stellar systems

Large N systems interacting with long-range forces

F = G M m /r^2

Examples of stellar systems:

globular cluster

galaxy

cluster of galaxy

connection to celestial mechanics, statistical mechanics, and plasma physics

Overview of a typical galaxy (the Milky Way)

facts and puzzles

lecture hours:
Friday 10-12?

Effects of dust absorption & scattering

Interstellar Extinction $A_x=(m-m_0)_x$

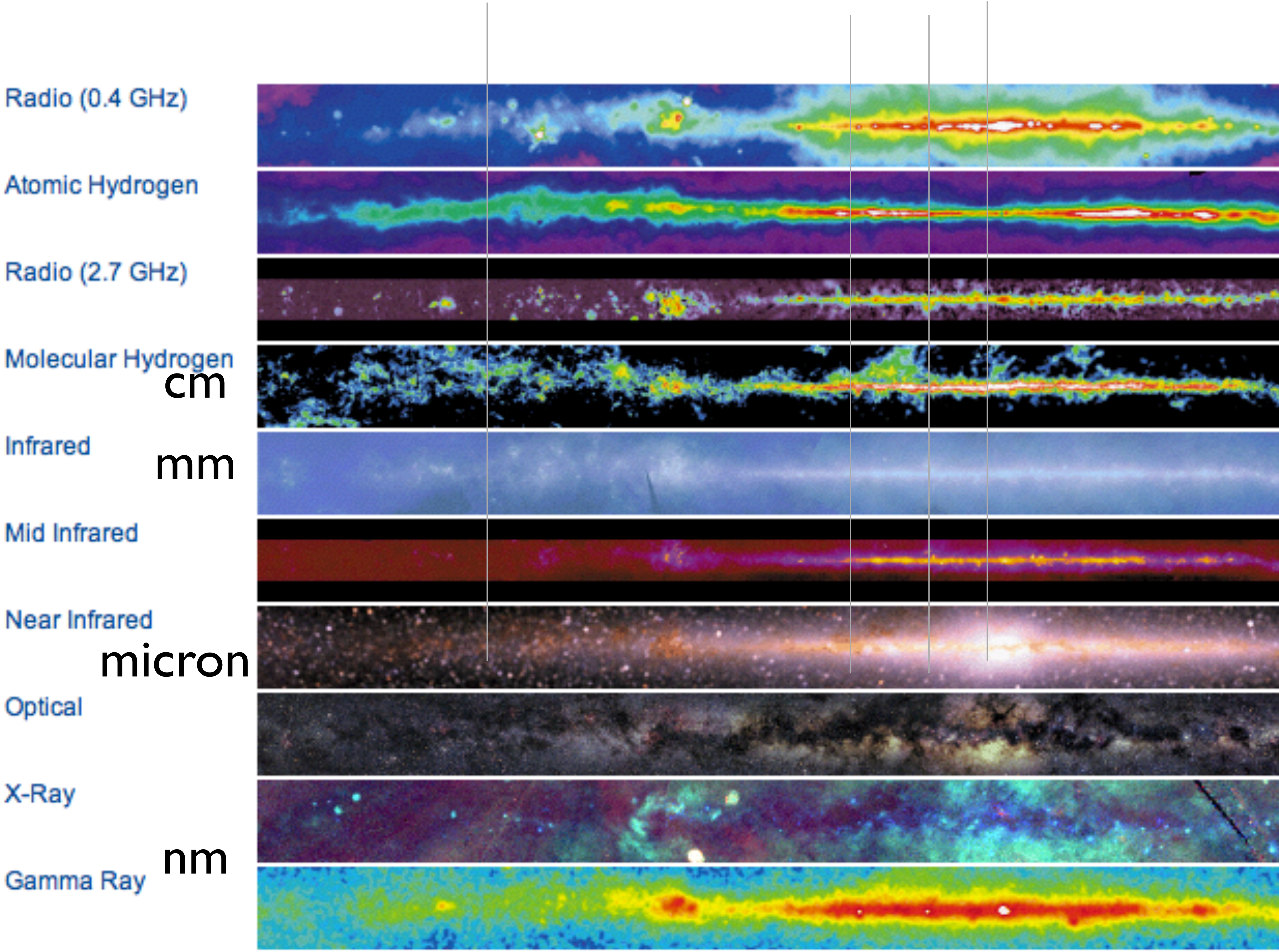
$A_B \sim 1.6$ mag (d/kpc) if $n_H \sim 1/cm^3$

galactic center stars suffer A ~ 30 mag, or $1/10^{12}$ photons pass through

Interstellar Reddening

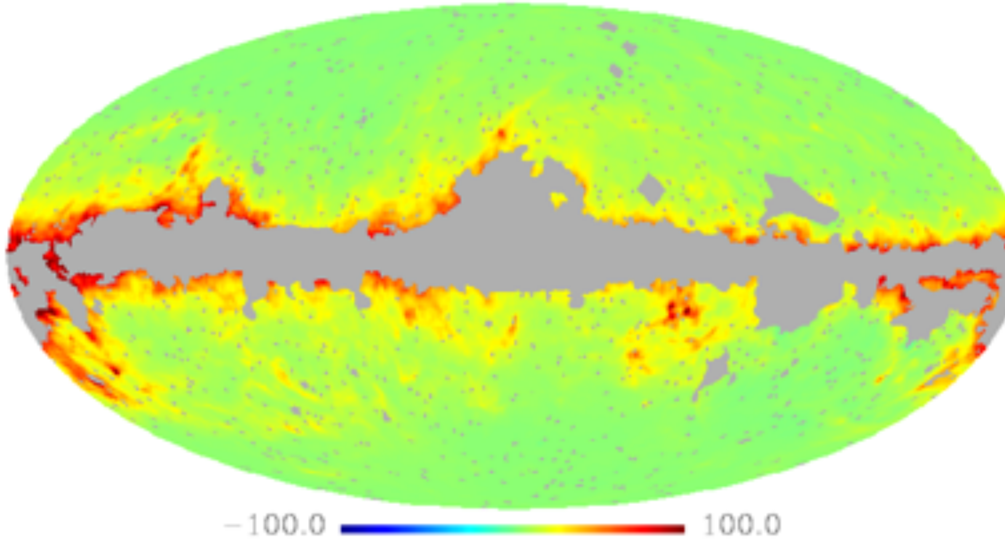
$E(B-V)=A_B-A_v \sim 0.5$ (d/kpc)

DIRBE 1.25, 2.2, 3.5 μm Composite

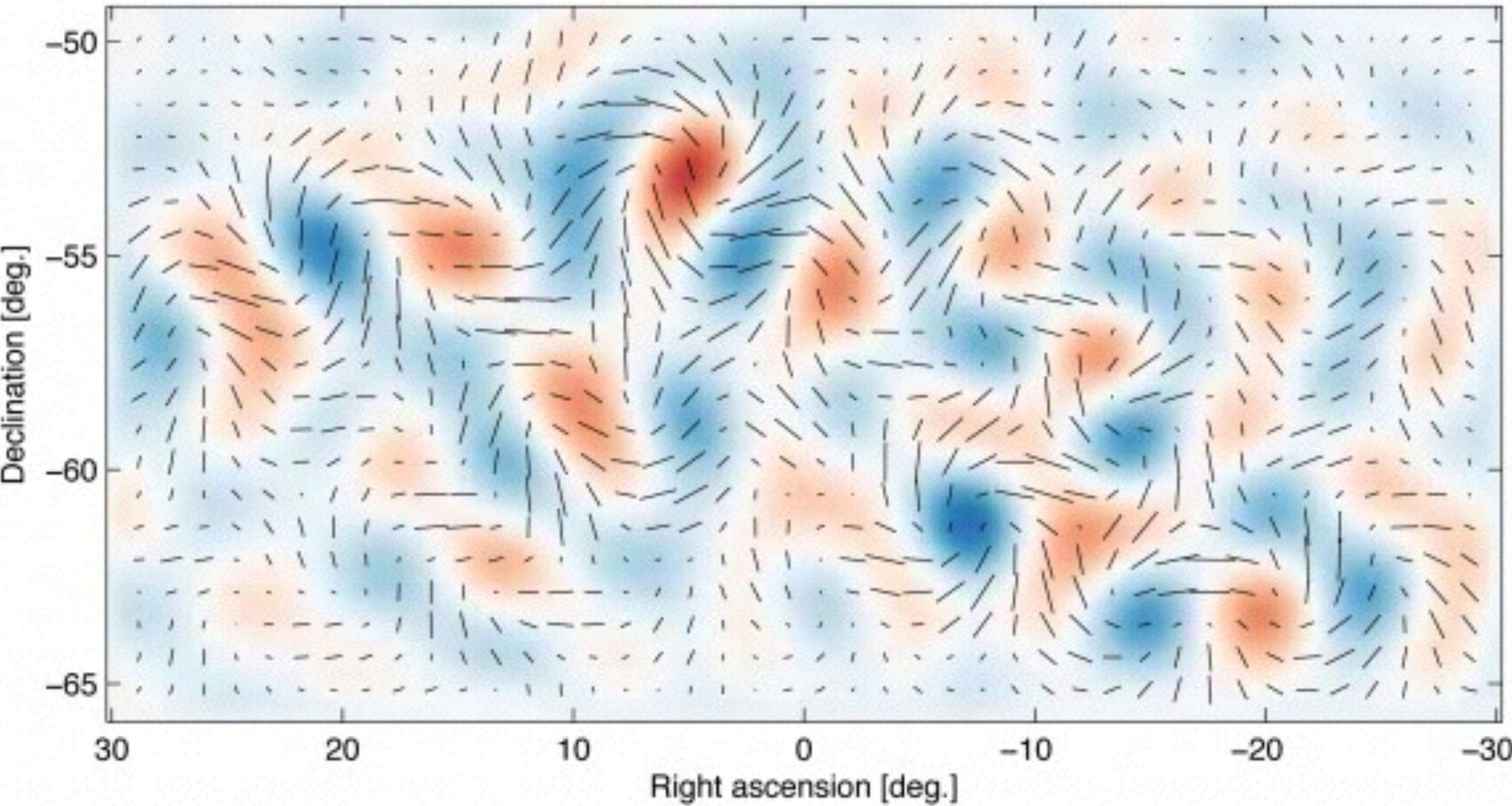


Radio (0.4 GHz)
Atomic Hydrogen
Radio (2.7 GHz)
Molecular Hydrogen
cm
Infrared
mm
Mid Infrared
Near Infrared
micron
Optical
X-Ray
nm
Gamma Ray

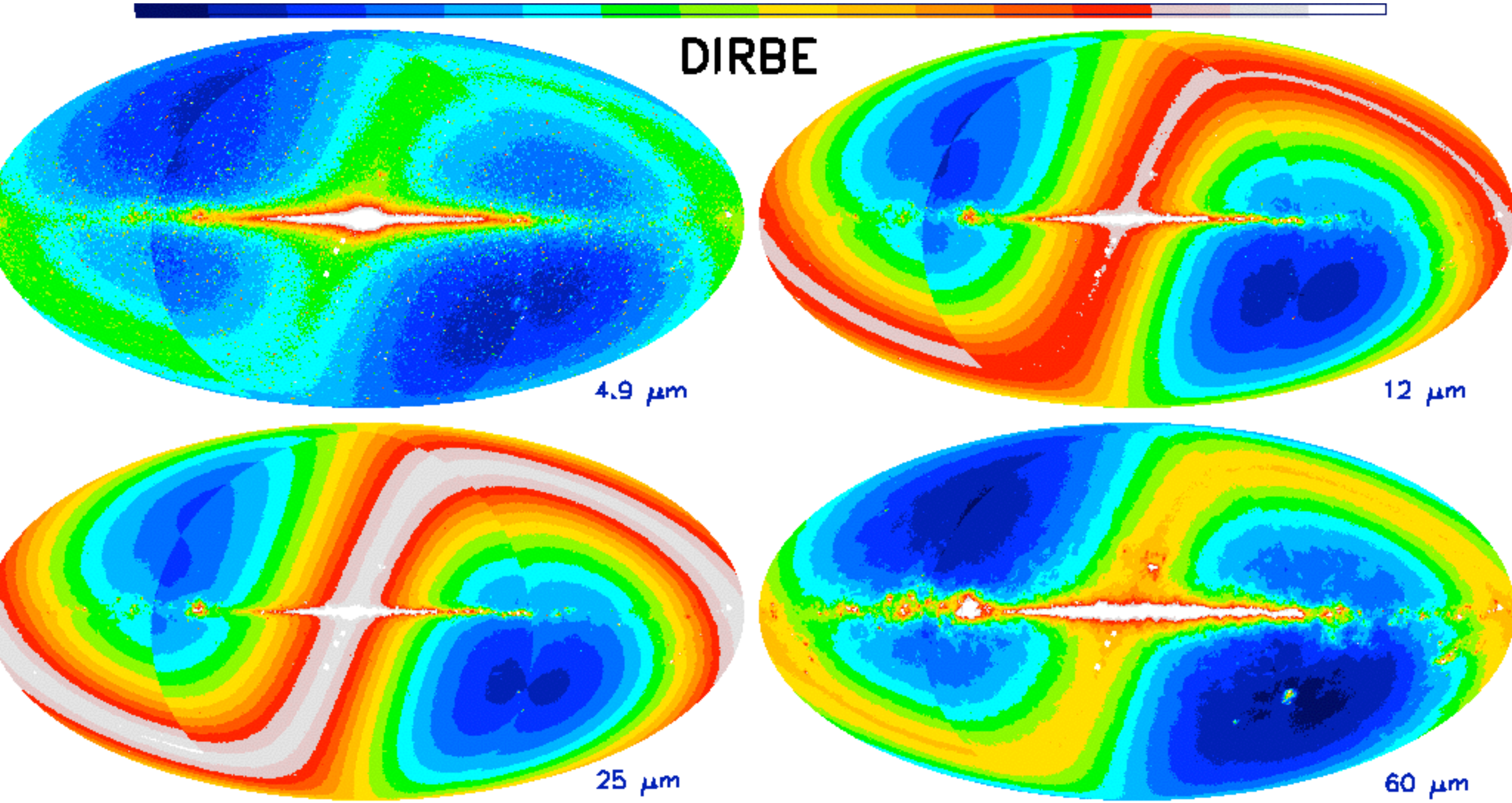
Dust a serious foreground for CMB

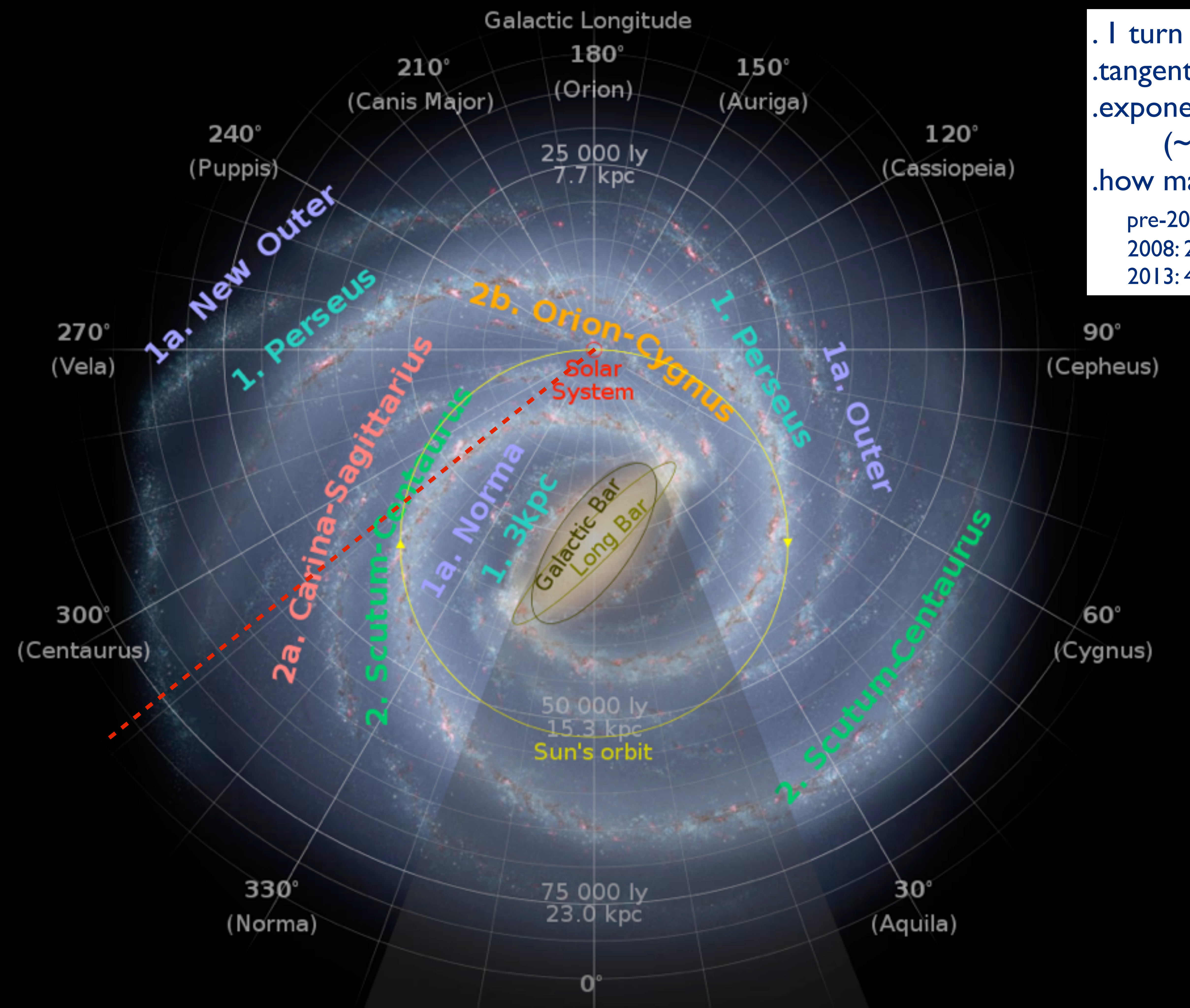


BICEP2—inflation?



Dust map (projected on ecliptic plane)

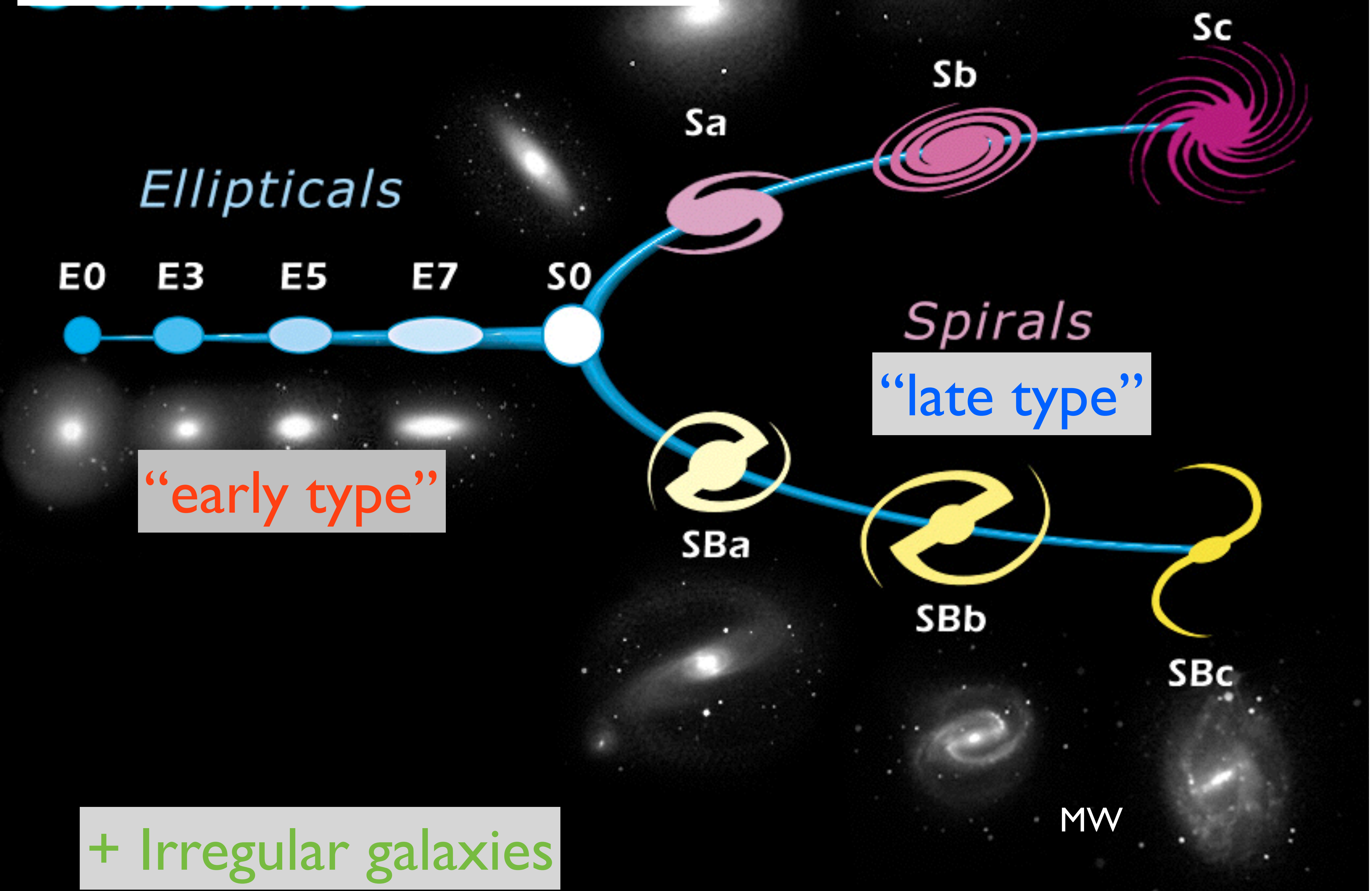




. 1 turn ~ 200Myrs
.tangent lines
.exponential disks (~2kpc)
.how many arms?

- pre-2008: 4 arms
- 2008: 2 arms
- 2013: 4 arms

Hubble sequence
(Hubble's tuning fork)



+ Irregular galaxies

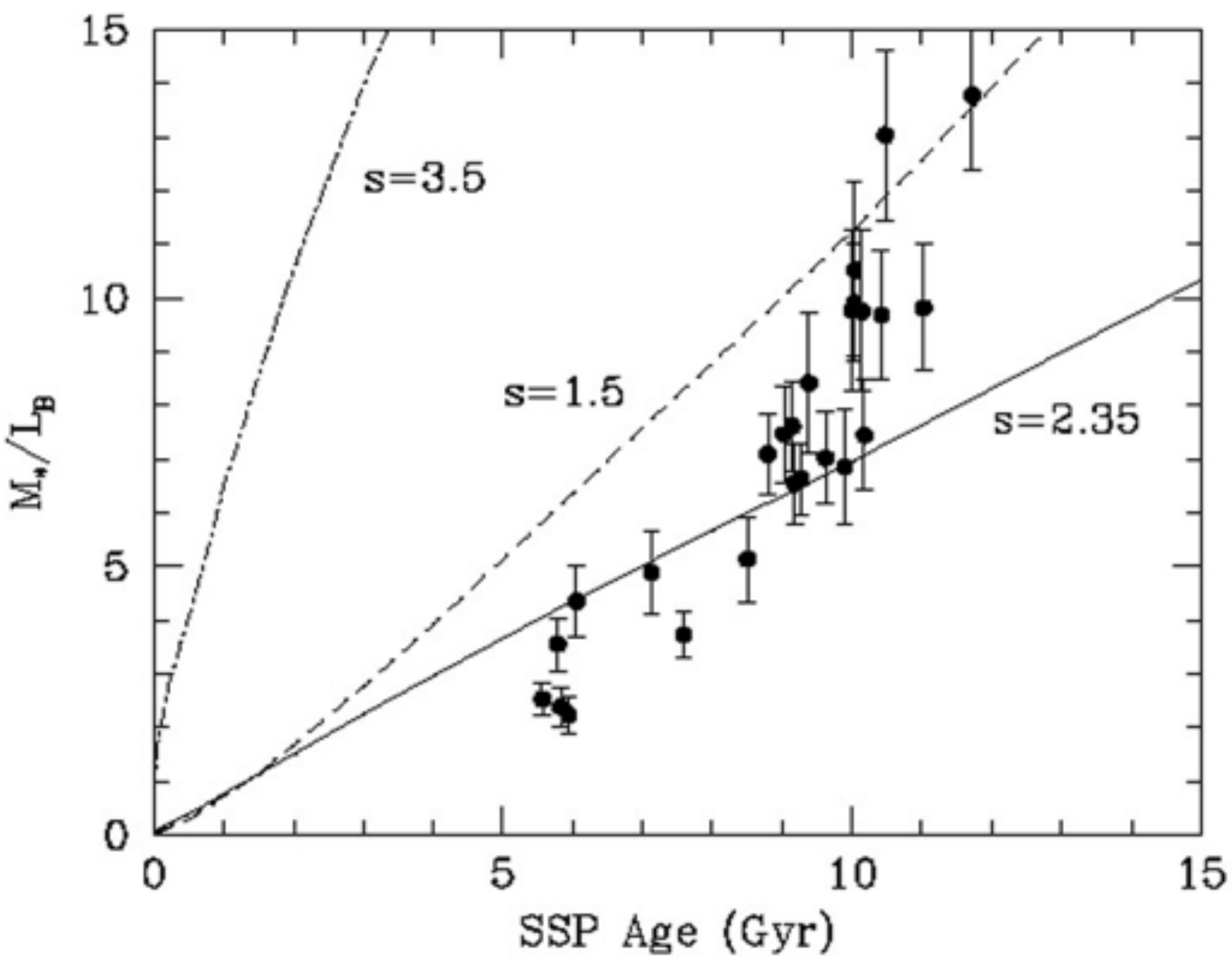
Mass-to-light ratio of stellar systems

the Sun:

$$\text{mass} = 1M_\odot, \text{Lumin} = 1L_\odot, \quad \text{mass/light} = 1 \ [M_\odot/L_\odot]$$

on main-sequence, light ~ mass^4
B2 main-sequence star: mass/light = 0.002
M2 main-sequence star: mass/light = 12.5

In a co-eval population of stars, mass/light increases with age.



theory: straight lines
s is slope for IMF,
larger s means more dwarves
s=2.35: Salpeter IMF

data: local ellipticals

Greggio & Renzini '11

Measured mass-to-light ratios locally:

Table 1.1 Inventory of the solar neighborhood — BT Chap. 1

component	volume density ($\mathcal{M}_\odot\,\mathrm{pc}^{-3}$)	luminosity density ($L_\odot\,\mathrm{pc}^{-3}$)	M/L
visible stars	0.033	0.05	~1
stellar remnants	0.006	0	0
brown dwarfs	0.002	0	0
ISM	0.050	0	0
total	0.09 ± 0.01	0.05	~2
dynamical	0.10 ± 0.01	–	~2

NOTES: Volume and luminosity densities are measured in the Galactic midplane and surface density is the total within ±1.1 kpc of the plane. Luminosity density and surface brightness are given in the R band. Dynamical estimates are from §4.9.3. Most other entries are taken from Flynn et al. (2006).

visible stars: alpha-Centauri system at 1.3 pc, so 0.2 star/pc^3, or ~ 0.1 M_{sun}/pc^3
ISM: $n_H \sim 1/cm^3$, so ~ 0.1 M_{sun}/pc^3
solar neighbourhood $M/L_R \sim 2$ (~ 2.5 if integrated to +/- 1.1 kpc)

all mass explained in our immediate neighbourhood

Measured mass-to-light ratios locally: (extend to +/- 1.1kpc)

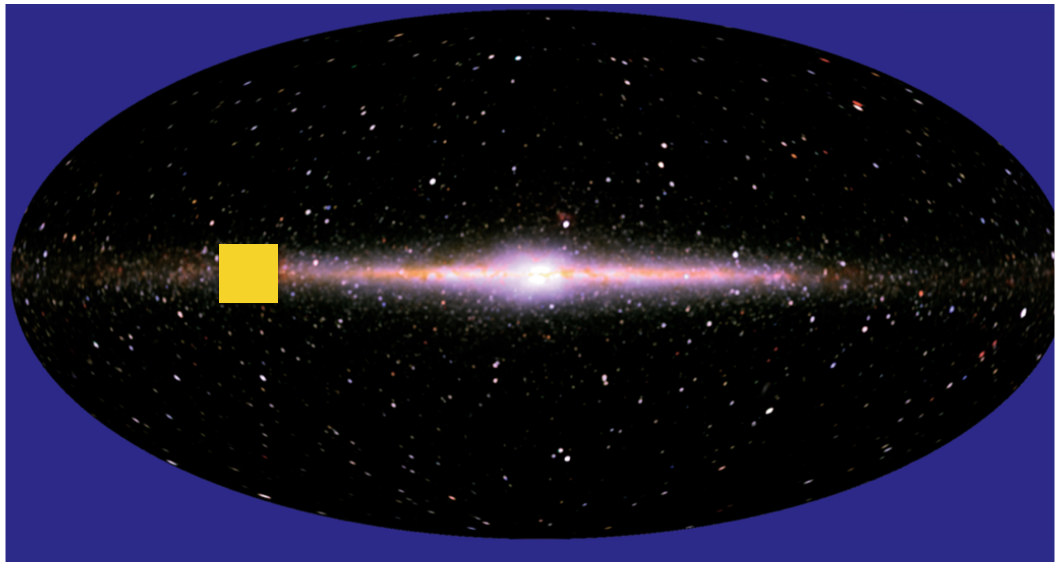
Table 1.1 Inventory of the solar neighborhood

BT Chap. 1

component	surface density ($\mathcal{M}_\odot\,\mathrm{pc}^{-2}$)	surface brightness ($L_\odot\,\mathrm{pc}^{-2}$)	M/L
visible stars	29	29	~1
stellar remnants	5	0	0
brown dwarfs	2	0	0
ISM	13	0	0
total	49 ± 6	29	~2
dynamical	74 ± 6	–	~3

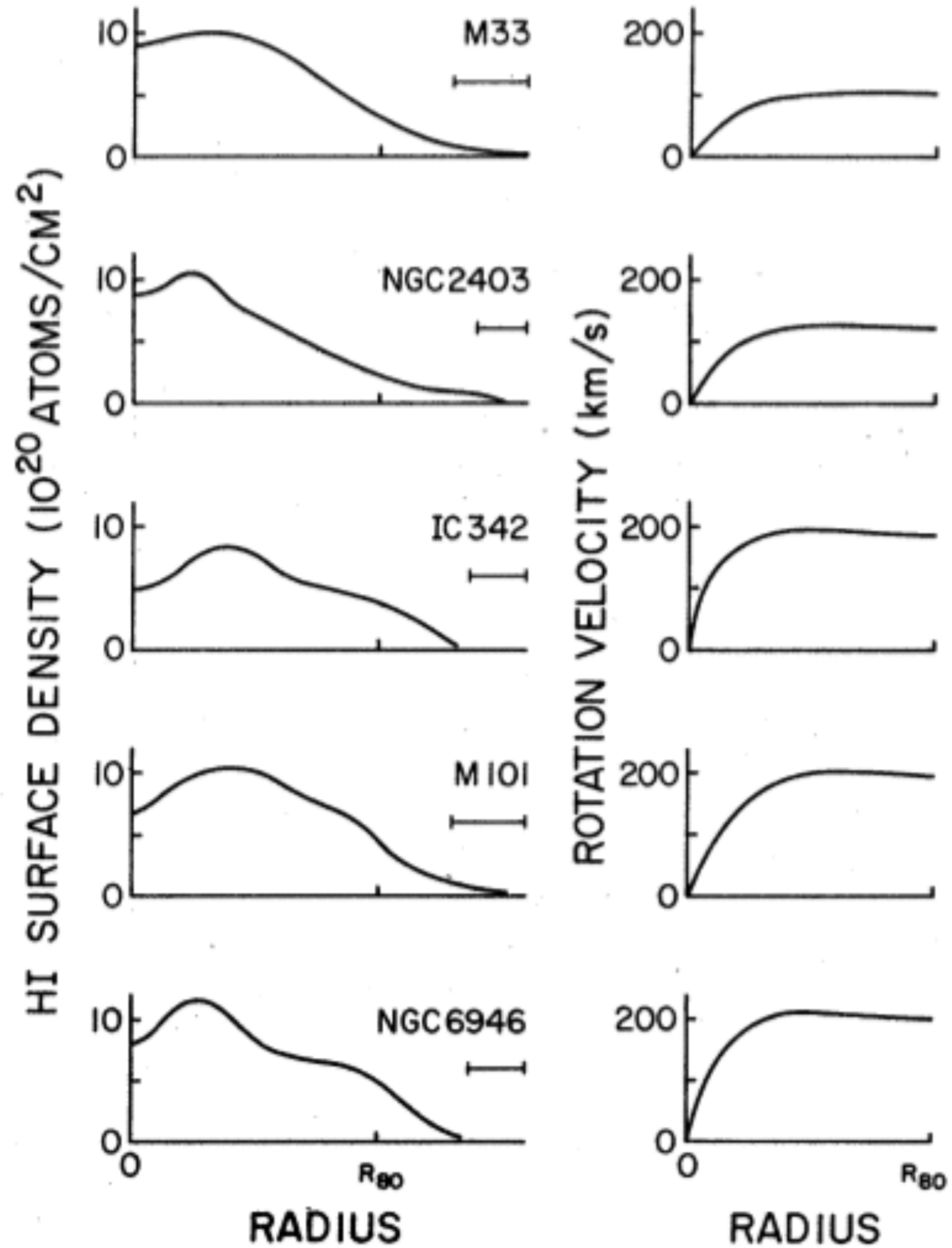
NOTES: Volume and luminosity densities are measured in the Galactic midplane and surface density is the total within ±1.1 kpc of the plane. Luminosity density and surface brightness are given in the *R* band. Dynamical estimates are from §4.9.3. Most other entries are taken from Flynn et al. (2006).

vertically (to +/-1.1kpc)
unexplained matter ~ explained matter



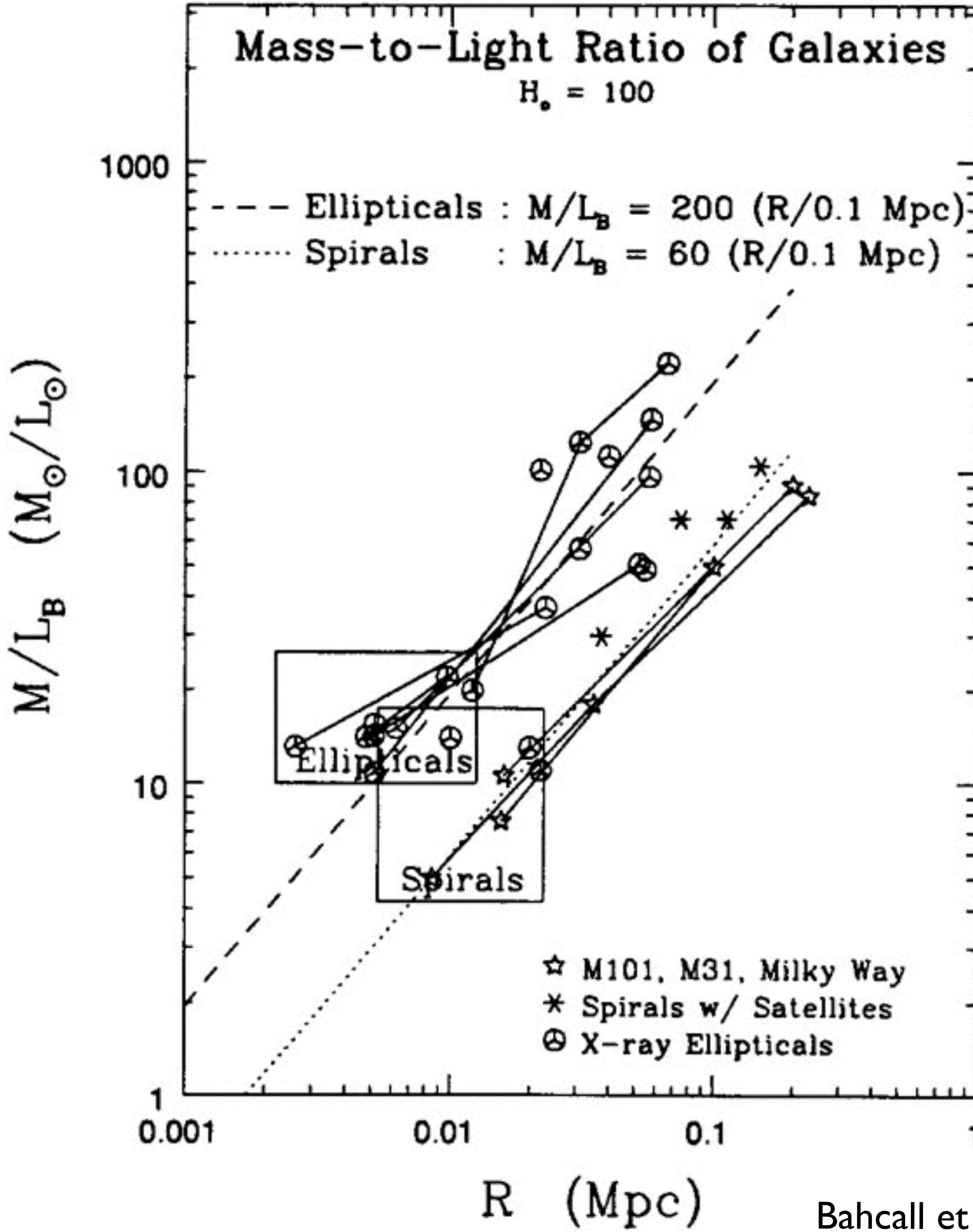
How to measure mass-to-light ratio?   -- whole galaxy

Galactic Rotation Curves



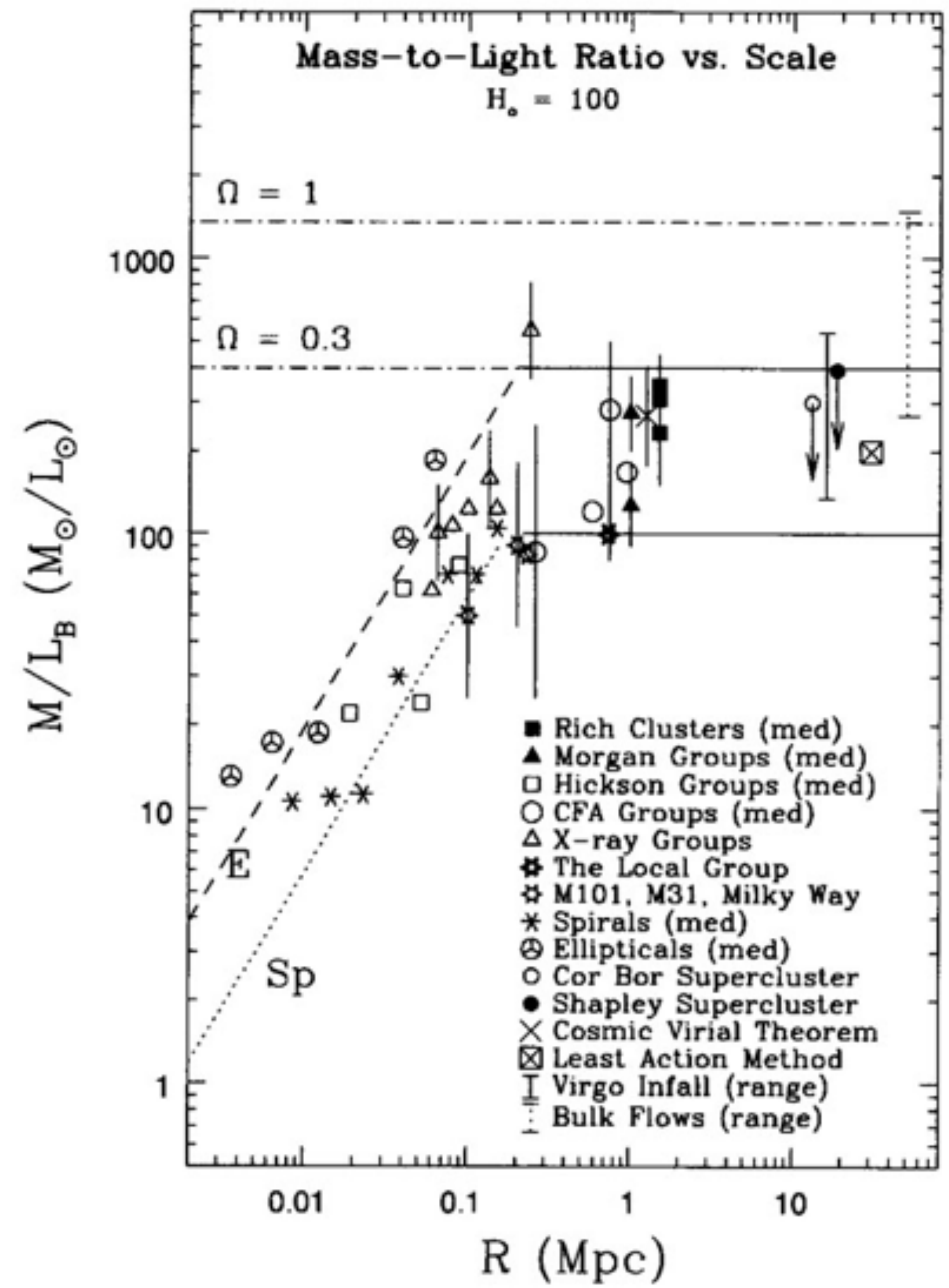
Rogstad & Shostak '72

FIG. 1.—Azimuthally averaged hydrogen surface densities and rotation velocities for five Scd galaxies. 'hese curves were obtained by appropriate smoothing of the two-dimensional maps. The bars under alaxy names indicate average radial beam diameters. R_{80} is the radius within which is found 80 percent f the observed H I.



Holmberg Radius (Holmber ’58):
The radius of an external galaxy at which the surface brightness is 26.6 mag/arcsec^2

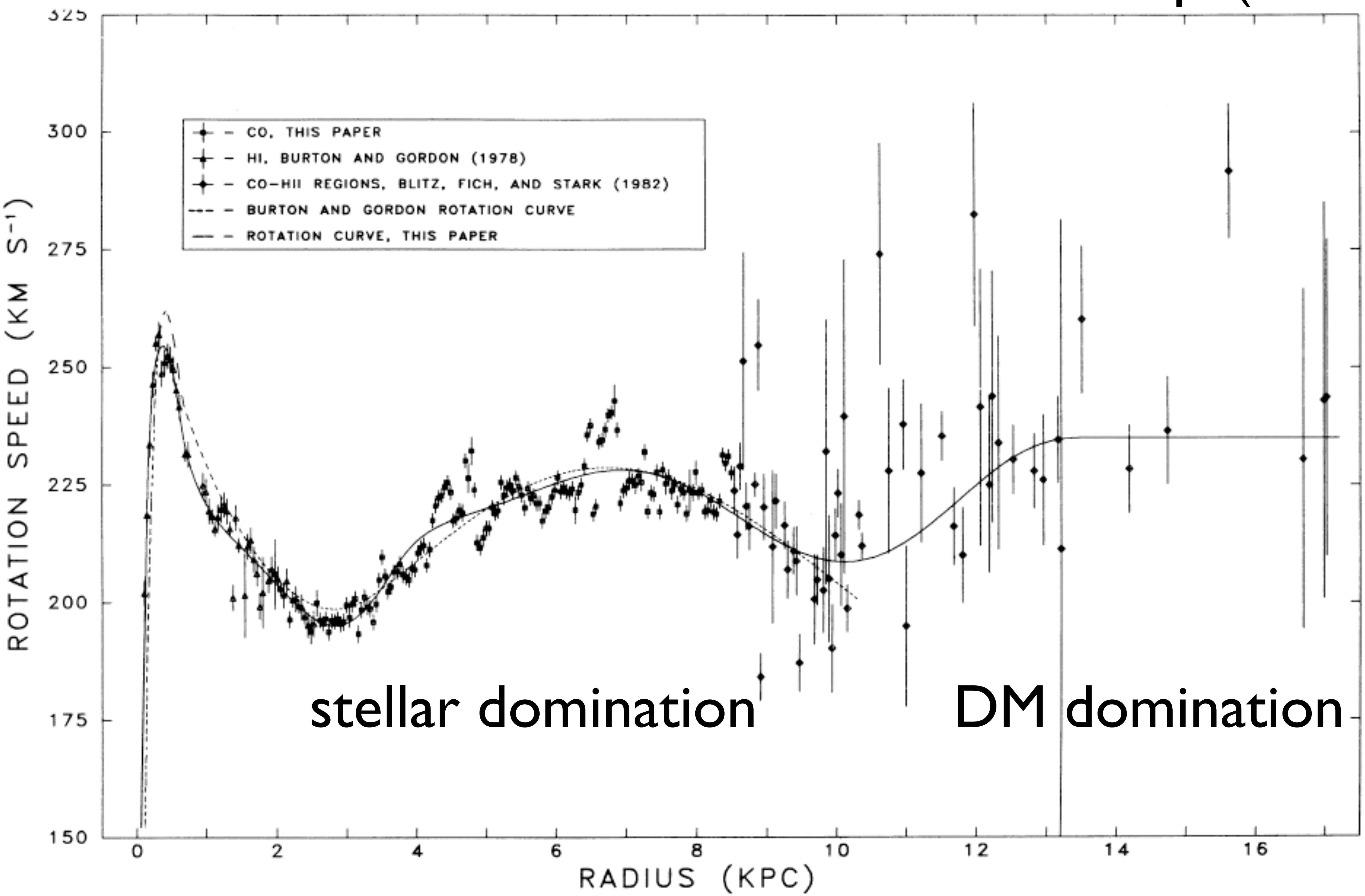
MW R_H ~ 20kpc



Bahcall et al ’95

Rotation curve of the Milky Way (Clemens '85)

$v \sim \sqrt{GM/R}$



EQUILIBRIUM DISK-BULGE-HALO MODELS FOR THE MILKY WAY AND ANDROMEDA GALAXIES

Lawrence M. Widrow
Department of Physics, Queen's University, Kingston, ON K7L 3N6, Canada; widrow@astro.queensu.ca

AND

John Dubinski
Department of Astronomy and Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada; dubinski@astro.utoronto.ca

Received 2005 January 27; accepted 2005 June 11

ABSTRACT

ıew set of self-consistent, equilibrium disk galaxy models that incorporate an exponential disk, a bulge, an NFW halo, and a central supermassive black hole. The models are derived from explicit ions for each component, and the large number of parameters permit detailed modeling of actual ent techniques that use structural and kinematic data such as radial surface brightness profiles, ro- bulge velocity dispersion profiles to find the best-fit models for the Milky Way and M31. Through ns of these models we explore their stability against the formation of bars. The models permit the ange of dynamical phenomenon with a high degree of realism.

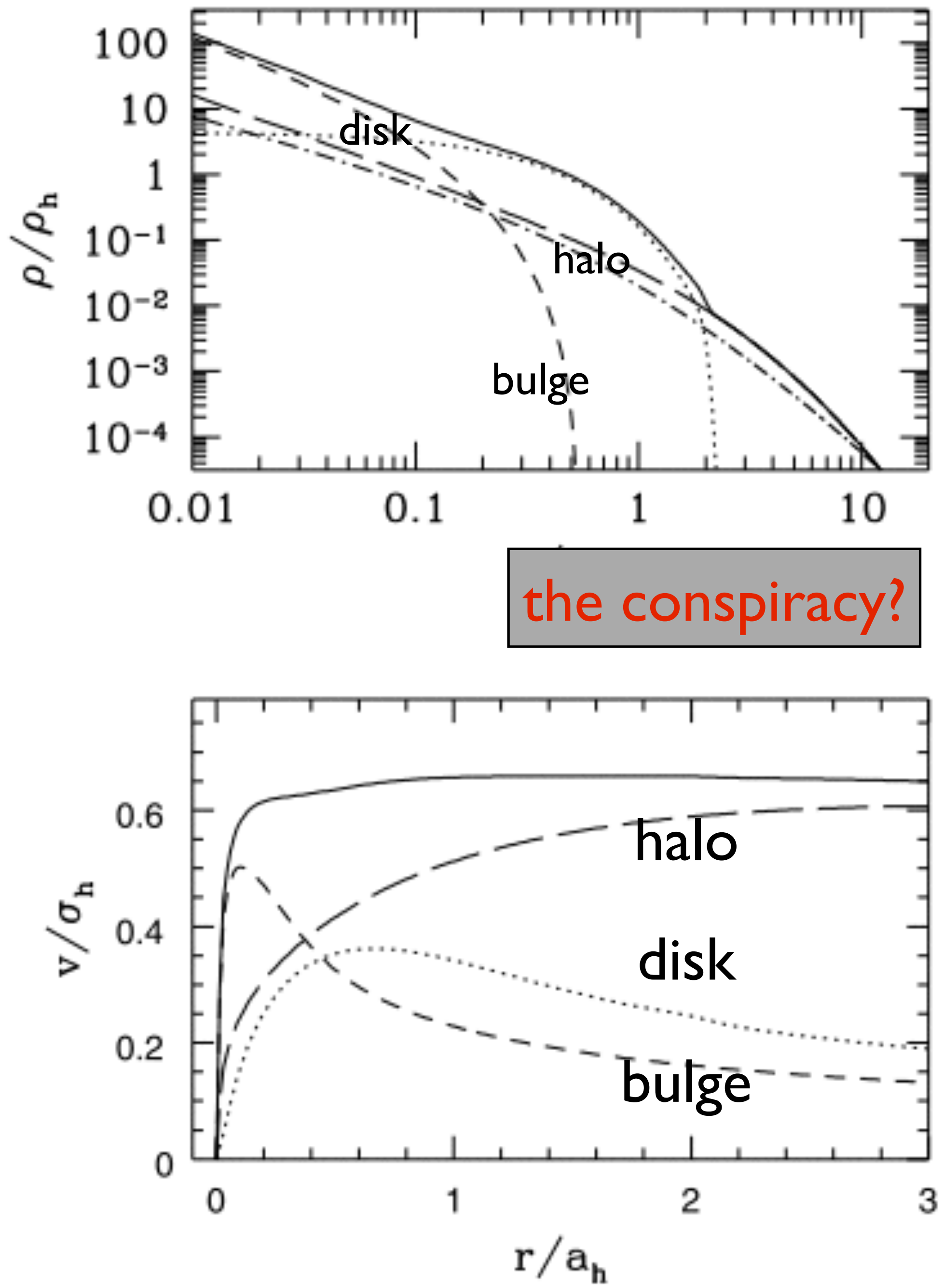


Fig. 2.—Density profile (*top*) and rotation curve (*bottom*) for the disk-bulge-halo model described in the text. Shown are the contributions from the disk (*dotted line*), bulge (*dashed line*), halo (*long-dashed line*), as well as the total density profile and rotation curve (*solid line*). Also shown is the halo model that results if the same halo parameters are used and the disk and bulge are not included (*dot-dashed line in the top panel*).

Annu. Rev. Astron. Astrophys. 1991. 29: 409–45

THE MASS OF THE GALAXY

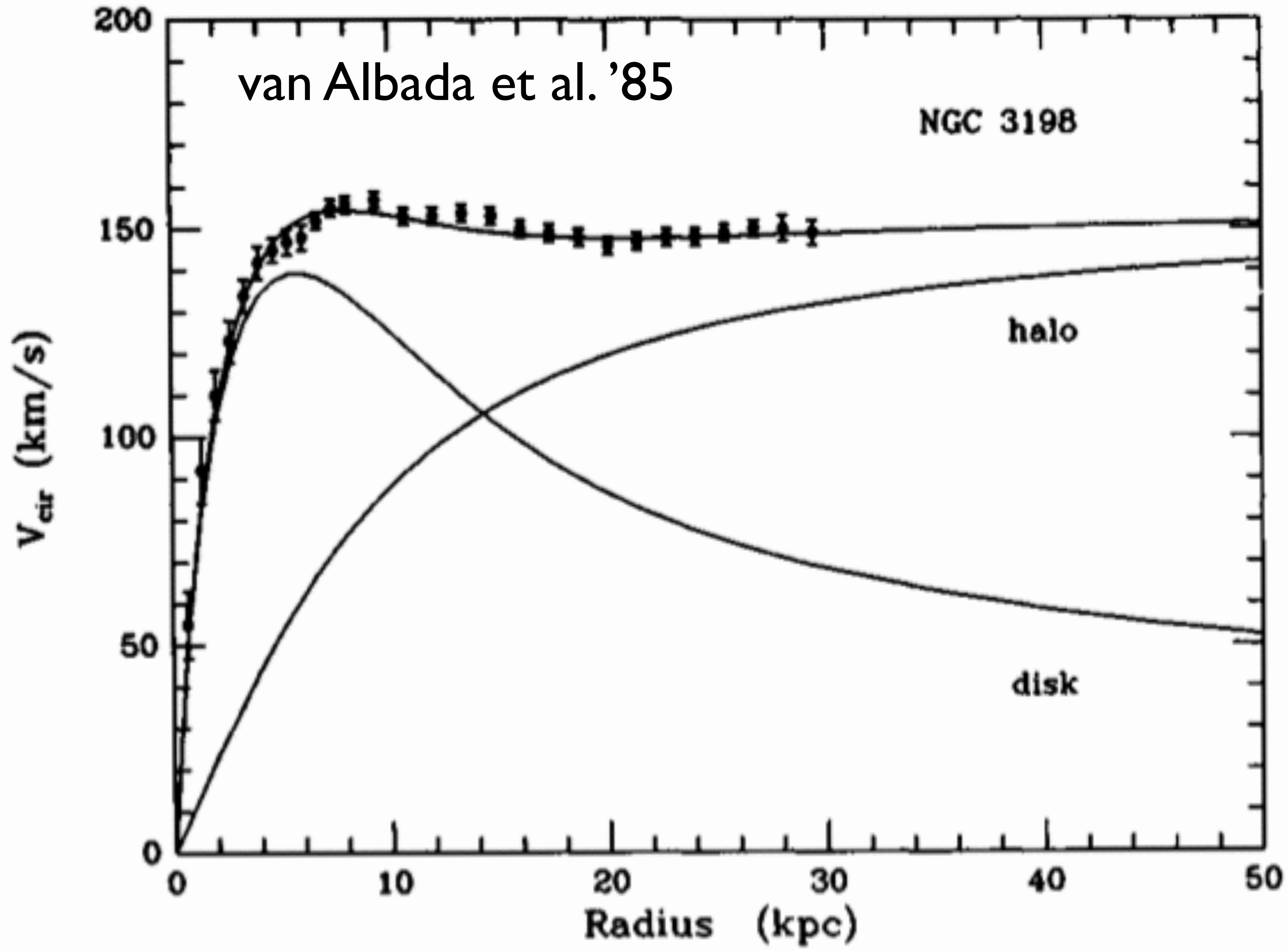
Michel Fich

Guelph-Waterloo Program for Graduate Work in Physics, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

Scott Tremaine

Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 1A1, Canada

DISTRIBUTION OF DARK MATTER IN NGC 3198



ial disk with maximum mass and halo to observed rotation curve (*dots with error bars*). The scale length of the
ion (60″, corresponding to 2.68 kpc). The halo curve is based on eq. (1), $a = 8.5$ kpc, $\gamma = 2.1$, $\rho(R_0) = 0.0040\ M_\odot$

decomposition non-unique (dep. on disk M/L value)

disk exponential, with scale length (in light) ~ 3kpc

disk-halo conspiracy?

something important about galaxy formation

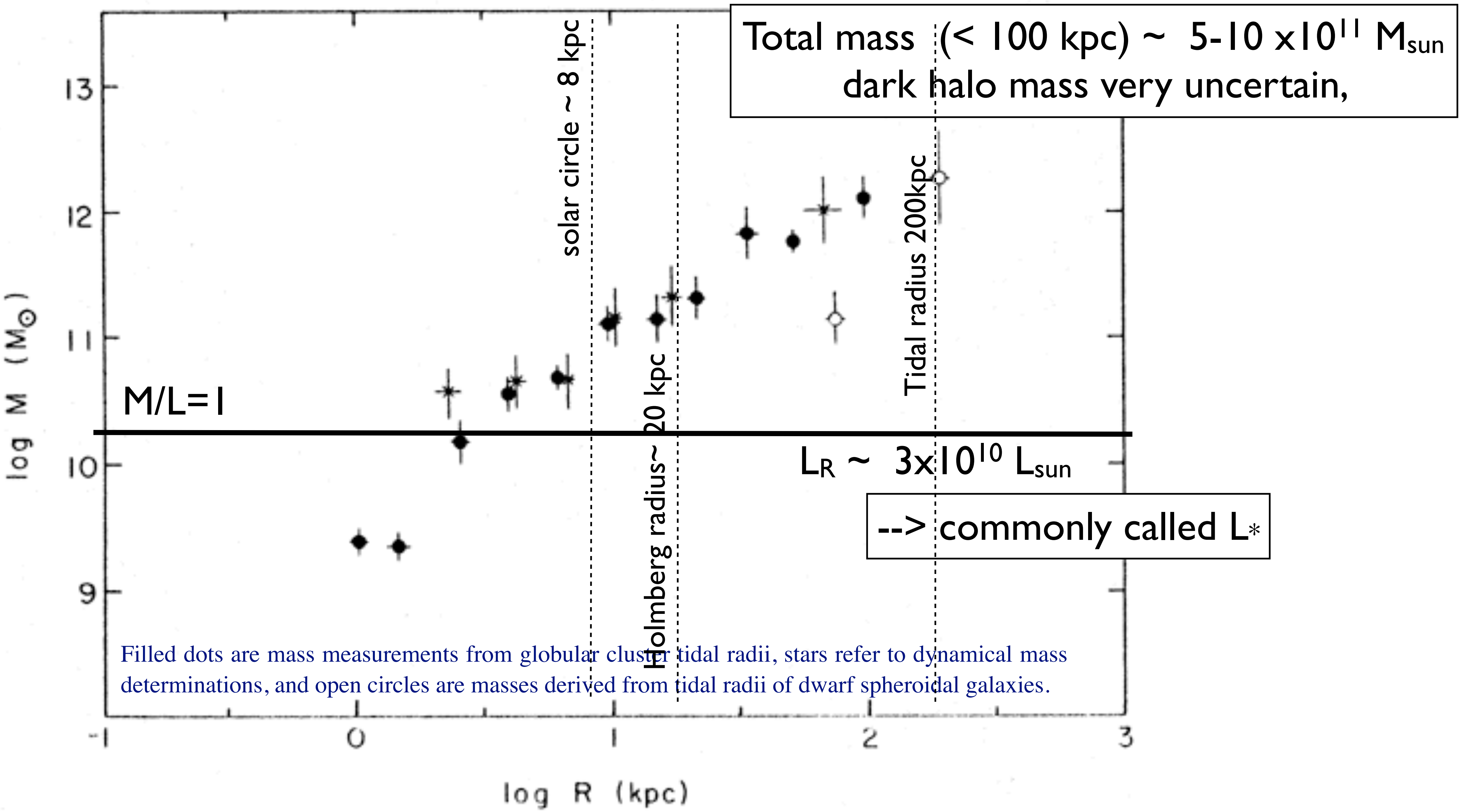
R_0 equal to 8 kpc. This allows a comparison of $\rho_{halo}(R_0)$ for the models with the halo mass density in the solar neighborhood ($\sim$0.01–0.02 $M_\odot$ pc^{-3}; Bahcall and Soneira 1980). Equation (1) is equivalent to

$$\rho_{halo}(R) = \rho_{halo}(0)\left[1 + \left(\frac{R}{a}\right)^{\gamma}\right]^{-1} .$$

MW @ 8kpc
disk: 0.1M_sun/pc^3
halo: 0.01 M_sun/pc^3

Enclosed mass in the Milky Way

methods other than rotation curves



mass-to-light ratio rises outward

Milky way M/L_R (< 100kpc) ~ 15 - 30 (BT quotes 7-170)

galaxy clusters (average in universe) ~ 200

an L* galaxy is typical in the universe
-- the Schechter Luminosity function

$$\Phi(L)\, dL = n_* \left(\frac{L}{L_*}\right)^{\alpha} exp\left(-\frac{L}{L_*}\right)\, d\left(\frac{L}{L_*}\right)$$

Press & Schechter '74
Schechter '76

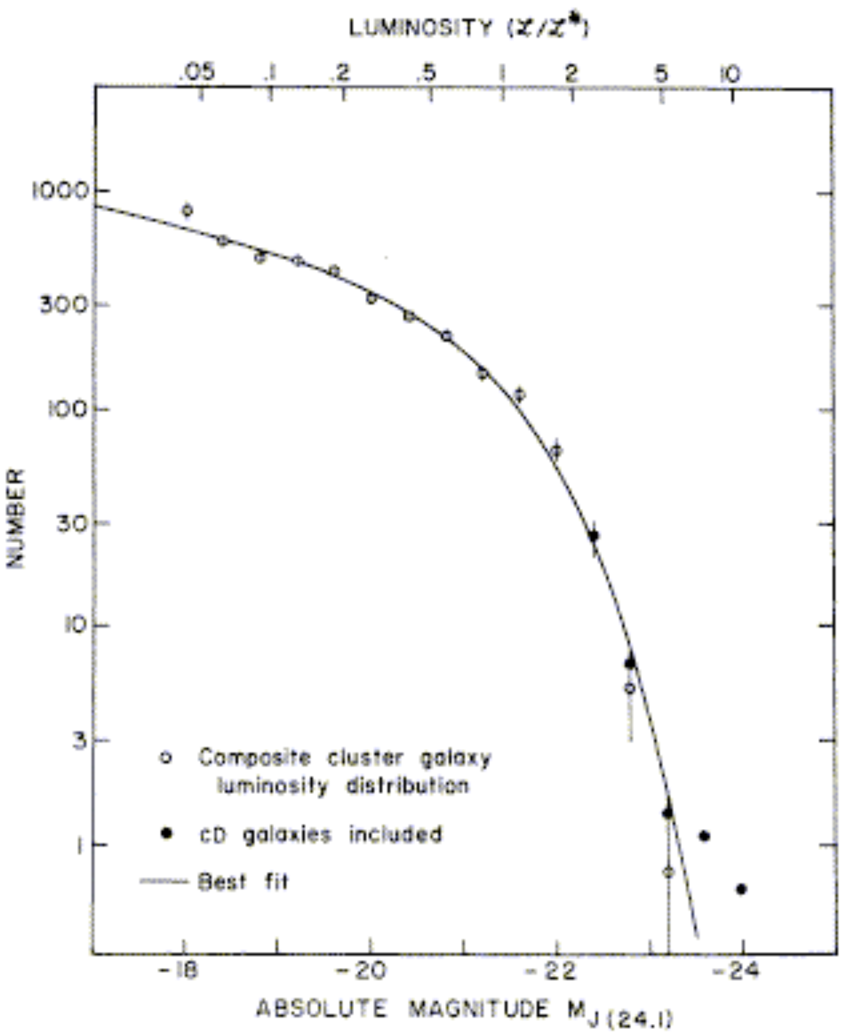
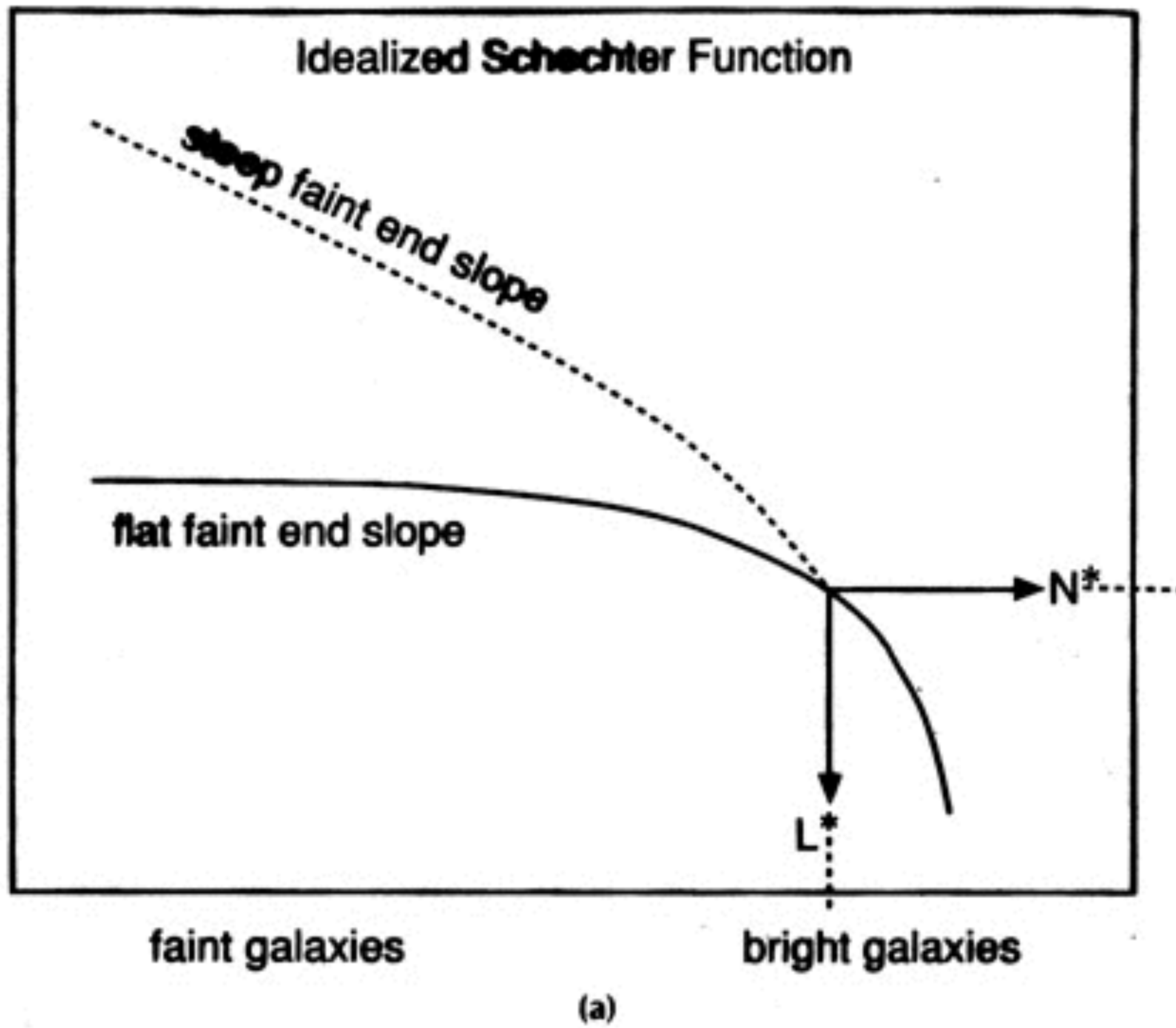


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.



While dark matter cosmology seems well established, one remaining central challenges is to understand how galaxies form.

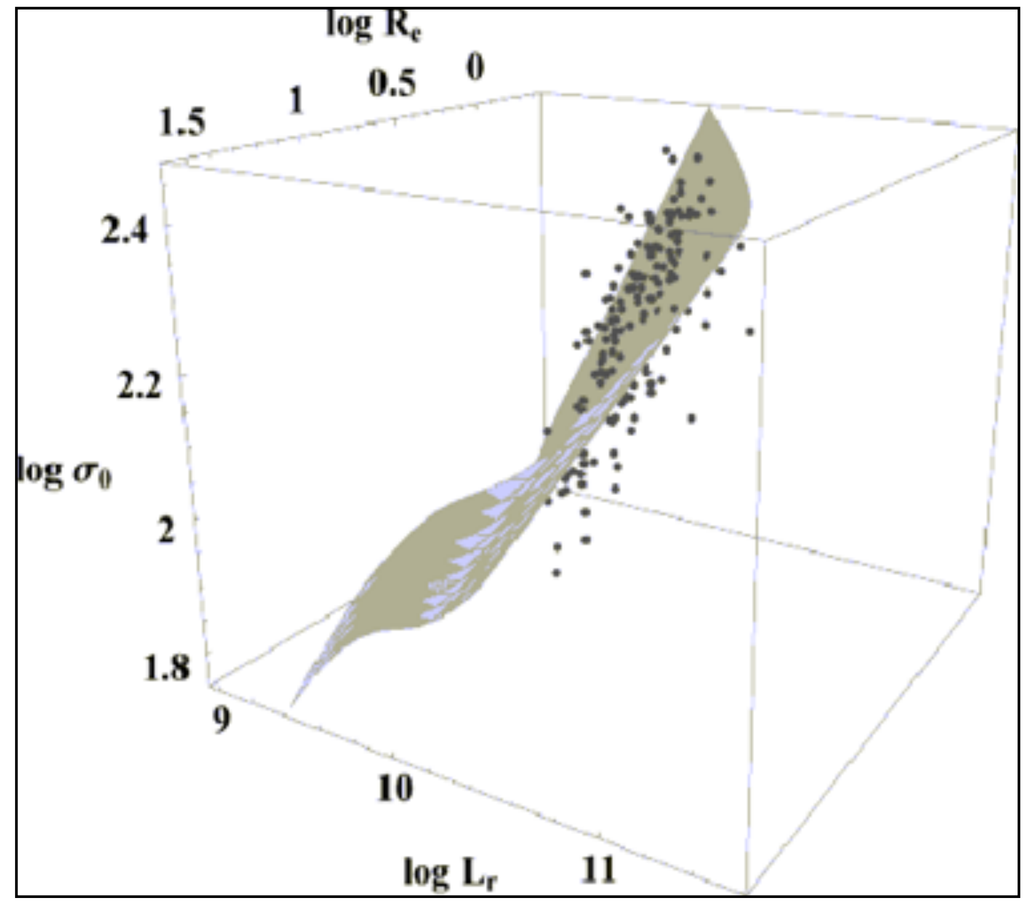
Theory vs. Observations:

. global properties

. individual components

Fundamental planes:

some properties of a galaxy that are observed to correlate with other properties.



examples:

the Faber-Jackson law -- velocity dispersion/Luminosity

the Tully-Fisher law -- rotation velocity/Luminosity

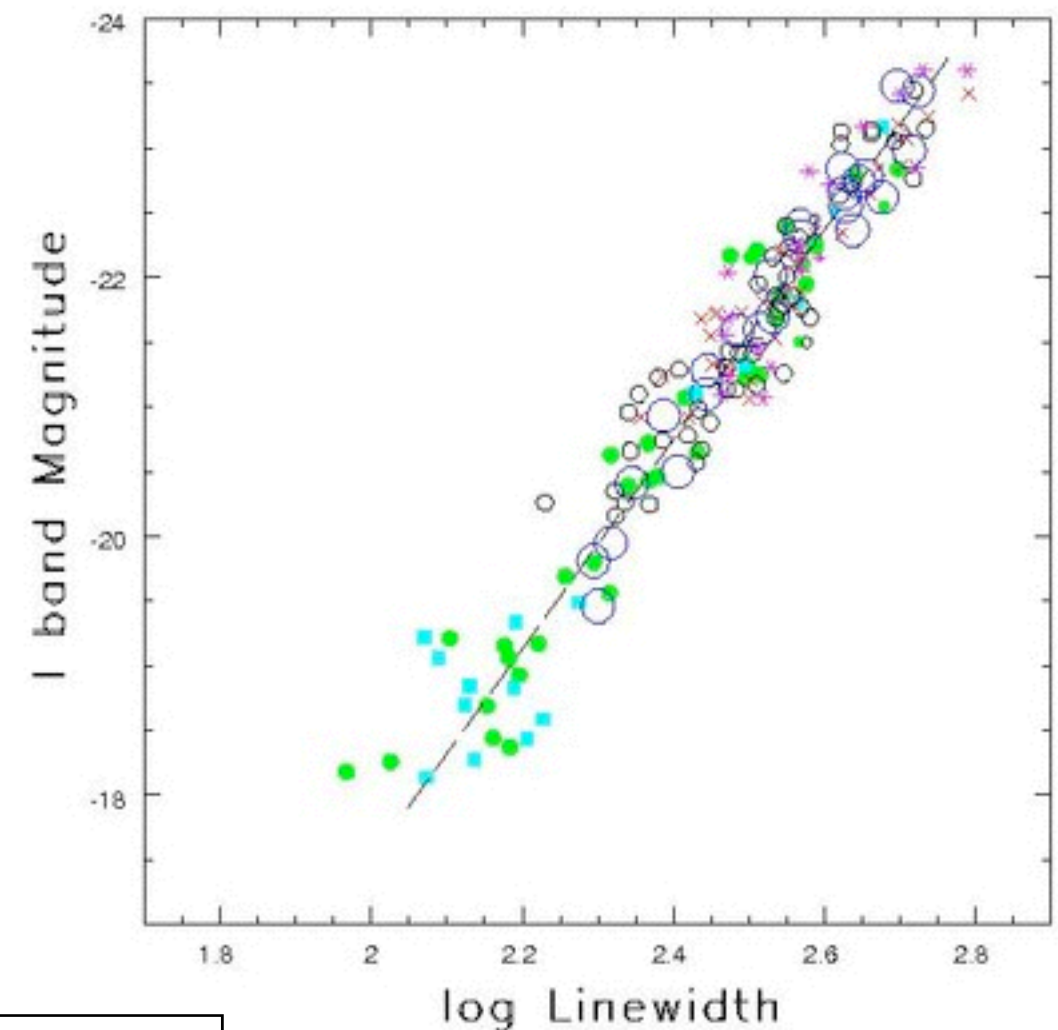
the Kormendy relation -- surface brightness/size

the M-sigma relation -- central blackhole mass/dispersion

The Tully-Fisher Relation for disk galaxies

$L \propto V^{\alpha}$
L: galaxy luminosity,
V: characteristic velocity (rotation velocity)
$\alpha_B \approx 3.5$, $\alpha_{\text{IR}} \approx 4$

scatter ~ 0.2 mag
good enough for distance ladder



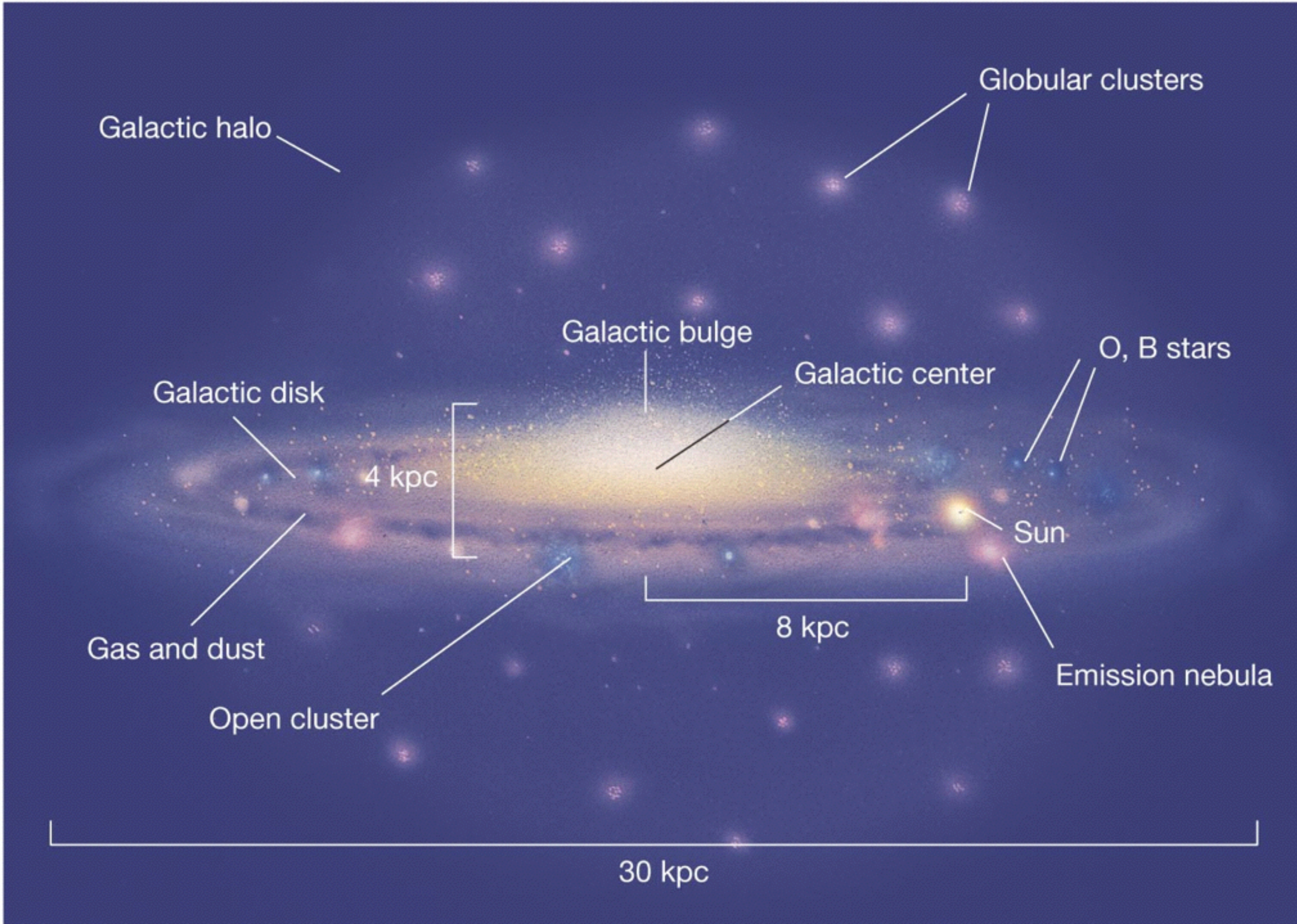
V is set by the DM halo, L is set by luminous matter

Let $v^2 \approx \frac{GM}{R}$ (Virial Theorem)
$M = (M/L) \times L = \gamma L$, where γ is the mass-to-light ratio
$\rightarrow L \approx \frac{V^2 R}{G\gamma}$

So $\frac{M}{R^2} \propto \frac{1}{\gamma}$

dark matter halo knows about the mass-to-light ratio

Components of the Galaxy



multiple components in the MW
&
the assembly history

- geometry of MW (thin/thick disks+bulge+halo, the distribution of star light)
- dark matter dominates at large distances (rotation curve)
- the local group (distance to LMC, SMC, dwarf galaxies,missing satellites)
- globular clusters (double MS, mass segregation)
- galactic center (BH, stellar cluster),

A correct assembly history produces these components, and explains the observed fundamental planes.

How many stars are in the MW?

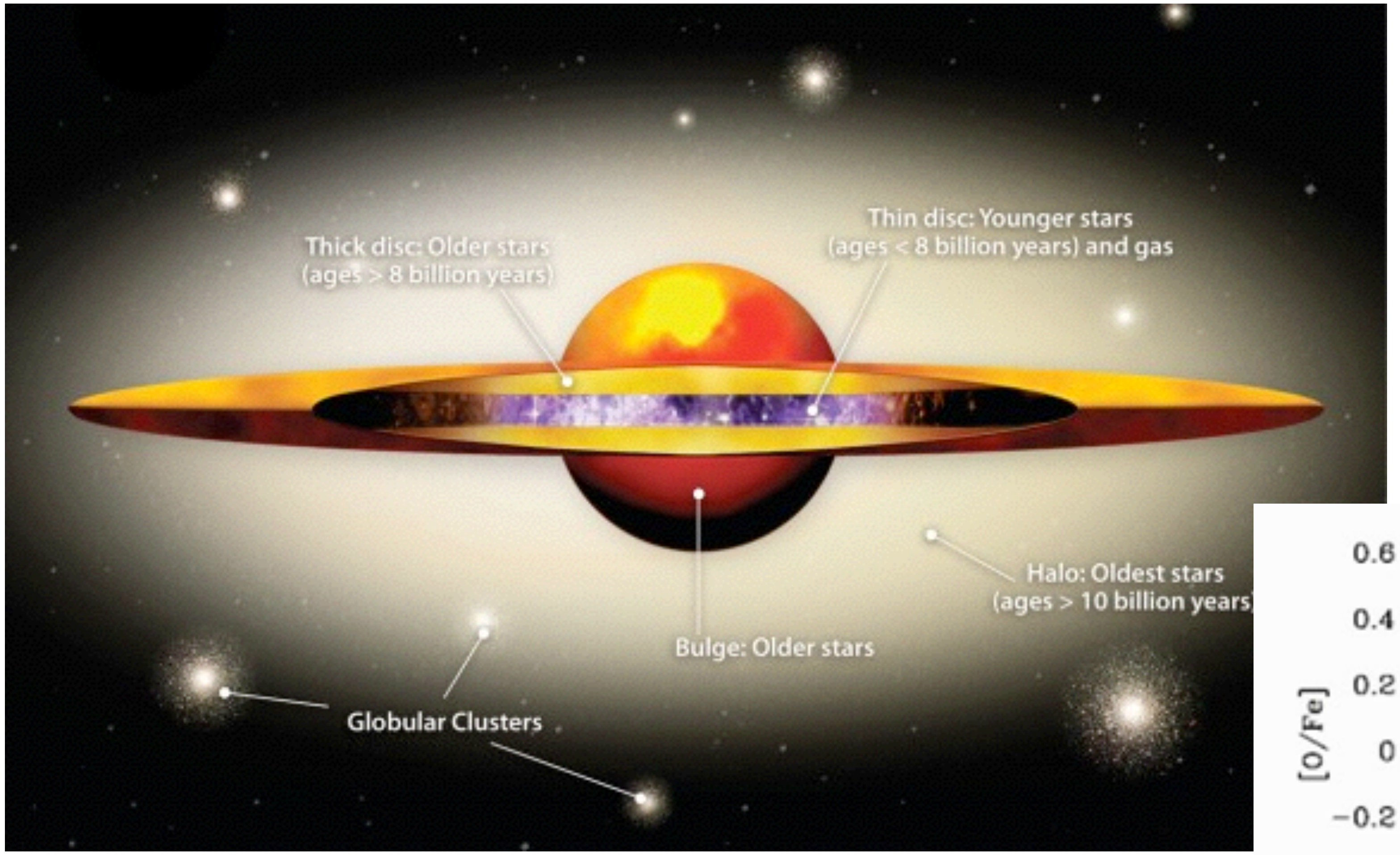
Table 1.2 Properties of the Galaxy

BT

Global properties:	
disk scale length R_d	(2.5 ± 0.5) kpc
disk luminosity	$(2.5 \pm 1) \times 10^{10}\, L_\odot$
bulge luminosity	$(5 \pm 2) \times 10^{9}\, L_\odot$
total luminosity	$(3.0 \pm 1) \times 10^{10}\, L_\odot$
disk mass	$(4.5 \pm 0.5) \times 10^{10}\, \mathcal{M}_\odot$
bulge mass	$(4.5 \pm 1.5) \times 10^{9}\, \mathcal{M}_\odot$
dark halo mass	$(2\,^{+3}_{-1.8}) \times 10^{12}\, \mathcal{M}_\odot$
dark halo half-mass radius	$(100\,^{+100}_{-80})$ kpc
disk mass-to-light ratio Υ_R	$(1.8 \pm 0.7)\Upsilon_\odot$
total mass-to-light ratio Υ_R	$(70\,^{+100}_{-63})\Upsilon_\odot$
black-hole mass	$(3.9 \pm 0.3) \times 10^{6}\, \mathcal{M}_\odot$
Hubble type	Sbc

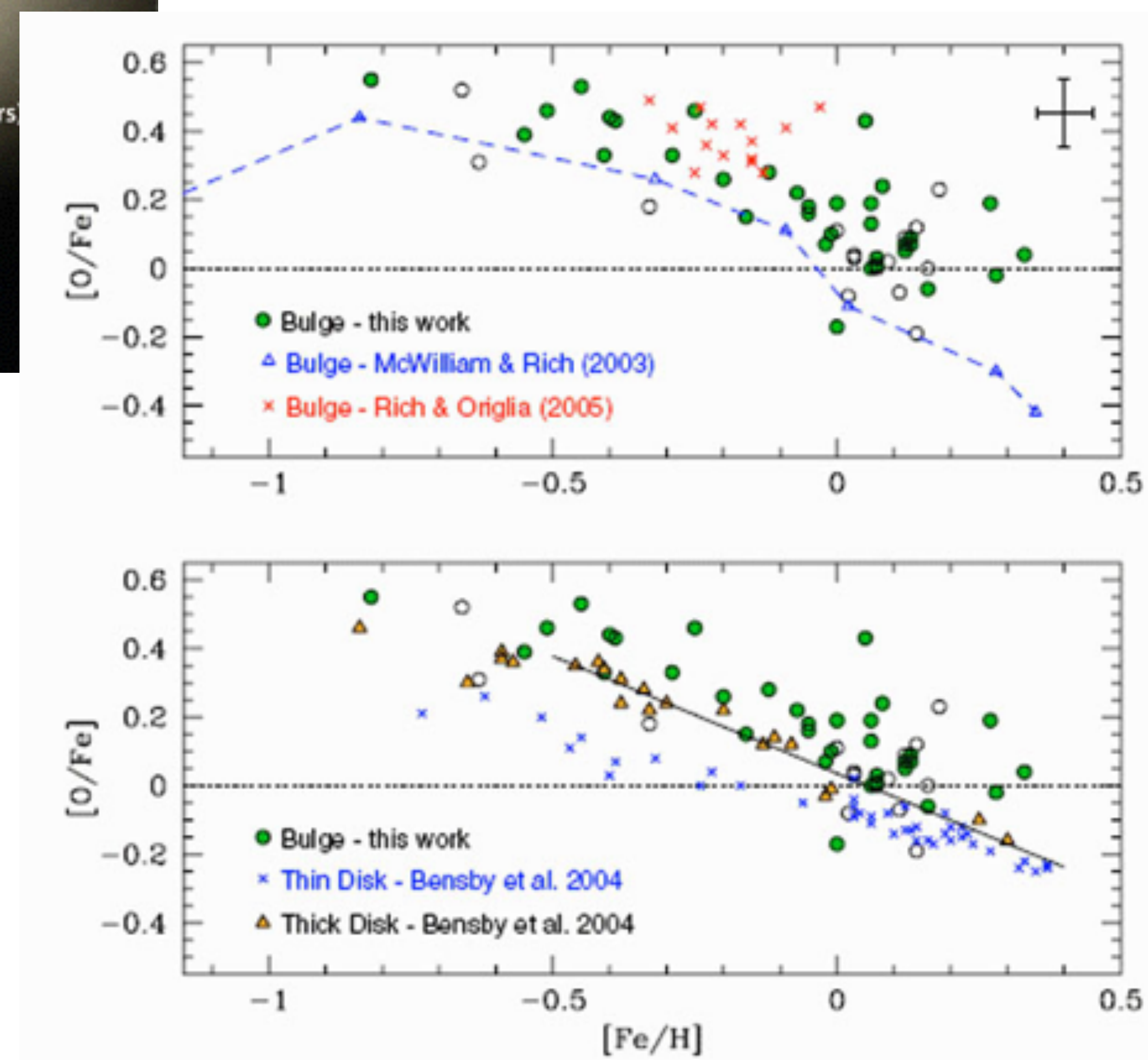
stellar halo mass (Bell et al '07) $(3.7 \pm 1.2) \times 10^{8} M_\odot$

Stellar Disk(s), 90%: thin + thick



origin of thick disk:

thin disk flattening up?
early star formation different?
mergers and stirrings?



- stars formed in disks (why?)

- we have two roughly equal mass disks (Gilmore & Reid 1983, arXiv1401.1835)
- vertical scale height: thin ~300pc; thick ~ 1kpc; radial scale length, thin ~ 3.6kpc, thick ~ 2kpc;
- thick disk exclusively old stars,
- different metallicity distributions
- the Sun is a thin-disk star

Theoretical Arguments for dark matter halo

Can a thin disk of stars be stable?

ON THE GRAVITATIONAL STABILITY OF A DISK OF STARS

ALAR TOOMRE
Department of Mathematics, Massachusetts Institute of Technology
Received August 17, 1963; revised January 18, 1964

ABSTRACT

This paper considers the question of the large-scale gravitational stability of an arbitrary, highly flattened stellar system, which is assumed initially to rotate in approximate equilibrium between its self-gravitation and the centrifugal forces. It is concluded that no such disk, if fairly smooth or uniform, can be entirely stable against a *tendency* to form massive condensations within its own plane, unless the root-mean-square random velocities of its constituents, in the directions parallel to that plane, are everywhere sufficiently large. Lacking such random motions, it is shown that the system must be vulnerable to numerous unstable disturbances, the dimensions of which may approach its over-all radius, and whose times of growth are to be reckoned in fractions of the typical periods of revolution.

The minimum root-mean-square radial velocity dispersion required in any one vicinity for the complete suppression of all axisymmetric instabilities is calculated (in collaboration with A. Kalnajs) as $3.36\, G\mu/\kappa$, where G is the gravitational constant, and μ and κ are the local values of the projected stellar density and the epicyclic frequency, respectively. From that, and the observed μ and κ, together with their uncertainties, this minimum for the solar neighborhood of our Galaxy is estimated to fall between 20 and 35 km/sec, a range which indeed encompasses the actual radial velocity dispersions of the most predominant types of stars in our vicinity. It is pointed out that both this curious agreement, and also the well-known discrepancy between the z- and r-velocity dispersions at least of the older disk stars, may be explainable in terms of past instabilities of this galactic disk.

Toomre said: not infinitely thin.

Ostriker & Peebles said: need dark matter **halo**

T= rotational energy
W=grav. energy

rotationally supported
T/|W| = 0.5

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

J. P. Ostriker
Princeton University Observatory
AND
P. J. E. Peebles
Joseph Henry Laboratories, Princeton University
Received 1973 May 29

ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

Subject headings: galactic

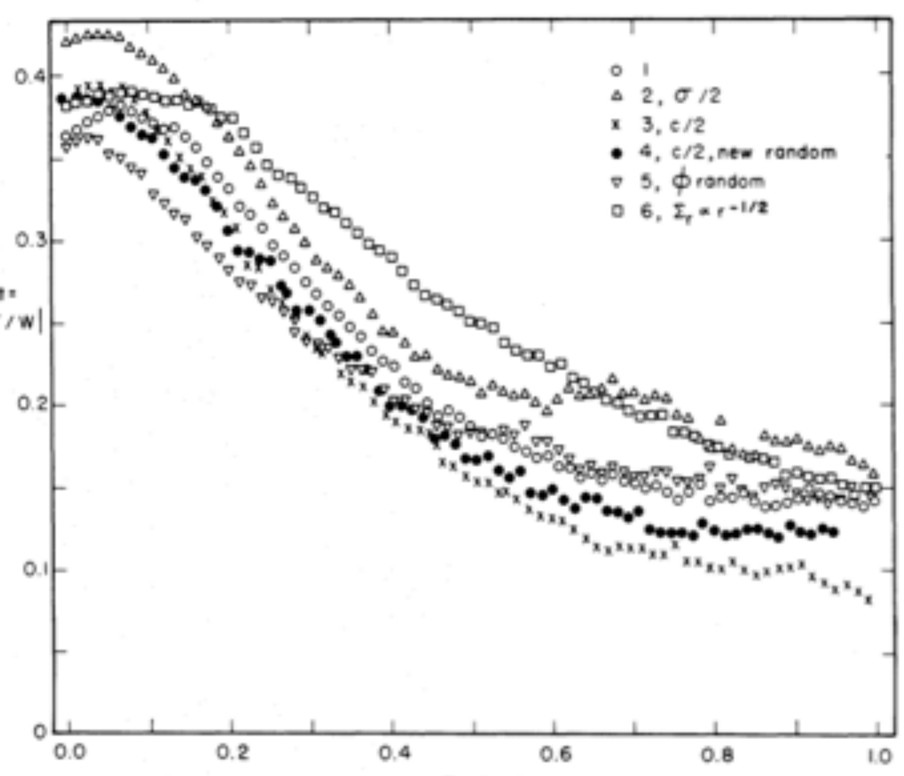


Fig. 2.—Evolution of the model galaxies. Abscissa is time measured in units of the orbit period r the outermost particles in the initial system under the assumption of circular orbits. Ordinate defined in equation 3.

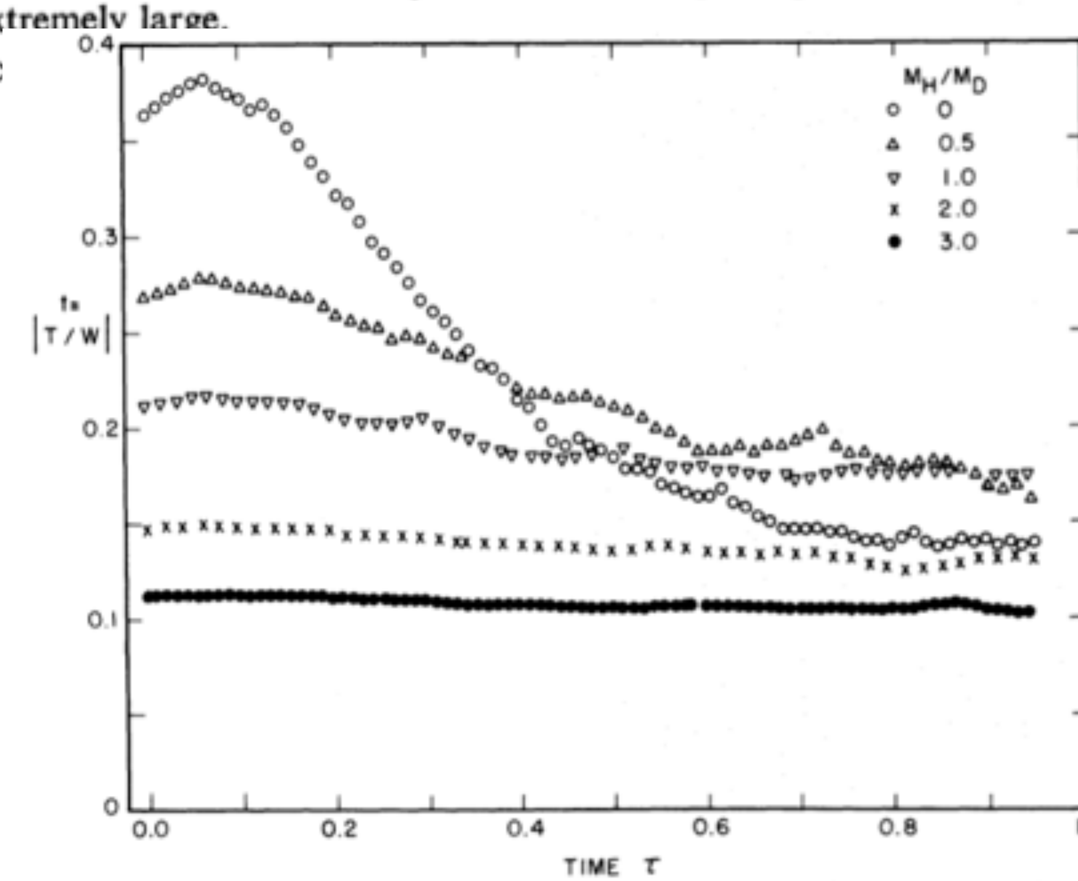
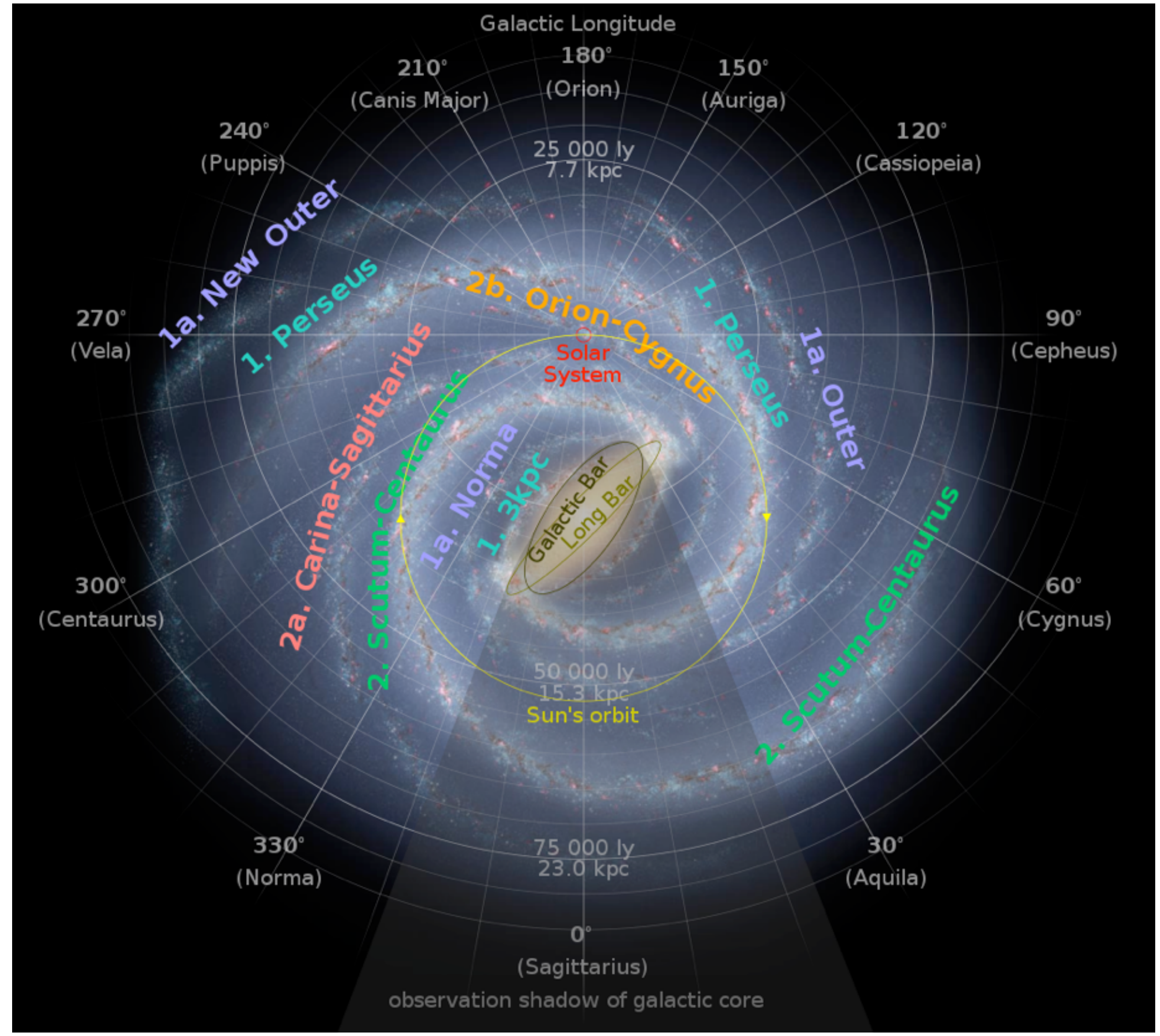


Fig. 6.—Effect of the halo on the evolution of the model galaxy

Spiral arms:
compression of stars and ISMs



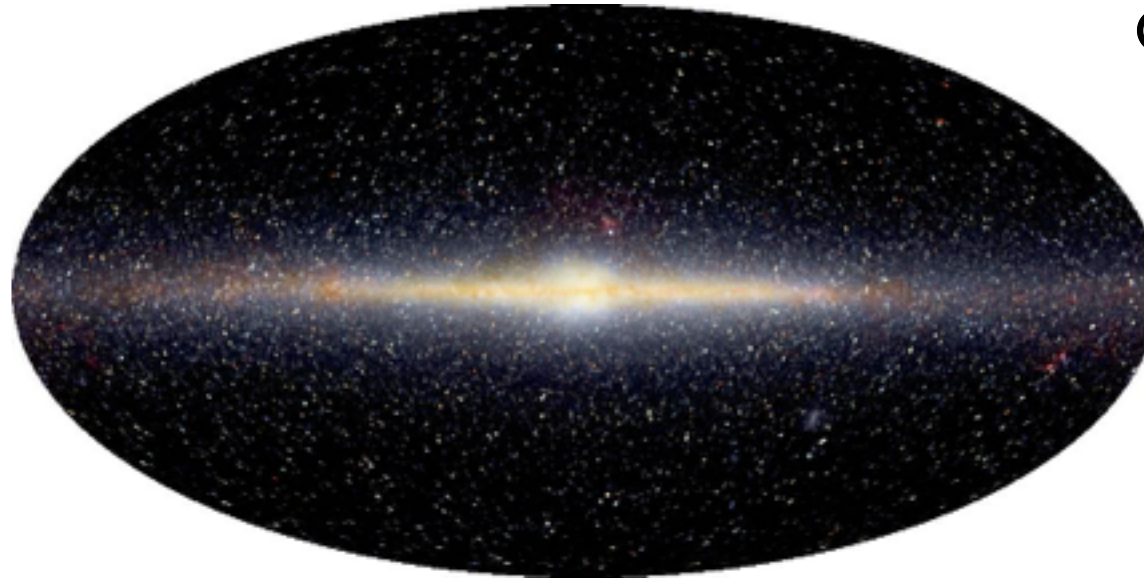
.ISM compression leads to star formation. So young stars are found in spiral arms.

.oddly, old disk stars are organized into 2-arm spirals('08) while young stars 4-arm ('13)

. are spiral arms long lived or transient?

. are spiral arms externally excited?

Bulge stars, 10%:



COBE map of MW showing the bulge

.vertical thickening of stars near the center (< 3kpc)
. common among disk galaxies
. some are classical bulges (mini-ellipticals), some are pseudo-bulges (bars)
. we have a long bar
. stars old (> 12 Gyrs), with a span of metallicities
. formation not understood: merger? secular process?
(little dark matter there)
. central region hosts massive blackholes

Halo stars, 1%:

halo likely from accreted dwarfs, as well as some stars ejected from center (HVS)

The halos are studded with Globular Clusters

globular cluster:

~ 10^5 stars, invariably old (in MW)
age ~ 10^4 dynamical time (typical galaxy/cluster ~a few)
central density: 10^4 M_sun/pc^3

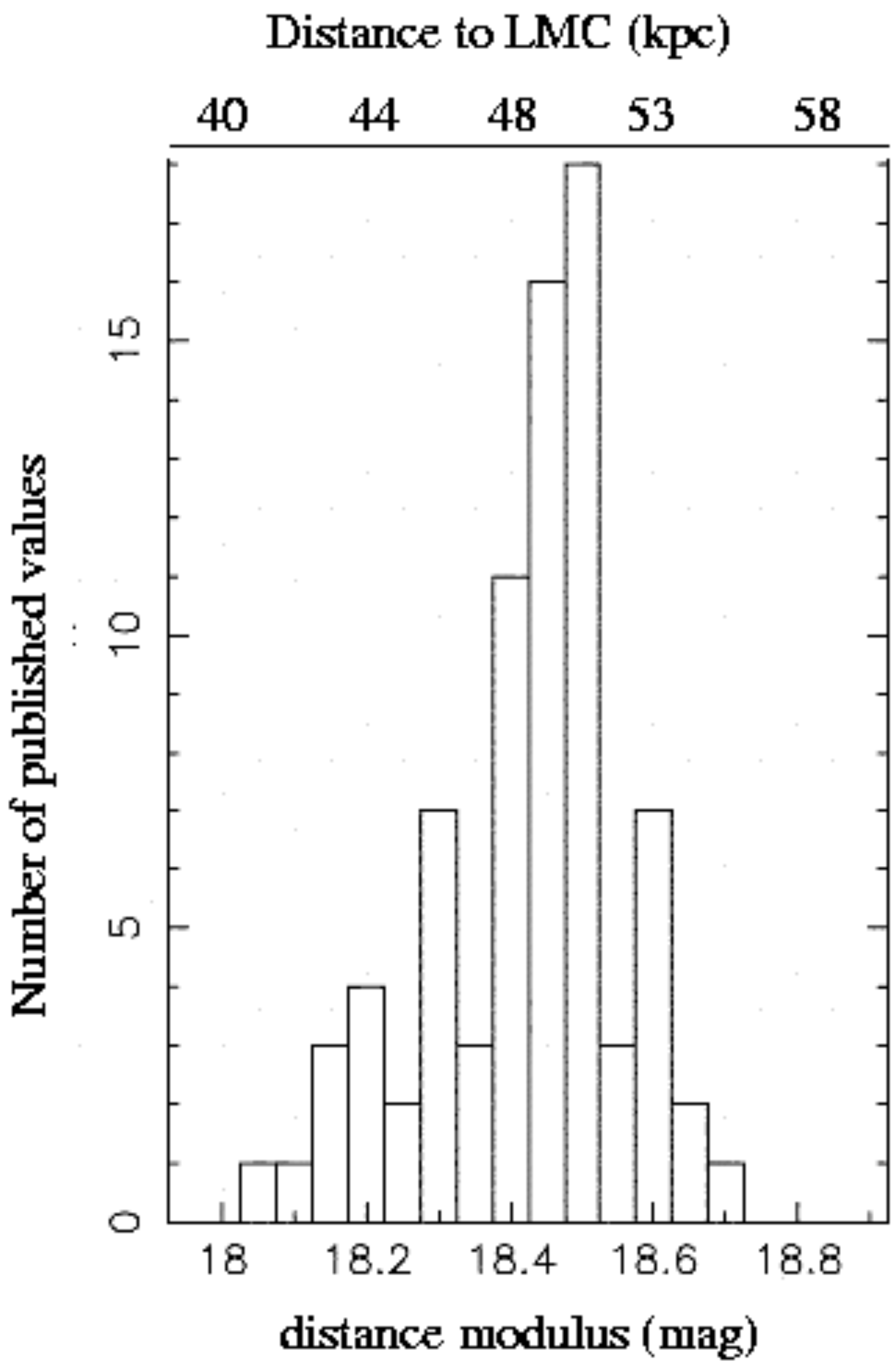
(solar neighbourhood: ~ 0.1 M_sun/pc^3)

Origin unclear

MW: ~200
Andromedae: ~ 500
M87: ~ 13,000

LMC/SMC

Distance to LMC/SMC



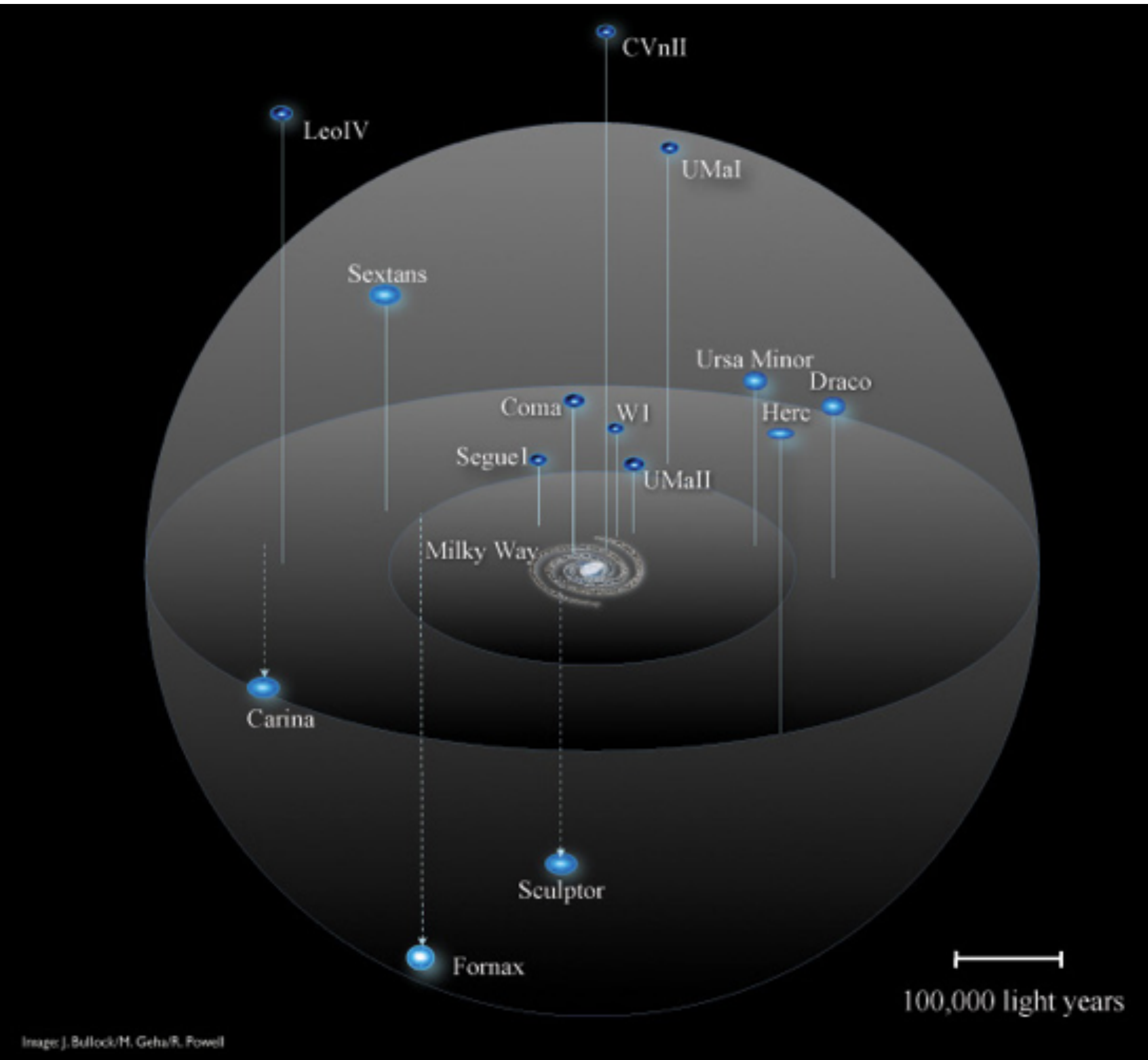
LMC distance sets the calibration of Cepheids, so affects all cosmological distance measurements, 10% error

methods include: RR Lyrae, Tip red giant, Mira, SN 1987A, main sequence fitting, eclipsing binary, red clump

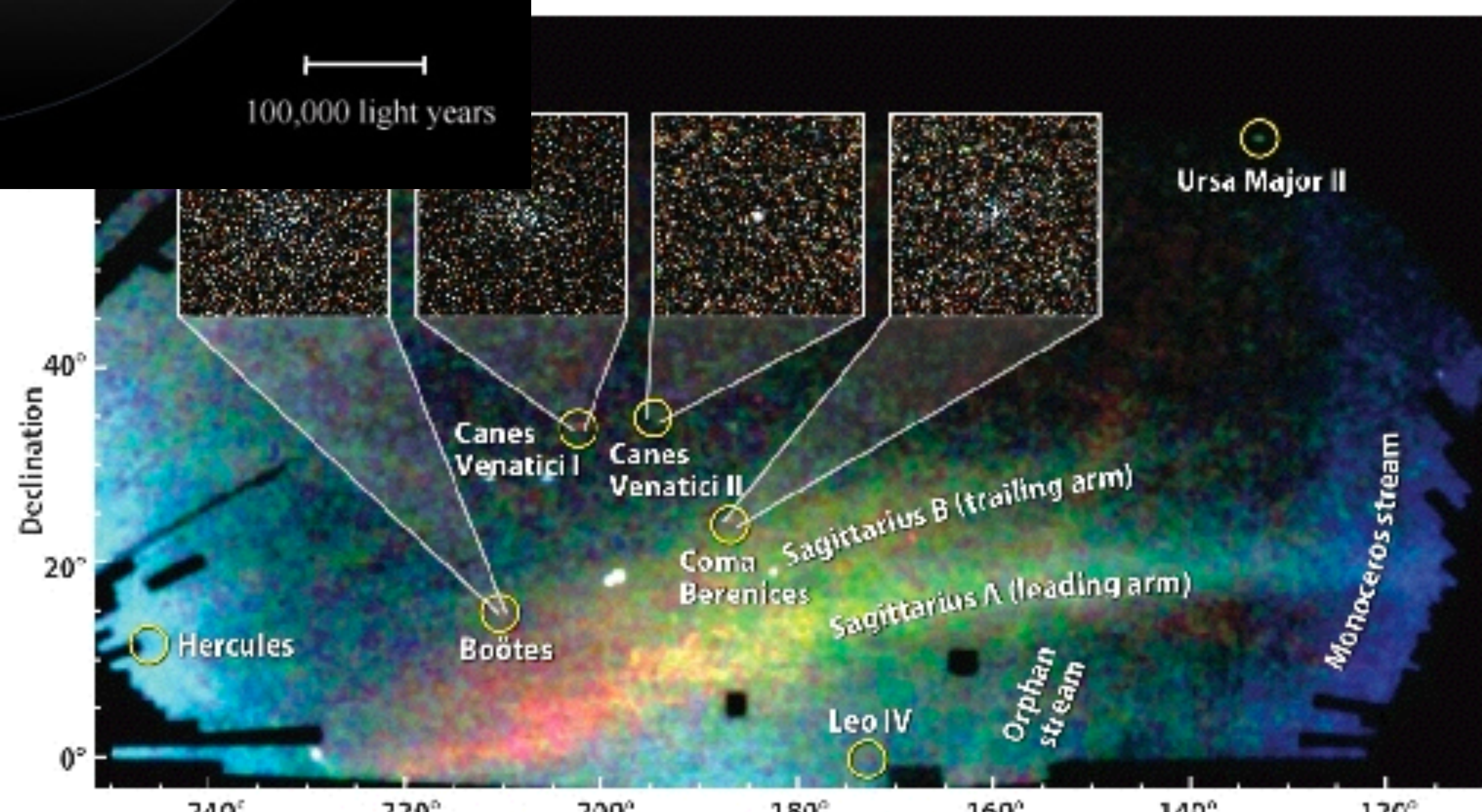
$$d = 10^{\frac{\mu}{5}+1}$$

distance modulus

HST team compiled previous data:
18.5+/-0.1 mag ('01)
later results tend to aggregate
(Schaefer '08)



Sloan Digital Star Survey stellar map of the northern sky, showing trails and streams of stars torn from disrupted Milky Way satellites. Insets show new dwarf companions (credit: V. Belokurov).



"Missing Satellite Problem"

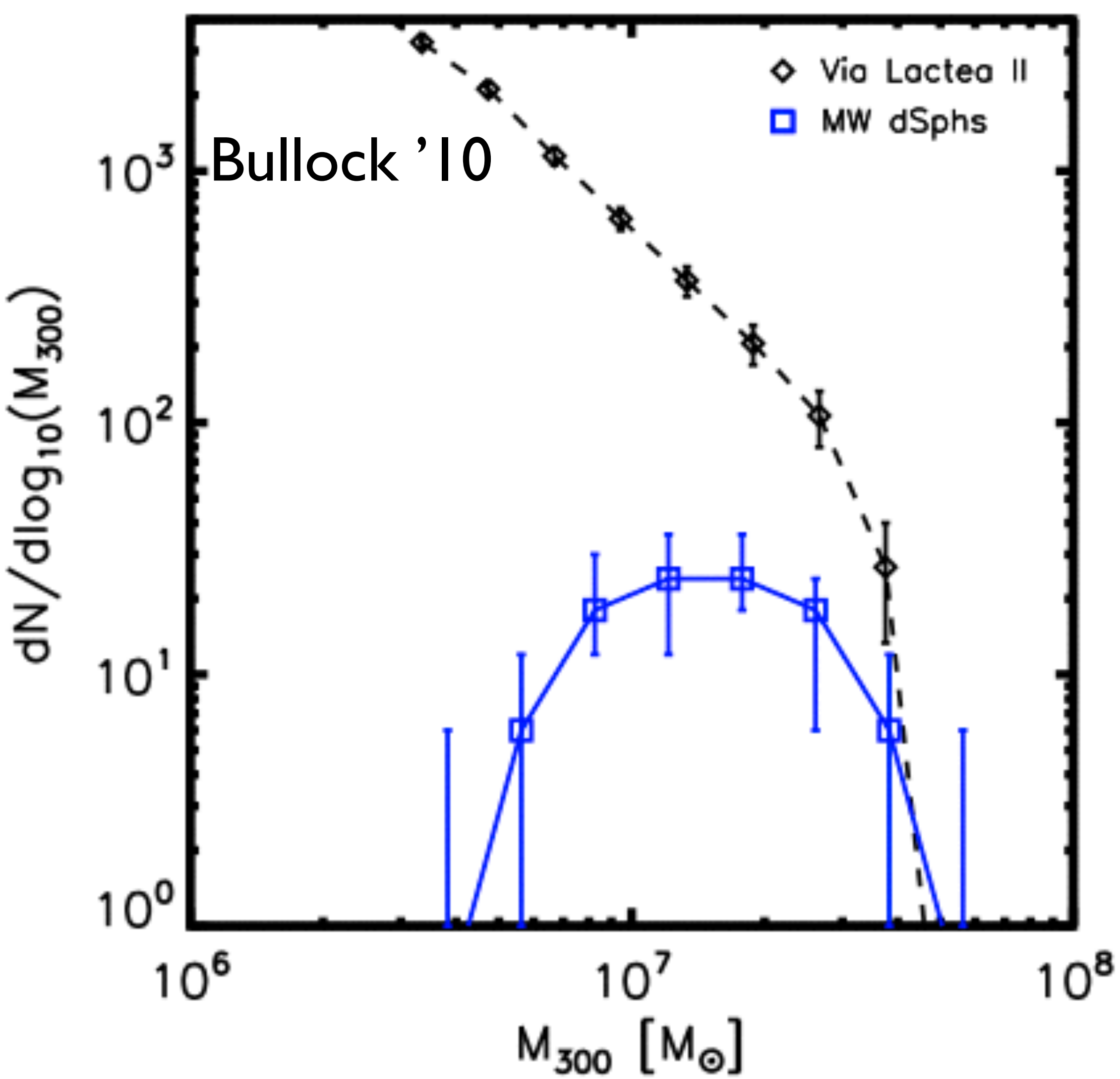


Fig. 1.6. Mass function for $M_{300} = M(< 300\text{pc})$ for MW dSph satellites and subhalos in the Via Lactea II simulation within a radius of 400 kpc. The dashed curve is the subhalo mass function from the simulation. The solid cu the median of the observed satellite mass function. The error bars on the obs mass function represent the upper and lower limits on the number of configur that occur with a 98% of the time (from Wolf et al., in preparation). Note th mismatch is about ~ 1 order of magnitude at $M_{300} \simeq 10^7 M_{\odot}$, and that it grows significantly towards lower masses.

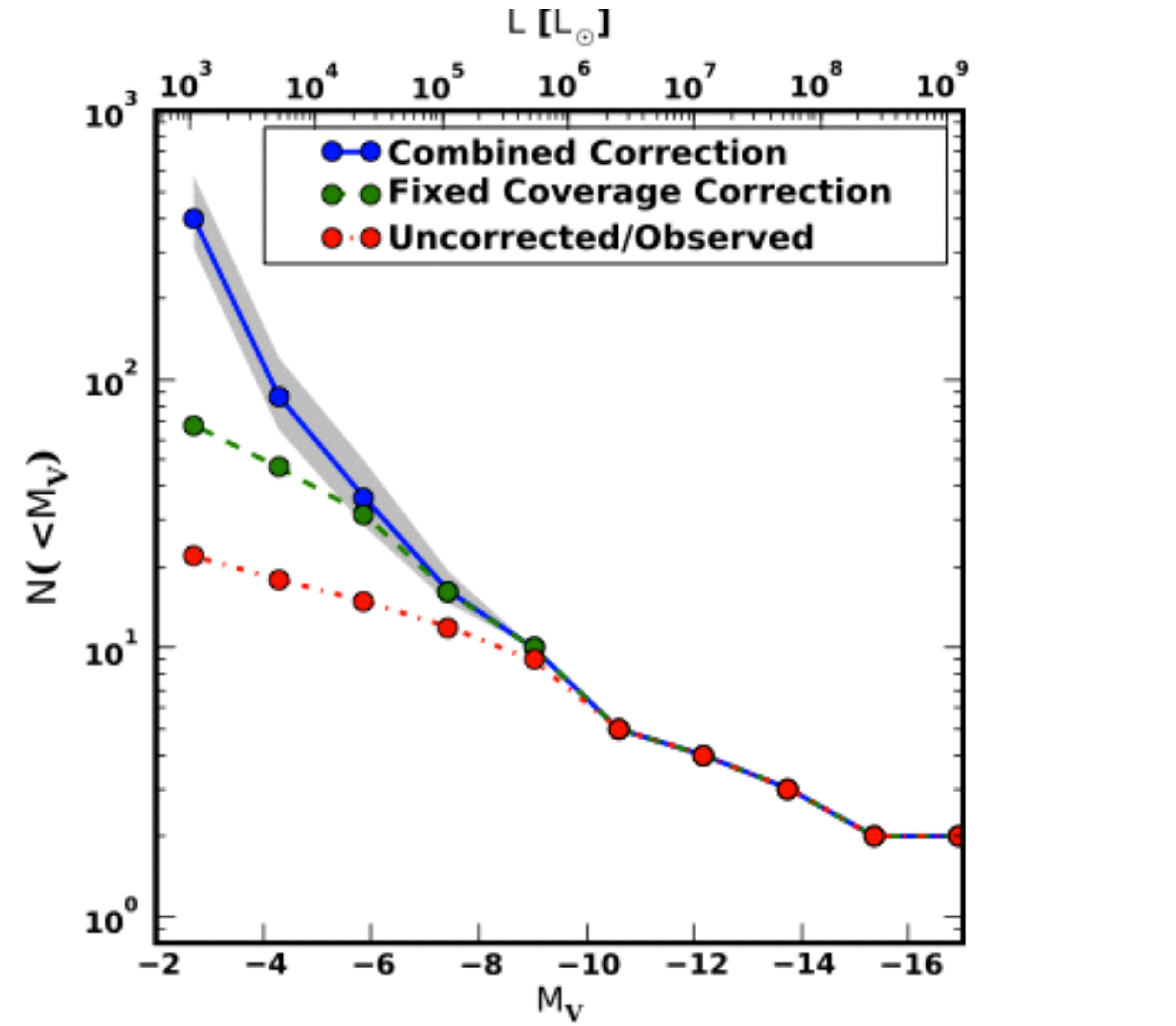


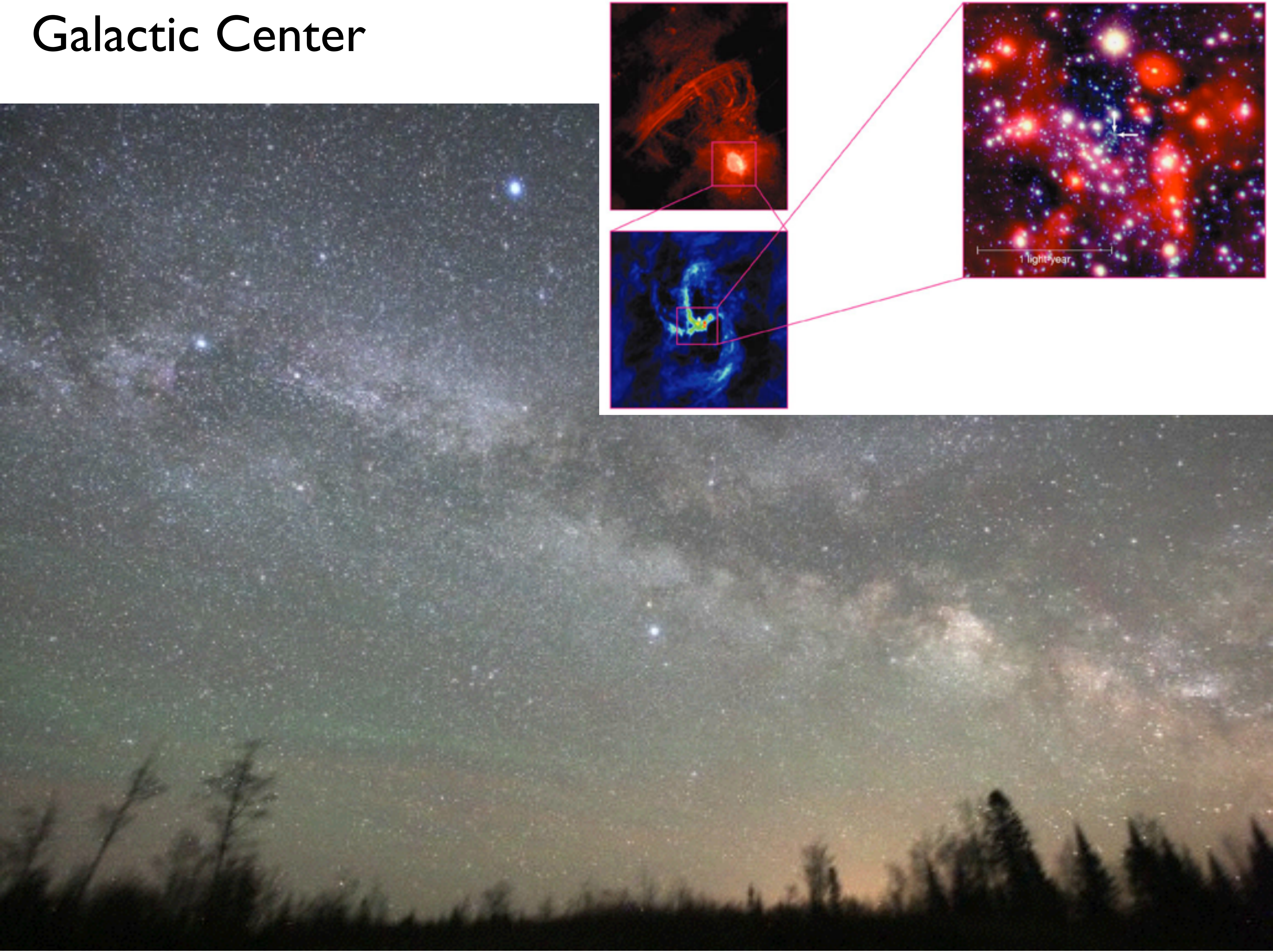
Fig. 1.11. Luminosity function of dSph galaxies within $R_h = 417$ kpc of the Su as observed (lower), corrected for only SDSS sky coverage (middle), and with lu minosity completeness corrections from Tollerud et al. (2008) included (upper Note that the brightest, classical (pre-SDSS) satellites are uncorrected, while ne satellites have the correction applied. The shaded error region corresponds to th 98% spread over mock observation realizations within the Via Lactea I halo.

Tidal Streams

dwarf galaxies incorporated into halos,
tidal stripping
shape of galactic potential (tri-axial?)

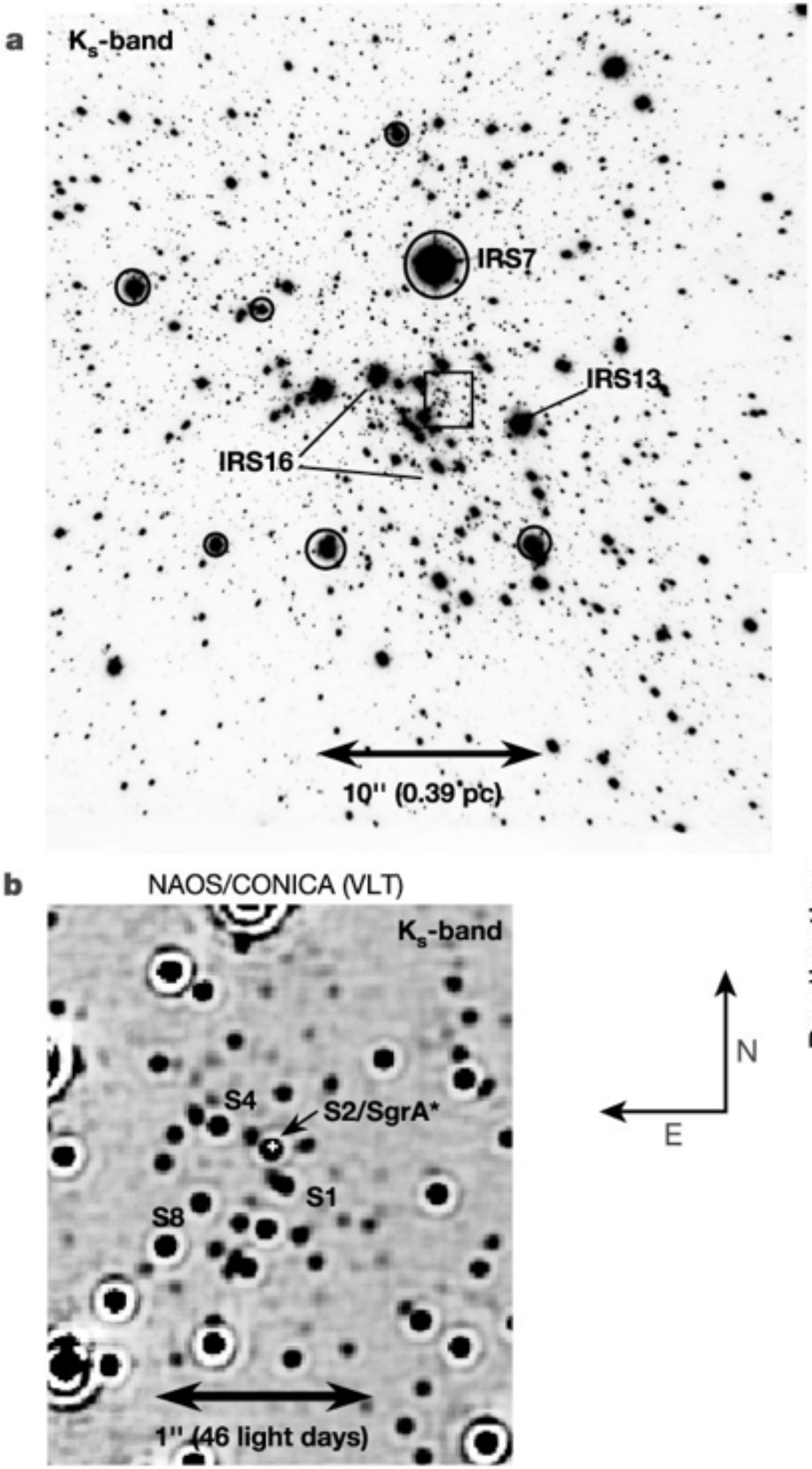
stellar tidal stream (NGC5907)

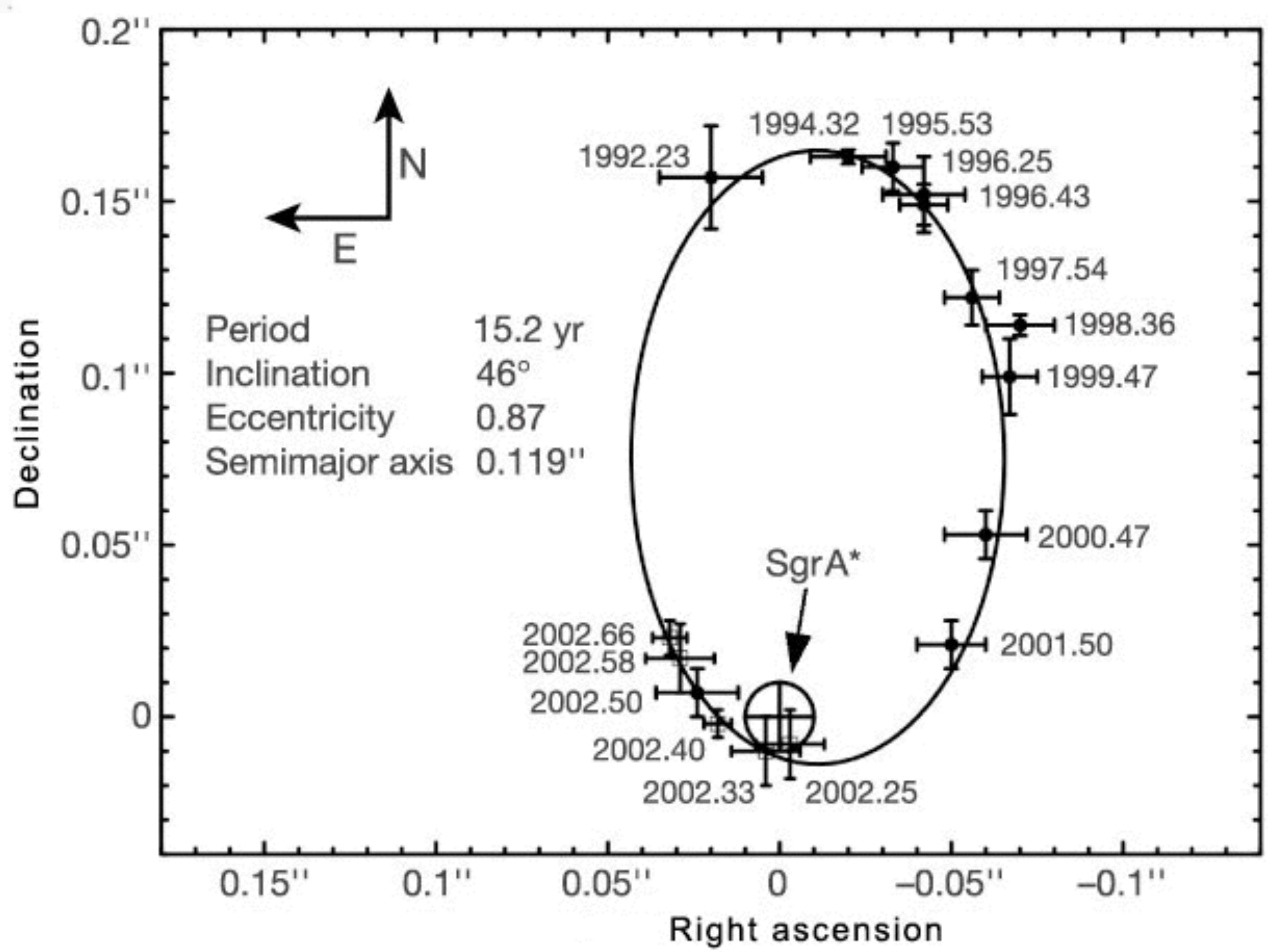
Galactic Center



Ks band image of the galactic center (Schodel et al ’02)

Schodel et al ’02, Ghez et al ’05,
Mbh =3.7x10^6 M_sun (R0/8kpc)^3





A FUNDAMENTAL RELATION BETWEEN SUPERMASSIVE BLACK HOLES AND THEIR HOST GALAXIES

LAURA FERRARESE[1]
Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095; laura@astro.ucla.edu
DAVID MERRITT
Department of Physics and Astronomy, Rutgers University, New Brunswick, NJ 08854; merritt@physics.rutgers.edu

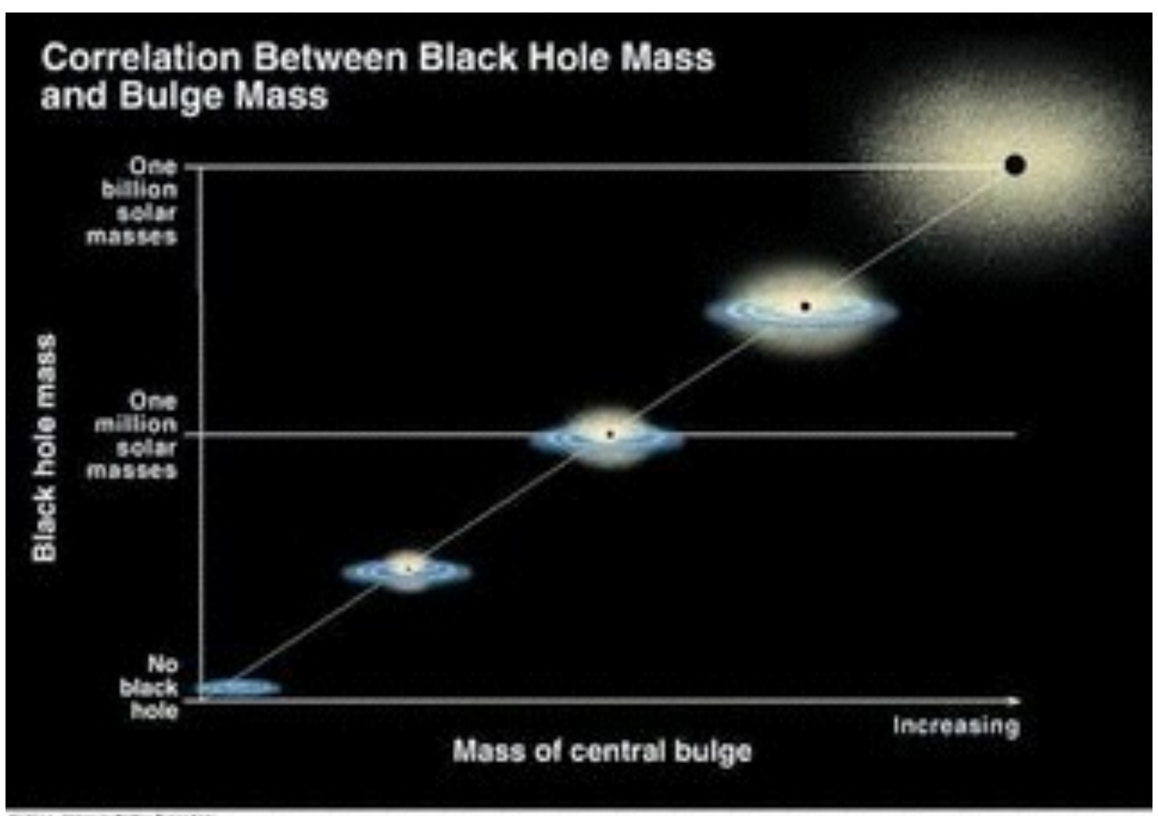
1900 citations

Received 2000 June 1; accepted 200

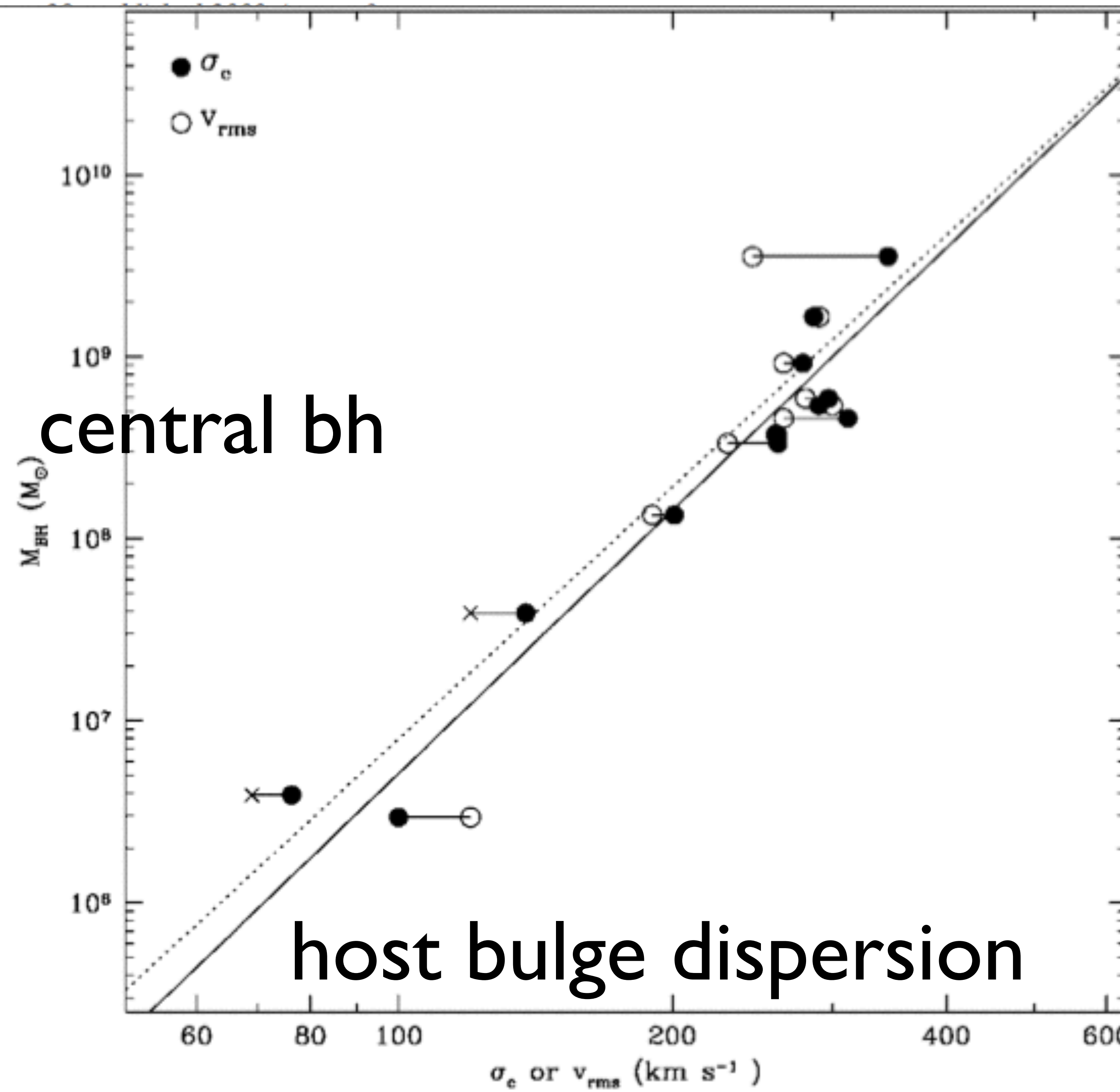
ABSTR

The masses of supermassive black holes correlate alm
bulges, $M_{\rm bh} \propto \sigma^{\alpha}$, where $\alpha = 4.8 \pm 0.5$. The relation is
luminosity, with a scatter no larger than expected on th
recently estimated by Magorrian et al. lie systematically
estimates, some by as much as 2 orders of magnitude. T
between black hole formation and the properties of the
Subject headings: black hole physics — galaxies: evoluti

M-sigma relation



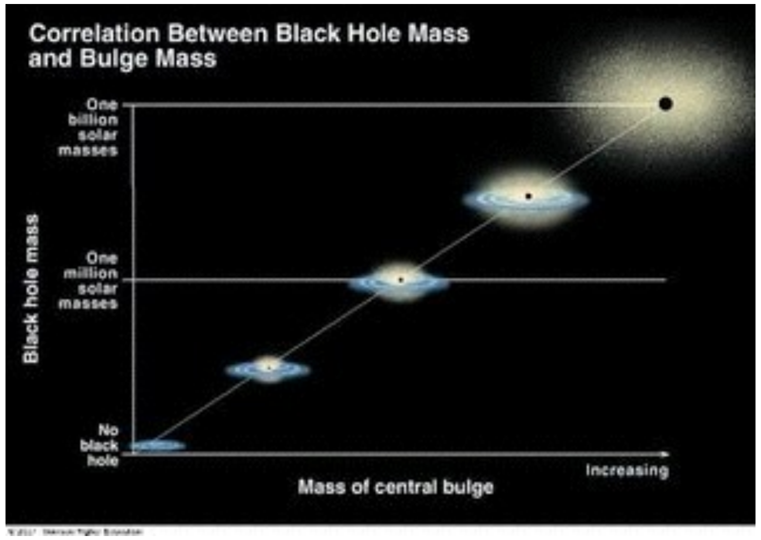
also Gebhart et al ’00



central bh

host bulge dispersion

FIG. 2.—BH mass vs. the central velocity dispersion σ_c of the host elliptical galaxy or bulge (*filled circles*) or the rms velocity $v_{\rm rms}$ measured at one-fourth of the effective radius (*open circles*). Crosses represent lower limits in $v_{\rm rms}$. The solid and dashed lines are the best linear fits using σ_c (as in Fig. 1*b*) and



Why surprising?

MW:
$M_{BH} \sim 4\times10^6\ M_{sun}$
$R_{sch} \sim 1km\ (M_{BH}/M_{sun})$
$\sim 4\times10^6$ km
$R_{influence} \sim 1$ pc $\sim 10^{13}$ km

$M_{bulge} \sim 4\times10^9\ M_{sun}$
$R_{bulge} \sim 1kpc \sim 10^{16}km$

why care?

galaxy and central bh assembled in sync

if understand bh, then galaxy?

gas rich merger vs. dry mergers

the Dark Matter Halo

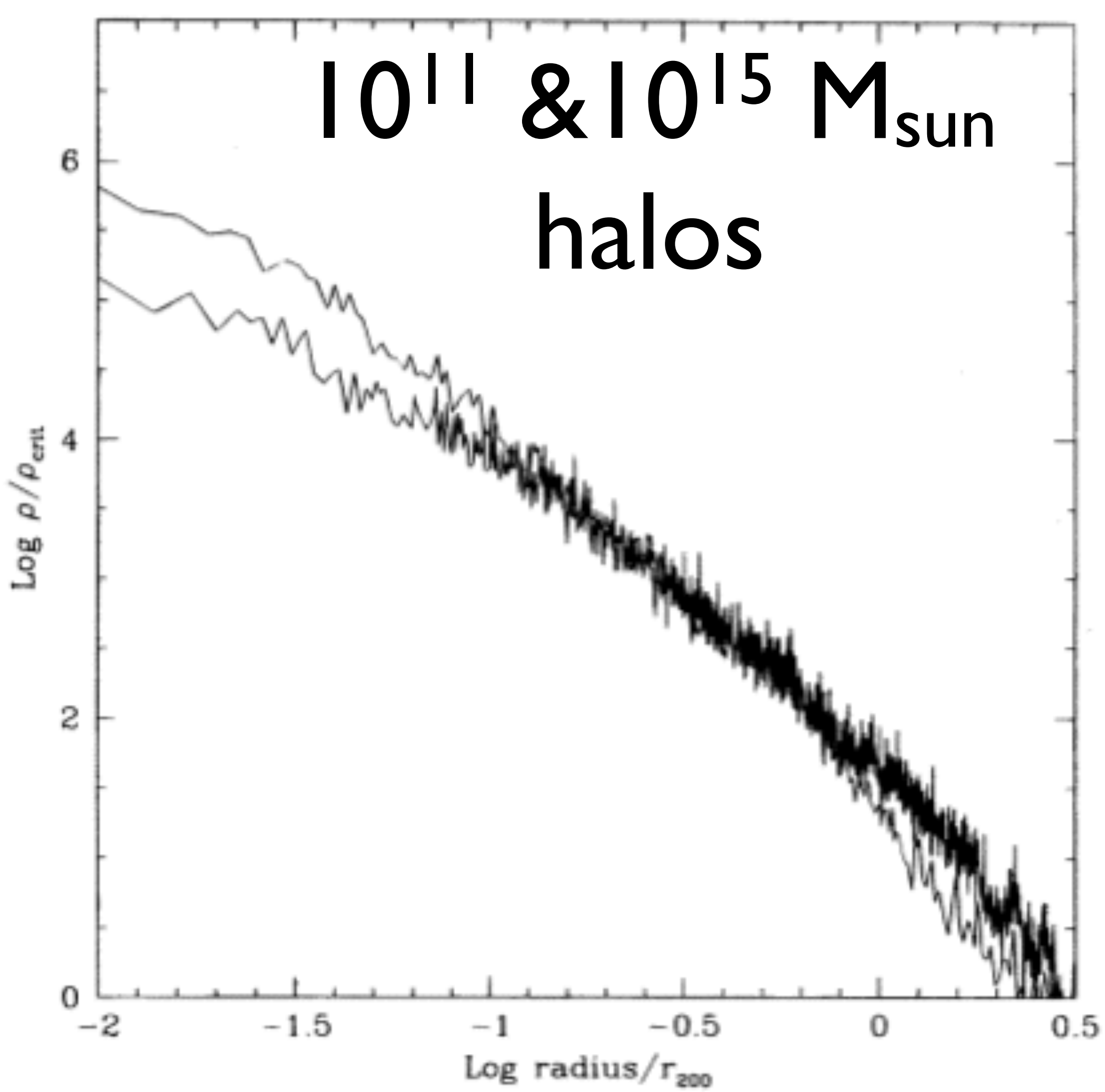
- rotation curves
- numerical simulations
- gravitational lensing
- dark matter annihilation

THE STRUCTURE OF COLD DARK MATTER HALOS

JULIO F. NAVARRO[1]
Steward Observatory, The University of Arizona, Tucson, AZ 85721
CARLOS S. FRENK
Physics Department, University of Durham, Durham DH1 3LE, England
AND
SIMON D. M. WHITE
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Strasse 1, D-85740, Garching, Germany
Received 1995 August 1; accepted 1995 December 4

ABSTRACT

We use *N*-body simulations to investigate the structure of dark halos in the standard cold dark matter cosmogony. Halos are excised from simulations of cosmologically representative regions and are



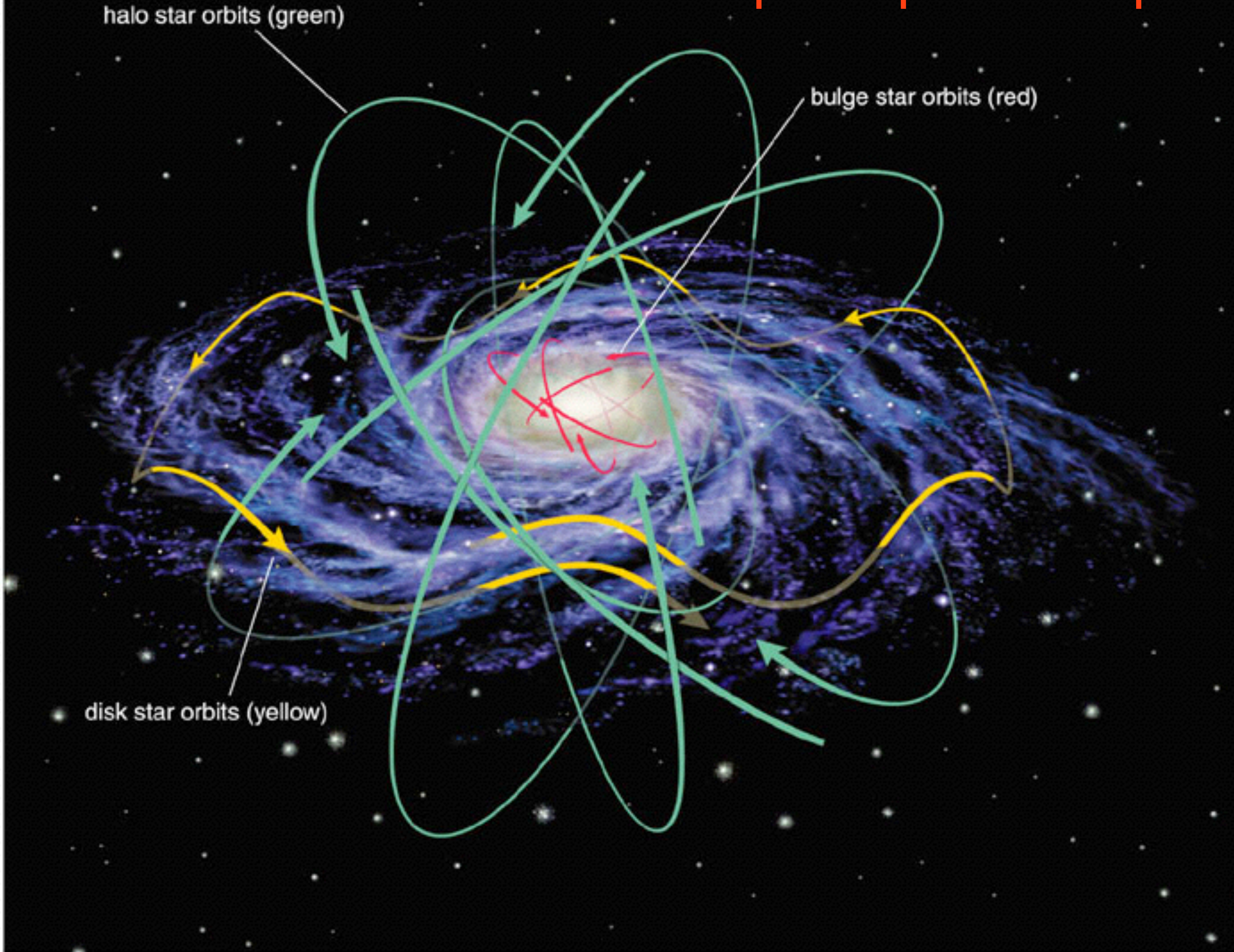
$$\rho(r) = \frac{\rho_0}{(r/a)(1 + r/a)^2}$$

gravitational collapse (in an expanding universe) gives an in-explicable universal profile

Conclusions:
multiple components in the MW, assembly history

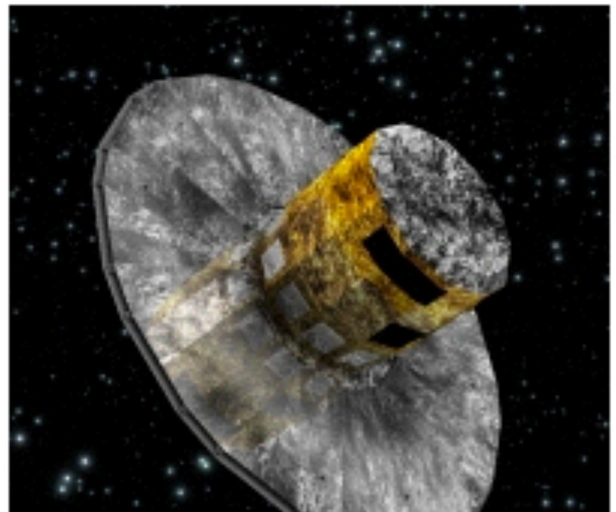
- geometry of MW (thin/thick disks+bulge+halo, the distribution of star light)
- dark matter dominates at large distances (rotation curve)
- the local group (distance to LMC, SMC, dwarf galaxies,missing satellites)
- globular clusters (double MS, mass segregation)
- galactic center (BH, stellar cluster),

orbits are not simple Keplerian ellipses



Why is galactic dynamics interesting now?

Gaia is an ambitious mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy. Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and



- measure the positions of ~1 billion stars both in our Galaxy and other members of the Local Group, with an accuracy down to 20 μas
- perform spectral and photometric measurements of all objects
- derive space velocities of the Galaxy's constituent stars using the stellar distances and motions
- create a three-dimensional structural map of the Galaxy

The gathered large datasets will provide astronomers with a wealth of information covering a wide range of research fields: from solar system studies, galactic astronomy, cosmology to general relativity.

ESA's GAIA mission

Launched Dec. 19, 2013
reached L2 point: Jan 8, 2014