Tidal streams as gravitational experiments

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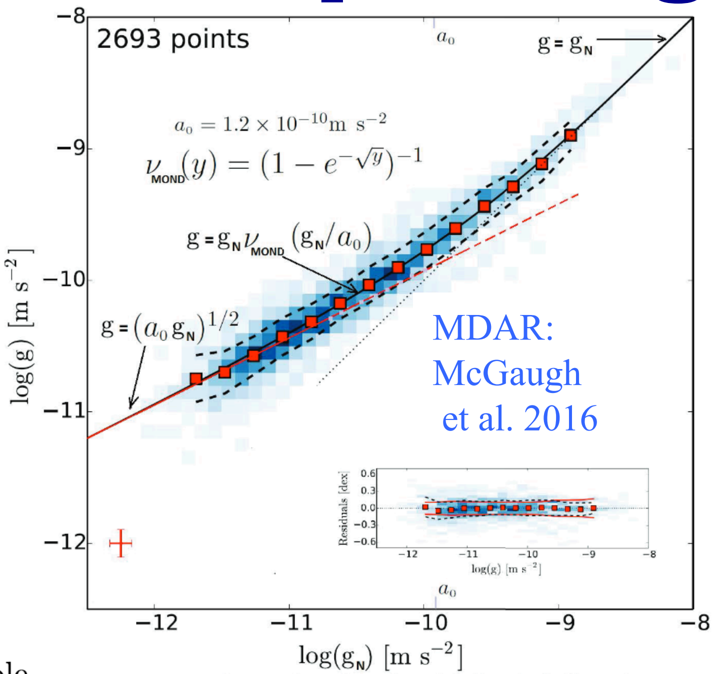
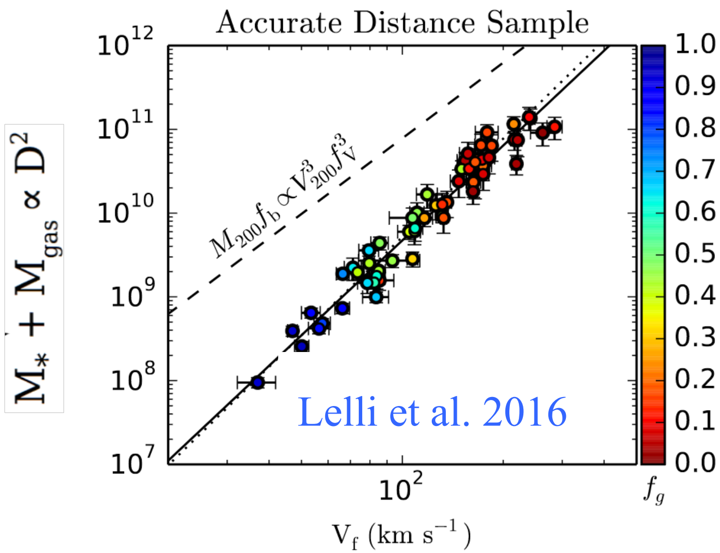
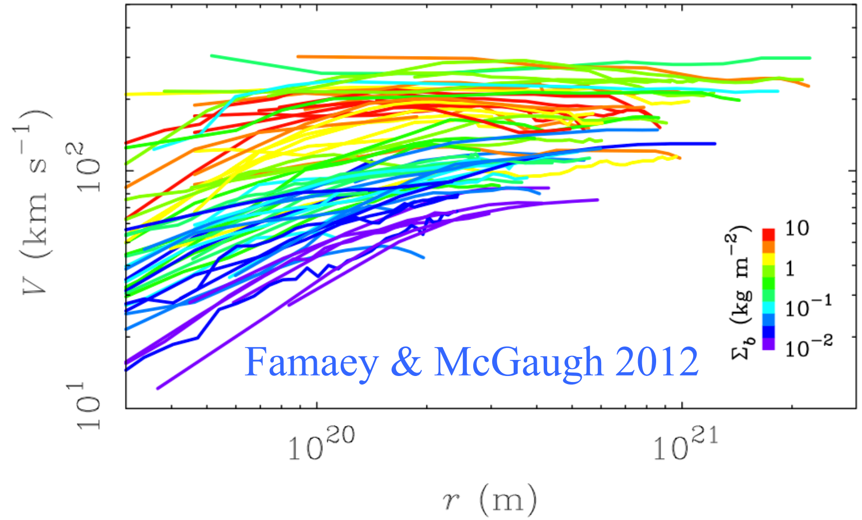
MOND paradigm







MOND paradigm

- Prediction: LSB rotation curves are similar if rescaled by scale-length

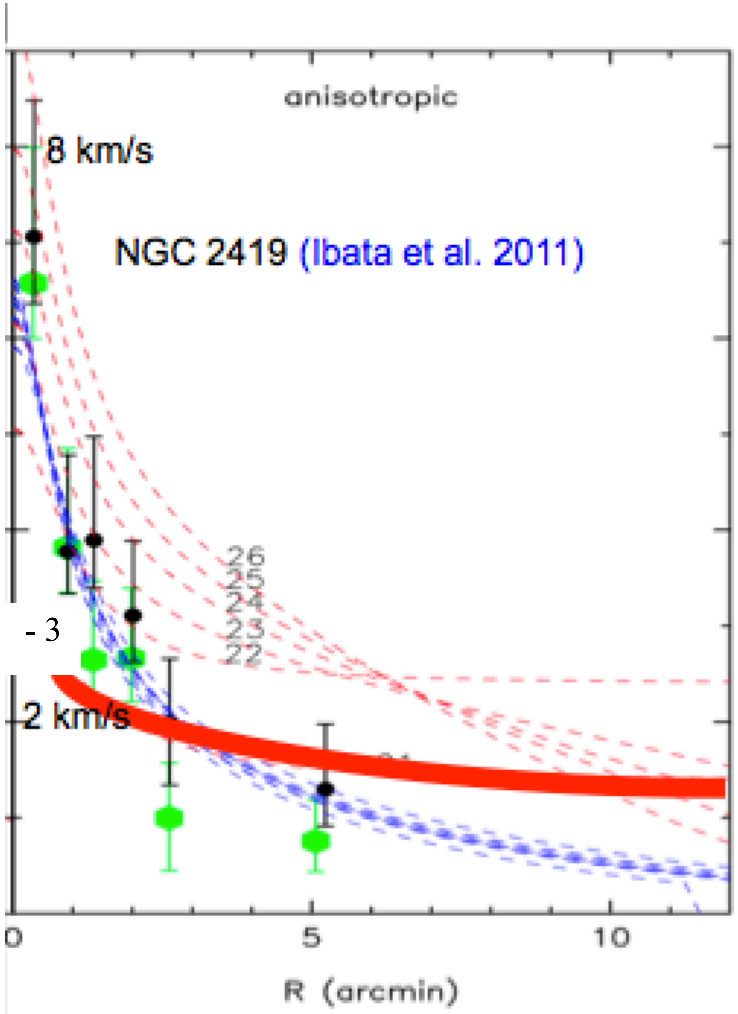
- Take two exponential disks of same baryonic mass in the low acceleration regime (central surf.density = $M_b/2\pi R_d^2$)

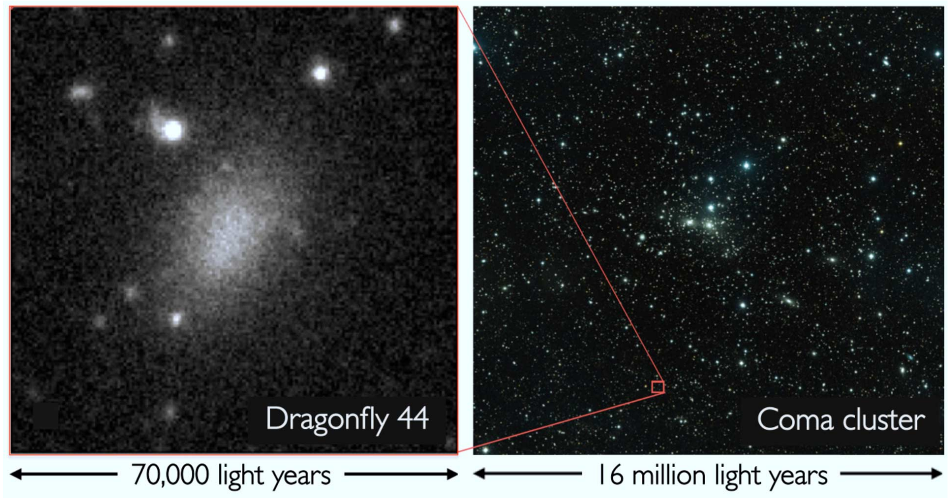
- $M_b(\alpha\ R_d)$ identical

- $V^2_{cb}(\alpha\ R_d) \sim G\ M_b(\alpha\ R_d)\ /\ \alpha\ R_d$

- If boost of gravity due to DM at $R=\alpha R_d$ is prop. to $1/\sqrt{g_n}$ (hence prop. to αR_d) , then $V_c(\alpha\ R_d)$ identical

MOND paradigm





Not everything works as well as for disk galaxies

MOND paradigm

- Emergence from feedback alone?

- Due to a fundamental reason?

    1) SIDM? or DM-baryons interactions? (see Justin's talk)

    2) More radical:

        2a) Fundamental nature of DM?
        (gravitational dipoles, surperfluid,…)

        2b) Modified Gravity (+ DM?)

        => Smoking gun: dynamical friction and EFE

MOND paradigm

$g = g_N$	if $g \gg a_0$
$g = (g_N\, a_0)^{1/2}$	if $g \ll a_0$

$$\nabla . \left[\mu\left(|\nabla\Phi| / a_0 \right) \nabla\Phi \right] = 4\pi G\, \rho_{bar}$$

AQUAL: Bekenstein & M (1984)

or

$$\nabla^2 \Phi = \nabla . \left[\nu\left(|\nabla\Phi_N| / a_0 \right) \nabla\Phi_N \right]$$

QUMOND: Milgrom (2010)

- Differing only slightly outside of spherical symmetry

- Both have possible relativistic counterparts

- Numerical Poisson solvers exist: recently, PoR (Phantom of Ramses) for QUMOND (Lüghausen, Famaey & Kroupa)

Superfluid dark matter

Idea of Berezhiani & Khoury: DM could have strong self-interactions and enter a superfluid phase when

- cold enough (i.e; their de Broglie wavelength λ ~ 1/(mv) is large
- dense enough (i.e. the interparticle separation is smaller than λ)

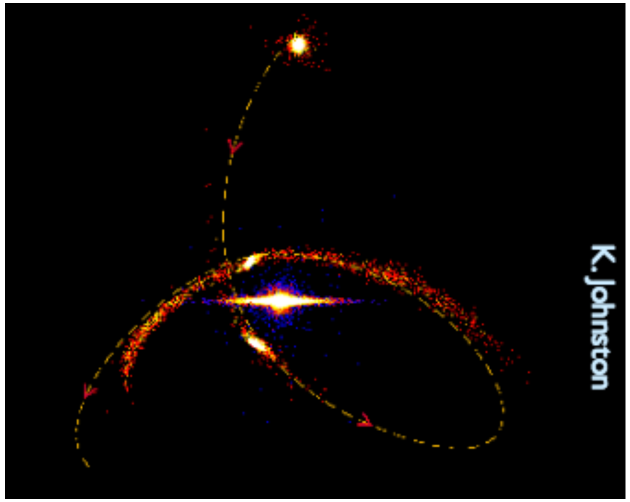
=> Superfluid core (~100 kpc in MW) where collective excitations (phonons) can couple to baryons and mediate a long-range force + NFW « normal » atmosphere

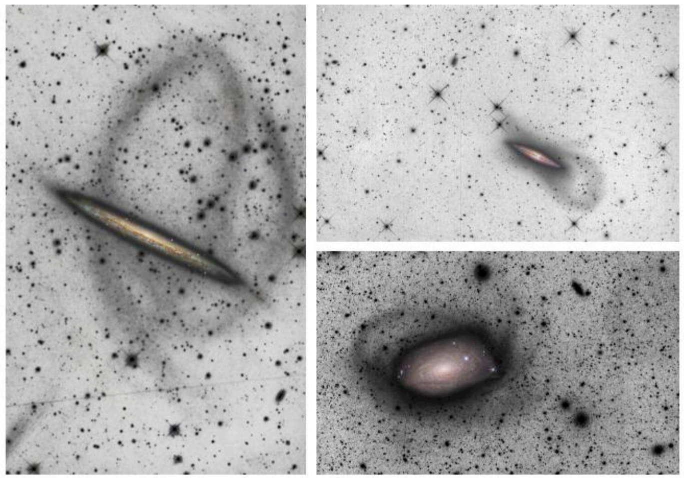
System	Behavior
Rotating Systems	
Solar system	Newtonian
Galaxy rotation curve shapes	MOND (+ small DM component)
Baryonic Tully–Fisher Relation	MOND for RCs (but particle DM for lensing)
Bars and spiral structure in galaxies	MOND
Interacting Galaxies	
Dynamical friction	Absent in superfluid core
Tidal dwarf galaxies	Newtonian when outside of superfluid core
Spheroidal Systems	
Star clusters	MOND with EFE inside galaxy host core - Newton outside of core
Dwarf Spheroidals	MOND with EFE inside galaxy host core - MOND+DM outside of core
Clusters of Galaxies	particle DM
Ultra-diffuse galaxies	MOND without EFE outside of cluster core

Tidal streams

Useful in principle to:

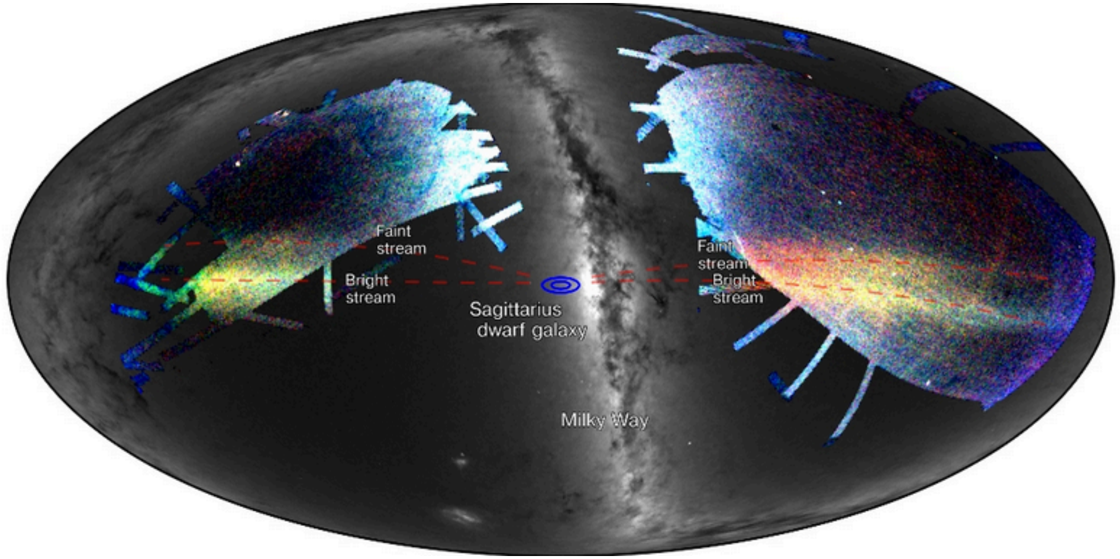
- Determine 3D shape of potential at large radii
- Detect DM subhalos
- Test gravity





In the MW: the Sagittarius Stream

- The Sgr dwarf (Ibata et al. 1994) is cannibalized by the MW and has a tidal stream extending to a full 360° on sky
- Currently located on the other side of the GC at d=25 kpc
- Majewski et al. (2004) use M giants to measure kinematics of stream members



Note that it is a rather complicated structure, with an old faint stream and a more recent bright stream.

Usually, models dont reproduce easily the faint stream, focus on the bright stream and the last 4 Gyr of orbit

Initial conditions

- Our adopted Milky Way model (B&T08):

› **ISM, thin and thick disk :**

$$\rho_d(R,z)=\frac{\Sigma_d}{2z_d}\exp\left(\frac{-R_m}{R_d}-\frac{R}{R_d}-\frac{|z|}{z_d}\right)$$

› **Bulge ~~(and DM halo)~~ :**

$$\rho_s(R,z)=\rho_0\left(\frac{m}{r_0}\right)^{-\gamma}\left(1+\frac{m}{r_0}\right)^{\gamma-\beta}\exp\left(\frac{m^2}{r_t^2}\right)$$

→ $M_{MW} = 5.6 \cdot 10^{10}\, M_\odot$

- Integrate point mass backwards in time for >4 Gyr until apocenter (~ 80 kpc)
- Throw progenitor from there
- Devise progenitor model: King profile

Initial conditions

- Sgr MOND King model:

$$\rho_K(\Psi) = \frac{4\pi\rho_1}{(2\pi\sigma^2)^{3/2}} \int_0^{\sqrt{2\Psi}} dv\, v^2 \left[\exp\left(\frac{\Psi - \frac{1}{2}v^2}{\sigma^2} \right) - 1 \right]$$

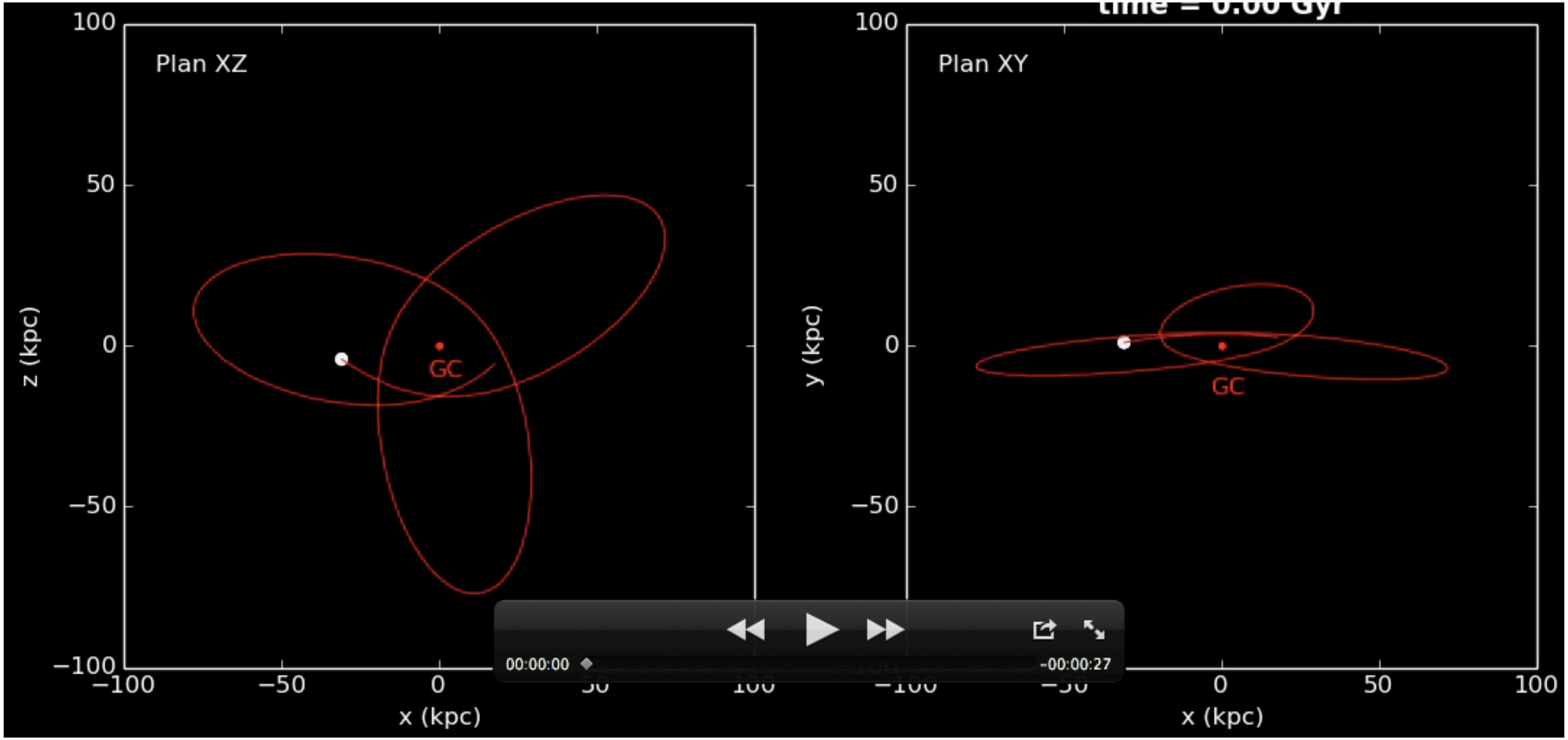
- Solve AQUAL Poisson equation outwards from r=0 where value and first derivative of ψ (=0) given

⇒ Get ψ and ρ and distribute v according to DF, model defined by 2 params (eg mass and half-light radius)

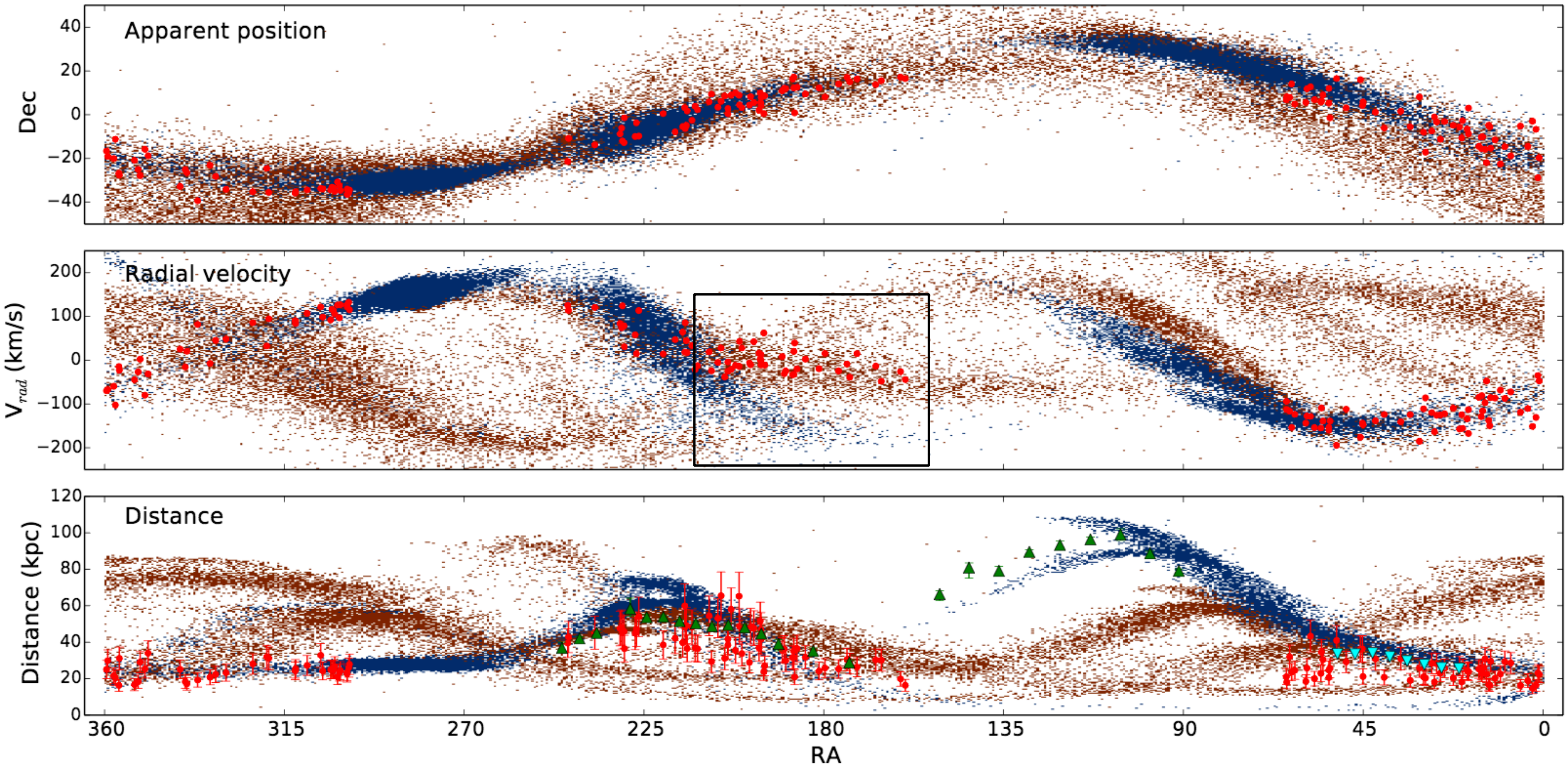
⇒ Throw stars into the PoR code!

- We use: $\mathbf{M_{Sgr} = 1.2 \times 10^8\ M_{sun}}$, $\mathbf{r_h = 610\ pc}$
  i.e. well in line with the stellar mass vs radius relationship for dwarf ellipticals

Initial progenitor			Final remnant		
Mass ($M_\odot$)	r_h (kpc)	σ_c (km.s^{-1})	Mass ($M_\odot$)	r_h (kpc)	σ_c (km.s^{-1})
1.2×10^8	0.61	24.0	5.1×10^7	0.64	11



Thomas et al. (2017)



No influence of EFE!

Problem of leading arm velocities not specific to MOND:
possible solutions include triaxial halo/hot gas corona, satellite galaxy (secondary stream), rotating progenitor, influence of LMC, … « bizarre dynamics »…

An interesting case: Pal 5 and its stream

- Close glob. cluster (23.5 kpc), tidal radius ~ 145 pc
- Grillmair & Smith (2001) estimate a mass of 5 x 10^3 M_{sun}

⇒ expected σ ~ 0.21 km/s

- Observed σ ~ 0.9 ± 0.2 km/s

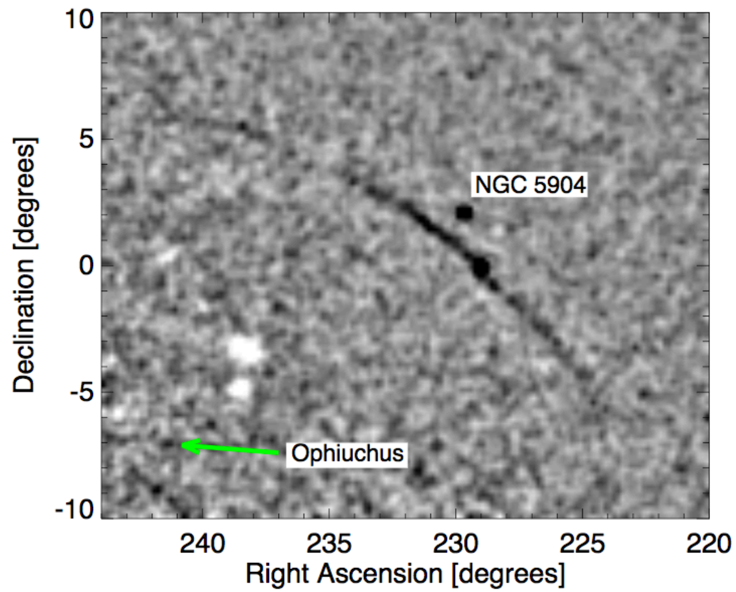
⇒ binaries??

- Tidal stream asymmetric:

trailing arm ~ 6 kpc long

leading arm ~ 3.5 kpc long

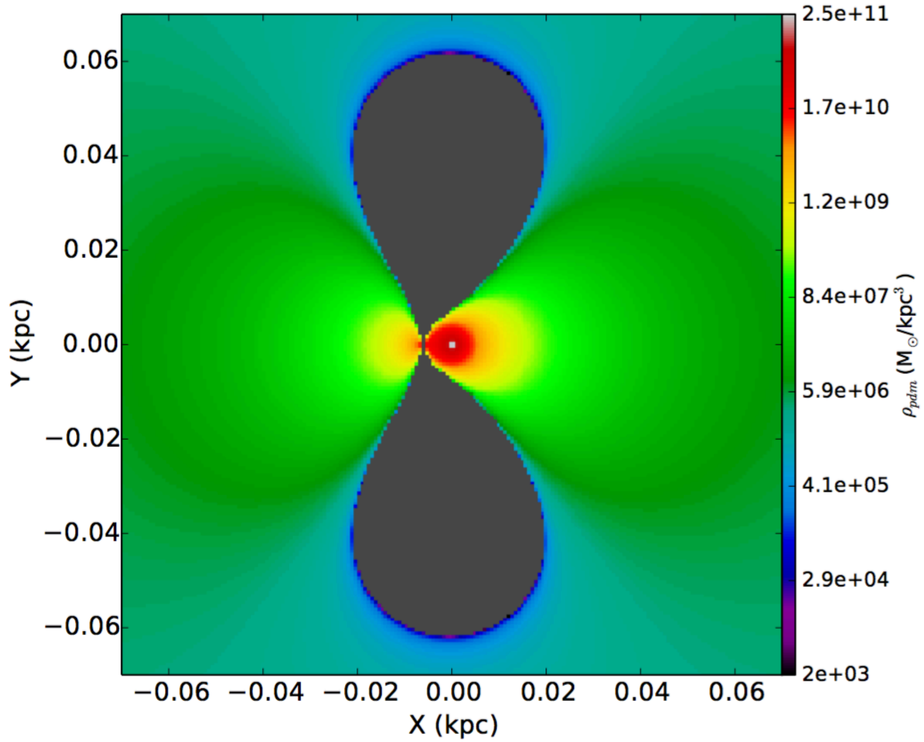
- Almost factor of 2 in stream surface brightness at 1 kpc from glob. cluster

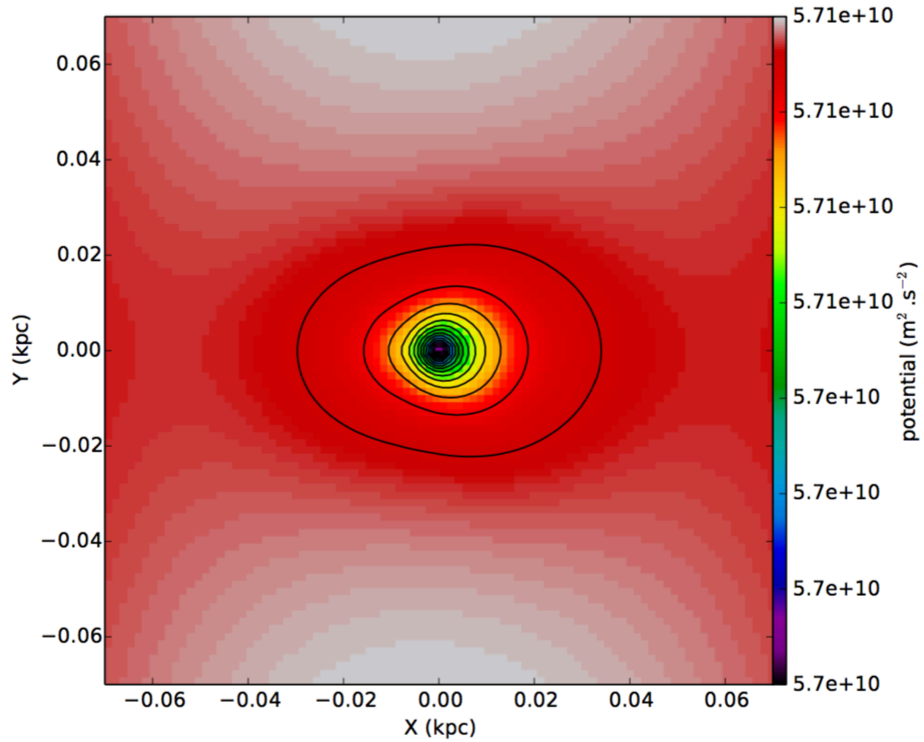


Bernard et al. (2016) Pan-STARRS1 observations

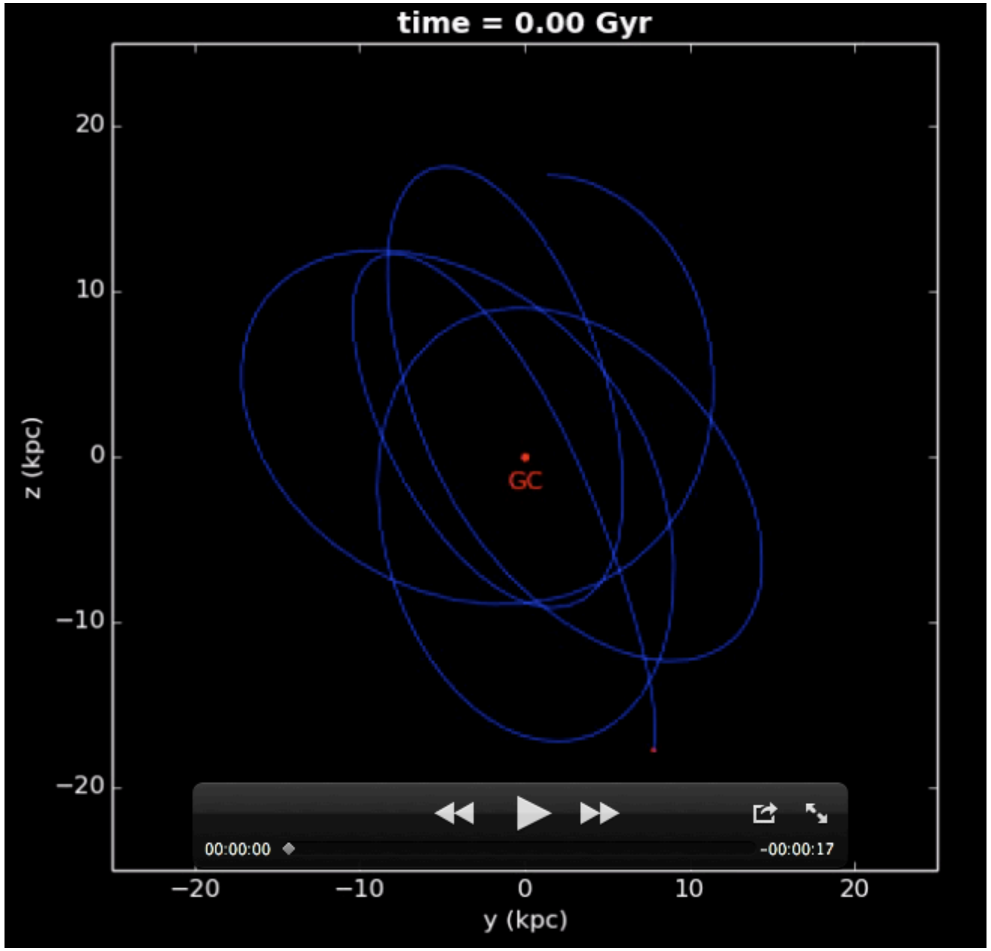
The EFE: breaking the SEP

Consider simple case of two point masses of 1.5×10^4 M_{sun} and 5.5×10^{10} M_{sun} separated by 14 kpc





Warning: no direct N-body code in MOND. Simulate GC with a King profile collisionless ansatz. Progenitor 2.6 x 10^4 Msun => remnant after 2 Gyr M = 6.5 x 10^3 M_{sun} & σ = 0.65 km/s



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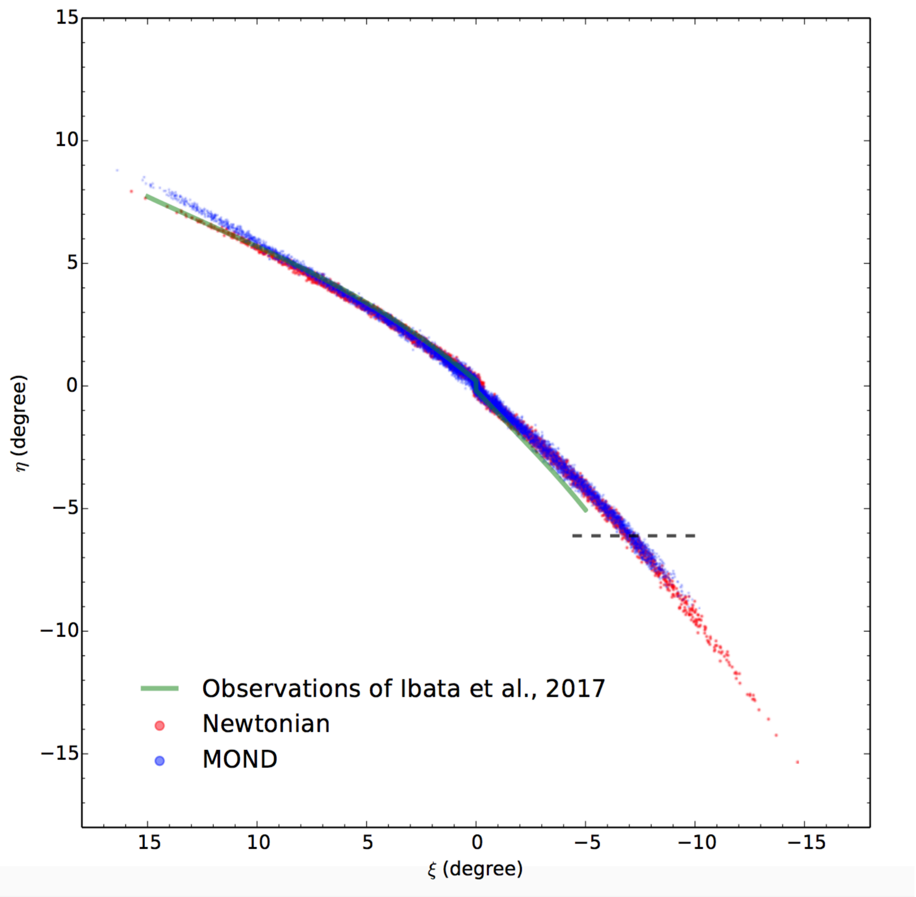

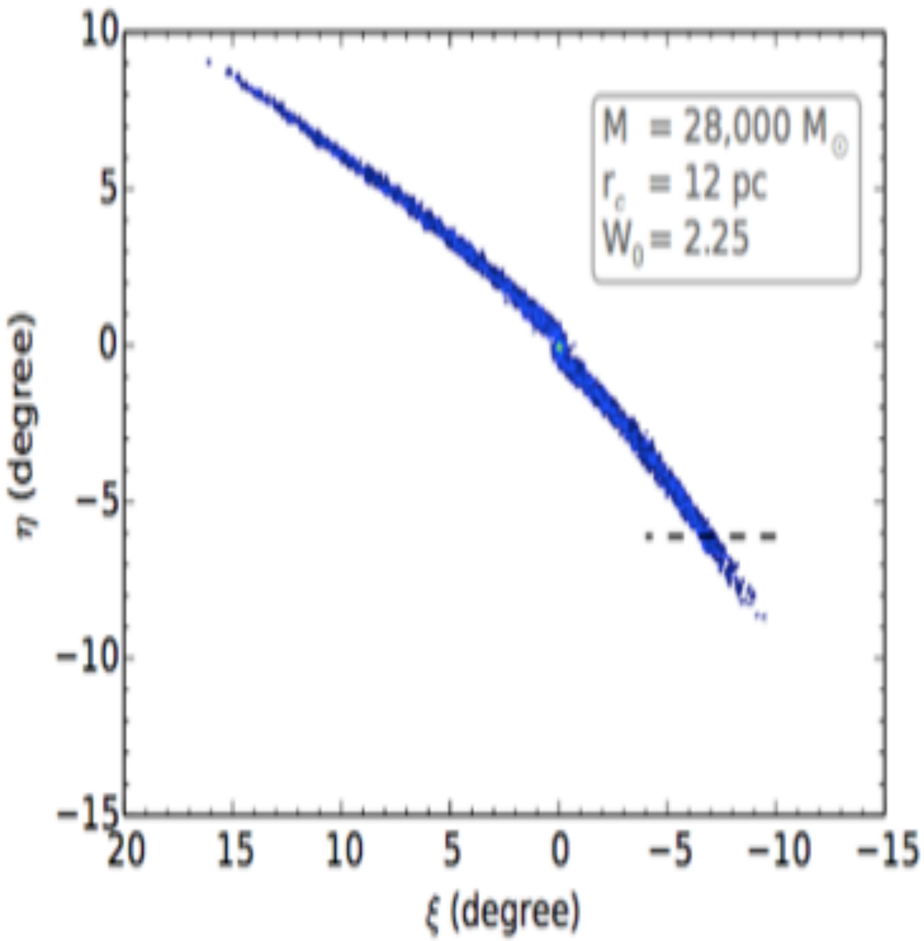

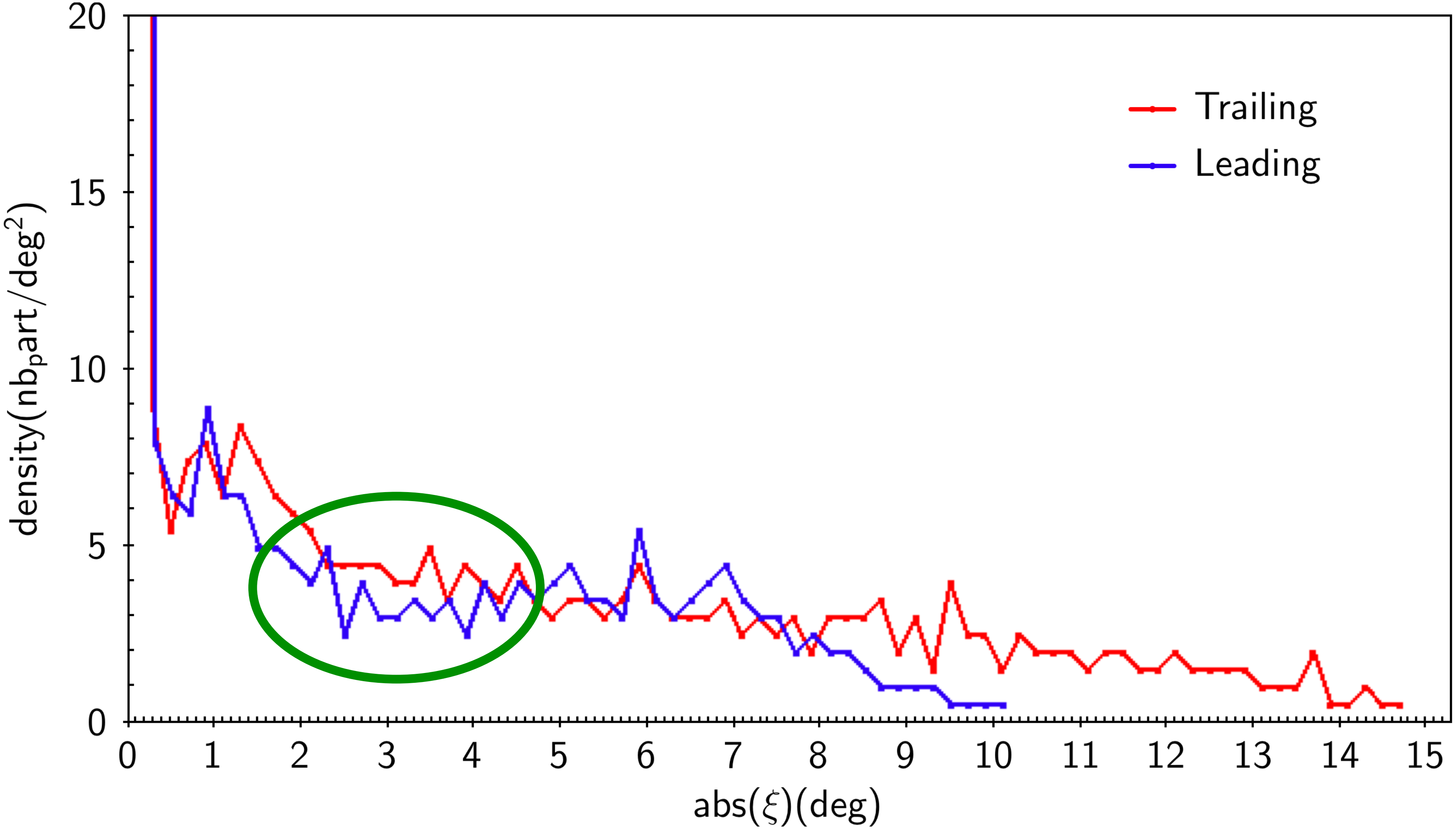

Trailing
Leading
density($nb_p art/deg^2$)
abs(ξ)(deg)
0
5
10
15
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Conclusion

MOND theories imply breaking the SEP
=> search for signatures to back or rule out

- Sgr stream: no influence of EFE, massive squashed corona helps fitting leading arm velocities
- Pal 5 stream: holds important clues: asymmetry could be linked to DM subhalos or the bar. In both cases, stream stars should reappear further away. In MOND, the breaking of the strong equivalence principle creates a true asymmetry
- Measuring the binary fraction and contribution to the velocity dispersion in Pal 5 also very important in the future…
- Construct ansatz for direct N-body code in MOND + check for lopsidedness of globular clusters

+POSSIBLE DEPENDENCE WITH RADIUS? (predicted by SFDM framework...)