A SYSTEMATIC METHOD TO IDENTIFY RUNAWAYS FROM STAR CLUSTERS PRODUCED FROM SINGLE-BINARY INTERACTIONS

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INTRODUCTION

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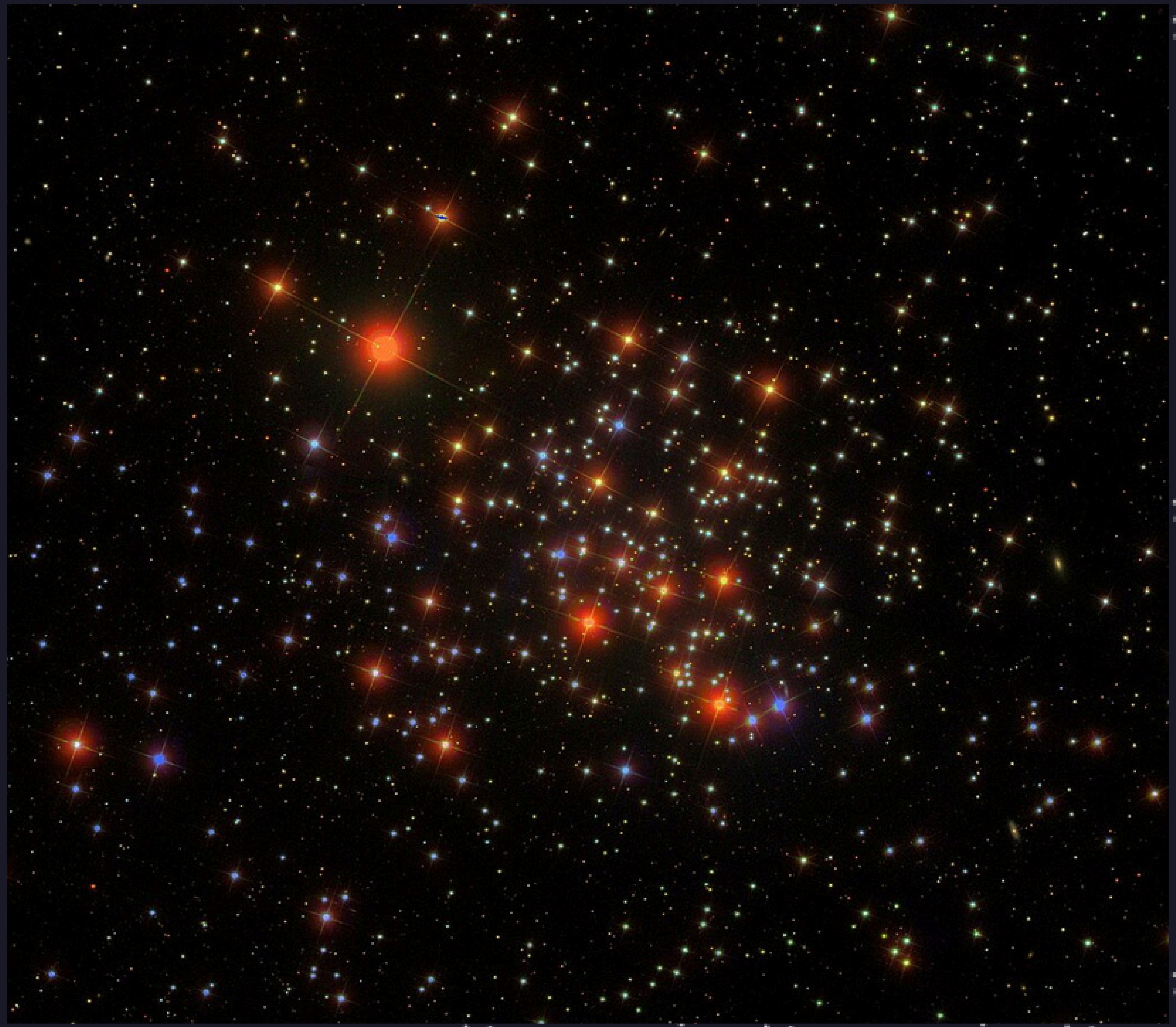


Messier 67 (SDSS, optical and near-infrared)
Sloan Digital Sky Survey

Stars Clusters

Groups of stars gravitationally bound.

Globular Clusters

Tight groups of ten thousand to millions of old stars.

Open Clusters

Made of tens to a few thousand stars and are often very young. Our first investigation focused specifically in the open cluster M67.

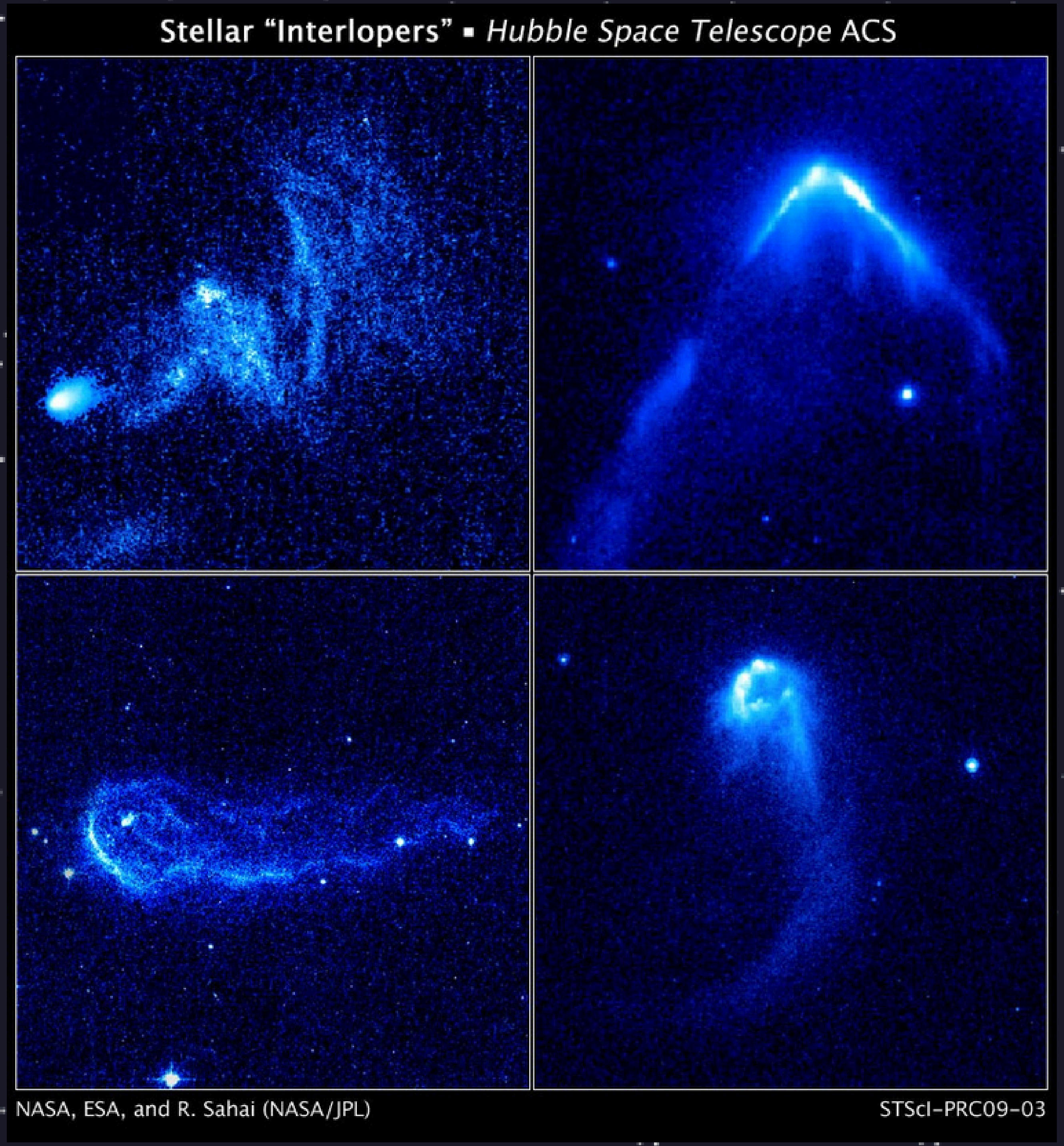
INTRODUCTION:

Clusters lose stars over time

Two body relaxation and/or runaway stars

Runaway Star (RS)

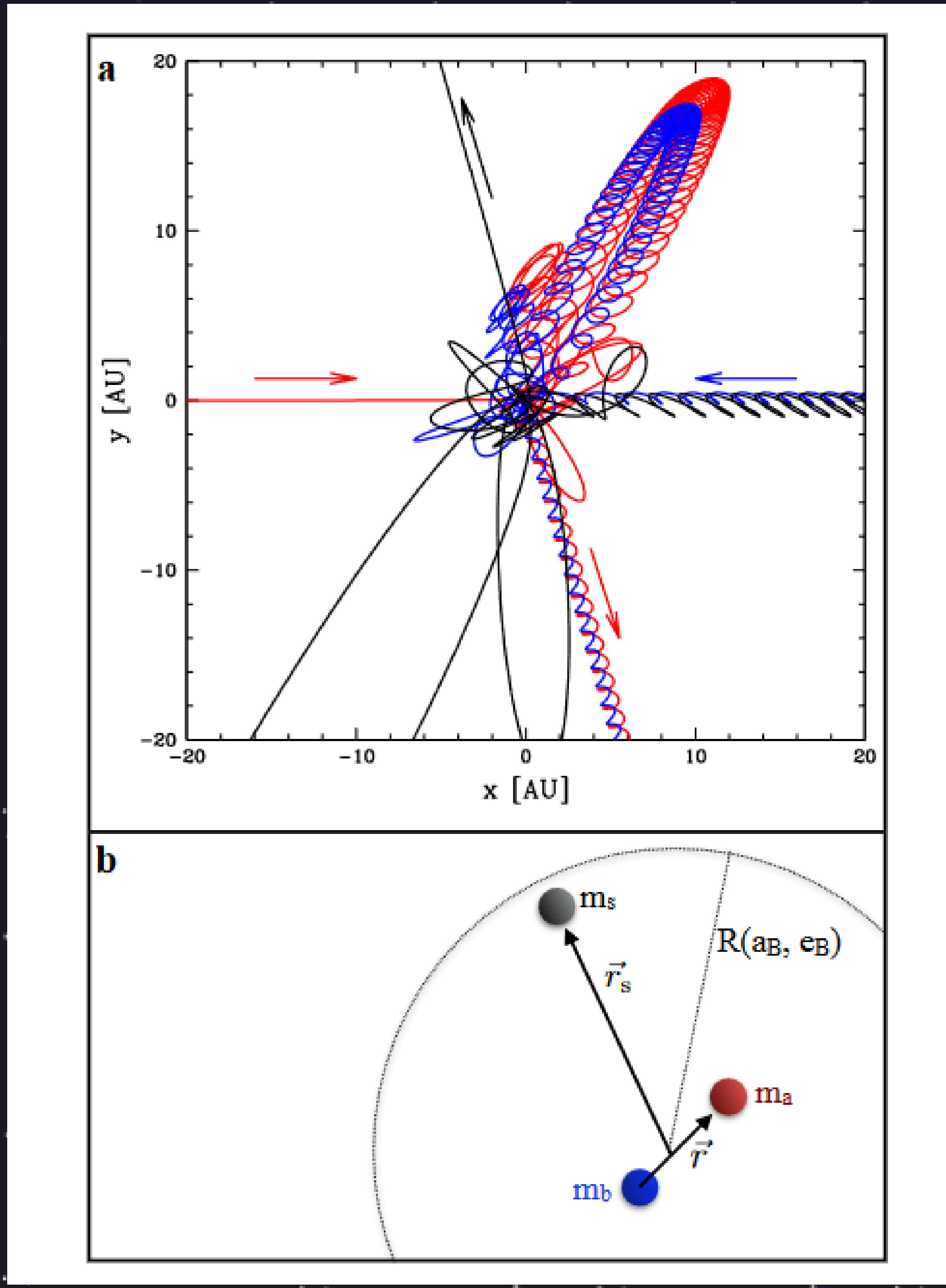
Stars liberated from a cluster with unusual kinematics, such as high velocties.



Runaway stars moving through regions of dense interstellar gas.
NASA - Hubble's Advanced Camera for Surveys

THREE-BODY DISINTEGRATION

- Interaction between a single star and a binary star.
- Disintegrate into a runaway single (RS) and a runaway binary (RB).
- Relative velocity determined by linear momentum conservation.



Single and binary interaction, ending in the ejection of both (Leigh and Stone 2019)

PREVIOUS INVESTIGATIONS

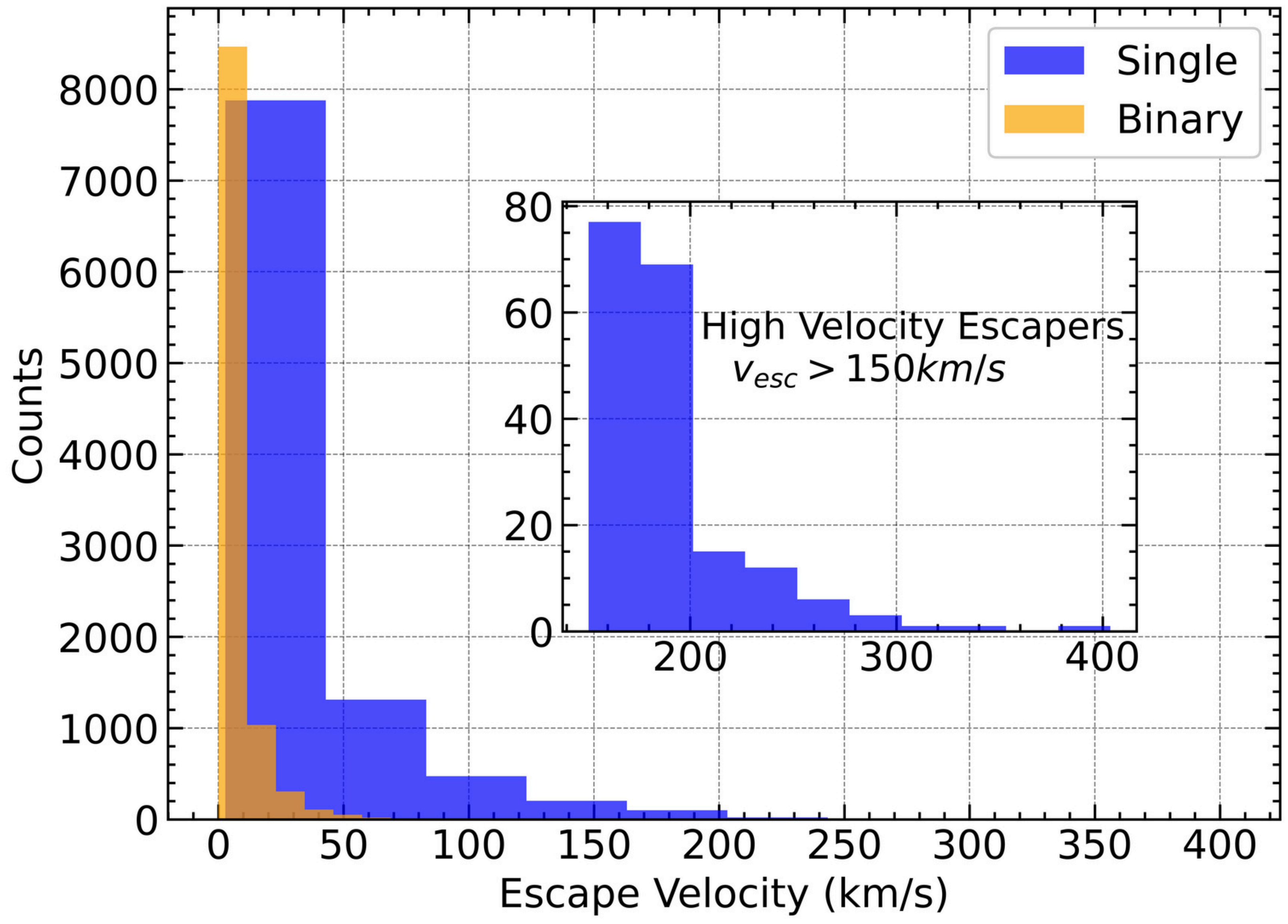
RSs have been the subject of extensive studies through simulations:

- Studies on dynamically ejected massive stars from young star clusters using simulations.
(Perets and Šubr, 2012, Fujii and Portegies Zwart, 2014, Oh et al., 2015, Andersson et al. 2020, Dall'Amico et al., 2021).

- RSs from old star clusters have been argued to be non-negligible, mostly due to three-body interactions.
(e.g. Weatherford et.al., 2023, Grondin et al., 2023a, Grondin et al., 2023b).

CORESPRAY GRONDIN ET AL. 2022

- Python-based code that uses three-body dynamics to simulate the creation of extra-tidal stars and their corresponding recoil binaries.



Histogram showing the predicted velocity distribution of escapers ejected in a Corespray simulation.
A. Herrera Urquieta et al. submitted.

PREVIOUS INVESTIGATIONS

Studies of RSs through observations:

- Studies of RSs changed with the launch of the Gaia mission.

  (Gaia Collaboration et al., 2022)

- As a result, numerous new RSs have been discovered.

  (e.g. Carretero-Castrillo et al., 2023, Liao et al., 2023, Li et al., 2023, Igoshev et al., 2022)

https://www.cosmos.esa.int/

IT IS POSSIBLE TO DETERMINATE THE POINT WHERE THEY GOT SEPARATED?

CAN WE PROVIDE A METHOD TO IDENTIFY BOTH OBJECTS IN THESE THREE-BODY DISINTEGRATIONS?

IS THE DATA GOOD ENOUGH TO DO THIS TASK?

WE PRESENT....

A NOVEL METHODOLOGY TO IDENTIFY RUNAWAYS

- Identification of RS/RB pairs from single-binary interactions in star clusters.

- **Generalized method** that can be applied to any cluster with **5D kinematics** information.

THEORETICAL EXPECTATIONS

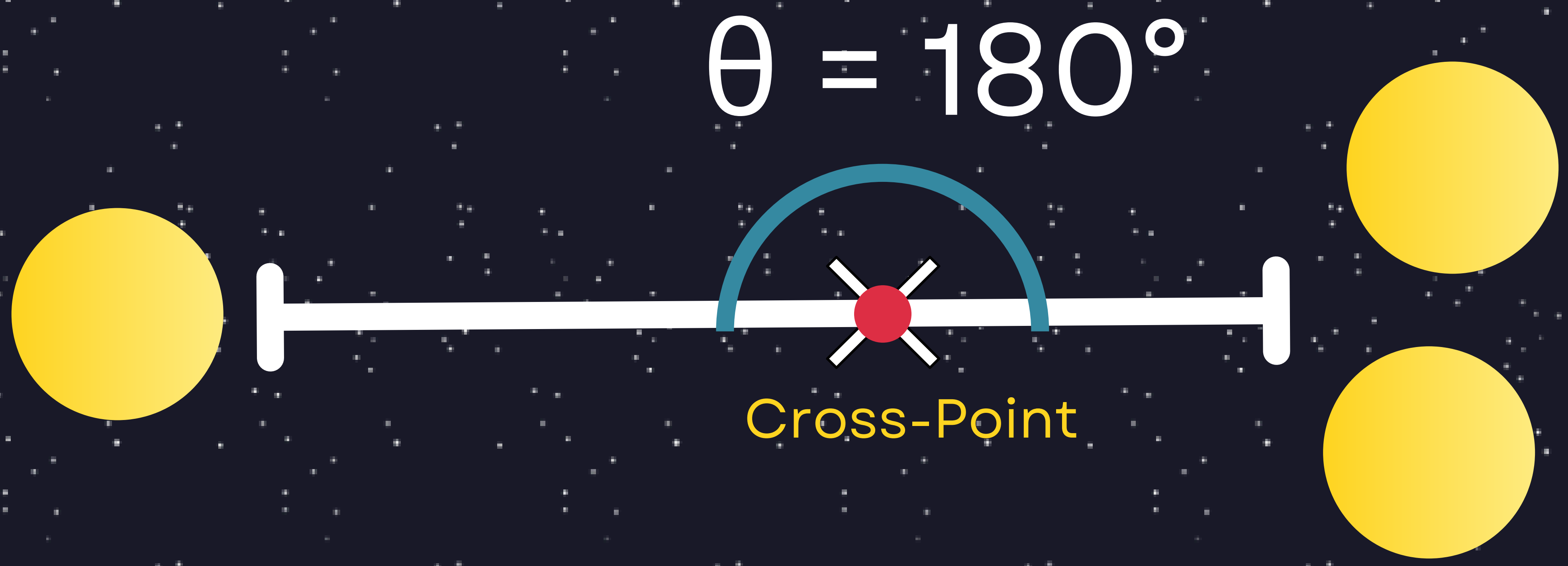
THEORETICAL EXPECTATIONS FOR THREE-BODY DISINTEGRATIONS

- ***Timescale and momentum conservation***-based arguments can be used.

- We search for both the ***RS and RB*** and the point in the sky where the three stars got separated.

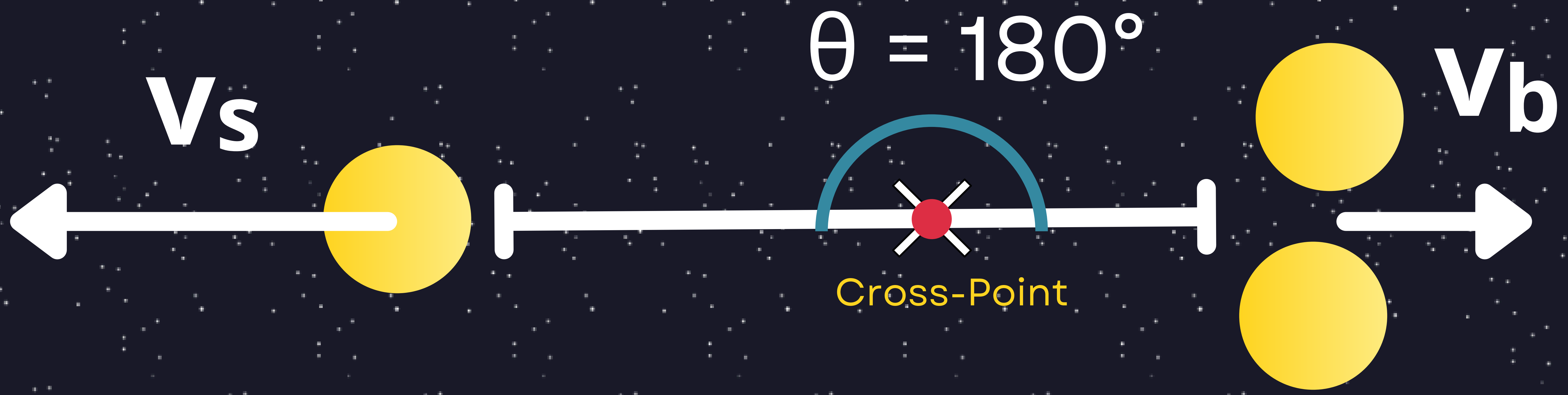
For every RS-RB pair, theory predicts:

- 180° angle between the (2D/3D) velocity vectors.



For every RS-RB pair, theory predicts:

- 180° angle between the (2D/3D) velocity vectors.
- $\frac{m_b}{m_s} > 2$ then $\frac{v_s}{v_b} > 2$



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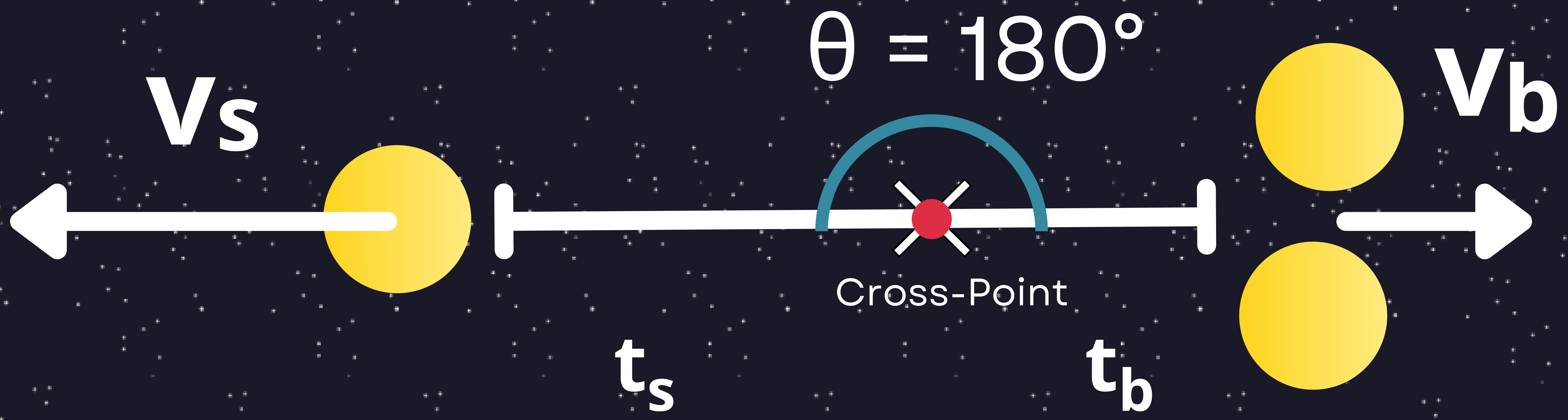
- $\frac{m_b}{m_s} > 2$ then $\frac{v_s}{v_b} > 2$
- Both traceback times from the currently observed positions to the hypothetical origin, namely where their velocity vectors "intersect", should be equal.



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- Both traceback times from the currently observed positions to the hypothetical origin (velocity vectors “intersect”), should be equal.
- Luminosities and colors consistent with an isochrone

METHODOLOGY

STUDY ON M67

- M67 as a testing ground for our method.
- Sufficiently high density that single-binary interactions are thought to occur frequently.

M67	VALUES
MASS	$2100 \pm 600\ [M_\odot]$ Bonatto et al. 2003
DISTANCE	$\approx 860\ [\mathrm{pc}]$ Cantat-Gaudin et al 2018
TIDAL RADIUS	$\sim 17\ [\mathrm{pc}]$ Keenan et al. 1973 Davenport et al. 2010 Kharchenko et al. 2013
ESCAPE VELOCITY	$2.6\ [\mathrm{km/s}]$ Georgiev et al. 2009
BINARY POPULATION	~ 50 % Aaron M. Geller et al 2021.

DATA: GAIA DR3

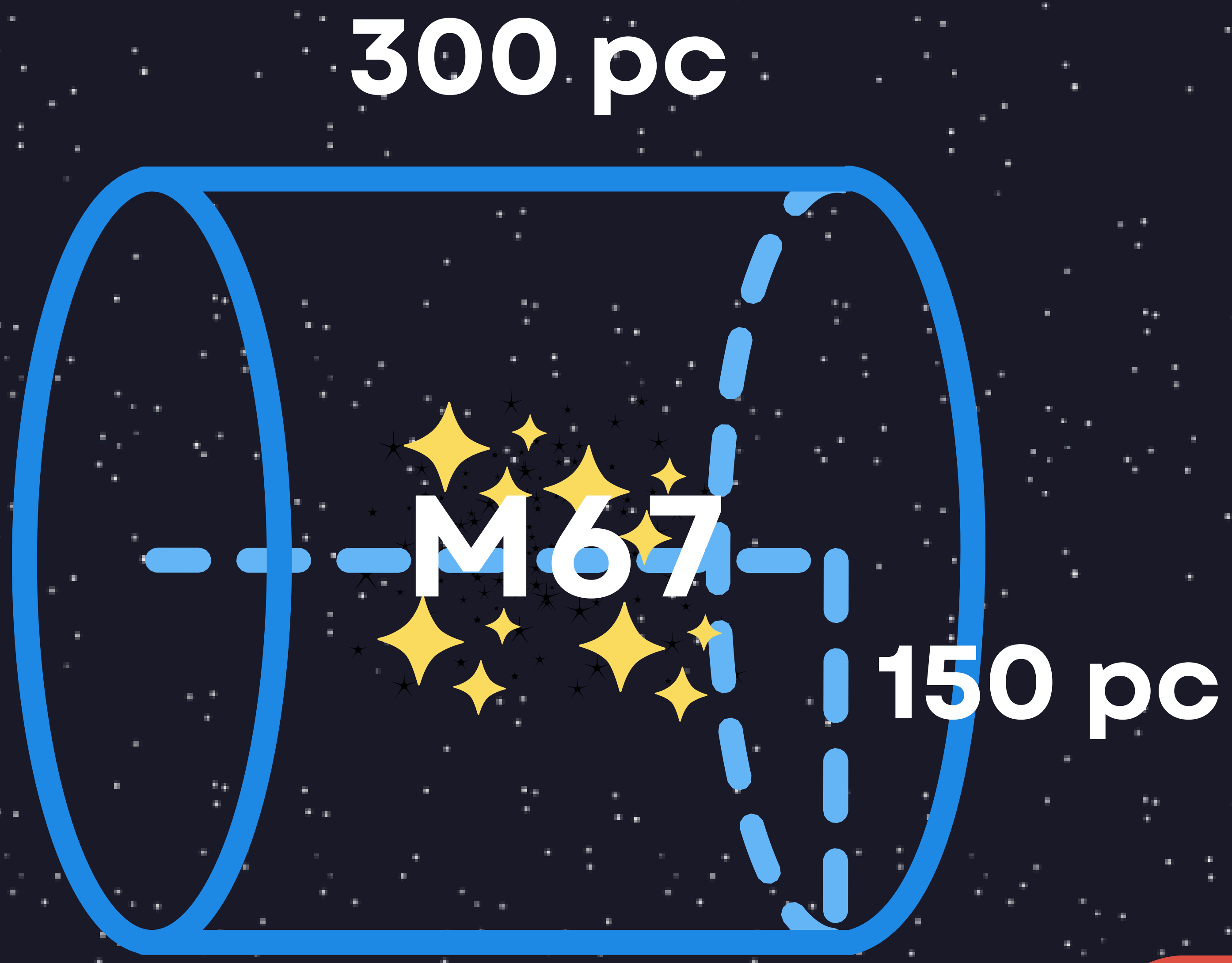
- This data release represents a major advance in the quantity and quality of available kinematic data.

- Ideally, we must build a 6-D phase space.

- Currently all we have is a complete 5-D phase space using the Gaia DR3 catalog, lacking reliable radial velocities.

- How far can we get with only 5-D? Pretty far!

SAMPLE SELECTION



GAIA DR3 CONE SEARCH:
1.9 MILLION SOURCES

→ CYLINDER CUT
203,190

→ ESCAPERS
15,354

→ PAIRS
117,864,981

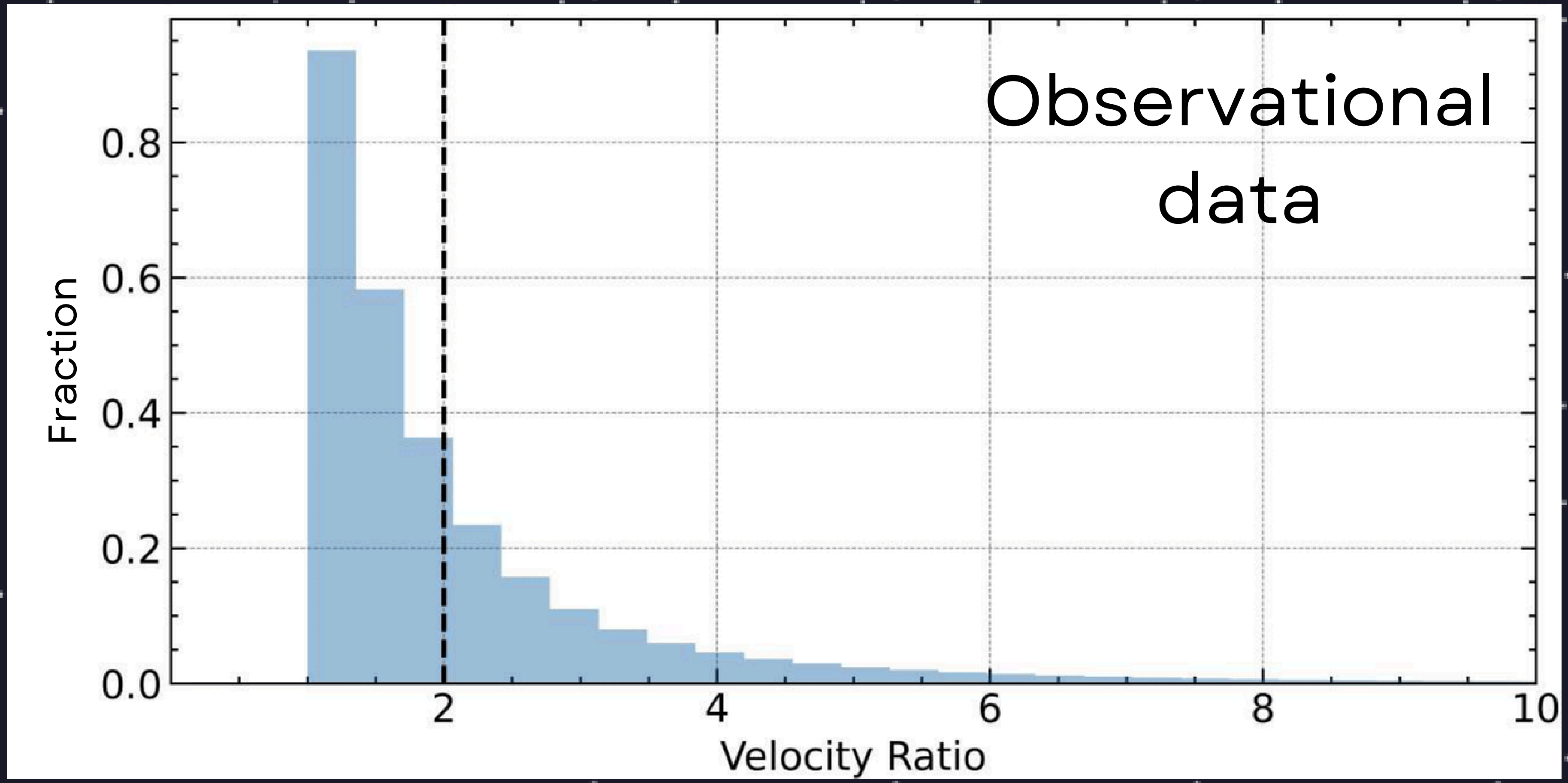
APPLYING THE CRITERIA TO ALL THE POSSIBLE PAIRS

- There are ~120 million pairs.

- How many pass all the selection criteria from theory to within 1σ?

RESULTS

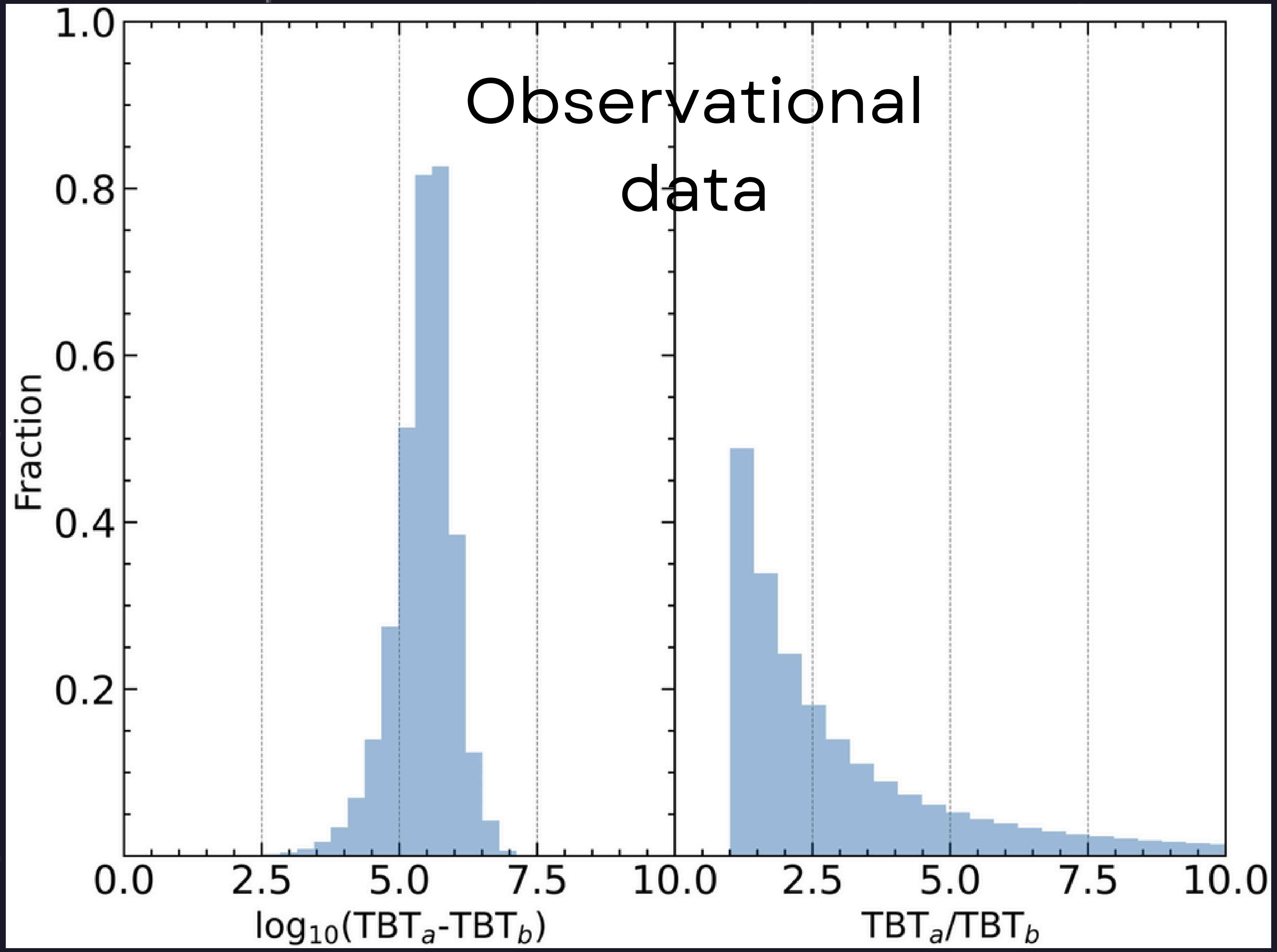
VELOCITY RATIO DISTRIBUTION



A. Herrera-Urquieta et al. submitted

- Sample is reduced by about a factor of 2 if we only include pairs with velocity ratios > 2.
- Including also that the fastest object must be dimmer, is a reduction of one order of magnitude

TRACEBACK TIME DISTRIBUTION

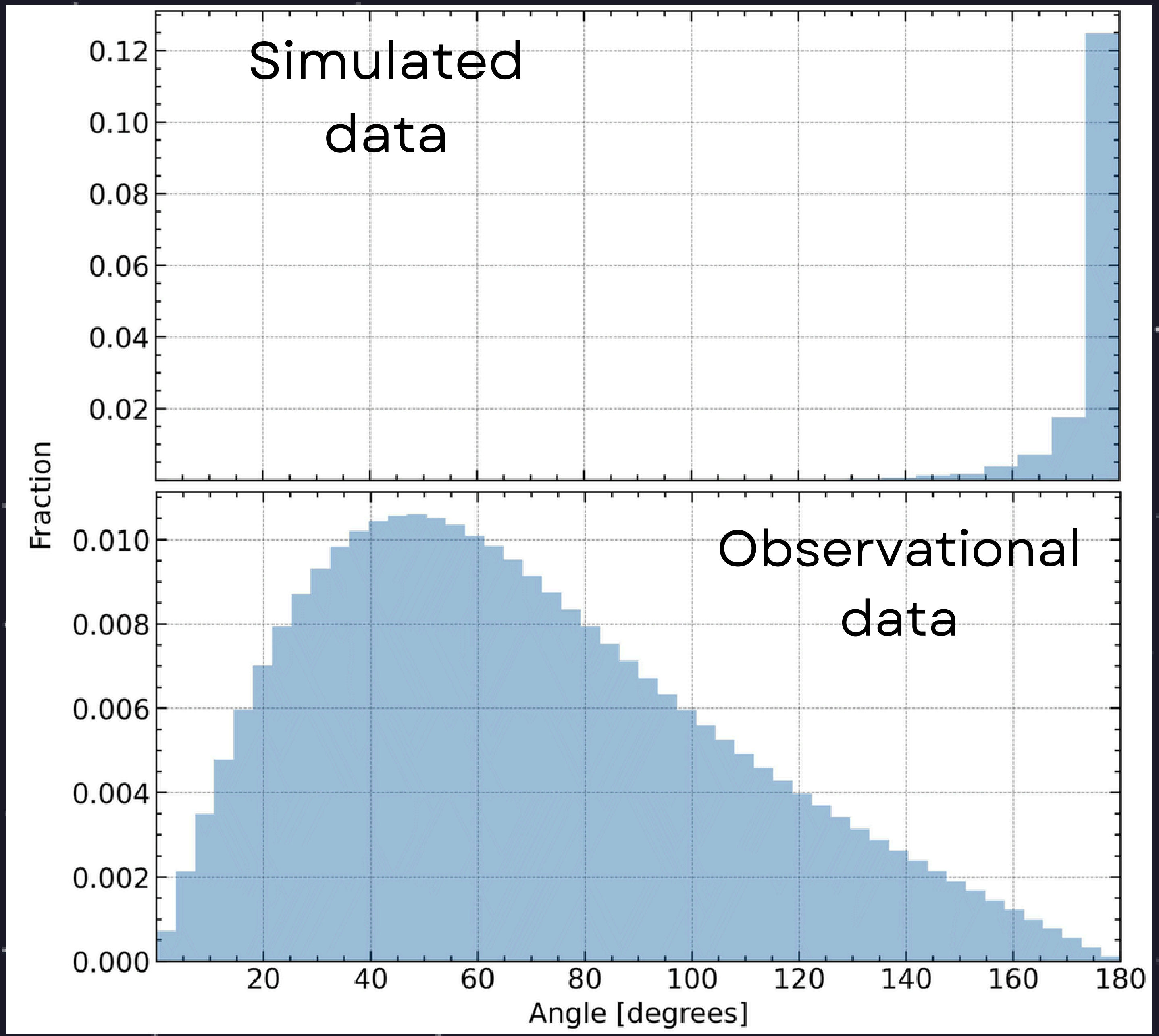


A. Herrera-Urquieta et al. submitted

- Traceback vectors intersect in time and space, reducing the sample by one order of magnitude.

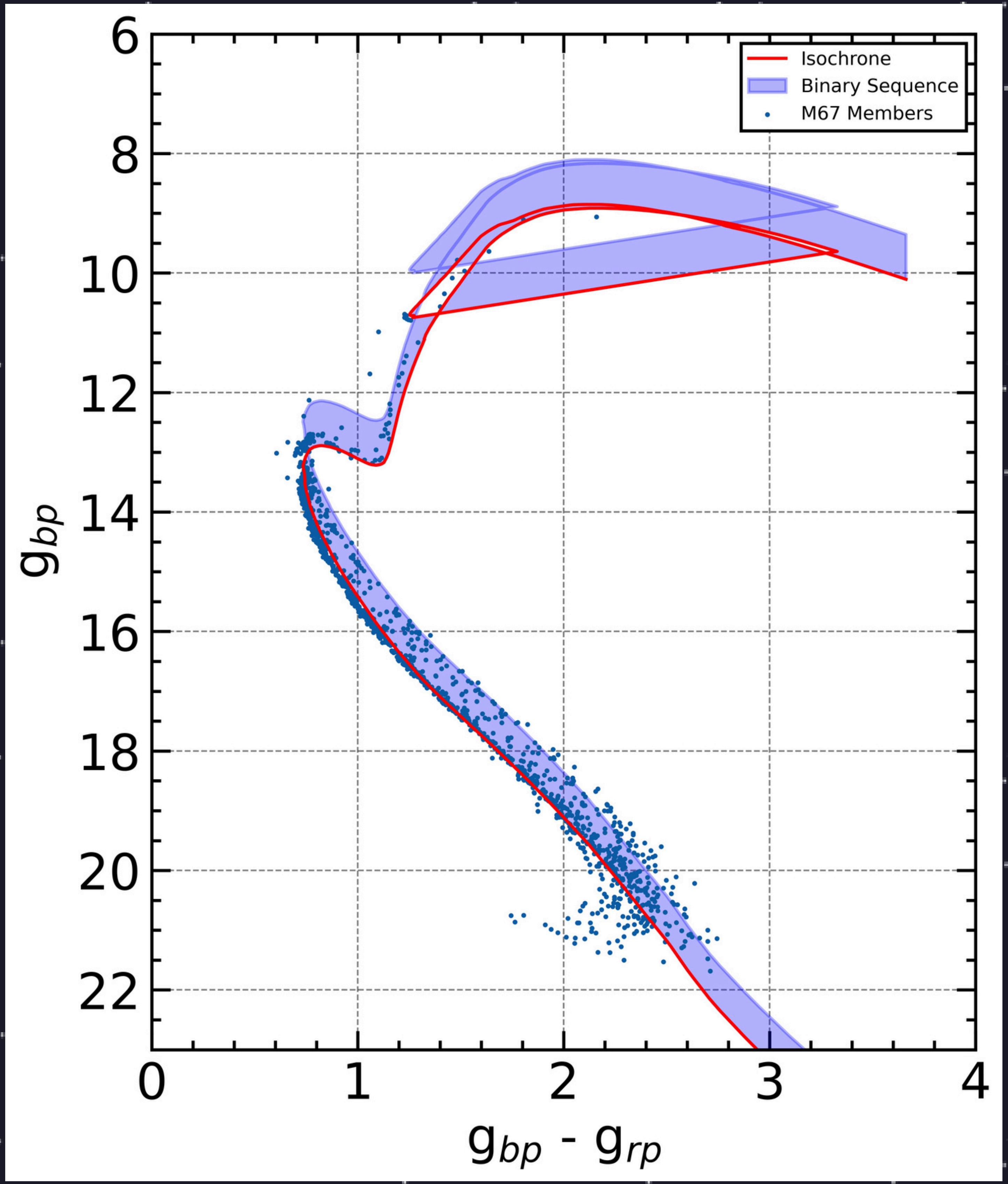
ANGLE DISTRIBUTION

- The angle between both velocity vectors fall within 1σ of 180°. Reduces our sample size by two orders of magnitude.



A. Herrera-Urquieta et al. submitted

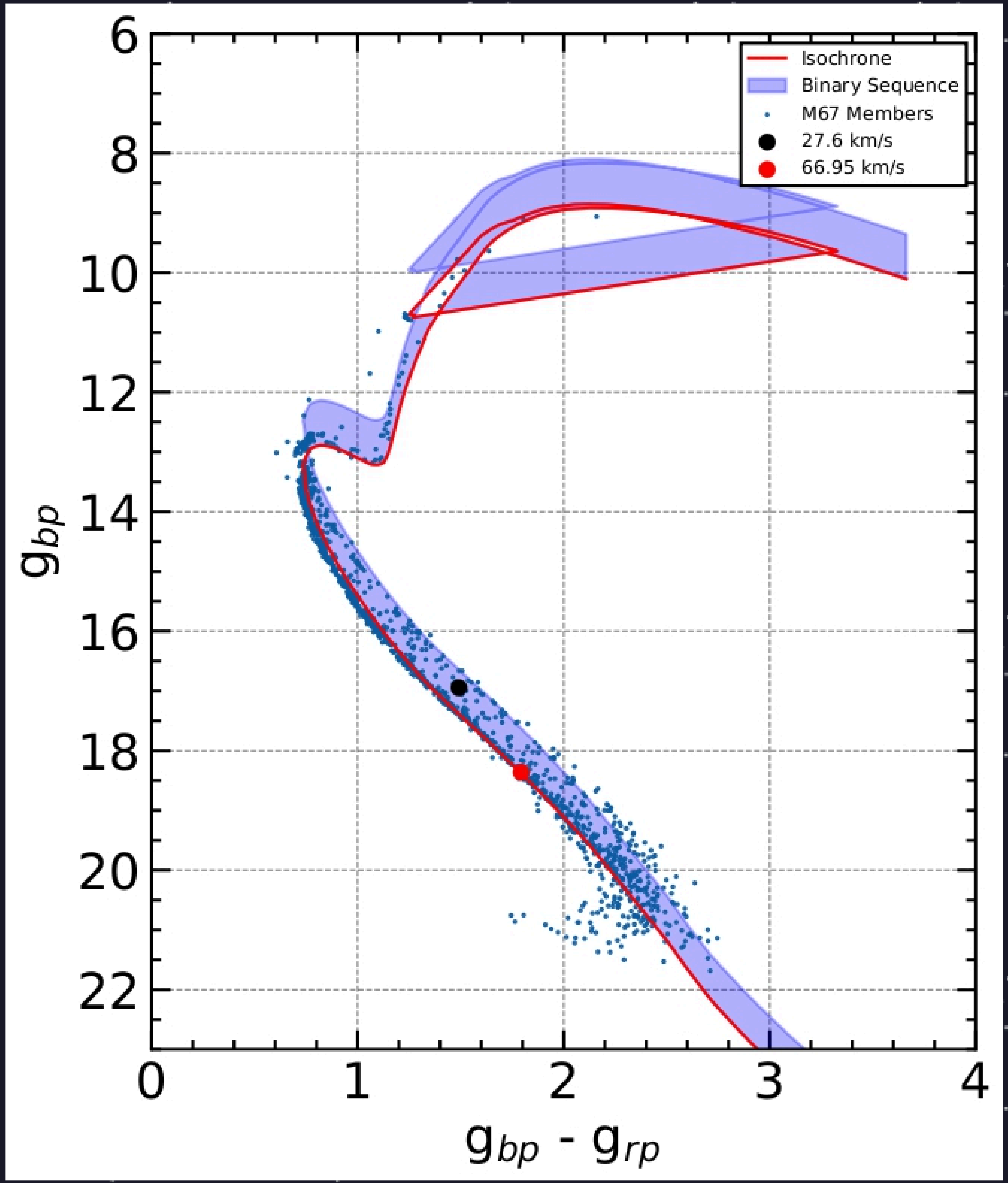
CMD FITTING



Cluster members of M67 obtained from Childs et al. 2023 red lines show the best-fitting isochrone as well as the equal-mass binary sequence shifted 0.75 mag above it (upper line)

A. Herrera-Urquieta et al. submitted

- The fastest and dimmer star lies on the isochrone, reducing the sample by two orders of magnitude.
- Applying all of the criteria previously introduced, reduced by eight orders of magnitude, from 10^8 to 1



A. Herrera-Urquieta et al. submitted

RESULTING PAIR

- We found something!

- The red and black dots correspond to, respectively, the faster and slower moving objects.

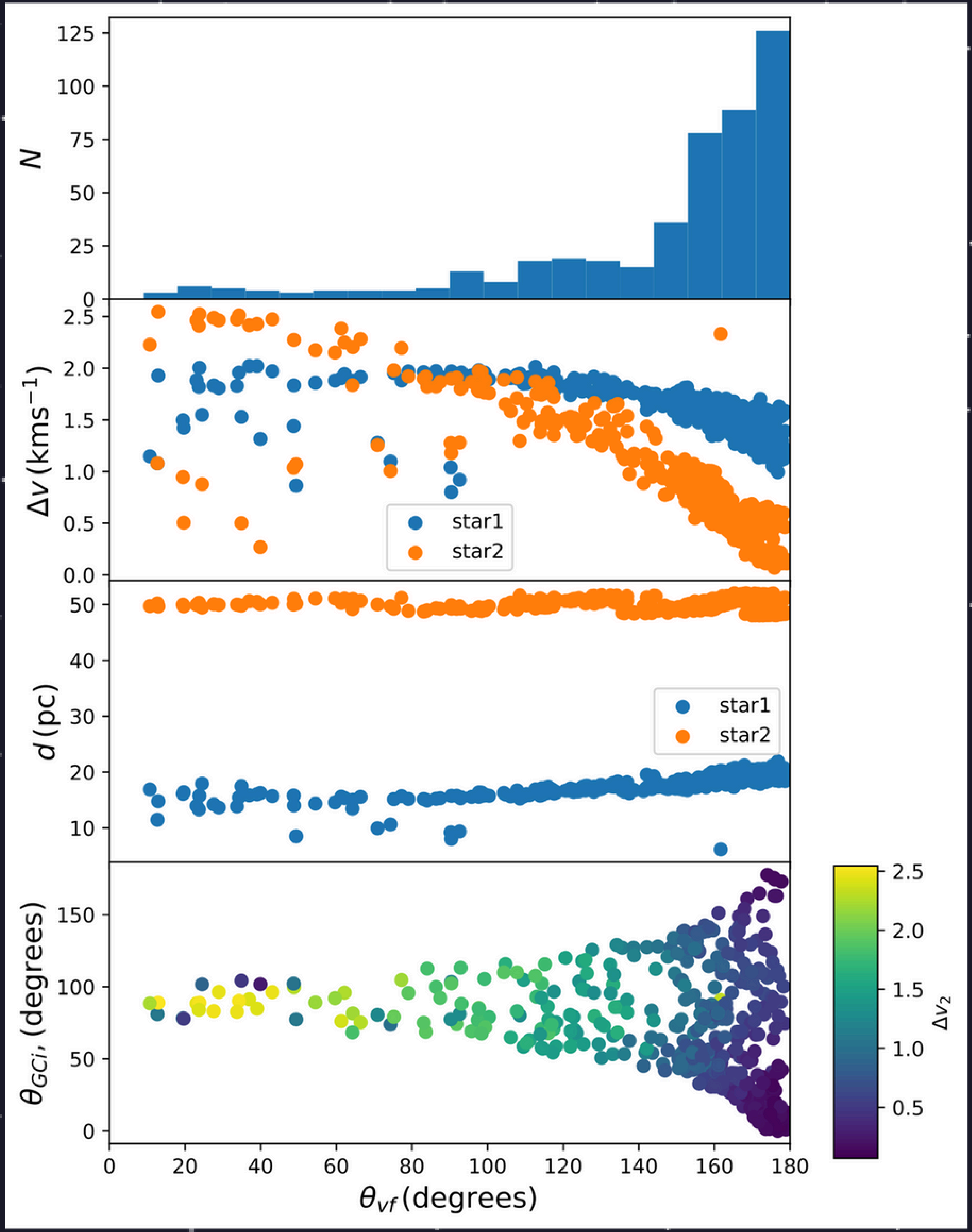
DISCUSSION

EFFECT OF THE GALACTIC POTENTIAL

STAR 1 = BINARY (HEAVY)
STAR 2 = SINGLE (LIGHT)

TOWARD GALACTIC CENTER $\theta_{GC} = 0 \rightarrow$

PARALLEL TO THE CLUSTER ORBIT $\theta_{GC} = 90 \rightarrow$



A. Herrera-Urquieta et al. submitted
Credit: Aaron Geller, Northwestern University

HOW MANY FALSE POSITIVES DO WE EXPECT?

- We generate four different tests shifting the center of the cluster.
- Sample of pairs five times greater than our main sample.
- Out of all these pairs, zero objects satisfy all of our criteria simultaneously

FUTURE WORK:

- It is important to bear in mind that our candidate pair is promising but still highly preliminary.
- Follow-up observations to confirm or reject the resulting pairs.
- Apply the code to more clusters.
- Add a black hole into the mix.

SUMMARY

- Systematic method to identify runaway stars ejected from star clusters from single-binary interactions
- Using M67 as a benchmark test case, we confront our expectations with a 5-D kinematic data set obtained from the GAIA DR3 catalog
- Of an initial sample size of roughly 10^8 pairs, only one satisfies all of our selection criteria
- While the results obtained in this study for M67 are promising, it is important to validate our method by applying it to other star clusters
- The candidates we identify are still highly preliminary, and subsequent (spectroscopic) observations and RVs could help confirm/reject them

BONUS


RUN
NO
WAIT

Thanks for your attention!

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