Probing the strong equivalence principle with Local Group globular clusters and their stellar streams

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The strong equivalence principle

- **Strong equivalence principle:** *the outcome of any local experiment (gravitational or not) in a freely falling laboratory is independent of the velocity of the laboratory and its location in spacetime.*

➡ **Results will always be the same**

MOND and the strong equivalence principle

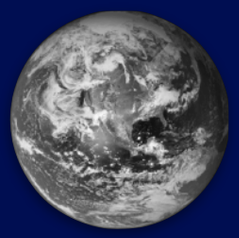
$$a_N \leq a_0$$

For the same density than Earth:
dust grain of 0.05 mm

$$\mathbf{a_N} = a_{N,obj} + a_{N,ext}$$

$$\mathbf{a_{obj}} = \nu\left(\frac{\mathbf{a_{N,obj}} + \mathbf{a_{N,ext}}}{a_0}\right)\mathbf{a_{N,obj}} + a_{N,ext}\left[\nu\left(\frac{\mathbf{a_{N,obj}} + \mathbf{a_{N,ext}}}{a_0}\right) - \nu\left(\frac{\mathbf{a_{N,ext}}}{a_0}\right)\right]$$

MOND and the strong equivalence principle



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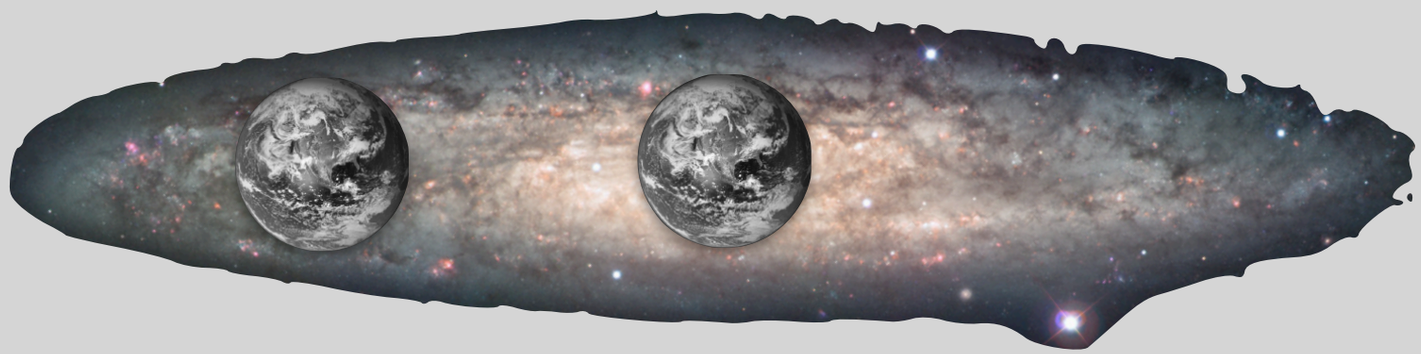
$$a_{N,obj} \gg a_{N,ext}$$

MOND dynamics

$$a_{N,obj} \leq a_{N,ext}$$
$$a_{N,ext} \leq a_0$$

Quasi-Newtonian dynamics



- In MOND the results of the experiment **depend** of the location of the object

➡ **Break the Strong Equivalence Principle**

$$a_{N,obj} < a_{N,ext}$$
$$a_{N,ext} \gg a_0$$

Newtonian dynamics

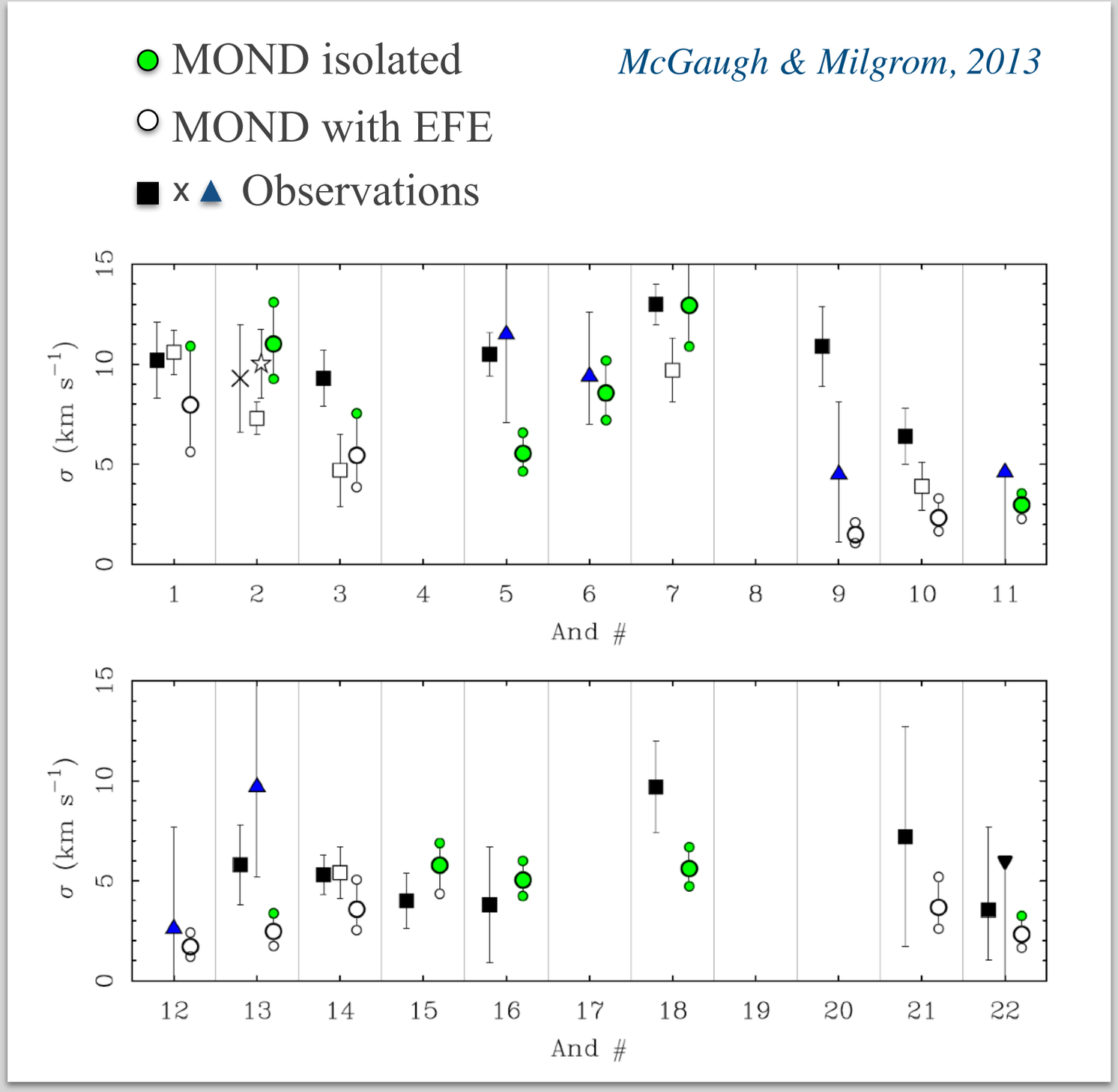
➡ **The external field effect**

The External Field Effect

- **EFE** might plays an important role for the **dynamics of satellite galaxies**

  ➡ e.g. M31's satellites

- But also:
  - Crater II (McGaugh+2018)
  - NGC1052-DF2 (Kroupa+ 2019)



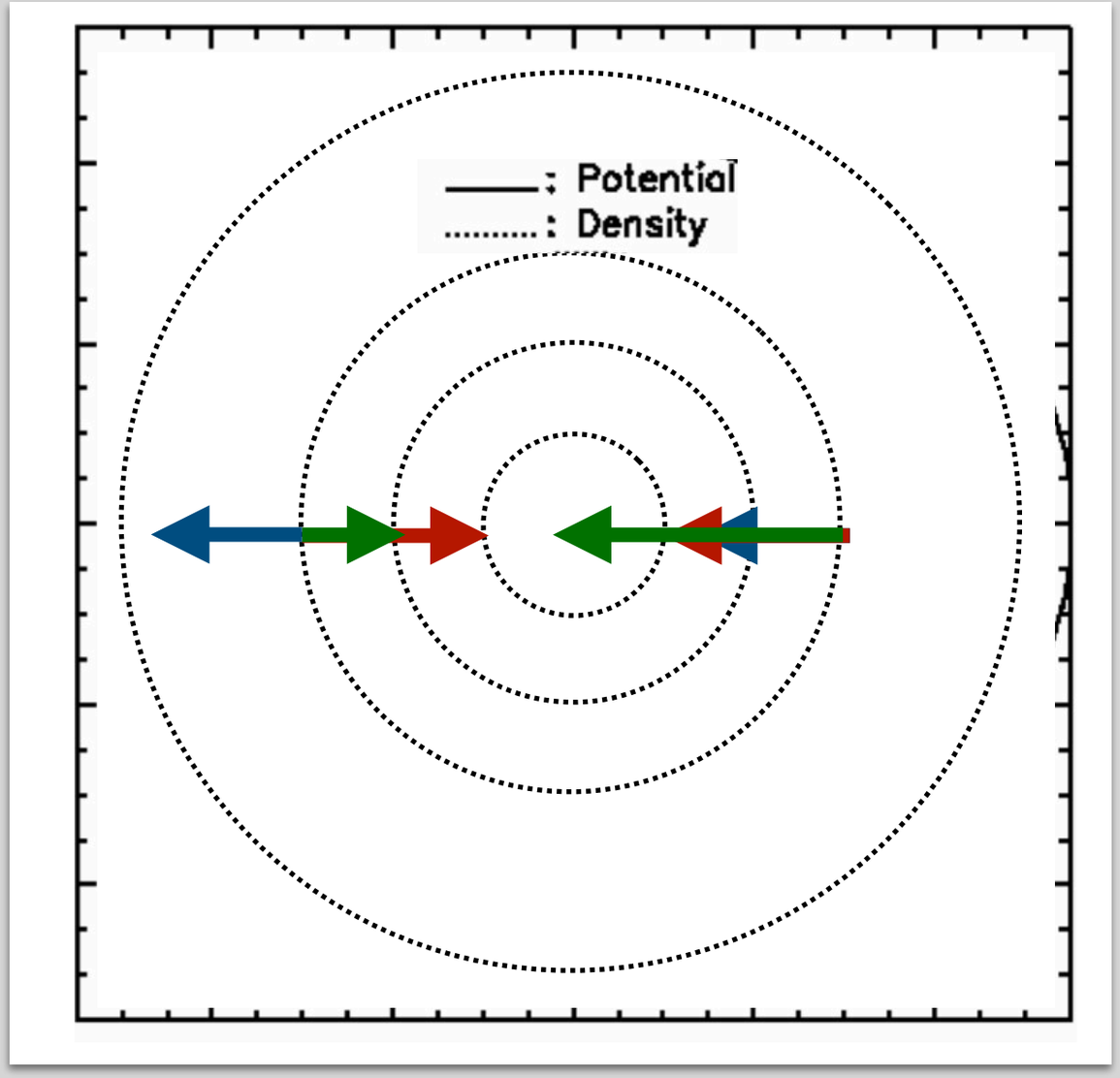
The lopsided effect of the EFE

- **EFE** not only perturb the global internal dynamics, but it also **shape the acceleration (potential)** of the object

➡ **e.g. galaxy in a galaxy cluster**

Legend

$a_{N,ext}$ $a_{N,obj}$ $a_{N,tot}$



Wu et al., 2010

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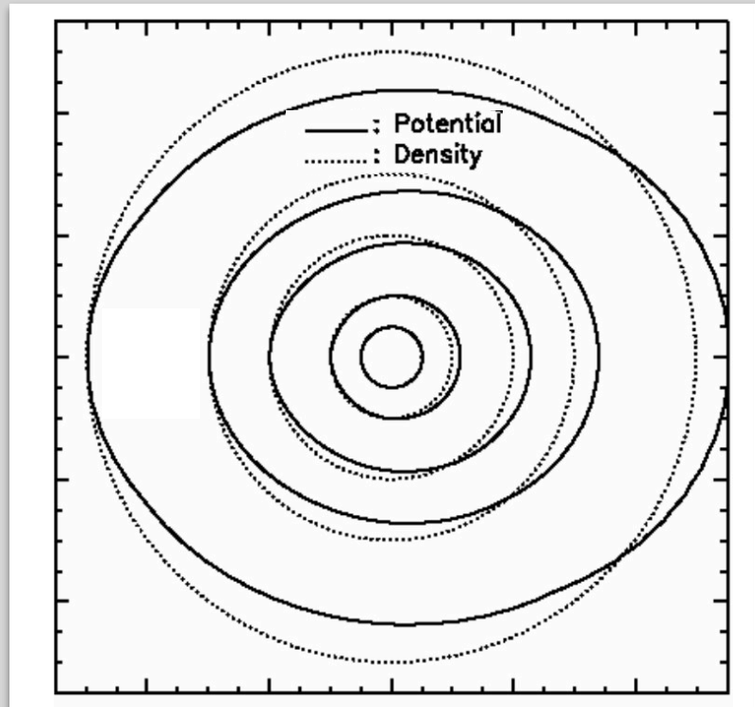
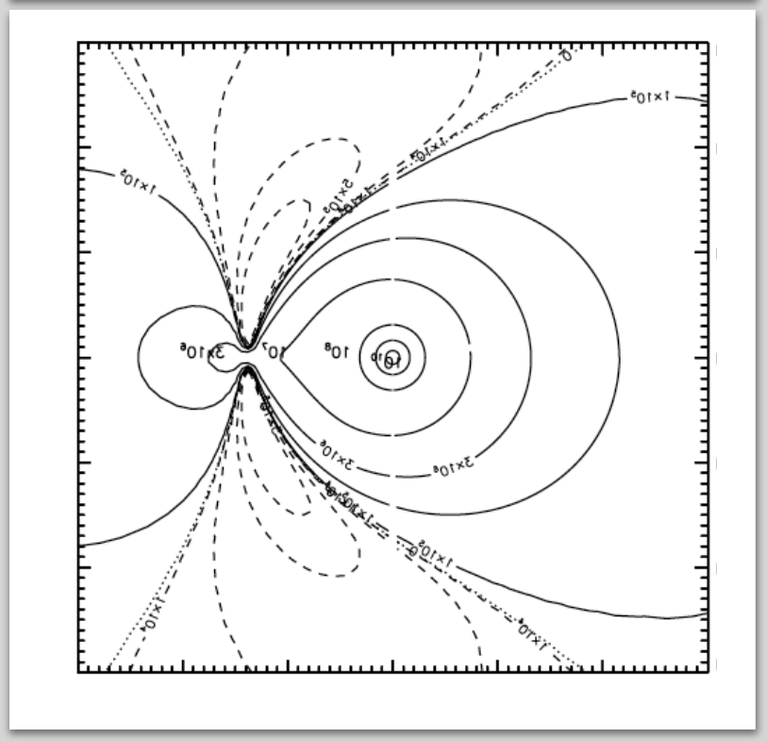


- **QuMOND formalism** : *Quasi-linear formulation of MOND*

$$\nabla^2\Phi = 4\pi G(\rho_b + \rho_{ph})$$

➡ **e.g. lobe of negative phantom dark matter**



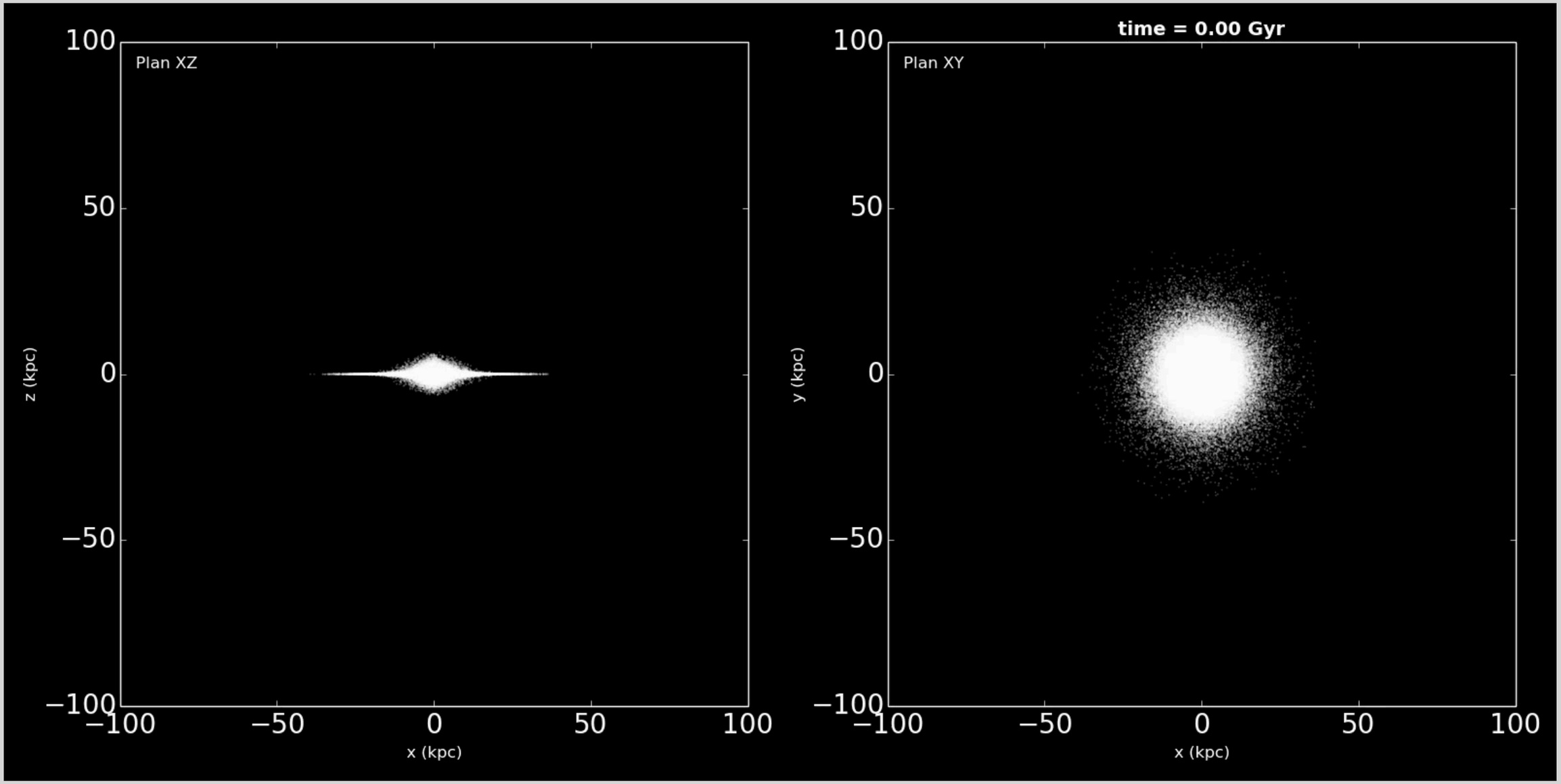
Knebe et al., 2009

<u>Pb for galaxy cluster</u>: Other phenomena can produce it (e.g. **ram pressure stripping**)

Globular clusters are better to probe the External Field Effect

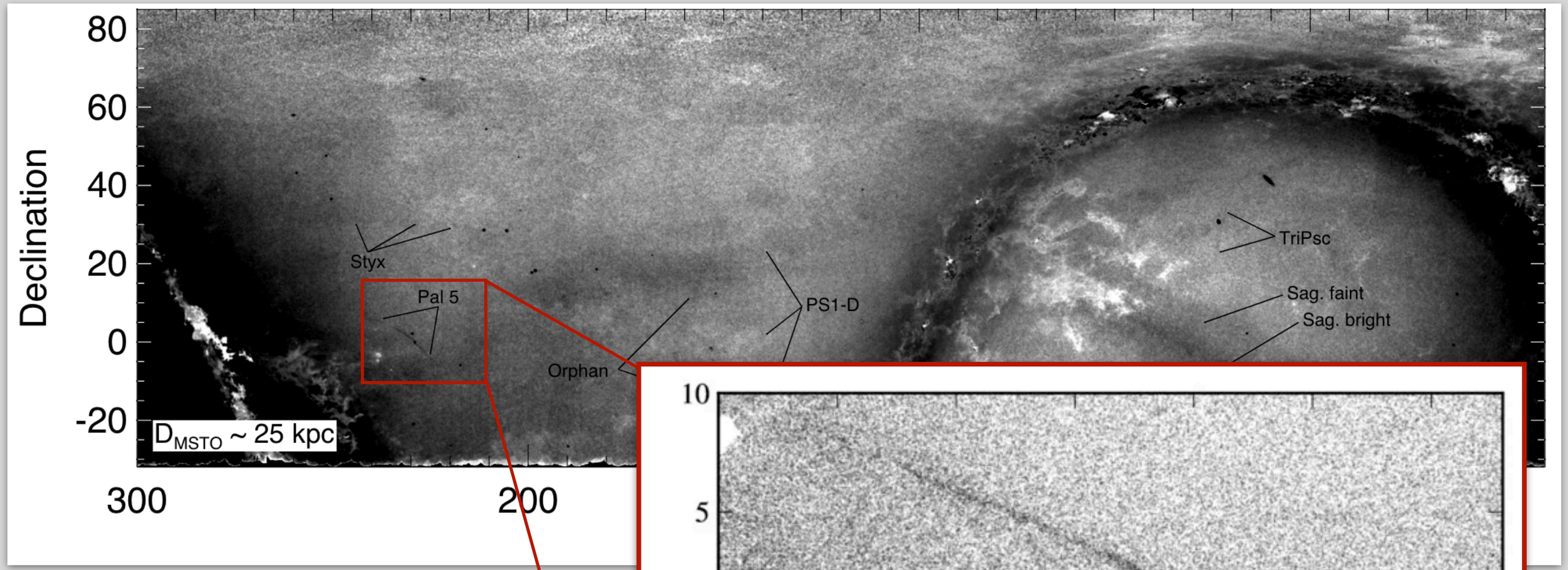
Stellar streams

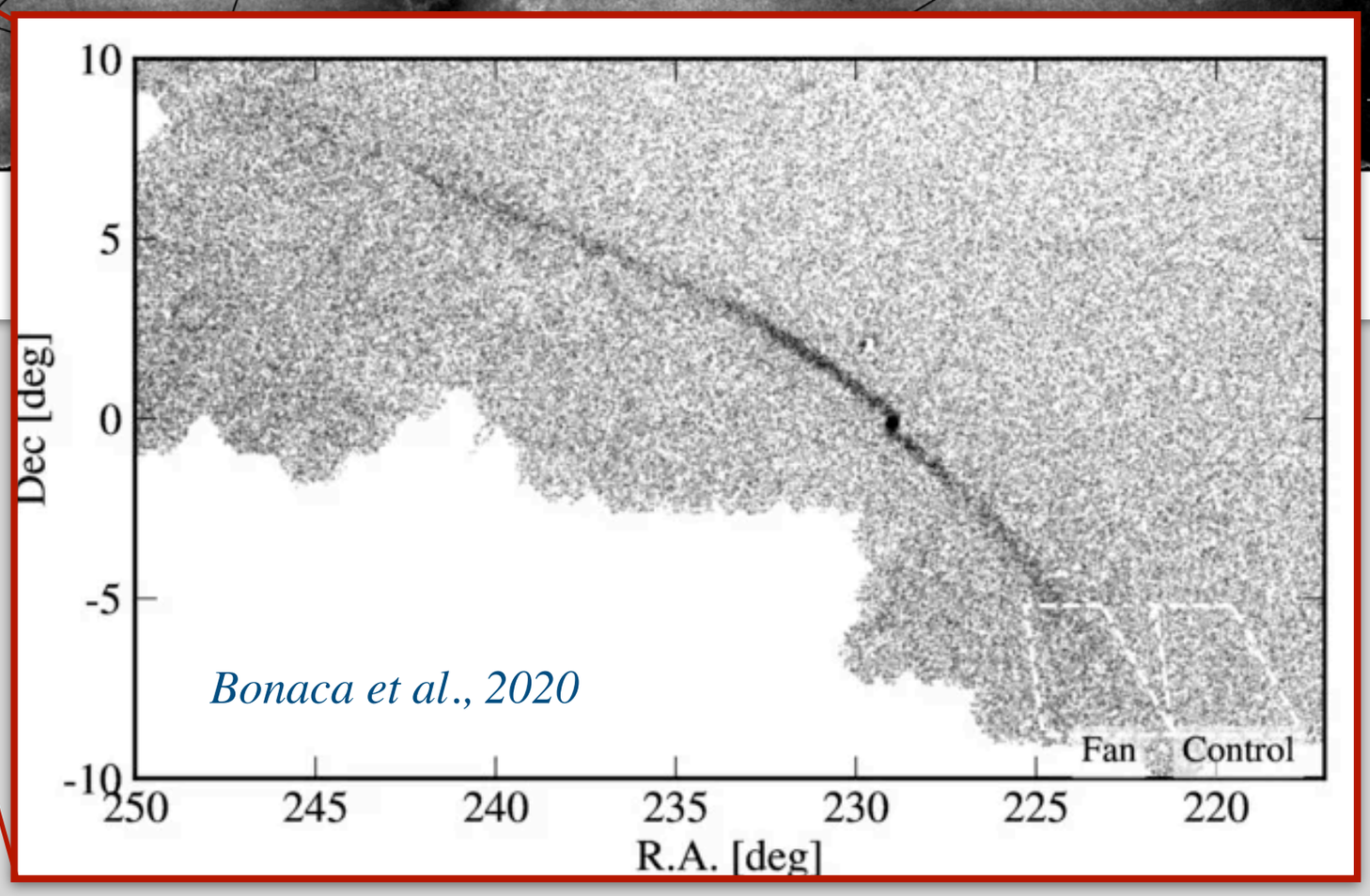
- Stellar streams are formed by the tidal disruption of dwarf galaxies or globular clusters



- More than **50 streams** known around the Milky Way
  … only 9 with surviving progenitor

Stellar streams



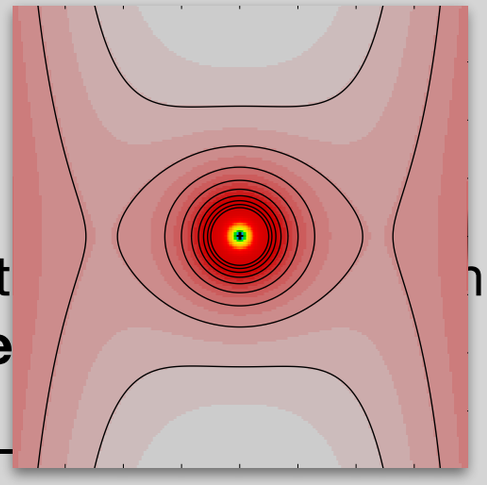


Asymmetry of the Pal 5 stream :

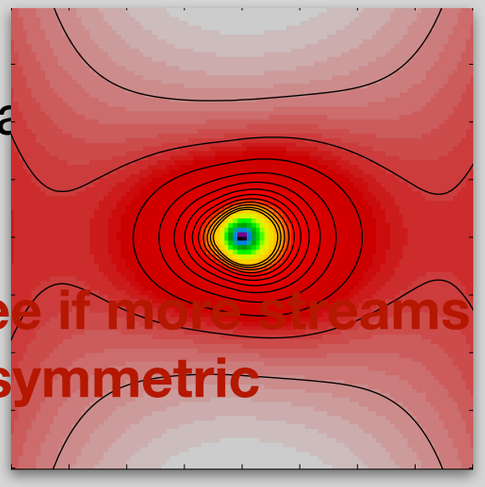
- Trailing arm 17°
- Leading arm 8°

Palomar 5 stream

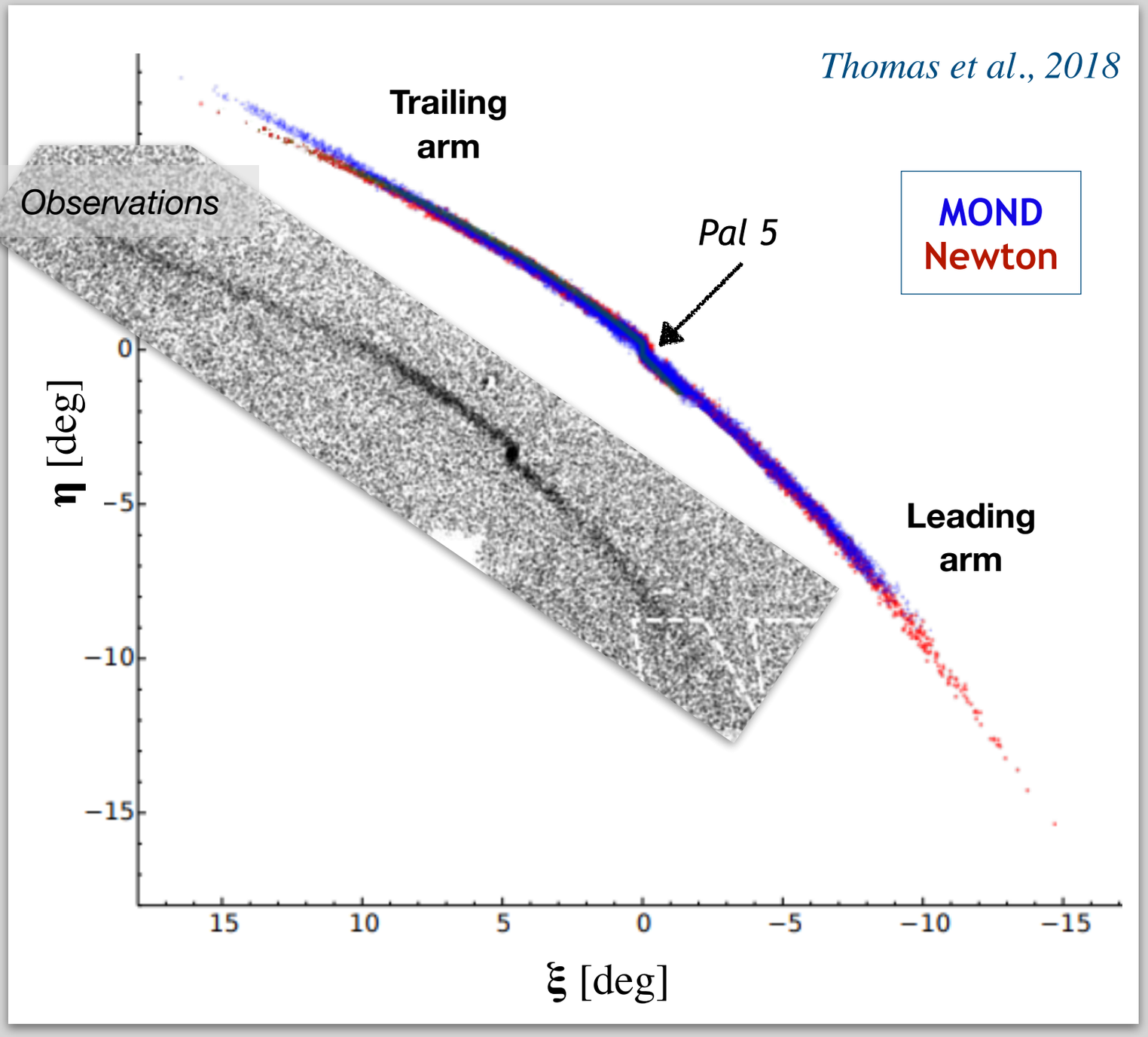
- **<u>In MOND</u>:** Pal 5 is **asymmetric**
- **<u>In Newton</u>:** Pal 5 is **symmetric**



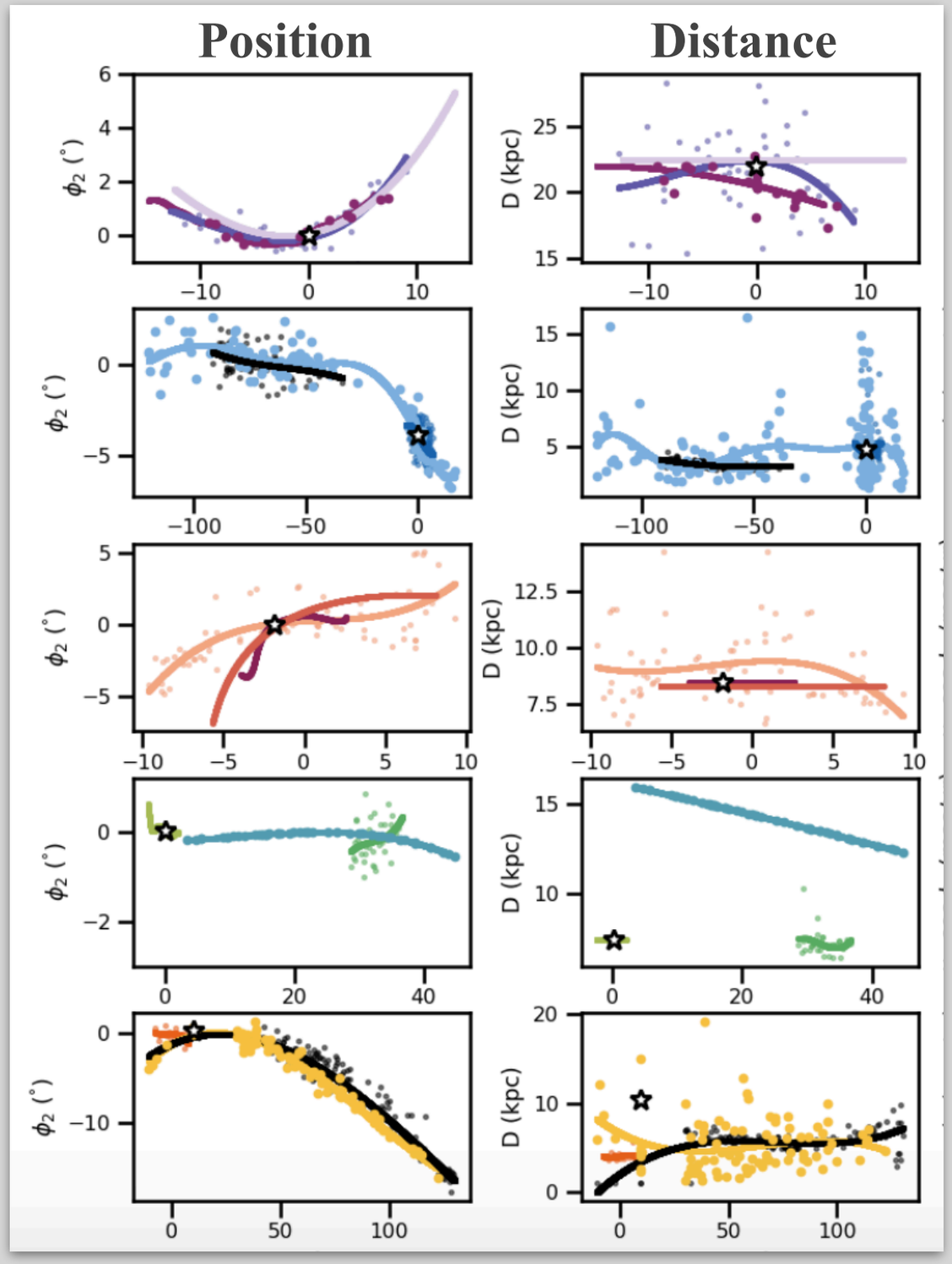
- But in **ΛCDM** t… be due to **exte…**
  - Flyby dark-…
  - GMCs
  - Galactic ba…



Need to see if more streams are also asymmetric



EFE in other streams?



Mateu 2022

Pal 5

NGC 3201 - Gjoll

M92

M5

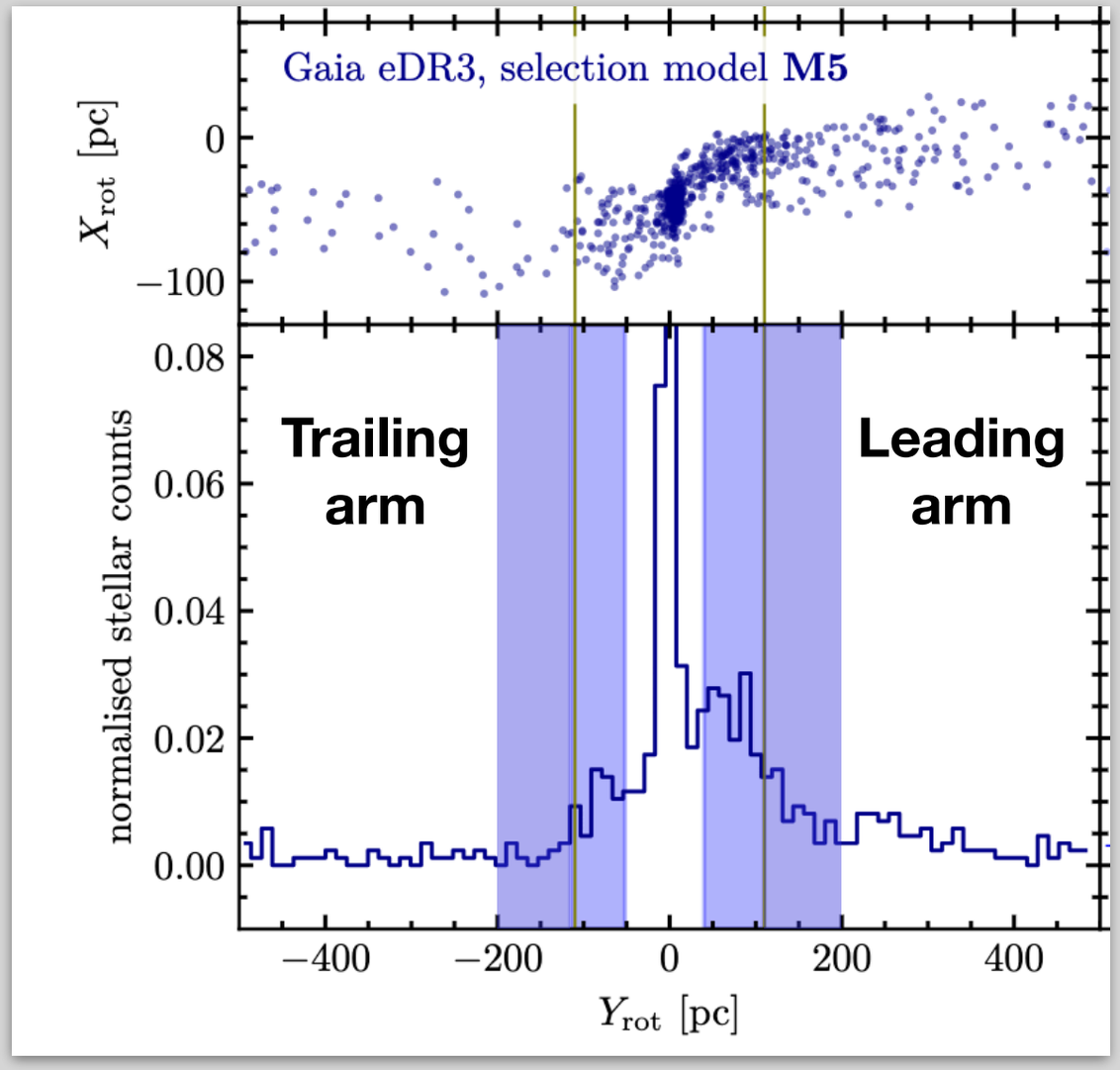
M68

Open clusters stream: Hyades

- Hyades stream is 800 pc long
- **Density asymmetry** leading/trailing arm

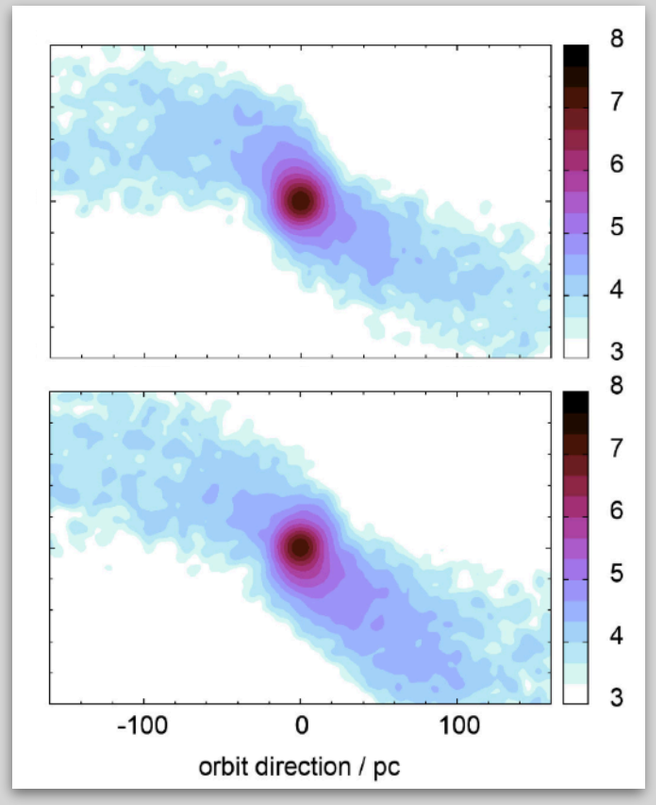
$$Q = \frac{N_{lead}}{N_{trail}} = 2.53 \pm 0.37$$ *Kroupa et al., 2022*

Jerabkova et al., 2022



Newton

MOND



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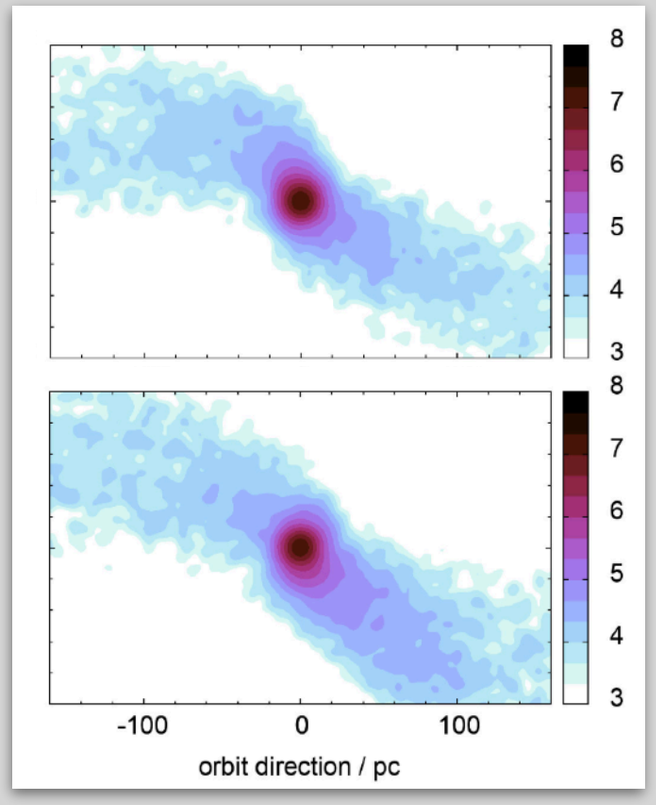
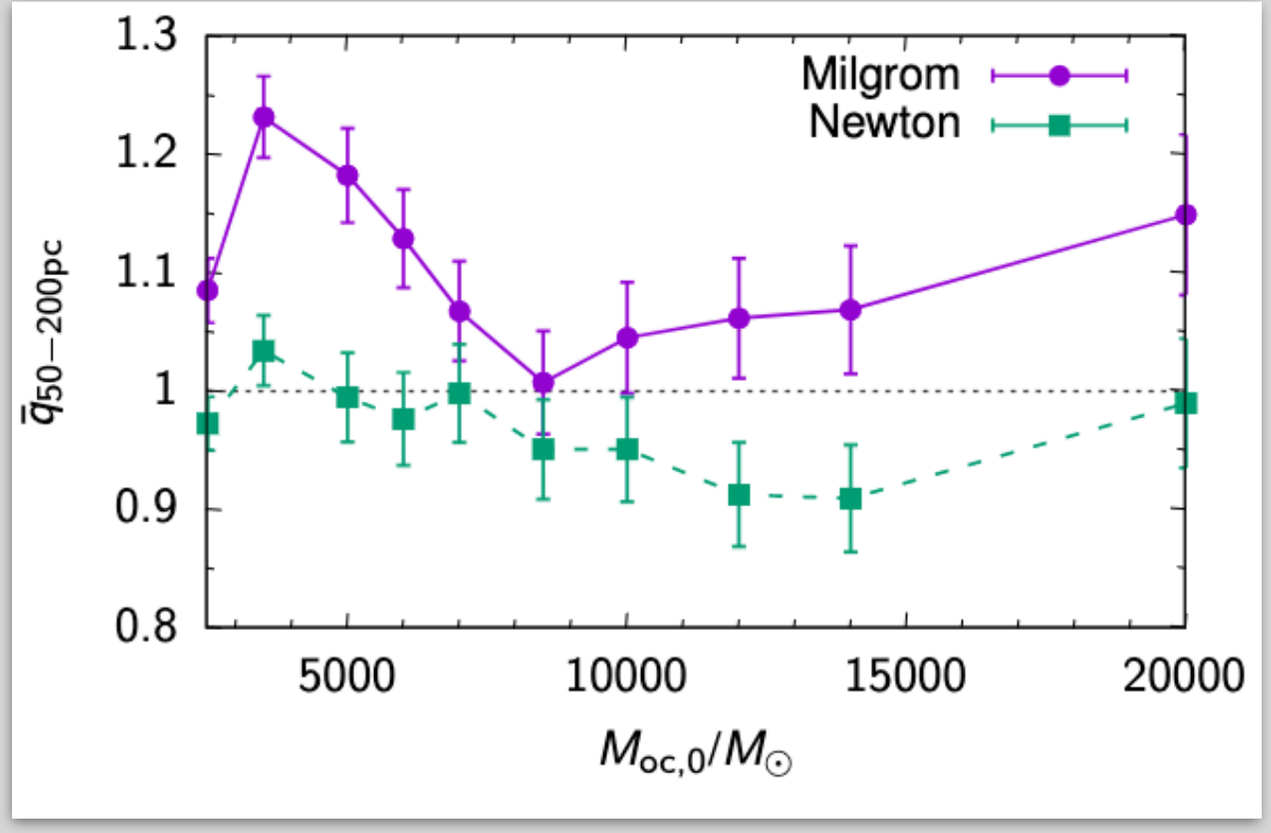
MOND

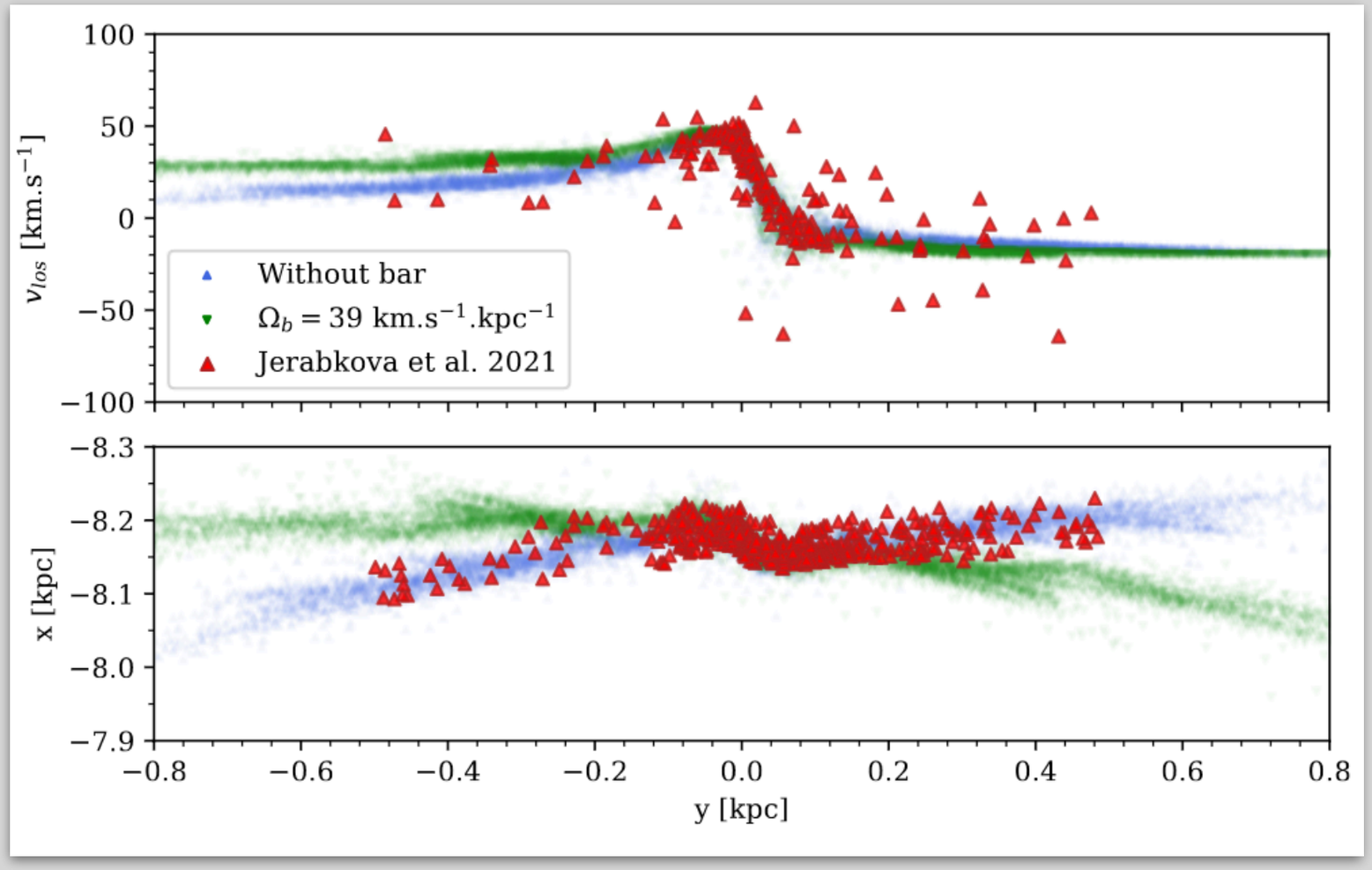




But…

The problem of the bar

Thomas et al., submitted



- **Previous observations of Hyades stream contain ~20% contaminants**
- The presence of the bar can change the track of the stream

- Previous observations $Q = 2.53 \pm 0.37$
- Track in the **absence of a bar** $Q \simeq 1.36$
- Track with a (fast) **bar** $Q \simeq 1.10$

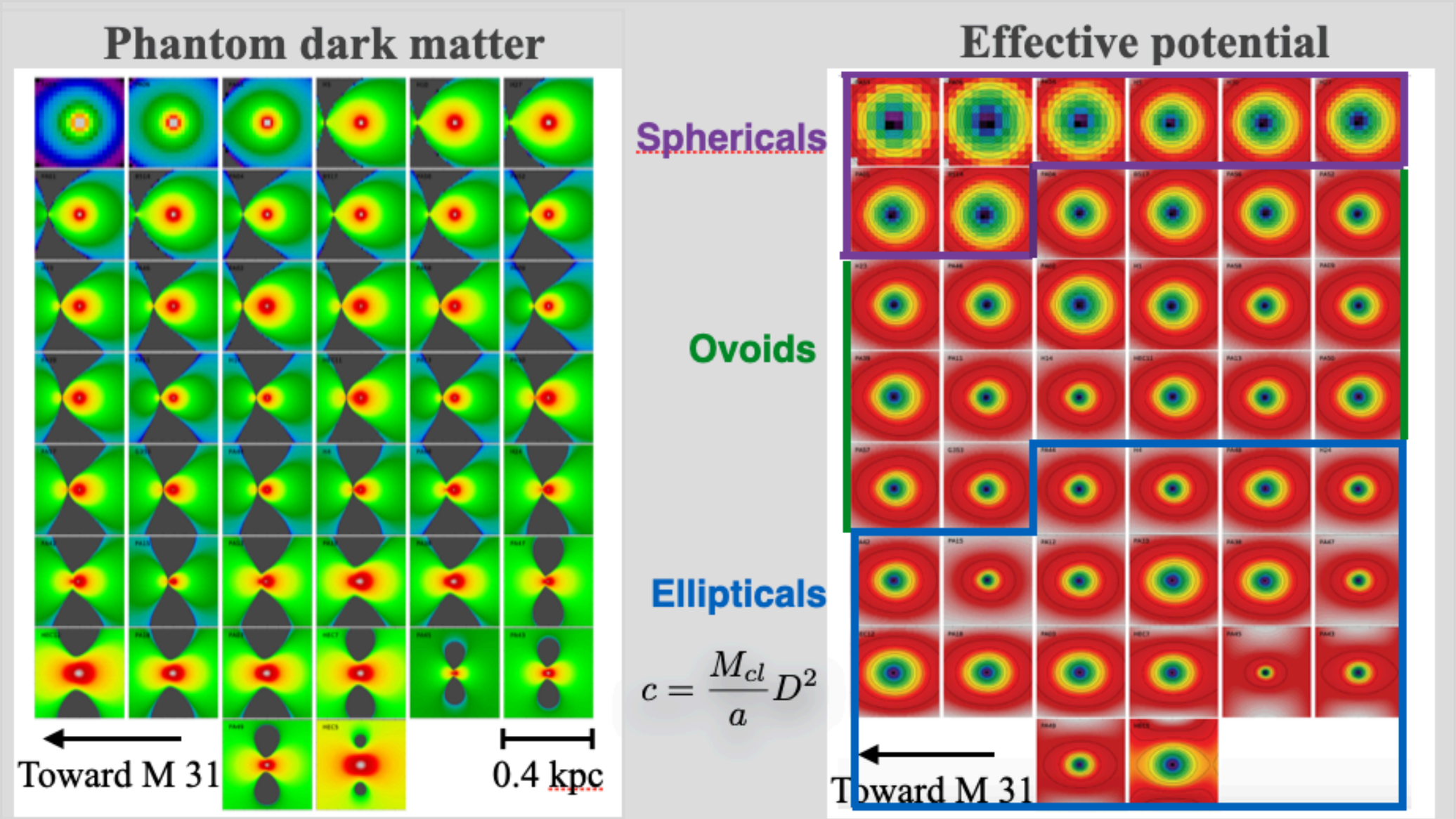
Asymmetry of the Hyades in MOND

$$Q \simeq 1.2 - 1.3$$

Future perspectives

Future perspectives

- **External field effect** can lead to have an egg-shape external morphology of a globular cluster
  - NOT ALWAYS TRUE



Future perspectives

- **External field effect** can lead to have an egg-shape external morphology of a globular cluster

  - NOT ALWAYS TRUE
  - **But an egg shape is not predicted in Newtonian gravity**

  - **2 perspectives:**
    - **Observational:** Detect and quantify the degree of lopsidedness
    - **Theoretical:** Do prediction in MOND

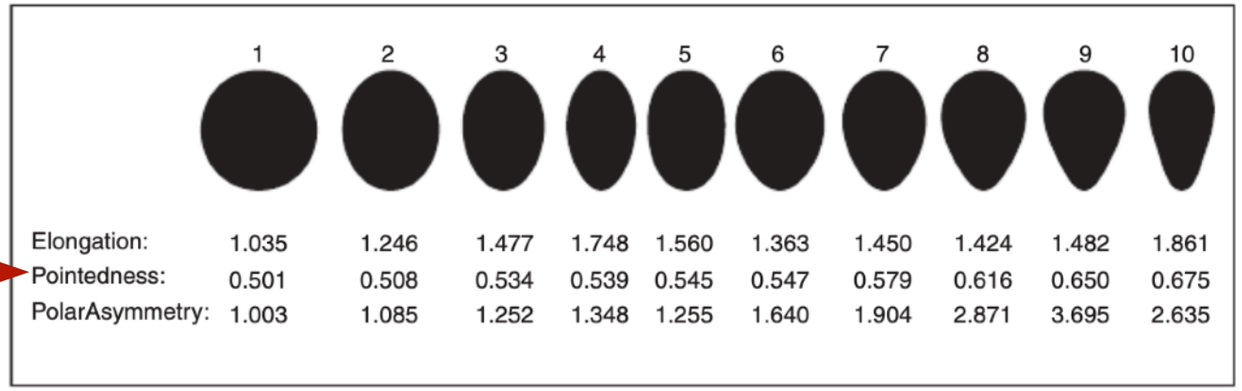
Observational perspectives

- **Observational:** Detect and quantify the degree of lopsidedness

HOW?

Accurately quantifying the shape of birds' eggs

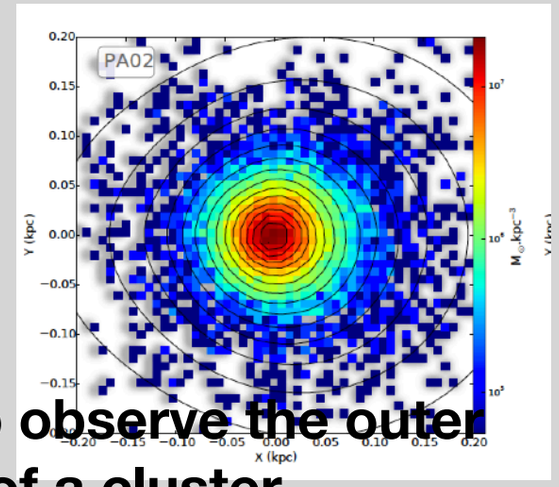
John D. Biggins[1] | Jamie E. Thompson[2] | Tim R. Birkhead[2]



	1	2	3	4	5	6	7	8	9	10
Elongation:	1.035	1.246	1.477	1.748	1.560	1.363	1.450	1.424	1.482	1.861
Pointedness:	0.501	0.508	0.534	0.539	0.545	0.547	0.579	0.616	0.650	0.675
PolarAsymmetry:	1.003	1.085	1.252	1.348	1.255	1.640	1.904	2.871	3.695	2.635

- **Pb to observe the outer part of a cluster**

Observational perspectives



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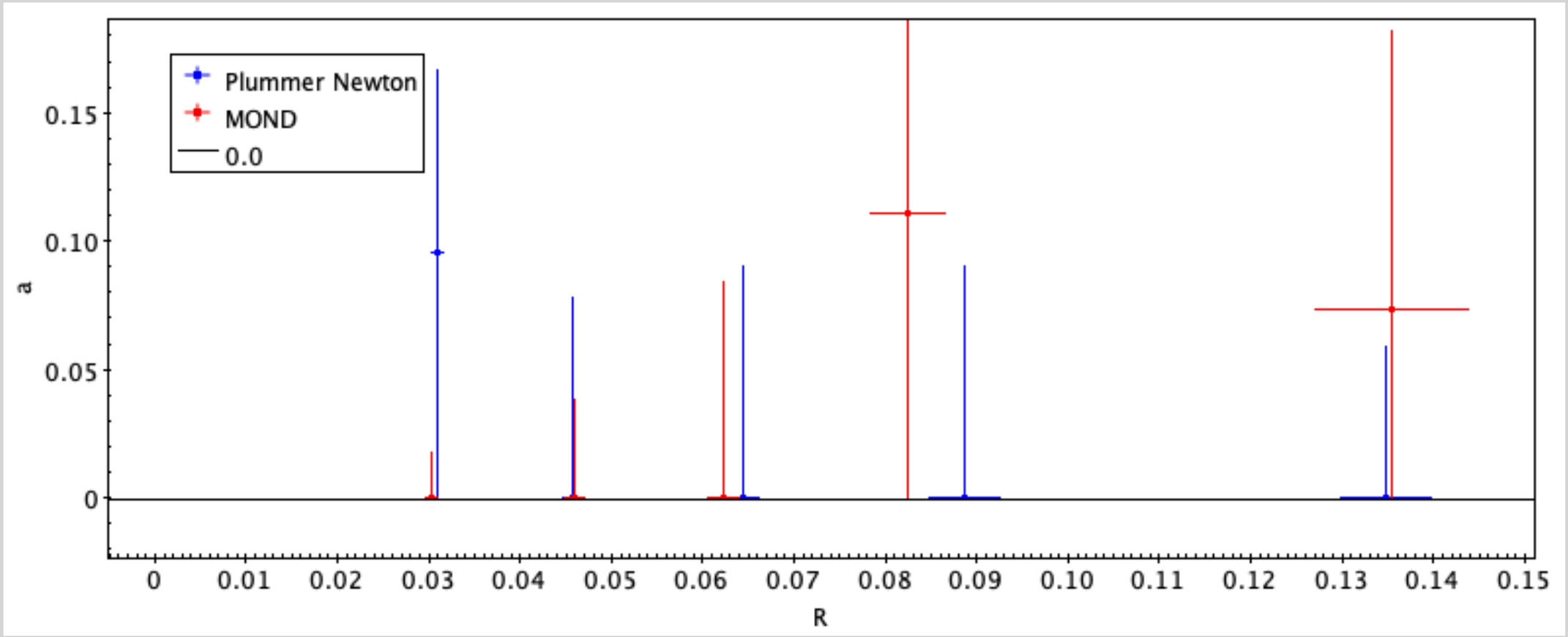


Observational perspectives

- **Pb to observe the outer part of a cluster**

In the Milky Way

- **With spectroscopic selection, to remove all contaminant**

Soon

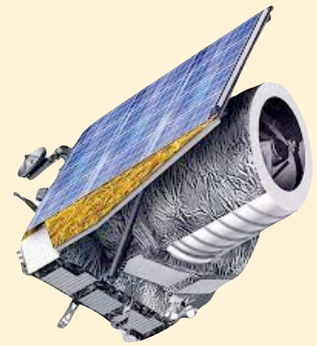
Next decade

+ to have better contraints on streams

In the Local Volume

- **Large statistic on integrated photometry**

➡ Up to ~20 Mpc with Euclid



Conclusions

- MOND break the strong equivalence principle ⟶ **External field effect**
  - ➡ Impact on the global dynamics of objects (e.g. dwarf galaxies)
  - ➡ **<u>Can</u> impact the morphology of objects (e.g. external part of globular cluster)**
    - ➡ **Lead to asymmetry in <u>some</u> stellar stream**

- Need to study more streams in MOND, to see if other stream can be asymmetric

- We **should** use next generation of instrument to mesure the pointless (egg-shape) of the globular clusters of the Local Volume ⟶ **Anostic test of the SEP/EFE**

- Need to model the clusters in MOND and to quantify their level of lopsideness

⟶ **Many work both on the observational and on the modelling side**

Extra

Banik & Kroupa 2019