Title: Is the Milky Way Ringing?

Date: Apr 08, 2014 11:00 AM

URL: http://pirsa.org/14040137

Abstract: Recent observations from three different astronomical surveys have revealed evidence for asymmetries about the Galactic midplane in the kinematics of solar neighborhood stars. These asymmetries appear, in part, as compression-rarefaction modes in the bulk motions of stars perpendicular to the midplane. I will discuss the hypothesis that these motions were caused by the recent passage of a satellite galaxy or dark matter subhalo through the Galactic disk. In short, we may be witnessing the early stages of a disk-heating event during which the Galaxy's disk relaxes to a new state after interacting with substructure from its own halo.


Is the Milky Way Ringing
Larry Widrow
Queen's University
Cosmology Seminar
Perimeter Institute, April 2014
photo by Nick Risinger

Collaborators

LMW et al. ApJL 2012
LMW et al MNRAS 2014, in press

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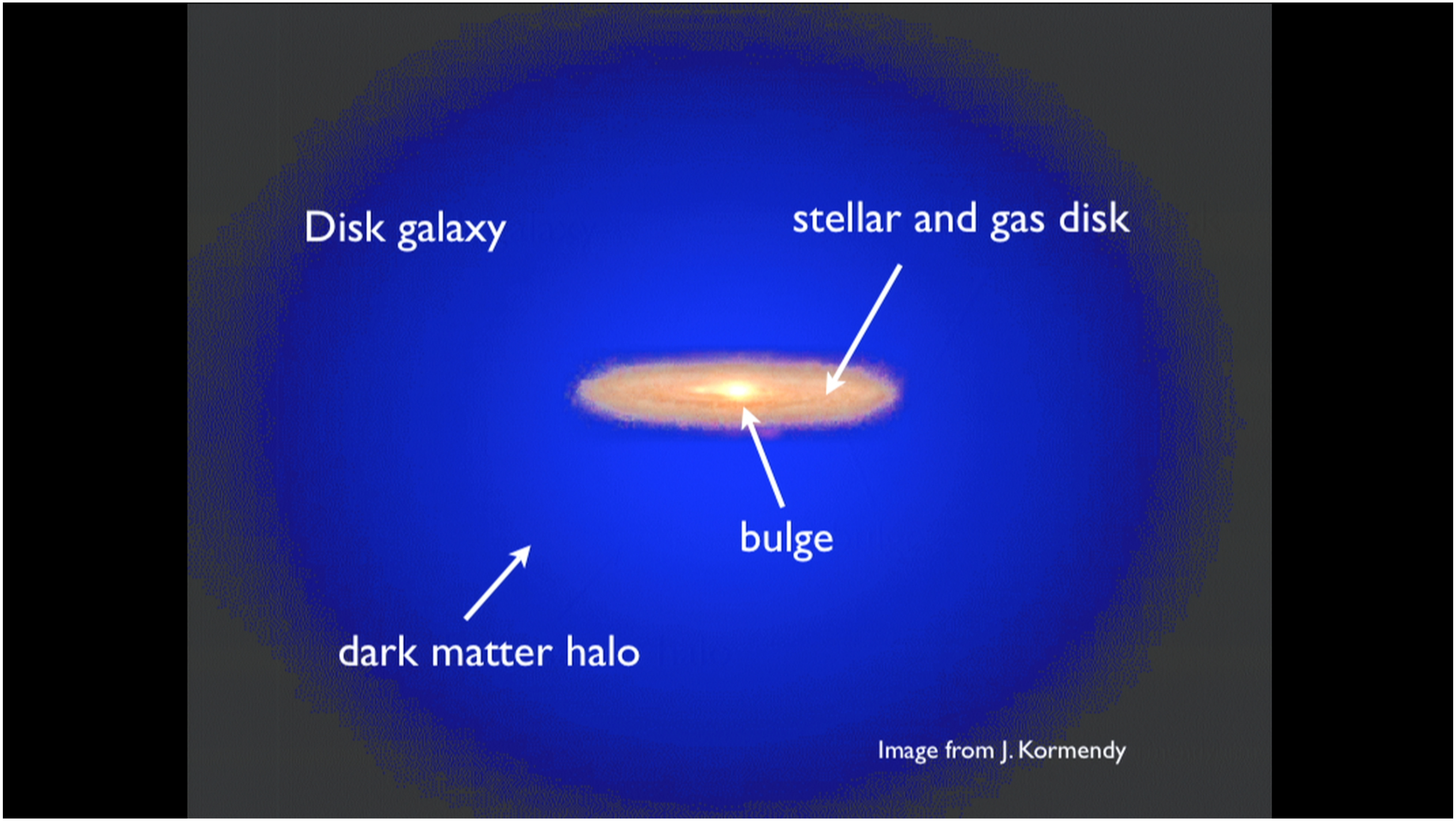
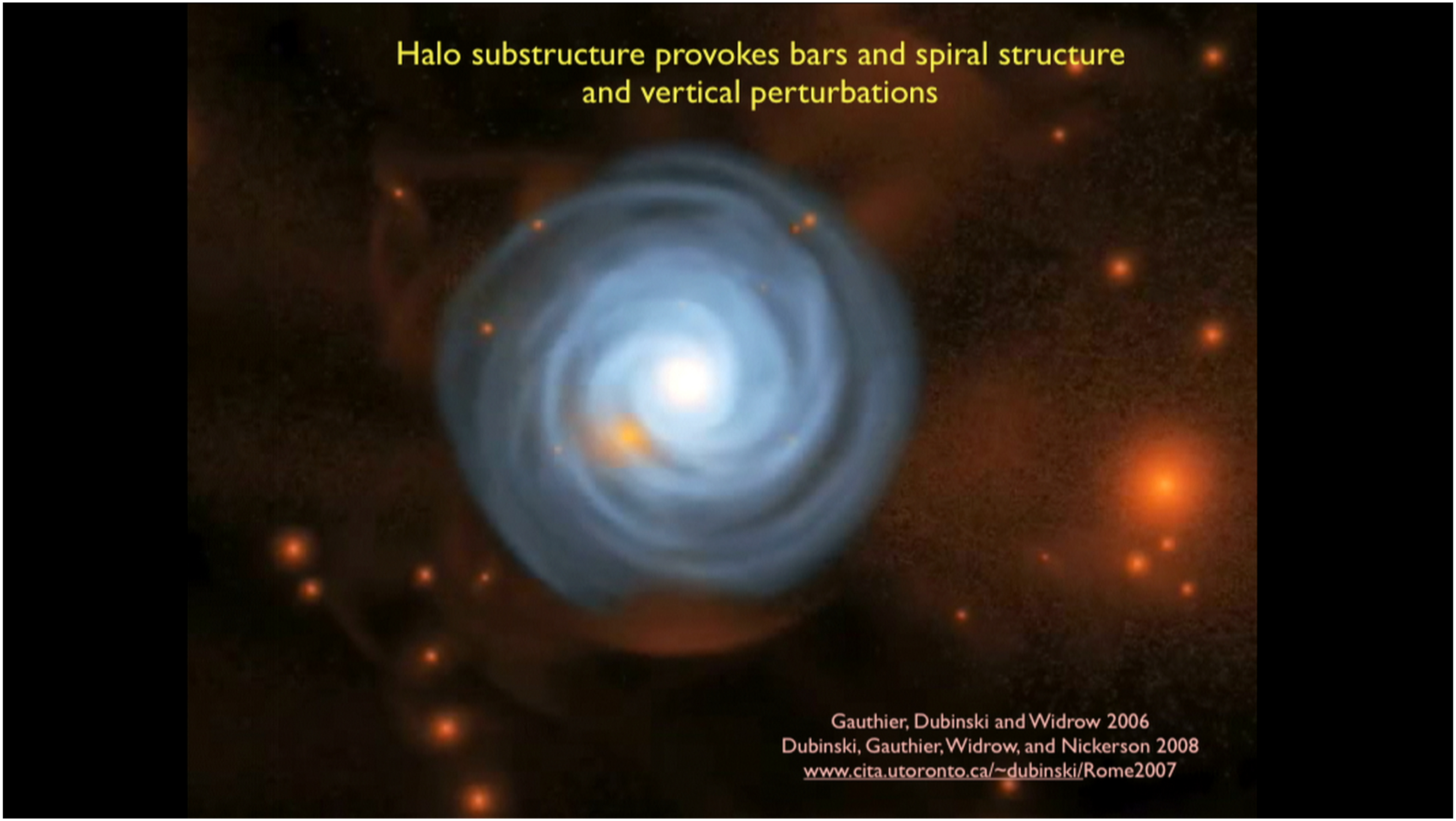
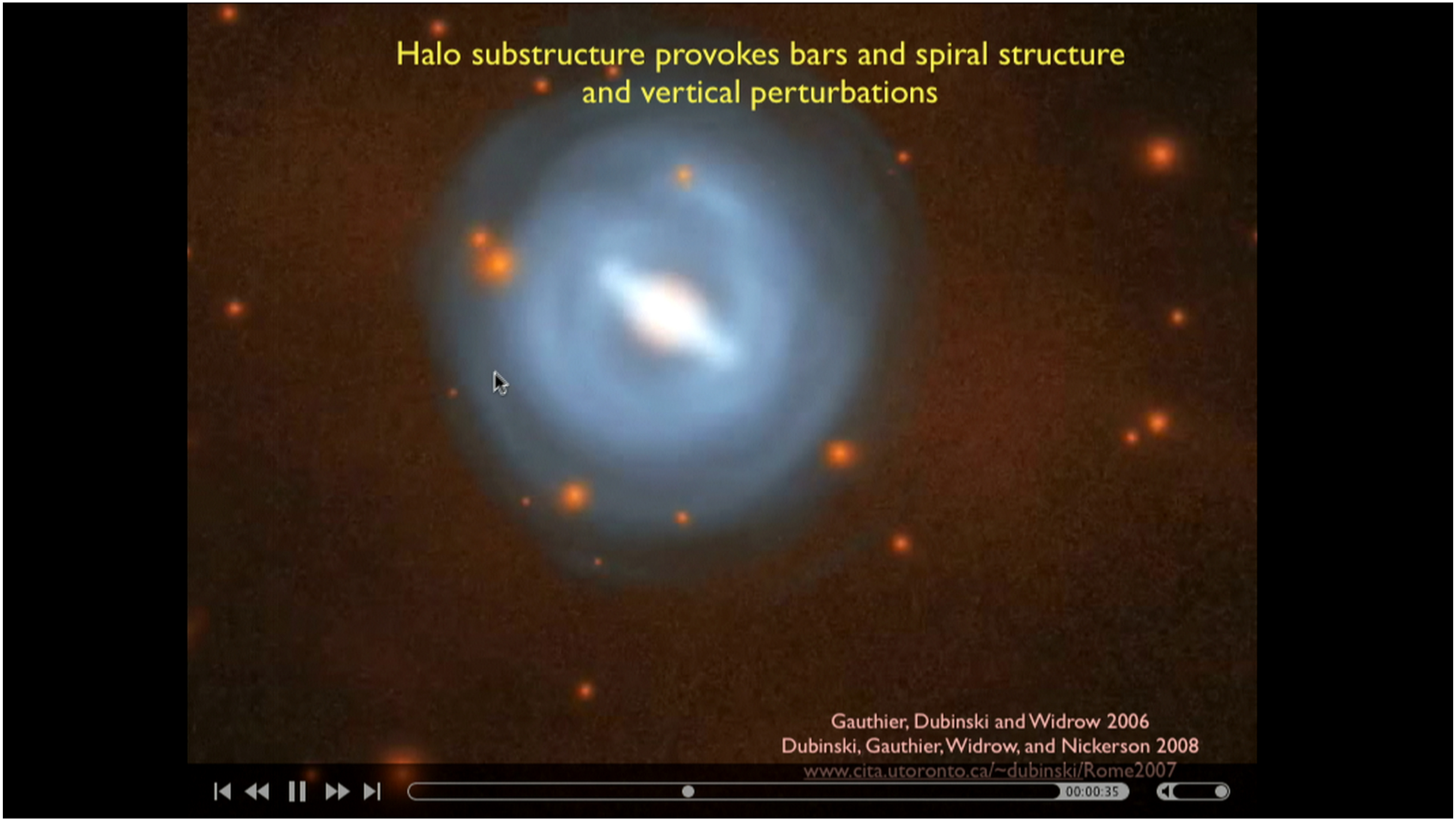

Disk galaxy
stellar and gas disk
bulge
dark matter halo
Image from J. Kormendy


z=0.0
High-resolution N-body simulations reveal significant substructure in dark matter halos. What effect does this substructure have on the stellar disks that live at the centres of these halos
figure from Diemand et al 2006
80 kpc


Halo substructure provokes bars and spiral structure
and vertical perturbations
Gauthier, Dubinski and Widrow 2006
Dubinski, Gauthier, Widrow, and Nickerson 2008
www.cita.utoronto.ca/~dubinski/Rome2007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Dubinski, Gauthier, Widrow, and Nickerson 2008
www.cita.utoronto.ca/~dubinski/Rome2007
00:00:35


Halo substructure provokes bars and spiral structure and vertical perturbations
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www.cita.utoronto.ca/~dubinski/Rome2007
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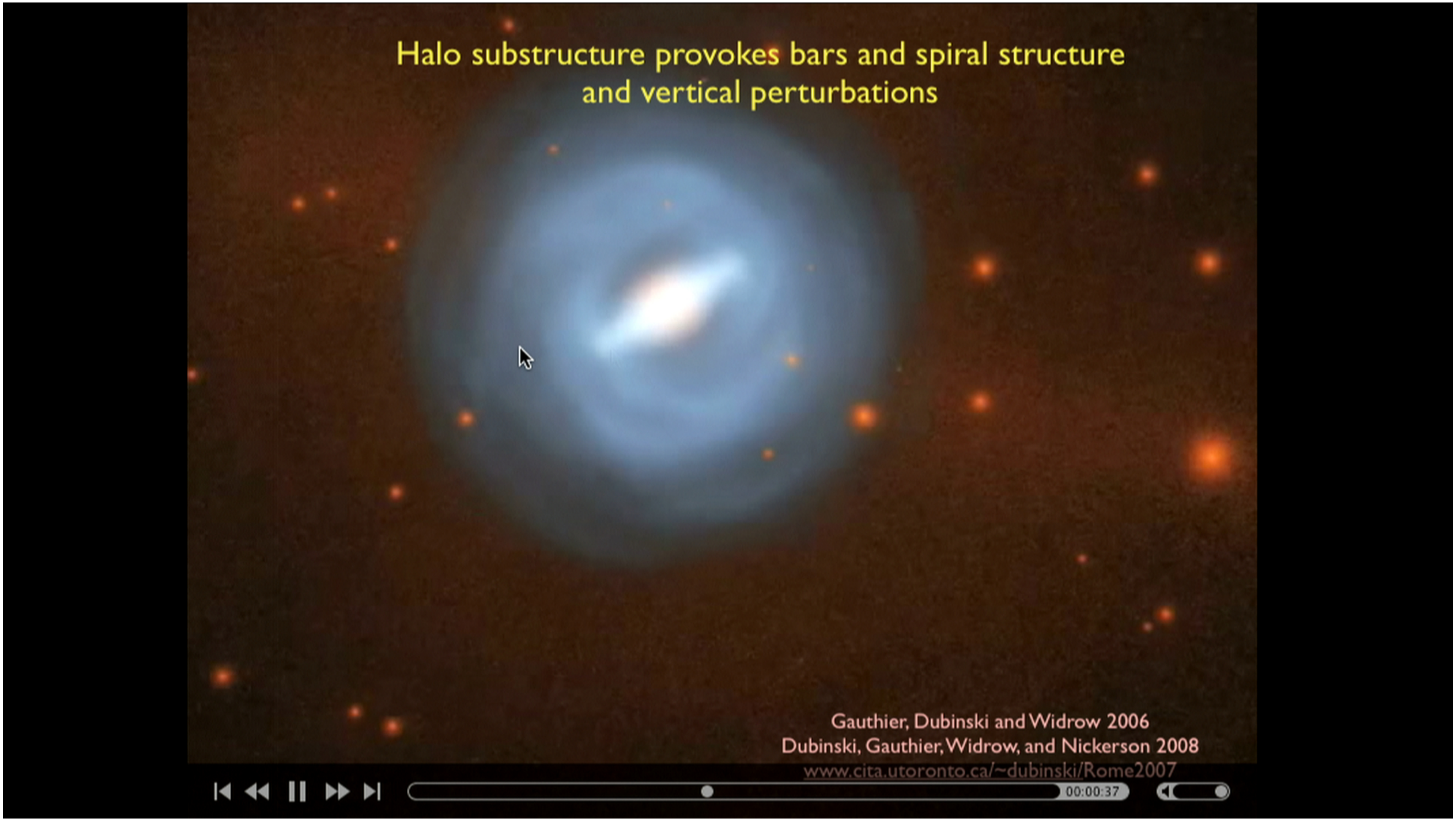
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www.cita.utoronto.ca/~dubinski/Rome2007
00:01:00


Halo substructure provokes bars and spiral structure
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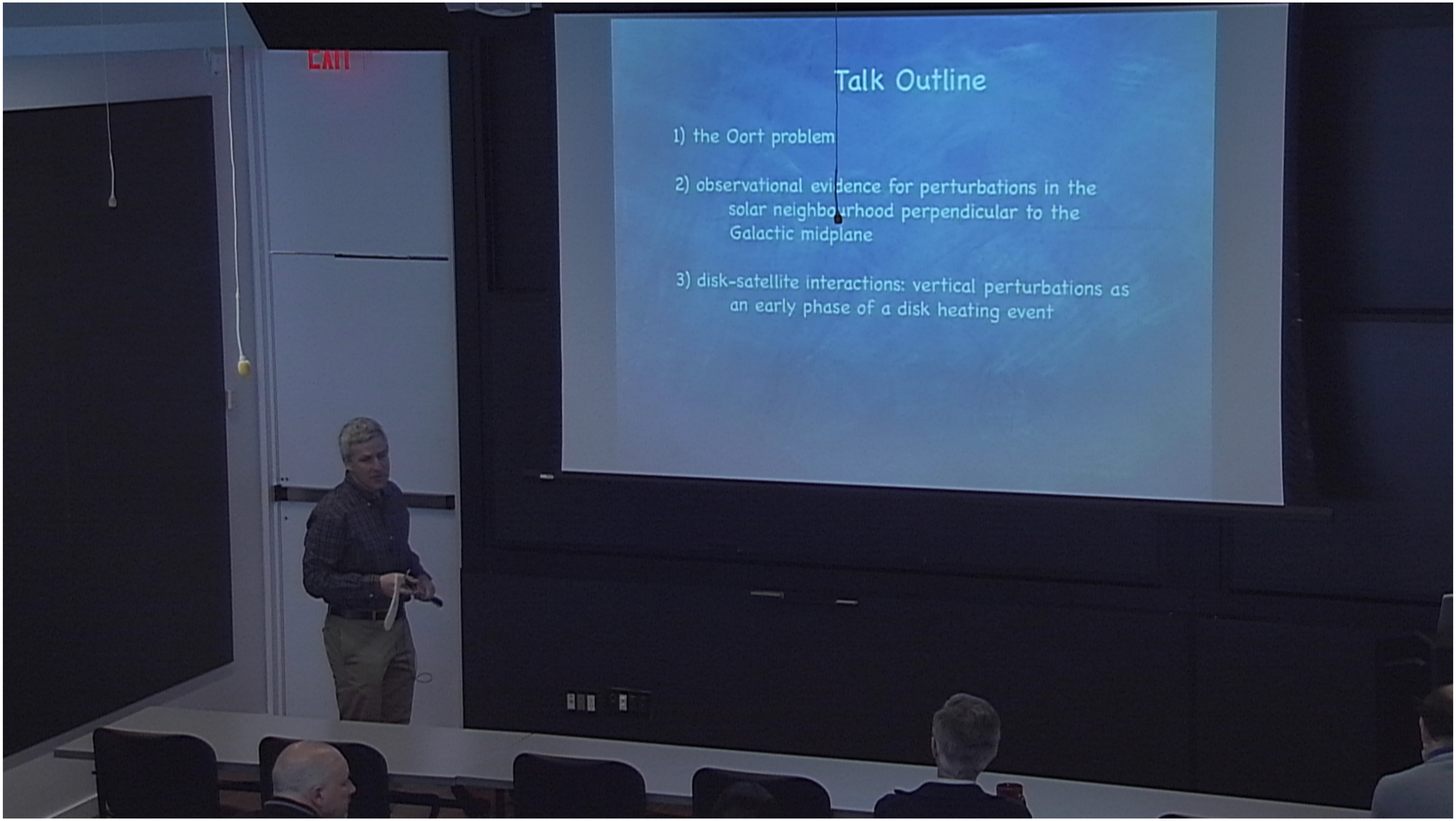
Talk Outline

1) the Oort problem

2) observational evidence for perturbations in the solar neighbourhood perpendicular to the Galactic midplane

3) disk-satellite interactions: vertical perturbations as an early phase of a disk heating event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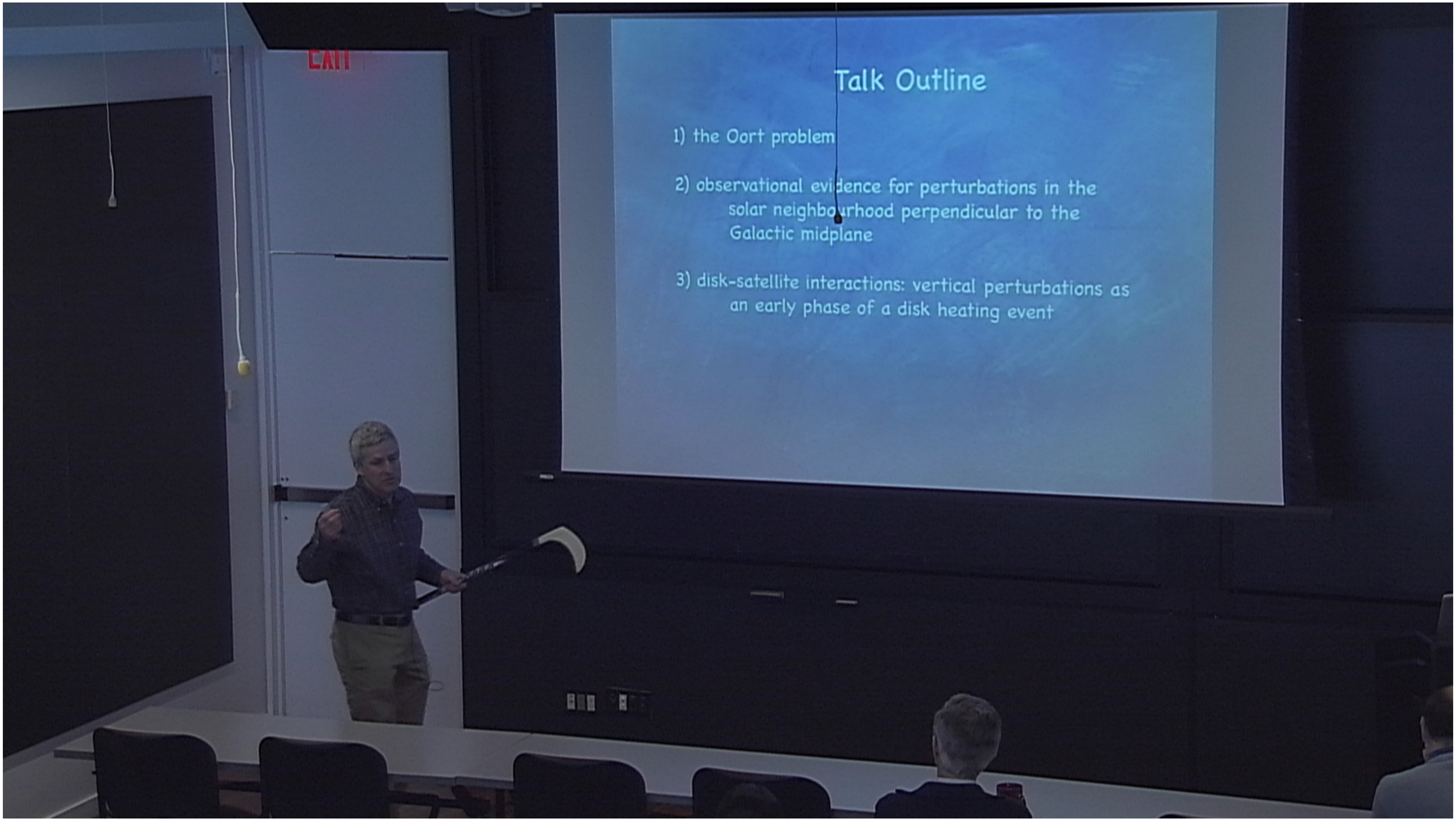
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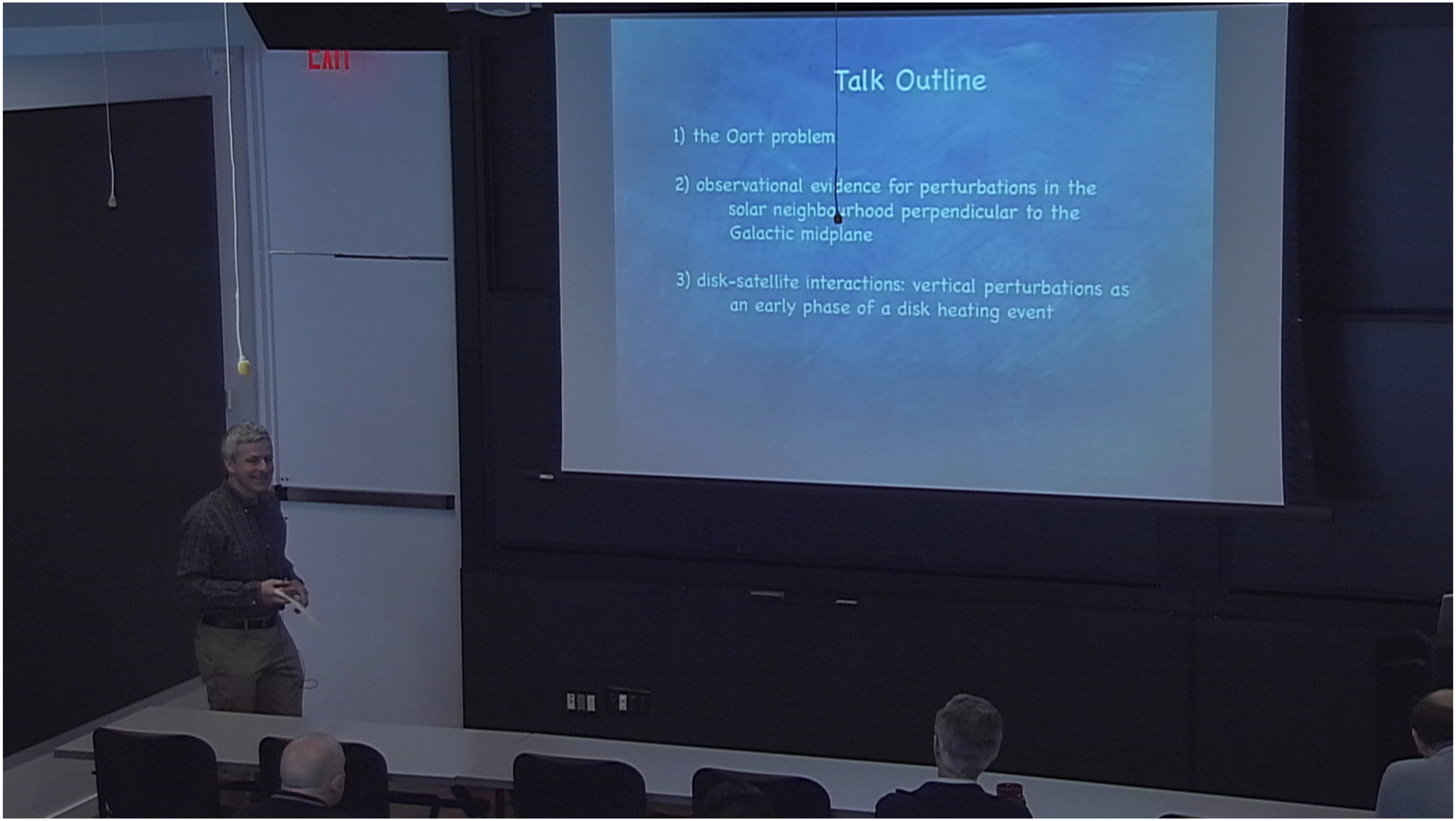
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BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

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.*

Jan Hendrik Oort, c. 1935

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.

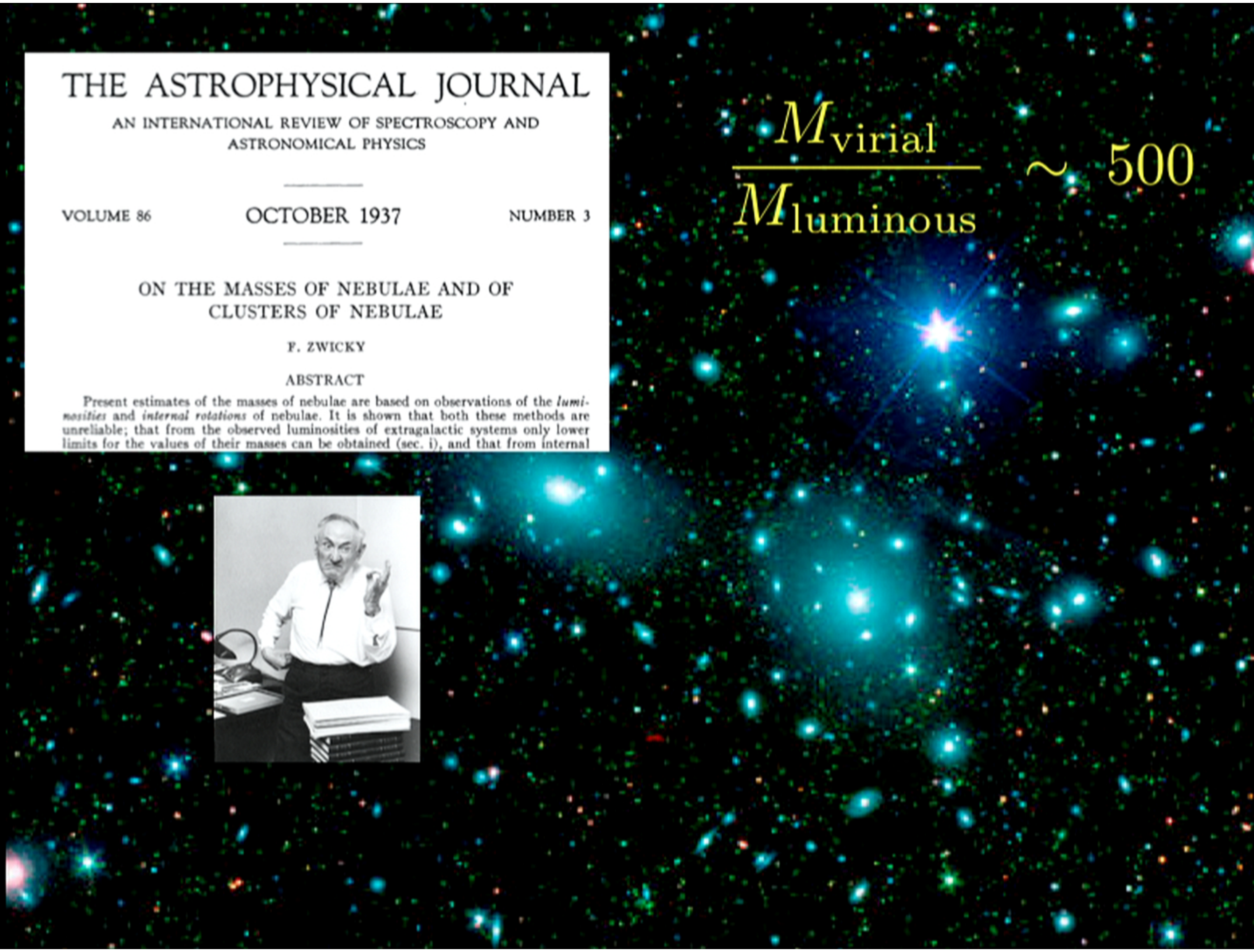
FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM[1]

By J. C. KAPTEYN[2]

1922

ABSTRACT

First attempt at a general theory of the distribution of masses, forces, and velocities in the stellar system.—(1) *Distribution of stars.* Observations are fairly well represented, at least up to galactic lat. 70°, if we *assume that the equidensity surfaces are similar ellipsoids of revolution*, with axial ratio 5.1, and this enables us to compute quite readily (2) *the gravitational acceleration at various points due to such a system*, by summing up the effects of each of ten ellipsoidal shells, in terms of the acceleration due to the average star at a distance of a parsec. The *total number of stars* is taken as 47.4×10^9. (3) *Random and rotational velocities.* The nature of the equidensity surfaces is such that the stellar system cannot be in a steady state unless there is a general rotational motion around the galactic polar axis, in addition to a random motion analogous to the thermal agitation of a gas. In the neighborhood of the axis, however, there is no rotation, and the behavior is assumed to be like that of a gas at uniform temperature, but with a gravitational acceleration ($G\eta$) decreasing with the distance ρ. Therefore the density Δ is assumed to obey the barometric law: $G\eta=-\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author finds that (4) *the mean mass of the stars* decreases from 2.2 (sun=1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming where the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine *the amount of dark matter* from its gravitational effect. (5) The *chief defects of the theory* are: That the equidensity surfaces assumed do not agree with the actual surfaces, which tend to become spherical for the shorter distances; that the *position of the center of the system* is not the sun, as assumed, but is probably located at a point some 650 parsecs away in the direction galactic long. 77°, lat. −3°; that the average mass of the stars was assumed to be the same in all shells in deriving the formula for the variation of $G\eta$ with ρ on the basis of which the variation of average mass from shell to shell and the constancy of the rotational velocity were derived—hence



THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

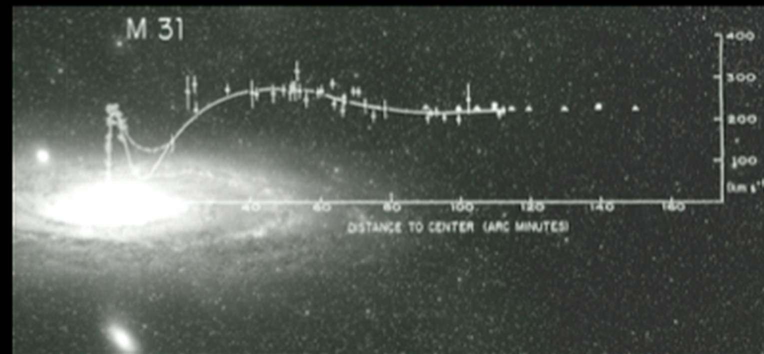
F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal

$$\frac{M_{\mathrm{virial}}}{M_{\mathrm{luminous}}} \sim 500$$

Scanned at the American Institute of Physics



ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21

ABSTRACT

Spectra of sixty-seven H II regions from 3 to 24 kpc from the nucleus of M31 have been obtained with the DTM image-tube spectrograph at a dispersion of 135 Å mm^{-1}. Radial velocities, principally from Hα, have been determined with an accuracy of ± 10 km sec^{-1} for most regions. Rotational velocities have been calculated under the assumption of circular motions only.

Beyond $R = 4$ kpc the total mass of the galaxy increases approximately linearly to $R = 14$ kpc, and more slowly thereafter. The total mass to $R = 24$ kpc is $M = (1.85 \pm 0.1) \times 10^{11}\ M_\odot$; one-half of it is located in the disk interior to $R = 9$ kpc. In many respects this model resembles the model of the disk of our Galaxy. Outside the nuclear region, there is no evidence for noncircular motions.

kinematic observations

$RA,\ DEC$ and subset of $\{d,\ v_{\rm los},\ \mu_\alpha,\ \mu_\delta\}$

$$\mathbf{a} = -\nabla\psi$$

assumptions about orbits

↓

gravitational potential

$$\nabla^2\psi = 4\pi G\rho$$

↓

mass distribution

photometric observations for $\rho_{\rm vis}$

↓

dark matter distribution

kinematic observations

$RA,\ DEC$ and subset of $\{d,\ v_{\rm los},\ \mu_\alpha,\ \mu_\delta\}$

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$$\nabla^2\psi = 4\pi G\rho$$

↓

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photometric observations for $\rho_{\rm vis}$

↓

dark matter distribution

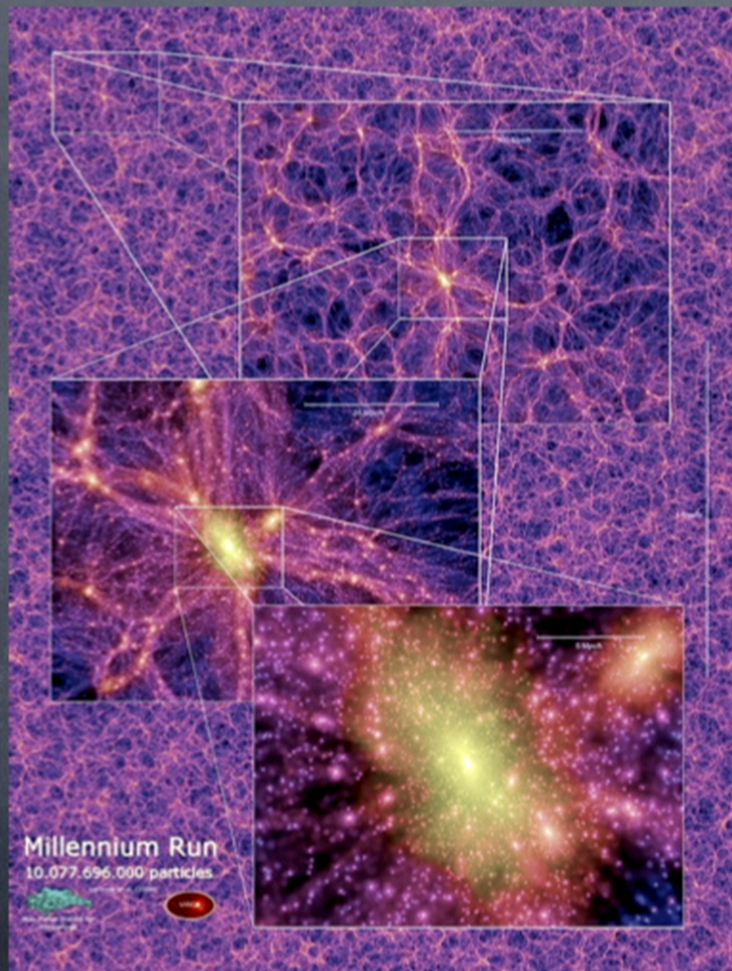
Rubin & Ford 1970

$$v_c^2 = \frac{GM(r)}{r}$$

flat rotation curve implies

$$M(r) \propto r \quad or \quad \rho(r) \propto r^{-2}$$

assumes tracers move on circular orbits
in the midplane and that the potential is axisymmetric

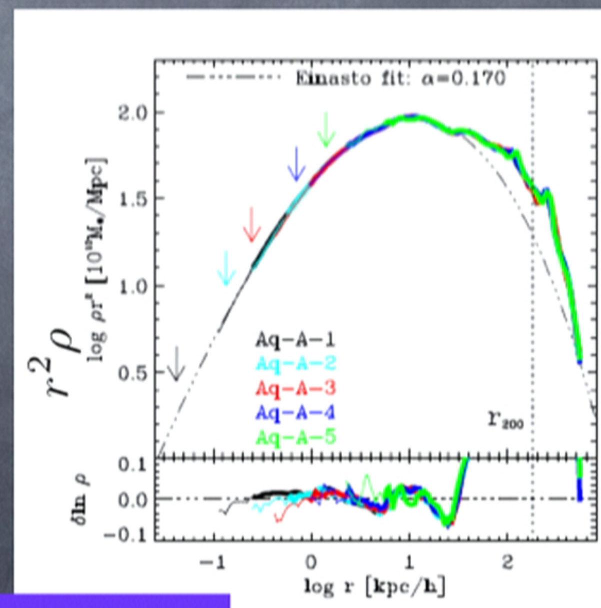


Springel et al (Virgo Consortium) 2005

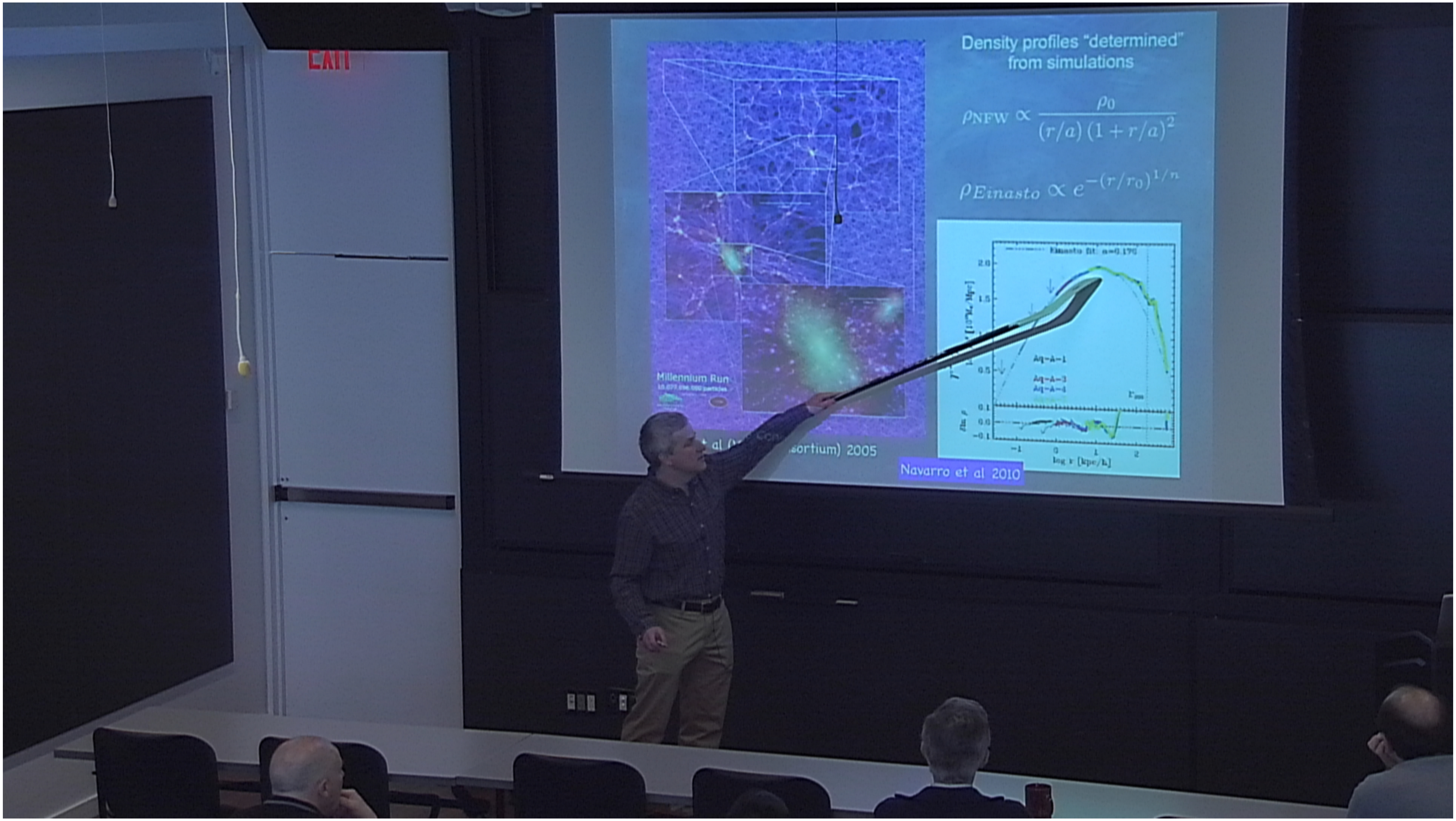
Density profiles "determined" from simulations

$$\rho_{\rm NFW} \propto \frac{\rho_0}{(r/a)\,(1+r/a)^2}$$

$$\rho_{Einasto} \propto e^{-(r/r_0)^{1/n}}$$



Navarro et al 2010



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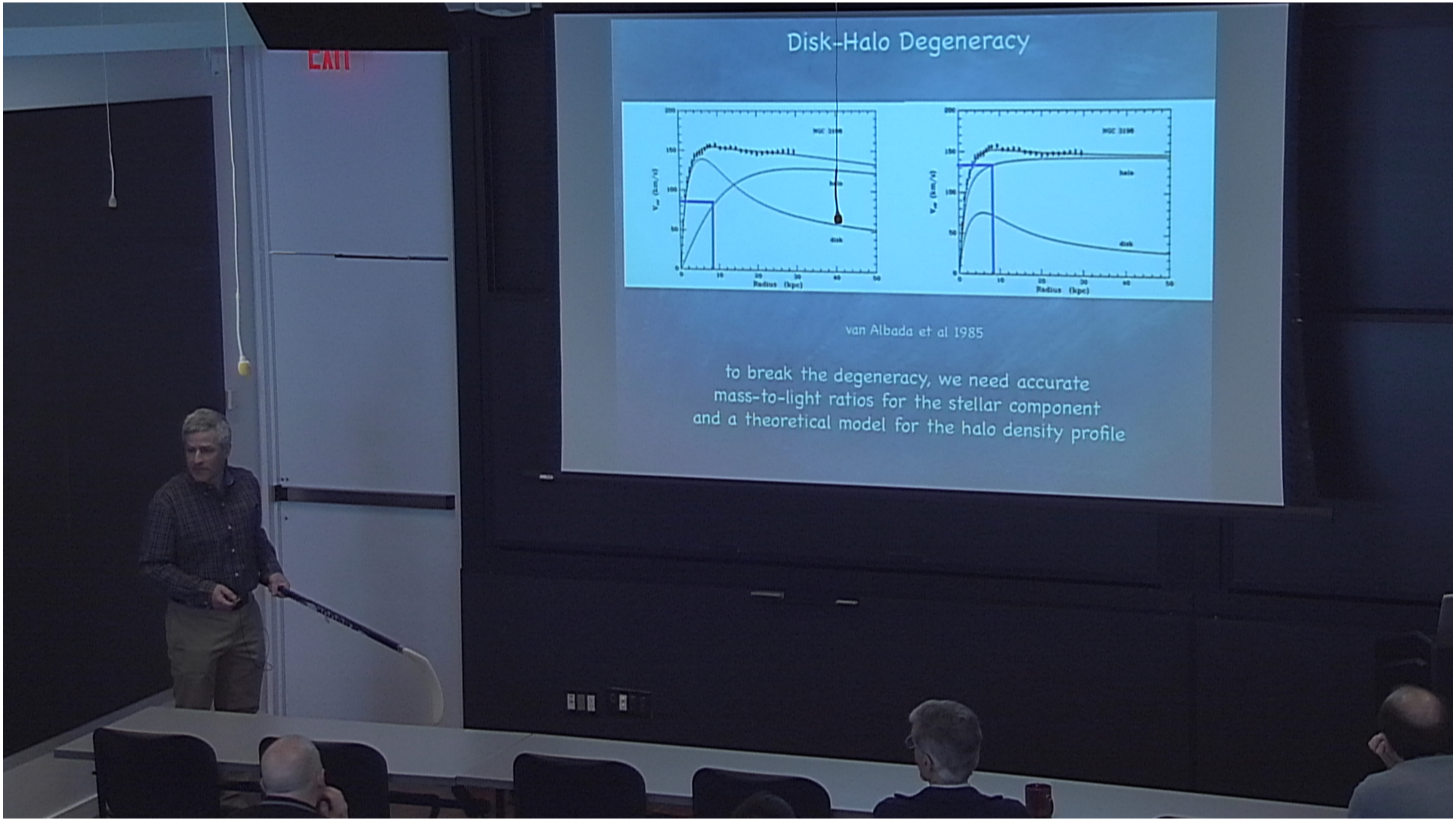
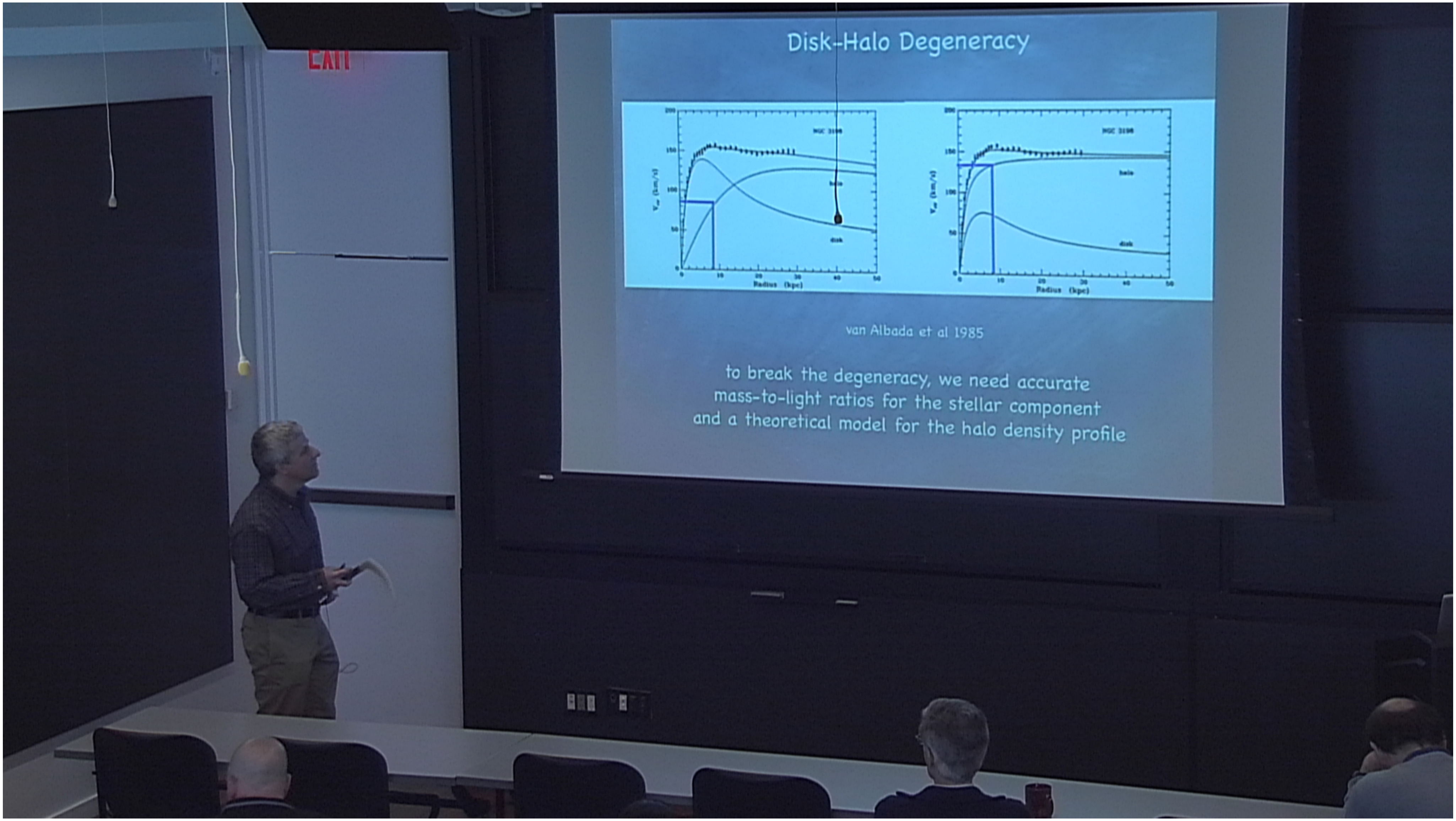
$\rho_{Einasto} \propto e^{-(r/r_0)^{1/n}}$
Millennium Run
sortium) 2005
Navarro et al 2010
Aq-A-1
Aq-A-3
Aq-A-4
log r [kpc/h]


Disk-Halo Degeneracy
NGC 3198
halo
disk
Radius (kpc)
van Albada et al 1985
to break the degeneracy, we need accurate
mass-to-light ratios for the stellar component
and a theoretical model for the halo density profile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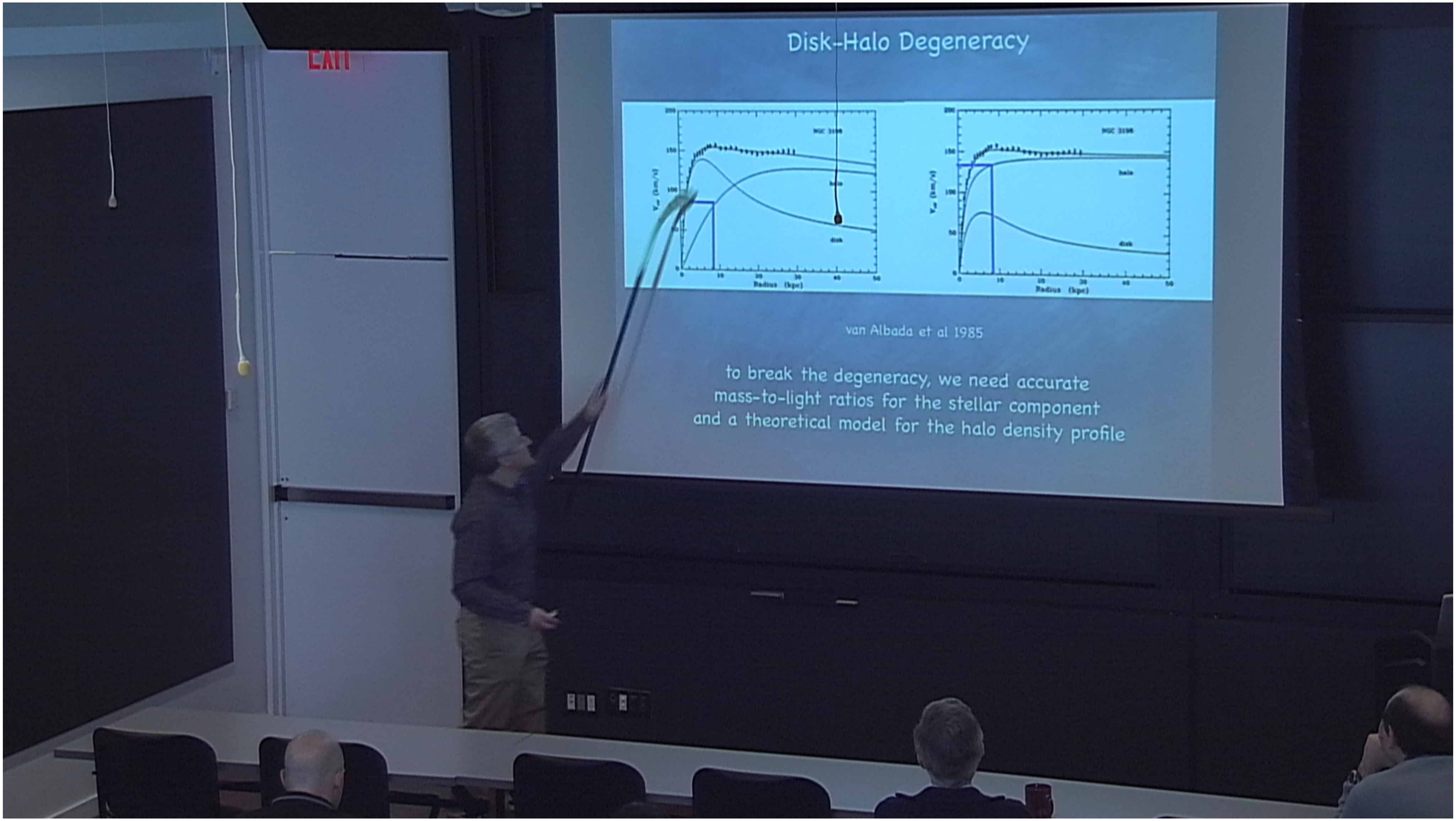

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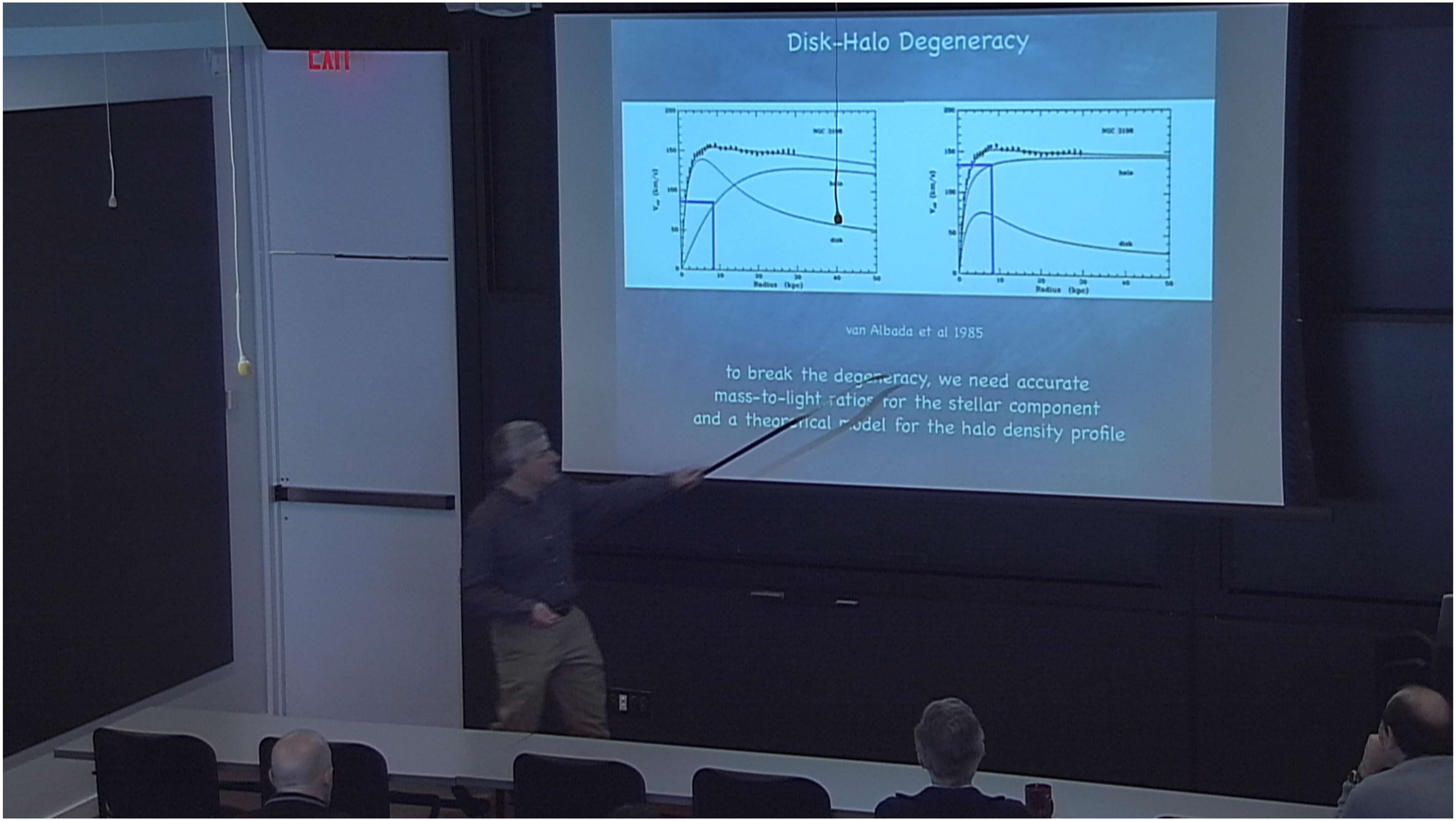
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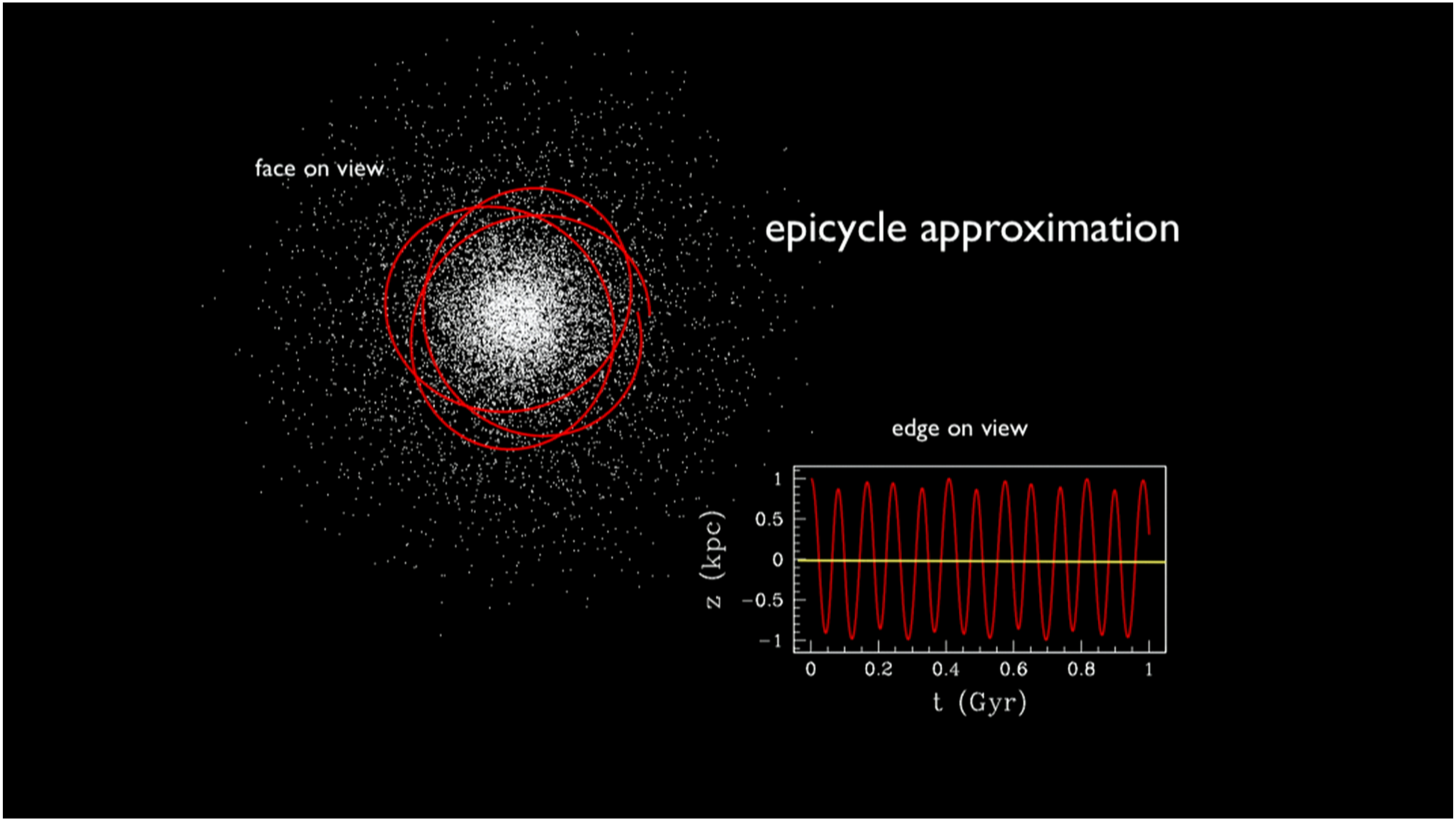
For the Oort problem decouple "z" dependence and ignore variations in the plane of the disk

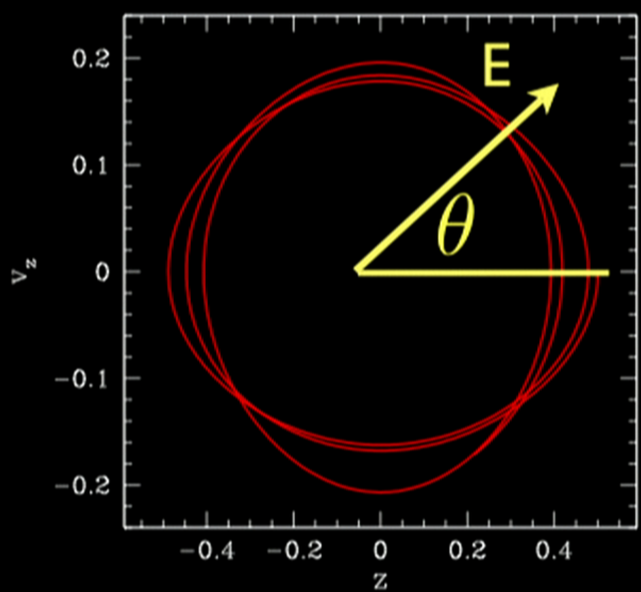
photo by Axel Mellinger

approximate integral of motion

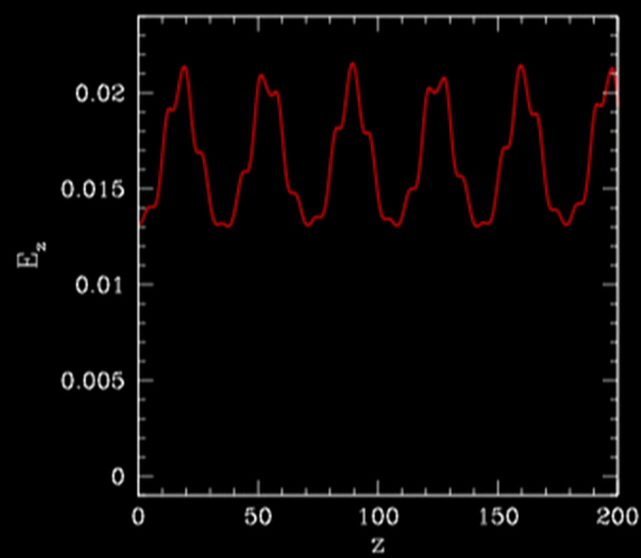
$$E_z = \frac{1}{2} v_z^2 + \Psi(z)$$


face on view
epicycle approximation
edge on view
z (kpc)
1
0.5
0
−0.5
−1
0
0.2
0.4
0.6
0.8
1
t (Gyr)

(Vertical) phase space motion of a star in a realistic Milky Way potential



vertical energy is an *approximate* integral of motion



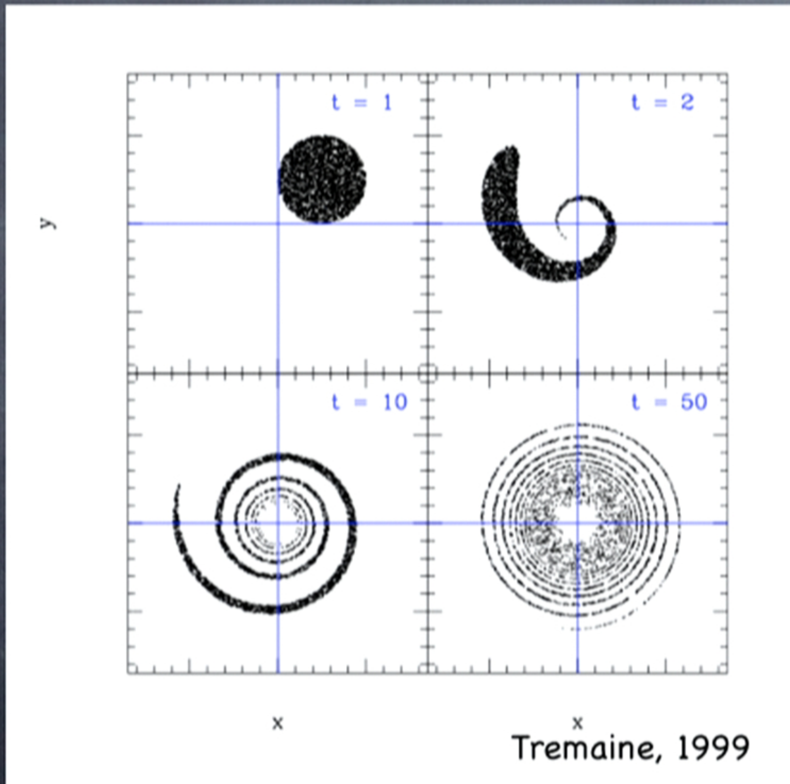
Disk stars are collisionless
(move under influence of mean gravitational field of Galaxy --- can ignore star-star encounters)
Describe by a phase-space distribution function

$$f(\mathbf{x}, \mathbf{v}, t) = \frac{dM}{d^3x d^3v}$$

Liouville's theorem
+
continuity equation gives
Collisionless Boltzmann equation
imcompressible fluid in 6D

$$\frac{df}{dt} = 0$$

Liouville's theorem



evolution of a system of particles described by the Hamiltonian

$$H(x, y) = \left(x^2 + y^2\right)^{1/2}$$

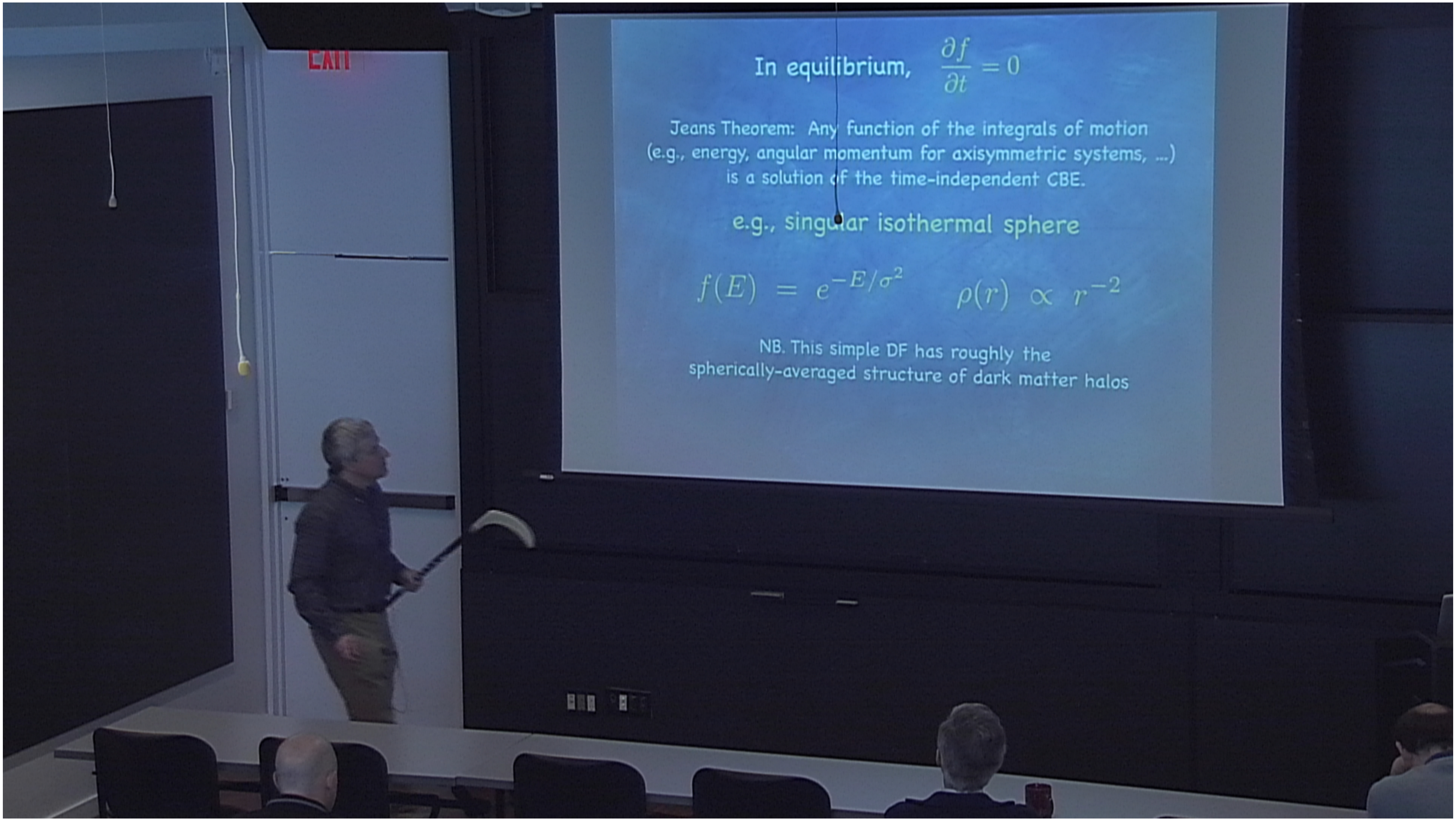
In equilibrium, $\frac{\partial f}{\partial t} = 0$

Jeans Theorem: Any function of the integrals of motion (e.g., energy, angular momentum for axisymmetric systems, ...) is a solution of the time-independent CBE.

e.g., singular isothermal sphere

$$f(E) = e^{-E/\sigma^2} \qquad \rho(r) \propto r^{-2}$$

NB. This simple DF has roughly the spherically-averaged structure of dark matter halos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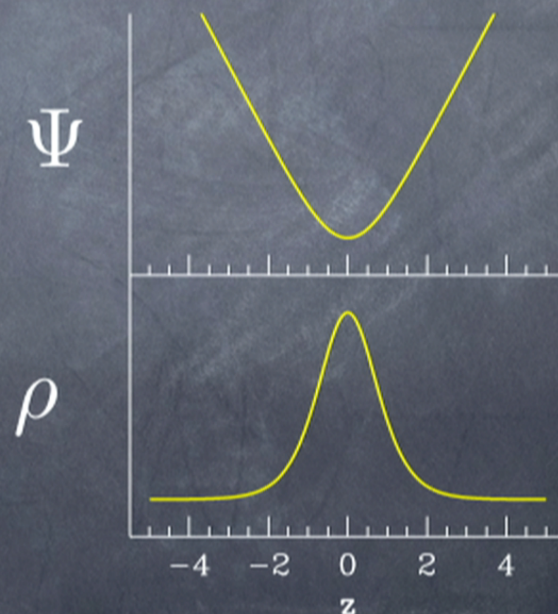
e.g., singular isothermal sphere
$f(E) = e^{-E/\sigma^2}$ $\rho(r) \propto r^{-2}$
NB. This simple DF has roughly the
spherically-averaged structure of dark matter halos
EXIT

Spitzer (1942) isothermal plane
(Binney & Tremaine, problem chap. 4)

$$\Psi(z) \;=\; \Psi_0 \ln\left(\cosh\left(z/z_d\right)\right)$$

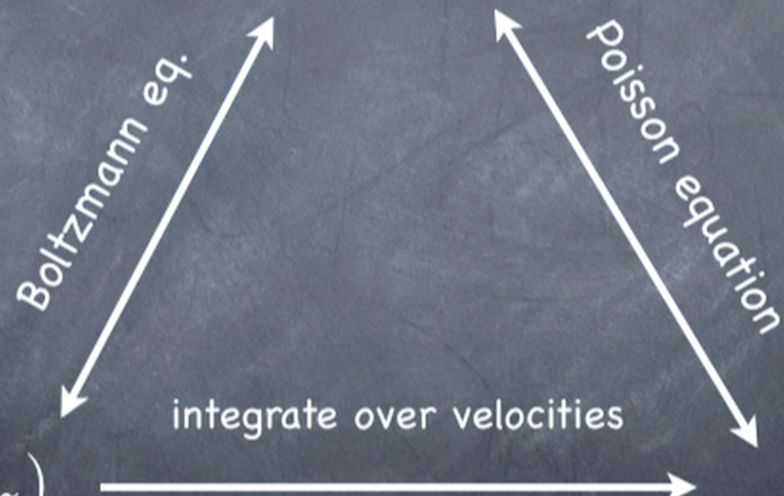
$$\rho(z) = \frac{\rho_0}{\cosh^2\left(z/z_d\right)}$$

$$f\left(E_z\right) \;=\; f_0 e^{-E_z/\sigma^2}$$



Spitzer assumes single component isothermal system. Relax these assumptions and we have the opportunity to infer dark matter density (the Oort problem)

$$\Psi(z),\ F(z) = -\partial\Psi/\partial z$$



$$f(E_z) \qquad \rho(z)$$

$$E_z = \frac{1}{2}v_z^2 + \Psi(R,z) - \Psi(R,0)$$

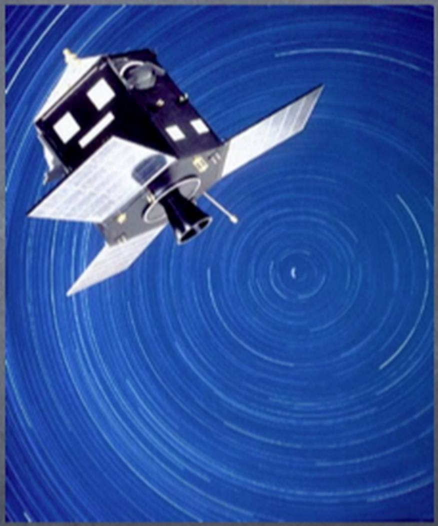
see Kuijken & Gilmore, 1989

Solar neighbourhood is one place where 6D phase space information for tracers (stars) is available

Hipparchos: 1989-1993
space astrometry mission of the
European Space Agency

precise measurements of
5 astrometric parameters:
angular coordinates
proper motion parallax

supplement with spectroscopic
radial velocities



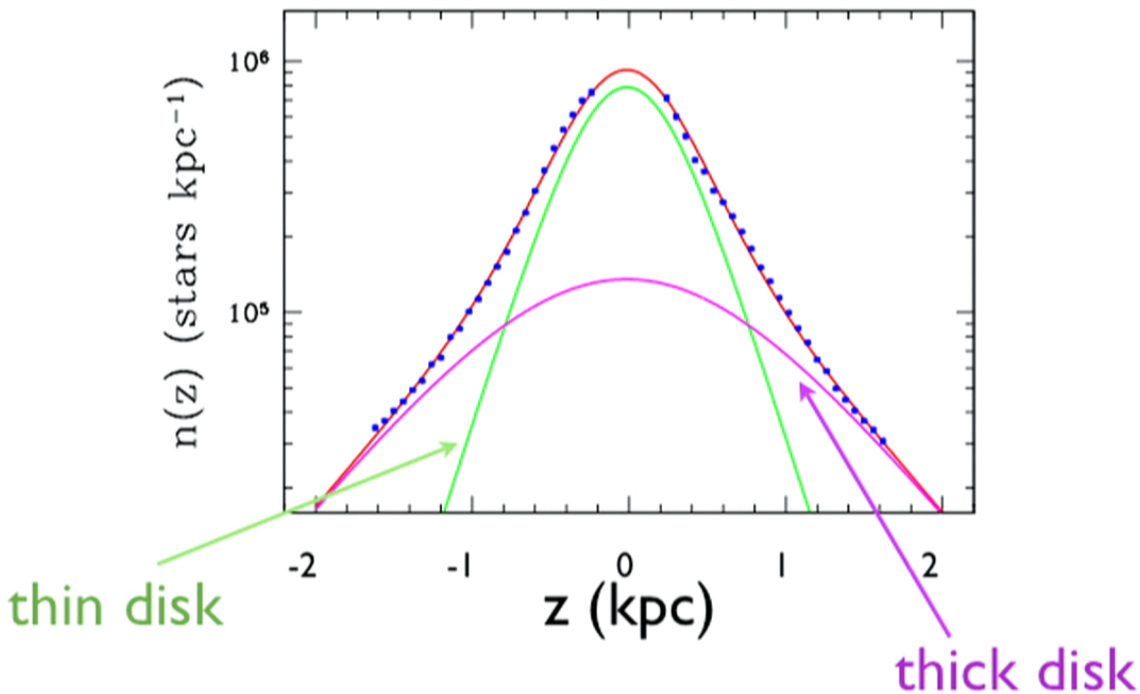
Sloan Digital Sky Survey

dedicated 2.5m telescope at
Apache Point, NM
collected data from 2000-2008
multi-color images for close
to 1M galaxies and 120K quasars

for our purposes, SDSS-DR8
provides positions and magnitudes
for 800K stars in the solar
neighborhood


Sloan Extension for Galactic Understanding and Exploration
SEGUE
provides spectra and proper motion
for subset of SDSS stars
we use a catalog of 11K solar
neighborhood stars with 6D phase
space information

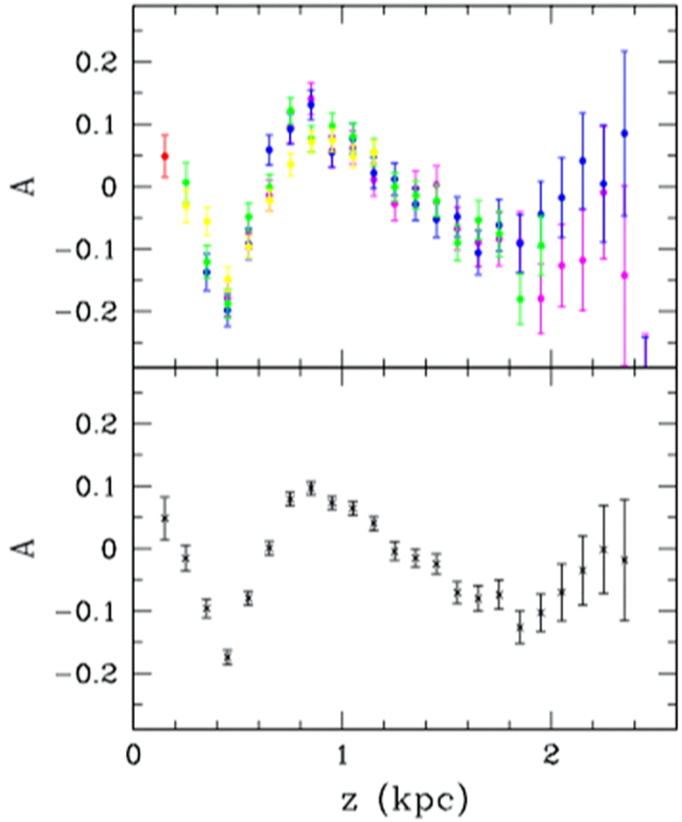
estimate of n(z) from 400K stars in SDSS-DR8



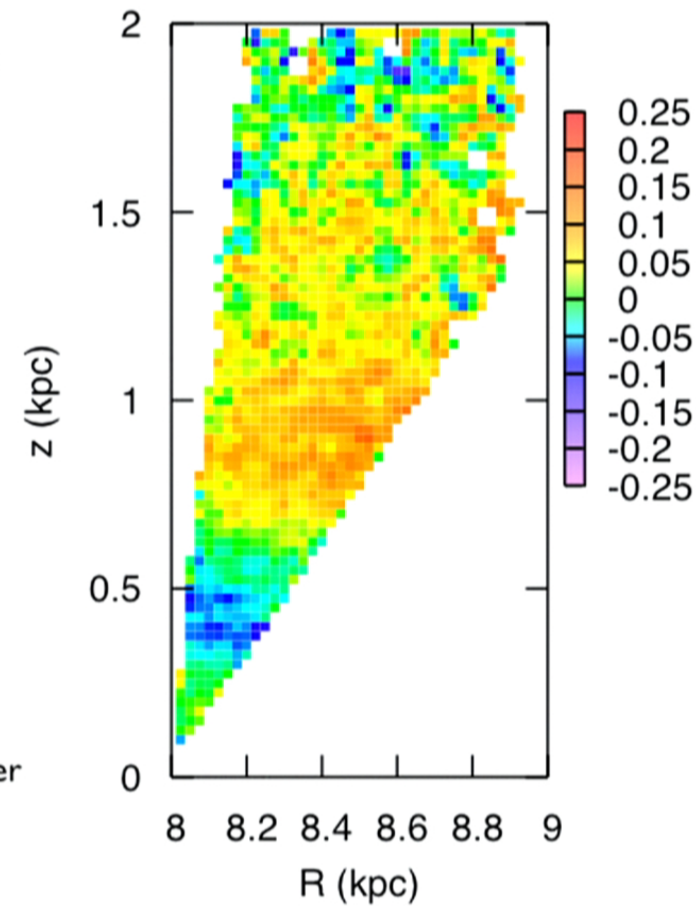
$$n(z) = n_0 \left(\frac{1}{\cosh^2 (z/z_1)} + \frac{f}{\cosh^2 (z/z_2)} \right)$$

North-South Asymmetry

$$A \equiv \frac{North - South}{North + South}$$



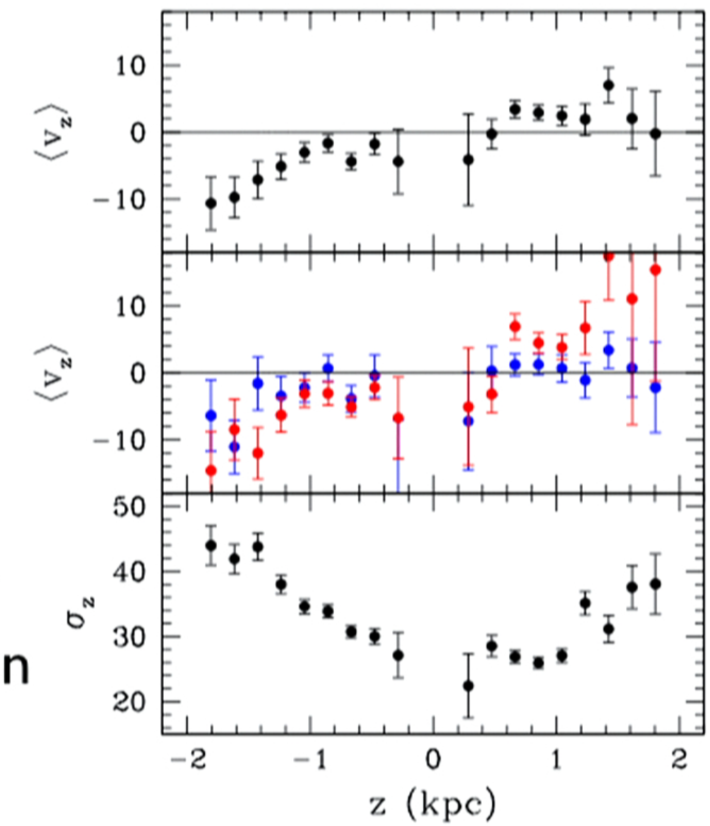
North-South asymmetry as a function of Galactocentric distance R and z



← to Galactic center

Velocity profiles from SEGUE

bulk velocity



velocity dispersion

velocity dispersion increases as we move from thin to thick disk

North-South Asymmetry in the photometric data and trends in the bulk velocity suggest a disk that is not in equilibrium.

Reason to question a basic assumption made in Oort-type analysis

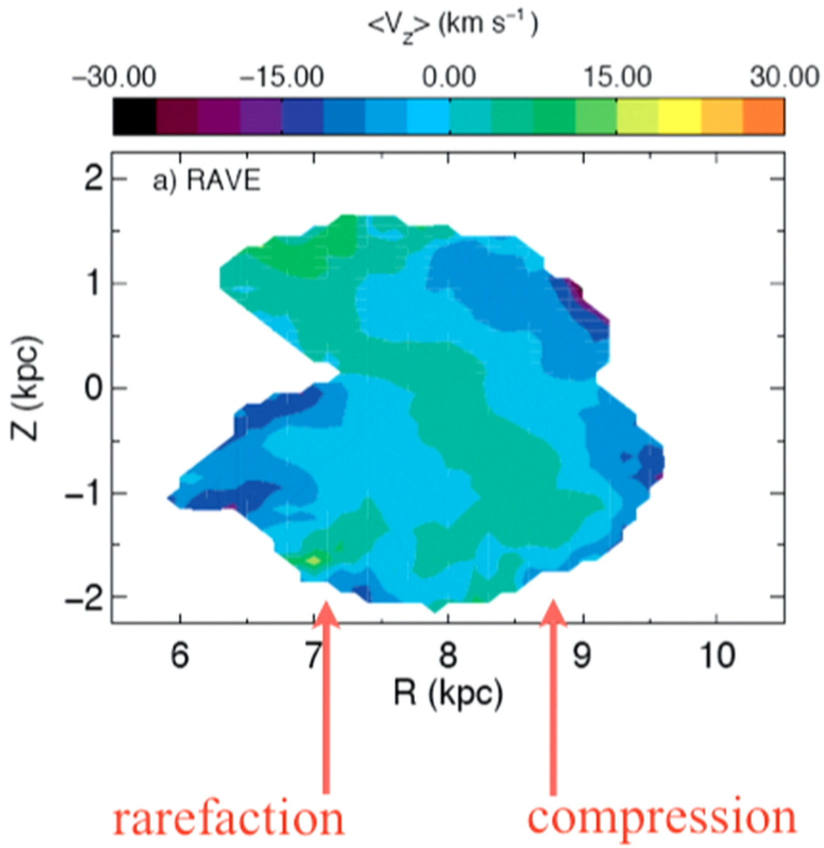
1932 August 17 Volume VI. No. 238.

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.*

On the whole the results are entirely satisfactory in so far as they show no systematic motions in a direction perpendicular to the galactic plane. The fact that for stars further than 100 parsecs to the north and to the south of the galactic plane there appears to be no trace of systematic relative motion lends some support to the assumption stated in the first section, that in the z-direction the stars are thoroughly mixed.

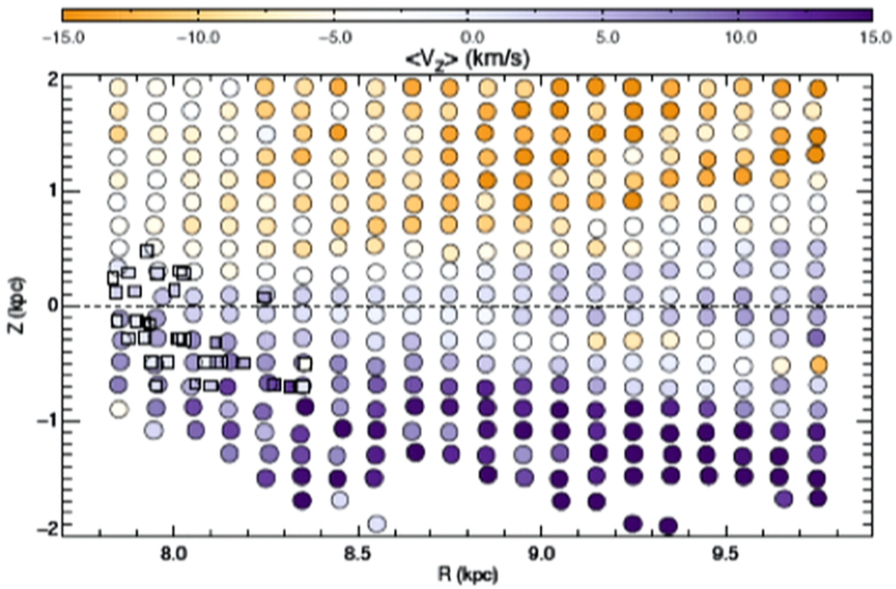
Williams et al 2013
RAVE radial velocities + literature proper motions
to map bulk motion in the solar suburb

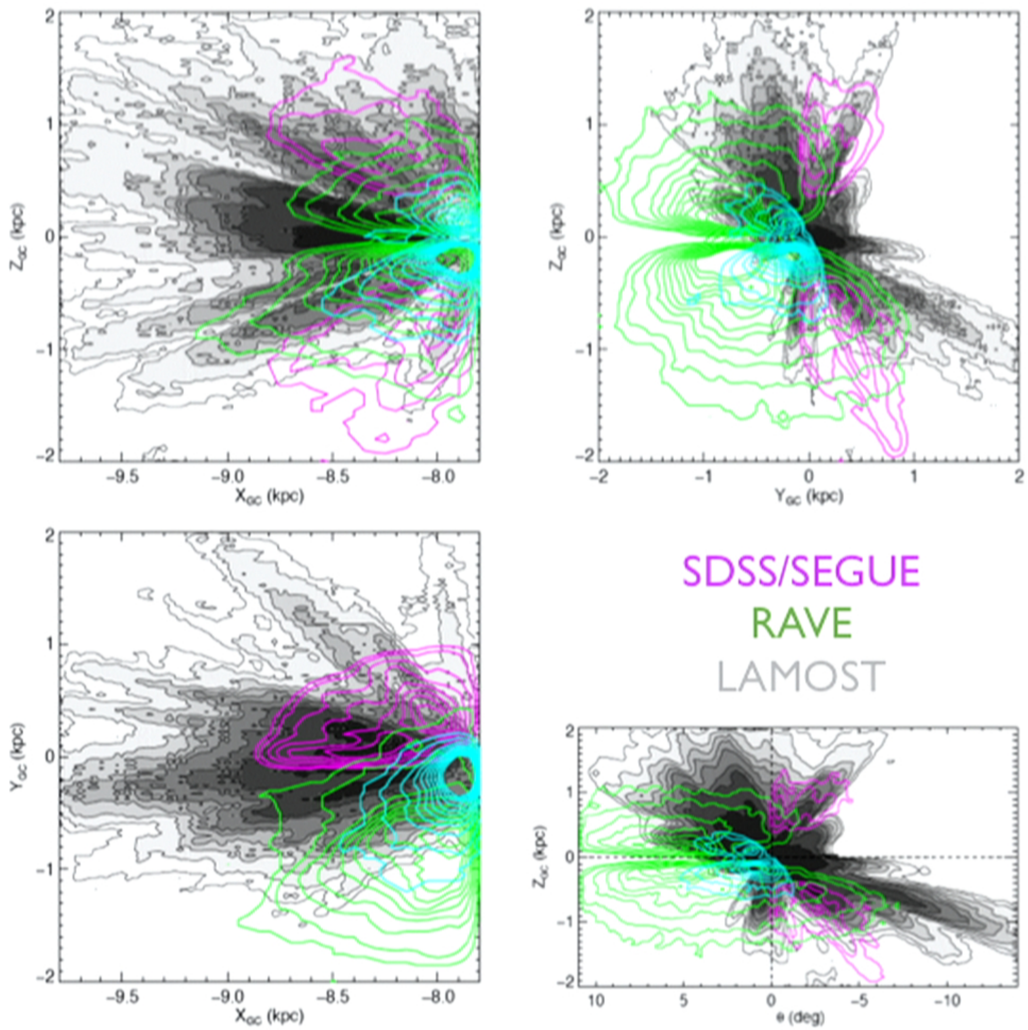


Carlin et al 2013
LAMOST radial velocities + literature PMs

Figure 1 LAMOST-

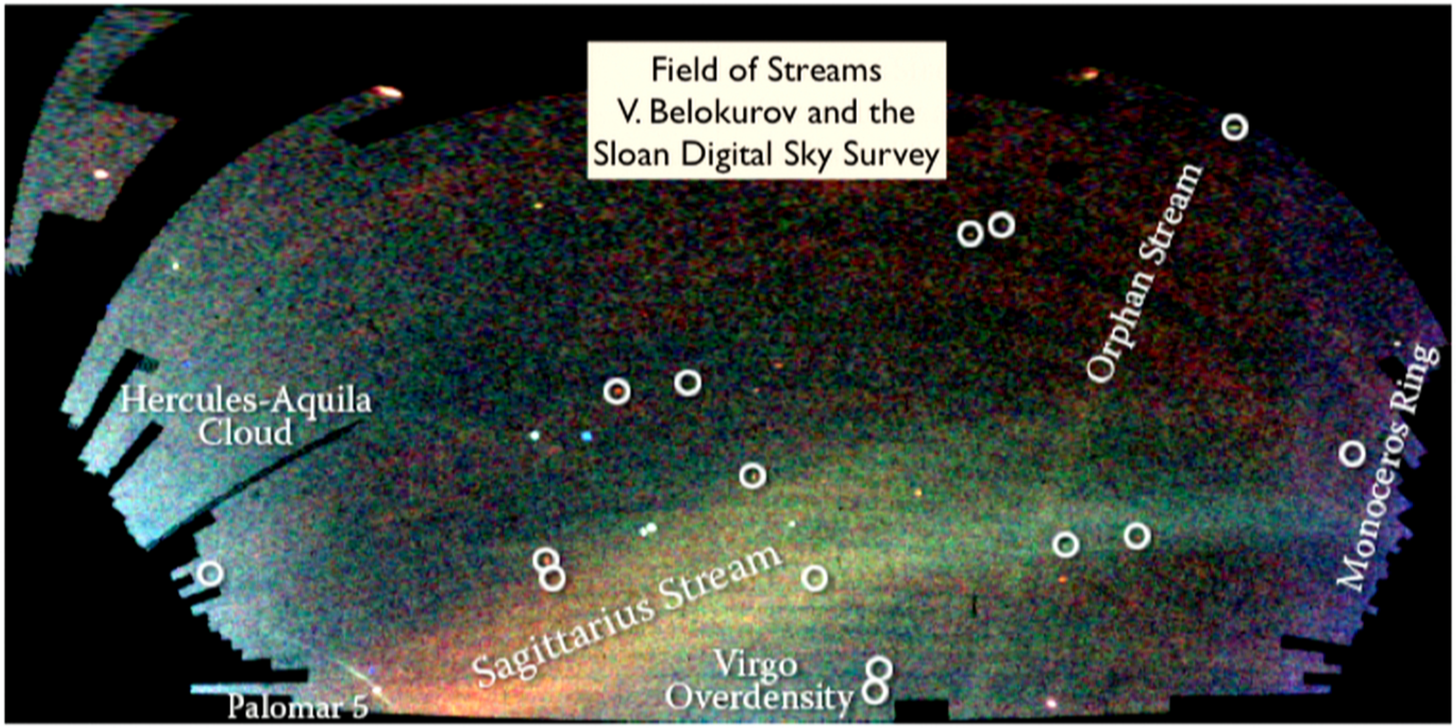
National Astronomical Observatories Chinese Academy of Sciences

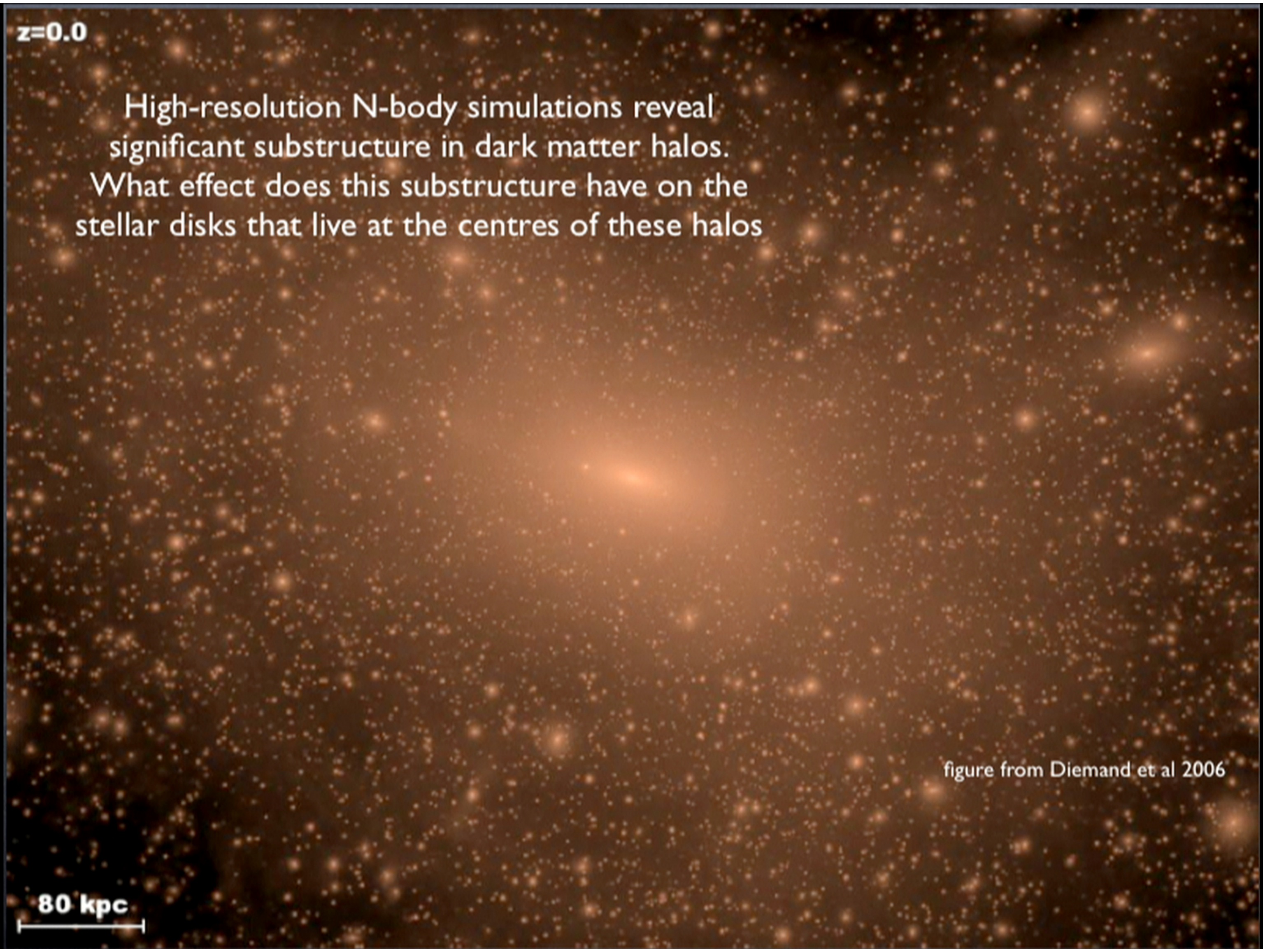




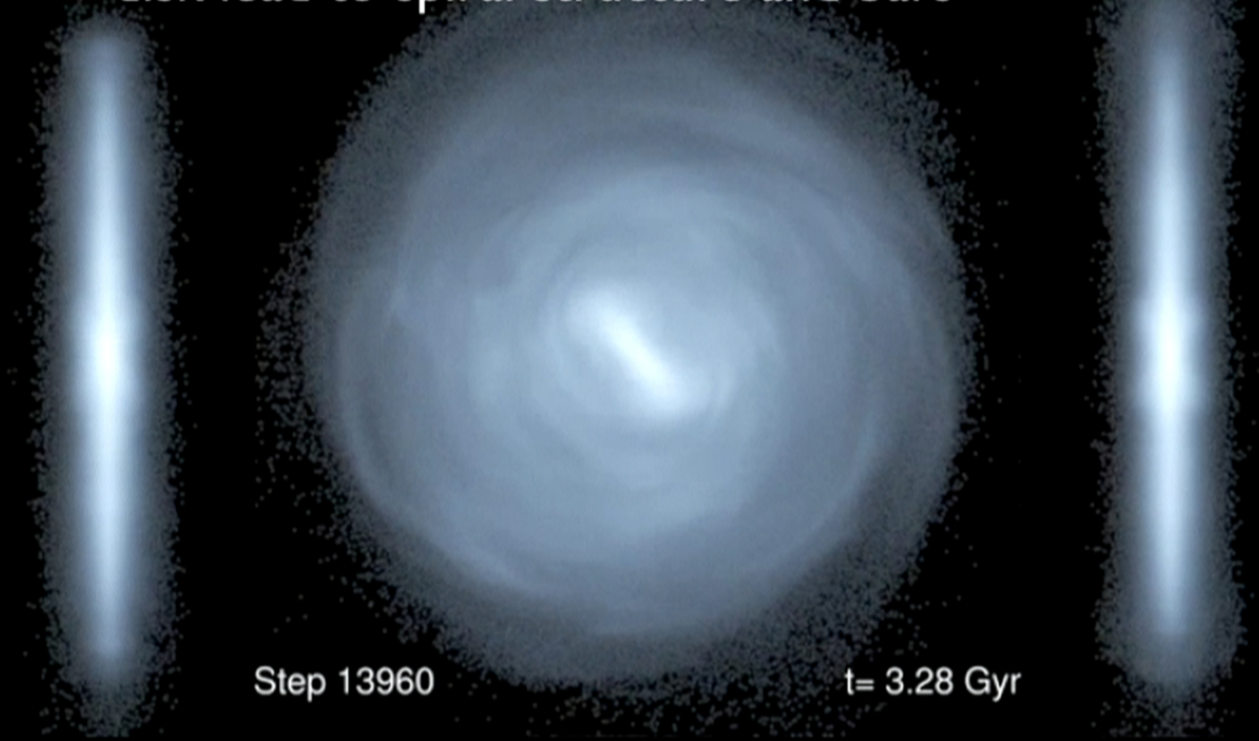
from Carlin et al 2013

One possibility: features in n(z) and bulk velocity arise from a stream of stars that is passing through the solar neighborhood




z=0.0
High-resolution N-body simulations reveal significant substructure in dark matter halos. What effect does this substructure have on the stellar disks that live at the centres of these halos
figure from Diemand et al 2006
80 kpc

growth of *unstable modes* in the plane of the disk lead to spiral structure and bars



Animation by J. Dubinski

In any self-gravitating system, perturbations grow if gravity dominates over "pressure"

In a stellar system, "pressure" arises from random motions of the stars

Jeans length minimum size for gravitational instability

$$\lambda_J = \left(\frac{\pi\sigma_z^2}{G\rho_0}\right)^{1/2} \gtrsim 2\,\mathrm{kpc}$$

Jeans (Toomre) instabilities may operate in the plane of the disk but generally not in the vertical direction

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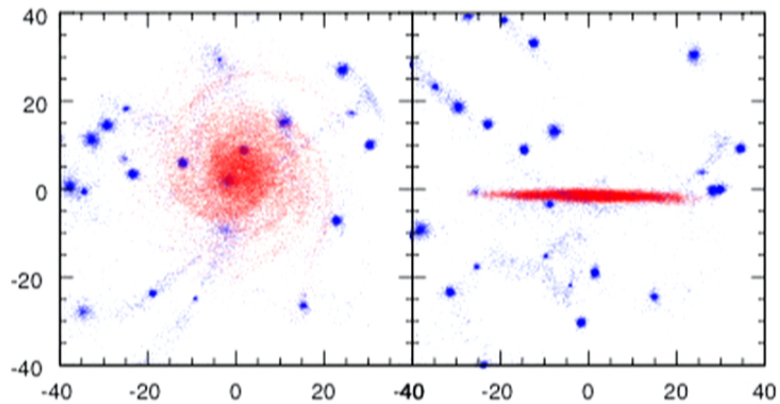
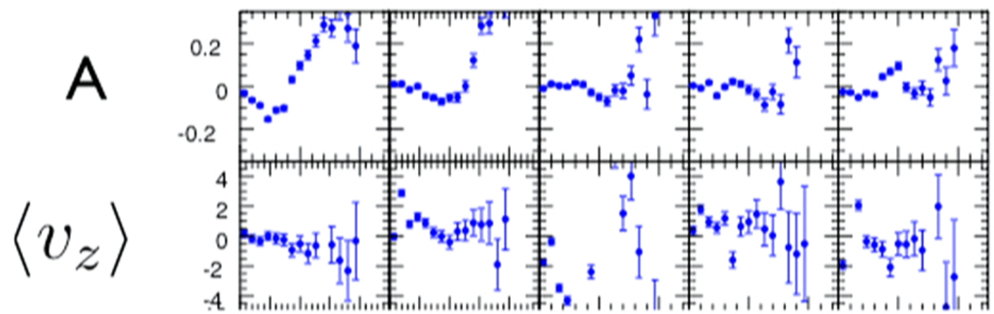
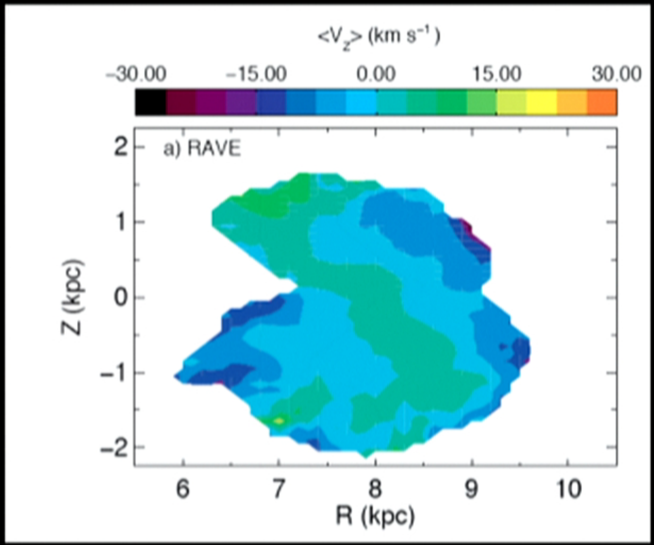
Jeans (Toomre) instabilities may operate in the plane of the disk but generally not in the vertical direction from Gauthier, Dubinski, and LMW

note: "resolution" of the data is significantly better than resolution in these simulations

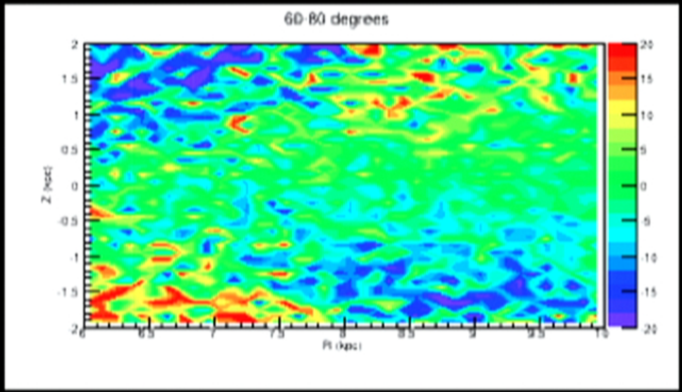




Williams et al 2013
Wobbly Disk paper from the RAVE collaboration



2 kpc, 20 degree region of Gauthier et al 2006 simulation



Cheng, Chequers, & Widrow...in prep

Properties of the solar neighborhood

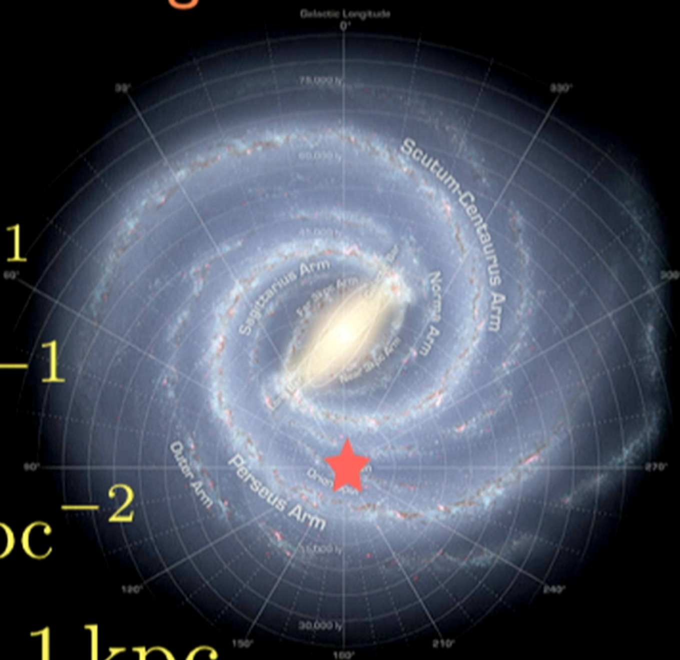
$$R_0 \simeq 8\ \mathrm{kpc}$$

$$v_z \sim 10 - 40\ \mathrm{km\,s^{-1}}$$

$$v_{\mathrm{LSR}} \sim 230\ \mathrm{km\,s^{-1}}$$

$$\Sigma \simeq 5 \times 10^7\ M_\odot\,\mathrm{kpc^{-2}}$$

$$z_{\mathrm{max}} \sim \mathrm{parsecs} - 1\,\mathrm{kpc}$$

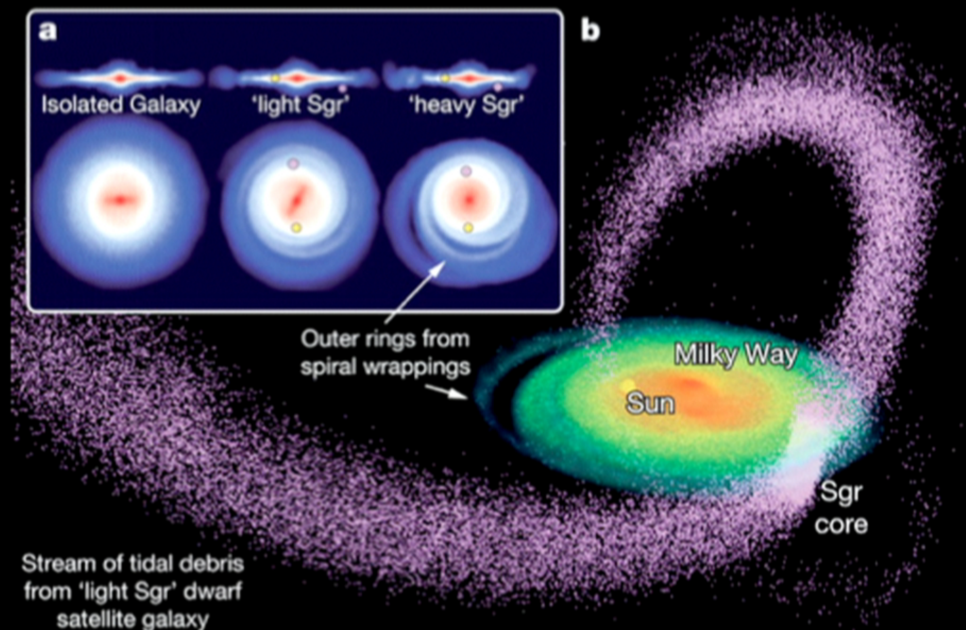


Annotated Roadmap to the Milky Way
(artist's concept)

NASA / JPL-Caltech / R. Hurt (SSC-Caltech) ssc2008-10b

A satellite with comparable surface density, in sync with rotation, in resonance with vertical motions of the stars will produce the strongest perturbations

Purcell et al (2011):
Sagittarius dwarf as architect of MW spiral structure
&
Gomez et al (2013):
Vertical waves induced by Sagittarius stream

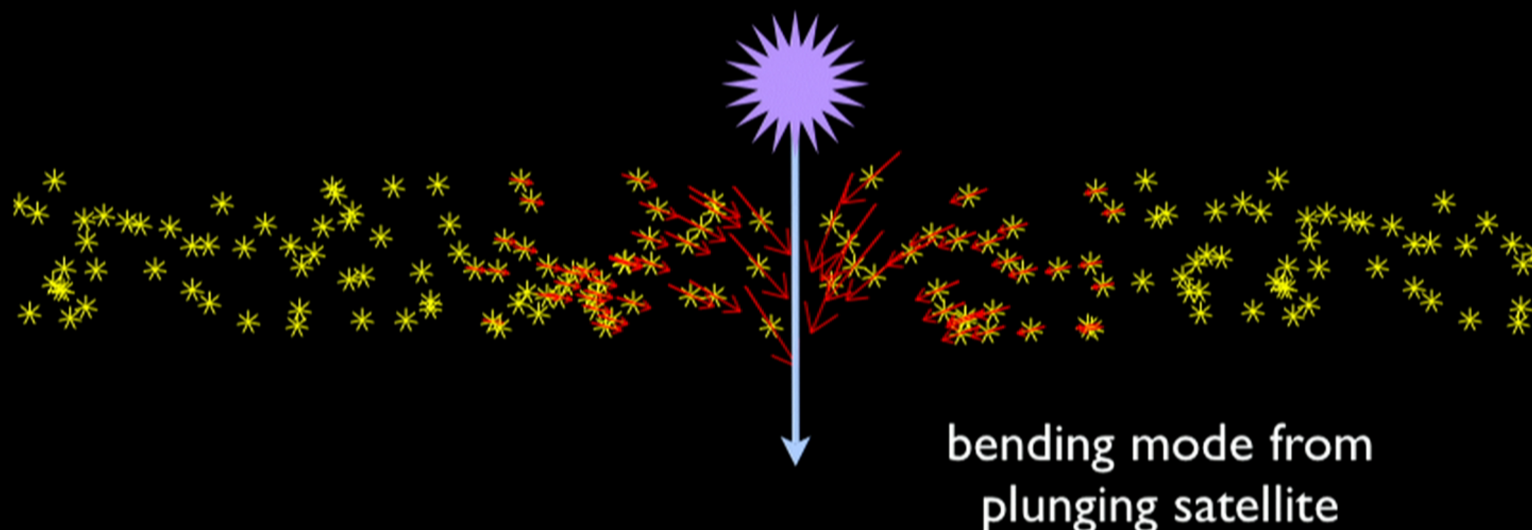


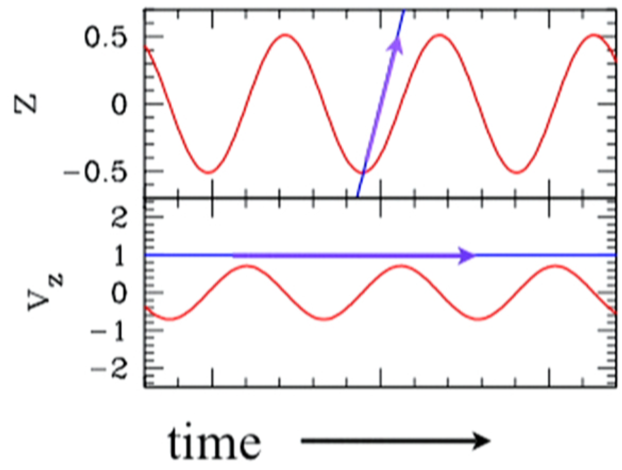
Excitation of vertical modes:

transfer of energy from satellite to disk stars

dynamical friction (Chandrasekhar 1943)

disk heating event (Toth & Ostriker 1992)

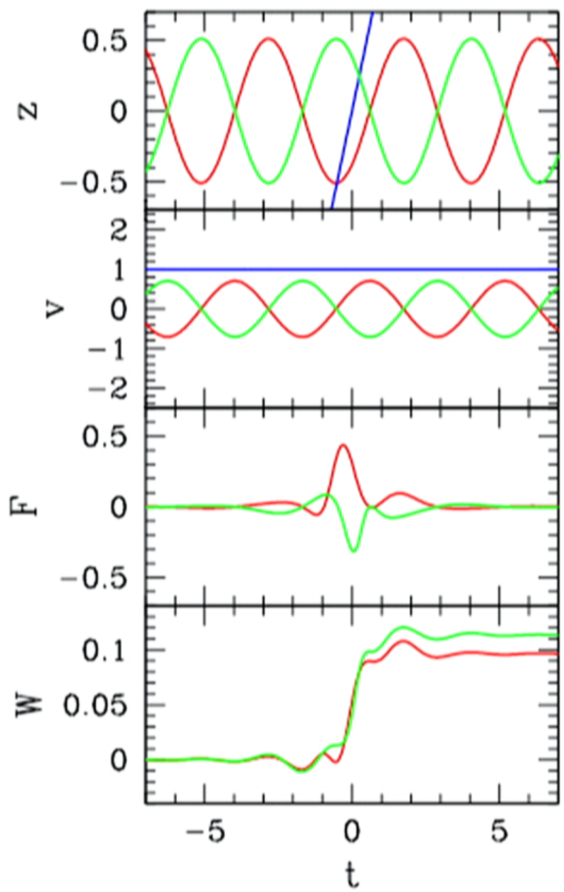




Position and velocity for a star and satellite

Here $v_{\rm sat} > v_{\rm star}$

Toy calculation uses unperturbed orbit to calculate W

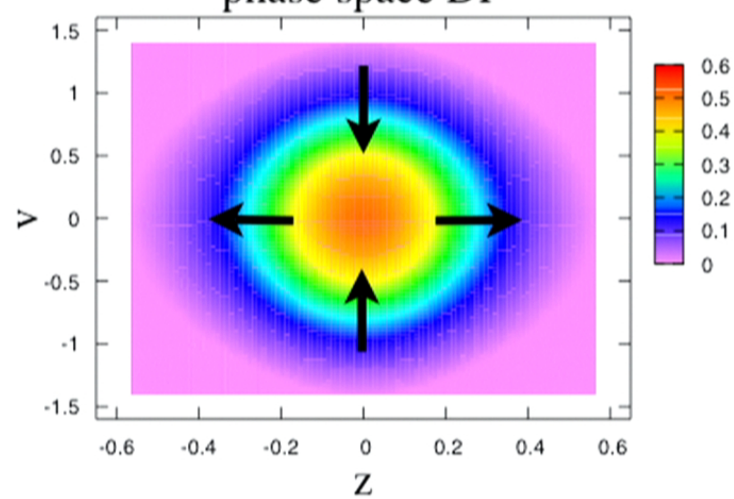


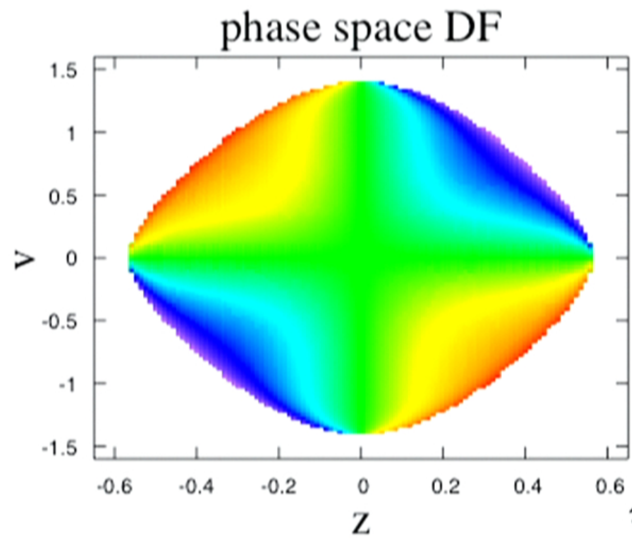
two stars differ in phase π

both *gain* energy from satellite

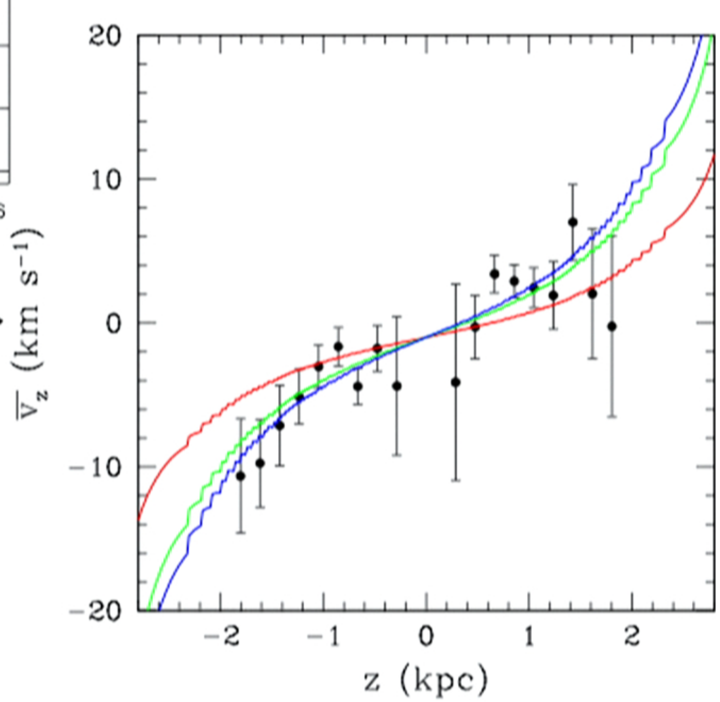
breathing mode

phase space DF





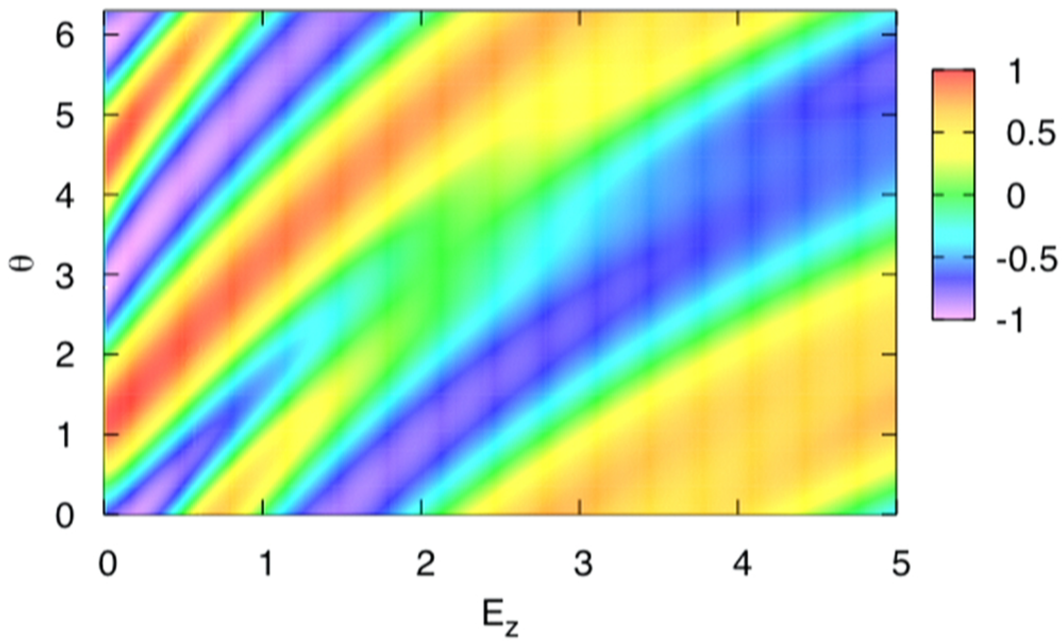
corresponding bulk velocity

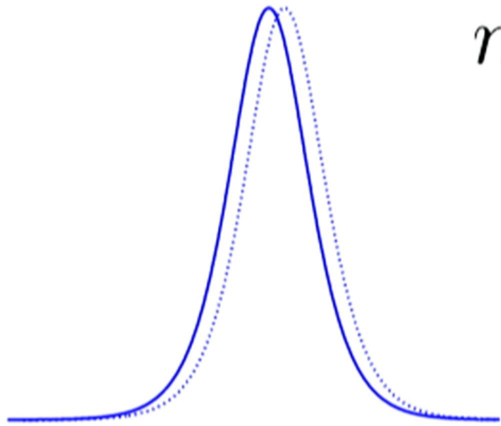


phase space perturbation for coherent vertical oscillation

Mathur 1990, Weinberg 1991, Widrow et al in press 2014

Change in energy as a function of star's energy and orbital phase



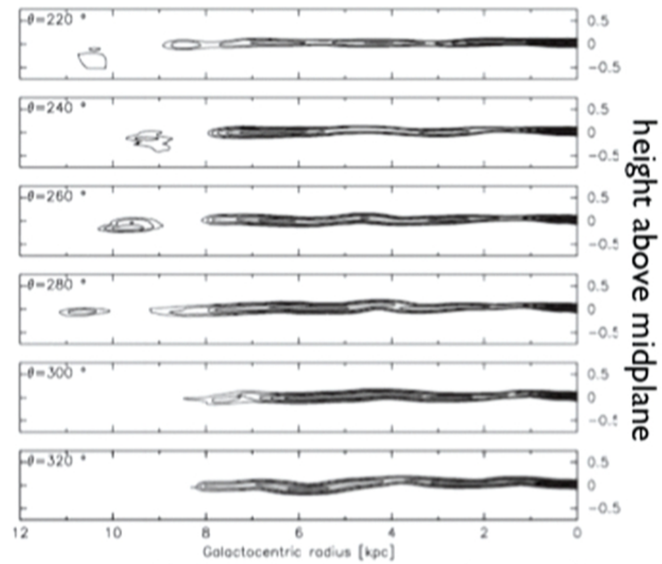


$$m = 0$$

Hubble Heritage Team

interpret in terms of

$z_\odot$ and $v_{z,\odot}$



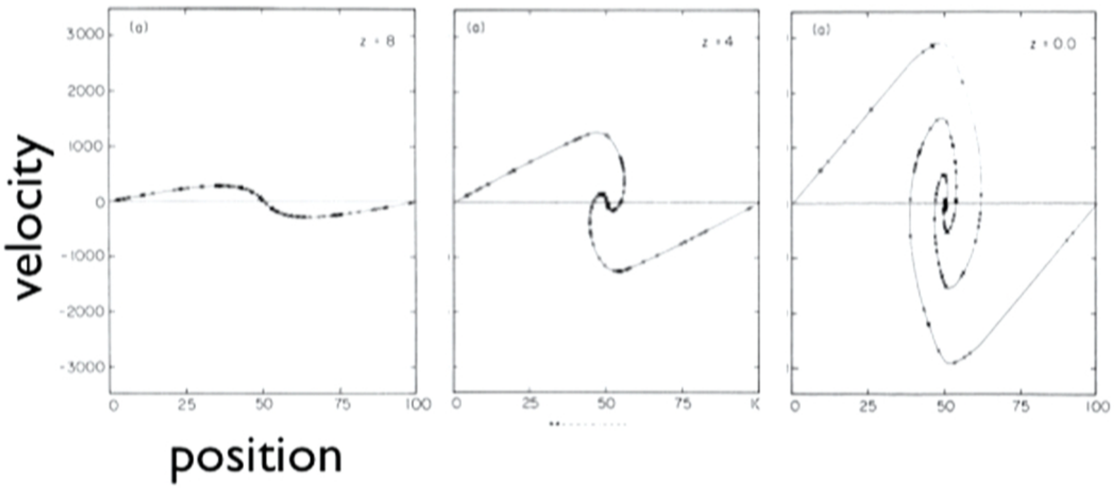
midplane displacement Interstellar medium,
Nakanishi and Sofue, 2006

N-body dynamics in one dimension

Each “particle” represents an infinite plane

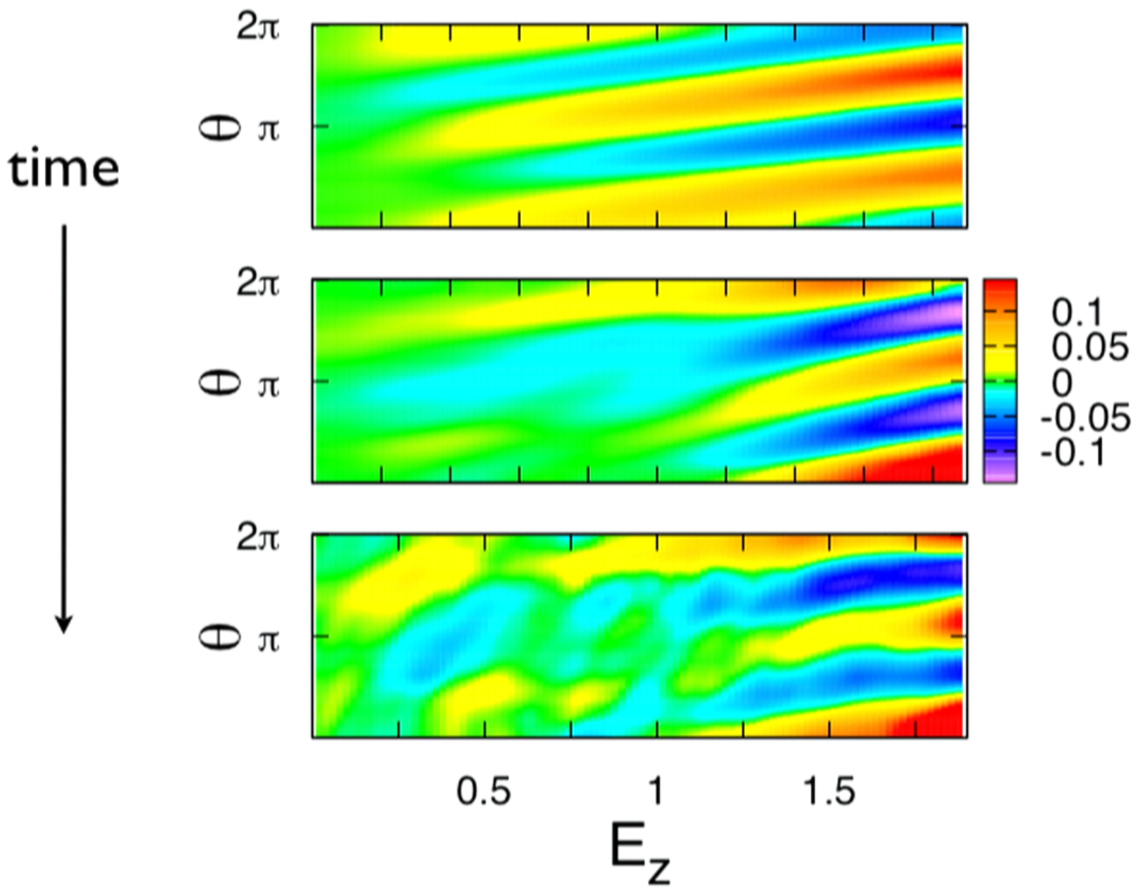
force on i’th particle
requires a simple sort to get all forces

$$F = 2\pi G\,(N_{\rm right} - N_{\rm left})m$$



1D cosmological simulation from Melott, 1983

results of a 1D simulation



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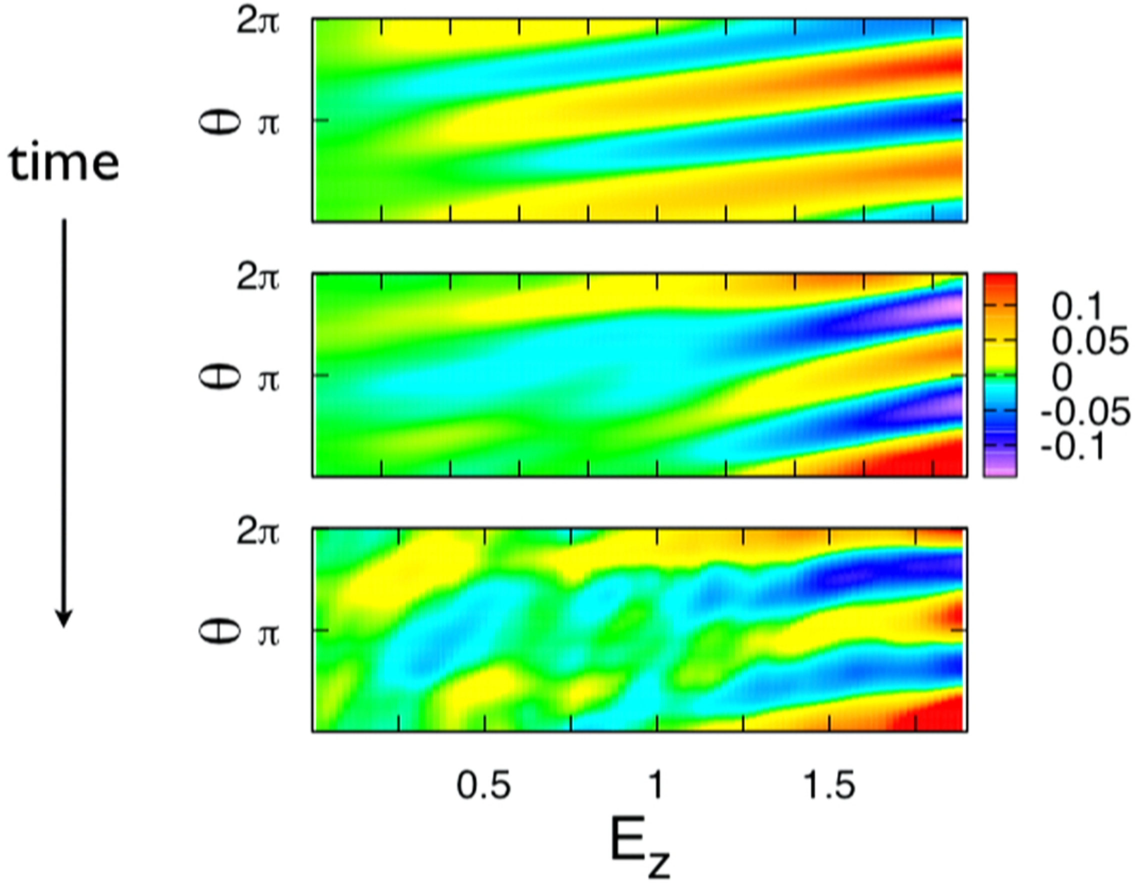
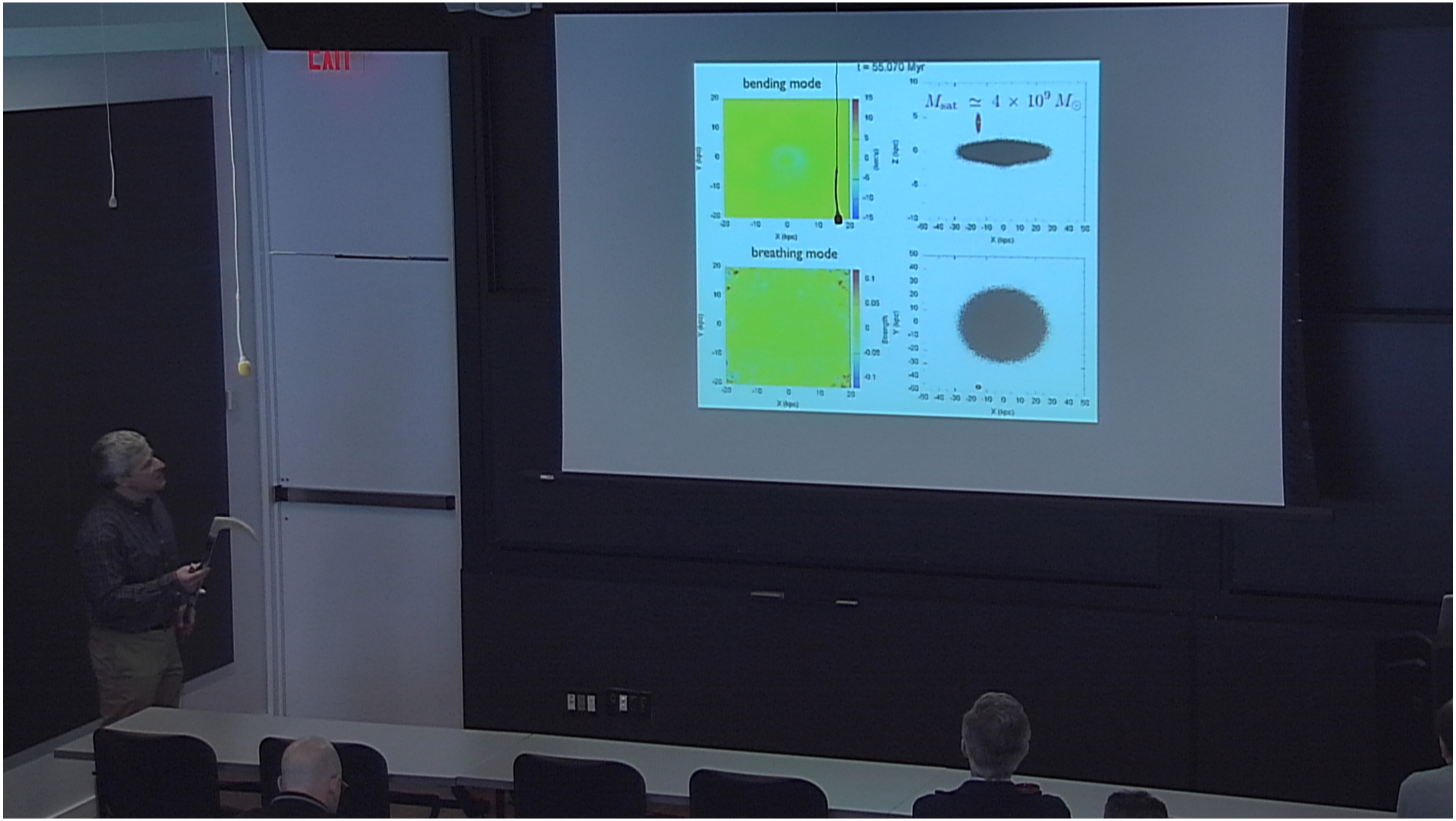
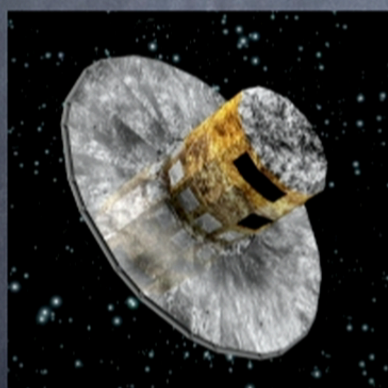



t = 55.070 Myr
bending mode
breathing mode
$M_{sat} \simeq 4 \times 10^9 M_\odot$

Summary and Outlook

Observational evidence for vertical perturbations
in the kinematics of solar neighborhood stars
is now seen in three surveys:
SDSS/SEGUE, RAVE, & LAMOST



Galactic dynamics community now
gearing up for data from GAIA
(launched in December, 2013):
precision astrometric data for 100M-1G stars

Theory

Vertical perturbations may represent the early stages of disk heating and thickening events

Generation and evolution of waves will involve:
resonant excitation of perturbations
coherent oscillations
(Mathur 1990, Weinberg 1991, Araki 1995, Sellwood et al 1998, LMW et al in press)
Landau damping and phase mixing
Differential rotation and shear
coupling to perturbations in the disk plane