The Nature and Orbit of the Ophiuchus Stream

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with

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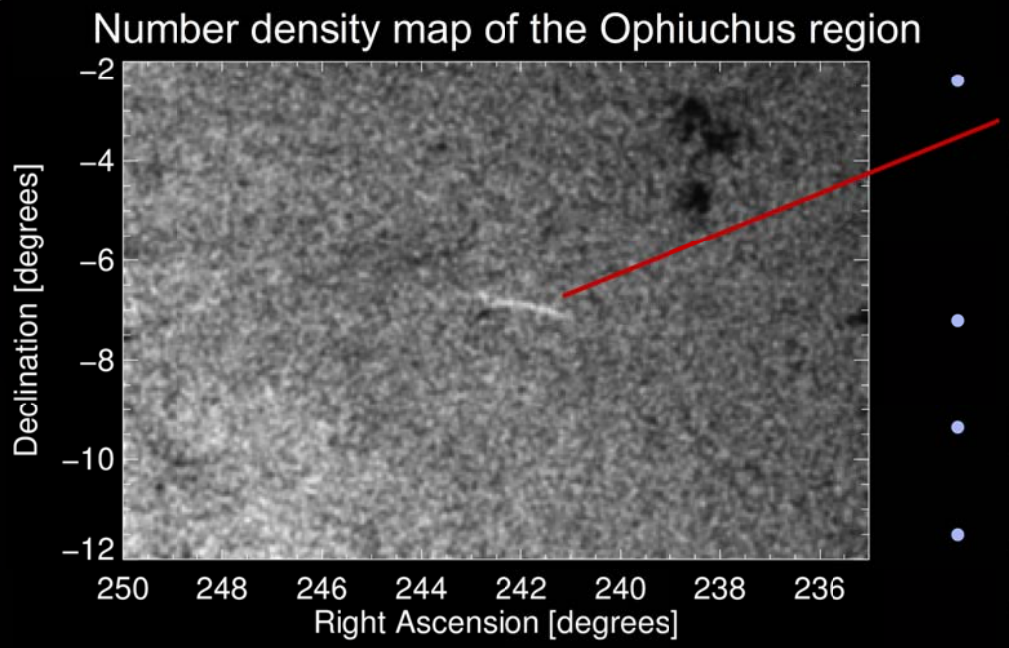
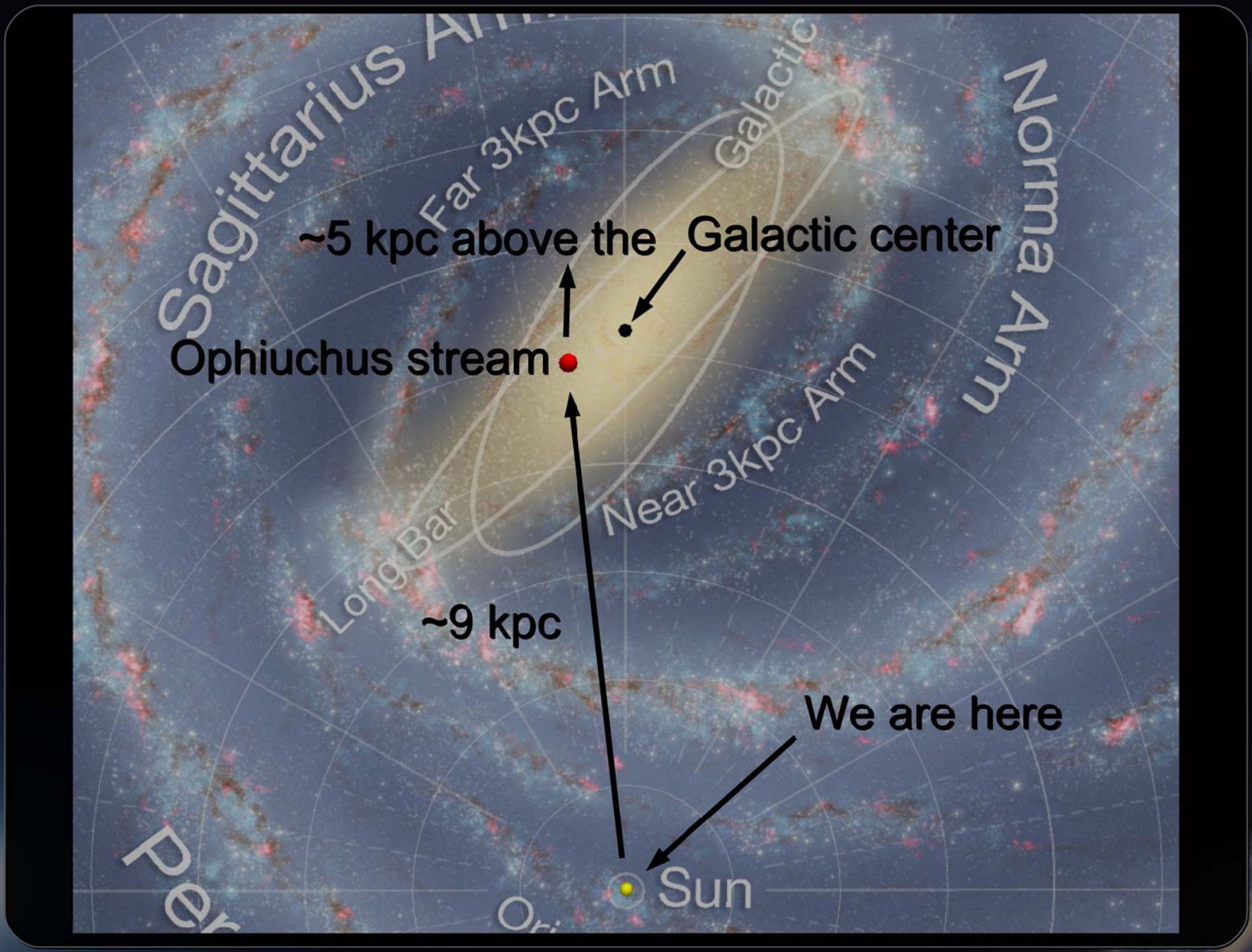
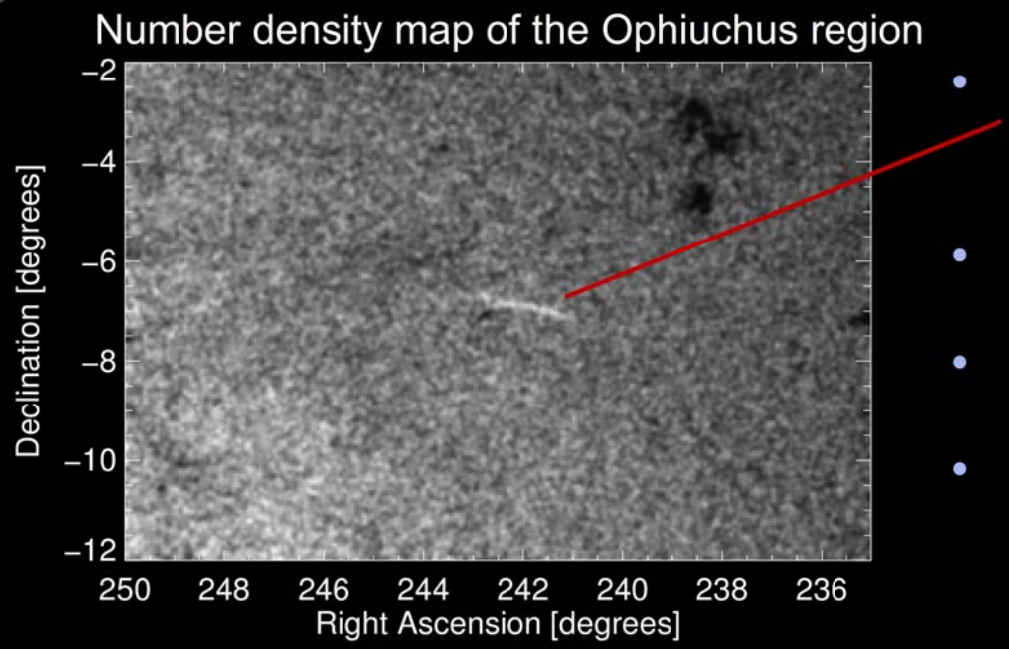
Introduction



- Discovered in the PanSTARRS1 (PS1) photometric catalog (Bernard et al. 2014)
- Old stellar population (>10 Gyr)
- Metal-poor ([Fe/H] ~ -1.3 dex)
- Apparently thin (17 pc) and short (~370 pc)


Sagittarius Arm
Far 3Kpc Arm
Galactic
Norma Arm
~5 kpc above the
Galactic center
Ophiuchus stream
Near 3Kpc Arm
Long Bar
~9 kpc
We are here
Sun

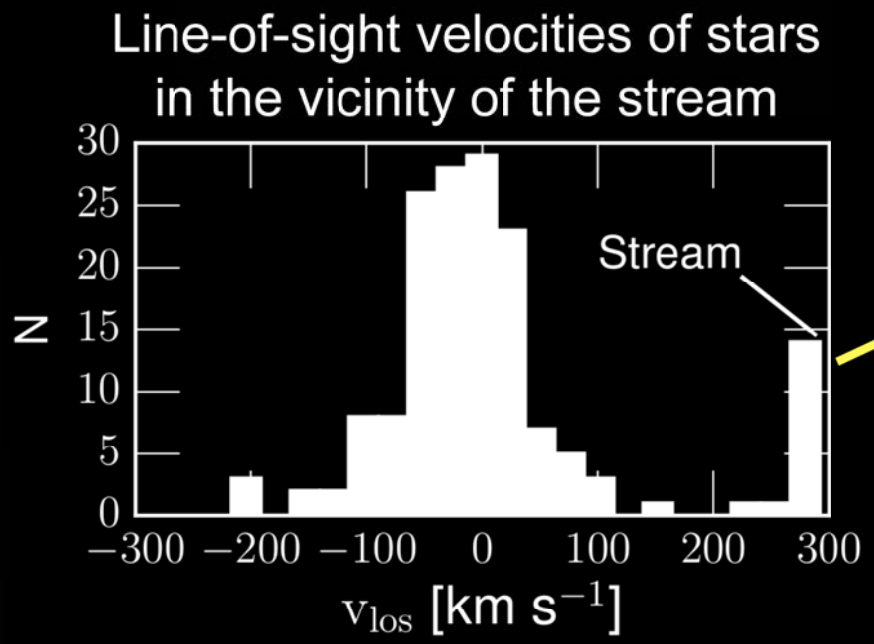
Unsolved Puzzles



- Discovered in the PS1 photo. catalog (Bernard et al. 2014)
- Old stellar population (>10 Gyr)
- Metal-poor ([Fe/H] ~ -1.3 dex)
- Apparently thin (17 pc) and short in projection (~370 pc)

- Unsolved puzzles:
  - Shortness of the stream: recently disrupted or viewing angle?
  - No visible progenitor
  - Need to know the orbit → need velocities, distances, and proper motions

Line-of-Sight Velocity

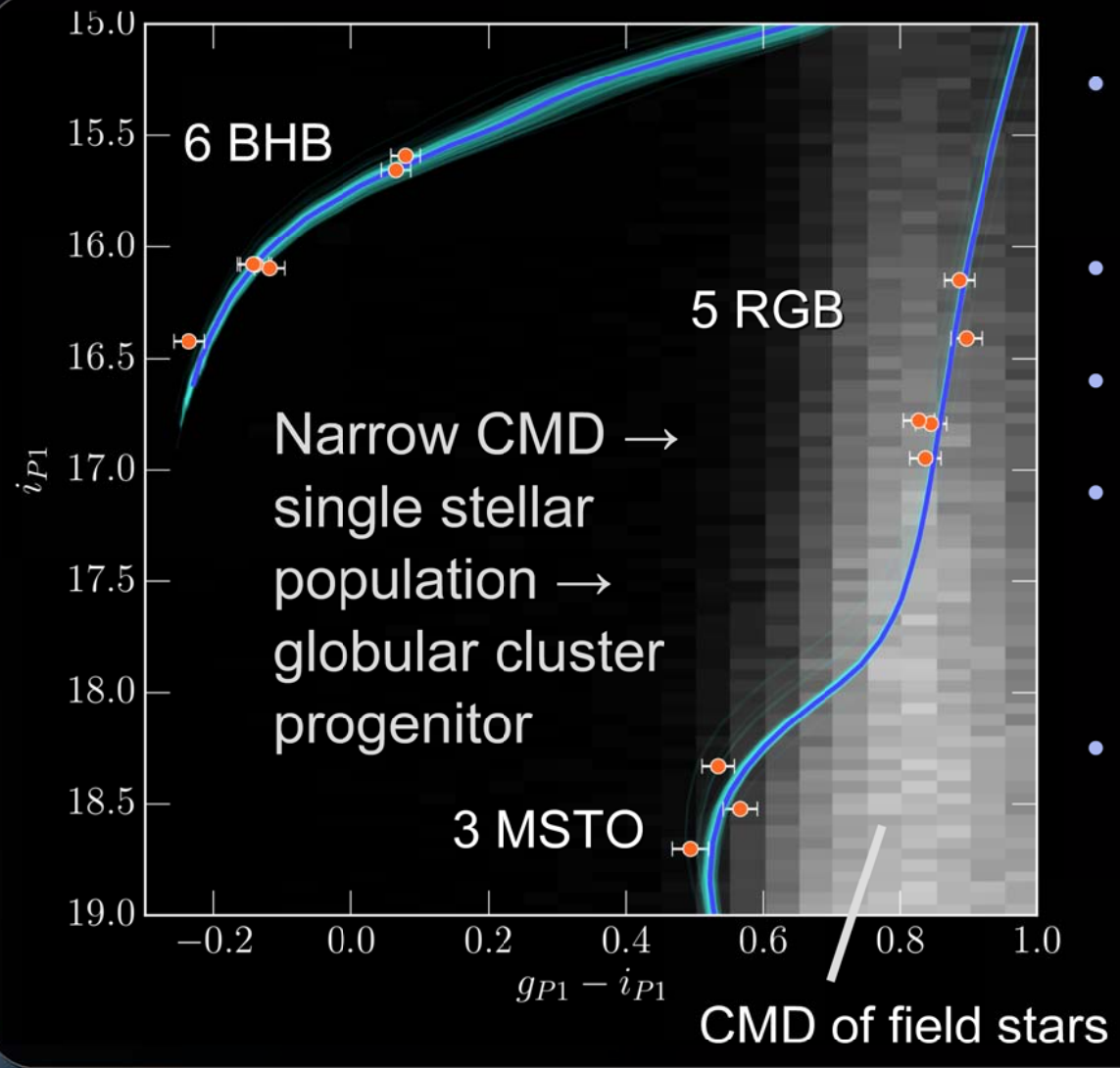


- Precise velocities (< 2 km/s)
- Identified 14 members (6 BHB, 5 RGB, 3 MSTO stars)
- Receding at v_{los} ~ 290 km/s and has a velocity gradient of 4±1 km/s/deg
- velocity dispersion < 0.5 km/s → kinematically cold stream
- α-enhanced, [Fe/H] = -2 dex, < 0.05 dex scatter in [Fe/H] → single stellar population (globular cluster progenitor)

Distance

- Fit CMD using 14 confirmed members
- Model with 8 parameters

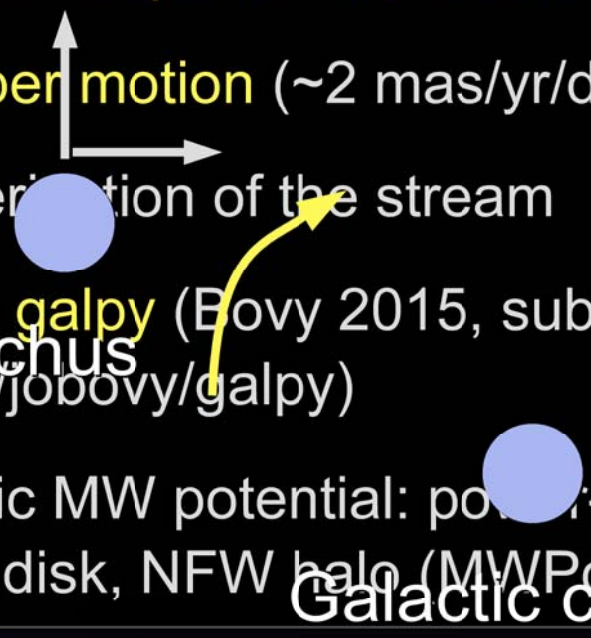
Distance



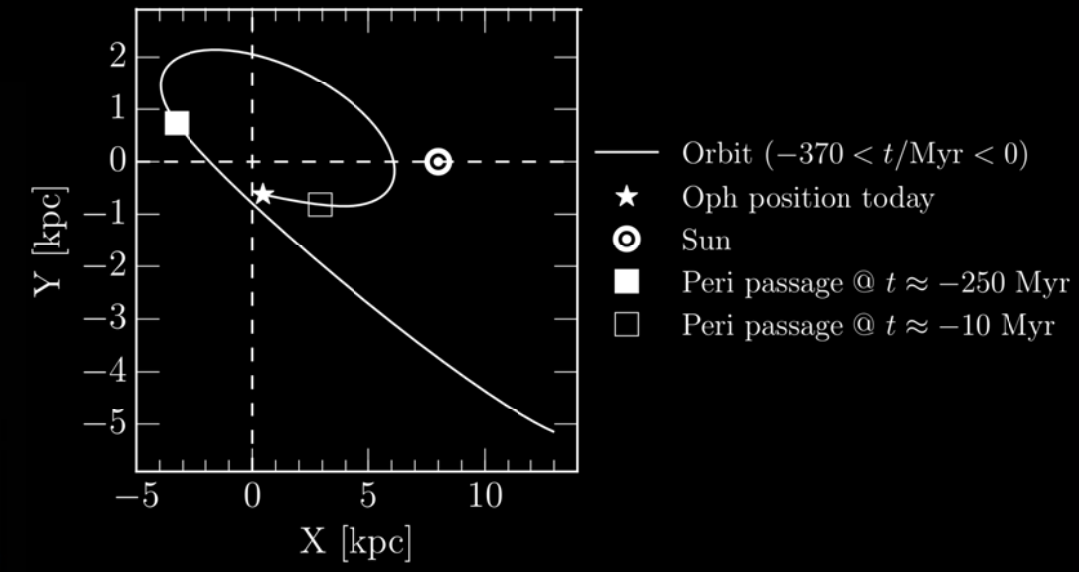
- Fit CMD using 14 confirmed members
- Model with 8 parameters
- Age: 12.7±0.3 Gyr
- Gradient in distance modulus (-0.23±0.03 mag/deg)
- Stream extends from 8 to 9.5 kpc in distance → 1.6 kpc long, not 370 pc!

Proper Motion and the Orbit of the Stream

- Proper motions: PS1 + 2MASS + recalibrated (using PS1) USNO-B catalog positions → precision of 2 mas/yr
- Use all stars in the vicinity that match the position and CMD of the stream (a probabilistic model with 20 parameters)
- Moving away from the plane and towards the Galactic center
- Gradients in proper motion (~2 mas/yr/deg, signif. at >2.5σ level)
- Full 6-D characterization of the stream
- Orbit fitting using galpy (Bovy 2015, submitted to ApJ; http://github.com/jobovy/galpy)
- Assume a realistic MW potential: power-law bulge with a cutoff, Miyamoto-Nagai disk, NFW halo (MWPotential2014 in galpy)

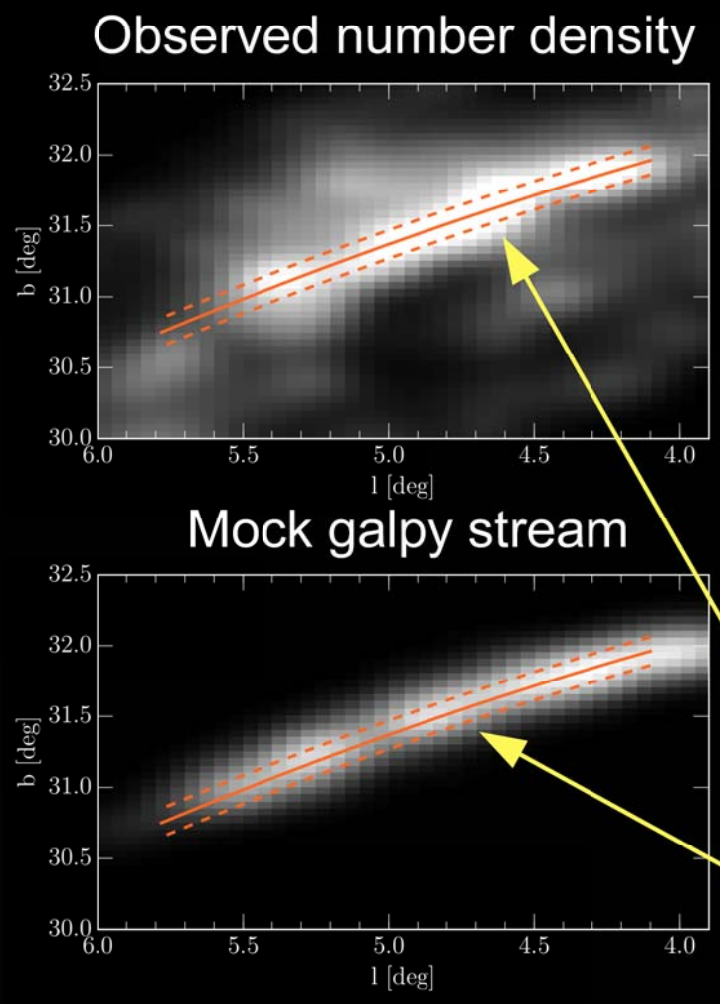


Orbit of the Ophiuchus Stream



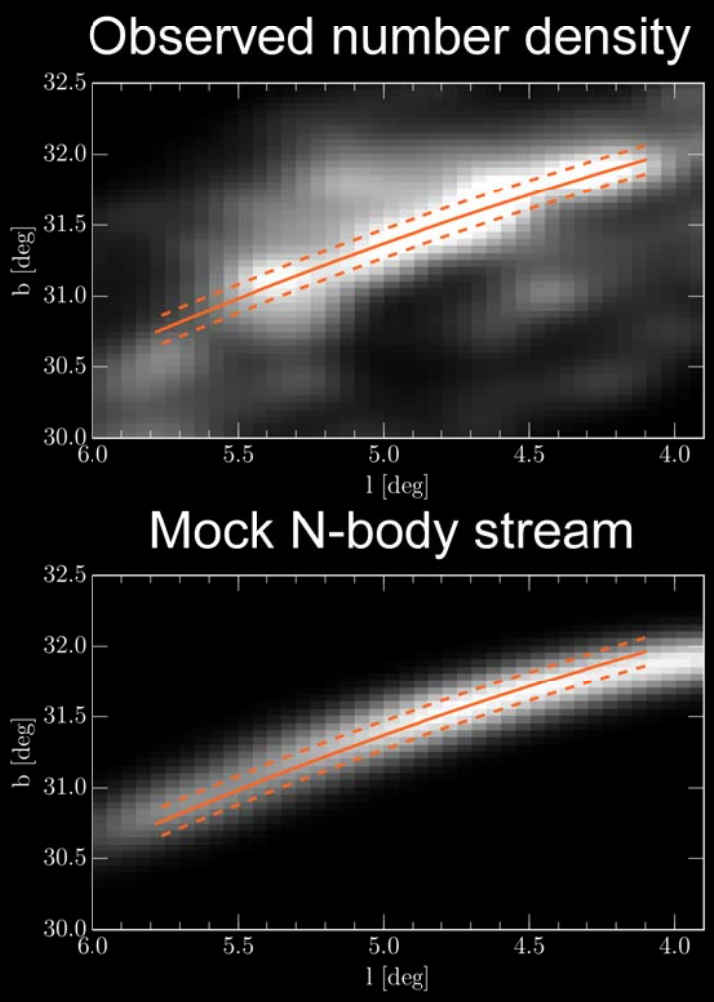
- Pericenter: 3.5 kpc
- Apocenter: 17.5 kpc
- Eccentricity: 0.67
- Periods: 360 Myr (orbital), 245 Myr (radial), 356 Myr (vertical)

Time of Disruption and Dynamical Mass



- Mock stream: need to adopt values for velocity dispersion σ_v and time of disruption t_{dis}
- For a fixed σ_v, t_{dis} proportional to length
- Good match for $\sigma_v \sim 0.4$ km/s, $t_{dis} \sim 170$ Myr
- Disrupted during the last disk+pericenter passage (~250 Myr ago)
- $\sigma_v \sim 0.4$ km/s $\rightarrow M_{dyn} \sim 2 \cdot 10^4 M_{sun}$
- No detectable progenitor

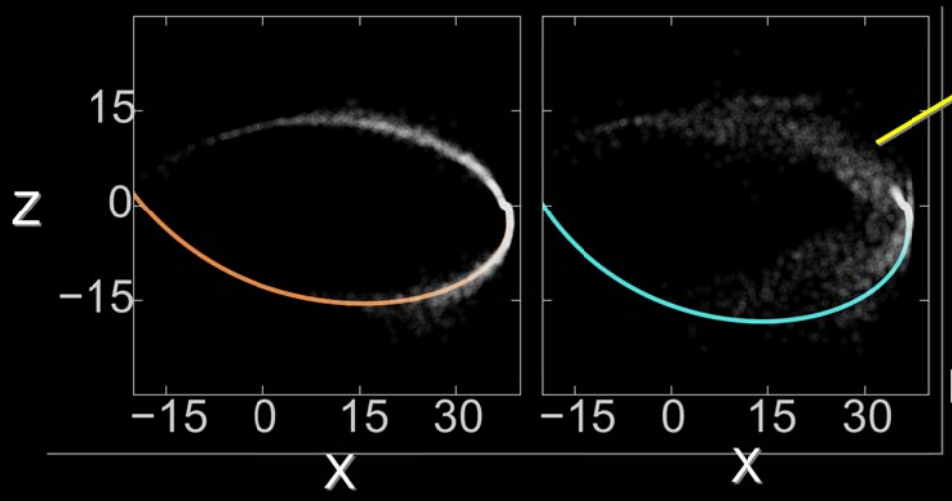
Where is the progenitor?



- Mock N-body stream (gyrfalcON, Dehnen 2000)
- Conditions: match width, length, and no detectable progenitor
- $M \sim 10^4\ M_{sun}$, $r_{tidal} \sim 90$ pc
- Stream is the progenitor
- $t_{evolve} < 400$ Myr → less than 400 Myr on this orbit
- Orbit change? Not likely.

Stream on a Chaotic Orbit or a Clumpy Dark Matter Halo?

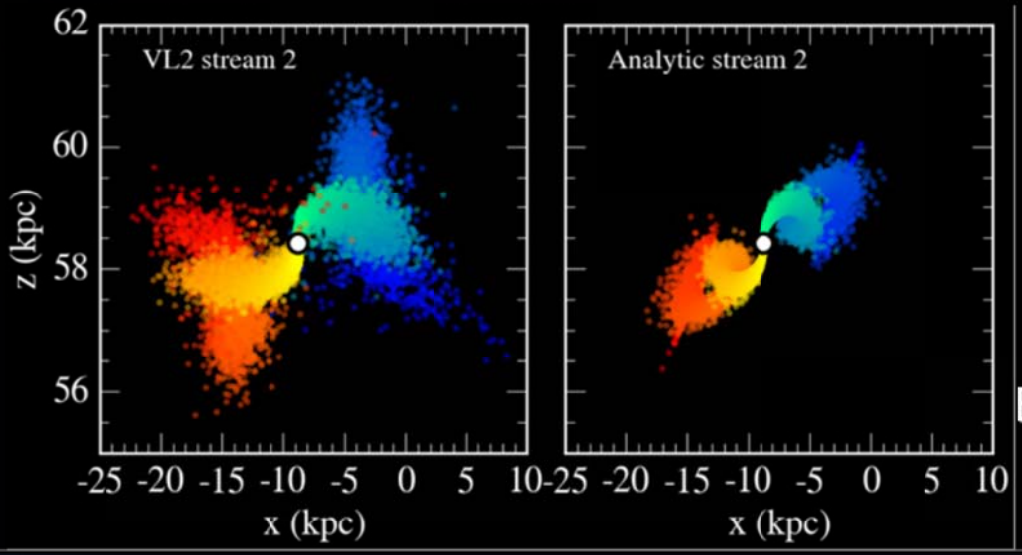
Mildly chaotic orbit



Diffuse tails

Strongly chaotic orbit

Price-Whelan (in prep)



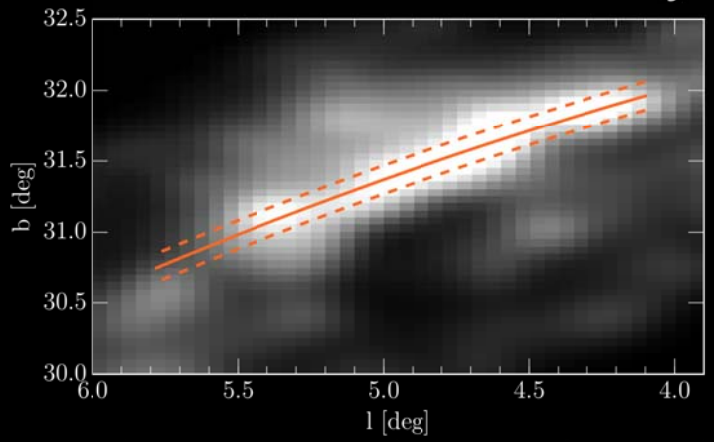
Bonaca et al. (2014)

Take-Home Messages

- We have fully characterized the Ophiuchus stream in position, kinematics, and color-magnitude space
- Progenitor: globular cluster ($M \sim 2 \cdot 10^4\ M_{sun}$, $r_t \sim 90$ pc)
- Puzzles solved:
  - Why is the stream short? Short due to viewing angle (and recent disruption ~250 Myr ago?).
  - Where is the progenitor? The stream is all that is left of the progenitor.
- New puzzle: Progenitor on the current orbit for ~400 Myr? Not likely. Subhalos altered the stream? Not very likely according to Bonaca et al. (2014). Stream on a chaotic orbit? Possibly.

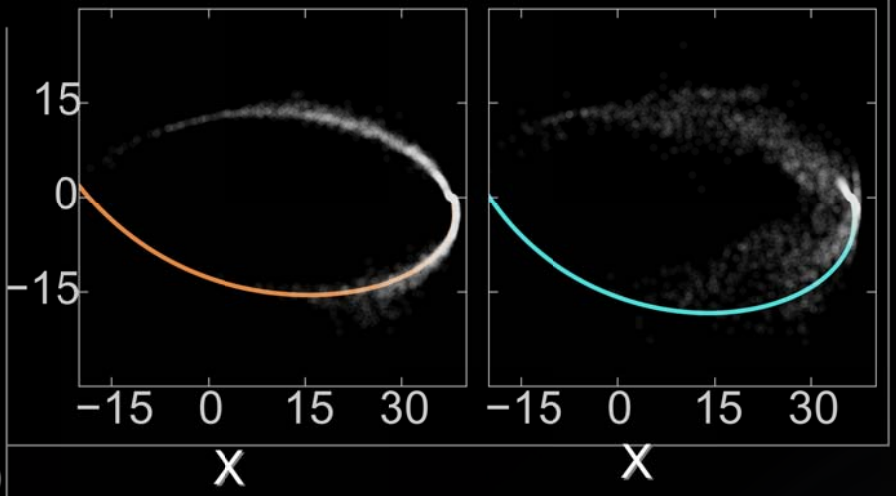
Ophiuchus stream: subhalos, chaos, or...?

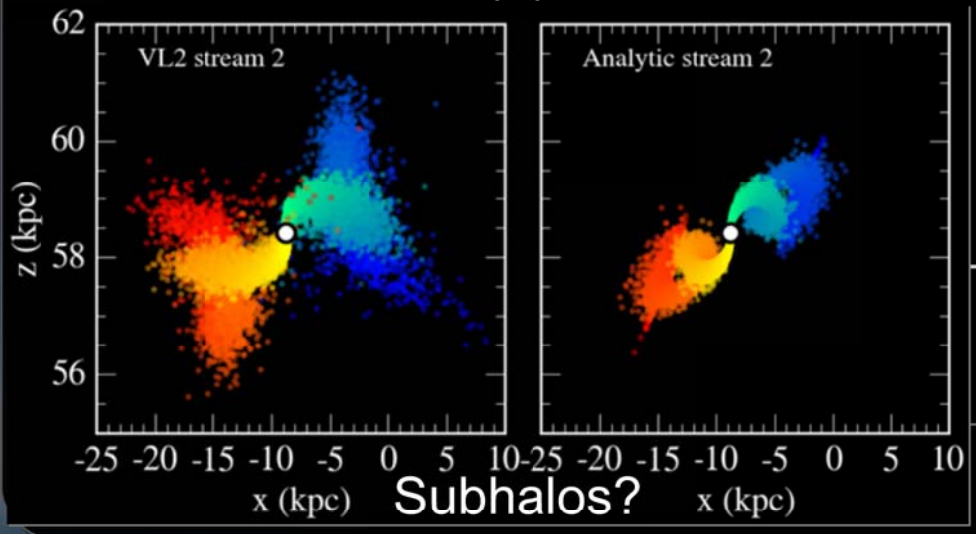
Observed number density



- $M \sim 10^4\ M_{sun}$, $r_{tidal} \sim 90$ pc, $t_{evolve} < 400$ Myr
- Less than 400 Myr on this orbit?

Chaotic?





Subhalos?