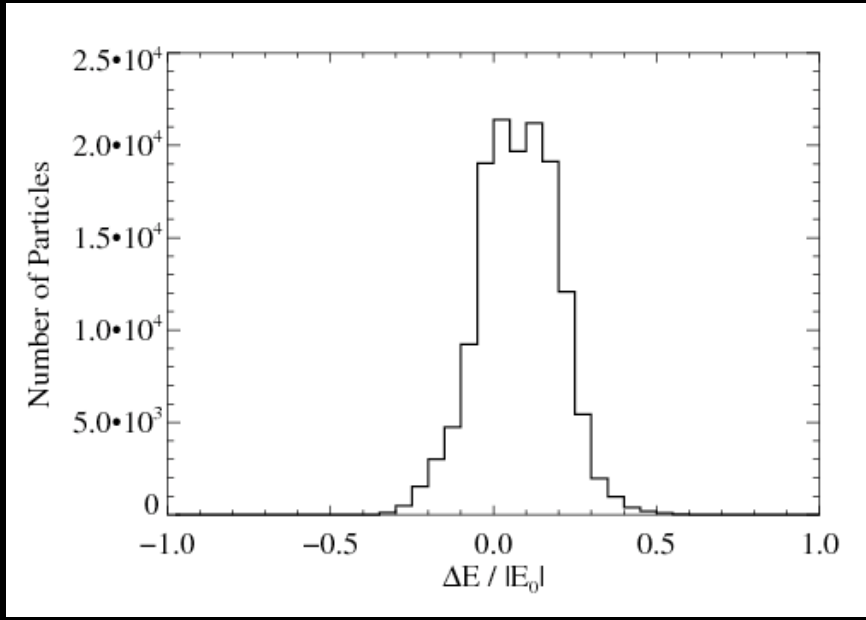
Subhalo distance (log scale)

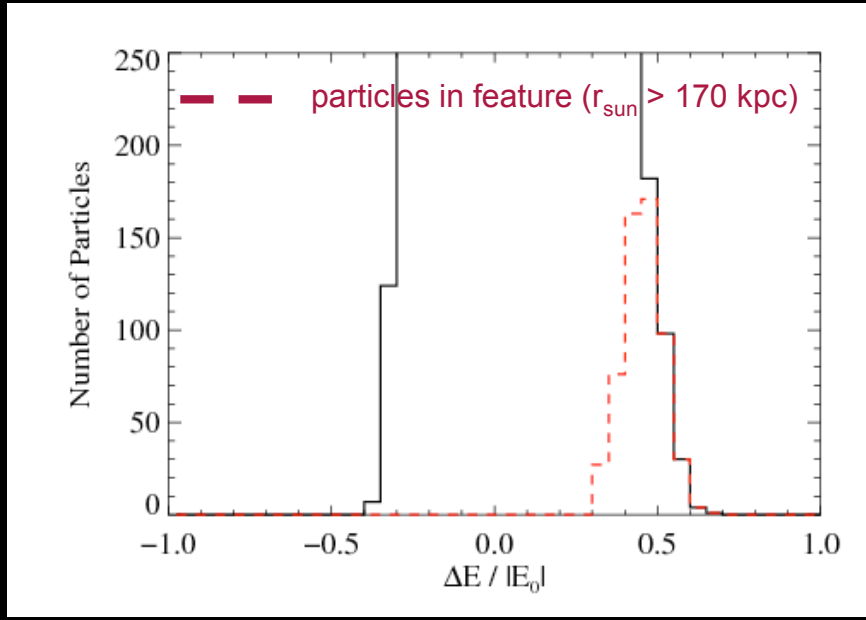
Time (Gyr)

Large changes in energy strongly correlated with close encounters with massive subhalo

Distribution of energy changes

all particles





- Distribution is approximately Gaussian, and particles in feature occupy high end of distribution
- Particles at large distances account for most particles with large energy gains ($\Delta E / |E_0| > 45\%$)
- Not many particles with large energy gains NOT present in feature

Future Directions

- Observations!!!
- Effect of smaller subhalos: significant heating or stronger clustering?
- Clustering of debris in sky projection: also in configuration space? why?
- Simulations of object like globular cluster: intrinsically colder debris may more easily show signatures of substructure
- Live halo, disk, bulge: would halo wake enhance effects of substructure? could dynamical friction play a significant role in some scenarios?
- N-body substructure: would internal heating soften interactions?

Conclusions

- Substructure can shift the location of debris (very important for modeling!)
- Halo shape and orbital path strongly influence structure of tidal streams, generally more important than substructure for overall stream formation
- Substructure leads to clumping in sky projection, and sometimes smaller velocity dispersions
- Unique signature of substructure: particles kicked to large distances, strongly correlated with interactions with massive substructures
- In contrast with previous studies: Cannot rule out substructure with a coherent stream, but can detect substructure with unique signature!