Gaps in tidal streams

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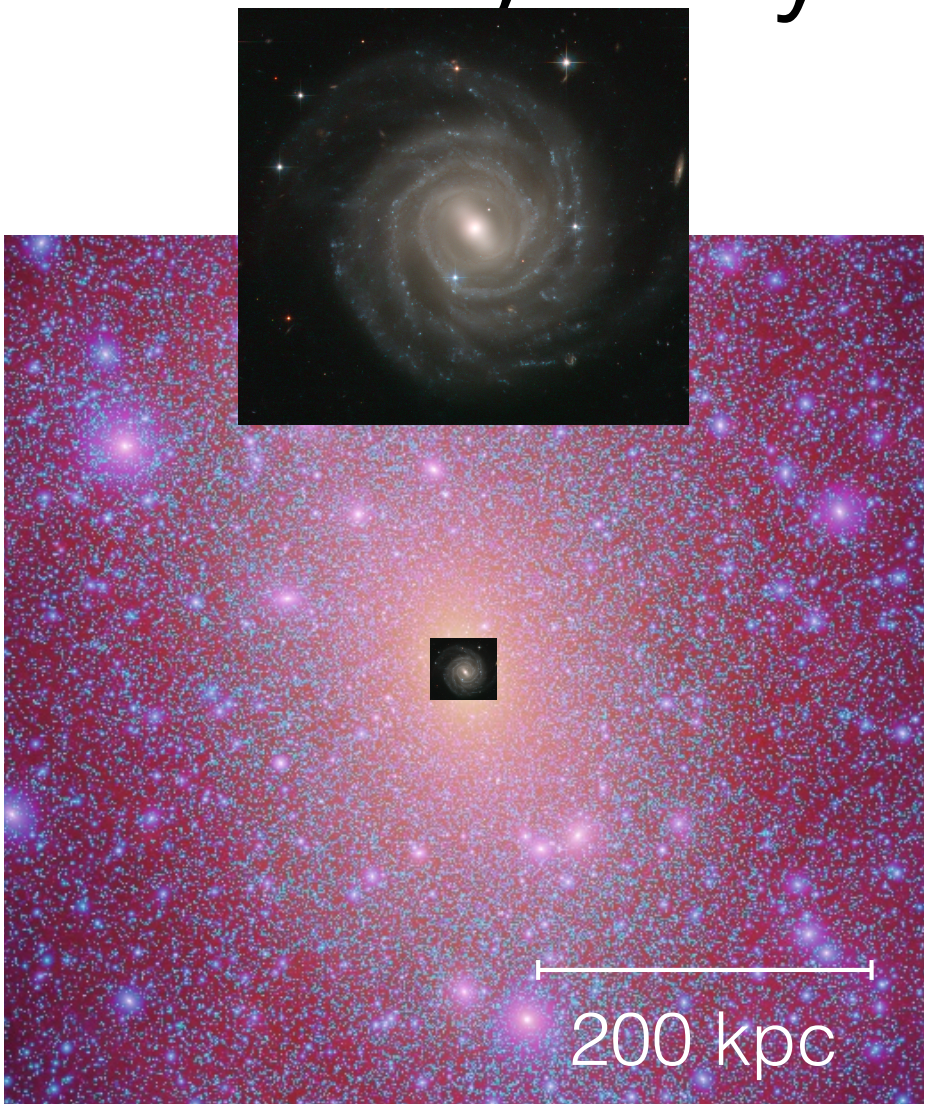
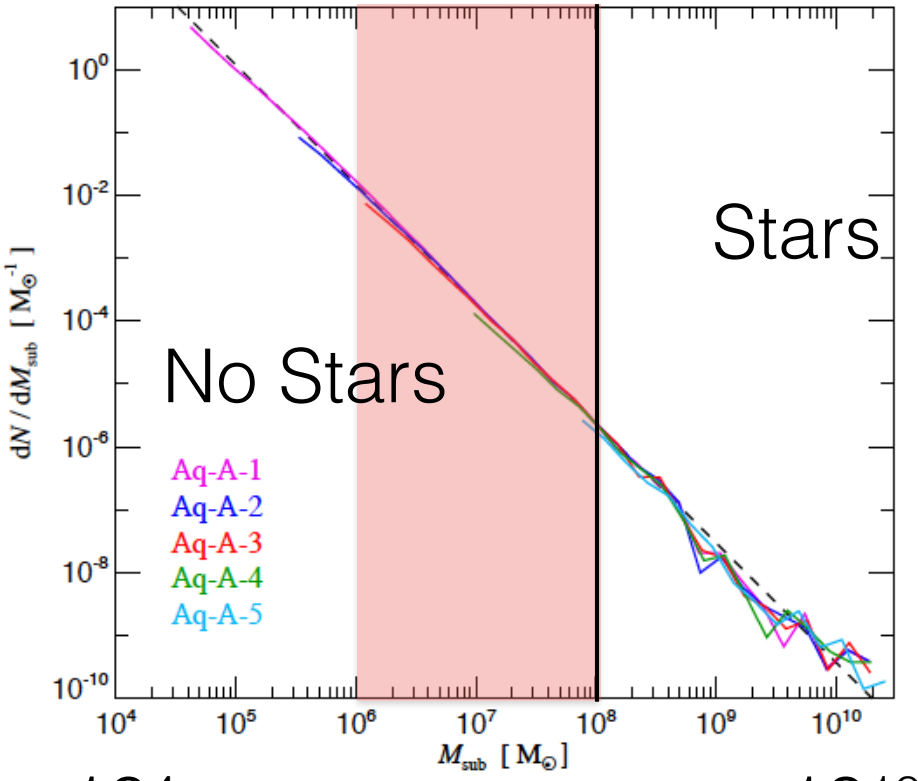
University of Surrey

Stellar halos across the cosmos,
MPIA, July 4th 2018

Milky Way Substructure



Halo mass function

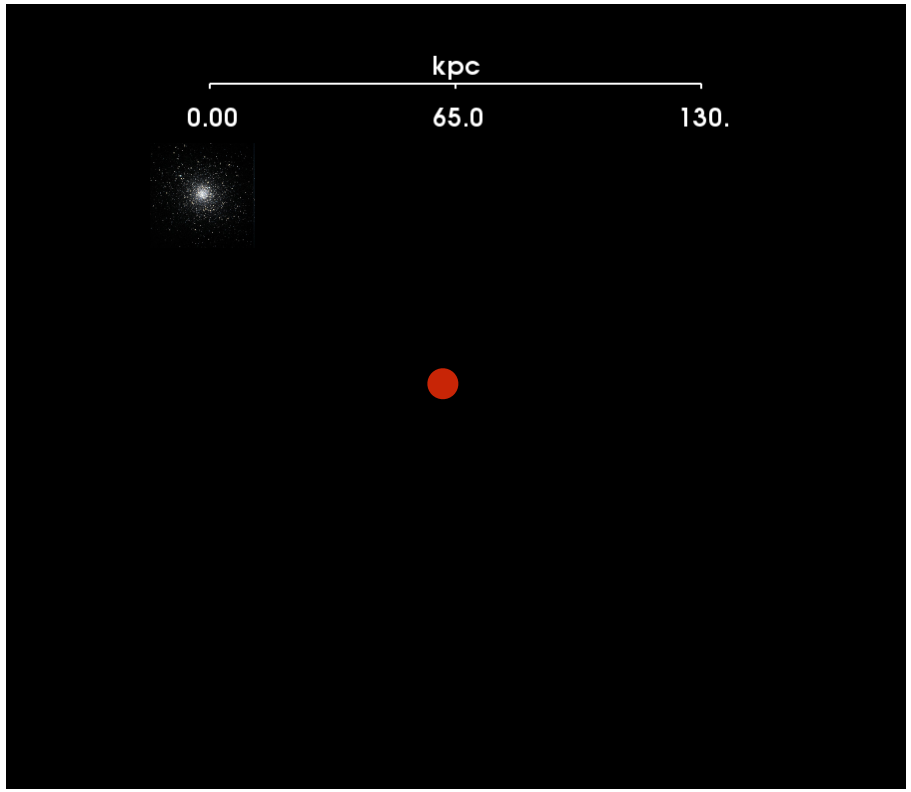


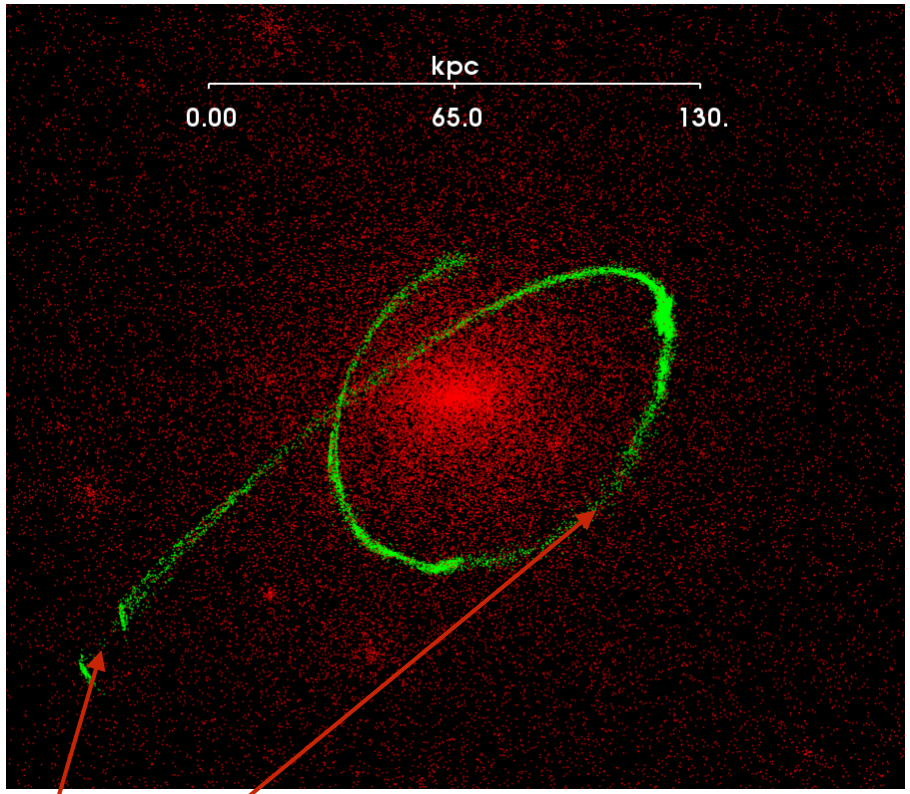
10^4 Mass ($M_\odot$) 10^{10}

Aquarius, Springel et al. 2008

Image credit:ESA/Hubble & NASA

Tidal Streams from Globular Clusters



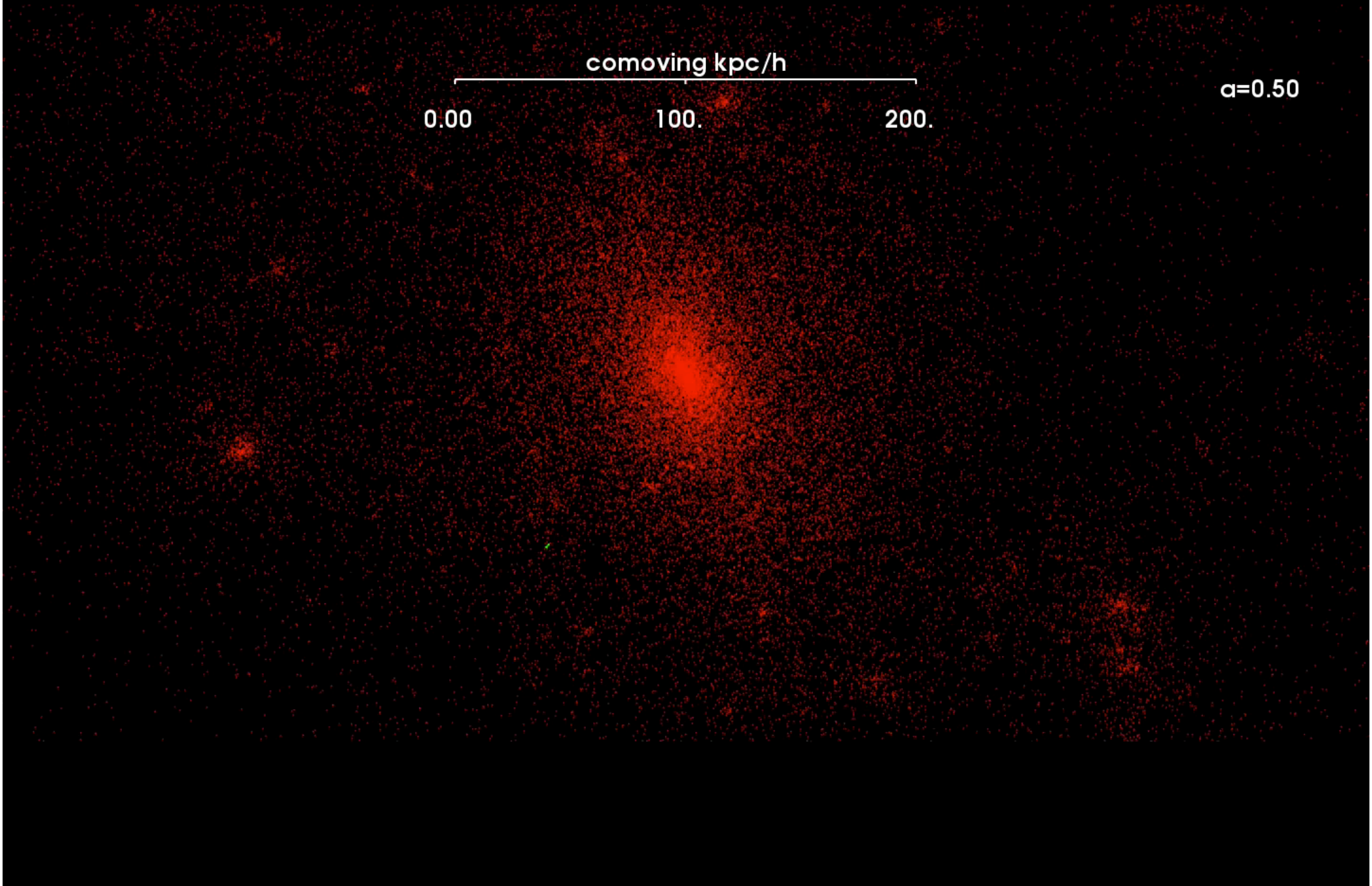


Smooth Potential

Lumpy Potential

Interaction with substructure

Ibata et al. 2002, Johnston et al. 2002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Outline

- How do gaps grow/evolve?
- How many gaps are expected in the known streams around the Milky Way?
- Gaps in known streams

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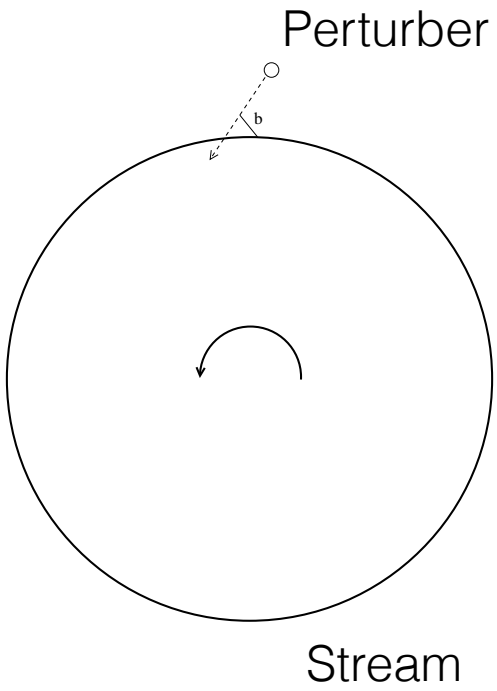
Analytic Toy Model for Gaps

Setup

- Stream on circular orbit
- No position/velocity dispersion
- Plummer sphere perturber
- Arbitrary spherical host potential
- Arbitrary impact geometry



Approach

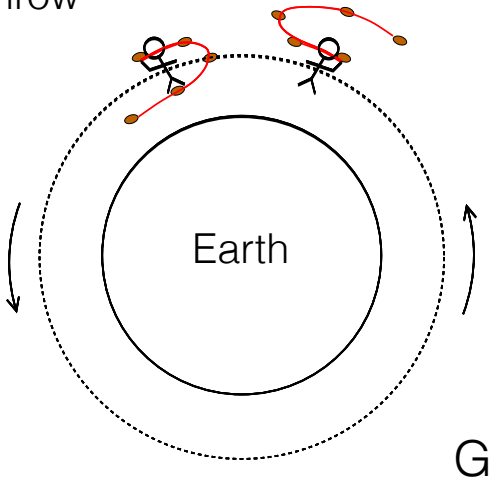
- Impulse approximation for velocity kicks
- Compute resulting orbits at first order
- Compute resulting stream shape
- Similar to Carlberg 2013, Yoon, Johnston, Hogg 2011

Erkal & Belokurov 2015a

Cartoon of Gap Formation

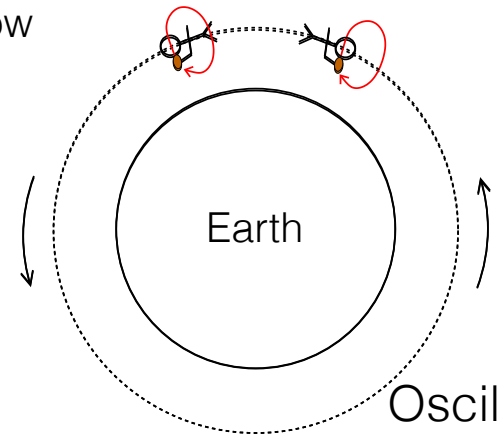
Orbital Mechanics 101
aka Football in Space

Tangential Throw



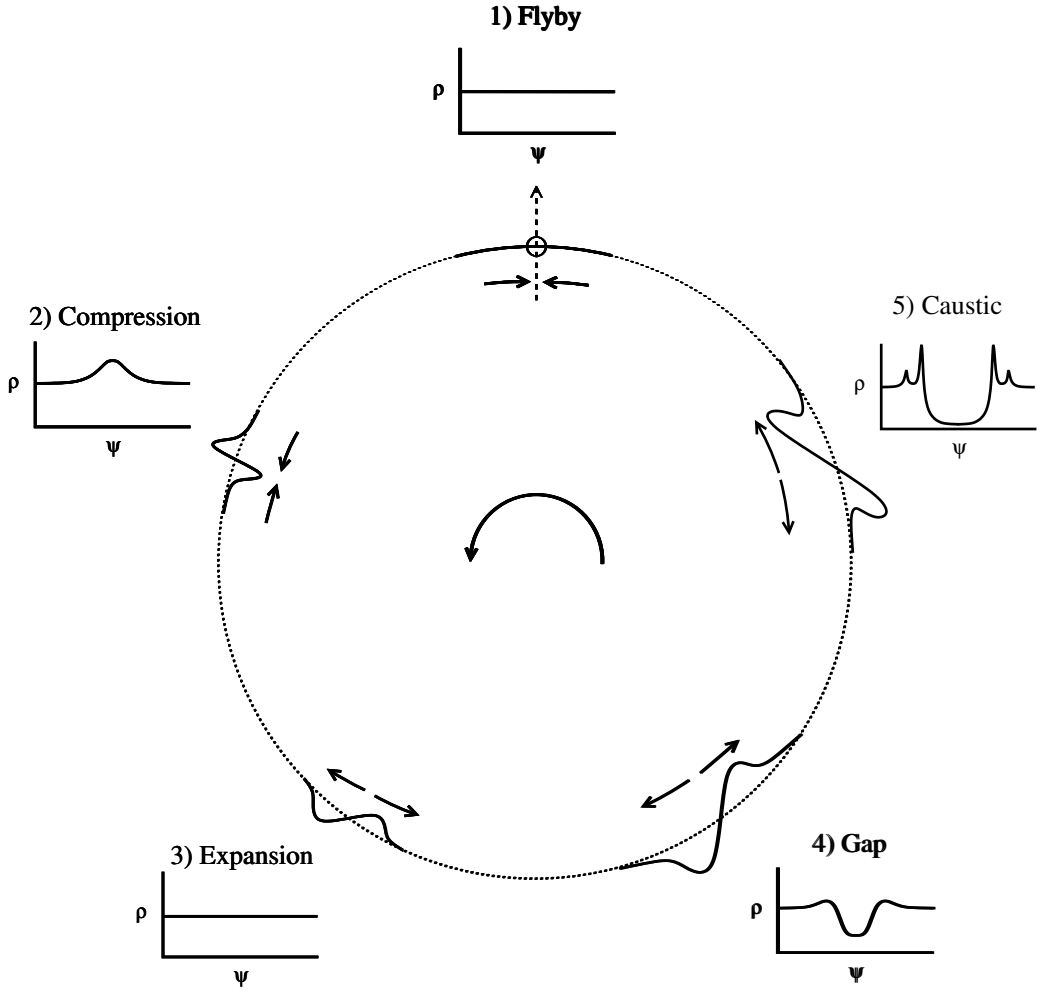
Gap!

Radial Throw



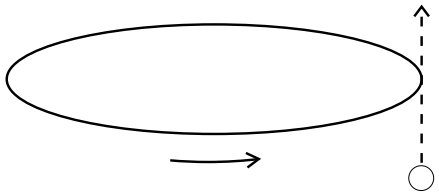
Oscillations!

Gap Formation (also in Space)

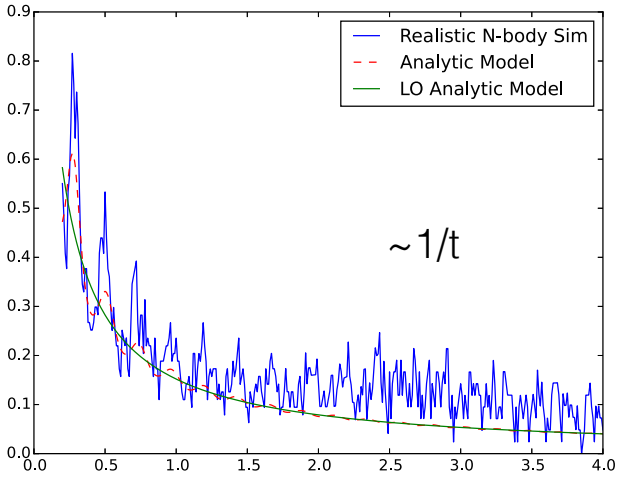


N-body example

- Stream generated by progenitor on circular orbit at 10kpc
- NFW host potential
- 10^8 $M_\odot$ Plummer sphere, 250pc scale radius
- Direct impact on stream

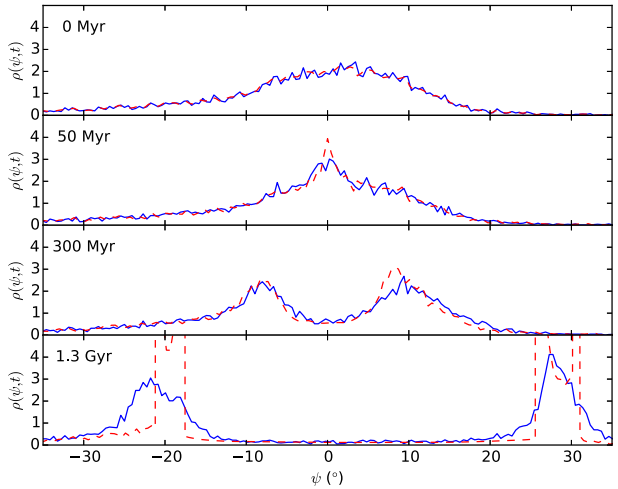


Gap density



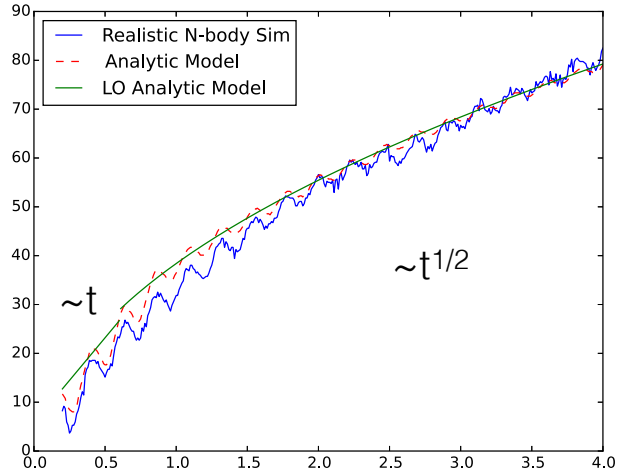
Time in Gyr

Density along stream



Sky angle (o)

Gap size (o)

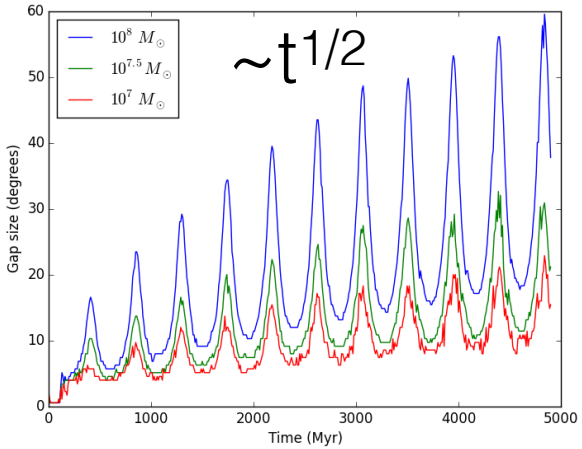


Time in Gyr

Same picture roughly holds for realistic streams

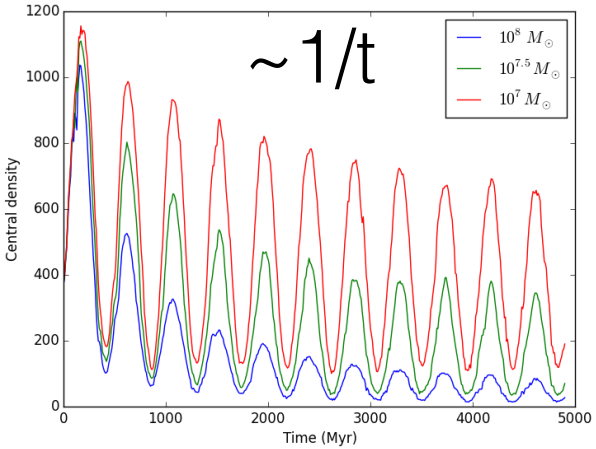
- Simple model misses two important aspects:
  - Streams are not generally on circular orbits
  - Stream material has a distribution in E,L

Gap size



Time

Gap density



Time

Sanders, Bovy, Erkal 2016

Outline

- **How do gaps grow/evolve?**
- How many gaps are expected in the known streams around the Milky Way?
- Gaps in known streams

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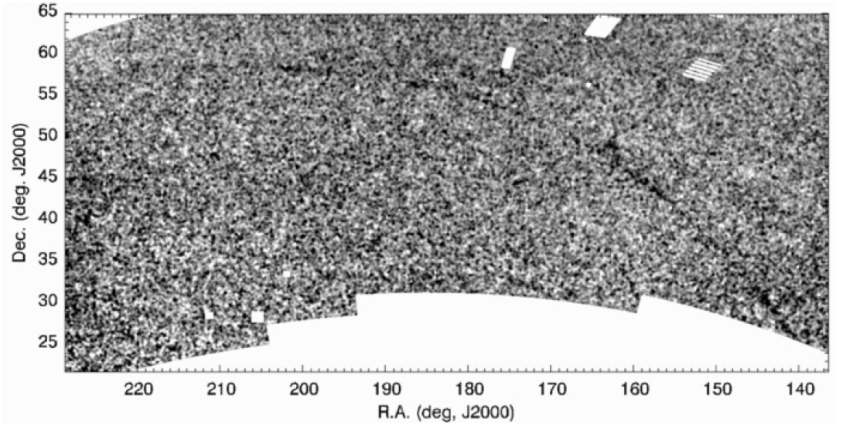
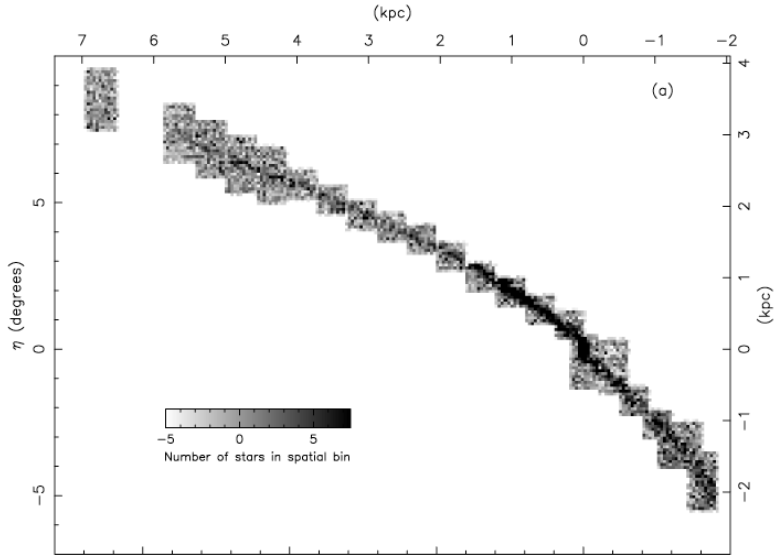
Streams around the MW

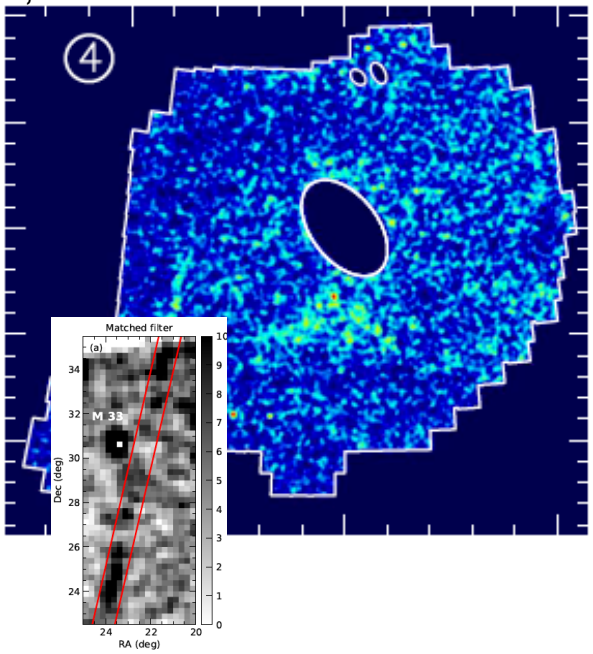
~ 15 globular cluster streams around MW



GD1, Grillmair & Dinatos 2006



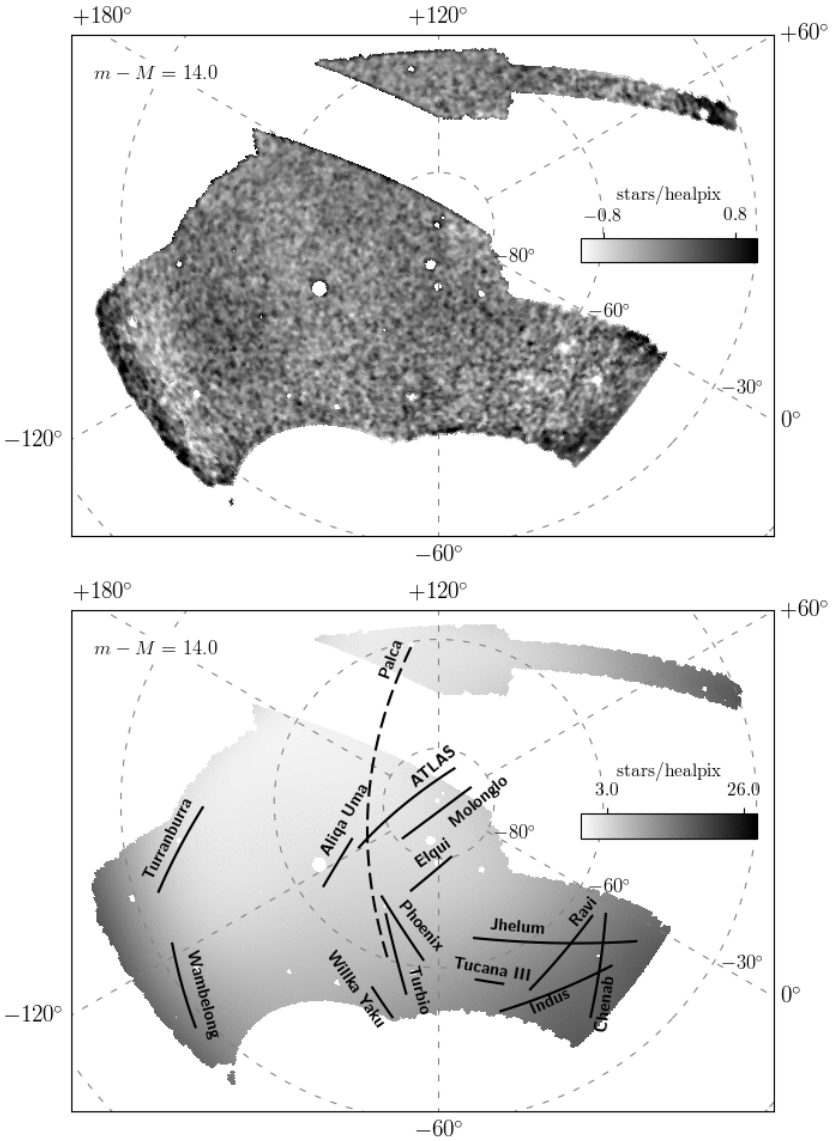
Pal 5, Odenkirchen et al. 2002
Ibata et al. 2016



Tri/Psc - Bonaca et al. 2012
Martin et al. 2014

Streams around the MW

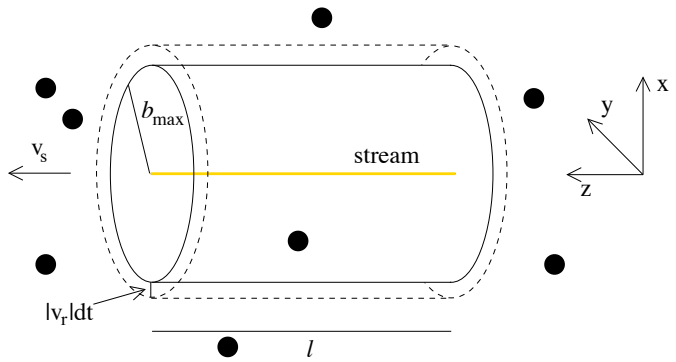
Streams in DES



Shipp + 2018

How many subhaloes fly near the stream?

- Flux through cylinder around stream (same approach as Yoon et al. 2011, Carlberg 2012)



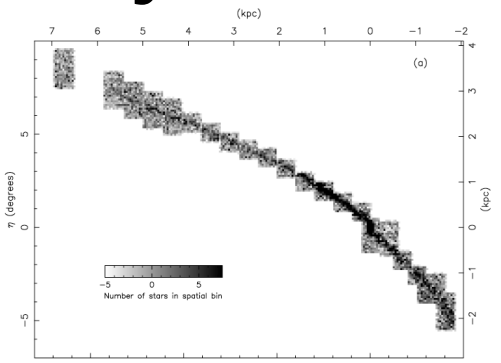
$$N_{enc} \propto n_{sub} l b_{max} \sigma t$$

N_{enc} ~ (number density)x(stream length)x(stream age)

- Also get velocity distribution

Erkal, Belokurov, Bovy, Sanders 2016

How many subhaloes fly near the stream?



Ibata et al. 2016

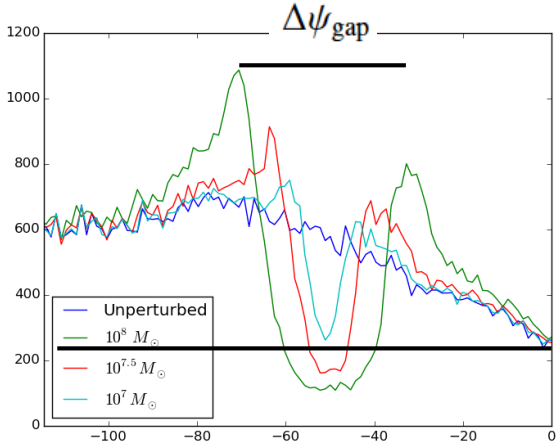
- Pal 5
  - ~3.4 Gyr old (Kuepper et al. 2015)
  - # density of subhaloes scaled down from Aquarius (Springel et al. 2009)
  - length from observations (Odenkirchen et al. 2002)
  - disk depletes substructure by 3 (D'Onghia et al. 2010, Penarrubia et al. 2010, Sawala et al. 2016)

10^5-10^6 M⊙: ~26 within 2 r_s
10^6-10^7 M⊙: ~10 within 2 r_s
10^7-10^8 M⊙: ~4 within 2 r_s

Erkal, Belokurov, Bovy, Sanders 2016

How many gaps are created?

- Use gap size and gap depth from model
- Subhalo properties from VLII (Diemand et al. 2008)
  - Match M-v_{max} relation with Plummer spheres
- Know number of interactions, sample properties of flyby, get distribution of gap properties



Stream density

f_{cut}

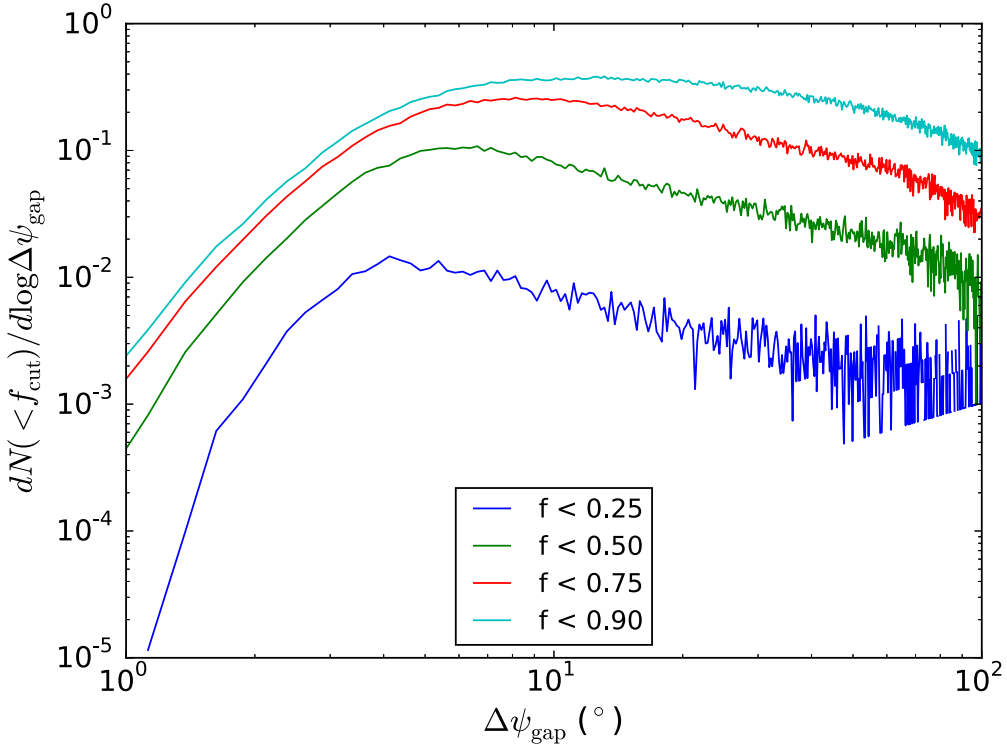
Angle along stream

Erkal, Belokurov, Bovy, Sanders 2016

Properties of Gaps

- Distribution of gap sizes for LCDM spectrum from 10^5-10^8 M⊙

Normalized distribution



Gap size

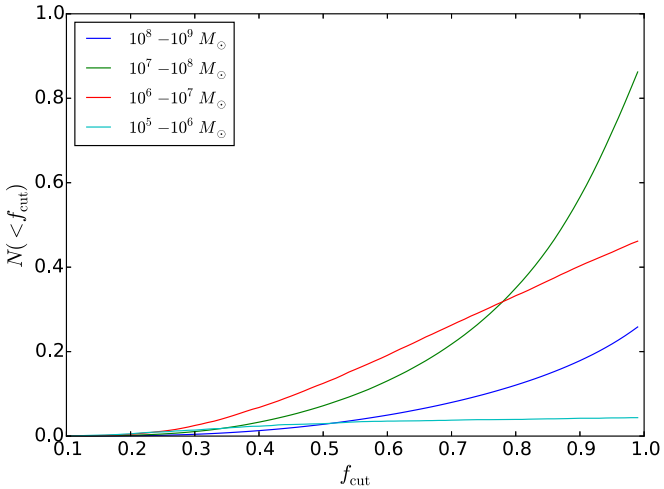
Guides the scale on which to search for gaps

Erkal, Belokurov, Bovy, Sanders 2016

So… how many gaps?

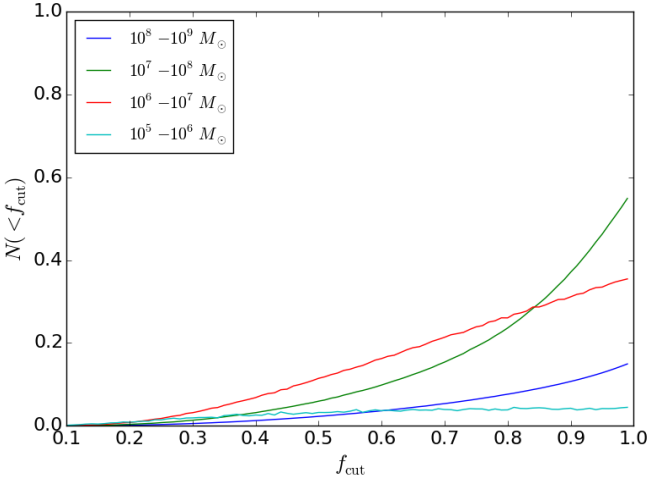
Number of gaps deeper than threshold

Pal 5
0.7 gaps with f < 75%

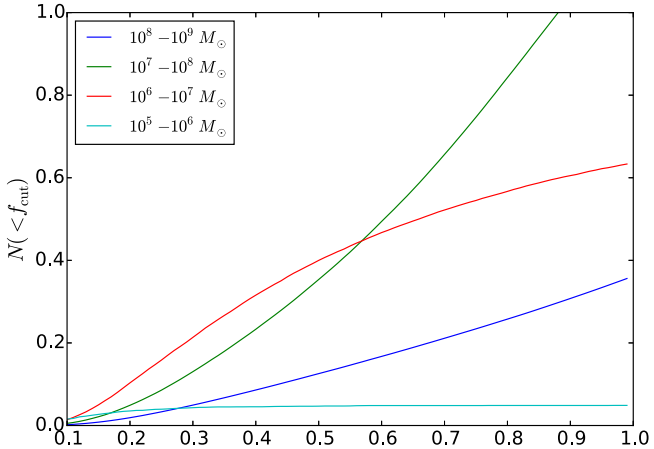


Density threshold

GD1
0.6 gaps with f < 75%



Tri/Psc
1.6 gaps with f < 75%



~3 gaps expected
in all three streams

Erkal, Belokurov, Bovy, Sanders 2016

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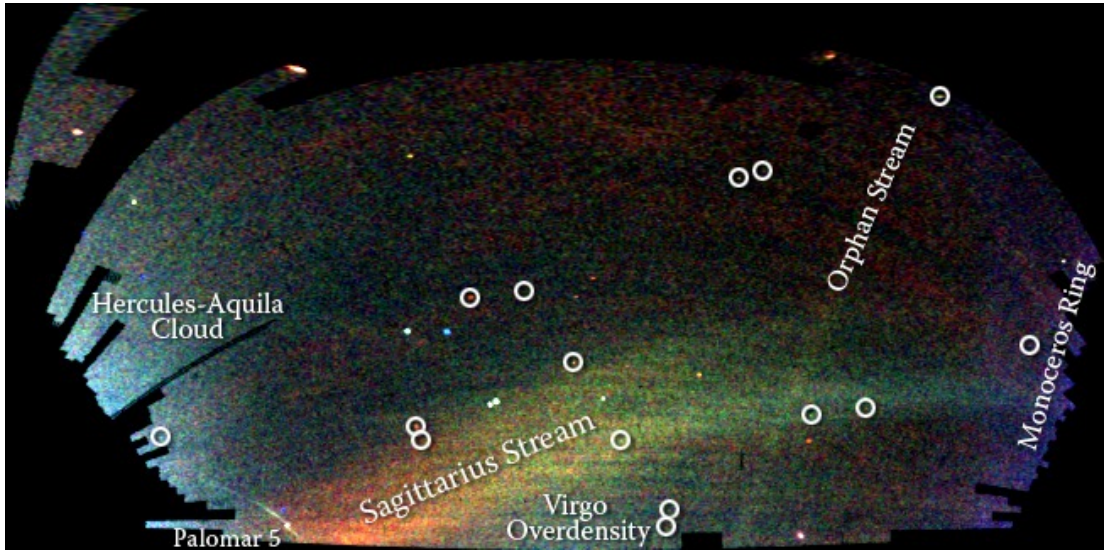
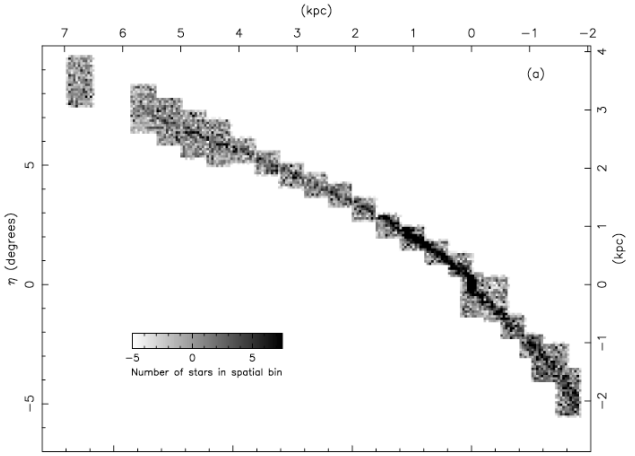
Gaps in Pal 5

- Nearby cold/long stream (~ 1km/s dispersion, ~10 kpc long)
- Progenitor still intact
- Deep data with CFHT (Ibata et al 2016)
- Proper motion for progenitor (Fritz & Kallivayalil 2015)
- Radial velocities along stream (Odenkirchen et al 2009, Kuzma et al 2015)



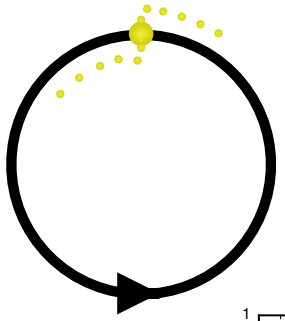
Belokurov/SDSS

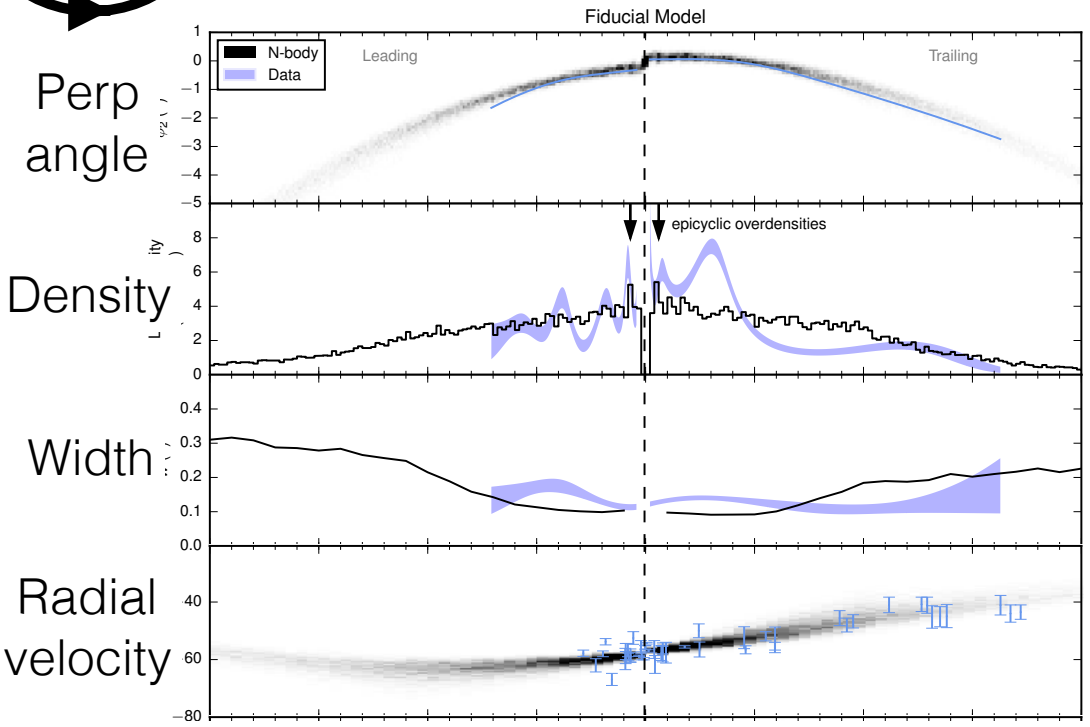
Gaps in Pal 5



Ibata et al 2016

- How should unperturbed stream look?
  - Equal amounts of material in leading and trailing arm
  - Symmetric density since no significant distance gradient (Ibata et al 2016)
  - Relatively smooth density along stream with little small scale structure
  - Epicyclic over densities near progenitor



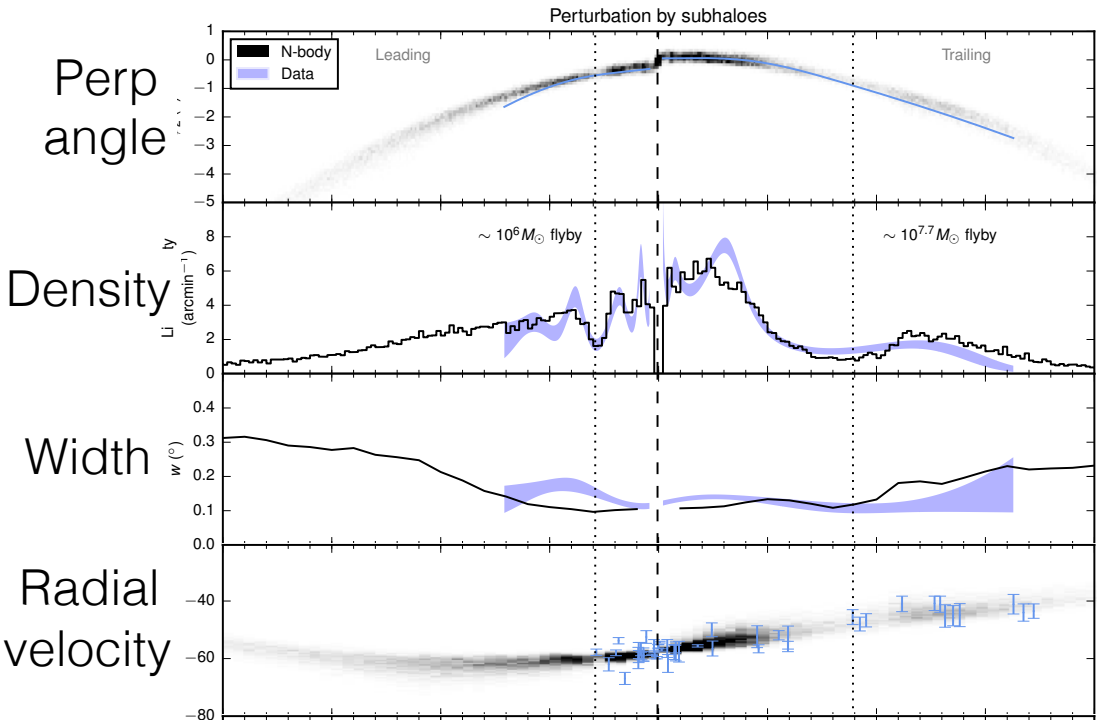


Angle along stream

Erkal, Koposov, Belokurov 2017

Gaps in Pal 5

- 2 gaps
  - ~ 2 degrees (10^6-10^7 M⊙)
  - ~ 9 degrees (10^7-10^8 M⊙)
- Observed width is more uniform



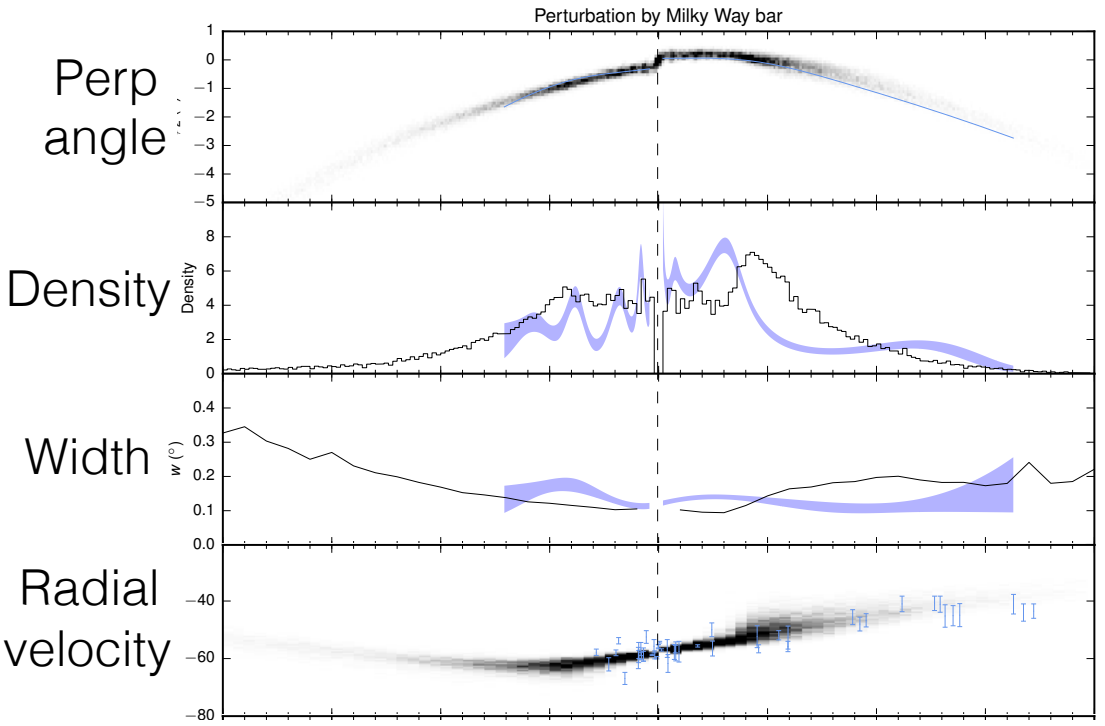
Expected 0.7 gaps so ~3x LCDM

10^6-10^7 M⊙ ~ 9-18 keV thermal relic WDM

Erkal, Koposov, Belokurov 2017

Gaps in Pal 5

- Alternative mechanisms
  - GMCs (Amorisco+ 2016): 10^6-10^7 $M_\odot$ within solar circle (Rice + 2016), 0.65 gaps expected
  - Globular clusters: < 1/6 rate expected from subhaloes (Erkal, Koposov, Belokurov 2017)
  - MW Bar: Rotating bar creates differential torque along stream (Erkal, Koposov, Belokurov 2017, Pearson+2017)
  - MOND can create asymmetries in tidal streams (Thomas+2018, Wu+2010)

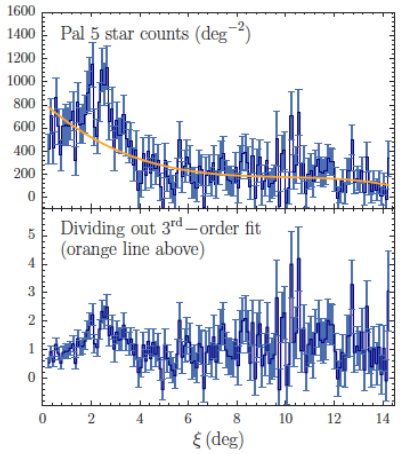


Erkal, Koposov, Belokurov 2017

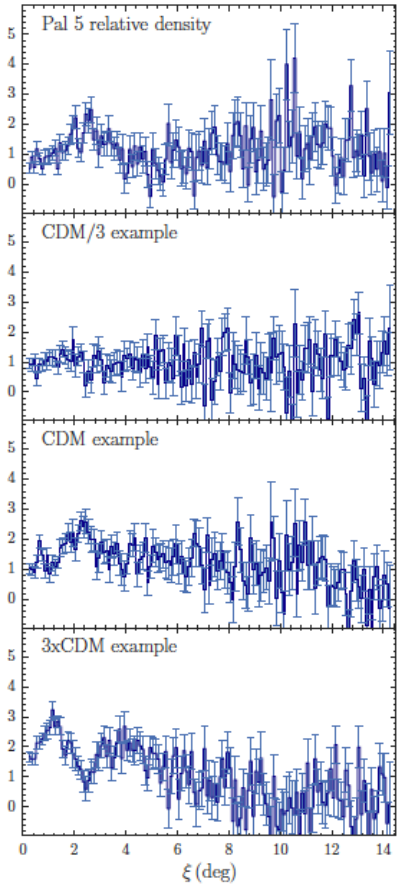
Gaps in Pal 5

- Alternative statistical approach
  - Measure power spectrum/bispectrum of density fluctuations (Bovy, Erkal, Sanders 2017)
  - Streams and perturbations generated in action-angle space (Sanders, Bovy, Erkal 2016)
- Idea (ABC)
  - Select normalization of LCDM subhaloes
  - Perturb stream with subhalo flybys
  - Keep if power/bispectrum on large scales matches data
  - Get constraint on LCDM normalization

Data



Realizations



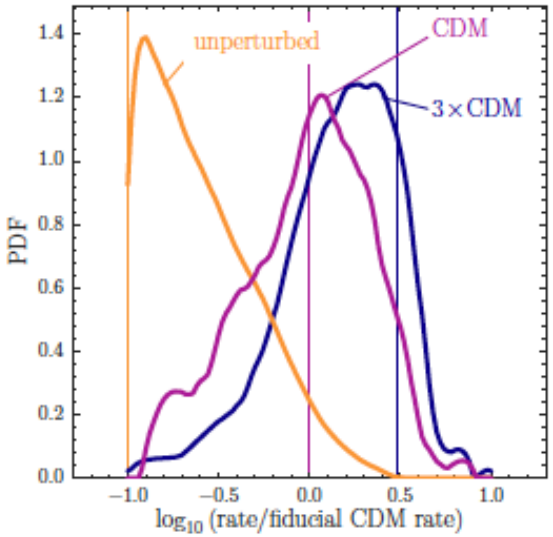
Bovy, Erkal, Sanders 2017

Gaps in Pal 5

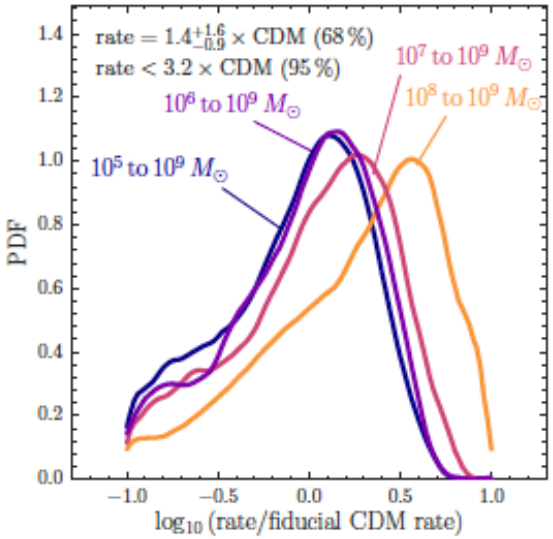
- Tested with N-body streams

- Pal 5 consistent with 1.5-9 LCDM, consistent with gap counting

N-body inference



Pal 5 inference



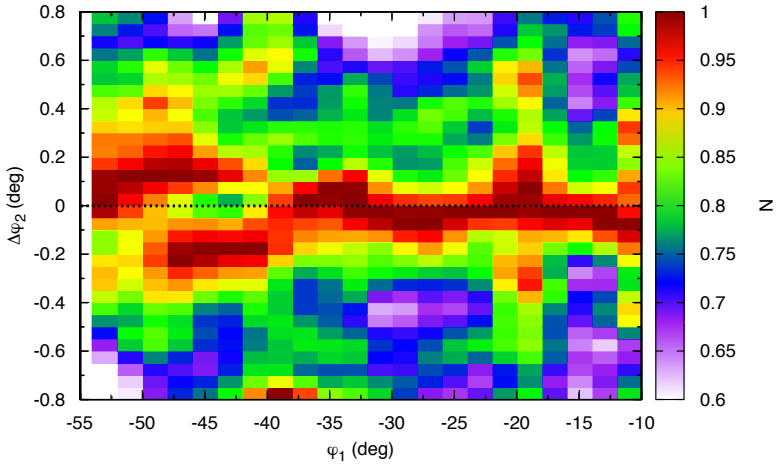
Bovy, Erkal, Sanders 2017

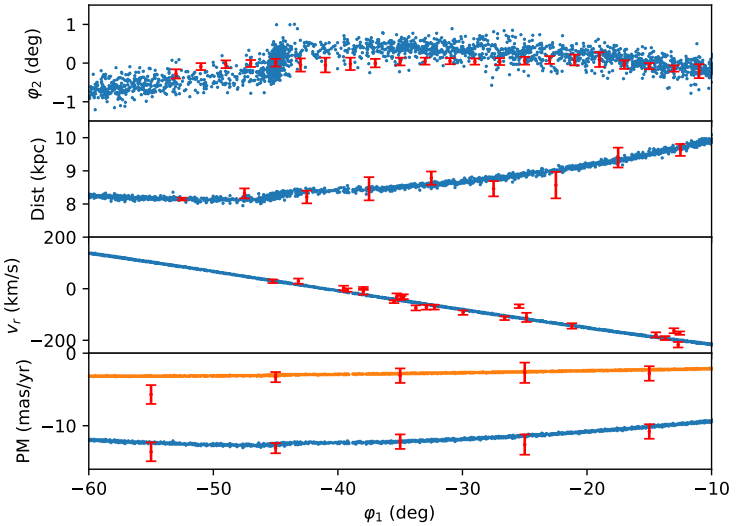
Gaps in GD-1

CFHT data

Simulation

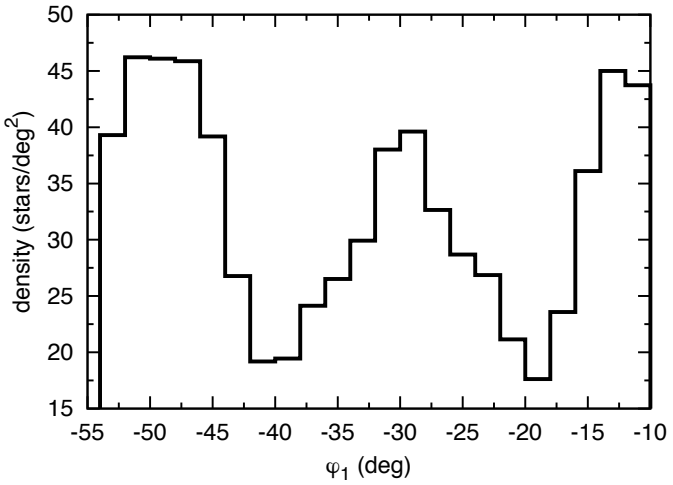
Stream on sky





Angle along stream

Stream density



Angle along stream

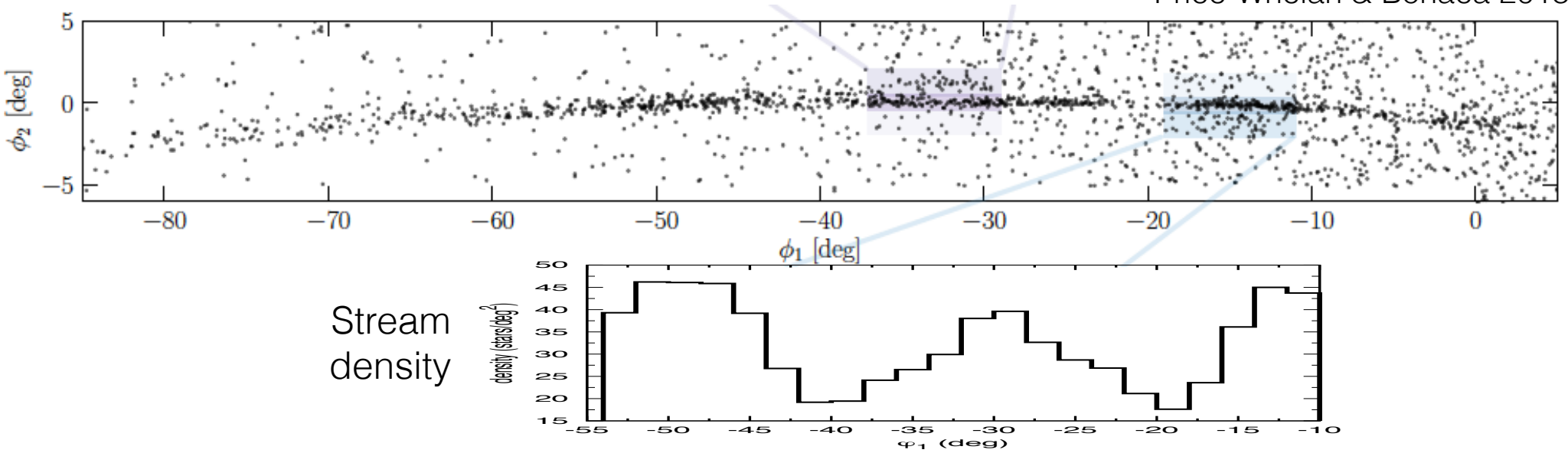
- Hard to interpret since no progenitor
- Wiggles and density variations
- Still working on interpretation

de Boer + 2018

Gaps in GD-1

Gaps confirmed with Gaia

Price-Whelan & Bonaca 2018



Angle along stream

de Boer + 2018

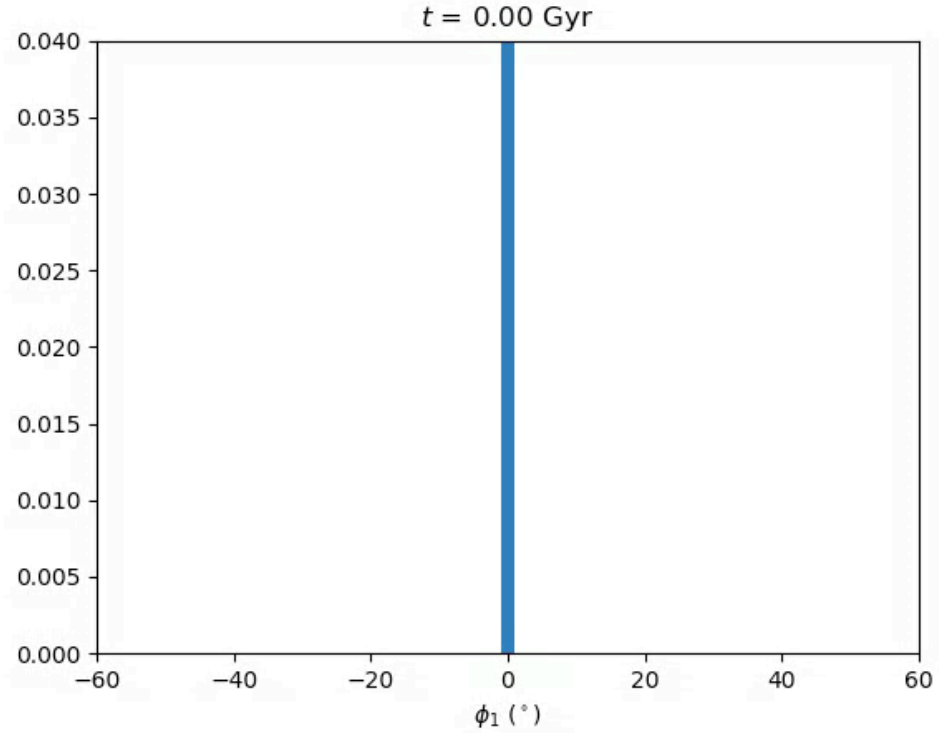
3 gaps in GD-1

Wiggles in the stream track, stars off-stream

Gaps in GD-1

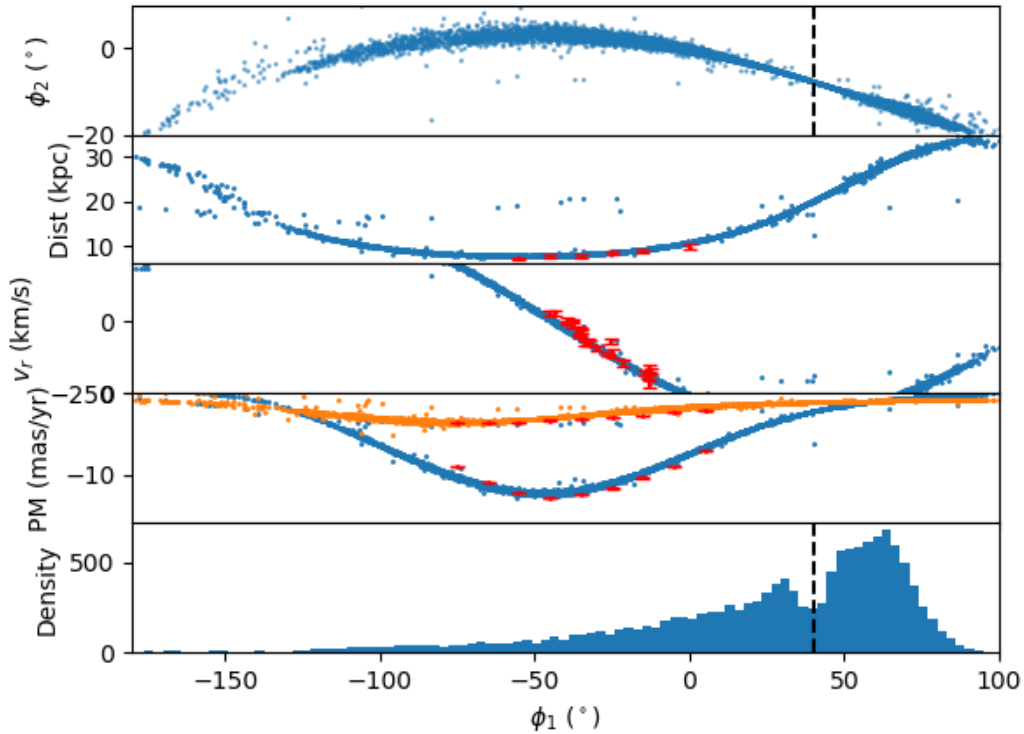
Progenitor disruption creates a gap

Stream density



Angle along stream

Stream observables

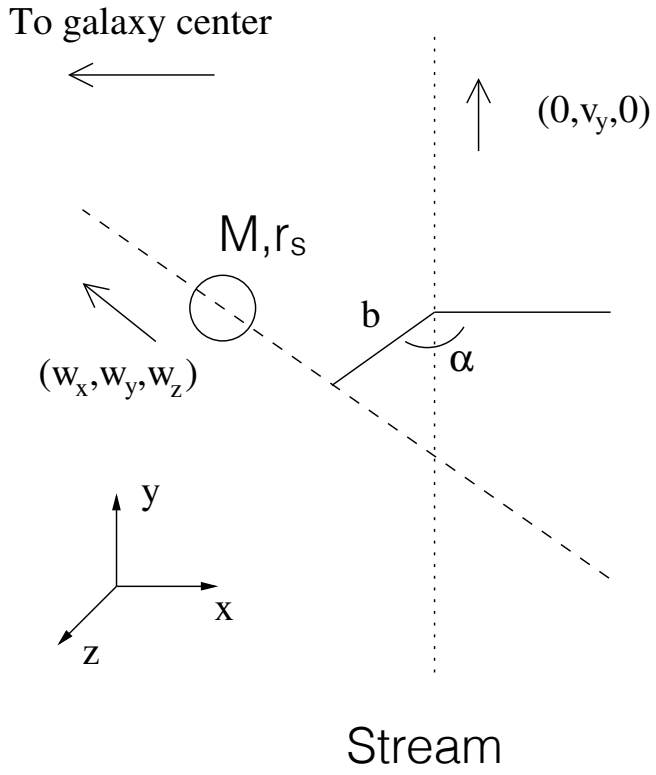


Angle along stream

Erkal & Gieles in prep.

Recovering Subhalo Properties

- Gap properties depends on 7d parameter space:
  - Subhalo mass
  - Scale radius
  - 3 velocities
  - Impact parameter
  - Time since impact
- Can we constrain these from observations of a gap?



Erkal & Belokurov 2015b

Stream observables

- Analytic model predicts 6d shape of perturbed stream

10^7 M⊙, r_s=250 pc

Distance

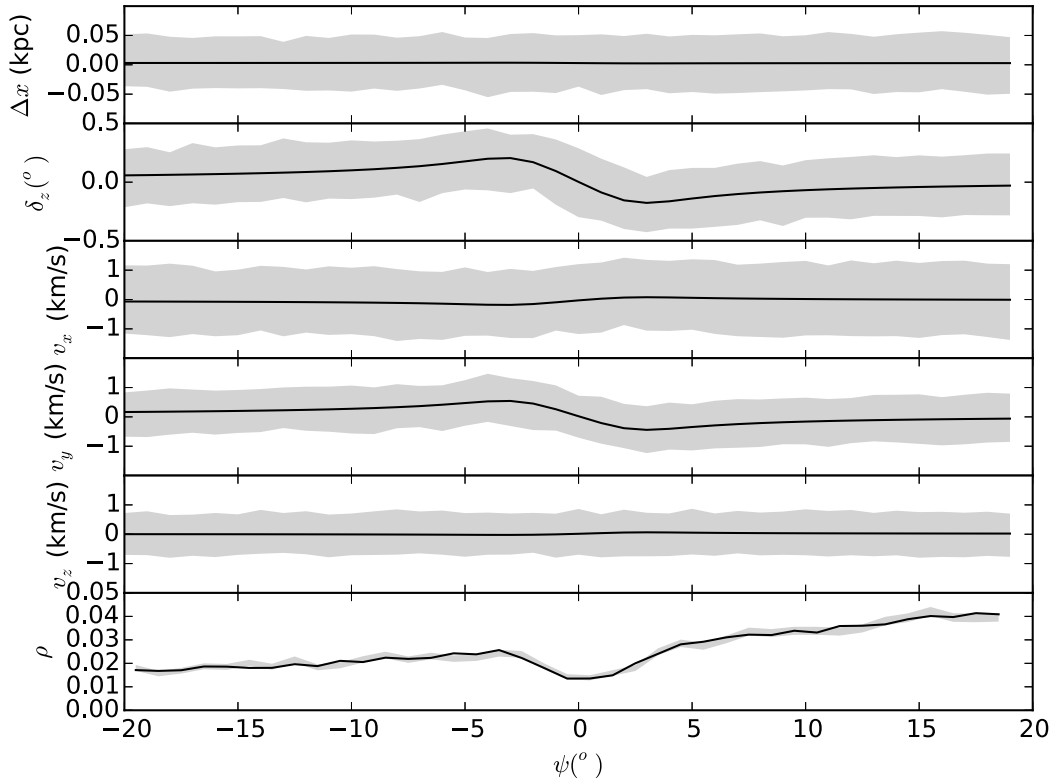
Declination angle

Radial velocity

Tangential velocity

Vertical velocity

Density

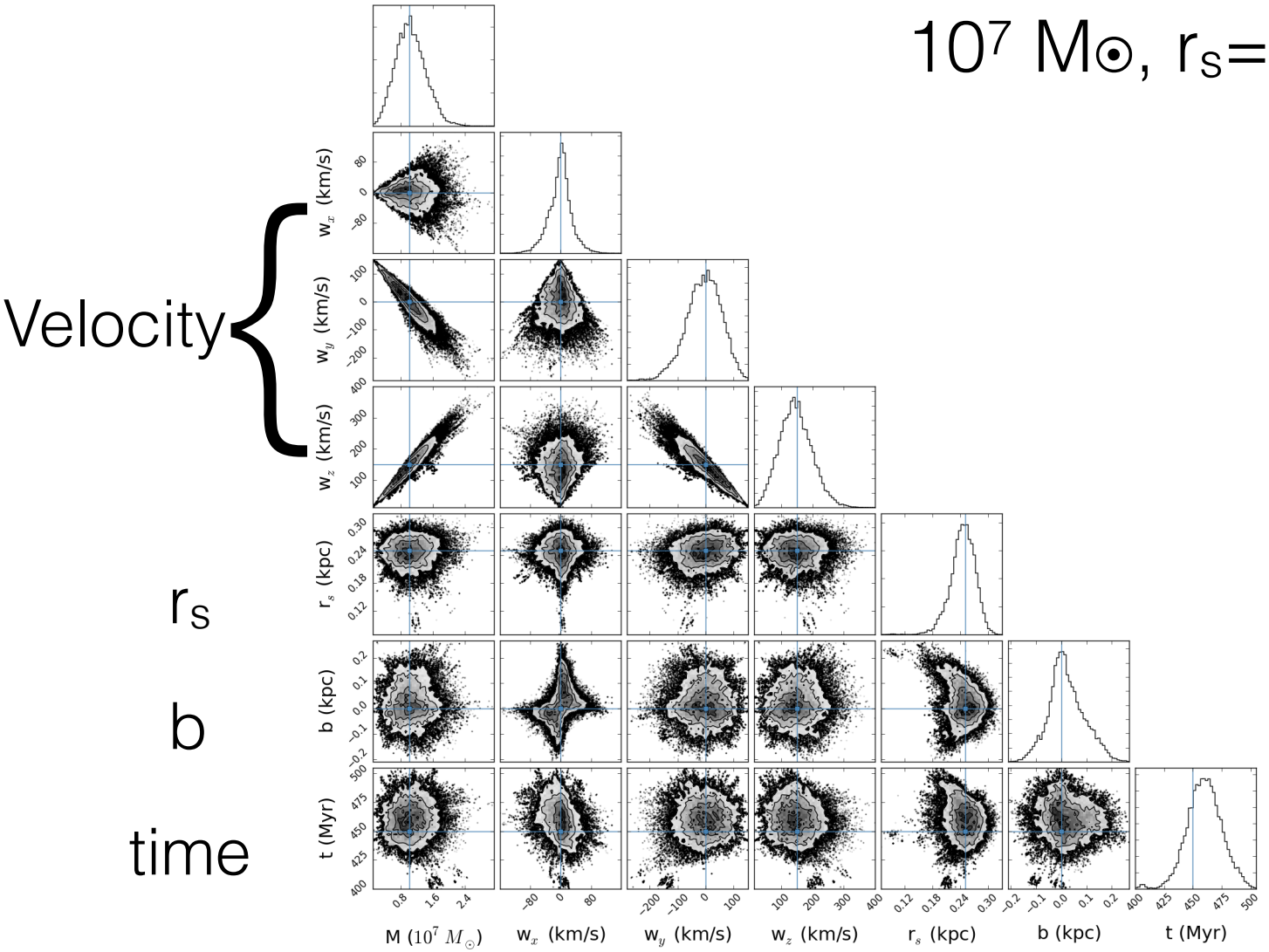


Angle along stream

Inference with emcee

LSST Errors

10^7 M⊙, r_s=250 pc



Erkal & Belokurov 2015b

Mass Velocity r_s b time

Observational Strategy

	Pal 5	GD-1
• Measure density and centroid along stream	✓	✓
• Look for density variation with accompanying wiggle	✓-	✓-
• Follow up with radial velocities	In progress	
• Develop tools to model gaps in real streams	In progress	
• Fit gap!		

Conclusions

- Kicks from subhaloes change orbital periods and create gaps
- Expect ~1 deep gap per long stream
- Pal 5 contains 2 gaps and is consistent with ~ 3x LCDM
- Small gap consistent with 10^6-10^7 $M_\odot$ subhalo, > 9-18 keV WDM
- GD-1 has 3 gaps (1 from progenitor?), ~ 3x LCDM
- Next step: perform inference for observed gaps
- Can be used for constraints on any DM model