The dynamics of tidal tails

(or how to do cosmology with the Galaxy)

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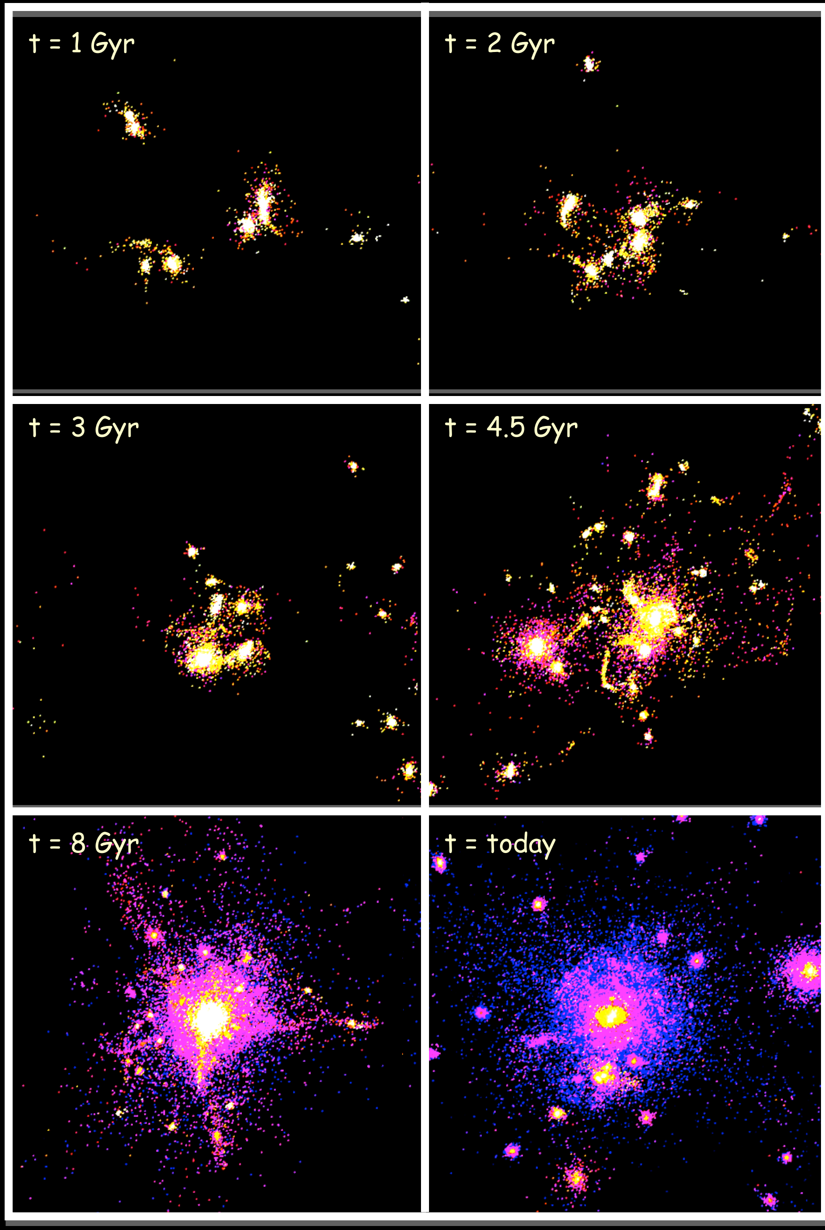
Testing the hierarchical paradigm. I. Mergers

- Stellar halo contains direct imprints of merger history

- Tidal streams/substructures

  We need to find them and understand (model) their behaviour

  - Were mergers important for Milky Way?
  - How often and when did they happen?
  - What do they tell us about the building blocks? What were their properties?



Testing the hierarchical paradigm. II

Is this “picture” correct?

- Are galaxies like the Milky Way embedded in dark matter halos like those predicted by the cosmological model?

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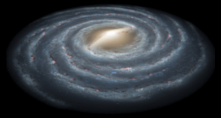

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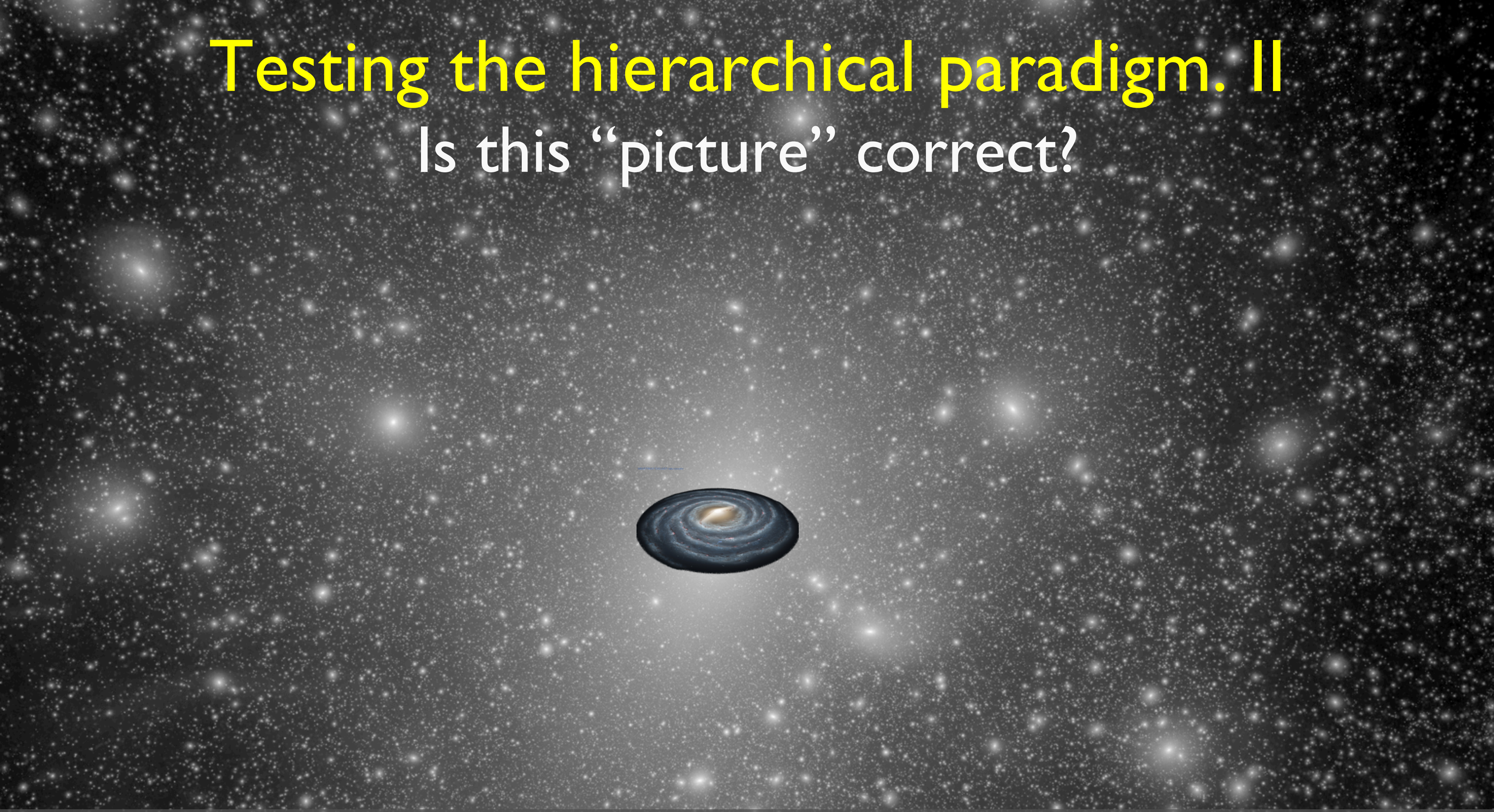
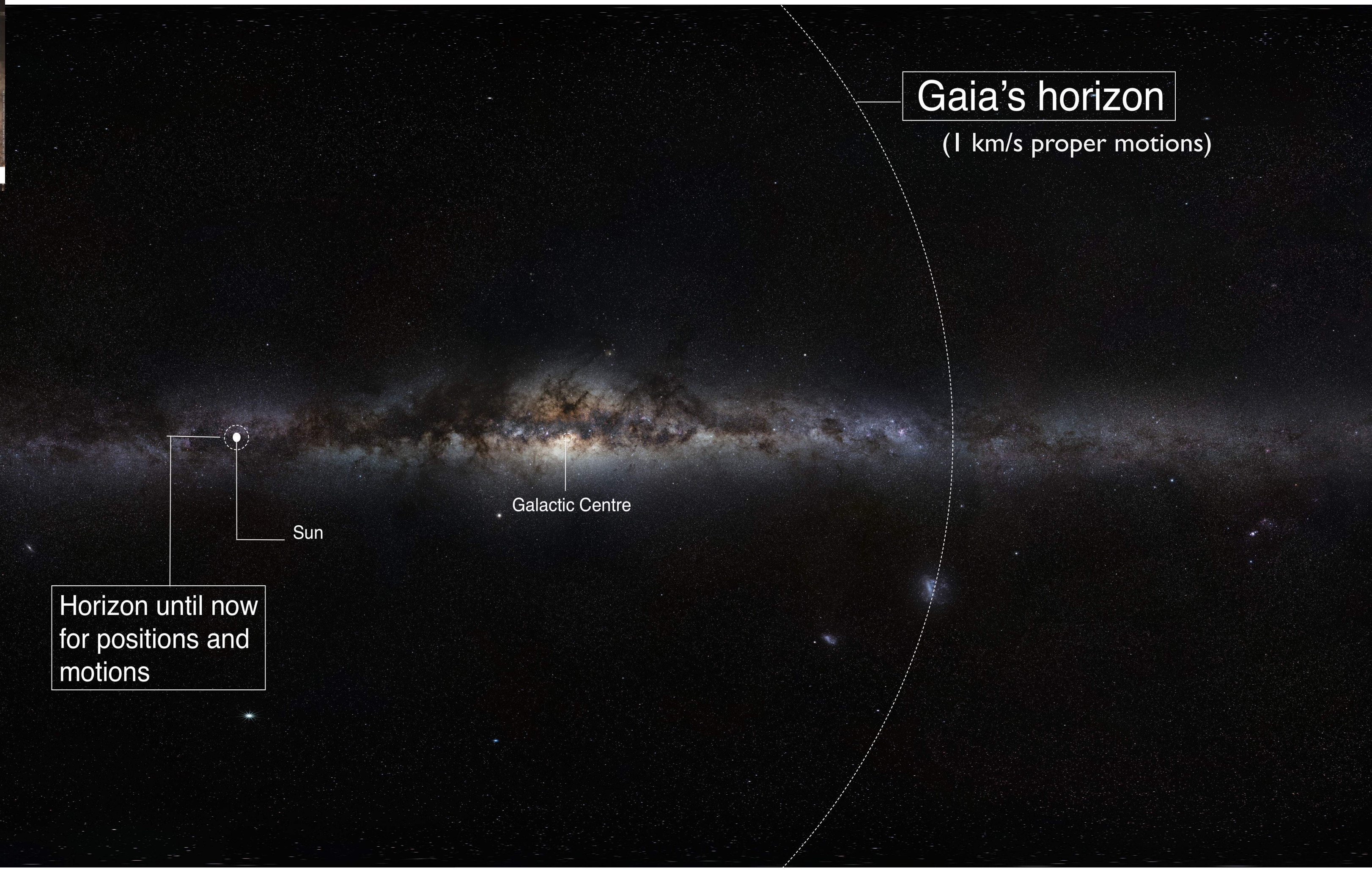


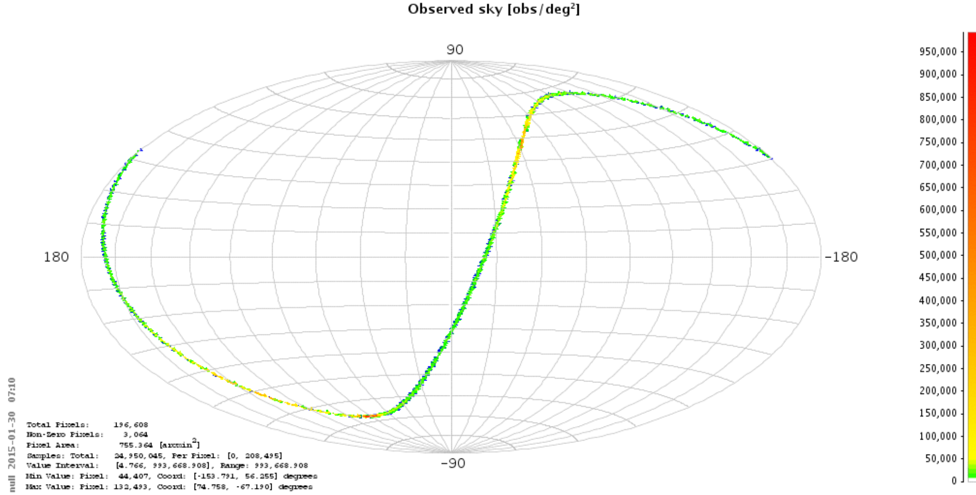
- Are galaxies like the Milky Way embedded in dark matter halos like those predicted by the cosmological model?
- How much dark matter is there?
  - how is it distributed? Shape, density profile, granularity, time-evolution
  - what is the dark matter?

The Gaia revolution: starting now!



Gaia will measure positions and motions of stars for 10^9 stars (10,000 x larger than predecessor); over a volume 100,000 larger; 1,000 more precisely ➔ <u>transformational</u>

- •Simultaneous astrometry, photometry, spectroscopy
- •Complete to G = 20 (V = 20-22), G = 16 for spectroscopy
- •Whole sky already observed!
- •First data release in mid-2016 (positions + G magnitude)
- •DR2 in Jan 2017: full phase-space



up to 21 million objects/deg²

By Jan. 2015, 16 billion photom/astrom transits, 1.6 billion spectroscopic

Performance predictions for G2V star			
V magnitude	Astrometry (parallax)	Photometry (BP/RP integrated)	Spectroscopy (radial velocity)
3 to 12	5–14 μas	4 mmag	
3 to 12.3			1 km s^{-1}
15	24 μas	4 mmag	
15.2			15 km s^{-1}
20	540 μas	60 (RP) – 80 (BP) mmag	

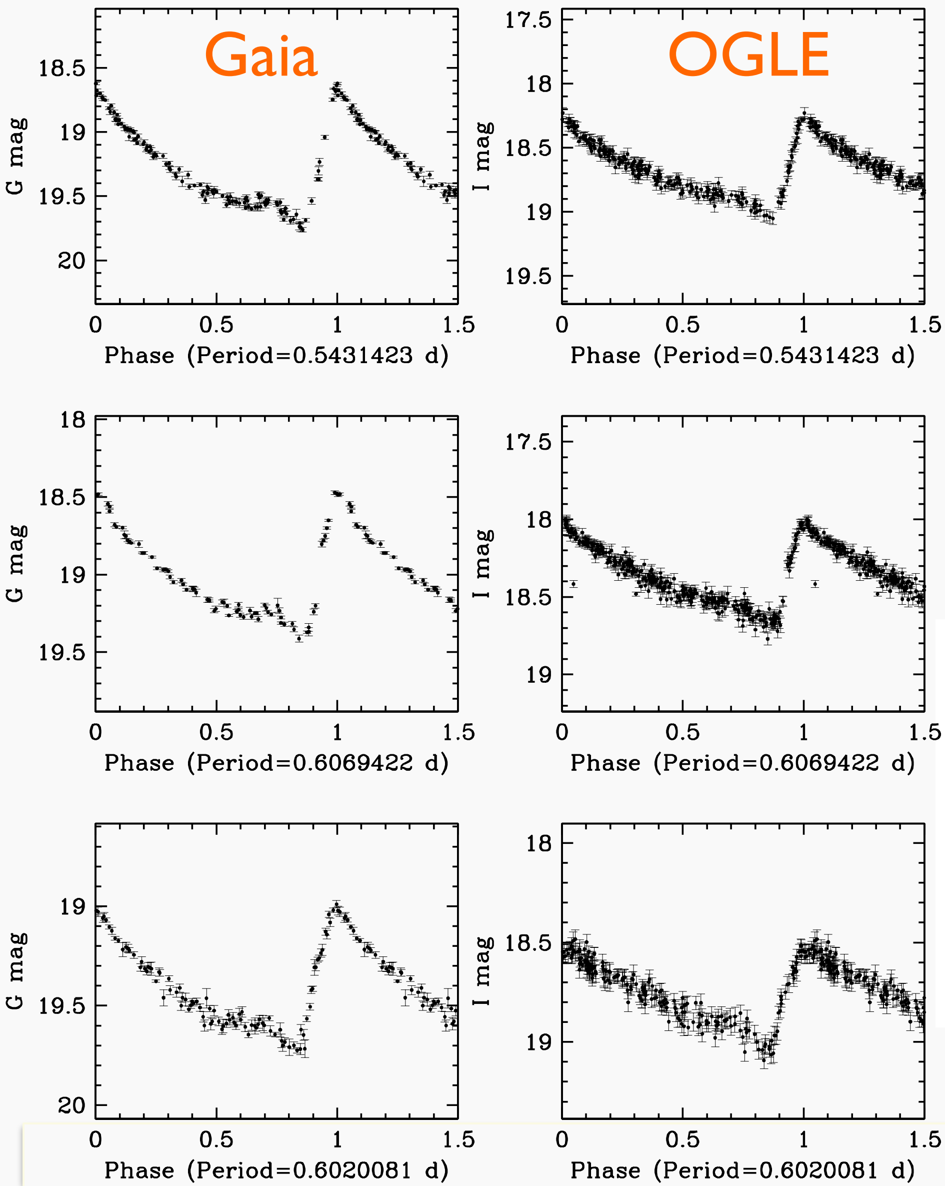
Calculations by: Airbus DS, D. Katz, C. Jordi, L. Lindegren, J. de Bruijne

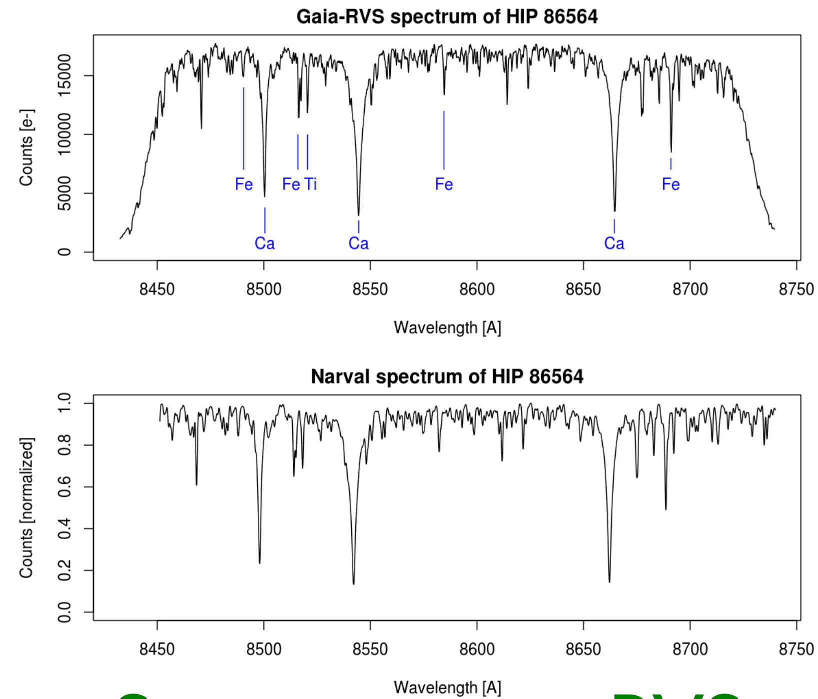
Up-to-date information always at:
`http://www.cosmos.esa.int/web/gaia/science-performance`

Courtesy of Anthony Brown & Gaia/DPAC

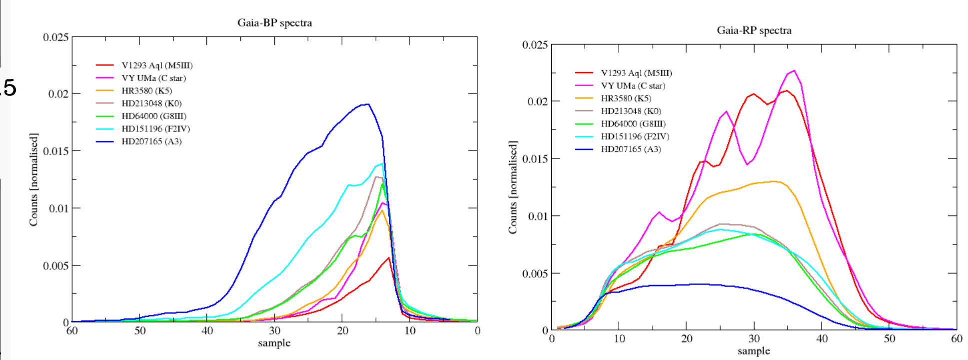
“Image of the week” http://www.cosmos.esa.int/web/gaia/

Photometry RR Lyrae in the LMC





Spectroscopy: RVS



Spectro-photometry

astrophysical parameters

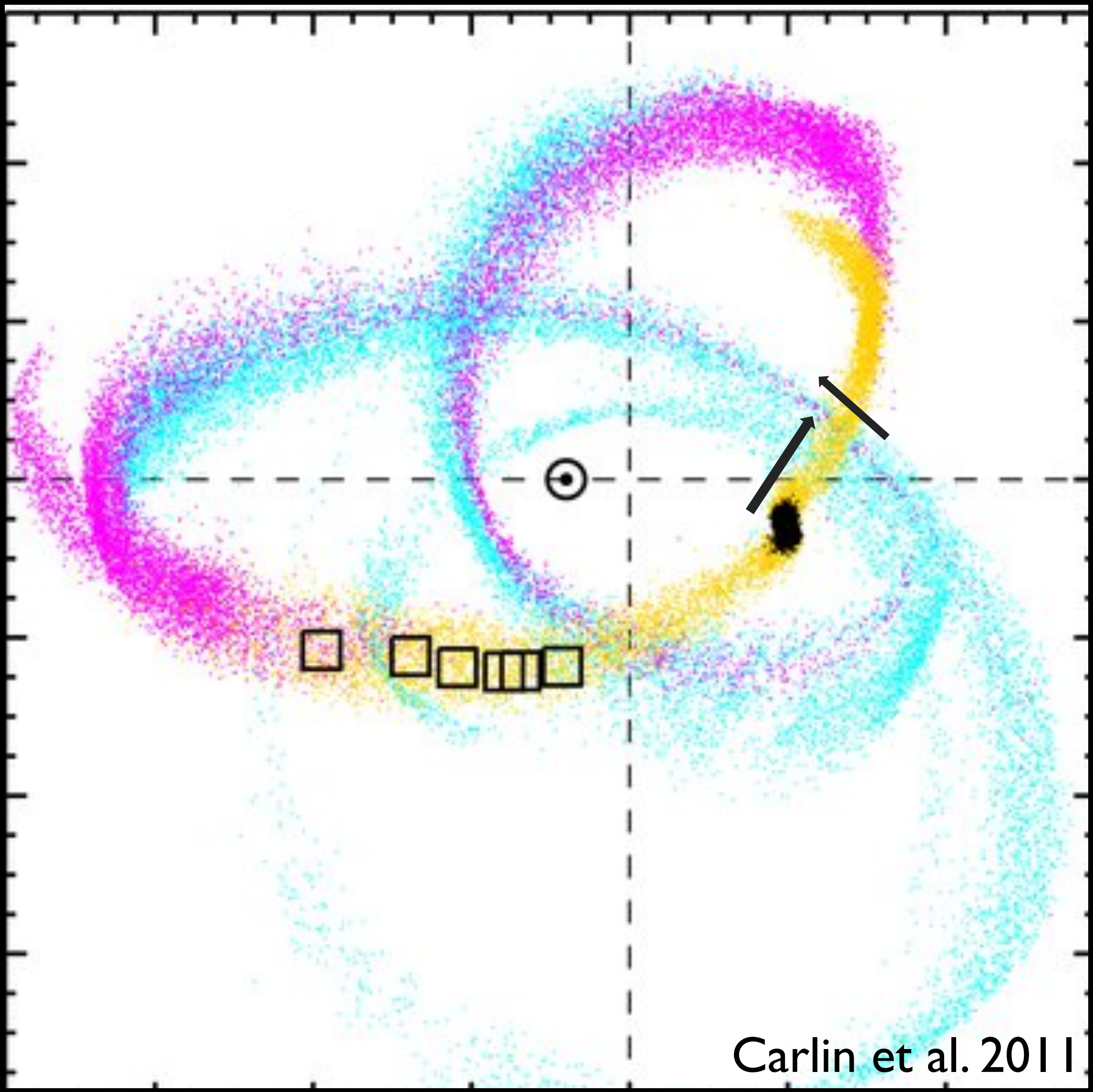
Back to streams

Streams in physical space

A single object can give rise to multiple, spatially crossing streams

We can speak of leading or trailing streams if mapping is close to continuous (connect the pieces)

A priori we might not know if two structures/ streams in space have the same parent



Carlin et al. 2011

Streams in action-angle space

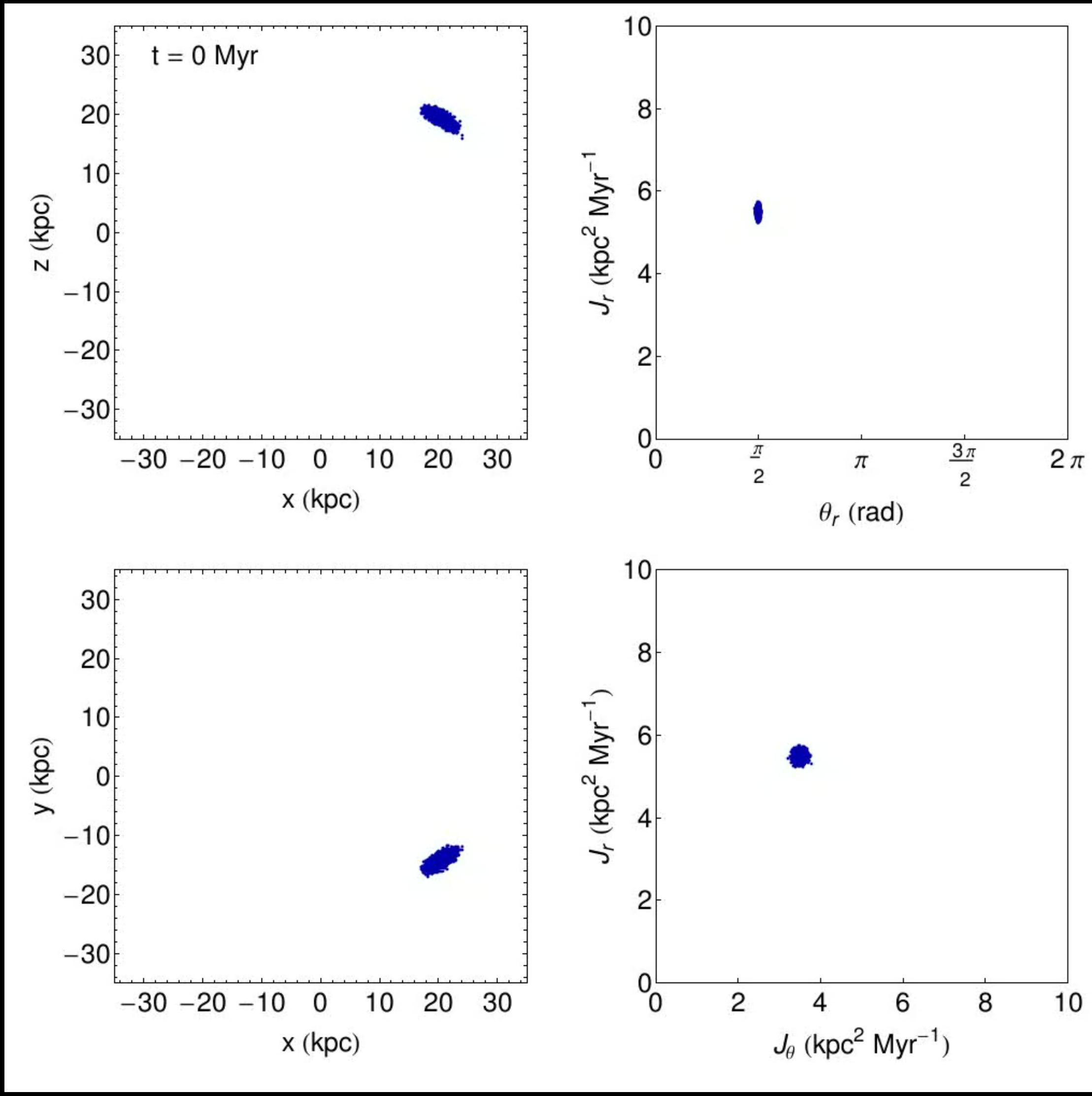
- Action-angle evolution is simple:

$$\theta = \theta_0 + \Omega(J)\, t$$
$$J = J_0$$

  - streams spread out in angle
  - actions are adiabatic invariants

- <u>Behaviour is very simple in action-angle space</u>
  - difficulty is to find actions/angles for any non-spherical potential (Bovy 2014; Sanders & Binney 2013, 2014)
  - Caveat: assume stars feel only host after released

- Stars from same object should be maximally clustered in action-space in right potential *(talk by Sanderson)*
  - even if potential changed with time



Sanderson et al. 2015

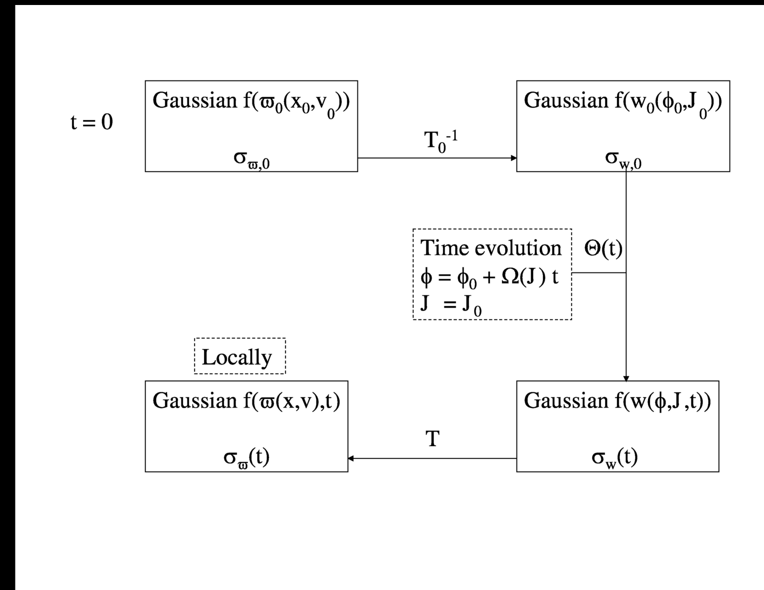
How do we understand the evolution?

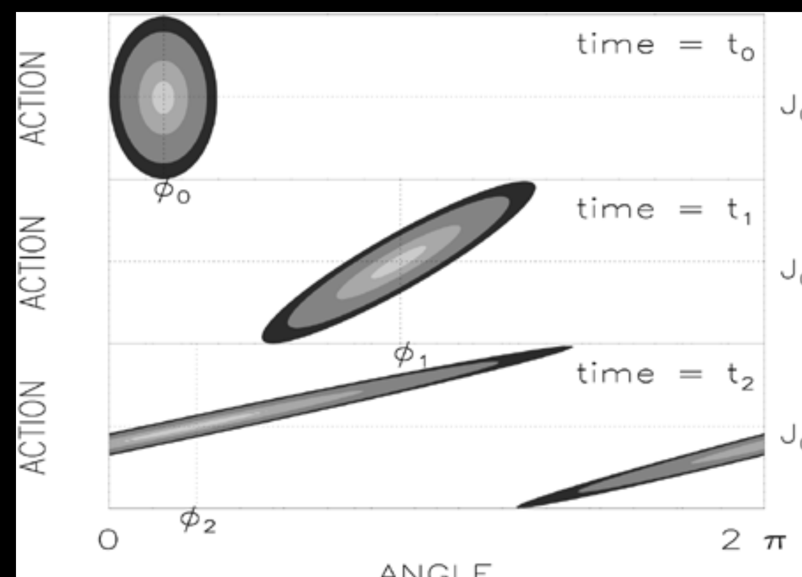
Principle:

Follow *df* evolution in action-angle space

$$\Delta\theta_i \sim \Delta\Omega_i t \sim \frac{\partial\Omega_i}{\partial\mathbf{J}}\Delta\mathbf{J}\ t$$

$$\Delta\theta = \mathbf{H}\ \Delta\mathbf{J}\ t$$





Helmi & White (1999)

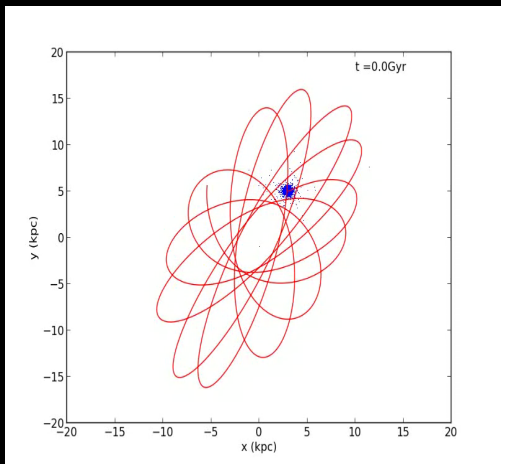
Predict properties in observable space:

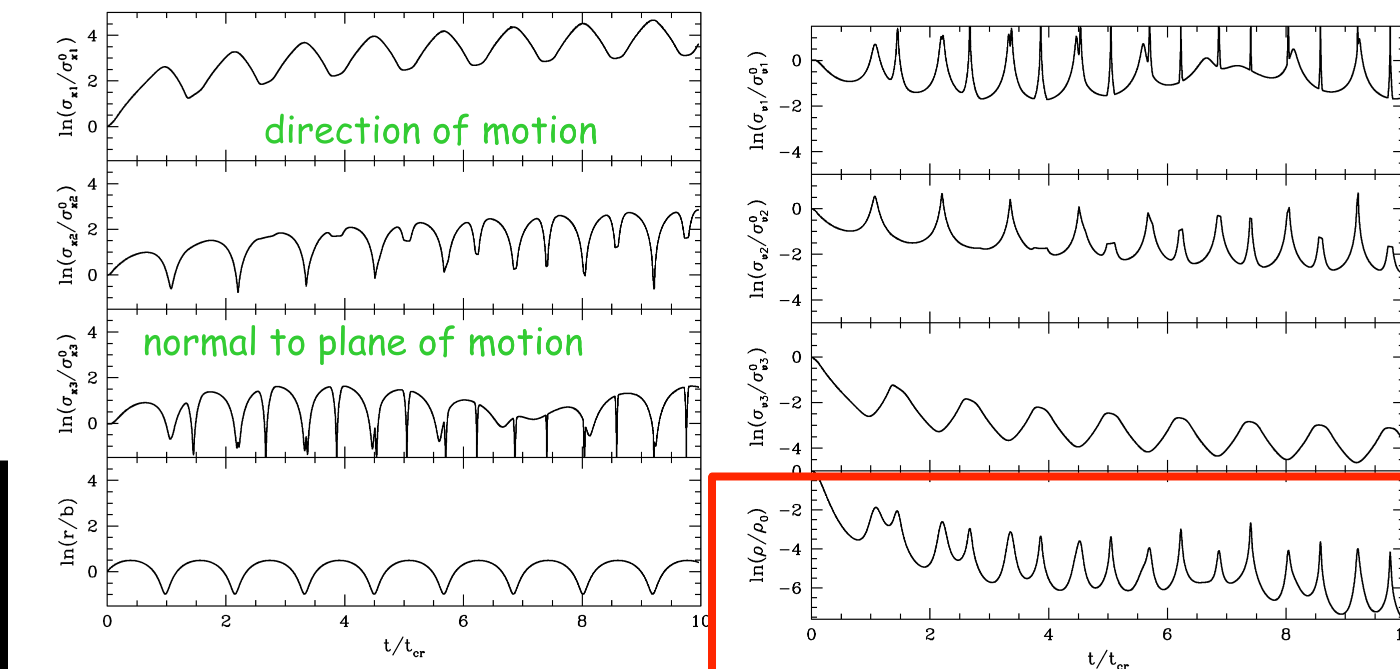
- Perform local linear coordinate transformation to (x,v)
- Determine the width, extent and velocity dispersion along a stream as *f(t)*

Evolution of streams in a spherical potential

spatial properties

velocity dispersion

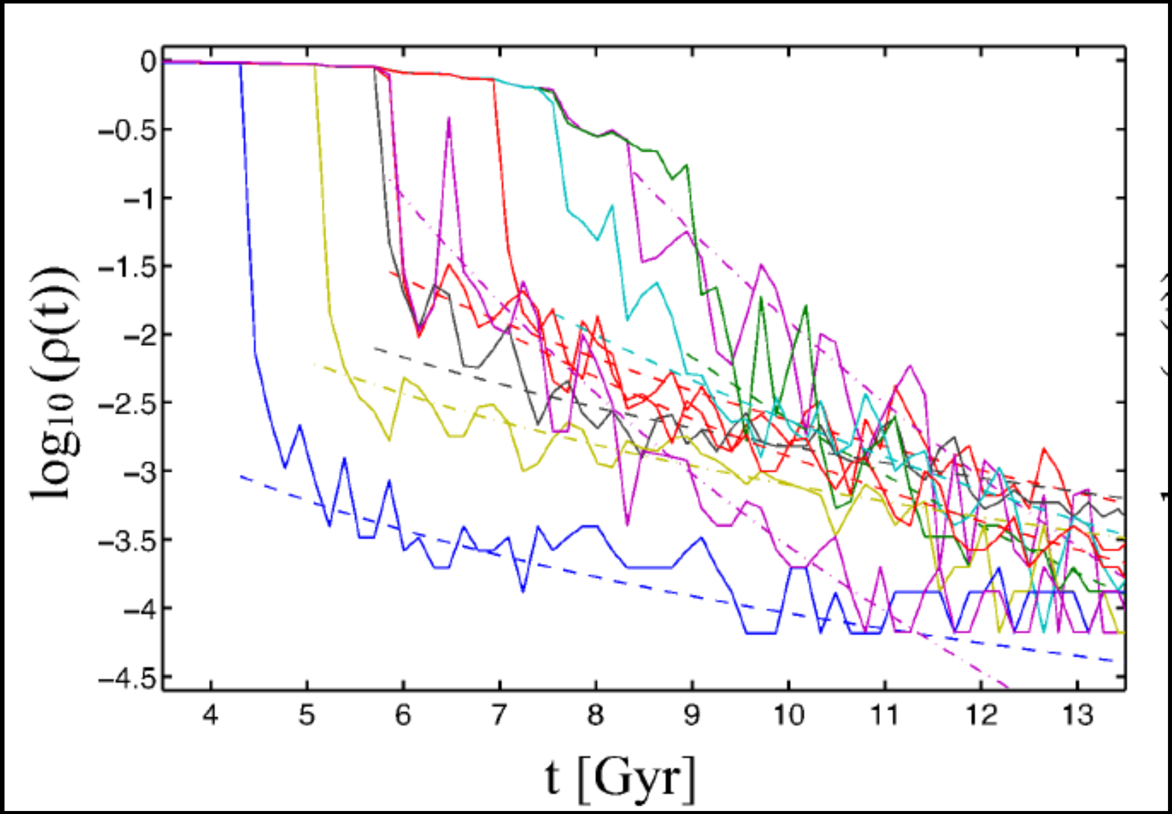


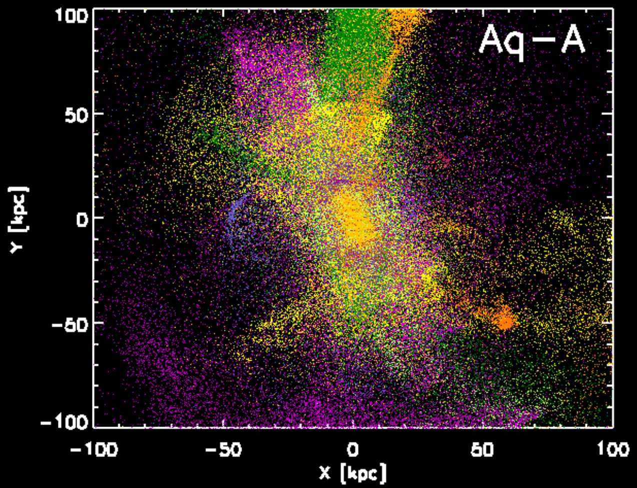


Helmi & Gomez 2007

- Stream elongated along direction of motion, and thicker in plane of motion
- Width of stream normal to plane of motion is ~ constant (spherical pot.)
- Velocity dispersion decreases as 1/t (conservation of phase-space density)
- Density decreases as $1/t^2$ (2D problem; axisym or triaxial $1/t^3$)

Streams in cosmological simulations?





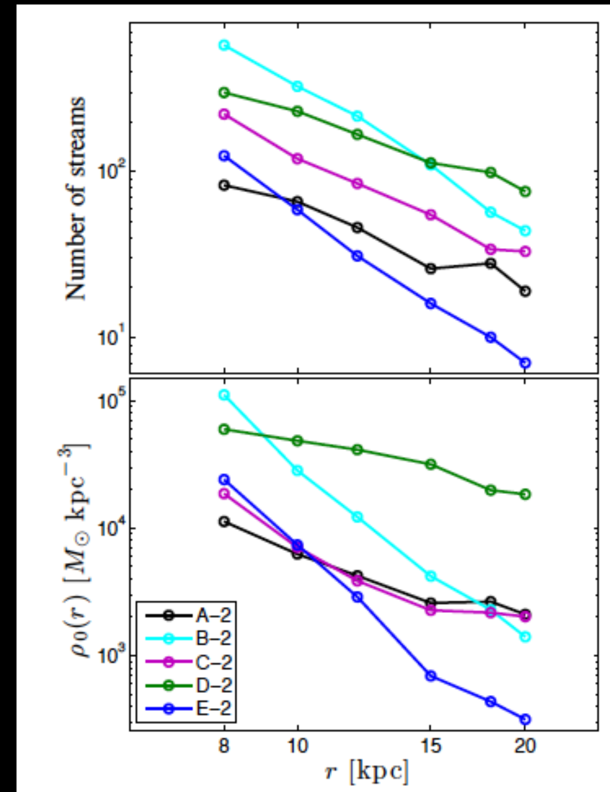
Gomez et al. (2014)

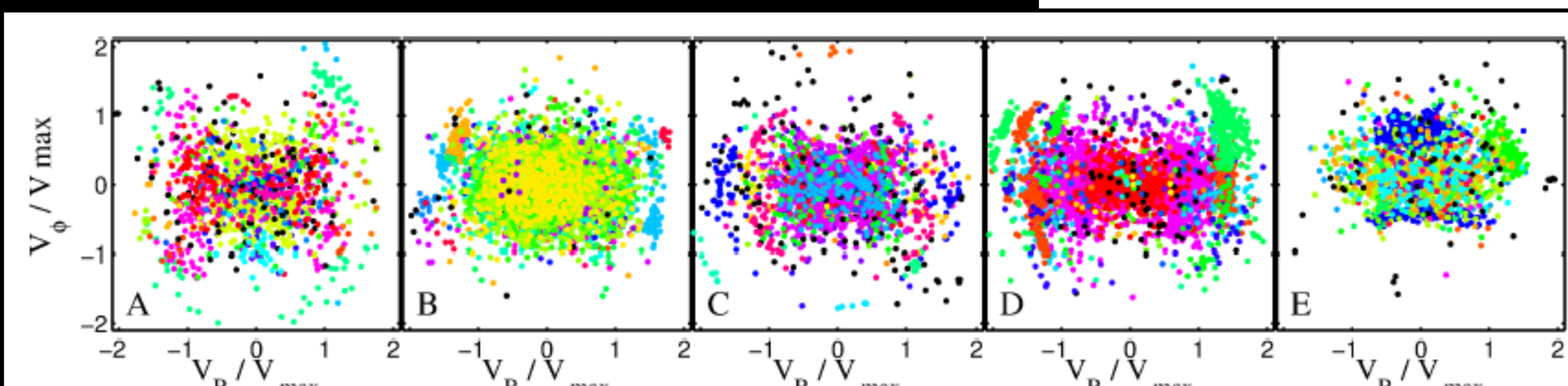
- Cosmological simulations show similar behaving streams
- No strong chaos, power law rather than exponential divergence of orbits

(poster Maffione)

Inner/nearby stellar halo in Aquarius

- Few objects contribute here: 75% of stars near Sun from 3-5 parents
- Memory in kinematics (despite “chaotic” build-up)
  - ~ 400 streams crossing Solar neighbourhood
  - Should be identifiable with Gaia





Gomez et al. 2014

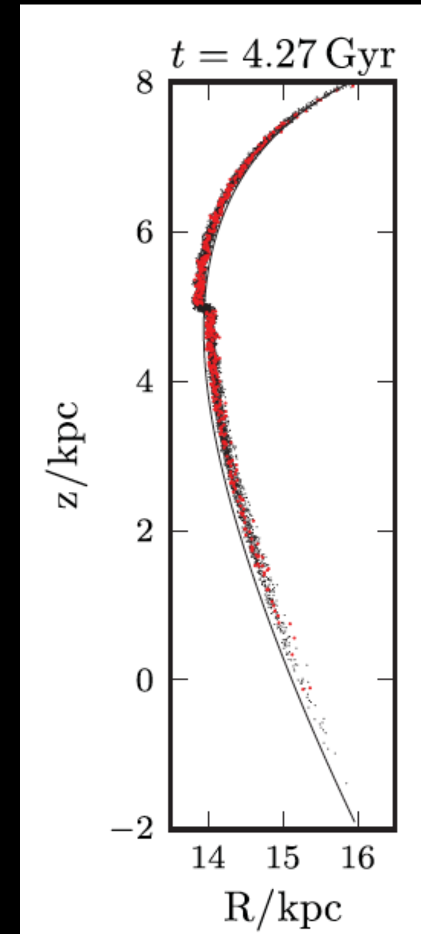
Streams and the potential

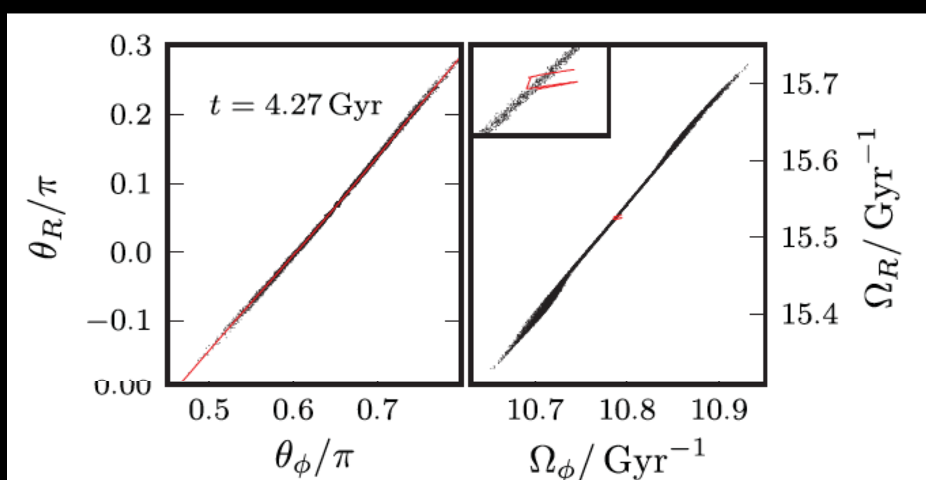
- Computation of angles, actions and frequencies depends on potential assumed

$$\Delta\theta_r \sim \Delta\Omega_r t \qquad \Delta\theta_\phi \sim \Delta\Omega_\phi t$$

$$\frac{\Delta\theta_r}{\Delta\theta_\phi} = \frac{\Delta\Omega_r}{\Delta\Omega_\phi}$$

- In true potential, streams on straight lines with same slope in angle and in frequency space (Sanders & Binney 2014)

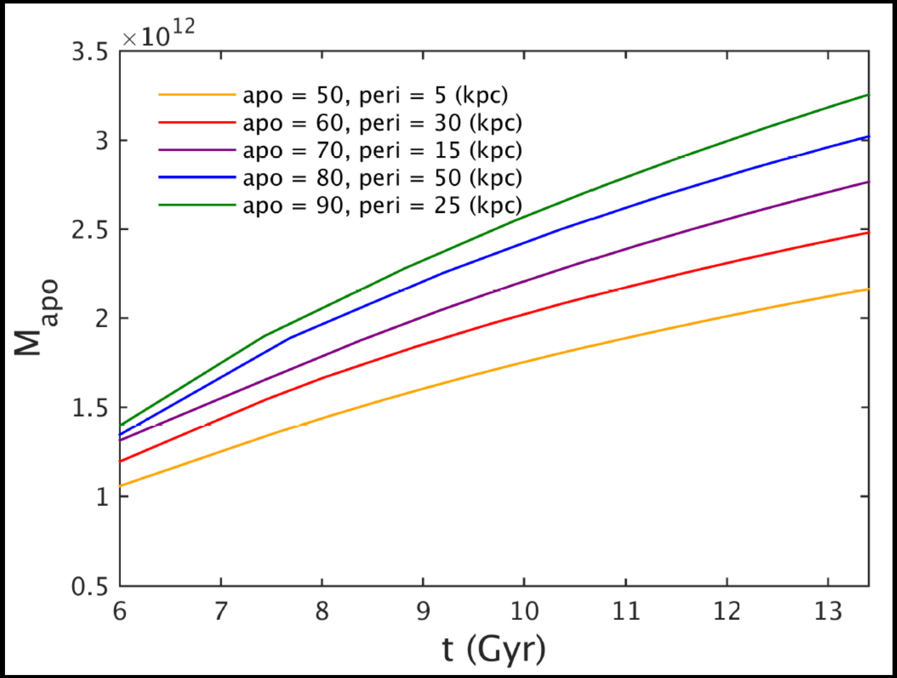




Streams and time-evolution

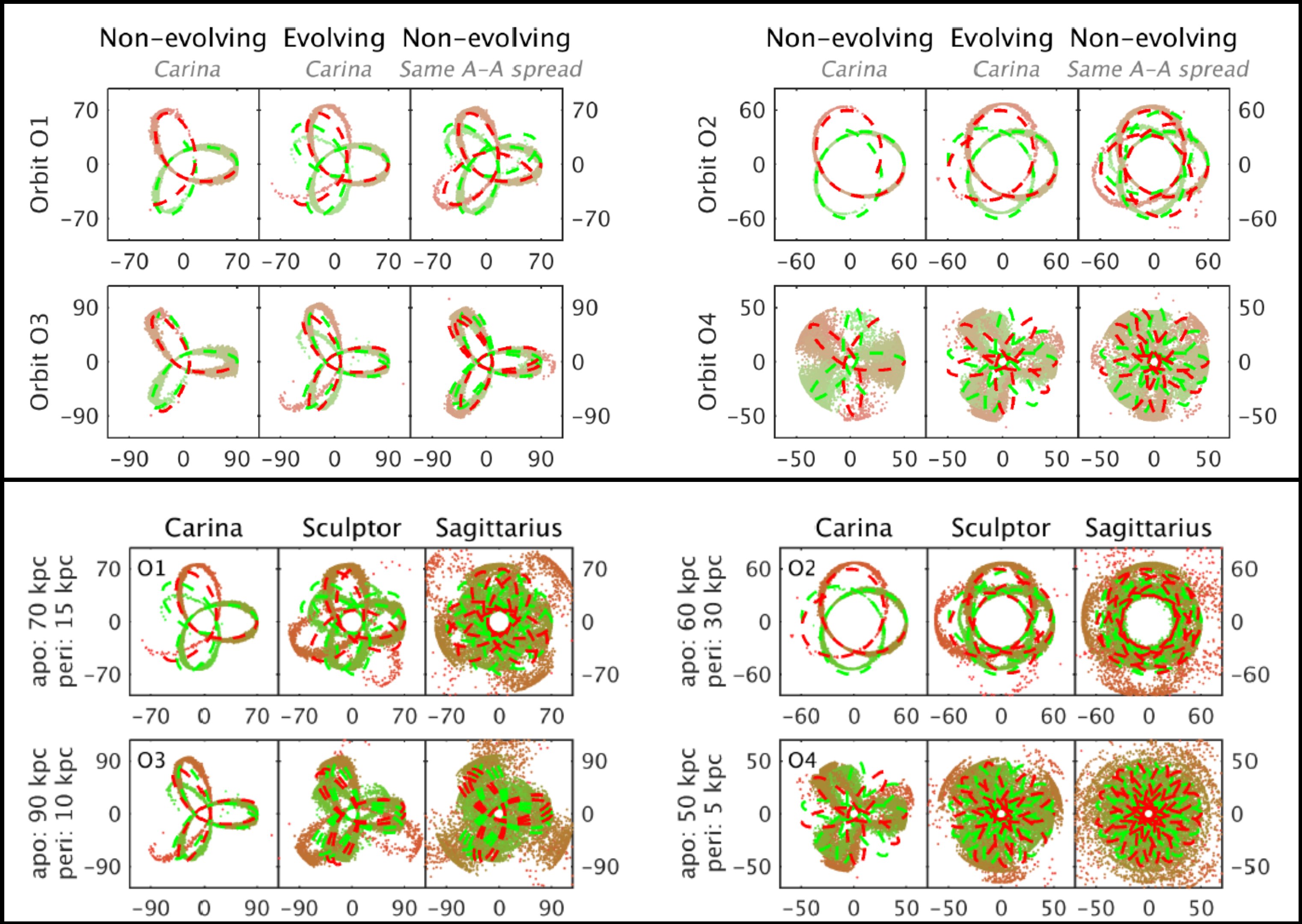
- What are the signatures of time-evolution? Can it be measured?
- Model growth of a spherical halo:
  - inside out, cosmological mass-growth $M \sim \exp(-a_g z)$
  - doubles its mass with orbits considered
  - numerical simulations and analytic formalism based on A-A variables

- Different progenitors + different orbits



Buist & Helmi, 2015

Numerical simulations: imprints of time-evolution



Buist & Helmi, 2015

- Precession in orbital plane differs and misalignment is seen, ±10deg
- To see impact of time evolution: need long streams, preferably on radial orbits

Analysis in action-angle space

- With time-dependence one cannot use original A-A variables
- Actions are adiabatic invariants (depending on orbit)
- Frequencies and angles are not

$$\dot{J}_i = -\frac{\partial H'}{\partial \theta_i} = -\dot{\alpha}\frac{\partial}{\partial \theta_i}\frac{\partial W}{\partial \alpha}(\mathbf{J}, \boldsymbol{\theta}, \boldsymbol{\alpha}),$$
$$\dot{\theta}_i = \frac{\partial H'}{\partial J_i} = \Omega_i(\mathbf{J}, \boldsymbol{\alpha}) + \dot{\alpha}\frac{\partial}{\partial J_i}\frac{\partial W}{\partial \alpha}(\mathbf{J}, \boldsymbol{\theta}, \boldsymbol{\alpha}).$$

$$\langle \dot{\theta}_i \rangle \approx \Omega_i(\mathbf{J}, \boldsymbol{\alpha}) + \mathcal{O}(\dot{\boldsymbol{\alpha}}^2, \ddot{\boldsymbol{\alpha}}).$$

- Angles:

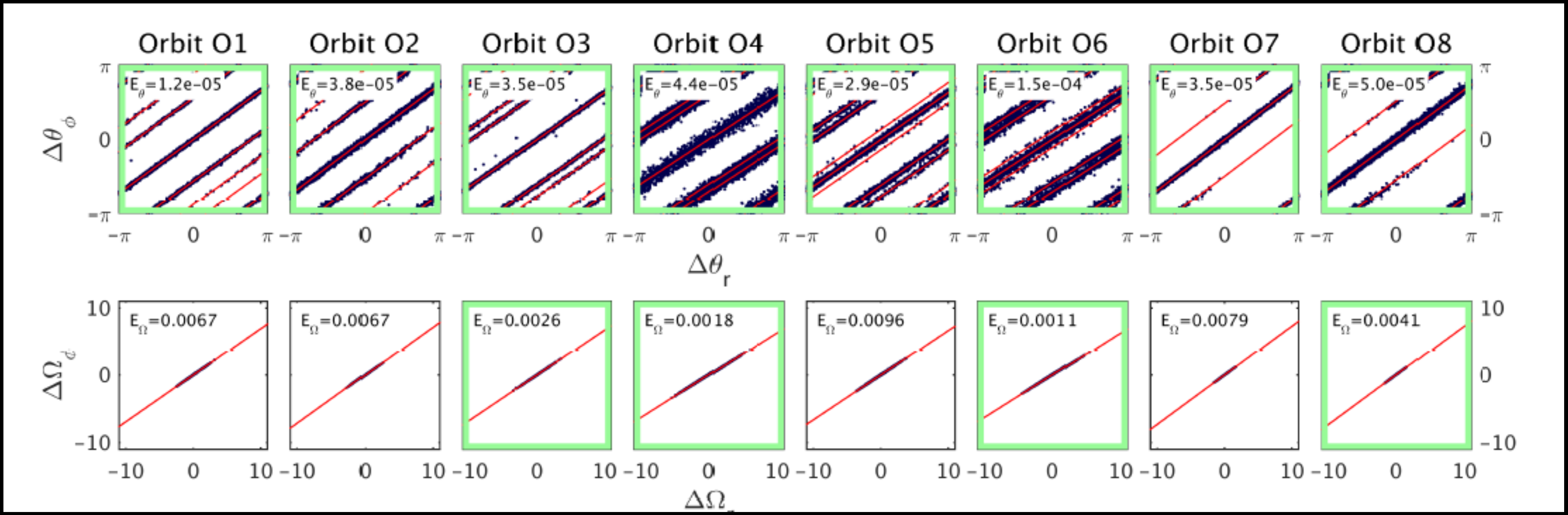
$$\theta_i(t) \approx \theta_i(0) + \int_0^t \Omega_i(\mathbf{J}, \boldsymbol{\alpha}(t))dt,$$

- With present-day potential, compute angles and frequencies
- For an ensemble of particles, streams no longer on *same* straightlines in angle and in frequency space

$$\frac{\Delta\theta_r}{\Delta\theta_\phi} = \frac{\int \Delta\Omega_r dt}{\int \Delta\Omega_\phi dt} \neq \frac{\Delta\Omega_r}{\Delta\Omega_\phi}$$

- Differences are small, ~ 0.01 – 0.025 depending on growth rate

Measurable?



- Error convolution in observable space: ε_{los} ~ 10 km/s, ε_{π} ~ ε_{μ} ~ 1%
- Streams behave well, slope difference is still measurable for most experiments
  - frequency space more strongly affected by errors
  - PASS if difference between original and error-convolved slope < 0.005

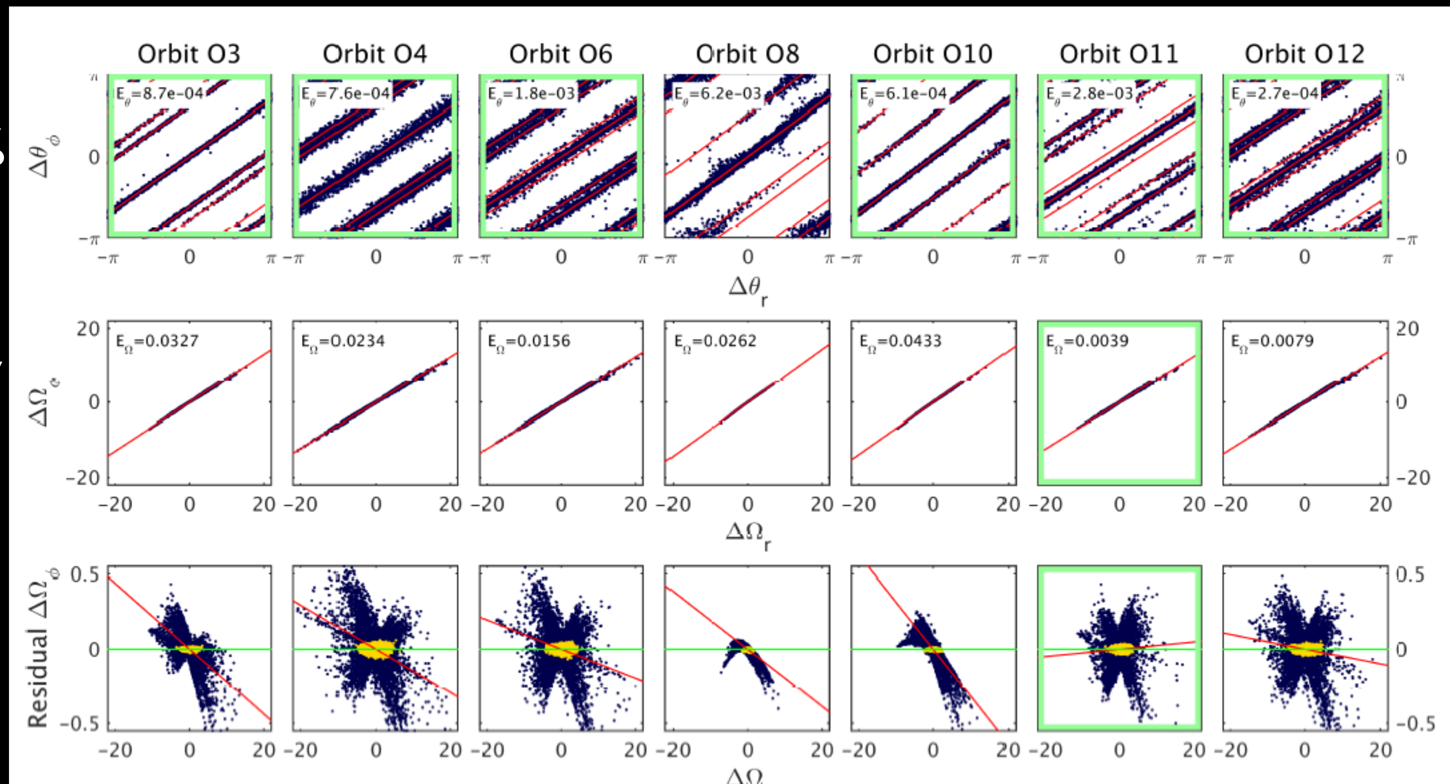
Measurable with more realistic errors?

Errors now

$\varepsilon_\pi \sim \varepsilon_\mu \sim 10\%$

Frequency space strongly affected

Very few streams pass

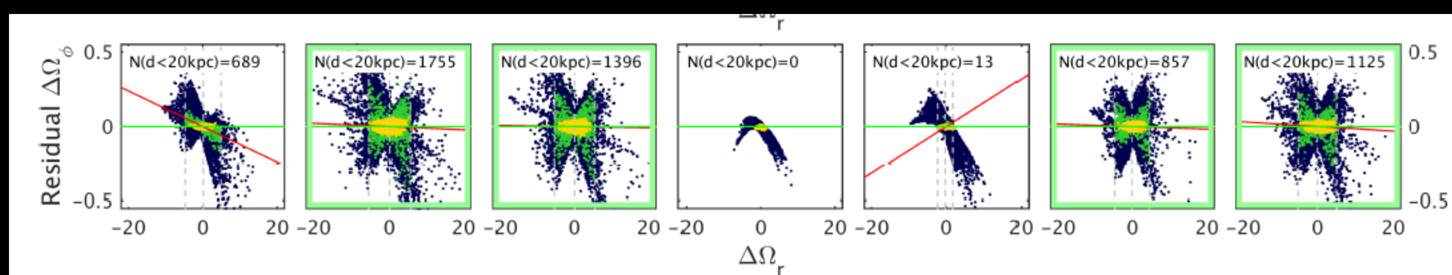


Restrict dataset

$\varepsilon_\pi \sim \varepsilon_\mu \sim 10\%$

$\varepsilon_d < 2$ kpc

$|\Omega_r - \langle\Omega_r\rangle| < \sigma_\Omega$



More streams can be used and growth can be measured

Summary

- Dynamics of stellar streams best understood using action-angle
  - Streams on straightlines in angle and in frequency space if true potential
  - Constrain Galactic potential parameters
  - Time-evolution imprinted in differences in straightlines slopes
  - Appear to be measurable in foreseable feature

- What's next
  - Finding hundreds of streams predicted by LCDM in Gaia
  - Formation of the stellar halo (in-situ vs accreted, timescales, progenitors)
  - Better understanding of signatures of subhalos on streams as ultimate test of LCDM


Thank you!