Graduate Seminar Series

Stellar Populations: Theory & Technique

A Comprehensive Review of Resolved and Unresolved Systems

Based on Conroy (2013), Tolstoy et al. (2009), and Gallart et al. (2005)

The "Archaeological" Approach

Near Field Cosmology

Resolved Populations: We observe individual stars (RGB, MS, HB) in the Milky Way and Local Group (d ~ 1 Mpc).

Allows for detailed Star Formation Histories (SFH) $SFR(t, Z)$ and chemically tagged kinematics.

Far Field Cosmology

Unresolved Populations: We observe the integrated light of entire galaxies (d > 10 Mpc).

Relies on **Stellar Population Synthesis (SPS)** to deconvolve the compressed spectral energy distribution (SED).

Refs: Tolstoy et al. (2009); Conroy (2013)

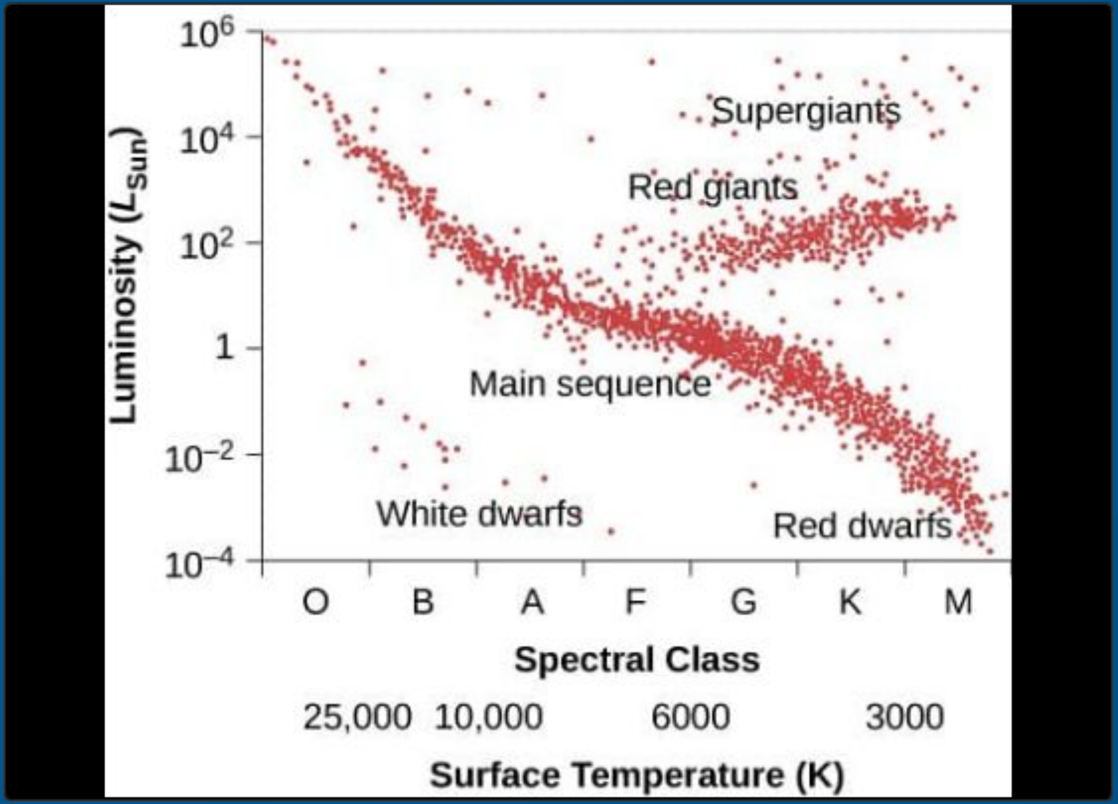
Part I: Resolved Populations

Inputs from Gallart et al. (2005) & Tolstoy et al. (2009)

The Fundamental Tool: CMD

Anatomy of the Color-Magnitude Diagram

- **Main Sequence Turn-off (MSTO):** The most precise age indicator. $L_{TO} \propto M^{\sim 3.5}$.
- **Red Giant Branch (RGB):** Locus depends on metallicity (and age). Prone to degeneracy.
- **Horizontal Branch (HB):** Core Helium burning. Morphology (red vs blue) sensitive to Z, age, and mass loss.
- **Red Clump (RC):** Metal-rich counterpart to HB. Standard candle.



Synthetic CMD Method (Gallart et al. 2005)

The Inversion Problem

We cannot analytically invert a CMD to get the SFH due to observational errors and stellar density variations. We use **Forward Modeling**.

We simulate the observational process (completeness, photometric error) to generate a synthetic CMD.

The Matrix Equation

$$N_{obs} = M \times N_{theor}$$

Where M is the completeness matrix. We minimize χ^2 (or use Poisson likelihood) between the observed and model Hess diagrams.

Ref: Gallart et al. (2005) ARA&A

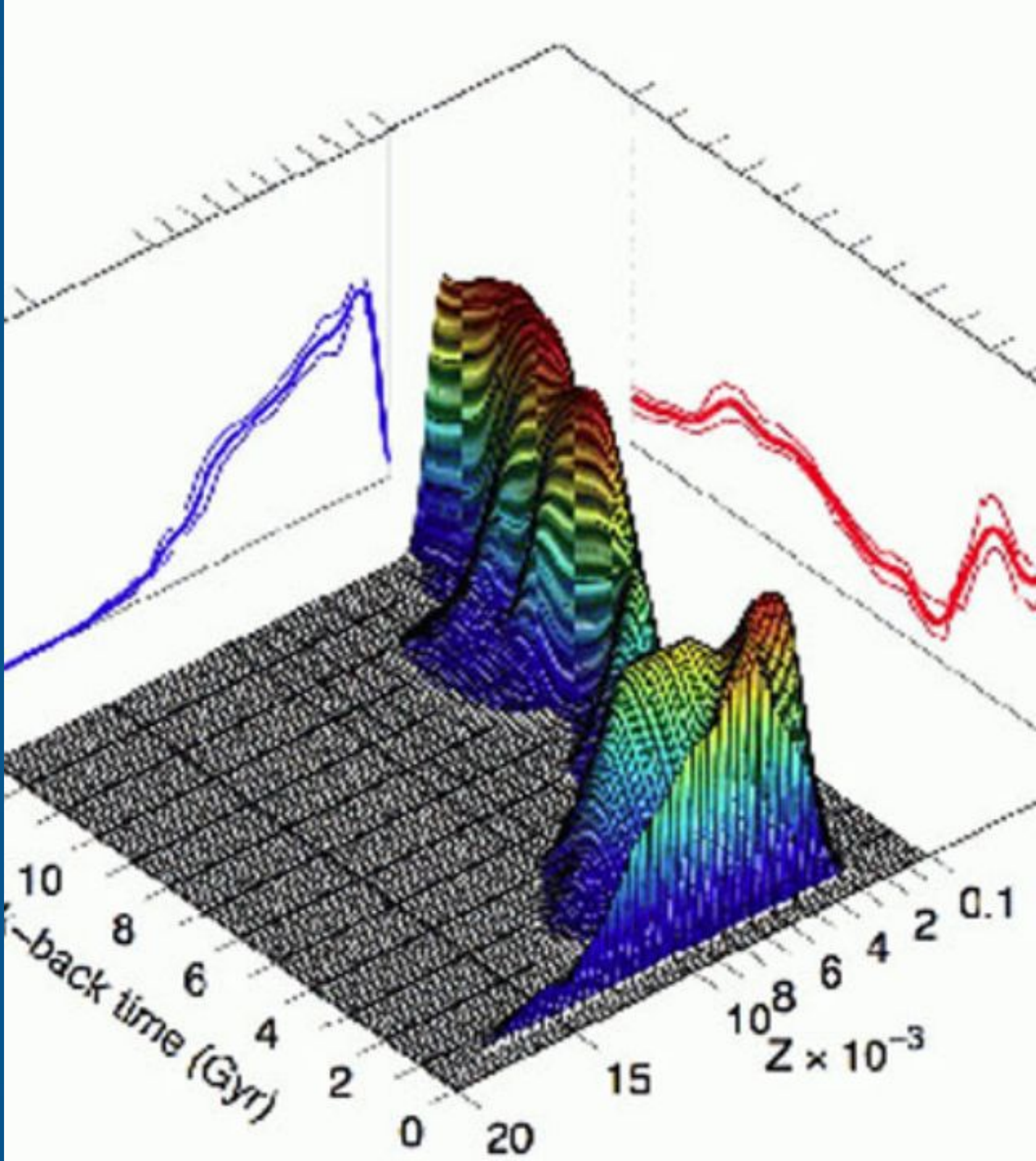
Hess Diagrams

Visualizing Stellar Density

A Hess diagram replaces individual points with a stellar density map (color-coded). This is crucial for dense fields where points overlap.

Gallart's Technique: By comparing the observed Hess diagram (left) with the best-fit synthetic model (right), we can quantitatively recover the Star Formation Rate as a function of time, $SFR(t)$.

Residuals (bottom panels) reveal systematics in stellar evolution models or missing physics (e.g., binary fractions).

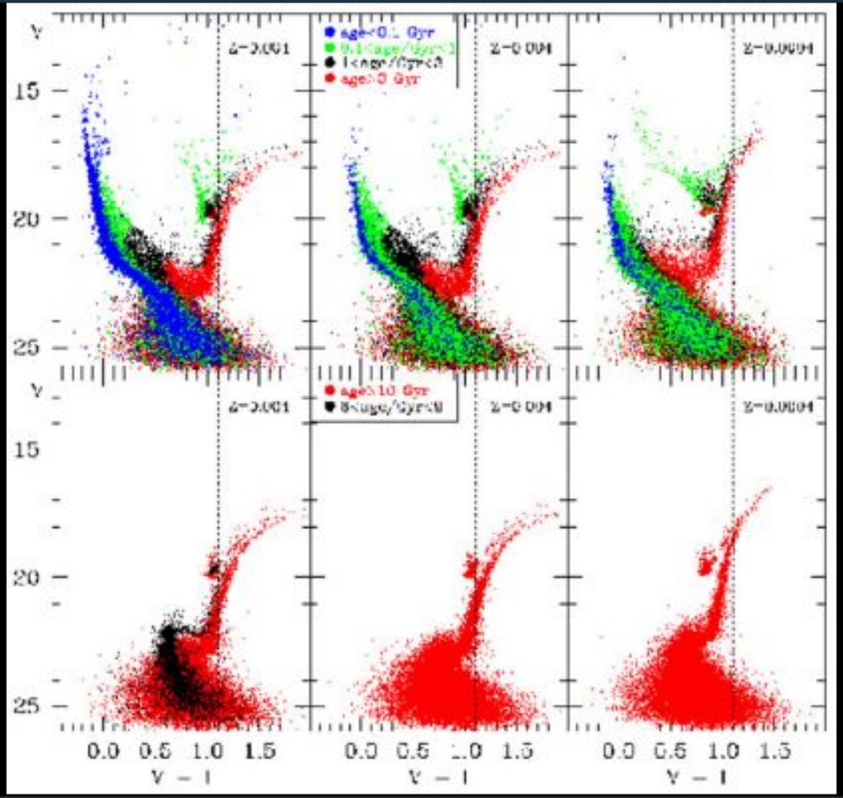


SFH of Local Group Dwarfs

Complex Histories (Tolstoy et al. 2009)

There is no "simple" dwarf galaxy. The Local Group reveals a stochastic variety of formation histories:

- **Ancient Bursts:** Some dSphs formed most stars >10 Gyr ago (e.g., Cetus, Tucana) but with different quenching times.
- **Extended Formation:** Others (e.g., Fornax, Leo I) show continuous or episodic star formation until < 1 Gyr ago.
- **Gas Loss:** Evolution driven by internal feedback vs. environmental stripping (ram pressure).



Chemical Evolution Concepts

Alpha Elements

O, Mg, Si, Ca. Produced in Core Collapse SNe (Type II). Timescale: ~10 Myr (Instantaneous).

Iron Peak

Fe, Cr, Ni. Produced primarily in Type Ia SNe (White Dwarf accretion). Timescale: ~1 Gyr delay.

The Clock

The ratio $[\alpha/Fe]$ measures the relative contribution of SNe II vs Ia. It is a timer for the duration of star formation.

Ref: Tolstoy et al. (2009)

The "Knee" in $[\alpha/Fe]$

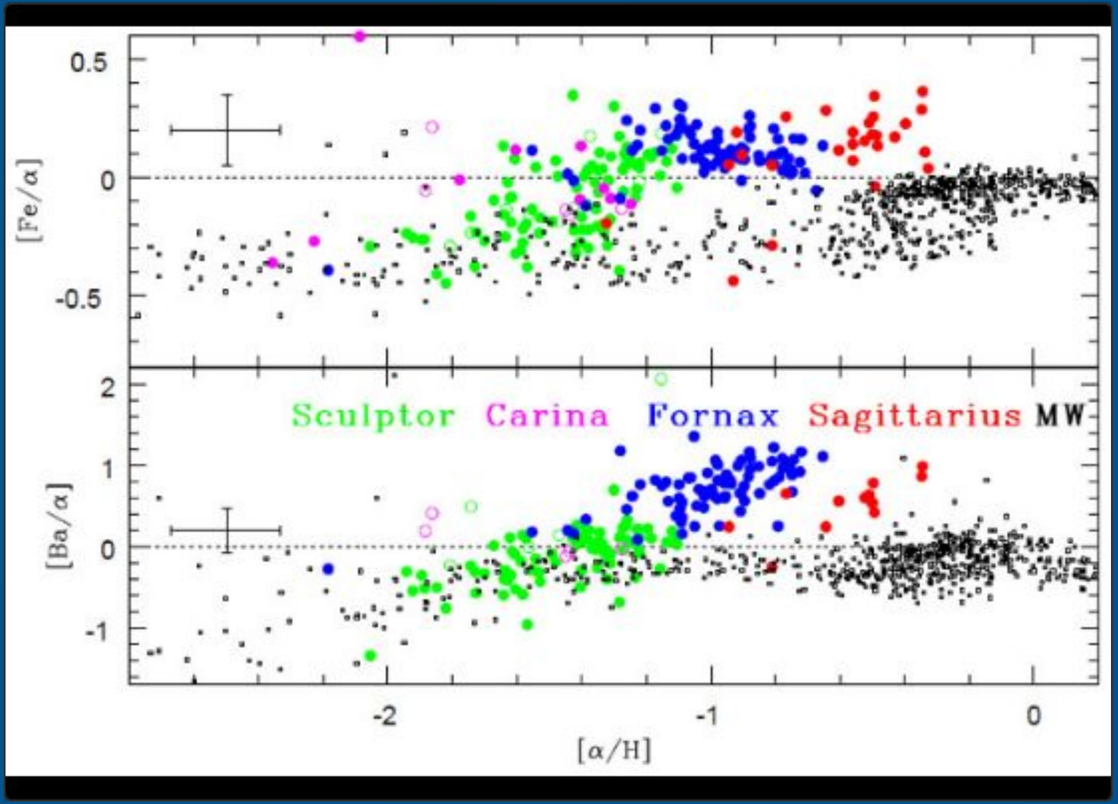
Dwarfs vs. The Halo

Tolstoy (2009) demonstrated that dSphs have a different chemical track than the MW Halo.

The Knee: The metallicity where $[\alpha/Fe]$ turns down indicates when Type Ia SNe kicked in.

- **MW Halo:** Knee at high metallicity $\rightarrow$ High SFE (rapid enrichment).
- **dSphs:** Knee at low metallicity $\rightarrow$ Low SFE (slow enrichment).

Conclusion: The MW Halo was NOT built from accretion of galaxies like current dSphs.



Part II: Unresolved Populations

Inputs from Conroy (2013)

The Compression Problem

Integrated Spectra

For most of the universe, we only receive the sum of light from $10^9 - 10^{11}$ stars.

We lose the CMD. We lose spatial resolution. We must rely on **Stellar Population Synthesis (SPS)** to infer physical properties.

Key Features: The 4000Å Break (opacity of metal lines in cool stars) is the primary age indicator for old populations, correlating with the MSTO temperature.

The SPS Equation (Conroy 2013)

The Synthesis Integral

The flux F_λ of a galaxy at time t is the convolution of the Star Formation History (SFR) and the Chemical Enrichment History (Z) with Simple Stellar Populations (SSP).

$$F_\lambda(t) = \int dt' \int dZ \, SFR(t-t', Z) \, S_\lambda(t', Z) \, e^{-\tau_\lambda}$$

Where S_λ is the SSP spectrum (per unit mass) and τ_λ represents dust attenuation.

Model Ingredients & Uncertainties

Isochrones

Governed by stellar evolution theory (Padova, MIST, BaSTI). Major uncertainties: Mass loss rates, convective overshoot, rotation.

Spectral Libraries

Empirical (MILES, ELODIE): Real stars, limited coverage. **Theoretical (MARCS):** Complete coverage, physics-dependent.

IMF

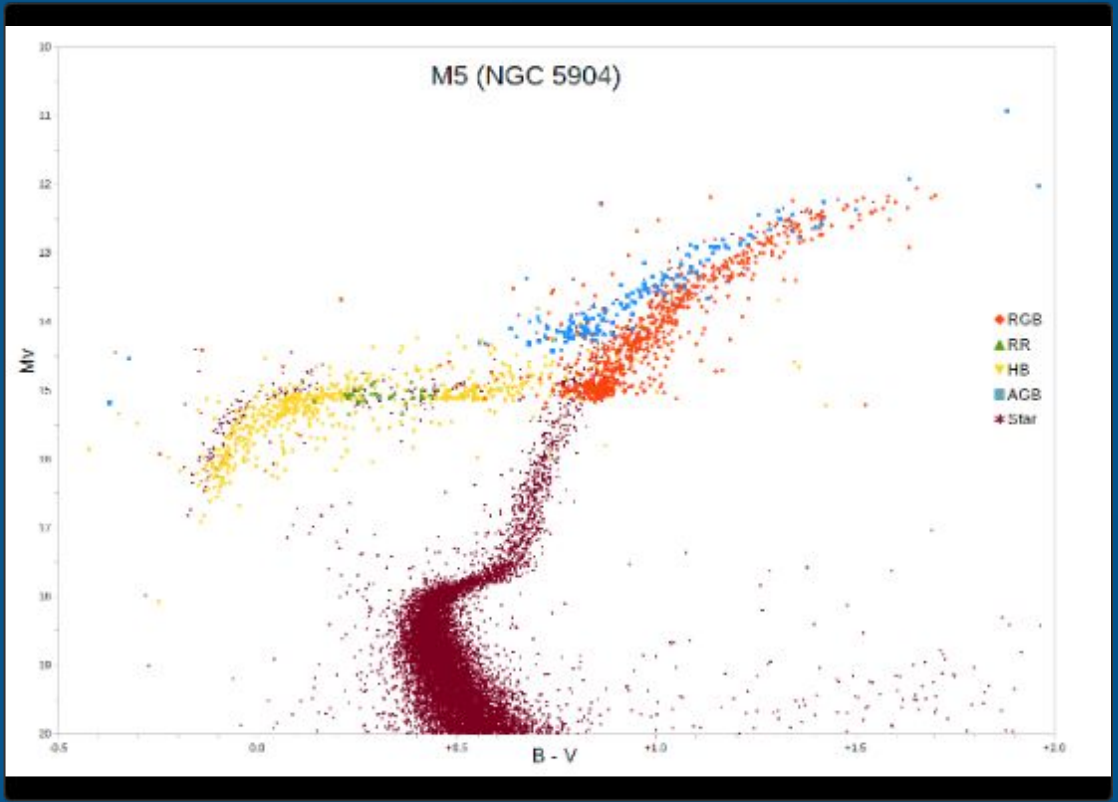
The weighting function. Determines the Mass-to-Light ratio and the normalization of the entire integral.

The TP-AGB Phase Challenge

Dominating the Near-IR

Conroy (2013) highlights the Thermally Pulsing Asymptotic Giant Branch (TP-AGB) as a critical systematic.

- **Cool & Luminous:** Dominates NIR flux for ages 0.2 - 2 Gyr.
- **Physics:** Hard to model (pulsations, mass loss, dredge-up).
- **Impact:** Poor modeling leads to factor-of-2 errors in Stellar Mass ($M_\star$) derived from SED fitting.



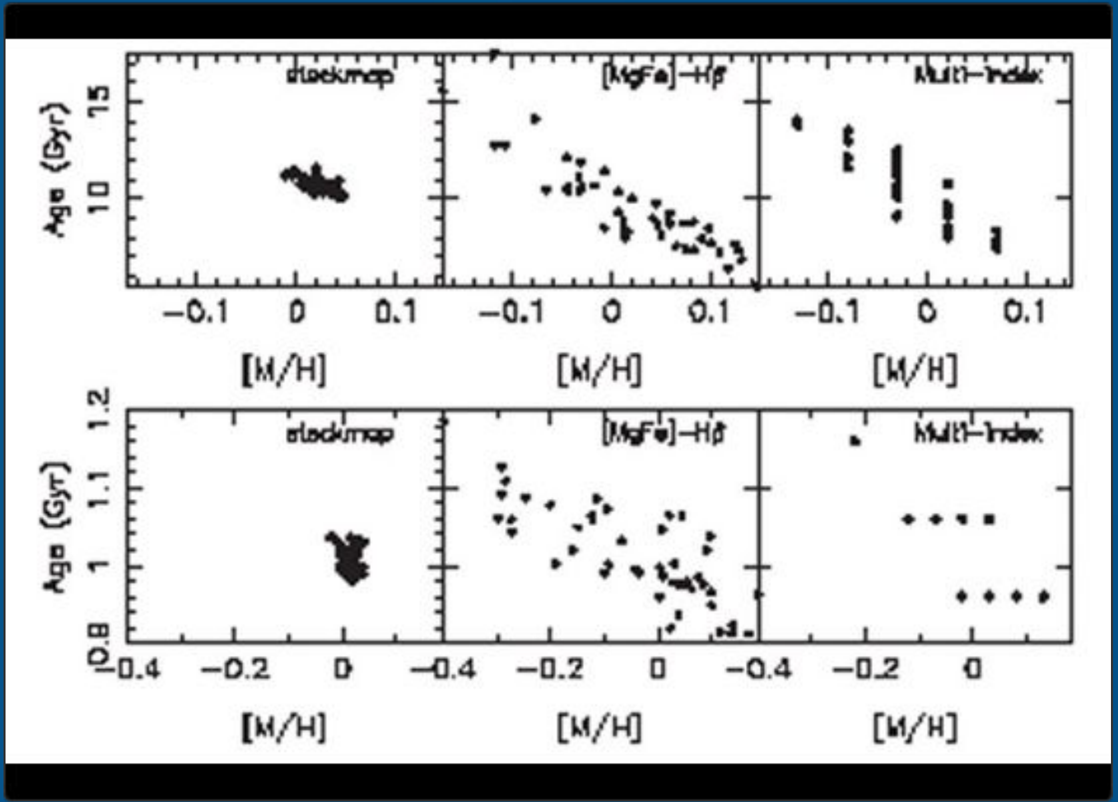
Breaking Degeneracy: Lick Indices

Age-Metallicity Degeneracy

Broadband colors cannot distinguish Old+Metal-Poor from Young+Metal-Rich. Both are red.

Solution: Orthogonal Spectral Indices.

- **Hβ (Balmer Lines):** Sensitive to T_{eff} of MSTO. Primary **Age** indicator.
- **[MgFe] (Metal Lines):** Sensitive to opacity in RGB atmospheres. Primary **Metallicity** indicator.



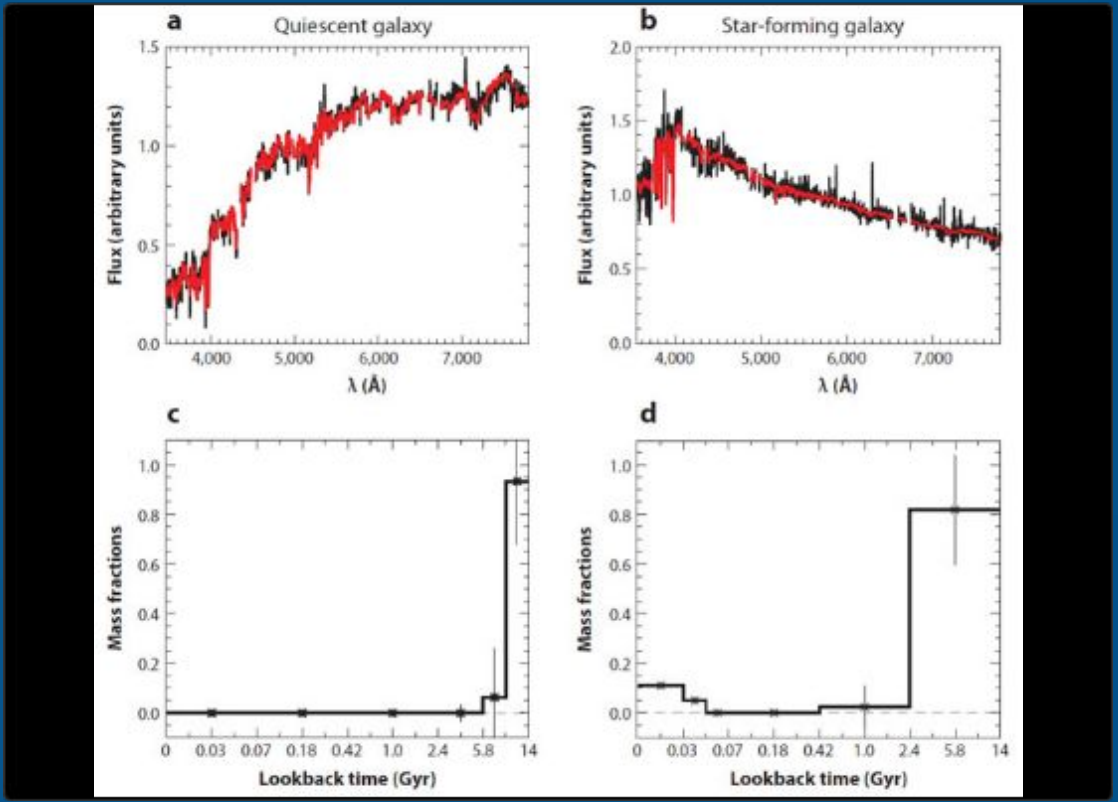
Beyond Indices: Full Spectral Fitting

Maximizing Information

Modern codes (e.g., pPXF, FAST) fit the entire pixel space of the spectrum rather than isolated indices.

Advantages:

- Simultaneously recovers Kinematics (V, σ) and Populations (Age, Z).
- Utilizes lower S/N data by aggregating signal.
- Can mask gas emission lines automatically.



The IMF Debate (Conroy 2013)

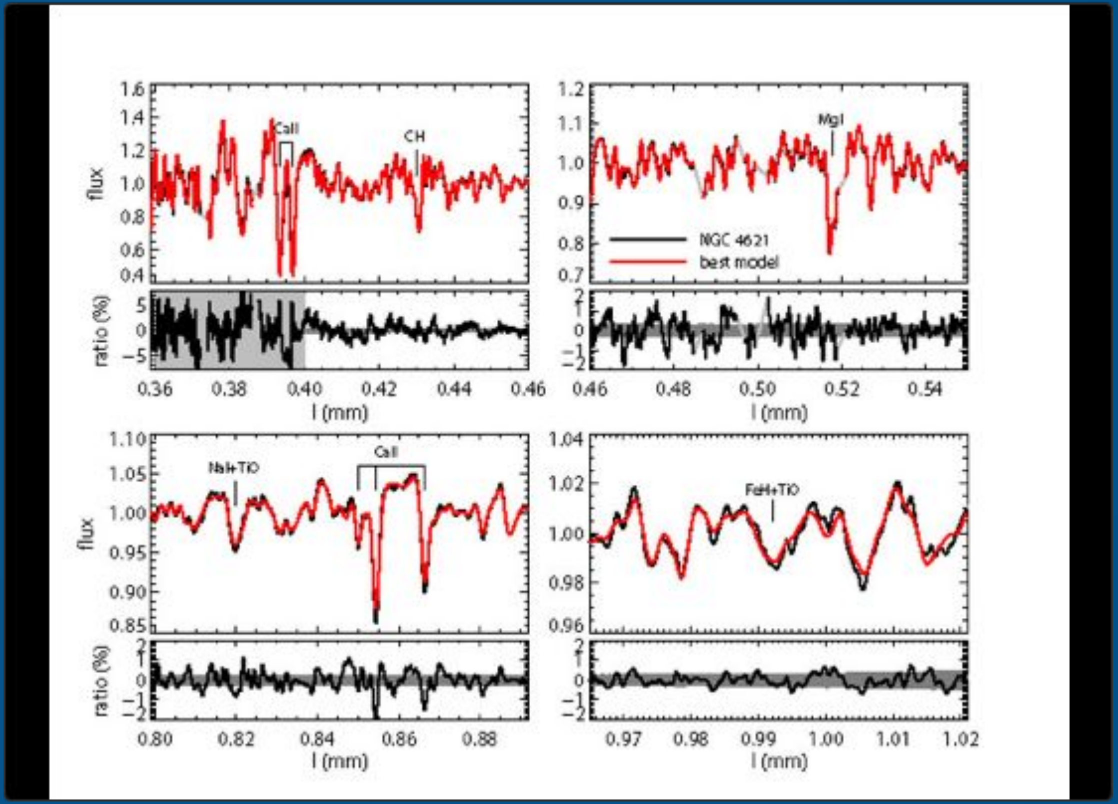
Is the IMF Universal?

Traditionally assumed to be Kroupa/Chabrier everywhere.

Conroy (2013) presents strong evidence for variability in massive Ellipticals.

Evidence: Gravity-sensitive features (Na I doublet, Wing-Ford FeH) are stronger in massive ETGs, indicating an excess of low-mass ($< 0.5 M_\odot$) dwarfs.

Result: "Bottom-heavy" IMF ($\alpha > 2.3$) in galaxy cores.



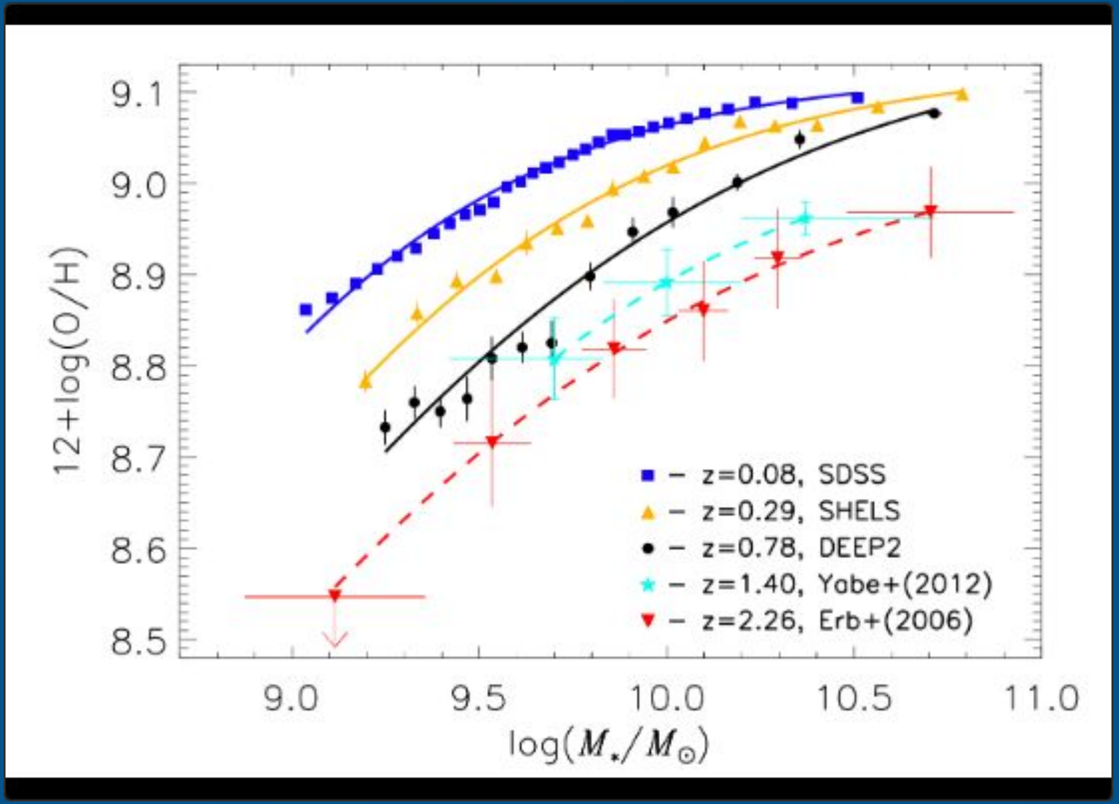
Abundance Ratios & Downsizing

Formation Timescales

Integrated light studies show that $[\alpha/Fe]$ correlates positively with velocity dispersion (σ).

Interpretation: Massive galaxies formed in very short, intense bursts (high SFE), quenching before Type Ia SNe could dilute the alpha-enhancement.

This "Downsizing" (massive galaxies form oldest stars) contradicts naive hierarchical clustering models.

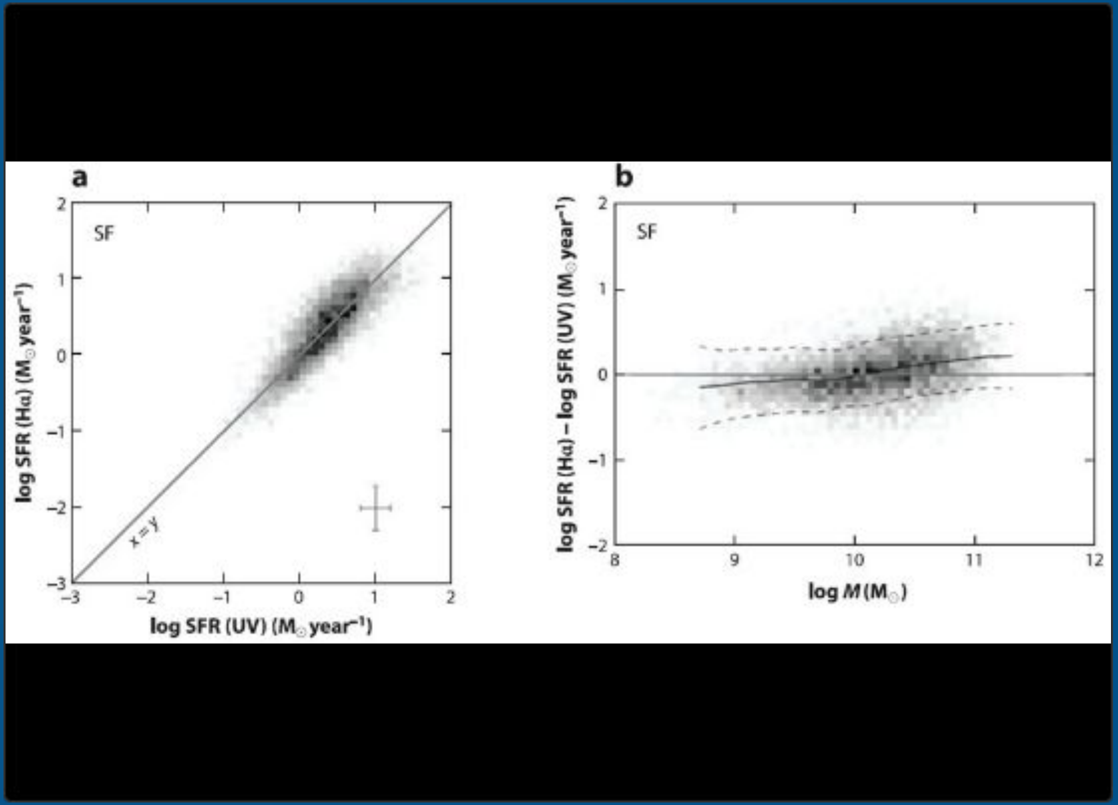


The "Outshining" Problem

The Frosting Effect (Conroy 2013)

Young, massive stars are exponentially brighter than old stars ($L \propto M^{3.5}$).

- **Bias:** A young sub-population comprising <1% of the mass can contribute >50% of the optical light.
- **Age Discrepancy:** "Light-weighted" age is significantly younger than "Mass-weighted" age.
- **Hidden Mass:** The old stellar backbone is often hidden beneath this young "frosting," complicating $M_\star$ estimates.



Light-weighted vs. Mass-weighted Age (Conroy 2013)

Synthesis: Two Regimes Compared

Parameter	Resolved (Tolstoy/Gallart)	Unresolved (Conroy)
Primary observable	CMD (Star counts, magnitudes)	Integrated Flux (F_λ)
Age Precision	High (MSTO) absolute ages	Moderate (Lick Indices/SED)
SFH Recovery	Time-resolved $SFR(t)$	Light-weighted average
Major Systematic	Distance, Reddening, Binaries	TP-AGB, IMF, Outshining
Key Insight	Dwarf galaxy chemical evolution	Massive galaxy formation & IMF

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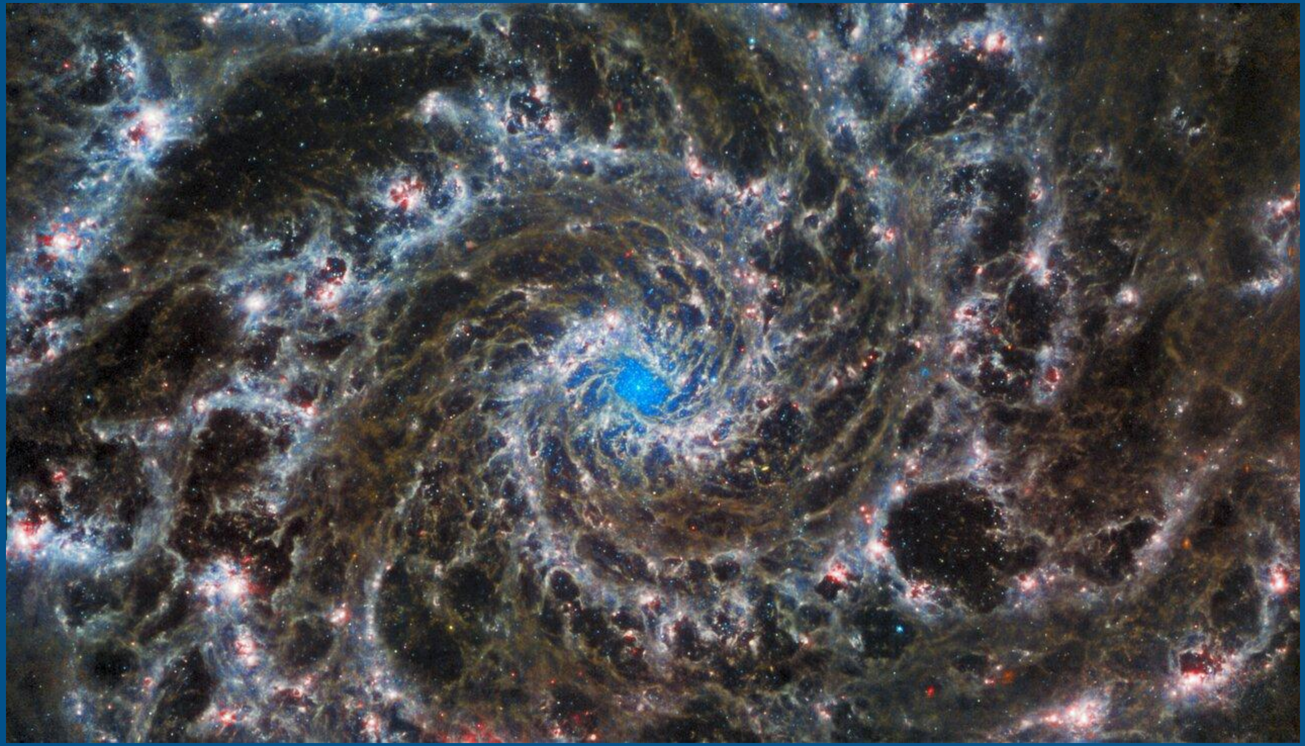
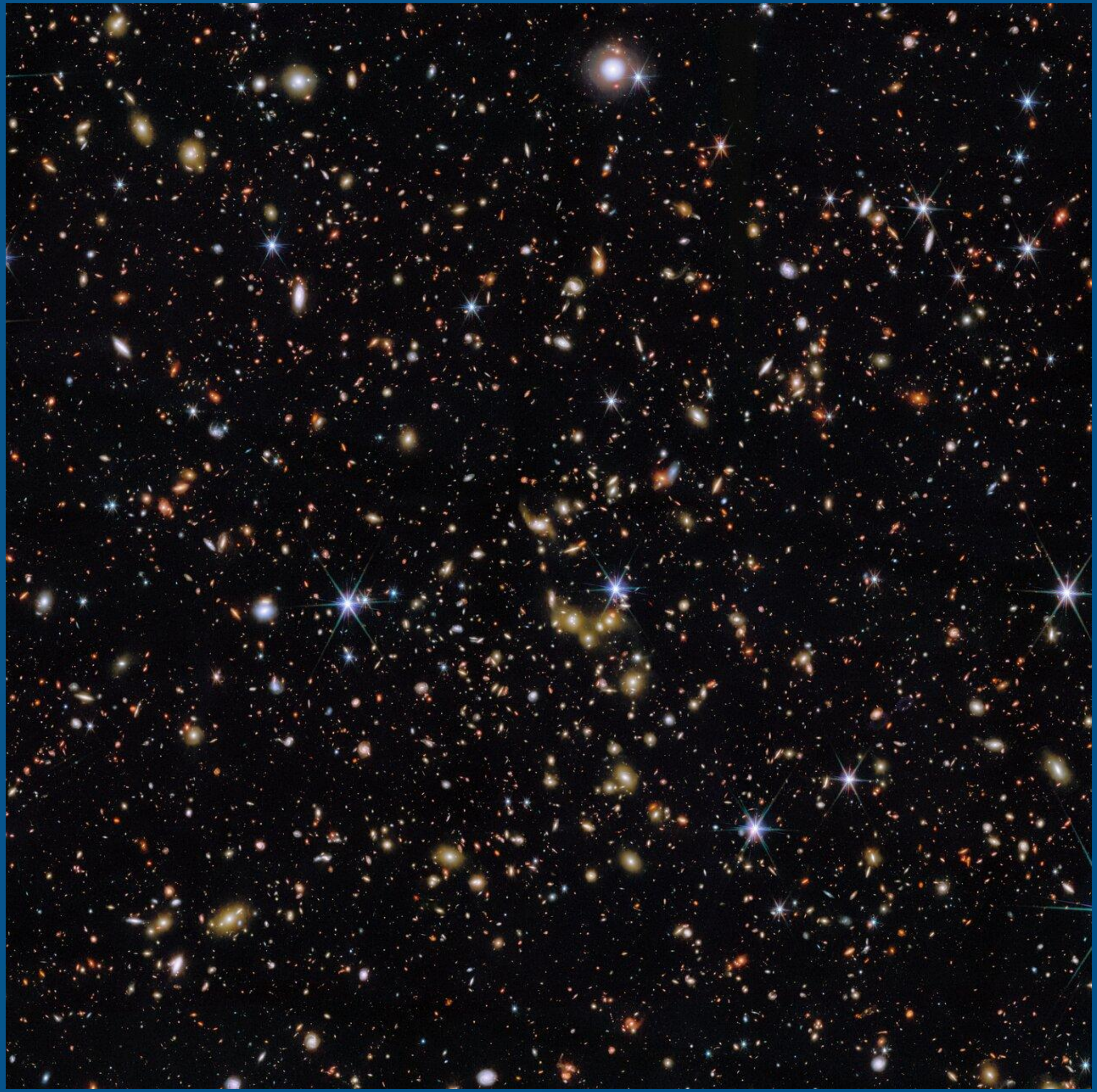
WLM Dwarf Galaxy

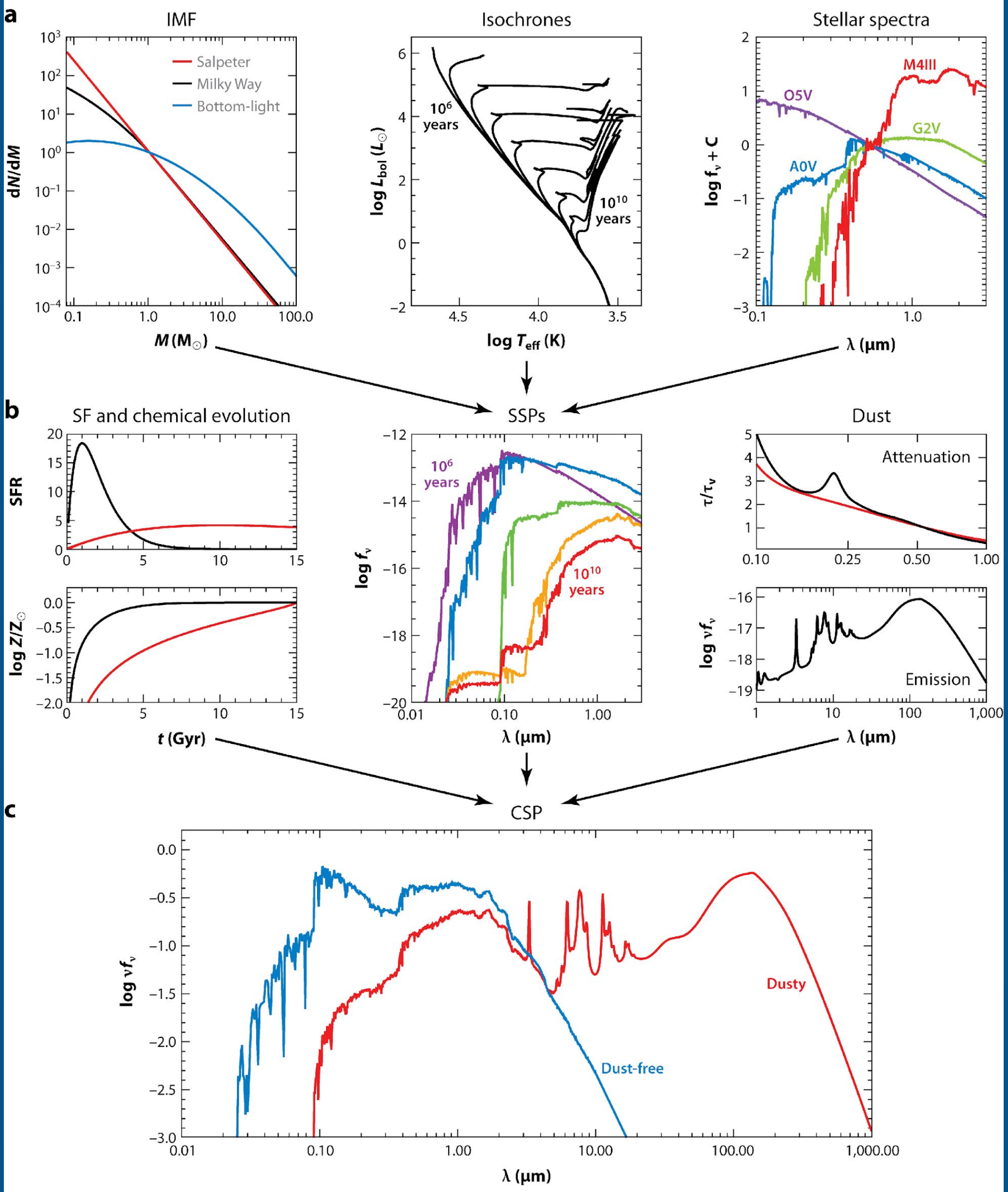
(JWST)



NGC 628 -- JWST

COSMOS-Webb -- JWST





Conroy C. 2013.
Annu. Rev. Astron. Astrophys. 51:393–455

Figure 1

from

Conroy (2013)