The role of binary stars in evolutionary population synthesis studies of galaxies

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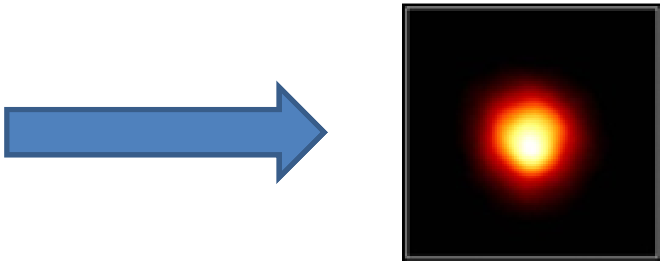
1. What is EPS?

- Evolutionary Population Synthesis (EPS) is an approach to derive the physical parameters of stellar populations of galaxies from the Spectral Energy Distributions(SEDs) observed.



1. What is EPS?

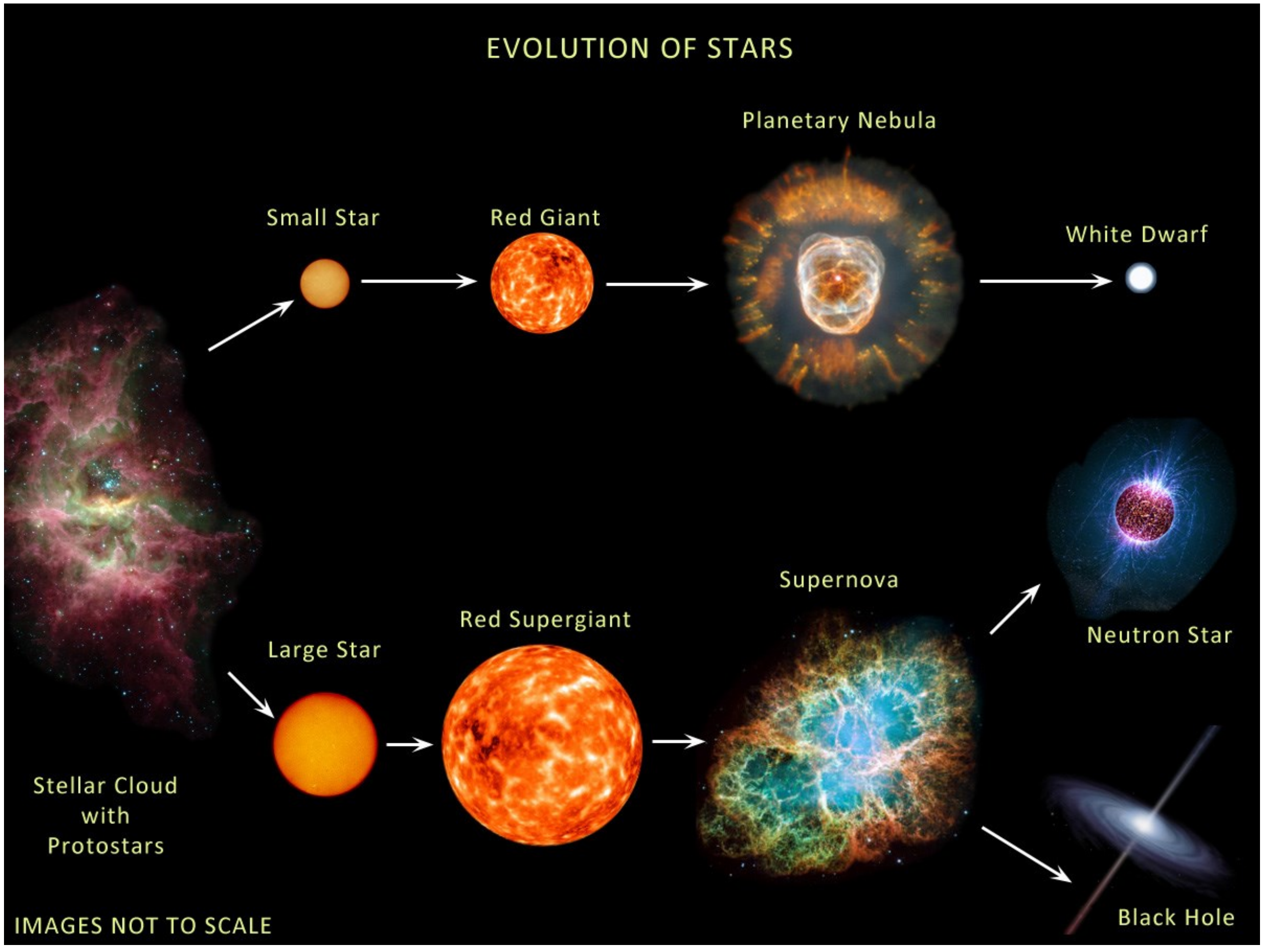
The ingredients of an EPS model:

Star Formation Rate -> how many stars?
Initial Mass Function -> how much mass of each star?

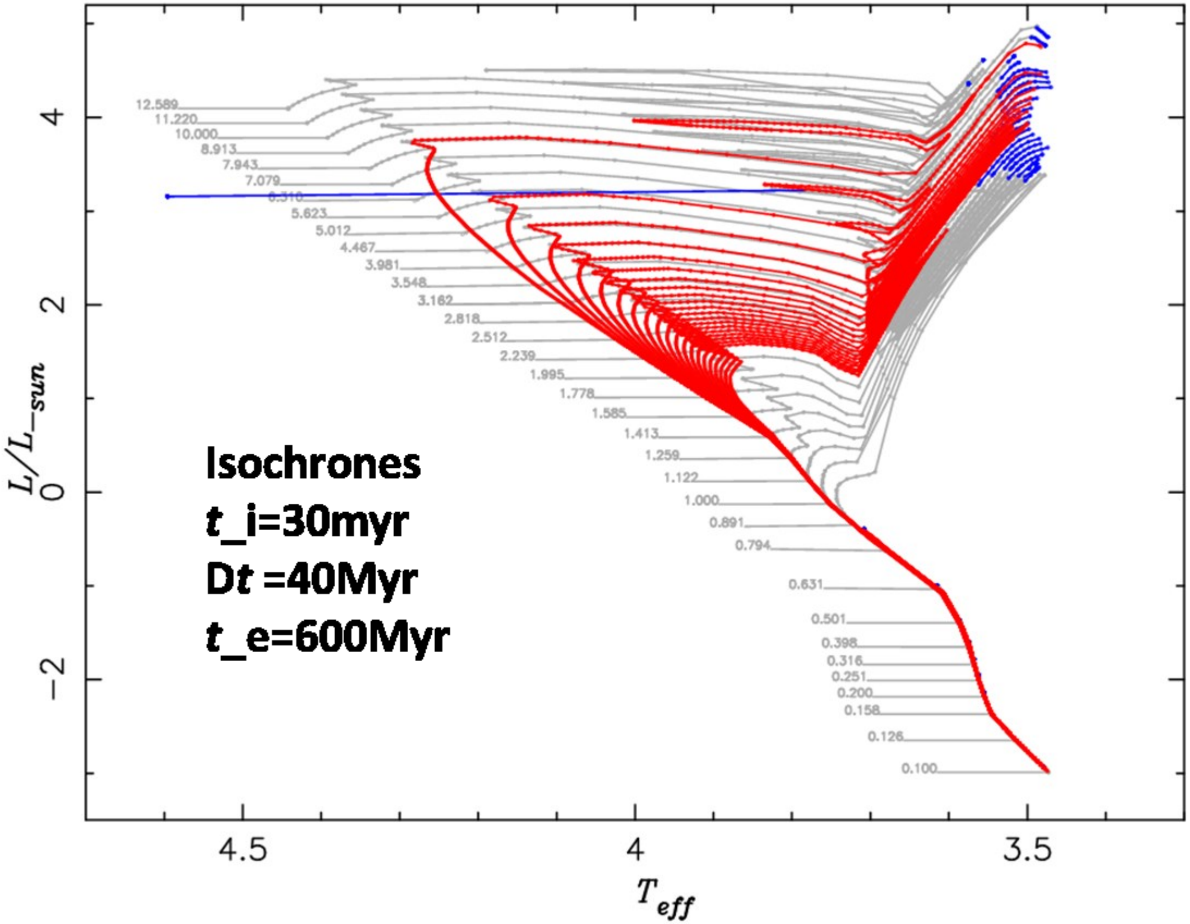
Stellar Evolution Models -> how they evolve?
Model Stellar Atmospheres -> how their spectra?

Integrated SED
(the sum of all the spectra of the stars)

2. How a single star evolves?



2. How a single star evolves?

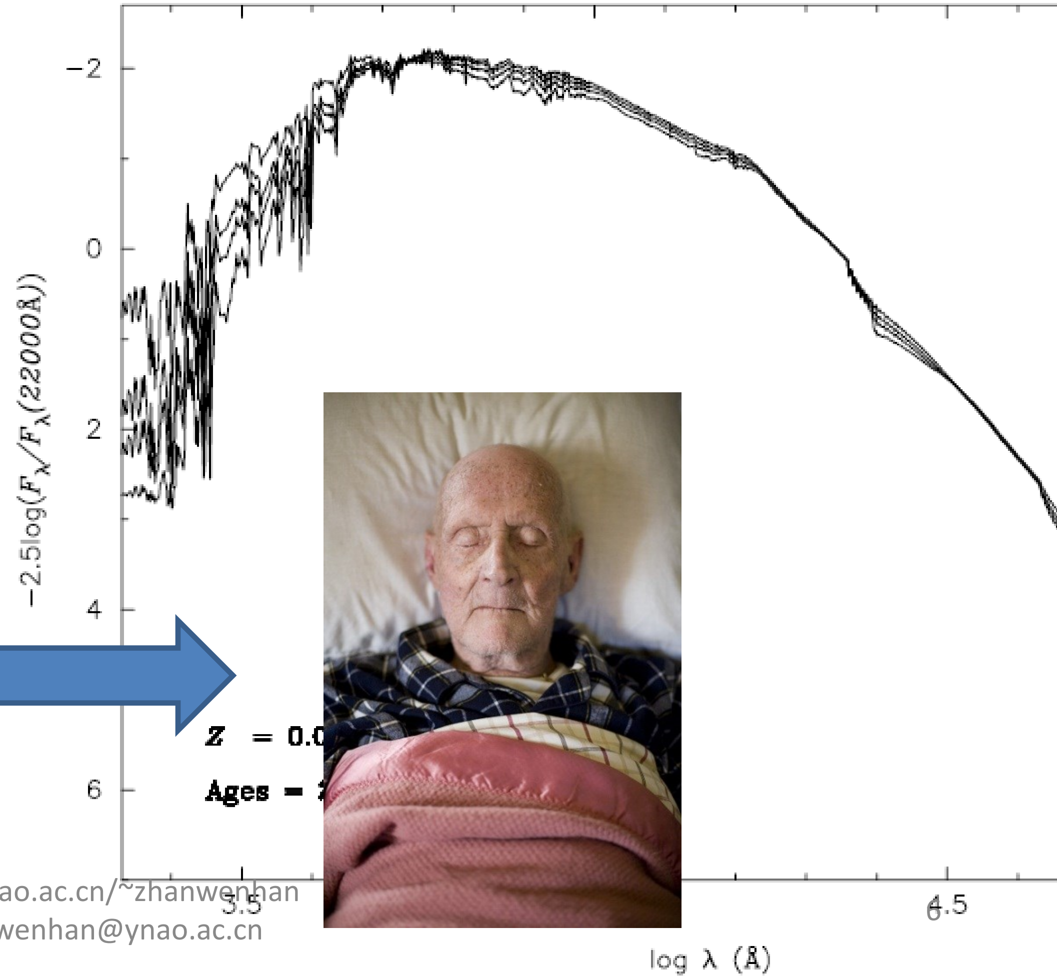


2. How a single star evolves?

The evolution is “Hot to cold”

Hot spectra -> Young

Cold spectra -> old



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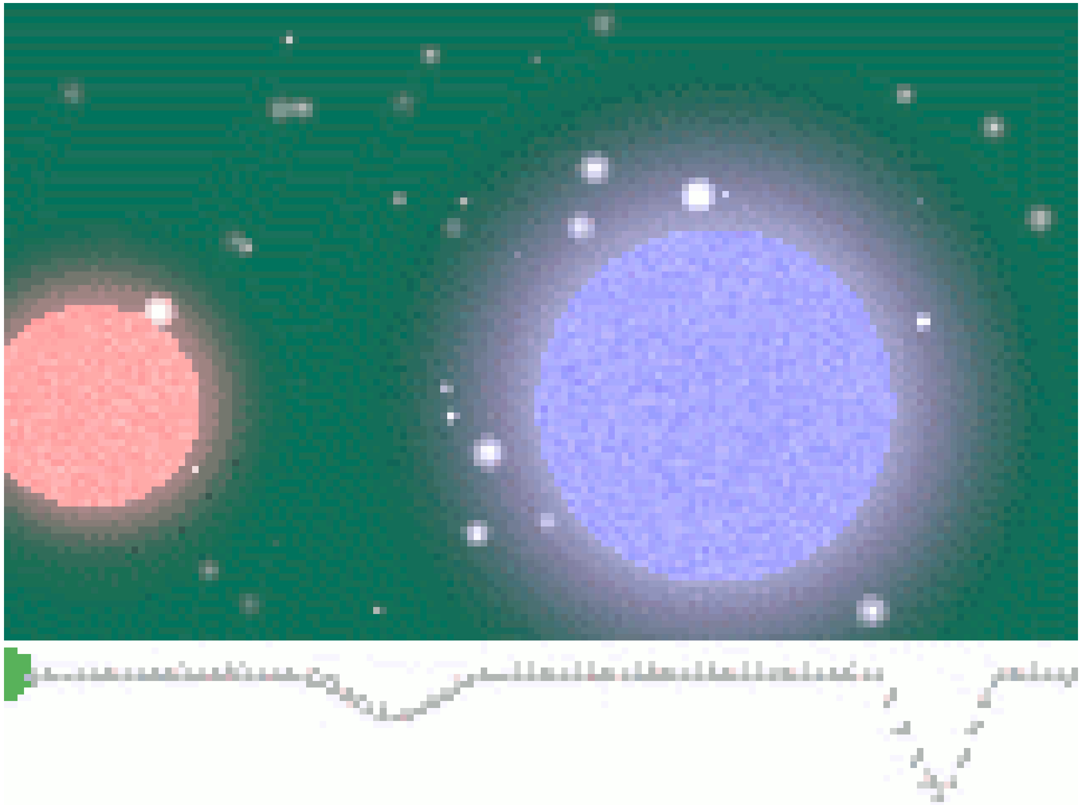
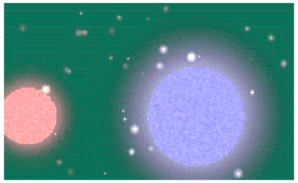
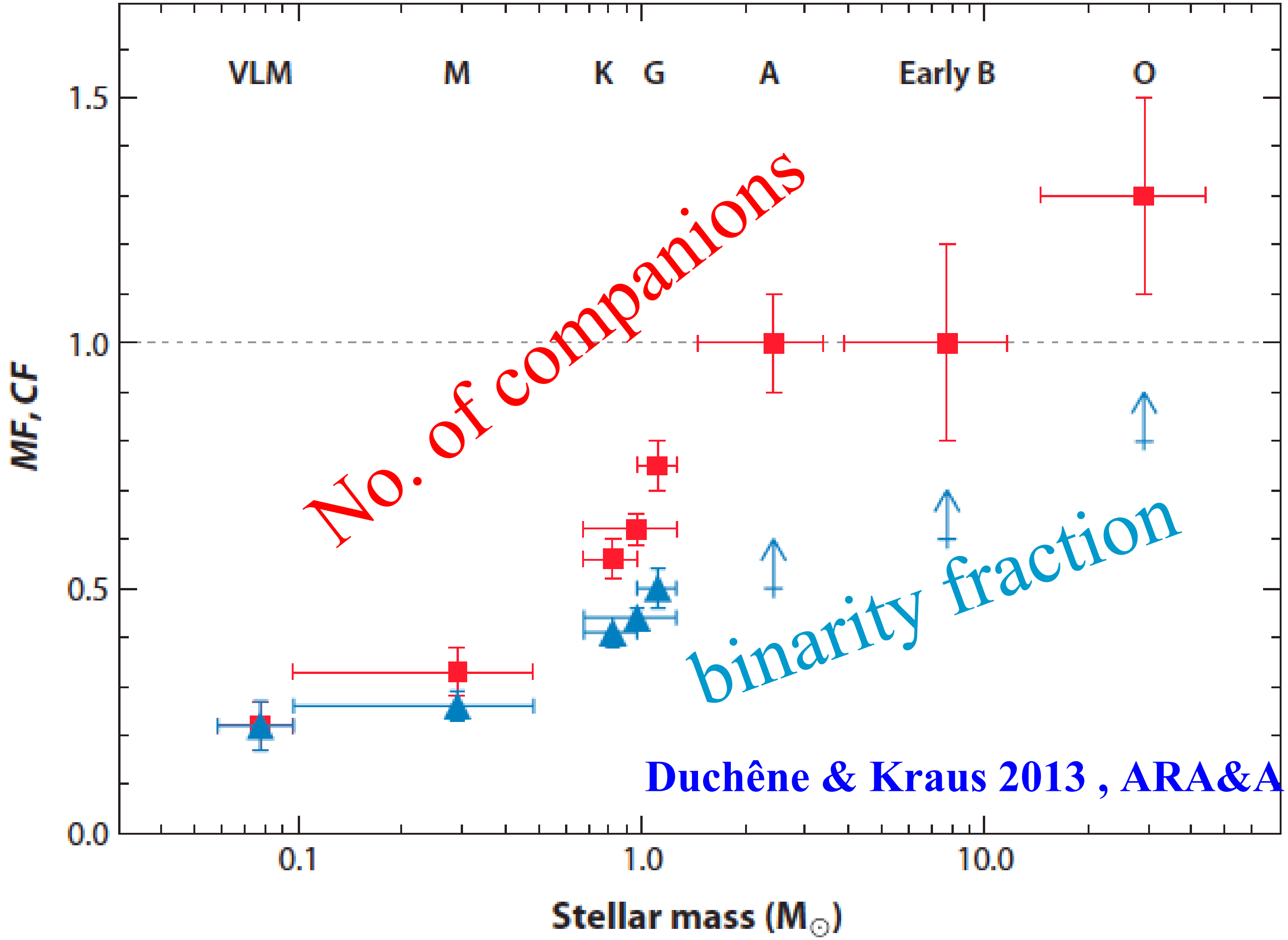
3. How a binary evolves?

Most stars are in binaries!

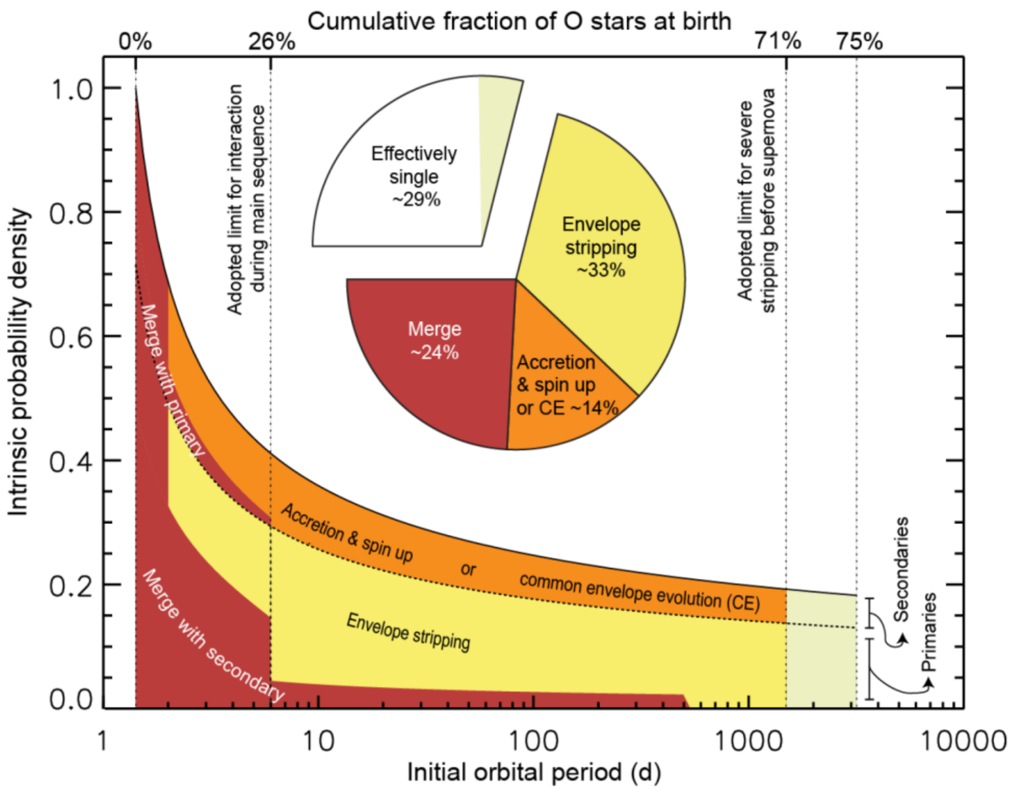


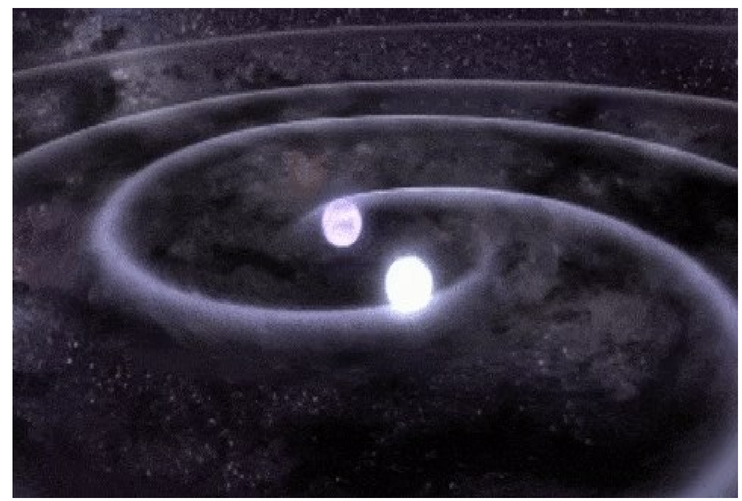
Half of the stars are in binaries





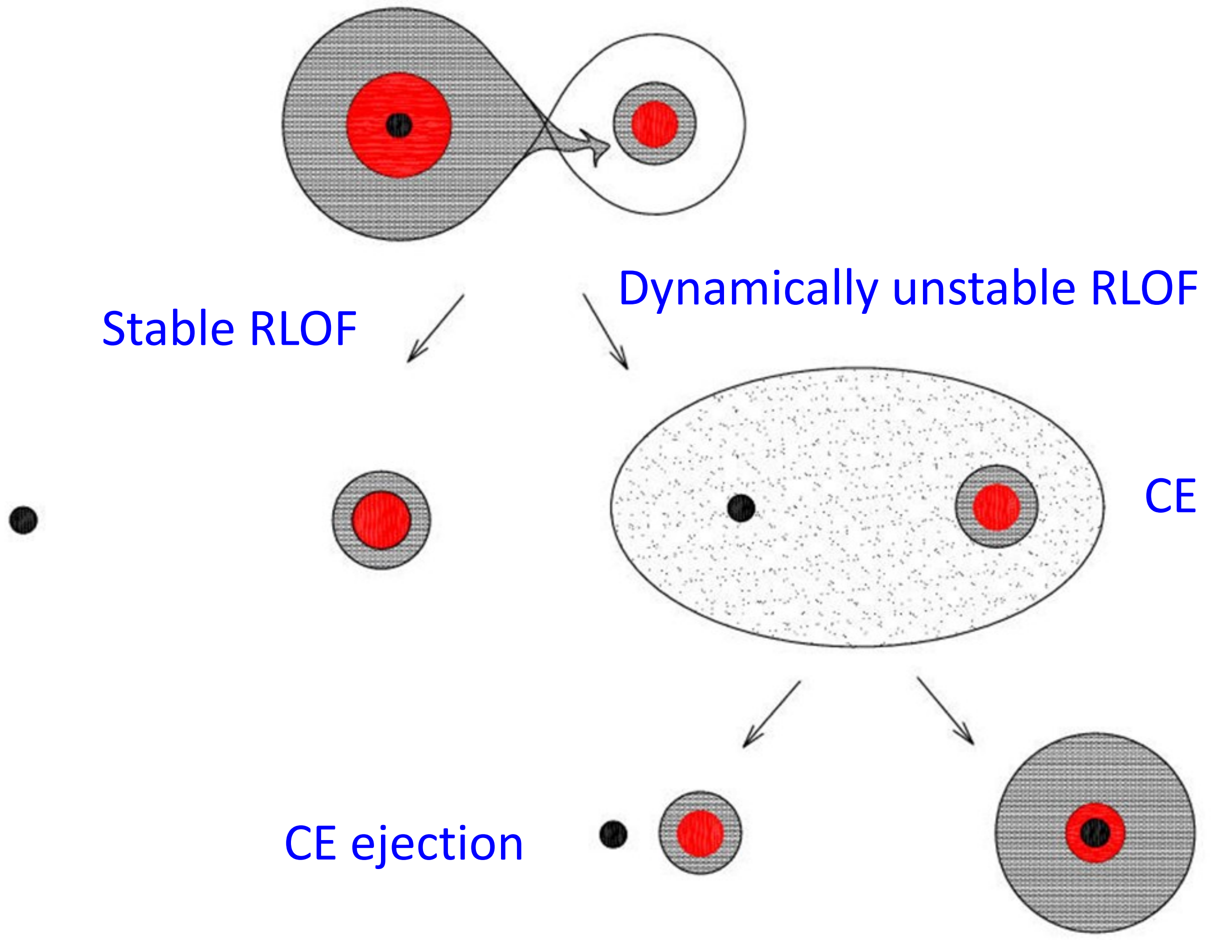
Binary interaction dominates the evolution of massive stars



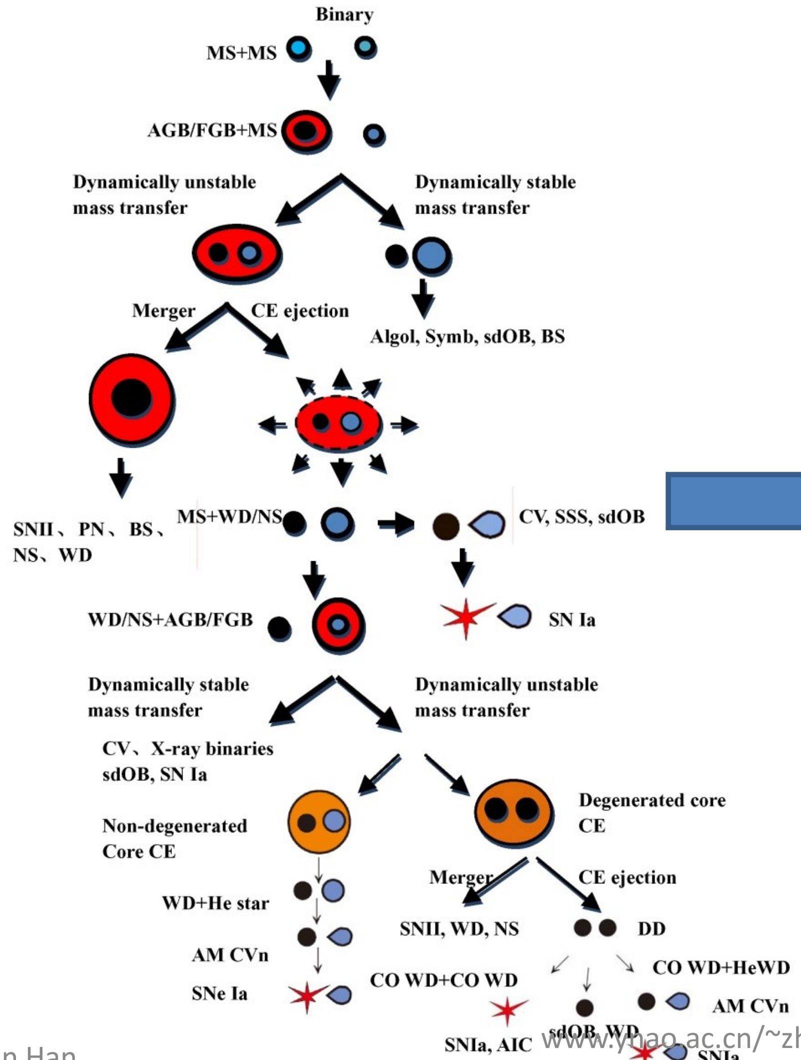


Sana et al 2012 Sci

3. How a binary evolves?

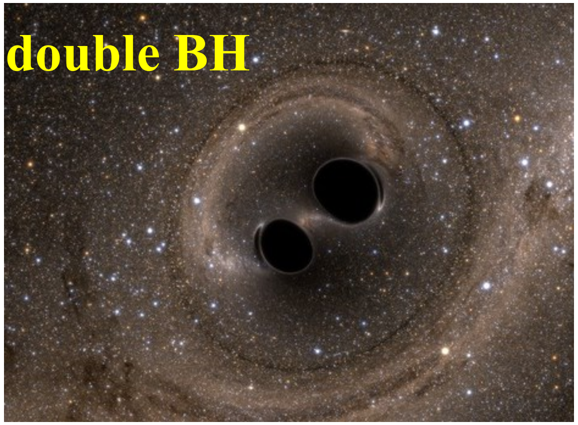


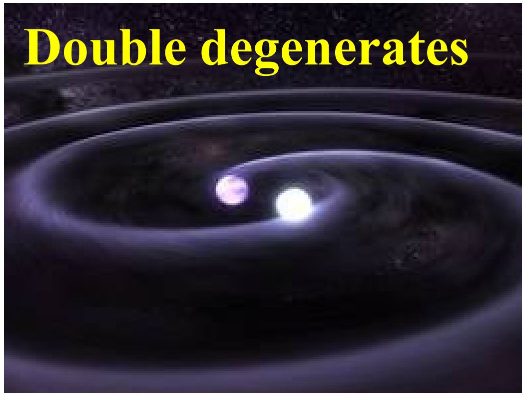
3. How a binary evolves?

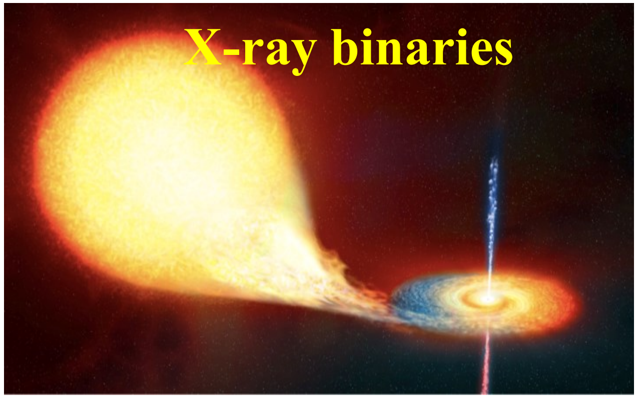


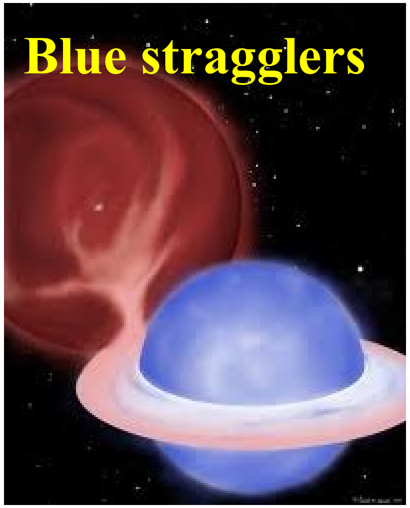
Type Ia supernovae
X-ray binaries
Short gamma-ray bursts
Millisecond Pulsars
....
....
Hot subdwarfs
Blue stragglers
.....

Binary evolution produces extotic objects



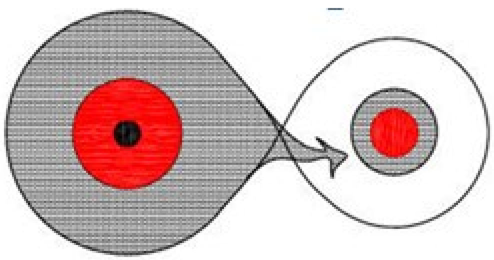






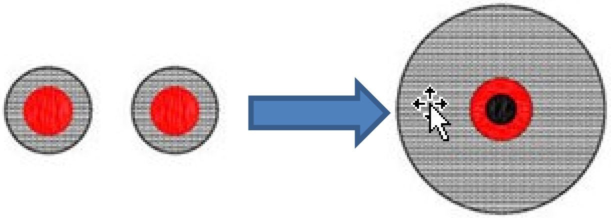
3. How a binary evolves?

- RLOF removes stellar envelope
  →hot core exposed
  →(core can be ignited)



- A star grows in mass via accretion
  →rejuvenation (hotter)

- Coalescence of a binary
  → a more massive star (hotter)



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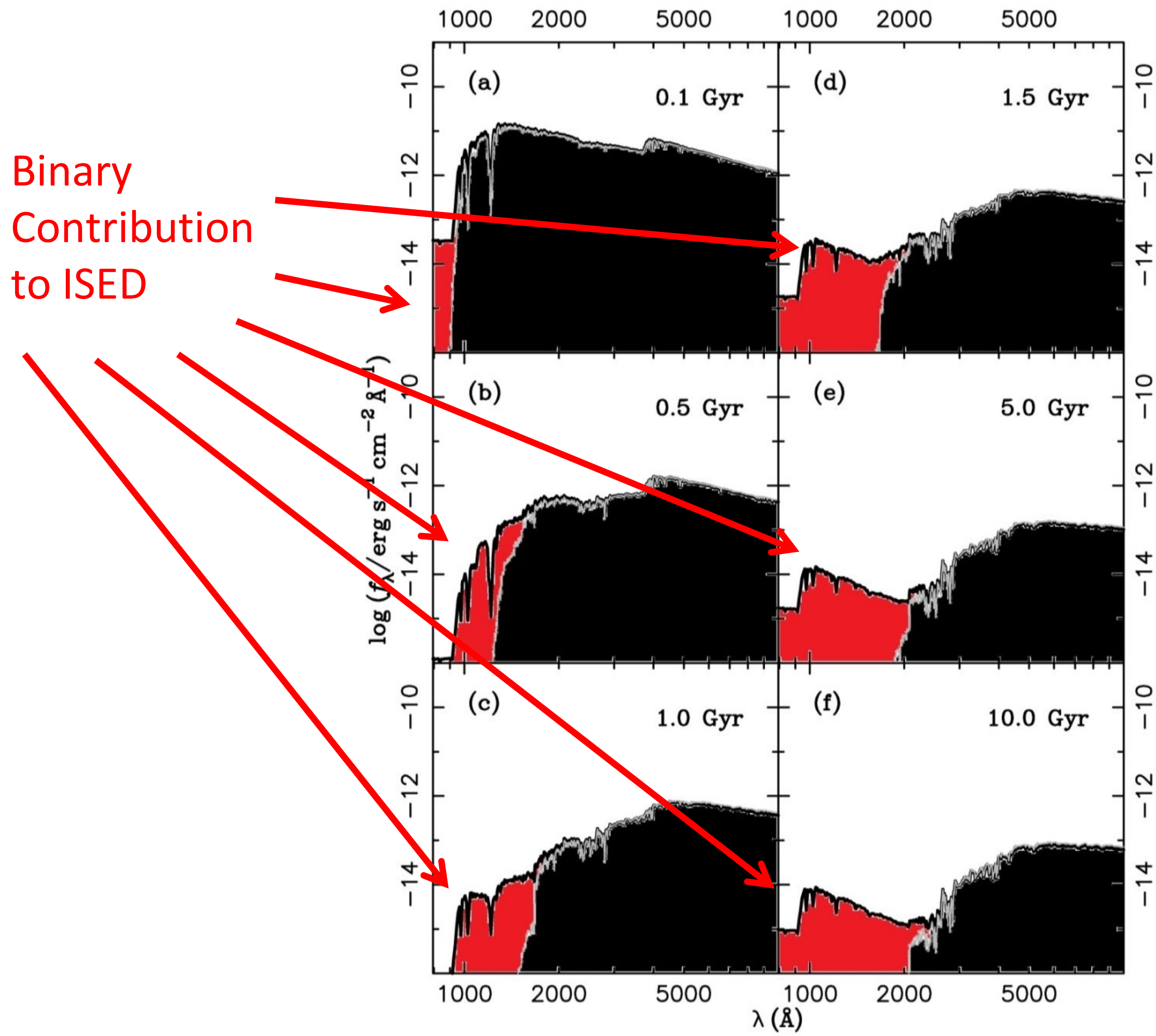
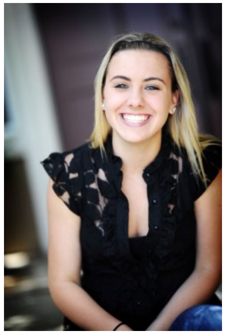

Binary Contribution to ISED
(a)
0.1 Gyr
(b)
0.5 Gyr
(c)
1.0 Gyr
(d)
1.5 Gyr
(e)
5.0 Gyr
(f)
10.0 Gyr
1000
2000
5000
λ (Å)
−10
−12
−14
log (fλ/erg s−1 cm−2 Å−1)

3. How a binary evolves?

- Binary interactions rejuvenate stars!
  similar to cosmetics,

 to make  look like 

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History of EPS studies

- Tinsley (1968)

- Rapid progress since 90's

✓ GISSEL98 or BC03 model (Bruzual+ 1993, 2003)
✓ PopSTAR model (Molla+ 2009)
✓ STARBURST (Leitherer+ 1999)
✓ PEGASE (Fioc+ 1997)
✓ Yunnan model (Zhang+ 2004, Han+ 2007, Chen+ 2015)

The Yunnan Model

- ✓ stellar evolutionary tracks
  (Cambridge stellar evolution code STAR)
- ✓ BaSeL spectral library
- ✓ Binary interactions (blue stragglers, hot subdwarf stars, accreting WDs, rejuvenated stars, ……)

Binaries first included: Zhang+ 2004, A&A, 415, 117

Hot subdwarfs: Han+ 2007, MNRAS, 380, 1098

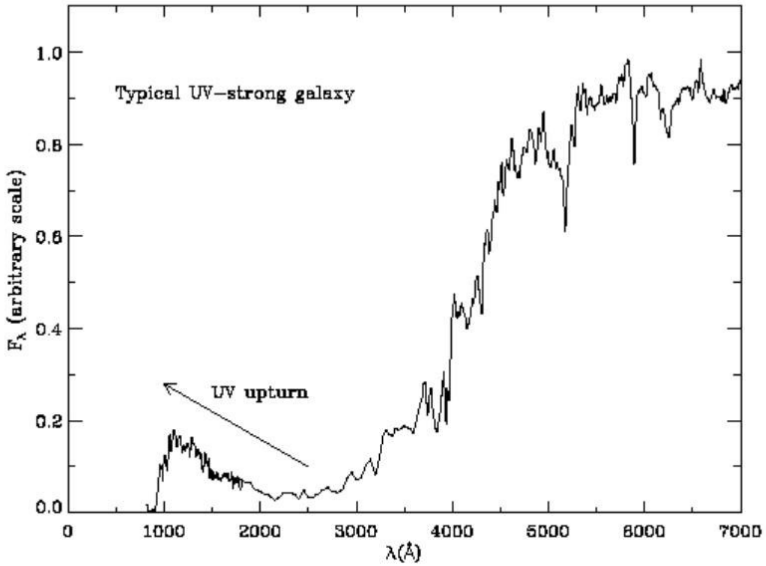
Blue stragglers: Chen+ 2009, MNRAS, 395, 1822

SFR calibration: Zhang+ 2012, MNRAS, 421, 743

Ionizing sources: Zhang+ 2015, MNRAS, 447, L21

Accreting WDs: Chen+ 2015, MNRAS, 453, 3024

4. Hot subdwarf stars and far-UV excess



Elliptical galaxies:

- Old, cold stellar popultion,
  far-UV spectrum should be dark.
- 1969: OAO-2 discovered
  the far-UV radiation
  (UV-upturn, far-UV excess， UV rising-branch, UV rising flux, UVX)
- A puzzle for more than 30 years
- UV-upturn Originates from hot subdwarf stars.

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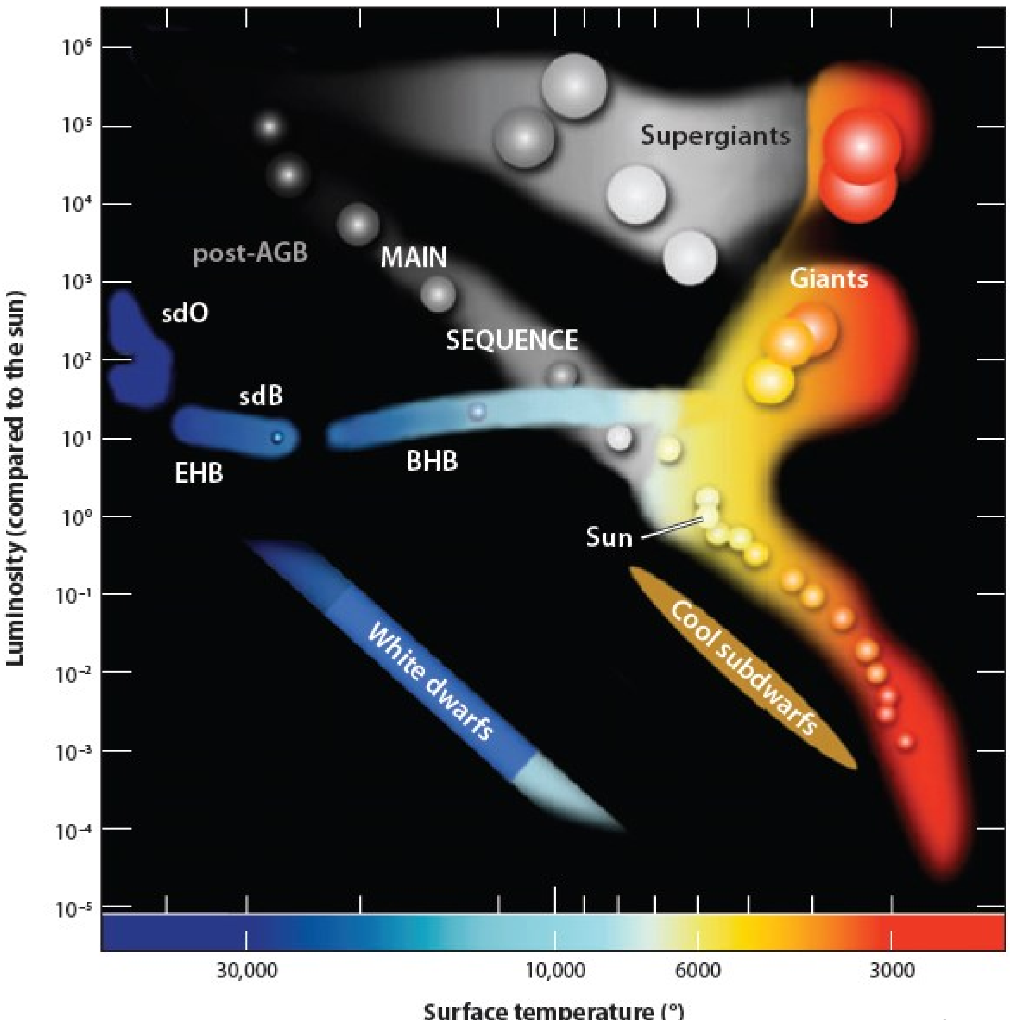
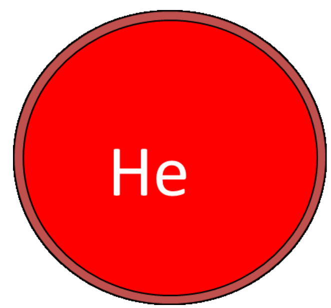
What is hot subdwarf stars?



Core-helium burning stars with very thin envelopes



$$M \sim 0.5 M_\odot$$

$$M_{\rm env} \leq 0.02 M_\odot$$

[redacted]

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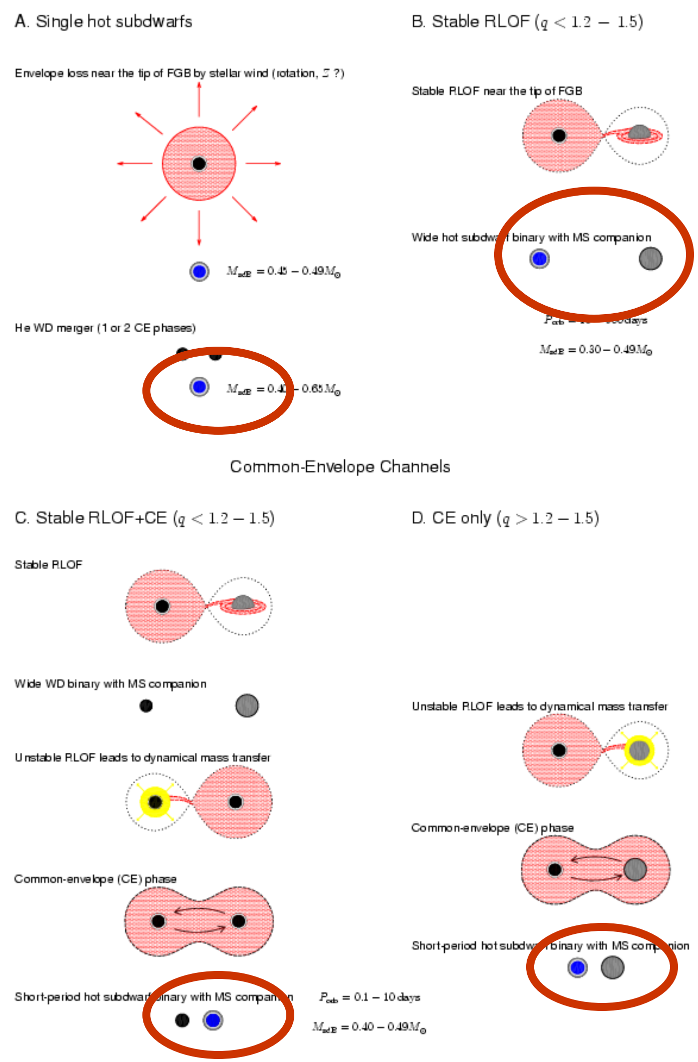
Binary model for hot subdwarfs

For both binary and single hot subdwarfs .

Han et al., 2002, MNRAS, 336, 449

Han et al., 2003, MNRAS, 341, 669

Han, 2008, A&A, 484, L31



It would be "a priori" to apply binary hot subdwarf model to UV upturn problem

Binary hot subdwarf model + BPS →

hot subdwarf population

+

Energy flux from model stellar atmospheres of hot subdwarf stars

↓

UV flux

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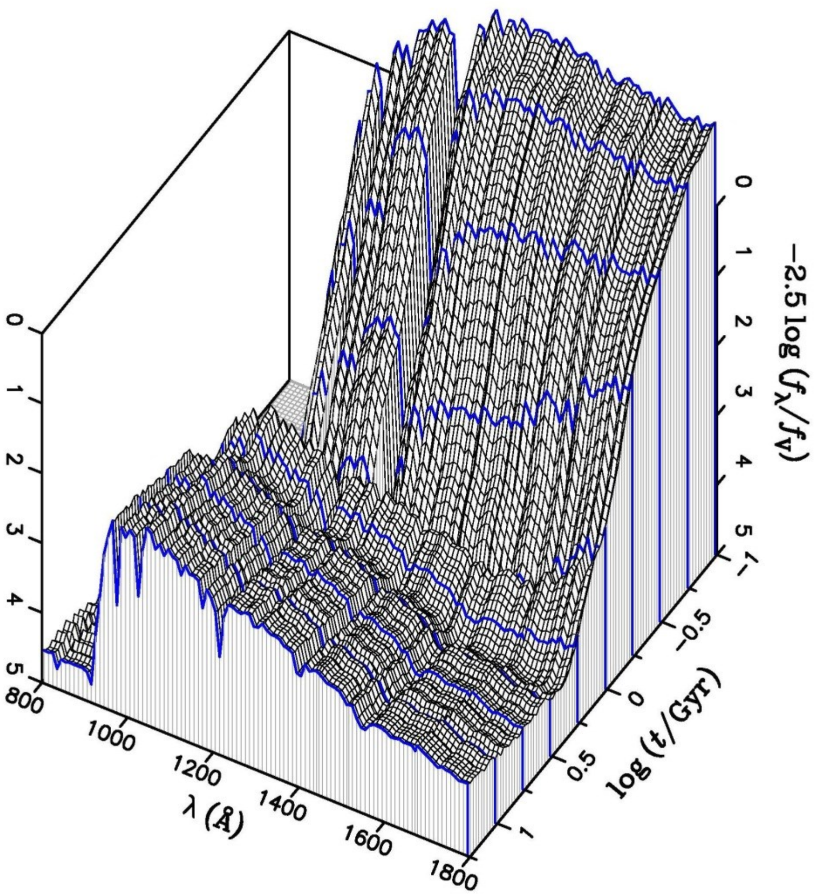
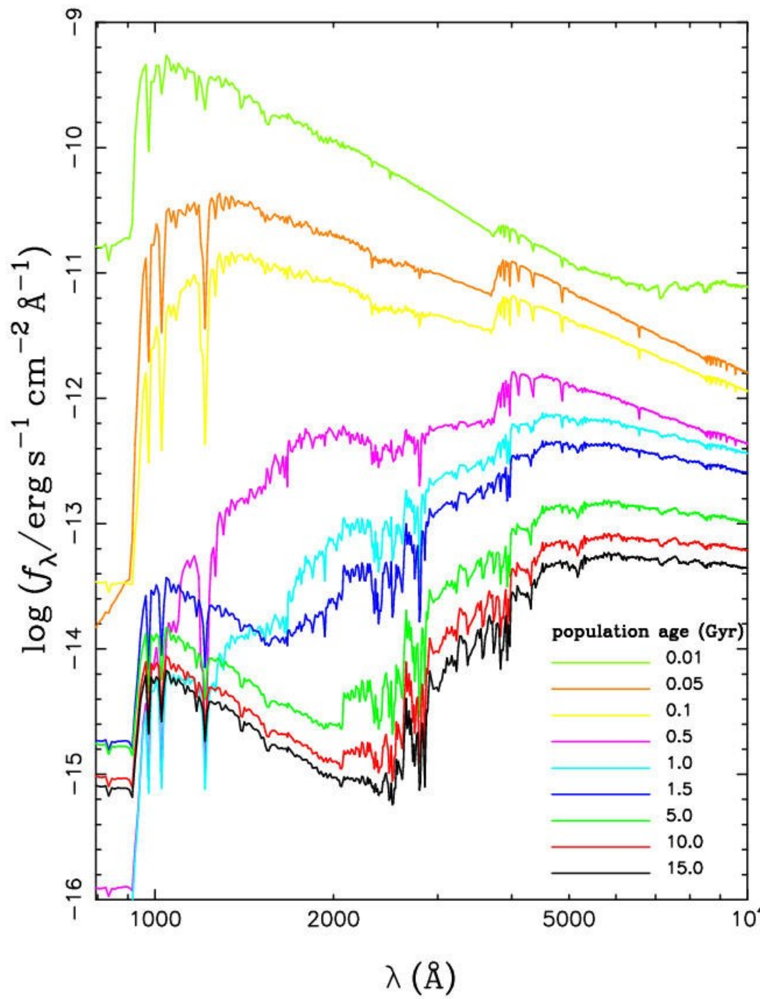
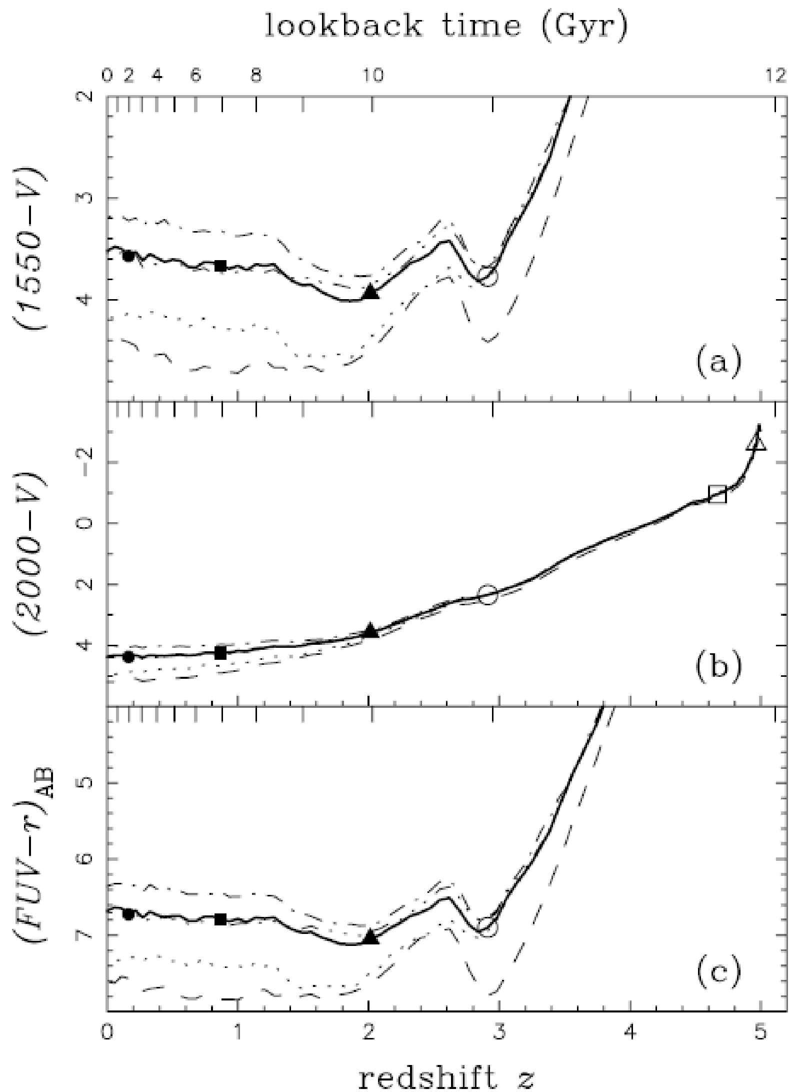
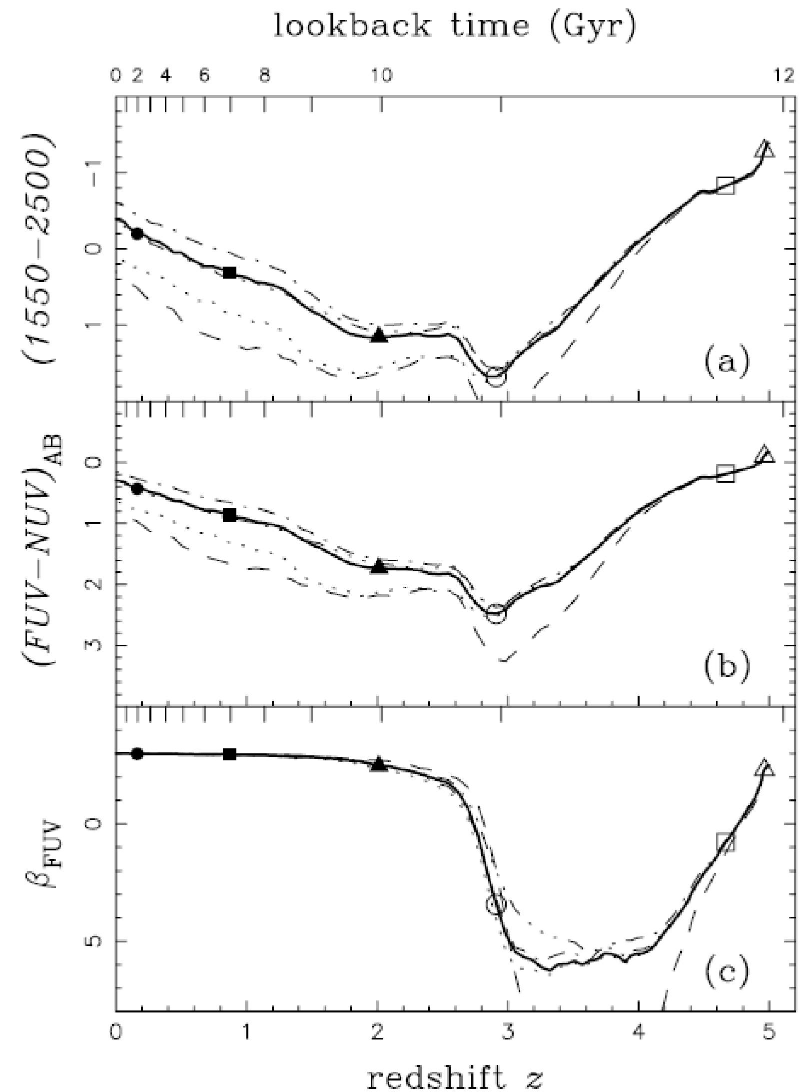
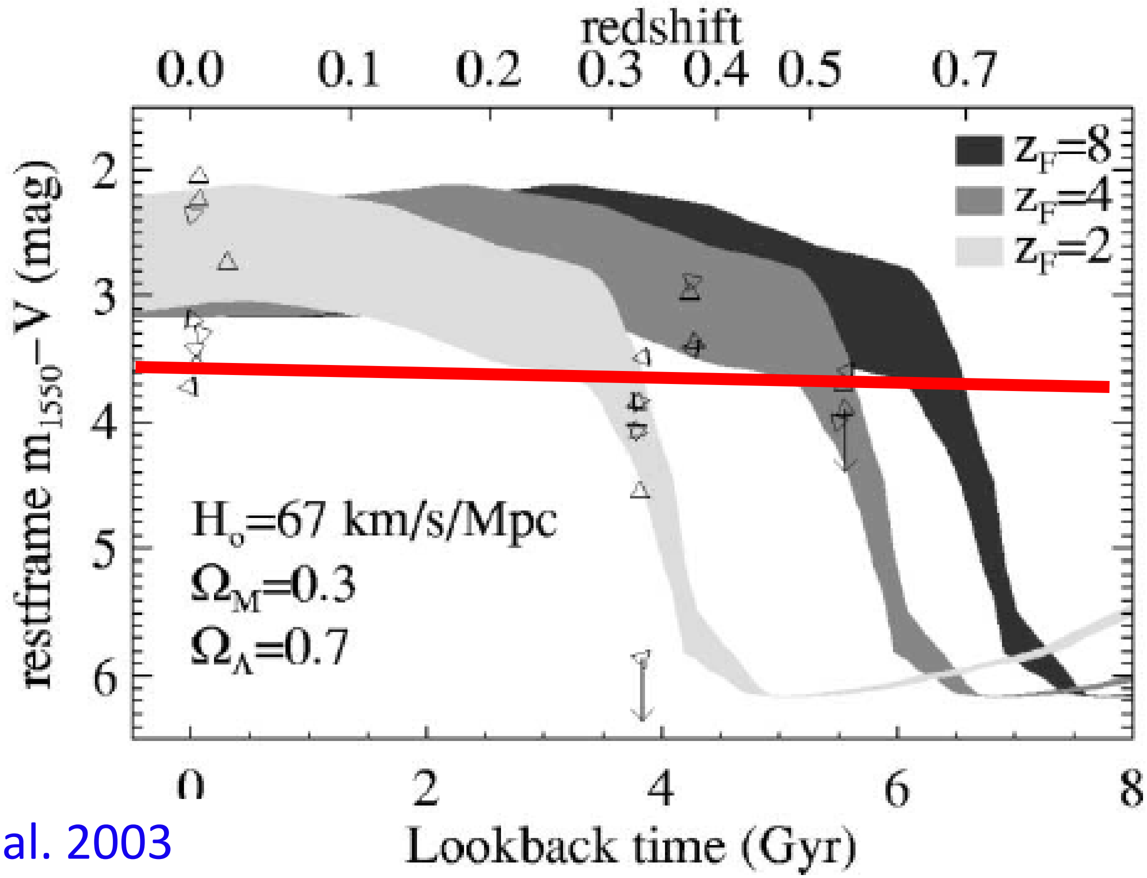
Han, et al., 2007, MNRAS, 380, 1098






lookback time (Gyr)
0 2 4 6 8 10 12
(1550−V)
2
3
4
(a)
(2000−V)
−2
0
2
4
(b)
$(FUV-r)_{AB}$
5
6
7
(c)
0 1 2 3 4 5
redshift z


lookback time (Gyr)
0 2 4 6 8 10 12
(1550−2500)
−1
0
1
(a)
$(FUV-NUV)_{AB}$
0
1
2
3
(b)
β_{FUV}
0
5
(c)
0 1 2 3 4 5
redshift z



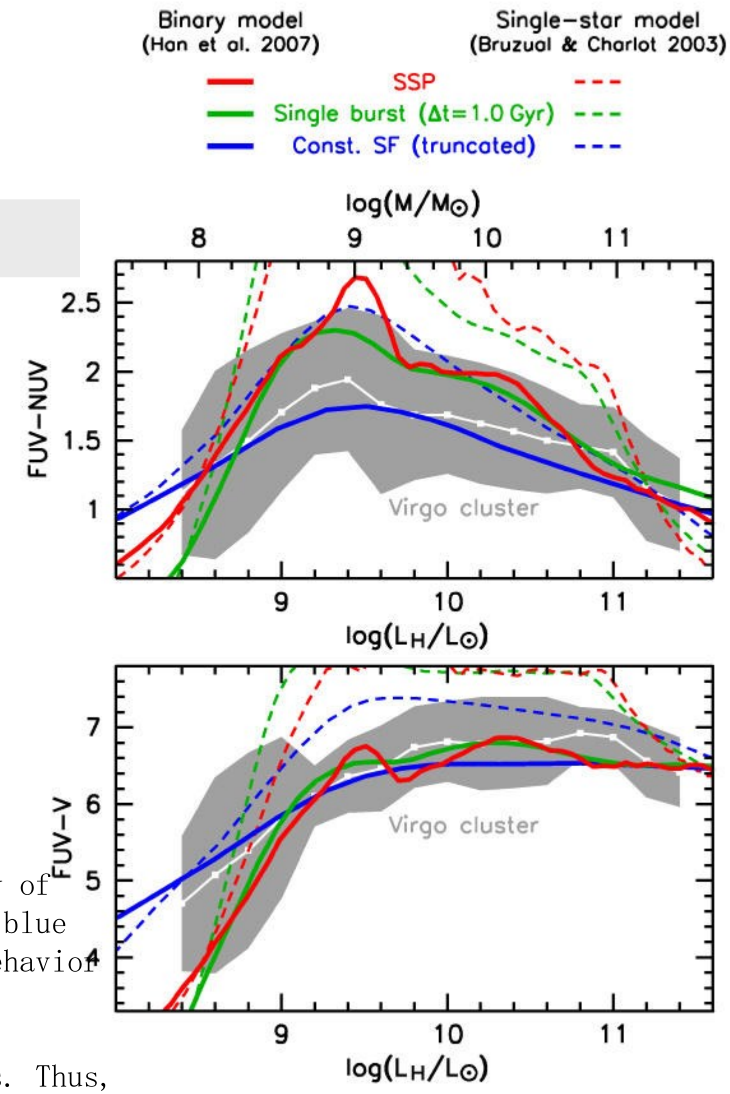
Brown et al. 2003

FIG. 2.—Evolution of the rest-frame $m_{1550} - V$ color according to the models of Tantalo et al. (1996; *shaded regions*), assuming a reasonable cosmology and three different epochs of galaxy formation (*labeled*). The sudden onset of UV emission is caused by the appearance of metal-rich hot HB stars, with the spread in colors bounded by models at $M = 3 \times 10^{12}$ and $M = 10^{12}\ M_\odot$. The timing of the onset is much more sensitive to z_f than to the cosmological parameters. The triangles represent the colors measured to date for quiescent E and S0 galaxies. The statistical uncertainties (Table 1) are small with respect to the variation from cluster to cluster, except for the 1 σ limits shown (*arrows*).

Virgo Cluster

Lisker et al., 2008, ApJ, 680, 1042

- **No dichotomy between stellar population properties of dwarfs and giants.**

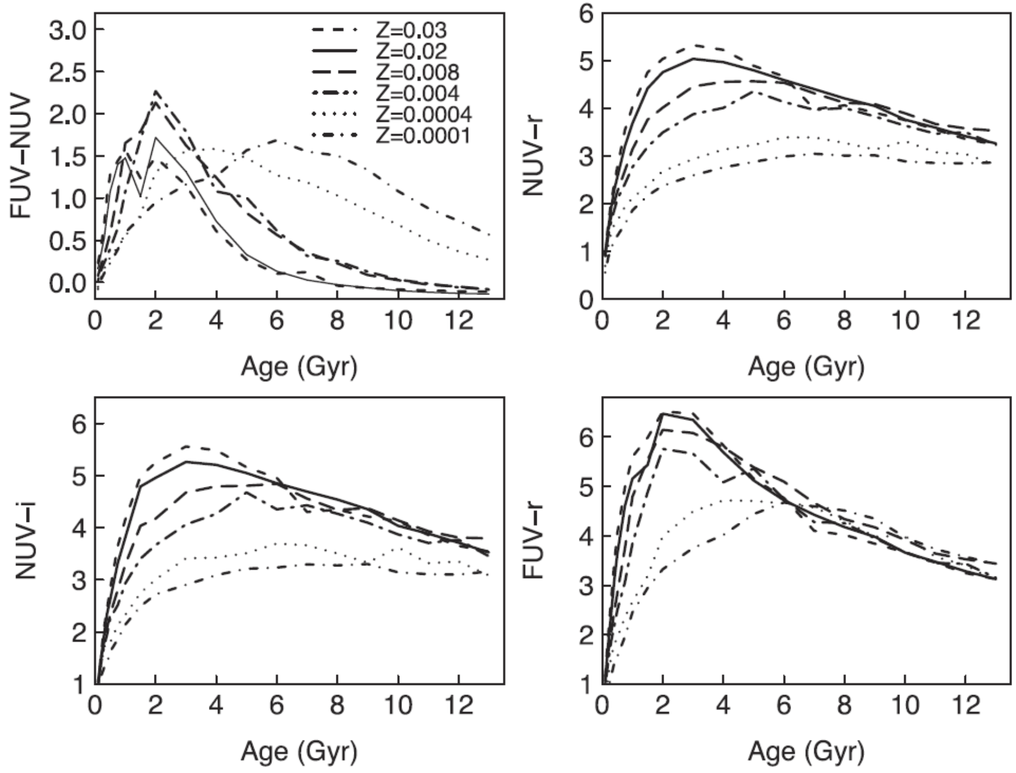


FUV-NUV is reddest at about the dividing luminosity of dwarf and giant galaxies, and becomes increasingly blue for both brighter and fainter luminosities. This behavior can be easily explained by the binary model with a continuous sequence of longer duration and later truncation of star formation at lower galaxy masses. Thus, in contrast to previous conclusions, the GALEX data do not require a dichotomy between the stellar population properties of dwarfs and giants. Their apparently opposite behavior in FUV-NUV occurs naturally when the

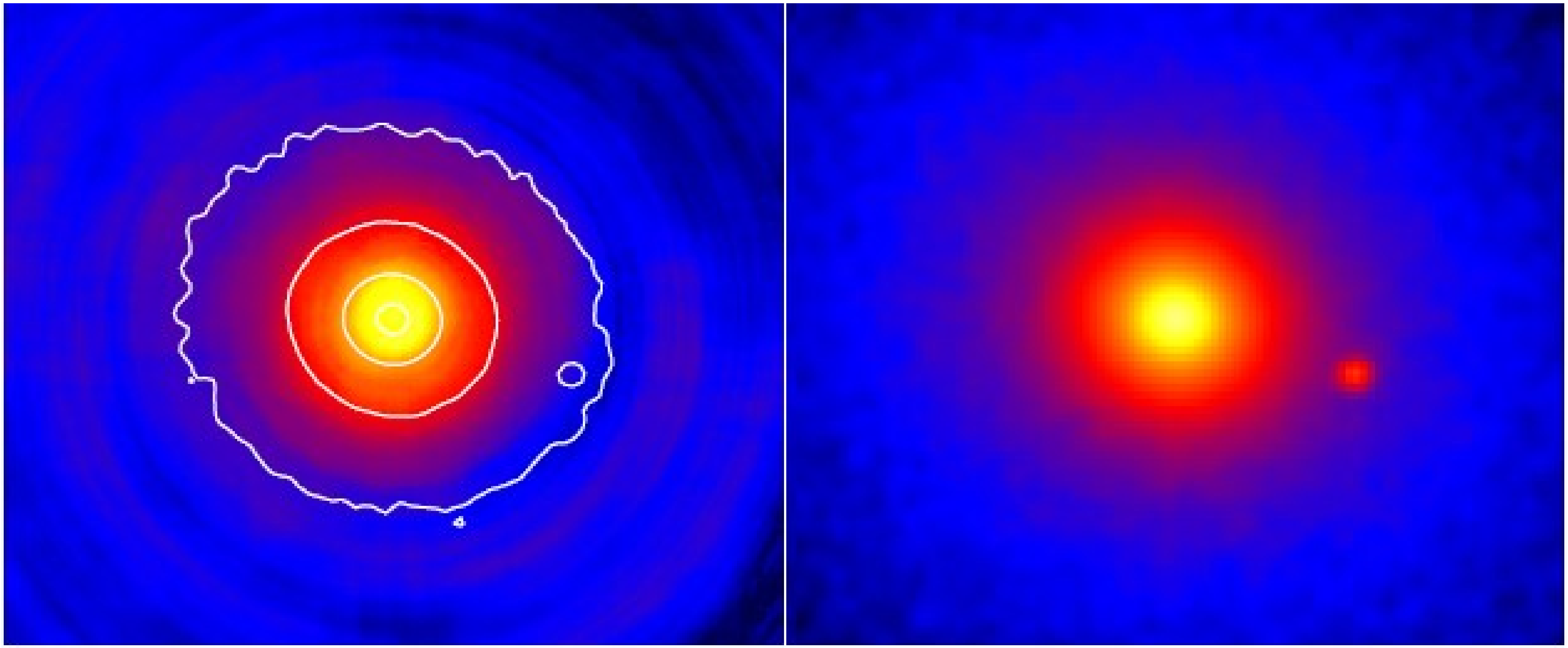
- UV-upturn is universal (from dwarf to giant ellipticals)

- The magnitude of UV-upturn does NOT depend much on metallicity or redshift.

F. Hernández-Pérez and G. Bruzual A.



5. Accreting WDs and Soft X-ray emission from elliptical galaxies



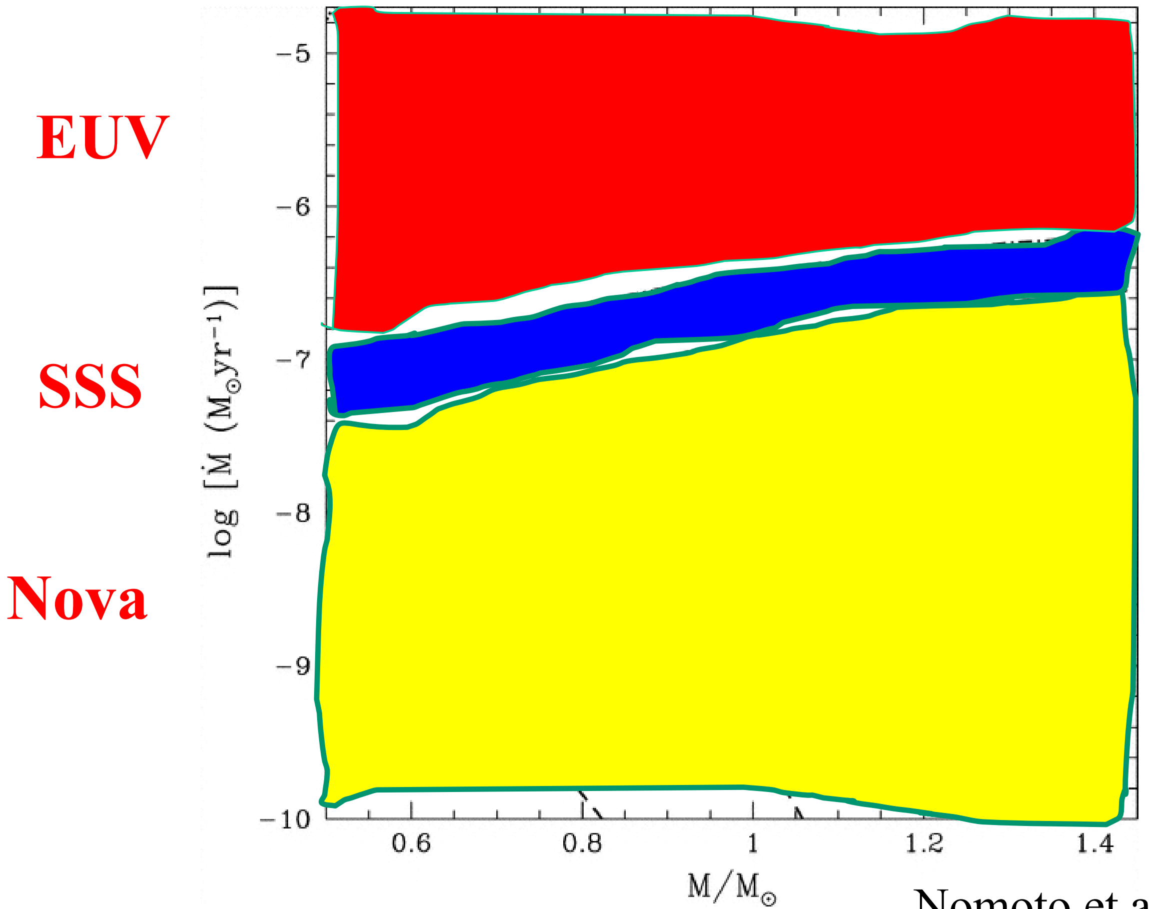
adaptively smoothed image of the unresolved X-ray emission (detected point sour
›ared with the near-infrared (K-band) image of the galaxy (right panel). Conto
ically spaced near-infrared brightness isophotes.

Revnivtsev+ 2007

Gilfanov+ 2010

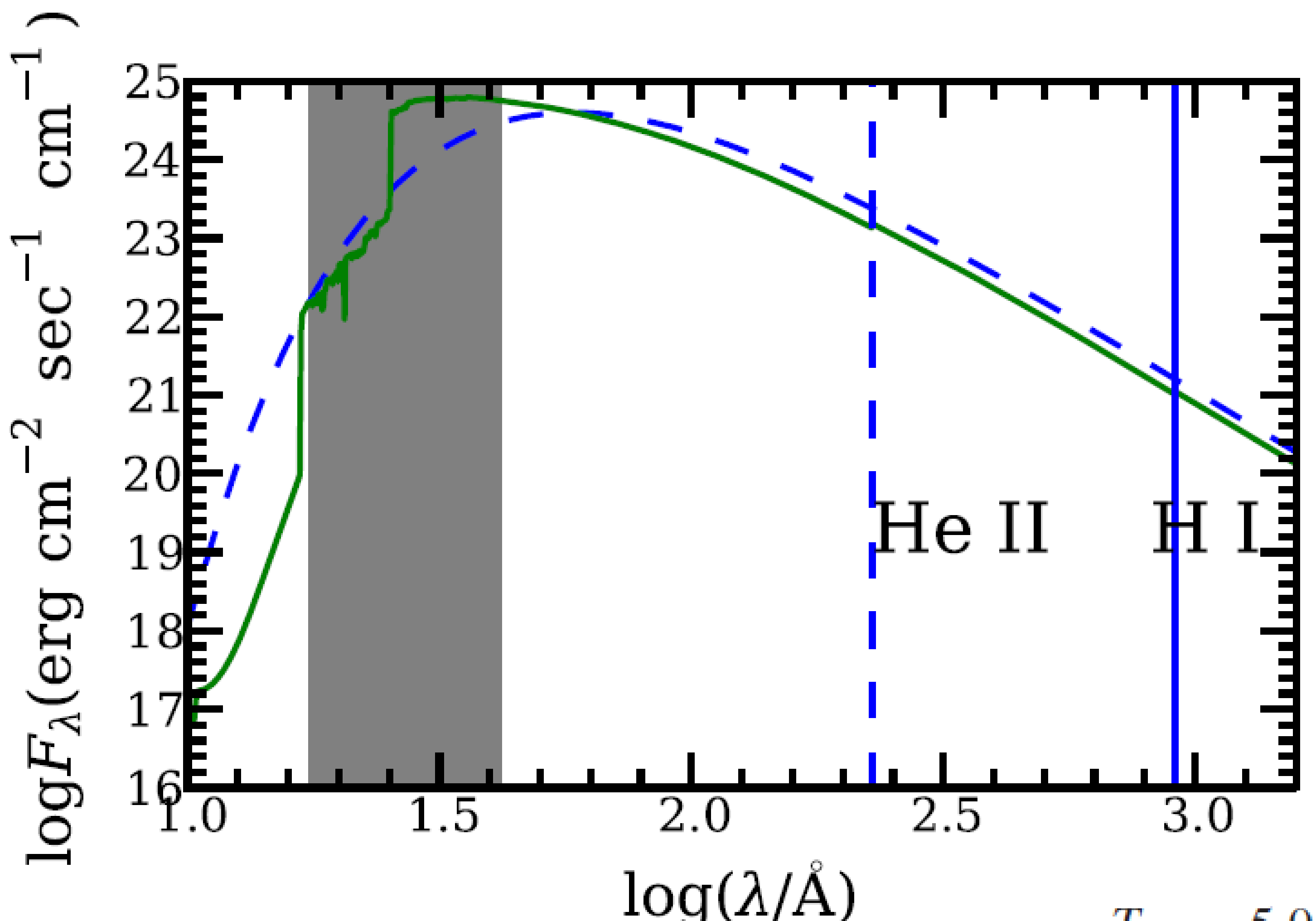
Accreting WDs

Accreting WDs



Nomoto et al., 2007, ApJ, 663, 1269

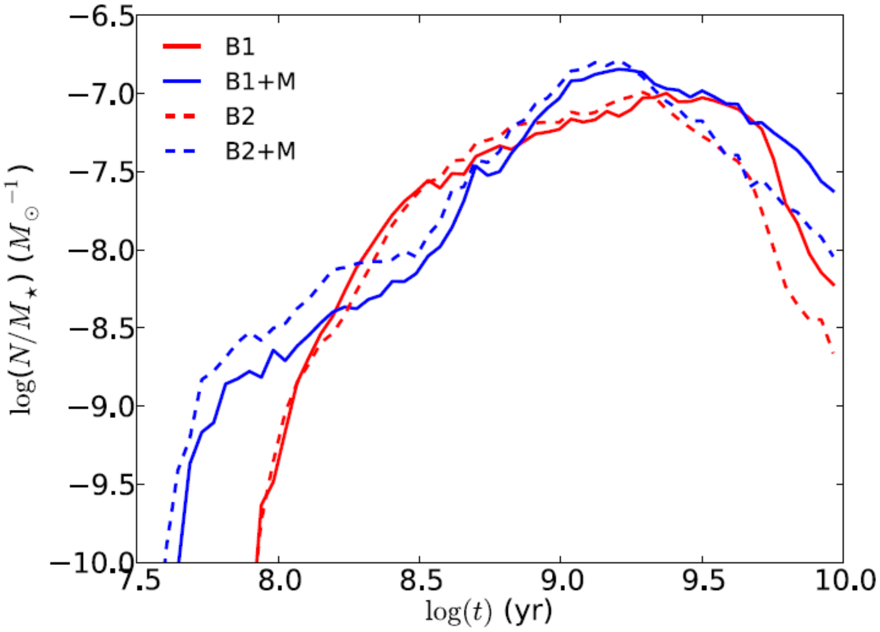
Spectrum of an accreting WD



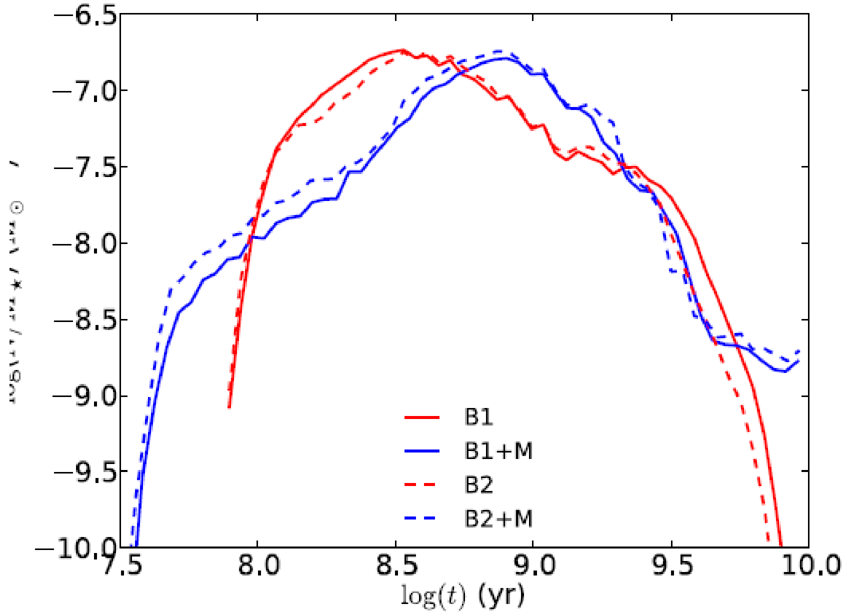
Chen+ 2014, 2015

$T_{\rm eff} = 5.0 \times 10^5$ K.

No. of accreting WDs

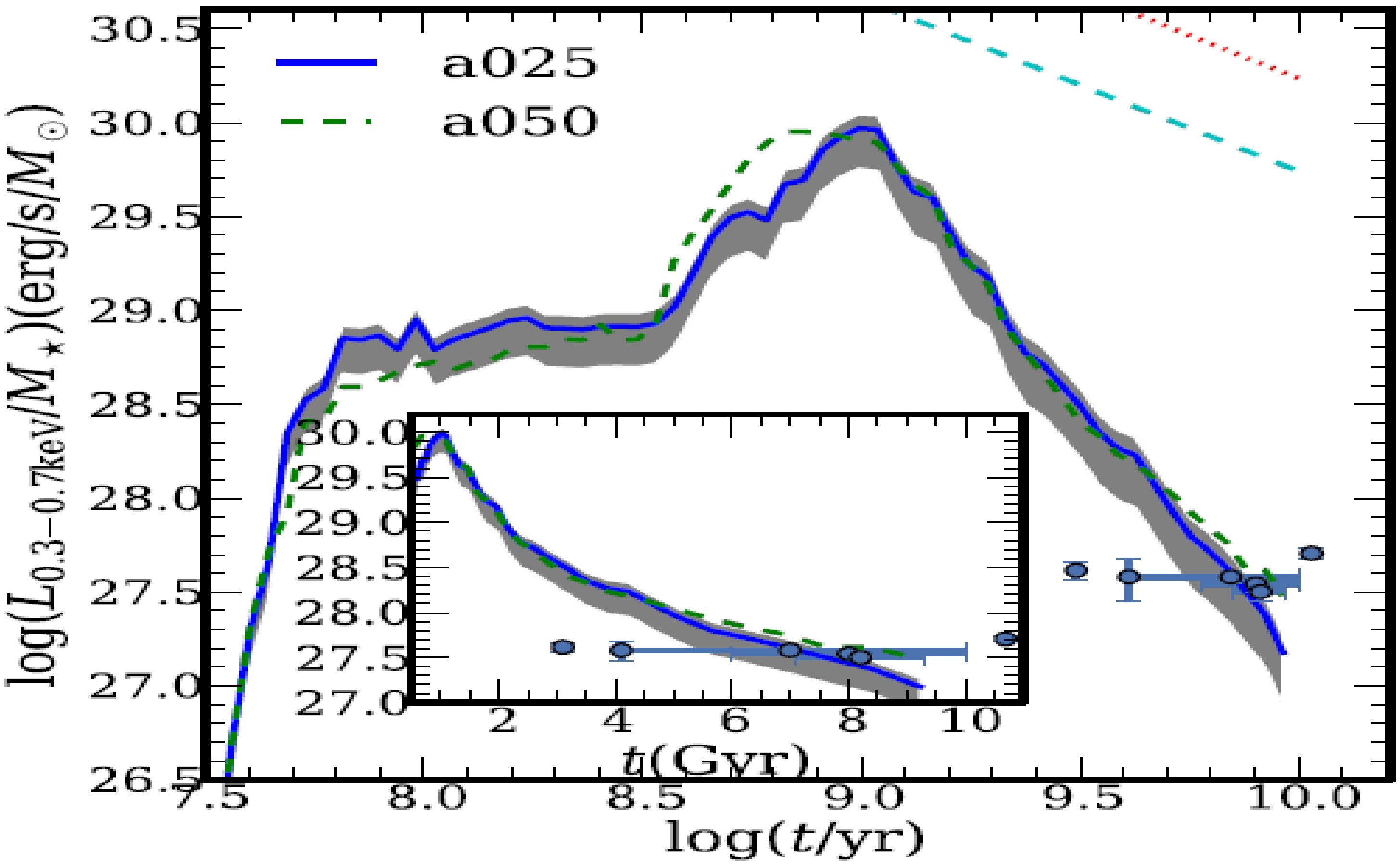


SNBWD



RAWD

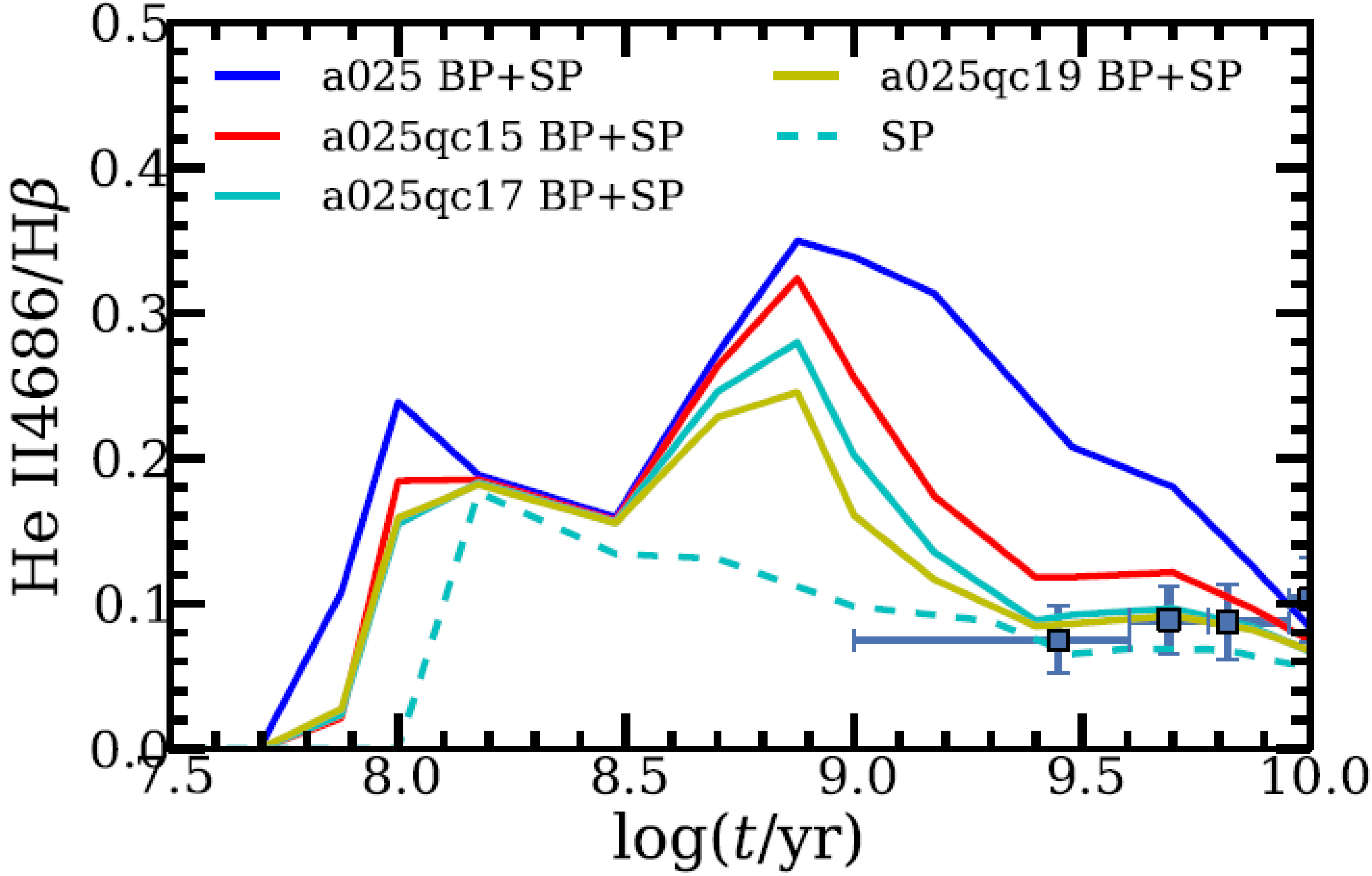
Evolution of soft X-ray emission



Chen+ 2014, 2015

Observations: Bogdan+ 2010, Zhang+2012

Evolution of EUV



Yunnan Model:

Stellar mass smaller（by 10%）
fainter（by 0.2mag）
bluer（by 0.2-0.4mag）
Mass-light ratio bigger（by 10-20%)
UV flux larger（by 2 orders of mag）
EUV flux larger
X-ray emission

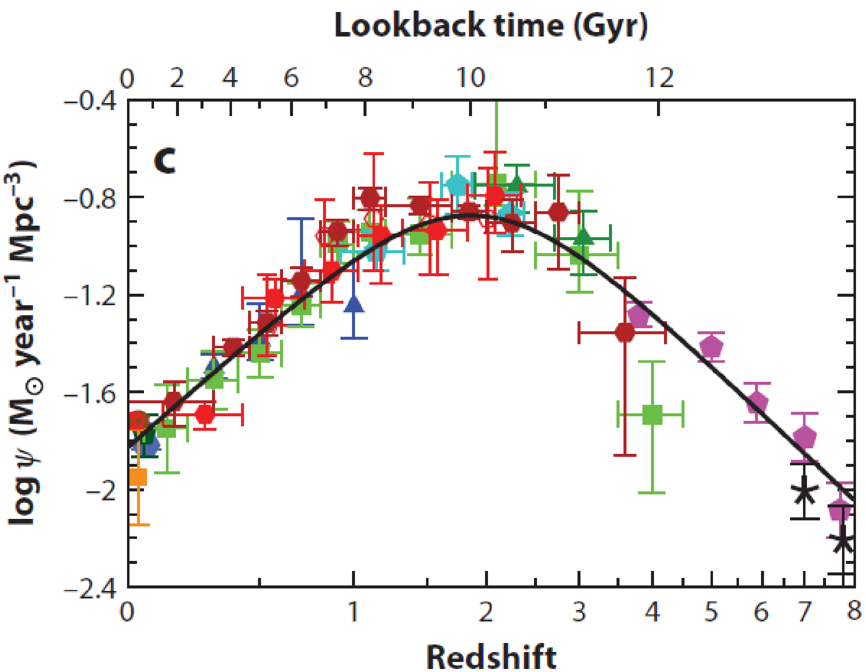
Parameters derived:

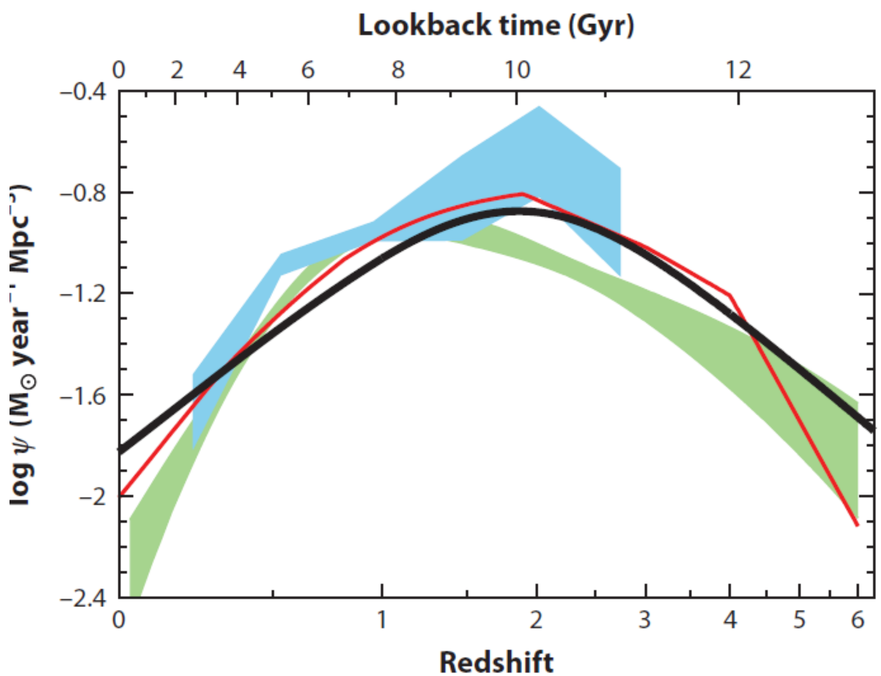
Age larger（by 20% to a few times）
Metallicity larger（by 20%）
Photometric redshift (much more accurate for blue-faint-galaxies）
Ionizing sources (middle age）
Far-IR bump（？）
SFR (by 60%, 0.2dex)

Zhang+ 2004, 2010, 2012, 2013, 2014
Chen+ 2014， 2015

Binary interactions are important for SEDs of old stellar population (e.g. elliptical galaxies) at short wavelength.

Star Formation plays an important role in the origin and evolution of galaxies





Madau+ 2014, ARA&A

SFR indicators can be defined from the X-ray to the radio, to probe the MASSIVE star formation rate.

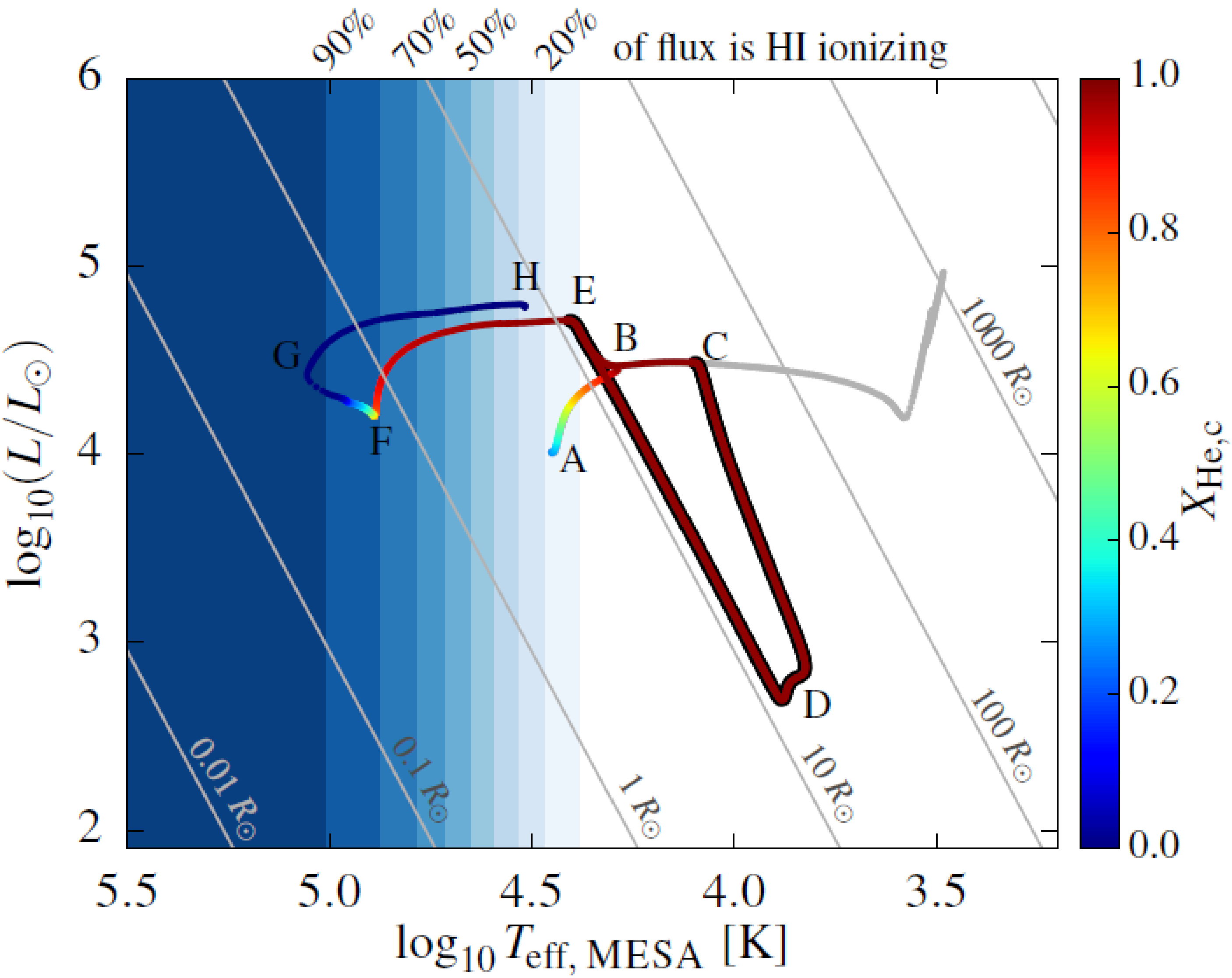
- ✓ X-ray
- ✓ UV
- ✓ Recombination line
- ✓ Emission line
- ✓ FIR
- ✓ radio

References:

Dopita+ 2002
Gilbank+ 2012
Grimm+ 2003
Kewley+ 2002, 2004
Lee+ 2009
Li+ 2010
Moustakas+ 2006
Murphy+ 2011
Narayanan+ 2008
Ranalli+ 2003
Rosa-Gonzalez+ 2002

Ionizing spectra of stars that lose their envelope through interaction with a binary companion: role of metallicity

Y. Götberg[1], S. E. de Mink[1], and J. H. Groh[2]



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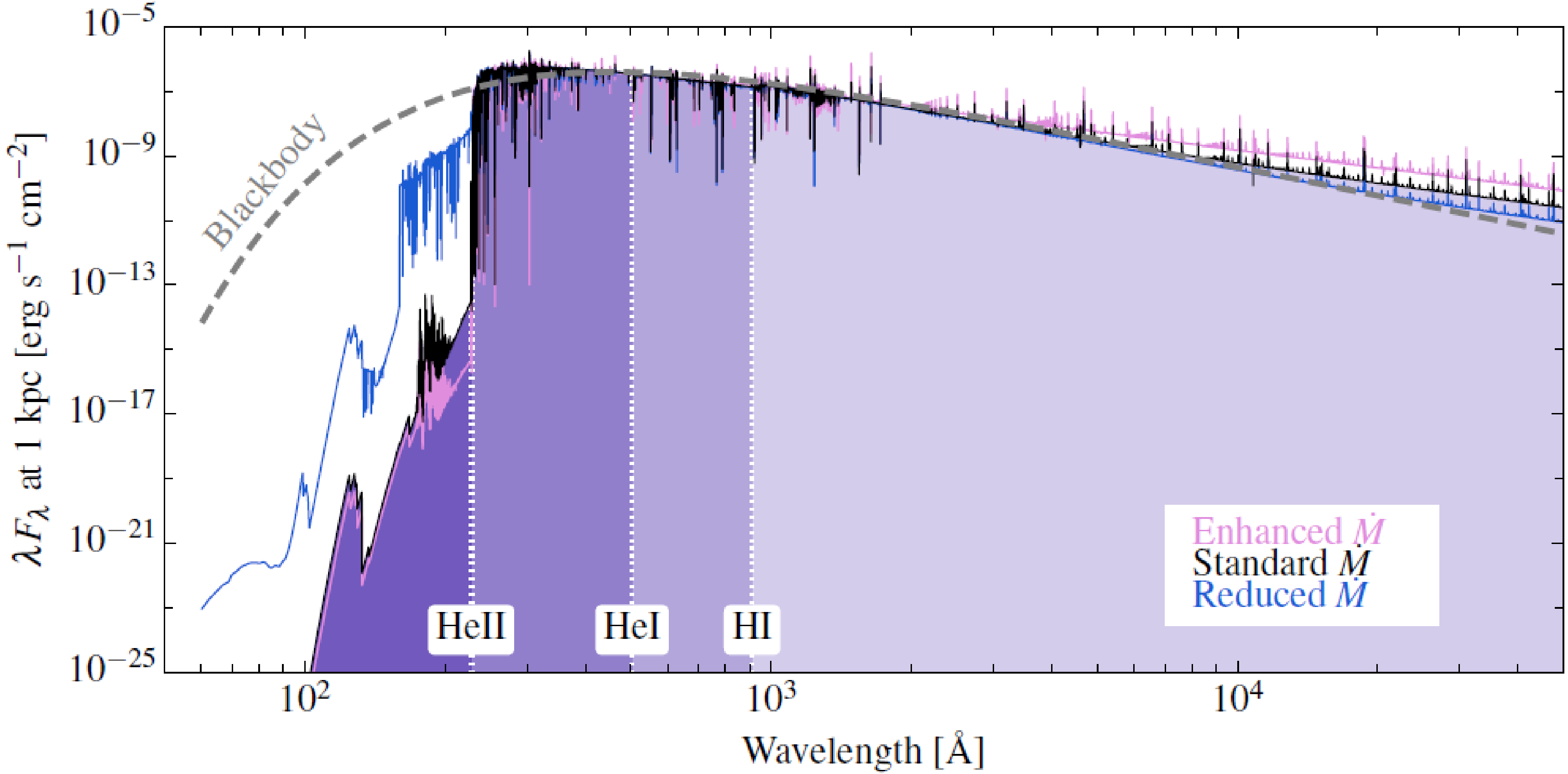
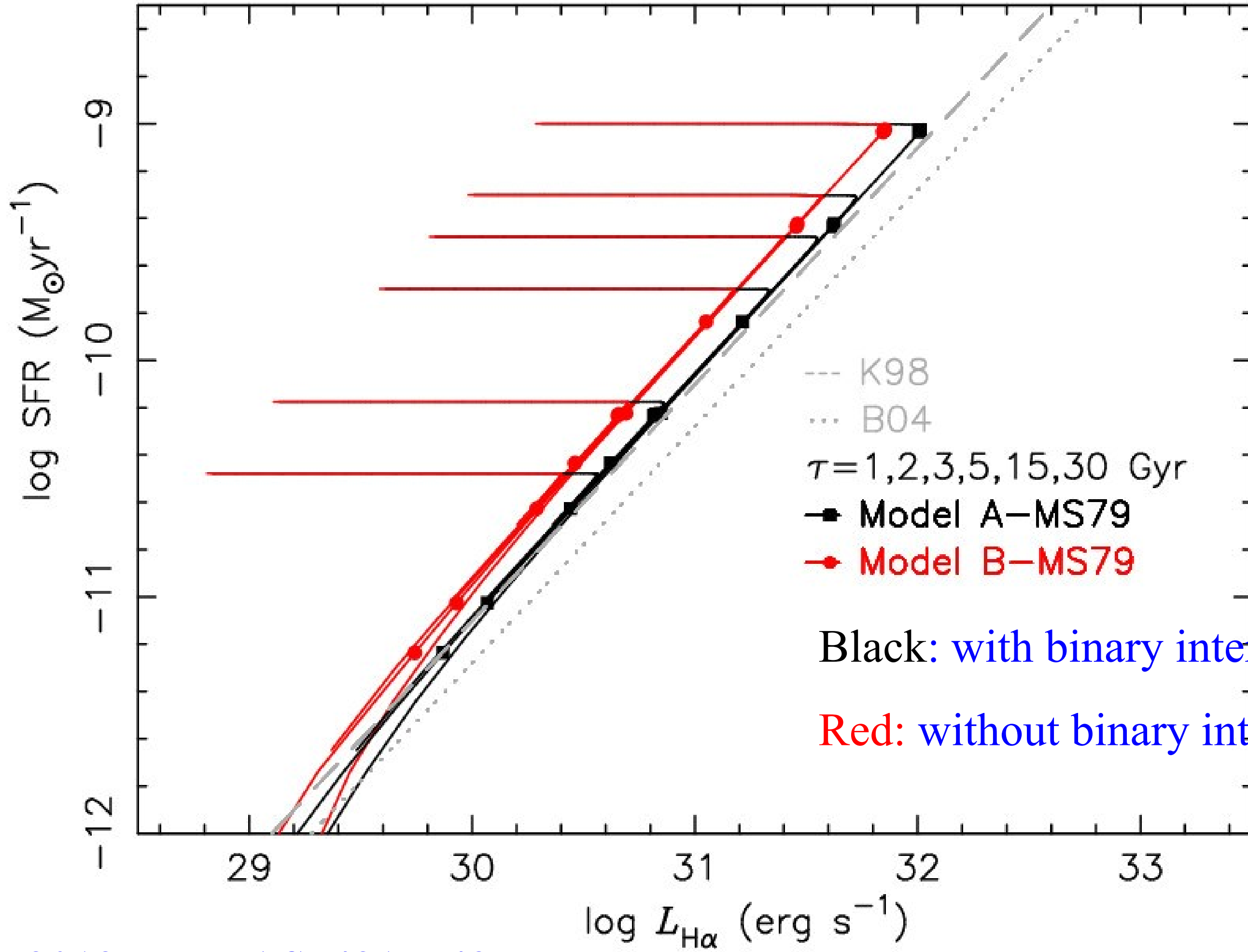
Götberg, De Mink & Groh: Ionizing spectra of stars that lose their envelope through interaction with a binary companion



$$\eta = \frac{f_{\rm strip}}{f_{{\rm WR},\,60\,M_\odot}} \times \frac{Q_{0,\,\rm strip}}{Q_{0,\rm WR}} \times \frac{\Delta t_{\rm strip}}{\Delta t_{\rm WR}} \times \left(\frac{M_{\rm strip,\,init}}{M_{\rm WR,\,init}}\right)^{-2.35}$$

$$= \frac{0.33}{1.0} \times \frac{1.19\times10^{48}\,{\rm s}^{-1}}{2.8\times10^{49}\,{\rm s}^{-1}} \times \frac{1.2\,{\rm Myr}}{0.4\,{\rm Myr}} \times \left(\frac{12\,M_\odot}{60\,M_\odot}\right)^{-2.35} \approx 1.8$$

SFR-L(Hα) decreases by ~0.2dex

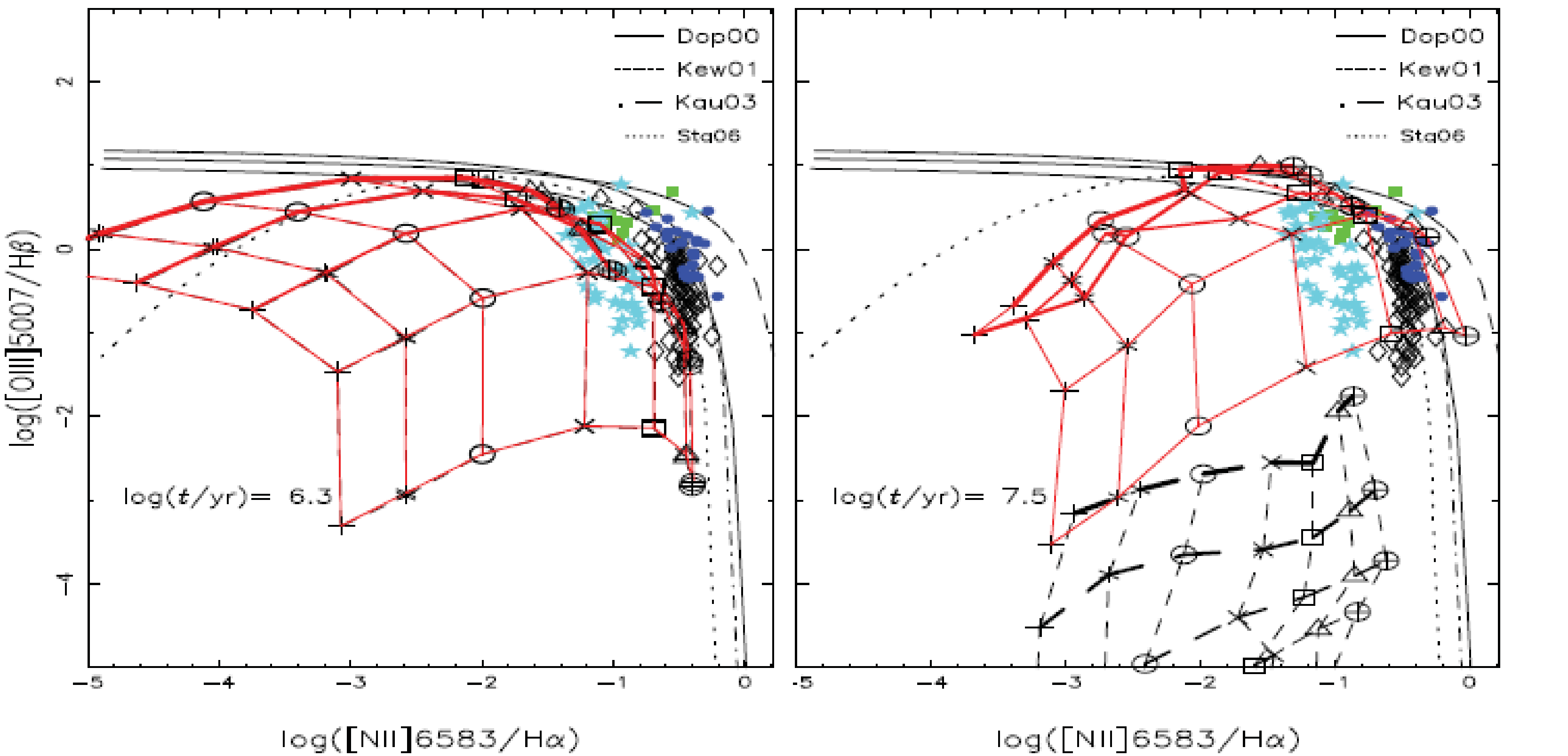


Black: with binary interactions

Red: without binary interactions

Zhang+ 2012, MNRAS, 421, 743

Intermediate age stellar populations as ionizing sources of HII regions



Red: with binary interactions

Zhang+ 2015, MNRAS, 447, L21

Black: without binary interactions

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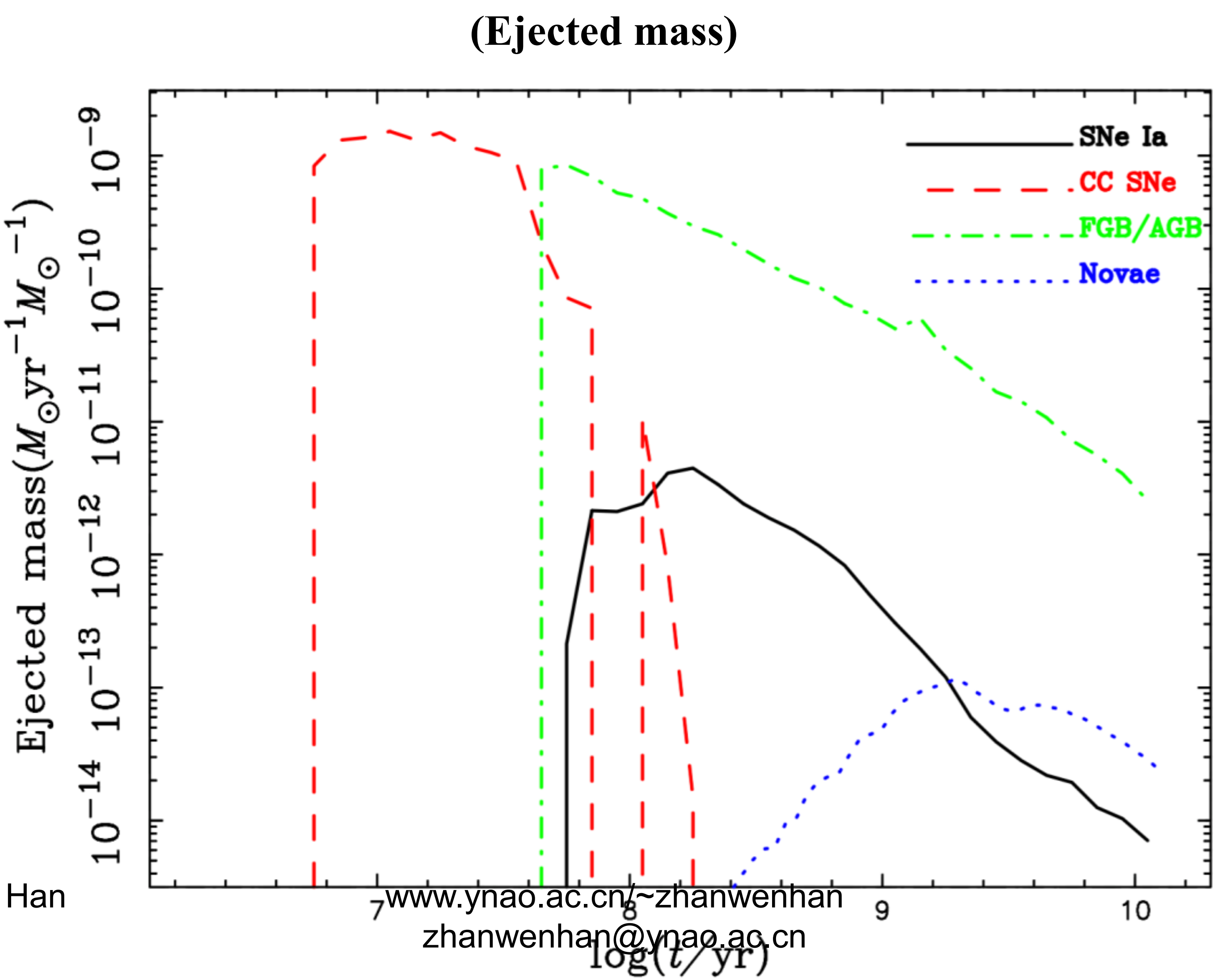
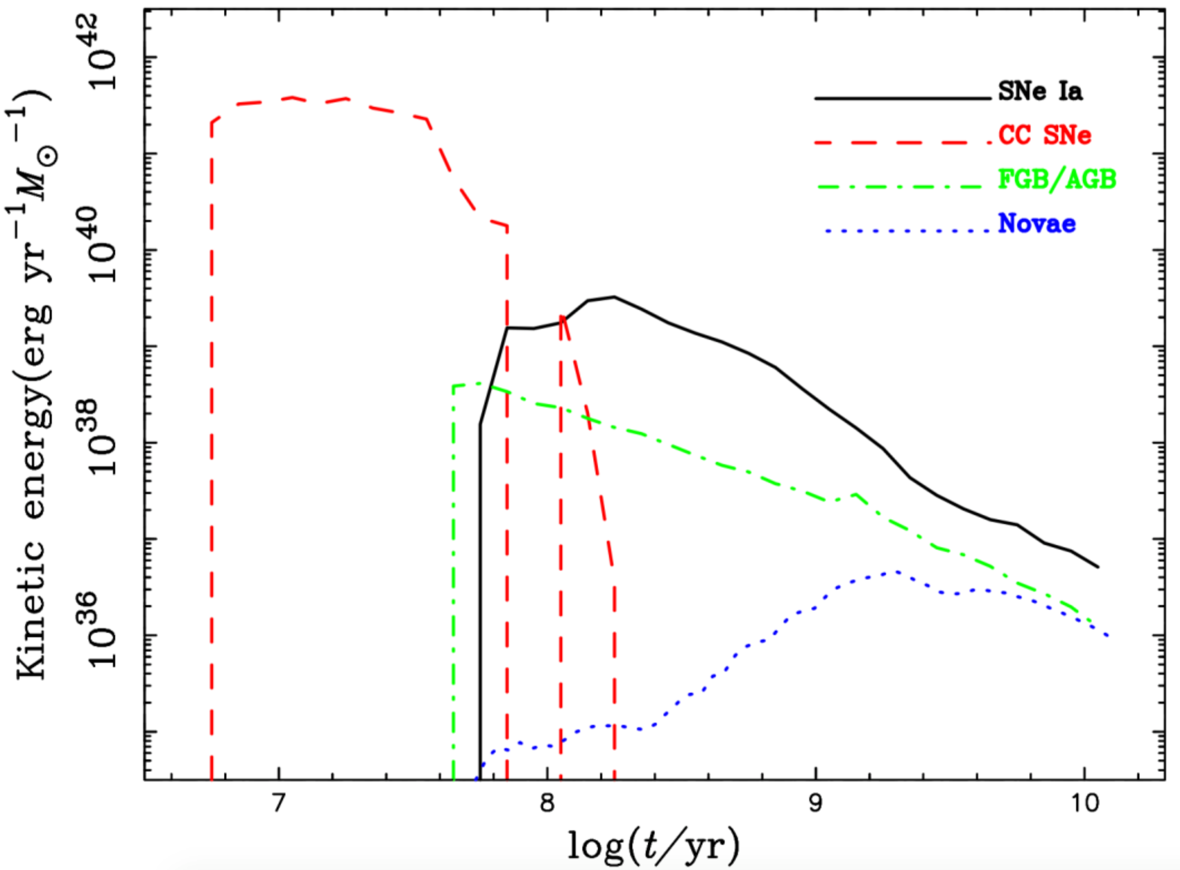
Thanks !

Stellar feedback in isolated early-type galaxies



Stellar feedback in isolated early-type galaxies

(Kinetic energy)



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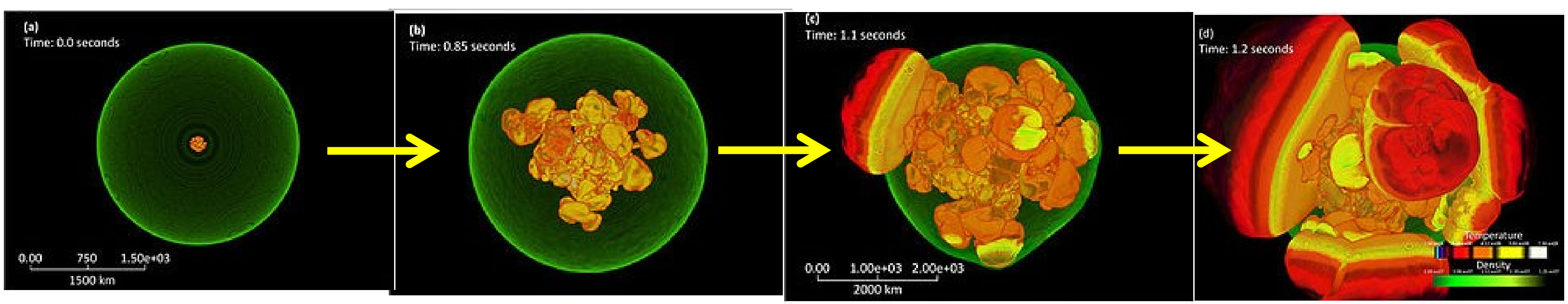
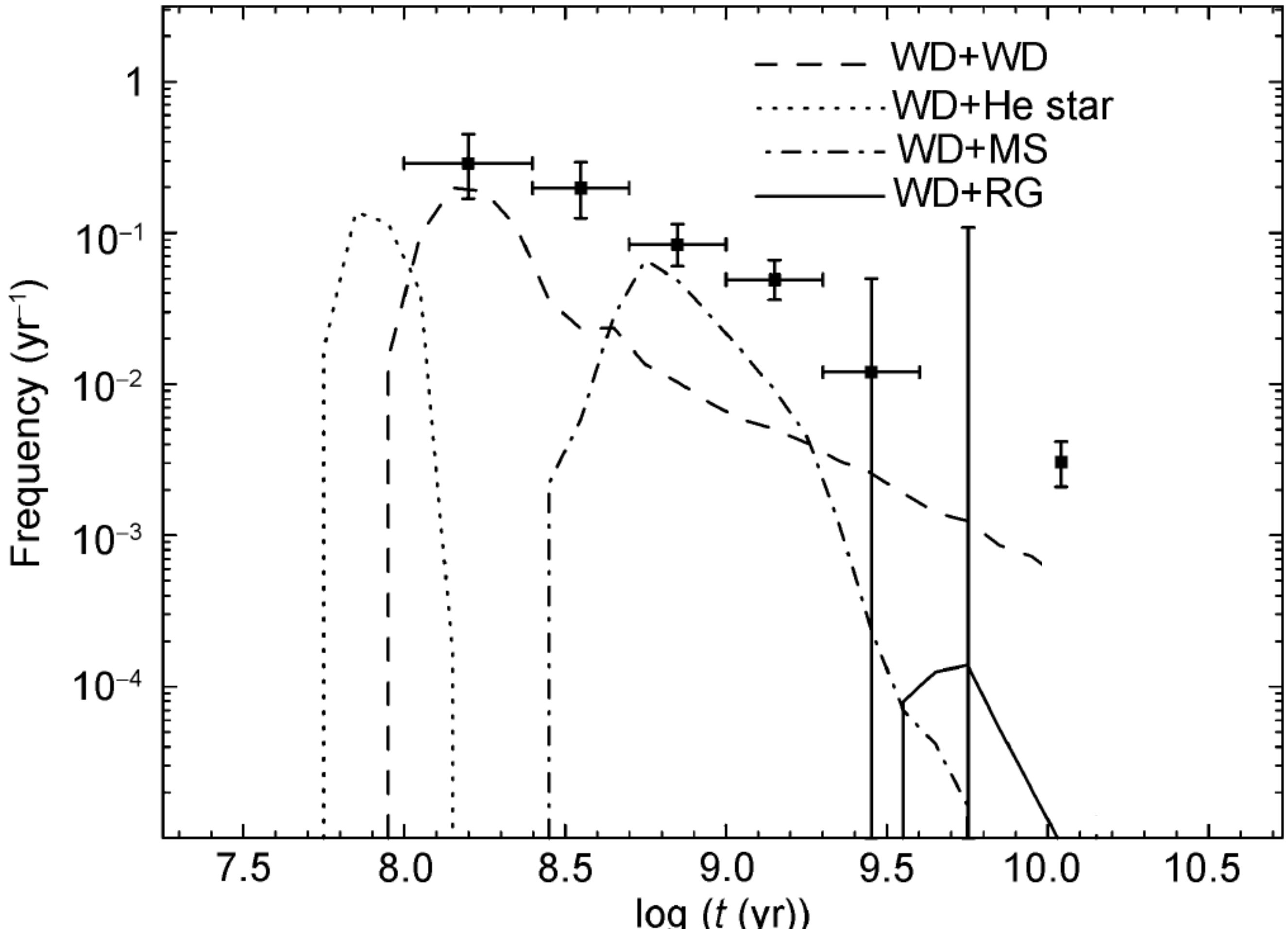
SNe Ia

Thermonuclear Explosions of CO WDs at ~1.4Msun

carbon ignition under degenerate conditions →
thermonuclear runaway →
incineration and complete destruction of the star 10^{51}ergs



SN Ia rates for single star burst



Wang+ 2010

Observations: Totani+ 2008