Stellar population synthesis:

star formation history(SFH), dust attenuation

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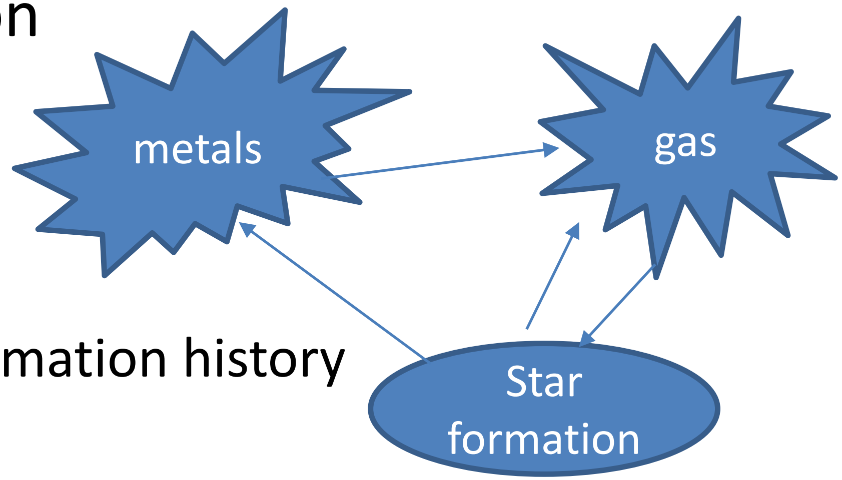
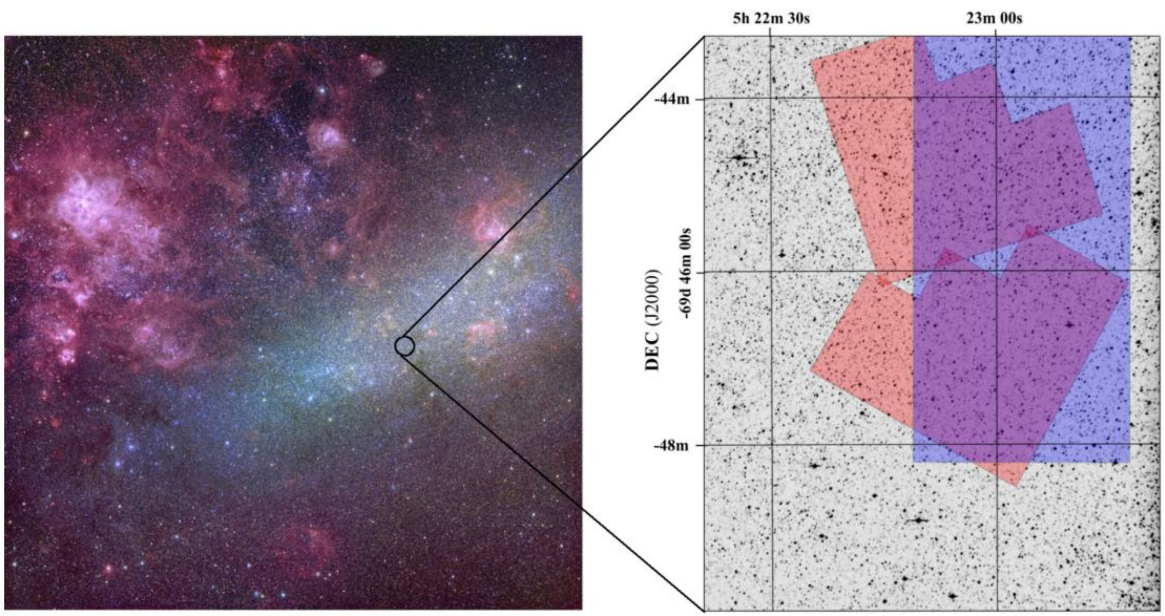
Star formation history (SFH)

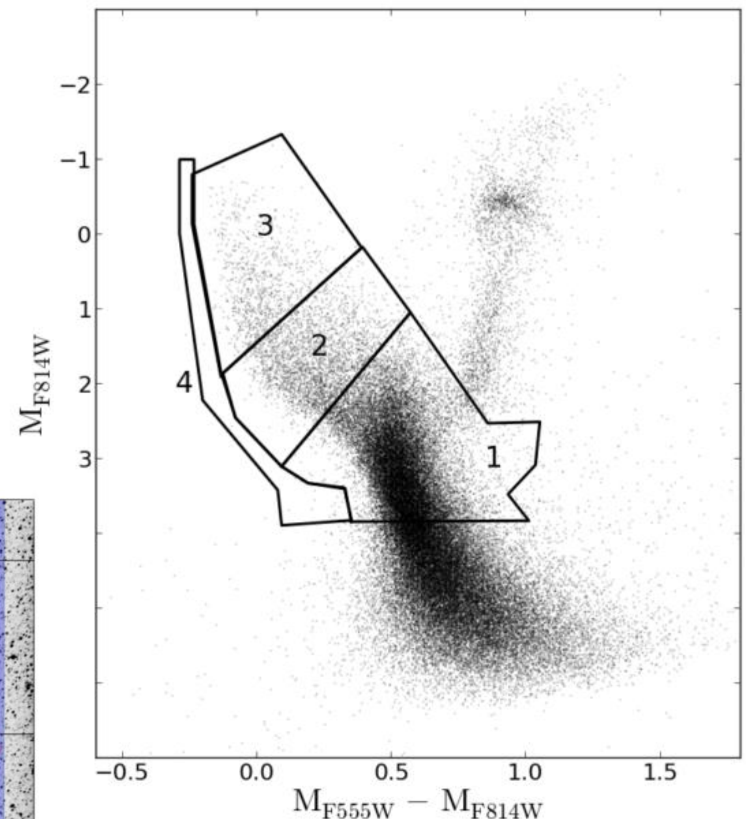
- Star formation rate (SFR) as function of time
- Key ingredient of stellar population studies of galaxies
  - SFH + IMF + stellar evolution
  - Gas
    - SFR – gas relation
  - Metalicty
    - Gas accretion history, star formation history
  - Dust
    - Gas – metalicity



stellar color-magnitude diagrams

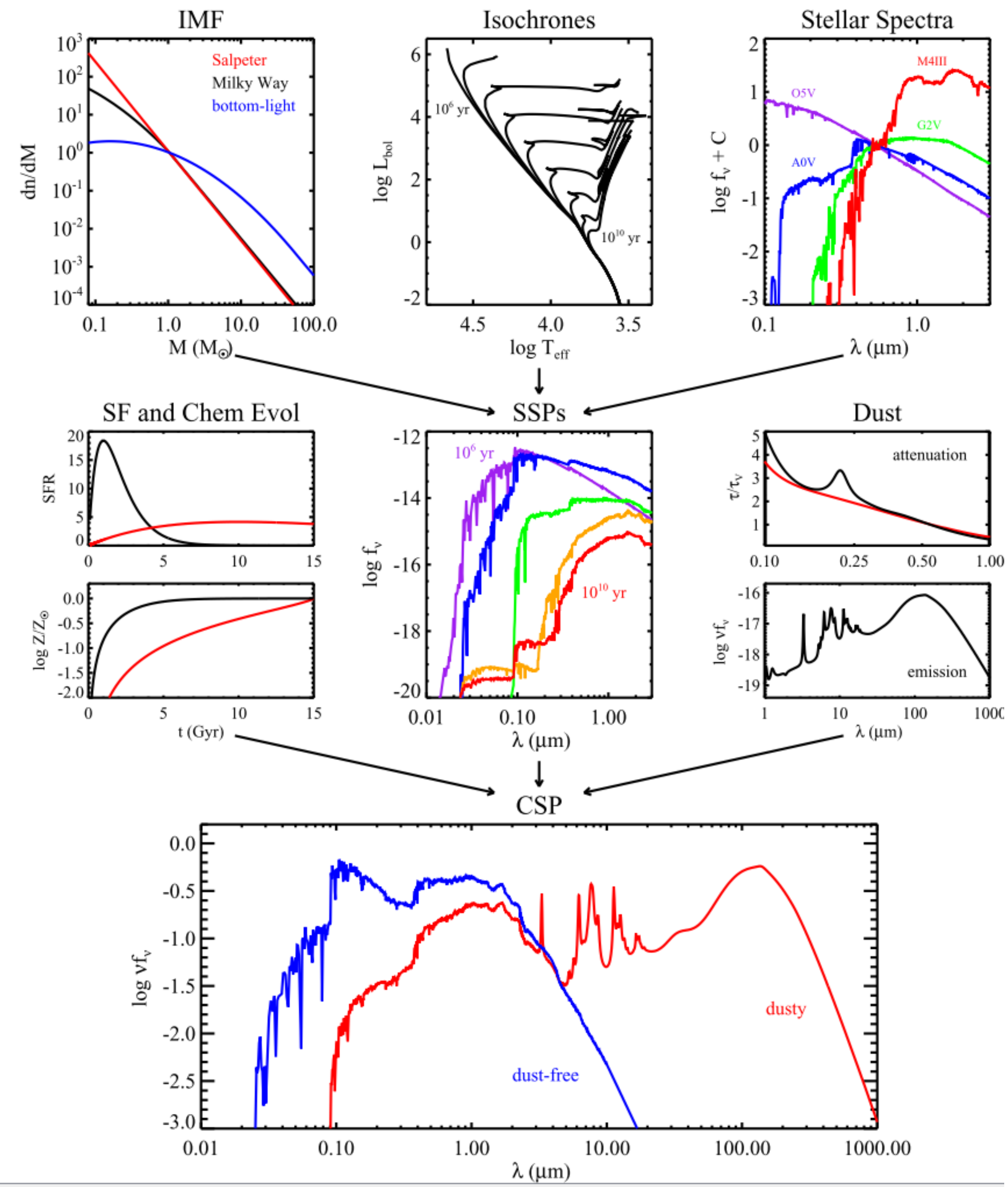
- Resolved stellar population
  - HST, nearby galaxies
    - Main sequence turnoffs
- Still model dependent
  - IMF, binary fraction, distance
  - dust, observational error
  - IAC-star: minimum χ^2





LMC bar, Ruiz-Lara et al. 2015

Un-resolved stellar population CSP models



Conroy 2013

Parameterized SFH

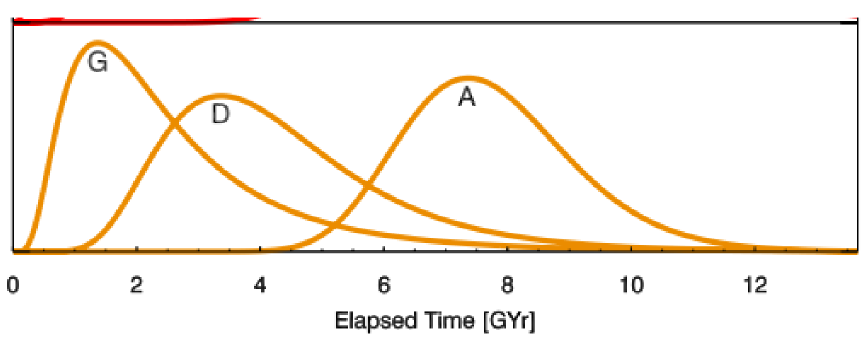
- **Exponential model (τ):** SFR=A*exp(-t/ τ)
  - Delayed exponential
    - SFR=A*t*exp(-t/ τ)
  - Two exponential model

$$\mathrm{SFR}_{\mathrm{old}}(t) = \mathrm{SFR}_{0,\mathrm{old}} \cdot e^{-\frac{(t-t_1)}{\tau_1}}$$

$$\mathrm{SFR}_{\mathrm{young}}(t) = \mathrm{SFR}_{0,\mathrm{young}} \cdot e^{-\frac{(t-t_2)}{\tau_2}}$$

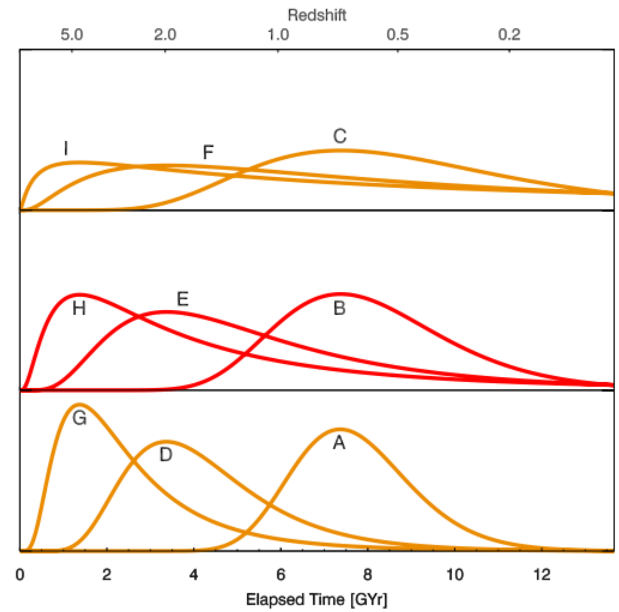
$$\mathrm{SFR} = (1 - f_{\mathrm{ySP}})\mathrm{SFR}_{\mathrm{old}}(t) + f_{\mathrm{ySP}}\mathrm{SFR}_{\mathrm{young}}(t).$$

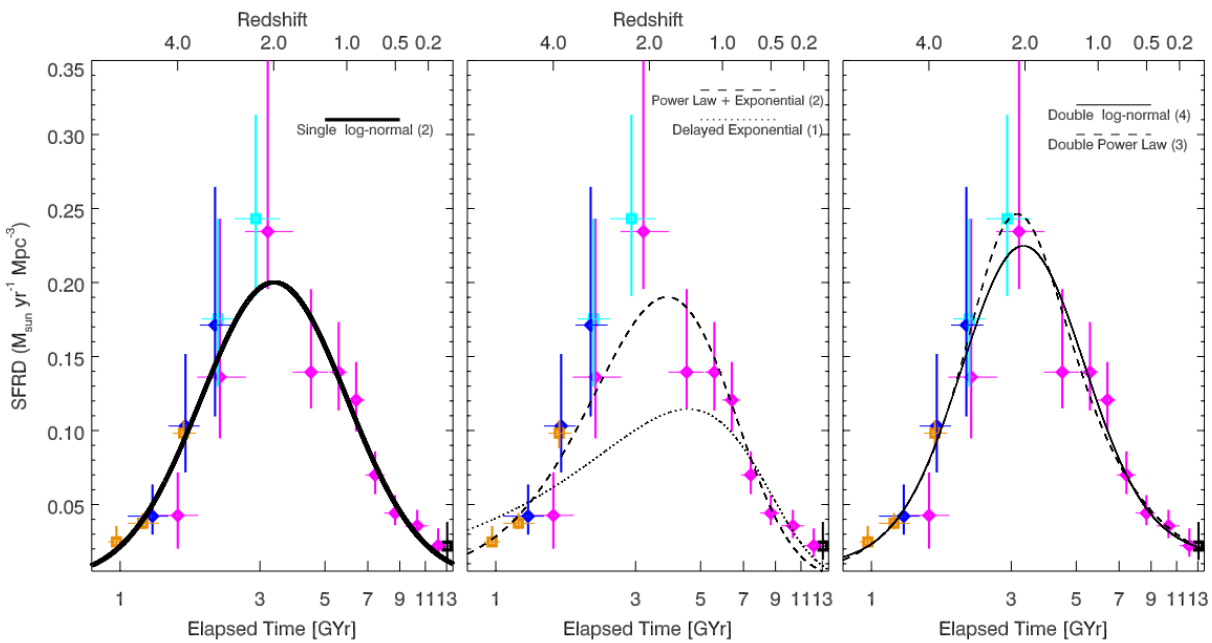
- **Log-normal SFH**
  - Gladders et al. 2013



Log-normal SFH(Gladders et al. 2013)

$$\mathrm{SFR}(t, t_0, \tau) = \frac{1}{t\sqrt{2\pi\tau^2}} e^{-\frac{(\ln t - t_0)^2}{2\tau^2}},$$





of $z = 1$. We show first that the cosmic SFRD is remarkably well described by a simple log-normal in time. We next postulate that this functional form for the ensemble is also a reasonable description for the SFHs of individual galaxies. Using the measured sSFRs for galaxies at $z \sim 0$ from Paper III in this series, we then construct a realization

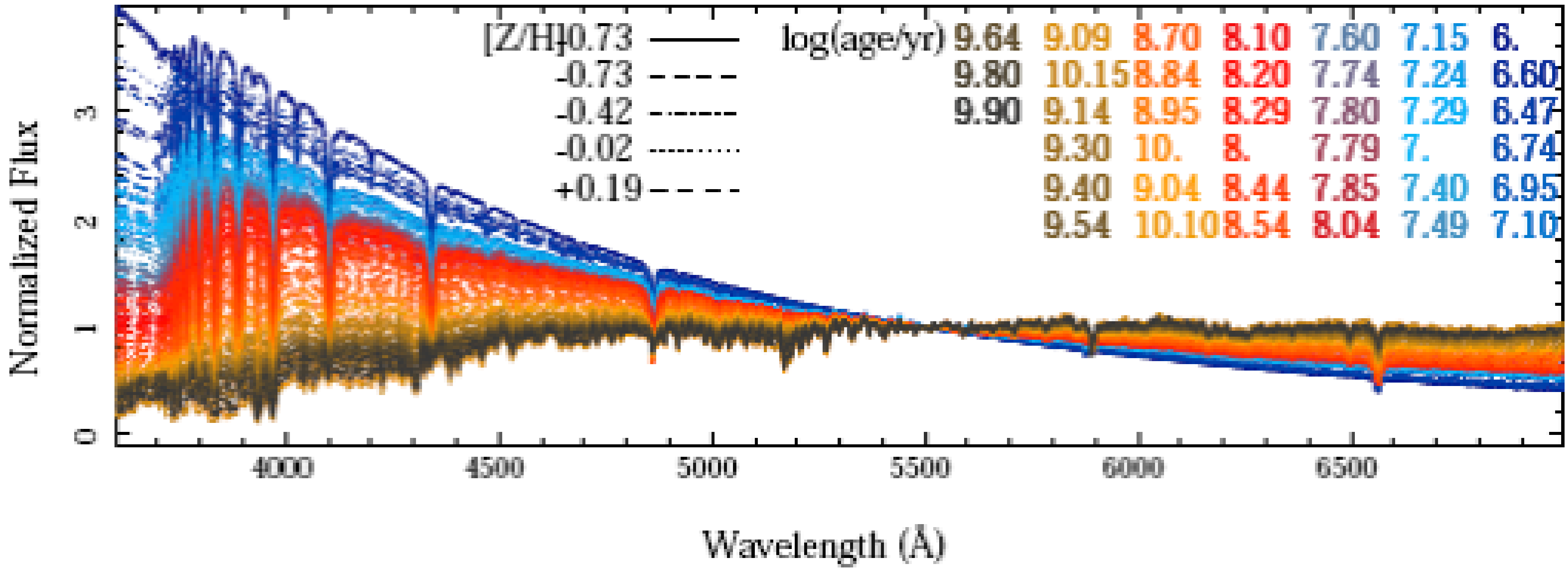
Non-Parametric SFH

- Discretization SFH, linear combination of SSPs
  - Full spectrum fitting

$$s_i \approx \sum_{j=1}^{n} B_{i,j}\, x_j\,, \quad i \in \{1,..,m\}\,, \qquad B^0(\lambda,t,Z) \triangleq \int_{M_{\min}}^{M_{\max}} \mathrm{IMF}(m)\, S(\lambda,m,t,Z)\, \mathrm{d}m\,,$$

- Code
  - STARLIGHT (Cid Fernandes et al. 2005)
  - STECMAP (Ocvirk et al. 2006)
  - pPXF (Cappellari 2004)
  - Many others

Single Stellar population(SSP)



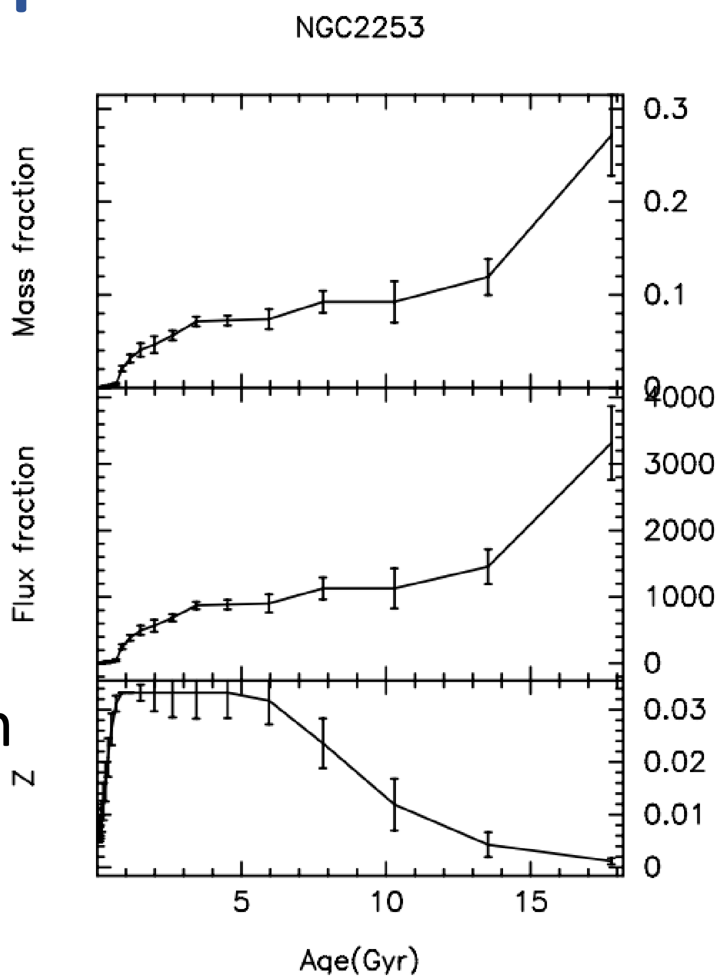
- SSP: function of age
  - Depend on IMF, stellar physics (e.g. binary fraction)
- SSPs are very similar when t>1Gyr

Recover SFH: ill-posed problem

- SSPs are similar when t>1Gy
- Age-Metallicity degeneration
  - Old age ←→ high metallicity

- Age-Metallicity Relation (AMR)
  - Gas → SFR → Metals → AMR
  - Old age → low metallicity

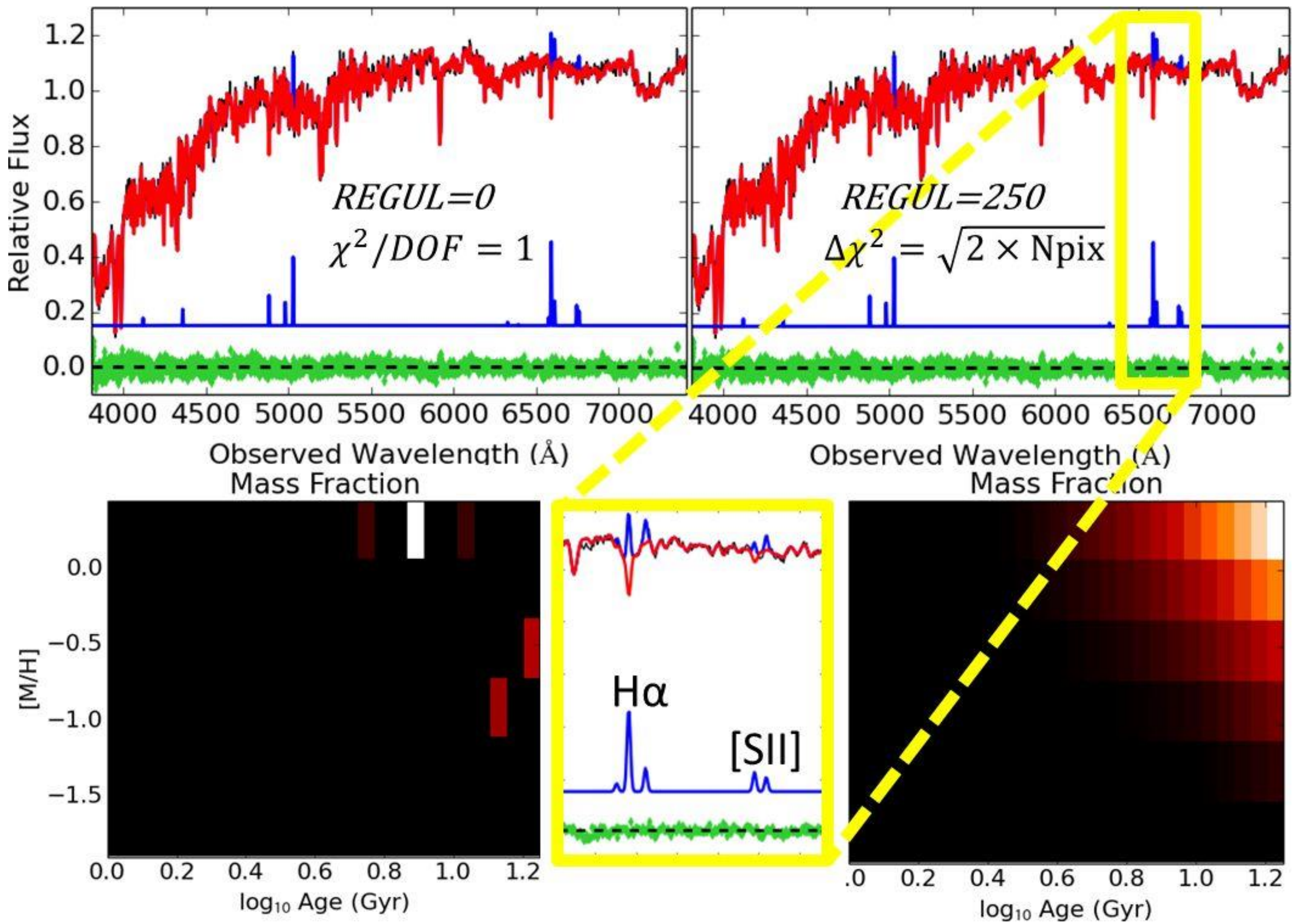
- Typically, the mean age, rather than the SFH derived from CSP is meaningful
  - e.g. STARLIGHT



Sánchez-Blázquez et al. 2014

Penalized Pixel-Fitting
pPXF: *regularization*

standard approach to solve ill-posed problems.



STECKMAP: Bayesian approach

$$Q_\mu = \chi^2(s(x, Z, g)) + P_\mu(x, Z, g),$$

Penalizing

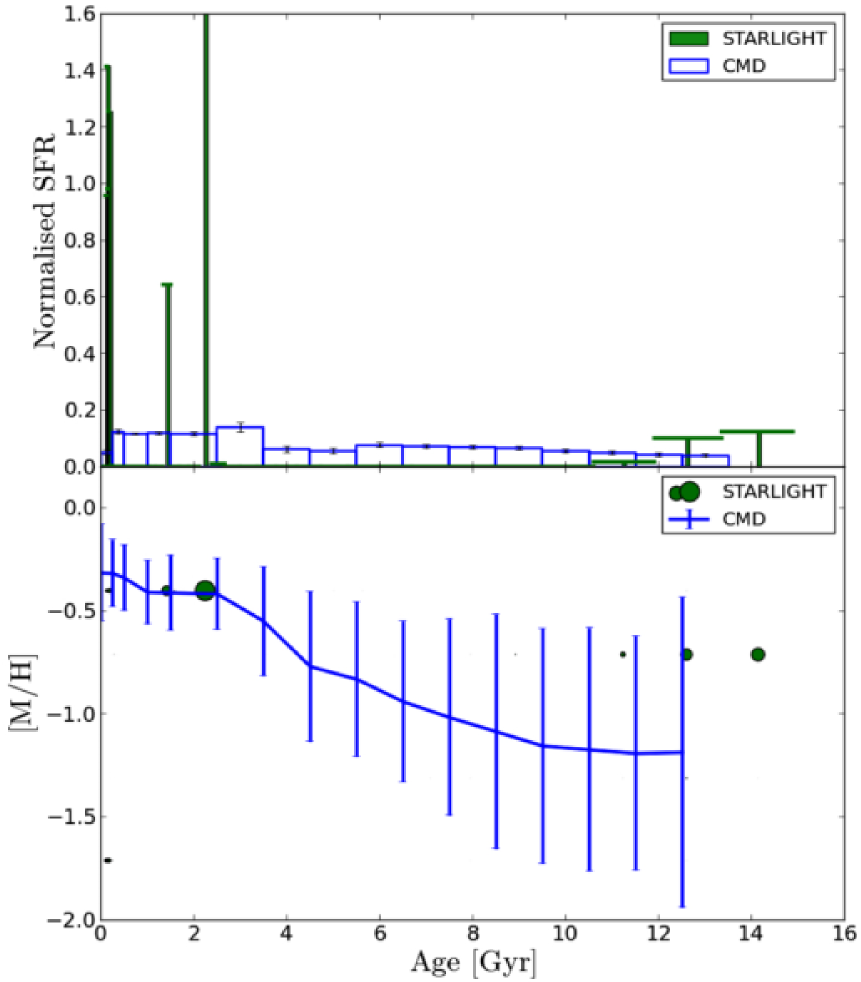
$$P_\mu(x, Z, g) = \mu_x P(x) + \mu_Z P(Z) + \mu_v P(g).$$

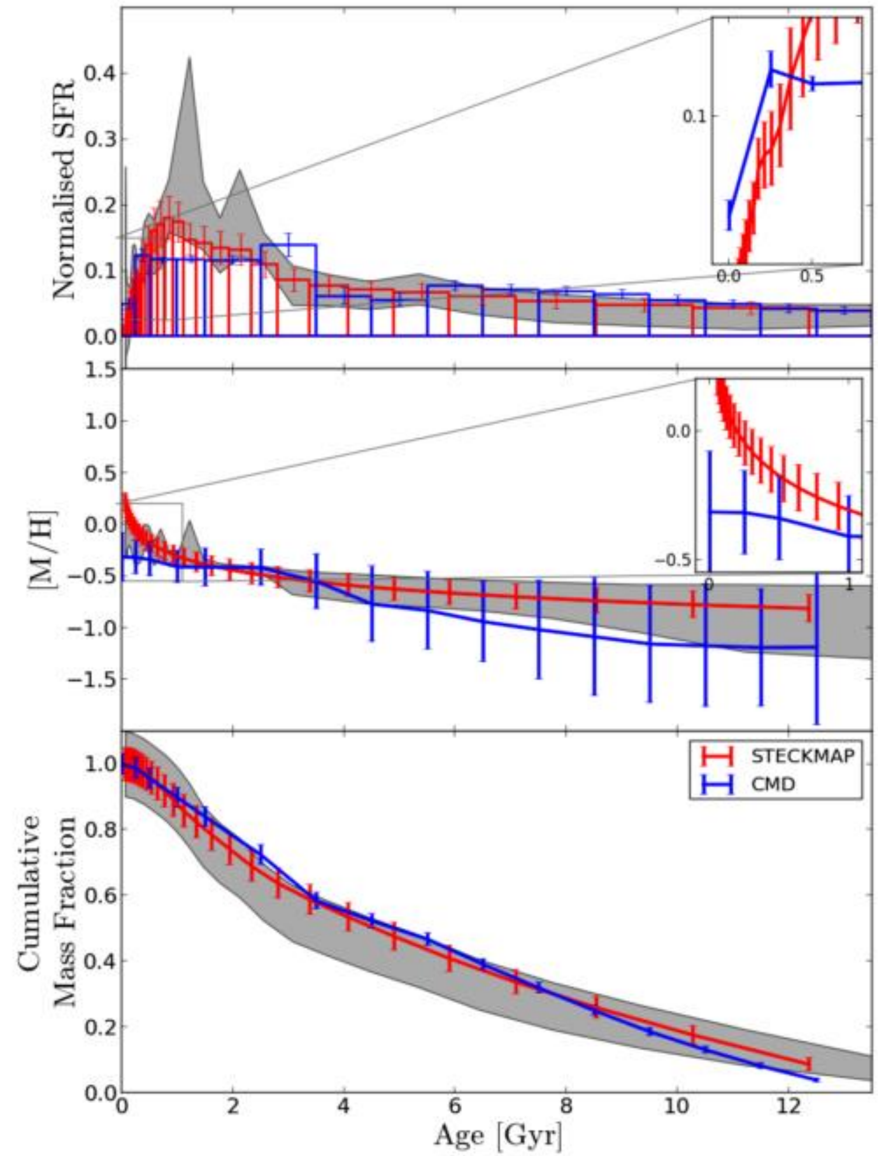
μ_x, μ_Z, and μ_v are the smoothing parameters

- the stellar age distribution
- the metalicity distribution
- the line-of- sight velocity distribution

STECKMAP

STARLIGHT



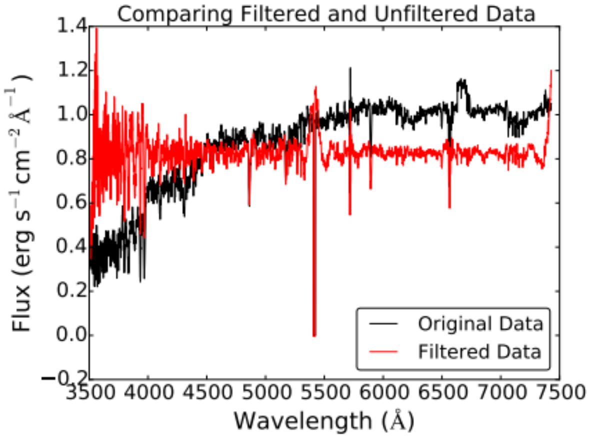


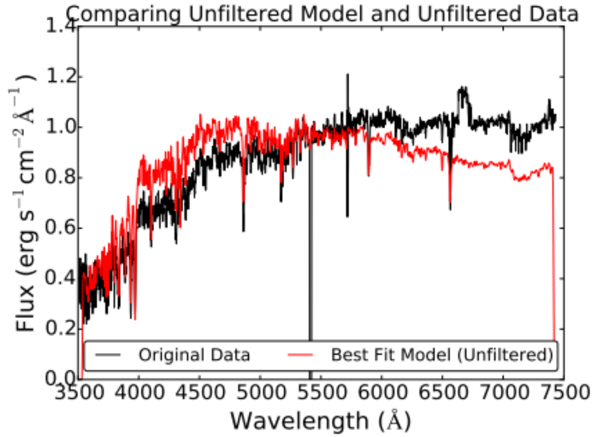
Ruiz-Lara et al. 2015

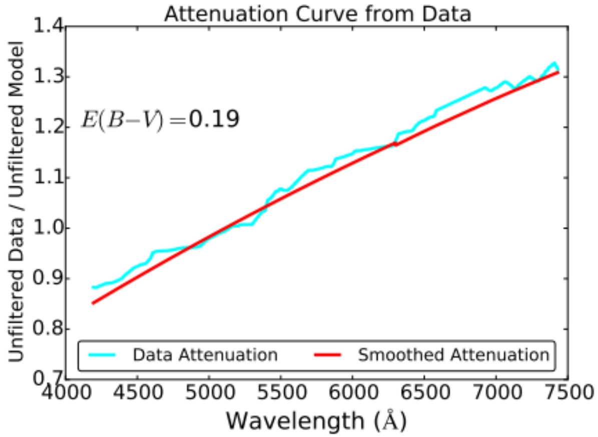
FIREFLY (Goddad et al. 2016)

- Minimum number of SSPs to recover the spectrum
  - Bayesian Information Criterion, $BIC = \chi 2 + k \ln(n);$

- Dust attenuation: high pass filter

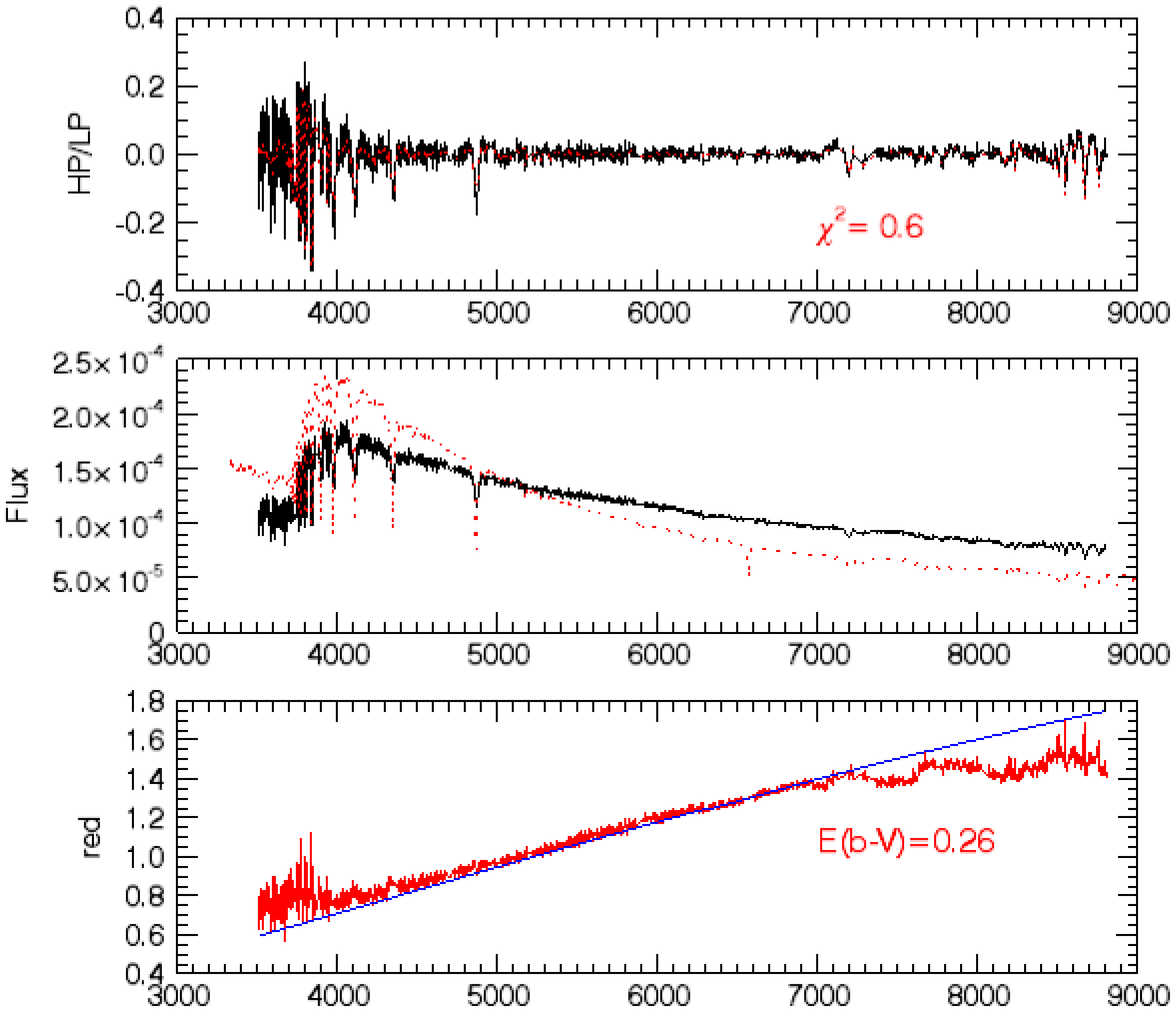






FIREFLY：消光曲线的形状

- $Log(Spec)=Log(Spec_0*red)=log(LP')+log(HP)$
  - $LP'=LP*red$
- $Log(spec_0)=\Sigma a_i*log(SSP_i)$ 星族合成
- $Log(SSP_i)=log(LP_i)+log(HP_i)$
- $Log(HP)=\Sigma a'_i*log(HP_i)$ --- 高通道的星族合成
  - $a'_I = a_i$?
- $Log(Red)=log(Spec)-\Sigma a_i*log(HP_i*LP_i)$



HP/LP
χ^2= 0.6
Flux
red
E(b-V)=0.26

Dust attenuation in galaxies

- Attenuation VS extinction
- Extinction: dust screen $I(\lambda)= I_0(\lambda)EXP(-\tau(\lambda))$
- Attenuation: Effective reddening
- Spec=Spec0*red
- Red=k(λ)*E(B-V)
  - k(λ): attenuation curve
    - Dust properties
    - Dust/star geometry
  - E(B-V)：amount of dust

Degeneracy

- Dust: change the continuum shape
  - Well-determined with full spectrum fitting if the continuum is well calibrated
- Young stellar population (t<1Gyr)
  - Continuum shape (very blue colors)
  - Young SSPs → High temperature ← lower metallicity
- Post starburst (t~1Gyr)
  - A type stars (Balmer absorption lines, Hdelta)
  - Contaminated by emission lines of ionized gas
- Older stellar population (SSPs are very similar)
  - Very difficult (limited information, strong degeneracy)
    - D4000 break (higher for older SSPs)

Recent development on CSP models(SED fitting)

- Better SSP
  - Bayesian approach
  - E.g. Bayesian evidence on IMF （Zhou et al. 2019）
  - Mastar
- Including more data
  - Combine far-infrared emission
    - Dust absorption (energy balance)
  - Combine emission lines
    - Leaky UV photons (cloudy)
  - AGN contamination?
  - e.g. CIGALE
- Better code: extra constrains on Age-Metallicity relation
  - Chemical evolution model

Scientific Questions

- Space resolved stellar population synthesis
  - Galaxy formation/quenching: inside-out or outside-in?
    - How connected with environment?
  - Local star formation on kpc scale(MaNGA)
    - SFR – Ha luminosity
    - Gas – dust (Ha/Hb ratio)
  - Stellar/Dust/gas geometry

Statistics

- N (spaxels) (S/N (OIII, NII, Ha>3))
  - 3250,000 in MPL-8
  - spaxels are not independent
- Unique questions
  - Where does star formation peak?
  - What does the `AGN’ spaxels (BPT diagram) not in nuclei region mean?
- C-MaNGA workshop