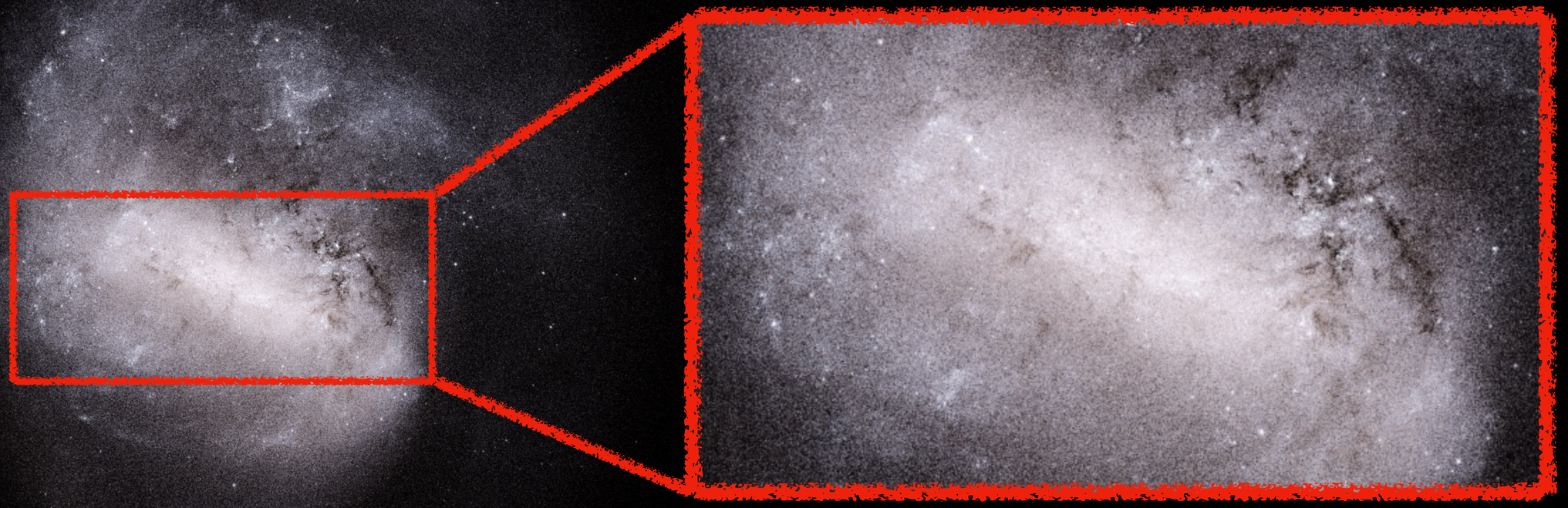
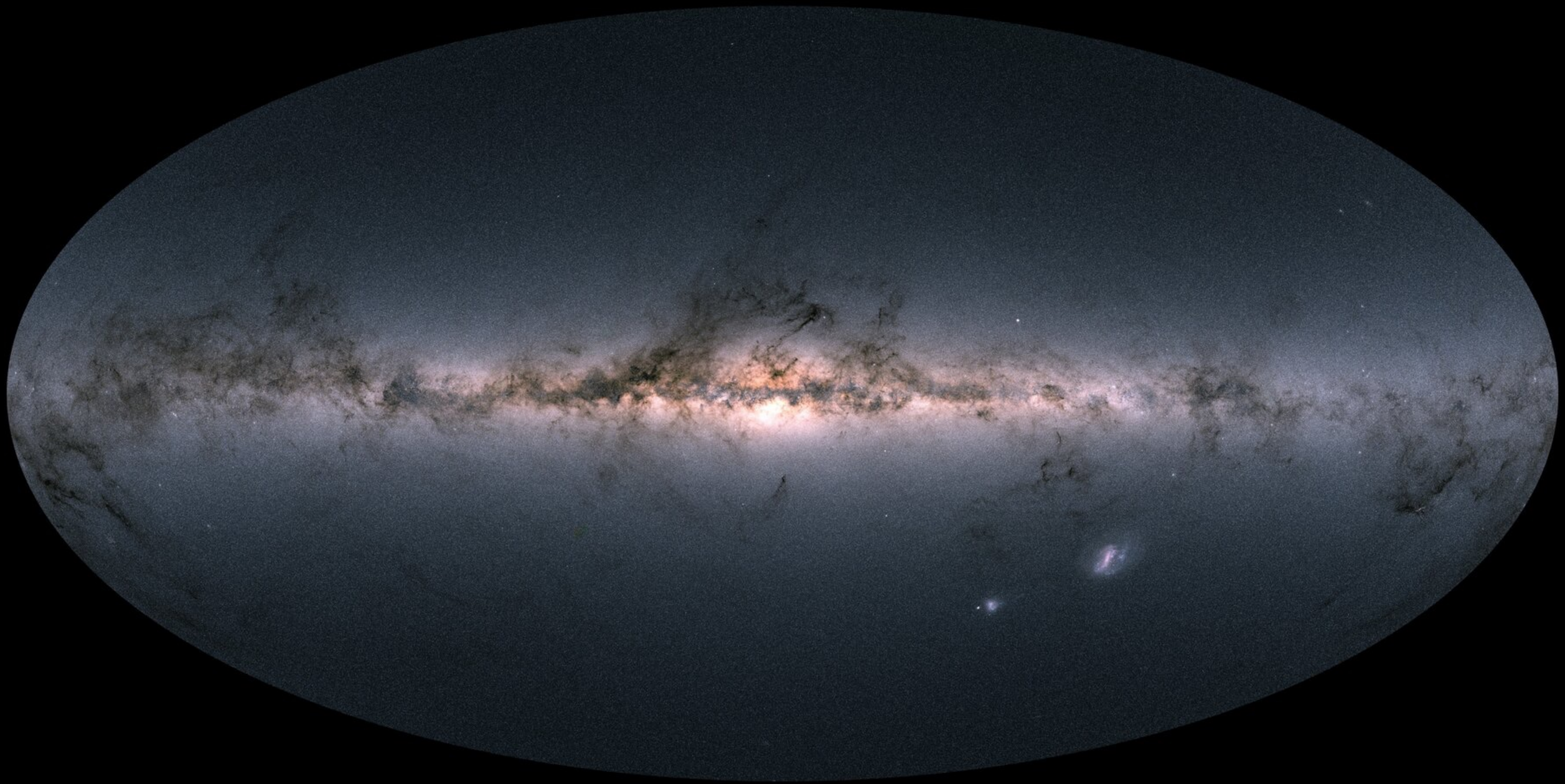
In collaboration with: L. Chemin, S. Roca-Fàbrega,
M. Romero-Gómez, X. Luri, et al.

The **LMC bar pattern speed**

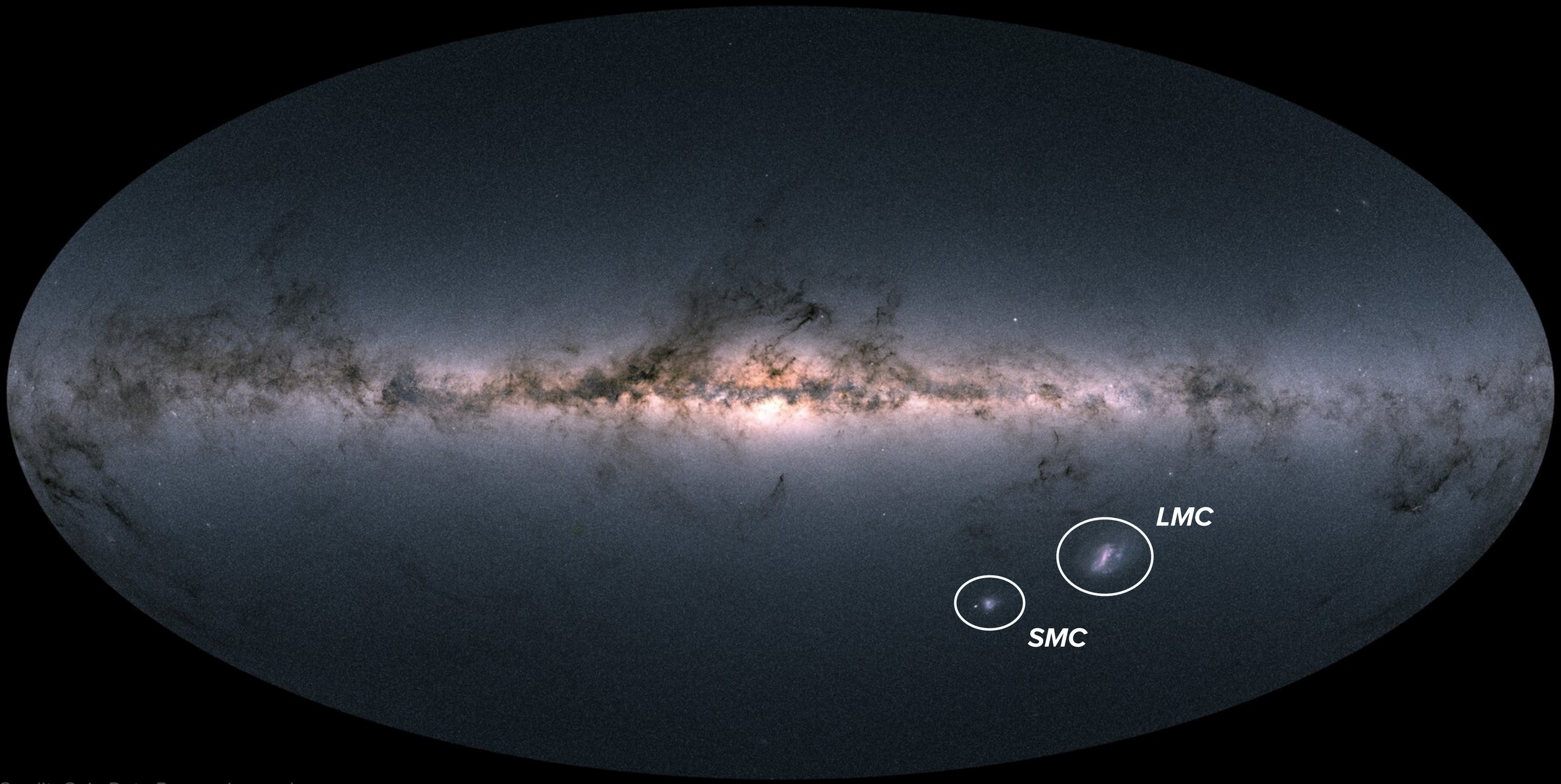


Image(s) credit: Ó. Jiménez-Arranz
Available at www.oscarjimenezarranz.com

Óscar Jiménez Arranz
Lund University



Credit: Gaia Data Processing and
Analysis Consortium (DPAC); A. Moitinho et al.



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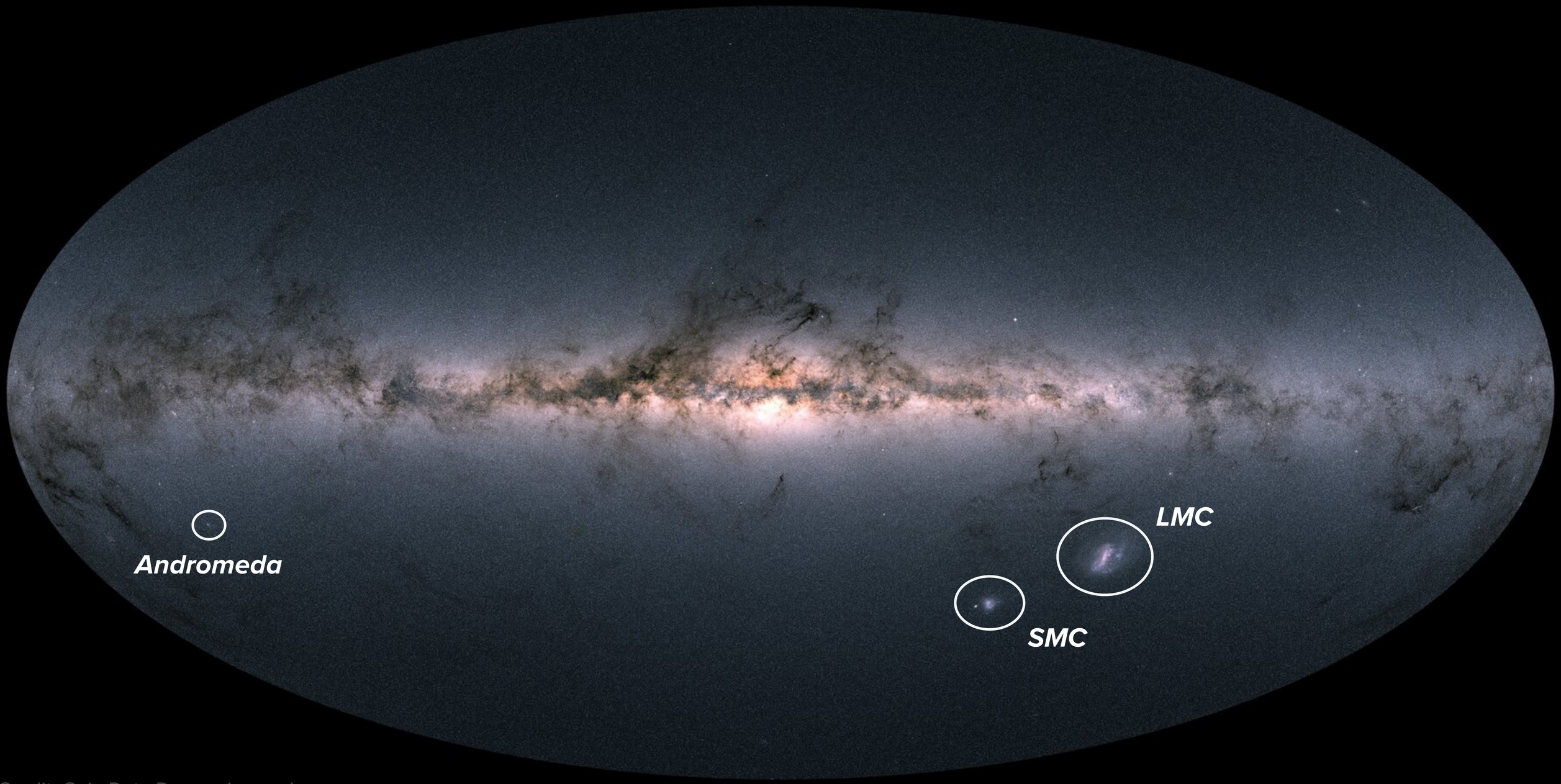

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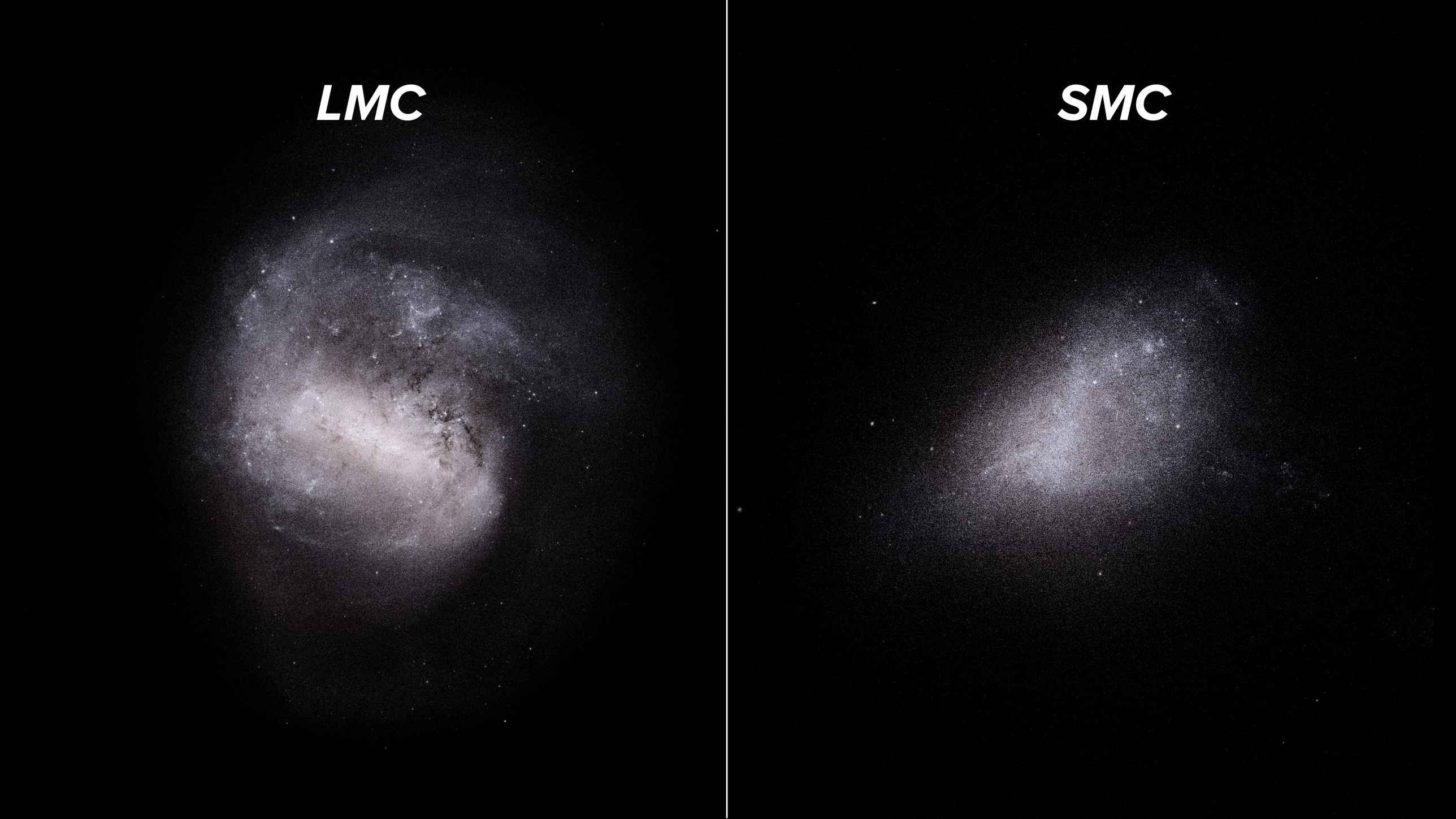
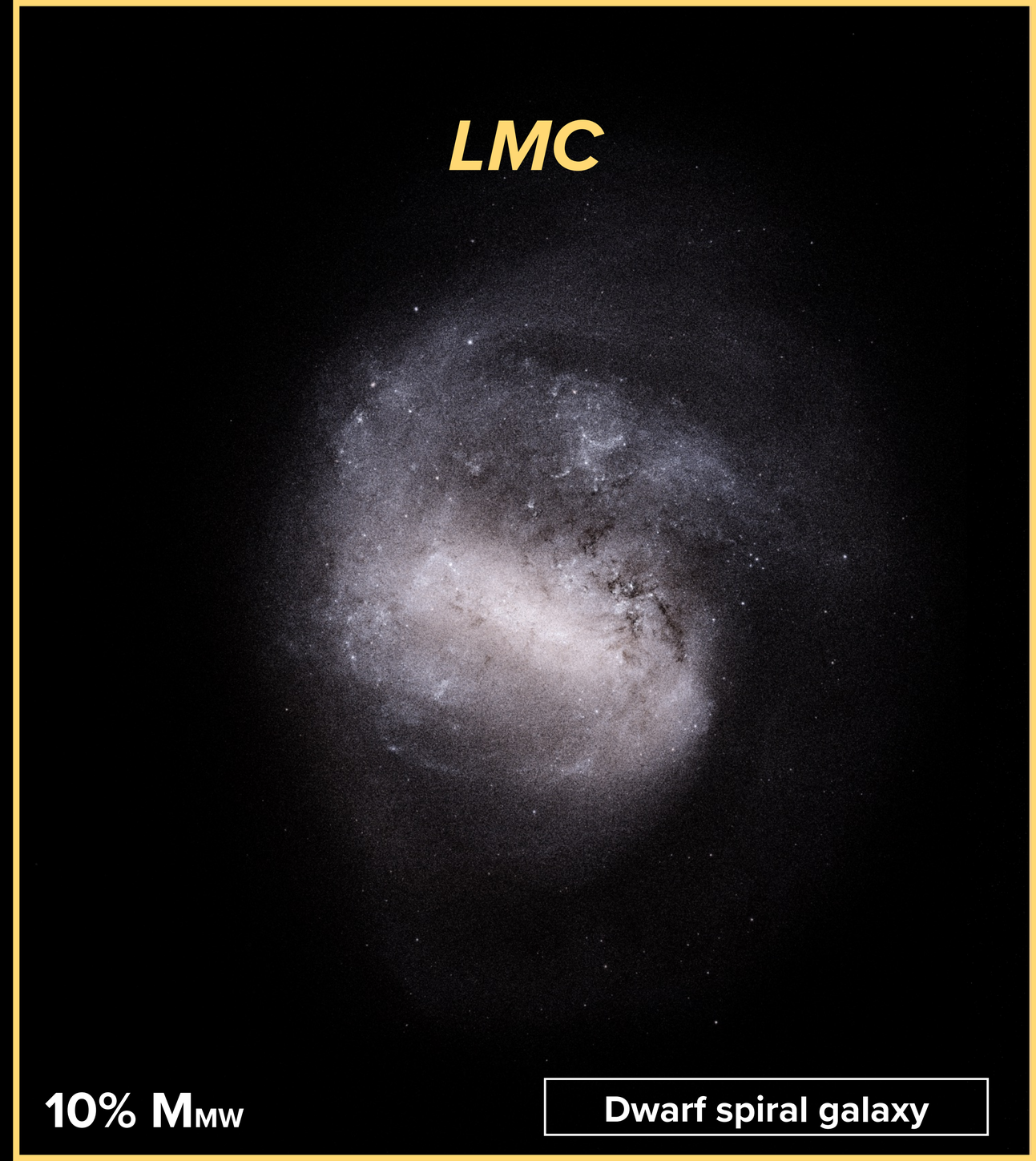

LMC
SMC

LMC

SMC

LMC

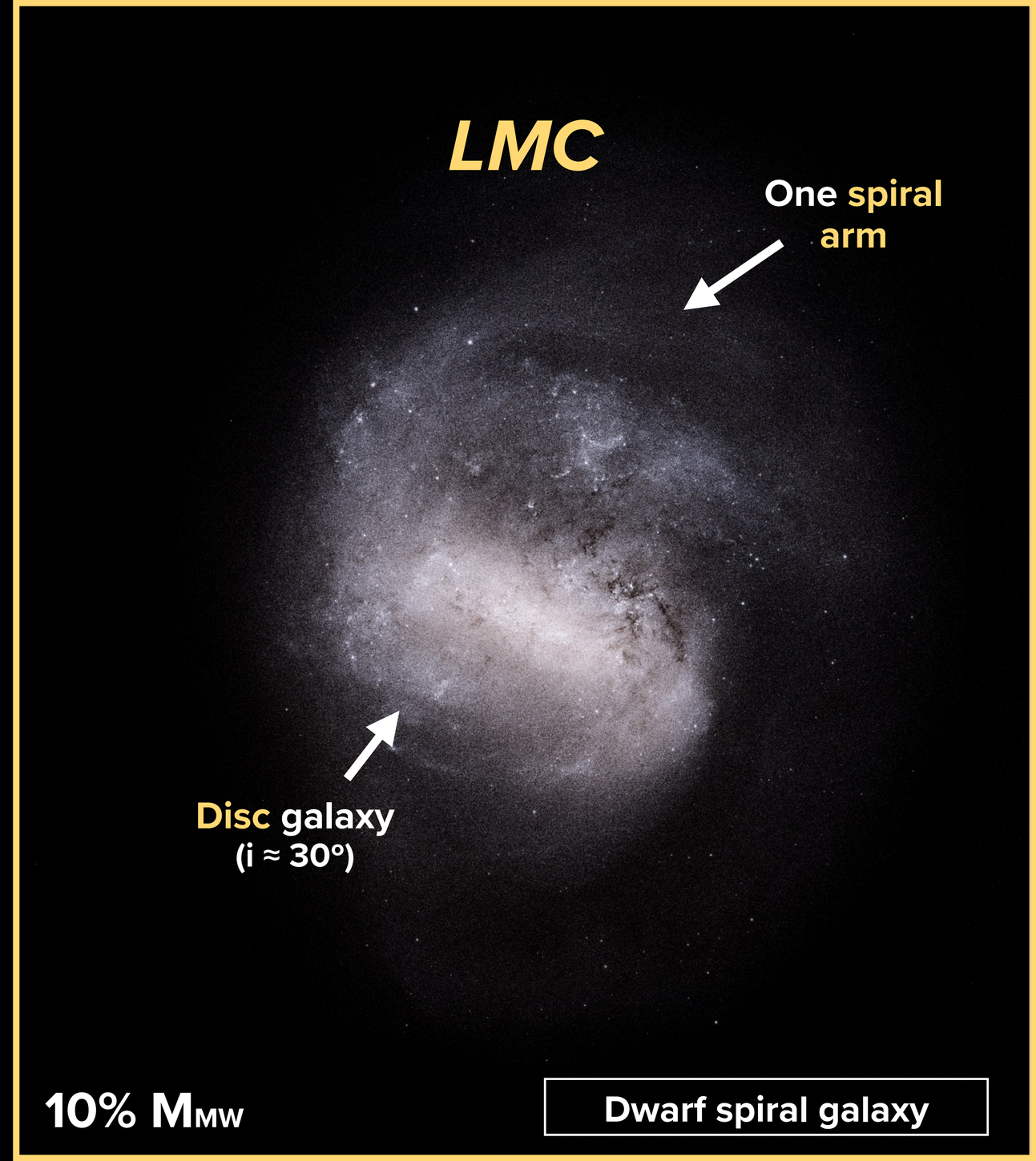


10% M_{MW}

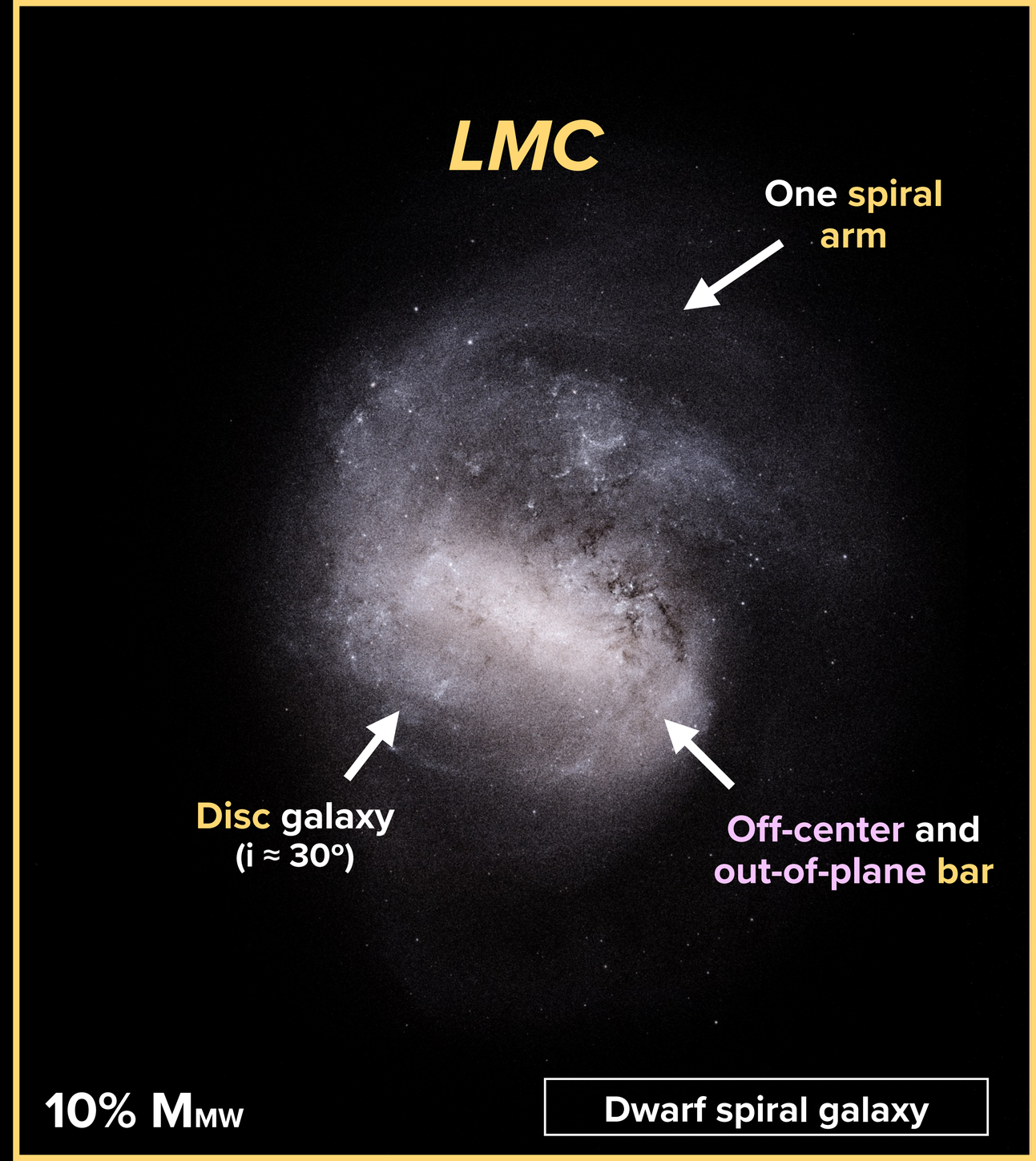
Dwarf spiral galaxy

SMC


LMC
SMC
Disc galaxy
(i ≈ 30°)
10% MMW
Dwarf spiral galaxy

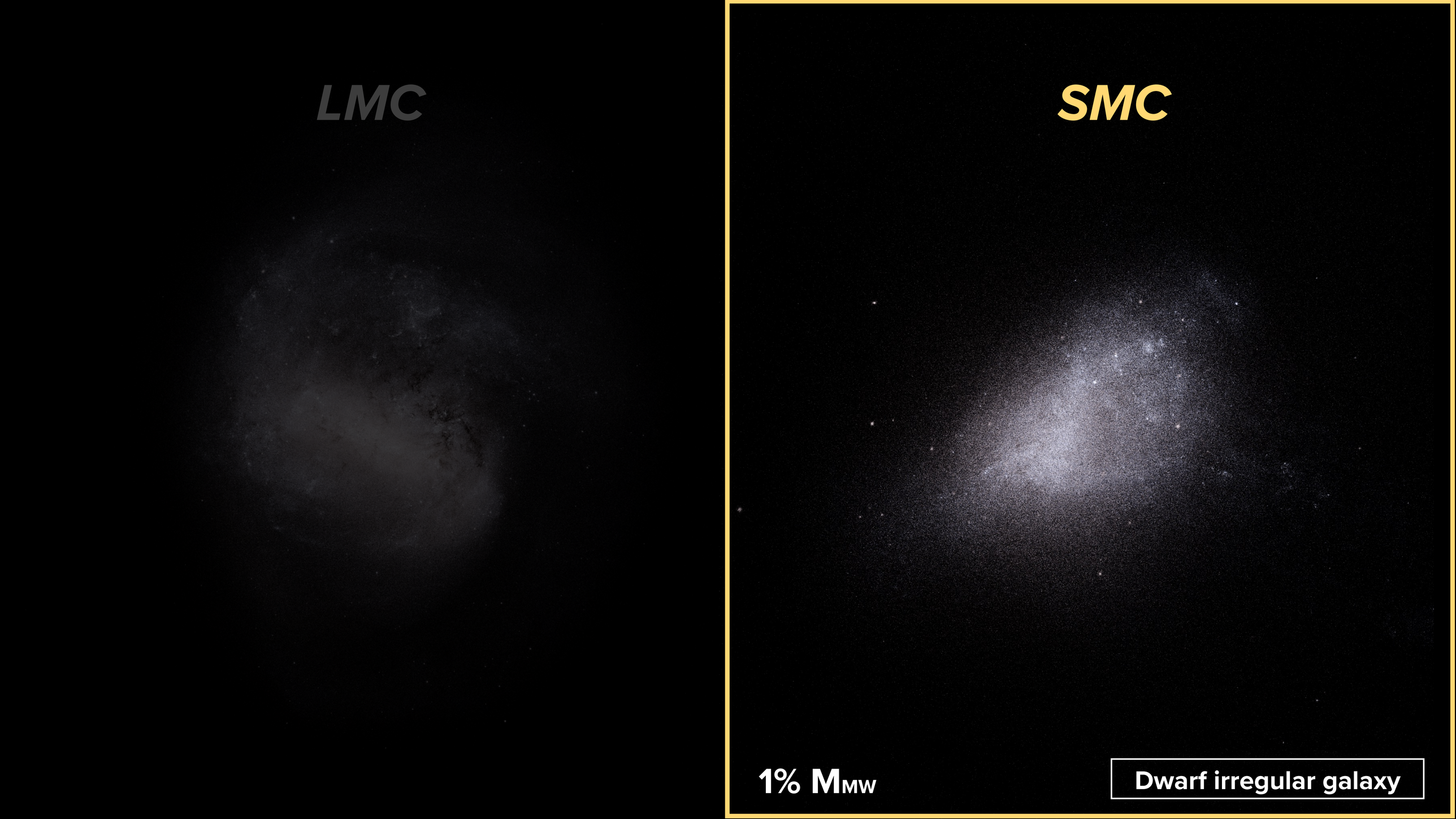

LMC
One spiral arm
Disc galaxy
(i ≈ 30°)
10% MMW
Dwarf spiral galaxy

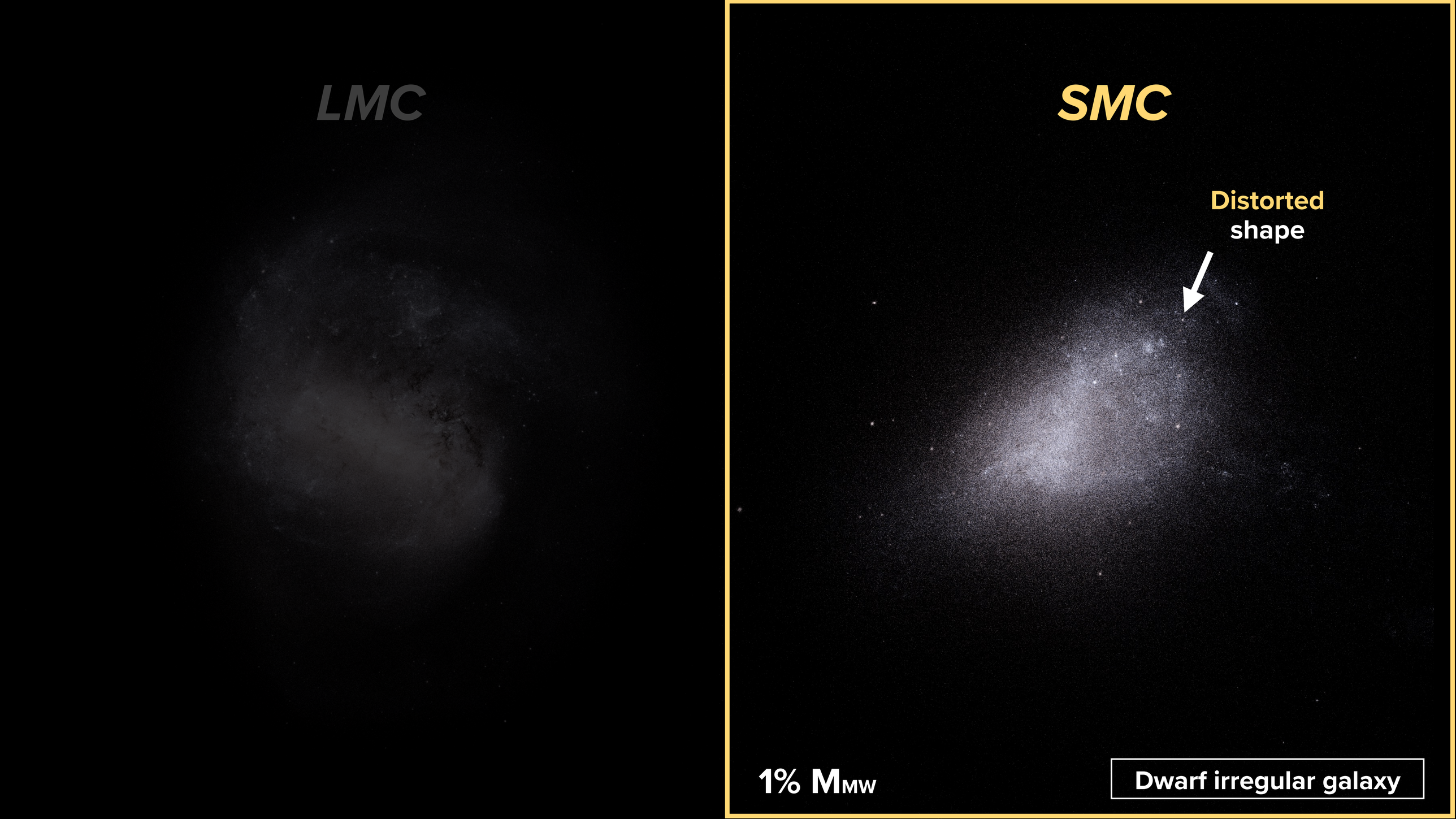

SMC

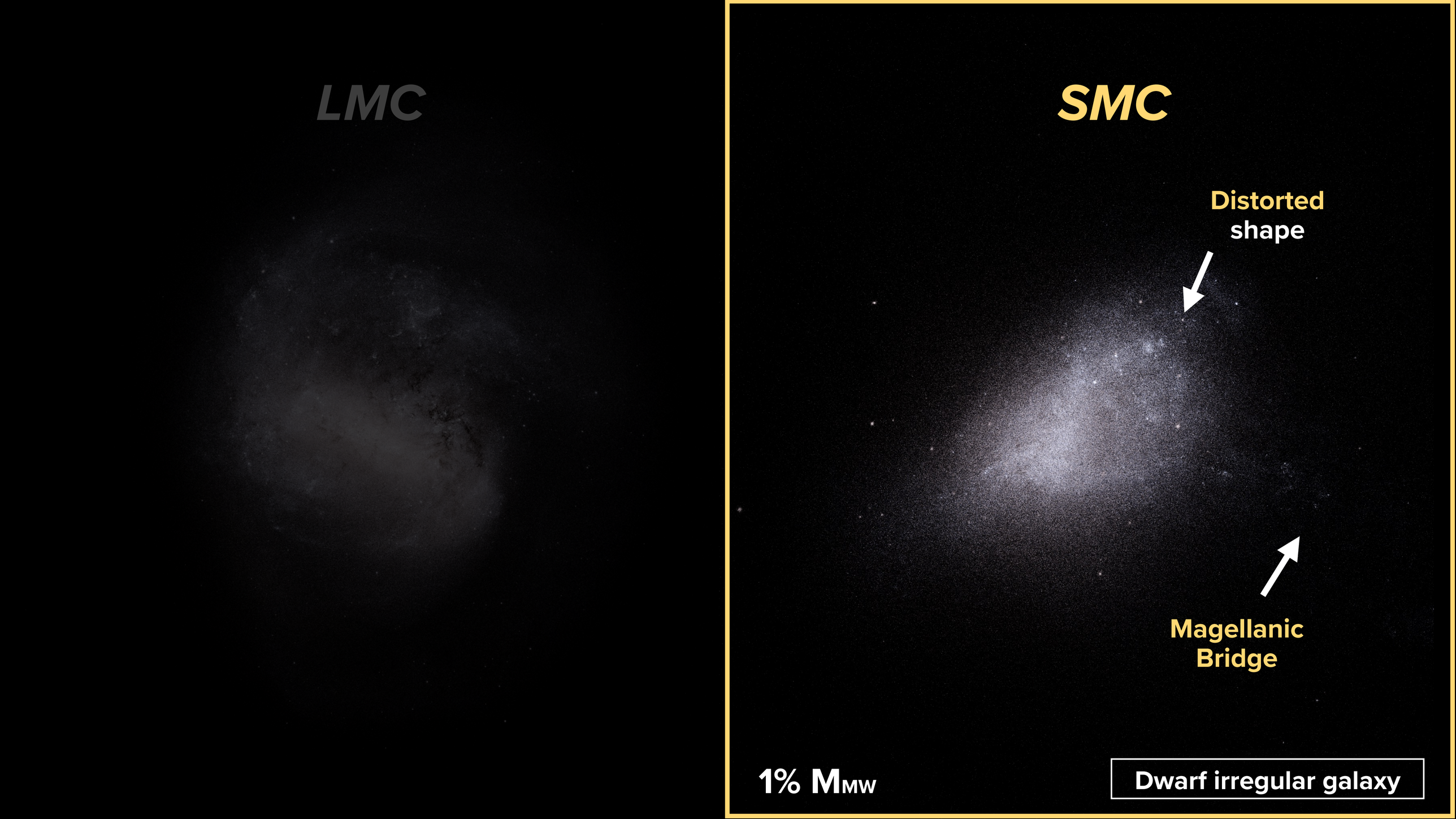

LMC
One spiral arm
Disc galaxy
(i ≈ 30°)
Off-center and out-of-plane bar
10% MMW
Dwarf spiral galaxy

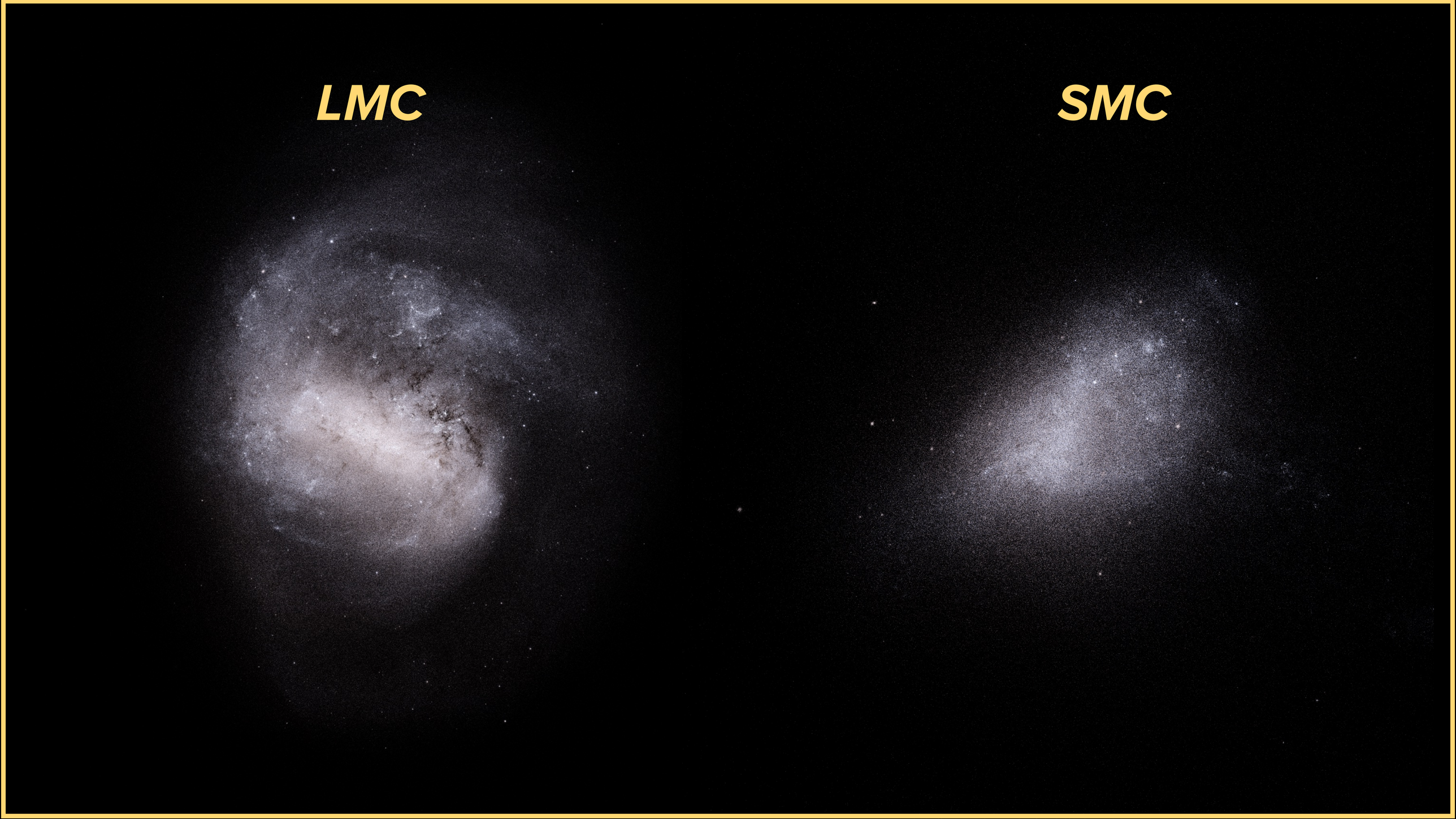

SMC


LMC
SMC


LMC
SMC
1% MMW
Dwarf irregular galaxy


LMC
SMC
Distorted shape
1% MMW
Dwarf irregular galaxy

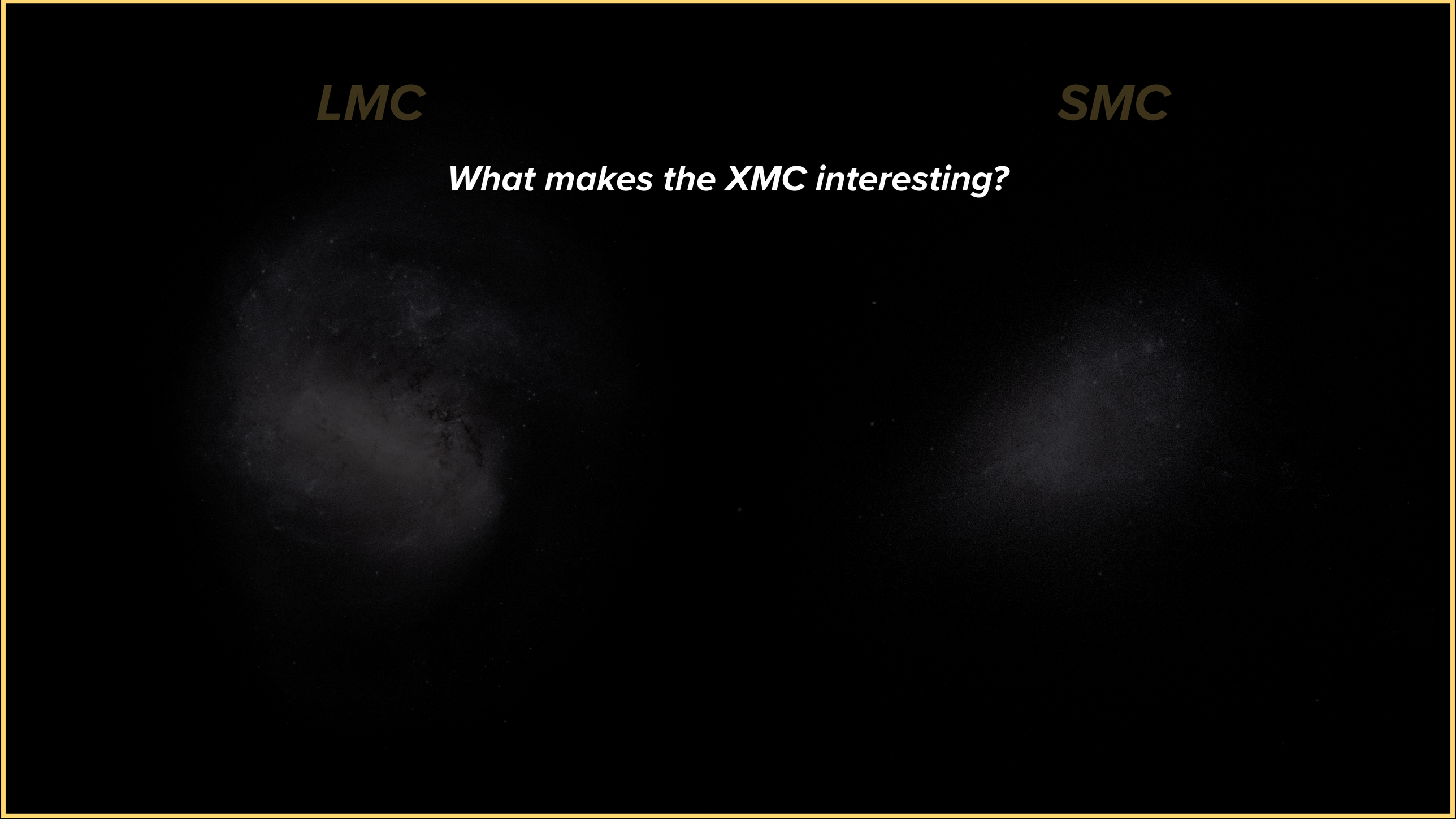

LMC
SMC
Distorted shape
Magellanic Bridge
1% MMW
Dwarf irregular galaxy

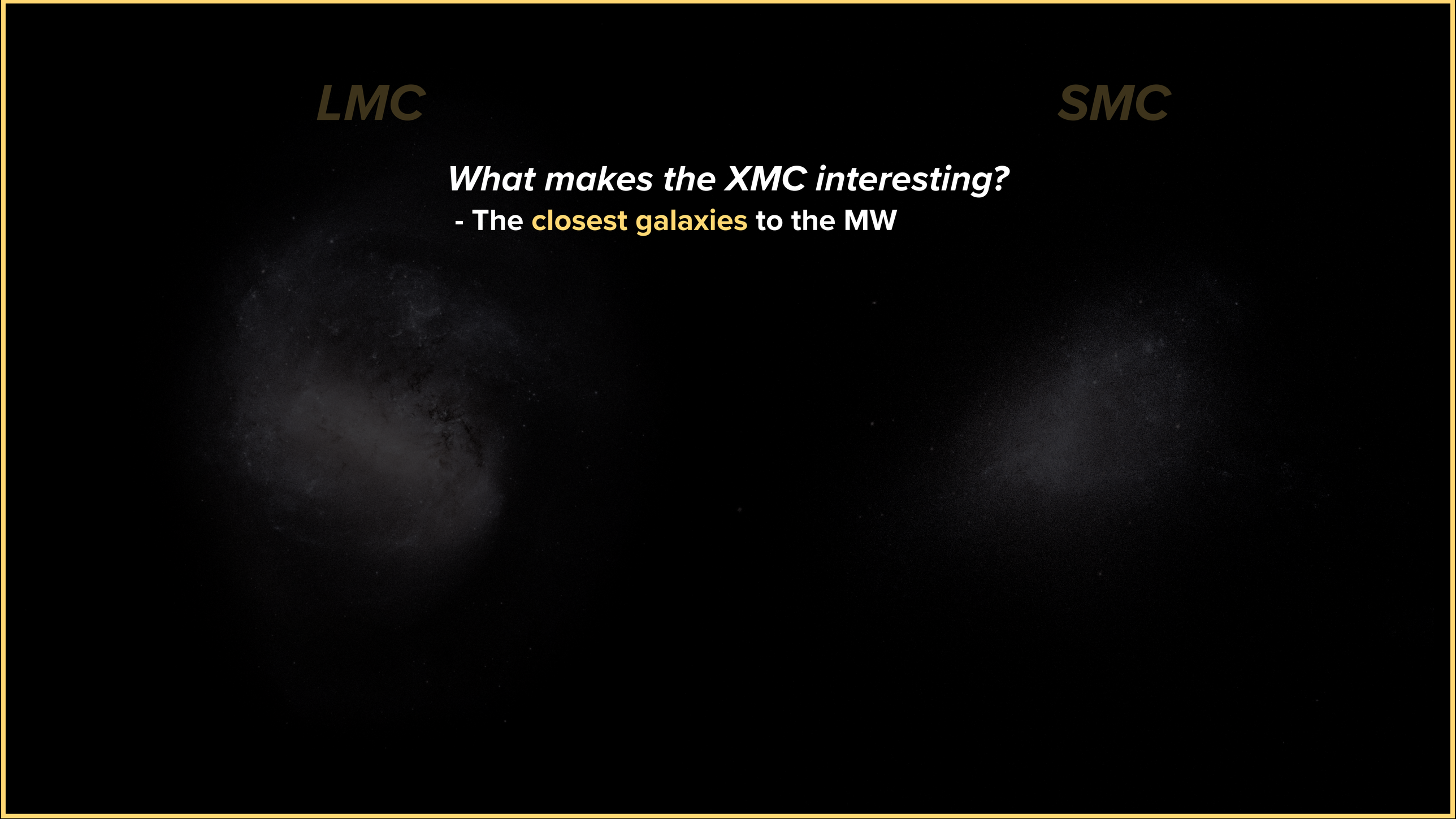

LMC
SMC

LMC

SMC

What makes the XMC interesting?





What makes the XMC interesting?

- The closest galaxies to the MW

LMC

SMC

What makes the XMC interesting?

- The closest galaxies to the MW
  (astrometric information for million stars)

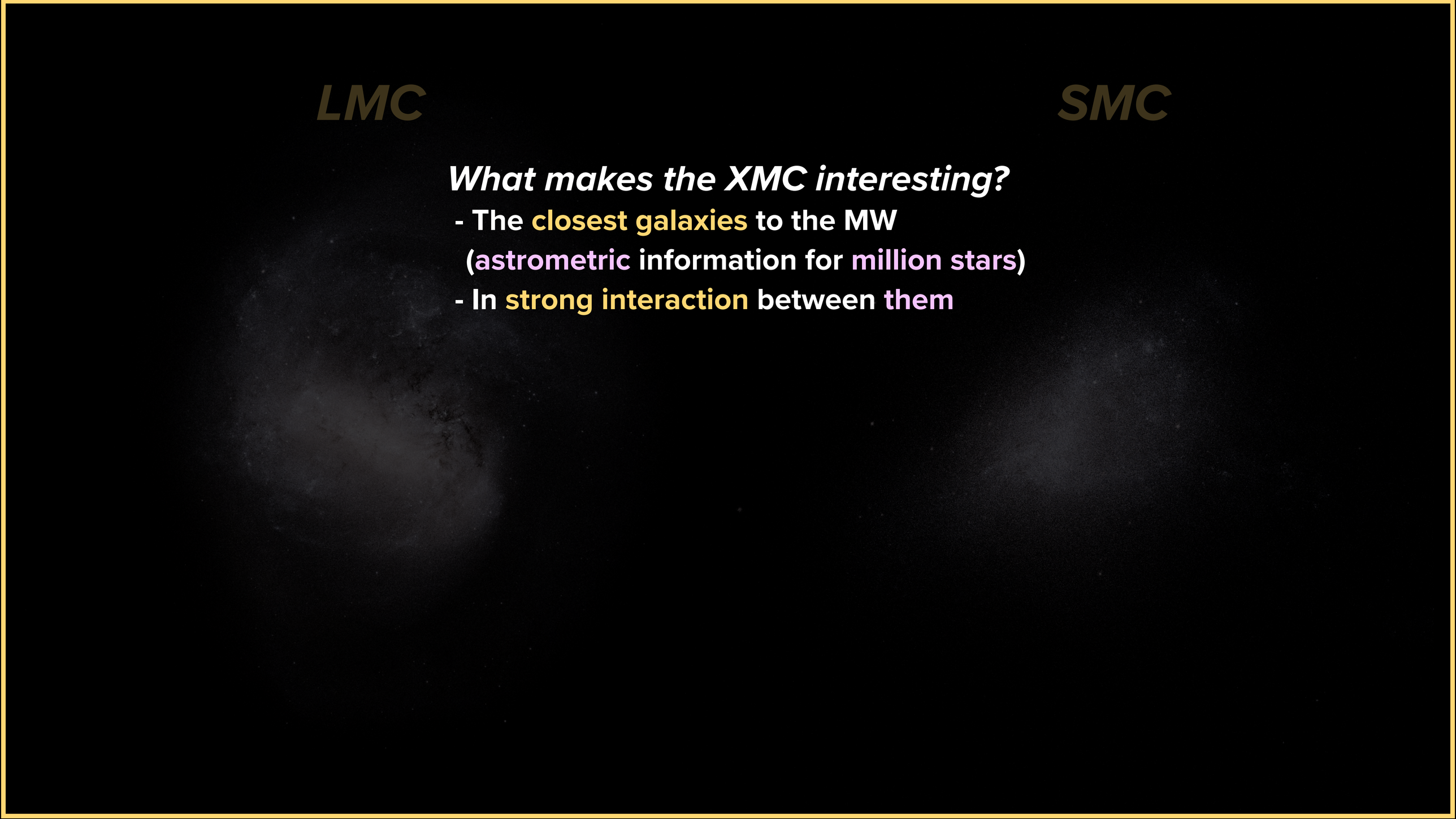
LMC

SMC

What makes the XMC interesting?

- The closest galaxies to the MW
(astrometric information for million stars)

Across the
whole disc!



What makes the XMC interesting?

- The closest galaxies to the MW
  (astrometric information for million stars)
- In strong interaction between them

LMC

SMC

What makes the XMC interesting?

- The closest galaxies to the MW
  (astrometric information for million stars)
- In strong interaction between them

The XMC are the perfect laboratory for testing methodologies and models designed for the study of external and interacting galaxies

Outline

- Motivation
- Context and Goals
- Results
- Conclusions

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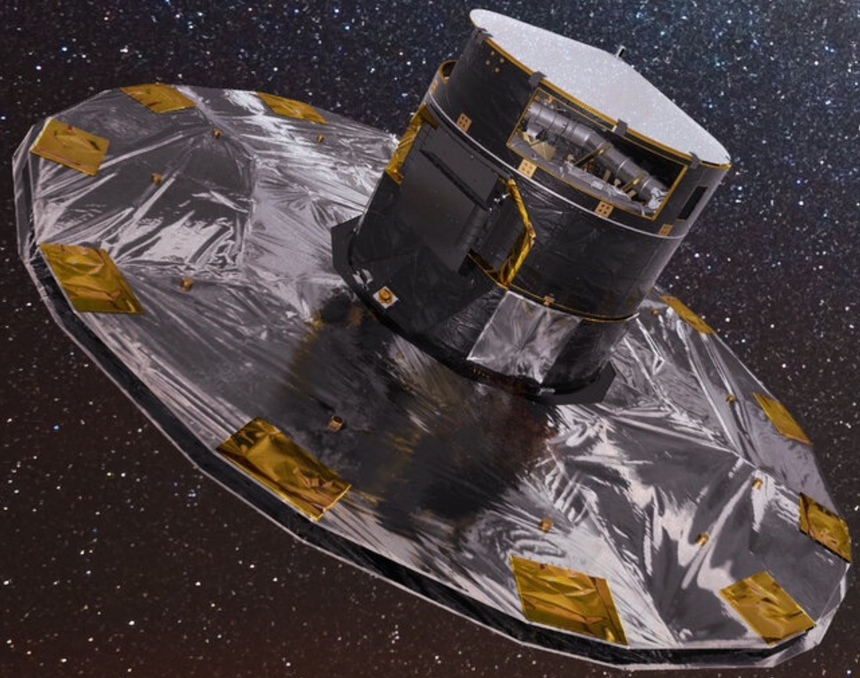
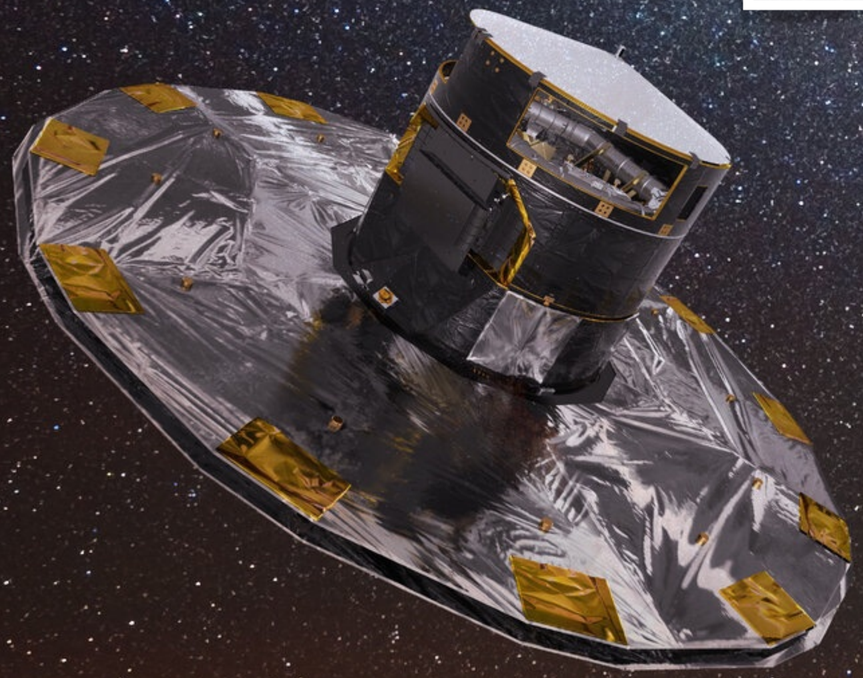
Gaia (ESA)



Gaia (ESA)

Gaia (2013 - 2025) provides **astrometric, photometric (**and **spectroscopic) data** for almost **2.000M stars.**



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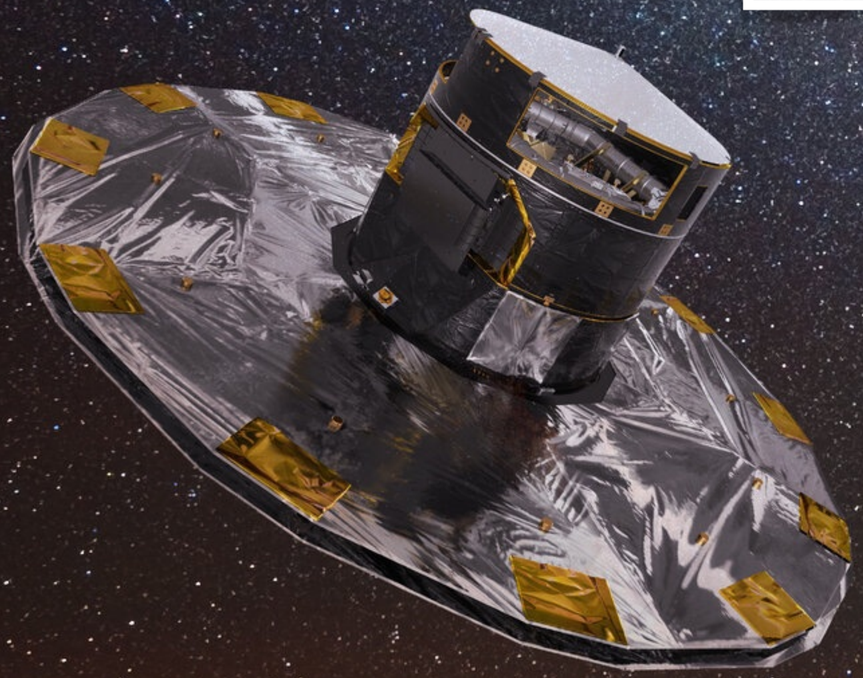
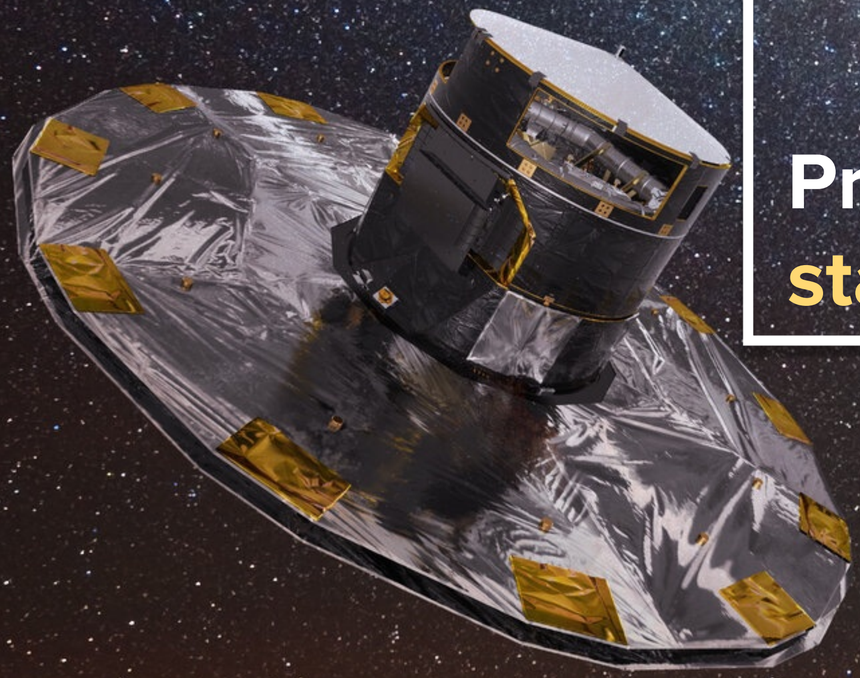


Gaia (ESA)



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Predecessor: Hipparcos (1989) with **100k stars**.

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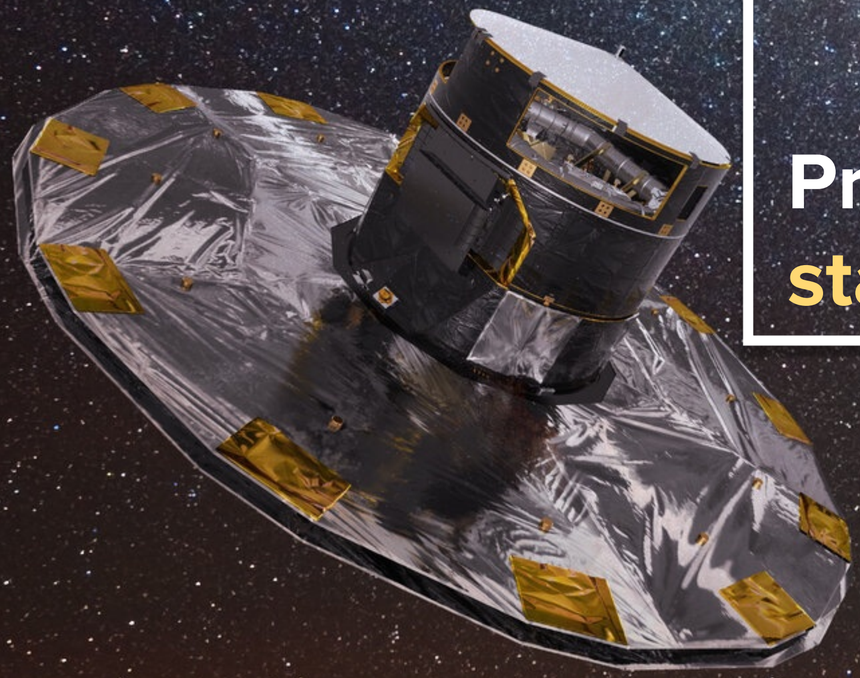

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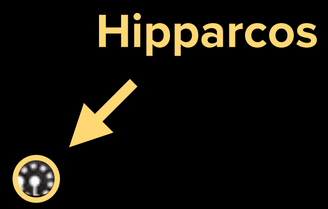
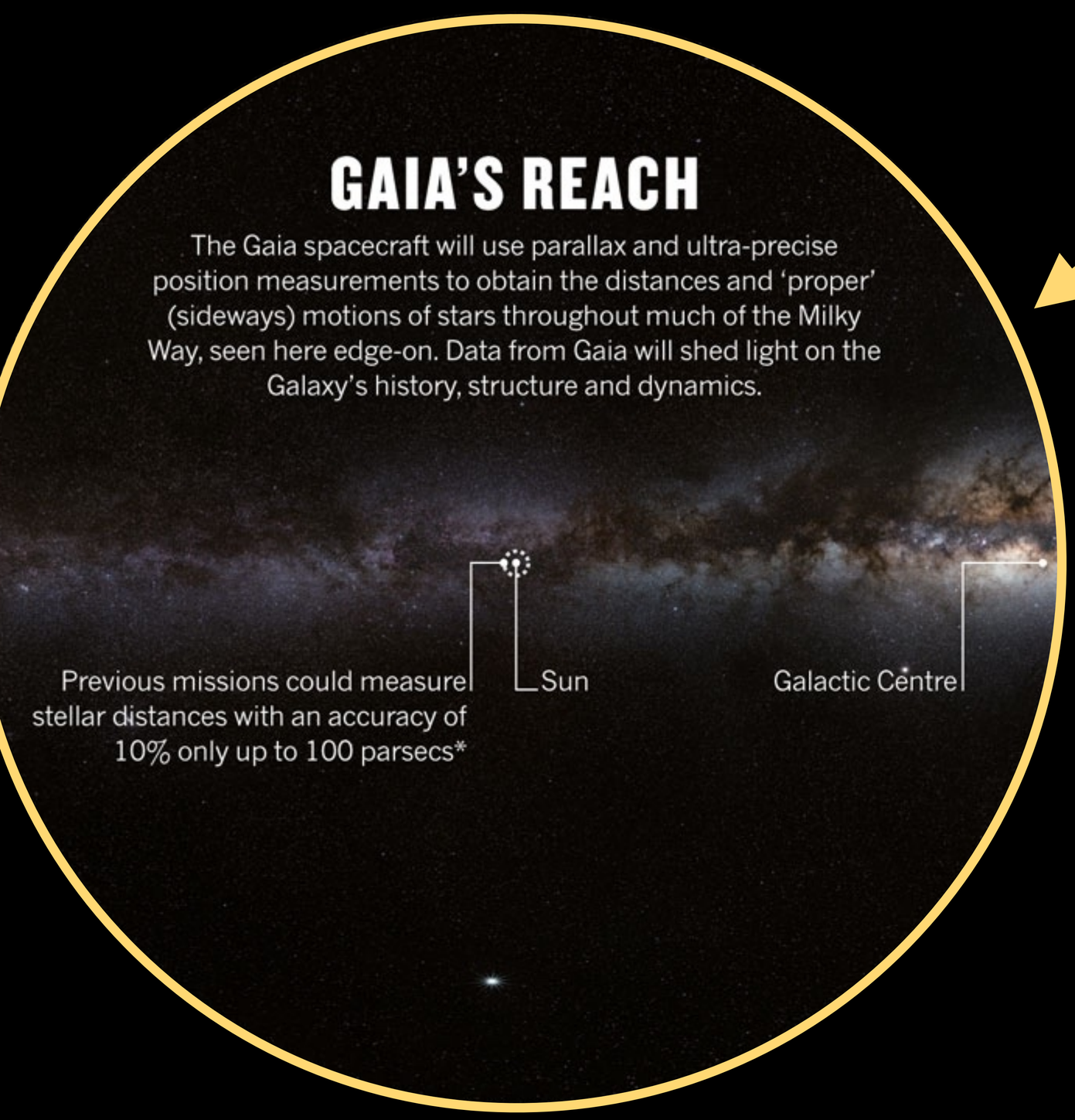
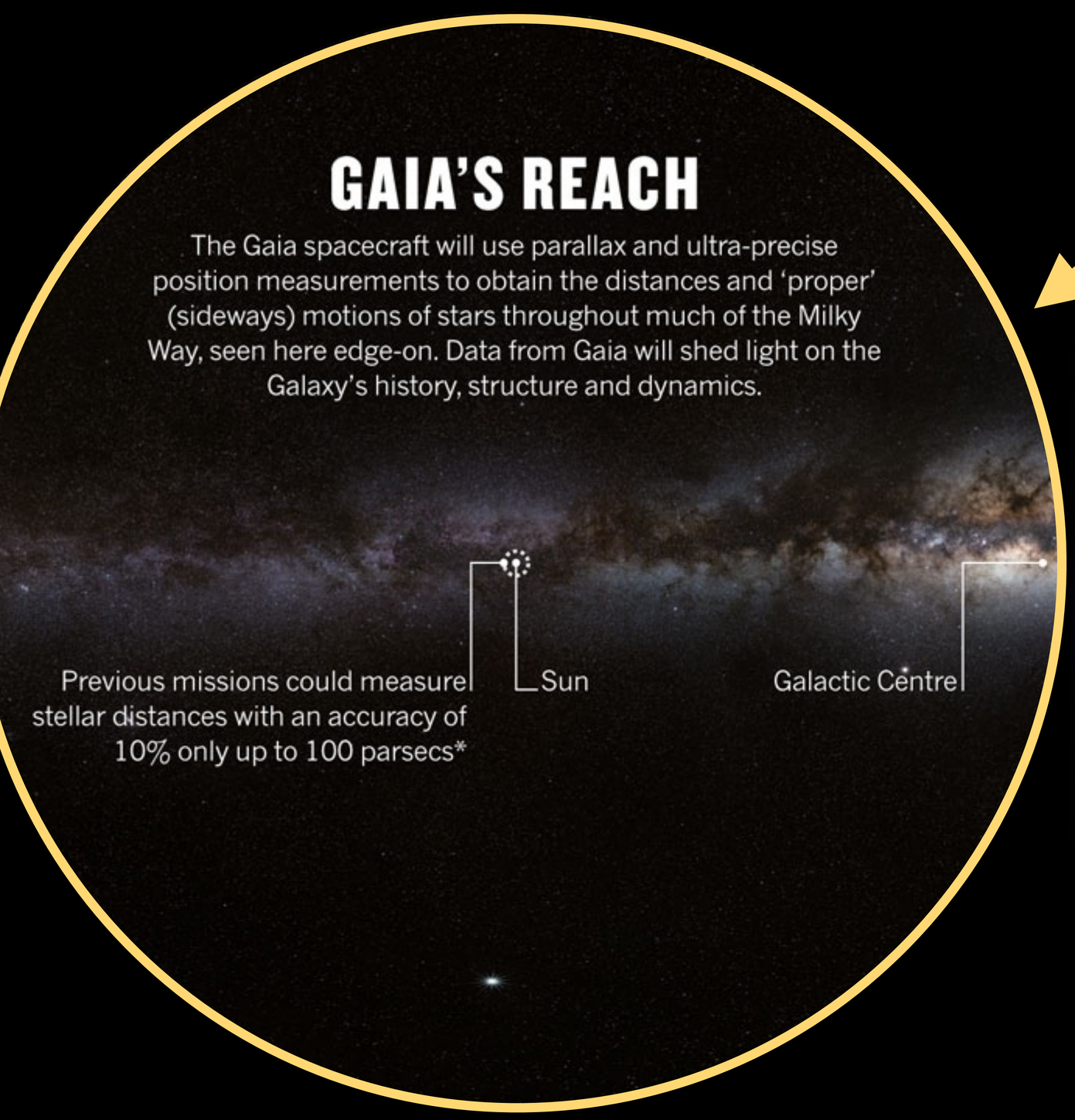
Predecessor: Hipparcos (1989) with **100k stars**. **Ratio of 1 : 20.000 (!!!)**

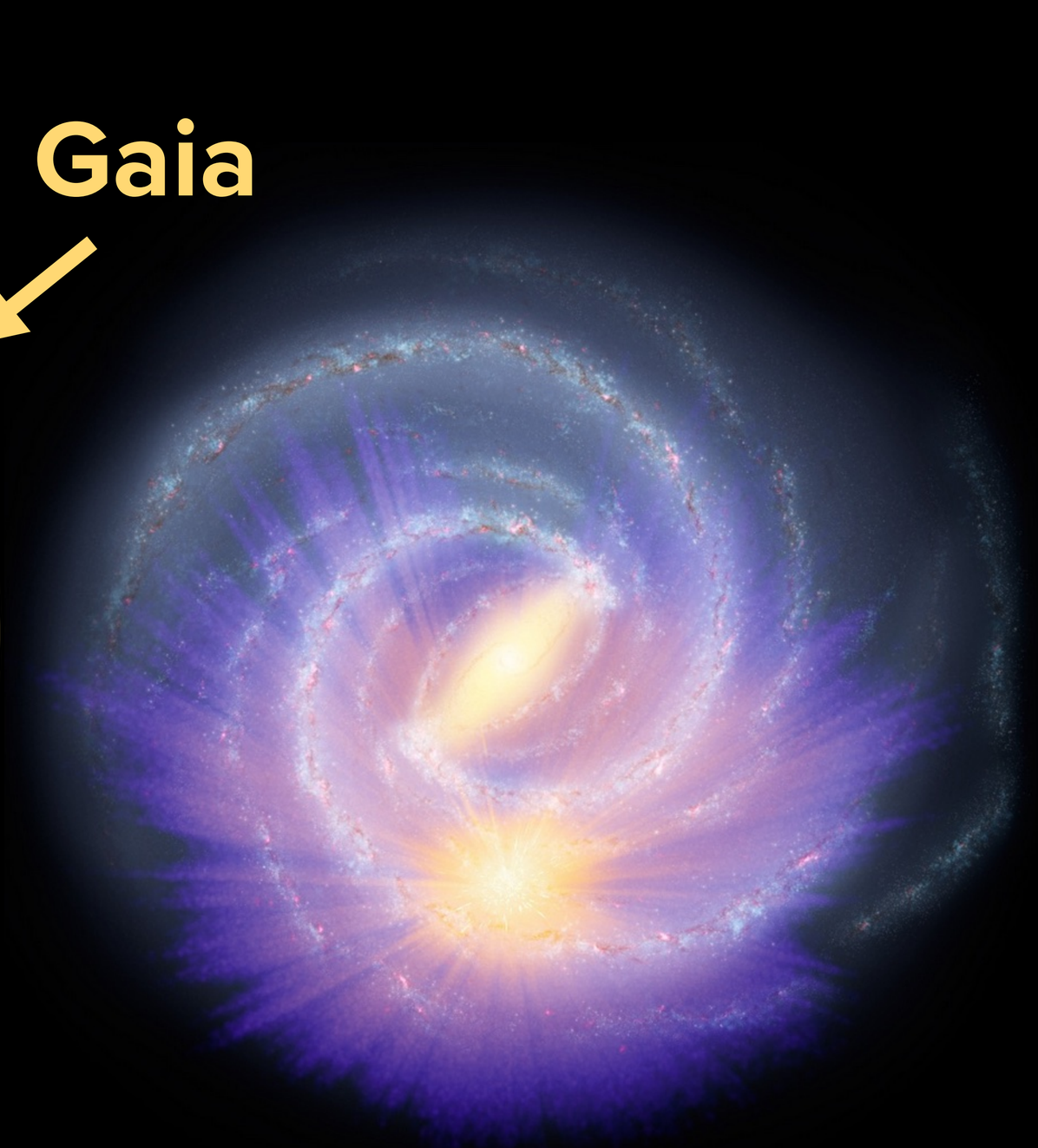

Hipparcos

Gaia

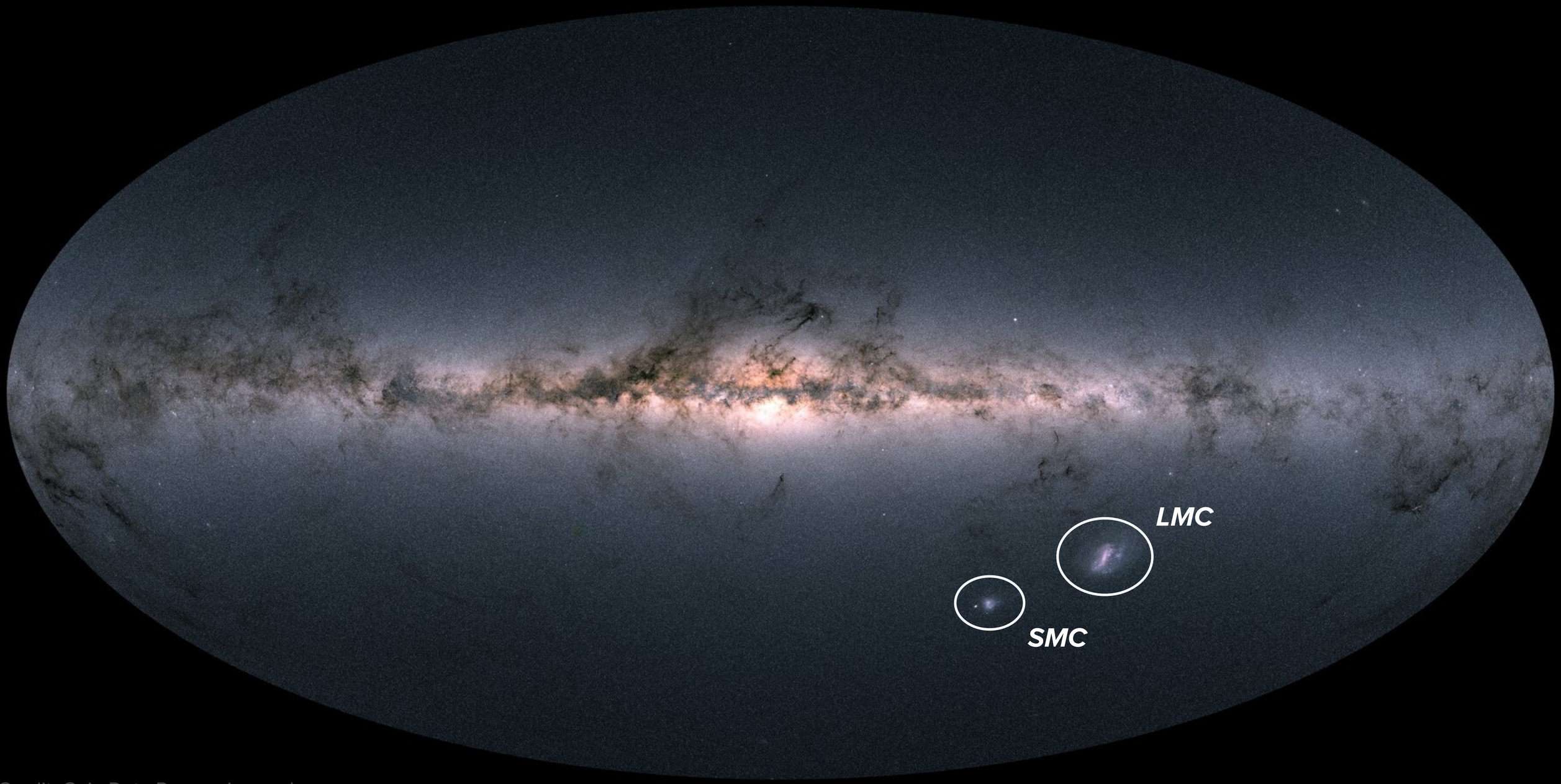

GAIA'S REACH
The Gaia spacecraft will use parallax and ultra-precise position measurements to obtain the distances and 'proper' (sideways) motions of stars throughout much of the Milky Way, seen here edge-on. Data from Gaia will shed light on the Galaxy's history, structure and dynamics.
Previous missions could measure stellar distances with an accuracy of 10% only up to 100 parsecs*
Sun
Galactic Centre

Gaia





Credit: Data: ESA/Gaia/DPAC, A. Khalatyan (AIP) & StarHorse team;
Galaxy map: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)



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  (Ó. Jiménez-Arranz et al. 2023a)
  - **Neural network classifier for the selection of clean LMC samples**

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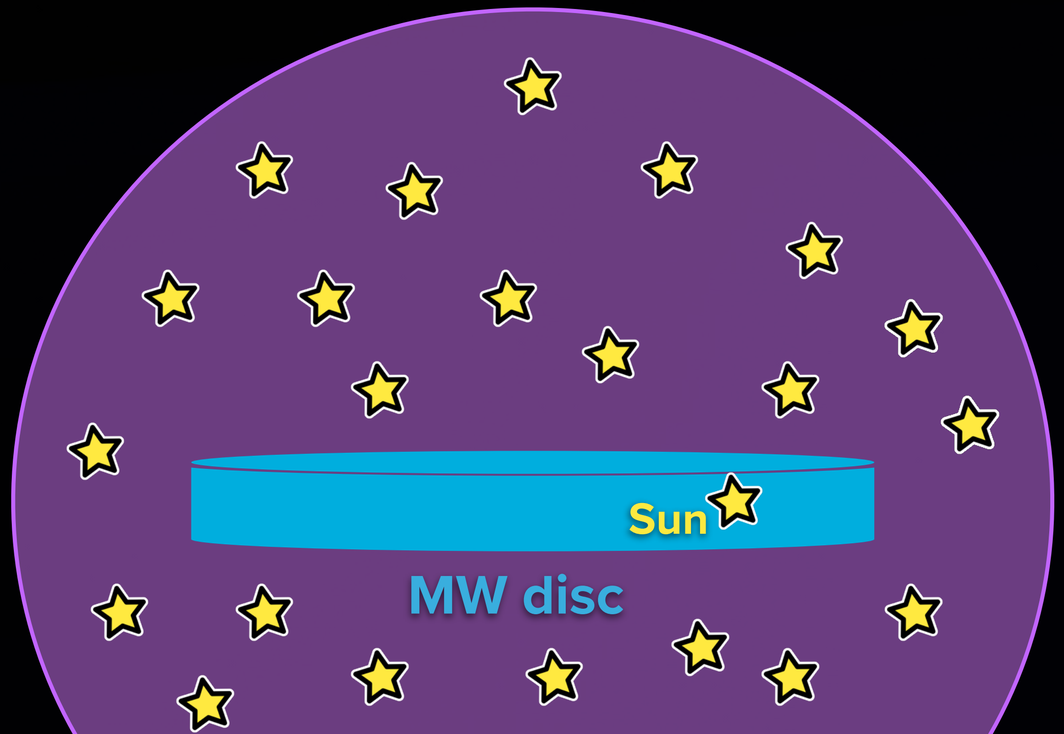

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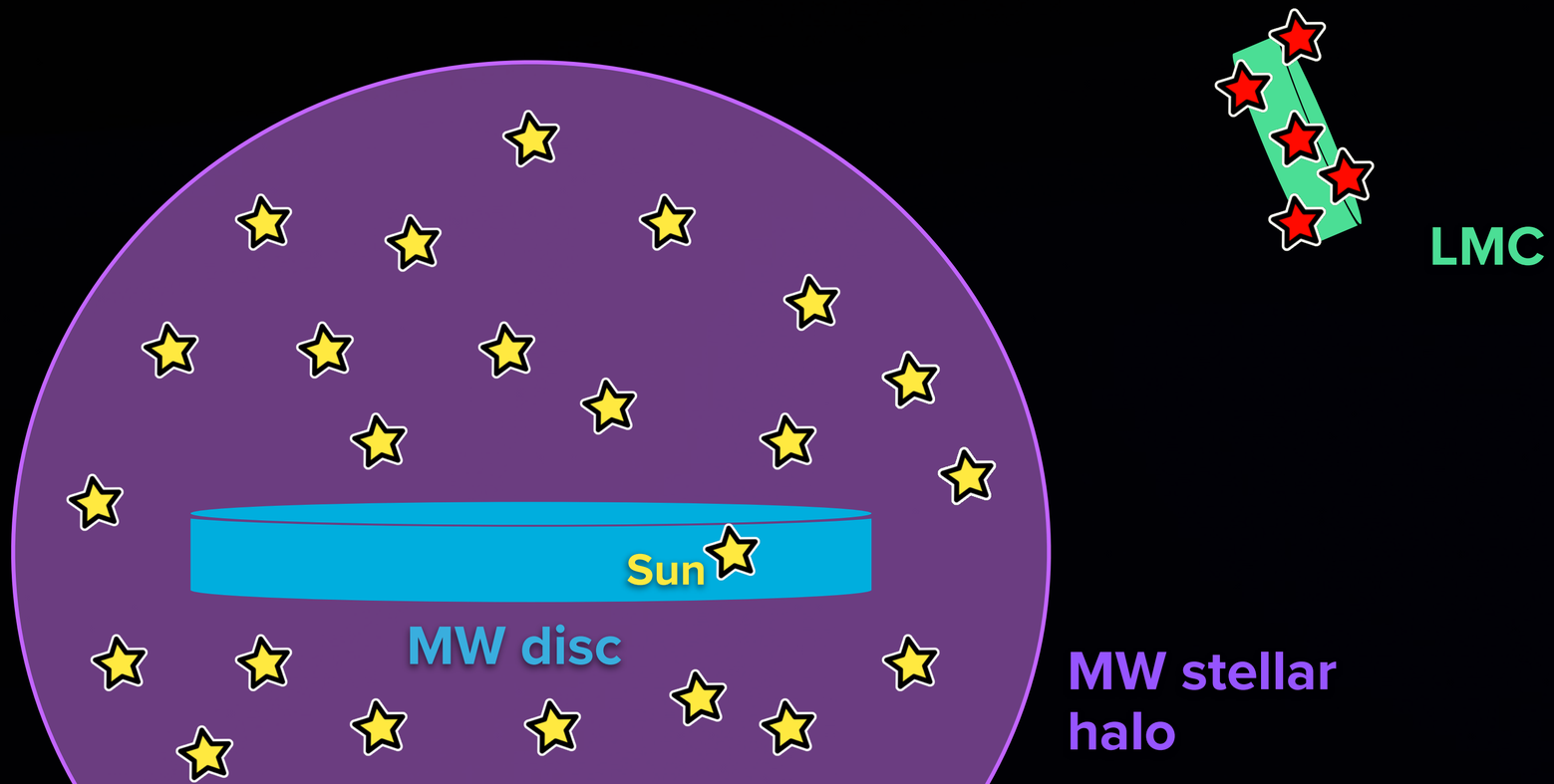

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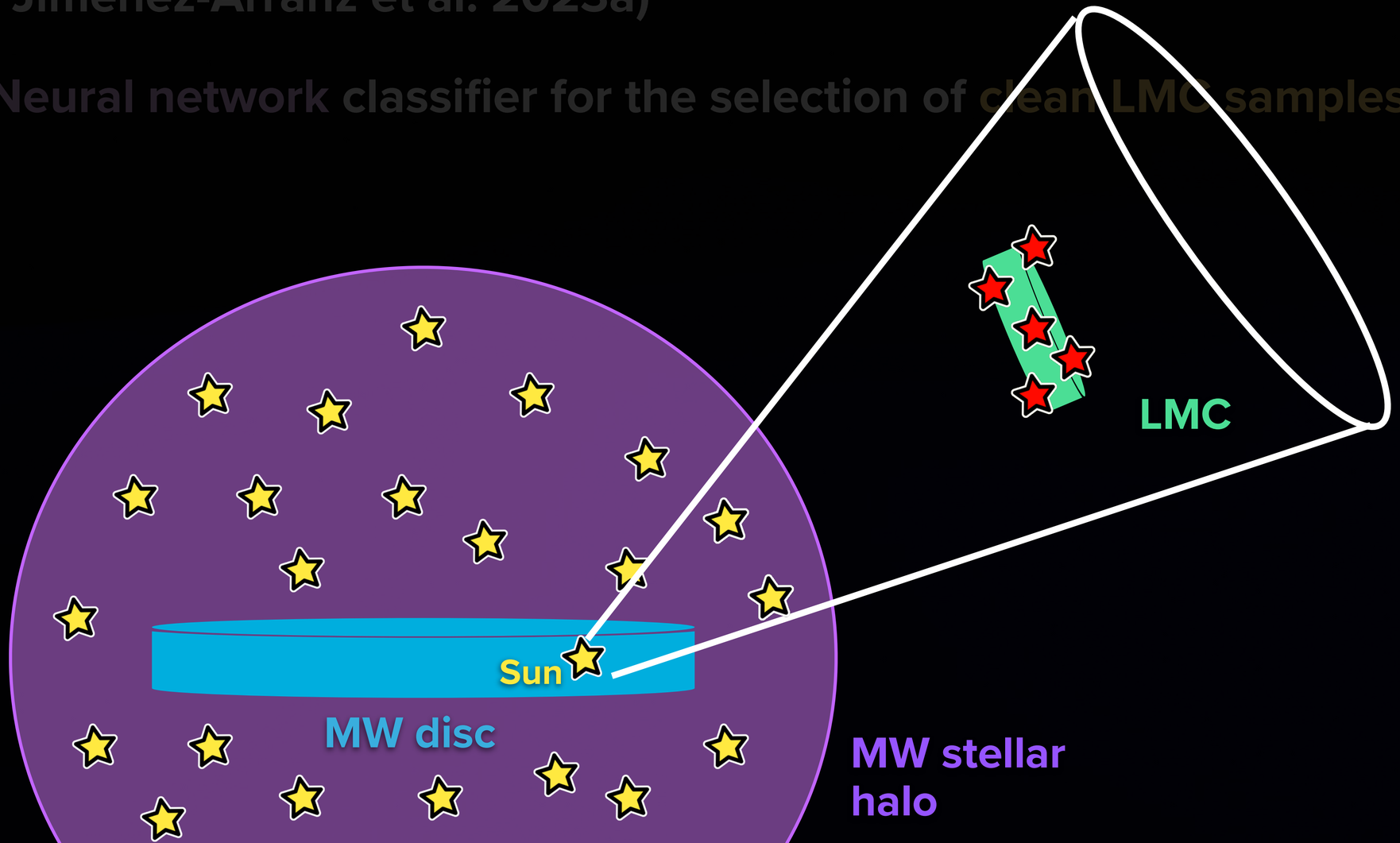

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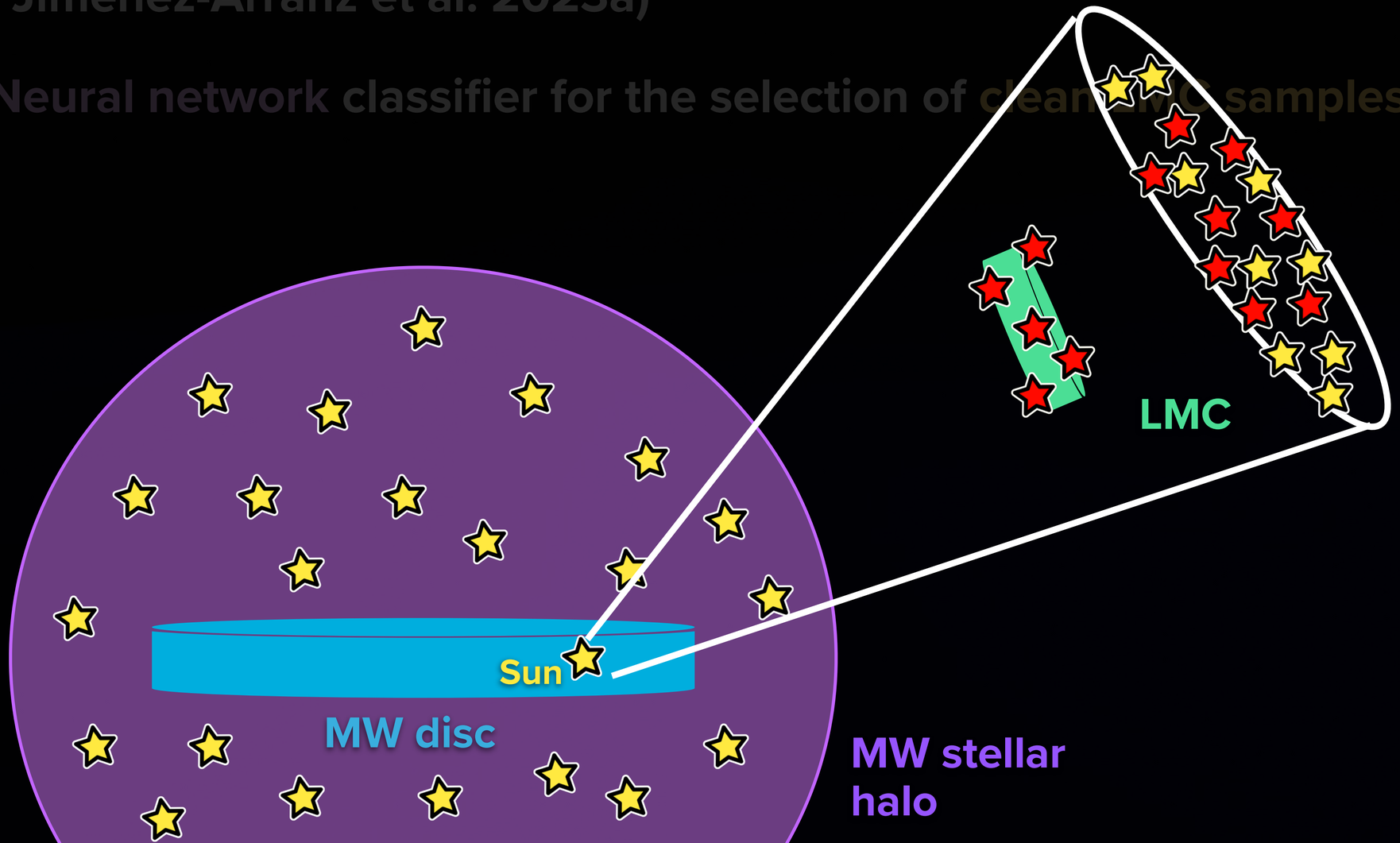

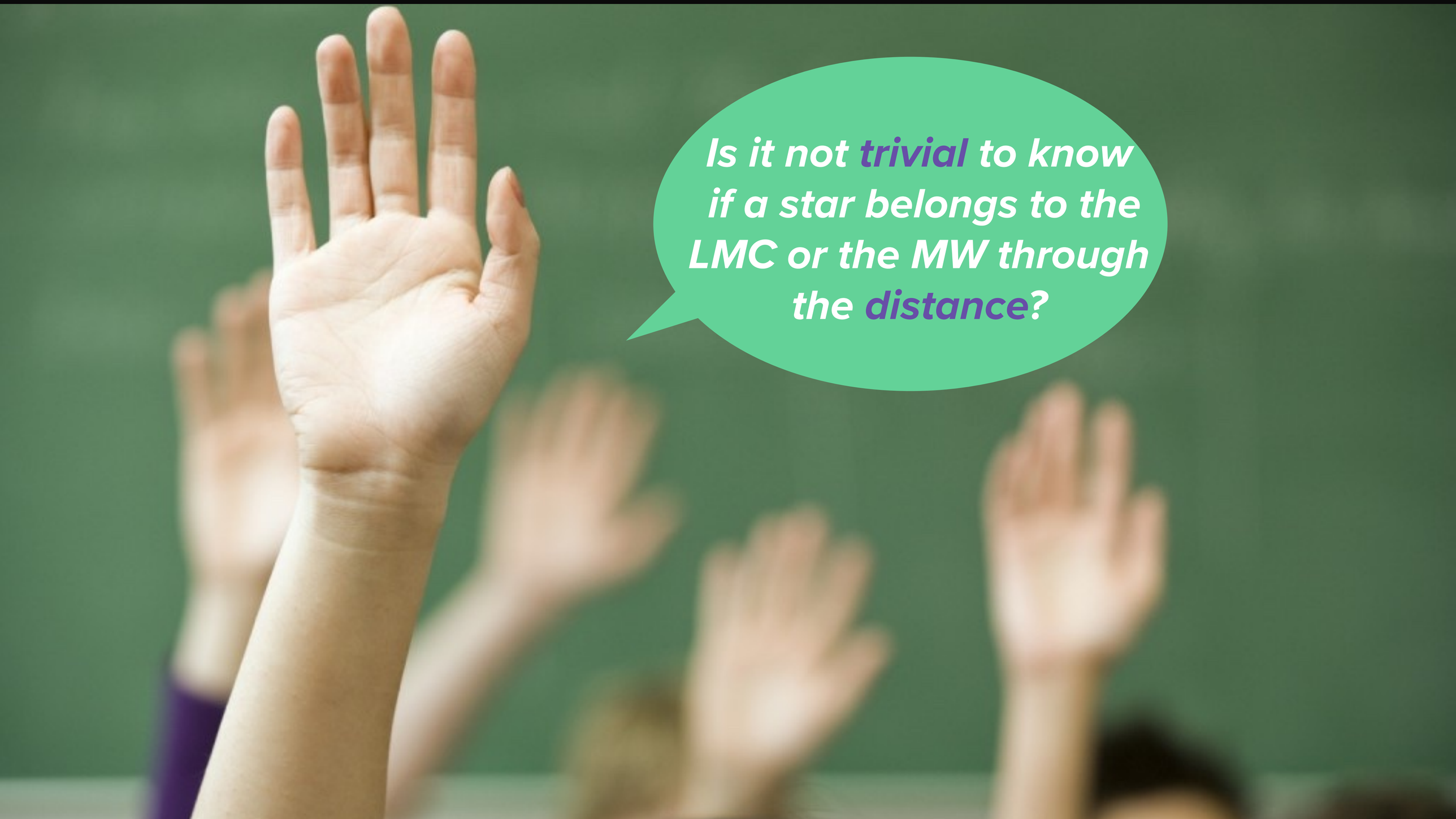
Is it not trivial to know if a star belongs to the LMC or the MW through the distance?


Is it not trivial to know if a star belongs to the LMC or the MW through the ~~distance~~?
parallax
Not a good proxy at XMC's distances

LMC/MW classifier

- Neural Network
  - Input: Gaia astrometry and photometry (11 variables)
  - Output: Probability P of being a LMC star

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We propose three different samples:

- **LMC Complete sample** [P > 0.01]
- **LMC Optimal sample** [P > 0.52]
- **LMC Truncated-Optimal sample** [P >0.52 + G < 19.5]

LMC/MW classifier

- Neural Network
  - Input: Gaia astrometry and
  - Output: Probability P … bei

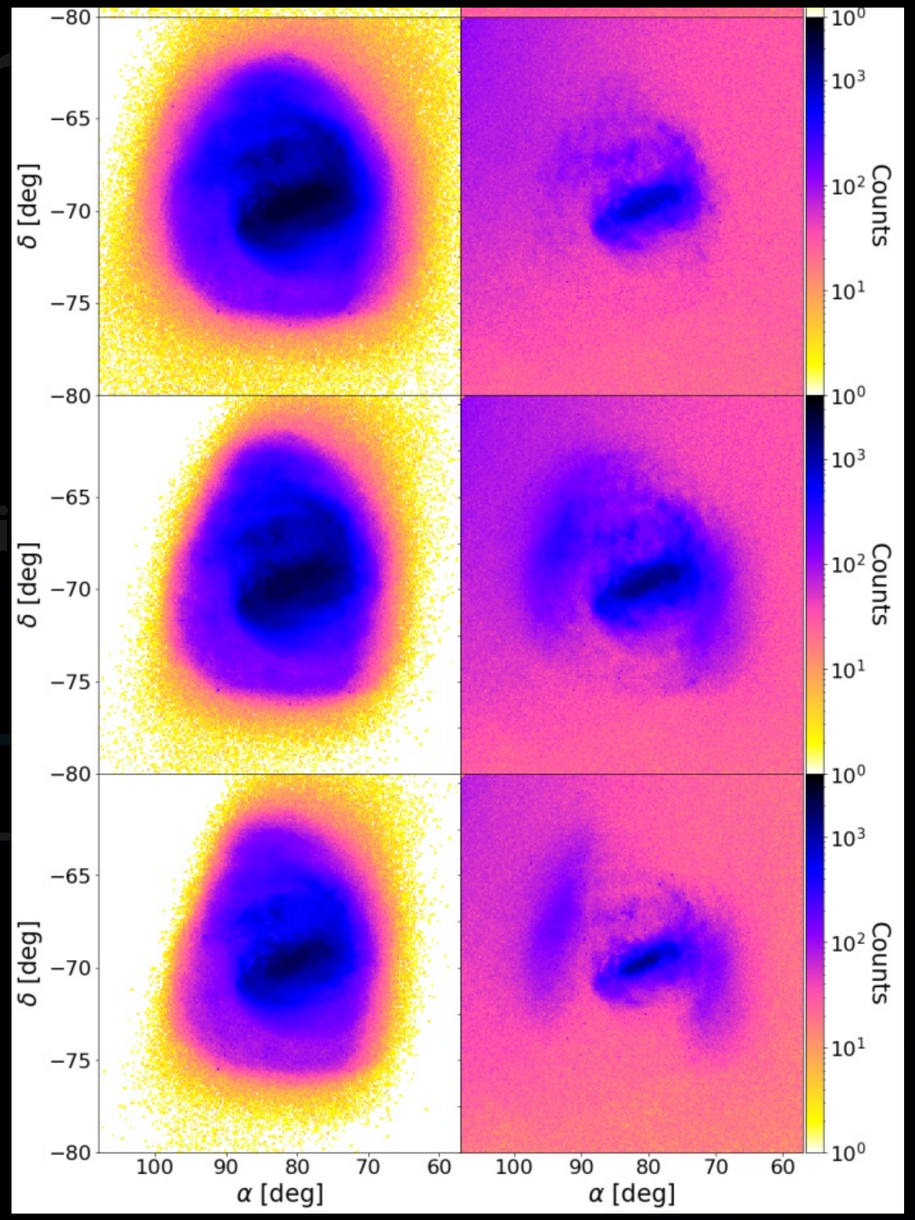
MW

0

LMC Complete sample

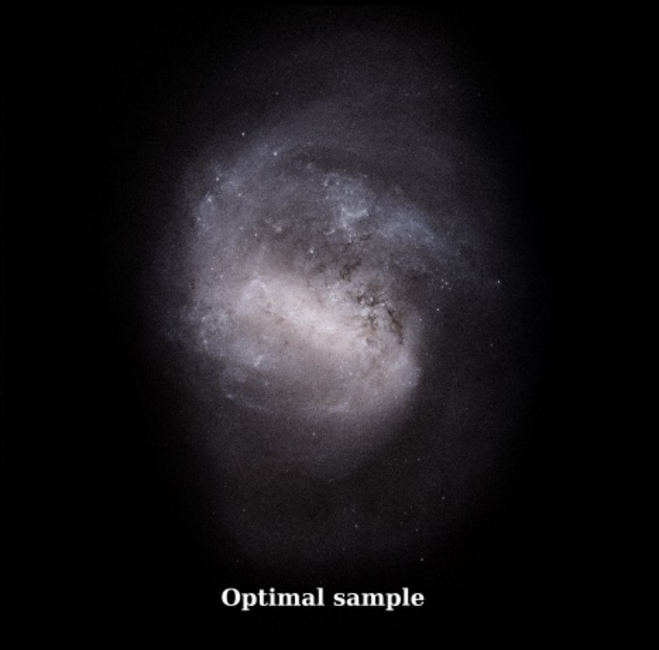
LMC Optimal sample

LMC Truncated-Optimal sample

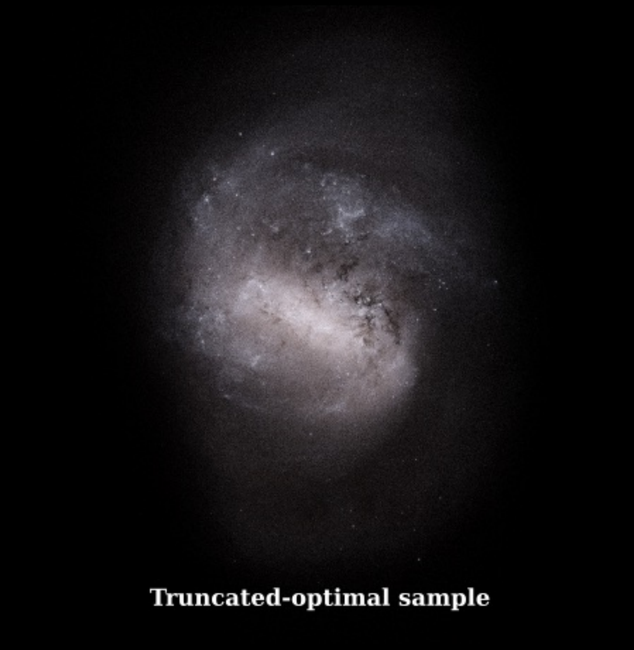


18M stars
(LMC+MW)

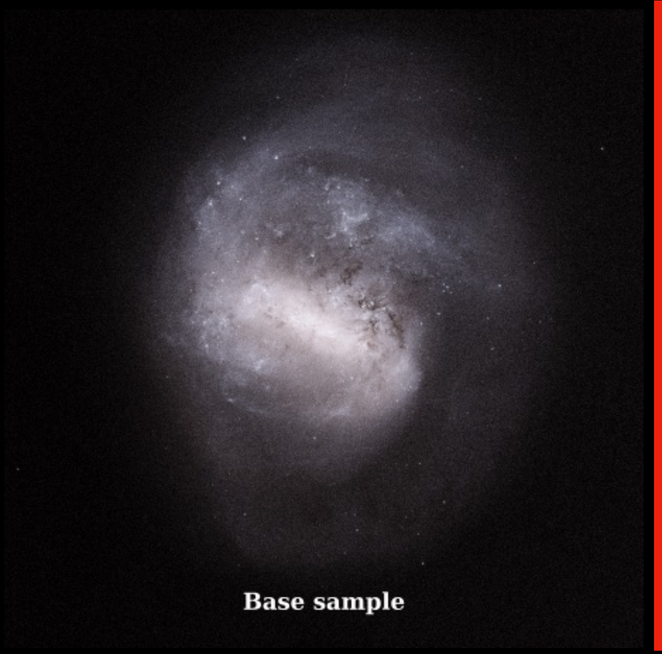
12M stars



10M stars



6M stars



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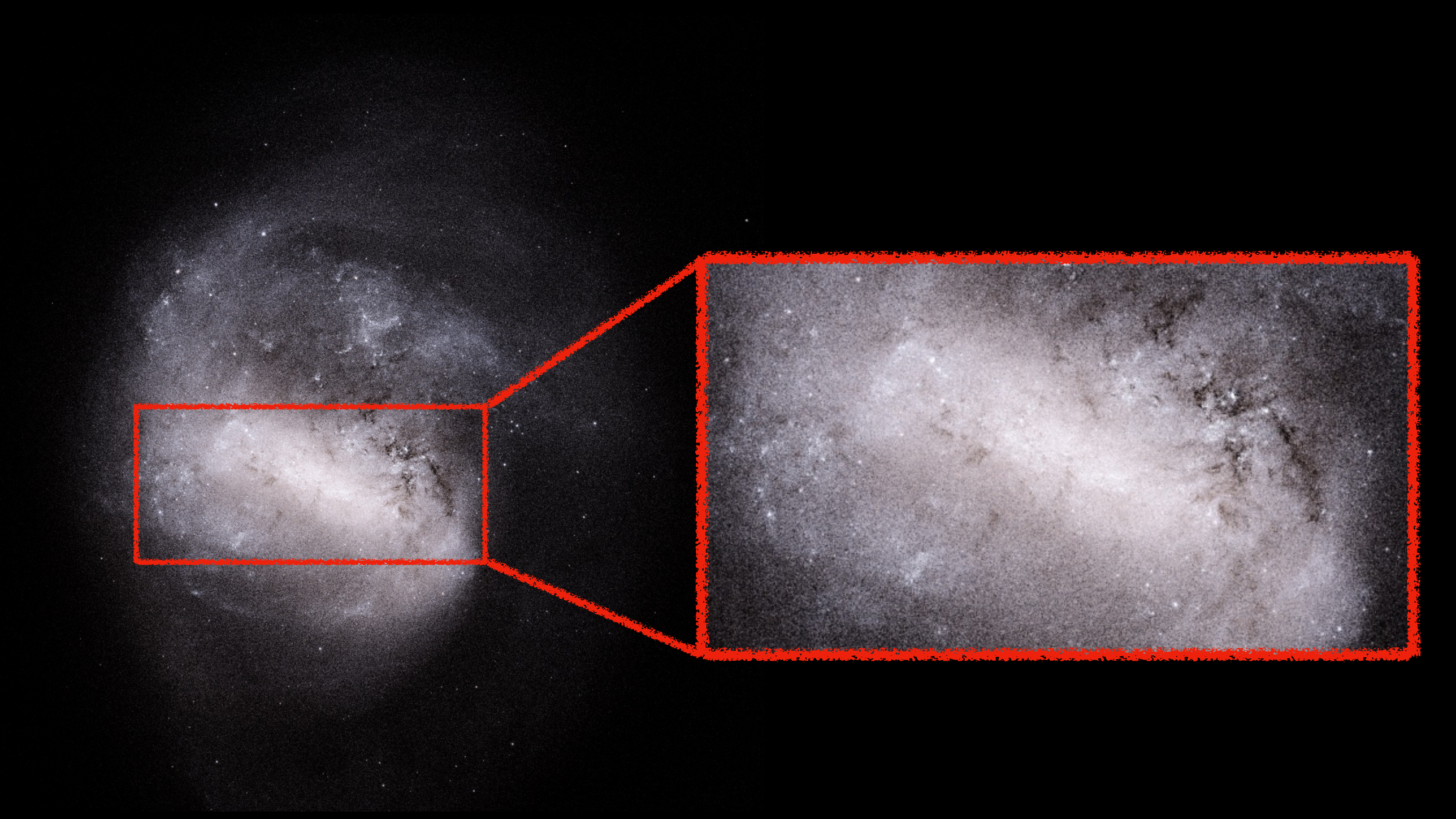

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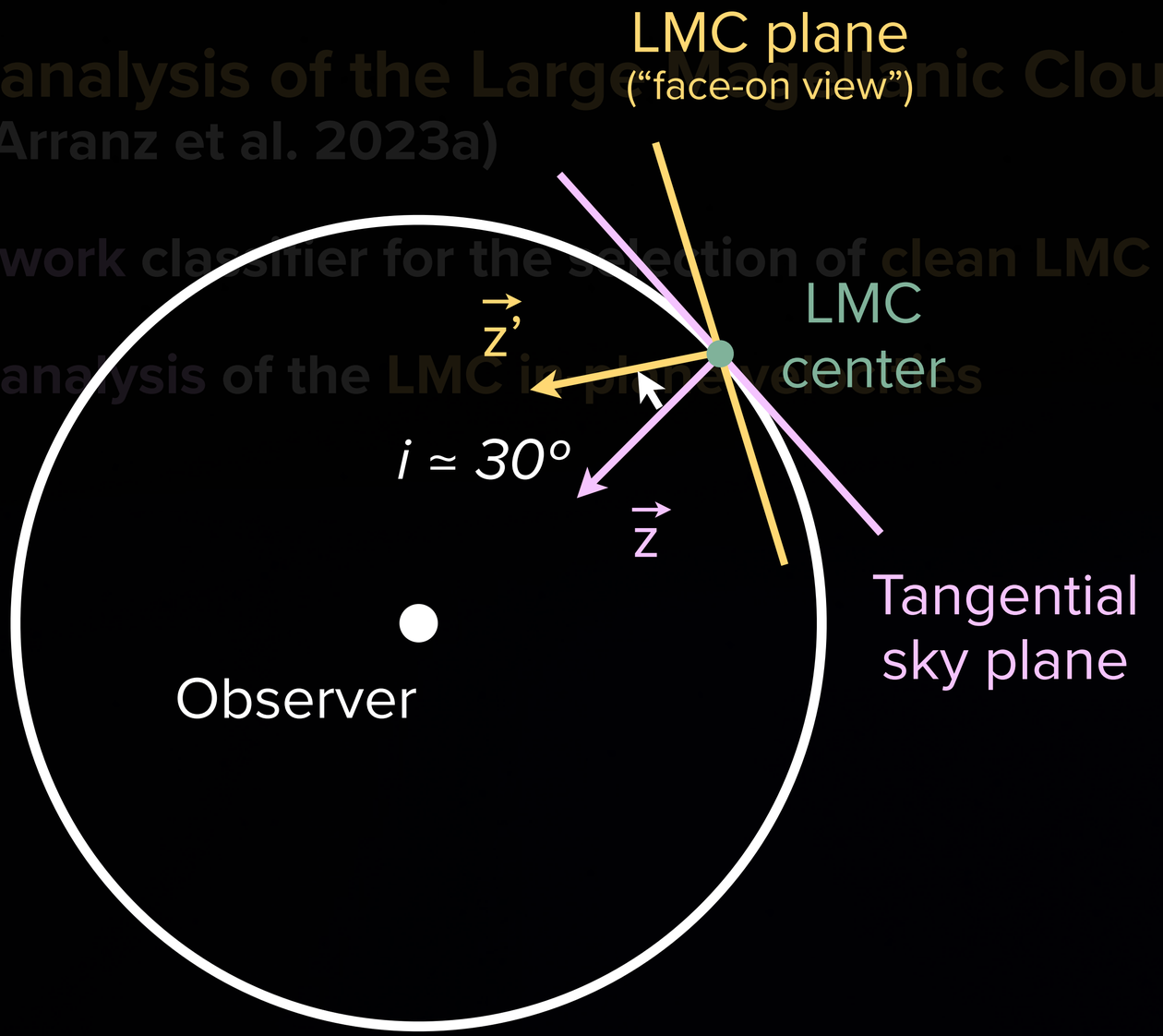
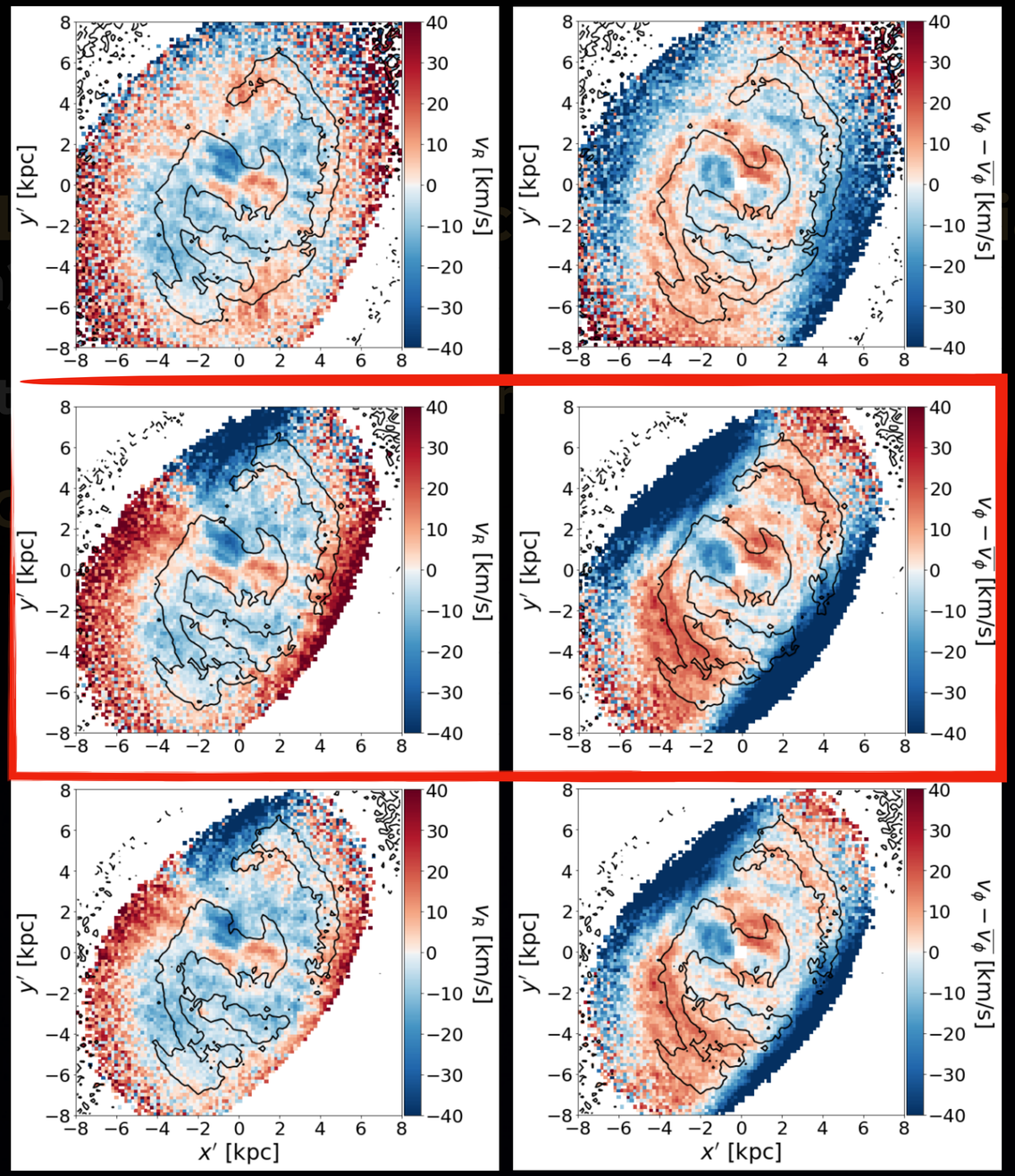


- Kinematic analysis of the L… …a DR3
  (Ó. Jiménez-Arranz et al. 2023a…
  - Neural network classifier for t…
  - Kinematic analysis of the LMC…

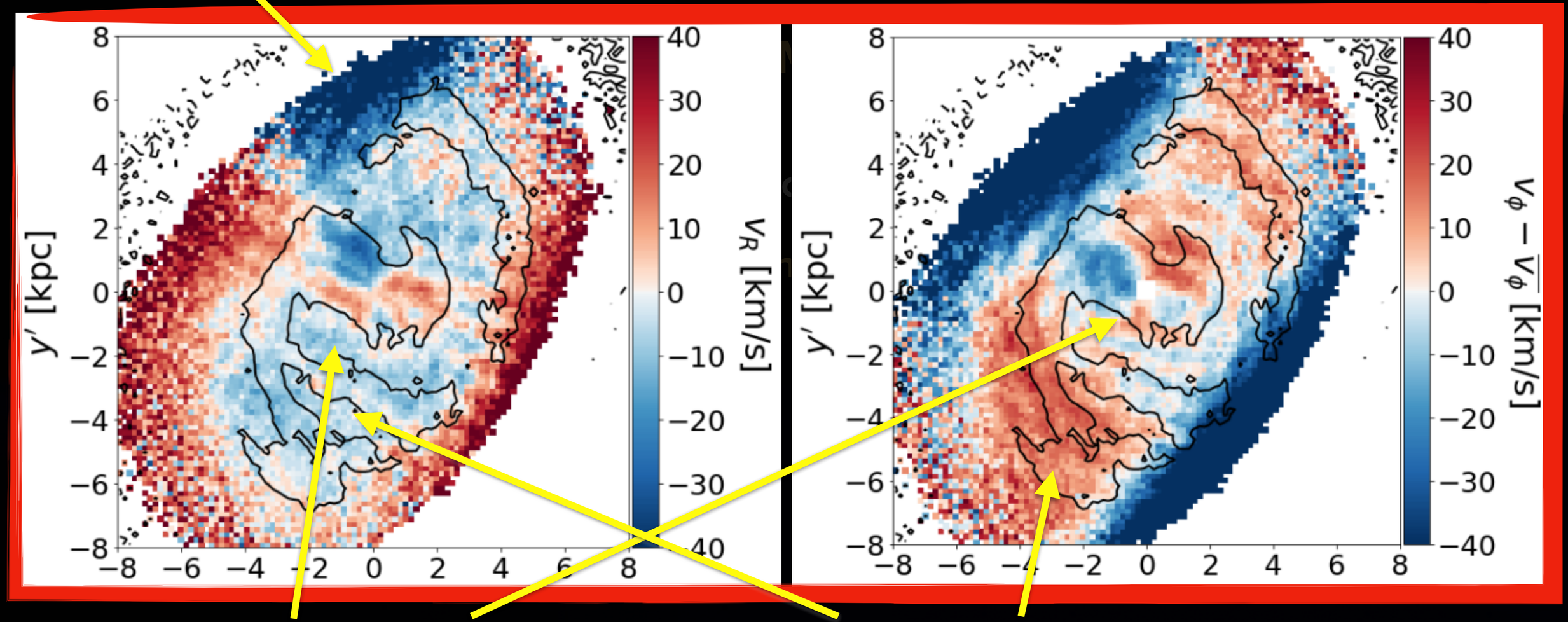
LMC optimal sample

Radial velocity



Magellanic Bridge?
(M. Schölch, in prep.)

LMC optimal sample



Confirmation of the **quadrupole** trend in the **bar**. It is **asymmetric**.

In the part of the **arm** attached to the bar, **inward motion** and a **rotation faster** than that of the disc.

- **The bar pattern speed of the Large Magellanic Cloud**
  (Ó. Jiménez-Arranz et al. 2024a)
  - **Three different methods** to infer the **LMC bar pattern speed:** (using Gaia proper motions and Vlos)
    - **Tremaine** and **Weinberg** method (1984)
    - **Bisymmetric model** of the **tangential velocity** (Gaia Collaboration, Drimmel, et al 2022)
    - **Dehnen** method (2023)

  - **Tested** on **simulations before applied** to the **LMC clean sample(s):**
    - **B5** (S. Roca-Fàbrega+13)**: isolated MW**-like galaxy
    - **KRATOS** (Ó. Jiménez-Arranz+24b)**: interacting LMC**-like galaxy

Tremaine and Weinberg method

$$\Omega_p \sin i = \frac{\langle V_{\rm los} \rangle}{\langle X \rangle}$$

Line-of-sight velocity version
(30k stars)

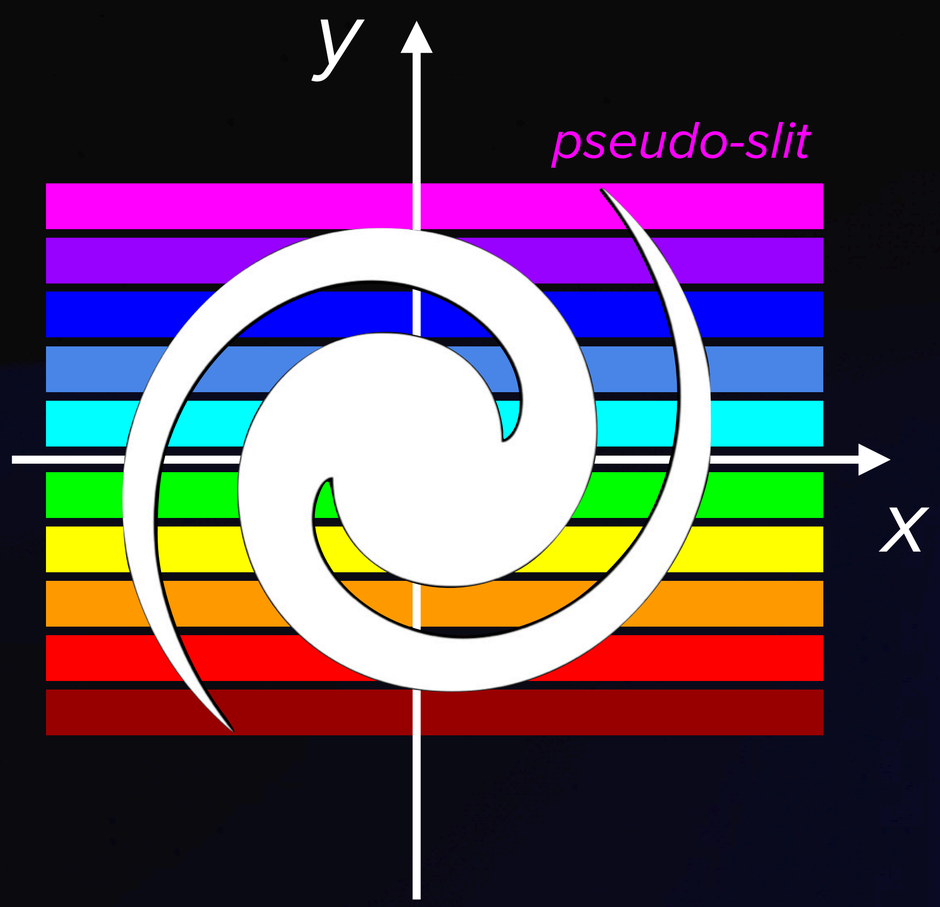
$$\Omega_p = \frac{\langle v_y \rangle}{\langle x \rangle}$$

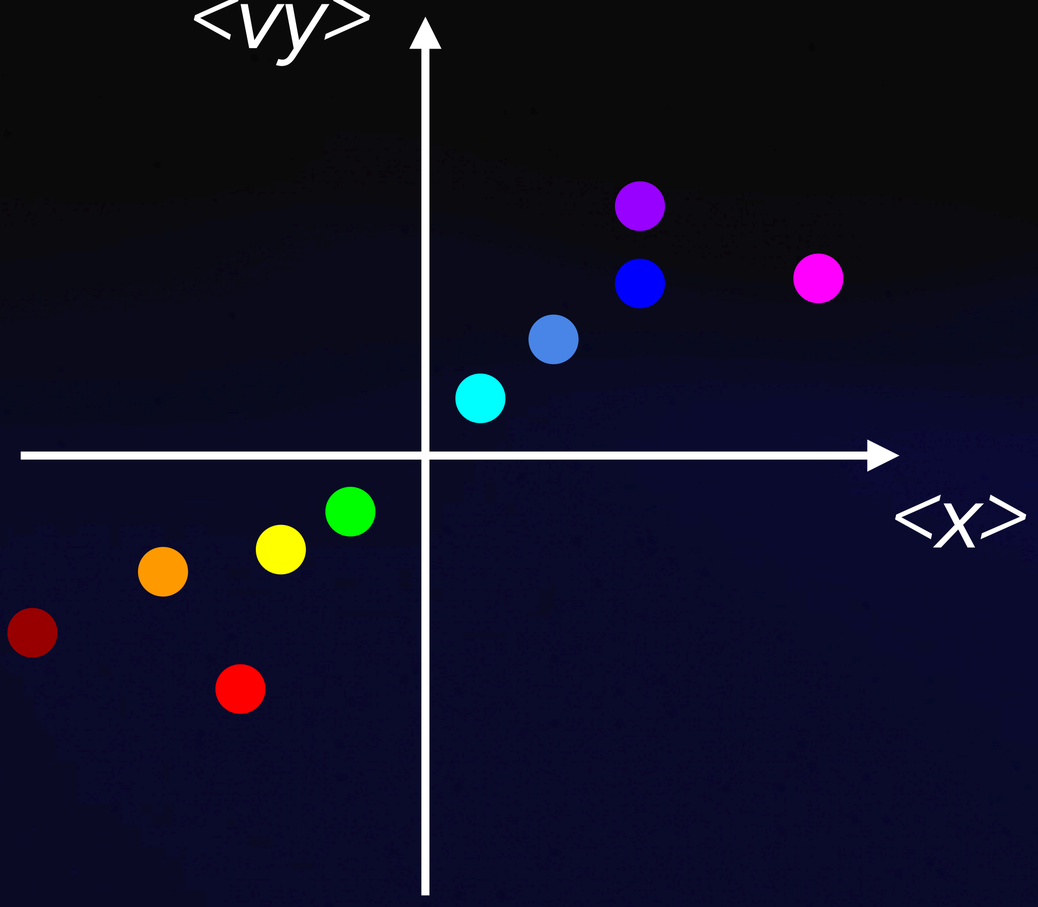
In-plane velocity version
(10M stars)

Tremaine and Weinberg method

$$\Omega_p = \frac{\langle v_y \rangle}{\langle x \rangle}$$

In-plane velocity version
(10M stars)





Tremaine and Weinberg method

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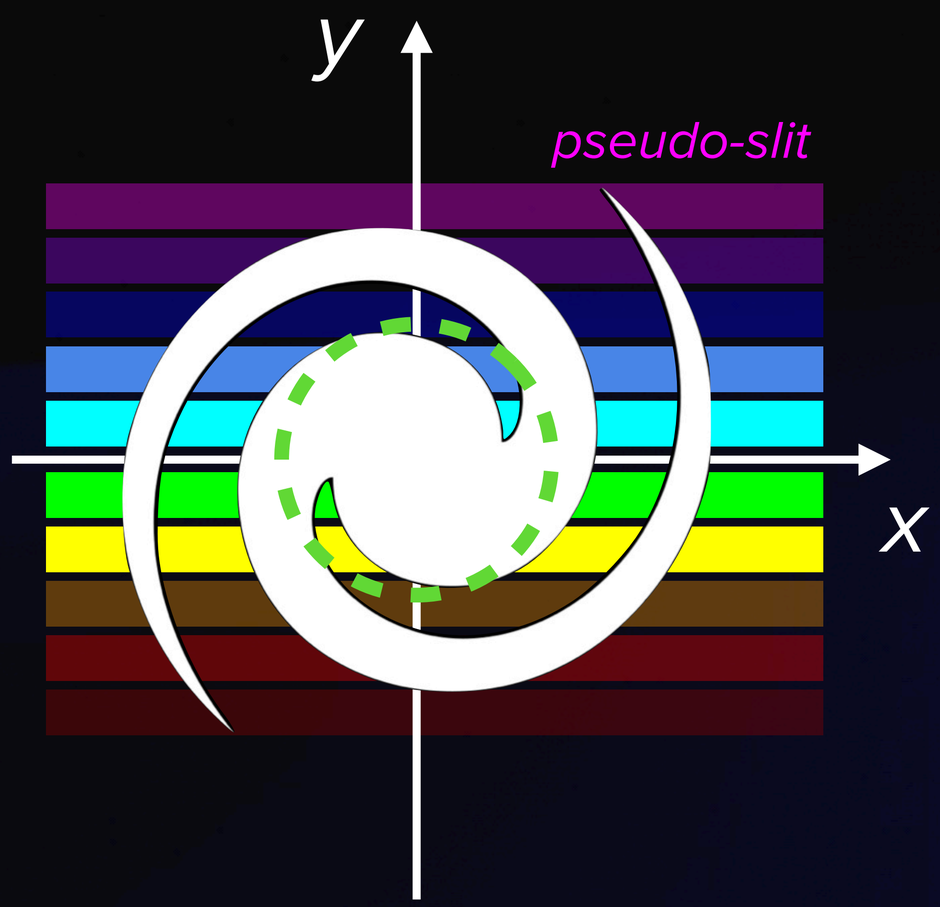
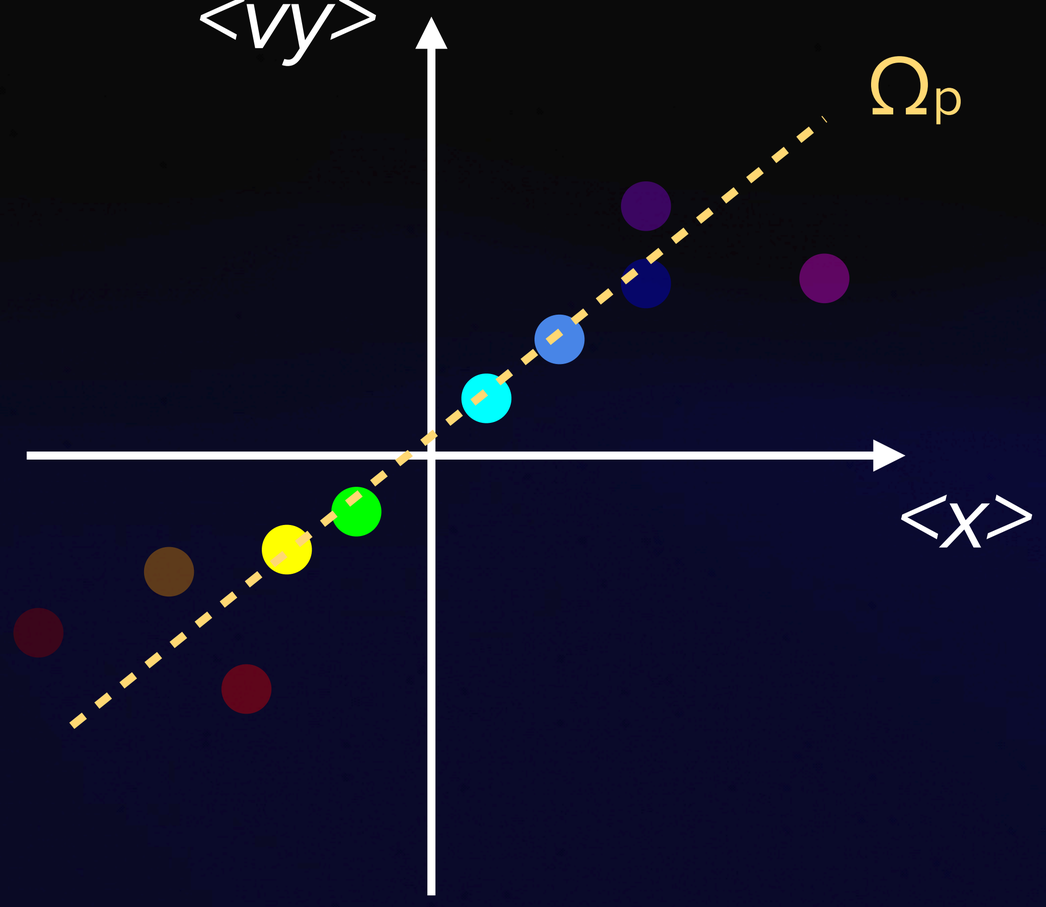
In-plane velocity version
(10M stars)





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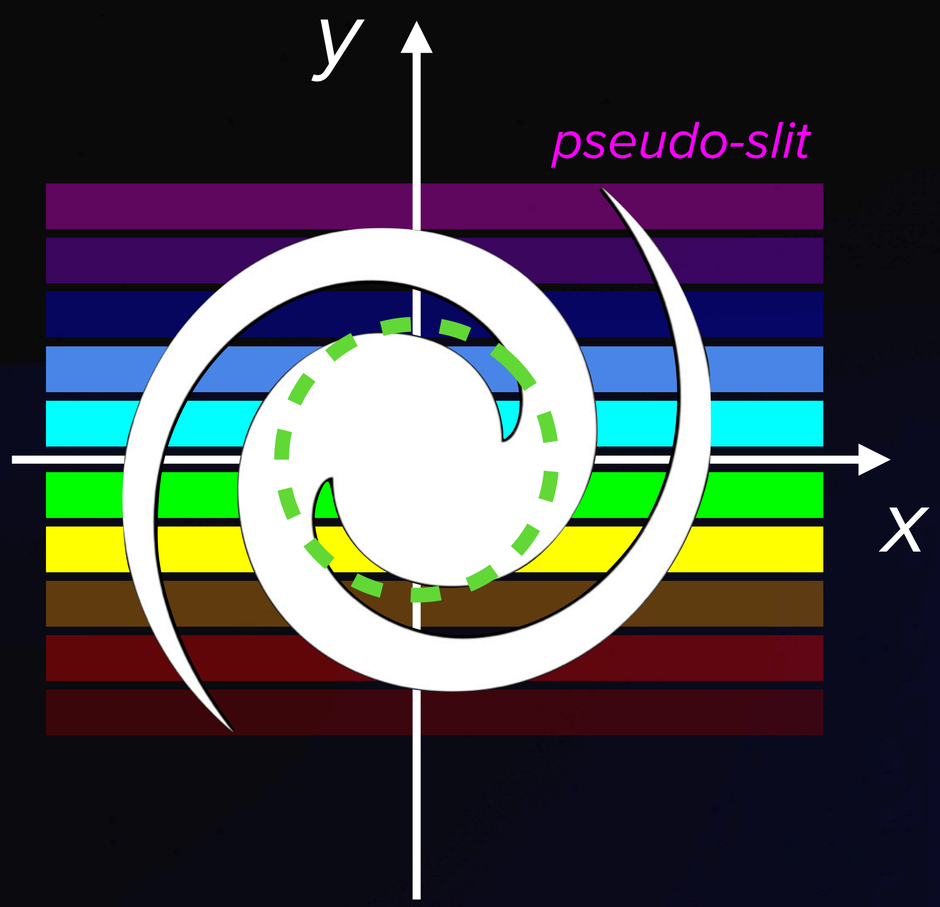
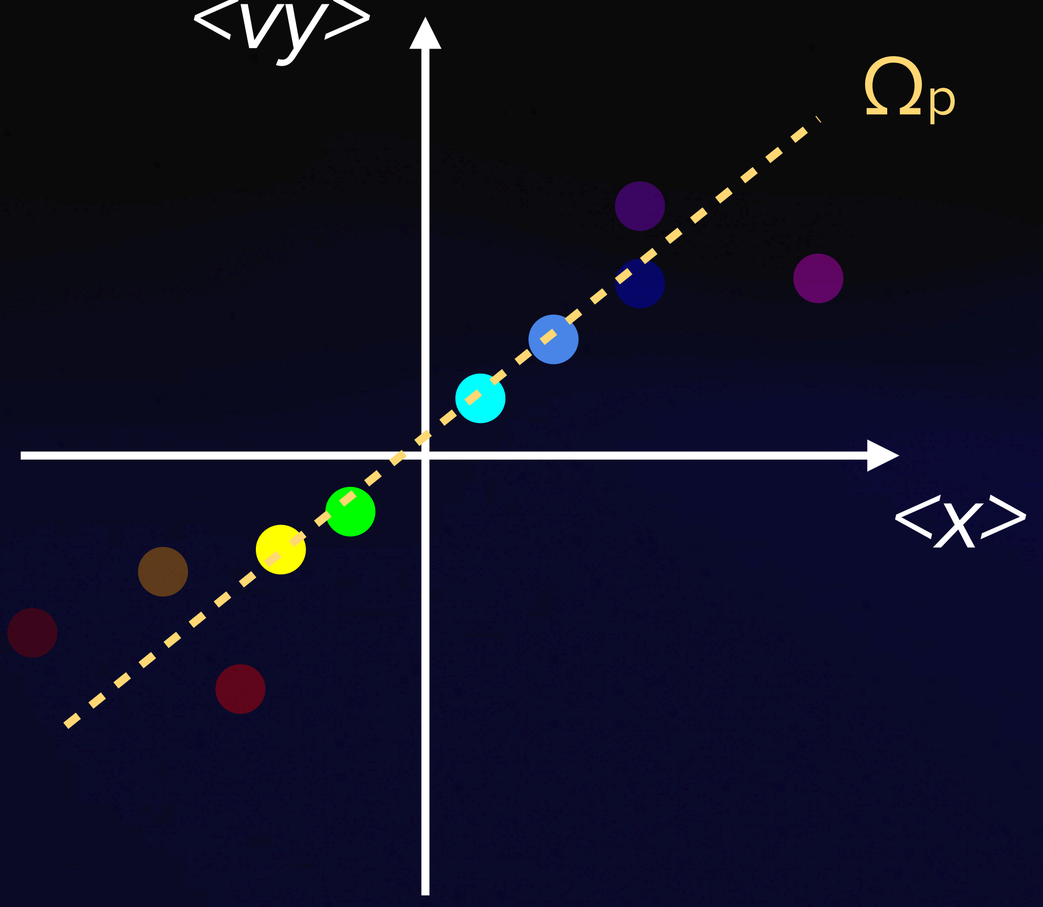
In-plane velocity version
(10M stars)



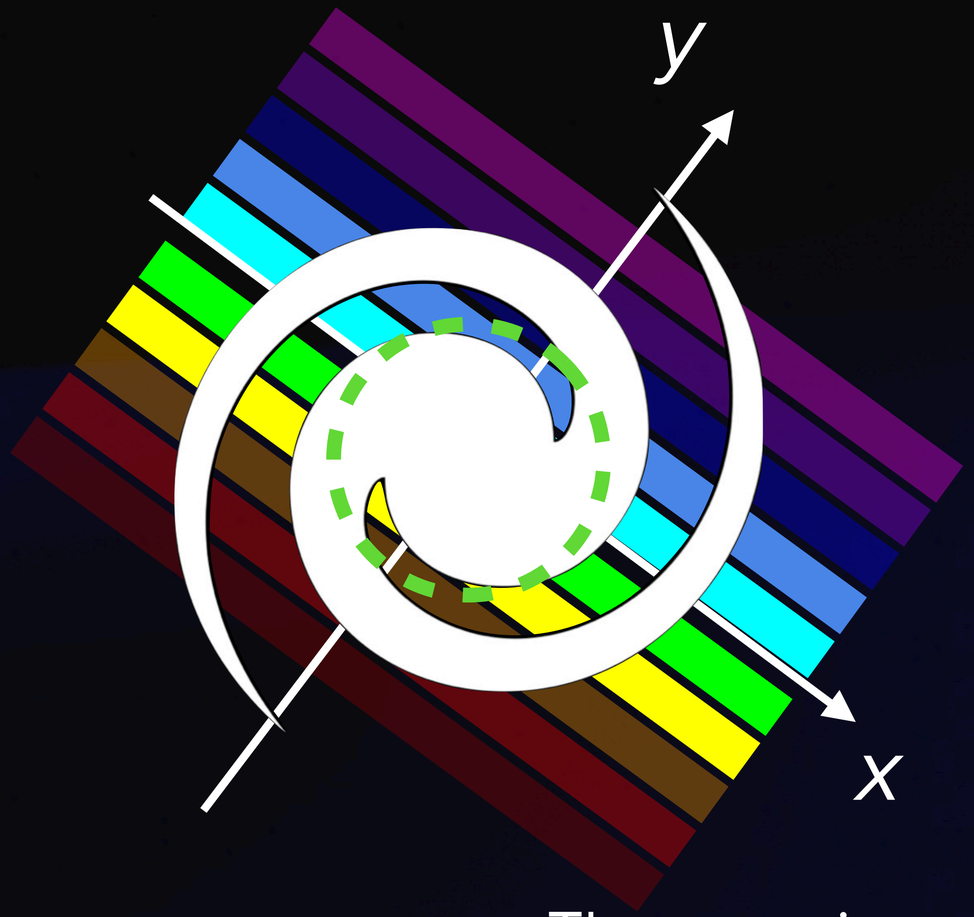


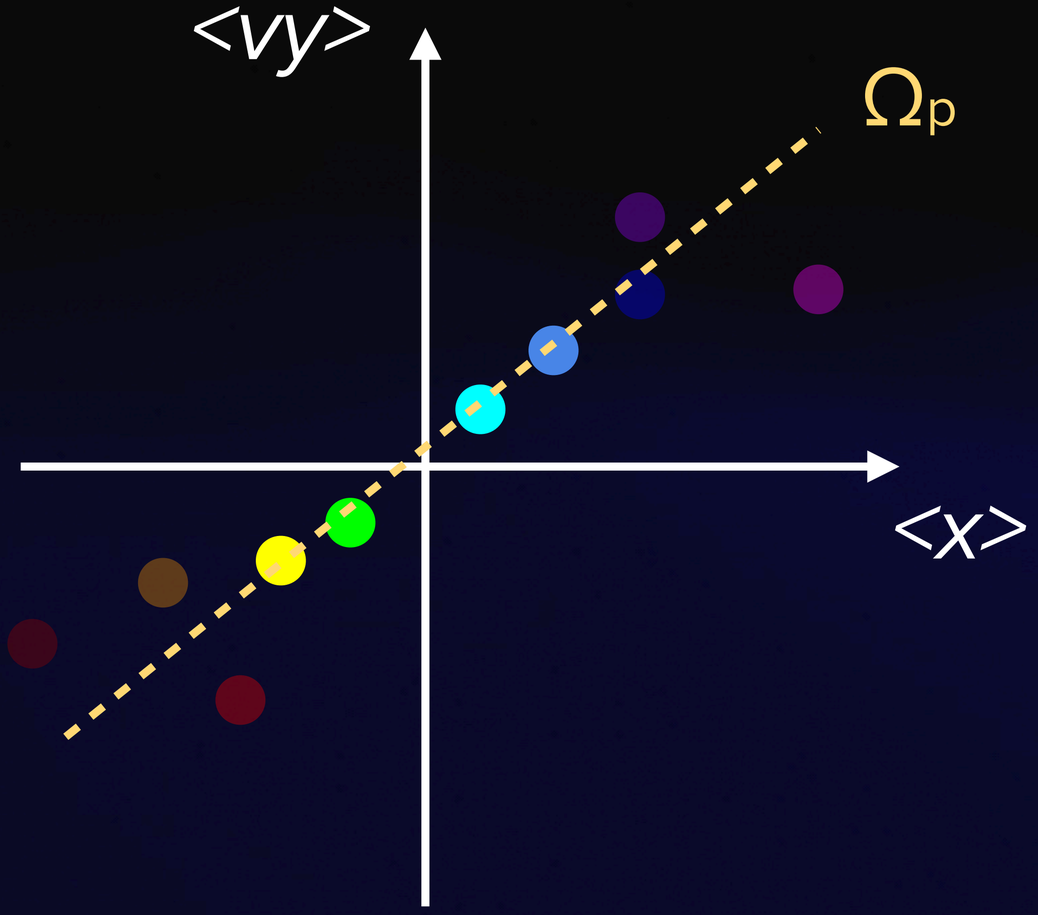
The x-y axis can be arbitrary chosen!

Tremaine and Weinberg method

$$\Omega_p = \frac{\langle v_y \rangle}{\langle x \rangle}$$

In-plane velocity version
(10M stars)





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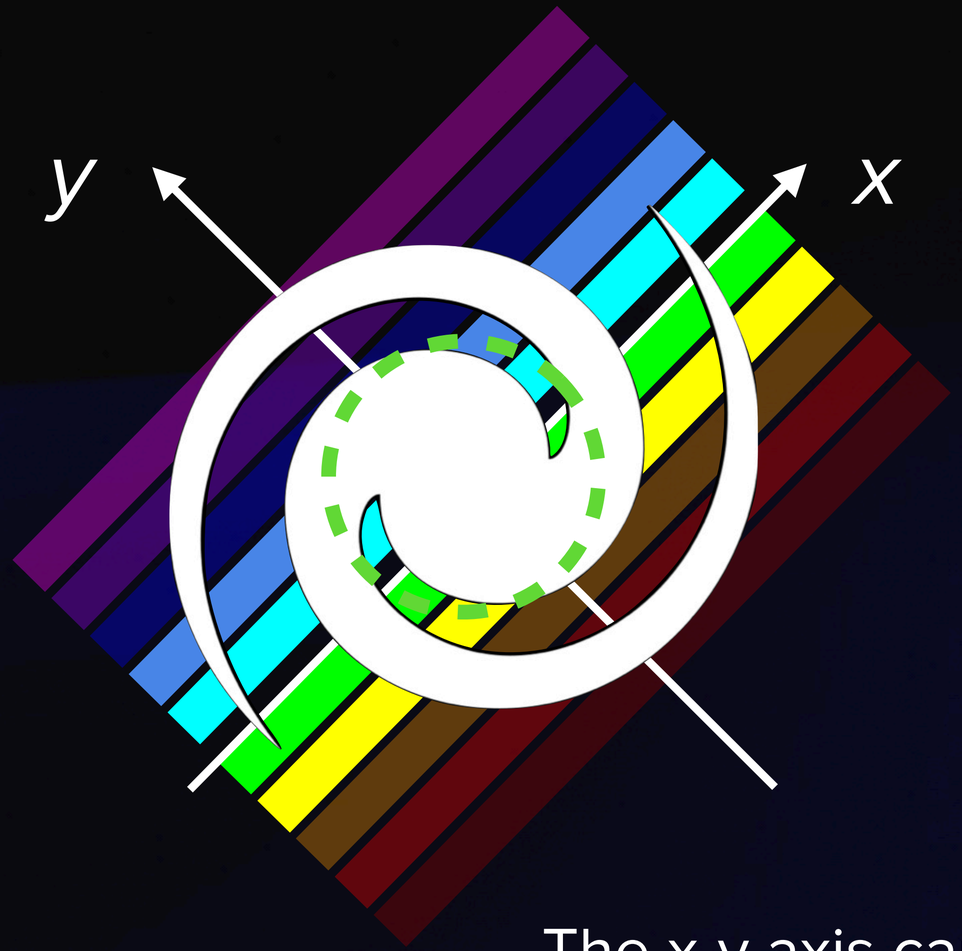
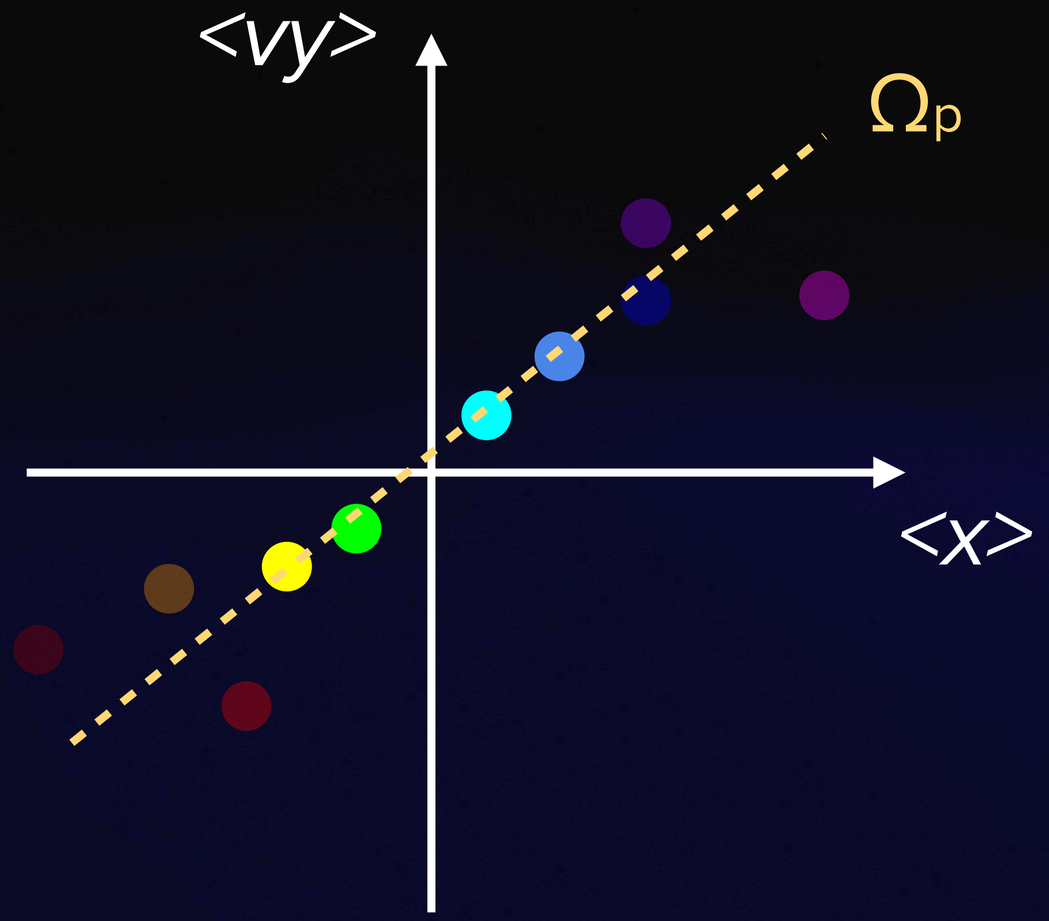
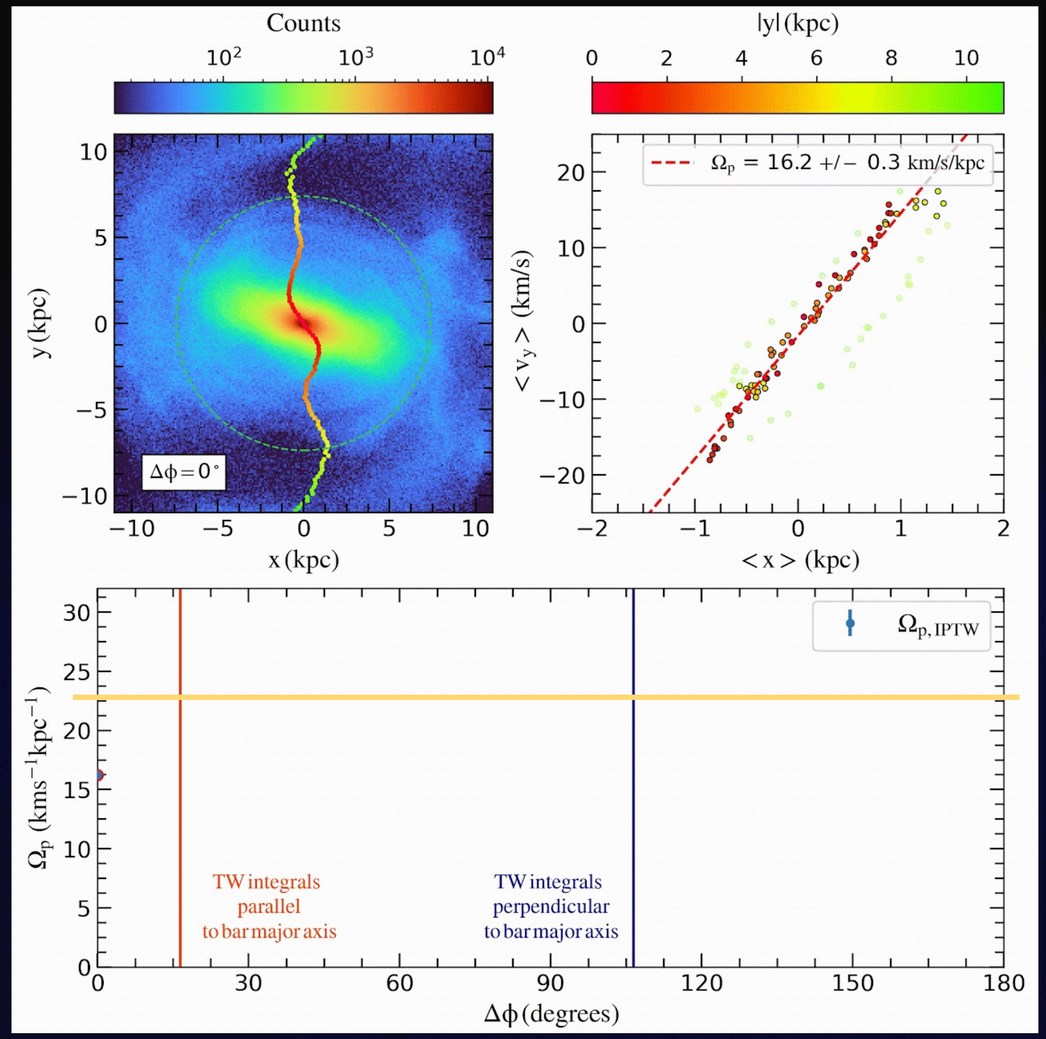




The x-y axis can be arbitrary chosen!

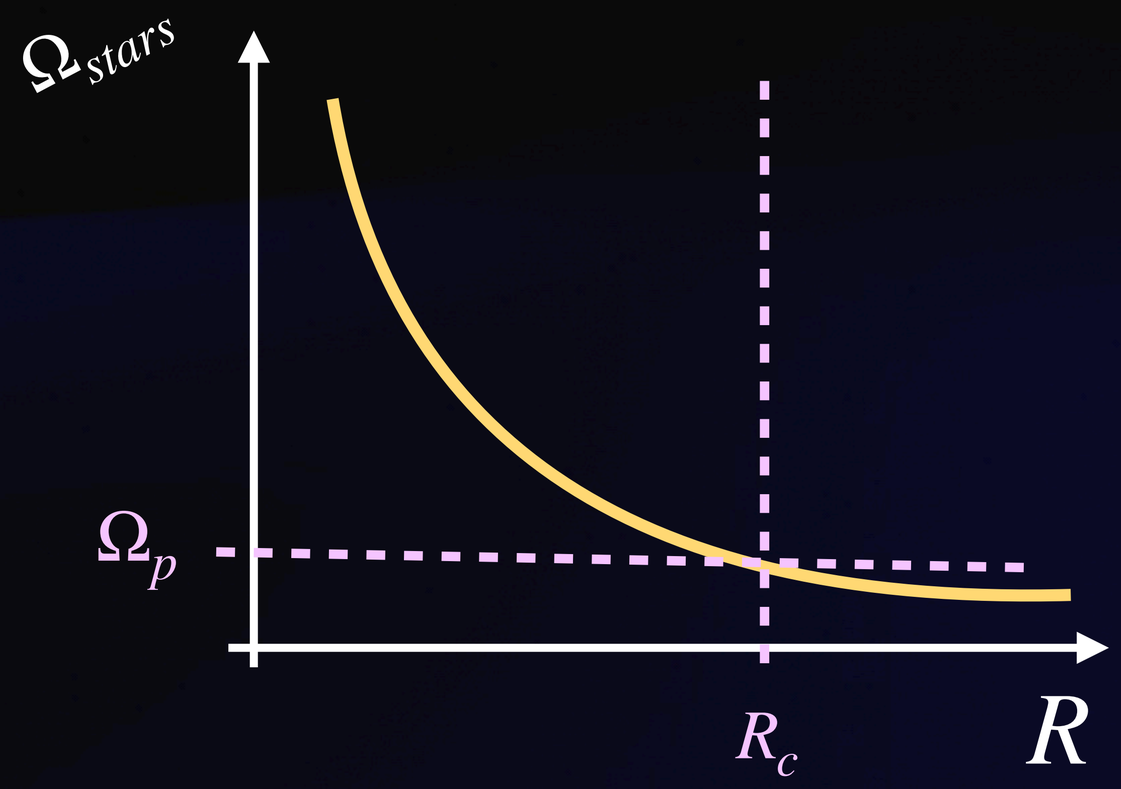
Tremaine and Weinberg method

Not able to recover the simulations' bar pattern speed



Bisymmetric model of the tangential velocity

- **Empirical model** to find the **corotation radius Rc**



Recovers well the simulations' bar pattern speed

Dehnen method

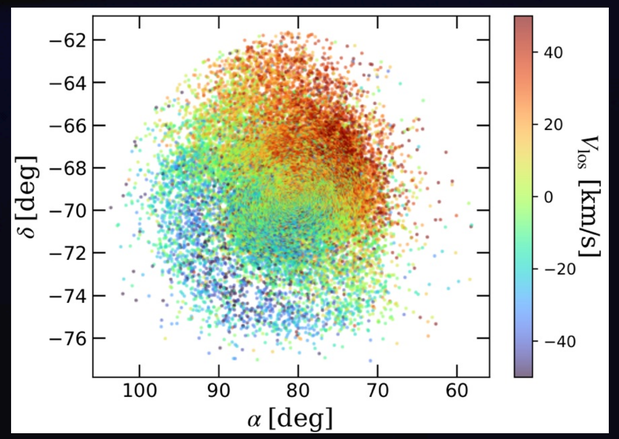
- Intended for single snapshots simulations
- Modification of the TW method, where the bar region is masked

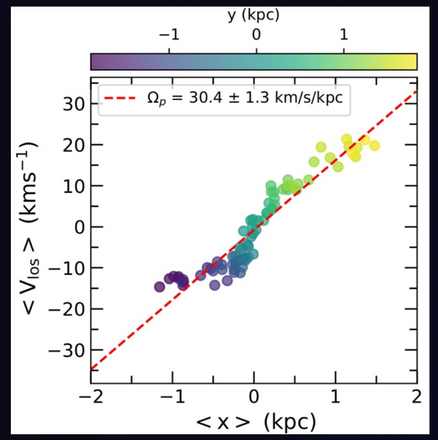
Recovers well the simulations' bar pattern speed

Outline

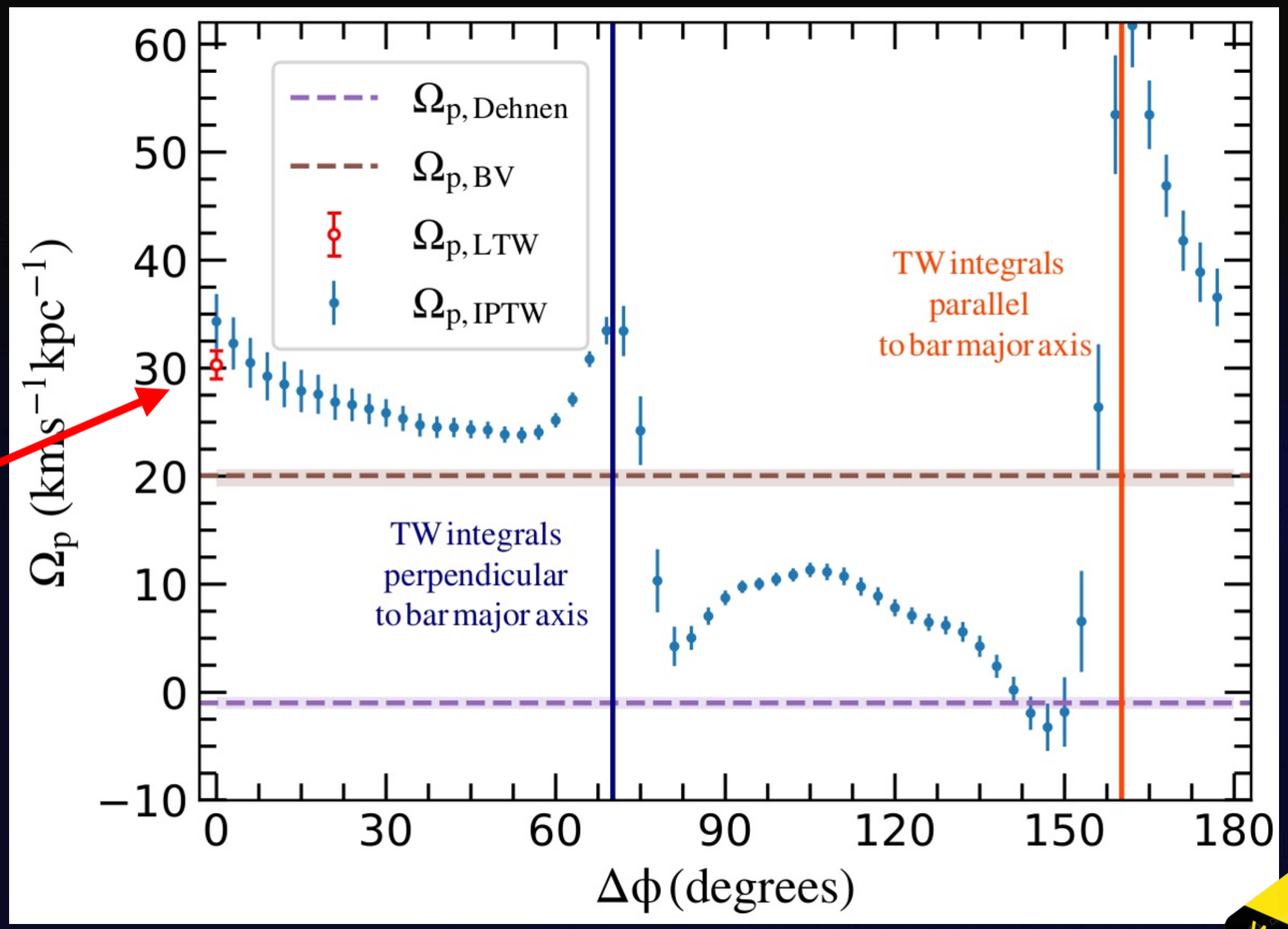
- Motivation
- Context and Goals
- **Results**
- Conclusions

Tremaine and Weinberg method (applied to the LMC)





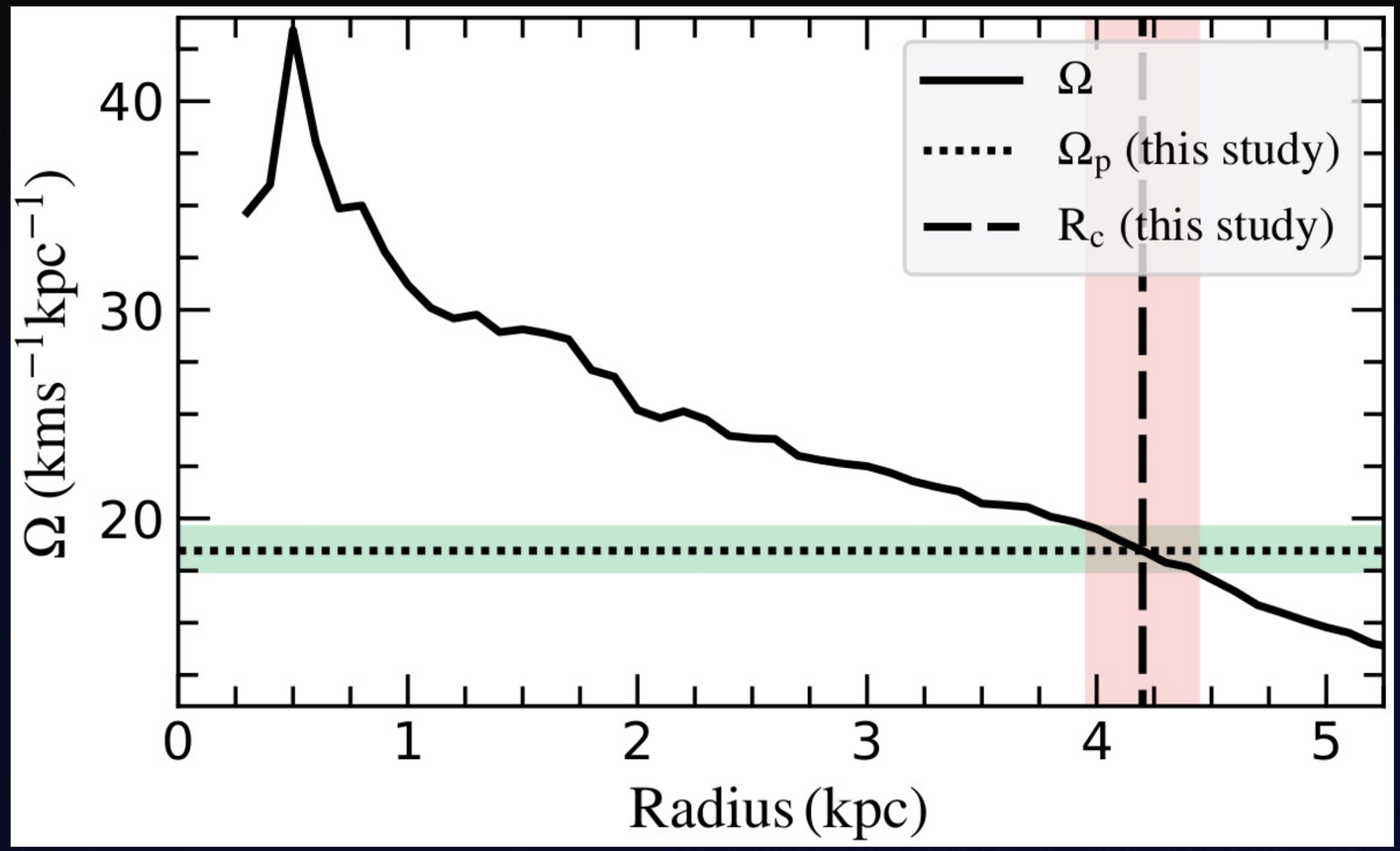
Line-of-sight velocity version
(30k stars)



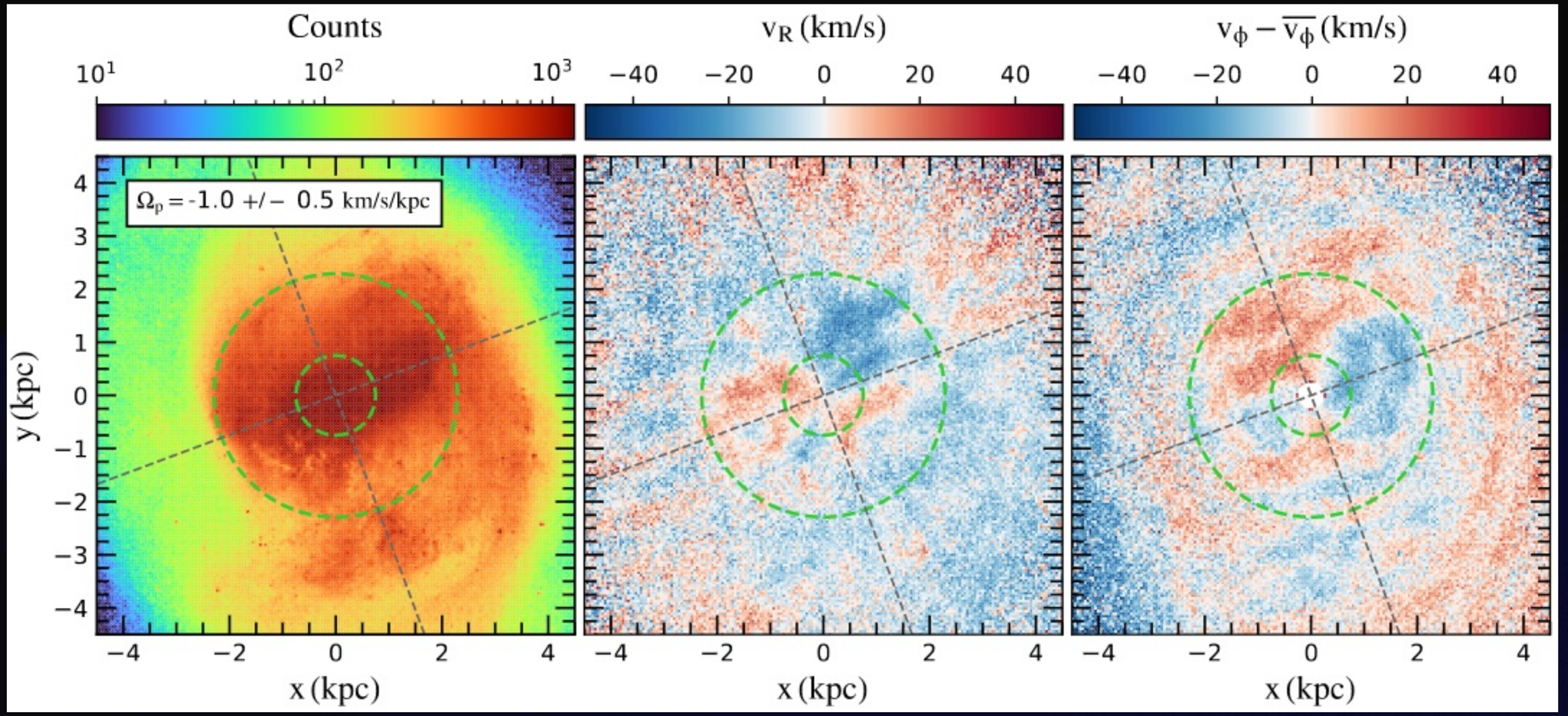
Bisymmetric model of the tangential velocity
(applied to the LMC)

$$R_c = 4.20 \pm 0.25 \text{ kpc}$$

$$\Omega_p = 18.5^{+1.2}_{-1.1} \text{ km s}^{-1} \text{ kpc}^{-1}$$



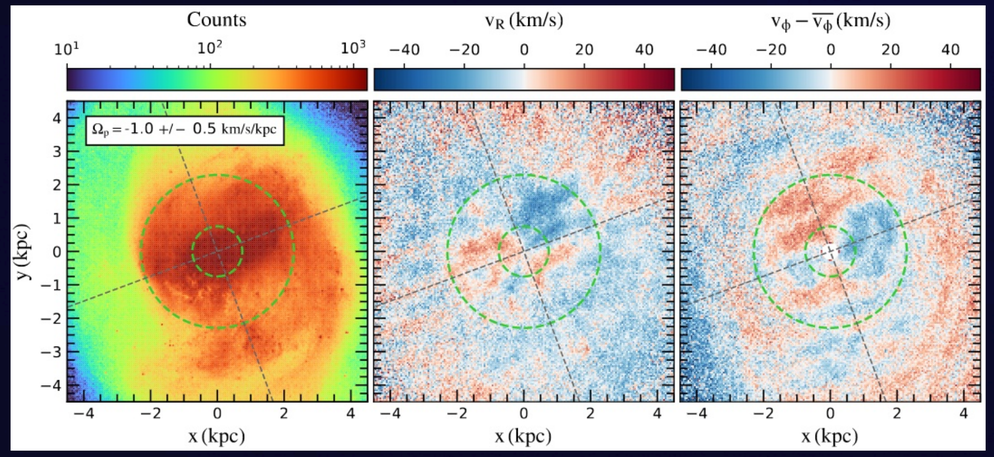
Dehnen method (applied to the LMC)



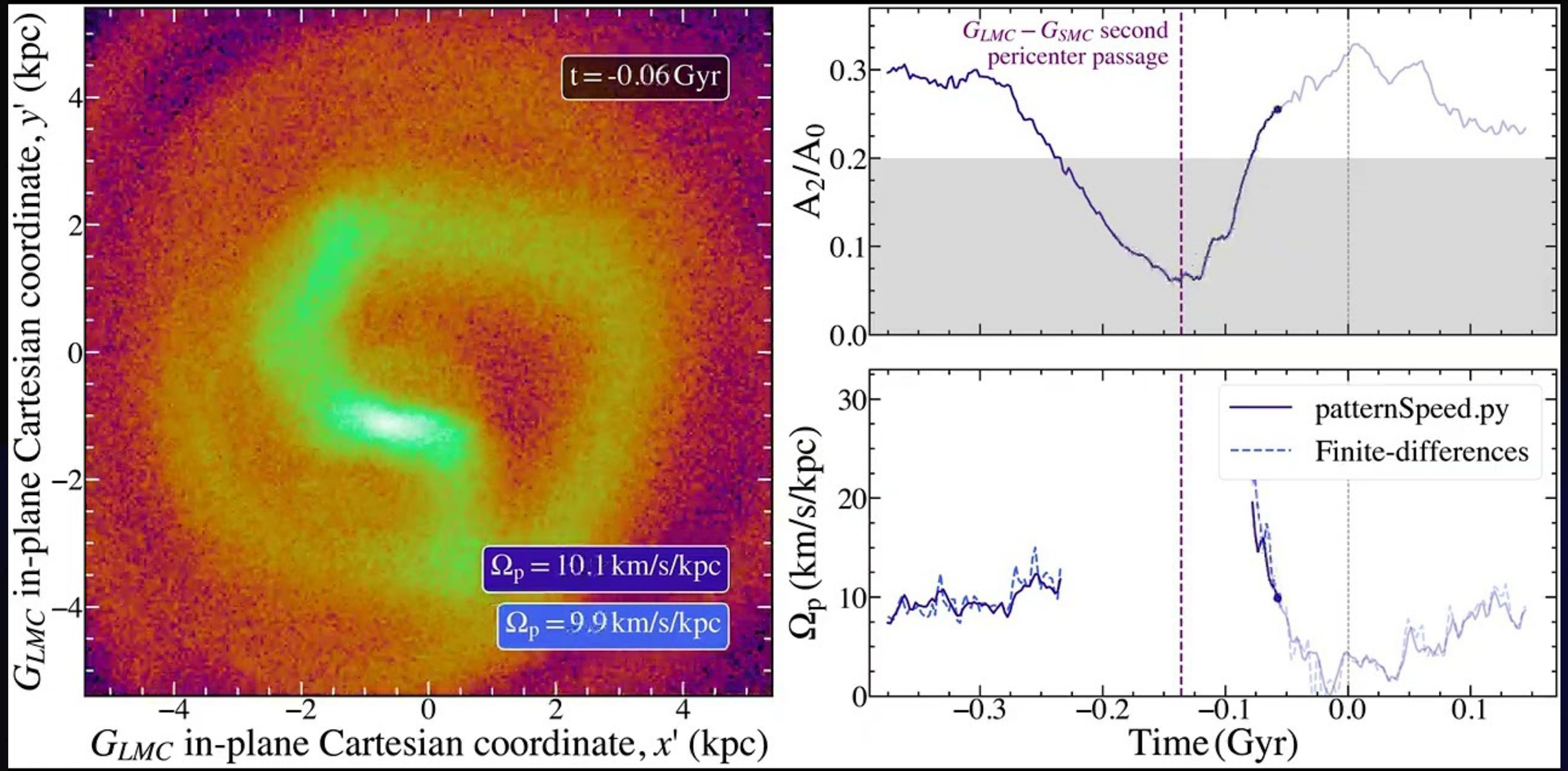
The LMC may be hosting a non-rotating bar!

Dehnen method (applied to the LMC)

- Found in numerical simulations, but for very specific configurations (Collier & Madigan 2023)
- Possible external origin: interaction with the SMC and/or the MW
- An almost non-rotating LMC bar would indeed not show any corotation within the disc
- Result sensible to:
  - Dust extinction / completeness
  - Counter-rotating m=1 mode

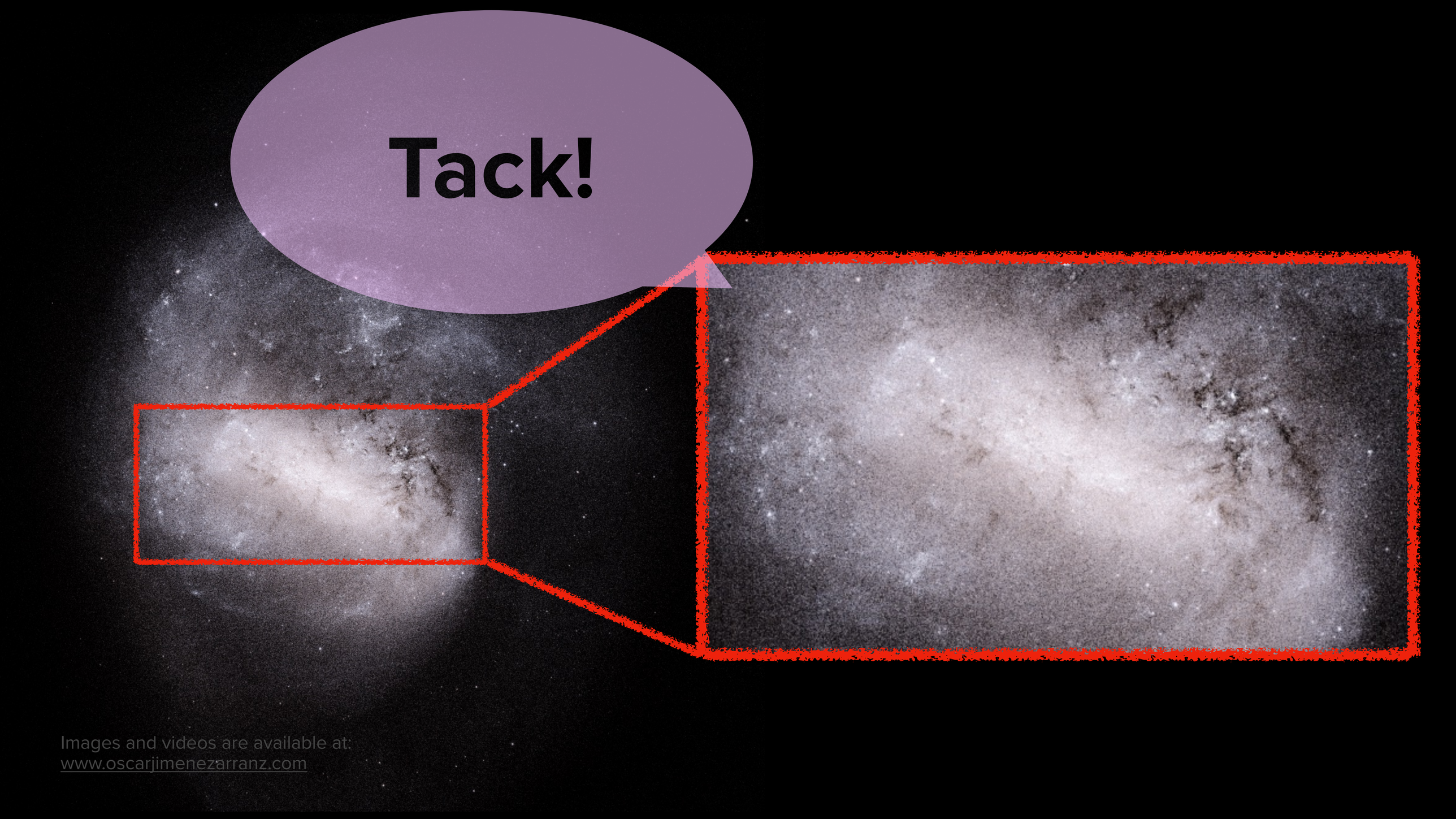


- **Tidal interaction can stop galactic bars: on the LMC non-rotating bar (Ó. Jiménez-Arranz and S. Roca-Fàbrega 2025b)**
  - We found that 2 simulations of the KRATOS suite (Jiménez-Arranz+24a) present an LMC-like galaxy with stopped bar due to the interaction with the SMC
  - Bar pattern speed derived:
    - 1) Finite differences
    - 2) Dehnen method

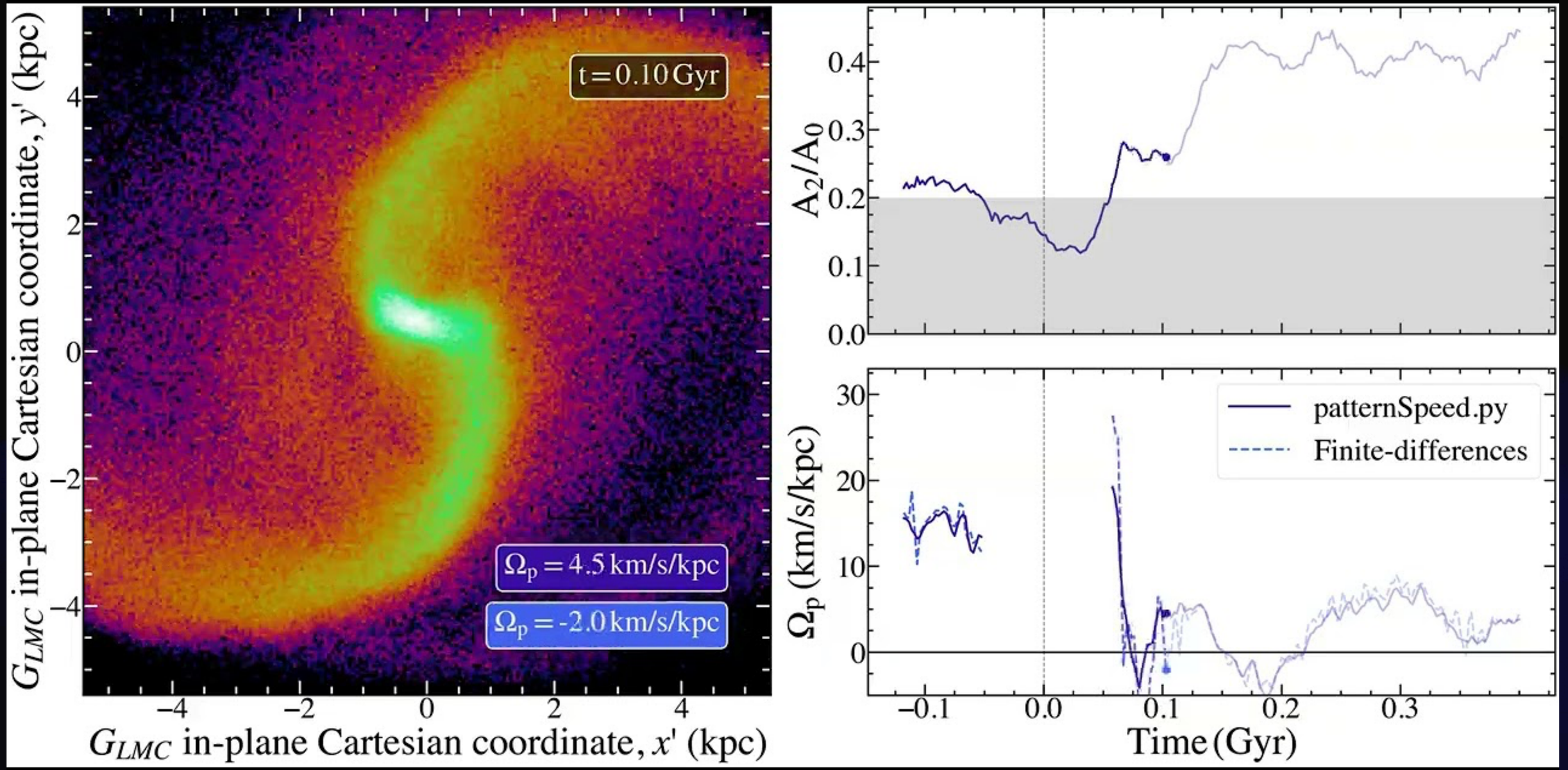

t = -0.06 Gyr
Ω_p = 10.1 km/s/kpc
Ω_p = 9.9 km/s/kpc
G_{LMC} in-plane Cartesian coordinate, y' (kpc)
G_{LMC} in-plane Cartesian coordinate, x' (kpc)
$G_{LMC} - G_{SMC}$ second pericenter passage
A_2/A_0
Ω_p (km/s/kpc)
patternSpeed.py
Finite-differences
Time (Gyr)

Conclusions

- Gaia DR3 provides more than 10 millions LMC stars with proper motion information
- Three different methods provide three different LMC bar pattern speed
- The Dehnen methods recovers an almost non-rotating bar
- The KRATOS suite of simulations shows that this may be possible due to the recent LMC-SMC interaction



Images and videos are available at:
www.oscarjimenezarranz.com


t=0.10 Gyr
$\Omega_p = 4.5$ km/s/kpc
$\Omega_p = -2.0$ km/s/kpc
G_{LMC} in-plane Cartesian coordinate, y' (kpc)
G_{LMC} in-plane Cartesian coordinate, x' (kpc)
A_2/A_0
Ω_p (km/s/kpc)
patternSpeed.py
Finite-differences
Time (Gyr)