What shapes galaxy SEDs?

What shapes galaxy SEDs?

- Stars
- Dust
- Gas

- Key papers
  - Kennicutt 1998; Worthey 1994; Bell & de Jong 2001; Condon 1992; Bell 2003; Calzetti 2001
  - Osterbrock's book…

Orientation 1

Energy balance optical : IR is ~ 50:50 in massive galaxies (like the Milky Way)

Both optical and IR have combination of

~black body

\+

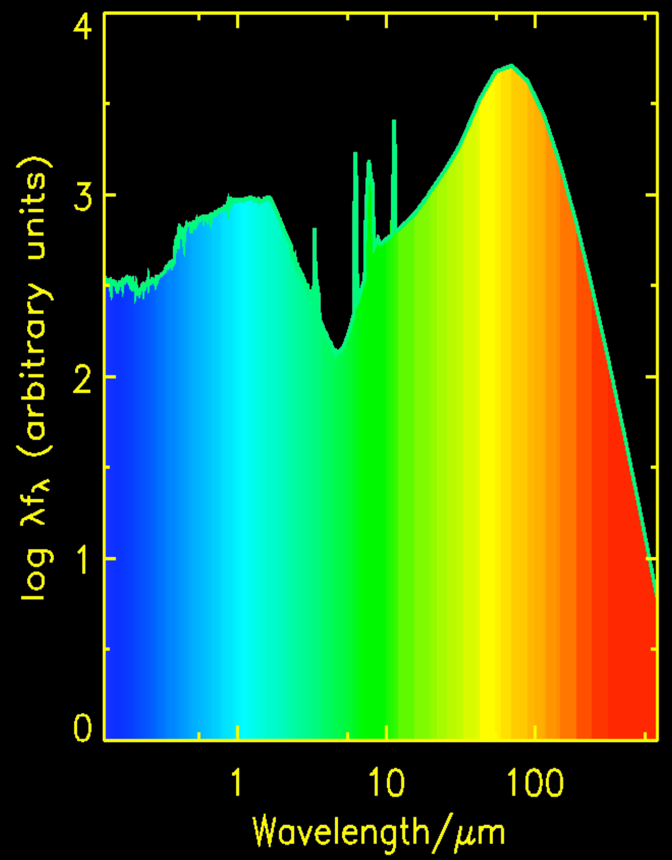
narrower features

Sources:

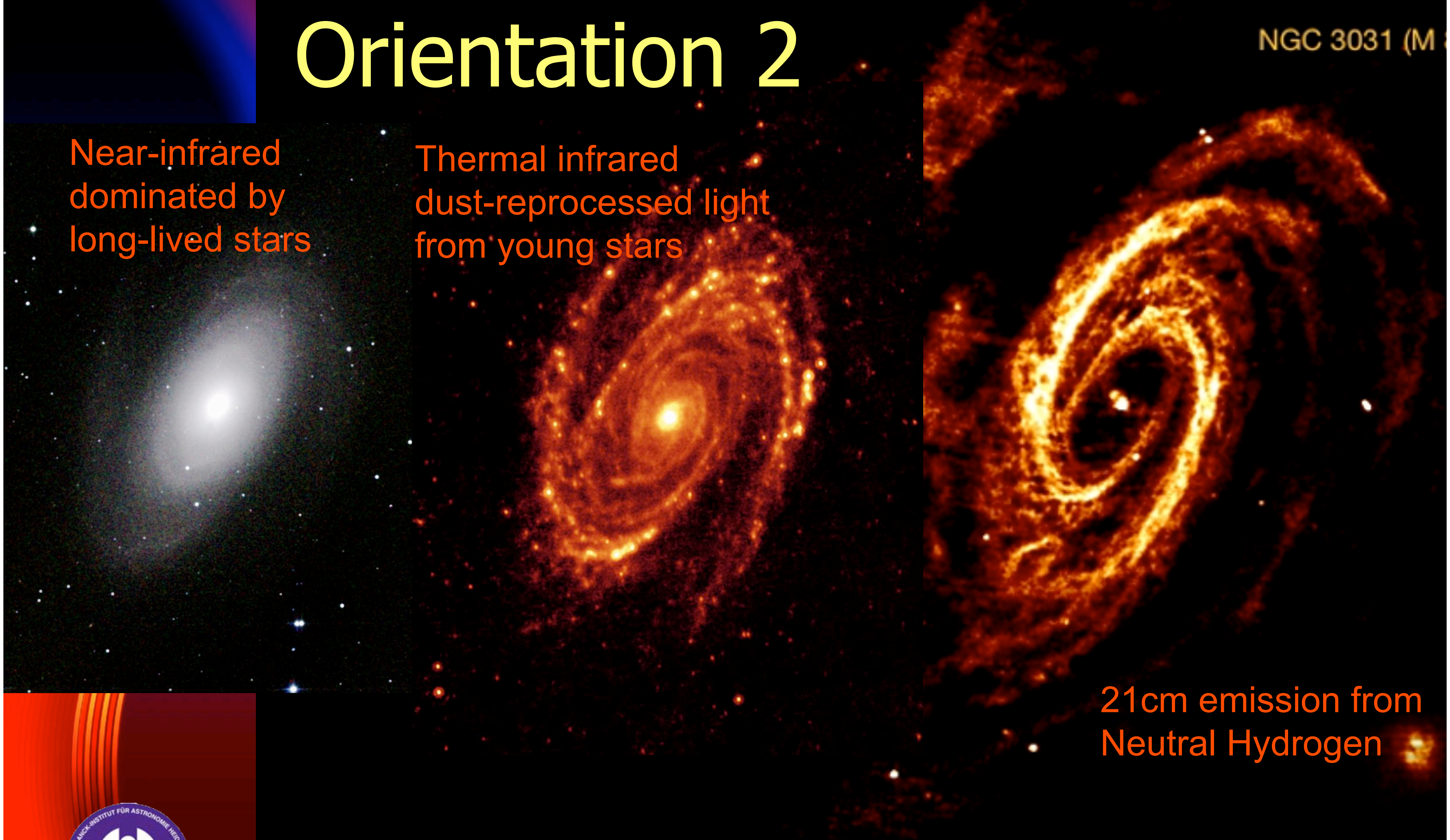
Stars

Dust

Gas



Orientation 2



1 Stars

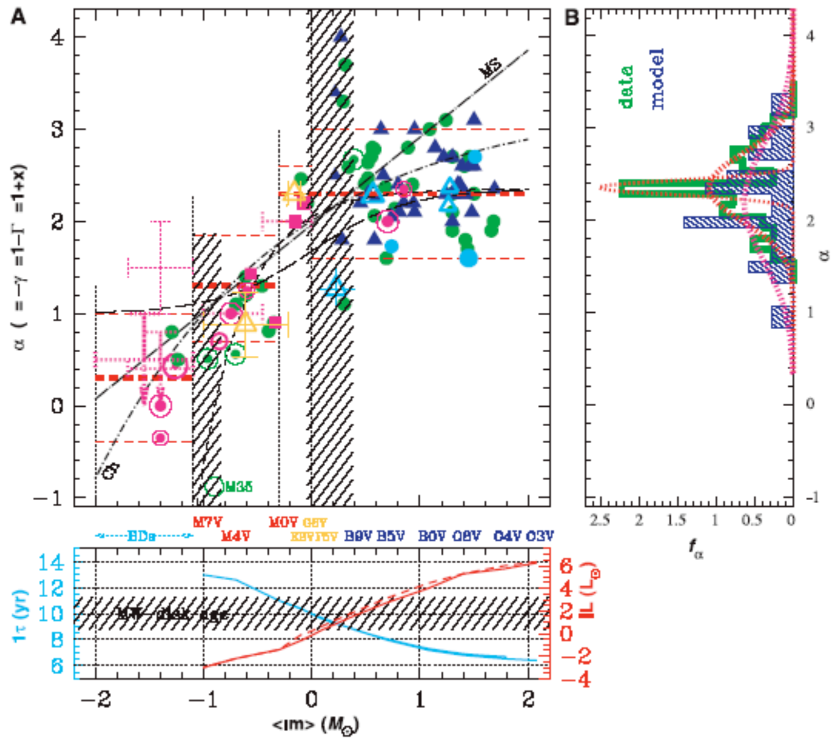
- Complex mix of stellar spectra
- Flux at one wavelength:

$$\int \int \int f_\lambda(M,Z,t)\ \psi(t,Z)\ n(M)\ dM\ dZ\ dt$$

  - n(M) - the stellar IMF
  - $\psi(t,Z)$ - the star formation history
  - $f_\lambda(M,Z,t)$ - stellar library, complicated…

1.1 The stella

- Critical assumption
  - Universally-applica
  - In what follows ch
    Chabrier (2003) IM



2.2. The universal IMF

The available constraints can be conveniently summarised by the multiple-part power-law IMF (see Kroupa 2001b for details),

$$\xi(m) \propto m^{-\alpha_i} = m^{\gamma_i}, \tag{1}$$

where

$$\begin{aligned}
\alpha_0 &= +0.3 \pm 0.7 \quad , \quad 0.01 \le m/M_\odot < 0.08, \\
\alpha_1 &= +1.3 \pm 0.5 \quad , \quad 0.08 \le m/M_\odot < 0.50, \\
\alpha_2 &= +2.3 \pm 0.3 \quad , \quad 0.50 \le m/M_\odot < 1.00, \\
\alpha_3 &= +2.3 \pm 0.7 \quad , \quad 1.00 \le m/M_\odot,
\end{aligned} \tag{2}$$

and $\xi(m)\,dm$ is the number of *single stars* in the mass interval m to $m + dm$. The uncertainties correspond approximately to 99 per cent confidence intervals for $m \gtrsim 0.5\,M_\odot$ (Fig. 1), and to a 95 per cent confidence interval for $0.1 - 0.5\,M_\odot$ (KTG93). Below $0.08\,M_\odot$ the confidence range is not well determined.

1.2 Star formation history $\psi(t,Z)$

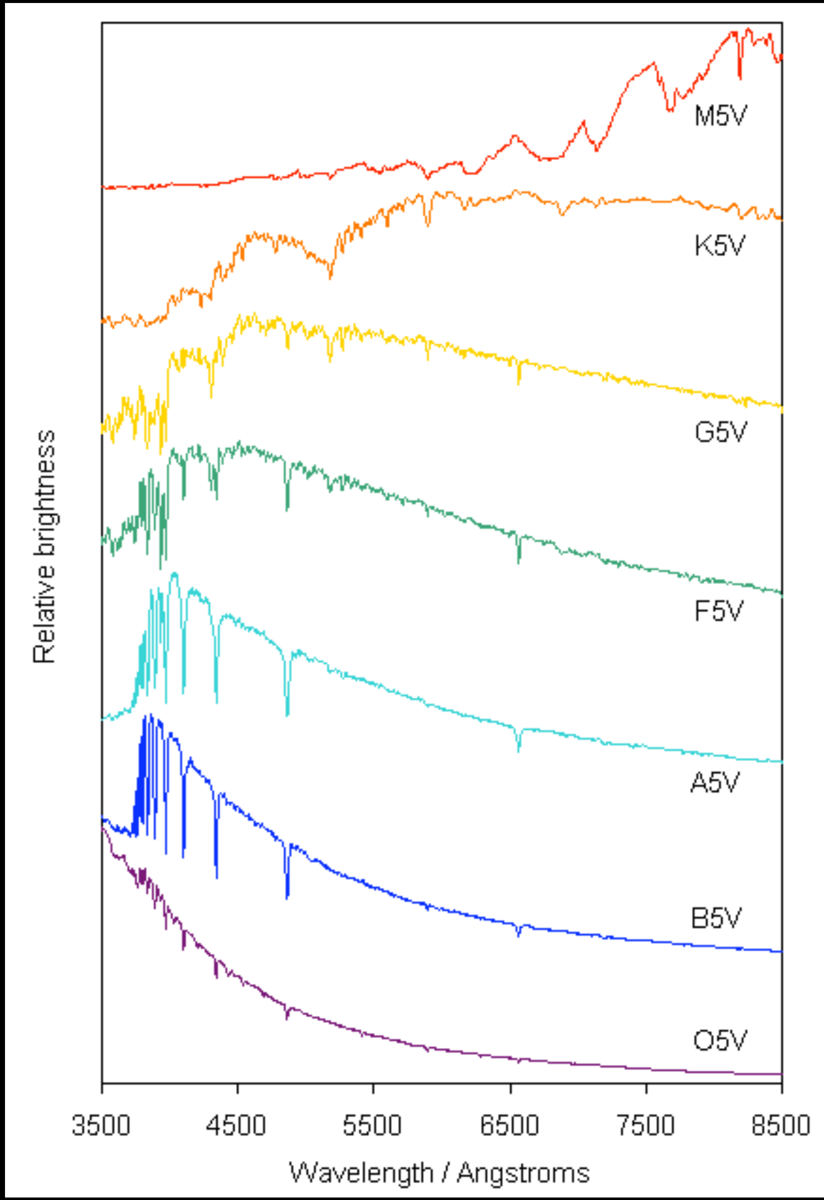
- Often the parameter of interest
- Points to note:
  - Z expected to evolve - in most cases it is ~OK to neglect Z evolution and simply solve for/assume <Z>
  - Because young stars so bright
    - What one assumes about recent SFH is important
    - What one assumes about ancient SFH less so…

1.3 Stellar library $f_\lambda(M,Z,t)$

- Straight sum of luminosities
  - Young main sequence very bright
    - blue
  - Post-main sequence short-lived but bright
    - Often red
  - Low-mass stars (those that make up the bulk of the mass) very faint
- ‘Luminosity-weighted’
- Skews one’s view towards young/post-MS stars…

Color-Temperature

- Hot stars (primarily young) are blue
- Cooler stars are red
  - Giants (rare,bright)
  - Main sequence (common,faint)

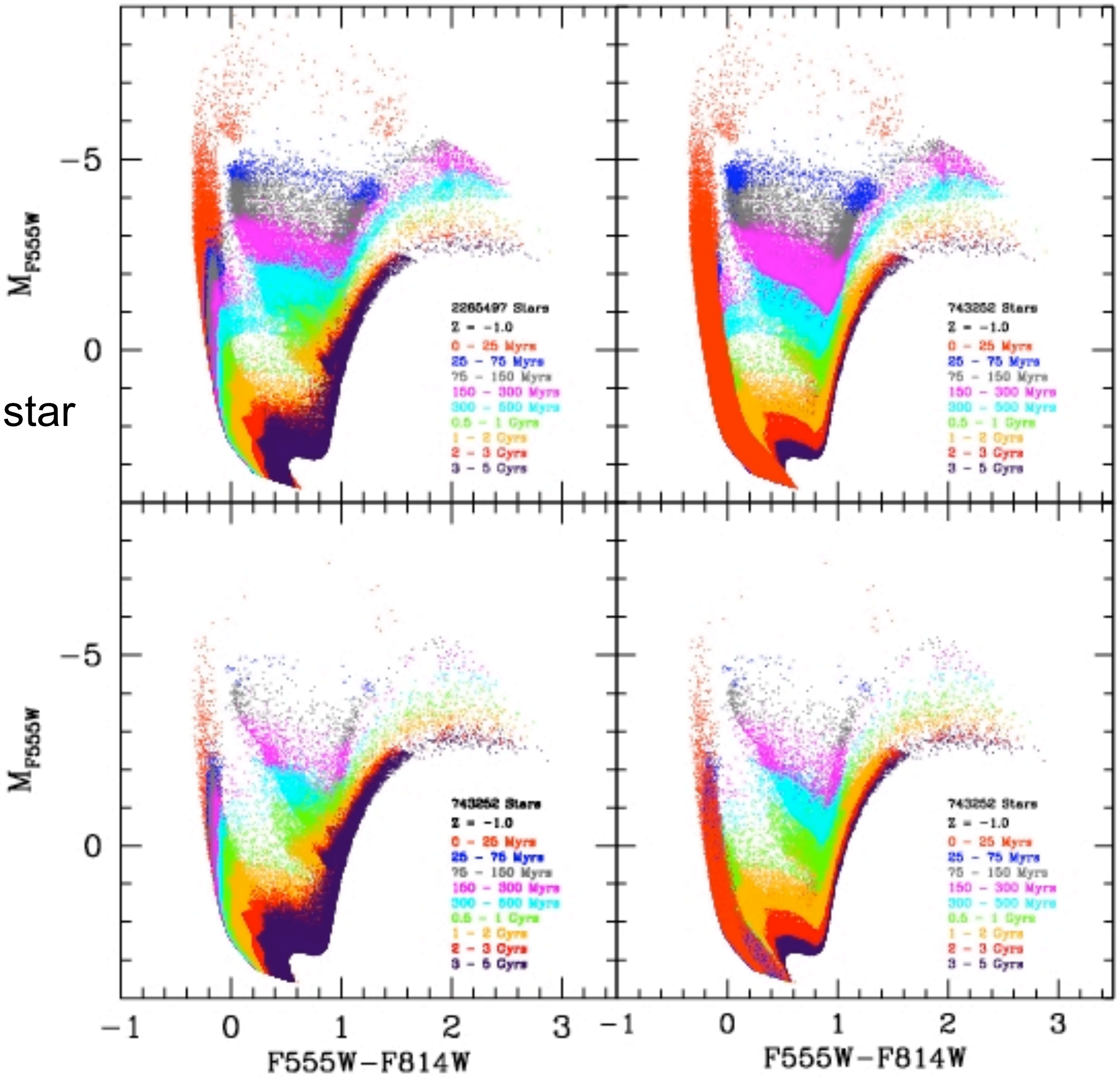


What does this look like?
SFR * IMF * flux for individual stars (before it's integrated over all stars…)
~ the integrand…

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

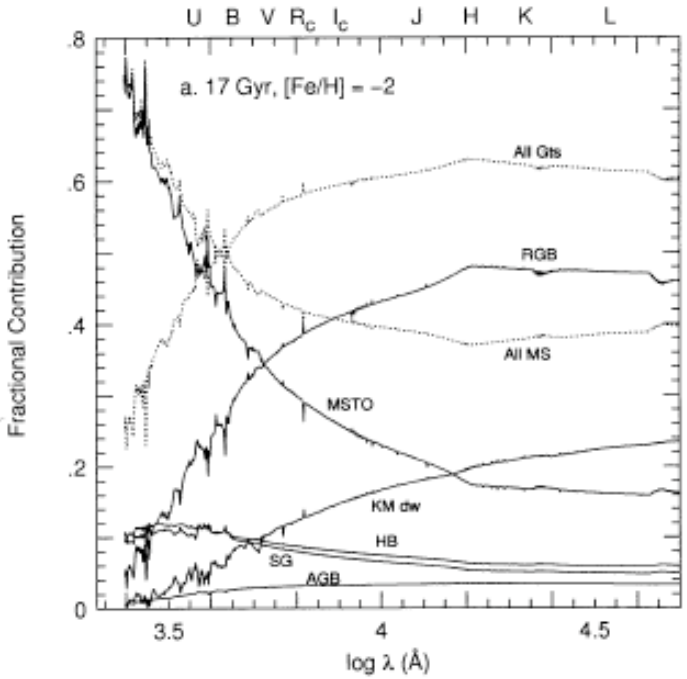
Top panels:
Increasing SFR to emphasize recent star formation

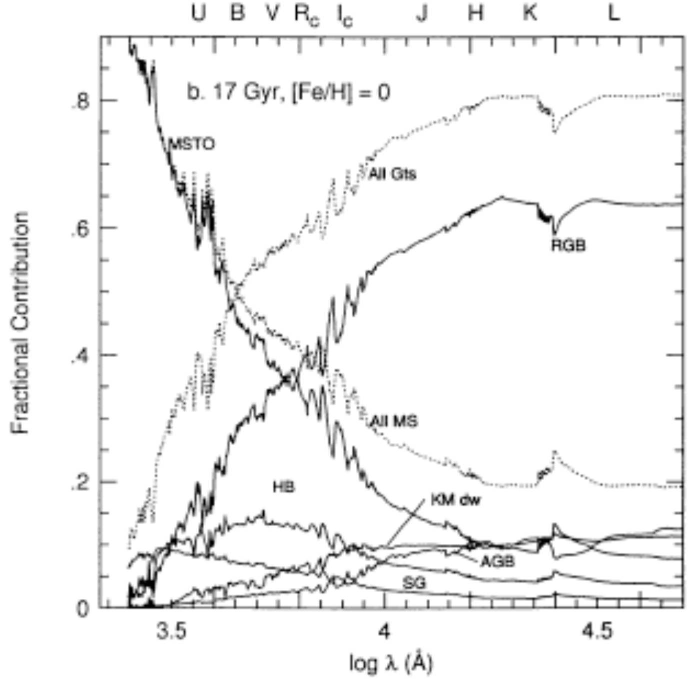
Bottom panels:
constant SFR.



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

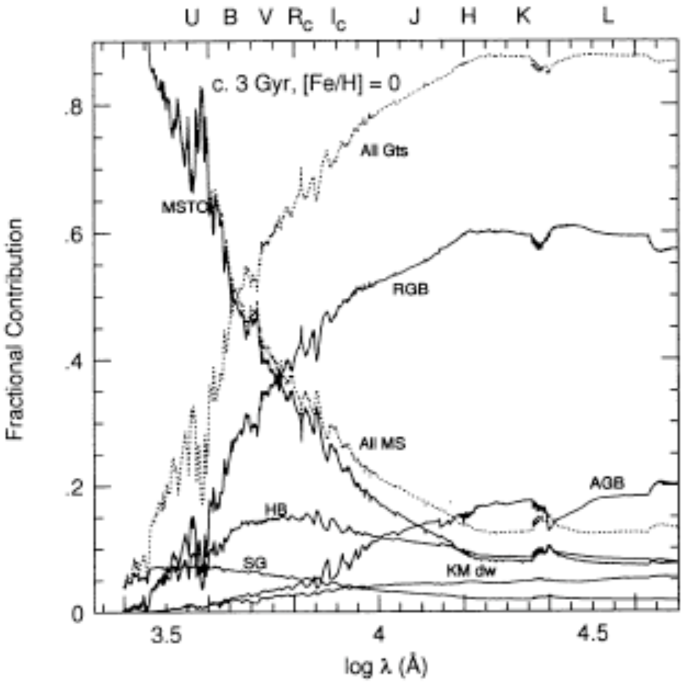
1.4 Results





1.4.1 λ dependence of contributions (Worthey et al. 1994)

FIG. 4a FIG. 4b

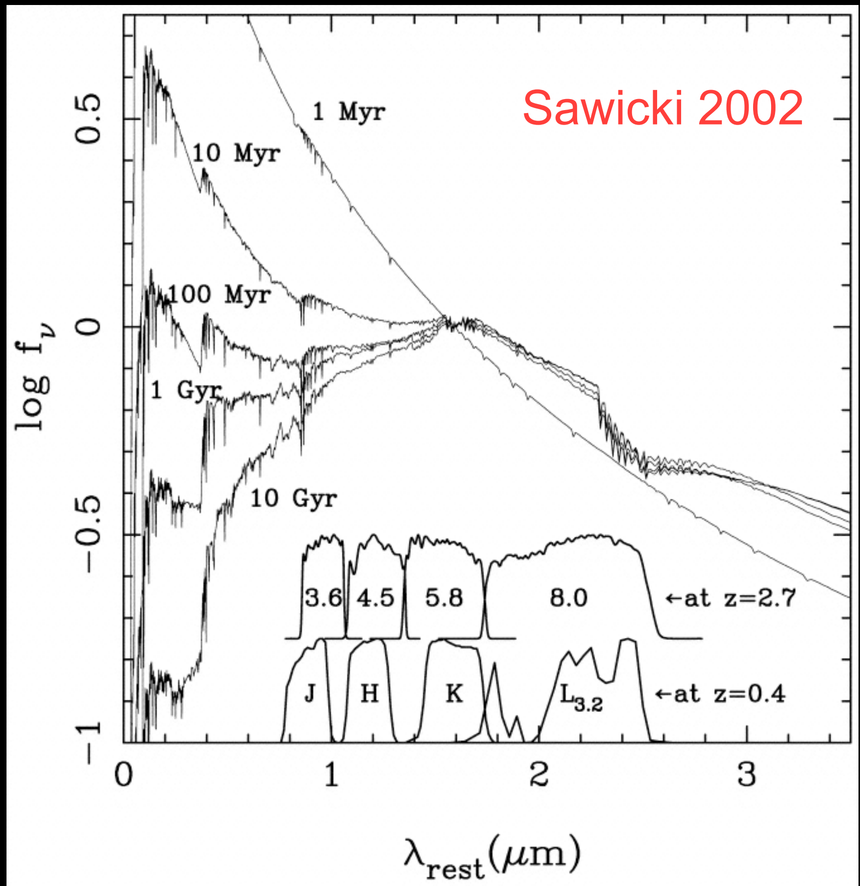


can reasonably expect the models to fit. Fitting function errors or wavelength-dependent errors ought to show up in these diagrams if they are present.

Looking through the diagrams, one sees that the Fe4383 (Fig. 49) index shows no significant offset from the models. There is a fair amount of breadth to the model sequence because young populations have weak Fe4383. Notice that in most of these diagrams M31 lies close to the [Fe/H] = +0.25, age = 8 or 12 Gyr symbols. Ca4455 (Fig. 50) is also in agreement with the models, as is Fe4531 (Fig. 51). Although many galaxies are scattered away from the main locus owing to the presence of nebular emission in the blue pseudocontinuum of the Fe5015 index (Fig. 52), the median locus is well traced by the models. Recall that the galaxy sample is heterogeneous, and emission effects have not been corrected. Fe5335 (Fig. 53) is well matched by the models, but Fe5406 (Fig. 54) suffers from a problem with nebular emission like that of Fe5015. Most galaxies in the Fe5709 plot (Fig. 55) land on the model locus, but M31 does not by several σ. Although it is tempting to speculate on possible causes for such a significant deviation,

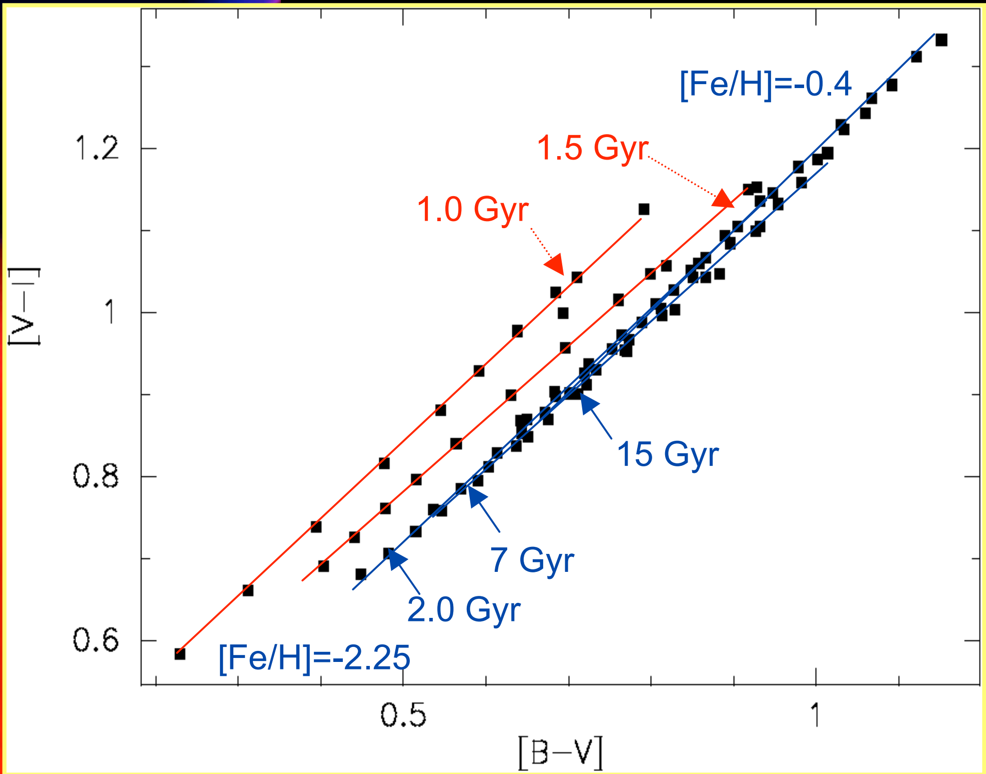
1.4.2 Distinctive / important features

- 4000 angstrom break
- 1.6um bump (from a minimum in H- opacity; much of the opacity from stars is from H-)…
- Most important absorption lines
  - Balmer lines, metal lines

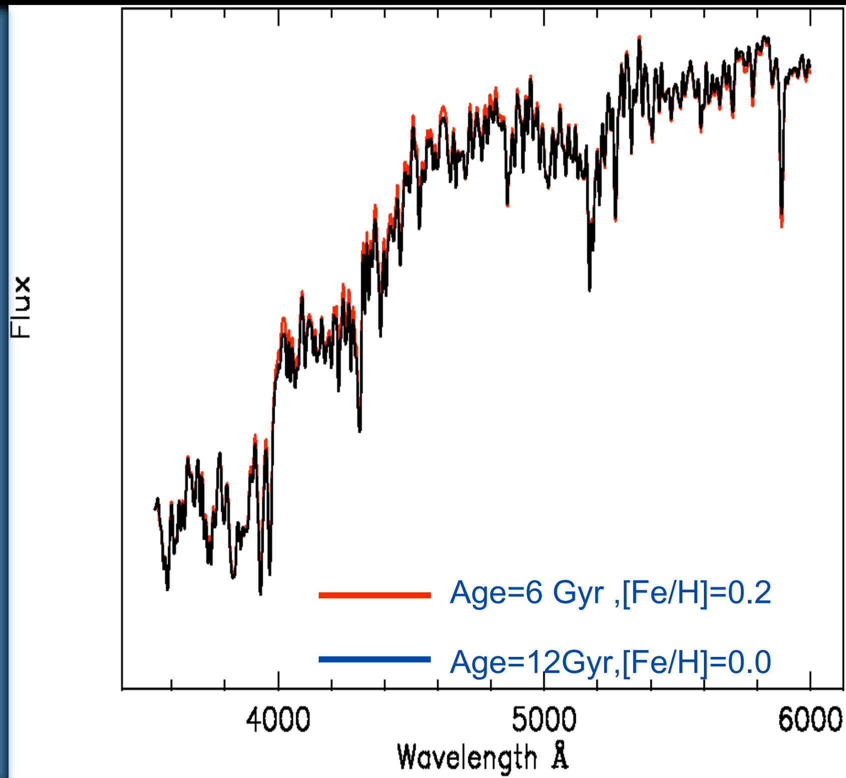


1.4.3 Age-metallicity degeneracy

- **The age-metallicity degeneracy:**
  - *Young, metal-rich populations strongly resemble old, metal-poor populations.*



Models: Bruzual & Charlot (2003)

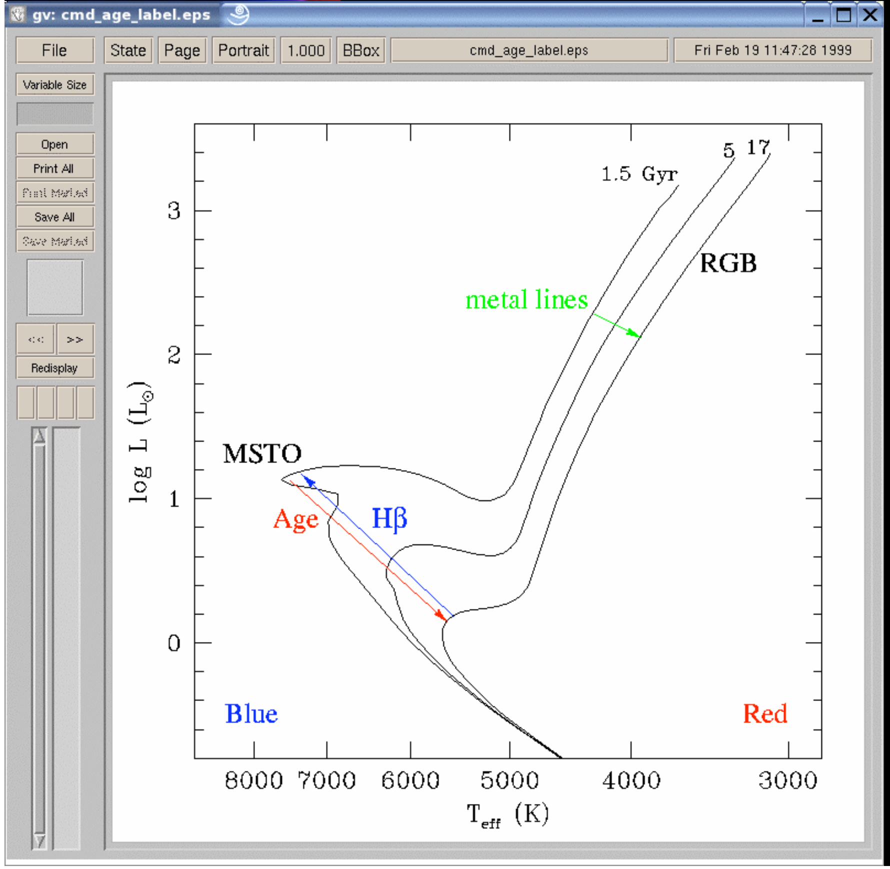


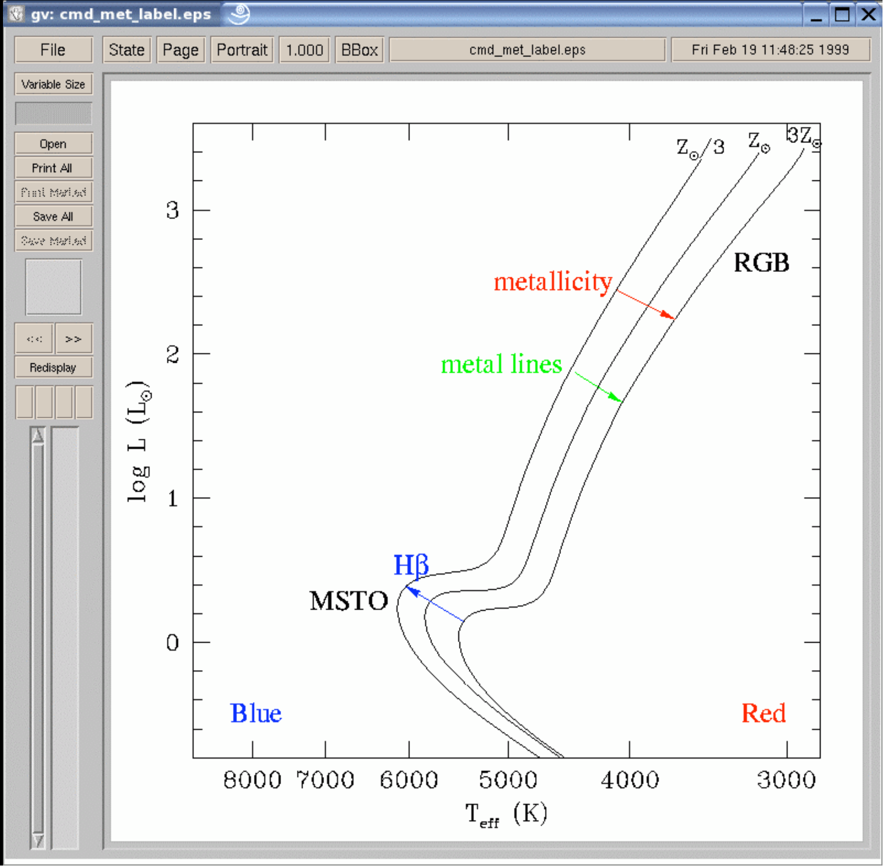
Models: Sanchez-Blazquez (Ph.D. thesis); Vazdekis et al. 2005 (in prep)

1.4.3 a Some discrimination

- Long wavelength baseline
- MSTO vs. giant-sensitive line indices

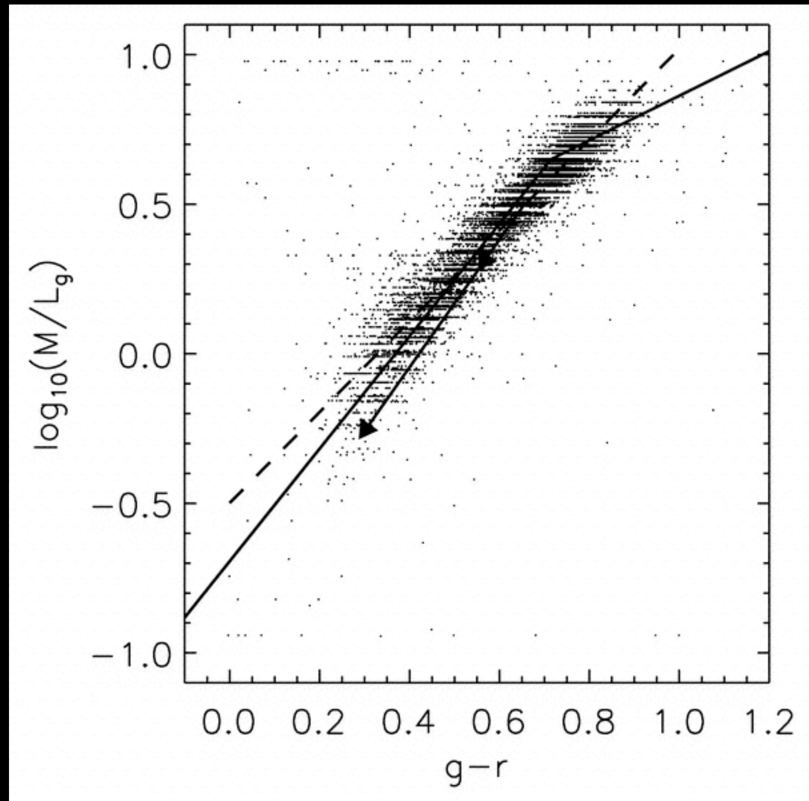
Trager 2000





1.4.4 Stellar masses

- Age-metallicity degeneracy can work for us…
- Stellar M/Ls close to unique function of SED shape
- Cheap estimation of stellar masses.



Bell et al. 2003

1.4.4.1 Normalisation : stellar IMF

- Normalisation depends on stellar IMF
- Salpeter IMF
  - too much mass in low-mass stars
- Chabrier / Kroupa 2001 OK…

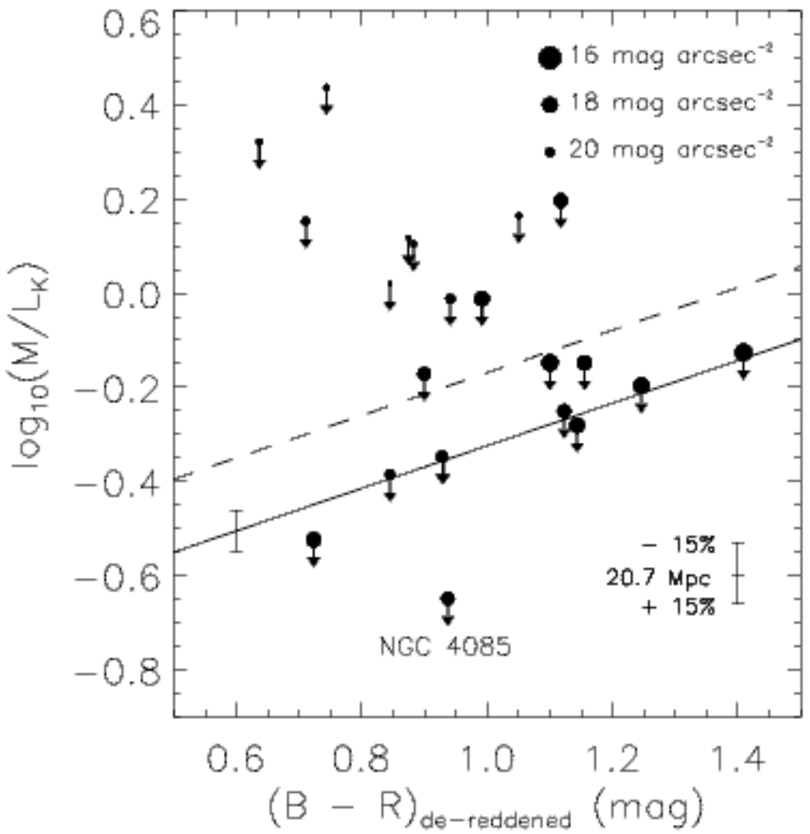
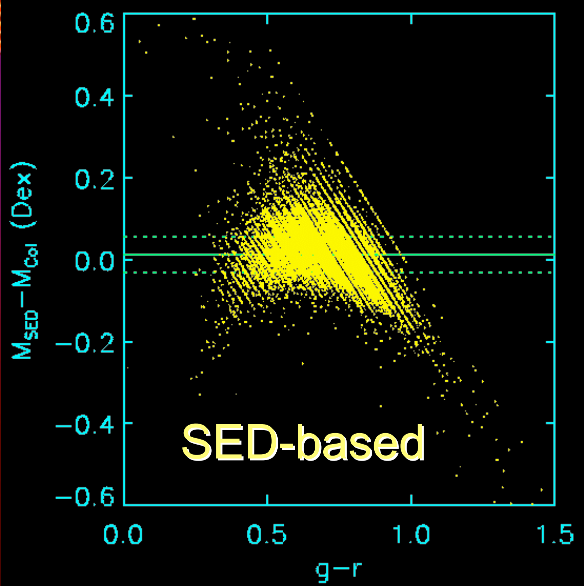


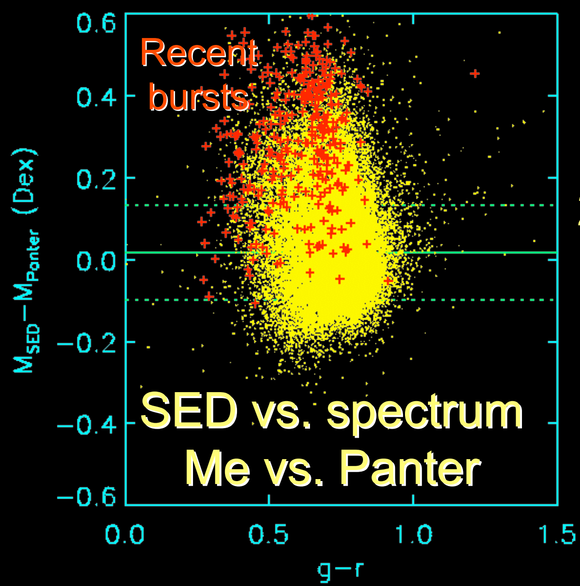
FIG. 6.— Observed K band maximum disk stellar M/Ls against de-reddened $B-R$ color. The data are from K band imaging and HI rotation curves from Verheijen (1997, Chapter 6), rescaled to a distance of 20.7 Mpc (Sakai et al. 2000): the effect on the maximum disk M/Ls of a ±15% Ursa Major Cluster distance error is also shown. Overplotted is the least-squares fit to the correlation between color and stellar M/L for the formation epoch with bursts model assuming a Salpeter (dashed line) and a scaled-down Salpeter IMF (solid line). We also show the RMS spread of the formation epoch with bursts model around the color–M/L relation on the solid line as an error bar. NGC 4085 is highlighted: it has a poorly resolved rotation curve, which biases the maximum disk M/L downwards. Symbol size is coded by inclination-corrected K band central surface brightness.

Heidelberg
March 2009

1.4.4.2 Stellar masses

- Assumption - universal IMF
- Methods
  - SED fitting Spectrum fitting
  - Comparison with dynamics: ~0.1 dex scatter





de Jong & Bell, 2002-2009; in prep.

Comparing M* for SDSS galaxies

1.4.4.3 Example stellar M/L calibns

TABLE A7

STELLAR M/L RATIO AS A FUNCTION OF COLOR

Color	a_g	b_g	a_r	b_r	a_i	b_i	a_z	b_z	a_J	b_J	a_H	b_H	a_K	b_K
$u-g$	−0.221	0.485	−0.099	0.345	−0.053	0.268	−0.105	0.226	−0.128	0.169	−0.209	0.133	−0.260	0.123
$u-r$	−0.390	0.417	−0.223	0.299	−0.151	0.233	−0.178	0.192	−0.172	0.138	−0.237	0.104	−0.273	0.091
$u-i$	−0.375	0.359	−0.212	0.257	−0.144	0.201	−0.171	0.165	−0.169	0.119	−0.233	0.090	−0.267	0.077
$u-z$	−0.400	0.332	−0.232	0.239	−0.161	0.187	−0.179	0.151	−0.163	0.105	−0.205	0.071	−0.232	0.056
$g-r$	−0.499	1.519	−0.306	1.097	−0.222	0.864	−0.223	0.689	−0.172	0.444	−0.189	0.266	−0.209	0.197
$g-i$	−0.379	0.914	−0.220	0.661	−0.152	0.518	−0.175	0.421	−0.153	0.283	−0.186	0.179	−0.211	0.137
$g-z$	−0.367	0.698	−0.215	0.508	−0.153	0.402	−0.171	0.322	−0.097	0.175	−0.117	0.083	−0.138	0.047
$r-i$	−0.106	1.982	−0.022	1.431	0.006	1.114	−0.052	0.923	−0.079	0.650	−0.148	0.437	−0.186	0.349
$r-z$	−0.124	1.067	−0.041	0.780	−0.018	0.623	−0.041	0.463	−0.011	0.224	−0.059	0.076	−0.092	0.019
Color	a_B	b_B	a_V	b_V	a_R	b_R	a_I	b_I	a_J	b_J	a_H	b_H	a_K	b_K
$B-V$	−0.942	1.737	−0.628	1.305	−0.520	1.094	−0.399	0.824	−0.261	0.433	−0.209	0.210	−0.206	0.135
$B-R$	−0.976	1.111	−0.633	0.816	−0.523	0.683	−0.405	0.518	−0.289	0.297	−0.262	0.180	−0.264	0.138

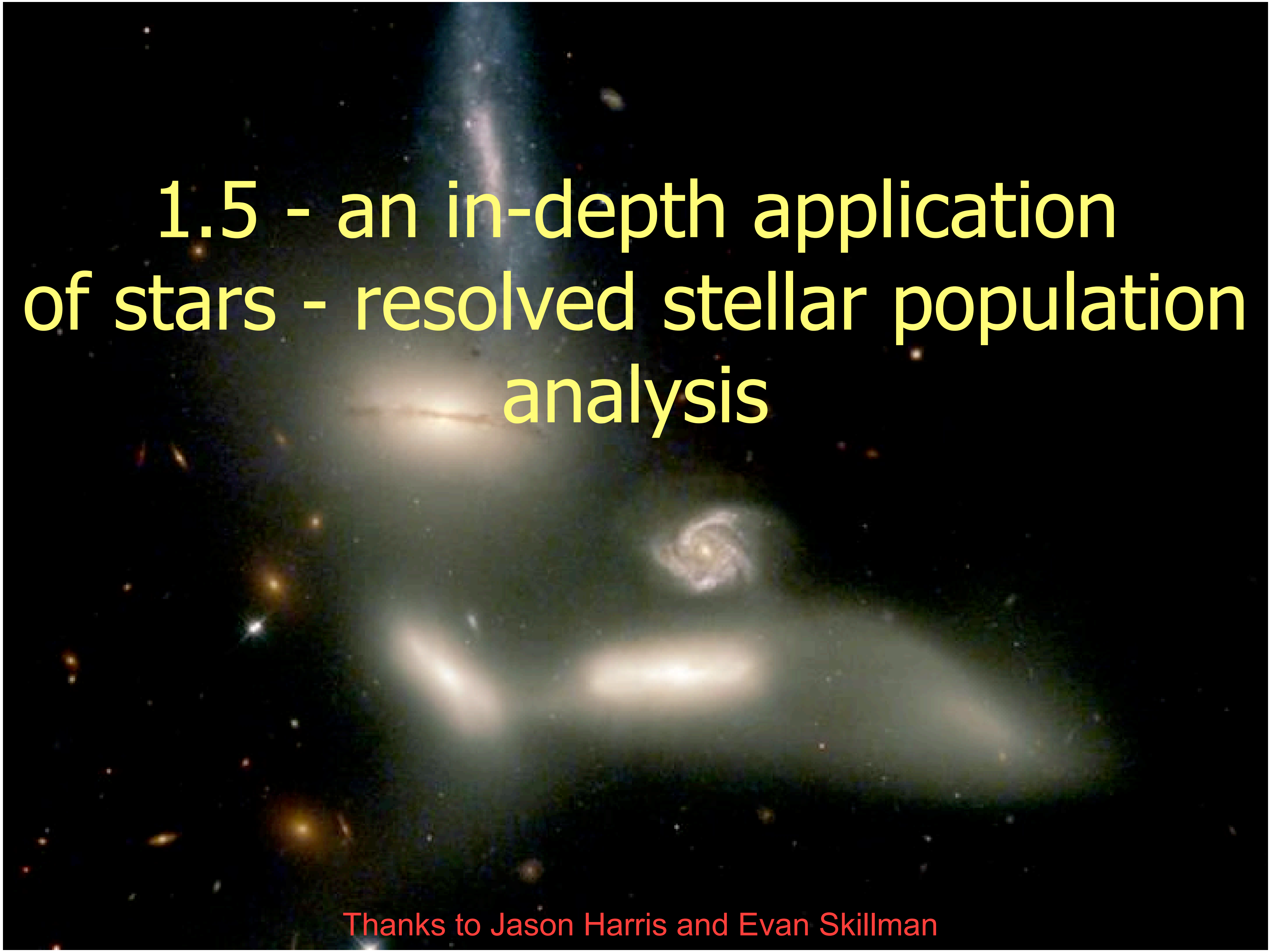
Note. — Stellar M/L ratios are given by $\log_{10}(M/L) = a_\lambda + (b_\lambda \times \text{Color})$ where the M/L ratio is in solar units. If *all* galaxies are sub-maximal then the above zero points (a_λ) should be modified by subtracting an IMF dependent constant as follows: 0.15 dex for a Kennicutt or Kroupa IMF, and 0.4 dex for a Bottema IMF. Scatter in the above correlations is ~ 0.1 dex for all optical M/L ratios, and 0.1–0.2 dex for NIR M/L ratios (larger for galaxies with blue optical colors). SDSS filters are in AB magnitudes; Johnson BVR and JHK are in Vega magnitudes.

Kroupa / Chabrier -- actually -0.1 dex (Borch et al. 2006)

Summary I : stars

- Almost all energy from galaxies is from stars (direct or reprocessed)
- Emergent spectrum is triple integral
  - IMF (often assume universal), SFH, stellar library
  - Straight sum of luminosities
    - Weighted towards young, post-MS stars
- Age/metallicity degeneracy
    - Some useful features comparing MSTO/Giants
- Stellar masses
    - Uses age/met degeneracy - colors/spectra
    - Good to 30% in good conditions

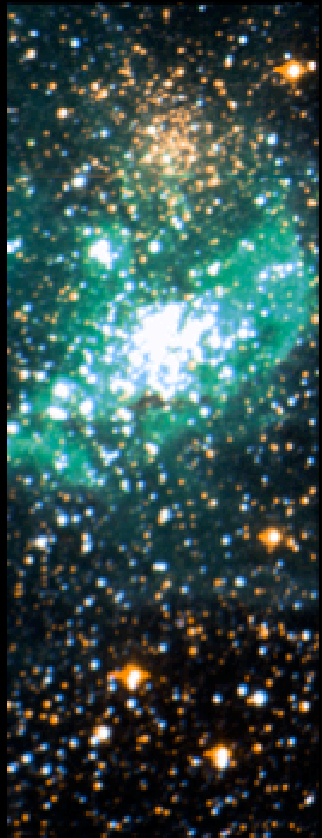
1.5 - an in-depth application of stars - resolved stellar population analysis



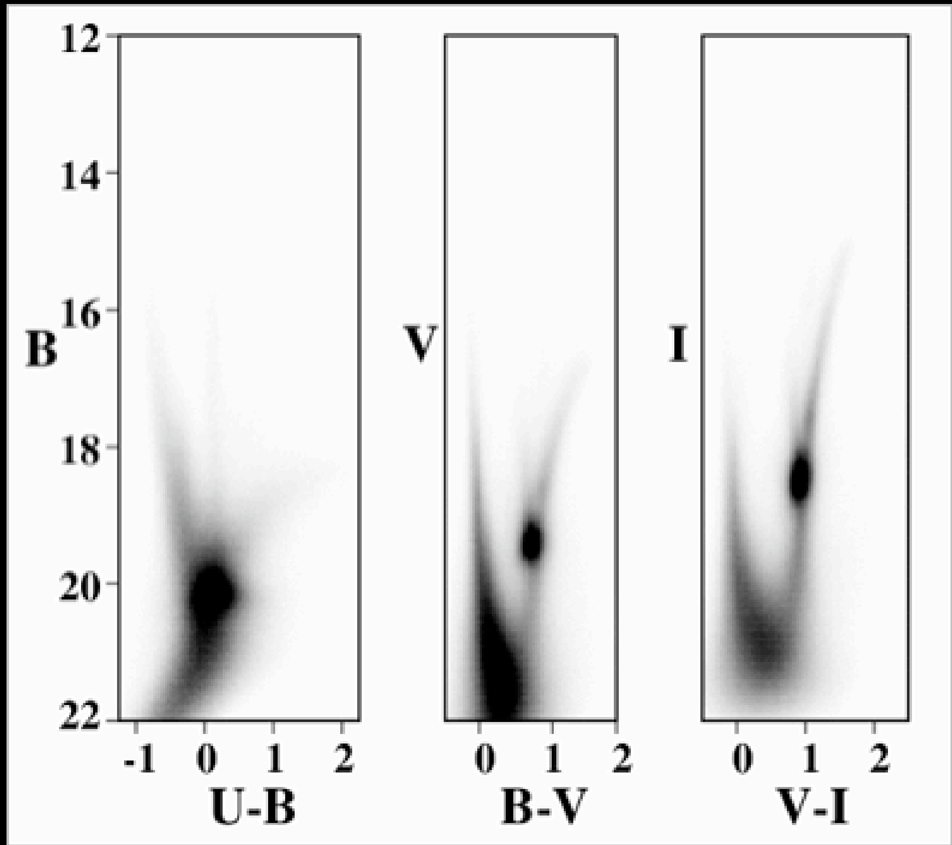
Thanks to Jason Harris and Evan Skillman

Not Just Another Pretty Fuzz

Content: Rich Stellar Populations



NGC 346



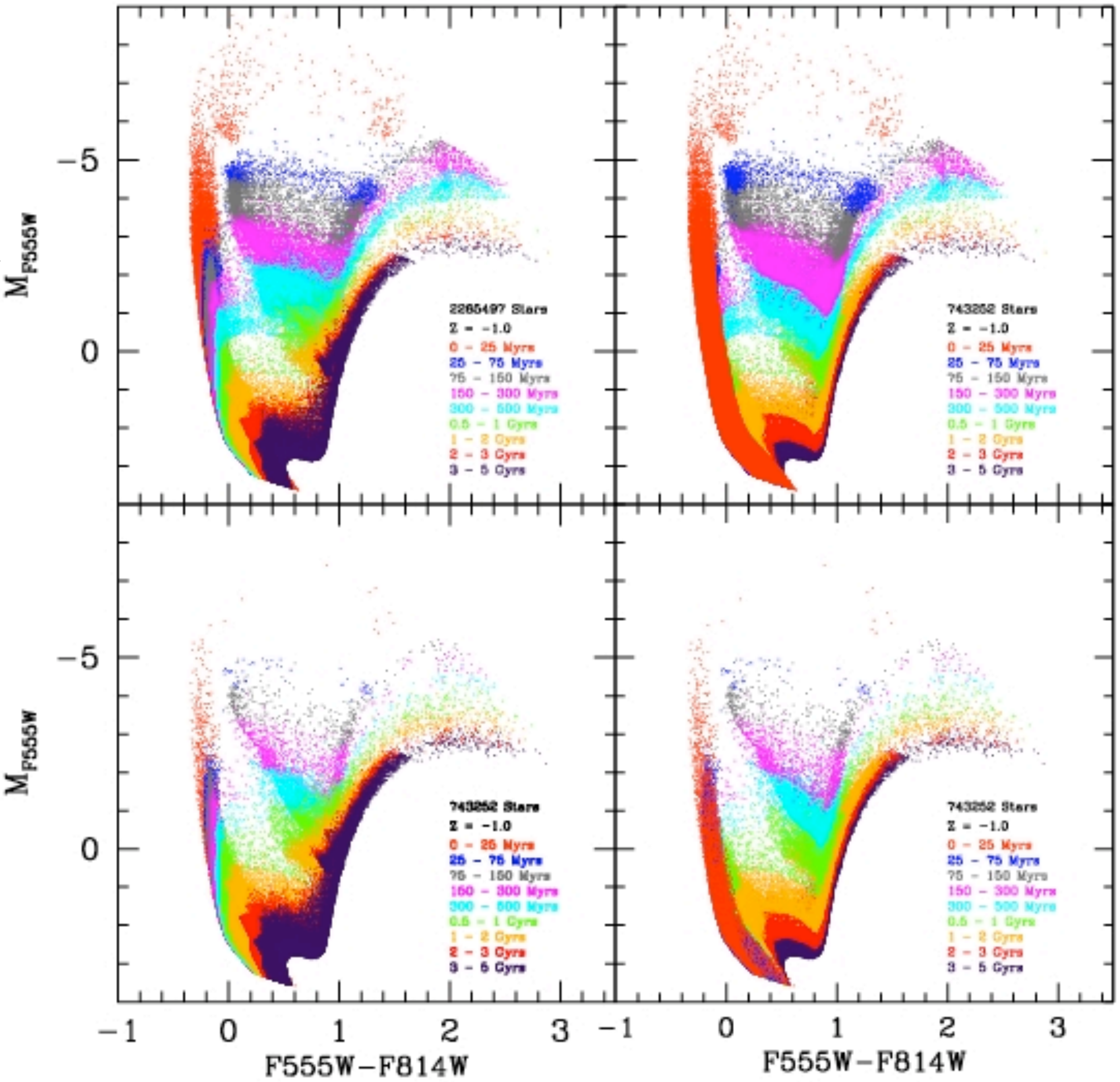
UBVI photometry of 6M SMC stars

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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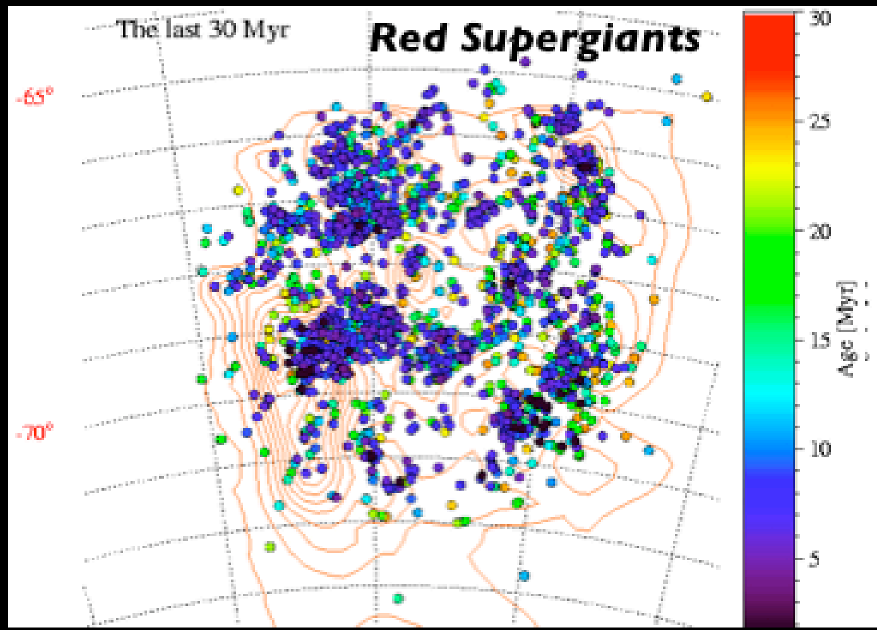

Grebel & Brandner (1998)

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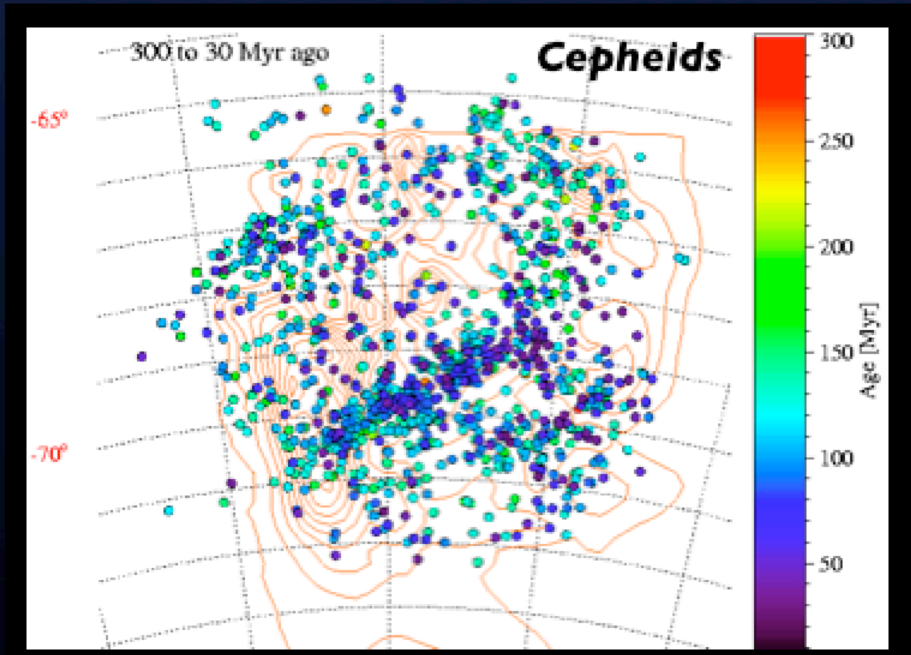


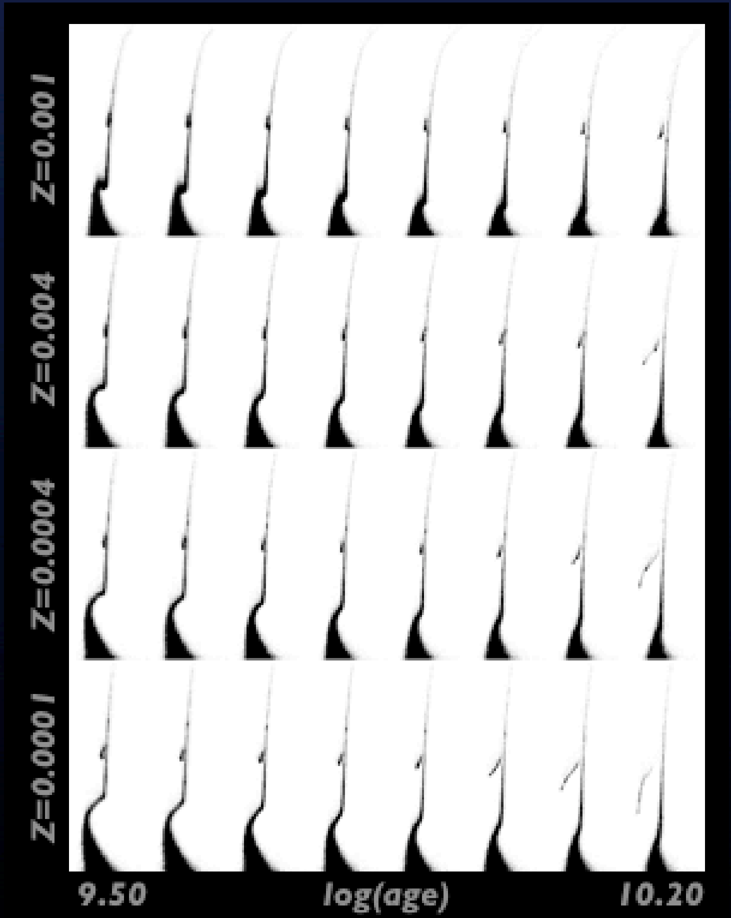
Grebel & Brandner (1998)

Star Formation Histories

Synthetic CMDs

Basic operation of synthCMD methods:

Construct synthetic CMD library from isochrones



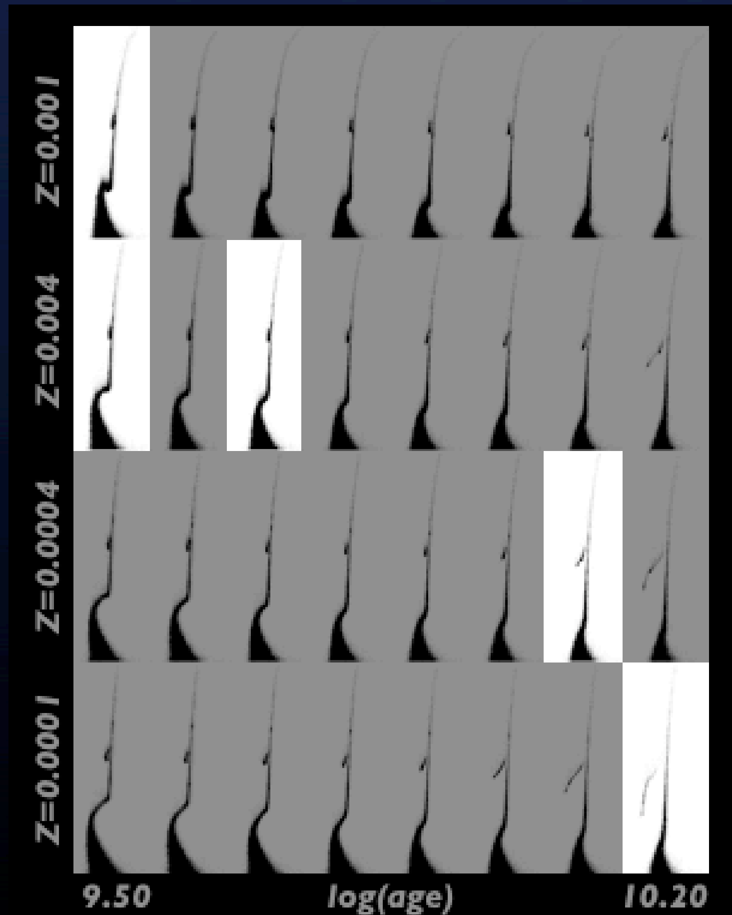
Star Formation Histories

Synthetic CMDs

Basic operation of synthCMD methods:

Construct synthetic CMD library from isochrones

Combine synthCMDs linearly to make composite model



Star Formation Histories

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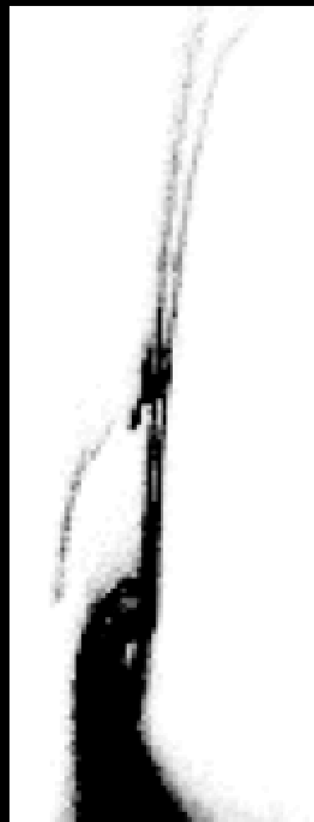


composite model

Star Formation Histories

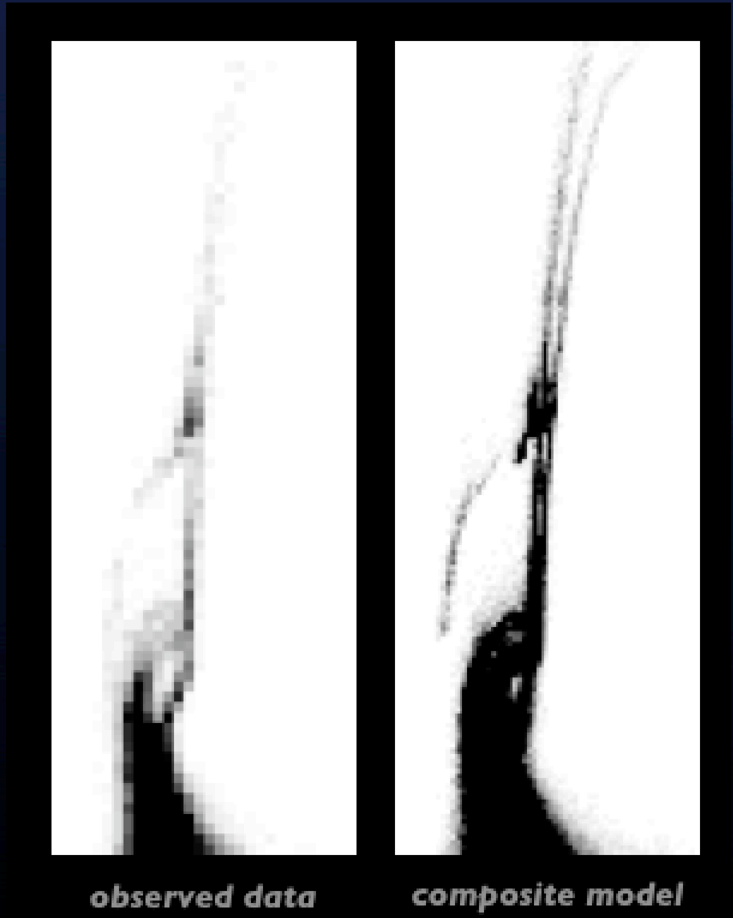
Synthetic CMDs

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



Star Formation Histories

Synthetic CMDs

Basic operation of synthCMD methods:

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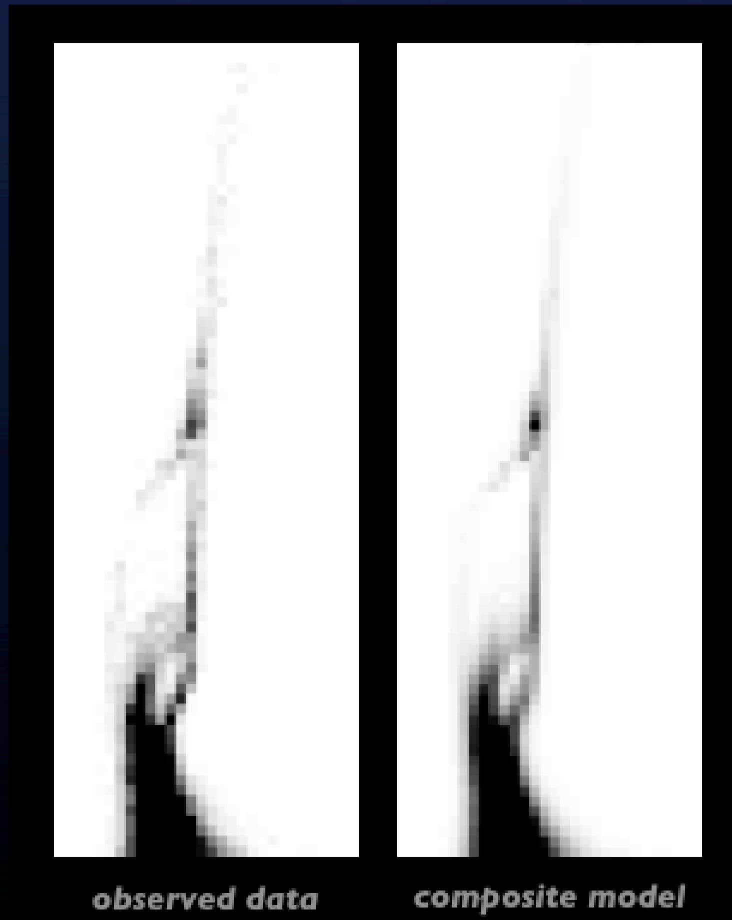
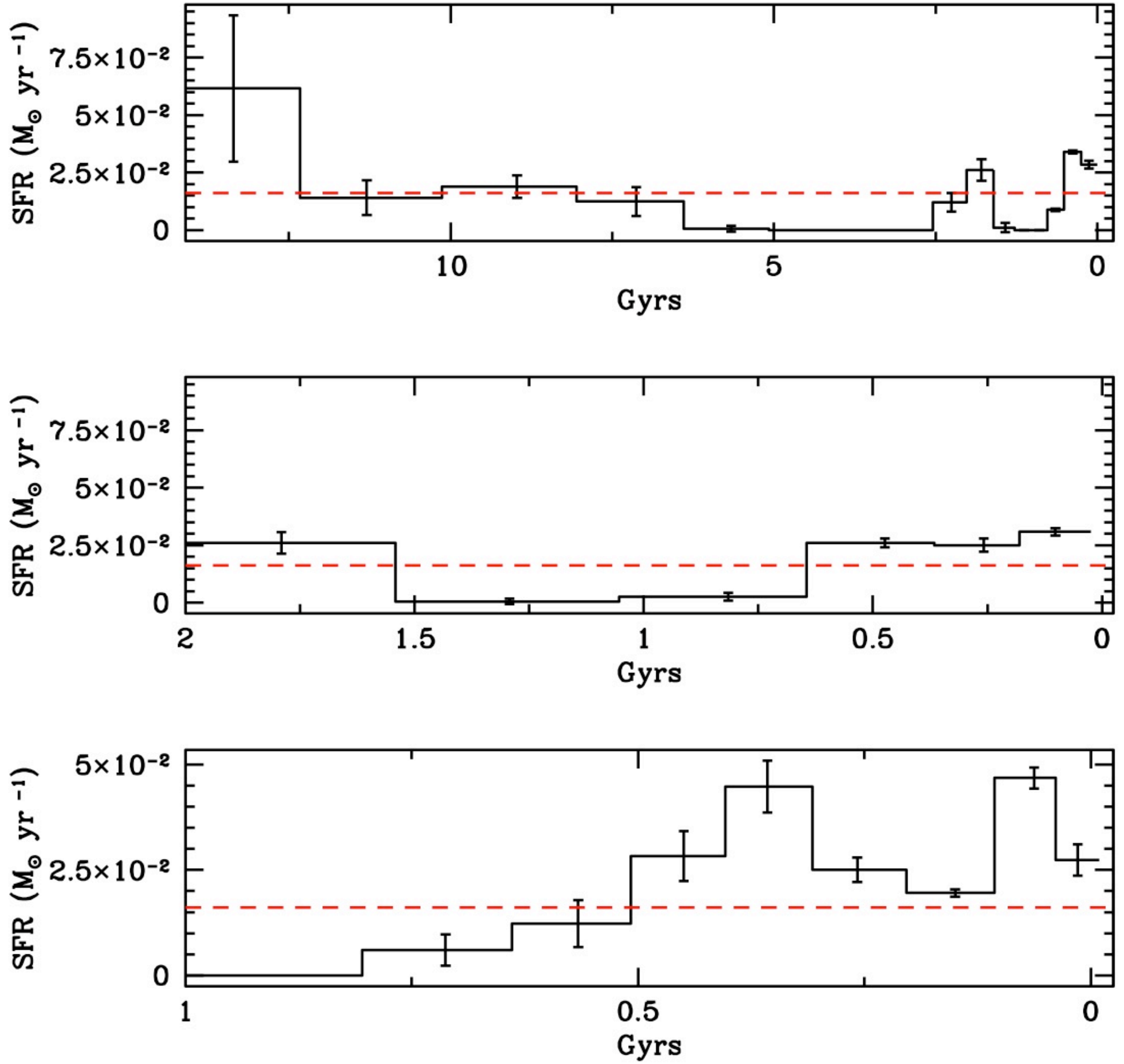


DDO 165 in the M81 group

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…



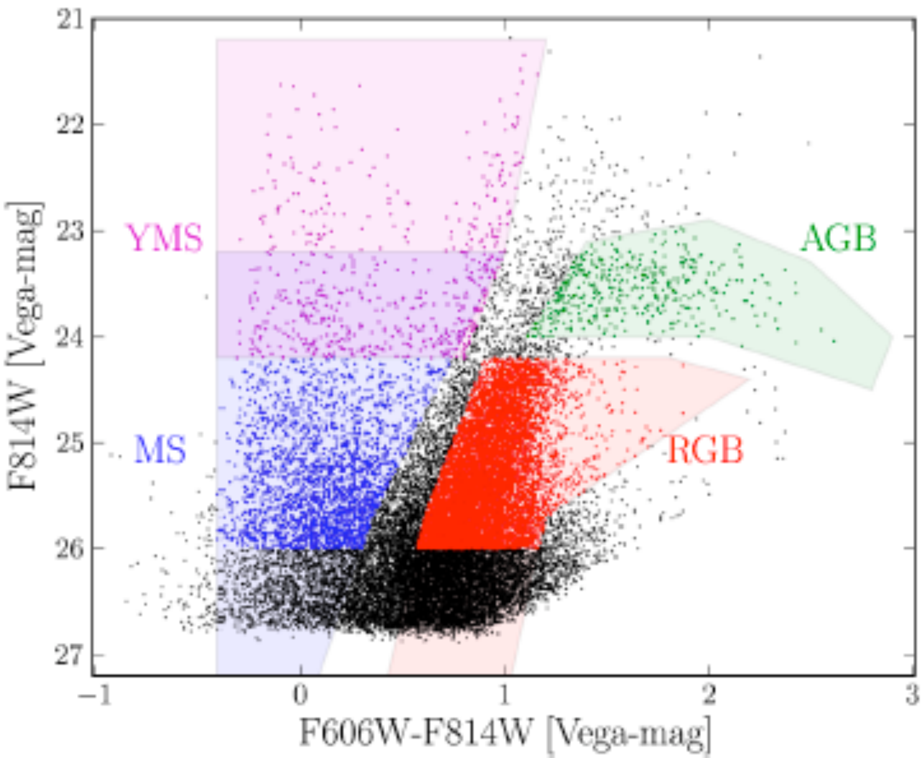
A Key Result….

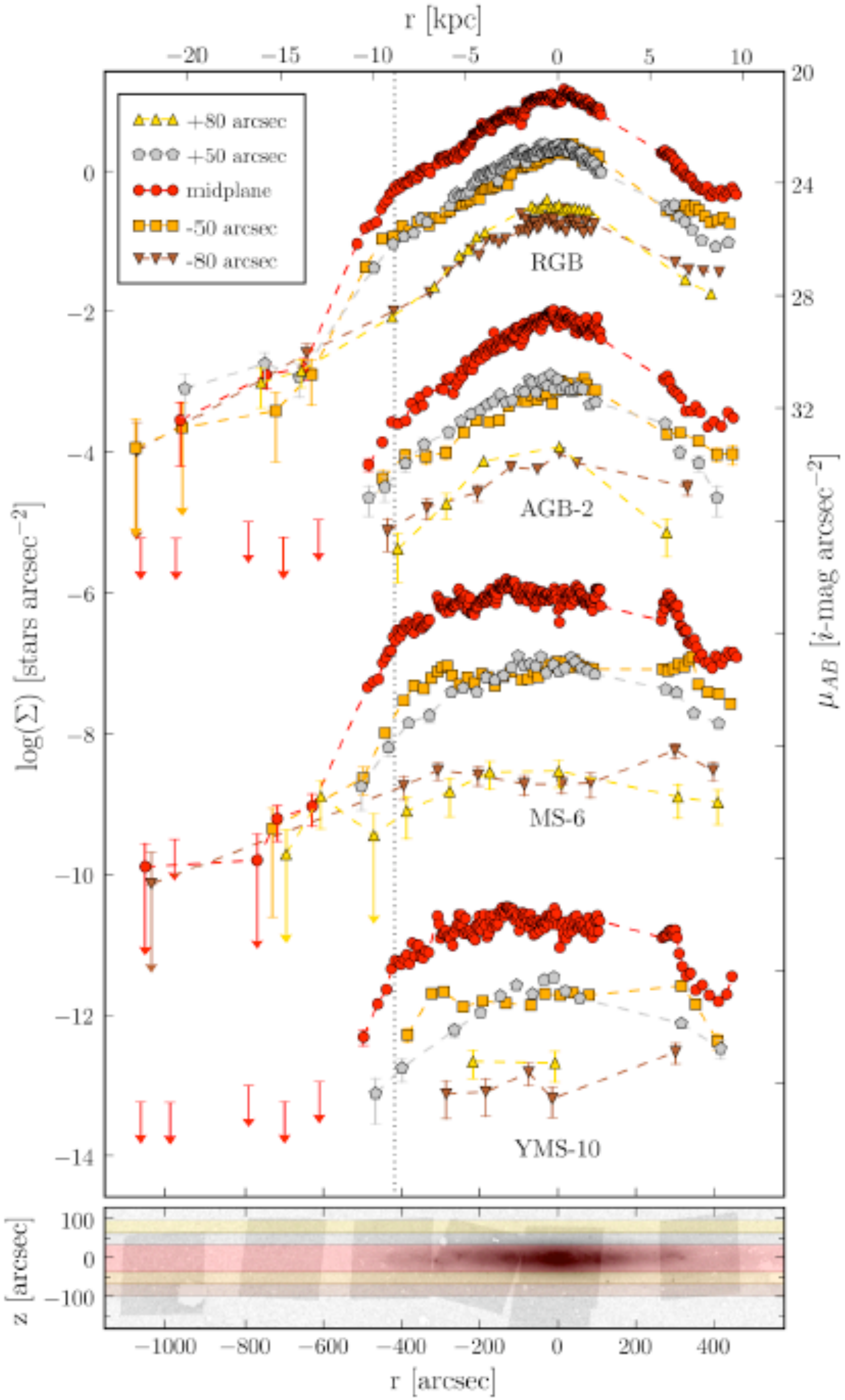
- Dolphin et al. 2005 (on astroph)
  - Irregulars --> Spheroidals through gas loss alone (I.e., SFHs at ancient times v. similar)

Results

de Jong et al. 2007

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





Summary II : CMDs

- 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?

Dust attenuation and emission

Thanks to Brent Groves

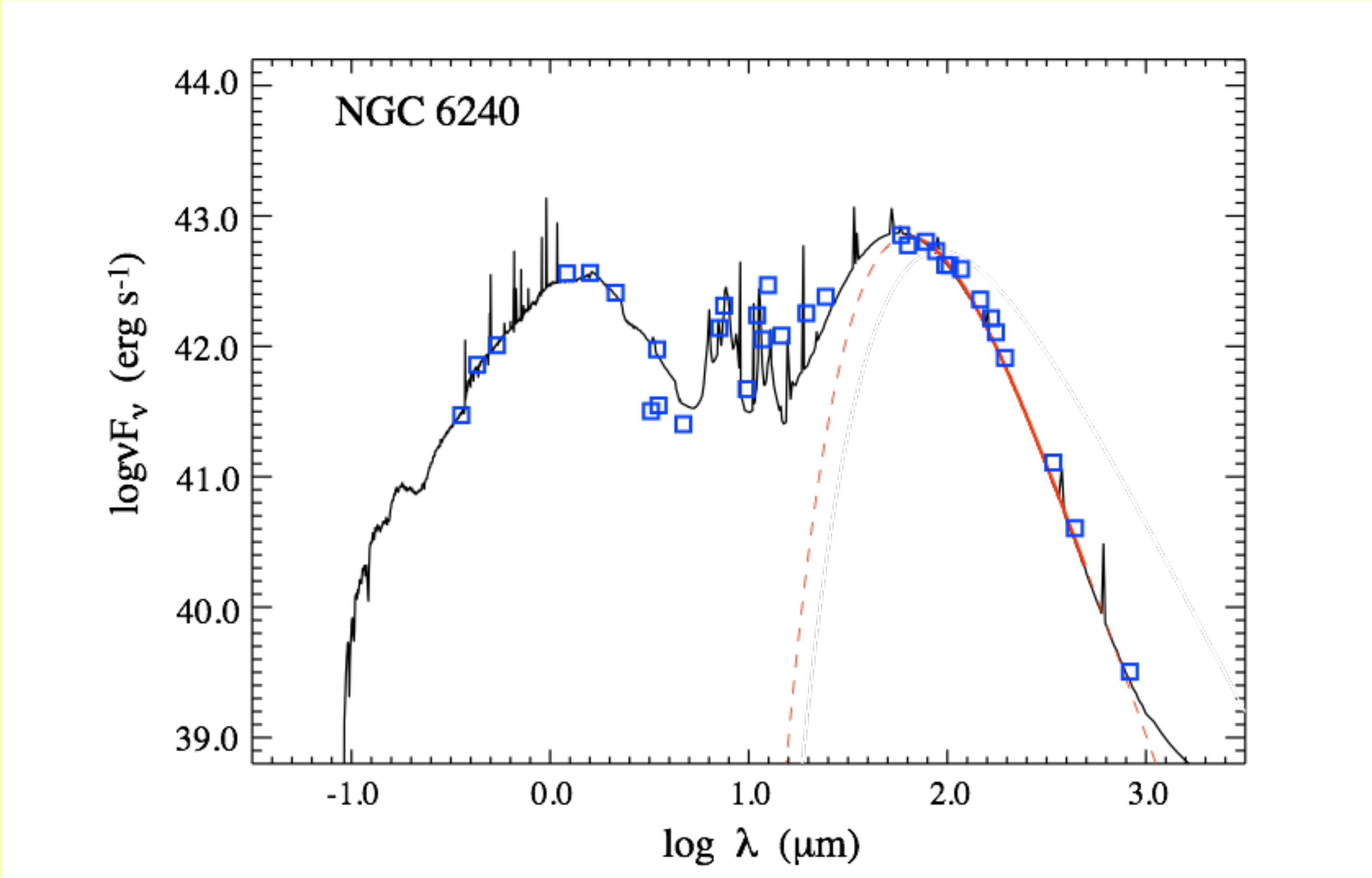
2. Dust

- Dust absorbs and scatters UV/optical light, energy heats grains and they emit in the thermal IR

- 2.1 - emission from dust grains
- 2.2 - extinction/attenuation

Spectrum

Stolen from a talk by Brent Groves



2.1.1 Dust - key concepts

- Absorption of UV/optical photons (1/2 to 2/3 of all energy absorbed + re-emitted)
- Grains re-emit energy

- Grain size distribution
  - PAHs - various benzene-style modes (very small, big molecules, band struc)
  - Very small grains - transient heating
  - Larger grains - eqm heating

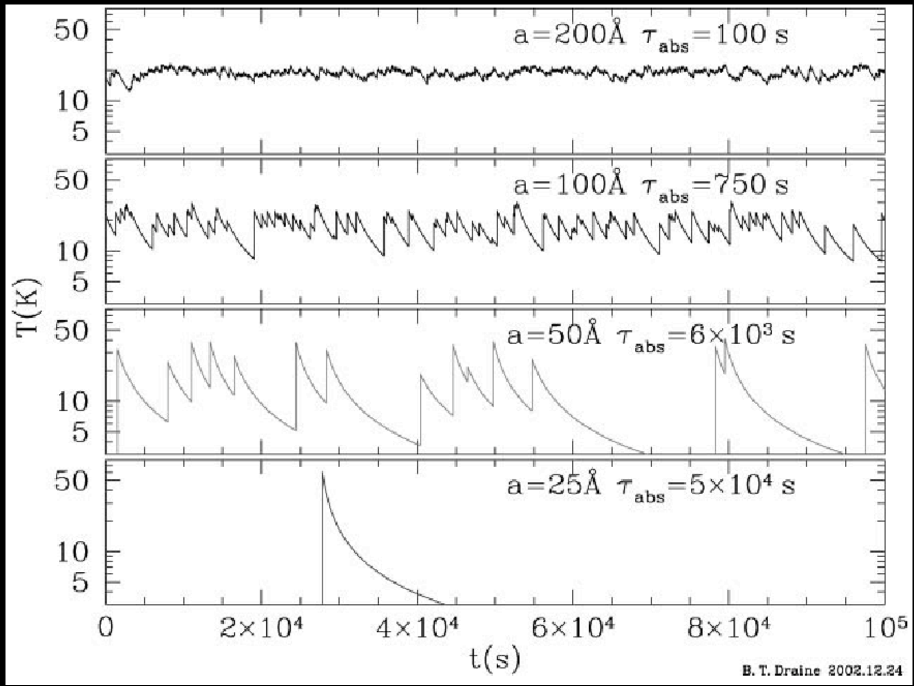
2.1.2 Dust - key concepts II

- Thermal equilibrium
  - $4\pi\ \sigma\ r^2\ T^4 = (L^*/\ 4\pi d^2)\qquad \pi\ r^2\ (1\text{-}A)$

    Emission   Local radn density   Absorption
  - $T^4 = (L^*/\ 4\pi d^2)\ \ (1\text{-}A)/4\sigma$
    - Independent of dust grain size
  - Challenge - name 3 or 4 situations when you've seen the consequences of this before…

2.1.2.1 Small grains not in equilibrium

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

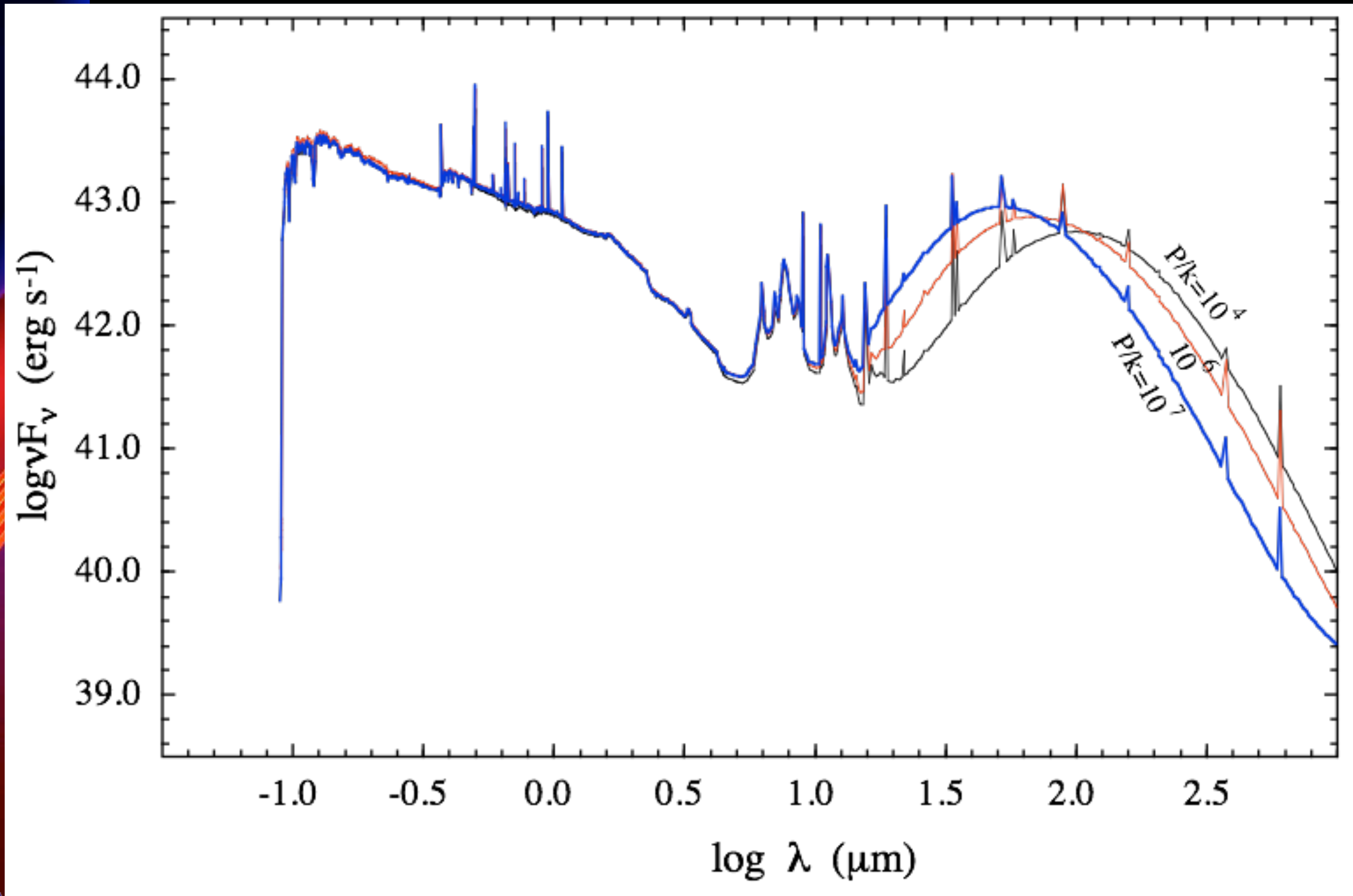


Credit: Brent Groves

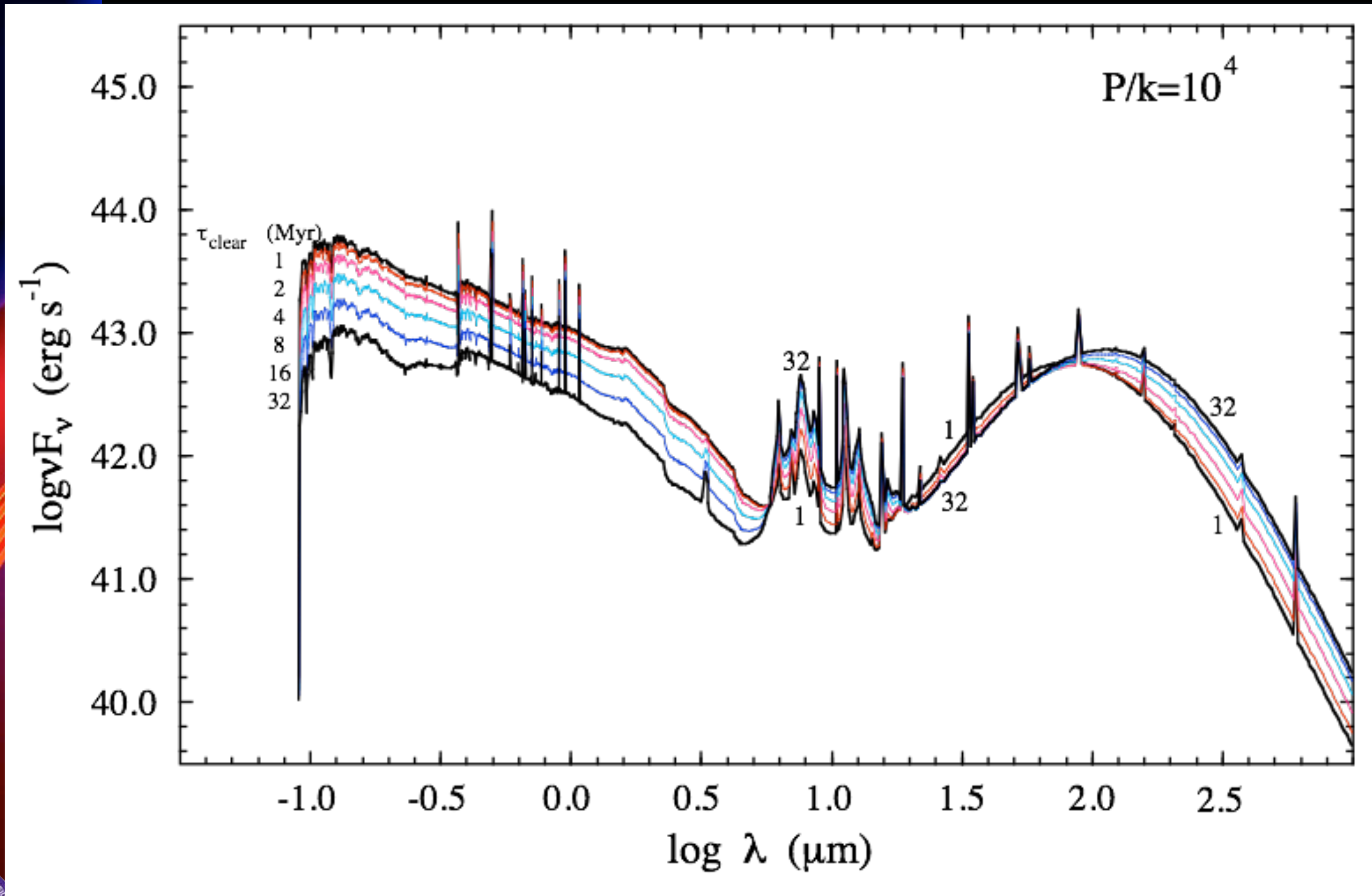
2.1.3 Ingredients of a dust model

- Grain size distribution
  - Solve for temperature distribution given radiation field
  - Paint on black bodies of that temperature
  - Add PAH features (usually by hand!)
- Radiation field from stellar models + geometry
- Dust geometry critical - controls how much energy absorbed and temp of emitting dust.
- Definition : Photodissociation Region
  - All regions of ISM where FUV photons dominate physical/chemical processes

2.1.3.1 Dust density…



2.1.3.2 Opacity…



2.1.4 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)

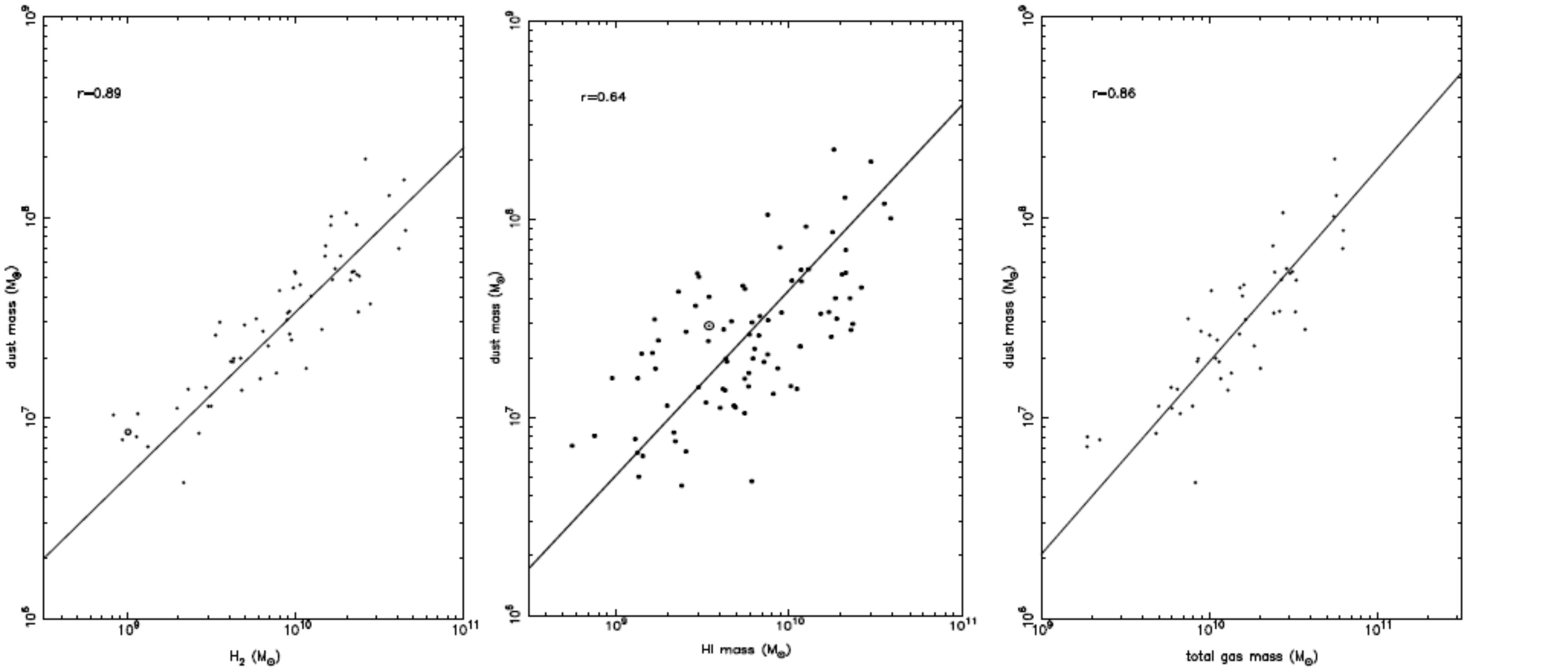
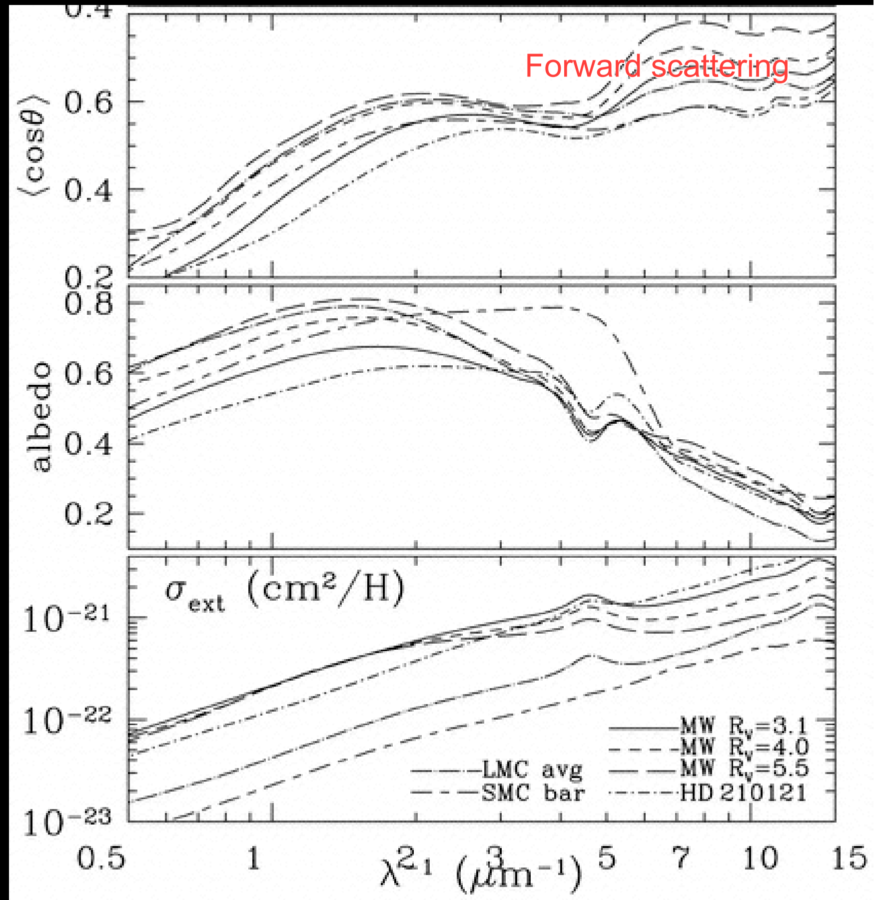


Figure 14. a) Dust mass versus H_2 mass, a solar symbol indicates the Milky Way values (Sodroski et al. 1994). The line is the best least squares fit (see Table 8 for fit parameters).
b) Dust mass versus HI mass, the line indicates the best least squares fit to the data. There is much more dispersion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

2.2 Extinction

- Absorption and scattering
  - Thus, geometry is critical
- Optically-thick distributions behave less intuitively

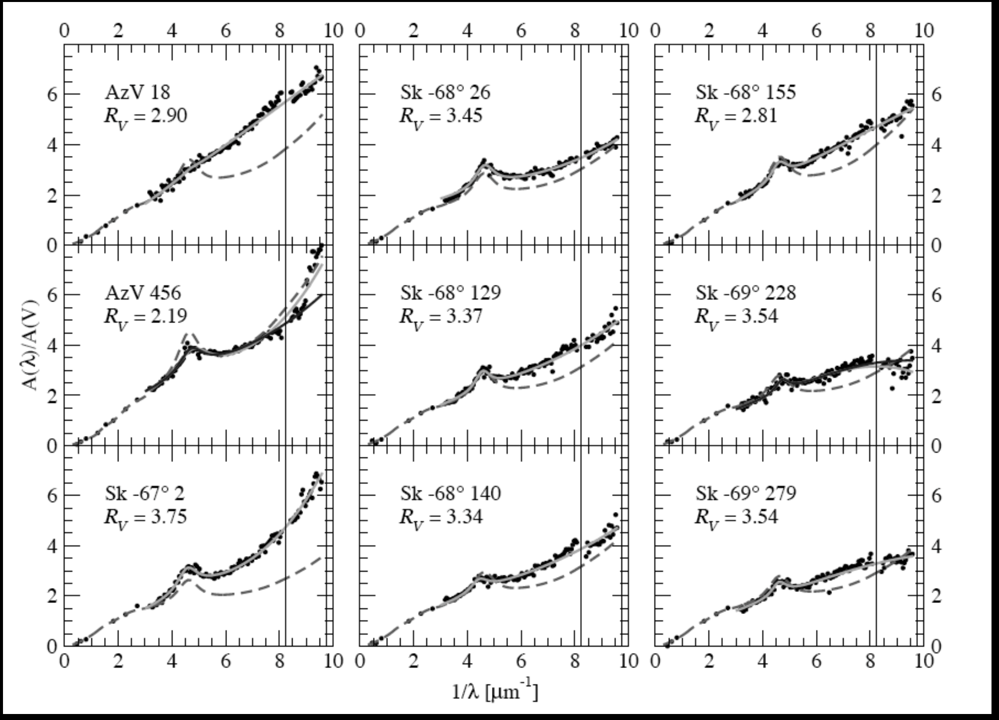


Draine 2003

2.2.1 Extinction

- Extinction curve is variable, esp in FUV
  - Argues shocks / radiation field from nearby star formation - Gordon et al. 2003

Cartledge et al. 2005



2.2.2 Attenuation vs. extinction

- Excinction curve = for a star, absorption and scattering
- Attenuation curve = for a galaxy, a complicated mix of absorption, scattering and geometry
  - See e.g., Witt & Gordon 2000 for a discussion…

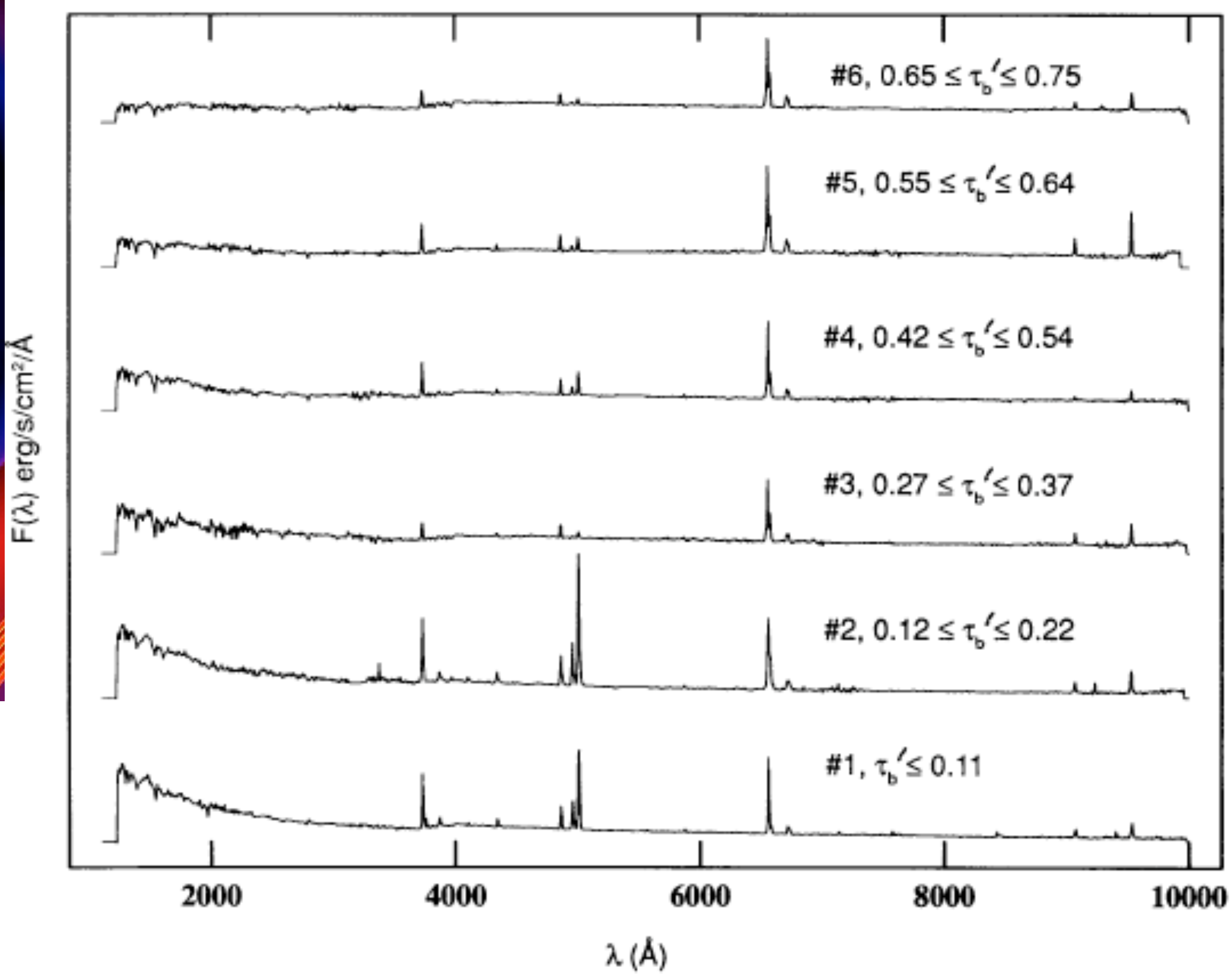
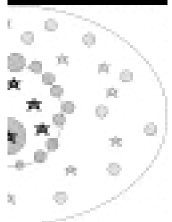


FIG. 17.—The spectra of the six templates are shown for increasing values of the extinction parameter τ_B^l, from the bottom to the top of the figure.

ng,



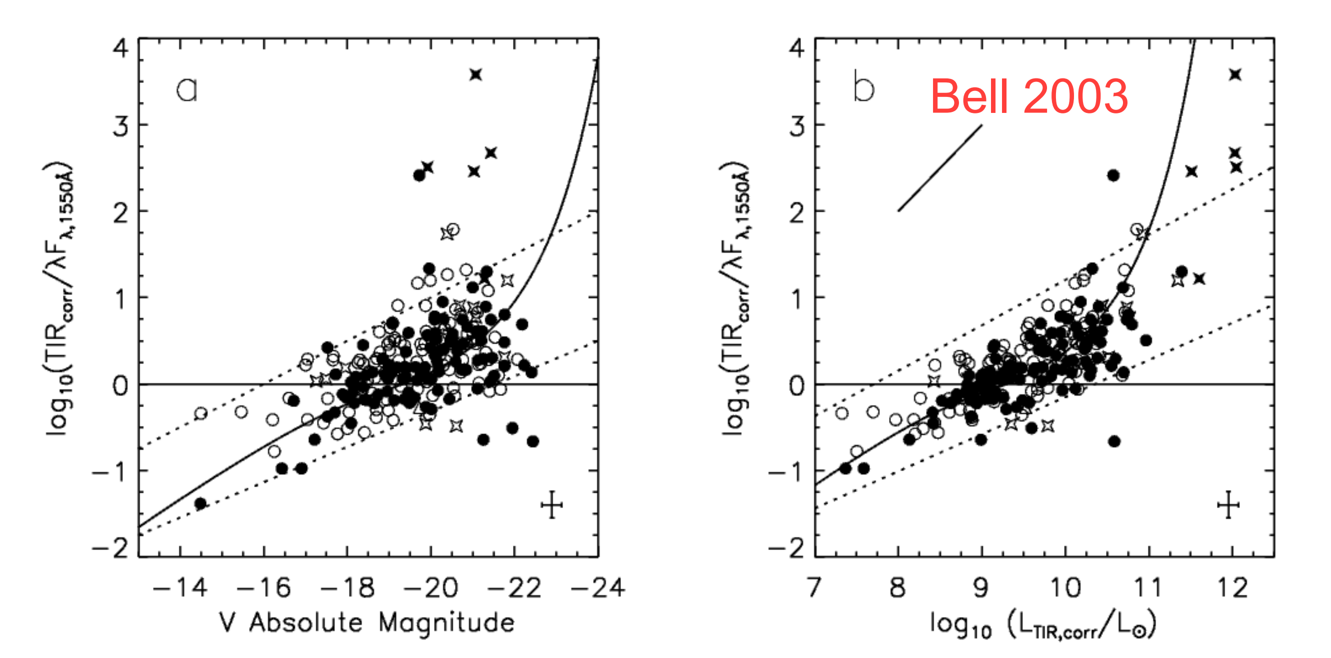
(7)

(8a)

for $0.12\ \mu m \leq \lambda < 0.63\ \mu m$. (8b)

2.2.4 Simple toy model consideration

- Optical depth ∝ gas surface density * metallicity
  - Motivation - dust/gas ∝ metallicity
  - Total dust column ∝ gas column



Eric Bell

Summary III : Dust

- Dust attenuates UV/optical/NIR
  - Depends dust properties (grain size/type)
  - Dust geometry + optical thickness crucial
  - Some empirical phenomenologies of limited use
    - Attenuation ~ 1/lambda (rough)…
- Energy heats dust --> thermal IR emission
  - Large grains thermal equilibrium - $T \propto \rho_{rad}^{1/4}$
  - Small grains single-photon heating (high temps)
  - V. small grains (PAH) single-photon, band emission
- Dust $\tau \propto \Sigma_{gas} Z$ roughly, scaling isn't that bad