# Neutrino Signatures from the First Stars

- Cosmic Chemical Evolution
- Early Reionization and Massive Stars
- Neutrino production and predicted fluxes

Daigne,Olive,Sandick,Vangioni
Daigne,Olive,Silk,Stoehr,Vangioni

# Elements of Cosmic Chemical Evolution

- Star Formation Rate, $\Psi$
  - Greatly enhanced at high redshift
- Initial Mass Function, $\varphi$
  - Bimodal distribution including massive mode
- Element Production
  - compared against observations in DLAs, the IGM and iron-poor stars
- Supernovae Rates

# Evolution of Structure

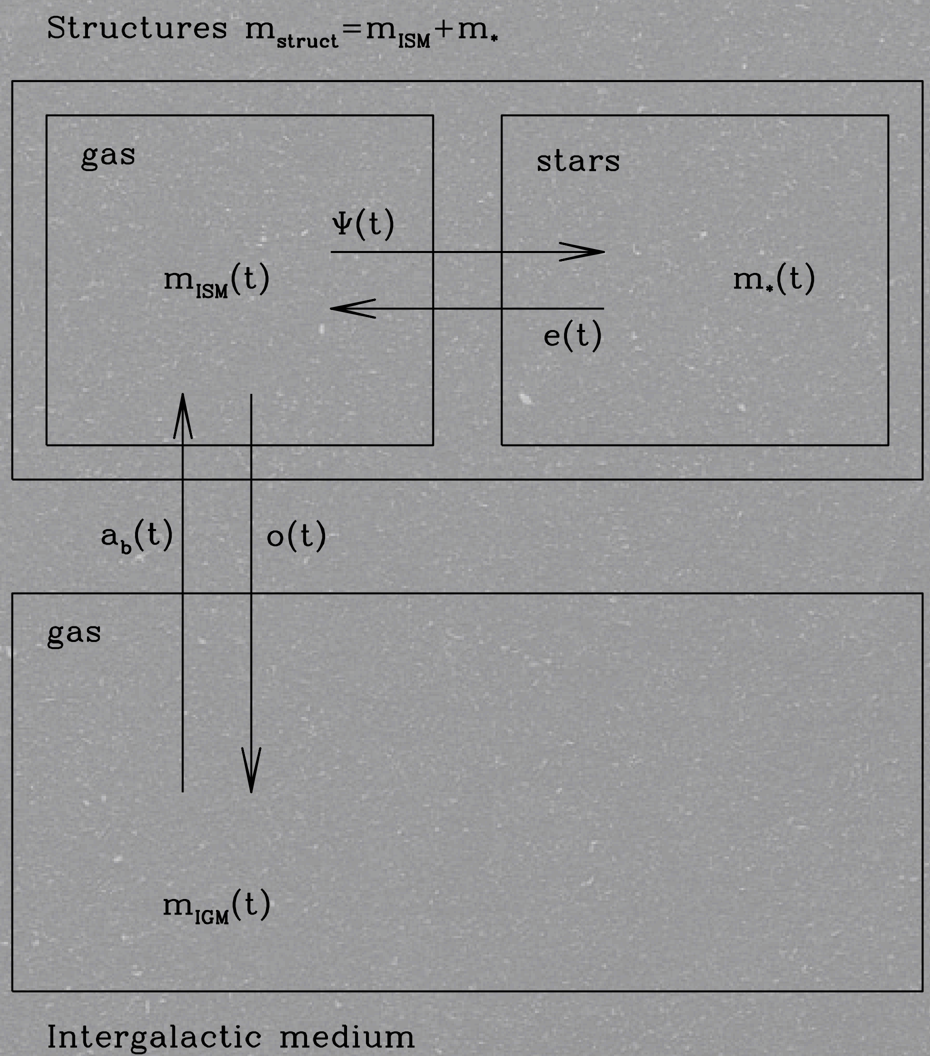
- Structure growth based on Press-Schechter formalism

$$\frac{dM_{\rm IGM}}{dt} = -\frac{dM_{\rm struct}}{dt} = -a_{\rm b}(t) + o(t),$$

$$\frac{dM_*}{dt} = \Psi(t) - e(t) \text{ and } \frac{dM_{\rm ISM}}{dt} = \frac{dM_{\rm struct}}{dt} - \frac{dM_*}{dt}\ .$$

$$f_{\rm b,struct}(z) = \frac{\int_{M_{\rm min}}^{\infty} dM\ M f_{\rm PS}(M,z)}{\int_0^{\infty} dM\ M f_{\rm PS}(M,z)}\ .$$

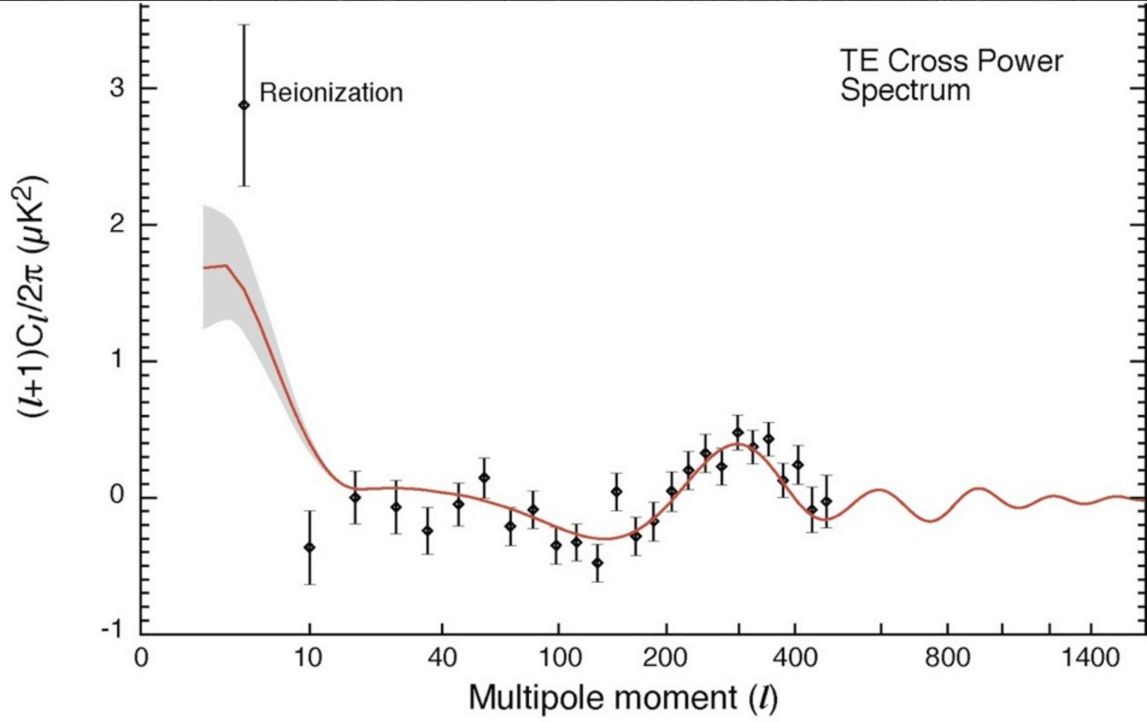
$$a_b \propto \frac{df_b}{dt}$$



# WMAP and Reionization

WMAP cross power spectrum ⇒ Universe reionized at high redshift z ~ 15 ⇒ population of massive stars

Kogut et al.
Cen
Haiman & Holder
Wyithe & Loebe
Bromm
Ciardi et al.



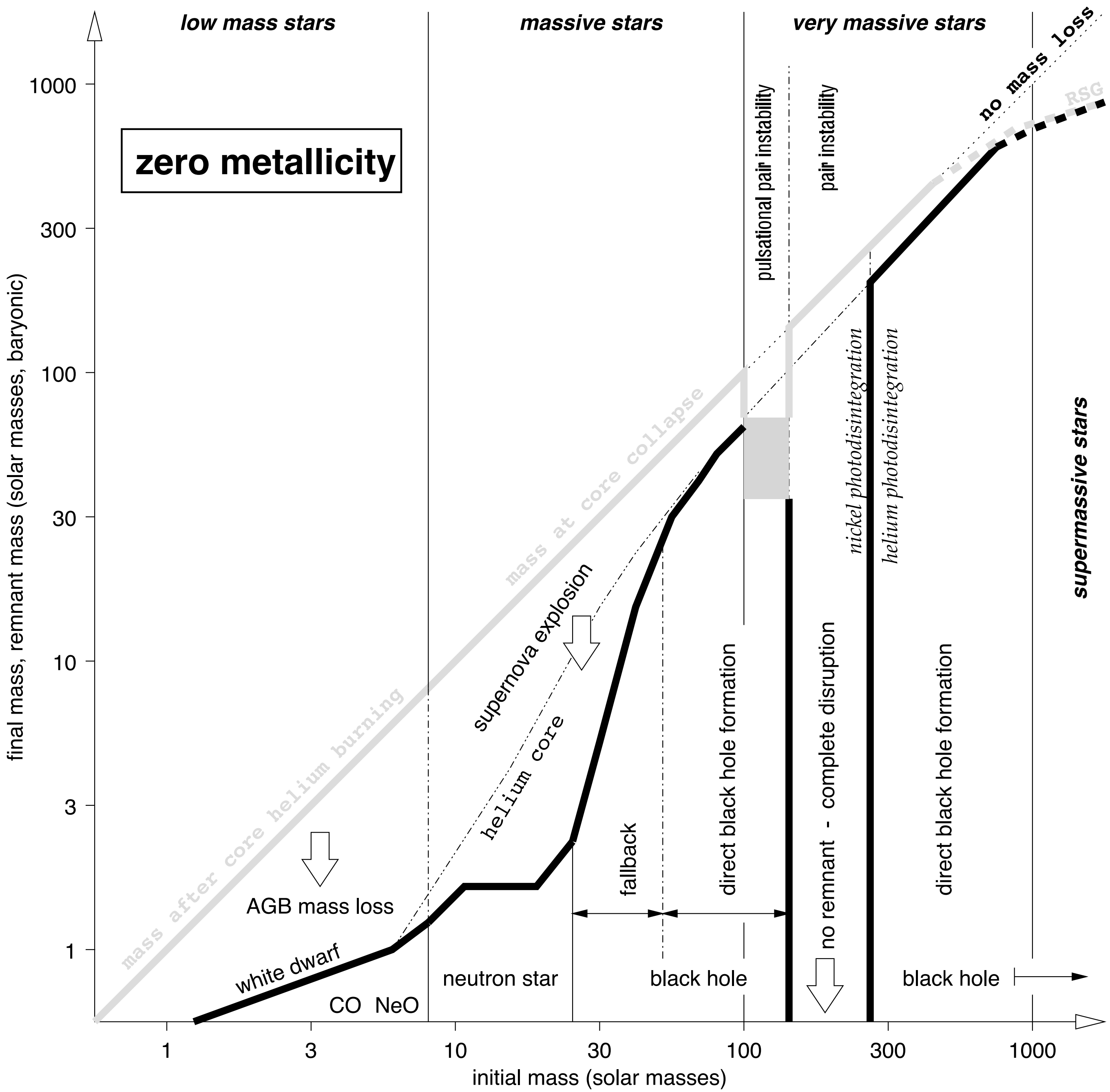
# Bimodal Star Formation

$$B(m,t,Z) = \Phi_1(m)\Psi_1(t) + \Phi_2(m)\Psi_2(Z)$$

- Normal Mode of Star Formation

  $0.1 < M_\odot < 100$ Model 0

- Massive Mode
  - $40 < M_\odot < 100$ Model 1
  - $140 < M_\odot < 260$ Model 2a
  - $270 < M_\odot < 500$ Model 2b


low mass stars
massive stars
very massive stars
zero metallicity
1000
300
100
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
no mass loss
RSG
pulsational pair instability
pair instability
mass at core collapse
nickel photodisintegration
helium photodisintegration
supermassive stars
supernova explosion
mass after core helium burning
helium core
AGB mass loss
fallback
direct black hole formation
no remnant - complete disruption
direct black hole formation
white dwarf
CO NeO
neutron star
black hole
black hole
1
3
10
30
100
300
1000
initial mass (solar masses)

# MiniHalos and the onset of star formation

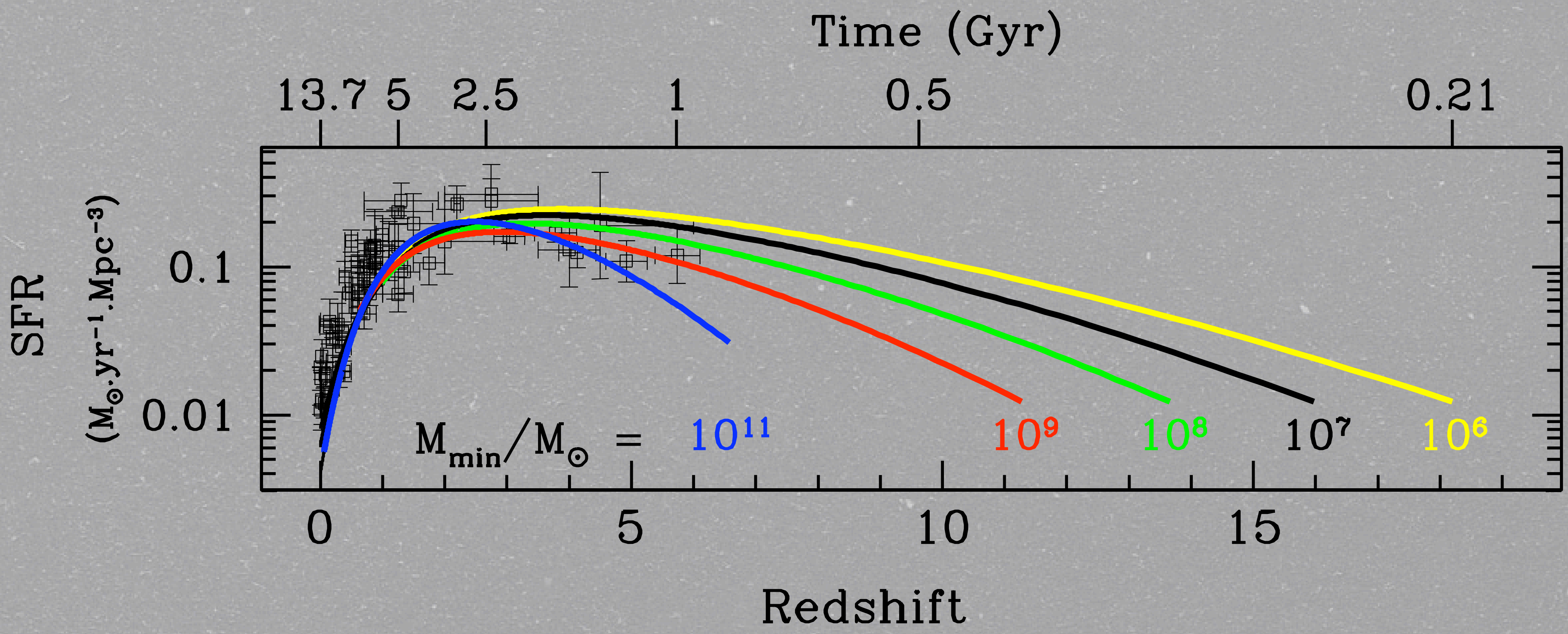
## Input Parameters

- Minimum Halo Mass: $10^6, 10^7, 10^8, 10^9, 10^{11}\, M_\odot$
- Onset of Star formation: $f_b = 0.01$
  - determines initial redshift for star formation
- Critical Metallicity: $Z_c$

  Bromm & Loeb
  Yoshida et al.
- Efficiency of outflow

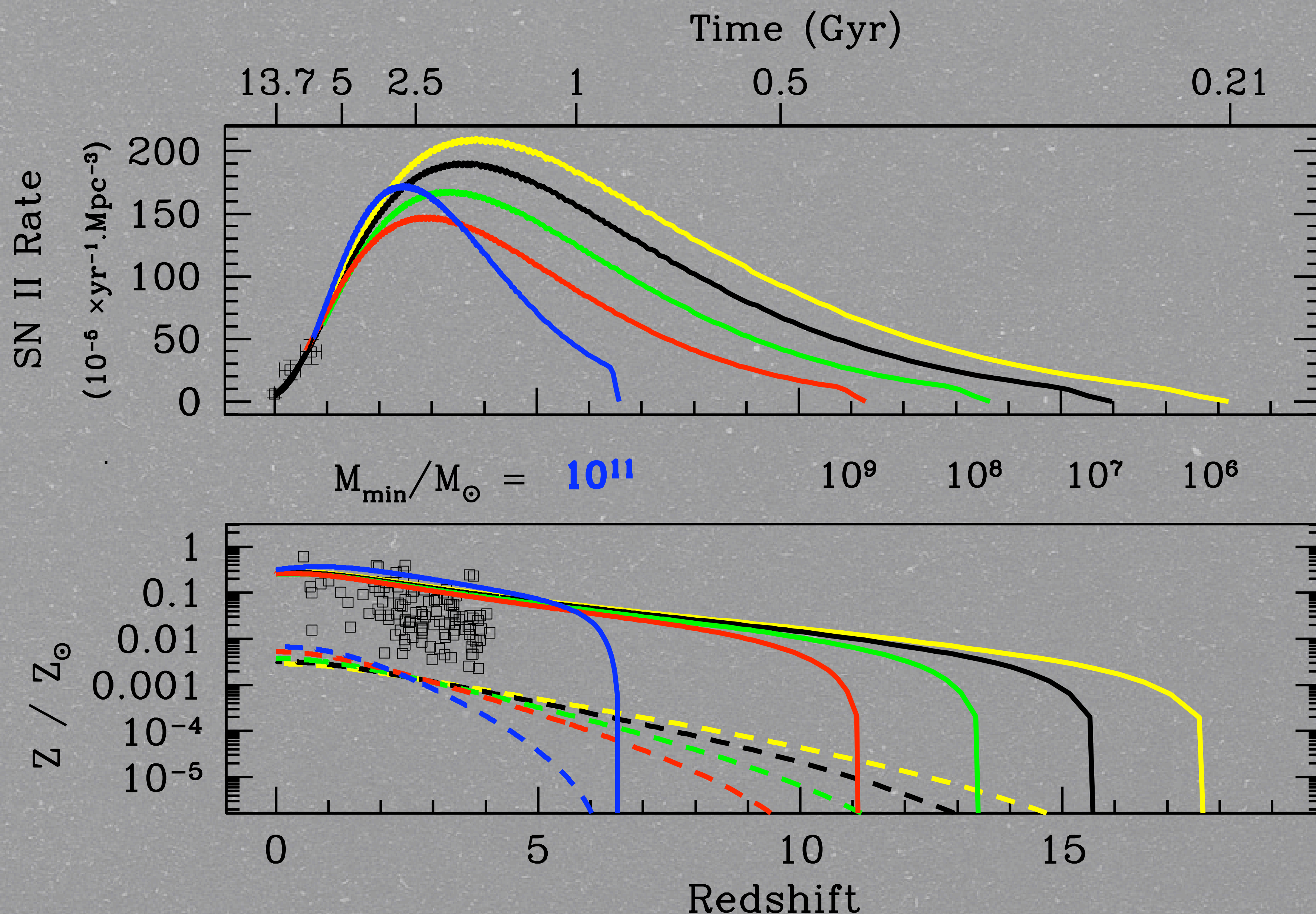
# Normal Mode of Star Formation

$\Psi(t) = \nu_1 \exp\left(-(t - t_{\rm init})/\tau_1\right)$ + Salpeter IMF

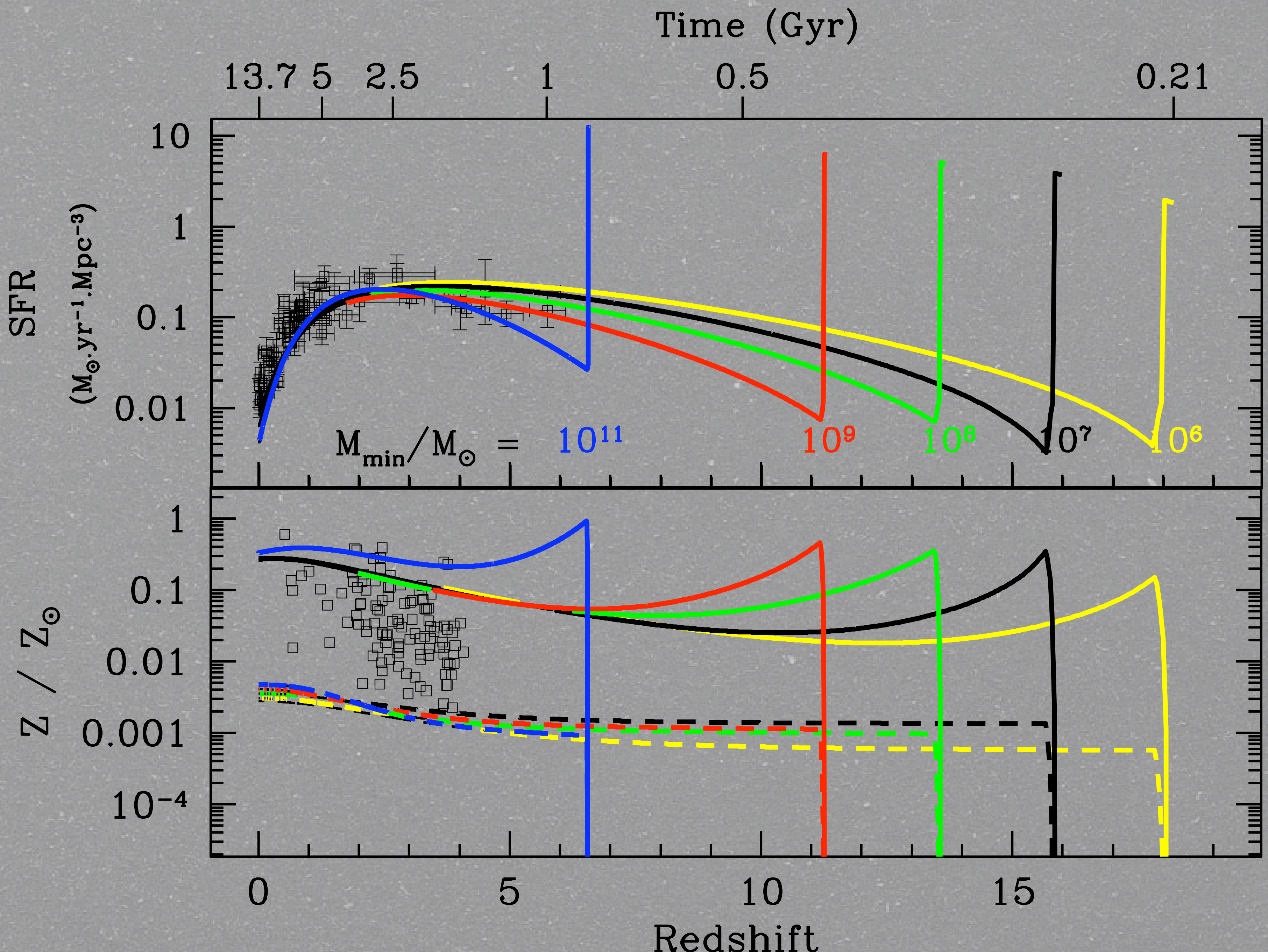



Eg. Hopkins

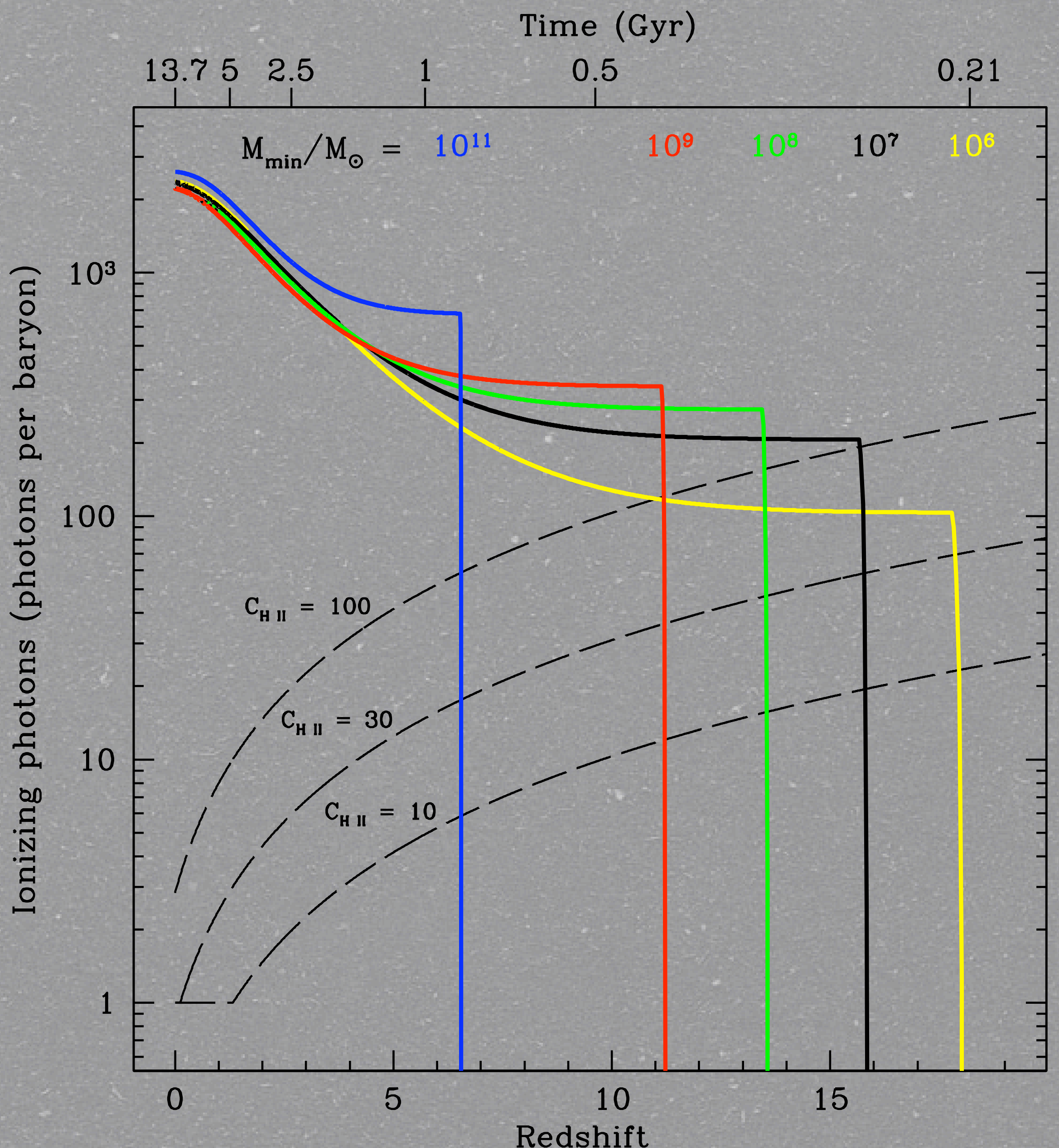
# Consequences



# Adding the massive mode

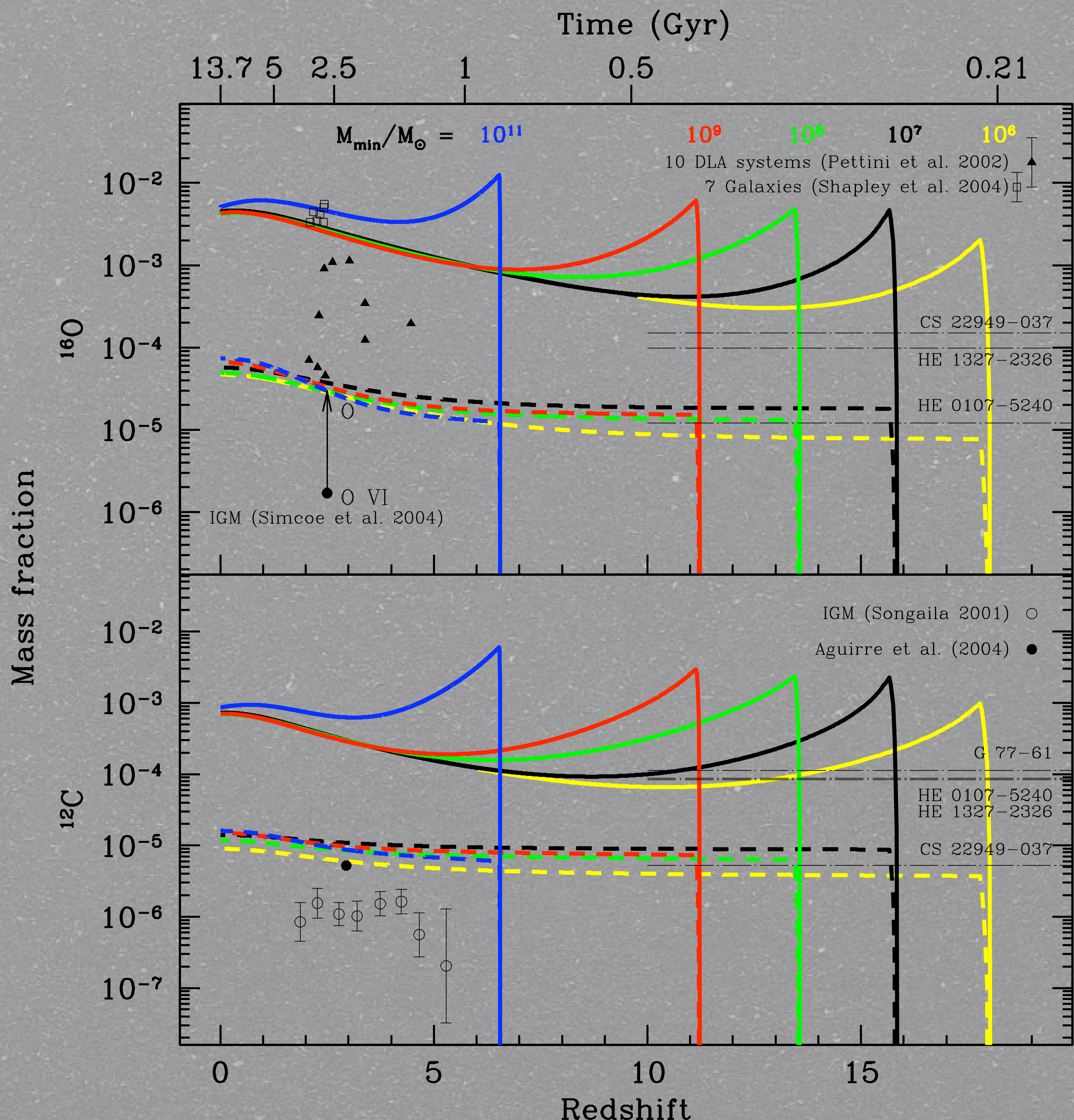


# Ionization



Time (Gyr)
13.7
5
2.5
1
0.5
0.21
$M_{min}/M_{\odot}$ = $10^{11}$ $10^{9}$ $10^{8}$ $10^{7}$ $10^{6}$
Ionizing photons (photons per baryon)
$10^3$
100
10
1
$C_{H\,II}$ = 100
$C_{H\,II}$ = 30
$C_{H\,II}$ = 10
0
5
10
15
Redshift

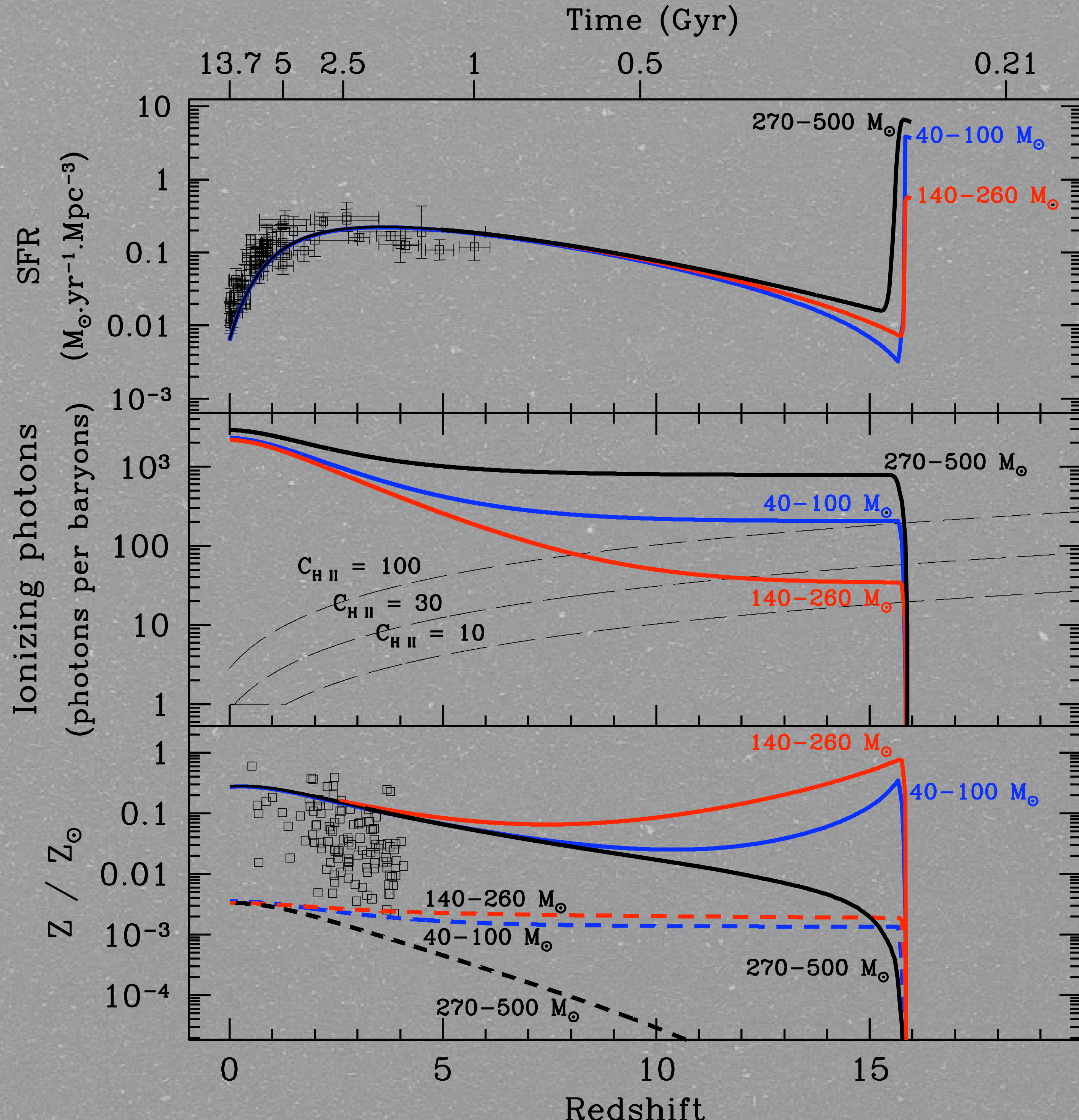
# Chemical Evolution



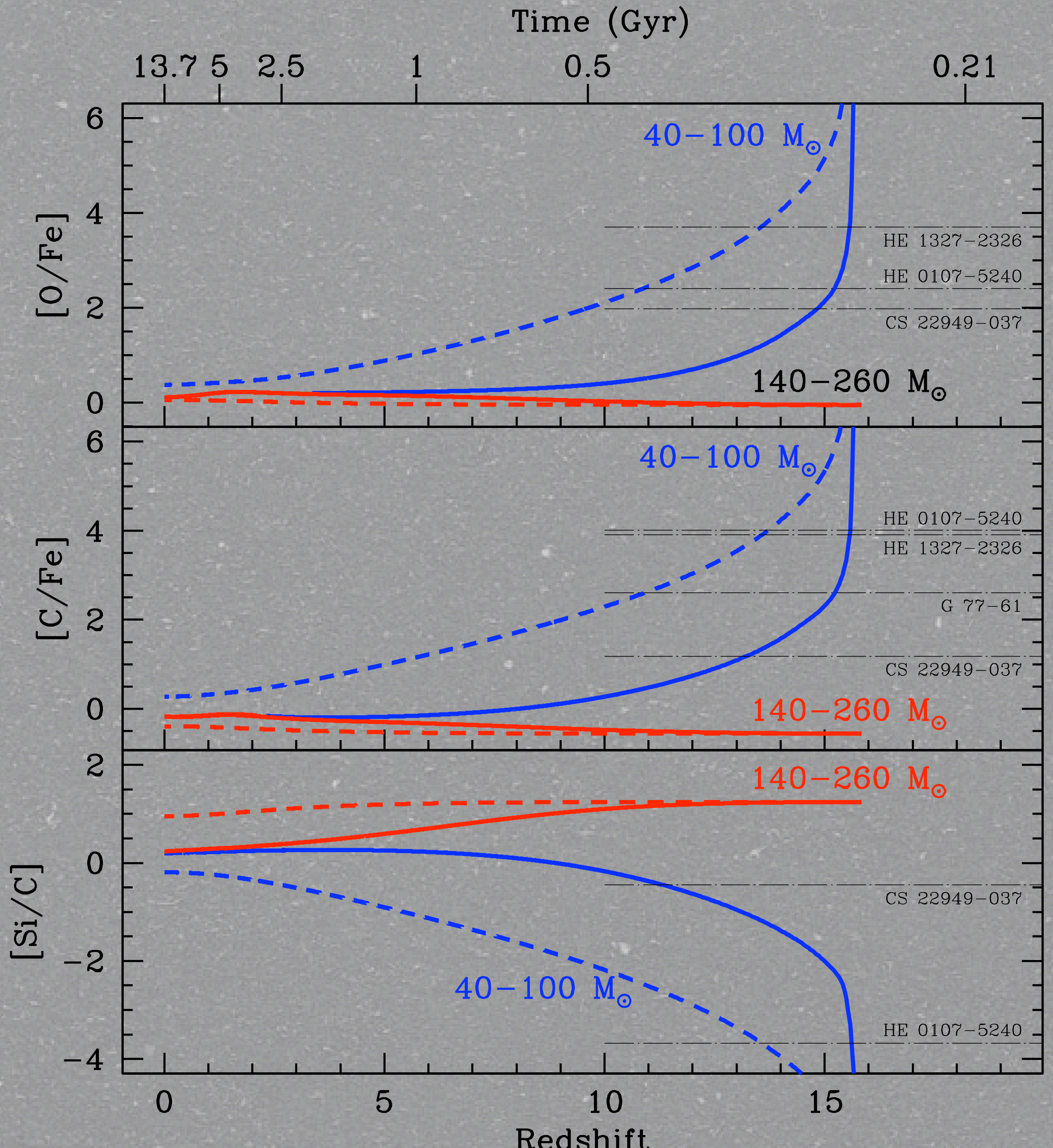
# Very Massive Stars

- Generally assumed that the first generation of stars were very massive
- Pair-instability supernovae

  Heger & Woosley
  - total disruption
  - significant metal production
  - difficulty to reionize
- 300+ solar mass stars
  - total collapse
  - no metal production
  - efficient at reionization



Time (Gyr)
13.7
5
2.5
1
0.5
0.21
SFR
($M_\odot$.yr$^{-1}$.Mpc$^{-3}$)
10
1
0.1
0.01
$10^{-3}$
270−500 $M_\odot$
40−100 $M_\odot$
140−260 $M_\odot$
Ionizing photons
(photons per baryons)
$10^3$
100
10
1
$C_{H\,II}$ = 100
$C_{H\,II}$ = 30
$C_{H\,II}$ = 10
270−500 $M_\odot$
40−100 $M_\odot$
140−260 $M_\odot$
Z / $Z_\odot$
1
0.1
0.01
$10^{-3}$
$10^{-4}$
140−260 $M_\odot$
40−100 $M_\odot$
140−260 $M_\odot$
40−100 $M_\odot$
270−500 $M_\odot$
270−500 $M_\odot$
0
5
10
15
Redshift



Time (Gyr)
13.7
5
2.5
1
0.5
0.21
[O/Fe]
40−100 M⊙
HE 1327−2326
HE 0107−5240
CS 22949−037
140−260 M⊙
[C/Fe]
40−100 M⊙
HE 0107−5240
HE 1327−2326
G 77−61
CS 22949−037
140−260 M⊙
[Si/C]
140−260 M⊙
CS 22949−037
40−100 M⊙
HE 0107−5240
Redshift

# Neutrino Production

There is an accumulated flux of supernova relic neutinos

$$\frac{dF_\alpha}{dE} = \int_0^{z_i} dz\,(1+z)\left|\frac{dt}{dz}\right| \int_{M_{min}}^{M_{max}} dm\,\phi(m)\,\psi\left(t-\tau(m)\right)\,N_{\nu_\alpha}(m)\,\frac{dP_\alpha}{dE'}$$

- Totani & Sato (1995) + Yoshi (1996)
- Ando, Sato, & Totani (2003) Ando (2004)
- Kaplinghat, Steigman, & Walker (2000)
- Strigari et al. (2004, 2005)
- Iocco et al. (2005)

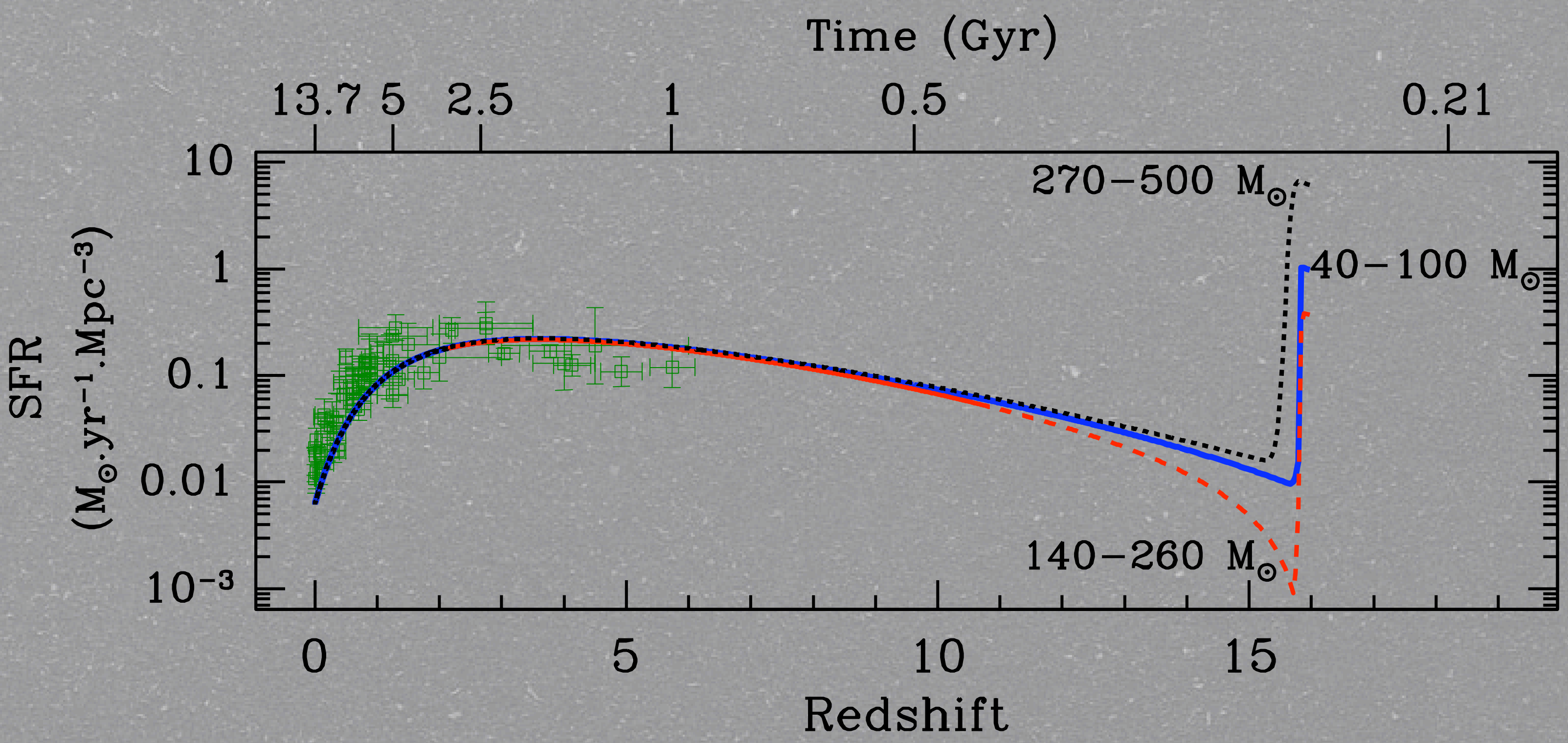
# Calculation Inputs

- Final State
  - neutron star $8M_\odot < m < 30M_\odot$ $E_\nu = 3 - 5 \times 10^{53} ergs$
  - black holes $m < 100M_\odot$ $E_\nu \sim .16(m - 20M_\odot)$
  - PISN $E_\nu = 3 - 5 \times 10^{53} ergs, \mathrm{but} \langle E_\nu \rangle = 1.2\mathrm{MeV}$
  - black Holes $E_\nu = 0.3m$
- Average neutrino energy
  - $\langle E_{\nu_e} \rangle = 13.3\mathrm{MeV}$
  - $\langle E_{\bar{\nu}_e} \rangle = 15.3\mathrm{MeV}$
  - $\langle E_{\nu_x} \rangle = 20.0\mathrm{MeV}$

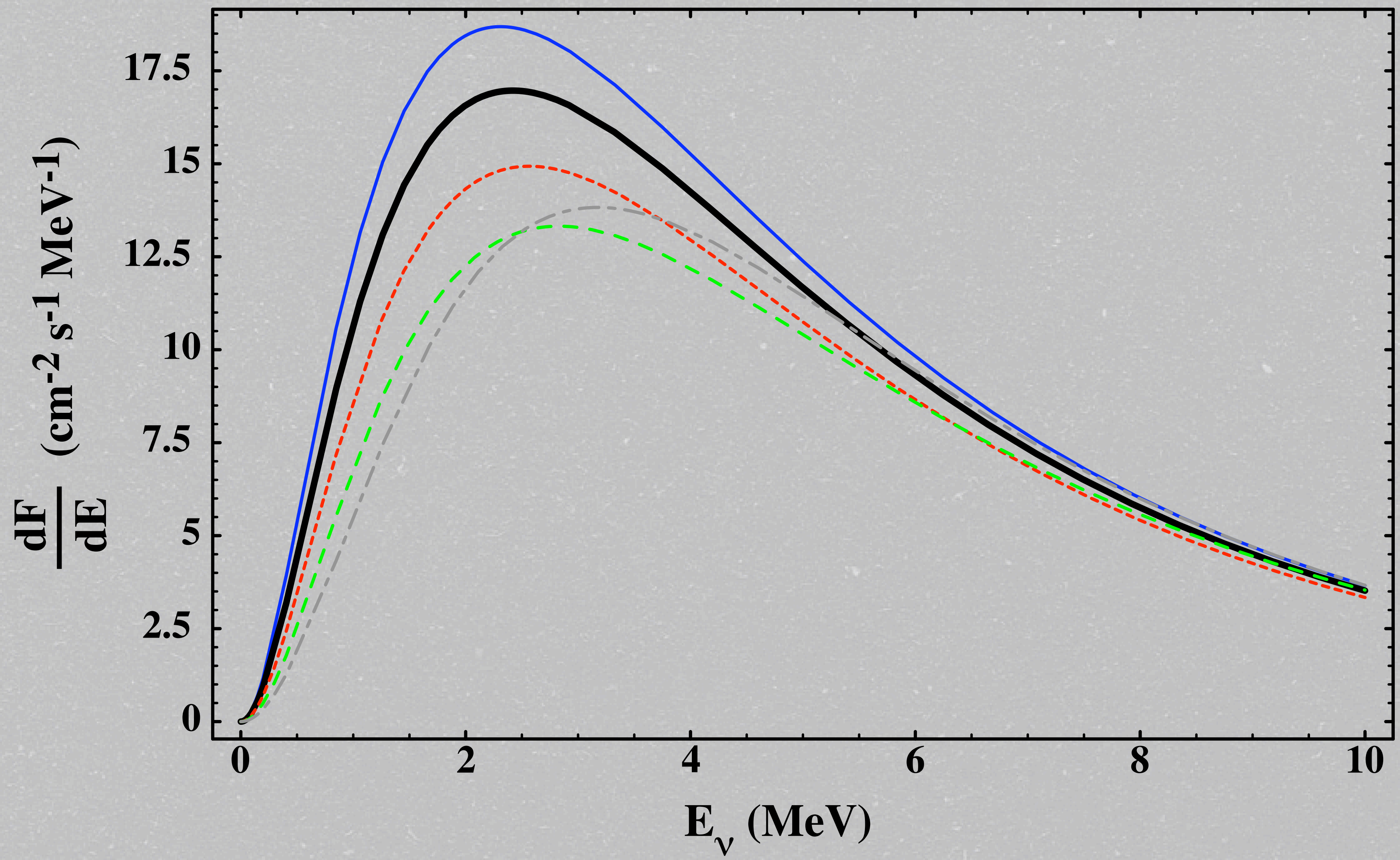
Totani et al.
Keil et al.
Iocco et al.

# More inputs

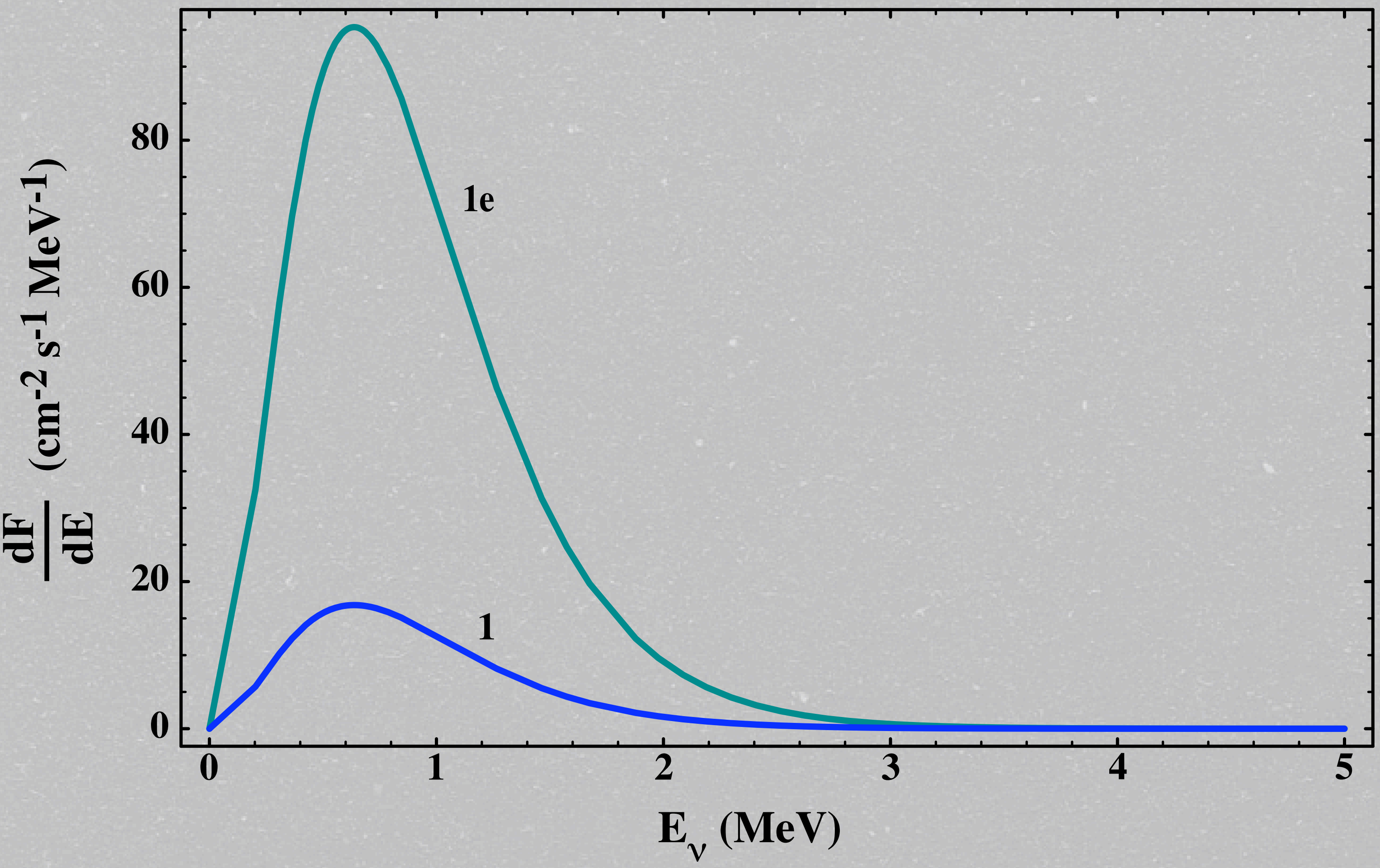
- $$N_{\nu_\alpha} = \frac{E_{cc}}{\langle E_{\nu_\alpha} \rangle}. \qquad \frac{dP_\alpha}{dE'} = \frac{2}{3\zeta_3 T_\alpha^3} \frac{E'^2}{e^{E'/T_\alpha} + 1}$$
- Λ-CDM cosmology $$\left|\frac{dt}{dz}\right| = \frac{9.78\, h^{-1}\,\mathrm{Gyr}}{(1+z)\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}$$



# Normal Mode Fluxes

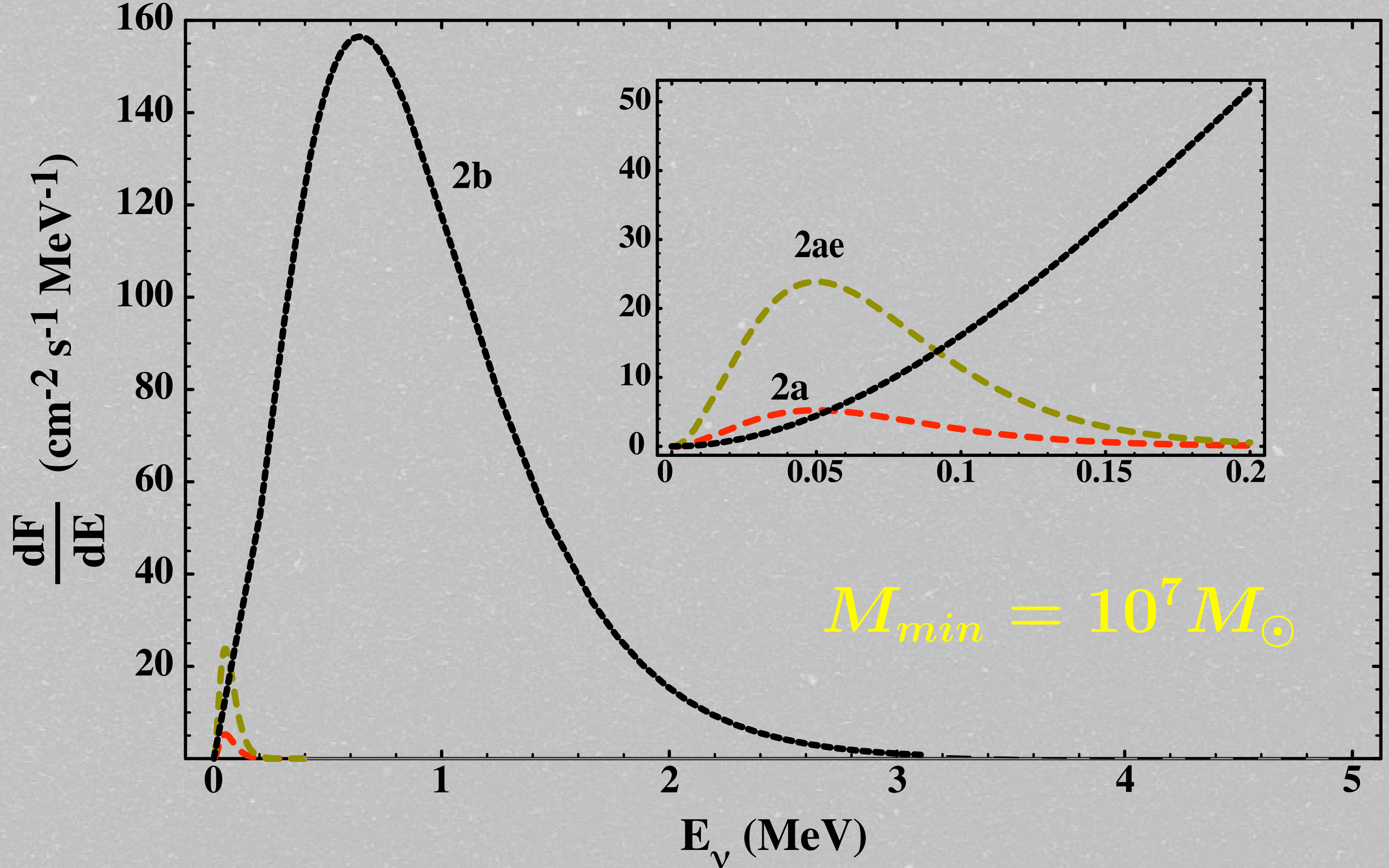


# Neutrino Flux for the massive mode of model 1

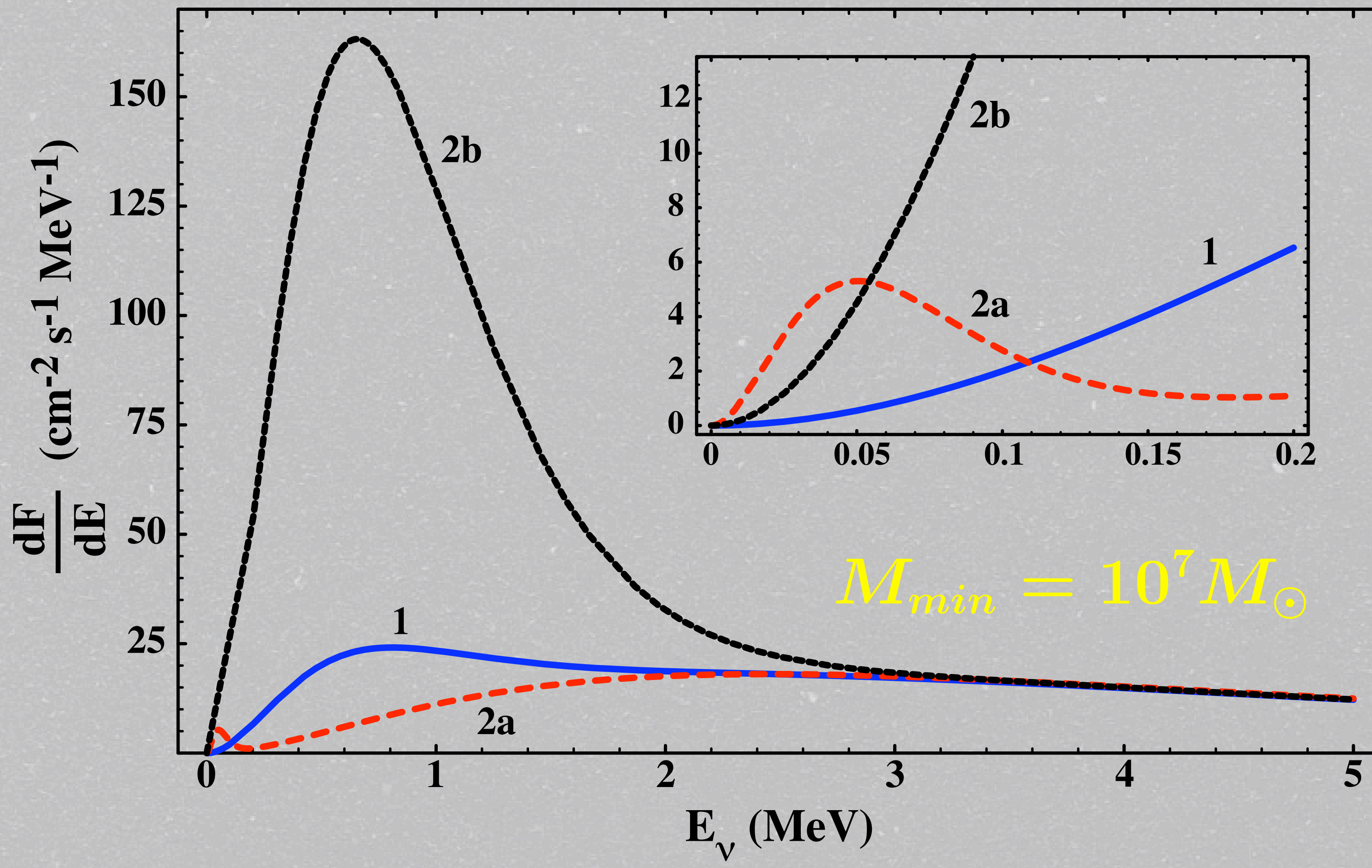



model 1e is an extreme model where 90% of the IGM metallicity is produced by the massive mode

# Neutrino Flux for the very massive pop III stars of model 2



# Total Neutrino Fluxes

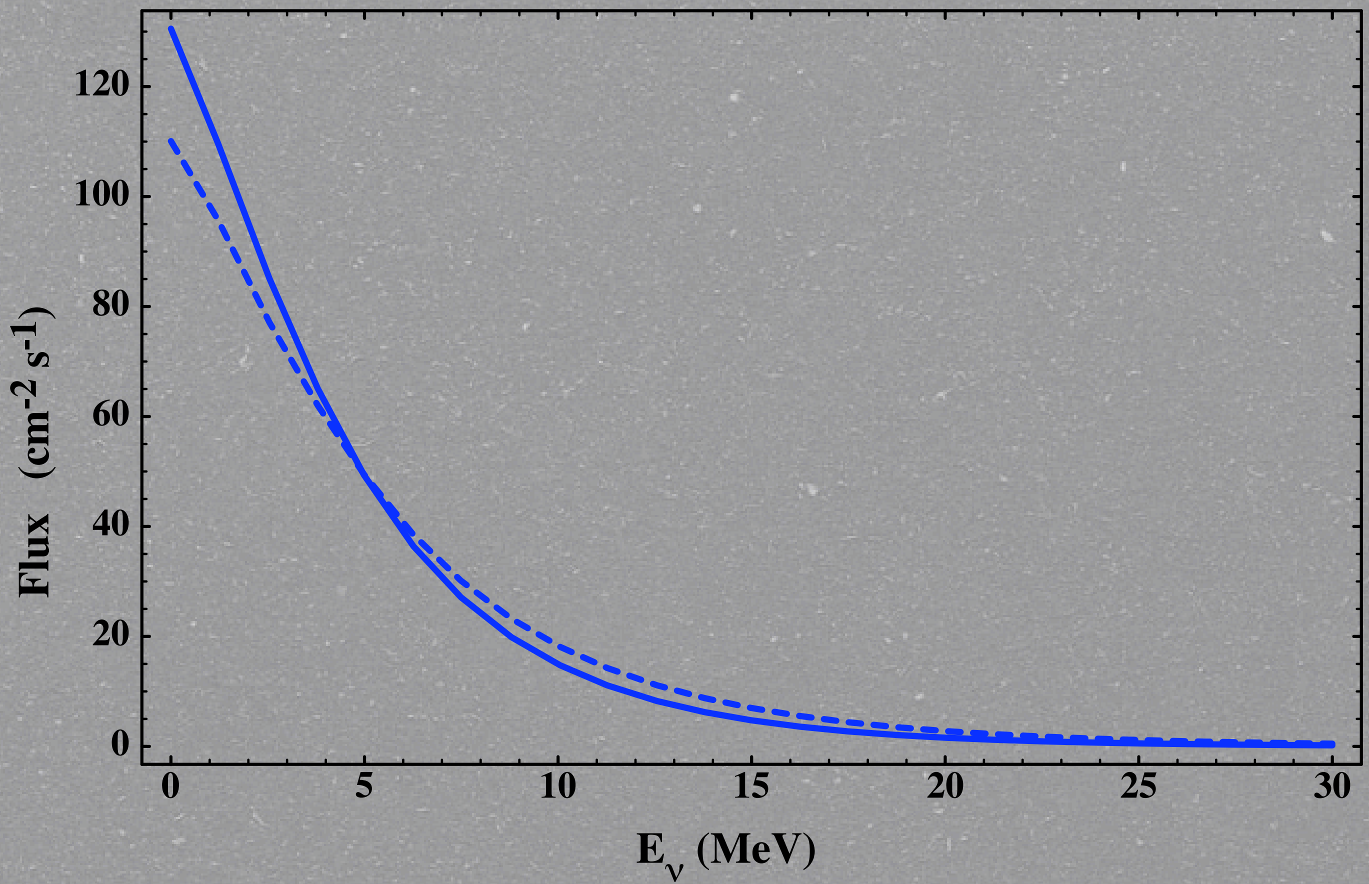


# Detectability

- SuperK flux limit: $\mathbf{1.2}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $\boldsymbol{E_\nu} > \mathbf{19}\mathrm{MeV}$

Malek et al.

$$F(E_{\rm thresh}) = \int_{E_{\rm thresh}}^{\infty} \frac{dF}{dE} dE$$

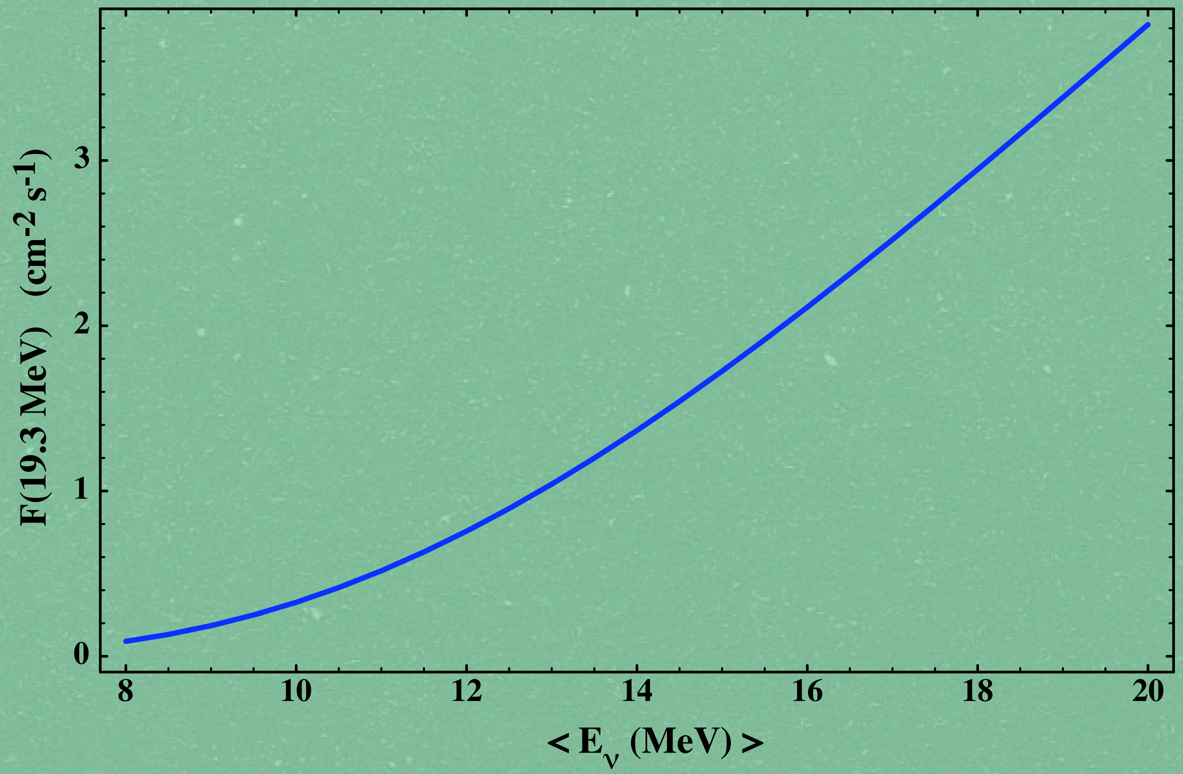


# Model comparisons to flux limit

| Model | SK Flux |
|---|---|
| 2.0 | 1.8 |
| 2.1 | 1.8 |
| 2.1osc | 3.2 |
| 2.1e | 1.9 |
| 2.2a | 1.9 |
| 2.2ae | 1.9 |
| 2.2b | 1.8 |
| 2.2bosc | 3.2 |

All models exceed upper limit!!

Sensitivity to assumed ν energies



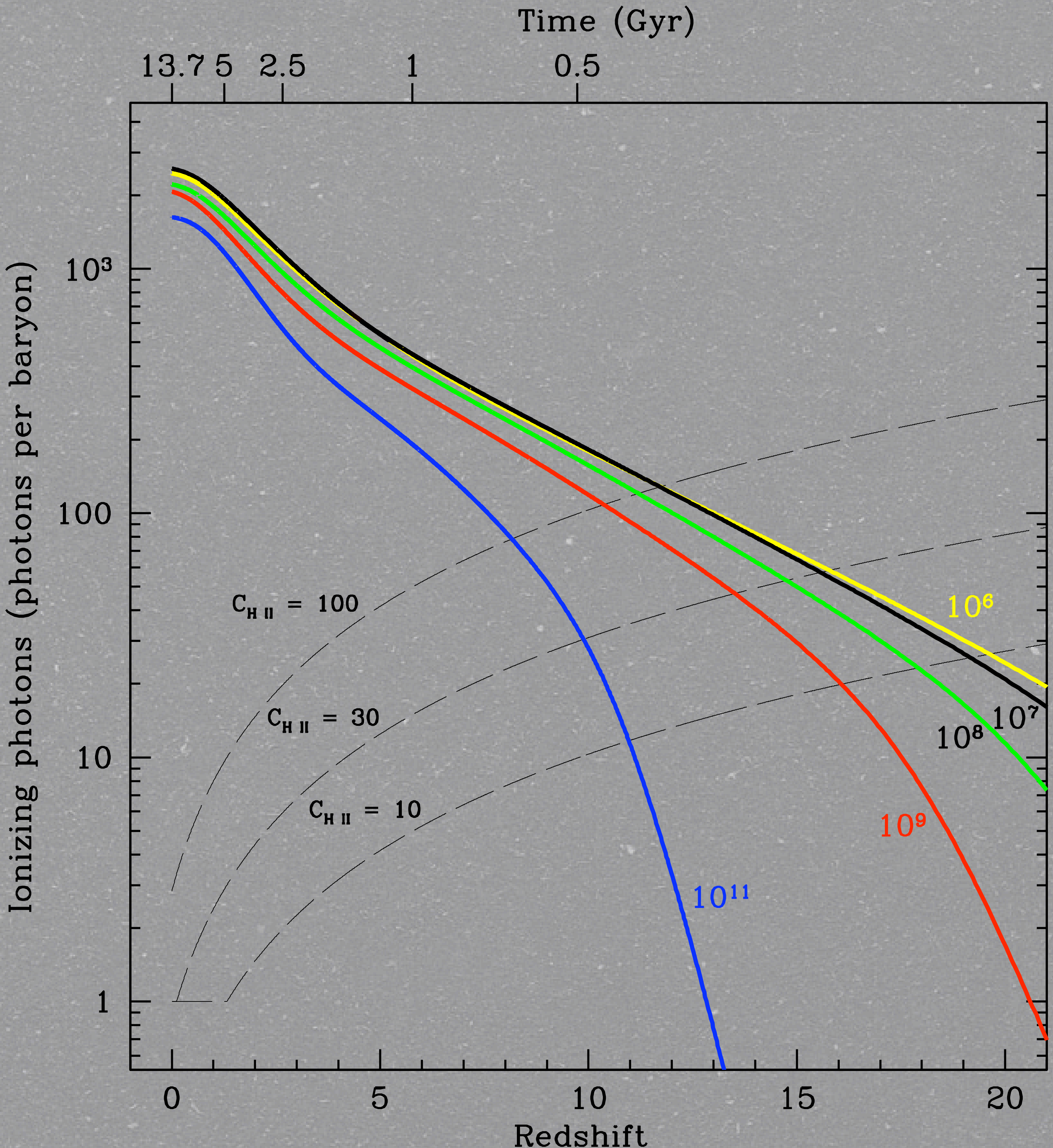

F(19.3) < 1.2 $cm^{-2}s^{-1}$ ⇒

$\langle E_\nu \rangle$ < 13.3 MeV

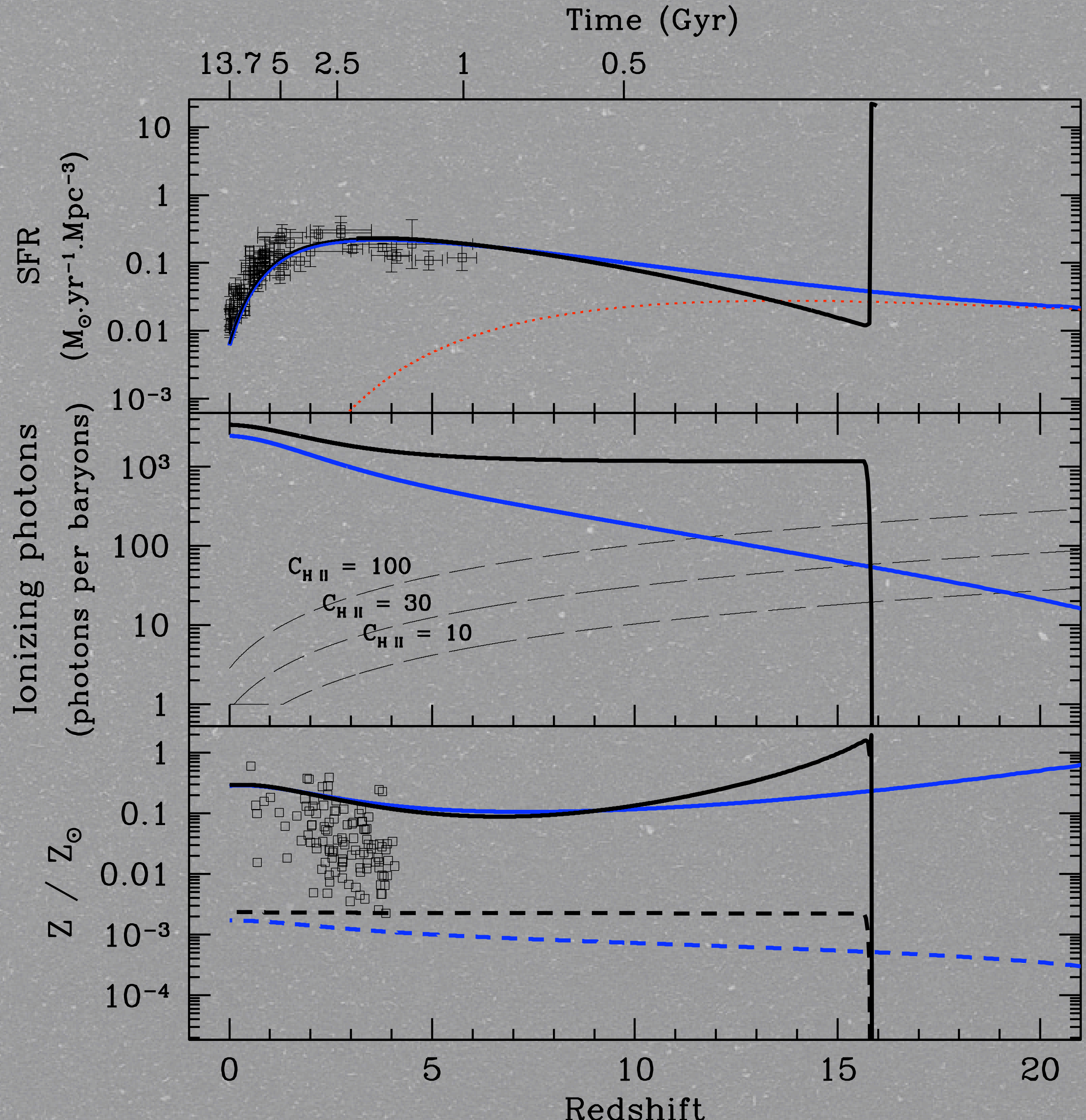
# A Non-burst model

- Rather than a rapid burst of pop III stars - an early more drawn out population
- start at z = 30
- Star formation rate:

$$\Psi_2(t) = \nu_2 M_{ISM} \exp\left(-Z_{IGM}/Z_{\rm crit}\right) ,$$

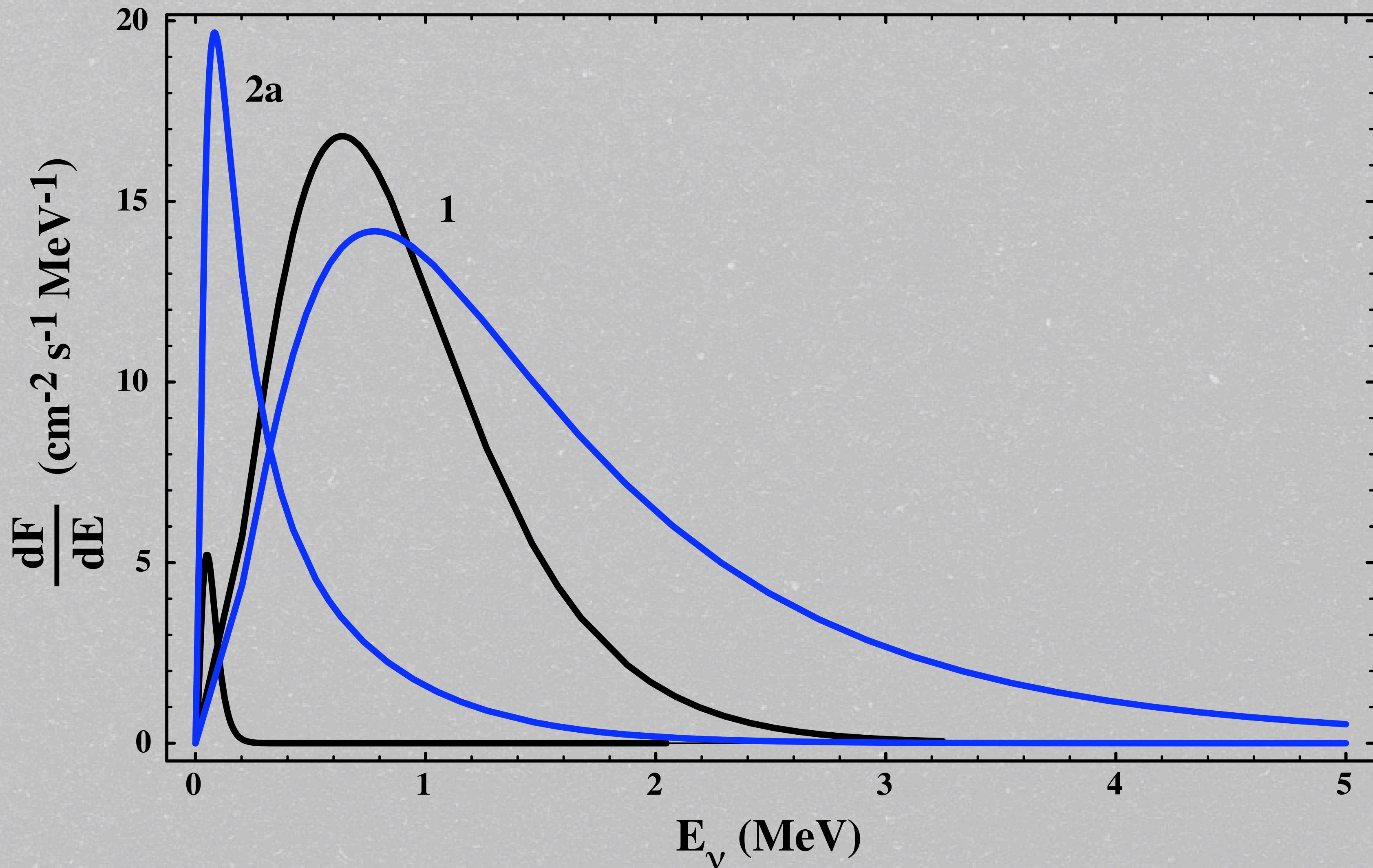


Time (Gyr)
13.7
5
2.5
1
0.5
Ionizing photons (photons per baryon)
10³
100
10
1
Redshift
0
5
10
15
20
C_H II = 100
C_H II = 30
C_H II = 10
10⁶
10⁷
10⁸
10⁹
10¹¹

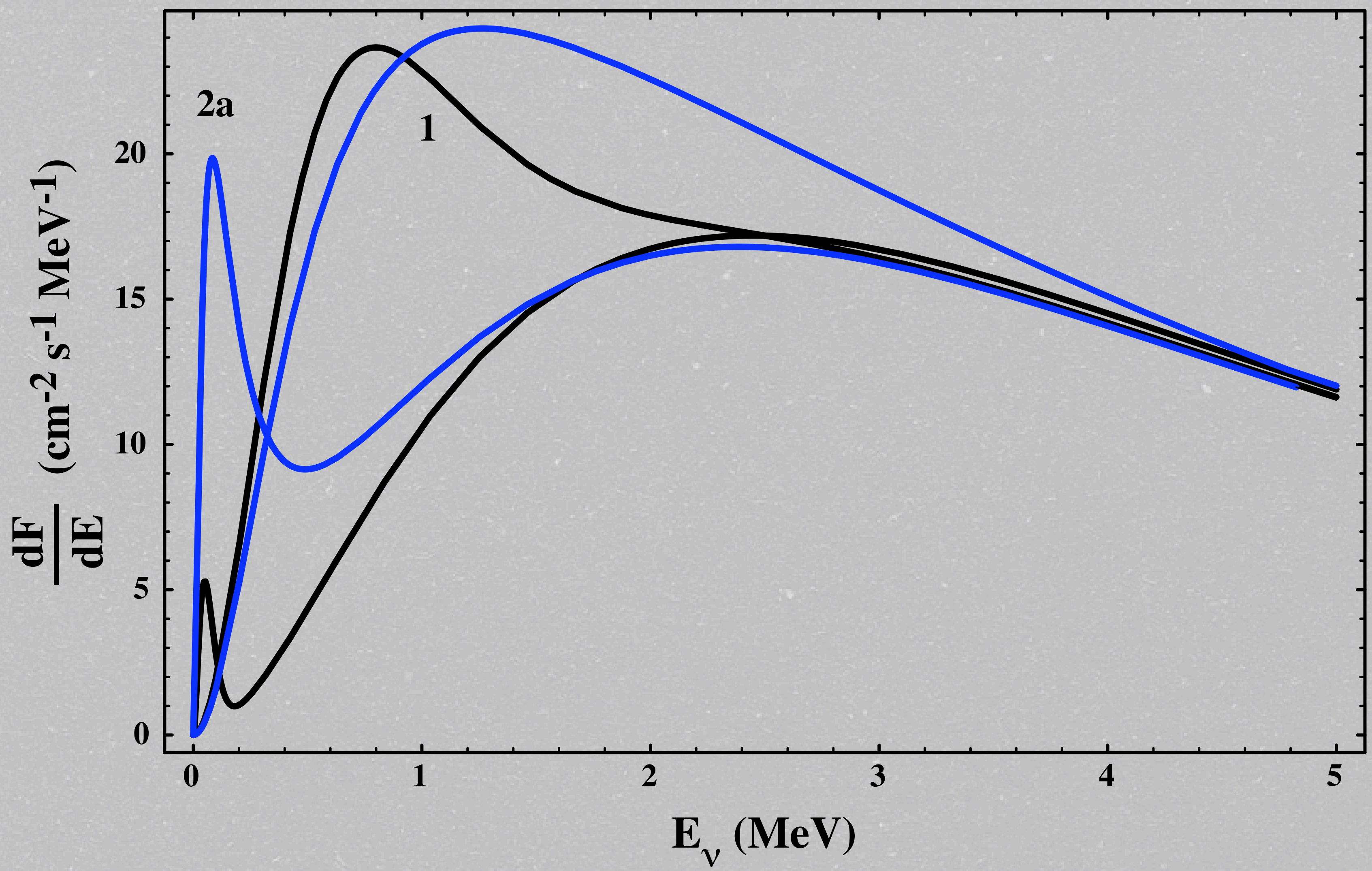


Time (Gyr)
13.7
5
2.5
1
0.5
SFR
(M⊙.yr⁻¹.Mpc⁻³)
10
1
0.1
0.01
10⁻³
Ionizing photons
(photons per baryons)
10³
100
10
1
C H II = 100
C H II = 30
C H II = 10
Z / Z⊙
1
0.1
0.01
10⁻³
10⁻⁴
0
5
10
15
20
Redshift

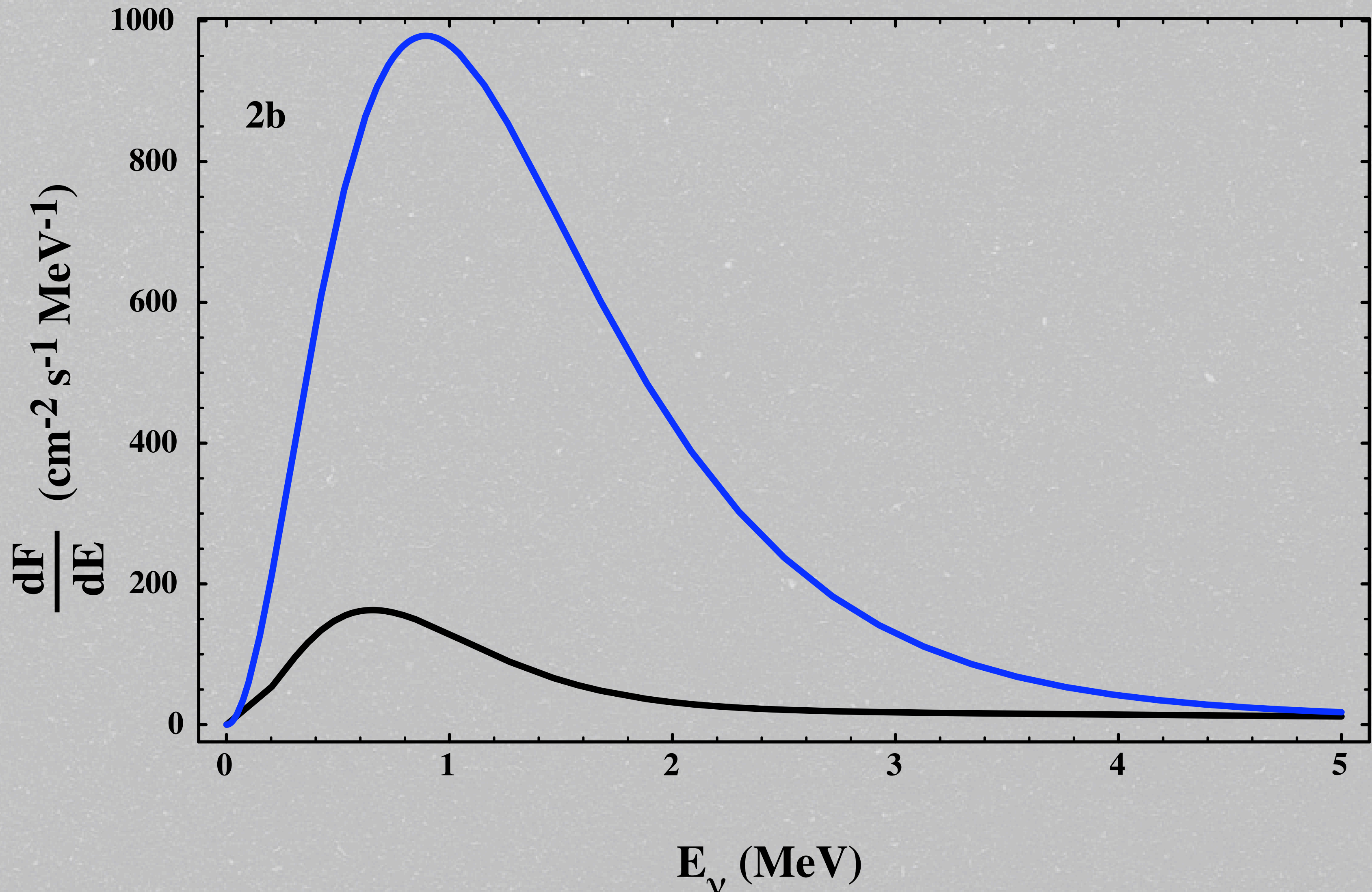
# Pop III neutrino fluxes



# Total Neutrino Fluxes



# Total Neutrino Fluxes



# Summary

- Reionization and metal enhancement play a role in determining the nature of early star formation
- Star formation at a redshift of 3-5 is greatly enhanced relative to today
- Neutrino signature should be observable!!
- Though there is a strong sensitivity to SN neutrino energetics