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

by François Hammer

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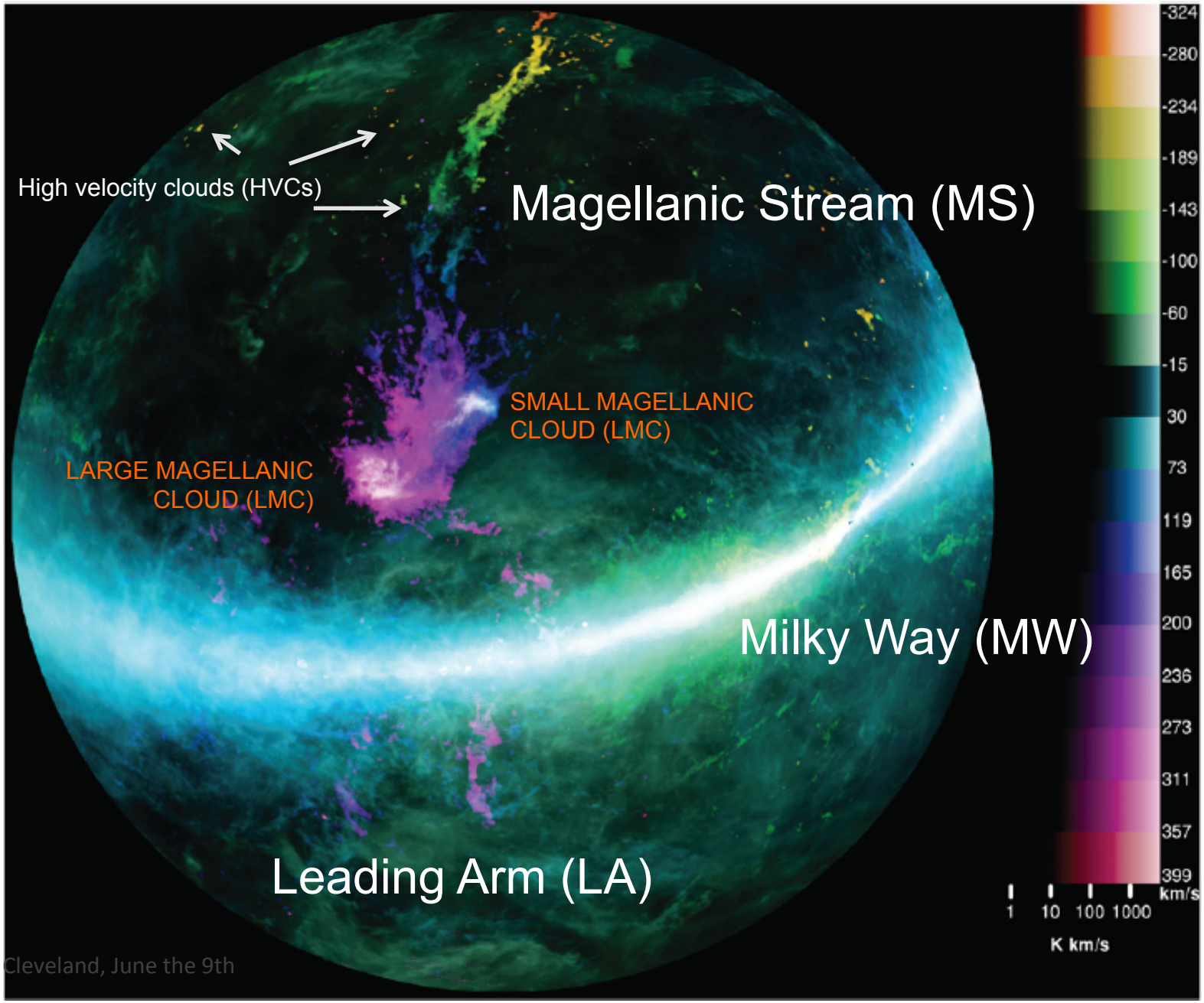
Galaxies Étoiles Physique et Instrumentation

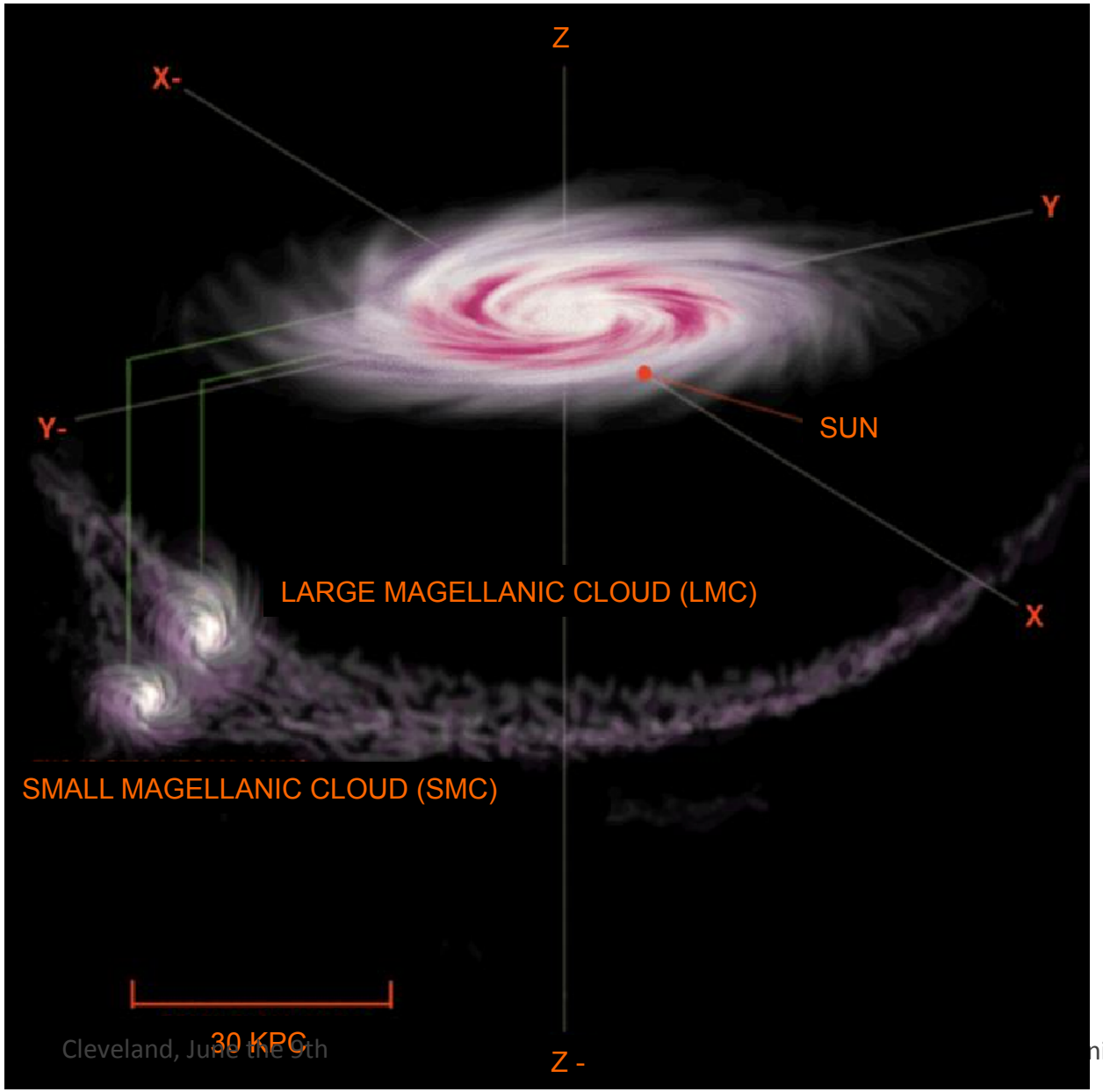
With Yanbin Yang, Hector Flores, Mathieu Puech, Sylvain Fouquet

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

Southern Hemisphere in HI from GASS

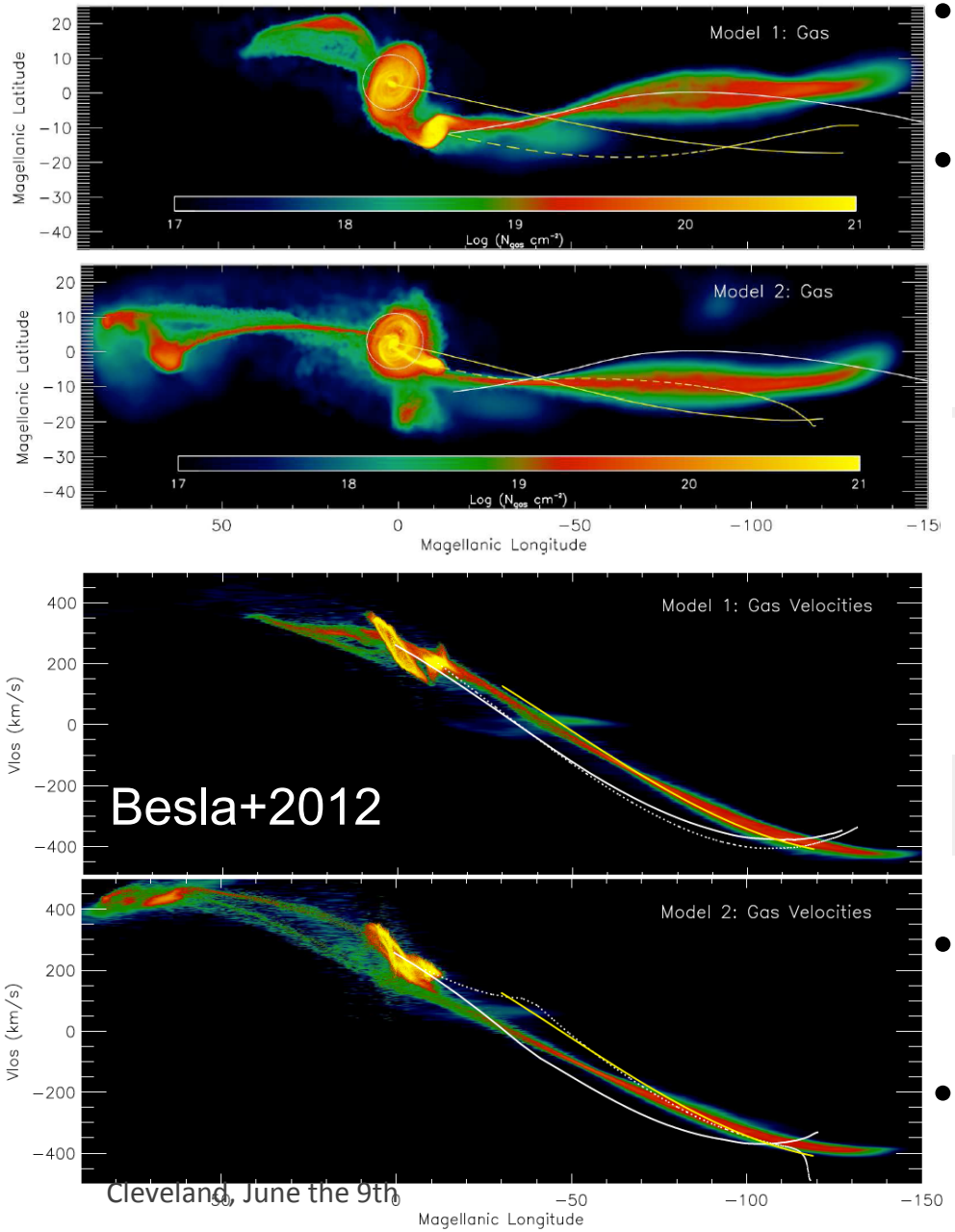


Explanation of the gigantic Magellanic Stream

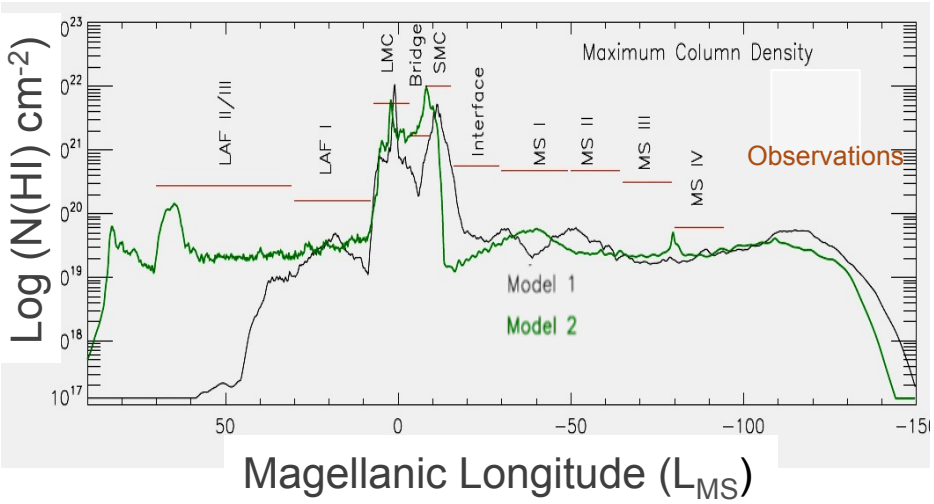


Firstly identified as the MS by Mathewson+74 after detections by van Kuilenburg and Wannier & Wrixon72

Why tidal models are not predictive?

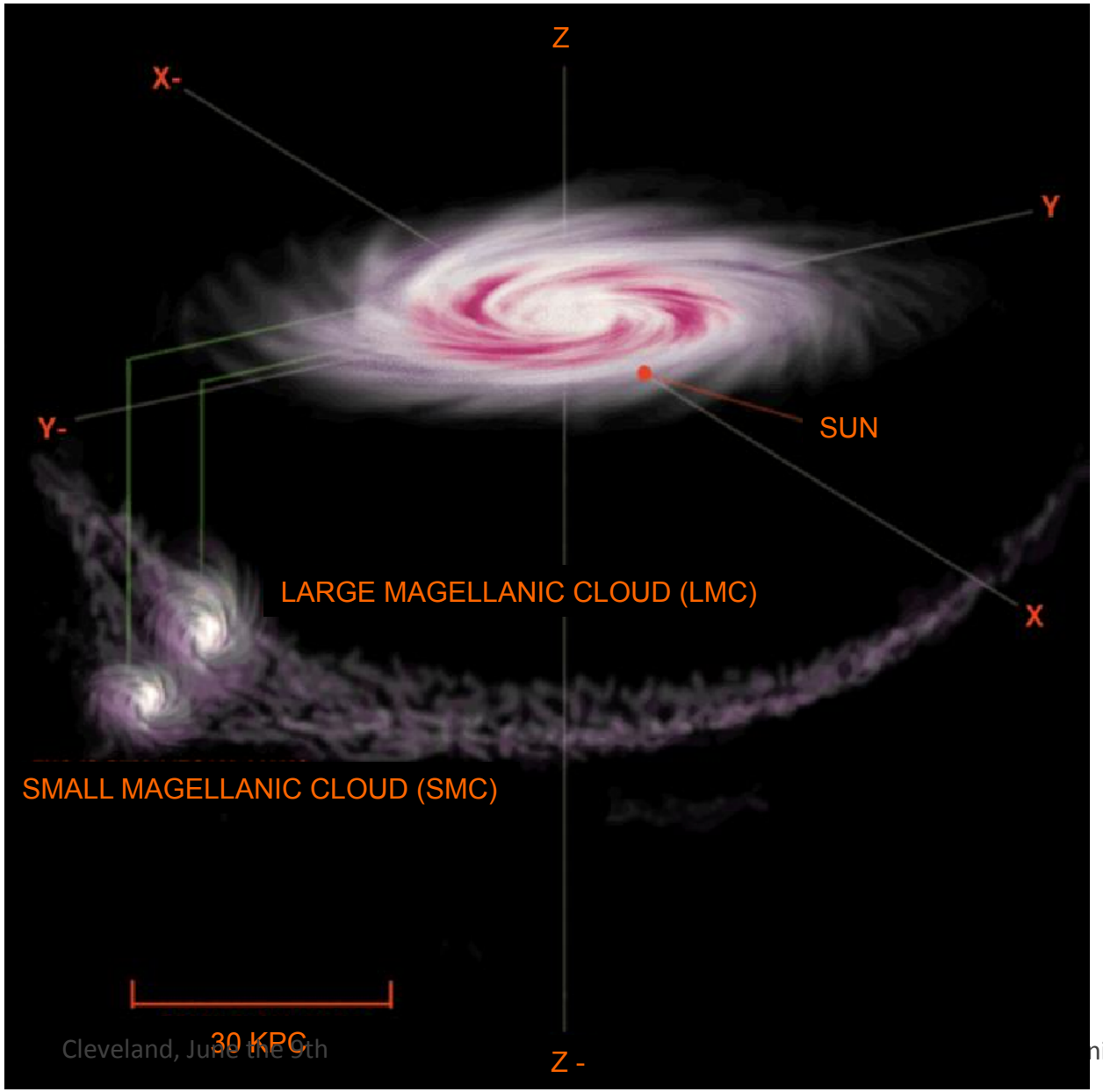


- Can't explain absence of stars
- Can't explain the filamentary structure nor the 4 Leading Arm structures



- Already lack 9/10 of N(HI)
- Could not explain large ionized gas amount (2 $10^9 M_O$, Fox+14)

Explanation of the gigantic Magellanic Stream



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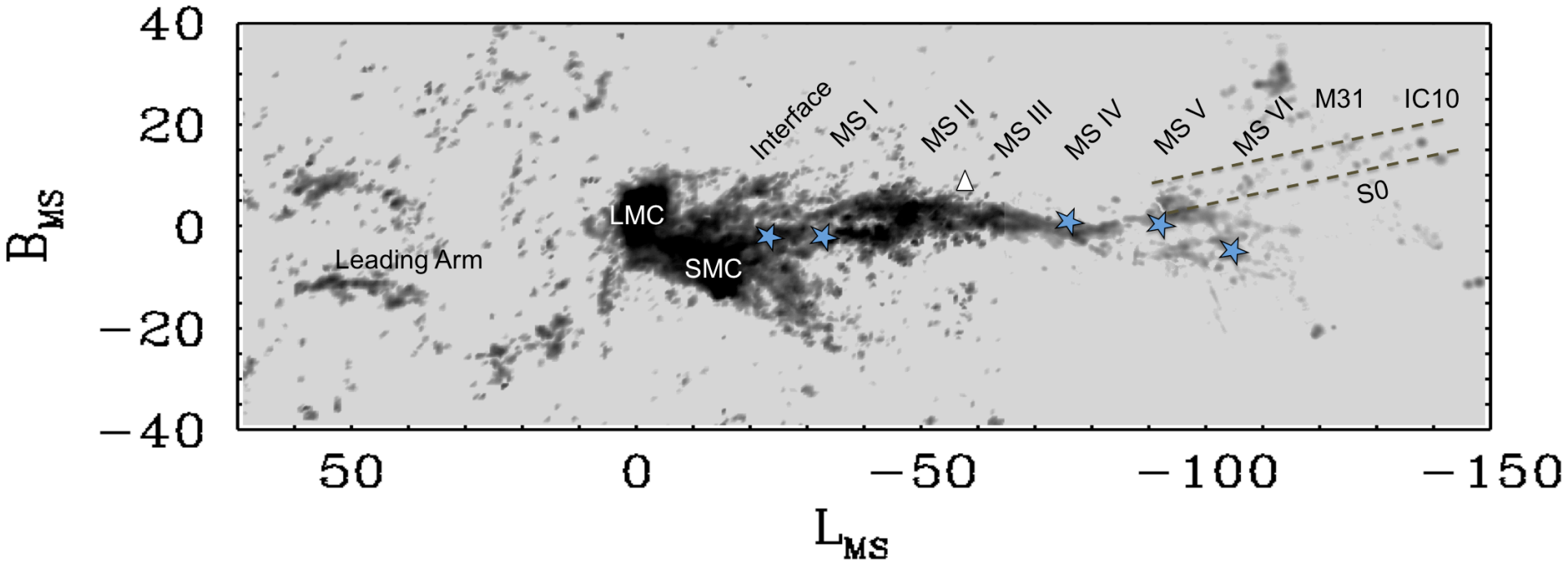
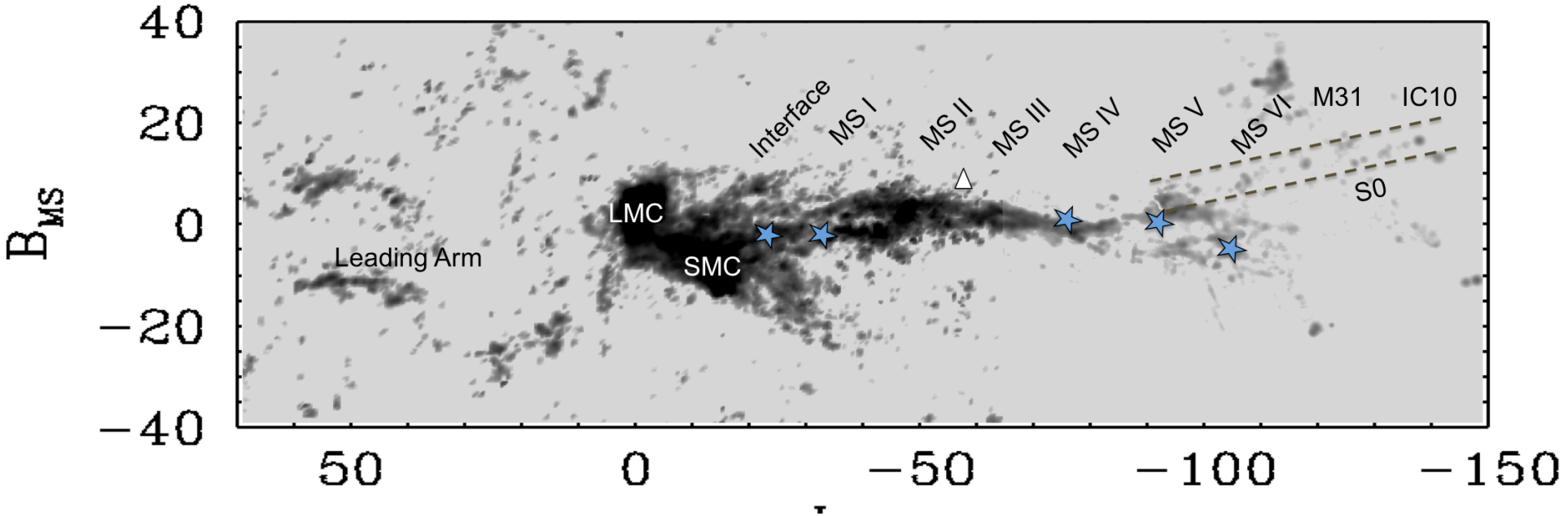
Mathewson (2012): still no satisfactory explanation since 1974

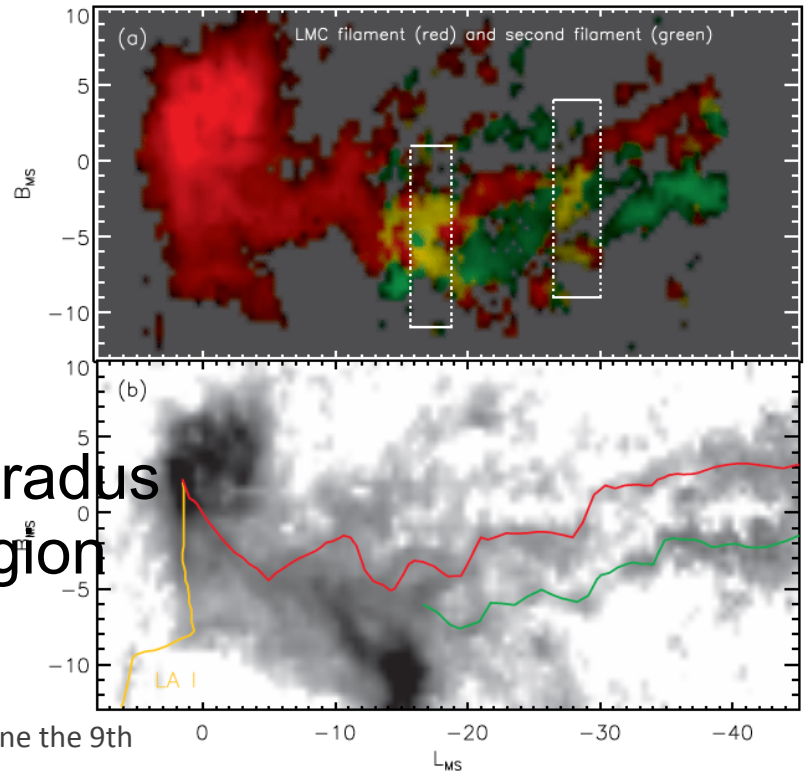
The filamentary structure of the MS



- Filamentary structure of the MS
- DNA-like appearance

Putman+03 and references therein

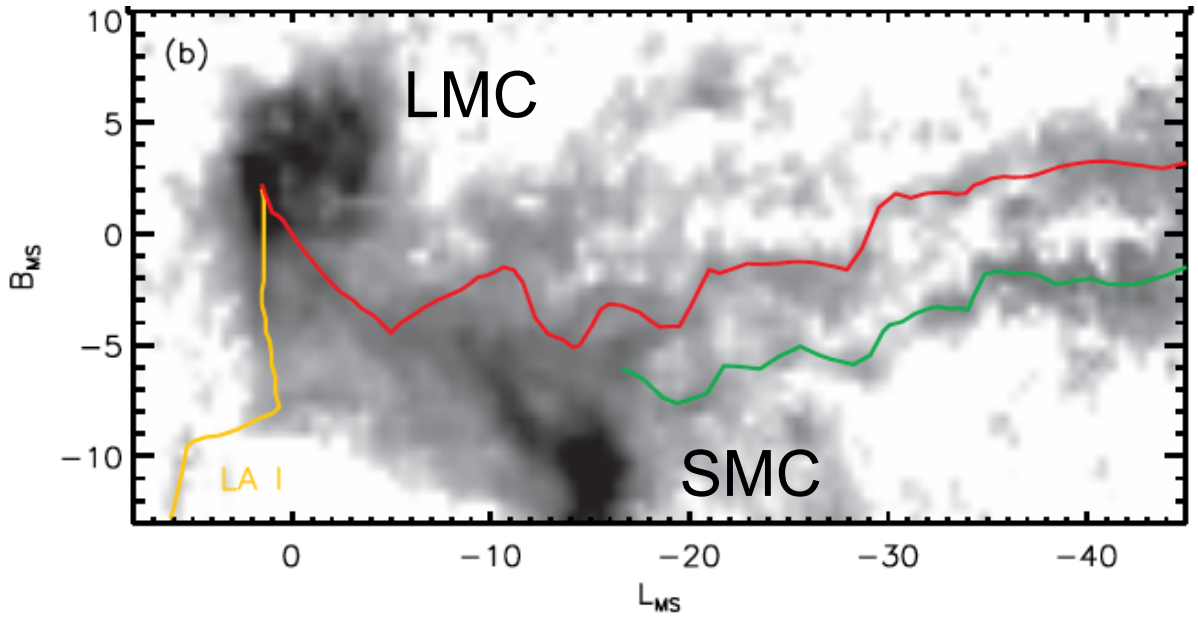


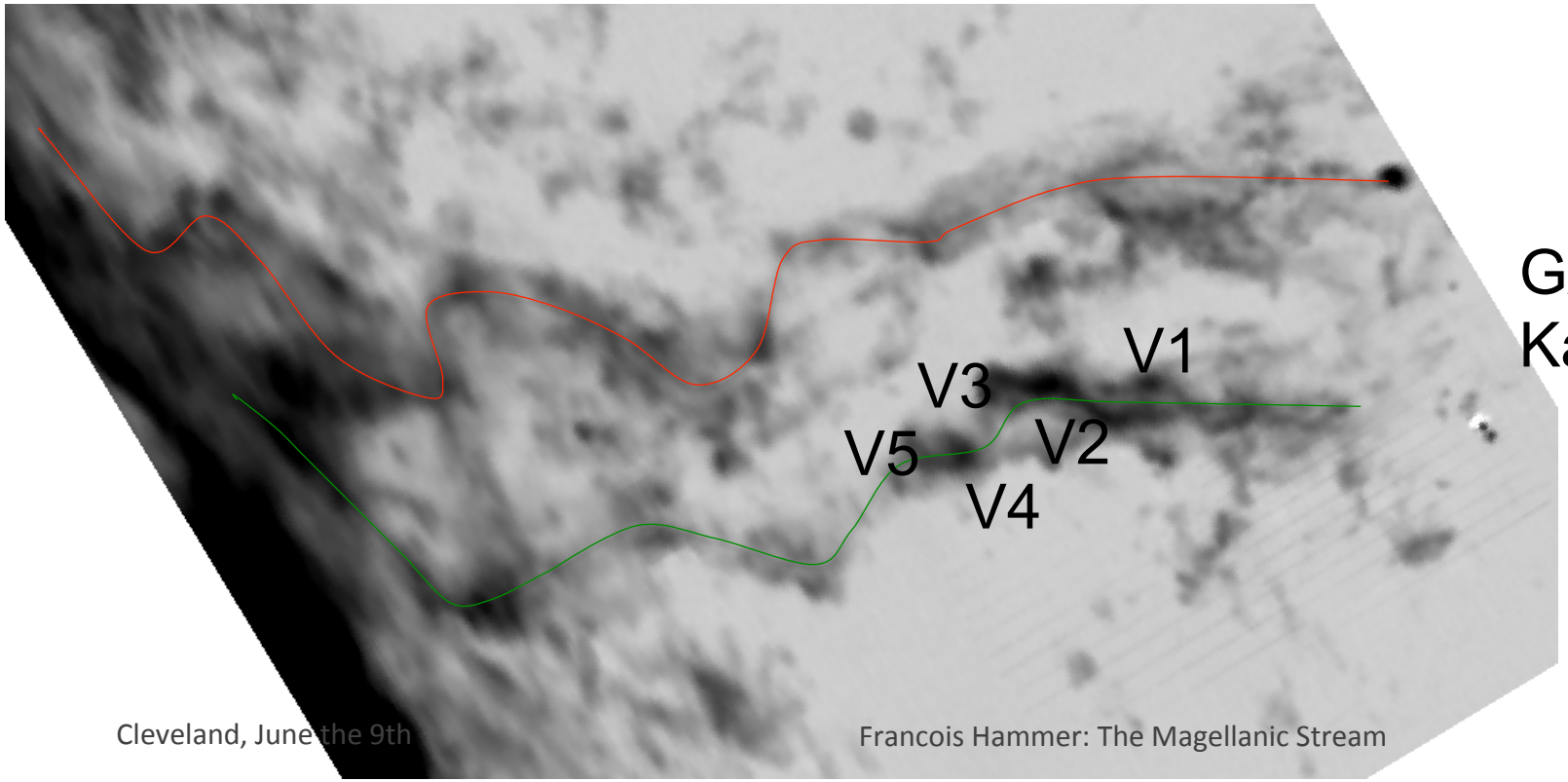


30 Doradus
SF region

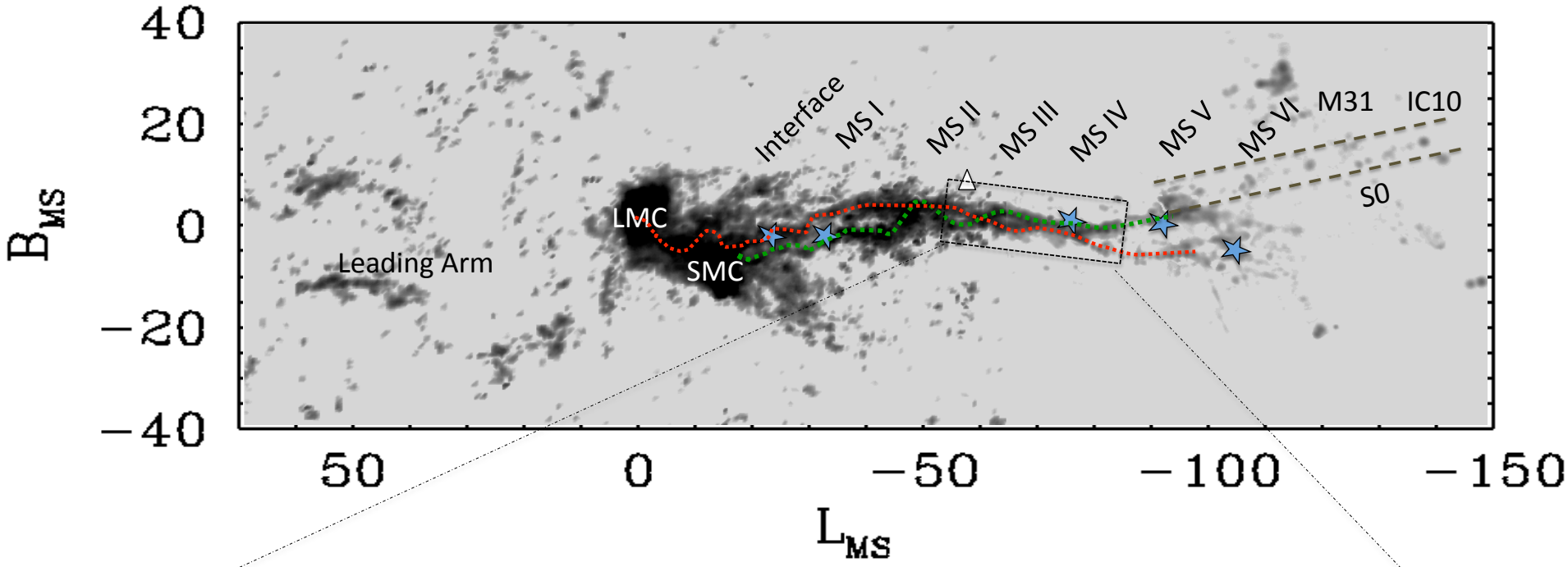
MS with 2 filaments

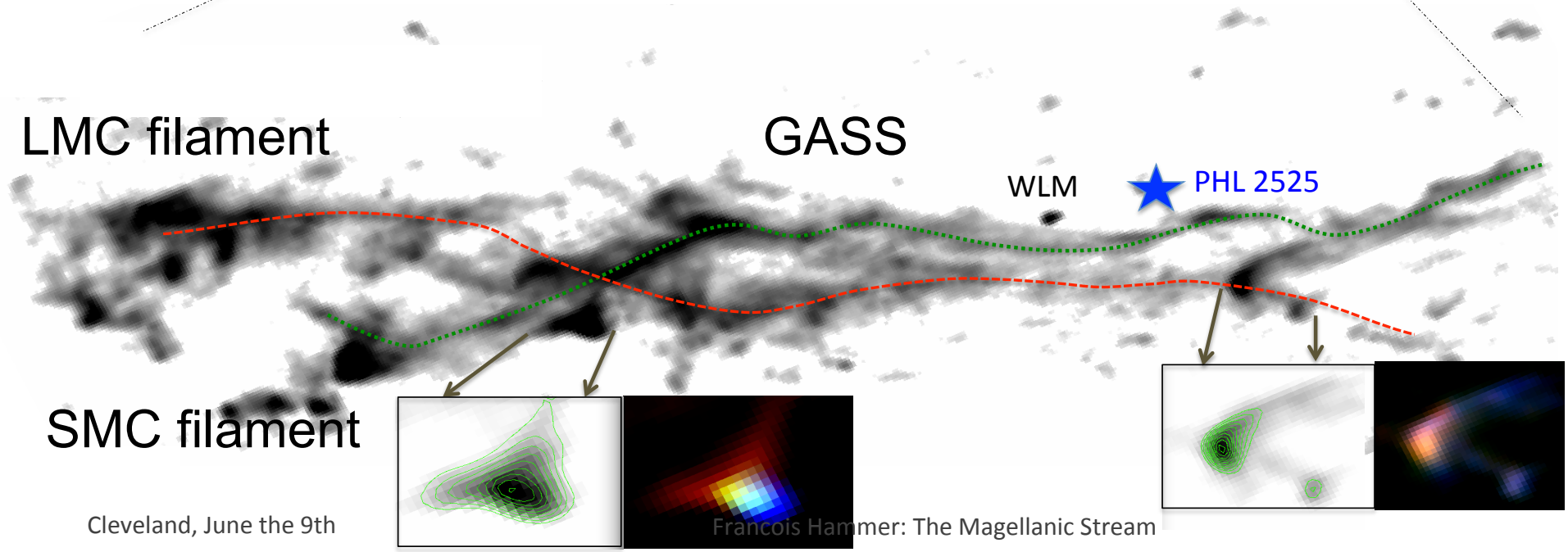
Nidever+08

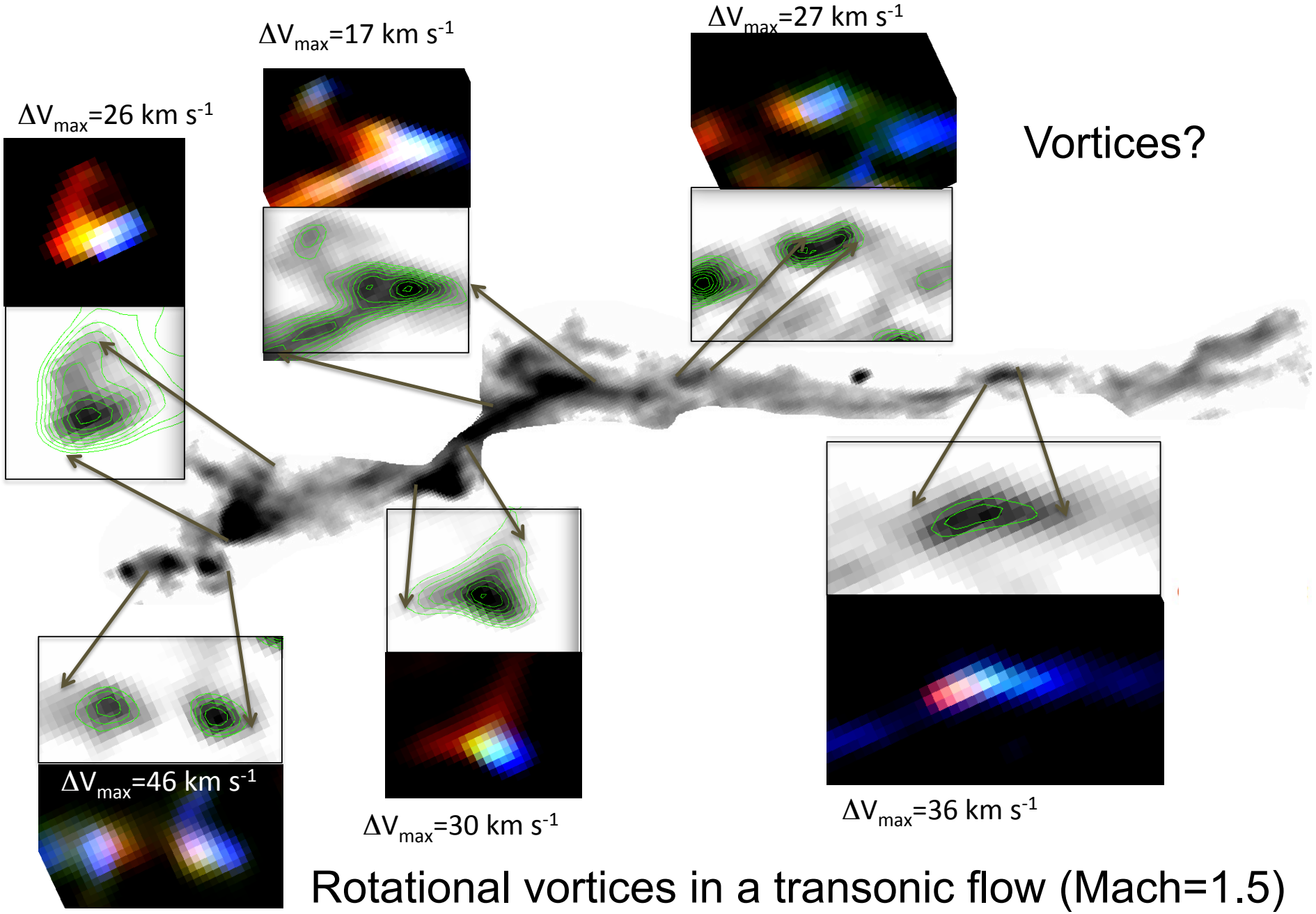




GASS
Kalberla+10

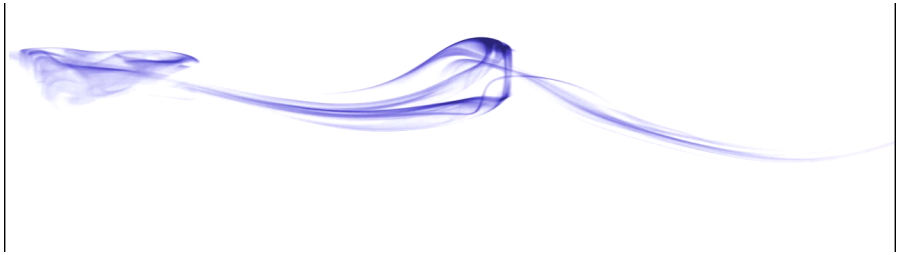

40
20
0
−20
−40
B_{MS}
50
0
−50
−100
−150
L_{MS}
Interface
MS I
MS II
MS III
MS IV
MS V
MS VI
M31
IC10
S0
LMC
SMC
Leading Arm


LMC filament
GASS
WLM
PHL 2525
SMC filament

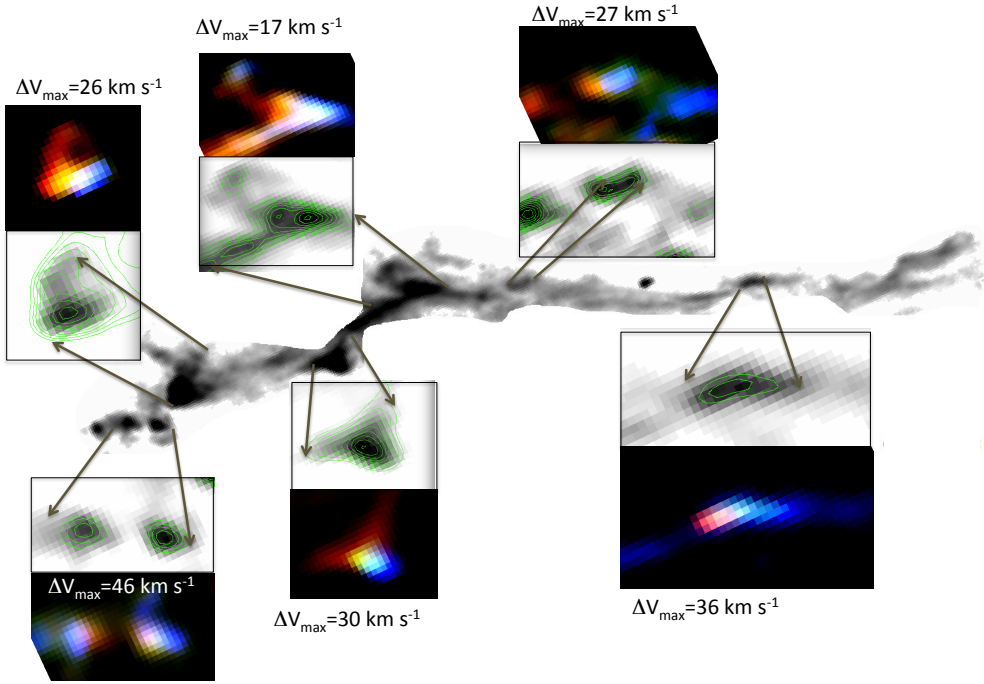


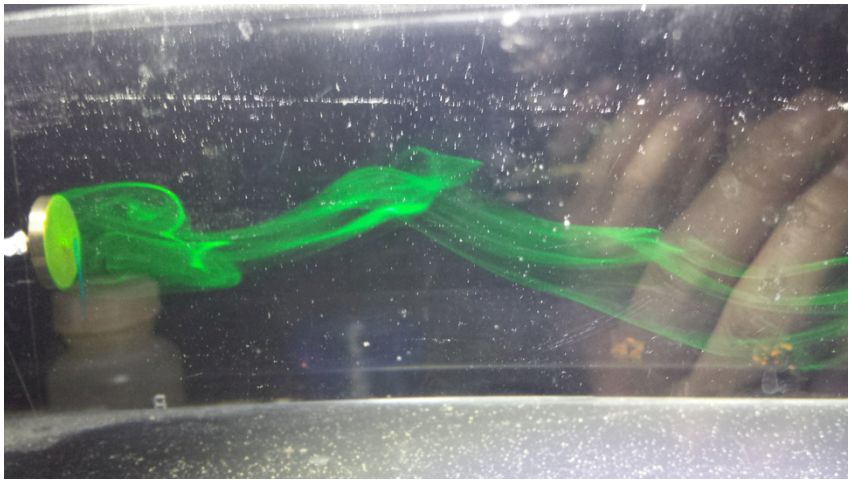
Rotational vortices in a transonic flow (Mach=1.5)

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

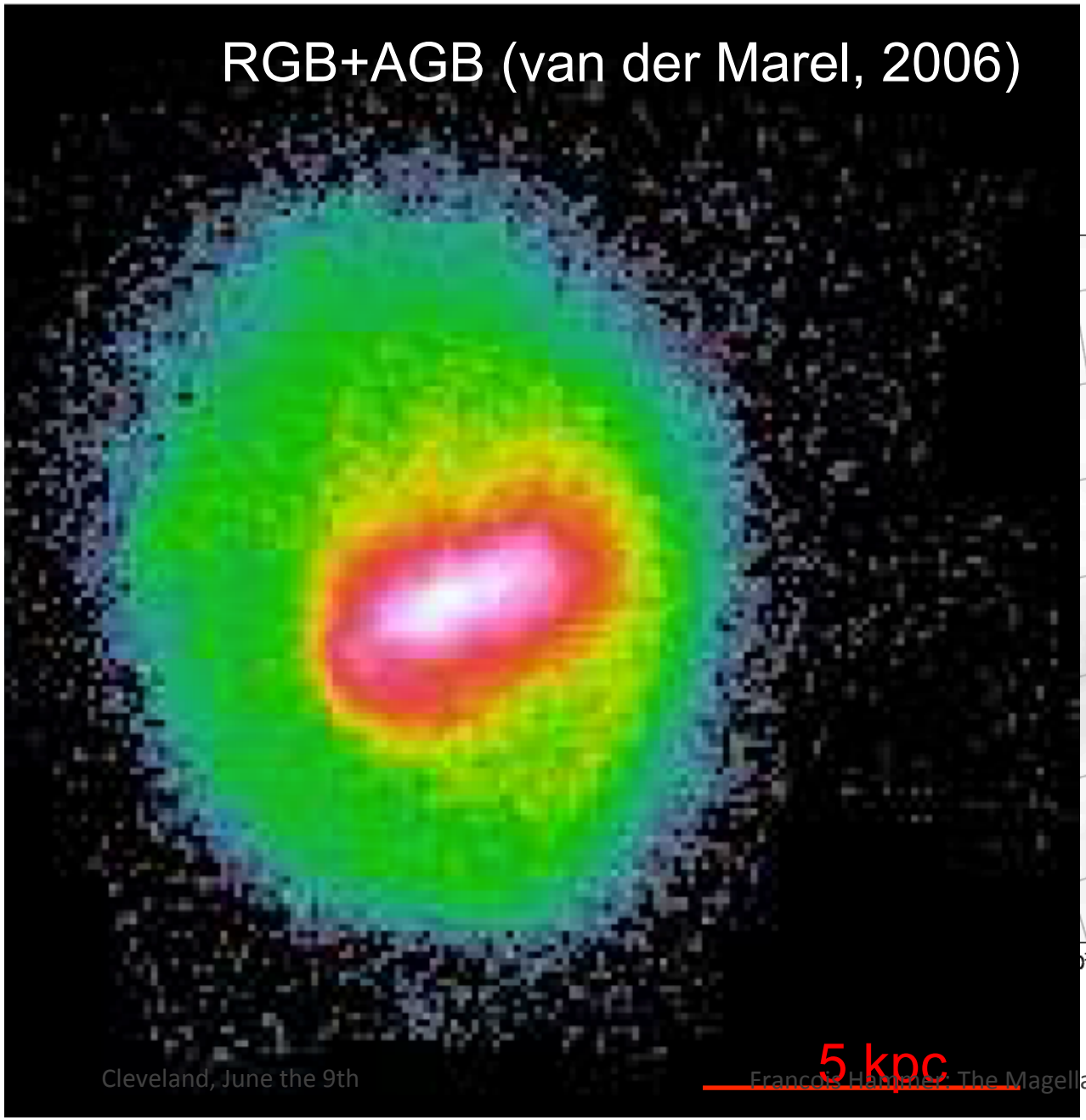
Evidences for a prominent halo hot gas affecting the Magellanic Stream & Clouds:

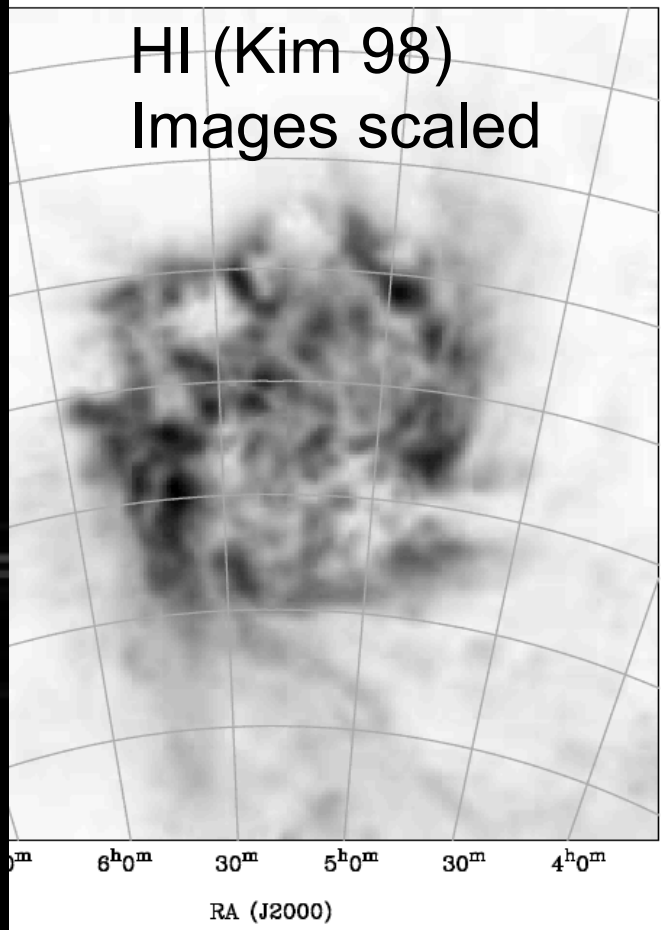
- Associated high velocity clouds are disrupted (multi-phases, Karlberla & Haud, 2006) ➔ $\rho_{hot} \sim 10^{-4}$ cm^{-3} at 50 kpc

- 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 $\rho_{hot} \sim 10^{-4}$ 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* $f_\mu \leq 1$ *(viscosity suppression factor, Roediger et al. 2013), implying a moderately turbulent MS*
- *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

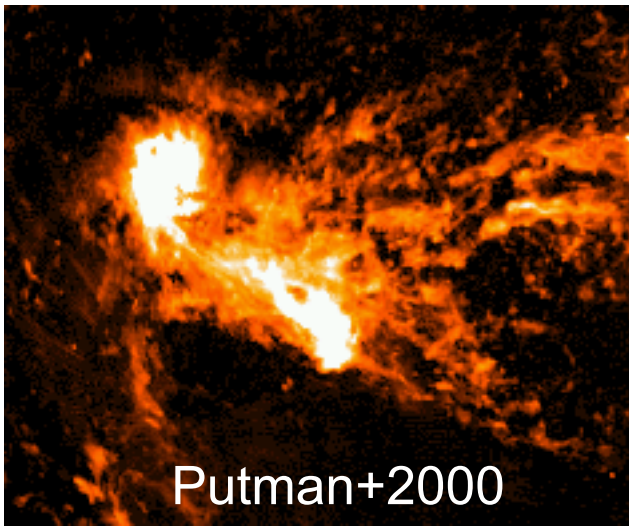
Evidenced by:

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 $10^{10} M_O$

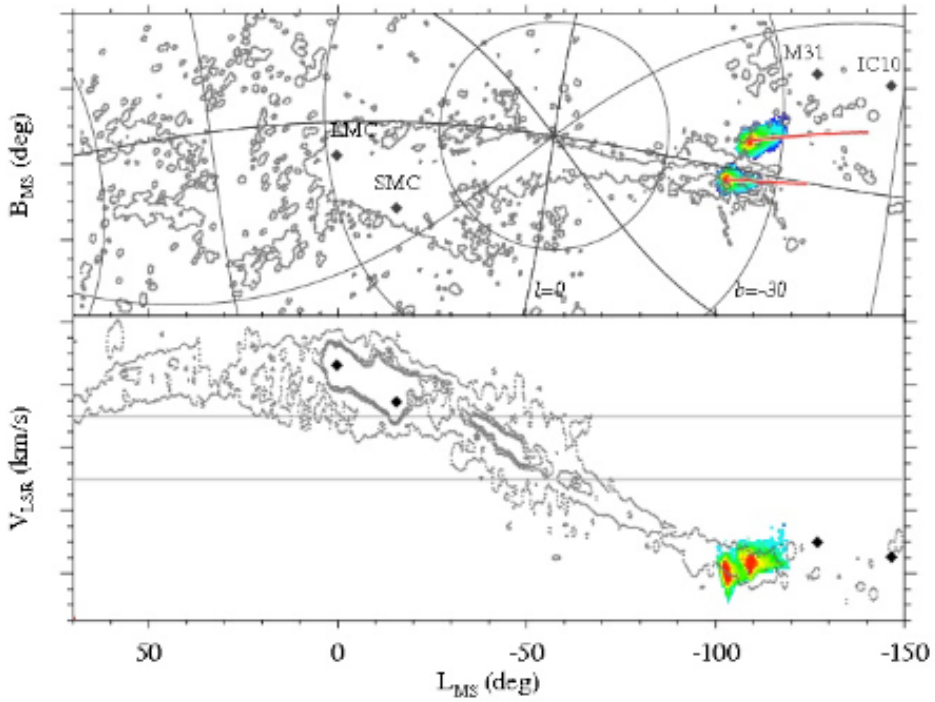
2 Gyr in isolation to equilibrate hot gas halo and cold gas in disk within the dark matter halo

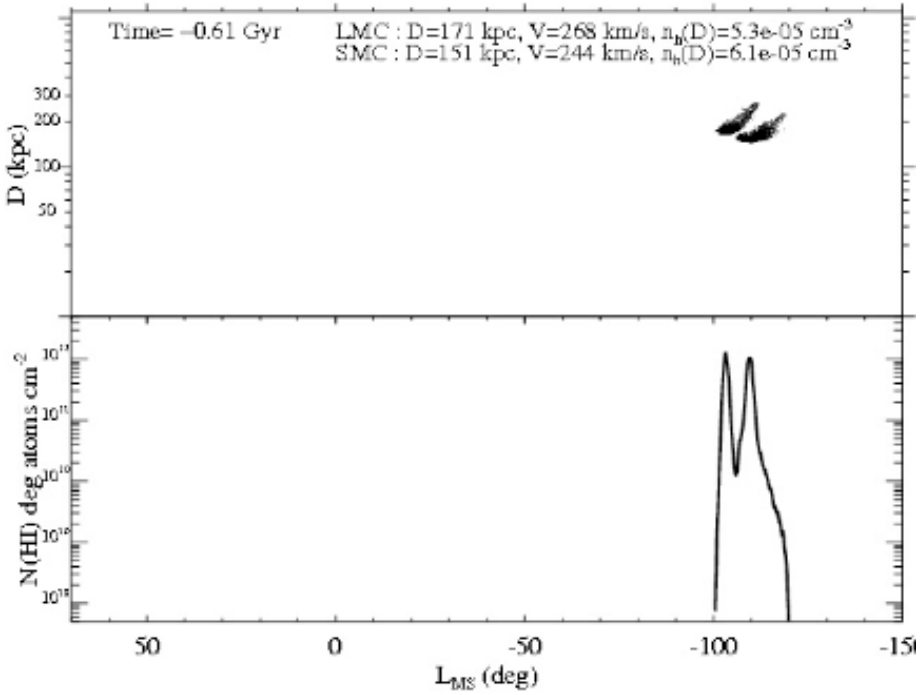
- Initial LMC: mass, 1.8-5 $10^9 M_O$; f_{gas}, 40-60%
- Initial SMC: mass ~ 0.7 LMC mass, f_{gas}, 40-70%

Reproduce present-day stellar and gas mass within 20% accuracy
Assume present-day locations and proper motions of both Clouds

Explanation of the gigantic Magellanic Stream

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





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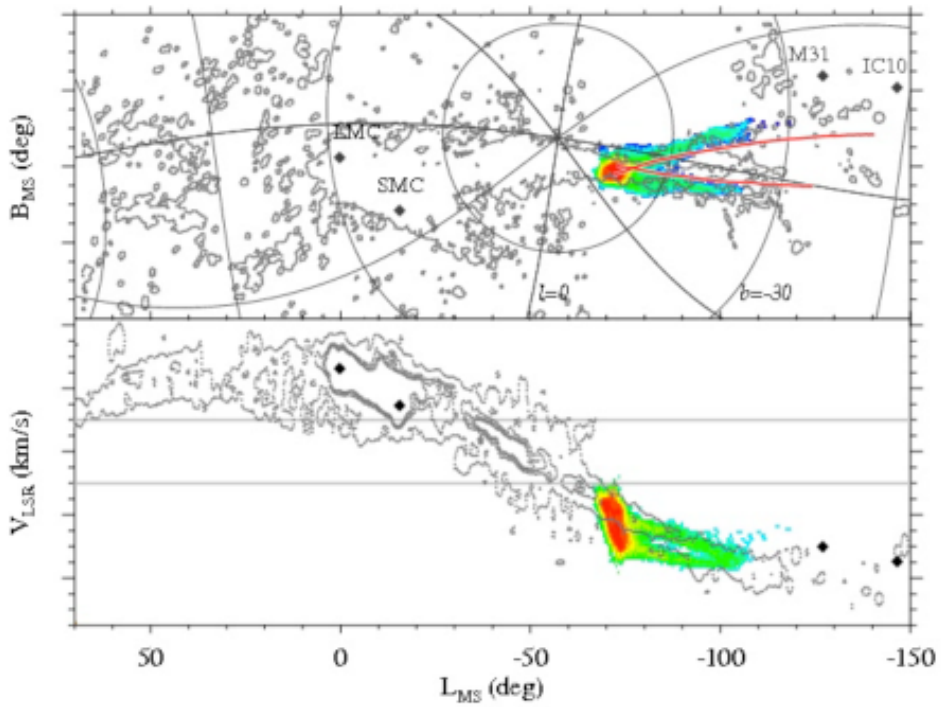

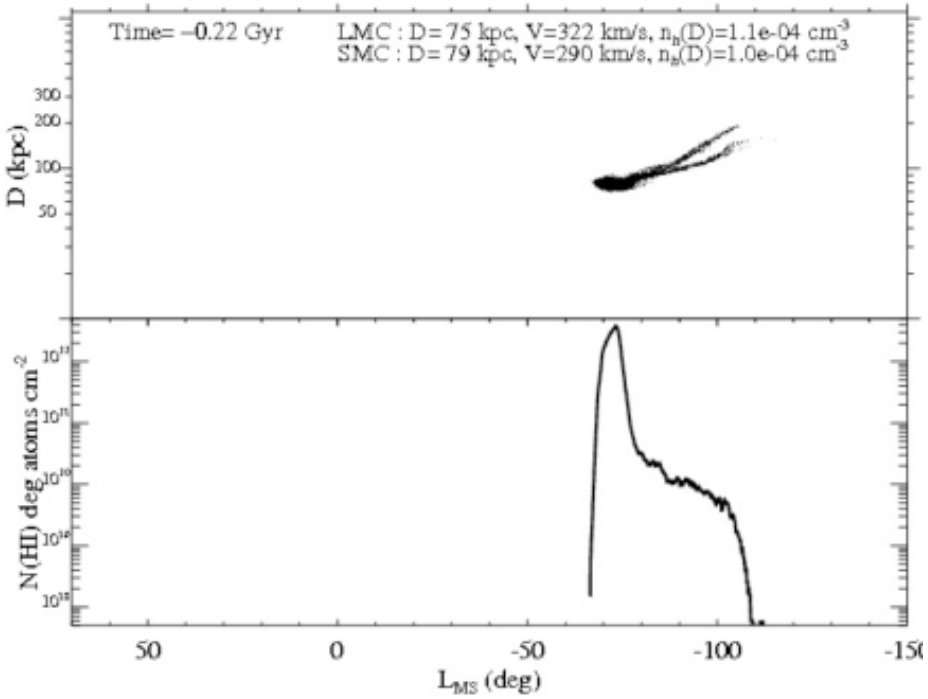

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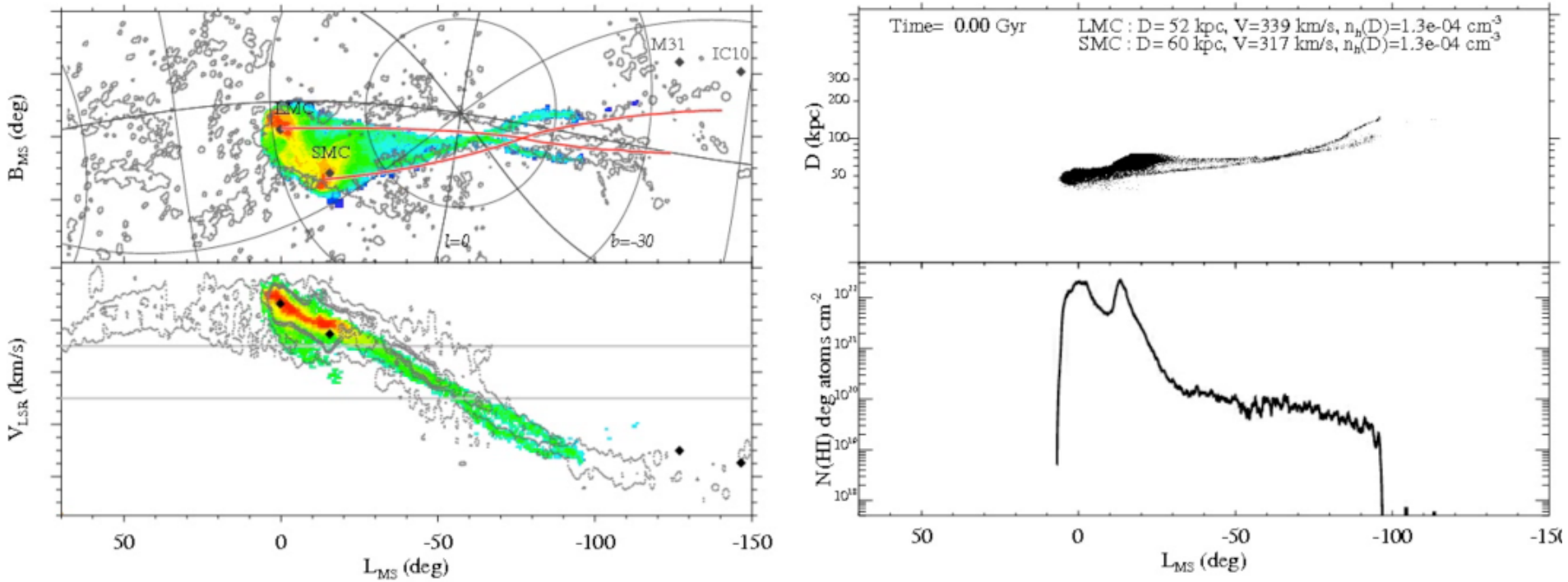
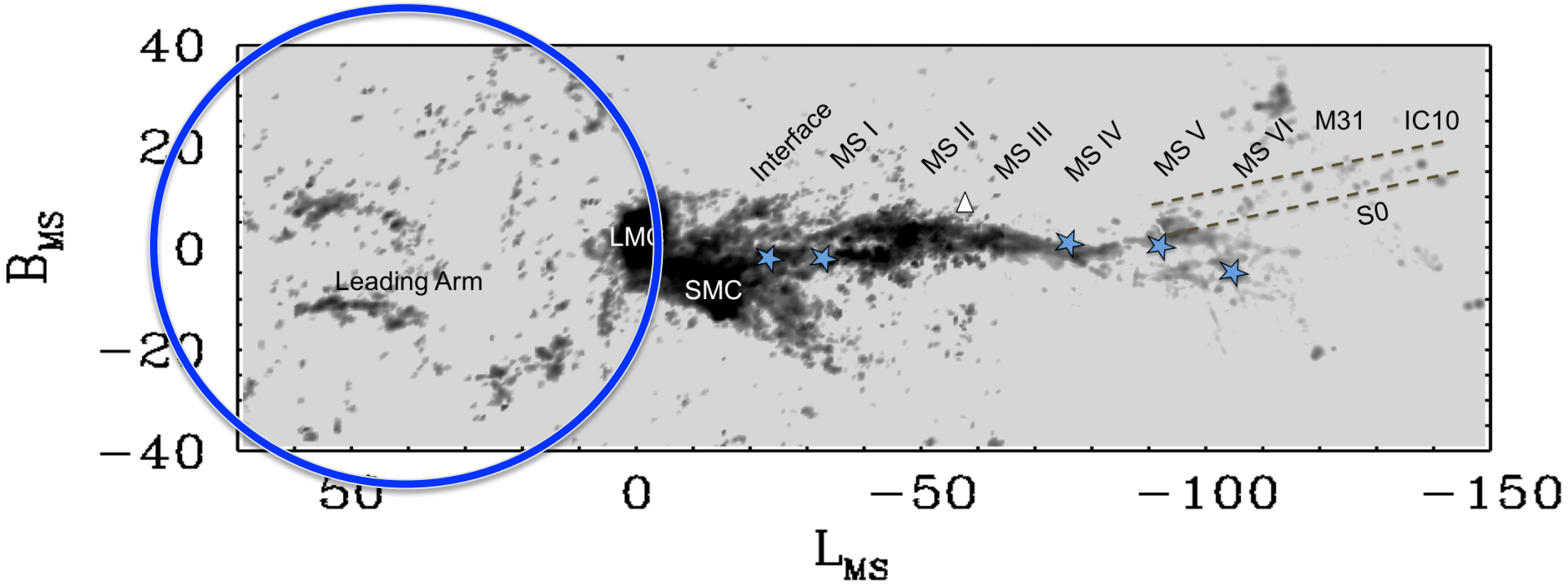


Francois Hammer: The Magellanic Stream

Formation of the Leading Arm (LA)

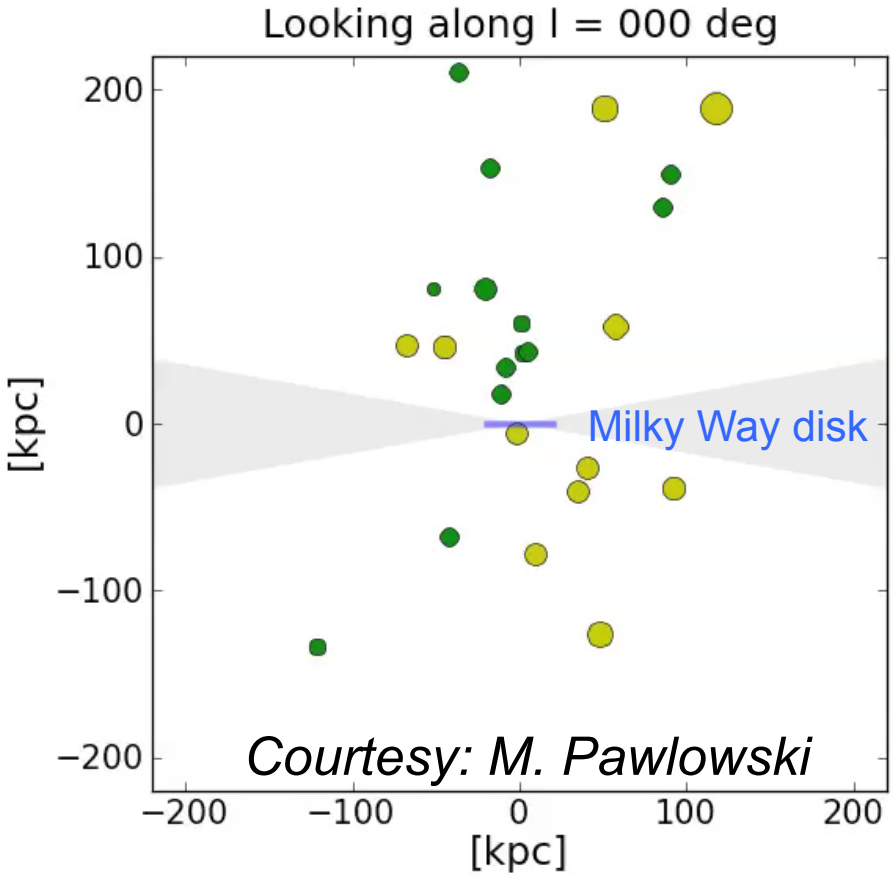


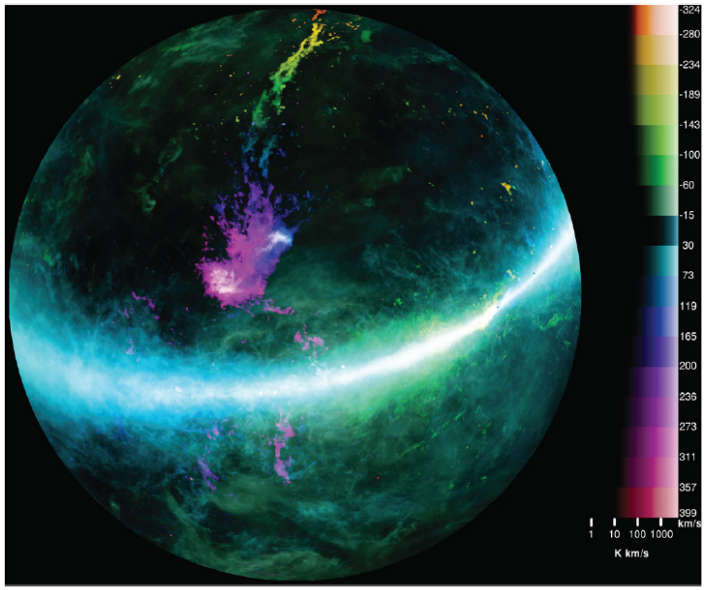
Former passages of leading and ram-pressure stripped dIrrs
(a la Lucio Mayer, 2009; LA firstly reproduced by Yang et al; 2014)

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

Vast Polar Structure surrounding the Milky Way

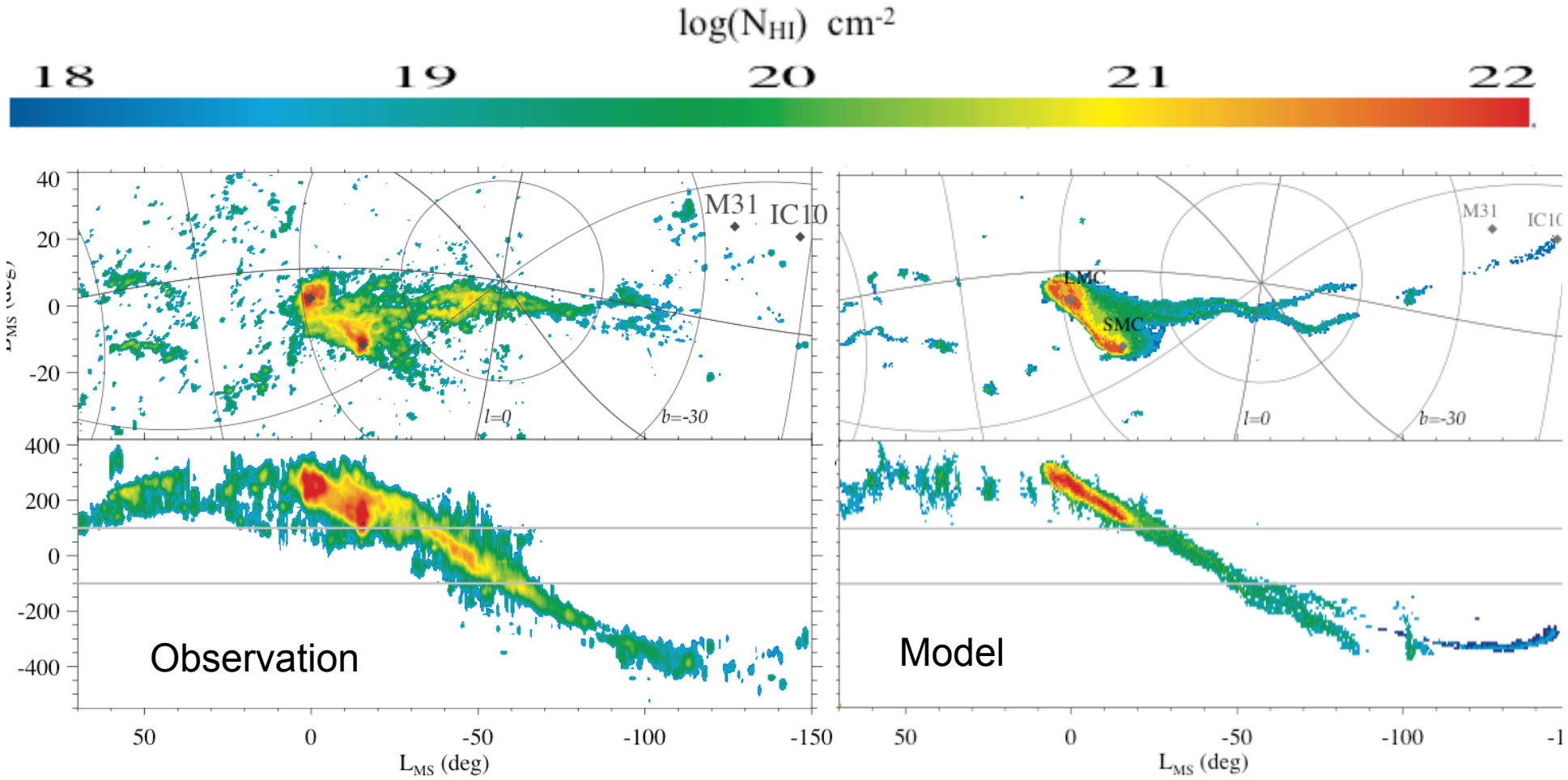
VPOS, *Pawlowski+12*





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)



Ram pressure + collision between Magellanic Clouds: the only model reproducing Magellanic Stream properties

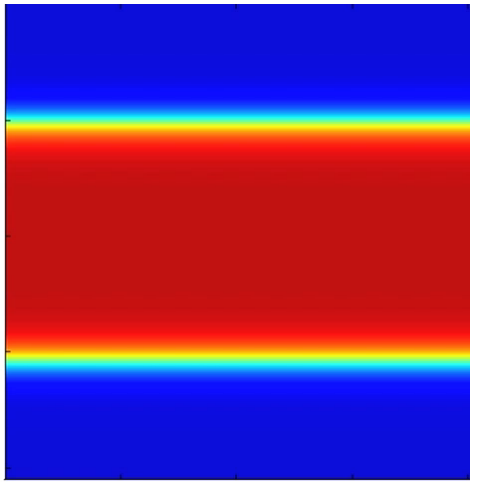
Don Matthewson: "much, much nearer the truth!"

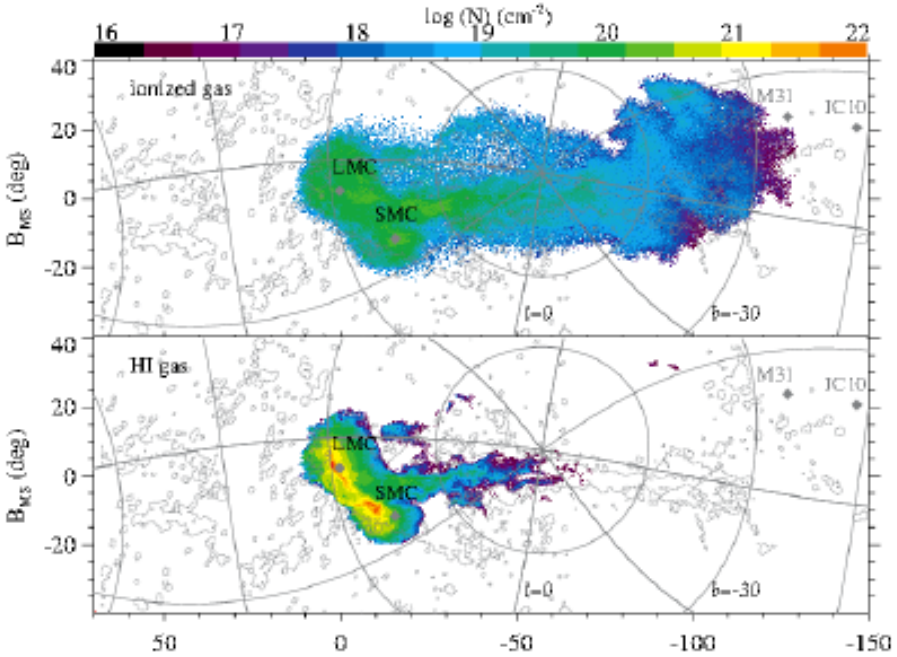
Magellanic Stream: a corner stone to understand the Local Group content and origin

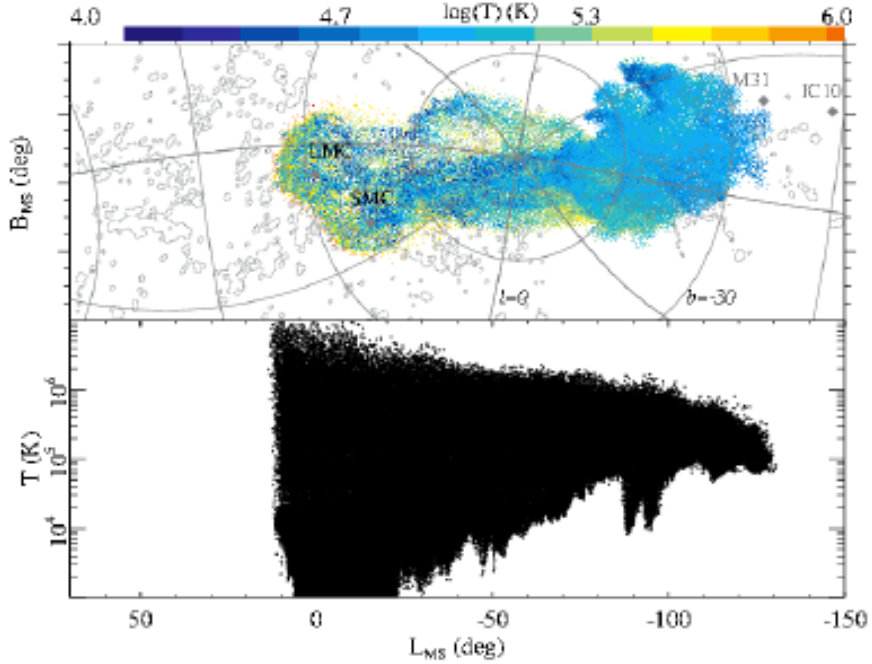
- Kinematics of the LMC affected by the recent collision with SMC: rotation **consistent with an absence of dark matter**
- Leading dwarfs to form the Leading Arm: progenitors of dSphs, which kinematics can be explained by gas removal (Yang+14), **consistent with tidal dwarfs**
- The role of the M31 formation in the Local Group: Stream tip end is pointing to the M31 system (IC10, Nidever+13)

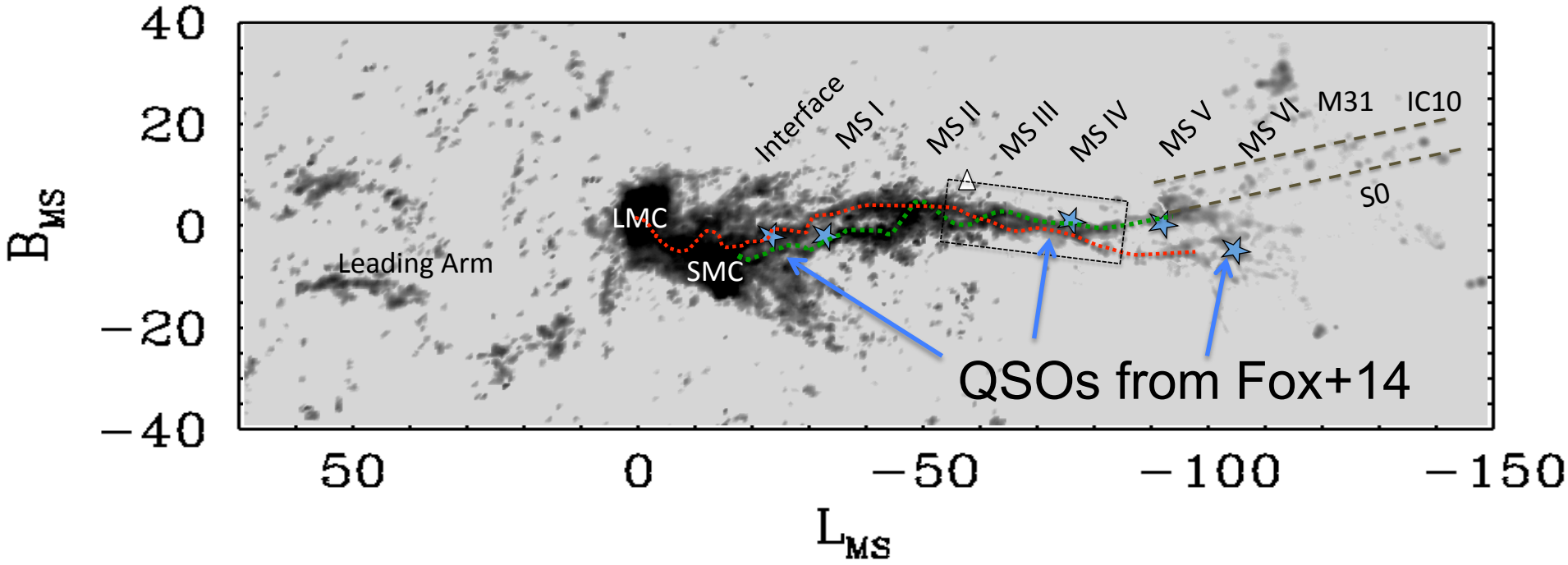
IN PROGRESS

- Implementing hydrodynamical solver (GIZMO, Hopkins, 2014) to reproduce KH instabilities (vortices) incl. SF in the Leading Arm (Casetti+14)
- The only chance to reproduce a gas deposition up to few 10^9Mo (ionized gas, Fox+14), i.e., close to the gas content of the Milky Way disk
- Also to reproduce the dispersion along the Stream

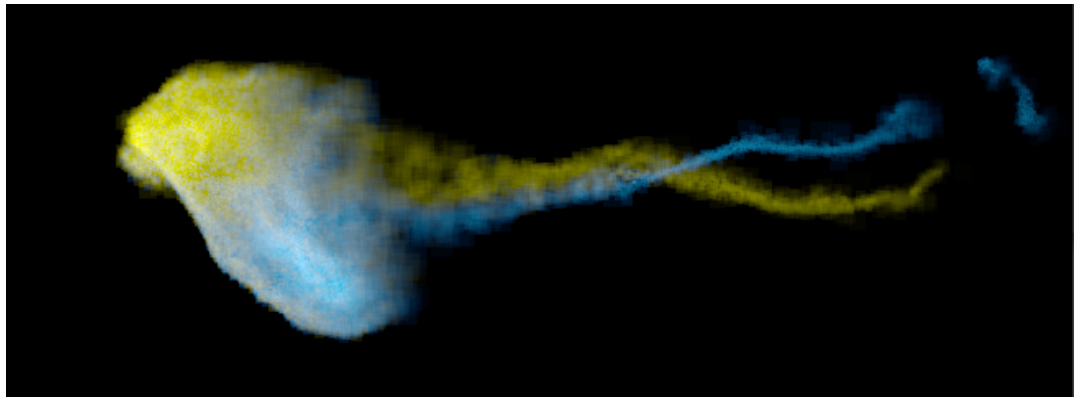








Yellow: LMC material
Blue: SMC material



Material from LMC filament systematically metal richer than from SMC filament

The mass of the LMC

Collision between the LMC & SMC ~ 200 Myr ago:

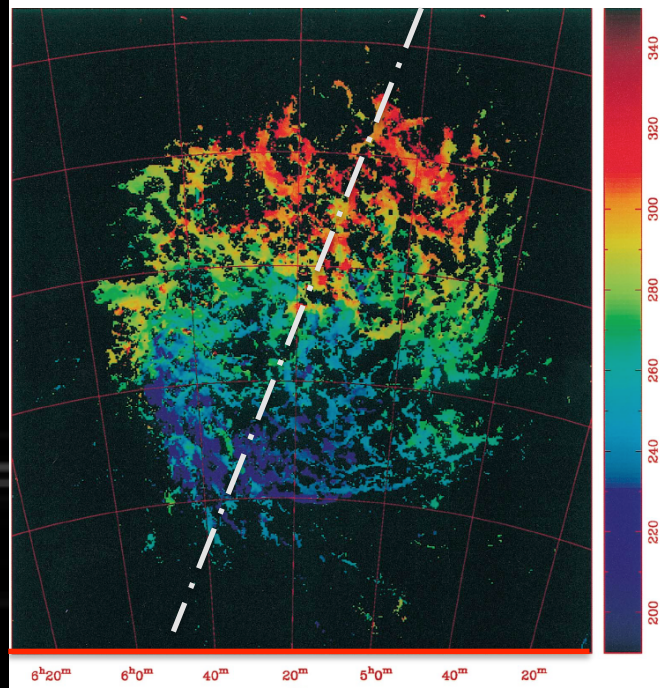
- Affect their past orbital motions
- Affect the apparent PM since the LMC has been assumed to be a pure rotating disk by van der Marel+14
- LMC disk shows 50° offset between morphology & kinematics PA (van der Marel+14)

It implies ram pressure model being consistent with LMC proper motions from Kallivayalil+13

RGB+AGB (van der Marel+06)

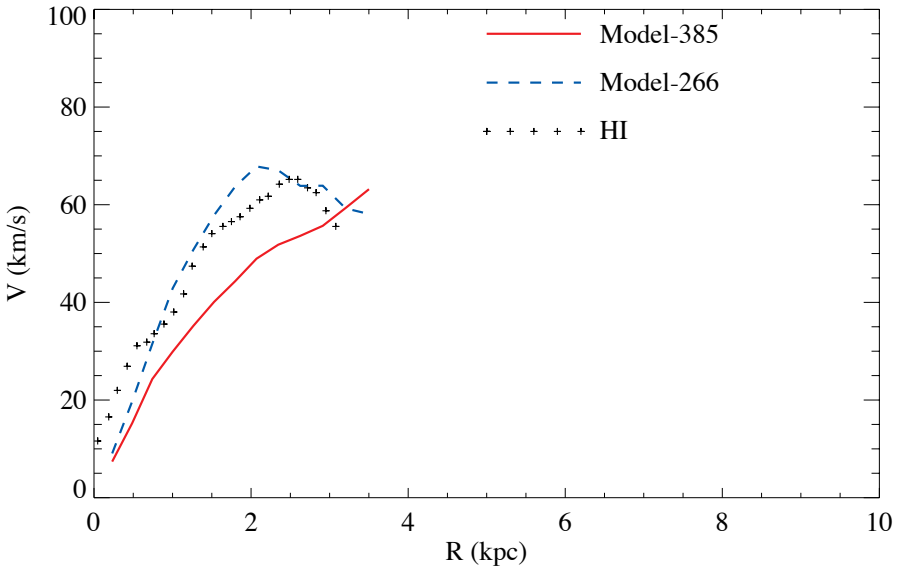
5 kpc

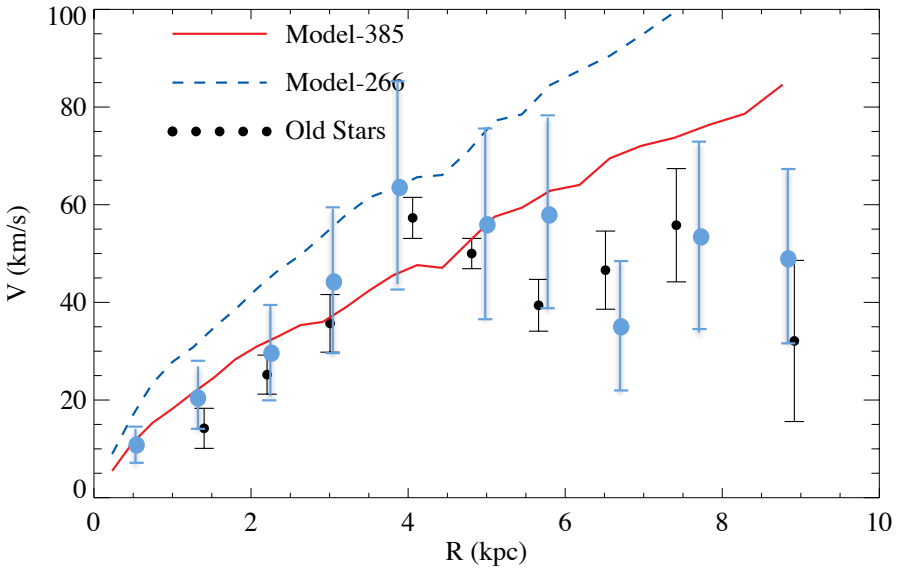
HI kinematics(Kim 98)

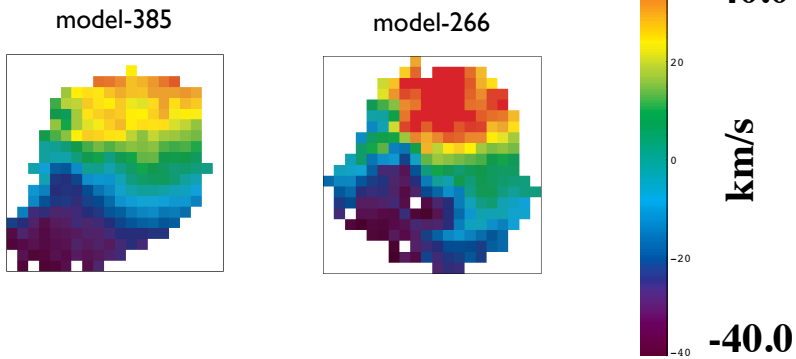


1◦ = 0.87 kpc for
D=50.1 kpc

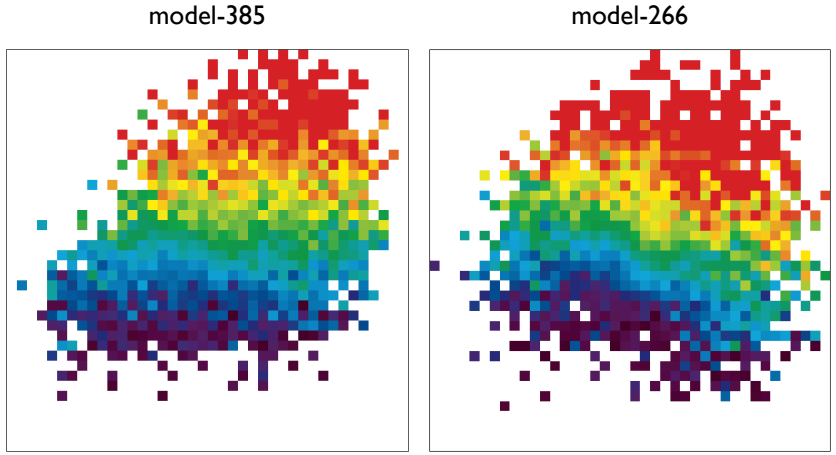
No Dark Matter in the Magellanic Clouds?





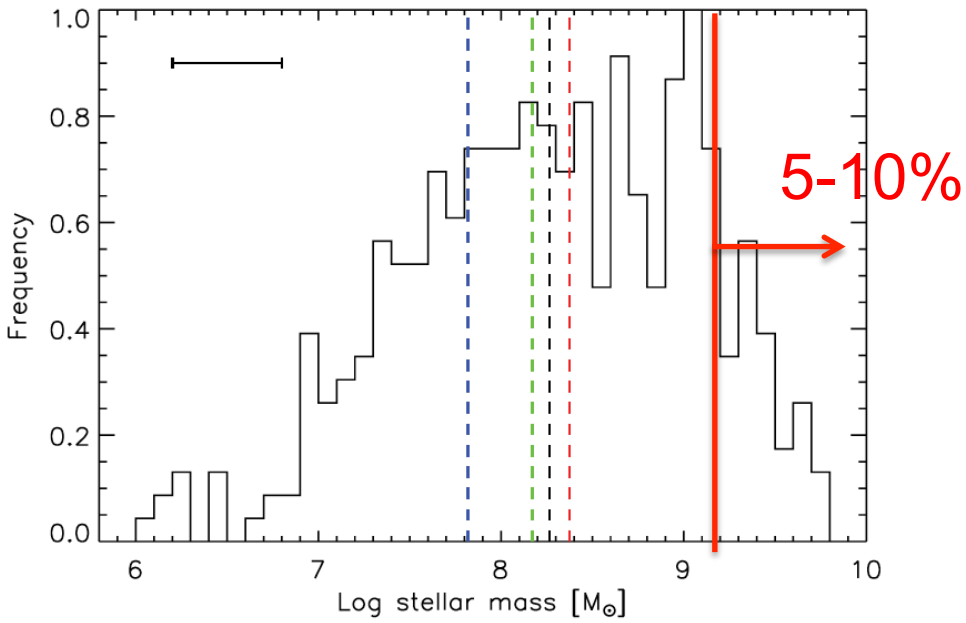


9.25 x 9.25 kpc



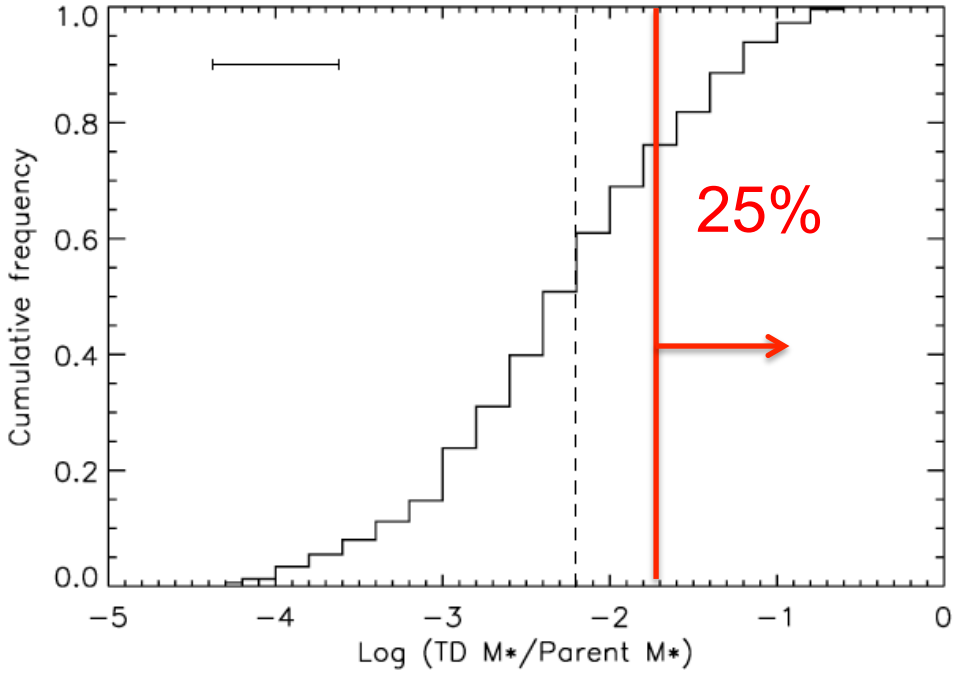
18.5 x 18.5 kpc

Could the LMC be a DM-free tidal dwarf?



Large statistics of TDGs from Kaviraj+12, SDSS merger remnants

With its stellar mass and mass ratio to M31 (1/55), LMC is eligible to be a tidal dwarf from a merger remnant



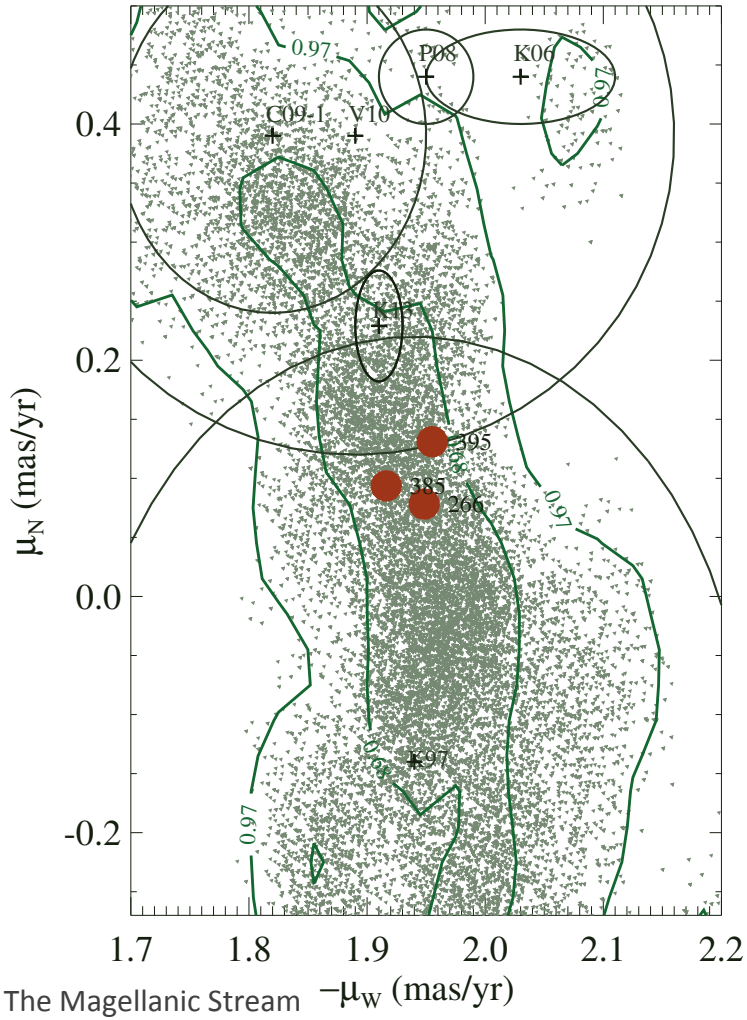
LMC proper motions

Consistency with LMC proper motion (PM, Kallivayalil+13)

Collision between the LMC & SMC 200-300Myr ago:

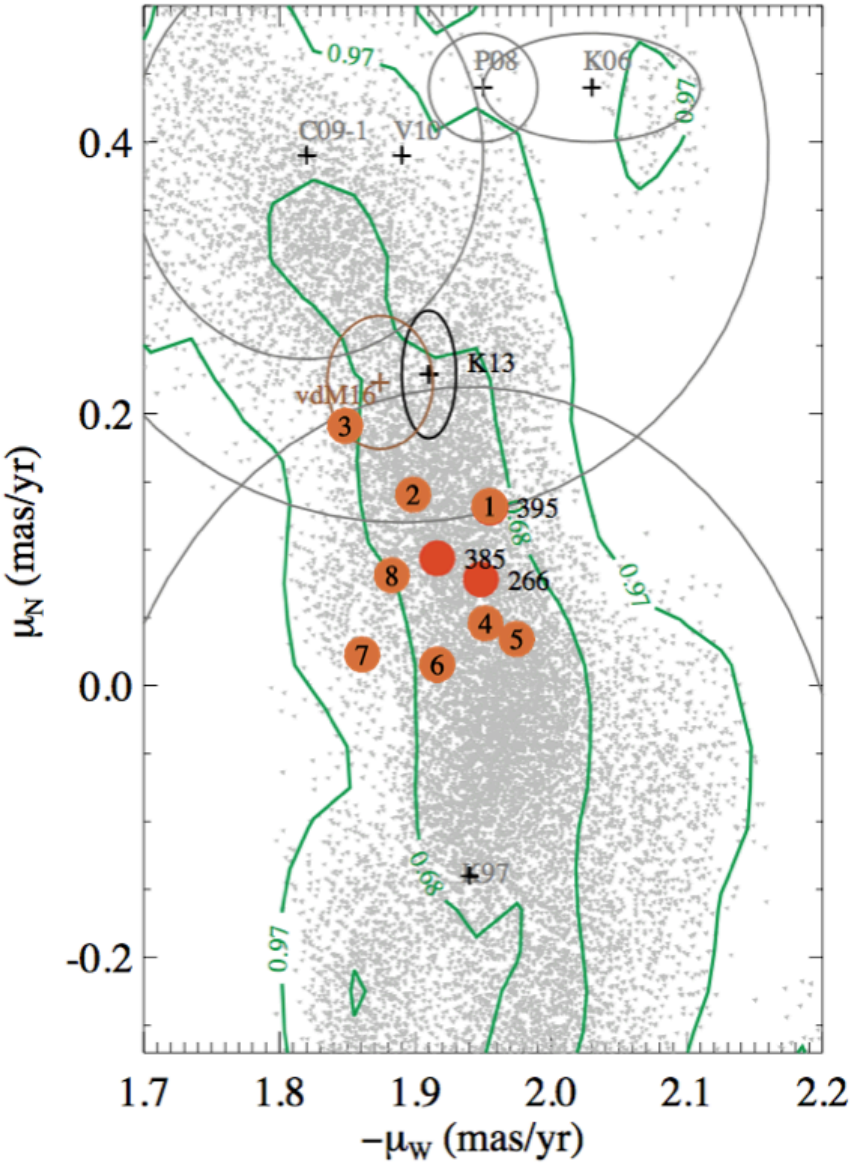
- Affect their past orbital motions
- Affect the apparent PM since the I assumed to be a pure rotating disk
- LMC disk shows 50° offset betwee kinematics PA (van der Marel+14)

Same calculations than van der Marel+14 but for a LMC disk after collision



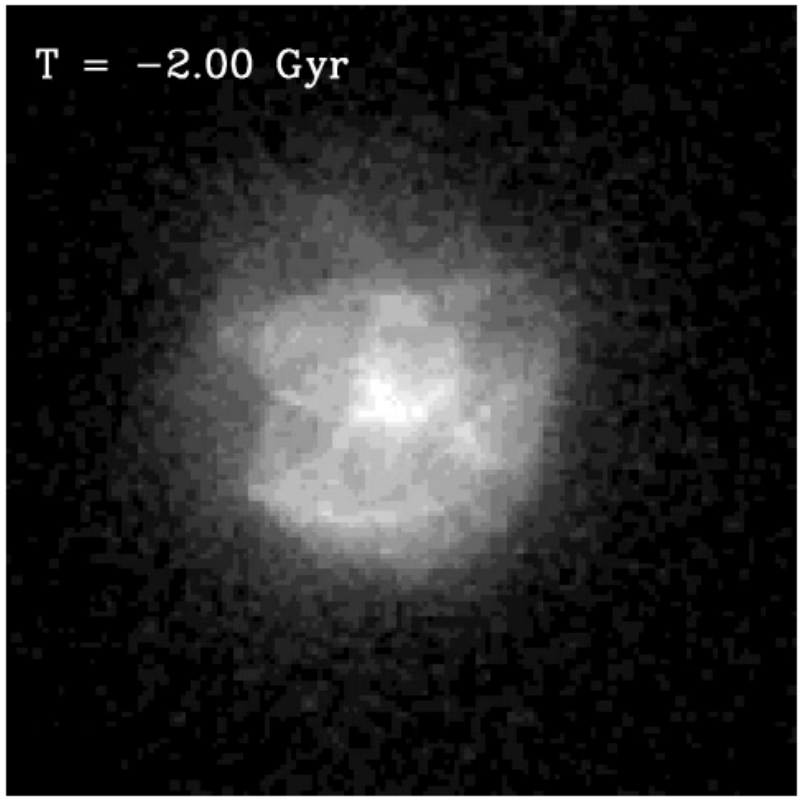
GAIA proper motions

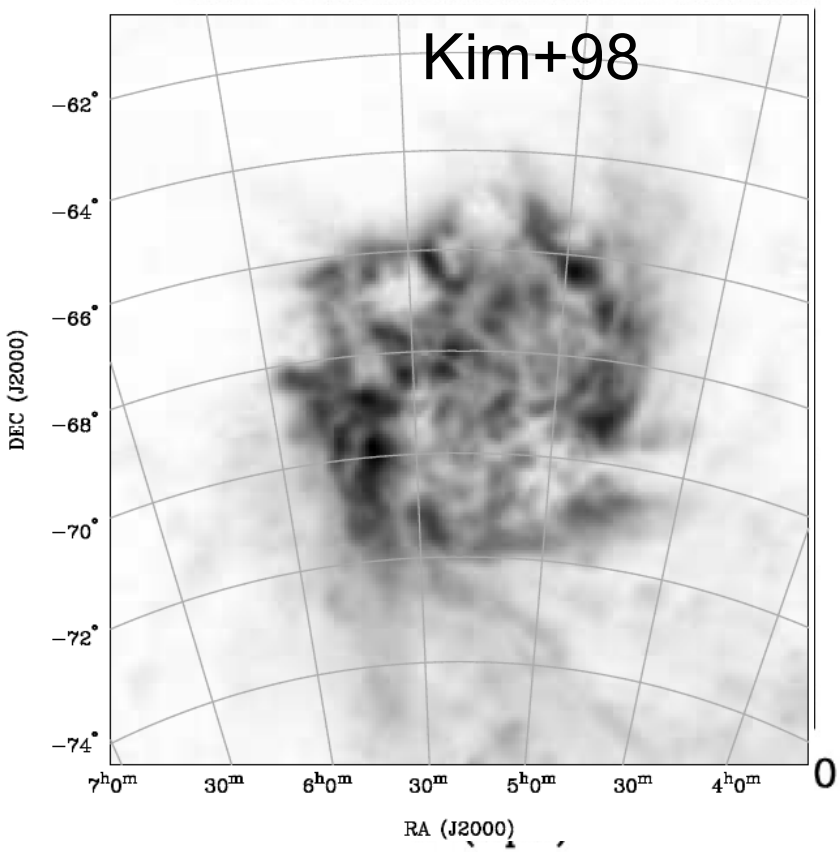
(van der Marel+16)



Physics and mass of the hot gas phase in the Milky Way halo

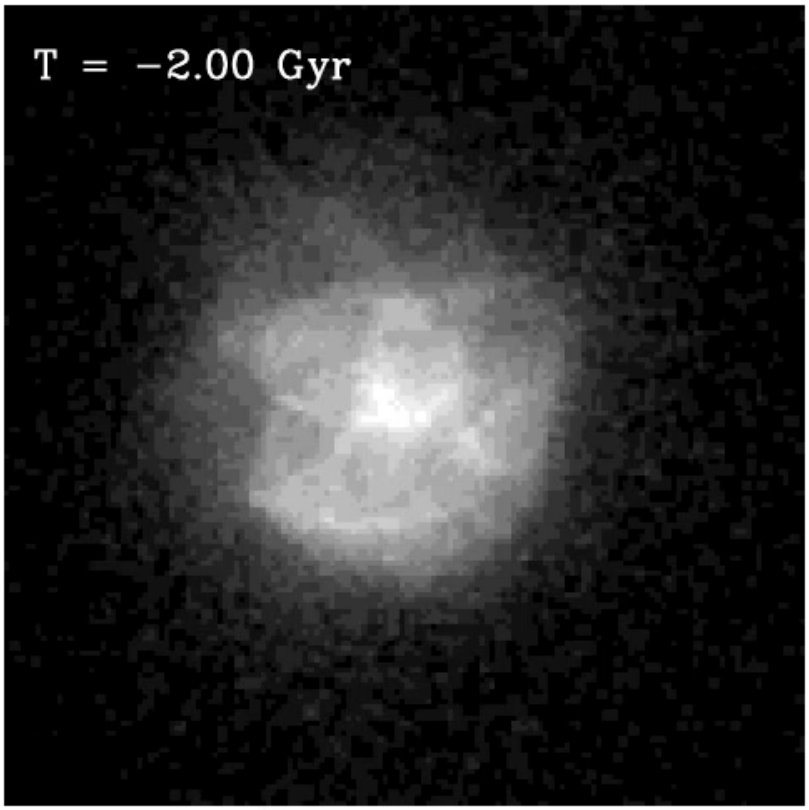
Feedback is expelling gas at the LMC outskirts, which is then subject to ram pressure to form the MS
Consistent with observations of 30 Doradus (Nidever+08)

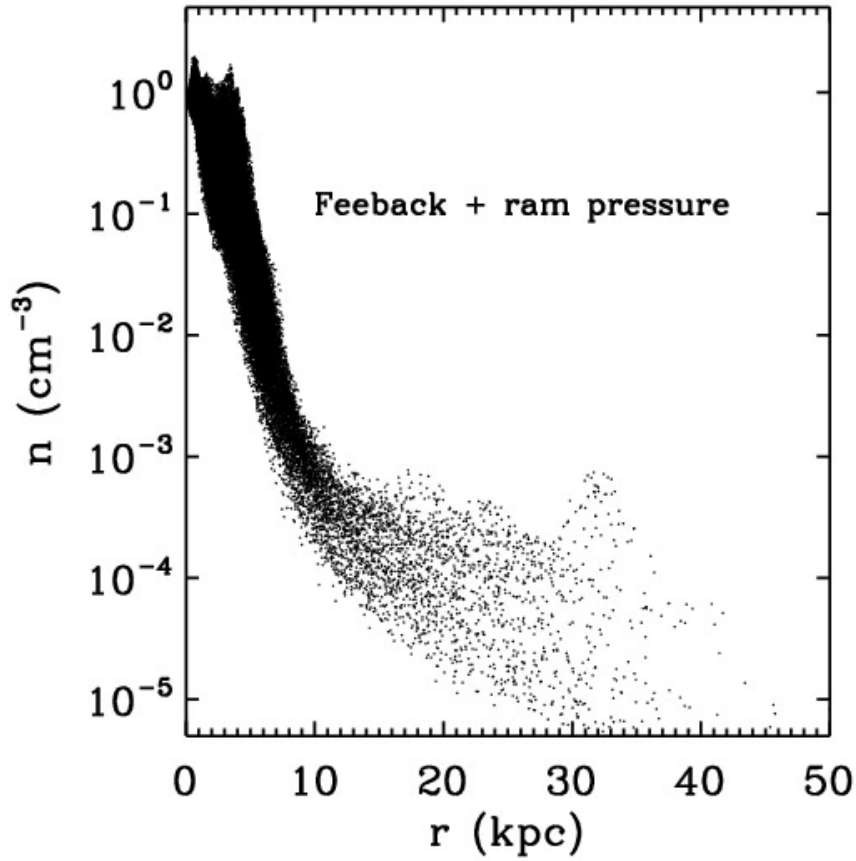




Feedback prescriptions: 5 times the median Cox+06 value

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)

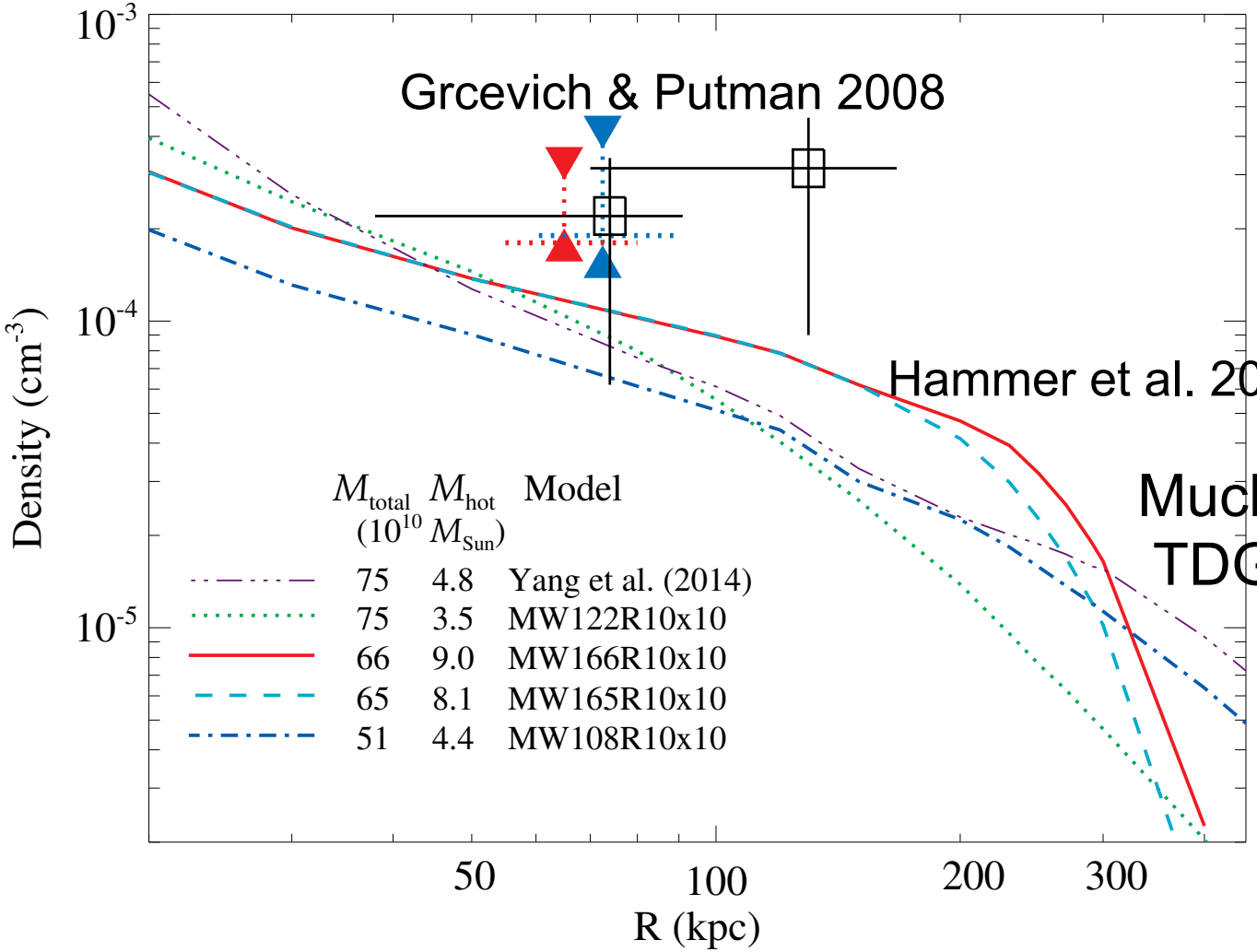




Collision is releasing far more gas perhaps sufficiently to report the 2 10^9 M_O of ionized gas reported by Fox+14

Mass of the hot gas of the MW?

Expected to be extremely high (Grcevich & Putman, 2008) if dwarfs were DM-dominated & arriving in a coordinated group

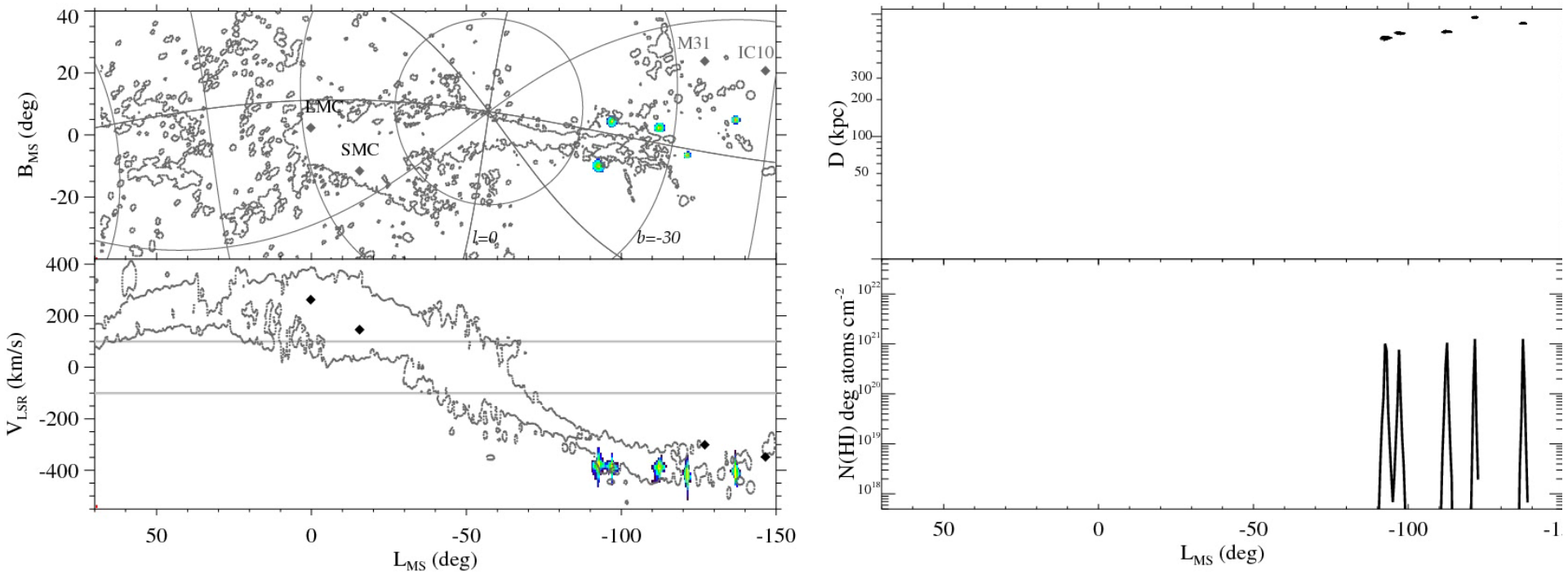


Much lower if caused by TDGs in a tidal tail

Many MW dSphs descendant of tidal dwarfs stripped of their gas?

Explanation of the whole Magellanic System

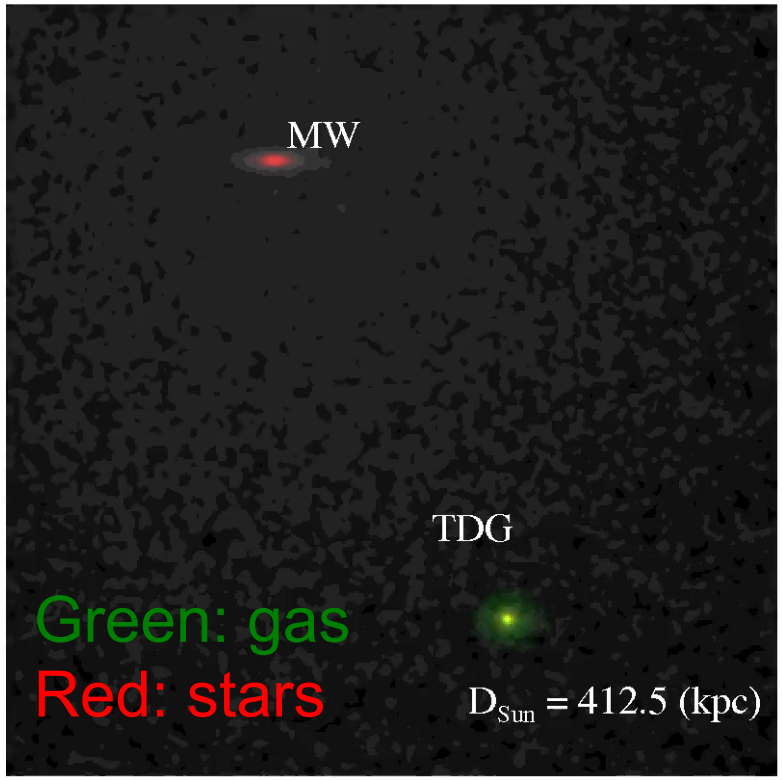
Gas of the Clouds and dSph progenitors stripped by ram-pressure exerted by the hot gas in the Milky Way halo
dSph progenitors follow same orbits than the LMC (VPOS)

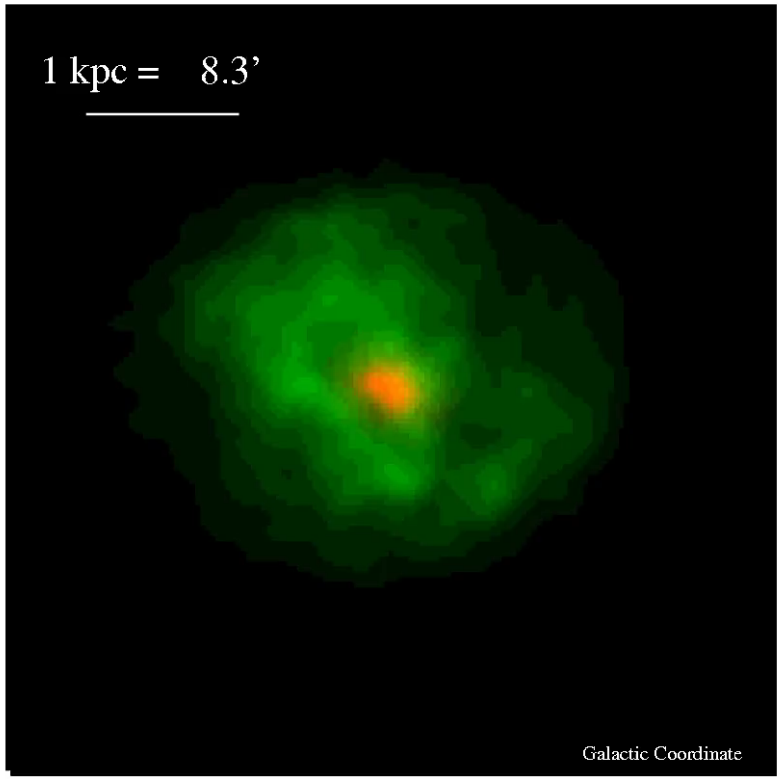


Hammer et al. 2015

Ram-pressure stripping exerted by halo hot gas to dwarfs

Yang et al., 2014 (see also Kroupa, 1997)

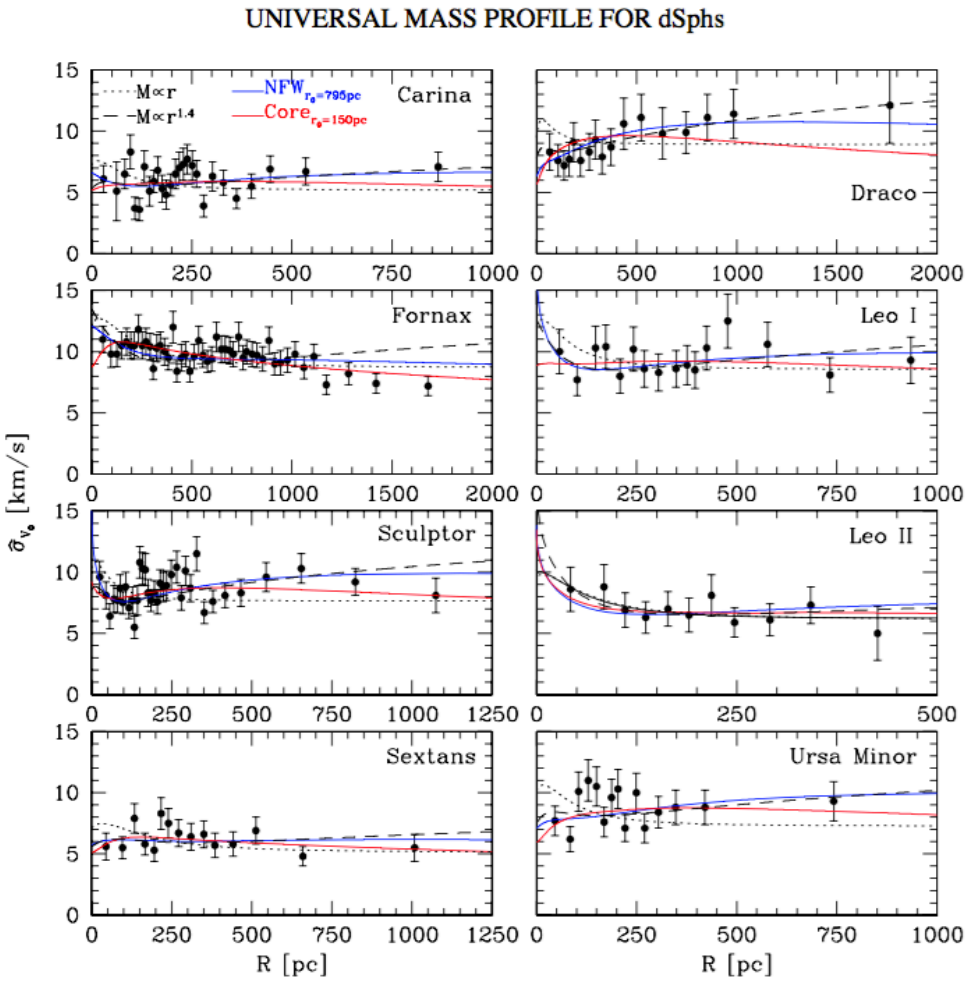




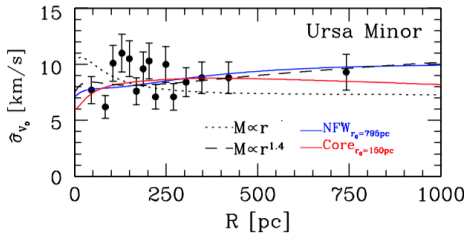
Yang+14

Prompt disruption & gas removal by hot gas facilitated by absence of DM and large velocity (here TDGs from a tidal tail ejected by an ancient merger at M31)

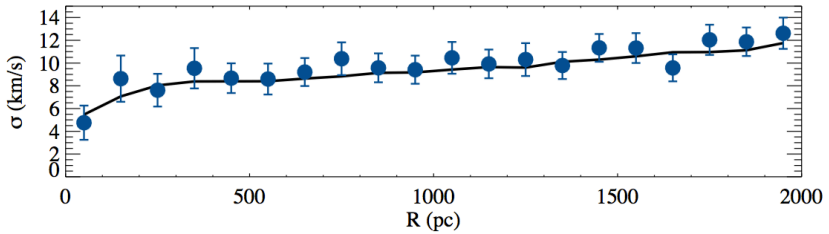
High values of velocity dispersion: large values of DM/L? Or simply expansion of stars in destroyed dwarfs?



Walker+2009, 2012



TDG9



$M_{stellar}$ ~ a few $10^5 M_O$

Yang et al. 2014: reproduce kinematic and all dSph properties, without dark matter