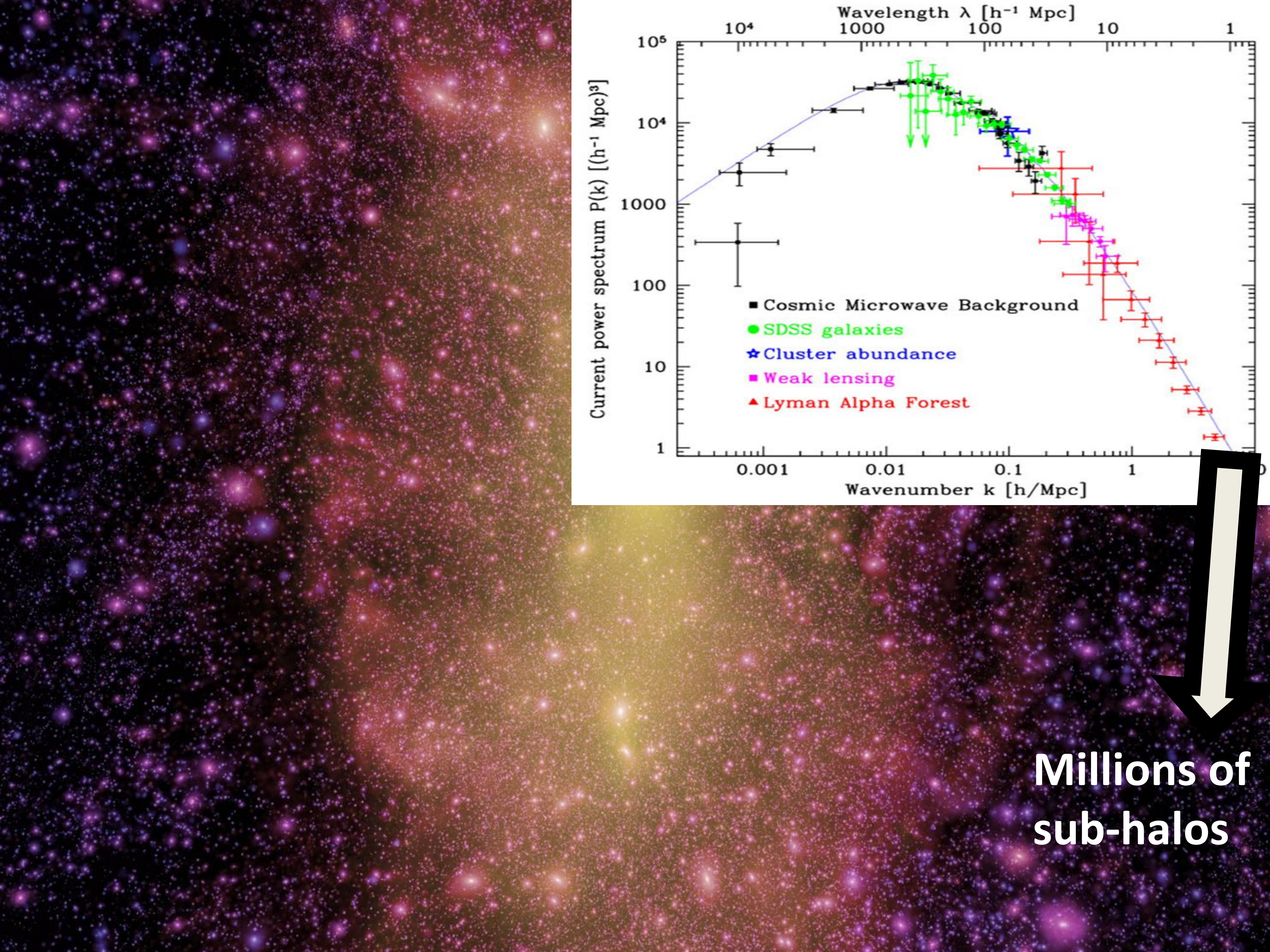
Counting Dark Matter Sub-halos: Gaps in Star Streams


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
10⁵
10⁴
1000
100
10
1
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
Wavenumber k [h/Mpc]
Millions of sub-halos

Sub-Halos

- $N(M) \sim M^{-1.9}$
  - $N \sim 10^6$ for $M > 10^6$ M_sun inside r<~400kpc
  - ~5-10% of the halo mass
  - Most of the mass in the top 30 or so
  - Known dwarf galaxies
- $N_{sub} \sim 1000$ inside 30kpc > 10^6 M_sun
- Sub-halo scale radius ~ $M^{0.43}$
  - Gravitational line scattering cross-section dominated by small masses, $\sim M^{-0.47}$


0.0139

Gap Dynamics

- Distant encounters produce no density changes
- Crossing encounters add and subtract angular momentum nearby
  - Stars pulled forward gain angular momentum, move outward to lower angular rotation rate: stars are donkeys
  - Develops into a gap with removed material folded onto the edge.

Rate of Gaps

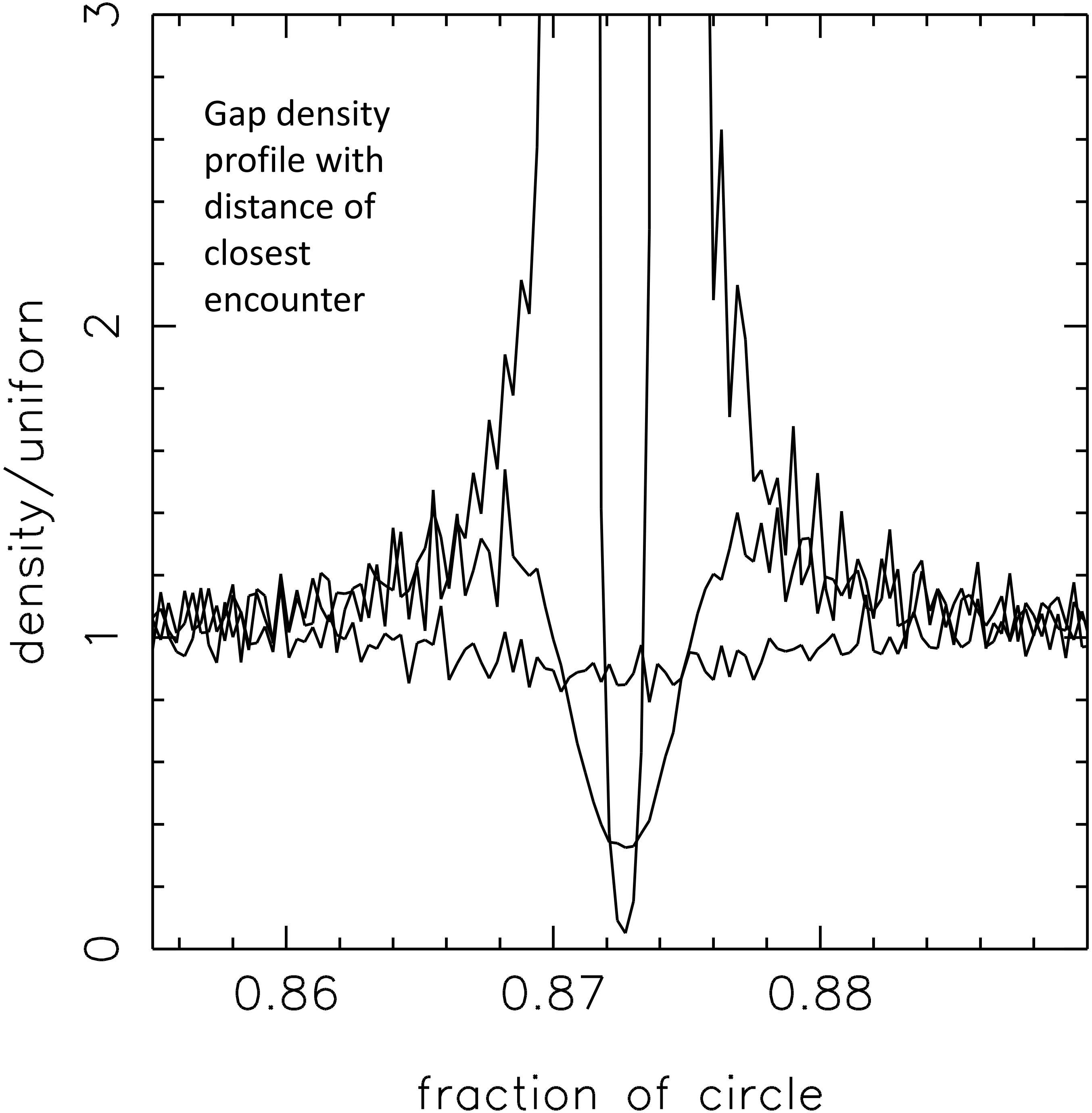
- Rate of Gap Creation: Depends on
  - Density of sub-halos, N(M)n(r) [Aquarius]
  - Rate at which sub-halos cross stream $v_\perp f(v_\perp)$
  - Maximum closest approach that leaves a gap, b
  - Smallest mass halo that leaves a visible gap

$$\mathcal{R}_{\cup}(r) = \int_M \int_{v_\perp} \int_0^{b_{max}} n(r) N(M) v_\perp f(v_\perp) \pi \, db \, dv_\perp \, dM.$$

~10^6 simulations of encounters of sub-halos with streams varying M, b, v, angles.

Results for cold streams apply to streams with width random J_r (radial velocities).

Real streams have some J_θ which can shear away gap.



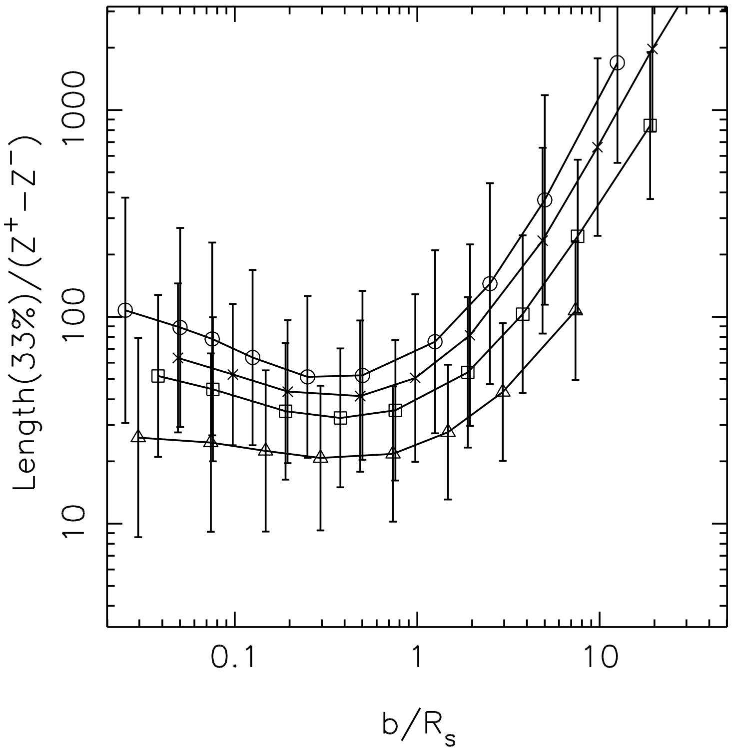
Gap Rate integral with cutoff M

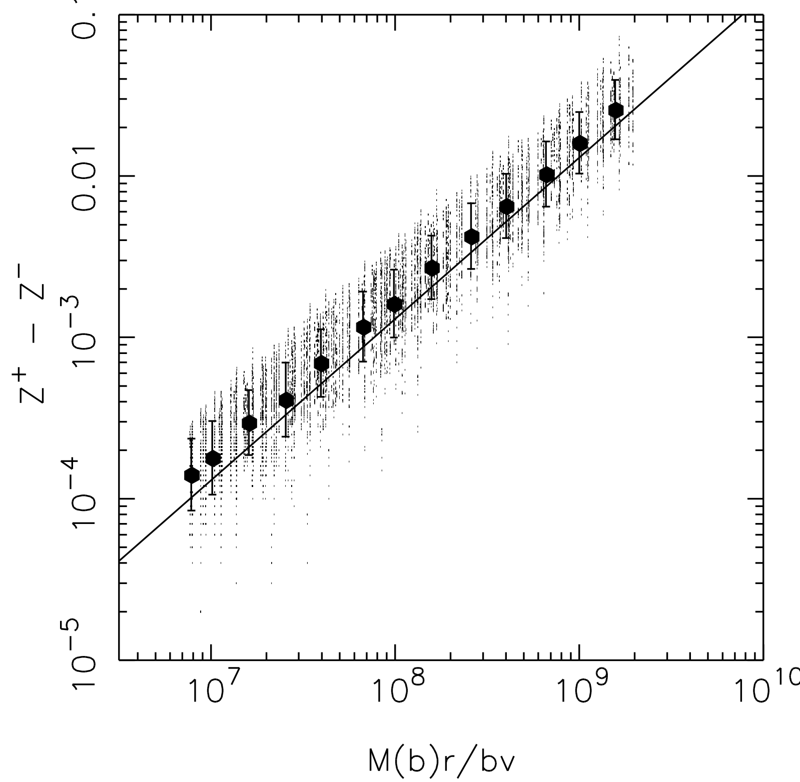
- **$N(M) = n_0 M^{-1.9}$** from Aquarius MW
- M_8 lowest mass sub-halo (x10^8 sun) to make a visible gap

$$\mathcal{R}_{\cup}(\hat{M}, r) = 0.0066 \left(\frac{r}{100\,\mathrm{kpc}}\right)^{0.23} \frac{n(r)/n_0}{6} \times \frac{\sigma}{120\,\mathrm{km\,s^{-1}}} \hat{M}_8^{-0.35}\,\mathrm{kpc}^{-1}\,\mathrm{Gyr}^{-1}$$

Gap lengths = β Δz

z=2GM/bv, b~$M^{0.43}$ (0.8kpc at 10^8 sun)





$$l(M_8) = 8.3\left(\frac{r}{30\,\mathrm{kpc}}\right)^{0.37} M_8^{0.41}\,\mathrm{kpc}$$

GAP RATE vs LENGTH/STREAM WIDTH

- Due to epicyclic motion in stream.
- Width gives M that gives smallest gap
- Smallest gap ~ 1-2.5 x width (1 used below)

A little steeper at small r

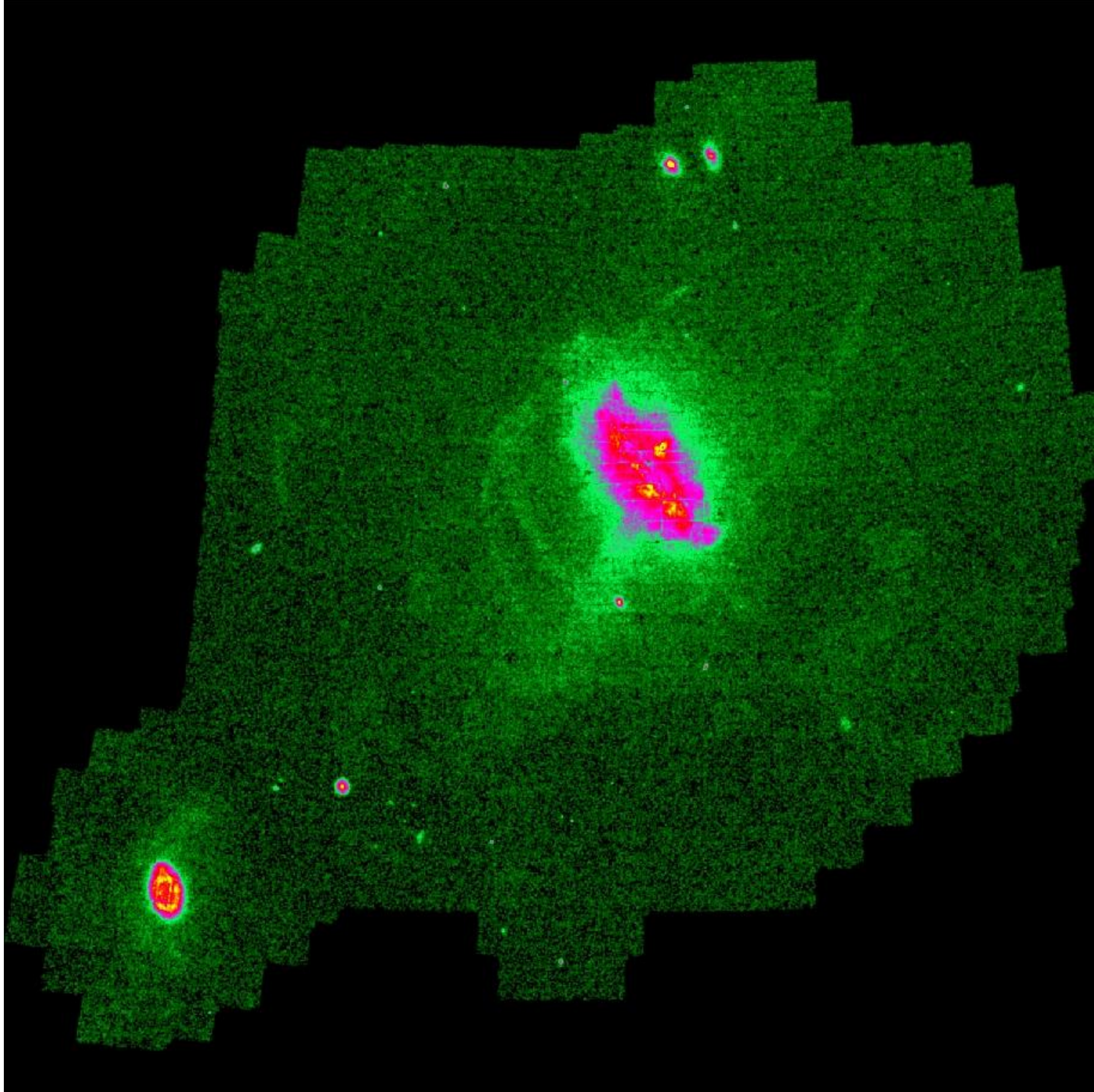
$$\mathcal{R}_{\cup}(w,r) = 0.059 \left(\frac{n(r)/n_0}{6}\right) \times \left(\frac{r}{100\,\mathrm{kpc}}\right)^{0.55} \text{ x } w^{-0.85}\,\mathrm{kpc}^{-1}\,\mathrm{Gyr}^{-1}$$

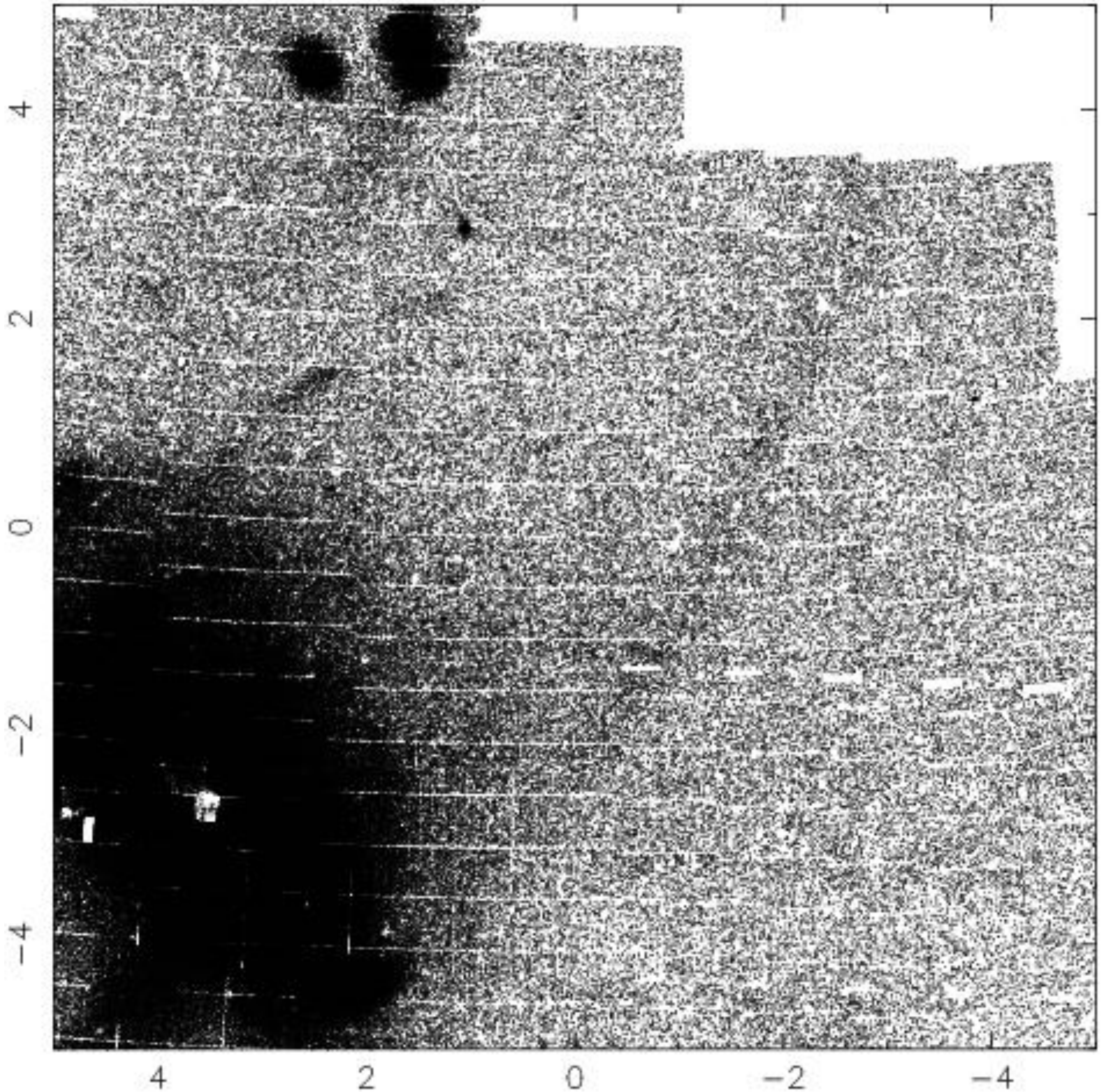
Some real streams

- M31 (Pandas)
- Milky Way streams
  - (mostly with Carl Grillmair)

M31, M33 & Streams
~34mag/sq arcsec

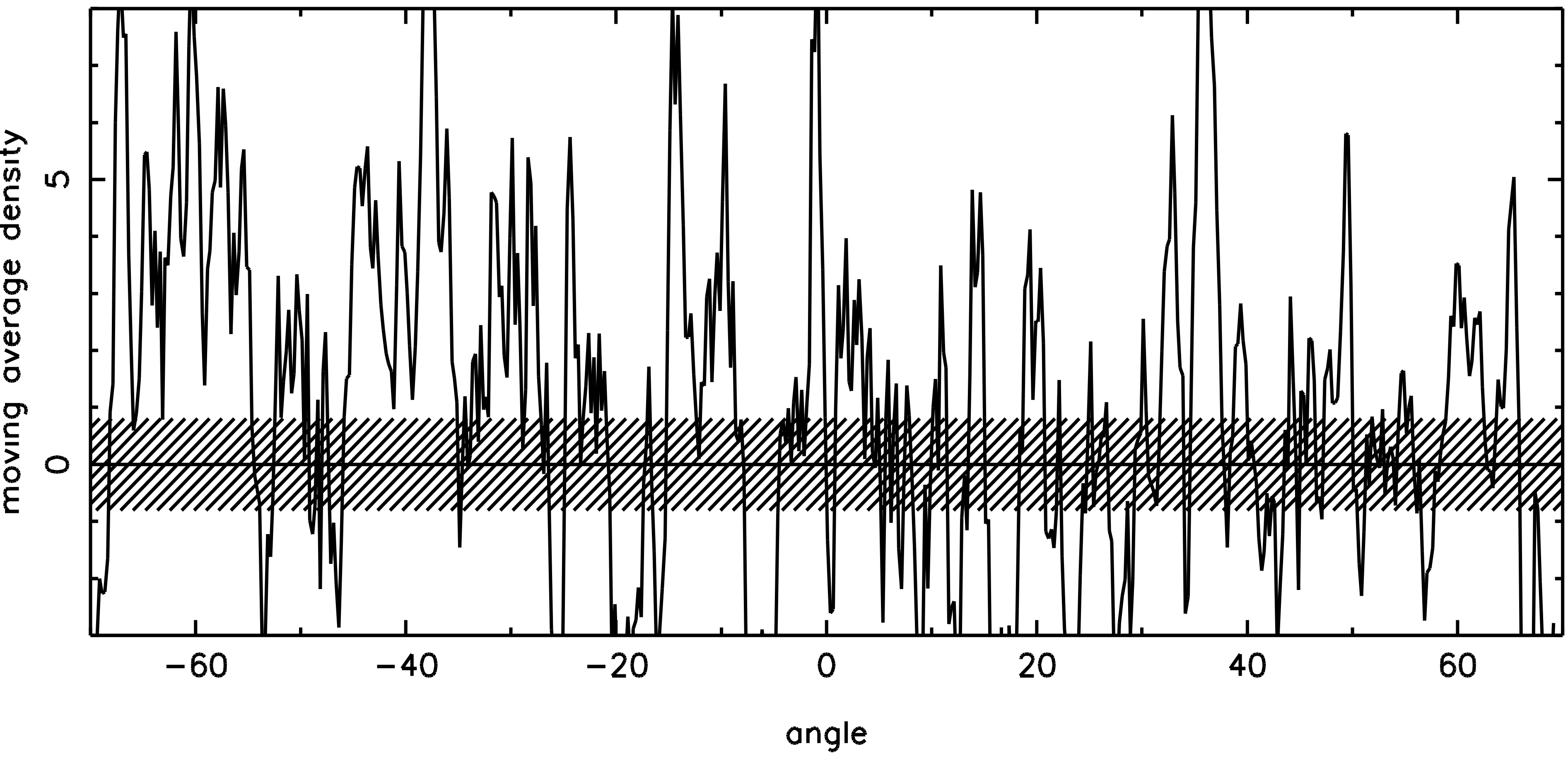
PANDAS





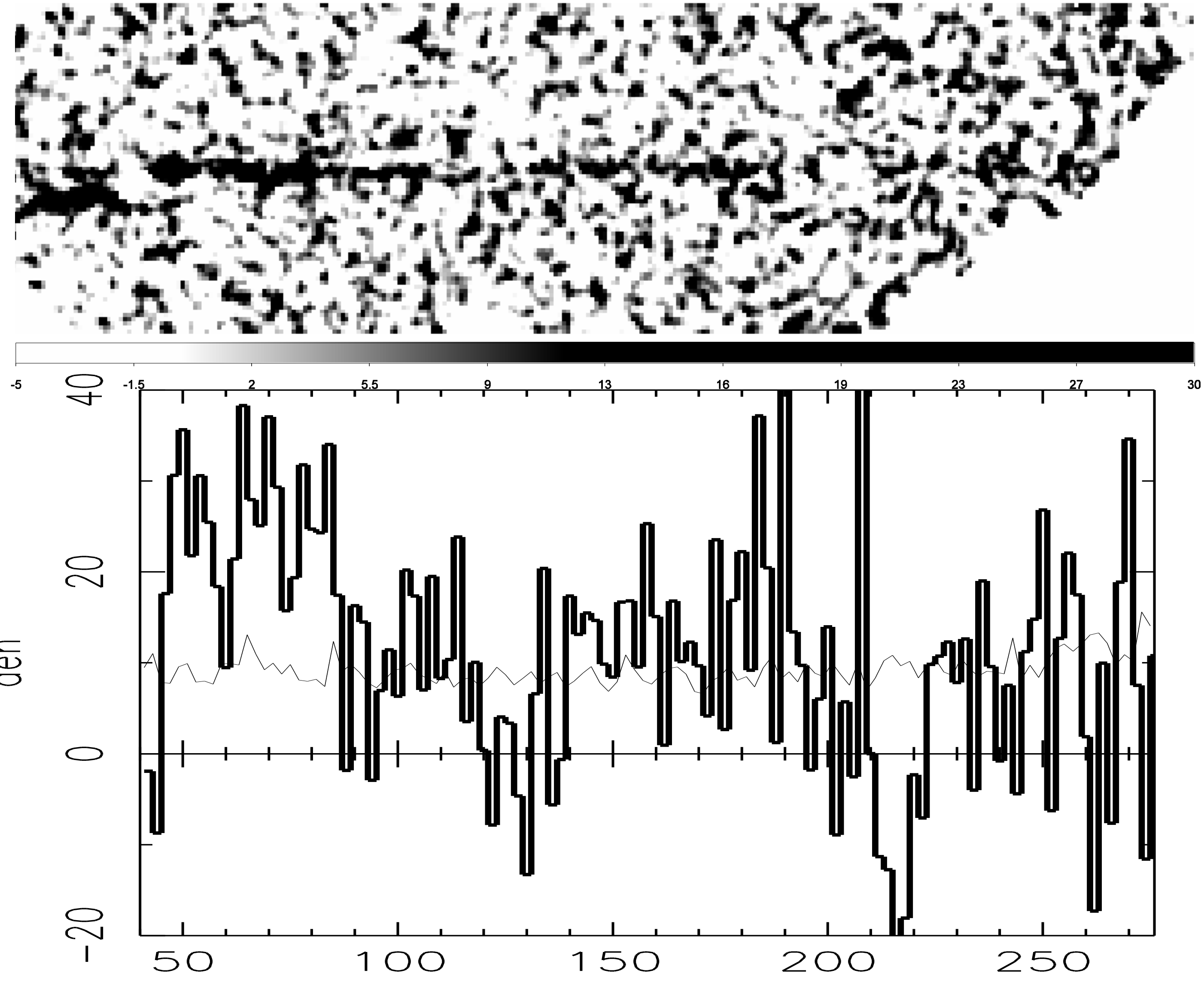
4
2
0
−2
−4
4
2
0
−2
−4

M31: ~12 gaps in ~200kpc

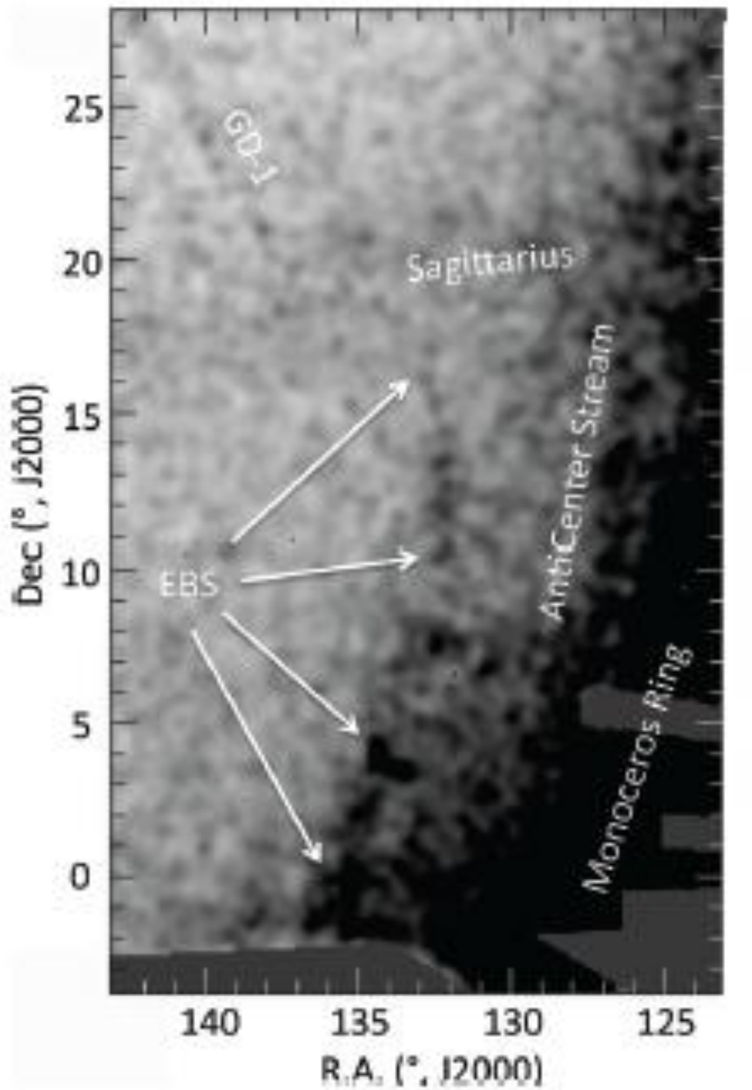


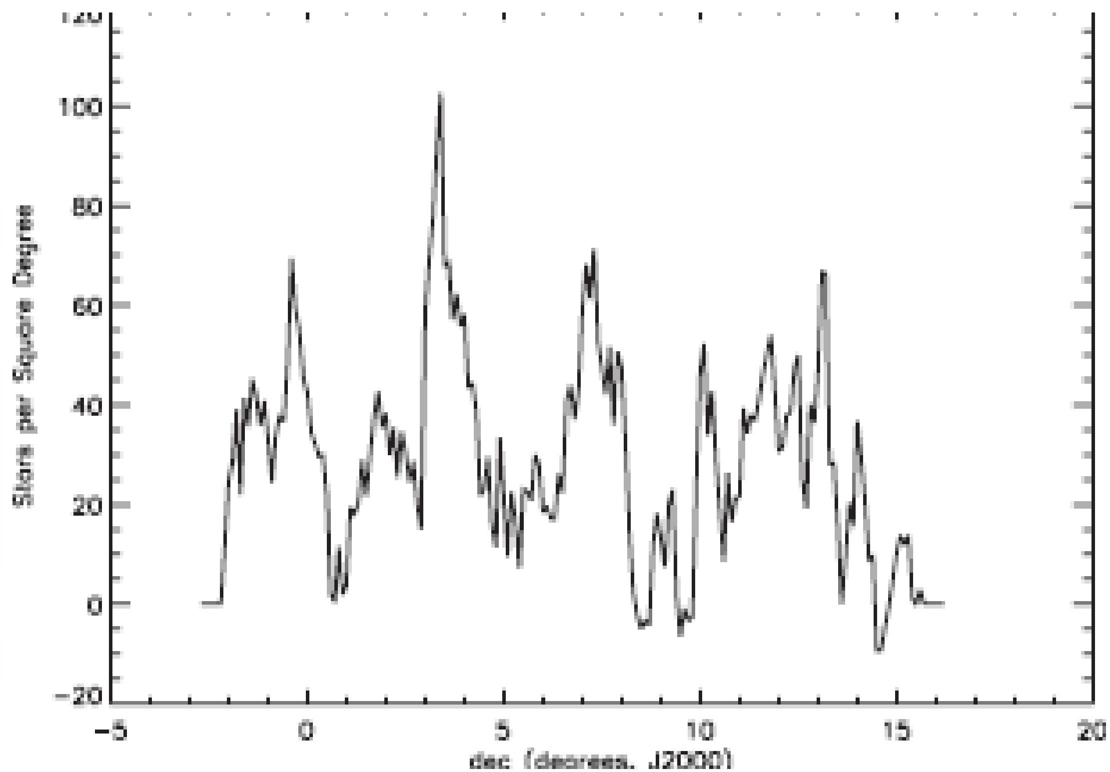
Pal 5: Grillmair/SDSS ~ 16 gaps/16 kpc

DR8:   1 lump + 6 gaps / 22 kpc

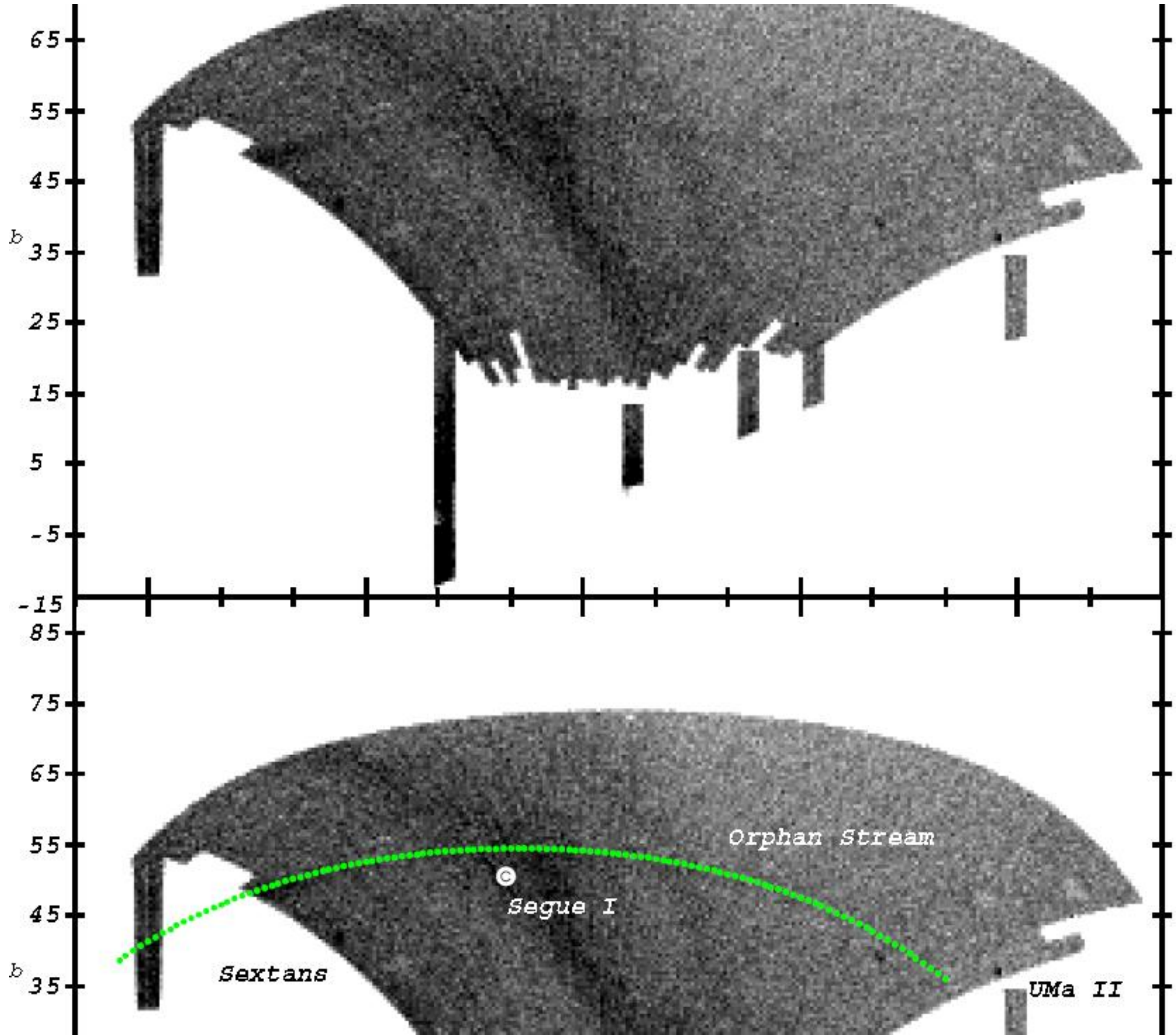


Grillmair: Eastern Banded Structure ~8 gaps/ 16 kpc

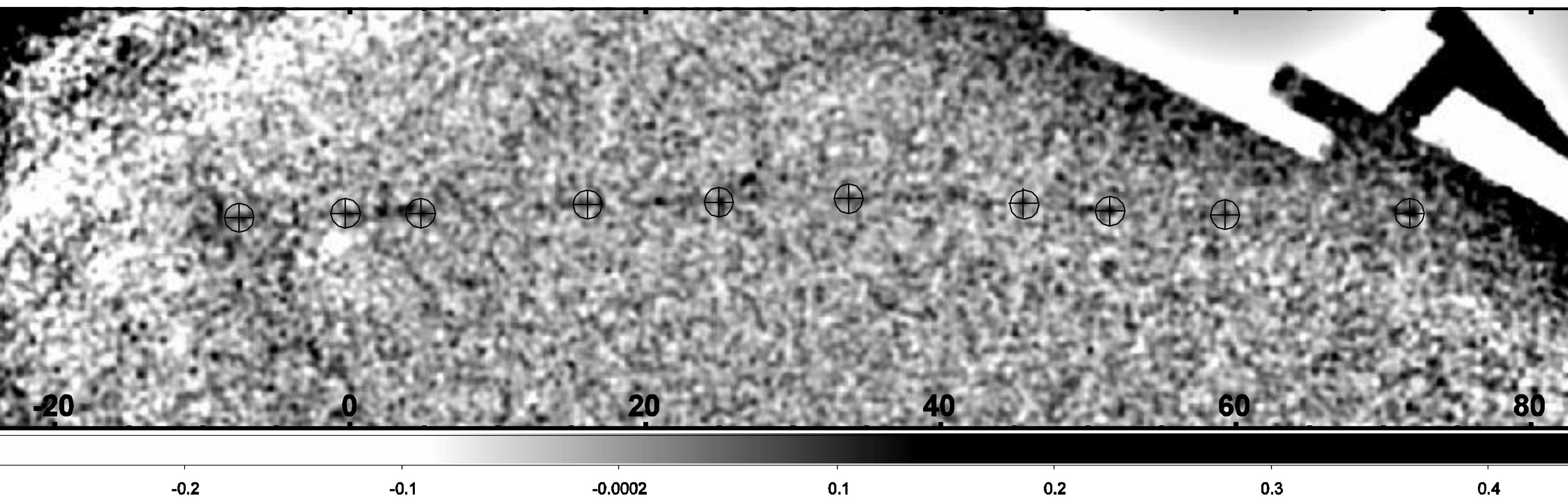


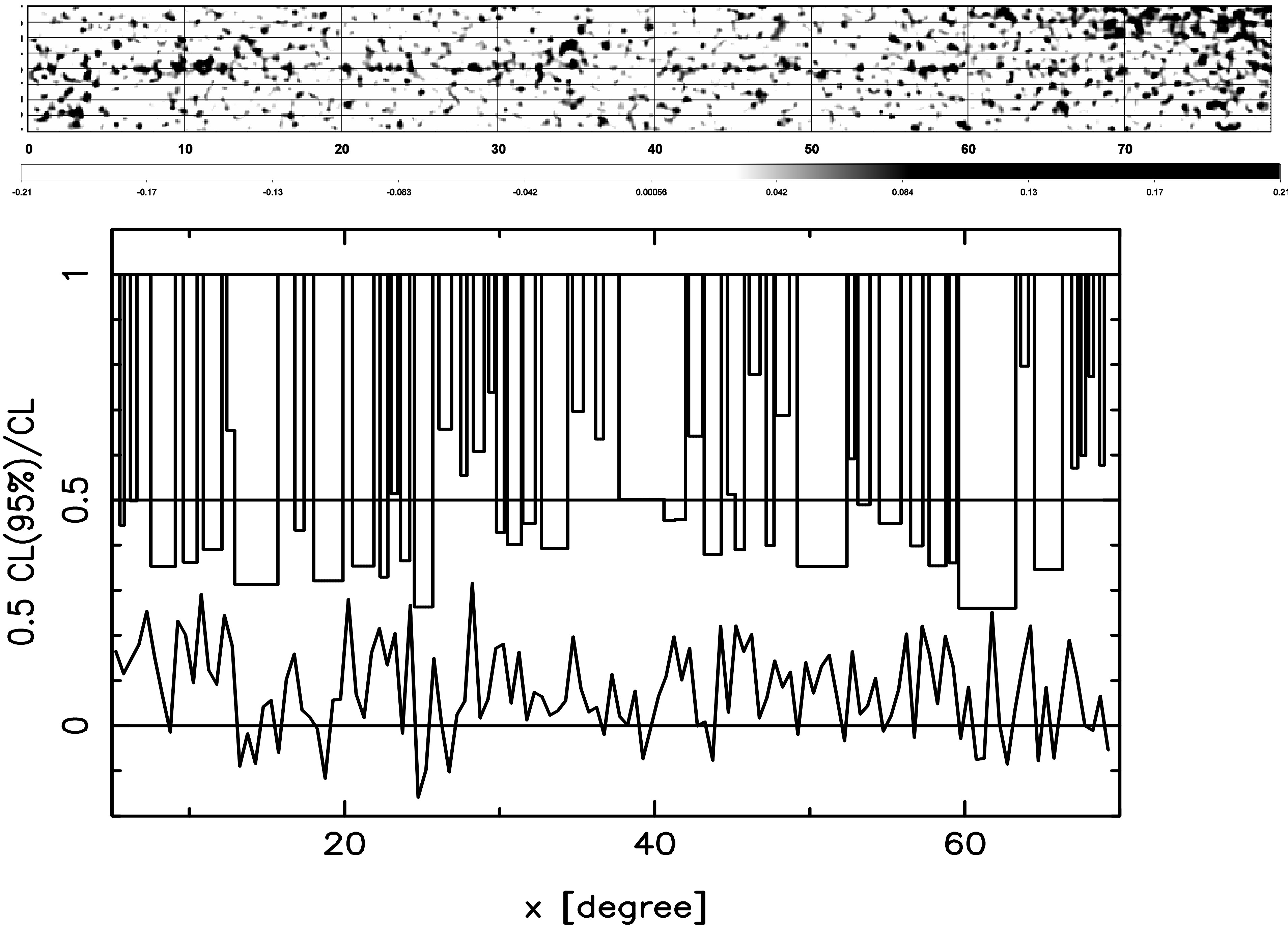


Orphan Stream: 2 gaps?



GD-1:
0.4x100 degrees





0
10
20
30
40
50
60
70
-0.21
-0.17
-0.13
-0.083
-0.042
0.00056
0.042
0.084
0.13
0.17
0.21
0.5 CL(95%)/CL
1
0.5
0
20
40
60
x [degree]

GD-1

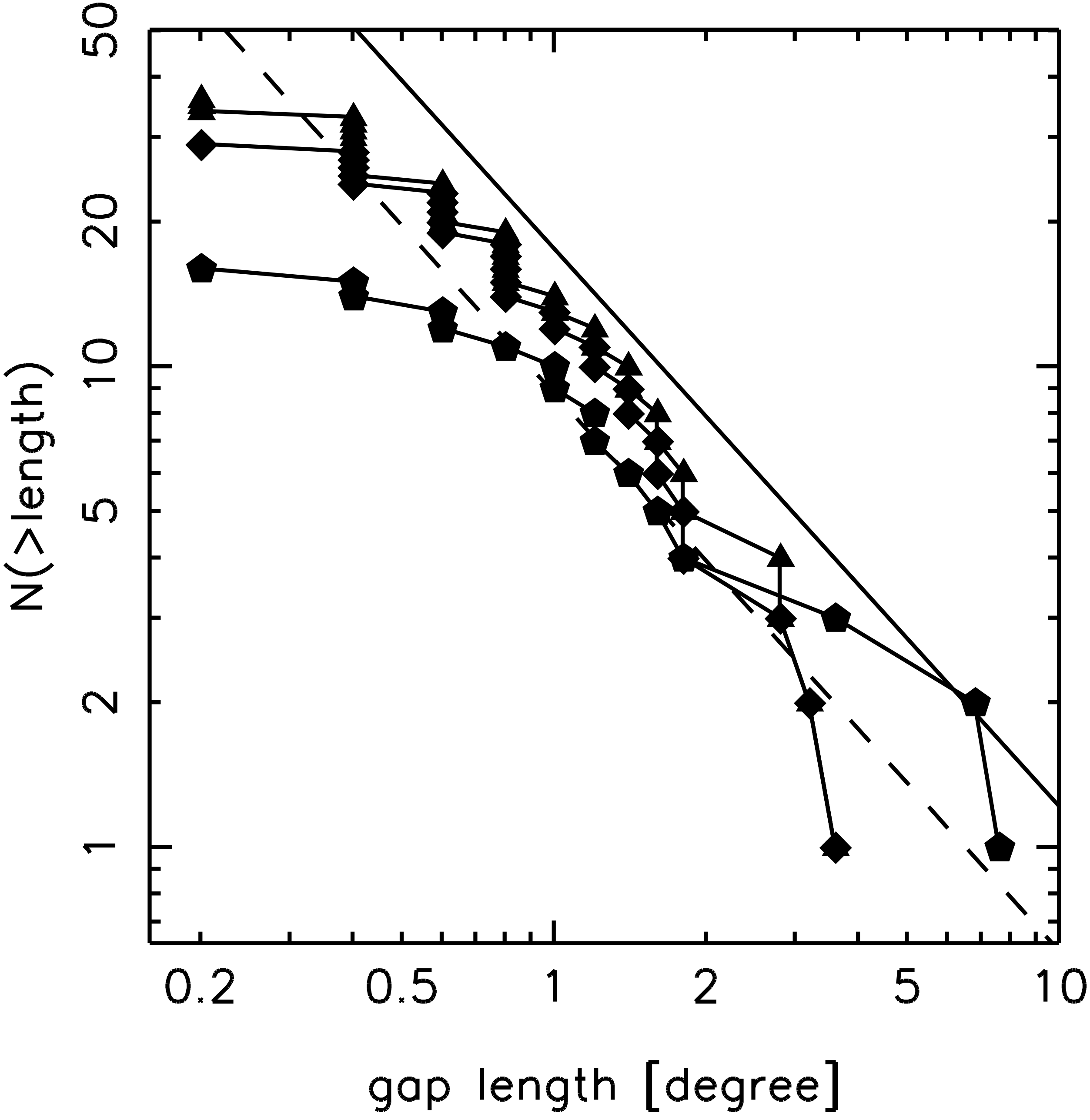
- Narrowest known stream
- Sensitive to smaller mass halos
- 8kpc (close)
- Highest confidence gaps
- Remarkably distribution of gap sizes looks like the LCDM prediction, down to 10^6 M_sun

GD-1

Gap Size Distribution compared to LCDM prediction

at GD-1 1 degree is 0.15 kpc

2×10^6 M_sun

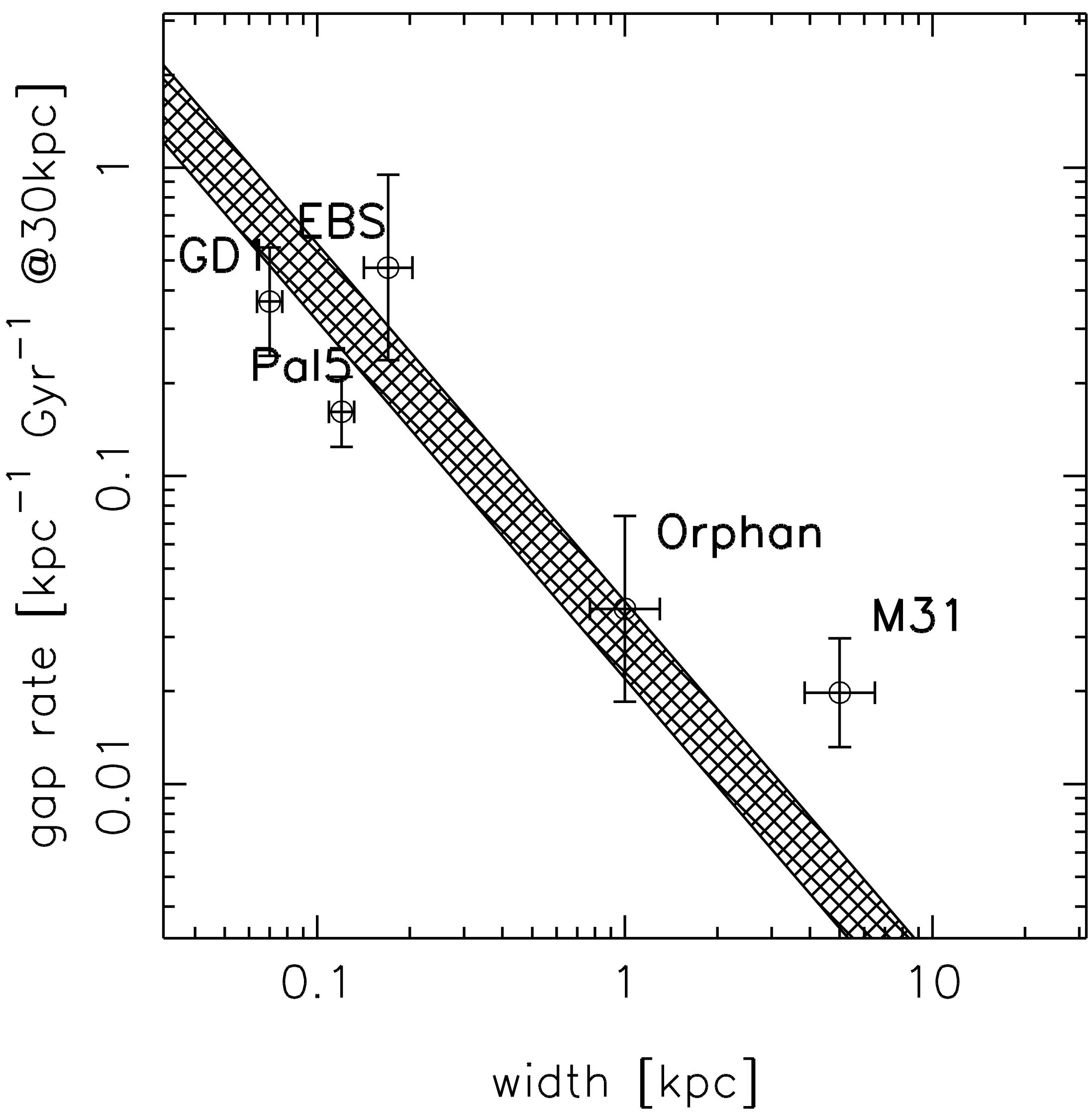


Gaps in Star Streams

Ages 5-10Gyr

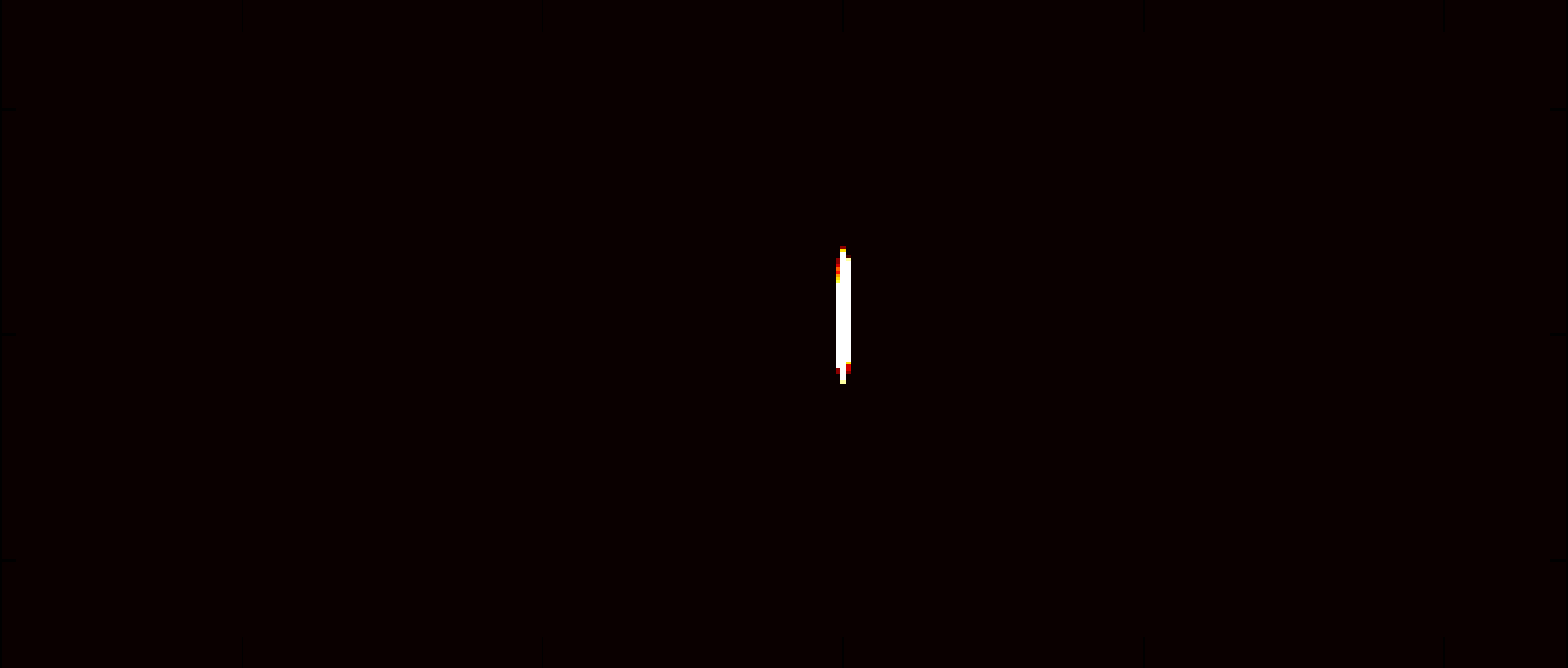
Stream	Gaps	Gaps kpc^{-1} Gyr^{-1}	Width kpc	Galactic radius kpc
M31	12±2	0.012	5	100
Pal5	6±3	0.17	0.2	19
EBS	8±4	0.49	0.17	15
Orphan	2±1	0.037	0.2	30
GD-1	16	0.38	0.07	15

Total Gap-Rate vs Width
(line uses smallest gap 2.5xwidth)



Progenitor object substructure confusion?

- Tidal lobes, pericenter passage, lumps
- Most mix out down the stream
- Generally predict varying 2D structure along the stream, which is not currently detected at large distance (Pal 5 epicycles are seen).



Summary

- Stream gaps are a sub-halo counting tool, sensitive to smallest mass sub-halos
- Basic dynamics clear: detailed simulations underway
- Statistics of gaps improving: much to be done
- Data: SDSS 1/5 sky, relatively shallow but **uniform**
  - Requires ~1000 M>= 10^6 sub-halos <30kpc
  - Implies total MW population ~ 10^5 to 400 kpc r_{50}
- Factor of ~3 agreement with LCDM predictions, although results allow a turndown around 10^6 M_sun scale.