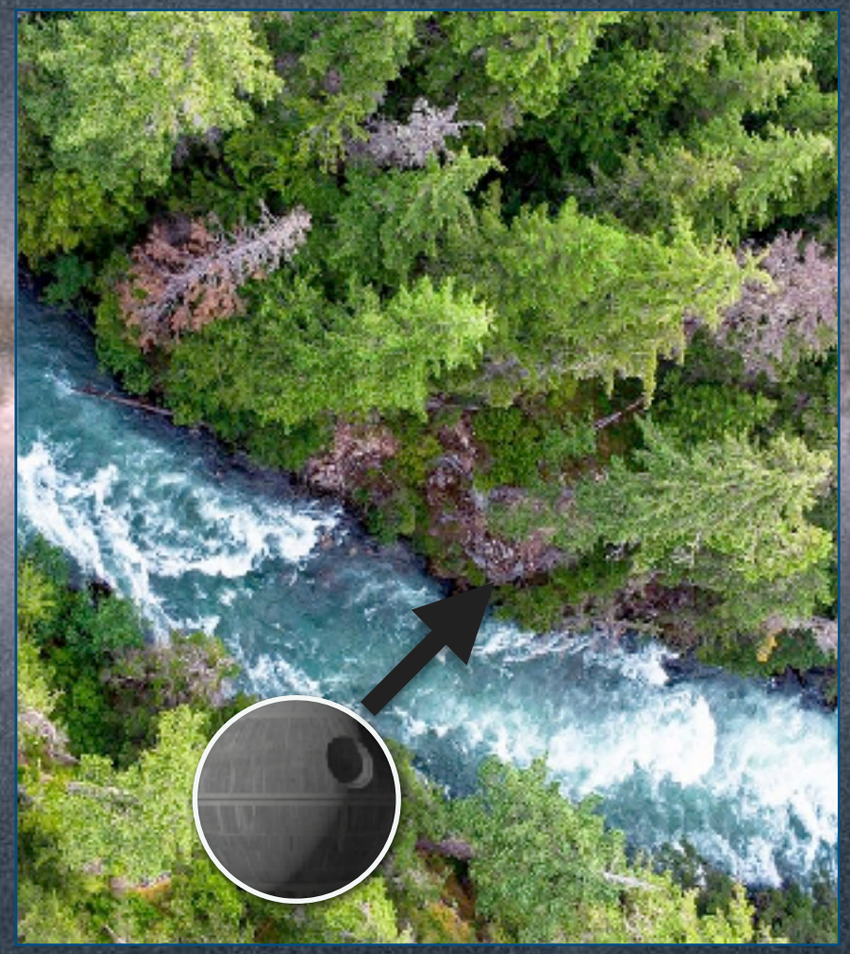
Subhalo-induced stellar gaps

Guillaume THOMAS

Instituto de Astrofísica de Canarias

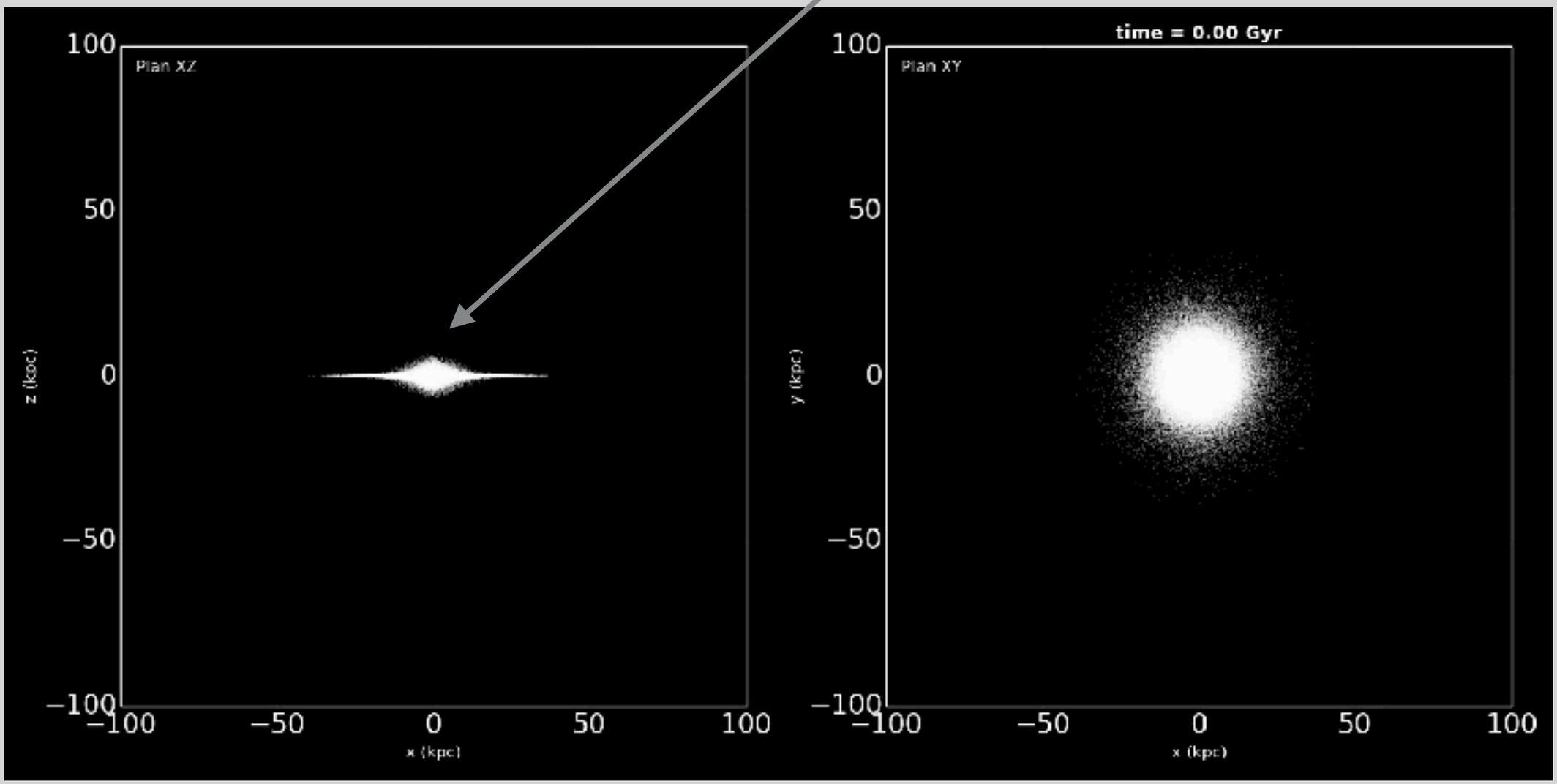


EXCELENCIA SEVERO OCHOA

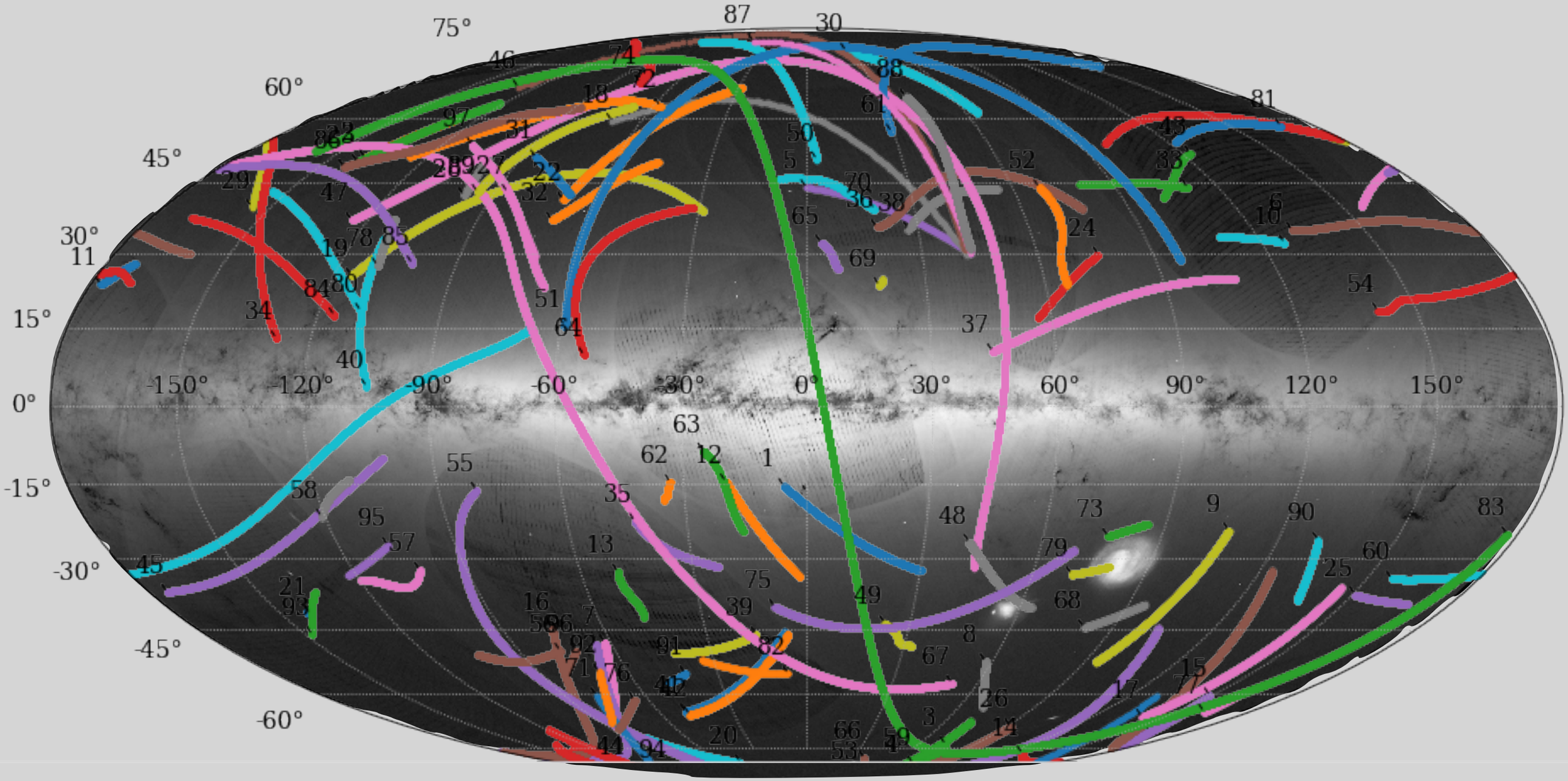
GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA E INNOVACIÓN

What is a stellar stream ?

The stellar streams



The stellar streams

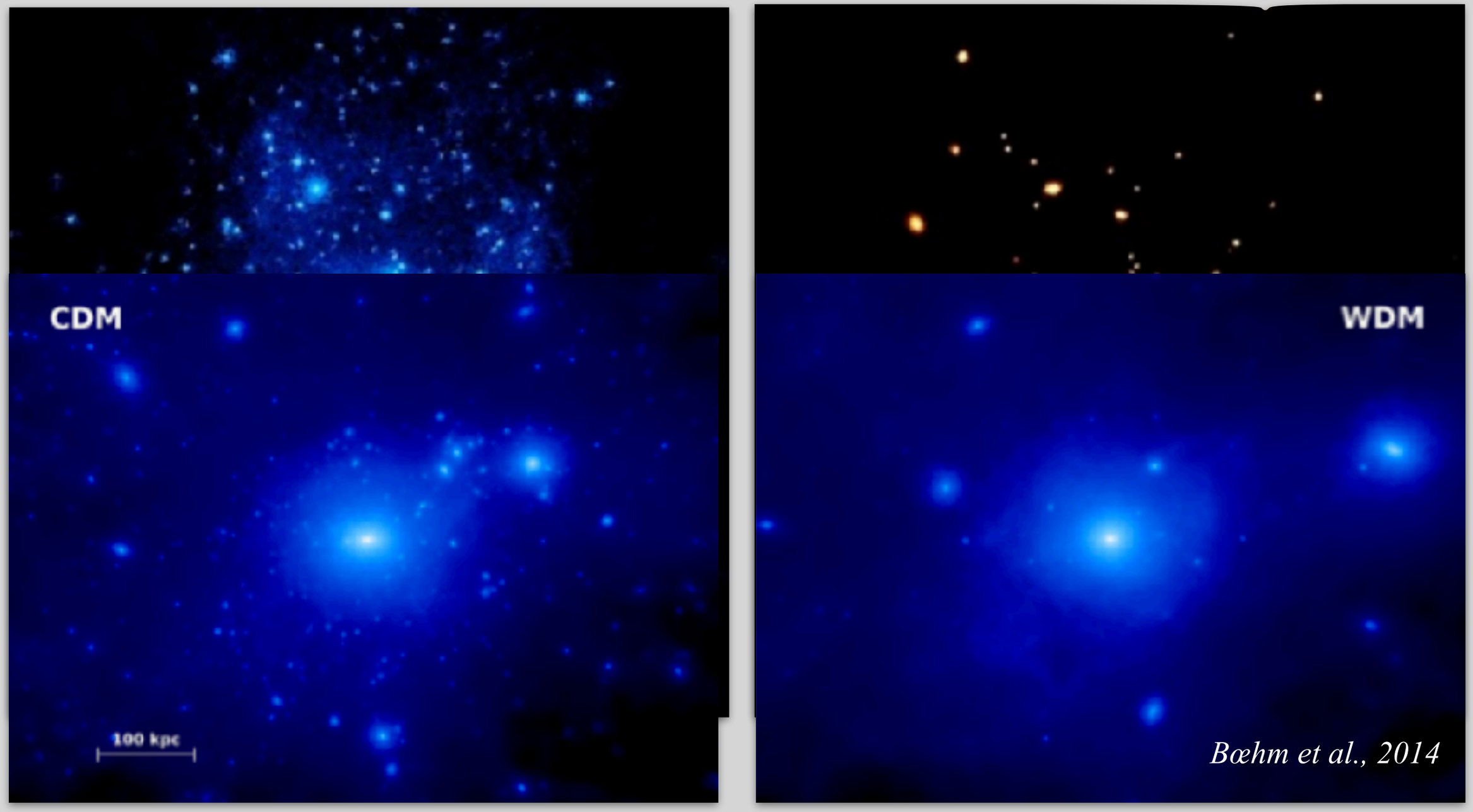


Quantify the number of dark matter sub-haloes with stellar streams

Why ?

Dark Matter

Stars



How ?

Dwarf galaxies

Globular clusters

Message from webpage

The *Pristine* survey – XVIII.
C-19: Tidal debris of a dark matter-dominated globular cluster?

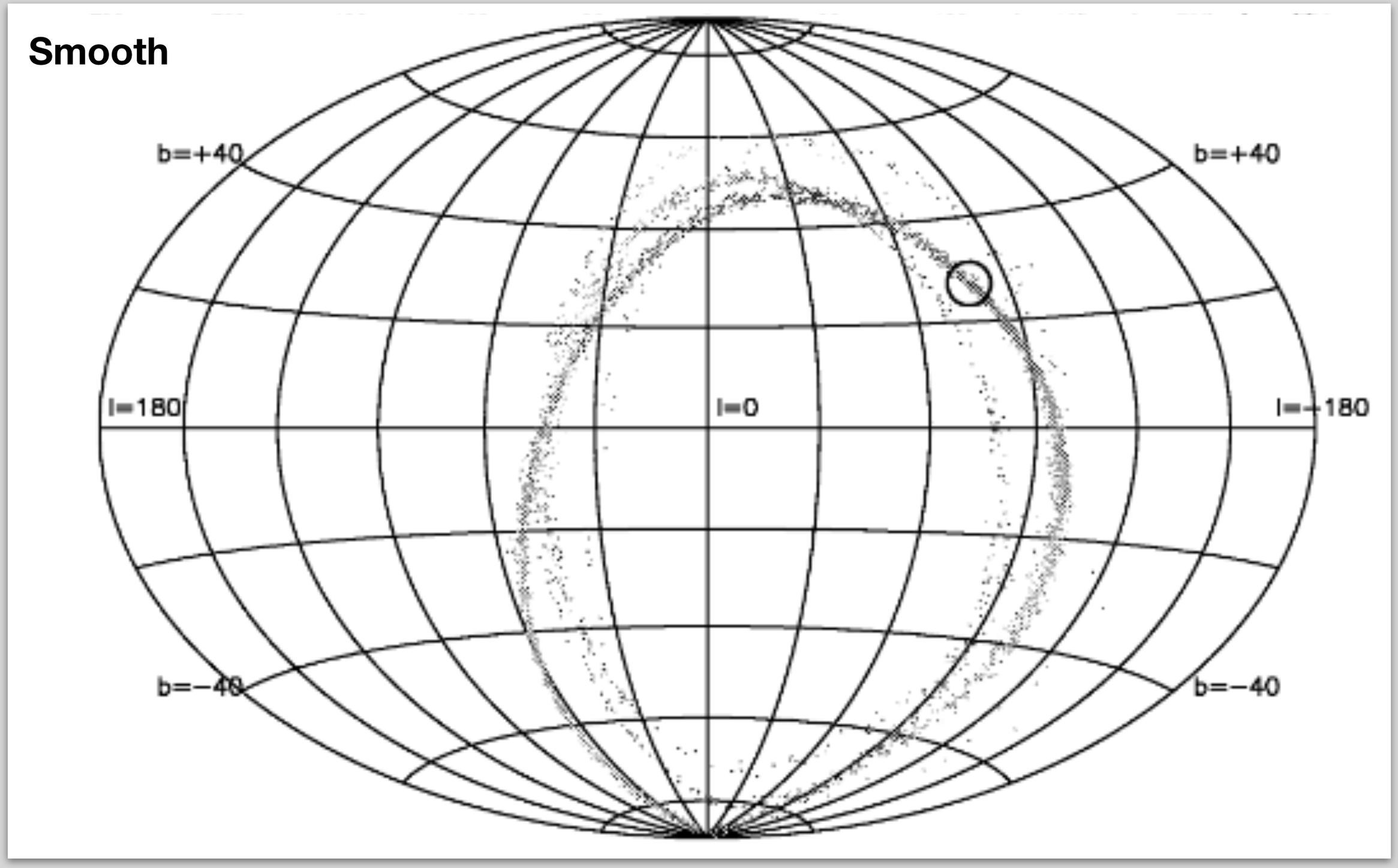
Raphaël Errani[1]★, Julio F. Navarro[2], Rodrigo Ibata[1], Nicolas Martin[1], Zhen Yuan[1],
David S. Aguado[3,4], Piercarlo Bonifacio[5], Elisabetta Caffau[5],
Jonay I. González Hernández[6,7], Khyati Malhan[8], Rubén Sánchez-Janssen[9],
Federico Sestito[2], Else Starkenburg[10], Guillaume F. Thomas[6,7], Kim A. Venn[2]

OK

- **Dark matter dominated**
  - ➡ Dynamically hot streams
- Low brightness

- **No dark matter**
  - ➡ Dynamically cold streams
- High brightness

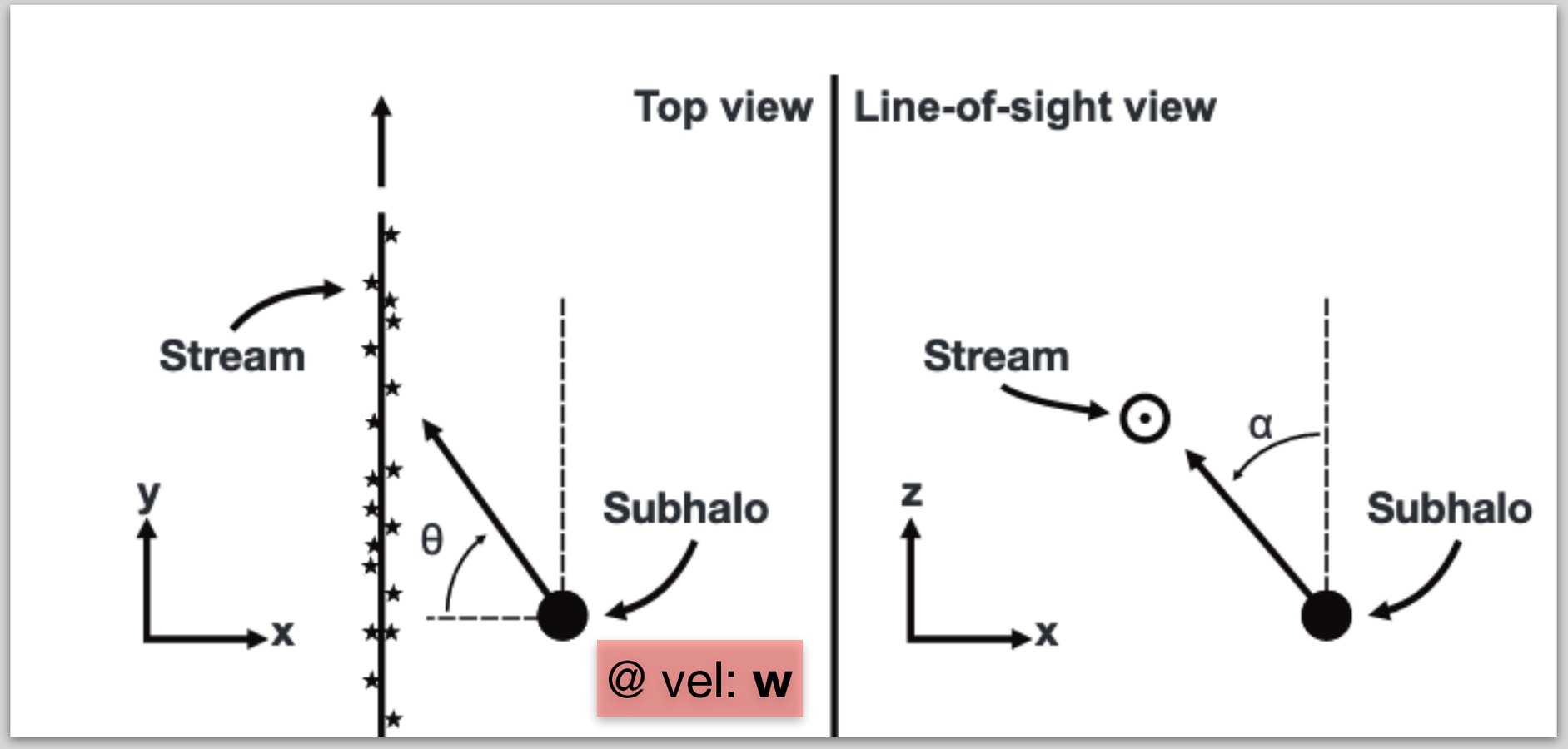
DM subhalo gaps



Ibata et al. 2002; Johnston et al. 2002

DM subhalo gaps

- DM interaction with cold stream can be described by the **impulse approximation**



Koppelman & Helmi, 2021

DM subhalo gaps

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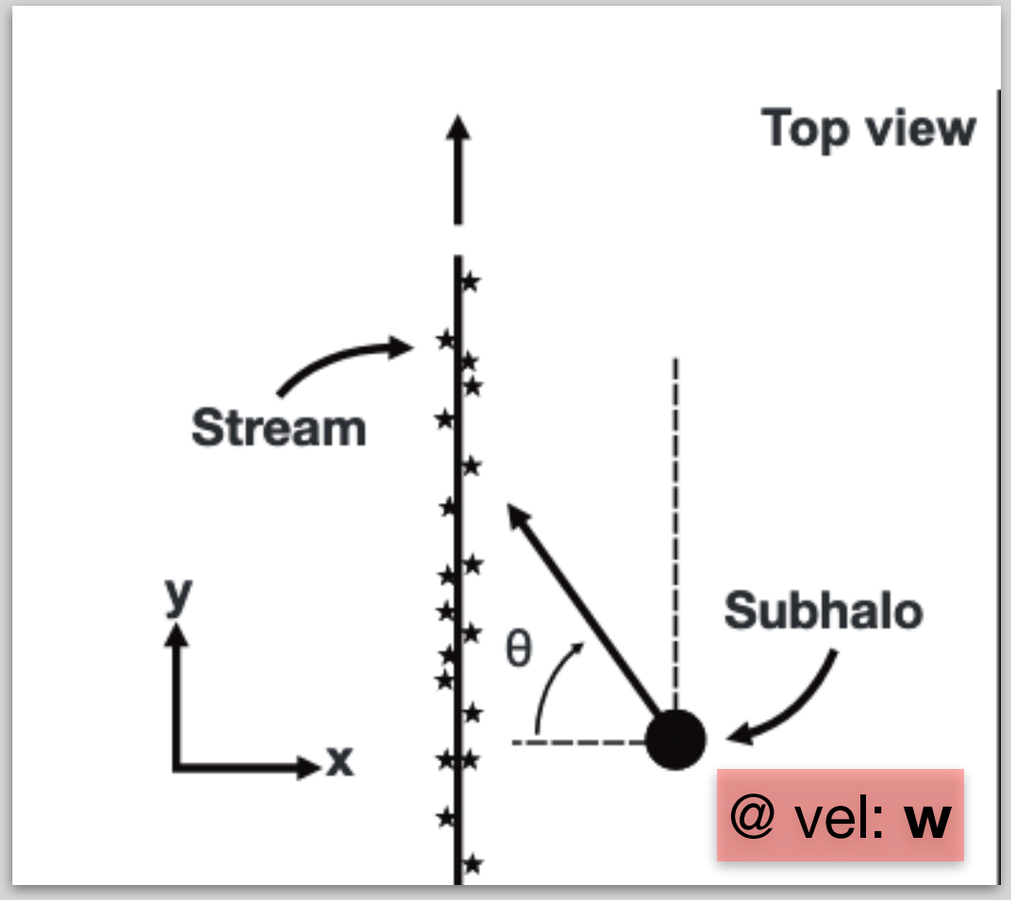
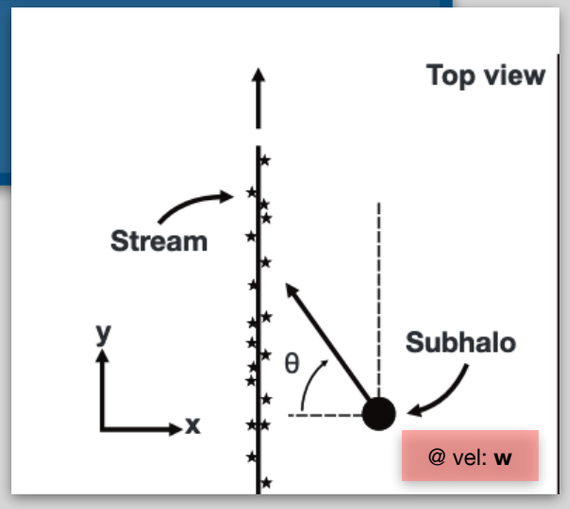


Koppelman & Helmi, 2021
Erkal et al. 2015, 2016
Yoon et al. 2011
Carlberg 2009, 2012, 2013

DM subhalo gaps

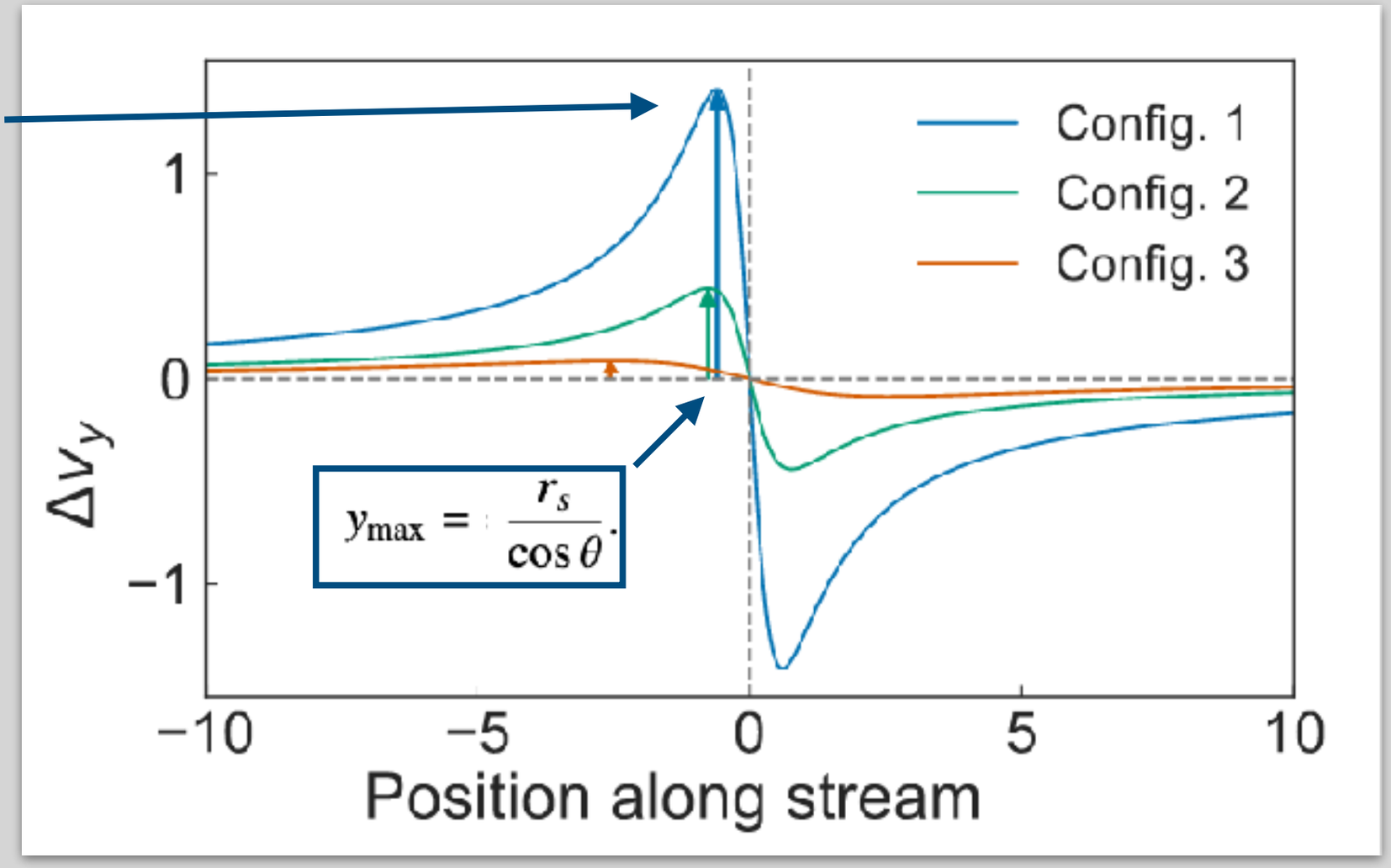


- DM interaction with cold stream can be described by the **impulse approximation**

Change of velocity:

$$\Delta v_i = \int_{-\infty}^{\infty} a_i(\boldsymbol{x}, \boldsymbol{w}, M, r_s)\mathrm{d}t,$$

$$\Delta v_i^{\max} = -\frac{2GM}{w}\frac{w^2 x_i - w_i w_y y_{\max}}{(r_s^2 + y_{\max}^2)w^2 - (y_{\max} w_y)^2}$$



Koppelman & Helmi, 2021
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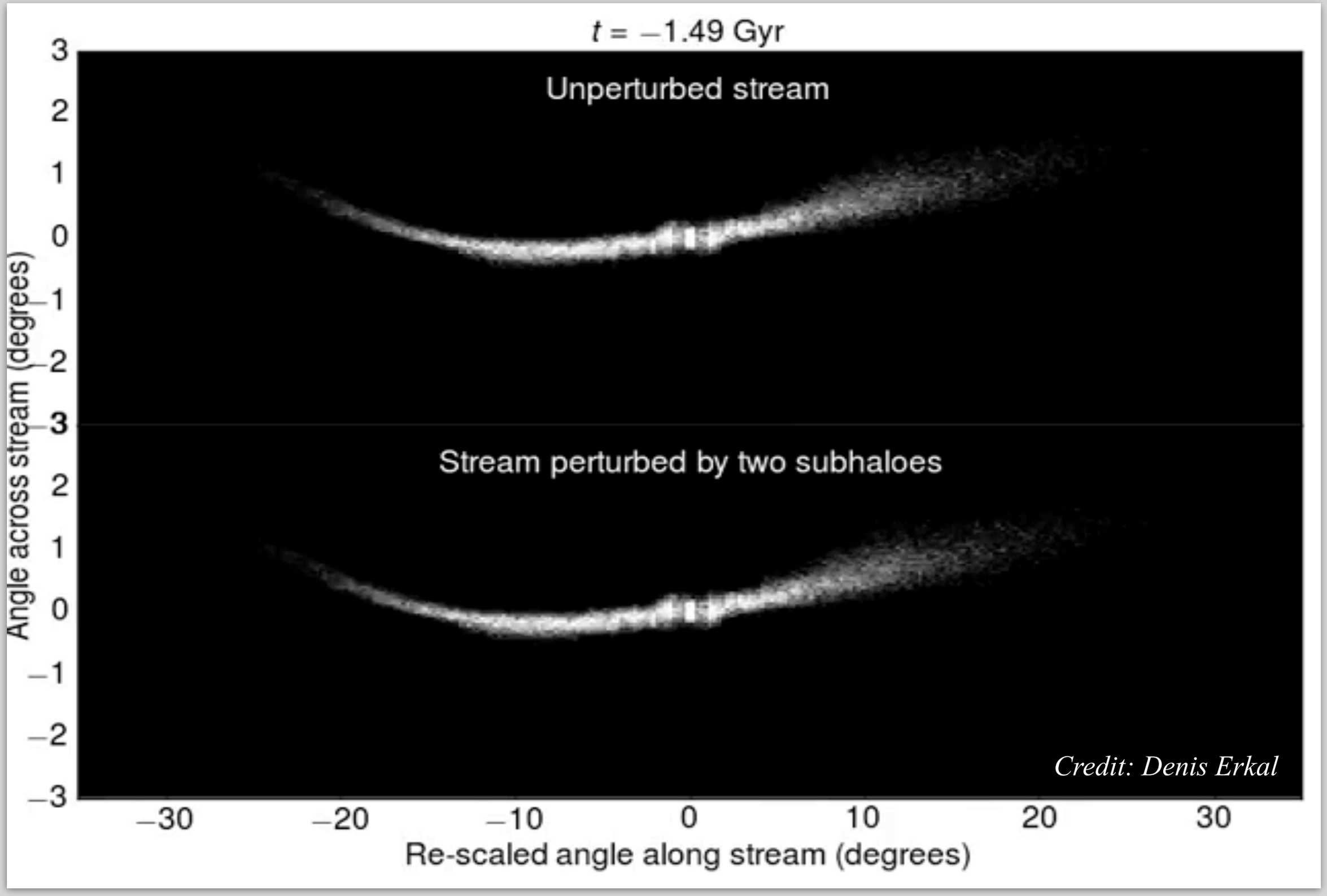
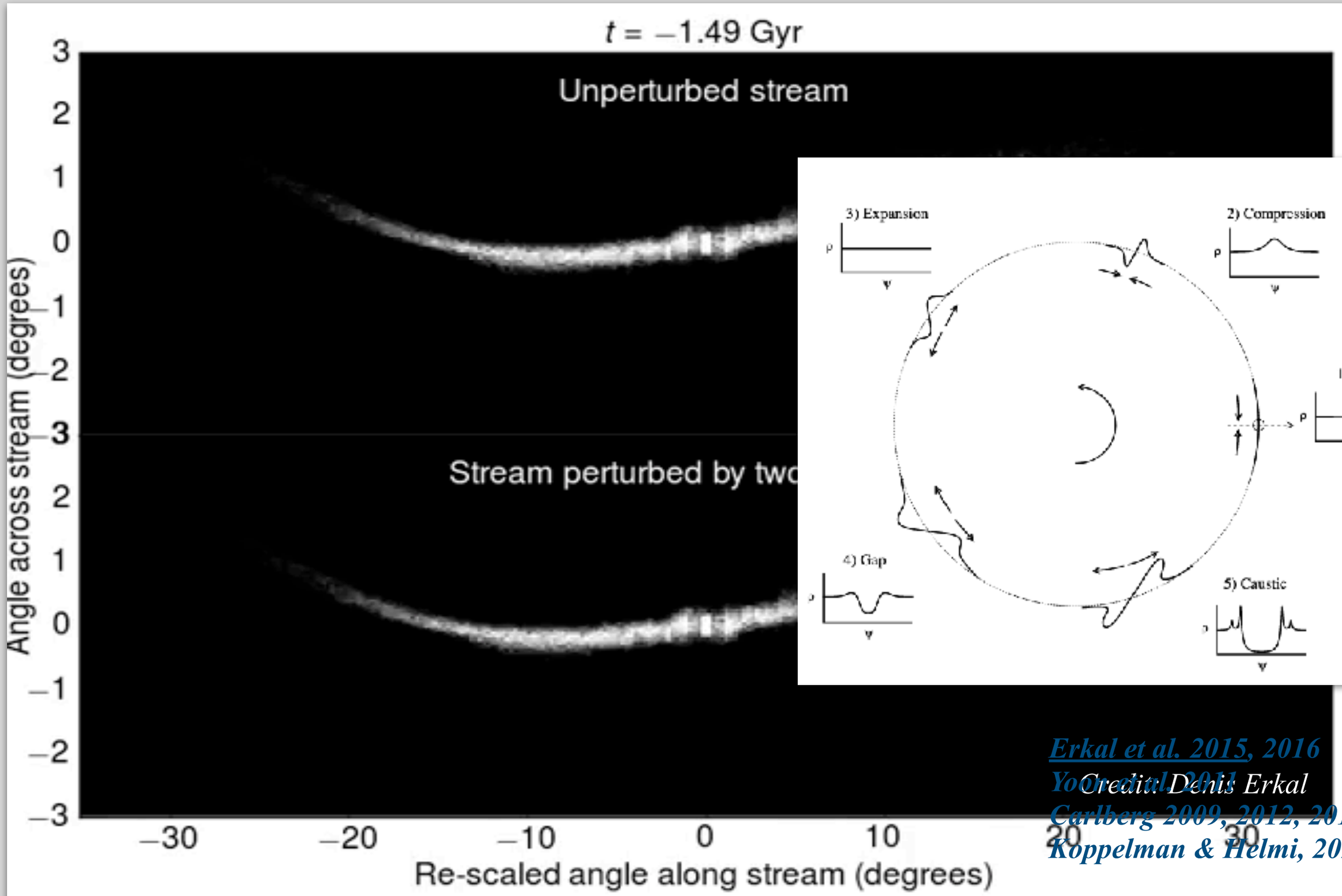
DM subhalo gaps



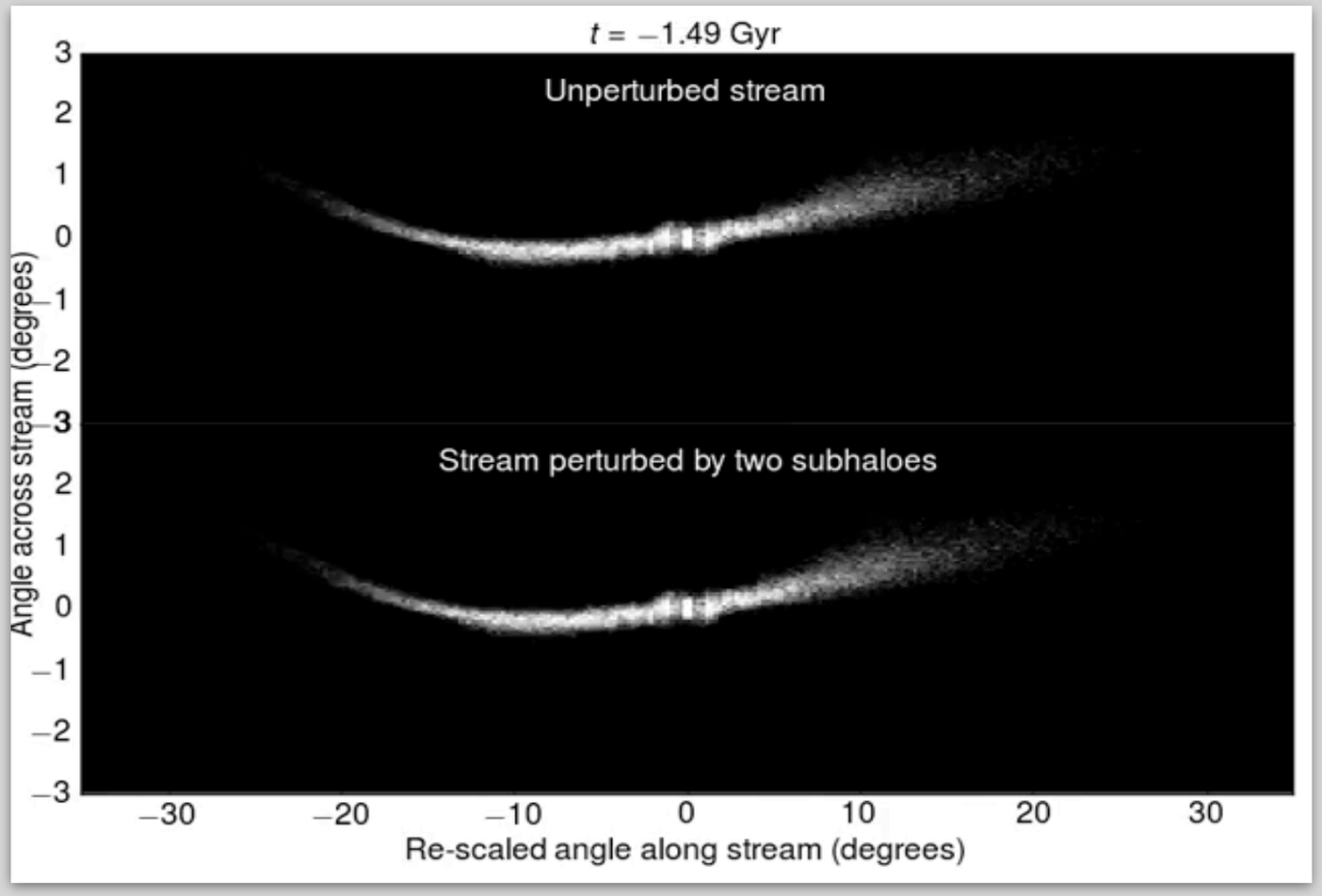
DM subhalo gaps

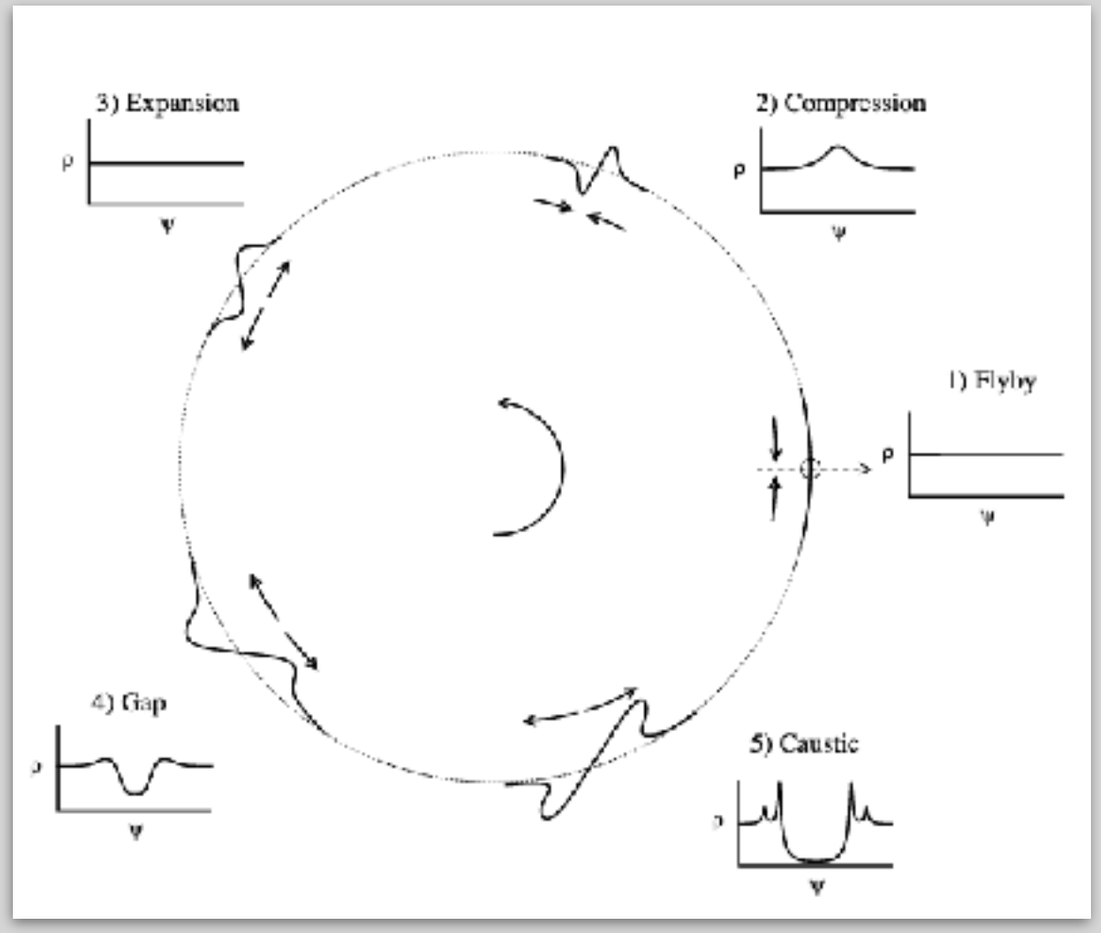


Credit: Denis Erkal

Erkal et al. 2015, 2016
Yoon et al. 2011
Carlberg 2009, 2012, 2013
Koppelman & Helmi, 2021

DM subhalo gaps





Erkal et al. 2015, 2016
Yoon et al. 2011
Carlberg 2009, 2012, 2013
Koppelman & Helmi, 2021

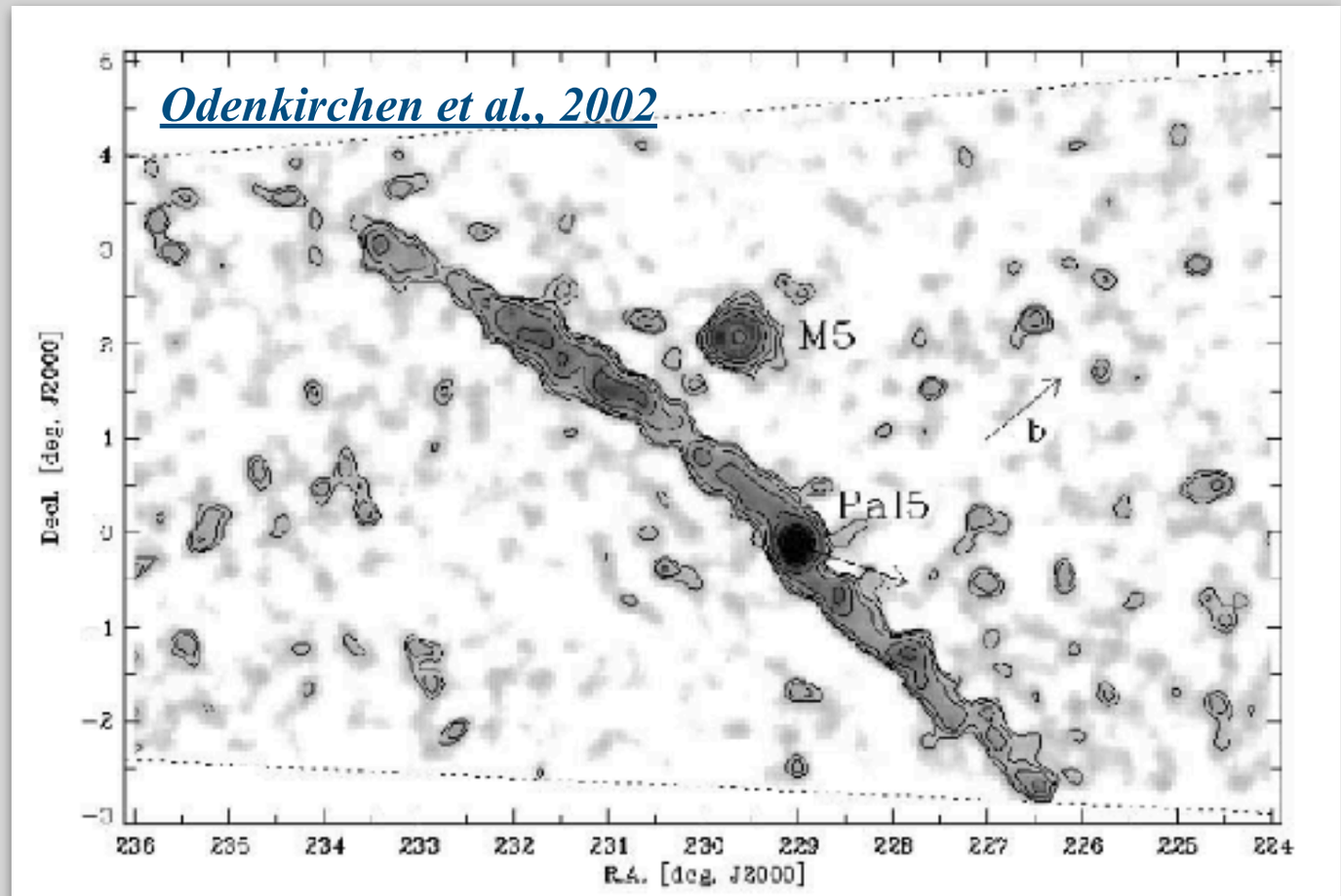
Do we see gaps along stellar streams?

Gaps in Pal 5 & GD-1 streams

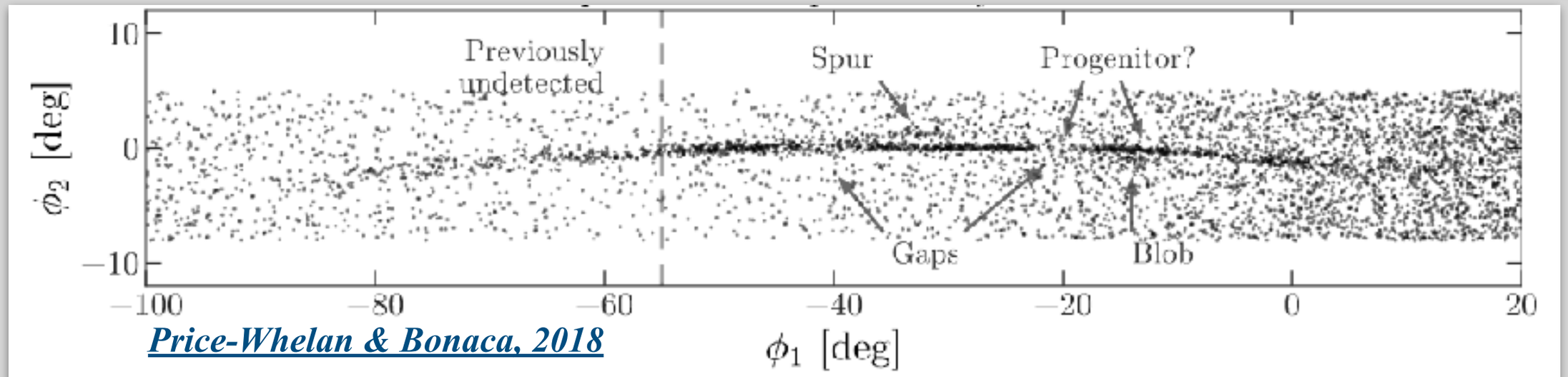
***Carlberg et al. 2012*:**
5 gaps at 99% confidence in Pal 5

Price-Whelan & Bonaca,2018:
2 gaps in GD-1

Pal 5



GD-1



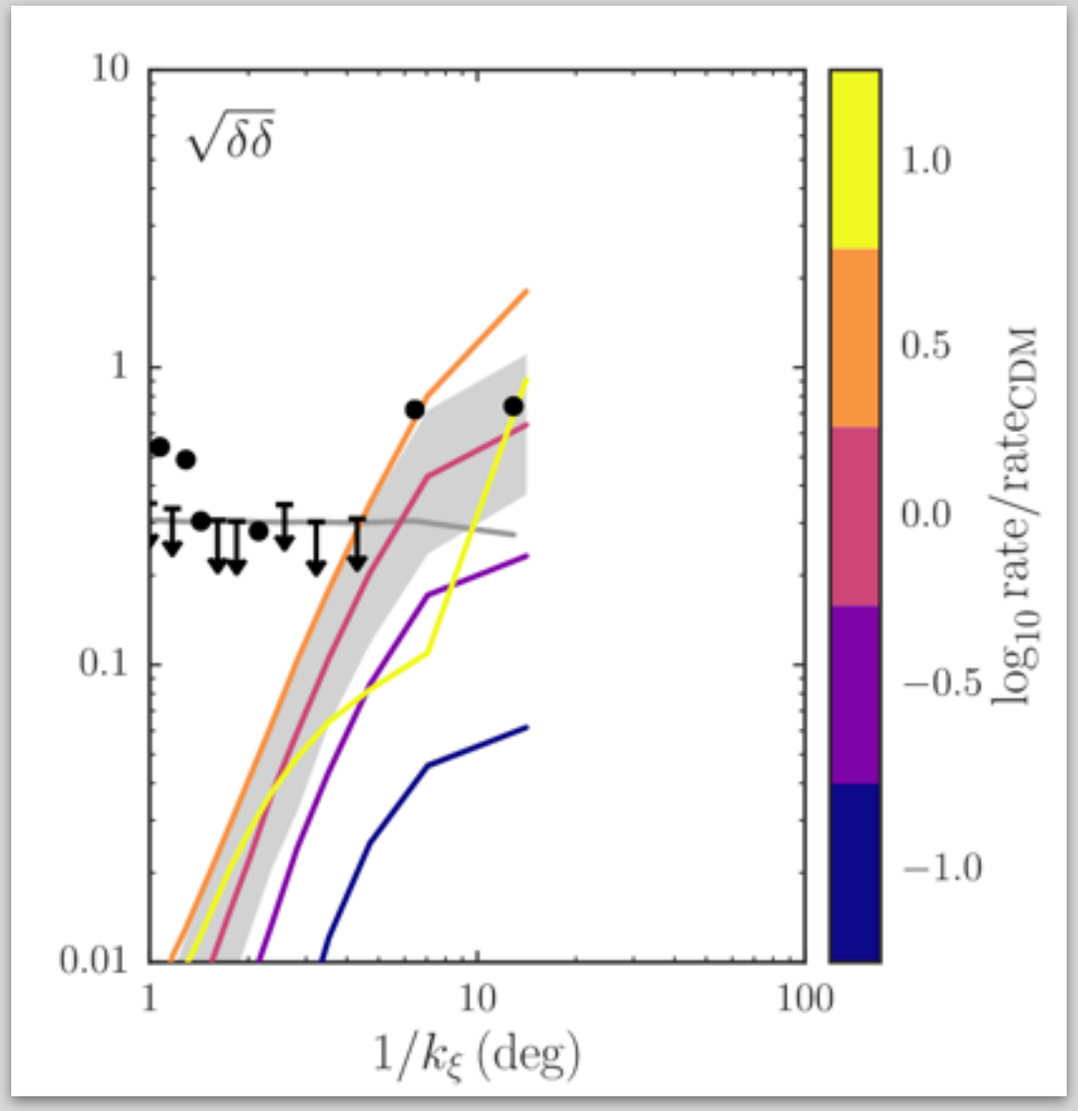
Are the gaps ONLY caused by DM sub-haloes?

1. External perturbers

Gaps make with external perturbers

- Power spectrum of the density fluctuation

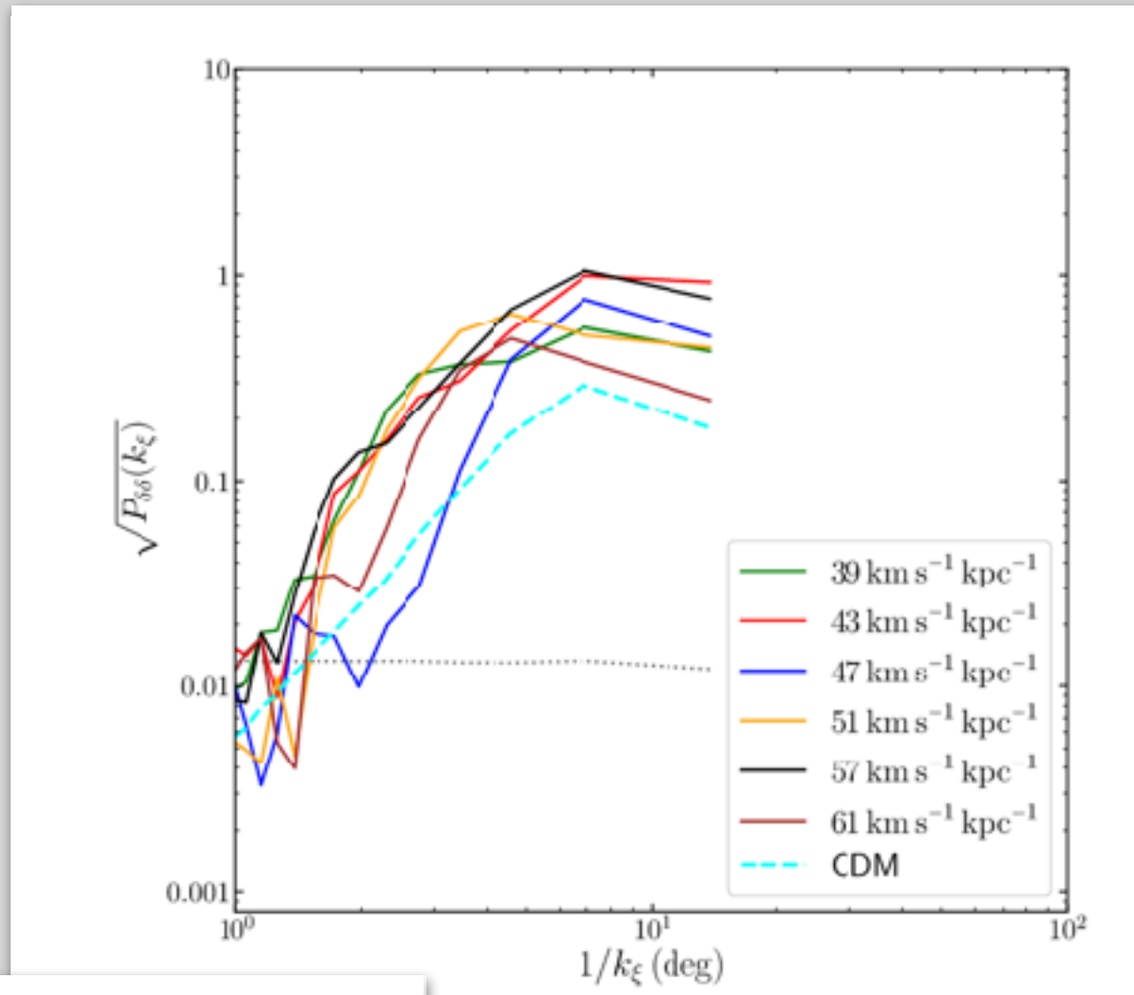
Pal 5

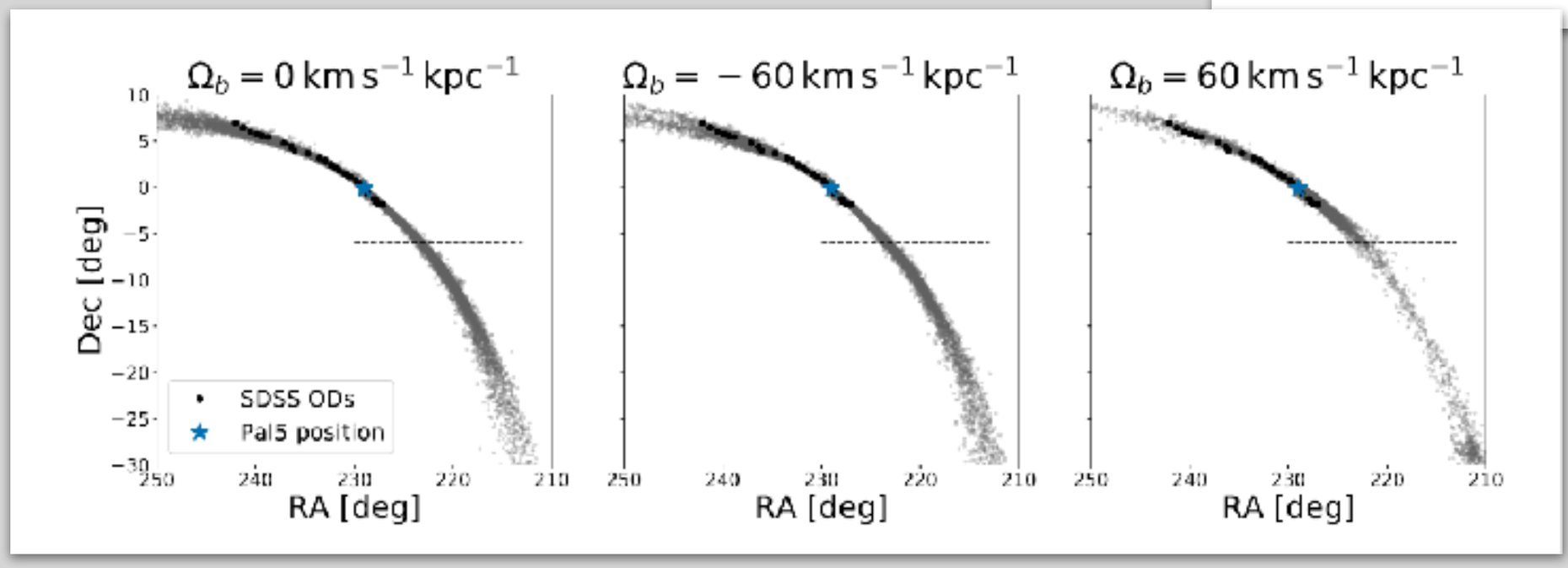


Bovy et al., 2017

Gaps make with external perturbers

- Galactic bar
  - ➡ Gaps on large scales
  - ➡ No affect of the age of the bar
  - ➡ Only for prograde streams





Banik & Bovy, 2019
Pearson et al, 2017
Hattori et al., 2016

Gaps make with external perturbers

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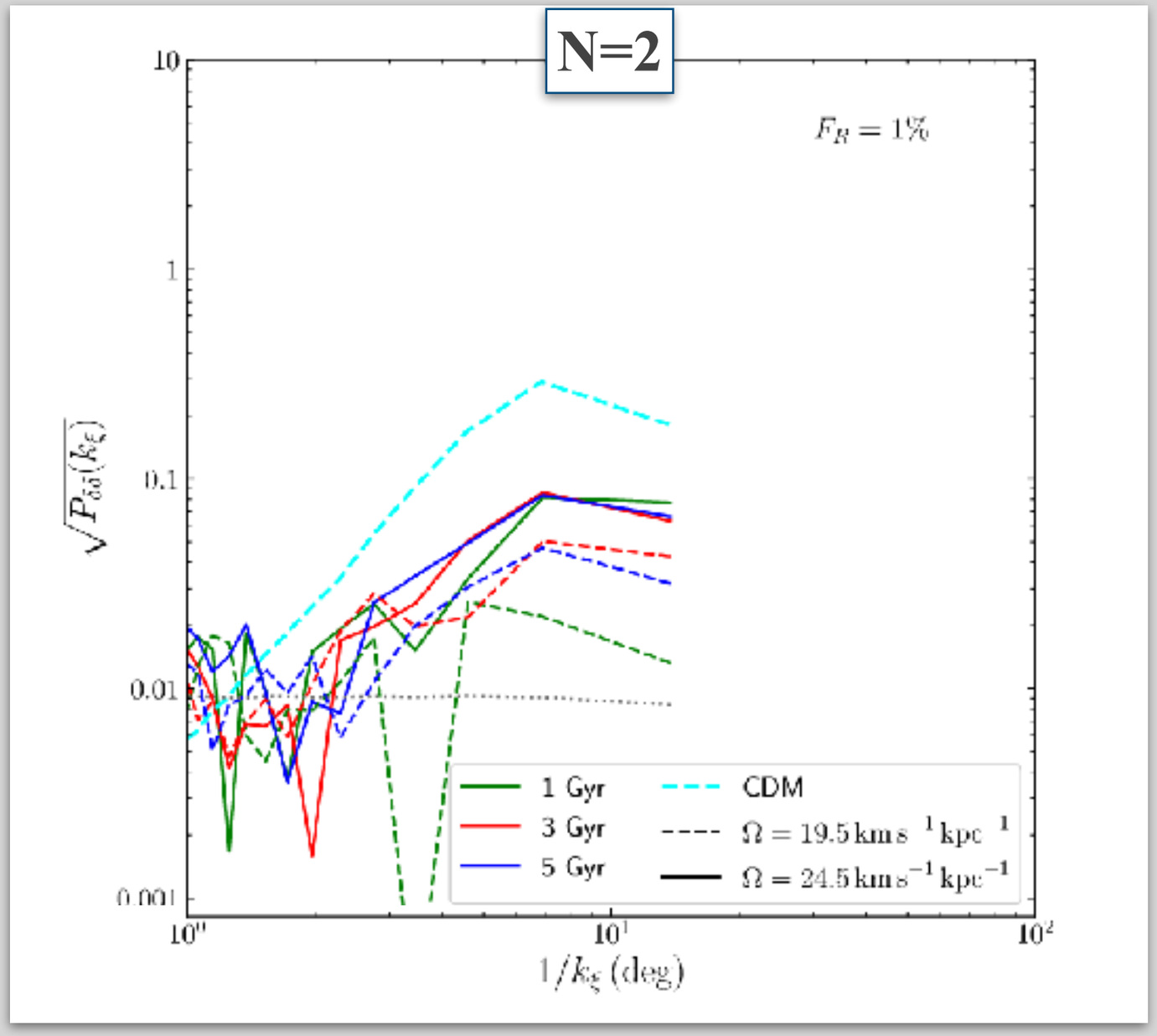
- Spiral arms



Banik & Bovy, 2019

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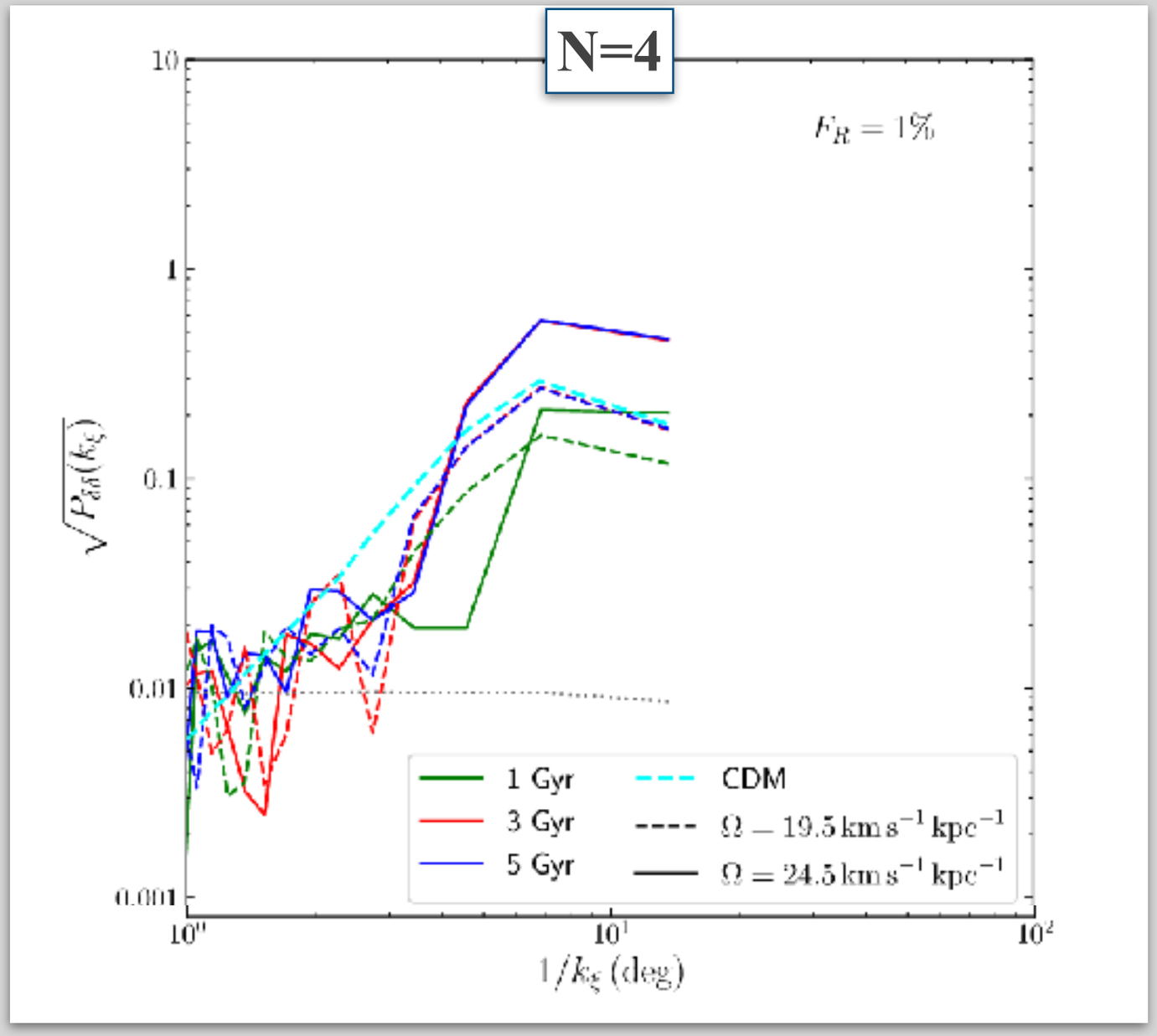
  - ➡ + arm => larger gaps
  - ➡ Large scale gaps (> 4°)



Banik & Bovy, 2019

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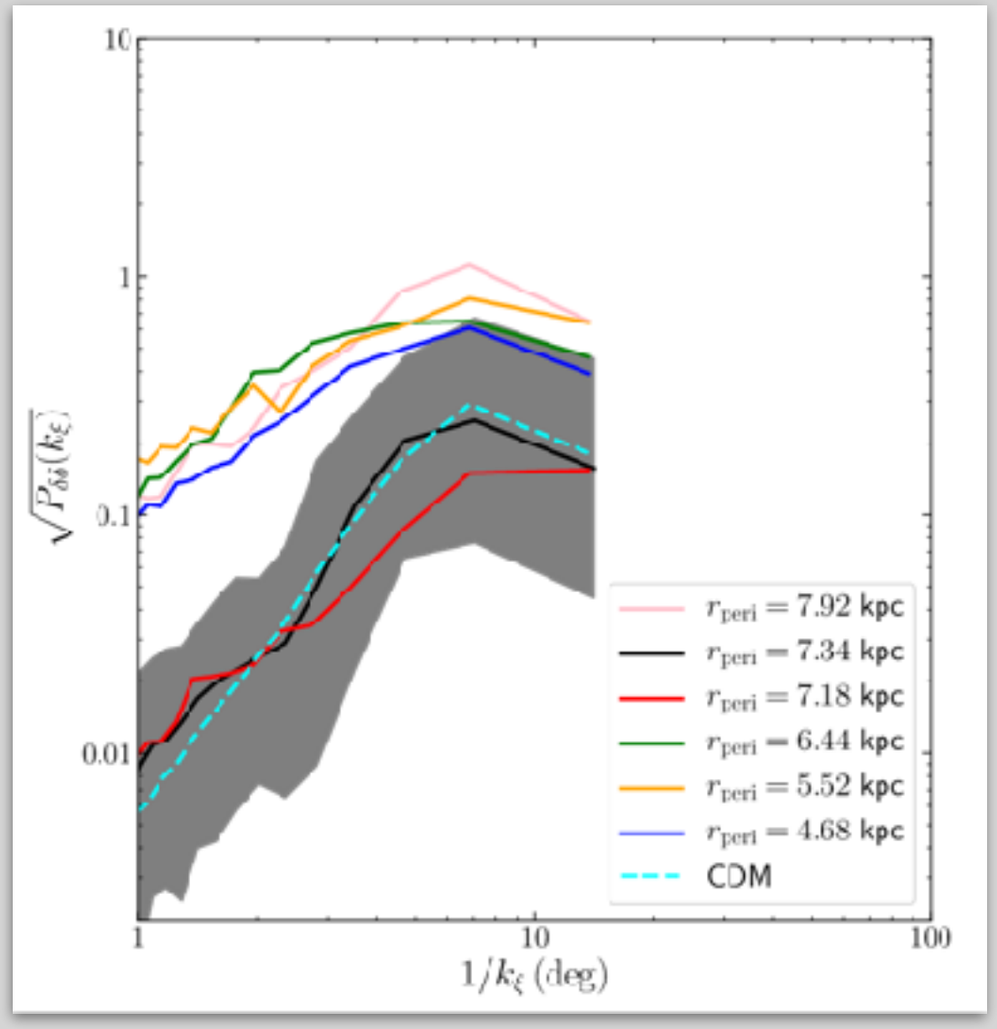
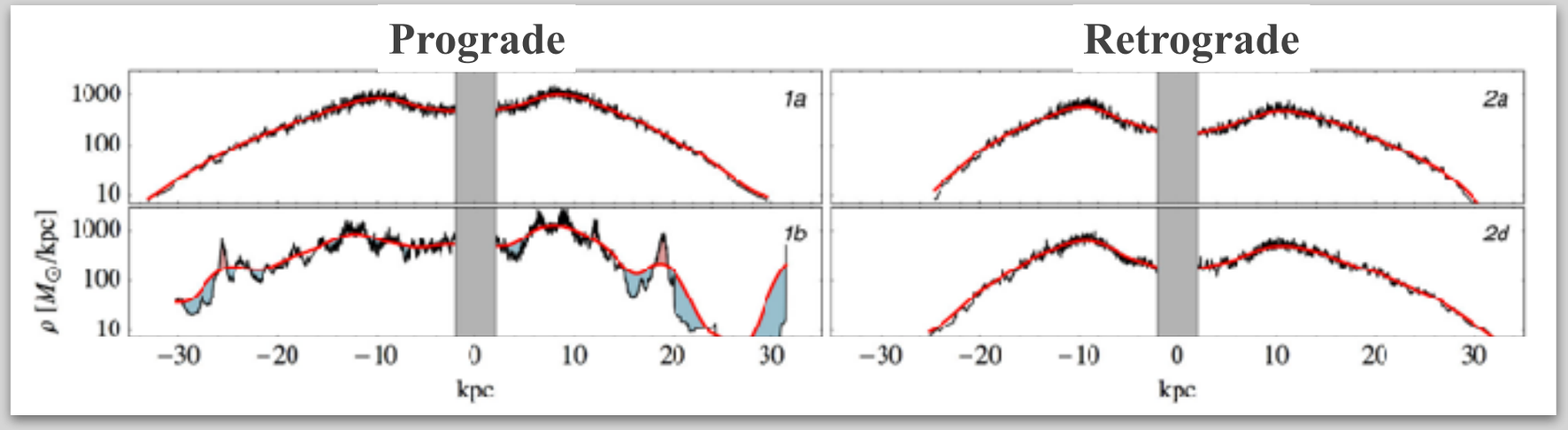
- Giant Molecular Clouds (GMC)
  - ➡ Similar effect than DM sub-halo
  - ➡ Strength depend of the pericentre





Banik & Bovy, 2019
Amorisco et al., 2016

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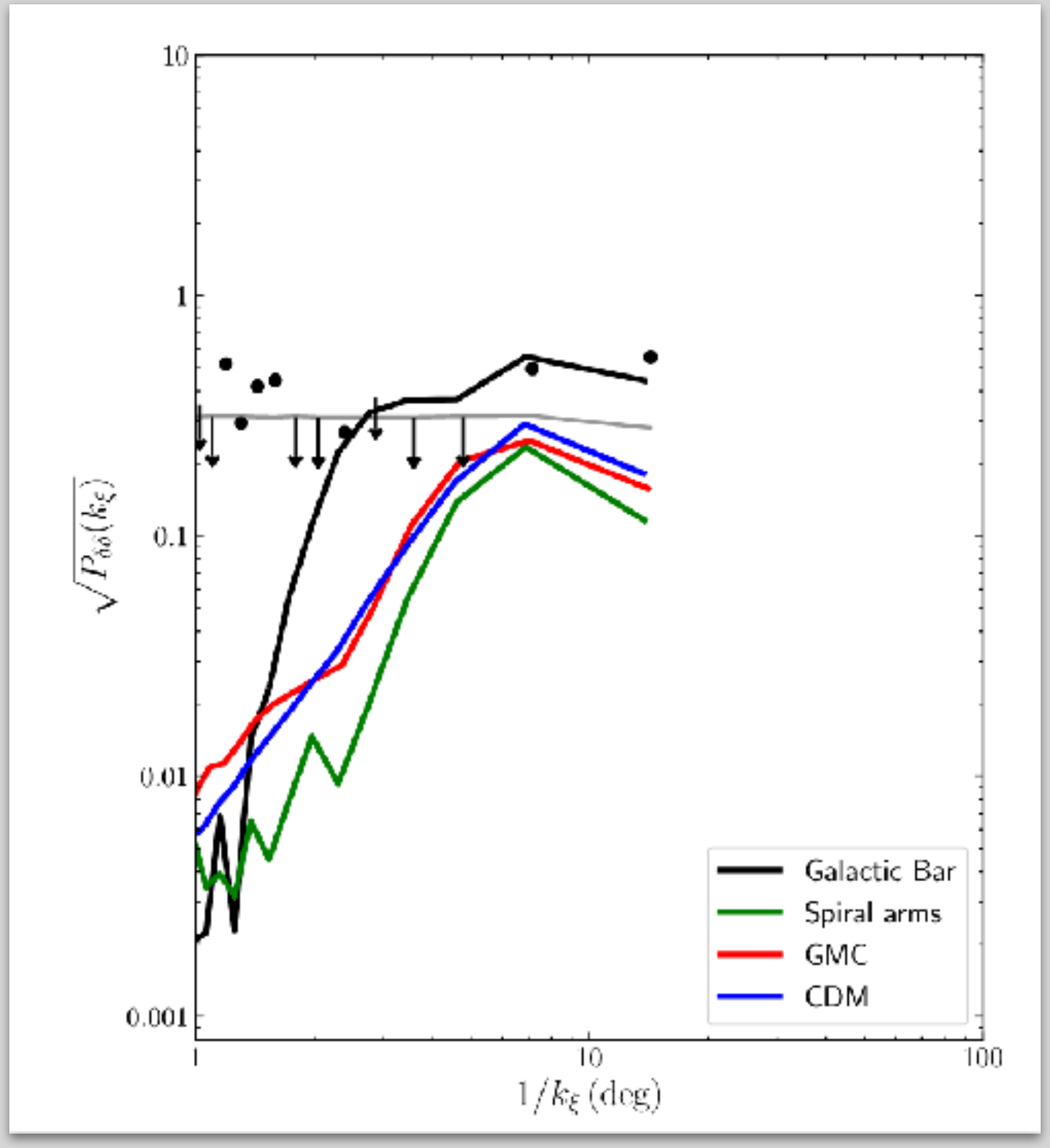
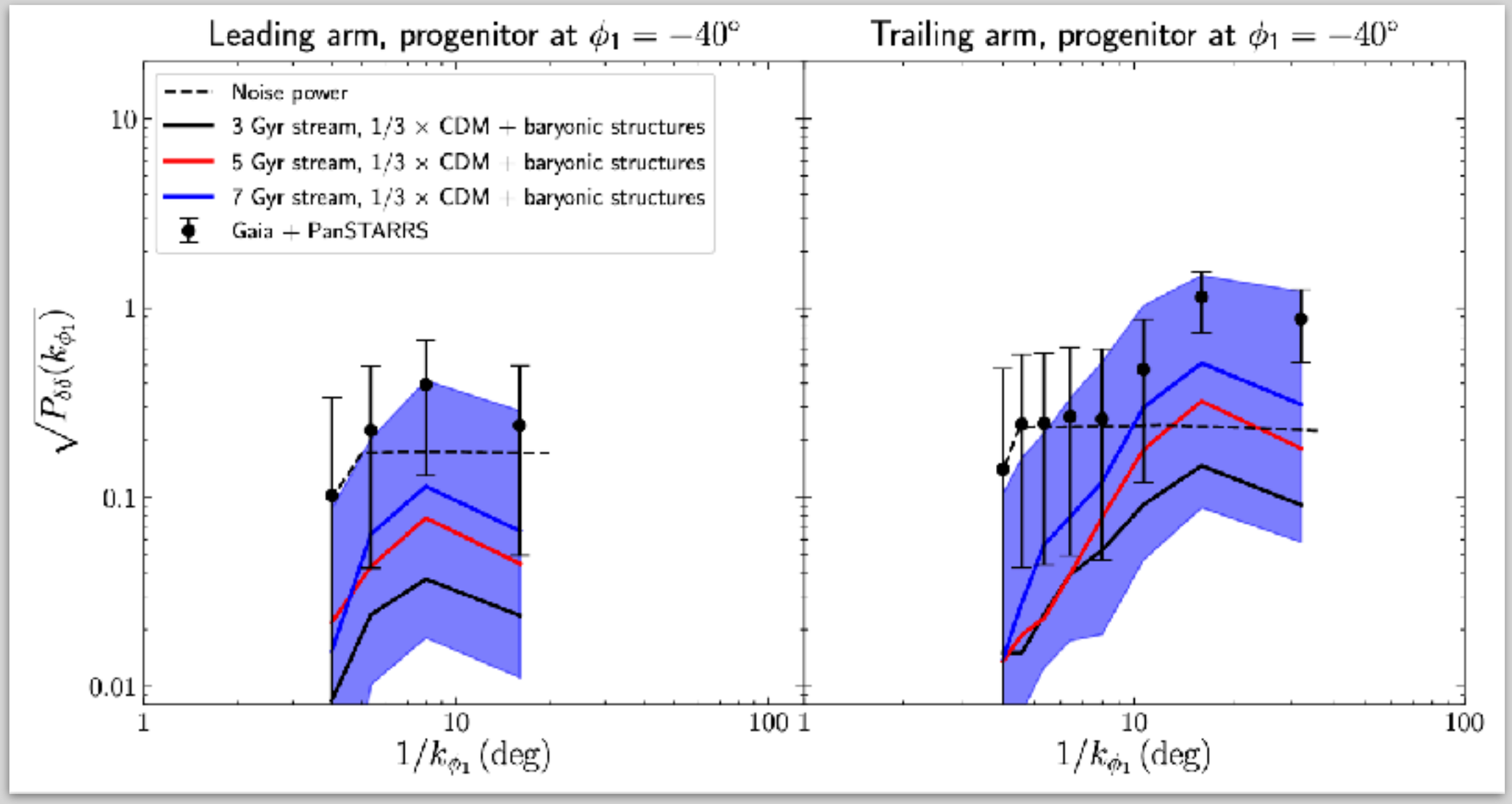


Baryonic external perturbers can explain the density fluctuations seen in Palomar 5

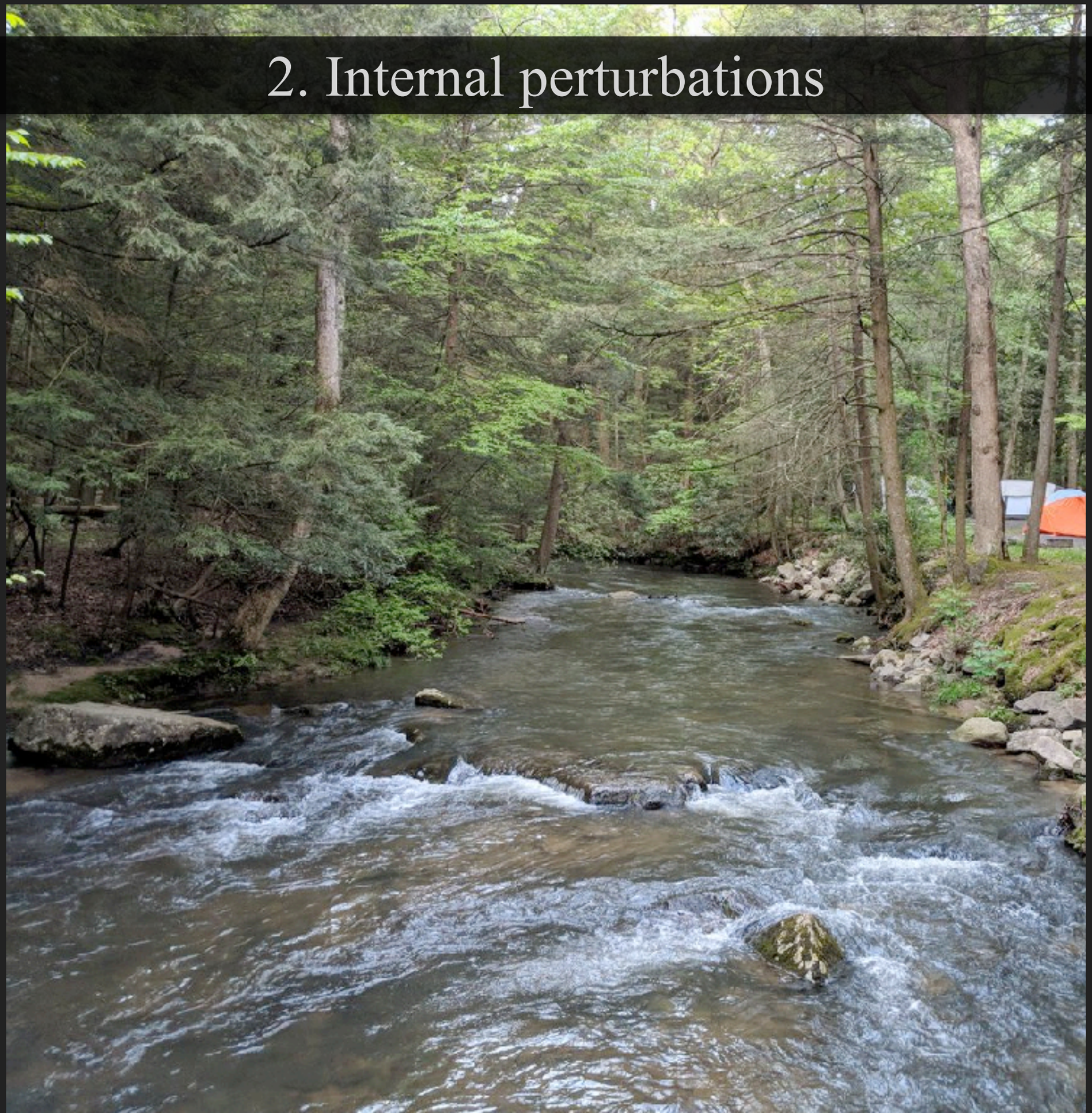
Banik & Bovy, 2019

Gaps in GD-1



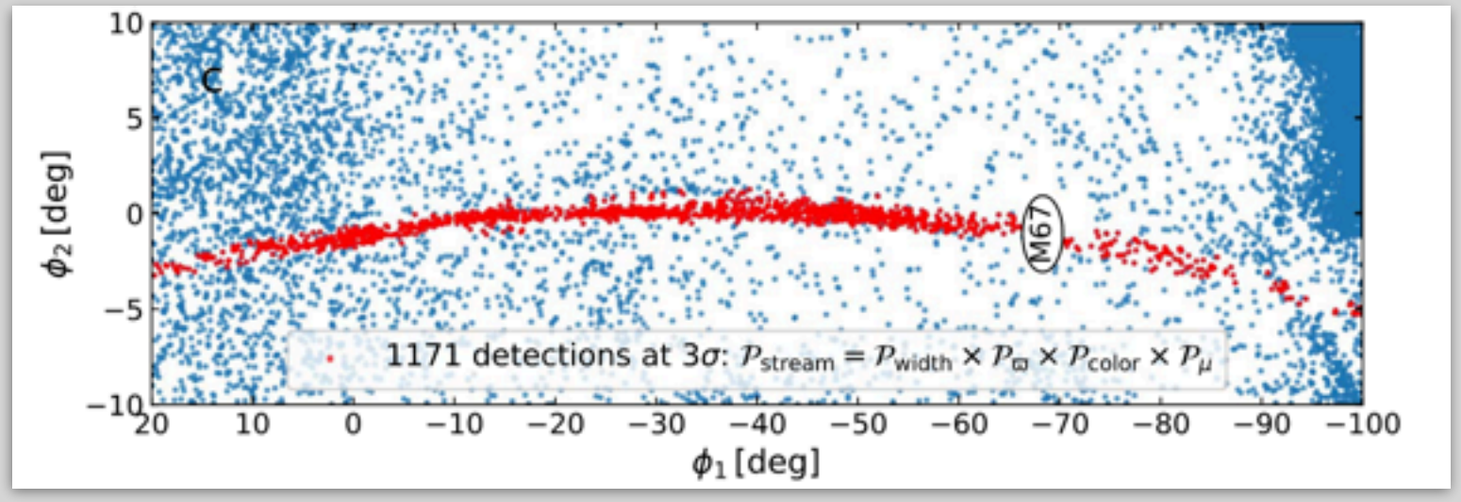
Banik & Bovy, 2021

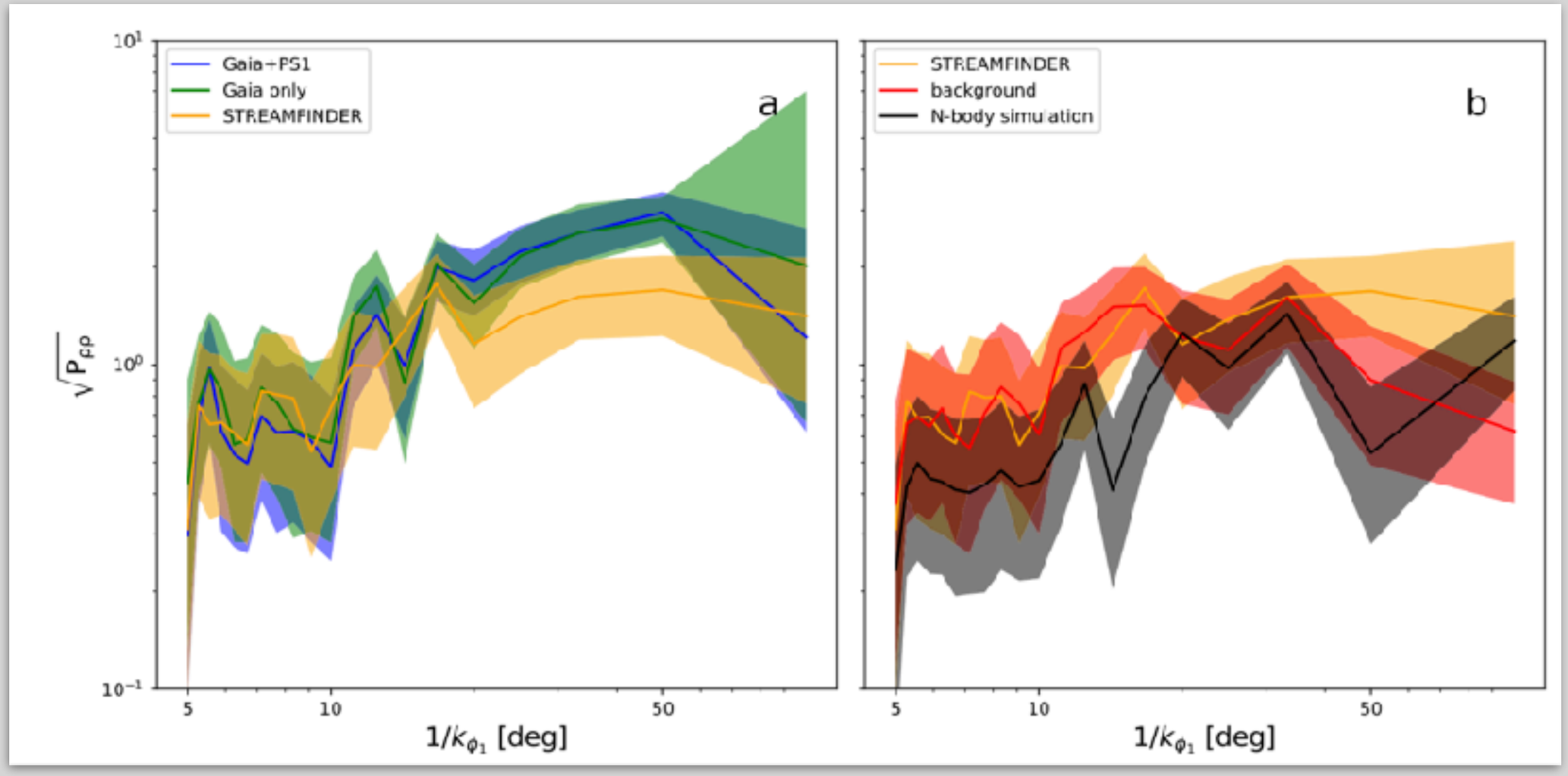
2. Internal perturbations



Gaps in GD-1

- GD-1 stream
  - ➡ Stars selected using Gaia + PS with STREAMFINDER
  - ➡ N-body model with 30,000 $M_\odot$





Ibata, Thomas et al., 2020

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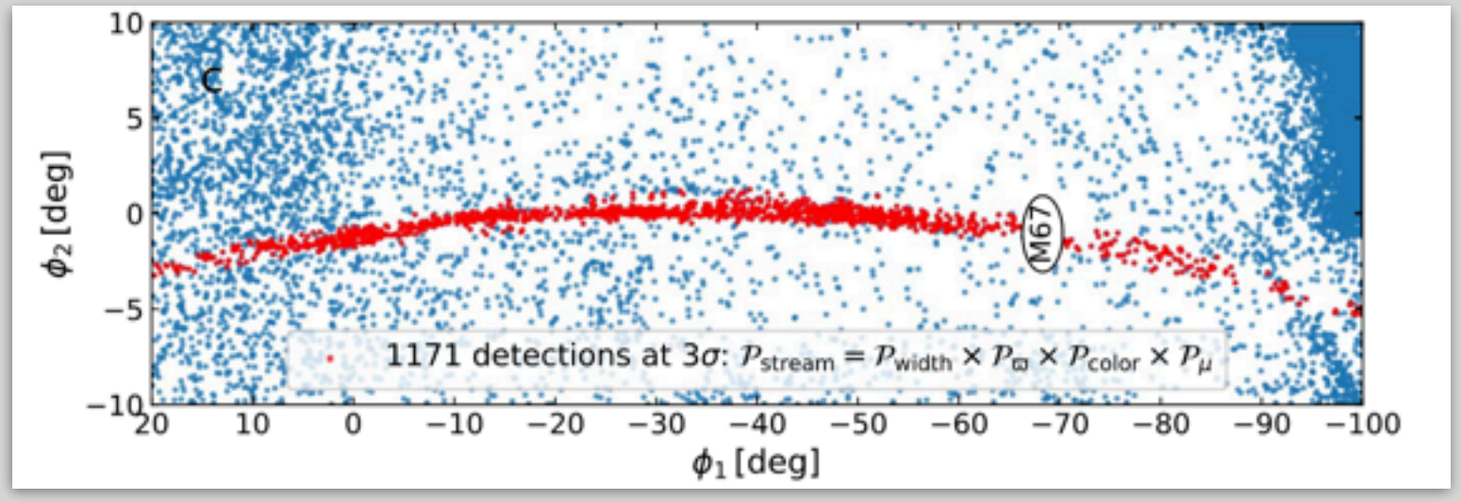
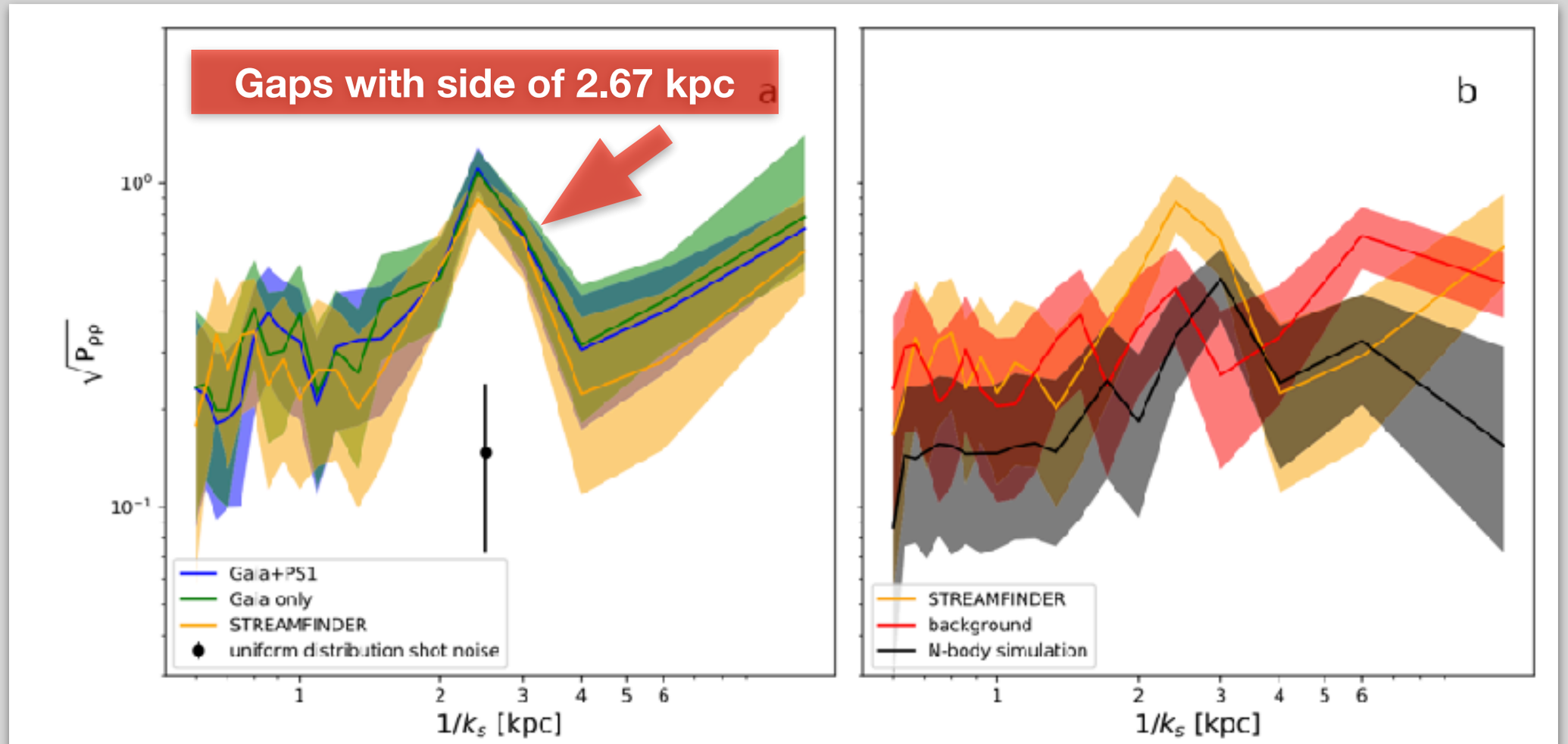
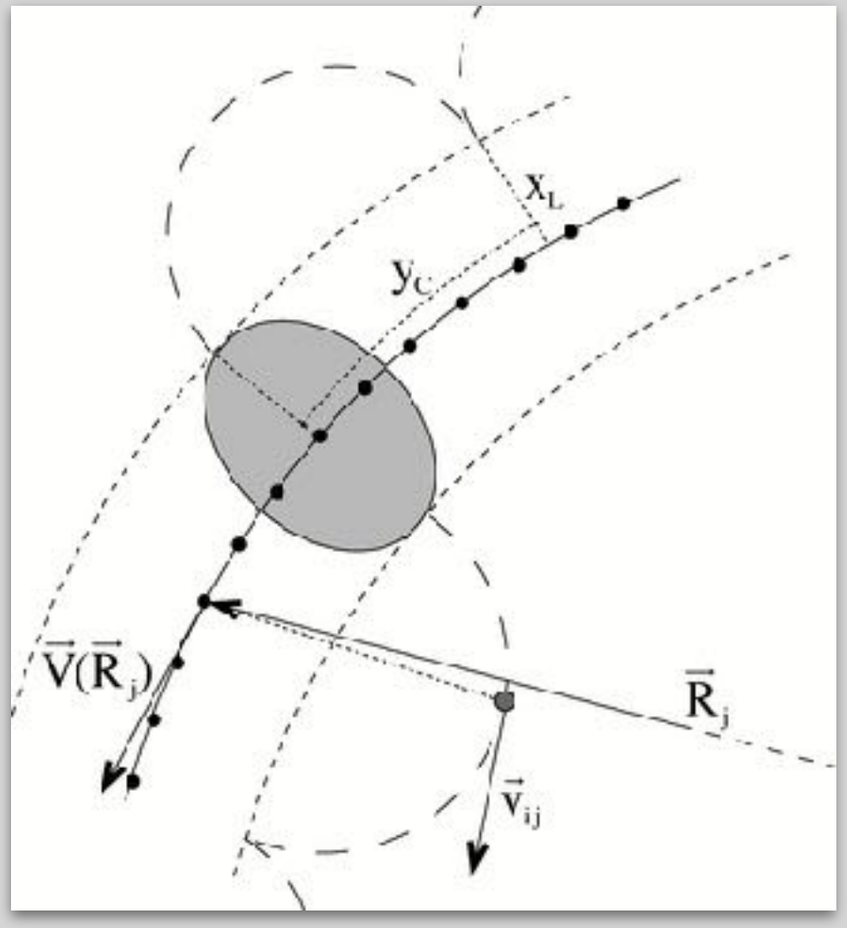
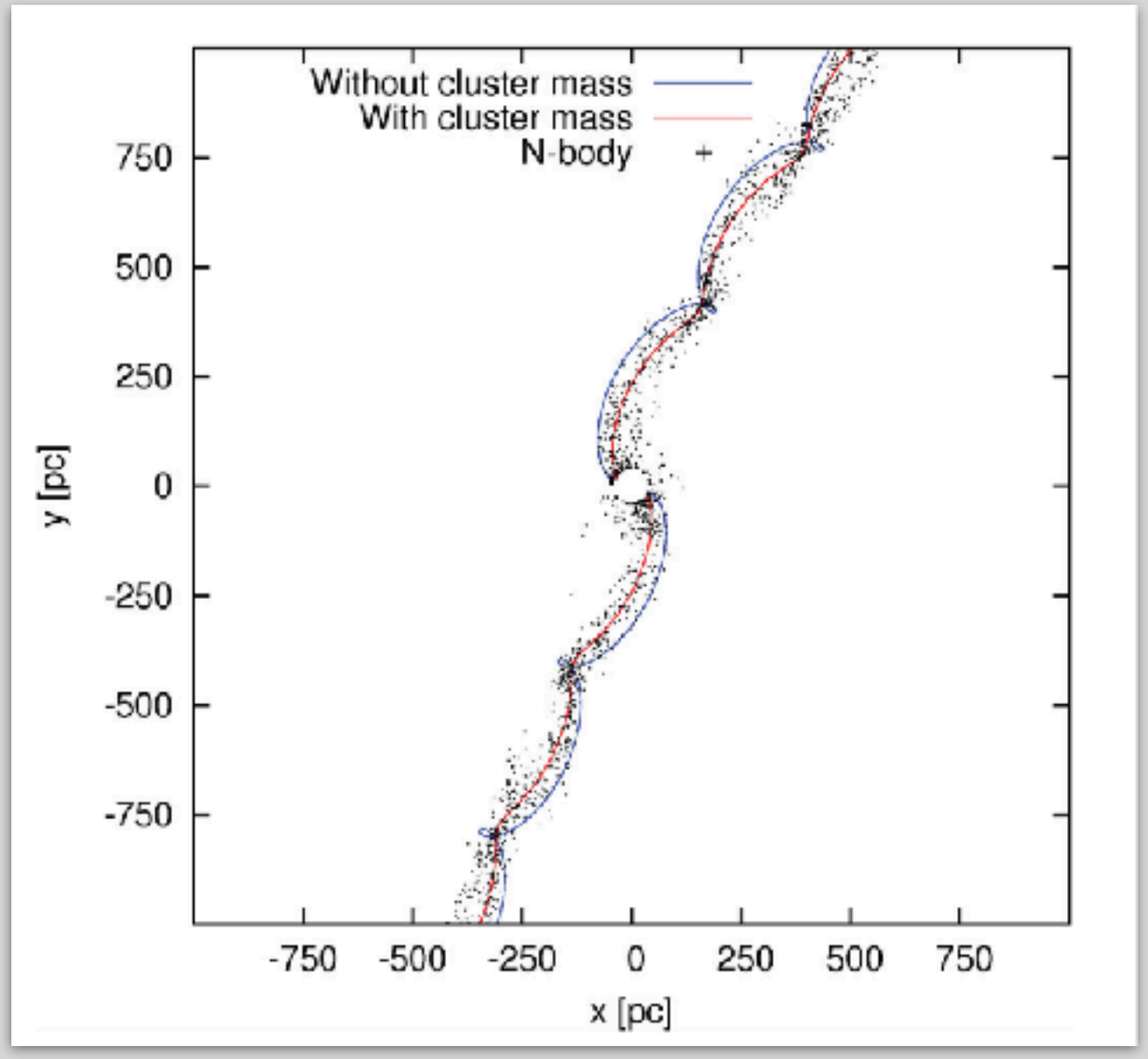




Ibata, Thomas et al., 2020

Epicycle motions





- Epicycle motions
  - ➡ Create regular pics (and gaps)
  - ➡ Amplitude diminish with length of the streams

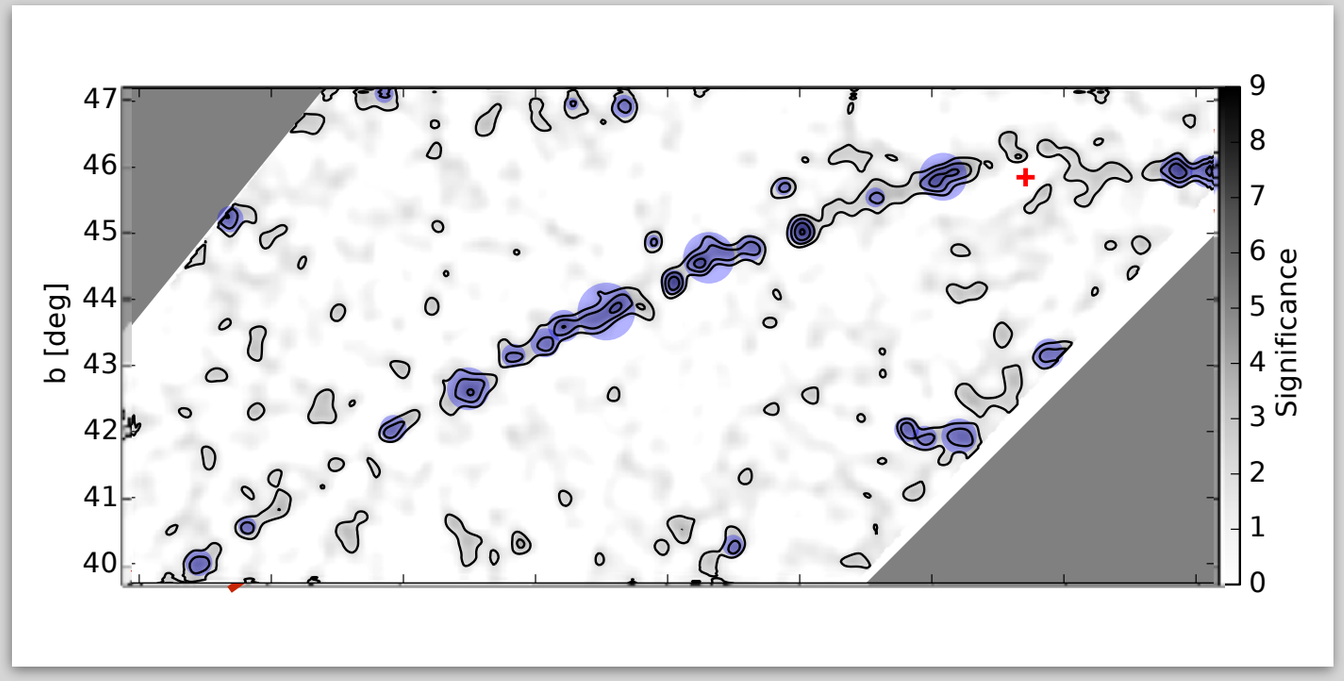
Küpper et al, 2008, 2010, 2012
Mastrobuono-Battisti et al., 2013
Thomas et al., 2016
Sanders et al., 2016
Ibata, Thomas et al., 2020
Jerabkova et al., 2021

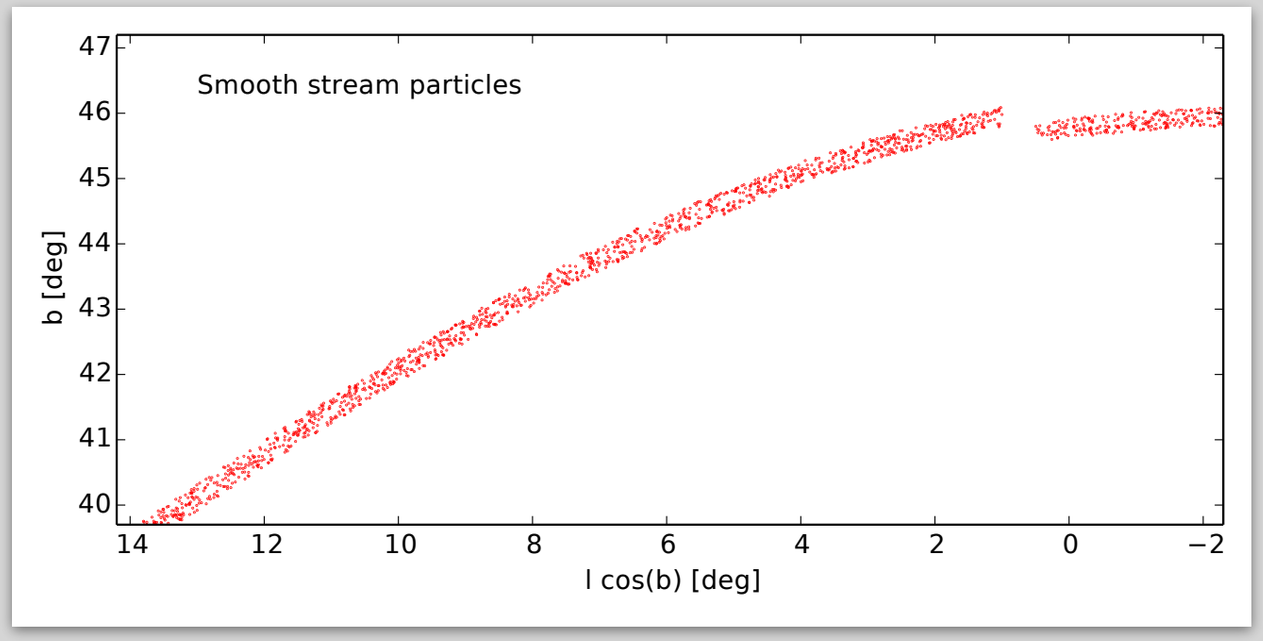
3.Observational effect

Observational artefacts

- Photometric uncertainties and inhomogeneities of large surveys can create artificial gaps
  - ➡ Gaps along Pal 5 in SDSS

Thomas et al., 2016

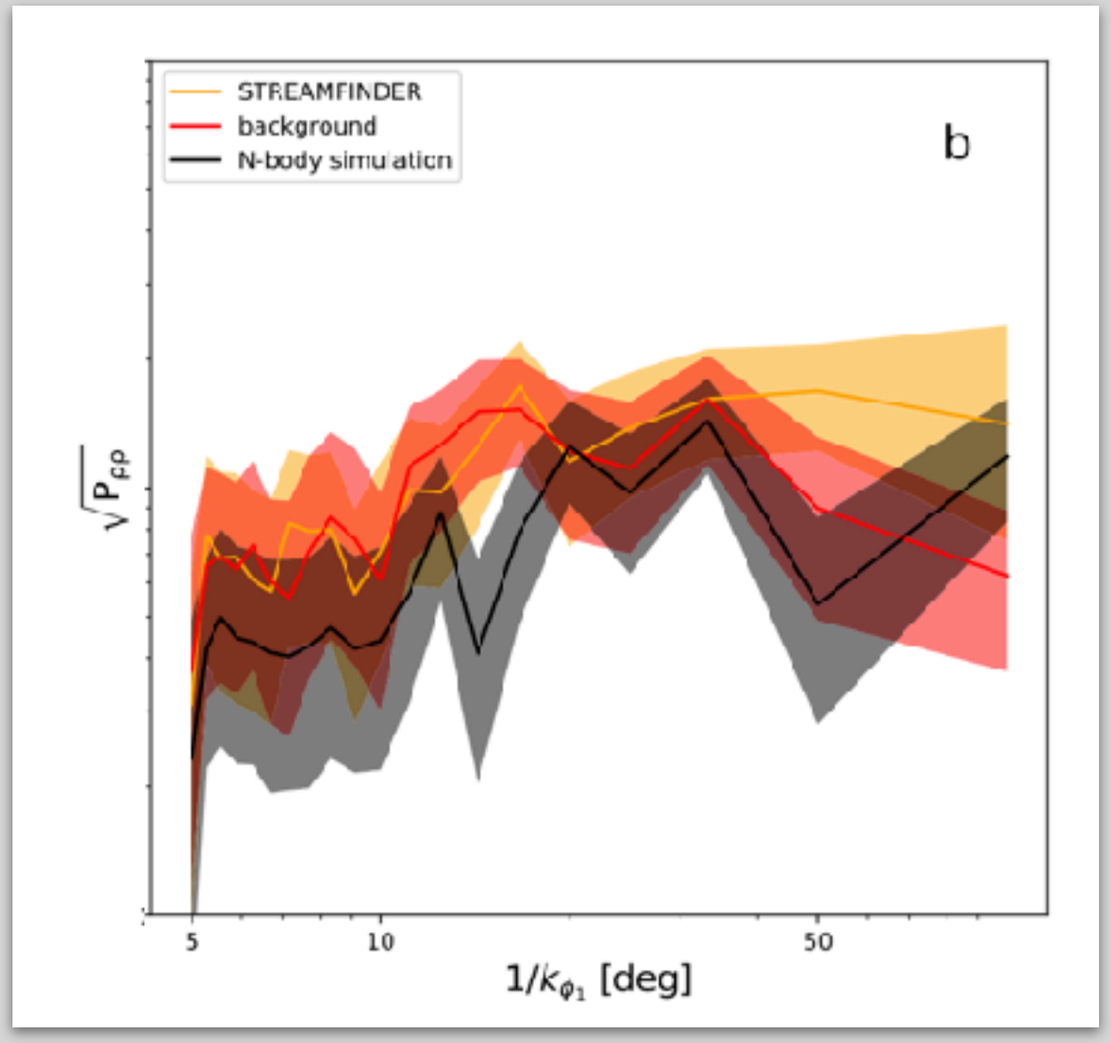


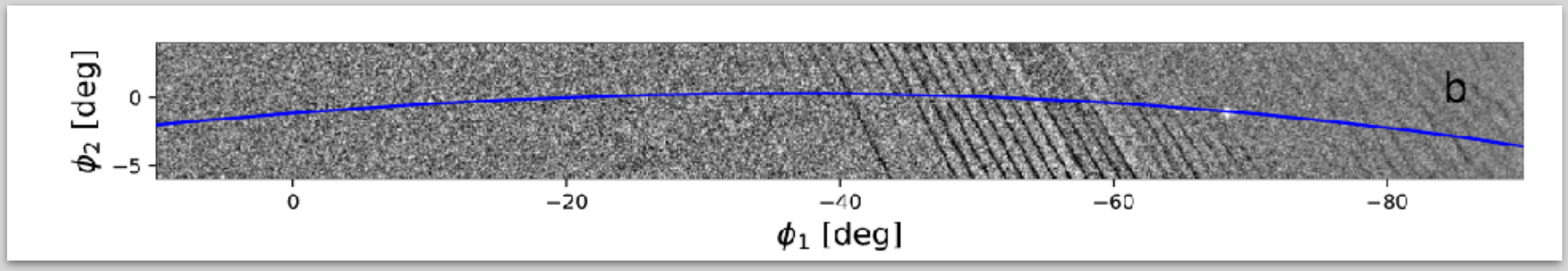


Observational artefacts

- Photometric uncertainties and inhomogeneities of large surveys can create artificial gaps
  - ➡ Gaps along Pal 5 in SDSS
  - ➡ Small gaps along GD-1 in Gaia

Ibata, Thomas et al., 2021





Conclusions and My Two cents

Conclusion

- **Cold stellar streams** can be used to **quantify** the number of **dark matter sub-haloes**

BUT …

Gaps can be also the consequence of:

- **External perturbers**
  - ➡ Galactic Bar
  - ➡ Spiral arms
  - ➡ GMC
  - ➡ LMC/Sgr/ Other objects

(see *de Boer et al. 2020, Li et al. 2021, Shipp et al. 2021, Malhan et al. 2021*)

- **Internal perturbation**
  - ➡ Epicycle motion
  - ➡ Progenitor dissolution *(see Webb & Bovy, 2018)*
  - ➡ Stellar mass black holes? *(see Gieses et al., 2021)*

- **Observational artefacts**
  - ➡ Photometric uncertainties
  - ➡ Inhomogeneities in the surveys
  - ➡ Scanning law

My 2 cents

- **No conclusive proof of the existence of gaps induced by dark matter sub-haloes yet**

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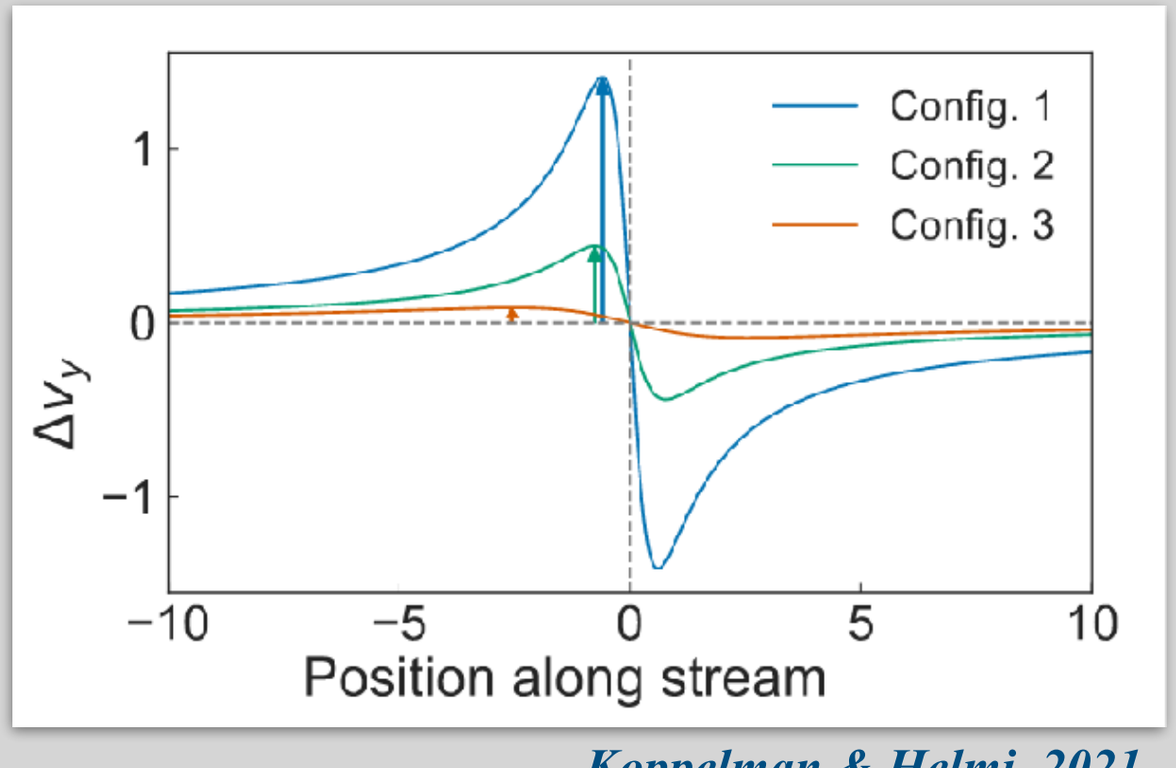
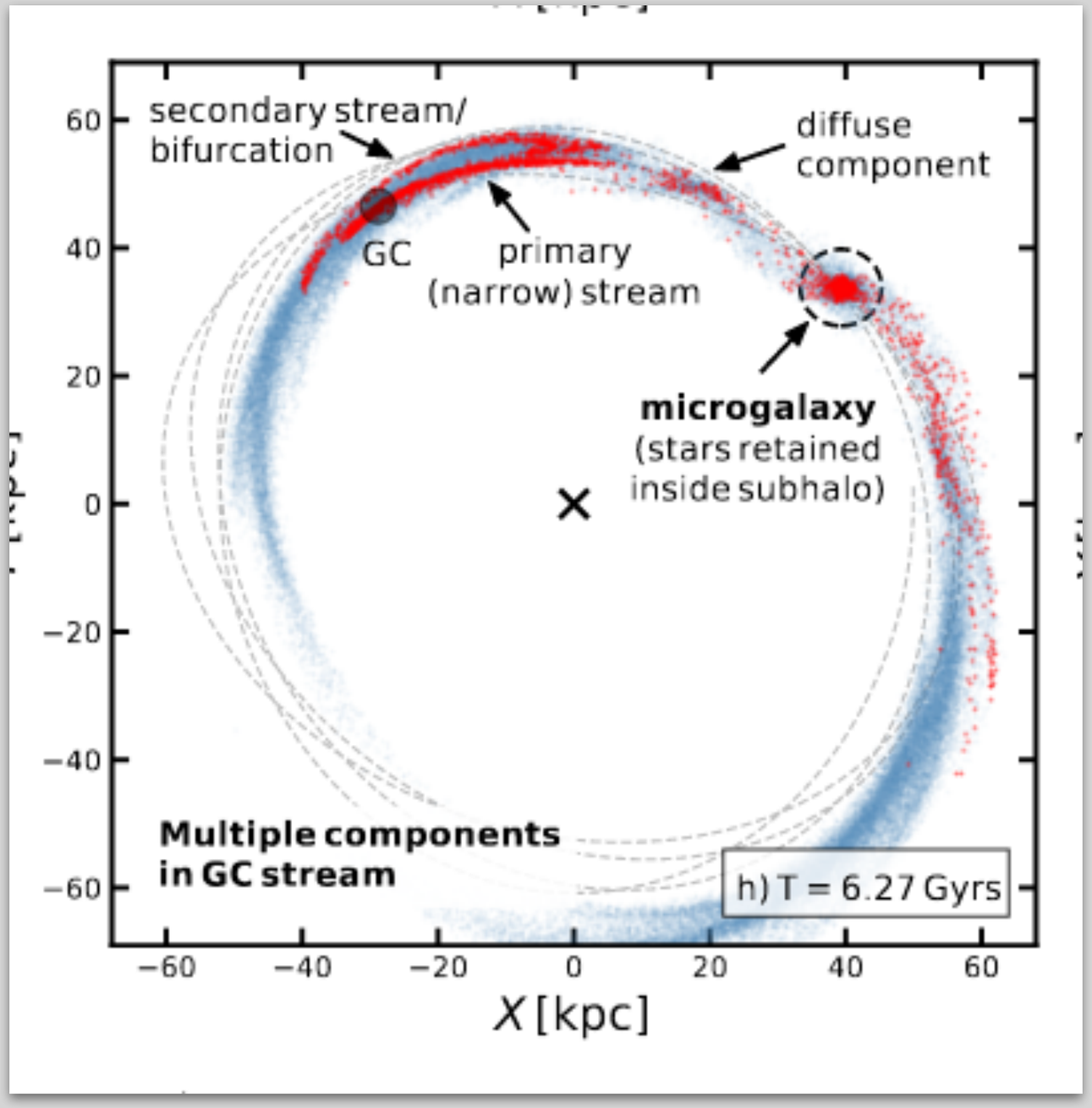


Koppelman & Helmi, 2021

- It should be done conjointly with:
  - ➡ **Study of the velocity perturbation**: precision of 300 m/s
  - ➡ **Proper N-body simulations**, including as many feature as possibles (external+ internal+ observational biases): very complicated and can be made on case to case base

Extra



Malhan et al. 2021