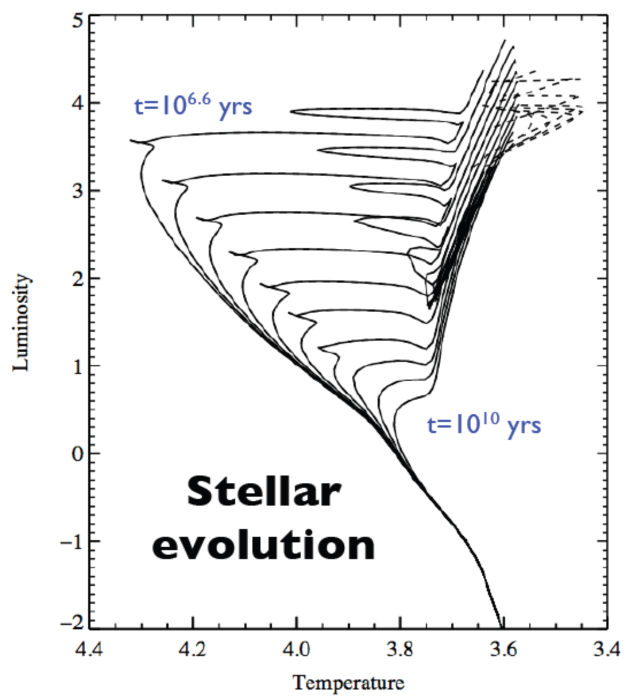
CHEMICAL ABUNDANCES FROM INTEGRATED SPECTRA

STELLAR POPULATION SYNTHESIS

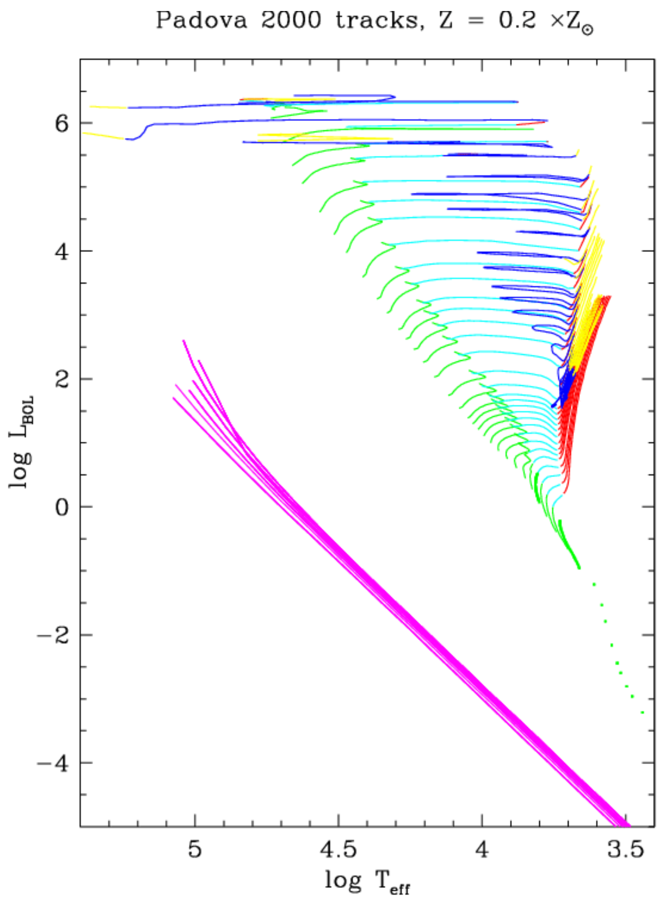
Evolving Stellar Populations

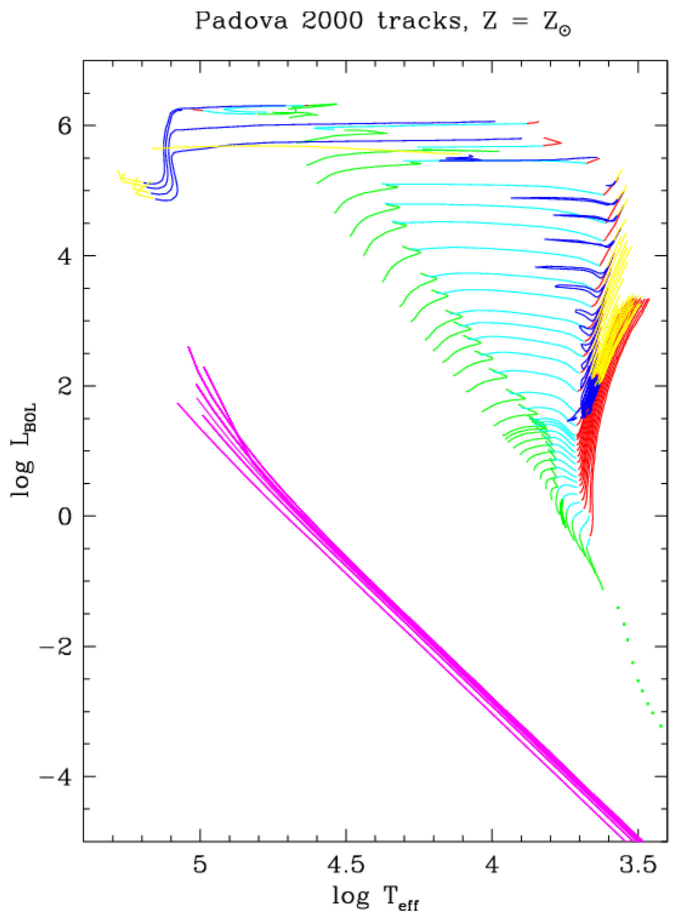
Stellar Pulation synthesis

- The stellar evolution theory provide the $T_{ef}(m,Z,t)$ y $L(m,Z,t)$ describing the time evolution of effective temperature, T_{ef} , and luminosity, L, of a star with mass, m, and metalicity, Z.
- For given values of m and Z, the functions $T_{ef}(t)$ and $L(t)$ describe parametrically the evolutionary track in the H-R Diagram (HRD) of such stars..



Evolutionary tracks





- At t=0 the stars of a SSP are distributted along the Zero Age Main Sequence (ZAMS) according to a given Initial Mass Function (IMF). acuerdo a la IMF.
- The Spectral Energy Distribution (SED) of the SSP at time t is given by

$$S_\lambda(t,Z) = \int_{m_l}^{m_u} S_\lambda(m,t,Z)\phi(m)dm$$

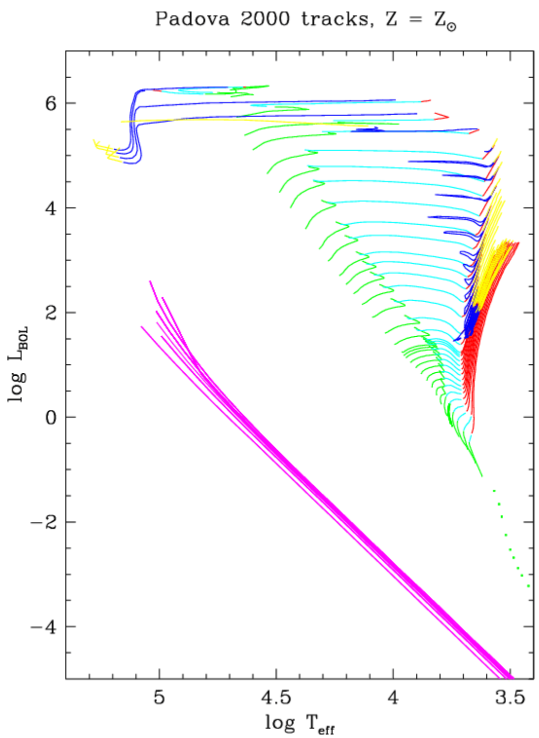
SED of stars with mass m and metallicity Z at time t

Initial Mass Function IMF)

UAM UNIVERSIDAD AUTONOMA DE MADRID

The algebra of Stellar Population Synthesis

Grupo de Astrofísica
Universidad Autónoma de Madrid



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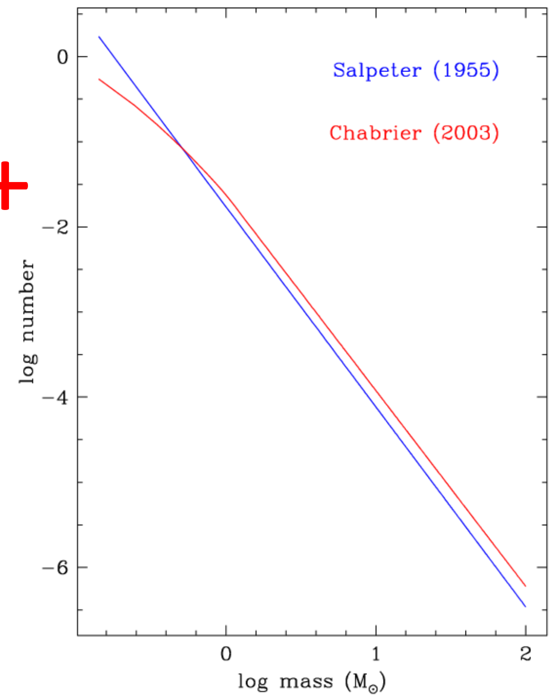

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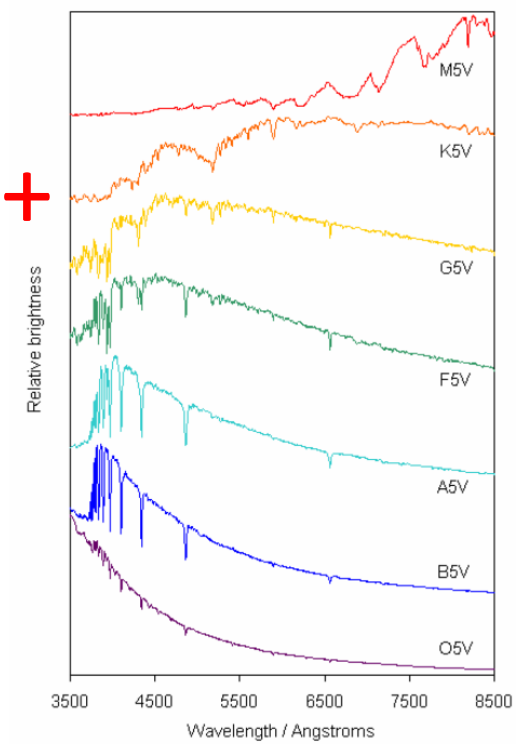
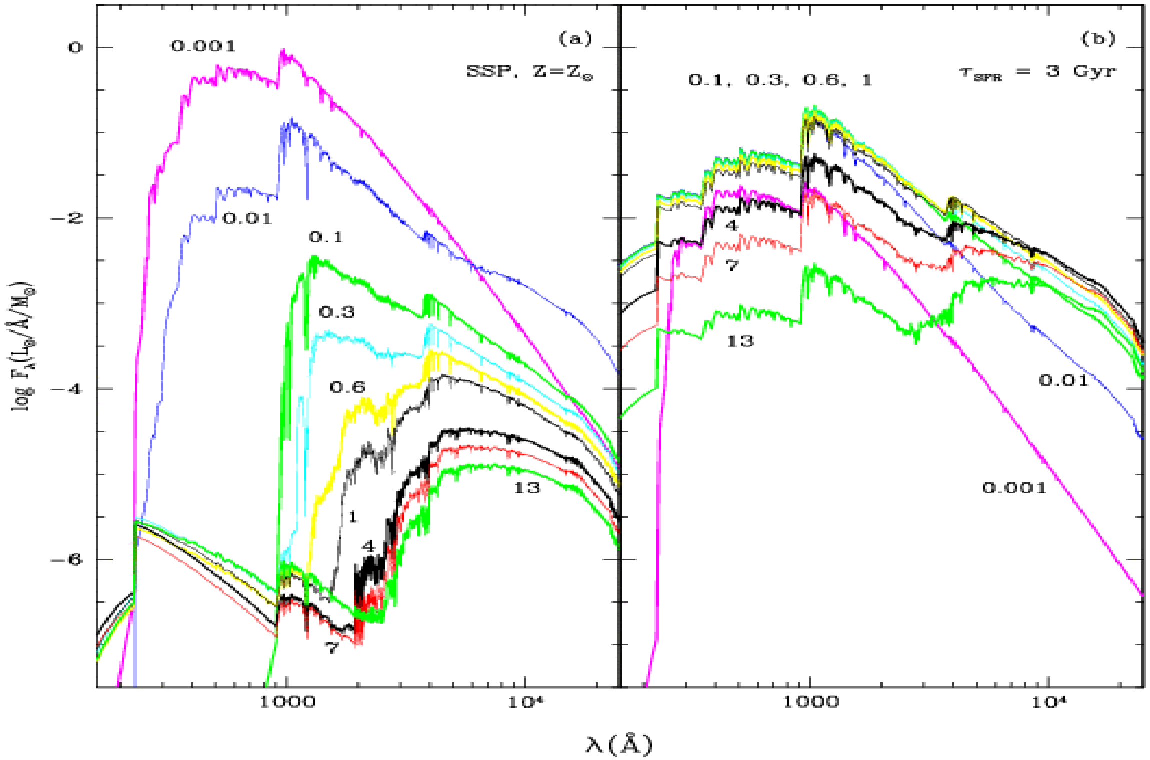


Isochrones

Initial Mass Function

Stellar Spectral Atlas

Results



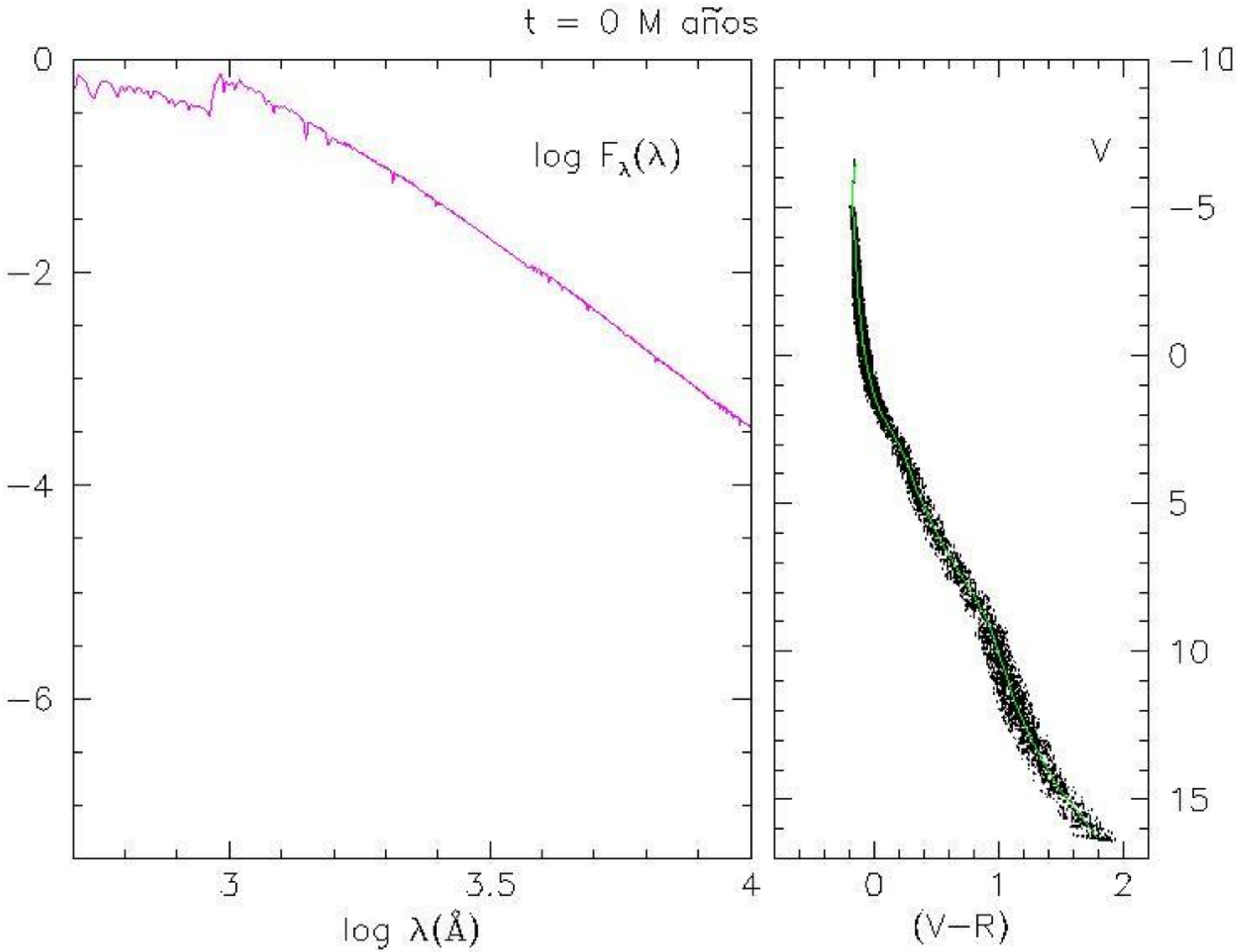
Solar metallicity,
different ages in Ga

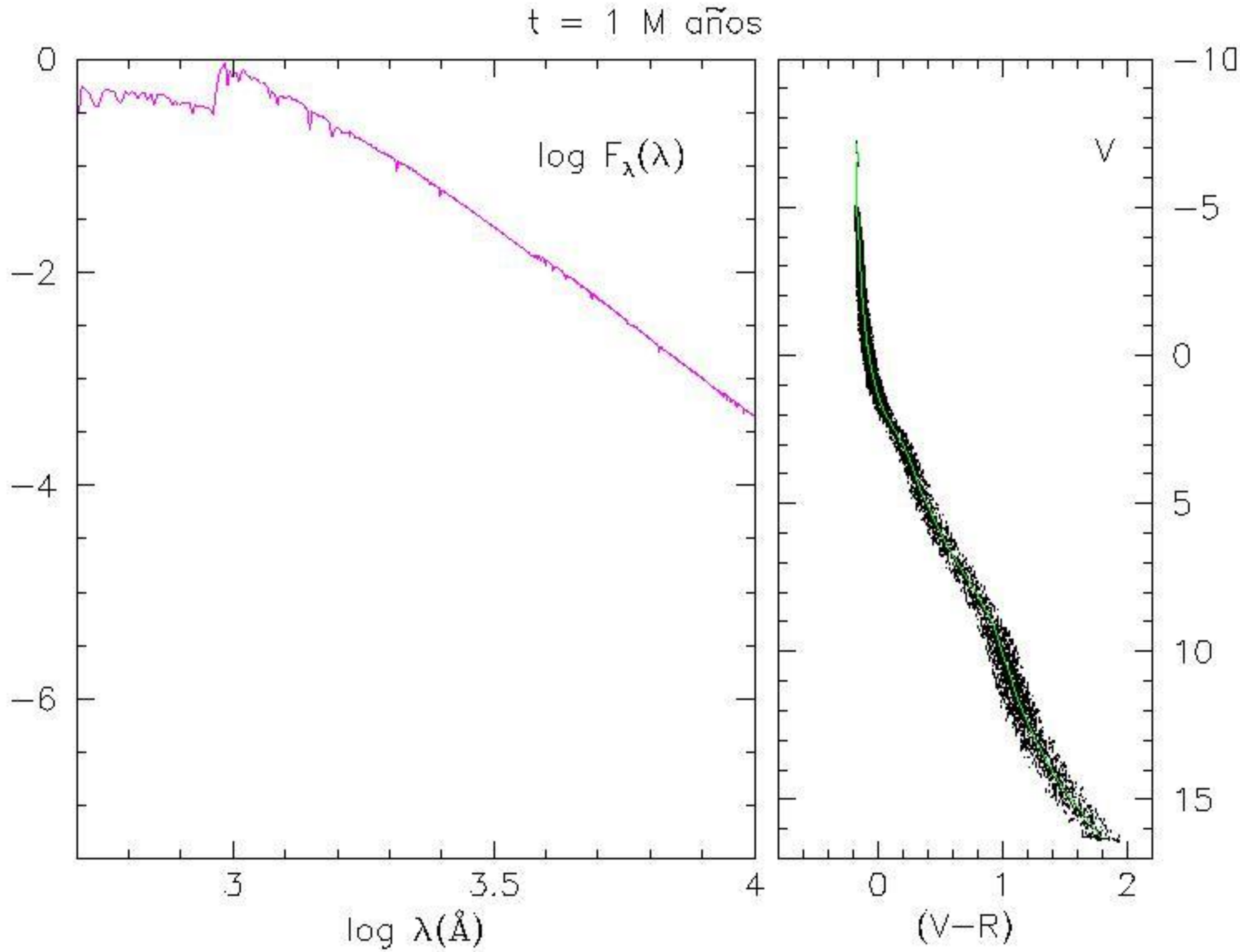
Age 3 Ga ,
different Z in solar units

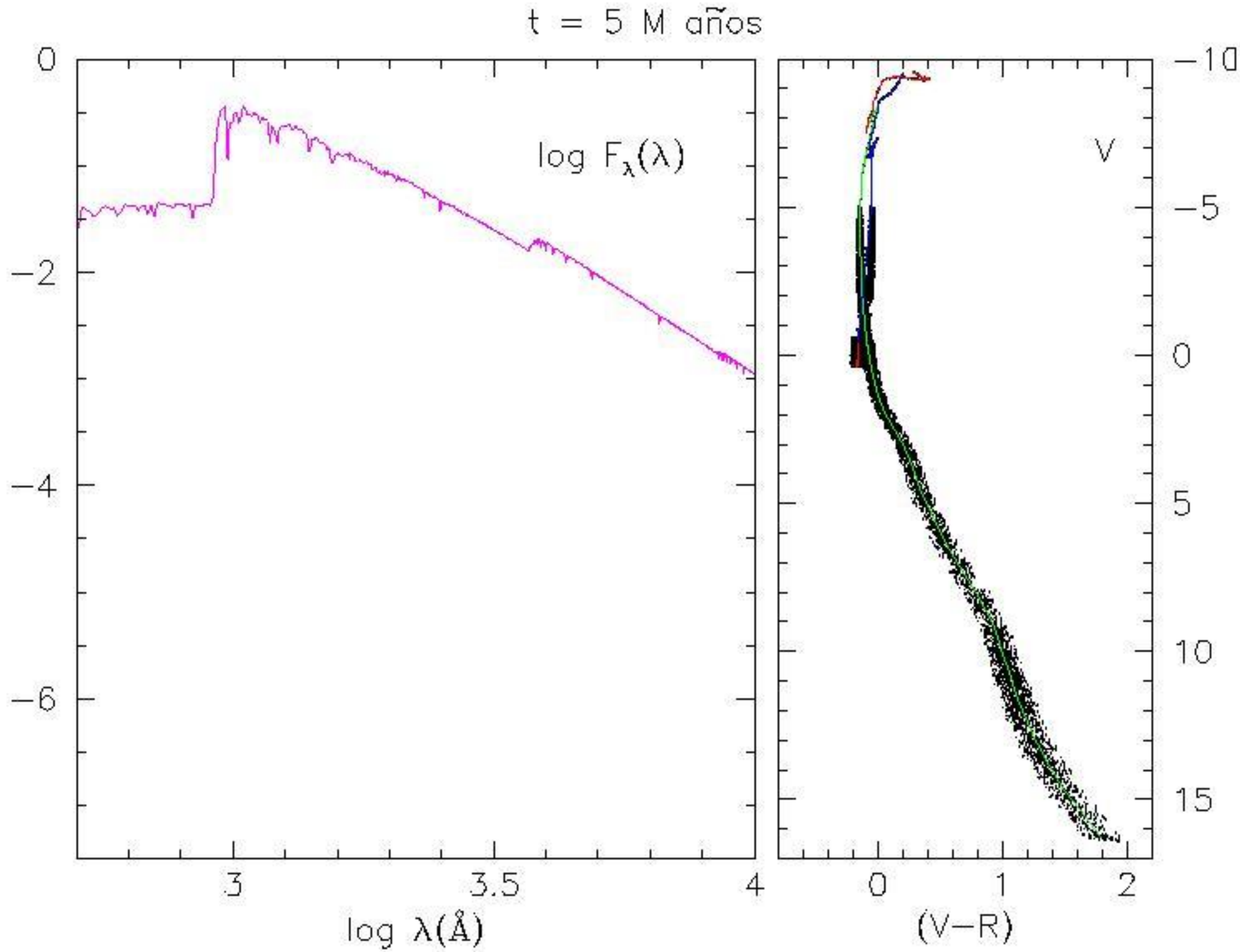
Example of evolutionary sequence: Single Stellar Population of solar metallicity calculated with stellar population synthesis models by
Bruzual and Charlot (2003)

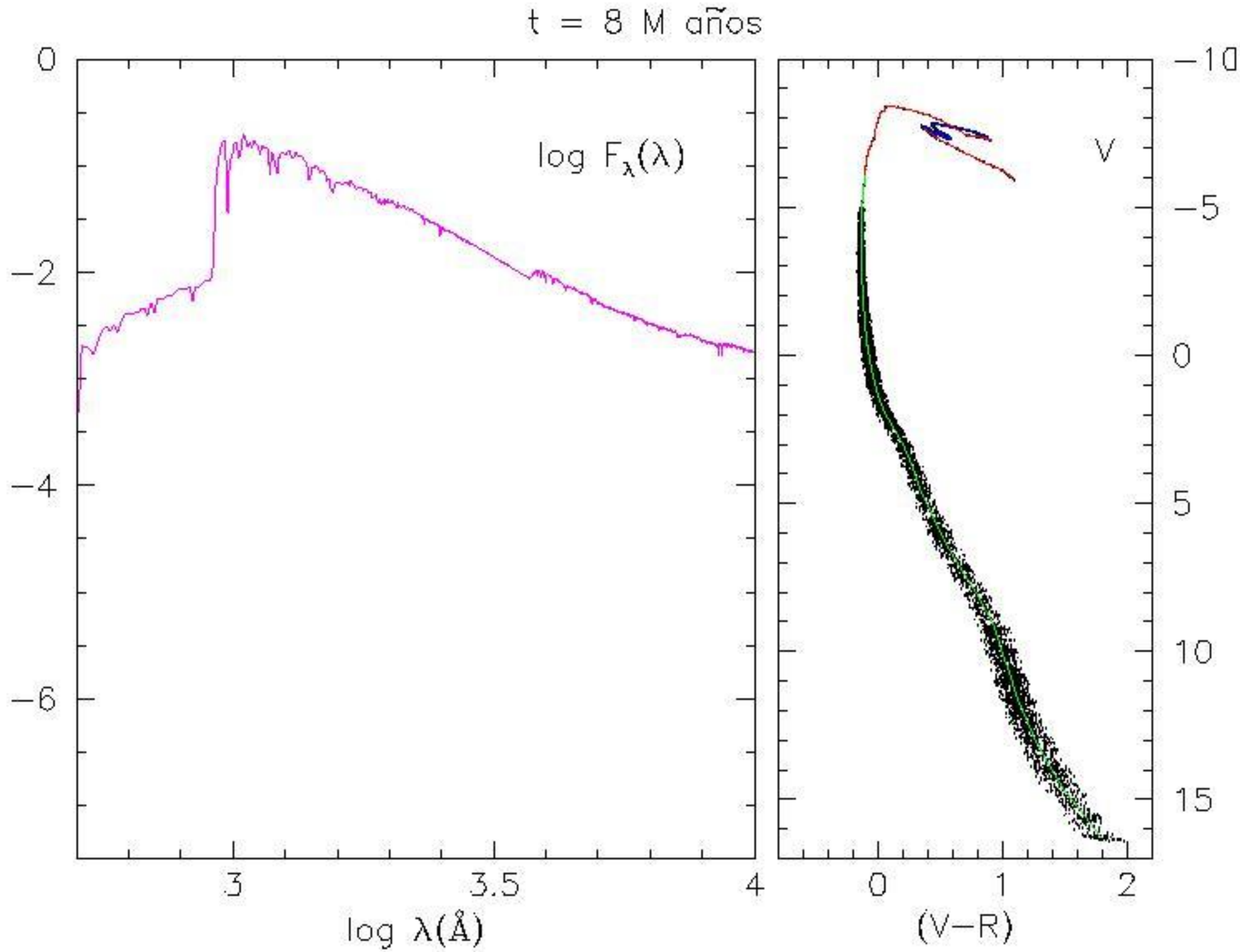
Dr Gustavo Bruzual

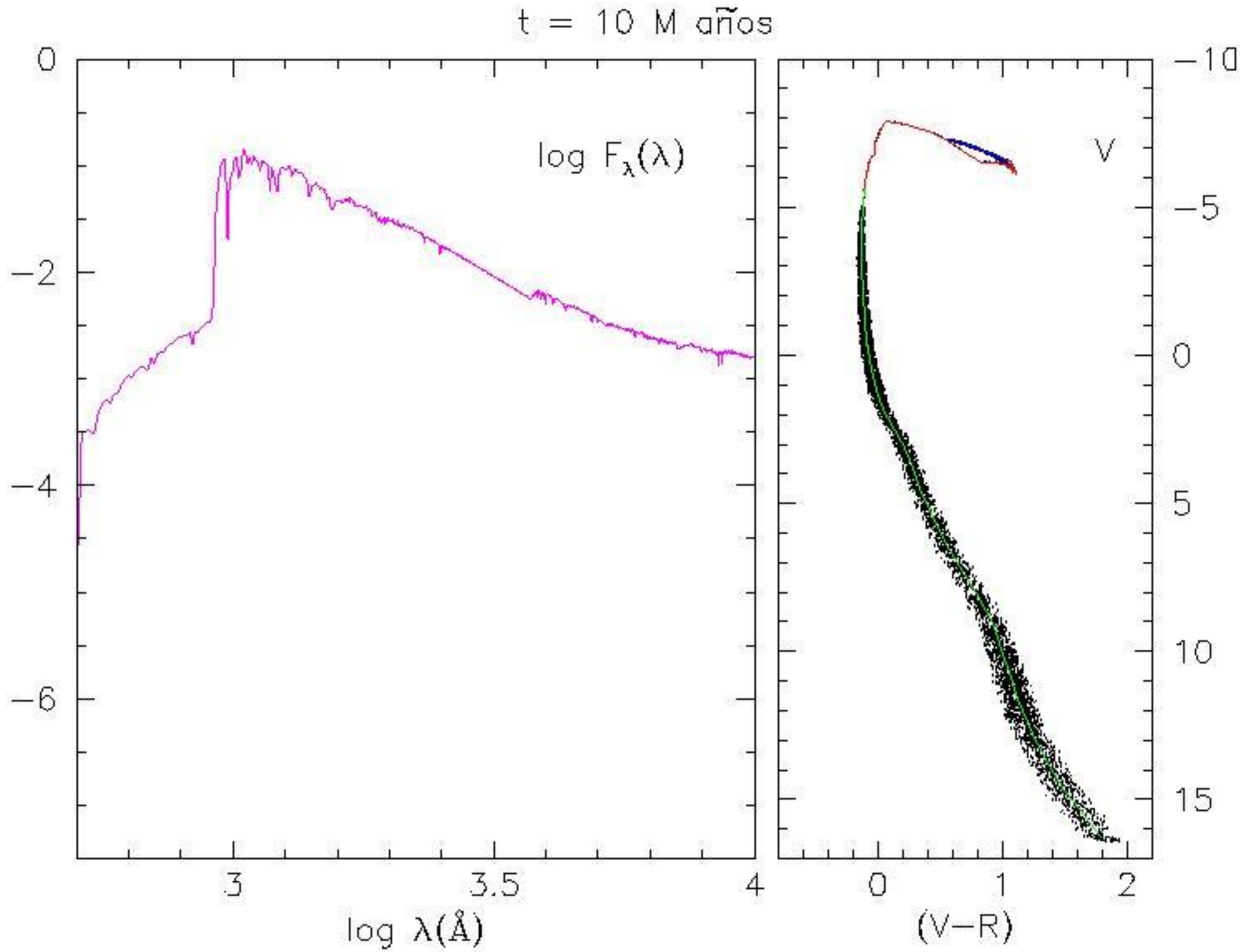
Dr Stéphane Charlot

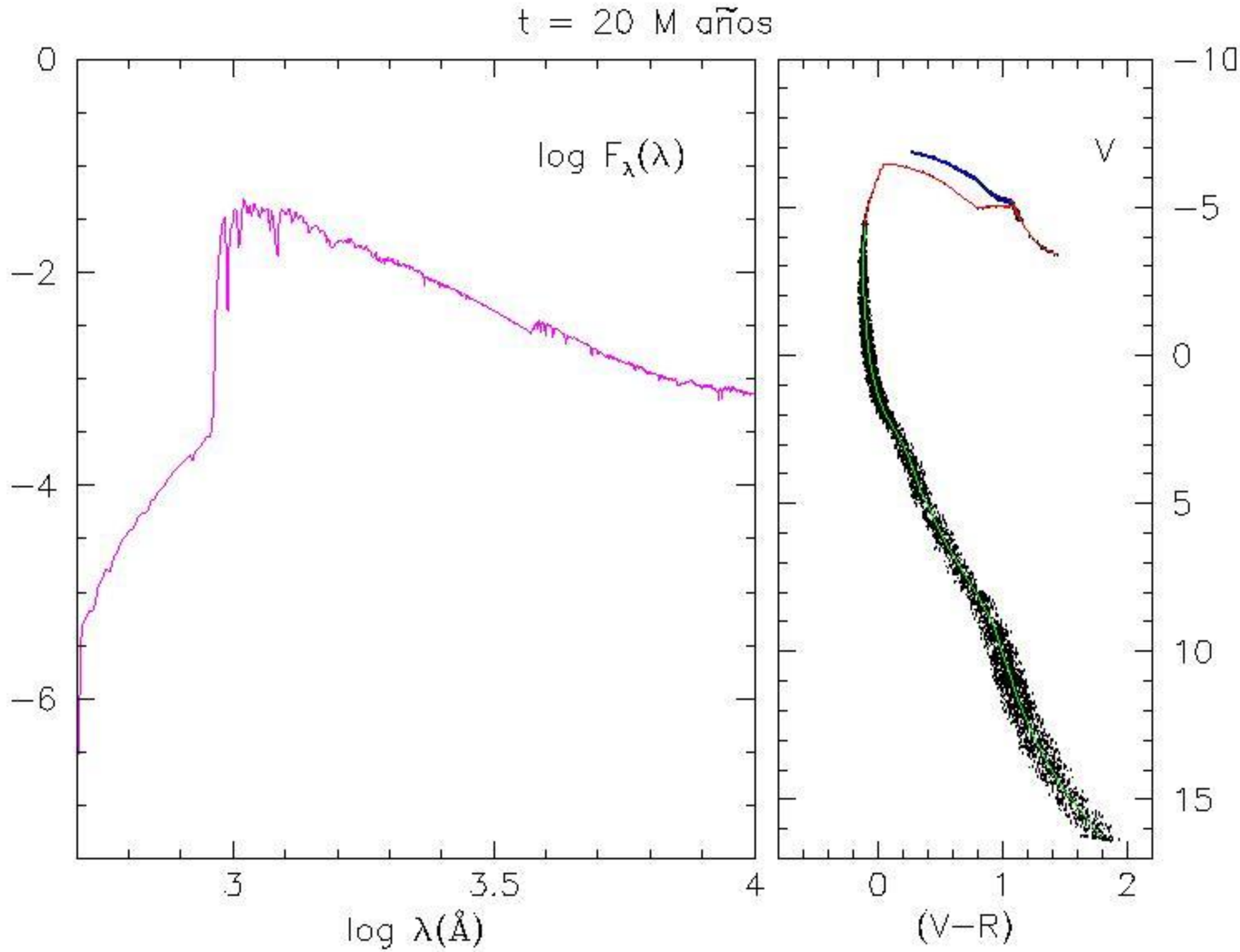

t = 0 M años
log $F_\lambda(\lambda)$
V
0
−2
−4
−6
3
3.5
4
log λ(Å)
−10
−5
0
5
10
15
0
1
2
(V−R)

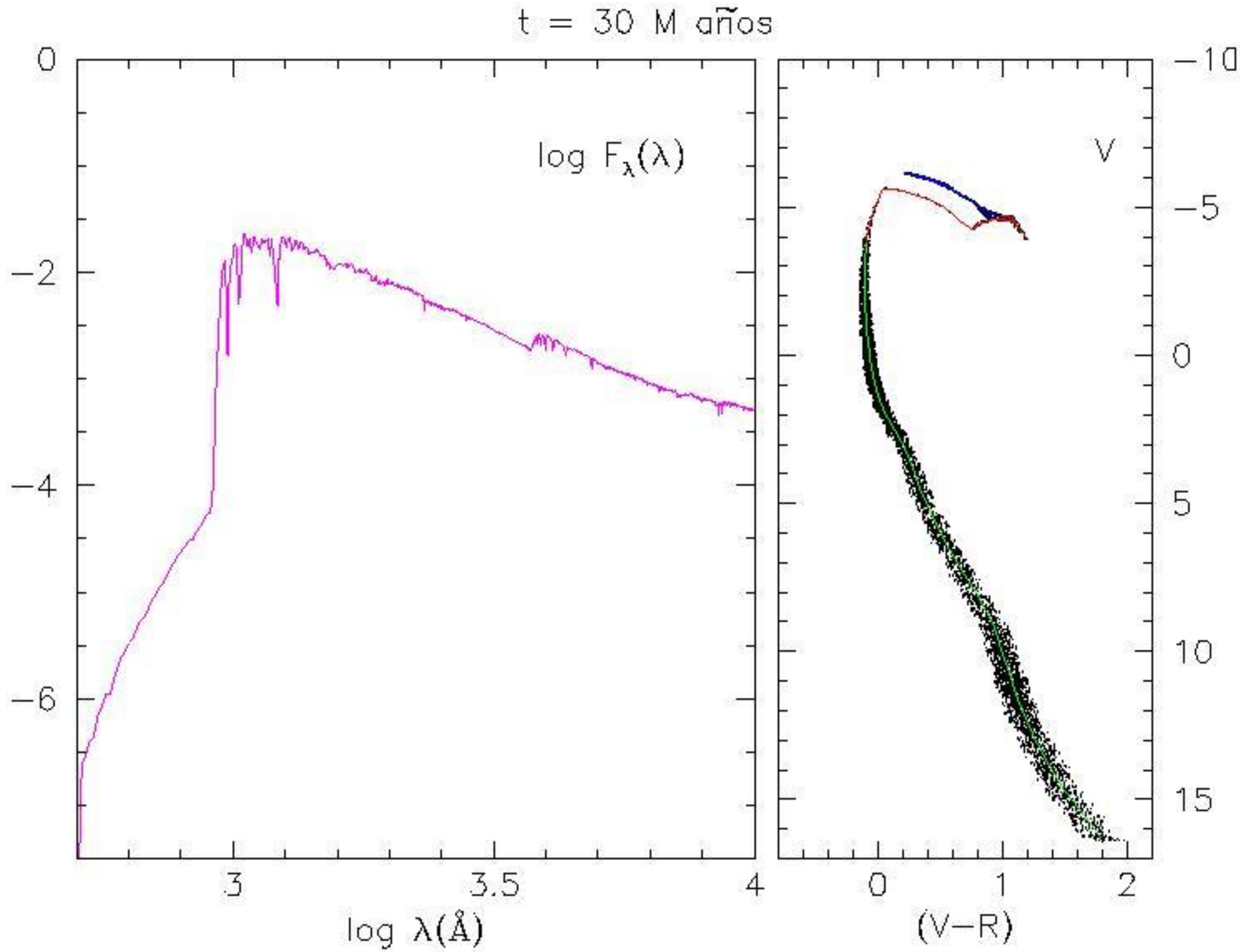

t = 1 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

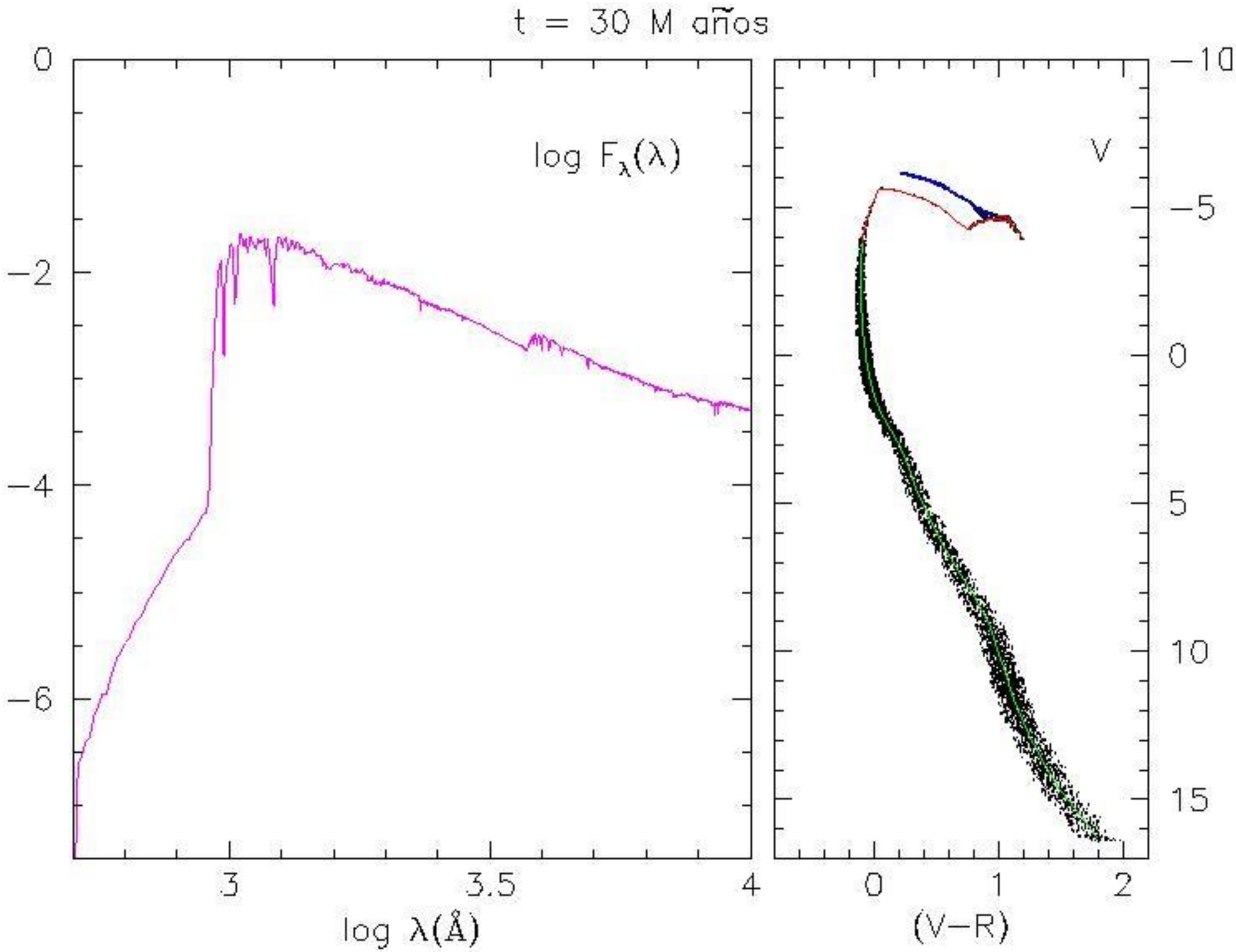

t = 5 M años
log F_λ(λ)
V
0
−2
−4
−6
3
3.5
4
log λ(Å)
−10
−5
0
5
10
15
0
1
2
(V−R)

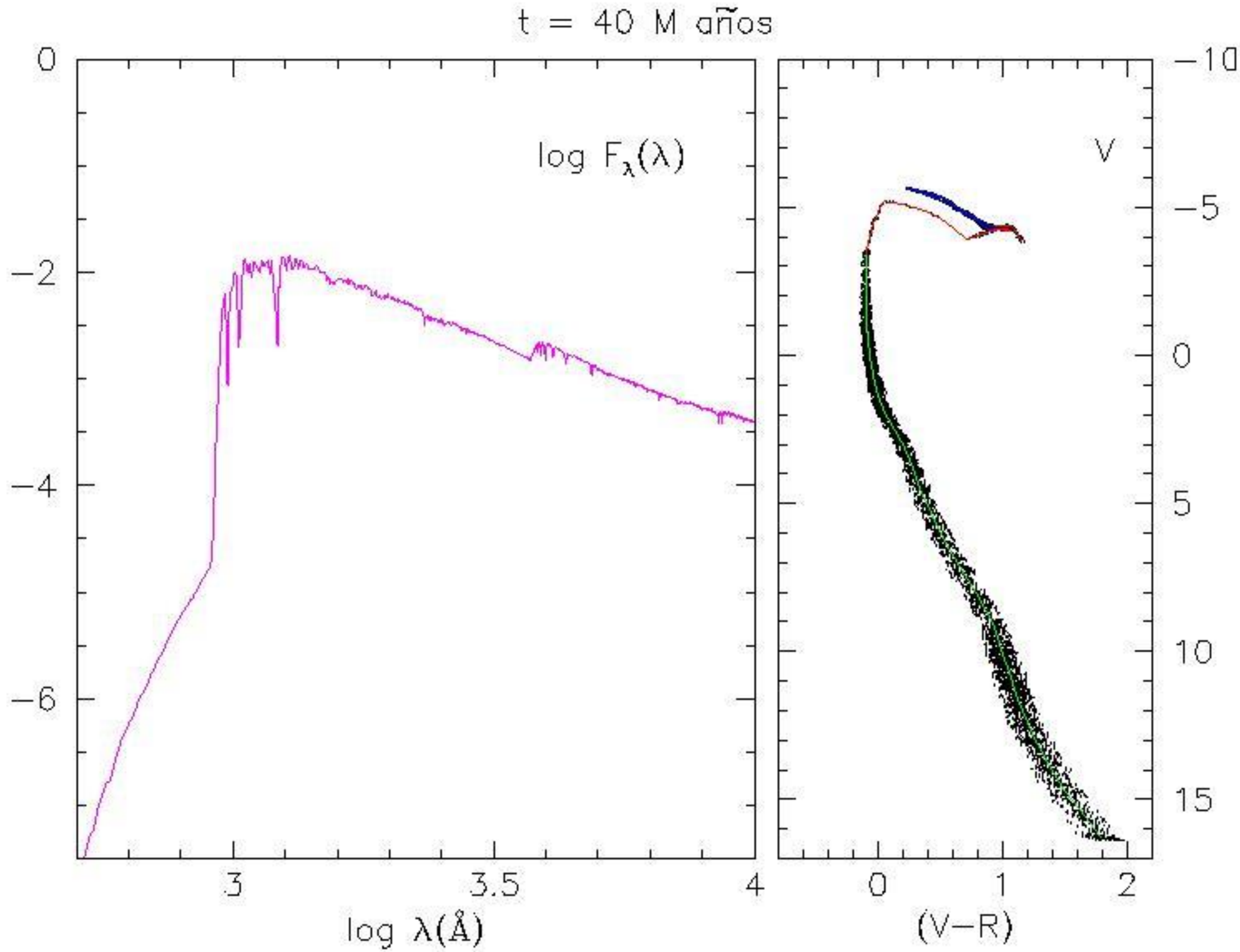

t = 8 M años
log $F_\lambda(\lambda)$
V
0
−2
−4
−6
3
3.5
4
log λ(Å)
−10
−5
0
5
10
15
0
1
2
(V−R)

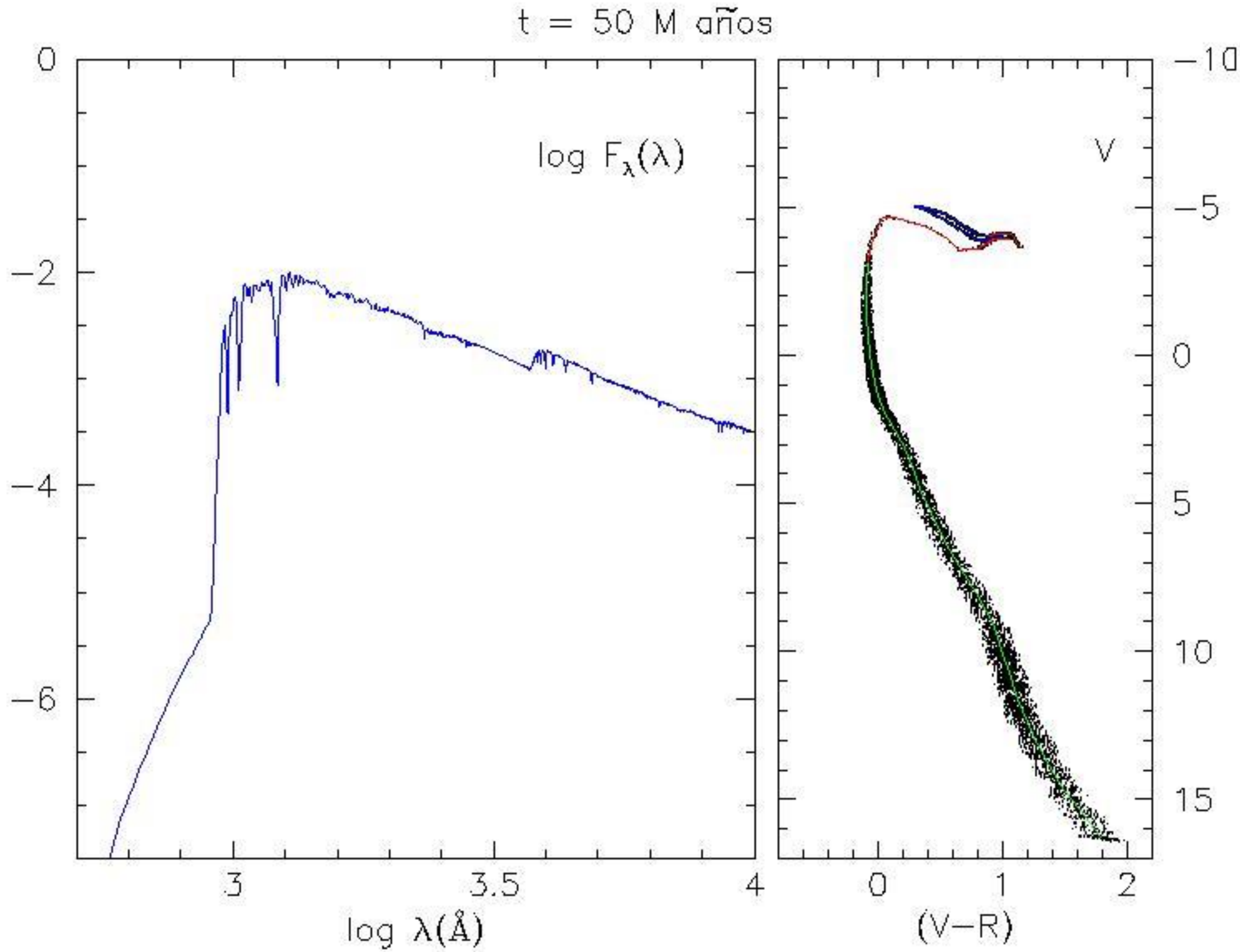

t = 10 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

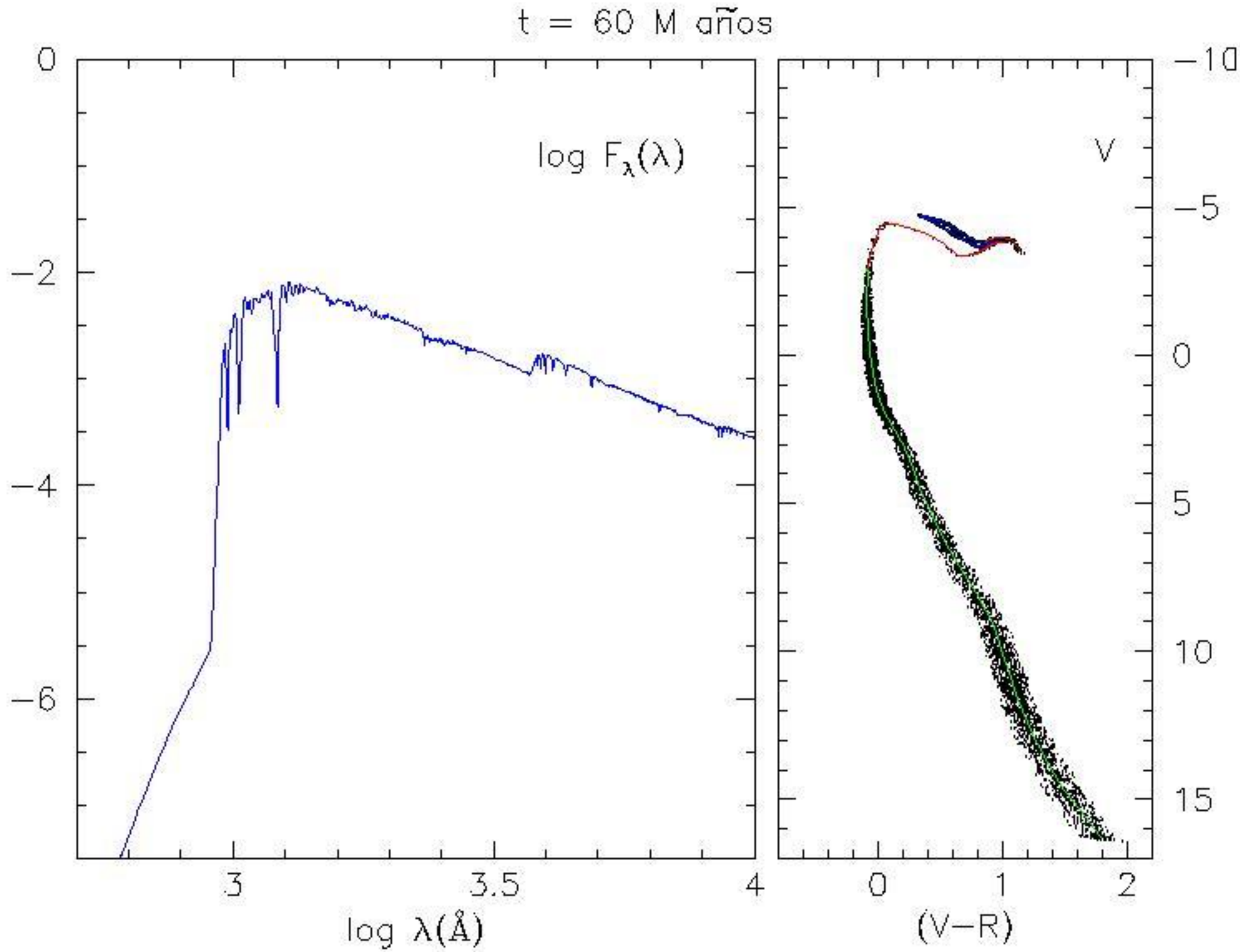

t = 20 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

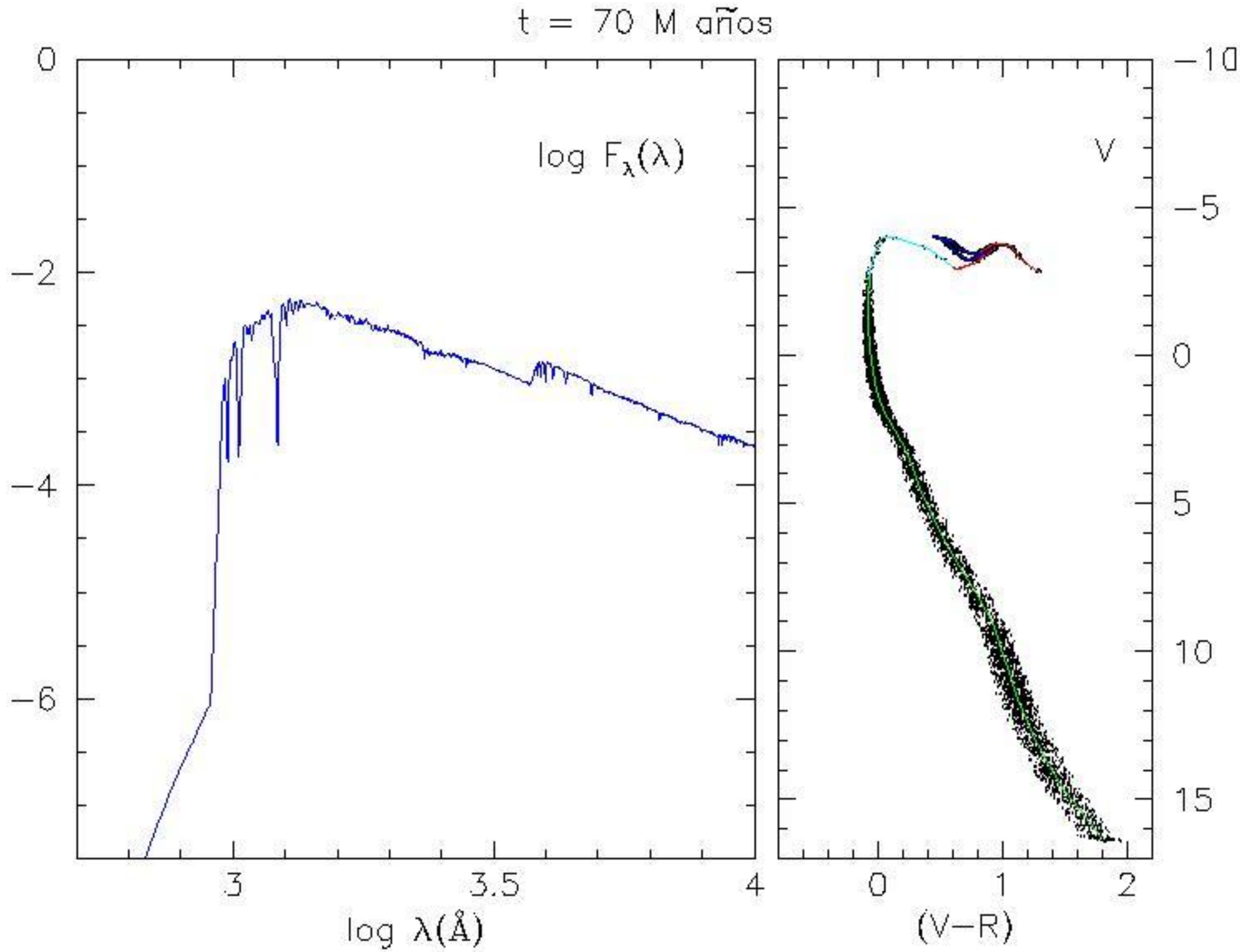

t = 30 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

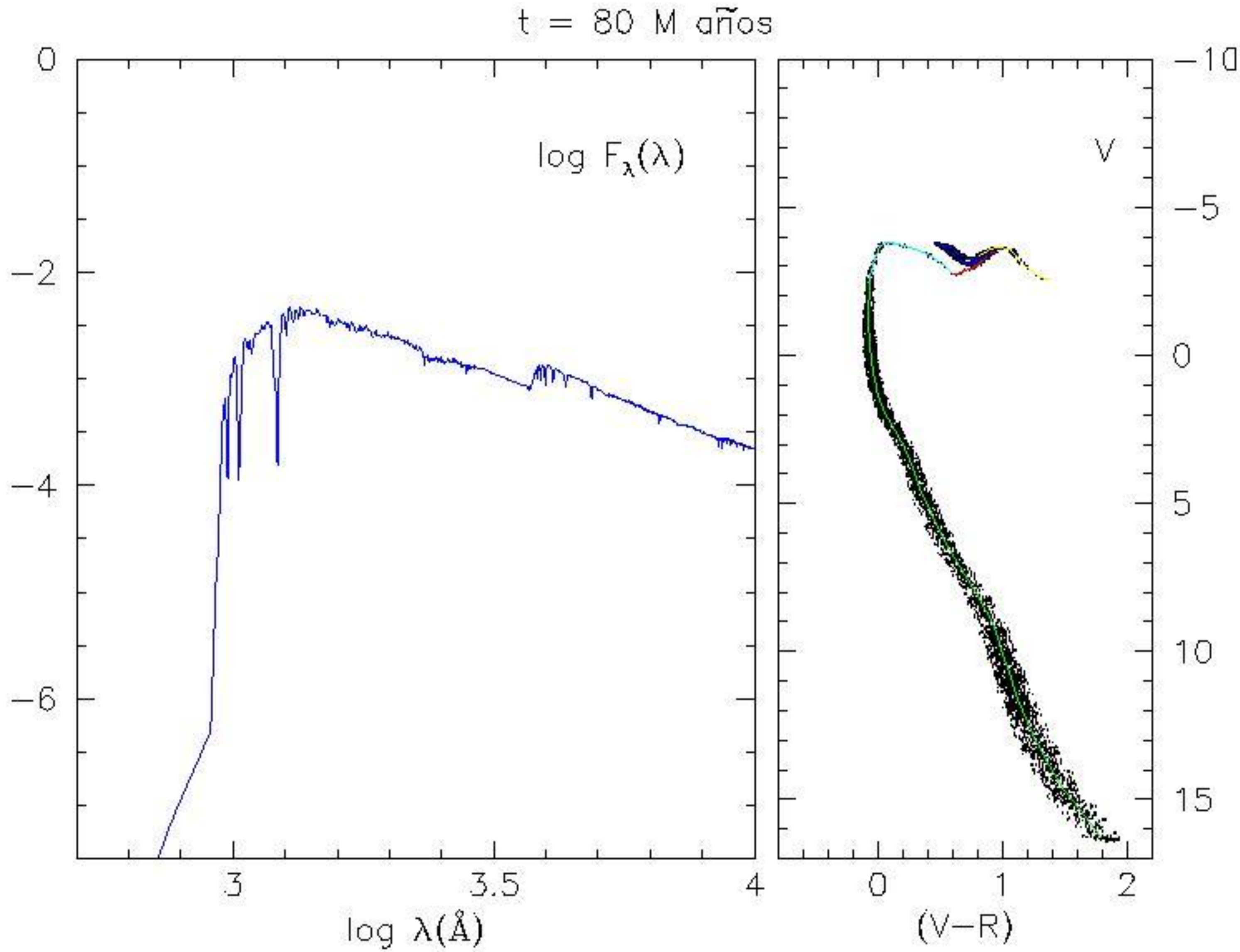

t = 30 M años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2

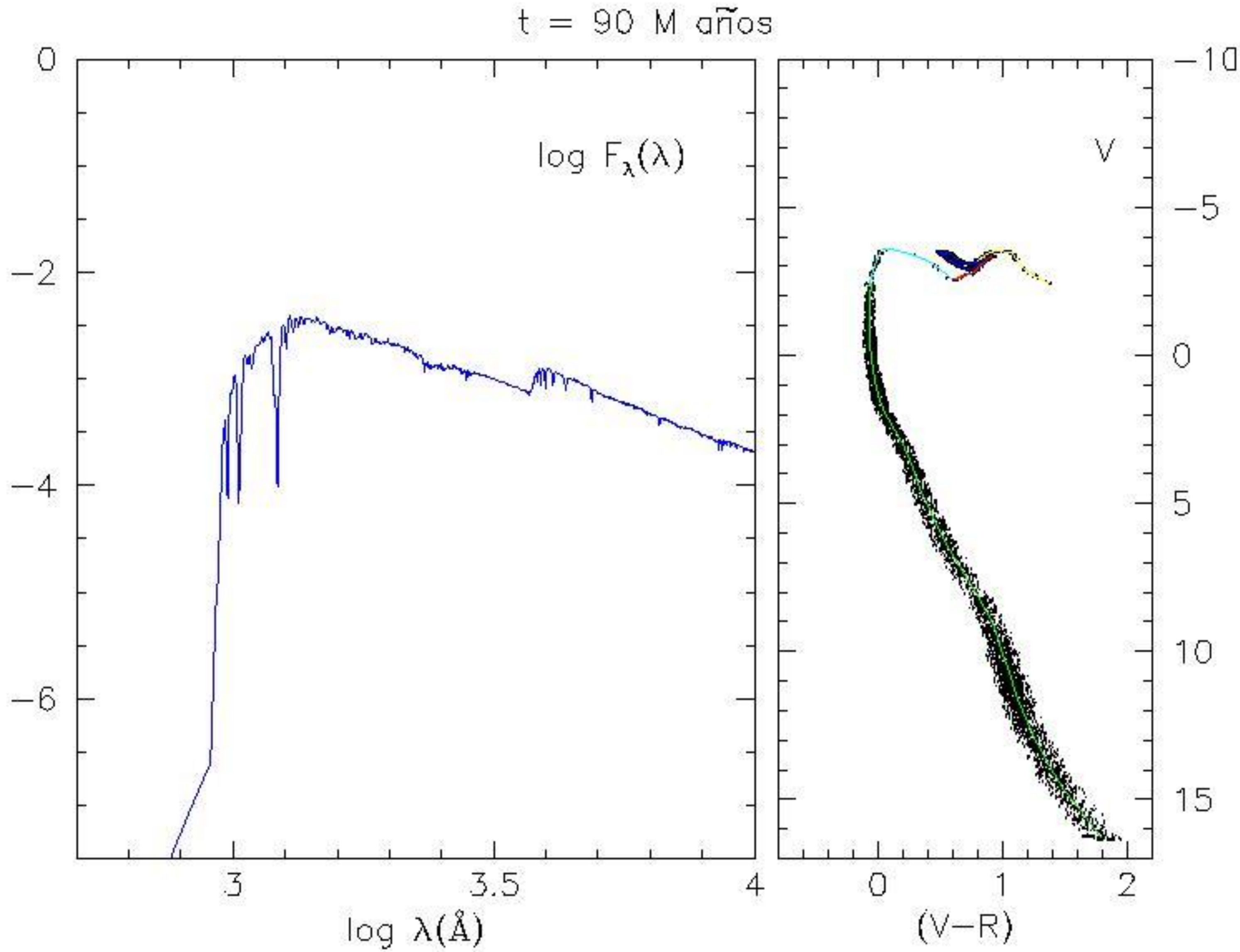

t = 40 M años
log Fλ(λ)
log λ(Å)
0
−2
−4
−6
3
3.5
4
V
(V−R)
−10
−5
0
5
10
15
0
1
2

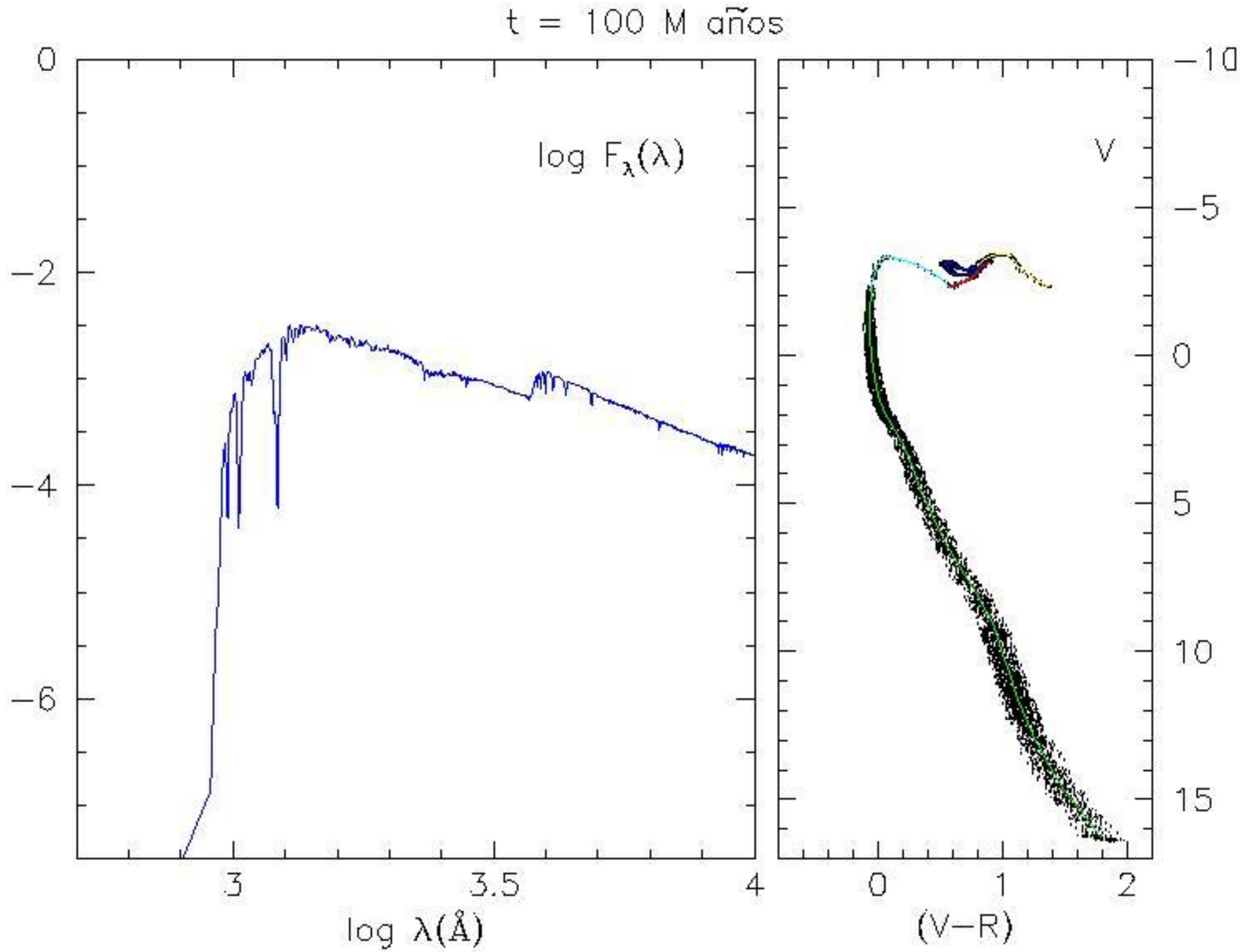

t = 50 M años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2

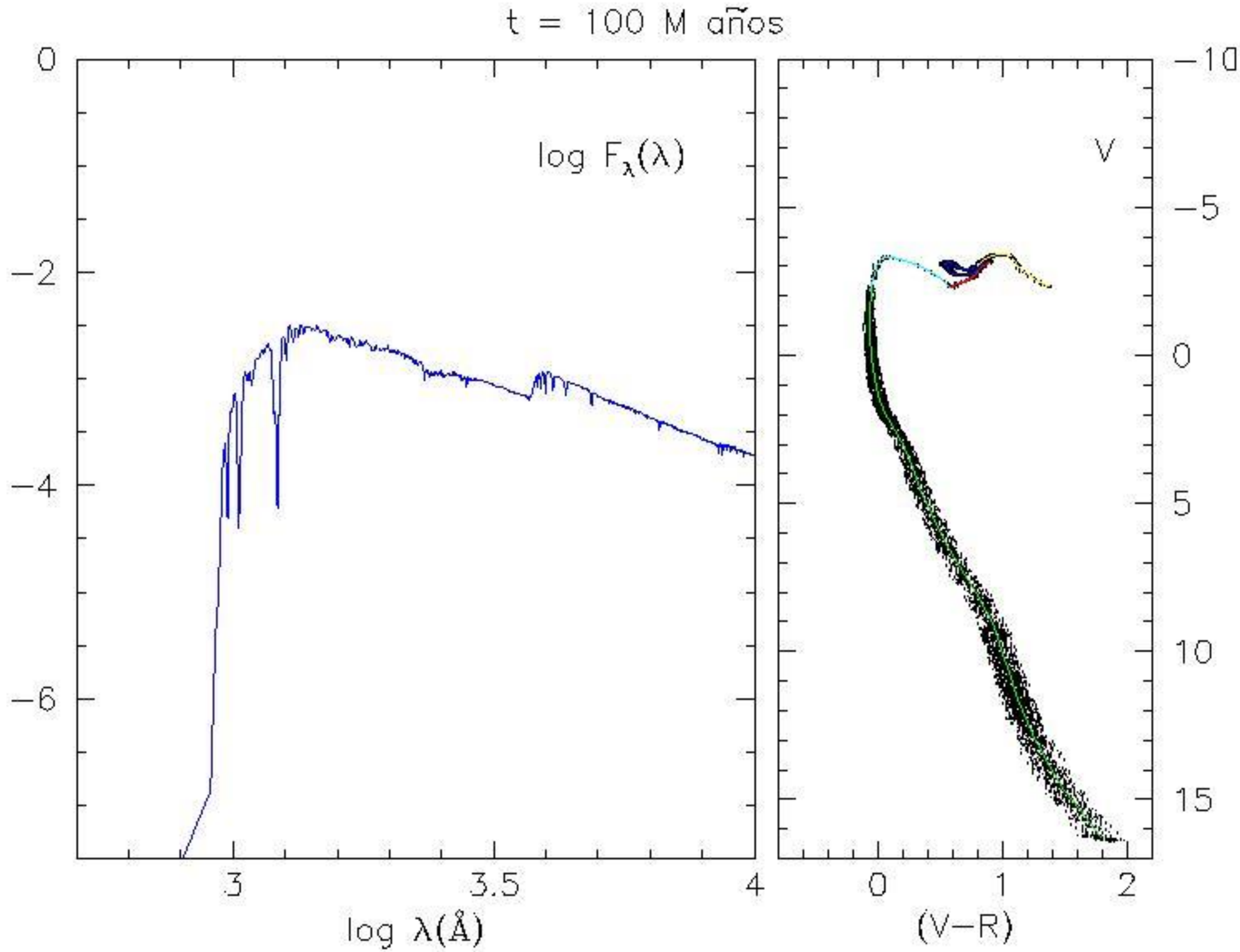

t = 60 M años
log $F_\lambda(\lambda)$
log λ(Å)
0
−2
−4
−6
3
3.5
4
V
−10
−5
0
5
10
15
0
1
2
(V−R)

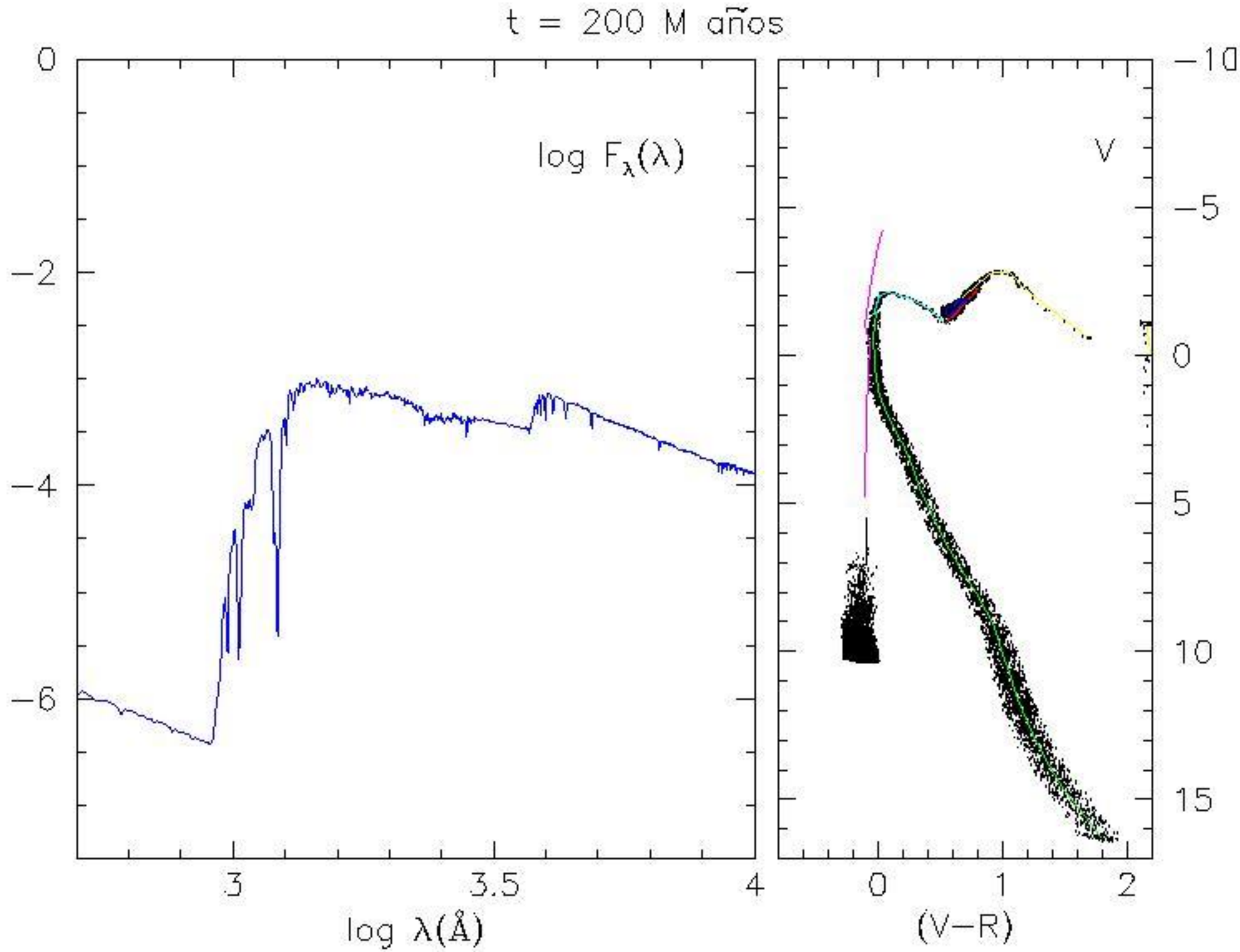

t = 70 M años
log $F_\lambda(\lambda)$
V
0
−2
−4
−6
3
3.5
4
log λ(Å)
−10
−5
0
5
10
15
0
1
2
(V−R)

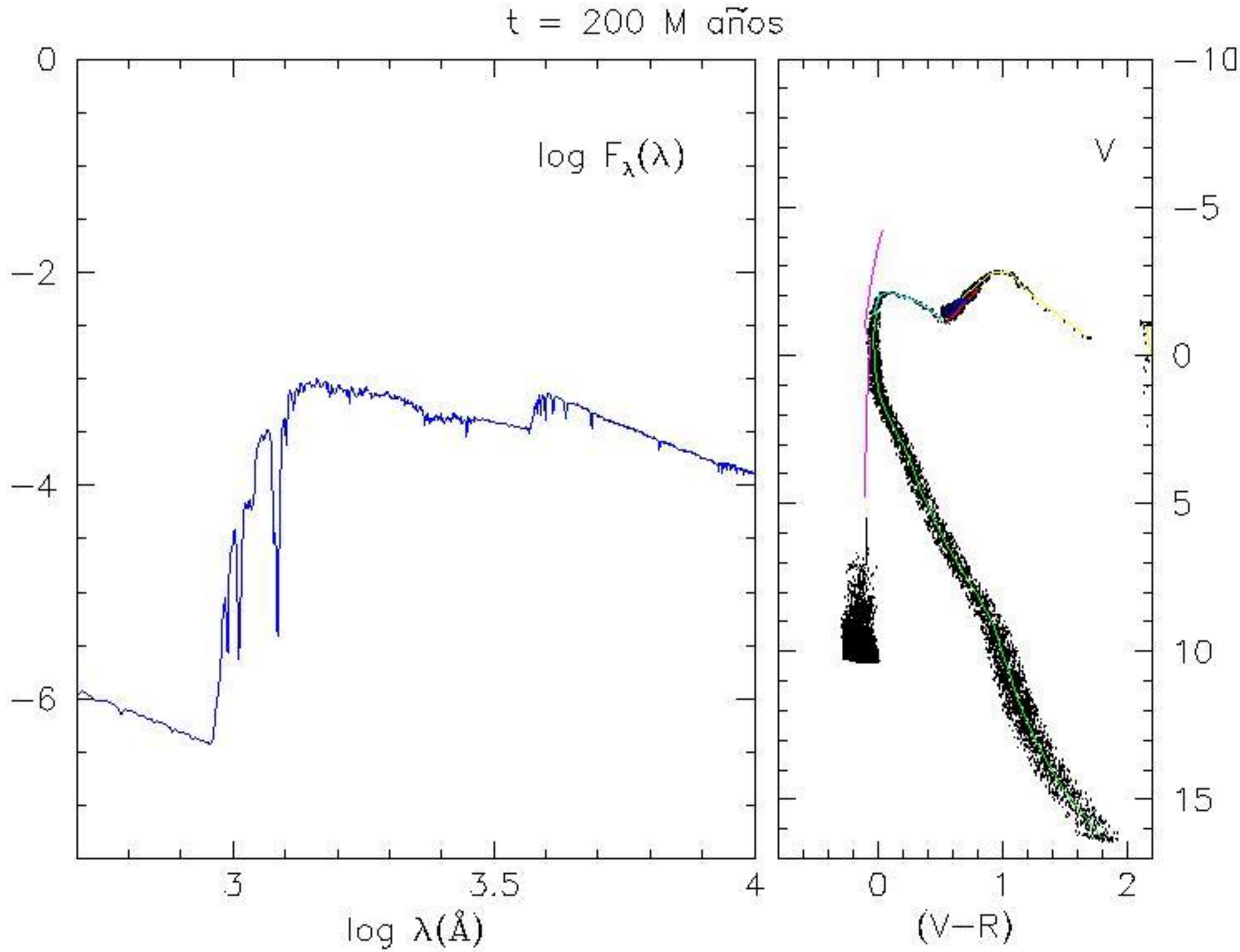

t = 80 M años
log $F_\lambda(\lambda)$
V
0
−2
−4
−6
3
3.5
4
log λ(Å)
−10
−5
0
5
10
15
0
1
2
(V−R)


t = 90 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

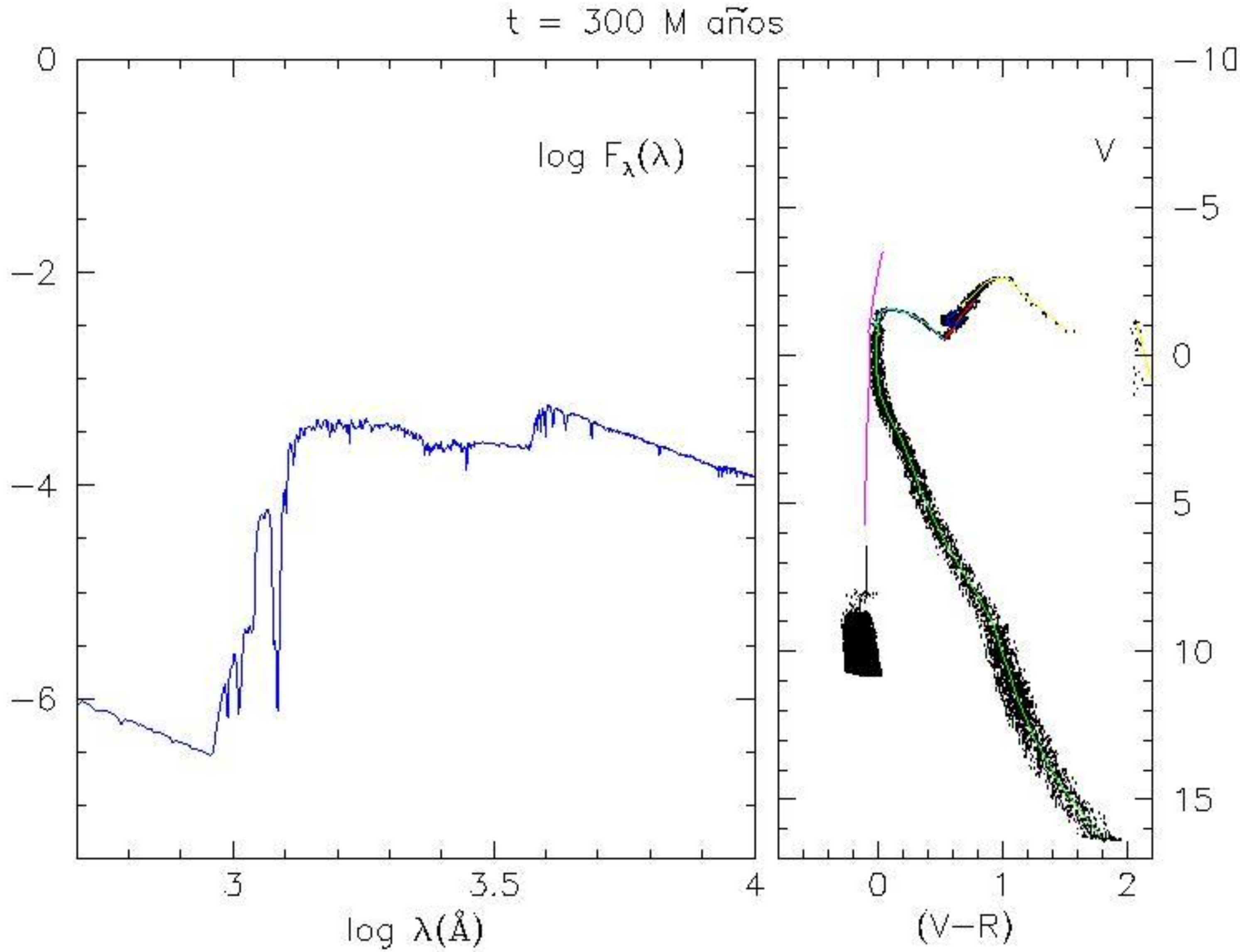

t = 100 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

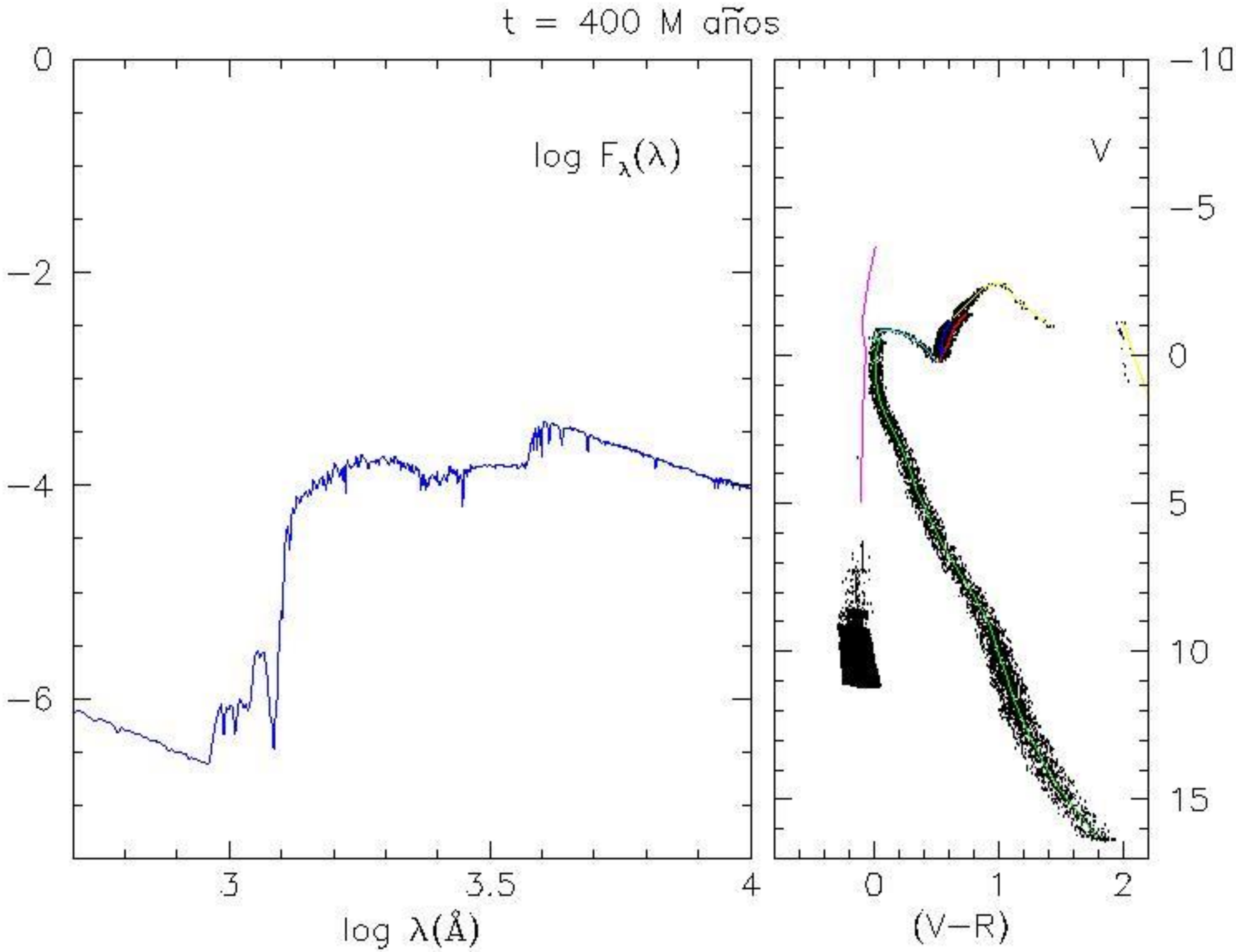

t = 100 M años
log F_λ(λ)
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2

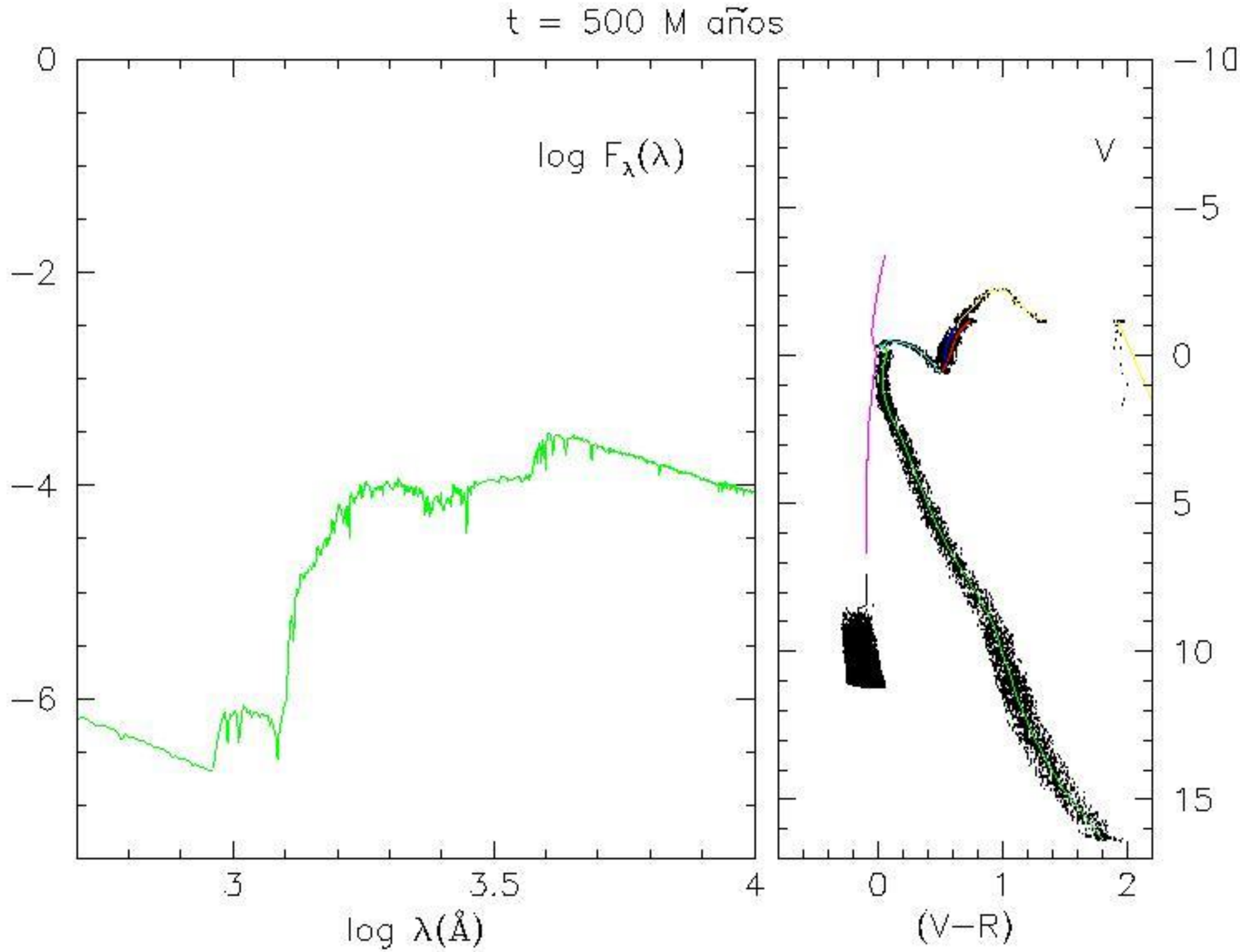

t = 200 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

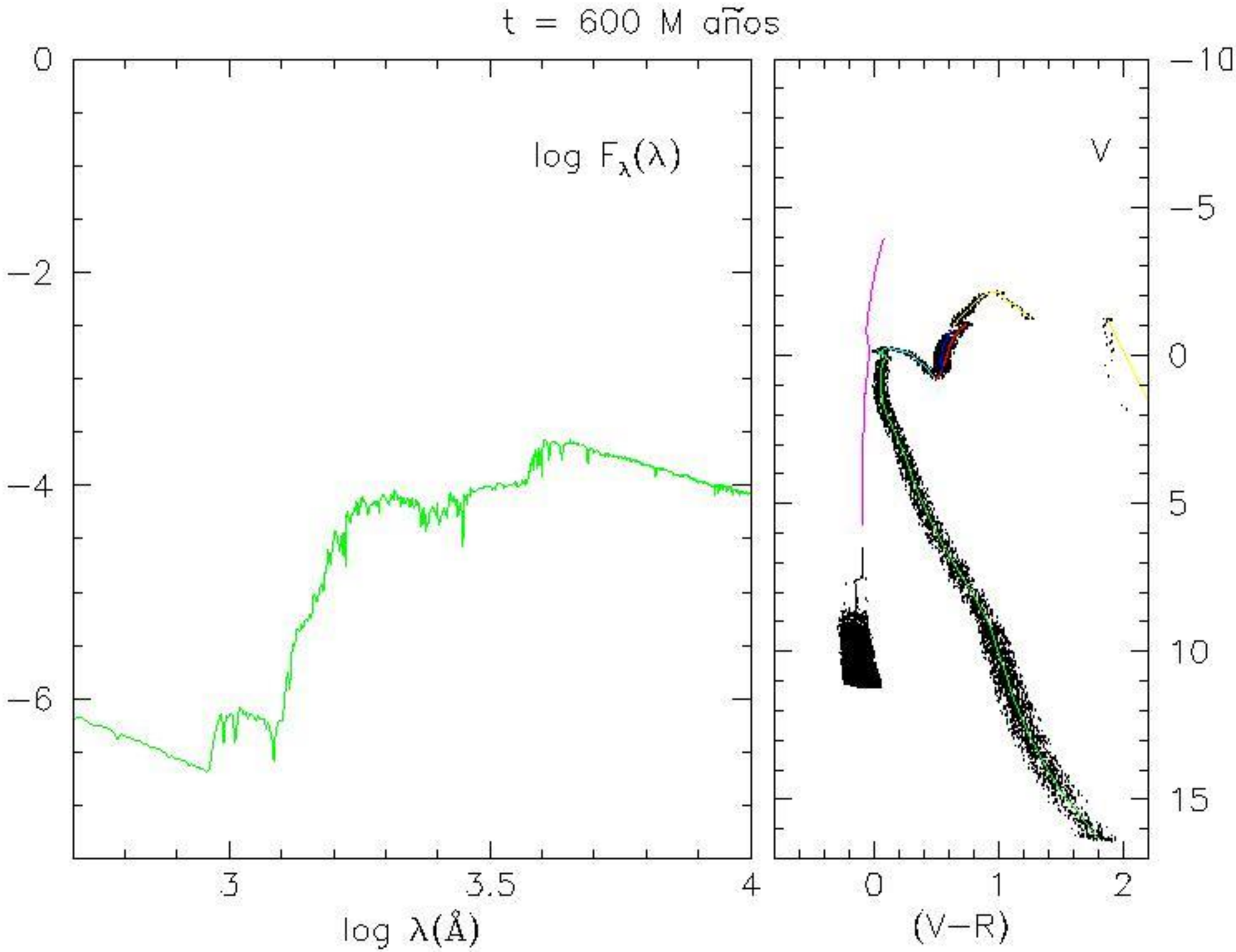


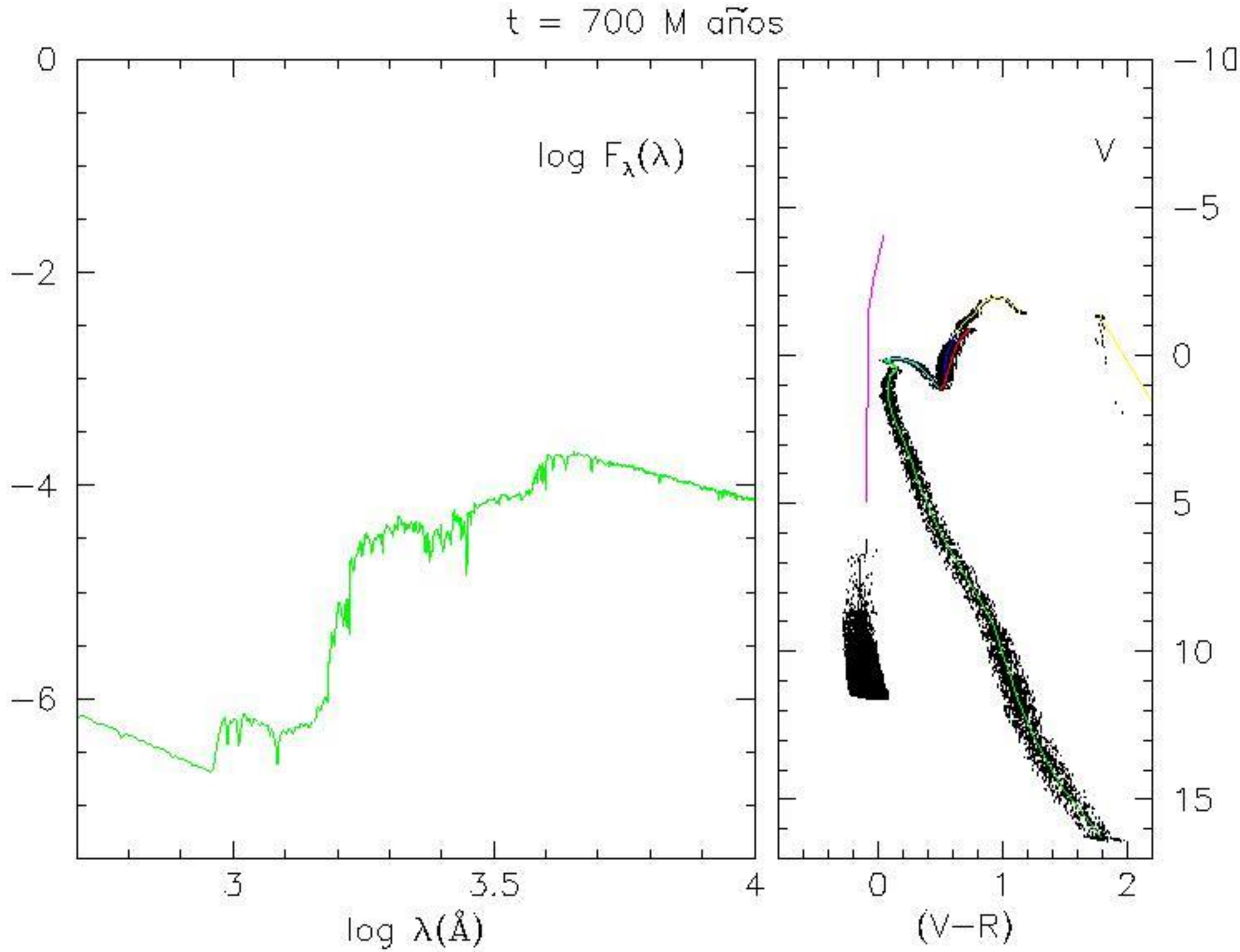
t = 200 M años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
1
2


t = 300 M años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2

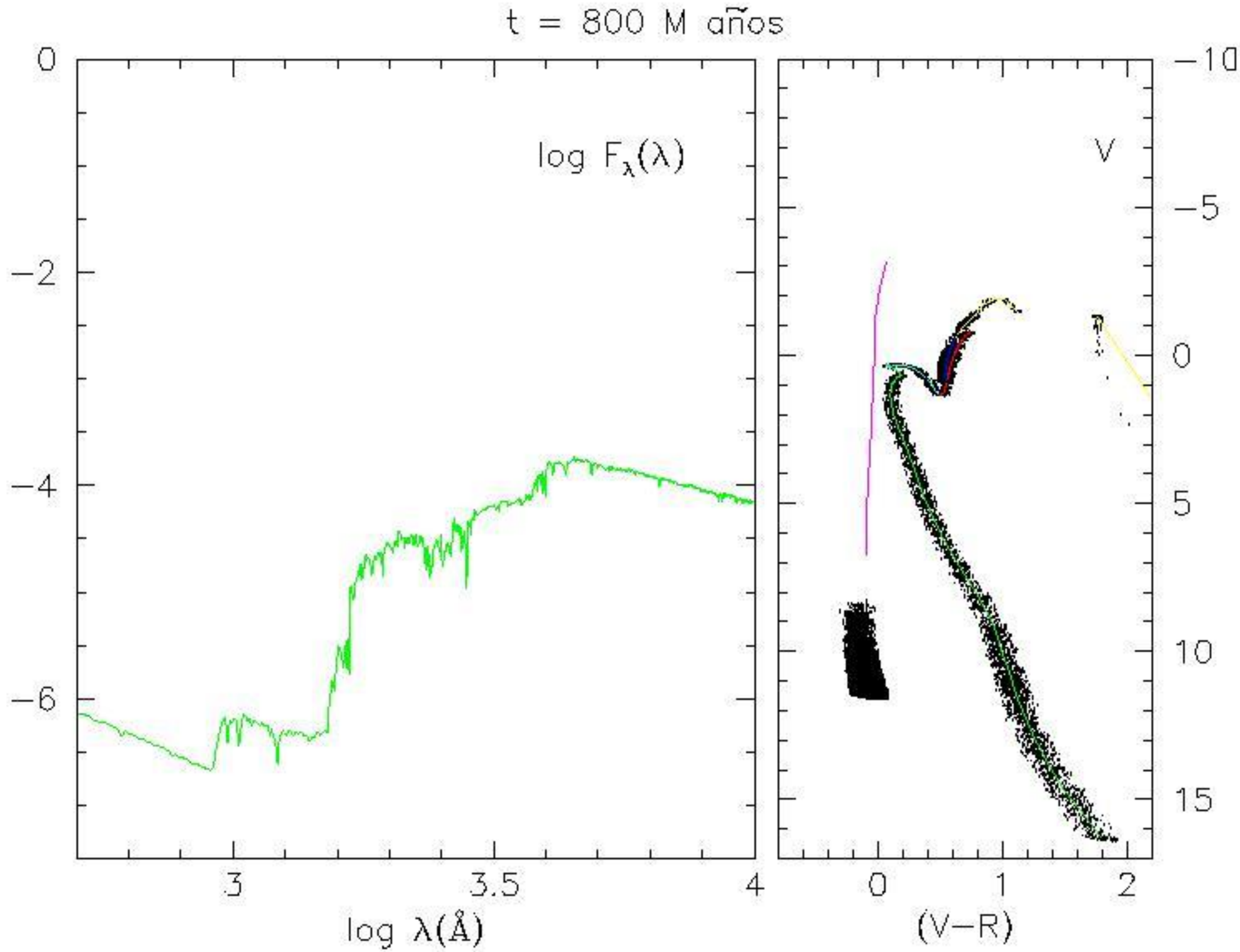

t = 400 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

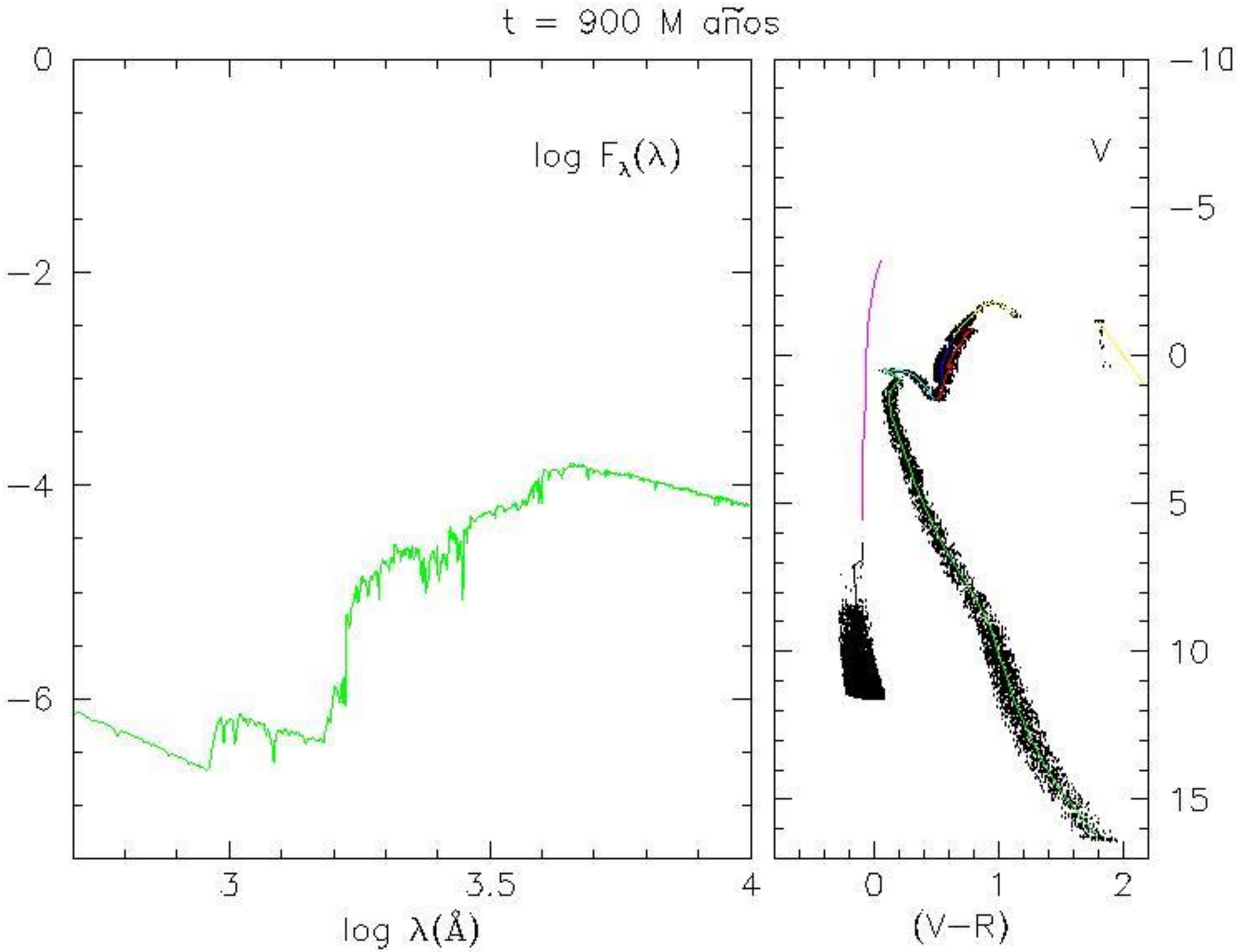

t = 500 M años
log $F_\lambda(\lambda)$
V
0
−2
−4
−6
3
3.5
4
log λ(Å)
0
1
2
(V−R)
−10
−5
0
5
10
15

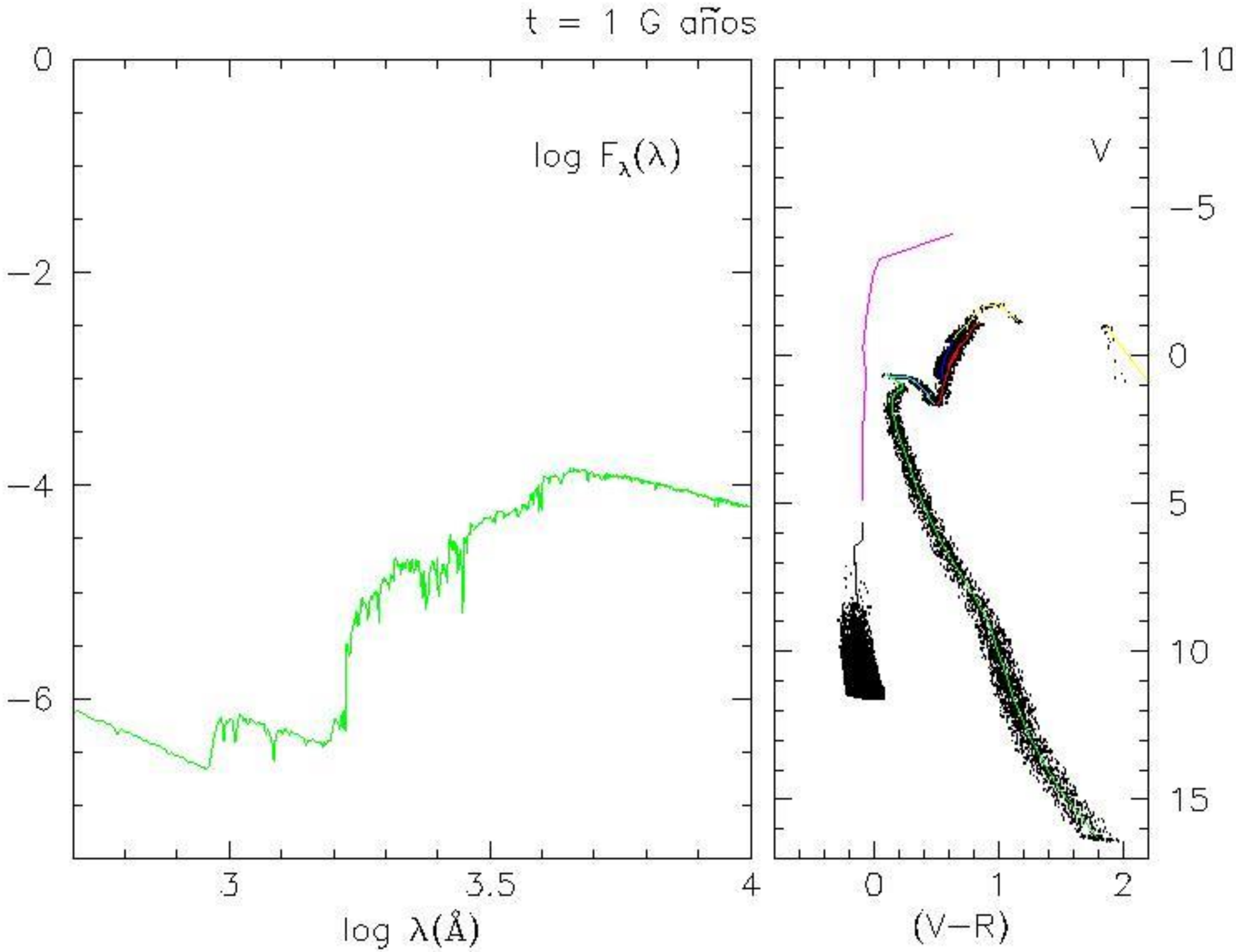

t = 600 M años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)

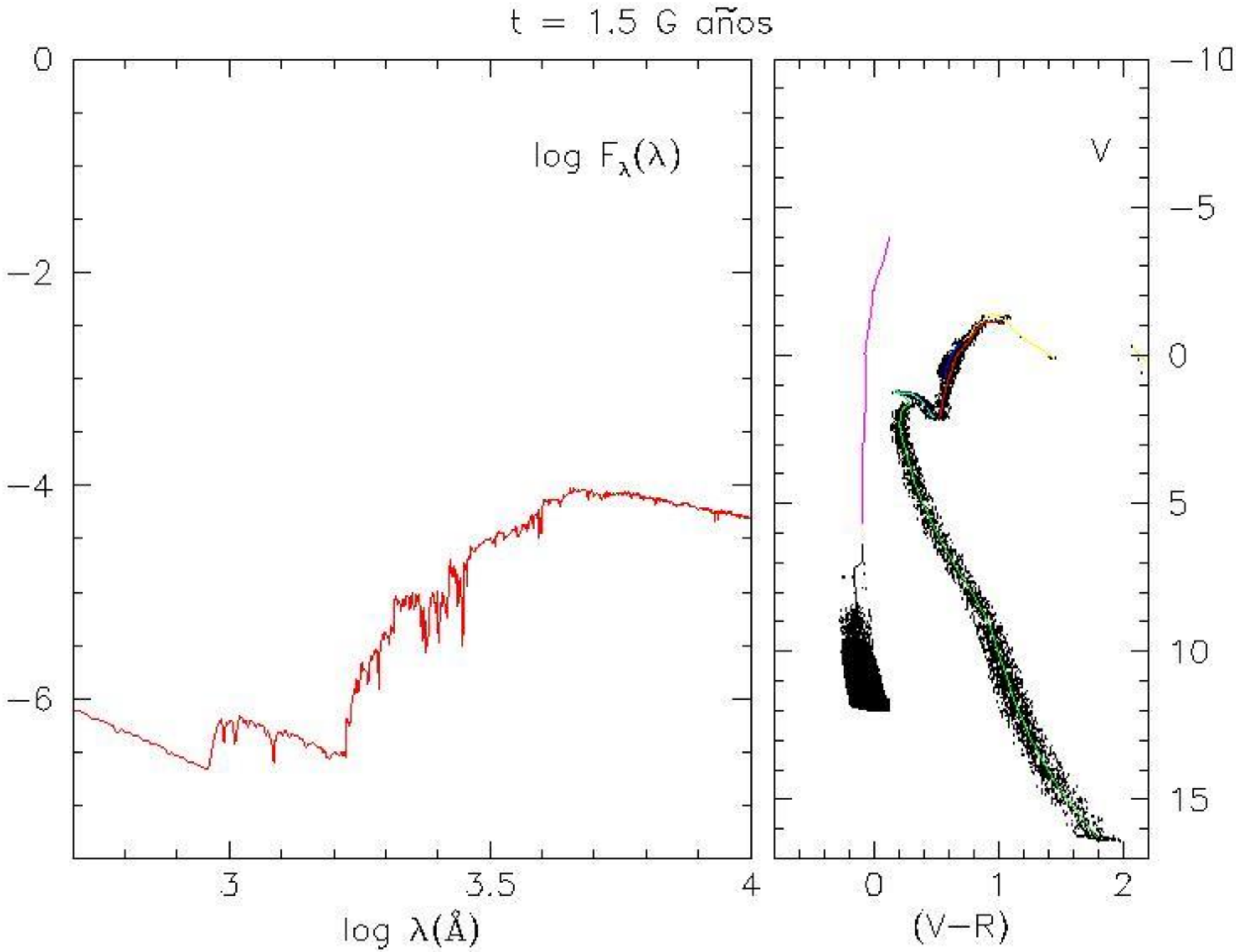


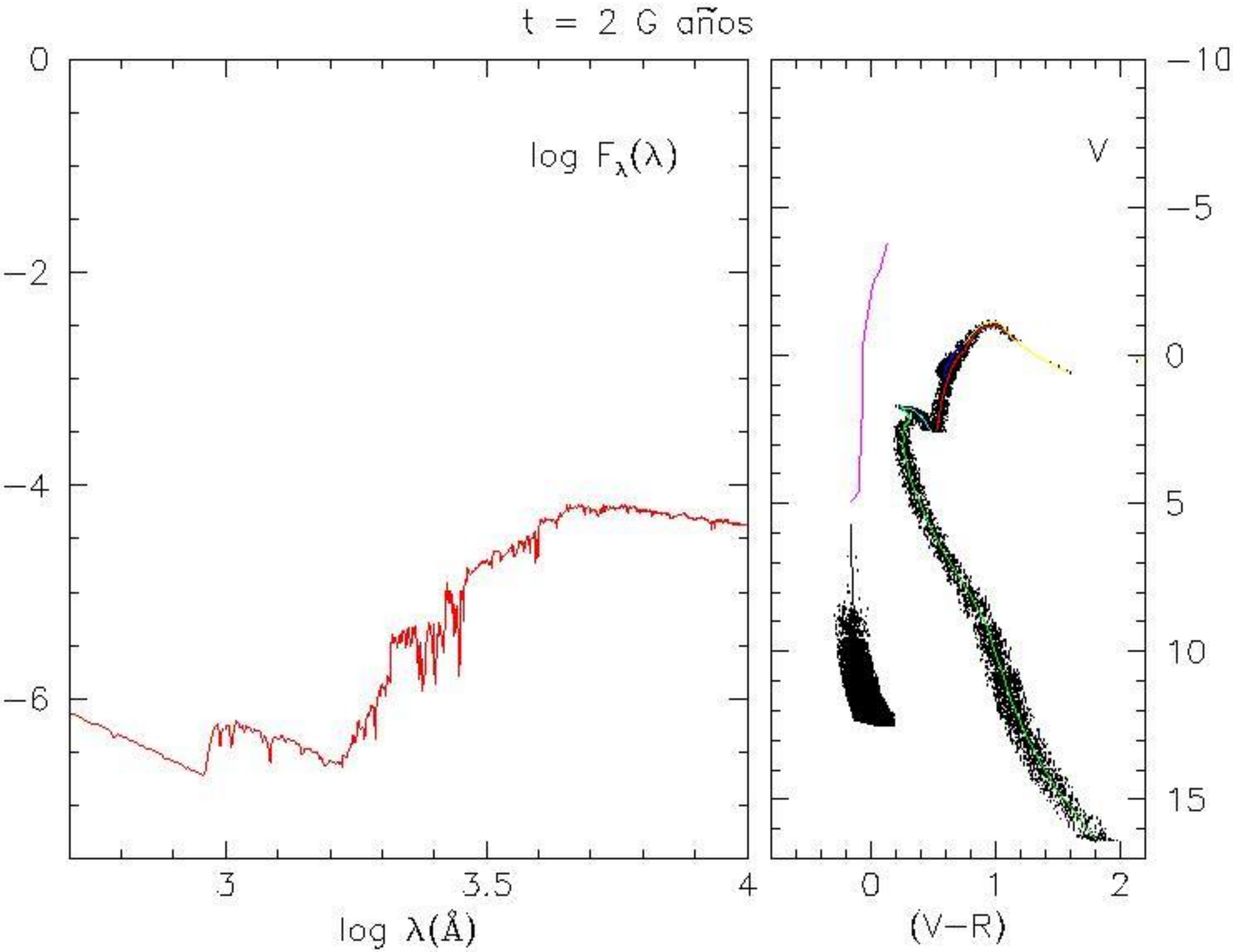
t = 700 M años
log $F_\lambda(\lambda)$
V
0
−2
−4
−6
3
3.5
4
log λ(Å)
−10
−5
0
5
10
15
0
1
2
(V−R)

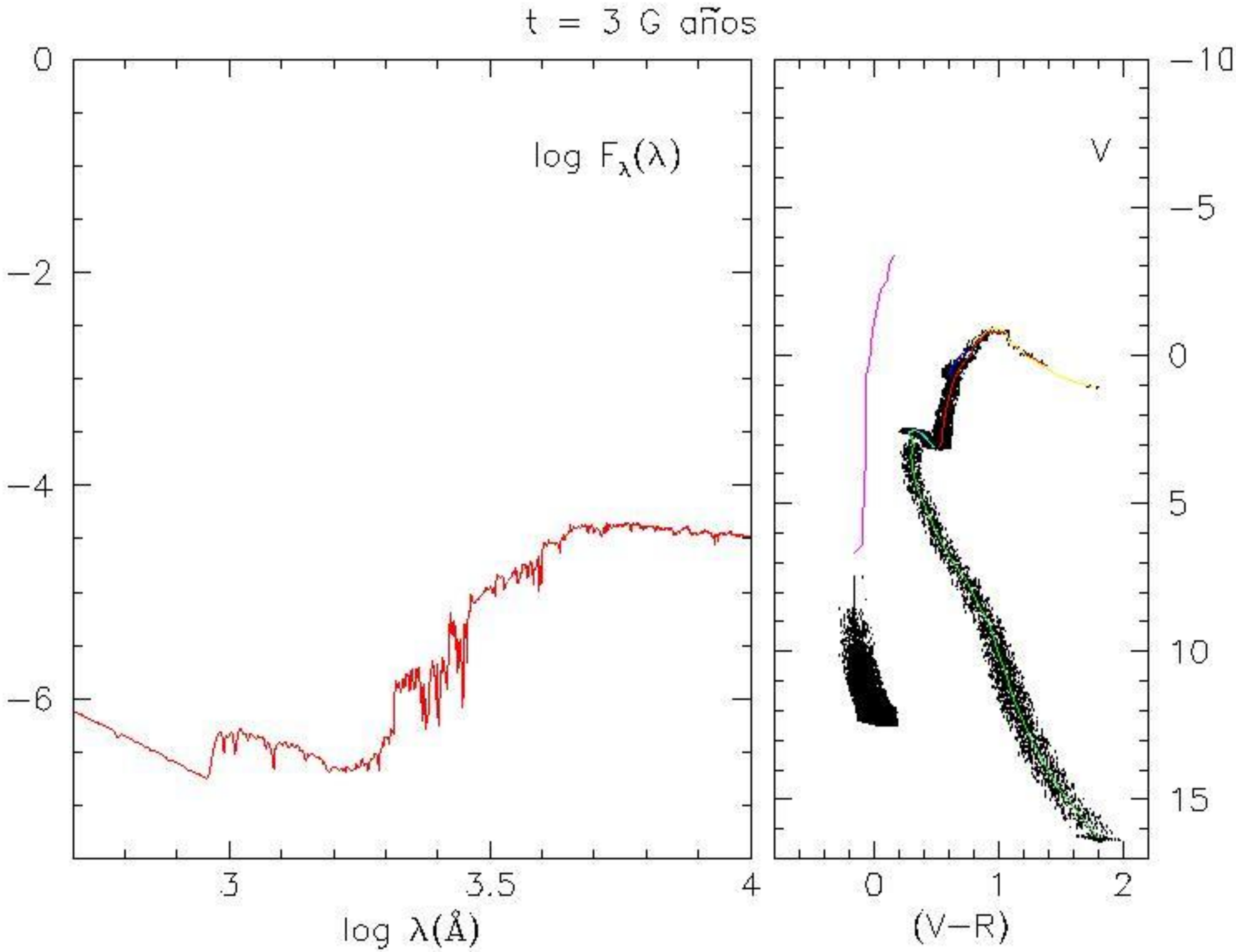

t = 800 M años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

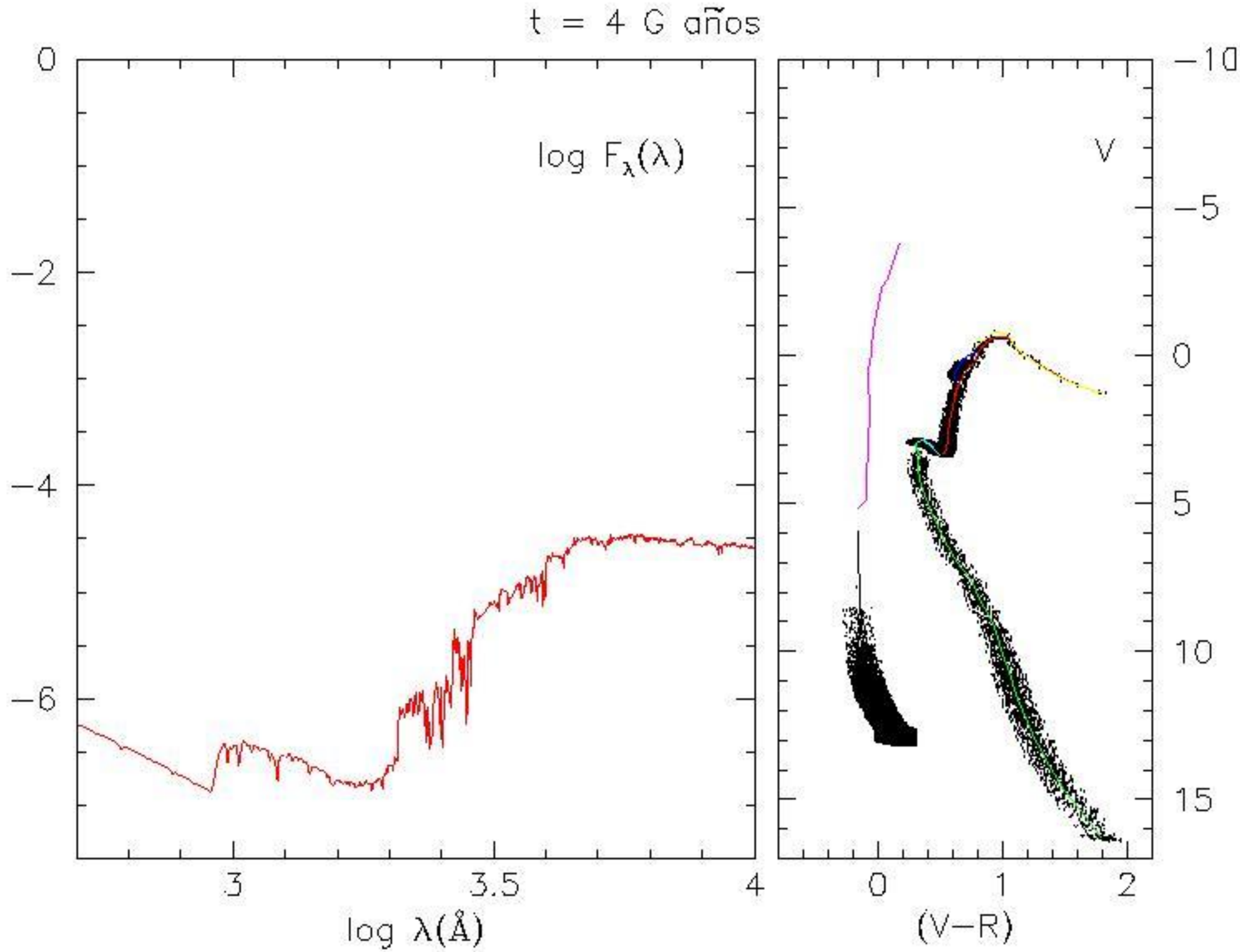

t = 900 M años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)

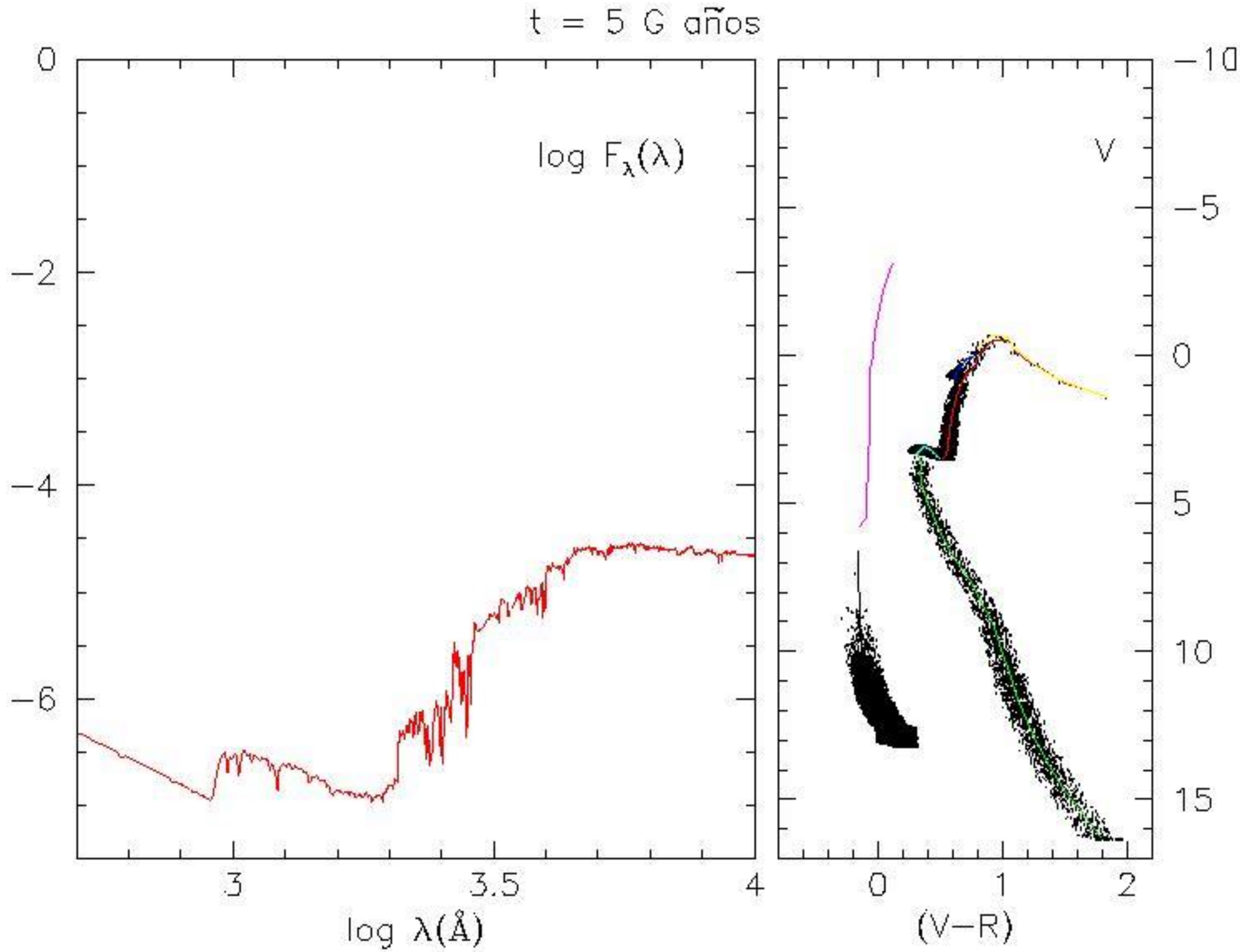

t = 1 G años
log $F_\lambda(\lambda)$
log λ(Å)
0
−2
−4
−6
3
3.5
4
V
(V−R)
−10
−5
0
5
10
15
0
1
2

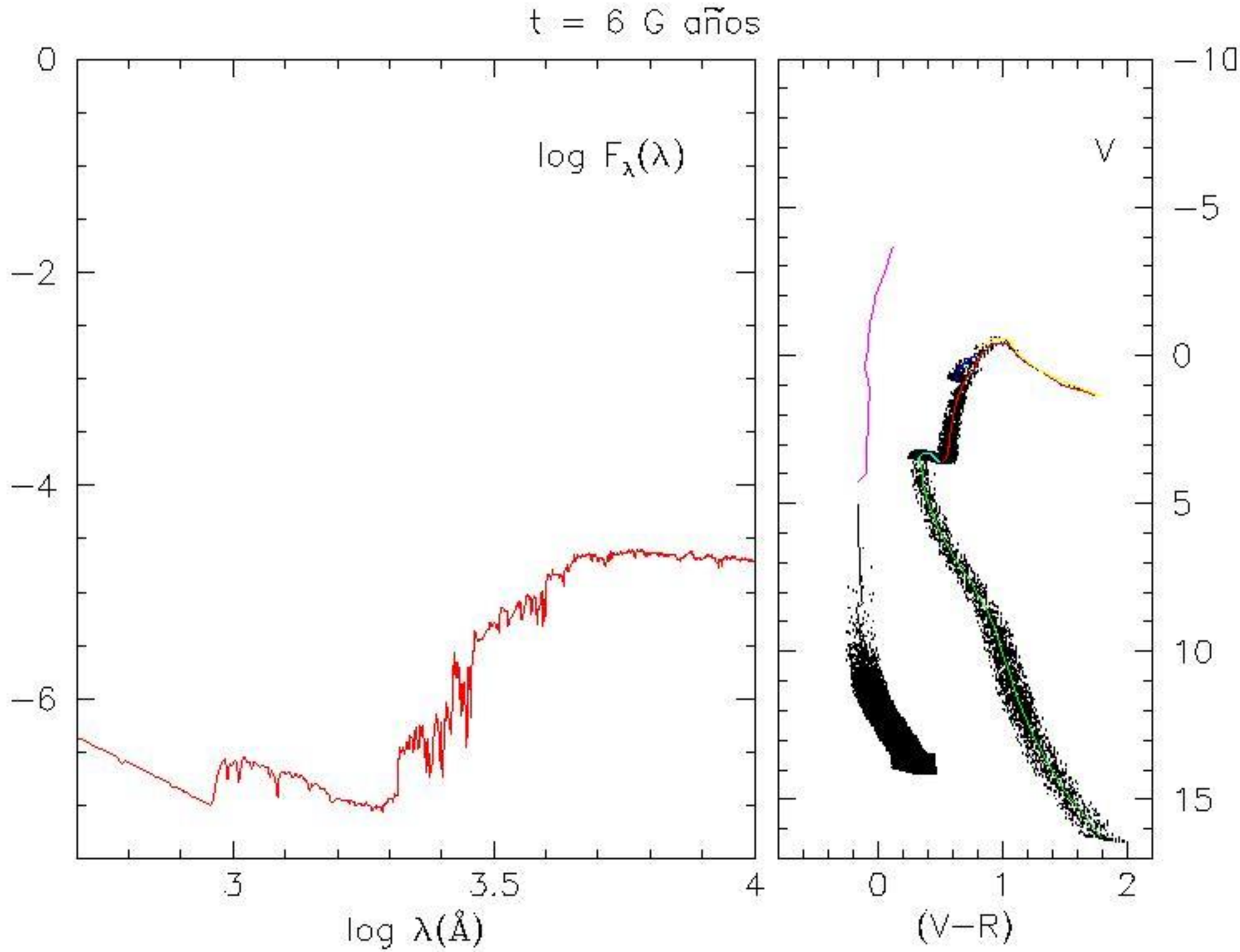

t = 1.5 G años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2

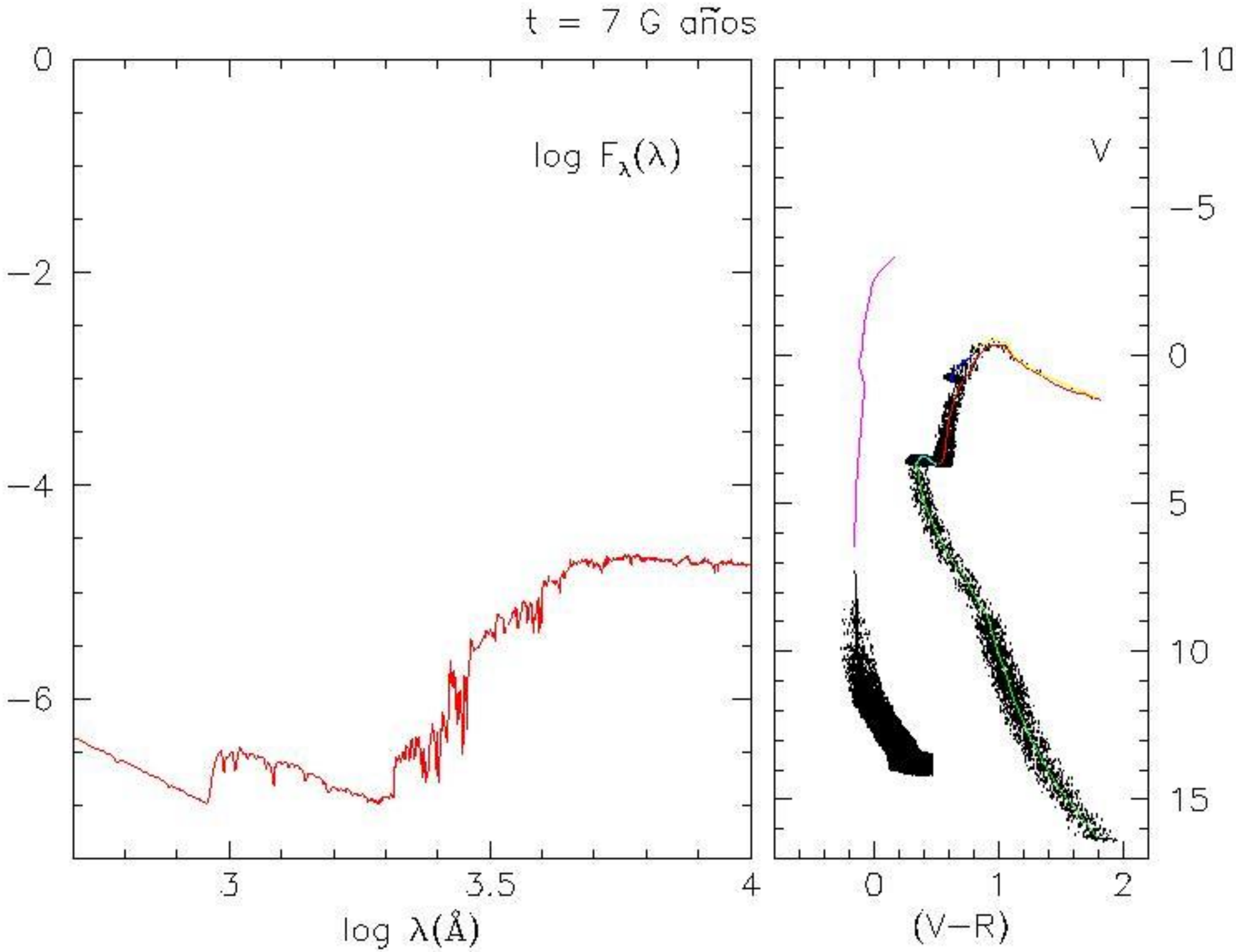

t = 2 G años
log $F_\lambda(\lambda)$
V
0
−2
−4
−6
3
3.5
4
log λ(Å)
−10
−5
0
5
10
15
0
1
2
(V−R)

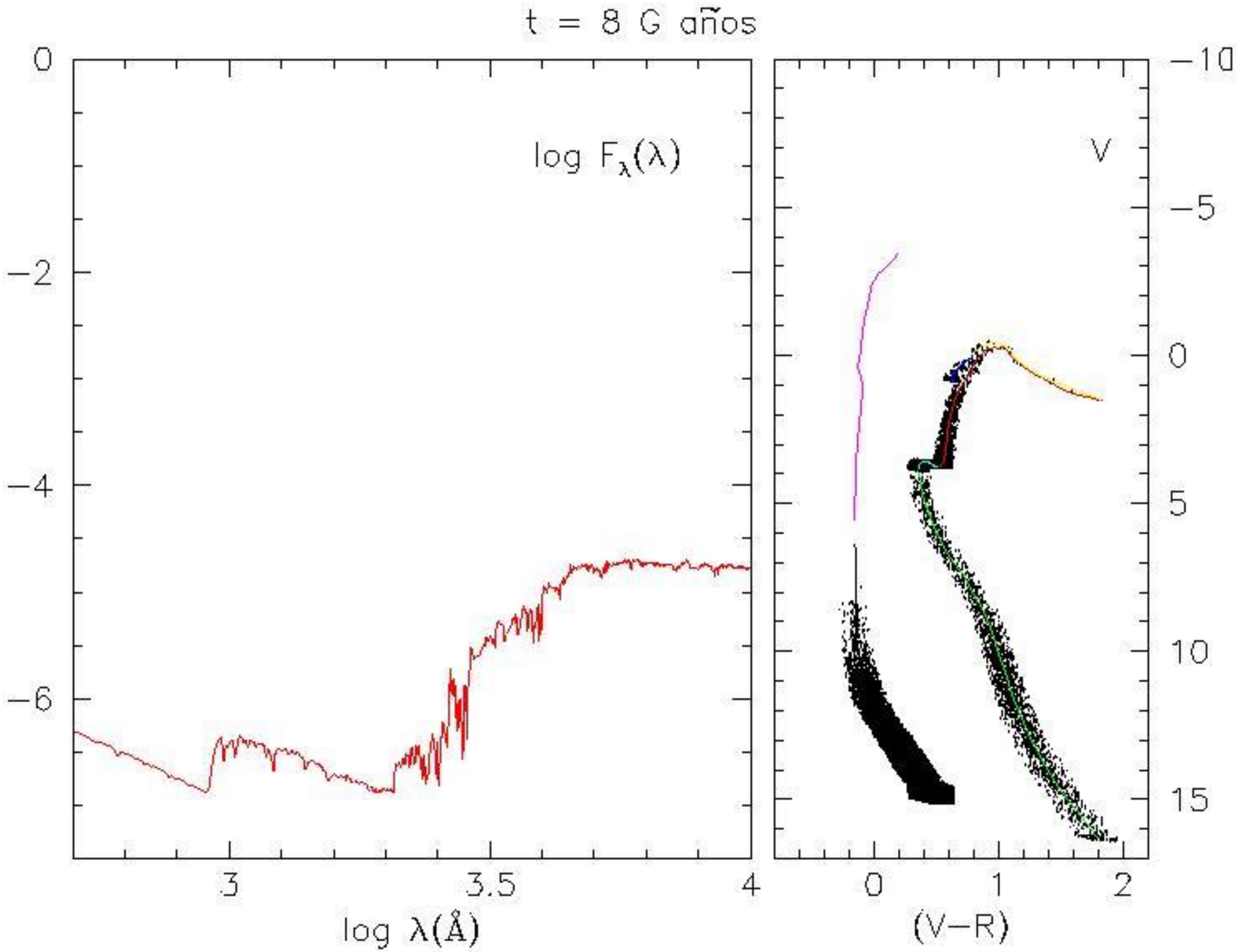

t = 3 G años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

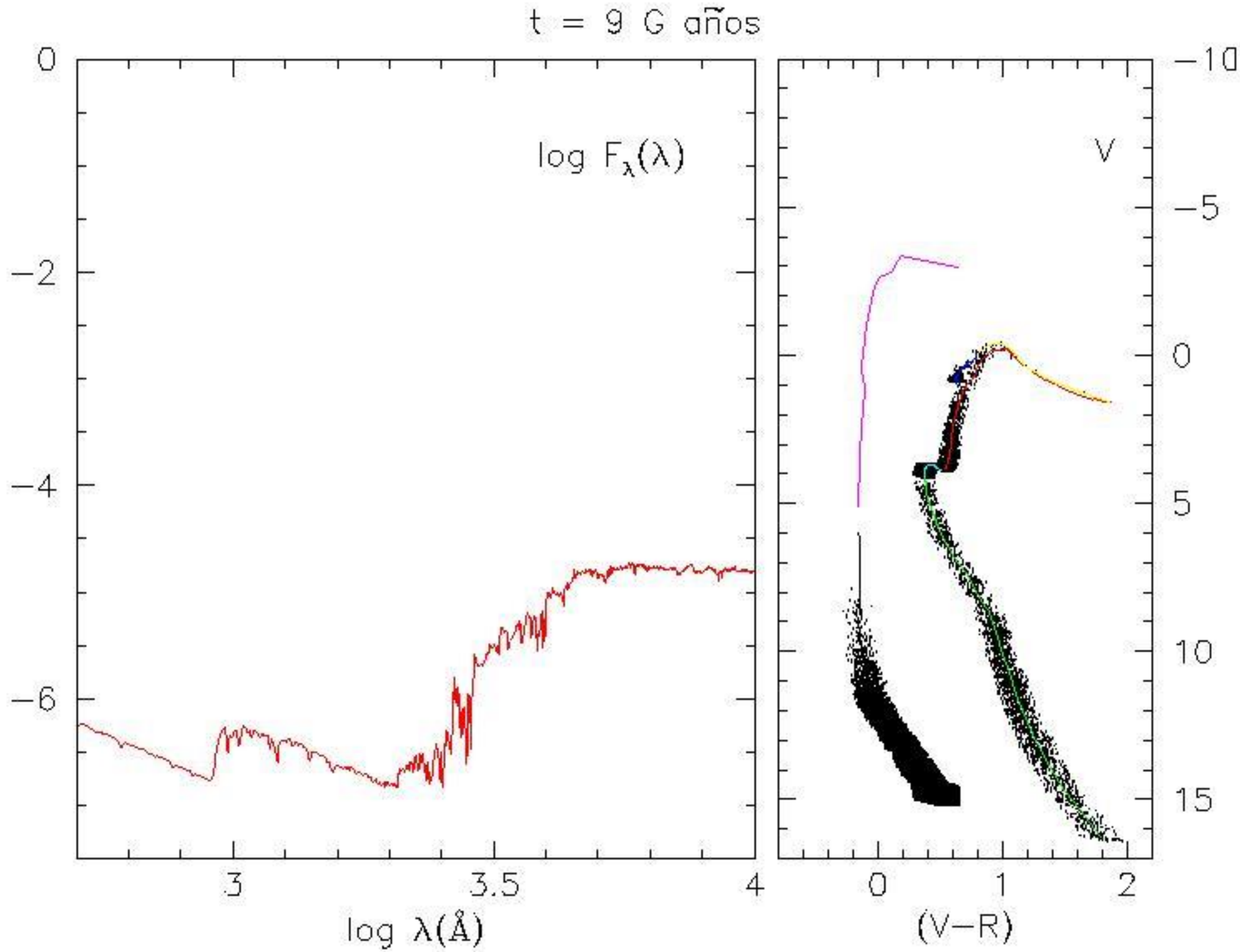

t = 4 G años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2

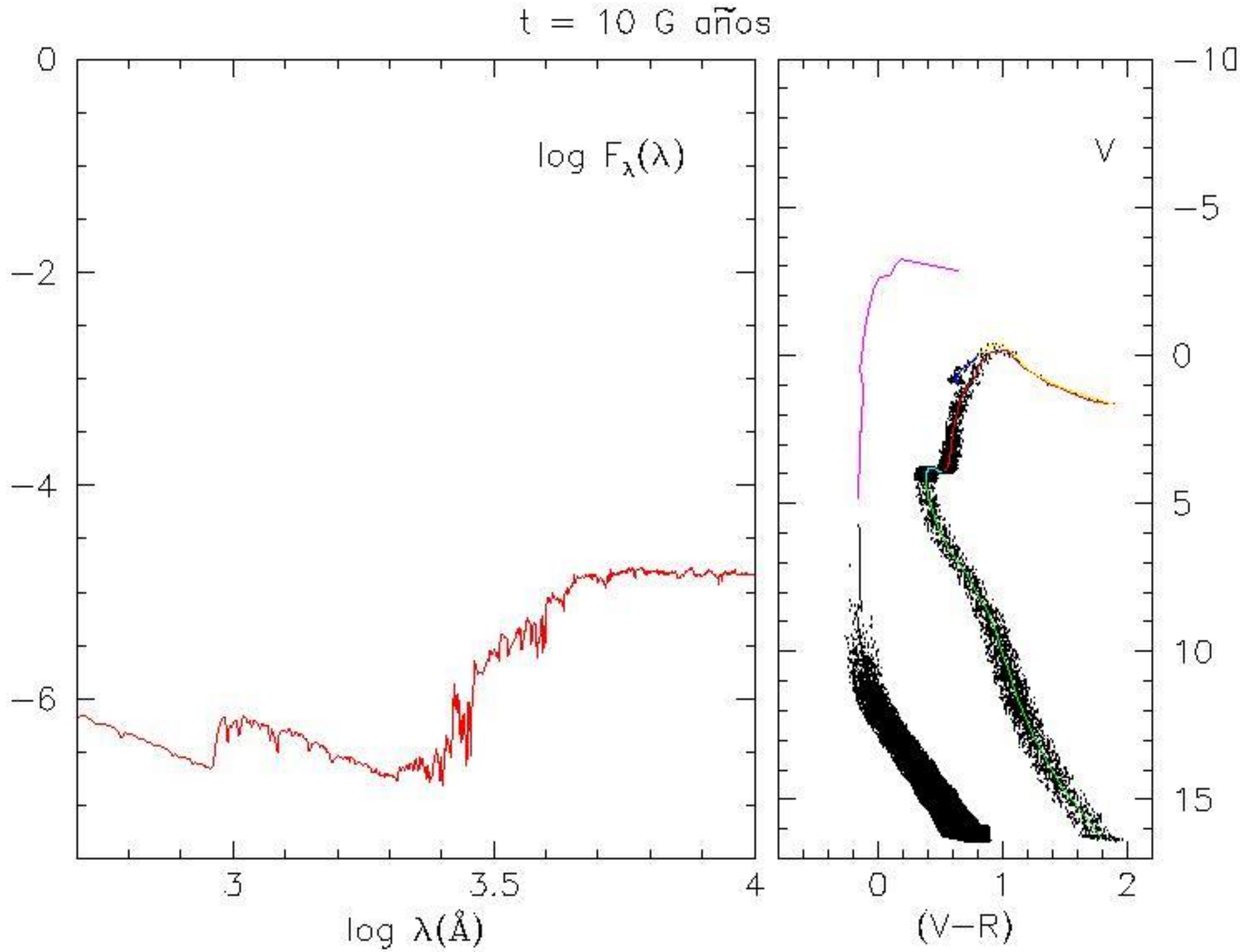

t = 5 G años
log $F_\lambda(\lambda)$
log λ(Å)
0
−2
−4
−6
3
3.5
4
V
(V−R)
−10
−5
0
5
10
15
0
1
2

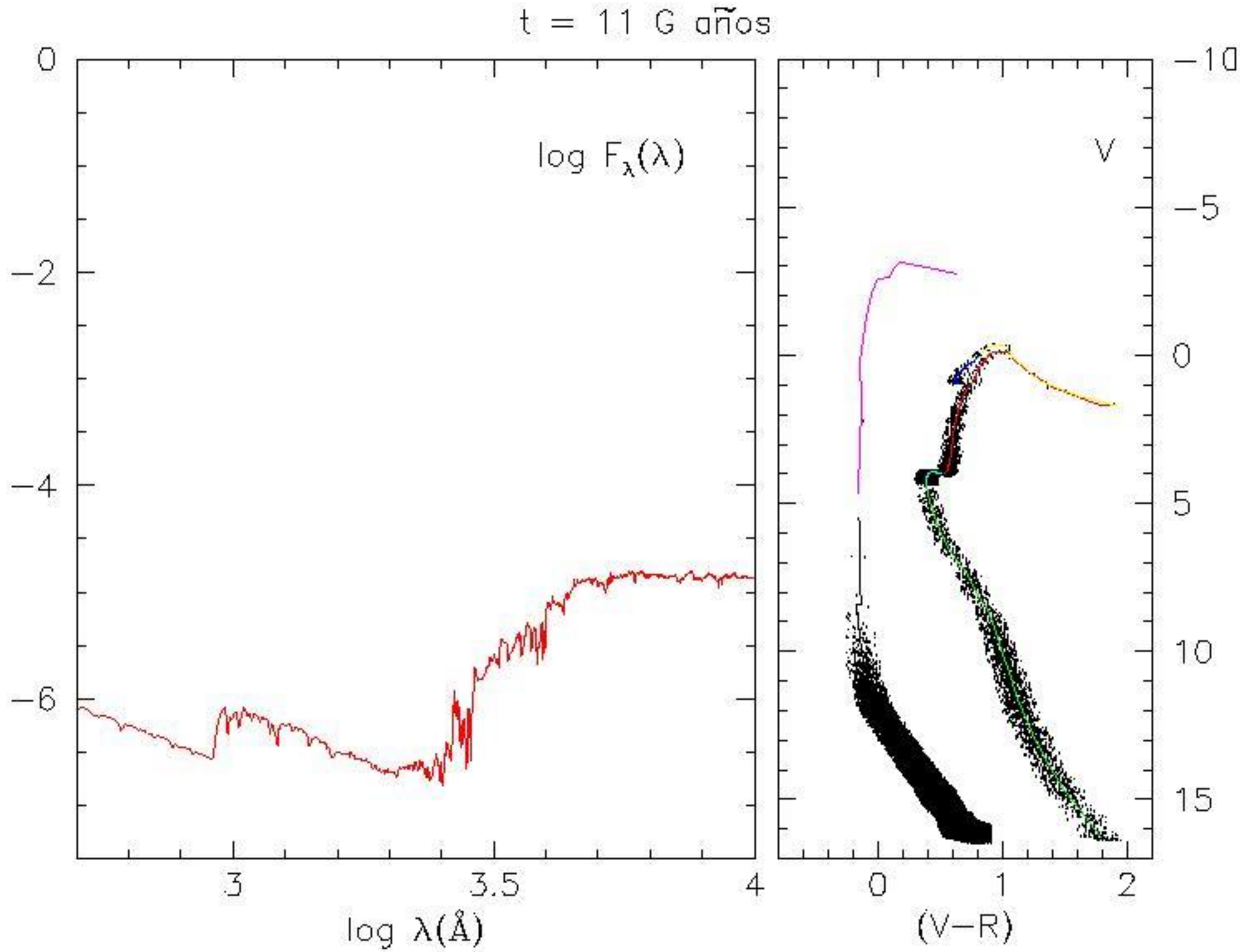

t = 6 G años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

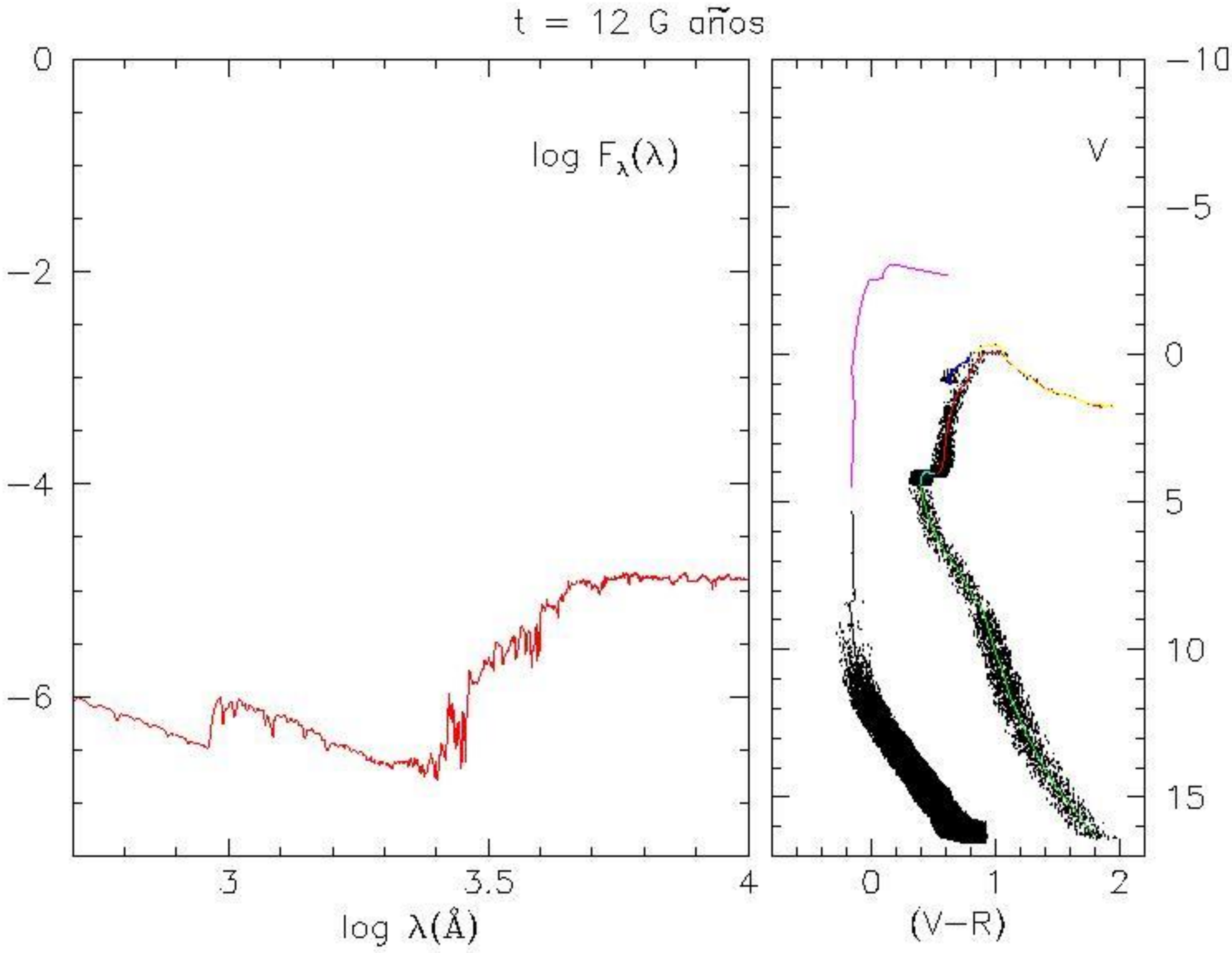

t = 7 G años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
0
1
2
−10
−5
0
5
10
15


t = 8 G años
log $F_\lambda(\lambda)$
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)

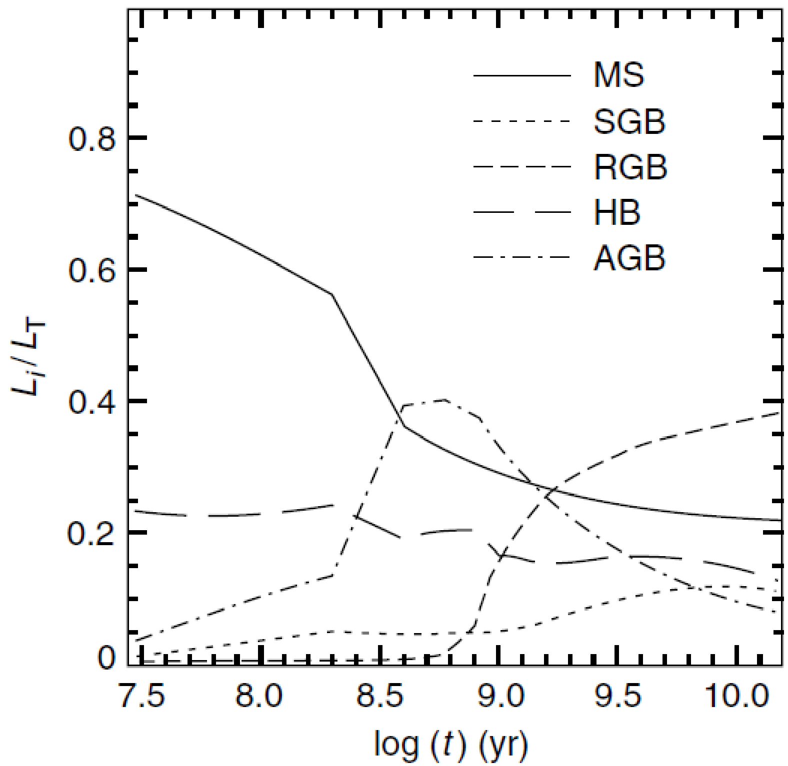

t = 9 G años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2


t = 10 G años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2

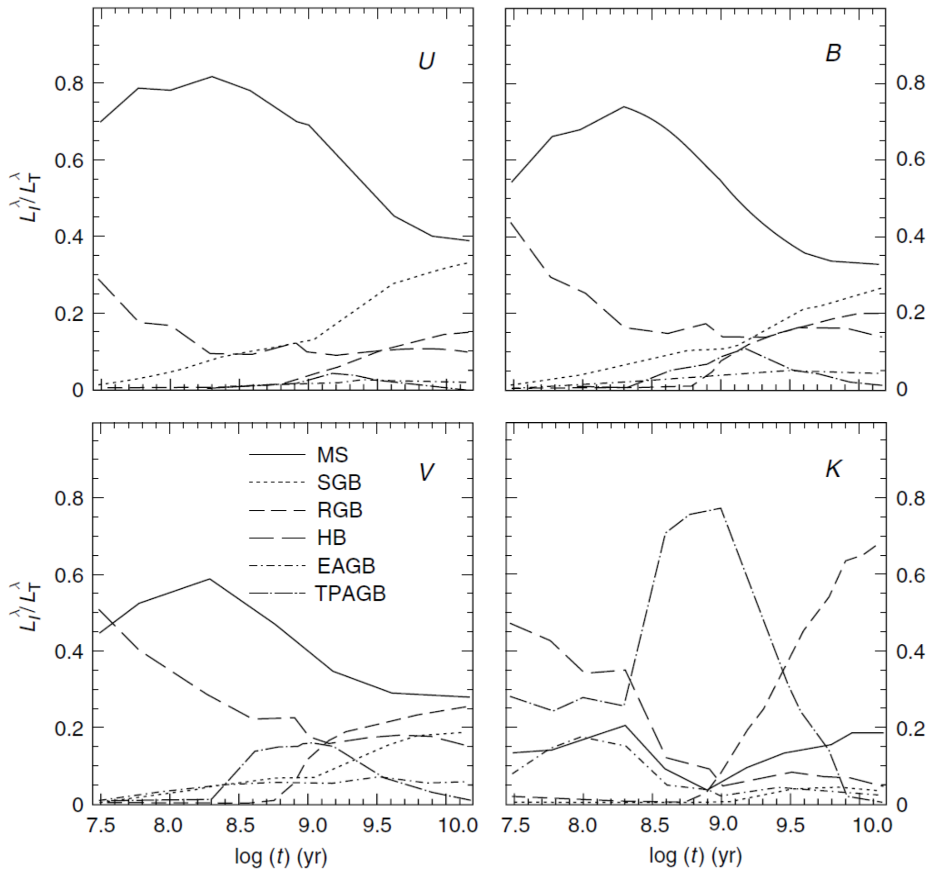

t = 11 G años
log F$_\lambda$(λ)
0
−2
−4
−6
3
3.5
4
log λ(Å)
V
−10
−5
0
5
10
15
0
1
2
(V−R)


t = 12 G años
log $F_\lambda(\lambda)$
log λ(Å)
V
(V−R)
0
−2
−4
−6
3
3.5
4
−10
−5
0
5
10
15
0
1
2

Contribution to the total bolometric luminosity by stars in their various evolutionary phases

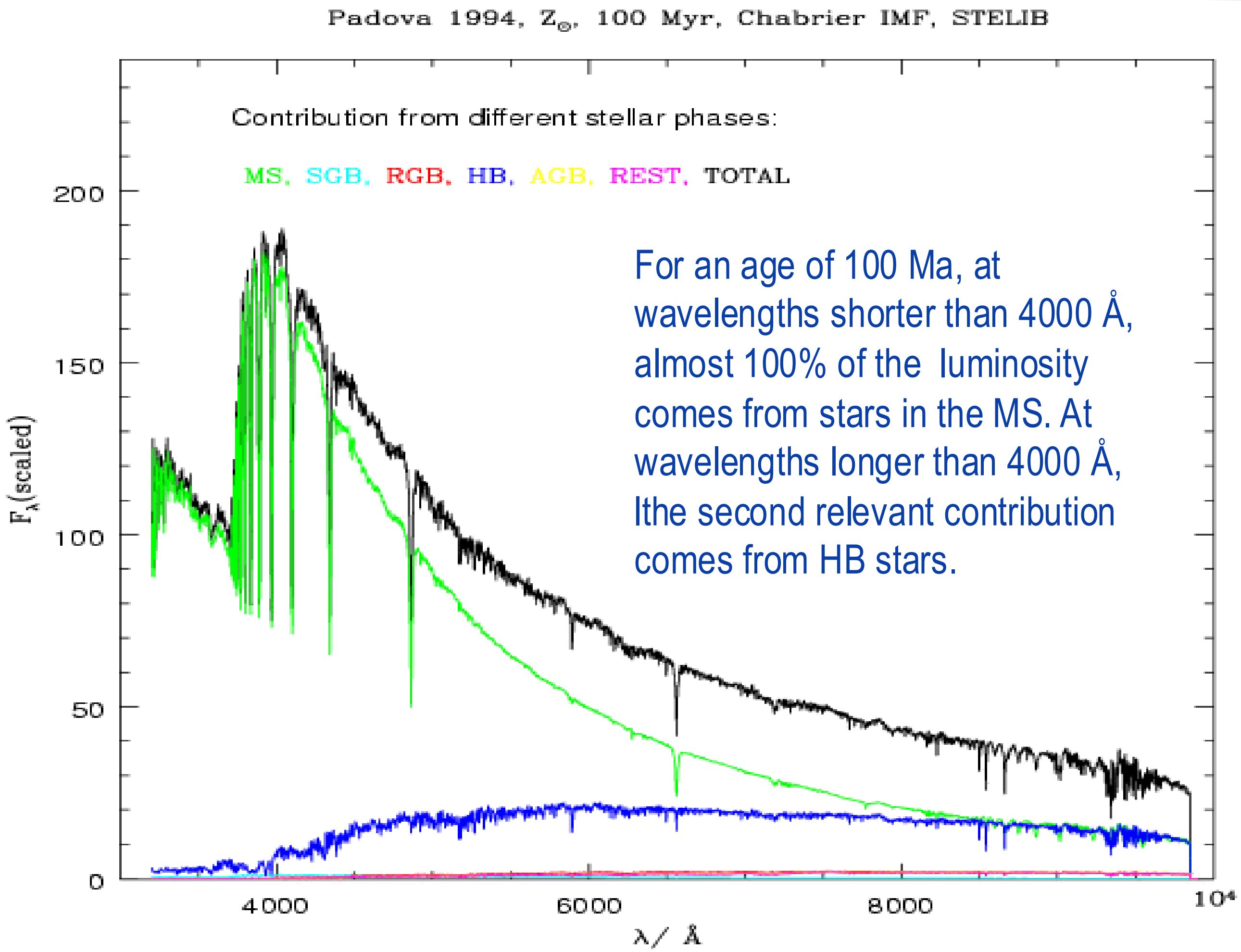


Contributions in the different photometric band passes



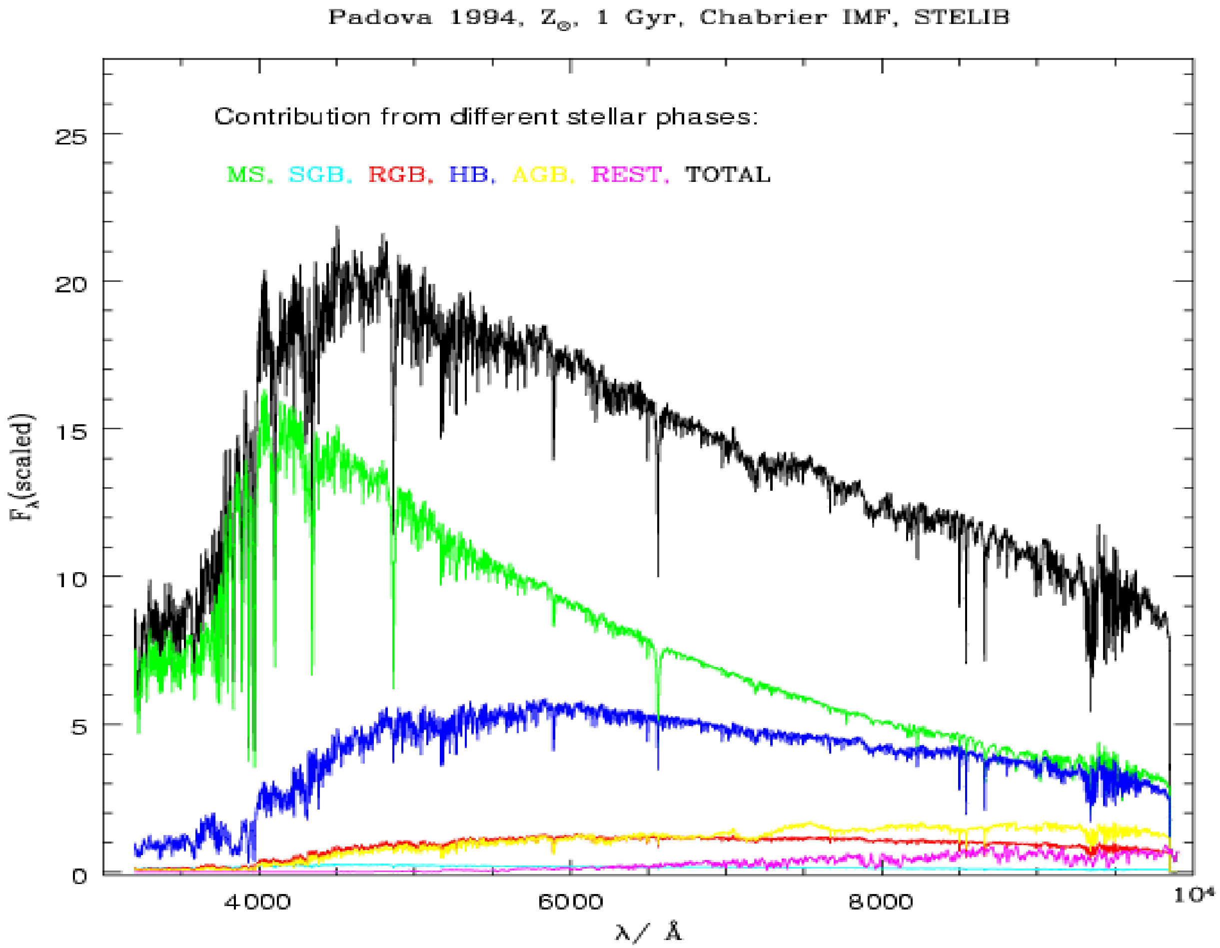
Contribution to the total luminosity by stars in their corresponding evolutionary phases, in various photometric band passes.

Contribution from different stellar phases at an age of 100 Ma

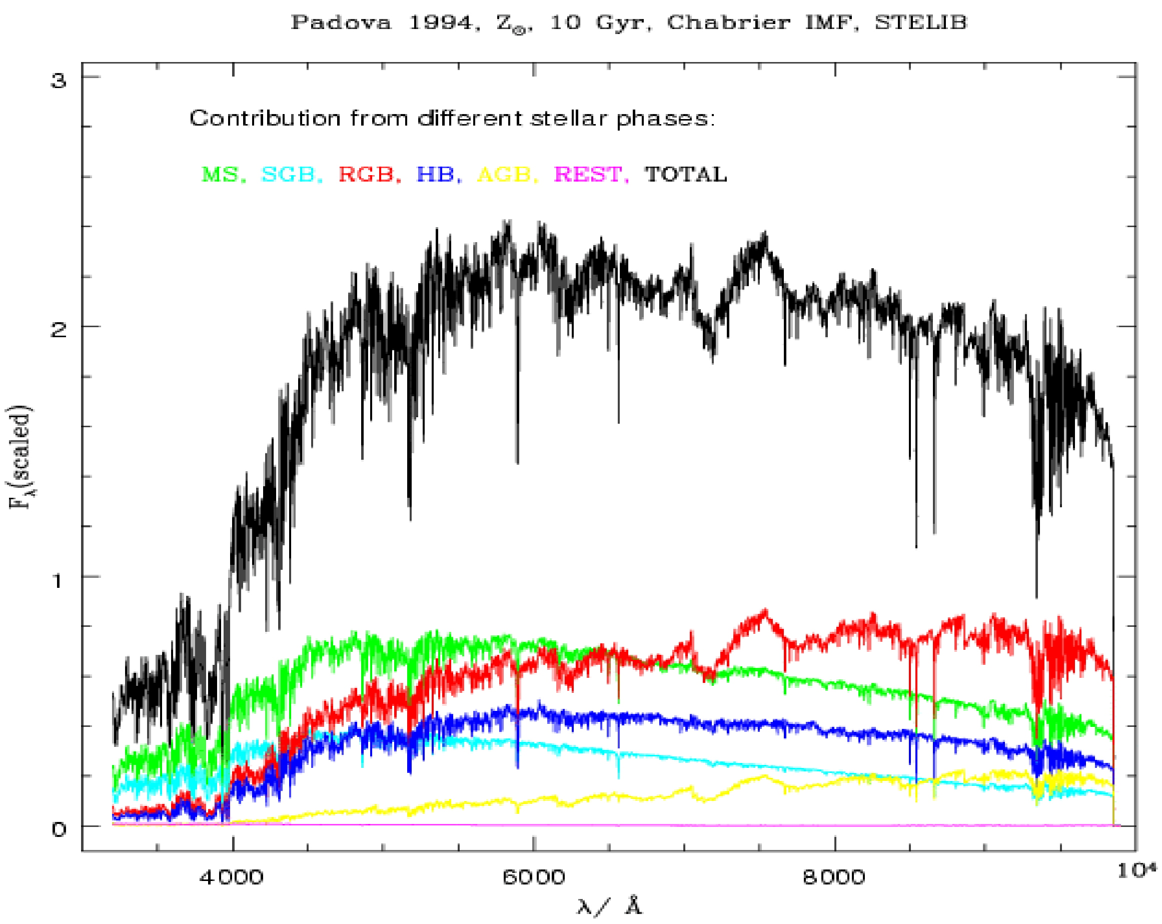


For an age of 100 Ma, at wavelengths shorter than 4000 Å, almost 100% of the luminosity comes from stars in the MS. At wavelengths longer than 4000 Å, lthe second relevant contribution comes from HB stars.

Contribution from different stellar phases at an age of 1 Ga



Contribution from different stellar phases at an age of 10 Ga



At an age of 10 Ga, at wavelengths longer than 6000 Å , the major contribution comes from RGB stars.

Composite Stellar Populations (CSP)

- Composite stellar populations (CSP), according to a given Star Formation History (SFH), can be expressed as a combination of a series of instantaneous star formation bursts (SFB) ≡ SSP
- La SED de una CSP se puede escribir como:

Chemical evolution enters here

$$S_\lambda(t) = \int_0^t S_\lambda^{SSP}\left[t', Z(t - t')\right] \psi(t - t')\, dt'$$

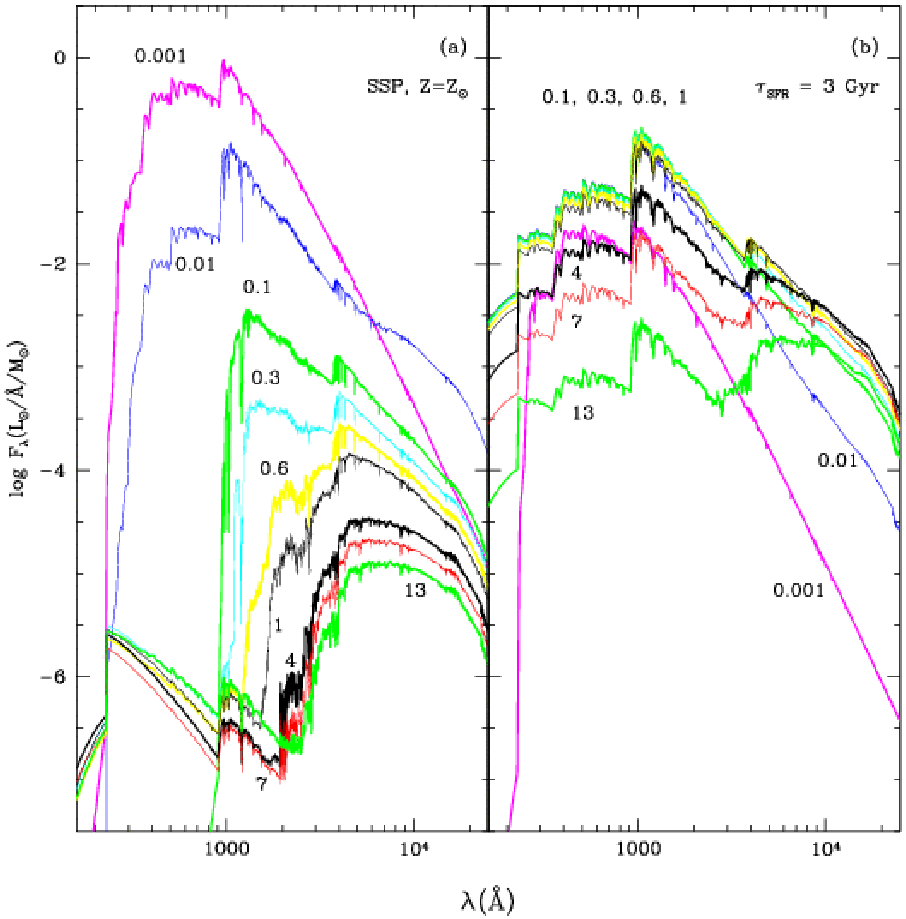
SED of a SSP of age t´

Star Formation Rate (SFR)

Star Formation Rate (SFR)

- The SFR, $\psi(t)$, is the amount of gas transformed in stars by unit time.
- The function $Z(t)$, is the chemical enrichment law coming from chemical evolution modelsl.
- The IMF is supposed to be time independent.
- For a given SSP, $\psi(t\text{-}t')=\delta$.

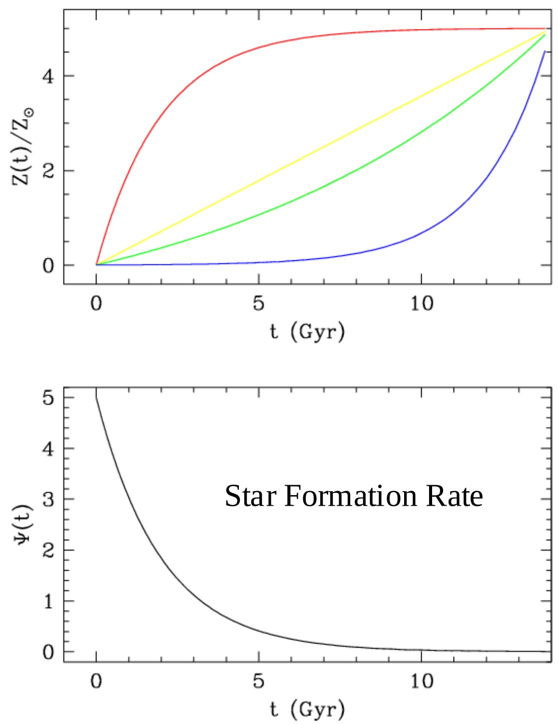
Spectral evolution

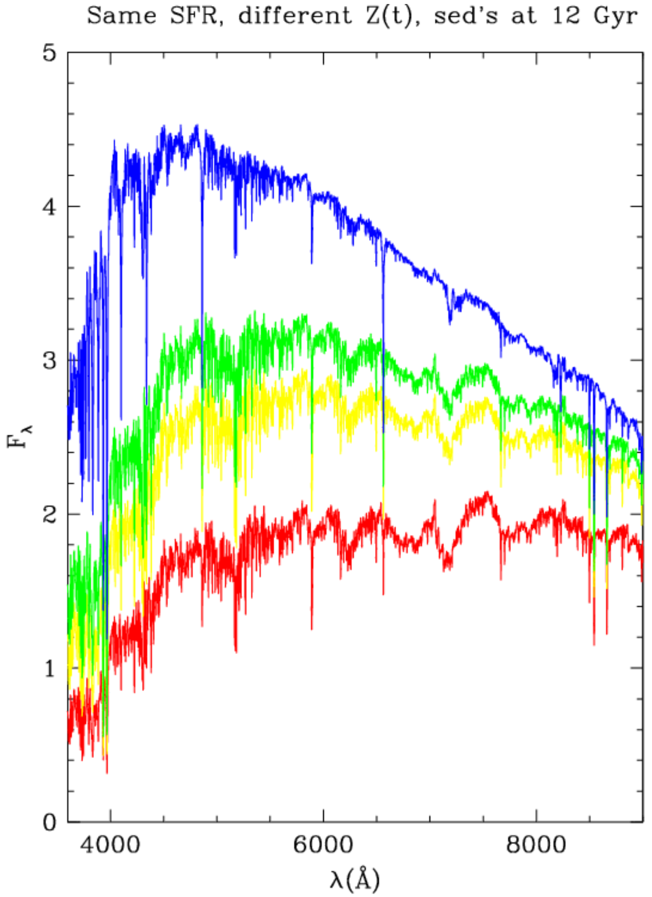


- SSP vs composite stellar populations.
- The SFR follows an exponential functions of the kind $\psi(t) \propto e^{-t/\tau}$

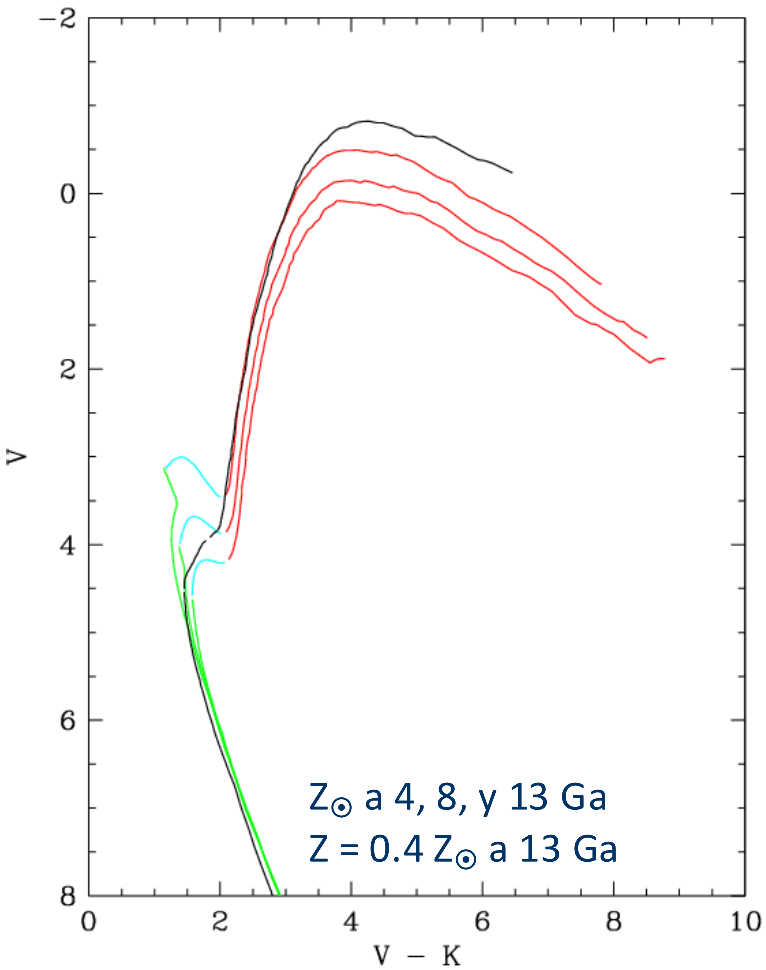
Composite stellar populations with time-dependent metallicity

Chemical enrichment law predicted by different chemical evolution models.



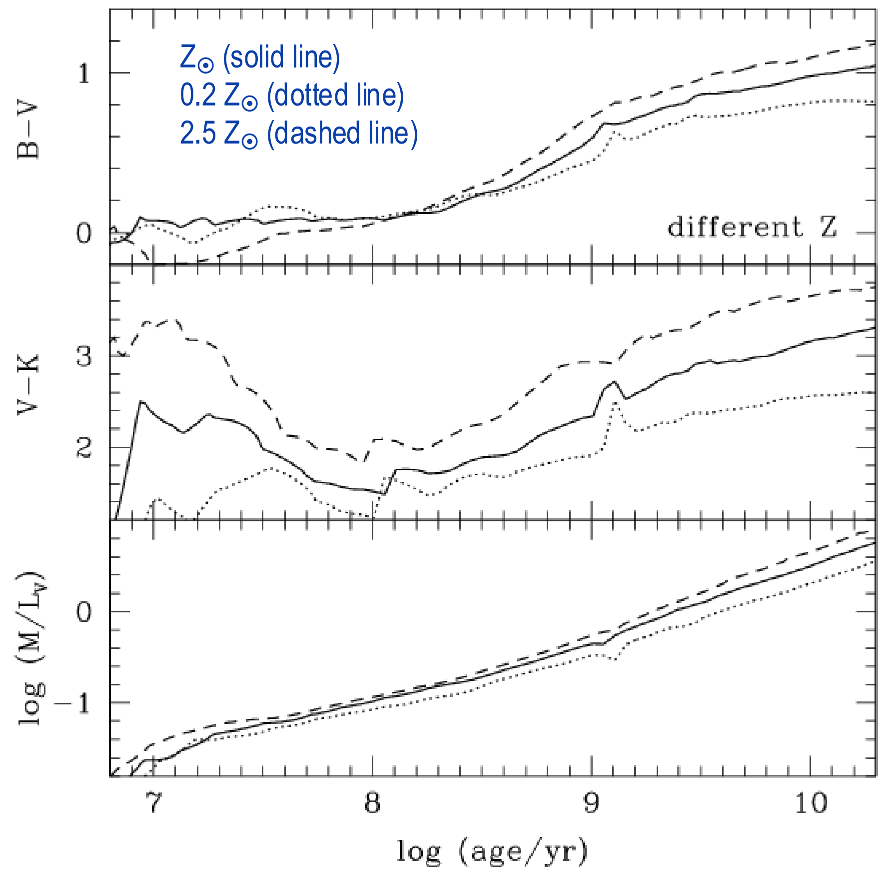


Age-metallicity degeneracy



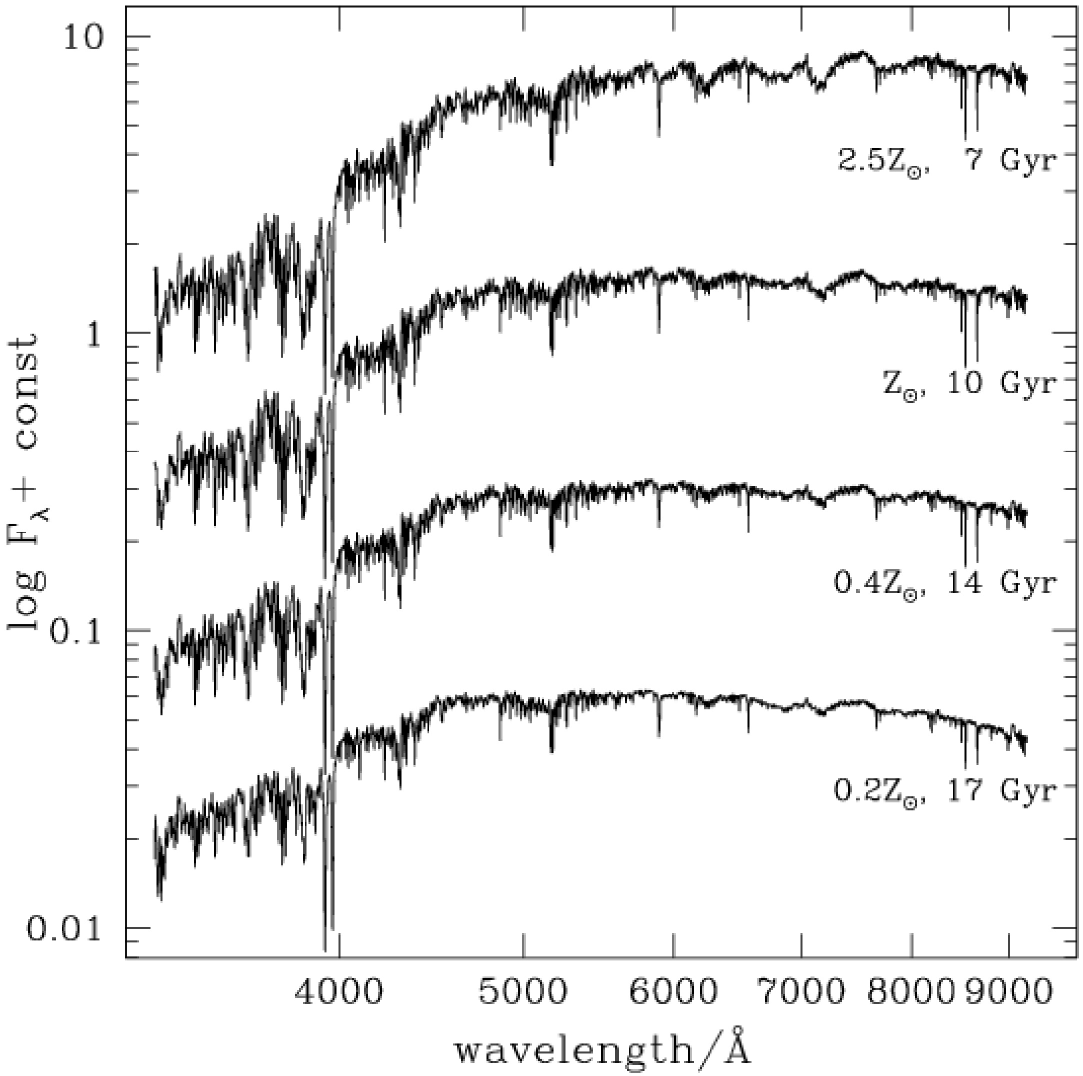
- Old, low metallicity stellar populations look like young stellar populations of higher metallcity.
- Stellar populations with the same value of Poblaciones estelares con el mismo valor de $age \cdot Z^{3/2}$ show almost the same colours.
- To break the age-metallicityv degeneration additional information is required.

Age-metallicity degeneracy



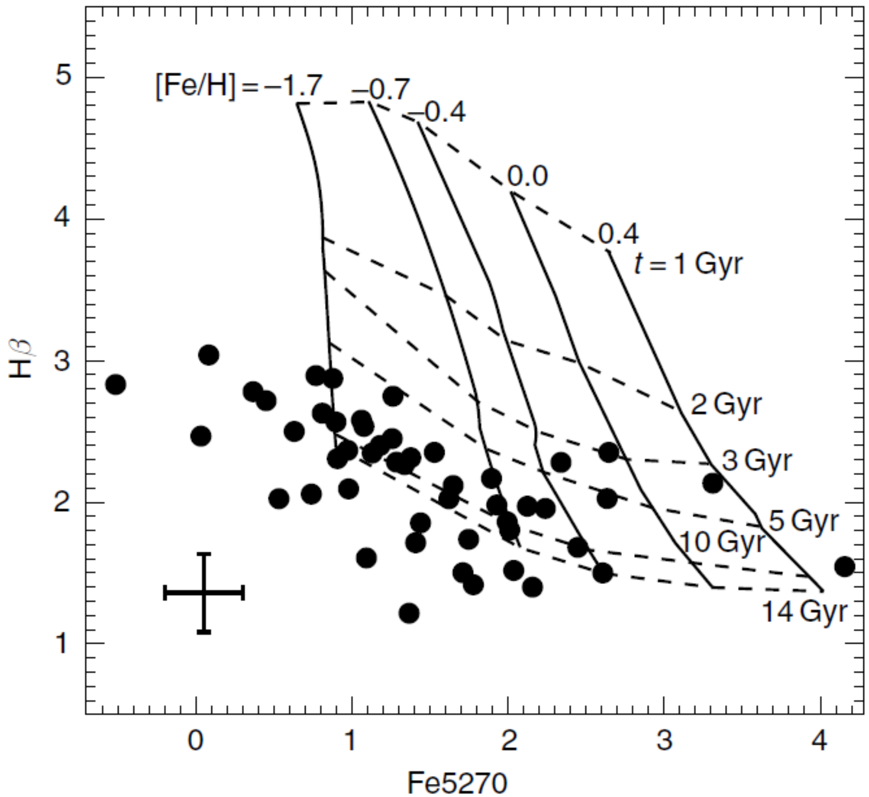
- SSP colours as a function of age.
  - $Z_\odot$ (solid line)
  - 0.2 $Z_\odot$ (dotted line)
  - 2.5 $Z_\odot$ (dashed line)

Age-metallicity degeneracy



- Also present in the SEDs.
- Note the colour similarity, but the difference in the spectral absorption line intensities.

Braking the age-metallicity degeneracy



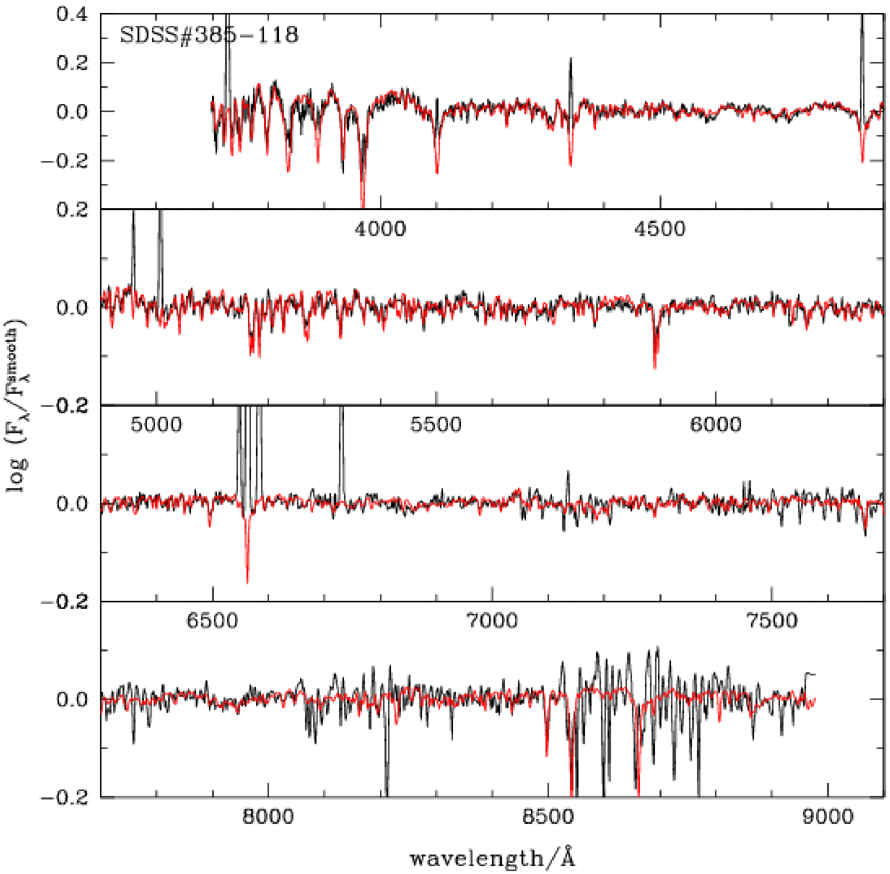
Solic circles $\equiv$ globular cluster data

- The Balmer lines are sentisive to age while the metal absorption lines are sensitive to Z.
- The intensities of these two types of lines can be used to disentangle age and metallcity.

Applications of Stellar Population Synthesis

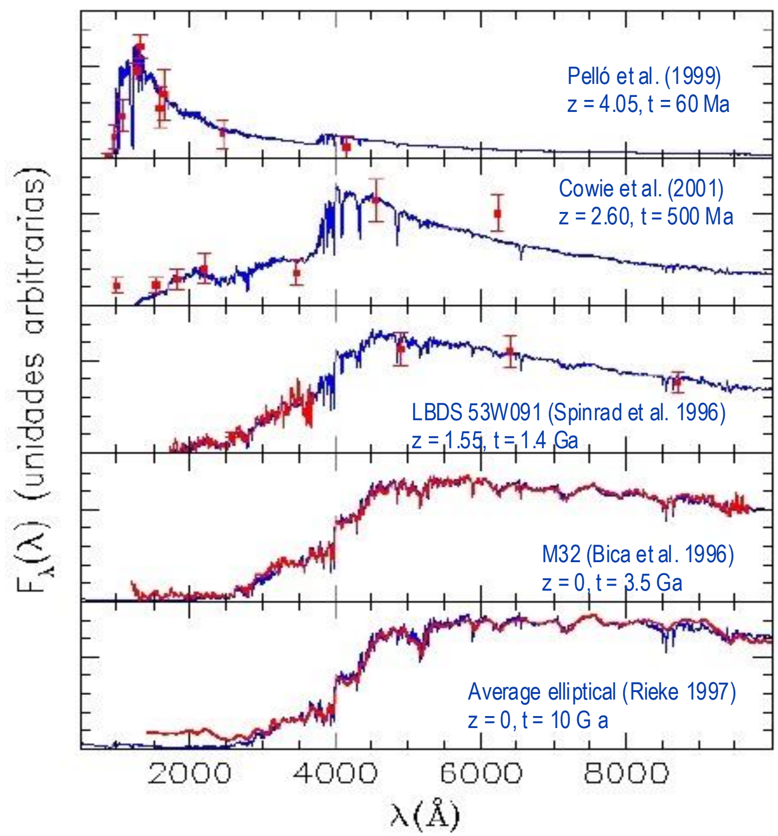
- **Stellar clusters**
  - CMDs of open and globular clusters.
  - Integrated magnitudes and colours.
  - Integrated SEDs.
  - Surface brightness fluctuations.
- **Galaxies**
  - Integrated SEDs.
  - Star Forfation Histories (SFH).
  - Metallicity evolution.
  - Line intensity index interpretation.
  - Age determination.
  - Emission line intensities.
  - Interstellar dust effects.
  - Analysis of large Galaxy surveys (SDSS, MNGA, etc …)

Galaxy spectra



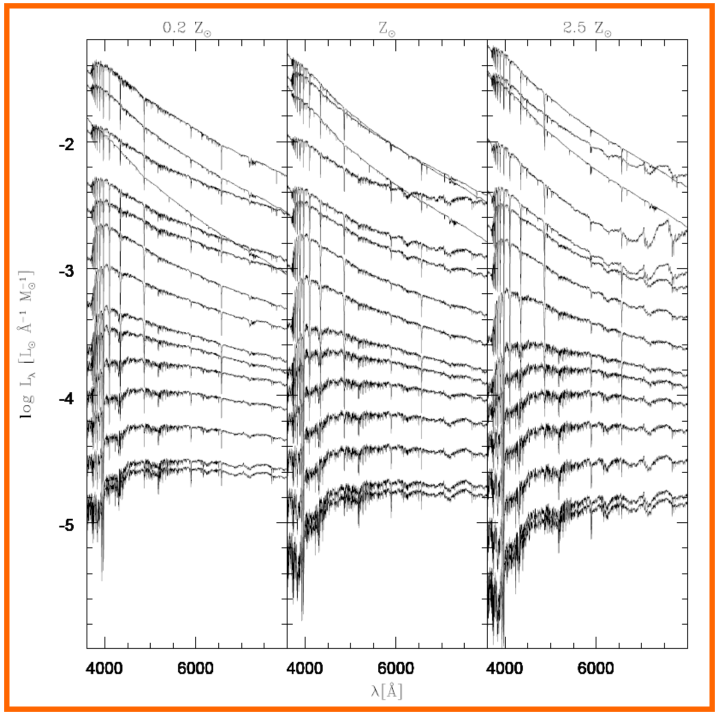
- SPS model fit, in red, to a SDSS galaxy spectrum (3500-9000 Å), in black.
- Emission lines not included in the fit.
- These fits allow to estimate the SFH and Z(T) law for a given galaxy.

Estimating Galaxy ages from spectral energy distributions (SEDs)

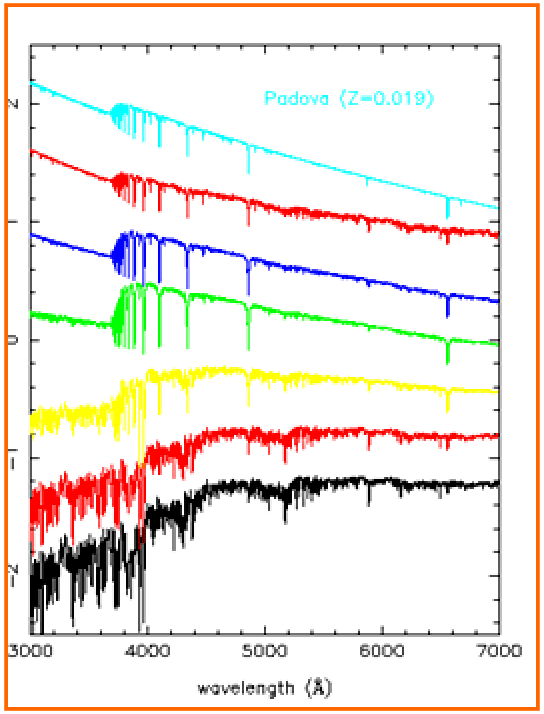


- Plausible evolutionary sequences at different redshifts between z=4 y z=0
- The youngest galaxies do not seem to be at higher redshifts.

Model Spectral Energy Distributions (SEDs)

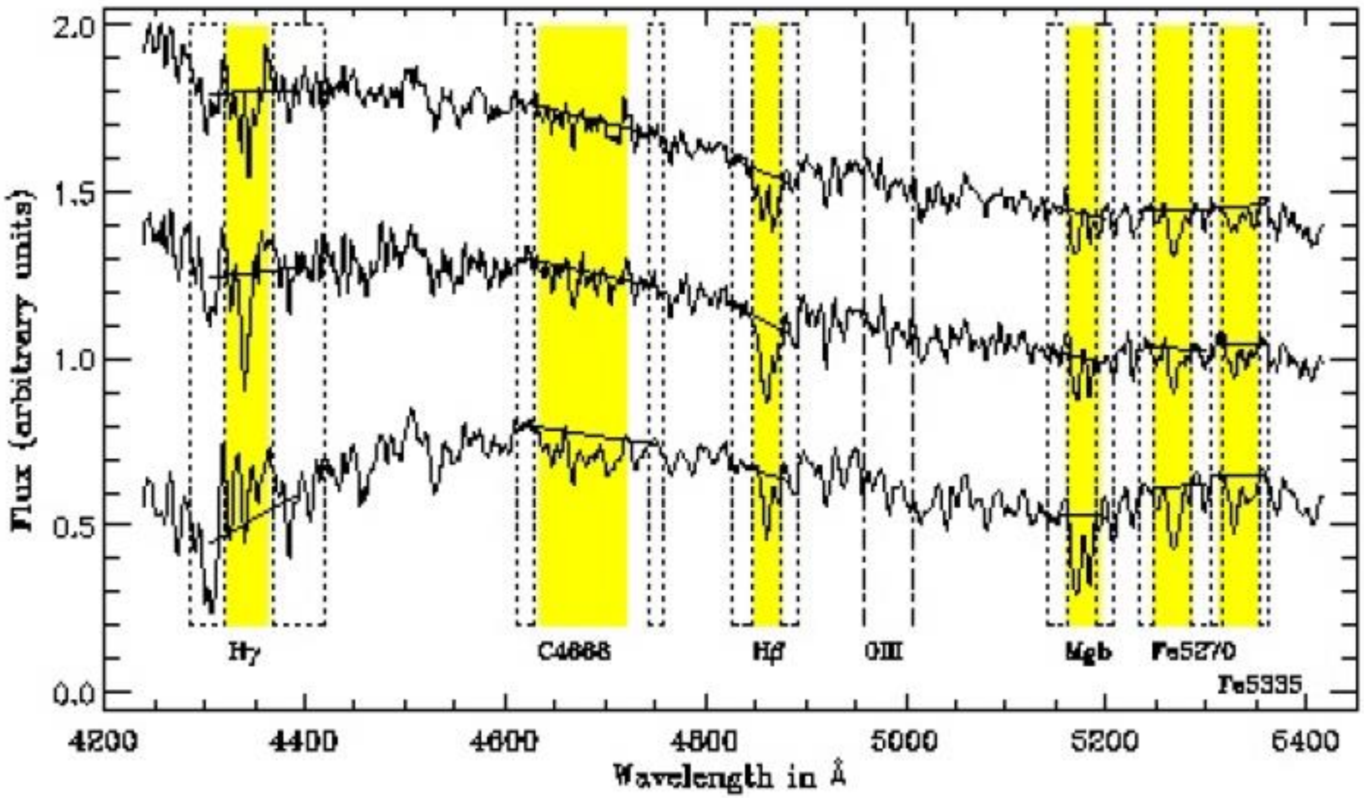


Bruzual & Charlot 2003



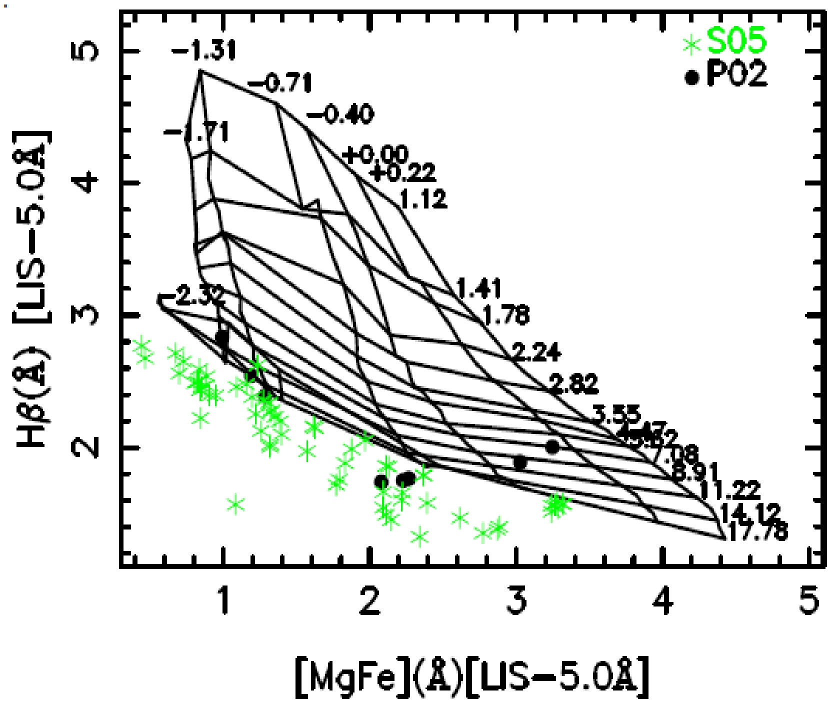
Gonzalez Delgado 05

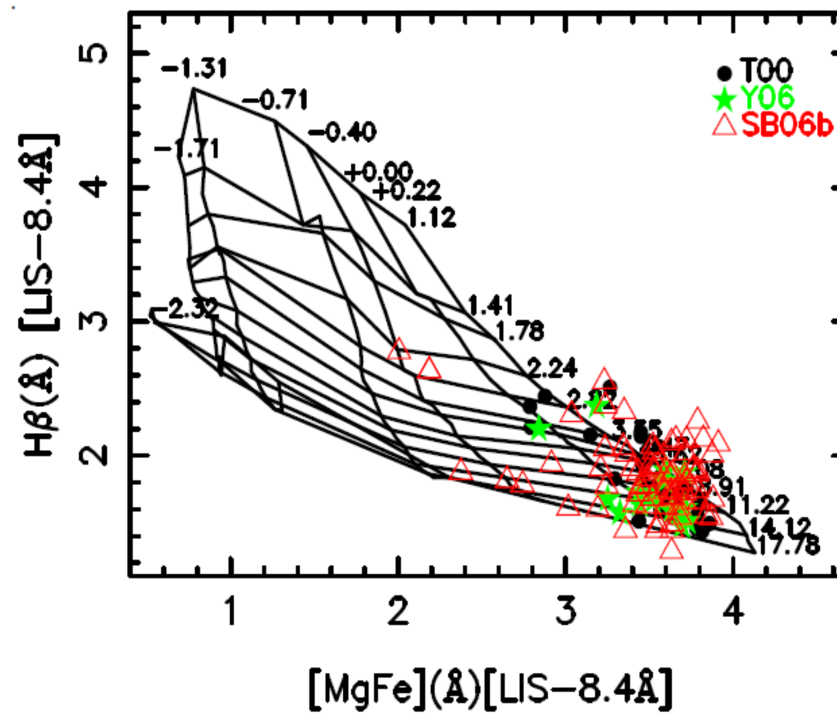
Absorption features measured through integrated indices



Lick index definition (*Worthey et al. 1994, ApJS, 94, 687*)

Breaking the age-metallicity degeneracy

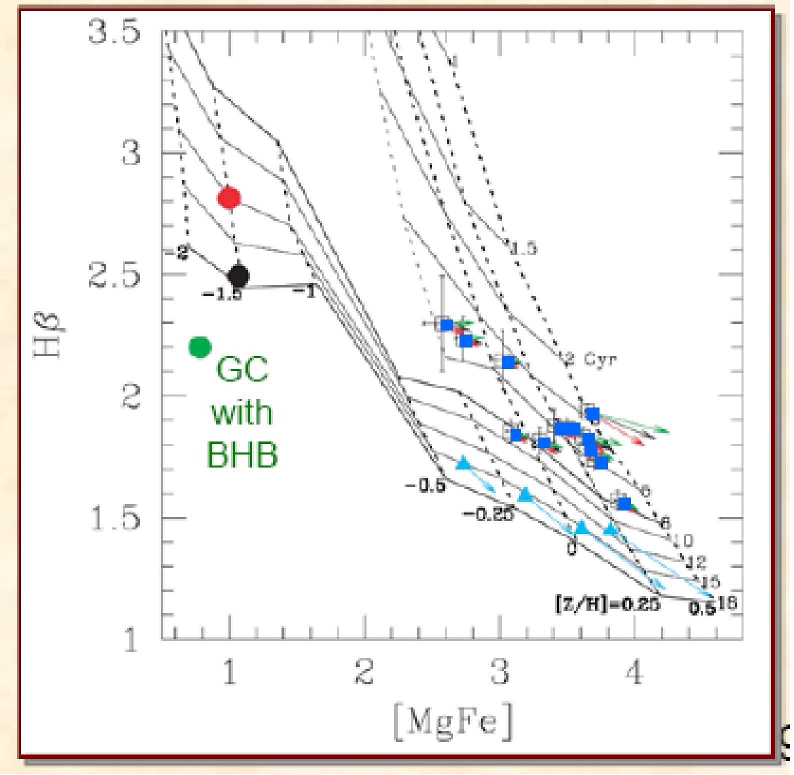




Vazdekis et al. 2010, MNRAS, 404, 1639

Results for elliptical galaxies

- Based on this kind of diagrams, the global metallicity of ellipticals, [Z/H], is between 0.0 and +0.4 dex
- Main uncertainties come from inaccuracies in the models and the age-metallicity degeneracy.
- Some contribution by "youngish" populations in ellipticals is nowadays accepted.



Trager et al. 2005, MNRAS, 362, 2