What do we need to know about galaxy formation?

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Hubble Science Legacy Workshop
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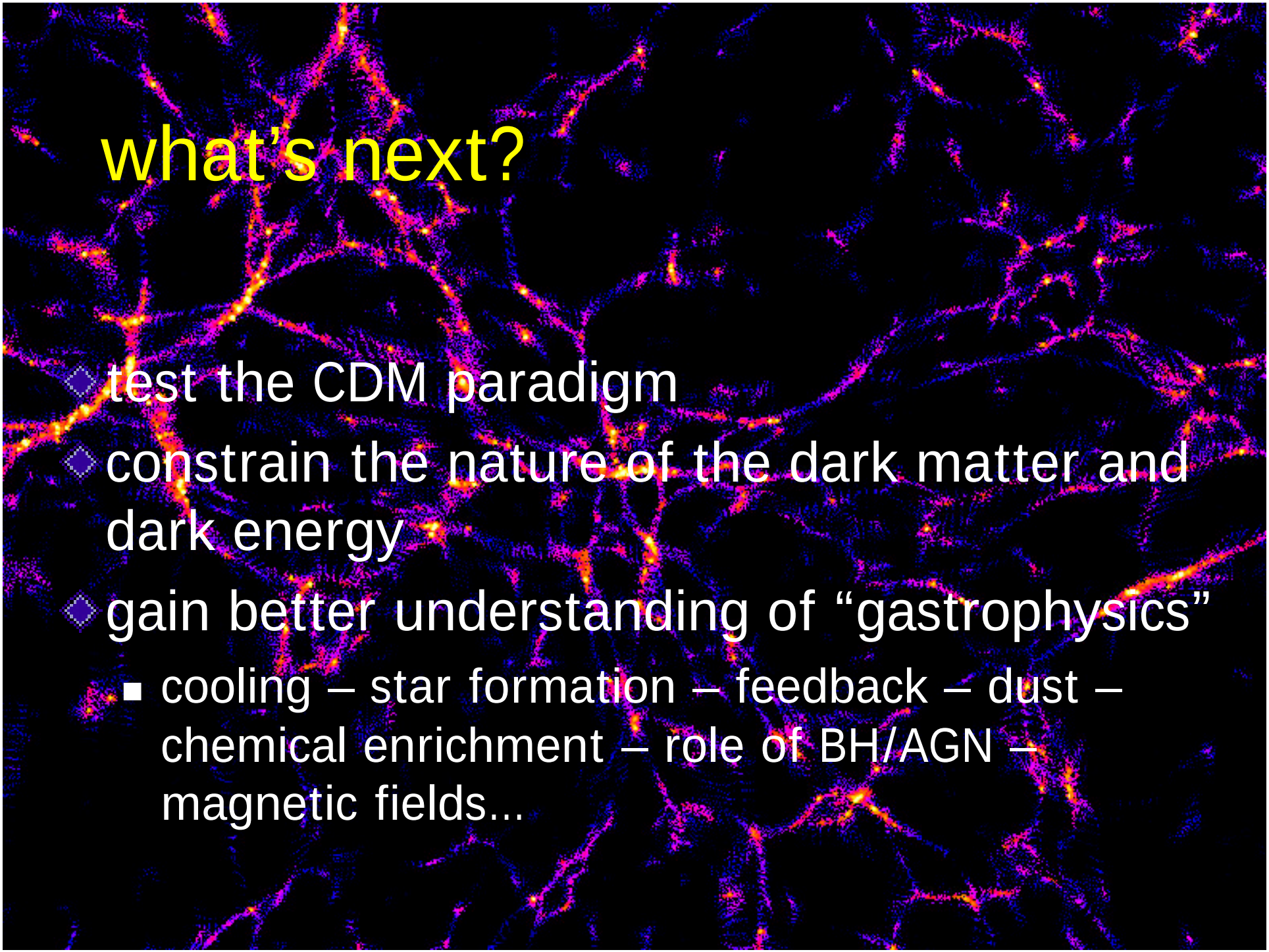
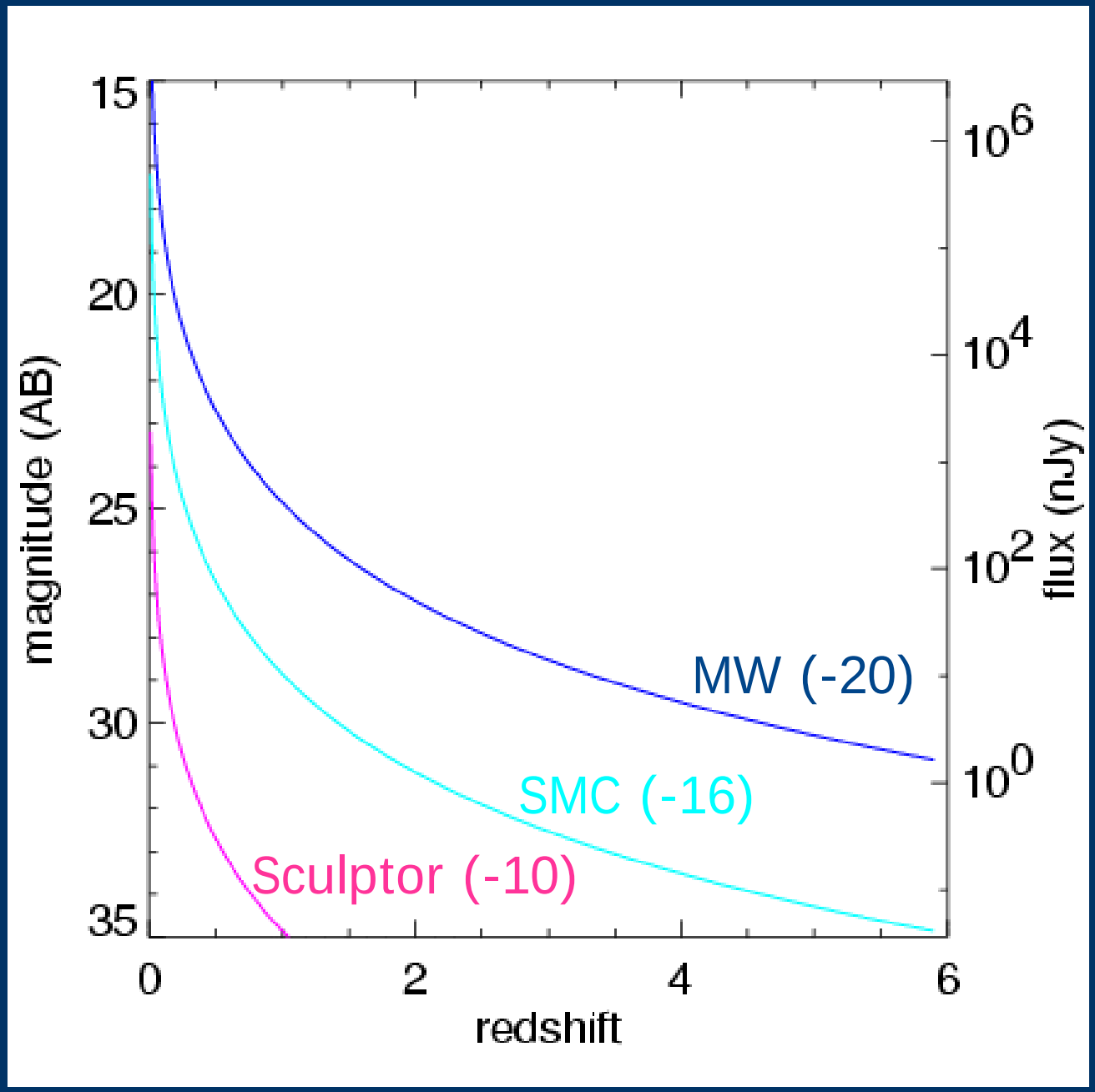
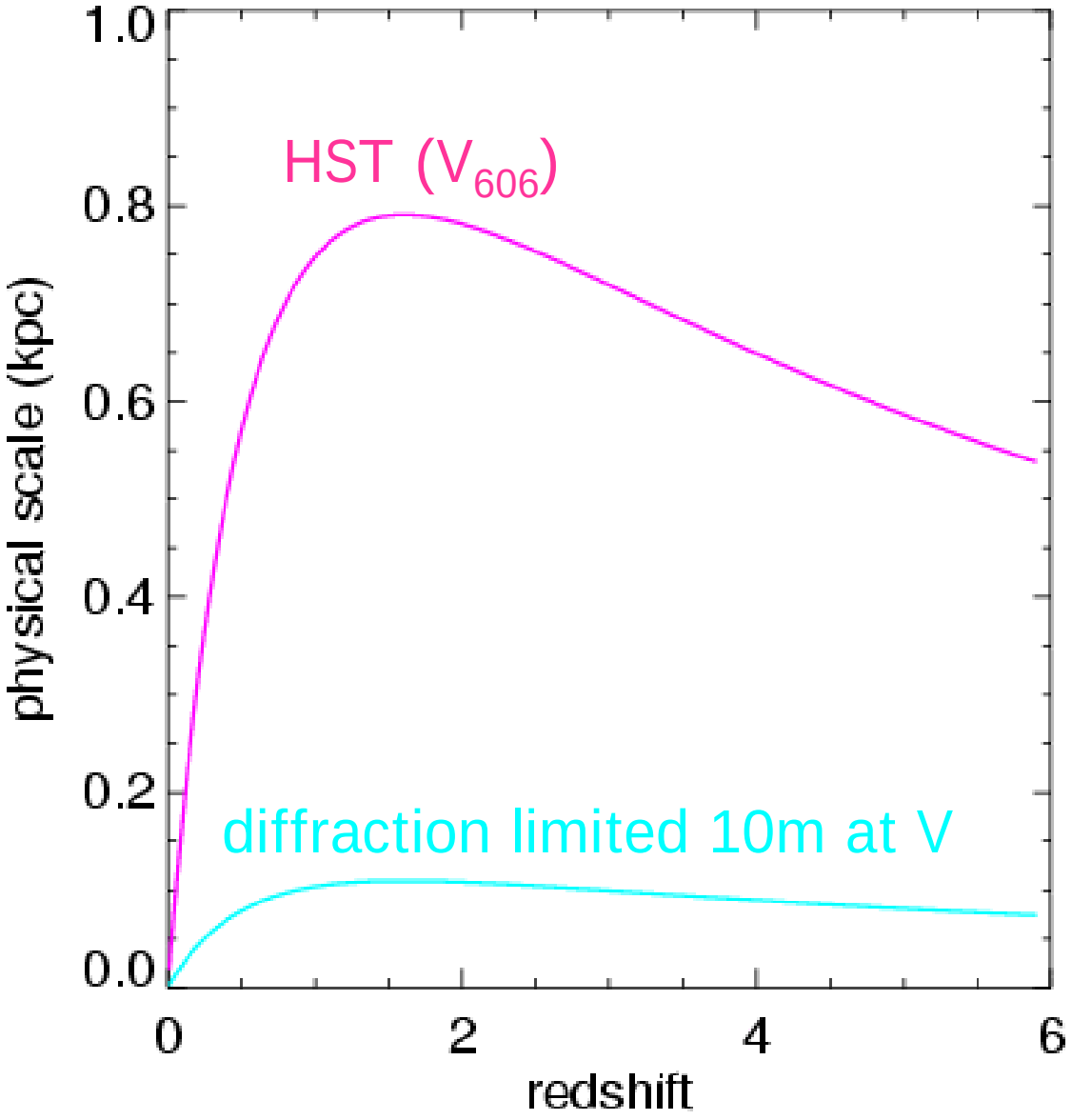


what's next?

- test the CDM paradigm
- constrain the nature of the dark matter and dark energy
- gain better understanding of "gastrophysics"
  - cooling – star formation – feedback – dust – chemical enrichment – role of BH/AGN – magnetic fields...


15
20
25
30
35
magnitude (AB)
0
2
4
6
redshift
10^6
10^4
10^2
10^0
flux (nJy)
MW (-20)
SMC (-16)
Sculptor (-10)


1.0
0.8
0.6
0.4
0.2
0.0
physical scale (kpc)
HST (V606)
diffraction limited 10m at V
0
2
4
6
redshift

galaxy observations with NHST

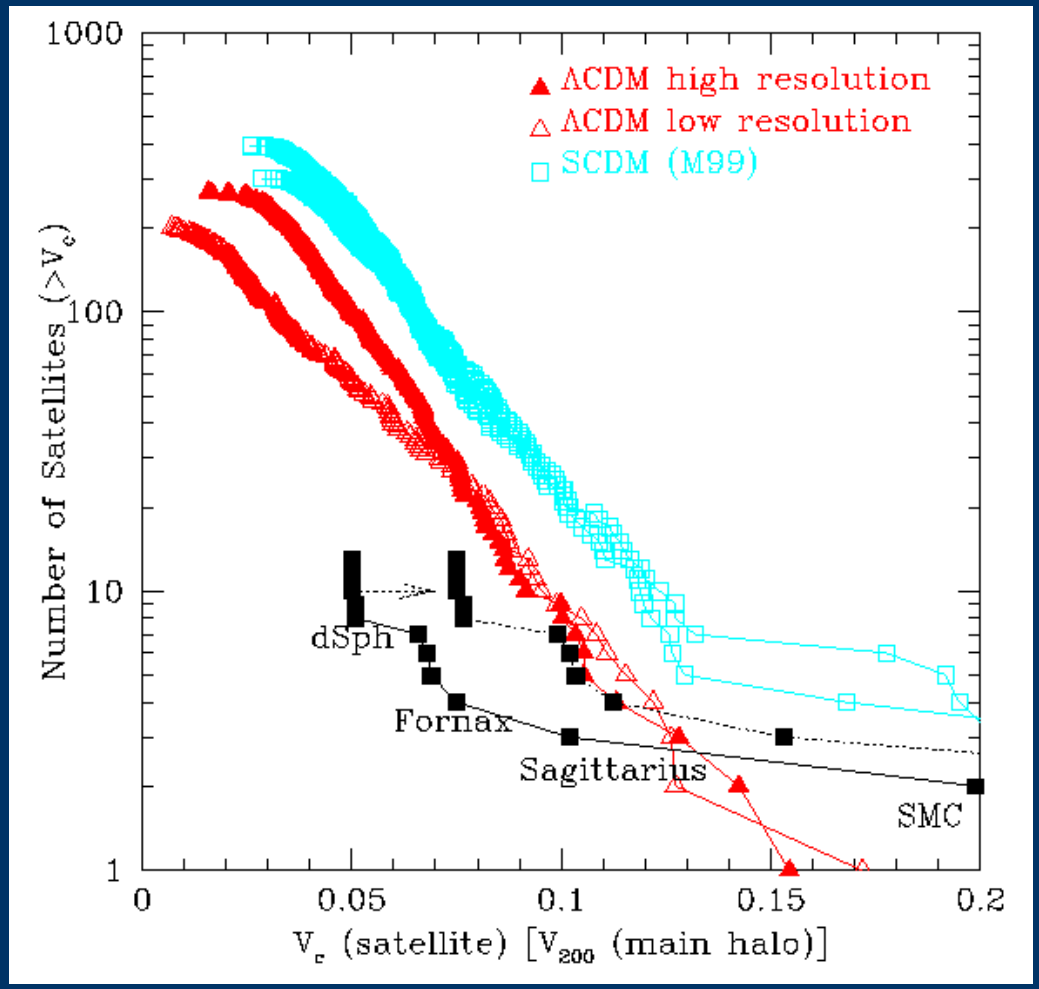
- kinematics and stellar populations of dwarf galaxies ($z<1$)
- high resolution (sub-kpc) imaging and kinematics of more luminous intermediate to high redshift galaxies ($1<z<5$)

trouble for CDM?
problems on small scales

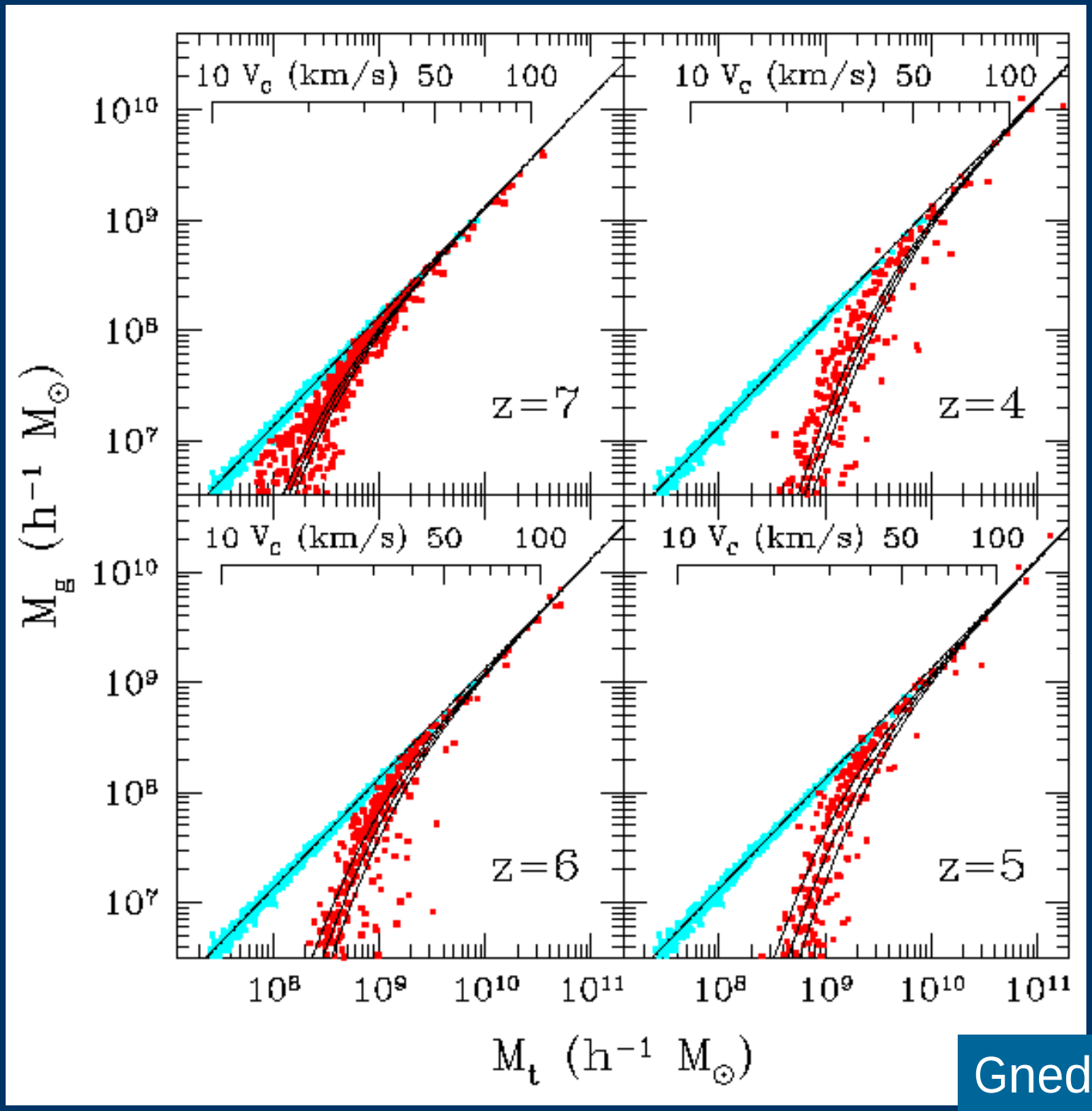
- too much substructure on dwarf galaxy scales?
- dark matter halos too “cuspy” in center?
- angular momentum distribution J(r) incompatible with exponential disks?

the substructure "crisis"

Moore et al. 1999
Klypin et al. 1999



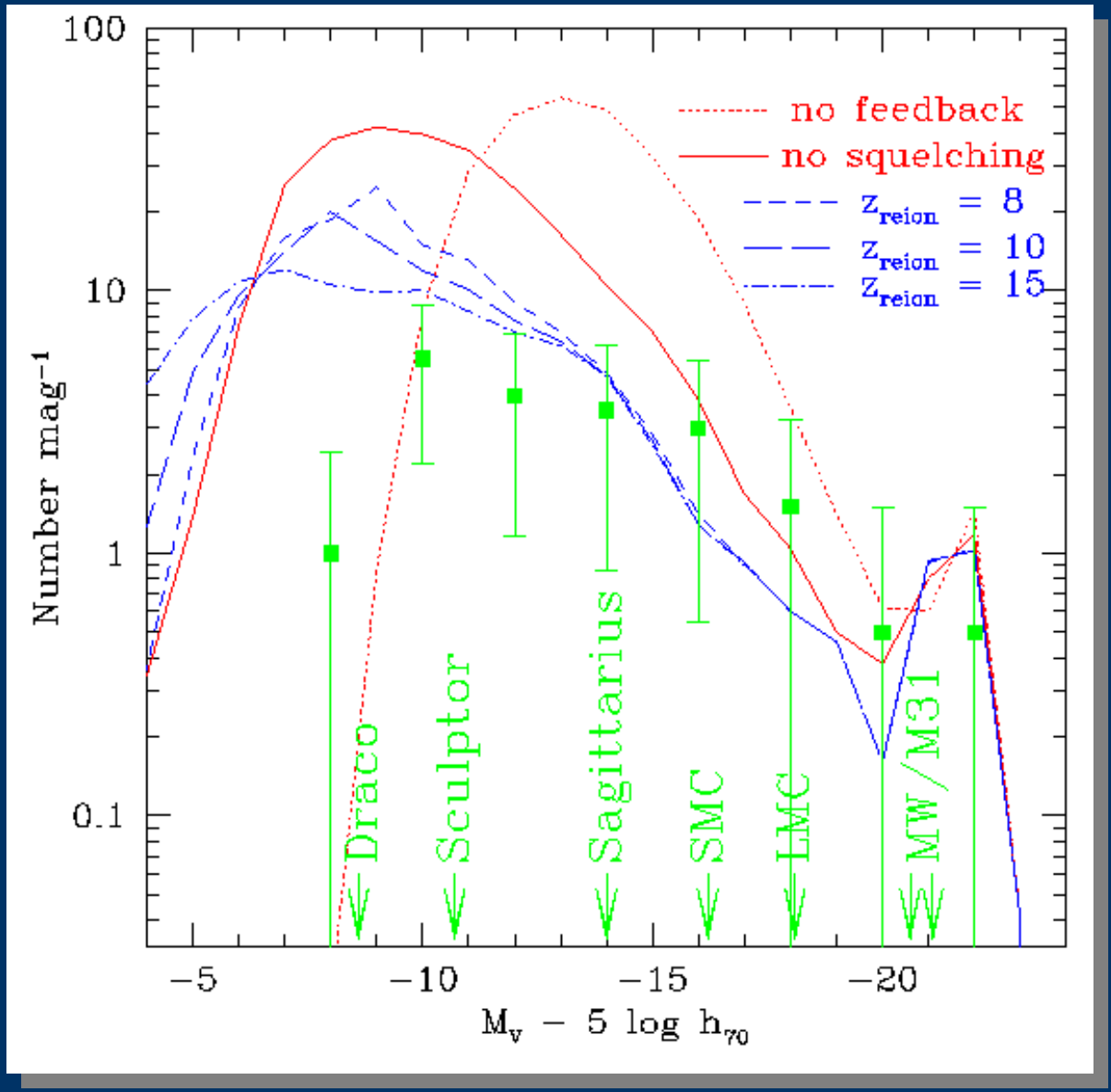
Font et al. 2001


10 V$_c$ (km/s) 50 100
z=7
z=4
z=6
z=5
10^{10}
10^{9}
10^{8}
10^{7}
10^{8} 10^{9} 10^{10} 10^{11}
M$_g$ (h^{-1} M$_\odot$)
M$_t$ (h^{-1} M$_\odot$)

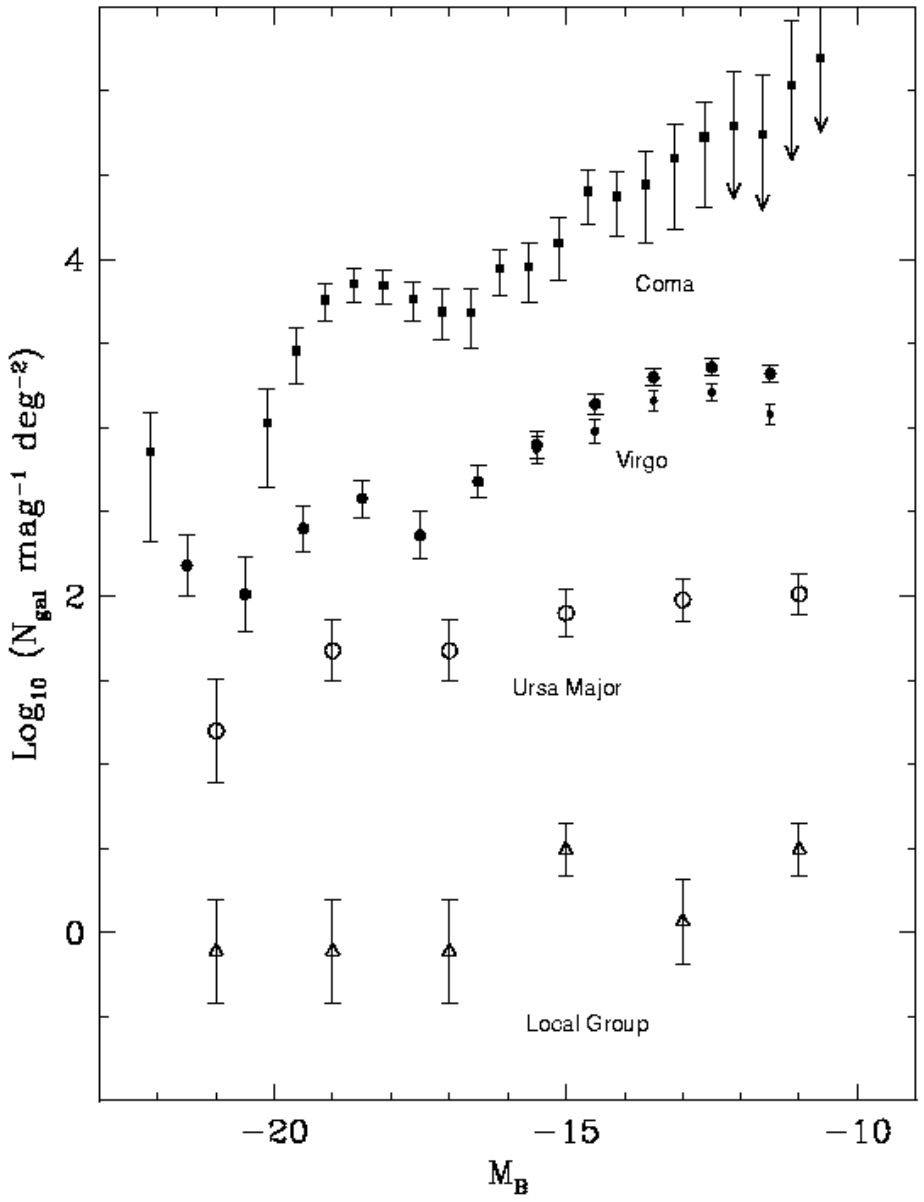
Gnedin 2000

resolved by photoionization?

see also Bullock, Kravtsov & Weinberg 2000; Benson et al. 2002



rss 2002

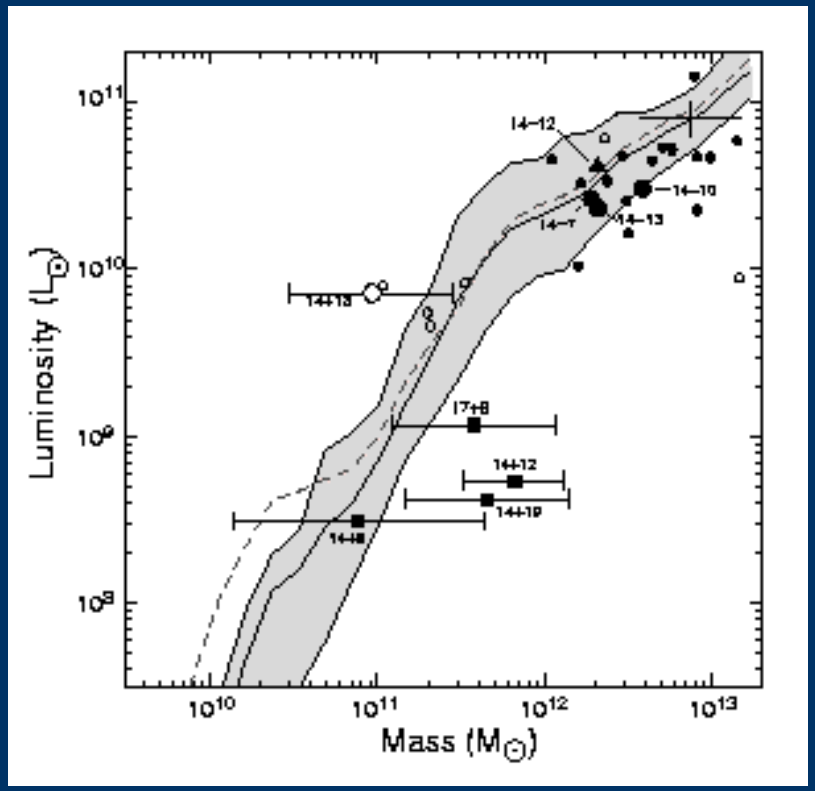


The faint-end slope of the luminosity function:
is there an environmental dependence?

CDM prediction:
in dense environments,
more dwarf halos collapse
before re-ionization
→dwarf-to-giant ratio
larger in over-dense regions

Tully, rss, Trentham & Verheijen 2002

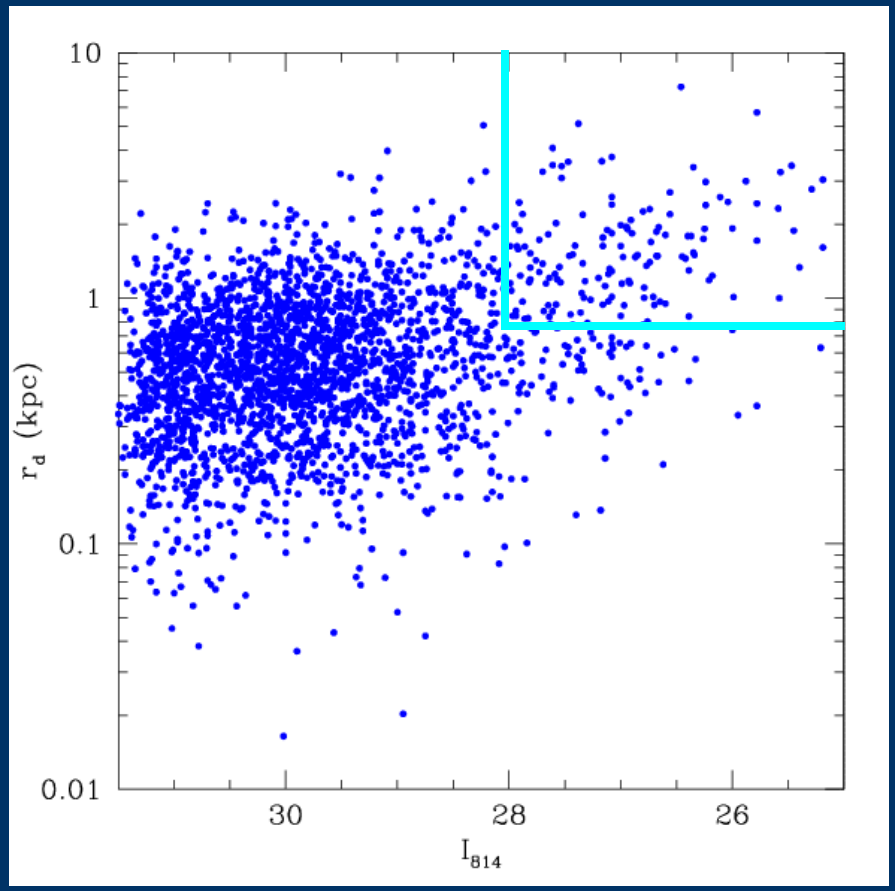
search for barren dark halos

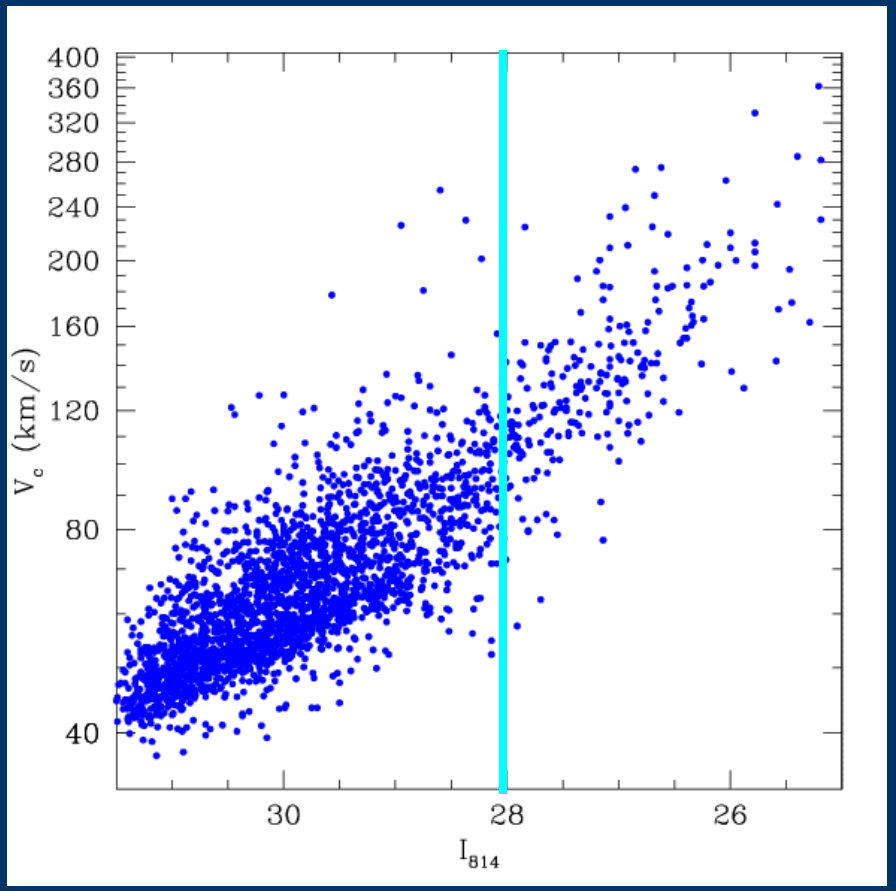


- dwarf groups with very high mass-to-light ratios (Tully, rss, Trentham & Verheijen 2002)
- direct detection via lensing (Metcalf & Madau 2001)?

what do we expect to see at z=3?

predictions from semi-analytic models

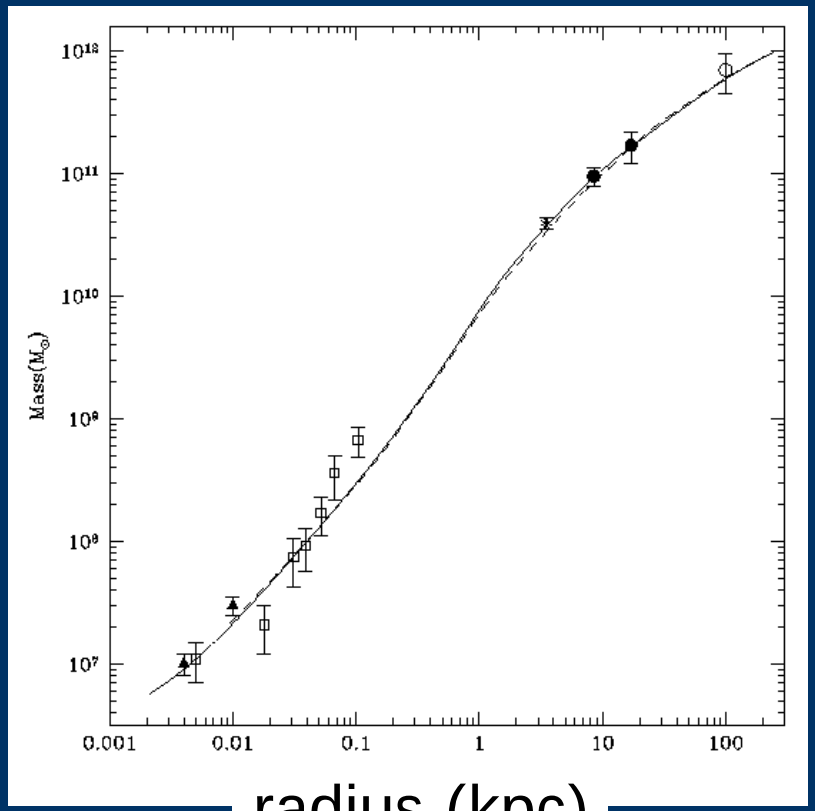




cusps and angular momentum

- are CDM halo mass profiles consistent with galaxy kinematics?
  - need complete samples to understand statistics
  - need to understand how baryons modify profiles
- is the angular momentum profile of halos predicted by CDM consistent with the structure of galactic disks and spheroids?
  - segregation: $J_{DM} \rightarrow J_{bar}$ (magnitude and direction)
  - transfer
    - bars/spiral arms, viscosity
    - feedback (SN/AGN)?

galaxy mass profiles



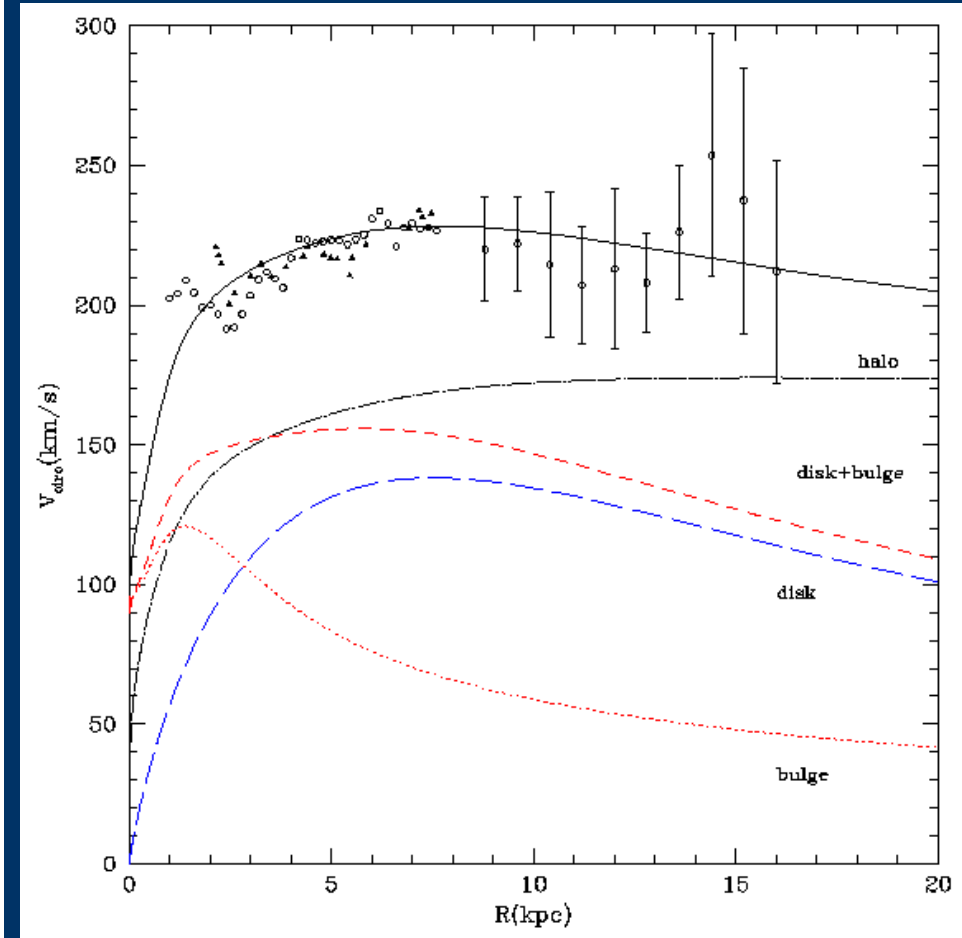
- high resolution kinematics from sub-kpc to 100 kpc scales can constrain properties of DM halos + modification by baryons

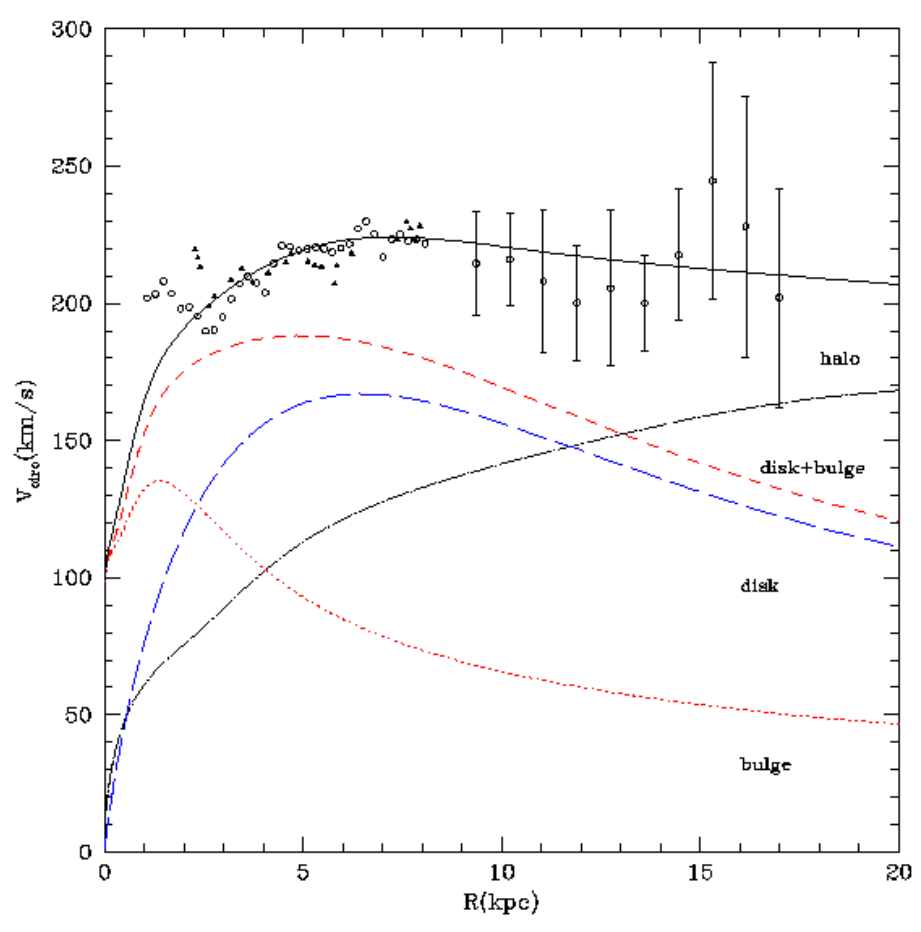
stellar/gas kinematics

satellites & lensing

Angular momentum conserved

Angular momentum transferred

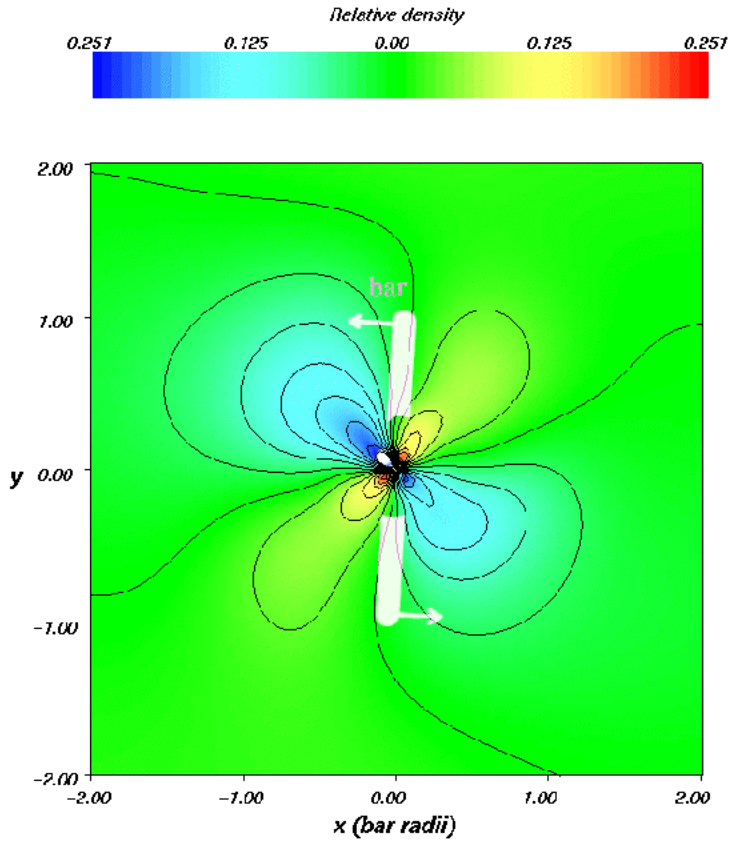


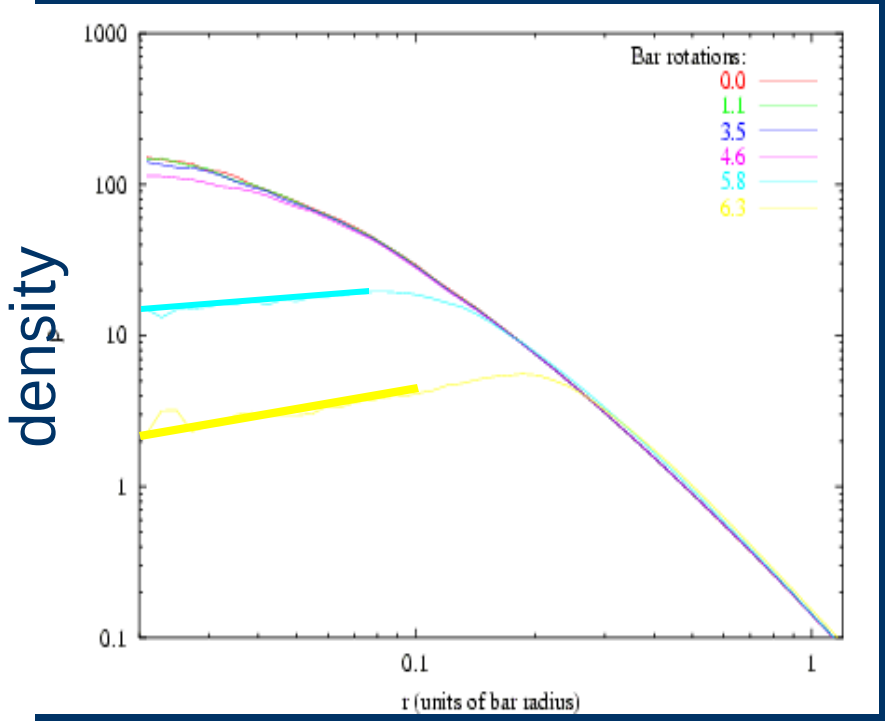


ΛCDM models for the Milky Way

Klypin, Zhao & rss 2002

cusps destroyed by primordial rotating bars?





radius (units of bar radius)

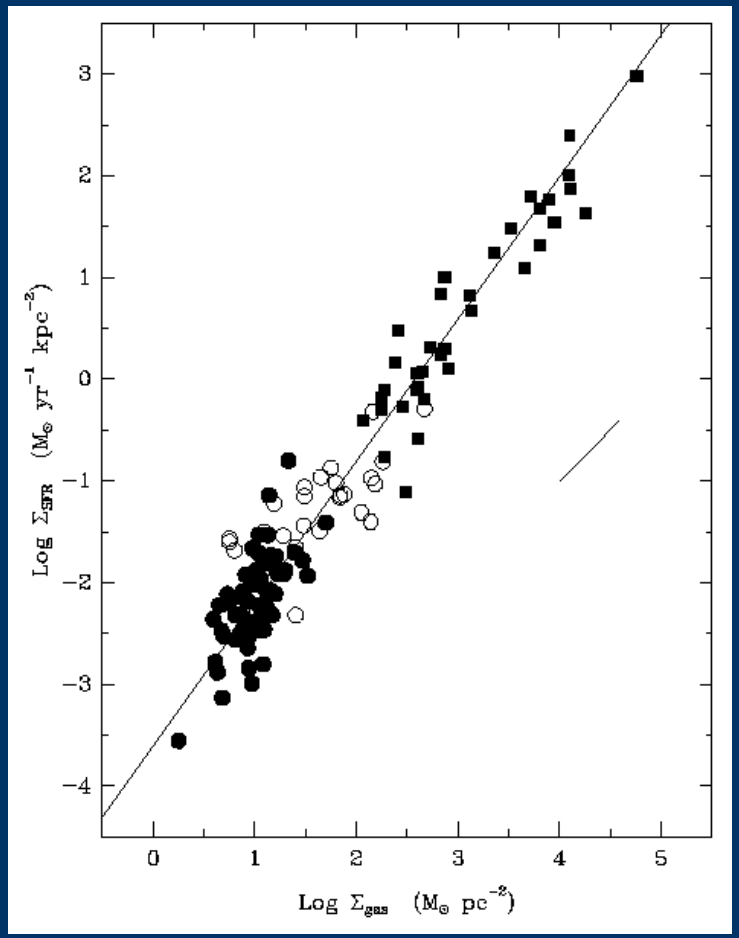
Weinberg & Katz, preprint

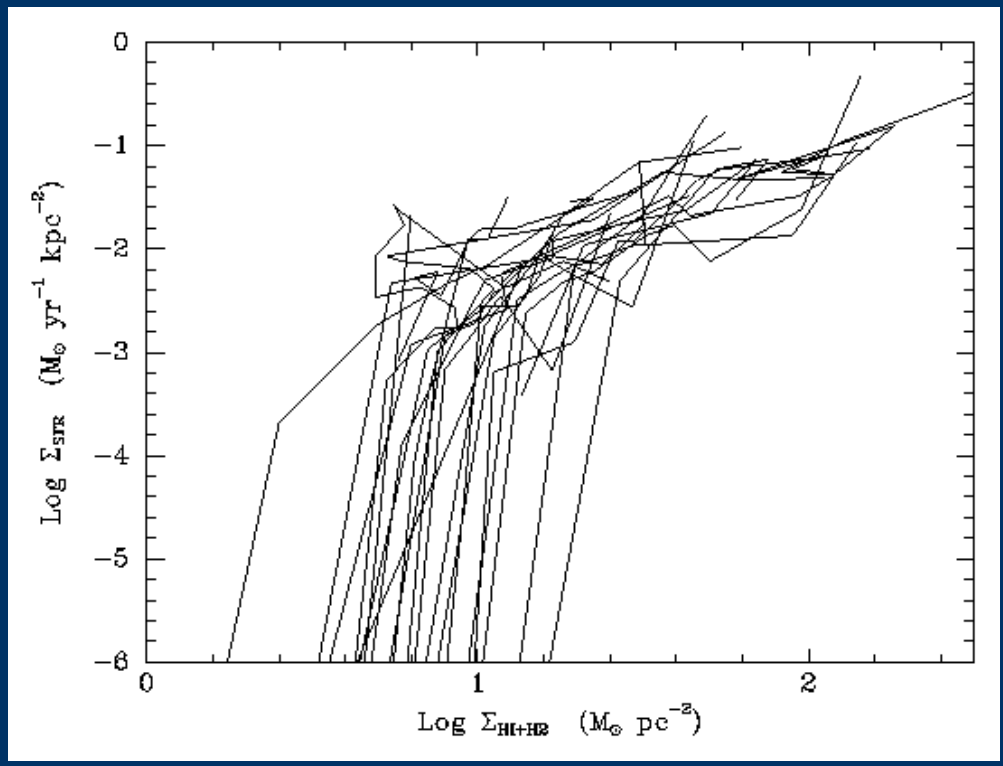
star formation

- what determines how efficiently a galaxy can turn cold gas into stars?
- how does this efficiency scale with redshift/galaxy properties?
- what is the physical basis of empirical scaling laws (e.g. Kennicutt)
- is the IMF universal in space and time? why does it have the observed shape?

star formation in galaxies

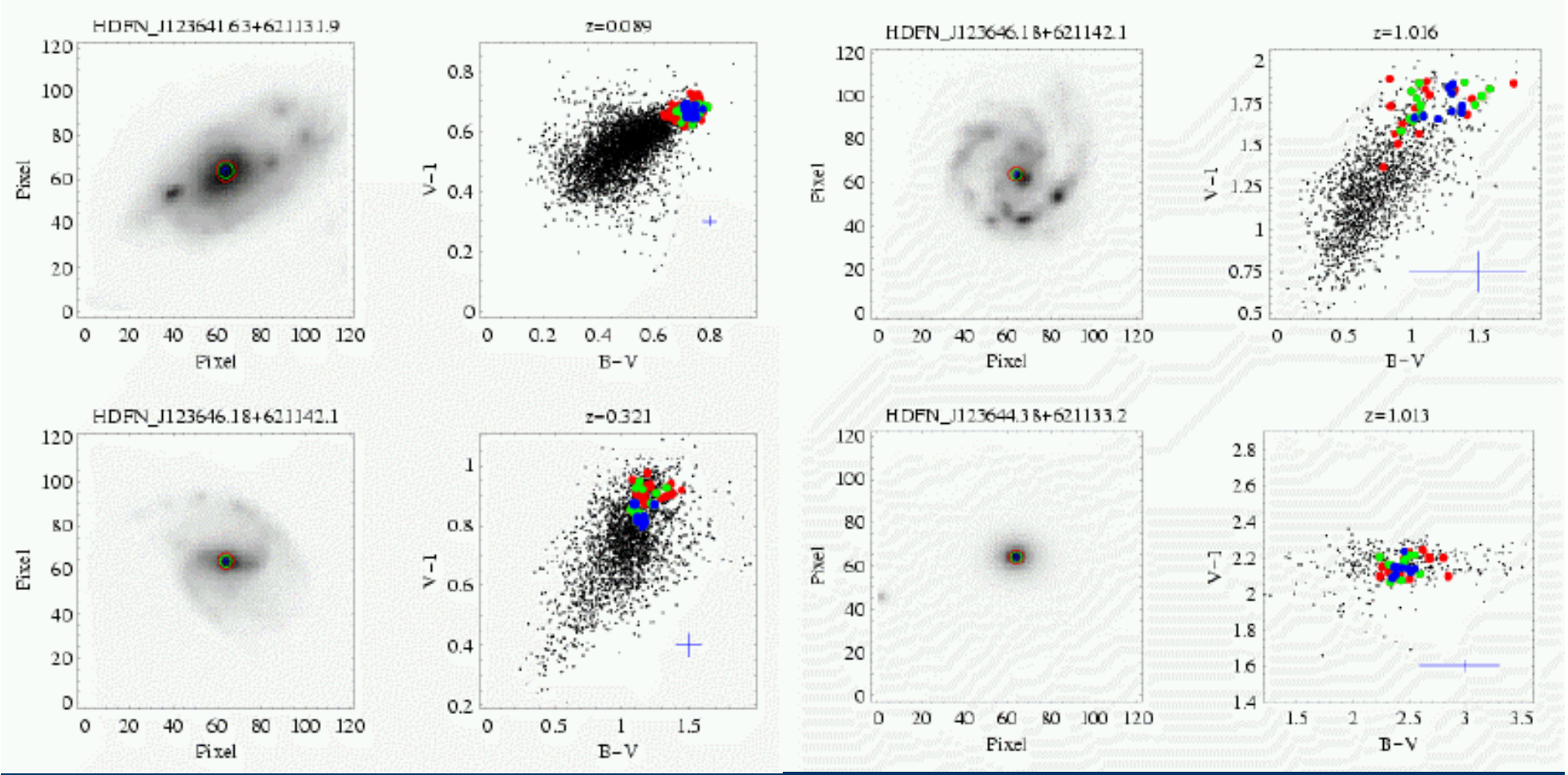
study Kennicutt-type relations at z>2 with ALMA + new Hubble?





Kennicutt 1998

spatially resolved star formation histories from fossil evidence



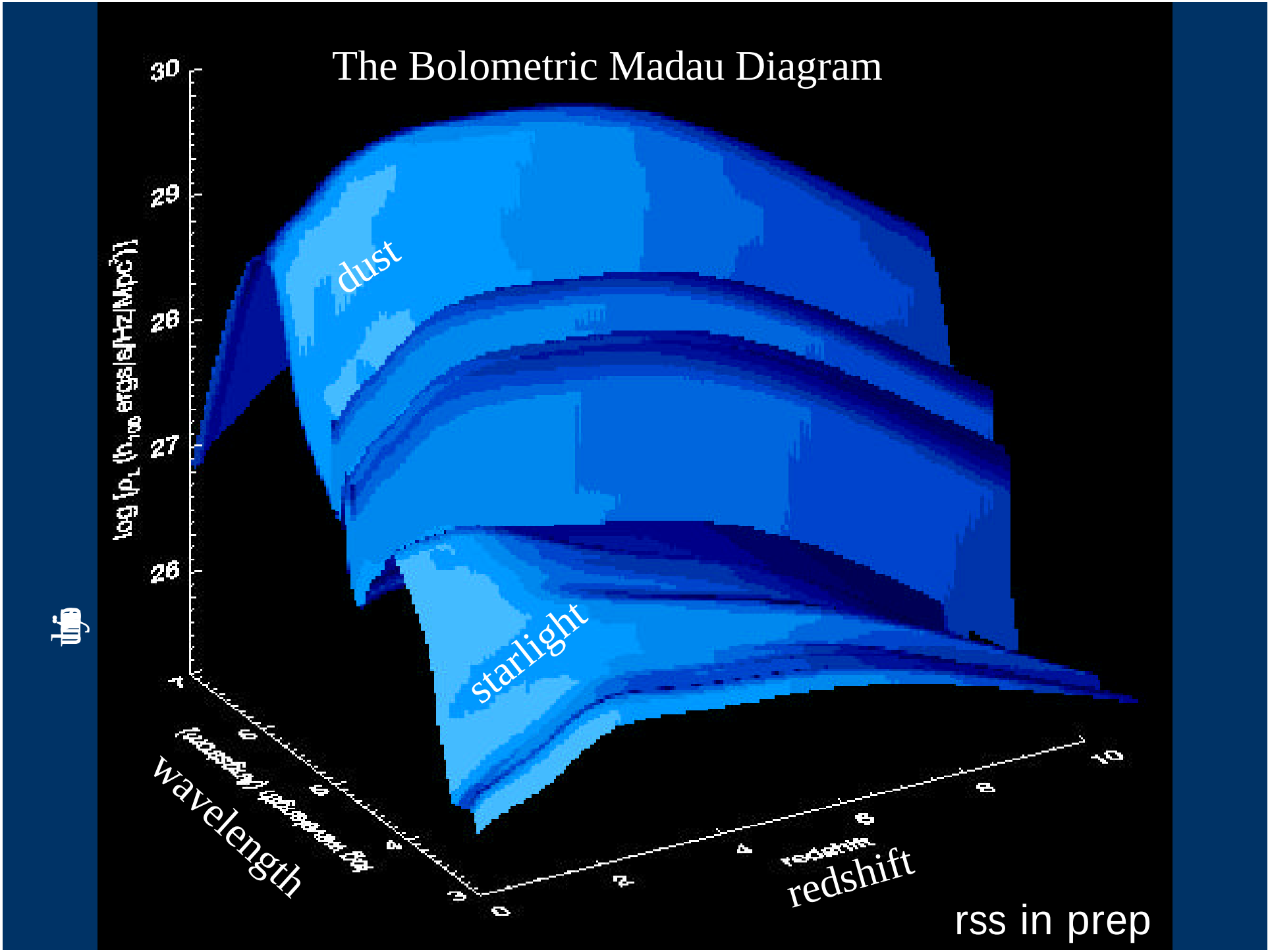
Ellis et al. 2001

feedback

- what does the energy from massive stars and SN do to the ISM/IGM/ICM? how does this impact future generations of stars?
  - positive/negative?
  - thermal/kinetic/pressure?
  - turbulence/outflows?
- what about AGN?

heavy elements and dust

- how efficiently are metals expelled from DM halos?
  - efficient early enrichment of IGM
  - thermal signatures
- what determines the degree of optical/UV extinction a galaxy experiences?
  - mass of dust?
  - dust geometry, density, composition?
  - age of stellar population?


The Bolometric Madau Diagram
dust
starlight
wavelength
redshift
rss in prep

what determines galaxy “type”?

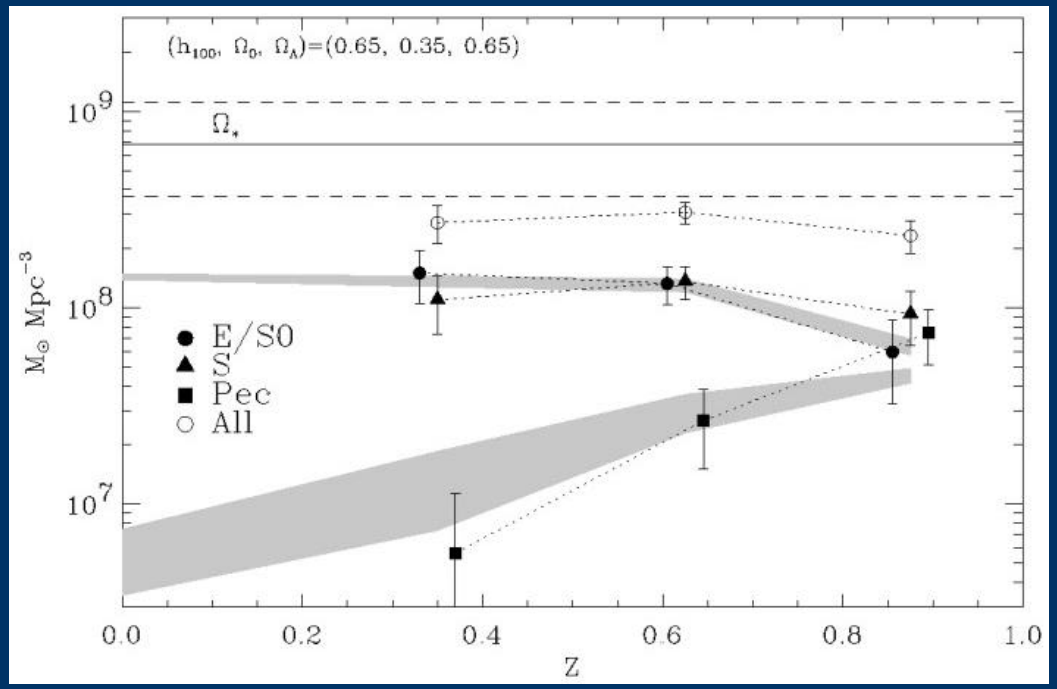
- which of the many observational “sequences” are truly fundamental?
  - B/T, V/σ, color, spectral type...
- when was the Hubble sequence as we know it established?
  - role of mergers
  - spheroid formation

scaling relations

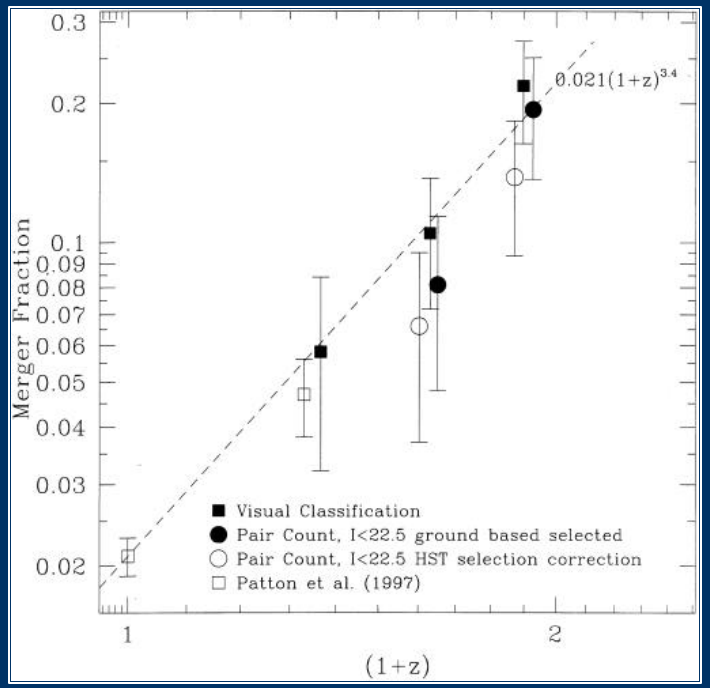
- what is the physical origin of scaling relations like the Tully-Fisher relation and the fundamental plane?
- why do they have so little scatter?

the merger rate as a function of epoch

a direct test of the hierarchical assembly of galaxies



Brinchmann & Ellis 2000

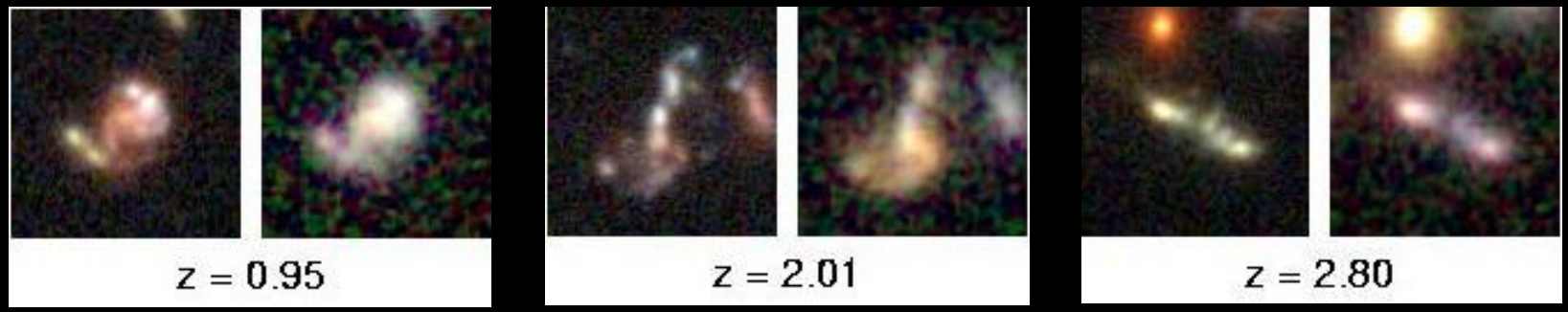


Le Fevre et al. 2000

Galaxy Cluster MS1054-03 **HST** • WFPC2

PRC99-28 • STScI OPO • P. van Dokkum (University of Groningen), ESA and NASA

measure the
merger rate
as function of
environment,
redshift
galaxy type,
mass, luminosity
to z=5



Ferguson et al. 2001

Wish list: super-Sloan

- high resolution kinematics and multiband imaging for complete sample of galaxies, reaching well below L_* (z=0-5)
- multiphase information: neutral, ionized, and molecular gas
- metallicity indicators
- dust content (FIR/UV)
- coordinate with IGM and lensing data