

Studying Distant Galaxies

A Handbook of Methods and Analyses

Distant galaxies encapsulate the various stages of galaxy evolution and formation from over 95% of the development of the universe. As early as twenty-five years ago, little was known about them, however since the first systematic survey was completed in the 1990s, increasing amounts of resources have been devoted to their discovery and research. This book summarises for the first time the numerous techniques used for observing, analysing, and understanding the evolution and formation of these distant galaxies.

In this rapidly expanding research field, this text is an every-day companion handbook for graduate students and active researchers. It provides guidelines in sample selection, imaging, integrated spectroscopy and 3D spectroscopy, which help to avoid the numerous pitfalls of observational and analysis techniques in use in extragalactic astronomy. It also paves the way for establishing relations between fundamental properties of distant galaxies. At each step, the reader is assisted with numerous practical examples and ready-to-use methodology to help understand and analyse research.

François Hammer worked initially in general relativity and made the first modeling of gravitational lenses prior to their spectroscopic confirmation. Following this, he became co-leader of the first complete survey of distant galaxies, the Canada-France-Redshift Survey. This led to the discovery of the strong decrease of the cosmic star formation density measured from UV light as $z=1$, which, alongside Hector Flores, they confirmed as biconometric and dual independent. With Mathieu Puech, they then pioneered the 3D spectroscopy of distant galaxies, leading to a major increase of understanding the dynamic state of distant galaxies evidenced by the scatter of the Tully-Fisher relation. This led them to propose, with the addition to the team of Myriam Rodrigues, that galactic disks may survive or be rebuilt in gas-rich mergers, a scenario that is consistent with contemporary cosmological simulations. Besides extensive observational experience, the authors have led, or are leading, several instruments implemented or to be implemented at the largest telescopes, including VLT/Graffia, VLT-X-shooter, VLT/MOONS and E-ELT/MOSAIC. They have also developed several observational techniques in adaptive optics, and in sky subtraction for integral field units and fibre instruments.

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Hammer
Puech
Flores
Rodrigues



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François Hammer, Mathieu Puech,
Hector Flores & Myriam Rodrigues



World Scientific

The Magellanic Stream: the 'ram pressure plus collision' scenario

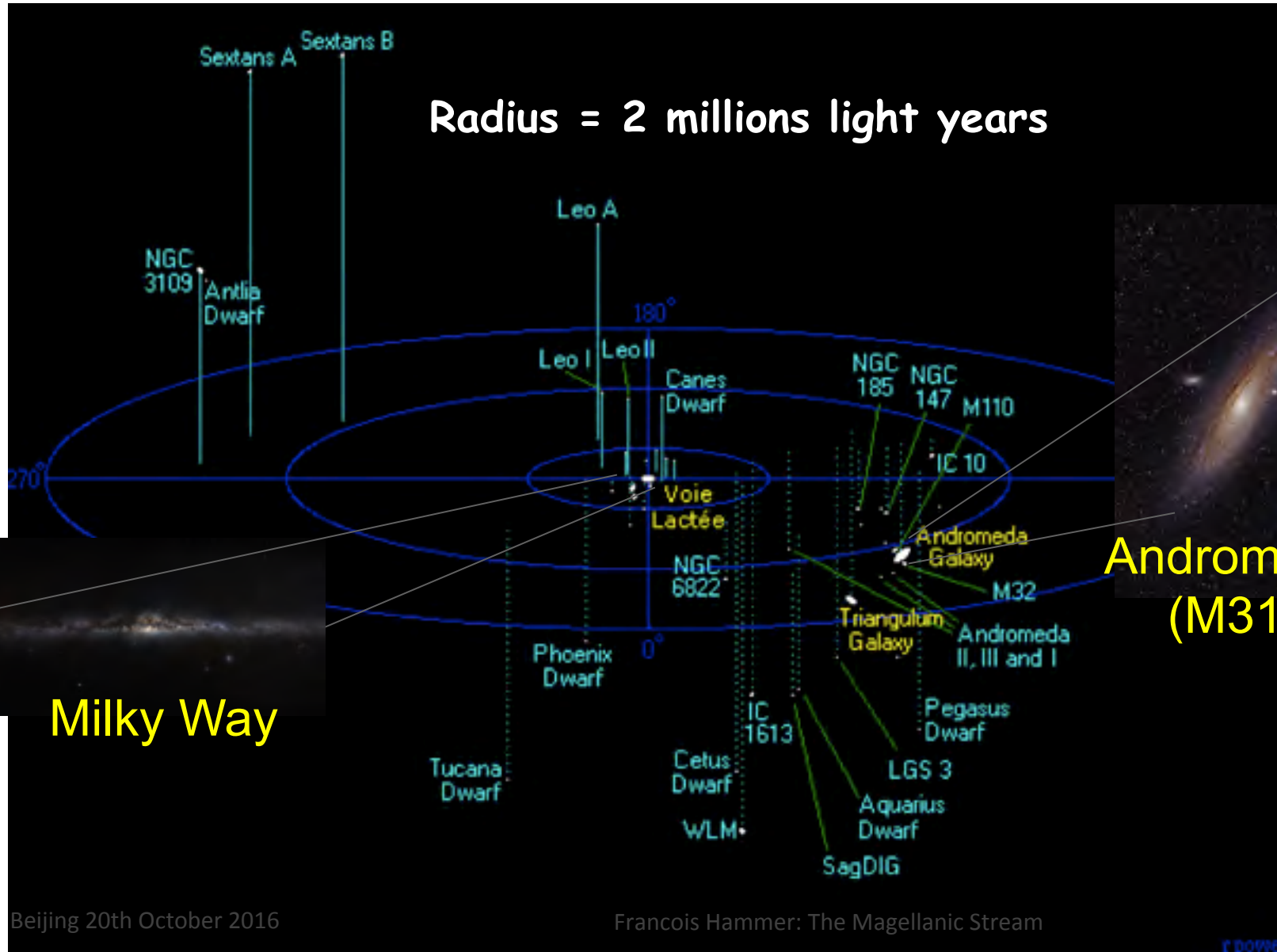
by François Hammer



With Yanbin Yang, Hector Flores, Mathieu Puech, Sylvain Fouquet

See paper and videos in <http://lia-origins.obspm.fr/images/videos/>

The Local Group



The Milky Way: a quiescent history



Past history of the Milky Way:

- Halo shows almost no evolved stars
- No major merger since the last 10-11 billions years

IS THE MILKY WAY A REPRESENTATIVE GALAXY?

The Milky Way versus M31 and other spirals

Hammer et al. 2007, ApJ, 662, 322

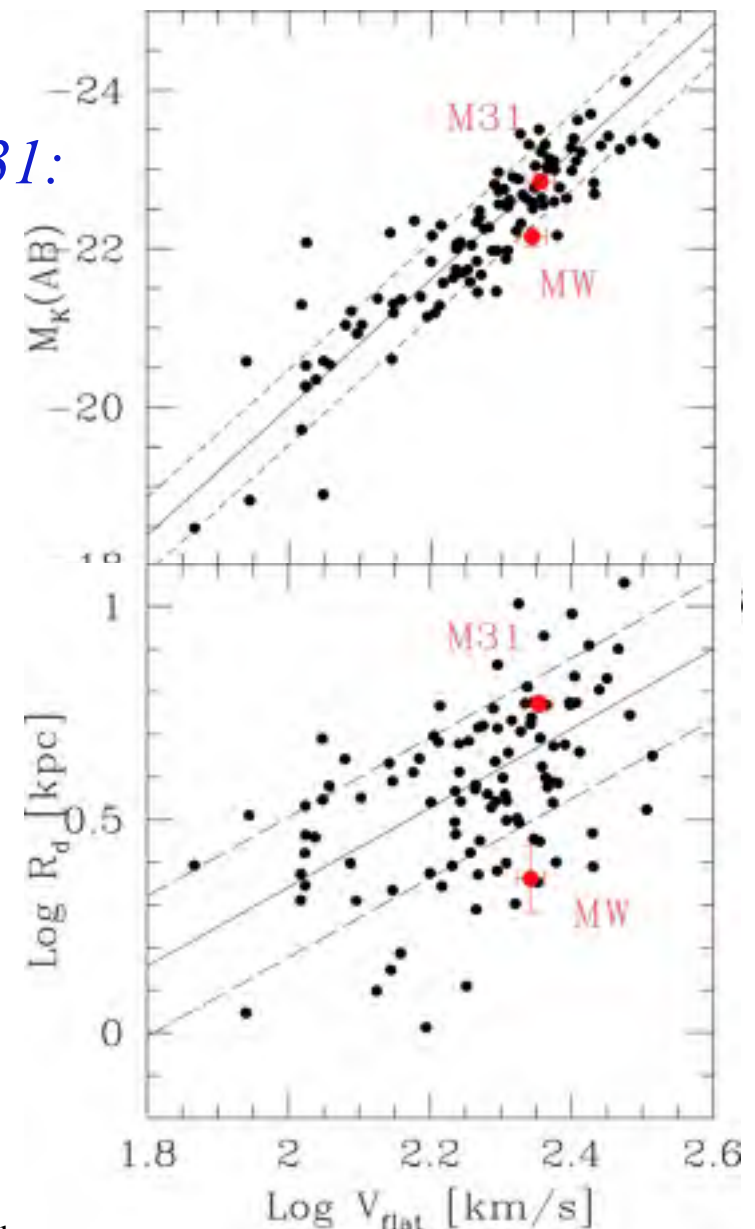
Accurate measurements for the MW and M31:

M_K & R_{disk} (COBE/DIRBE, Hipparcos...)
and V_{flat} measured at the optical radius

Compared to other spirals (SDSS):

- the MW has a too small stellar mass, radius & angular momentum;
- **M31 is rather typical.**

In the $(M_K, R_{disk}, V_{flat})$ volume, there are only 7+/-1% of Milky Way-like galaxies.



The Milky Way versus M31 and other spirals

Hammer et al. 2007, ApJ, 662, 322

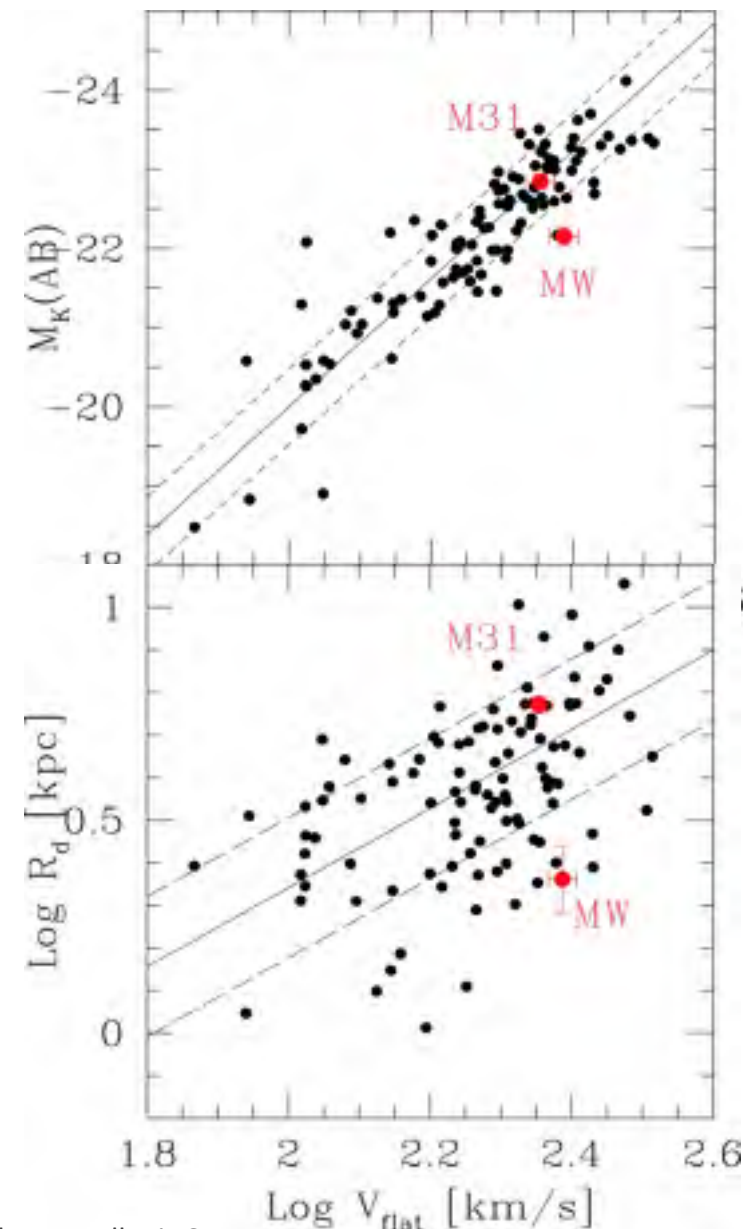
Accurate measurements for the MW and M31:

M_K & R_{disk} (COBE/DIRBE, Hipparcos...)
with $V_{flat}(MW)=244\text{km/s}$ from Reid et al. (2009) and Bovy, Hogg & Rix (2010)

Compared to other spirals (SDSS):

- the MW has a too small stellar mass, radius & angular momentum;
- **M31 is rather typical.**

In the $(M_K, R_{disk}, V_{flat})$ volume, there are only $\sim 1-2\%$ of Milky Way-like galaxies.



The Milky Way: a quiescent history ... but

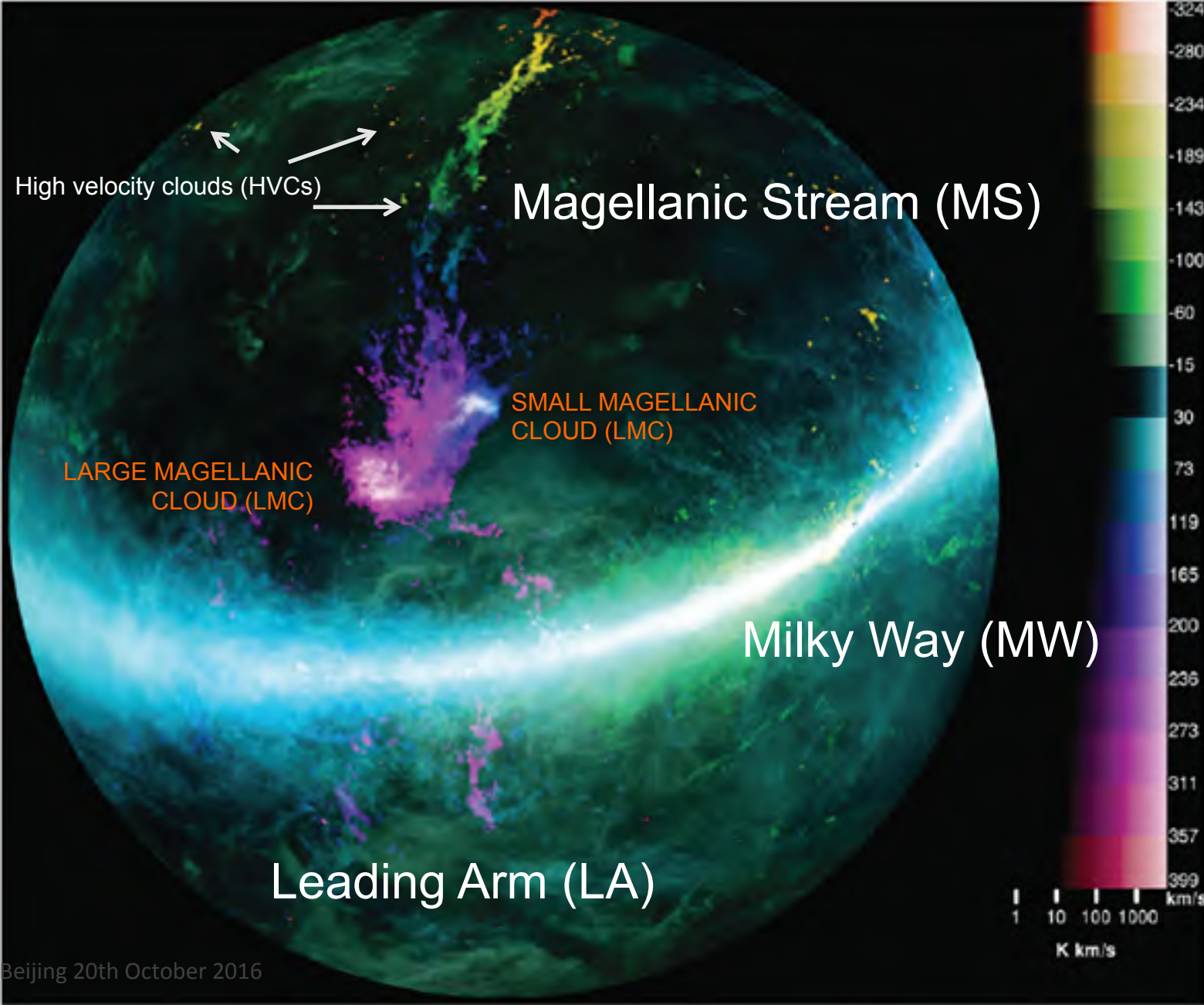


Past history of the Milky Way:

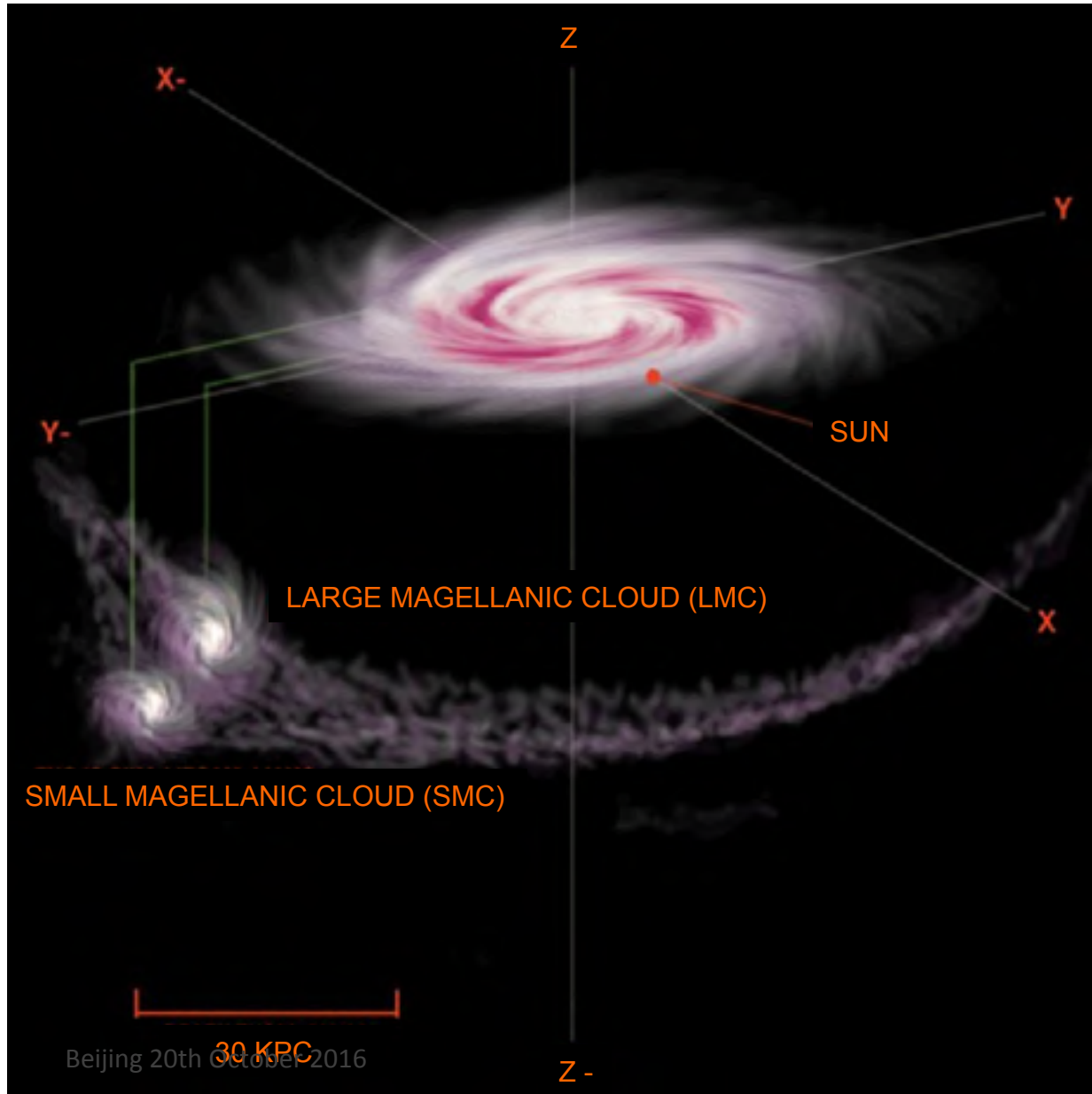
- Halo shows almost no evolved stars
- No major merger since the last 10-11 billions years
- **Today: infall of the Magellanic Clouds together with $\sim 3 \cdot 10^9 M_{\odot}$ of gas (Magellanic System, Fox+14) almost the gas in the MW disk!**

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

Southern Hemisphere in HI from GASS

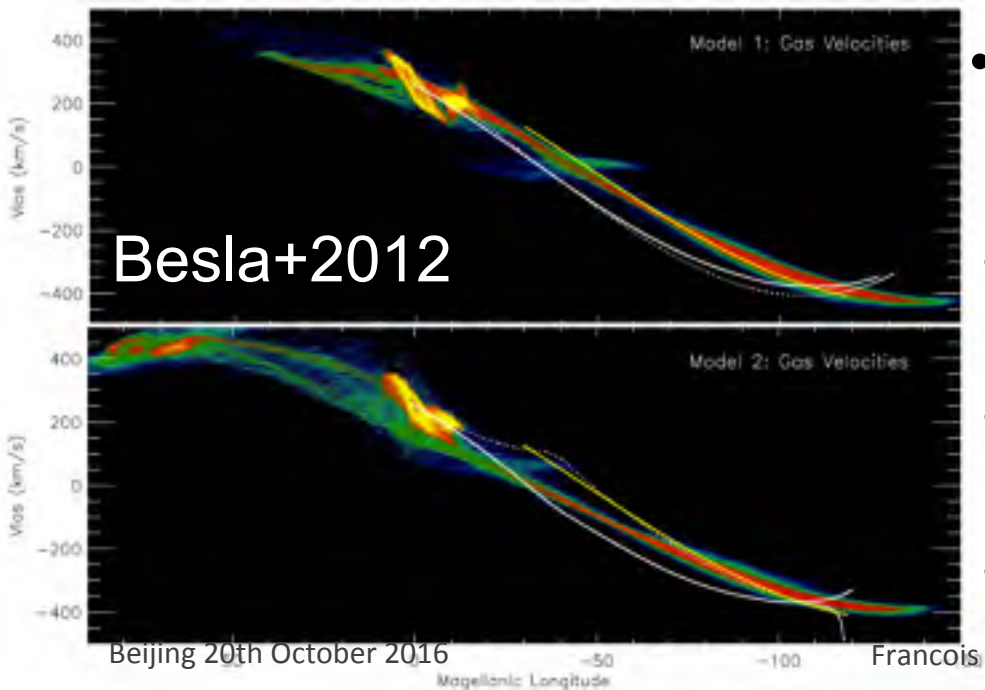
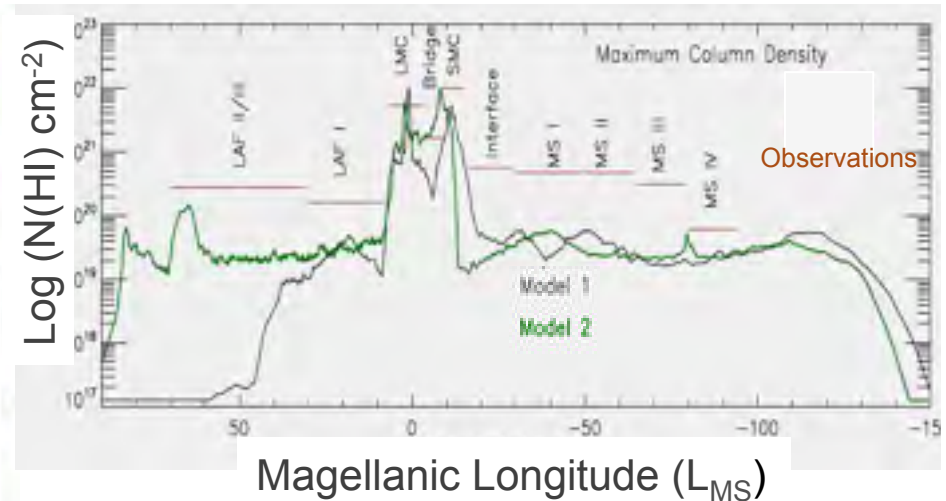
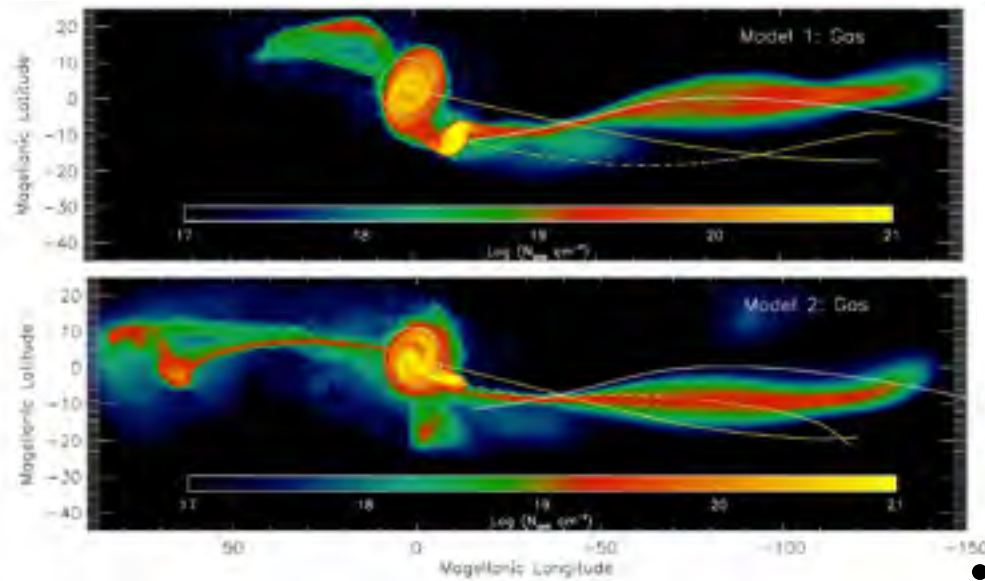


Explanation of the gigantic Magellanic Stream



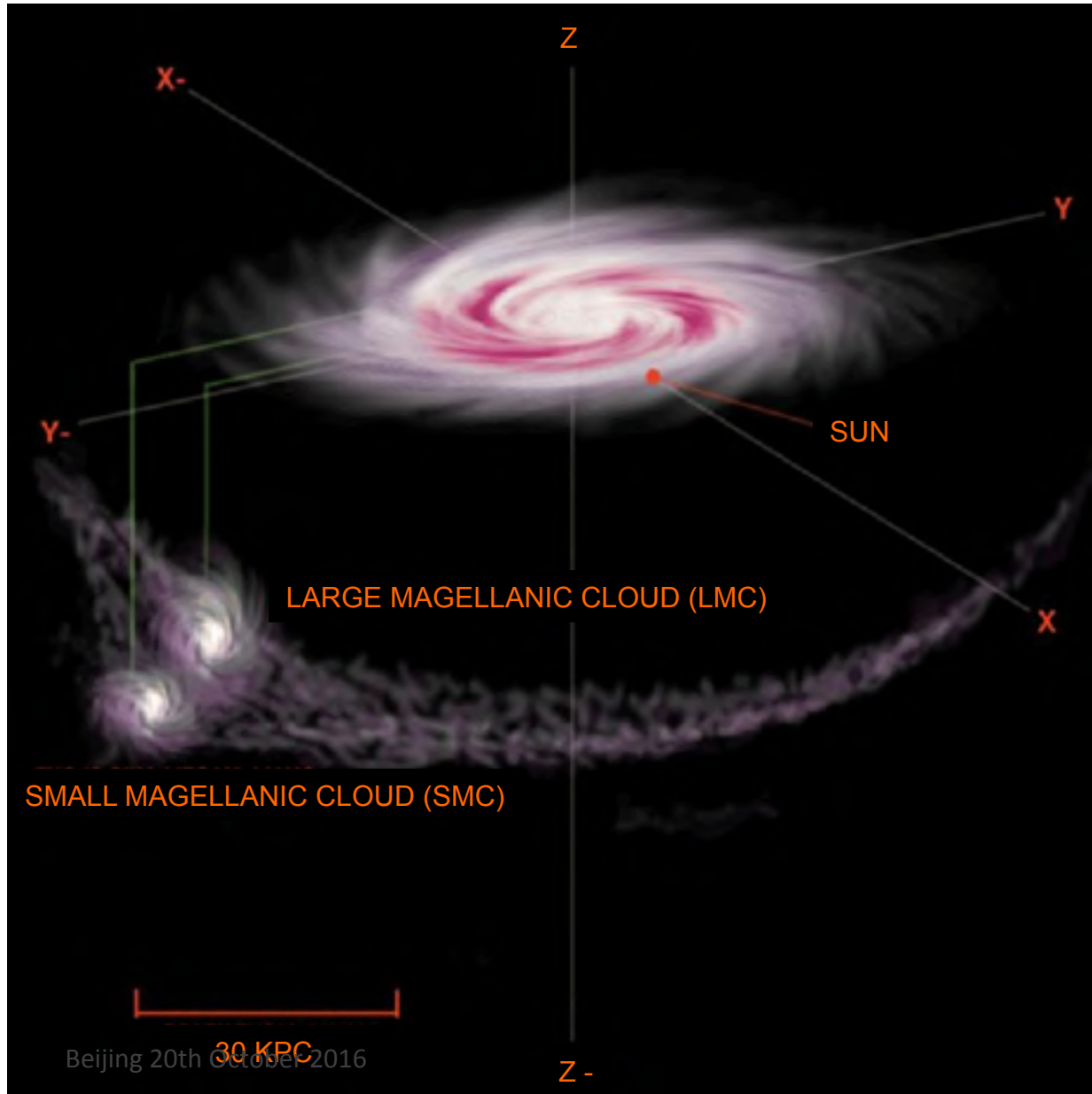
Firstly identified as the MS by Mathewson+74 after detections by van Kuilenburg and Wannier & Wrixon72

The dearth of predictions from tidal models



- Already lack 9/10 of N(HI)
- Could not explain large ionized gas amount ($2 \cdot 10^9 M_{\odot}$, Fox+14)
- Can't explain absence of stars
- Can't explain the filaments
- Could not reproduce the 4 Leading Arm structures

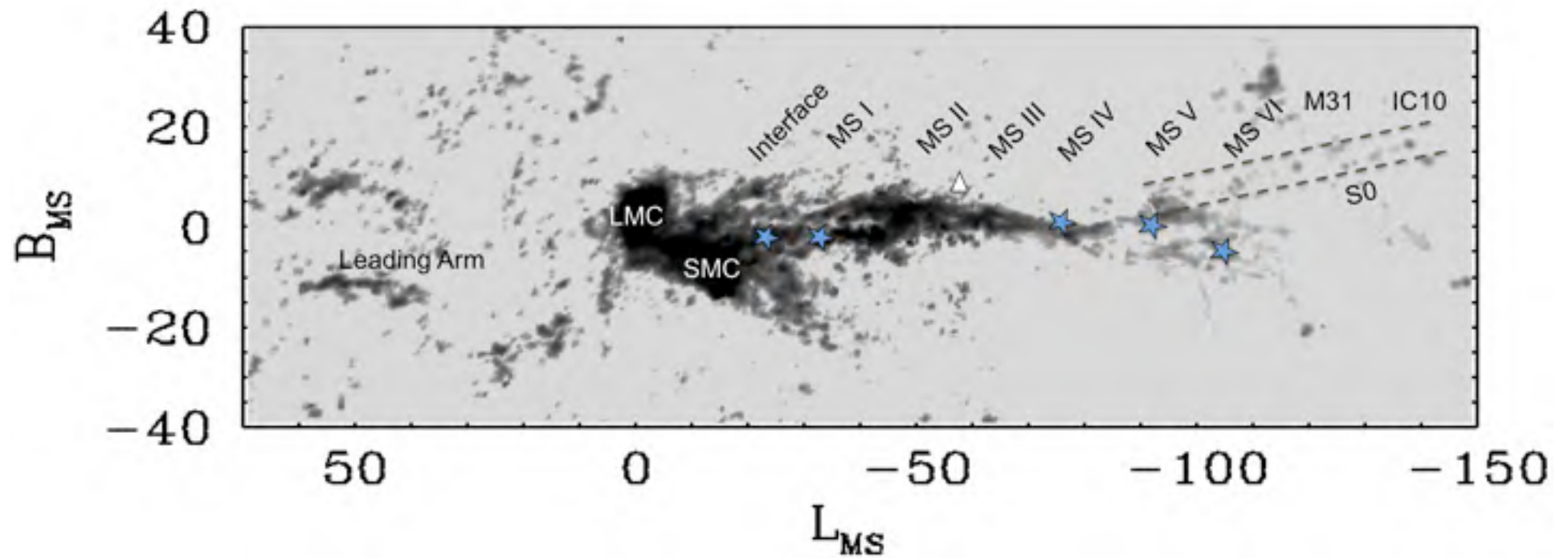
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Firstly identified as the MS by Mathewson+74 after detections by van Kuilenburg and Wannier & Wrixon72

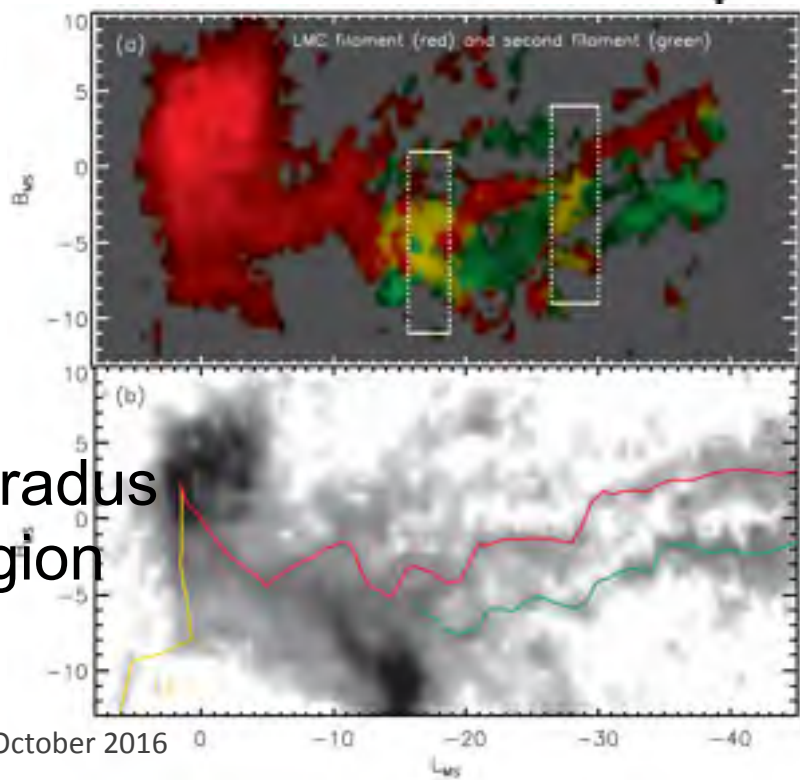
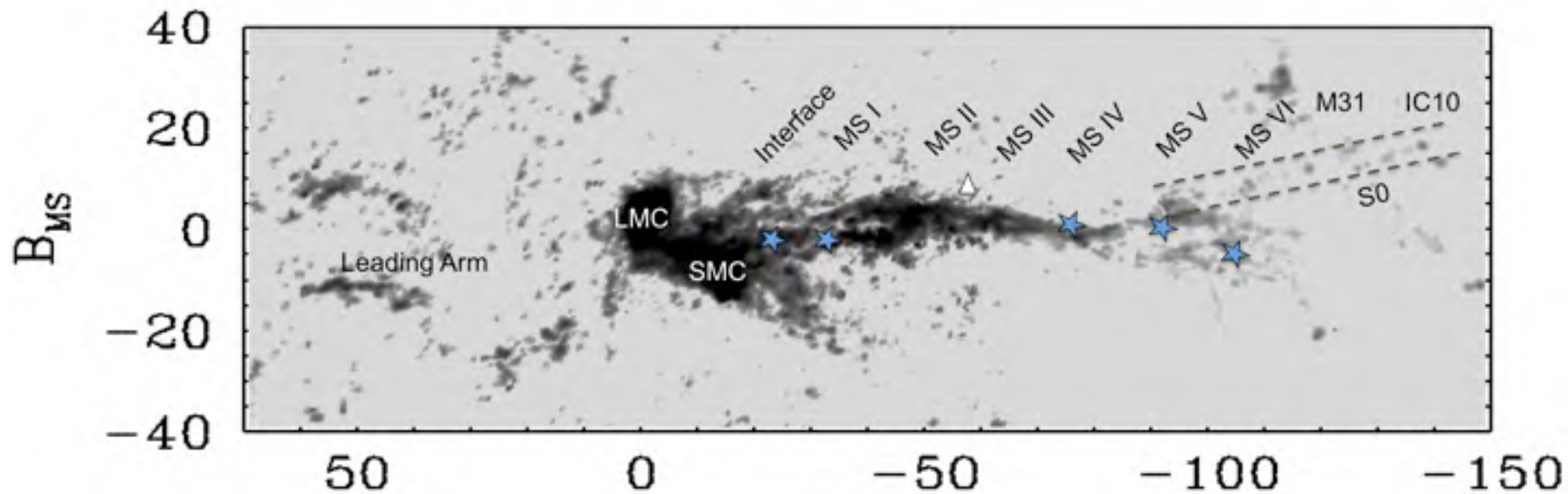
Mathewson (2012): still no satisfactory explanation since 1974

The filamentary structure of the MS



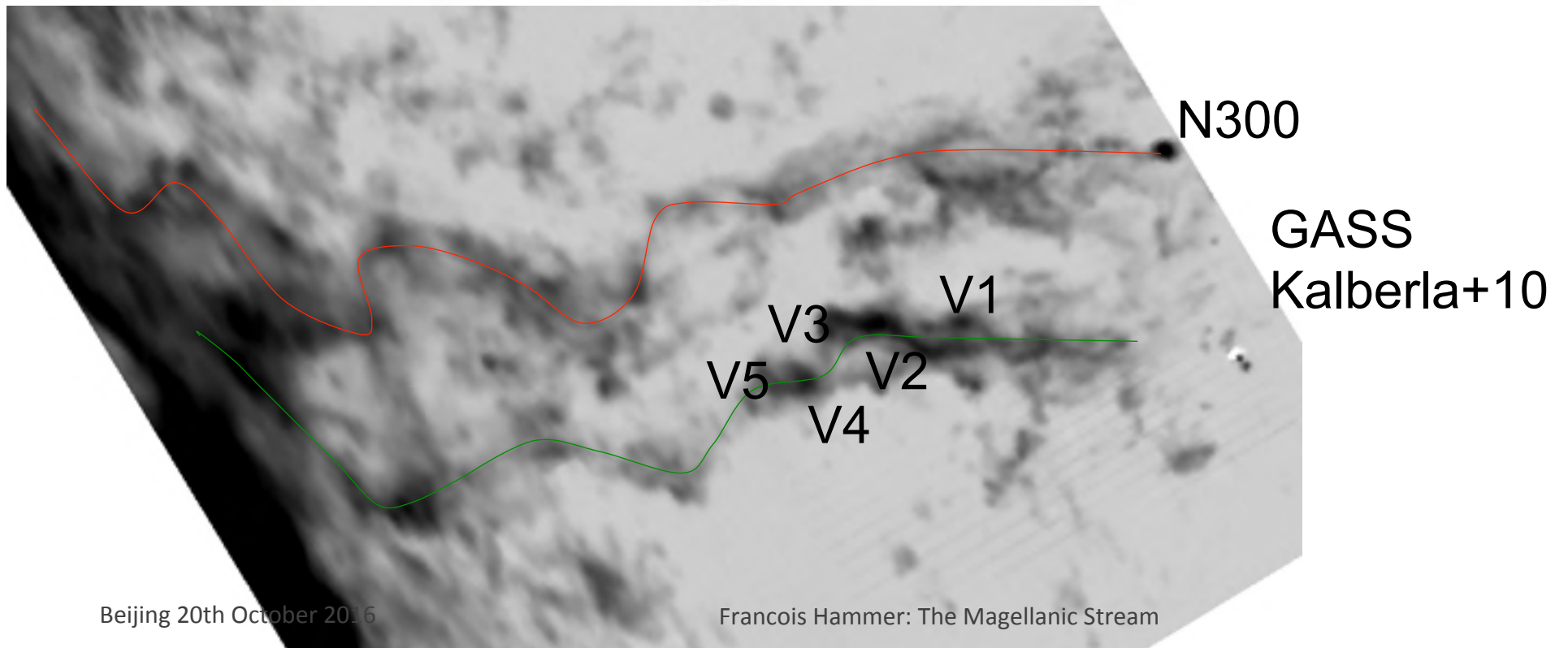
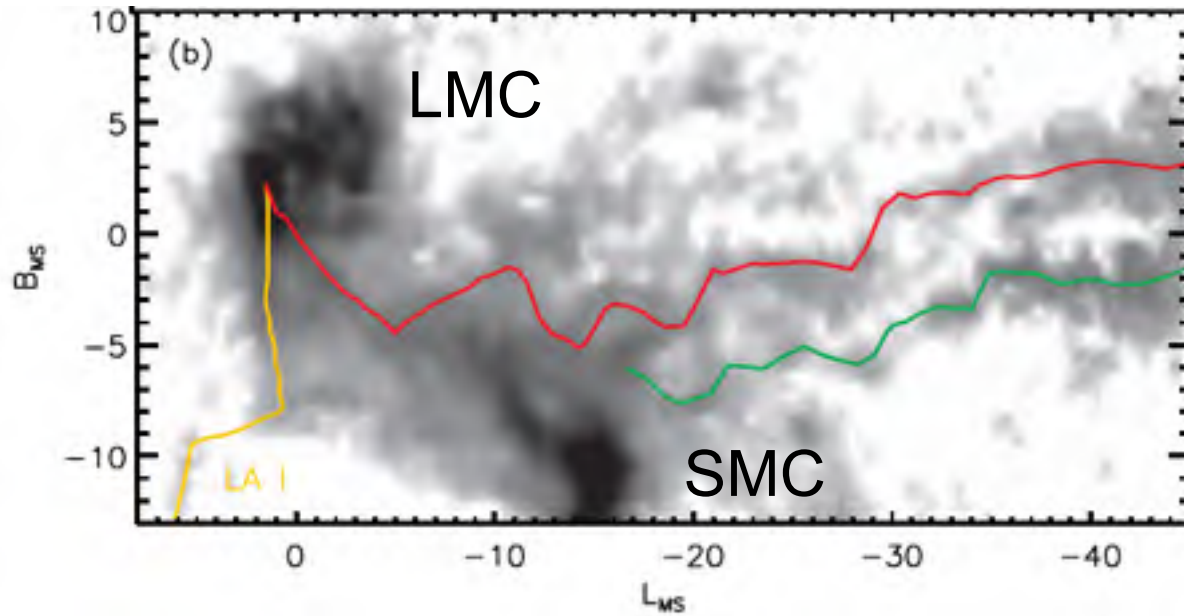
- Filamentary structure of the MS
- DNA-like appearance

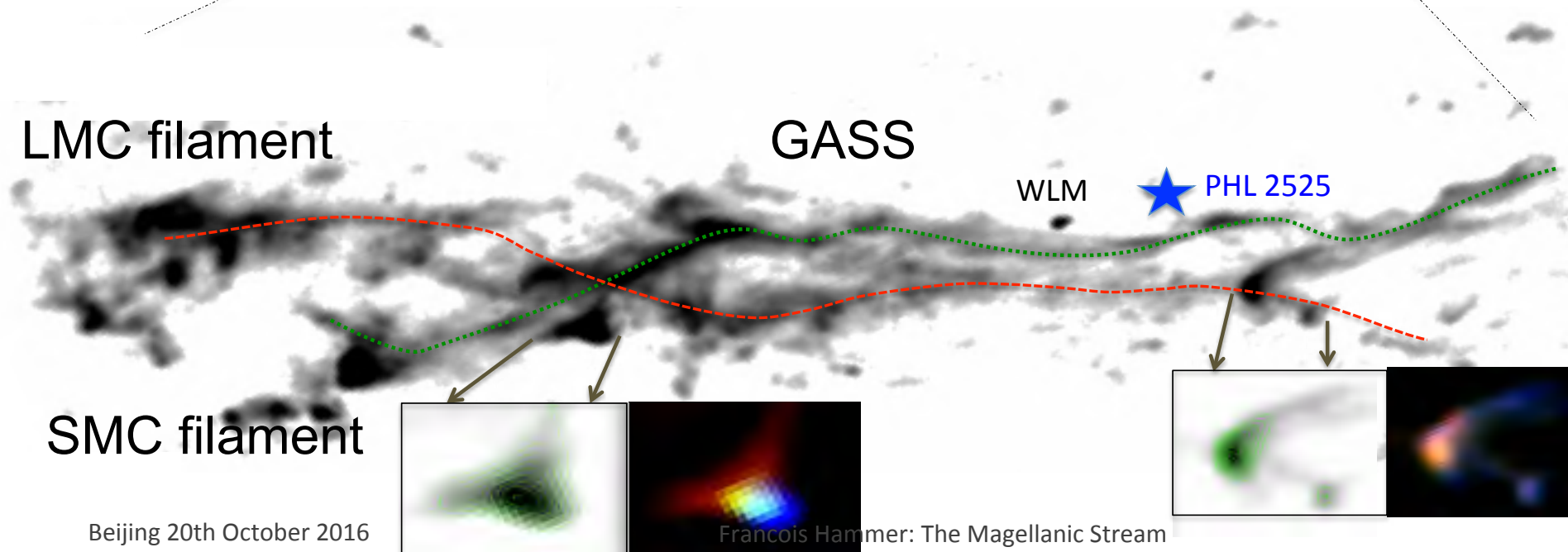
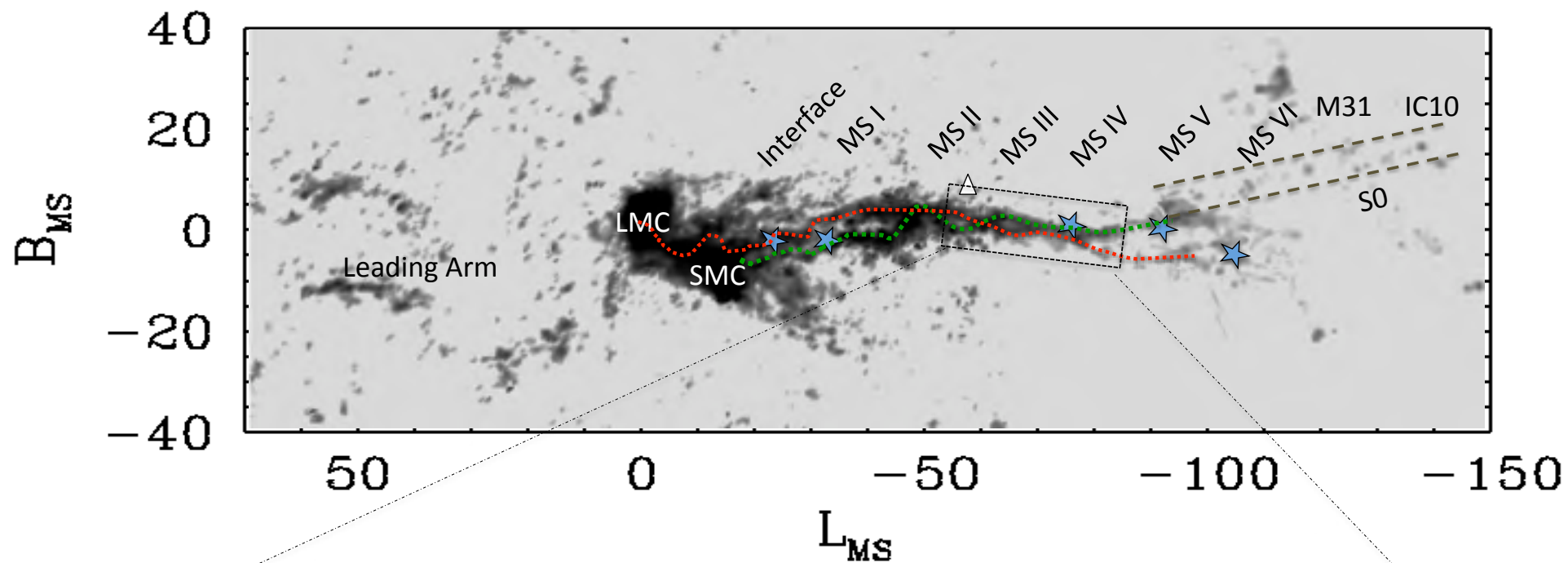
Putman+03 and references therein



30 Doradus
SF region

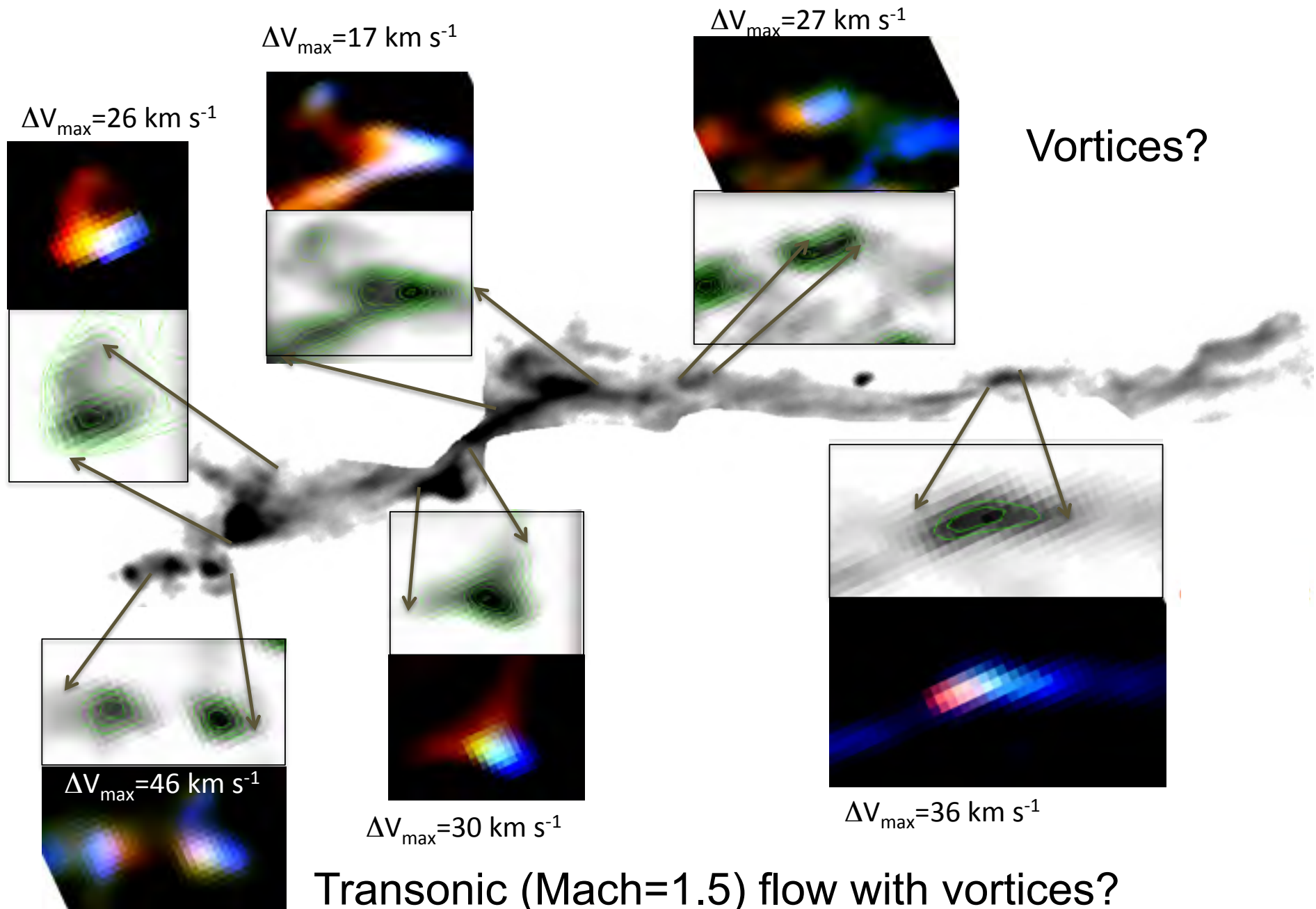
MS with 2 filaments
Nidever+08



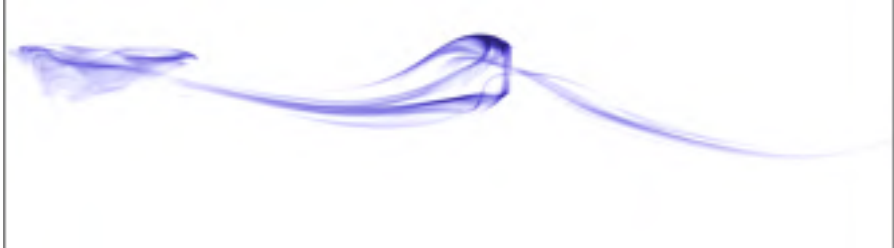


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Francois Hammer: The Magellanic Stream



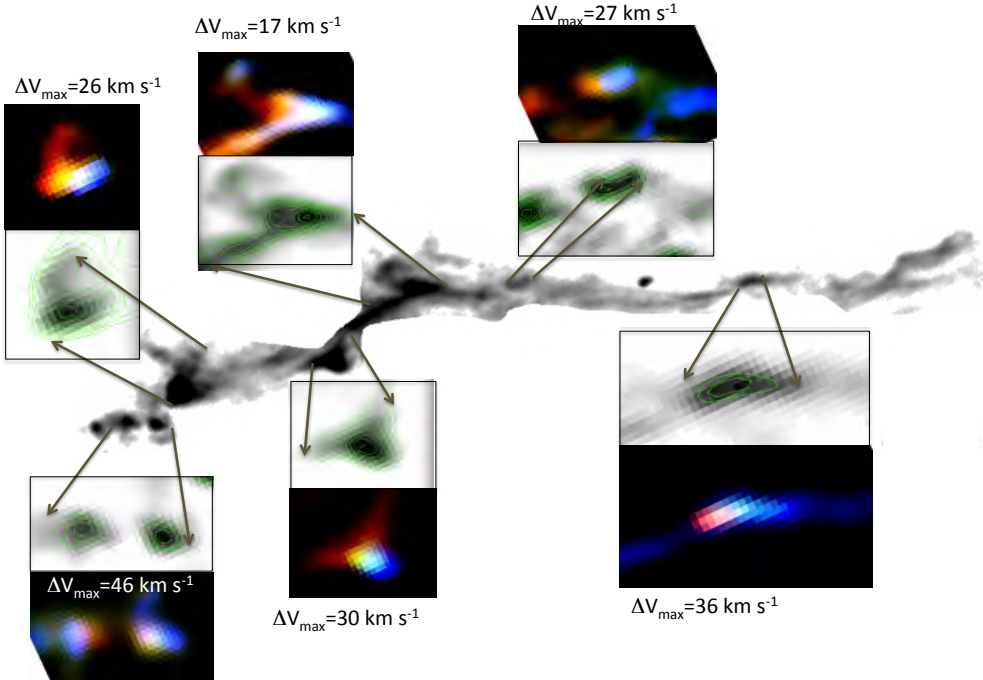
Similar behaviour than hydrodynamical flows with similar (Re, Strouhal) numbers, including vortices (or hairpin shedding)



First wake instabilities on a flow, Re=400, Wesfreid et al. 2014



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Francois Hammer: The Magellanic Stream

Ram pressure exerted by the hot gas (10^6K) of the Milky Way halo

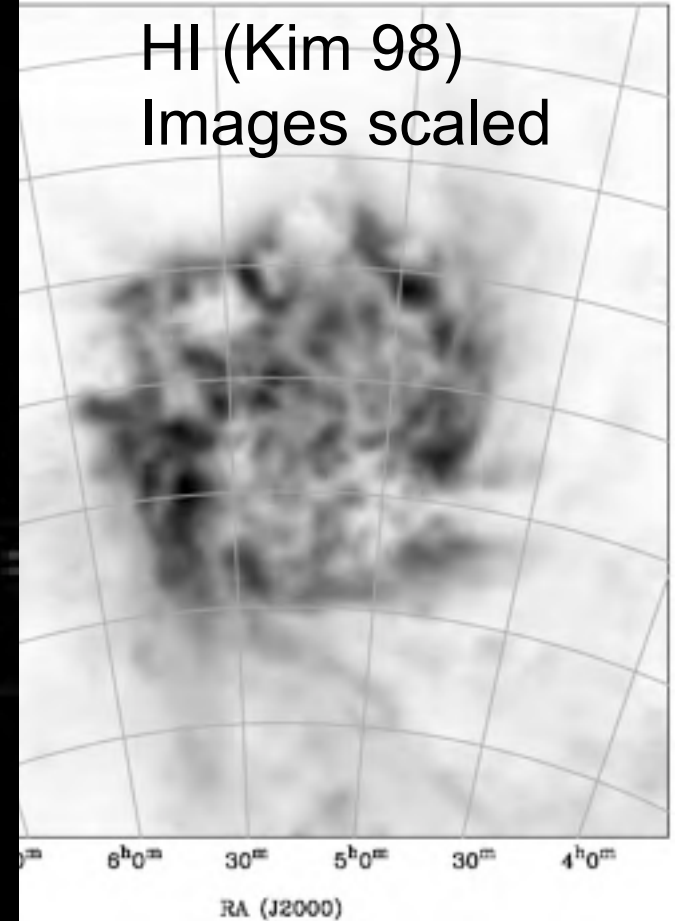
Evidences for a prominent halo hot gas affecting the Magellanic Stream & Clouds:

- Associated high velocity clouds are disrupted (multi-phases, Karlberla & Haud, 2006) $\rightarrow \rho_{\text{hot}} \sim 10^{-4} \text{ cm}^{-3}$ at 50 kpc
- X-ray observations (Gupta et al., 2012, Hodges-Kluck, Miller & Bregman, 2016)
- LMC gas disk has shrunk (Nidever, 2013)

The unusual properties of the LMC disks

RGB+AGB (van der Marel, 2006)

HI (Kim 98)
Images scaled



5 kpc

Ram-pressure plus collision scenario

Hammer et al. 2015

- Evidence for $\rho_{\text{hot}} \sim 10^{-4} \text{ cm}^{-3}$ at the MS distance (Kalberla & Haud, 2006)
- consistent with the fact that the LMC HI disk has been shrunk
- Gas of the Magellanic Clouds stripped by ram-pressure exerted by the hot gas in the Milky Way halo
- Feedback is expelling gas at the LMC outskirts, consistent with observations of 30 Doradus (Nidever+08)
- The Magellanic Stream: Two gigantic transonic filaments
- $Re = 445 \times f_{\mu}^{-1}$ with $f_{\mu} \leq 1$ (viscosity suppression factor, Roediger et al. 2013), implying a moderately turbulent Stream
- $Mach \sim 1.5$ ($V_{\text{sound}} \sim 200 \text{ km/s}$, $V \sim 300 \text{ km/s}$)

Ram-pressure plus collision scenario

Hammer et al. 2015

~ 200 Myr old collision between the
Magellanic Clouds

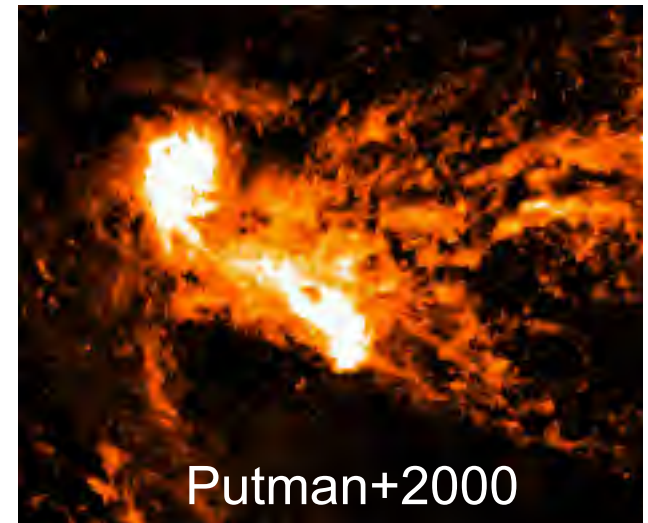
Evidenced by:

the Bridge

same SFH peak of the Clouds

proper motions

Relics in GASS data (anomalous HVCs)



Modelling

GADGET2 (2 M particles)

- Milky Way: total mass, 5 to 8 $10^{11}M_{\odot}$
hot gas mass, 3 to 9 $10^{10}M_{\odot}$

2 Gyr in isolation to equilibrate hot gas halo and cold gas in disk
within the dark matter halo

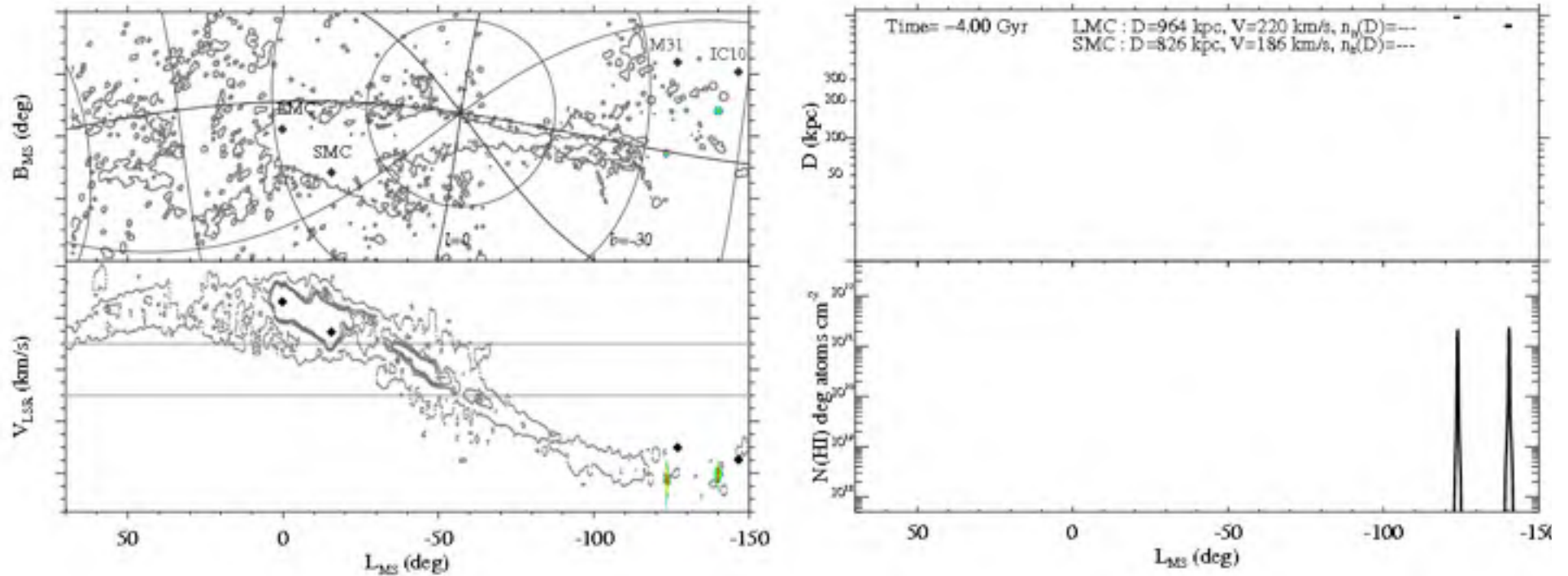
- Initial LMC: mass, 1.8-5 10^9M_{\odot} ; f_{gas} , 40-60%
- Initial SMC: mass ~ 0.7 LMC mass, f_{gas} , 40-70%

Reproduce present-day stellar and gas mass within 20% accuracy

Explanation of the gigantic Magellanic Stream

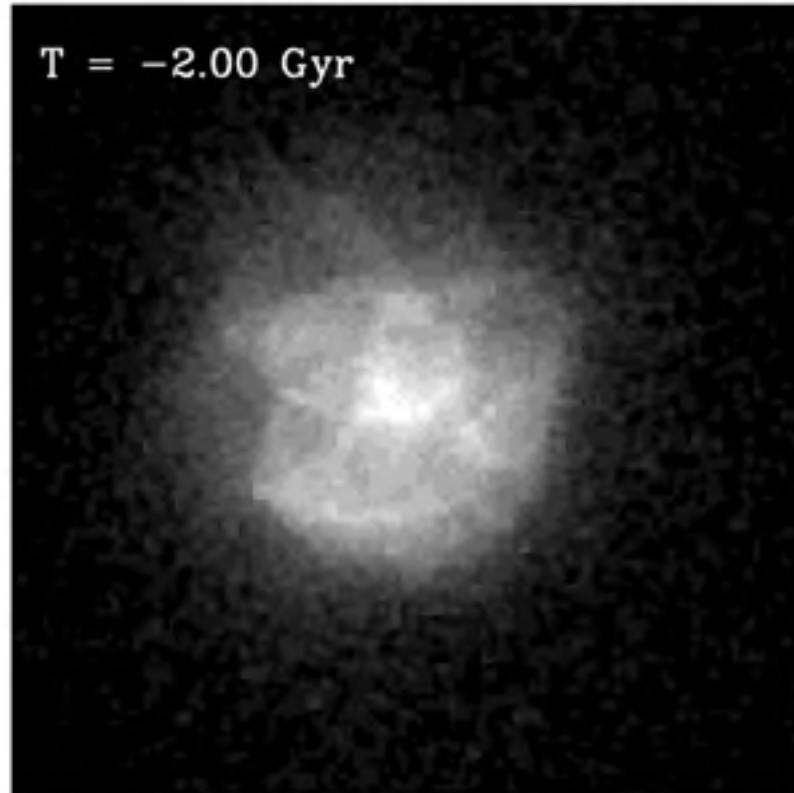
Hammer et al. 2015

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

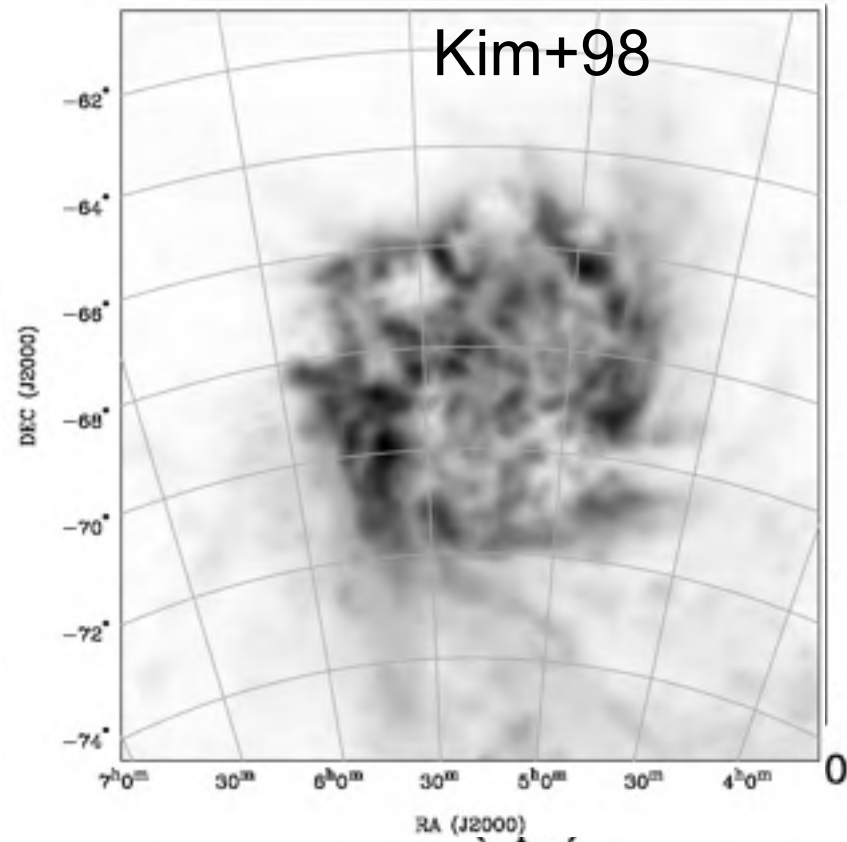


Feedback is expelling gas at the LMC outskirts, which is then subject to ram pressure to form the MS

Consistent with observations of 30 Doradus (Nidever+08)

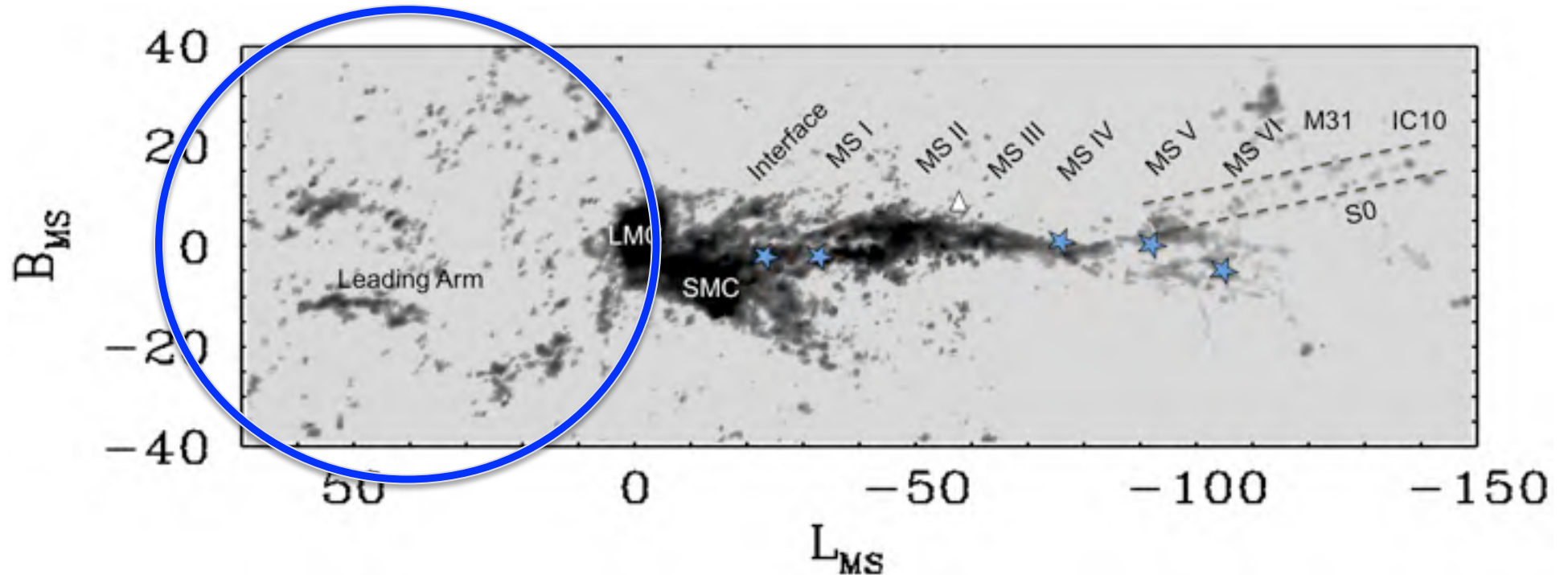


19.8 x 19.8 kpc²



Feedback prescriptions: 5 times the median Cox+06 value

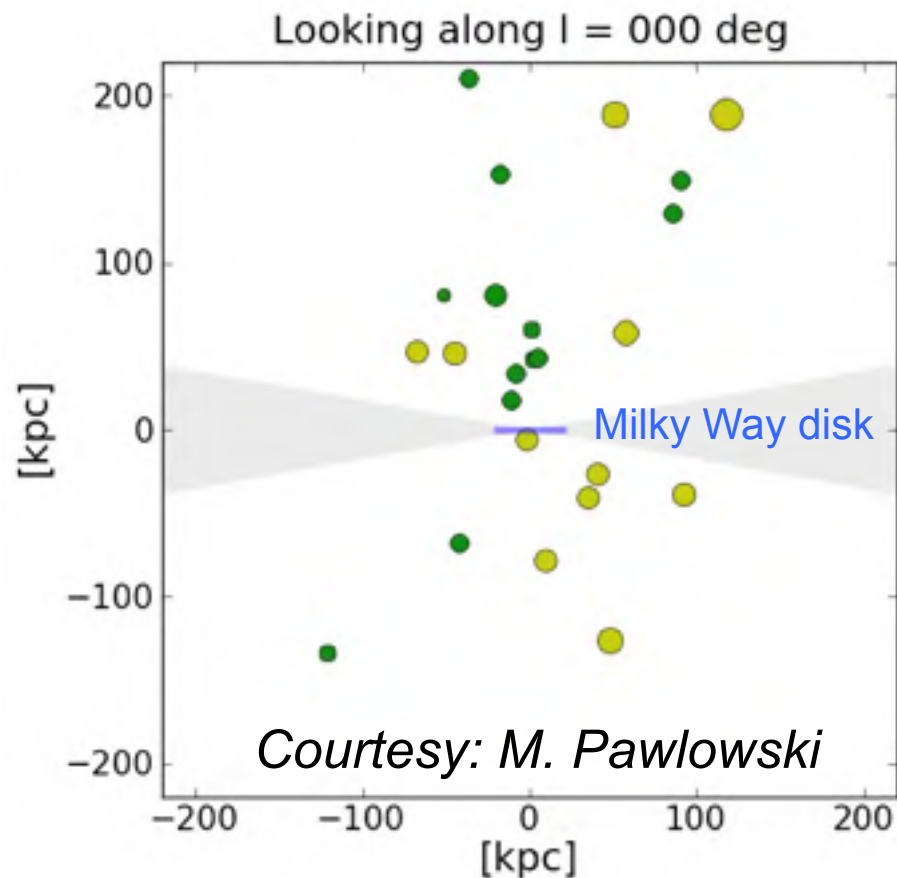
Formation of the Leading Arm



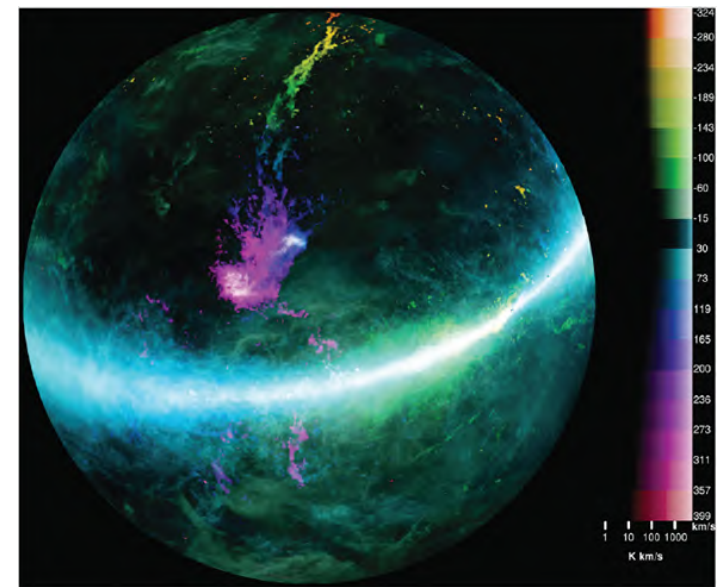
Former passages of leading and ram-pressure stripped dlrrs
(*a la Lucio Mayer, 2009; LA firstly reproduced by Yang et al; 2014*)

Similar orbits than LMC's, ALL material being part of the VPOS
(*Pawlowski14*)

VPOS: Vast Polar Structure surrounding the Milky Way, which includes classical dSphs, Magellanic Clouds and the Stream



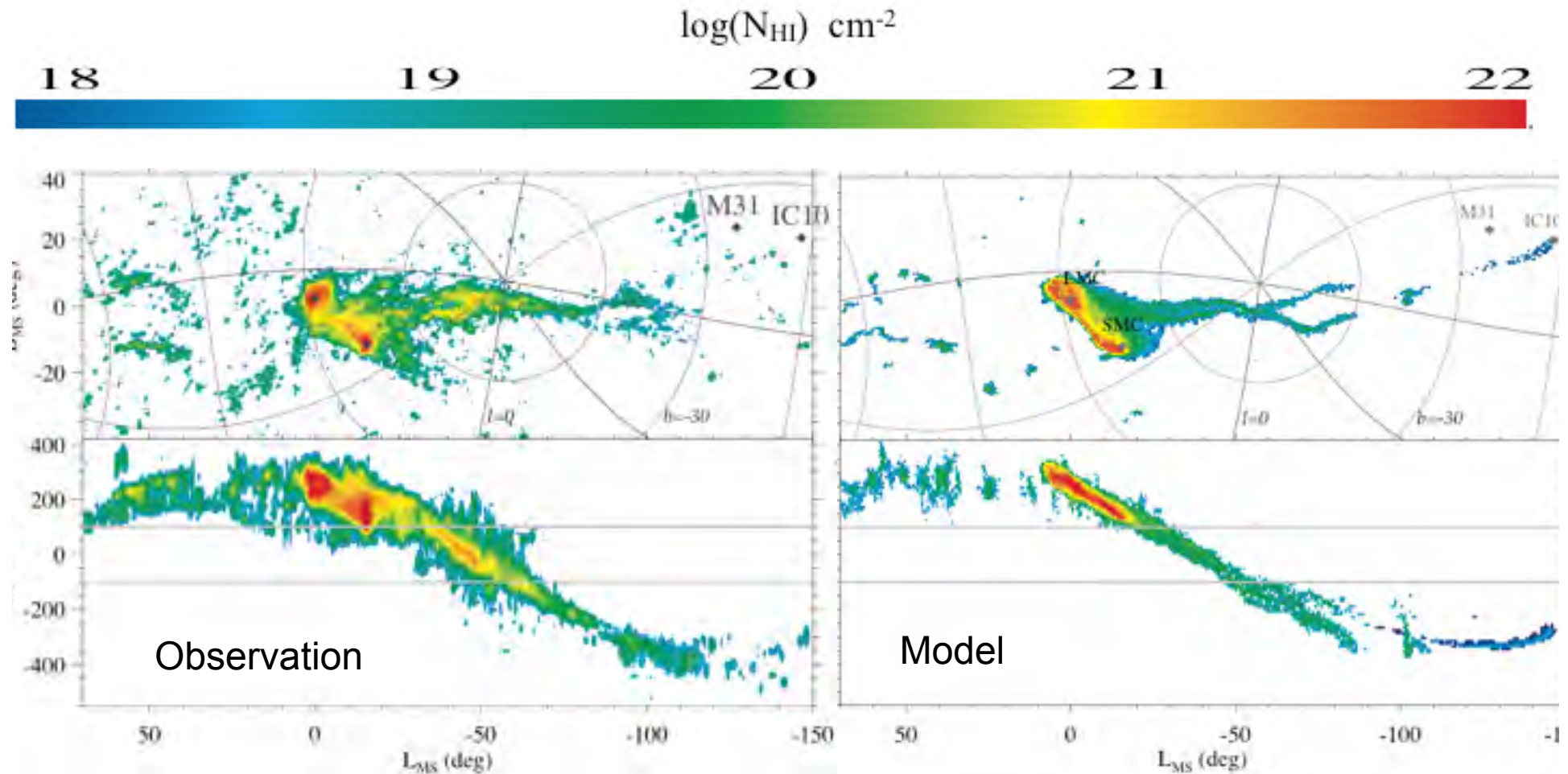
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The Magellanic Stream

Explanation of the gigantic Magellanic System

Gas of the Clouds and dSph progenitors stripped by ram-pressure exerted by the hot gas in the Milky Way halo, dSph progenitors follow similar orbits than the LMC (VPOS)



The Magellanic System: a corner stone to understand

- how galaxies are fed by gas (to form stars)
- to understand the Local Group content and origin
- Ram pressure + collision between Magellanic Clouds: by far the only model reproducing Magellanic Stream properties
- Implementing hydrodynamical solver (GIZMO, Hopkins, 2014) to reproduce Kelvin-Helmholtz instabilities, the LMC-SMC collision & ionized gas
- Test the dark matter content of dSph (Yang+14) and Cloud progenitors
- Stream tip end is pointing to the M31 system (IC10, Nidever+13): what is the role of the ancient gas-rich merger that formed M31 (Hammer+10)?

