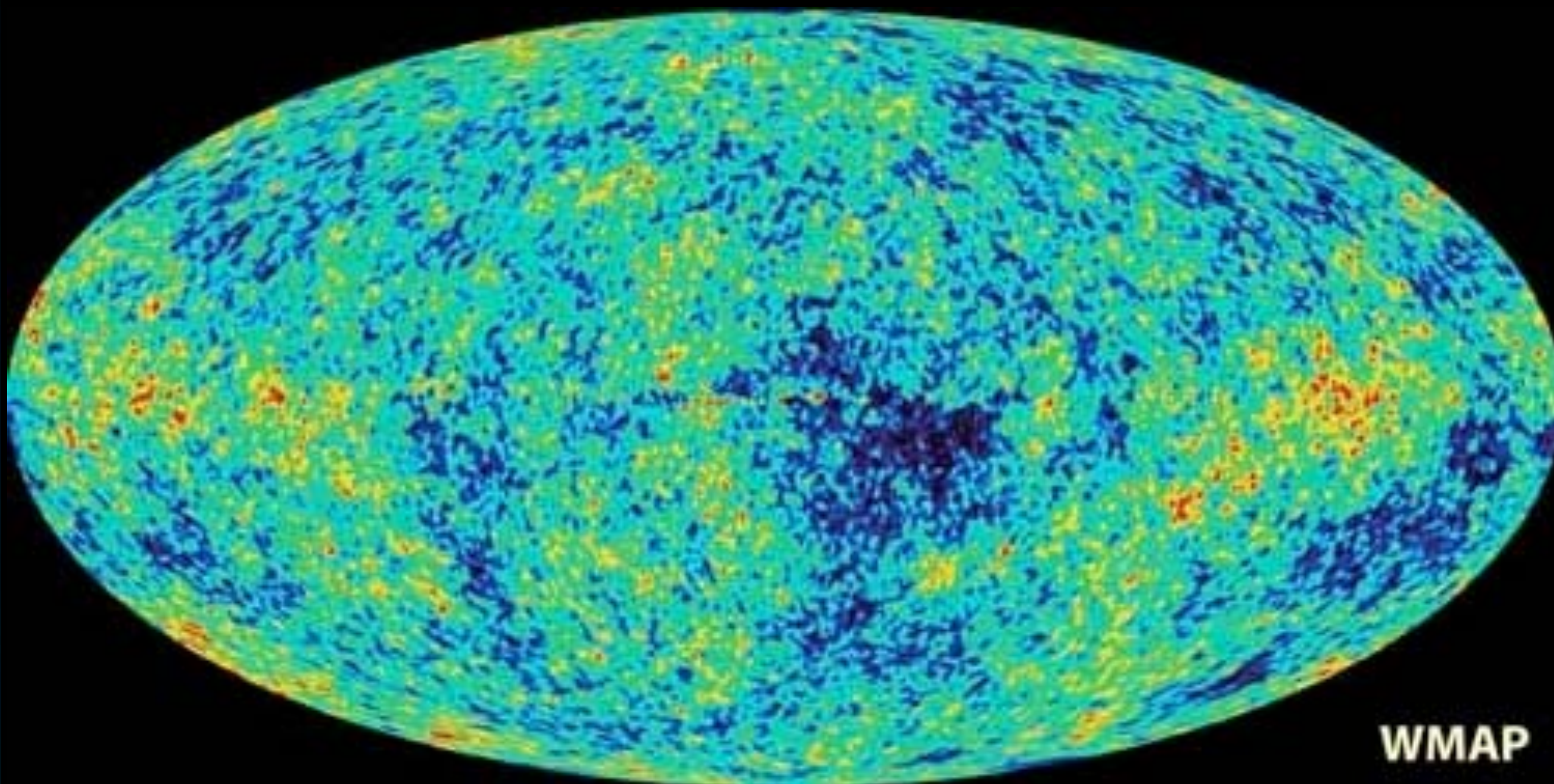
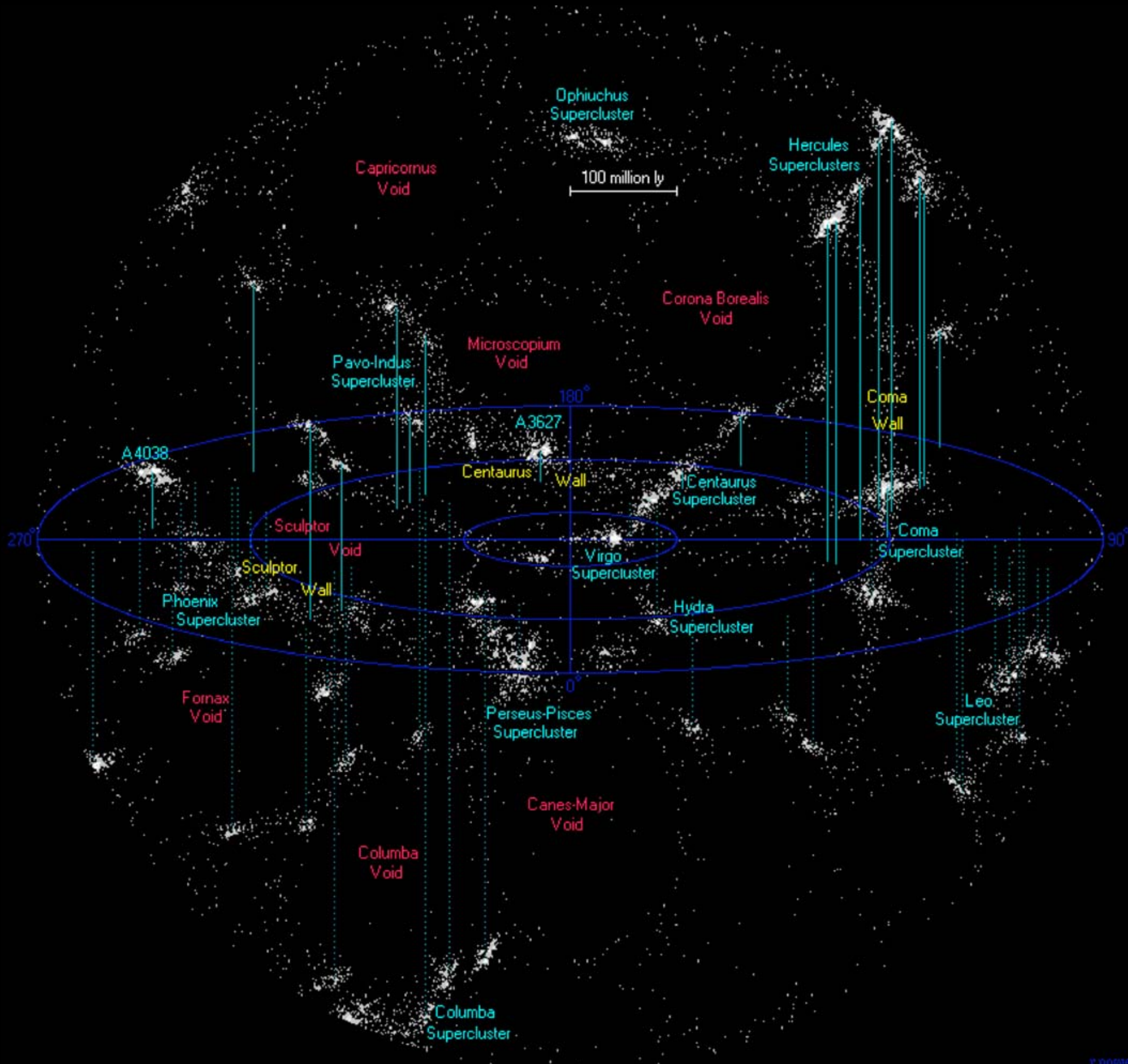
The Dynamics of the Galaxies in the Local Group

Roeland van der Marel (STScI)

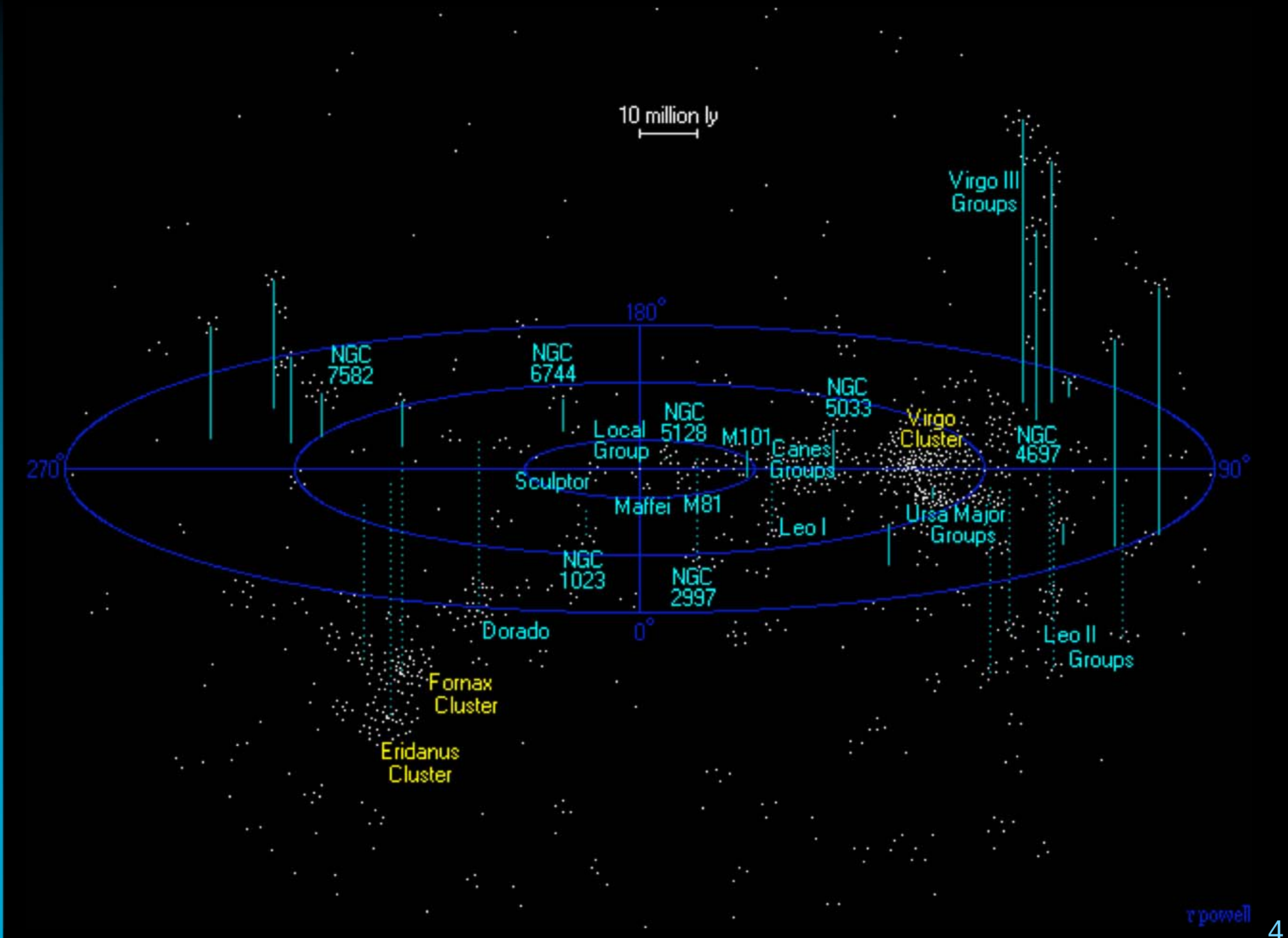

WMAP

[R. Powell]



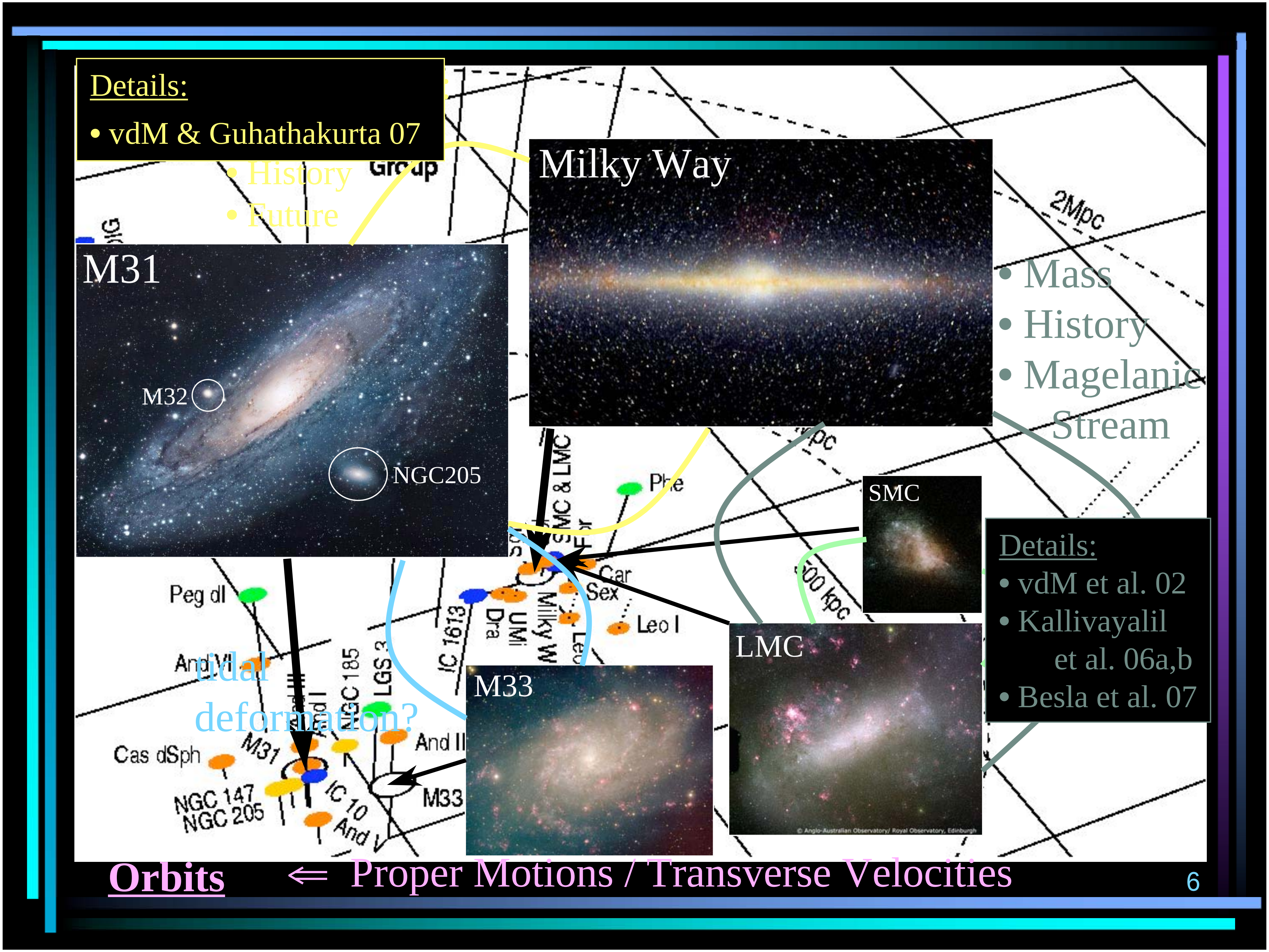
Ophiuchus
Supercluster
Hercules
Superclusters
Capricornus
Void
100 million ly
Corona Borealis
Void
Microscopium
Void
Pavo-Indus
Supercluster
180°
Coma
Wall
A3627
A4038
Centaurus
Wall
Centaurus
Supercluster
270°
Sculptor
Void
Coma
Supercluster
90°
Virgo
Supercluster
Sculptor
Wall
Phoenix
Supercluster
Hydra
Supercluster
0°
Fornax
Void
Perseus-Pisces
Supercluster
Leo
Supercluster
Canes-Major
Void
Columba
Void
Columba
Supercluster
r.powell

[R. Powell]


10 million ly
180°
270°
90°
0°
Virgo III
Groups
NGC
7582
NGC
6744
NGC
5033
Virgo
Cluster
NGC
5128
Local
Group
M101
Canes
Groups
NGC
4697
Sculptor
Maffei
M81
Ursa Major
Groups
Leo I
NGC
1023
NGC
2997
Dorado
Leo II
Groups
Fornax
Cluster
Eridanus
Cluster
r powell

Why Study the Local Group?

- Nearest opportunity for study of fossil record of hierarchical structure formation in the Universe
  - Best spatial resolution
- Many observational surveys
  - 2MASS/DENIS, SDSS, RAVE, GAIA, SIM, wide-field ground-based programs, etc.
- Many recent insights
  - Continuous discovery of new dwarf galaxies, tidal streams, etc.
- Structure, Dynamics and Populations of Galaxies $\Rightarrow$ Formation and Evolution of Galaxies

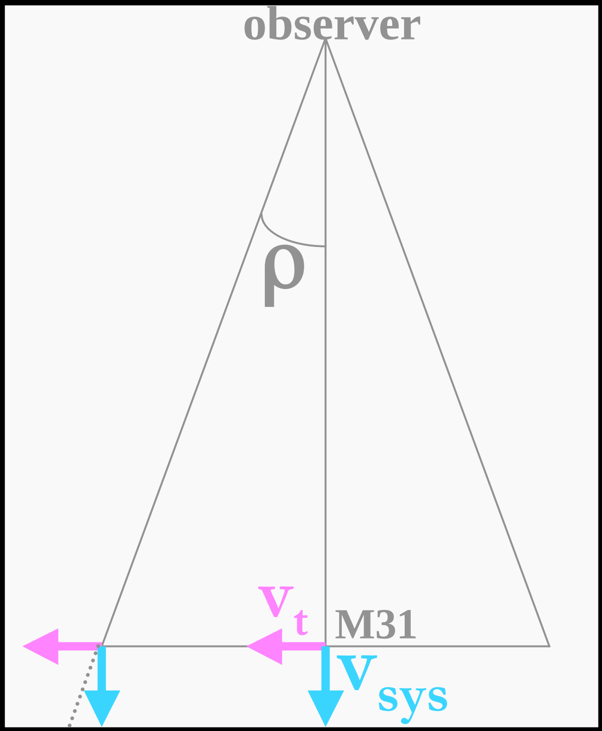

Details:
• vdM & Guhathakurta 07
• History
• Future
Group
M31
M32
NGC205
Milky Way
2Mpc
• Mass
• History
• Magelanic
Stream
SMC
LMC
M33
Details:
• vdM et al. 02
• Kallivayalil
et al. 06a,b
• Besla et al. 07
Phe
Car
Sex
Leo I
Peg dI
And VI
tidal
deformation?
Cas dSph
NGC 147
NGC 205
M31
IC 10
And V
NGC 185
LGS 3
IC 1613
And II
M33
UMi
Dra
SMC & LMC
Orbits ⇐ Proper Motions / Transverse Velocities

M31 Transverse Velocity: Observational Constraints

- Proper Motion: No proper motion measurement currently exists
  - D = 770 ± 40 kpc $\Rightarrow$ 100 km/s ~ 27 μas/yr
- Transverse velocity: Can be estimated using indirect methods
  - Line-of-sight velocities of M31 satellites (17x)
  - Proper Motions of M31 satellites (2x)
  - Line-of-sight velocities of Local Group satellites (5x)

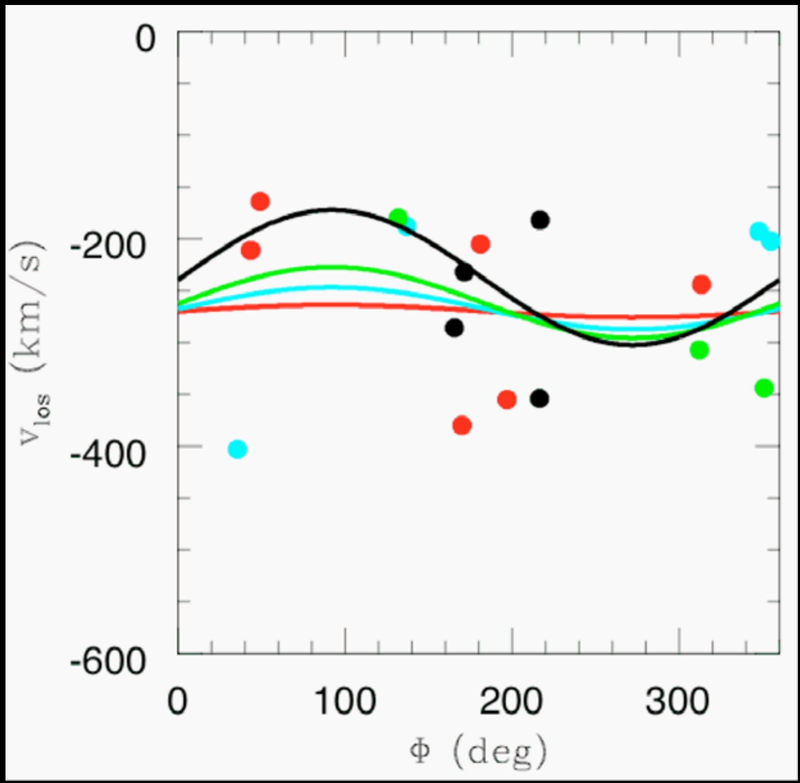
M31 Transverse Velocity:
1. Satellite Line-of-Sight Velocities

- Assumptions:
  - On average, the M31 satellites follow the motion of M31 through space
    $\underline{v}_{sat} = \underline{v}_{M31} + \underline{v}_{\Delta}$
  - Peculiar velocities are random with velocity dispersion σ
- Simple geometry:
  - An M31 transverse velocity yields a line-of-sight component for its satellites
    $v_{los} = v_{sys} \cos \rho$
    $+ \; v_t \; \sin \rho \; \cos (PA - \Theta_t)$

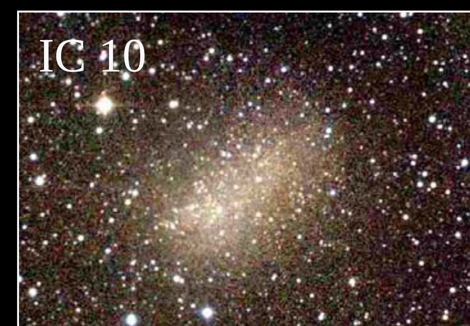


M31 Transverse Velocity:
1. Satellite Line-of-Sight Velocities

- Fit to available data
  - v_W = -136 ± 148 km/s
  - v_N = -5 ± 75 km/s
  - σ = 76 ± 13 km/s
- No obvious sinusoidal variation visible to the eye
  - $\underline{v}$ = 0 consistent with data



M31 Transverse Velocity:
2. Satellite Proper Motions



- Two M31 satellites have measured proper motions
  - M33 & IC10 (Brunthaler et al. 2005, 2007)
  - VLBI measurements of water masers
  - 5-10 μas/yr accuracy
  - No water masers known in M31 itself .....
- Full 3D velocity vector known
  - Yields estimate of M31 velocity vector:

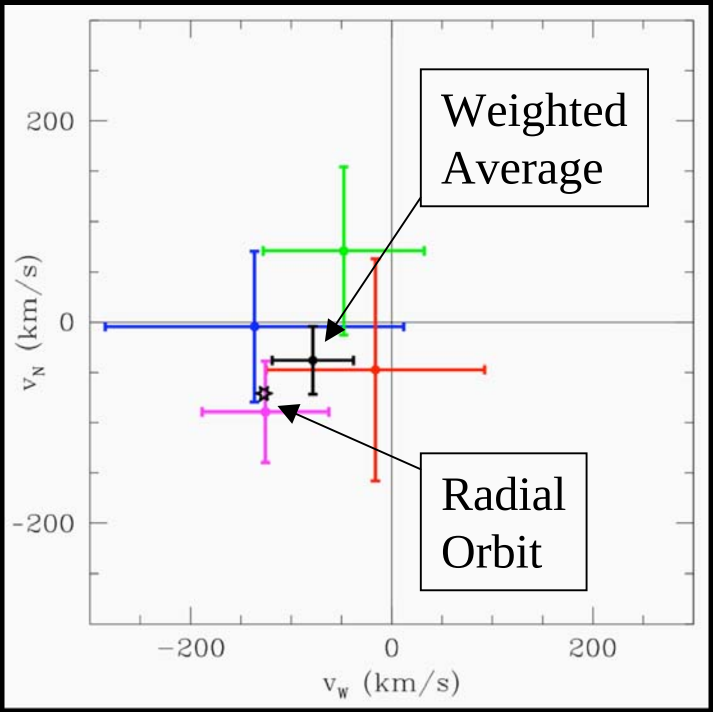
    $\underline{v}_{M31} = \underline{v}_{sat} + \underline{v}_{\Delta}$
  - $\underline{v}_{\Delta}$ acts as Gaussian error bar of 76 km/s
- Results:
  - v_W = -50 ± 80 km/s [M33] or -16 ± 80 km/s [IC10]
  - v_N = 71 ± 84 km/s [M33] or -47 ± 81 km/s [IC10]

M31 Transverse Velocity:
3. Local-Group Satellite Velocities

- 5 galaxies in the outer fringes of the Local Group
  - WLM, Aquarius, Leo, Tucana, Sag DIG
  - not part of the Milky Way of M31 subgroups
  - ~ 1 Mpc from Local Group Barycenter
- Assumption:
  - On average, these galaxies follow the motion of the Local Group Barycenter through space
- Implications (Einasto & Lynden-Bell 1982)
  - Yields estimate of Local Group Barycenter velocity
  - Yields estimate of M31 velocity
  - Very weak dependence on Milky Way / M31 mass ratio
- Results:
  - $v_W = -126 \pm 63$ km/s
  - $v_N = 89 \pm 50$ km/s

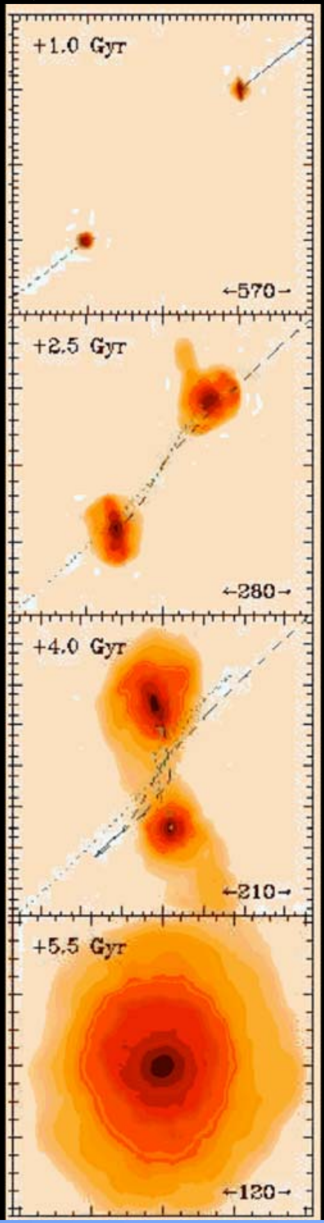
M31 Transverse Velocity: Observational Summary

- Different estimates consistent
- Weighted average
  - v_W = -78 ± 40 km/s
  - v_N = 38 ± 34 km/s
- ~10 μas/yr accuracy
- Galactocentric rest frame
  - Correct for solar reflex motion
  - V_{tan} = 42 km/s (< 56 km/s @68%)
  - V_{rad} = -130 km/s ± 8 km/s (from observed v_{los})
- Note: CMB dipole might yield another estimate, but currently limited by Zone of Avoidance (Loeb & Narayan 2008)



M31-Milky Way Orbit

(Cox & Loeb 08)



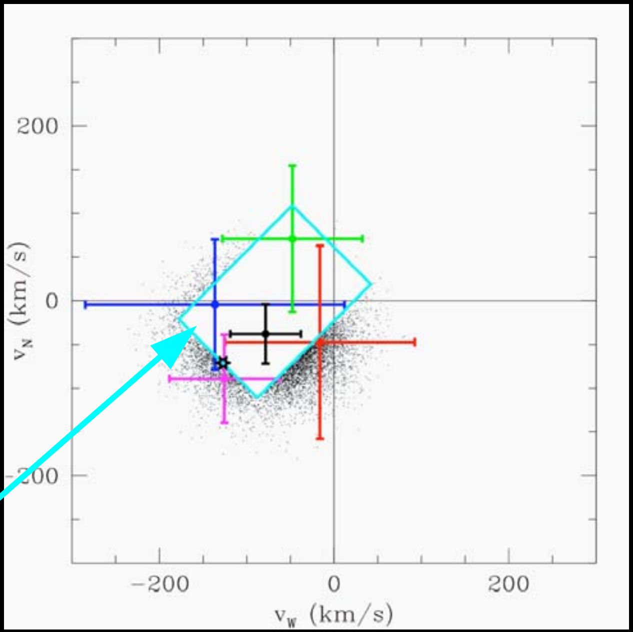
- Local Group Timing Argument (Kahn & Woltjer 1959)
  - Local Group decoupled from Hubble Flow soon after Big Bang
  - Milky Way and M31 were receeding, but their gravitational attraction produced the current approach
- Kepler orbit sufficient to describe motion
  - Model parameters: M, a, η, e
  - Observables: D, vrad, vtan, T_0 (WMAP: 13.73 ± 0.15 Gyr)
- Results:
  - Pericenter = a(1-e) = 23 kpc (< 41 kpc 68% conf)
  - Period = $2 \pi (a^3/GM)^{1/2}$ = 16.70 ± 0.26 Gyr
  - Milky and M31 will merge in 3.0 ± 0.3 Gyr

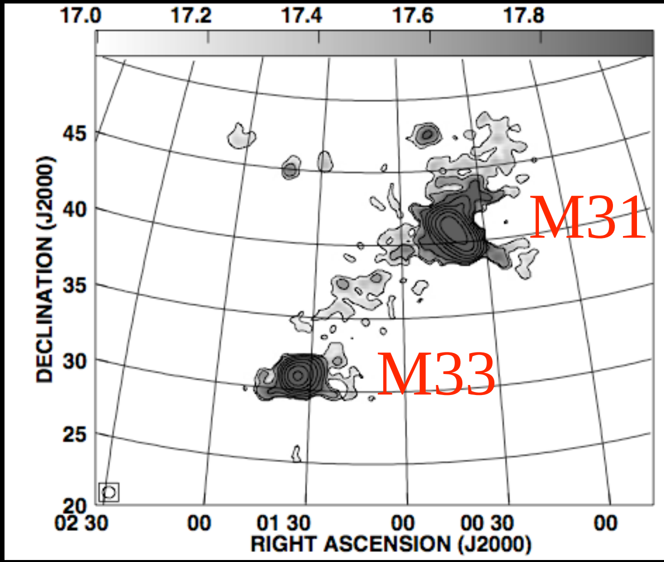
Local Group Mass

- Individual galaxy masses
  (Klypin et al. 02: dynamical constraints + ΛCDM halos)
  - Milky Way : $M \sim 1.0 \times 10^{12}\ M_\odot$
  - M31 : $M \sim 1.6 \times 10^{12}\ M_\odot$
  - Masses factor 2 higher still barely consistent with data
- Galaxies bound
  - Minimum mass for binding: $M = 1.7 \pm 0.3 \times 10^{12}\ M_\odot$
  - Unbound “chance encounter” very unlikely
- Timing mass for bound orbit: $M = 5.6 \pm 0.8 \times 10^{12}\ M_\odot$
- Theoretical studies (e.g., Li & White 2008):
  - uncertainty of timing mass estimate ~41%

M31-M33 Orbit

- M33 appears quite regular
- Loeb et al. 05 studied which orbits would have led to disruption of >20% of M33 stars
  - Simple test particle calculations
  - Assumed mass $M_{M31} \sim 3.0 \times 10^{12}\ M_{\odot}$
- Observed M31 v_{trans} falls in middle of excluded region
  - R_{peri} = 28 kpc, R_{apo} = 220 kpc, T = 2.3 Gyr
  - Inconsistent at 82% confidence
- Conclusions:
  - May indicate that M31 mass was overestimated
  - HI bridge may be indicative of past interaction (see also Bekki 2008)

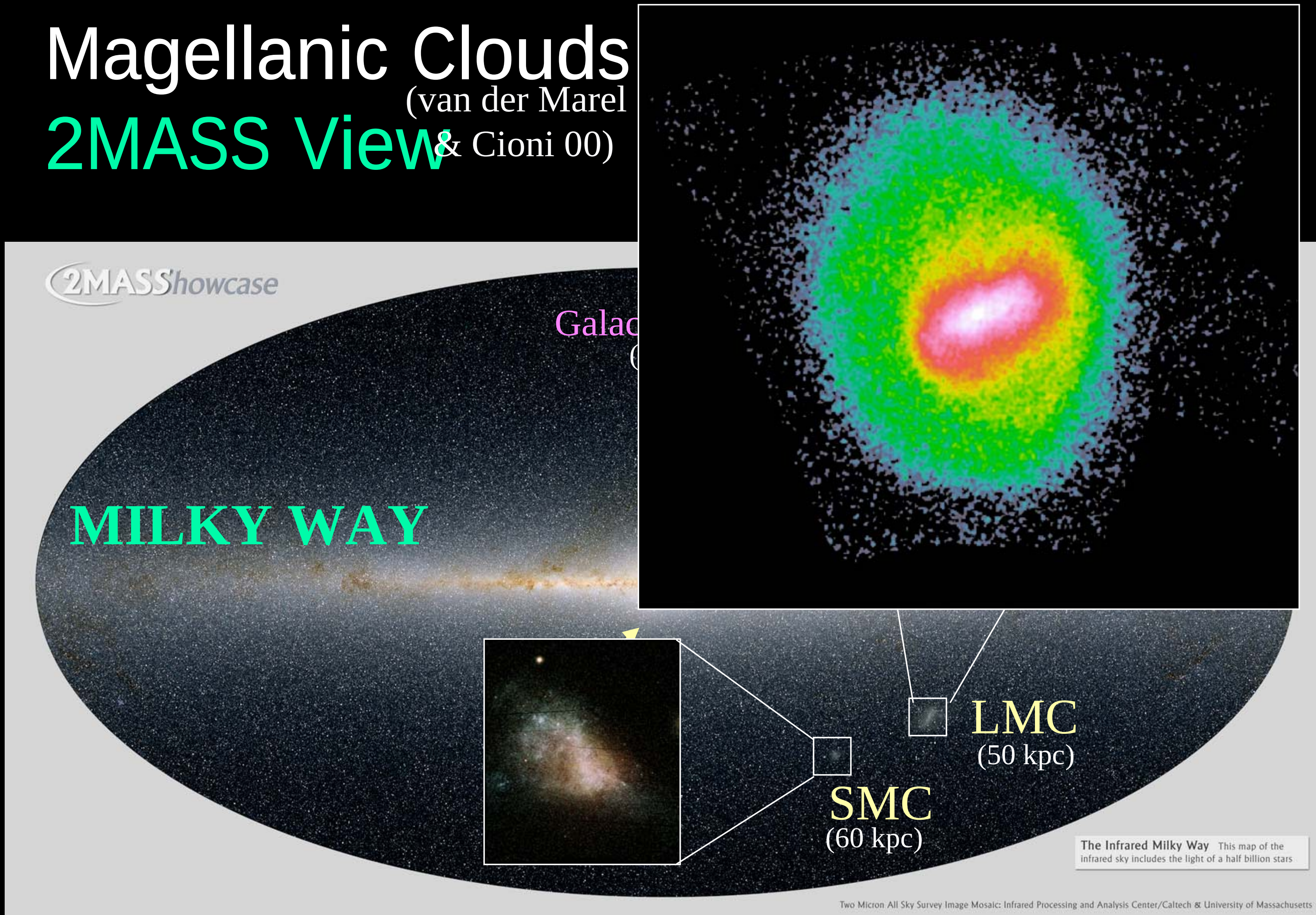




[Braun & Thilker 2004]

Magellanic Clouds
2MASS View

(van der Marel & Cioni 00)



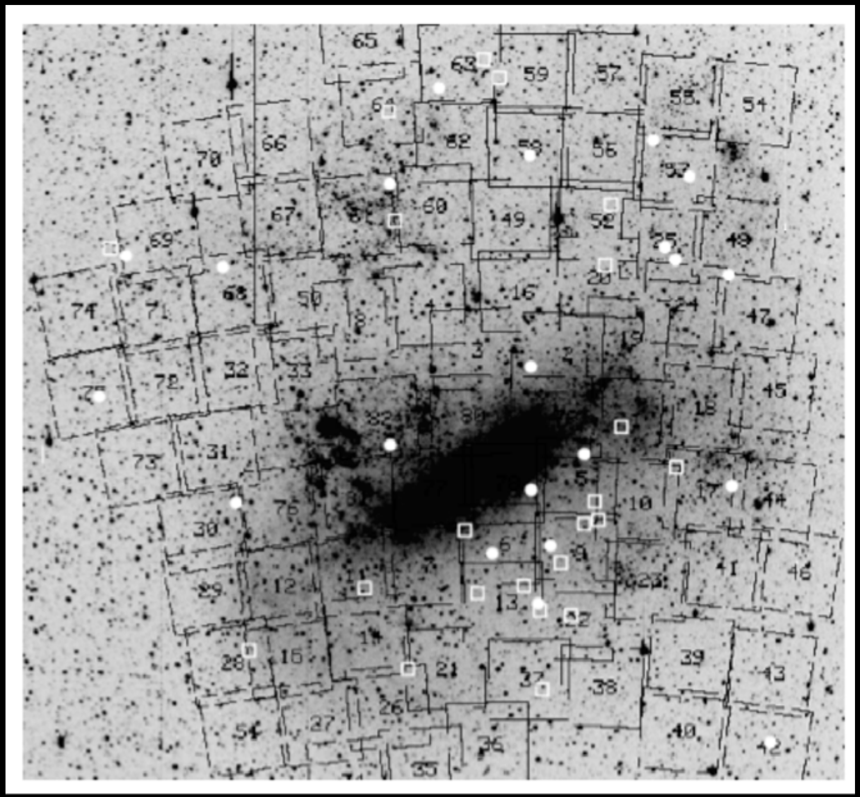
(Zaritsky & Harris)

LMC/SMC Proper Motion

- Magellanic Clouds 15 times closer than M31 $\Rightarrow$ proper motions observationally accessible
- Previous efforts have demonstrated that high accuracy is difficult to achieve
- Previous results did not have sufficient accuracy to meaningfully constrain the dynamics of the Magellanic system

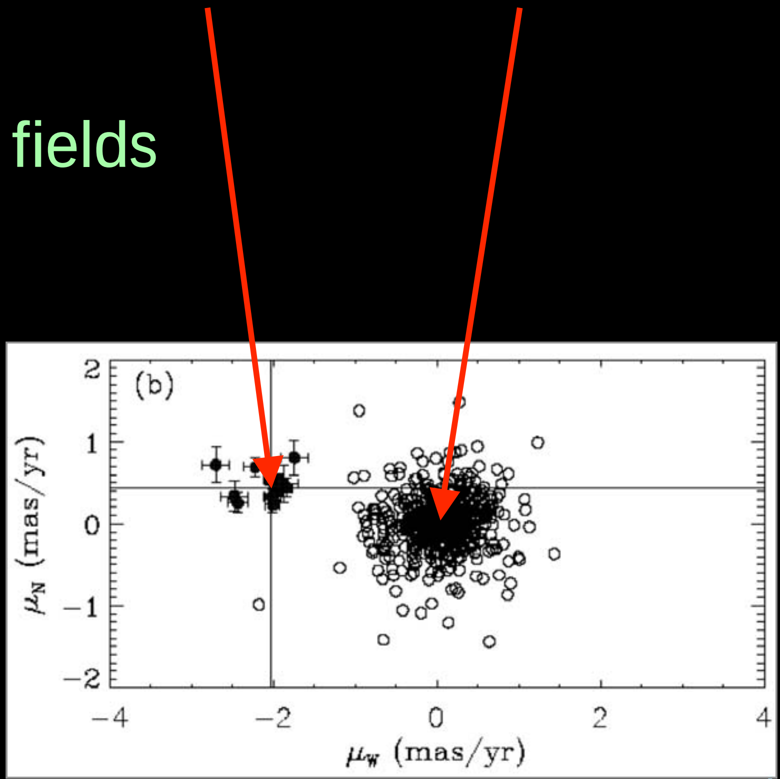
LMC/SMC proper motion
The HST/ACS Advantage

- Hubble Space Telescope
  - Very stable space platform
- Advanced Camera for Surveys
  - Very small pixels on High Resolution Camera (28 mas)
  - Very accurate geometric distortion solution
- Background quasars
  - Identified from MACHO and spectroscopically confirmed (Geha et al 02)



LMC/SMC Proper Motion HST/ACS Implementation

- Imaging of LMC/SMC star fields centered on quasars
- Determine shifts in positions of quasars vs. stars
- 2-year baseline
- 21 LMC and 5 SMC quasars fields
- ~0.005 pix accuracy/field
- (Small) Field-dependent corrections applied for geometry and rotation



LMC Proper Motion HST/ACS Results

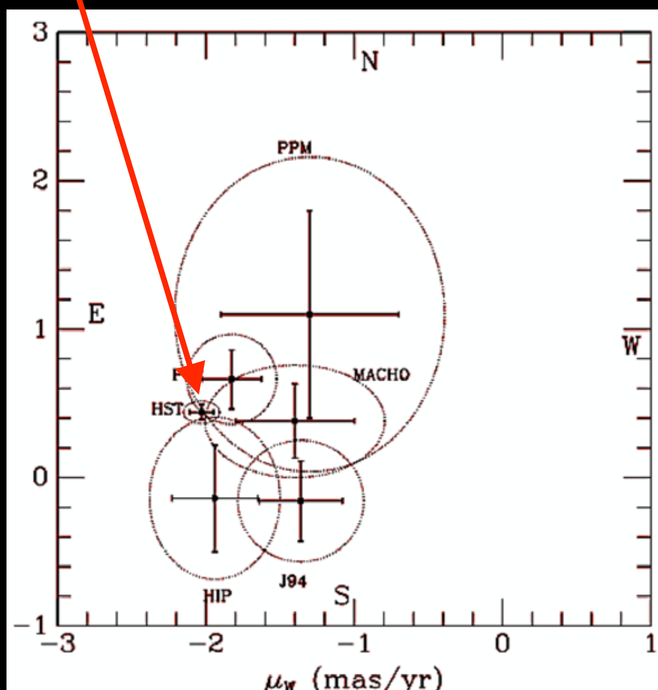
(Kallivayalil et al. 2006a,b)

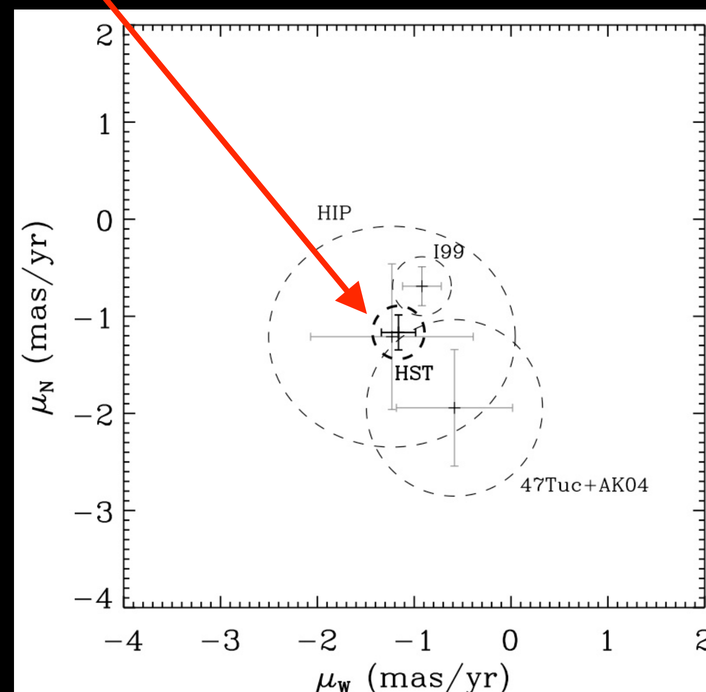
Much improved accuracy with respect to previous work

Confirmed by Piatek et al. (2008) through independent analysis of same data

- LMC:
  μ_W = -2.03 ± 0.08
  μ_N = 0.44 ± 0.05

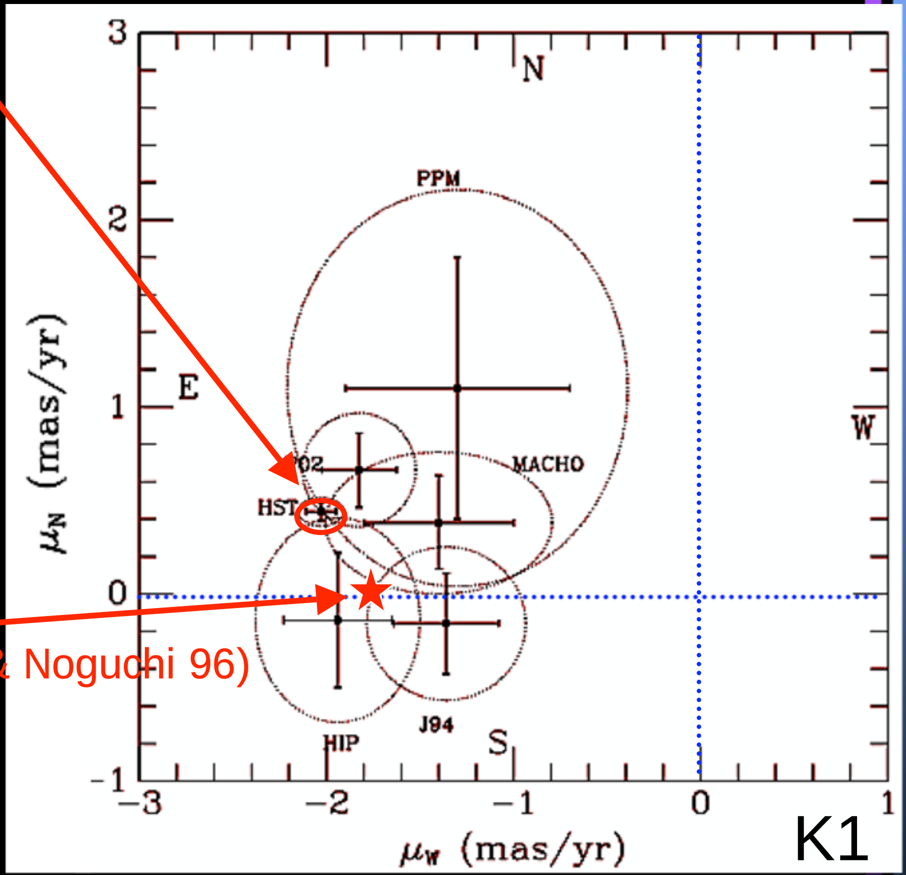
SMC:
-1.16 ± 0.18 mas/yr
-1.17 ± 0.18 mas/yr





Proper Motion Data-Model Comparison

- Observed Proper motion implies
  - V_{tan} = 367 ± 18 km/s
  - V_{rad} = 89 ± 4 km/s
  - |v| = 378 ± 18 km/s
- Inconsistent with Magellanic Stream models
  - Clouds assumed bound to MW
  - Logarithmic dark halo potential
  - Period ~ 2 Gyr ⇒ multiple previous passages
  - v_{tan} = 287 km/s
- Orbit
  - Agreement that v_{rad} << v_{tan} ⇒ Clouds just past pericenter
  - Clouds move much faster than previously believed



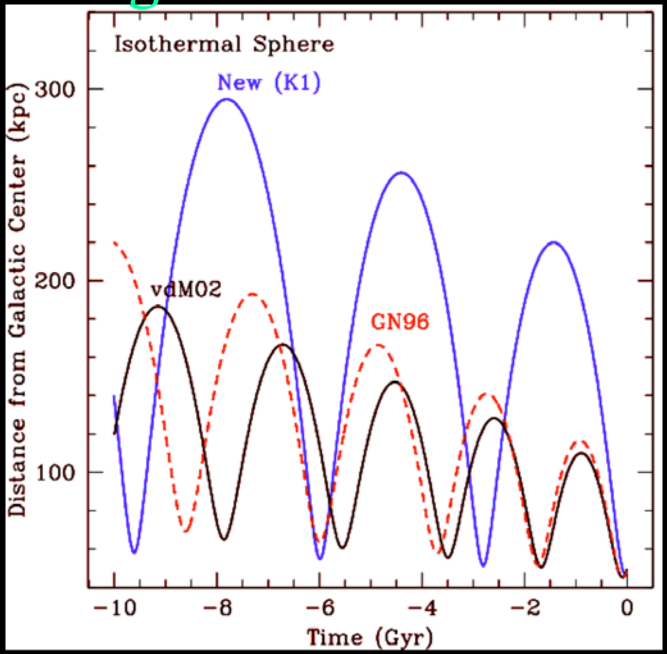
New Exploration of LMC/SMC Orbits around the Milky Way

(Besla et al. 2007)

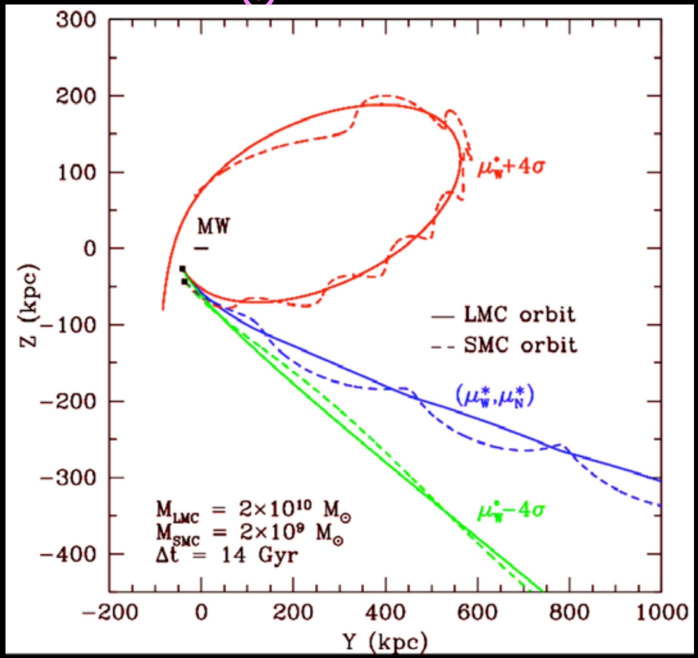
- Fixed Milky Way Potential
  - Disk + Bulge + Hot Halo + Dark Halo
    (Lambda CMD motivated NFW, adiabatically contracted)
  - More realistic than logarithmic potential
- Simple Point-Mass orbits for LMC/SMC
  - Integrated backwards in time
  - From current conditions (+Monte-Carlo realizations of errors)
  - Includes dynamical friction prescription

Dependence on Milky Way Potential

Logarithmic Potential



10^{12} $\mathbf{M_\odot}$ ΛCMD Halo



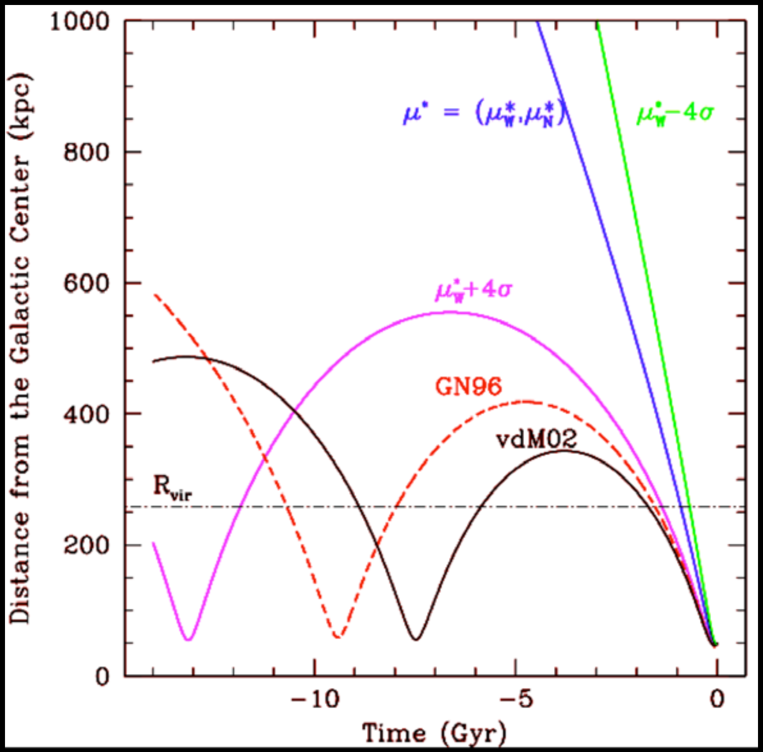
- New Proper Motion
  - Larger period
  - Larger apocenter

~ Escape Velocity
  - Parabolic orbit, First Passage

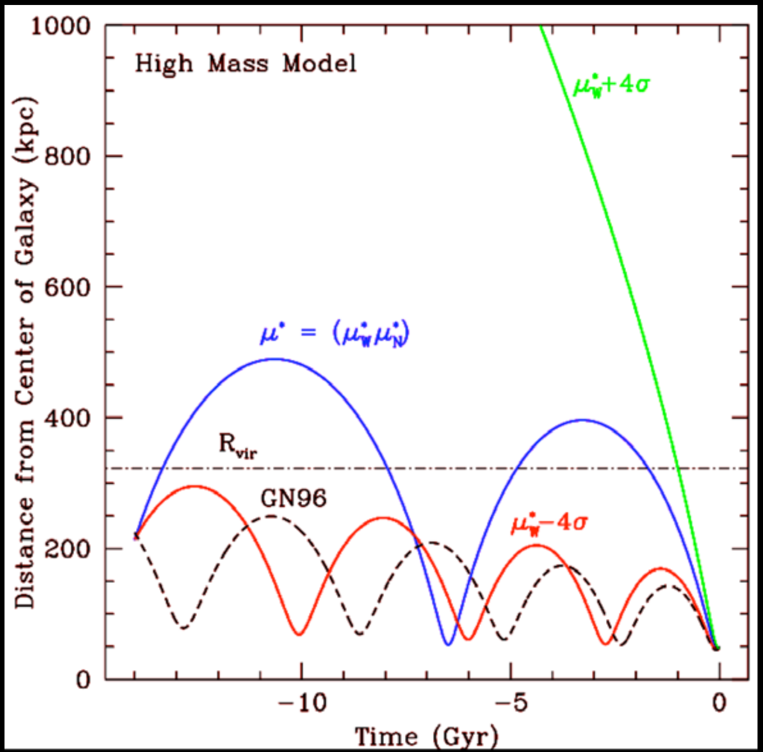
Dependence on Milky Way Halo Mass

(See also Shattow & Loeb 2008)

10^{12} $M_\odot$ ΛCMD Halo



2 x 10^{12} $M_\odot$ ΛCMD Halo



Note: MW-type halo should be half as massive ~8 Gyr ago (Wechsler et al.02)

Note: Orbits not materially affected by M31 (Kallivayalil et al. in prep)

Other Evidence for a First Passage Scenario

MW Satellites

Name	Type	D_{Gal} (kpc)
N5139	GC	6
Sgr	dSph	19
LMC	Ir	50
SMC	Ir	63
UMi	dSph	69
Dra	dSph	79
Sex	dSph	86
Scl	dSph	88
N 2419	GC	92
Car	dSph	94
UMa	dSph	105
For	dSph	138
Leo II	dSph	205
Leo I	dSph	270
Phe	dIr/dSph	405
NGC 6822	Ir	500

M31 Satellites

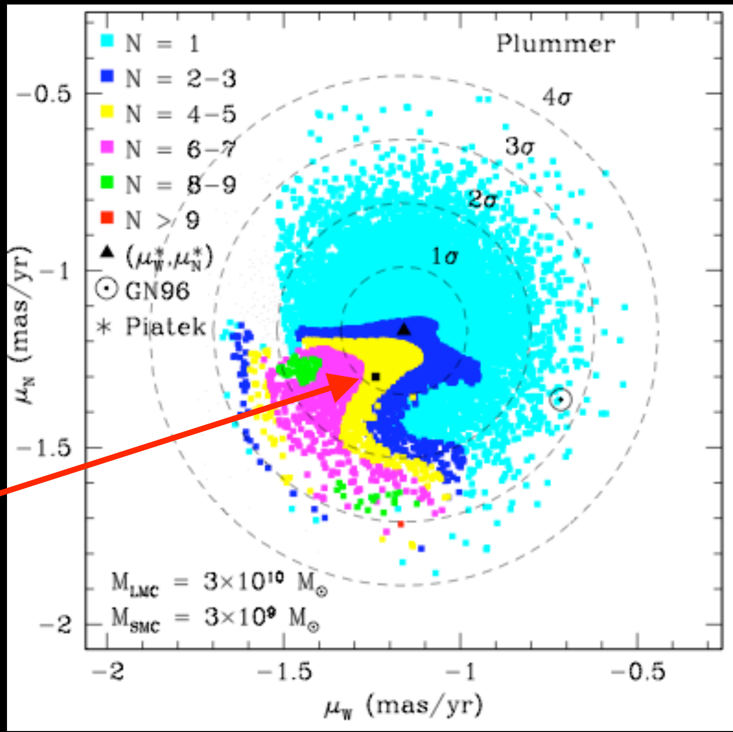
Name	Type	D_{M31} (kpc)
B327	GC	3
M32	E2,N	6
Hux C1	GC	13
Hux C3	GC	14
G1	GC	35
Hux C2	GC	37
NGC 205	E5pec	40
And IX	dSph	42
And I	dSph	59
And III	dSph	76
And V	dSph	110
And X	dSph	112
NGC 147	Sph	145
And II	dSph	185
NGC 185	Sph	190
M33	Sc	208
And VII	dSph	219
IC 10	Ir	260
And VI	dSph	269
Pisces	dIr/Sph	269
Pegasus	Ir(?)	474
IC 1613	Ir	508

Local Group Demographics
(van den Bergh 06)
Irr galaxies (satellites with high gas fractions) are all located at large Galactocentric radii, except for the Magellanic Clouds

Cosmological Simulations
(Kazantzidis et al. 07):
- 70% of halos have accreted an LMC-type galaxy in past 5 Gyr)
- Long-term satellites on orbits with small pericenters very rare

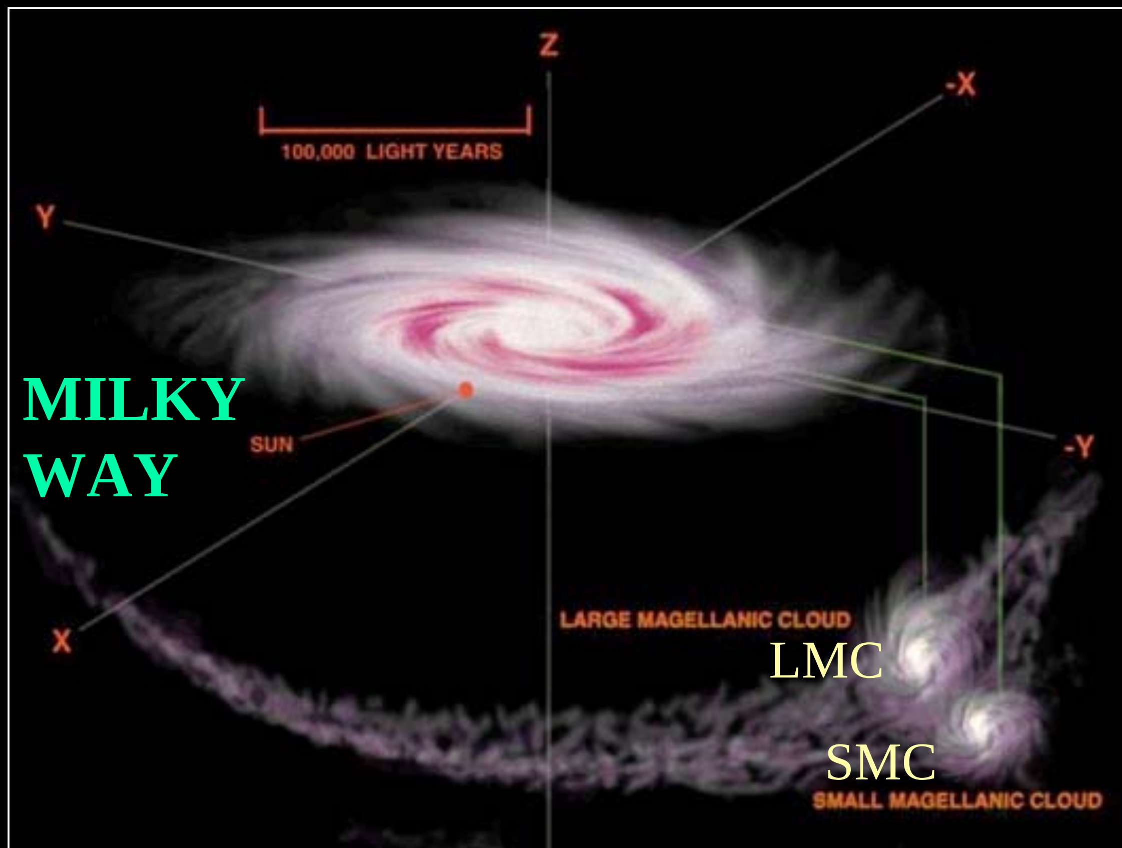
Are the LMC and SMC bound to each other?

- Integrate orbits of LMC and SMC back in time
- LMC/SMC orbits exist within the 1-sigma error ellipse that have had multiple previous pericenter passages, e.g
  - @300 Myr (~ Mag bridge forms)
  - @1.5 Gyr (~ Mag Stream forms)
- Observational accuracy not sufficient to establish whether or not LMC/SMC are in fact bound



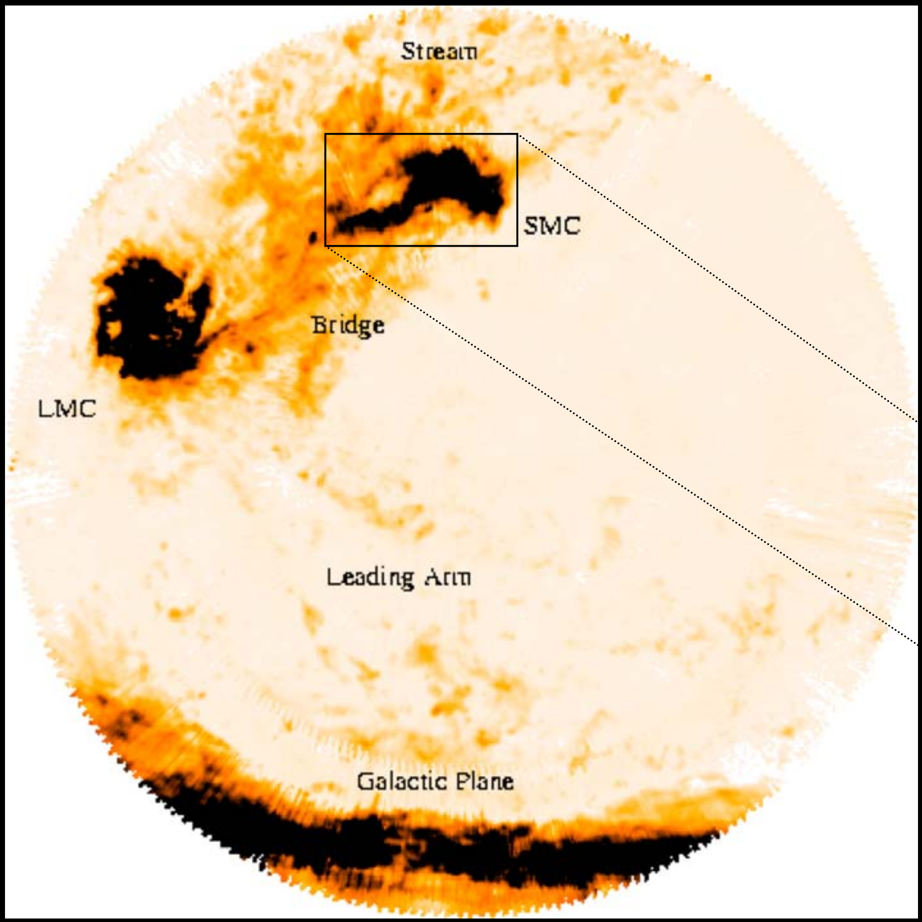
[Besla et al. 2008]

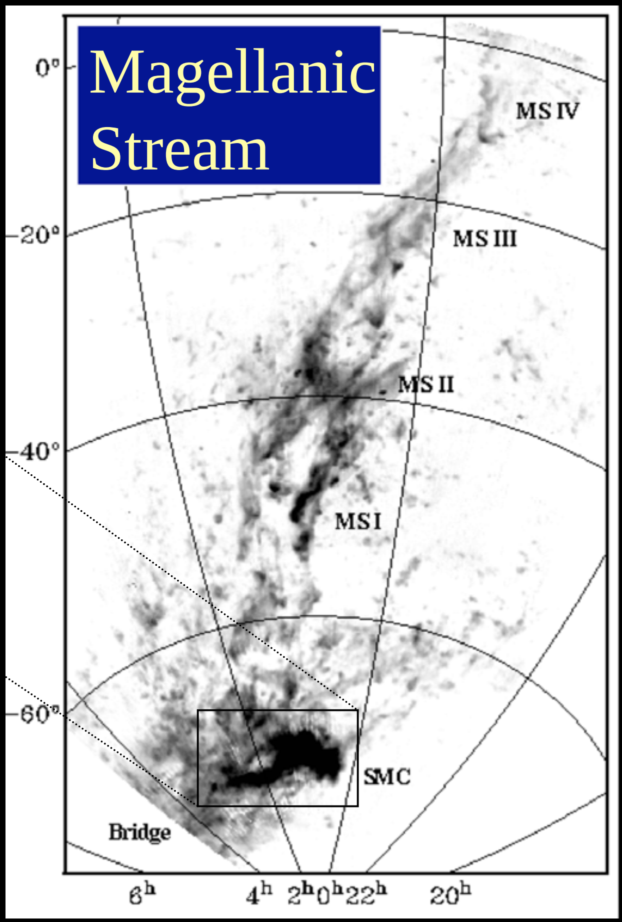
Magellanic Clouds System: Milky Way Interaction



[Dallas Parr (CSRIO)]

Magellanic Stream



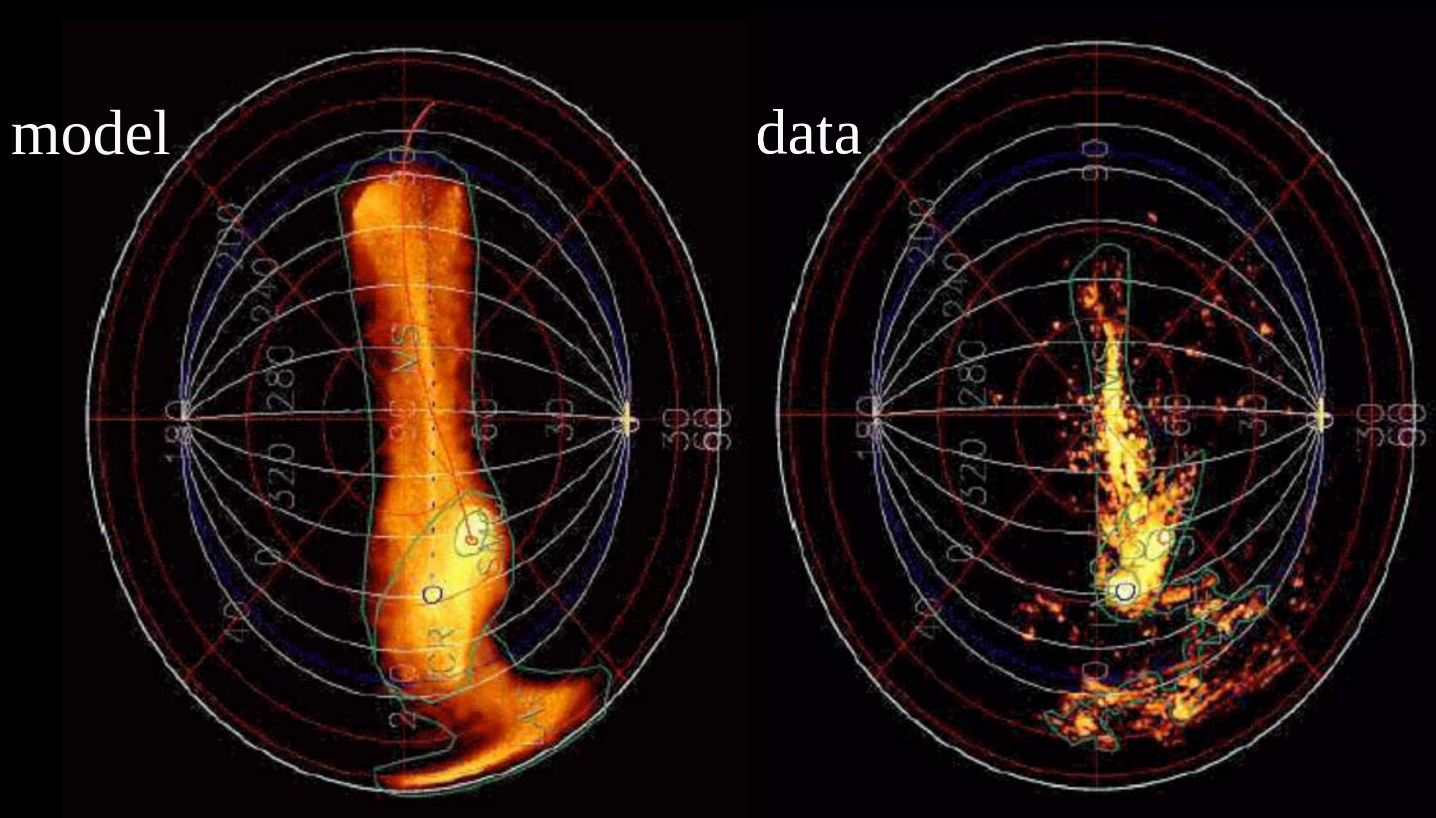


[Putman et al.]

Magellanic Stream Models

- Hold the promise to constrain
  - History of the Milky Way / LMC/ SMC system
  - Dark matter halo of the Milky Way
- Observational constraints
  - Position of Stream
  - HI column density variation along Stream
  - HI line-of-sight velocity variation along Stream
  - Absence of stars in Stream
  - Asymmetry between Leading and Trailing Stream
- Many plausible models constructed over the years
  - Little agreement on dominant physical process

Magellanic Stream:
Tidal Model

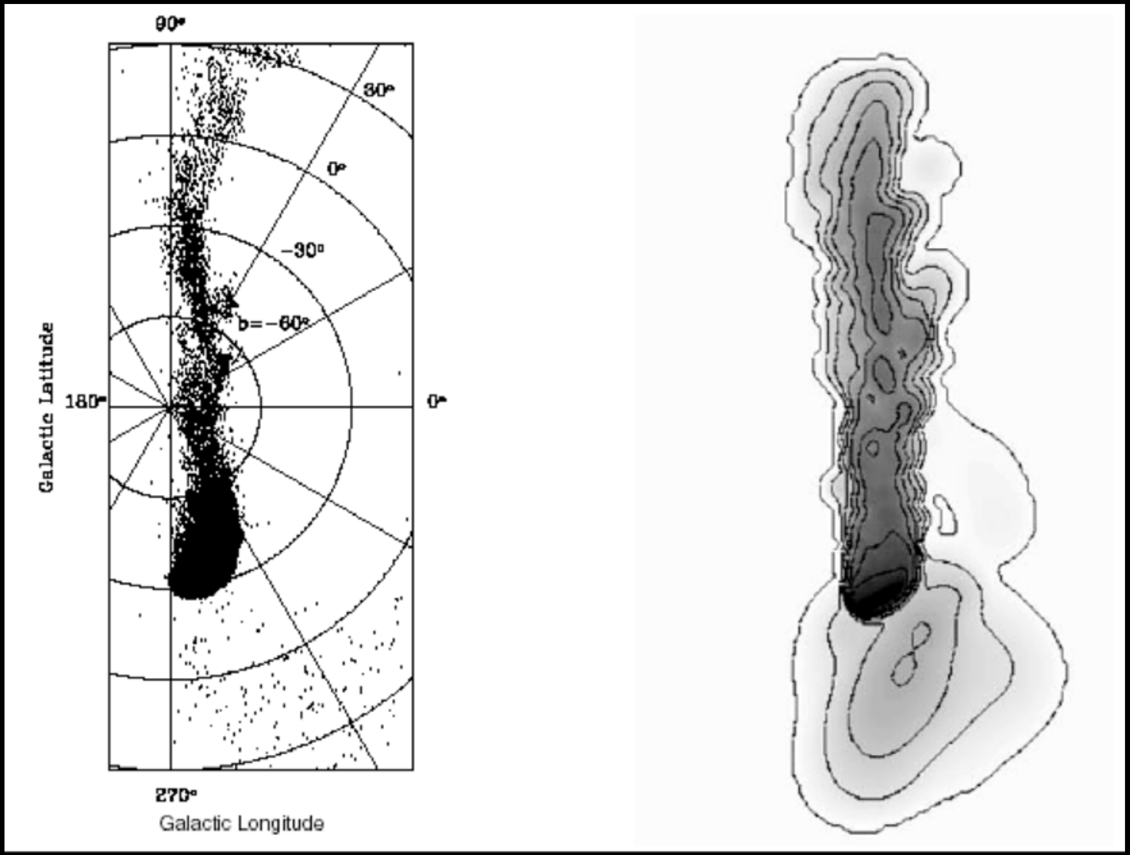


Recent example: Connors et al. (2005)

- Stream formed ~1.5 Gyr ago from SMC gas during the last close LMC-SMC encounter

Magellanic Stream:
Ram-Pressure Model

model

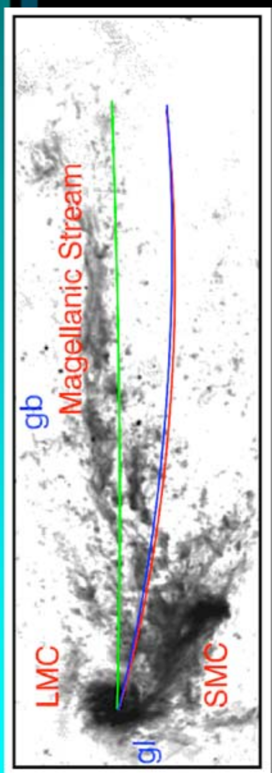


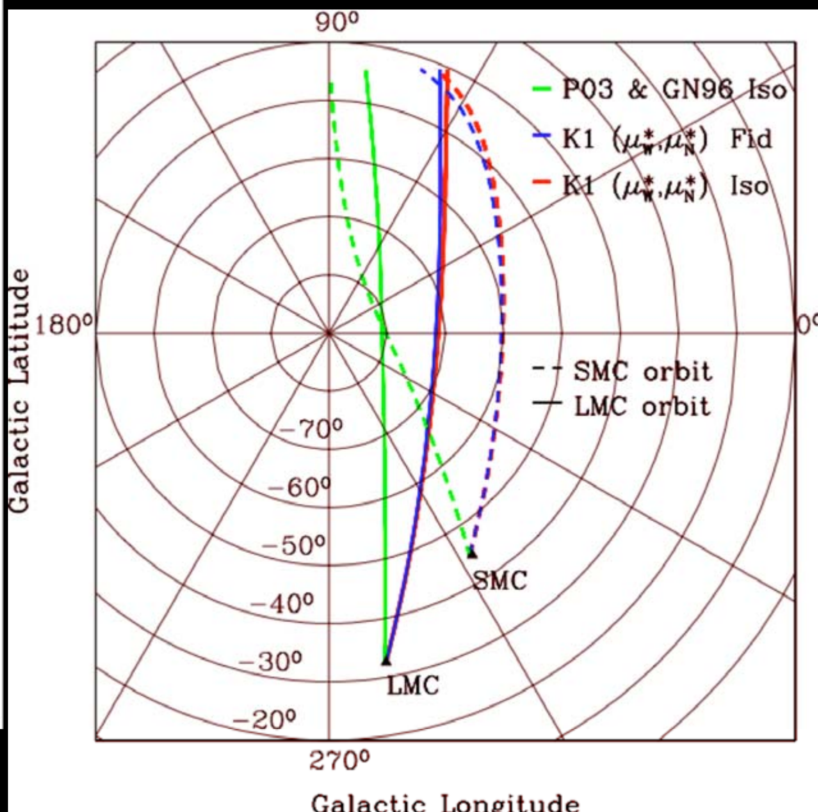
data

Recent example: Mastropietro et al. (2005)

- Stream formed from LMC gas due to ram pressure stripping by a low-density ionized halo (SMC not modeled!)

Comparison of Orbit to Magellanic Stream Location





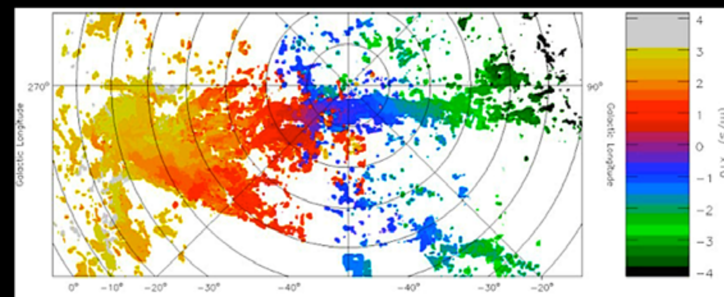
- Newly calculated orbits are not co-located in the sky with the Magellanic Stream
  - Inconsistent with tidal models

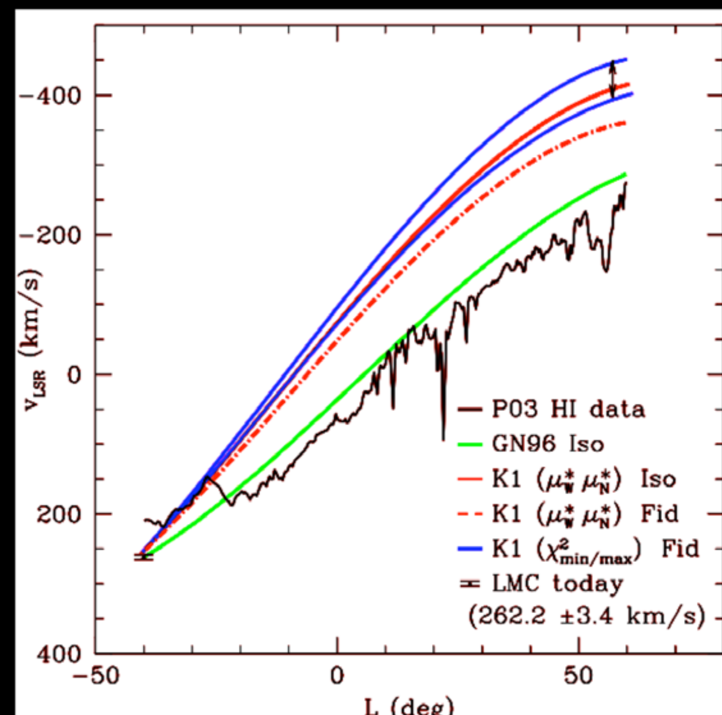
Independent of
  - Dark Halo profile
  - Dark Halo axial ratio
  - PM West-component

Driven by PM North-component
  - HST result identical to average of ground-based data
  - many-sigma different from Gardiner & Naguchi (1996)

HI velocity gradient comparison

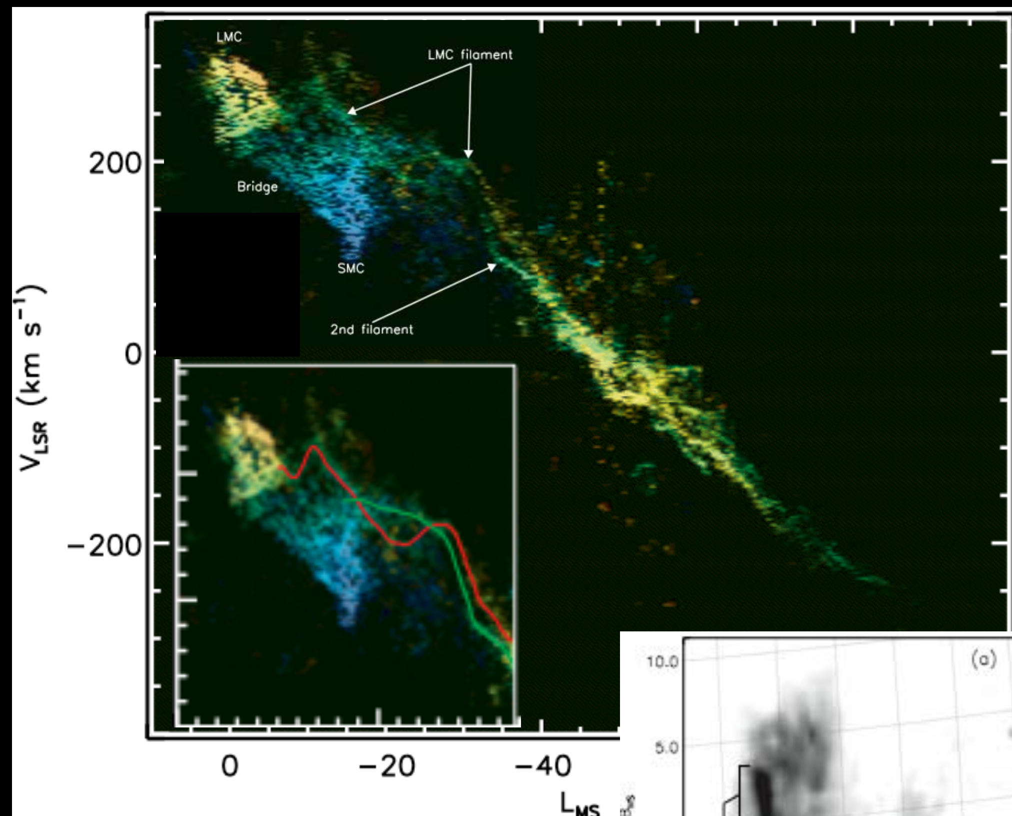
- Newly calculated orbits have higher V_{LSR} gradient along orbit than observed in HI along Stream
- Newly calculated orbits do not cross the Milky Way disk plane
  - Inconsistent with “traditional” ram-pressure models
- Different models/ingredients needed to explain all this:
  - Added drag?
  - Misaligned drag?
  - Initial extended LMC HI disk?
  - Asymmetric removal? (Roediger & Bruggen 2006)
  - Outflow? Gas from LMC?

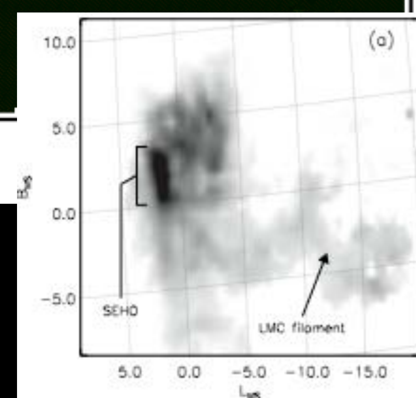




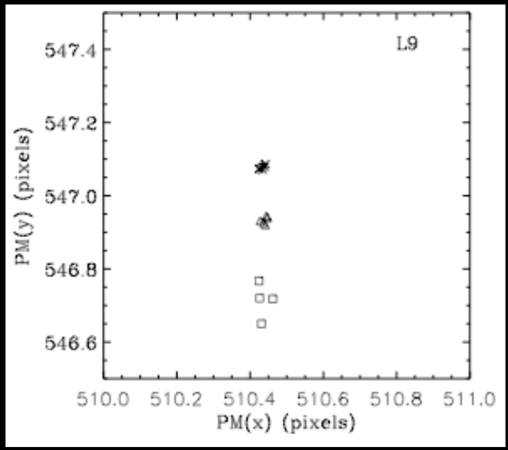
New insights from Leiden-Argentine-Bonn HI Survey

- Nidever et al. 07:
  - Two distinct filaments in space and velocity
  - One filament and most Leading Arm (>50% of total gas) can be traced back to star-forming region 30 Dor in LMC
  - Outflows from supergiant shells important





Ongoing/Future PM work



[Kallivayalil et al. 2008]

- LMC/SMC (Kallivayalil et al.)
  - 3rd epoch w/ HST/WFPC2 in progress
    - 5 yr baseline - lower astrometric accuracy
    - Check for systematic errors
  - 4th epoch w/ HST/ACS+WFC3 approved for Cycle 17
    - 6 yr baseline - higher astromeric accuracy
    - Factor ~3 decrease in random errors expected
  - Internal kinematics, Rotational parallax, ...
- M31 (vdM et al.)
  - 2nd epoch w/ HST/ACS+WFC3 approved for Cycle 17
    - Brown's deep M31 fields as 1st epoch: 4-6 year baseline
    - ~100 Background galaxies as astrometric reference
    - Predicted random errors ~ 10 uas; Systematic errors?
- GAIA/SIM

Conclusions

- Much improved understanding of orbits of main Local Group galaxies
  - M31-Milky Way orbit nearly radial
  - M31-M33 orbit tighter than previously believed
  - LMC and SMC consistent with being bound together
  - LMC+SMC may on first Milky Way passage
- Local Group mass still uncertain to with factor ~2
- New insights open door to proper understanding of Magellanic Stream