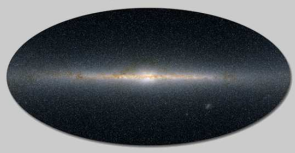


Warps and Wiggles

Martin D. Weinberg
UMass Astronomy
weinberg@astro.umass.edu

September 30, 2008



Motivation

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Outer Spiral arms

Inner gas

Warp excitation

Dynamics of warps

Satellites and
substructure

Movies

Halo wake

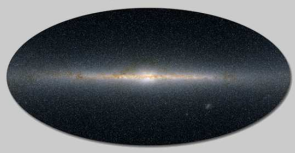
1st passage?

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Implications

- History of a galaxy is critical in determining its present state
 - ◆ Satellite decay and disruption
 - ◆ Bombardment by substructure
 - ◆ “Cold-mode” streams, “hot-mode” infall, fountains . . .
- Outer Galaxy sensitive to the transition between the baryonic- and dark-matter-domination
 - ◆ Properties of the dark matter halo
 - ◆ MOND (?)



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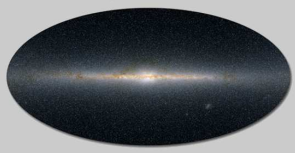
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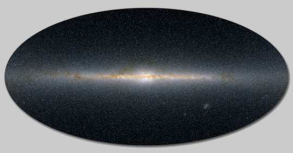
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⇒ Connection to the neutral gas layer



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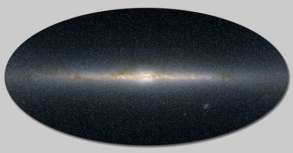
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 - ◆ HI asymmetries
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 - ◆ Inner MW offsets, scale height?
- Warping as an example
 - ◆ How warps work
 - ◆ LMC: bound or unbound?
 - ◆ Gas response (New while at KITP)
- Implications and next steps



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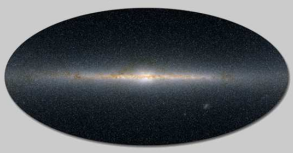
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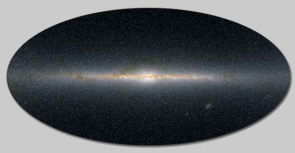
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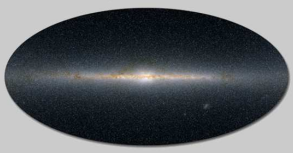
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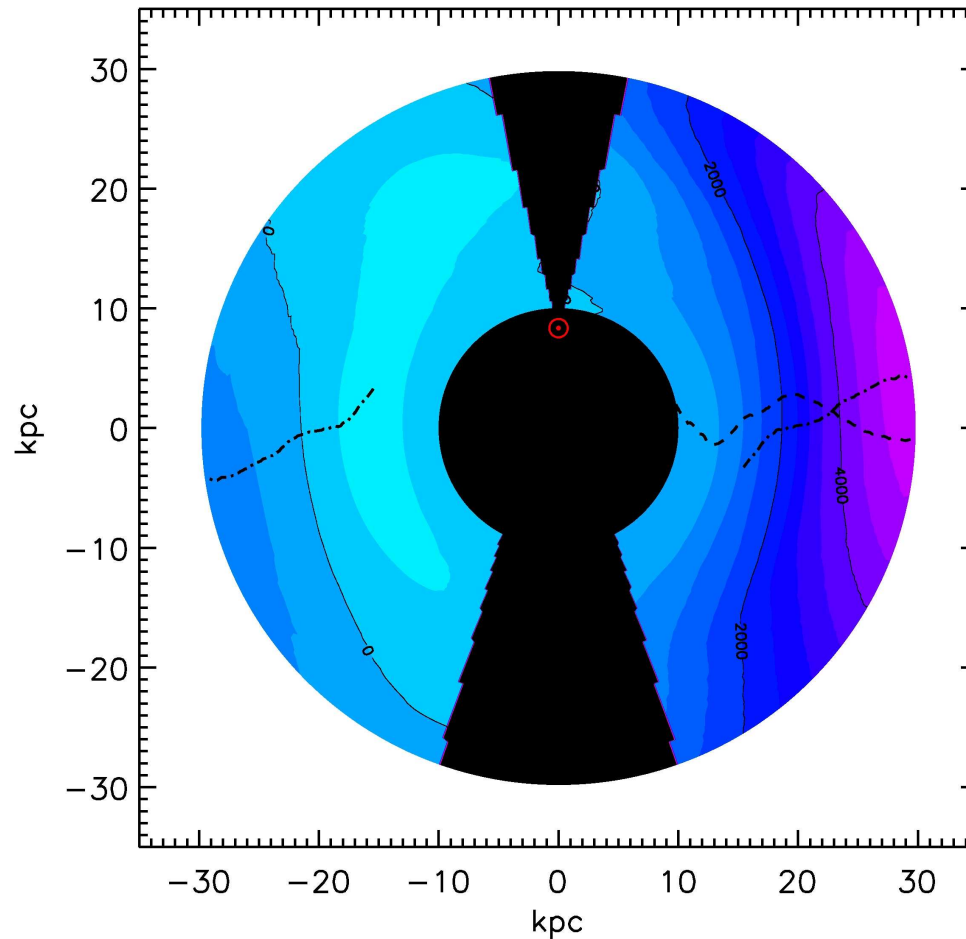
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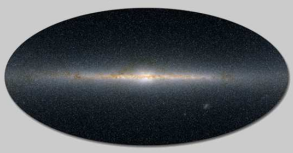
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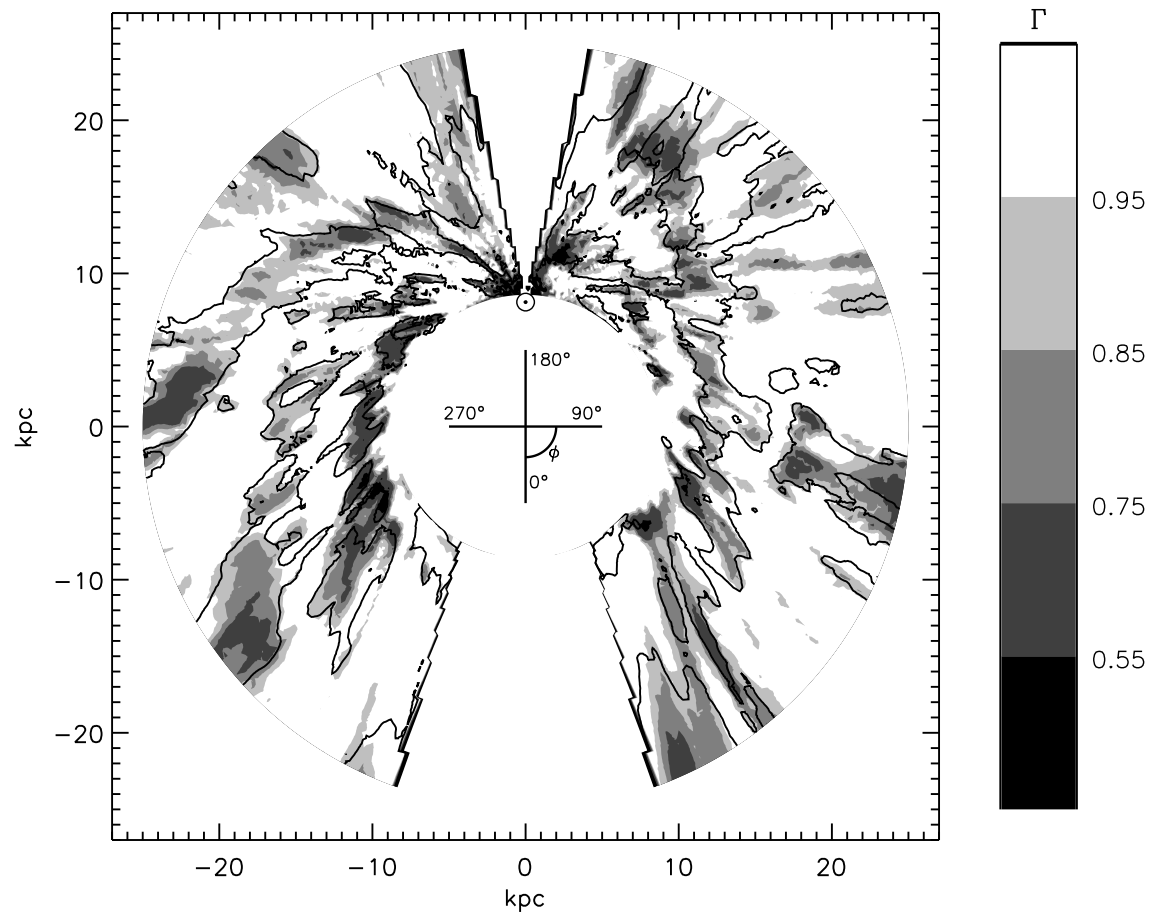
Warp height (color coded), Levine et al. 2006

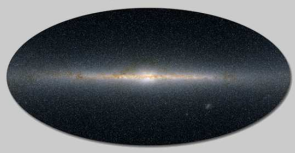


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■ HI from Levine et al. 2006

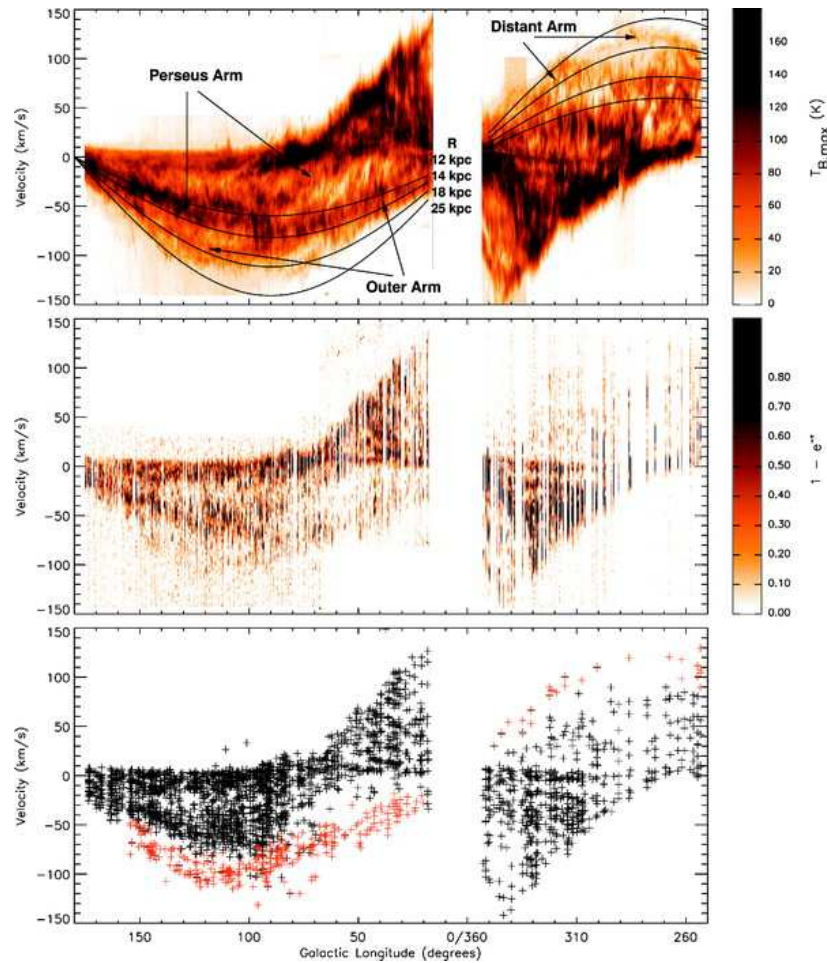


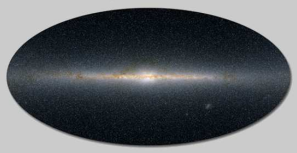


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■ Also by HI absorption from Strasser et al. 2007

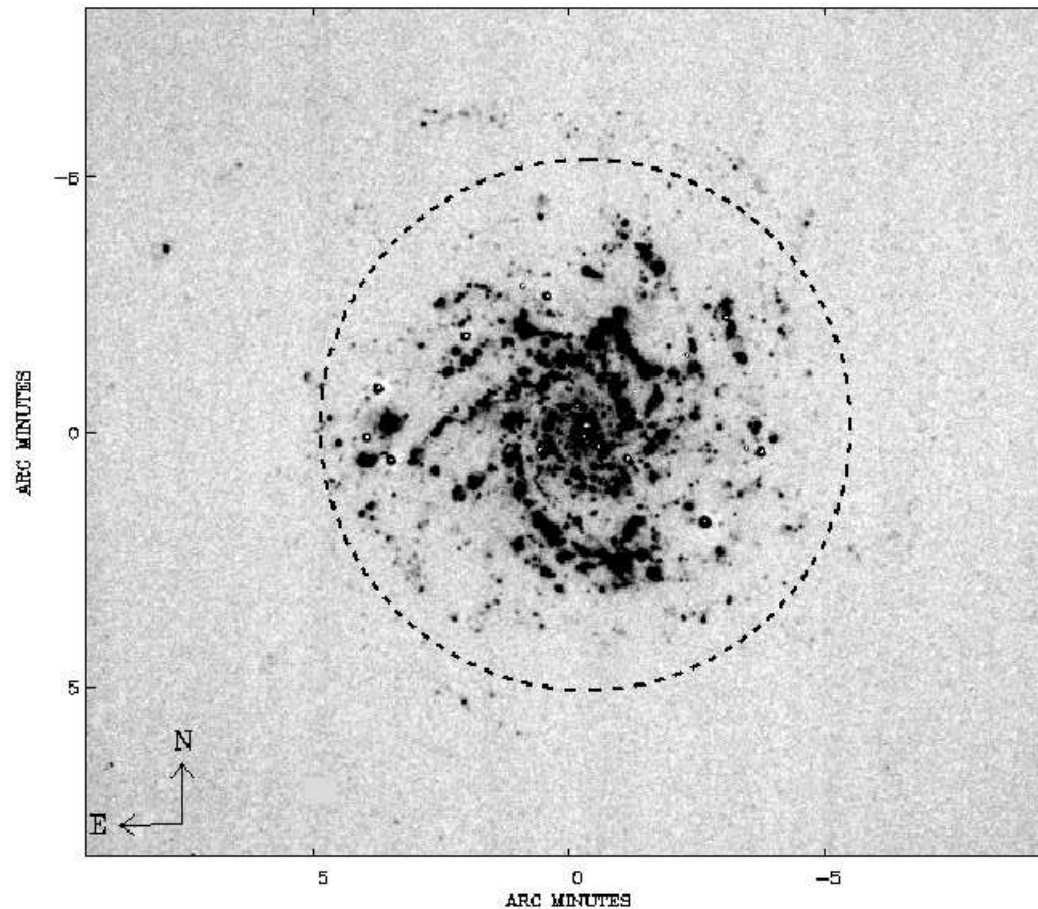


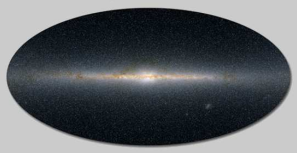


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- $H\alpha + [NII]$ continuum-subtracted image of NGC 628 from Ferguson, Wyse & Gallagher 1998

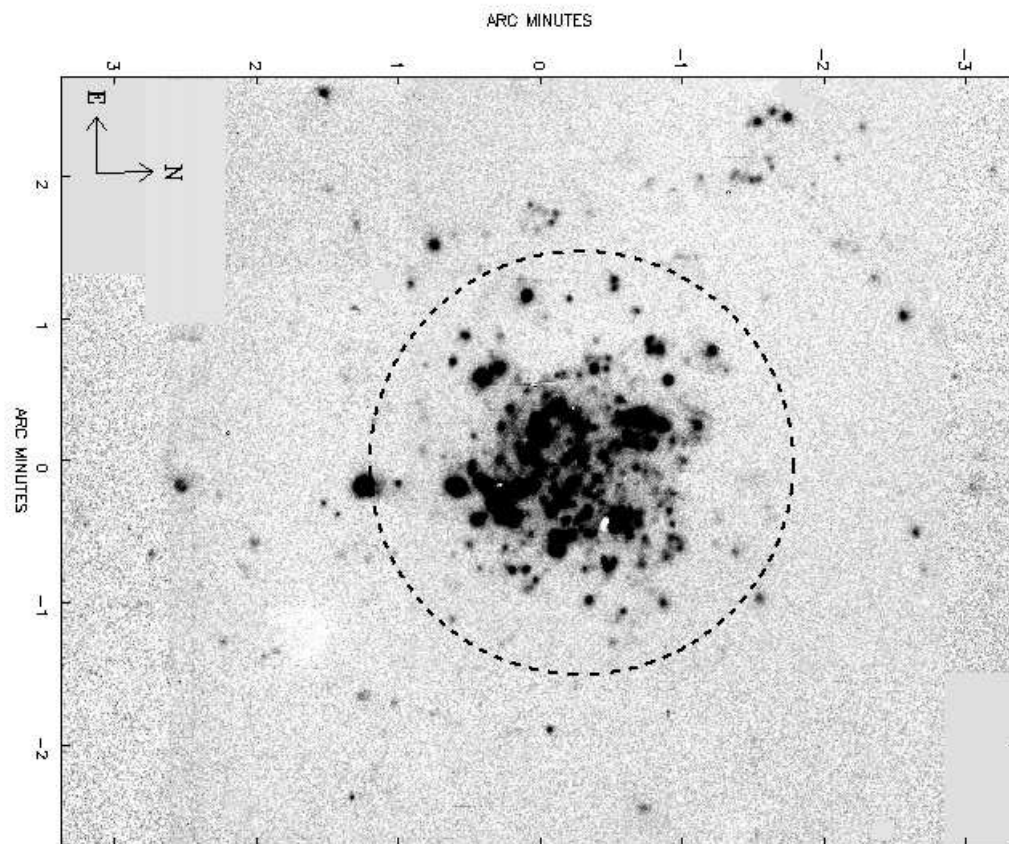


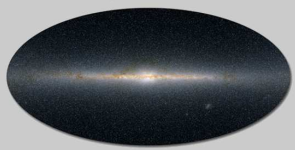


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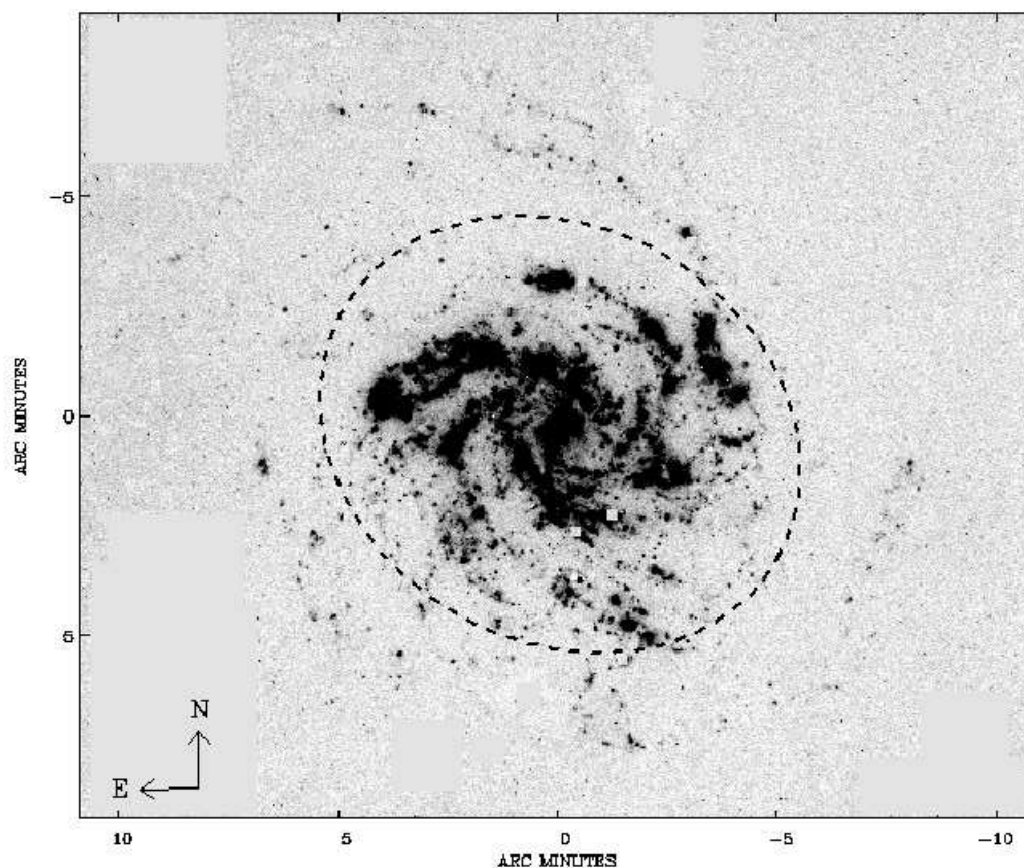


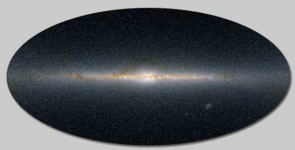


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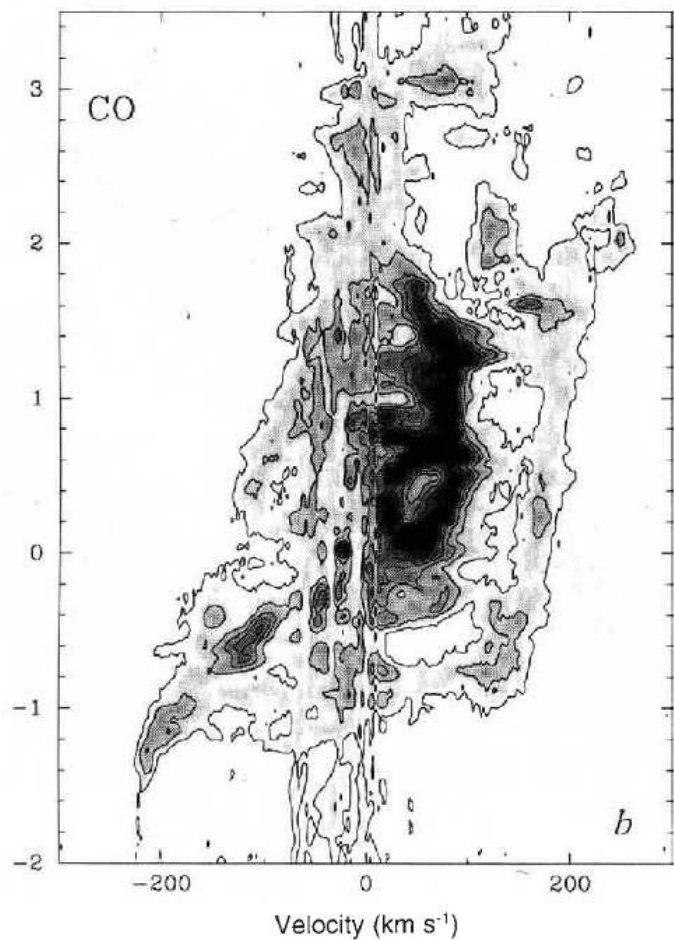
Halo wake

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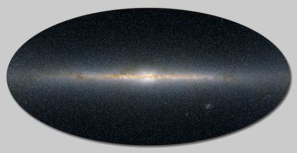
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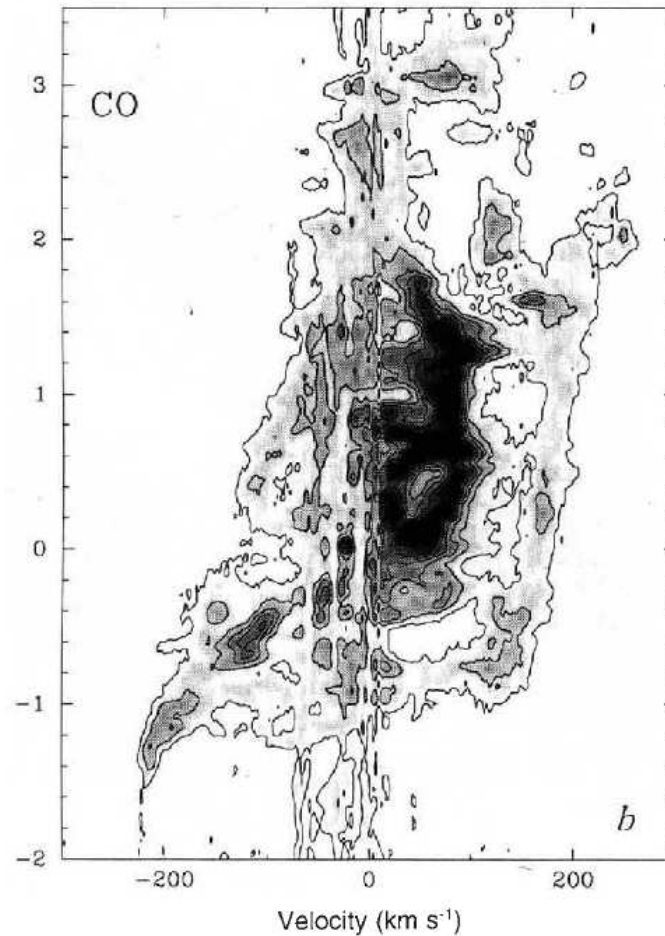


Gas at the Milky Way center,
Blitz et al. 1993



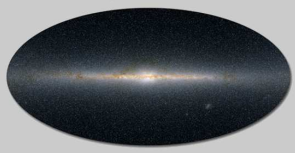
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≈ 100 pc offset!

Gas at the Milky Way center,
Blitz et al. 1993



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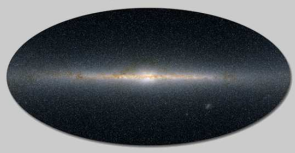
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Case study: warp... proposed theories:

1. Modes
2. Response to triaxial halo
3. Response to asymmetric disk accretion (cold streams)
4. Response to satellites & bombardment



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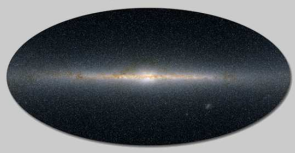
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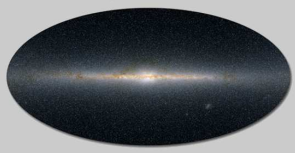
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Case study: warp... proposed theories:

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 2. Response to triaxial halo
 3. Response to asymmetric disk accretion (cold streams)
 4. Response to satellites & bombardment ←this talk
- ◇ All of the above???

If you hit a bell it rings, it doesn't matter how you hit it ...



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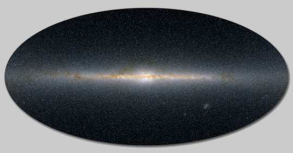
1st passage?

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Implications

- Any large-scale feature is a collective effect
- Collective response has discrete and continuous parts
 - ◆ Discrete parts are self-similar and may damp (modes)
 - ◆ Continuous parts mix (like wave packets)



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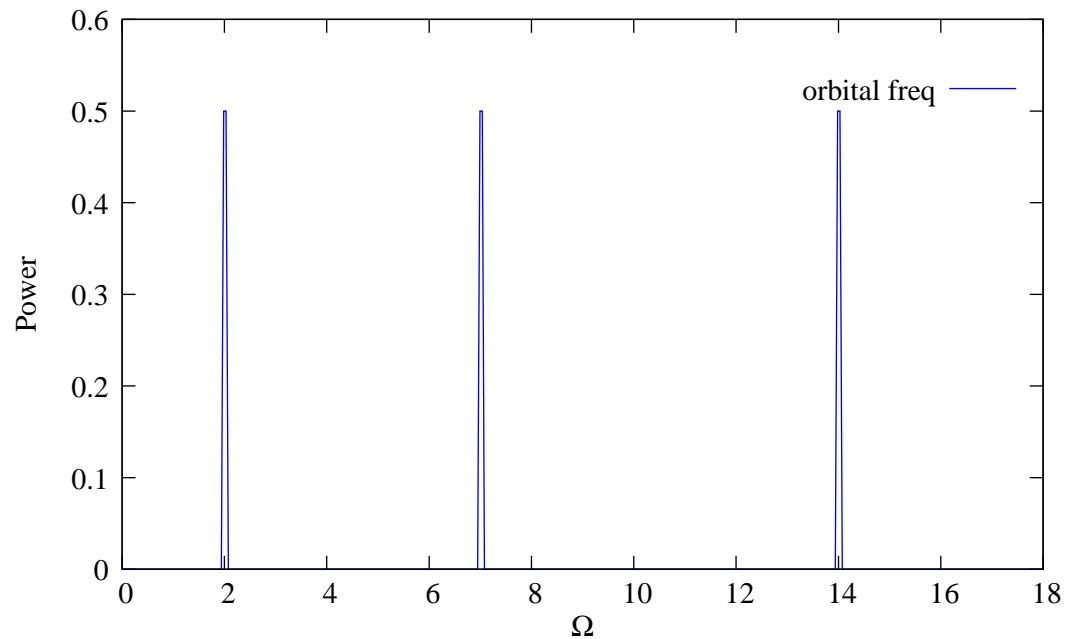
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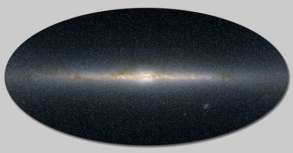
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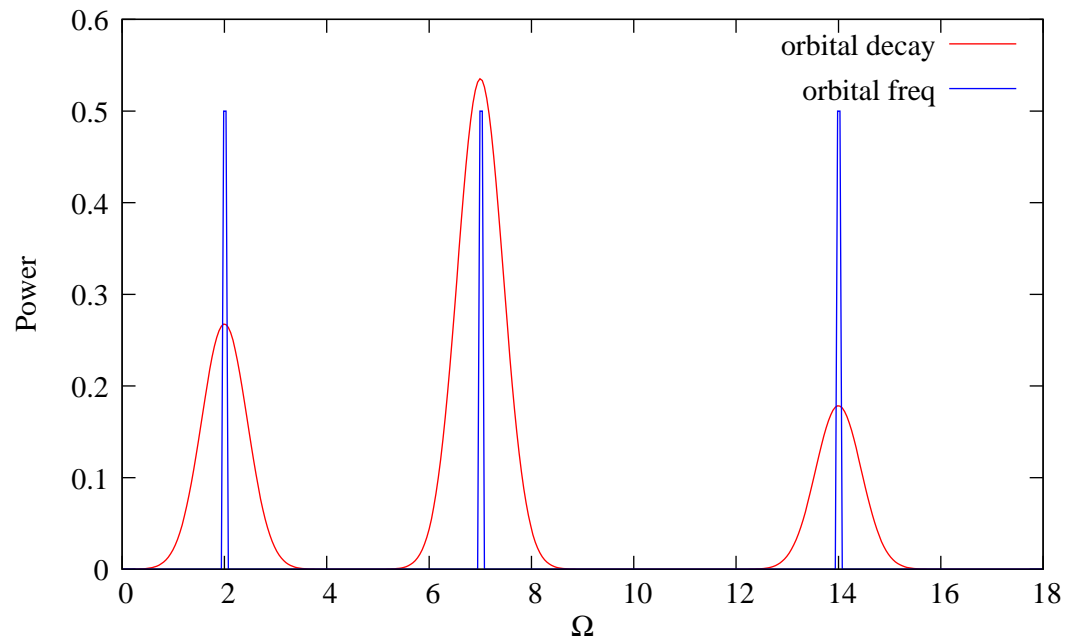


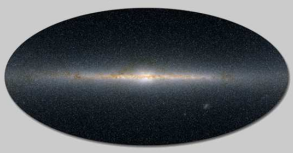


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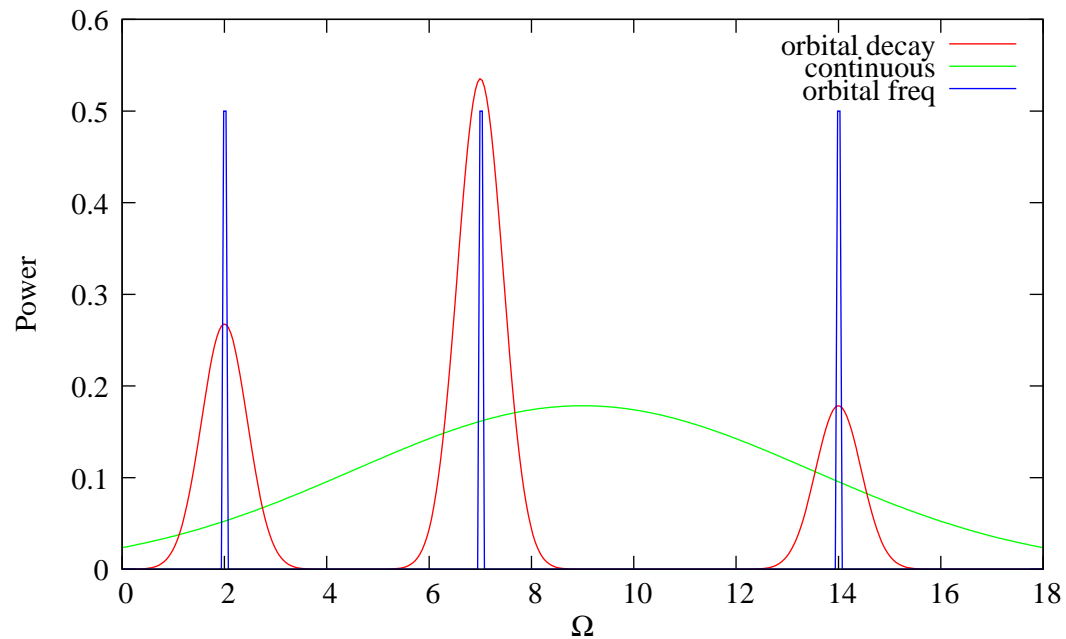


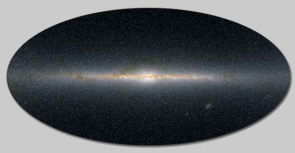


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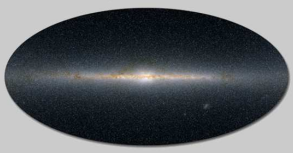
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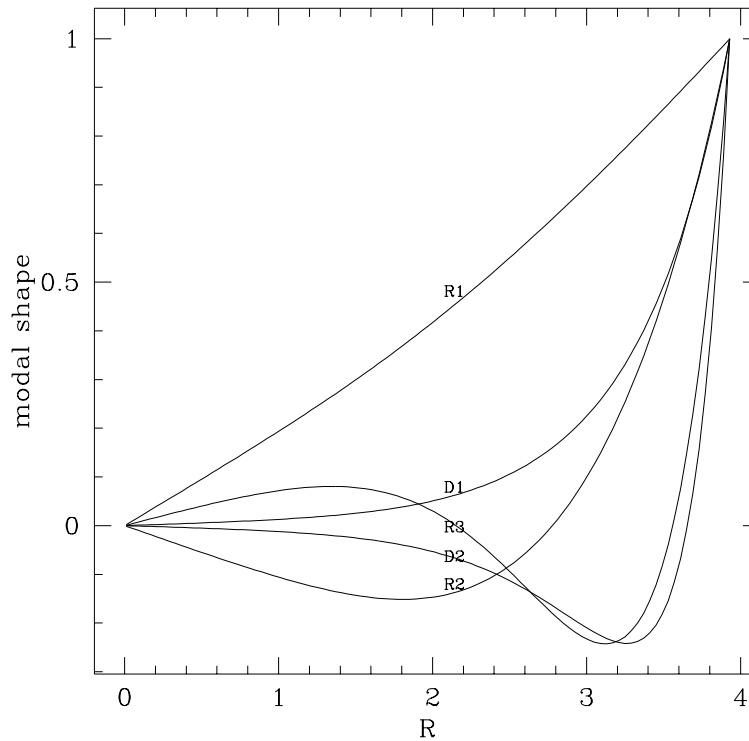
- Any large-scale feature is a collective effect
- Collective response has discrete and continuous parts
 - ◆ Discrete parts are self-similar and may damp (modes)
 - ◆ Continuous parts mix (like wave packets)
- We need to think about natural structure (e.g. modes)!
 - ◆ Important for ALL warp theories
 - ◆ More generally: all time-dependent interactions



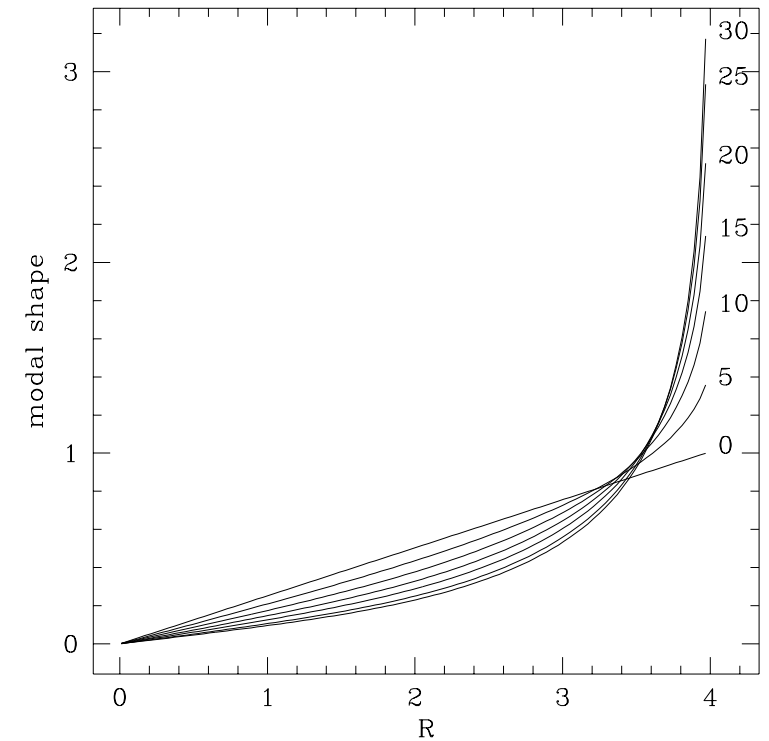
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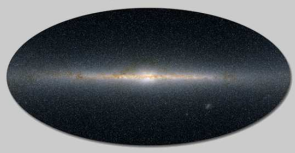
Example: $m = 1$ bending mode, thin disk



Halo-embedded disk



Tipping mode with halo mass



Satellites and substructure

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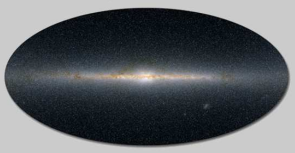
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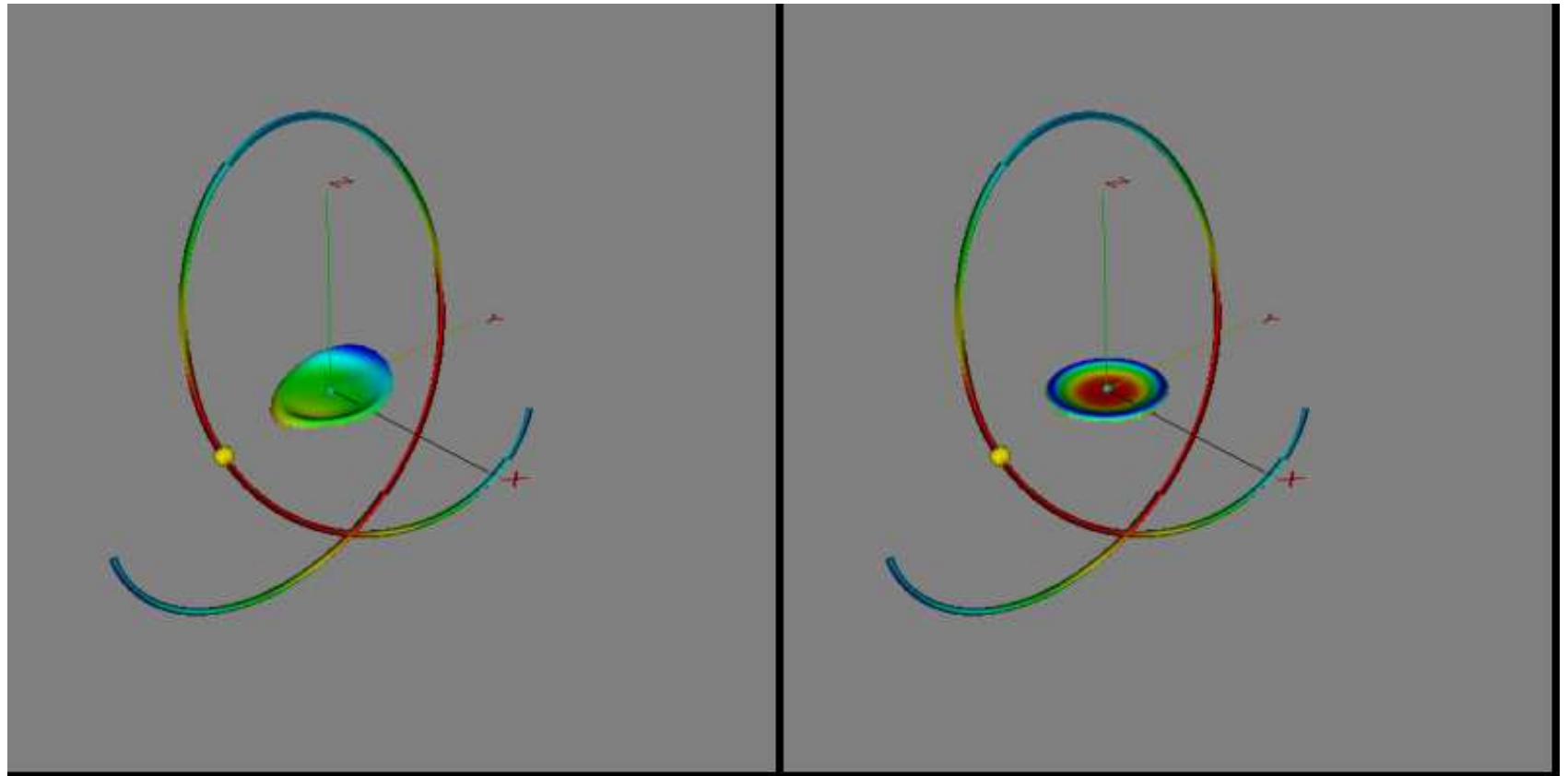
Implications

- Satellite (Magellanic Clouds) distort
 - ◆ the halo by exciting wakes
 - ◆ the disk directly by the tidal force
- The halo wake distorts the disk
- Halo wake close to disk \Rightarrow large effect!
- Perturbation theory (struggle for simulations)
 - ◆ “Matrix mechanics” (e.g. Weinberg 1990s)
 - ◆ Hunter-Toomre 2-d bending (1969)

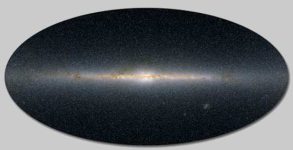


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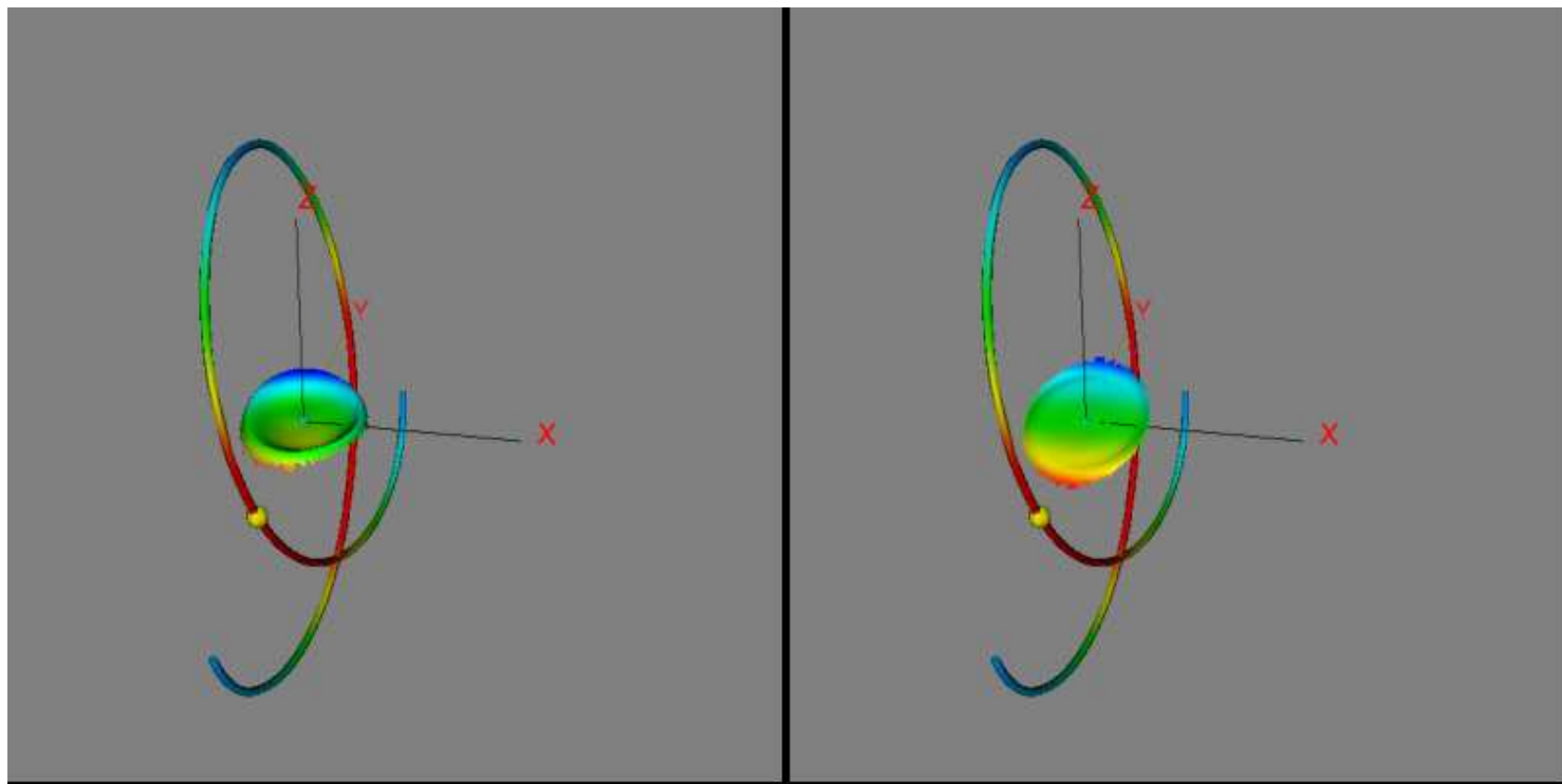


Total (left) and $m = 0$ (right)

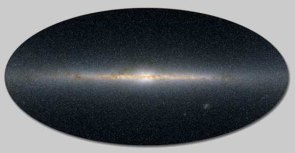


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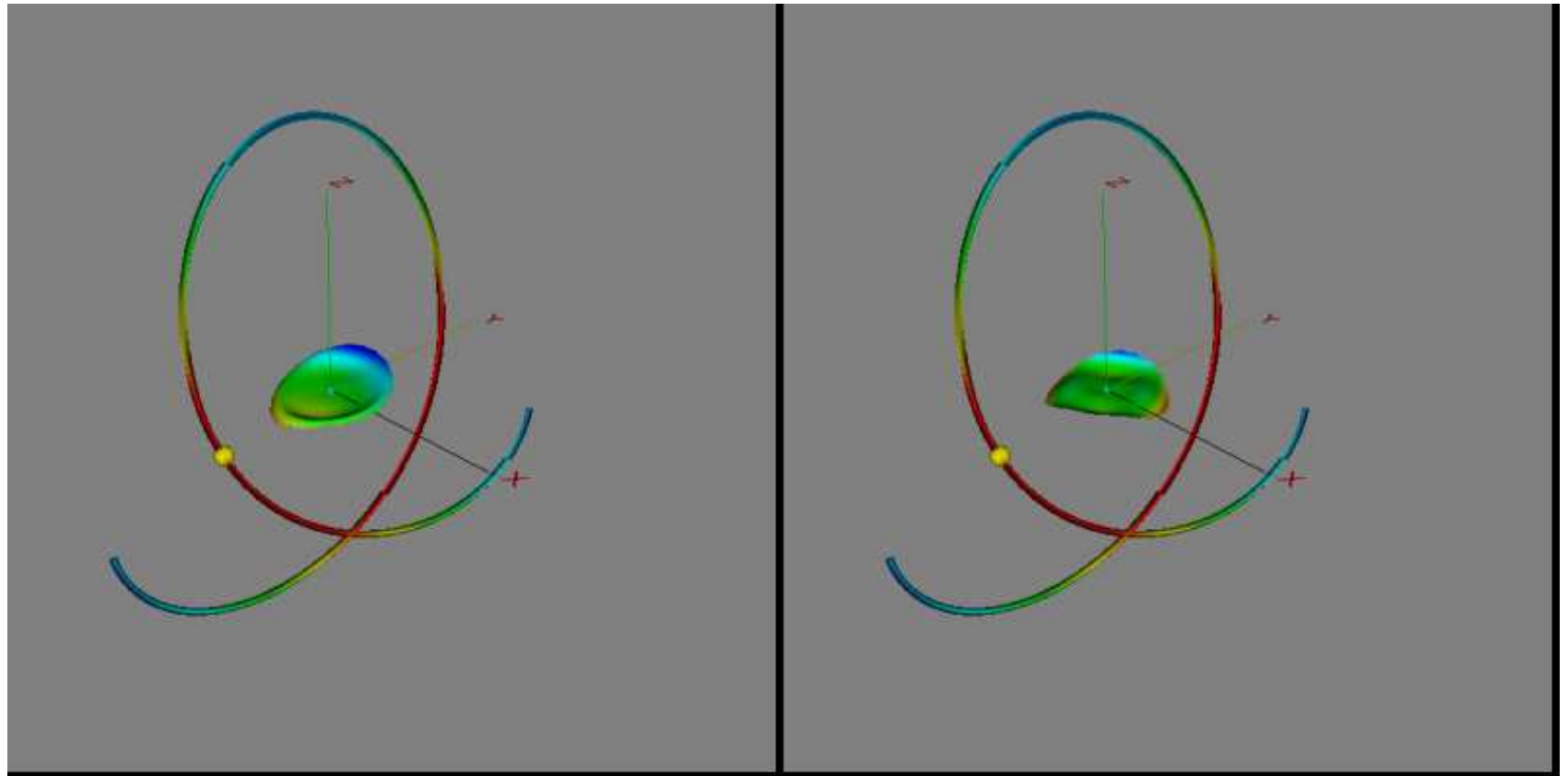


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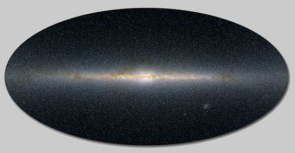


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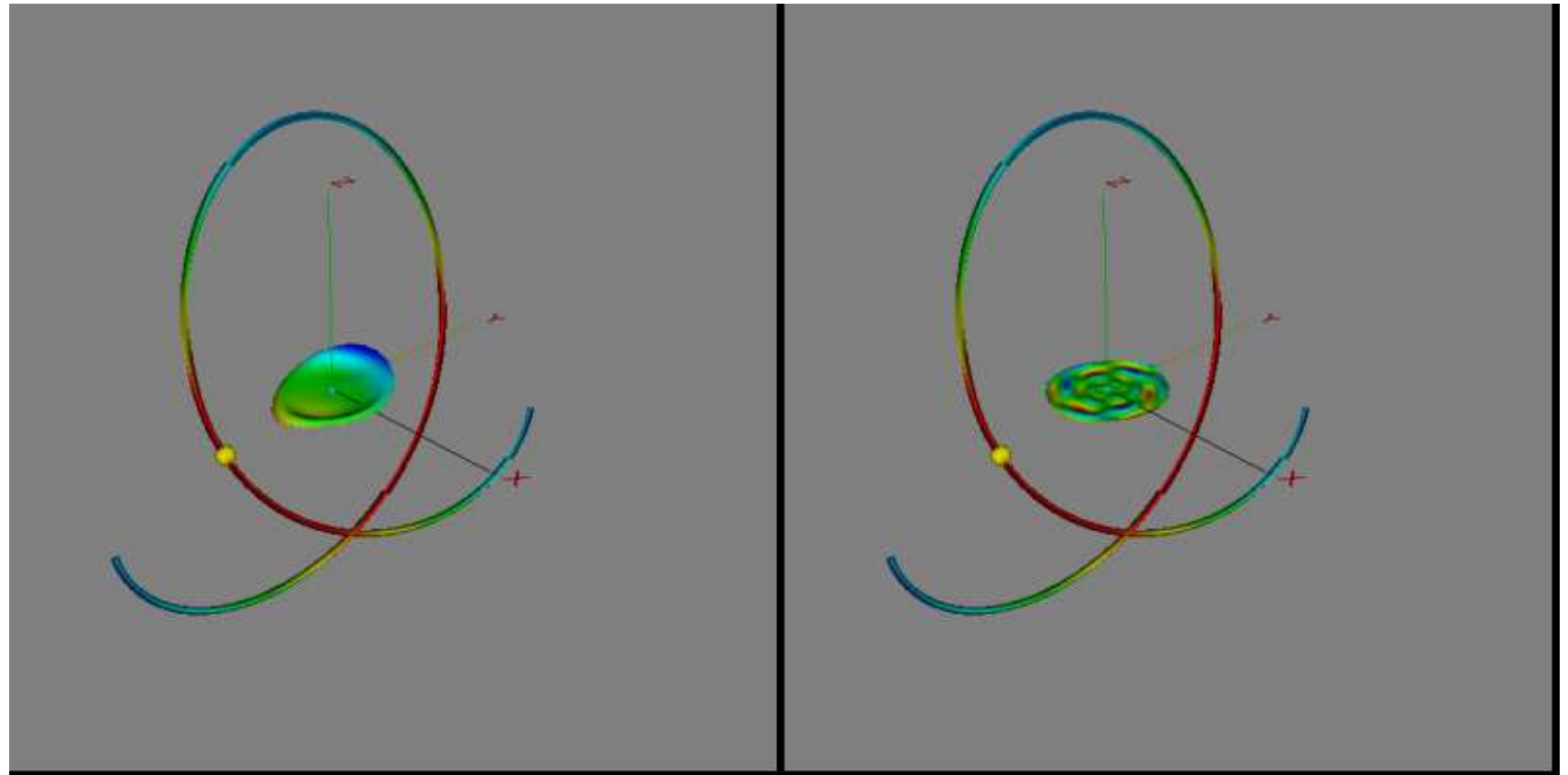


Total (left) and $m = 2$ (right)

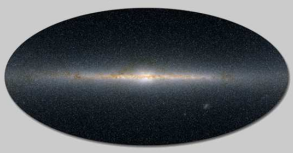


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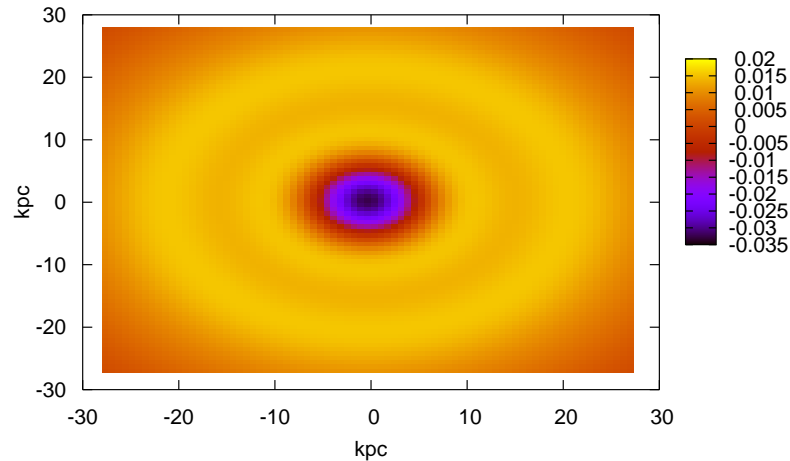


Total (left) and $m = 3$ (right)

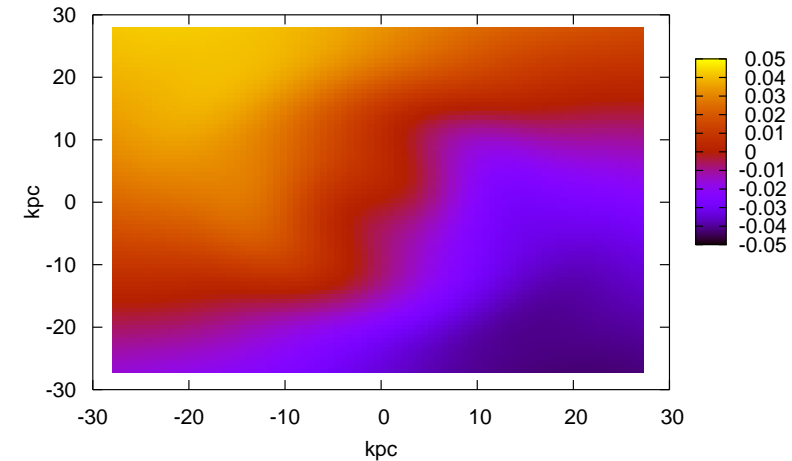


Halo wake

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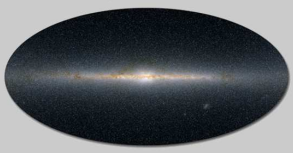


$m = 0$ vertical force from halo wake at disk plane



$m = 1$ vertical force from halo wake at disk plane

- Warp is shifted by π/m from force symmetry axis ($m > 0$)
- Will/can slosh inner and outer galaxy in opposite directions



Halo wake

Motivation

Plan

The Milky Way Warp

Outer Spiral arms

Inner gas

Warp excitation

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Movies

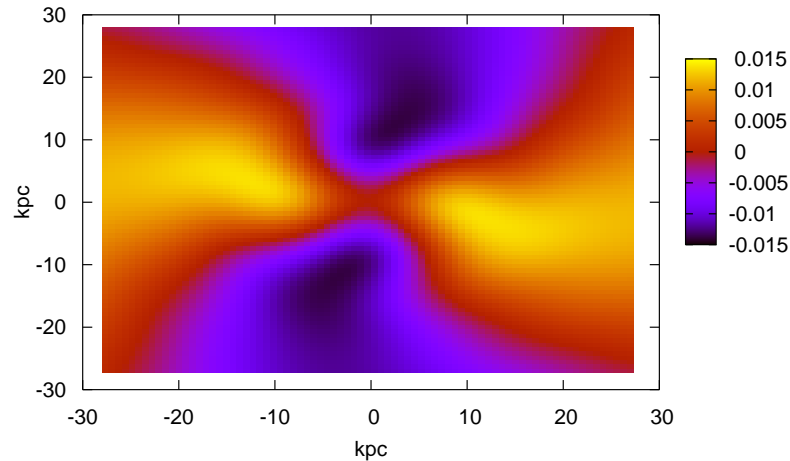
Halo wake

1st passage?

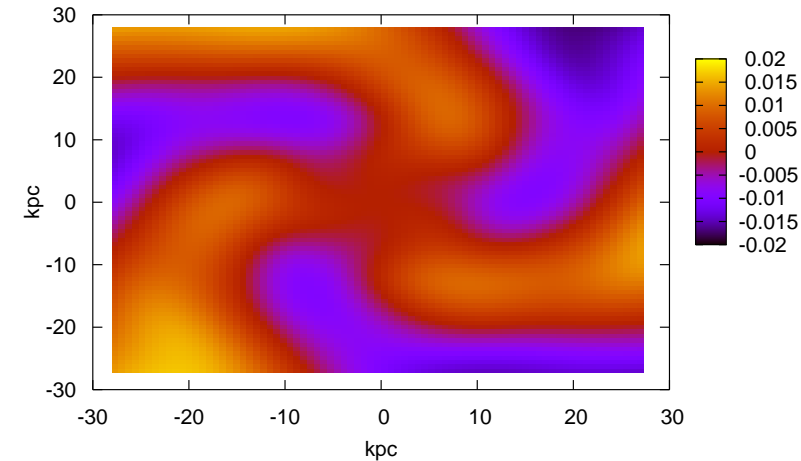
Neutral gas

DSMC simulation

Implications

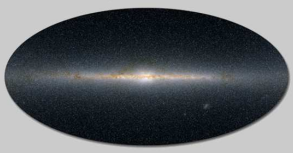


$m = 2$ vertical force from halo wake at disk plane



$m = 3$ vertical force from halo wake at disk plane

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Halo wake

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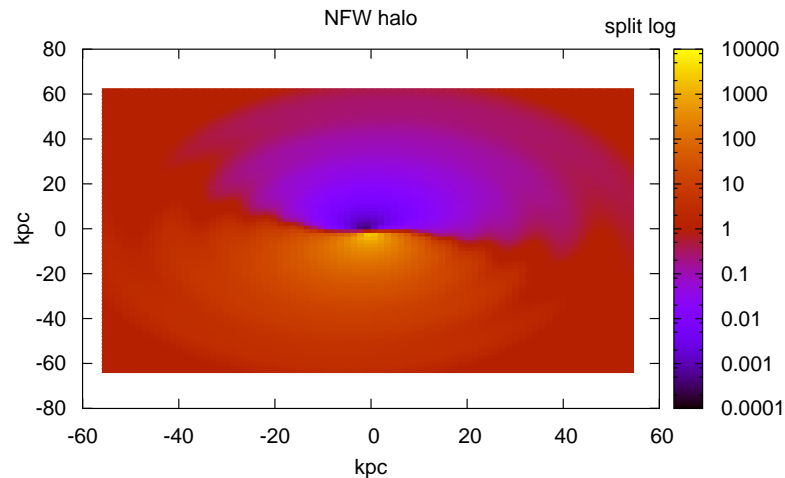
Halo wake

1st passage?

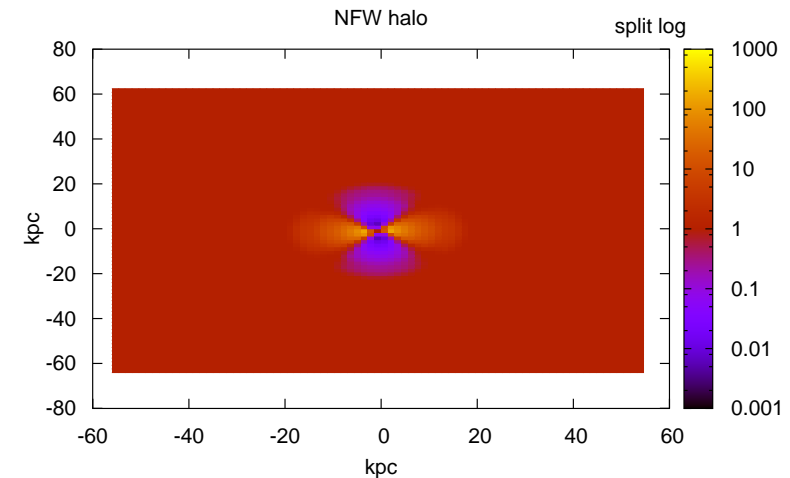
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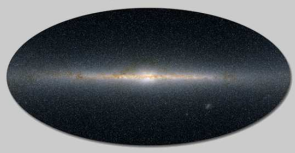


$m = 1$ potential from halo wake
in disk plane



$m = 2$ potential from halo wake
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An LMC first passage?

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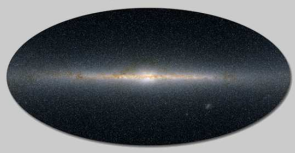
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DSMC simulation

Implications

- Lower overall mass implied by Λ CDM dark halo model
- Large space velocity confirmed from recent proper motion measurements (Kallivayalil et al. 2006)
- \implies LMC may not be orbiting but on first approach!



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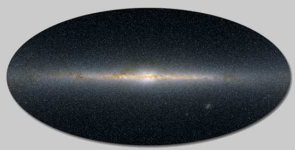
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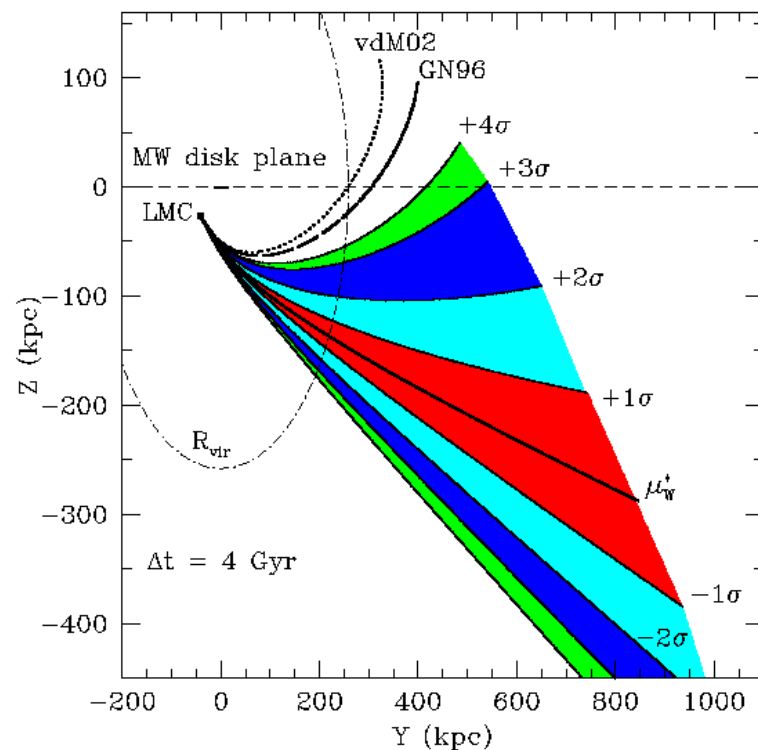
“Highly unlikely that LMC excites a warp”

Besla et al. 2007

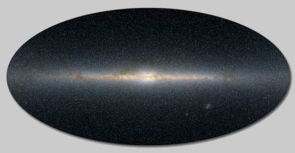


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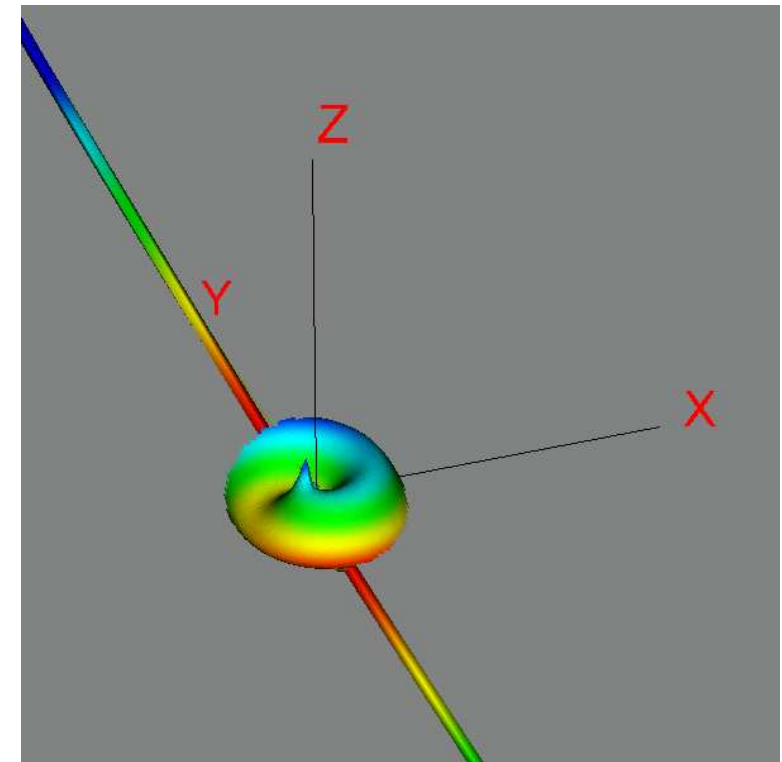
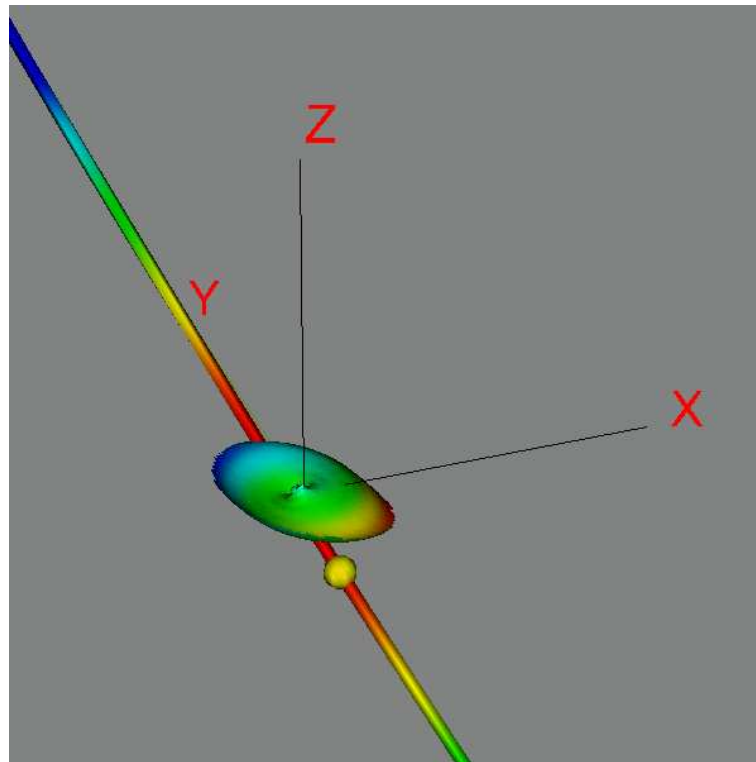


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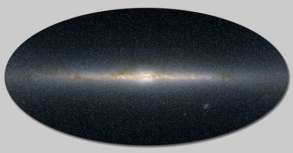


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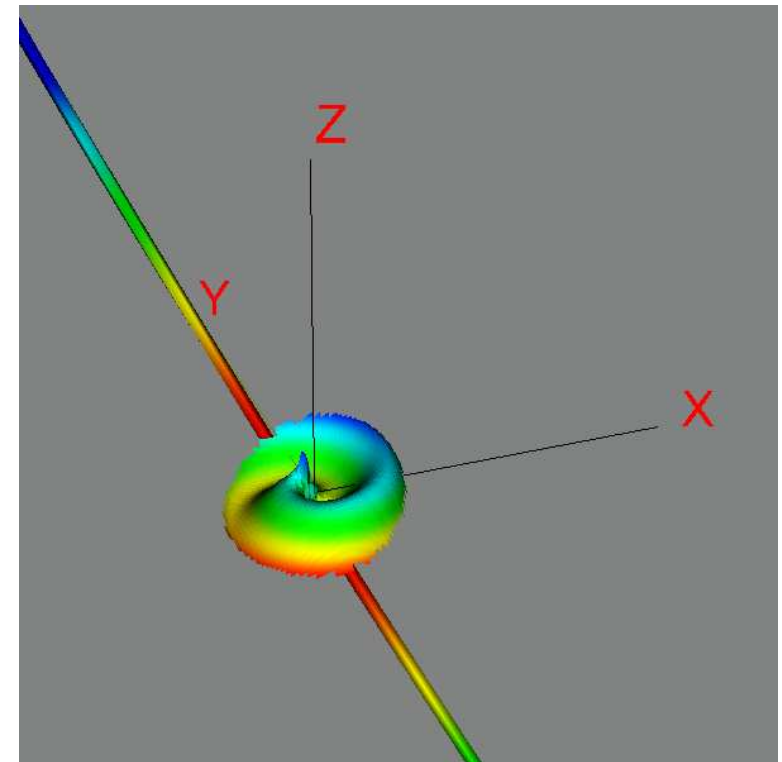
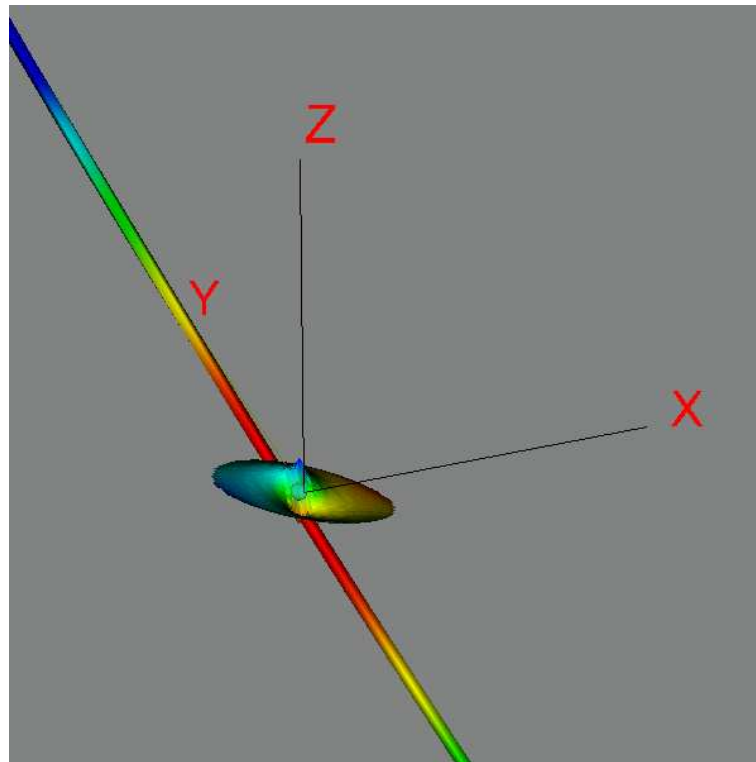


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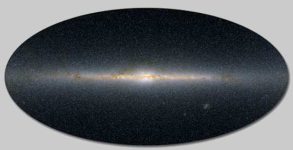


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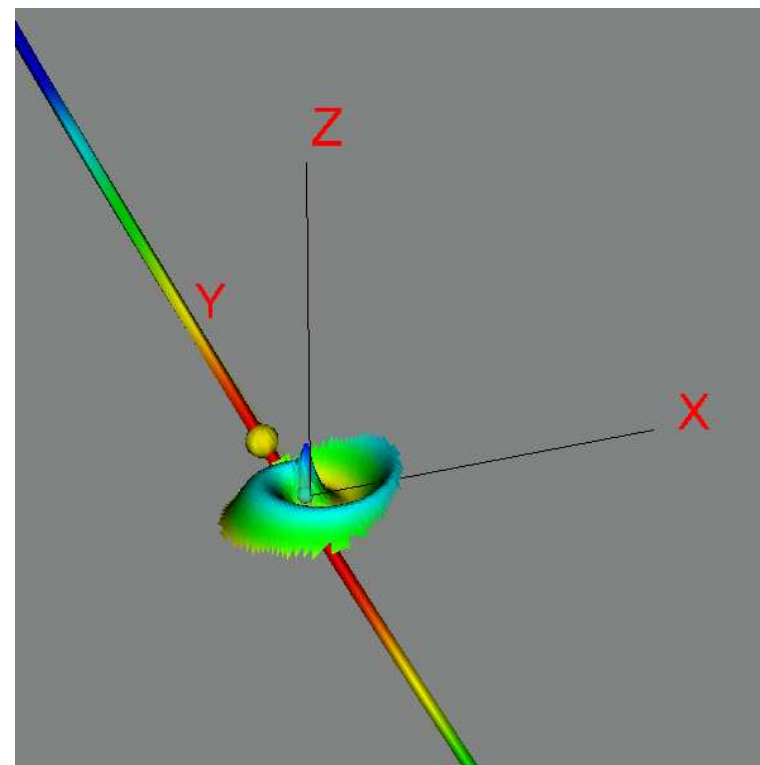
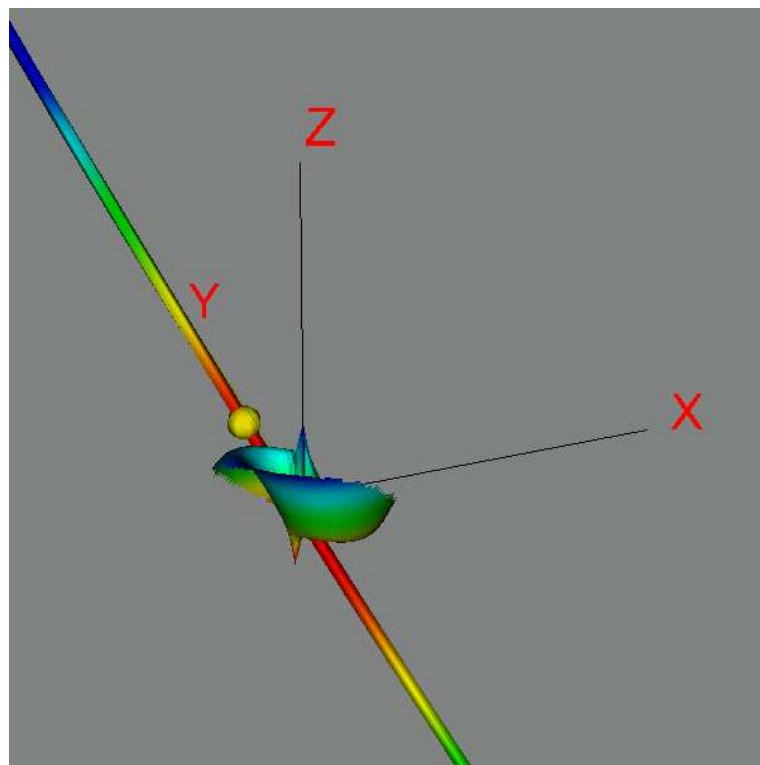


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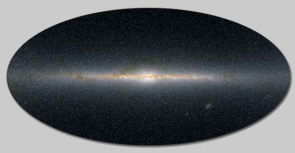
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An LMC first passage?

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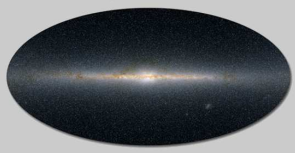
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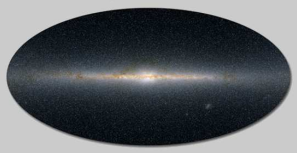
- Could predict LMC orbit and mass based on warp given exact Milky Way parameters



What does the gas *really* do?

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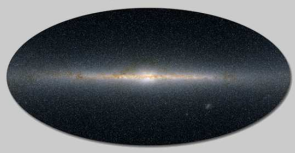
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- Pattern speed is supersonic, so ...
- Gas shocks, angular momentum removed \Rightarrow gas inflow
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 - ◆ Detailed calc in progress



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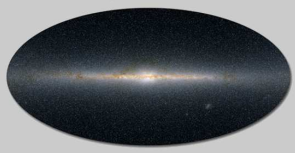
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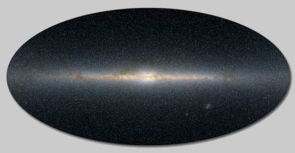
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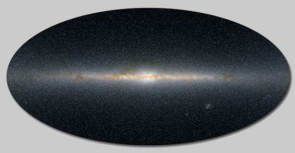
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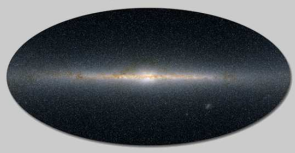


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Perhaps the halo “noise” is the major driver of disk structures (bars, spiral arms, etc.) not self-excitation??



Gas forcing by a satellite

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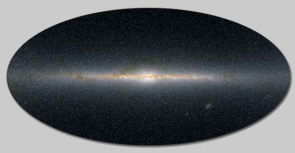
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DSMC simulation

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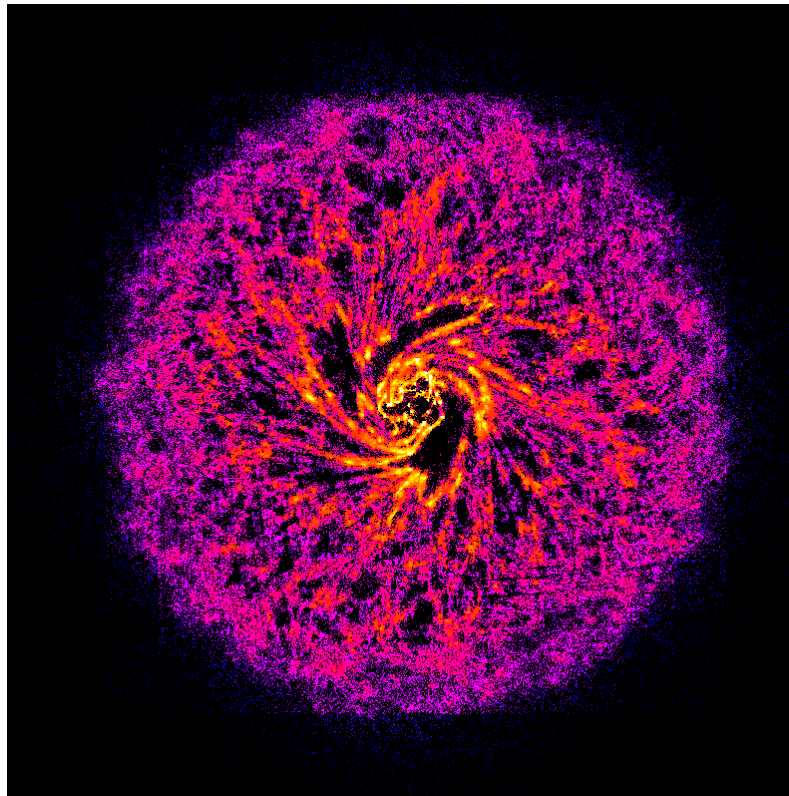
- Parallel DSMC code (Direct Simulation Monte Carlo, 100% shock capturing)
- Live halo, live stellar disk, 3-d gas but no self gravity

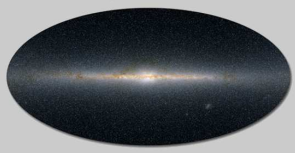


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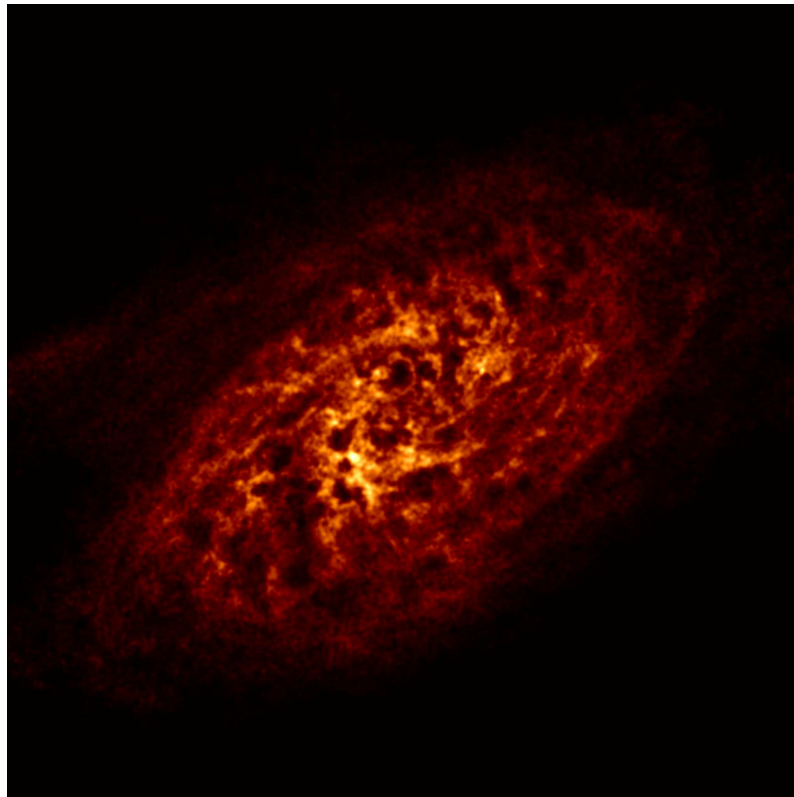




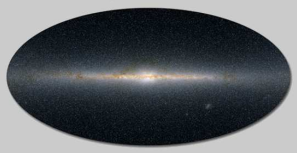
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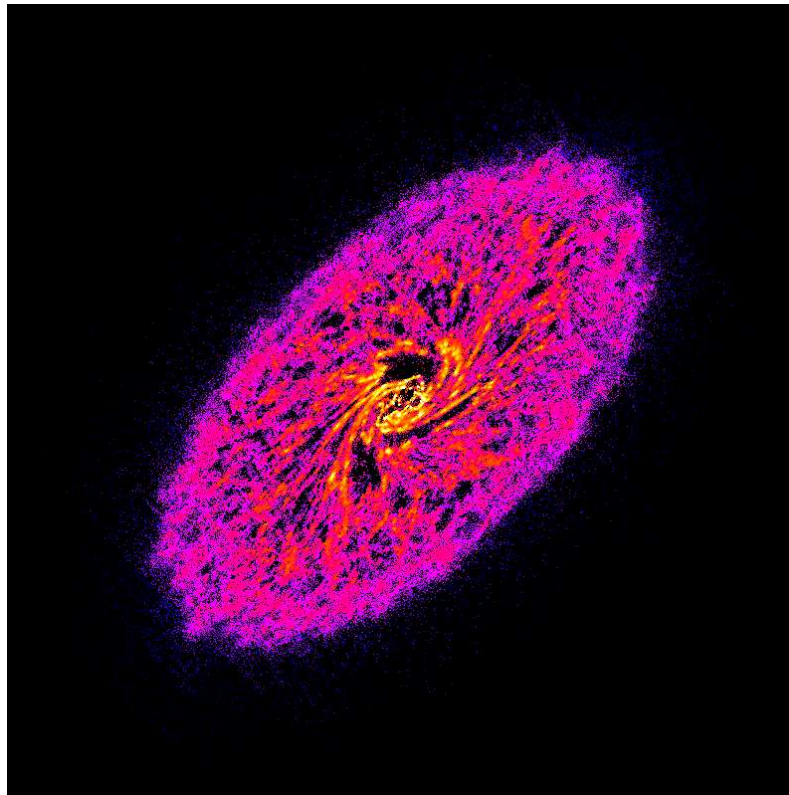
NGC 2403, HI (in M81 group, SAB)

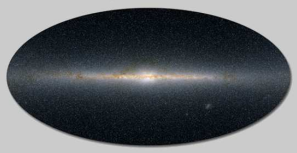


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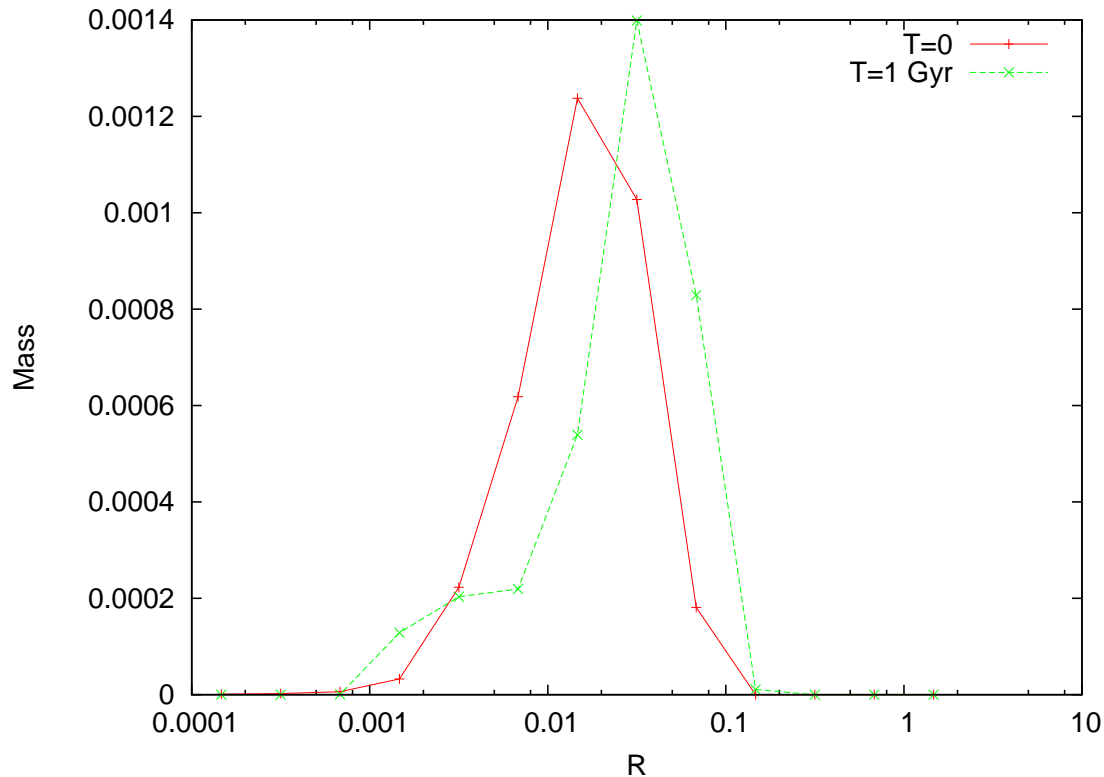


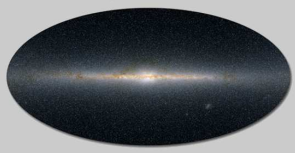


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■ N-body simulations

- ◆ Bending modes and multiscale interactions difficult
- ◆ N-body bending predictions agree

(e.g. Tsuchiya 2003, Bailin & Steinmetz 2005)

■ Other warping theories [~~Occam's Razor~~]

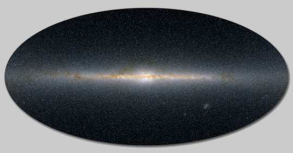
- ◆ Cosmic infall

(e.g. Ostriker, E. & Binney 1989, Ing-Guey & Binney 1999, Shen & Sellwood 2006)

- ◆ Triaxiality (e.g. Binney 1990)

■ MOND

- ◆ No halo, increase the force of gravity at large distances
- ◆ \Rightarrow Different disk modes! Outer disk!!!



Implications

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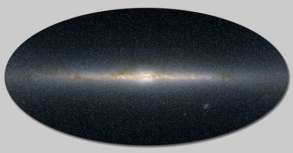
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DSMC simulation

Implications

- Substructure detection/other galactic systems
 - ◆ Coherent warping dominated by the largest subhalo/dwarf
 - ◆ Excitation of outer disk by the cumulative subhalo population
 - ◆ Heating of the disk by bending modes (homogenize scale height?)
 - ◆ HI structure survey!!
- Does halo structure cause spiral arms?
- Does noise drive cold gas accretion?
- Lots more work!



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The End