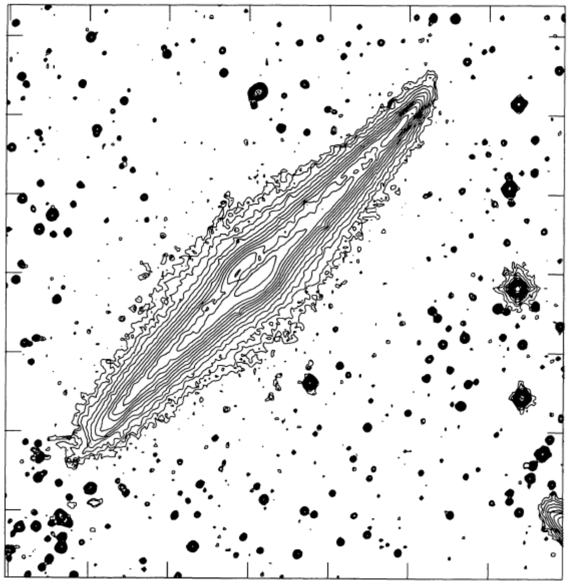
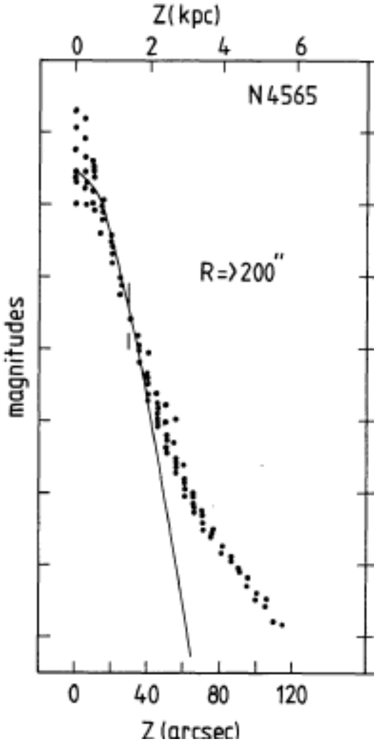
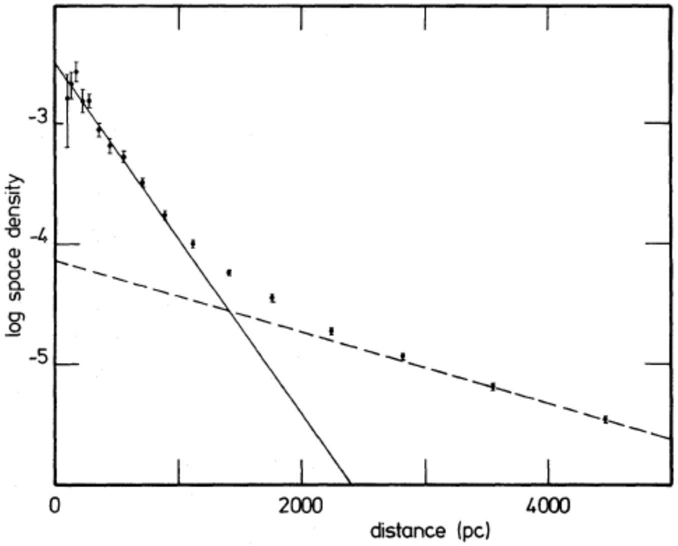
Thick disks in galaxies



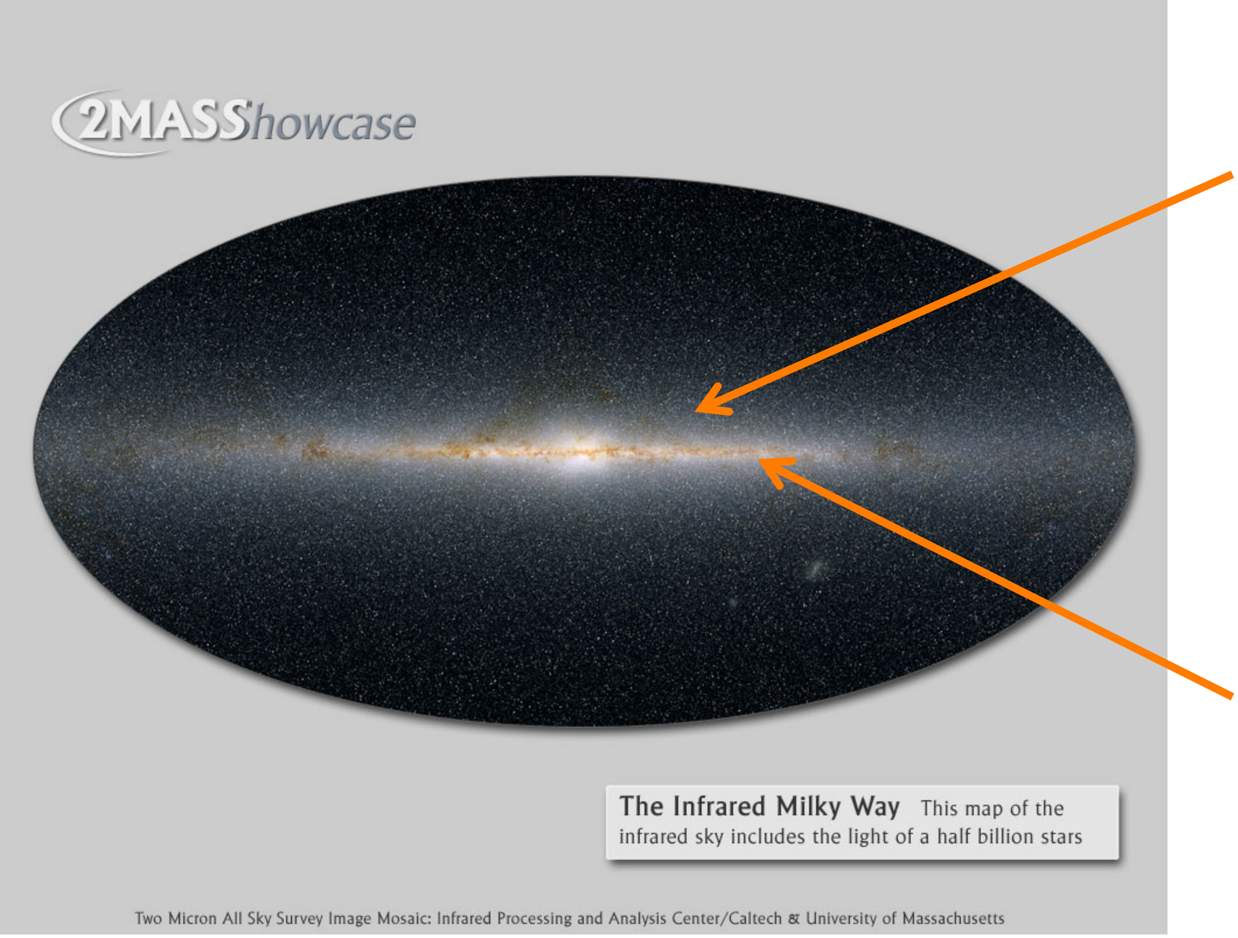


External galaxies:
NGC 4565, van der
Kruit and Searle
1981

Milky Way:
Gilmore and
Reid 1983



Oldest disk stars (~10 Gyr) in Milky Way's thick disk



Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Thick disk: hz=1kpc

Thin disk: nhz=.3 kpc

Milky Way thick disk stars

- Kinematically hotter than thin disk: asymmetric drift ~ 30 km/s; sigma_U,V,W~ (60,40,4nn0)
- Old stars: Edvardsson et al (1993)

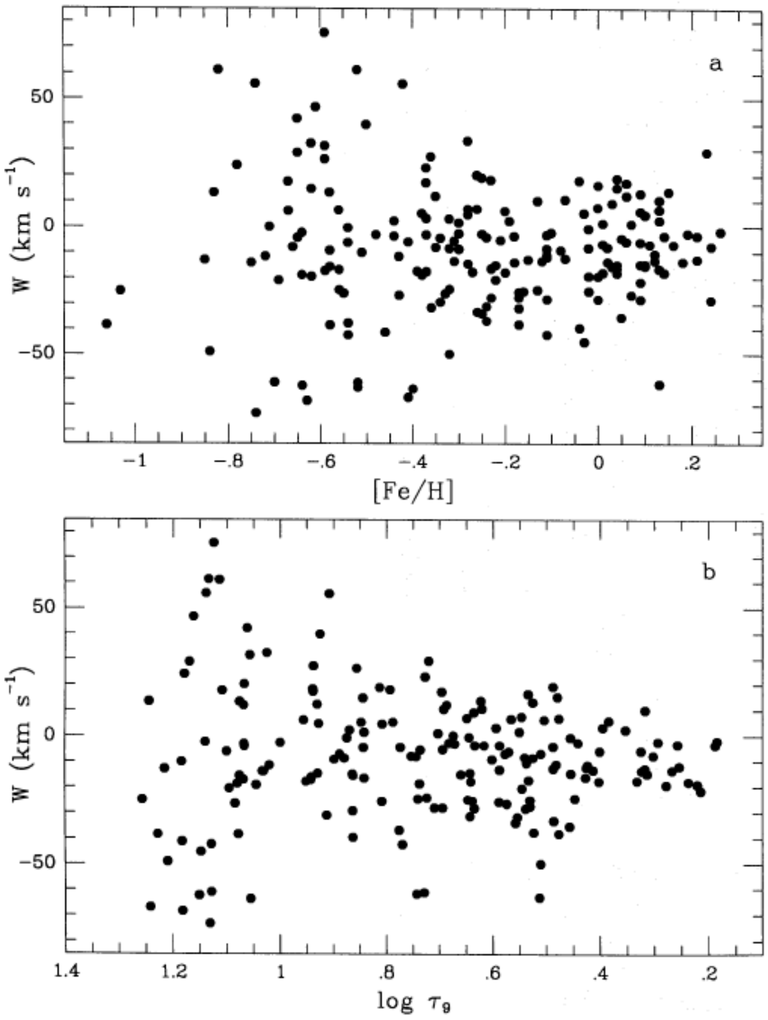


Fig. 16a and b. Stellar velocities perpendicular to the galactic plane, W, vs iron abundance **a** and age **b**, τ_9 is the age in 10^9 years

Ages of individual stars: still controversial, but

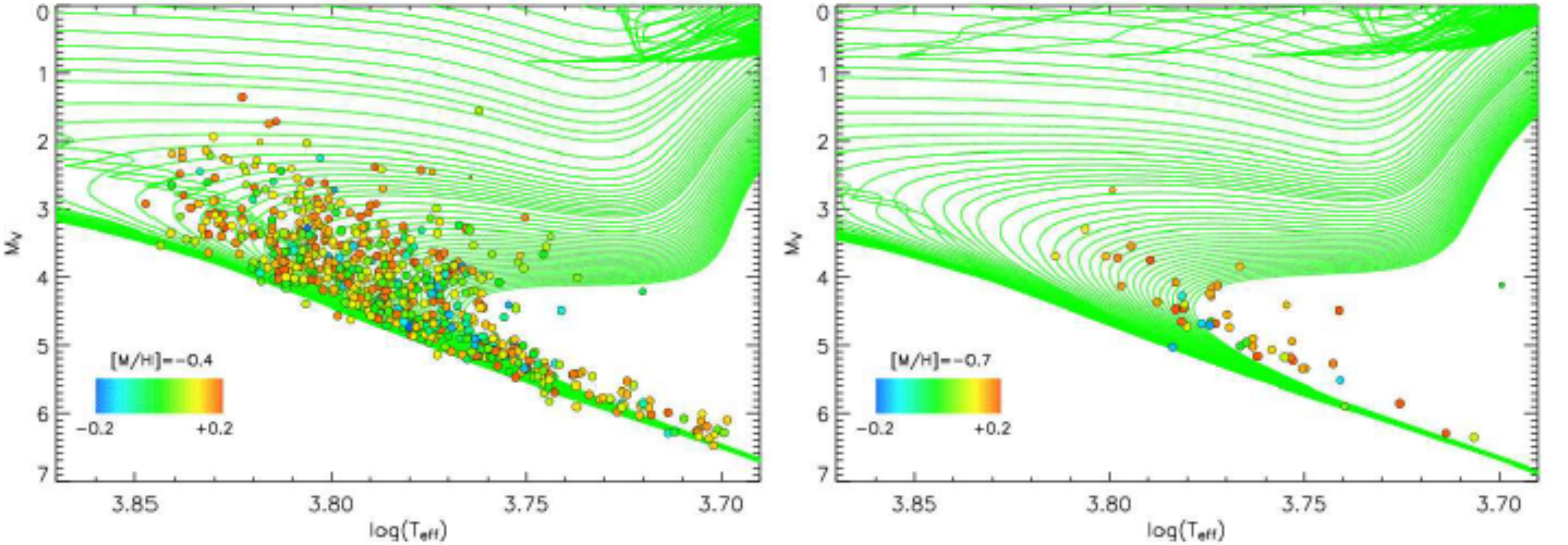
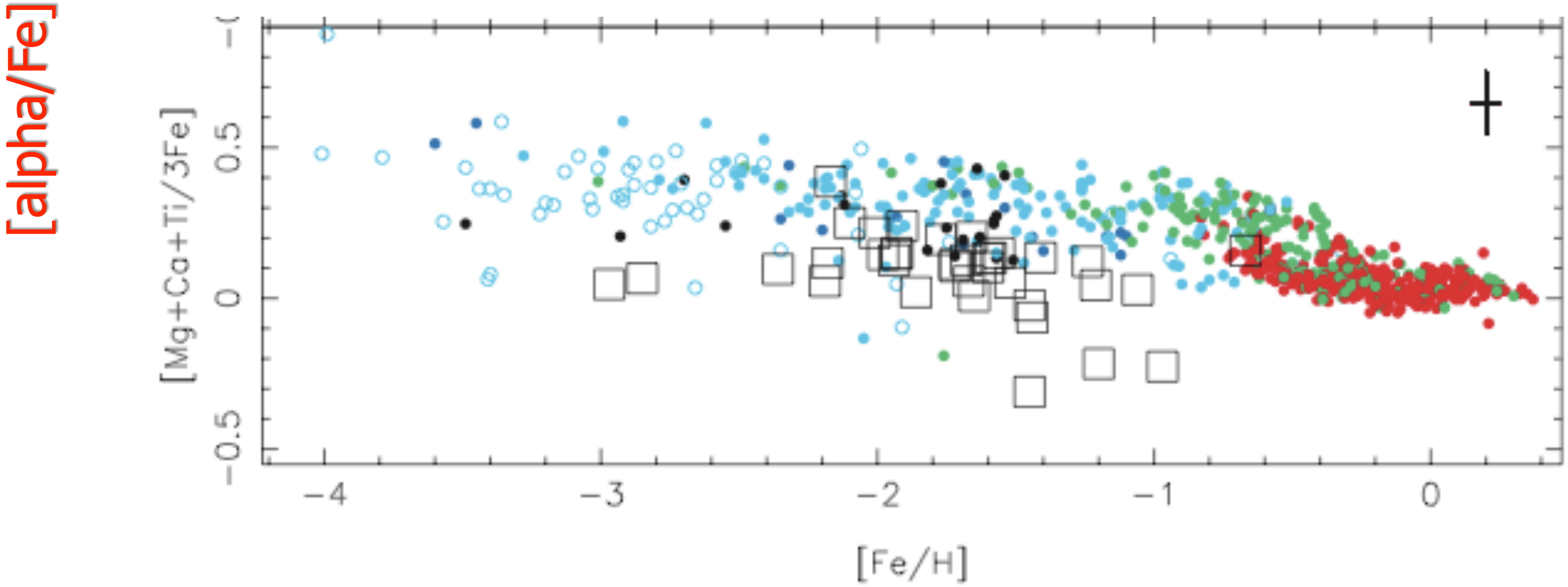


Fig. 12. BASTI isochrones for different ages at a given metallicity (continuous lines) compared to stars of similar [M/H], where the difference ±0.1 or ±0.2 dex is coded by colours. Larger symbols are for stars with higher parallax accuracy as labelled in the top left panel. Only stars in the *irfm* sample are shown.

Casagrande et al 2011

Chemical differences between thick and thin disk

- “Alpha” elements include Ca, Mg, Ti, Si
- Preferentially formed when massive stars go supernova (Type II SNe) ….. so stars formed in an early, quick phase of star formation will be enriched in these elements (high [alpha/Fe])
- Heavier Fe-peak elements formed more efficiently in Type Ia SNe ….. need to take the time to form a white dwarf (~1 Gyr)
- Stars formed by star formation over many Gyr will have more Fe relative to alpha elements (low [alpha/Fe])



Venn et al 04

Halo stars tend to have high [alpha/Fe] …. early rapid burst of star formation
(dSph stars have lower [alpha/Fe] …. longer duration of star formation)
Thin disk stars like the Sun have low [alpha/Fe] … many generations of enrichment over many Gyr

Thick disk stars near the Sun have high [alpha/Fe] …. clues to origin

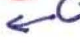
Formation theories abound

(1) Special events:

(a) accretion of small satellite which heats existing thin disk (Quinn and Goodman 1986, Walker, Mihos and Hernquist 1996, Velazquez and White 1999, Villalobos and Helmi 2008, Kazantzidis + 2008) and leaves its stars in disk as it disrupts

Thick disk formation scenarios

① Satellite accretion heats pre-existing disk



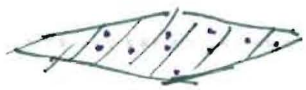
(a)

Dynamical friction with dark halo drags satellite toward center of halo .... energy and angular momentum transferred from satellite to halo

(b)

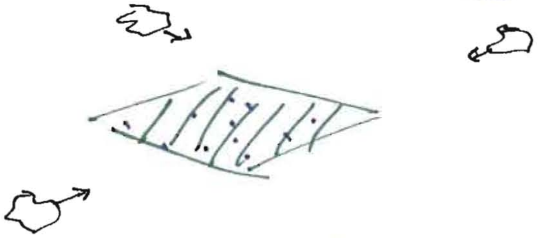
dynamical friction with disk stars drags satellite down into disk plane

$ (c)



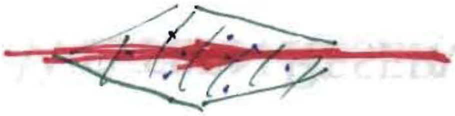
satellite heats existing disk, disrupts

(d)



time goes by. Gas flows toward disk & cools

(e)



New thin disk stars form from cooling gas

QUANTIFYING THE FRAGILITY OF GALACTIC DISKS IN MINOR MERGERS

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ABSTRACT

We perform fully self-consistent stellar dynamical simulations of the accretion of a companion ("satellite") galaxy by a large disk galaxy to investigate the interaction between the disk, halo, and satellite components of the system during a merger. Our fiducial encounter begins with a satellite in a prograde, circular orbit inclined 30° with respect to the disk plane at a galactocentric distance of 6 disk scale lengths. The satellite's mass is 10% of the disk's mass, and its half-mass radius is ~ 1.3 kpc. The system is modeled with 500,000 particles, which is sufficient to mitigate numerical relaxation noise over the merging time. The satellite sinks in only ~ 1 Gyr and a core containing $\sim 45\%$ of its initial mass reaches the center of the disk. With so much of the satellite's mass remaining intact, the disk sustains significant damage as the satellite passes through. At the solar circle we find that the disk thickens $\sim 60\%$, the velocity dispersions increase by $\Delta\sigma \simeq (10, 8, 8)$ km s^{-1} to $(\sigma_R, \sigma_\phi, \sigma_z) \simeq (48, 42, 38)$ km s^{-1}, and the asymmetric drift is unchanged at ~ 18 km s^{-1}. Although the disk is not destroyed by these events (hence "minor" mergers), its final state resembles a disk galaxy of an earlier Hubble type than its initial state—thicker and hotter, with the satellite's core enhancing the bulge. Thus minor mergers continue to be a promising mechanism for driving galaxy evolution.

Subject headings: galaxies: evolution — galaxies: interactions — galaxies: kinematics and dynamics — galaxies: structure — methods: numerical

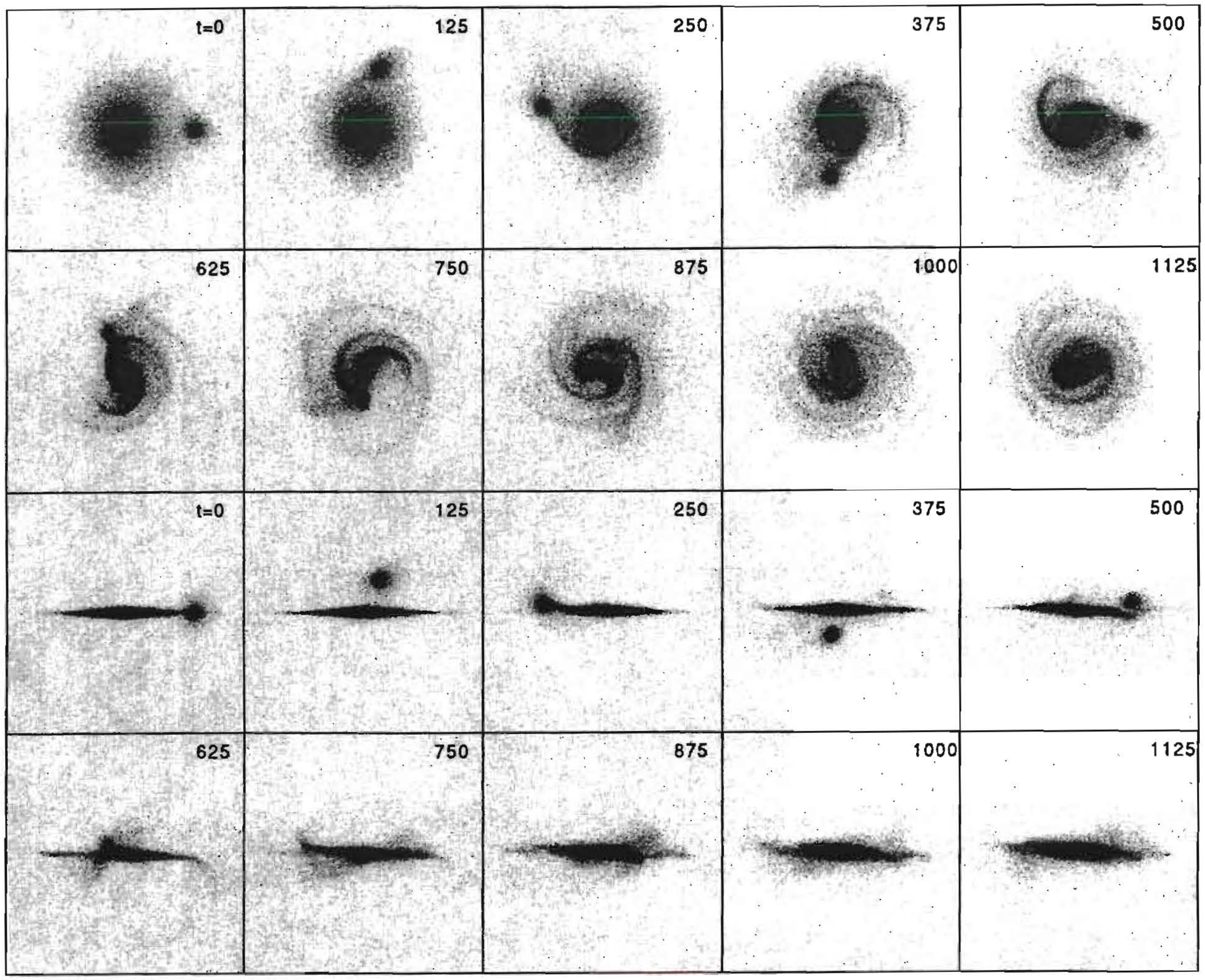


FIG. 5.—Face-on and edge-on views of the disk and satellite particles at equal intervals of ~125 Myr, starting at $t = 0$. The disk's global response to the satellite is quite apparent in the face-on panels, while the thickening and warping of the disk are apparent in the edge-on view. The global tilt is removed before further analysis by a rotation that aligns the total angular momentum vector of the disk particles with the z-axis. The satellite core arrives at the center in the penultimate frame.

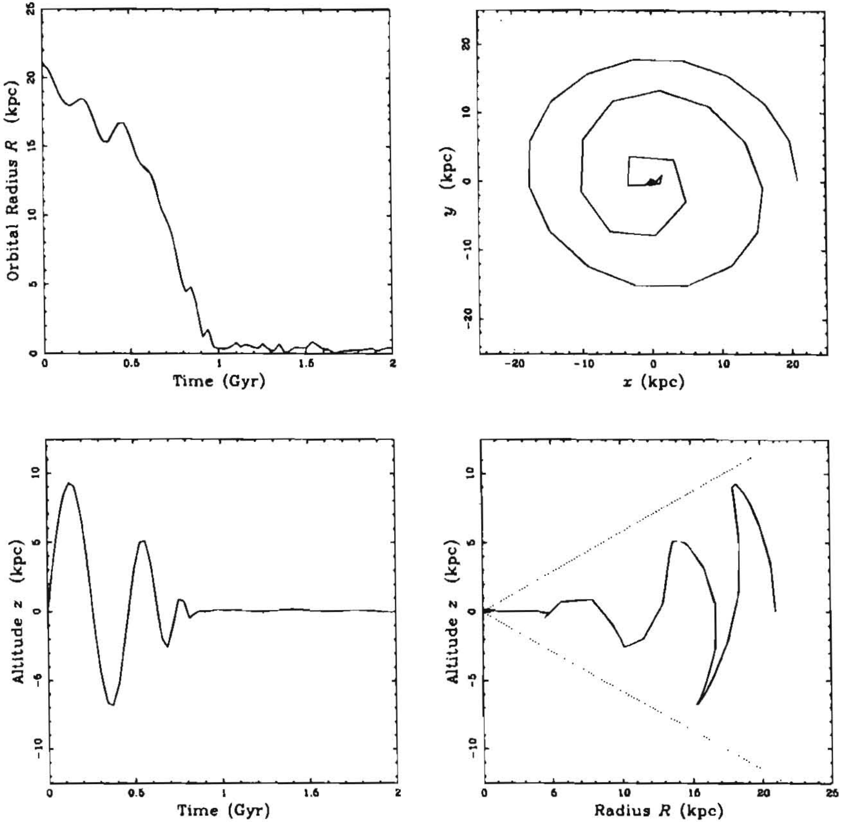


FIG. 6.—Satellite orbit. Clockwise from the upper left, the panels show the *cylindrical* radius vs. time, y vs. x (corresponding to the "face-on" view in Fig. 5), altitude vs. radius, and altitude vs. time. Our satellite completes fewer than two orbits before intersecting the solar circle, and our merger is all over by $t = 1$ Gyr. Note in particular that the satellite settles into a low-inclination orbit while it is still at a large radius. (For comparison, the dotted lines in the lower right panel show the initial inclination, $i = 30°$.)

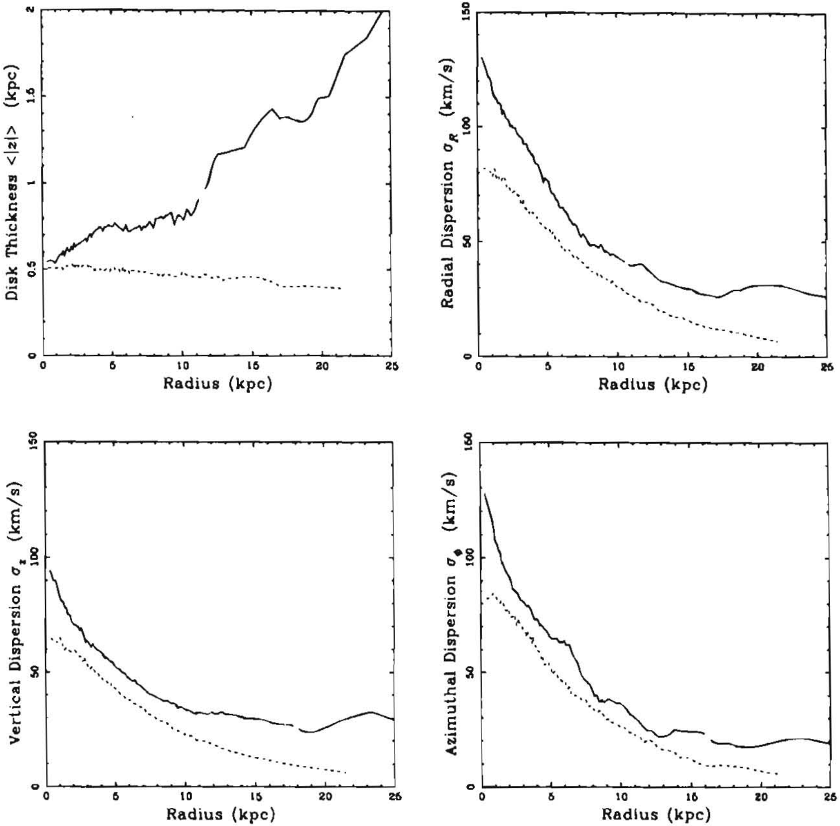
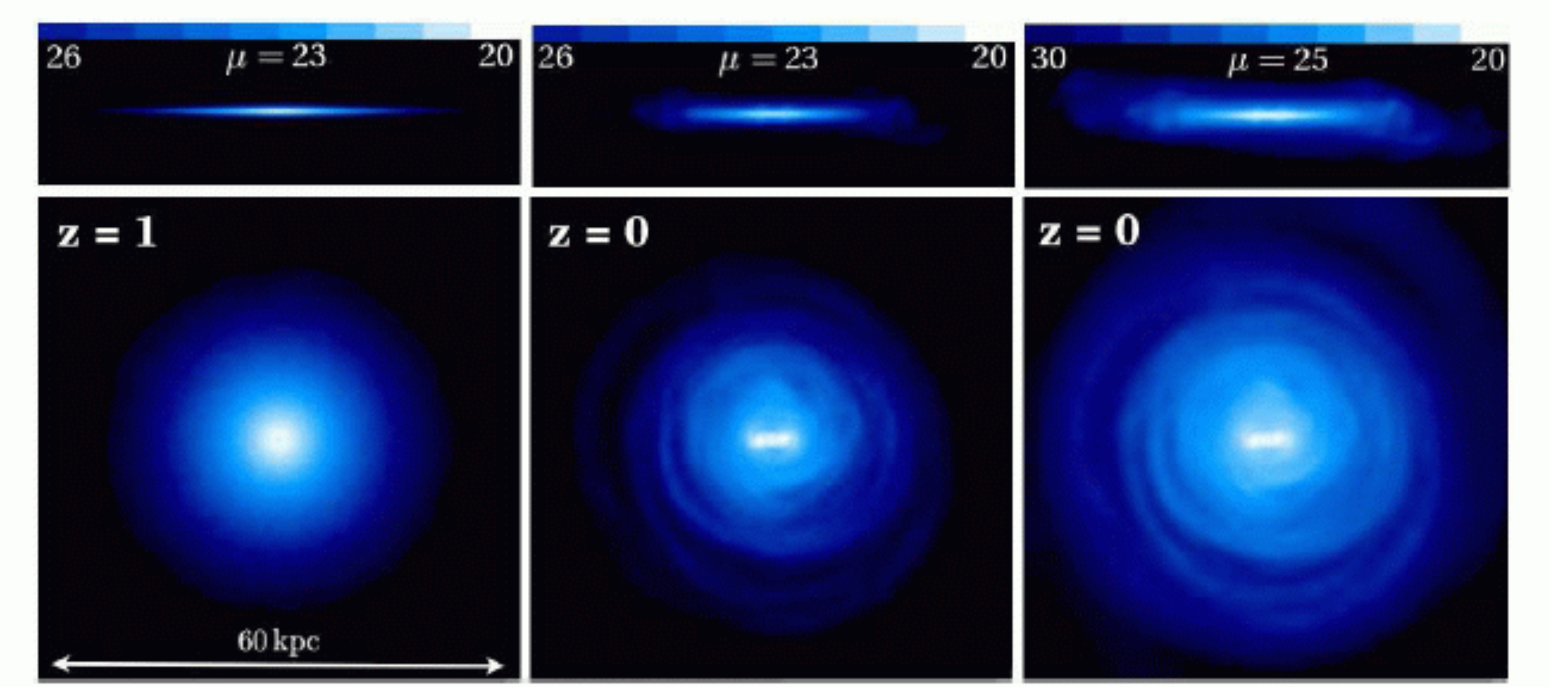


FIG. 9.—Postmerger disk structure. The solid curves show the disk in our encounter, and the dashed curves show the disk in the isolated galaxy. (This comparison accommodates both the initial transient and any common numerical relaxation effects.) Both are shown at $t = 1.19$ Gyr, which leaves time for things to settle down, although not much changes between $t = 1.0$ Gyr and $t = 1.2$ Gyr. After this time, the only significant changes are associated with the bar's vertical instability (see § 3). Note the greater radial extent of the disk that underwent the merger (*solid curves*), indicating conversion of satellite orbital energy to disk potential energy.

Formation theories abound

(a) Accretion of small satellite which heats existing thin disk and leaves its stars in disk as it disrupts (Quinn and Goodman 1986, Villalobos and Helmi 2008, Kazantzidis + 2008)

High [alpha/Fe] in early thin disk and in accreted satellite



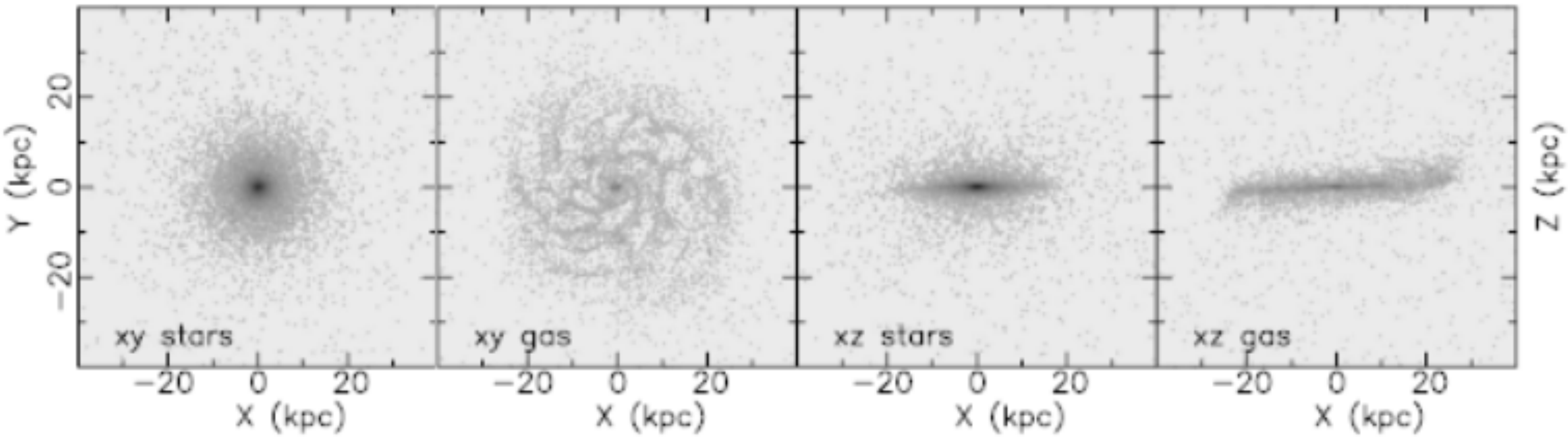
Kazantzidis et al 2008

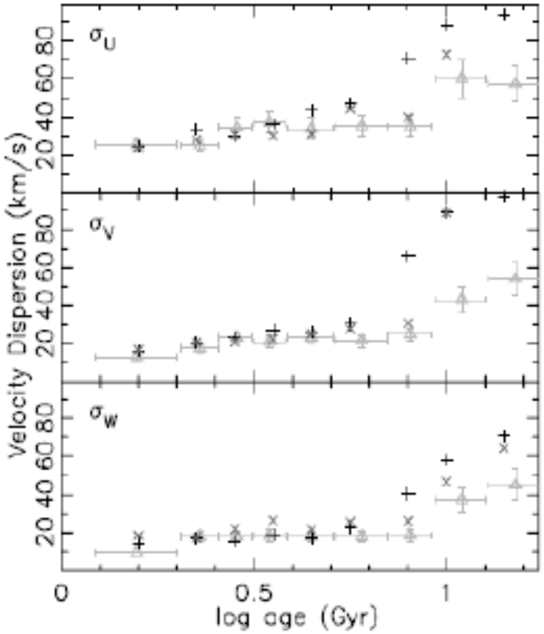
Formation theories abound

(b) Gas-rich mergers common in early universe; turbulent ISM can form thick disk before thin disk forms

(Brook+ 04,05,07, Springel and Hernquist 05, Robertson+ 06,Bournaud+ 09)

High [alpha/Fe] because of rapid early star formation





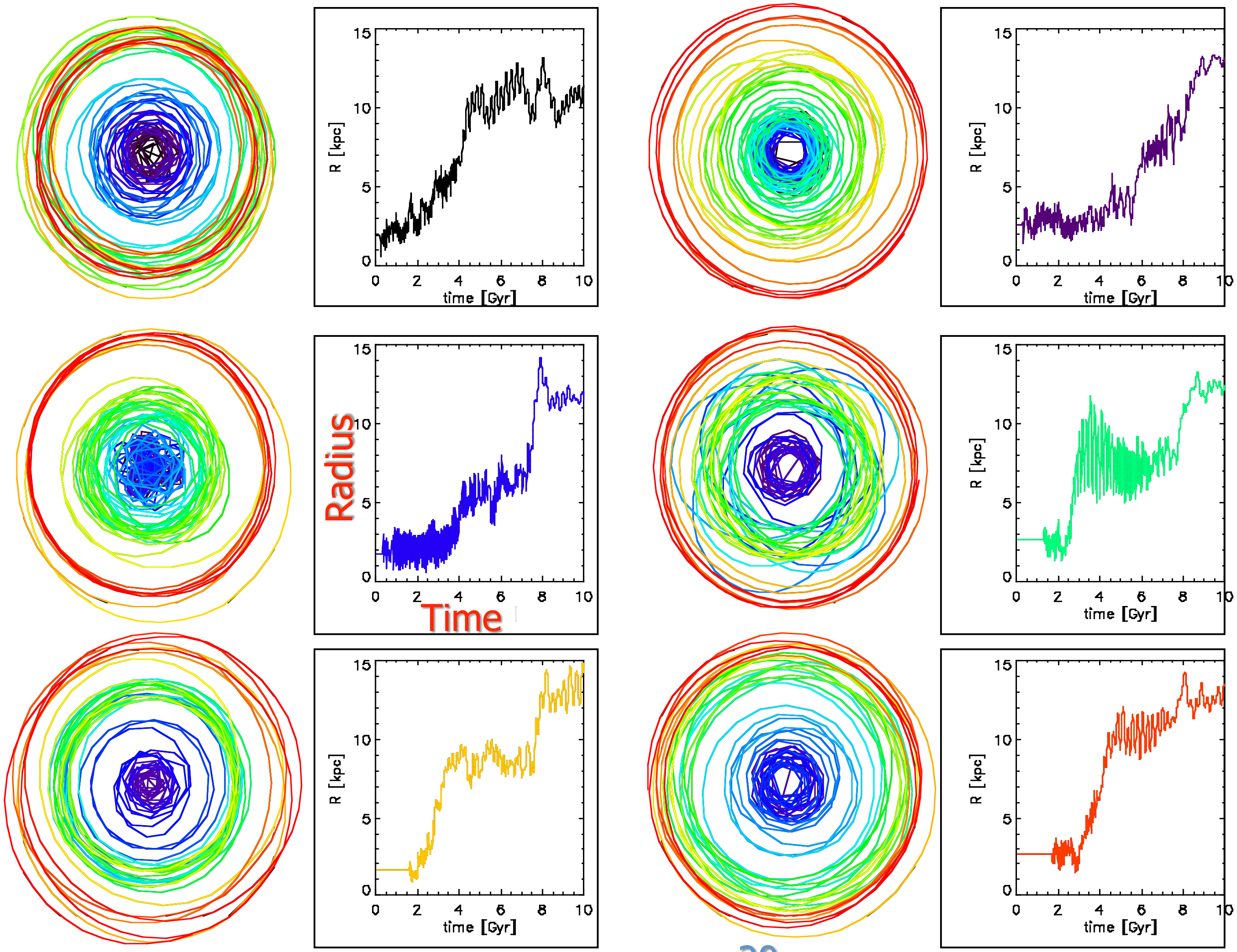
Brook+ 2004: early formation includes gas-rich mergers; disk can form but is hotter than later-forming thin disk

Formation theories abound

- (c) Secular (slow) disk evolution can mimic a thick disk via radial migration (Sellwood and Binney 2003, Schoenrich and Binney 2009, Roskar+2009)

- Encounters with giant molecular clouds and spiral arms can heat stars in thin disk a little, but not enough (process saturates)
- Radial migration uses resonant encounters with transient spiral arms to move stars from roughly circular orbit to another one …. angular momentum transferred

Angular momentum redistribution by (transient) Spiral Arms:



~ 20 kpc

(slide from Rok Roskar)

Mimicking a thick disk

- Radial migration can reproduce solar neighborhood thick disk observations without an extra component (Schoenrich and Binney 09,Roskar+08)
- Inner disk has higher surface density, so more restoring force.
- To make a constant scale height disk this requires higher vertical velocity dispersion
- Radial migration moves inner disk stars out; then they have a higher scale height
- Star formation in inner disk fast, so high [alpha/Fe]