

Winds, ionizing fluxes and spectra of the first generations of very massive stars in the early universe

Rolf-Peter Kudritzki

Institute for Astronomy, University of Hawaii

Kudritzki & Puls, 2000, ARAA 38, 613

Kudritzki et al., 2000, ApJ 536, 19

Bromm, Kudritzki, Loeb, 2001, ApJ 552, 464

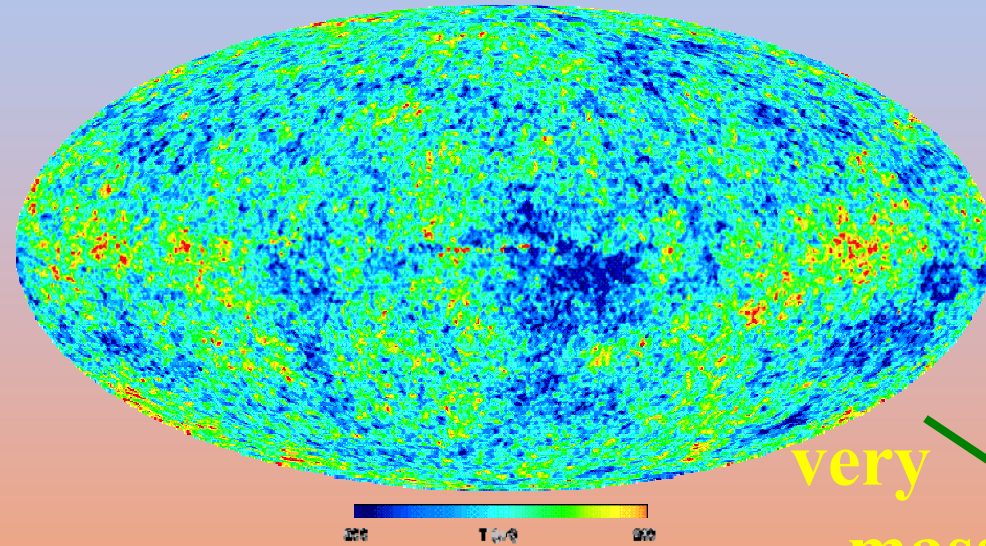
Kudritzki, 2002, ApJ 577, 389 - 408

Marigo, Chiosi, Kudritzki, 2003, A&A 399, 617

Rix, Pettini, Leitherer, Bresolin, Kudritzki, Steidel, 2004, ApJ 615, 98

Introduction

evolution of galaxies in early universe
heavily influenced by
first generations of very massive stars

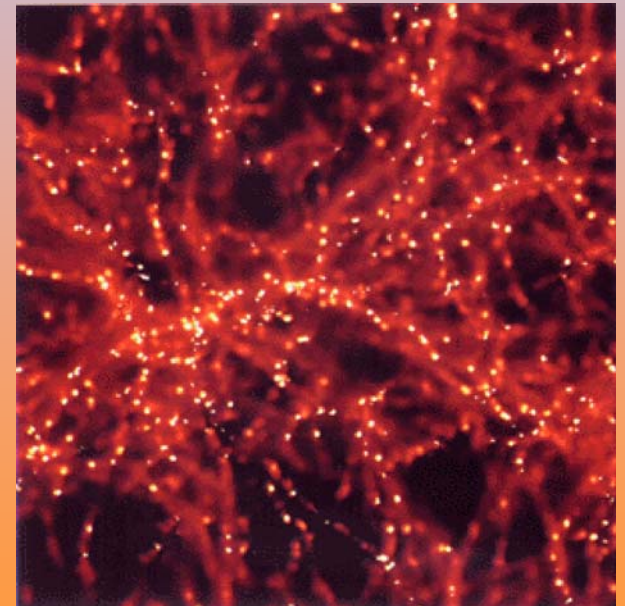


WMAP

cosmic web @ $z=3.5$

Springel & Hernquist, 2003

very massive stars



- $Z/Z_{\text{sun}} \leq 10^{-3} \rightarrow$ star formation preferably stars with
 $1000 M_{\text{sun}} > M > 100 M_{\text{sun}}$

*hydro-simulations: Abel et al., 2000, 2002
Bromm et al., 2000, 2002*

- contribution to re-ionization @ redshift $20 > z > 6$

*Carr et al. 1984, Couchman & Rees 86,
Haiman & Loeb 1997, Bennet et al. 2003,
Spergel et al. 2003, Becker et al. 2001,
Fan et al., 2001, Springel & Hernquist 2003*

- progenitors of GRBs at high redshift

*Bromm & Loeb 2002, Ciardi & Loeb 2001,
Kulkarni et al. 2000, Djorgovski et al. 2001,
Lamb & Reichart 2000*

- extreme Ly- α emitters at high redshift

*Kudritzki et al. 2001, Rhoads & Malhotra 2001
Malhotra & Rhoads 2002, Hu et al. 2003*

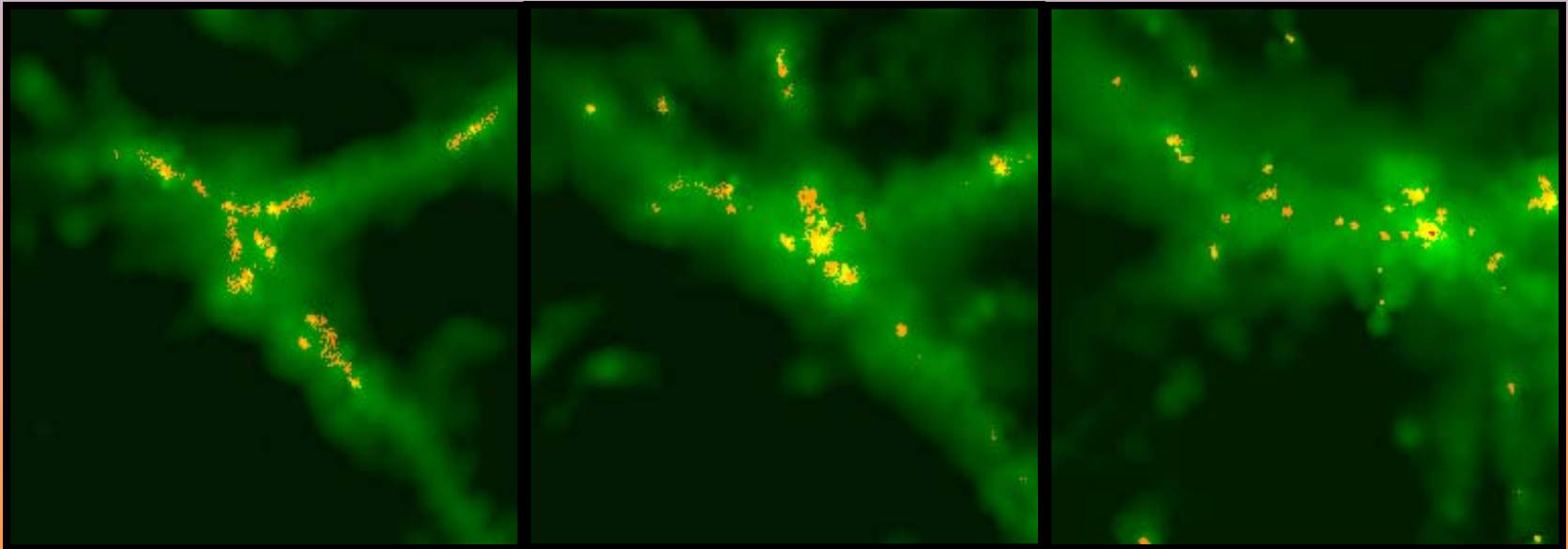
The first stars in the universe - clues from hydrodynamic simulations

- Hydrodynamic simulations by Davé, Katz, & Weinberg
 - Ly- α cooling radiation (green)
 - Light in Ly- α from forming stars (red, yellow)

$z=10$

$z=8$

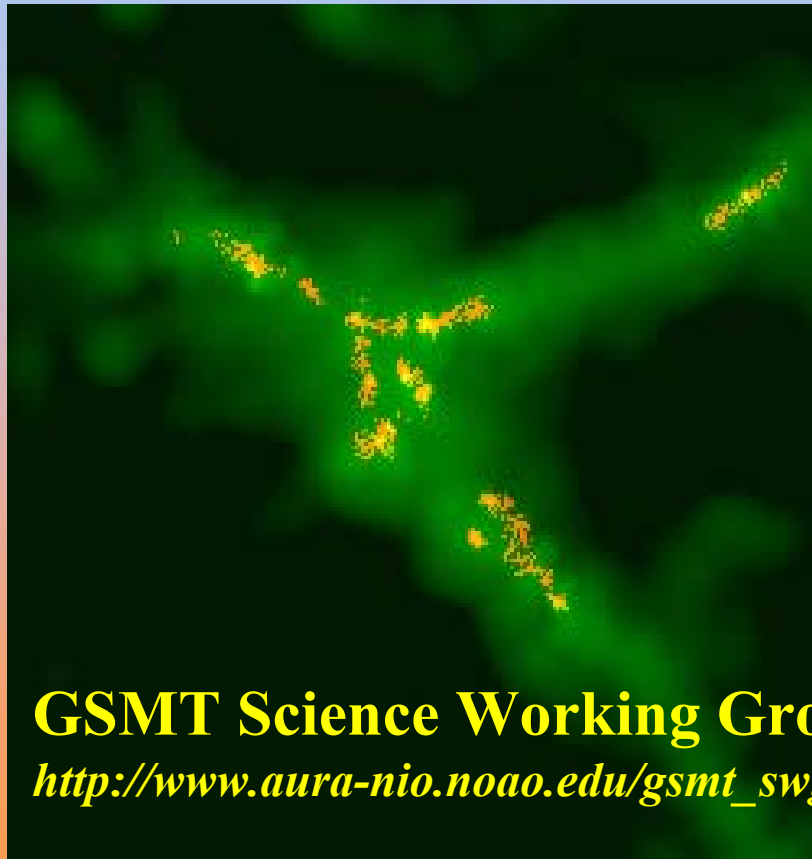
$z=6$



Stars forming at $z=10$!

Observable with a 30m telescope!

1 Mpc (comoving)



GSMT Science Working Group Report, 2003, Kudritzki et al.
http://www.aura-nio.noao.edu/gsmg_swg/SWG_Report/SWG_Report_7.2.03.pdf

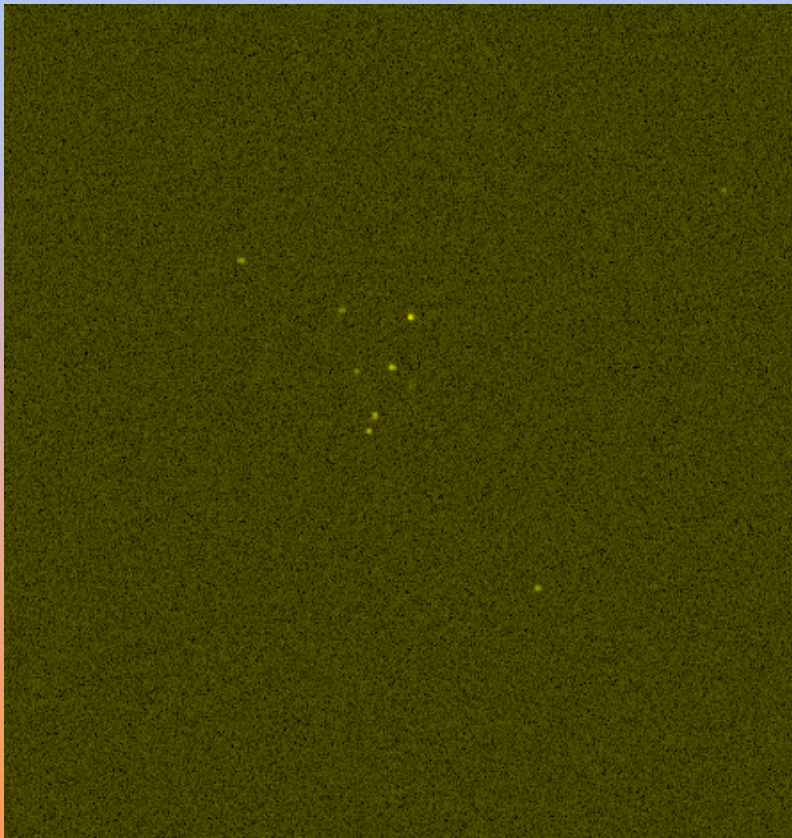
Simulation



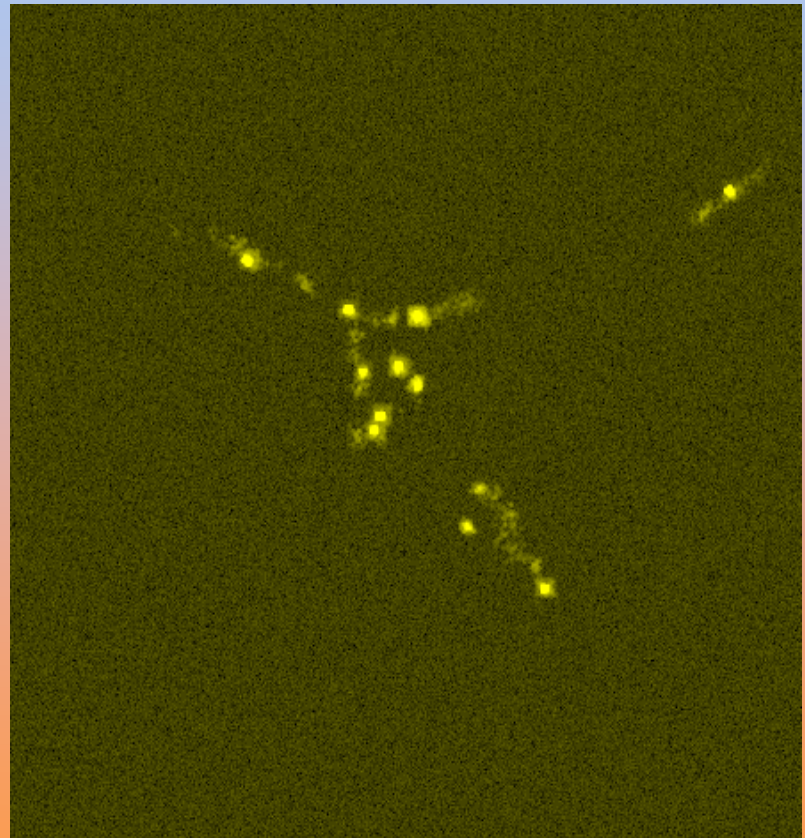
As observed through 30-meter
telescope $R=3000$, 10^5 seconds,
Barton et al., 2004, ApJ 604, L1

A possible IMF diagnostic at $z=10$

HeII ($\lambda 1640 \text{ \AA}$)
Standard IMF



HeII ($\lambda 1640 \text{ \AA}$)
Top-Heavy IMF, zero metallicity



(IMF + stellar model fluxes
from Bromm, Kudritzki,
& Loeb 2001, ApJ 552,464)

questions

evolution ?

spectra?

ionizing fluxes?

recombination lines?

↔ winds?

↙ old work

$$\dot{M} \propto \{Z/Z_{\odot}\}^{0.5 \dots 0.8}$$


for $0.01 \leq Z/Z_{\odot} \leq 3$

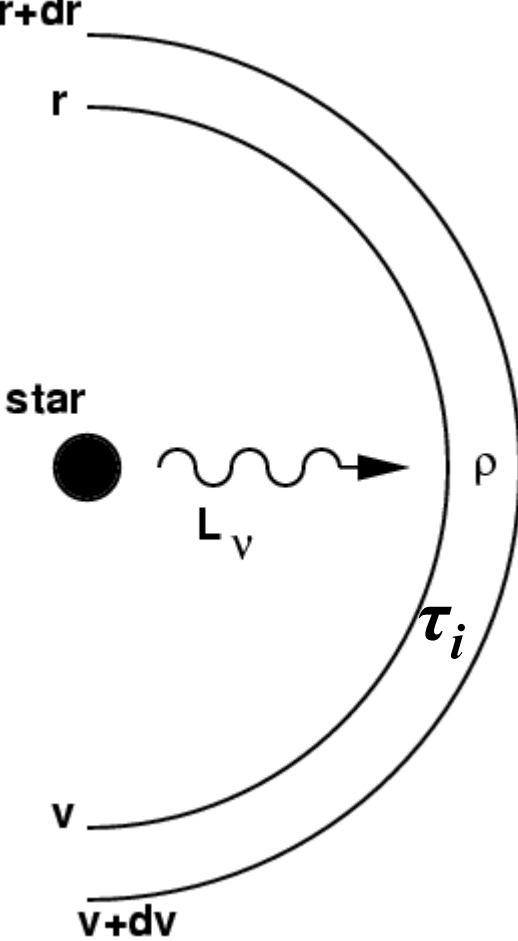
Kudritzki et al. 1987, Leitherer et al. 1992, Vink et al., 2001

Hydrodynamics of stationary line driven winds

$$\dot{M} = 4\pi r^2 \rho(r) v(r)$$

$$v(r) \frac{dv(r)}{dr} = -\frac{1}{\rho(r)} \frac{dP_{gas}(r)}{dr} - g(r) + g_{rad}(r)$$

$$g_{rad}(r) = g_{rad}^{Th} + g_{rad}^{bf,ff} + g_{rad}^{lines}$$




Contribution by one line i at ν_i

$$g_{\text{rad}}^i = \frac{\text{photon momentum absorbed by line } i}{\text{time mass}}$$

$$= \frac{1}{c} L_{\nu_i} (1 - e^{-\tau_i}) d\nu \frac{1}{4\pi r^2 \rho dr}$$

$$d\nu = \nu_i \frac{d\nu}{c}$$

$$g_{\text{rad}}^{\text{Th}}(r) = \frac{n_e \sigma_e L}{c 4\pi r^2 \rho}$$

$$g_{\text{rad}}^i = g_{\text{rad}}^{\text{Th}} \frac{1}{c} \frac{\nu_i L_{\nu_i}}{L} (1 - e^{-\tau_i}) \frac{1}{n_e \sigma_e} \frac{d\nu}{dr}$$

M_i

$$g_{\text{rad}}^{\text{lines}} = g_{\text{rad}}^{\text{Th}} M(t) \longrightarrow \text{line force multiplier}$$



$$M(t) = \frac{v_{\text{th}}}{c} \frac{1}{t} \sum_i \frac{\nu_i L_{\nu_i}}{L} (1 - e^{-\tau_i})$$

$$\tau_i(r) = k_i t(r) \quad \text{line optical depth}$$

$$k_i = \frac{\chi_i(r)}{n_e \sigma_e} \propto \frac{n_{\text{lower}}}{n_e} f_{\text{lu}} \lambda_i \quad \text{line strength}$$

$$t = n_e \sigma_e \frac{v_{\text{th}}}{dv/dr} \quad \text{optical depth parameter}$$

for very weak winds $\rightarrow t = n_e \sigma_e \frac{v_{th}}{dv/dr} \ll 1$

$\tau_i = k_i t(r) < 1$, for all lines
if $t^{-1} > k_{\max}$

$$M(t) = \frac{v_{th}}{c} \frac{1}{t} \sum_i \frac{\nu_i L_{\nu_i}}{L} (1 - e^{-\tau_i})$$

$$M_{max} = \frac{v_{th}}{c} \sum_i \frac{\nu_i L_{\nu_i}}{L} k_i \approx 2000 \leftarrow \text{O-stars @ } Z = 1 \text{ (Gayley, 1995)}$$

since for metal lines $k_i = k_i^{\odot} \frac{Z}{Z_{\odot}}$

$$\rightarrow M_{max} = 2000 \frac{Z}{Z_{\odot}} + M_{H,He}$$

necessary for wind (at very low metallicity):

$$g(r) - g_{rad}(r) = g(r)[1 - \Gamma\{1 + M(t)\}] \leq 0 \quad \Gamma = g_{rad}^{Th}(r)/g(r)$$



$$\Gamma \geq \Gamma_{min} = \frac{1}{1 + M_{max}} = \left\{1 + 2000 \frac{Z}{Z_{\odot}} + M_{H,He}\right\}^{-1}$$

minimum Γ for existence of line driven winds

Z/Z_{sun}	Γ_{min}
1.0	$5 \cdot 10^{-4}$
0.1	$5 \cdot 10^{-3}$
0.01	0.05
0.001	1/3 ←
0.0001	5/6 ←

winds only very close to Eddington-limit !!

depth dependence of line force $M(t)$

$$M(t) = \frac{v_{th}}{c} \frac{1}{t} \sum_i \frac{\nu_i L_{\nu_i}}{L} (1 - e^{-\tau_i}) \quad \tau_i(r) = k_i t(r)$$
$$t = n_e \sigma_e \frac{v_{th}}{dv/dr}$$

2 extreme cases:

$$k_{\max} = \max \{k_i\}, k_{\min} = \min \{k_i\}$$

$$t \leq t_s = k_{\max}^{-1} \Rightarrow M(t) = M_{\max} \propto \sum_i \frac{\nu_i L_{\nu_i}}{L} k_i = \text{const.}$$

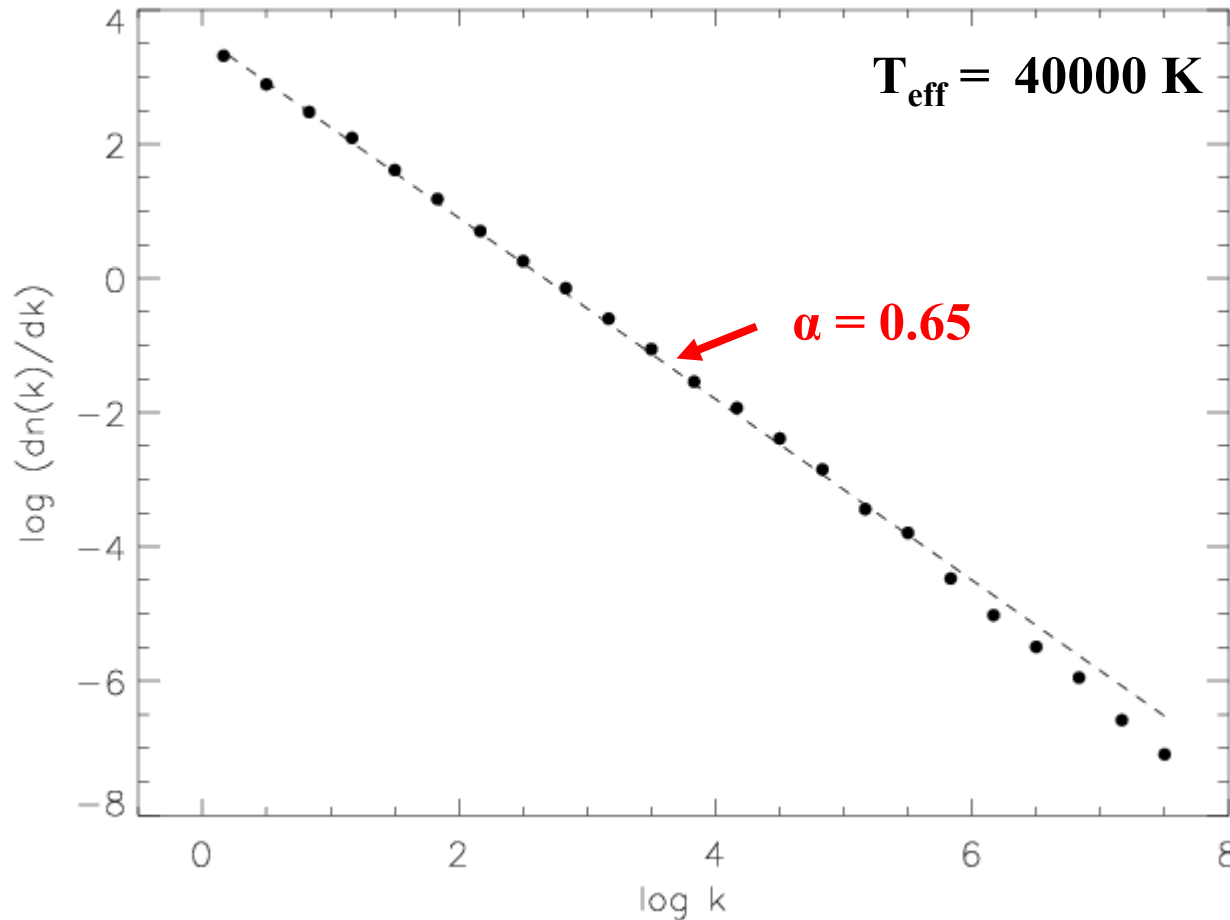
$$t \geq t_m = k_{\min}^{-1} \Rightarrow M(t) = \frac{1}{t} \propto \frac{1}{n_e} \frac{dv}{dr}$$

optical thickness of lines is crucial !

line strength distribution function

$$n(k, \nu) d\nu dk \propto k^{\alpha-2} dk$$

atomic line lists, NLTE:
{ k_i } for some 10^6 lines
→ power law



**Kudritzki & Puls,
2000, ARA&A
38, 613**

**see Puls et al. 2000,
A&AS 141, 23
for detailed
discussion**

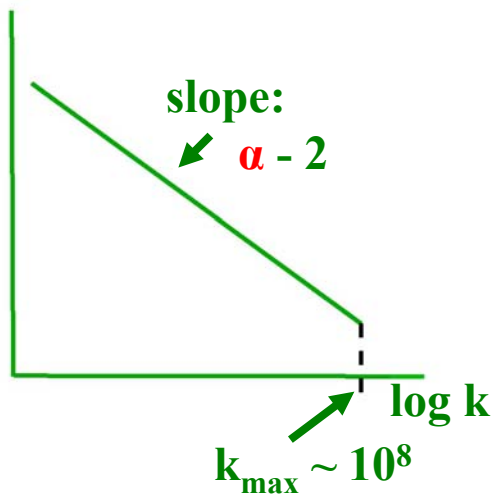
depth dependence of line force

$$n(k, \nu) d\nu dk \propto k^{\alpha-2} dk$$

$$M(t) \propto \frac{1}{t} \sum_i \frac{\nu_i L_{\nu_i}}{L} (1 - e^{-k_i t})$$

$$M(t) \propto N_{eff} \frac{1}{t} \int_0^{k_{max}} \{1 - e^{-tk}\} k^{\alpha-2} dk$$

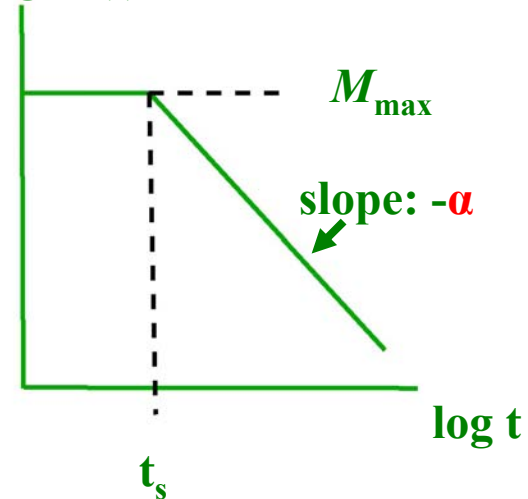
log n(k)



$$M(t) \propto N_{eff} \cdot t^{-\alpha}$$

$$N_{eff} \propto M_{max} k_{max}^{-\alpha}$$

log M(t)



$$v(r) \frac{dv(r)}{dr} = -\frac{1}{\rho(r)} \frac{dP_{gas}(r)}{dr} - g(r) \{1 + \Gamma M(t^{-\alpha})\}$$

$$t = n_e \sigma_e \frac{v_{th}}{dv/dr}$$

non-linear
eq. of motion



$$\dot{M} \propto N_{eff}^{\frac{1}{\alpha}} L^{\frac{1}{\alpha}} \{M_* (1 - \Gamma)\}^{1 - \frac{1}{\alpha}}$$

$$v_{\infty} \approx 2.24 \frac{\alpha}{1 - \alpha} v_{esc}^{phot}$$

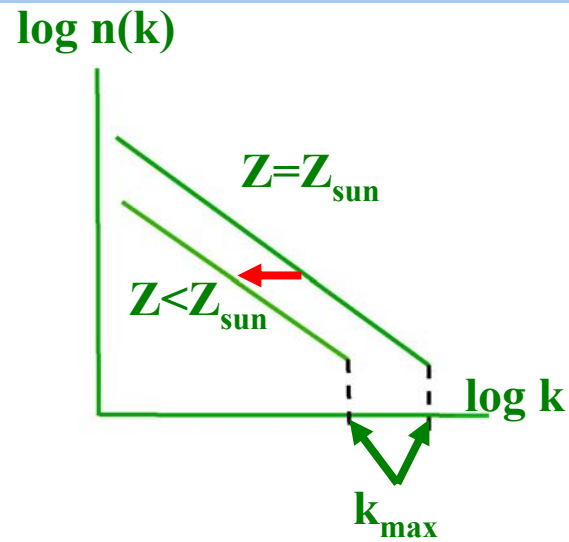
$$v_{esc}^{phot} = \left\{ 2G \frac{M_* (1 - \Gamma)}{R_*} \right\}^{\frac{1}{2}}$$

$$\dot{M} v_{\infty} \propto R_*^{-\frac{1}{2}} N_{eff}^{\frac{1}{\alpha}} L^{\frac{1}{\alpha}}$$

analytic solutions,
scaling relations

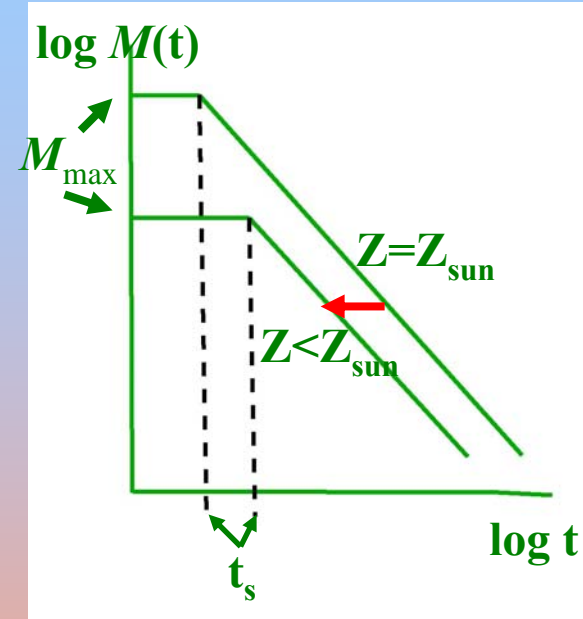
Kudritzki et al. 1989,
Puls, Kudritzki et al., 1996,
Kudritzki & Puls, 2000

metallicity $\longrightarrow k = k_{\odot} \frac{Z}{Z_{\odot}}$



$$k_{\text{max}} = k_{\text{max}}^{\odot} \frac{Z}{Z_{\odot}}$$

$$M_{\text{max}} = M_{\text{max}}^{\odot} \frac{Z}{Z_{\odot}}$$



$$N_{\text{eff}} = N_{\text{eff}}^{\odot} \left\{ \frac{Z}{Z_{\odot}} \right\}^{1-\alpha}$$

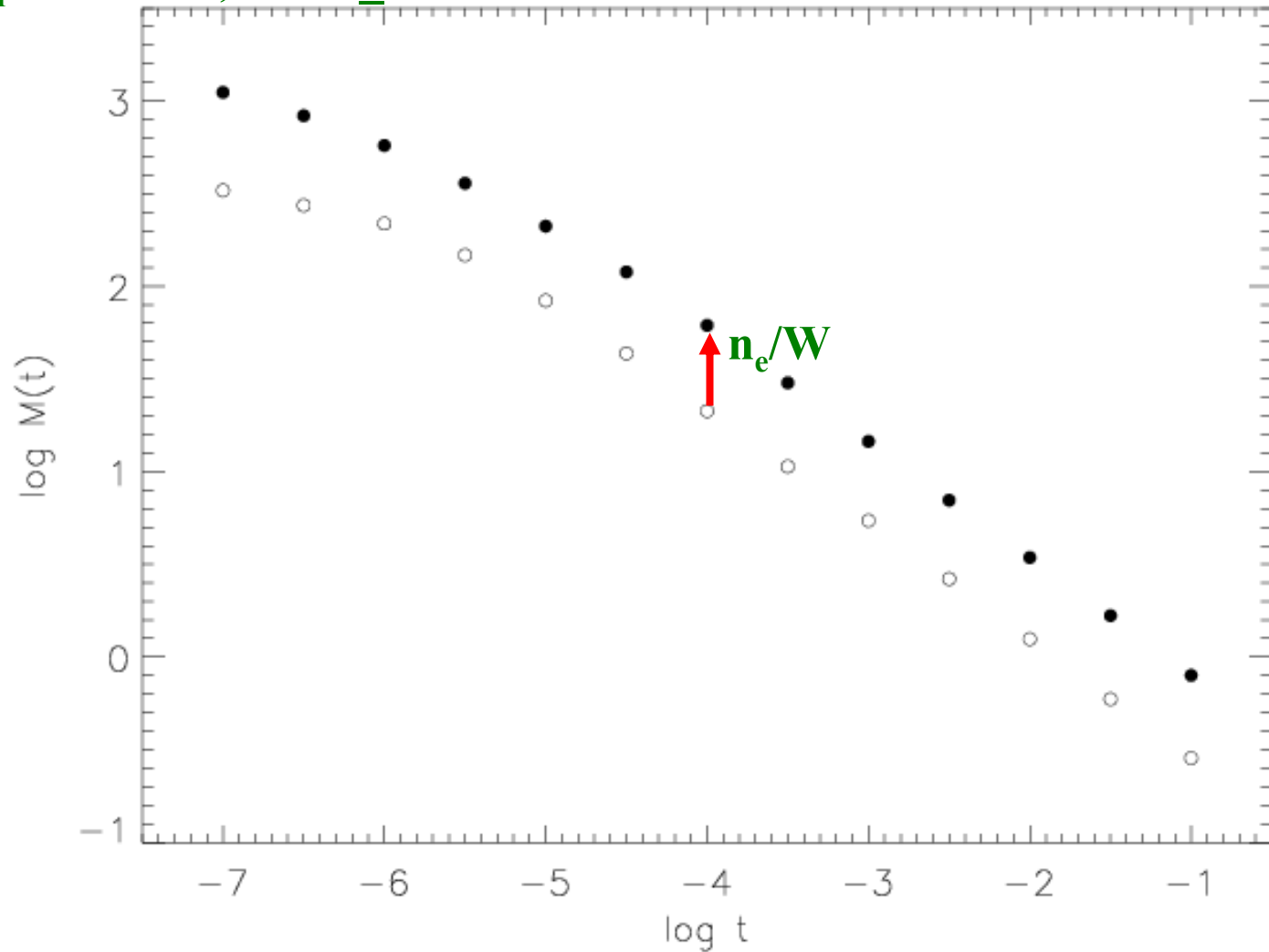
$$M(t) \propto \left\{ \frac{Z}{Z_{\odot}} \right\}^{1-\alpha} t^{-\alpha}$$

$$\dot{M} = \dot{M}_{\odot} \left\{ \frac{Z}{Z_{\odot}} \right\}^{\frac{1-\alpha}{\alpha}}$$

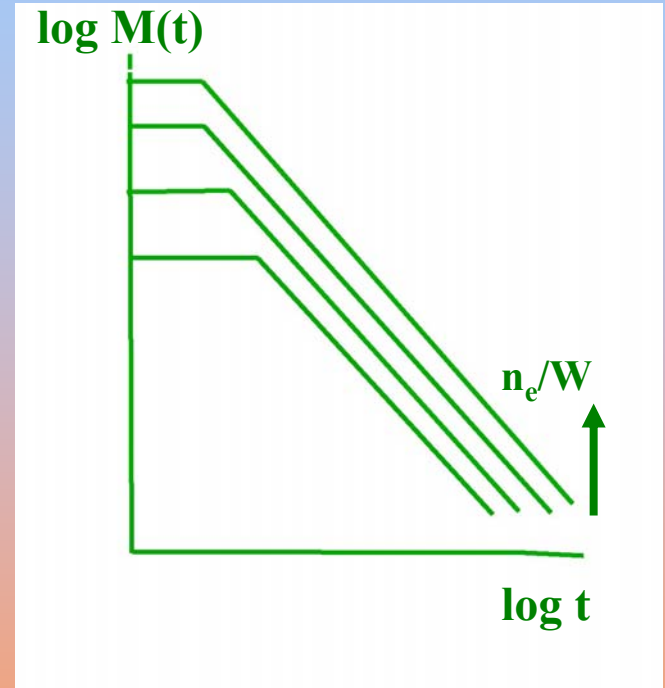
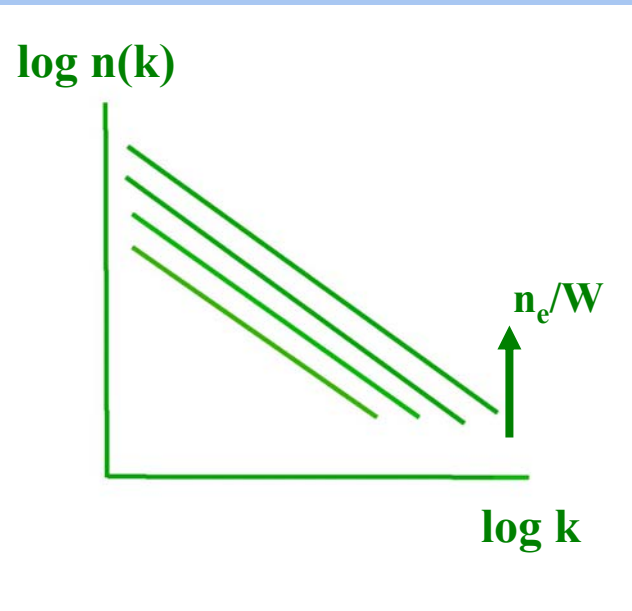
Abbot, 1982
 Kudritzki et al., 1989
 Puls, Kudritzki et al., 1996

Complication: $M(t, n_e/W)$

$T_{\text{eff}} = 50000\text{K}, Z = Z_{\text{sun}}$



ionization changes through wind: $N_{eff} \propto \left\{ \frac{n_e(r)}{W(r)} \right\}^\delta$



$$M(t) \propto \left\{ \frac{n_e(r)}{W(r)} \right\}^\delta t^{-\alpha}$$

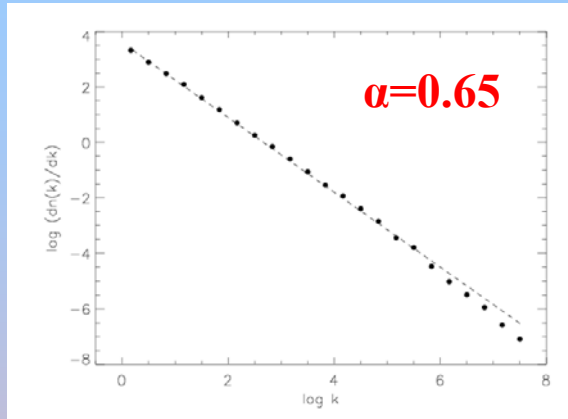
$$\dot{M} \propto N_{eff}^{\frac{1}{\alpha-\delta}} L^{\frac{1}{\alpha-\delta}} \propto \dot{M}_\odot \left\{ \frac{Z}{Z_\odot} \right\}^{\frac{1-\alpha}{\alpha-\delta}}$$

$$v_\infty \propto \frac{\alpha}{1-\alpha} e^{-2\delta} v_{esc}$$

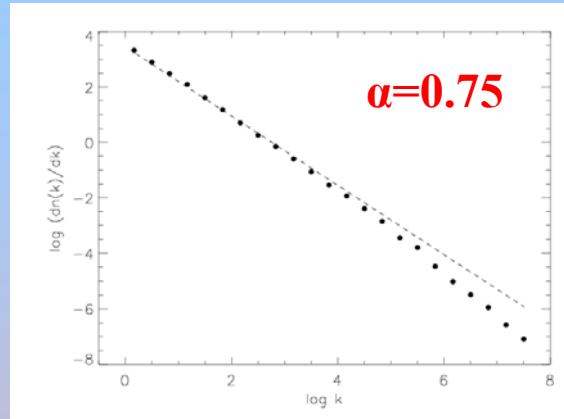
$\delta \approx 0.05$ to 0.1

Kudritzki et al., 1989
Puls et al., 1996,
Kudritzki & Puls, 2000

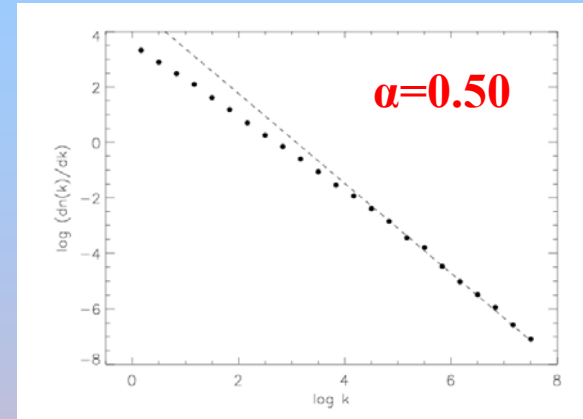
curvature of line strength distribution function



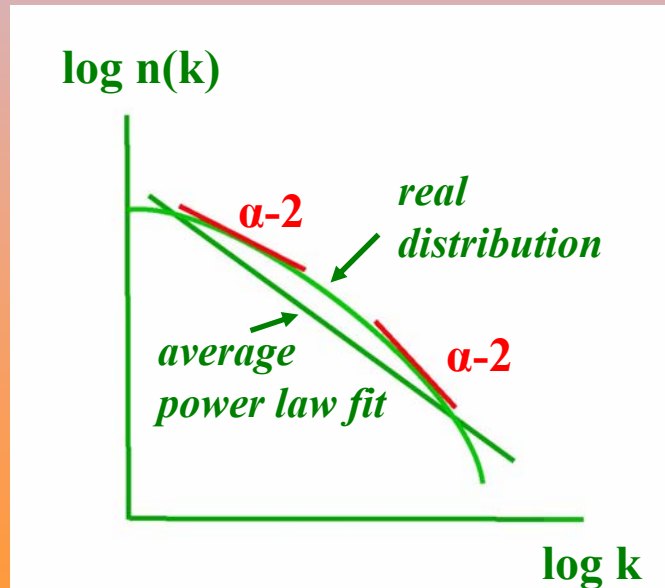
average fit



fit upper part



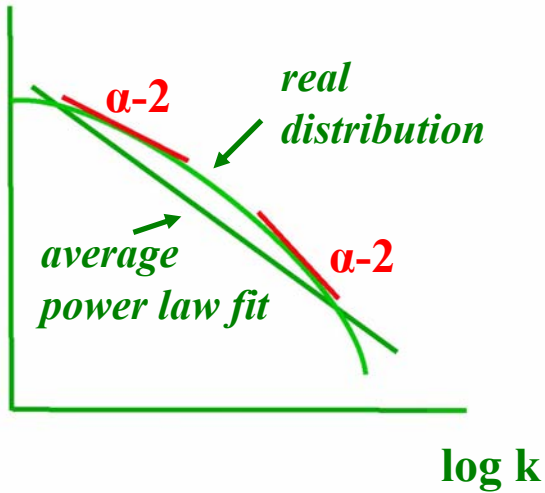
fit lower part



Kudritzki, 1998
Puls et al., 2000
Kudritzki & Puls, 2000

curvature of line strength distribution function

$\log n(k)$



contribution to $M(t)$ mostly from lines with $\tau = k \cdot t = 1$

$$M(t) \propto t^{-\alpha} \left(k = \frac{1}{t} \right)$$

for lower metallicity

- weaker winds
larger k contribute
 α smaller
- $k \sim Z/Z_{\text{sun}}$
distribution shifts
 α smaller

α smaller !

consequences:

$$v_{\infty} \propto \left\{ \frac{Z}{Z_{\odot}} \right\}^x$$

$$\dot{M} \propto \left\{ \frac{Z}{Z_{\odot}} \right\}^m$$

but no unique exponent !

numerical calculations

Kudritzki et al., 1987

$Z/Z_{\text{sun}} = 0.1 \dots 1.0$

$$\dot{M} \propto \left\{ \frac{Z}{Z_{\odot}} \right\}^{0.6 \pm 0.1}$$

$$v_{\infty} \propto \left\{ \frac{Z}{Z_{\odot}} \right\}^{0.15}$$

Leitherer et al., 1992

$Z/Z_{\text{sun}} = 0.01 \dots 3.0$

$$\dot{M} \propto \left\{ \frac{Z}{Z_{\odot}} \right\}^{0.8 \pm 0.1}$$

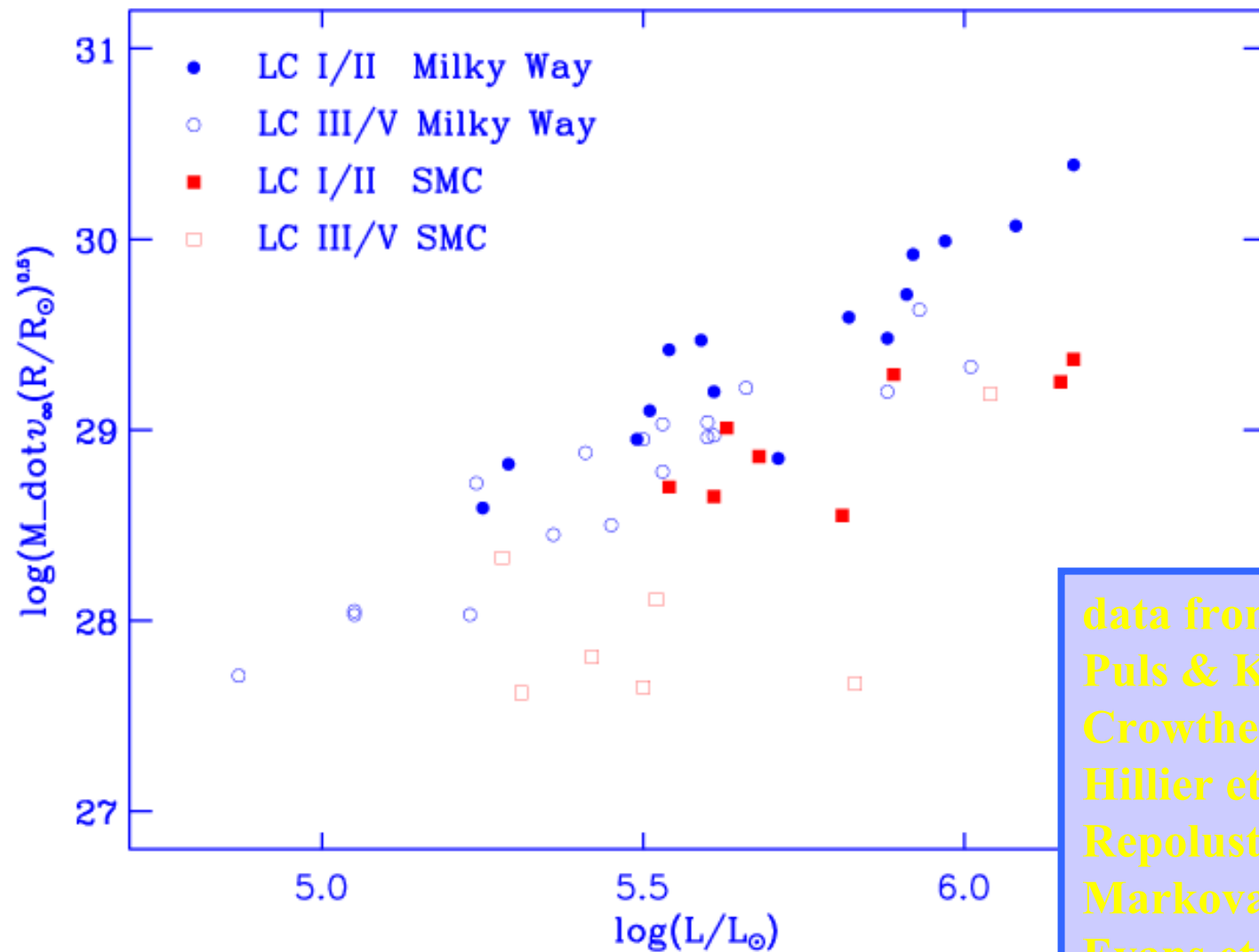
$$v_{\infty} \propto \left\{ \frac{Z}{Z_{\odot}} \right\}^{0.13}$$

Vink et al., 2001

$Z/Z_{\text{sun}} = 0.03 \dots 3.0$

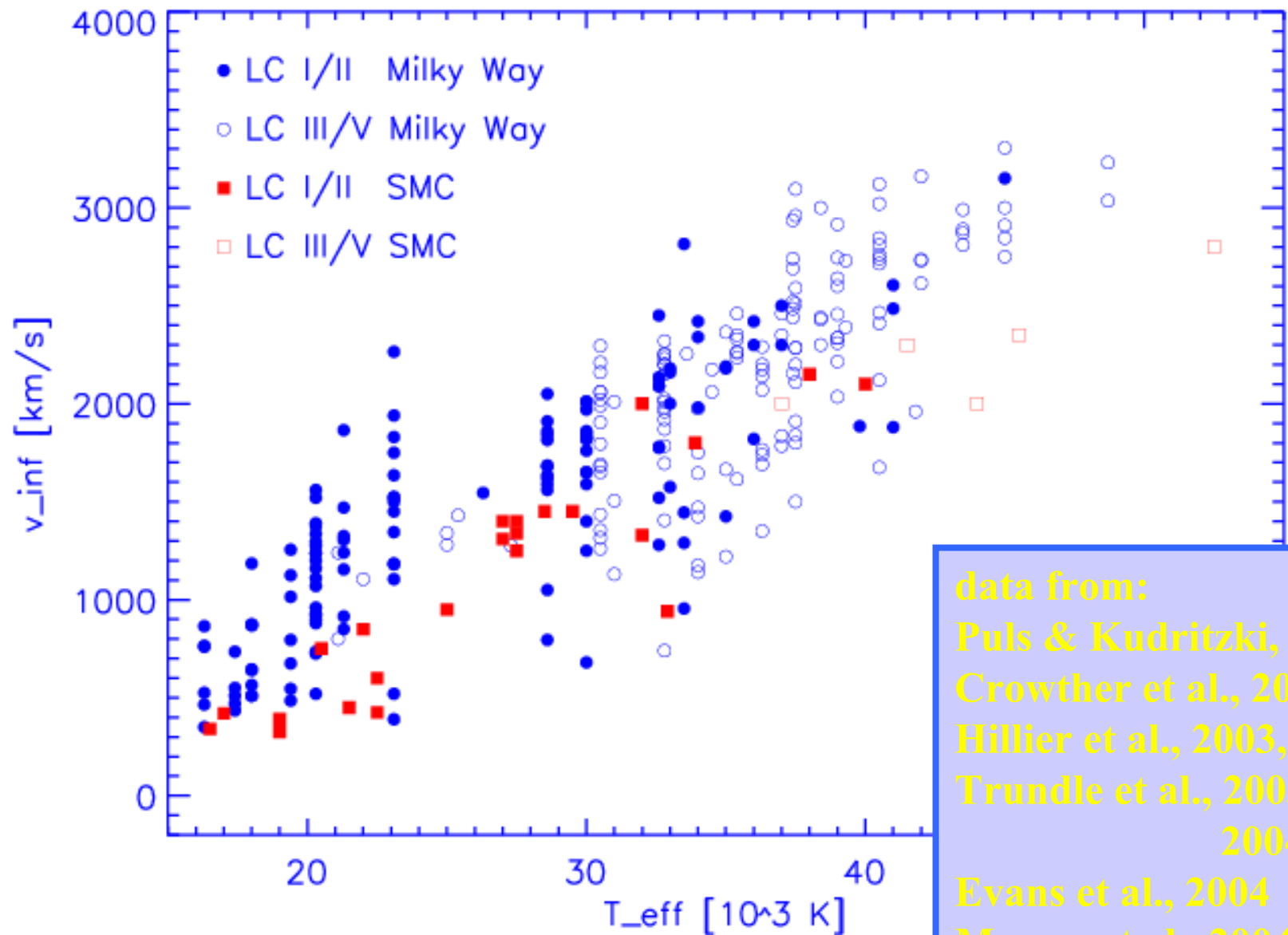
$$\dot{M} \propto \left\{ \frac{Z}{Z_{\odot}} \right\}^{0.69 \pm 0.1}$$

observed wind momenta and metallicity



data from:
Puls & Kudritzki, 2000
Crowther et al., 2002
Hillier et al., 2003,
Repolust et al., 2004
Markova et al., 2004
Evans et al., 2004
Massey et al., 2004

observed wind velocities and metallicity



data from:
Puls & Kudritzki, 2000
Crowther et al., 2002
Hillier et al., 2003,
Trundle et al., 2003
2004
Evans et al., 2004
Massey et al., 2004

Winds at very low metallicities – a challenge

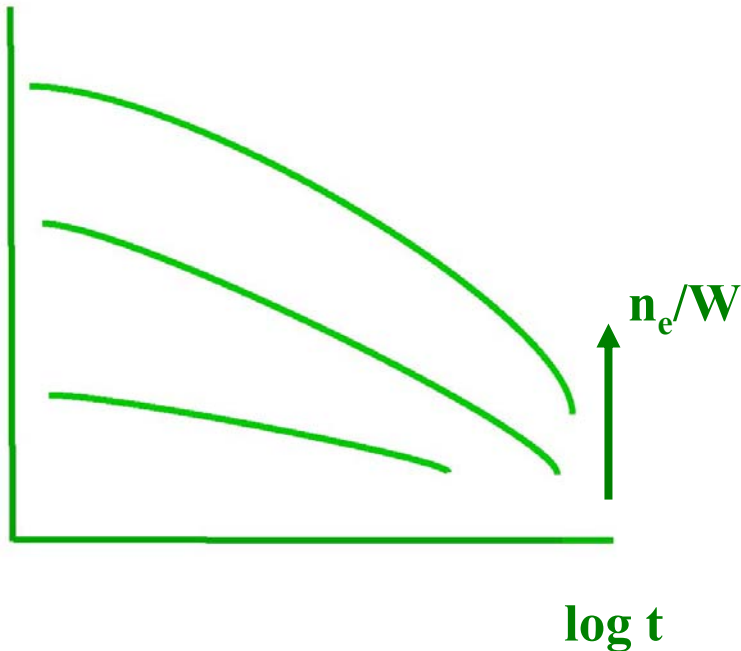
$$\frac{Z}{Z_{\odot}} \leq 10^{-2} \longrightarrow$$

- saturation of $M(t)$ at high t
 $k_{\max} t \approx 1$
→ strong curvature of $M(t)$

- n_e/W influences curvature

- force multipliers α, δ
depth dependent

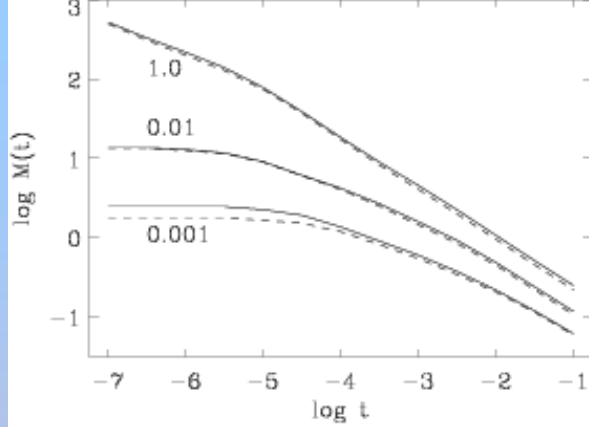
$\log M(t)$



$$M(t) \propto \left\{ \frac{n_e}{W} \right\}^{\delta(t, \frac{n_e}{W})} t^{-\alpha(t, \frac{n_e}{W})}$$

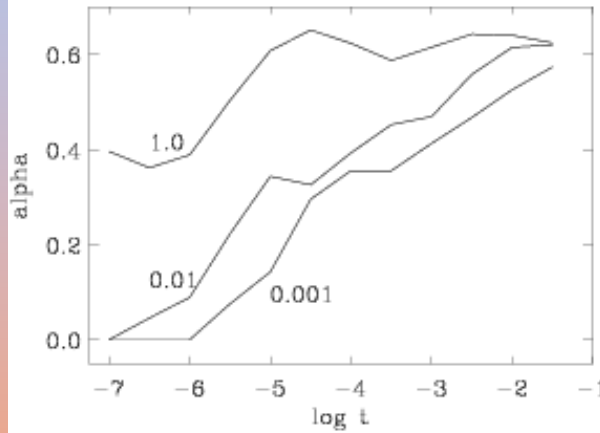
→ new approach needed !!!

$M(t, Z)$



$T_{\text{eff}} = 50000\text{K}$

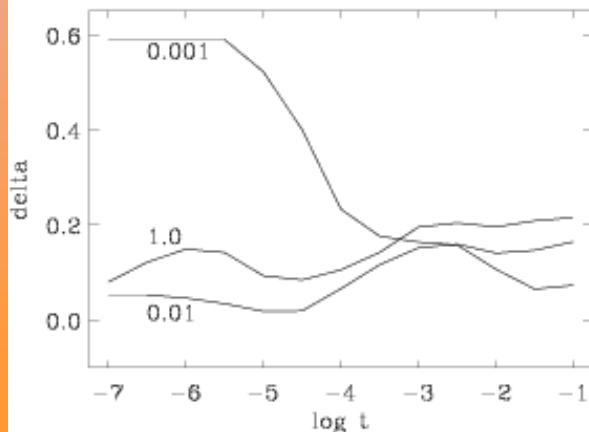
$\alpha(t, Z)$



$M(t), \alpha(t), \delta(t)$

$Z/Z_{\text{sun}} = 1.0$
 0.01
 0.001

$\delta(t, Z)$



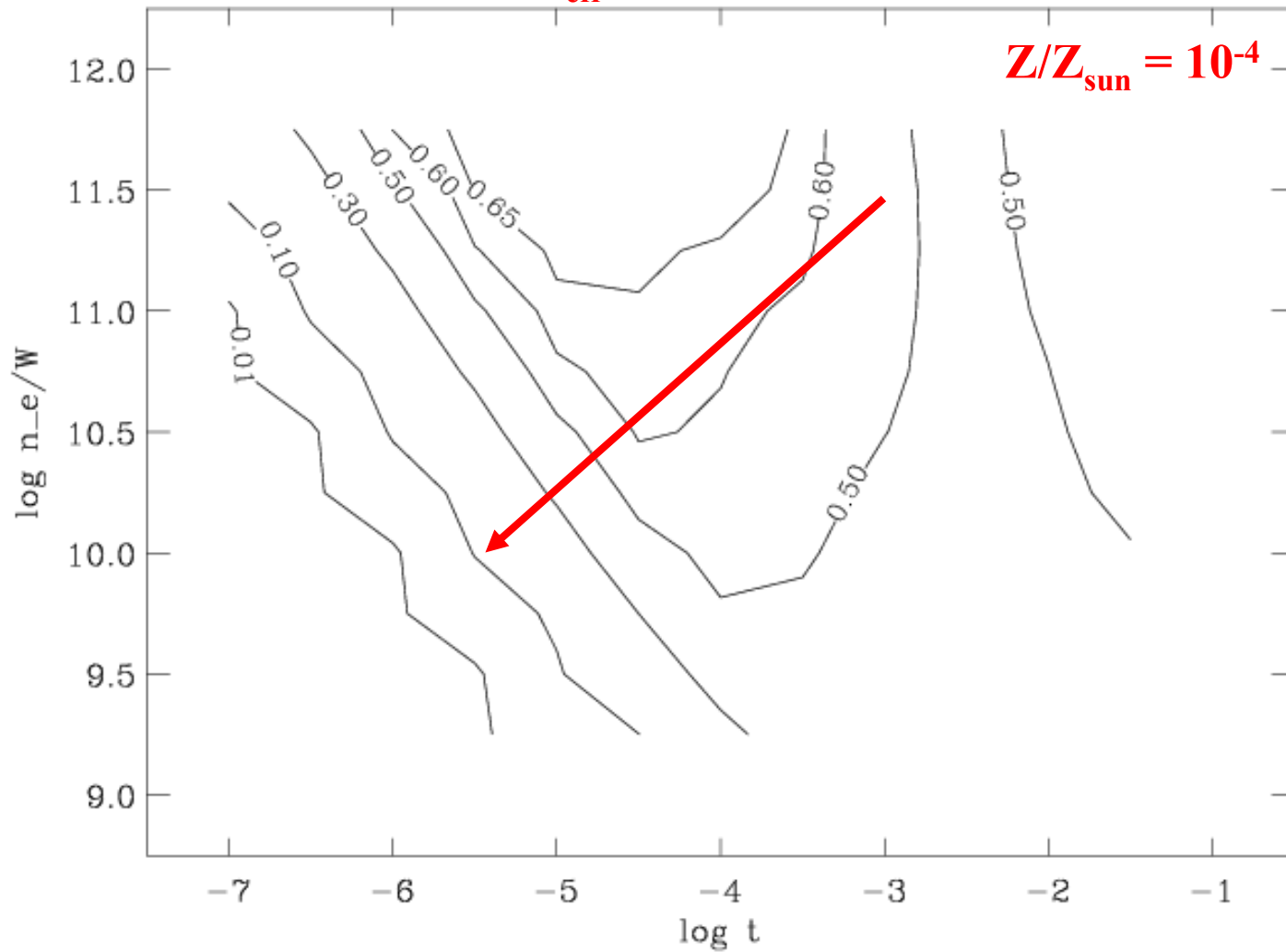
Kudritzki, ApJ 577, 389, 2002

millions of lines in NLTE

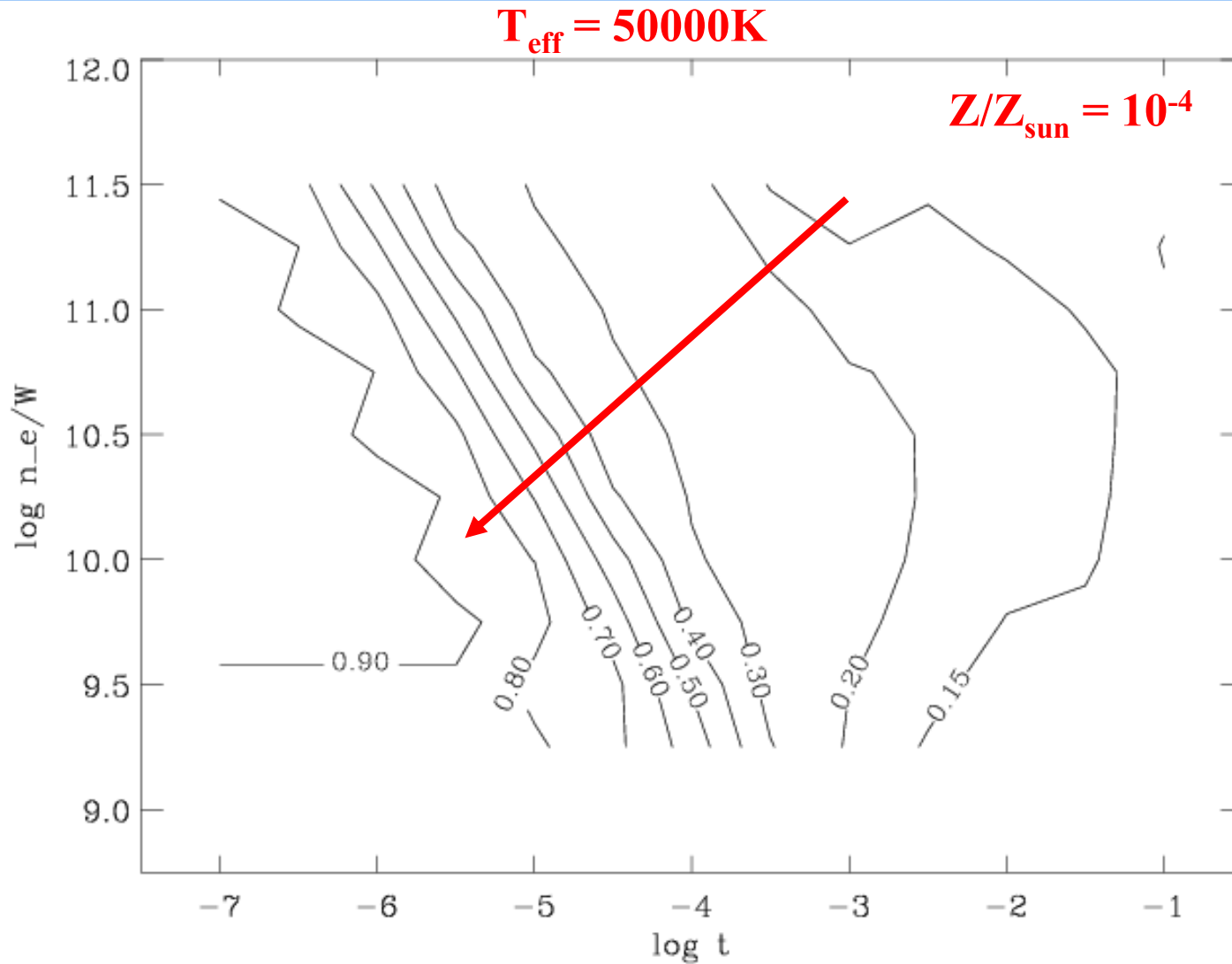
$\alpha(t, n_e/W)$

$T_{\text{eff}} = 50000\text{K}$

$Z/Z_{\text{sun}} = 10^{-4}$



$\delta(t, n_e/W)$



line driven winds with depth dependent line force multipliers

$$v(r) \frac{dv(r)}{dr} = -\frac{1}{\rho(r)} \frac{dP_{gas}(r)}{dr} - g(r) \{1 + \Gamma M\}$$

$$M = M(t^{-\alpha(t, n_e/W)}, (n_e/W)^{\delta(t, n_e/W)})$$

$$t = n_e \sigma_e \frac{v_{th}}{dv/dr}$$

For details of numerical of numerical solution including singularity and regularity conditions at critical point see

Kudritzki, ApJ 577, 389, 2002

wind models for evolved very massive stars at very low metallicity

$$10^{-4} \leq Z/Z_{\odot} \leq 1$$

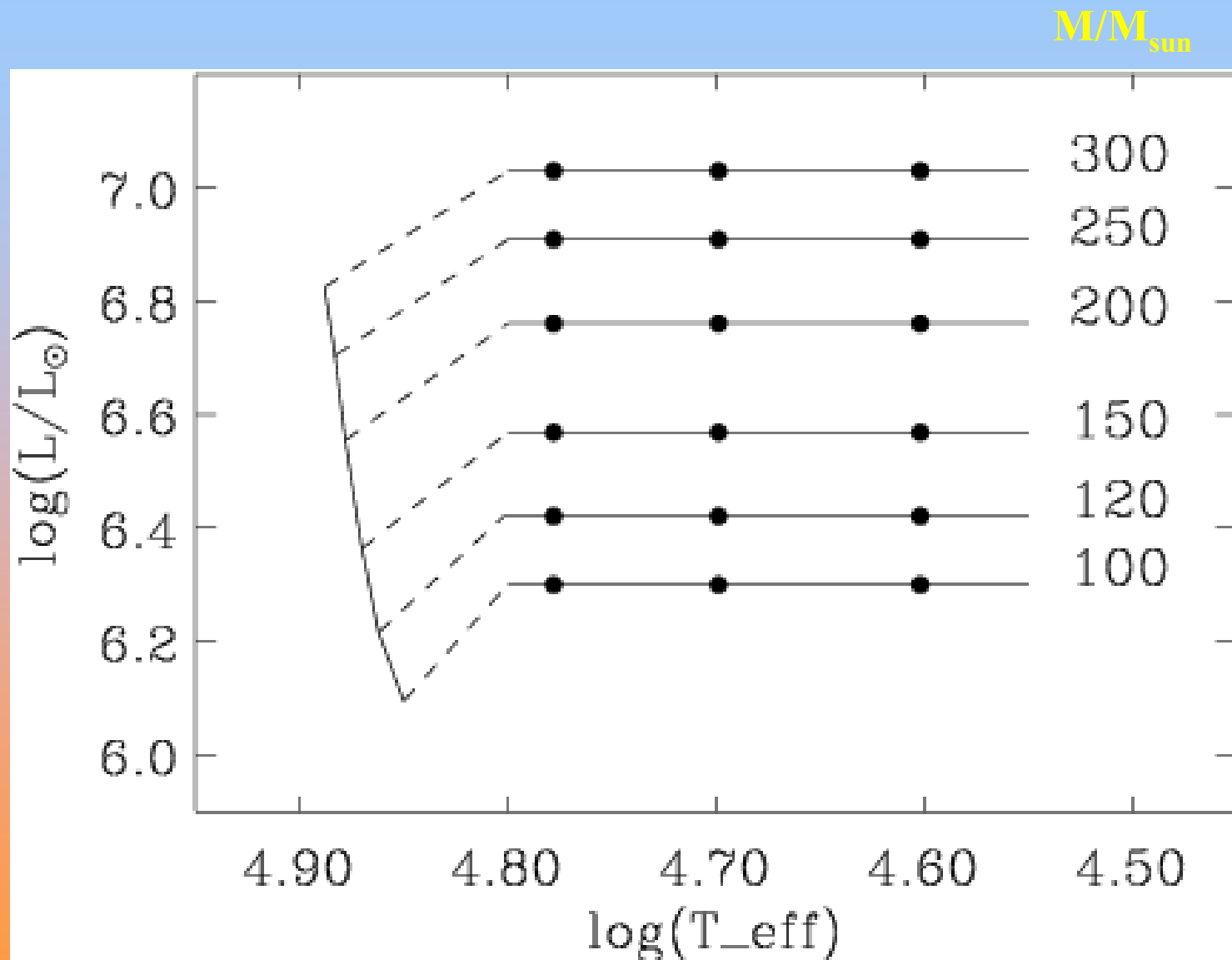
$$100M_{\odot} \leq M \leq 300M_{\odot}$$

$$40000K \leq T_{eff} \leq 60000K$$



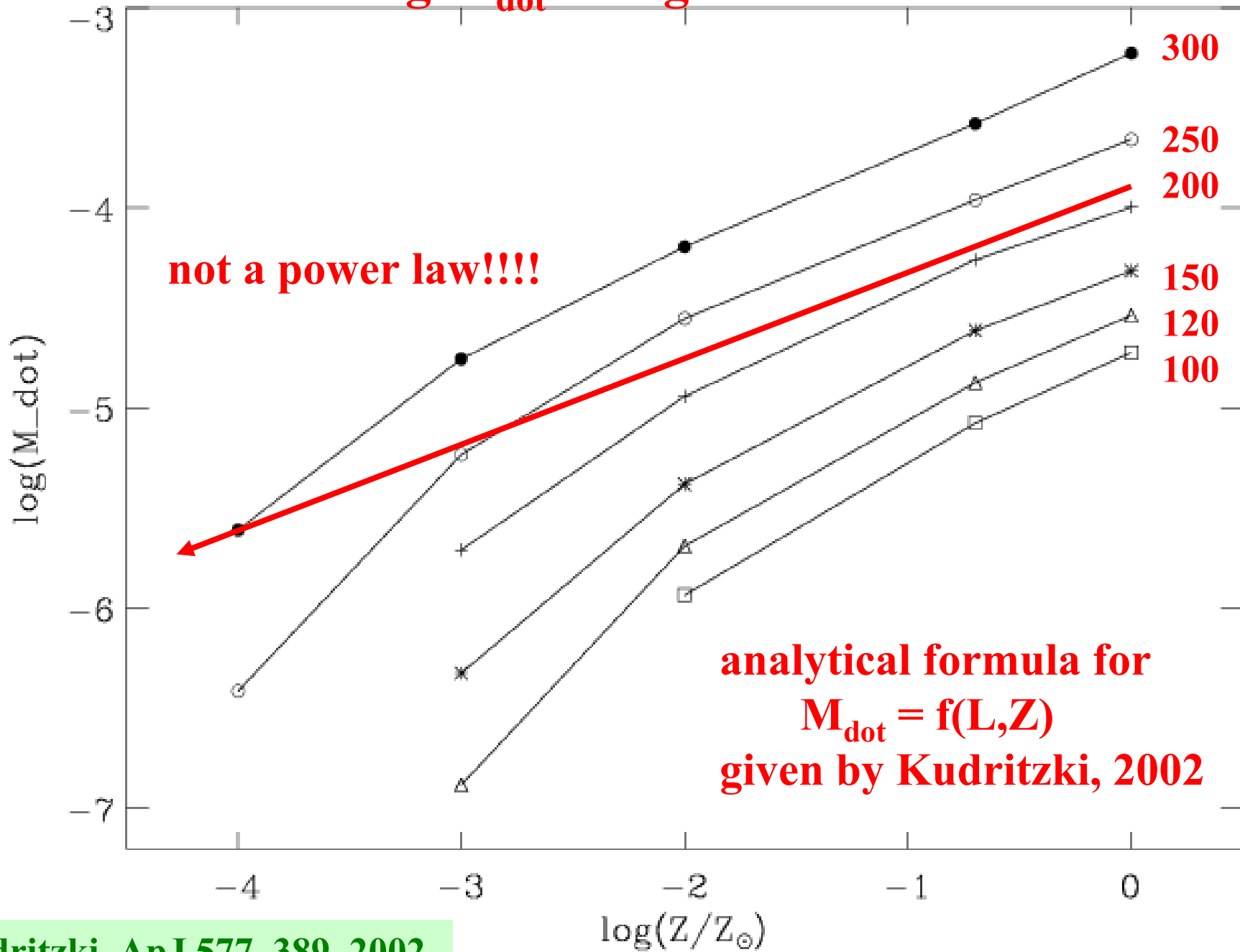
- winds
- ionizing fluxes
- spectra

the model grid



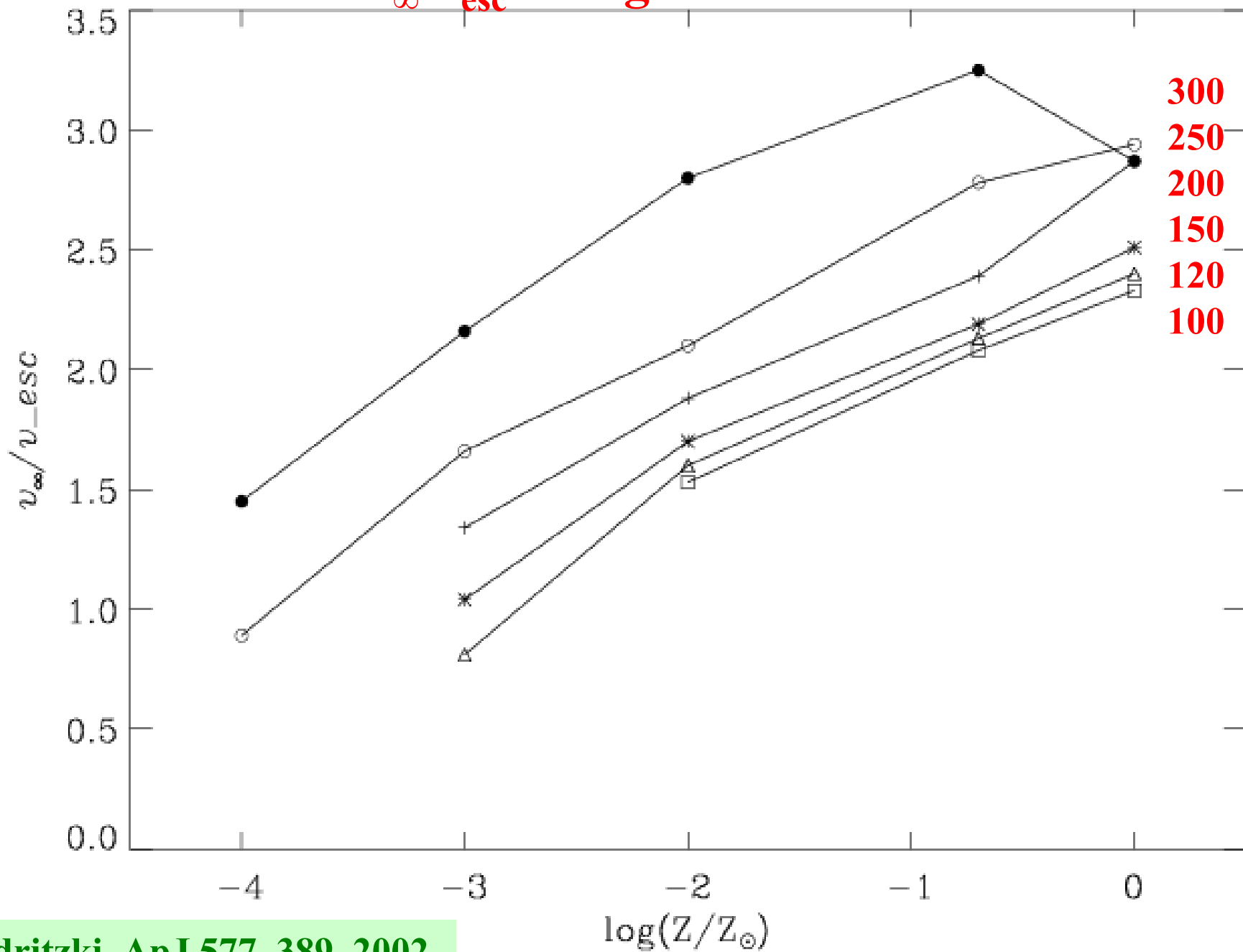
$\log \dot{M}$ vs $\log Z$

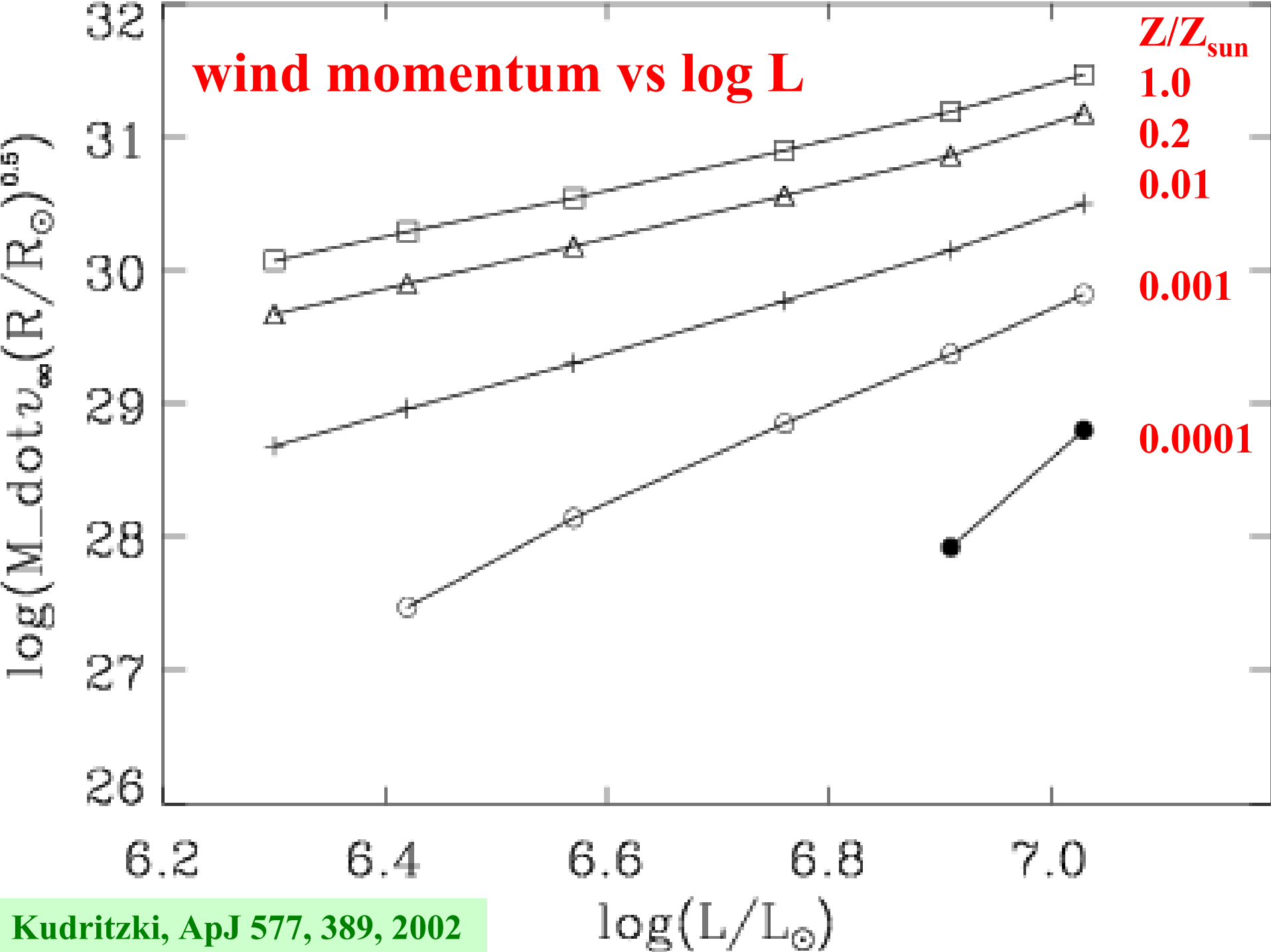
M/M_{sun}



v_∞/v_{esc} vs $\log Z$

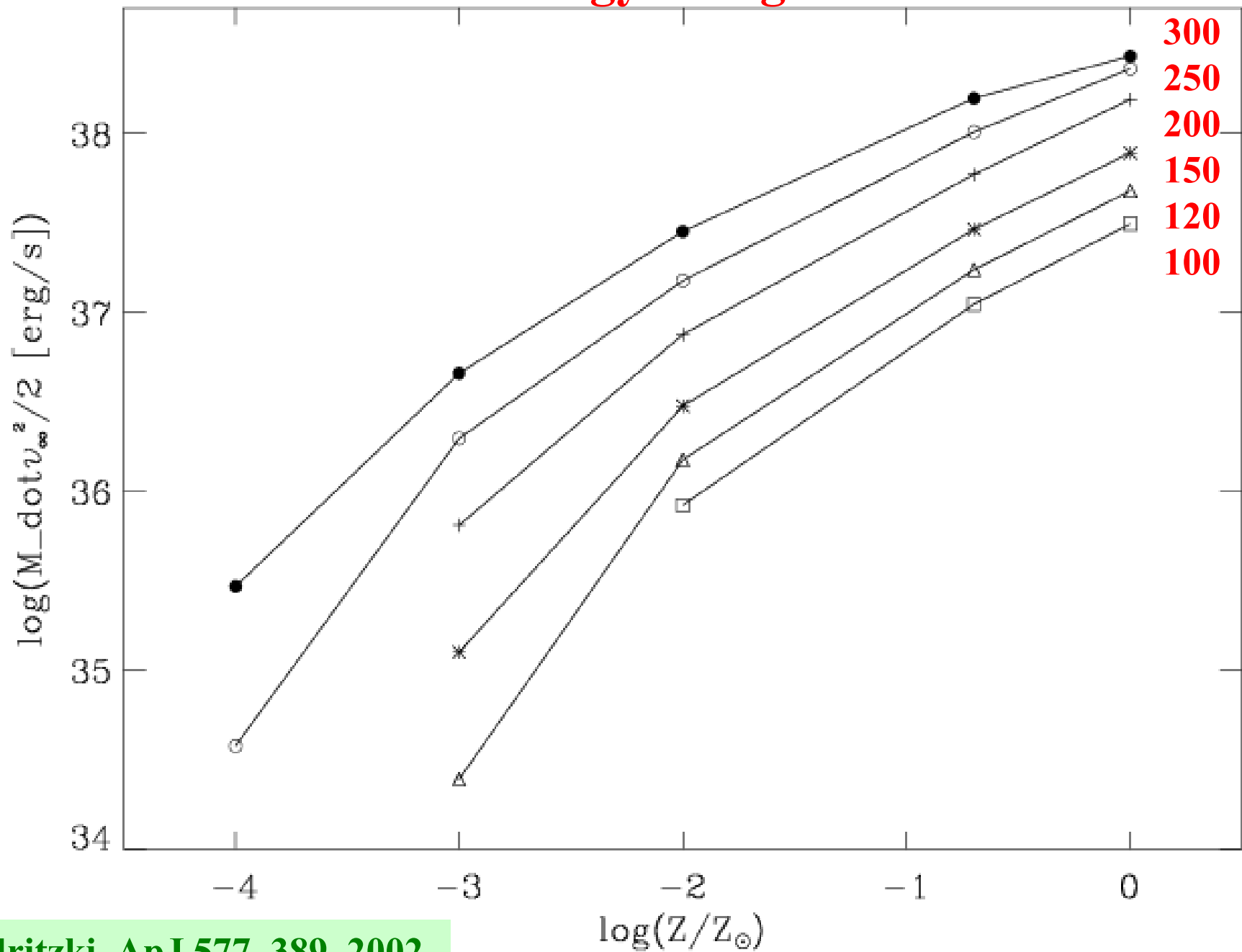
M/M_{sun}



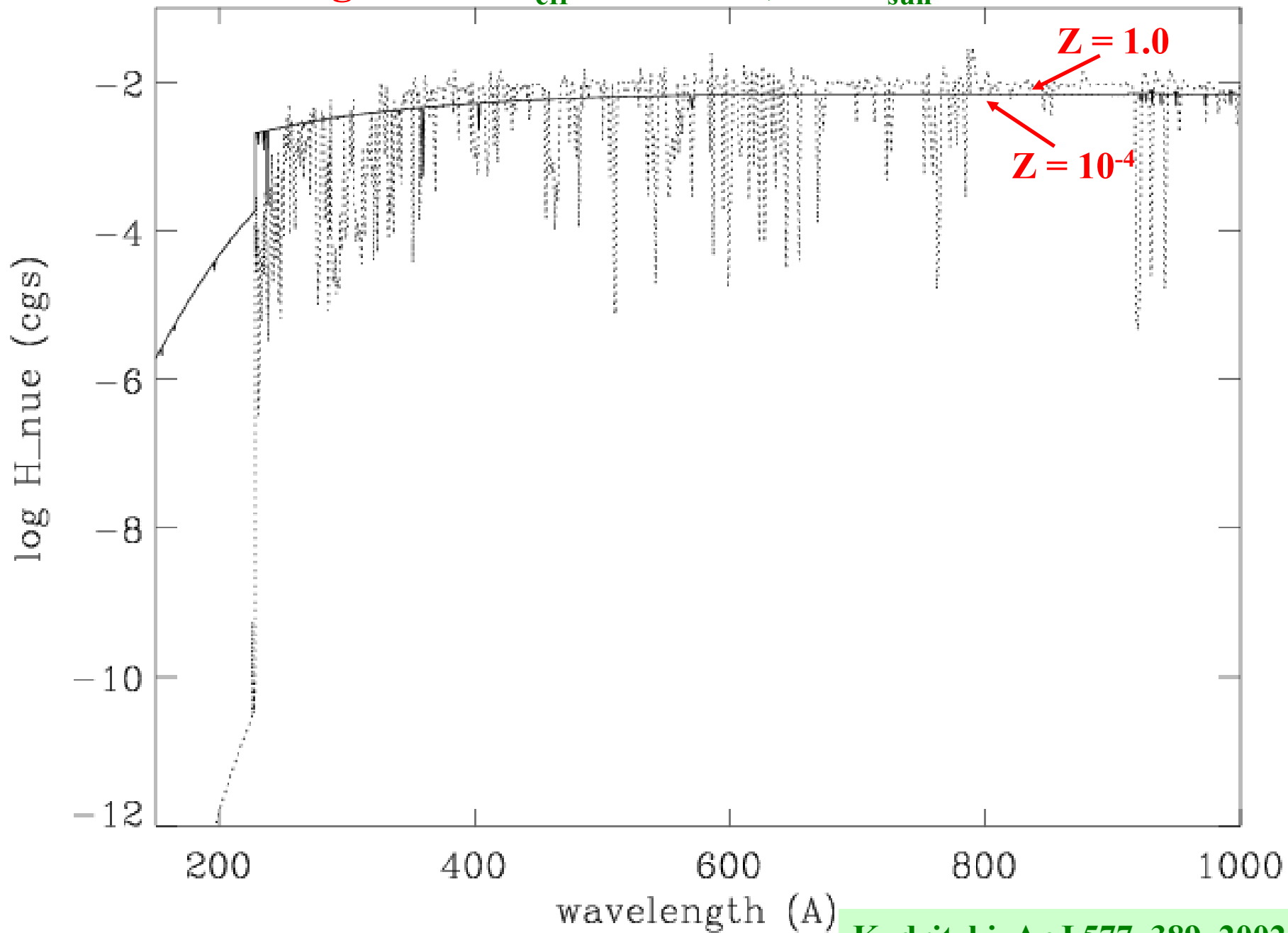


wind energy vs log Z

M/M_{sun}

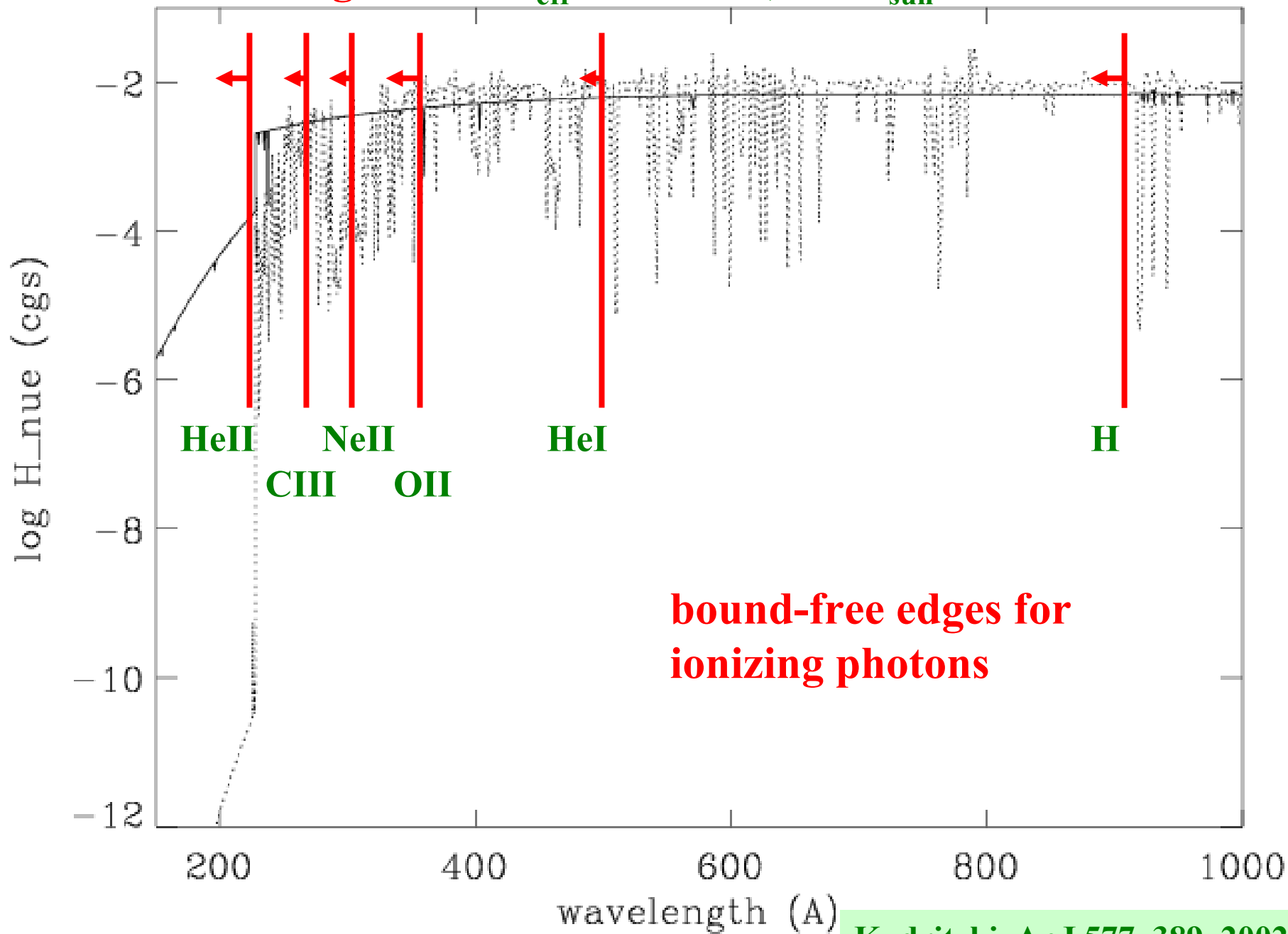


Ionizing fluxes: $T_{\text{eff}} = 60000\text{K}$, $M/M_{\text{sun}} = 250$



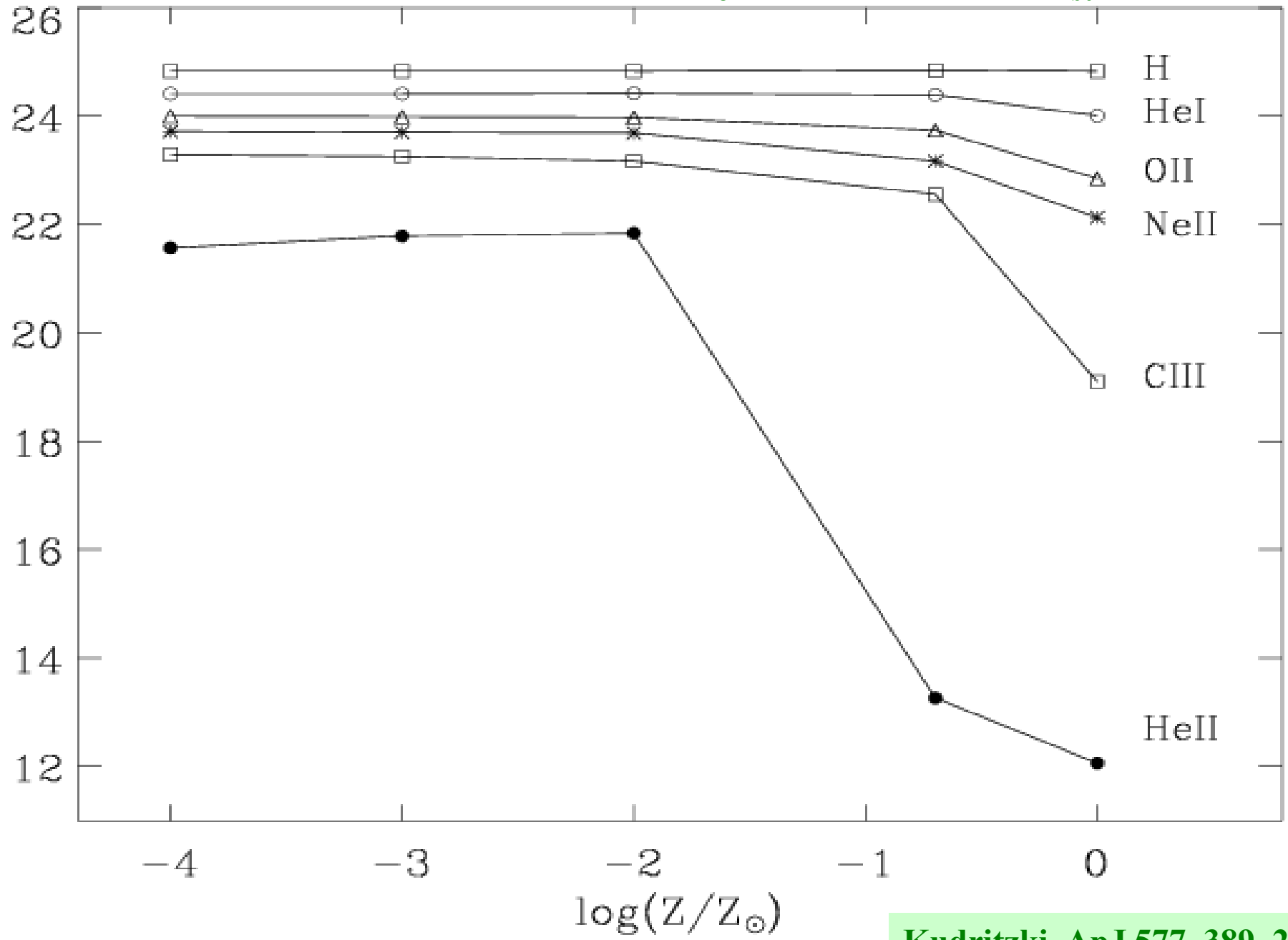
Kudritzki, ApJ 577, 389, 2002

Ionizing fluxes: $T_{\text{eff}} = 60000\text{K}$, $M/M_{\text{sun}} = 250$



**bound-free edges for
ionizing photons**

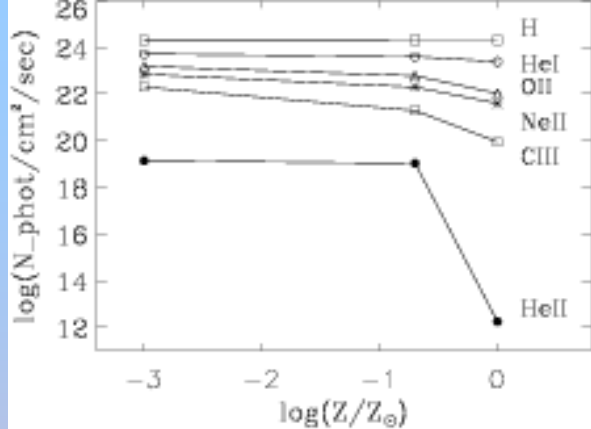
Number of ionizing photons: $T_{\text{eff}} = 50000\text{K}$, $M/M_{\text{sun}} = 300$



ionizing fluxes vs. metallicity, luminosity

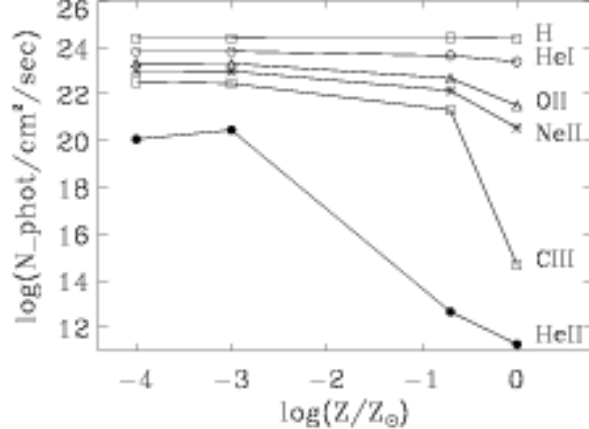
- **H and He I ionizing photons**
unaffected
- **O II, Ne II, C III photons**
moderately affected
- **He II photons**
strongly affected

120 M_{sun}



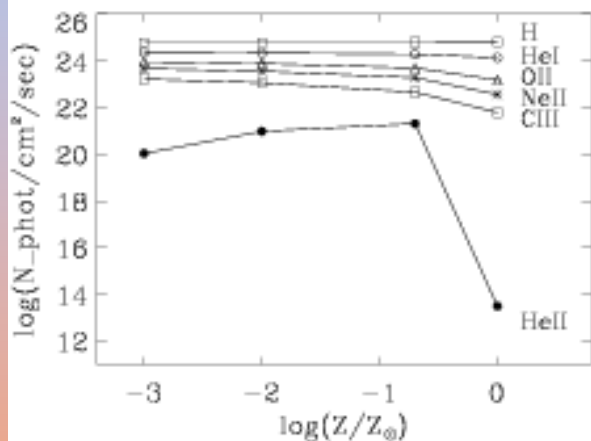
40000K

300 M_{sun}

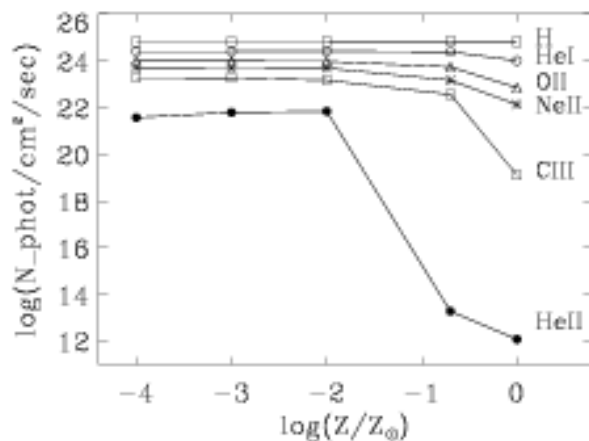


40000K

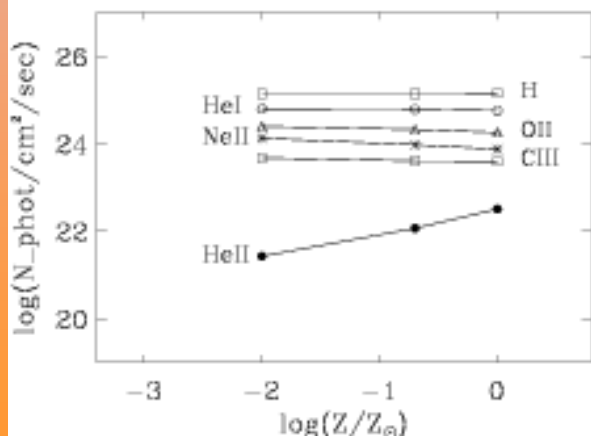
50000K



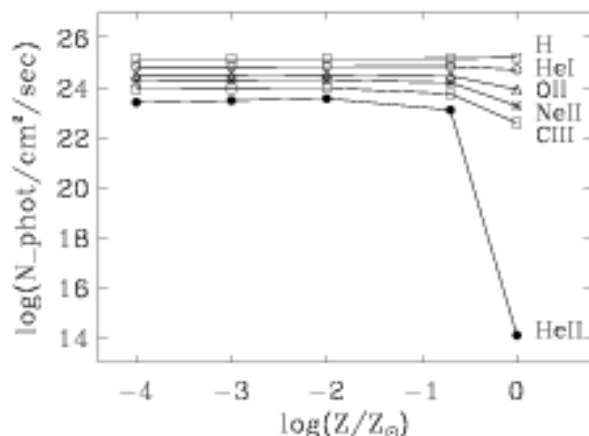
50000K



60000K

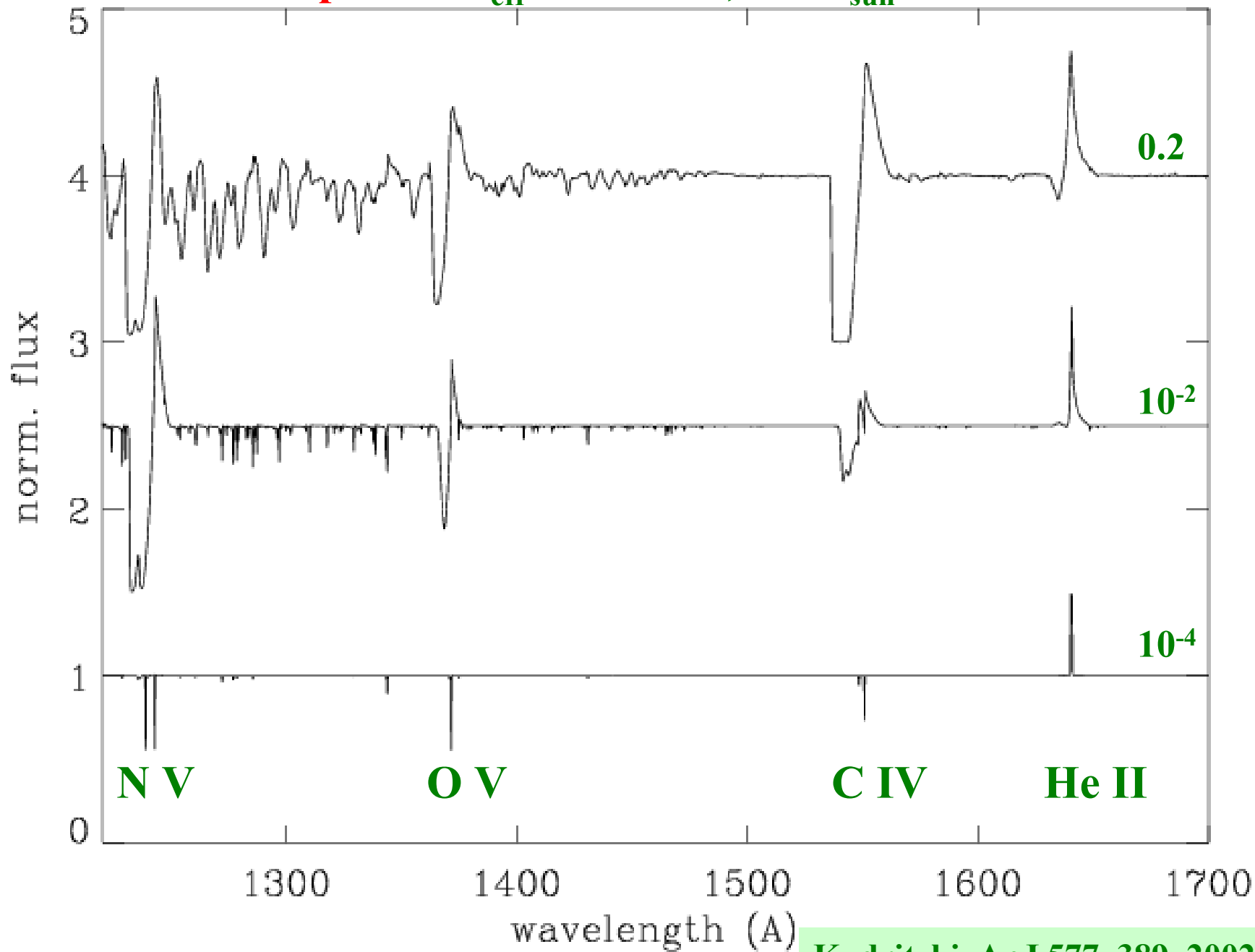


60000K



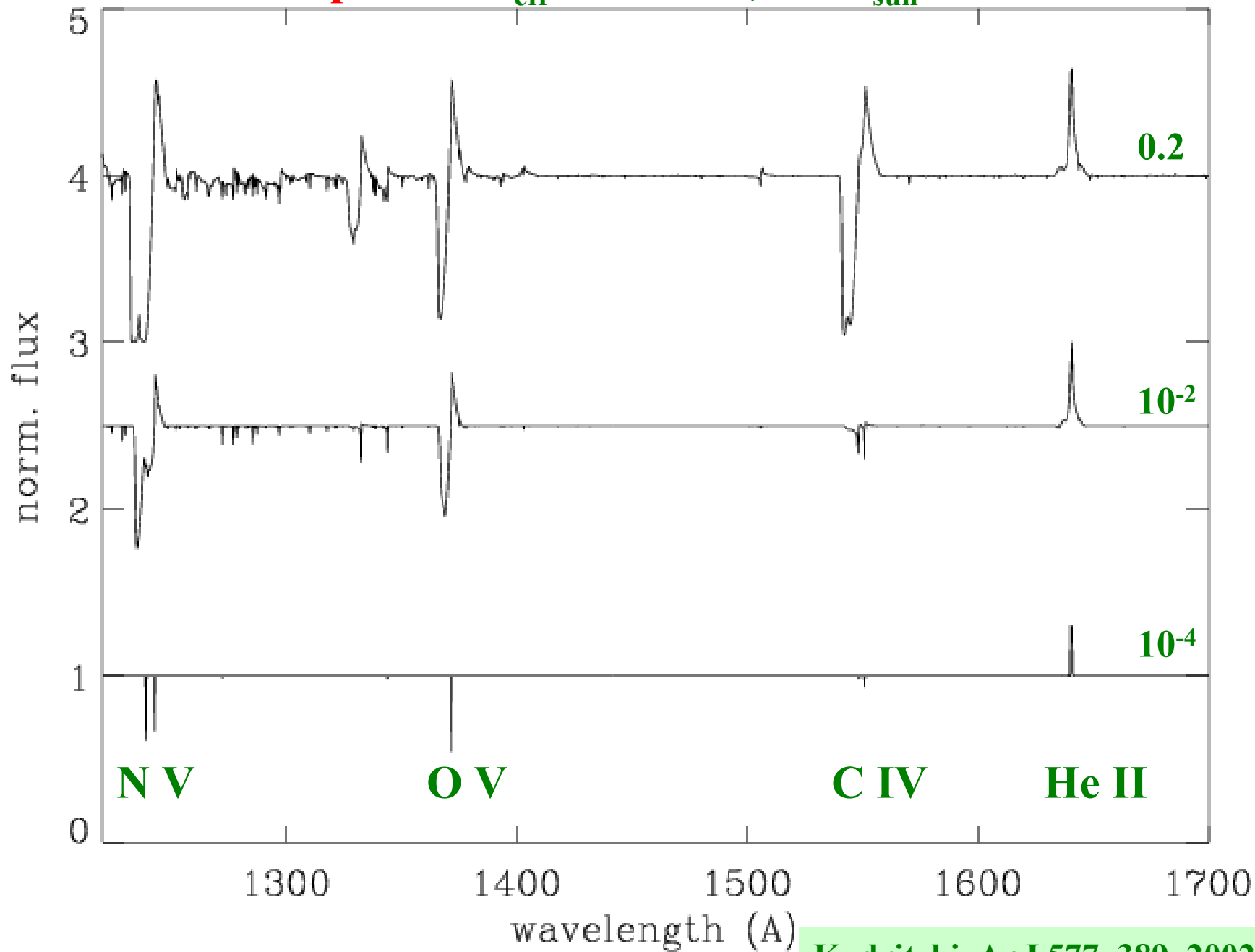
Spectra: $T_{\text{eff}} = 50000\text{K}$, $M/M_{\text{sun}} = 250$

Z/Z_{sun}



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Z/Z_{sun}



UV line spectra

- line diagnostics possible down to $Z/Z_{\text{sun}} = 10^{-4}$



GSMT
JWST

- wind features disappear at $Z/Z_{\text{sun}} = 10^{-3}$

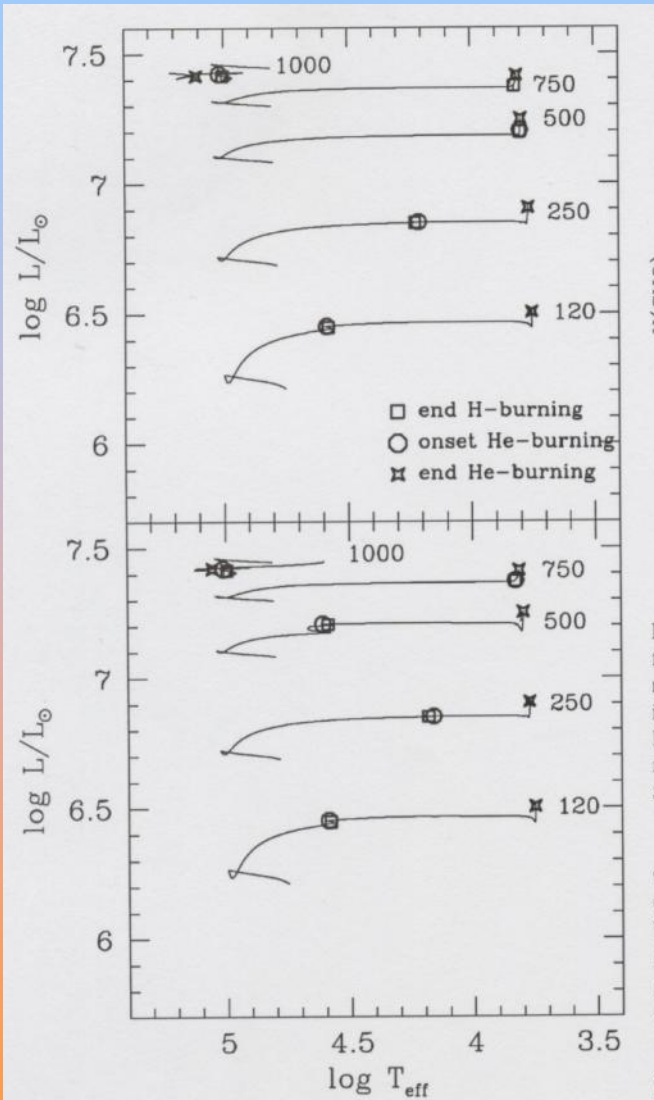
Applications

- **evolution of massive Pop III stars**
- **low metallicity starburst galaxies at high z**
- **the first stars in the re-ionization epoch**

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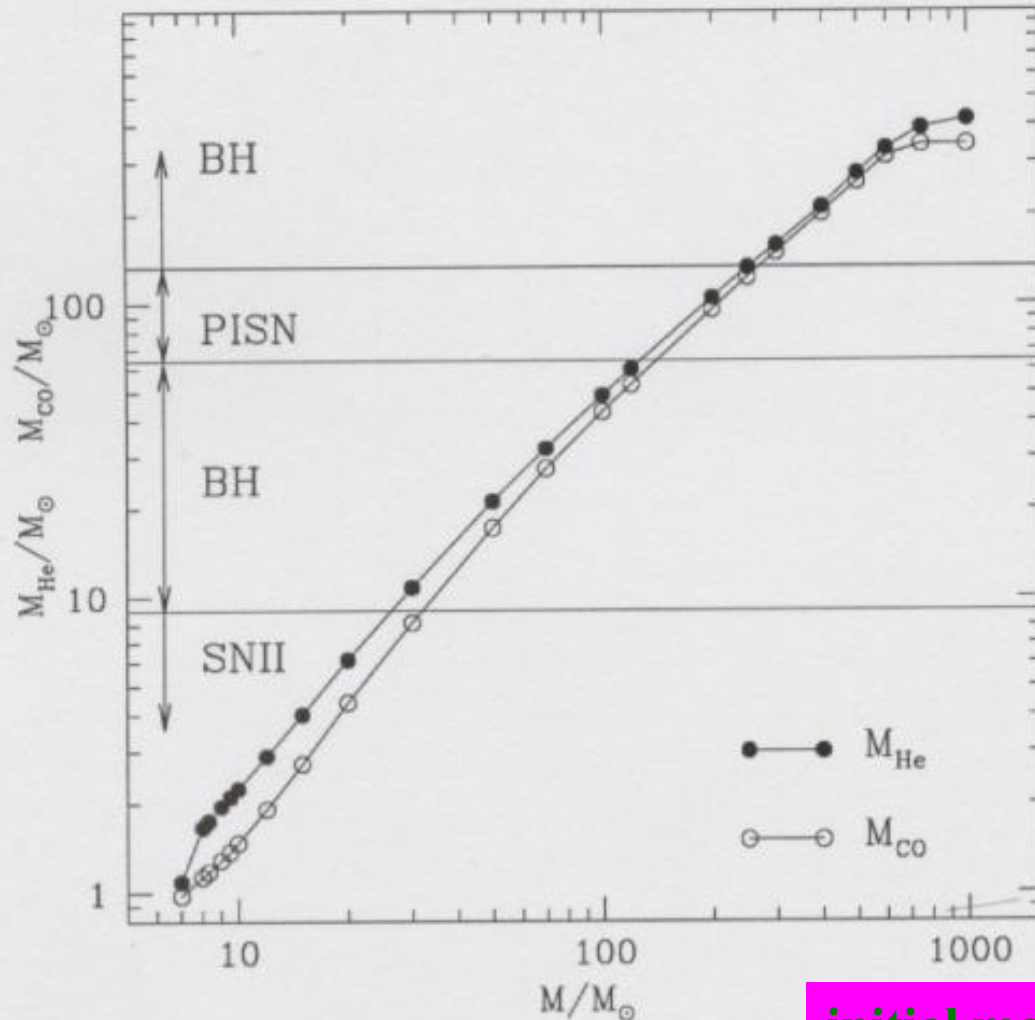
Evolution of massive Pop III stars with mass-loss



Marigo, Chiosi, Kudritzki
2003, A&A 399, 617

Final stages of massive Pop III stars

He & CO cores
at C ignition

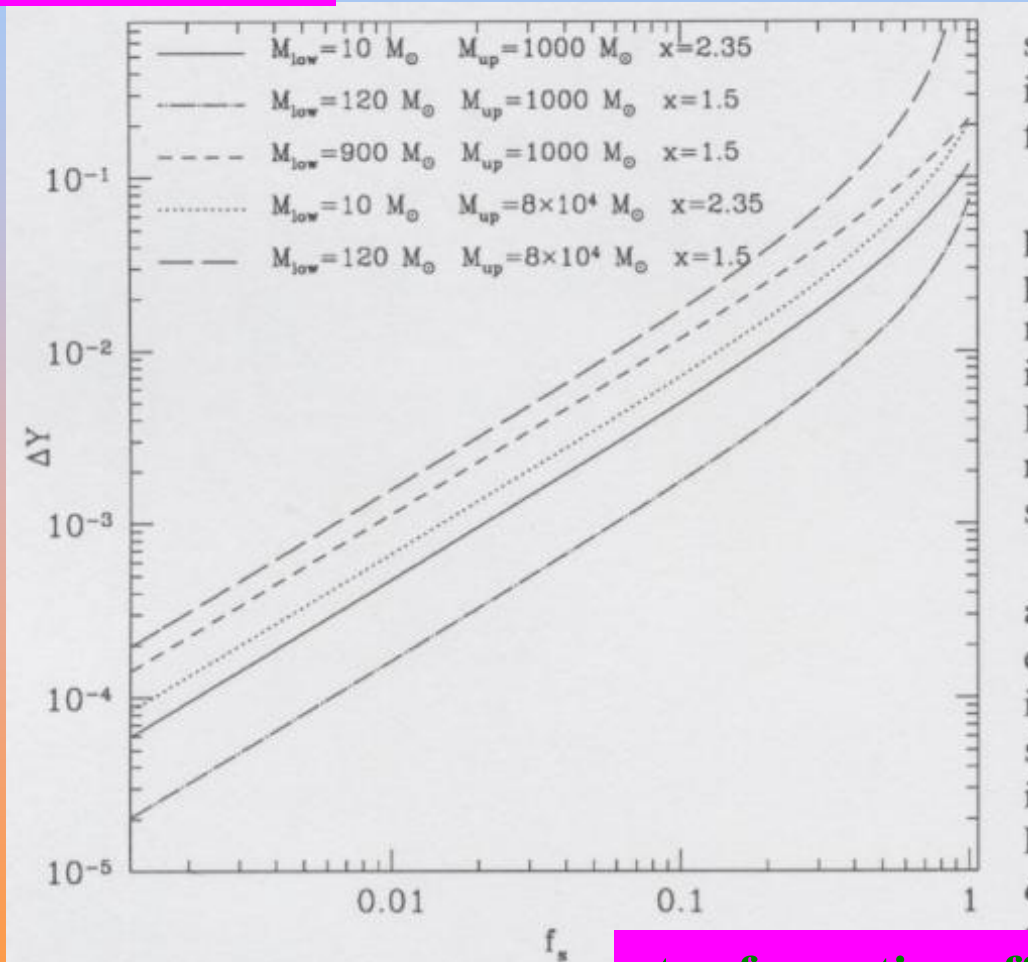


Marigo, Chiosi, Kudritzki
2003, A&A 399, 617

initial mass

He enrichment of ISM

He enrichment

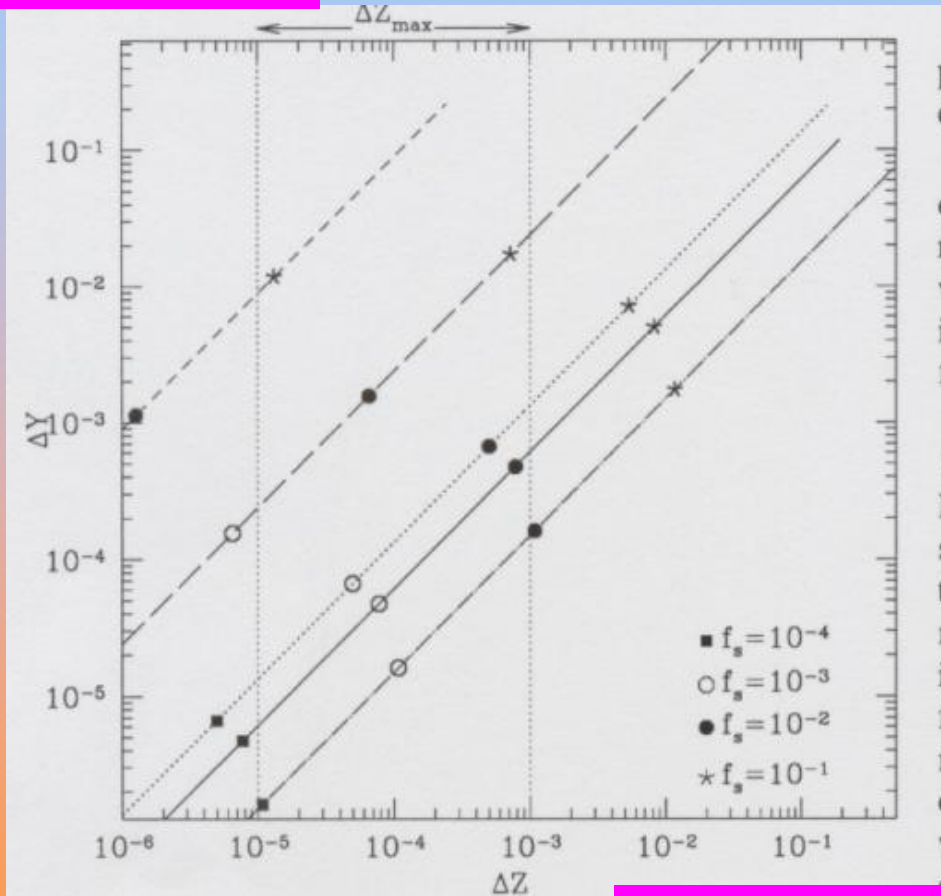


Marigo, Chiosi, Kudritzki
2003, A&A 399, 617

star formation efficiency

He vs Z enrichment of ISM

He enrichment



metallicity enrichment

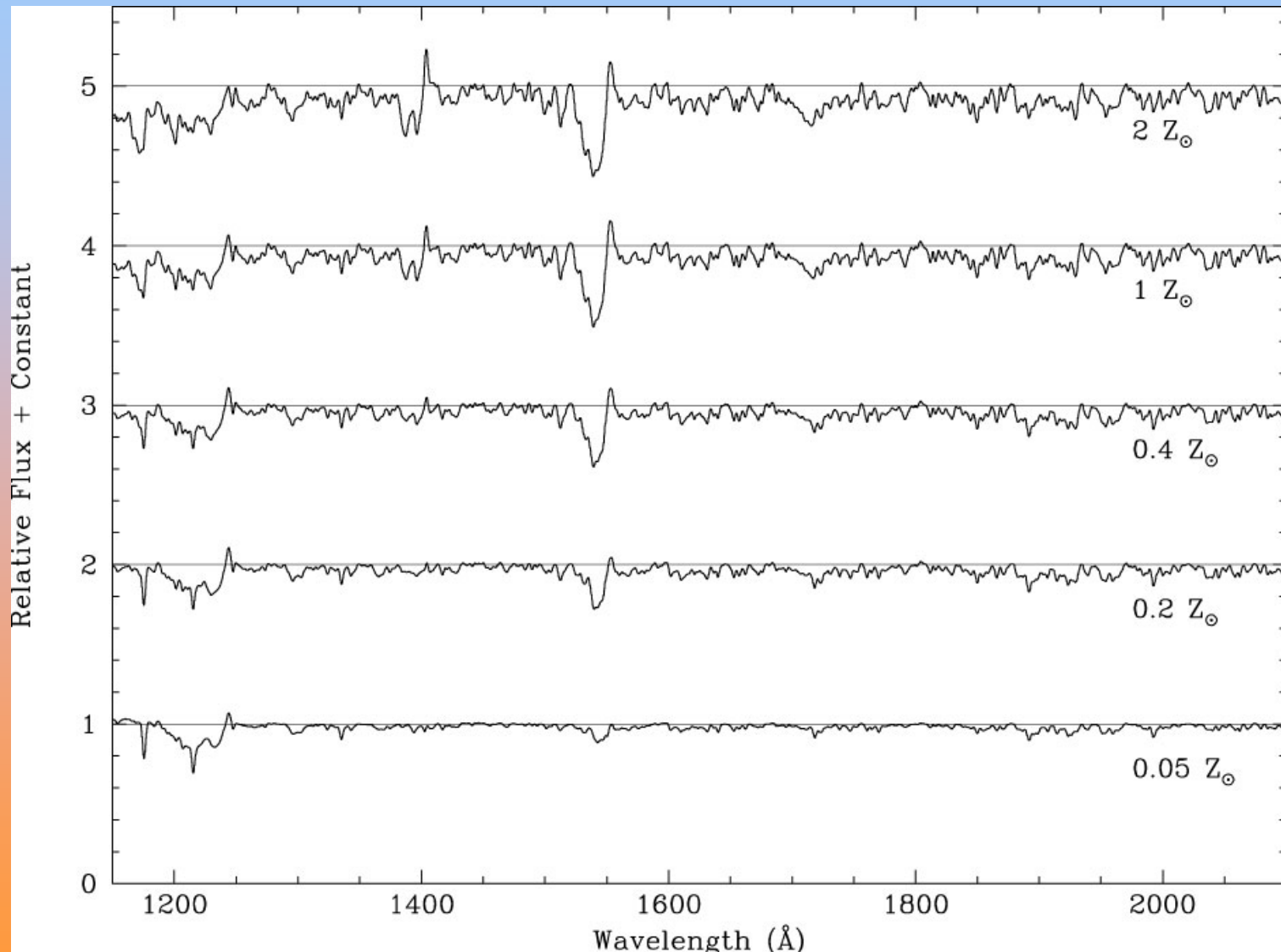
Marigo, Chiosi, Kudritzki
2003, A&A 399, 617

Applications

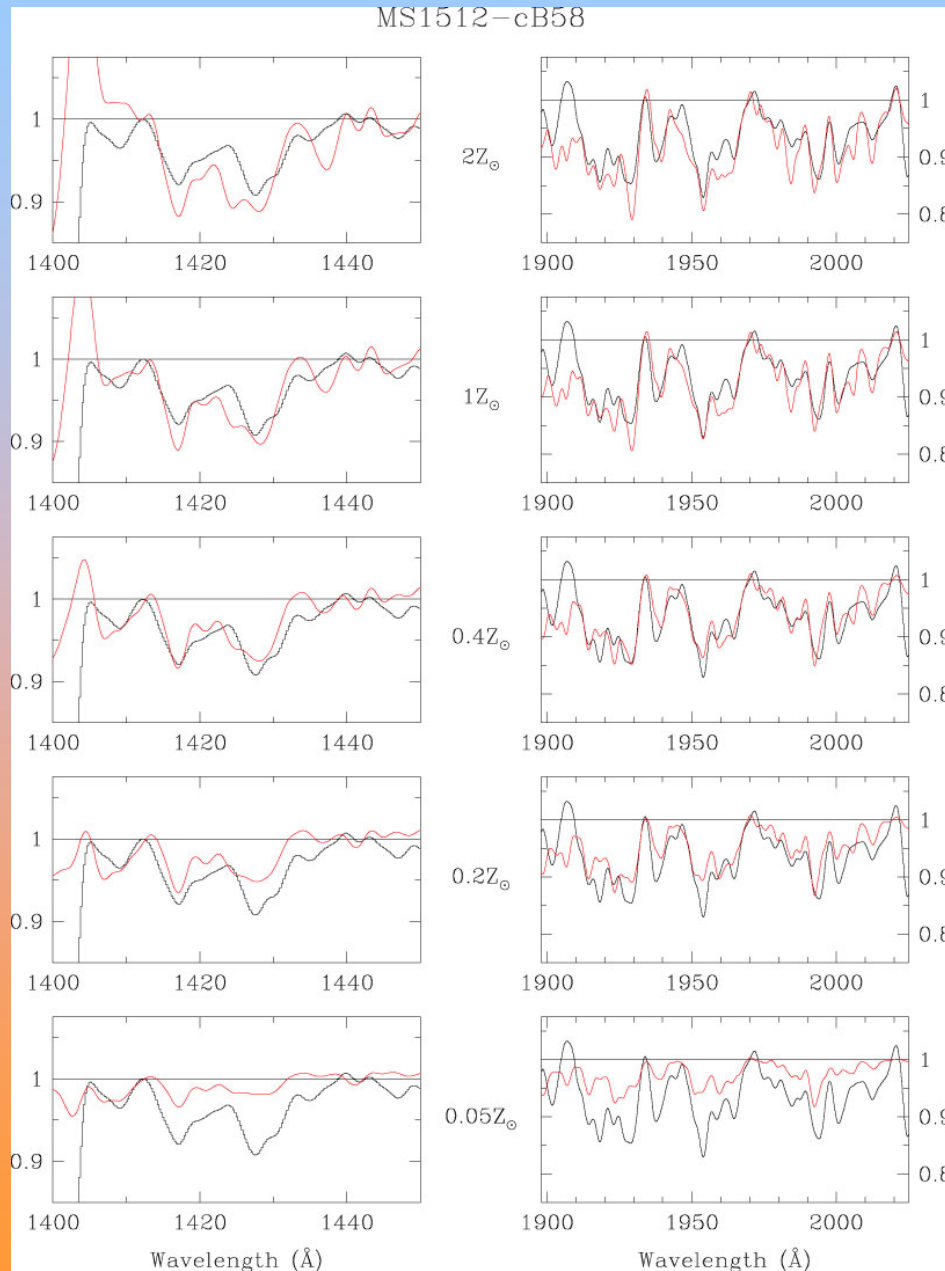
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Spectral diagnostics of high-z starbursts

Starburst models - fully synthetic spectra based on model atmospheres



Spectral diagnostics of high- z starbursts



cB58 @ $z=2.7$

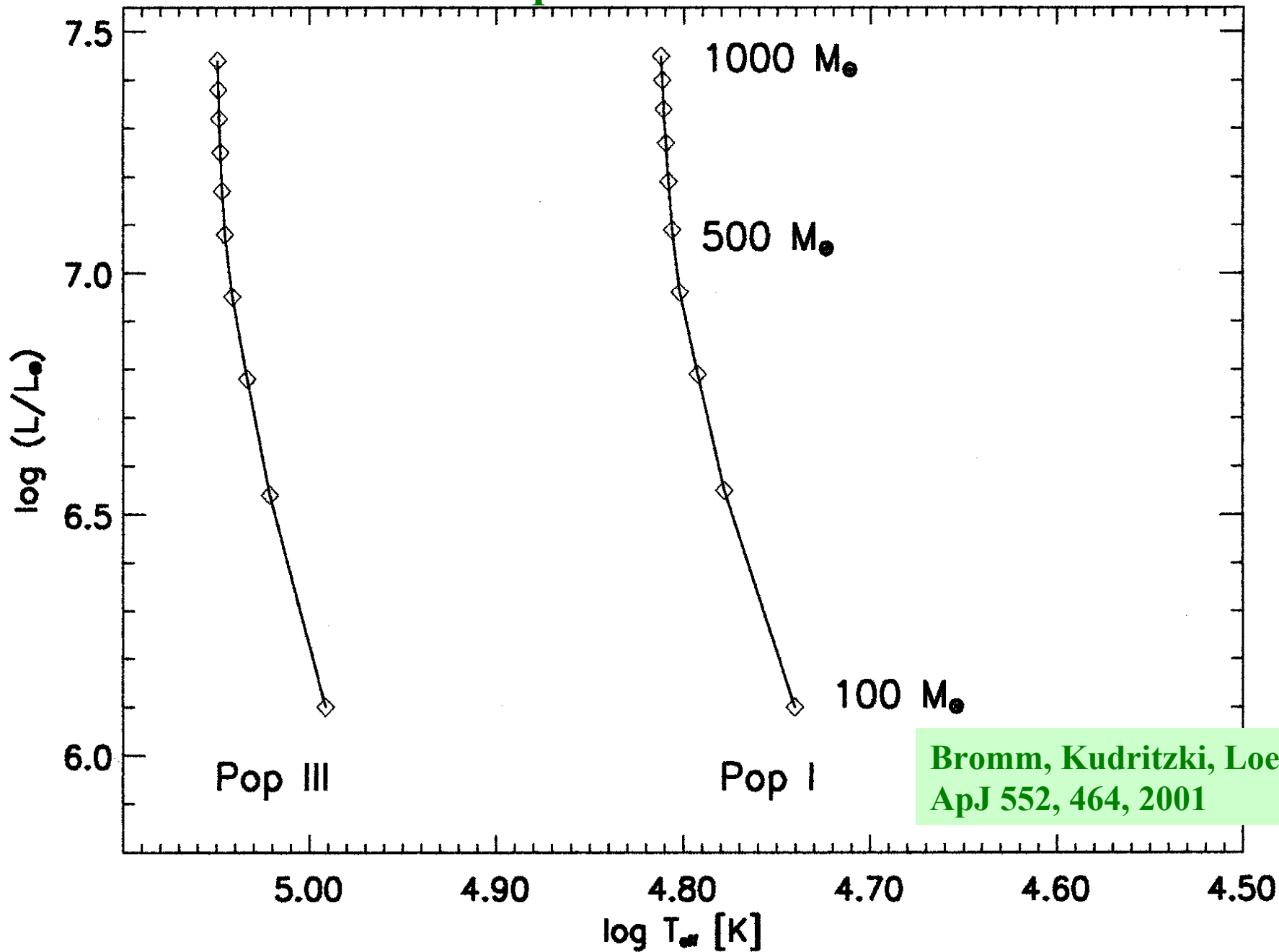
**fully synthetic spectra
vs. observation**

**Rix, Pettini, Leitherer,
Bresolin, Kudritzki, Steidel
2004, ApJ 615, 98**

Applications

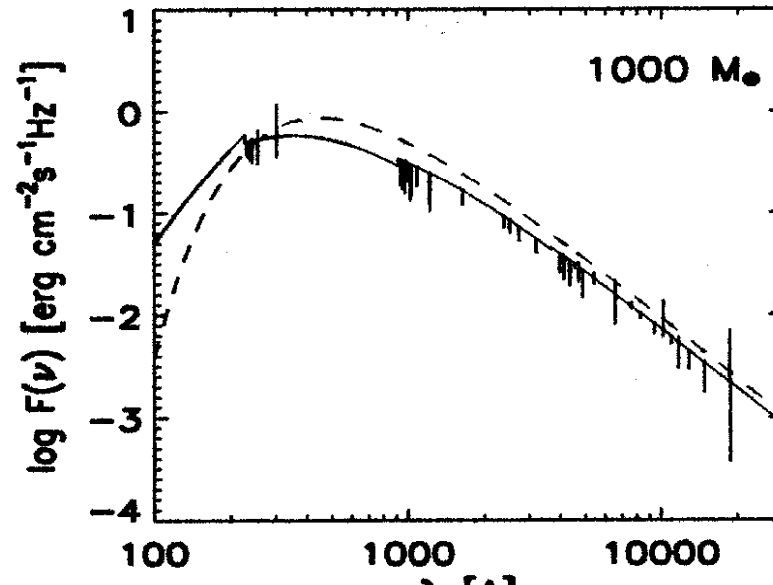
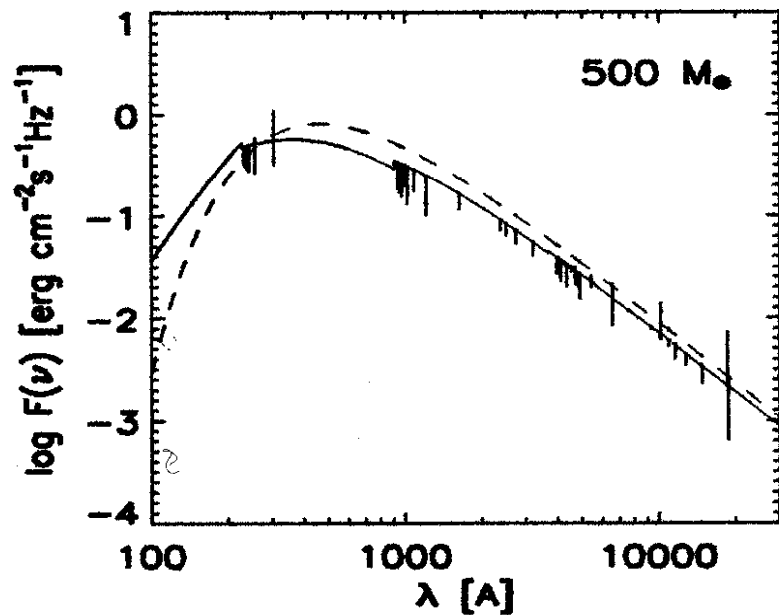
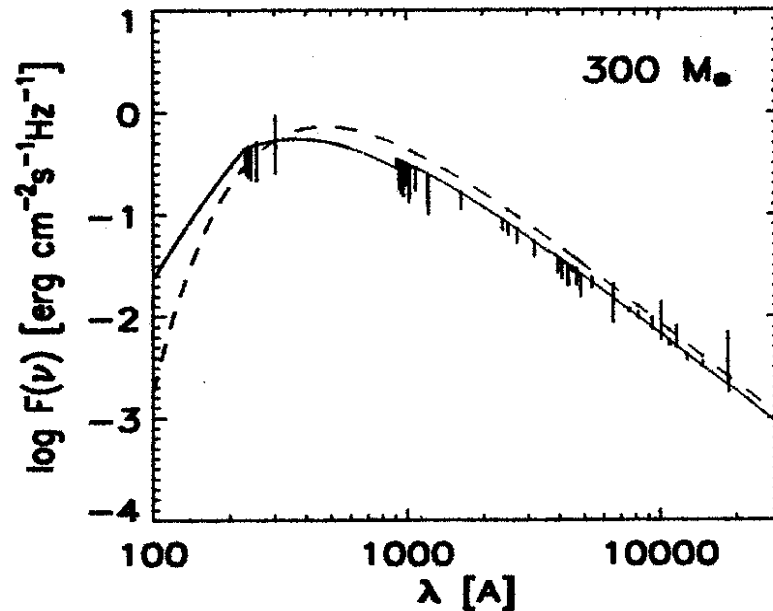
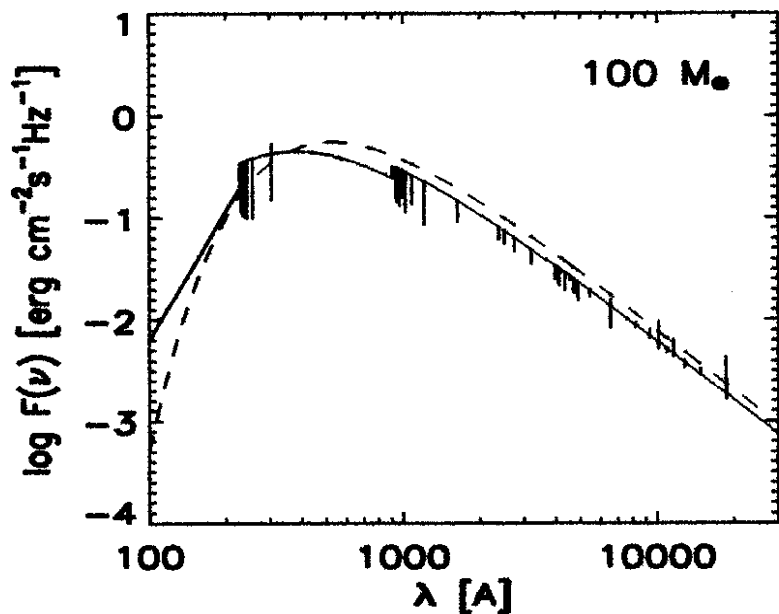
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Main sequence of the first stars

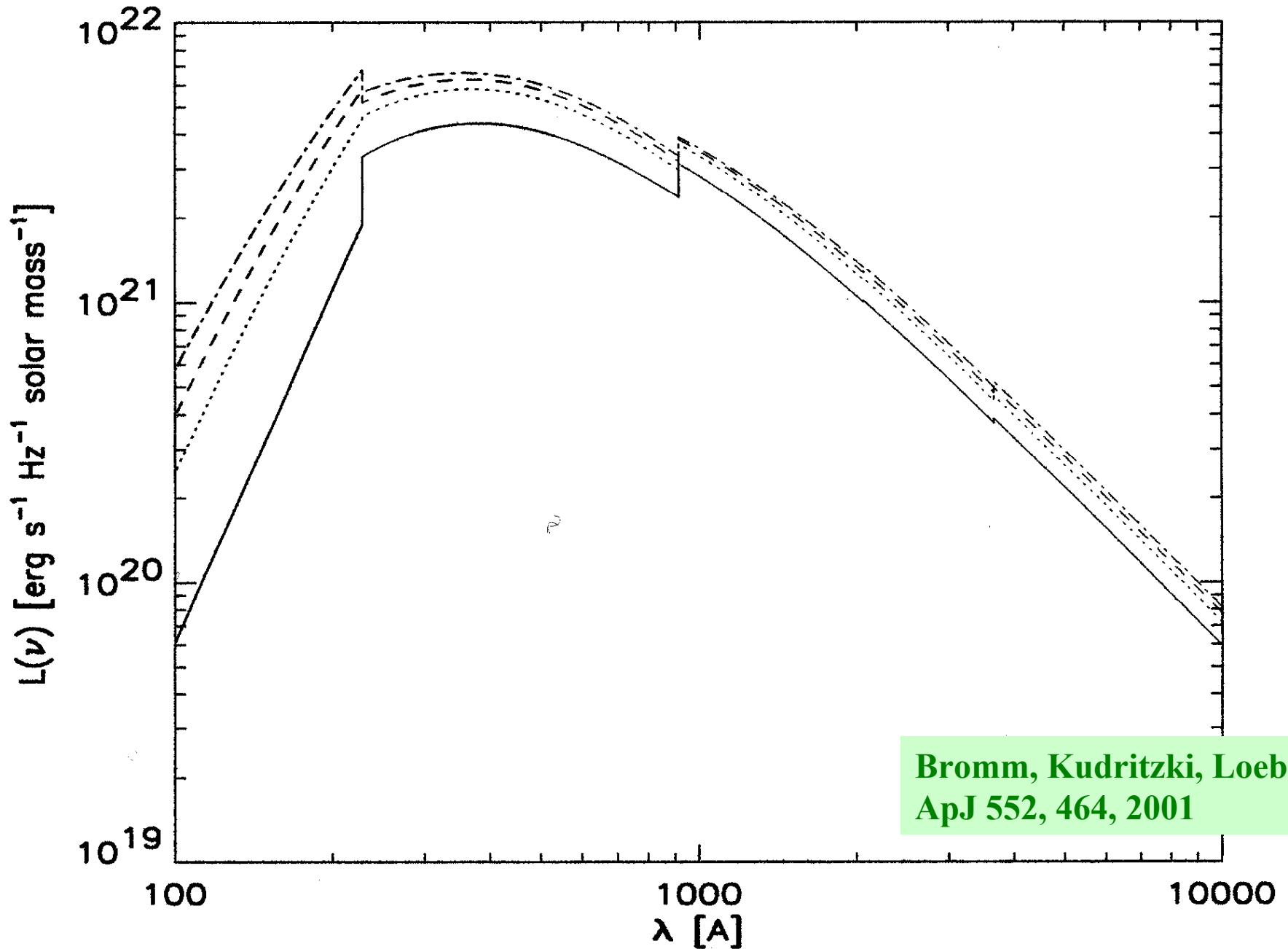


Bromm, Kudritzki, Loeb
ApJ 552, 464, 2001

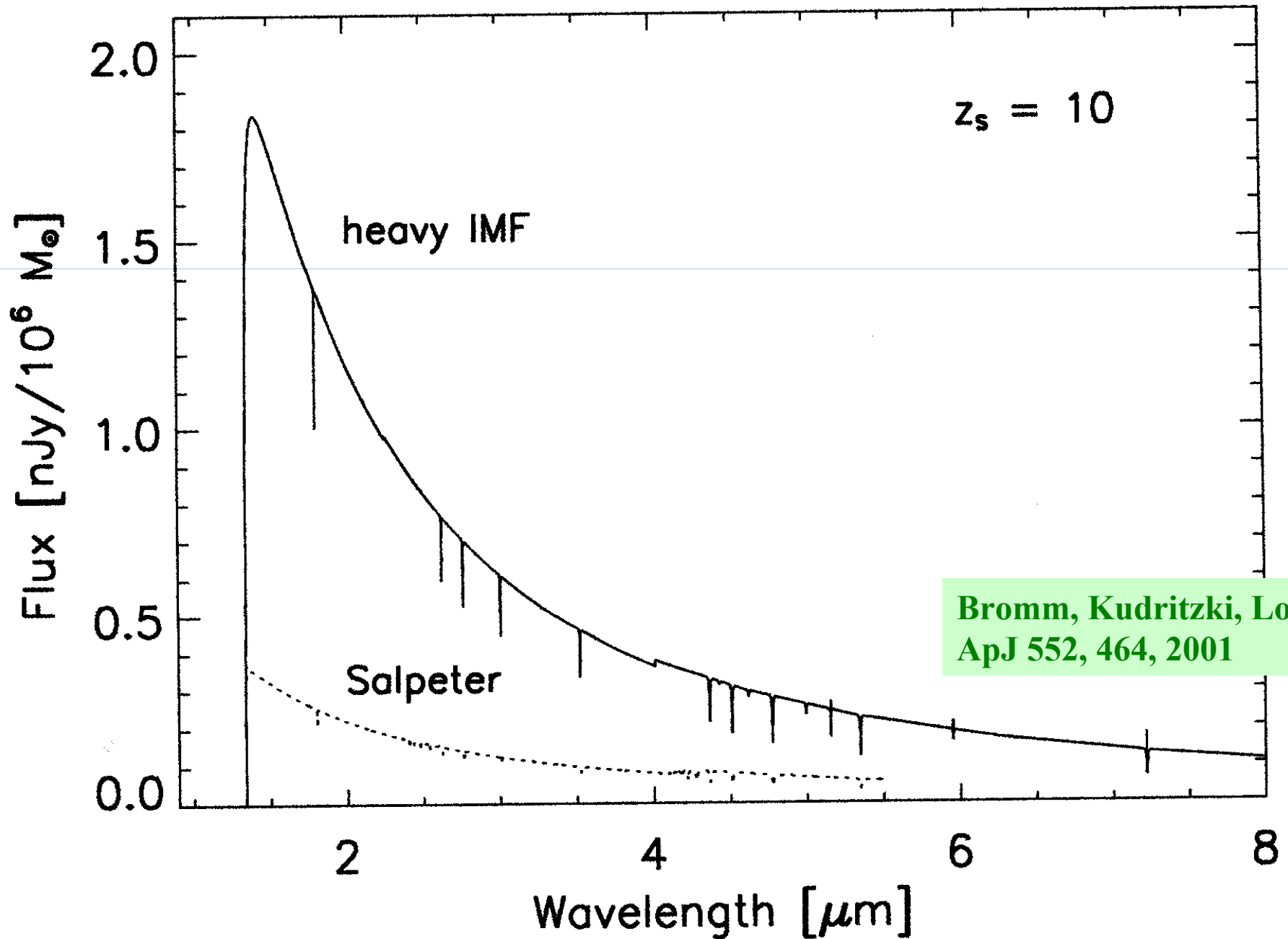
Spectra and SEDs of the first stars



L_ν / M is almost constant !!!



SED of a cluster of 10^6 stars at a redshift of 10



First very massive stars - conclusions

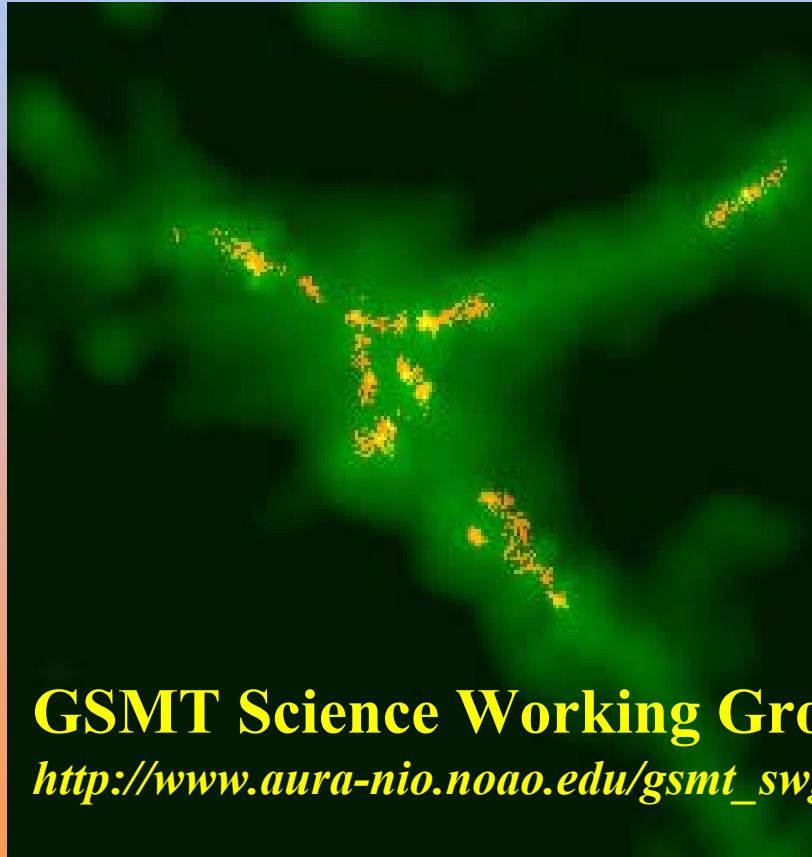
- generic SEDs \sim BB with $T \geq 10^5$ K
- rich H and HeII spectra
- L_v/M independent of stellar mass for $M \geq 200 M_{\text{sun}}$
- $N^{\text{phot}}(\text{H})/M_{\text{stars}}$ factor ten larger than for Salpeter IMF
- (HeII) hundred
- H and HeII recombination lines observable with 30m
- predicted continuum spectra for $10^6 M_{\text{sun}}$ cluster at $z=10$
 - detectable with JWST
 - SEDs, colors different from Salpeter IMF

Bromm, Kudritzki, Loeb
ApJ 552, 464, 2001
Schaerer, A&A 397, 527,
2003

Stars forming at $z=10$!

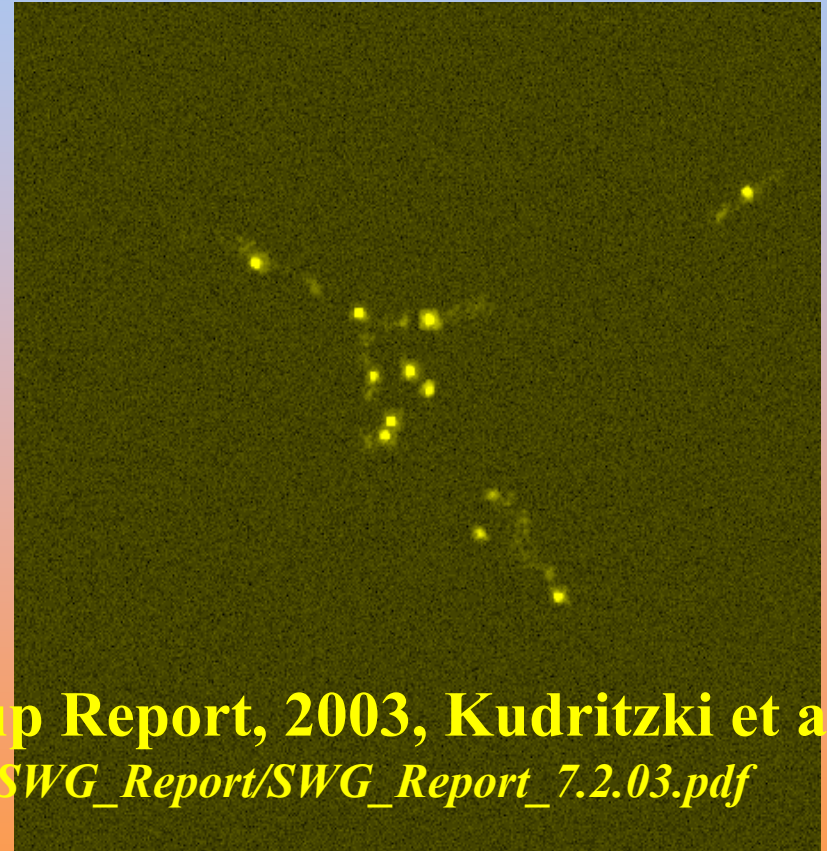
Observable with a 30m telescope!

1 Mpc (comoving)



GSMT Science Working Group Report, 2003, Kudritzki et al.
http://www.aura-nio.noao.edu/gsmg_swg/SWG_Report/SWG_Report_7.2.03.pdf

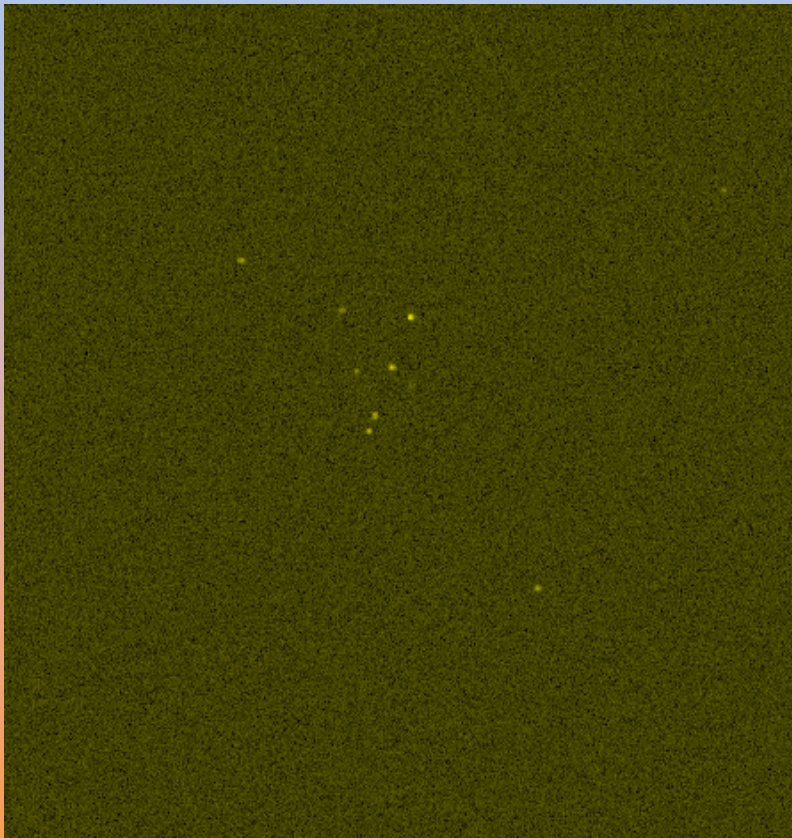
Simulation



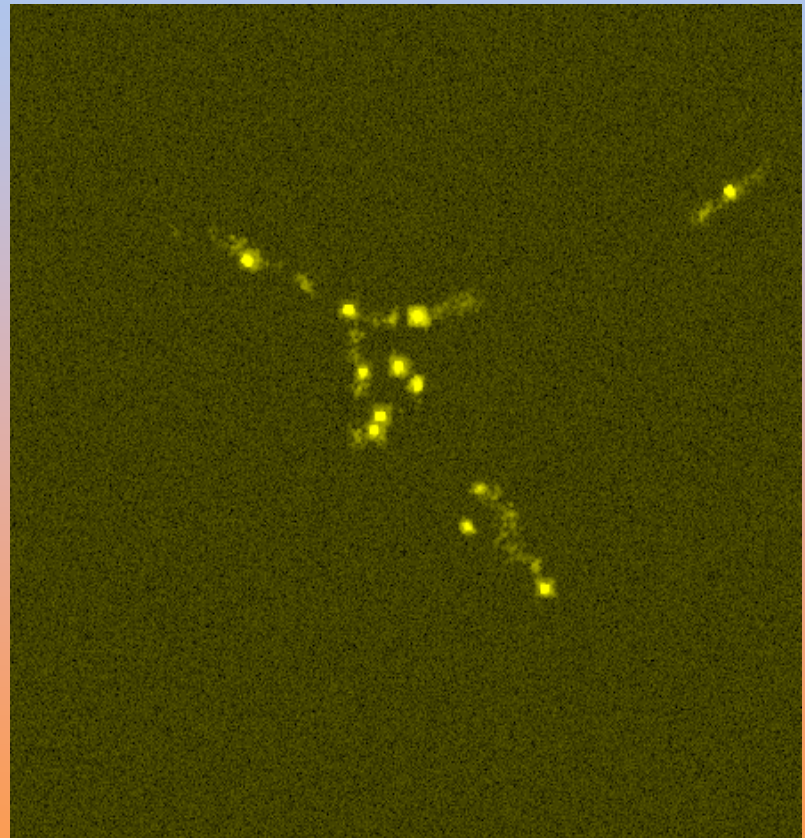
As observed through 30-meter
telescope $R=3000$, 10^5 seconds,
Barton et al., 2004, ApJ 604, L1

A possible IMF diagnostic at $z=10$

HeII ($\lambda 1640 \text{ \AA}$)
Standard IMF



HeII ($\lambda 1640 \text{ \AA}$)
Top-Heavy IMF, zero metallicity

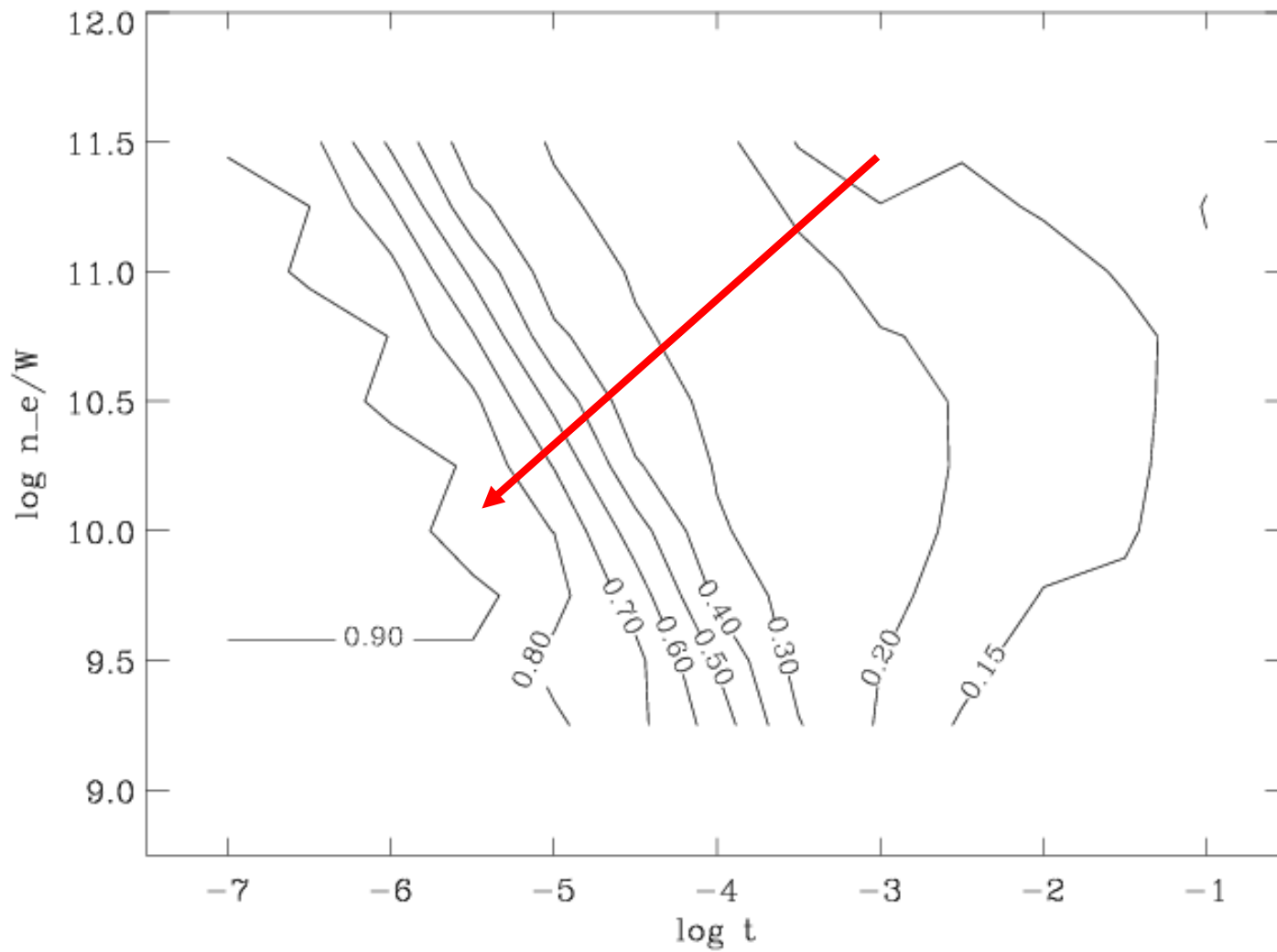


(IMF + stellar model fluxes
from Bromm, Kudritzki,
& Loeb 2001, ApJ 552,464)

Instabilities

- a few extremely low \dot{M}_{dot} models may suffer from de-coupling of H, He and metals (Kudritzki 2002, Krticka et al. 2003)
 - heating of winds or fallback of material
- strong increase of force multiplier parameter δ
 - bi-stability of radiative line force
- pulsational instabilities important for very massive stars, however see Baraffe, Heger & Woosley (2001): much weaker at low Z
- rotation → rotationally induced mass-loss (Maeder, Meynet)
- close to $\Gamma = 1$ → Shaviv, Owocki, Gayley porosity??

$$\delta(t, n_e/W)$$



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