Inferring Subhalo Properties from Gaps in Tidal Streams

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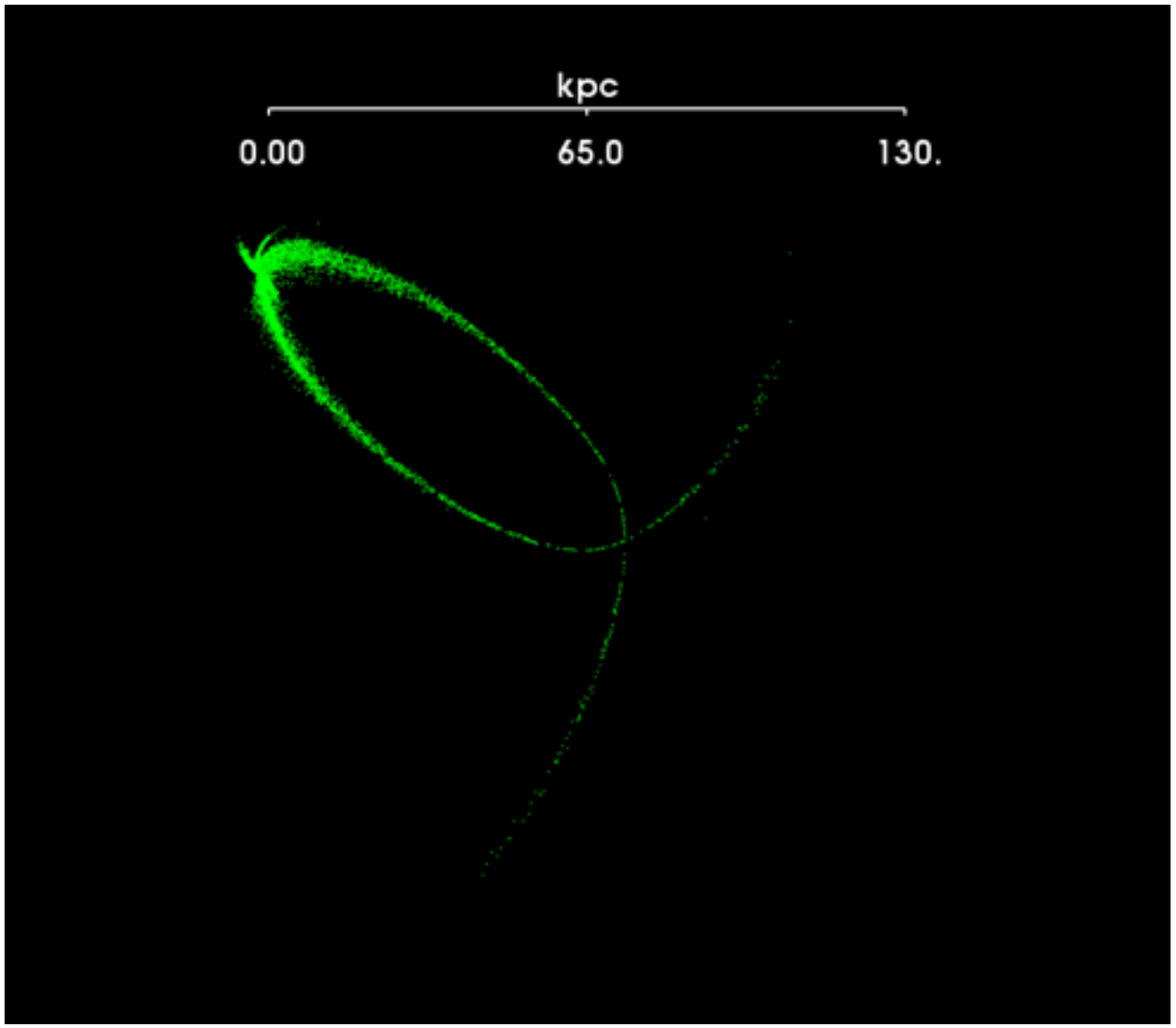
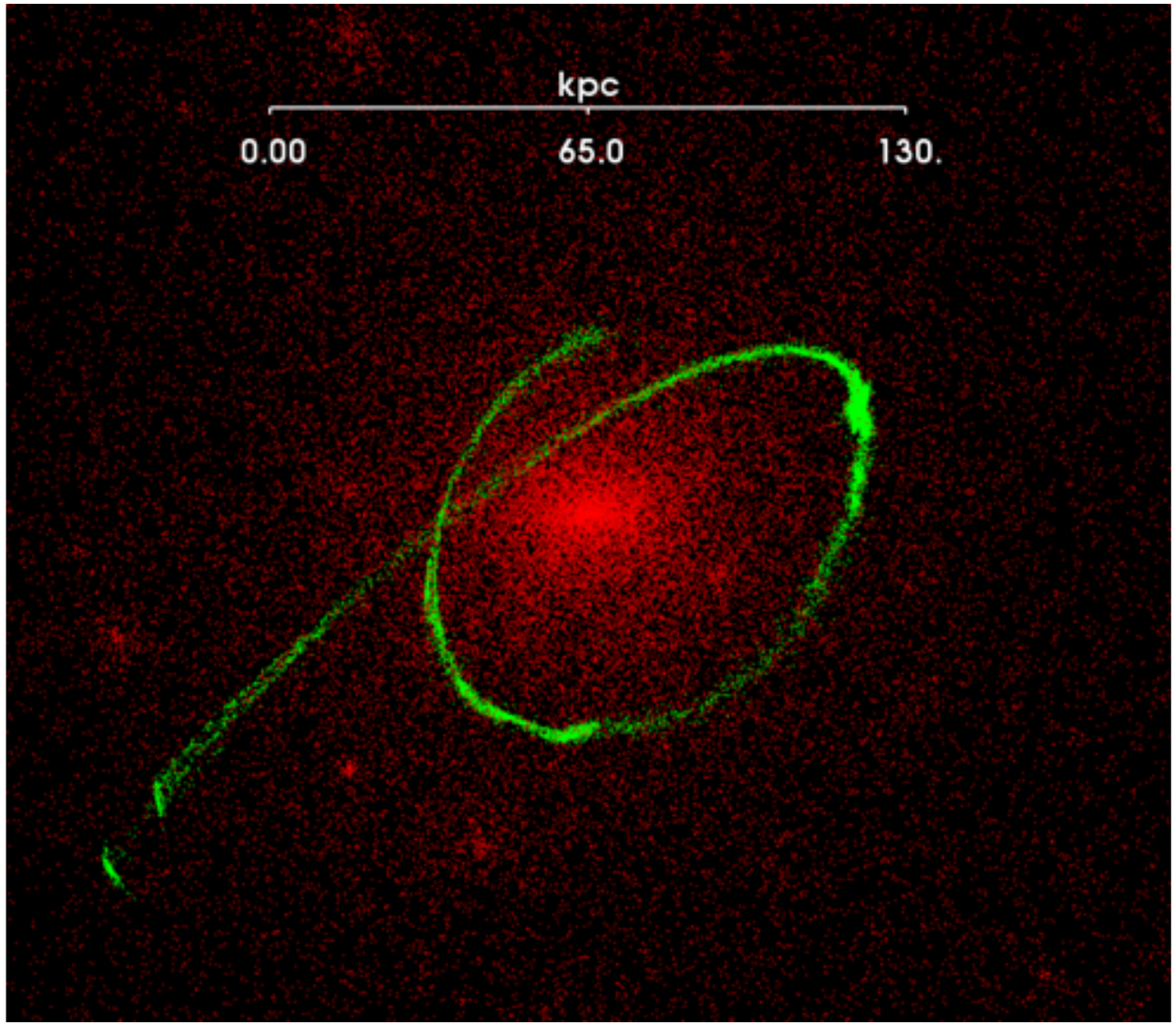
Satellites and Streams in Santiago, April 16, 2015

Erkal & Belokurov 1412.6035 - in press
Erkal & Belokurov 2015 - in prep

Tidal Streams



Smooth Potential

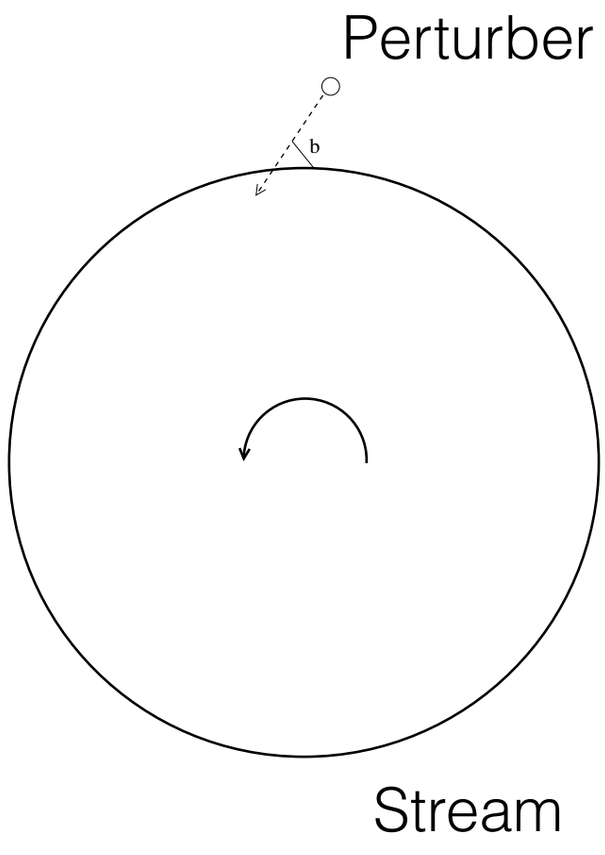


Lumpy Potential

Toy Model

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

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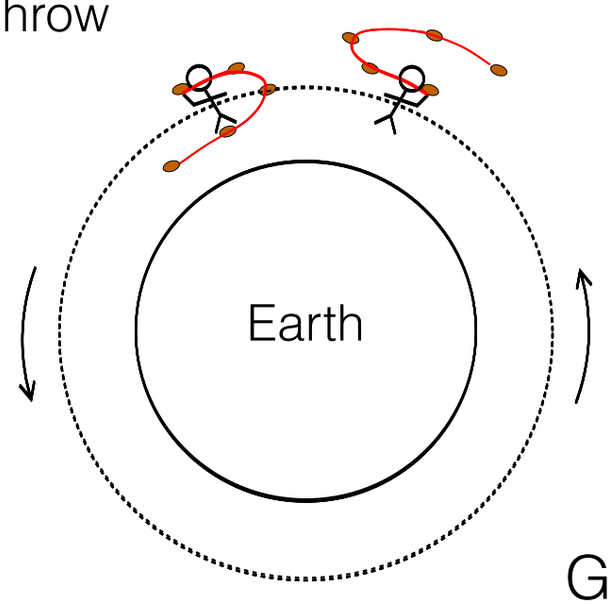
Cartoon of Gap Formation

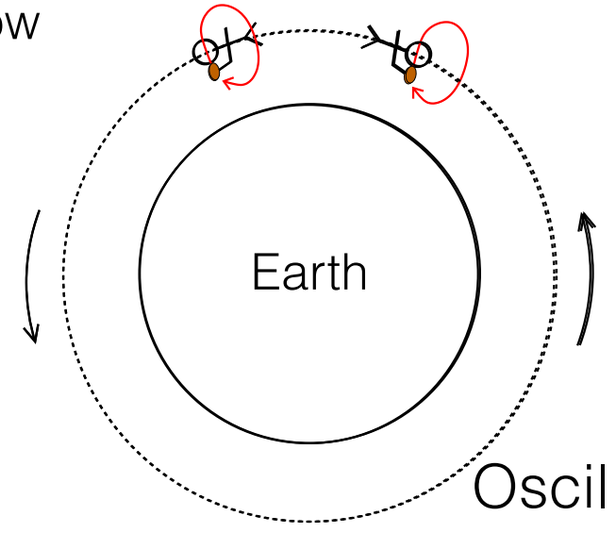
Orbital Mechanics 101
aka Football in Space

Tangential Throw



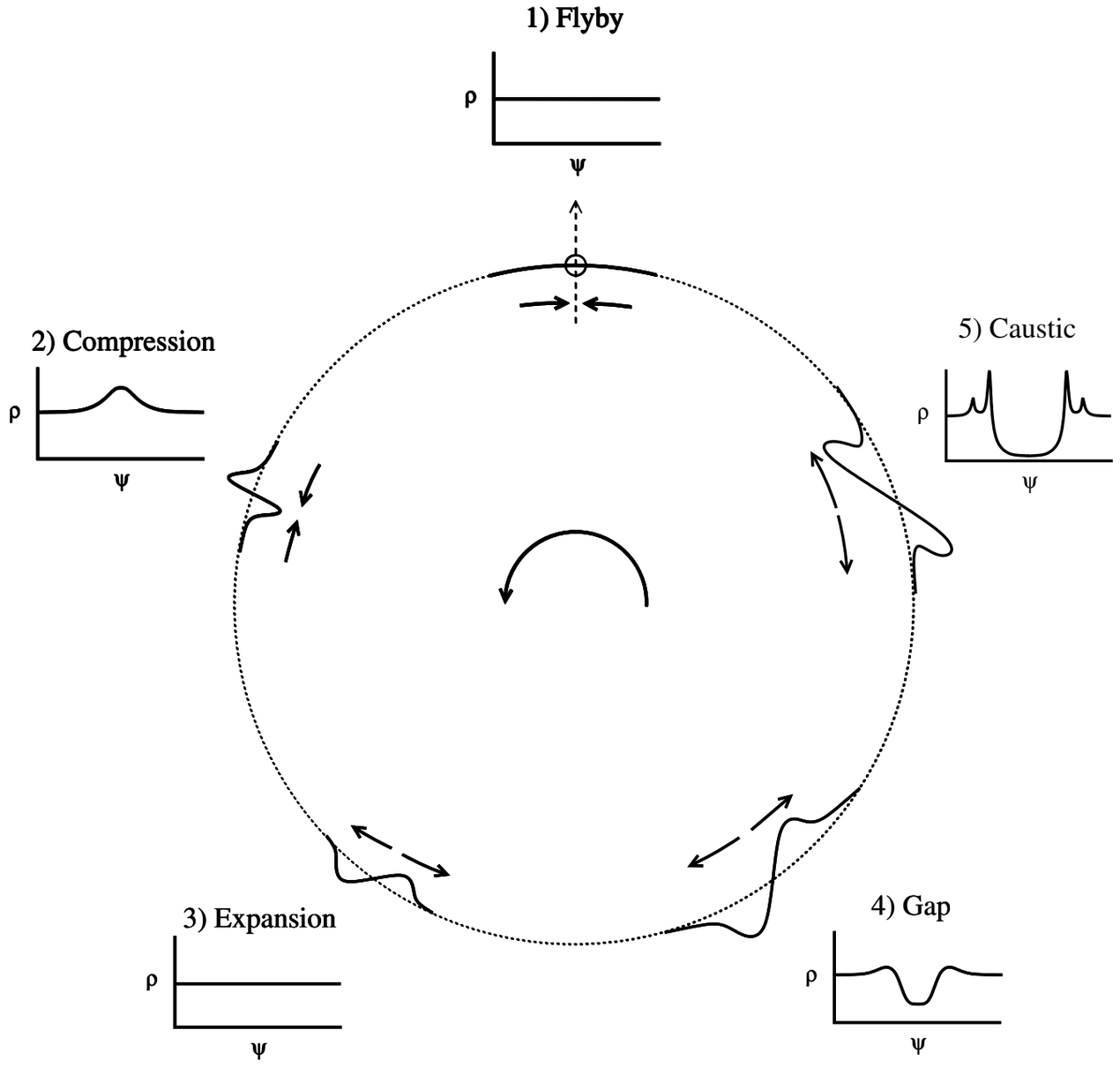
Gap!

Radial Throw



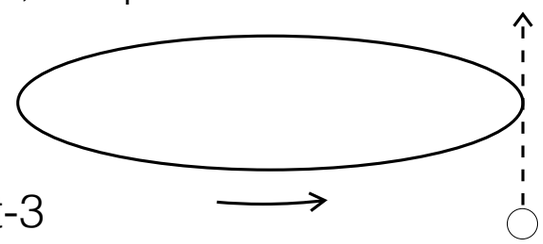
Oscillations!

Gap Formation (also in Space)

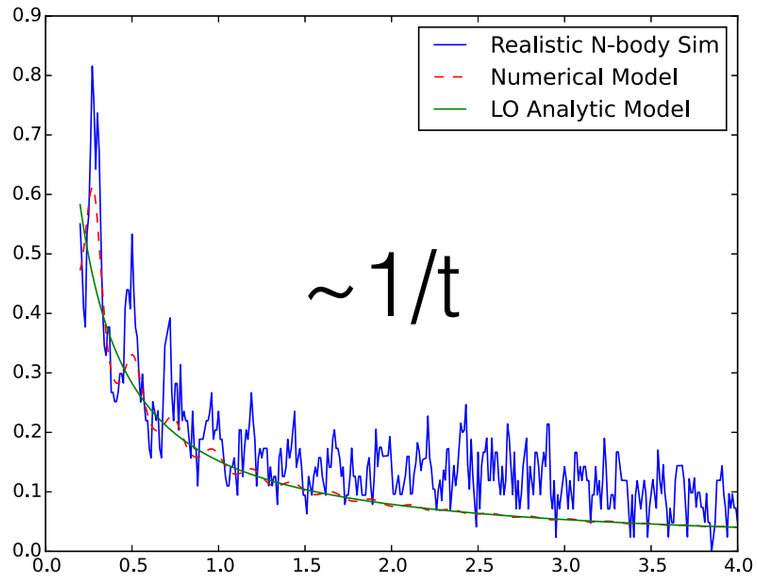


Model Predictions

- Stream generated by progenitor on circular orbit at 10kpc
- NFW host potential
- $10^8 M_\odot$ Plummer sphere, 250pc scale radius
- Direct impact
- 10^6 particles in Gadget-3

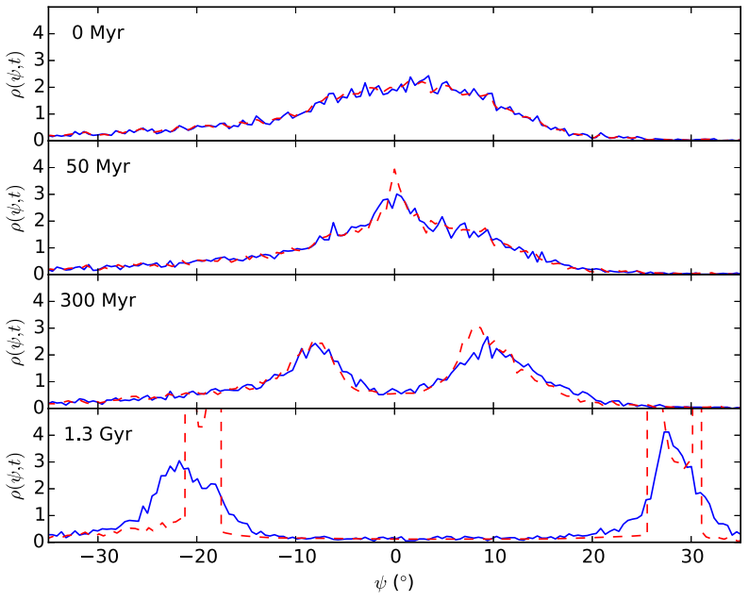


Gap density



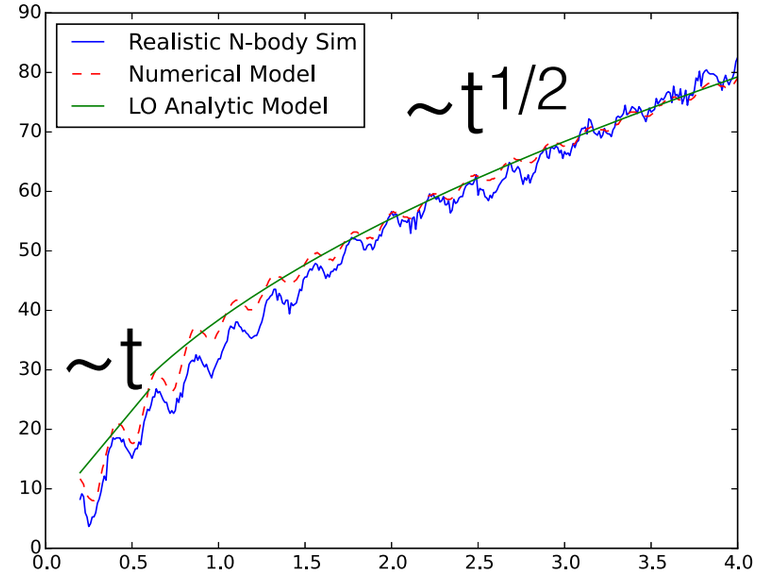
Time in Gyr

Density along stream



Sky angle (°)

Gap size (°)



Time in Gyr

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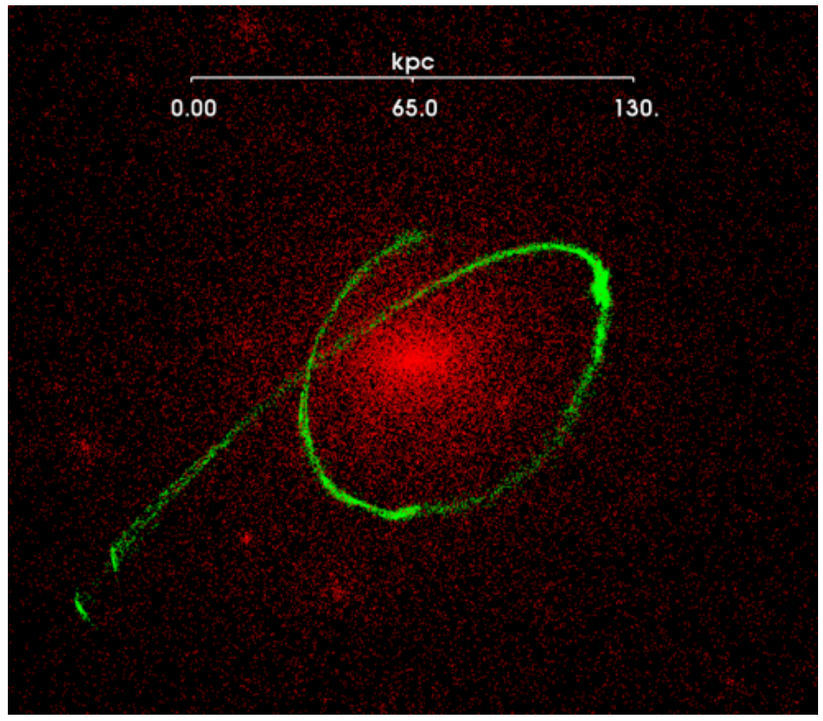
Recovering Subhalo Properties

- Gap properties depends on 7-d parameter space: M,r_s,b,3 v's,t
- Density profile constrains only 3 combinations



Need more constraints!

Additional constraints

- Model analytically predicts 6d shape of perturbed stream

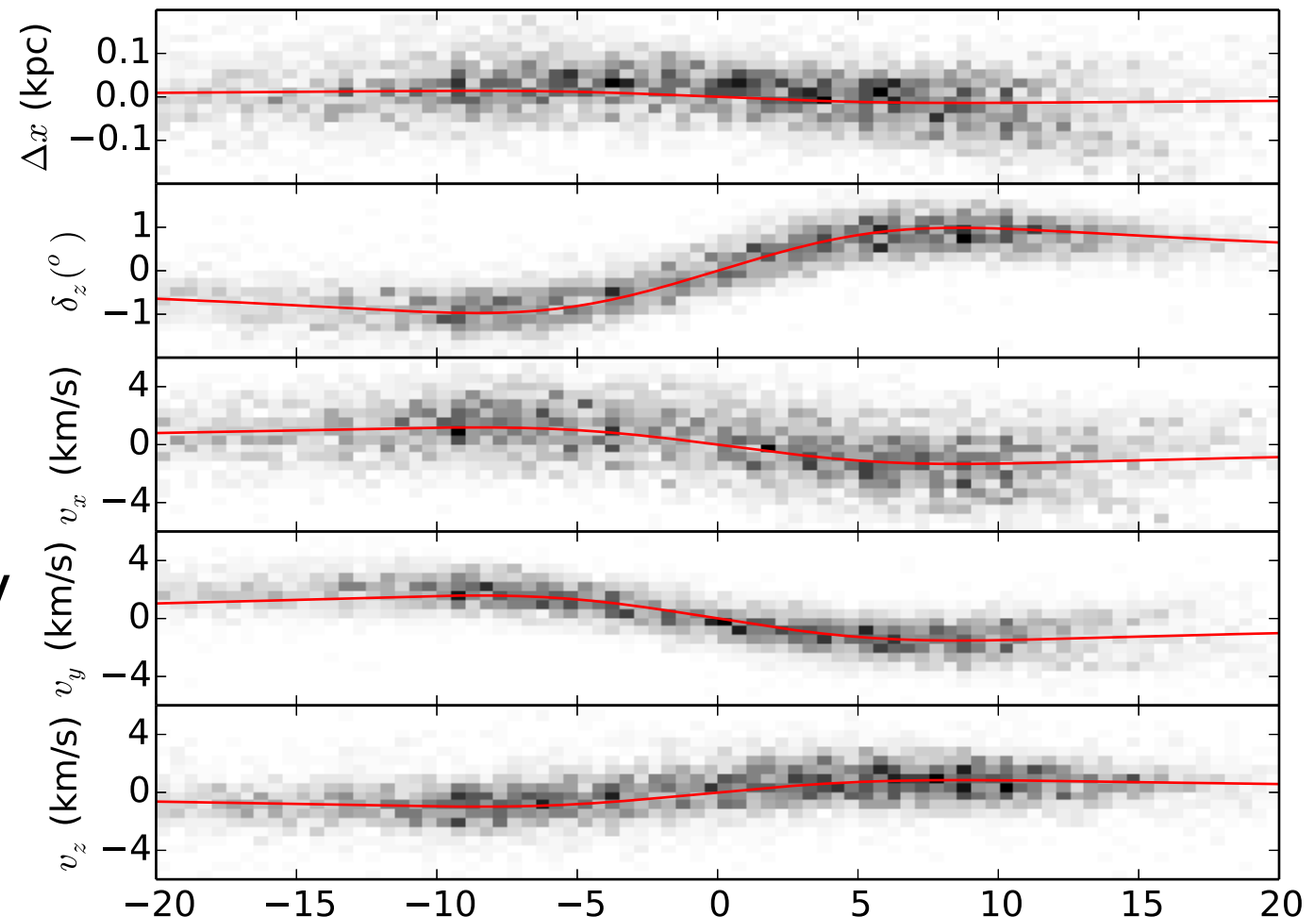
Distance

Declination angle

Radial velocity

Tangential velocity

Vertical velocity

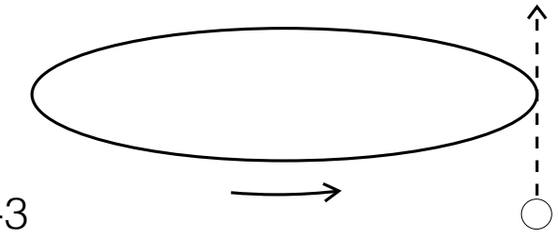


Inference example with realistic errors

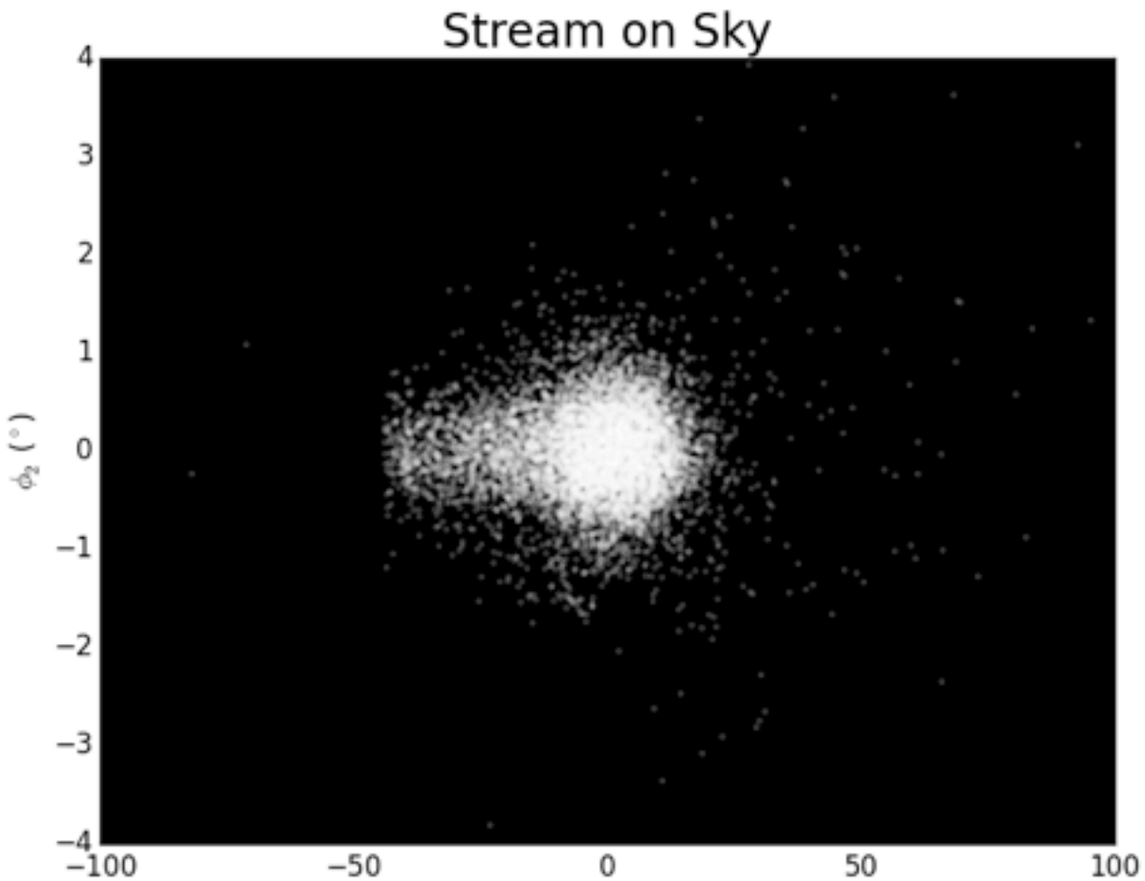
- Run three N-body simulations to generate gap from subhalo passage:
  - 1) 10^8 $M_\odot$, r_s = 625pc, 2) $10^{7.5}$ $M_\odot$, r_s = 395pc, 3) 10^7 $M_\odot$, r_s = 250pc
- Place stream at 10 kpc from the sun
- Draw stream stars from realistic mass function
- Observational uncertainties:
  - Gaia errors for parallax and proper motion
  - 1 km/s RV error to r = 19, 5km/s RV error at r=21
- Priors: strongest prior is Maxwellian velocity distribution
- Infer subhalo properties using analytic model for 6d stream shape

N-body Simulations

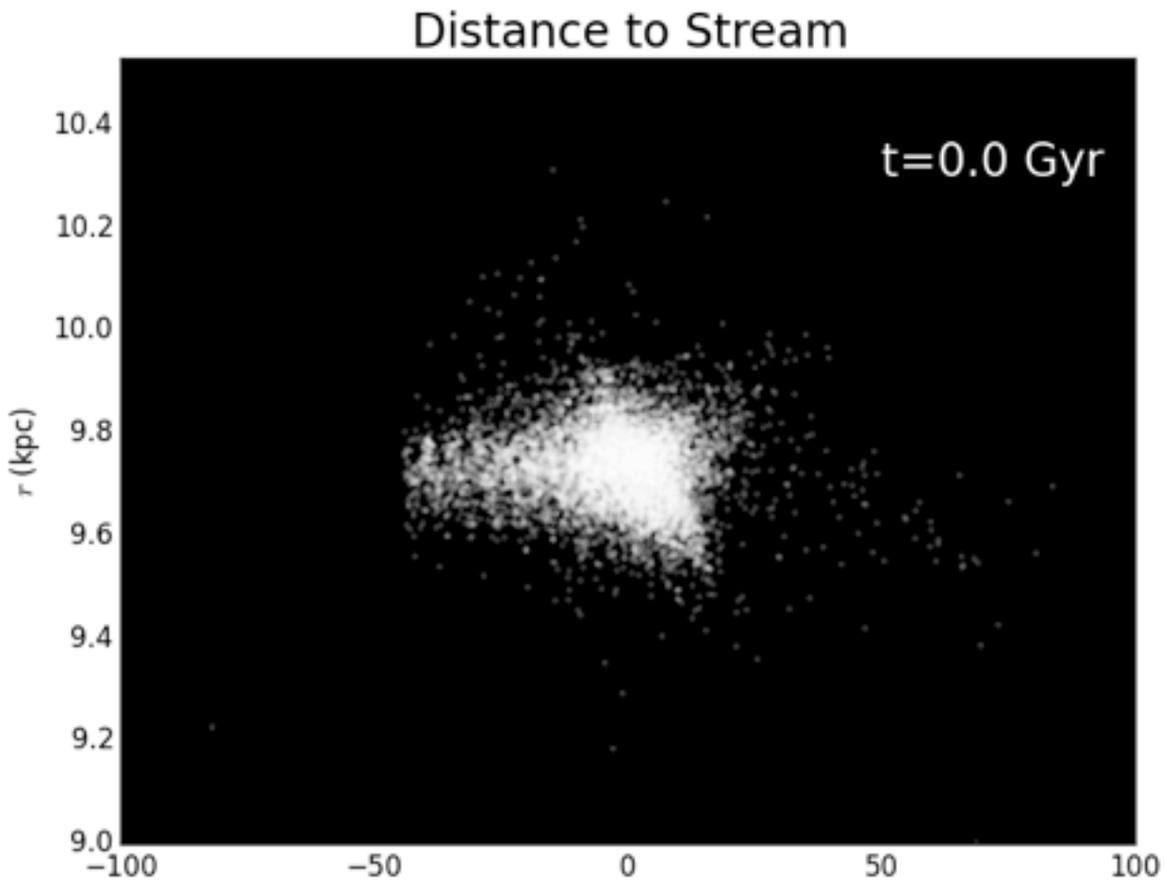
- Stream generated by progenitor on circular orbit at 10 kpc (M = 2.5x10^5 $M_\odot$, r_s=8pc)
- NFW host potential
- Direct impact geometry
- 10^6 particles in Gadget-3



10^8 $M_\odot$, r_s=625 pc

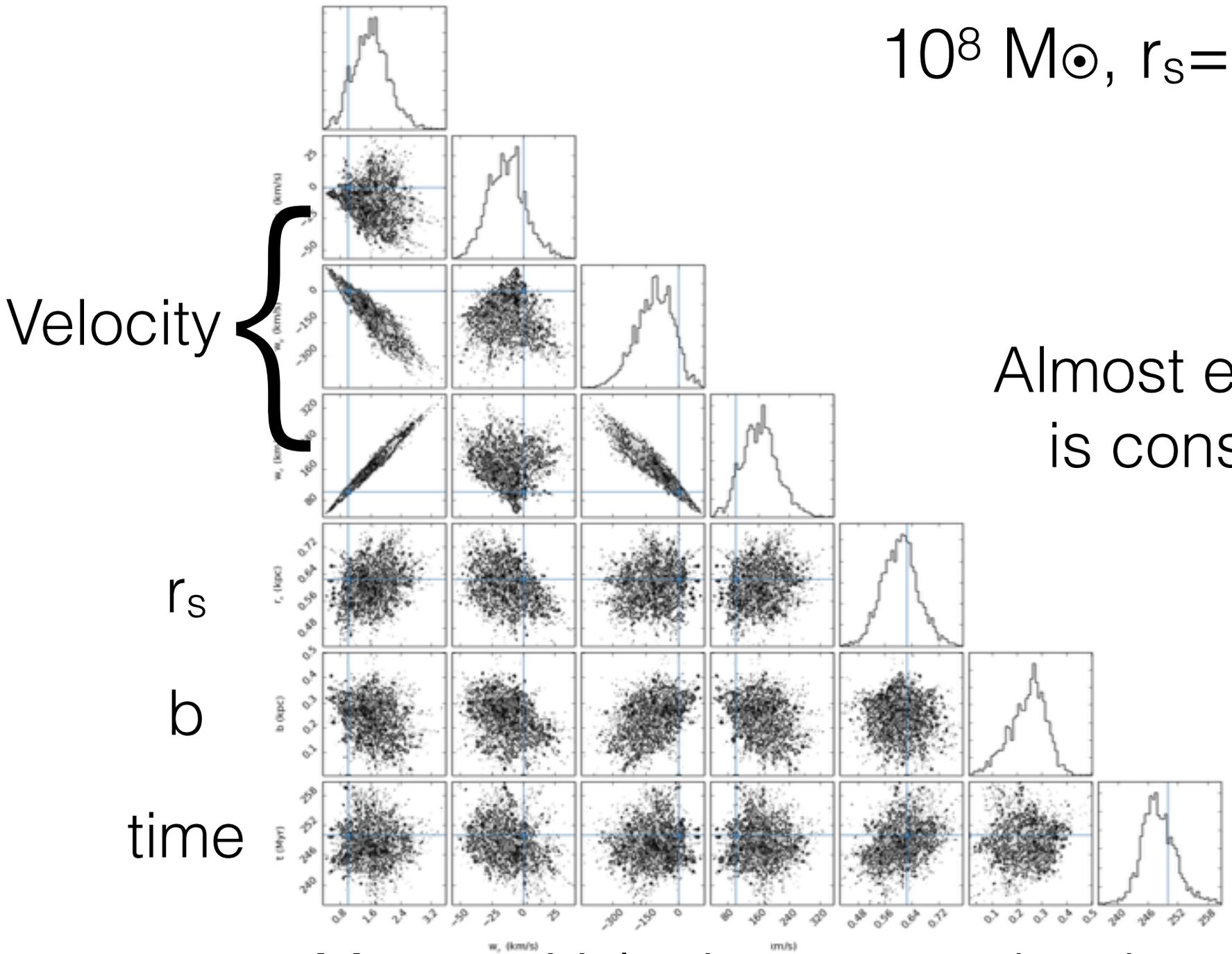


Angle along stream



Angle along stream

emcee Hammer Time

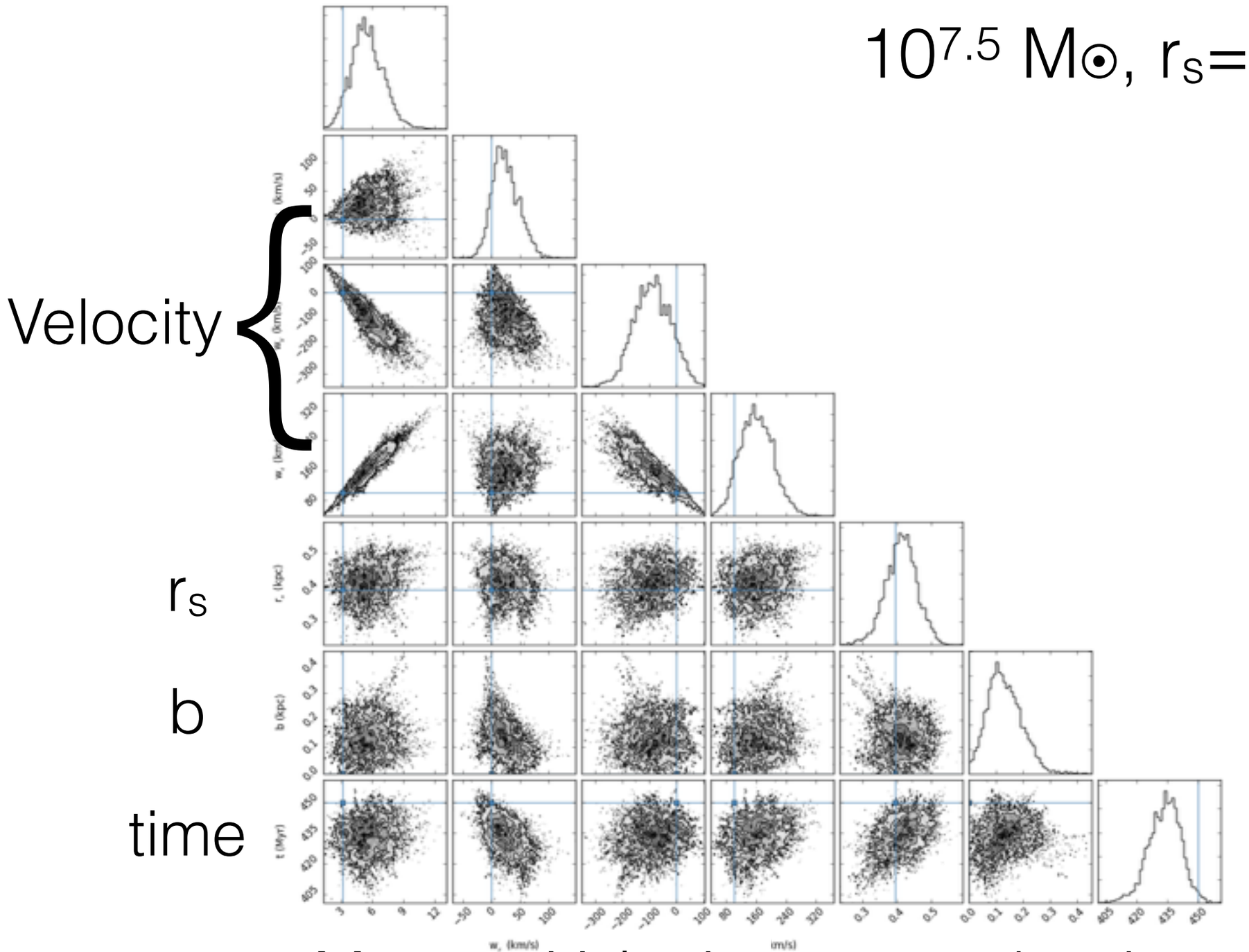


10^8 M⊙, r_s=625 pc

Almost everything is constrained

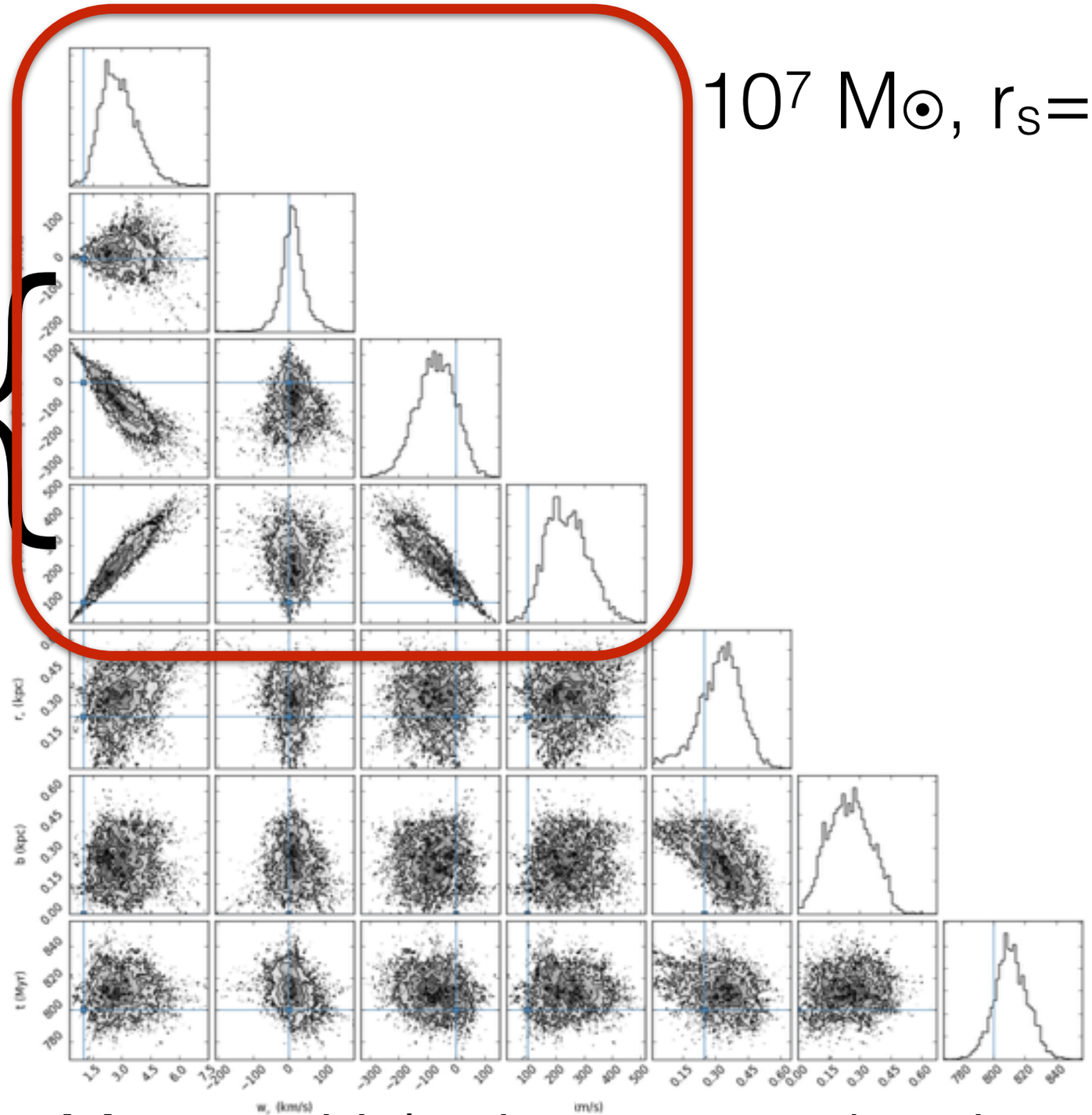
emcee Hammer Time

$10^{7.5}$ M⊙, r_s=395 pc



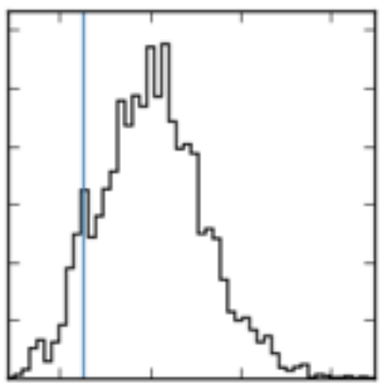
emcee Hammer Time

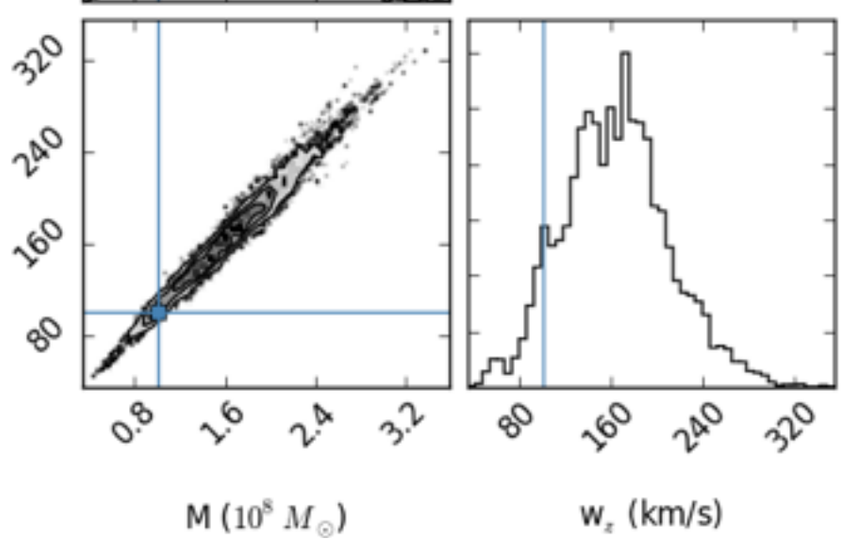
10^7 M⊙, r_s=250 pc



Mass-velocity degeneracy

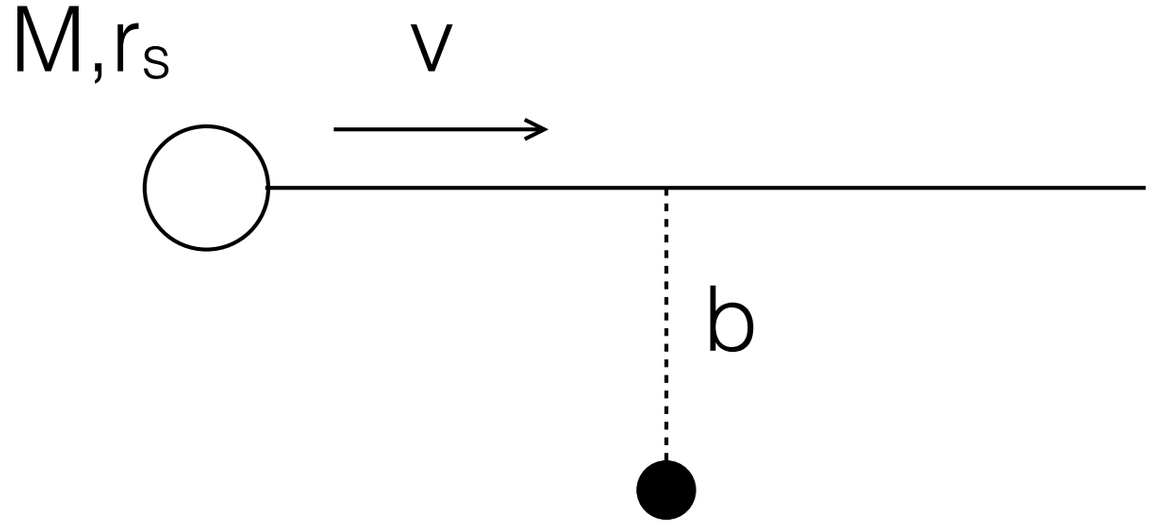
10^8 M⊙, r_s=625 pc





Mass (10^8 M⊙)

Velocity (km/s)



$$a \sim \frac{GM}{b^2 + r_s^2}$$

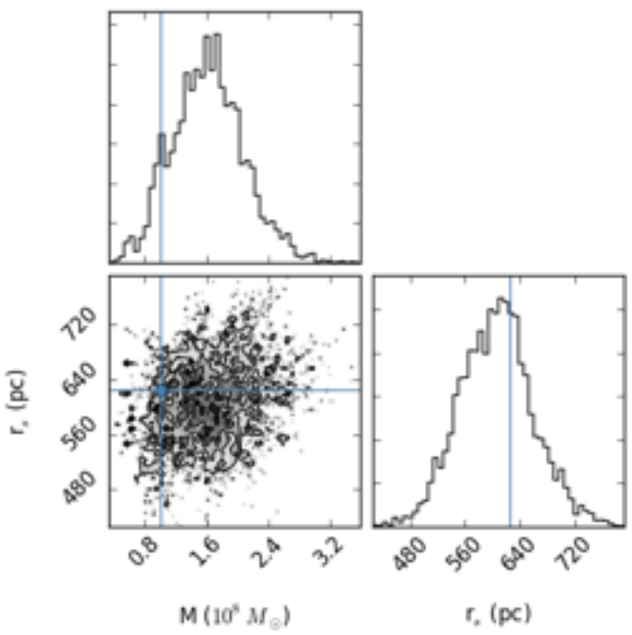
$$\Delta t \sim \frac{\sqrt{b^2 + r_s^2}}{v}$$

$$\Delta v = a\Delta t \sim \frac{M}{v} \frac{G}{\sqrt{b^2 + r_s^2}}$$

Can only constrain M/v!

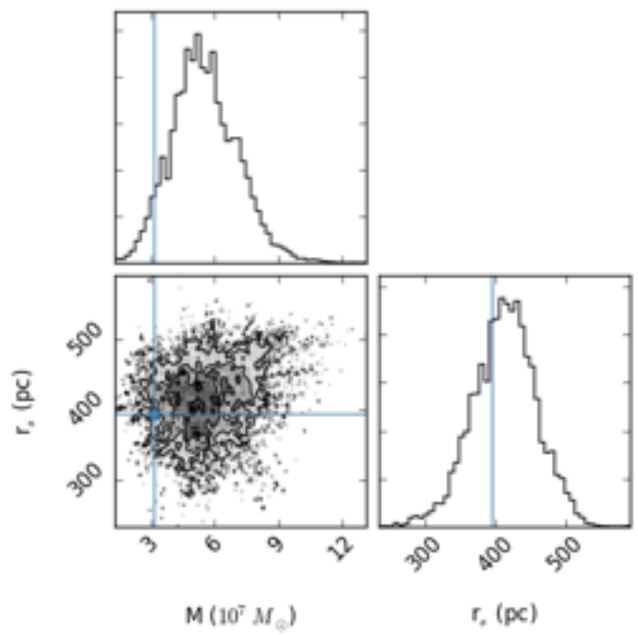
Mass and scale radius

10^8 M⊙, r_s=625 pc



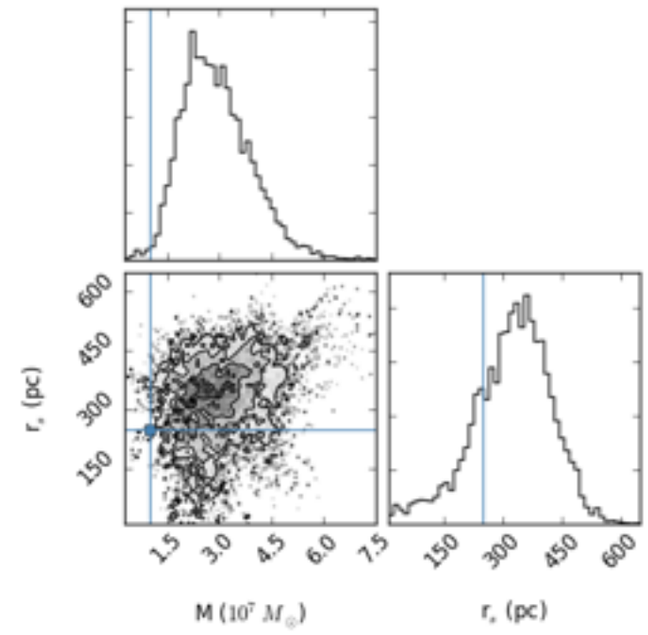
8x10^7 M⊙ - 2.6x10^8 M⊙

$10^{7.5}$ M⊙, r_s=395 pc



2x10^7 M⊙ - 9x10^7 M⊙

10^7 M⊙, r_s=250 pc



1.5x10^7 M⊙ - 5x10^7 M⊙

$10^{7.5}$ M⊙ is probably the useful limit for Gaia

What observables are needed?

- Can work out constraints of each observable from the analytic model

- Depends on the oscillation phase

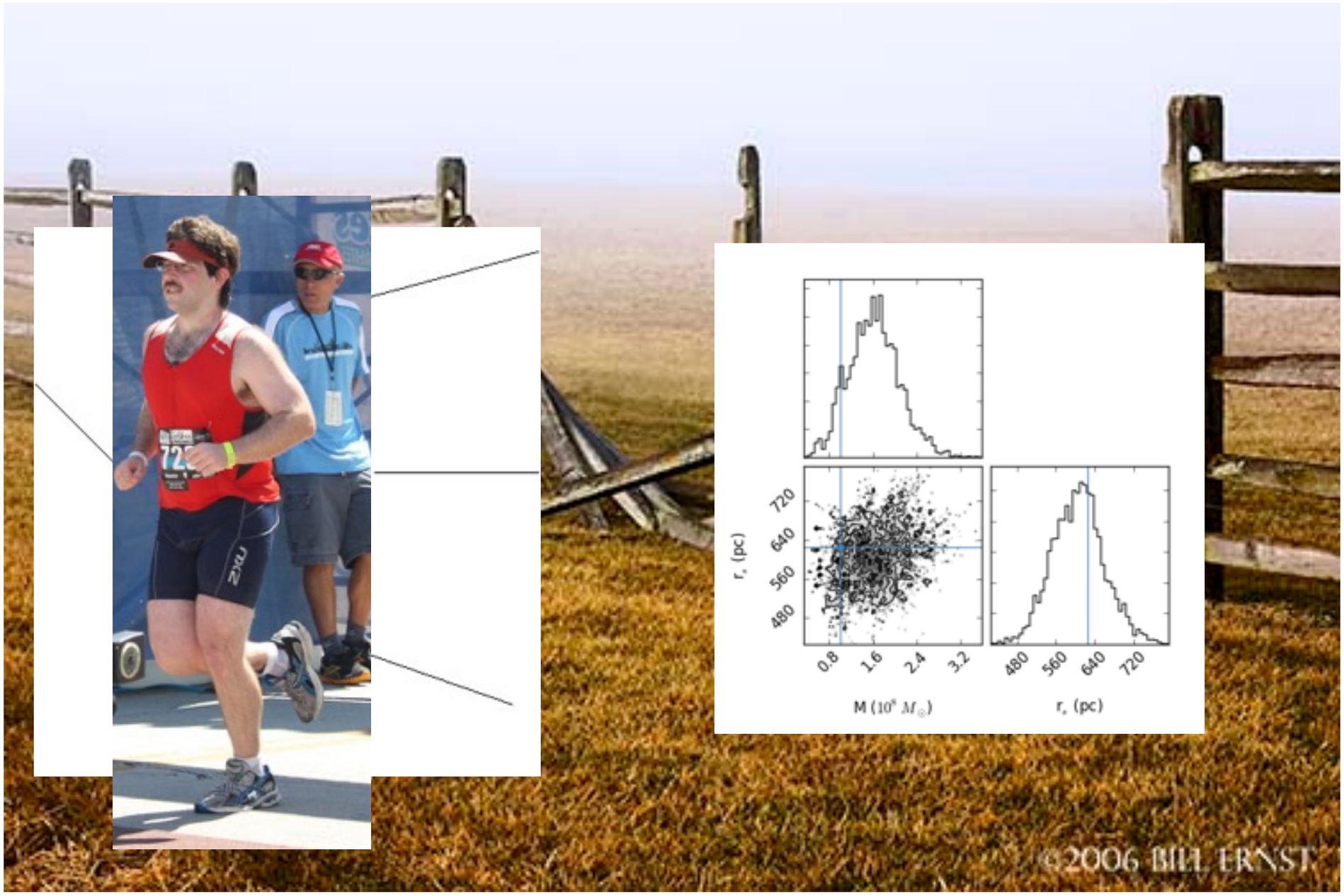
- Best case scenario: just need shape of stream on sky and radial velocities along stream

- Worst case scenario: need proper motions and distance gradient in gap

But how might one do this in reality?

- Numerical model for stream
- Numerically evaluate kicks from subhalo (NFW…)
- Numerically evaluate subsequent evolution
- Marginalize over uncertainties in potential, …
- Use stream model to constrain epicyclic feathering
- In short: very carefully

Conclusions



At least for circular fences and subhalos down to $10^{7.5}$ M⊙