Some thoughts on the evolution of thick disks and the Milky Way: where to go from here?

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Major themes of the conference:

- The MW and its dark side
- The MW disks
- The MW bulge + bar
- the MW halo and the Local Group
- Disks at low and high redshift
- Gas Accretion and star formation

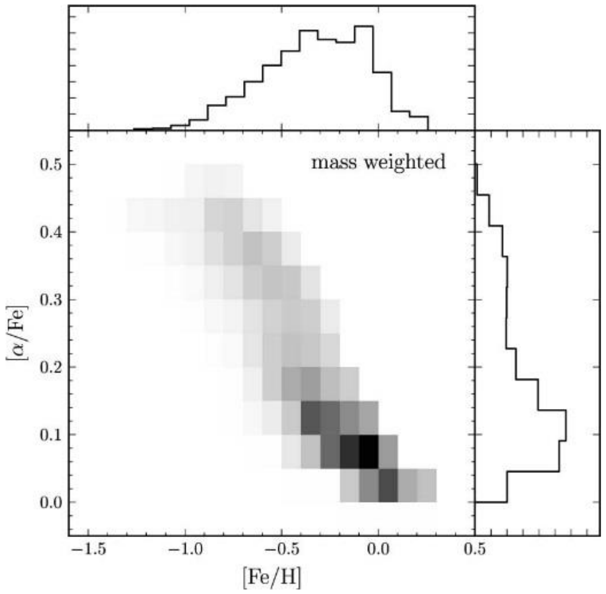
- now, with timing provided by α/Fe and the MDF, stellar ages, and simulations, plus surveys like APOGEE, RAVE, VVV, Gaia-ESO, LAMOST, Gaia, etc. we can connect these observations with evolutionary models.

… Anthony Brown, Javier Alonso-Garcia, Francois Combes

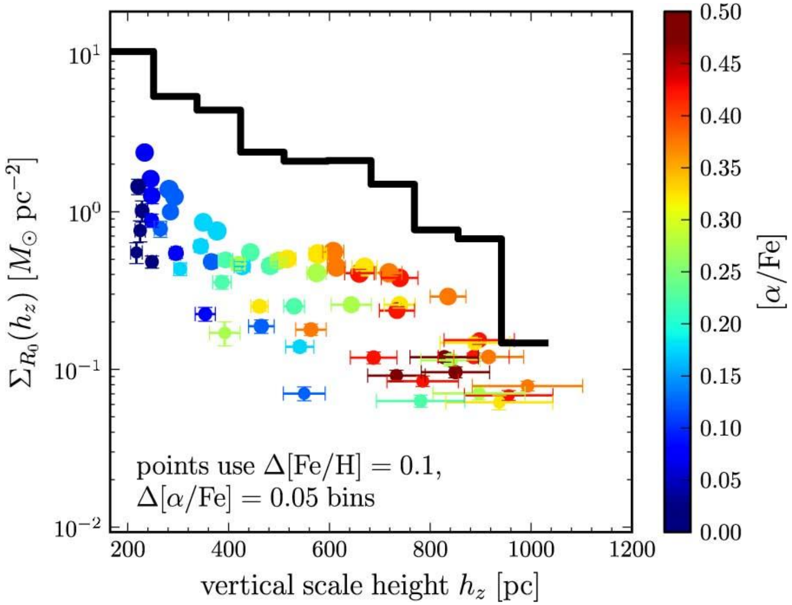
These themes center around the question:

What is the sequence of events that led to the formation of the Milky Way?

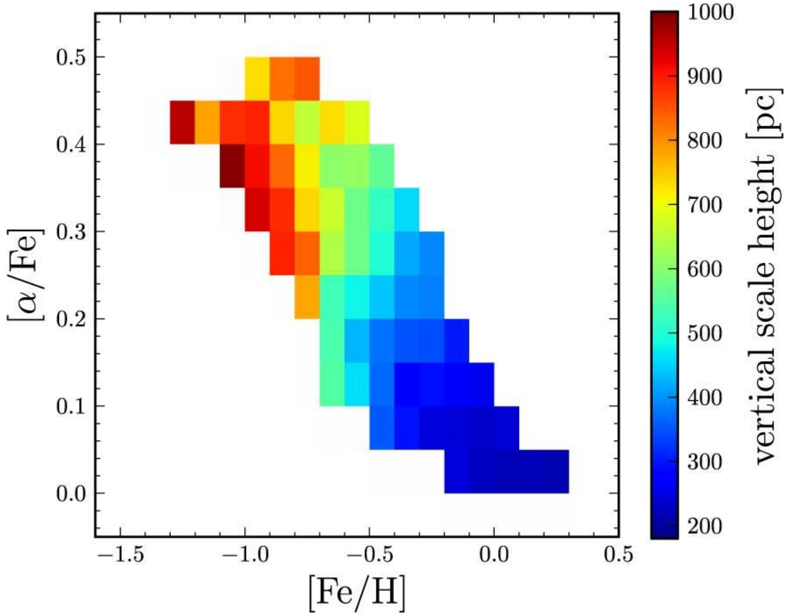
This question involves galaxy formation in a cosmological context, the MW neighborhood, MW accretion, SF, bar formation, spiral arms, stellar migration, …



Mass weighted distribution in α/Fe versus Fe/H space: not bimodal (Bovy 12a)



Distribution of surface density as a function of the scale height of that population: not bimodal (Bovy ‘12a)



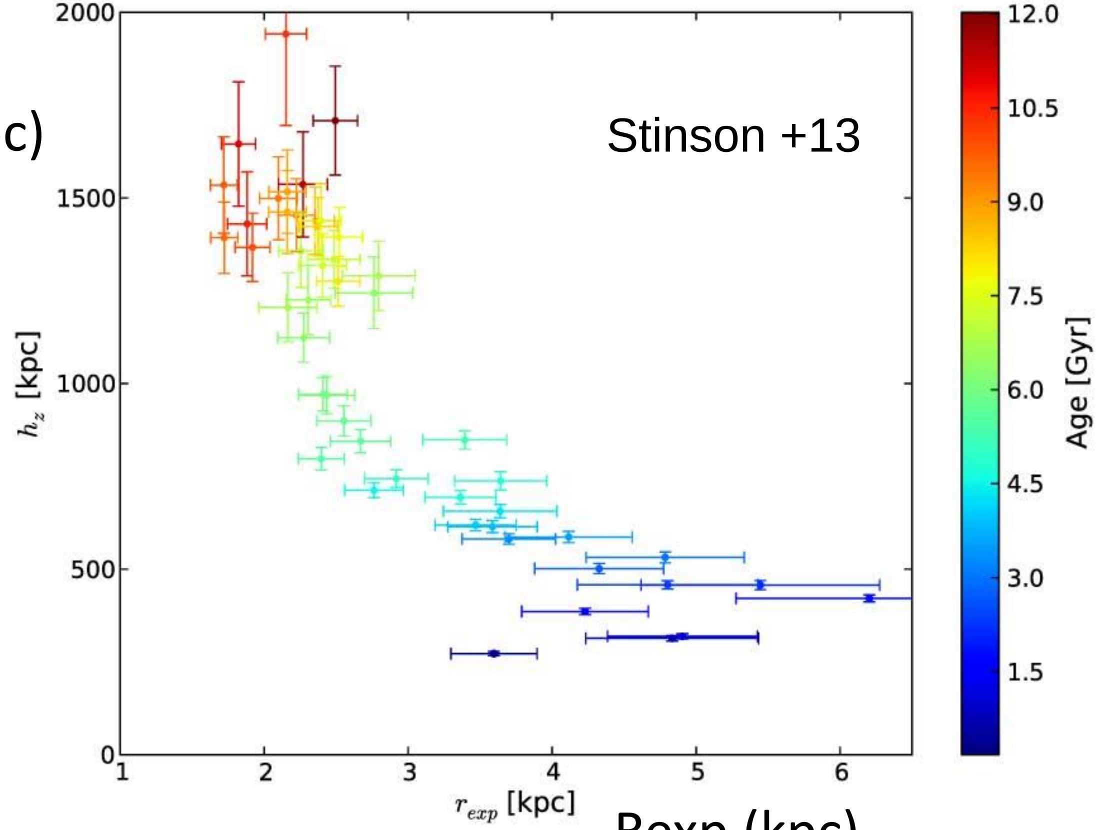
Height distribution in α/Fe versus Fe/H space: not bimodal (Bovy ’12b)

Was the transition from the old to the young disk smooth?

Jo Bovy

In MW simulations: R_D lengthens and H decreases continuously for younger stellar components in the present-day disk.

- Sanchez-Blazquez +09, Bird +13, Stinson +13, Aumer & White ’13, Martig +14, Minchev +15, Athanassoula +15, Madau +16, …



Hz (kpc)

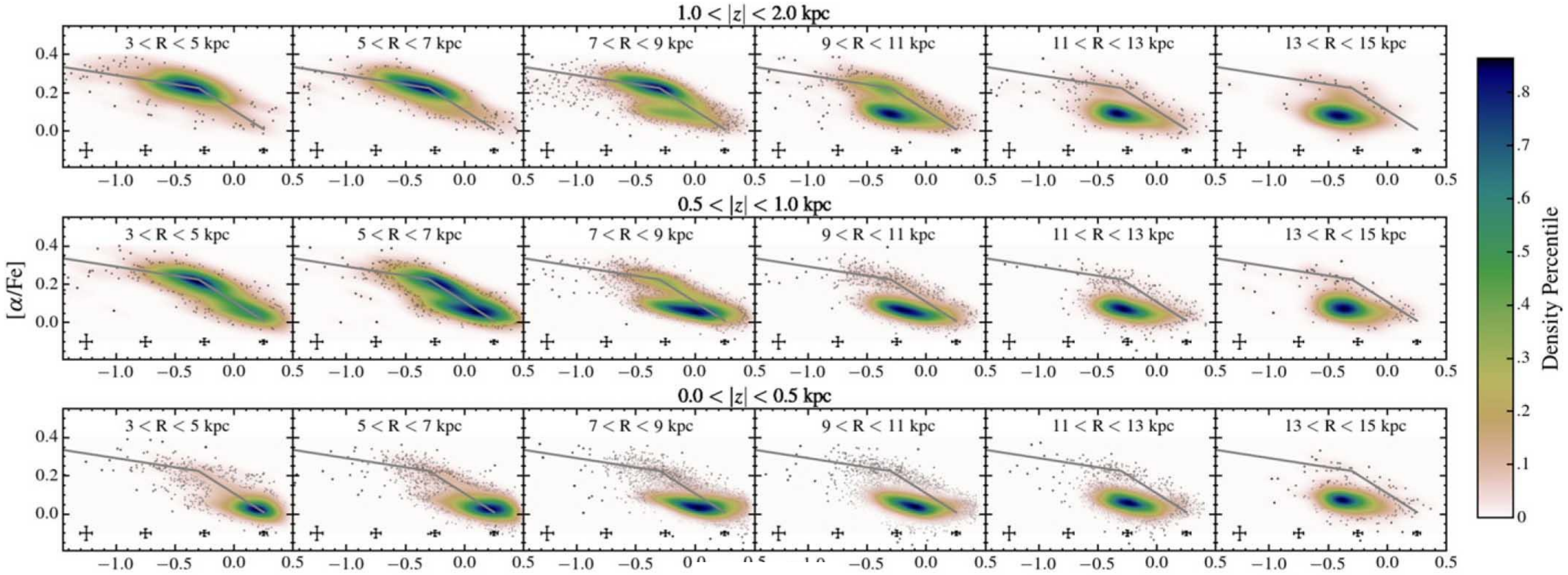
Stinson +13

Rexp (kpc)

Bird, Athanassoula, Minchev, Madau

But some observations show a bi-modal pattern:

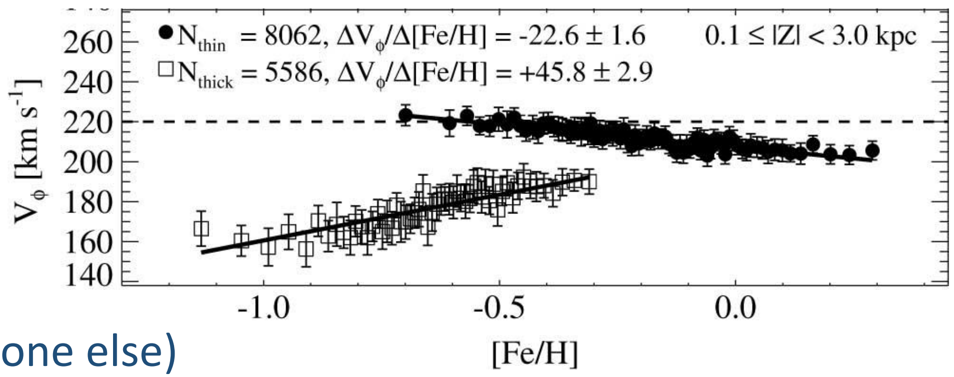
α/Fe



Fe/H

Hayden +15: 70,000 red giants from APOGEE survey: thick and thin sequences

Lee +11 17,000 G dwarfs
from SEGUE survey



Ken Freeman, Michael Hayden (and nearly everyone else)

Three Steps to the Formation of a MW-like Disk

1. Early on, the rates of accretion, star formation, interactions, and minor mergers are all high, making the disk highly turbulent.

- early time means it has "high α/Fe"
- high σ/V_{rot} means it is "thick"

- and because $R_{Jeans}/R_D \sim (\sigma/V_{rot})^2$ & $M_{Jeans}/M_{gal} \sim (\sigma/V_{rot})^4$,

SF clumps on the Jeans scale are big & massive, which means:

- is the clumps are long-lived, they can torque the disk & make a classical bulge
- stellar scattering is strong, which smooths chemical gradients, makes eccentric orbits

Madau, Robin, Minchev, Recio-Blanco, Bono, Lehnert

2. Gradually, the rate of accretion and bombardment slow down, the SFR and σ/V_{rot} drop, and H decreases with decreasing σ and increasing Σ

-At the same time, the angular momentum of the accreted material increases, so R_D increases.

- These steps are semi-continuous: the accretion consists of smooth streams and cooling halo gas, plus discrete gas clouds and dwarf galaxies.
- Thus, the thick to thin transition is physically semi-continuous
- and the earliest parts are distinguished by high α/Fe, EMP stars, etc

Frenk, Grillmair, Laporte, Johnston, Di Matteo, Grebel, Arias, Ibata, Hammer, Jethwa, Casetti, Garrison-Kimmel, Vivas, Hensler, Miglio, Bensby, De Laverny, Ting, Bovy, Hill, Anderson, Ishimaru, Tsujimoto, Fraternali, Richter, Sokolowska

3. When the cool part of the disk is massive enough, it may form a bar and the bar may buckle in the inner part

After these formative steps, the accretion and bombardment rate continue to decrease, the SFR continues to decrease as a result, and gravitational instabilities in the cool stellar component take the form of recurrent spiral waves. The cool stars heat up, the bar lengthens, some gas may accrete in the plane, …

The hot part of the disk is inert.

Kormendy, Famaey, Mel’nik, Dame, Diehl, Ness, Schultheis, Athanassoula, Portail, Haywood, Fragkoudi, Bird, Grand

Additional effects lead to the appearance of bimodality

- epicyclic motions (blurring)
  - at mid-radius, there are two different populations at the same moderate Fe/H:
    - old stars from the inner regions on the outer parts of their epicycles, and young stars from the outer regions on the inner parts of their epicycles
    - produce slow and fast azimuthal velocities, high and low a/Fe, high and low eccentricity, “thick disk” and “thin disk” … respectively
- migration of the guiding center radii
  - from bar/spiral corotation churning & GMC scattering
  - this is a measureable but modest effect for the thin disk, but apparently not important for the thick disk (Hayden +15)
- spirals which torque and stream the stars

Minchev, Hayden, Magrini, Wojno, Kawata, Prantzos, Grand, D’Onghia

Young disks are thick because their accretion rates are high. This point seems fundamental.

A disk has several equilibria:

1. In-the-plane equilibrium can be maintained by spiral-type or clump-type gravitational instabilities

> depending on the relative proportion of the rates of shear, gravitational instability, and dissipation

These instabilities regulate the Toomre Q~1-3 by stirring the disk to a point of marginal stability if the gas can cool.

Wetzel, Lehnert

2. Perpendicular to the plane, the vertical support is maintained by pressure, which depends primarily on the mass column density:

$$P \sim \frac{\pi}{2} G \Sigma^2$$

or, equivalently,

$$H = \frac{\sigma^2}{\pi G \Sigma}$$

for scale height

$$H = \frac{\Sigma}{2\rho} \quad \text{with} \quad \rho = \frac{P}{\sigma^2}$$

Lehnert, Minchev

3. In gas-dominated, warm-HI dominated regions, the bulk velocity dispersion approaches thermal equilibrium for the warm phase HI

$$\sigma \sim 6 \text{ km/s}$$

Q can be large because Σ is generally low.

H can be large too, because Σ is low. 3D effects important.

SF occurs in a minor, cool component.

Also, star formation generally operates on a dynamical timescale:

$$\Sigma_{\rm SFR} = \epsilon_{\rm ff}\Sigma/\tau_{\rm ff}$$

where the efficiency ε_{ff} is a few % and the free fall time is

$$\tau_{\rm ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

Gonzalez-Delgado, Wetzel, Leroy. Inutsuka

Three important cases:

1. For today's <u>outer disks and local dwarf irregulars</u>, σ ~ constant:

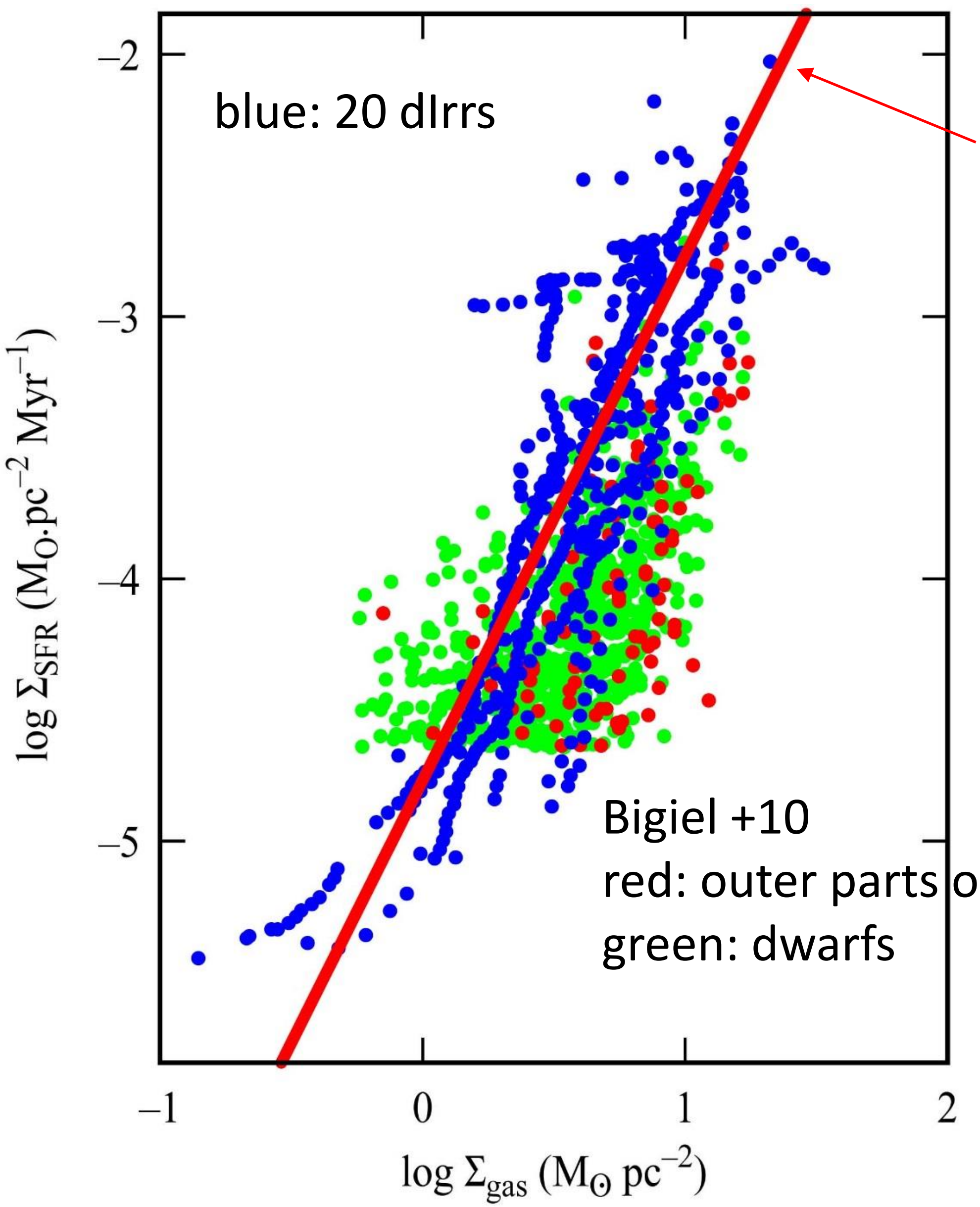
$$\Sigma_{\rm SFR} = (4/\sqrt{3})\epsilon_{\rm ff} G \Sigma_{\rm gas}^2/\sigma$$

which for typical $\varepsilon_{\rm ff}$ ~ 0.01 and σ = 6 km/s, gives

$$\frac{\Sigma_{\rm SFR}}{M_\odot\ {\rm pc}^{-2}\ {\rm Myr}^{-1}} = 1.7 \times 10^{-5} \left(\frac{\Sigma_{\rm gas}}{M_\odot\ {\rm pc}^{-2}}\right)^2$$

Elmegreen '15

KS relation for local dIrrs & outer spiral disks matches theory



blue: 20 dIrrs

Theory,
$1.7x10^{-5}\Sigma_{gas}^{2}$

Bigiel +10
red: outer parts of spirals
green: dwarfs

Elmegreen ‘15

2. For today’s main disks, H ~ constant:

$$\Sigma_{\rm SFR} = (4/\sqrt{3\pi})\epsilon_{\rm ff}(G/H)^{1/2}\Sigma_{\rm gas}^{3/2}$$

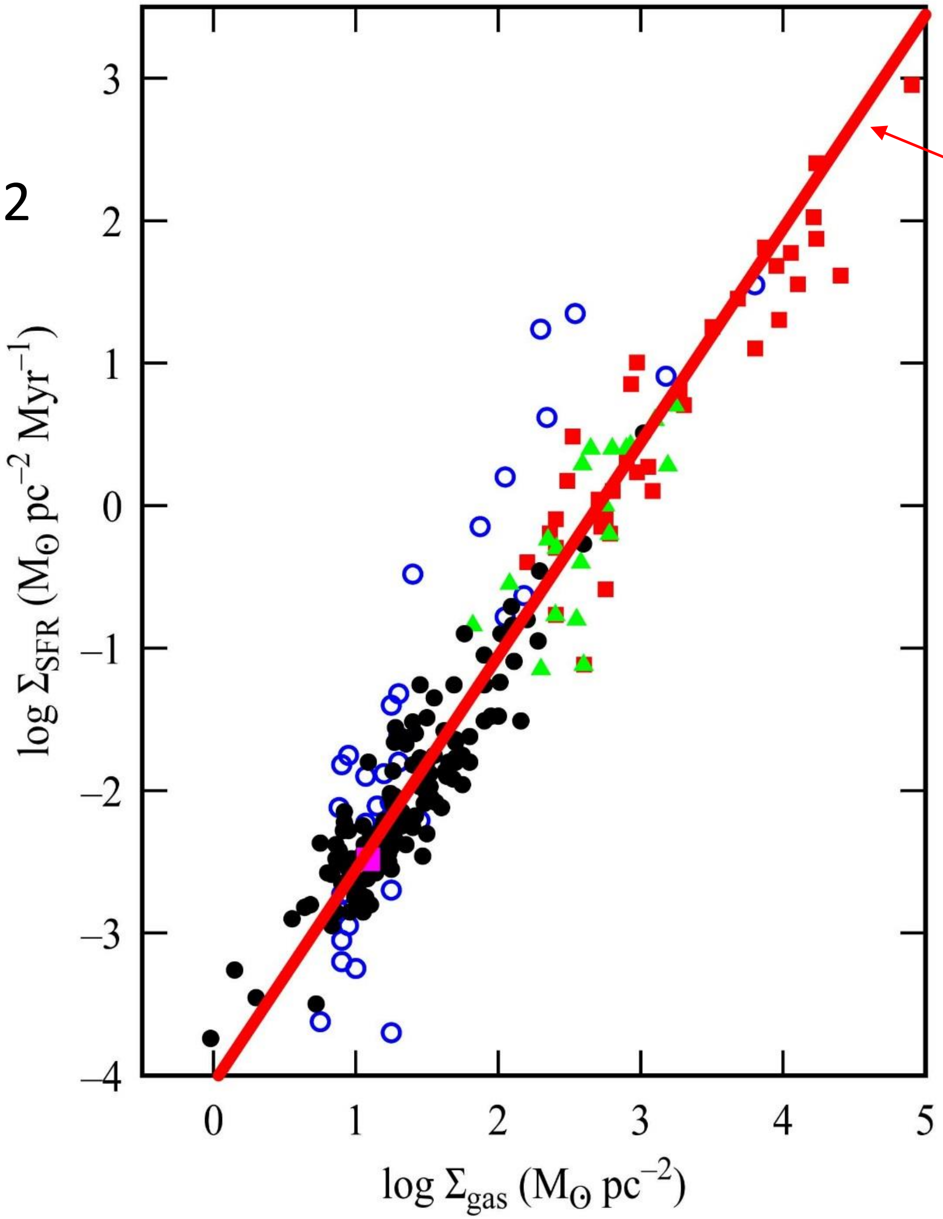
which for $\varepsilon_{\rm ff}$ ~ 0.01 and H = 100 pc, gives

$$\frac{\Sigma_{\rm SFR}}{M_\odot\ {\rm pc}^{-2}\ {\rm Myr}^{-1}} = 8.8\times 10^{-5}\left(\frac{\Sigma_{\rm gas}}{M_\odot\ {\rm pc}^{-2}}\right)^{1.5}$$

Elmegreen ‘15

KS relation for integrated galaxies matches theory

points from
Kennicutt & Evans ’12



Theory,
$8.8\text{x}10^{-5}\Sigma_{gas}^{1.5}$

Elmegreen ‘15

Leroy

3. For <u>high redshift disks</u>, the gas fraction is high and they may be regulated by Q ~ const.

$$\Sigma_{\rm SFR} = \left(\frac{4\epsilon_{\rm ff}\kappa^3}{3^{0.5}\pi^2 G Q^3} \right) H$$

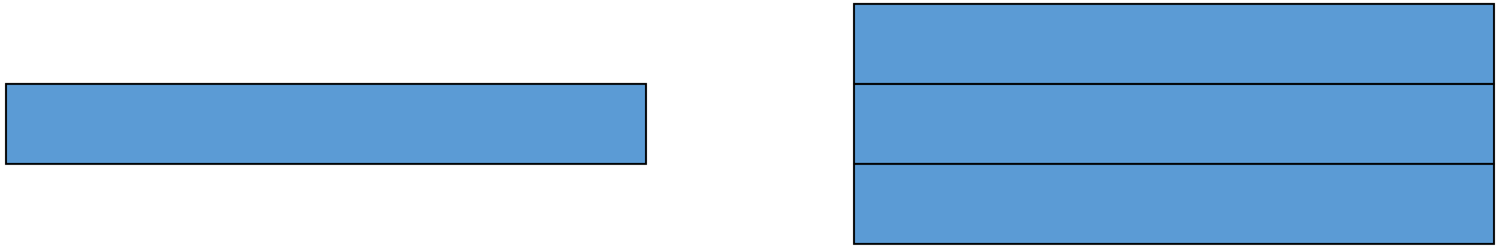
which for ε_{ff} ~ 0.01, κ from v_{rot}=150 km/s at R=2 kpc, Q=2,

$$\frac{\Sigma_{\rm SFR}}{M_\odot\ {\rm pc}^{-2}\ {\rm Myr}^{-1}} = 0.083 \left(\frac{H}{1\ {\rm kpc}} \right)$$

… no observations yet

For a given galaxy mass and size (i.e., κ) and over Gyr timescales,
Σ_{SFR} ~ accretion rate / area.

Thus: a high accretion rate/area → high Σ_{SFR} → high H:



Low Σ_{SFR}

High Σ_{SFR}

low Σ, low σ, low H

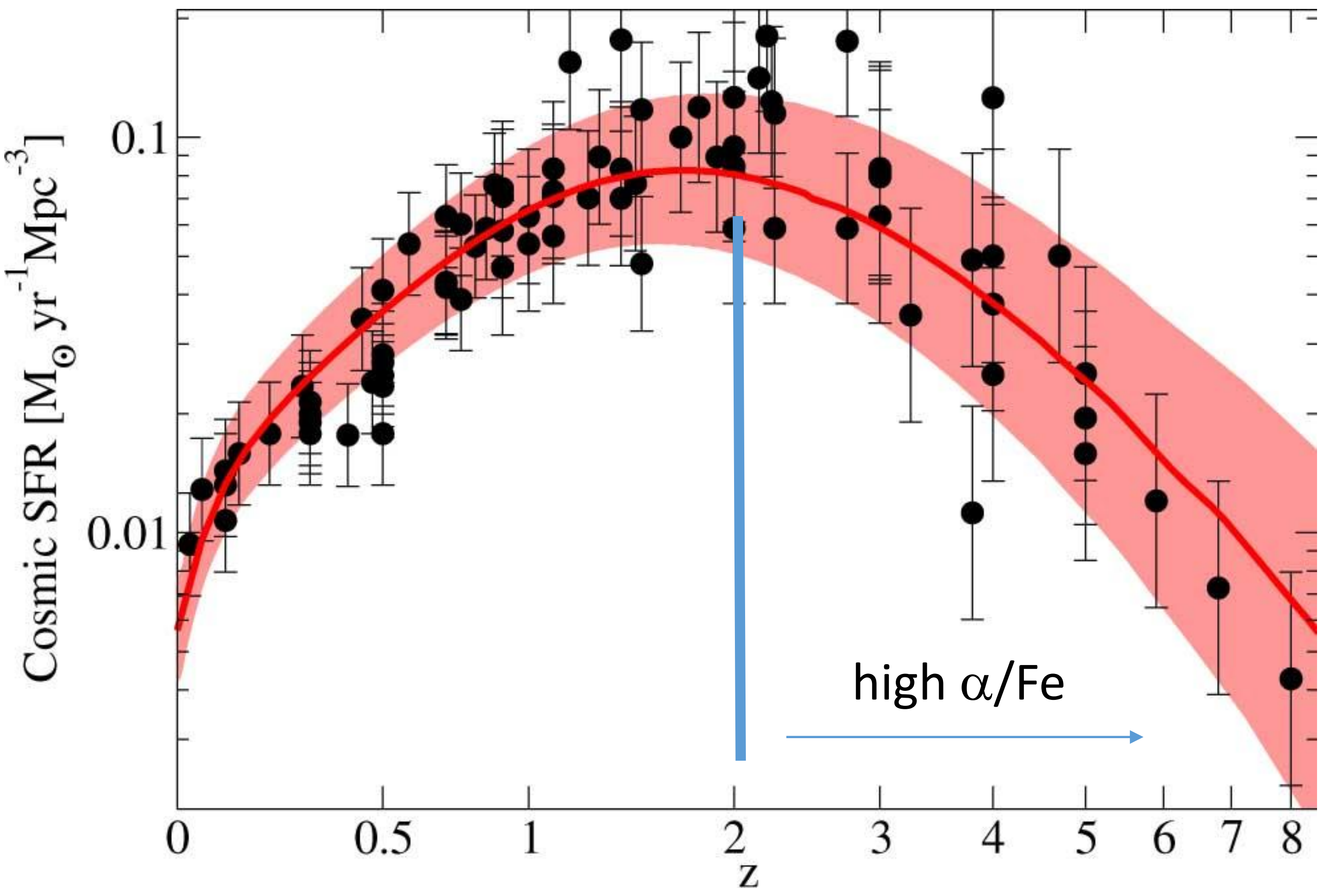
high Σ, high σ, high H

Because with Q ~ constant, the density is constant too:

$\rho=\kappa^2/8\pi G Q^2$,

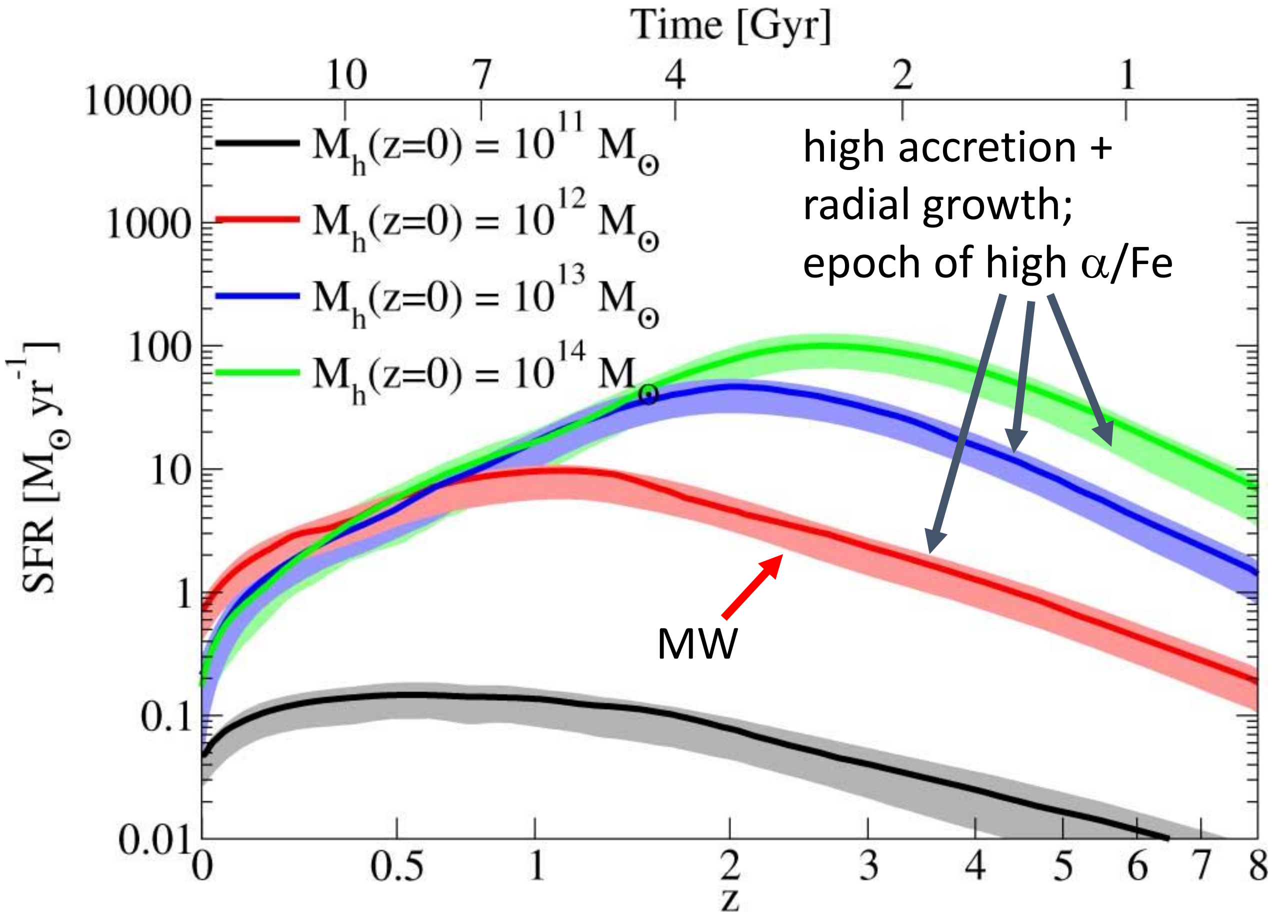
and then H propto Σ, σ propto Σ, and Σ_{SFR} propto Σ

Thickness ties in to the star formation history of the Universe



Behroozi +13

Madau



high accretion +
radial growth;
epoch of high α/Fe

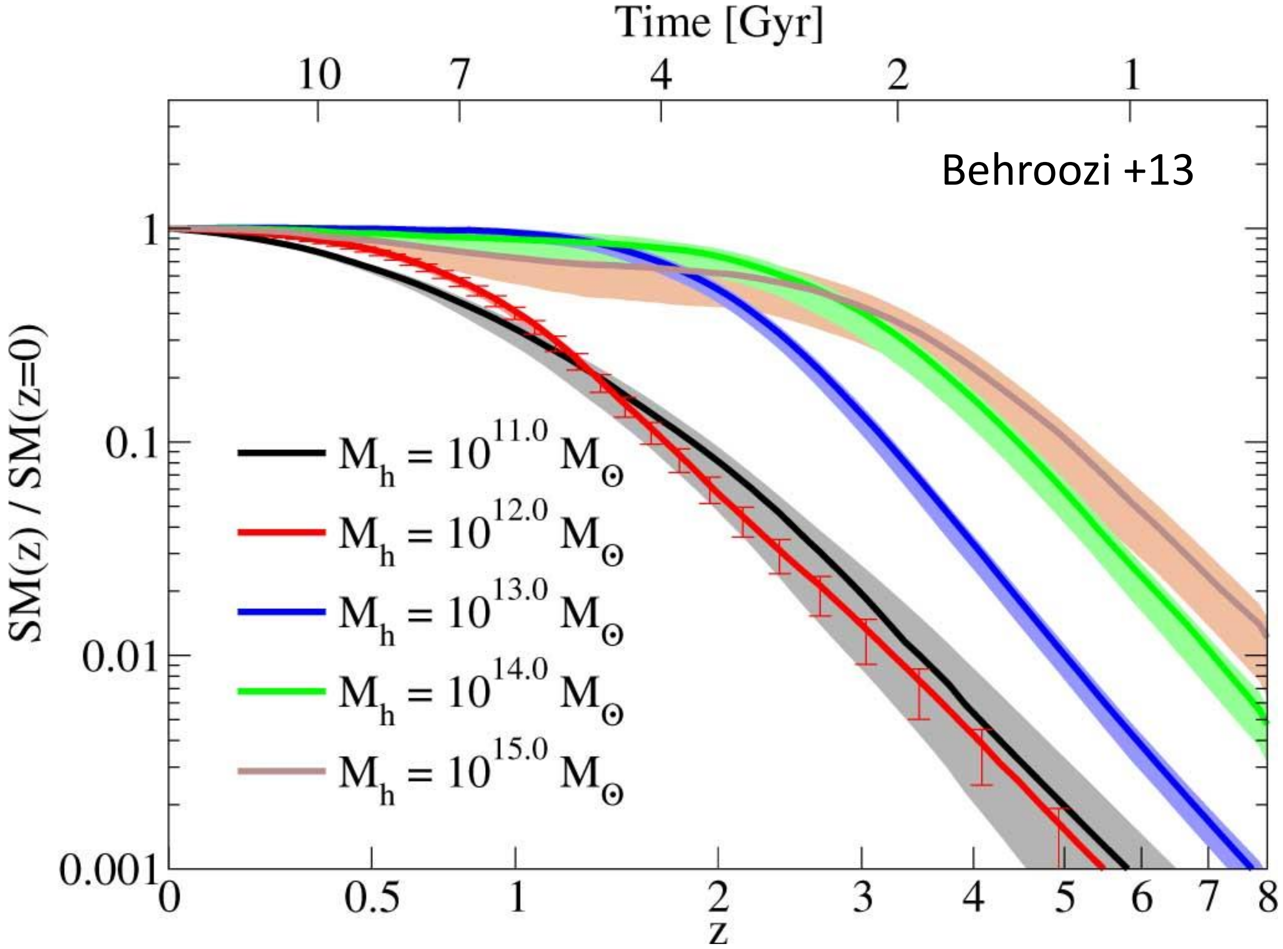
MW

Behroozi +13: SFR versus z and time for particular galaxies

Peak SFR for MW is at z~1. The high α/Fe disk formed before the time of peak SFR.
(The disk was still small in radius then.)

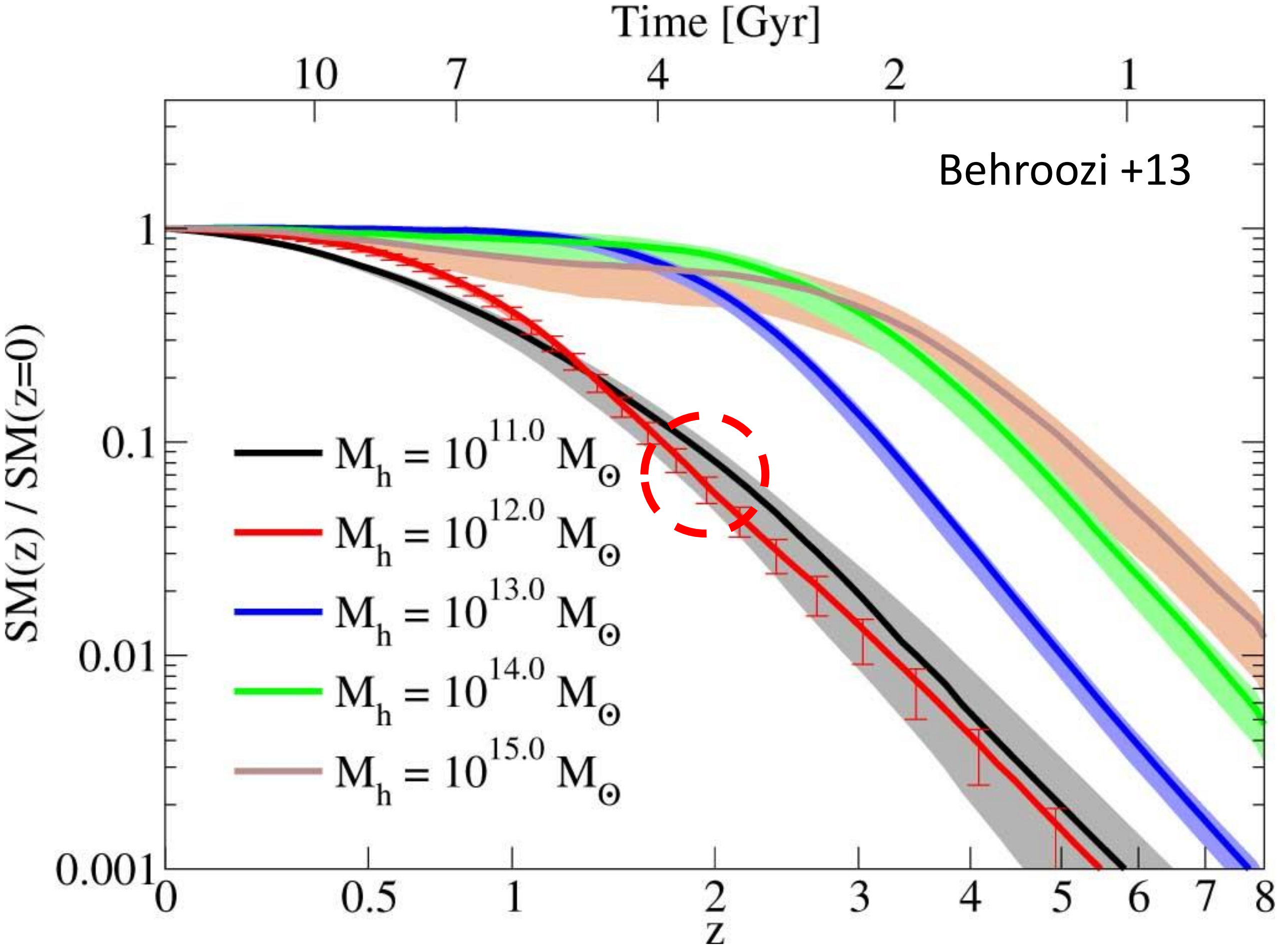
Freeman, Frenk, Huang, Salvadori, Bernard, Hidalgo, Wetzel

Fraction of today's stellar mass at various redshifts



The red curve is the growth rate of stellar mass for the MW

Fraction of today's stellar mass at various redshifts

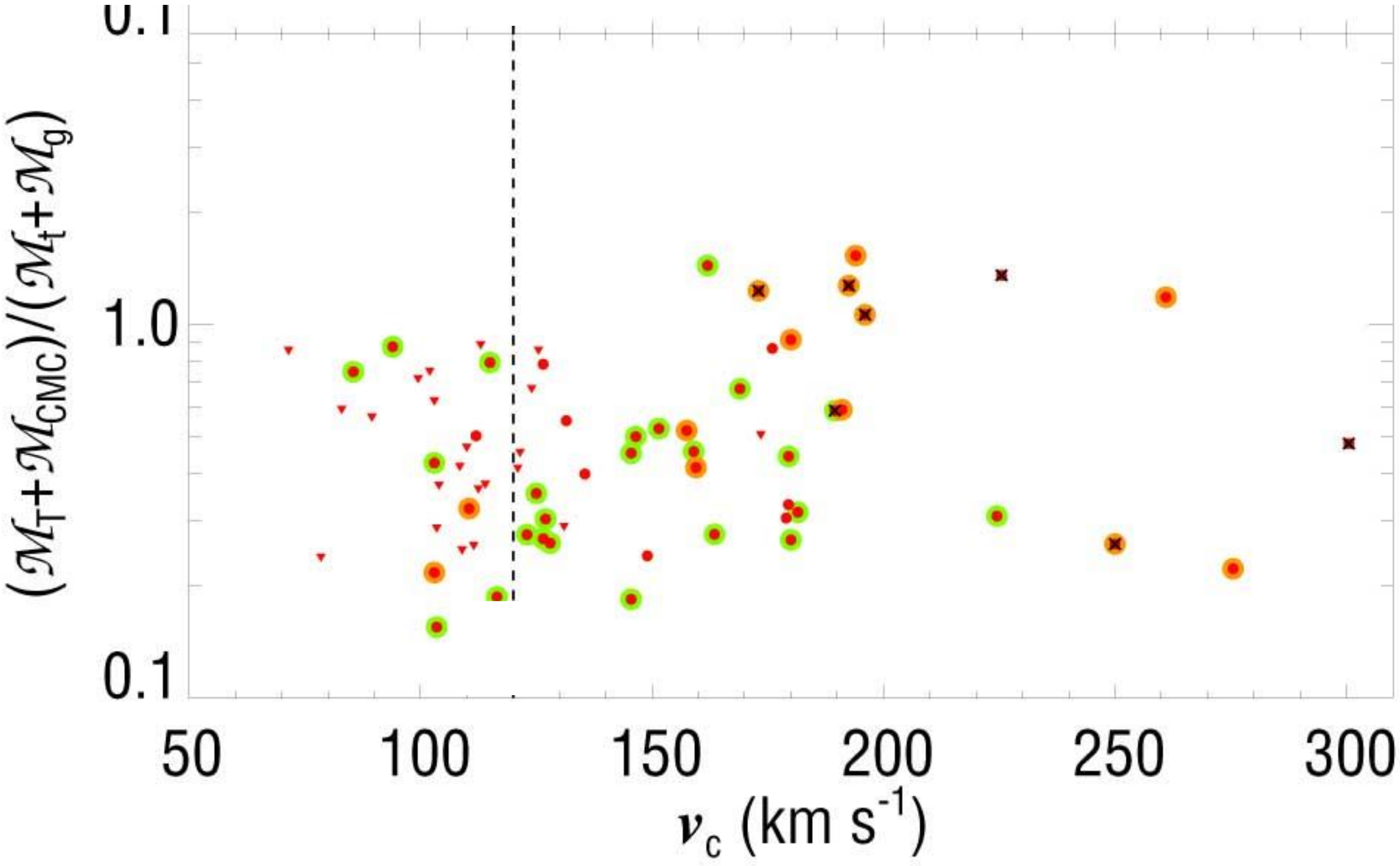


If $M_{thick} \sim 5 \times 10^9\ M_O$, $M_{thin} \sim 4 \times 10^{10}\ M_O$ and $M_{bar\text{-}bulge} \sim 2 \times 10^{10}\ M_O$, then

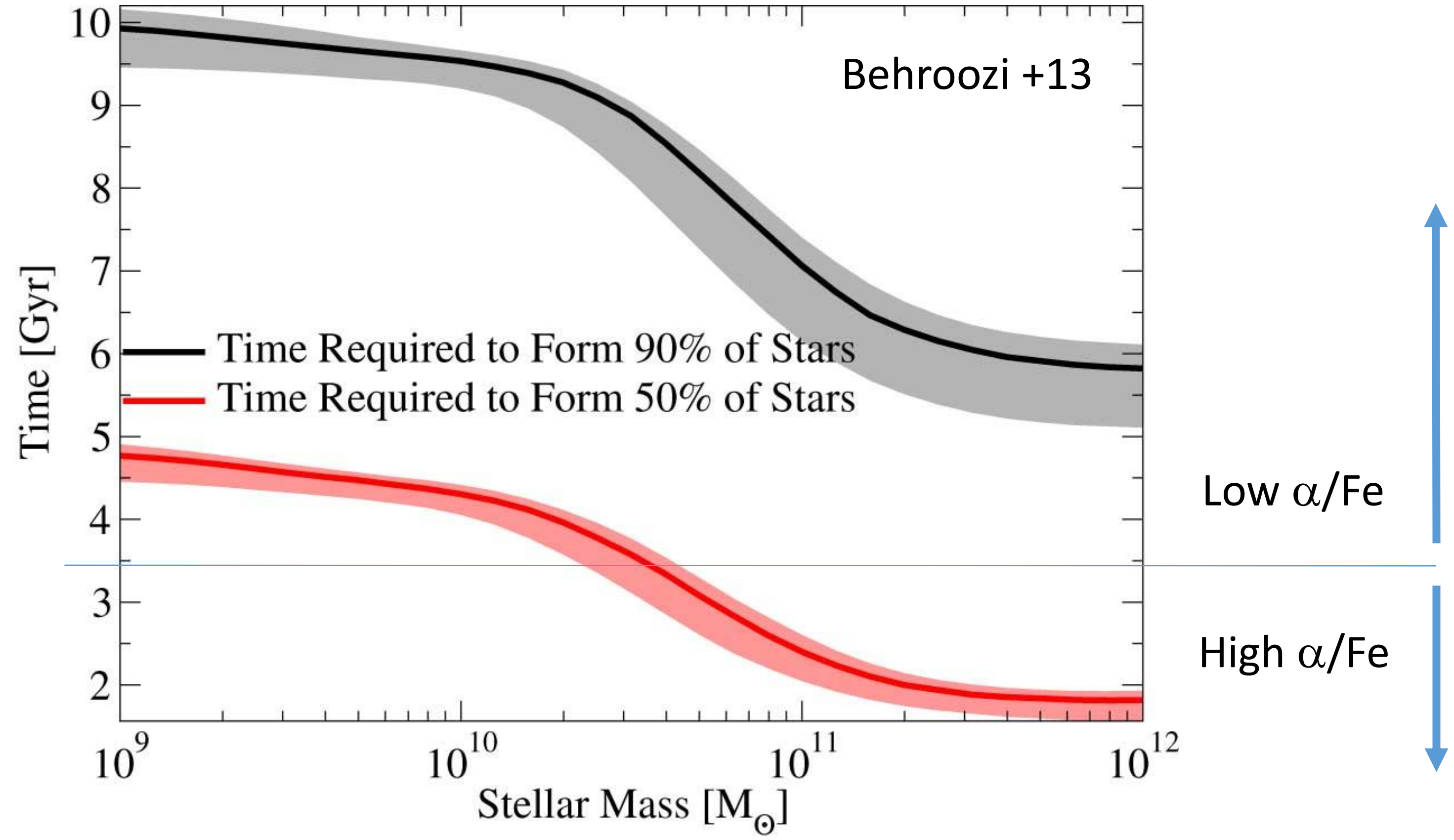
$M_{thick}/M_{total} = 8\%$ (Ken Freeman's talk) and the formation time was ~4 Gyr

Note, SNIa started at ~2 Gyr, but the MW was only 1/10 as massive then.

Comeron +14: The sum of the central mass concentration (“bulge” or “pseudobulge”, but not “boxy/peanut bulge”) and the thick disk is about the same ratio to the thin disk for all galaxies.   The “hot fraction” is ~30%



Madau



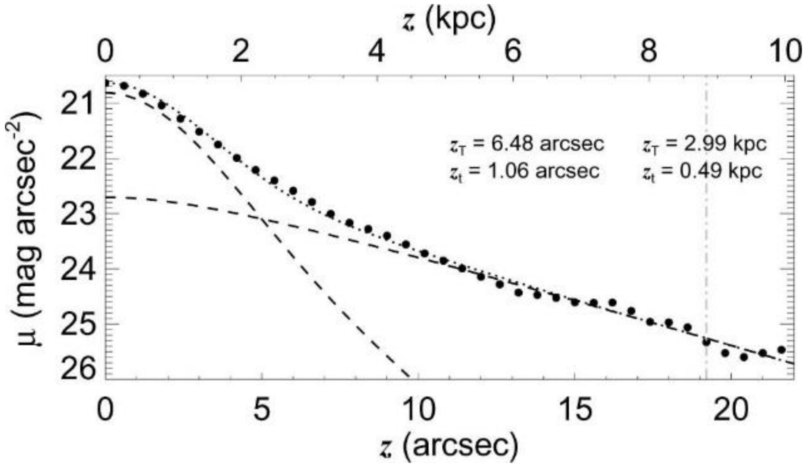
Thick disks + bulges have ~30% the present-day stars (slightly below red line).

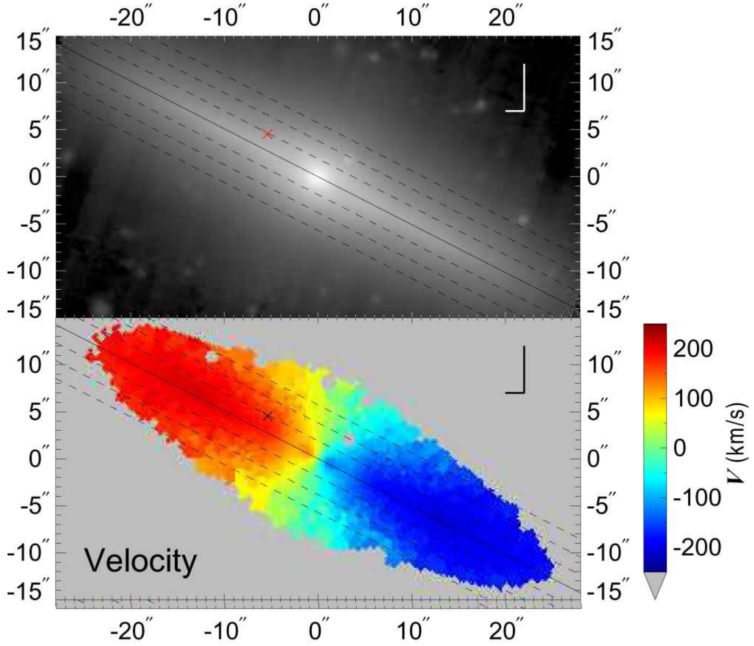
The high α/Fe time is always less than several Gyr

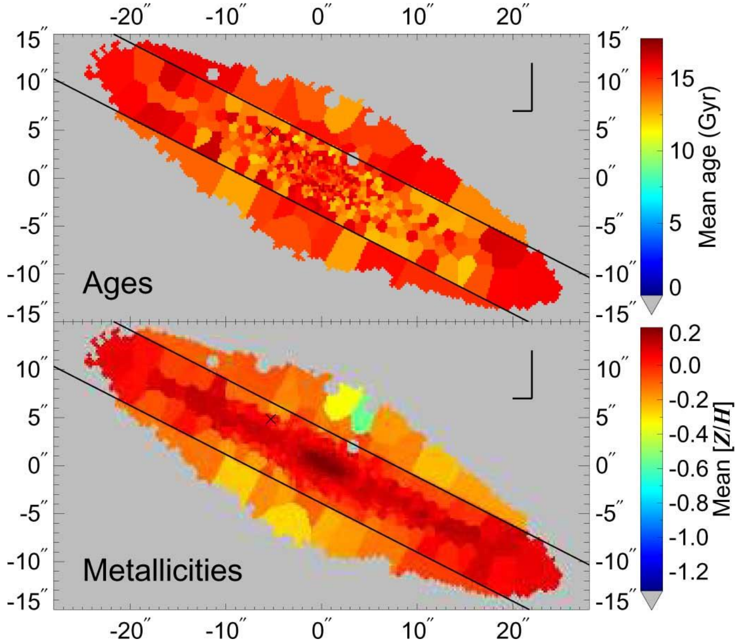
The MW has high α/Fe primarily in its hot component

Disks more massive than the MW should have high α/Fe also in their cool parts.

Disks less massive than the MW should have low α/Fe even in their hot parts (dIrr)





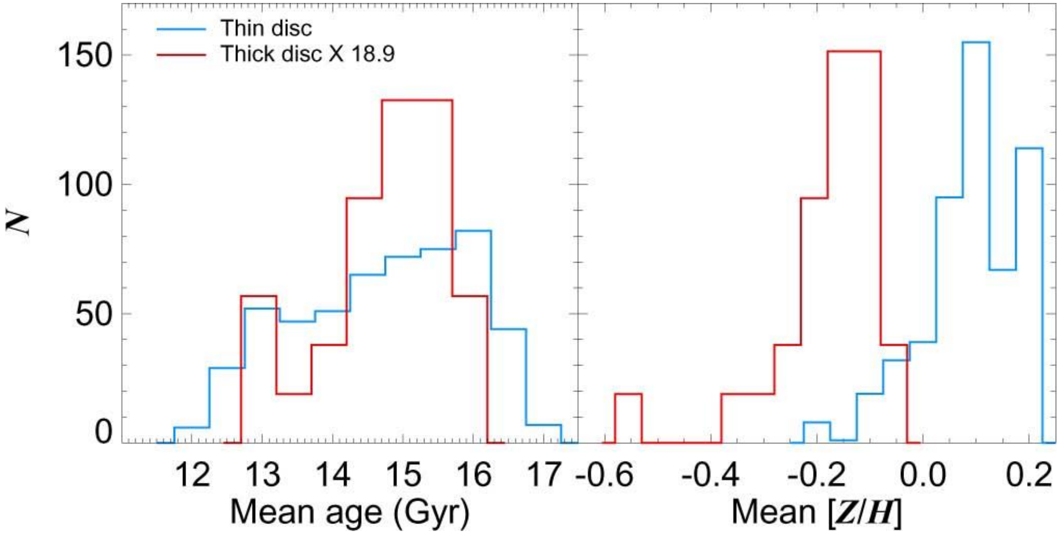


Comeron +16: ESO 243-49 (S0 gal. Vcir~200 km/s, old red disk) with the MUSE IFU

The thick disk is geometrically and kinematically <u>distinct</u> from the thin disk: high z extention & rotational lag.

The thick disk has <u>lower metallicity</u> than the thin disk.

But, the thick and thin disks have the about the <u>same age.</u>



Where do we go from here?

- Follow the timescale: evolution time is locally $\sim(G\rho)^{-1/2}$
  - the inner disks of most galaxies and most of the disks in massive galaxies form stars quickly compared to the age of the universe.
    - relatively old stars ("inside-out" SF), relatively old metallicities (high α/Fe), and relatively short gas consumption times so they have used up their gas (continuous accretion needed if there is gas)
  - the outer disks of most galaxies and all of low-mass galaxies form stars slowly compared to the age of the universe
    - gas builds up without conversion to stars (gas dominates stars) because they have a long consumption time
    - stars may have been scattered there by the relatively rapid processes in the inner disk.

Grebel, Bernard, Hidalgo, Gonzalez-Delgado

Where do we go from here?

Follow V_{rot}

Why do classical bulges vary with V_{rot}?

If classical bulges are from coalesced clumps in young galaxies, then the clumps have to live a long time at high V_{rot} and a short time at low V_{rot}.

But this is expected:

σ_{ISM} scales with V_{rot}
σ_{clump} scales with σ_{ISM}
Clump self-binding scales with σ_{clump}

→ Low mass clumps in low mass galaxies
should break apart

Conclusions

- The MW contains the evidence of its own evolution
  - the phases and physical processes are locked in the stars
- New MW surveys will soon cover most of the disk
  - distances, velocities, abundances, ages, ISM, structures
- Local Group surveys show the relics of accretion
  - globular clusters, halo stars, streams, cold and hot gas
- High redshift surveys with thousands of galaxies show the same and other processes
- Simulations now reproduce most of this, for both individual galaxies and the ensemble of galaxies