











ESTALLIDOS VII

Calibration of star formation rate tracers for short and long-lived star-forming episodes

Héctor Otí Floranes

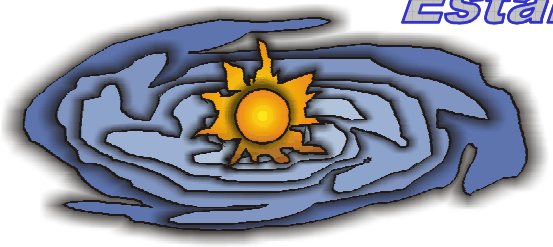
Dirigido por J. M. Mas Hesse

Laboratorio de Astrofísica Estelar y Exoplanetas

LAEX-CAB (CSIC-INTA)

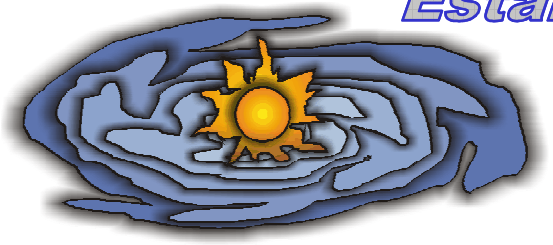
26-27 enero 2009

MICINN AYA 2007-67965



STAR FORMATION

- Isolated bursts: instantaneous bursts (IB)
  - No further formation after time=0
  - SFS: Star Formation Strength (M_o): initial mass
  - Seen in BCDGs
- Extended Bursts (EB): continuous star formation
  - Composite of IBs $\rightarrow$ EB
  - SFR: Star Formation Rate (M_o/yr): velocity of star formation
  - Seen in large spiral galaxies

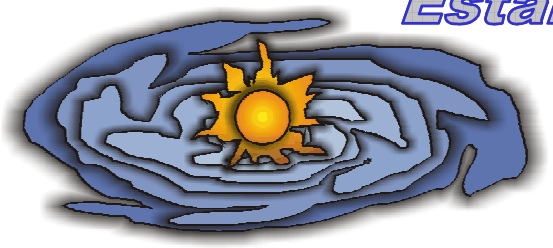


STARBURSTS

- Star formation measured by
  - SFR: Star Formation Rate (M_o/yr)
  - SFS: Star Formation Strength (M_o)
- IMF determines the derived SFR and SFS
  - slope
  - mass limits

  different IMF features $\Rightarrow$ different SFR/SFS values

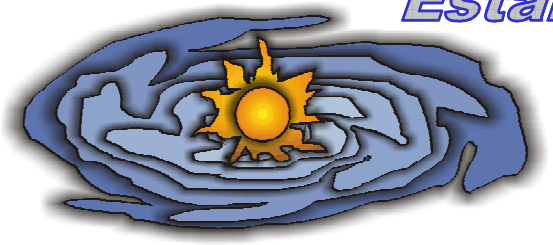
- Different SFR tracers:
  - UV
  - H_α: ionized gas
  - FIR: heated dust
  - Mechanical energy $\rightarrow$ X-rays
  - [OII]λ3727



- Paper in preparation:

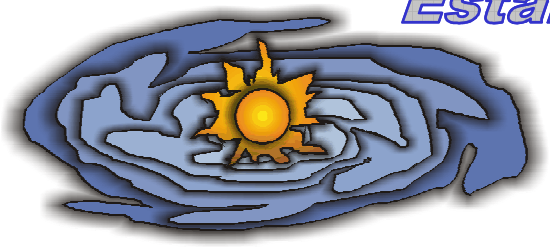
  Otí-Floranes & Mas-Hesse (2009)

- Using synthesis models, study the evolution of SFR/SFS-scaled magnitudes:
  - FIR
  - N_{Lyc}
  - UV
  - Mechanical Energy (stellar winds + SNe)
  - Others
- Obtain SFR & SFS calibrations for each of them
  - SFR=A*Mag / SFS=B*Mag
- Calibrate the tracers: metallicity, age, etc.



POPULATION SYNTHESIS MODELS

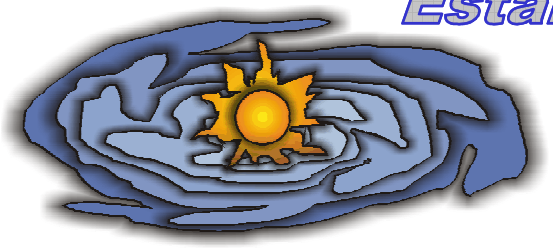
- Initial population with Initial Mass Function:
  - IMF(M) $\propto M^{-2.35}$ (M=2-120 M_o)
- Evolution of stars:
  - Isochrones: evolution of intrinsic properties (T_{eff}, L_{bol}, etc.)
  - Libraries: isochrones data $\rightarrow$ measurable magnitudes (luminosities, colours, etc.)
- SFR: two types of models
  - EB (extended models, SFR): constant star formation
  - IB (instantaneous bursts, SFS): no further formation (usual age 4-6 Myr)
- Unless stated: Z_o
- Age < 250 Myr
- Models used:
  - CMHK02 (Cerviño, Mas-Hesse & Kunth)
  - SB99 (Leitherer et al.)



IMF CORRECTION

- Compare our calibrations with those from:
  - Kennicutt (1998)
  - Condon (1992)
  - Salim et al. (2007)
- But they consider different mass limits (us M=2-120 M_o)
- IMF correction: IMPORTANTE
  - Study the ratio r=Magnitude(2-120) / Magnitude(M_{low}-M_{up})
  - It depends on:
    - Magnitude studied: FIR, UV, N_{Lyc}
    - Age
    - Star Formation History assumed: EB or IB
  - SFR(2-120)=A*Mag(2-120)

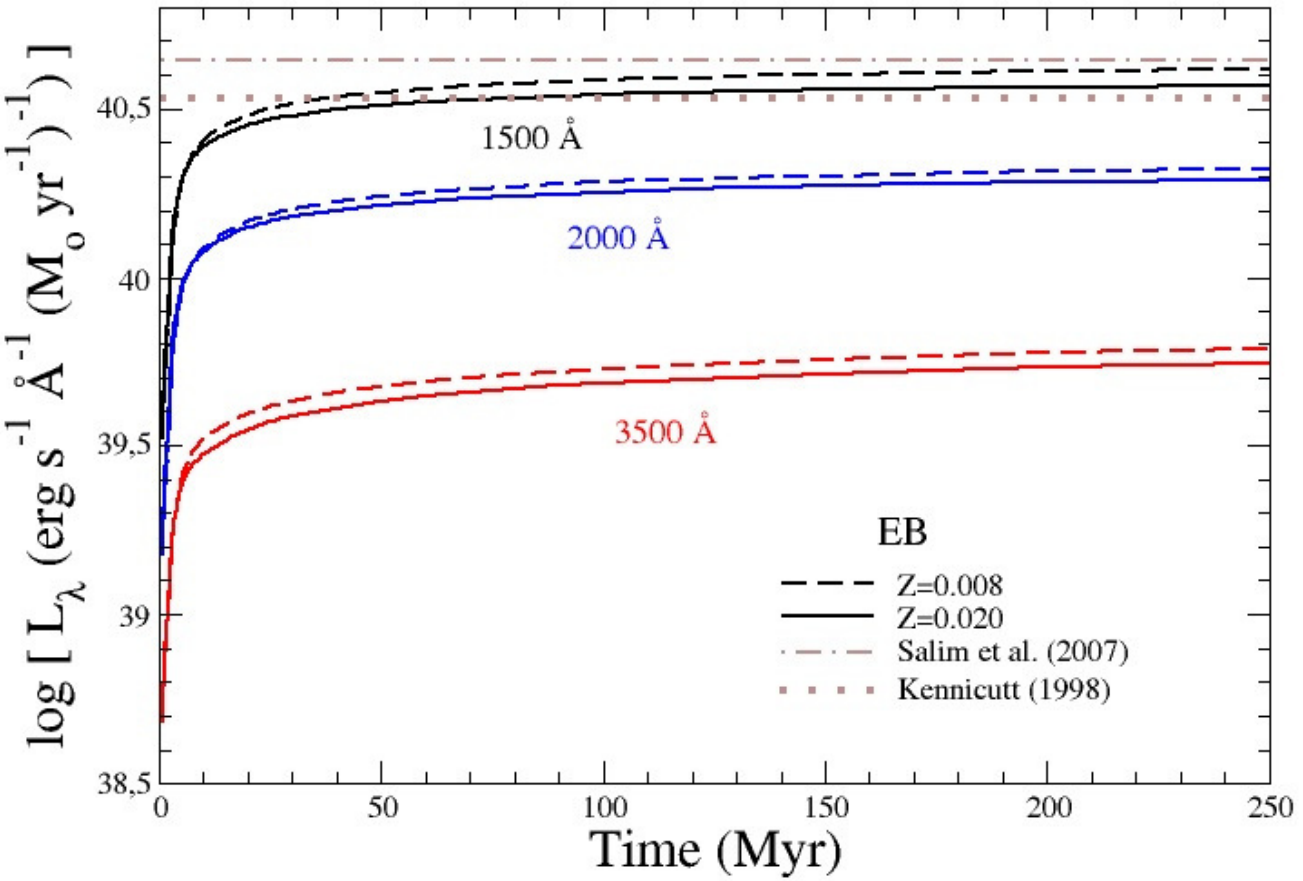
  $\Rightarrow$ SFR(M_{low}-M_{up})=A*r Mag(M_{low}-M_{up}) $\Rightarrow$ A' = A*r



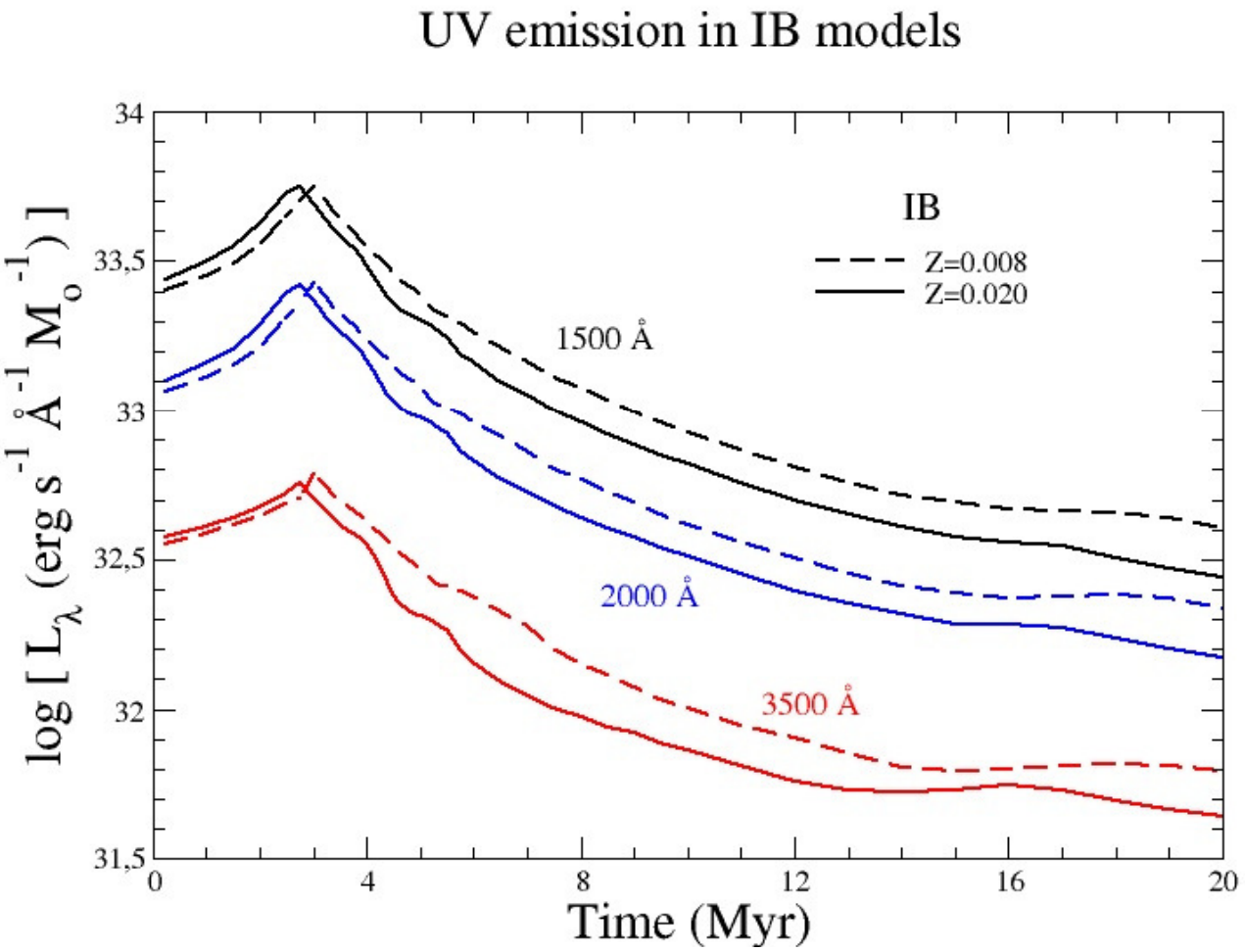
UV EMISSION 1

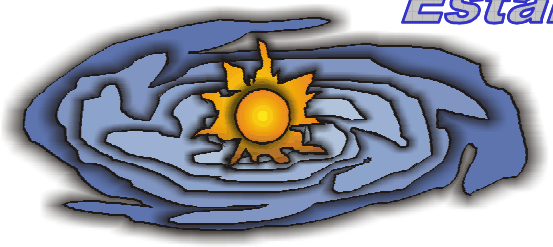
- Direct tracer of star formation
- But severely affected by extinction
- L_{1500}, L_{2000} and L_{3500} (U-band)

UV EMISSION 2



UV EMISSION 3





FIR EMISSION 1

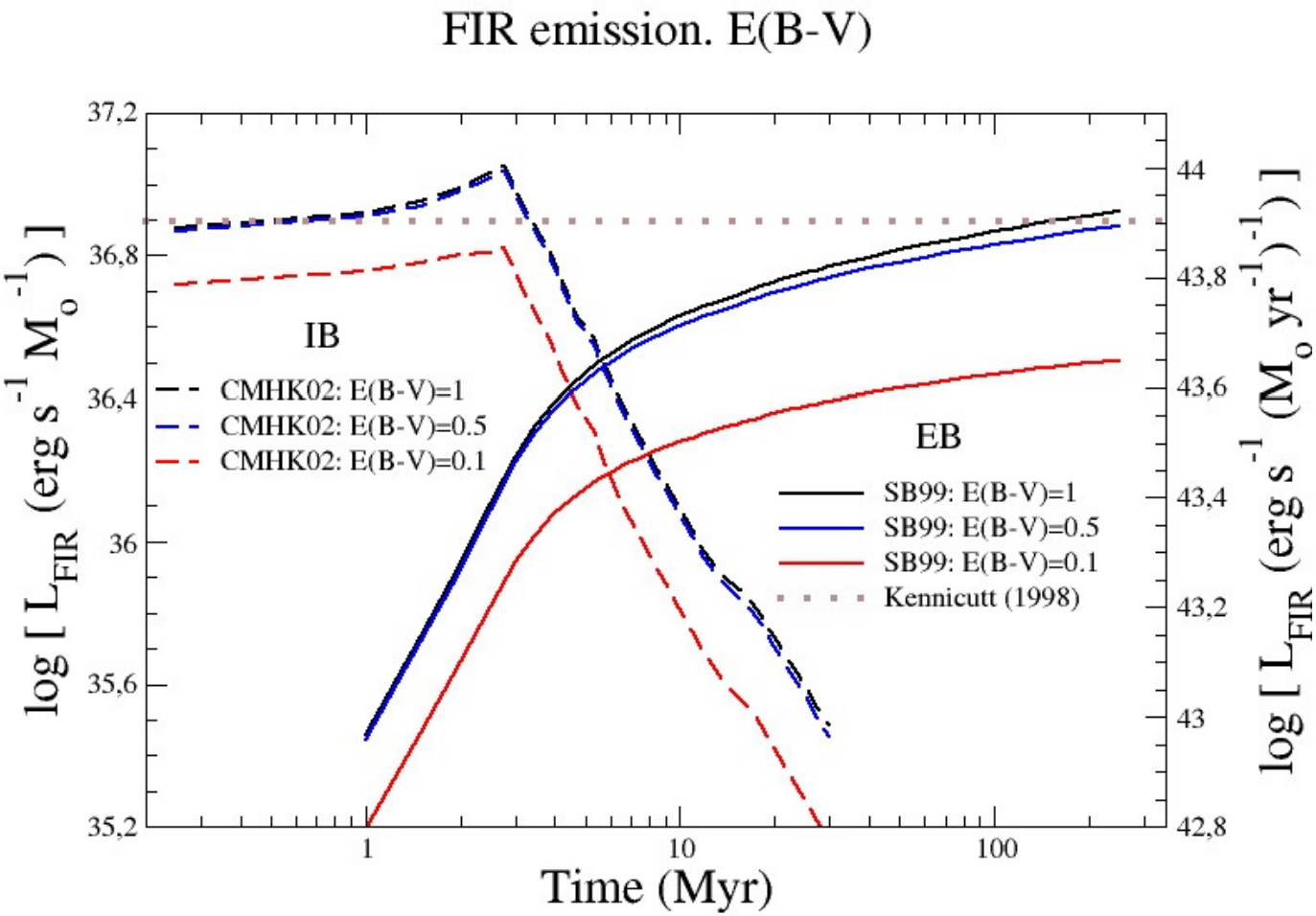
- We assume thermal equilibrium of dust

  $\Rightarrow$ All energy absorbed is reemitted

- Parameters:
  - Cardelli et al. (1989) extinction law (R_V=3.1)

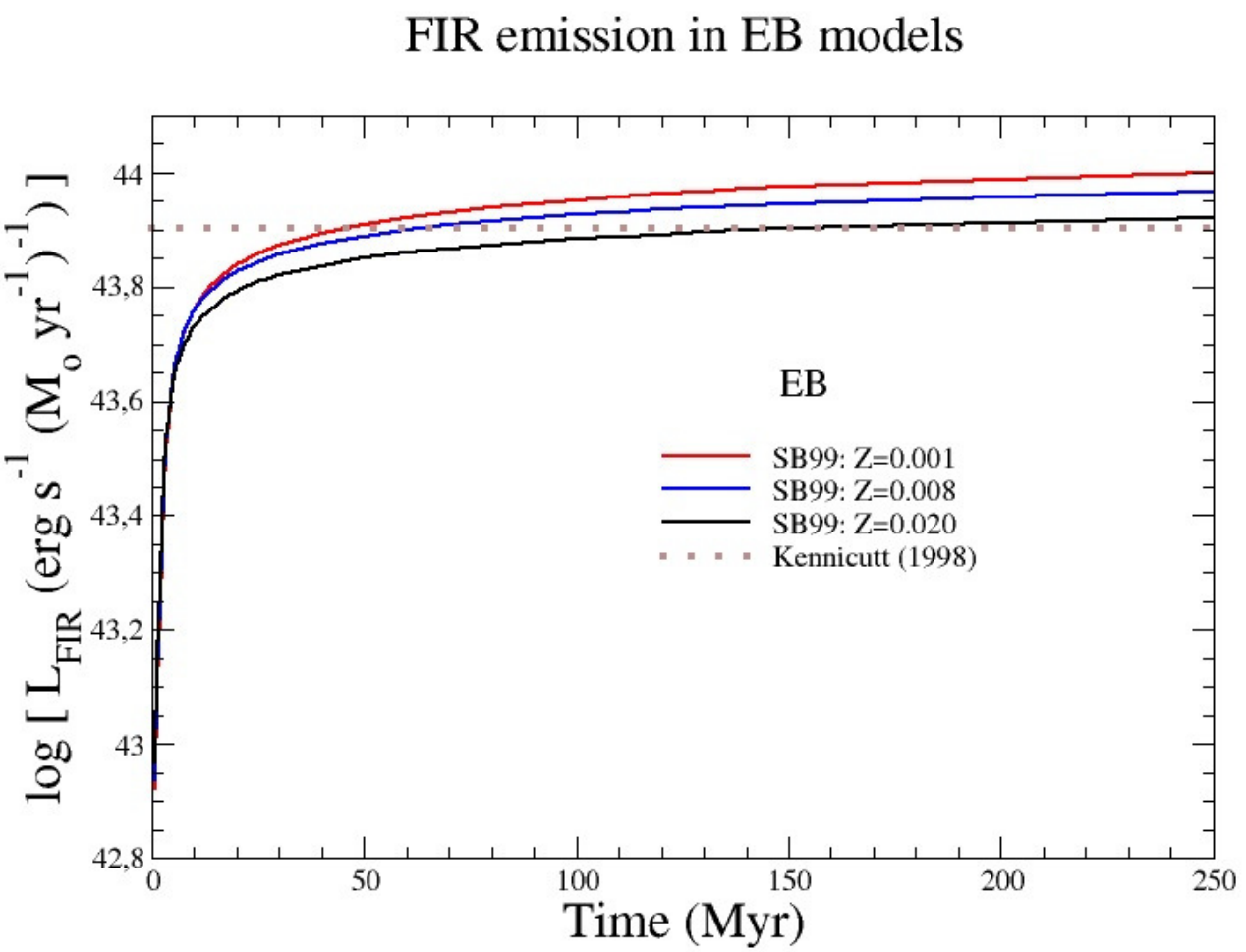
    + 30% ionizing photons + 100% Lyα
  - E(B-V): colour excess E(B-V)=0.1-1
- Similar behaviour to UV radiation

FIR EMISSION 2



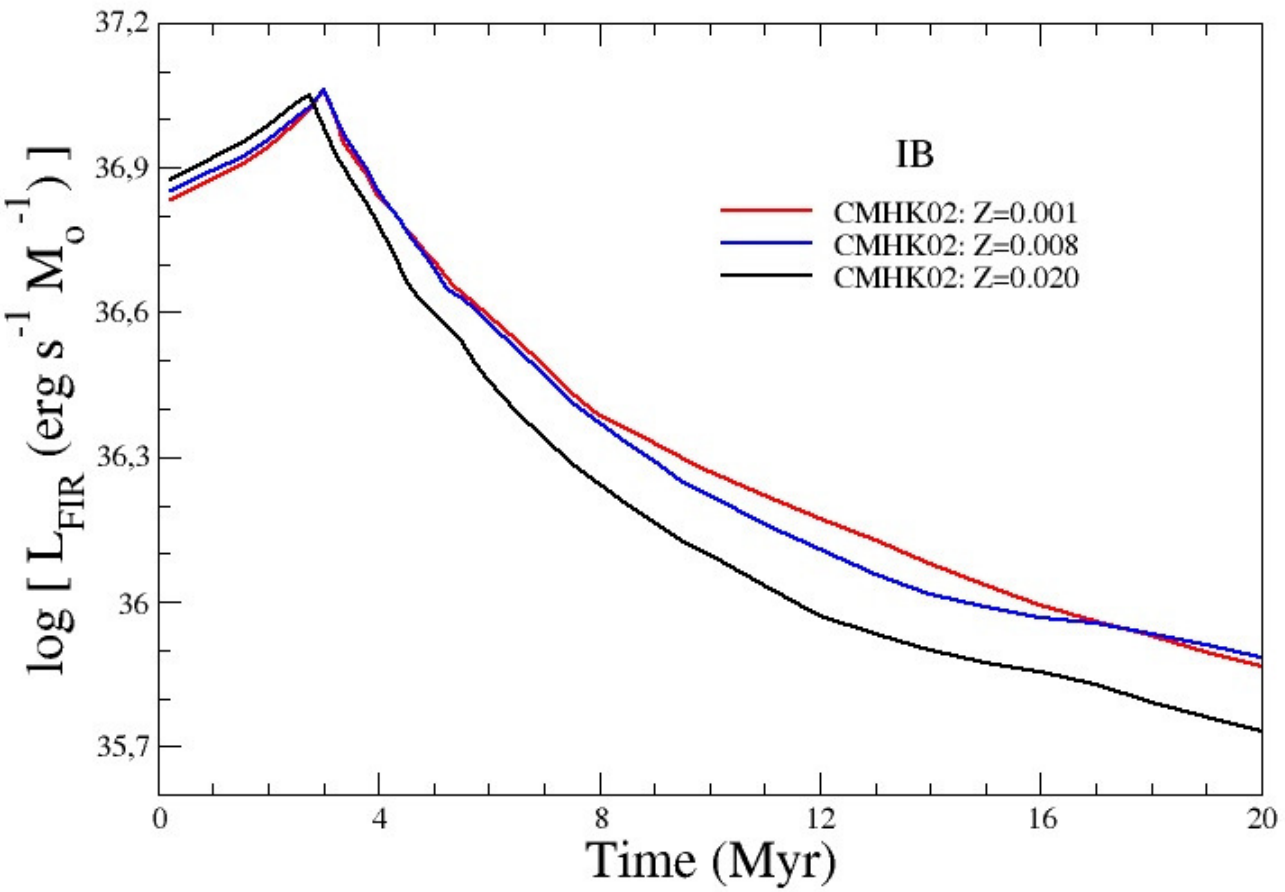
Saturation for E(B-V)>0.5 ⇒ E(B-V)=1

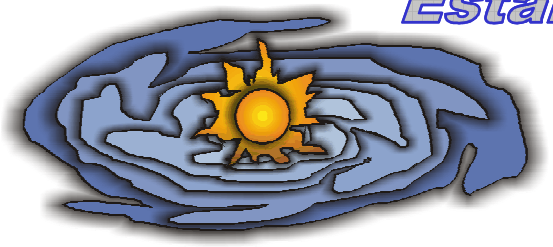
FIR EMISSION 3



Kennicutt only appropiate for long-lived (~50Myr) starbursts

FIR EMISSION 4



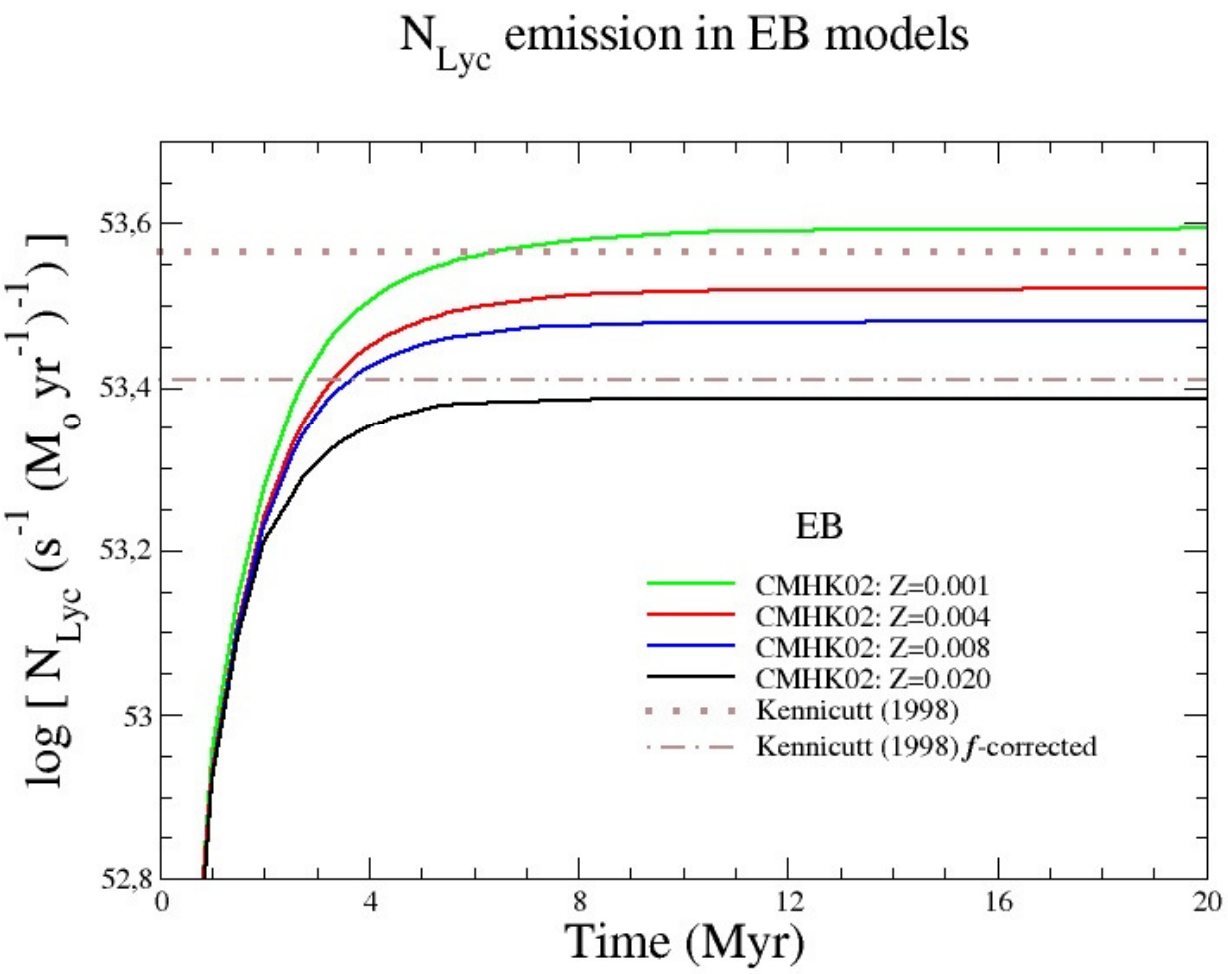


IONIZING PHOTONS 1

- Photons with λ<912 Å can ionize H atoms

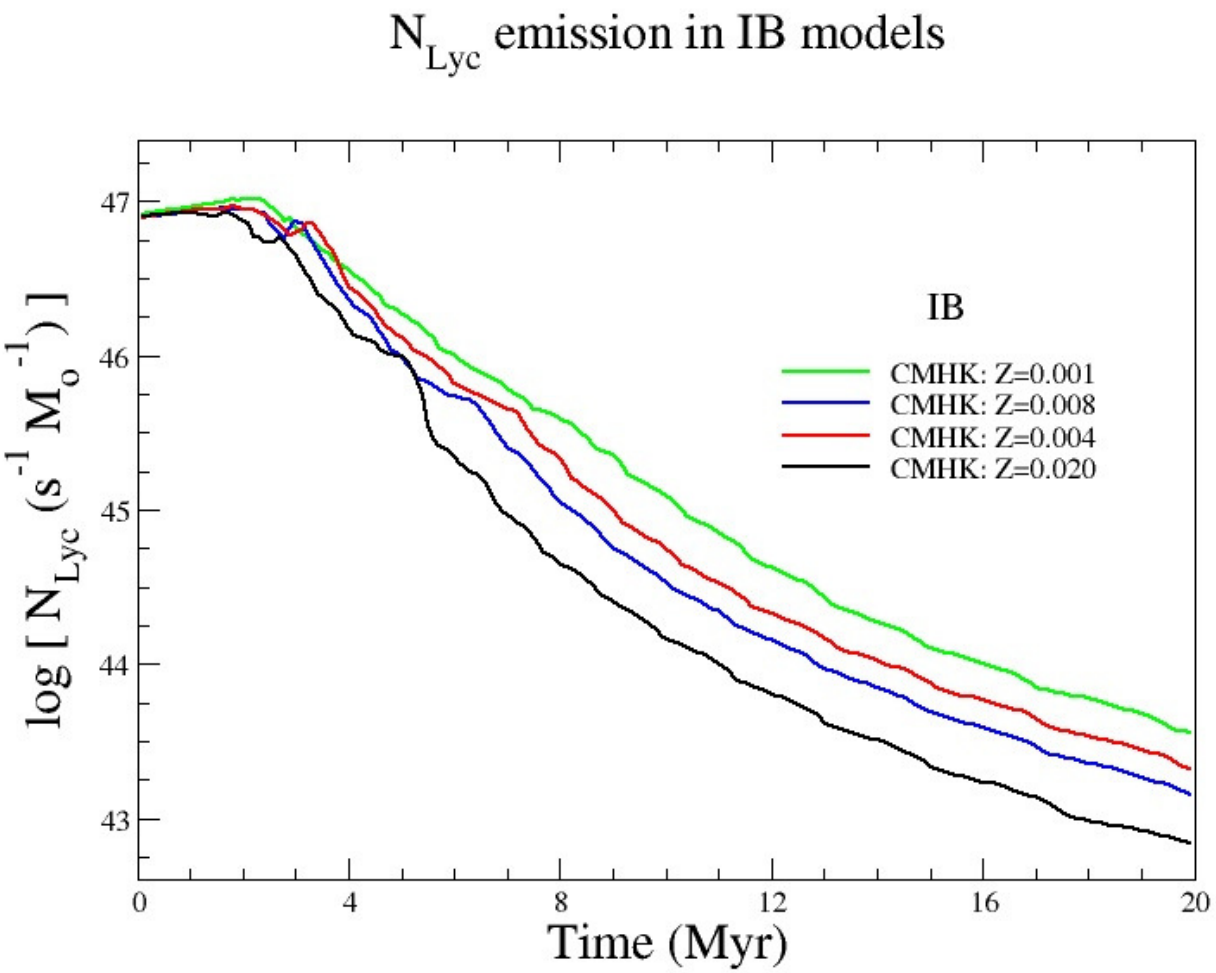
  $\Rightarrow$ Balmer lines (among others)
- Assume a fraction 1-f=0.3 is absorbed by dust before ionization $\rightarrow$ f-correction
- Based on this one, SFR and SFS calibrations for Hα and Lyα can be obtained

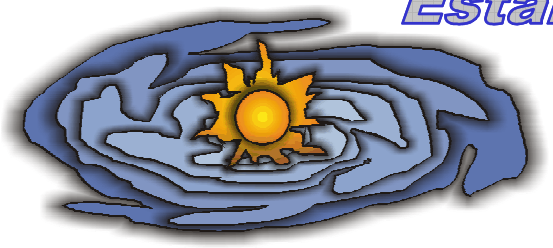
IONIZING PHOTONS 2



EB: attains rapidly the steady state

IONIZING PHOTONS 3

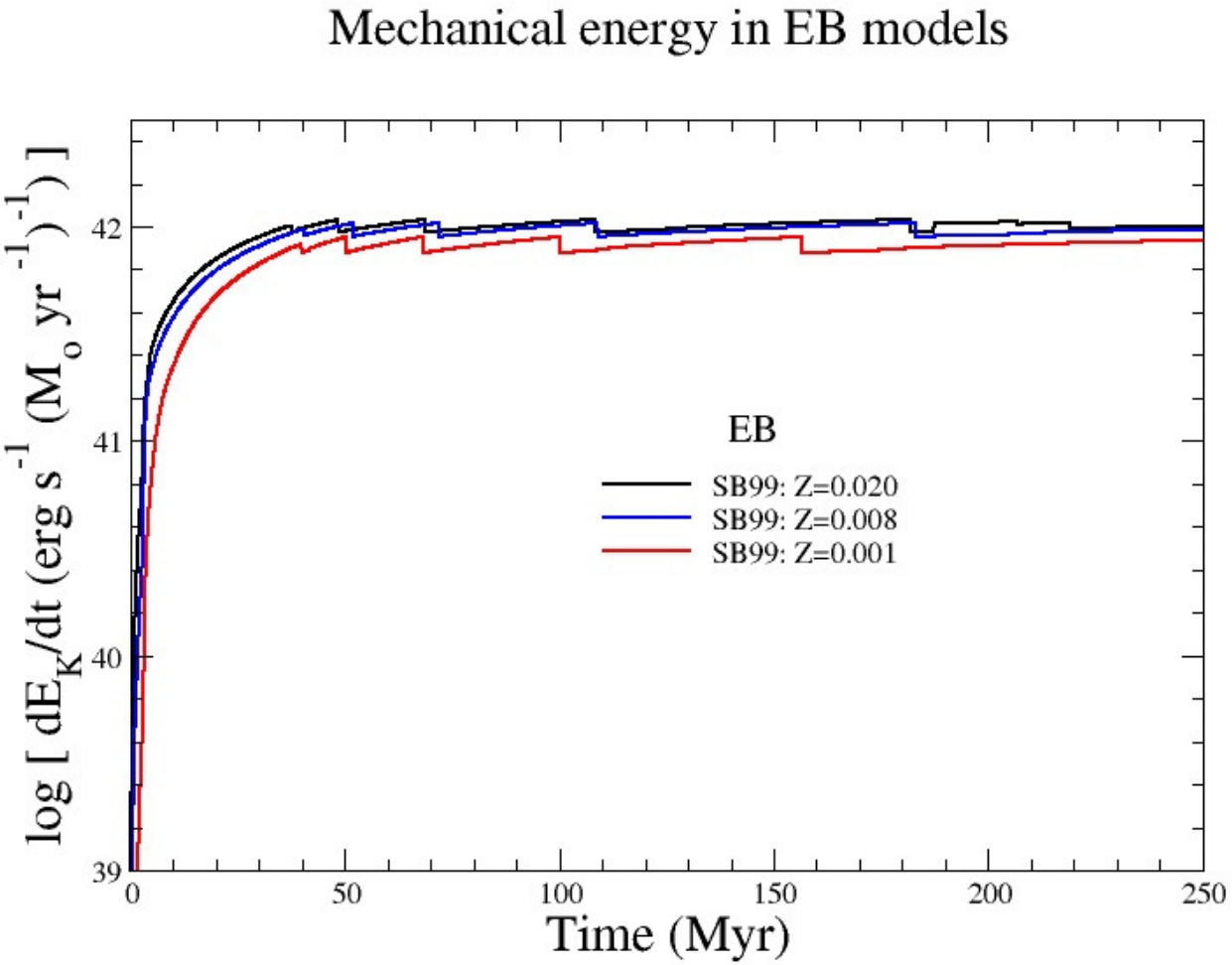




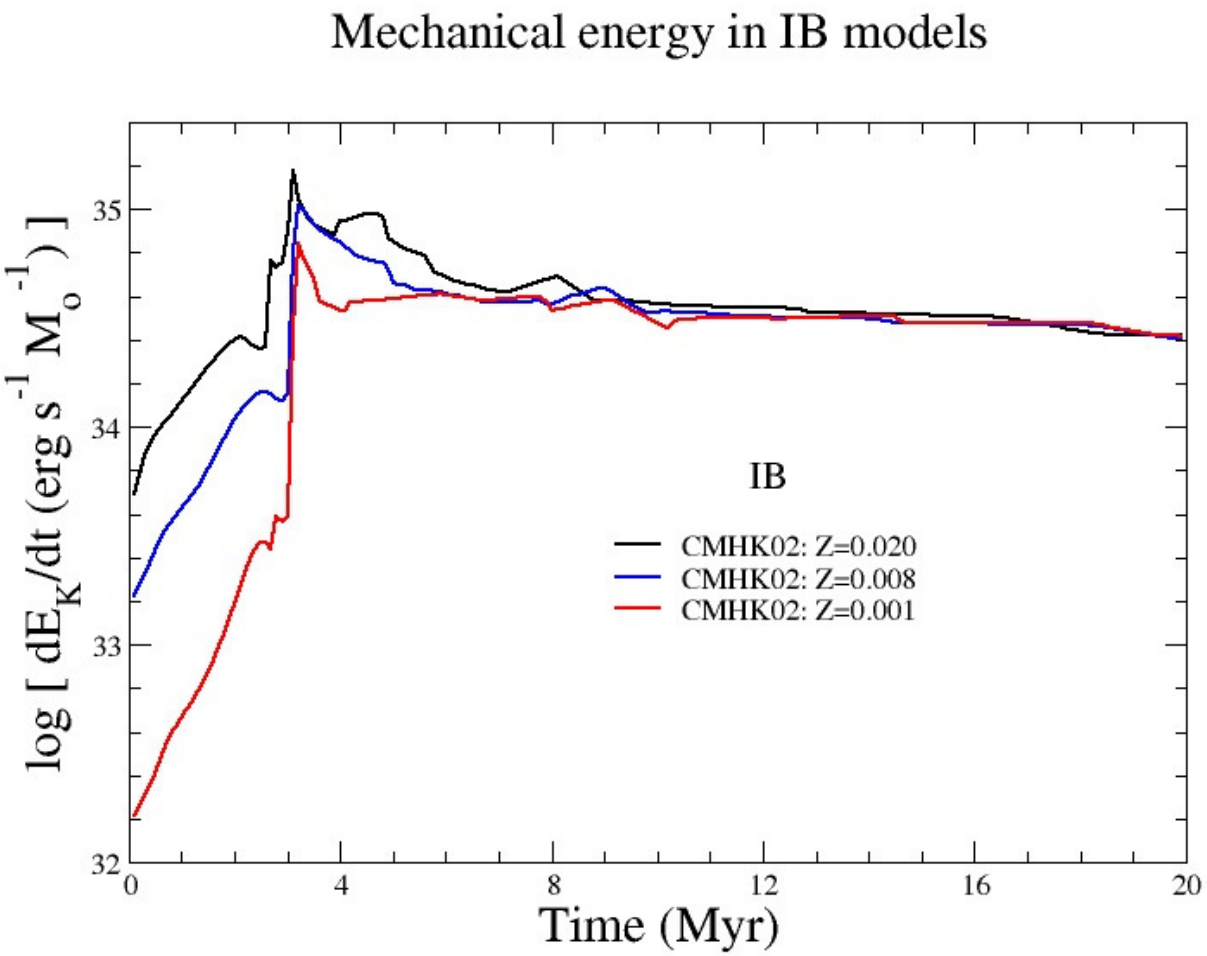
MECHANICAL ENERGY 1

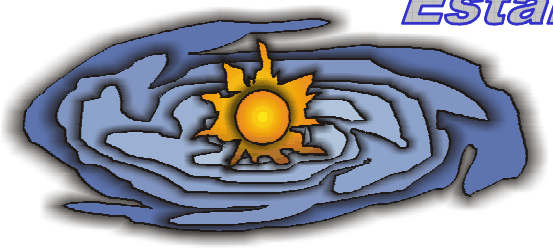
- Winds from massive stars and SNe inject mechanical energy into the medium
- dE_K/dt: energy injected per unit of time
- Dominance:
  - Early ages: winds
  - When massive stars commence to die: SNe
- Metallicity:
  - When Z↓ ⇒ power of winds ↓, number of WR stars ↓

MECHANICAL ENERGY 2



MECHANICAL ENERGY 3

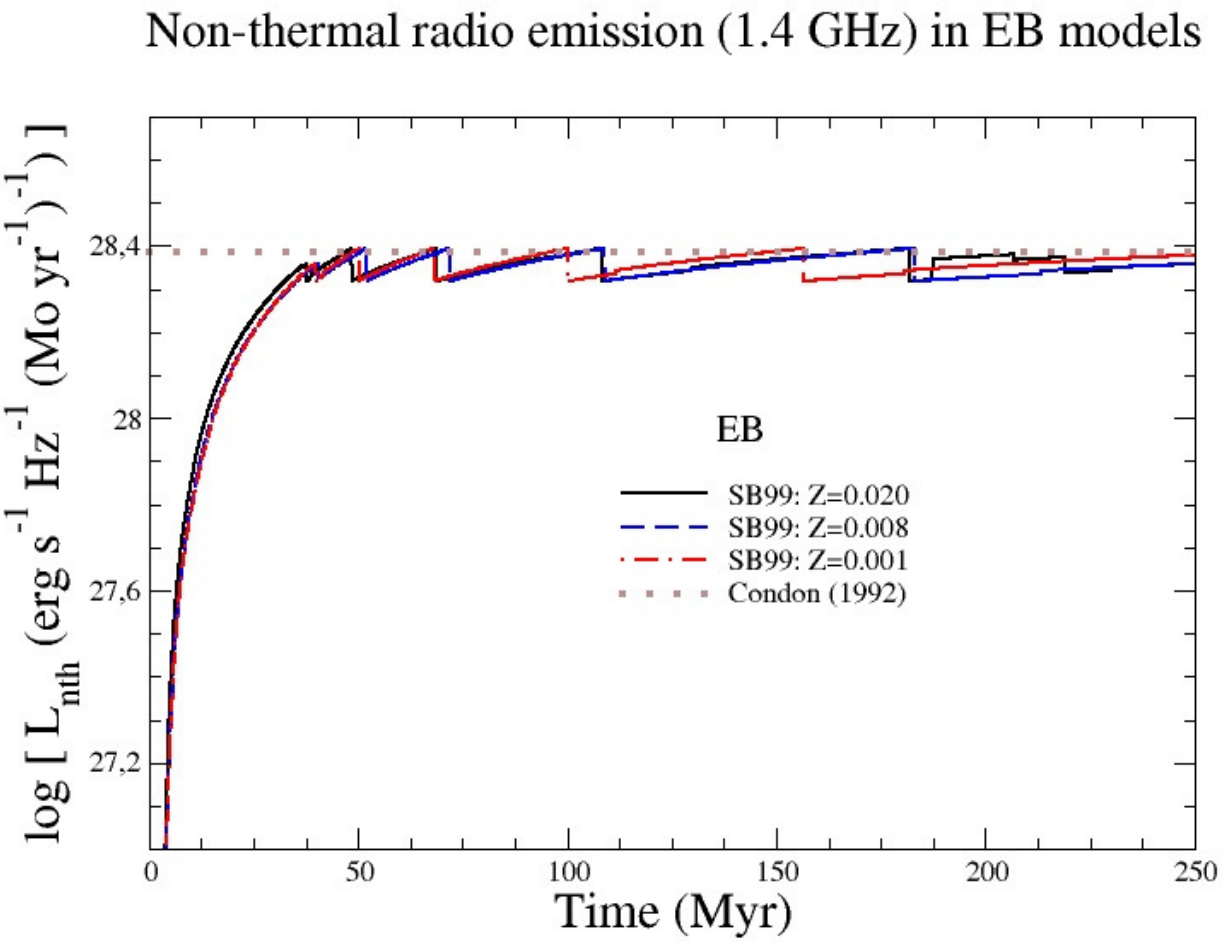




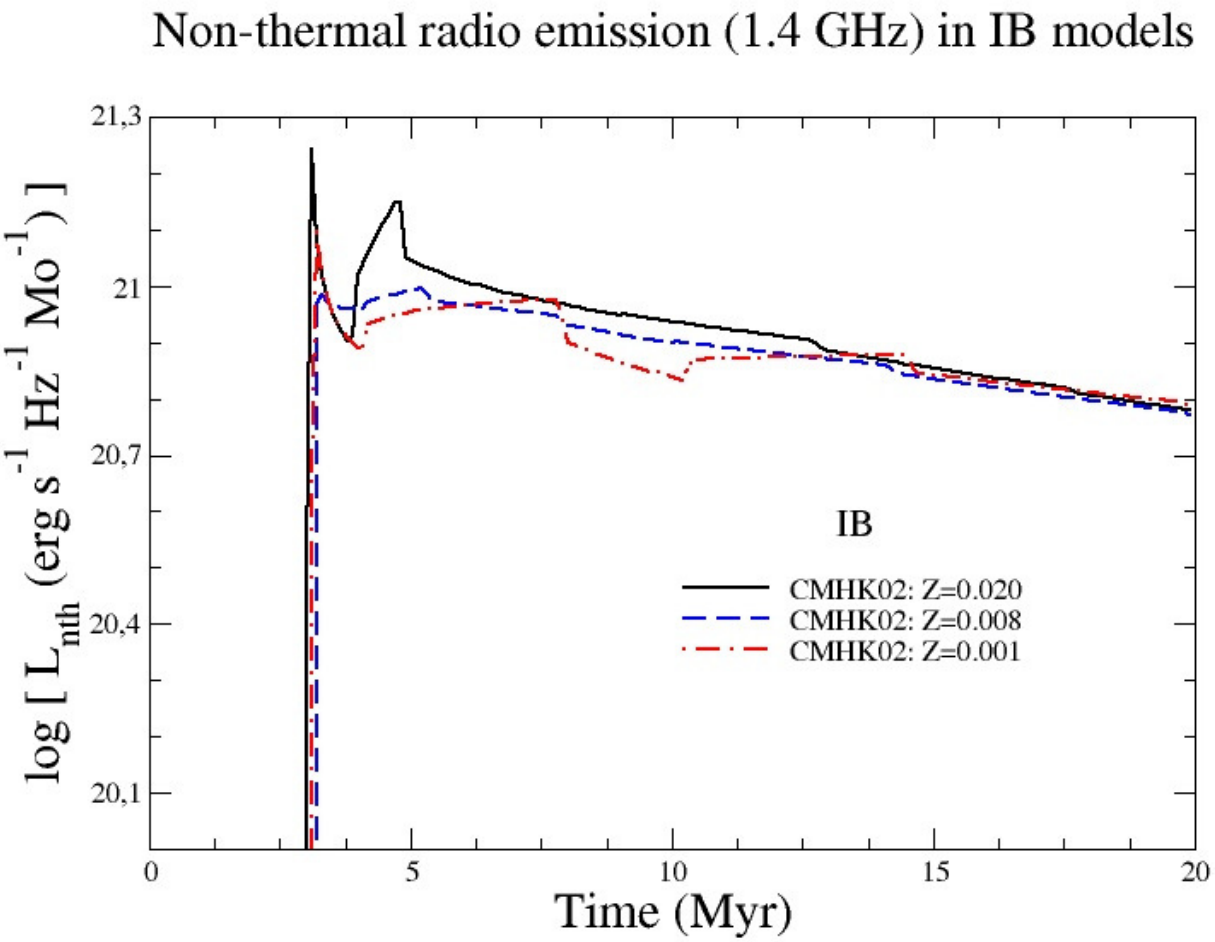
RADIO EMISSION

- Two contributions
  - Thermal: free-free transitions
    - Emission $\propto N_{Lyc}$ (Rubin 1968) $\Rightarrow$ Analagous behaviour to N_{Lyc}
    - SFR calibration by Condon (1992) agrees with ours due to a double disagreement:
      - No f-correction is performed
      - Hα emission is subestimated
  - Non-thermal: synchrotron radiation from e^- accelerated by SNe
    - Emission $\propto$ SN rate, Condon (1992) but α=-0.9

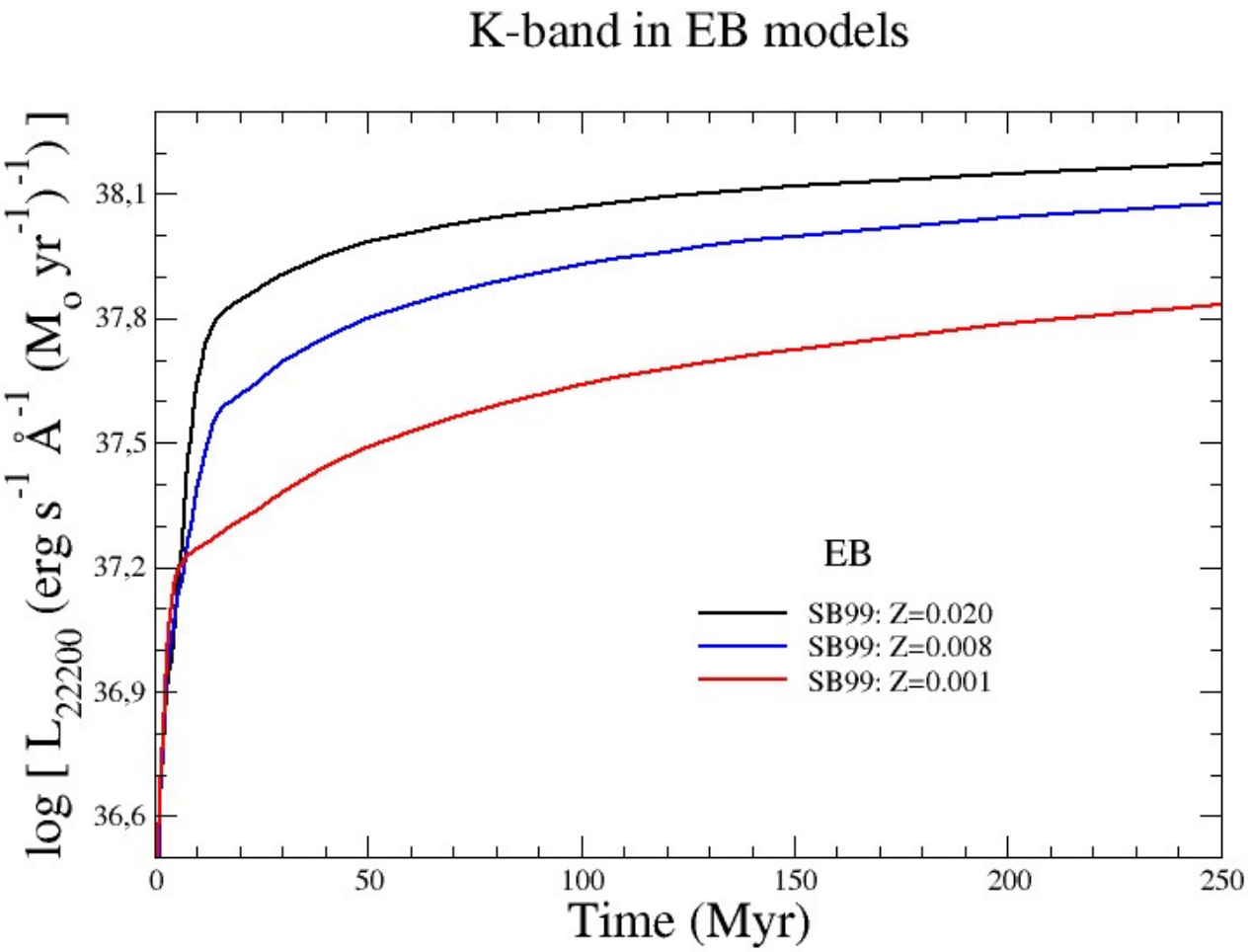
NON-THERMAL RADIO EMISSION 1



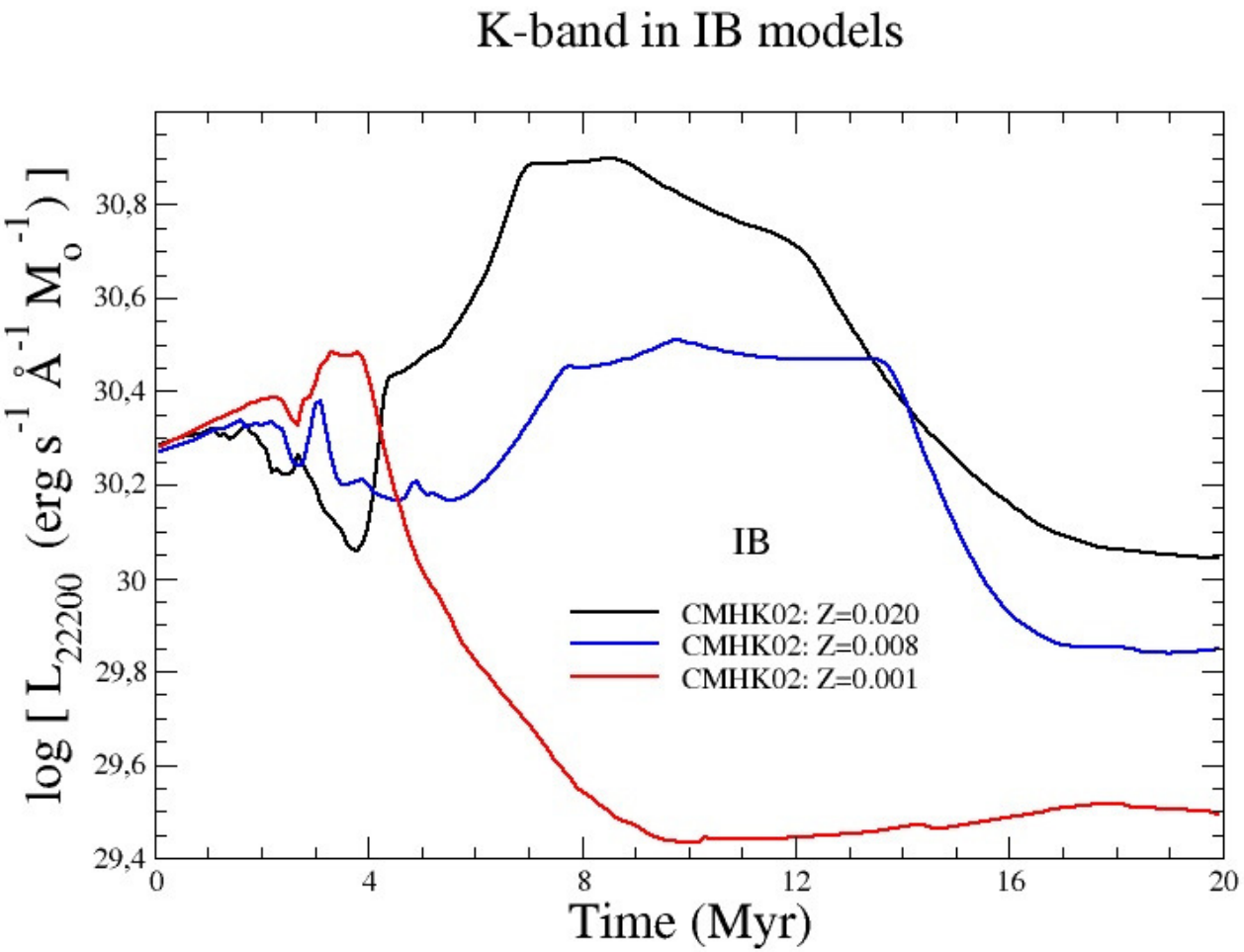
NON-THERMAL RADIO EMISSION 2



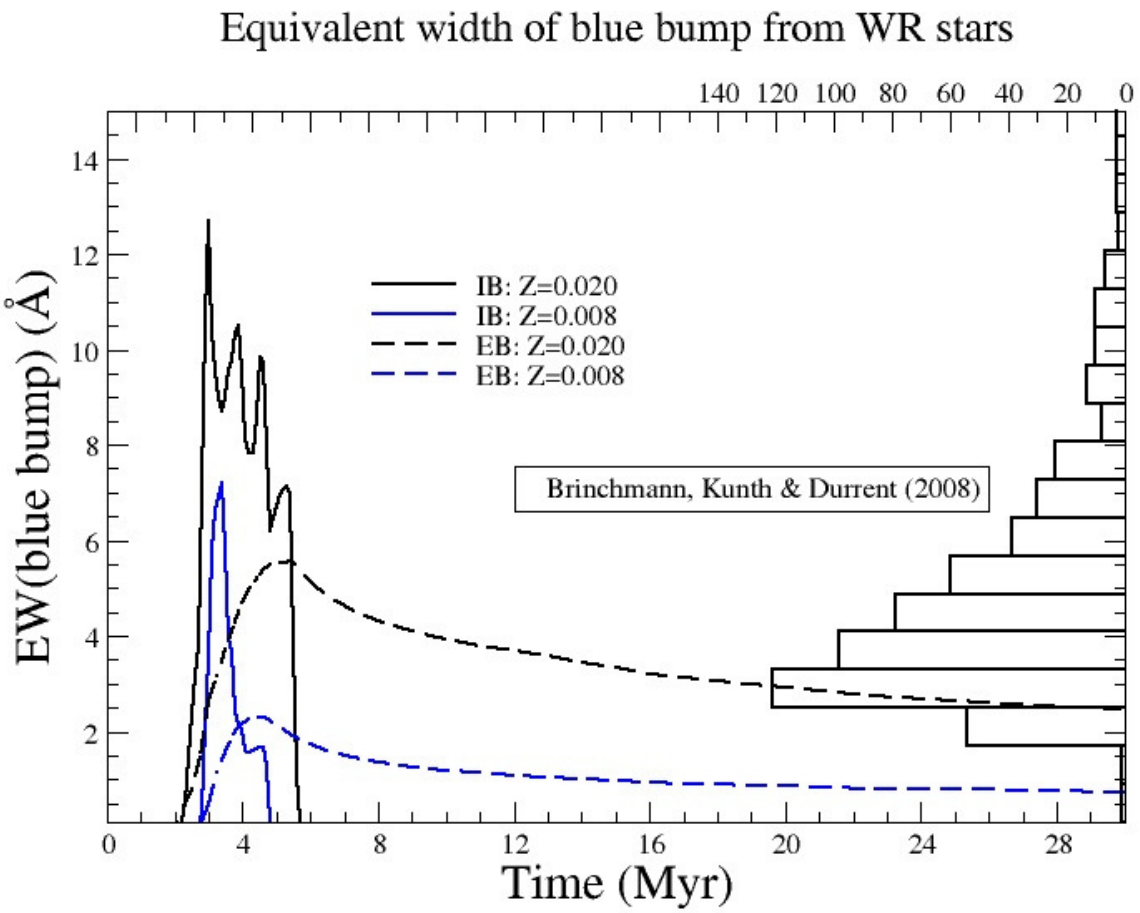
K-BAND 1


K-band in EB models
log [L2200 (erg s-1 Å-1 (Mo yr-1)-1)]
38,1
37,8
37,5
37,2
36,9
36,6
0
50
100
150
200
250
Time (Myr)
EB
SB99: Z=0.020
SB99: Z=0.008
SB99: Z=0.001

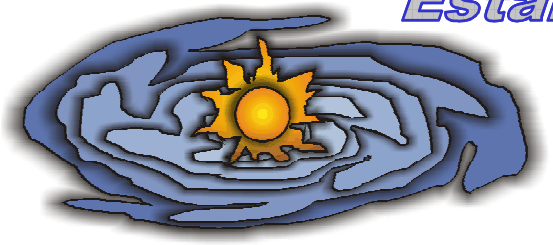
K-BAND 2


K-band in IB models
log [L22200 (erg s-1 Å-1 Mo-1)]
30,8
30,6
30,4
30,2
30
29,8
29,6
29,4
0
4
8
12
16
20
Time (Myr)
IB
CMHK02: Z=0.020
CMHK02: Z=0.008
CMHK02: Z=0.001

IB MODELS



EB models can not account for most values
IB models must be considered → SFS calibrations



EB: SFR CALIBRATION

SFR(M_o/yr) = A * magnitude

Magnitude	EB (10 Myr)	EB (30 Myr)	EB (250 Myr)
L_{1500}	4.1×10^{-41}	3.3×10^{-41}	2.7×10^{-41}
L_{2000}	8.4×10^{-41}	6.6×10^{-41}	5.1×10^{-41}
L_{3500}	3.4×10^{-40}	2.6×10^{-40}	1.8×10^{-40}
FIR (1-1000 μm)	1.9×10^{-44}	1.5×10^{-44}	1.2×10^{-44}
N_{Lyc}	4.1×10^{-54}	4.1×10^{-54}	4.1×10^{-54}
Hα	3.0×10^{-42}	3.0×10^{-42}	3.0×10^{-42}
$Ly\alpha_{int}$	2.5×10^{-43}	2.5×10^{-43}	2.5×10^{-43}
$Ly\alpha_{corr}$ (f_{esc}=0.1)	2.5×10^{-42}	2.5×10^{-42}	2.5×10^{-42}
dE_K/dt	2.2×10^{-42}	1.1×10^{-42}	9.9×10^{-43}
L_{softX} (0.4-2.4 keV)	8×10^{-41}	2×10^{-41}	-
L_{th} (1.4 GHz)	2.7×10^{-28}	2.7×10^{-28}	2.7×10^{-28}
L_{nth} (1.4 GHz)	1.4×10^{-28}	5.1×10^{-29}	4.4×10^{-29}
L_{4400}	6.5×10^{-40}	4.2×10^{-40}	2.2×10^{-40}
L_{5500}	1.1×10^{-39}	7.2×10^{-40}	3.6×10^{-40}
L_{22000}	2.3×10^{-38}	1.2×10^{-38}	6.7×10^{-39}

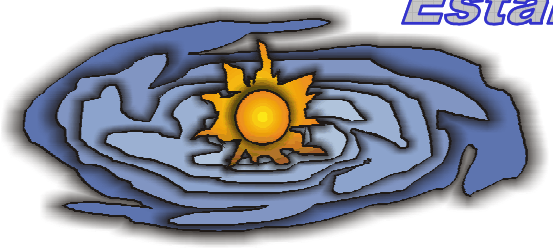


EB: 2-120 $M_o \rightarrow$ 0.1-100 M_o

SFR(2-120 M_o) = A * magnitude → SFR(0.1-100 Mo) = A*r * magnitude

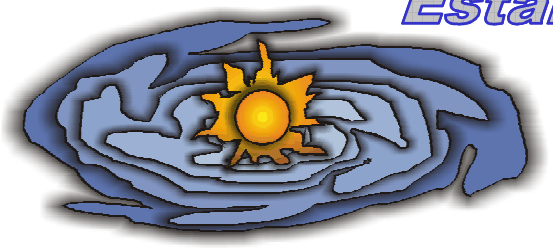
These are the r values:

Magnitude	EB (10 Myr)	EB (30 Myr)	EB (250 Myr)
L_{1500}	3.6115	3.5707	3.5413
L_{2000}	3.6286	3.5794	3.5308
L_{3500}	3.6683	3.5963	3.4734
FIR (1-1000 μm)	3.6549	3.6025	3.5260
N_{Lyc}	3.9355	3.9446	3.9446
Hα	3.9355	3.9446	3.9446
$Ly\alpha_{int}$	3.9355	3.9446	3.9446
$Ly\alpha_{corr}$ (f_{esc}=0.1)	3.9355	3.9446	3.9446
dE_K/dt	3.7325	3.5645	3.5481
L_{th} (1.4 GHz)	3.9355	3.9446	3.9446
L_{nth} (1.4 GHz)	3.4914	3.4435	3.4435
L_{4400}	3.5436	3.4694	3.2841
L_{5500}	3.5278	3.4538	3.2578
L_{22000}	3.4973	3.4458	3.3620



CONCLUSIONS 1

- Robust calibrations of SFR and SFS based on several tracers have been obtained using synthesis models
- Appropriate calibrations should be used depending on the burst properties
  - Star formation regime: EB or IB **VERY IMPORTANT**
  - Age **VERY IMPORTANT, especially in IB models**
  - Metallicity: importance depends on magnitude
  - E(B-V), etc.



CONCLUSIONS 2

- Comparison with previous calibrations (after IMF corrections):
  - Kennicutt (1998):
    - UV: good agreement at all ages > 30 Myr
    - FIR: applies only at ages > 50 Myr
    - N_{Lyc}/Hα/Lyα: after correction for prior dust absorption, at ages > 8 Myr
  - Condon (1992): we follow same prescriptions