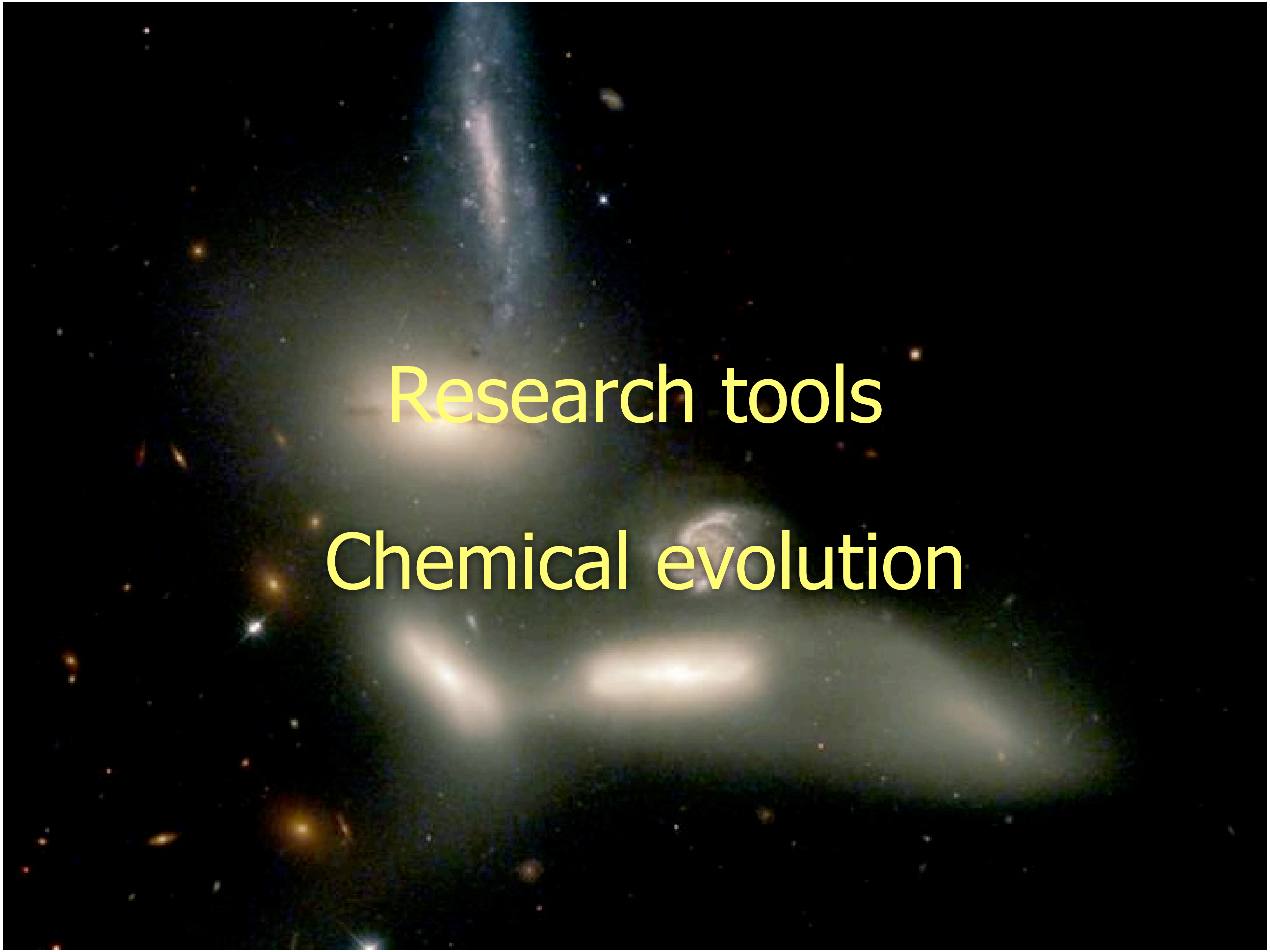

Research tools
Chemical evolution

# Principles: formation

- Heavy elements made in nucleosynthesis
  - Most He made in Big Bang, otherwise all made as part of stellar evolution
  - Nucleosynthesis in stars
  - R-process
  - S-process

- Pagel (1997) an excellent introduction…

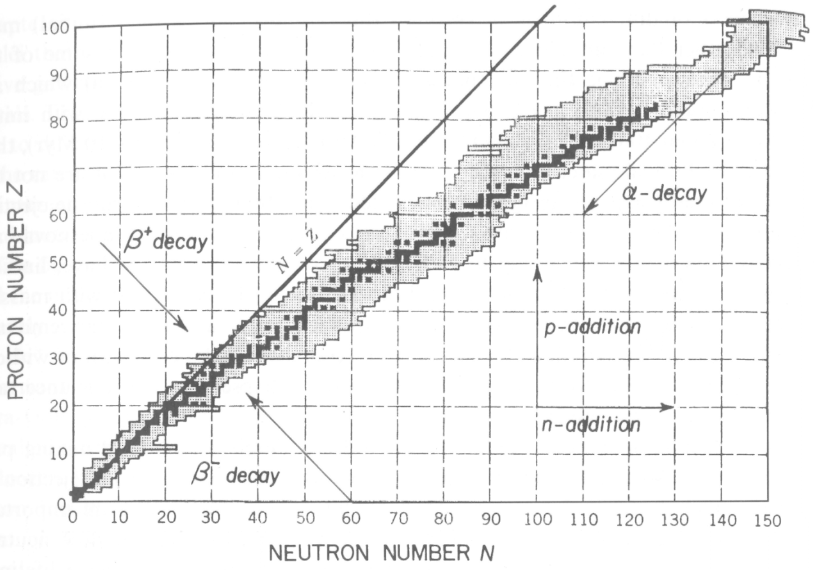



**Fig. 1.2.** Chart of the nuclides, in which $Z$ is plotted against $N$. Stable nuclei are shown in dark shading and known radioactive nuclei in light shading. Arrows indicate directions of some simple nuclear transformations. After K.S. Krane, *Introductory Nuclear Physics*, ©1988 by John Wiley & Sons. Reproduced by permission of John Wiley & Sons, Inc.

nucleus outside the valley undergoes spontaneous decays, while in accelerators, stars and the early universe nuclei are transformed into one another by various reactions.

(2) The binding energy per nucleon varies with $A$ along the stability valley as shown in Fig. 1.3, and this has the following consequences:

(a) Since the maximum binding energy per nucleon is possessed by $^{62}$Ni, followed closely by $^{56}$Fe, energy is released by either fission of heavier or fusion of lighter nuclei. The latter process is the main source of stellar energy, with the biggest contribution (7 MeV per nucleon) coming from the conversion of hydrogen into helium (H-burning).

(b) Some nuclei are more stable than others, e.g. the $\alpha$-particle nuclei $^4$He, $^{12}$C, $^{16}$O, $^{20}$Ne, $^{24}$Mg, $^{28}$Si, $^{32}$S, $^{36}$Ar, $^{40}$Ca. Nuclei with a couple of $A$-values (5 and 8) are violently unstable, owing to the nearby helium peak. Others are stable but only just: examples are D, $^{6,7}$Li, $^9$Be and $^{10,11}$B, which are destroyed by thermonuclear reactions at relatively low temperatures.

(3) Nuclear reactions involving charged particles ($p$, $\alpha$ etc.) require them to have enough kinetic energy to get through in spite of the electrostatic repulsion of the



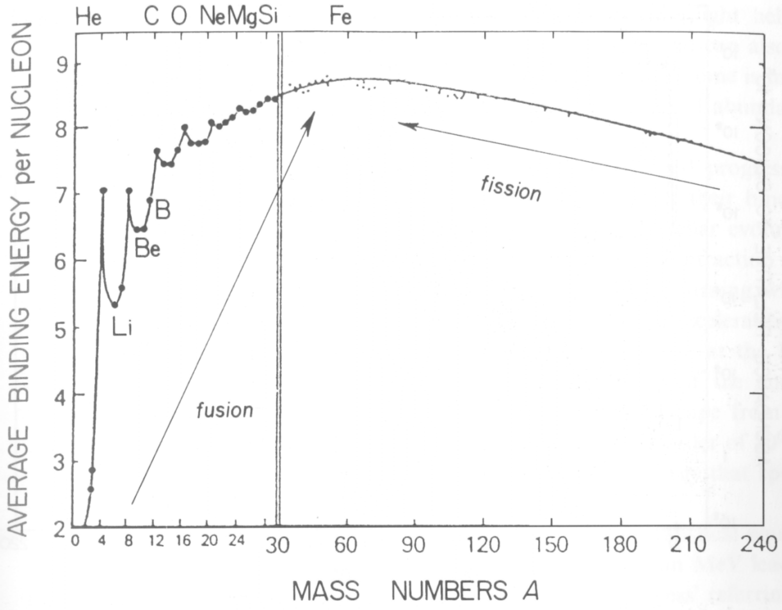



**Fig. 1.3.** Binding energy per nucleon as a function of mass number. Adapted from Rolfs & Rodney (1988).

target nucleus (the 'Coulomb barrier'); the greater the charges, the greater the energy required. In the laboratory, the energy is supplied by accelerators, and analogous processes are believed to occur in reactions induced in the ISM by cosmic rays (see Chapter 9). In the interiors of stars, the kinetic energy exists by virtue of high temperatures (leading to *thermonuclear* reactions) and when one fuel (e.g. hydrogen) runs out, the star contracts and becomes hotter, eventually allowing a more highly charged fuel such as helium to 'burn'.

There is no Coulomb barrier for neutrons, but free neutrons are unstable so that they have to be generated *in situ*, which again demands high temperatures.

## 1.3 The local abundance distribution

Fig. 1.4 shows the 'local galactic' abundances of isobars, based on a combination of elemental and isotopic determinations in the Solar System with data from nearby stars and emission nebulae. These are sometimes referred to as 'cosmic abundances', but because there are significant variations among stars and between and across galaxies this term is best avoided. The curve shows a number of features that give clues to the origin of the various elements:

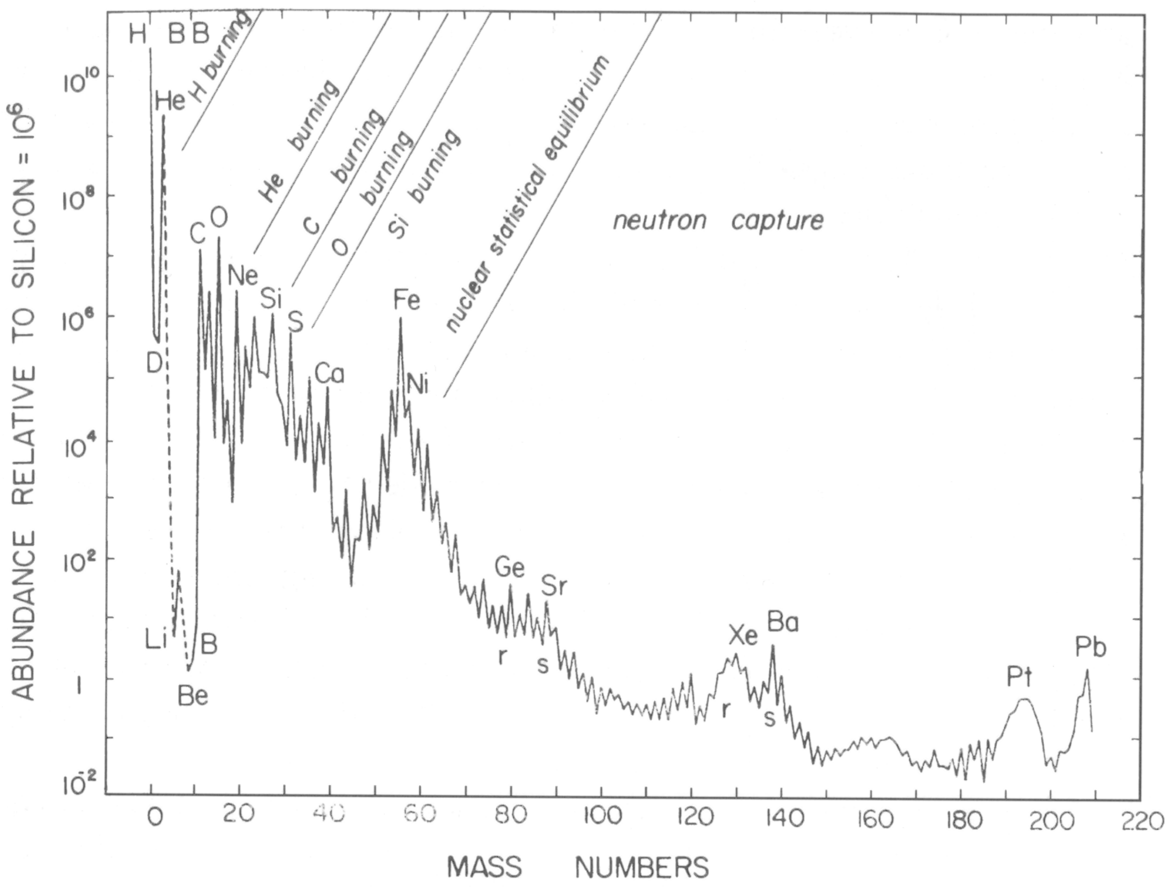
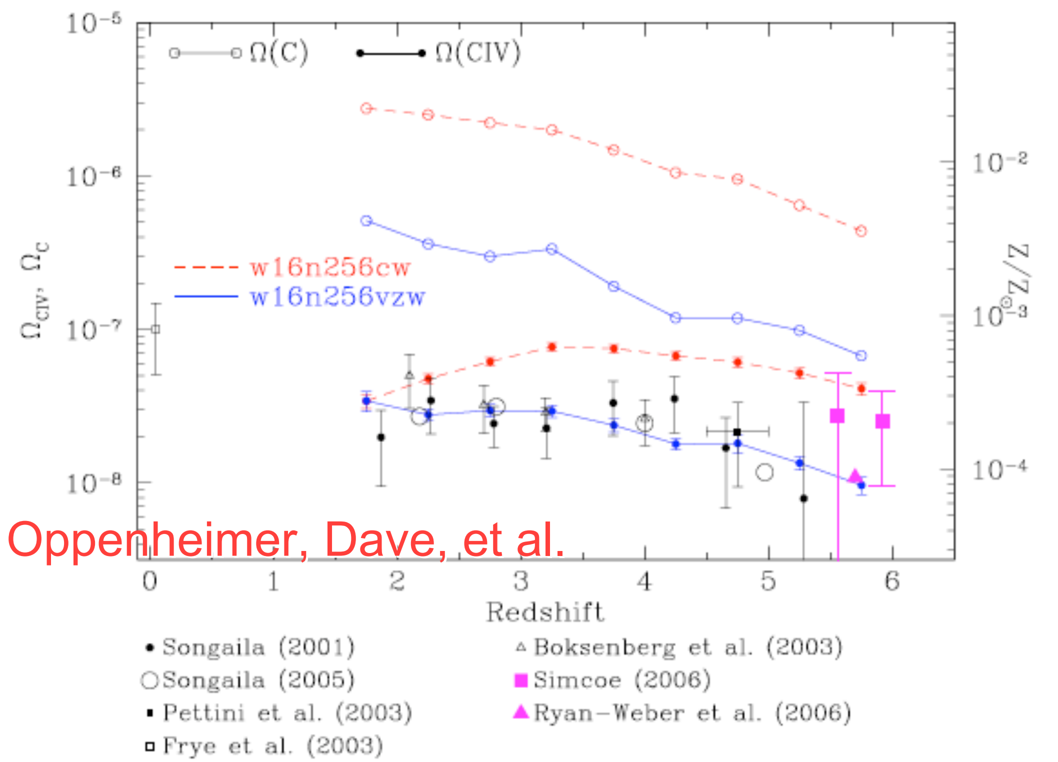



**Fig. 1.4.** The 'local galactic' abundance distribution of nuclear species, normalised to $10^6$ $^{28}$Si atoms, adapted from Cameron (1982).

# Principles: redistribution

- Supernovae and stellar winds - redistributes these metals and can drive galactic winds….




Oppenheimer, Dave, et al.

# Approximation : IRA

- Instantaneous Recycling approximation
  - Because much of enrichment is prompt (with enrichment timescale << Hubble time) can assume it happens instantaneously
    - Makes math simpler (tractable)
    - OKish for alpha elements
    - BAD for Iron, CNO, heavy elements

# IRA world…

- $dM_{met}$ = (y-Z)*SFR(1-R) - [metals in outflow] + [metals in infall]
- $dM_{gas}$ = -SFR(1-R) - outflow + infall
- dM* = SFR(1-R)
- Z = Mmet/Mgas

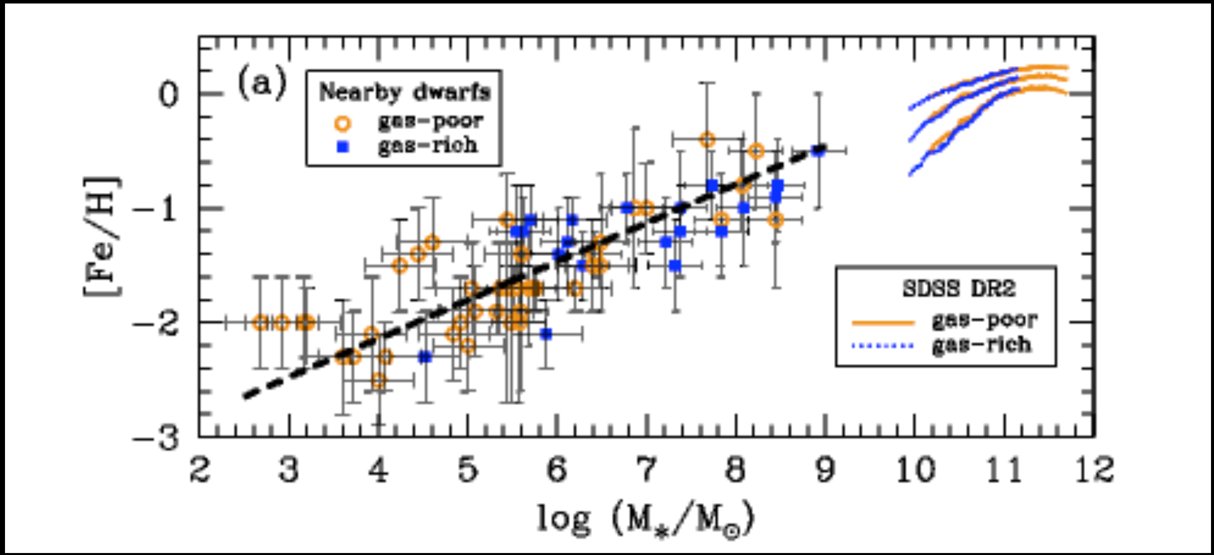
# A closed box

- CLOSED BOX - no metals or gas in or out, full mixing in box
- Then
  - $dg = -ds$
  - $g\, dZ/ds = -g\, dZ/dg = y_{true}$ yield
  - Therefore, $Z = y_{true} \ln M/g = y_{true} \ln(1/f_{gas})$
- Can define $y_{eff} = Z/\ln(1/f_{gas})$

Yield that a system would have to get a metallicity at a given $f_{gas}$

# Some key results

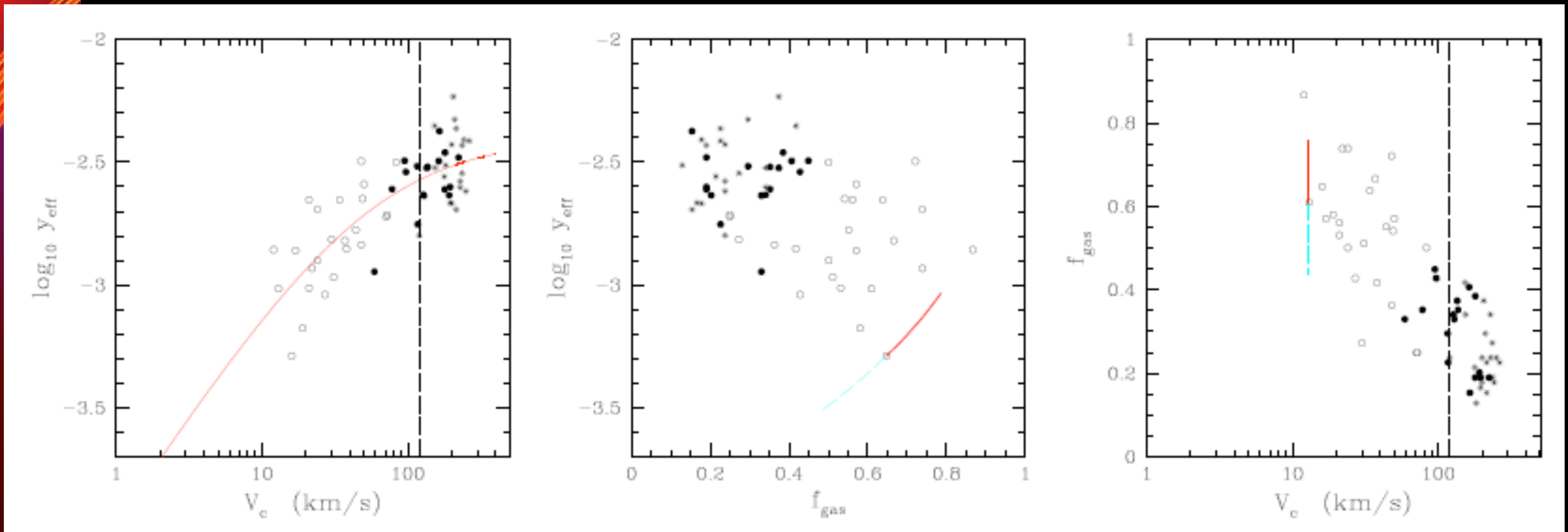
Lee, Bell, Somerville 2008




- Metallicity-mass relation
- Same for gas-rich and gas-poor galaxies
  - Can go from one to the other by just losing gas…

# Key results II

- Metal-enriched outflows are ~only way of driving down yeff, but only in systems with a lot of gas…
- Main driver or metal-mass relation is low SFE, modulated by metal-enriched outflows.




Dalcanton 2007

# Relative abundances as a cosmic clock…

- One of the key diagnostics of timescales of galaxy evolution is relative abundances
  - Alpha/Fe, N/O, etc…

Schiavon 2006

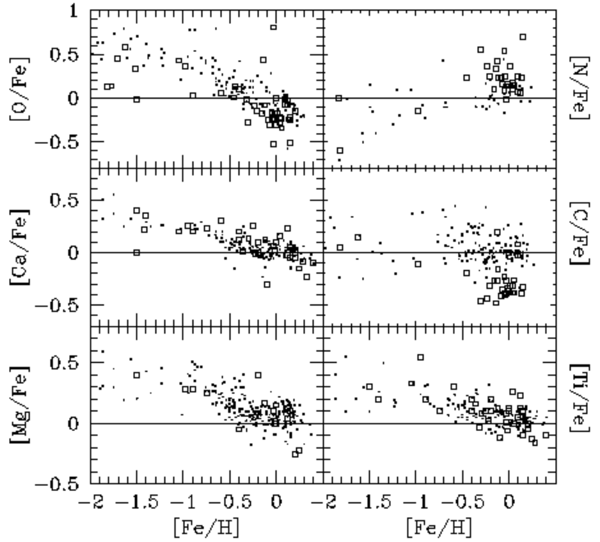



Fig. 3.— Abundance pattern of the input stellar library. Dwarfs and giants are marked by small dots and open squares, respectively.

Eric Bell

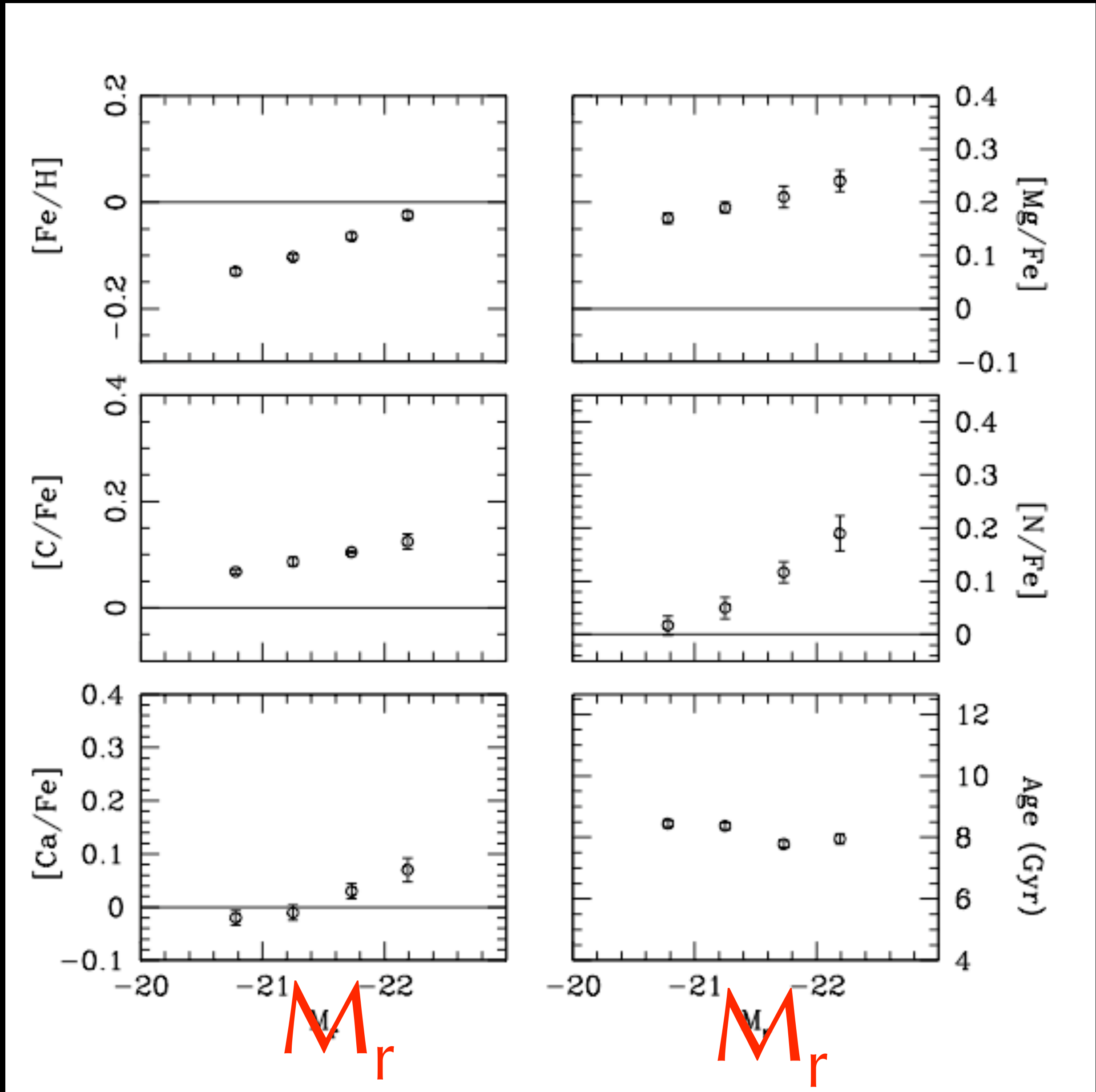
# Abundance Pattern

Schiavon 2006

[Fe/H]

[C/Fe]

[Ca/Fe]




[Mg/Fe]

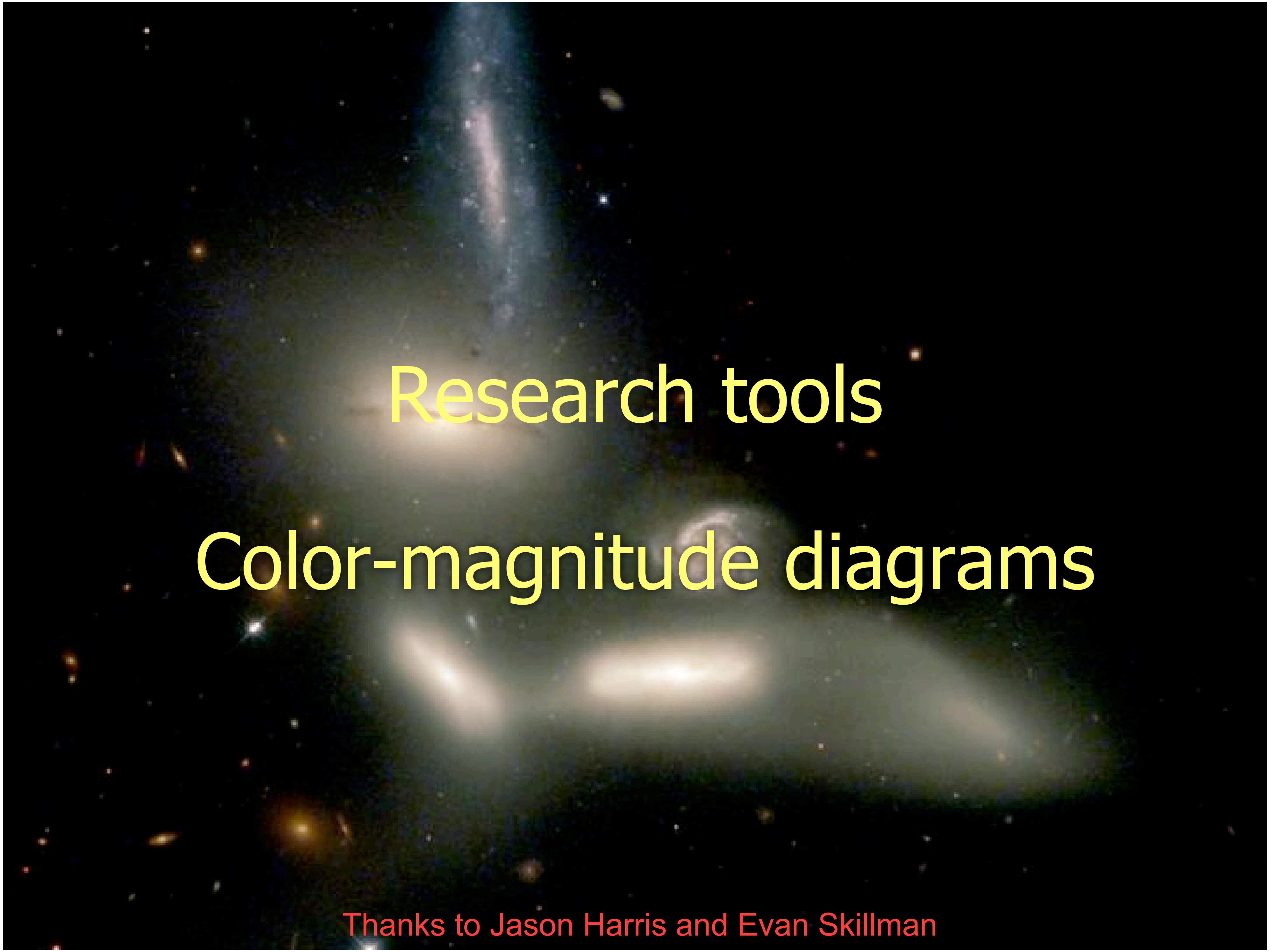
[N/Fe]

Mean Age (Gyr)

Eric Bell

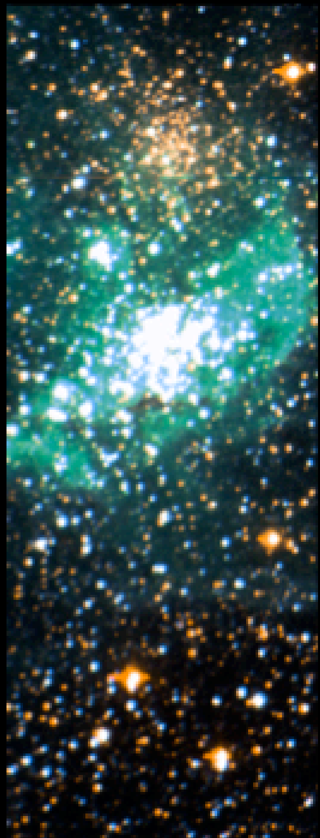
# Summary I

- Chemical Evolution
  - ‘garbage’ of stellar evolution,
  - does not go away (so valuable diagnostic),
  - but does get moved around (so not trivial to interpret)
  - Different origins of elements --> diverse chemical clocks (alpha elements, Iron, nitrogen, R-process, S-process) which need to be used with care
  - Key result : metallicity--mass relation, supports interpretation of this relation as evolutionary clock
  - Feedback : metals spread all over the intergalactic medium, so we know they get blown out, just where and when?

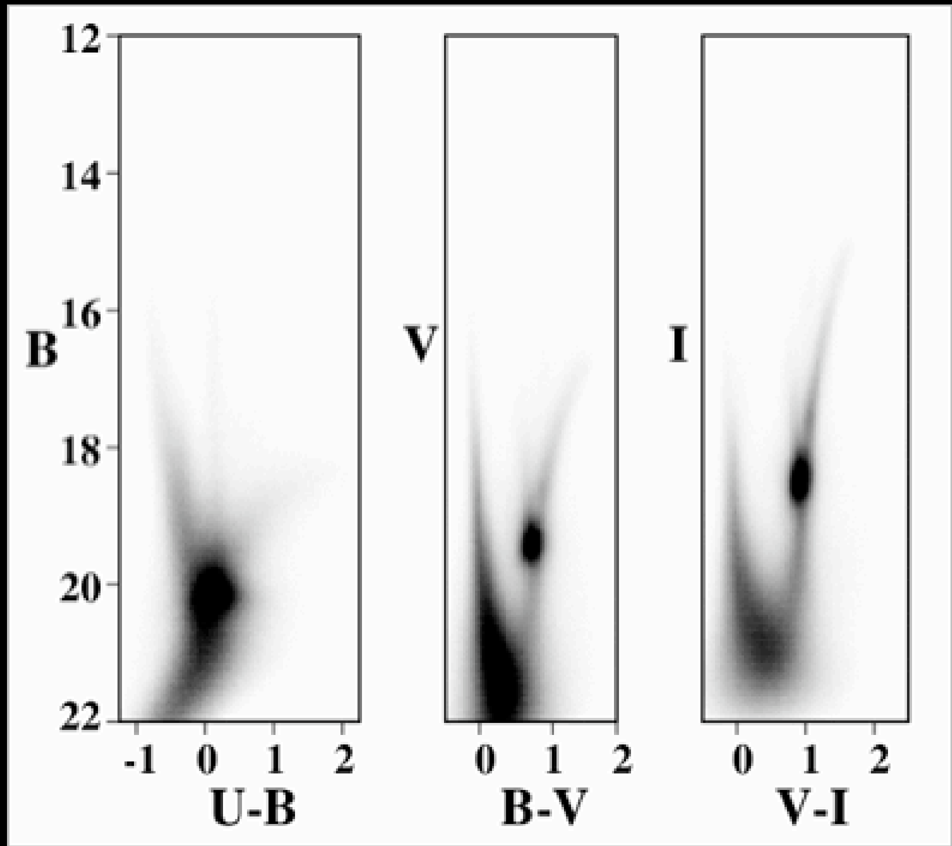

Research tools
Color-magnitude diagrams
Thanks to Jason Harris and Evan Skillman

# Not Just Another Pretty Fuzz

## Content: Rich Stellar Populations



NGC 346



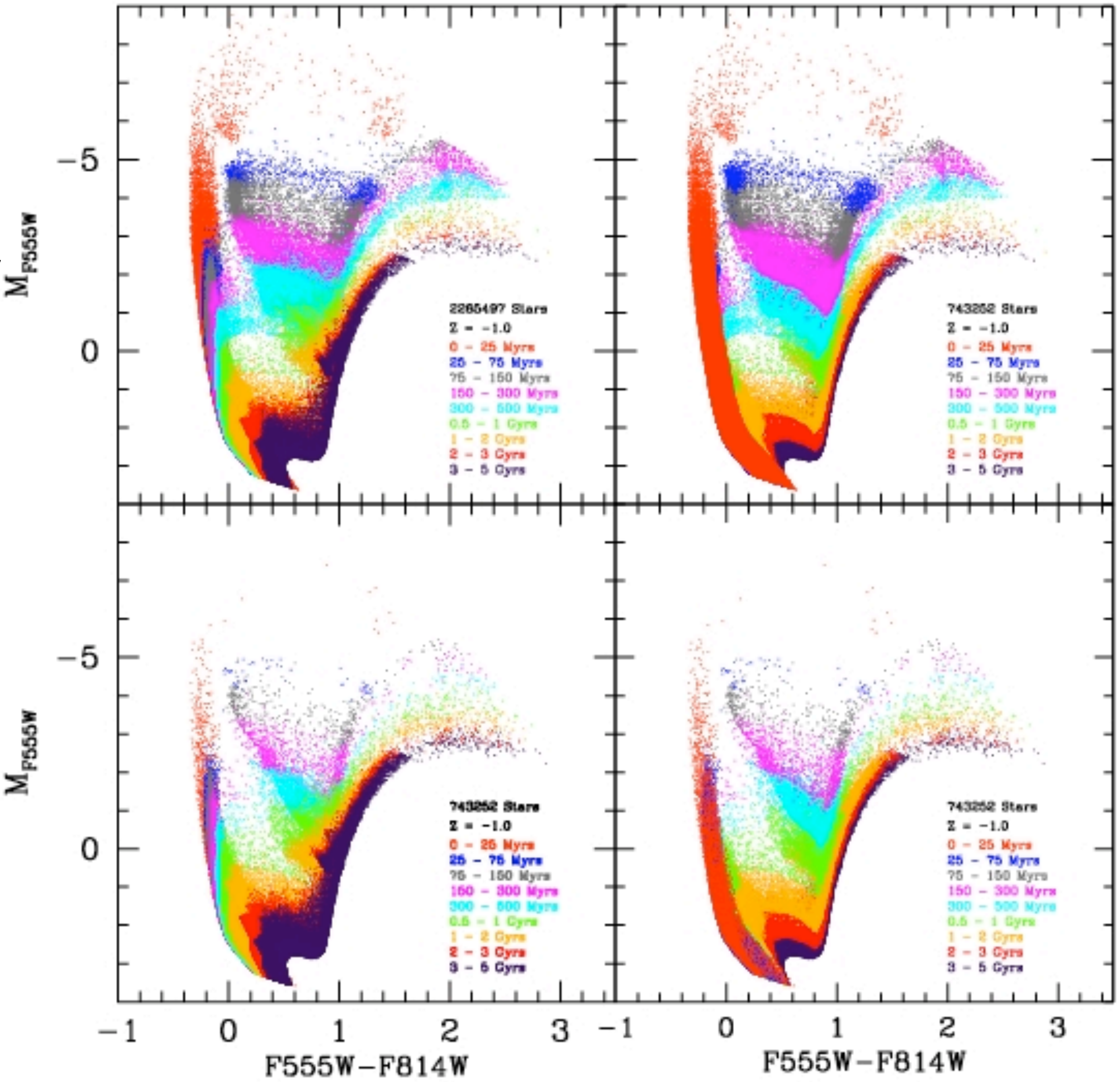

UBVI photometry of 6M SMC stars

Synthetic CMDs created by D. Weisz using Dolphin's codes

Left: "Painted" young to old    Right: "Painted" old to young

Top panels: Increasing SFR to emphasize recent star formation

Bottom panels: constant SFR.



# Star Formation Histories

## Stellar Types

OB Stars
Wolf-Rayet Stars
HII Regions
Main sequence stars
Red giants
AGB and Carbon stars
Red clump stars
Planetary Nebulae
LPVs
RR Lyrae stars
White Dwarfs

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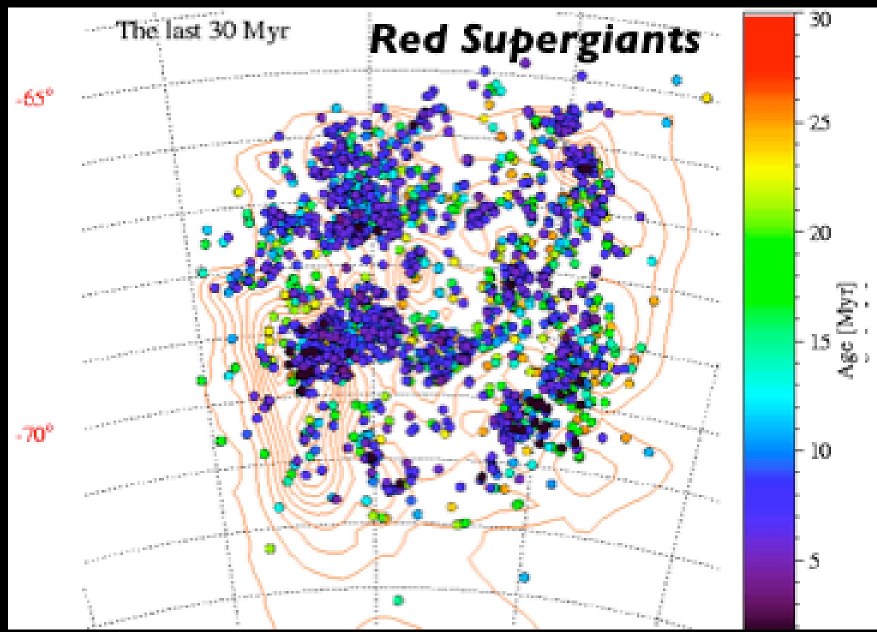


Grebel & Brandner (1998)

# Star Formation Histories

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- Wolf-Rayet Stars
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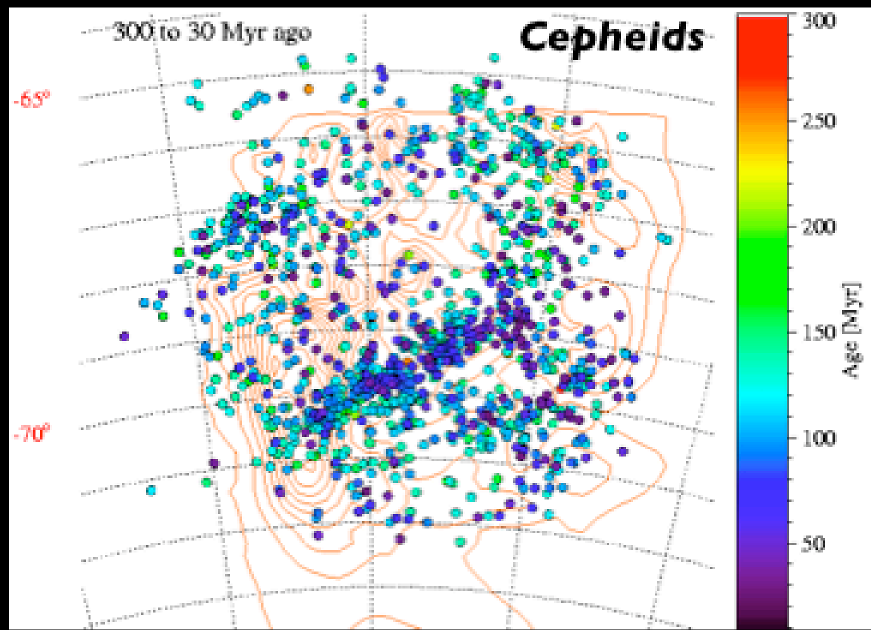


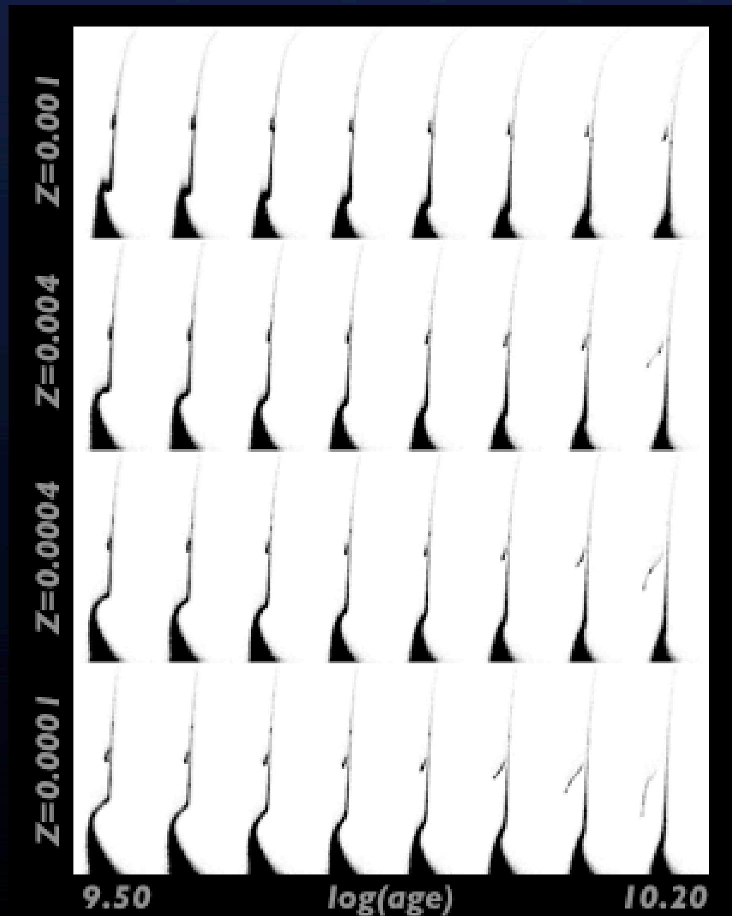

Grebel & Brandner (1998)

# Star Formation Histories

## Synthetic CMDs

### Basic operation of synthCMD methods:

**Construct synthetic CMD library from isochrones**



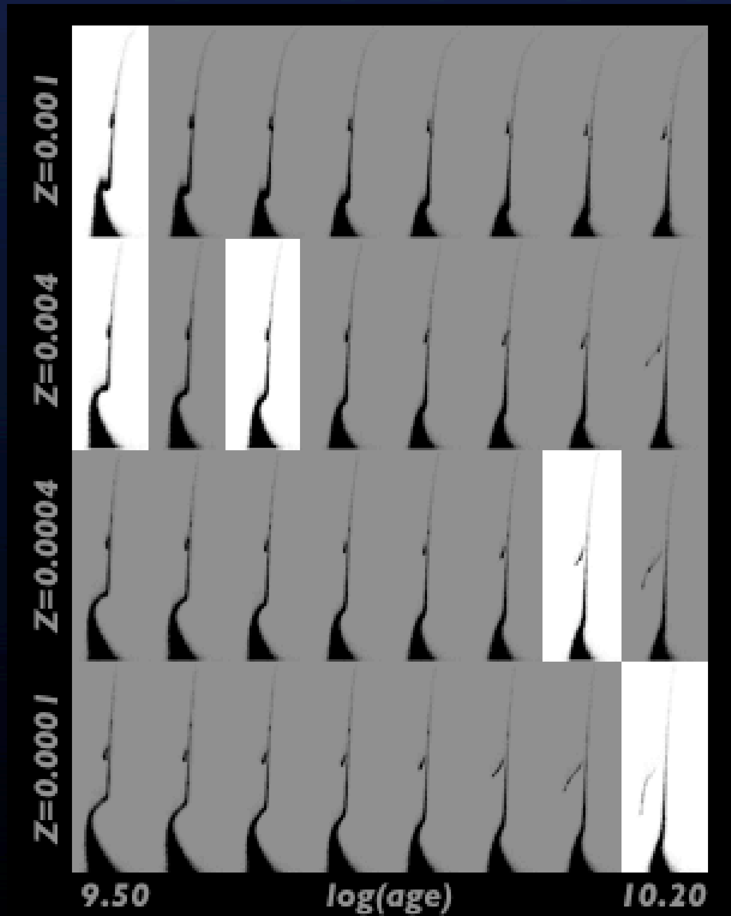
# Star Formation Histories

## Synthetic CMDs

### Basic operation of synthCMD methods:

Construct synthetic CMD library from isochrones

Combine synthCMDs linearly to make composite model



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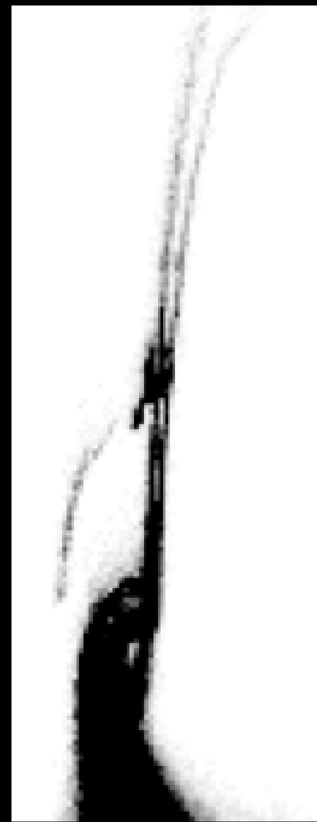


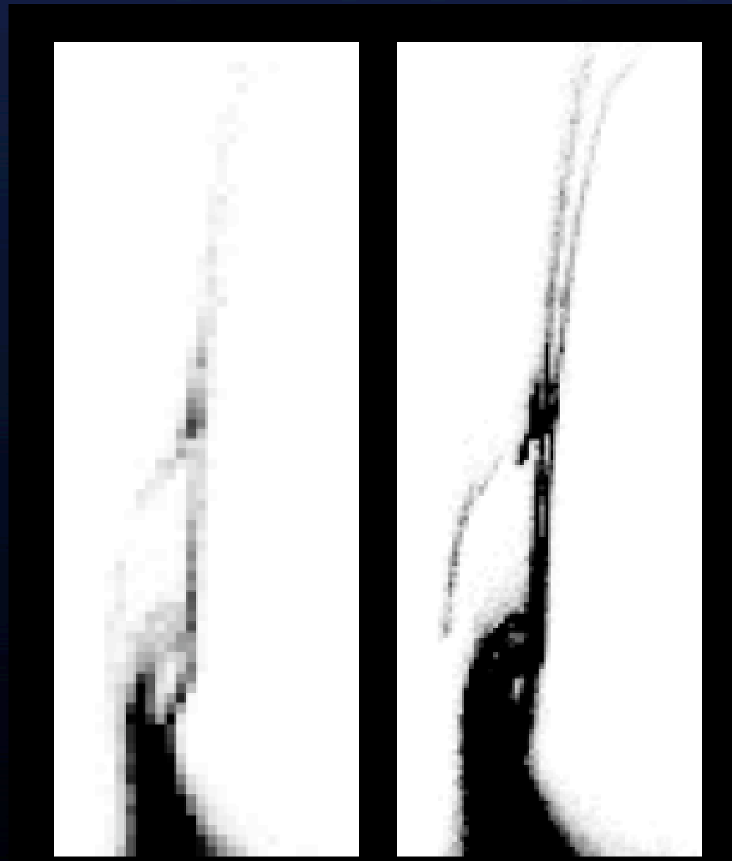
composite model

# Star Formation Histories

## Synthetic CMDs

### Basic operation of synthCMD methods:

- Construct synthetic CMD library from isochrones
- Combine synthCMDs linearly to make composite model
- Adjust synthCMD amplitudes until composite model matches target data set



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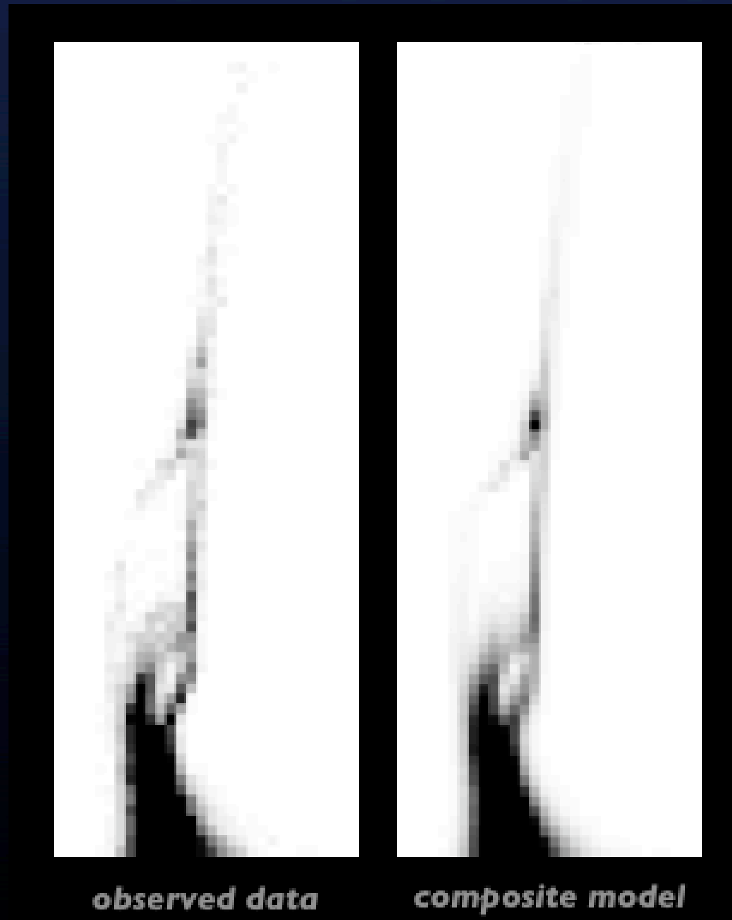
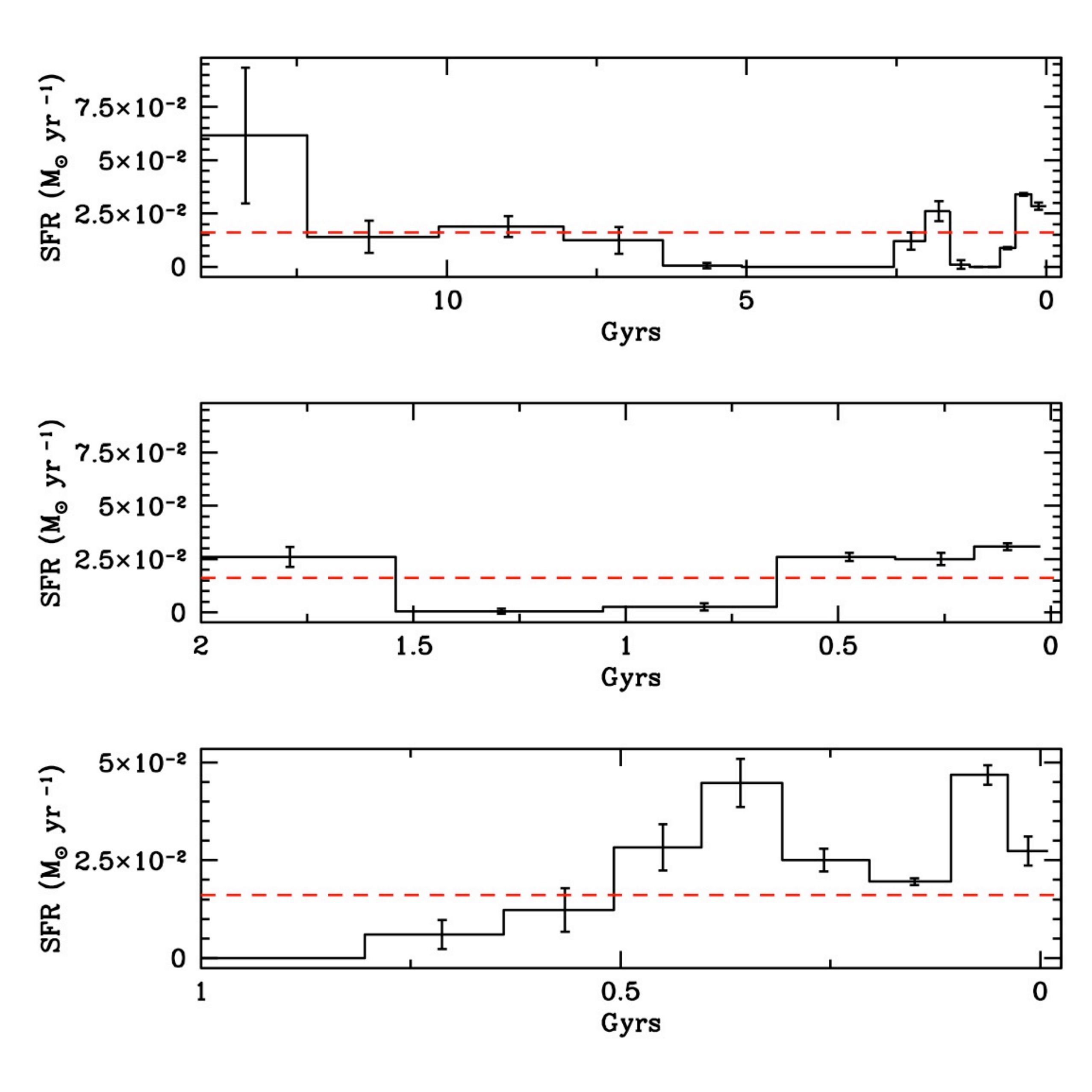


DDO 165 in the M81 group

Complete Star Formation History

Note resolution at recent times better than ancient pops.

Key result : star formation histories of dwarf galaxies tend to be bursty…



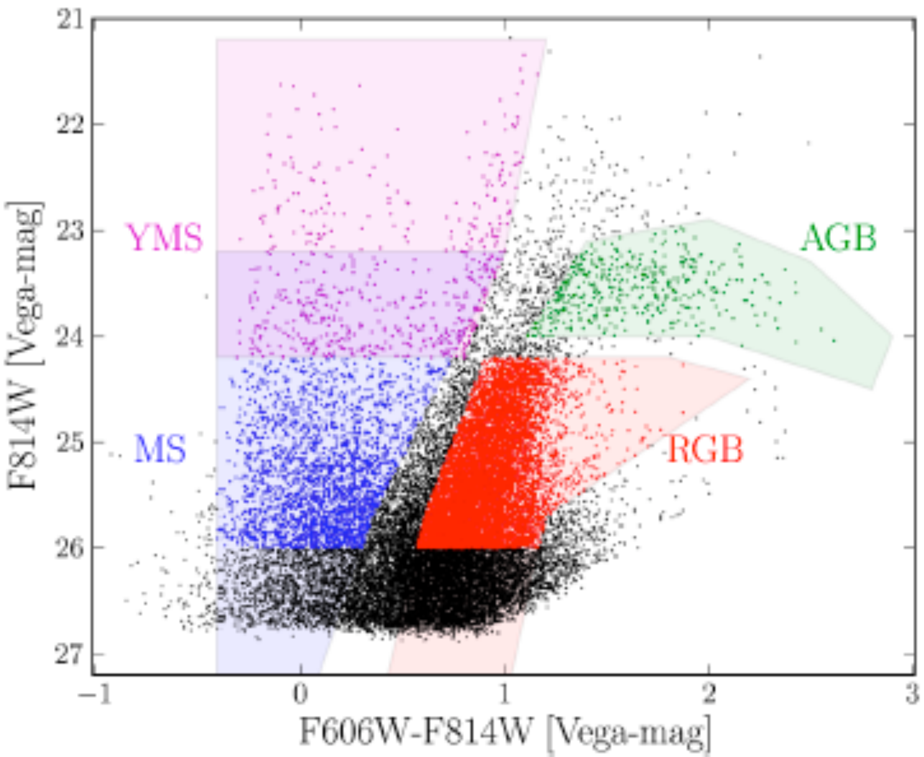
# A Key Result….

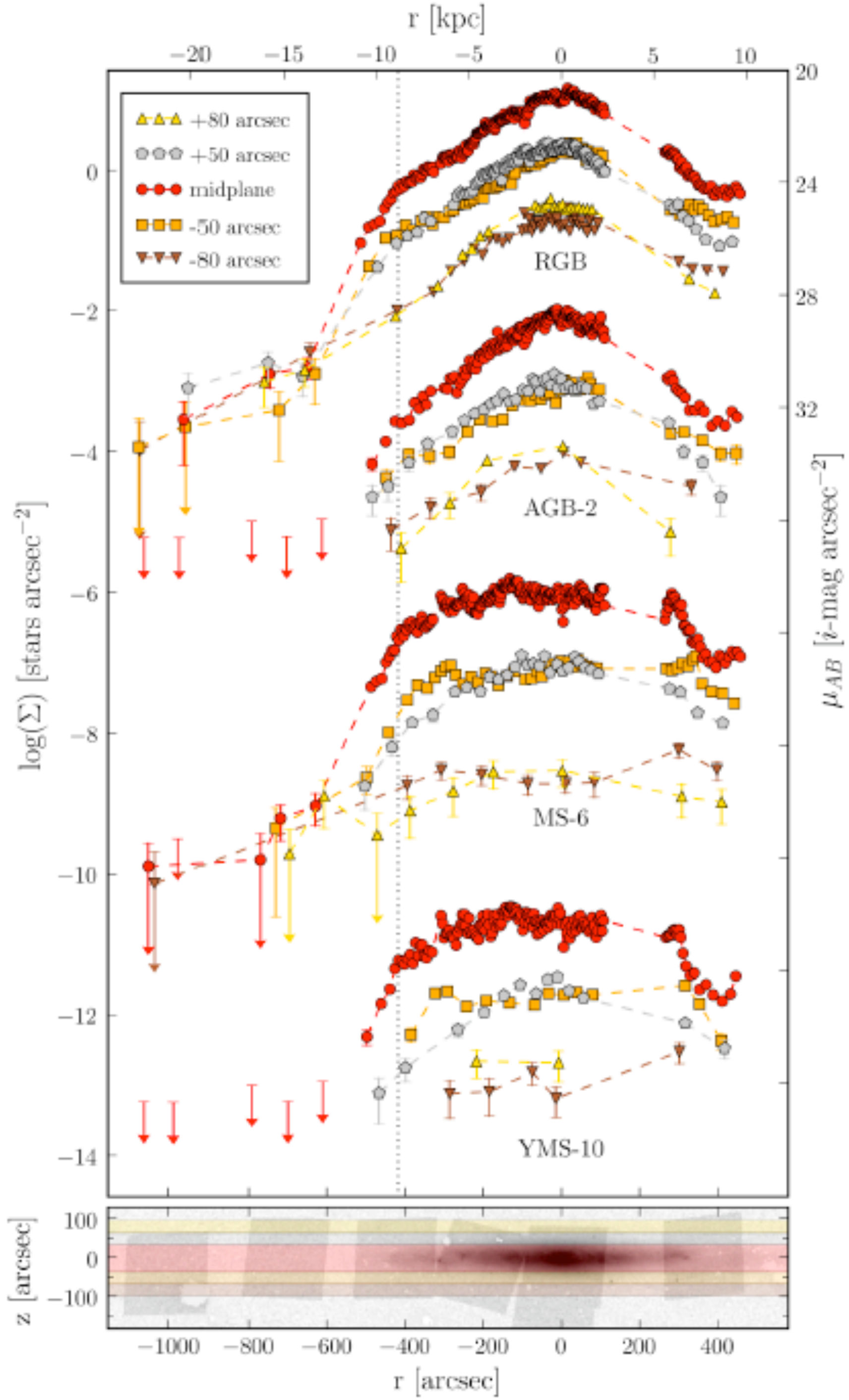
- Dolphin et al. 2005 (on astroph)
  - Irregulars --> Spheroidals through gas loss alone (I.e., SFHs at ancient times v. similar)

# Results

de Jong et al. 2007

Stellar truncations also in old populations; not *just* star formation thresholds…



# Summary II

- Color-magnitude diagrams
  - Very powerful
  - If get to main sequence turn off for old stars
    - Star formation history
      - Resolution good for recent star formation, worse for ancient times
    - Some chemical evolution history (better if have a few red giant spectra, helps a lot)
  - If you don't get to main sequence turn off
    - Some SFH information remains but tricky to do well because it's all post-main sequence based
  - Method
    - Match distribution of stars in color-magnitude space, maximise likelihood (e.g., minimise chi^2)
  - Key result : star formation histories of dwarf galaxies have considerable bursts
  - Key result : star formation histories of gas-rich and gas-poor dwarfs different only in last couple Gyr - gas removal only difference?

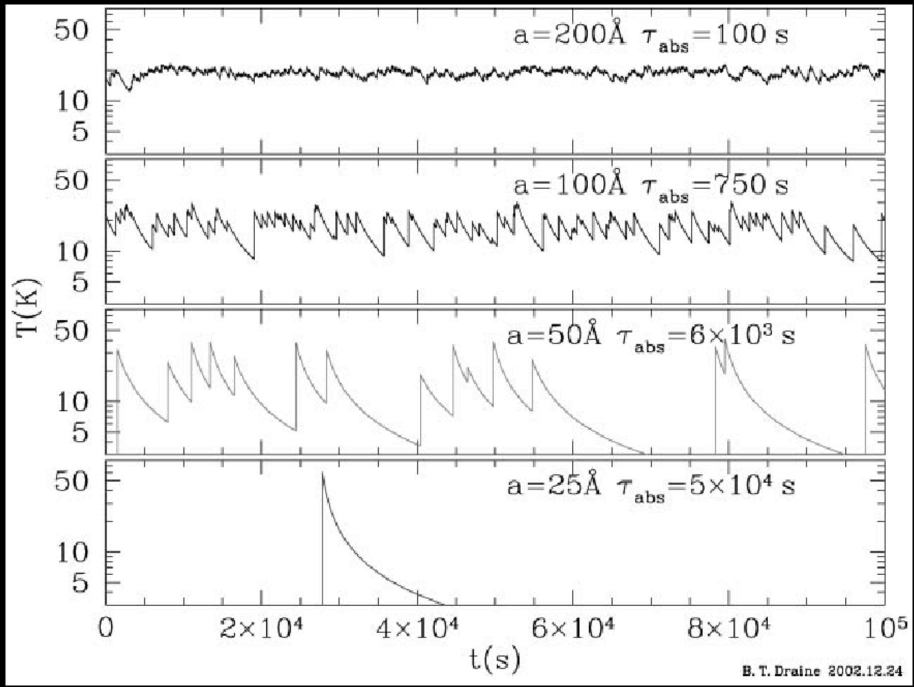

Research tools
Diagnostics of ISM and dust…
With thanks to Brent Groves

# Heating Dust

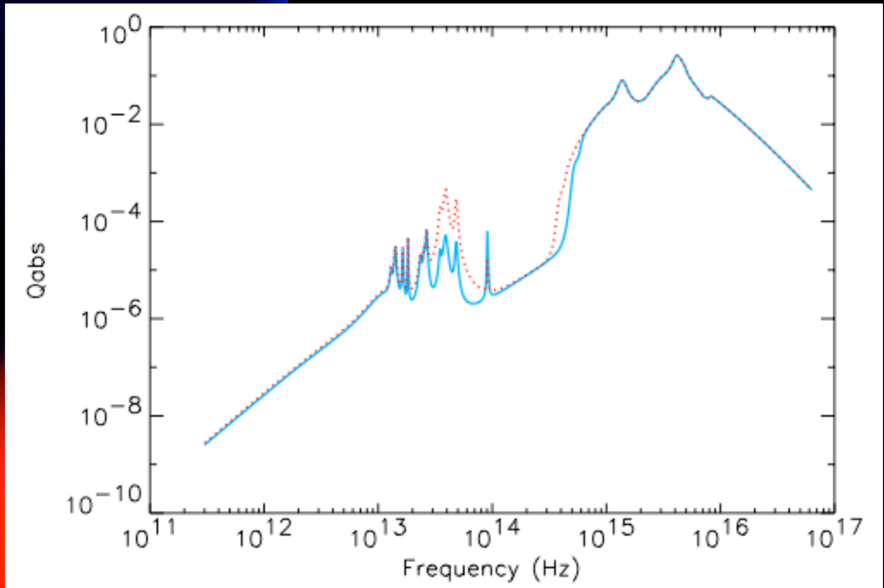
- As the grains absorb the incident photons they heat up and emit thermal radiation
- For large grains, the absorption and emission reach an equilibrium state so that the grain has a steady temperature
- For small grains however things become stochastic...

# Hot & Cold

- Smallest grains
  - have small cross-section
  - hence low photon heating rate
- However, small grains also
  - have low specific heat
  - one photon causes large increase in Temperature



# Quick & Dirty Dust IR




- Solve for Grain Temperature Probability Distribution
- Convolve with Blackbody and integrate over dust sizes and types to get IR emission
- Include the emission from PAH

# From Star to Finish (SED)

- Use stellar synthesis code (STARBURST99) to generate stellar spectrum of different aged bursts

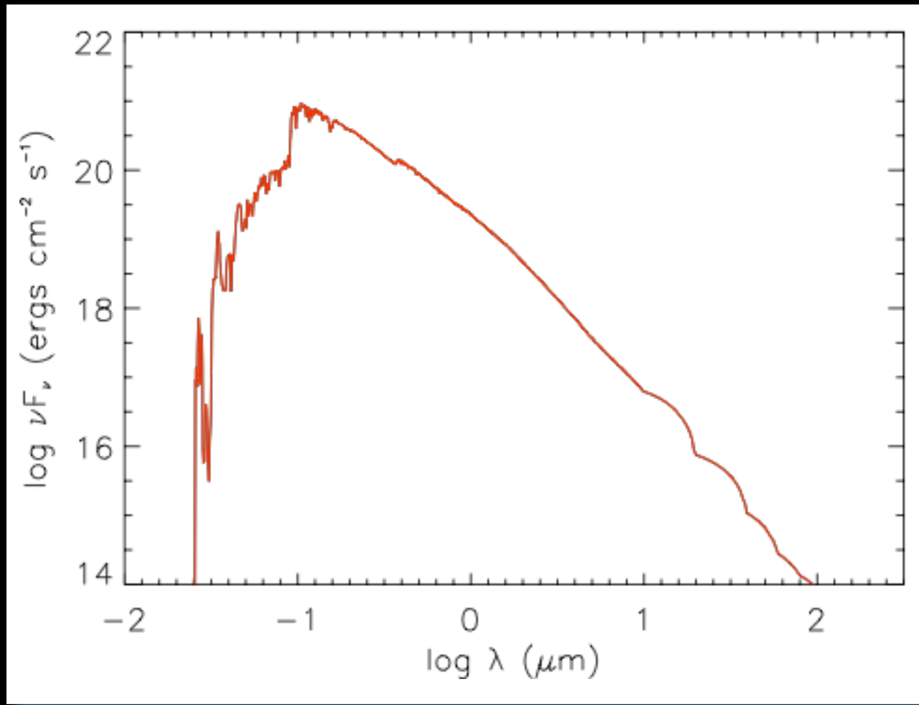
- Use radiative transfer code (MAPPINGS) to determine HII spectrum and hot dust extinction and emission

- Use MAPPINGS to determine spectrum of warm dust & PAH extinction and emission

- Pass final spectrum through (diffuse, cold) dusty screen

# Making Stars

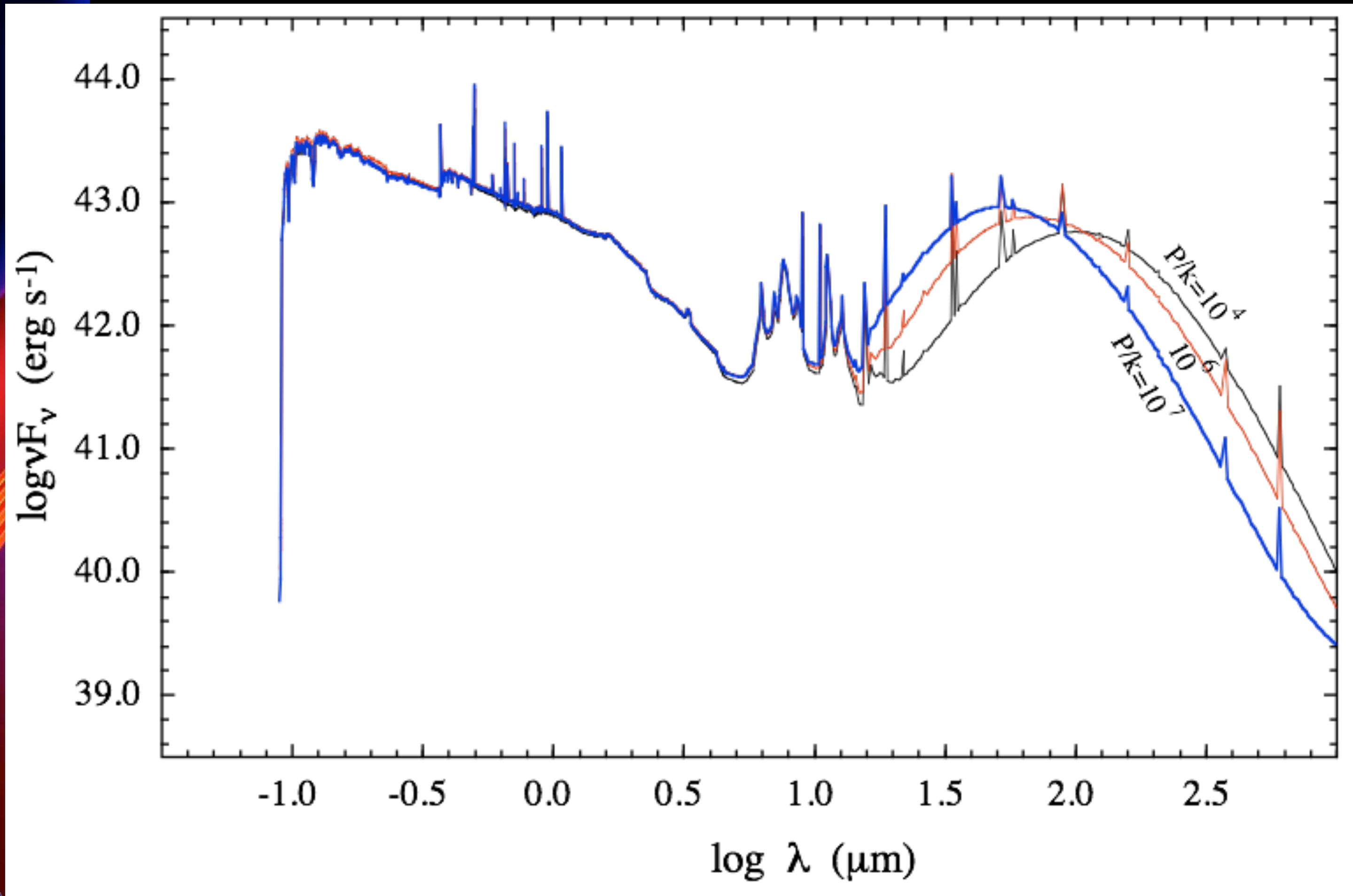
- The Stellar Emission
  - Instantaneous bursts of $10^4$ M$_\odot$ sampled at intervals of 1 Myr up to 10 Myr
  - Continuous at 1 M$_\odot$ yr$^{-1}$ up to $10^8$ yrs for >10 Myr population



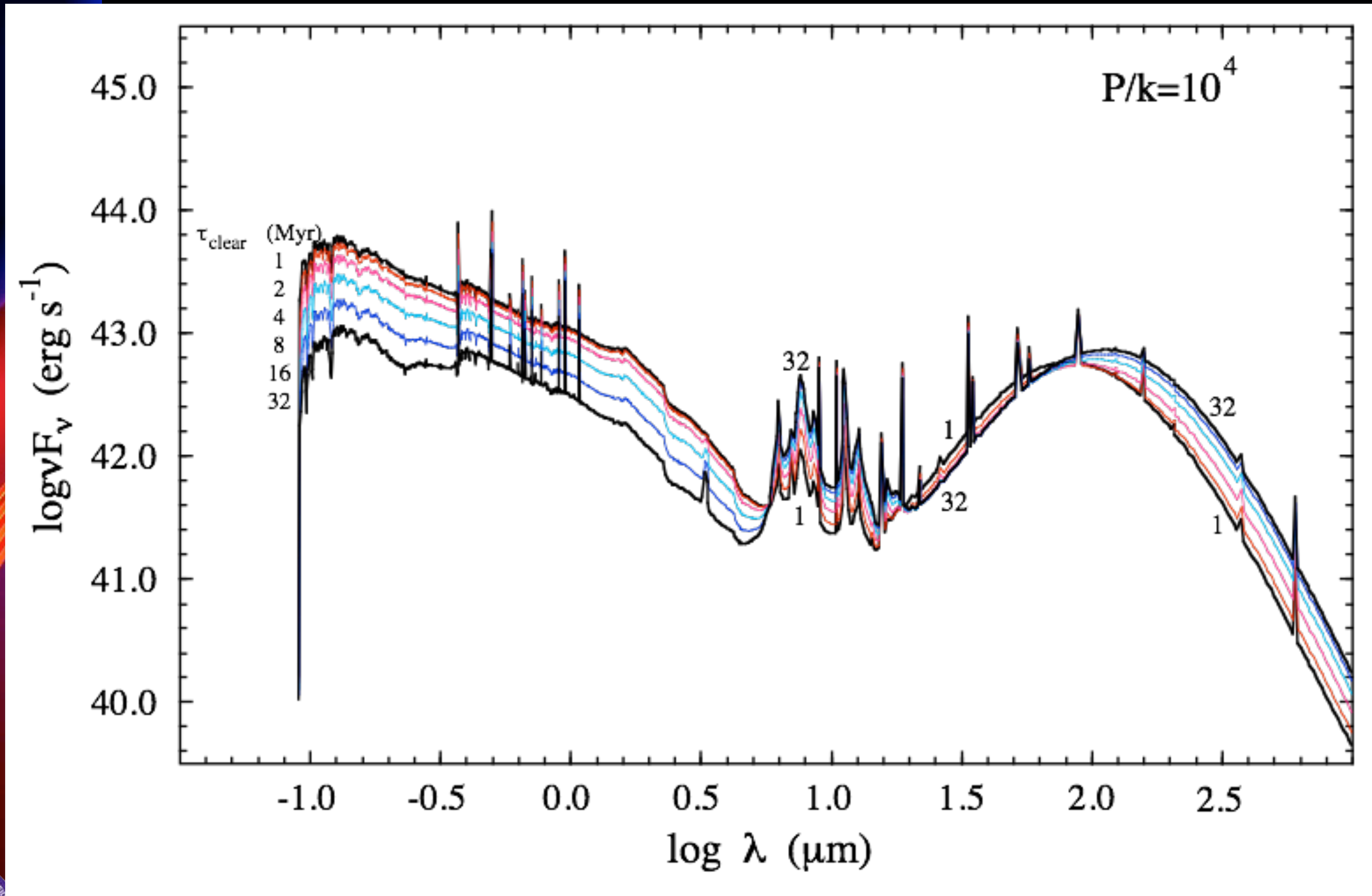
# ingredients

- The Photodissociation Region
  - All regions of ISM where FUV photons dominate physical/chemical processes
  - Molecular cloud covers fraction of HII region
  - Absorbs Far-UV and gives warm dust and PAH emission
  - Explore clearing timescale (~covering fraction) of PDR clouds
  - $f(t)=exp(-t/\tau_{clear})$
  - $\tau_{clear}$=1, 2, 4, 8, 16 and 32 Myr

# Under Pressure



# Seeing through...



# Case study: dust masses

- Mass = flux * d^2 / (dust cross section per unit mass * planck function(at a temperature T, at measured frequency)
  - *highly* uncertain, need longest wavelengths possible and understand what fraction of dust is at which temperatures
  - Long wavelength cross section uncertain
- End up with gas/dust of ~200-300 (Sodroski et al. 1994; Dunne et al. 2000)

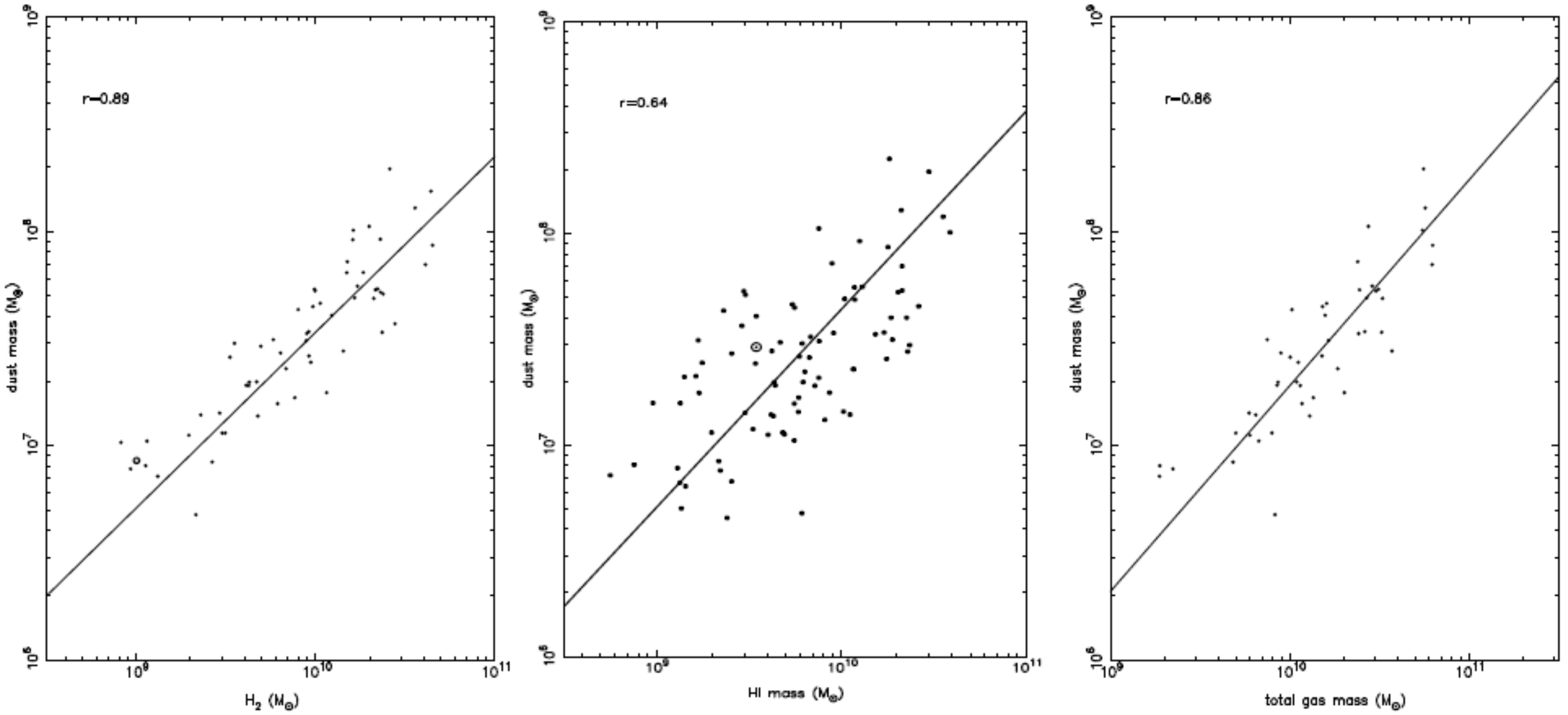



**Figure 14.** a) Dust mass versus $H_2$ mass, a solar symbol indicates the Milky Way values (Sodroski et al. 1994). The line is the best least squares fit (see Table 8 for fit parameters).
b) Dust mass versus HI mass, the line indicates the best least squares fit to the data. There is much more dispersion than for Fig. 14a.
c) Dust mass versus $H_2$ + HI mass.

- End up with gas/dust of ~200-300 (Sodroski et al. 1994; Dunne et al. 2000)

# Gas

- Almost information from gas comes from emission lines…
  - As $e^-$ fall through energy levels --> recombination radiation (radio through to optical/UV/X-ray)
  - Forbidden lines (long transition times, e.g., ~hours), denoted by [OIII]
  - Fine structure lines - coupling between the spin and orbital ang. Mom of an $e^-$
    - $1/137^2$ times as large as between main levels (~FIR), e.g., OI at 63 and 145um, CII at 158um are hugely important cooling lines (why sodium D is a doublet)…

# Gas (cont)

- Hyperfine transitions
  - Nuclear spin and e- spin (2000x smaller still)
  - HI when flips from parallel to antiparallel, 21cm radiation, timescale ~10Myr
- Molecules
  - Vibrational transitions (few um for common molecules e.g., HCN, CO, CS)
  - Rotational transitions (mm regime), excited by collisions with $H_2$ molecules (e.g., CO at 1.3 and 2.6mm CO1-0; excited at $n(H_2) \sim 10^3 cm^{-3}$ and T~10-20K for excitation); higher transitions need larger densities / higher temperatures

# Gas (cont)

- Larger dipole moments
  - Faster decays back to ground state, and denser gas reqd. to cause emission.
    - E.g., ammonia, HCN, CS (10,100,1000x denser than CO), SiO requires densities higher still
- Symmetric molecules
  - E.g., $H_2$, rotational transitions $137^2$ times slower (least energetic transition is at 20um, only shocked gas at T~1000K can emit at all)
  - Absorption lines in the UV, need an absorber…

$^{12}$CO lower dens

$^{13}$CO, CS, HCN traces progressively denser phases

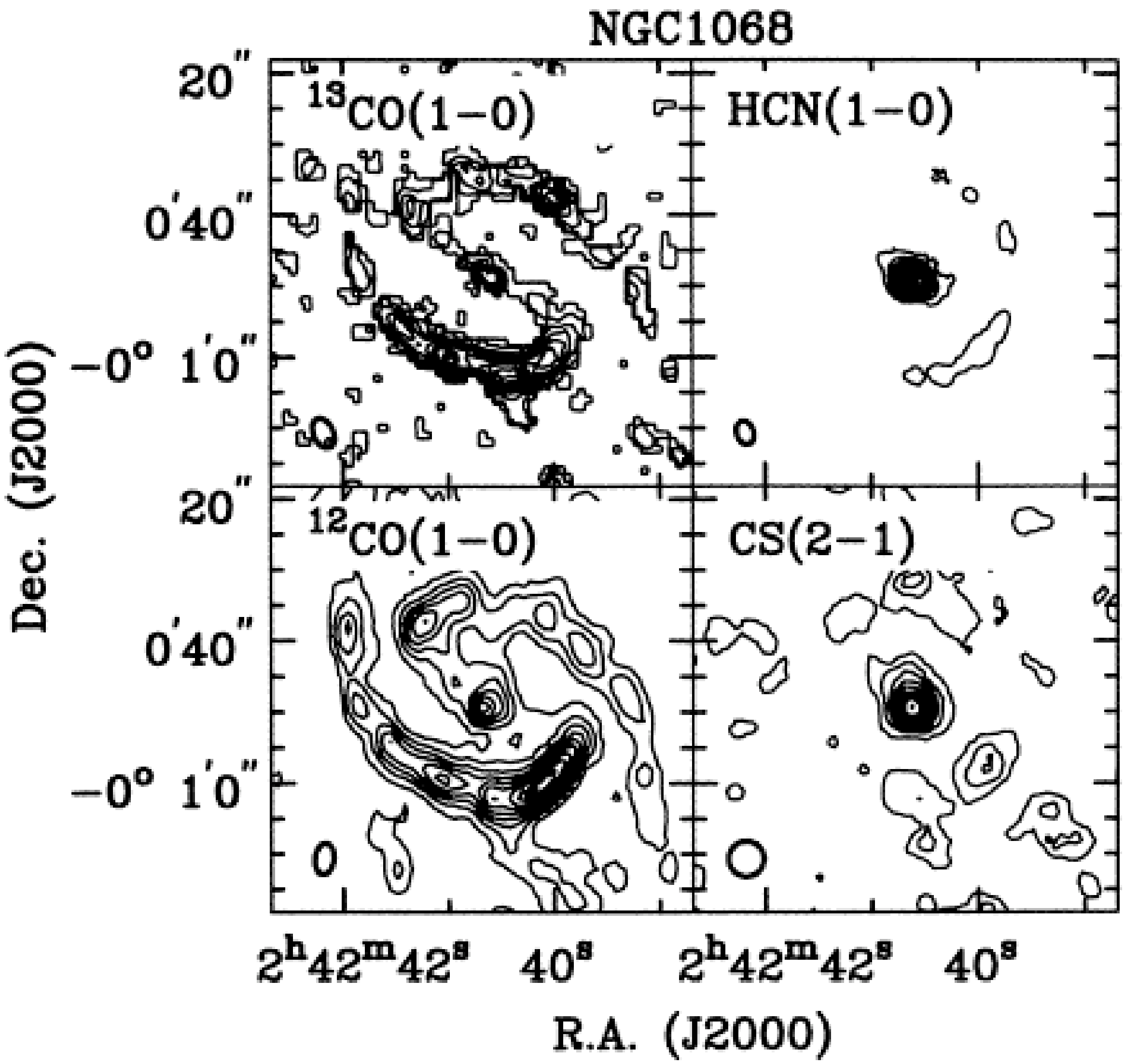



Figure 4. $^{12}$CO 1–0 (left, 4″ resolution) and HCN 1–0 (right, 2″.5 resolution) mm-interferometer maps of NGC 1068, taken with the Plateau de Bure mm-interferometer (Tacconi et al. 1994, 1996).

# How does one turn that into $H_2$ mass?

- Virial estimator
  - Gravitational mass of cloud from sigma^2 r vs. luminosity in CO, CS, HCN, etc…
  - Have to have confidence that you're looking at an area where sigma^2 and r reflect just support of one cloud
- Dust-to-gas method
  - Calibrate HI to dust mass ratio (dust mass from long wavelength emission).
  - Go to an area with CO in that galaxy
  - Assume that H_2 to dust mass ratio same as HI to dust mass ratio (I.e., dust to gas does not depend on what form the gas takes, not a stupid thing to assume)
  - Then can use dust mass in that CO-dominated region to estimate H_2 mass in that region, then calibrate CO-to-H_2 ratio…

# HI and $H_2$ (from CO)

- $M_{HI} = 2.36\times10^5\ D^2(\mathrm{Mpc}) \int S(\mathrm{Jy})dv(\mathrm{kms}^{-1})$
- $M_{mol} = 1.61\times10^4\ D^2(\mathrm{Mpc})\ S_{co}$ Wilson & Scoville 90
- Often CO is given as a surface brightness, and one needs to integrate over the beamsize oneself or integrate over the galaxy (if larger than the beam)

**5. DISCUSSION**

We estimate the total mass of molecular hydrogen within the 55″ telescope beam (Table 3) from

$$M_{H_2} = 4.78[\pi/(4 \ln 2) I_{CO} d_b^2]\epsilon^{-1}\ (M_\odot), \qquad (2)$$

where $I_{CO}$ is the integrated CO line flux in units of K km $s^{-1}$ ($T_R^*$ scale), $d_b^2$ is the telescope beam diameter in units of parsecs at the distance of the galaxy, and ε is the main-beam efficiency of the telescope (0.84 at 115.3 GHz for the 12 m telescope as of 2000 January). This formula assumes a Gaussian beam and a standard Galactic value of the CO-to-$H_2$ conversion factor $X = N(H_2)/\int T(CO)dV = 3.0\times10^{20}$ $cm^{-2}$ (K km $s^{-1}$)$^{-1}$, [where $T(CO) = T_R^*/\epsilon$; e.g., Young & Scoville 1991], which is applicable to molecular clouds at virial equilibrium. For galaxies where data were obtained at off-center pointings, the total $H_2$ mass was estimated by summing the individual spectra according to equation (3) of Sage (1993a).

# Summary III

- Gas and dust
  - Atomic hydrogen easy
  - Molecular hydrogen no dipole moment, so indirect probes (CO, HCN, etc) only which are calibrated to molecular hydrogen
  - Dust spectra; complicated
  - Long wavelength gives some access to dust masses, dust/gas ratio of ~200…
    - Challenge question - what should dust/gas ratio depend on?