# Astronomy 730

## Evolution

# Outline

- Evolution
  - Formation of structure
  - Processes on the galaxy scale
    - Gravitational collapse, merging, and infall
    - SF, feedback and chemical enrichment
    - Environment
    - Dynamical resonances and instabilities
  - Observations on the galaxy and cluster scale
    - High redshift galaxies
    - Intermediate redshift clusters
    - Archeological record

# How we think structure formed

- Process:
  - Start with distribution of fluctuations (i.e. dark matter halos)
  - Fill with baryons and let "gastrophysics" happen
    - Virialization of gas
    - Radiative cooling → disk formation
    - Photoionization from background
    - Star-formation → feedback
    - Chemical evolution

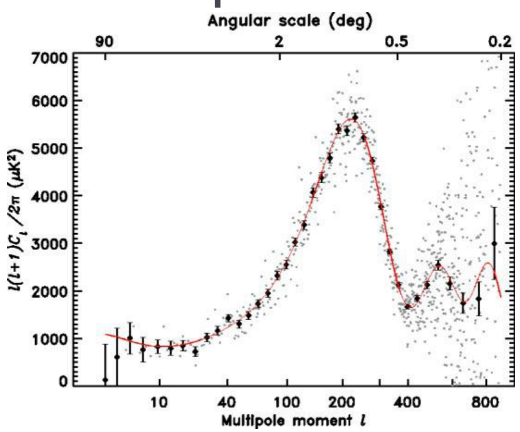
| Jeans mass and length: |
|---|
| $M_J = (\pi\lambda_J 3/6)\rho$ |
| $\lambda_J = (c_s/(3)^{1/2})(3\pi/8G\rho)^{1/2}$ |

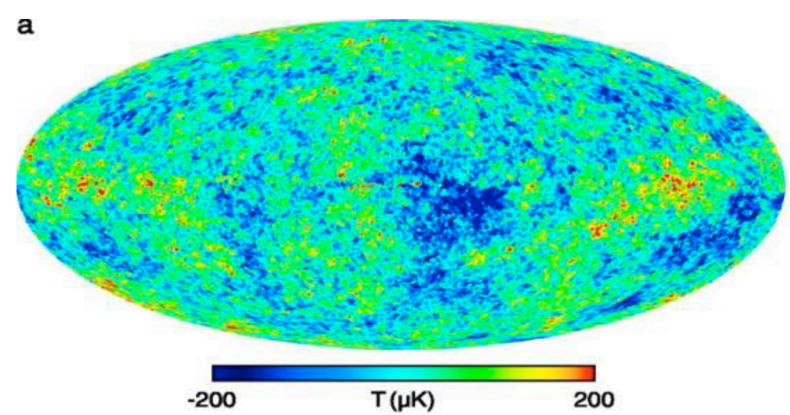
- What is the dark matter: *hot, warm, or cold?* (how long relativistic?)
- Hot Dark Matter (*top down*)
  - Neutrinos w/ E~10 eV → $mc^2 = 3k_BT$ (non-relativistic) occurs at $z \sim 2\times10^4$
    → Universe is hot, Jeans mass is large → $M \sim 10^{15} M_\odot$ (i.e. cluster masses)
    → density fluctuations $< 10^{15} M_\odot$ are damped out
  - $1^{st}$ structures to form are large clusters
  - galaxies form from fragmentation of larger structures (like star-formation)

  } Zeldovich pancakes
- Cold Dark Matter (*bottom up*)
  - Post recombination temperature → $M_J \sim 10^5 M_\odot$
  - $1^{st}$ structures to form were small

# From CMB to Large Scale Structure (LSS)

- CMB: 2.728±0.02 deg (K)
  - 0.03% deviations
- Very smooth but there are distortions
- Fluctuations on different scales
  - Angular scale corresponds to spatial scale today
- Power spectrum of fluctuations
  - Acoustic peaks in CMB



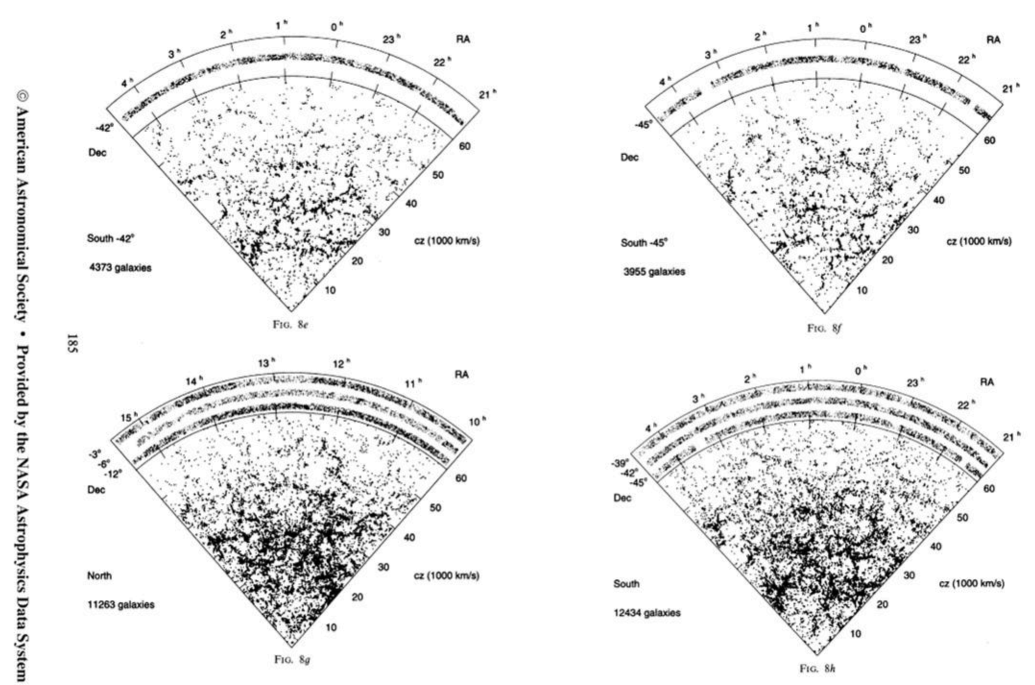
# What we expect

- Well, Hot or Cold?
  - Hot ➔ hard to make stars/galaxies so much younger than clusters
    - we also see evolution/growth in galaxy clusters at z ~ 0.7
  - Hot ➔ too easily makes large flattened things
  - Cold ➔ structure on all scales forms at same time
  - Cold ➔ matches galaxy two-point correlation
- CDM the winner
  - Hierarchical formation ➔ building galaxies via merging of large numbers of small galactic systems ➔ described via a "merger tree"

# Scales of structure today

- Individual galaxies ➔ 0.2-0.5 Mpc
- Galaxy groups ➔ 1-2 Mpc
- Clusters of Galaxies ➔ 2-4 Mpc
- Superclusters ➔ 5-10 Mpc
- Filaments ➔ tens of Mpc

Optical redshift surveys:



# Processes on the Galaxy Scale

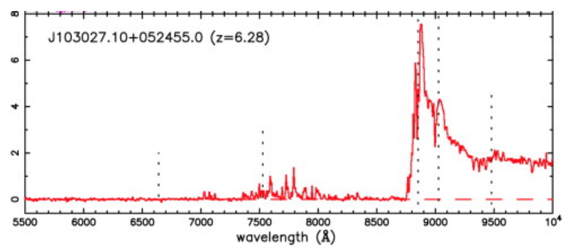
- Gravitational collapse, merging, and infall
- SF, feedback and chemical enrichment
- Environment
- Dynamical resonances and instabilities

# What do galaxies look like at high-z?

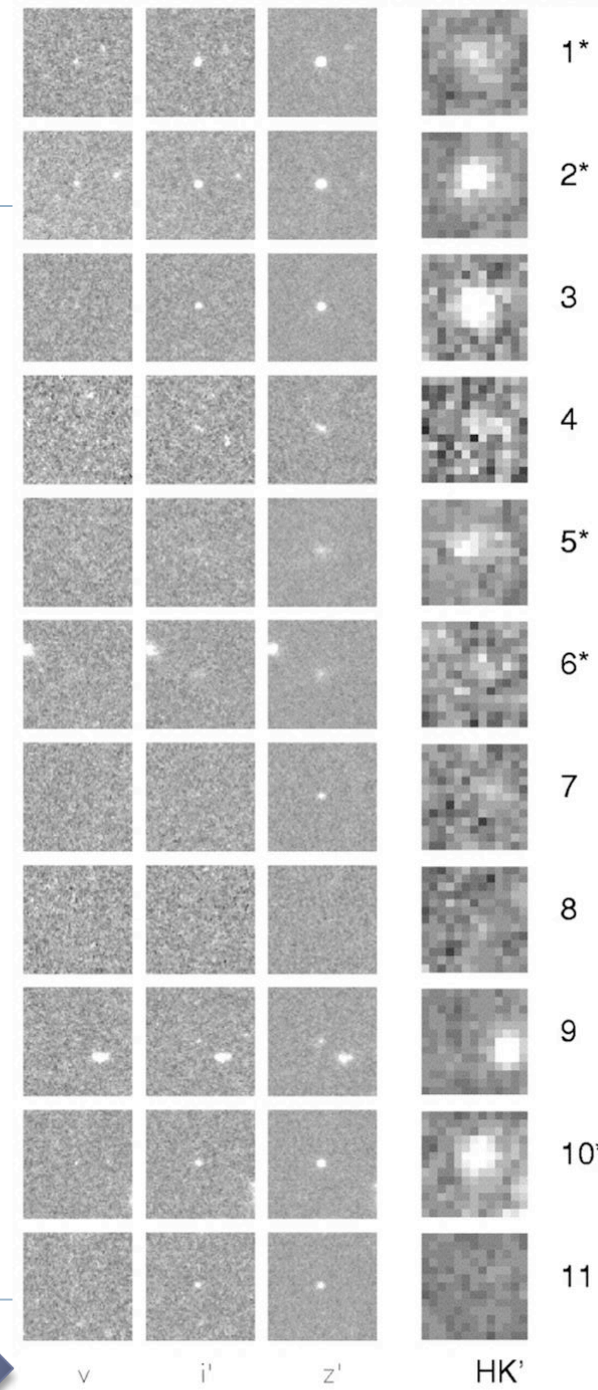
- Cosmological distances
  - Because the
    - Universe is smaller in the rest frame
    - Photons have lost energy along the way
  - $d_L = (1+z)R(t_0)r_{cm}$ ($r_{cm}$ = comoving distance)
  - $d_A = R(t_0)r_{cm}$
- "k-correction"
  - $k(z) = 2.5\log_{10}(1+z) - 2.5\log_{10}\{ (\int L_\lambda[\lambda/(1+z),t_0]d\lambda) / \int L_\lambda [\lambda,t_0]d\lambda \}$
    - Accounts for changes in wavelength of light due to z
- Redshift issues
  - Rest frame vs observed
  - Varying metallicity/extinction
  - Real distance determination

# Detecting High-z Galaxies

- “Dropouts” (Steidel, Pettini, Hamilton 1995)
  - Lyman break at 912 A ➔ dropoff in continuum flux, just shortward of Lyα line ➔ select filters accordingly
  - Absorption generated by the Lyα forest

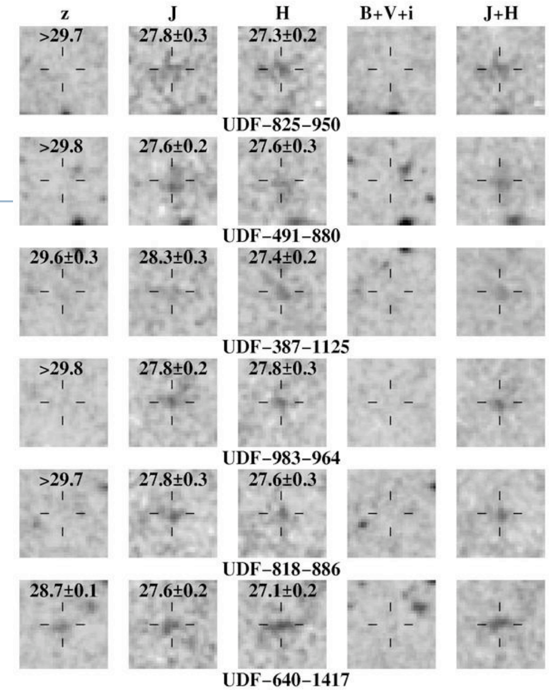


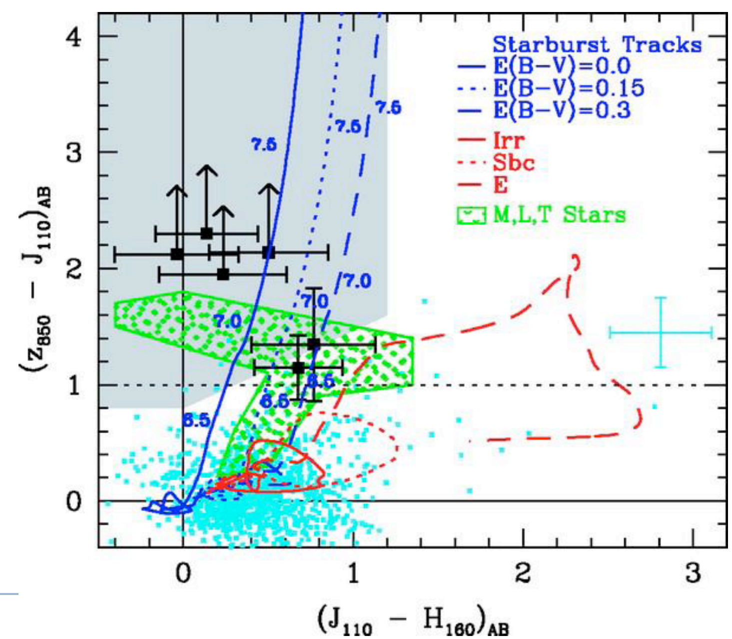

- Examples
  - Stanway et al (2005) ➔ surface density of i-band dropouts (HST, Keck)
    - z~6 star-bursting galaxies
    - No X-ray detections ➔ no quasars
    - Tiny sizes ~ 1.5 kpc
    - SFR ~ 10-25 M yr-1



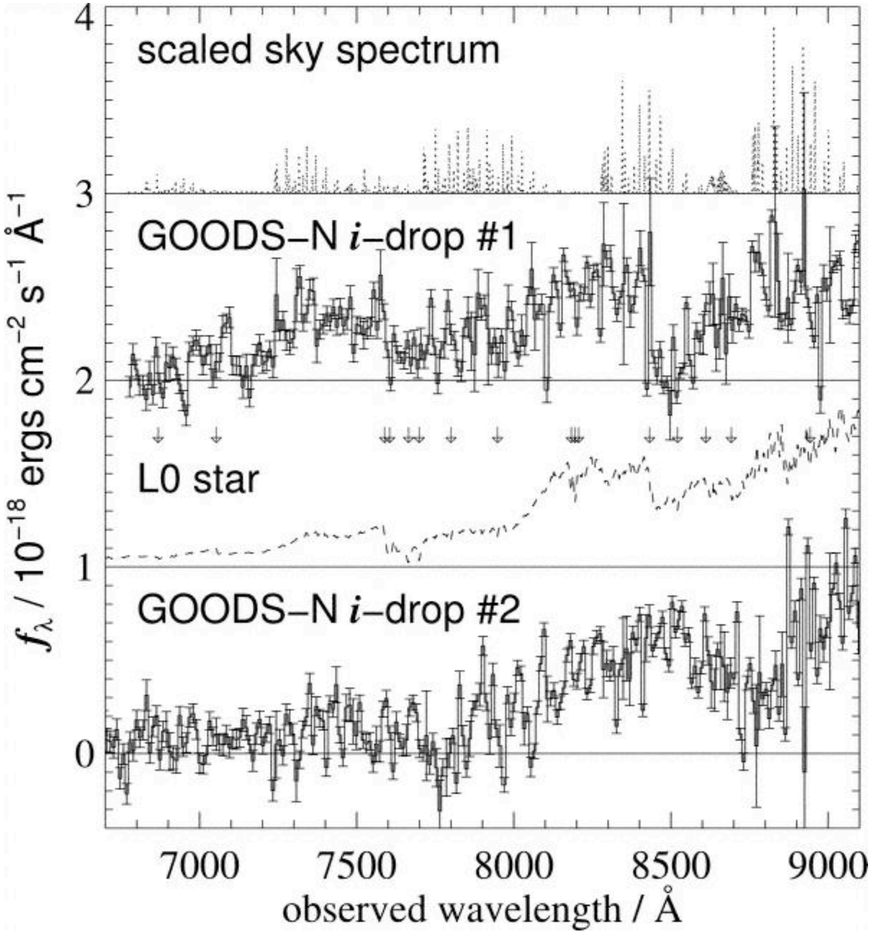
# Detecting High-z Galaxies

- "Dropouts"
  - Lyman break at 912 A ➔ dropoff in continuum flux, just shortward of Lyαline ➔ select filters accordingly
- Examples
  - Bouwens et al (2005) ➔ Near-IR spectrophotometry
    - z–J > 0.85 mag
      - z filter at 8500 A = 0.85 microns
      - J filter at 1.1 microns
    - no detection below 8500 A (z~7.3)
    - 5 sources with H (1.6microns) ~ 27 mag
      - Corresponds to rest-frame UV ➔ L*-like galaxies
    - No luminosity evolution as compared to z~3.8 sample
      - Account for redshift distance/size



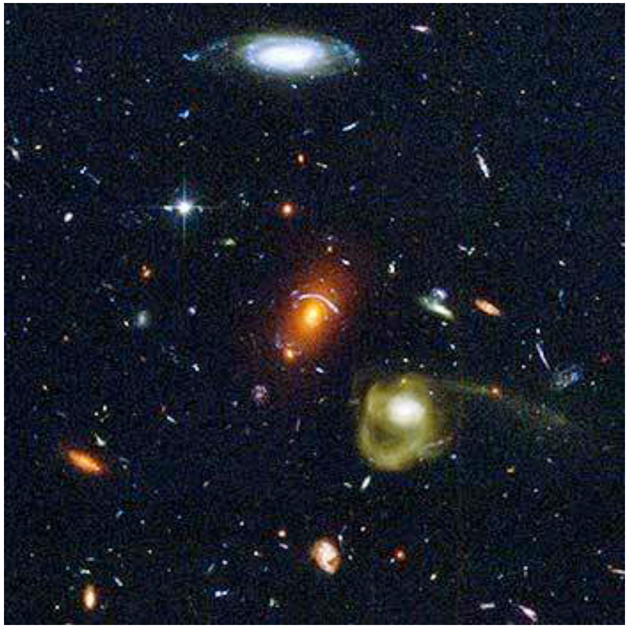



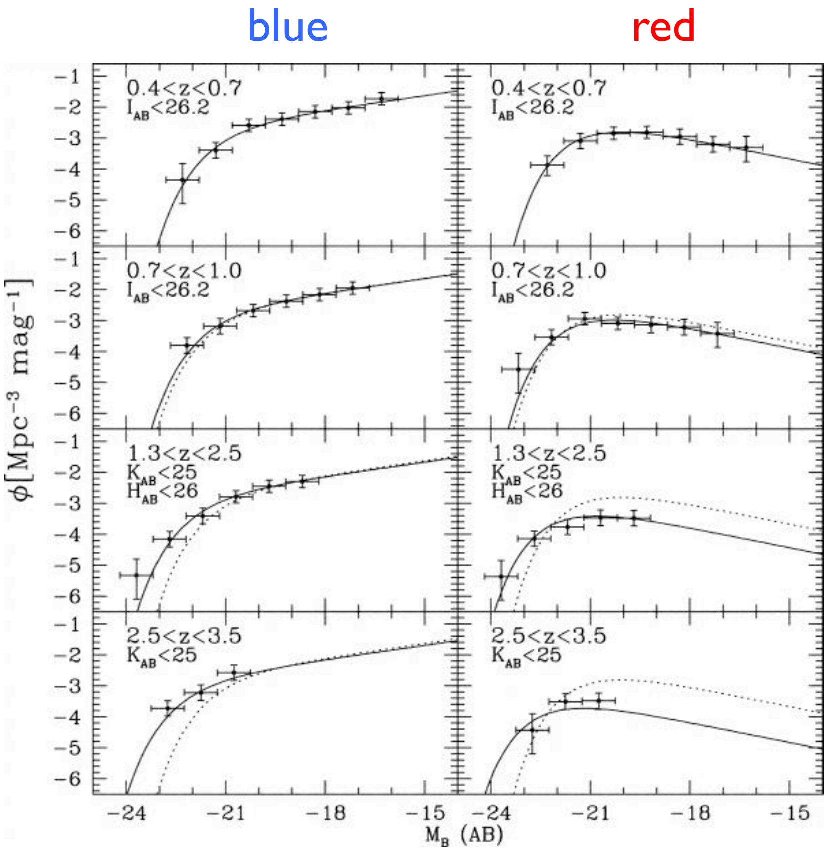
# Contamination: cool stars



# Metrics of evolution

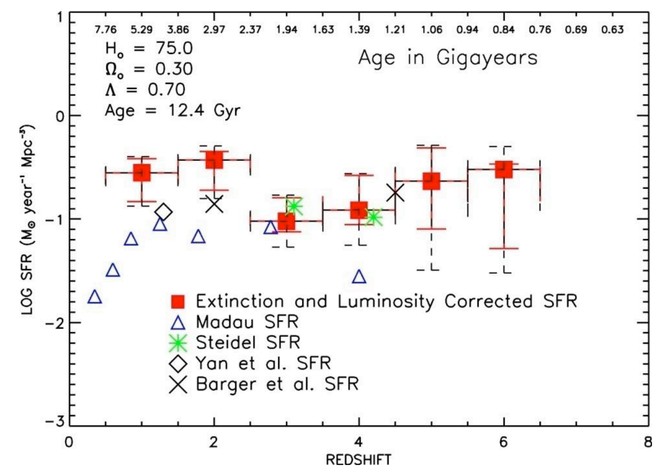
- Luminosity function/mass function
- Size distribution (i.e. how big are individual galaxies?)
  - Morphology distribution
- Star formation/stellar mass

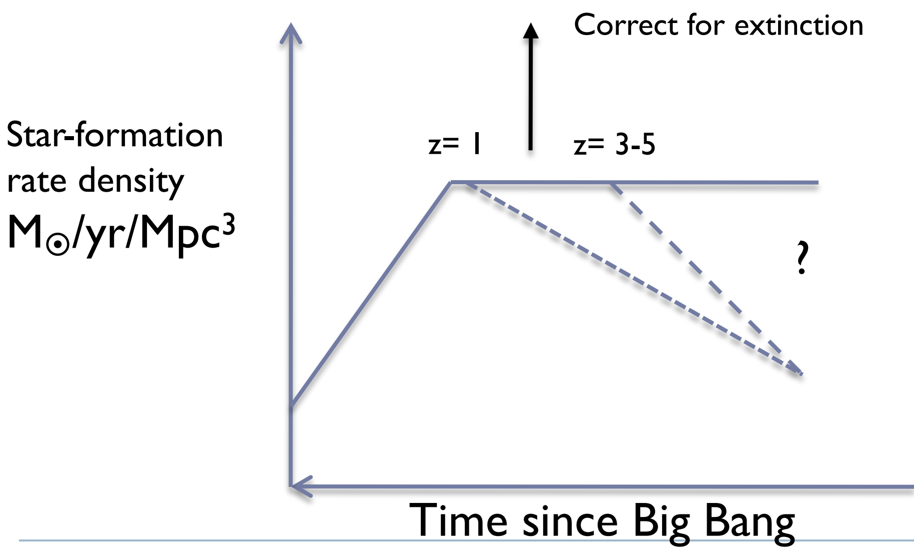


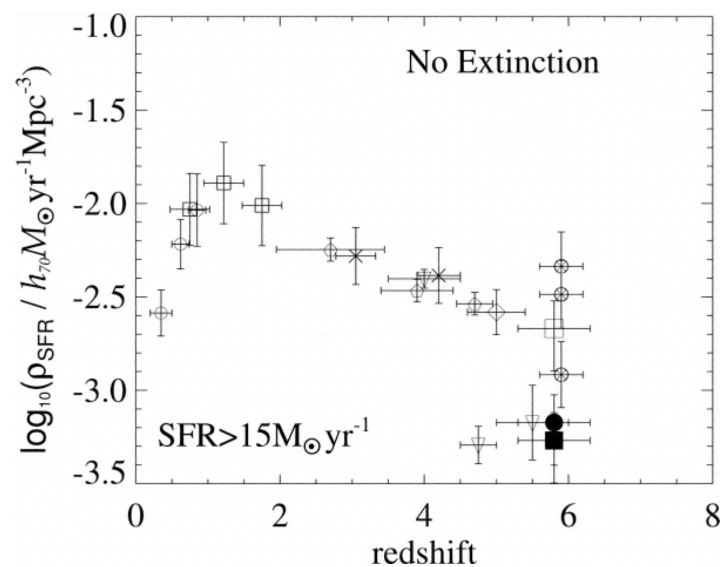


# Star Formation History of the Universe

- What fraction of stars formed when?
- Measure SFR at a variety of redshifts
  - Metrics for measuring the SFR….
    - Hα, radio continuum ➔ local
    - [O II]3727 at intermediate redshifts ➔ z ~ 3
    - UV continuum at high redshifts
    - (SKA will use radio continuum)

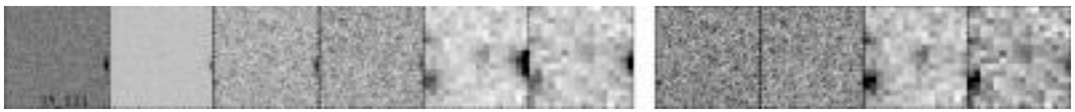


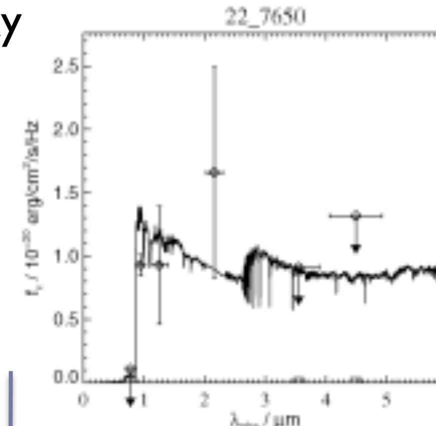



# Growth of stellar mass

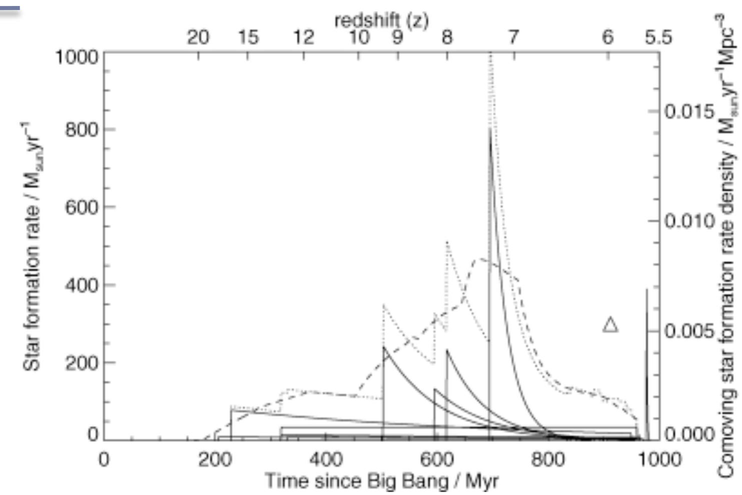
(a) Optical-NIR photometry + redshifts for many galaxies; here's one typical example.



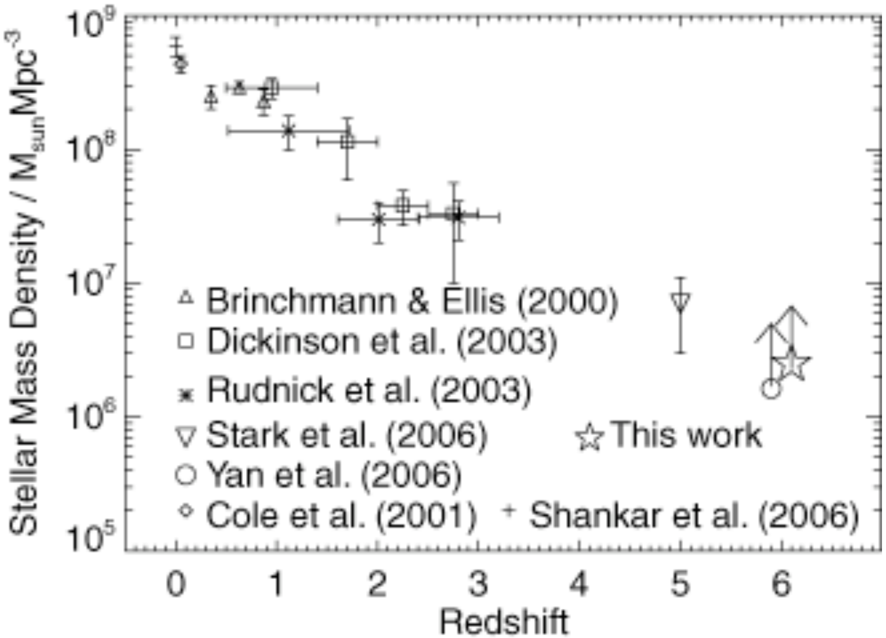
(b) Model SFR history for each individual galaxy




(c) Estimate ensemble SFR history




(d) Sum up contributions to total stars formed




- Eyles et al. 2006 MNRAS

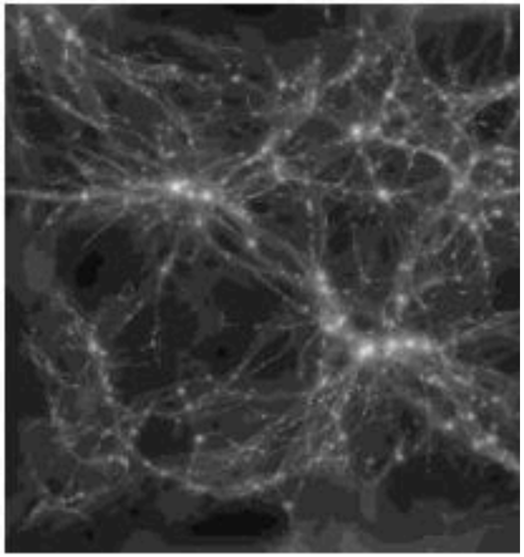
# What we think we know

- At high redshift galaxies were
  - Smaller, lumpier, and presumably more gas rich
  - Bluer…
    - More actively forming stars (per unit mass)…
  - Not as concentrated in clusters…
- What we'd like to know:
  - When and how quickly did gas settle into dark matter potentials?
  - When, where, and how did the gas get converted into stars?
  - When and how did the merging process of galaxies develop?
  - What is the relative importance of gas accretion *versus* merging?
  - How rapidly are galaxies still (trans)forming today?

- The door is wide open for you to make giant leaps in our understanding of how galaxies formed and evolved.

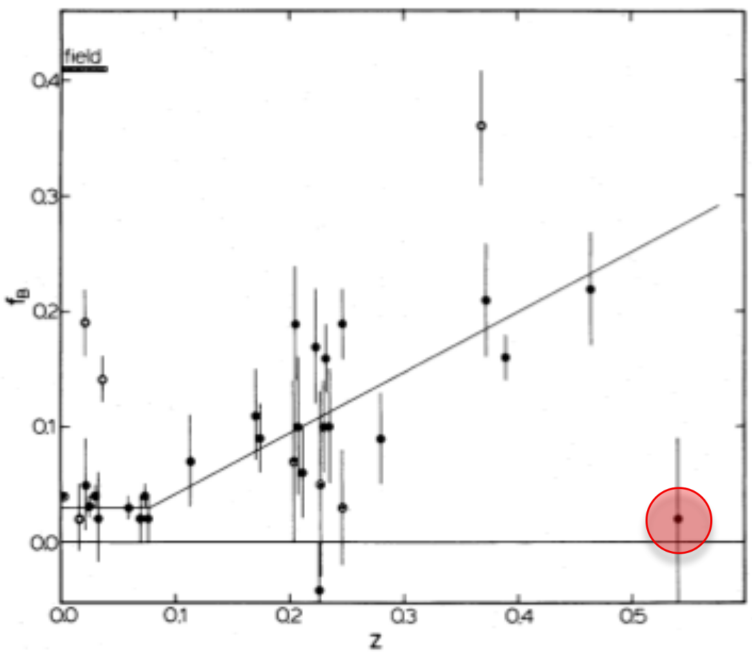
# Cluster Evolution

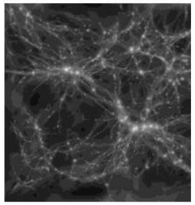
- Why might we expect it?
  - What does density determine?
- What might we expect, say, for evolutionary time-scales in dense environments relative to the field?
  - Stellar evolution?
  - Gas-consumption rates?
  - Dynamical processes (merging)?
- How would cluster selection-effects impact our assessment of evolution?
  - If density is important, what *types* of clusters will be most *easily* detected at *large* distances?
  - How about *projection* effects?



# Cluster Evolution: Butcher-Oemler Effect

- (Also known as the BO or "moving target" effect)
- Original claim: (1984, ApJ, 285, 426)
  - Moderate z clusters have larger fractions of blue galaxies
- Counter examples
  - e.g., CL0016+16
- Later amended to
  - spectroscopically younger:
    - "E+A" galaxies
      - ☐ Higher velocity dispersions
      - ☐ Less centrally concentrated
    - More AGN
    - More star-bursting galaxies
- Don't forget projection!
- Sample selection?



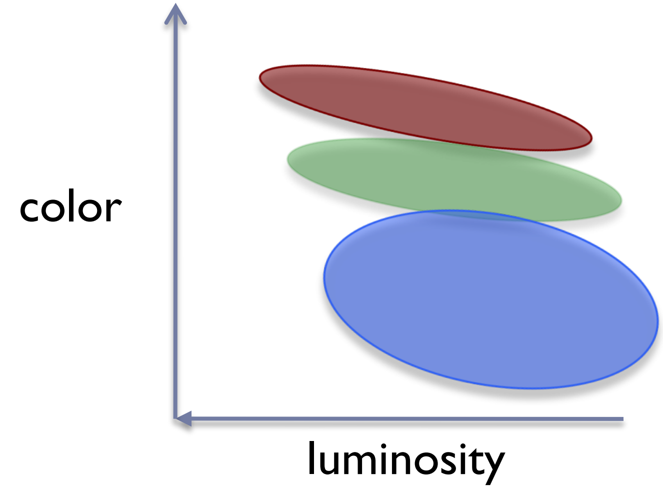



# Cluster Evolution: the red sequence

- If clusters had more blue galaxies yesterday

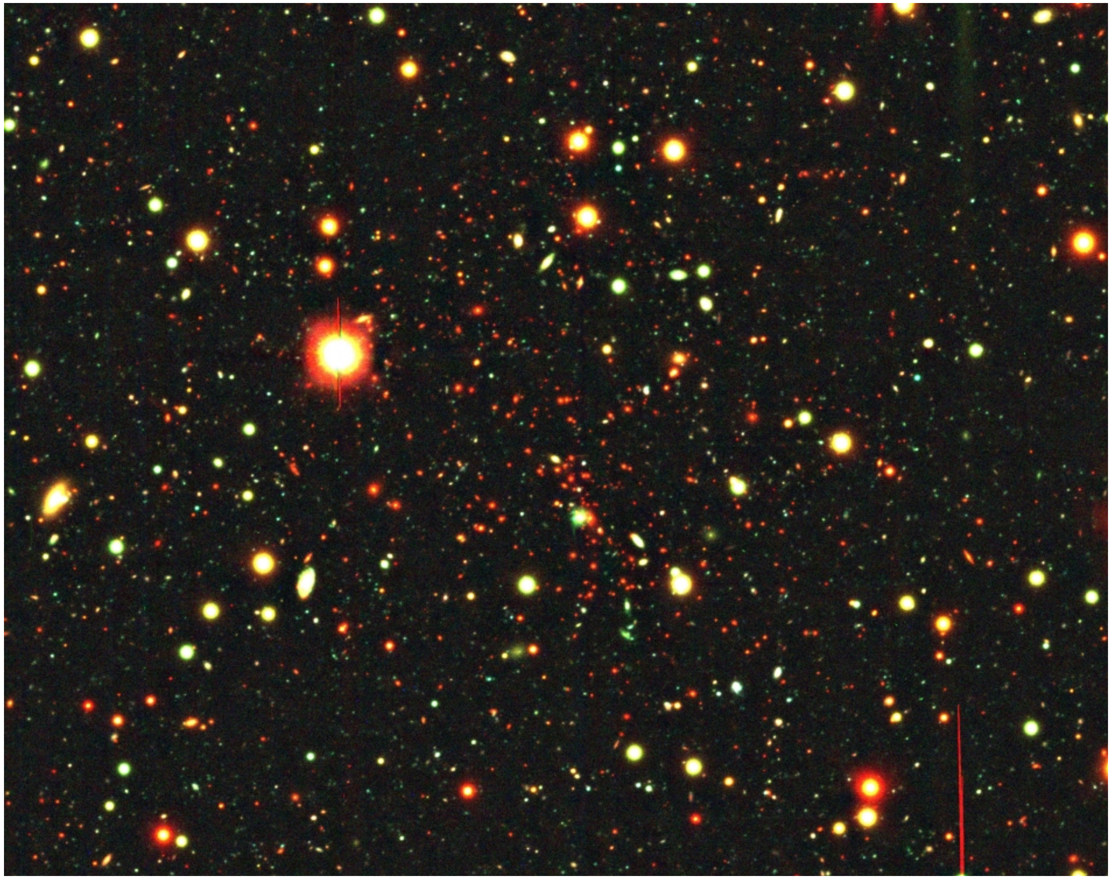
  ➔ they have become red by today.

  ➔The luminosity function (LF) for different morphological or spectral types should change with time
- Specifically, the LF for red galaxies should grow with time.
  - If the LF slope changes, that tells us whether the "growth" of the red populations is for high- or low-mass objects, i.e., what the blue galaxies at higher redshift are progenitors of today.
    - Crude spectral types:
      - Red sequence
        - Red and dead (today: E's and S0's)
      - Blue cloud
        - Vigorously star-forming (today: intermediate to late-type spirals and dIrrs)
      - Green valley
        - Weakly forming stars (today: early-type spirals and some lenticulars)

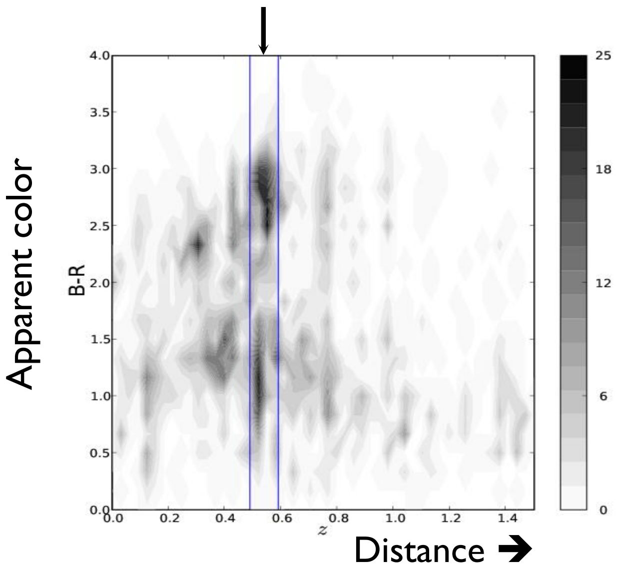


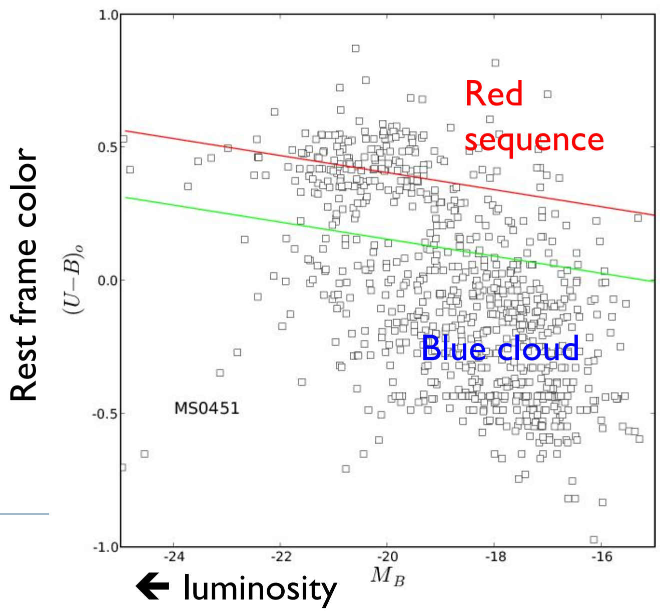
# At $z$=0.5, the red sequence is well-formed

MS0451: $z$=0.54, $\sigma$=1354 km/s, $L_x$=40e44 ergs/s



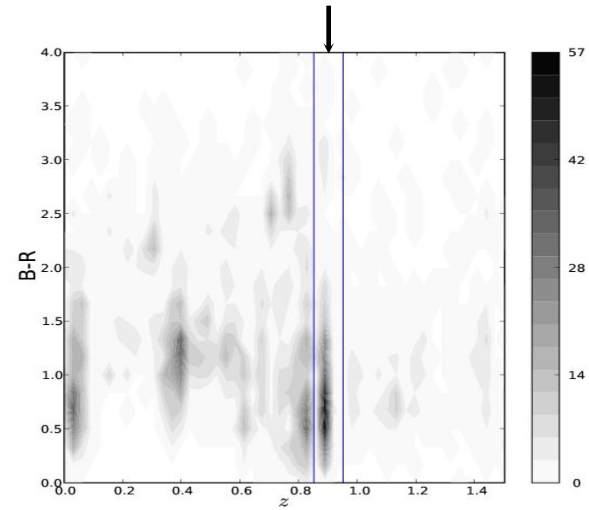
WIYN Long-Term Variability Survey: Crawford et al. 2006, 2008

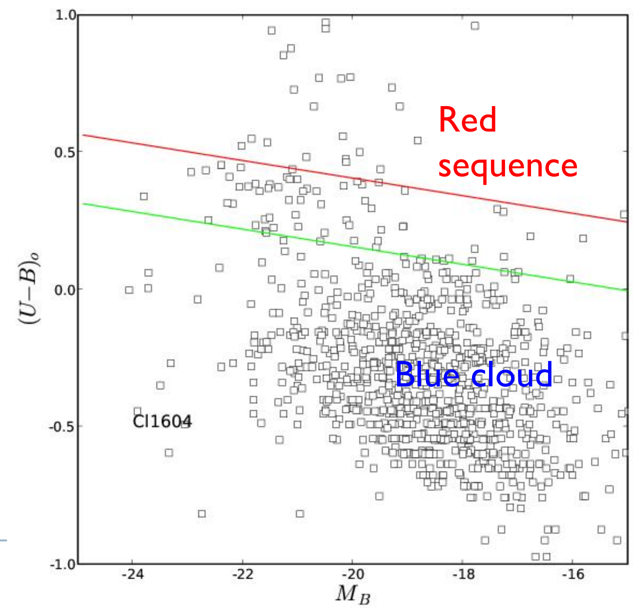


# At $z$=0.9, the blue cloud dominates . . . even in rich clusters

CL1604: z=0.9, σ=982 km/s, $L_x$=2e44 ergs/s




WIYN Long-Term Variability Survey

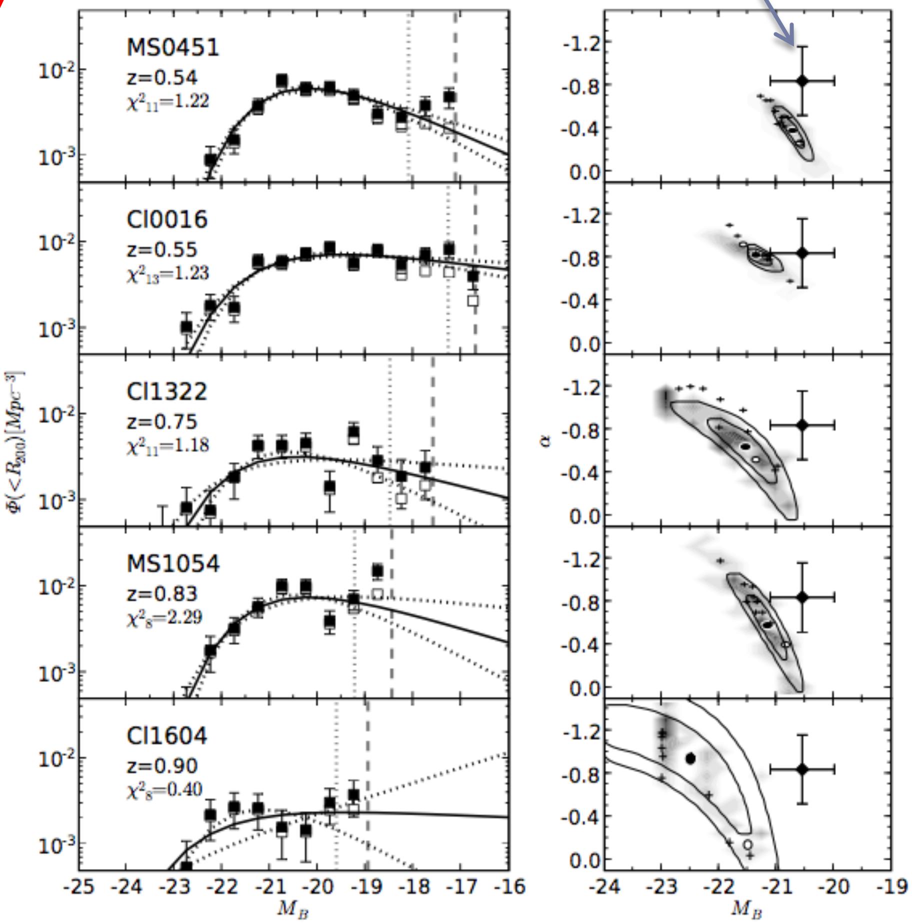
- Crawford et al. 2006, 2008

# Cluster luminosity functions to z=1

Red sequence Luminosity functions (RSLF)

Cluster RSLF

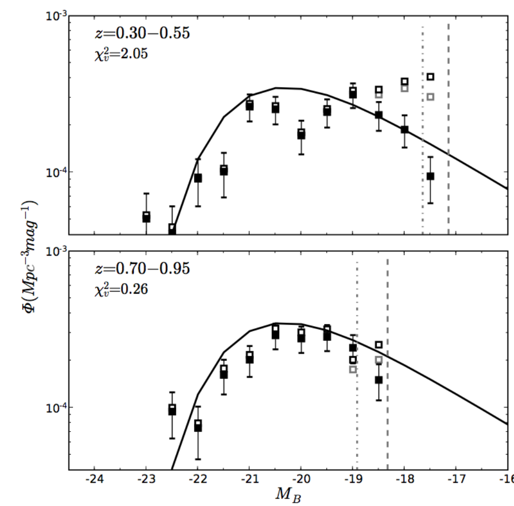
Low-z cluster values




Knee of LF

α is faint-end slope; more negative α means steeper, upward slope

The field RSLF

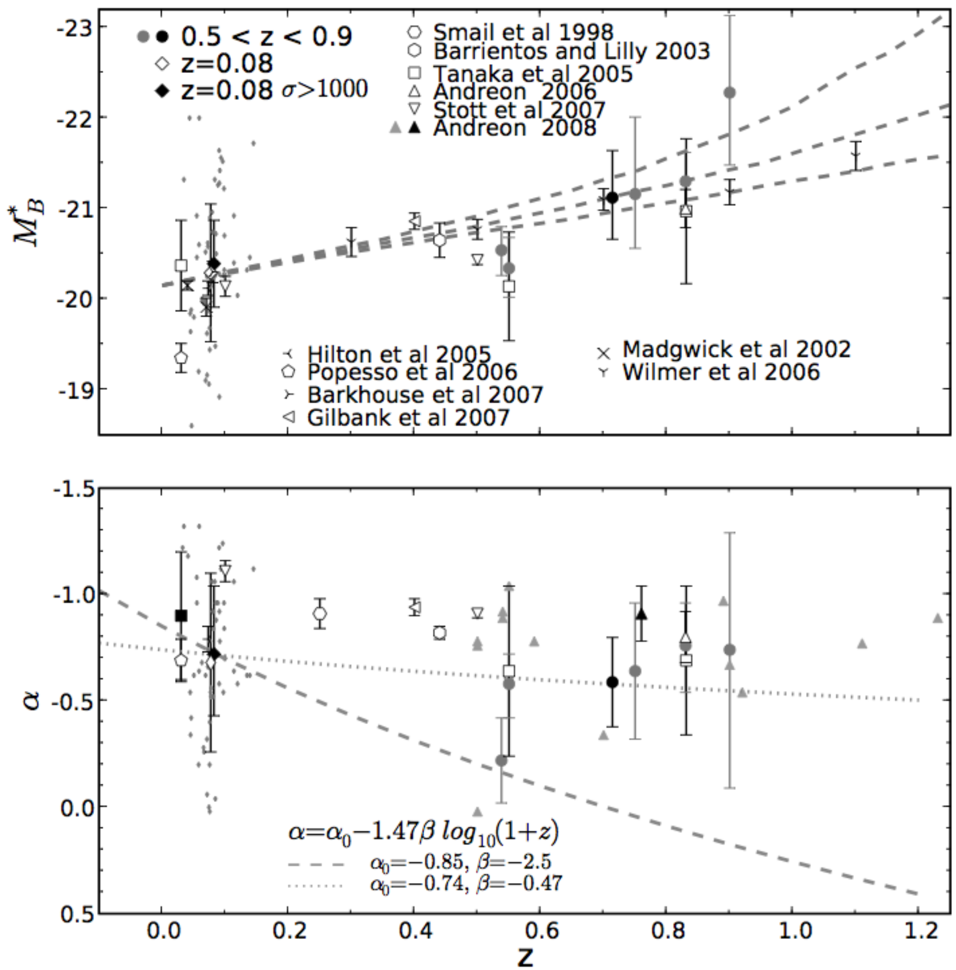



Crawford et al. 2009

# Luminosity Function Evolution

Consistent with *passive** luminosity evolution

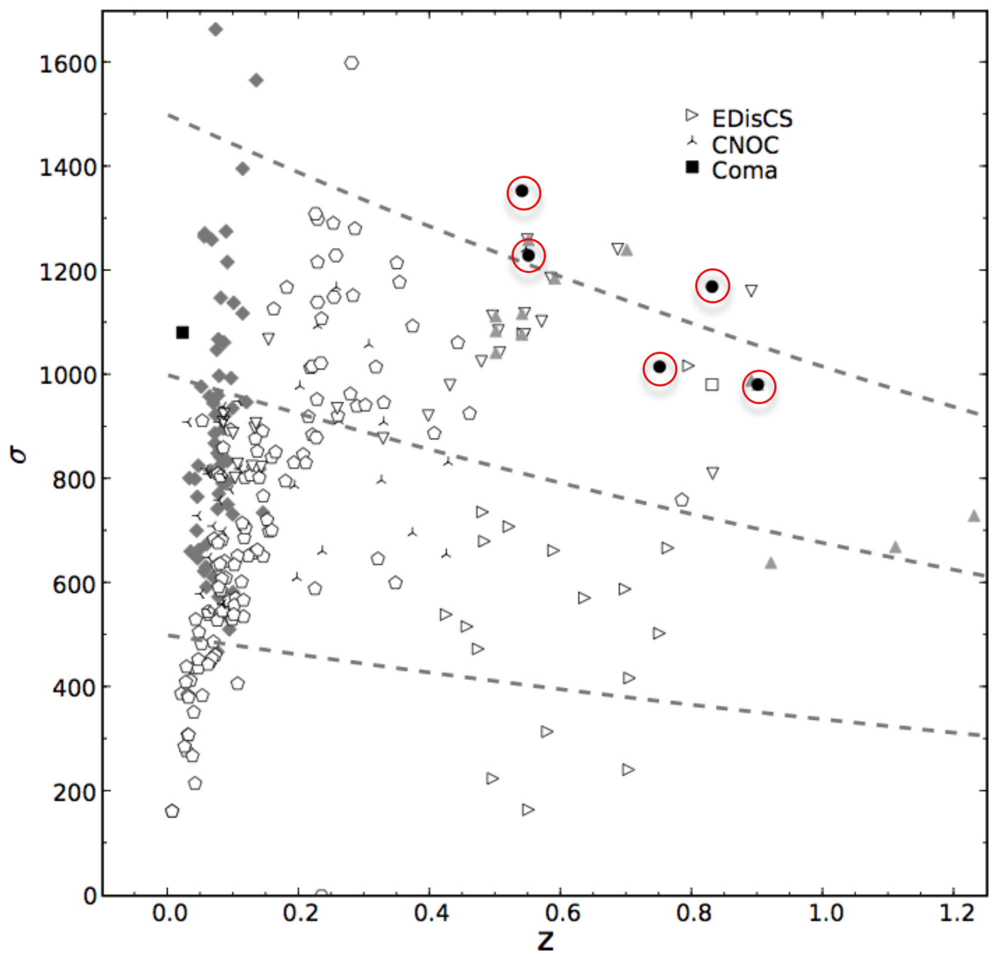
* *Passive evolution* refers to the evolution of stellar populations in the HR diagram (CMDs) in the absence of further star-formation.



# Don't forget selection effects…

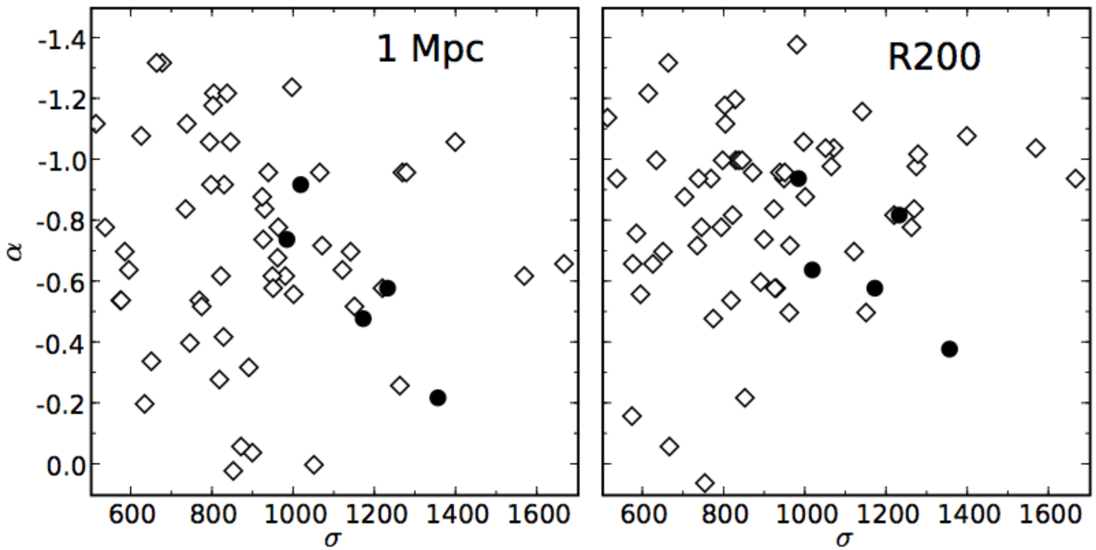
Cluster mass, or its proxy, σ, grow with time as more an more mass falls in to and virializes with the cluster potential.

The clusters studied most intensively at higher redshifts are as large or larger than most known clusters in the local volume (they are rare).



# …Combined with cosmological variance

Faint-end slope of the red-sequence LF




- Clusters exhibit a wide range of faint-end slopes.
- If there is a correlation with other cluster properties (there must!) it has not yet been determined.
- It does appear that the inner-cluster regions have larger (more positive) α, indicative of a relative dearth of dwarf systems.

- What's the cold gas doing?

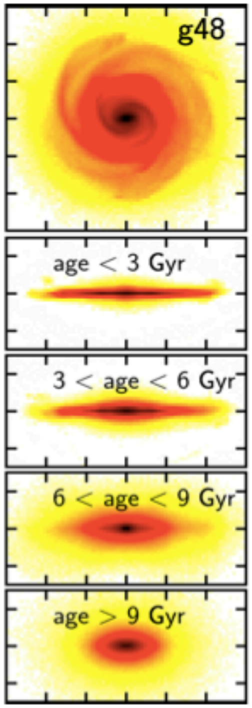
# The archeological record versus in situ observations at high redshift

- Heating versus cooling
  - Do stellar populations thicken in disk over time or does the gas cool and leave 'tidal marks' in the stellar fossil record?
  - Evidence that galaxies at higher redshift are more pressure-supported ($V/\sigma$ increases with time, even in disks), e.g., Simons et al. 2016, 2017.
- Galaxy shapes
  - Today almost all galaxies are oblate spheroids
  - Some massive ellipticals show mild triaxiality
  - Above z=2, their appears to be a significant increase in the number of prolate galaxies.
    - Are these stable? Are there any low-z analogs?

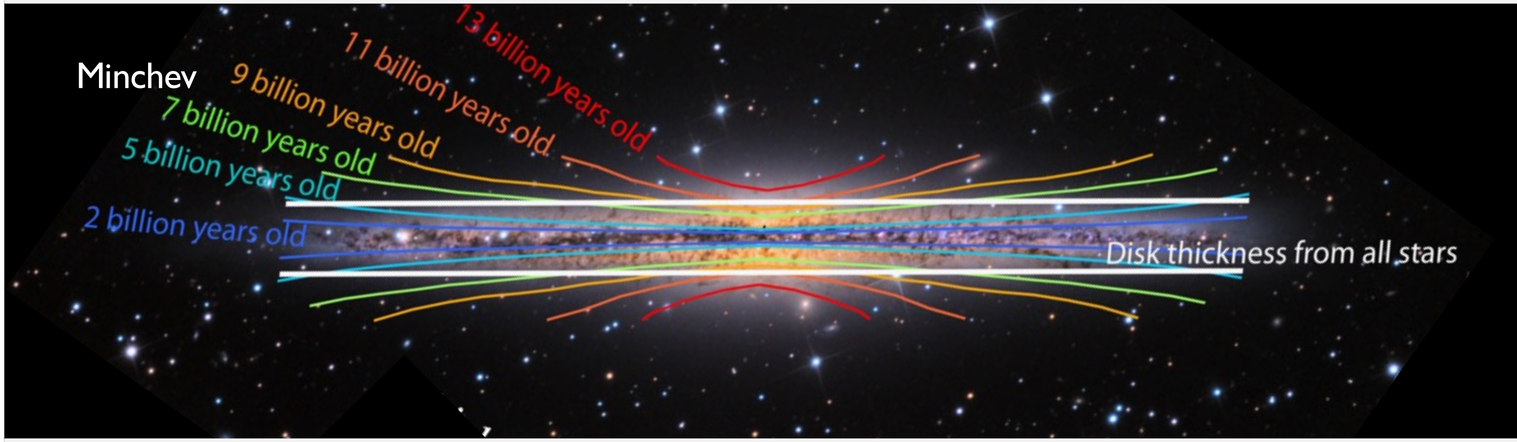
# Disk Stratification: nested mono-age populations

in phase space

Mono-age stellar populations




Martig+2014a,b

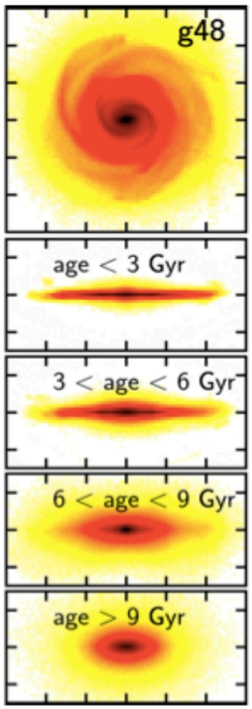



NGC 891

# Disk Stratification: settling and heating

in phase space

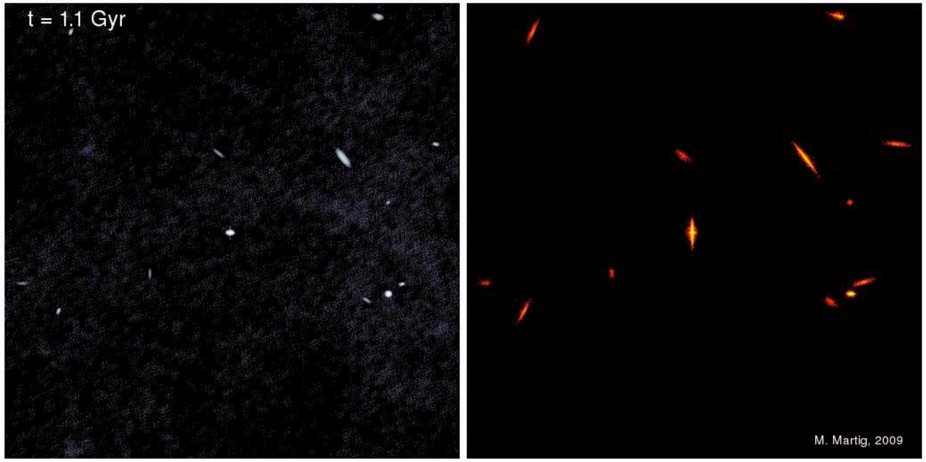
Mono-age stellar populations



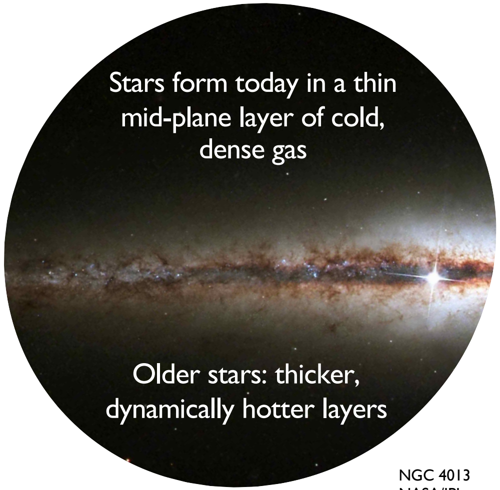

Martig+2014a,b

Dense gas

Collisionless stars




Gas dissipates; stars do not

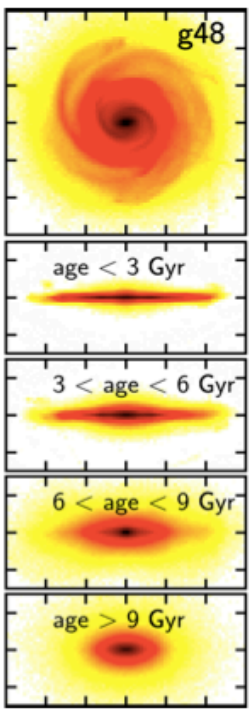



NGC 4013
NASA/JPL

# Disk Stratification

in phase space

Mono-age stellar populations




Martig+2014a,b

Bird+2013,2020:

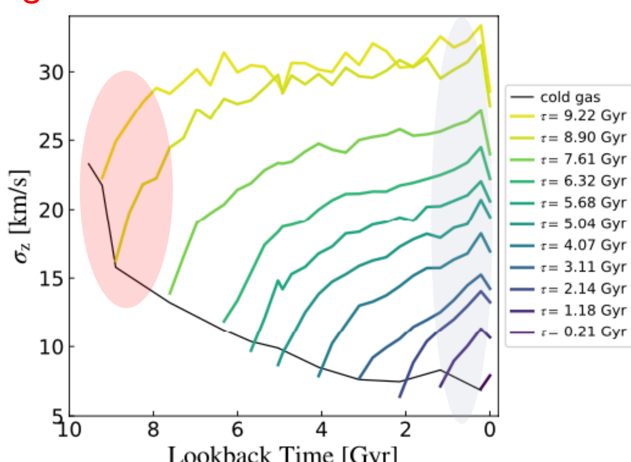
- ○ **Cooling gas**
- ○ **Heating stars**

Many ideas going back to Spitzer & Schwazrchild (1953)

- satellites
- Halo BH
- spiral arms, bars
- GMC, GC

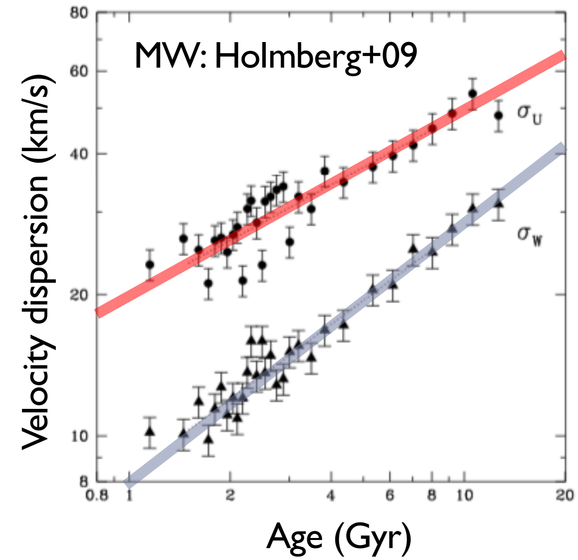
β

High redshift




Today

Age-velocity relation




$\sigma_r$

$\sigma_z$

$$\sigma(t) = \sigma_0 (1 + t/\tau_{\rm strat})^{\beta}$$

Milky Way: $\beta_r < \beta_z$

$0.2 < \beta < 0.6$

# Disk Stratification:

## Chemodynamics

**Age-velocity-metallicity relation: *discovered***

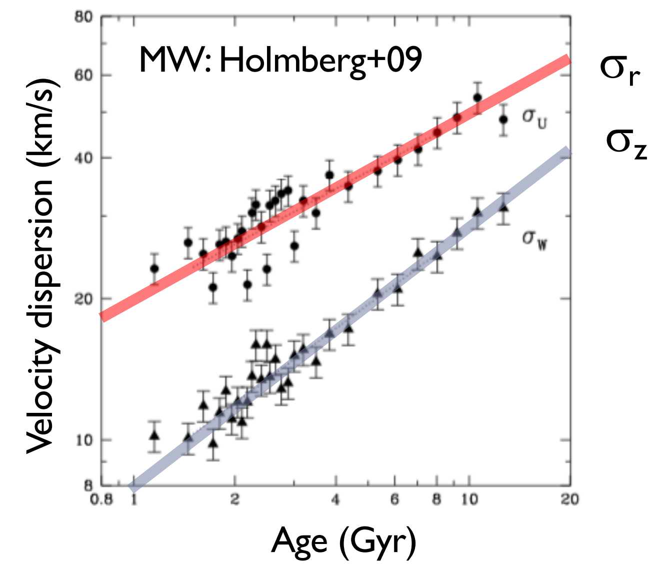
A CORRELATION BETWEEN THE SPECTROSCOPIC AND DYNAMICAL CHARACTERISTICS OF THE LATE F- AND EARLY G-TYPE STARS

NANCY G. ROMAN
Yerkes Observatory

1950ApJ...112..554R
*Received July 22, 1950*

Among the giants and dwarfs in the spectral range F5-G5, some stars have systematically weaker lines than others of the same spectral type and luminosity class…The velocities of the stars with weaker lines have larger dispersion than those with strong lines…

Age-velocity relation




$$\sigma(t) = \sigma_0(1 + t/\tau_{\rm strat})^\beta$$

Milky Way: $\beta_r < \beta_z$

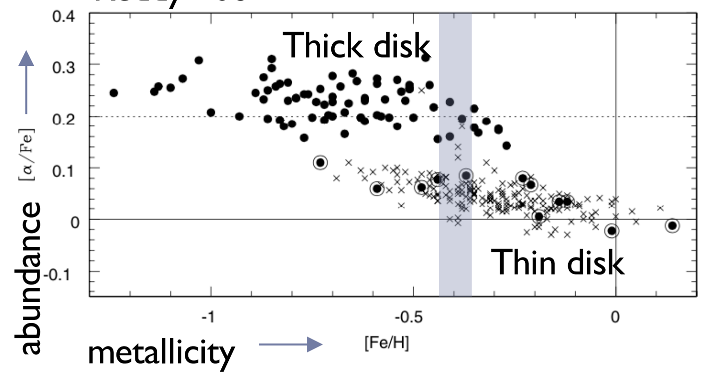
$0.2 < \beta < 0.6$

# Disk Stratification:
## Chemodynamics

Two *discrete* distributions in phase space *and* abundance

See also: Fuhrmann'98, Prochaska+'00, Feltzing+'03, Mishenina+'04, Bensby+'05.

Reddy+'06




**Age-velocity-metallicity relation: *understood***

CHEMISTRY AND KINEMATICS IN THE SOLAR NEIGHBORHOOD: IMPLICATIONS FOR STELLAR POPULATIONS AND FOR GALAXY EVOLUTION


ROSEMARY F. G. WYSE



1995, AJ, 110, 6

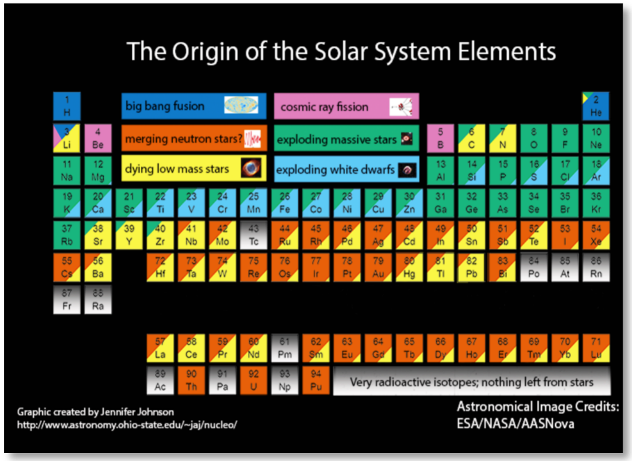


Department of Physics and Astronomy,[1] The Johns Hopkins University, Baltimore, Maryland 21218; Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England, United Kingdom, and Center for Particle Astrophysics, University of California, Berkeley, California 94720

GERARD GILMORE

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England, United Kingdom


The metallicity distribution of complete samples of long-lived stars has long been recognized as providing unique constraints on the early stages of chemical evolution of the Galaxy… Kinematic data for these same stars, as well as for a high-precision sample studied by Edvardsson et al. (A&A, 275, 101, 1993), provide <u>clear evidence that the abundance distribution below [Fe/H]~-0.4 contains *two* over-lapping distributions, the thick disk and the thin disk</u>… When combined with age and element ratio data, comprehensive constraints on the evolution of the disk will be available.

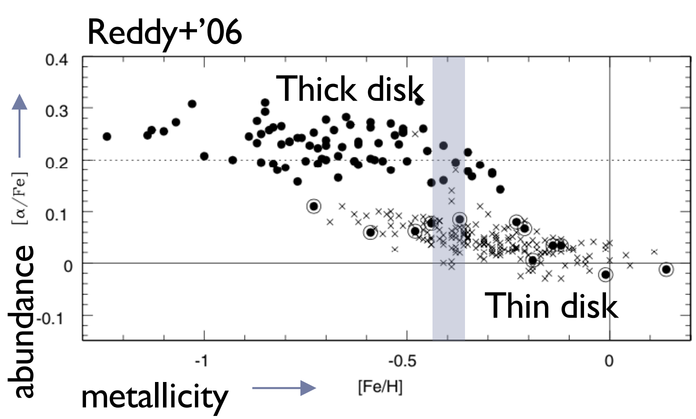


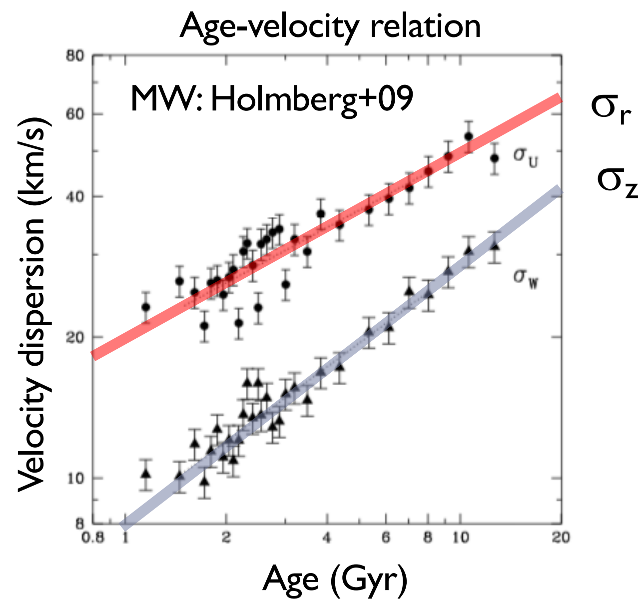

Weingberg+20,21, Griffith+20

# Disk Stratification

in phase space

Is stratification smooth, discrete, or both?
Stratification in other galaxies?
What do trends, e.g., with mass, tell us of origins?
    cooling gas *or*
    dynamical heating (what sources?)




$$\sigma(t) = \sigma_0(1 + t/\tau_{\rm strat})^{\beta}$$

Milky Way: $\beta_r < \beta_z$

$0.2 < \beta < 0.6$

# High redshift

- Prolate galaxies as precursors to disks
  - Another kind of disk "settling"
  - Based on inference from statistical distributions of b/a and a in deep HST and JWST images

- Early formation stages of bulges and massive spheroids
  - Wet compaction
  - Blue nuggets
  - Red nuggets

Zhang et al. 2022

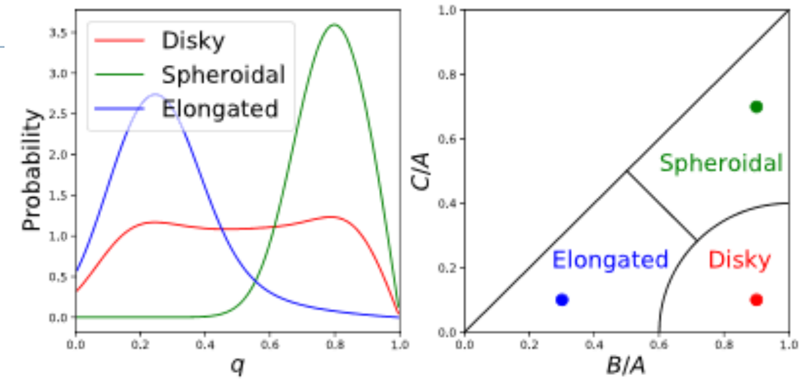



**Figure 2.** Left-hand panel: Examples of the projected axial ratio distribution of a discy (red), spheroidal (green), and elongated (blue) galaxy as seen from random viewing angles. Right-hand panel: Corresponding positions of the three case examples in intrinsic shape space, where *C/A* denotes the ratio of intrinsic minor- to major-axis length, and *B/A* the ratio of intermediate- to major-axis length. Where fractions of discy, spheroidal or elongated shapes are quoted, these are defined by the regions outlined in black.

Lapiner et al. 2023

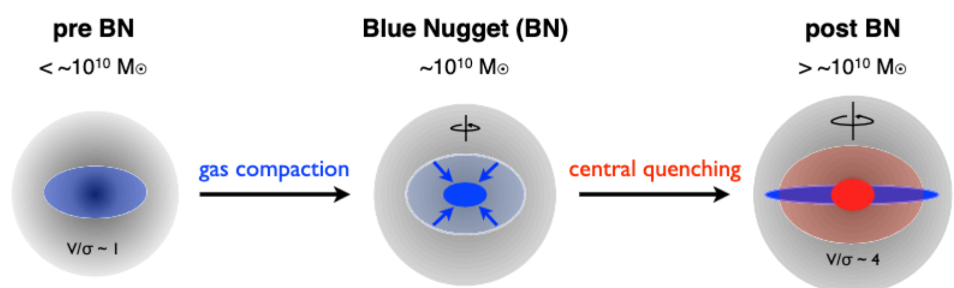



**Figure 1.** A cartoon illustrating the phases with respect to the BN at $M_s \sim 10^{10}\,M_\odot$. The pre-BN system is elongated, diffuse and perturbed, only marginally supported by rotation and with a DM-dominated core. Gas compaction leads to a compact star-forming BN, which is baryon dominated. Post-BN, the gas is depleted from the centre leaving behind a compact passive nugget, while a new extended rotation-supported gas disc/ring and/or a stellar envelope develop.