High Performance Calculation with supercluster In NAOC

Jianling WANG   (LAMOST—NAOC)

Scientific topics and results with HPC

- Stellar parameters calculation
- Modeling Nearby spiral formation with numerical imulations
- Galactic dynamic modeling.
- Dwarfs galaxies accretion into MW

Stellar parameters measurement with Bayesian inference

for large scale spectroscopy survey, e.g., LAMOST, APOGEE

References:

1. **Wang et al. 2016, MNRAS, 456,672**
   Measure the distance and extinction for stars in LAMOST survey with Bayesian method
2. **Wang et al. 2016, MNRAS, 460, 3179**
   Distance and extinction determination for APOGEE stars with Bayesian method
3. **Wang et al. 2022, RAA, under review.**
   Determination of Distance, extinction, Mass, and Age for Stars in LAMOST DR7

Theoretical background:

Bayesian method → observables + prior

(Burnett & Binney 2010; Binney et al. 2014)

With the Bayesian transformation, we can include the prior knowledge for further constrain the model :

$$p(\mathbf{x}) = p(\mathcal{M}) \sum_{i=1}^{3} p_i([\mathrm{M/H}])\, p_i(\tau)\, p_i(\mathbf{r})\, p(Av)$$

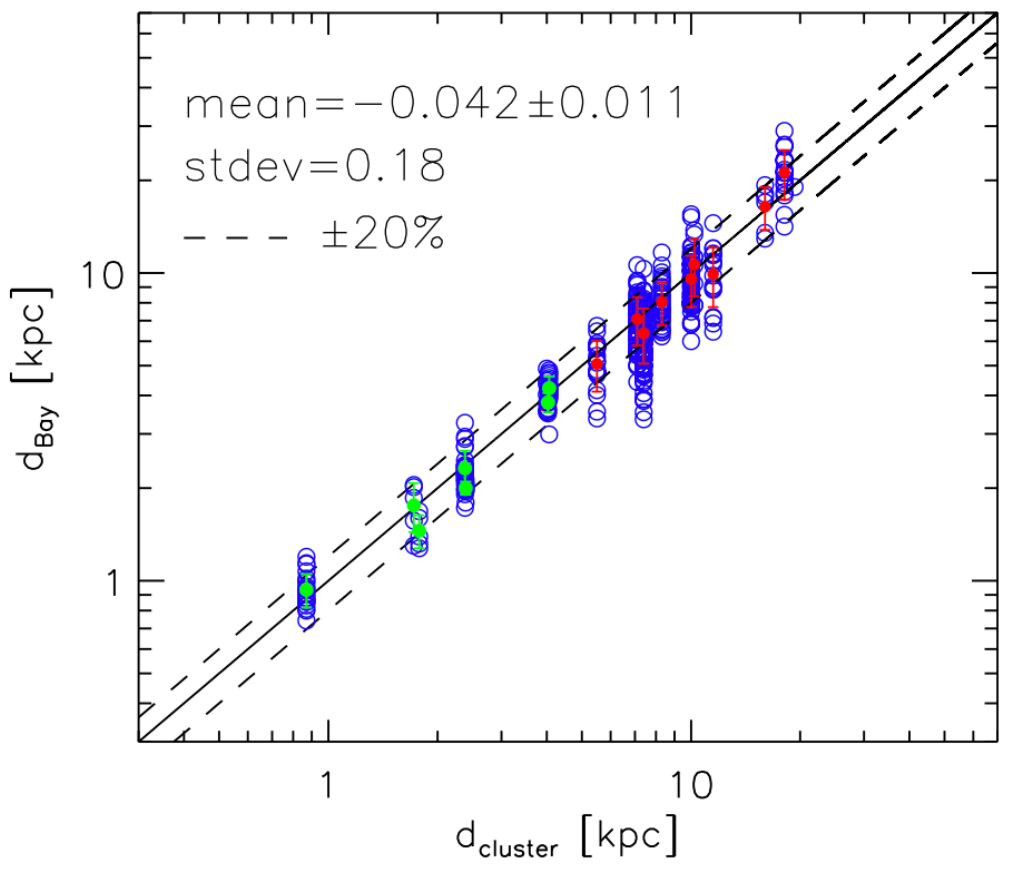
$$P(\mathbf{X}|\mathbf{O}) = \frac{P(\mathbf{X})}{P(\mathbf{O})} P(\mathbf{O}|\mathbf{X}),$$

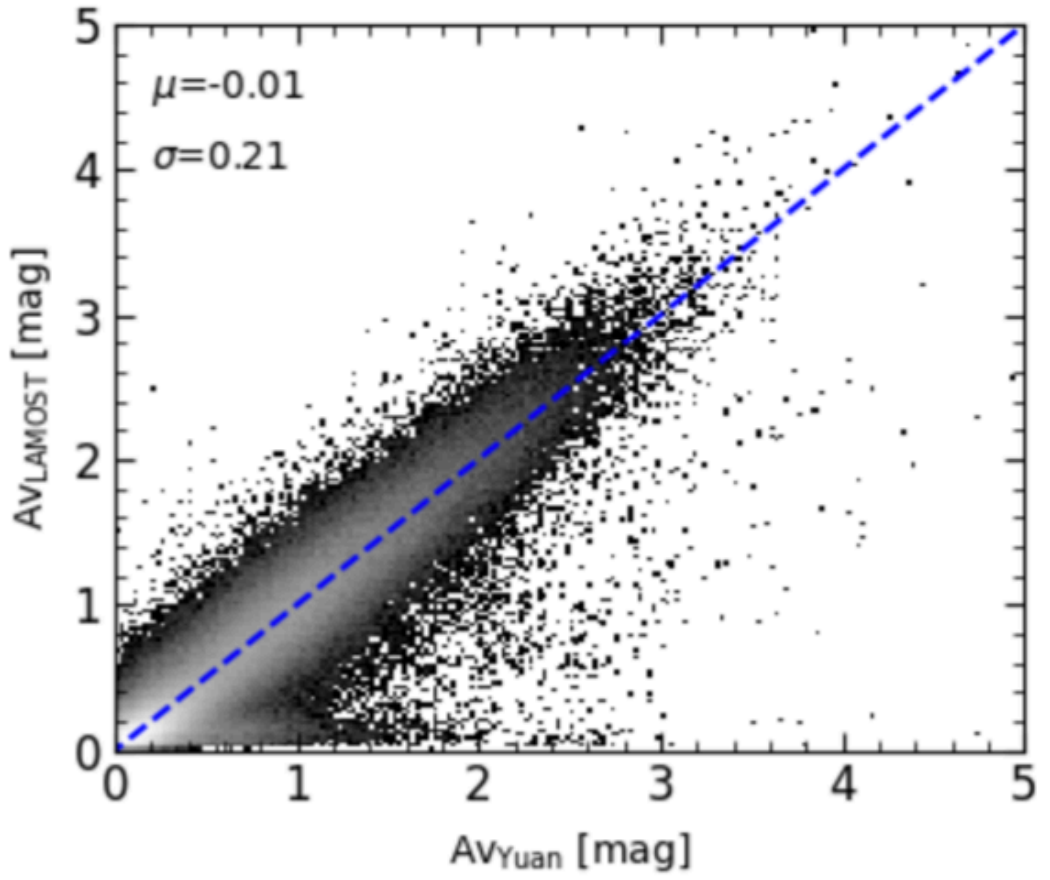
Construct the pdf for each star on the model space

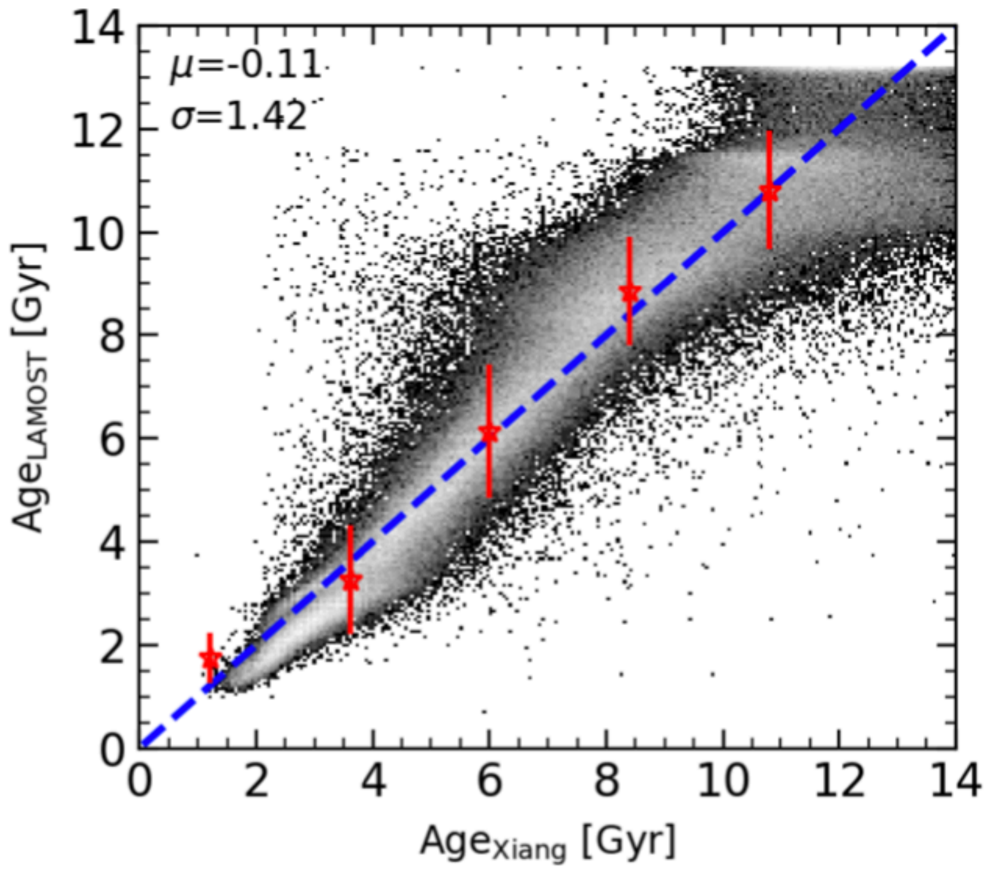
$$\mathcal{I}_{ik} = \int x_i^k \, p(\mathbf{x}|\bar{\mathbf{y}}, \boldsymbol{\sigma}_y, S)\, \mathrm{d}^6\mathbf{x},$$

Mean + errors

$P(\mathbf{X})$ is the prior probability, which reflect our prior knowledge of Milky Way.
$P(\mathbf{X}|\mathbf{O})$ is named by posterior probability which is the conditional probablity of parameter $\mathbf{X}$ given $\mathbf{O}$.
$P(\mathbf{O}|\mathbf{X})$ is the observated likelihood that given set of parameters $\mathbf{X}$ the set of observations $\mathbf{O}$ is made.







- Bayesian inferences
- Multi-dimensional integrations
- C+MPI

Nbody+Hydrodynamical simulations for local spiral formations

A new channel for spiral formation

Around half of local spirals have experienced a major merger

Reference:

1.*"Loops formed by tidal tails as fossil records of a major merger"*
Wang et al. 2012, A&A, 538, 121

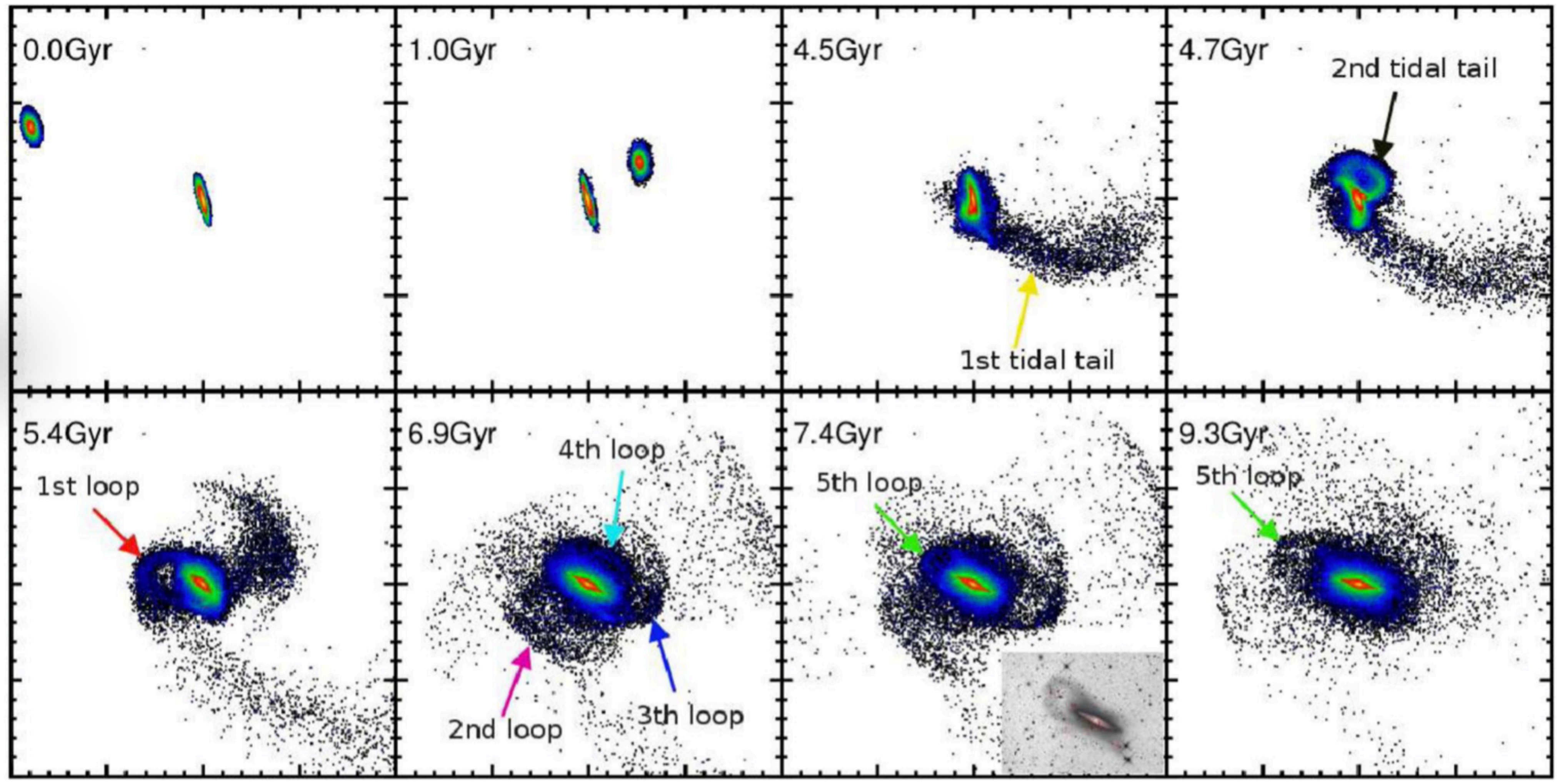
2.*"The NGC 4013 tale: a pseudo-bulged, late-type spiral shaped by a major merger"*
Wang et al. 2015, MNRAS, 452, 3551

3.*"Does M31 Result from an Ancient Major Merger ?"*
Hammer, Yang, Wang et al. 2010, ApJ, 725, 542

4.*"A 2-3 billion year old major merger paradigm for the Andromeda galaxy and its outskirts"*
Hammer, Yang, Wang et al. 2018, ApJ, 475, 2754

5.*"A recent major merger tale for the closest giant elliptical galaxy Centaurus A"*
Wang et al. 2020, MNRAS, 489, 2766

NGC 4013 formation by major merger simulations



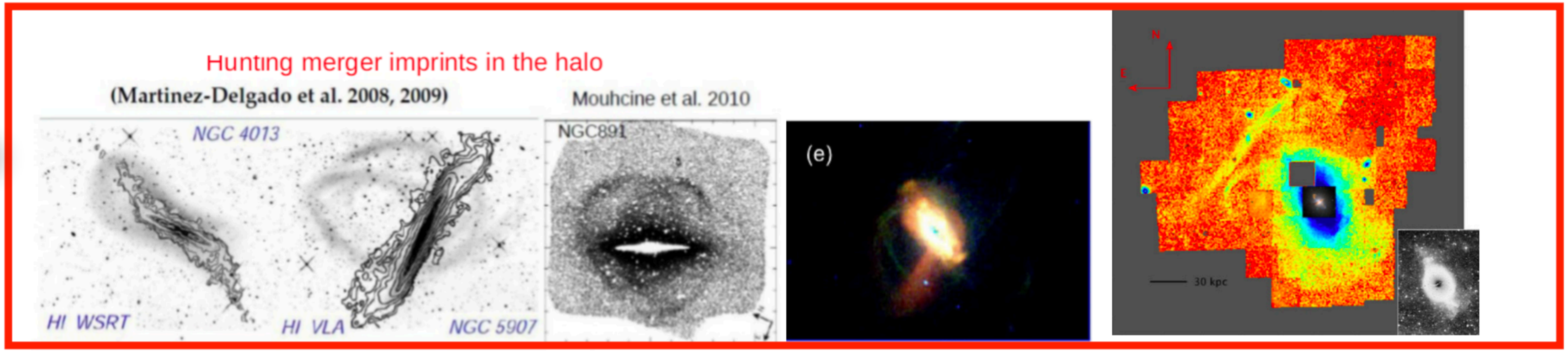
- Nbody+Hydrodynamics
- Gravitation + gas cooling, SF, feedback
- C+MPI

Nbody+Hydrodynamical simulations for local spiral formations

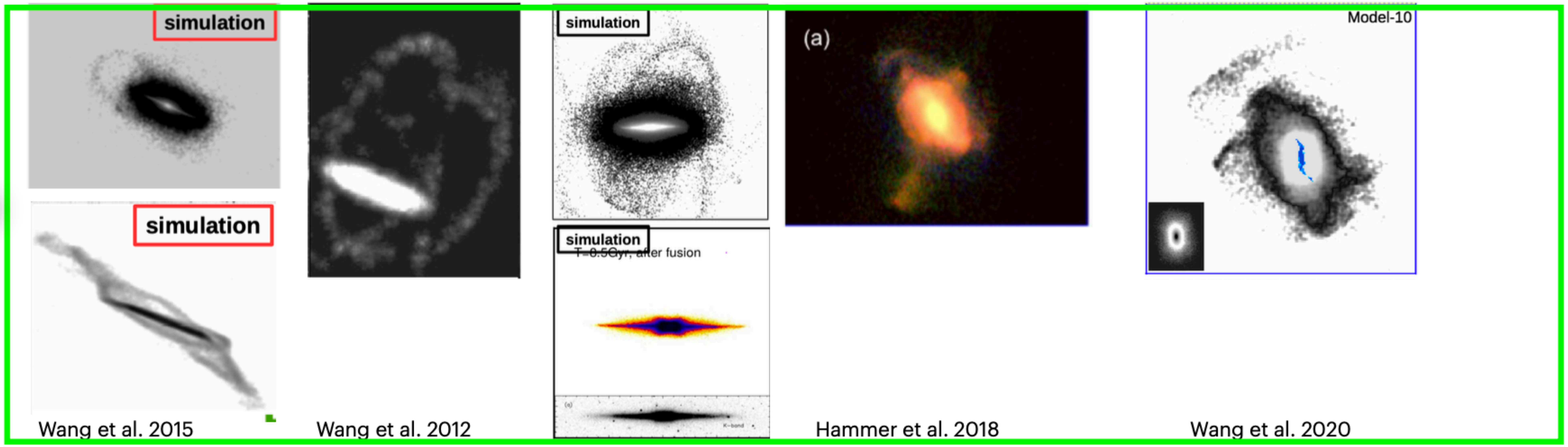
A new channel for spiral formation

Around half of local spirals have experienced a major merger

Observations data



Simulation models

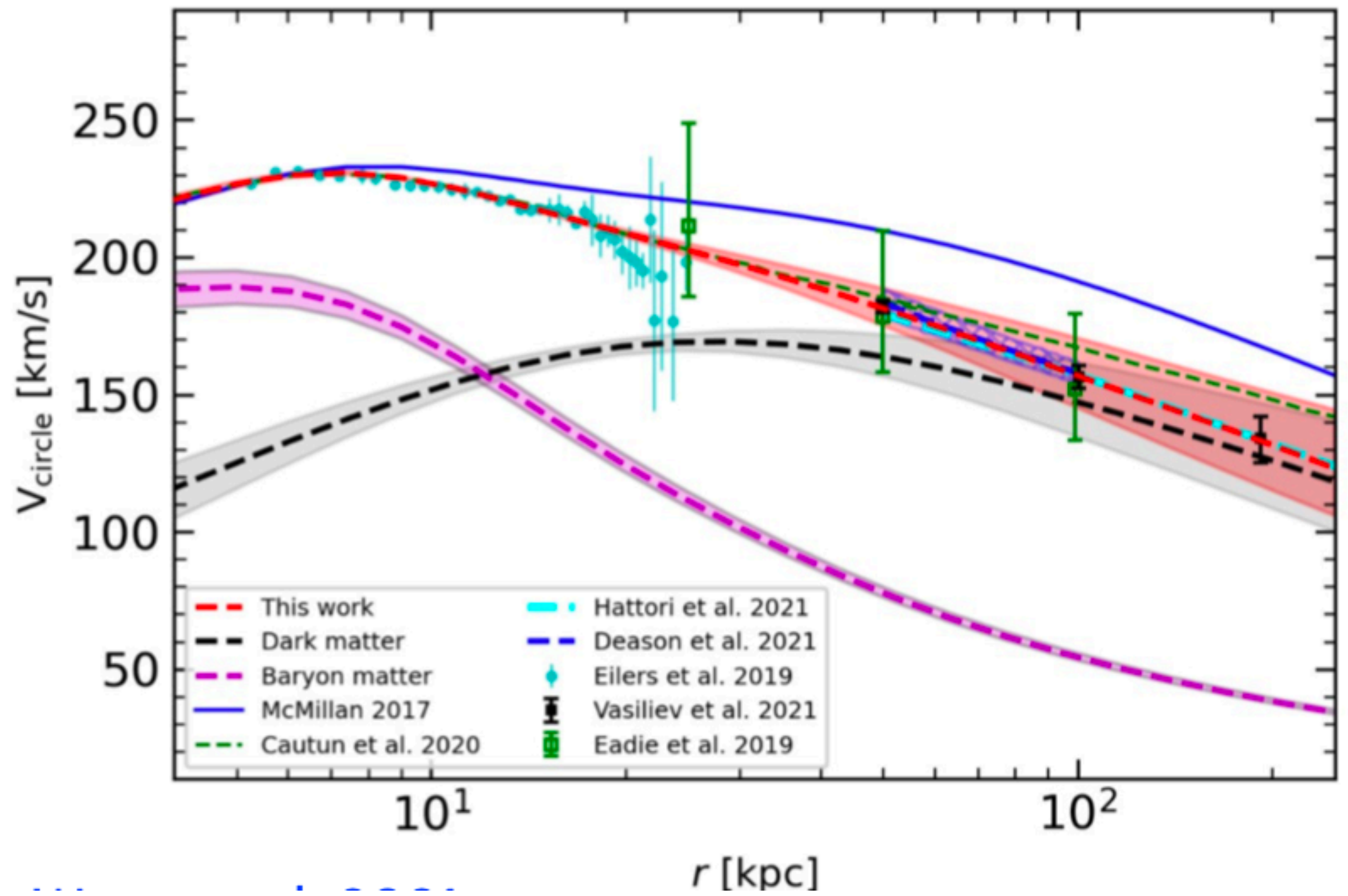


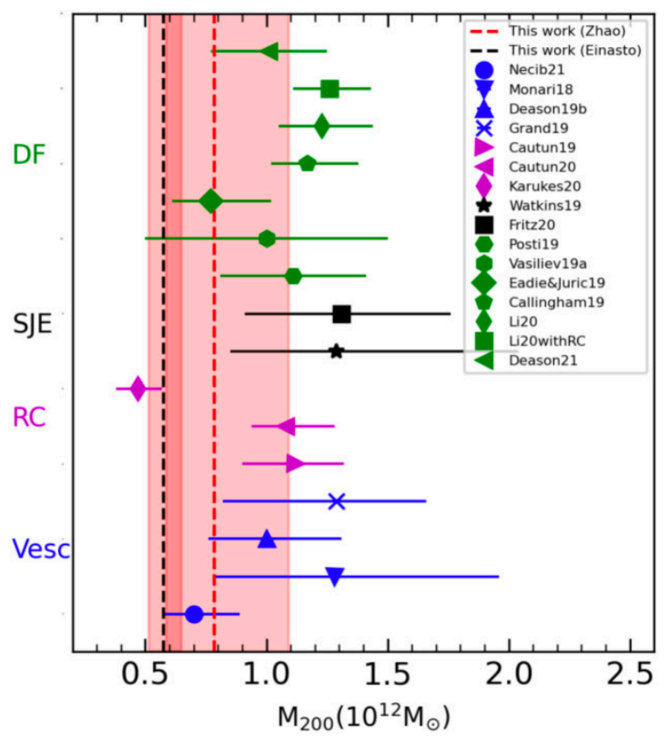
Galactic dynamic modelling

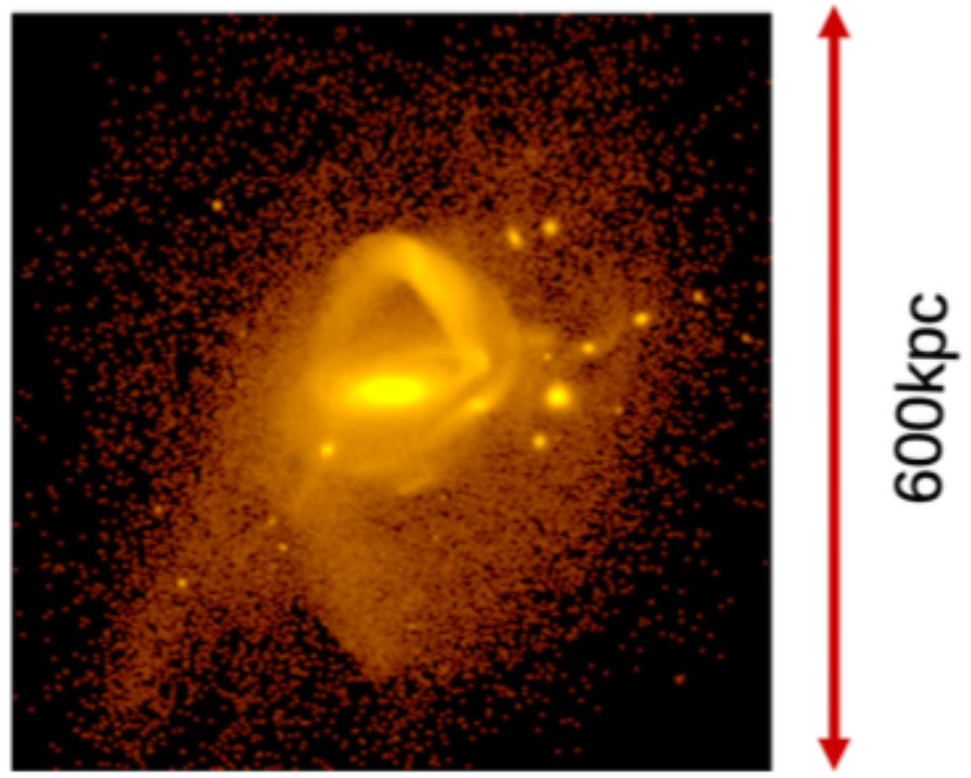
Action-based distribution function —> The total mass and rotation curve of Milky Way

Reference:

1. **Wang et al. 2022, MNRAS, 510, 2242**
   Milky Way total mass derived by rotation curve and globular cluster kinematics from *Gaia* EDR3







FIRE-2 Latter suites:
(Wetzel et al. 2016; Hopkins 2015; Hopkins et al. 2018)

–realistic cosmological hydrodynamical simulation
– generate mock catalogue of Gcs.
– adding observed uncertainties.
– Considering constraints Vc & Kz at 1.1 kpc

The Bayesian & MCMC (20 parameters)

Galactic gravitational potential (11; McMillian 2017):
- dark matter halo (Zhao 1996; Einasto 1965)
- gas disk
- stellar thick & thin disk
- bulge

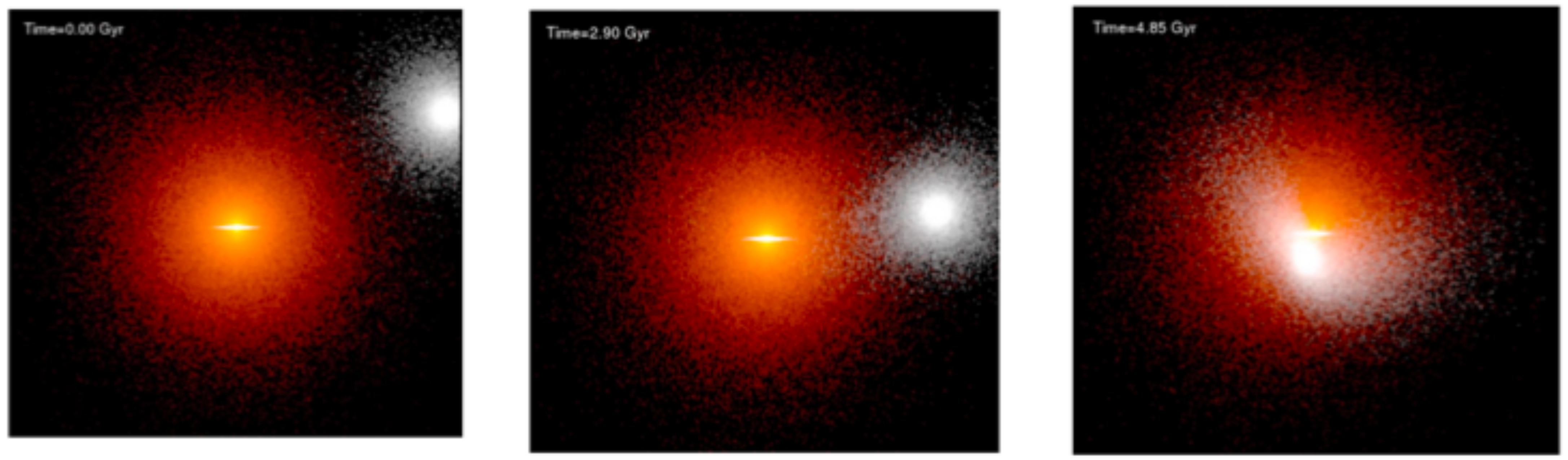
DF: double power-law (9; Das &Binney 2016; Vasiliev 2019)

$$f(\boldsymbol{J}) = \frac{M}{(2\pi J_0)^3}\left[1+\left(\frac{J_0}{h(\boldsymbol{J})}\right)^{\eta}\right]^{\Gamma/\eta}\left[1+\left(\frac{g(\boldsymbol{J})}{J_0}\right)^{\eta}\right]^{-B/\eta} \times\left(1+\tanh\frac{\kappa J_\phi}{J_r+J_z+|J_\phi|}\right). \quad (8)$$

Bayesian inference: $\Pr(M|D) = \frac{\Pr(D|M)\times\Pr(M)}{\Pr(D)}$

– **rotation curve.** (RGB: Eilers et al. 2019; C.Ceph.: Ablimit et al. 2020; Mroz et al. 2019)
– **vertical force** $K_{z,1.1\,\mathrm{kpc}}$ (Bovy & Rix 2013)

MW+LMC pairs:
–LMC: $1.5\times10^{11} M_{\odot}$
–induce reflex motion(Petersen & Peñarrubia 2020)
–induce the track motion of Sgr streams by Vasiliev et al. 2021.
–Southern local wake & Northern overdensity (Conroy et al. 2021)



- Monto-Carlo importance sampling
- MCMC
- Nbody+Hydrodynamics
- C+MPI, OpenMP

Nbody+Hydrodynamic simulation for the Magellanic System formation

References:

1. **Wang et al. 2019, MNRAS, 486, 5907**
   Towards a complete understanding of the Magellanic Stream Formation
2. **Wang et al. 2022, MNRAS, in press**
   Lessons from the Magellanic System and its modeling
3. **Wang et al. 2022, RAA, in preparation.**
   The Formation of LMC's Northern Arm: Implication from Its Distance and Metallicity

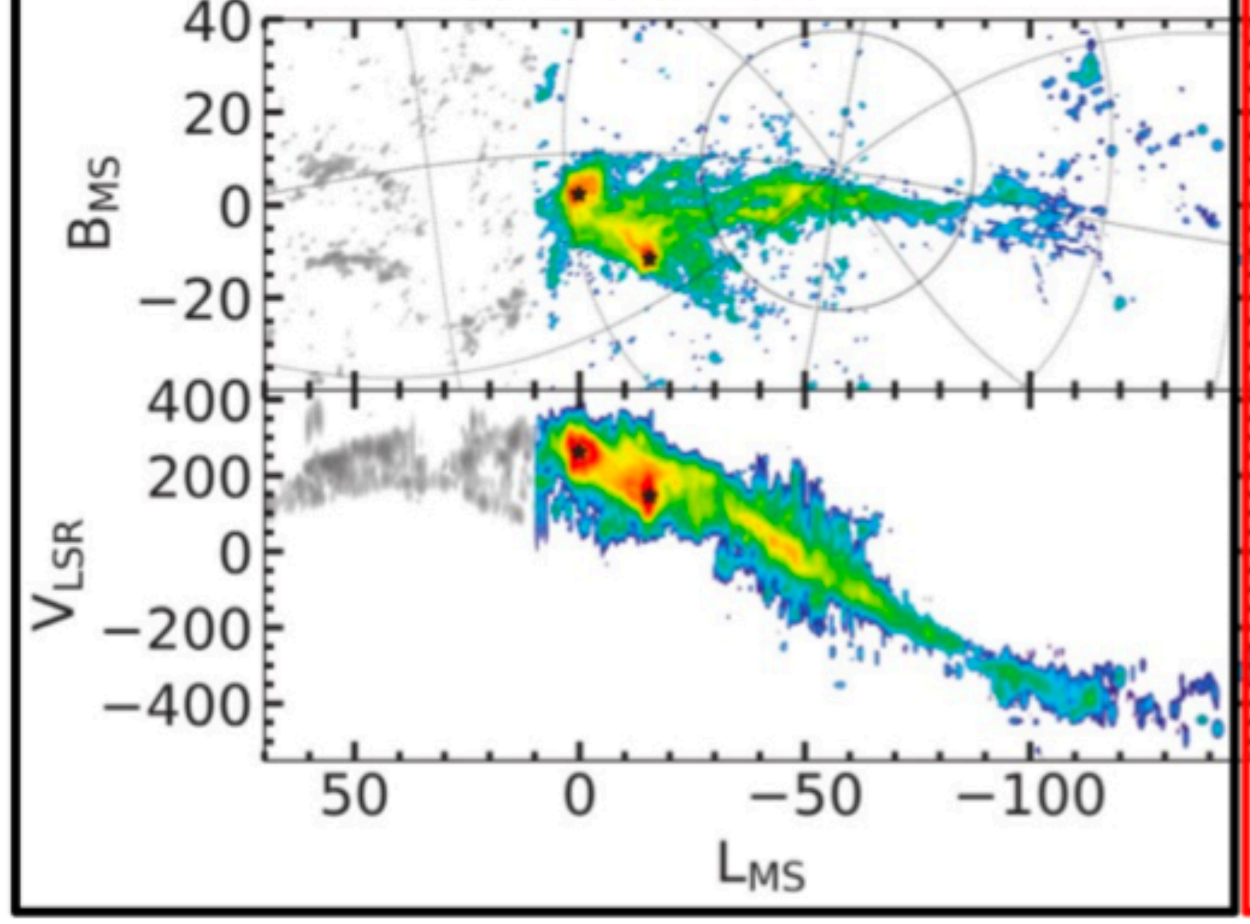
Ram-pressure+collision model

Reproduce:

- the two filaments naturally.
- Neutral gas kinematics.
- Neutral gas mass.
- Gas sky distribution.

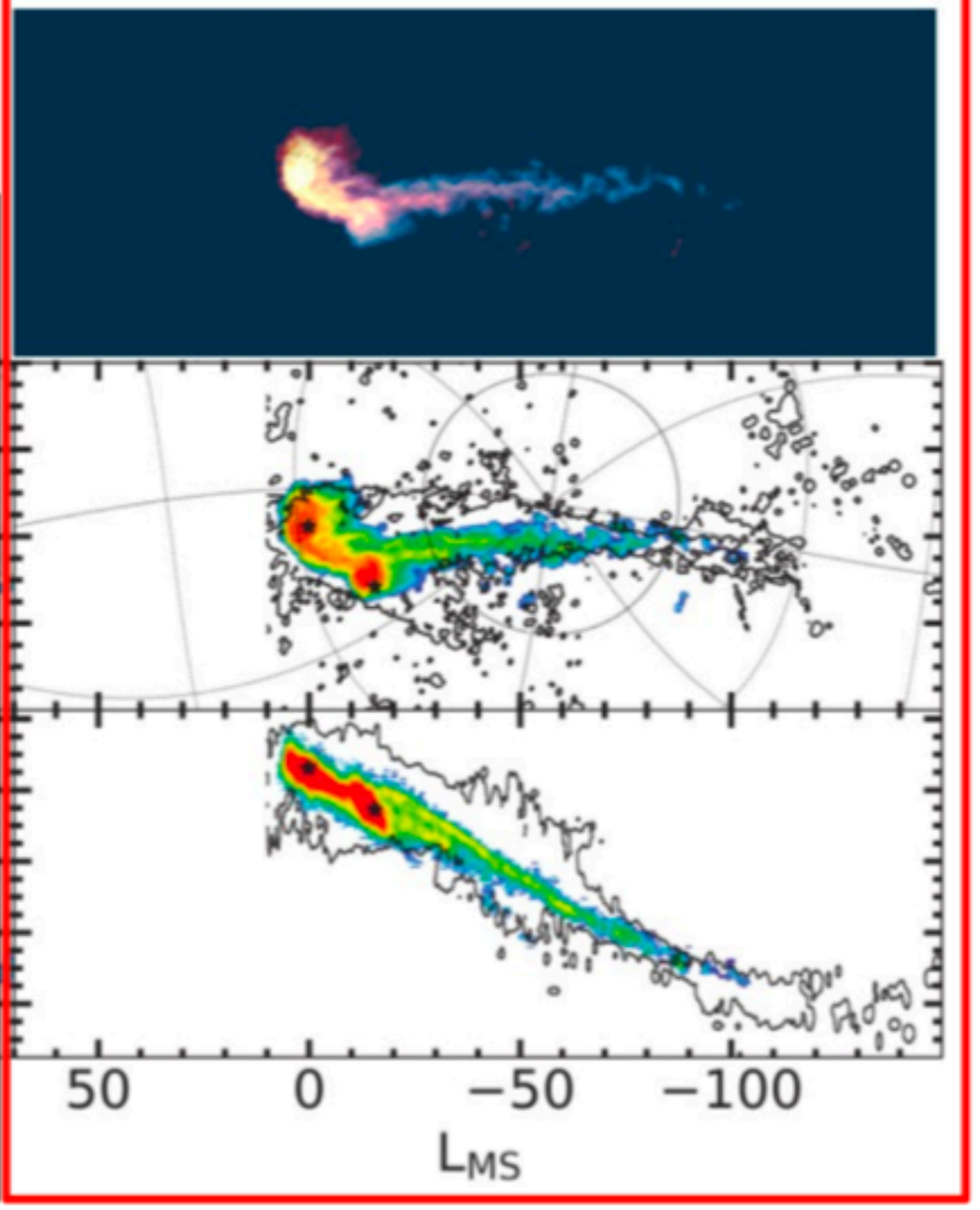
HI observation

Nidever et al. 2010

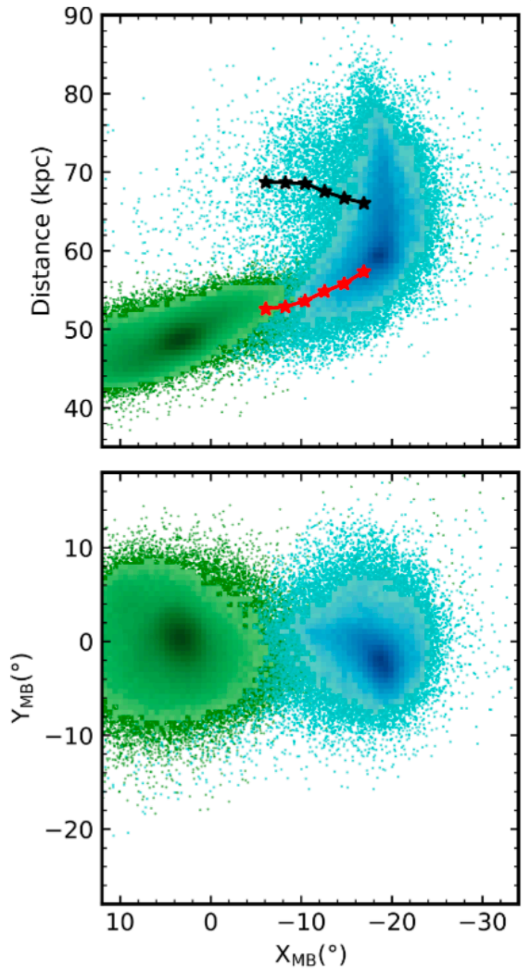


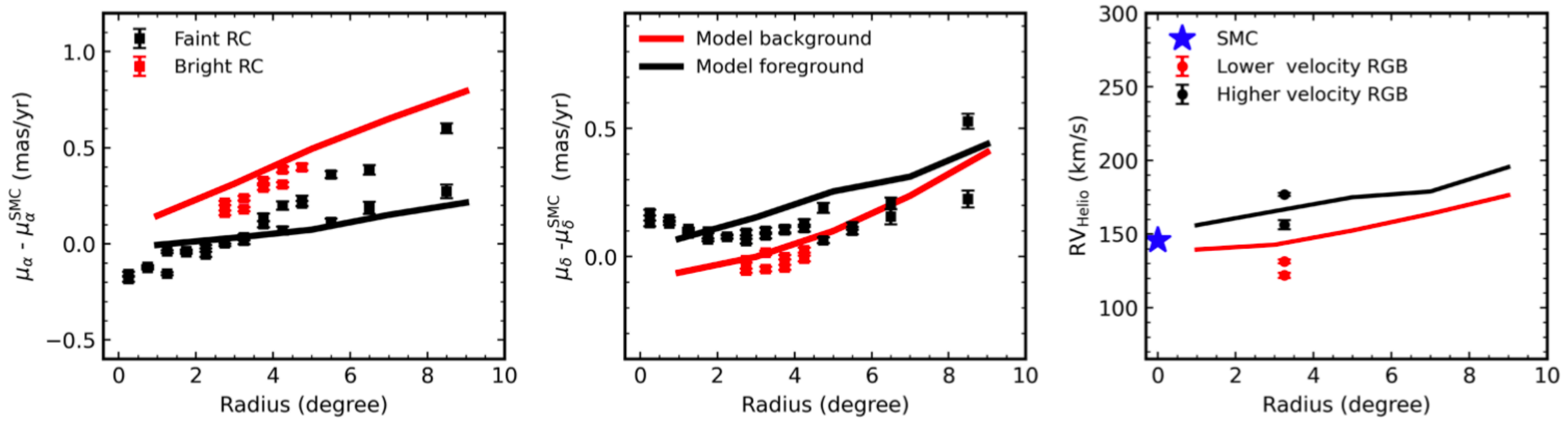
Simulation Model

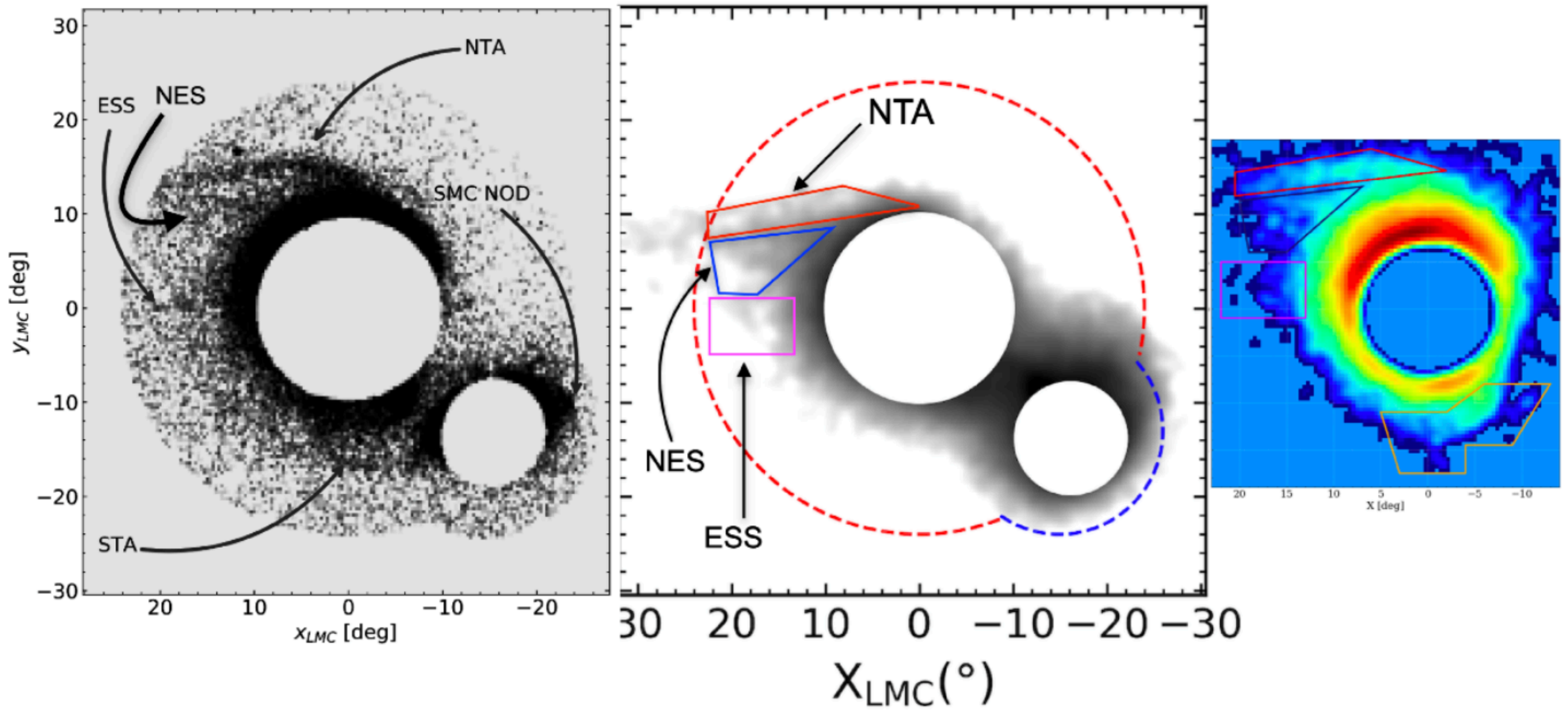
Wang et al. 2019



Lots of predictions are confirmed by observations







- Nbody+Hydrodynamics
- Gravitation + gas cooling, SF, feedback
- C+MPI

Great thanks to NADC

Excellent hardware and software

Excellent technique supports & service

Toward a complete understanding the formation of the Magellanic System

Jianling WANG — LAMOST

Collaborators:

- **Francois Hammer** (Paris Observatory, CNRS)
- **Yanbin Yang** (Paris Observatory, CNRS)
- **Vincenzo Ripepi** (INAF – Osservatorio Astronomico di Capodimonte, Italy)
- **Maria-Rosa L. Cioni** (Leibniz-Institüt für Astrophysik Potsdam, Germany)
- **Hector Flores** (Paris Observatory, CNRS)
- **Mathieu Peuch** (Paris Observatory, CNRS)

References:

1. “*THE MAGELLANIC STREAM SYSTEM. I. RAM-PRESSURE TAILS AND THE RELICS OF THE COLLISION BETWEEN THE MAGELLANIC CLOUDS*”
   Hammer et al., 2015, ApJ, 813, 110
2. *Towards a complete understanding of the Magellanic Stream Formation*
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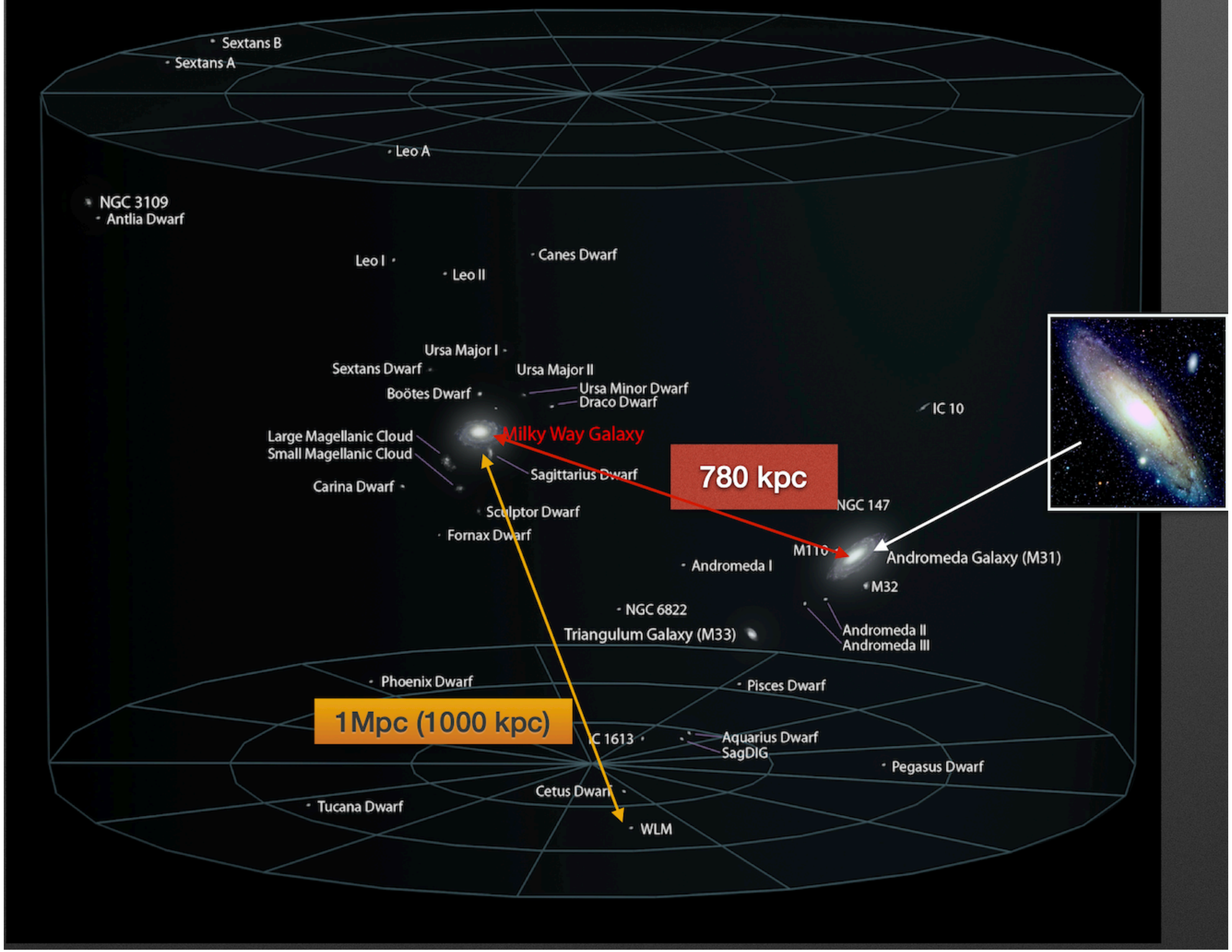
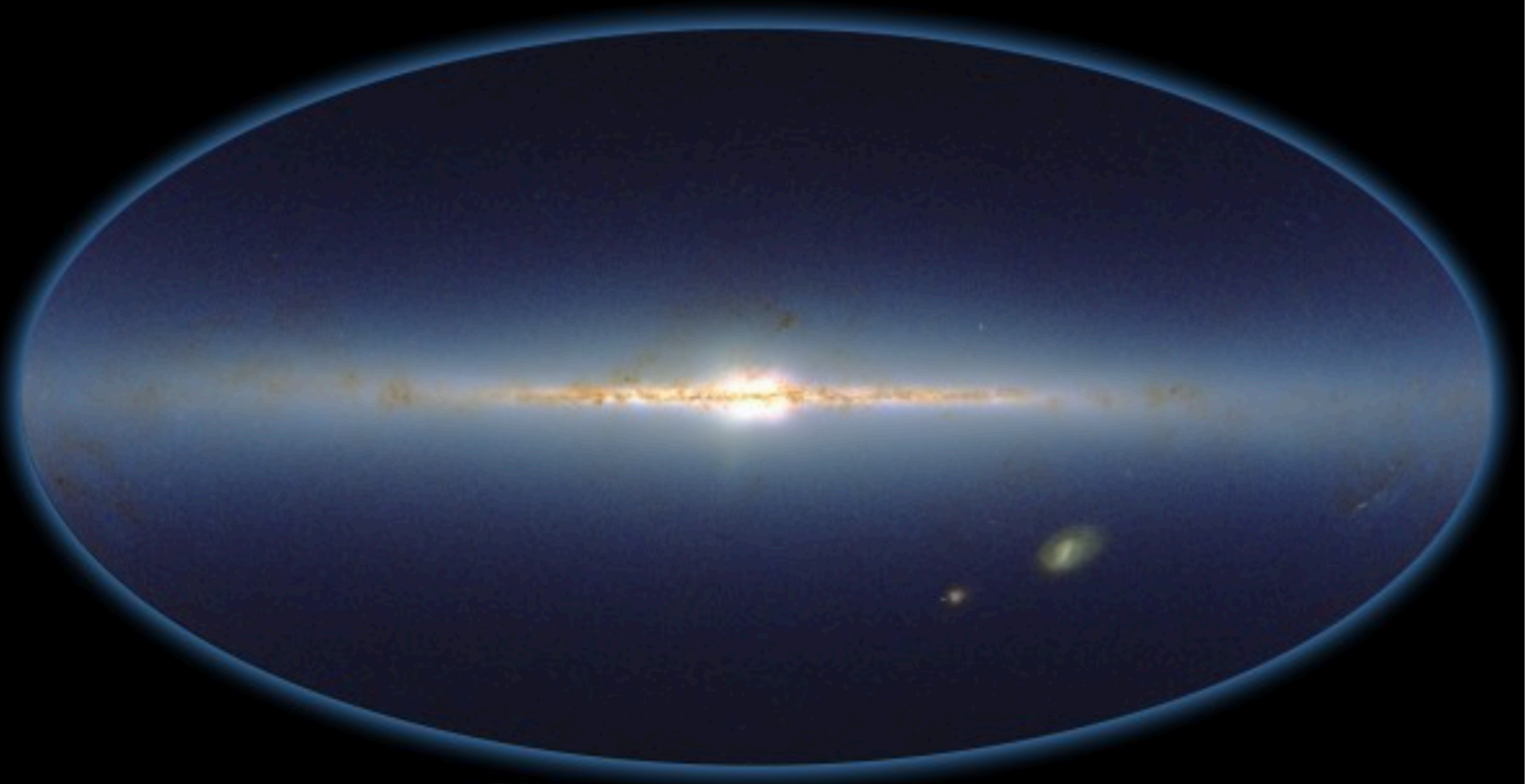
Outline

1. **The Magellanic Stream and the impasse:**
    1. *The properties of MS+MCs.*
    2. *The failures and impasse for understanding MS.*
2. **Our N-body+Hydrodynamic model:**
    1. “ram-pressure plus collision” model.
    2. What we have reproduced
3. **The confirmed predictions by our model:**
    1. *Many substructure: NTA, NES …*
    2. *The NTA morphology, distance, kinematics*
    3. *Two populations in the Bridges: their distance and kinematics*
4. ***Summary***

LOCAL GALACTIC GROUP



2MASS Covers the Sky

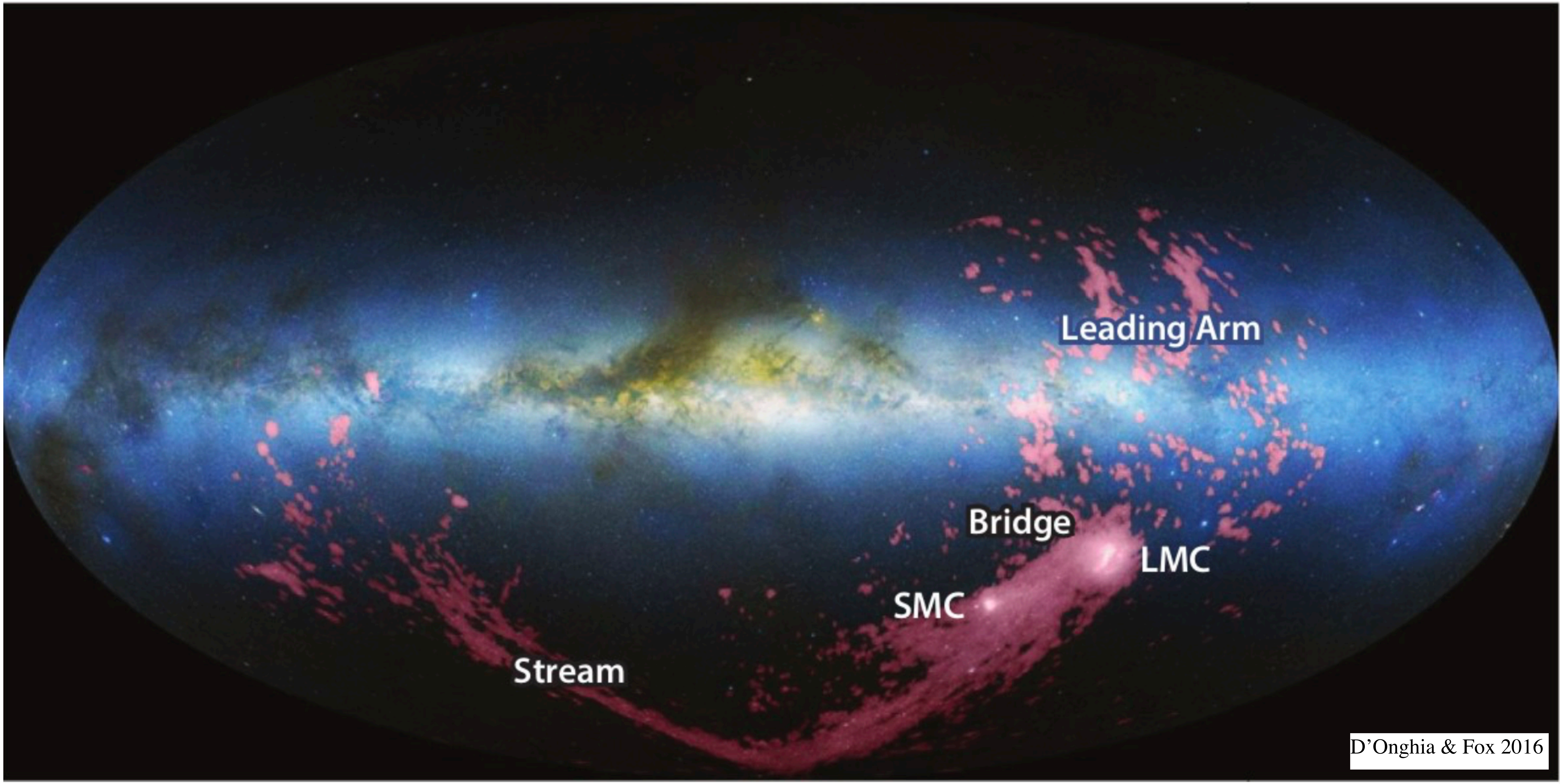


The Two Micron All Sky Survey

Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts

1. The Magellanic Stream and the impasse

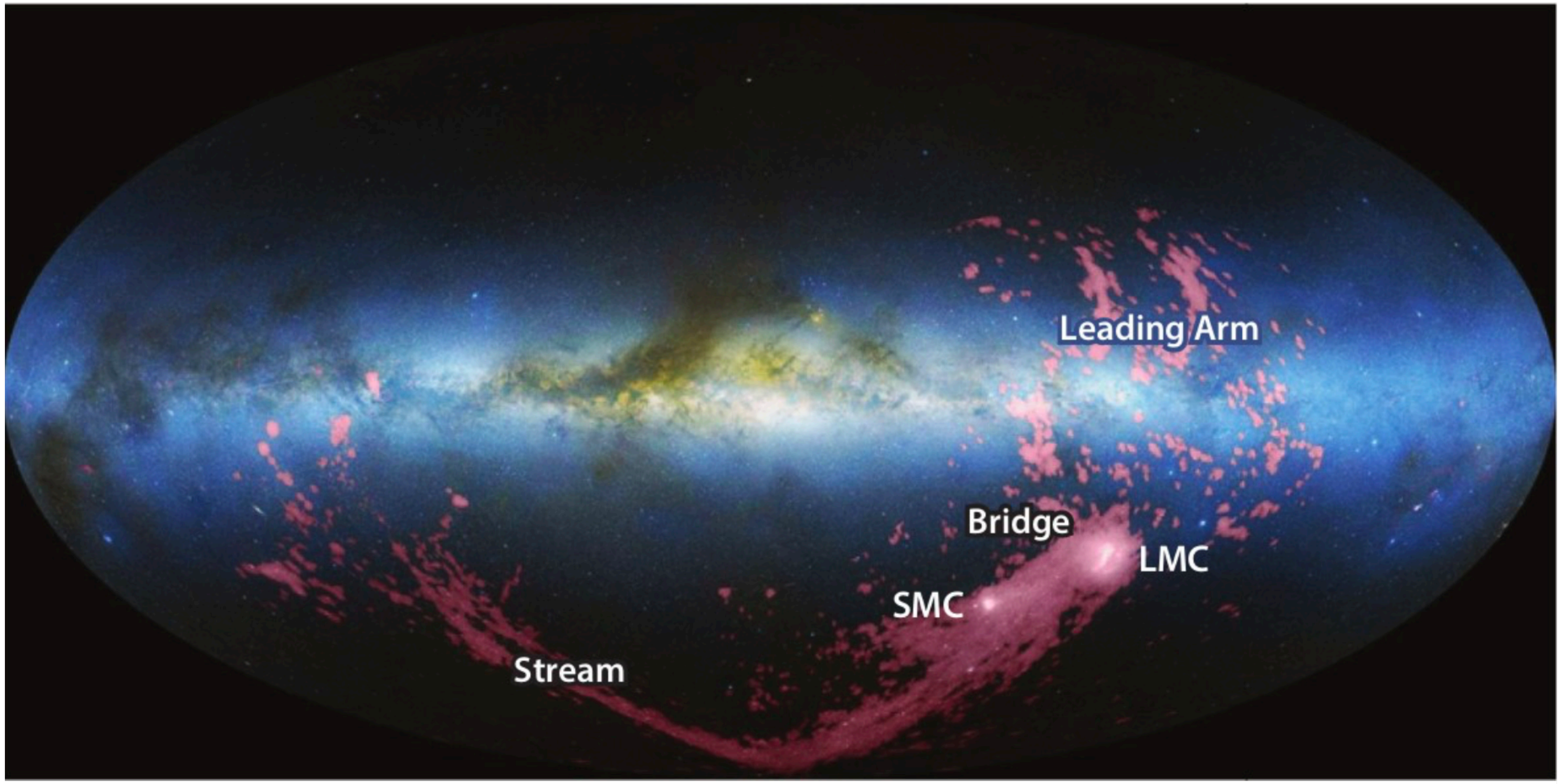
The HI Magellanic Stream: ~230° length, with Leading Arm

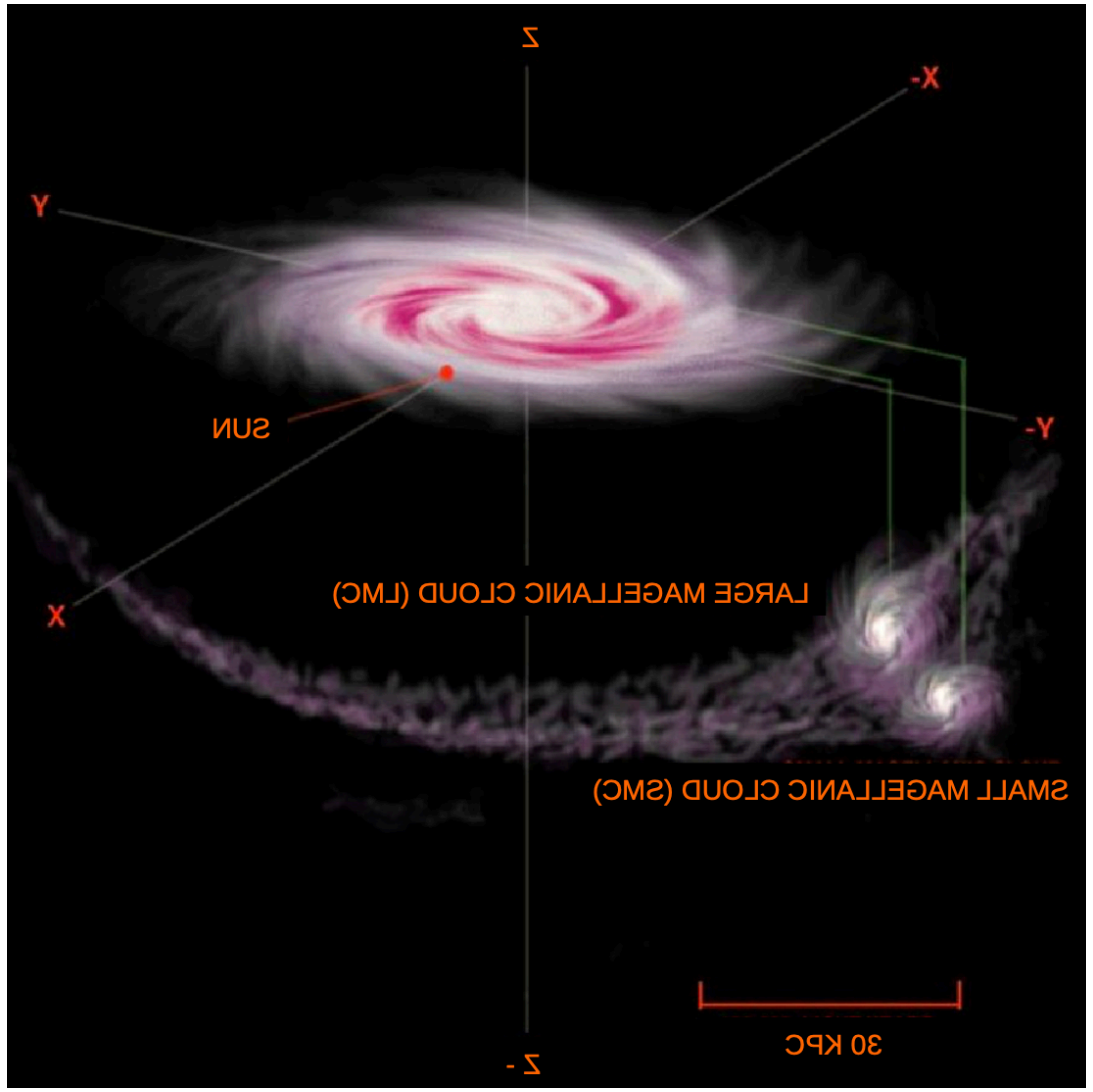


D’Onghia & Fox 2016

1. The Magellanic Stream and the impasse

No satisfied Explanation for the gigantic Magellanic Stream



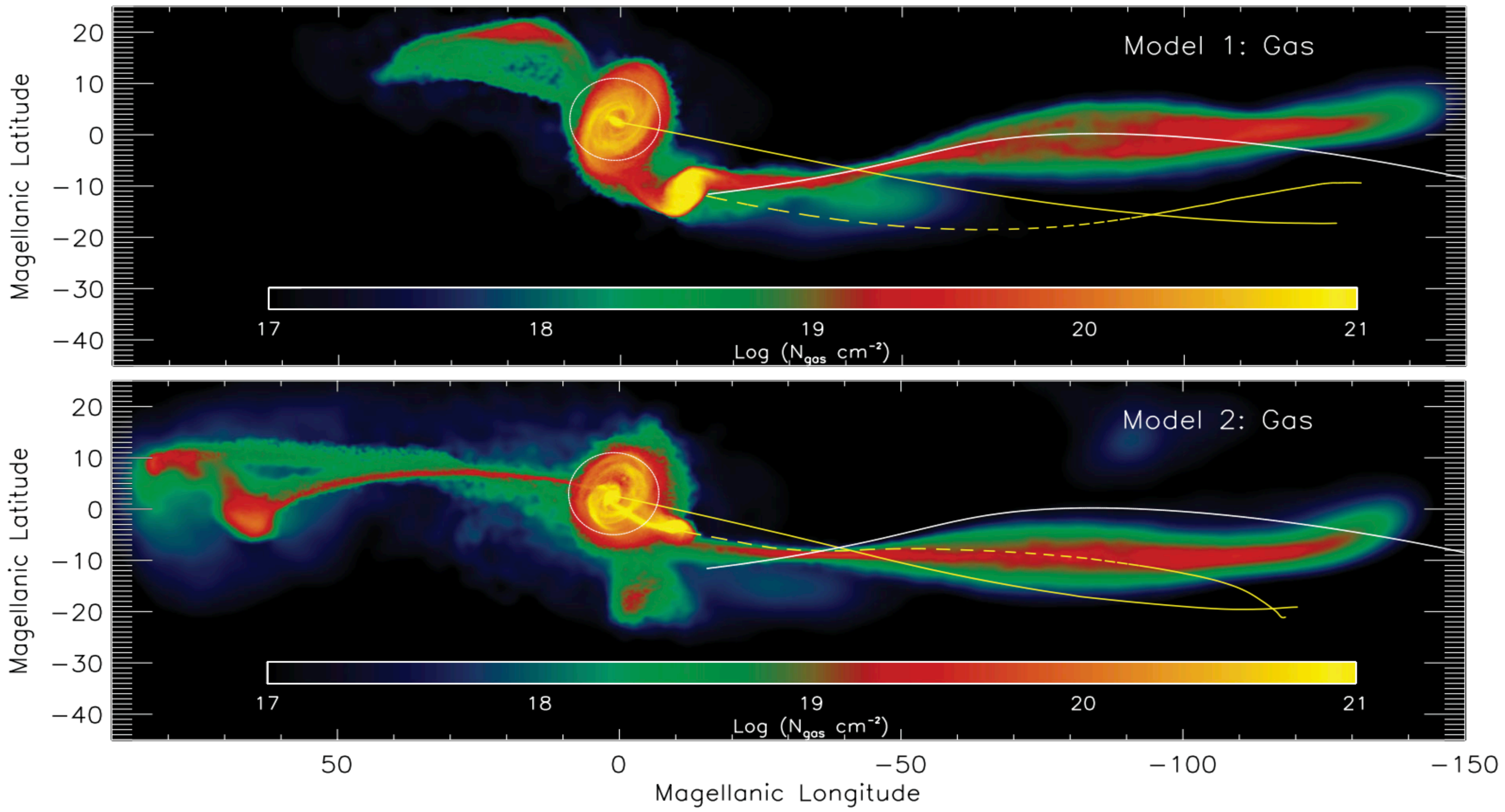


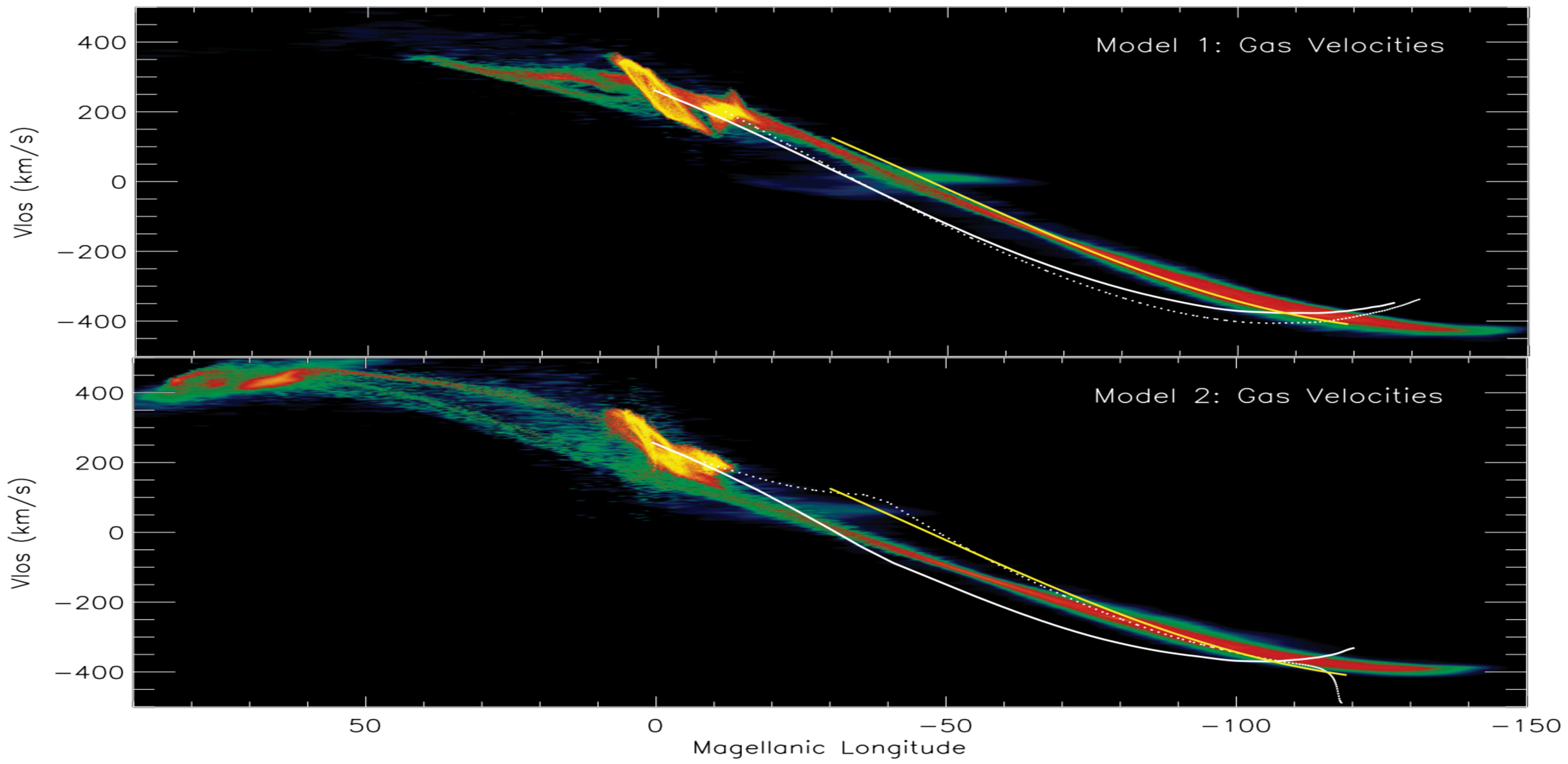
Firstly identified as the MS by Mathewson+74
after detections by van Kuilenburg and Wannier & Wrixon72

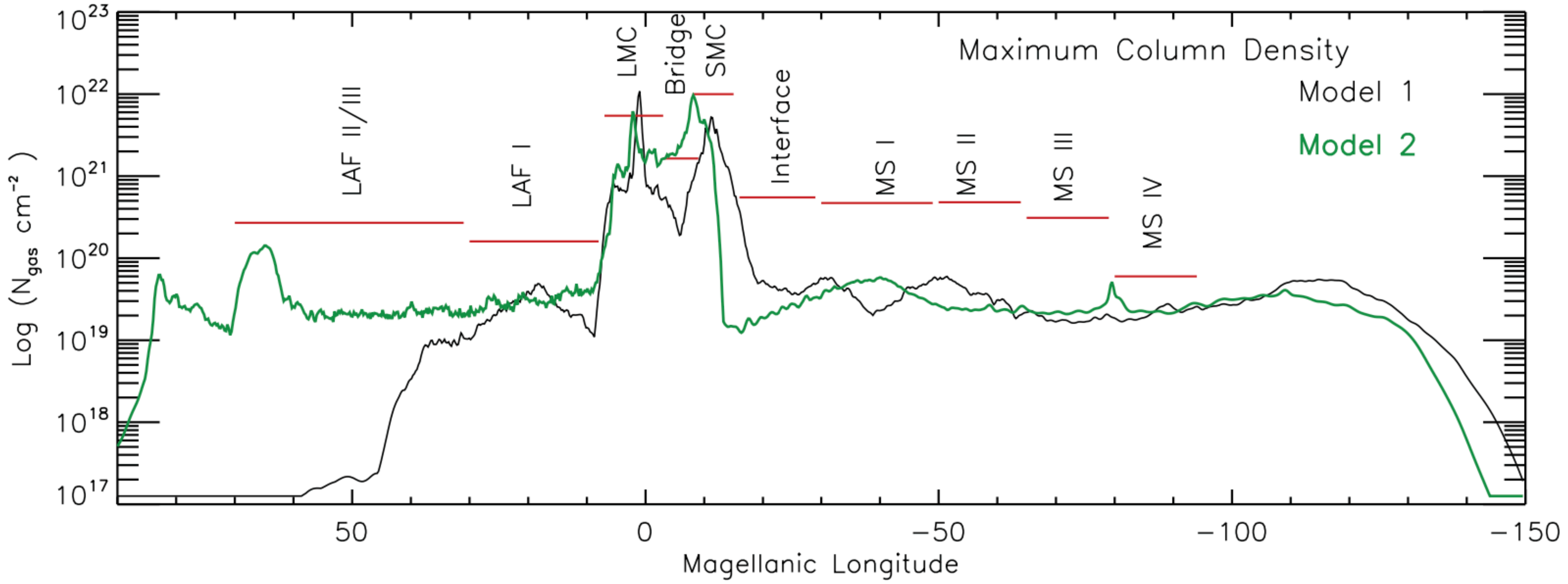
We are able to detect galaxies at z>6.
but we did not know the origin of MS yet

1. The Magellanic Stream and the impasse

The dearth of predictions from tidal models



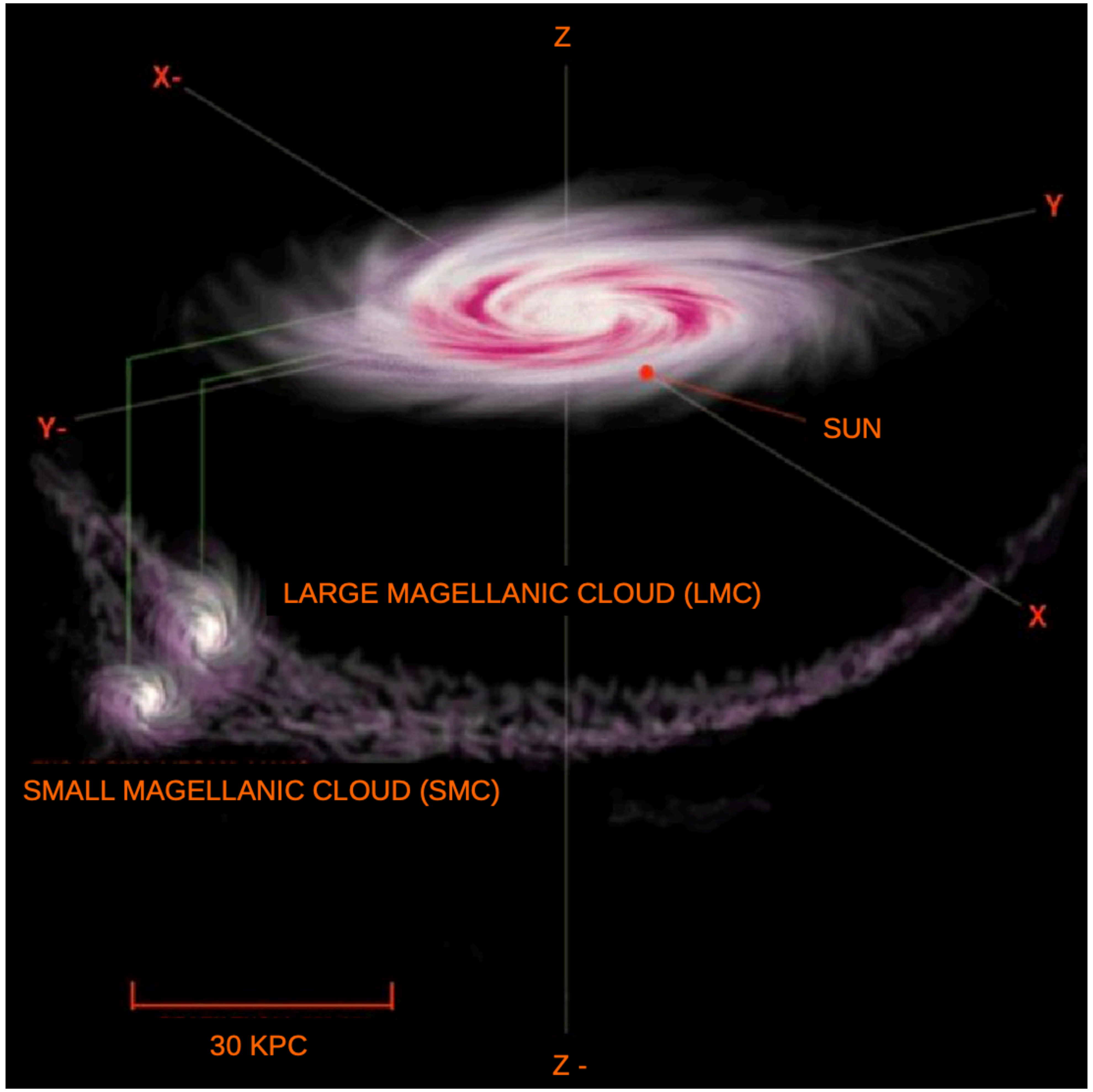




Besla et al. 2012

- Only reproduce 1/10 of N(HI).
- Can not explain large amount of ionized gas.
- Can not explain absence of stars.
- Can not explain two filaments.
- ……

1. The Magellanic Stream and the impasse



Journal of Astronomical History and Heritage, 15(2), 100-104 (2012).

DISCOVERY OF THE MAGELLANIC STREAM

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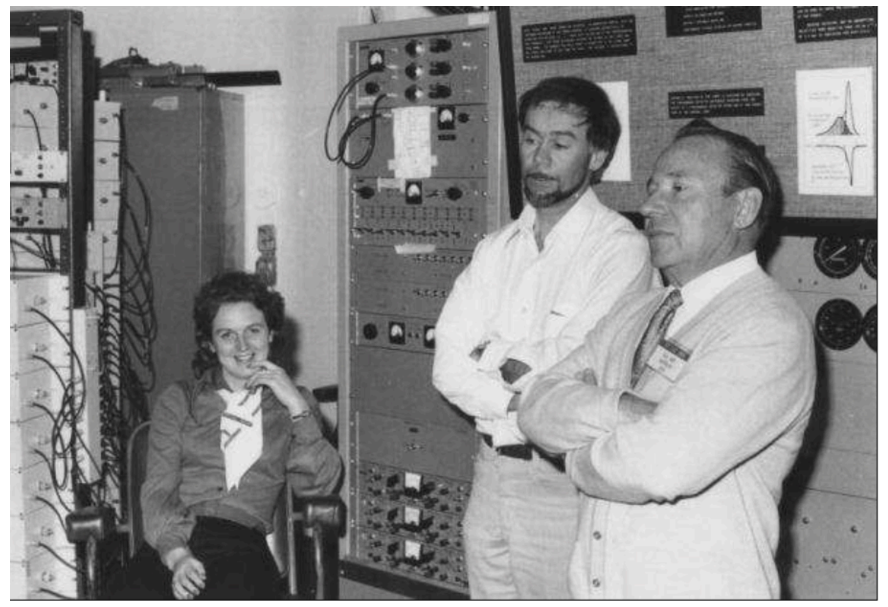
E-mail: pamaguire@ozemail.com.au

Abstract: The story of the discovery of the Magellanic Stream is told and the initial endeavours to find its origin described. These centred about either a tidal or a ram pressure origin. The splitting of the Small Magellanic Cloud into two fragments and the ubiquitous double HI profiles of the SMC, parts of the Bridge and the beginning of the Stream are central in determining the age of the Stream as 0.3 Gyr. However a composite map from recent surveys by a large number of observatories has extended the length of the Stream by 40° making the previous theories untenable. A new tidal model based upon the increased length of the Stream has estimated its age to be about 1.5 Gyr, five times the earlier estimates which were made using sound independent observational evidence. We seem to be no closer to understanding the origin of the Stream than when it was discovered nearly forty years ago.

5 CONCLUDING REMARKS

An impasse has been reached after 37 years of hard work by many astronomers, and we are now no closer to reaching an understanding of the origin of the Magellanic Stream than when I was in the Control Room of the 210-ft Parkes Radio Telescope pumping air some 40 years ago! Perhaps there is something very fundamental about our Galaxy that we don't know?



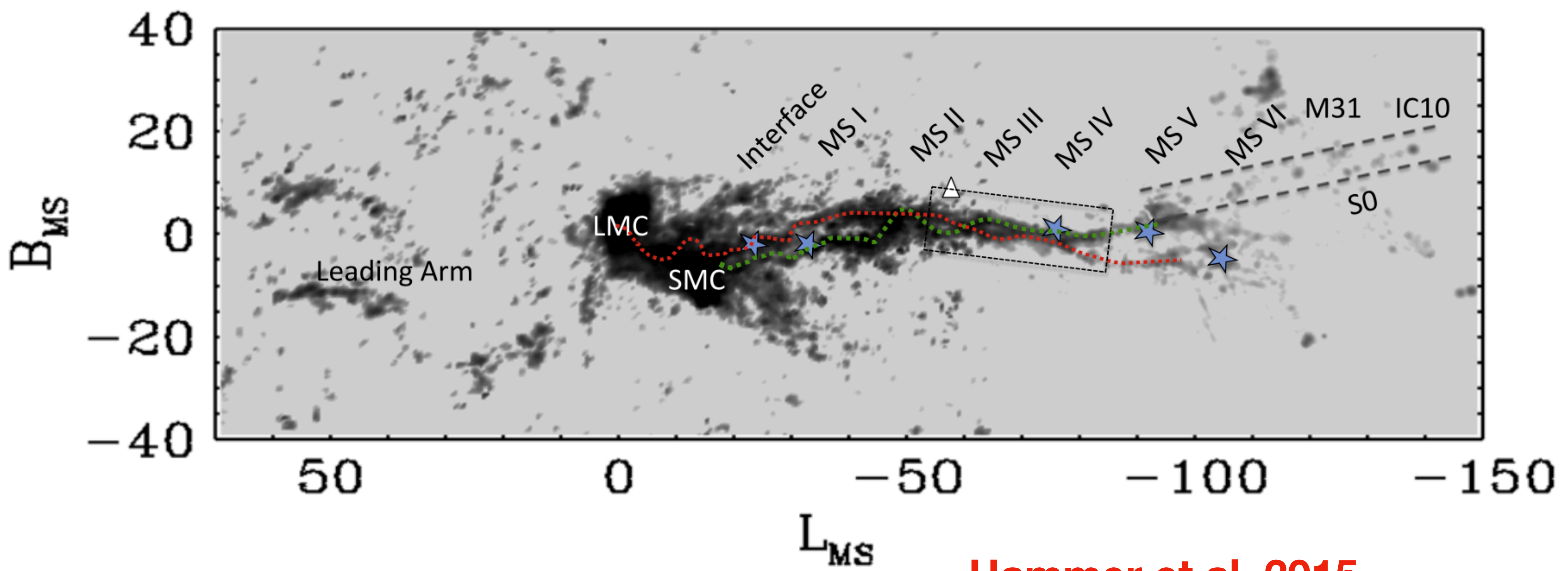
Firstly identified as the MS by Mathewson+74 after detections by van Kuilenburg and Wannier & Wrixon72

1. The Magellanic Stream and the impasse

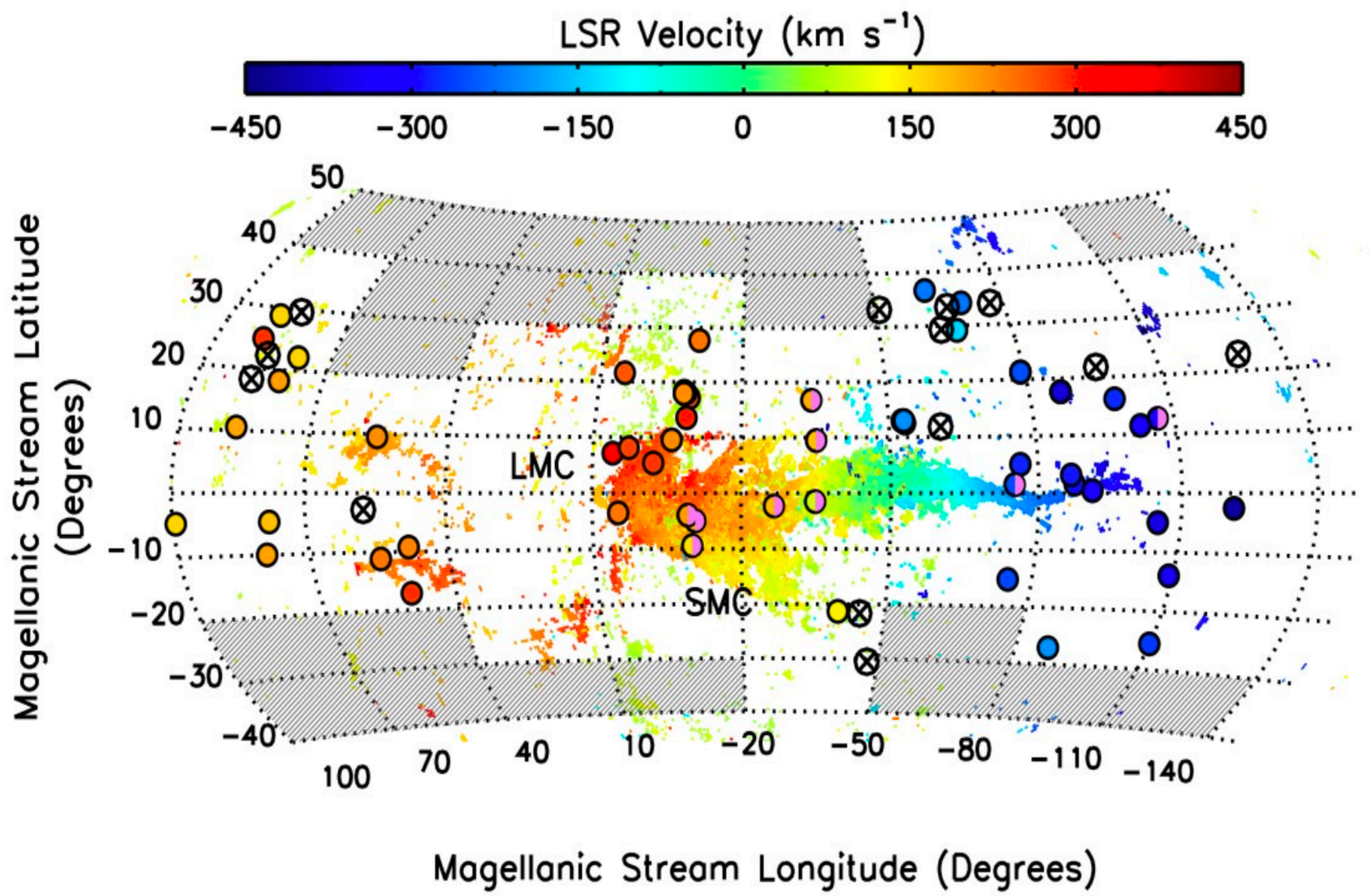
Large amount of ionized gas stripped along MS

Two filamentary DNA-like structure of MS

- **Morphology** (Hammer et al. 2015)
- **Kinematics** (Nidever et al. 2010)
- **Chemistry** (Fox et al. 2013, Richter et a. 2013)



Hammer et al. 2015



Fox et al. 2014

1. The Magellanic Stream and the impasse

Ram pressure exerted by the CGM gas of the Milky Way halo

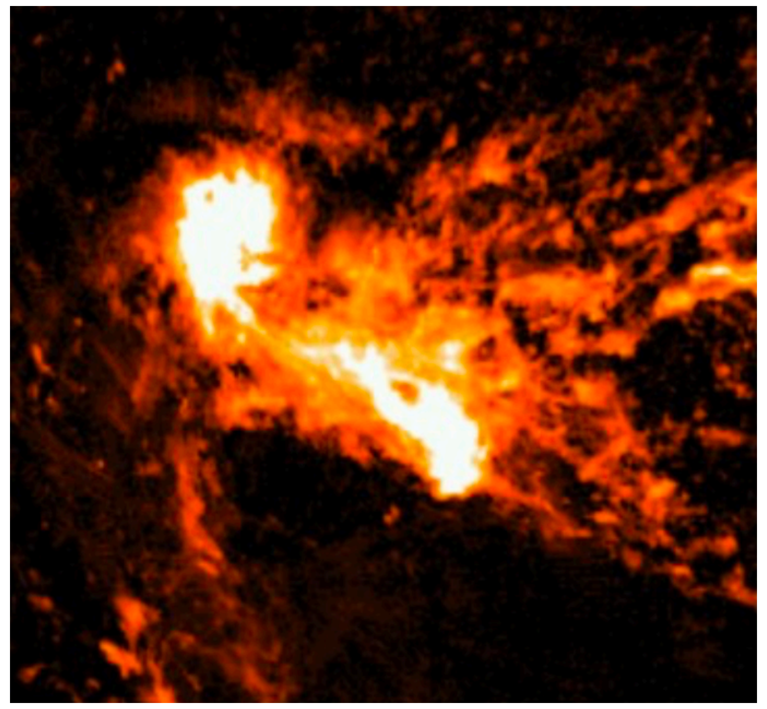
Evidences for a prominent Multiphase CGM gas affecting the Magellanic Stream and Clouds

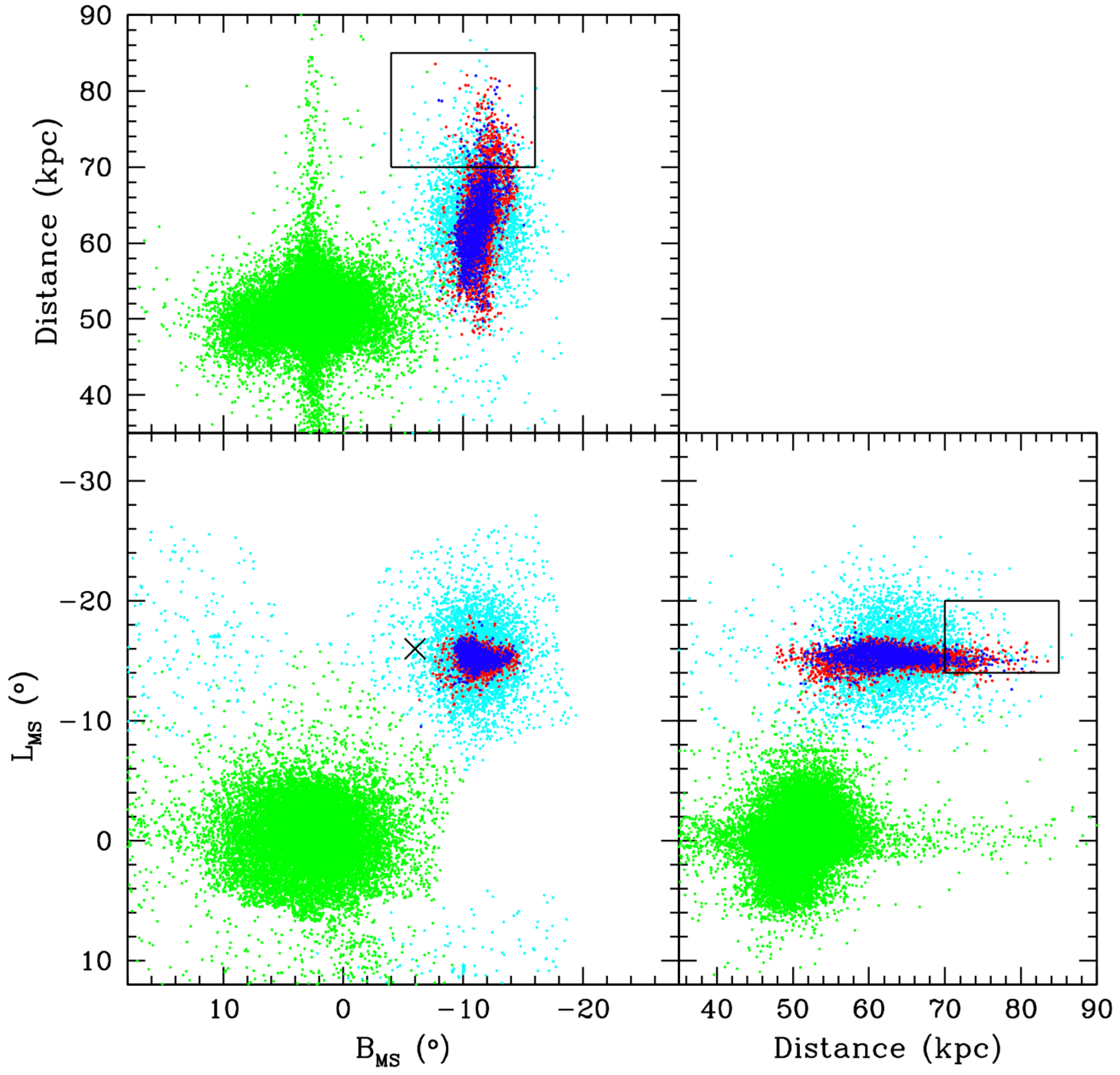
- Associated high velocity clouds are disrupted (multi-phases, Karlberla & Haud, 2006)
- X-ray observations (Gupta et al., 2012, Hodges-Kluck, Miller & Bregman, 2016)
- LMC gas disk has shrunk (Nidever, 2013)
- HST/COS spectra — QSO absorption line → Warm CGM (Zheng et al. 2019)

Evidence for recent collision between MCs

200~ 300 Myr old collision between the Magellanic Clouds.

- *the Bridge*
- *same SFH peak of the Clouds* (*Nidever+2013*)
- *proper motions* (*Kallivayalil et al. 2013*)
- *Relics in GASS data (anomalous HVCs)* (*Hammer et al. 2015; Putman et al. (2002, 2003)*)
- *Cigar 3D shape of SMC* (*Ripepi et al. 2017*)





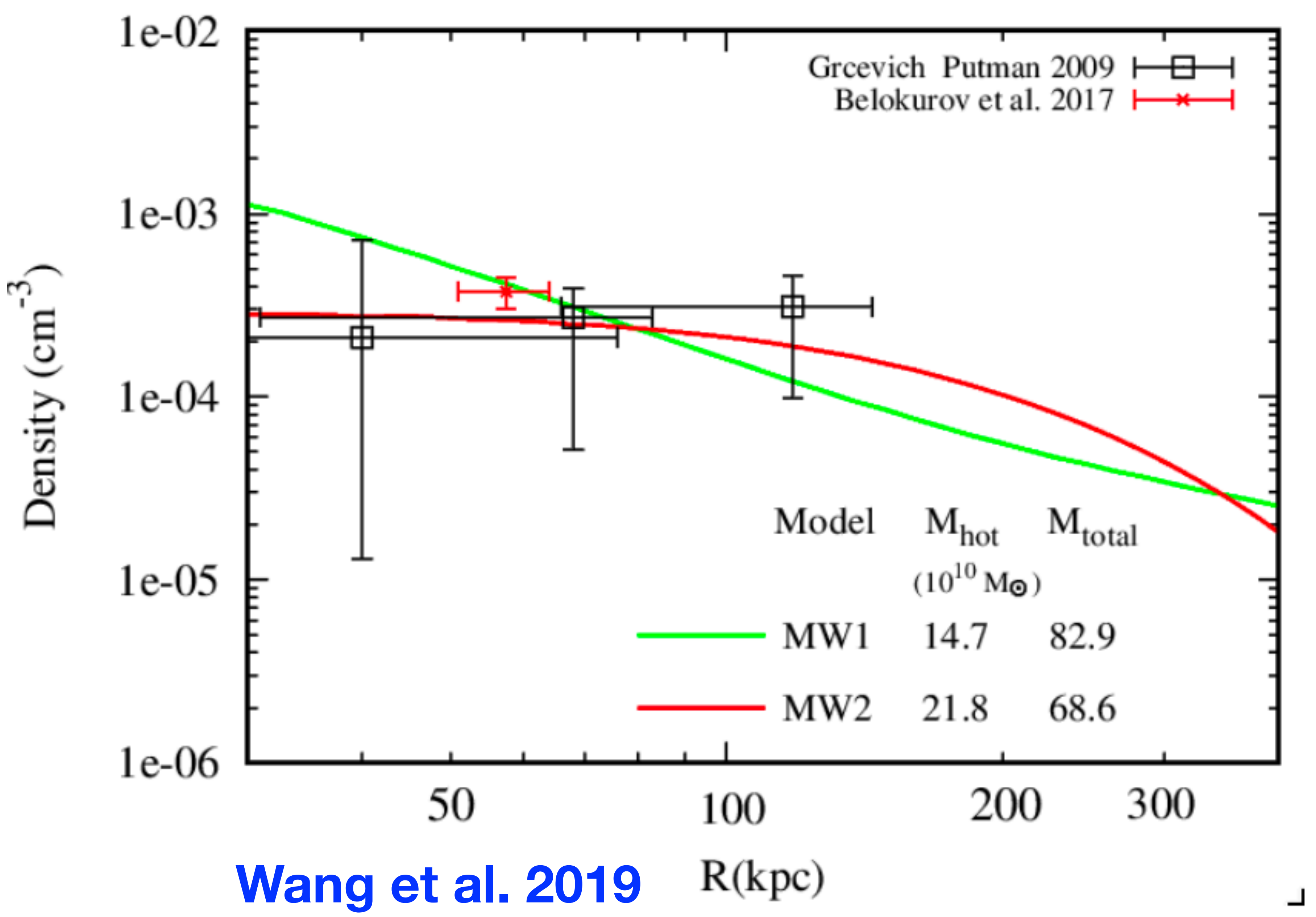
2. Our N-body+Hydrodynamic model

Modelling Magellanic System (Clouds & Streams)

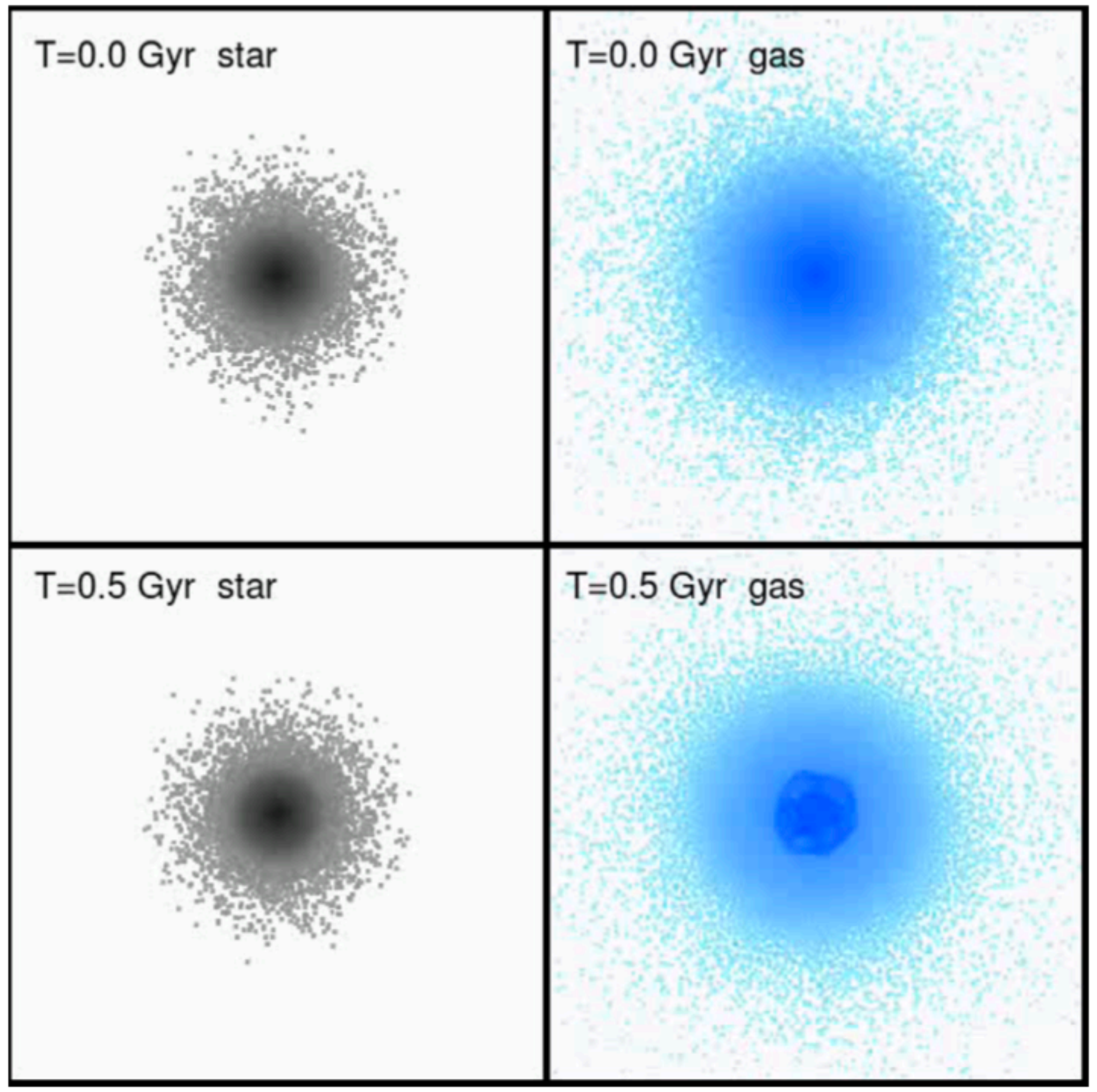
- Ram-pressure + collision model
- Milky Way model: hot gas corona & rotation curve.
- GIZMO: Nbody+hydrodynamic

Gas rich dwarfs for progenitors of MCs

MW model with hot corona



Wang et al. 2019

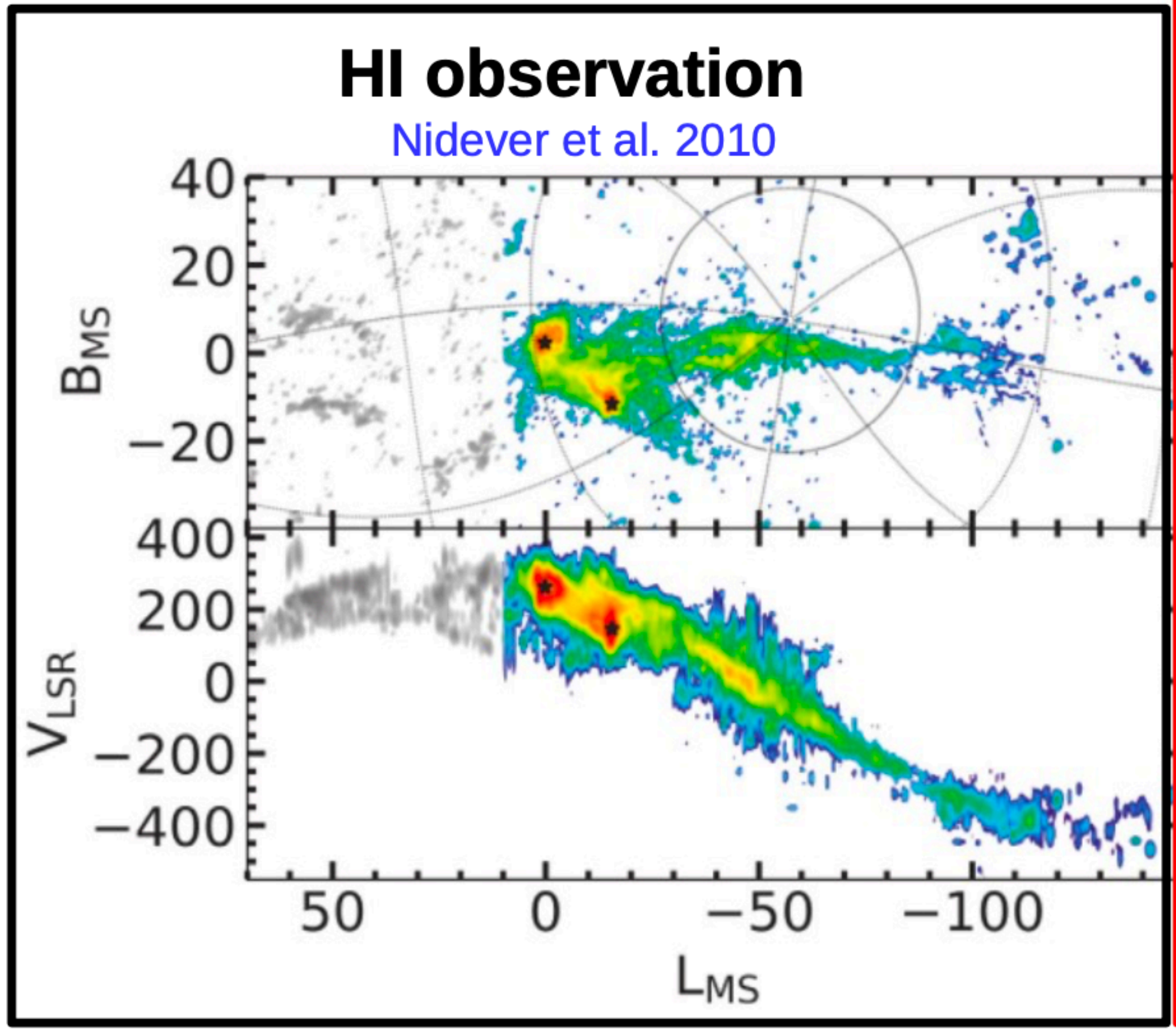


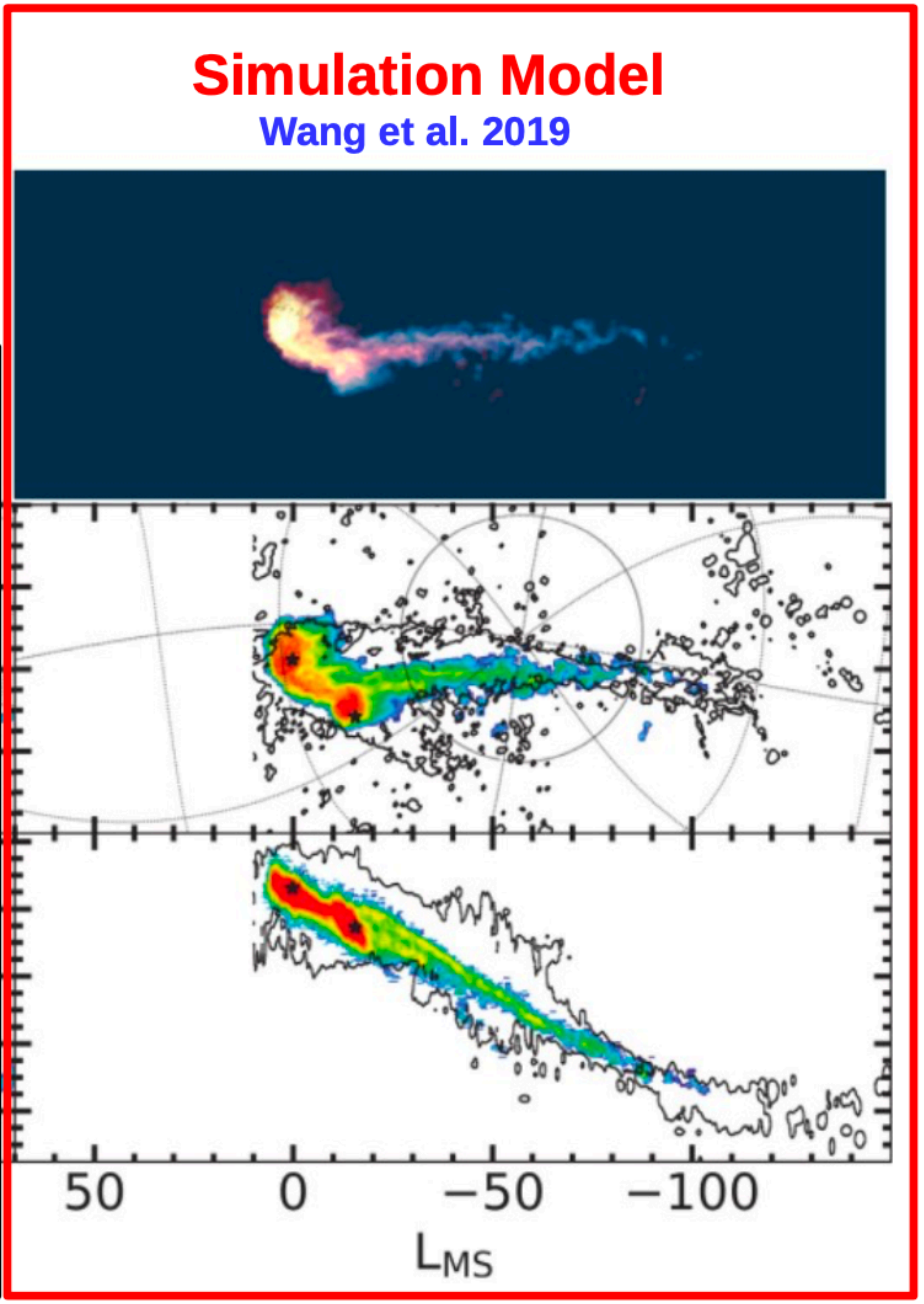
2. Our N-body+Hydrodynamic model

Ram-pressure+collision model

Reproduce:

- the two filaments naturally.
- Neutral gas kinematics.
- Neutral gas mass.
- Gas sky distribution.



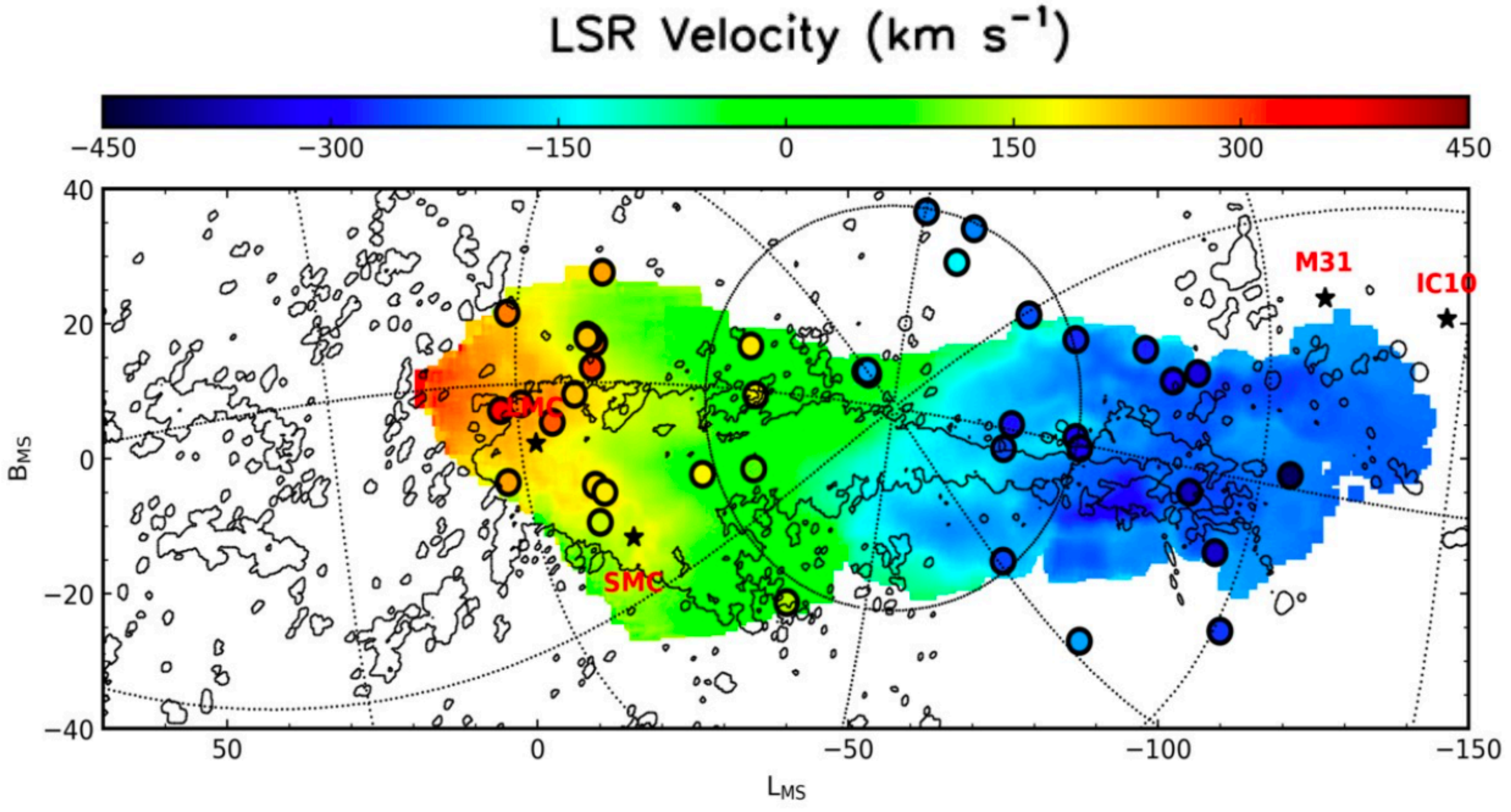


2. Our N-body+Hydrodynamic model

Gas of the Clouds stripped by ram-pressure exerted by the hot gas in the Milky Way halo

2. Our N-body+Hydrodynamic model

Warm+hot gas mass and gas velocity



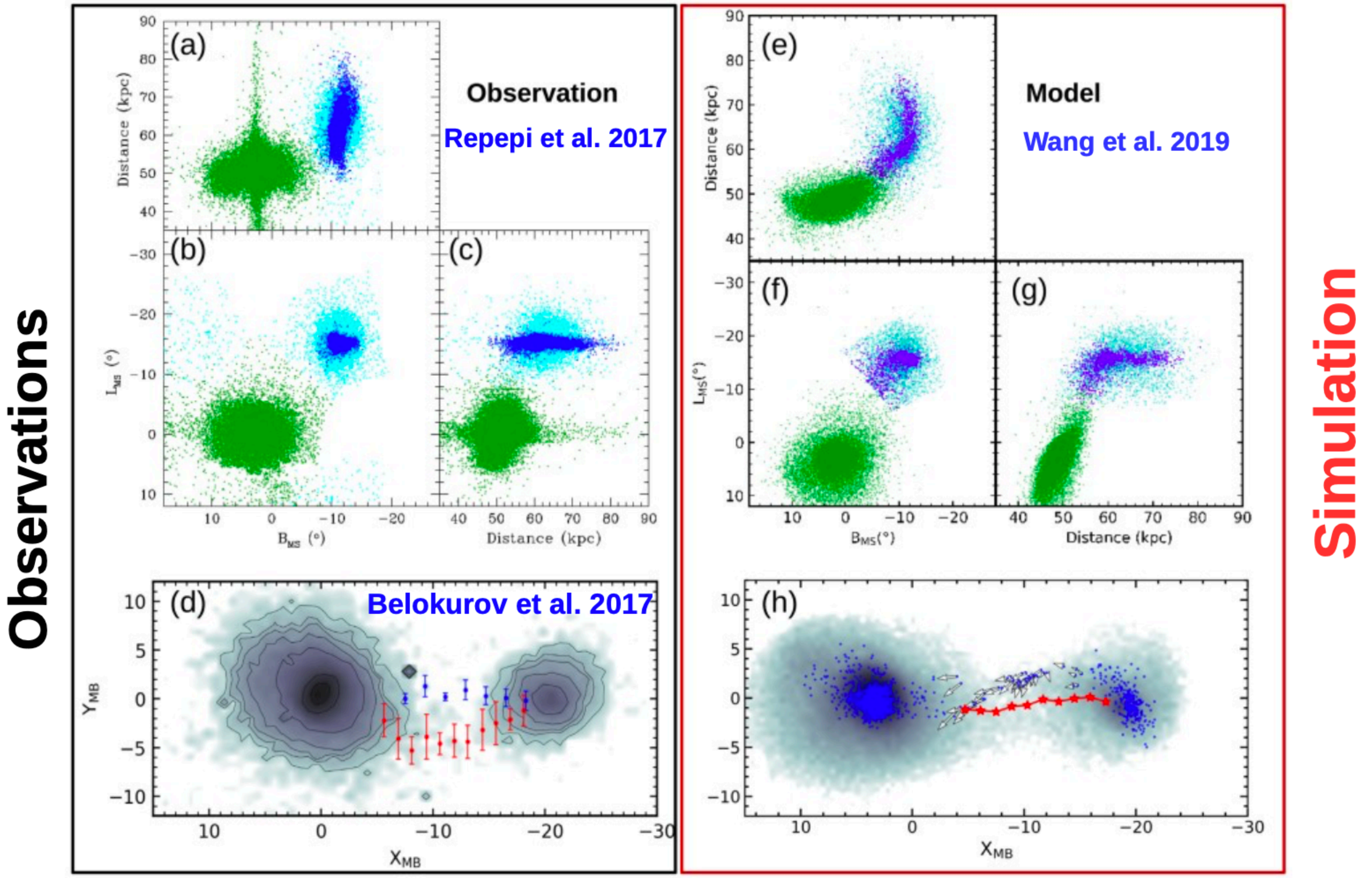
- Color region: simulation (Wang et al. 2019)
- Color circle : velocity of UV absorption (Fox et al. 2014)

The mass in Warm+hot gas:

Observation: ~1x10^9 M$_\odot$

Simulations: 0.8-0.93x10^9 M$_\odot$

- The stretched young stars in SMC (~30 kpc)
- The offset of Young and Old stars in the Bridge region.



The power of “ram-pressure+collision” model

(Hammer et al. 2015; Wang et al. 2019; Wang et al. 2022a; Wang et al. 2022b)

Many predictions have been confirmed by observations!

3. The confirmed predictions by our model

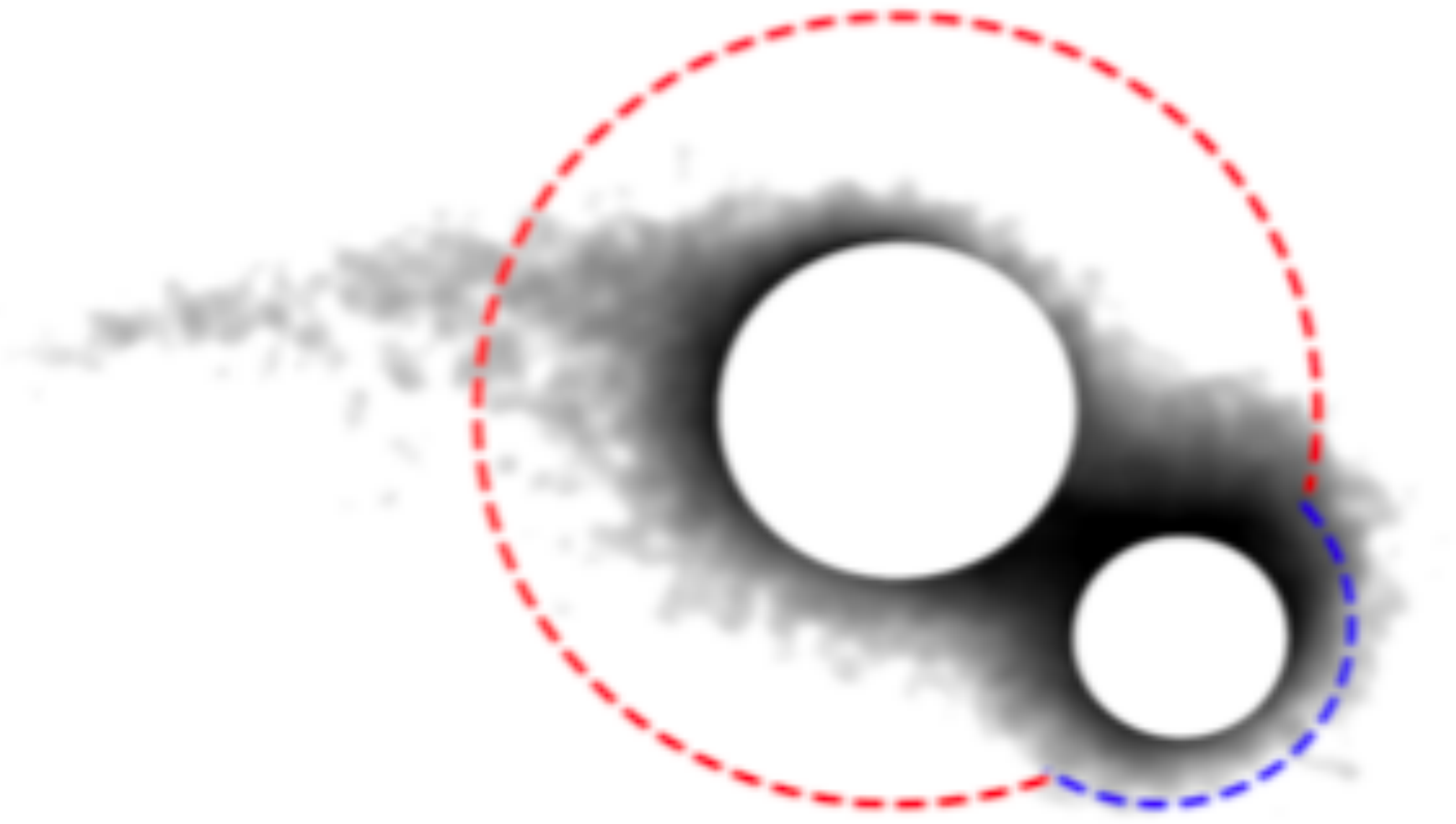
Two populations distributed in the Bridge region:

Wang et al. 2022b

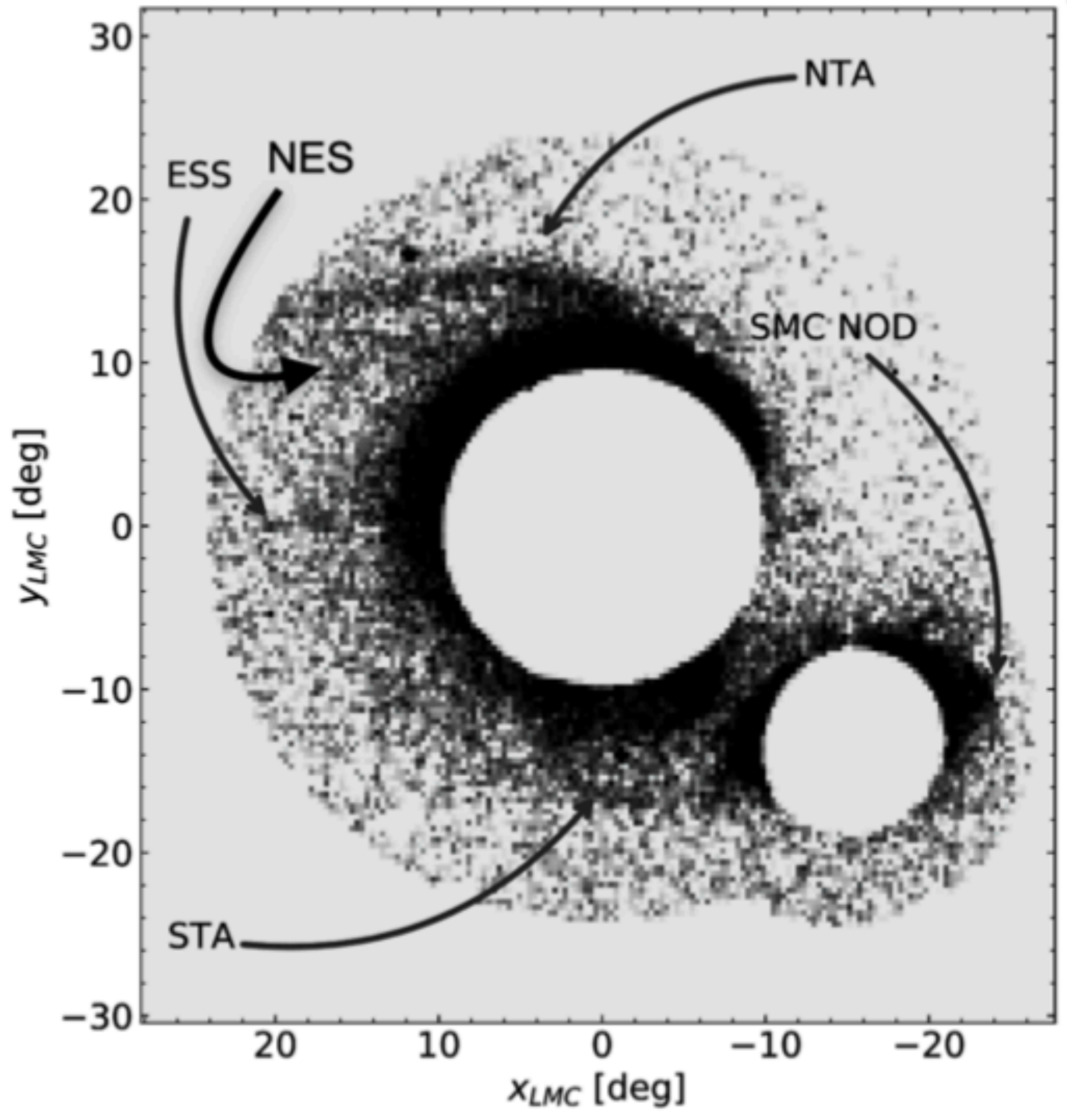
3. The confirmed predictions by our model

Substructures : NTA, NES, ESS

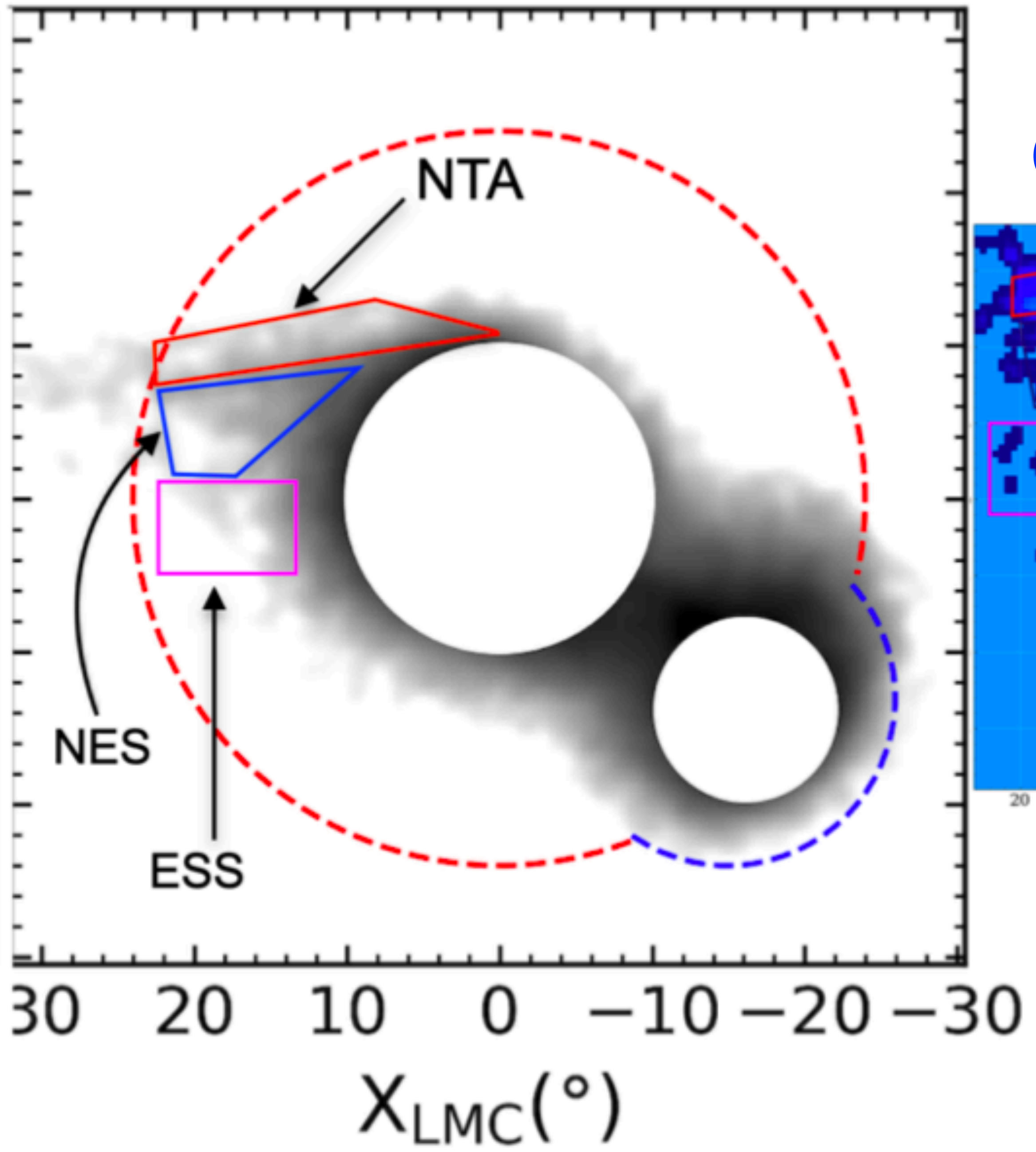
Simulation Model



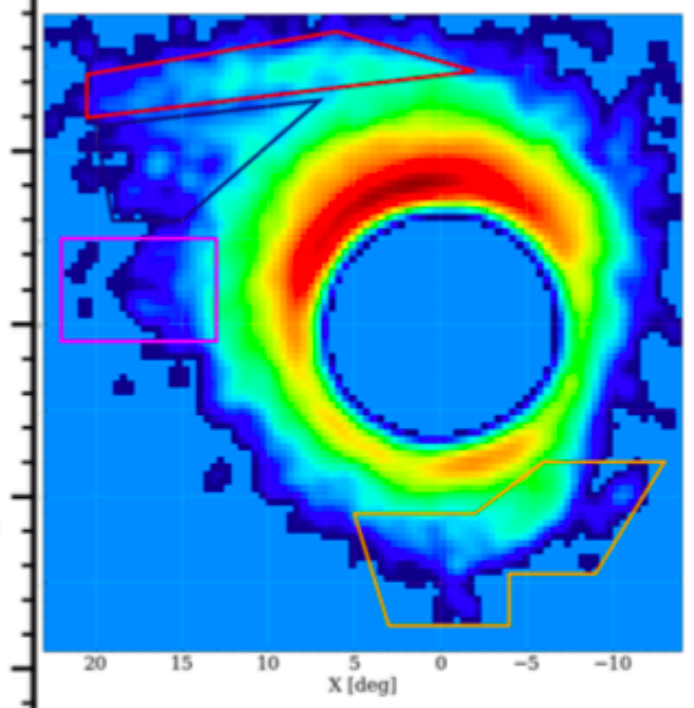
Gaia EDR3



Simulation Model



Gaia EDR3

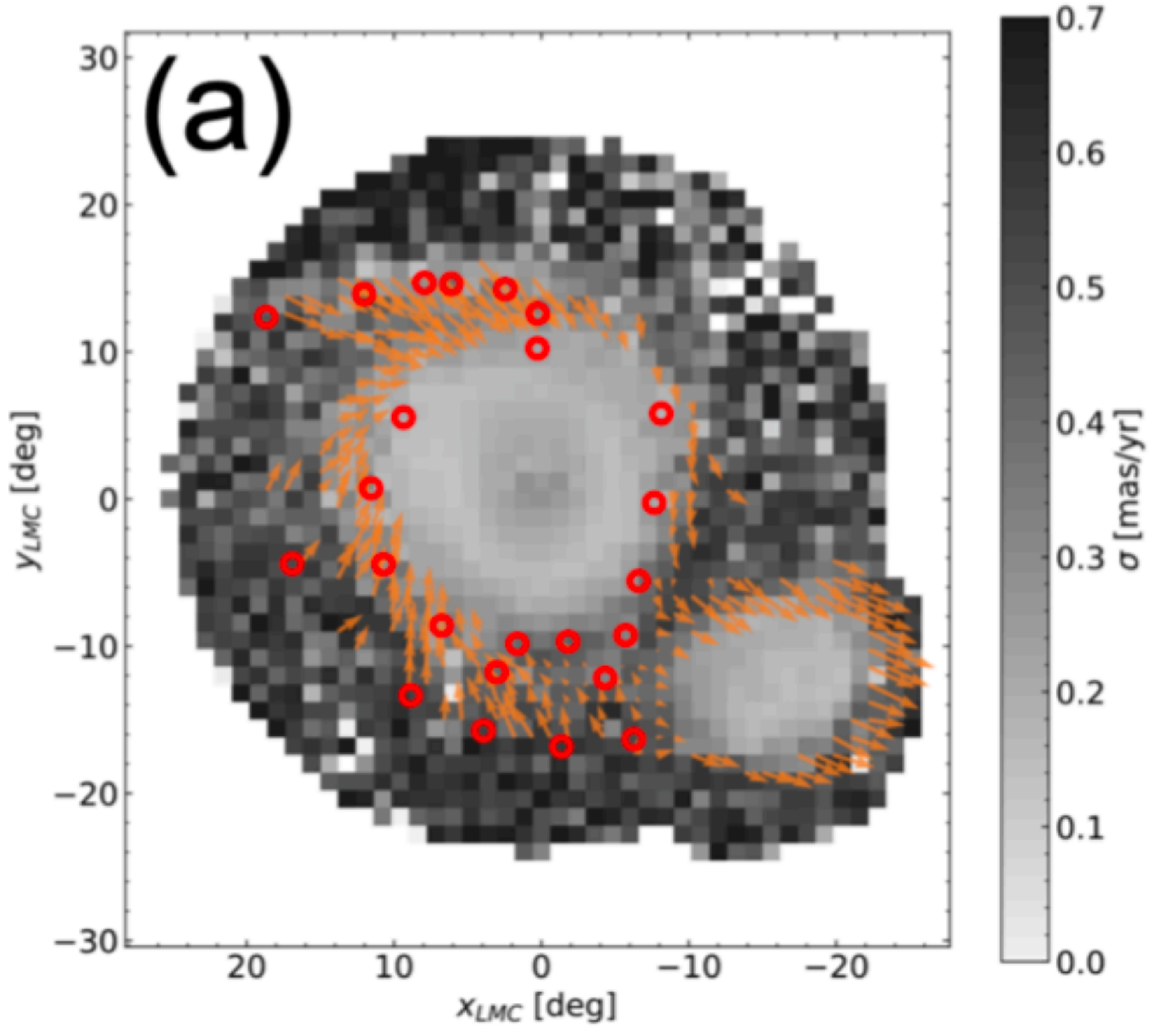


Wang et al. 2022b

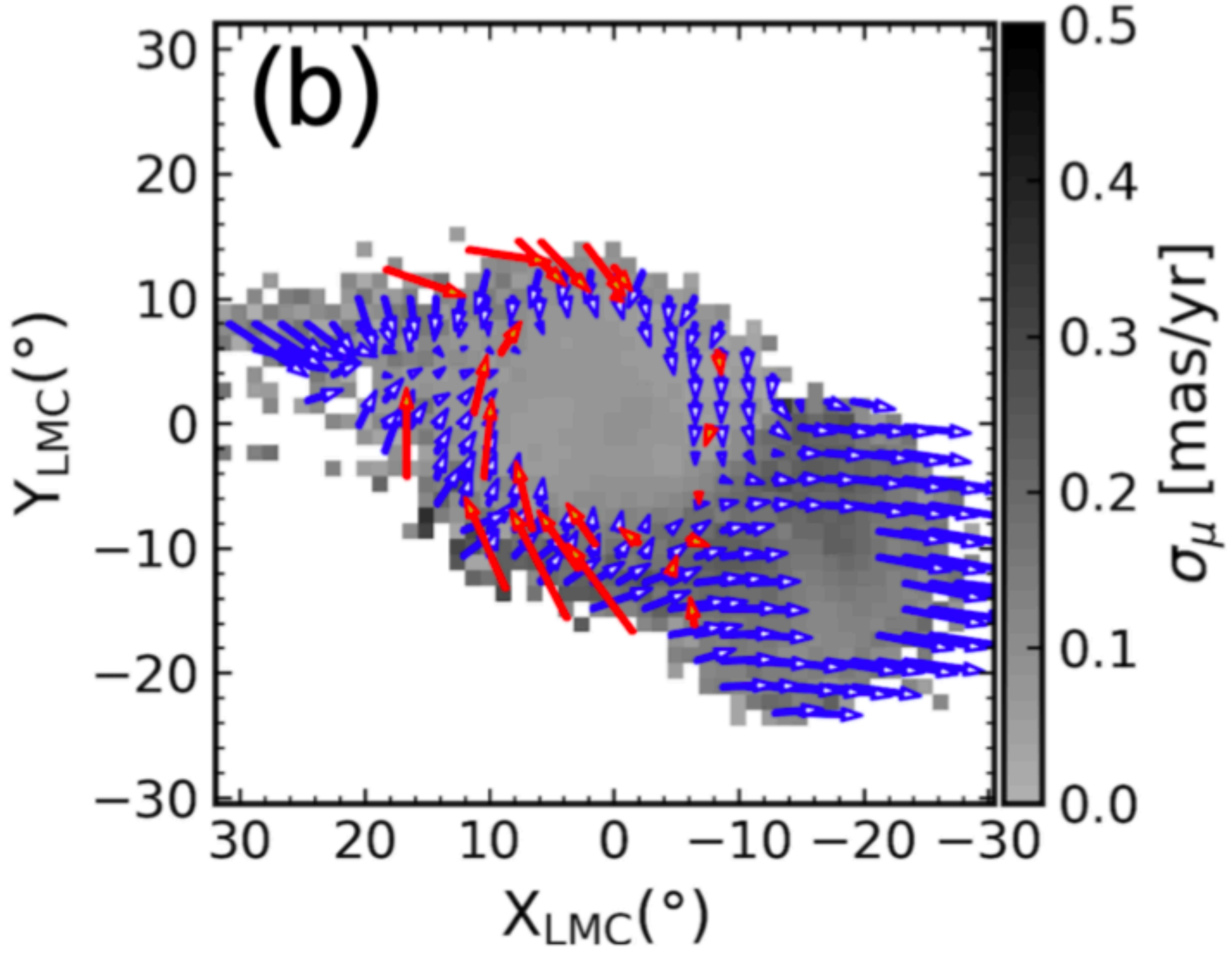
3. The confirmed predictions by our model

The Kinematics of MCs systems

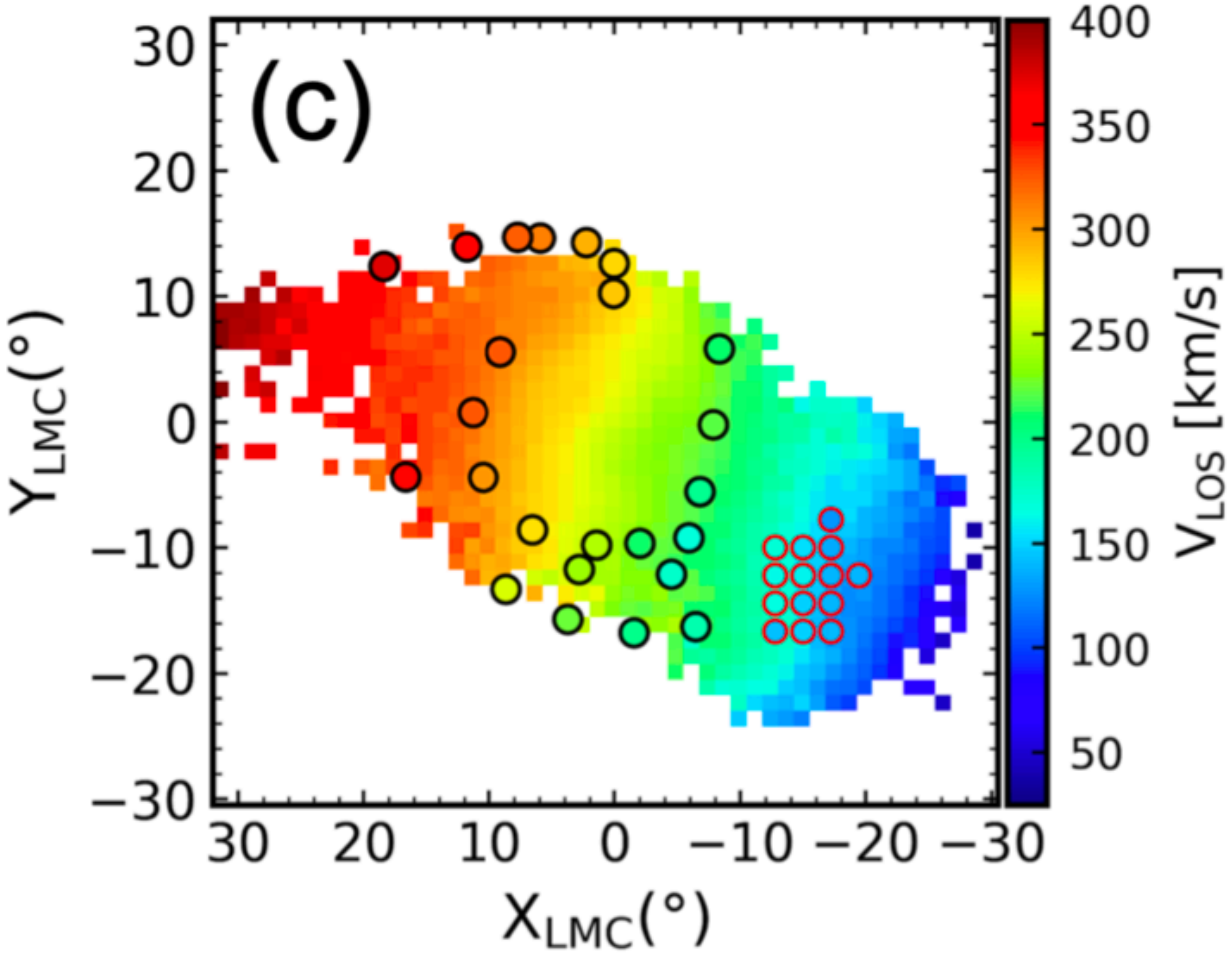
Gaia EDR3



Simulation Model



Simulation Model

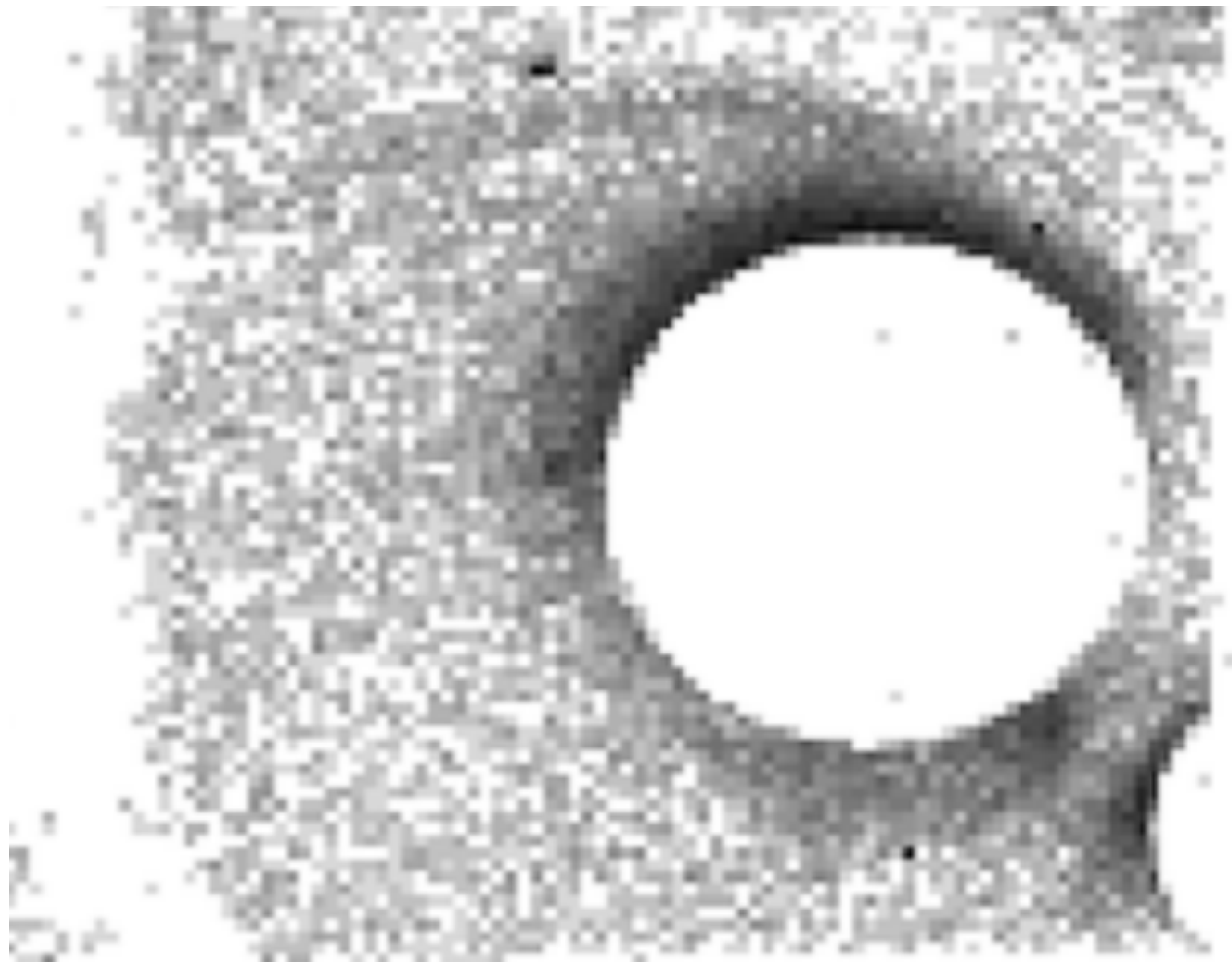


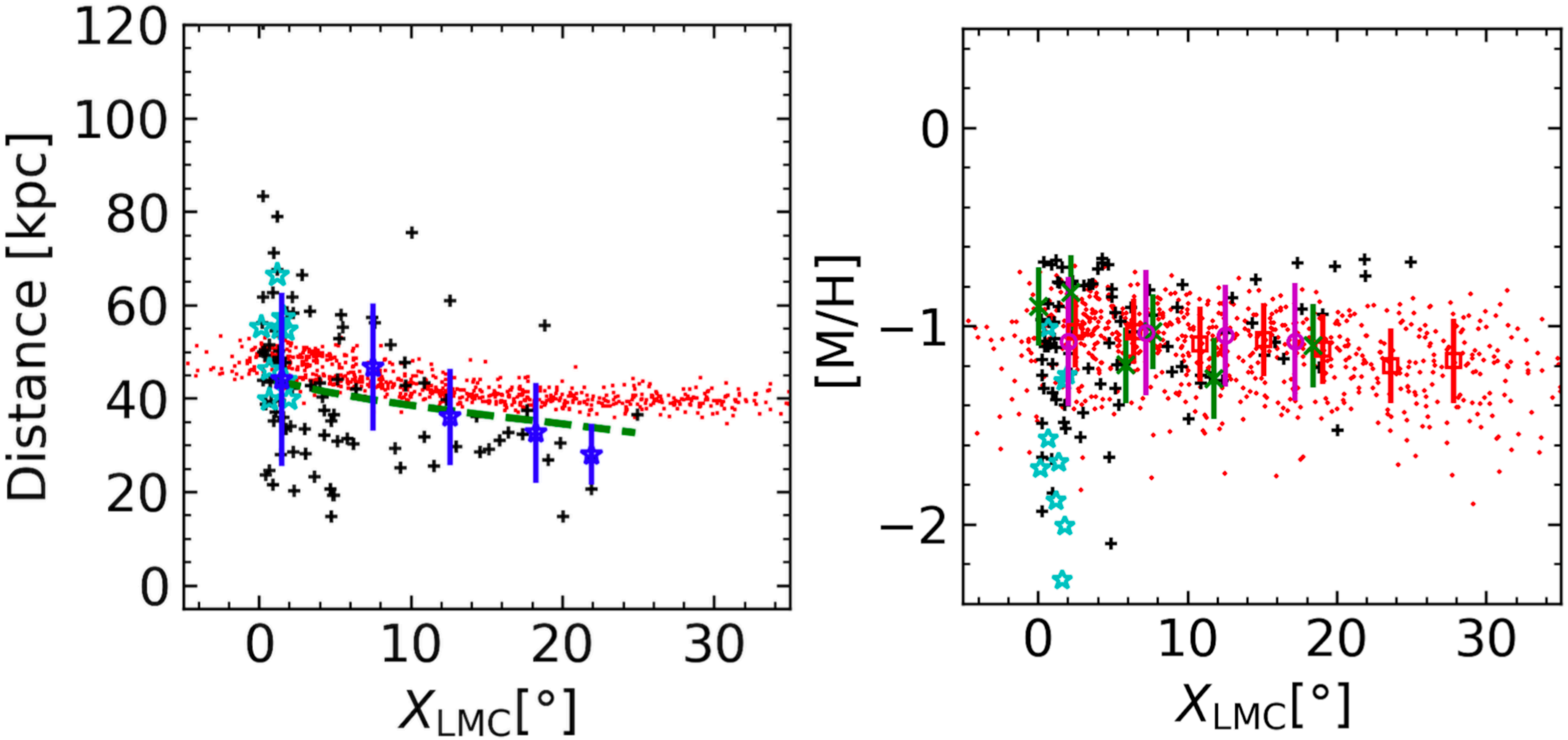
Wang et al. 2022a

3. The confirmed predictions by our model

Distance and metallicity of Northern Tidal Arm

Gaia EDR3





Wang et al. 2022b

New facilities
New observations

e.g., JWST, GAIA, SKA:
HI, star streams, LA….

New finds: Unveiling the origin of Magellanic System

We are waiting for many years !!!

“ram-pressure+collision” model

(Hammer et al. 2015; Wang et al. 2019; Wang et al. 2022a; Wang et al. 2022b)

The Magellanic System: a corner stone

- **With modern hydrodynamic code GIZMO, we simulate the Magellanic System and Clouds formation.**
  - Our model reproduce **boththe HI and HII gas position and kinematic** distribution, as well as the amount for both phases of gas.
  - Many stellar features are reproduced with our model:
- **Many prediction have been confirmed by new observations, which validate the model.**
  - Two populations in the Bridge: distance & kinematics
  - Substructures: NTA, NES, distance, metallicity, kinematics
- **Provide a strong constraint on the hot gas in the MW halo: 3 to 4 times more than the stellar mass !**
- **"Ram pressure + collision" model: by far the only model reproducing Magellanic Stream & Clouds properties.**

Many thanks for your attention !