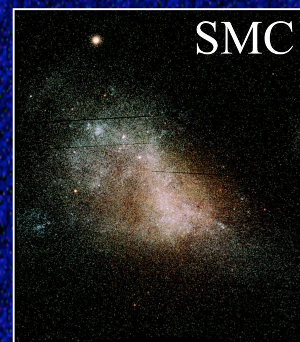
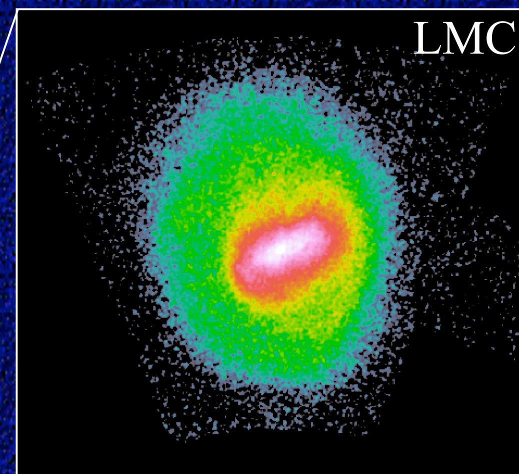
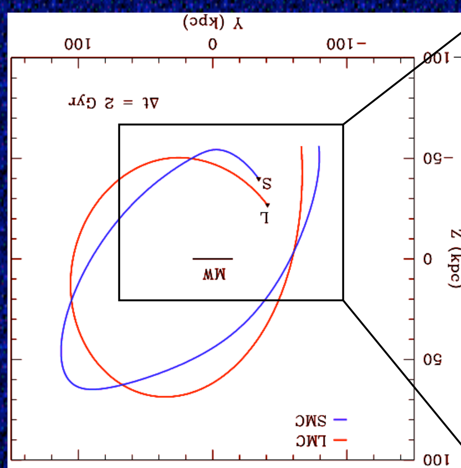
The Magellanic Clouds and Stream: Probes of the Milky Way Halo

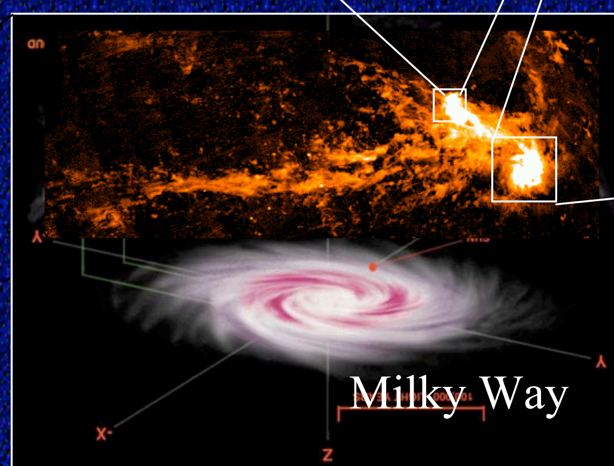
Roeland van der Marel





Proper motions: Nitya Kallivayalil
Orbit calculations: Gurtina Besla





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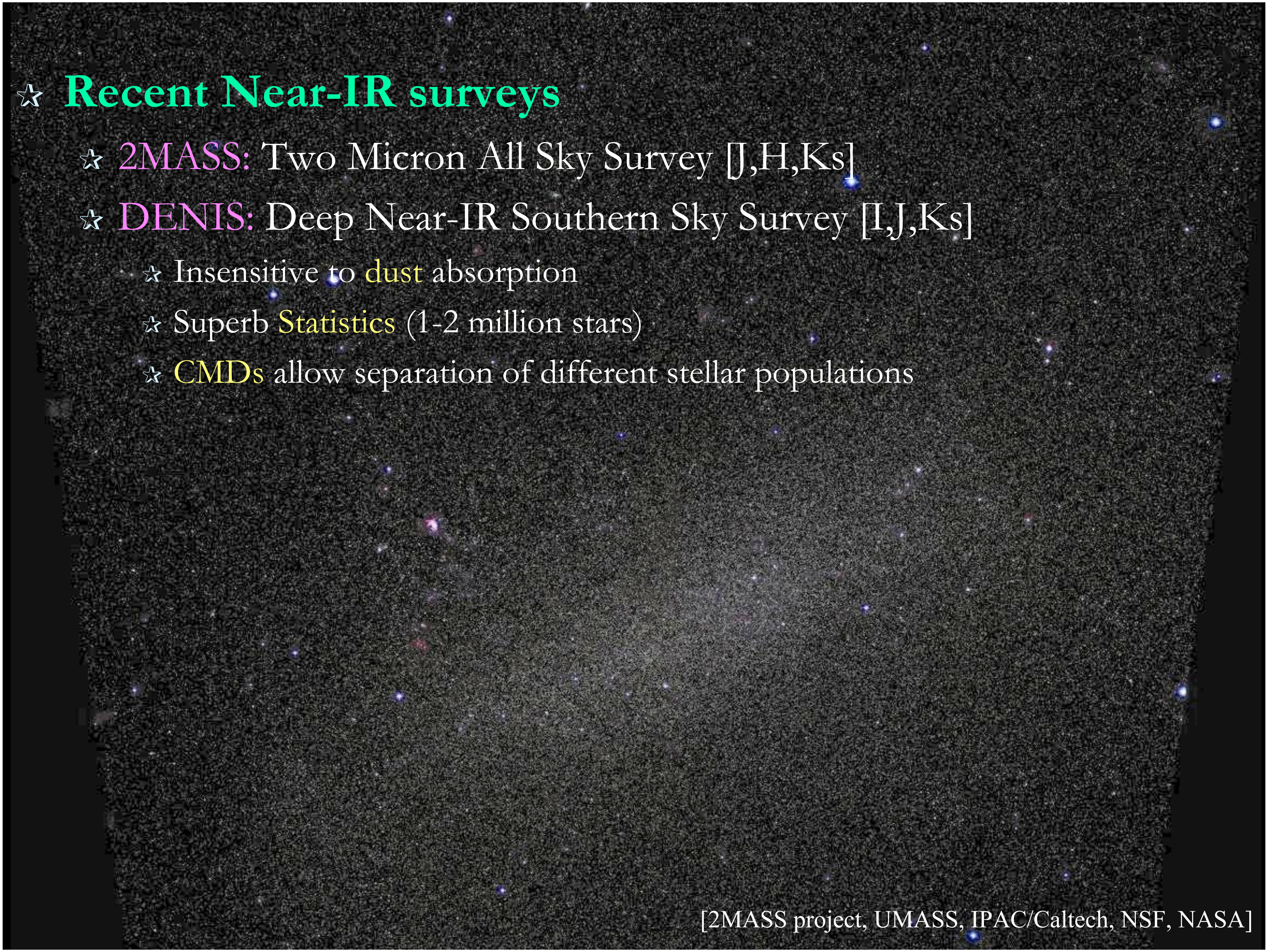
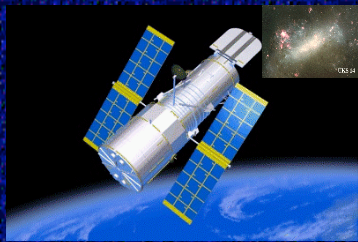
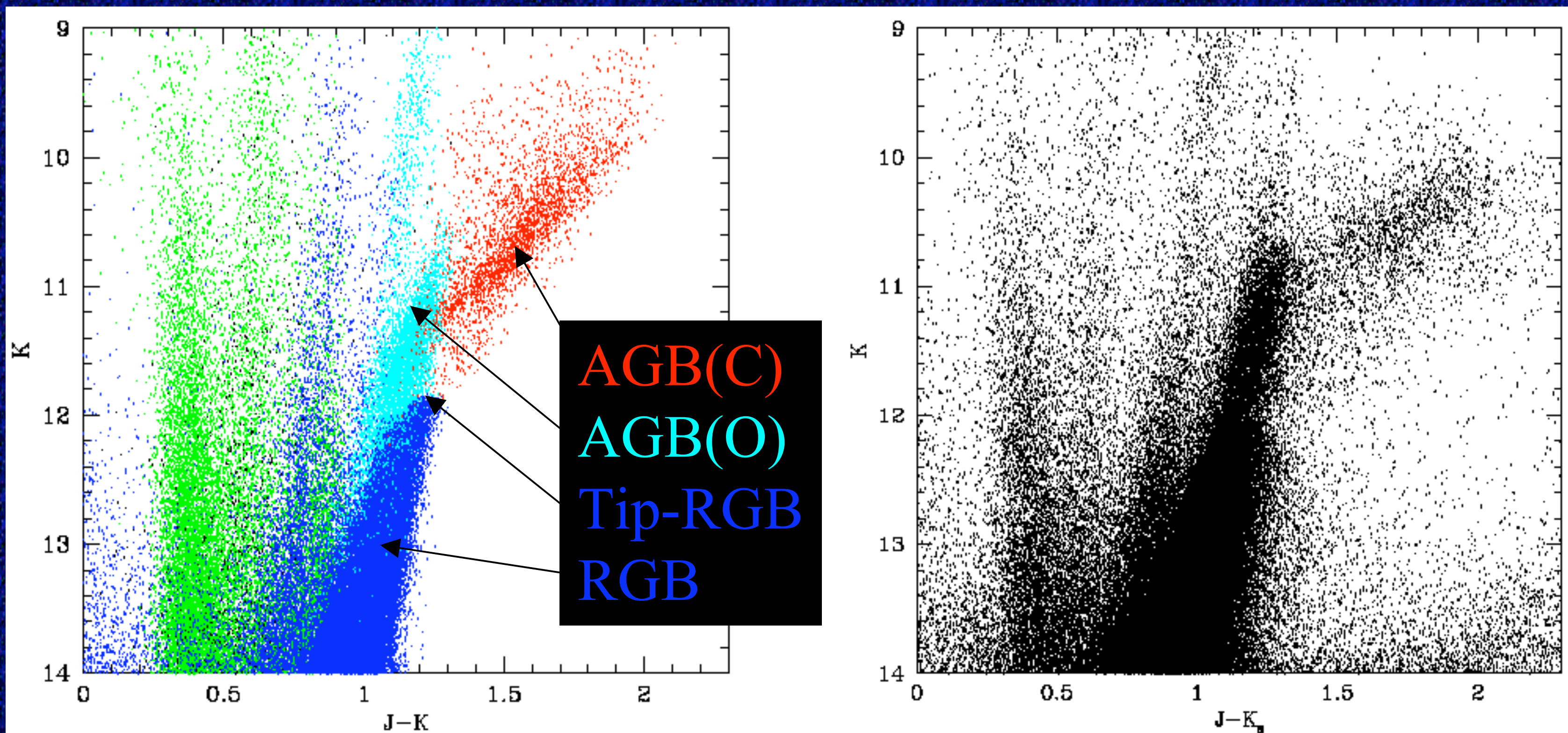
- **Recent Near-IR surveys**
  - 2MASS: Two Micron All Sky Survey [J,H,Ks]
  - DENIS: Deep Near-IR Southern Sky Survey [I,J,Ks]
    - Insensitive to dust absorption
    - Superb Statistics (1-2 million stars)
    - CMDs allow separation of different stellar populations



[2MASS project, UMASS, IPAC/Caltech, NSF, NASA]



LMC Near-IR CMD



[Marigo et al. (Padua models)]

[2MASS]

- ☆ CMD allows extraction of the intermediate age/old population: AGB/RGB stars ⇒ tracer of underlying mass distribution

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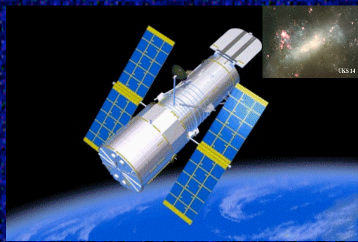
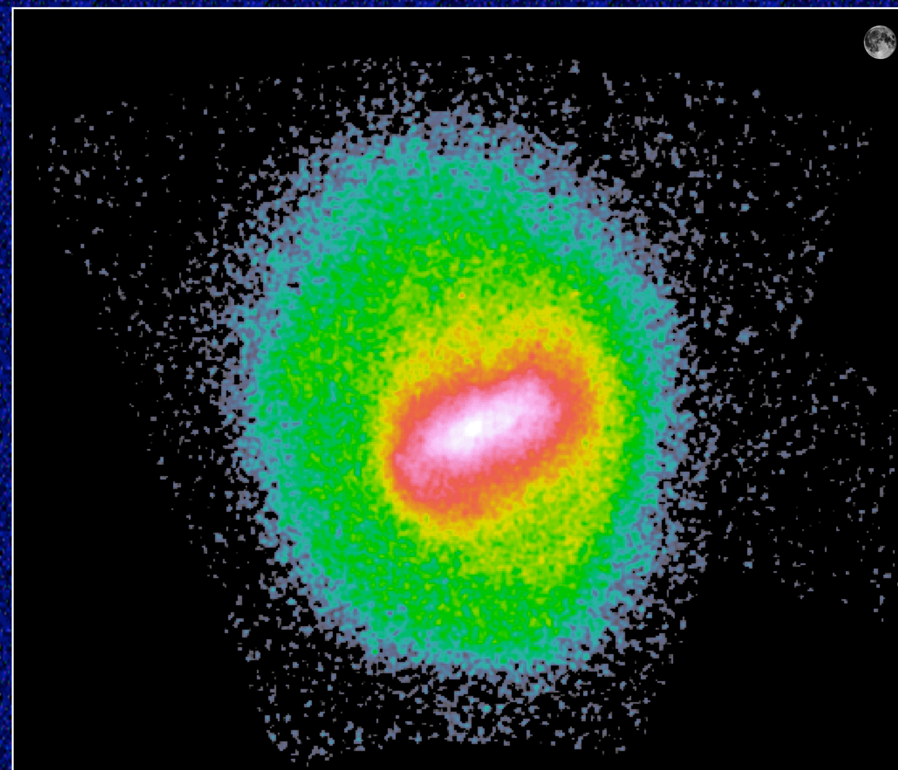


LMC Morphology: Near-IR Selected RGB & AGB Stars

- **vdM (2001):** **Smooth morphology** **(contrast to optical)**

- **Surface Density Profile ~ Exponential**
- **At large radii:**
  - $PA_{maj} = 189 \pm 1$ deg
  - $\varepsilon = 0.20 \pm 0.01$

2MASS+DENIS stellar number density image



23x21 degrees (1 degree = 0.875 kpc)

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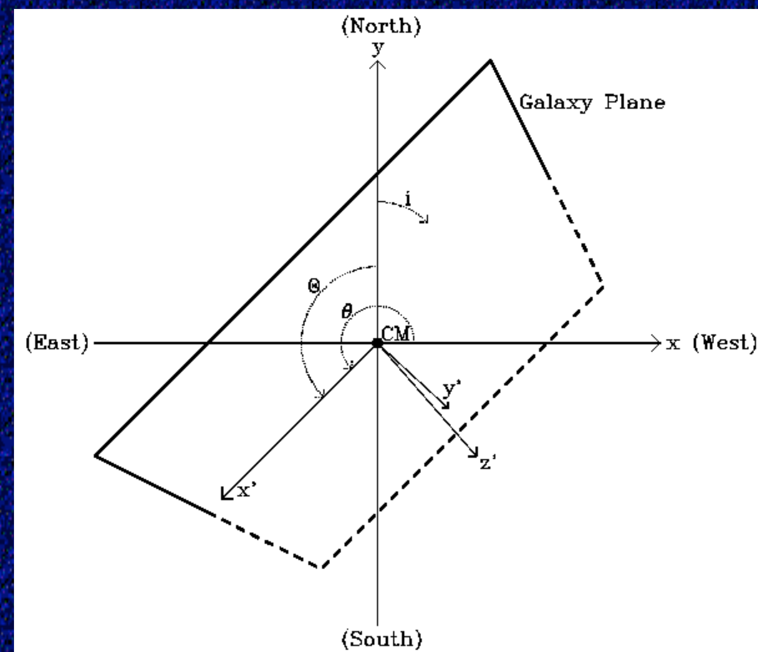
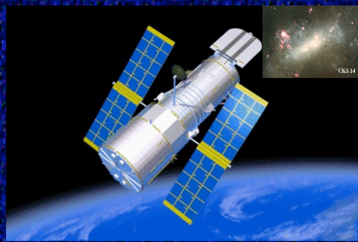
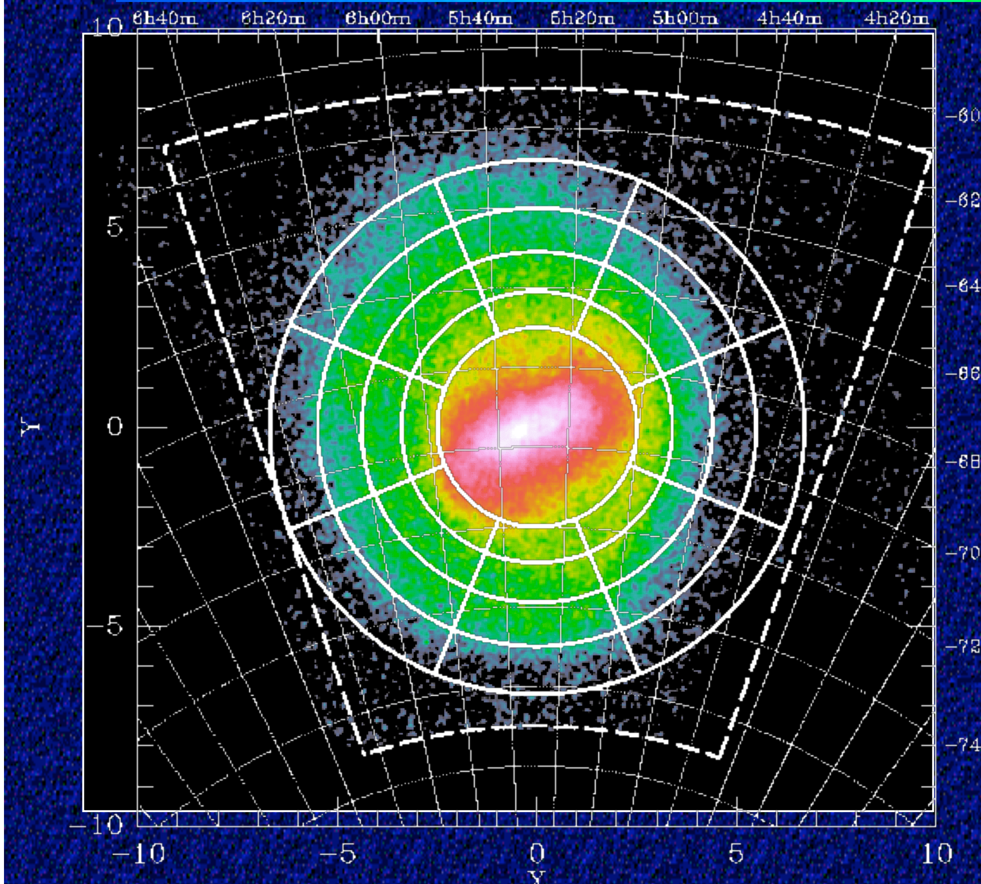
LMC: Viewing Angles

- ☆ **Viewing angles describe our vantage point w.r.t. LMC plane**
  - ☆ i = inclination angle
  - ☆ Θ = line of node pos. angle
- ☆ **Geometrical determination**
  - ☆ Magnitude variations from distance variations to an inclined plane:
    0.038[mag] r[deg] tan i sin (PA - Θ)
- ☆ **vdM & Cioni (2001): use positional dependence of well-defined features in the near-IR CMDs**
  - ☆ RGB Tip
  - ☆ AGB Modal Magnitude

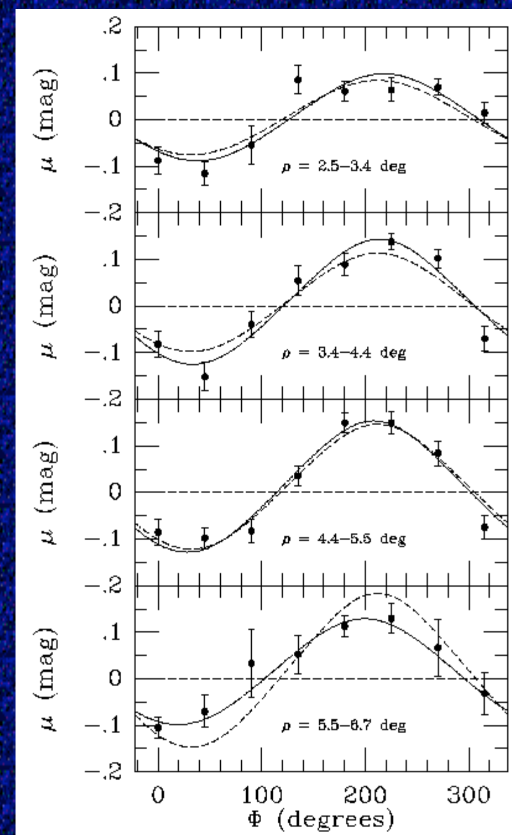




Magnitude Variations along Rings



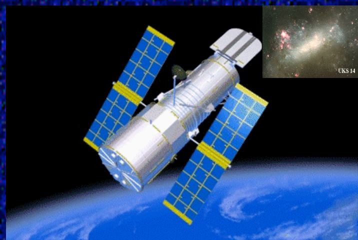
Polar grid on sky



Sinusoidal magnitude variations

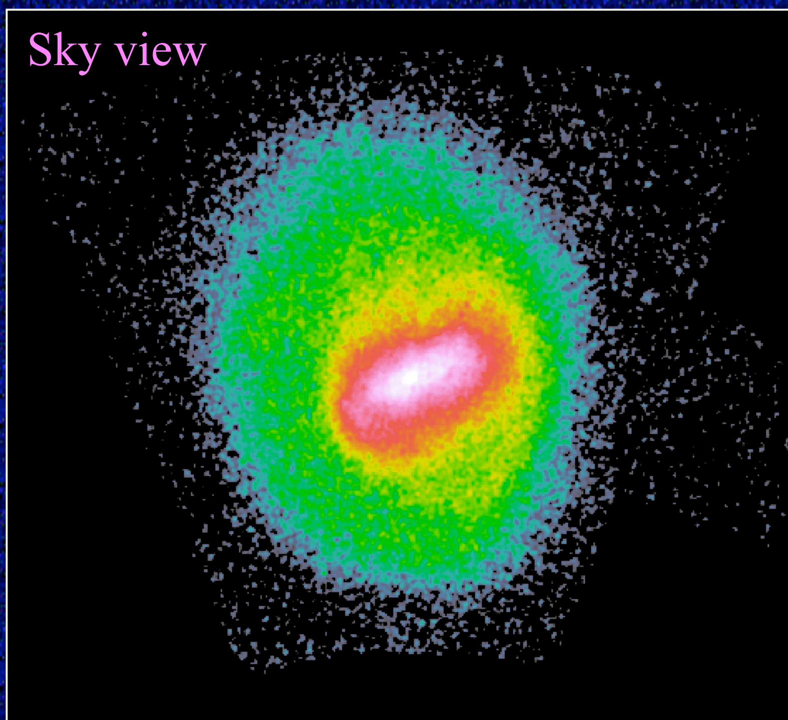
i = 34.7 ± 6.2 deg

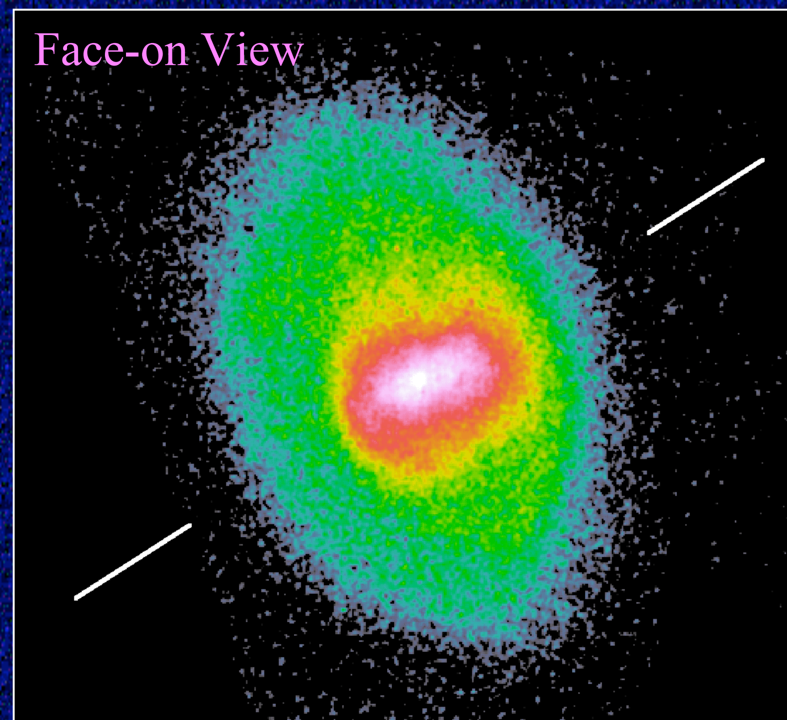
Θ= 122.5 ± 8.3 deg

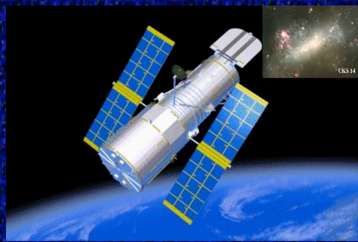


The Deprojected (face-on) view of the LMC

- ☆ $\Theta \neq PA_{maj} \Rightarrow$ **LMC disk is not circular** ($\varepsilon = 0.31$)

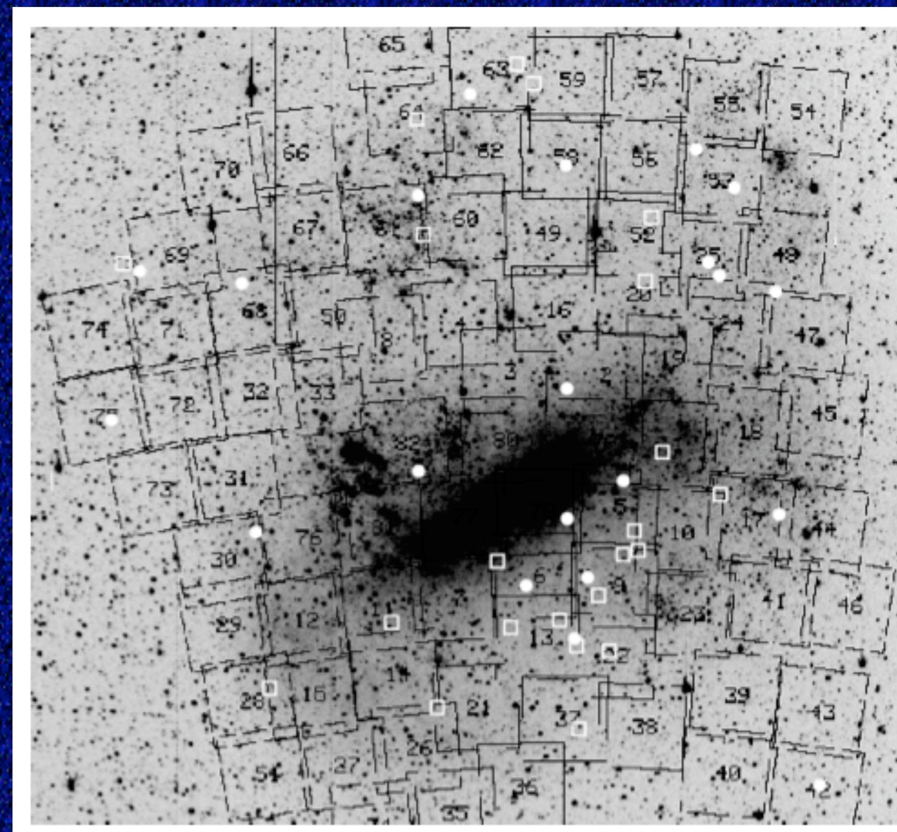


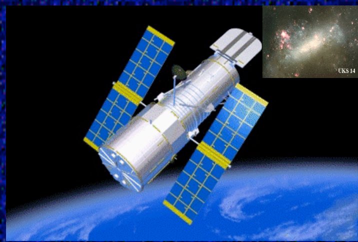




LMC/SMC proper motion
Improved Measurements

- Use **HST/ACS** to image LMC/SMC star fields centered on background quasars
- Determine shifts in stellar positions w.r.t. quasars

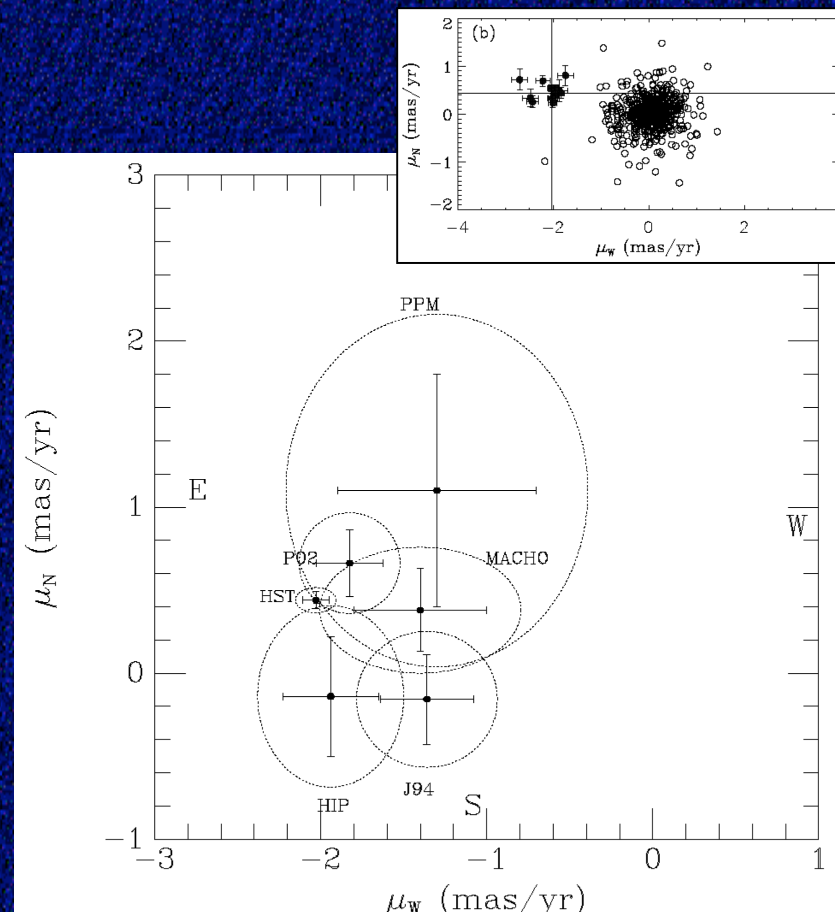


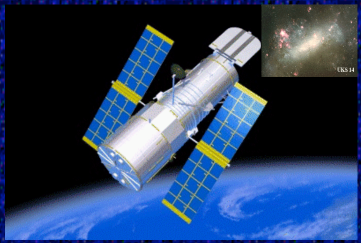


LMC Proper Motion **Results**

(Kallivayalil, vdM, Alcock et al. 2006a,b)

- 21 LMC and 5 SMC QSO fields
- 2-year baseline
  - (Cyc 16: 5yr w/ WFPC2)
- Random ORIENTs
- ~0.005 pix accuracy/field
- **LMC:**
  - μ_W = -2.03 ± 0.08 mas/yr
  - μ_N = 0.44 ± 0.05 mas/yr
- **SMC:**
  - μ_W = -1.16 ± 0.18 mas/yr
  - μ_N = -1.17 ± 0.18 mas/yr





Modeling the Line-of-Sight Velocity Field

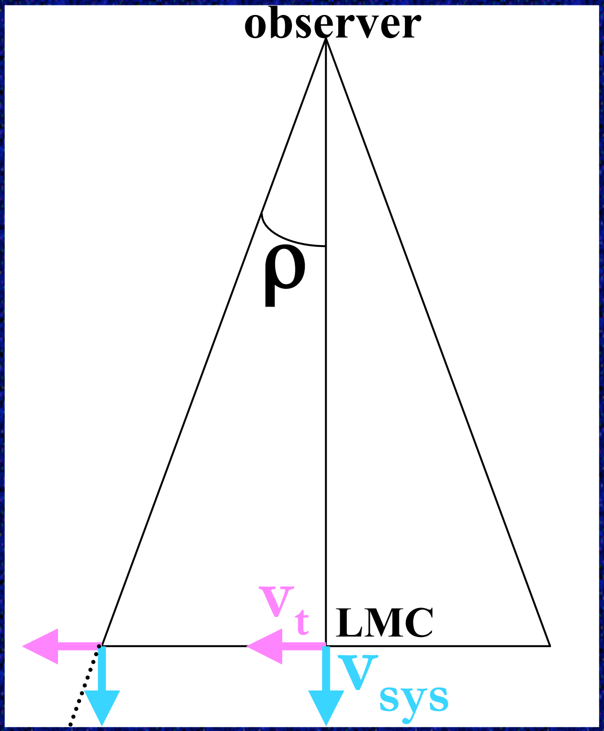
$v_{los}\,(\rho, PA) =$

$+\ f\,V(R)\ \sin i\ \cos\,(PA - \Theta)$

$+\ v_{sys}\cos\rho$

$+\ v_t\ \sin\rho\ \cos\,(PA - \Theta_t)$

$+\ D_0\,(di/dt)\ \sin\rho\ \sin\,(PA - \Theta)$



Previous studies have not properly take the full complexity of this equation into account.

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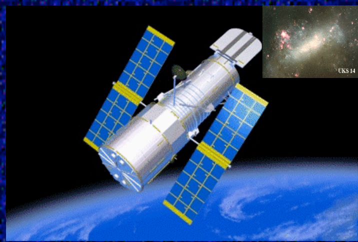
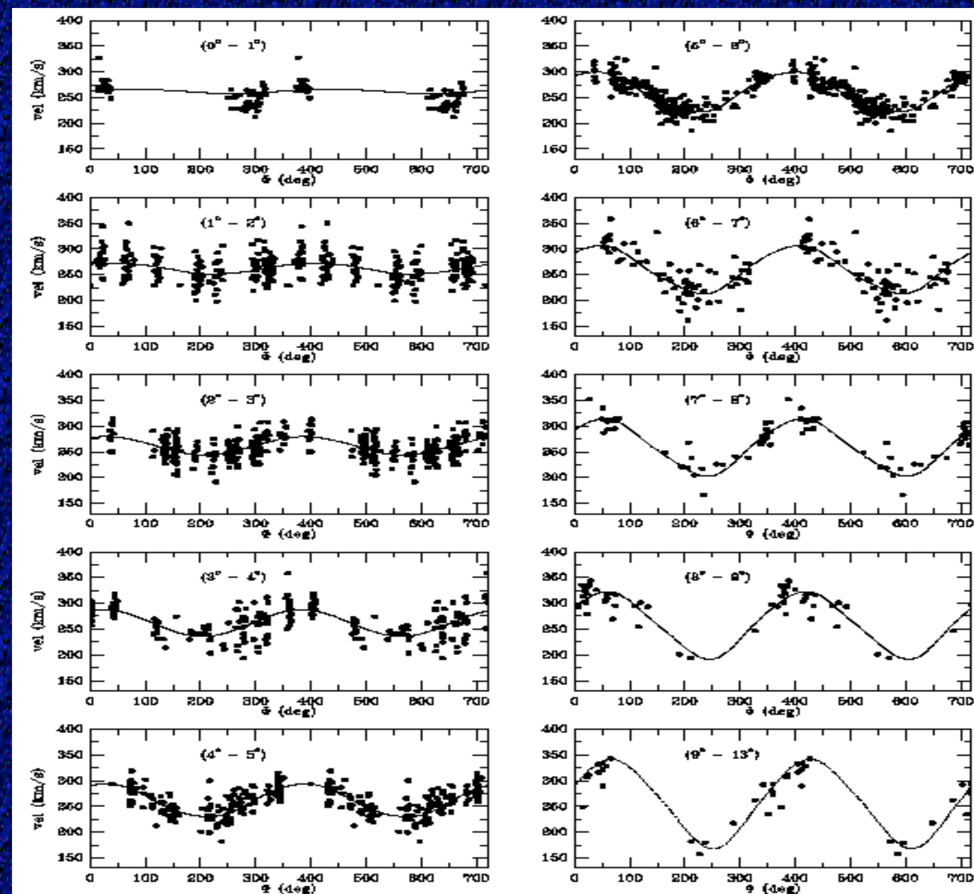


Fit to Carbon Star Data

- ✰ **vdM, Alves, Hardy, Suntzeff (2001)**

1041 Carbon stars:

- ✰ Kunkel et al. (1997)
- ✰ Hardy et al. (2002)



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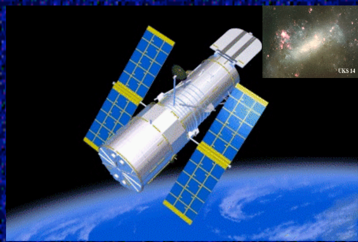
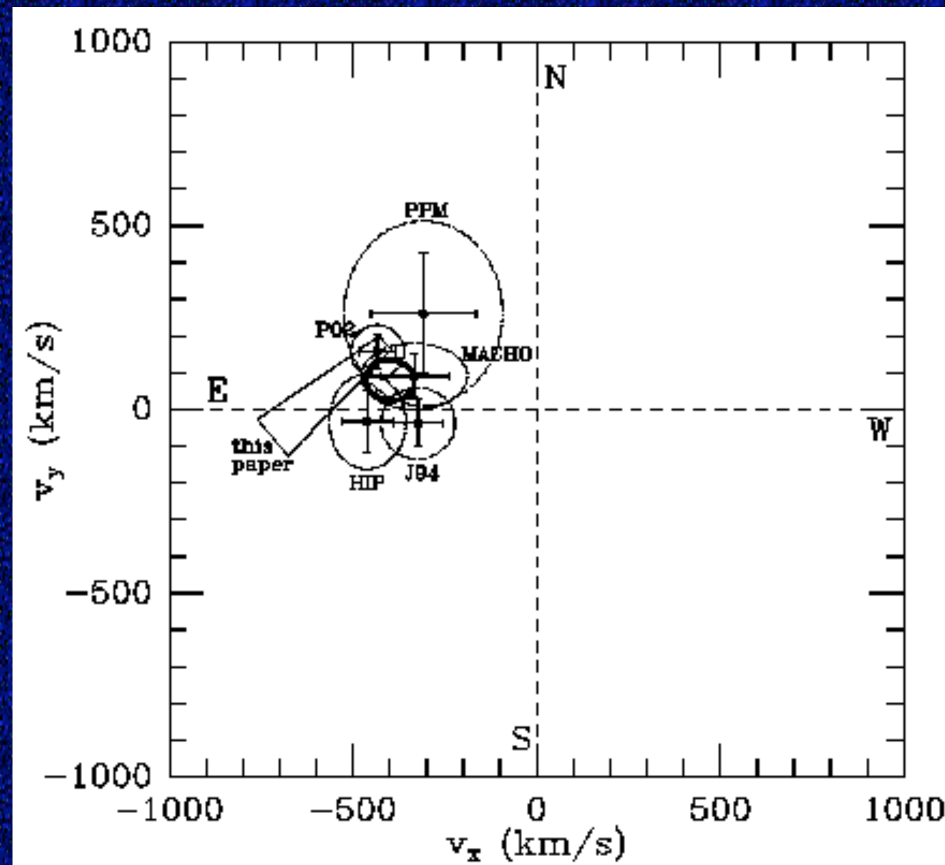


The LMC Transverse Velocity

- The line-of-sight velocity field allows a determination of the LMC transverse velocity, if one assumes:
  - m-M = 18.50
  - di/dt = 0
- ⇒ consistent with proper motion data



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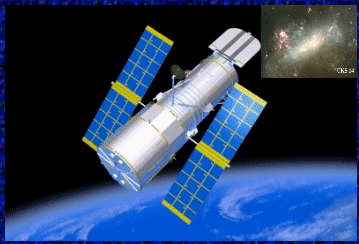
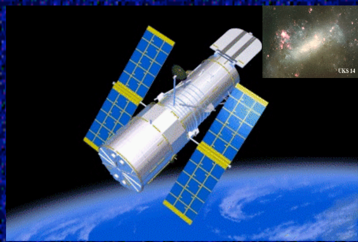
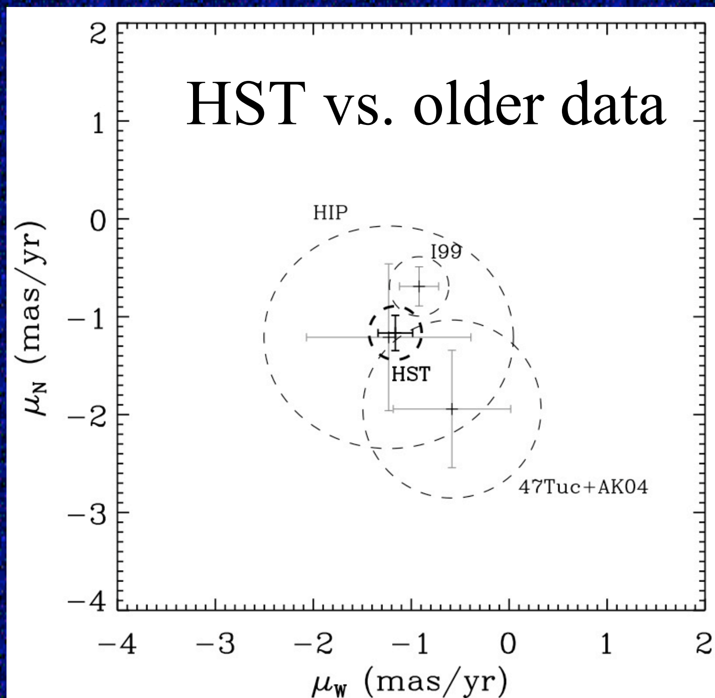


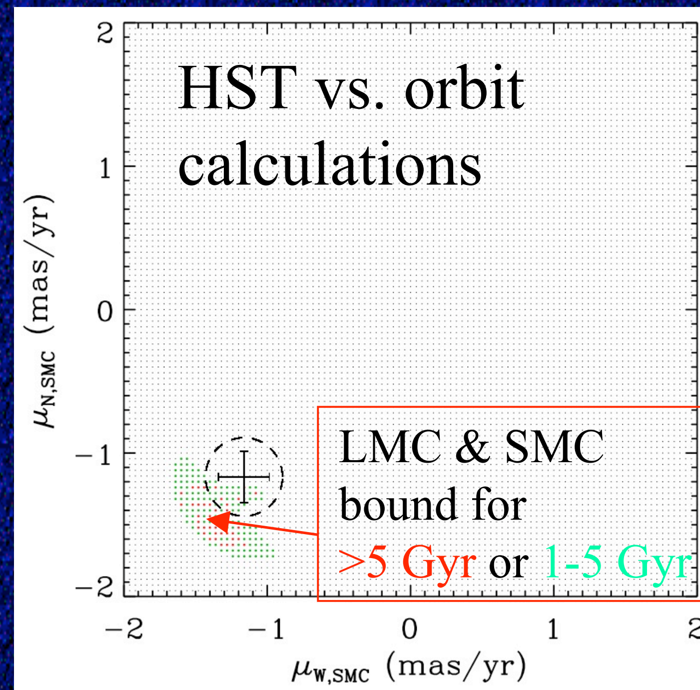
LMC: Thickness

- **LMC: V/ σ = 3.5 ± 0.9**
- **Compare:**
  - Milky Way thick disk: V/ σ = 3.9
  - Milky Way thin disk: V/ σ = 8.9
- **LMC disk is thicker than previously believed**
  - Consistent with predictions of Milky Way tidal influence
  - Microlensing predictions unaffected (depend on σ only)
  - Self-lensing still cannot account for all observed lensing events (Mancini et al. 2004)

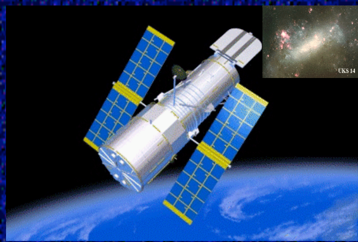


SMC Proper Motion





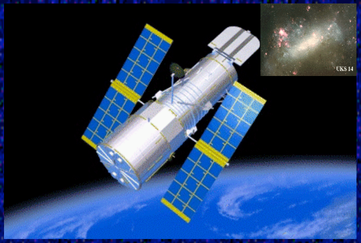
- ☆ **Bound LMC/SMC orbits exist with the 1-sigma error ellipse**



Magellanic Clouds
Orbit Properties

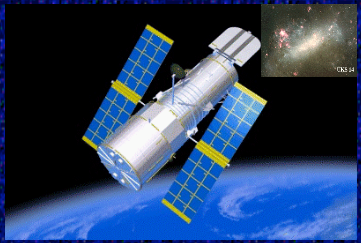
- **Previous work**
  - Assume logarithmic potential
  - Estimate proper motion from Magellanic Stream models
    - Gardiner & Noguchi (1996): v_{tan} = 287 km/s
    - $v_{rad} << v_{tan}$ ⇒ Magellanic Clouds just past pericenter

  } Period ~2 Gyr ⇒ **multiple passages**
- **New insights**
  - Better cosmological understanding of dark halo profiles
  - Clouds move significantly faster than previously argued
    - HST: v_{tan} = 367 ± 18 km/s



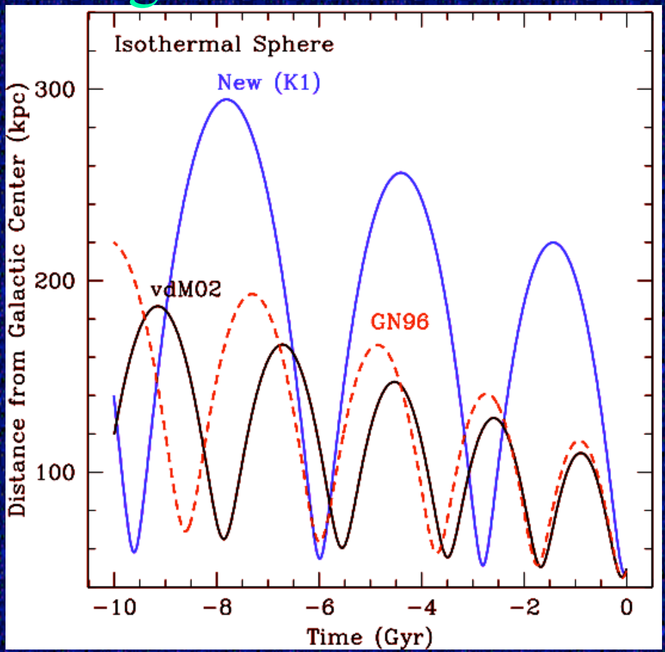
New Exploration of Orbits
Besla et al. (2007)

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

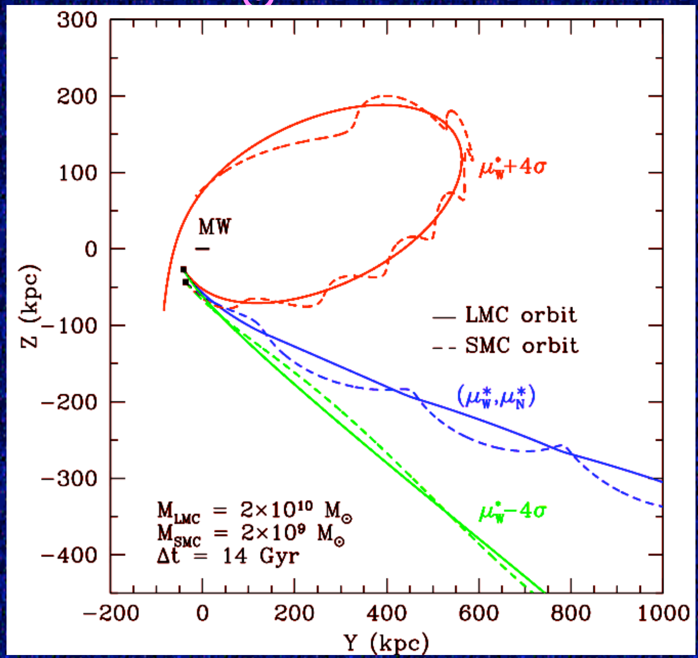


Dependence on Milky Way Potential

Logarithmic Potential



10^{12} $M_{\odot}$ ΛCMD Halo



- **New Proper Motion**
  - Larger period
  - Larger apocenter
- **~ Escape Velocity**
  - Parabolic orbit, First Passage
  - or: More Massive ~2 x 10^{12} $M_{\odot}$ DH

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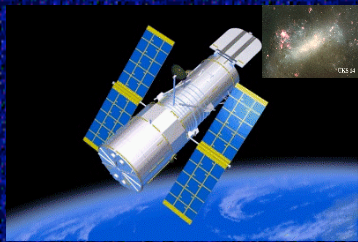


Likelihood of a First Passage Scenario

van den Bergh 2006

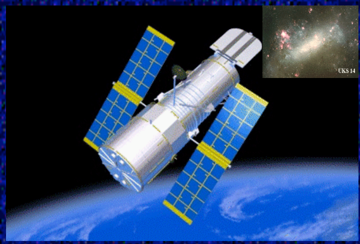
MW Satellites

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

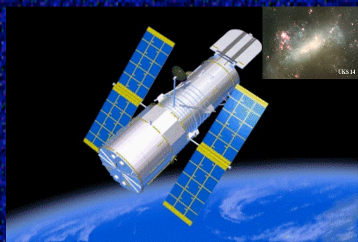
Name	Type	D_{M31} (kpc)
B327	GC	3
M32	E2,N	6
Hux C1	GC	13
Hux C3	GC	14
G1	GC	35
Hux C2	GC	37
NGC 205	E5pec	40
And IX	dSph	42
And I	dSph	59
And III	dSph	76
And V	dSph	110
And X	dSph	112
NGC 147	Sph	145
And II	dSph	185
NGC 185	Sph	190
M33	Sc	208
And VII	dSph	219
IC 10	Ir	260
And VI	dSph	269
Pisces	dIr/Sph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

- **Local Group Demographics**
  - All Irr galaxies (satellites with high gas fractions) are located at large Galactocentric radii, except for the Magellanic Clouds
- **Theory**
  - Bullock et al. (2007, in prep.): 70% of halos have accreted an LMC-type galaxy in the past 5 Gyr
  - accreted = first falls within a ~300 kpc virial radius.

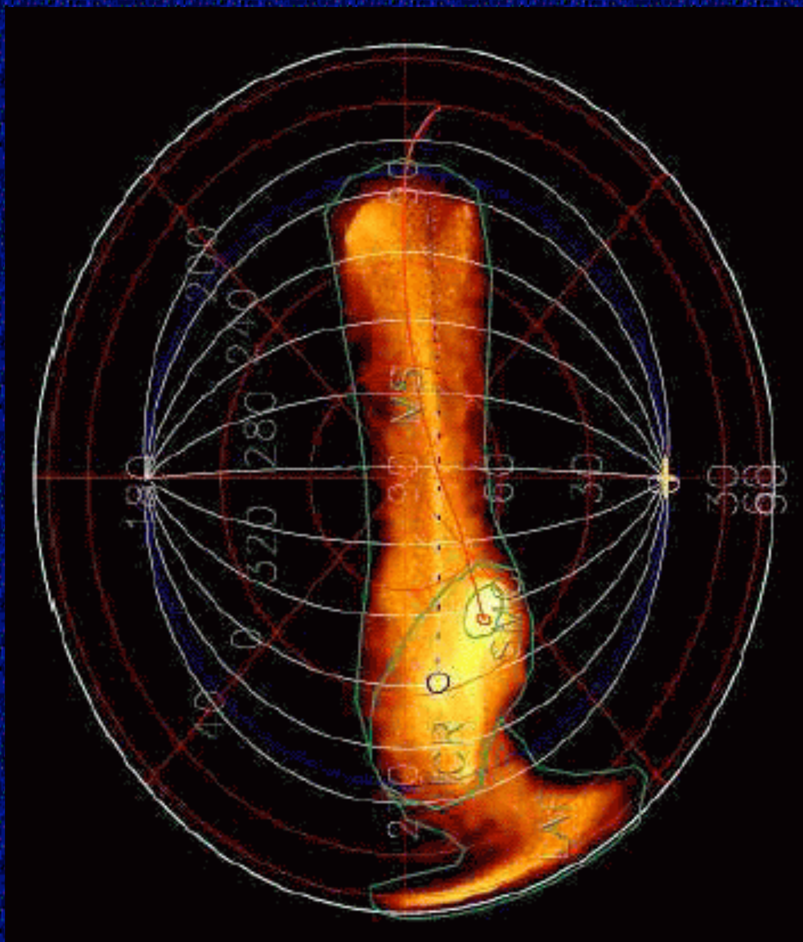


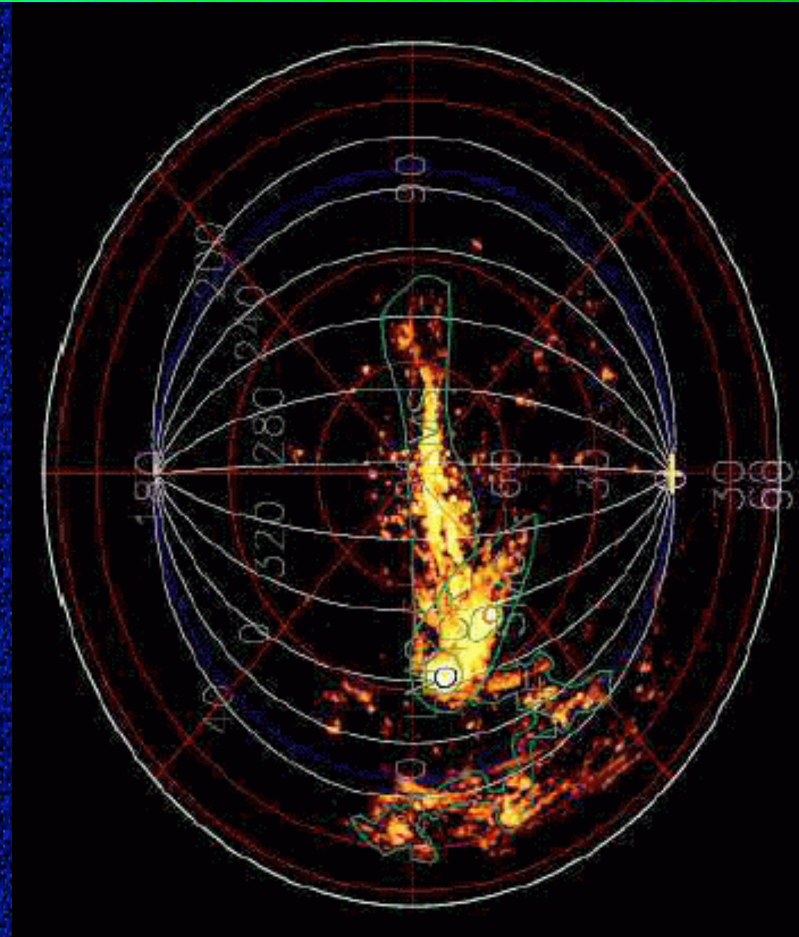
Magellanic Stream: Models

- ✰ **Many plausible models constructed over the years**
  - ✰ Multiple passages almost always assumed
- ✰ **Little agreement on dominant physical process**
  - ✰ Tidal stripping
    recent example: Connors et al. (2005)
    - ✰ Stream formed ~1.5 Gyr ago from SMC gas during the last close LMC-SMC encounter
  - ✰ Ram-pressure stripping
    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!)



Magellanic Stream:
Tidal Model





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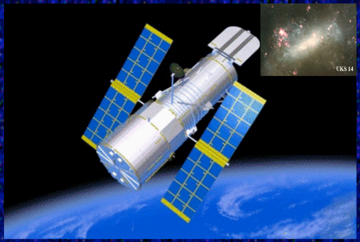
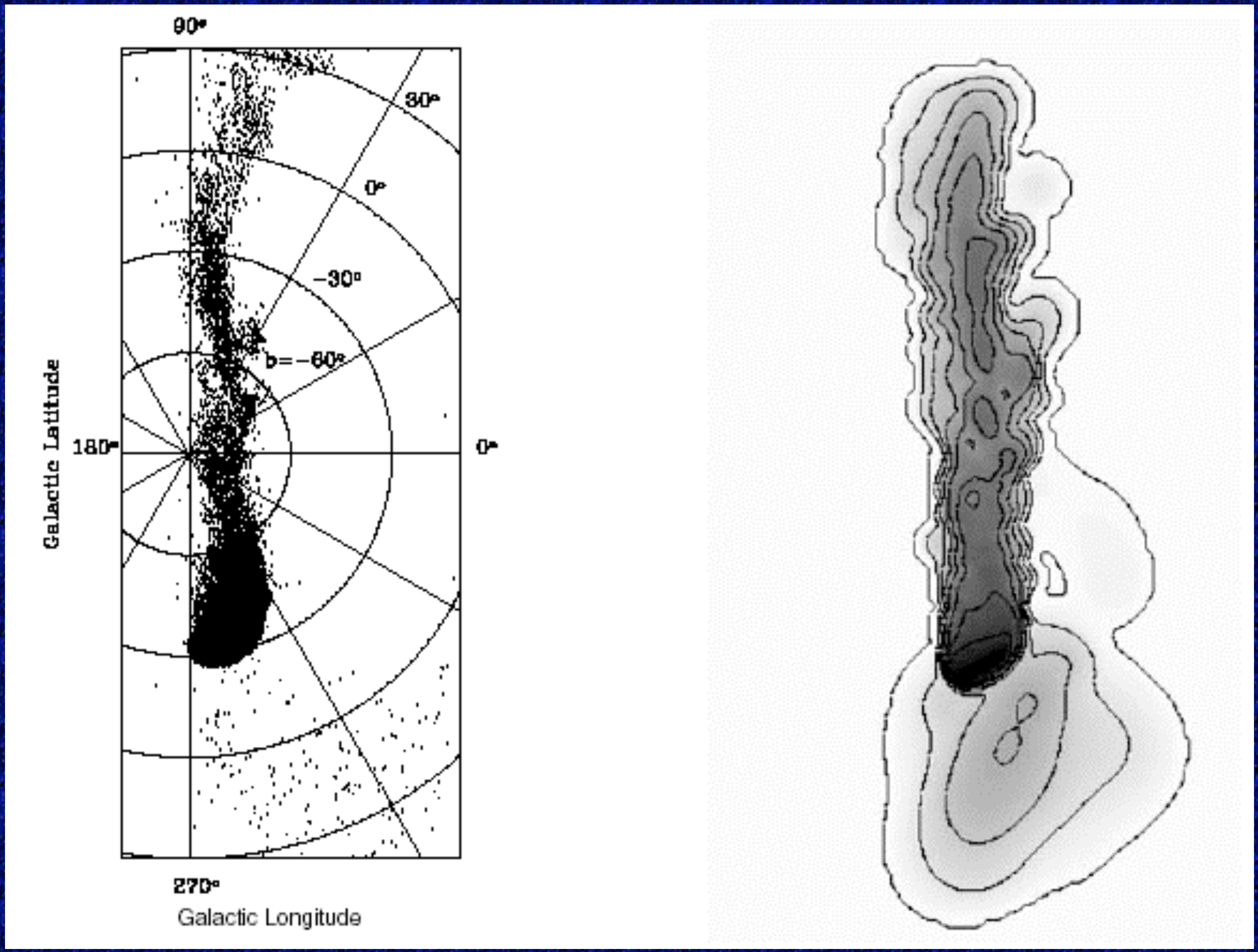


Magellanic Stream:
Ram-Pressure Model



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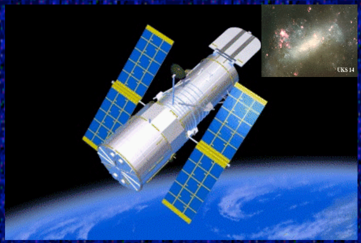
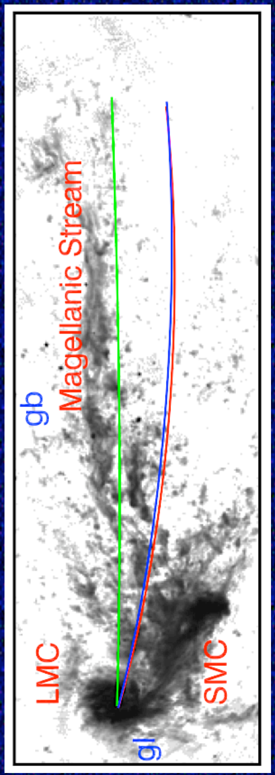
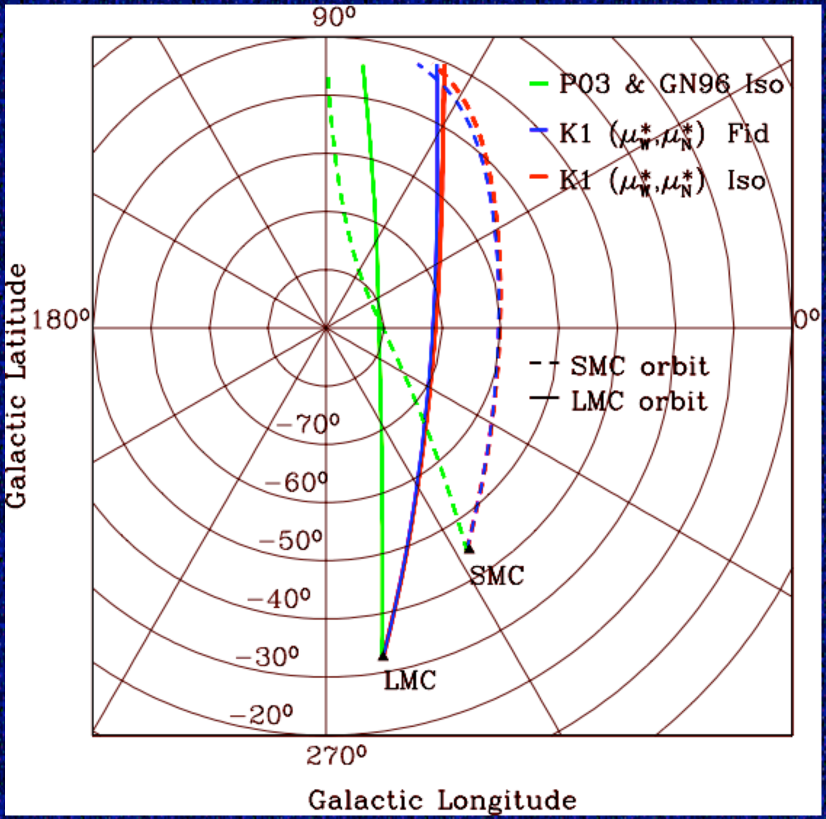
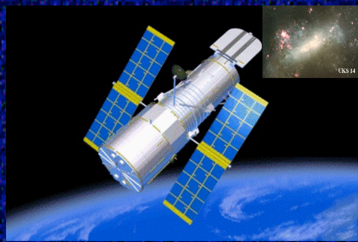


Comparison of Orbit to Magellanic Stream Location



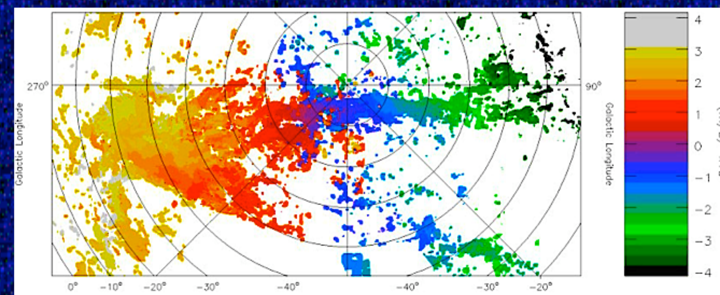


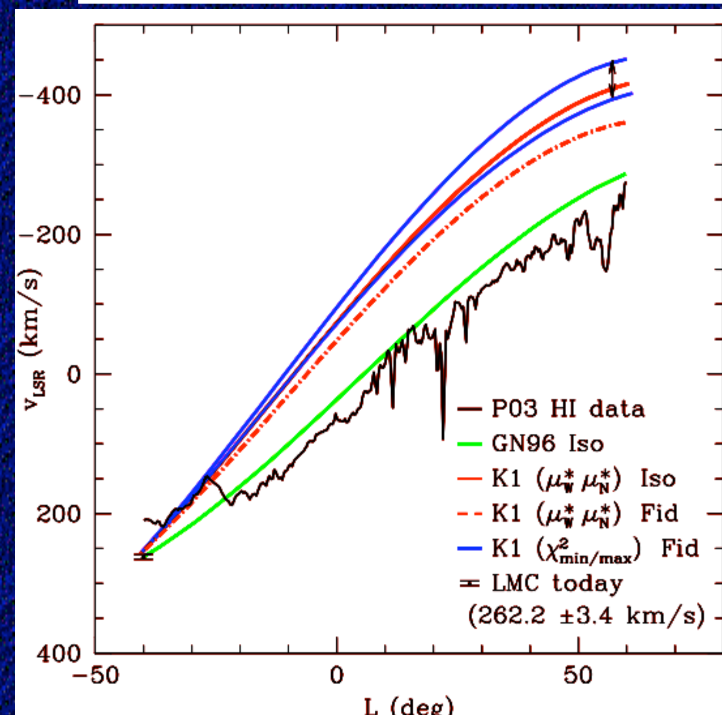
- **Newly calculated orbits are not co-located in the sky with the Magellanic Stream**
- **Independent of**
  - Dark Halo profile
  - Dark Halo axial ratio
  - PM West-component
- **Driven by PM North-component**
  - HST result identical to average of ground-based data
  - many-sigma different from Gardiner & Naguchi (1996)



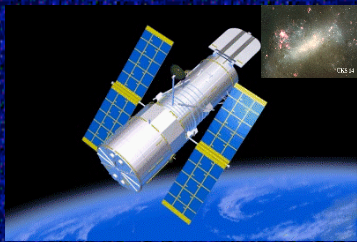
HI velocity gradient comparison

- V_{LSR} gradient along orbit not the same as HI gradient along Stream
- The extent to which this is expected depends on the physical processes that form the Stream





Roeland van der Marel - Space Telescope Science Institute
marel@stsci.edu http://www.stsci.edu/~marel



Conclusions

- Our understanding of the **Magellanic Clouds,** their structure, and their interaction with the **Milky Way** is improving continuously
- **Proper Motions & Orbit Calculations**
  - Magellanic Clouds may be on their first passage about the Milky Way and/or
  - Milky Way may be more massive than typically believed
- **Strong motivation to revisit existing Magellanic Stream models**