Title: In the Balance: Statis and Disequilibrium in the Milky Way

Speakers: Lawrence Widrow

Series: Cosmology & Gravitation

Date: March 29, 2022 - 11:00 AM

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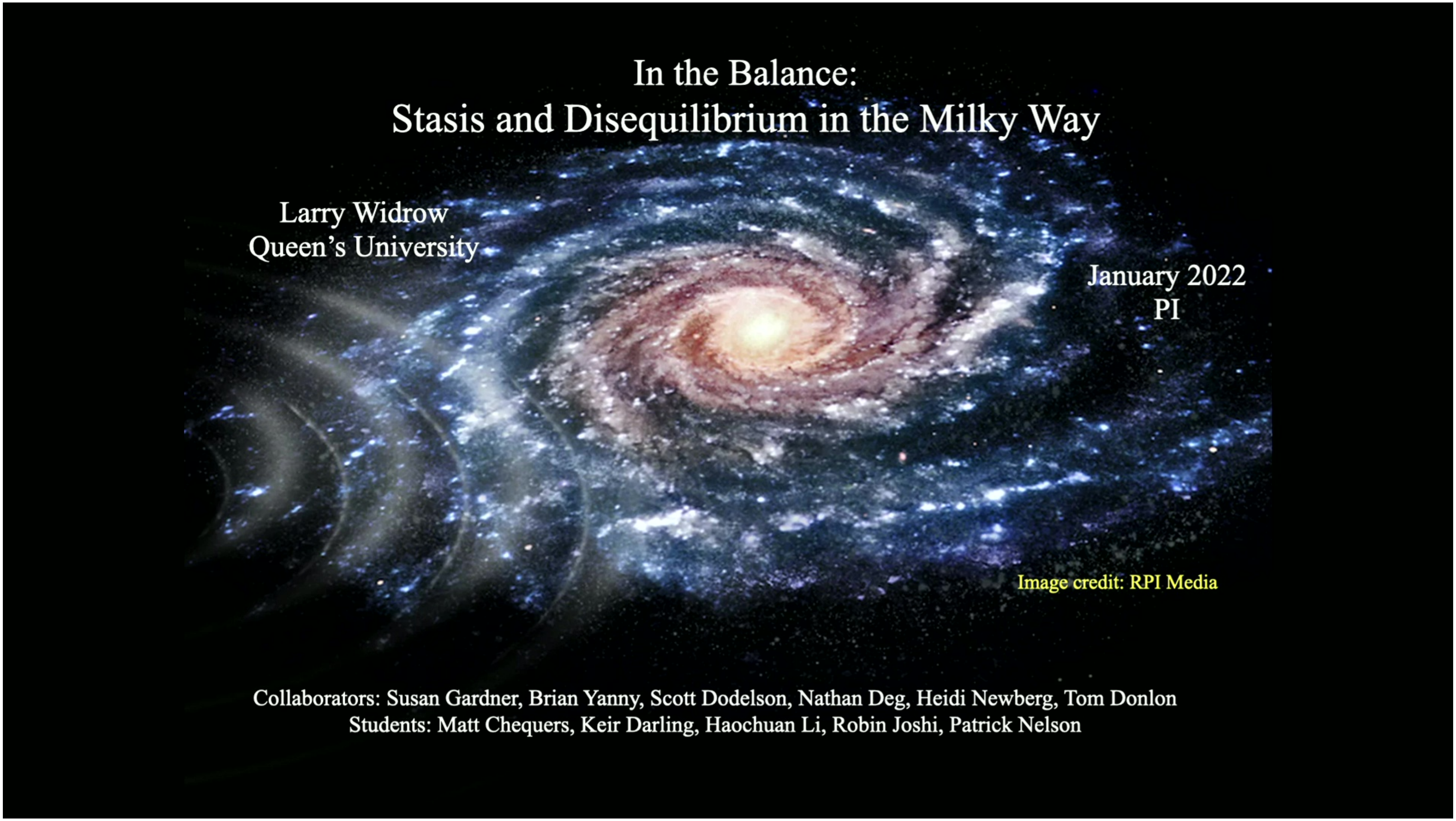
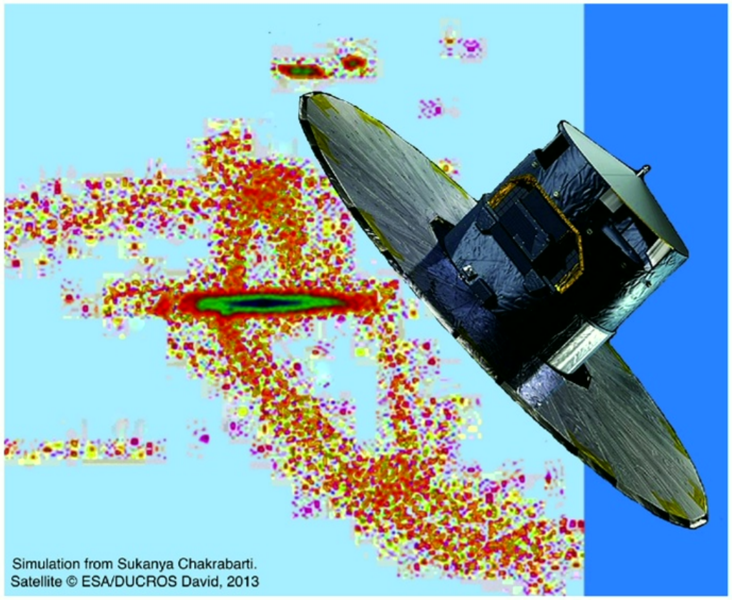
Abstract: The disk of the Milky Way comprises some 100 billion stars on nearly circular orbits about the Galactic centre. Over the next few years, the Gaia Space Telescope will measure positions and velocities for over 1% of these stars. By combining equilibrium models of the Galaxy with these observations we can construct the Galactic rotation curve, which allows us to infer the large-scale structure of the dark matter halo. We can also construct a model for the mass distribution in the Solar Neighbourhood, which allows us to infer the local density of dark matter. However, even a cursory study of the Milky Way reveals structures that signal a departure from equilibrium. The most prominent of these are the Galactic bar, spiral arms, and warping of the outer disk. I will describe recent observations of some more subtle departures from equilibrium and discuss ways in which these observations can lead to refined models of the Galaxy and a more complete picture of the Galaxy's dynamics.

Zoom Link: https://pitp.zoom.us/j/98802402146?pwd=K3RPYlNMR2hMcXFMUm5SclU3djdiZz09


In the Balance:
Stasis and Disequilibrium in the Milky Way
Larry Widrow
Queen's University
January 2022
PI
Image credit: RPI Media
Collaborators: Susan Gardner, Brian Yanny, Scott Dodelson, Nathan Deg, Heidi Newberg, Tom Donlon
Students: Matt Chequers, Keir Darling, Haochuan Li, Robin Joshi, Patrick Nelson

In the Balance: Stasis and Disequilibrium in the Milky Way

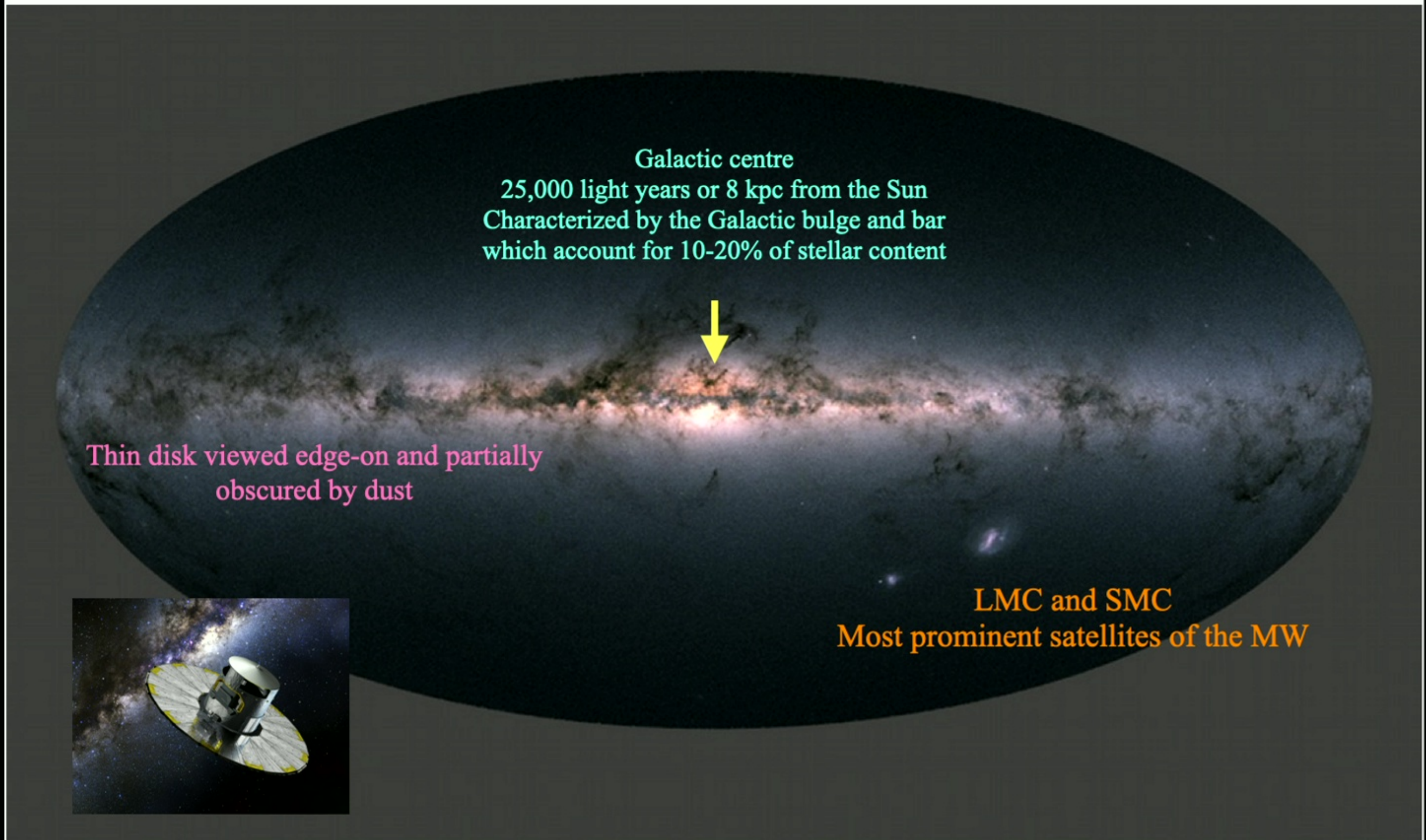
Title borrowed from a workshop at the Kavli Institute for Theoretical Physics, UC Santa Barbara, April 1-4, 1 BPE

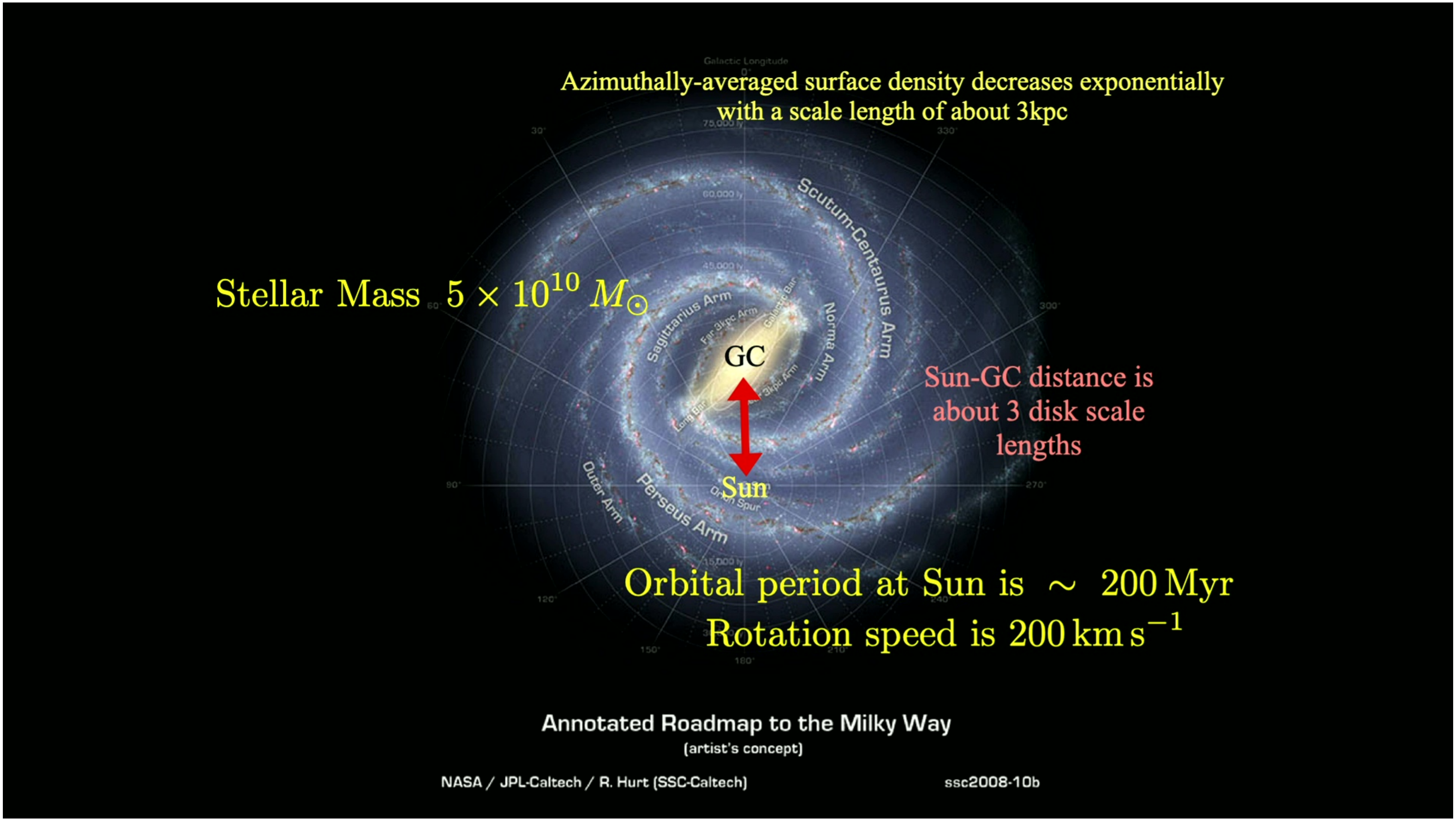


Overview

Equilibrium models for disk galaxies
Local gravitational field and dark matter density — the Oort problem
Disequilibrium in the Milky Way
Phase spirals and the Oort problem revisited

Milky Way Galaxy: the closest edge-on galaxy to the Sun




Azimuthally-averaged surface density decreases exponentially
with a scale length of about 3kpc
Stellar Mass $5 \times 10^{10}\, M_\odot$
GC
Sun
Sun-GC distance is about 3 disk scale lengths
Orbital period at Sun is $\sim$ 200 Myr
Rotation speed is $200\,\mathrm{km\,s^{-1}}$
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Perseus Arm
Outer Arm
Annotated Roadmap to the Milky Way
(artist's concept)
NASA / JPL-Caltech / R. Hurt (SSC-Caltech)
ssc2008-10b

Model for stellar disk

$$f\,(\mathbf{r},\,\mathbf{v},\,t)$$

f describes the density of stars as a function of position and velocity — phase space distribution function

$$\Psi\,(\mathbf{r},\,t)$$

Gravitational potential

Stars in the disk are assumed to be "collisionless" — mean field dynamics

Star-star encounters in the disk are exceedingly rare.
The same cannot be said for globular clusters and open star clusters.

Potential and DF are connected through Poisson's equation and the collisionless Boltzmann equation

Model for stellar disk

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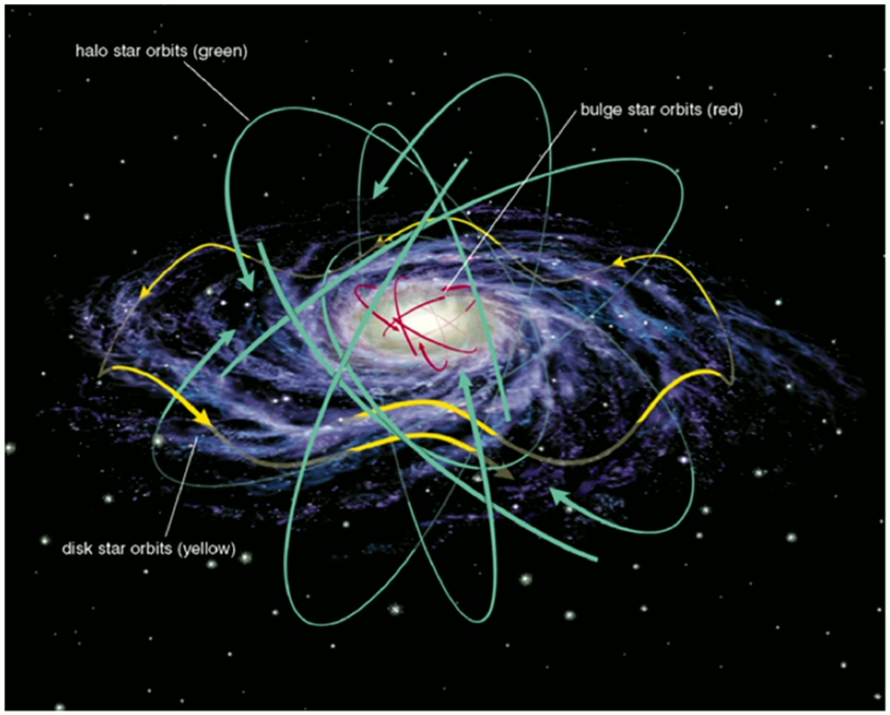
The DF and potential of an equilibrium model are time-independent

Equilibrium models for the Galaxy generally assume axisymmetry and symmetric about the midplane.

A model for the disk is built out of individual orbits, which are nearly circular about the Galactic centre.

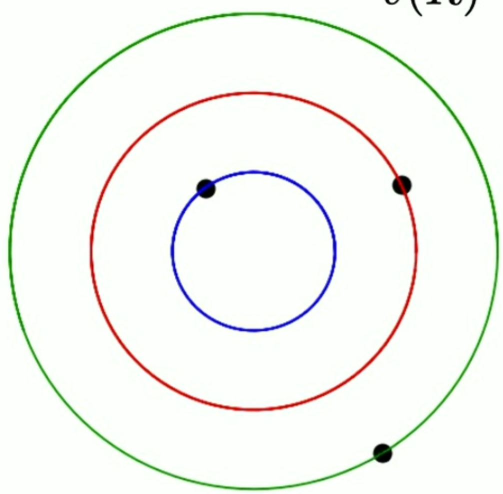
Disk is dynamically cold; bulge and stellar halo are dynamically hot



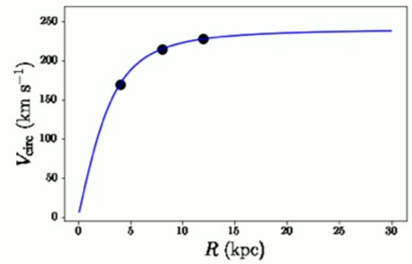
Pearson Education Inc. 2005

Stellar orbits can be best thought of as the superposition of three oscillatory motions
Begin with the circular motion about the Galactic centre

$$v(R) = \sqrt{r|F(R)|} \simeq \left(\frac{GM(R)}{R}\right)^{1/2}$$



M(R) is the mass enclosed by radius R
Formula is approximate since it assumes spherical symmetry

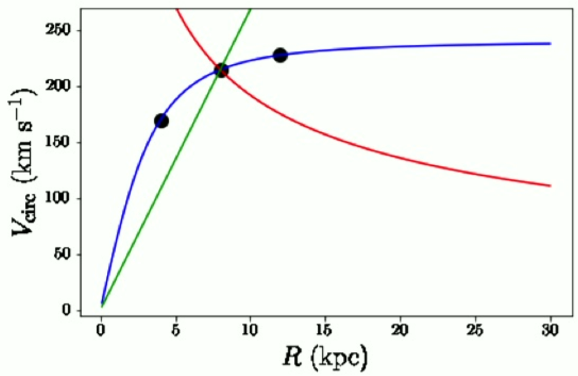


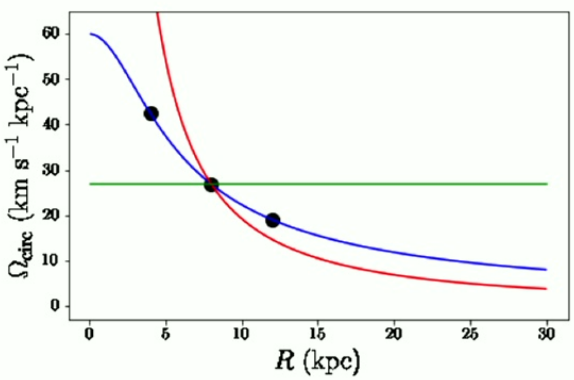
Galactic rotation curves are intermediate between two special cases for the potential

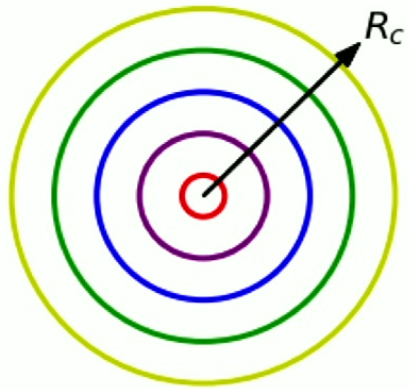
Kepler potential — point mass at centre

Harmonic potential — constant density

Galactic potential







Angular momentum: $L_z = \Omega(R_c)R_c^2$

Conserved in axisymmetric, time-independent model

R_c is radius of circular orbit with L_z and is a proxy for radius R

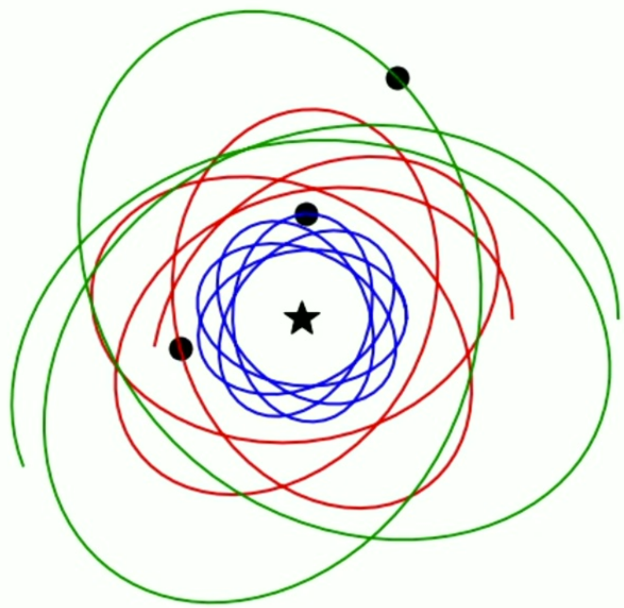
Distribution of stars on orbits as a function of R_c

determines the surface density of the disk

$$\Sigma(R_c)$$

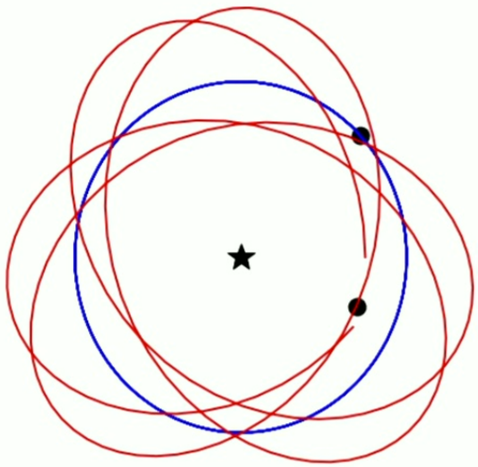
As mentioned before, galactic potentials are intermediate between the Kepler and solid body problems

$$\Omega \ < \ \kappa \ < \ 2\Omega$$

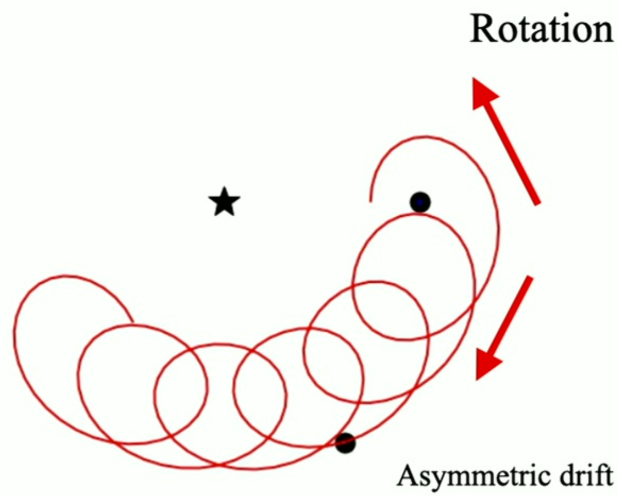


The Kepler and constant density problems are the only potentials that admit closed elliptical orbits. You may wish to ponder the significance of this statement in quantum mechanics.

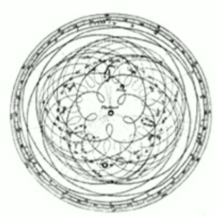
Rosette orbits (red) lag behind the circular orbit with the same angular momentum (blue).
In the rotating frame of the circular orbit, the original star makes epicyclic motions.



Inertial frame

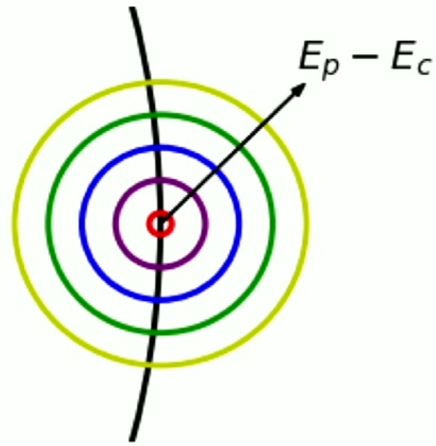


Rotating frame



Reminiscent of epicycle (Ptolemaic) model for the solar system

For fixed Lz, circular orbit
is the minimum energy orbit



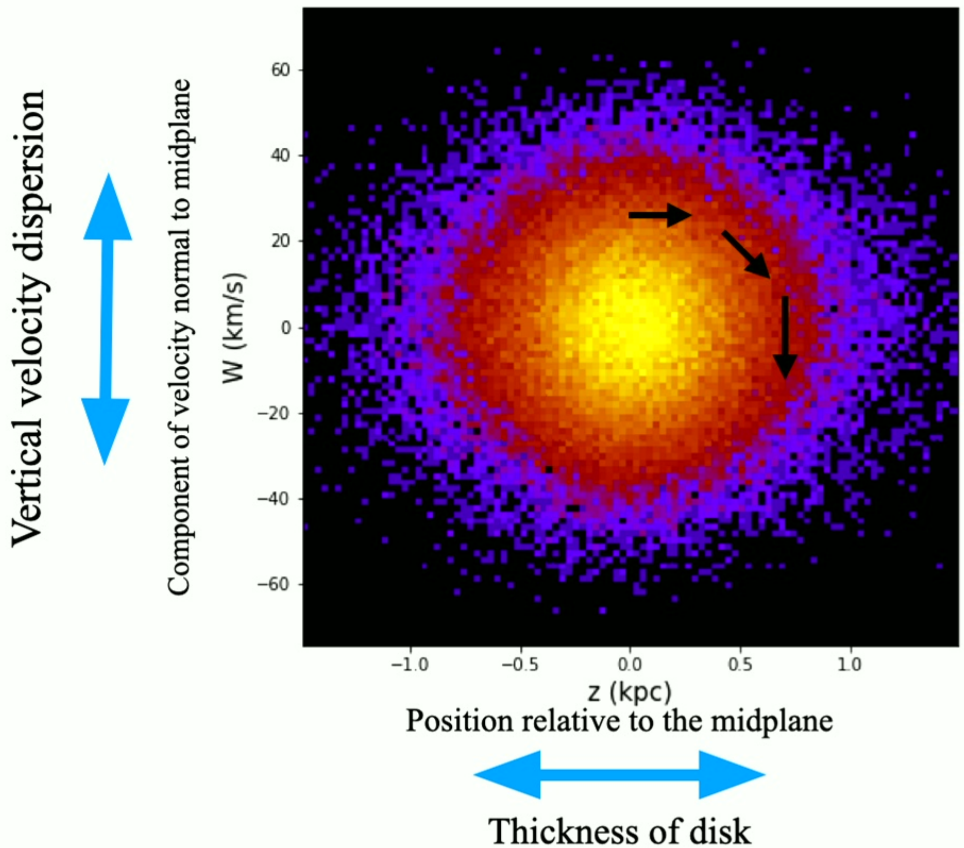
Stars orbit in R, ϕ, v_R, v_ϕ-space at frequency κ

Distribution in $v_R - v_\phi$ plane
is determined by some function $f(E_p - E_c)$

E_p is the in-plane energy

E_c is the energy of a star with L_z on a circular orbit

Distribution of stars near the Sun in position relative to midplane z and component of velocity perpendicular to mid plane, v_z



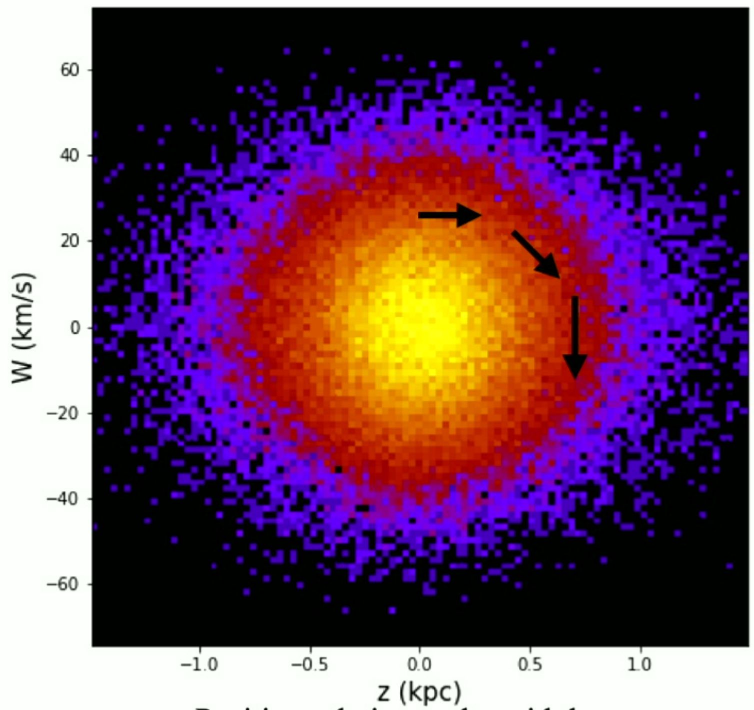
Individual stars orbit clockwise in the z-v_z plane

This figure is from an idealized N-body model

Distribution of stars near the Sun in position relative to midplane z and component of velocity perpendicular to mid plane, v_z

Vertical velocity dispersion

Component of velocity normal to midplane

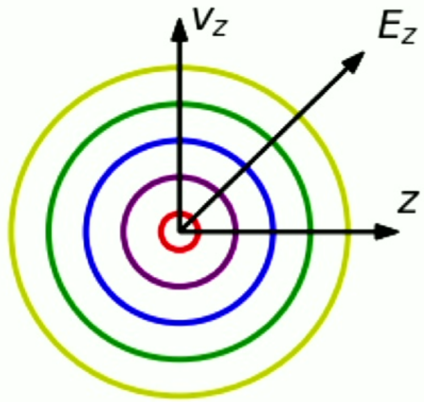


Position relative to the midplane

Thickness of disk

Individual stars orbit clockwise in the z-v_z plane

This figure is from an idealized N-body model

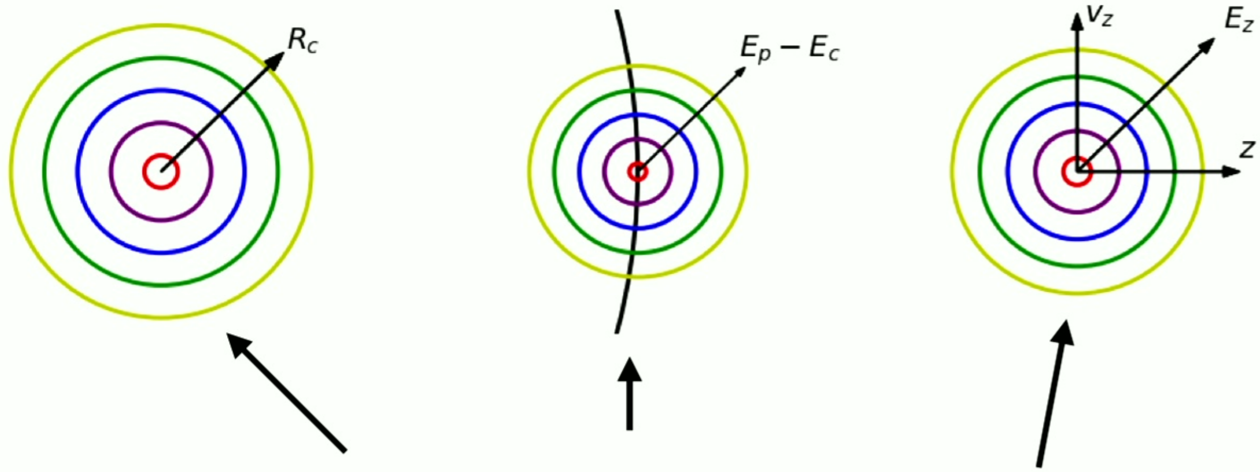


Stars orbit in the $z - v_z$ plane at frequency ν

Distribution in $z - v_z$ plane is determined some function $f_z(E_z)$ where $E_z = \frac{1}{2}v_z^2 + \psi(z)$ is the vertical energy

Quasi-isothermal distribution functions for stellar disk

Kuijken & Dubinski (1995), LMW, Pym & Dubinski (2008) (GalactICS code)
Binney 2010, Binney and McMillan (2016) use actions J_R and J_z instead of E_R and E_z



$$f(\mathbf{r},\,\mathbf{v}) \sim \Sigma(R_c)e^{-(E_p-E_c)/\sigma_R^2}e^{-E_z/\sigma_z^2}$$

Starting point for theoretical discussions (e.g., perturbation theory)
Initial conditions for N-body experiments
Template for interpreting observations (finding most suitable equilibrium model to data)

Quasi-isothermal distribution functions for stellar disk

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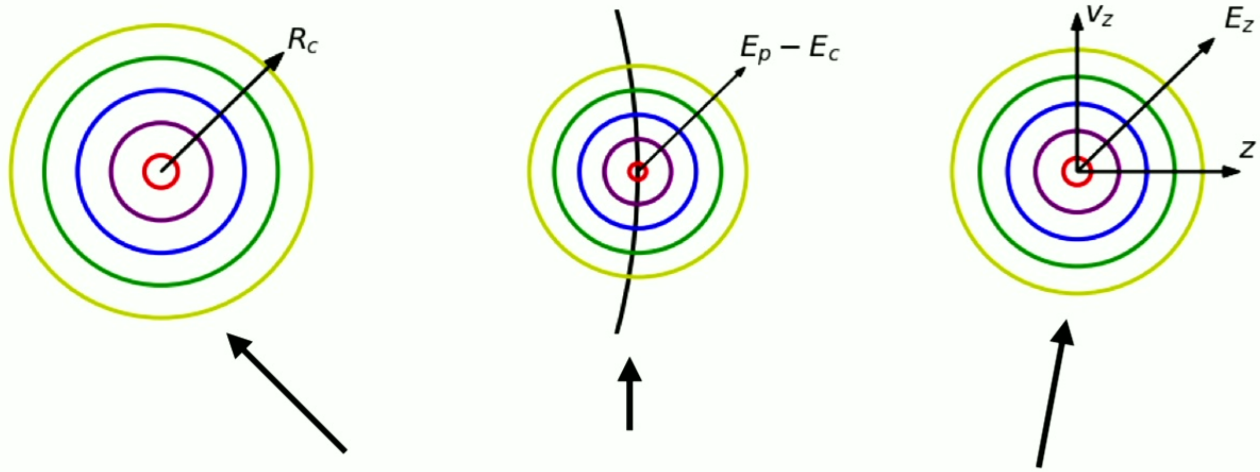

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Starting point for theoretical discussions (e.g., perturbation theory)
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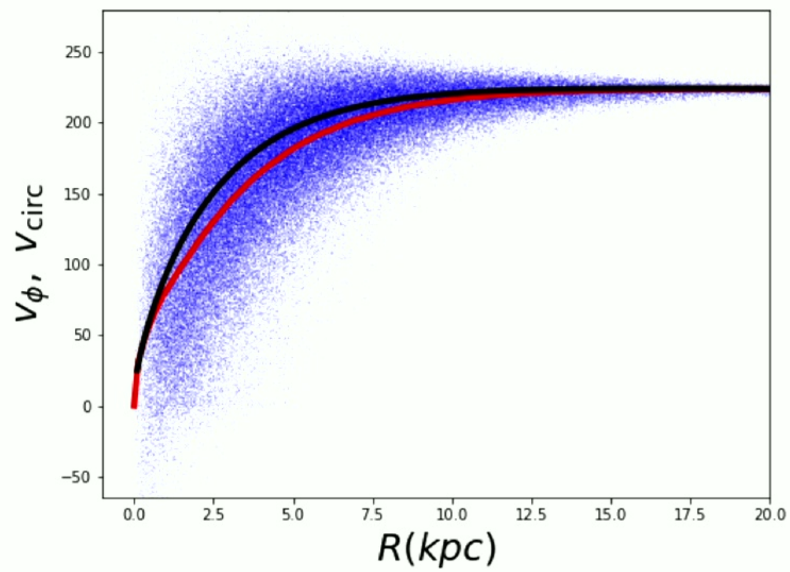
Equilibrium models provide framework for inferring the azimuthally-averaged potential (radial force) in mid plane

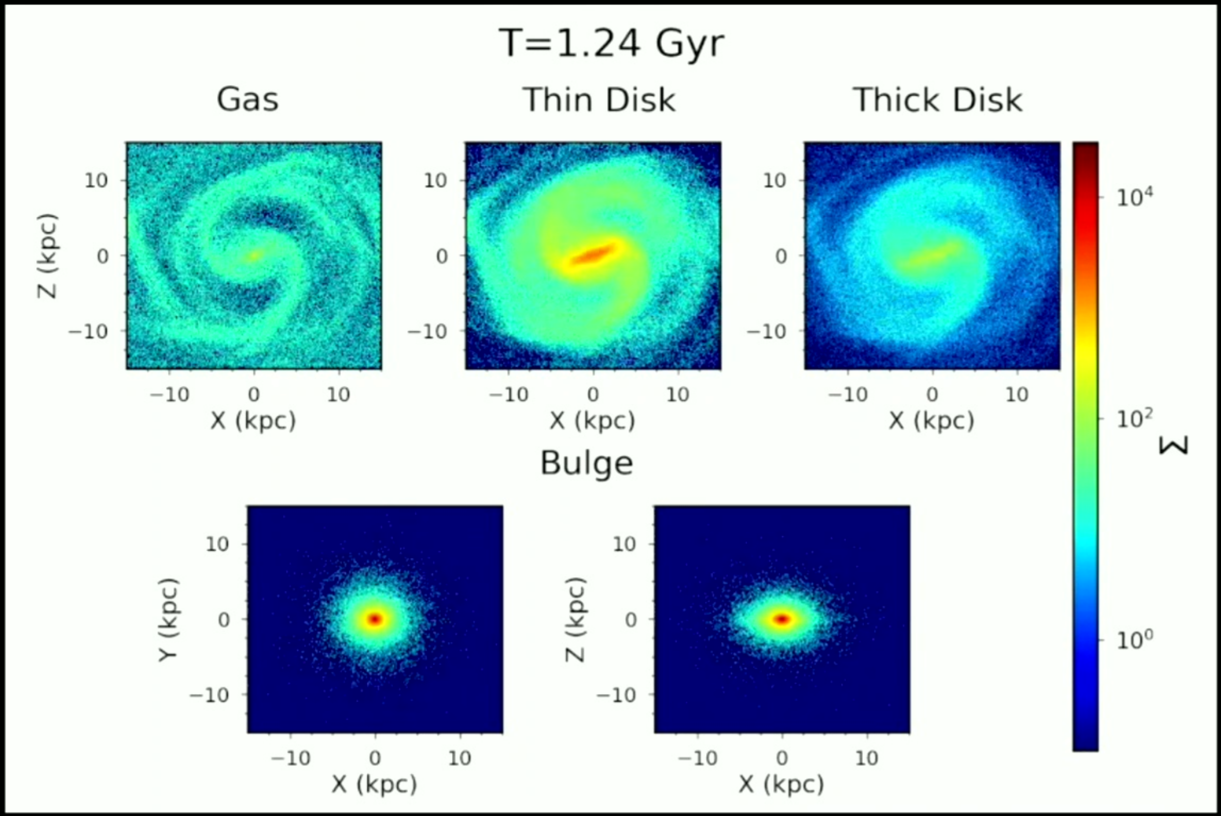
Blue points from N-body realization of *f(r,v)*

Black curve $v(R) = \sqrt{r|F(R)|}$

Red curve is mean v_{ϕ}. (includes asymmetric drift)



3 component disk + bulge + halo MW-ish model



Animation courtesy of Nathan Deg
See Deg, LMW, et al 2019

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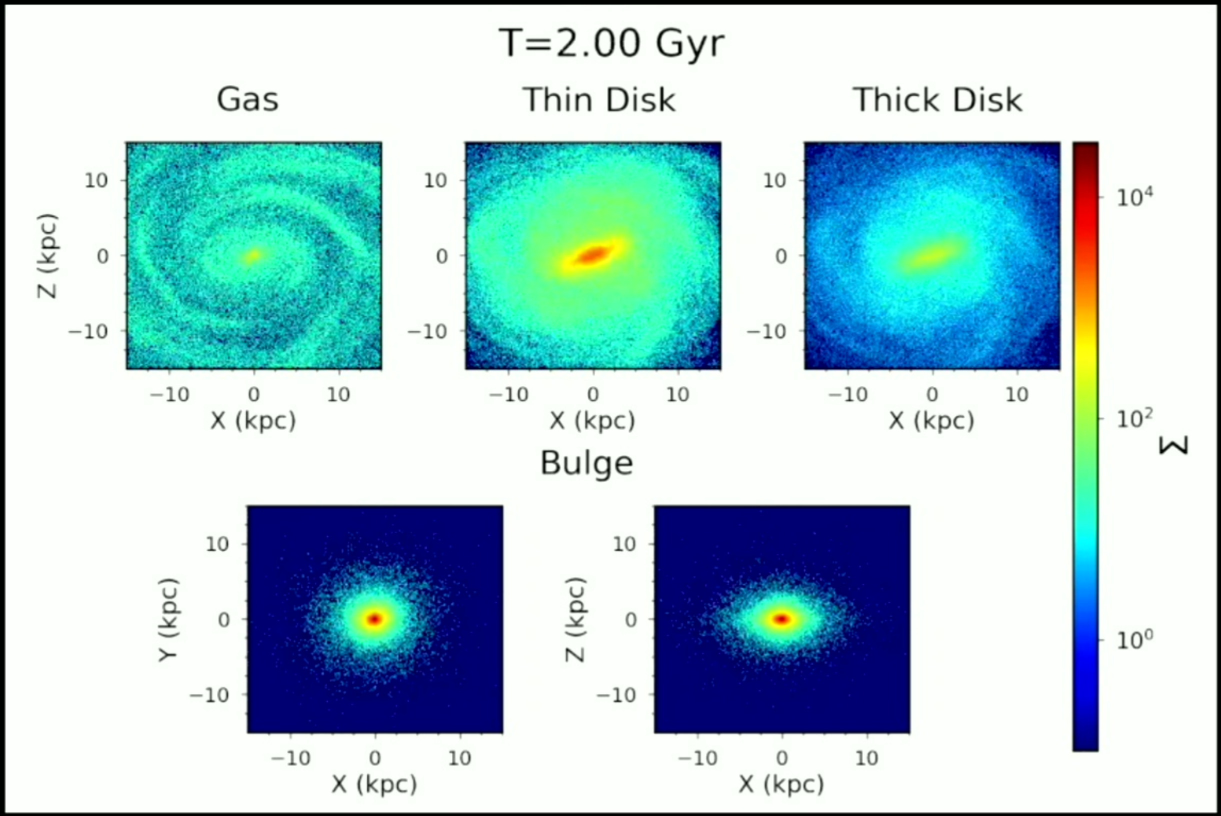
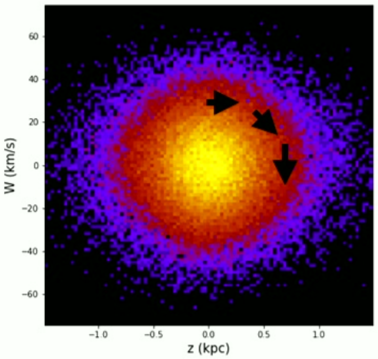
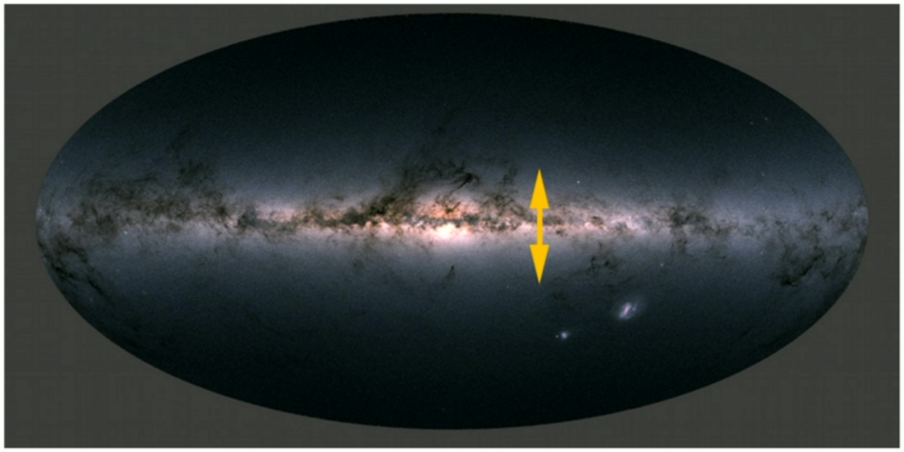


Animation courtesy of Nathan Deg
See Deg, LMW, et al 2019

If we assume that the stars are in vertical equilibrium, then we can write down an equation reminiscent of the equation for hydrostatic equilibrium.
This equation describes the balance of gravitational force and "pressure gradient".

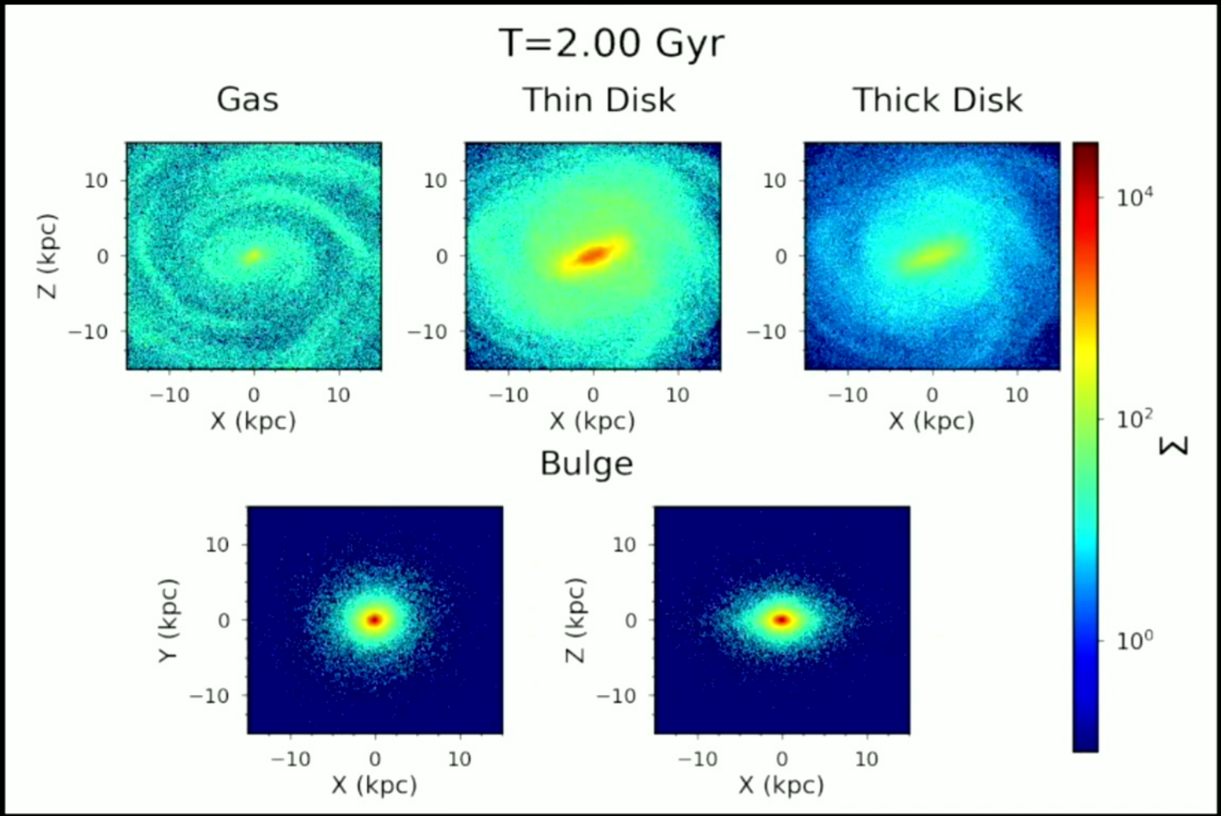




$$\rho \frac{d\psi_z}{dz} = \frac{d}{dz}\left(\rho\sigma_z^2\right)$$

Gravitational force "pressure" gradient

3 component disk + bulge + halo MW-ish model



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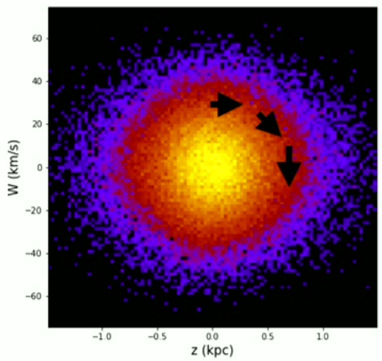

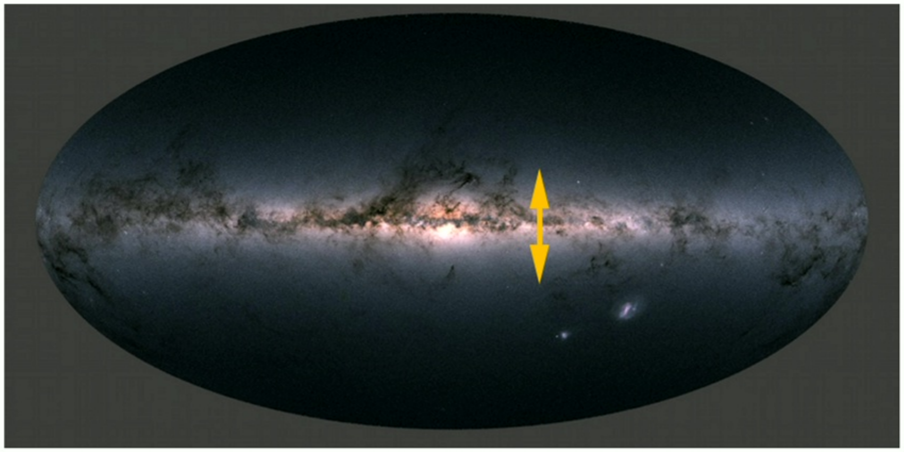

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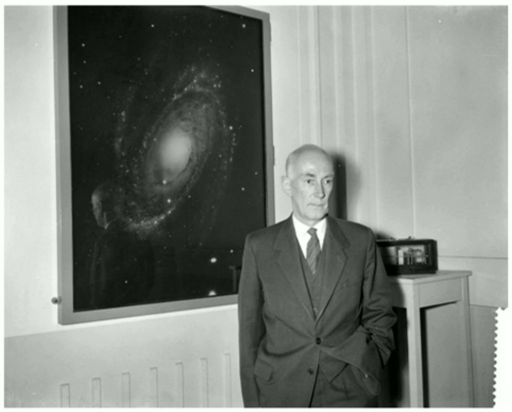
Gravitational force "pressure" gradient

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 Volume VI. No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*



A third purpose was the derivation of an accurate value for the total amount of mass, including dark matter, corresponding to a unit of luminosity in the surroundings of the sun.

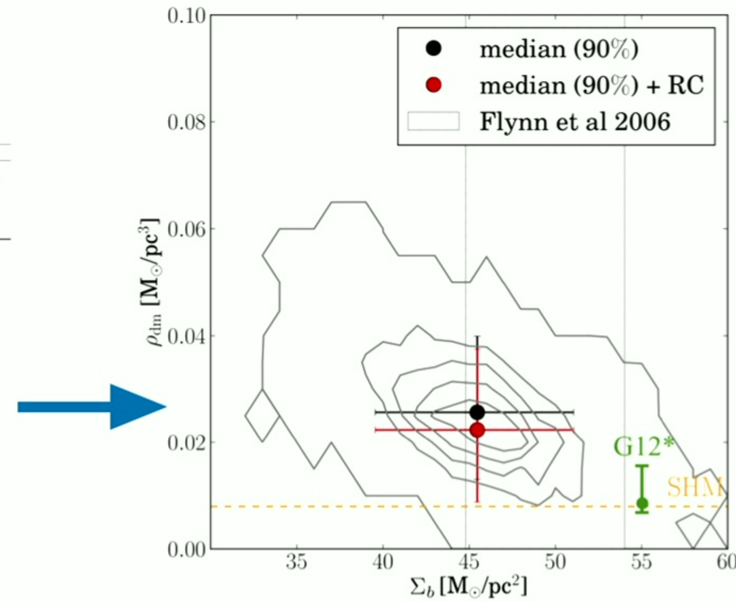
See also earlier papers by Jeans and Kapteyn

Label	Reference	Description	Sampling	ρ_{dm} [$M_\odot\,pc^{-3}$]	ρ_{dm} [$GeV\,cm^{-3}$]
a) Local measures (ρ_{dm})					
Kapteyn	Kapteyn (1922)	–	–	0.0076	0.285
Jeans	Jeans (1922)	–	–	0.051	1.935
Oort	Oort (1932)	–	–	0.0006 ± 0.0184	0.0225 ± 0.69
Hill	Hill (1960)	–	–	-0.0054	-0.202
Oort	Oort (1960)	–	–	0.0586 ± 0.015	2.2 ± 0.56
Bahcall	Bahcall (1984a)	–	–	0.033 ± 0.025	1.24 ± 0.94
Bienayme†	Bienayme et al. (1987)	–	–	0.006 ± 0.005	0.22 ± 0.187
KG†	Kuijken & Gilmore (1991)	–	–	0.0072 ± 0.0027	0.27 ± 0.102
Bahcall	Bahcall et al. (1992)	–	–	0.033 ± 0.025	1.24 ± 0.94
Creze	Creze et al. (1998)	–	–	-0.015 ± 0.015	-0.58 ± 0.56
HF†	Holmberg & Flynn (2000b)	–	–	0.011 ± 0.01	0.4 ± 0.375
HF†	Holmberg & Flynn (2004)	–	–	0.0086 ± 0.0027	0.324 ± 0.1
Bienayme	Bienaymé et al. (2006)	–	–	0.0059 ± 0.005	0.51 ± 0.56
Latest measurements					
MB12	Moni Bidin et al. (2012)	CSF	412	0.00062 ± 0.001 [0 ± 0.001]	0.023 ± 0.042 [0 ± 0.042]
BT12	Bovy & Tremaine (2012)	CSF	412	0.008 ± 0.003	0.3 ± 0.11
G12	Garbari et al. (2012)	VC	2×10^3	$0.022^{+0.015}_{-0.013}$	$0.85^{+0.57}_{-0.5}$
G12*	Garbari et al. (2012)	VC + Σ_b	2×10^3	$0.0087^{+0.007}_{-0.002}$	$0.33^{+0.26}_{-0.075}$
S12	Smith et al. (2012)	CSF	10^4	0.005 [no error] [0.015]	0.19 [0.57]
Z13	Zhang et al. (2013)	CSF	10^4	0.0065 ± 0.0023	0.25 ± 0.09
BR13	Bovy & Rix (2013)	CSF + MAP	10^4	0.006 ± 0.0018 [0.008 ± 0.0025]	0.22 ± 0.07 [0.3 ± 0.094]
b) Global measures assuming spherical symmetry ($\rho_{dm,ext}$)					
S10	Salucci et al. (2010)	NP	–	0.011 ± 0.004	0.43 ± 0.15
CU10	Catena & Ullio (2010)	NFW; SP	–	0.0103 ± 0.00072	0.385 ± 0.027
WB10	Weber & de Boer (2010)	NFW/ISO; WP	–	0.005 - 0.01	0.2 - 0.4
I11	Iocco et al. (2011)	gNFW; WP; ML	–	0.005 - 0.015	0.2 - 0.56
M11	McMillan (2011)	NFW; SP	–	0.011 ± 0.0011	0.4 ± 0.04

There's a long history of attempts to use Oort's method and variations to infer the infer the local dark matter density

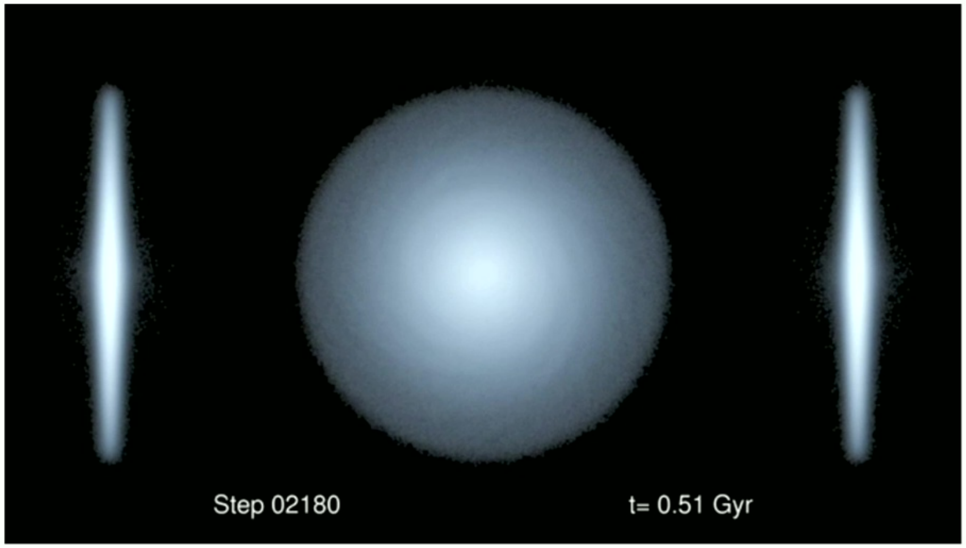
See review by Read 2014

$1\ GeV\,cm^{-3}$



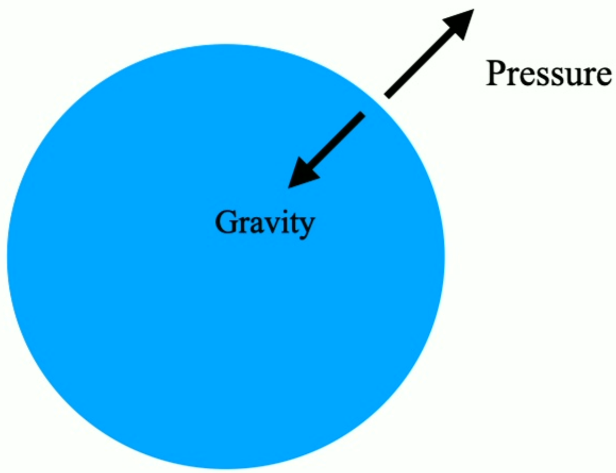
The departure from equilibrium in galaxies is manifest!

Bars, spiral structure and warps can emerge from internal dynamics in disks via gravitational instabilities



Simulation by J. Dubinski; ICs from LMW, Pym, Dubinski 2005

The instability is akin to the Jeans instability where gravity wins over the random motions of the stars (kinetic pressure)



$$F_g = \rho \frac{GM_{\rm encl}}{R^2} \sim G\rho^2 R$$

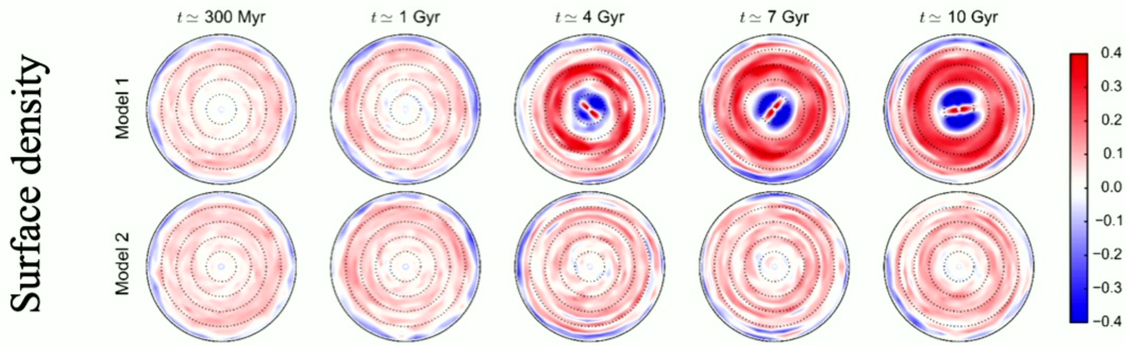
$$F_p = \frac{dp}{dr} \sim \rho \frac{\sigma^2}{R}$$

$$R_J \sim \frac{\sigma}{\sqrt{G\rho}}$$

If a density perturbation has a scale larger than the Jeans length, gravity wins and the region collapses.

The formation of spiral structure and bars also involves a conspiracy of gravitational collapse, differential rotation, and epicyclic motions

Bending of the disk (warps and corrugation) can also be generated by internal disk dynamics seeded by small-amplitude perturbations



Chequers & LMW 2017

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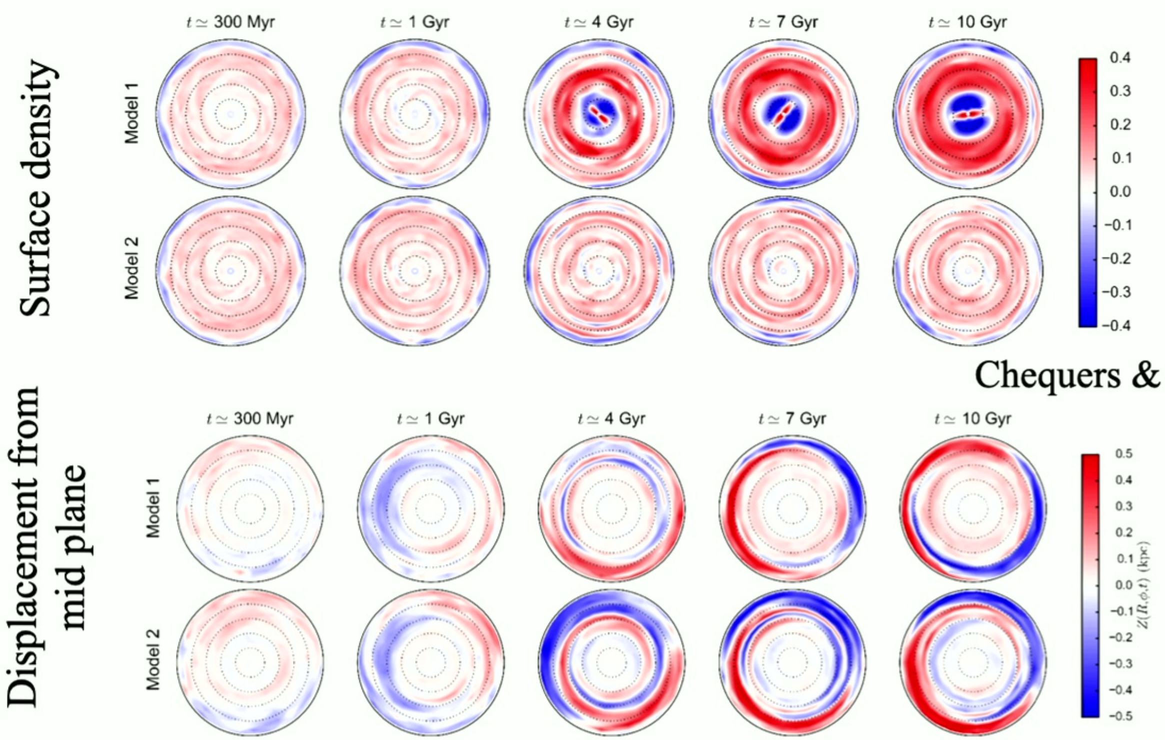


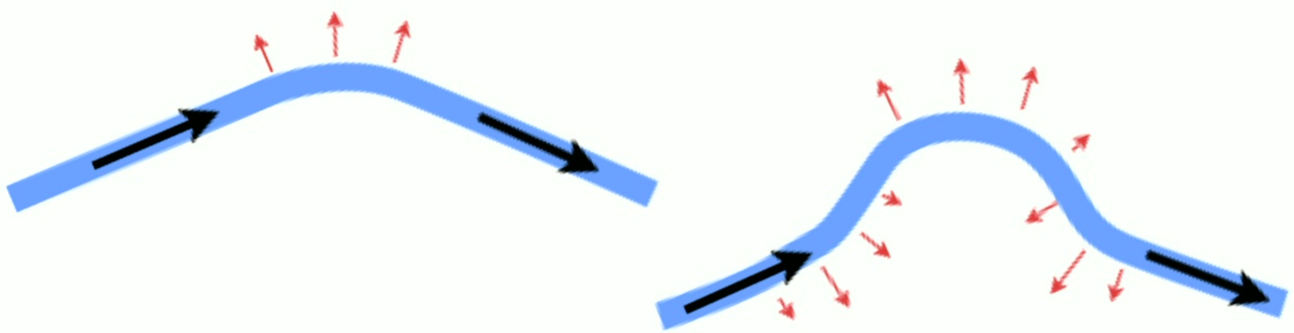
Chequers & LMW 2017

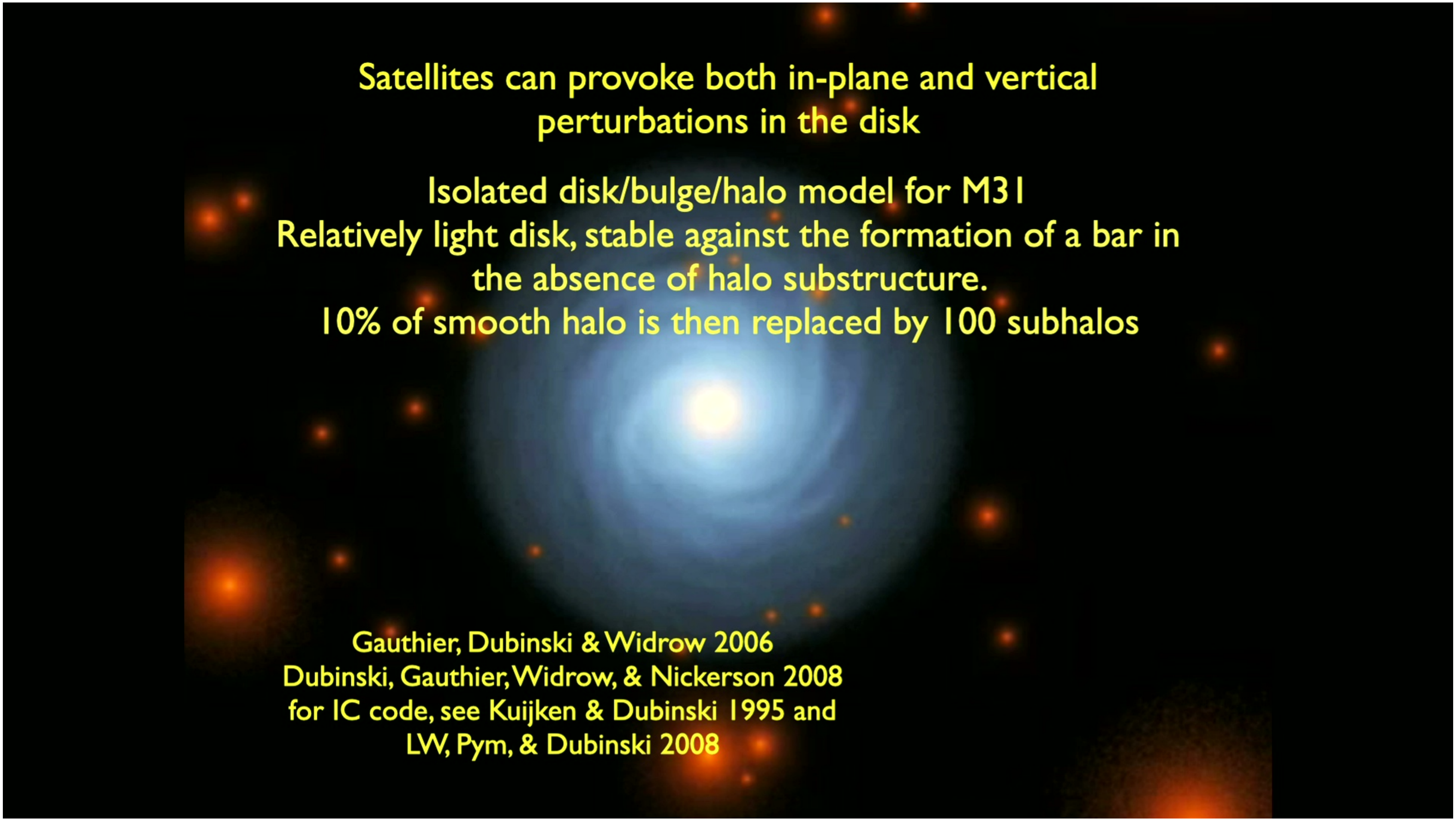
See also Sellwood & Debattista 2021

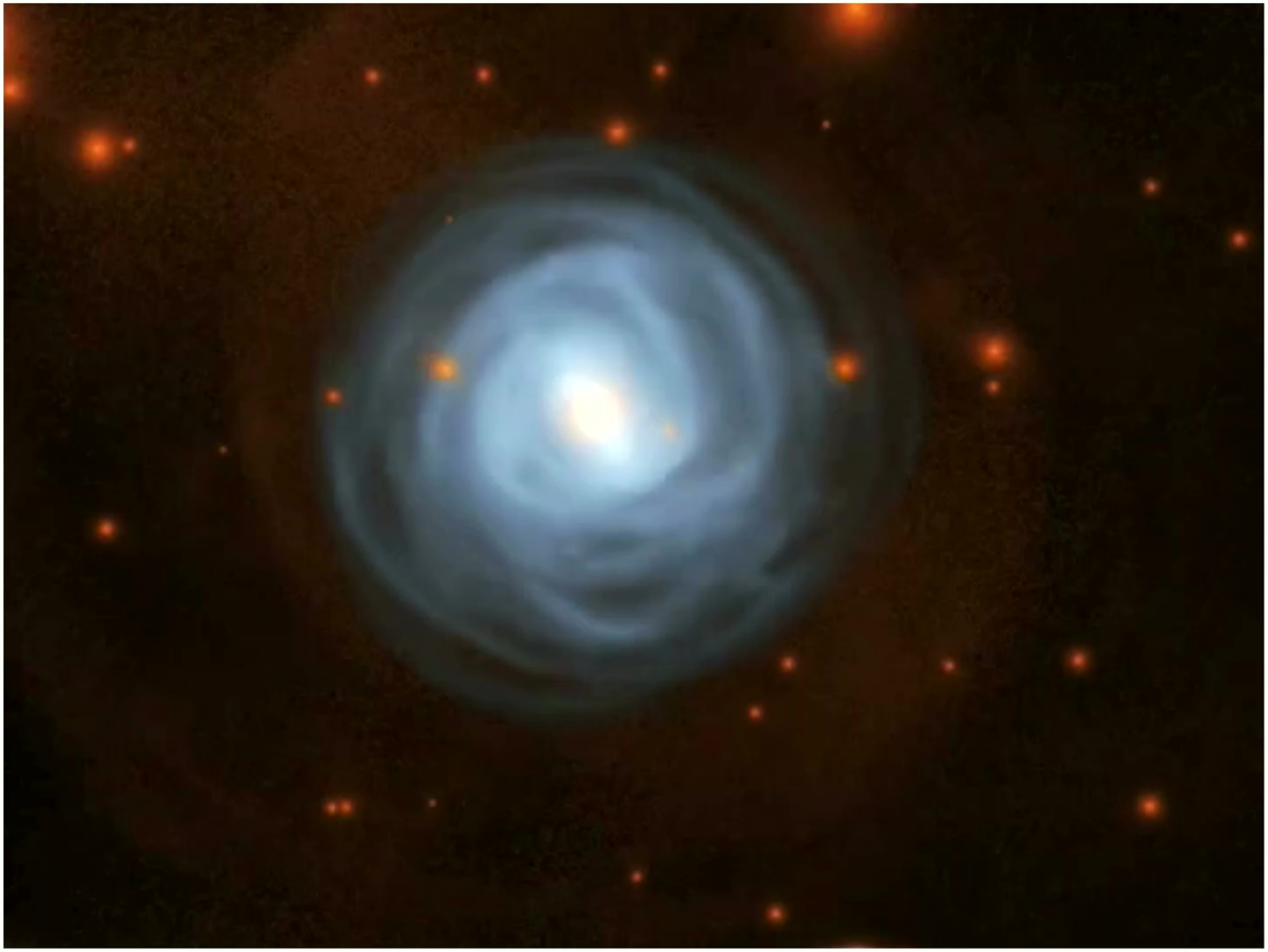
Warps are bending waves of the disk and involve a competition between the destabilizing centrifugal force as particles pass through a bend and the restoring gravitational force.

Perturbations with wavelength less than the Jeans length tend to be unstable

Bending instability is complementary to the Jeans instability



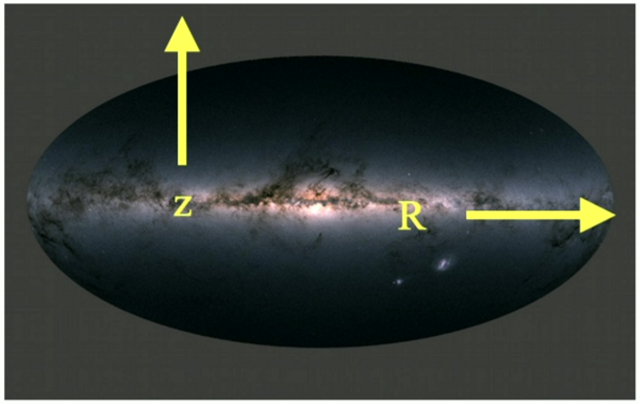

Satellites can provoke both in-plane and vertical perturbations in the disk
Isolated disk/bulge/halo model for M31
Relatively light disk, stable against the formation of a bar in the absence of halo substructure.
10% of smooth halo is then replaced by 100 subhalos
Gauthier, Dubinski & Widrow 2006
Dubinski, Gauthier, Widrow, & Nickerson 2008
for IC code, see Kuijken & Dubinski 1995 and
LW, Pym, & Dubinski 2008

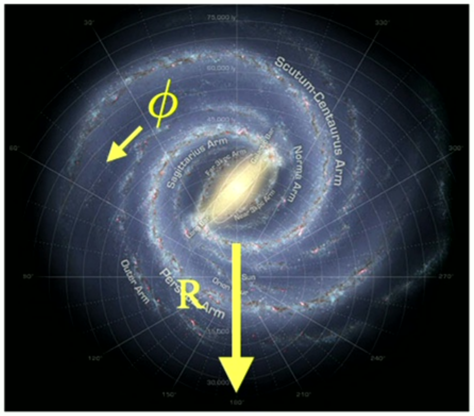


Brief interlude on astrometric observations

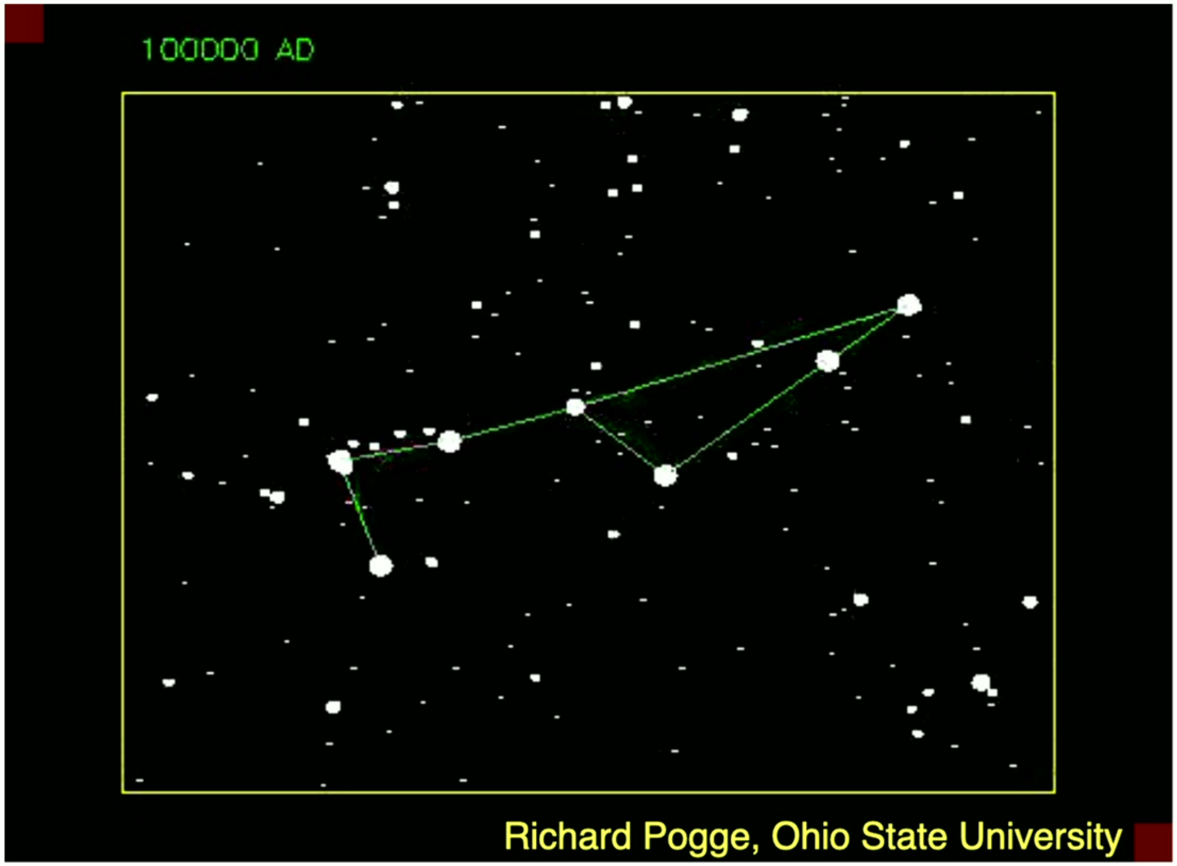
Astrometric observations are made in 6D phase space
using Galactic Coordinates

R, z, ϕ, and accompanying velocity components



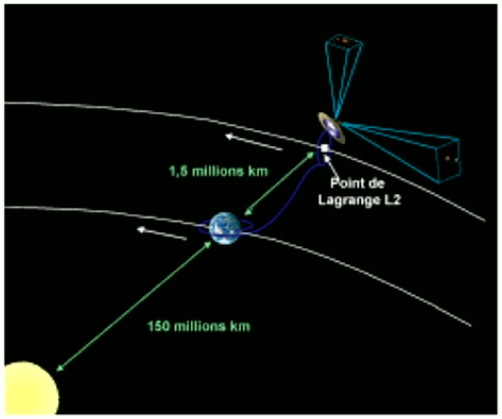


Big Dipper stars: proper motion over 200,000 years
Gaia aims to measure proper motions over 5 years!

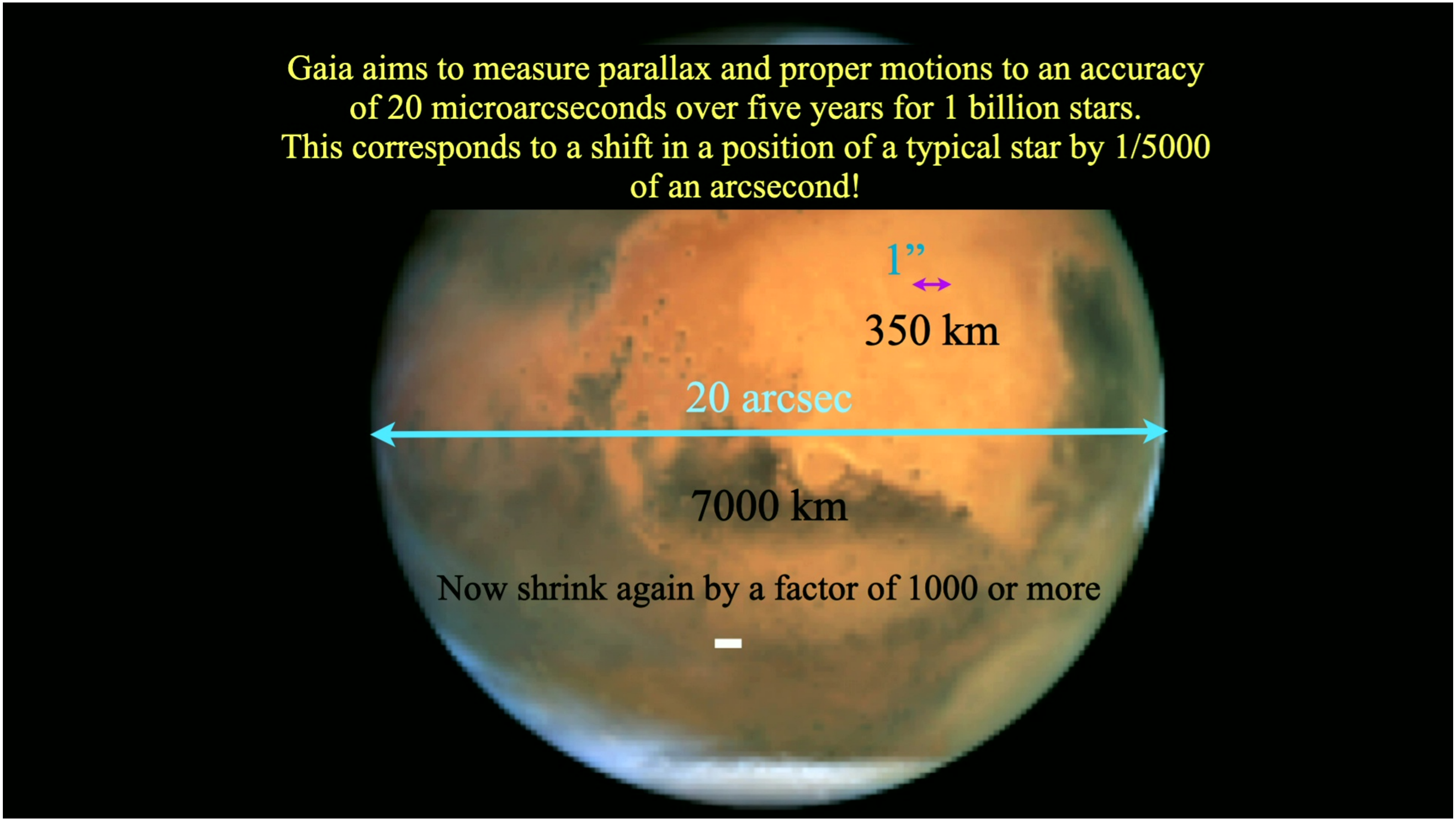


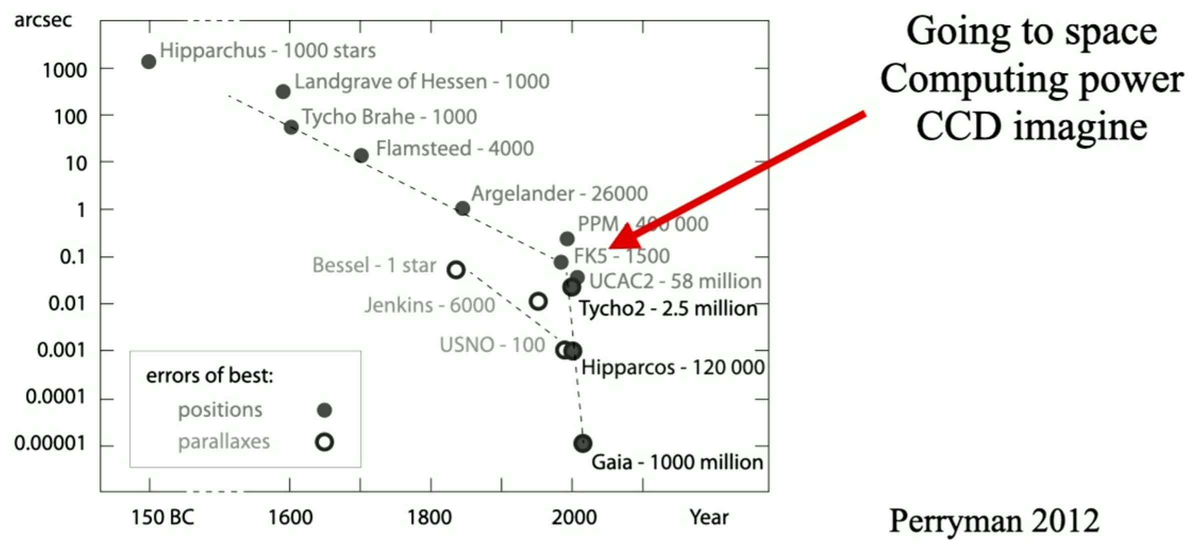
The field of Galactic dynamics is being propelled forward by data from the Gaia Space Telescope, a facility built and operated by the European Space Agency.

19 December 2013



Today


Gaia aims to measure parallax and proper motions to an accuracy of 20 microarcseconds over five years for 1 billion stars.
This corresponds to a shift in a position of a typical star by 1/5000 of an arcsecond!
1”
350 km
20 arcsec
7000 km
Now shrink again by a factor of 1000 or more



Perryman 2012

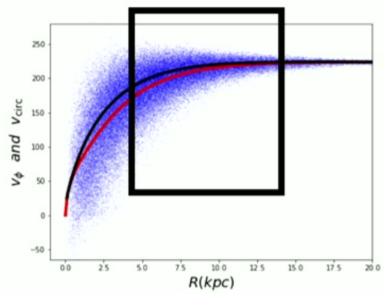
Data Release 2 (April 2018)
position + proper motion for 1.3 billion stars; radial velocities for 7M stars

Data Release 3 (April 2022): radial velocities for 33M stars

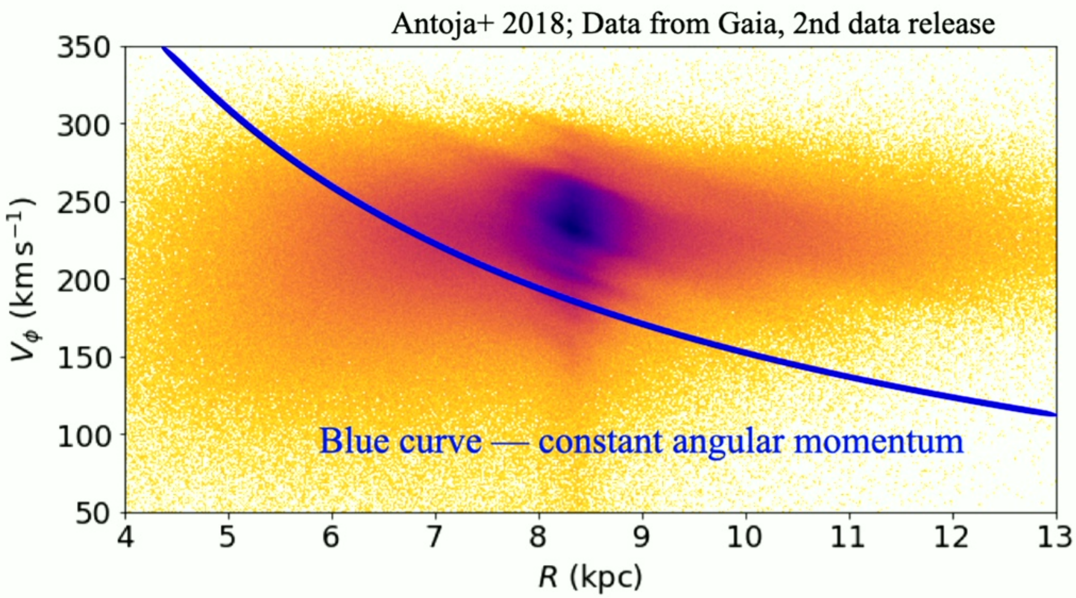
Two more DR's are planned in the coming years
All data are made public without any proprietary period

Gaia, as well as earlier surveys such as SDSS, RAVE, and LAMOST have revealed subtle and intriguing evidence of disequilibrium.
One example is from rotation curve data in the Solar Neighbourhood

V_ϕ - R distribution shows features that suggest phase mixing of stars with similar L_z

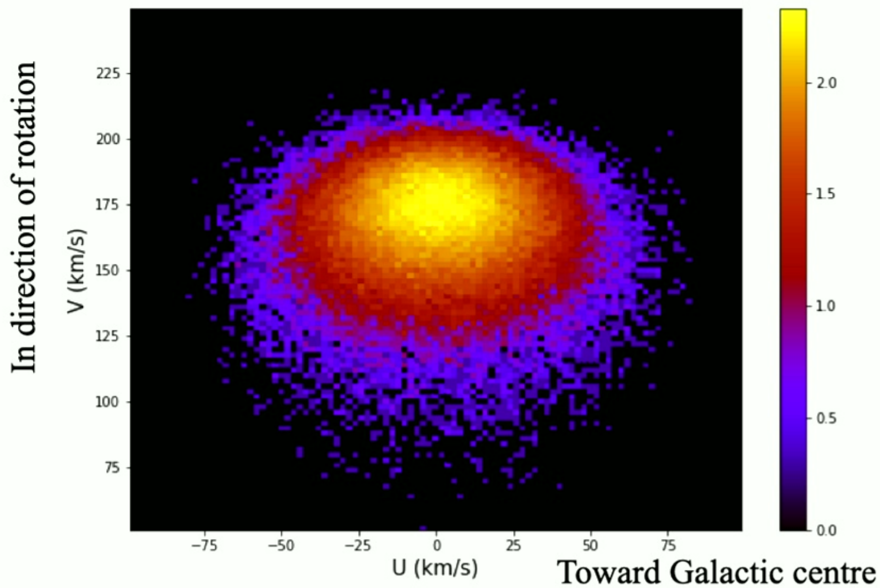


Equilibrium model



Consider next the $v_R - v_\phi$ distribution (epicyclic motion)

Here's what it looks like for the quasi-isothermal model



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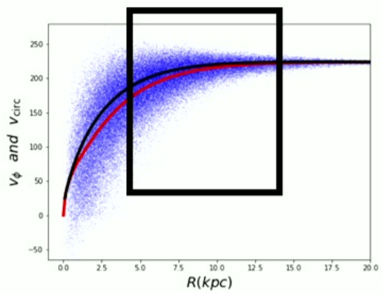

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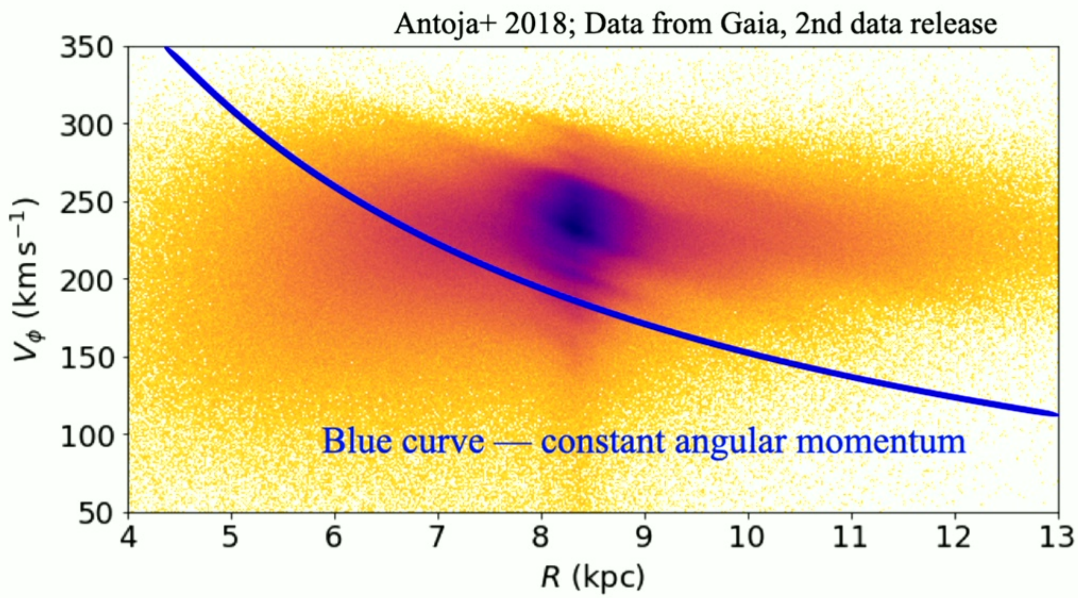

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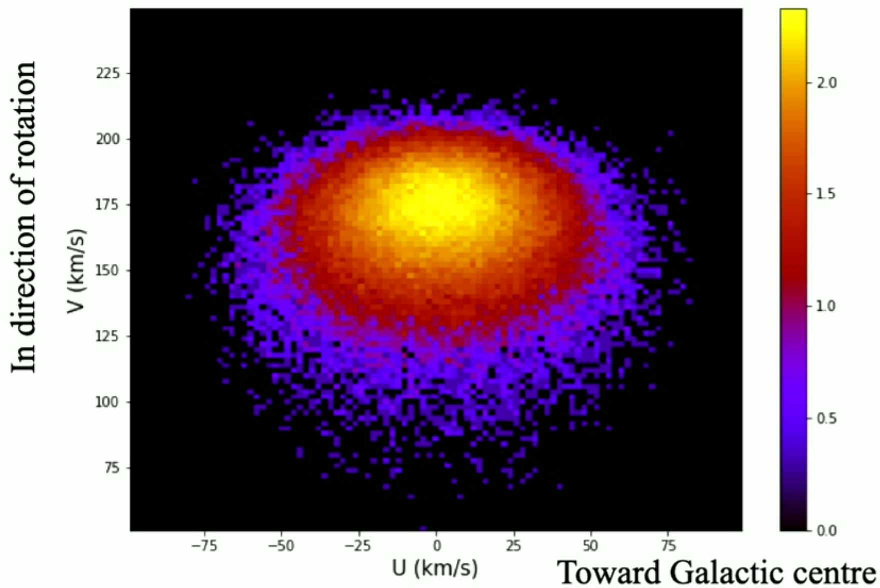
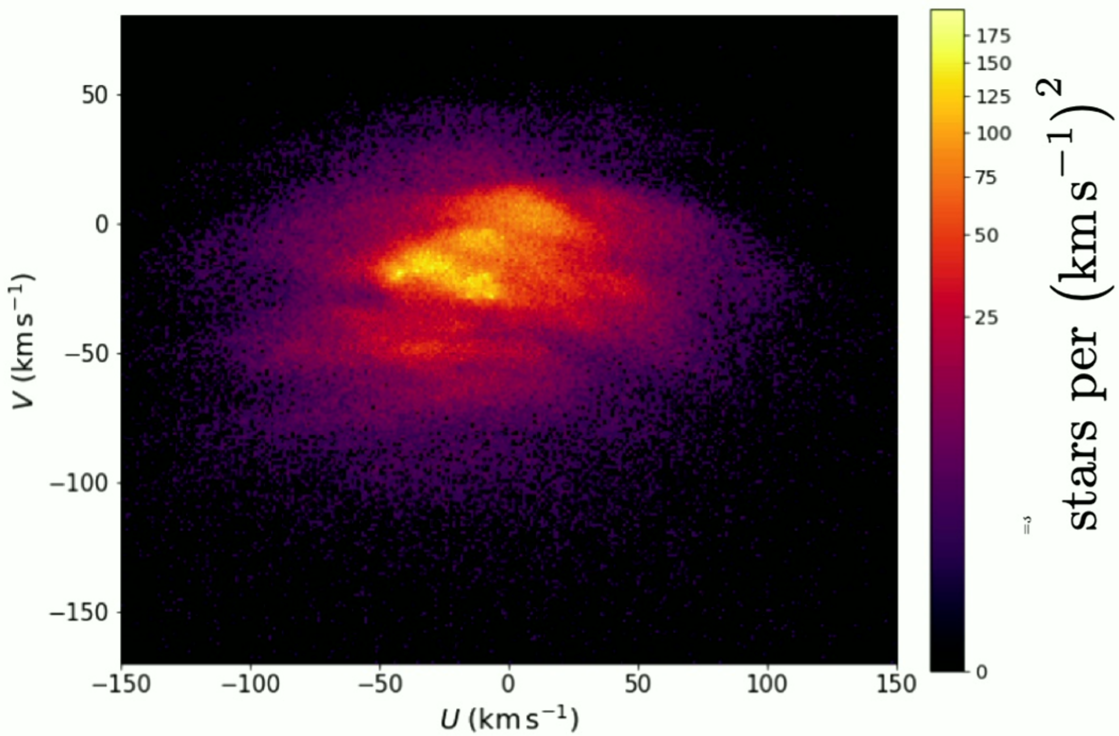


The actual distribution of stars in this plane in the Solar Neighbourhood has numerous features called moving groups.
One possibility is that these stars are on orbits in resonance with the bar



UV phase space from Gaia, Data Release 2

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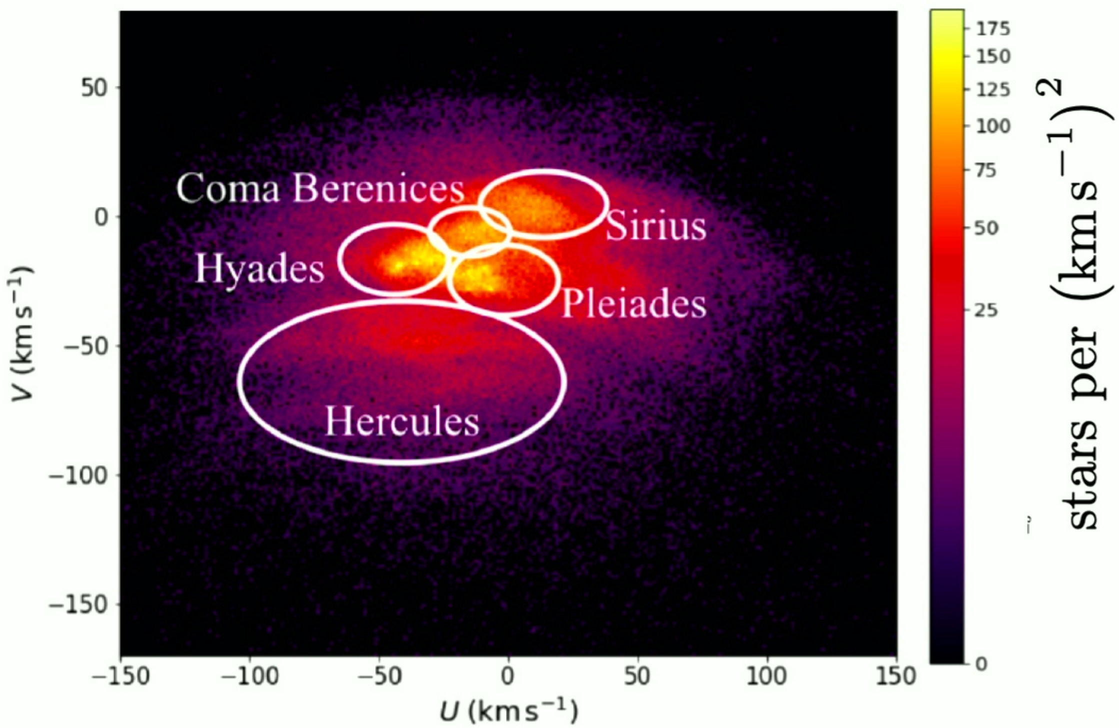

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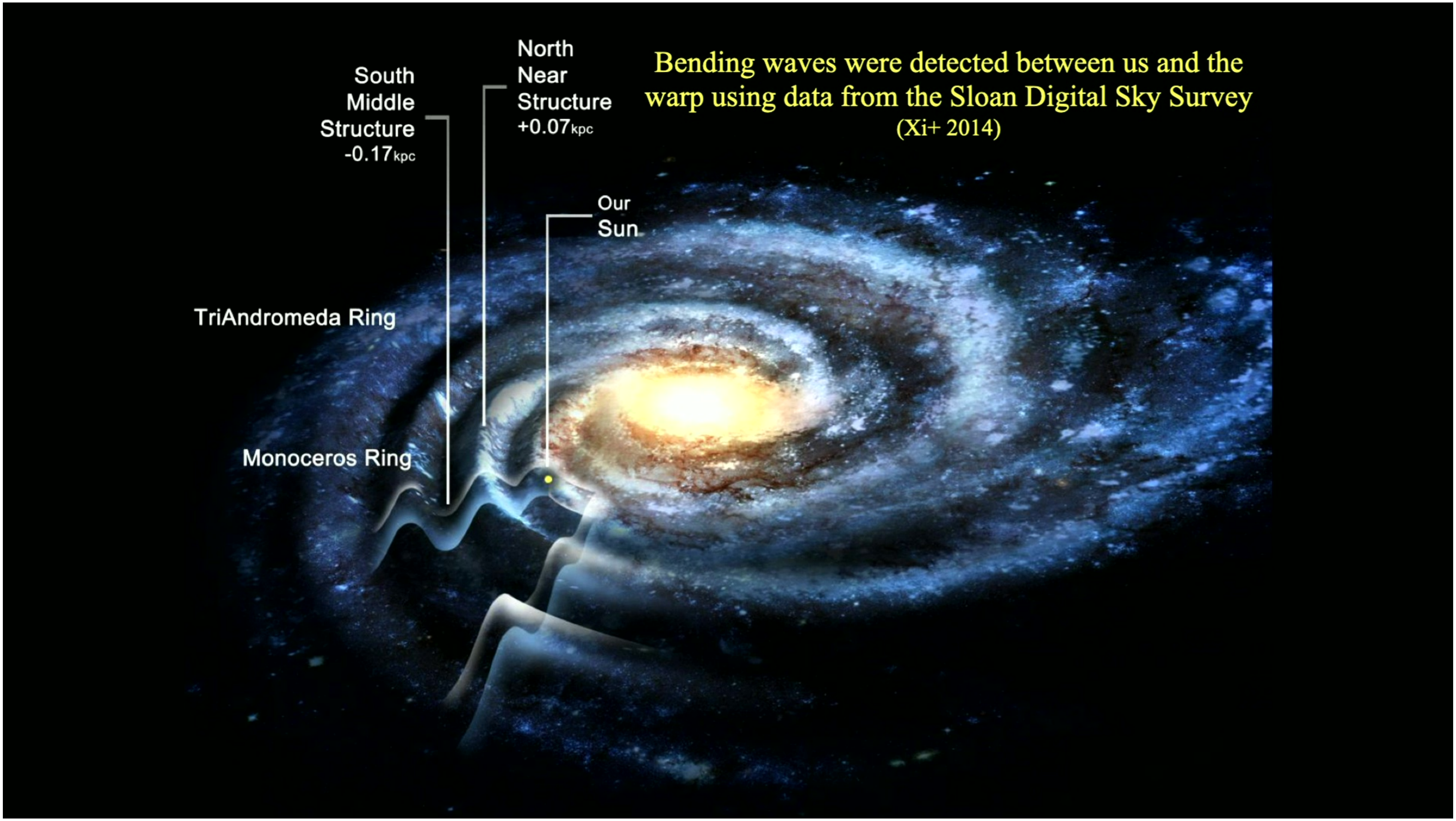
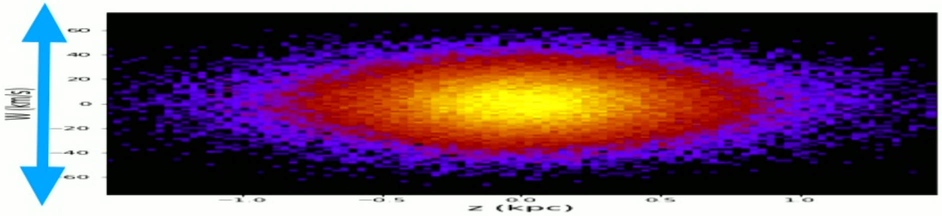
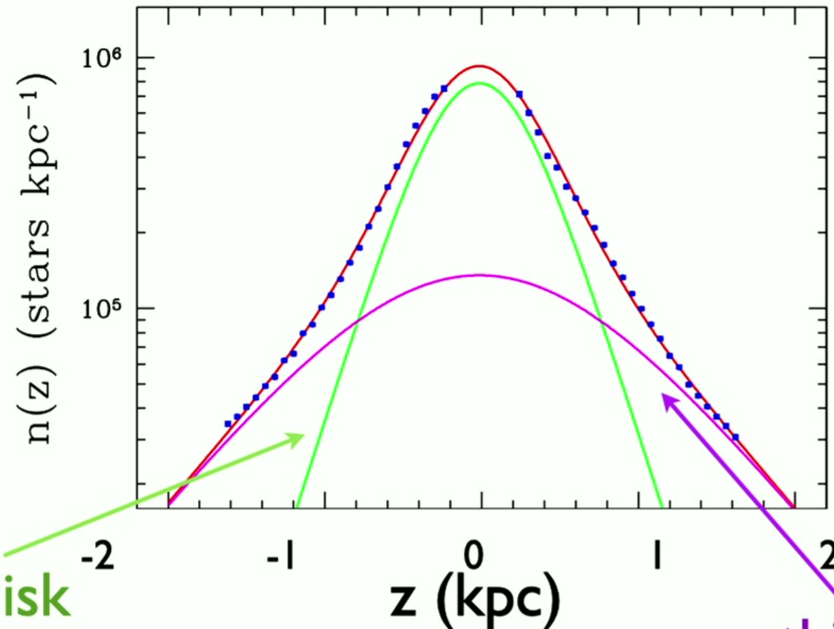

Bending waves were detected between us and the warp using data from the Sloan Digital Sky Survey
(Xi+ 2014)
South Middle Structure -0.17kpc
North Near Structure +0.07kpc
Our Sun
TriAndromeda Ring
Monoceros Ring

Integrate over velocity to get number density as function of z

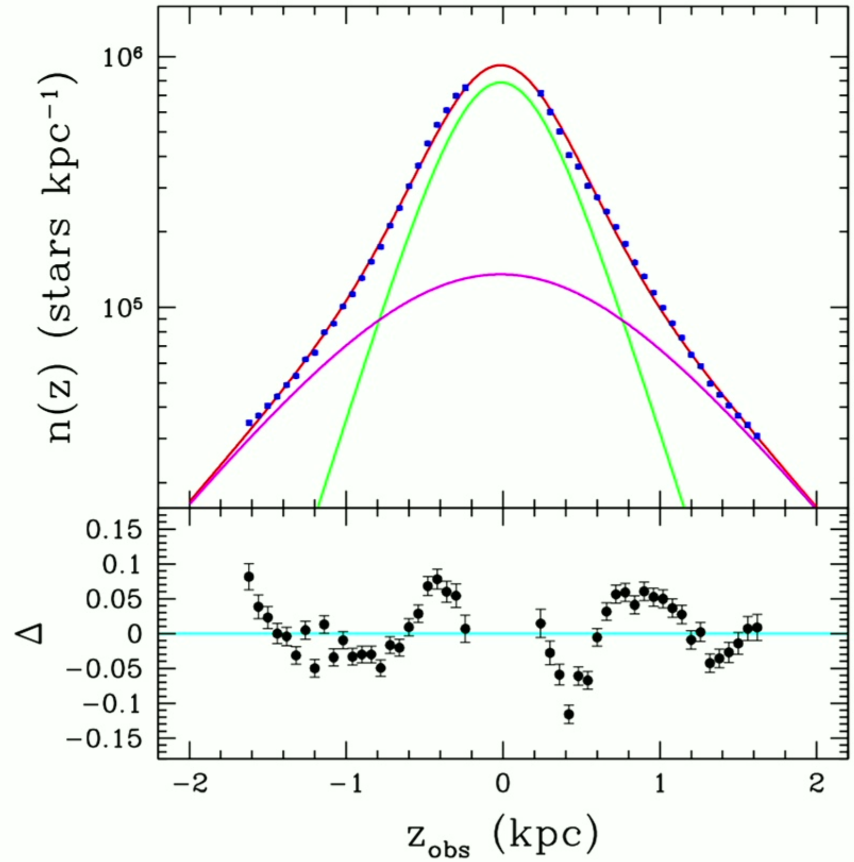




LMW+ 2012

Residuals to a simple two-disk model have a clear asymmetry about the mid plane of the Galaxy

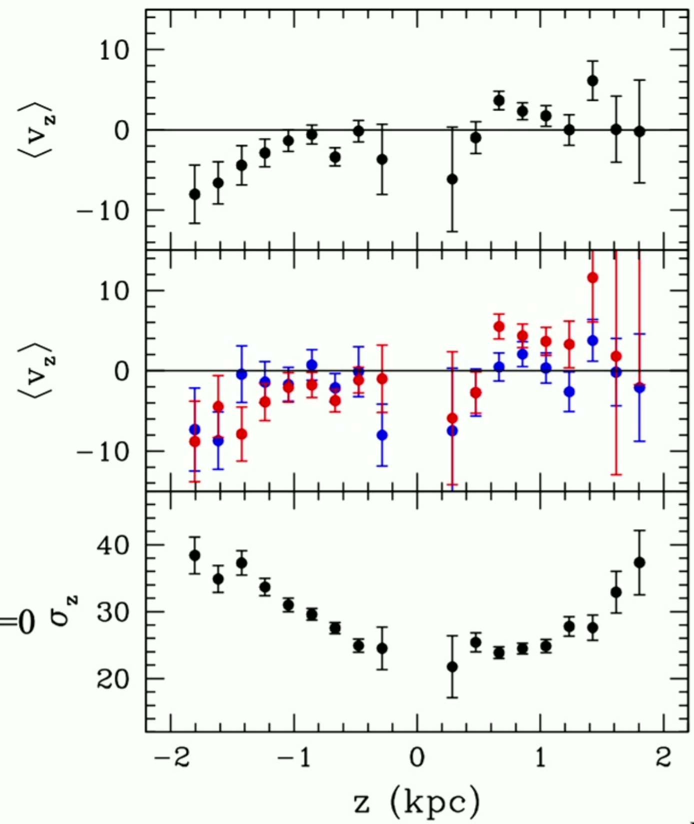
At first, the north-south asymmetry was viewed as an annoyance that might hinder our attempt to infer the gravitational potential.
We came to realize that they might be a new signal of disequilibrium in the Solar Neighbourhood



See also Yanny & Gardner 2013 with SEGUE
Bennett & Bovy 2018 with GDR2

Asymmetries also appear in the first and second vertical velocity moments

Mean vertical motion as a function of z.
Should be zero in equilibrium model



Velocity dispersion
Should be symmetric about z=0

Velocity dispersion increases with z as we reach into the thick disk

LMW+12

See also Williams+13 (RAVE) and Carlin+13 (LAMOST

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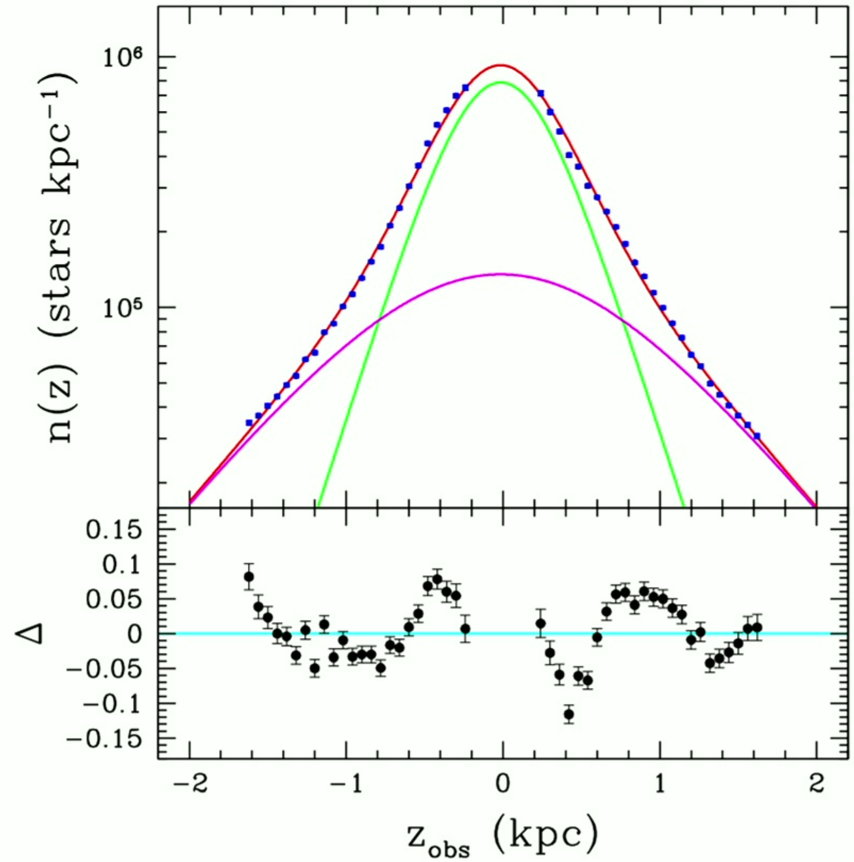

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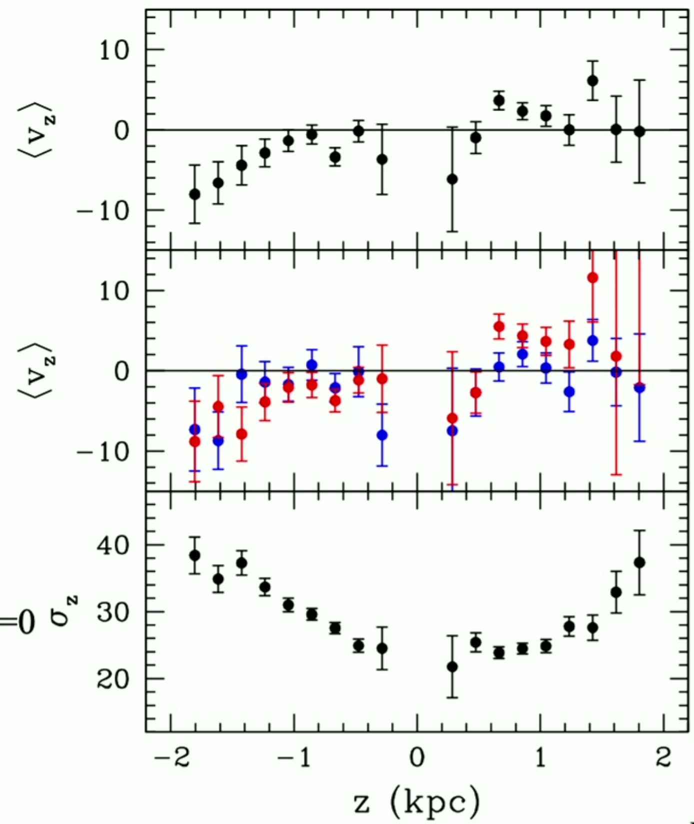

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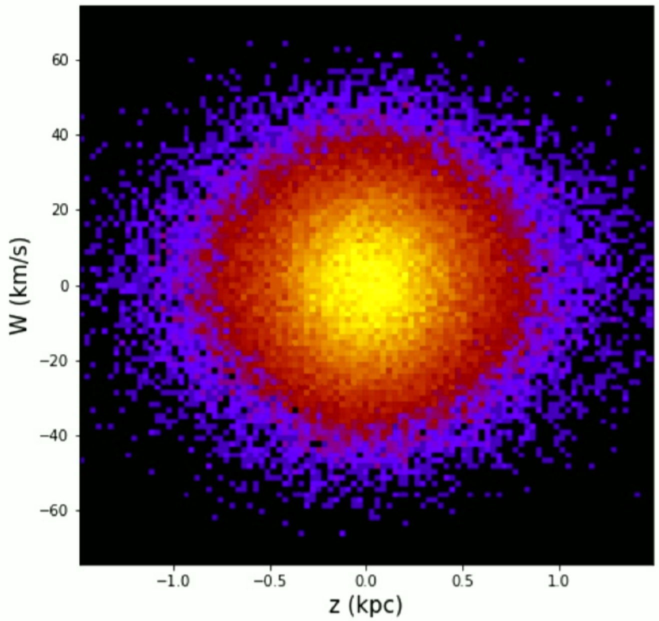
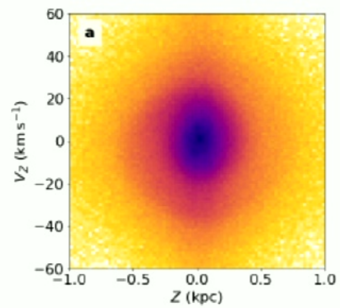
Phase Space Spirals in the z-v_z plane

Arc in Galactocentric R/integrate over ϕ, V_R and V_ϕ

Equilibrium

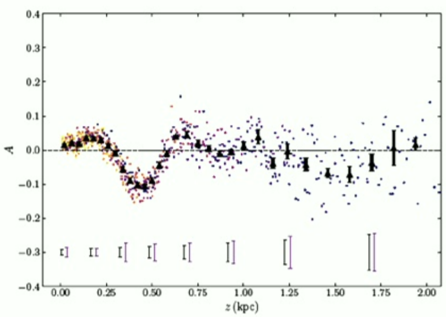




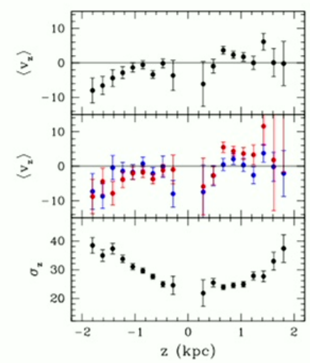
Integrate over v_z

$$\int dv_z v_z f$$

Asymmetry



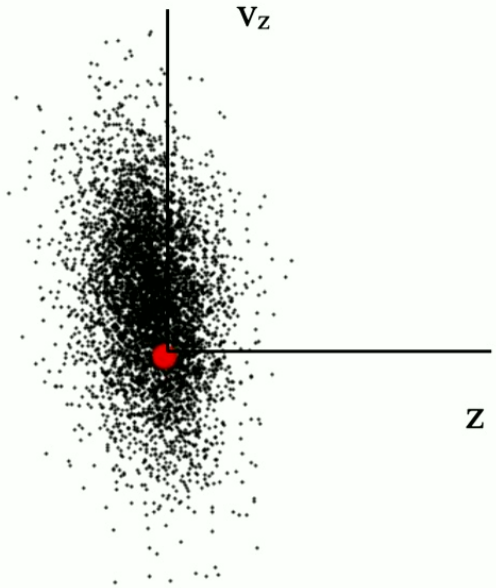
Z



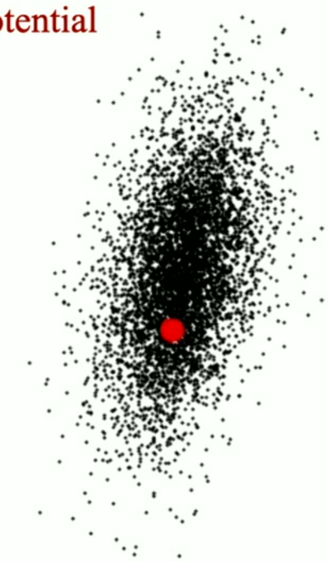
What is the origin of the vertical phase space spirals?

Consider a distribution of stars in z-v_z phase space that's been perturbed from it's equilibrium distribution (localized kick perpendicular to the disk plane)

harmonic potential



anharmonic potential



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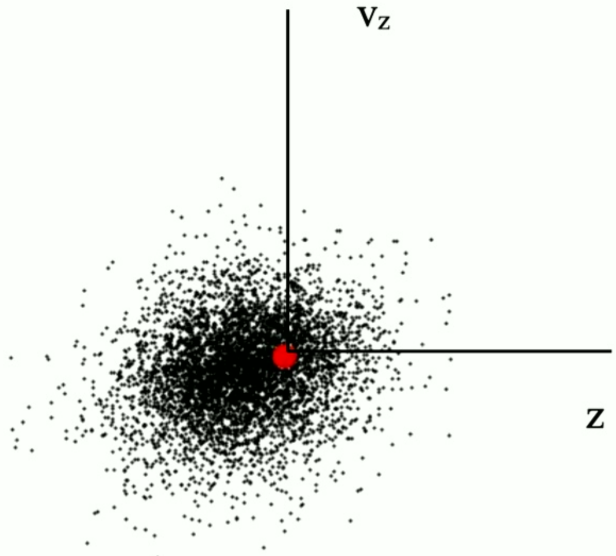

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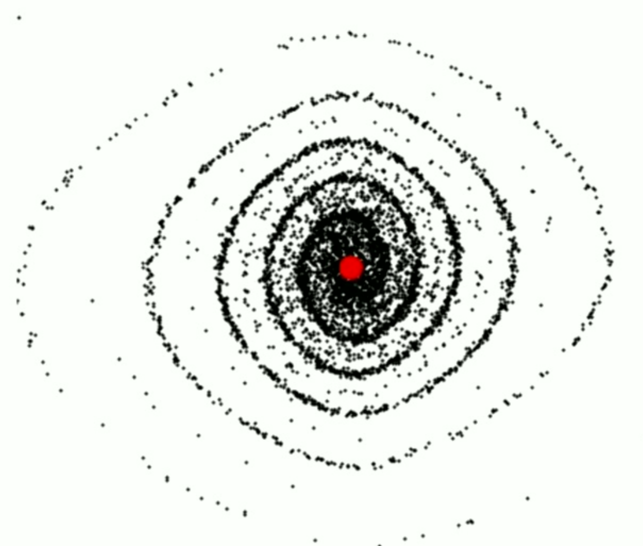

Open Questions

Is there a common origin or dynamical connection between different manifestations of disequilibrium?

Are corrugations in the disk and the local phase spirals transient phenomena from some recent event or features of disk that is being continually disturbed?

What is driving the departures from equilibrium? Internal gravitational instabilities or interactions with outside agents such as satellite galaxies.

Self-gravity is clearly important in the formation of bars and spiral structure. Is self-gravity also important for the phase spirals or can they be understood as simple kinematic phase mixing.