Forecasting the Population of Globular Cluster Streams

in Milky Way-type galaxies

The Milky Way Assembly Tale

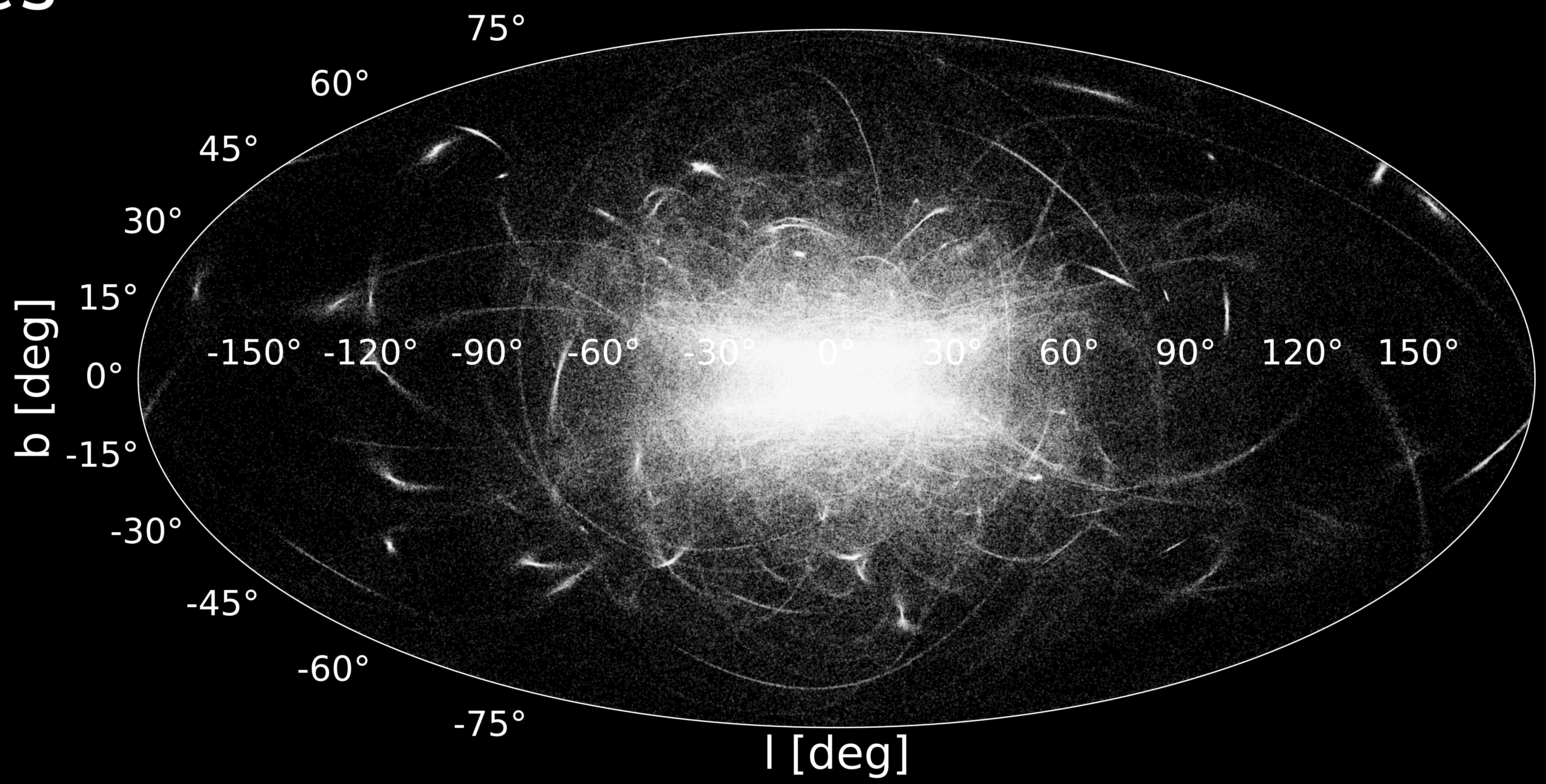
May 28th, 2024

Sarah Pearson

Niels Bohr Institute

University of Copenhagen

@spacewsarah



In collaboration with: Ana Bonaca, Yingtian Chen & Oleg Gnedin

Arxiv: 2405.15851

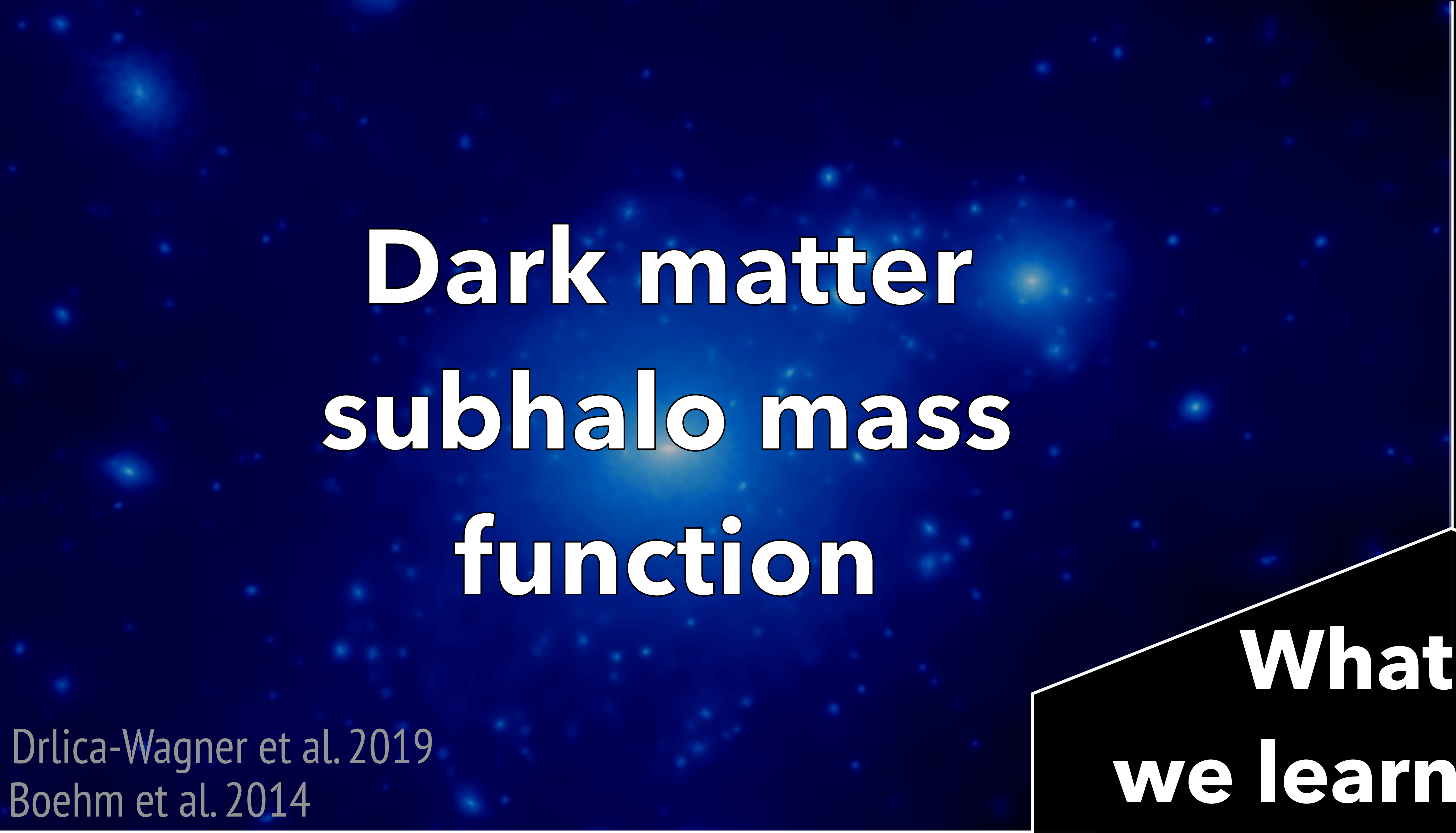
VILLUM FONDEN
erc
European Research Council
Established by the European Commission
MARIE CURIE ACTIONS
UNIVERSITY OF COPENHAGEN

Credit: ESA/gaia/DPAC


GD − 1
Fjörm
Kshir
M 5
Sylgr
([Fe/H] = − 2.9)
Orphan
Pal 5
ω cen +
Fimbulthul
Galaxy Picture :
ESA/Gaia/DPAC
Stellar streams :
Malhan et al. (2018, 19)
Ibata et al. (2021, 23)
Hríd
Gjöll
C − 19
([Fe/H] = − 3.4)
Phlegethon
Indus
NGC 1261
Leiptr
Atlas
Jhelum
Phoenix
Blue: d ~ 1 kpc (heliocentric)
Red: d > 30 kpc (heliocentric)
Credit: Khyati Malhan


How many streams
are we missing?
GD − 1
Fjörm
Kshir
M 5
Pal 5
Sylgr
([Fe/H] = − 2.9)
Orphan
Galaxy Picture :
ESA/Gaia/DPAC
Stellar streams :
Malhan et al. (2018, 19)
Ibata et al. (2021, 23)
Phlegethon
Indus
Gjöll
C − 19
([Fe/H] = − 3.4)
NGC 1261
Leiptr
Jhelum
Phoenix
Atlas
Credit: Khyati Malhan


How many streams are we missing?
…and what will we learn if we find them?
GD − 1
Fjörm
Kshir
M 5
Pal 5
Sylgr
([Fe/H] = − 2.9)
Orphan
Galaxy Picture :
ESA/Gaia/DPAC
Stellar streams :
Malhan et al. (2018, 19)
Ibata et al. (2021, 23)
C − 19
([Fe/H] = − 3.4)
Phlegethon
Indus
Gjöll
NGC 1261
Leiptr
Jhelum
Phoenix
Atlas
Credit: Khyati Malhan



Dark matter subhalo mass function

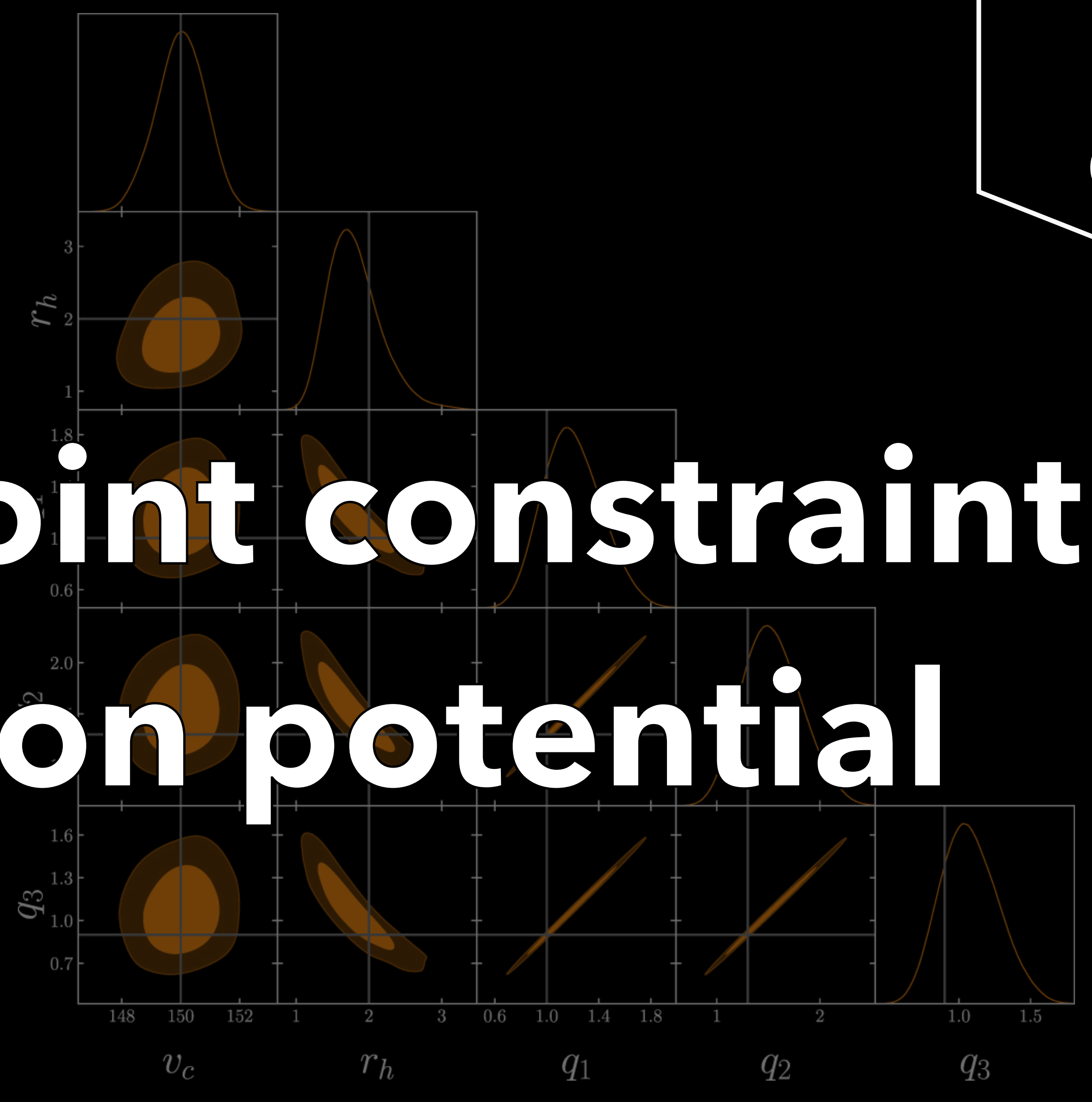
Drlica-Wagner et al. 2019
Boehm et al. 2014

Response to live halo

Dillamore et al. 2022

What can we learn from a **full sample** of MW streams?

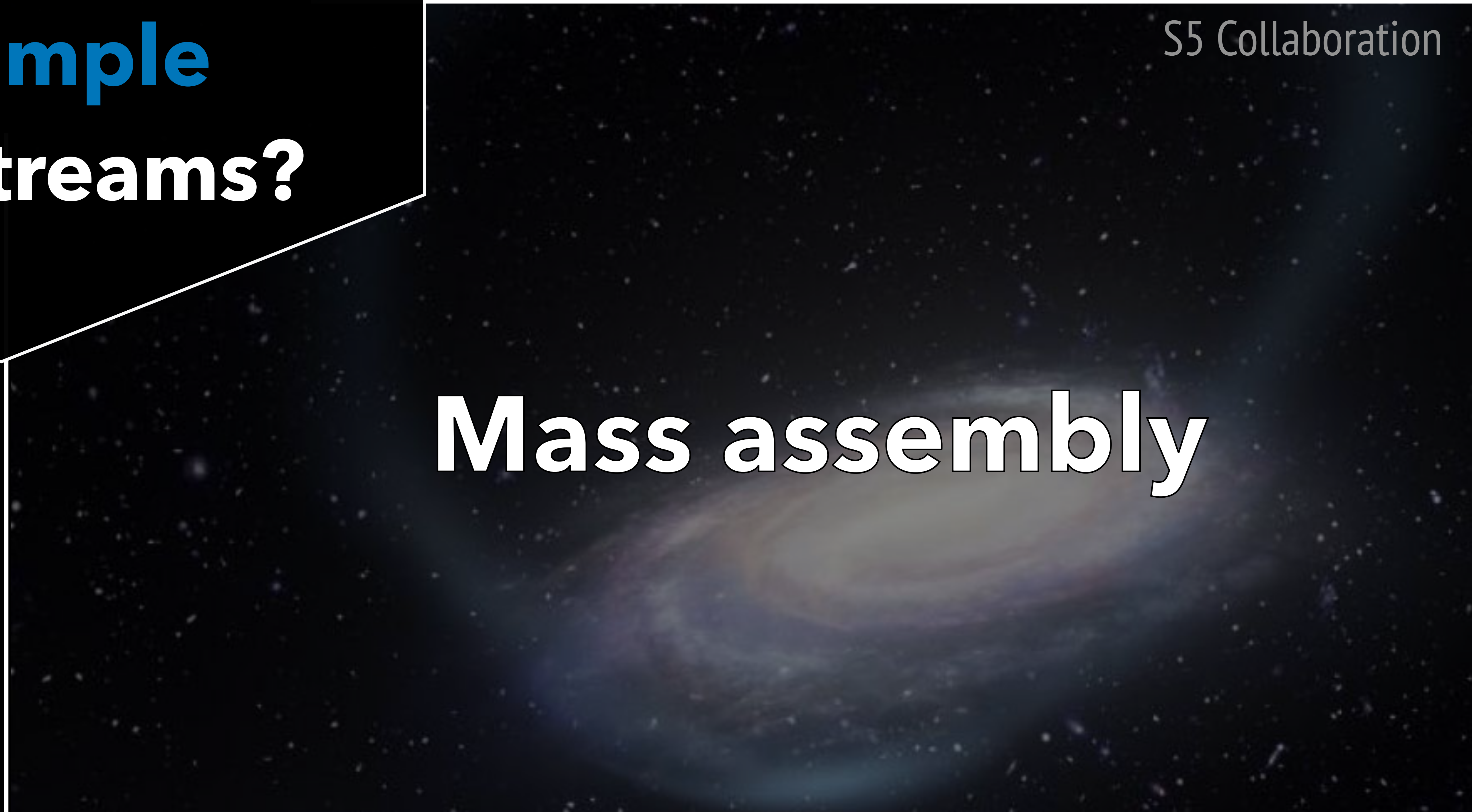
Nibauer et al. 2022



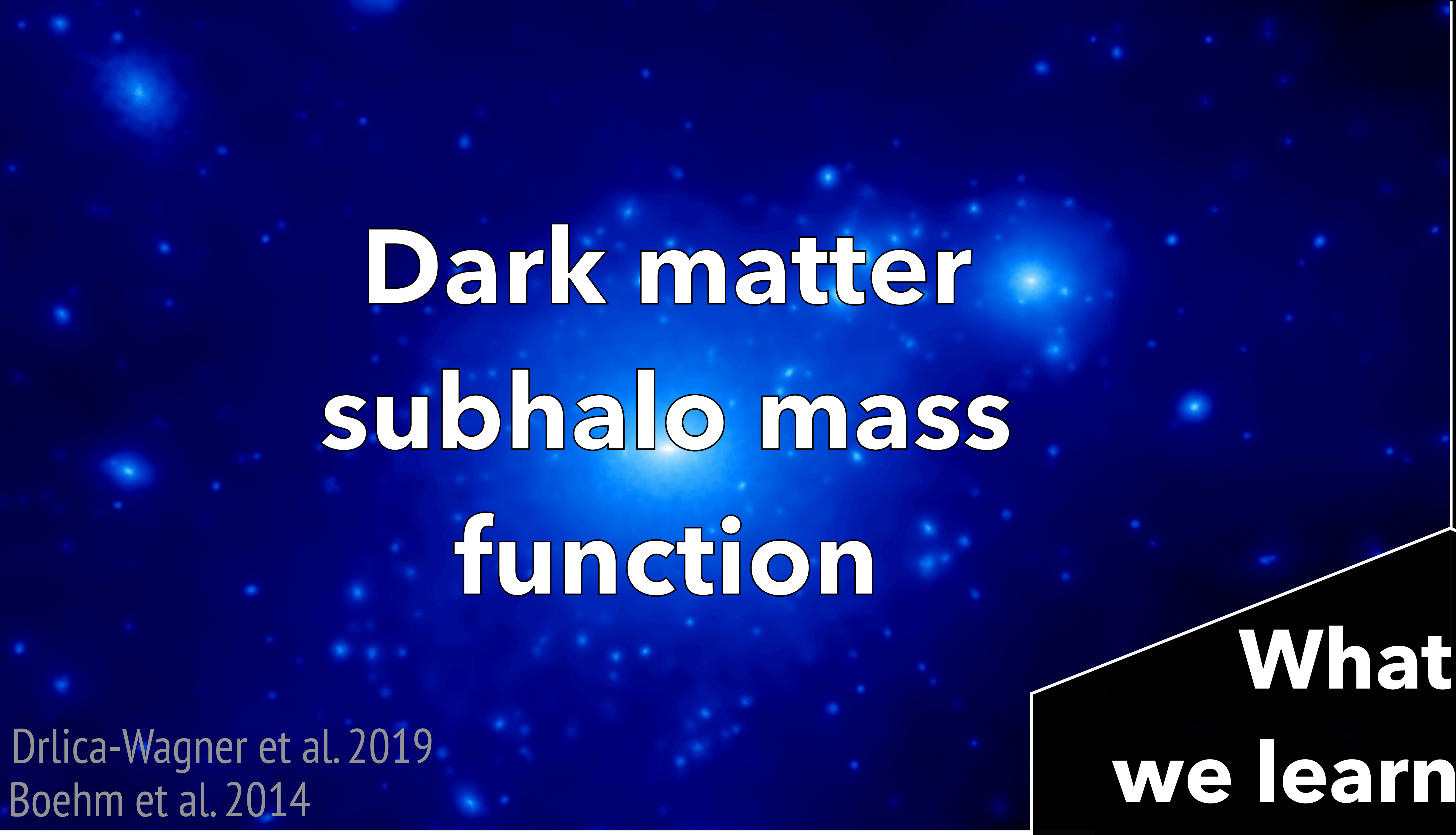
Joint constraint on potential

See also
Bovy et al 2016
Bonaca & Hogg 2018

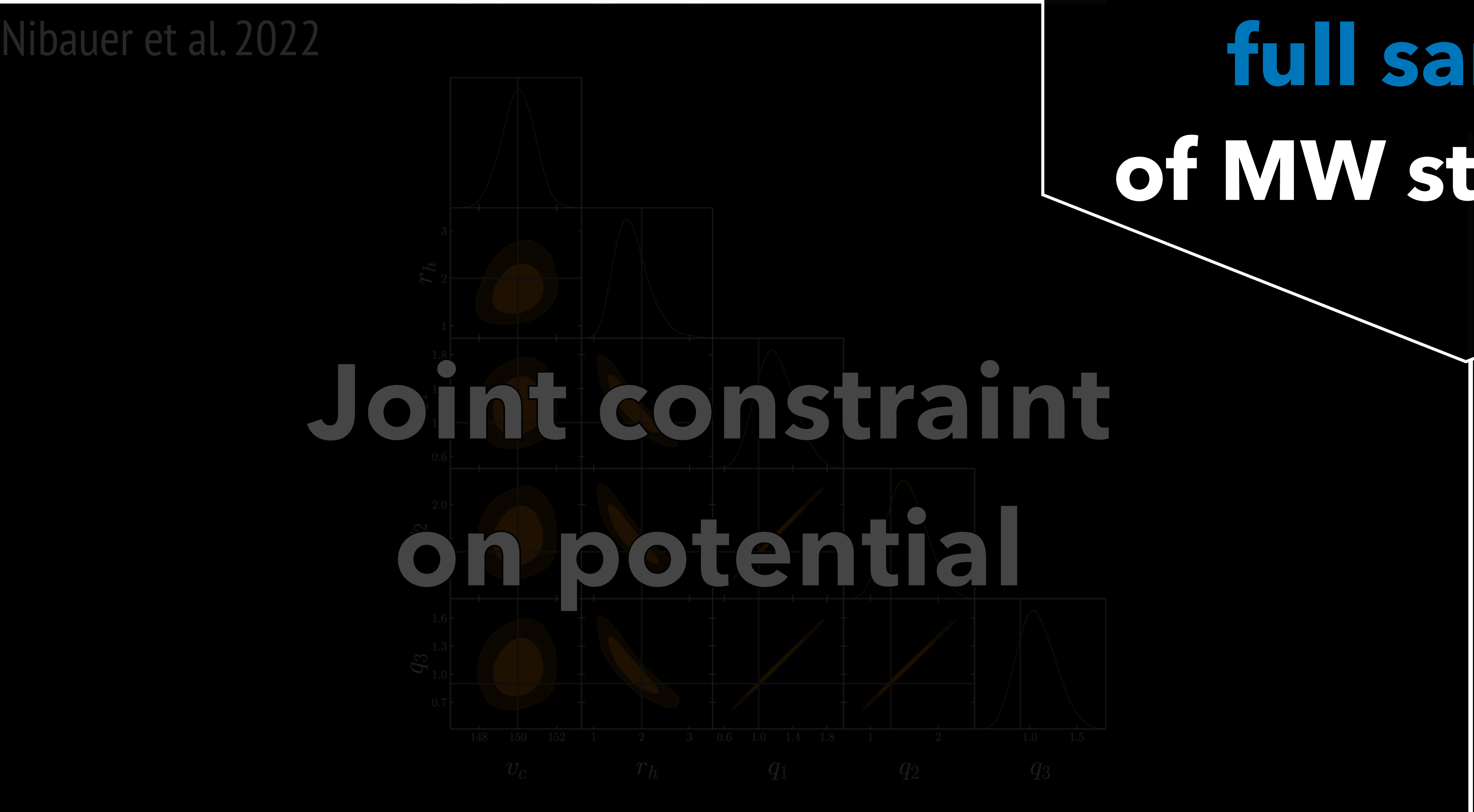
S5 Collaboration

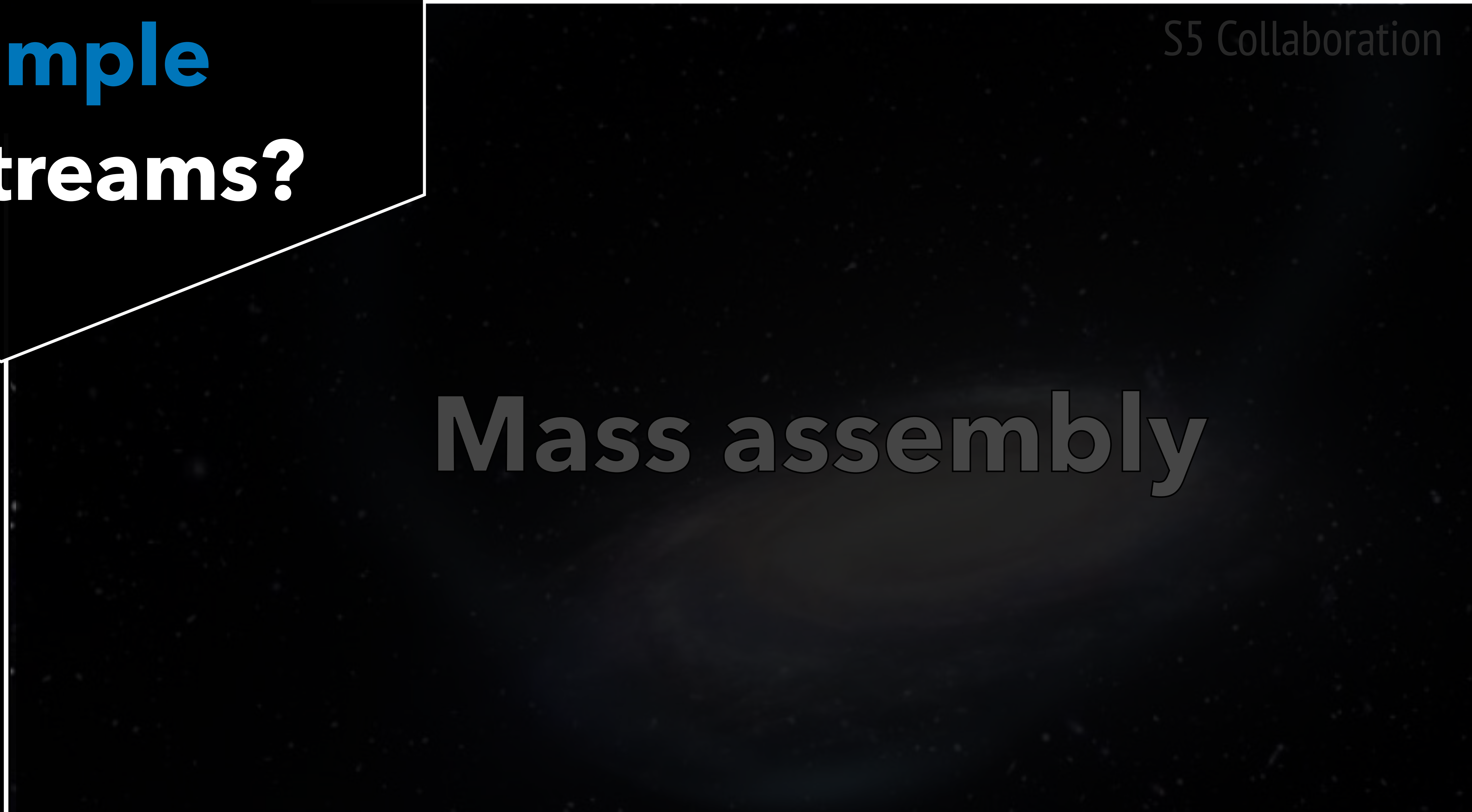


Mass assembly



What can
we learn from a
full sample
of MW streams?

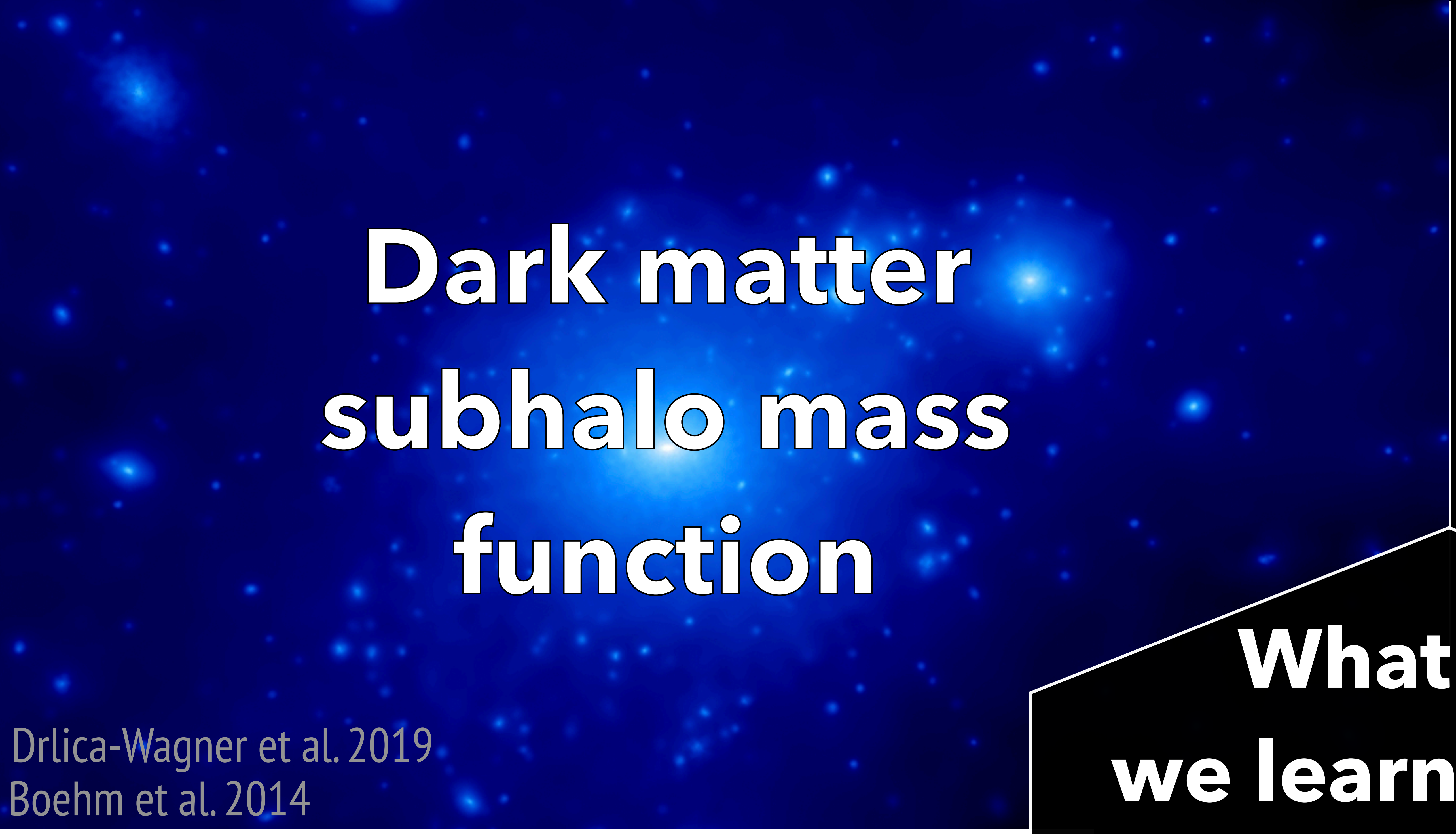





Dark matter subhalo mass function
Drlica-Wagner et al. 2019
Boehm et al. 2014
Pal 1
Pal 5
BH 176
Time of stripping [Gyr]
Response to live halo
Dillamore et al. 2022
What can we learn from a full sample of MW streams?
Nibauer et al. 2022
S5 Collaboration
Joint constraint on potential
Mass assembly

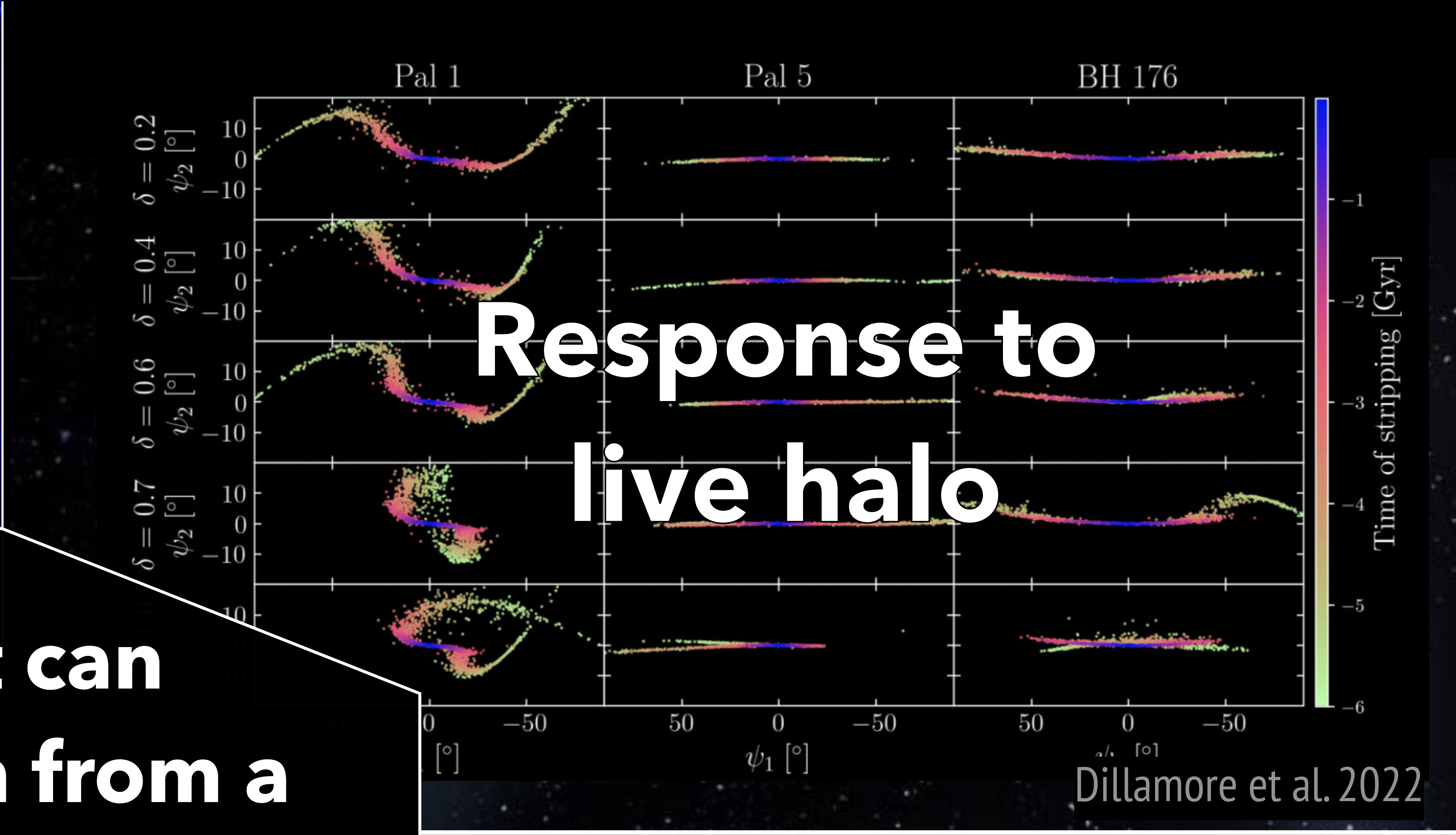

Dark matter subhalo mass function
Drlica-Wagner et al. 2019
Boehm et al. 2014
Pal 1
Pal 5
BH 176
Time of stripping [Gyr]
Response to live halo
Dillamore et al. 2022
What can we learn from a full sample of MW streams?
Nibauer et al. 2022
Joint constraint on potential
See also
Bovy et al 2016
Bonaca & Hogg 2018
S5 Collaboration
Mass assembly

What can we learn from a **full sample** of MW streams?



Dark matter subhalo mass function

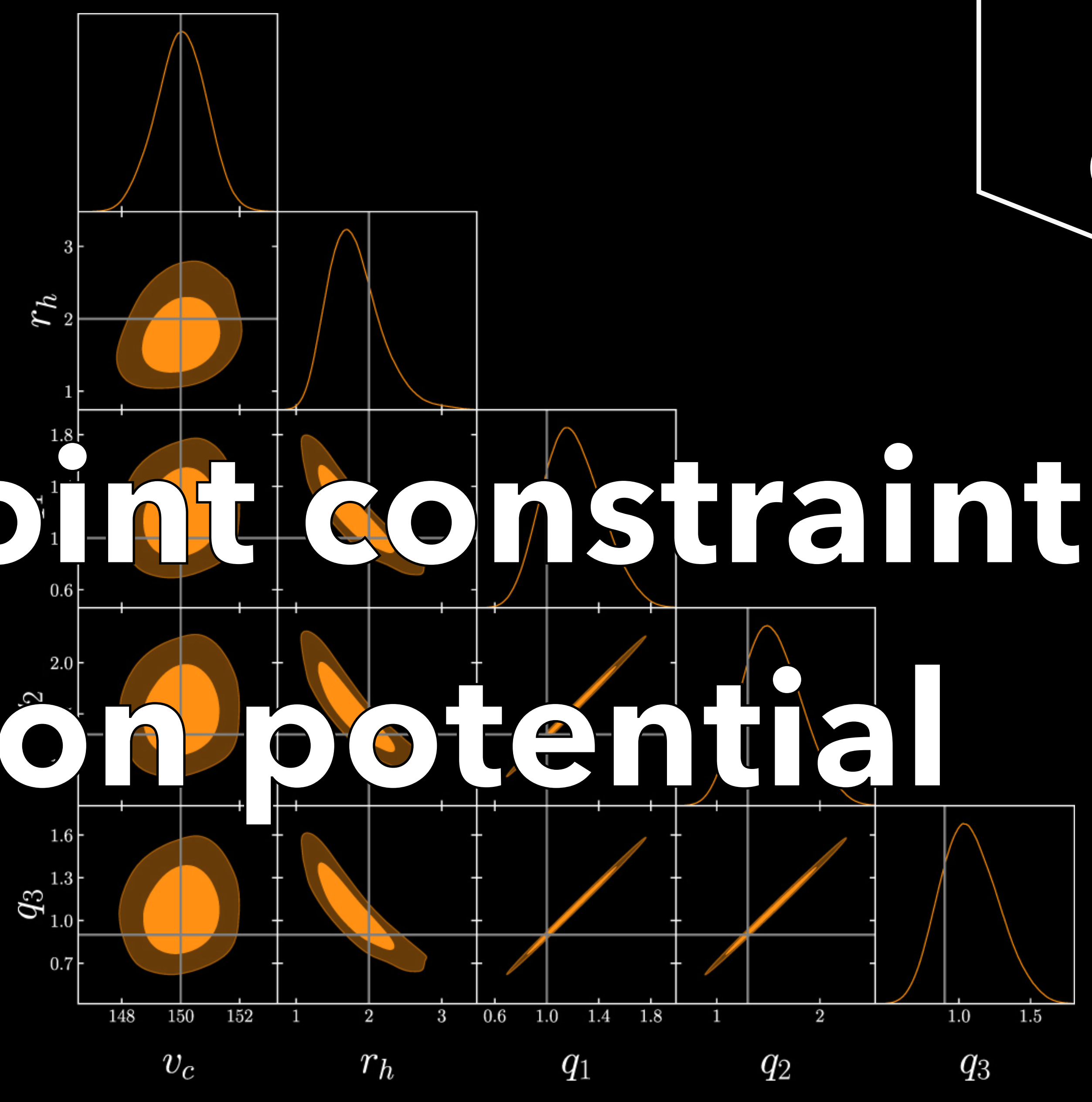
Drlica-Wagner et al. 2019
Boehm et al. 2014



Response to live halo

Dillamore et al. 2022

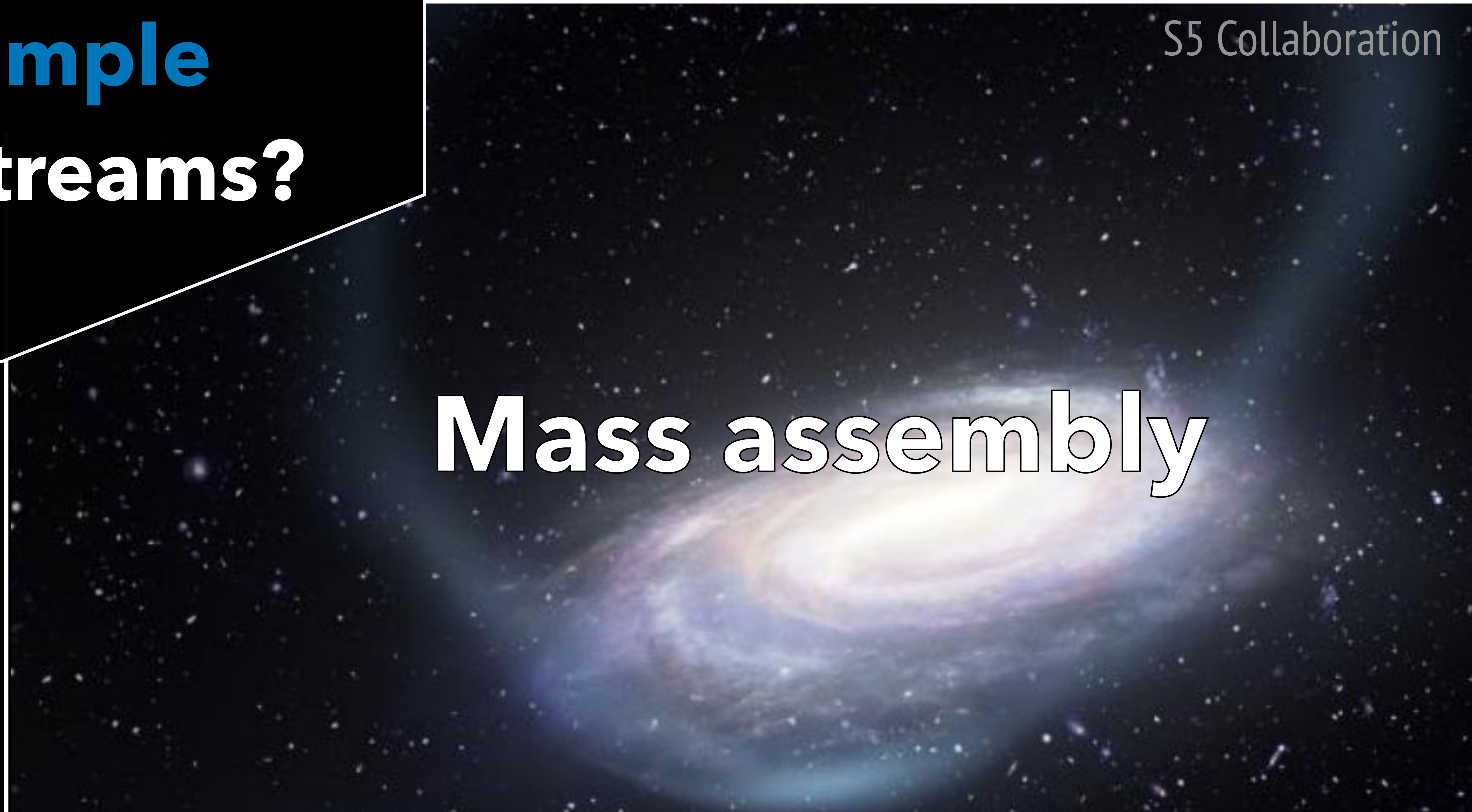
Nibauer et al. 2022



Joint constraint on potential

See also
Bovy et al 2016
Bonaca & Hogg 2018

S5 Collaboration



Mass assembly

Forecasting

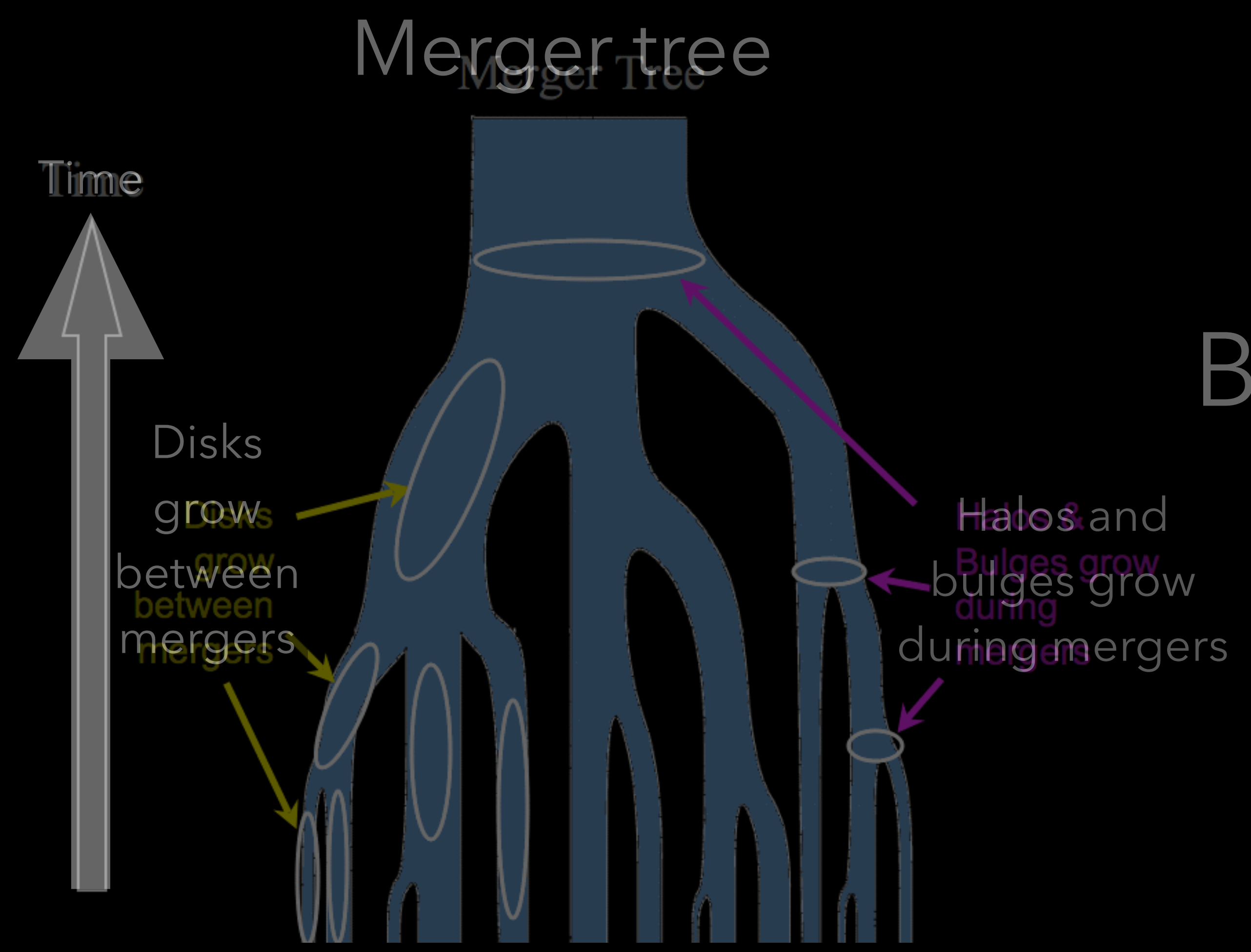
the missing population of

Milky Way globular cluster streams

How do we start?

Hierarchical model of globular cluster formation

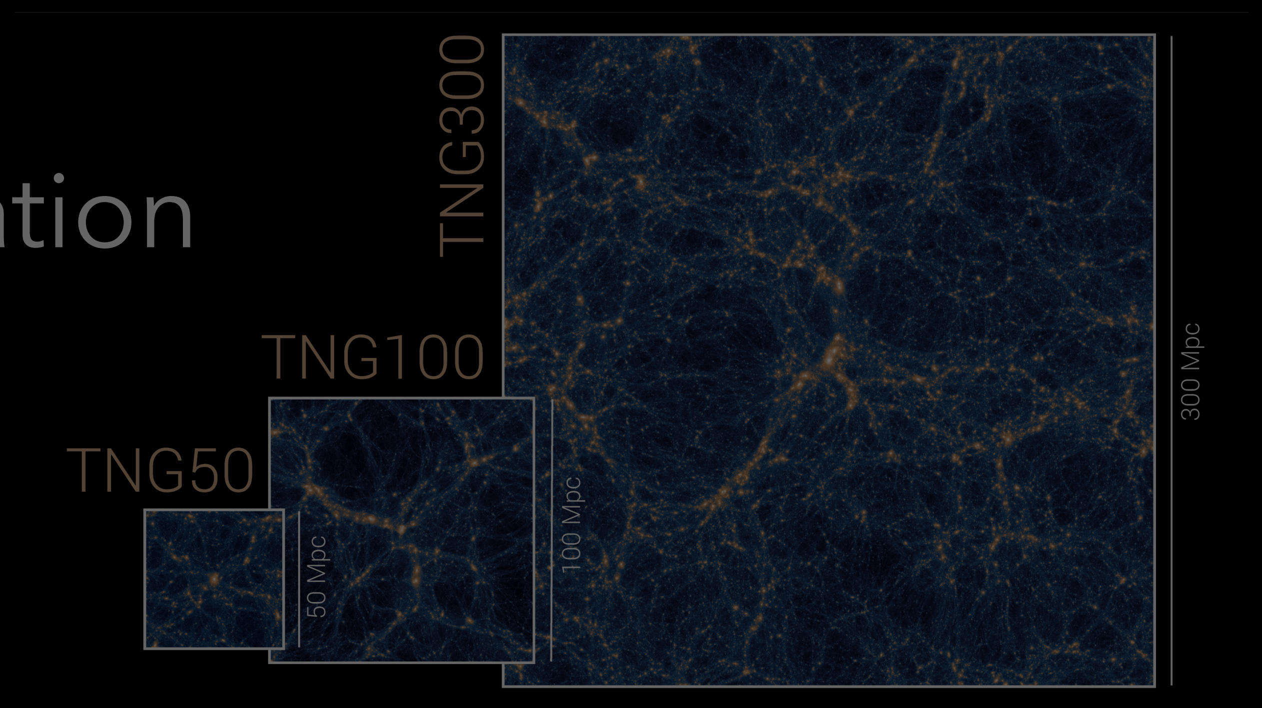
Chen & Gnedin 2022, Chen & Gnedin 2023



Illustris TNG50

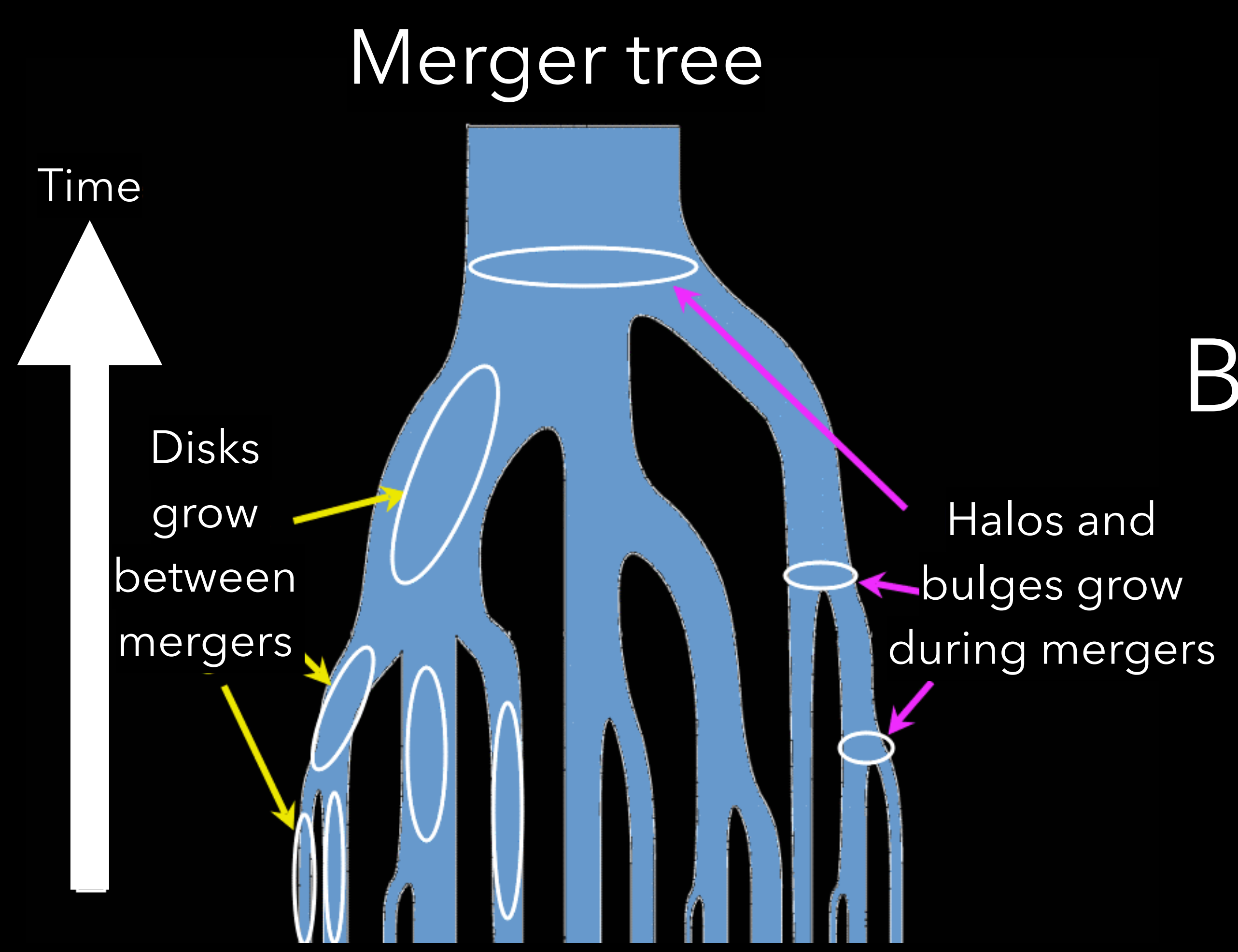
Background hydrodynamical cosmological simulation

Nelson et al. 2019



Hierarchical model of globular cluster formation

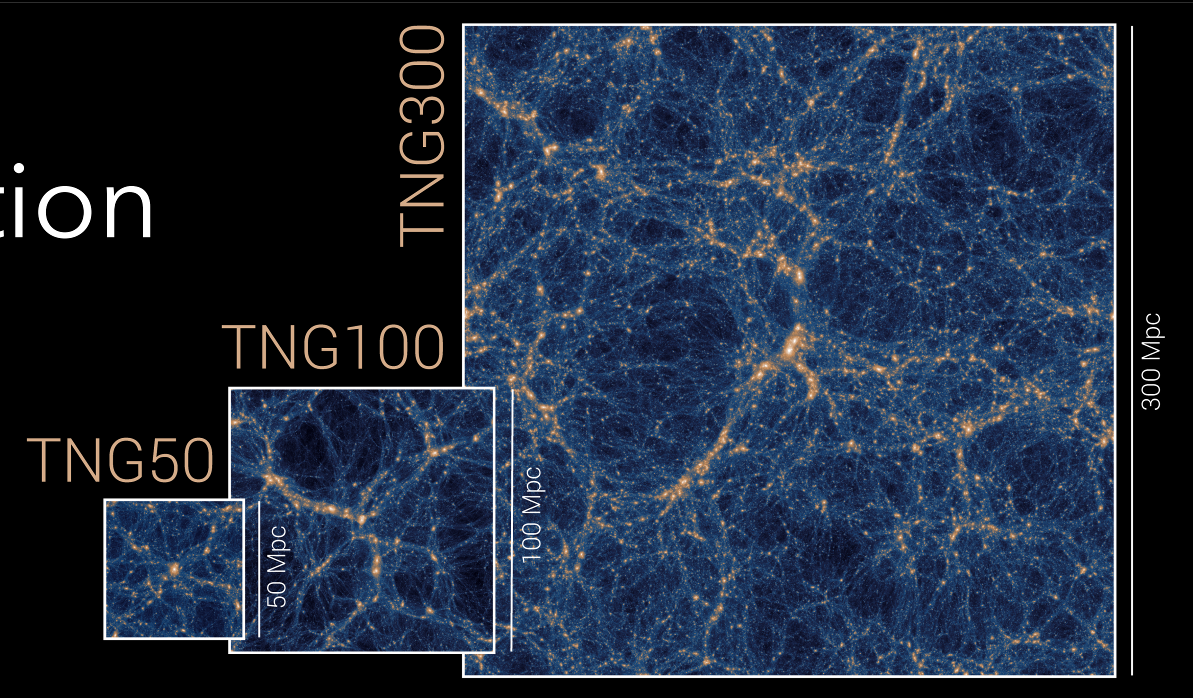
Chen & Gnedin 2022, Chen & Gnedin 2023



Illustris TNG50

Background hydrodynamical cosmological simulation

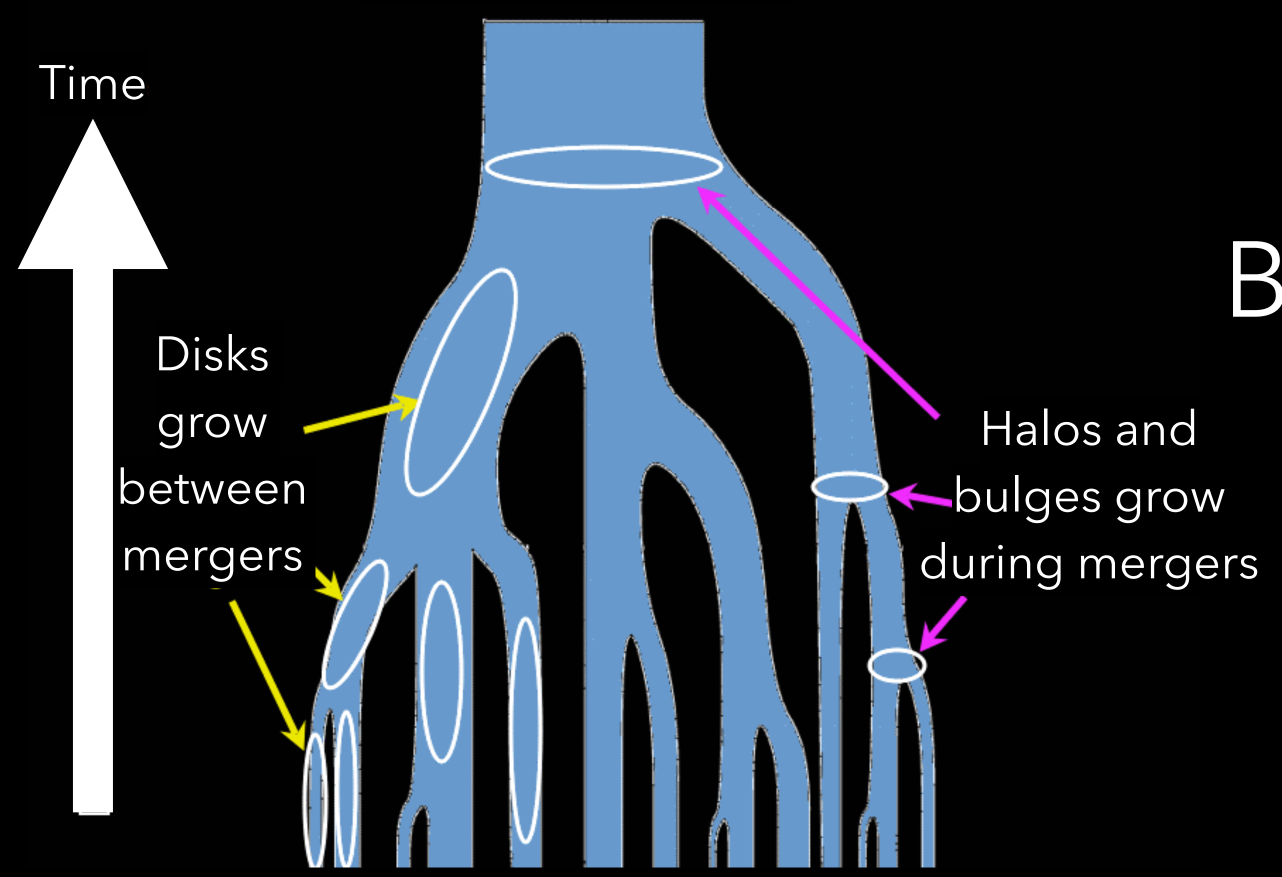
Nelson et al. 2019



Hierarchical model of globular cluster formation

Chen & Gnedin 2022, Chen & Gnedin 2023

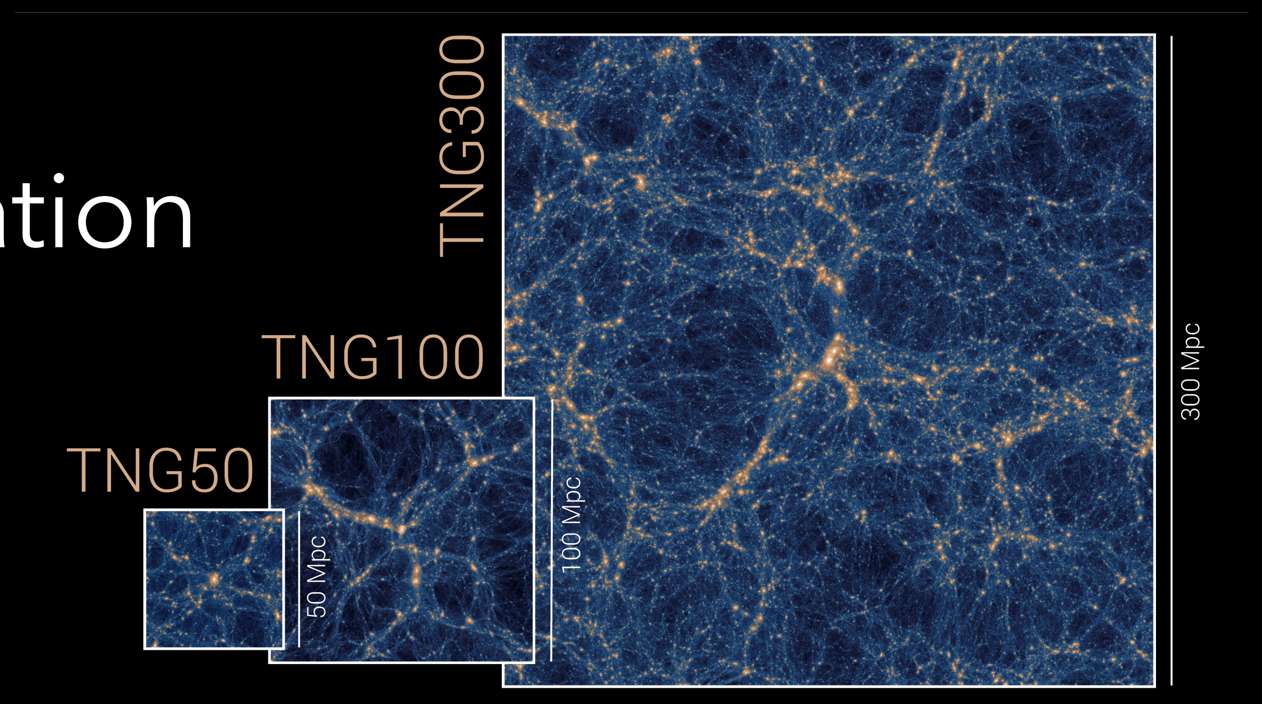
Merger tree

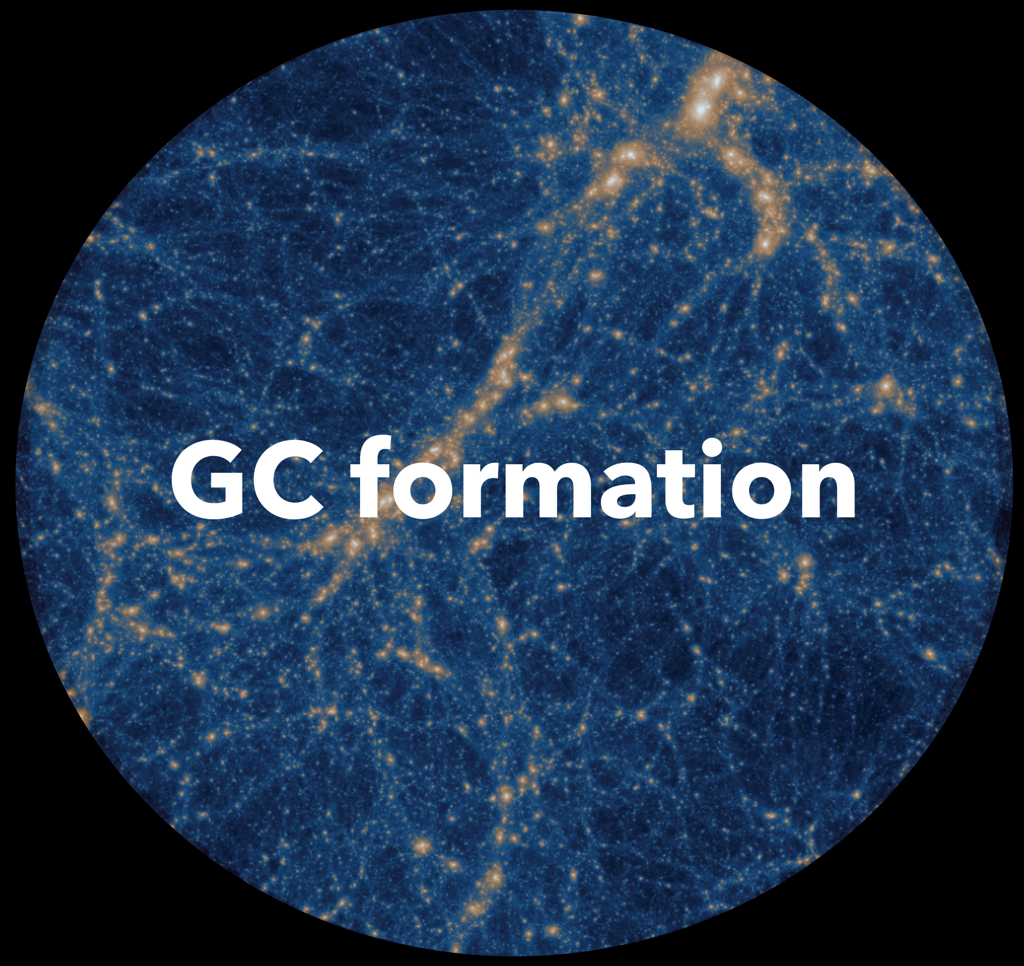


Illustris TNG50

Background hydrodynamical cosmological simulation

Nelson et al. 2019



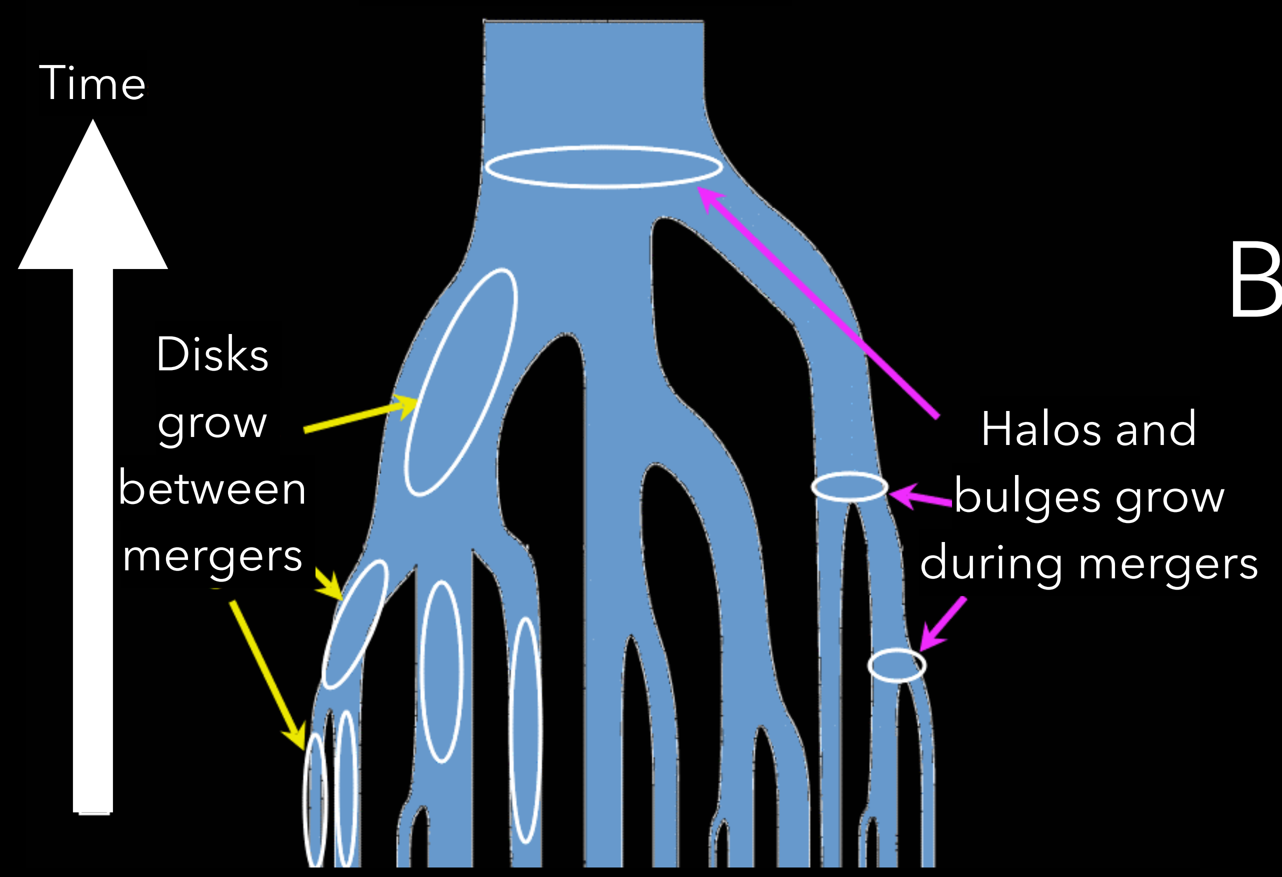


Kravtsov & Gnedin 2005

Hierarchical model of globular cluster formation

Chen & Gnedin 2022, Chen & Gnedin 2023

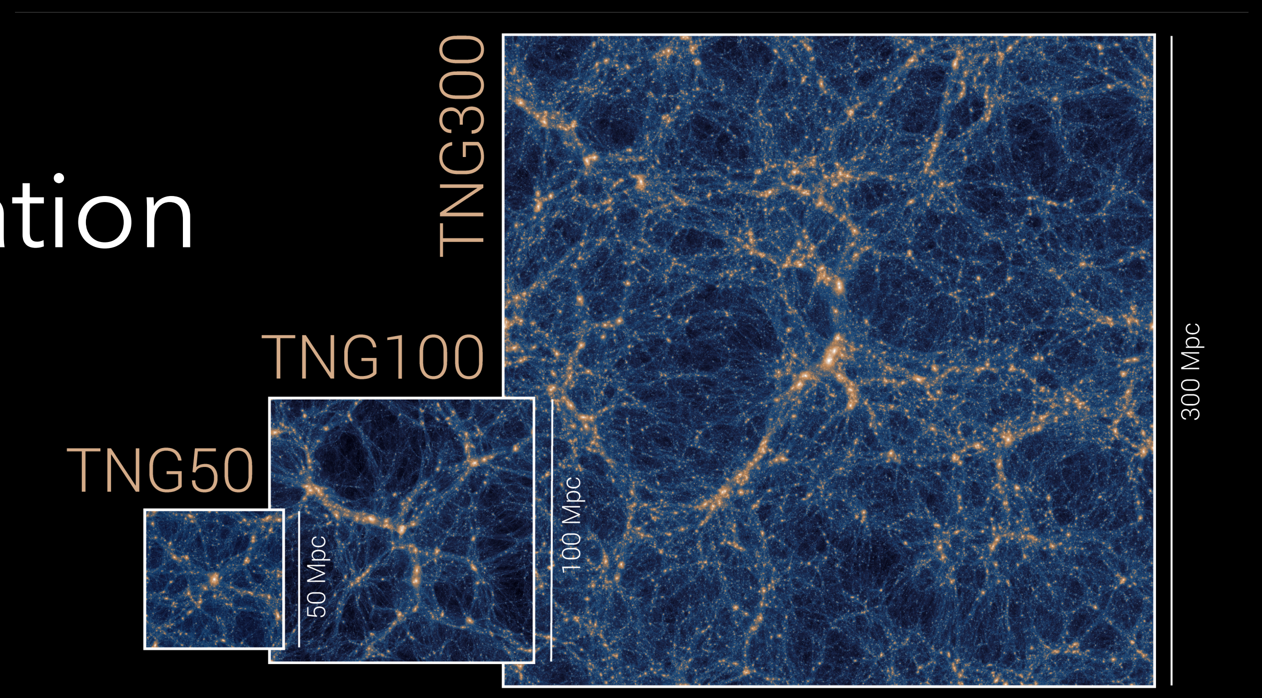
Merger tree

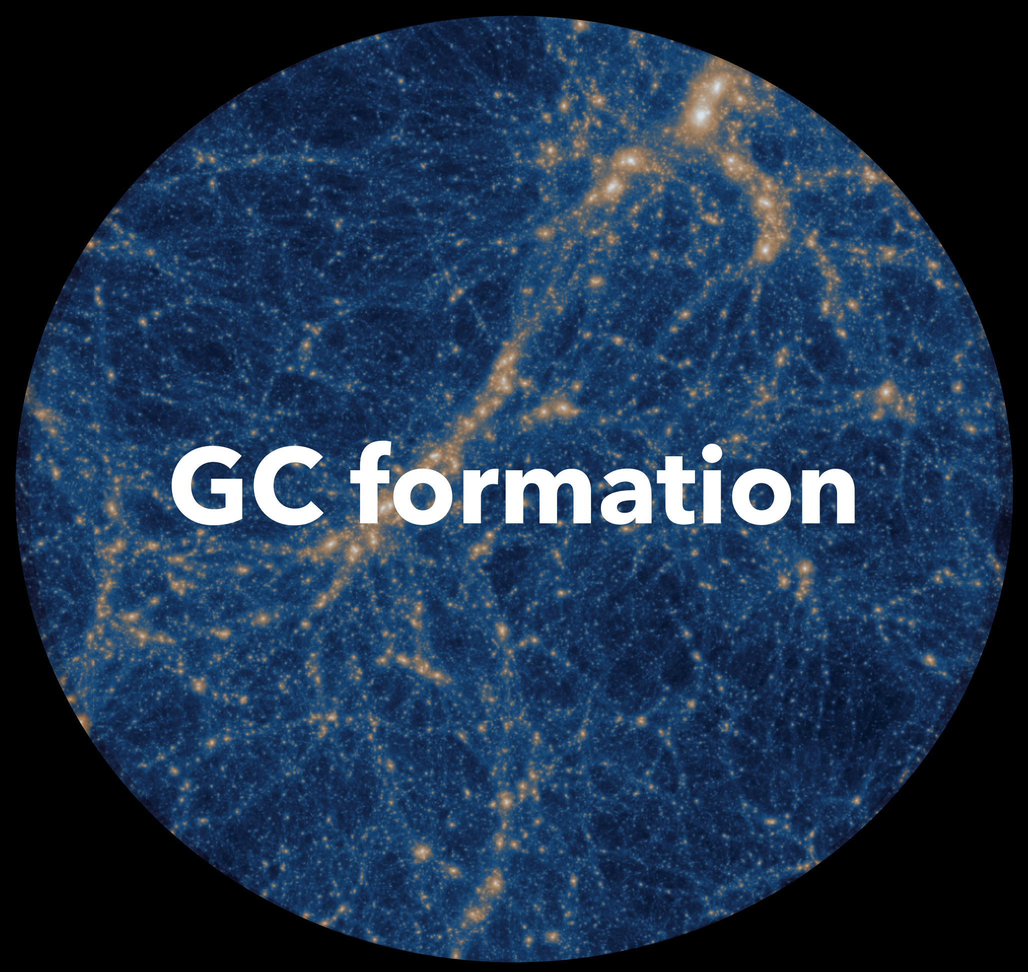


Illustris TNG50

Background hydrodynamical cosmological simulation

Nelson et al. 2019





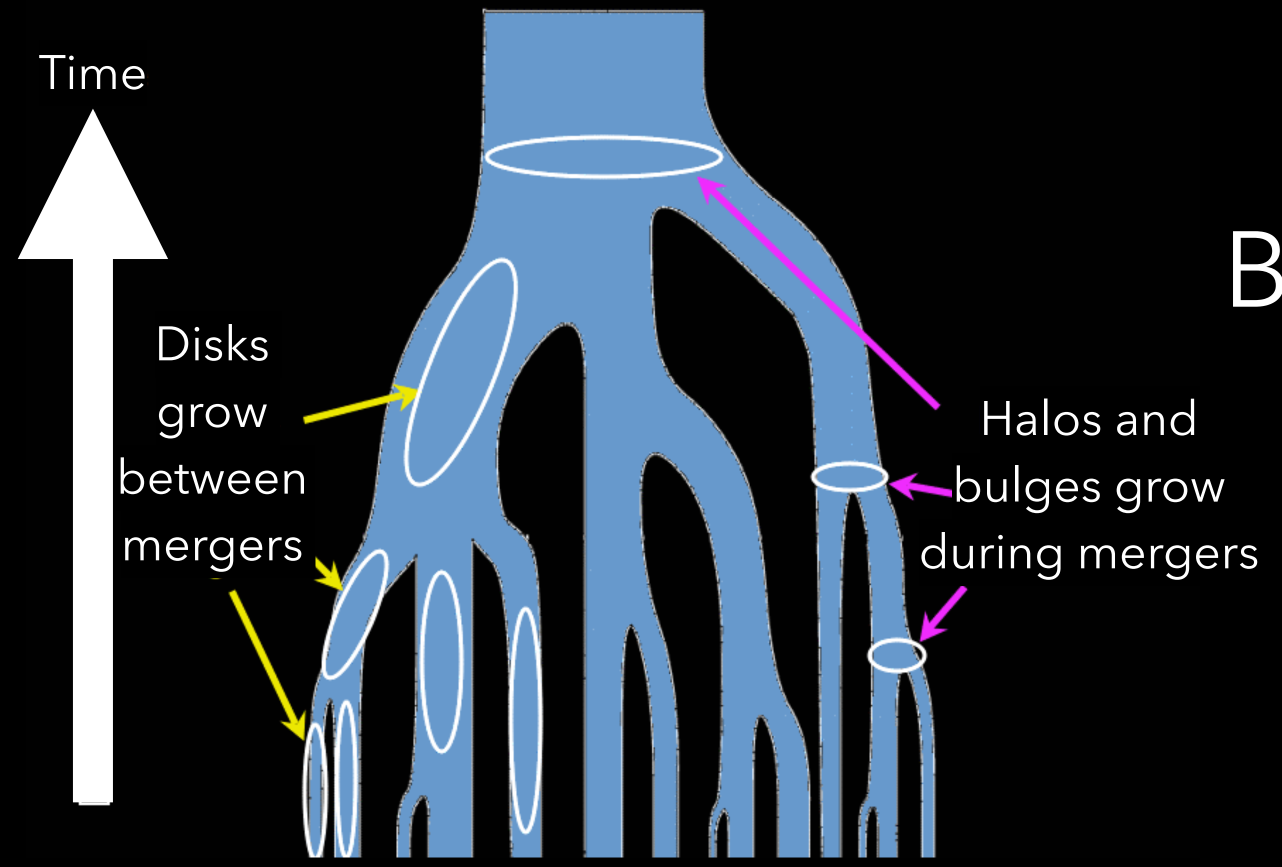
Kravtsov & Gnedin 2005

Schechter 1976

Hierarchical model of globular cluster formation

Chen & Gnedin 2022, Chen & Gnedin 2023

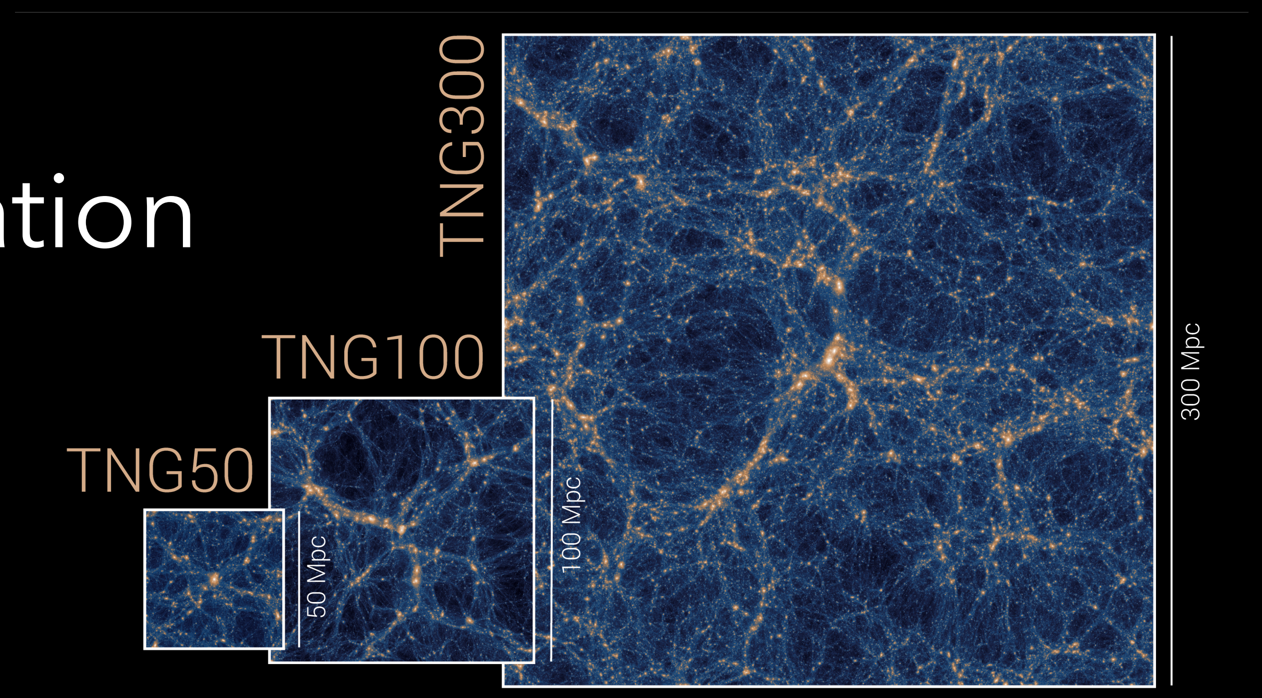
Merger tree

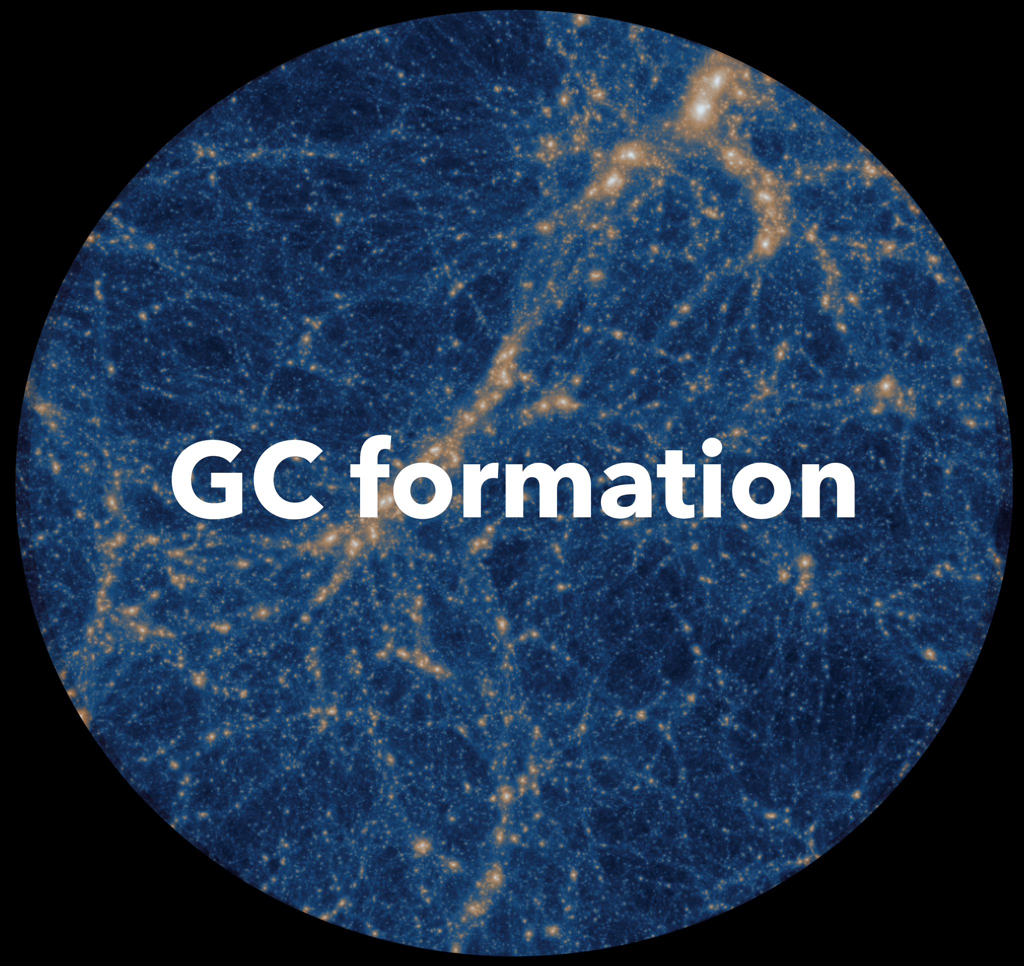


Illustris TNG50

Background hydrodynamical cosmological simulation

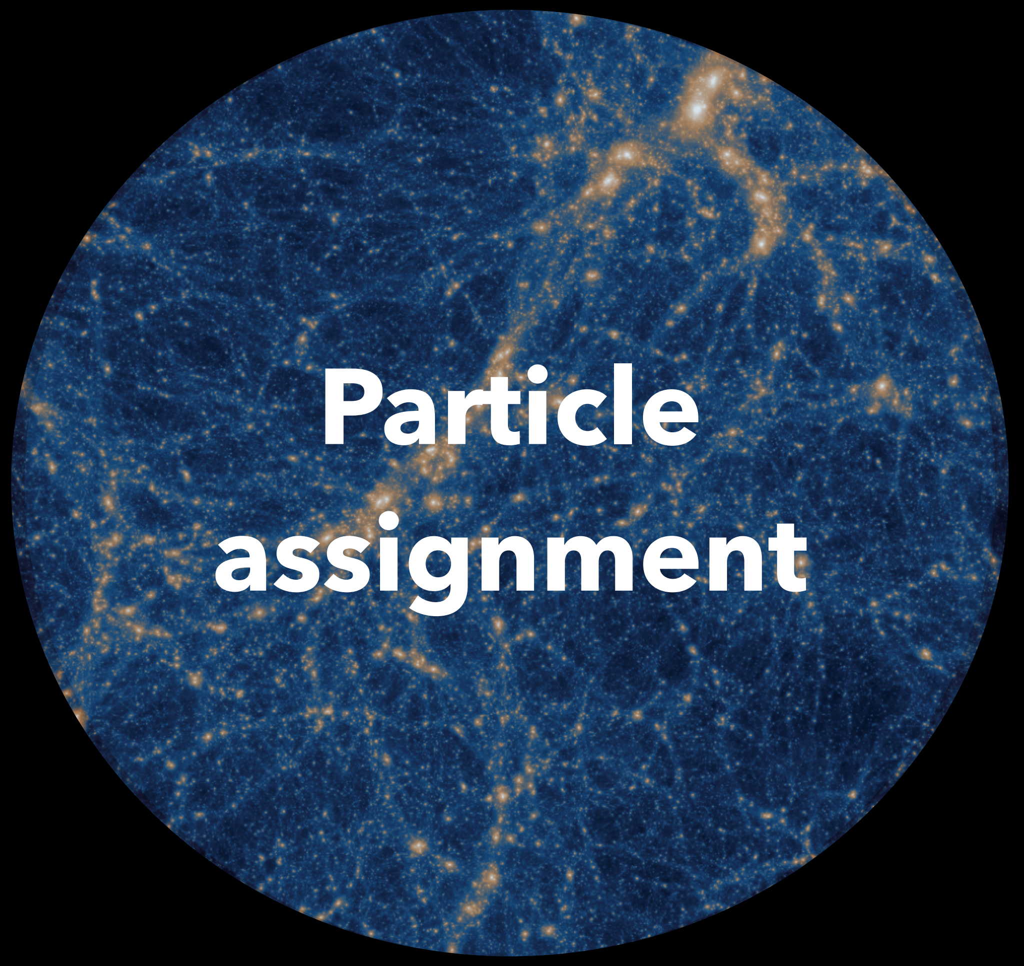
Nelson et al. 2019





Kravtsov & Gnedin 2005

Schechter 1976

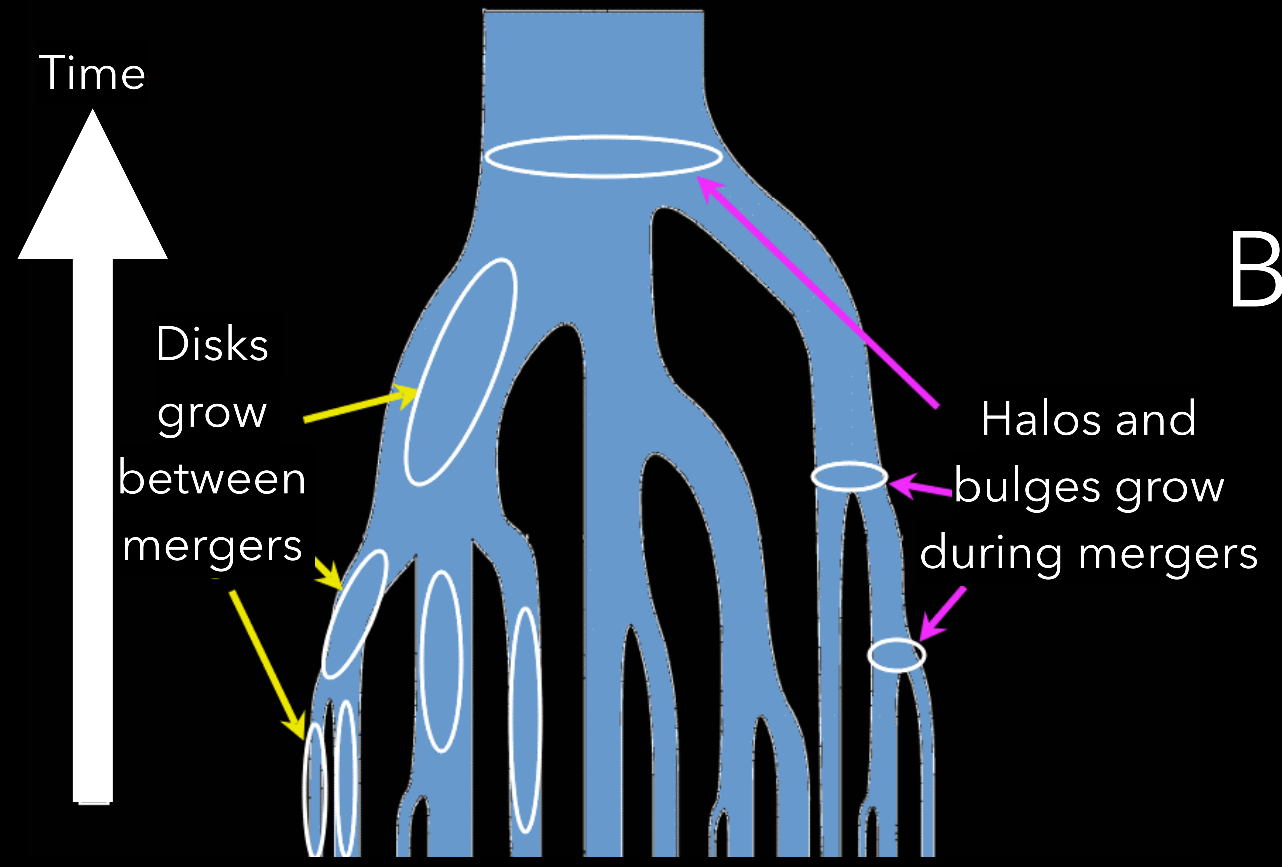


Nelson et al. 2019

Hierarchical model of globular cluster formation

Chen & Gnedin 2022, Chen & Gnedin 2023

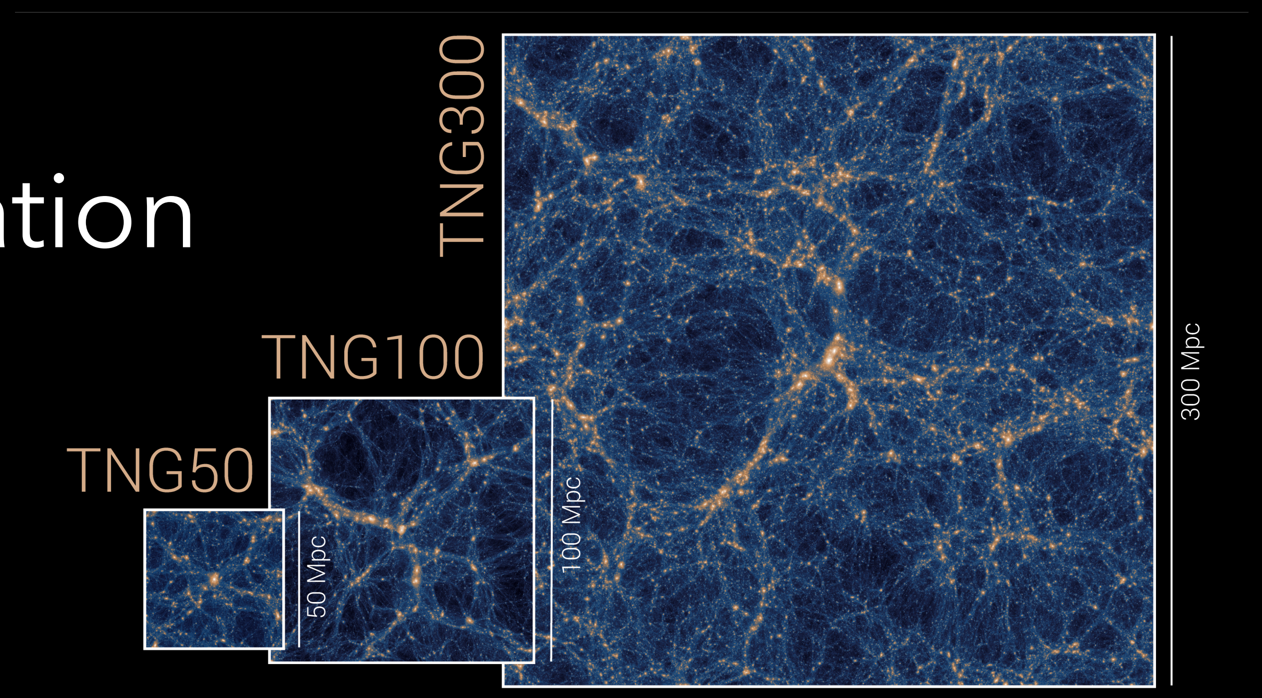
Merger tree

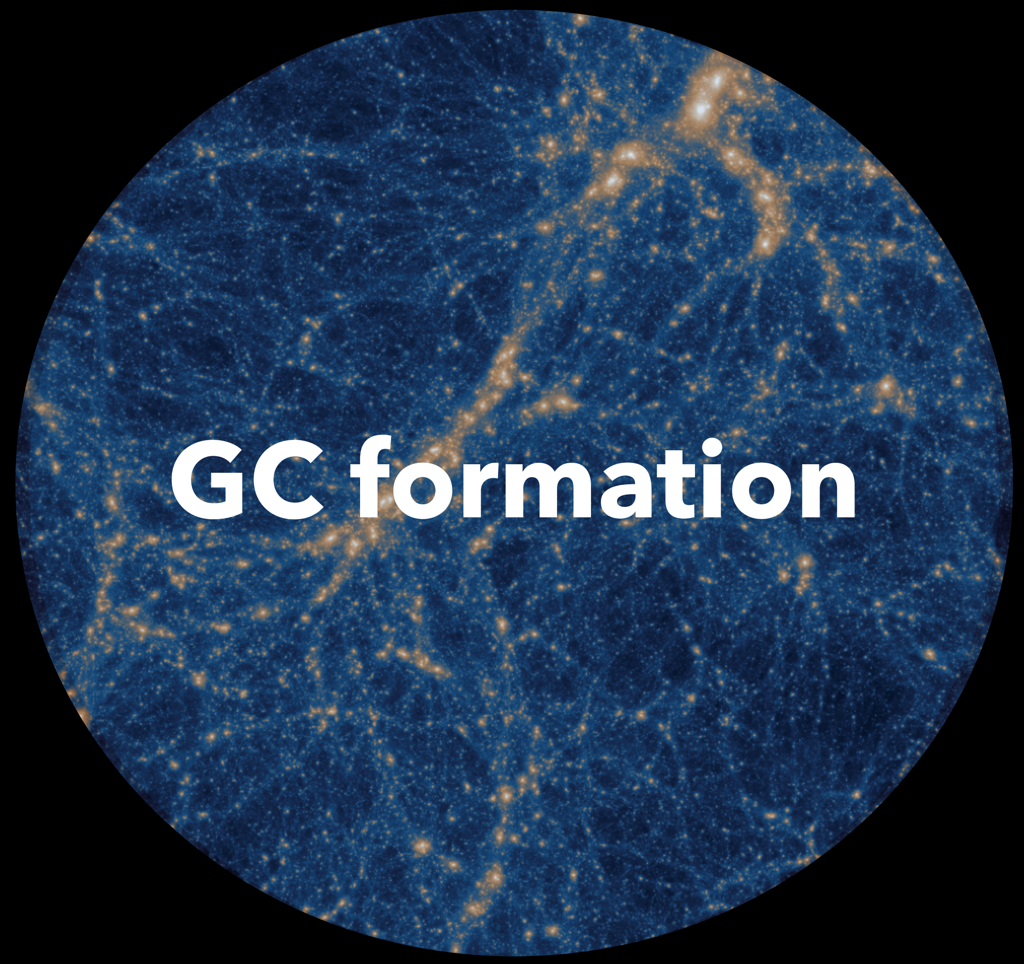


Illustris TNG50

Background hydrodynamical cosmological simulation

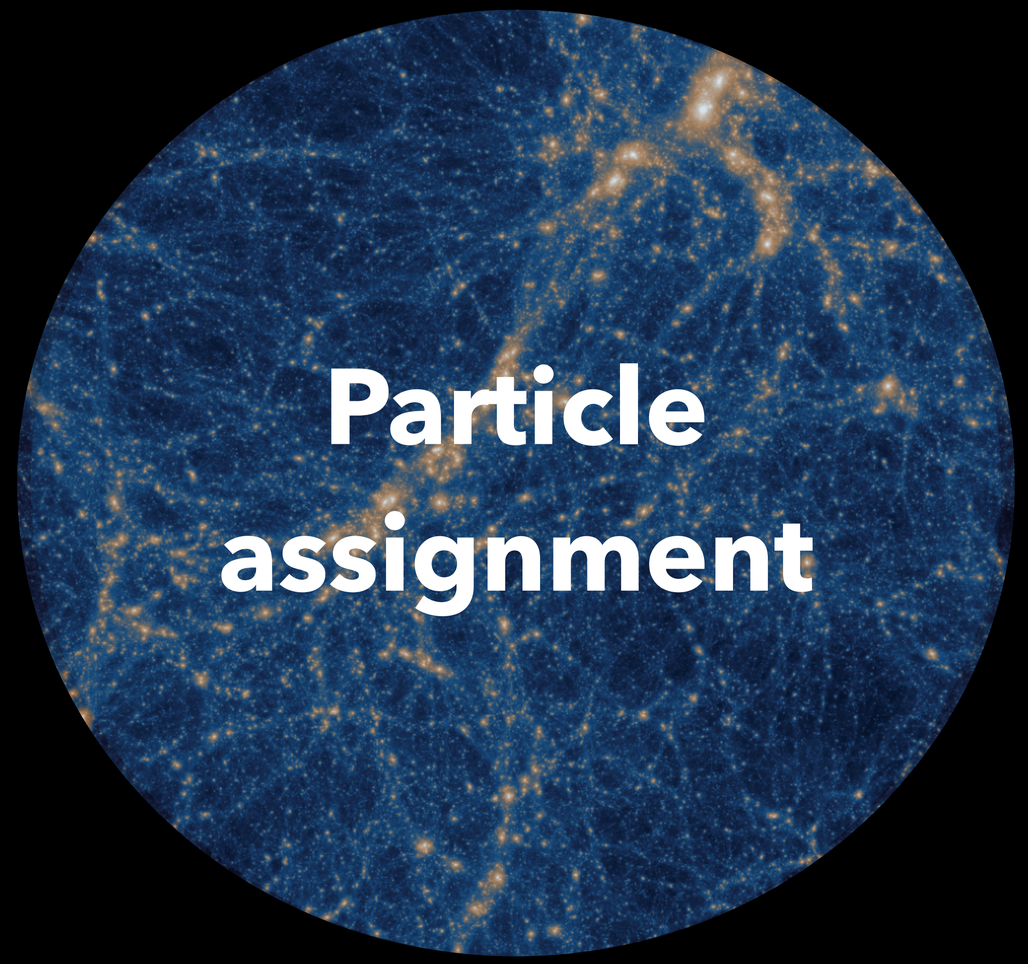
Nelson et al. 2019



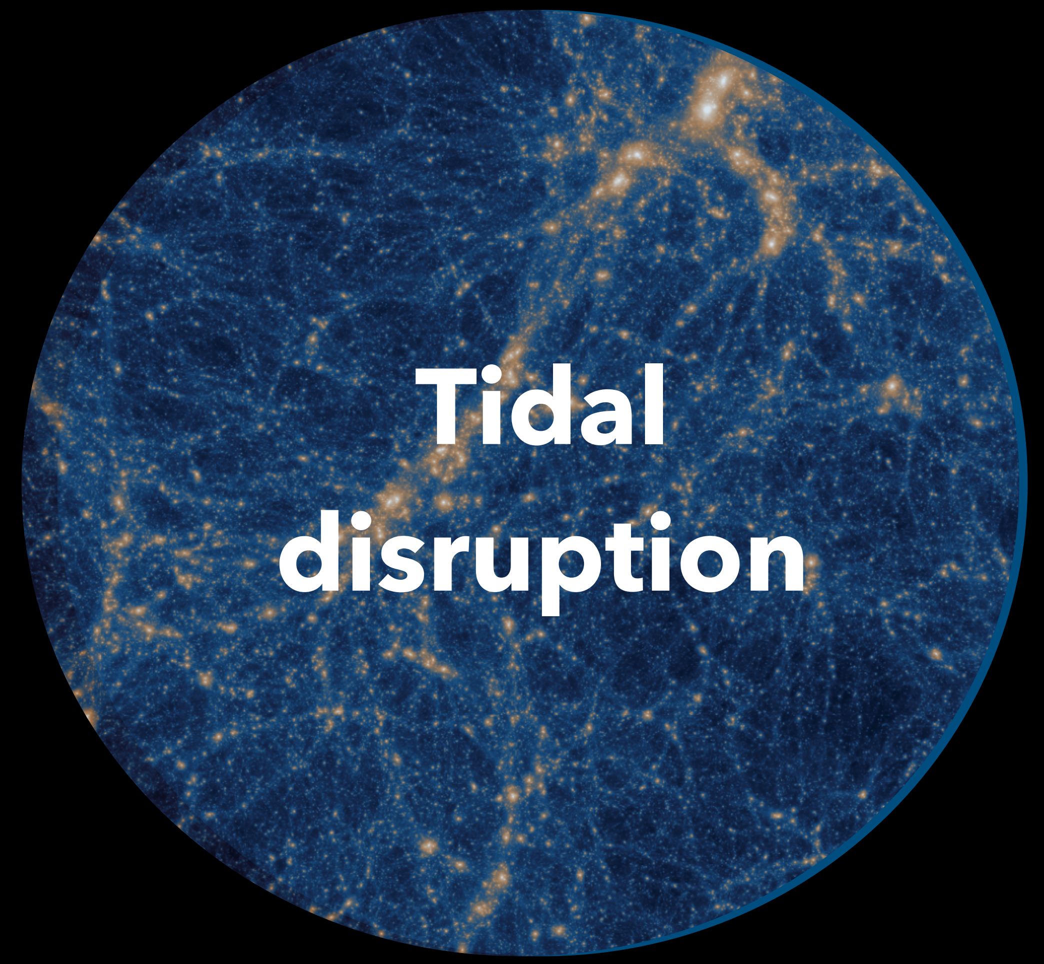


Kravtsov & Gnedin 2005

Schechter 1976



Nelson et al. 2019

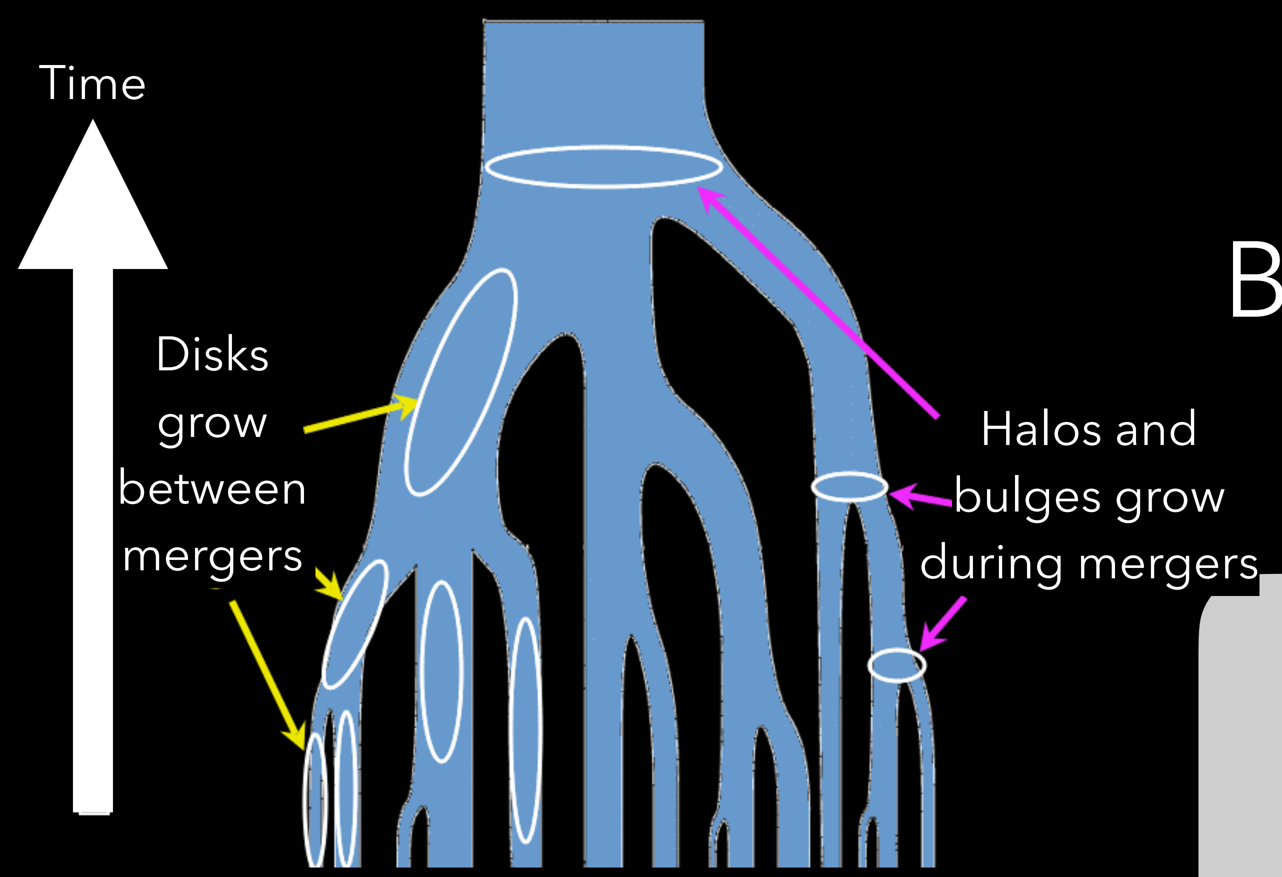


Gieles & Gnedin 2023

Hierarchical model of globular cluster formation

Chen & Gnedin 2022, Chen & Gnedin 2023

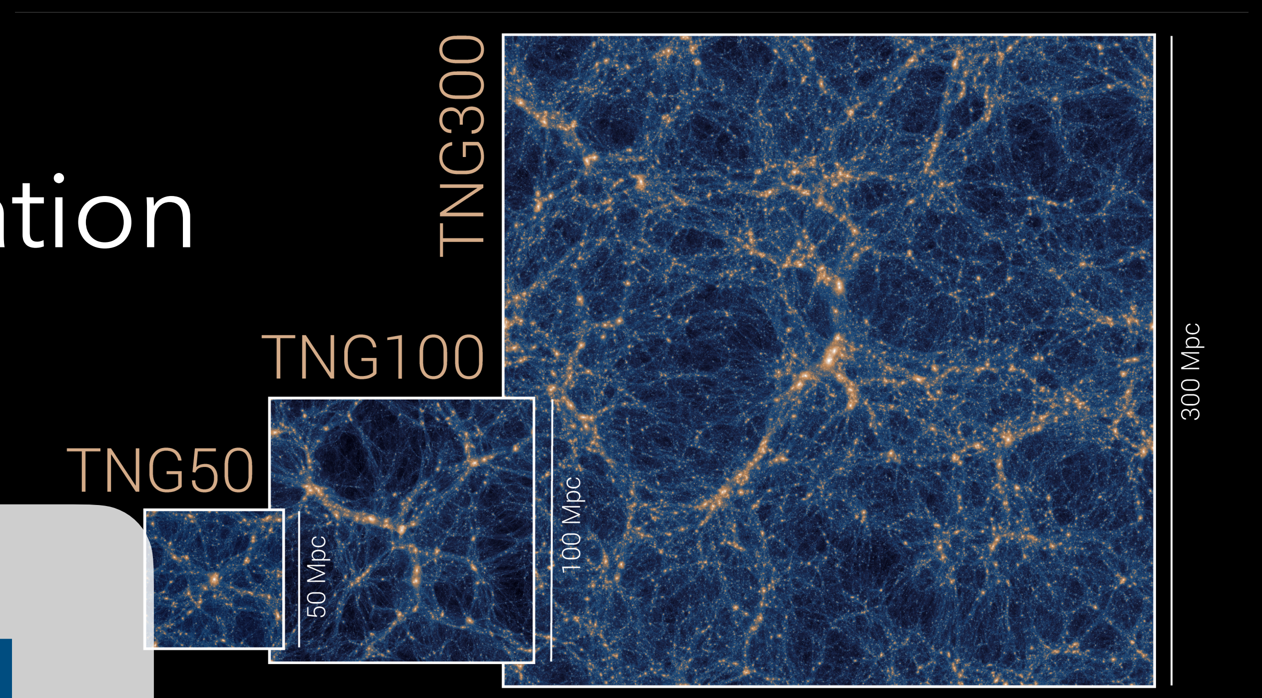
Merger tree



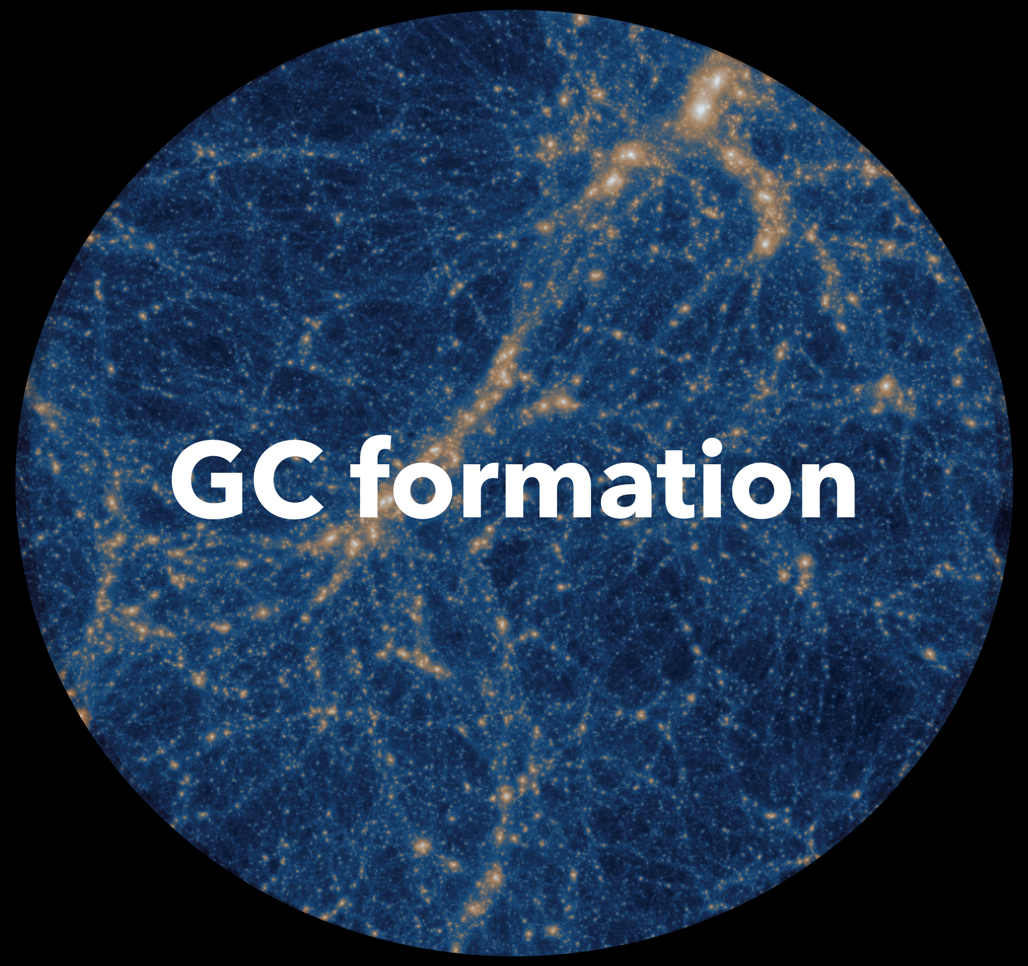
Illustris TNG50

Background hydrodynamical cosmological simulation

Nelson et al. 2019

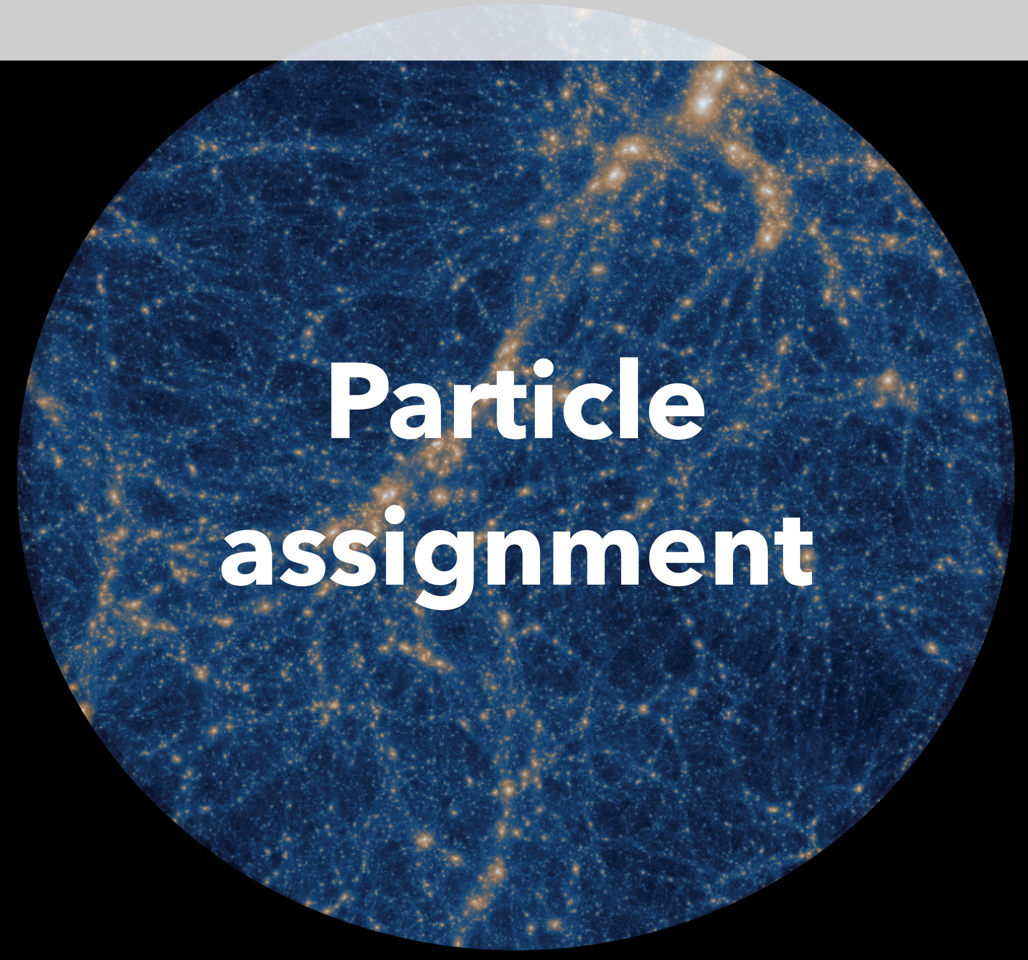


Reproduces **kinematics, metallicities, and spatial distribution** of observed MW GCs.

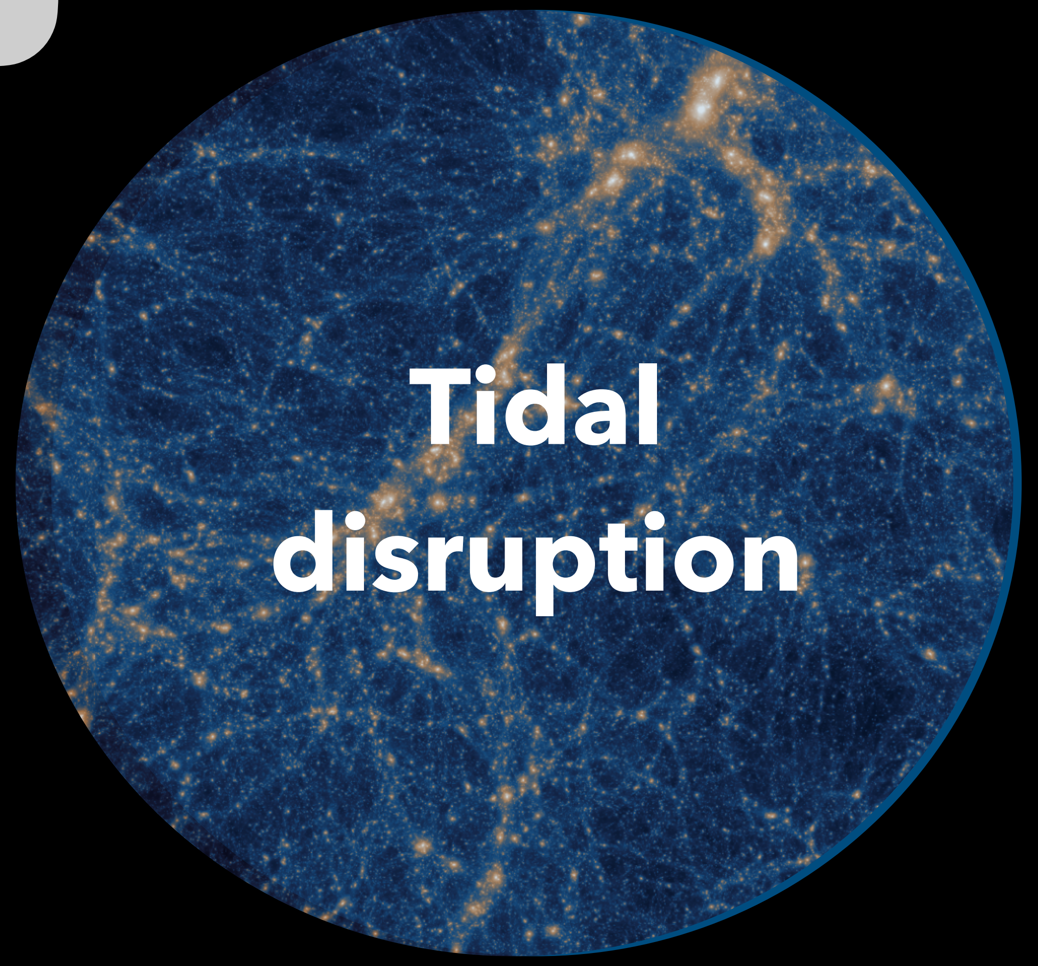


Kravtsov & Gnedin 2005

Schechter 1976



Nelson et al. 2019

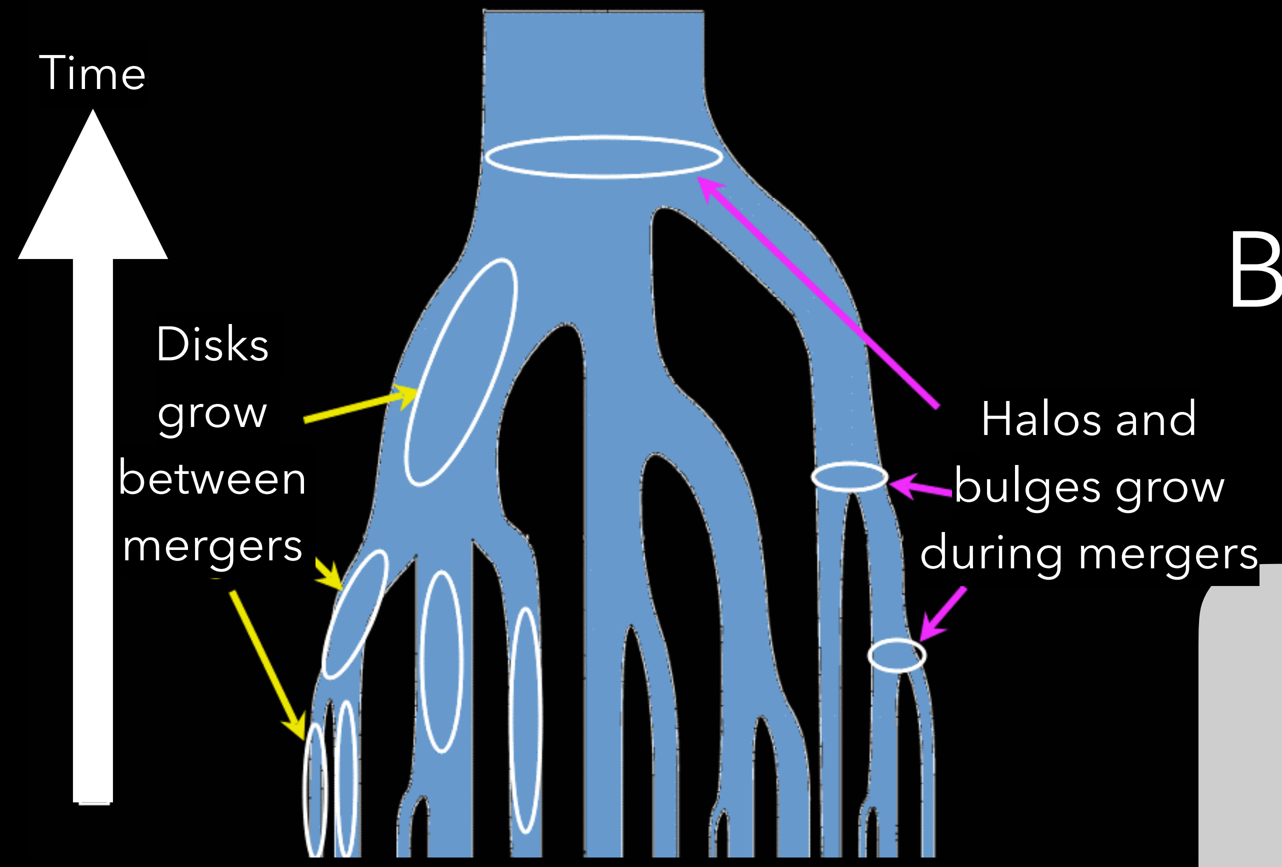


Gieles & Gnedin 2023

Hierarchical model of globular cluster formation

Chen & Gnedin 2022, Chen & Gnedin 2023

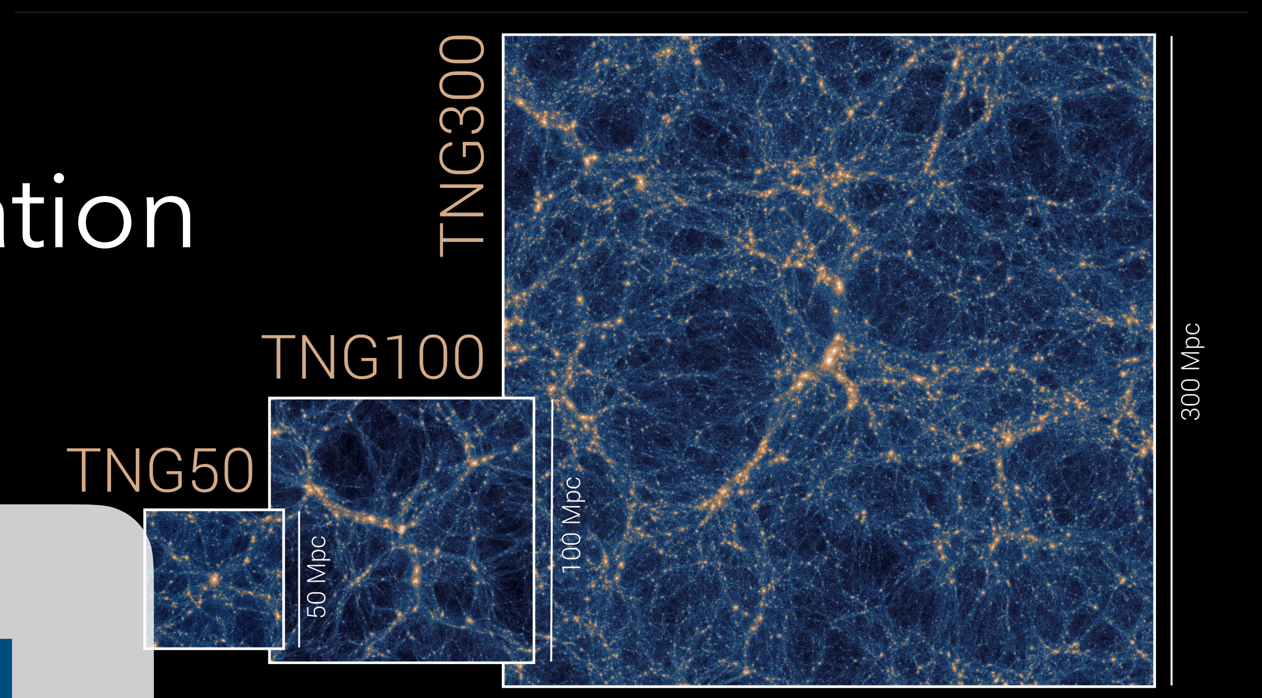
Merger tree



Illustris TNG50

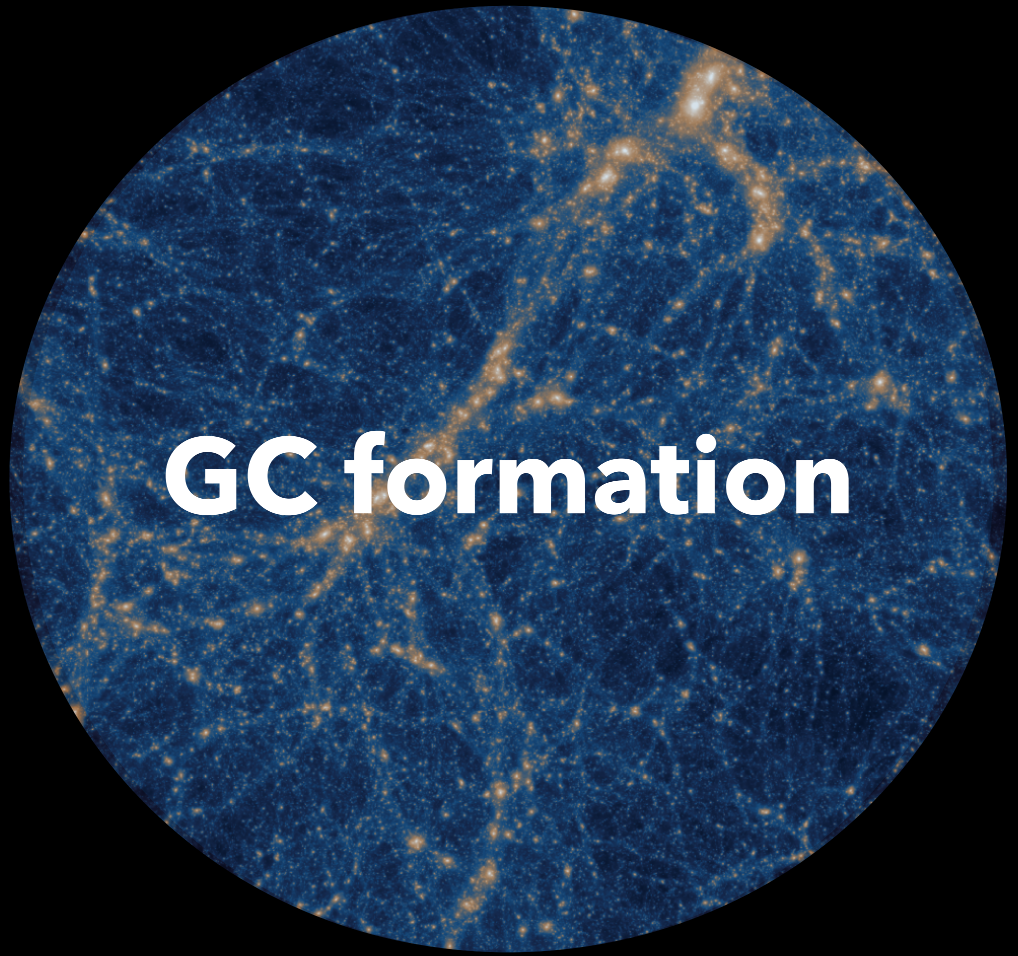
Background hydrodynamical cosmological simulation

Nelson et al. 2019



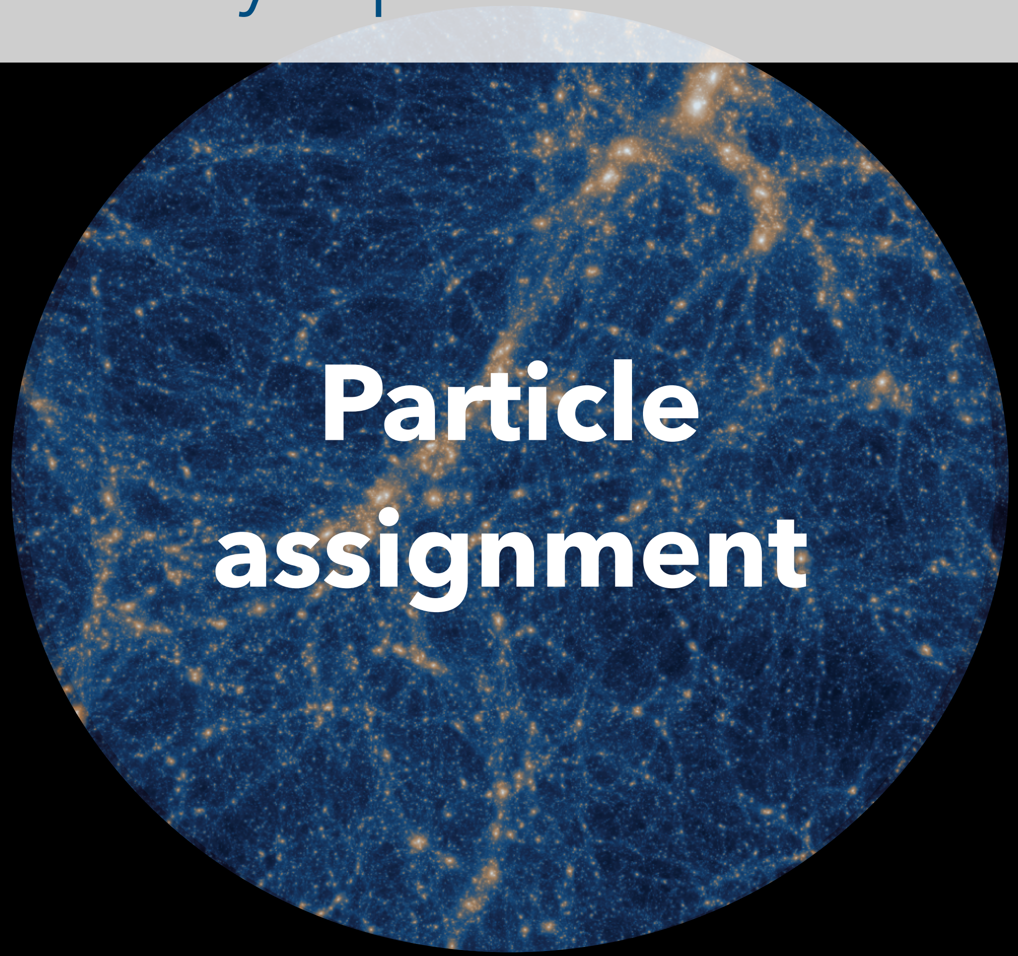
Reproduces **kinematics, metallicities, and spatial distribution** of observed MW GCs.

Let's assume they reproduce streams too….



Kravtsov & Gnedin 2005

Schechter 1976



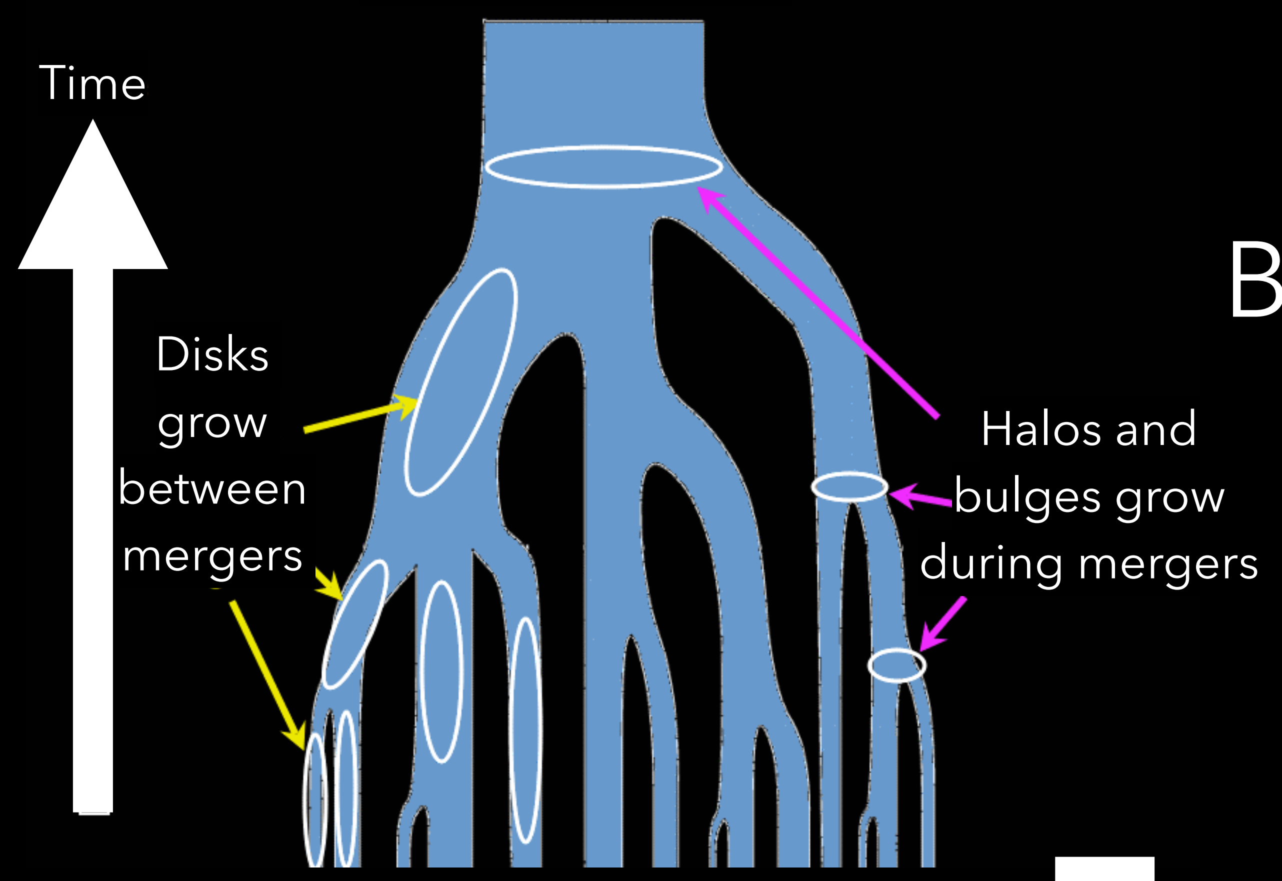
Nelson et al. 2019

Gieles & Gnedin 2023

Hierarchical model of globular cluster formation

Chen & Gnedin 2022, Chen & Gnedin 2023

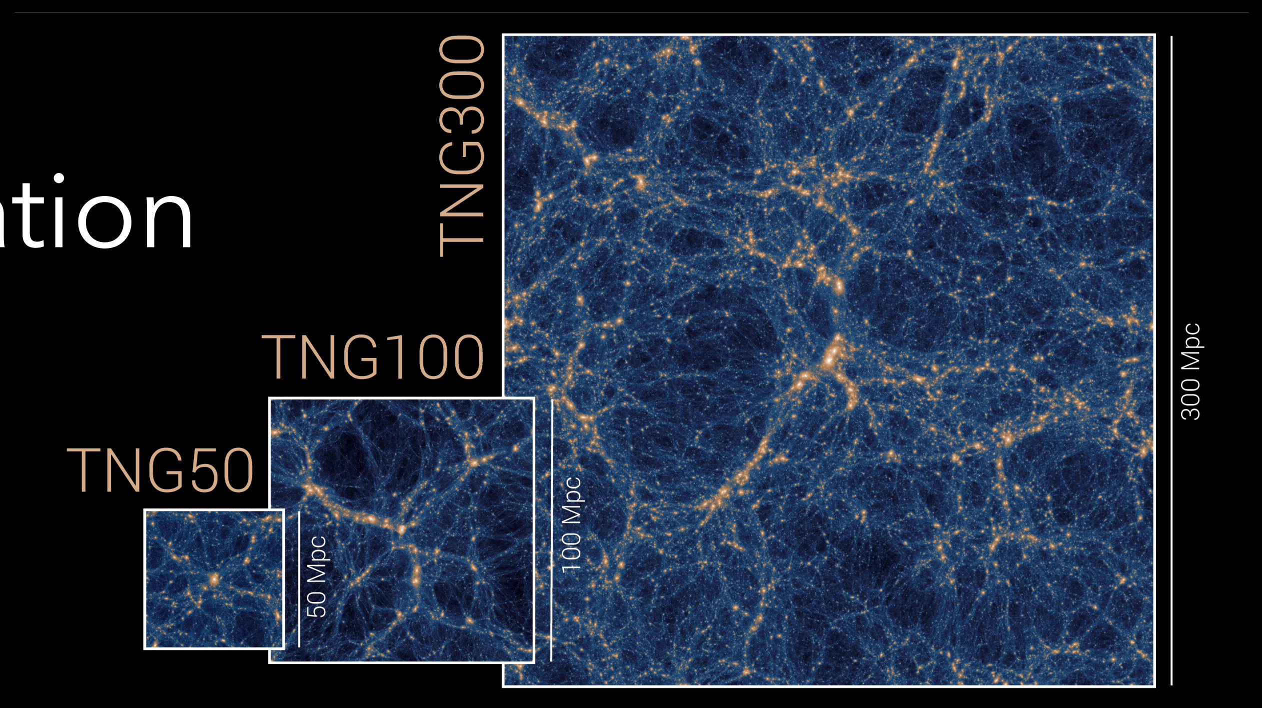
Merger tree



Illustris TNG50

Background hydrodynamical cosmological simulation

Nelson et al. 2019

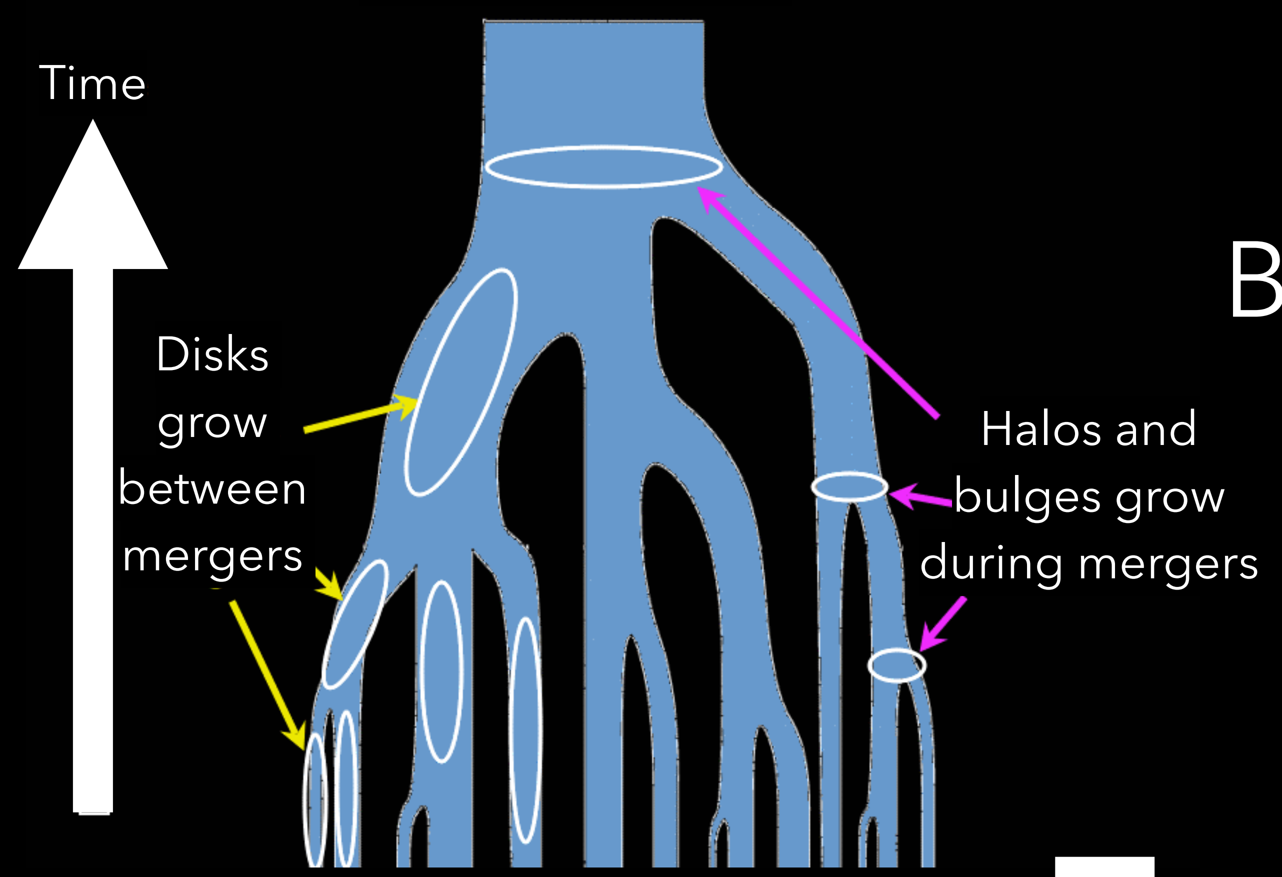


From the catalogs we have...

- Time of cluster formation/ accretion
- Position of cluster/remnant at present day
- Cluster mass at brith
- Time of dissolution
- Cluster age/metallicity

Hierarchical model of globular cluster formation

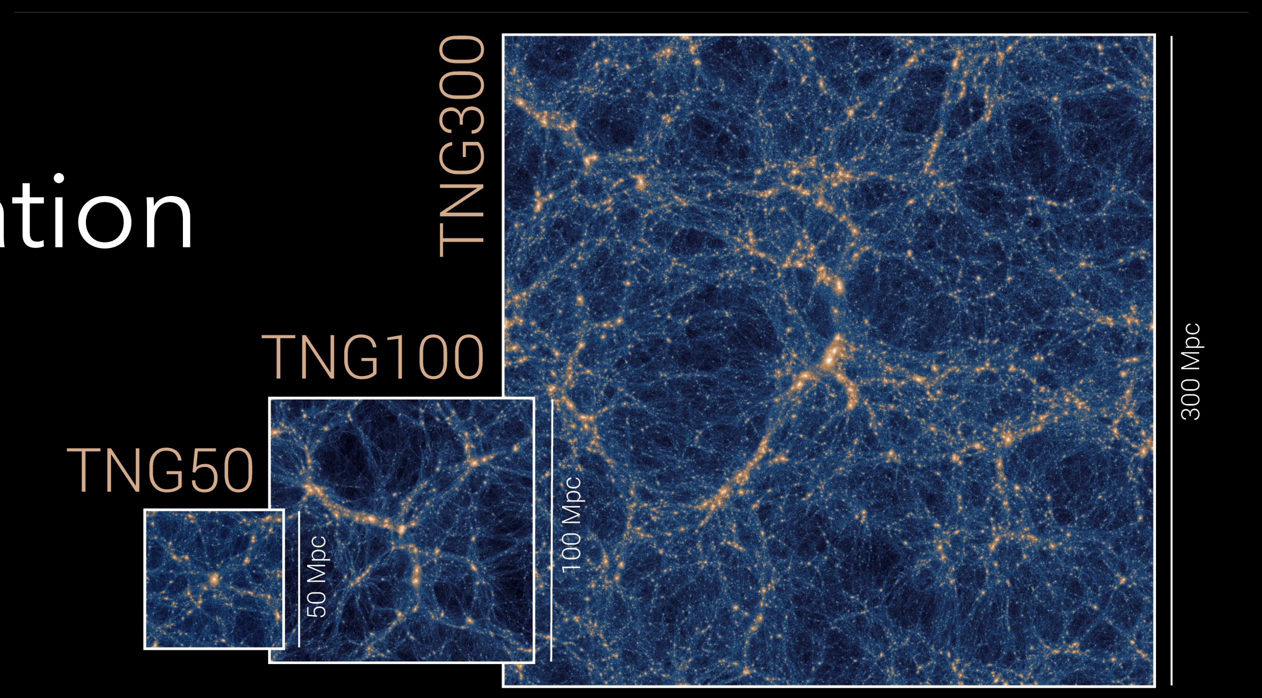
Chen & Gnedin 2022, Chen & Gnedin 2023



Illustris TNG50

Background hydrodynamical cosmological simulation

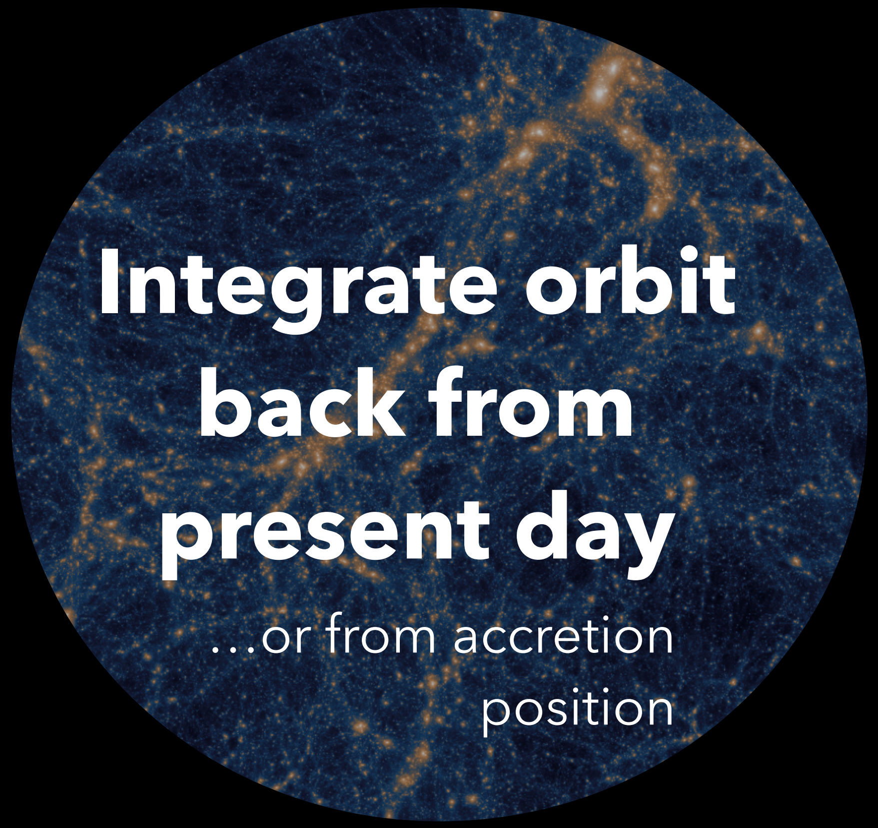
Nelson et al. 2019

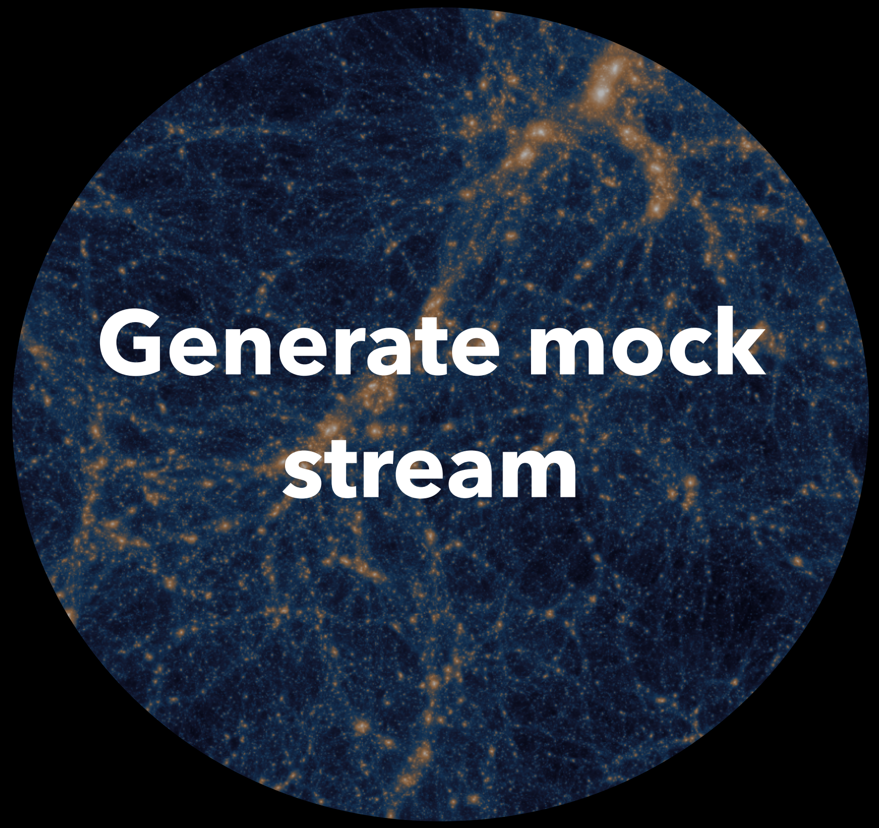


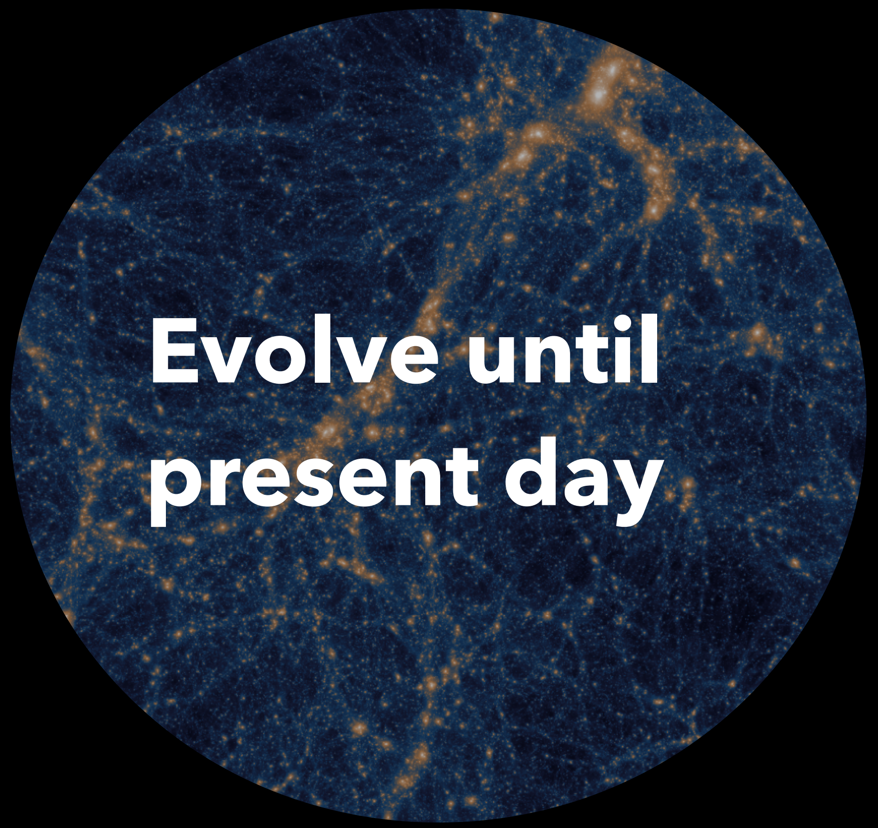
From the catalogs we have...

- Time of cluster formation/ accretion
- Position of cluster/remnant at present day
- Cluster mass at brith
- Time of dissolution
- Cluster age/metallicity

We generate mock streams as a **self-consistent extension** of the model







Approximate potential

Fardal et al. 2015

Credit: Adapted from A. Price-Whelan

Integrate orbit back from present day

...or from accretion position

Generate mock stream

Stop generating new stars at time of dissolution

Evolve until present day

Populate streams with stars

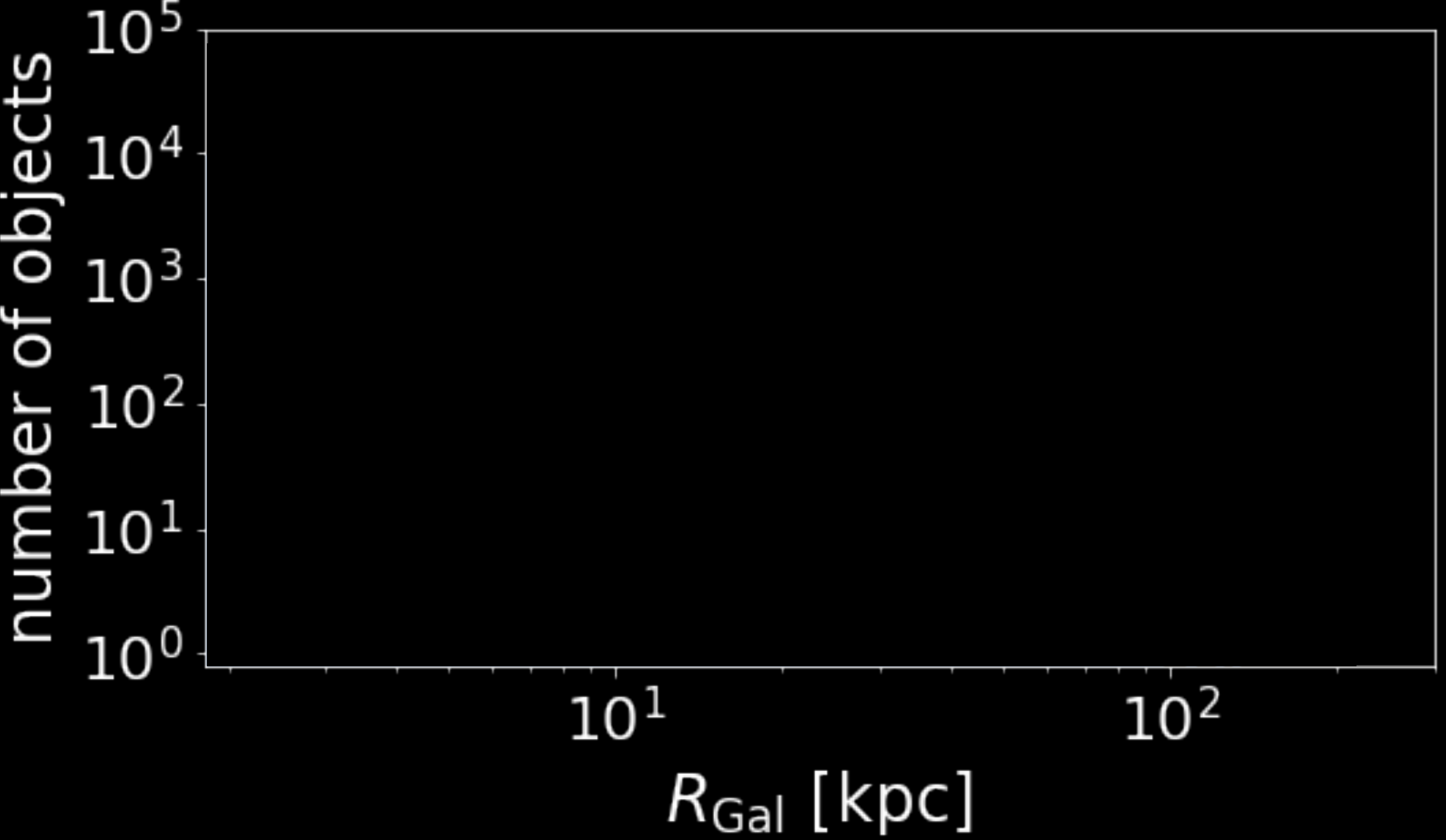
Estimate stellar mass of stream stars from Kroupa IMF

Luminosity of stars from isochrones given mass, age, Z of cluster

Convert to apparent magnitudes

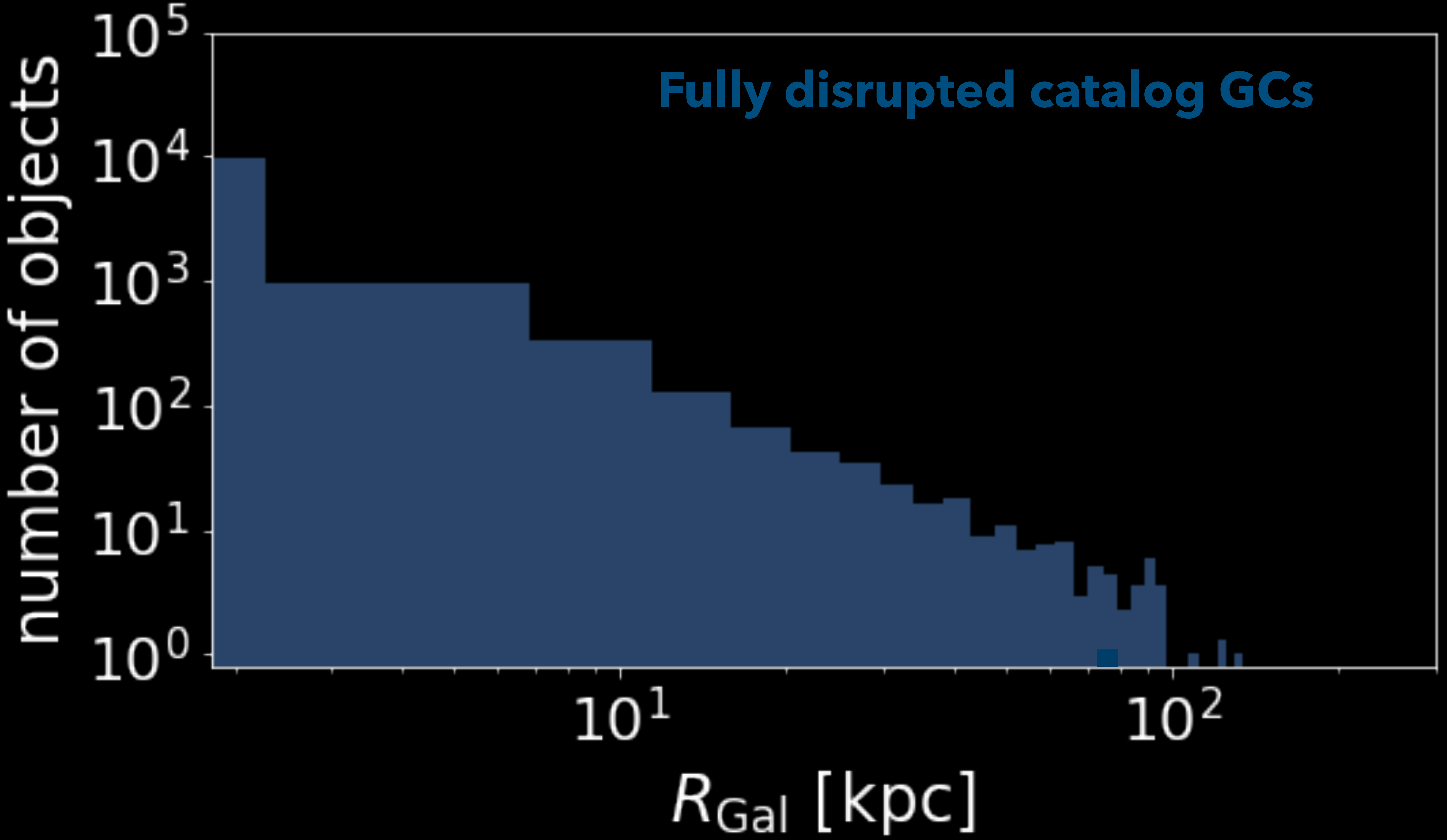
LSST photometry

Spatial distribution of disrupted objects



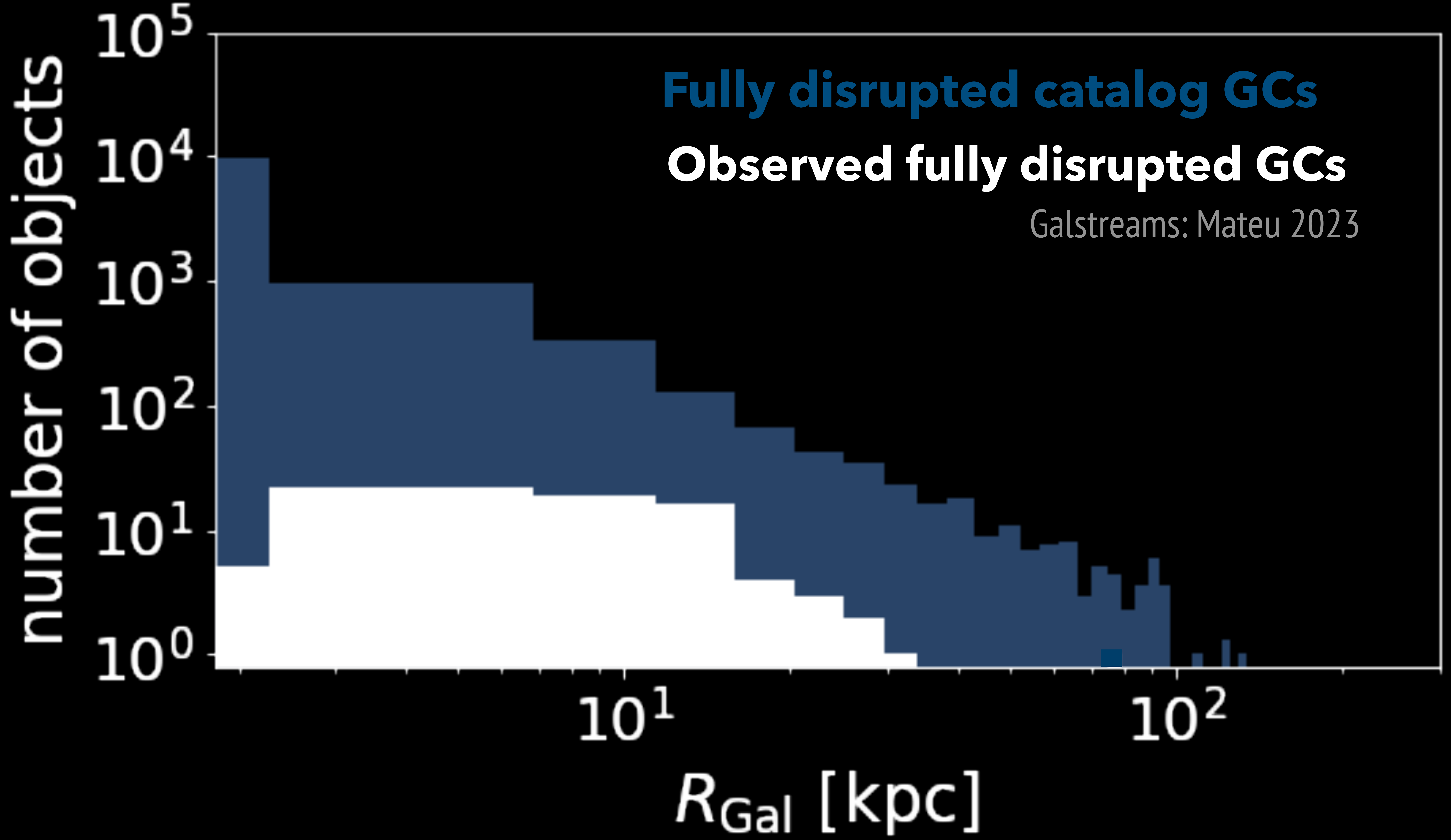
Pearson, Bonaca et al. 2024

Spatial distribution of disrupted objects



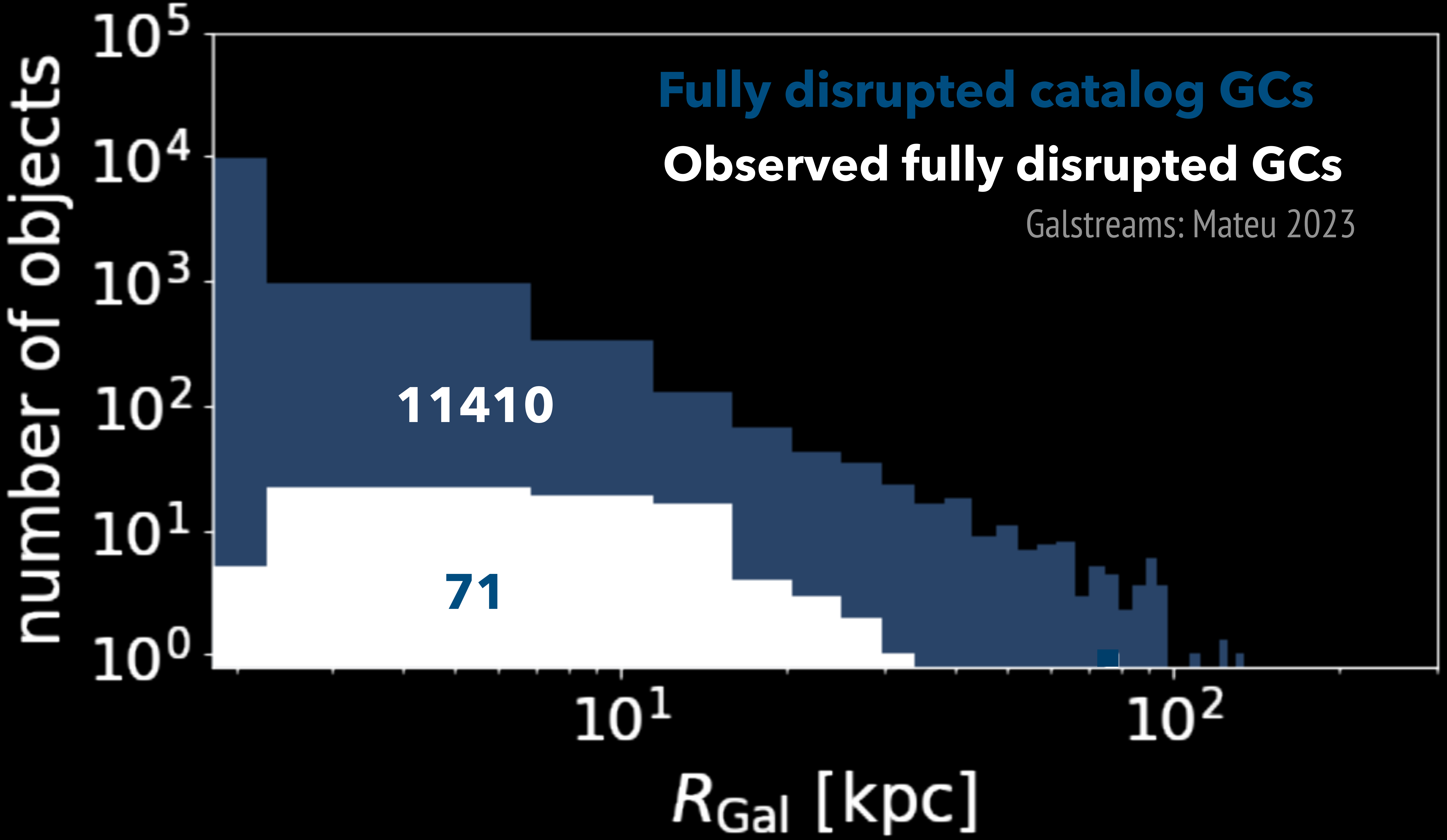
Pearson, Bonaca et al. 2024

Spatial distribution of disrupted objects



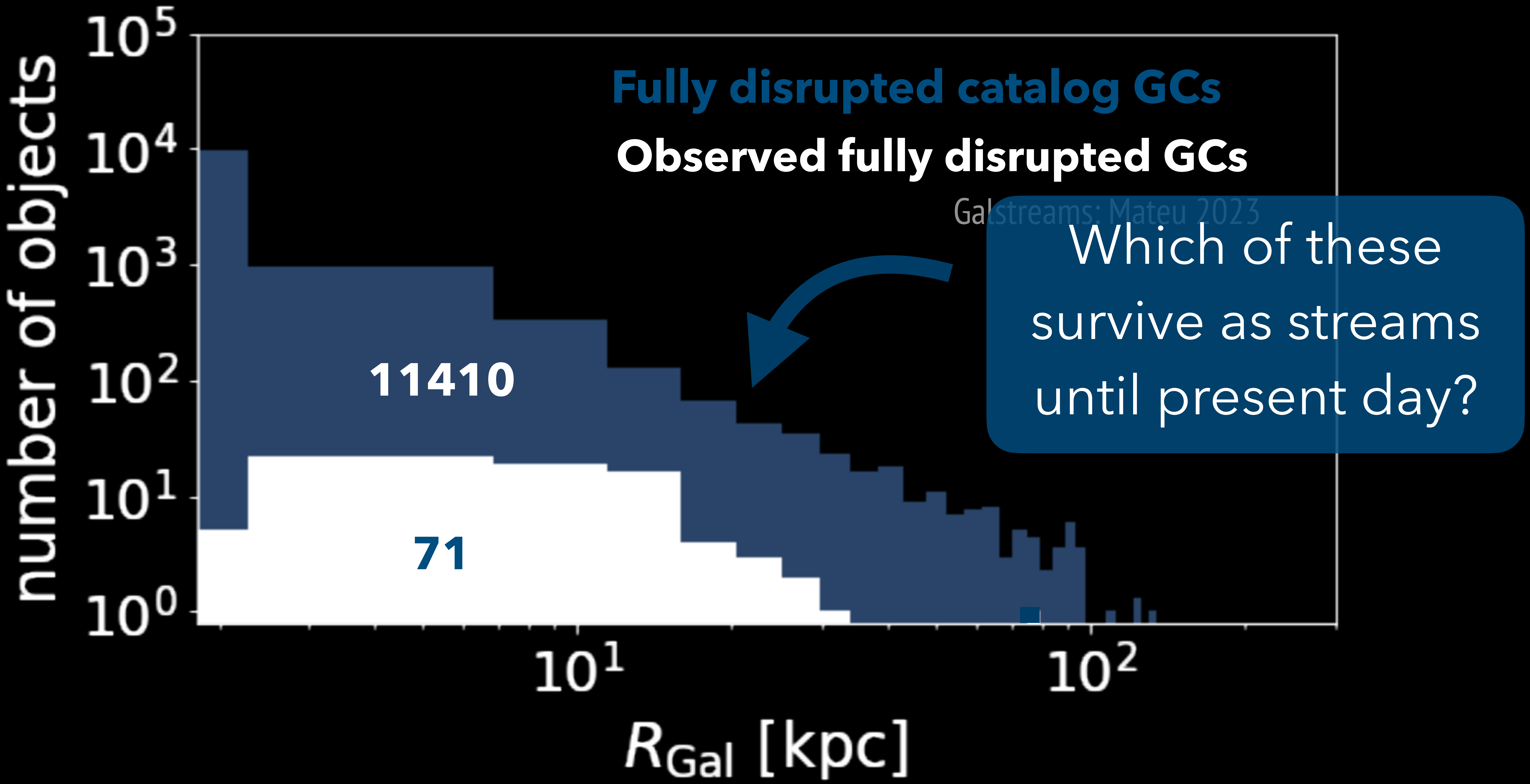
Pearson, Bonaca et al. 2024

Spatial distribution of disrupted objects



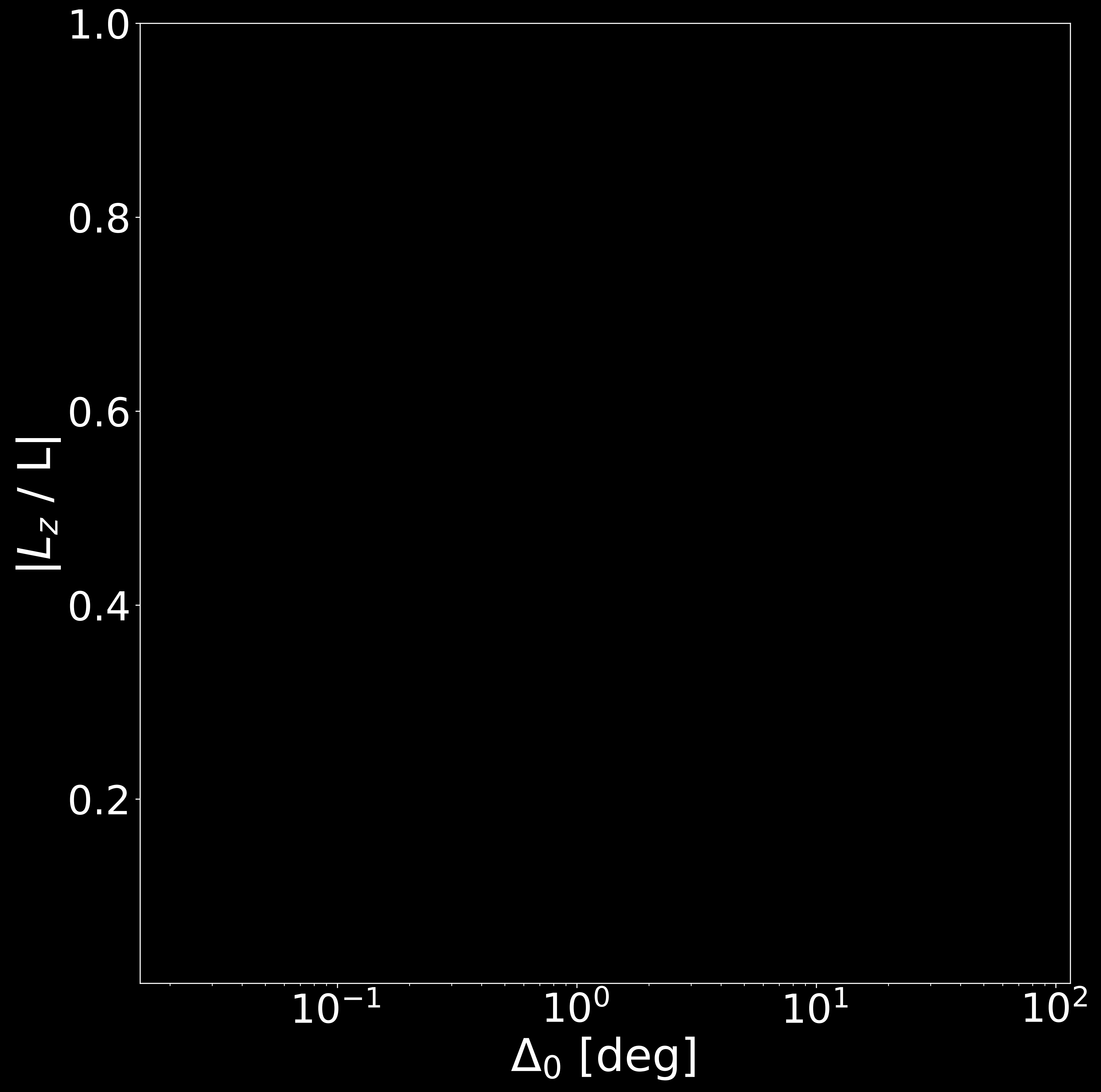
Pearson, Bonaca et al. 2024

Spatial distribution of disrupted objects



Pearson, Bonaca et al. 2024

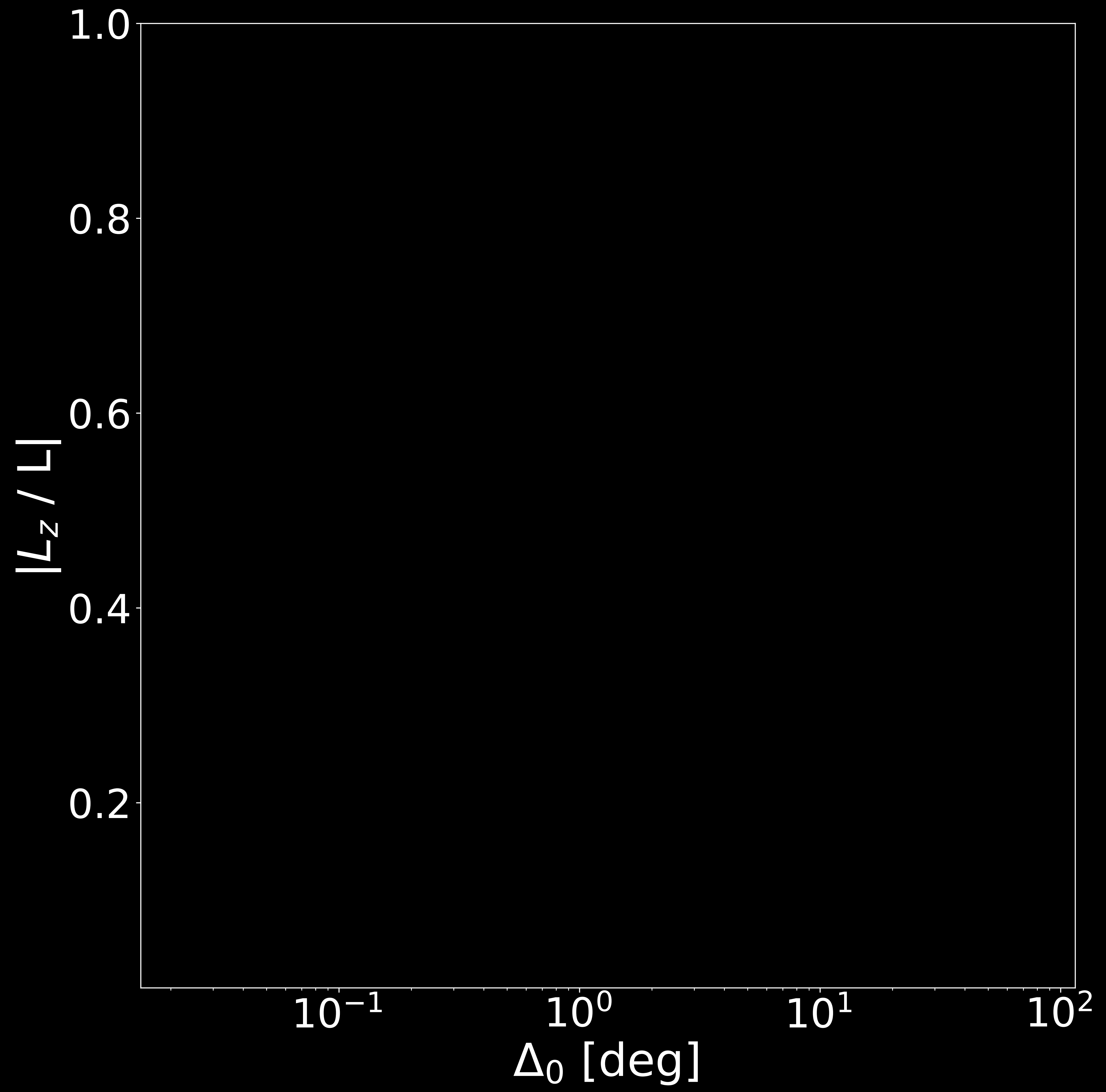
How stream-like is the debris at present day?



Pearson, Bonaca et al. 2024

How stream-like is the debris at present day?

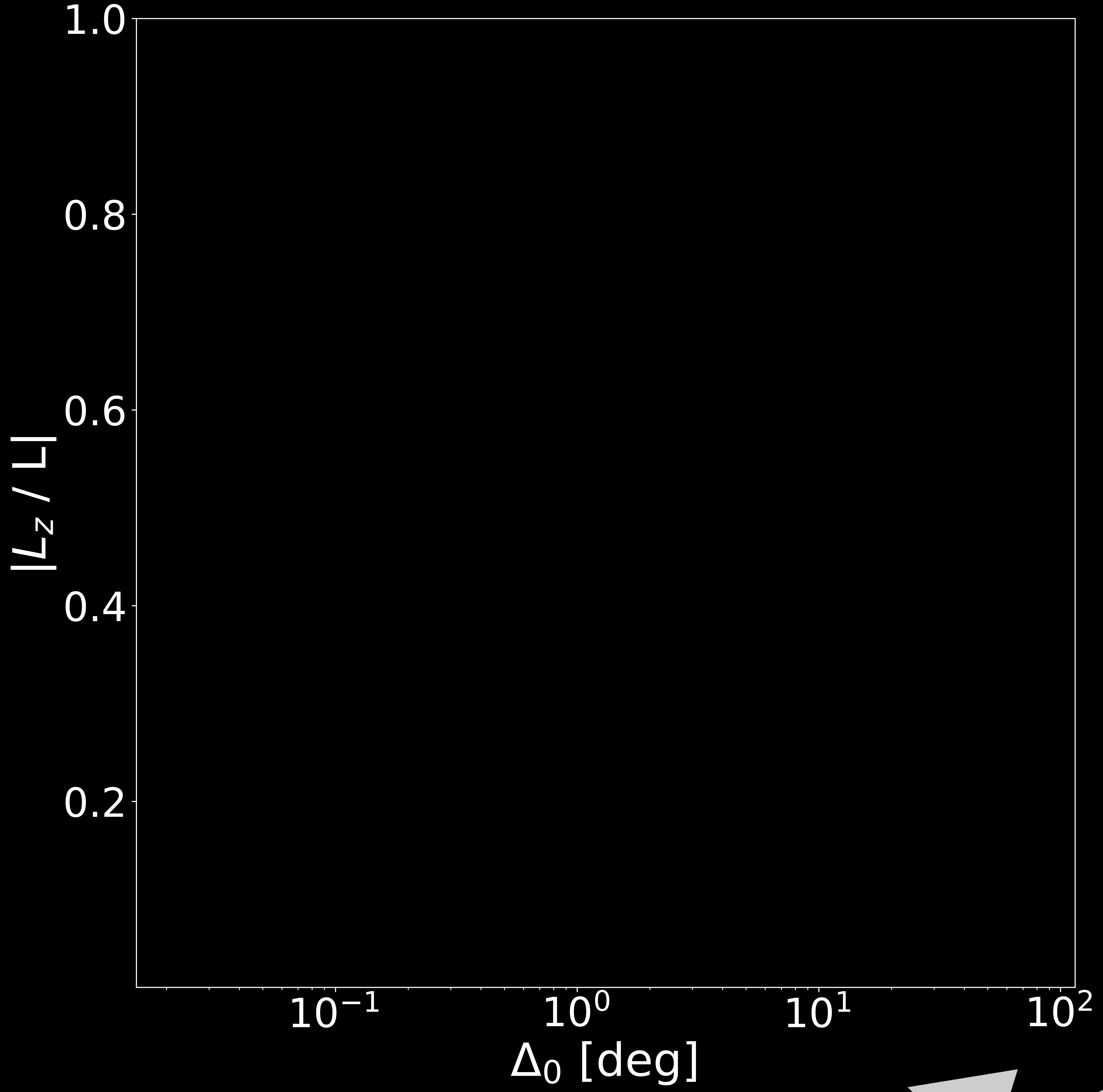
If ~1: only rotating in the disk plane



Pearson, Bonaca et al. 2024

How stream-like is the debris at present day?

If ~1: only rotating in the disk plane



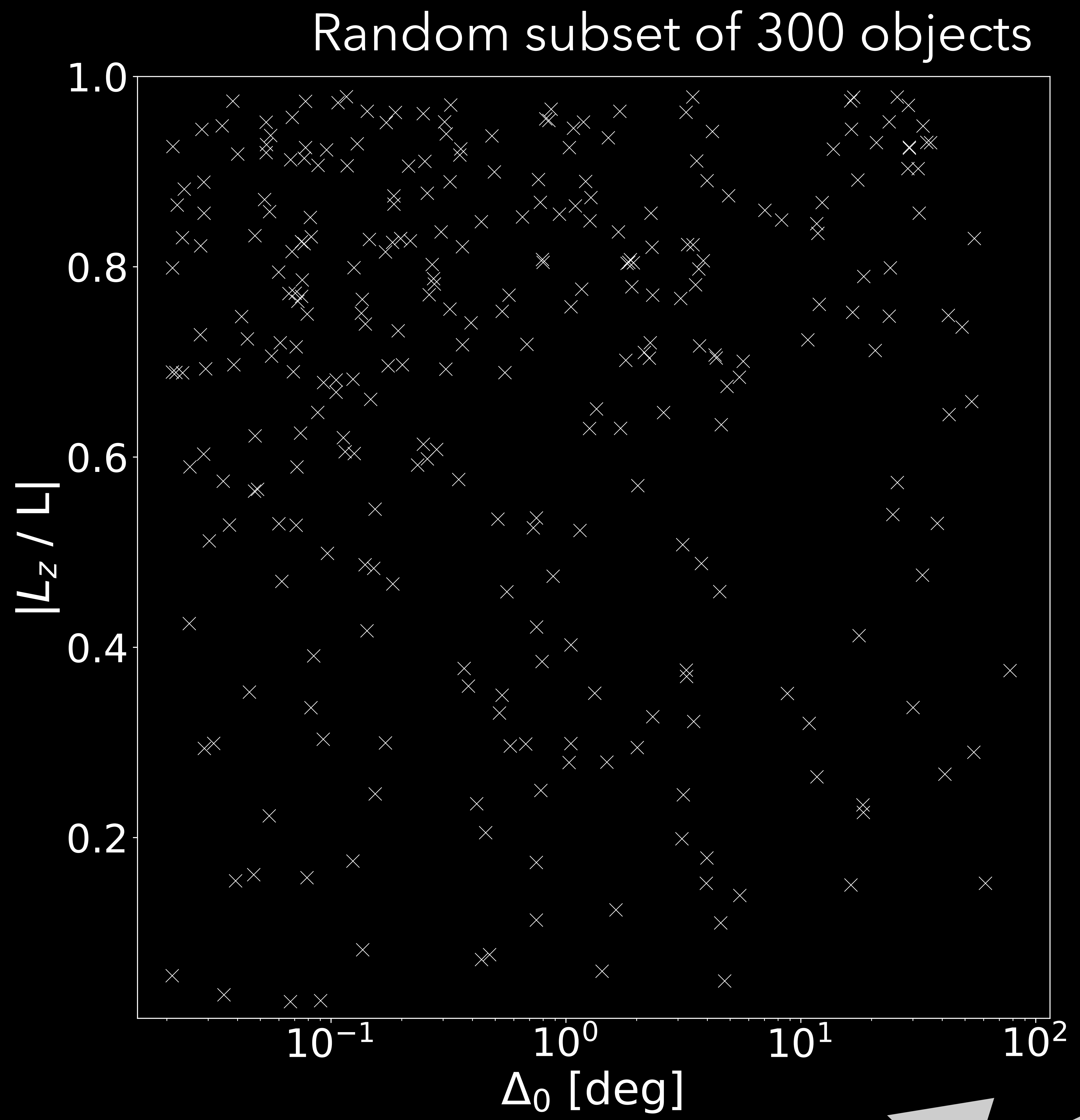
"Streaminess criterion"

$$\Delta_0 = \sqrt{\mathrm{med}(b)^2 + \mathrm{med}(l)^2}$$

Pearson, Bonaca et al. 2024

How stream-like is the debris at present day?

If ~1: only rotating in the disk plane



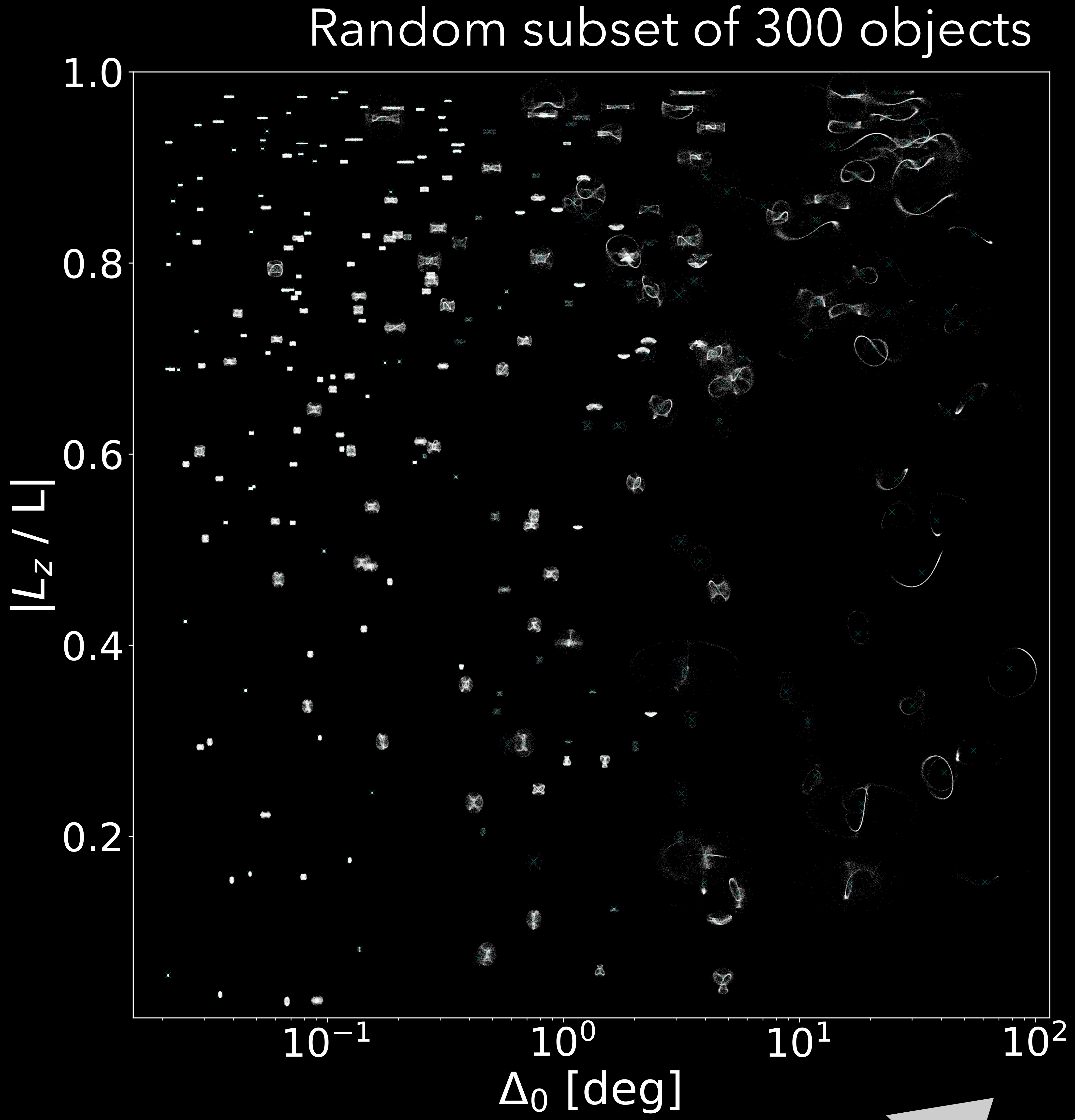
"Streaminess criterion"

$$\Delta_0 = \sqrt{\mathrm{med}(b)^2 + \mathrm{med}(l)^2}$$

Pearson, Bonaca et al. 2024

How stream-like is the debris at present day?

If ~1: only rotating in the disk plane



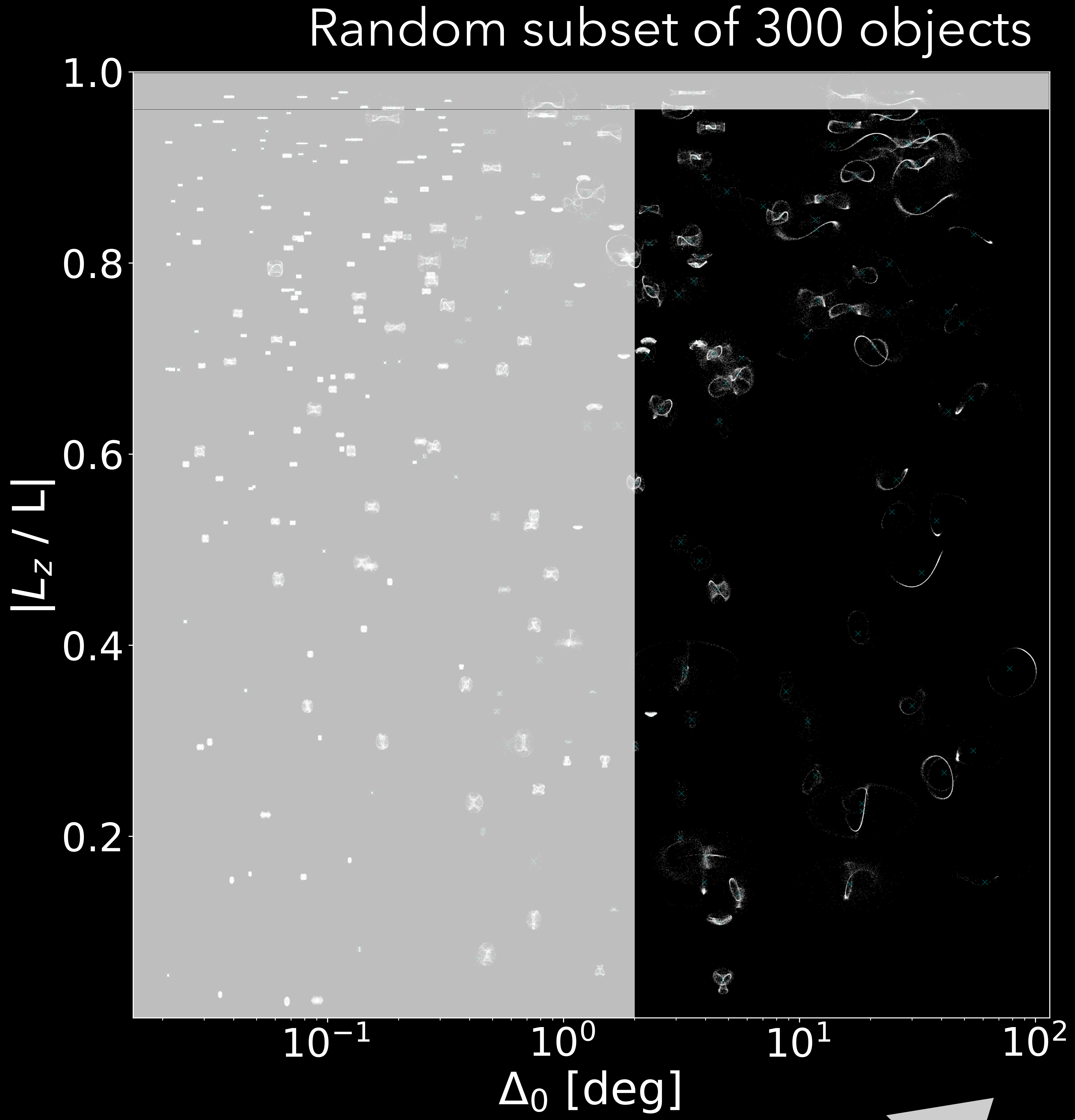
"Streaminess criterion"

$$\Delta_0 = \sqrt{\mathrm{med}(b)^2 + \mathrm{med}(l)^2}$$

Pearson, Bonaca et al. 2024

How stream-like is the debris at present day?

If ~1: only rotating in the disk plane



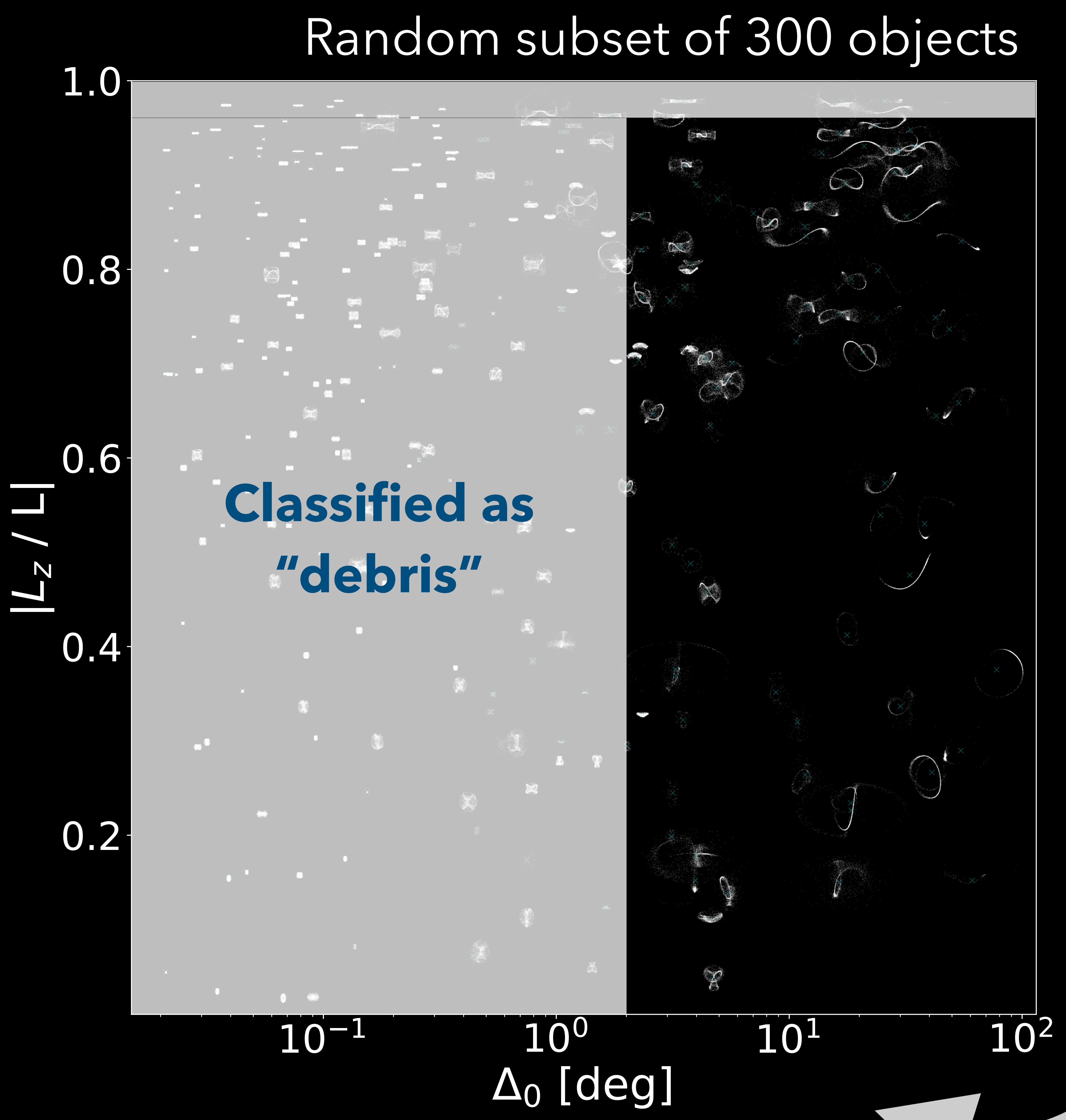
"Streaminess criterion"

$$\Delta_0 = \sqrt{\mathrm{med}(b)^2 + \mathrm{med}(l)^2}$$

Pearson, Bonaca et al. 2024

How stream-like is the debris at present day?

If ~1: only rotating in the disk plane



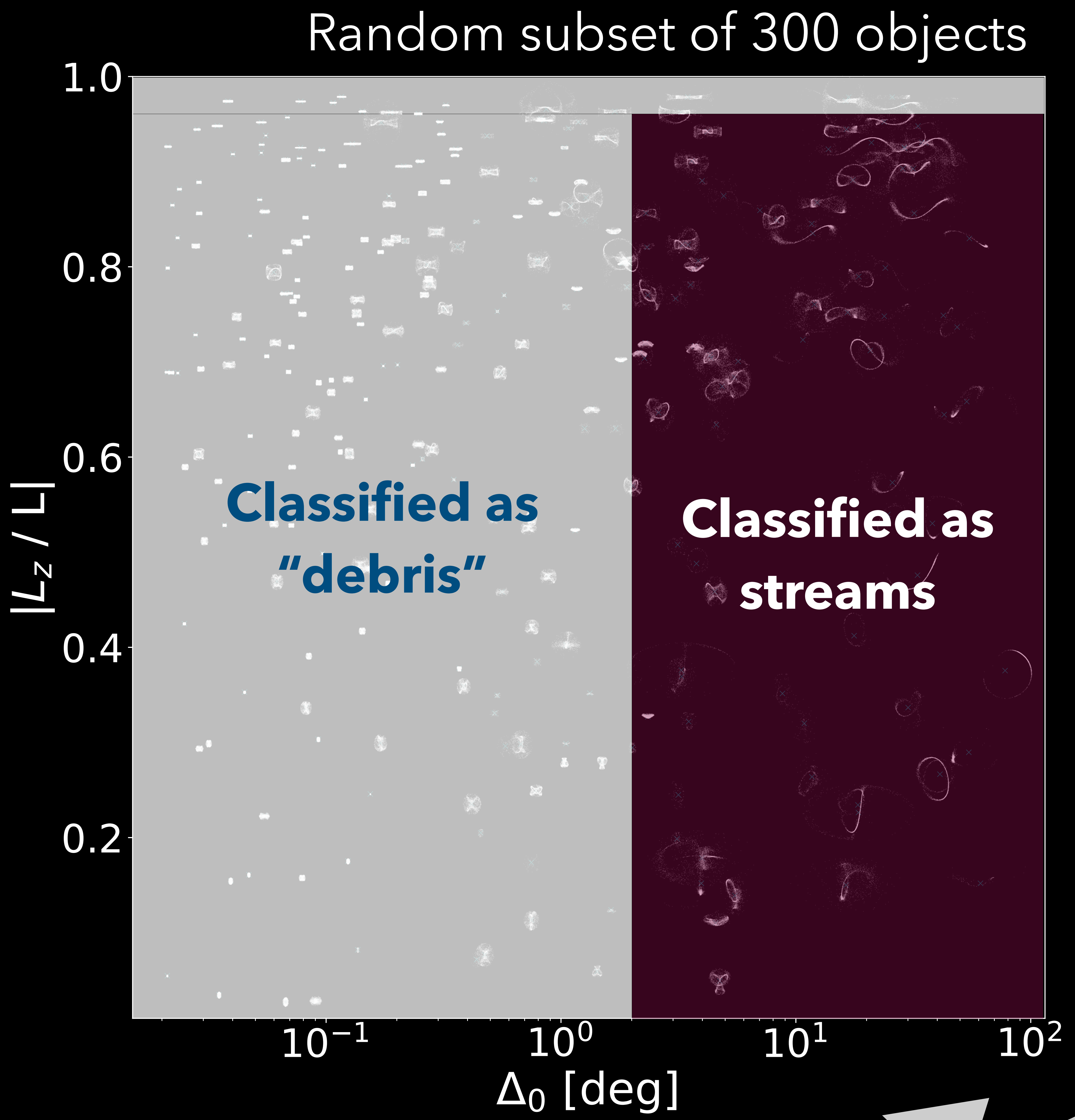
"Streaminess criterion"

$$\Delta_0 = \sqrt{\mathrm{med}(b)^2 + \mathrm{med}(l)^2}$$

Pearson, Bonaca et al. 2024

How stream-like is the debris at present day?

If ~1: only rotating in the disk plane

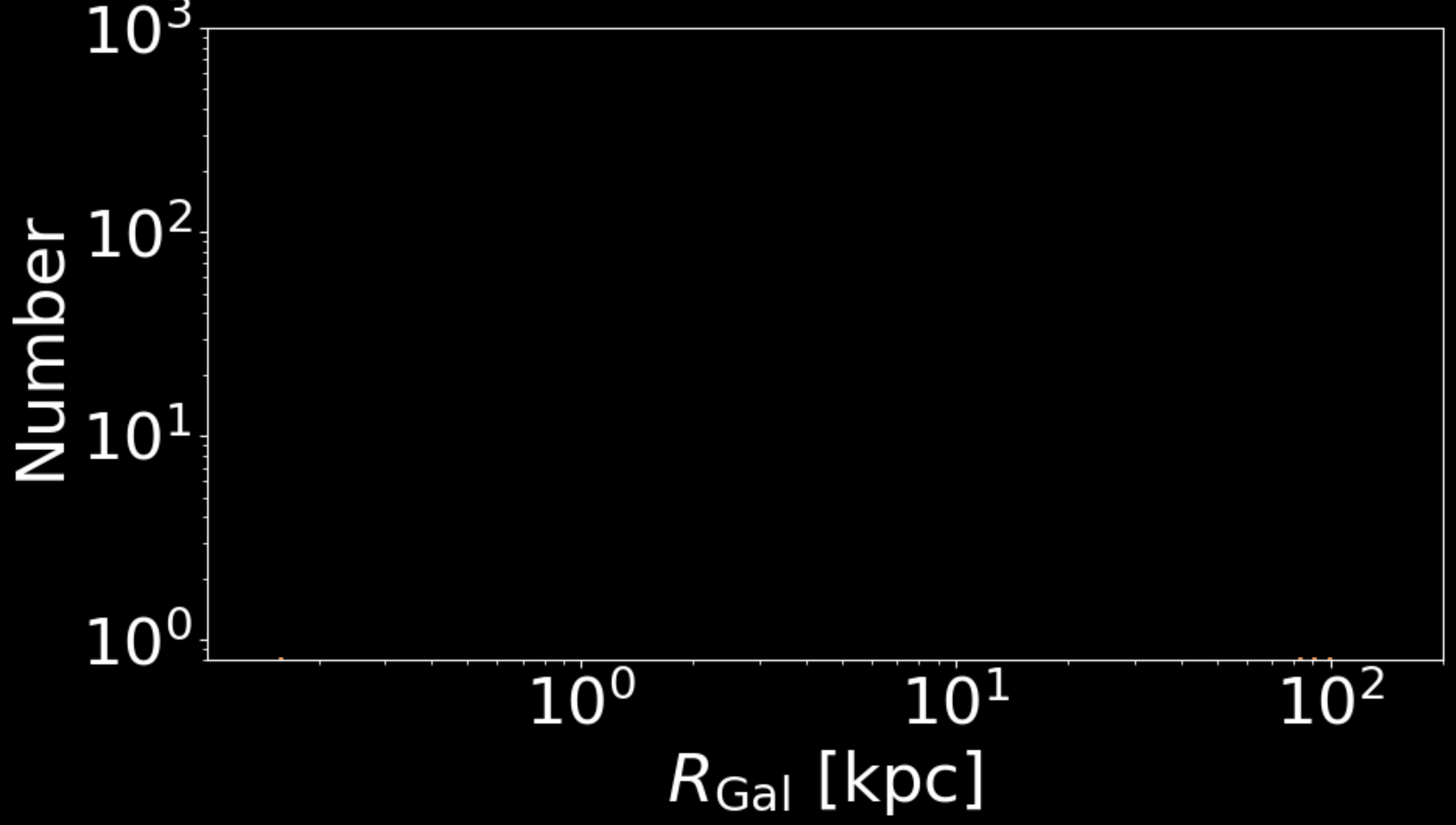


"Streaminess criterion"

$$\Delta_0 = \sqrt{\mathrm{med}(b)^2 + \mathrm{med}(l)^2}$$

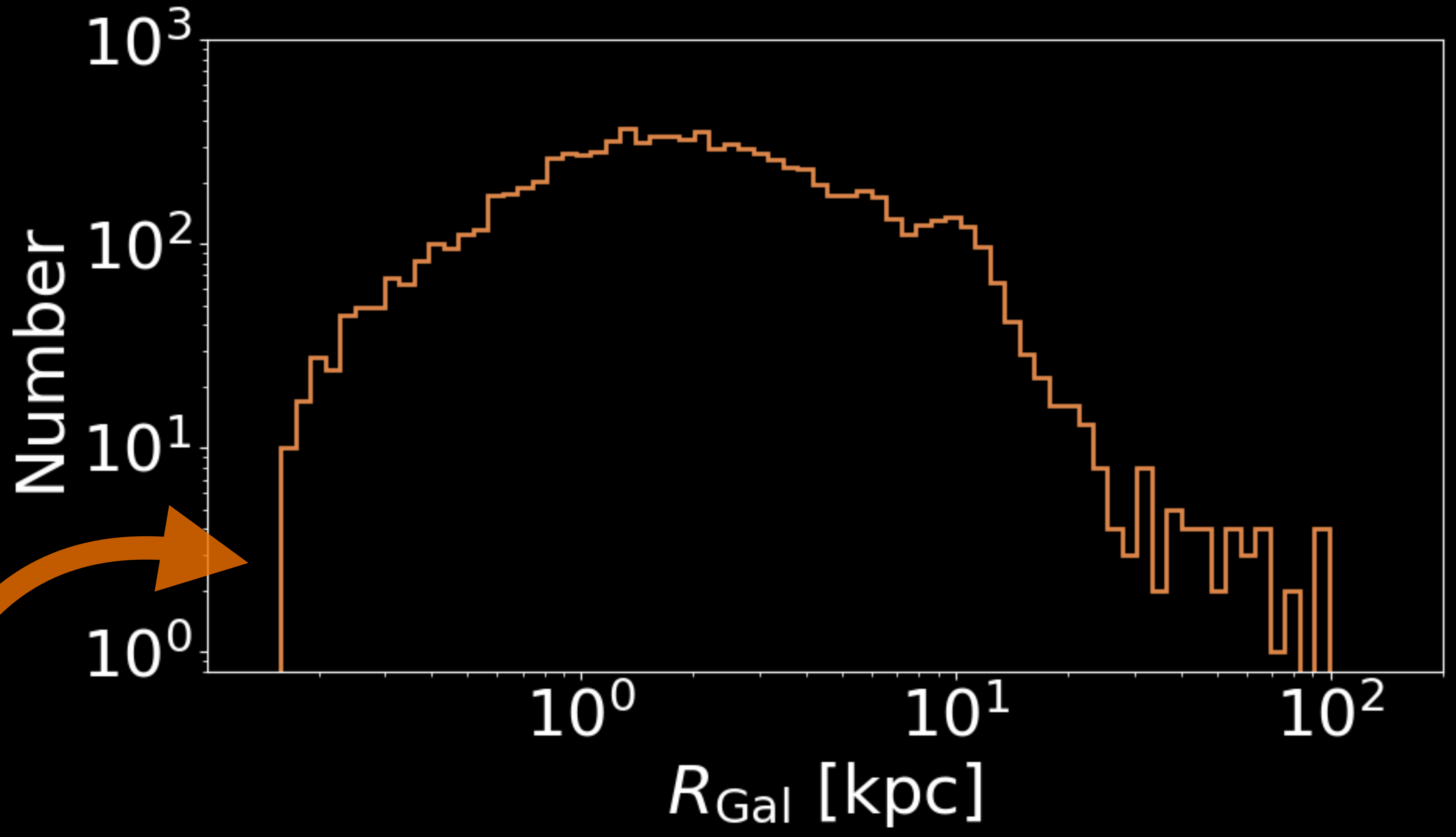
Pearson, Bonaca et al. 2024

Distribution of debris and surviving streams



Pearson, Bonaca et al. 2024

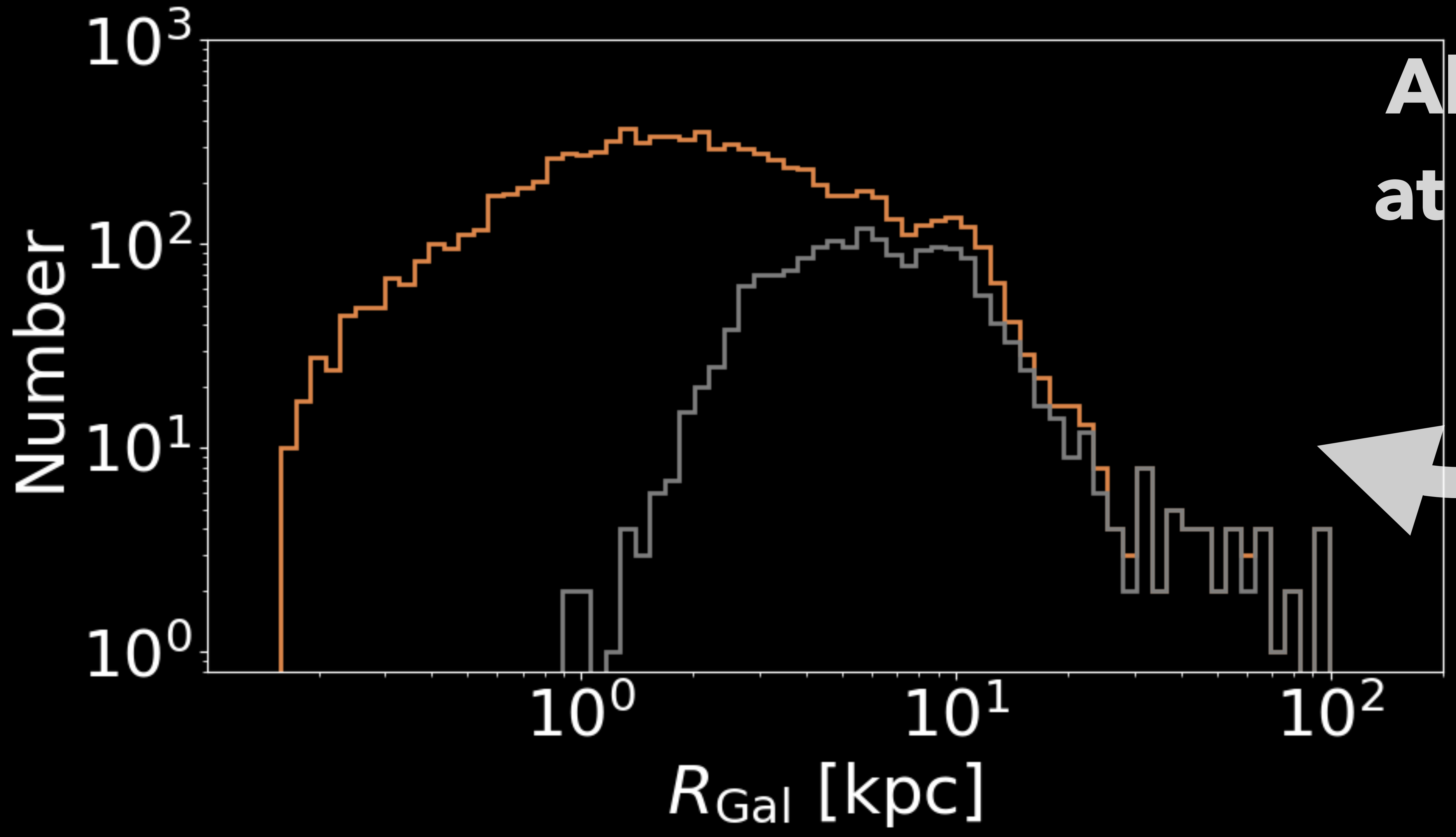
Distribution of debris and surviving streams



All fully disrupted clusters classified as "debris" (8984 objects)

Pearson, Bonaca et al. 2024

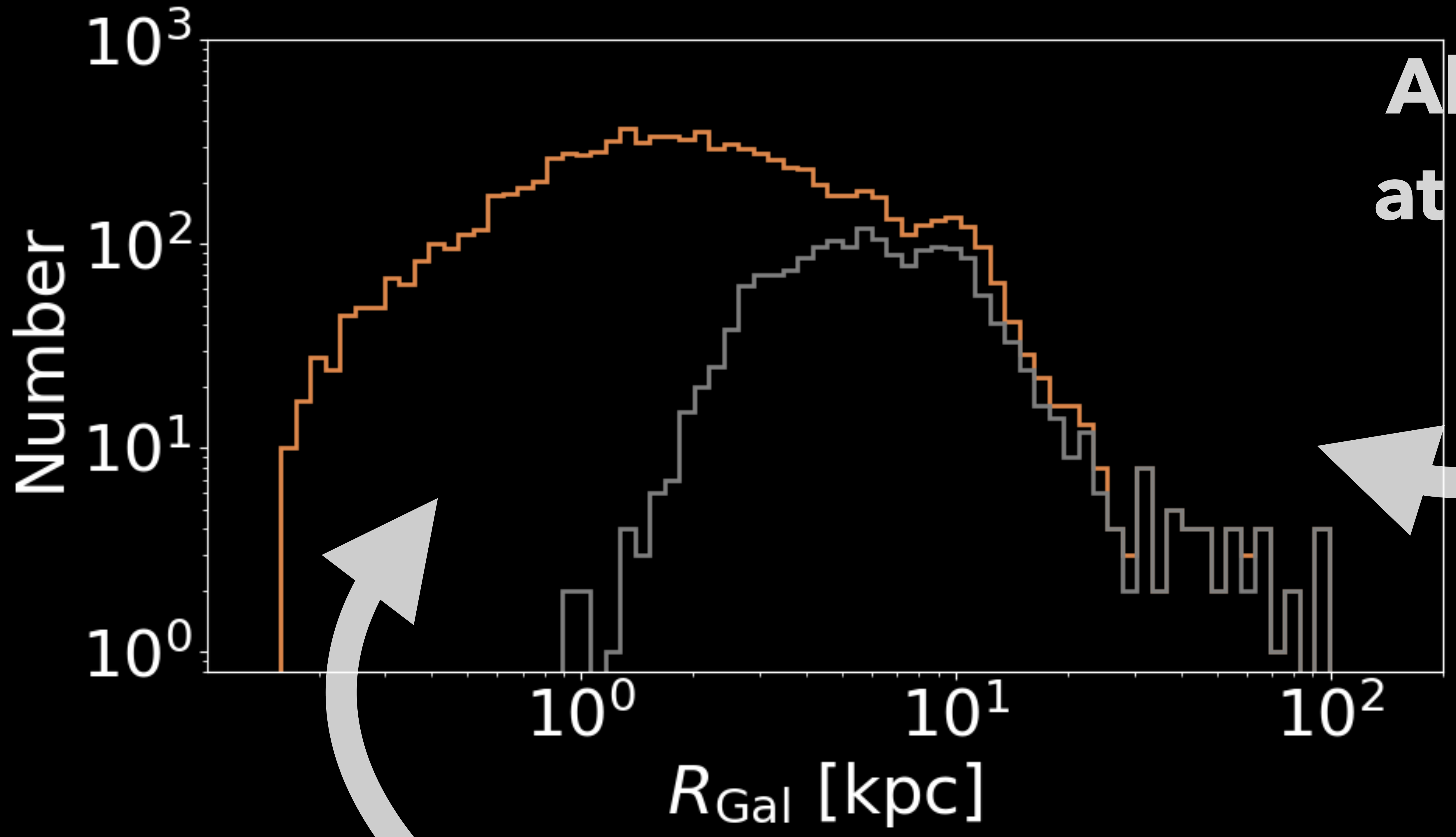
Distribution of debris and surviving streams



All surviving streams at present day (1803)

Pearson, Bonaca et al. 2024

Distribution of debris and surviving streams

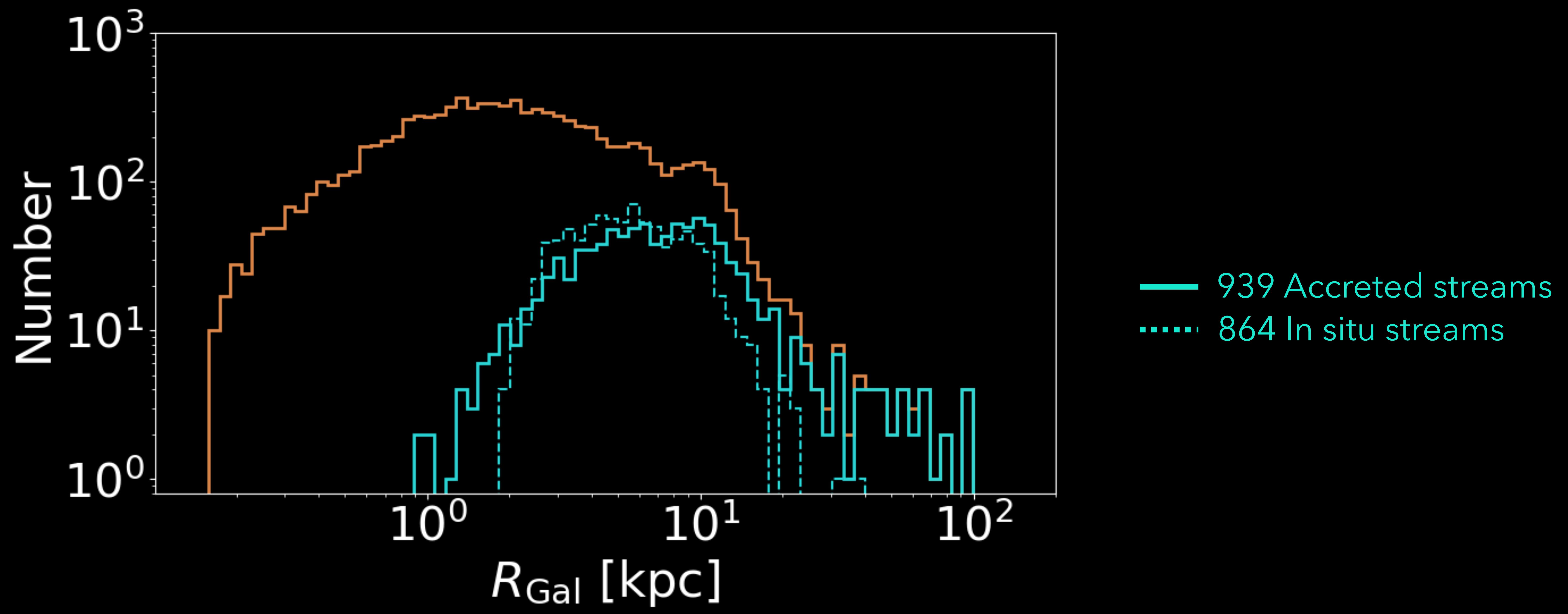


All surviving streams at present day (1803)

Streams fully disrupted in bulge

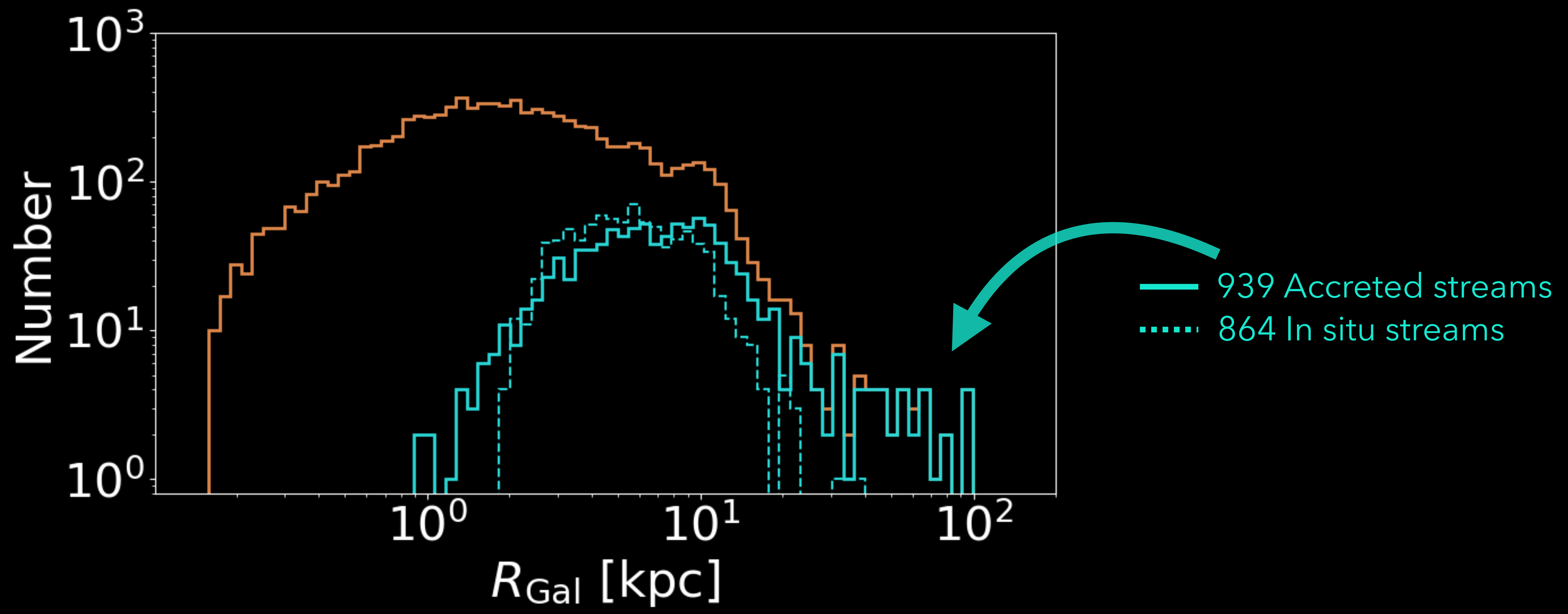
Pearson, Bonaca et al. 2024

Distribution of debris and surviving streams



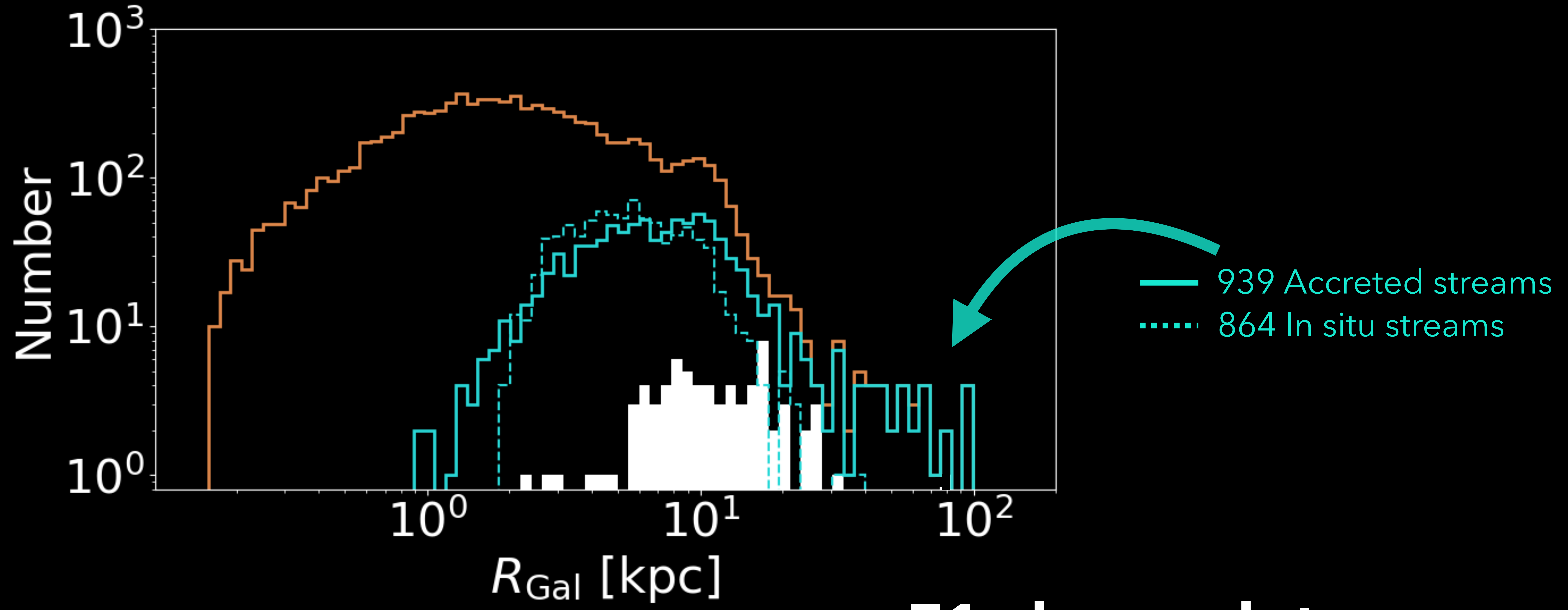
Pearson, Bonaca et al. 2024

Distribution of debris and surviving streams



Pearson, Bonaca et al. 2024

Distribution of debris and surviving streams

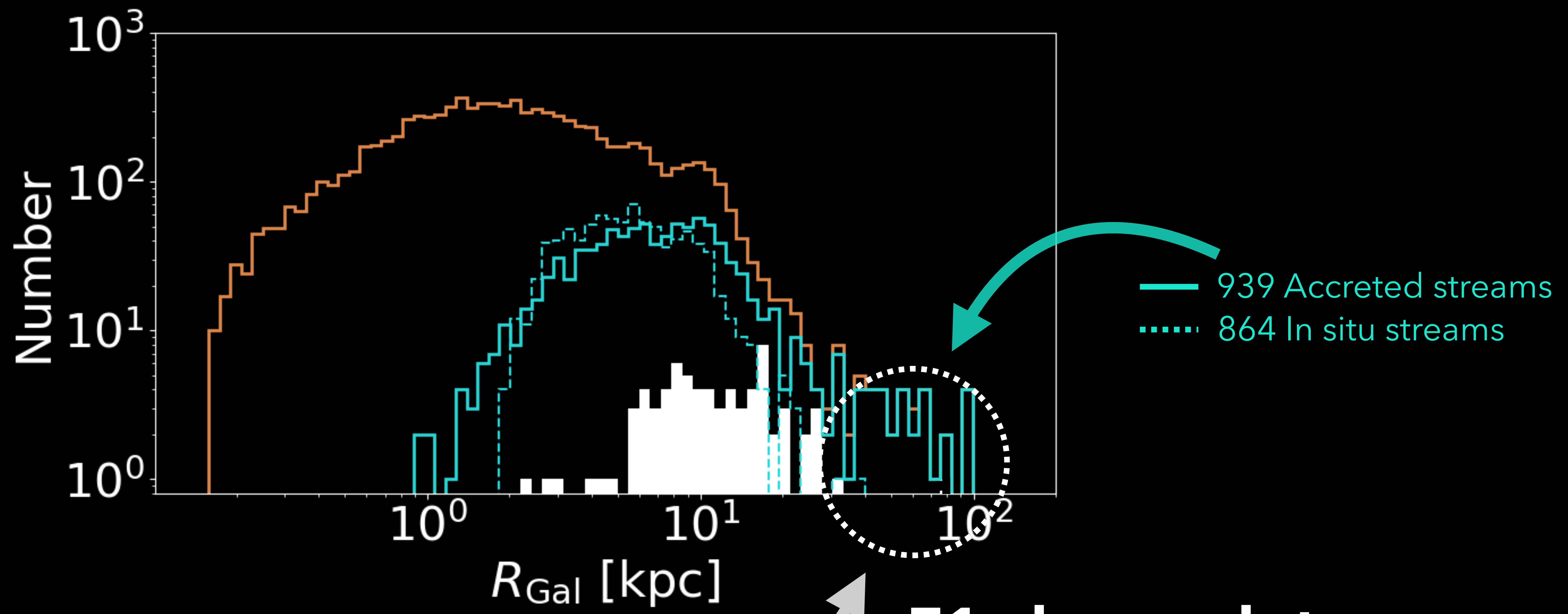


71 observed streams

(galstreams)

Pearson, Bonaca et al. 2024

Distribution of debris and surviving streams



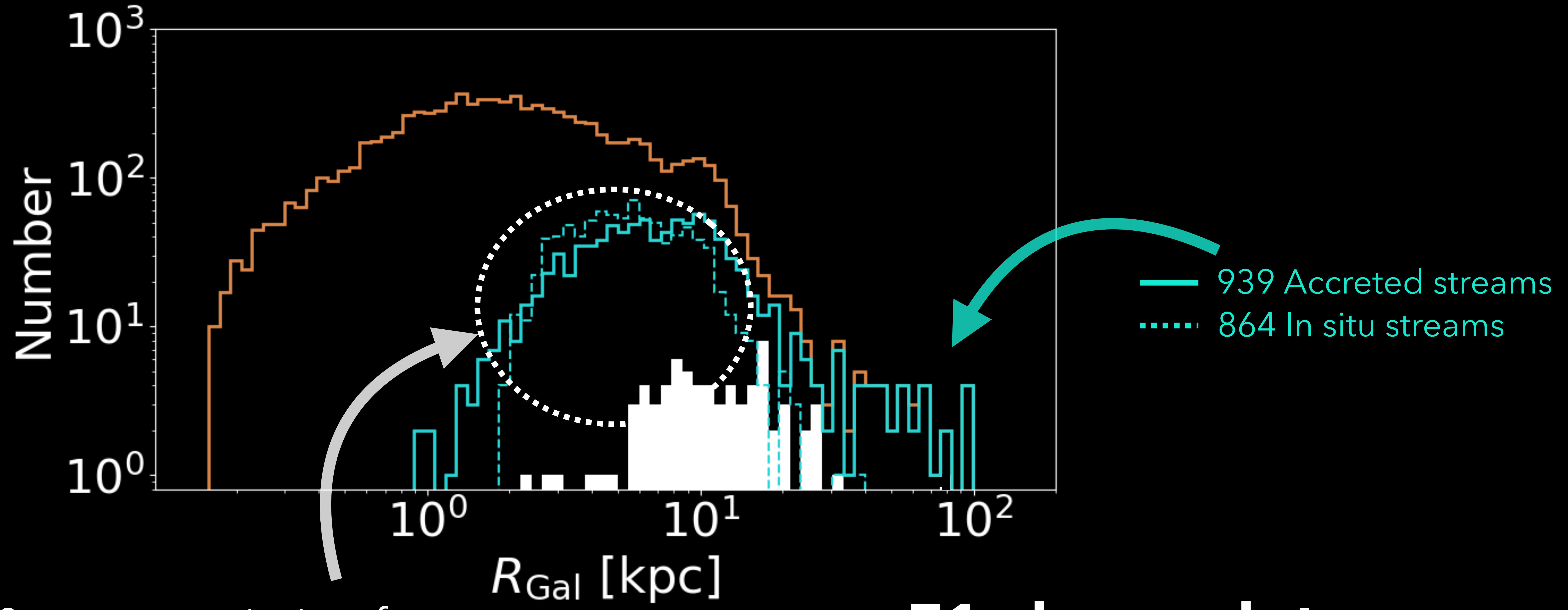
GC streams in outskirts where they are not perturbed by the Galactic bar, molecular clouds, spiral arms

71 observed streams
(galstreams)

Pearson et al. 2017, Erkal et al. 2017, Banik et al. 2019

Pearson, Bonaca et al. 2024

Distribution of debris and surviving streams

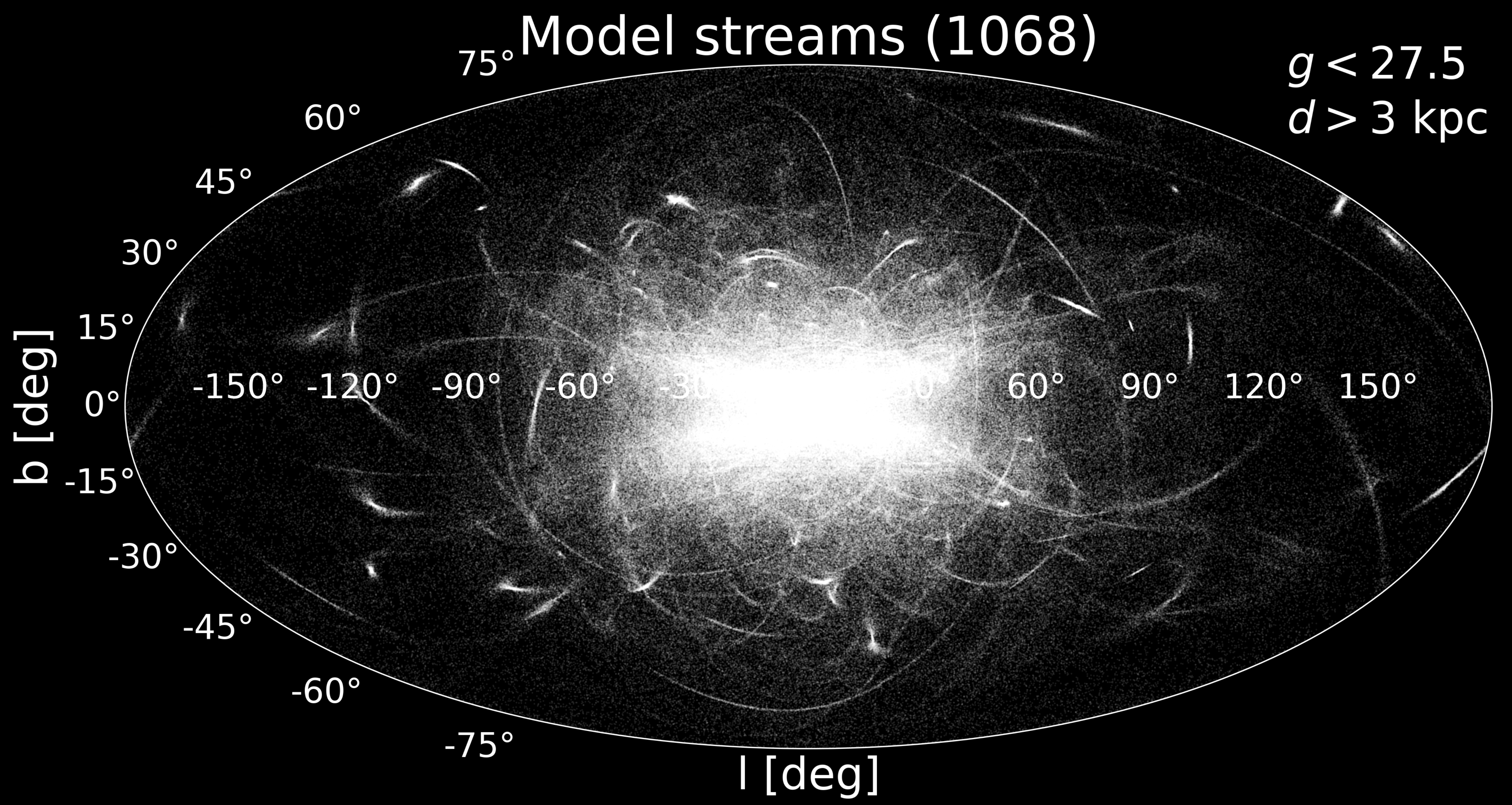


~1000 streams missing from our data in the inner Galaxy

71 observed streams

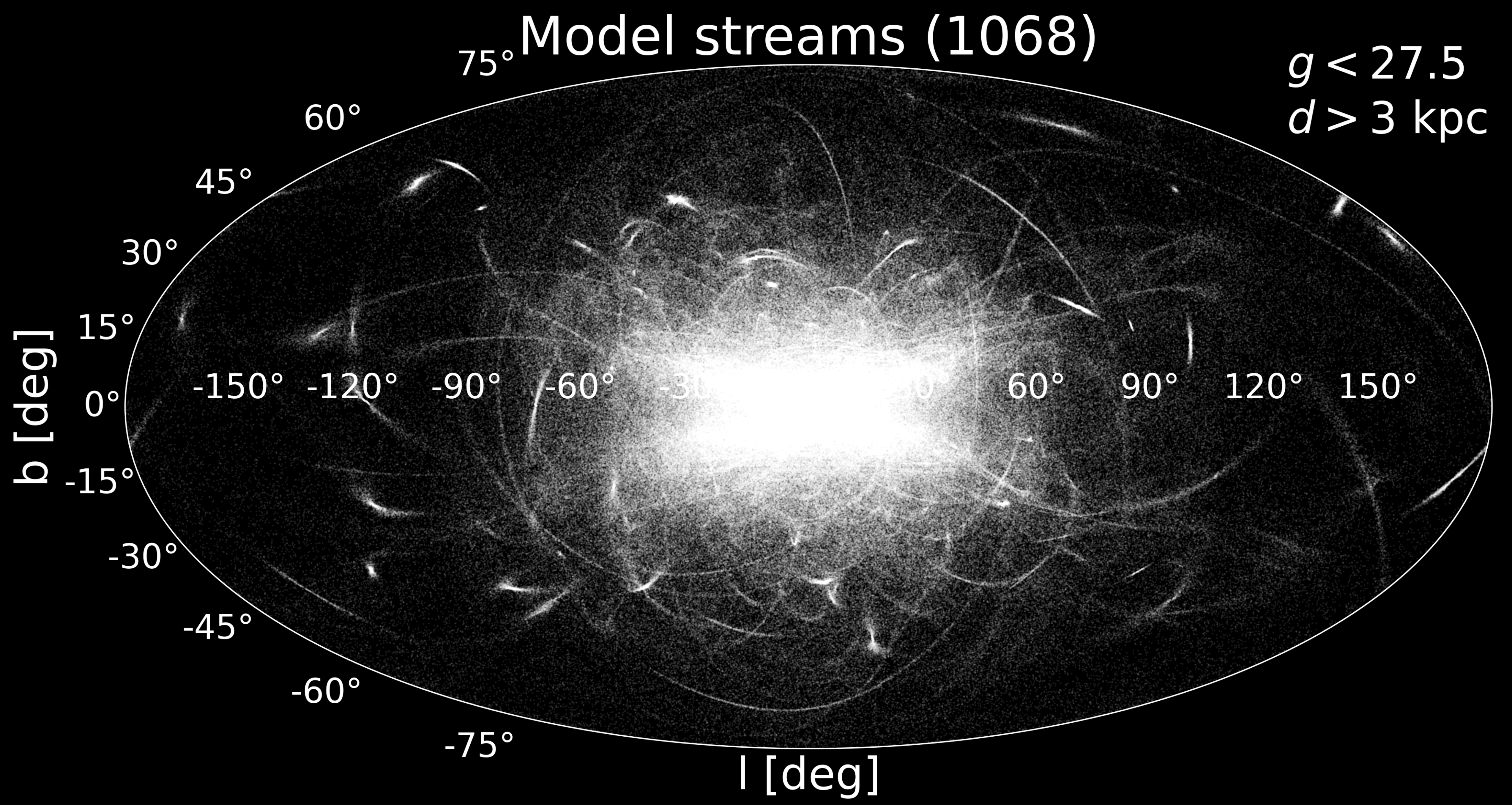
(galstreams)

Pearson, Bonaca et al. 2024

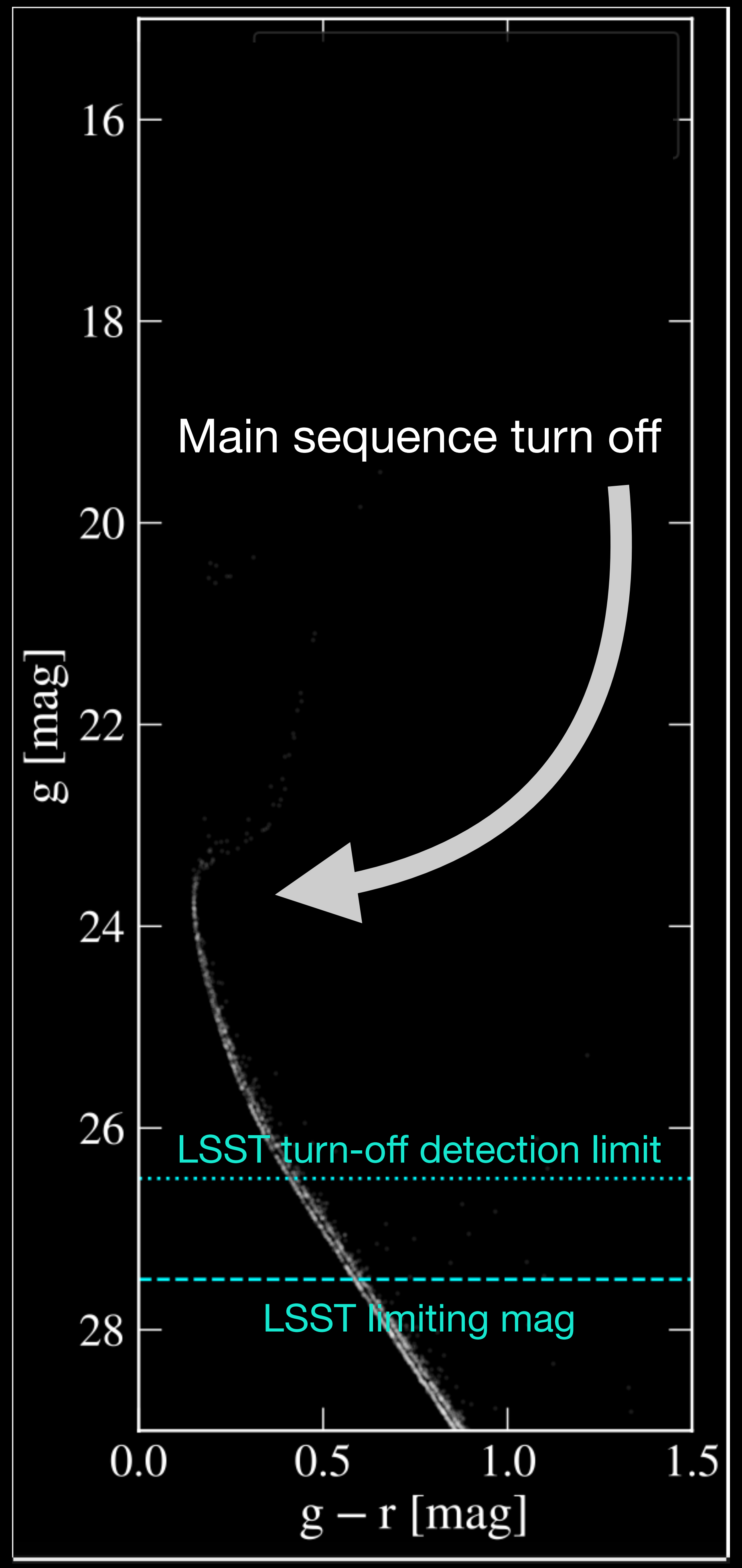


Can we observe these?

Pearson, Bonaca et al. 2024

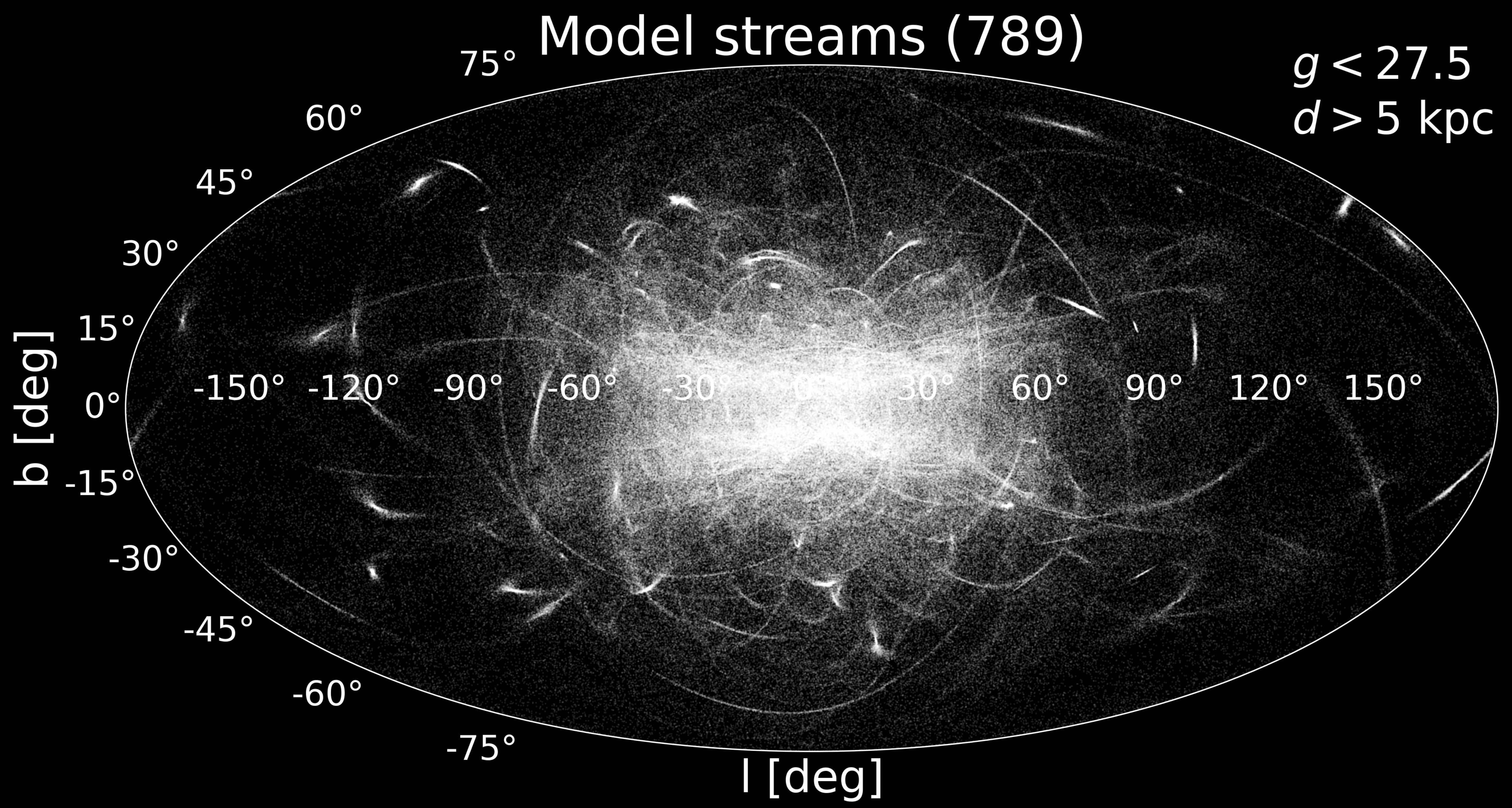


CMD



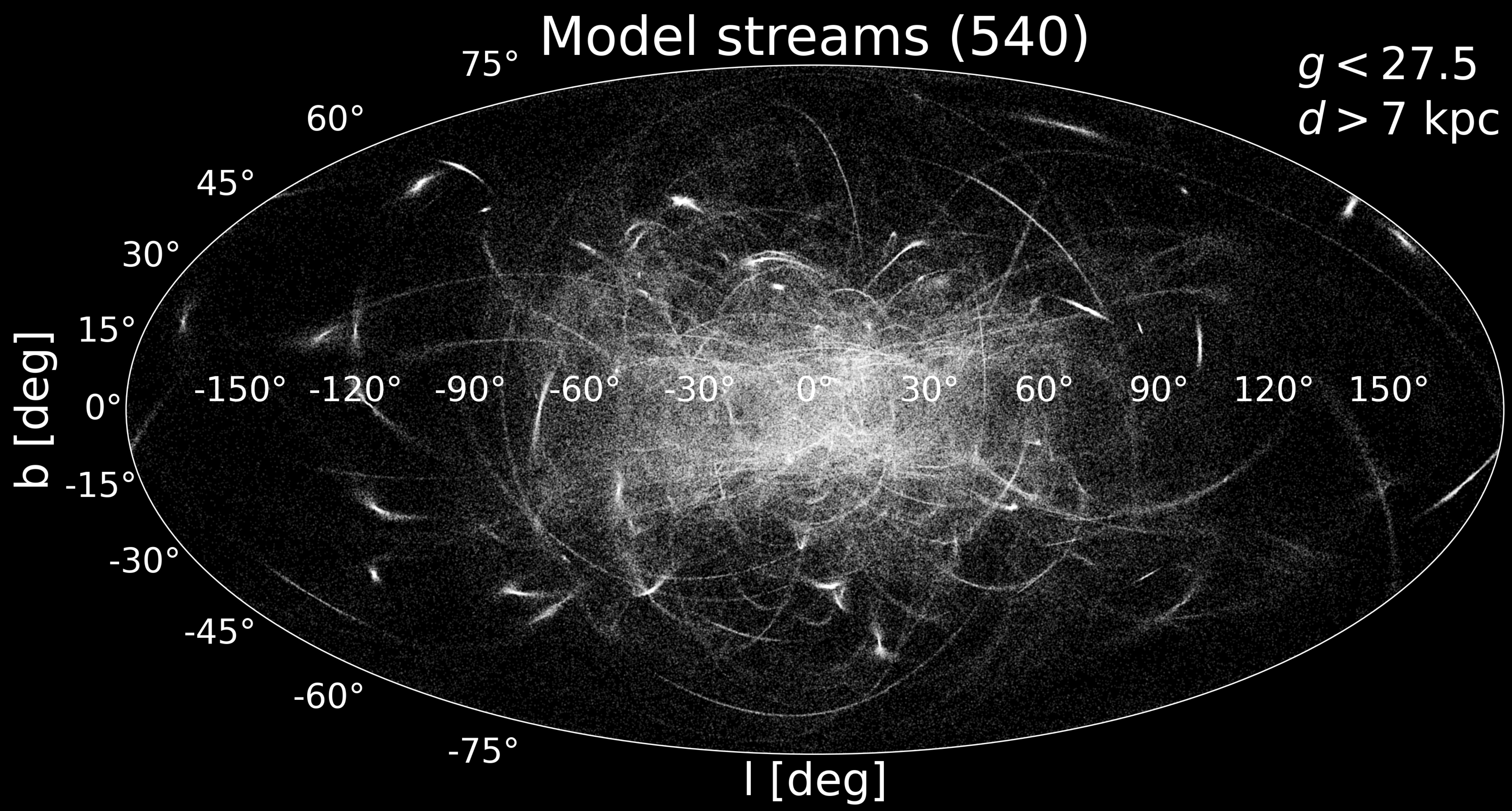
Can we observe these?

Pearson, Bonaca et al. 2024



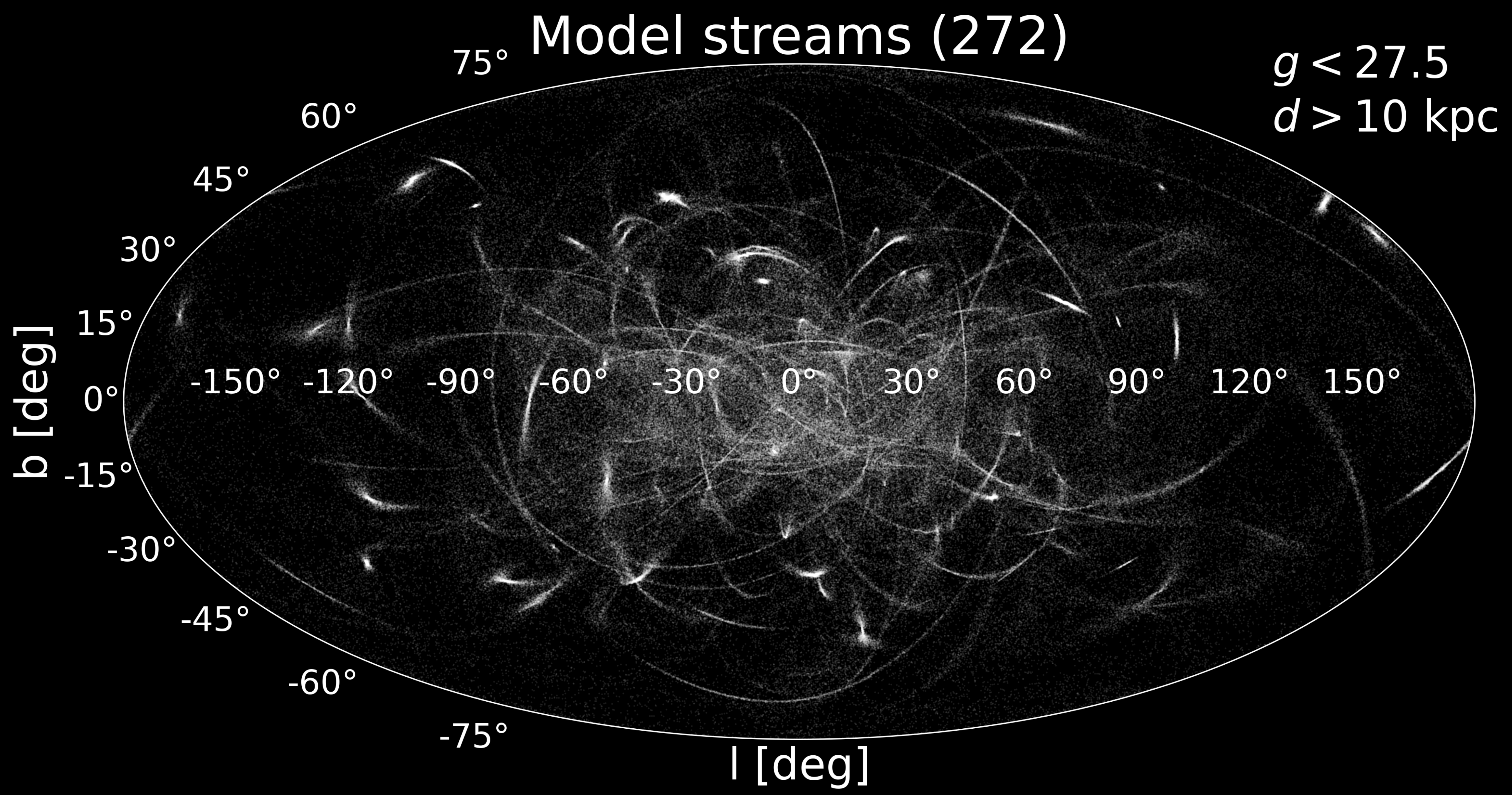
Can we observe these?

Pearson, Bonaca et al. 2024



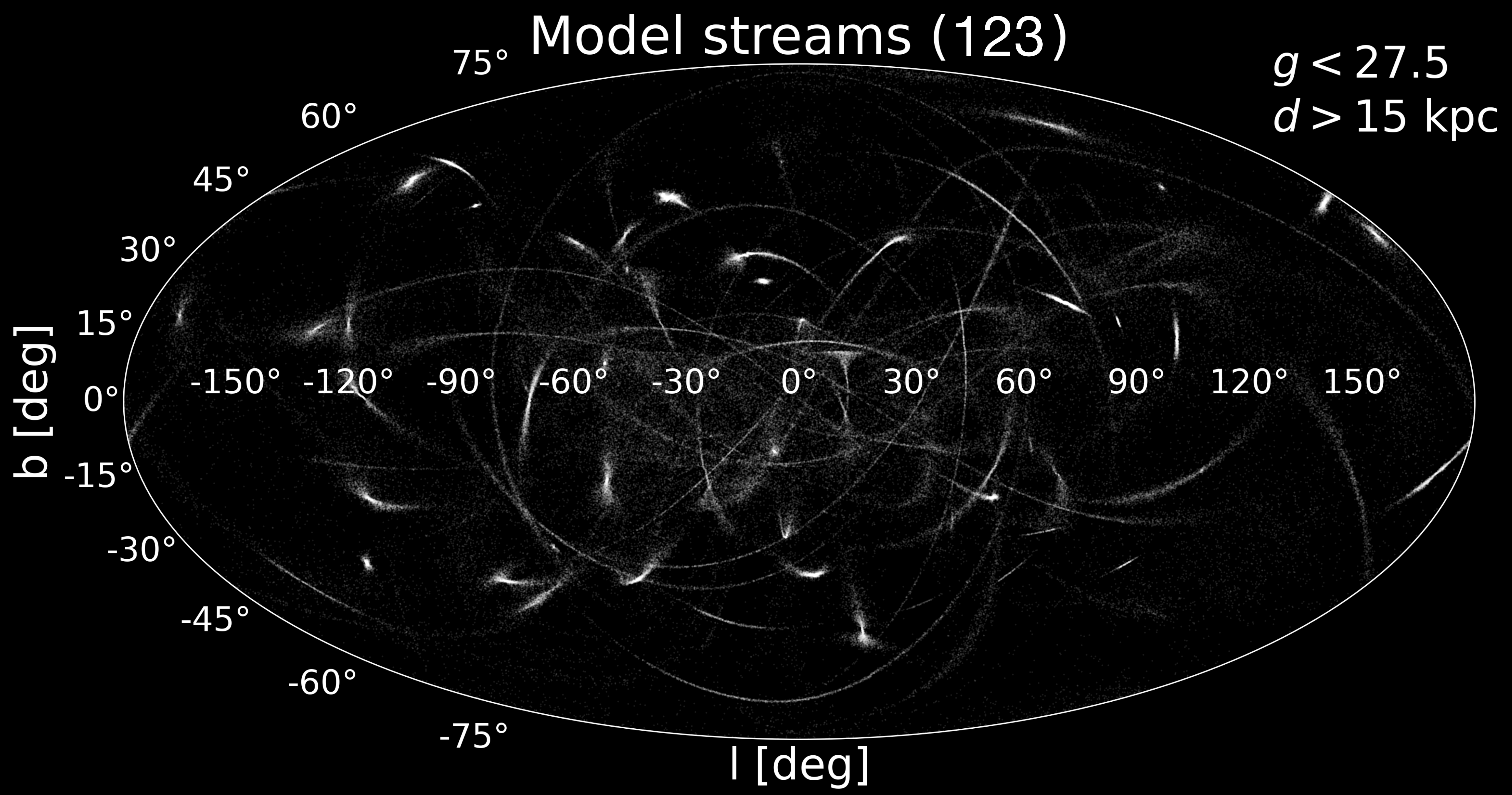
Can we observe these?

Pearson, Bonaca et al. 2024



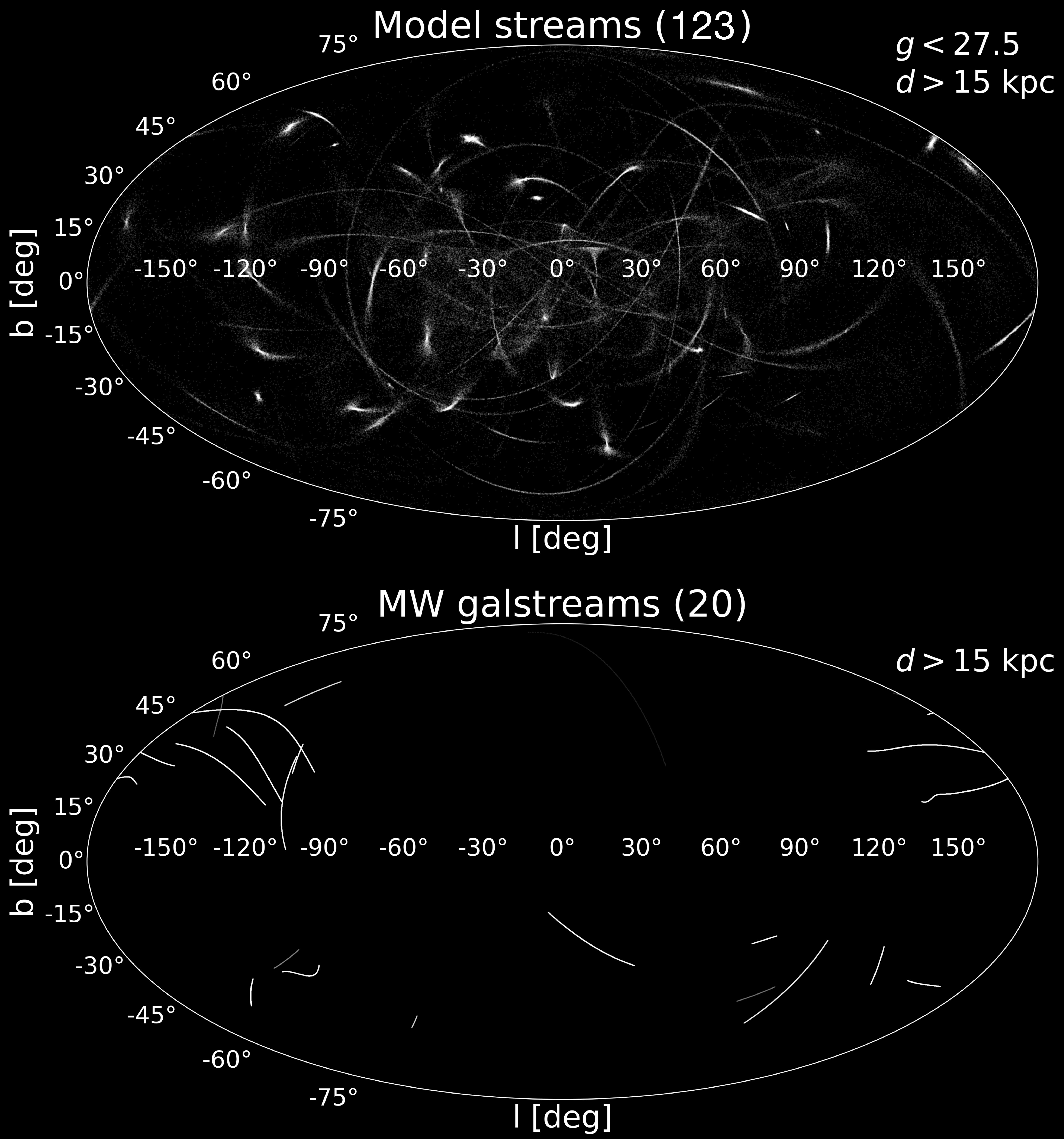
Can we observe these?

Pearson, Bonaca et al. 2024

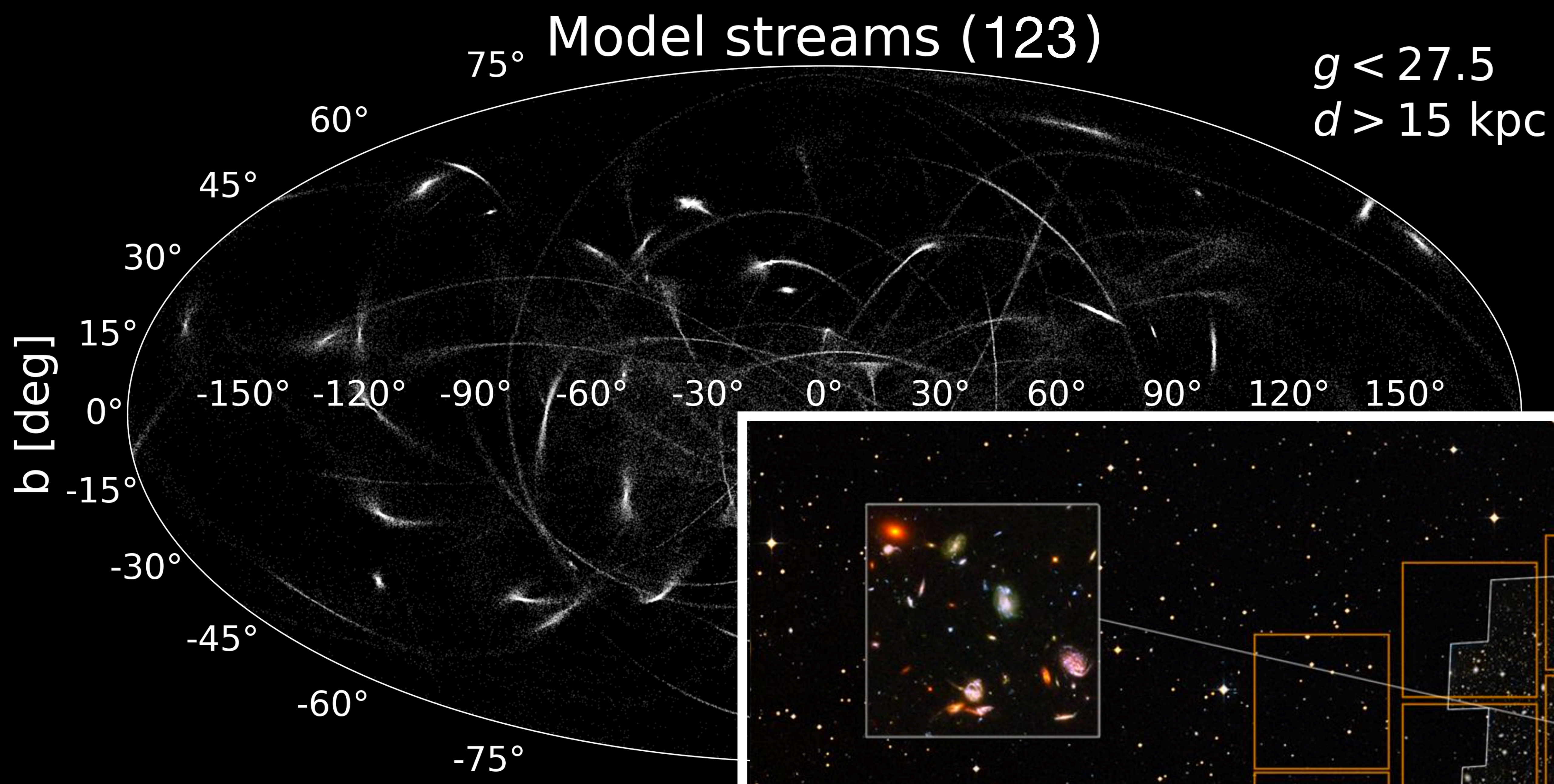


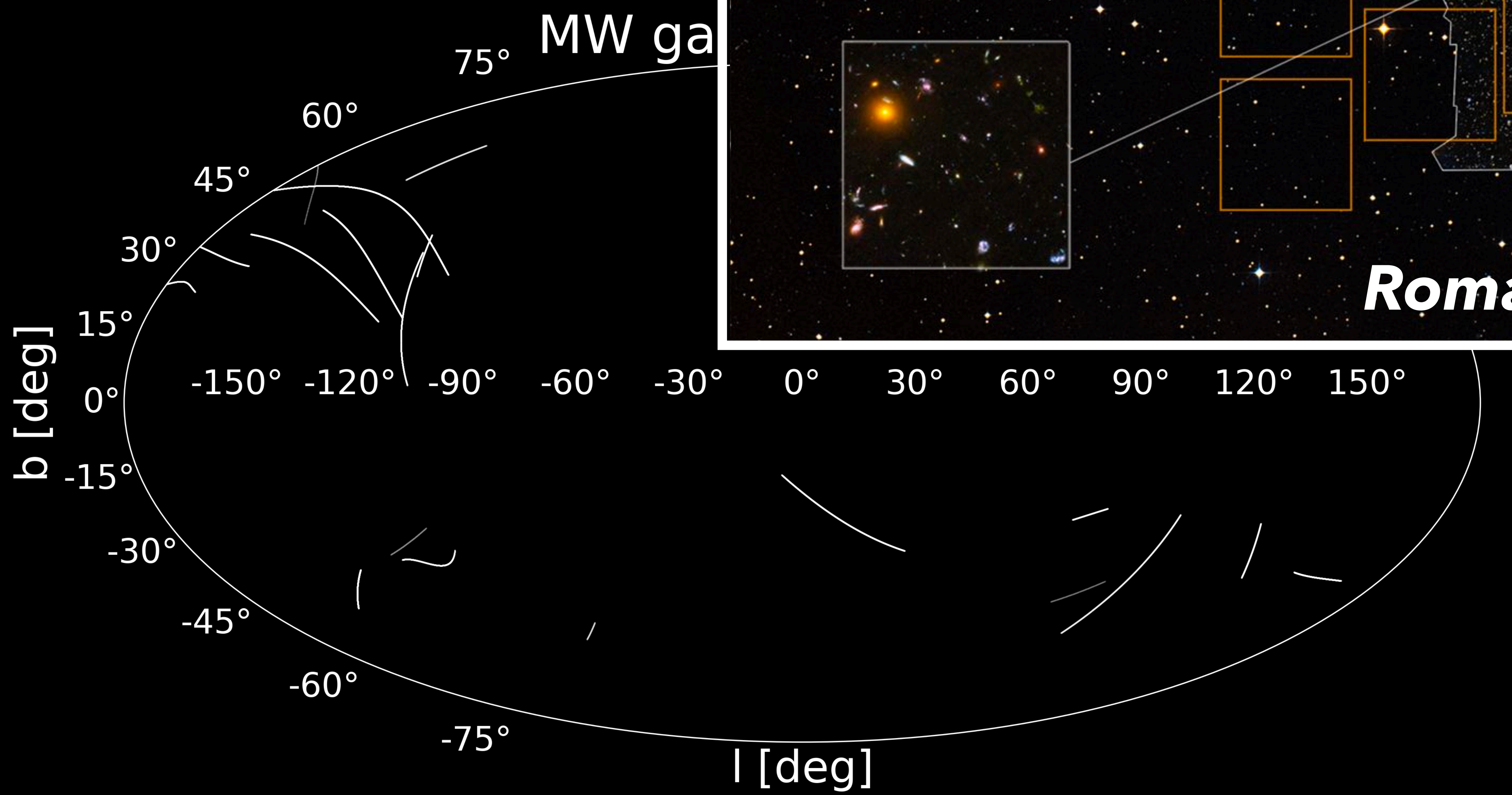
Can we observe these?

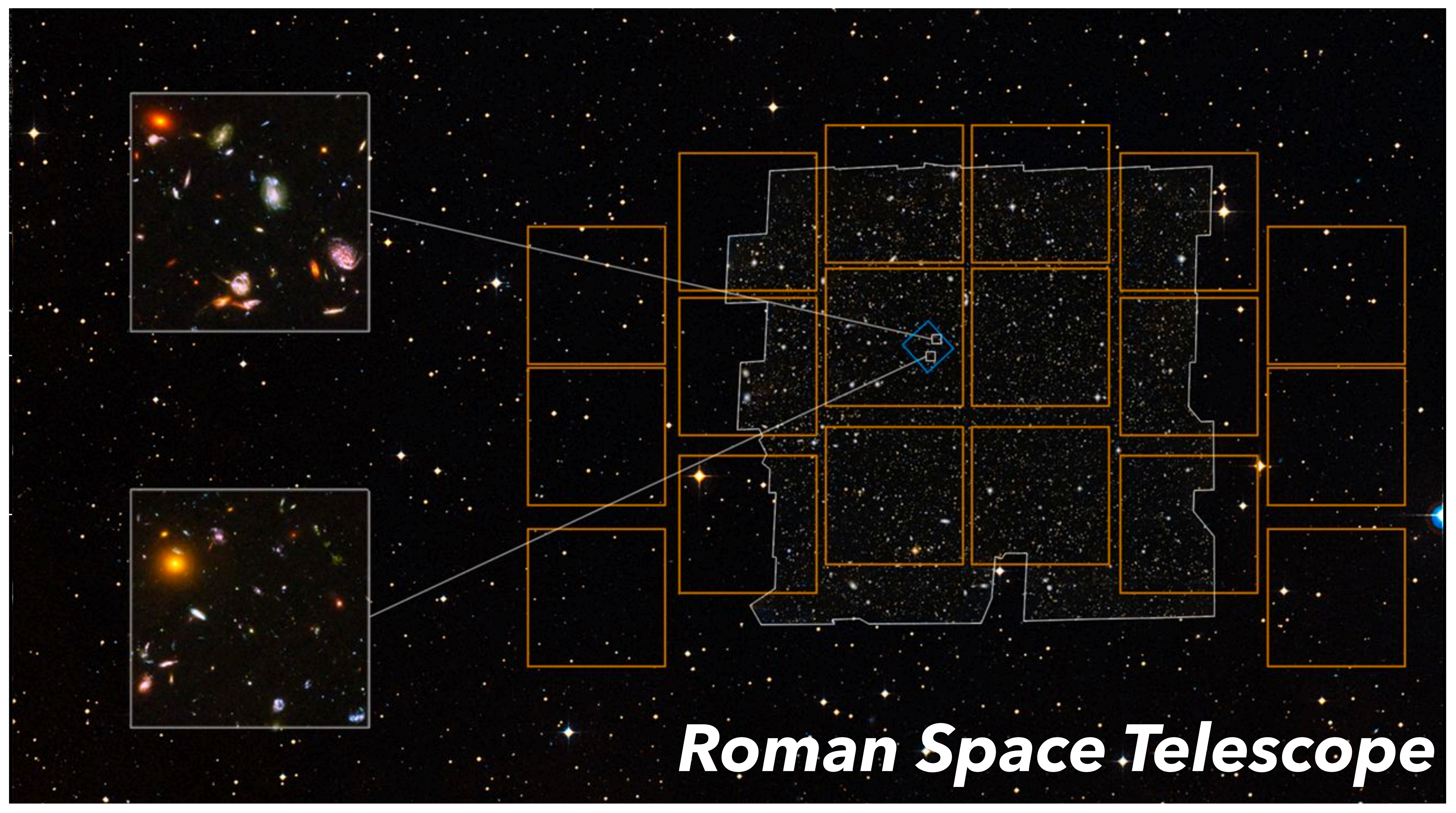
Pearson, Bonaca et al. 2024



Pearson, Bonaca et al. 2024







Aganze, Pearson et al. 2024
Pearson et al. 2022a
Pearson et al. 2019

Pearson, Bonaca et al. 2024

Summary

<10% of the surviving GC streams in the Milky Way have been discovered to date

The surviving GC streams in the outskirts are from accreted objects

LSST can discover many of the remaining streams

Roman can find these in M31 and dwarfs

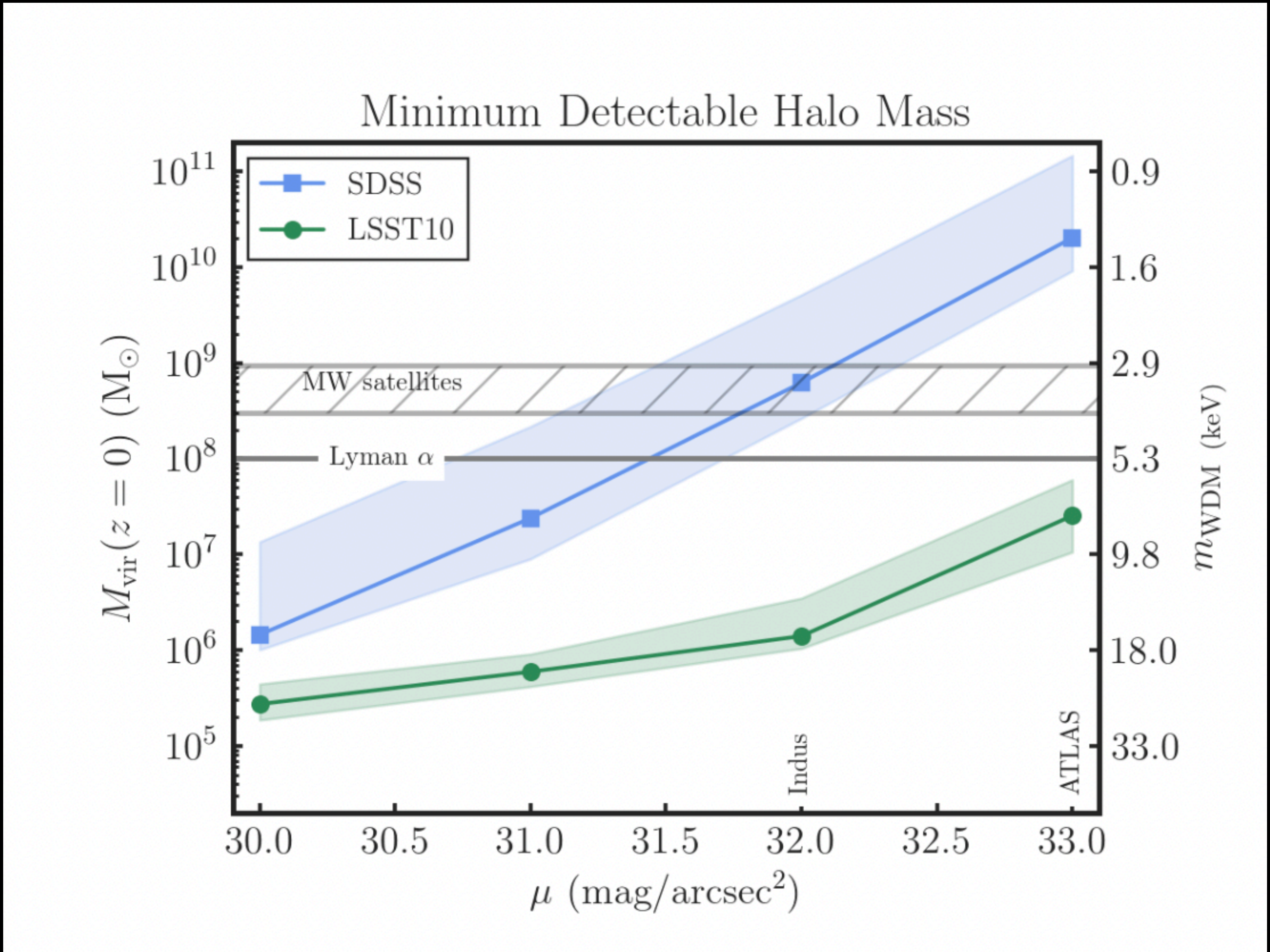
Arxiv: 2405.15851

VILLUM FONDEN

erc
European Research Council
Established by the European Commission

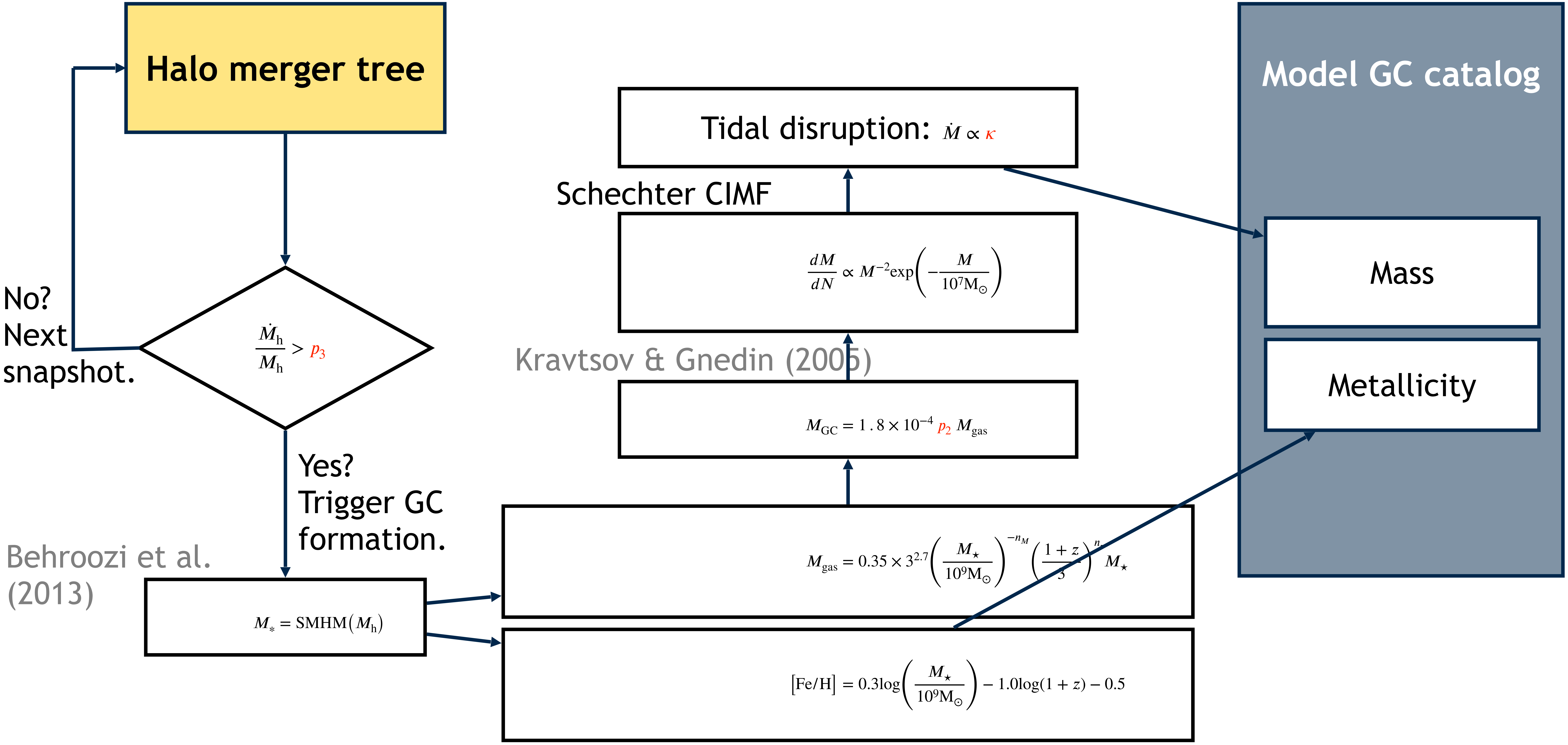
MARIE CURIE ACTIONS

UNIVERSITY OF COPENHAGEN

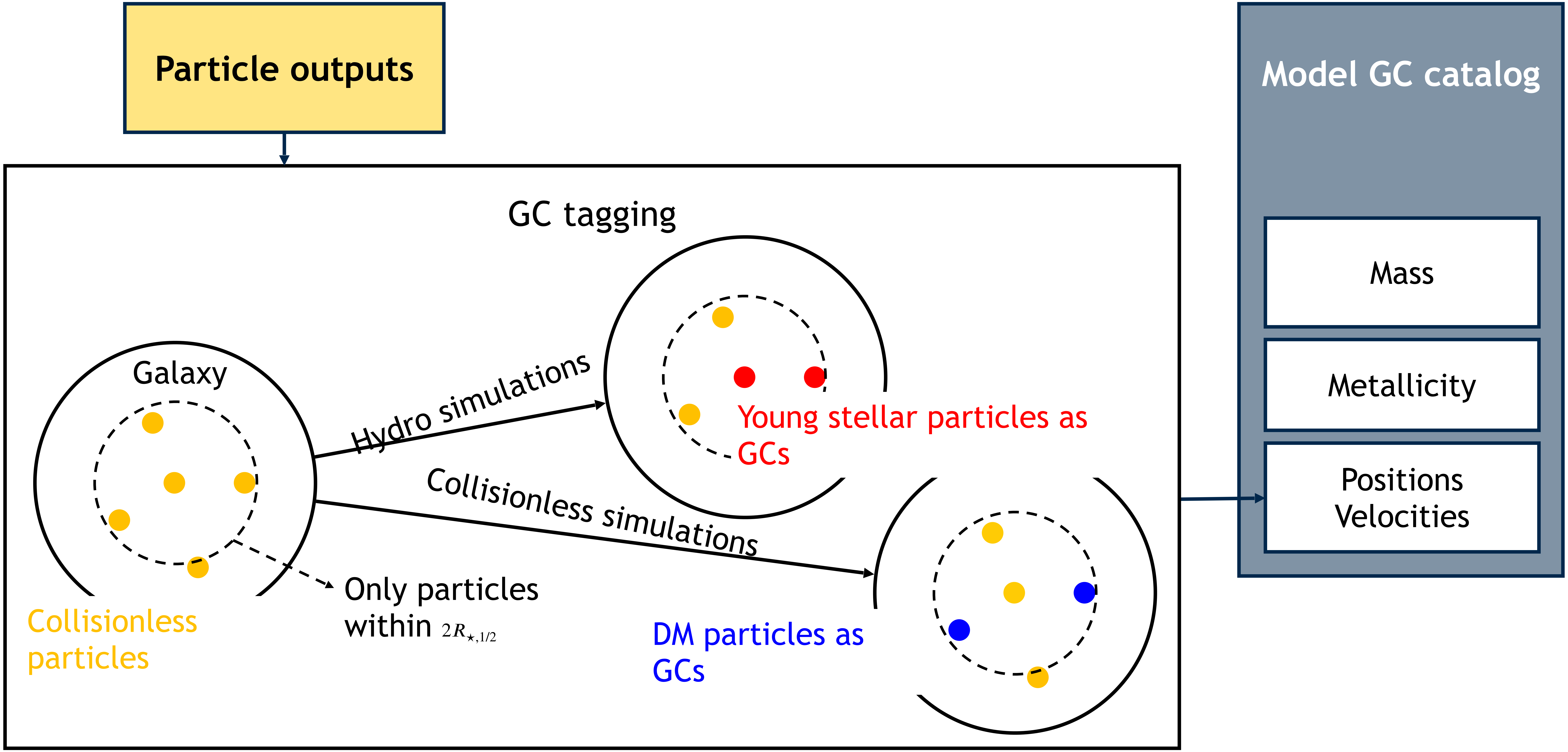


Drlica-Wagner et al. 2019

Our model: post-processing of simulations



Our model: GC Tagging (since Chen & Gnedin 2022, arXiv:2203.00599)



https://github.com/ybillchen/GC_formation_model

Our model: Calibration of model parameters