R. Cid Fernandes

Fossil methods applied to U/LIRGS: Challenges, Strategies and Results

Spectral synthesis (the "art" of retrieving the star formation history of galaxies by means of spectral analysis using the most up to date spectral models for stellar populations) progressed enormously in the past half decade or so, fostering equally large advances in our understanding of galaxy evolution. Systems with intense star formation and large amounts of dust, however, are still challengingly complex to model. This contribution illustrates these difficulties by applying modern spectral synthesis techniques to Luminous and Ultra Luminous Infra-Red galaxies. A new version of the code STARLIGHT was developed to handle these systems, which incorporates optical spectra plus Far-IR data in order to constrain the star formation history of these (mostly interacting) galaxies. Strategies to overcome the difficulties and degeneracies involved are presented.

Fossil methods (spectral synthesis) applied to U/LIRGS:

Challenges, Strategies & Results

Roberto Cid Fernandes & Rosa Gonzalez Delgado

Outline

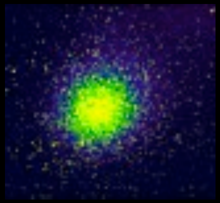
(1) Spectral fitting:
+ STARLIGHT & its (too) many applications
(a highly over-rated, but pretty useful code :-)

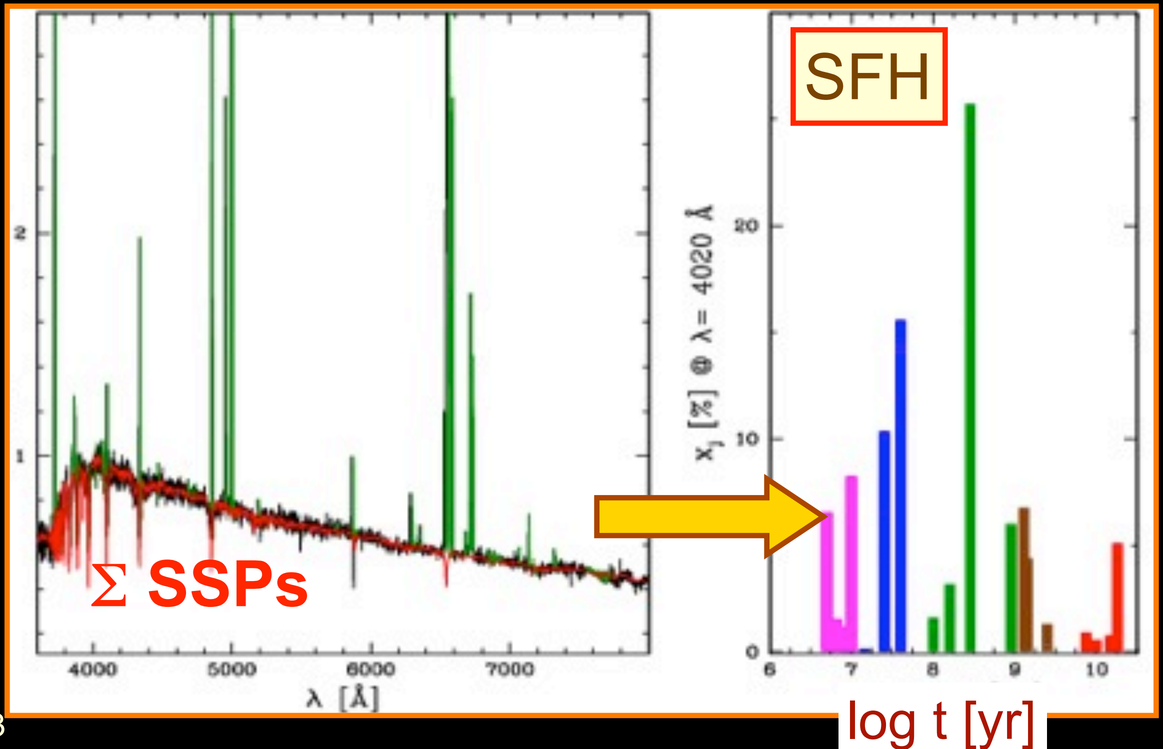
(2) Challenge:
+ Population dependent extinction

(3) Strategy:
+ Model dust emission to constrain optical fits

(4) Results:
+ (preliminary) spectral fits & SFHs of U/LIRGS

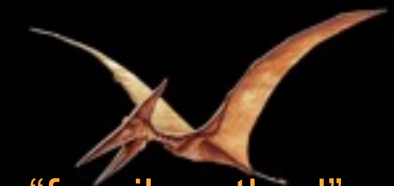
(1) STARLIGHT: A quick tour

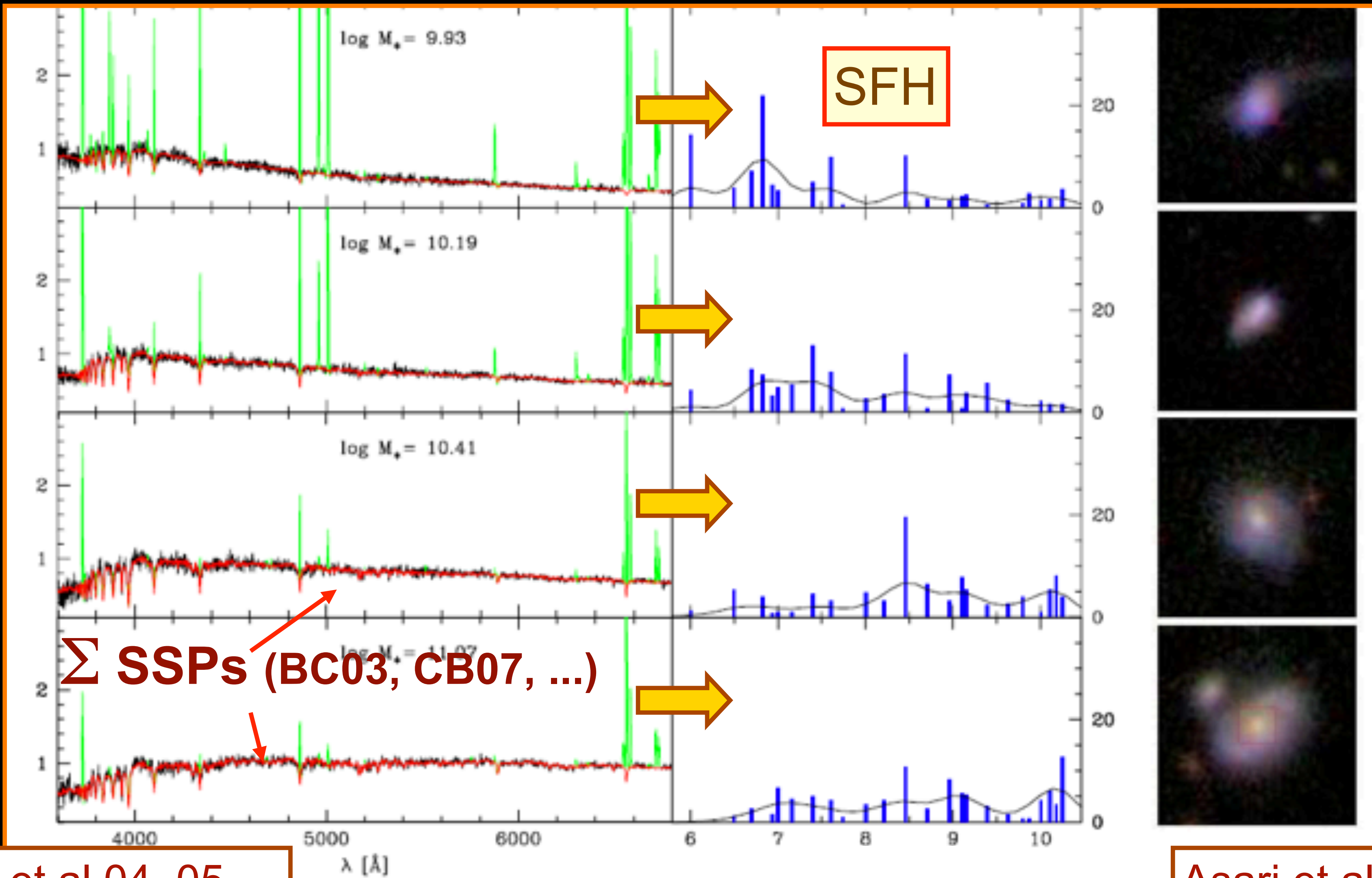
 $= M_1$  $+ M_2$  $+ M_3$  $+ \ldots$



STARLIGHT

Recovers the SF **History** of a galaxy from its spectrum


“fossil method”

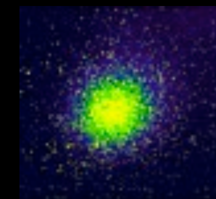


CF et al 04, 05 …

log t* [yr]

Asari et al 07

STARLIGHT [not ©!]: Decomposing galaxy spectra

 $= M_1$  $+ M_2$  $+ M_3$  + ...

$$L_{gal}(\lambda) = \sum_{t,Z} M_{SSP}(t,Z) \times SSP(\lambda;t,Z) \times e^{-\tau(\lambda)}$$

Observables

Full spectrum:

F_λ

SFH:

mass or light fractions

➔ Pop vector

Spectral Base

SSPs from

BC03, Granada, Pegase, "CB07",, Vazdekis, …

Dust:

1 τ_V?

2τ_V?

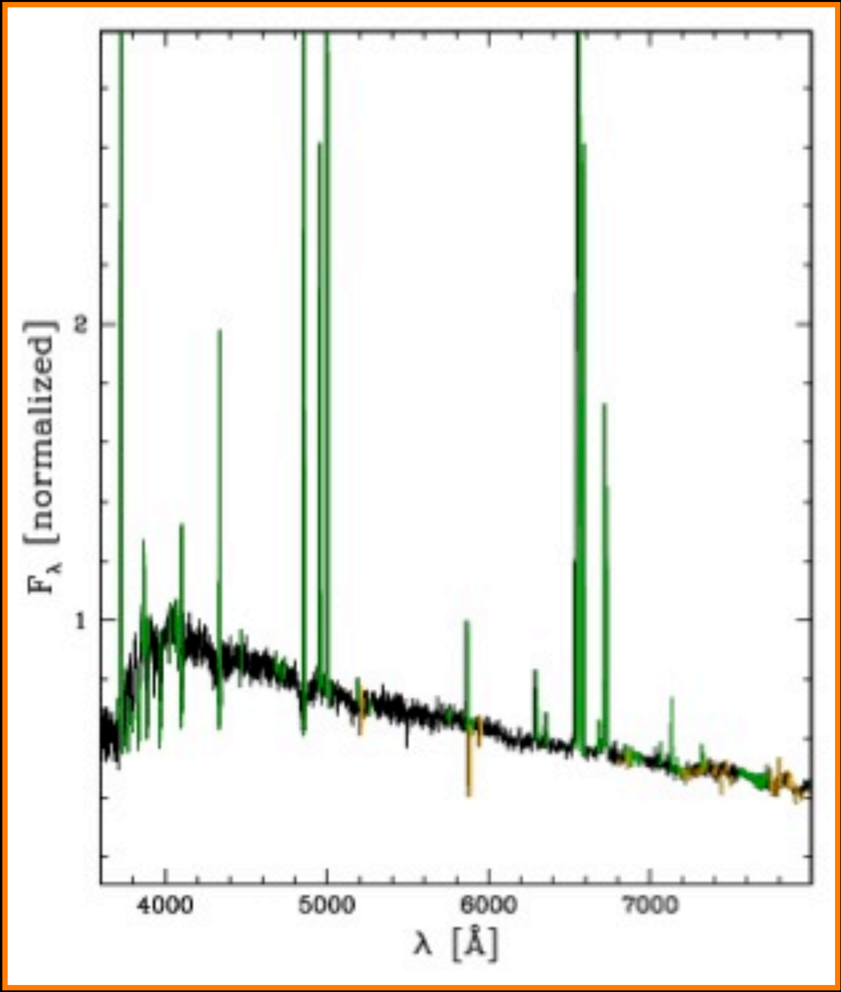
$\tau_V(t,Z)$?

…

Inverse Population Synthesis: Input

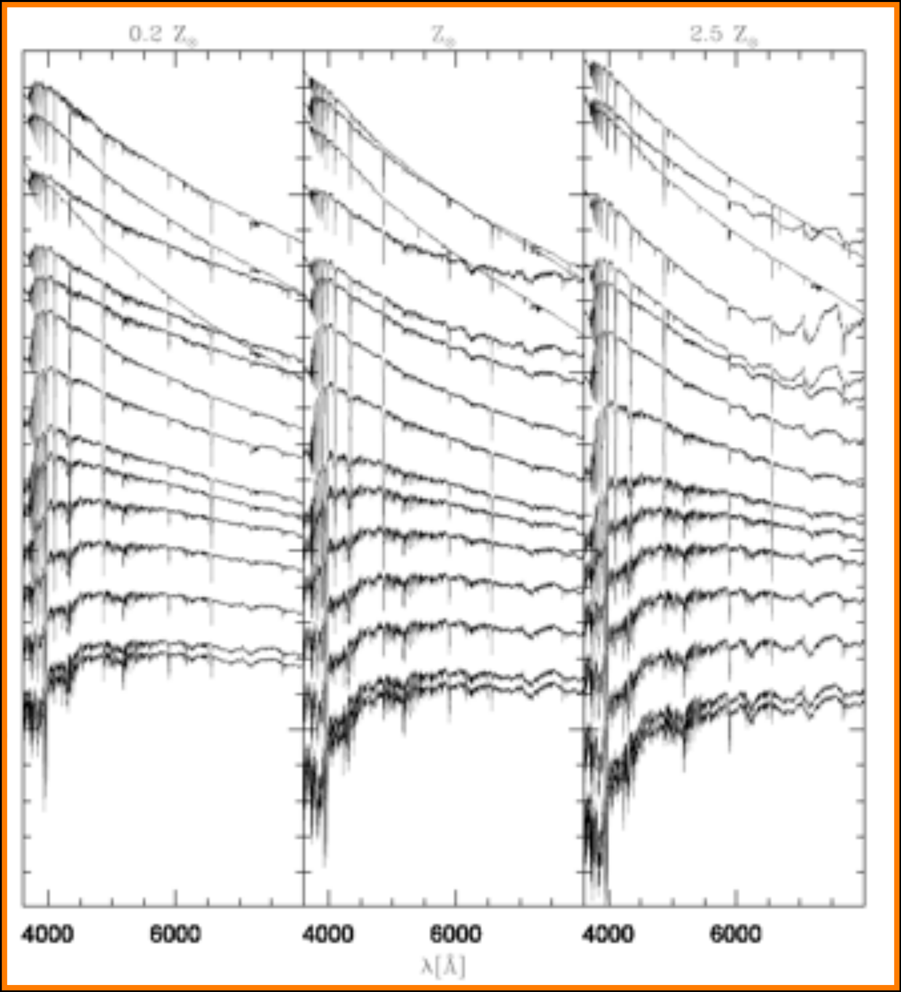
Observed spectrum

eg, a SF galaxy from the SDSS



Spectral Base

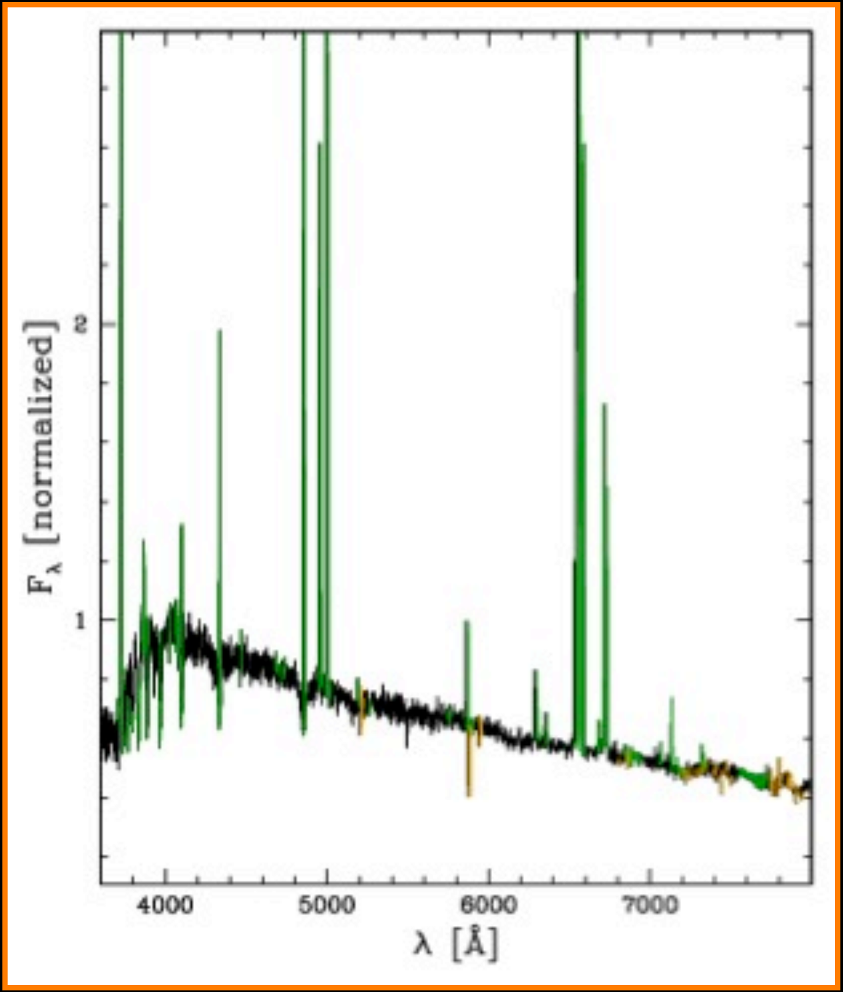
eg, N = 45 SSPs from BC03



Inverse Population Synthesis: Input

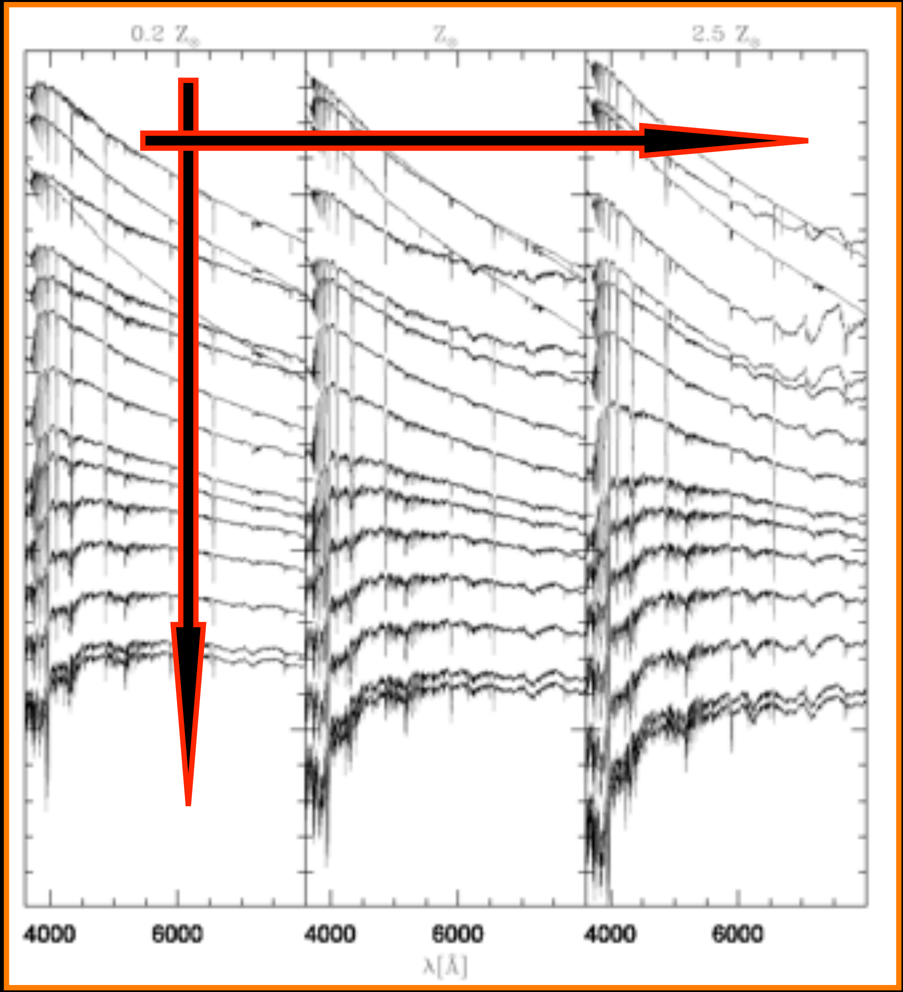
Observed spectrum

eg, a SF galaxy from the SDSS



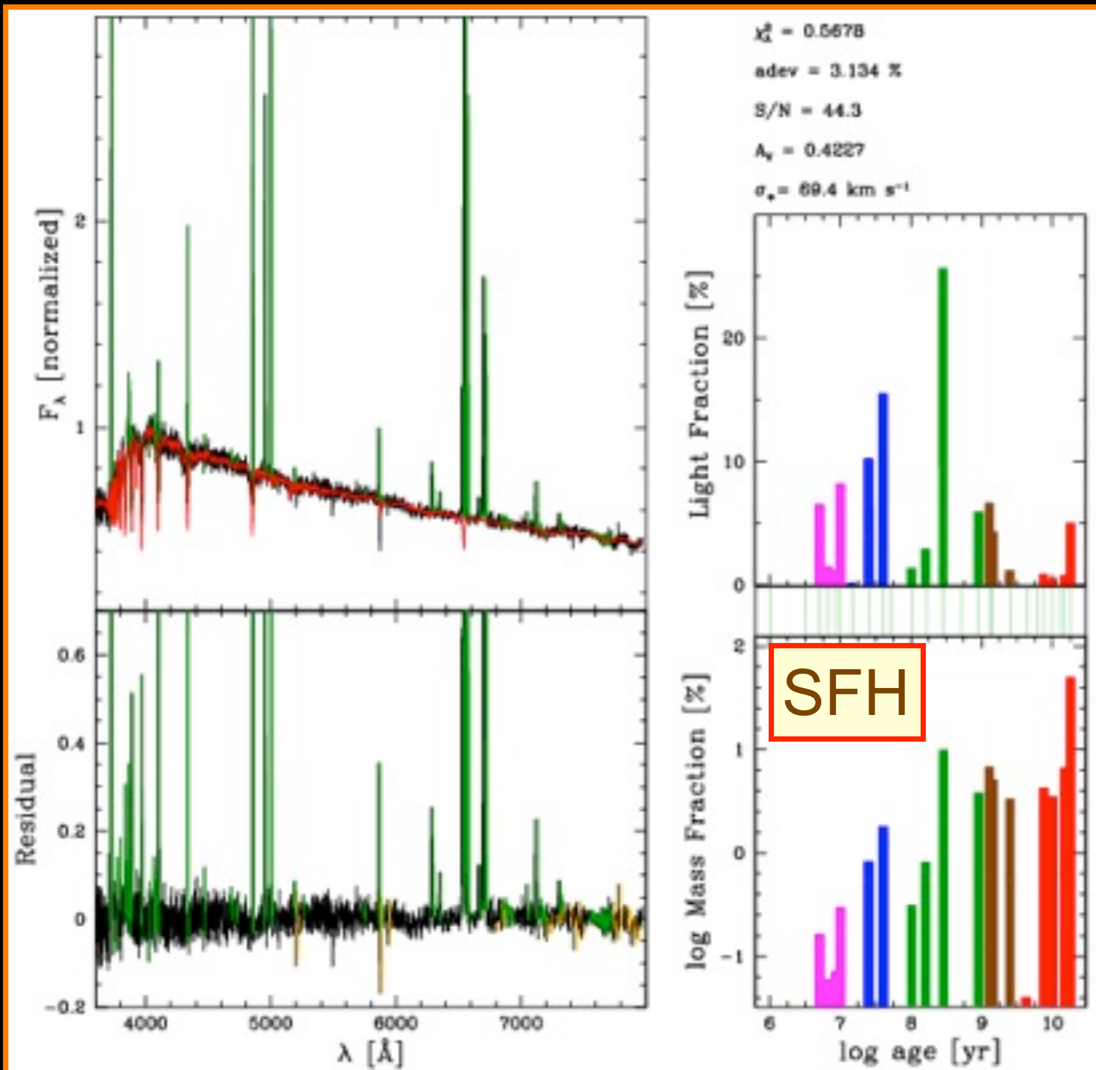
Spectral Base

eg, N = 45 SSPs from BC03



Inverse Population Synthesis: Output

Observed spectrum + Base + Inversion method = SFH



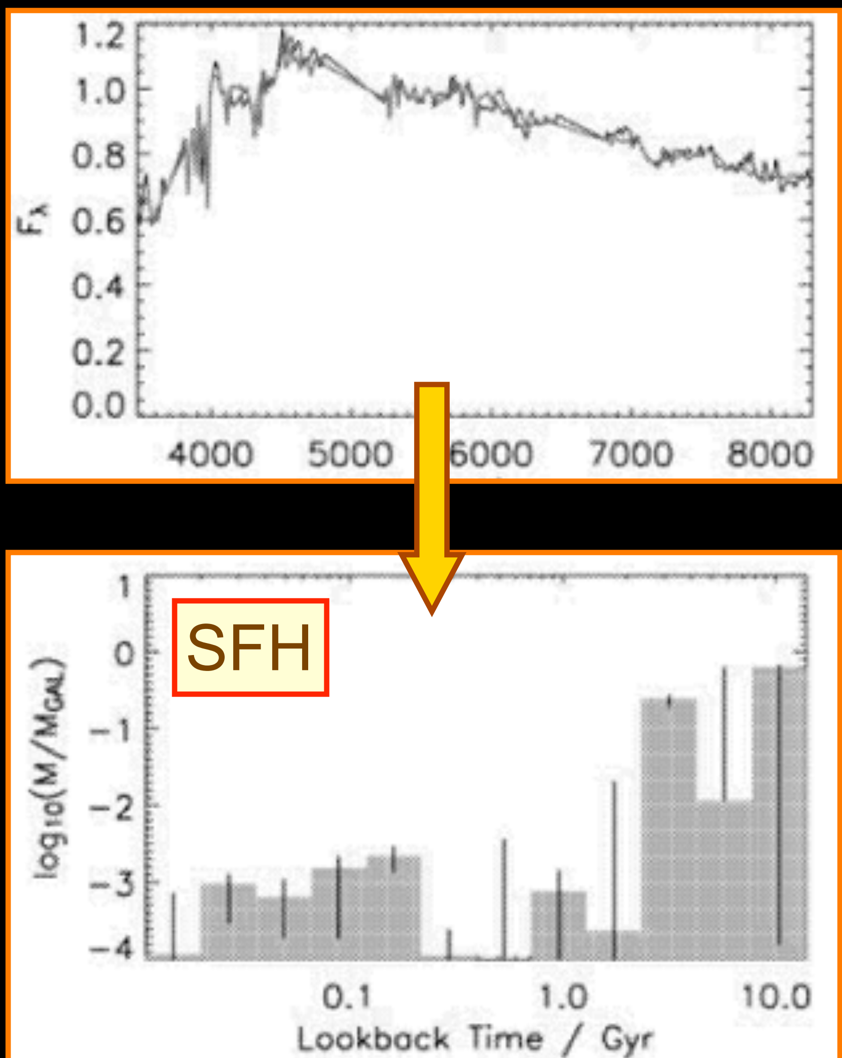
(A) Observables:
- full spectrum N_λ = 1000~4000 pixels

(B) Spectral base:
- N_* = 25 x 6 = 150 (!) SSP(λ)'s from BC03

(C) Inversion method:
- Markov Chains exploration …
- non-parametric ☺

Inverse Population Synthesis: Output

Observed spectrum + Base + Inversion method = SFH

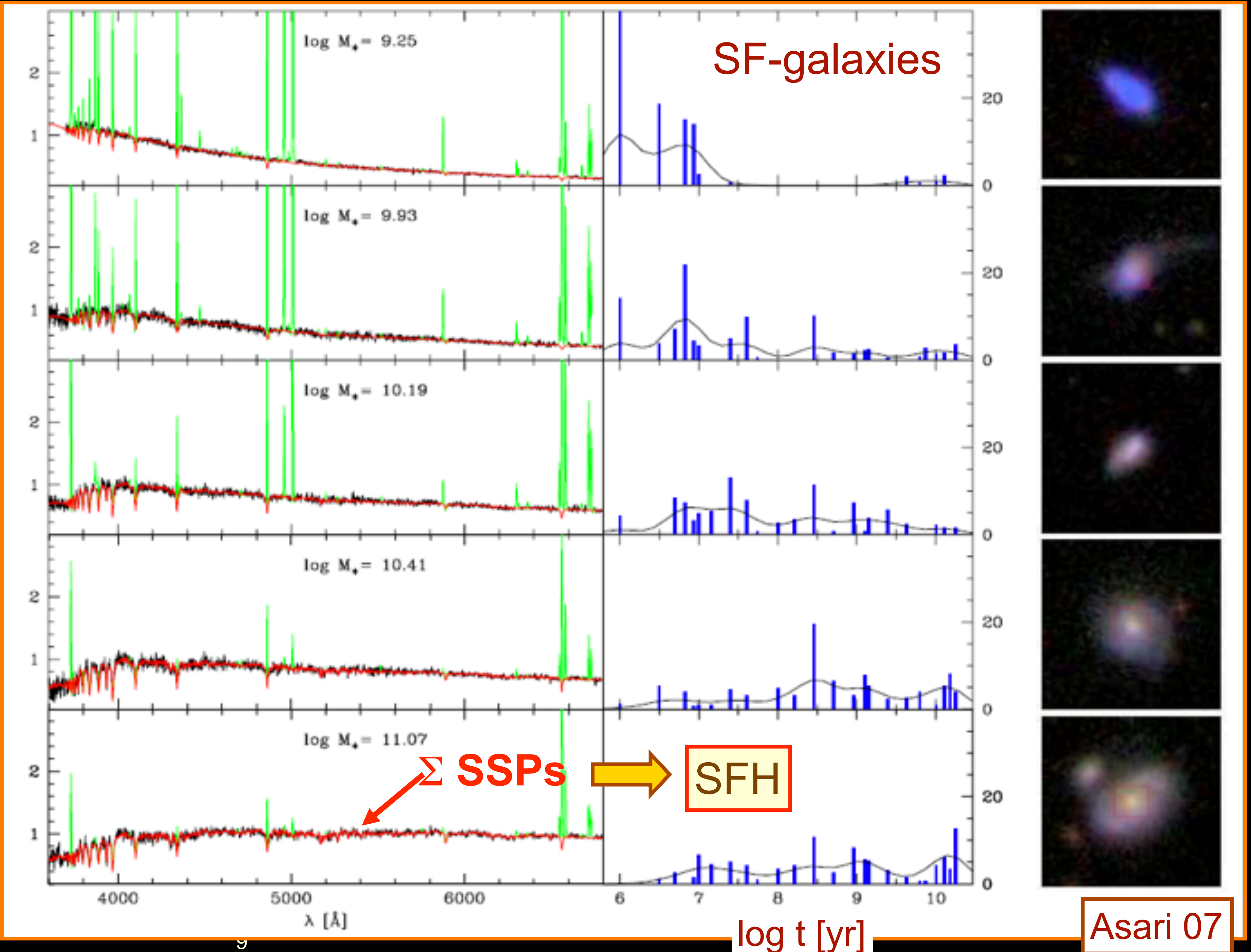


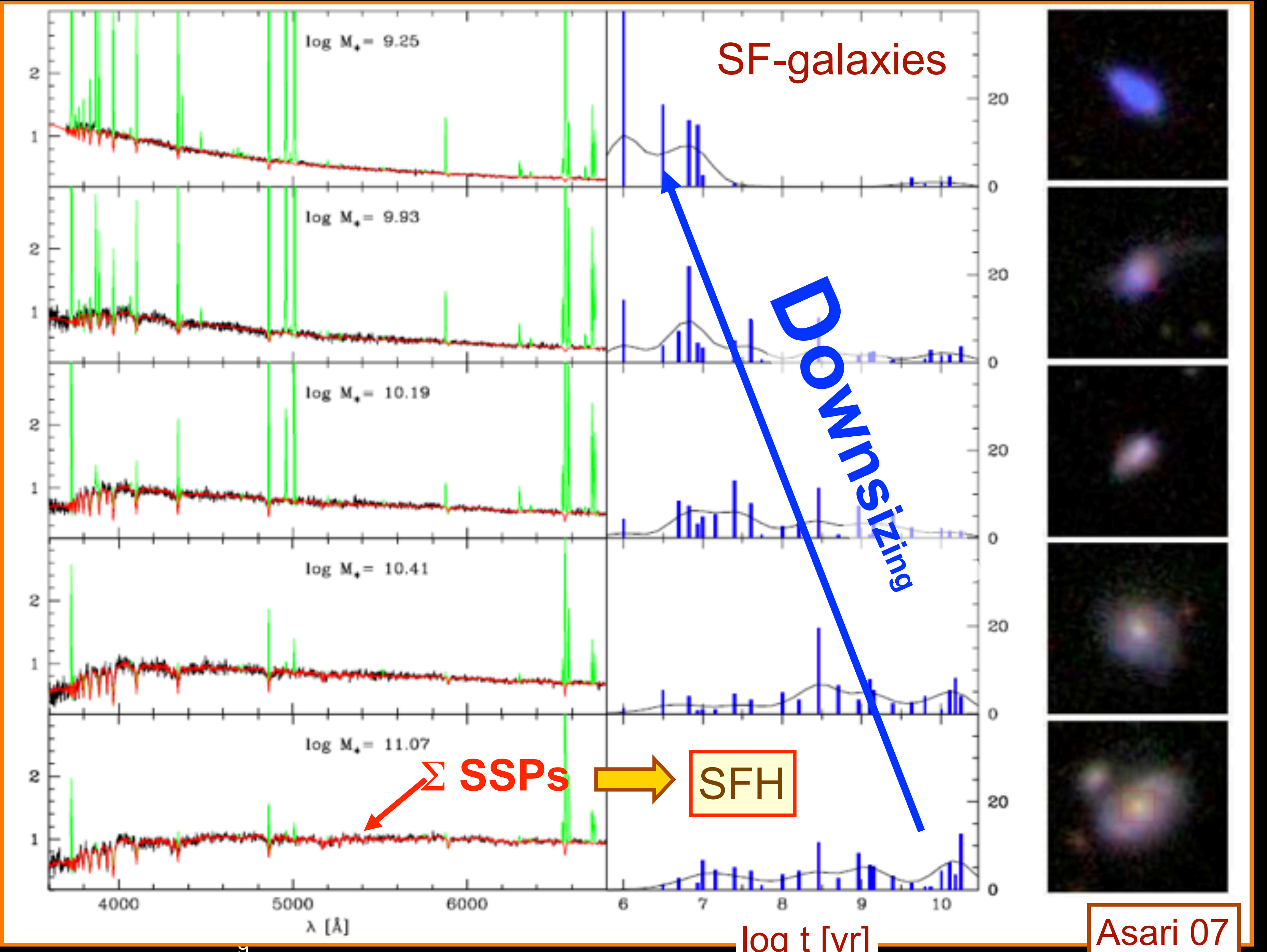
(A) Observables:
- full spectrum compressed to N_λ = 25 pixels...

(B) Spectral base:
- N_* = 12 “finite bursts” of different ages (BC03)

(C) Inversion method:
- MOPED ...
- non-parametric ☺

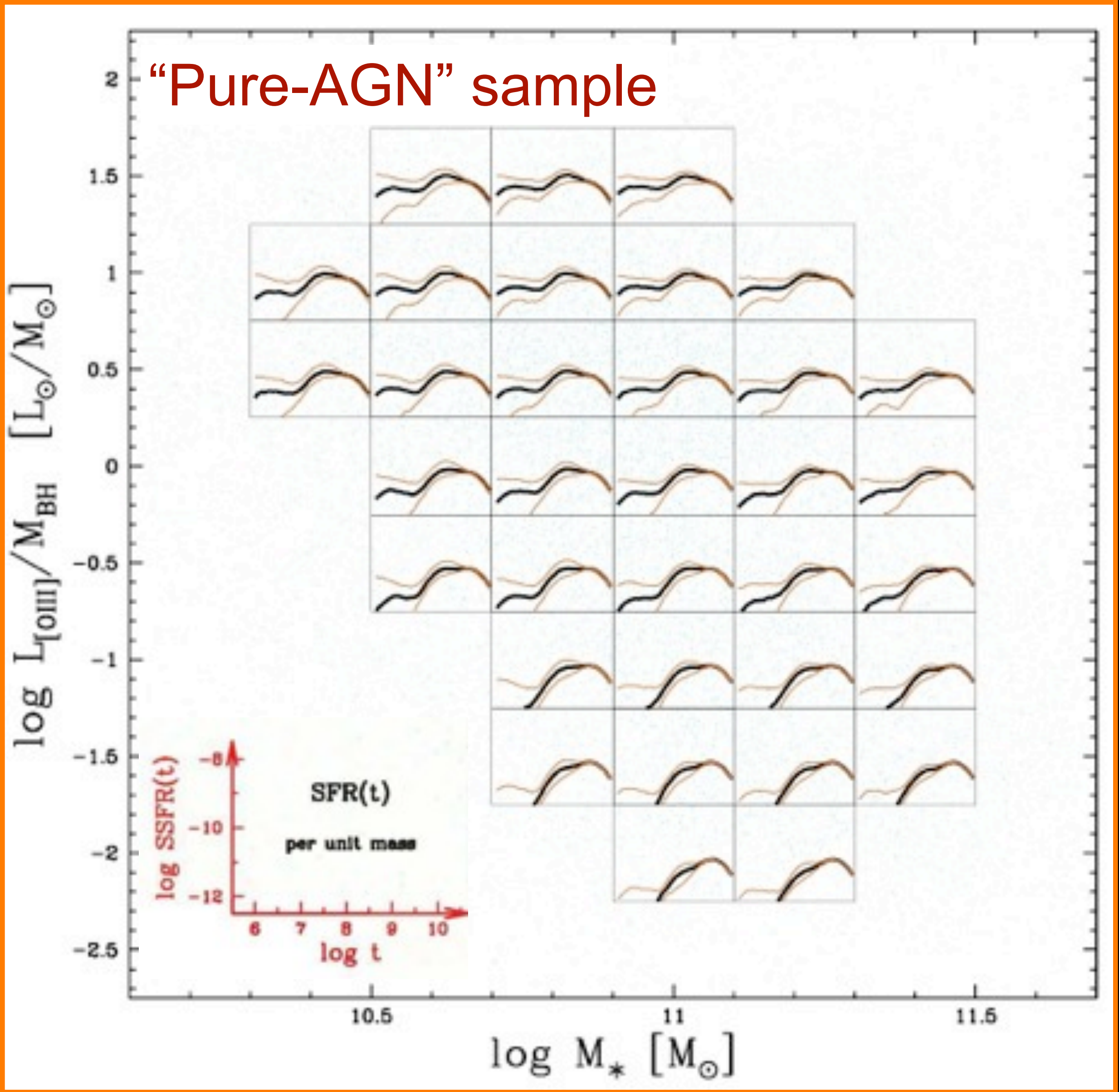
(D) Tricks / Details:
- **1 extinction model**
- NO kinematics ☺


SF-galaxies
log M* = 9.25
log M* = 9.93
log M* = 10.19
log M* = 10.41
log M* = 11.07
Σ SSPs
SFH
λ [Å]
log t [yr]
Asari 07

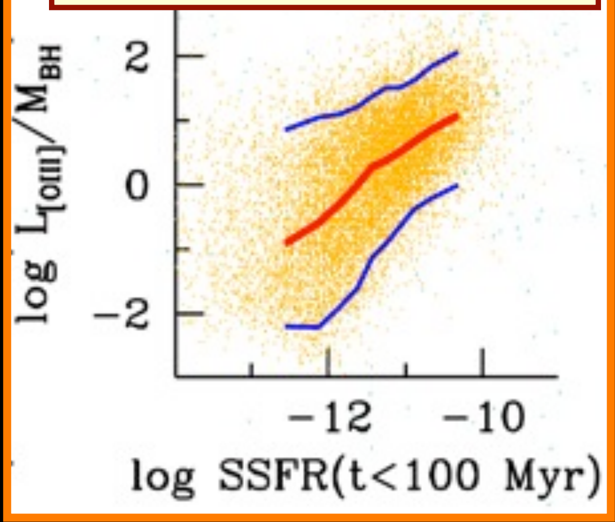


SF-galaxies
log M* = 9.25
log M* = 9.93
log M* = 10.19
log M* = 10.41
log M* = 11.07
Σ SSPs
SFH
Downsizing
λ [Å]
log t [yr]
Asari 07

The Starburst-AGN (dis)connection

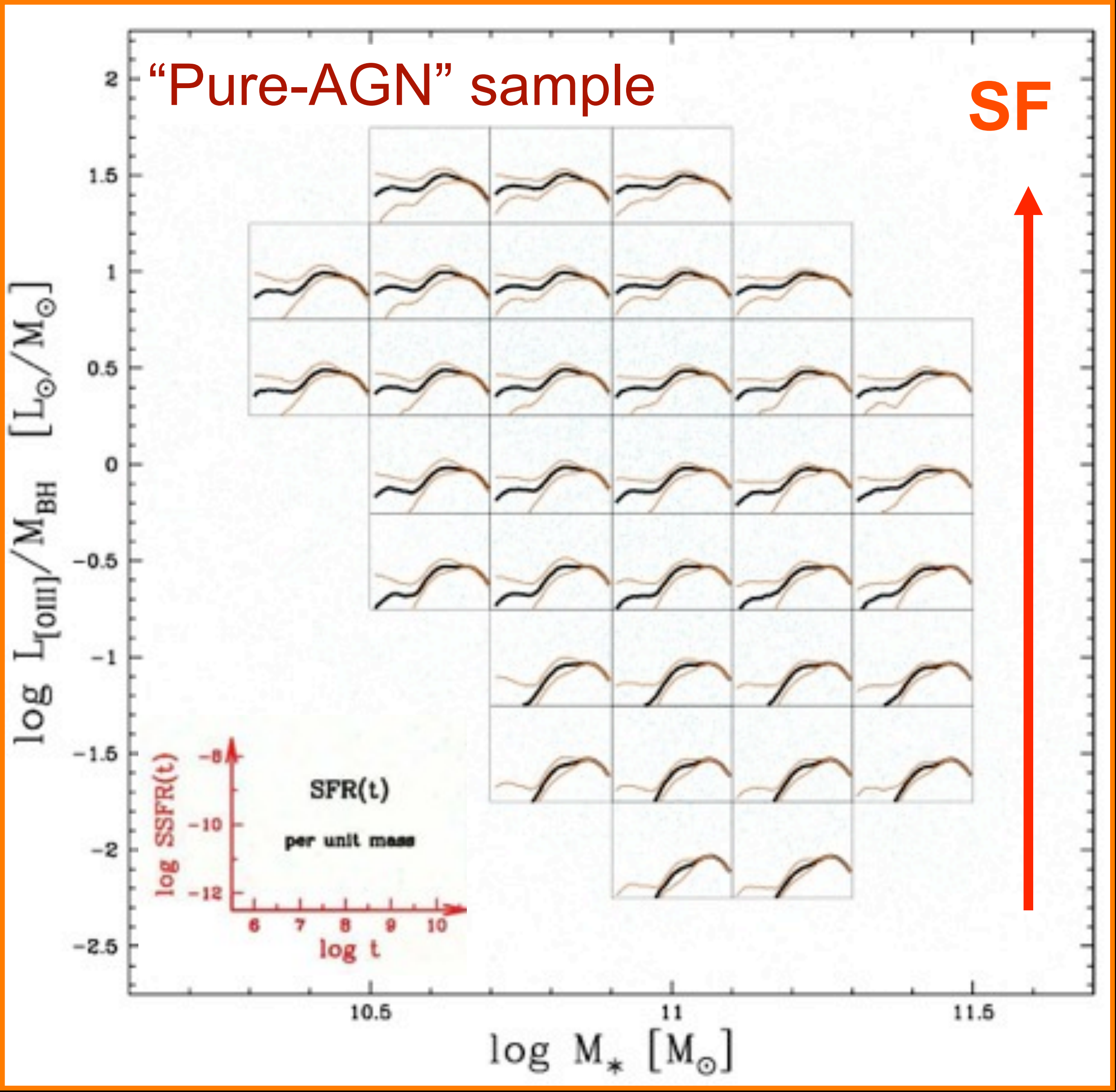


Specific BH & SF rates correlate

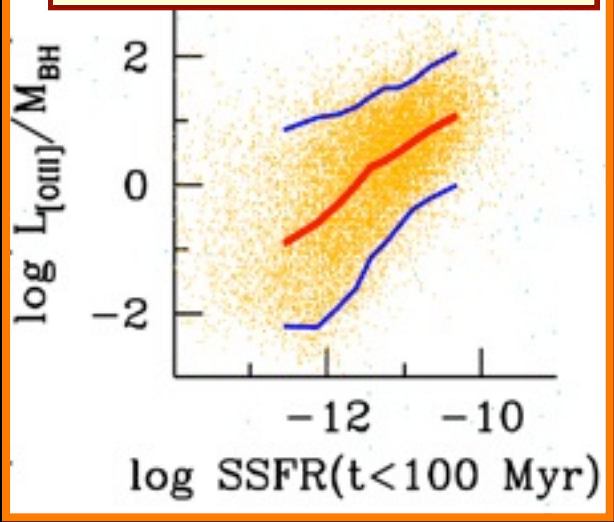


"BHs grow more efficiently in galaxies which form stars more efficiently".

The Starburst-AGN (dis)connection

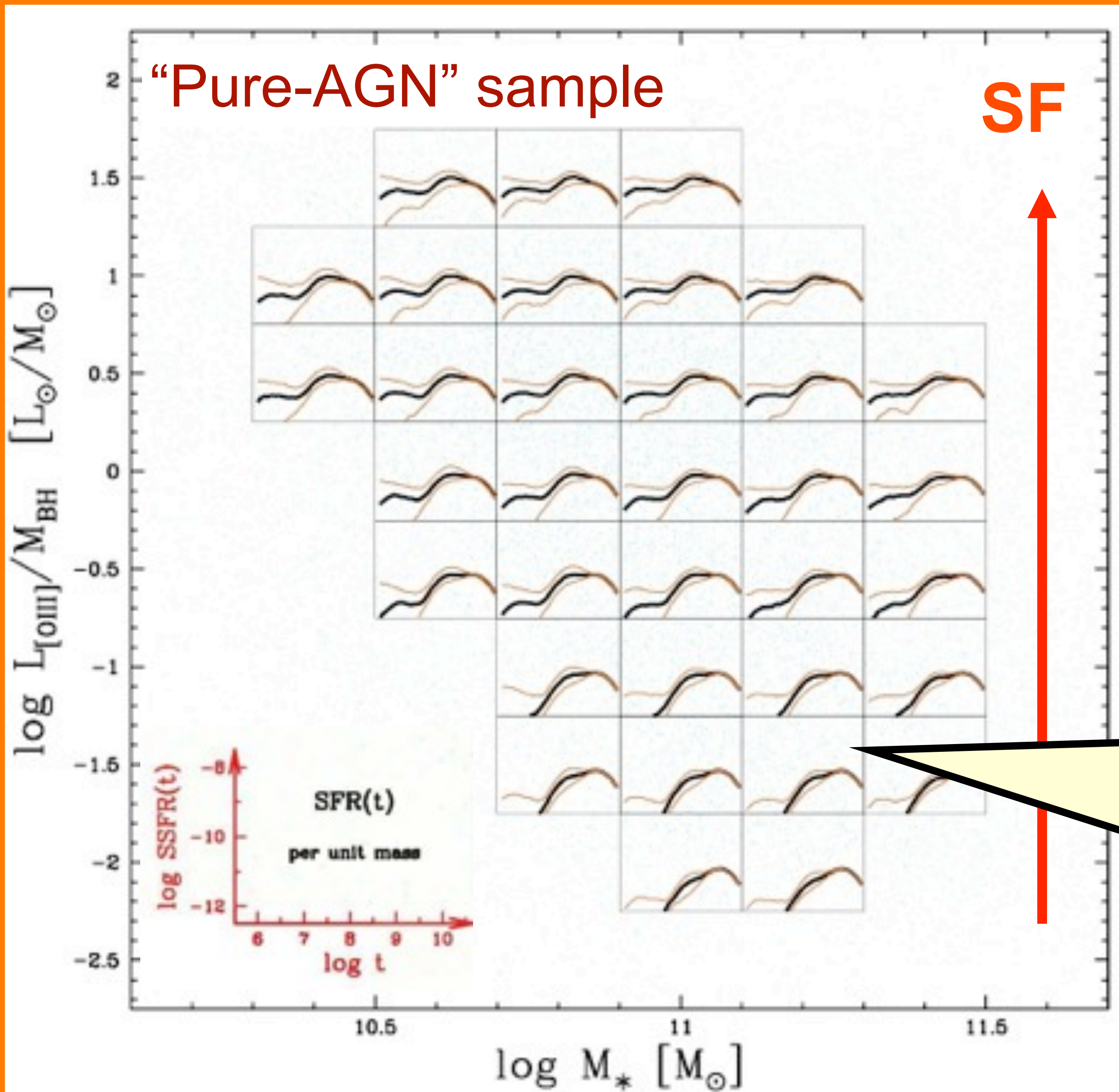


Specific BH & SF rates correlate

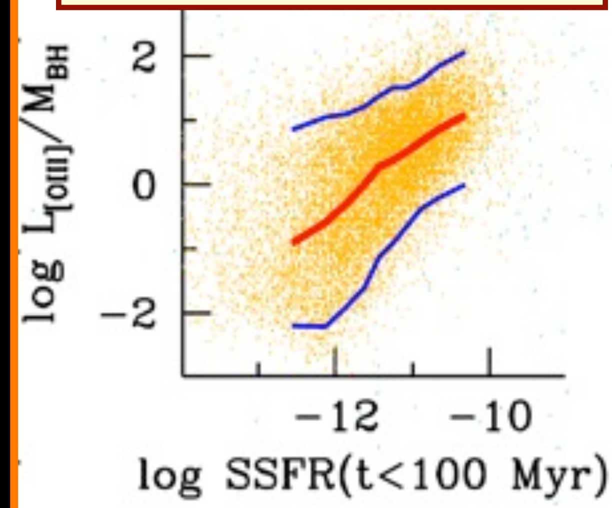


"BHs grow more efficiently in galaxies which form stars more efficiently".

The Starburst-AGN (dis)connection



Specific BH & SF rates correlate

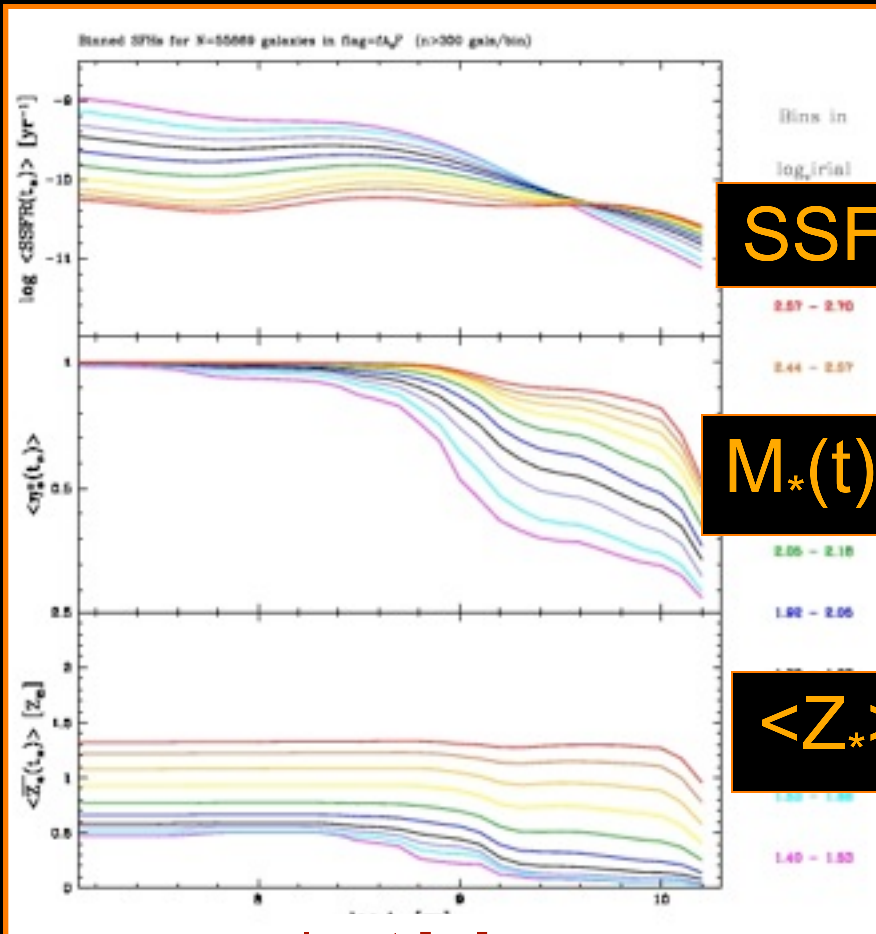


SFR(now) = 0!
Retired Galaxies, ionized by their old stars
(Stasinska 2008)

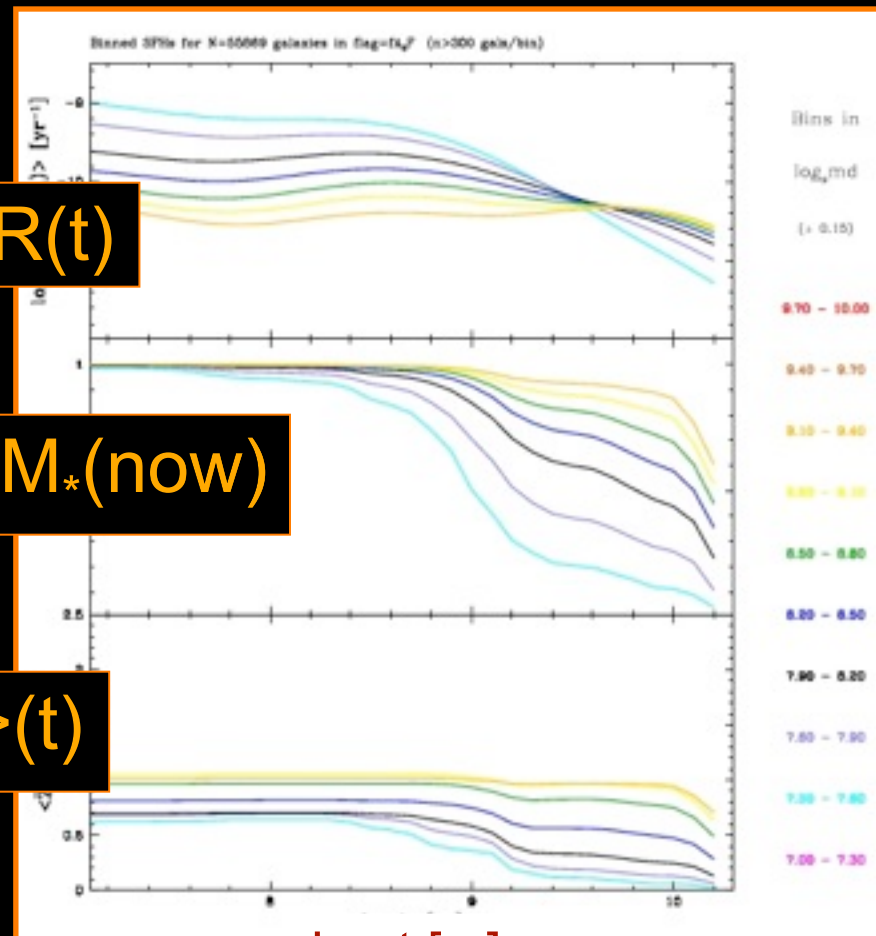
SFHs & $Z_*(t)$ – Star Forming Galaxies

Bins in $v_{esc} \sim (GM/R)^{1/2}$

Bins in surface density



log t [yr]



log t [yr]

SSFR(t)

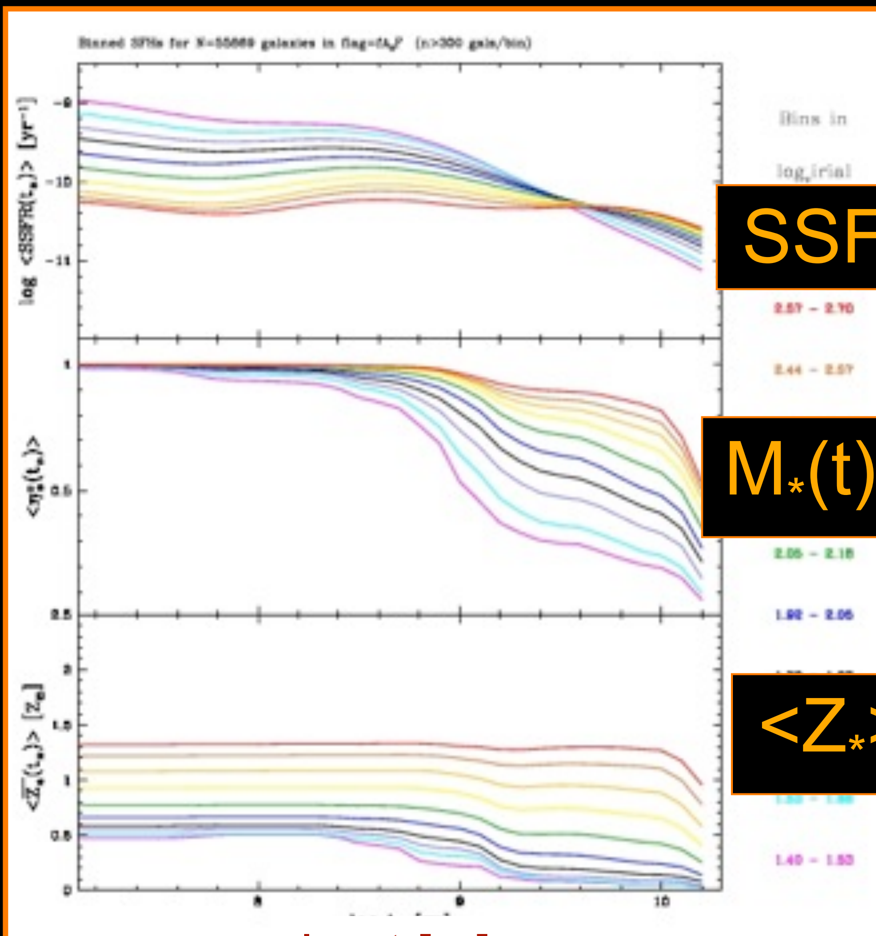
$M_*(t)/M_*(now)$

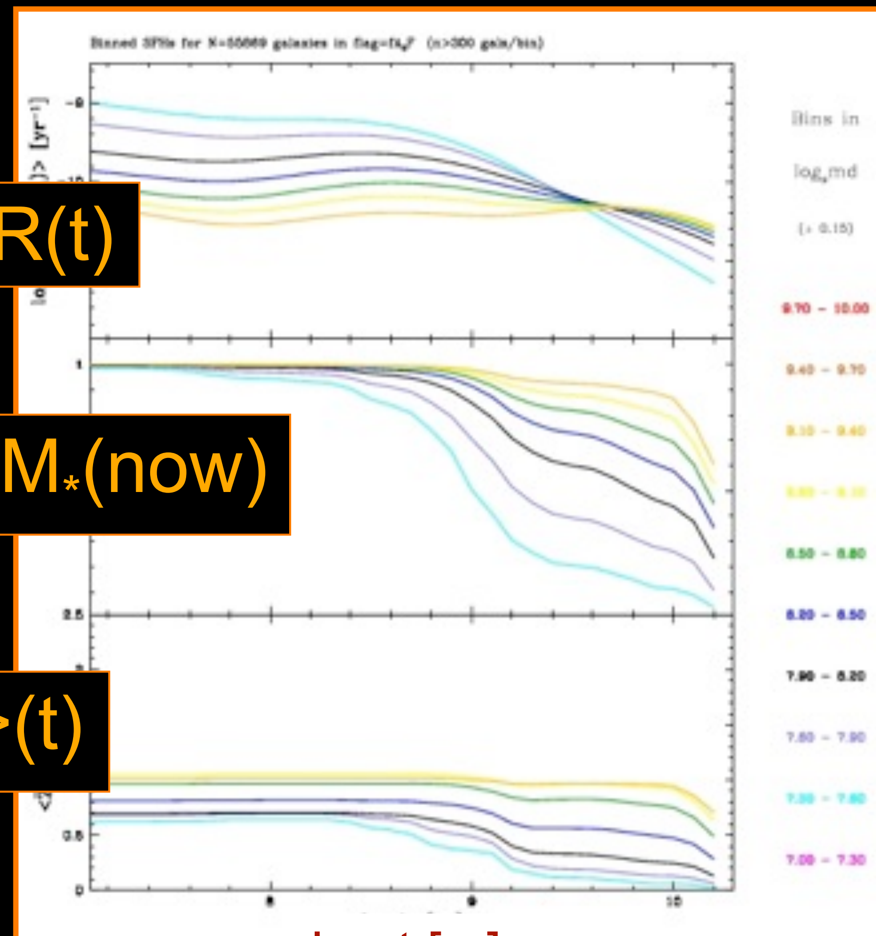
$\langle Z_* \rangle(t)$

SFHs & $Z_*(t)$ – Star Forming Galaxies

Bins in $v_{esc} \sim (GM/R)^{1/2}$

Bins in surface density





SSFR(t)

$M_*(t)/M_*(now)$

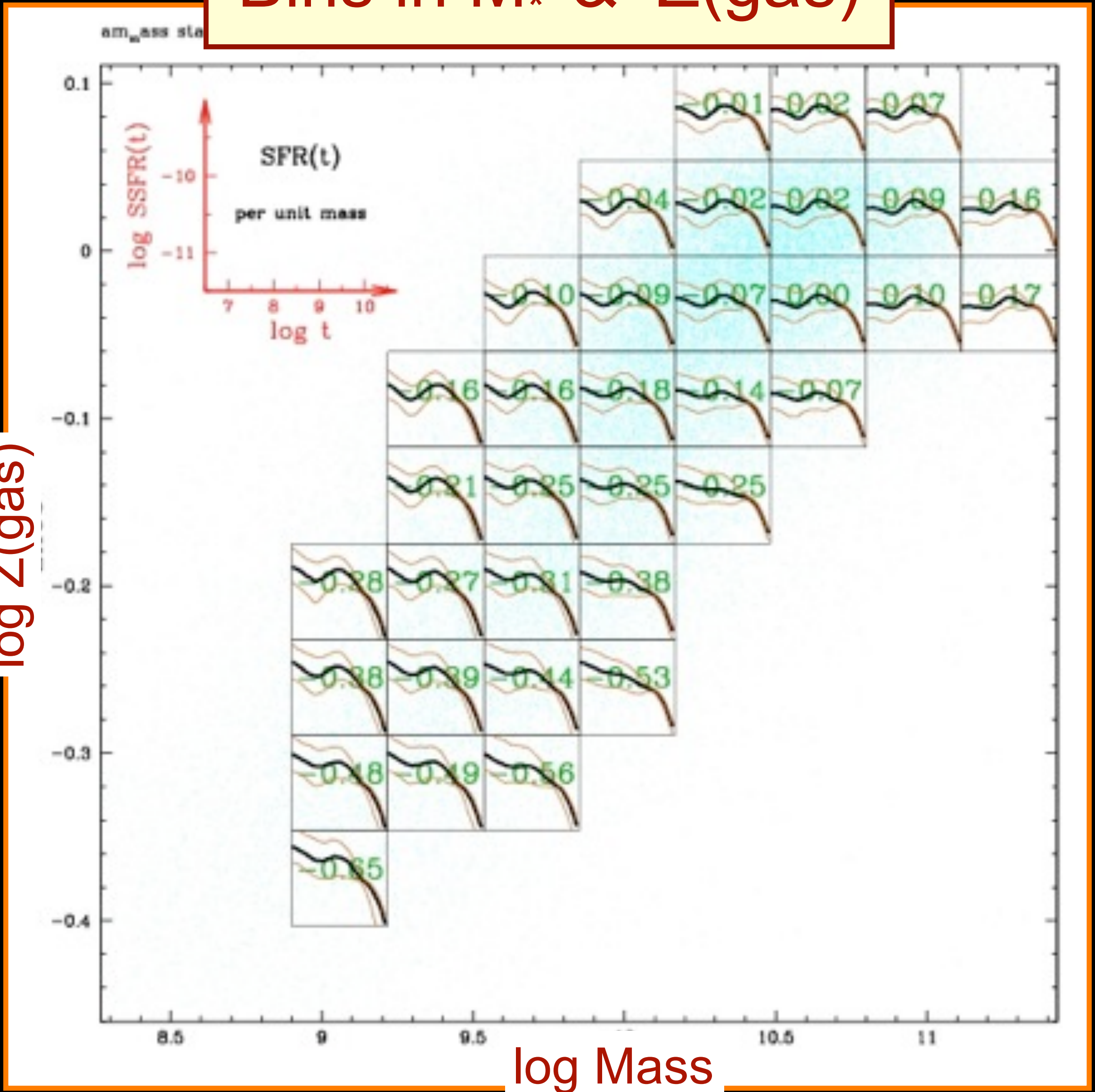
$<Z_*>(t)$

log t [yr]

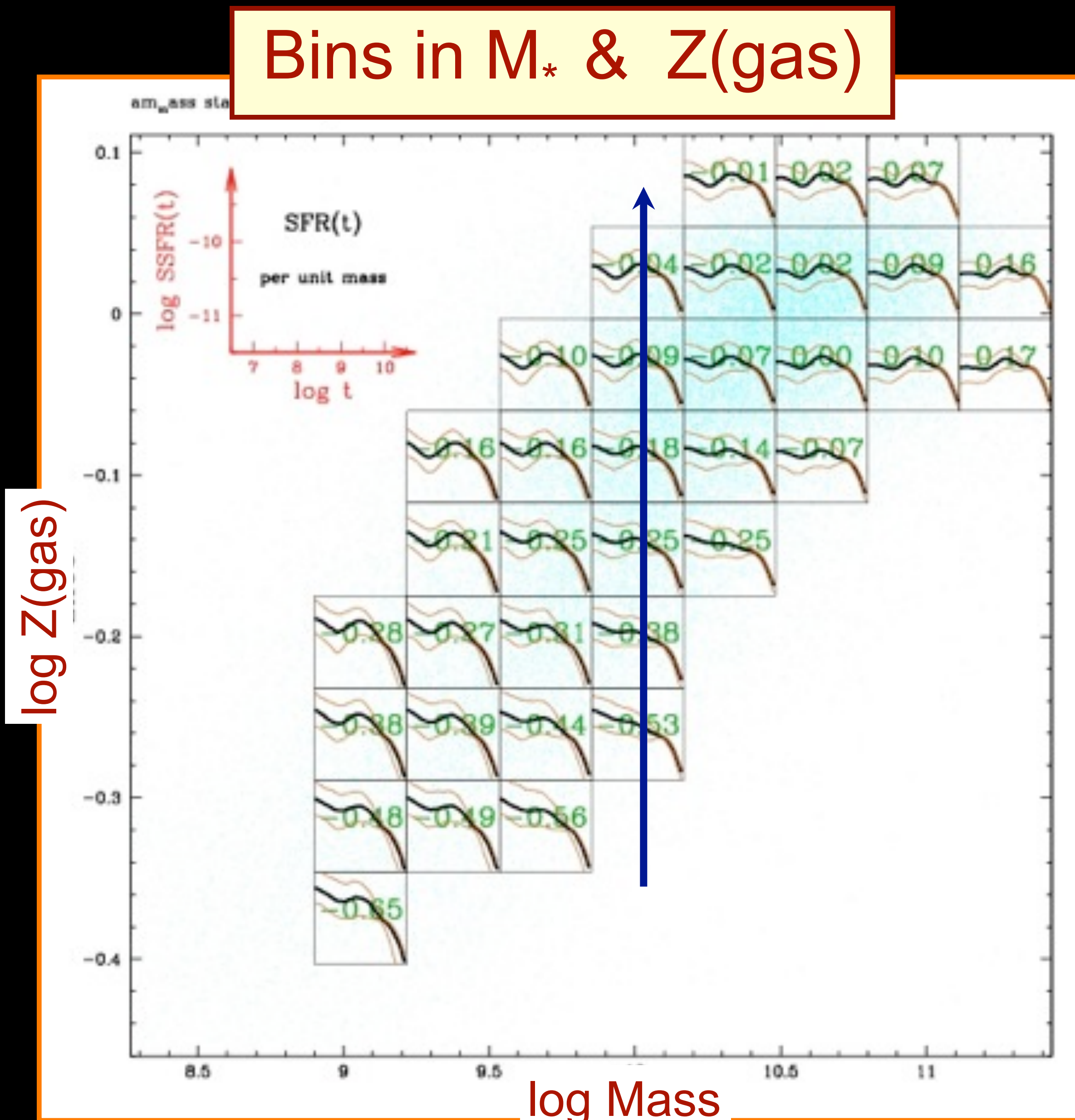
log t [yr]

SFHs & $Z_*(t)$ – Star Forming Galaxies

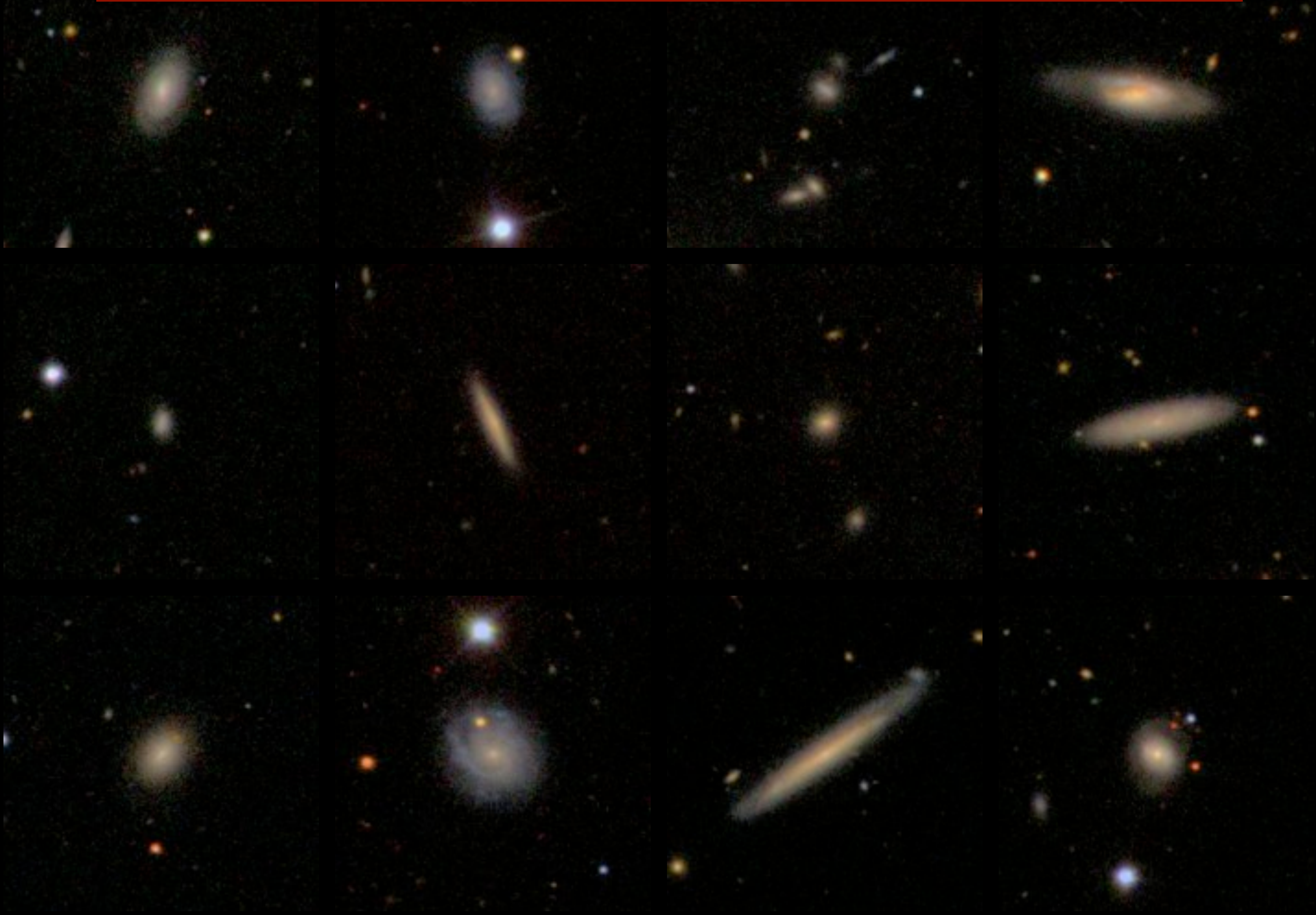
Bins in M_* & Z(gas)



SFHs & $Z_*(t)$ – Star Forming Galaxies



Weak-[OIII] sources: The most massive & metal rich SFs



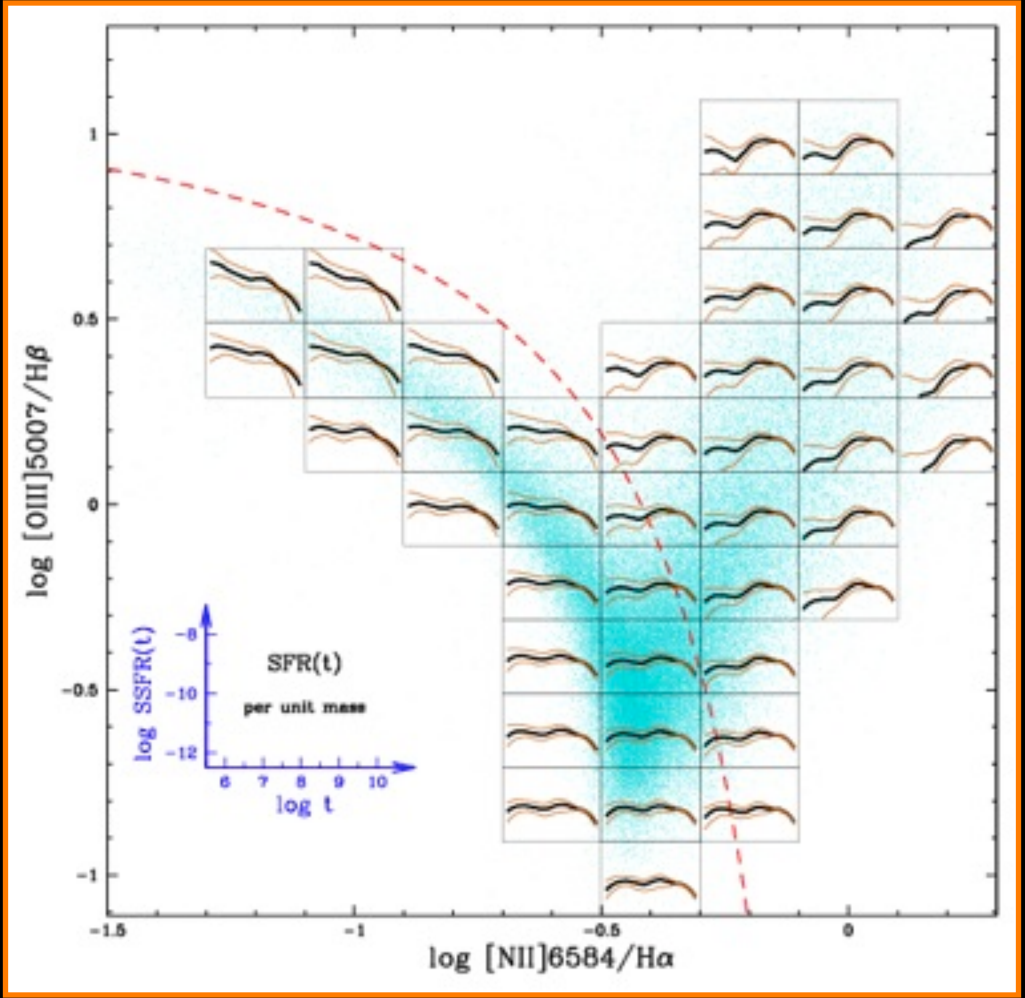
Starlight

Spectral Synthesis Code

SEAGal

GRUPO DE ASTROFÍSICA GAS - UFSC BRASIL

www.starlight.ufsc.br



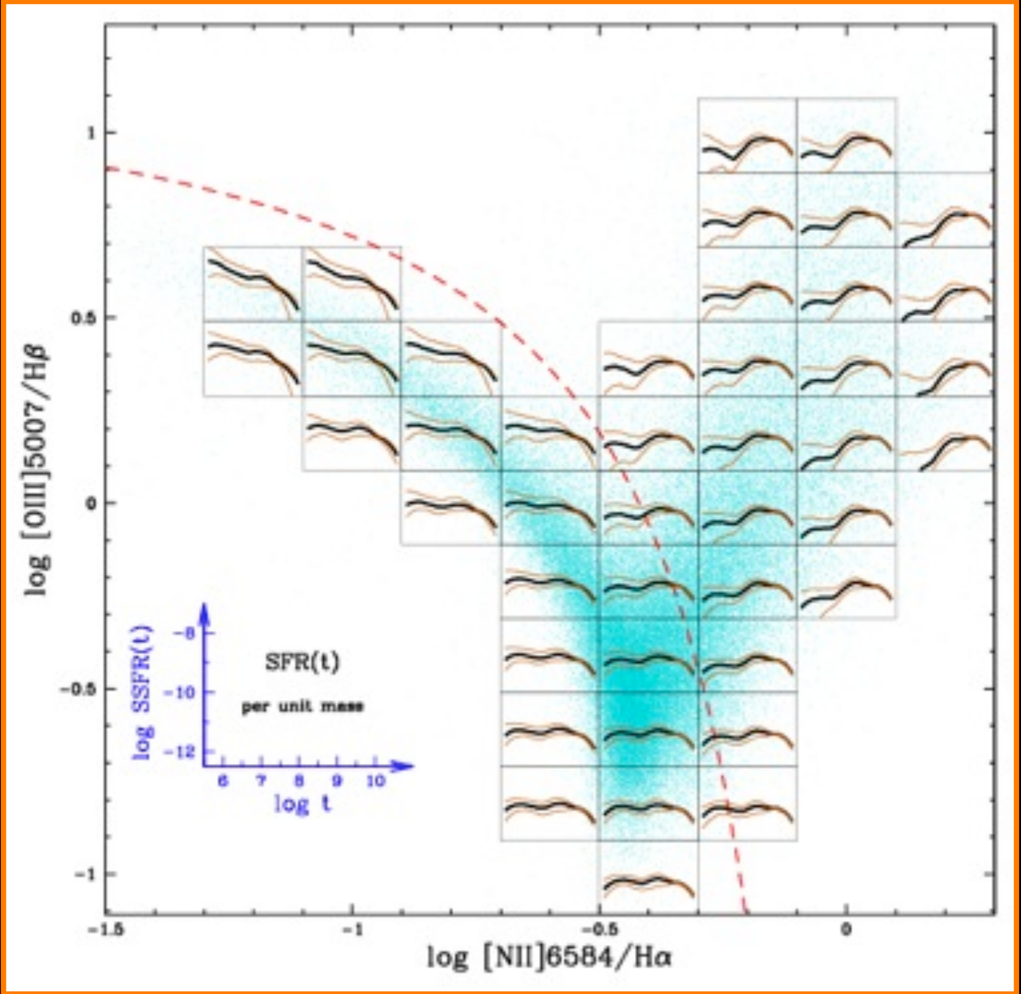
SEAGal

Starlight

Spectral Synthesis Code

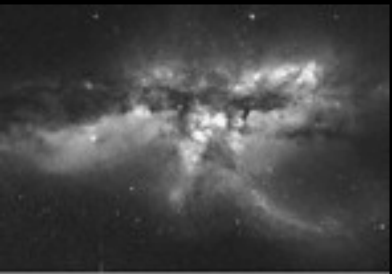
GRUPO DE ASTROFÍSICA
GAS - UFSC
BRASIL

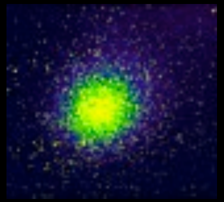
www.starlight.ufsc.br

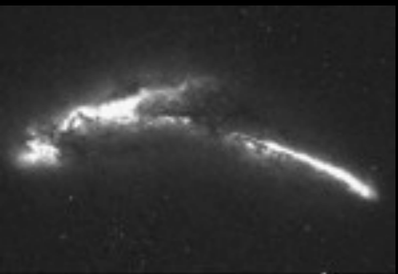


BUT . . . .

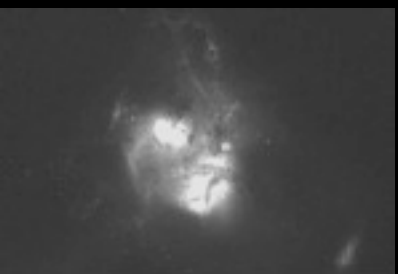
(2) STARLIGHT w/multiple extinctions: The challenge!

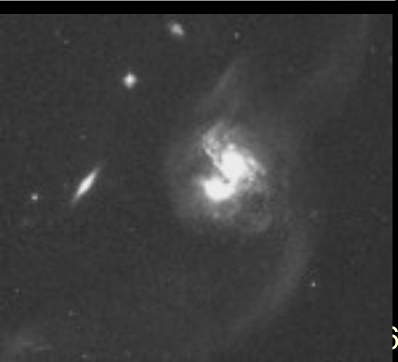


= M_1  + M_2  + M_3  + ...



$$= \sum_{t,Z} M_{SSP}(t,Z) \times SSP(\lambda;t,Z) \times e^{-\tau(\lambda)}$$



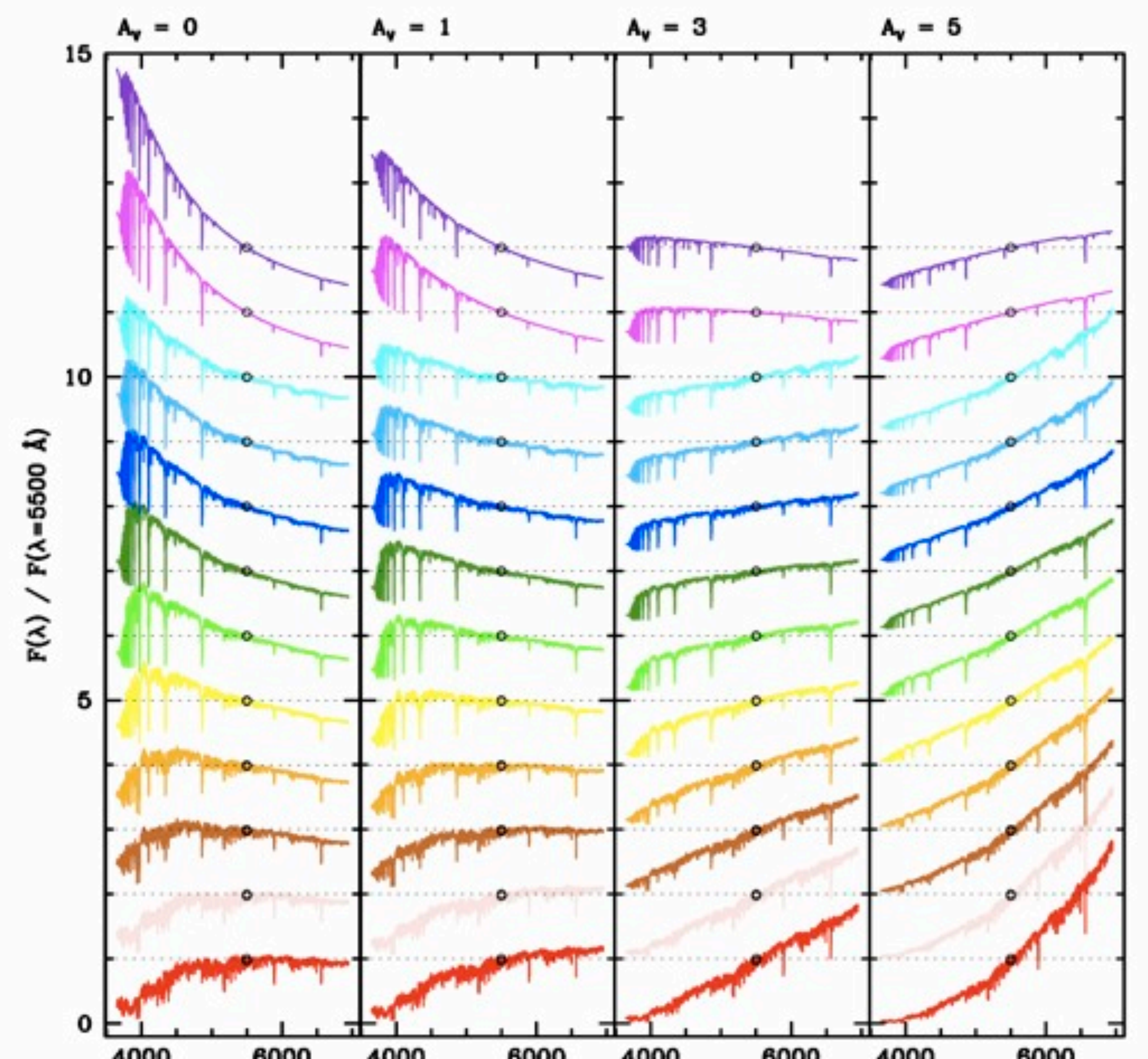


SFH:* *mass or light fractions* ➔ *Pop vector

Spectral Base
SSPs from
BC03, Granada, Pegase, "CB07",, Vazdekis, …

Dust:
1 τ_V*?*
2τ_V*?*
$\tau_V(t,Z)$*?*
…

(2) The Challenge: Dusty SSPs



(3) Strategy: $L_{IR} = L_{dust}$ as a constraint

Inoue 2001…

Reprocessed light: $R =$

- $R_{ion} = Ly\alpha + LCE$
- $R_{UVopt} = \sum L^0(\lambda)\,[1 - e^{-\tau(\lambda)}]\,\Delta\lambda$

$RLy\alpha = \beta_D\, f\, L_{ion}$

$RLCE = (1 - f)\, L_{ion}$

$f = f(\tau)$ = fraction of ion radiation absorbed by gas (= photoionization)

→ Standard choices: $\beta_I \sim 1/3$; $\beta_D \sim 1/3$

τ = ? $\tau_{TOT} = \tau_{ISM} + \tau_{Birth\text{-}Cloud}$ → $\tau_{Birth\text{-}Cloud} = \beta_I\, \tau_{TOT}$

$f(\tau)$ = ? ← eq 8 of Petrosian et al 1978 ~ $e^{-0.785\tau}$ (…)

⇒ Given $L^0(\lambda)$, τ_{TOT} & ext. law τ_λ/τ_V → predict R

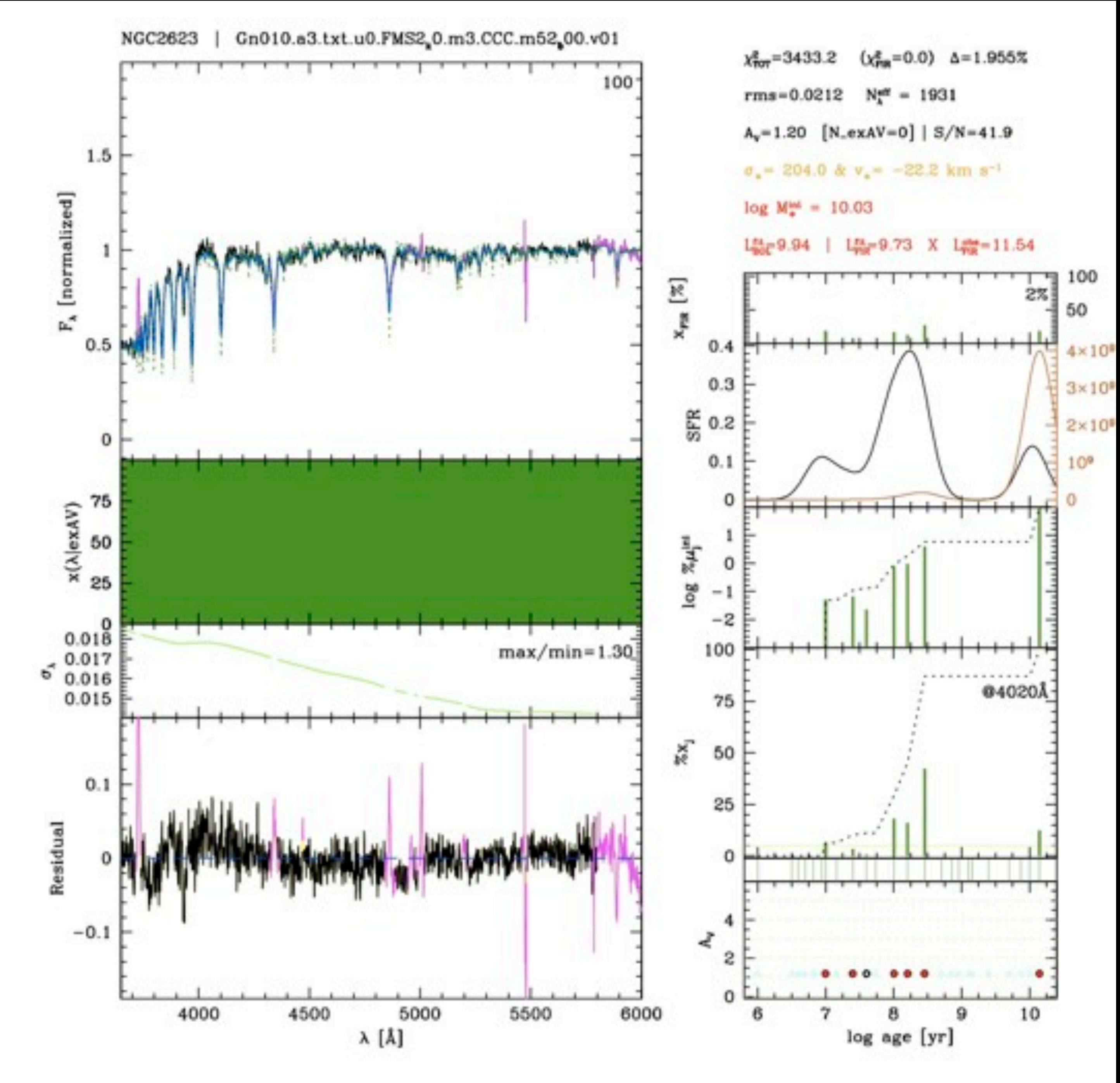
(4) (Very) Preliminary results

- ➔ Data: NOT & WHT spectra of LIRGS & ULIRGS
  ≠ apertures…

- ➔ Spectral fits with:
  - Base of "CB07" SSPs
  - 24 ages ("oversampling" philosophy)
  - 3 ≠ Z's (0.4, 1 & 2.5 solar)
  - 1, 2 & 3 ≠ "extra" extinctions
  - $R = L_{dust} \leq L_{IR}$ (IRAS) ➔ constraint only!
  - Ext curve = Calzetti + Leitherer (λ < 1846 Å)

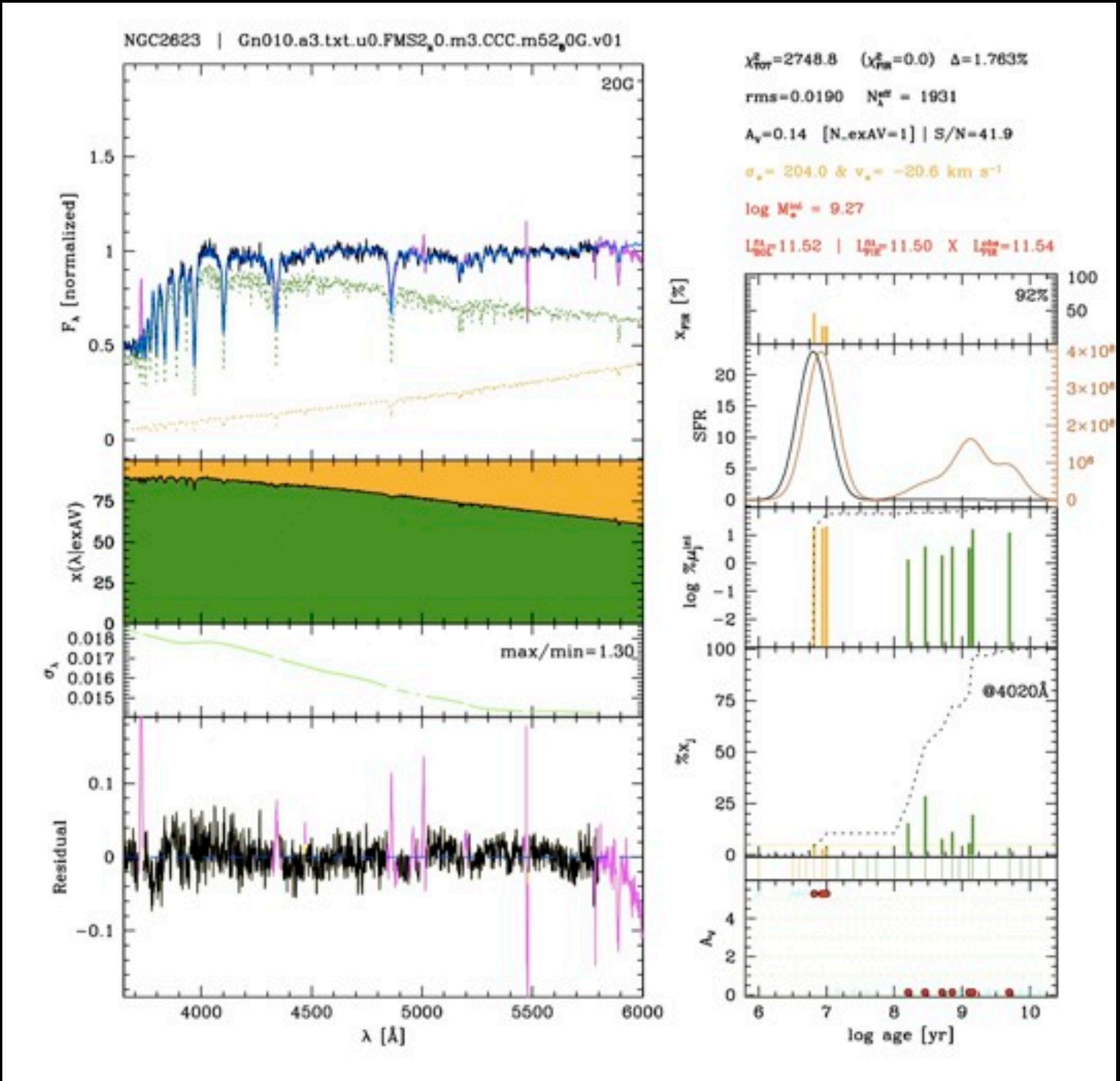
    (Cardelli law produce wild residuals!)
  - "CB07" SSPs
  - …

Ex 1



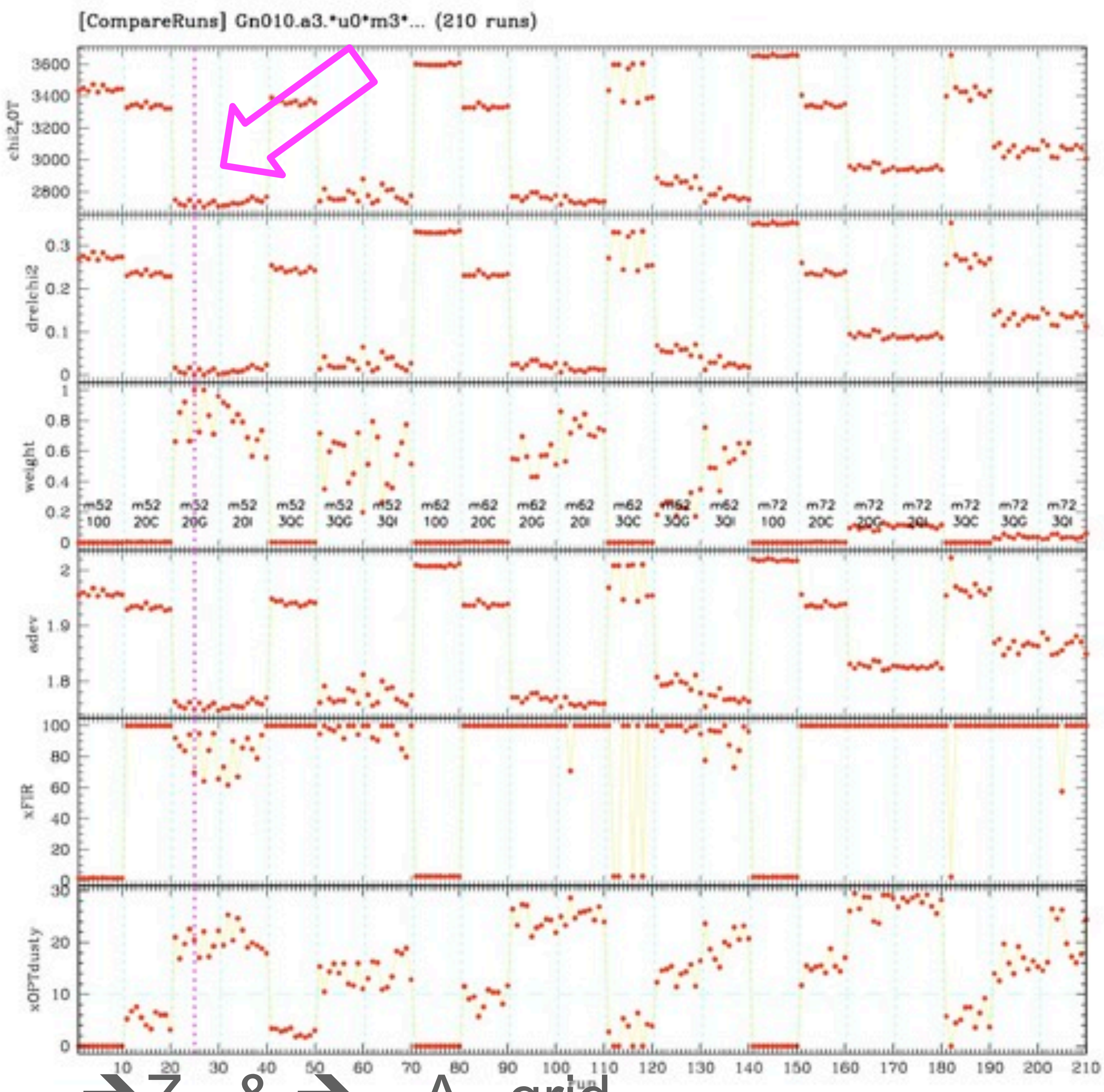
NGC2623 | Gn010.a3.txt.u0.FMS2_0.m3.CCC.m52_00.v01
rms=0.0212
A_V=1.20 [N_exAV=0] | S/N=41.9
log M = 10.03
F_λ [normalized]
x(λ|exAV)
σ_λ
max/min=1.30
Residual
λ [Å]
SFR
log age [yr]
@4020Å
2%

Ex 1



NGC2623 | Gn010.a3.txt.u0.FMS2_s0.m3.CCC.m52_s0G.v01
20G
F_λ [normalized]
x(λ|exAV)
max/min=1.30
Residual
λ [Å]
rms=0.0190
A_V=0.14 [N_exAV=1] | S/N=41.9
log M = 9.27
92%
SFR
@4020Å
log age [yr]

Ex 1



χ^2

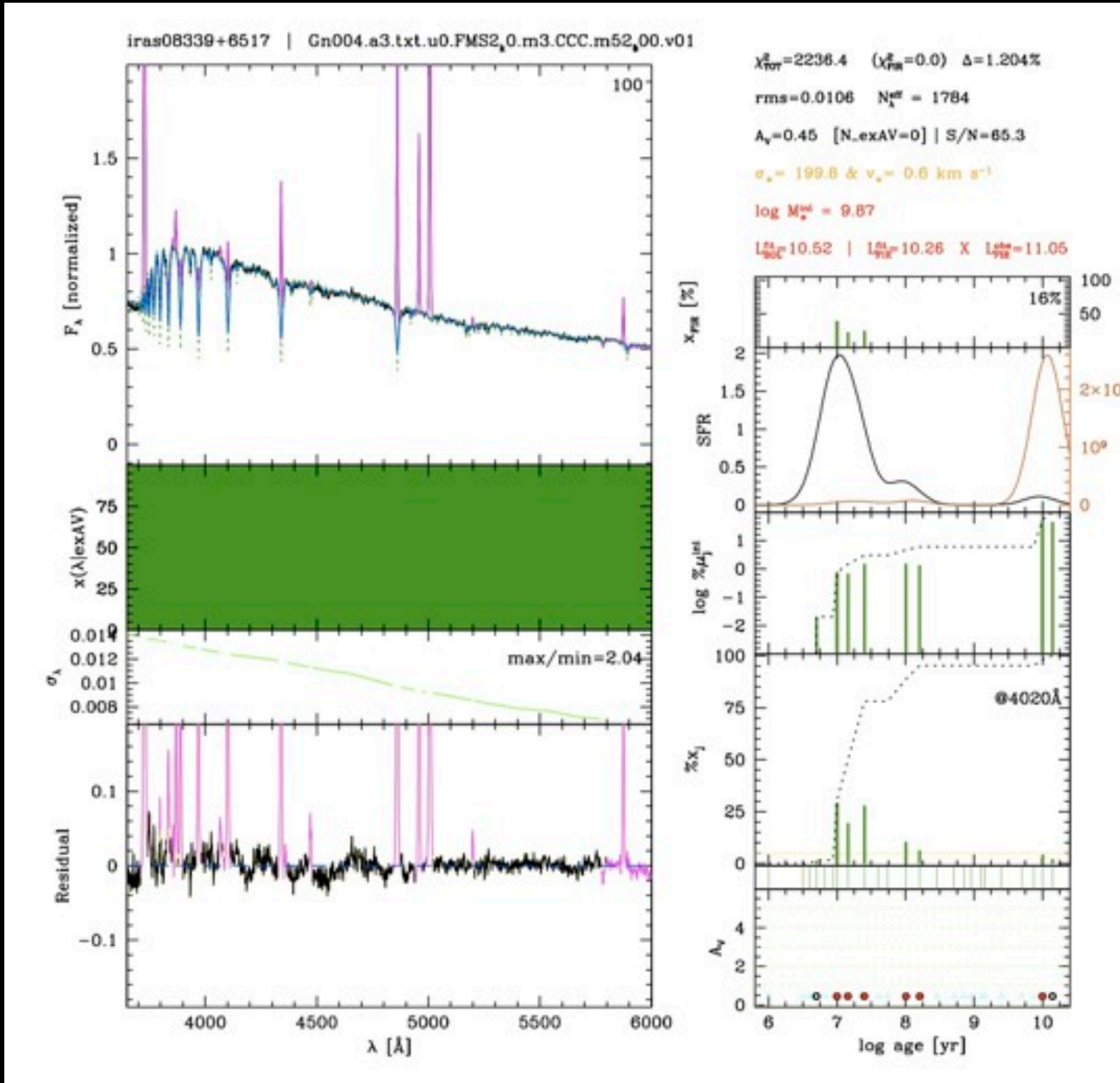
...

IR%

OPT%

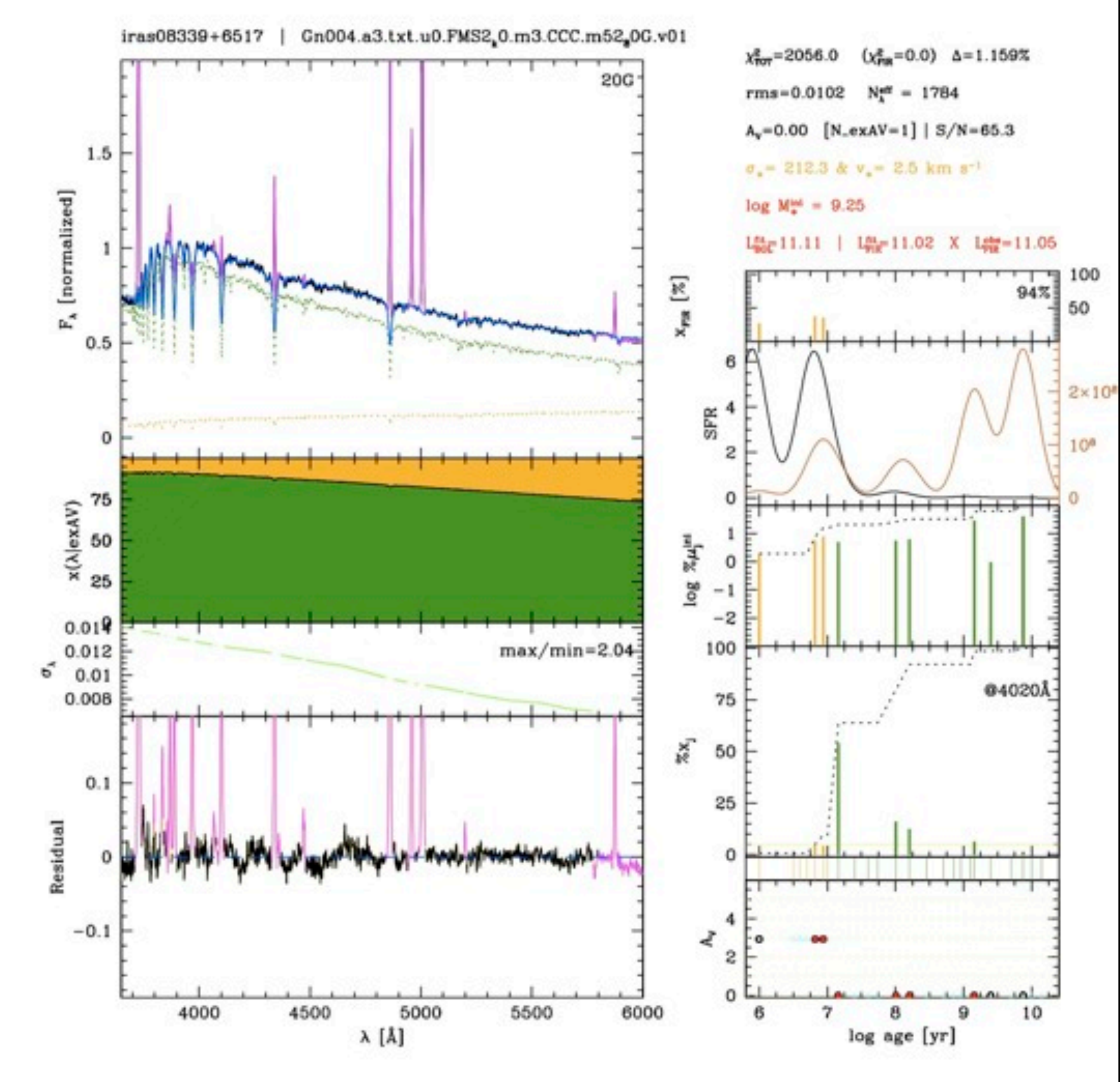
➔Z_* & ➔ A_V grid…

Ex 2



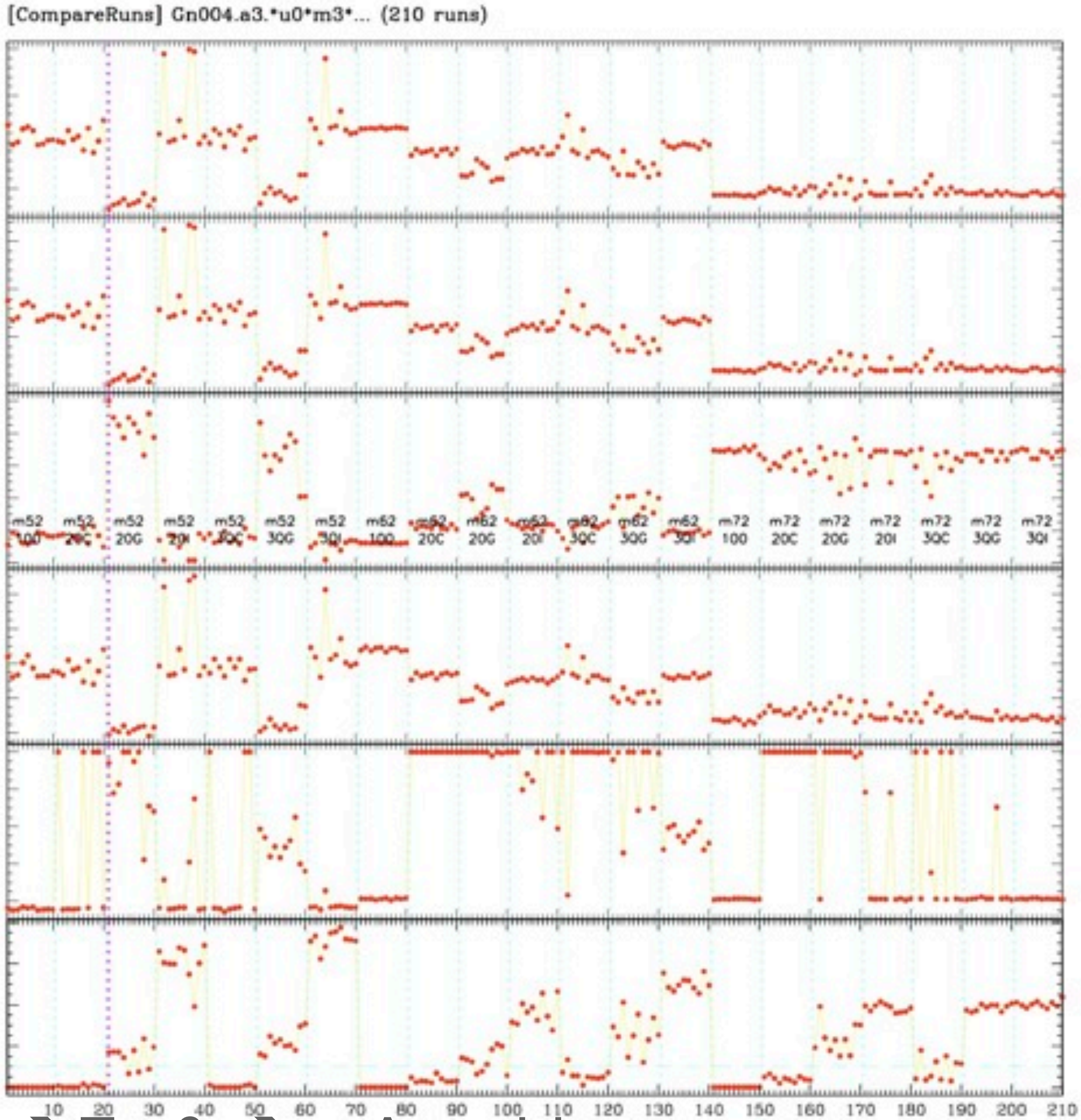
iras08339+6517 | Gn004.a3.txt.u0.FMS2_0.m3.CCC.m52_00.v01
χ^2_{TOT}=2236.4 (χ^2_{FIR}=0.0) Δ=1.204%
rms=0.0106 N_λ^{eff} = 1784
A_V=0.45 [N_exAV=0] | S/N=65.3
σ_*= 199.8 & v_*= 0.6 km s^{-1}
log M_*^{ini} = 9.87
F$_\lambda$ [normalized]
x(λ|exAV)
max/min=2.04
Residual
λ [Å]
SFR
@4020Å
log age [yr]

Ex 2



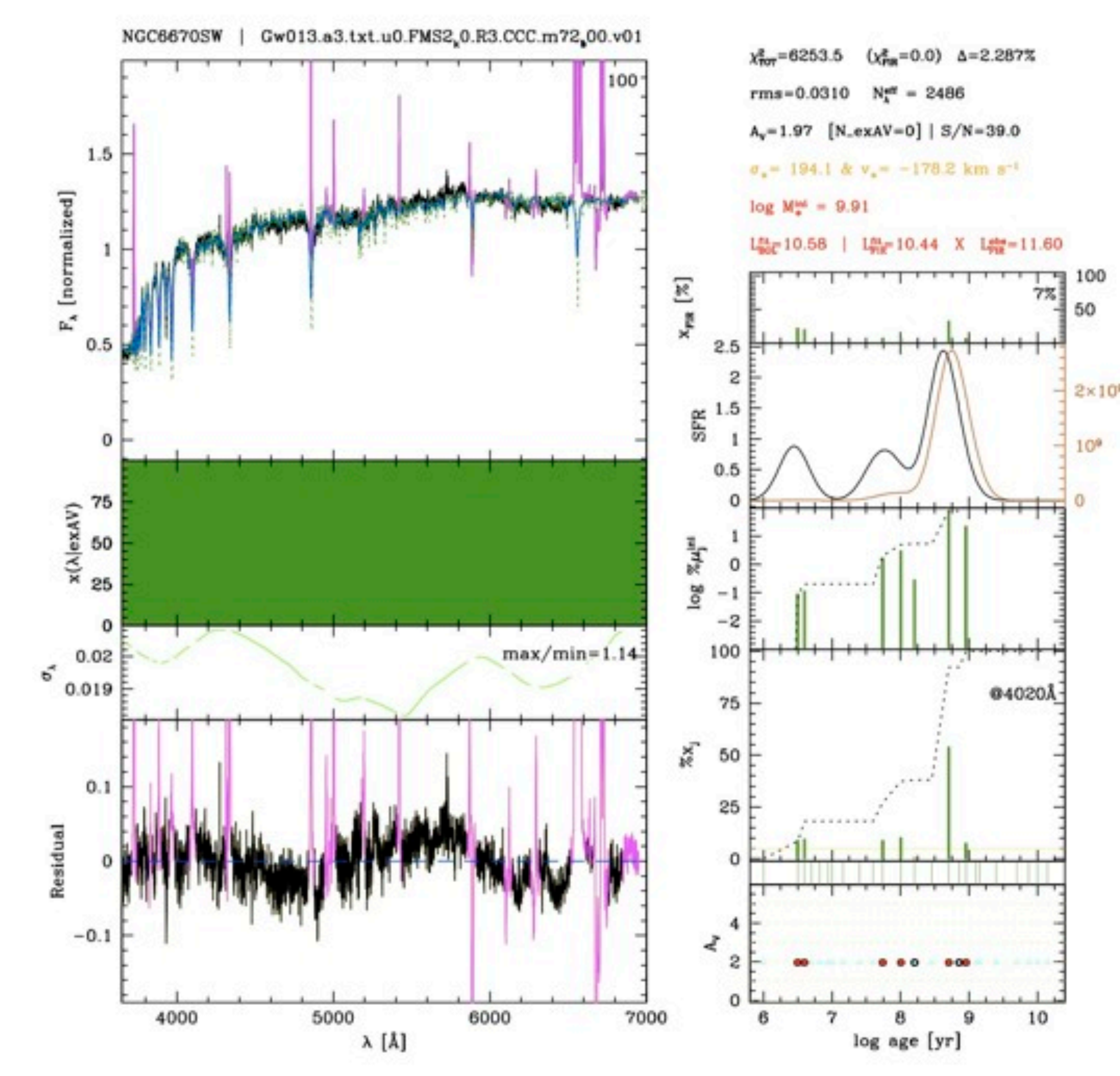
iras08339+6517 | Gn004.a3.txt.u0.FMS2_0.m3.CCC.m52_0G.v01
rms=0.0102
A_V=0.00 [N_exAV=1] | S/N=65.3
log M = 9.25
20G
F_λ [normalized]
x(λ|exAV)
max/min=2.04
Residual
λ [Å]
94%
SFR
@4020Å
log age [yr]

Ex 2


[CompareRuns] Gn004.a3.*u0*m3*... (210 runs)
chi2_OT
dreichi2
weight
adev
xFIR
xOPTdusty
run
m52 10C
m52 20C
m52 20G
m52 20I
m52 3QC
m52 3QG
m52 3QI
m62 10C
m62 20C
m62 20G
m62 20I
m62 3QC
m62 3QG
m62 3QI
m72 10C
m72 20C
m72 20G
m72 20I
m72 3QC
m72 3QG
m72 3QI

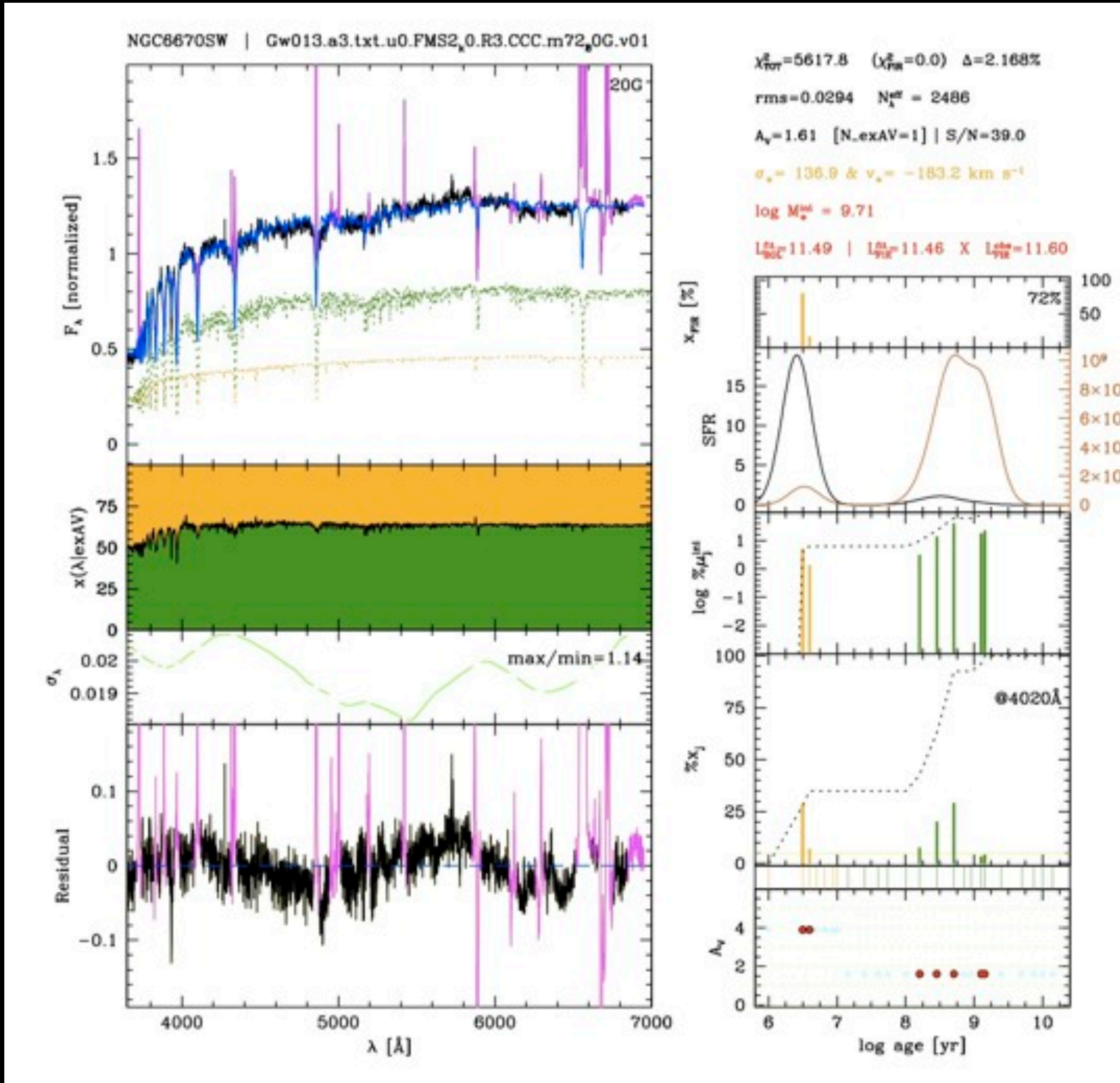
➔Z* & ➔ A_V grid…

Ex 3



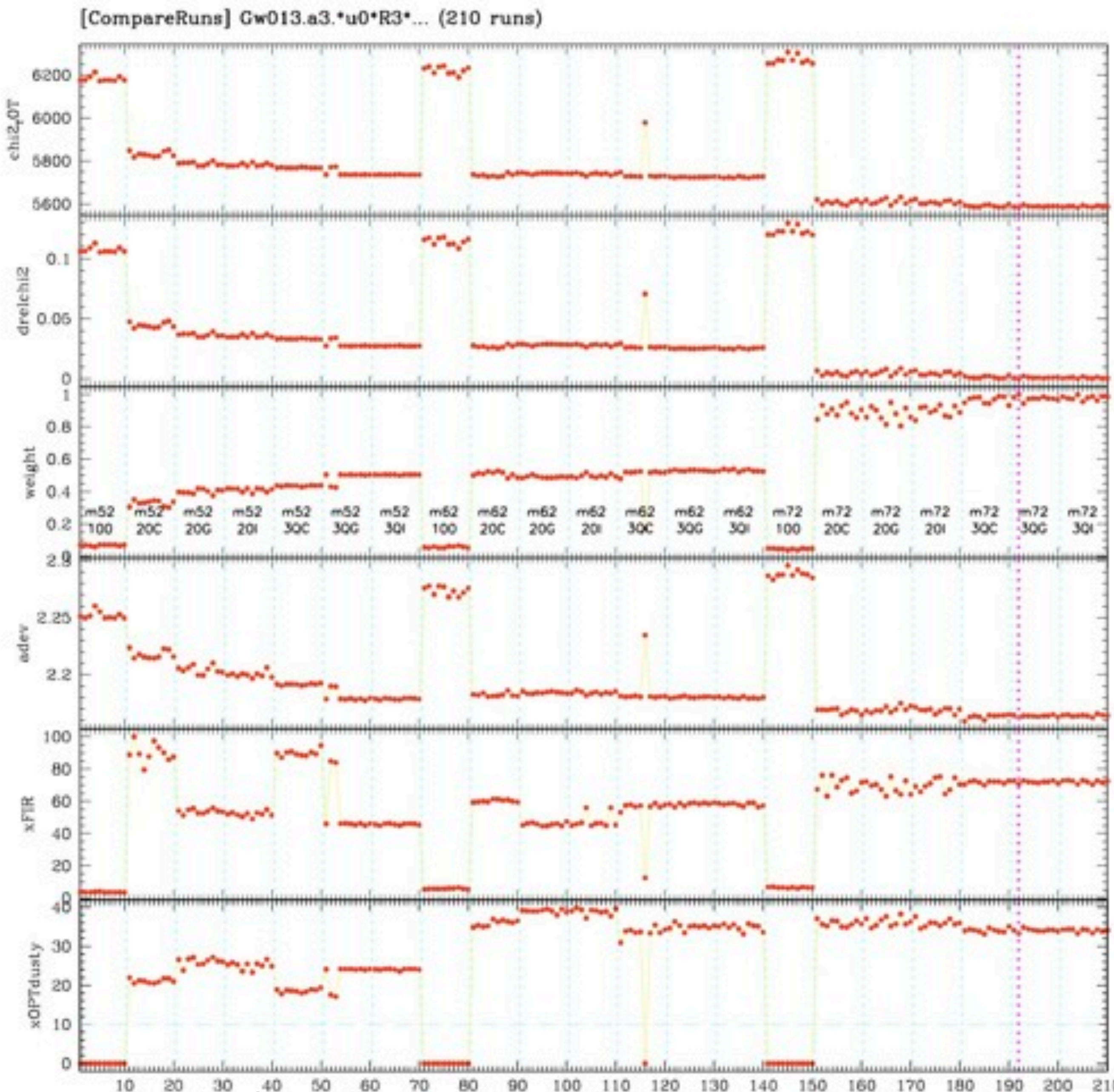
NGC6670SW | Gw013.a3.txt.u0.FMS2_λ0.R3.CCC.m72_*00.v01
F_λ [normalized]
x(λ|exAV)
σ_λ
max/min=1.14
Residual
λ [Å]
rms=0.0310
A_V=1.97 [N_exAV=0] | S/N=39.0
log M_*^ini = 9.91
SFR
@4020Å
log age [yr]

Ex 3



NGC6670SW | Gw013.a3.txt.u0.FMS2_k0.R3.CCC.m72_s0G.v01
20G
rms=0.0294
S/N=39.0
log M = 9.71
72%
@4020Å
max/min=1.14
F [normalized]
x(λ|exAV)
Residual
SFR
λ [Å]
log age [yr]

Ex 3

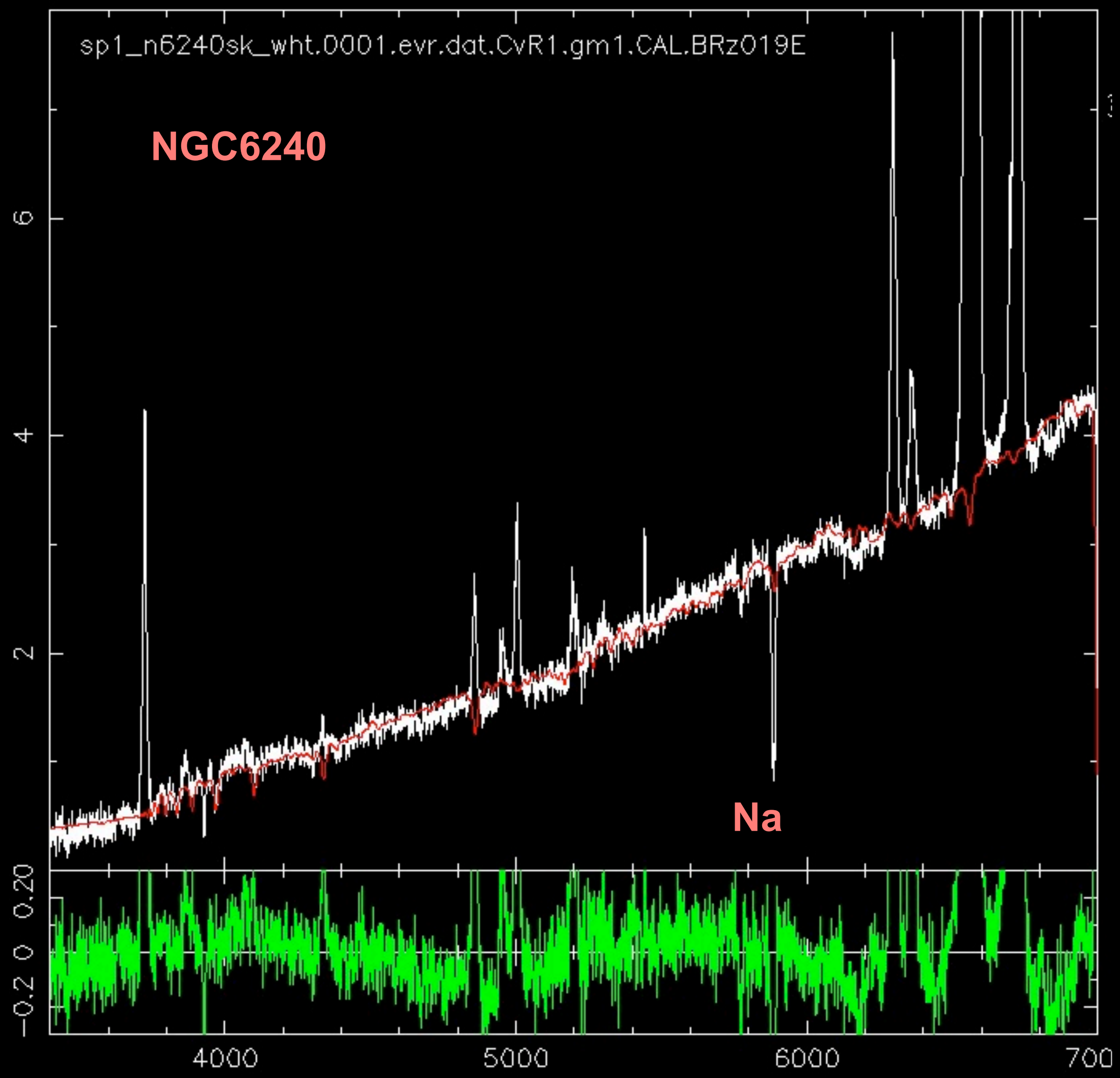

[CompareRuns] Gw013.a3.*u0*R3*... (210 runs)
chi2_OT
drelchi2
weight
adev
xFIR
xOPTdusty
m52 100
m52 20C
m52 20G
m52 20I
m52 30C
m52 30G
m52 30I
m62 100
m62 20C
m62 20G
m62 20I
m62 30C
m62 30G
m62 30I
m72 100
m72 20C
m72 20G
m72 20I
m72 30C
m72 30G
m72 30I
run

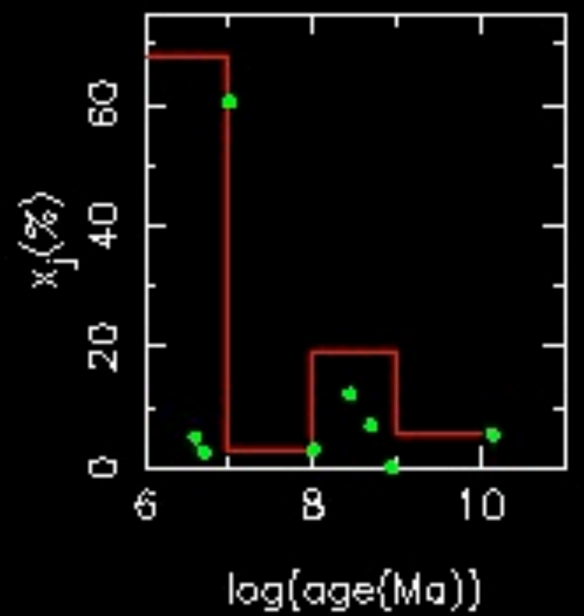
➔Z* & ➔ A_V grid…

Ex n>>1!

Stellar Population synthesis results for U/LIRGs

High extinction: Na and CaII lines





Av=3.02 <Av>=4.77

S/N=19.26 χ^2=2.6

(5) Lessons so far …

☺ Multiple extinctions improve spectral fits

☺ "A_V ~ 1 / age" comes out naturally

☺ L_{dust} constraint eliminates crazy solutions

😐 …but aperture miss-matches are worrying…

☹ Residuals often show suspicious bumps … ?Are we missing something?

☹ Too many plausible solutions… marginalize over model-space?

SEAGal

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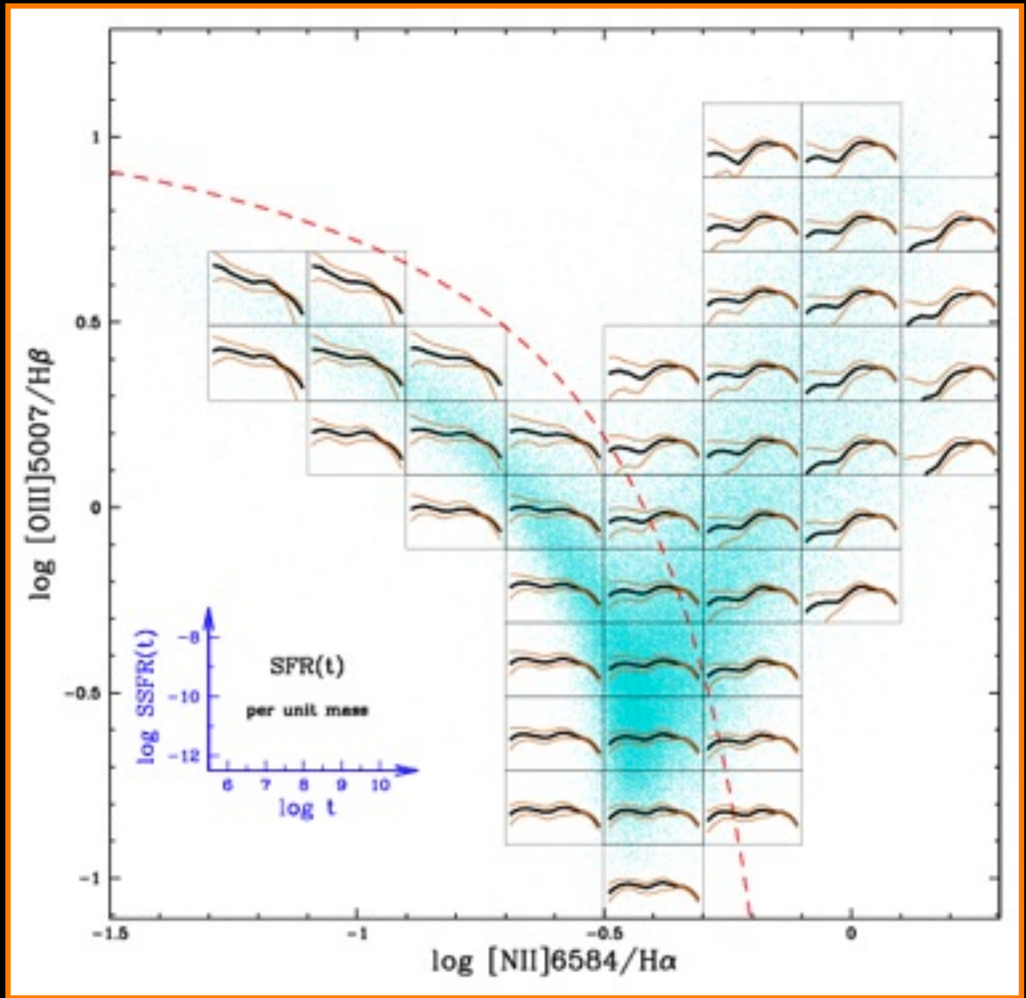

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