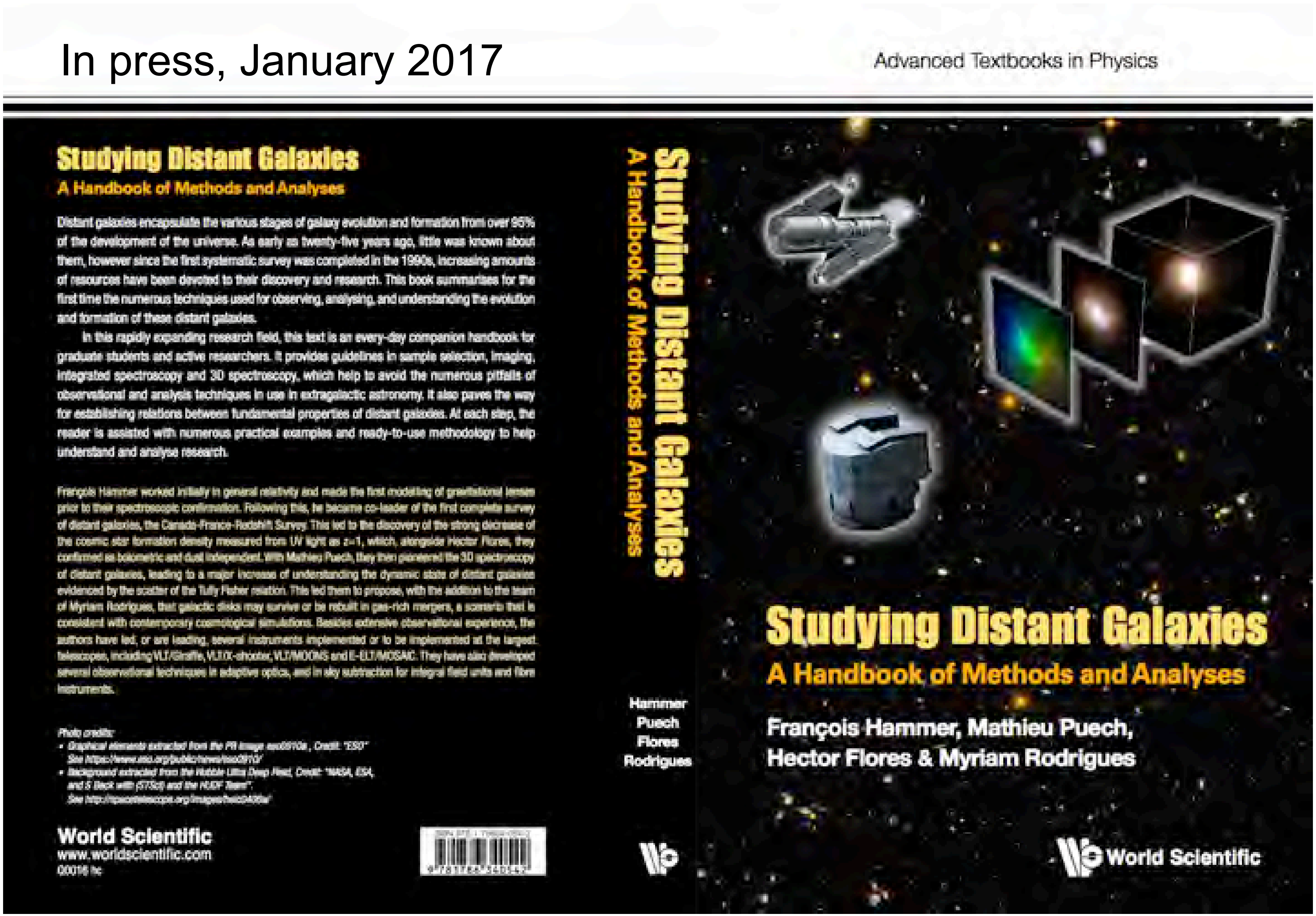
In press, January 2017



Francois Hammer

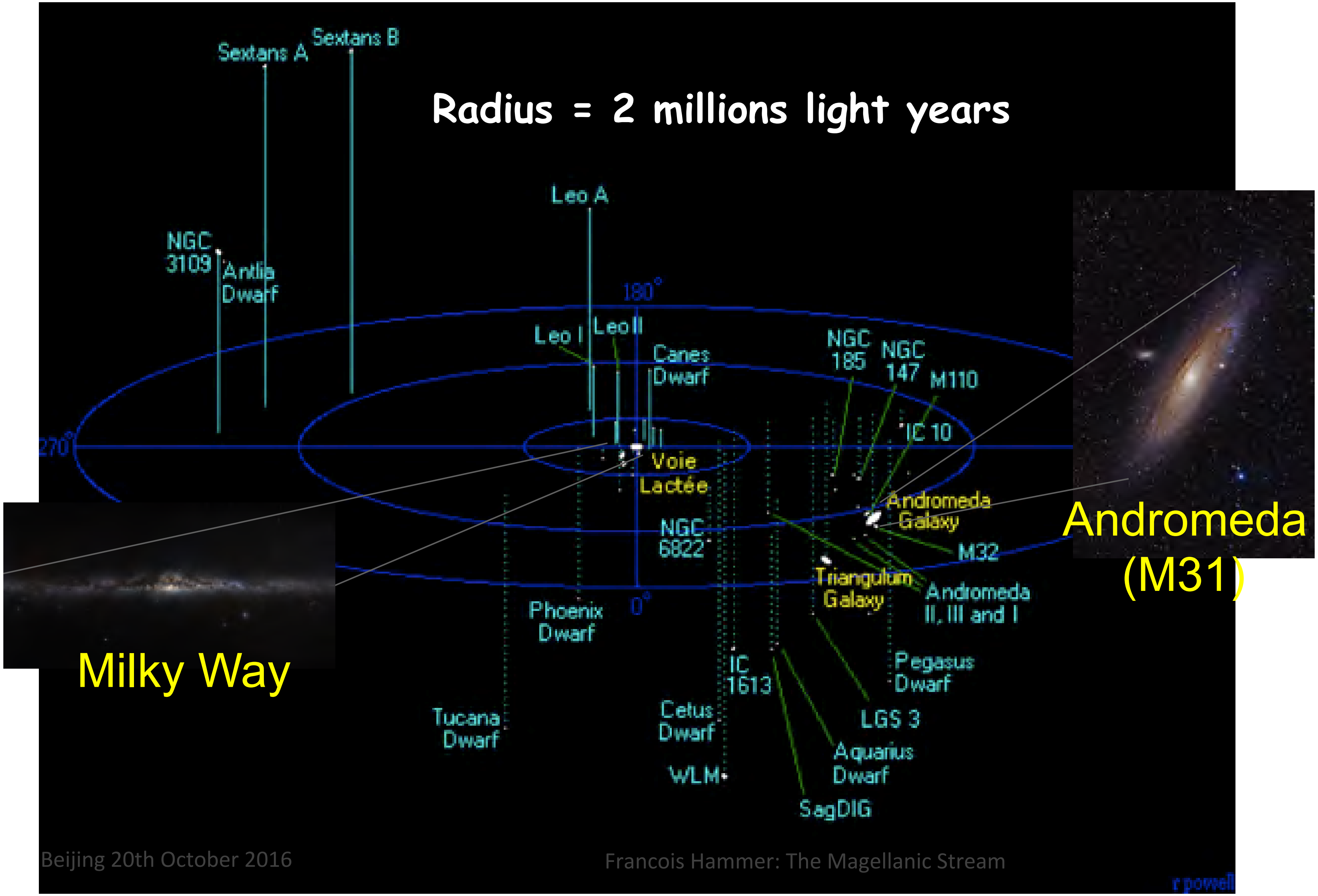
The Magellanic Stream: the ’ram pressure plus collision’ scenario

by François Hammer

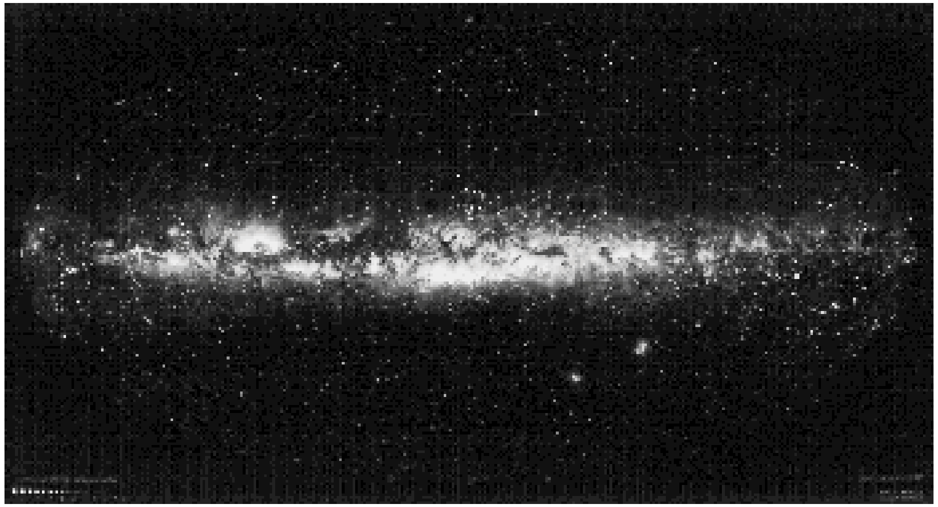
With Yanbin Yang, Hector Flores, Mathieu Puech, Sylvain Fouquet

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:

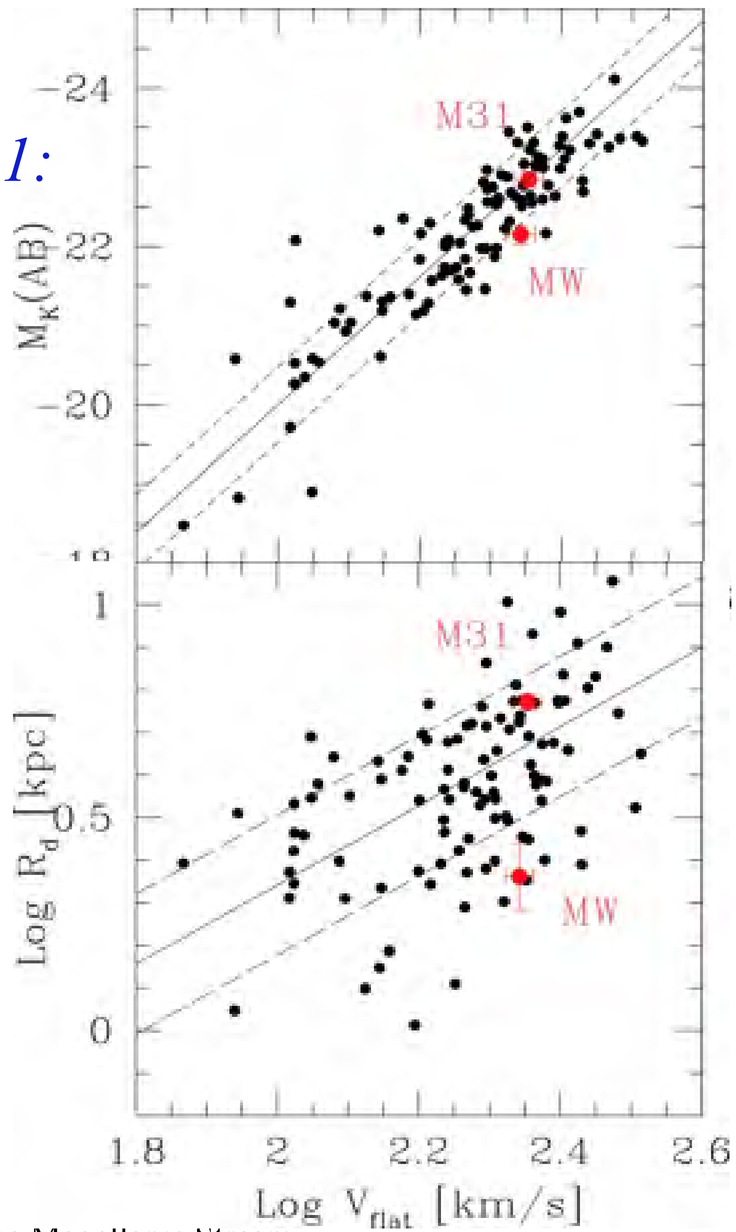
- Halo shows almost no evolved stars
- No major merger since the last 10-11 billions years

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

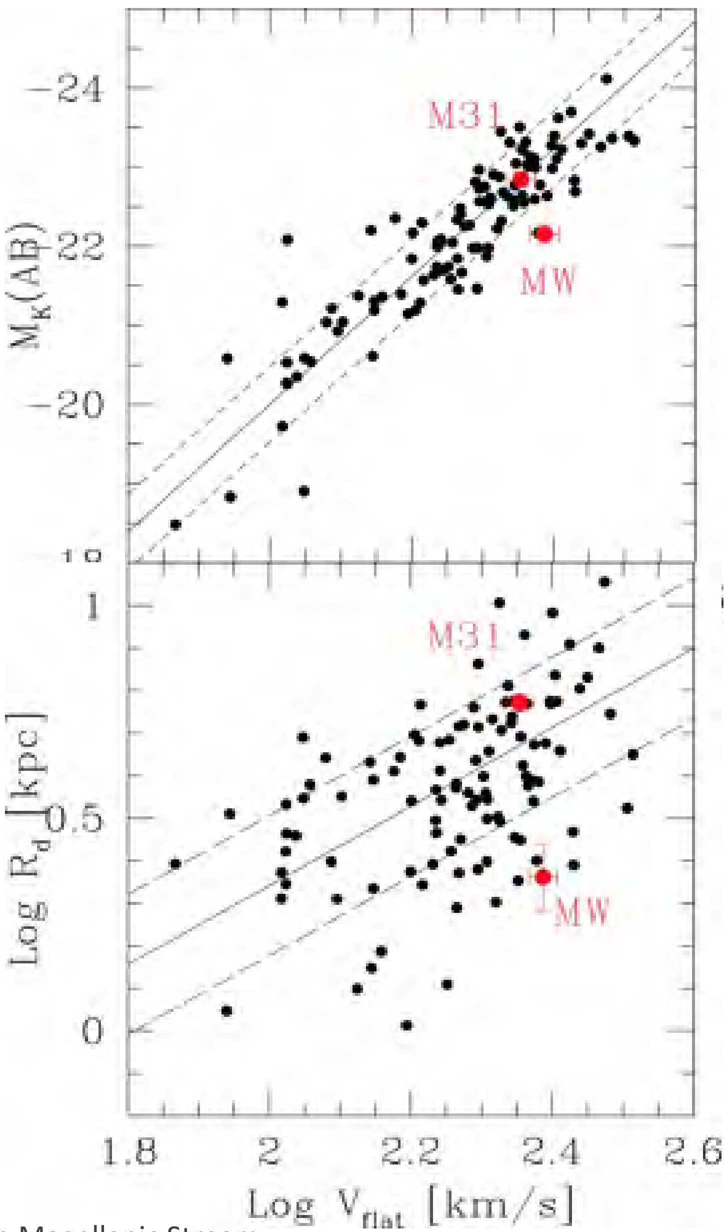
Hammer et al. 2007, ApJ, 662, 322

Accurate measurements for the MW and M31:

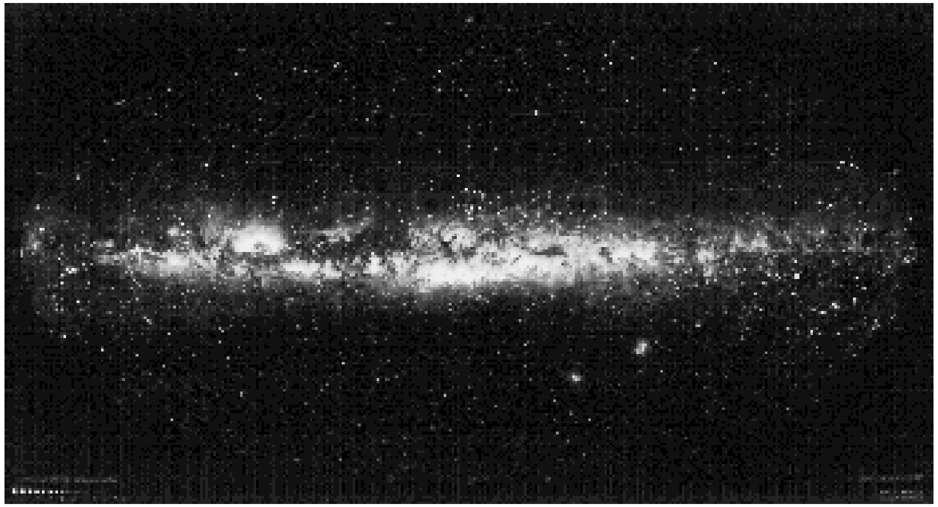
M_K & R_{disk} (COBE/DIRBE, Hipparcos…)
with V_{flat}(MW)=244km/s from Reid et al. (2009) and Bovy, Hogg & Rix (2010)

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 ~ 1-2% of Milky Way-like galaxies.



The Milky Way: a quiescent history … but



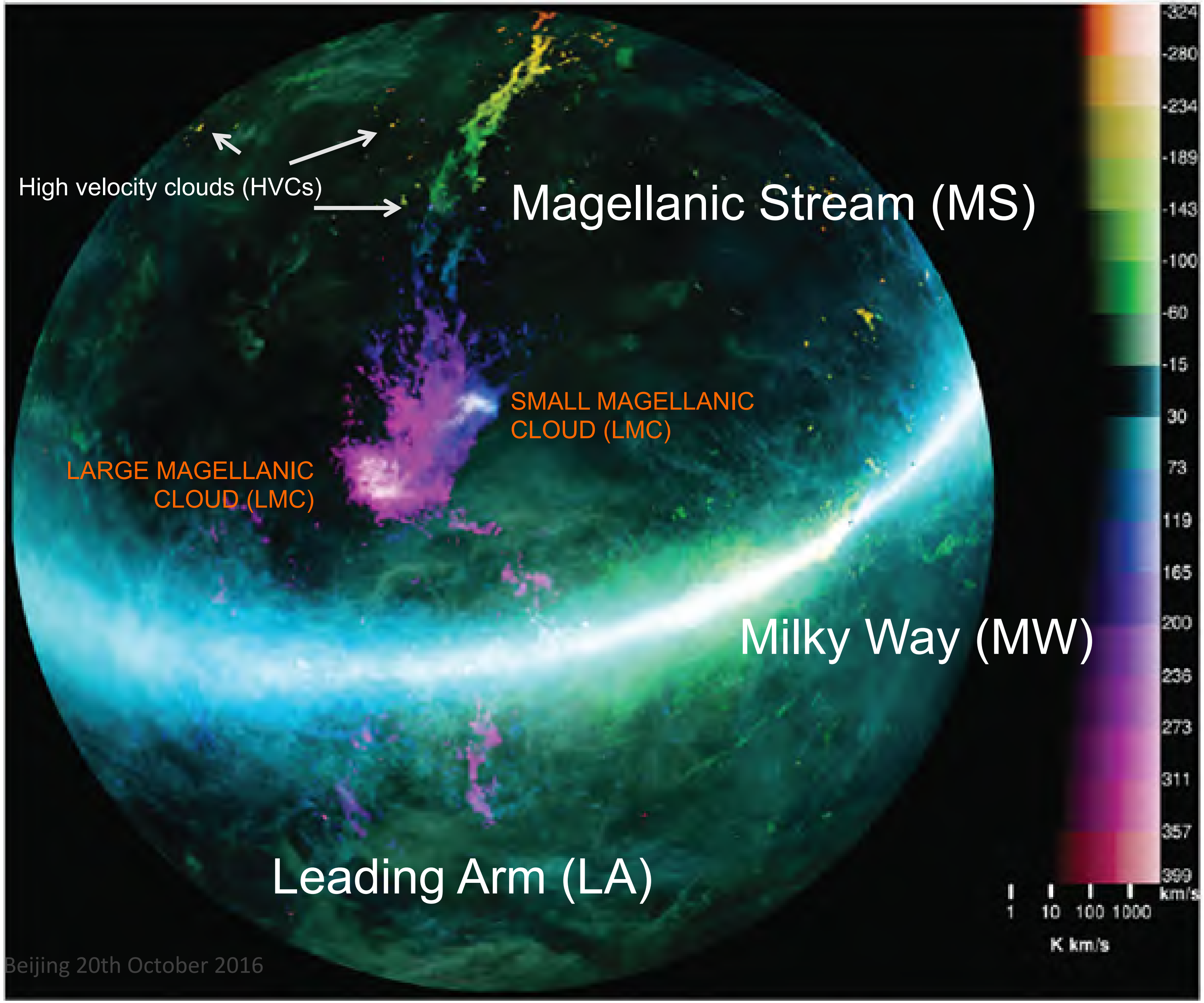
Past history of the Milky Way:

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

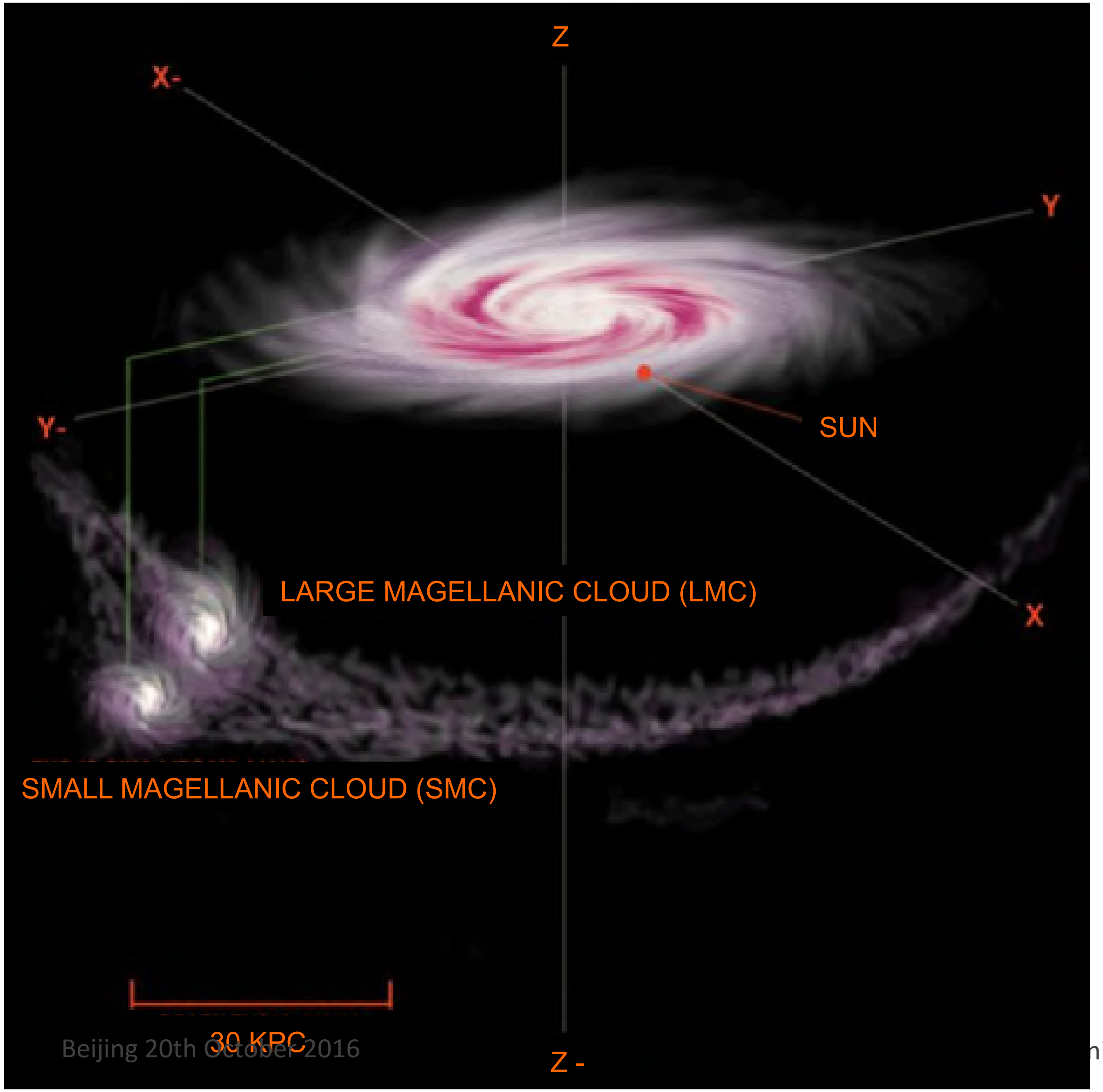
- **Today: infall of the Magellanic Clouds together with ~ 3 $10^9 M_o$ of gas (Magellanic System, Fox+14) almost the gas in the MW disk!**

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

Southern Hemisphere in HI from GASS

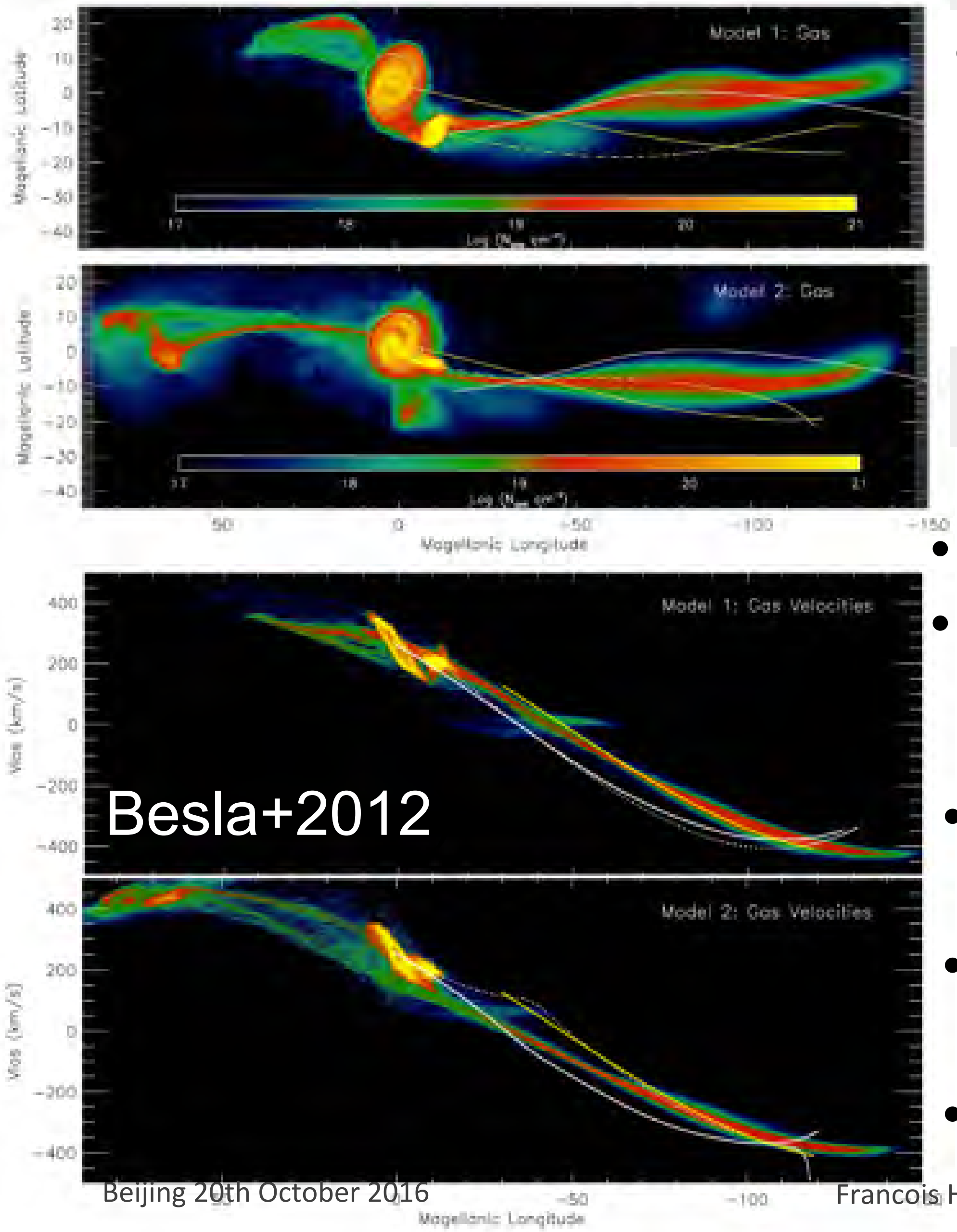


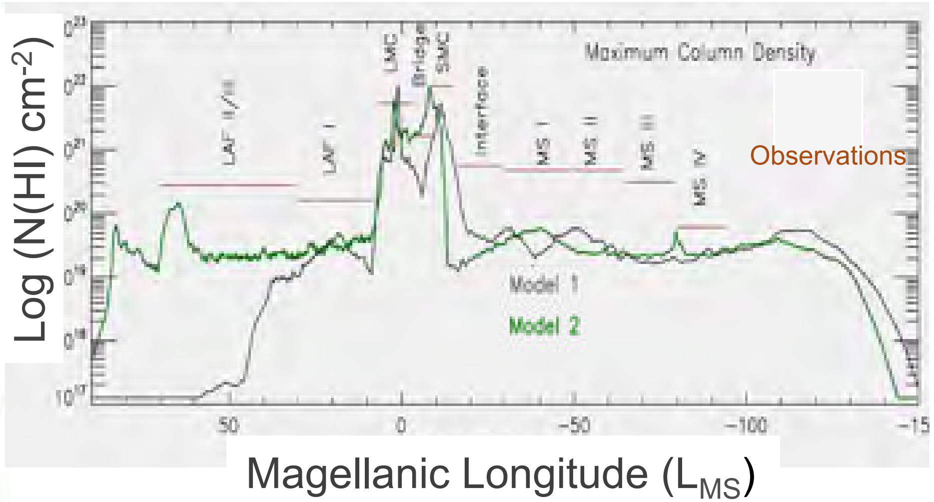
Explanation of the gigantic Magellanic Stream



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

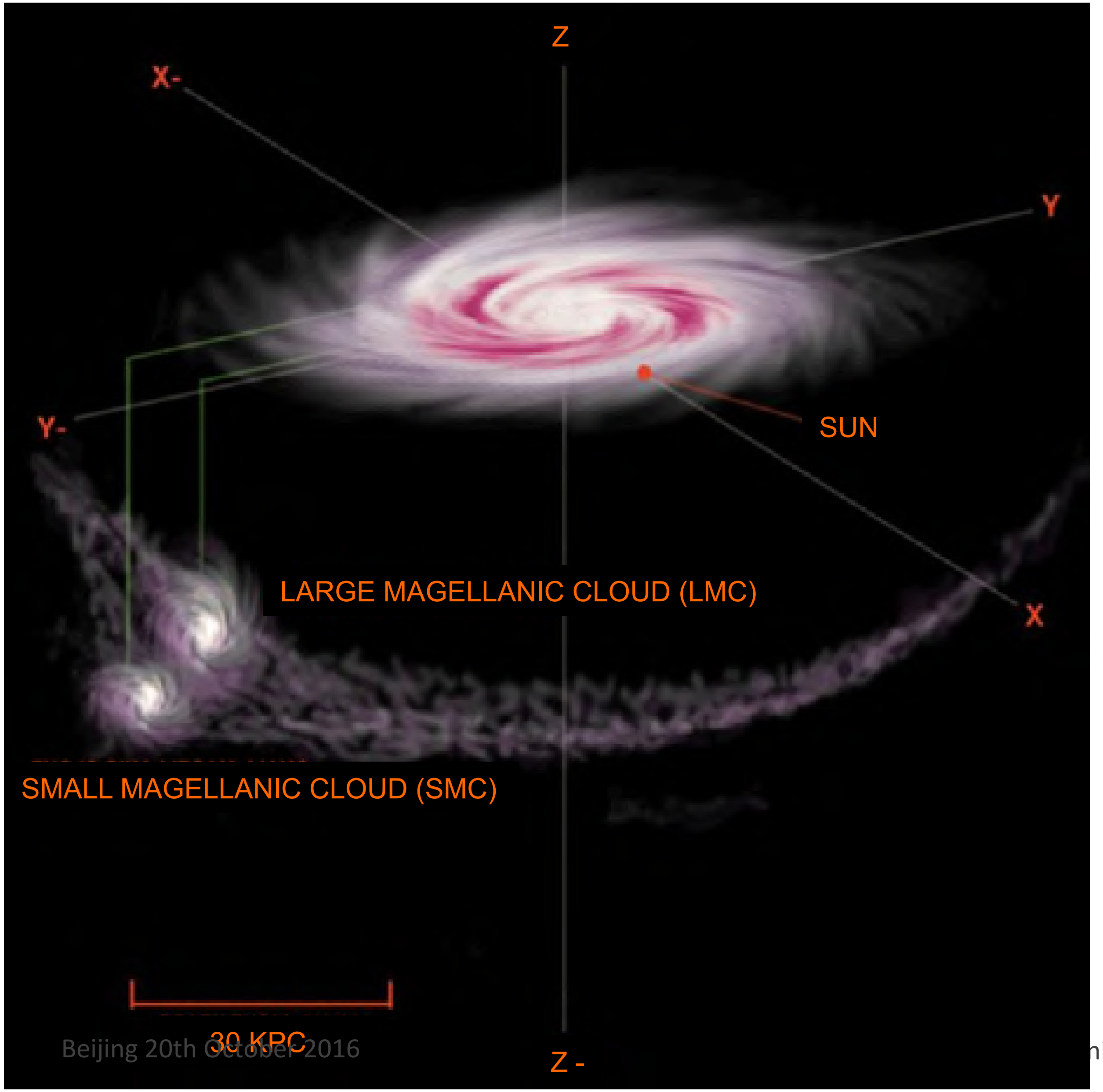
The dearth of predictions from tidal models





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

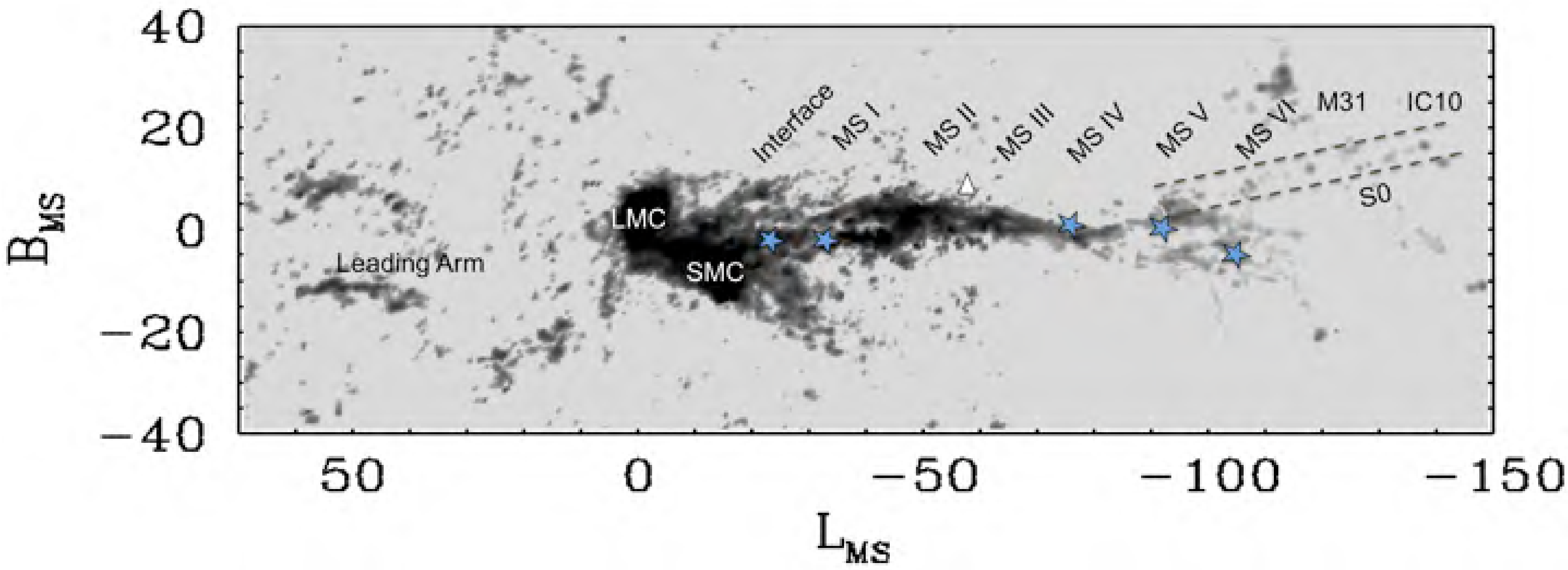
Explanation of the gigantic Magellanic Stream



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

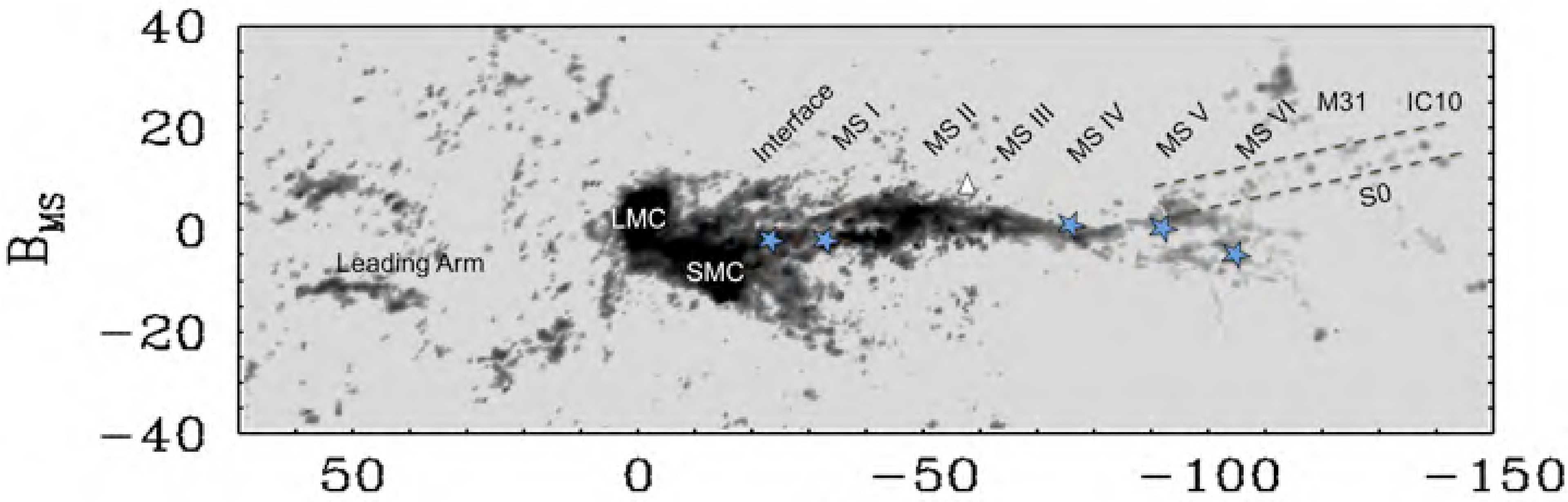
Mathewson (2012): still no satisfactory explanation since 1974

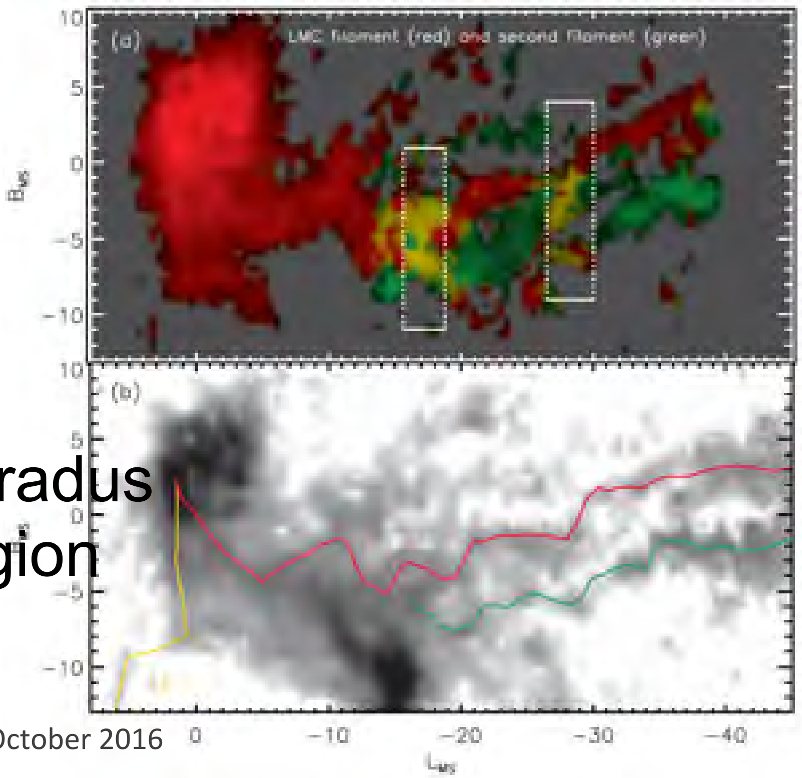
The filamentary structure of the MS



- Filamentary structure of the MS
- DNA-like appearance

Putman+03 and references therein

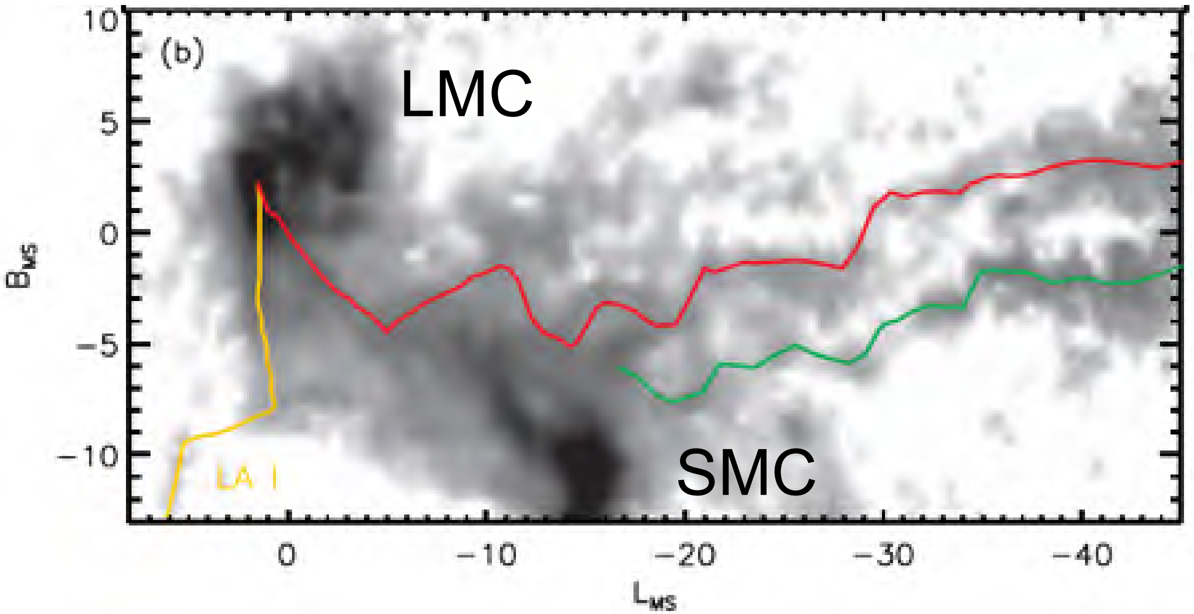


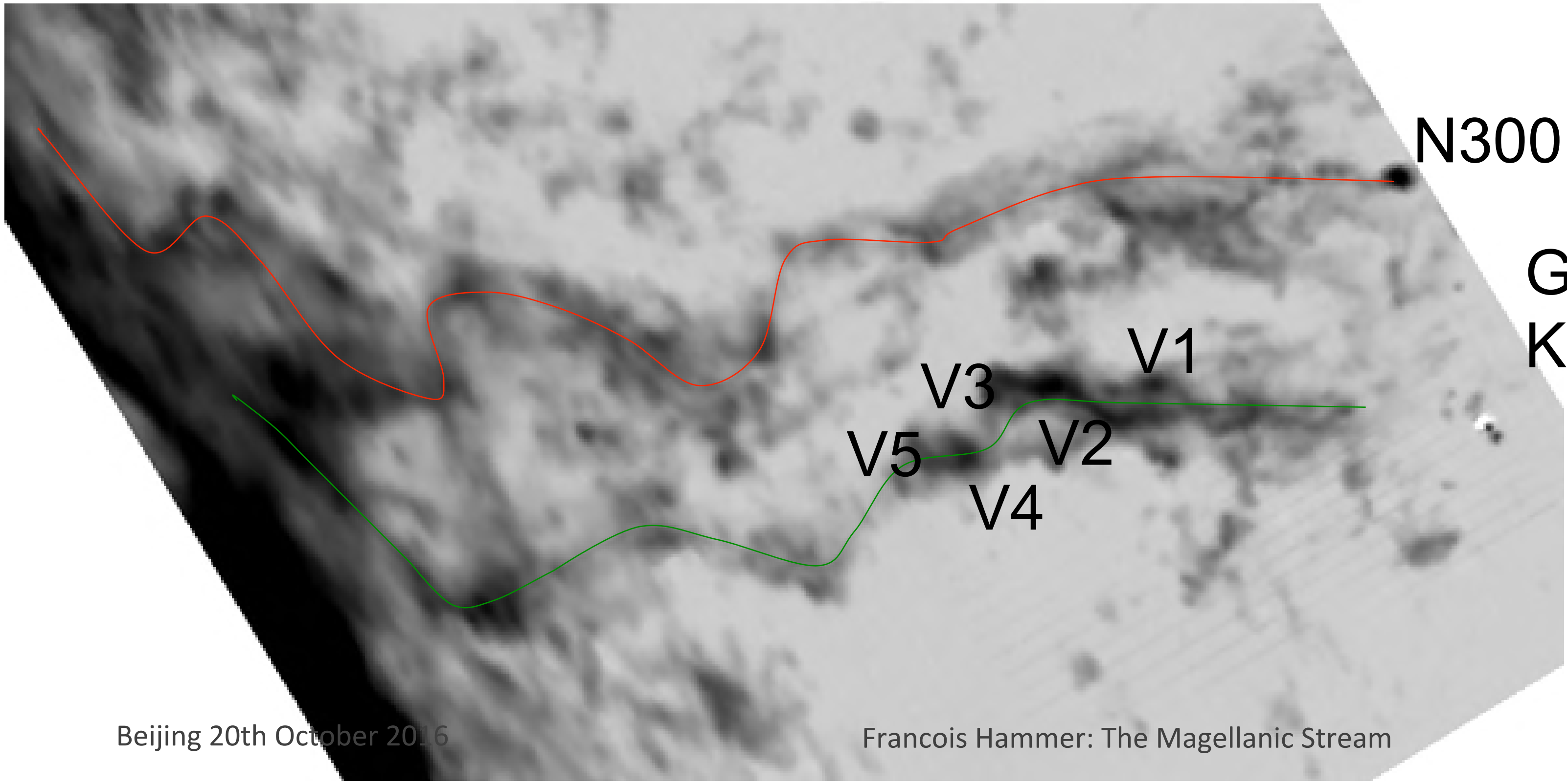


30 Doradus
SF region

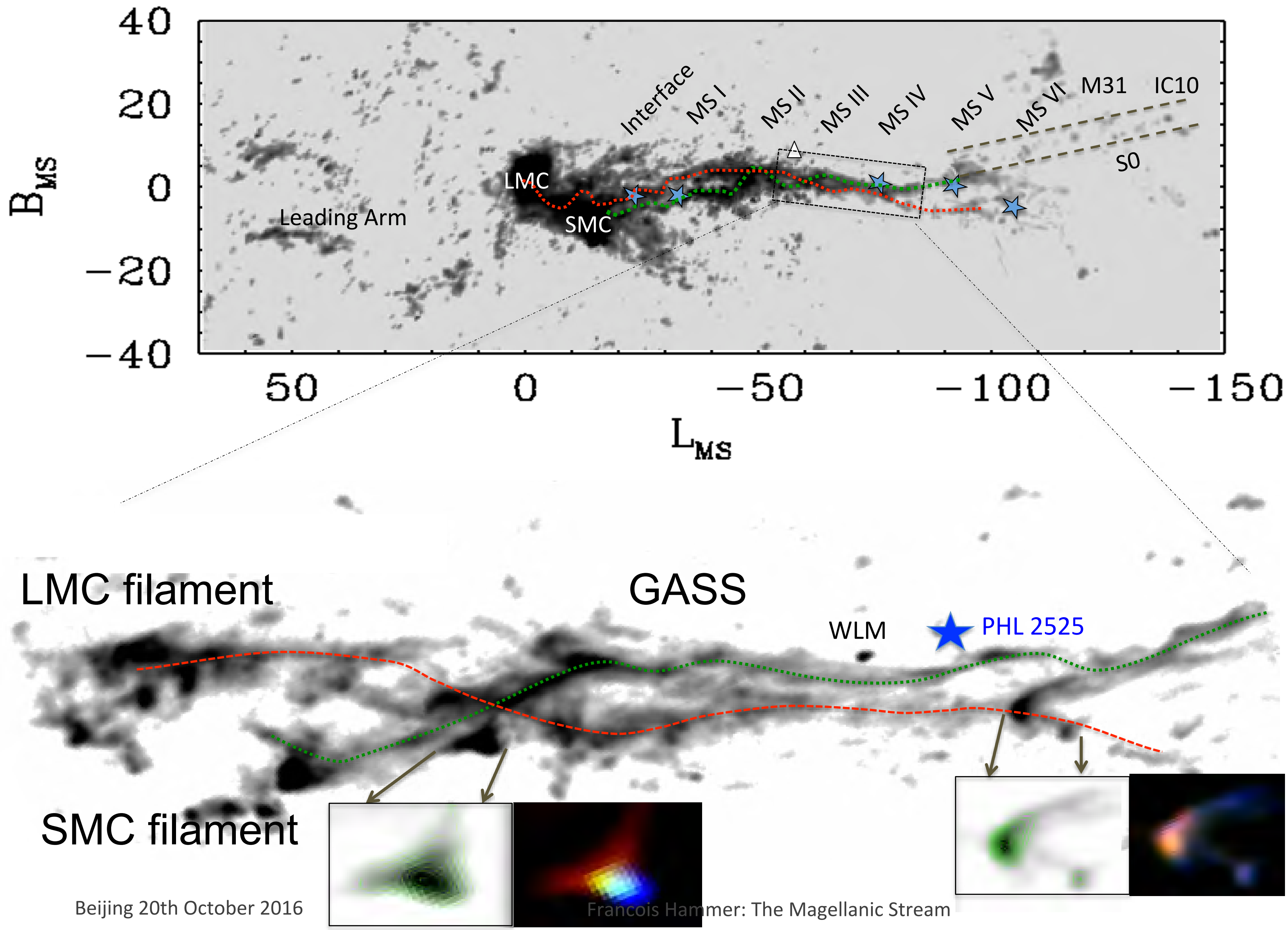
MS with 2 filaments

Nidever+08

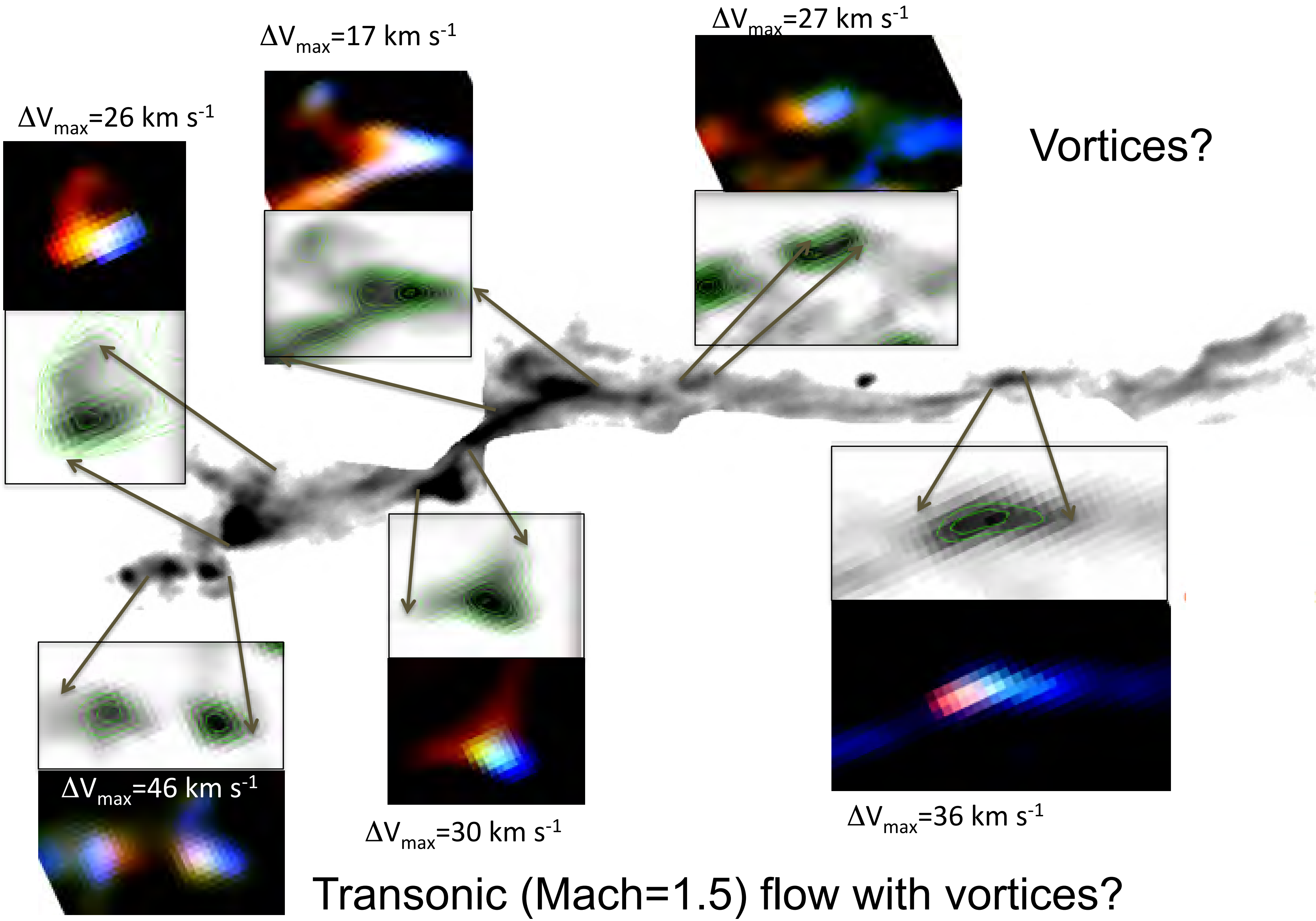




GASS
Kalberla+10

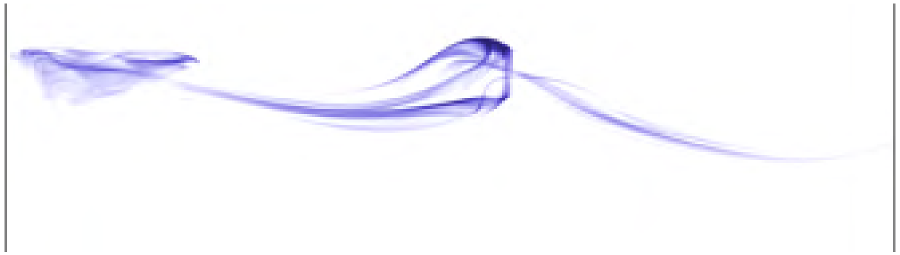


40
20
0
−20
−40
50
0
−50
−100
−150
B_{MS}
L_{MS}
Interface
MS I
MS II
MS III
MS IV
MS V
MS VI
M31
IC10
S0
LMC
SMC
Leading Arm
LMC filament
GASS
WLM
PHL 2525
SMC filament

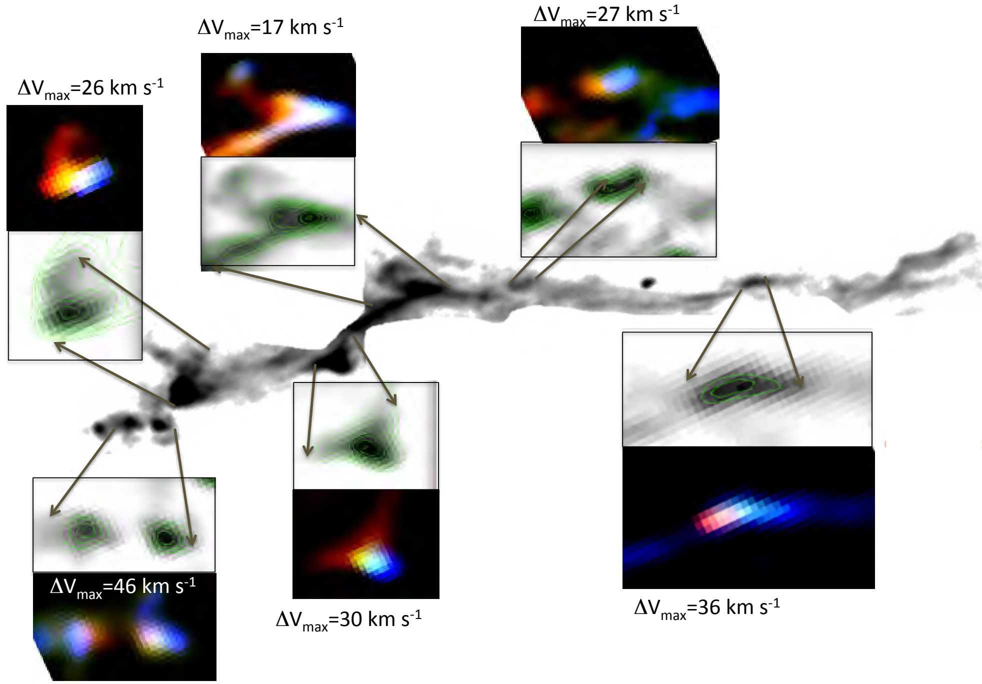


Transonic (Mach=1.5) flow with vortices?

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

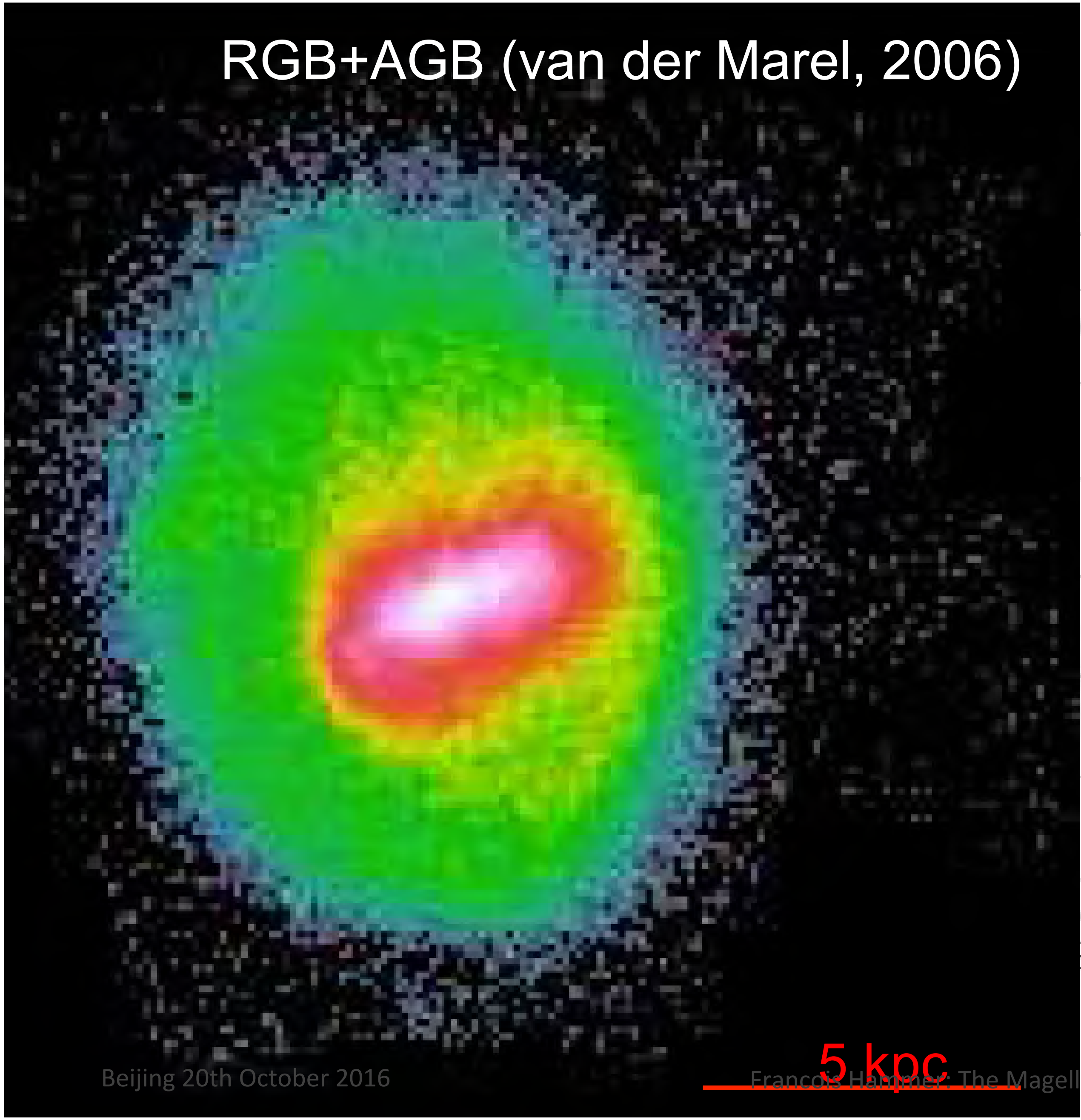


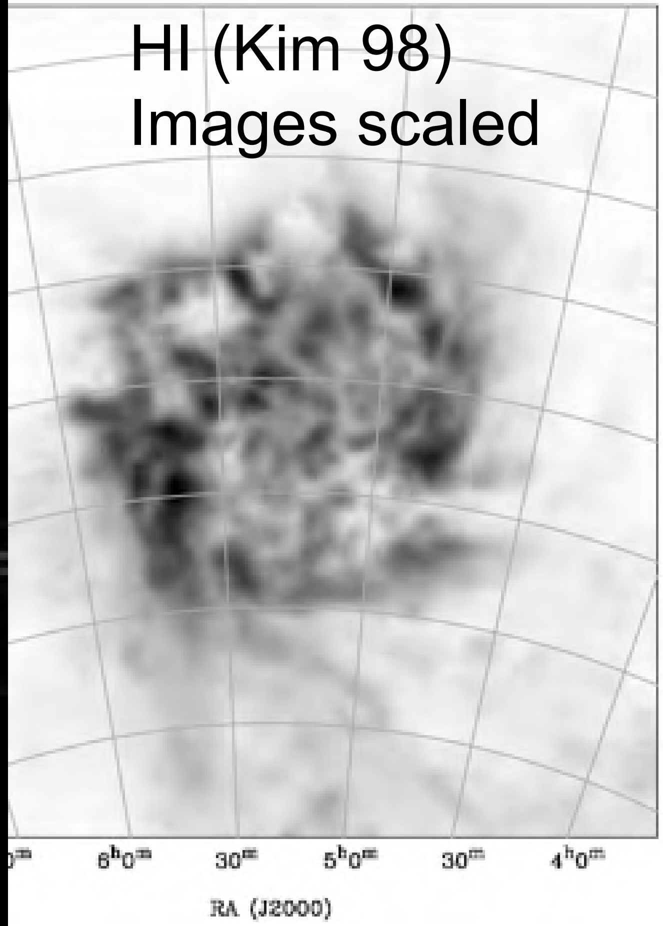
Ram pressure exerted by the hot gas (10^6K) of the Milky Way halo

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

- Associated high velocity clouds are disrupted (multi-phases, Karlberla & Haud, 2006) ➔ ρ_{hot}~ 10^{-4} 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





Ram-pressure plus collision scenario

Hammer et al. 2015

- Evidence for ρ_{hot}~ 10^{-4} 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 x f_{μ}^{-1} with f_{μ} ≤1 (viscosity suppression factor, Roediger et al. 2013), implying a moderately turbulent Stream*
- *Mach~ 1.5 (V_{sound} ~ 200 km/s, V ~ 300 km/s)*

Ram-pressure plus collision scenario

Hammer et al. 2015

~ 200 Myr old collision between the Magellanic Clouds

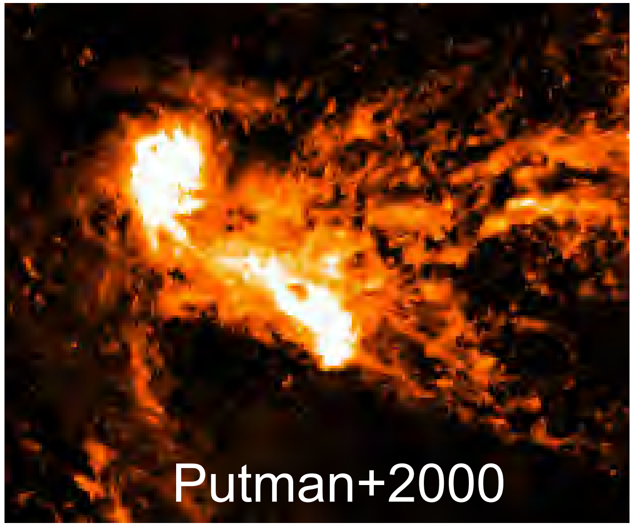
Evidenced by:

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 $10^{11} M_{O}$
  hot gas mass, 3 to 9 $10^{10} M_{O}$

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

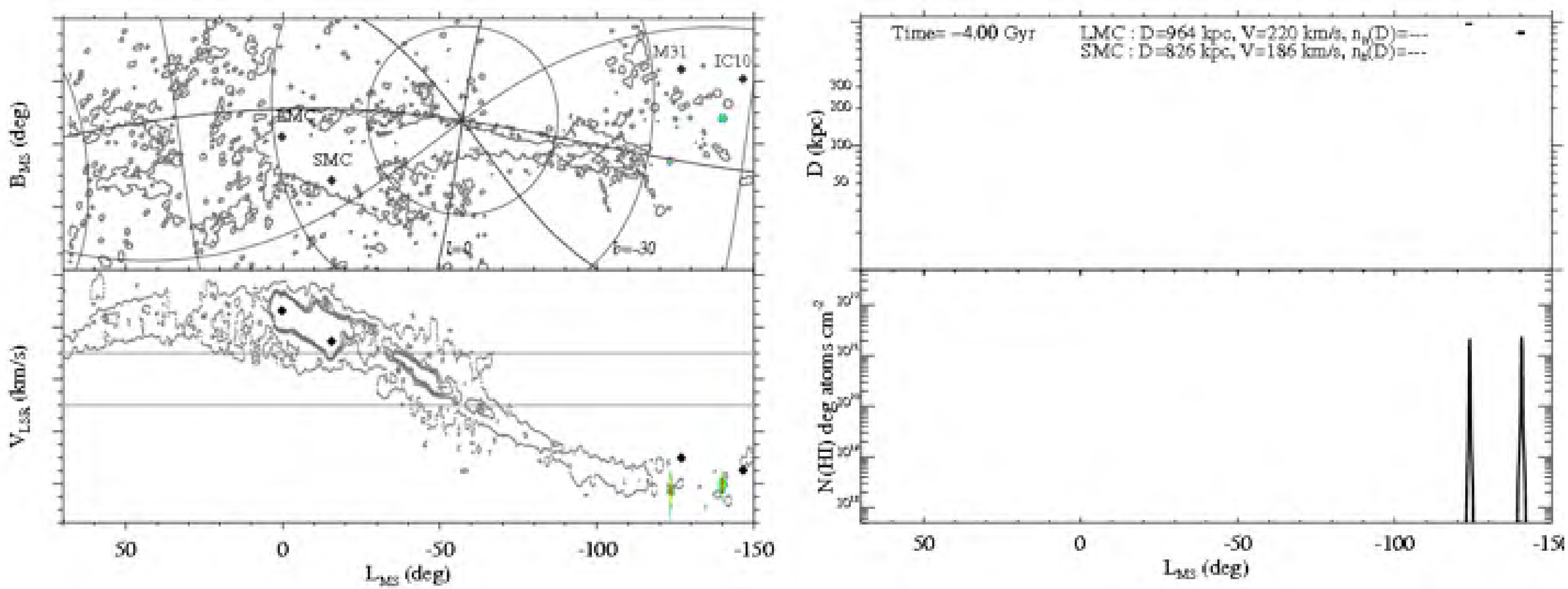
- Initial LMC: mass, 1.8-5 $10^{9} M_{O}$; f_{gas}, 40-60%
- Initial SMC: mass ~ 0.7 LMC mass, f_{gas}, 40-70%

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

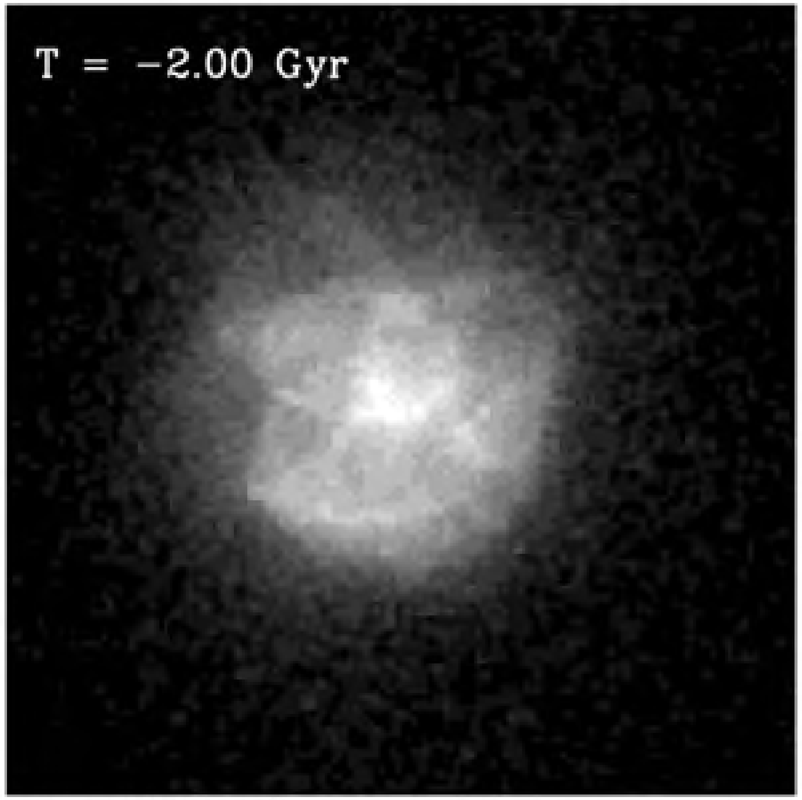
Explanation of the gigantic Magellanic Stream

Hammer et al. 2015

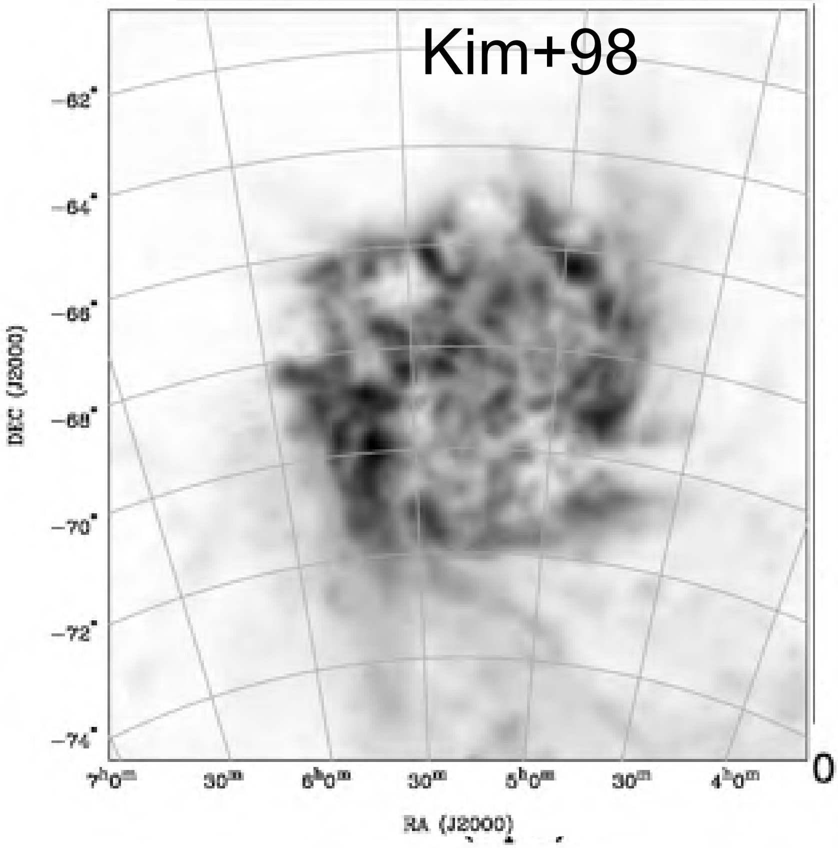
Gas of the Clouds stripped by ram-pressure exerted by the hot gas in the Milky Way halo



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)

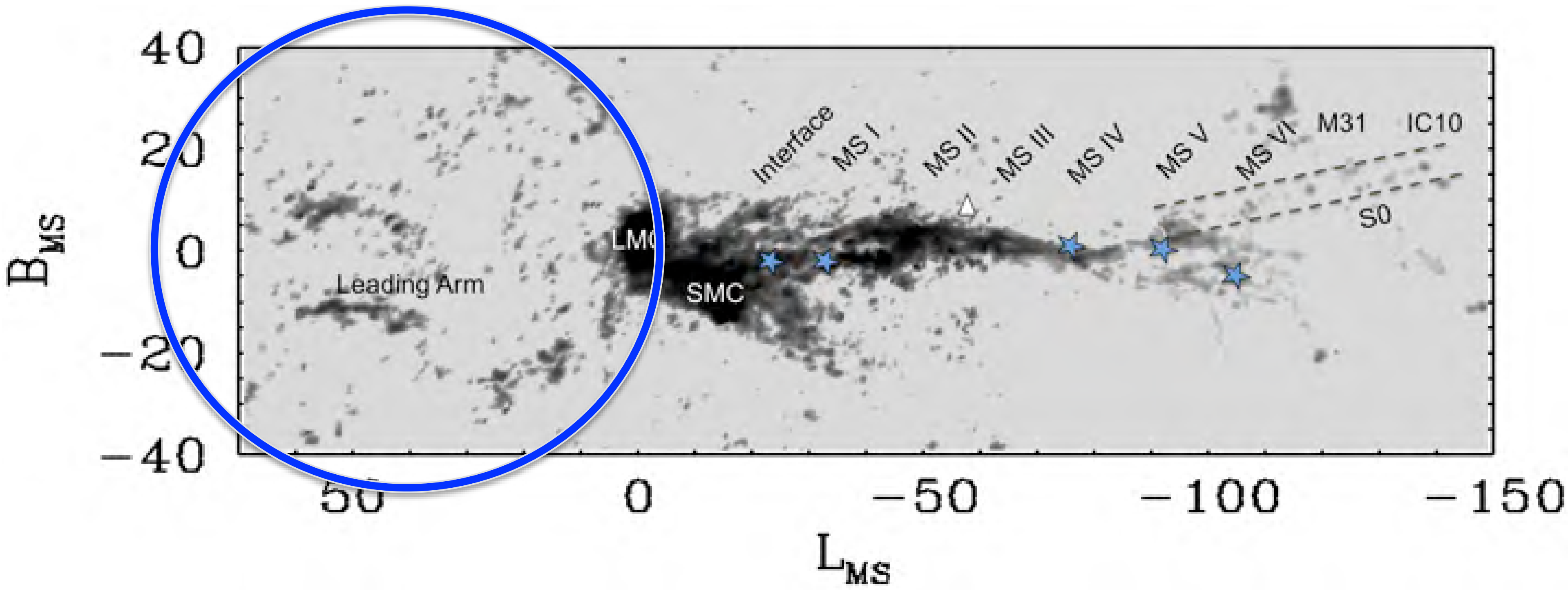


19.8 x 19.8 kpc²



Feedback prescriptions: 5 times the median Cox+06 value

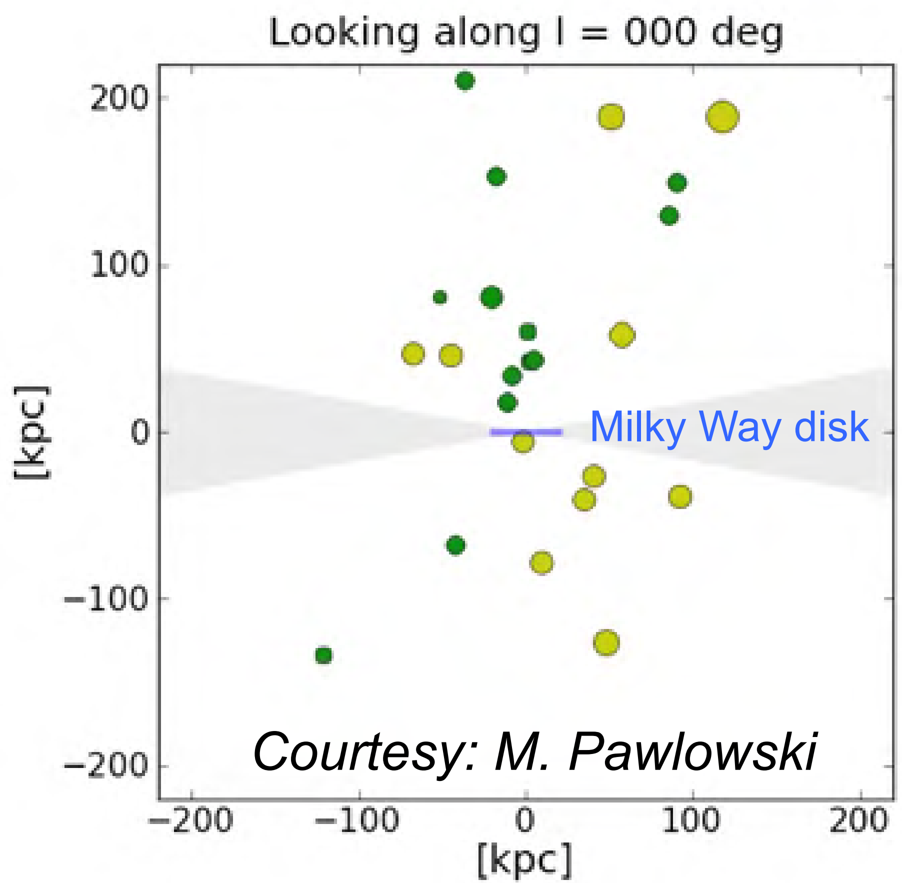
Formation of the Leading Arm

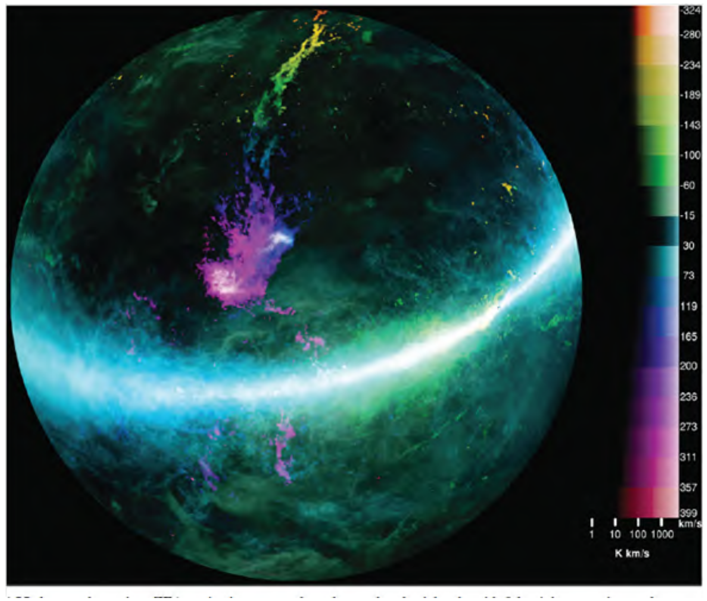


Former passages of leading and ram-pressure stripped dIrrs
(a la Lucio Mayer, 2009; LA firstly reproduced by Yang et al; 2014)

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

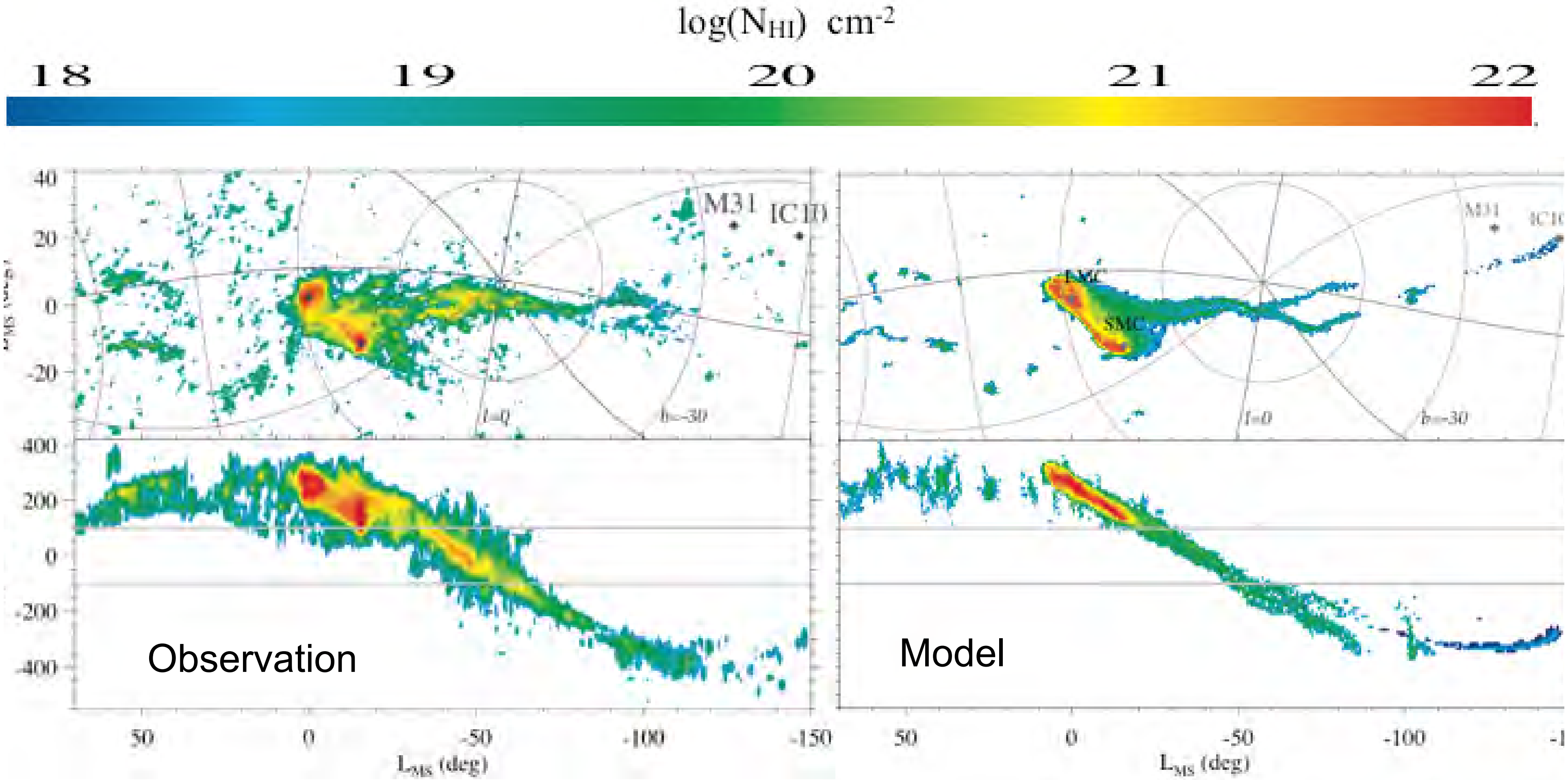
VPOS: Vast Polar Structure surrounding the Milky Way, which includes classical dSphs, Magellanic Clouds and the Stream





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)

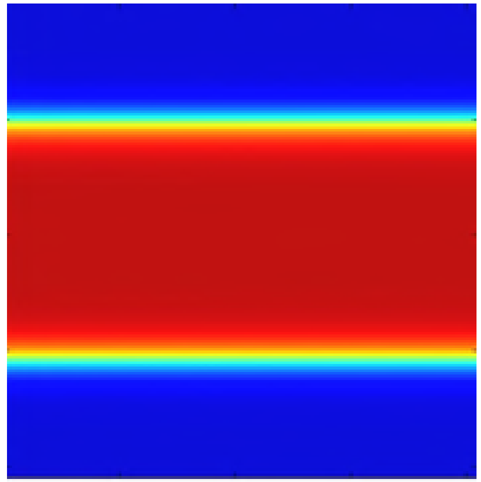


The Magellanic System: a corner stone to understand

- 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)?