CO band emission from circumstellar material: Tracer for Keplerian rotating disks, molecular outflows, and evolutionary states

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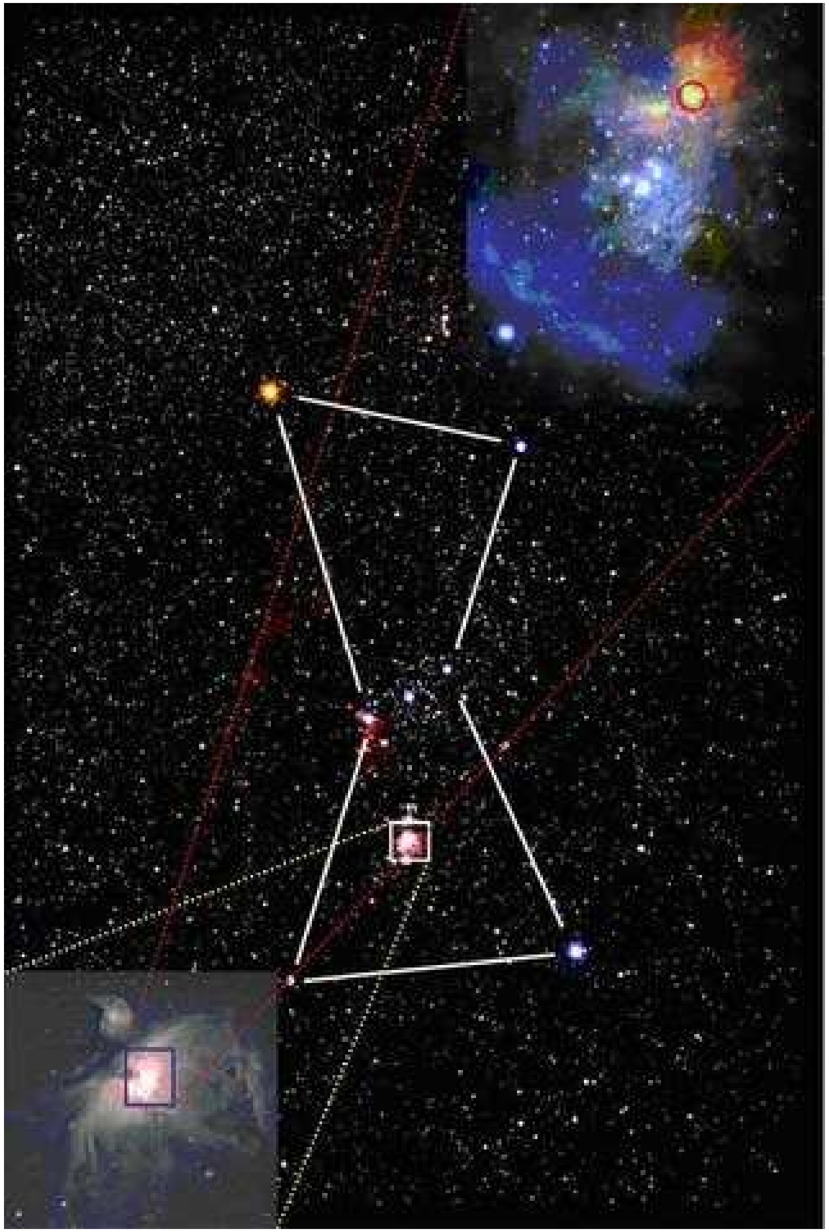
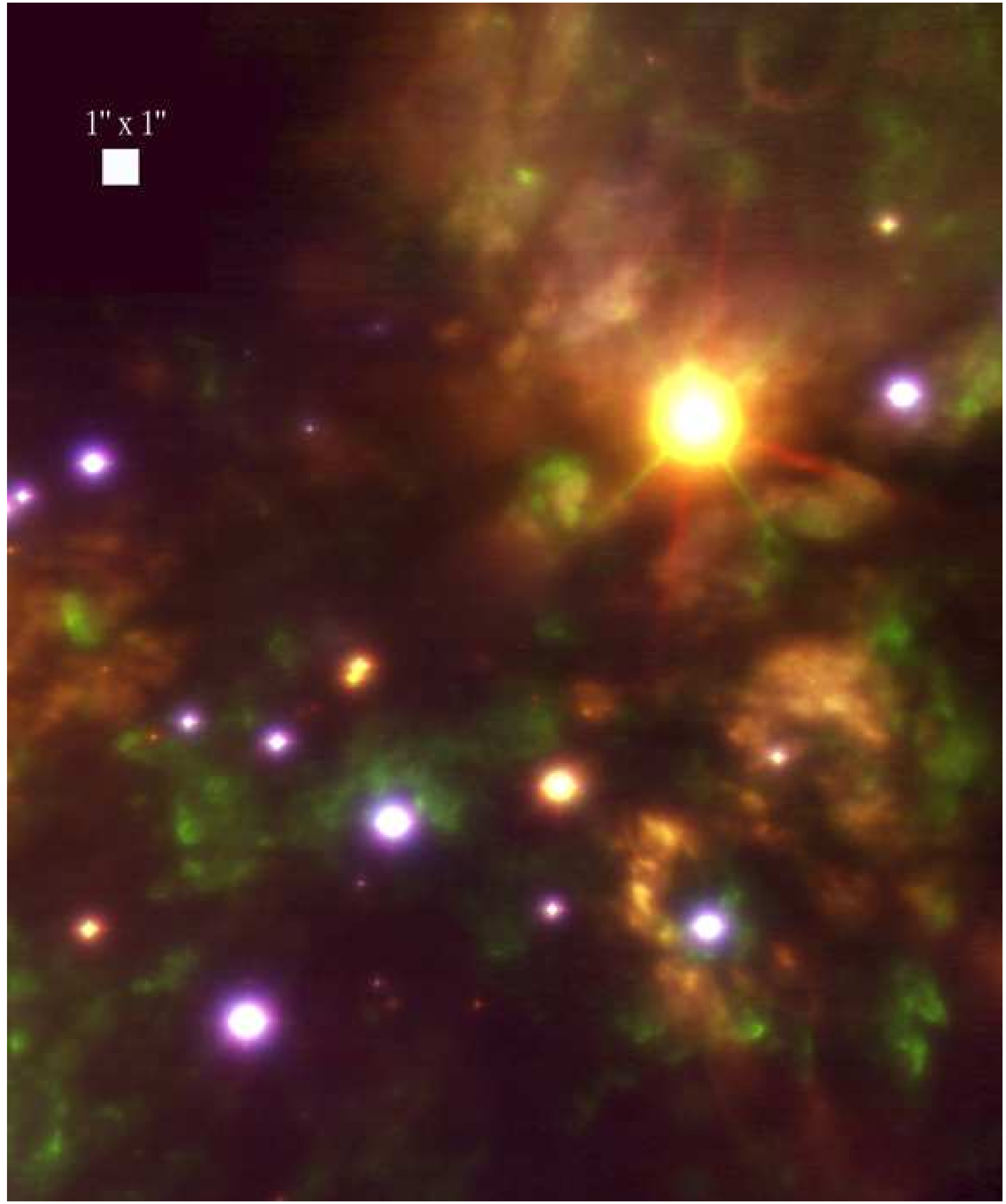
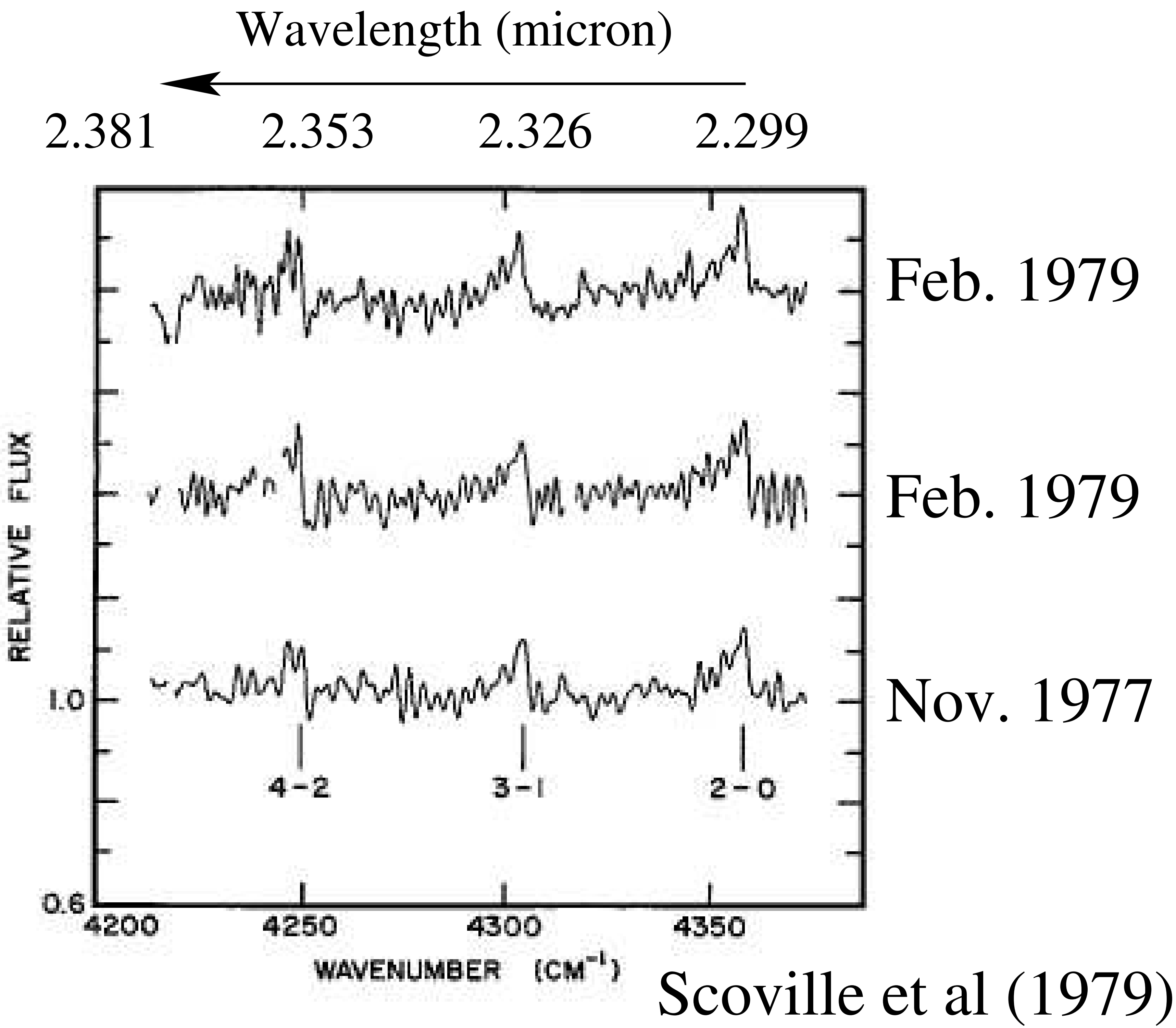
Outline

- CO-band detection from various objects
- Physics of CO-bands
- Tracing the kinematics of the circumstellar material
  * Keplerian rotation in circumstellar disks
  * Outflow from disk-forming winds
- CO-bands as age indicators
- Conclusions & Outlook

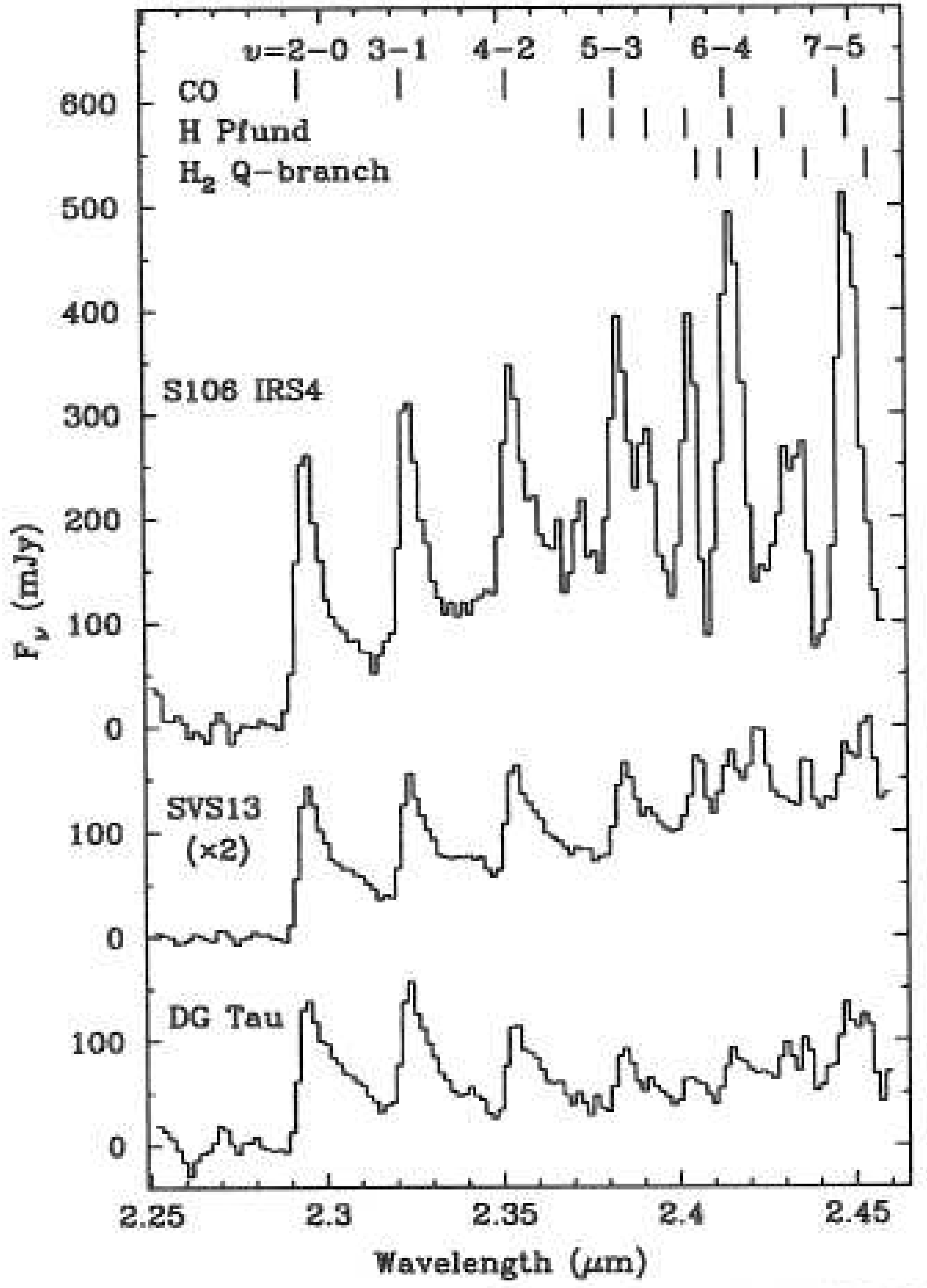
The BN−object in Orion





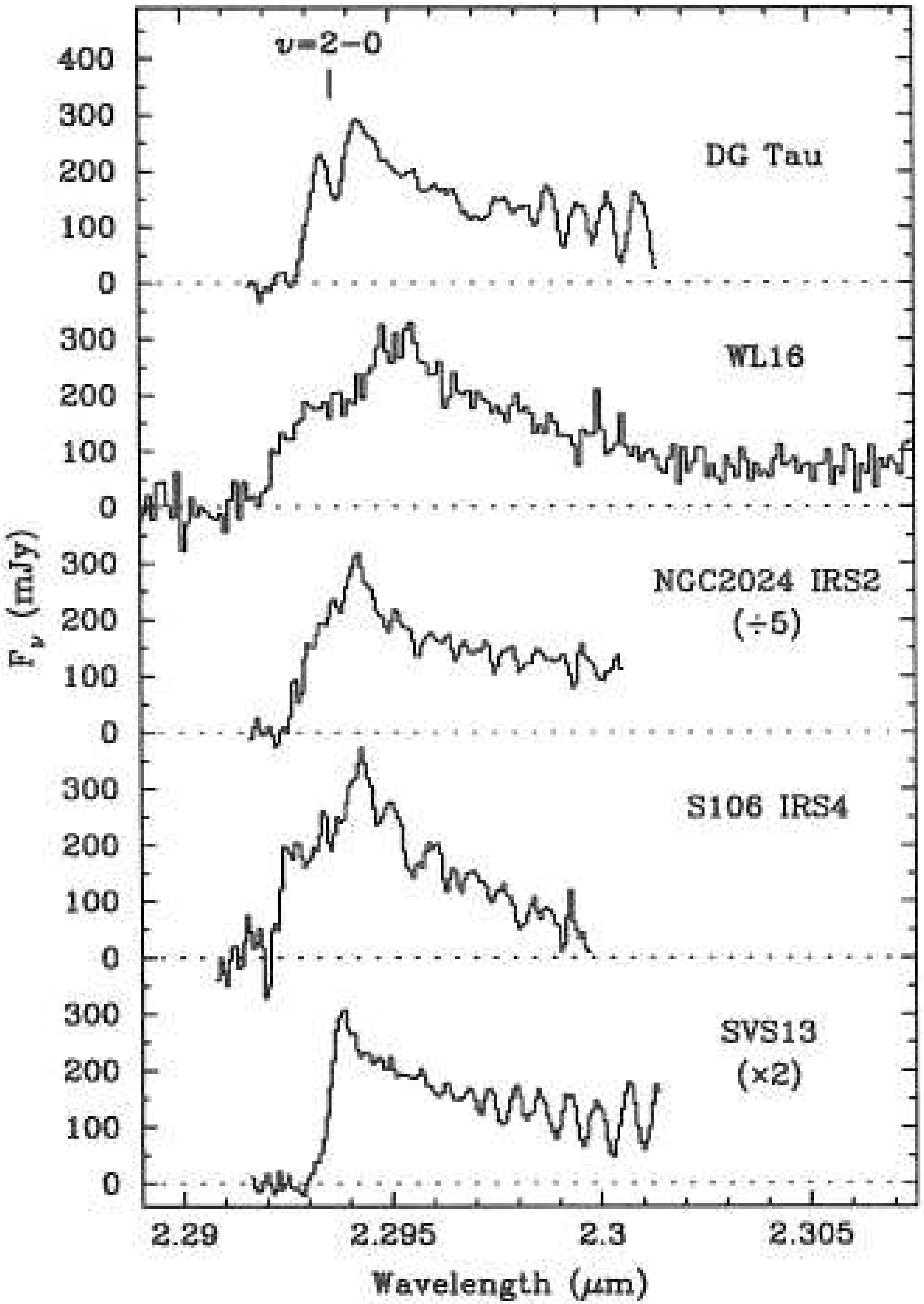


Wavelength (micron)
2.381
2.353
2.326
2.299
Feb. 1979
Feb. 1979
Nov. 1977
RELATIVE FLUX
1.0
0.6
4-2
3-1
2-0
4200
4250
4300
4350
WAVENUMBER (CM^{-1})
Scoville et al (1979)



CO–bands from young stellar objects (YSO)

Chandler et al. (1993)



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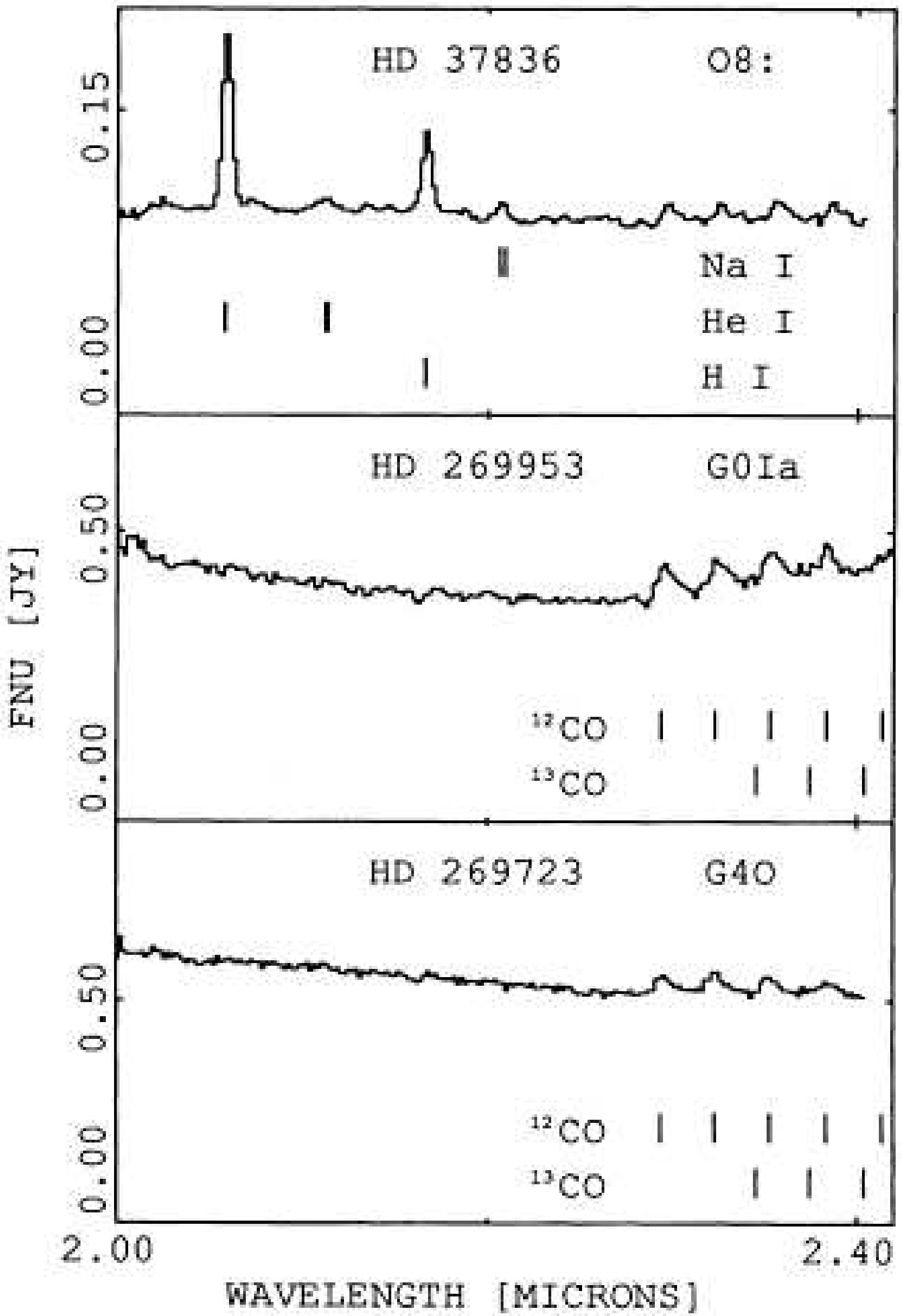
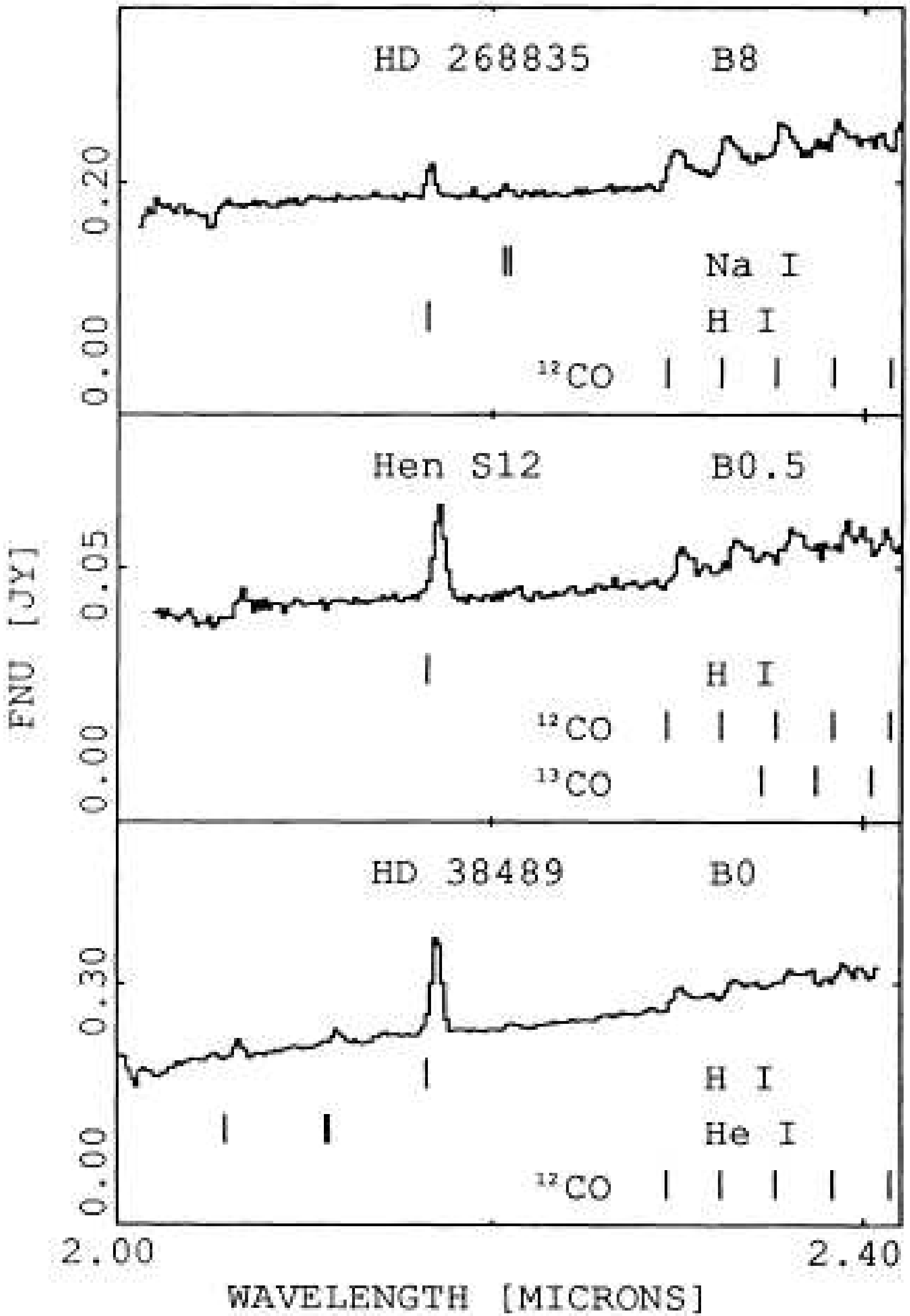


CO–bands from a peculiar O and two yellow supergiants in the Magellanic Clouds

McGregor et al. (1988)



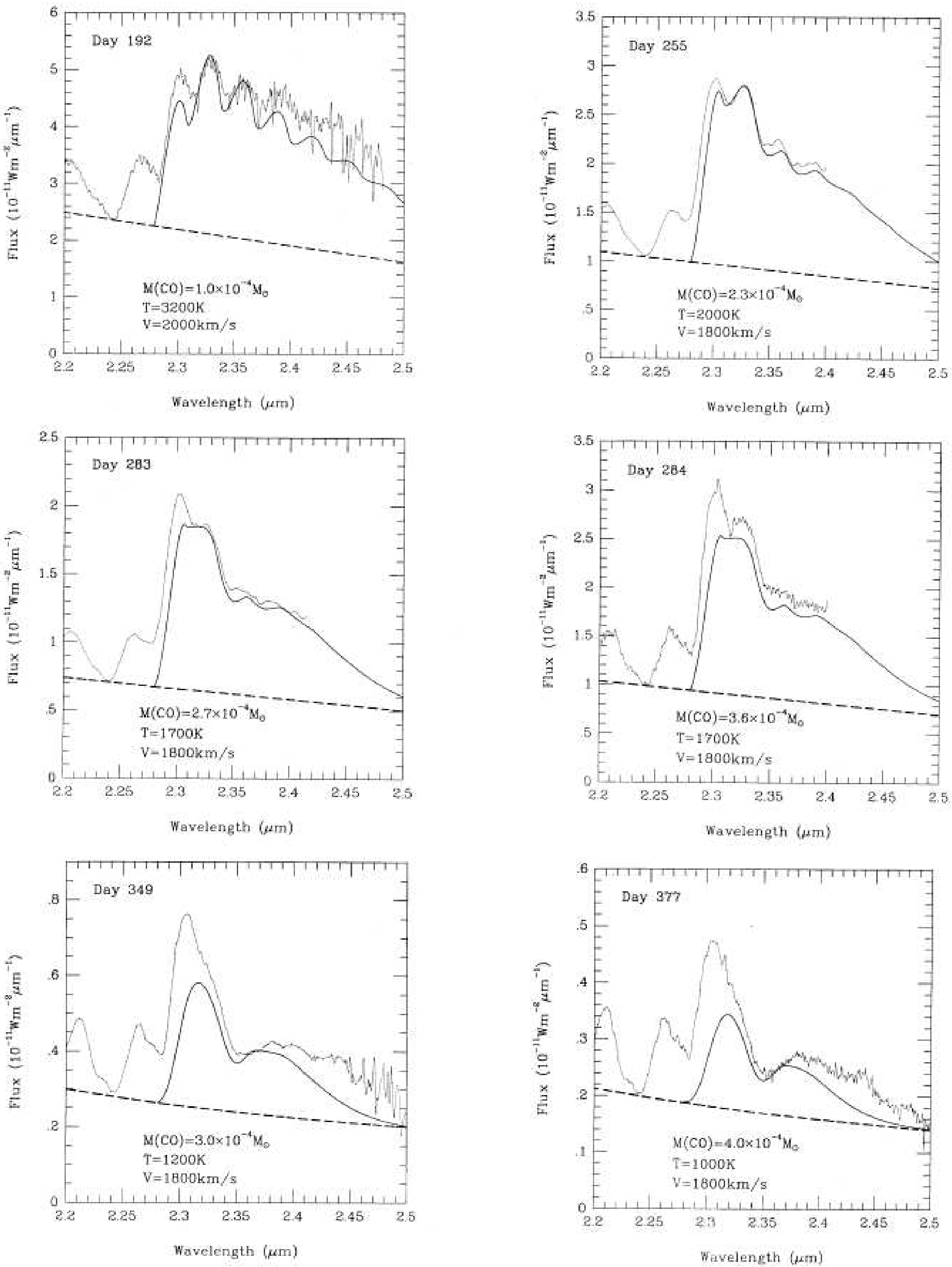
CO−bands from

B[e] supergiants

in the

Magellanic Clouds

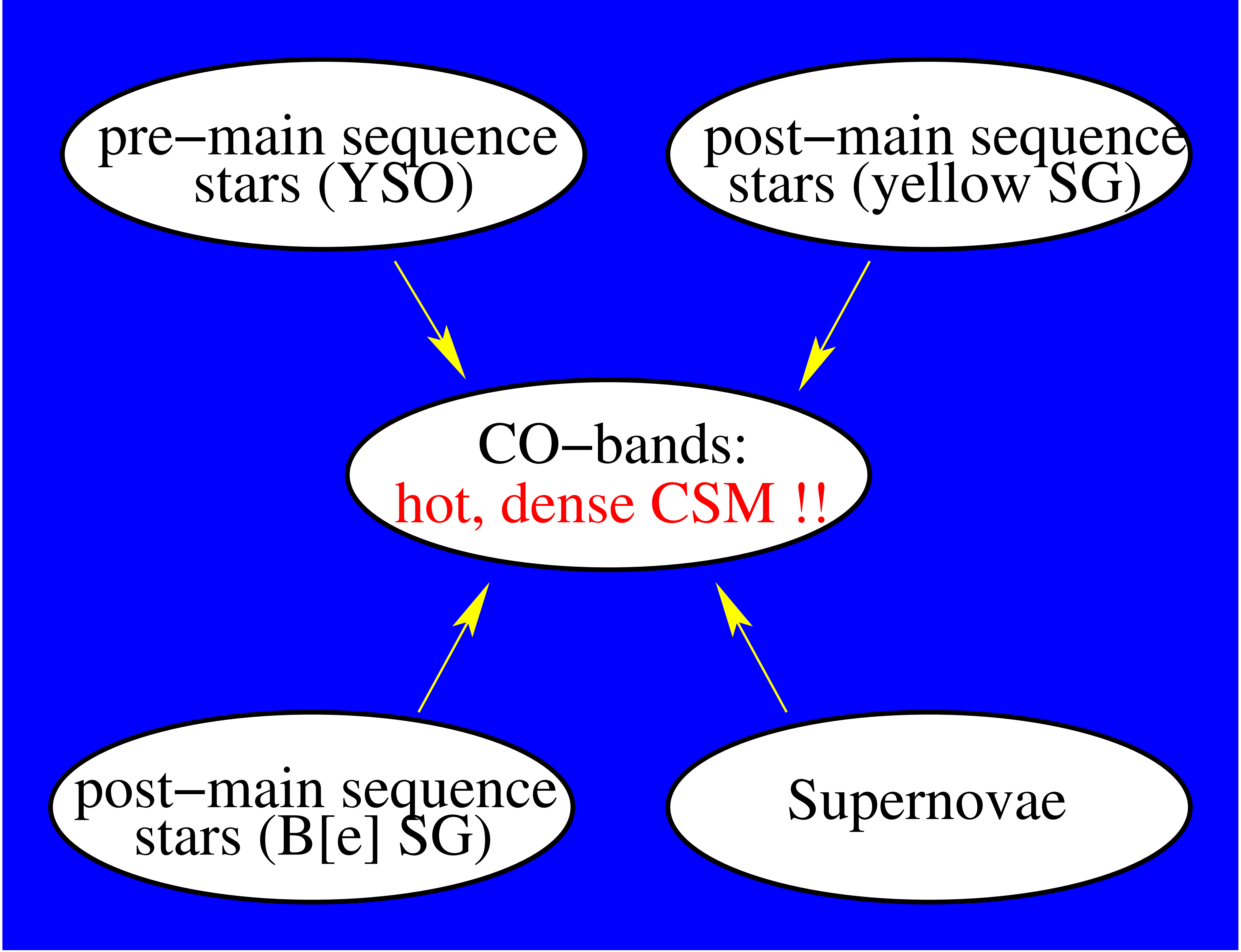
McGregor et al. (1988)



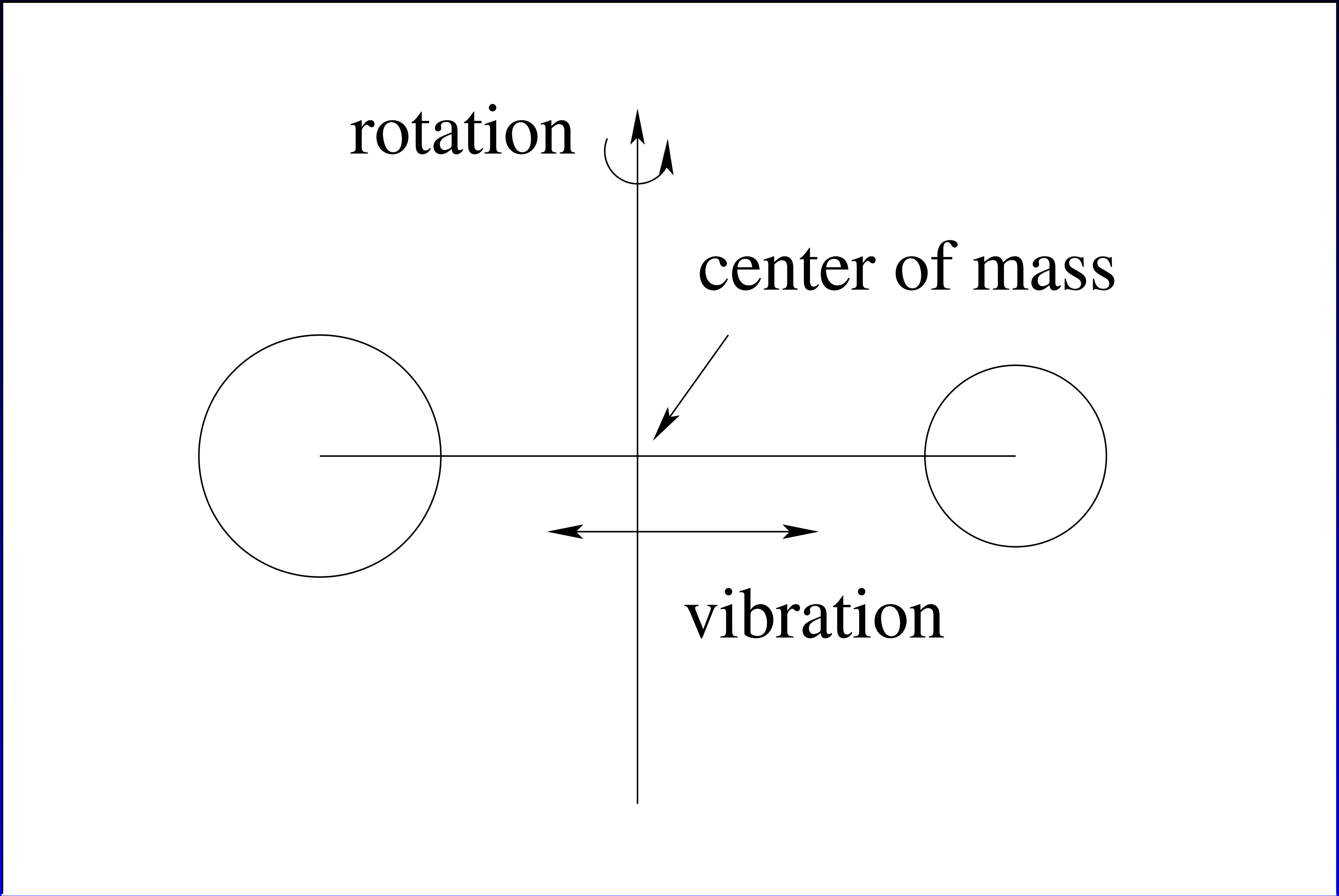
CO–bands from expanding and cooling remnants of Supernova explosions

SN 1987 A

Spyromilio & Leibundgut (1996)


pre−main sequence stars (YSO)
post−main sequence stars (yellow SG)
CO−bands:
hot, dense CSM !!
post−main sequence stars (B[e] SG)
Supernovae

Physics of diatomic molecules



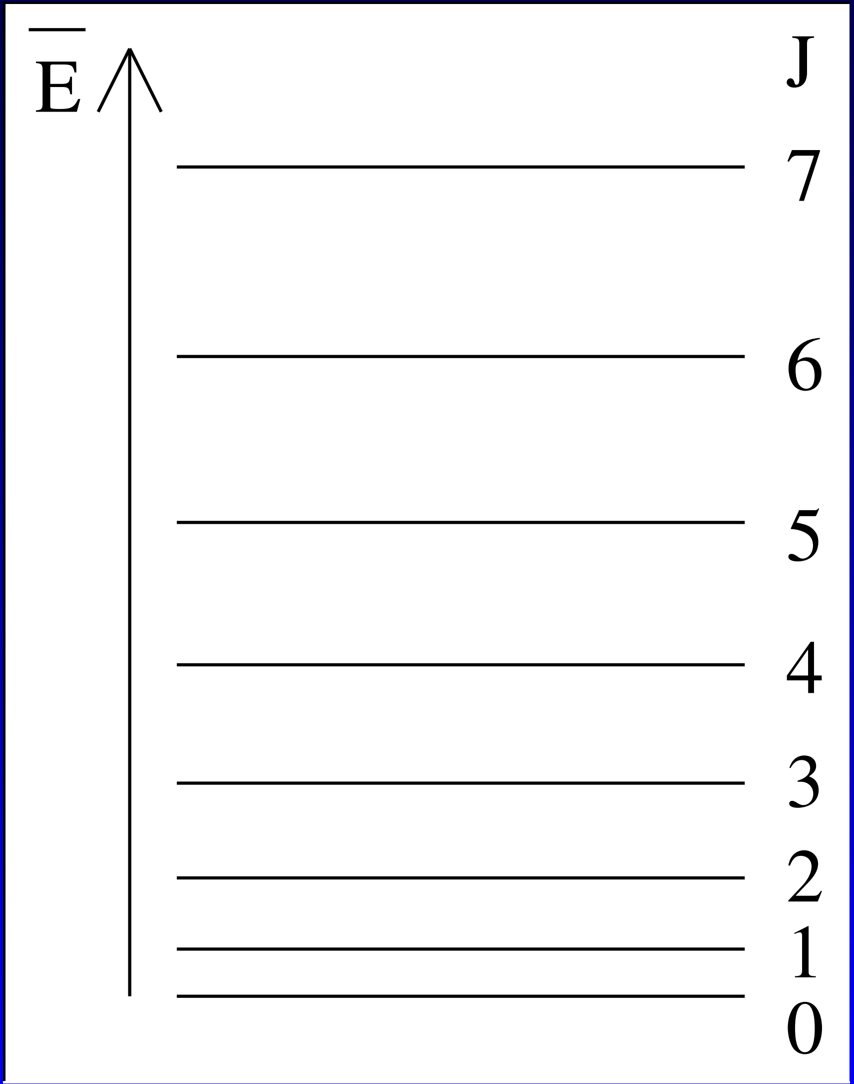
Simple rotational approach: Rigid rotator

Discrete energy values:

$$E_J \sim J\,(J+1)$$

Selection rules:

$$\Delta J = \pm 1$$



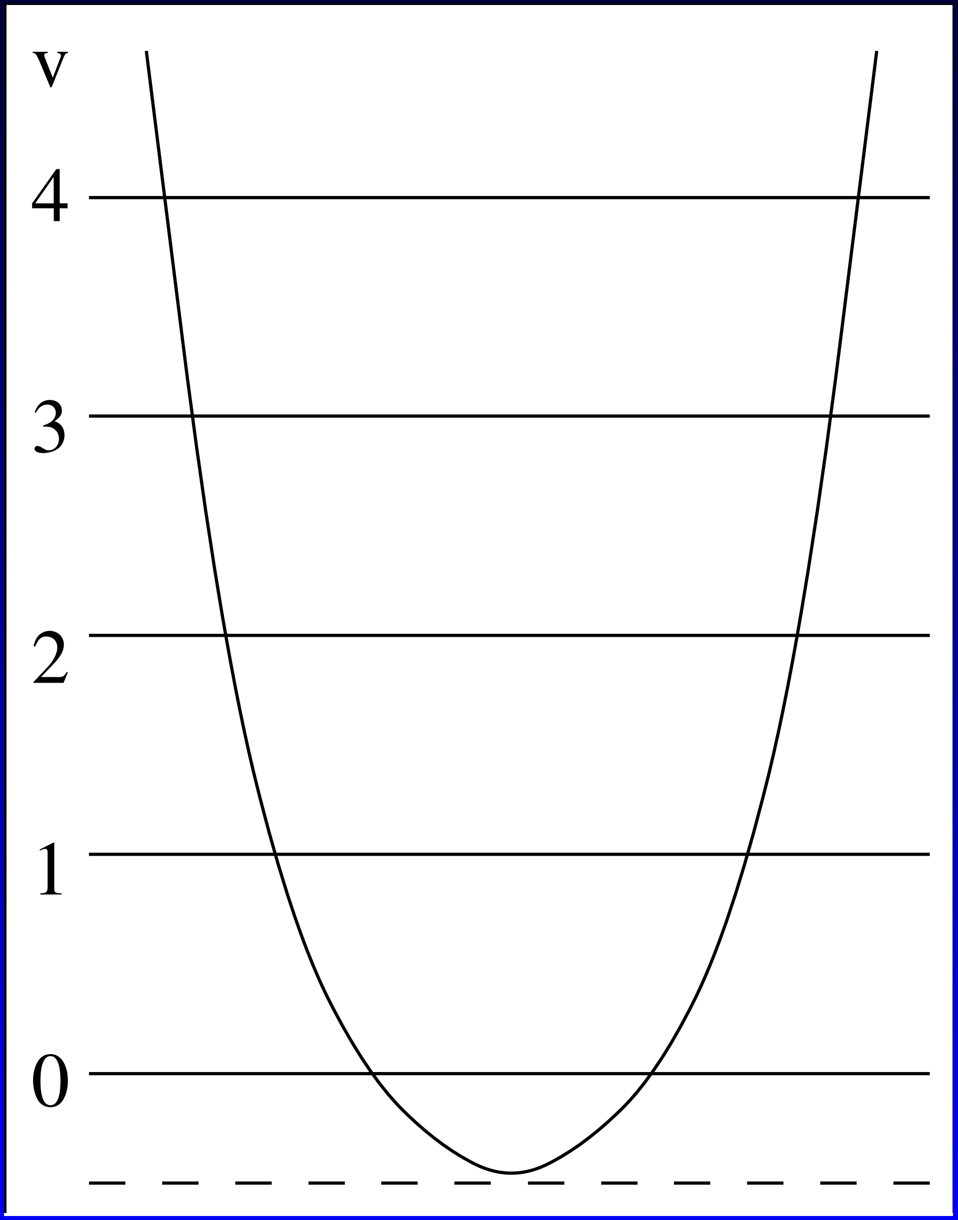
Simple vibrational approach: Harmonic oscillator

Discrete energy values:

$$E_v = h\nu \left(v + \frac{1}{2}\right)$$

Energy levels are equidistant

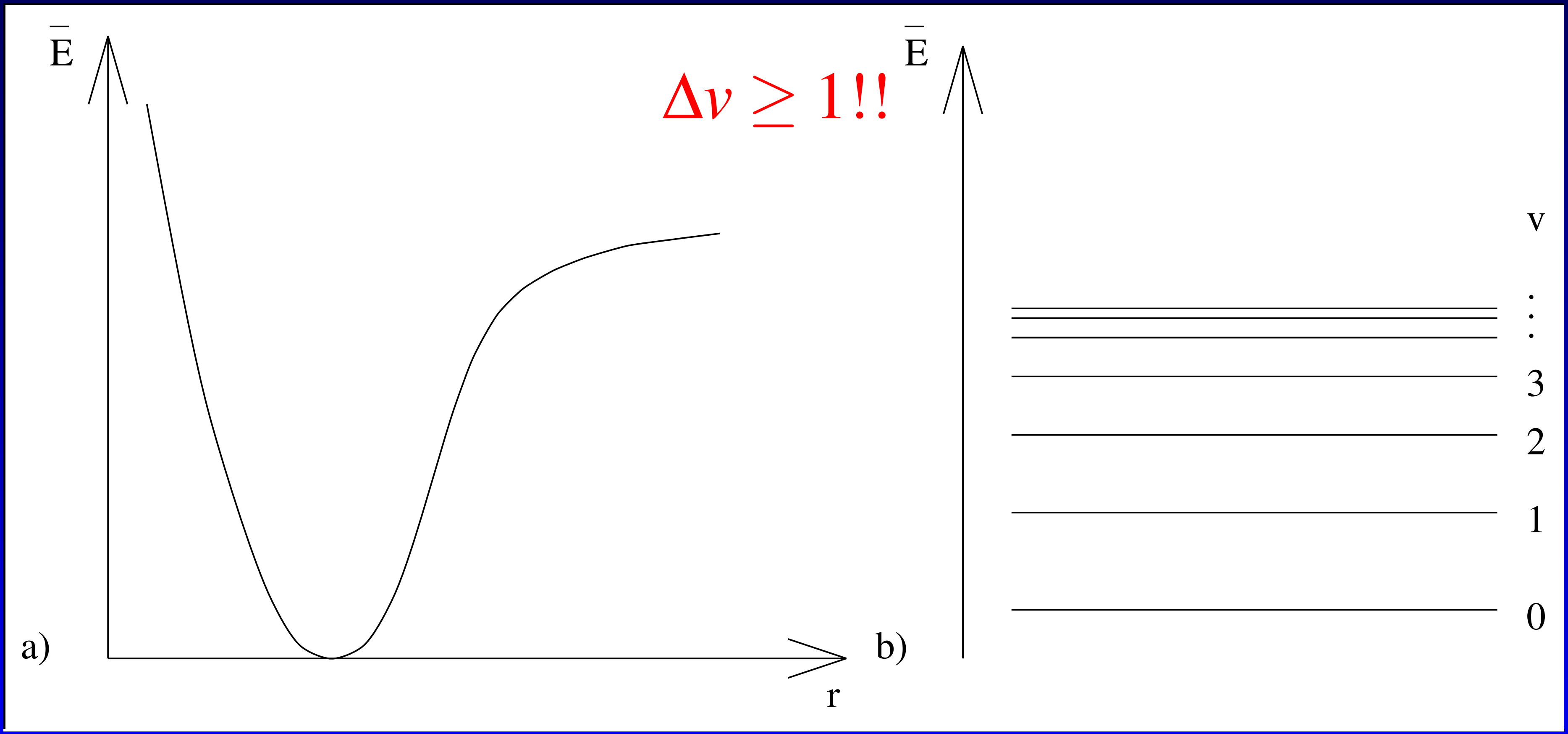
$$\Delta v = \pm 1$$



First improvement: Anharmonic oscillator

From quantum mechanics we find for the energy values:

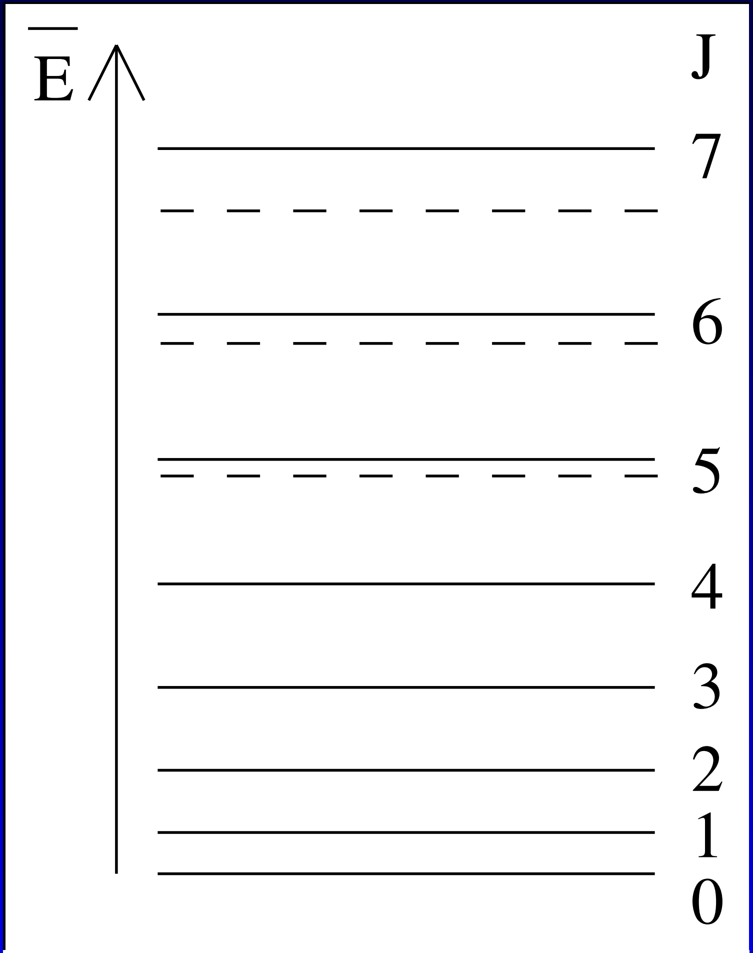
$$E_v \sim \left(v+\frac{1}{2}\right) - a\left(v+\frac{1}{2}\right)^2 + b\left(v+\frac{1}{2}\right)^3 + \ldots..$$



Second improvement: Non-rigid rotator

Energy values:

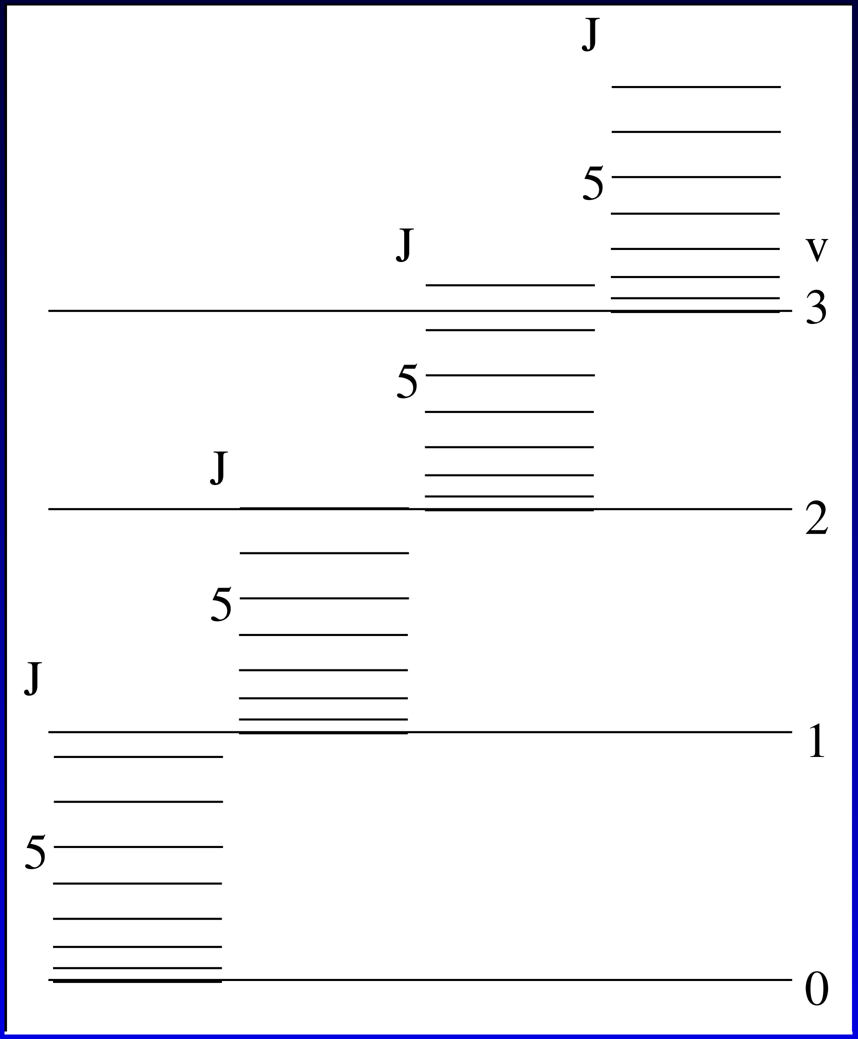
$$E_J \sim J\,(J+1) - xJ^2\,(J+1)^2 + yJ^3\,(J+1)^3 + \ldots..$$



Final model: Vibrating rotator

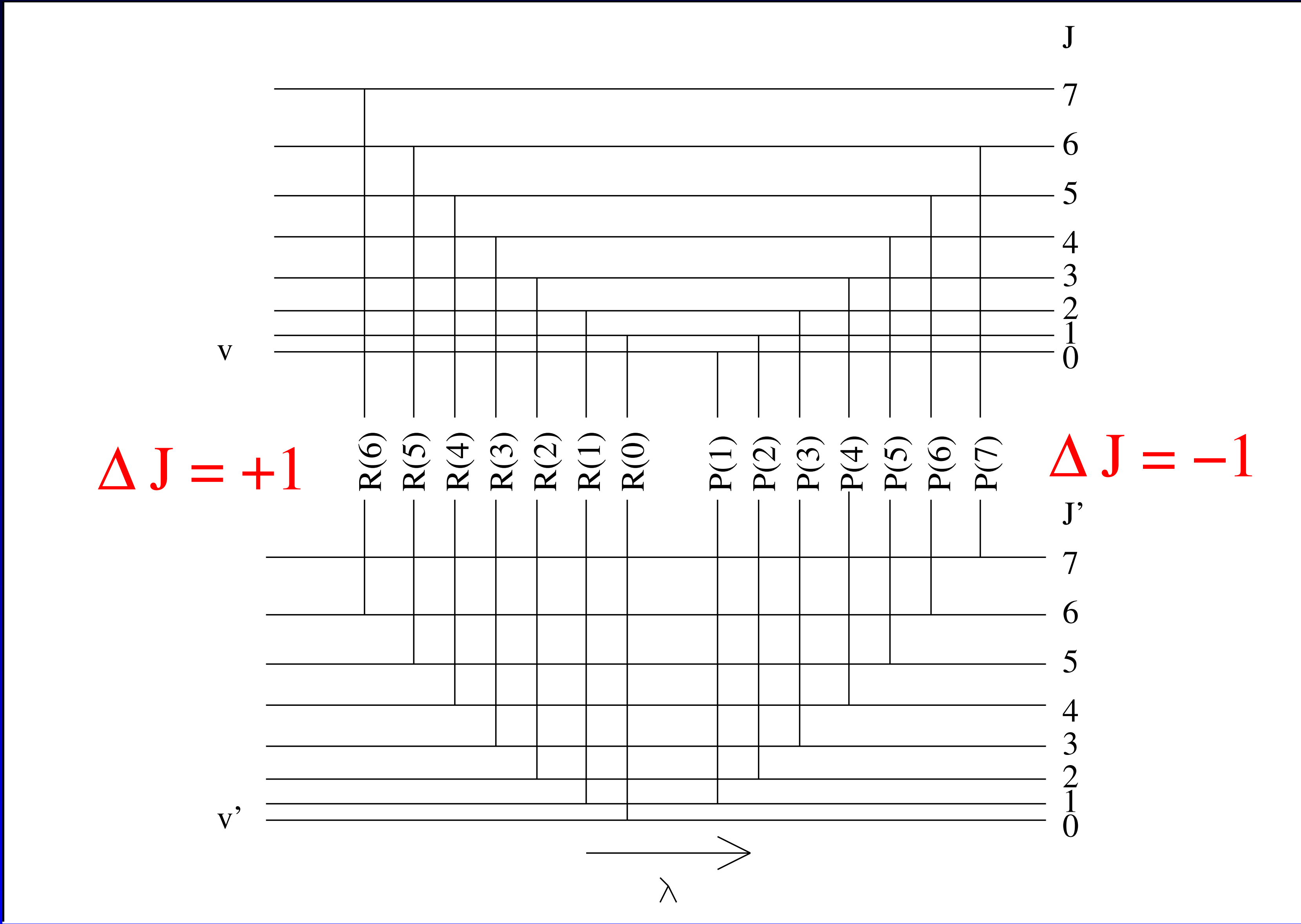
$$E_{v,J} = \sum_{k,l} Y_{k,l} \left(v + \frac{1}{2} \right)^k (J^2 + J)^l$$

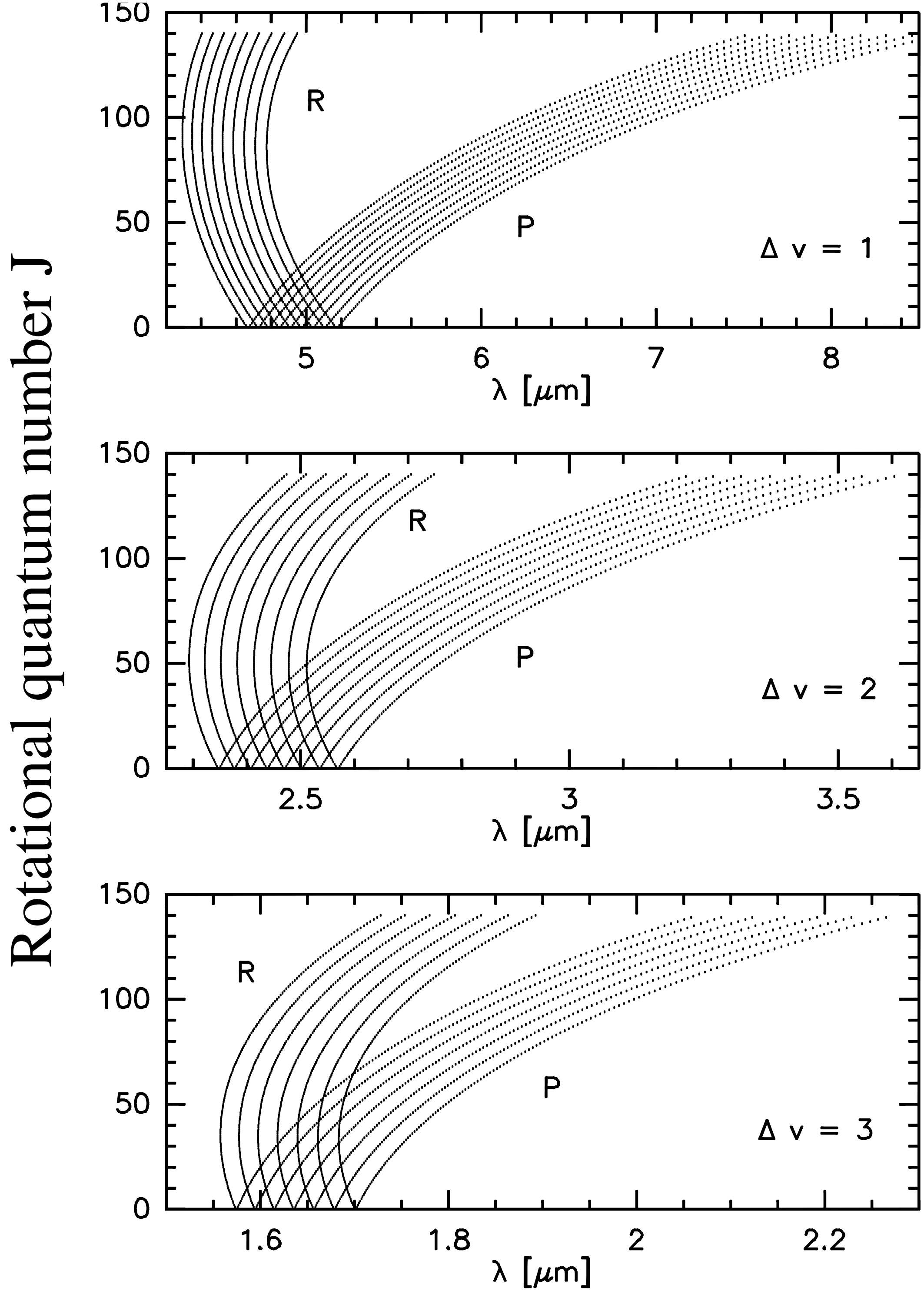
$Y_{k,l} =$ Dunham coefficients



Coupled transitions : Vibration-rotation bands

Valid selection rules: $\Delta J = \pm 1$ and $\Delta v = 0, 1, 2, \ldots$

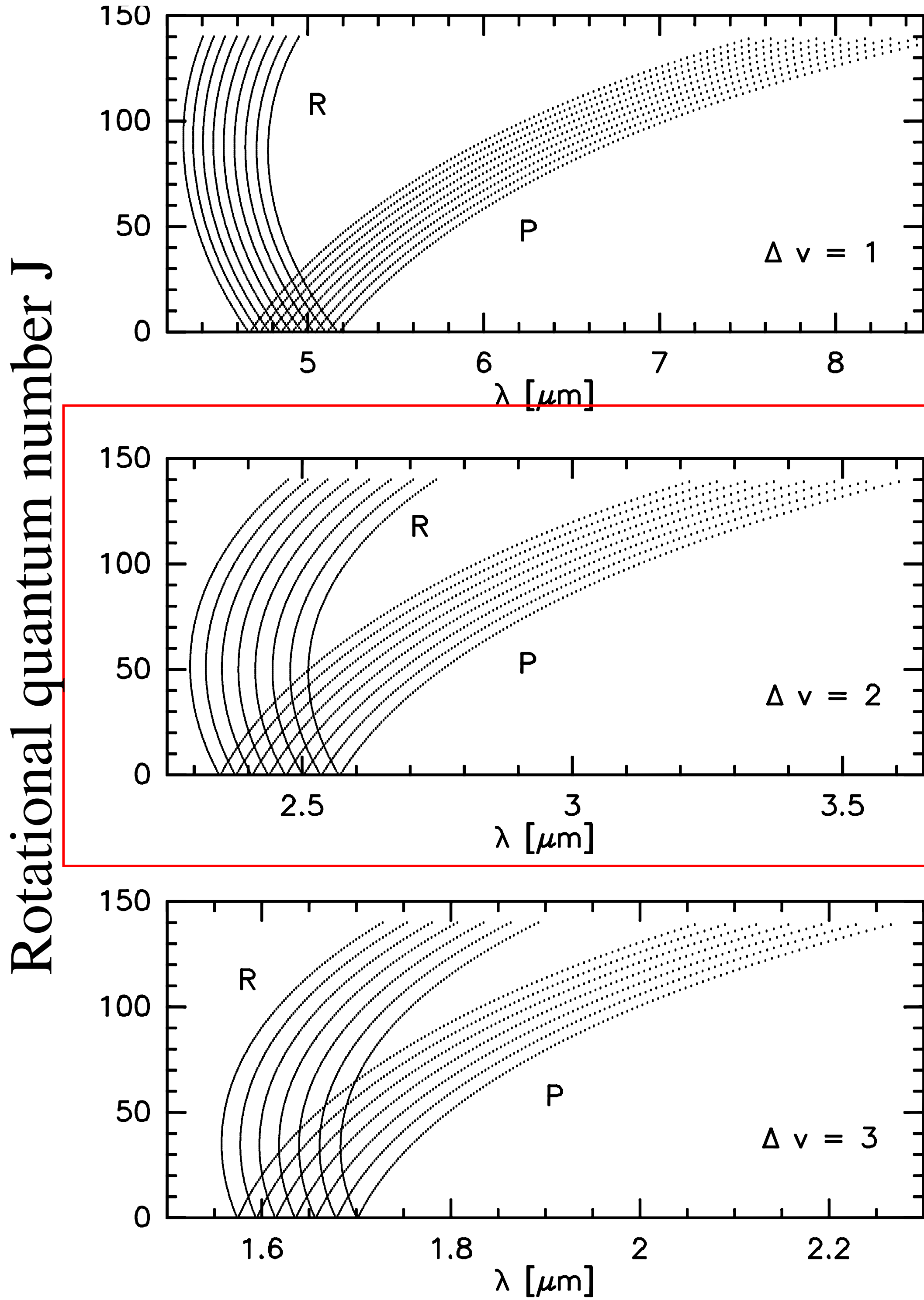




fundamental bands

first–overtone bands

second–overtone bands



fundamental bands

first–overtone bands

second–overtone bands

Emission spectrum of CO-bands

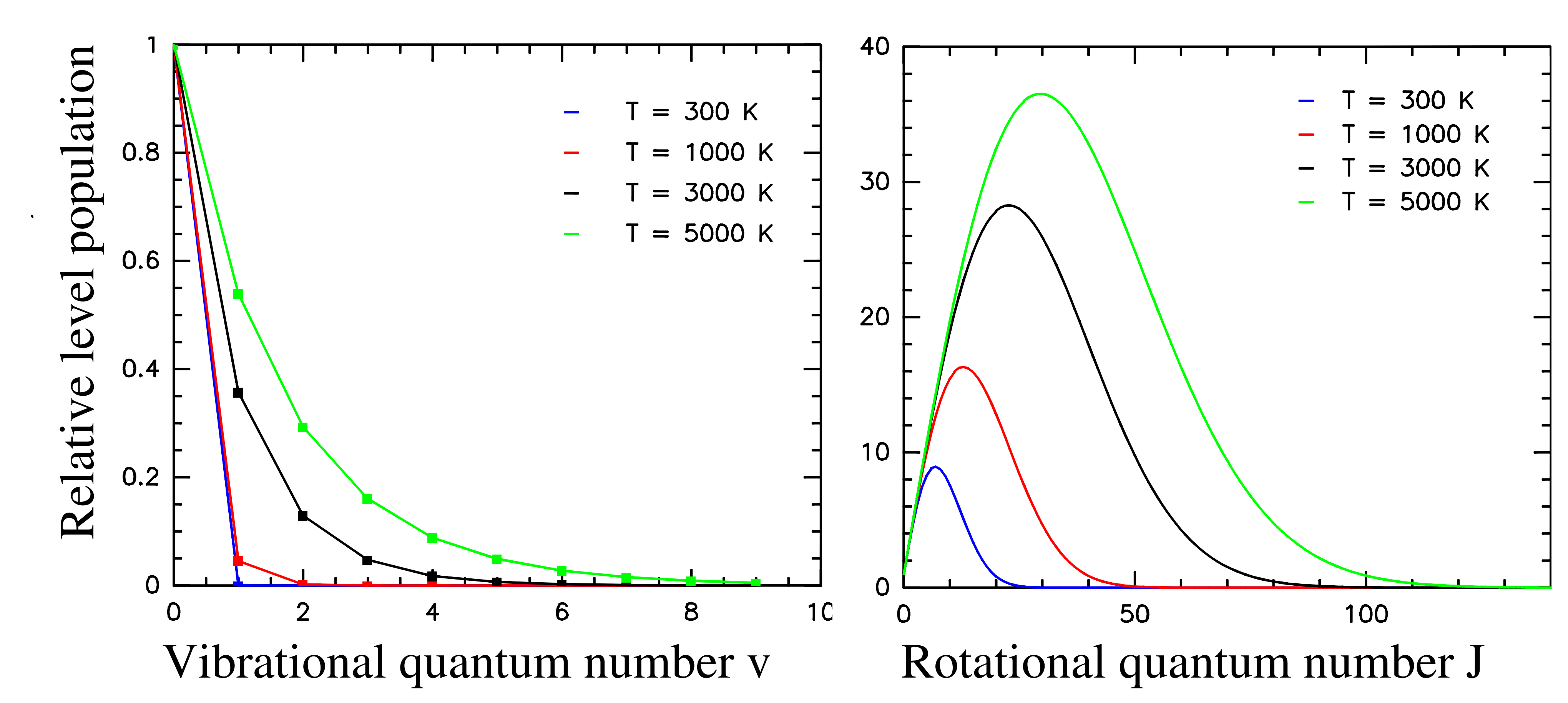
Line intensity in each individual vib-rot line is given by

$$I_{\nu_0} = \int N_{v,J} h\nu_{v,J;v'J'} A_{v,J;v'J'} d\Phi(\nu)\, d\nu$$

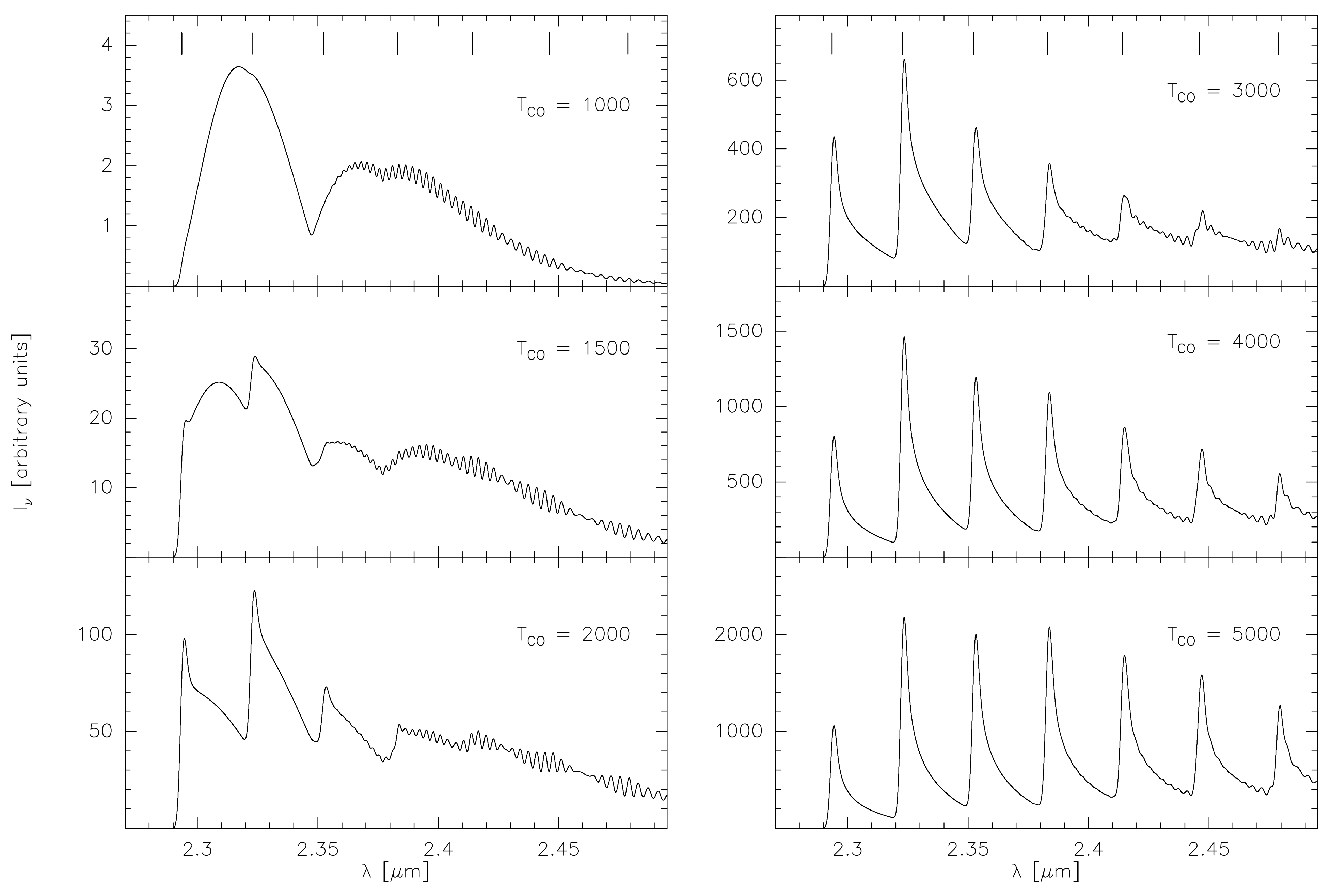
$N_{v,J}$: Level population

$A_{v,J;v'J'}$: Einstein coefficients of spontaneous emission

$\Phi(\nu)$: Profile function



Appearance of CO bands with temperature



Tracing the kinematics of the CSM

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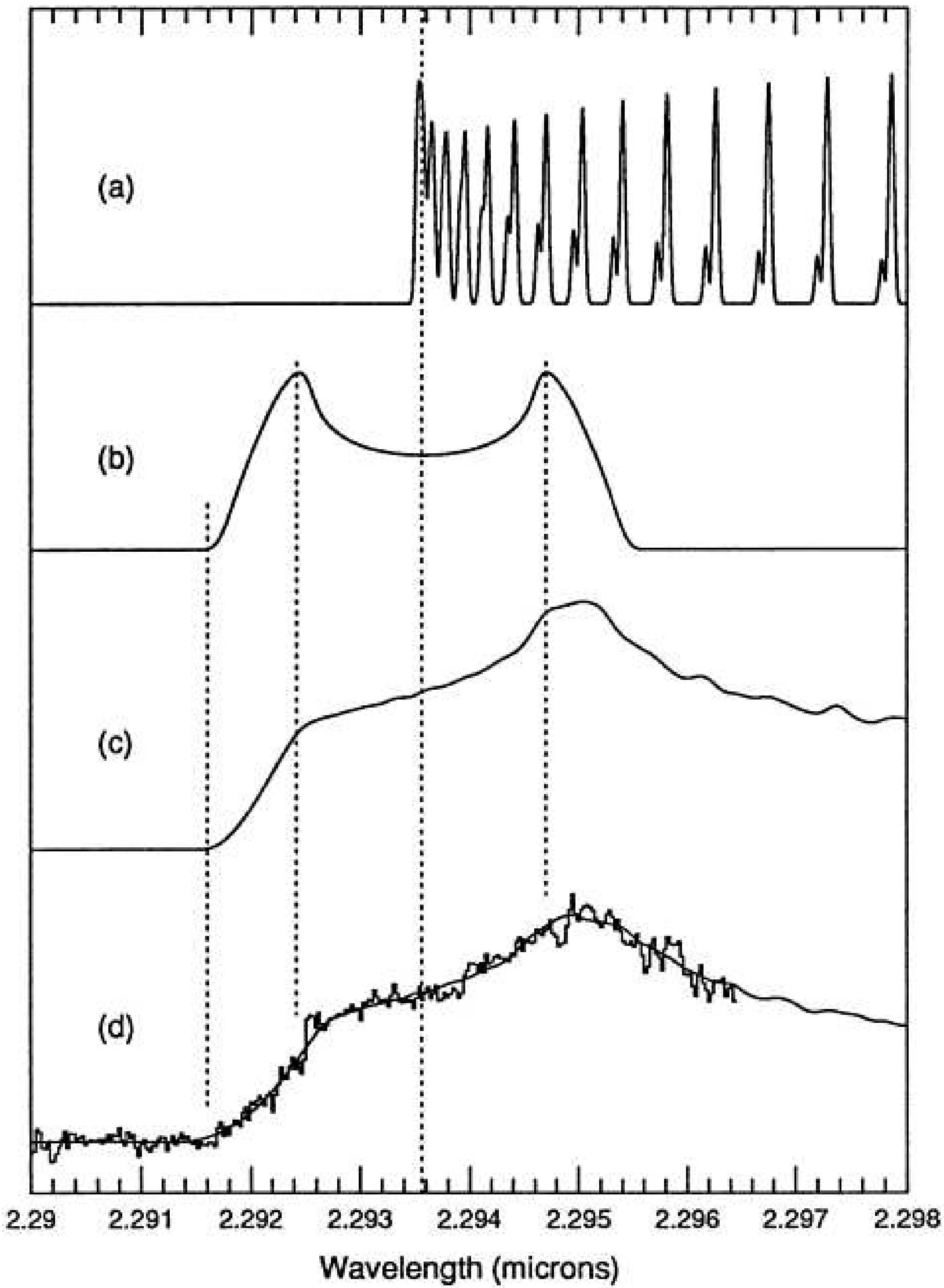
- In the case of evolved supergiants, CO might form in a dense (disk-forming?) equatorial wind (rotation versus outflow).



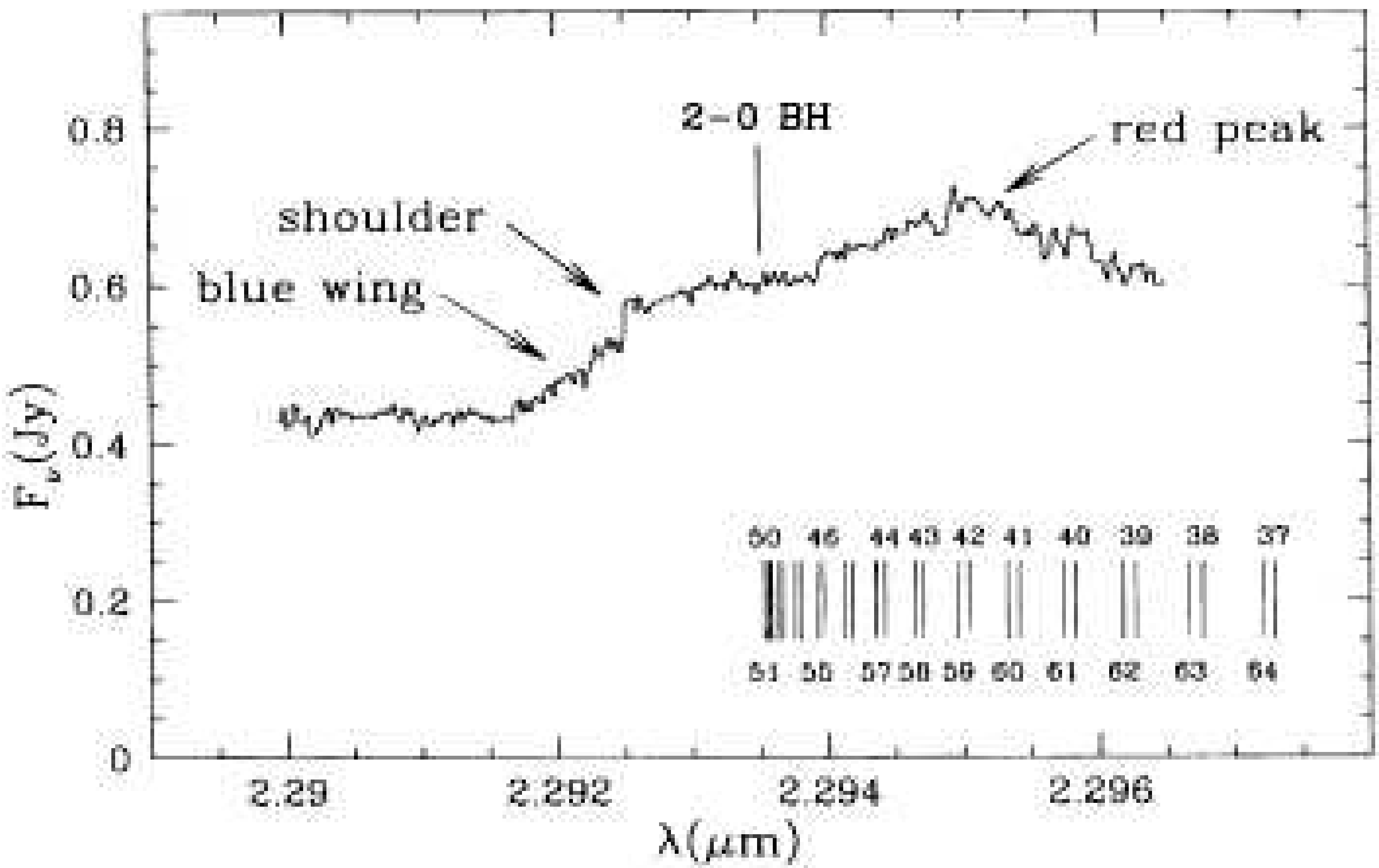
individual vib−rot lines
purely thermally broadened

have to be folded with
the profile function of
a Keplerian rotating disk

to result in a rather broad
band−head structure

that fits the observed one
for the YSO WL 16.

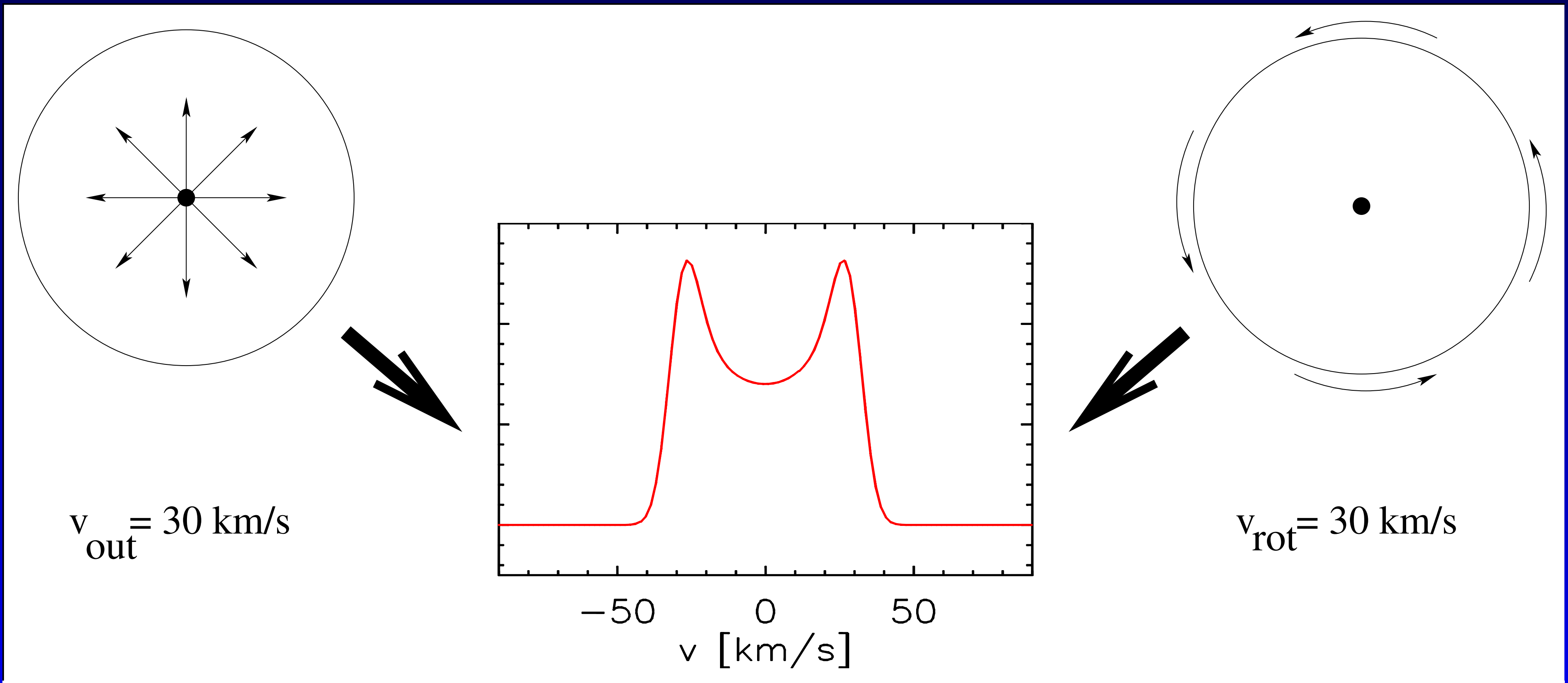
The typical characteristics of Keplerian rotation on the broadened band–head structure :

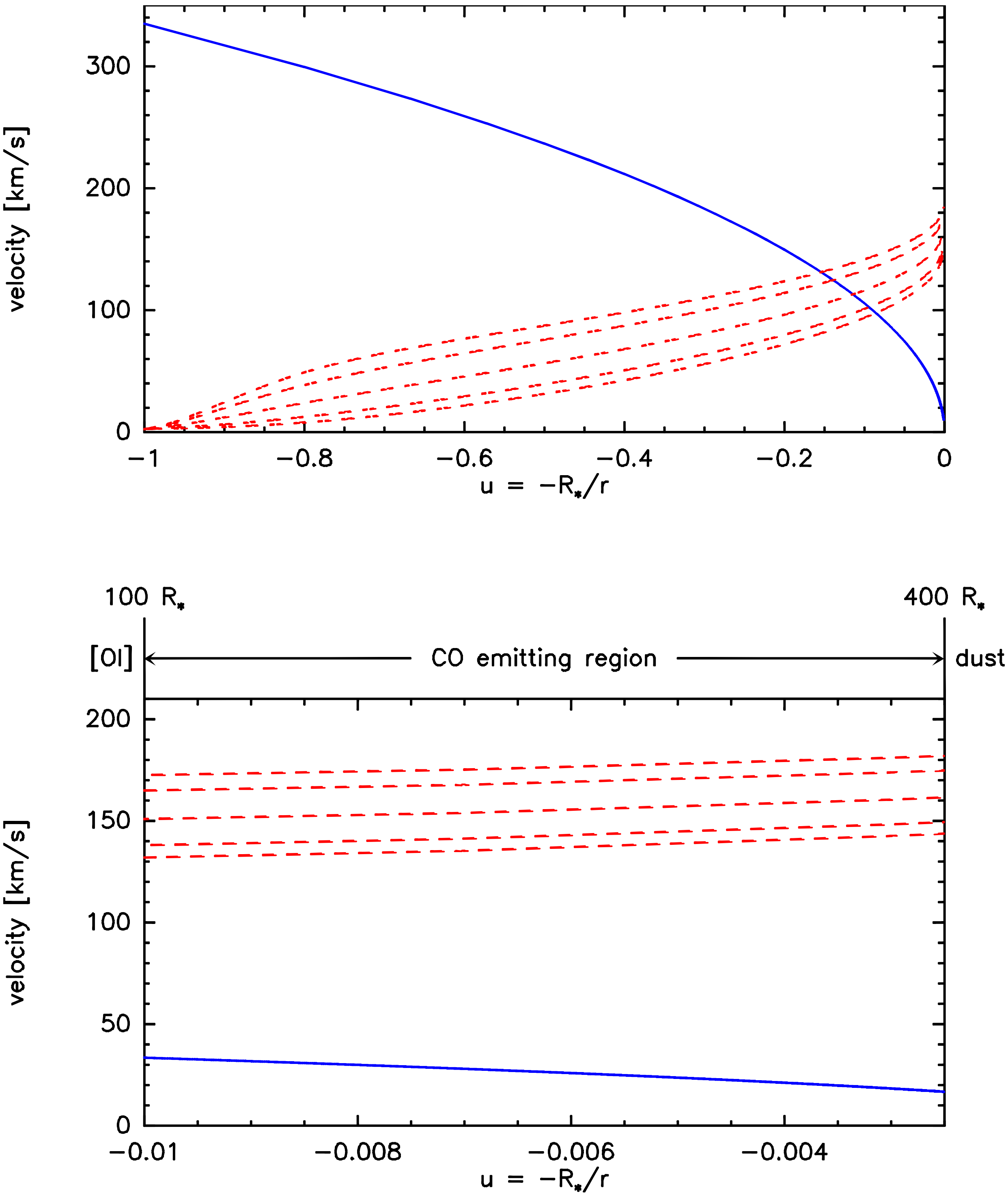


Supergiants: equatorial wind versus Keplerian disk

Both scenarios deliver **identical** line profiles !!

How to distinguish both scenarios ?





Supergiants:
wind versus disk ?

Non−sphericity of their CSM due to rapid rotation !

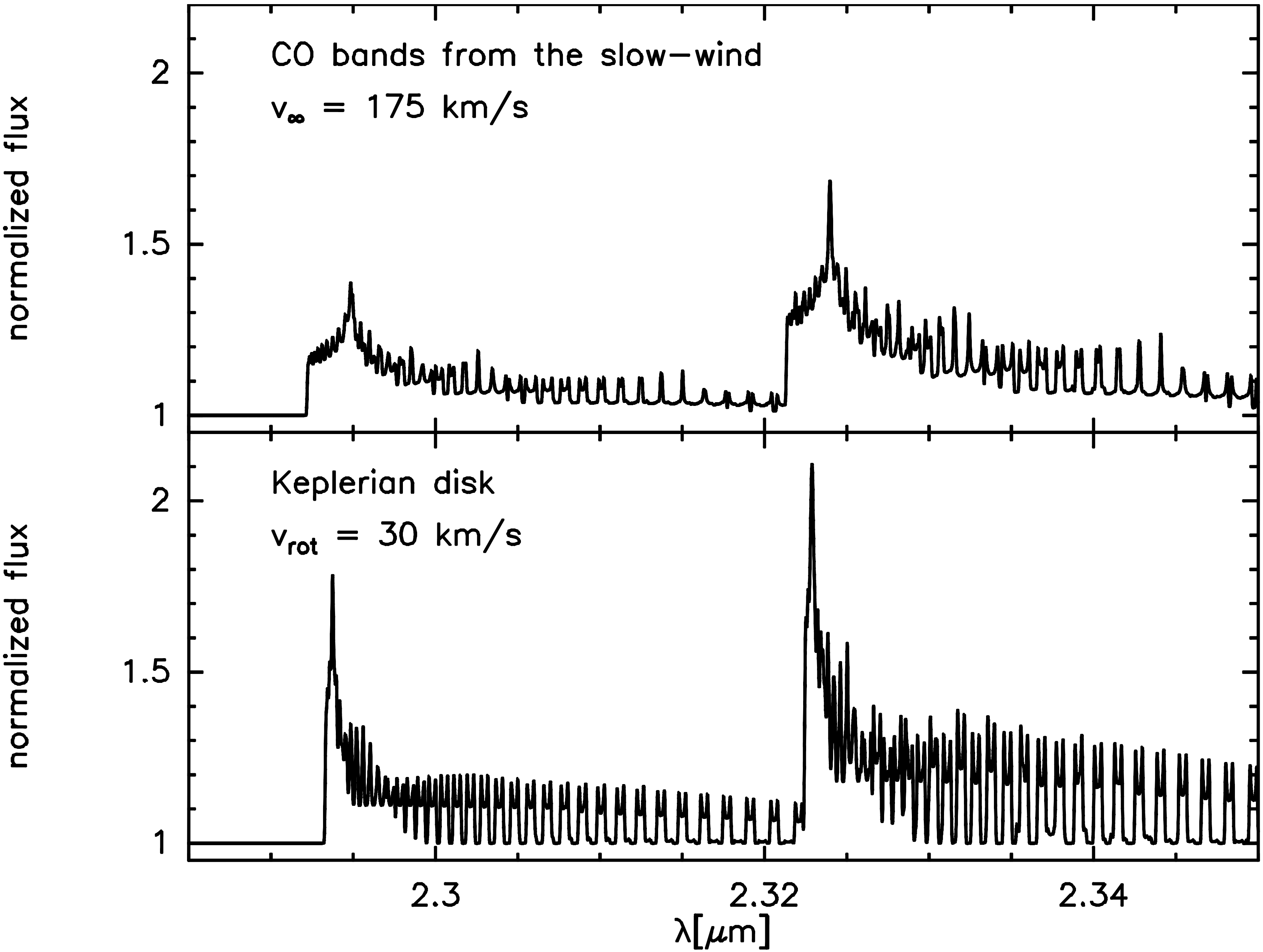
Rotating stars:

Slow−wind solution (Cure ’04; ’05)

red curves for stars with 65%, 70%, 80%, 90%, and 99% critical rotation

blue curve:
Keplerian rotation

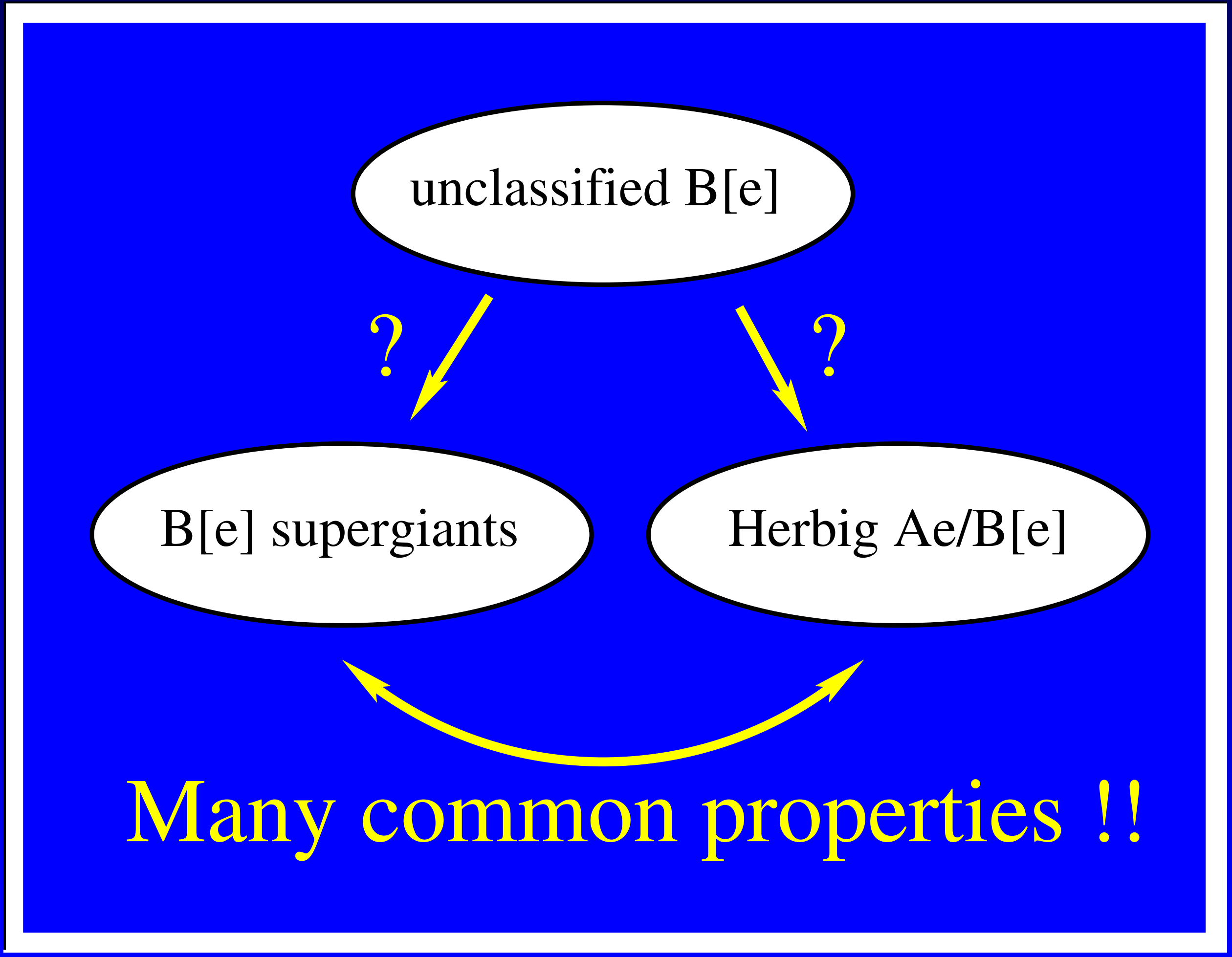
Resulting CO band spectra (first two band–heads) for the wind solution and the Keplerian disk solution



CO bands as age indicators

Classification problems: stars with dense CSM

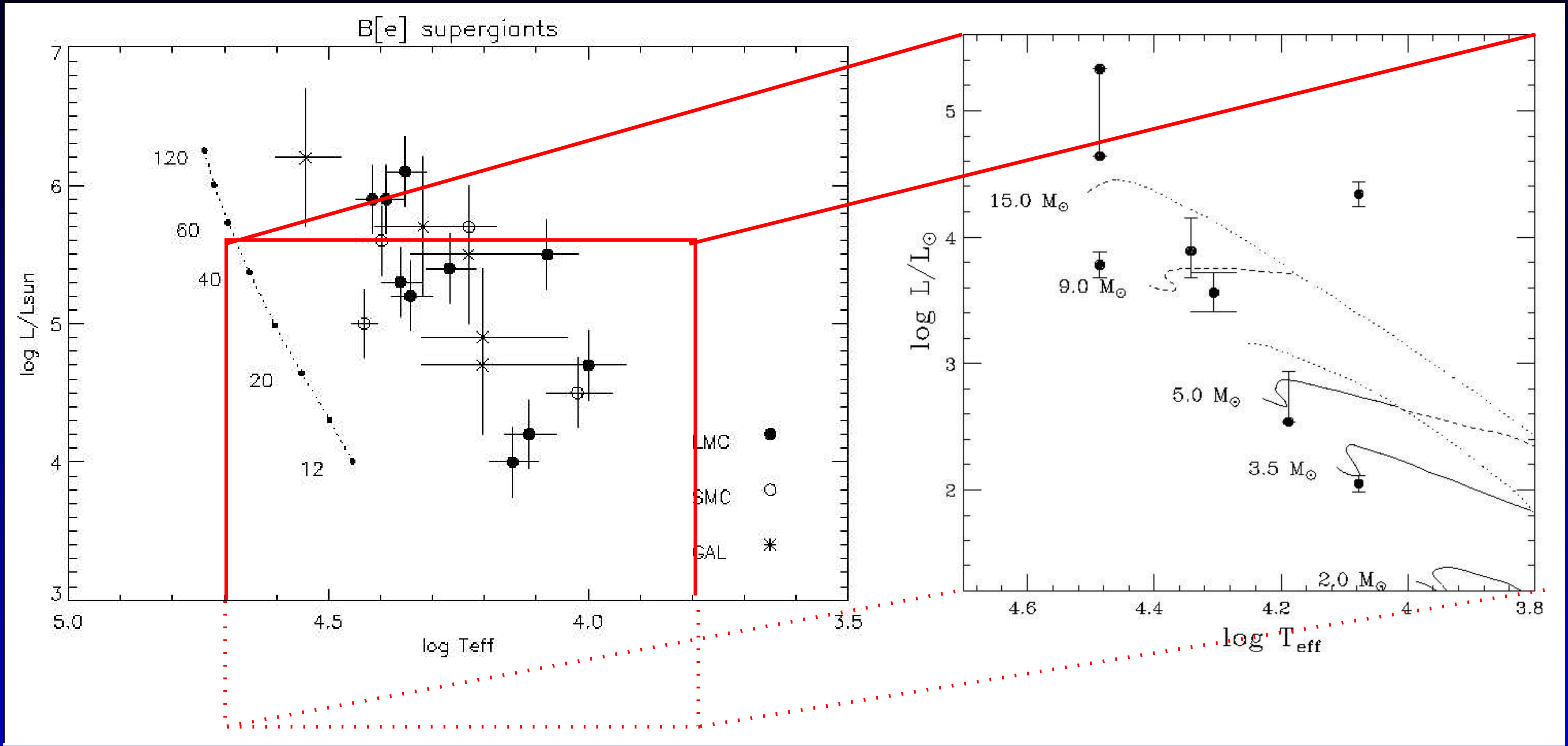
- Often unknown or uncertain distance (i.e. luminosity)
- Characteristics of more than one groups, e.g., of Herbig Ae/B[e] as well as of B[e] supergiants



Herbig Ae/B[e] versus B[e] supergiants

– Common properties –

- They share similar location in the HRD



Overlap of pre- and post-main sequence evolutionary tracks

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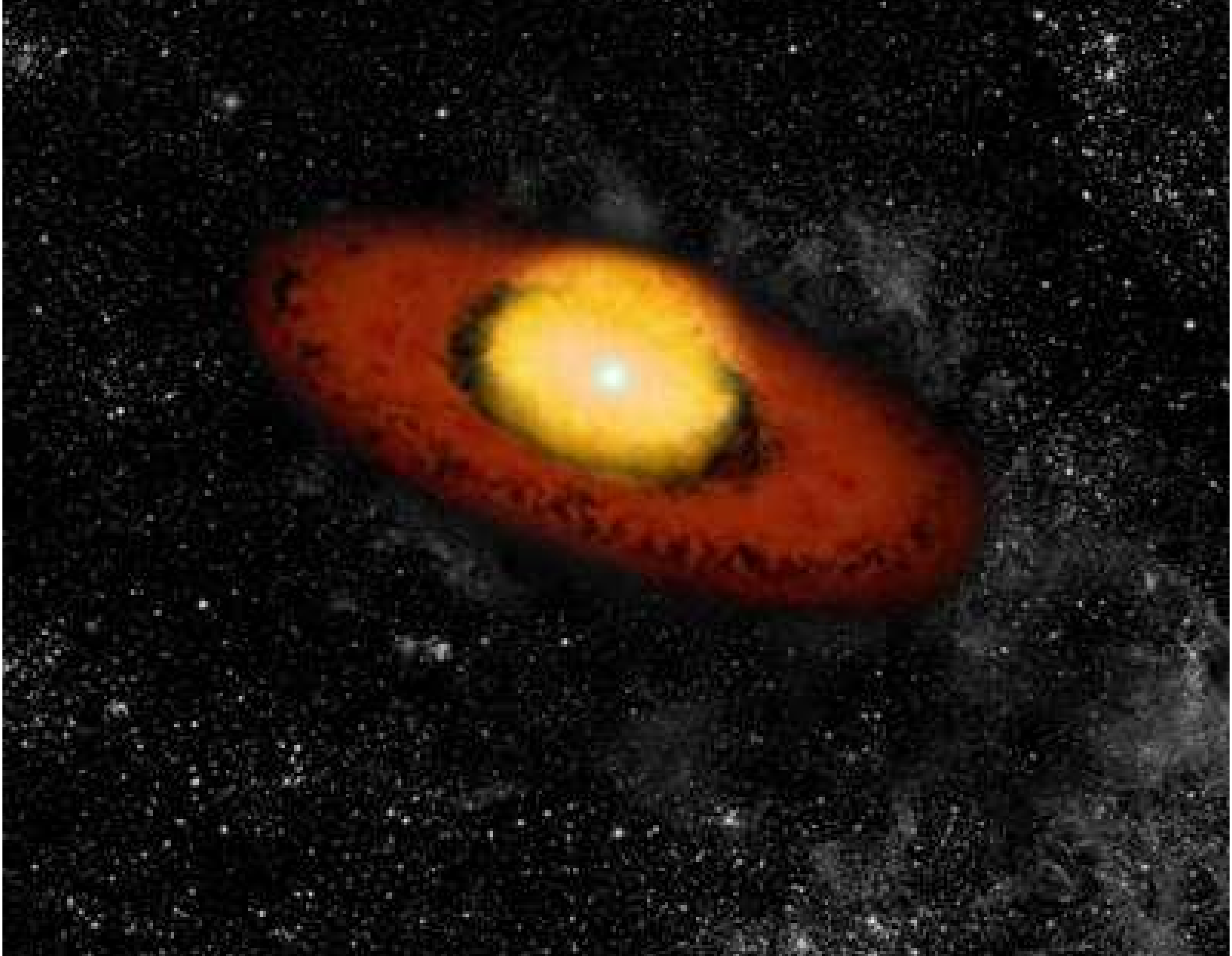

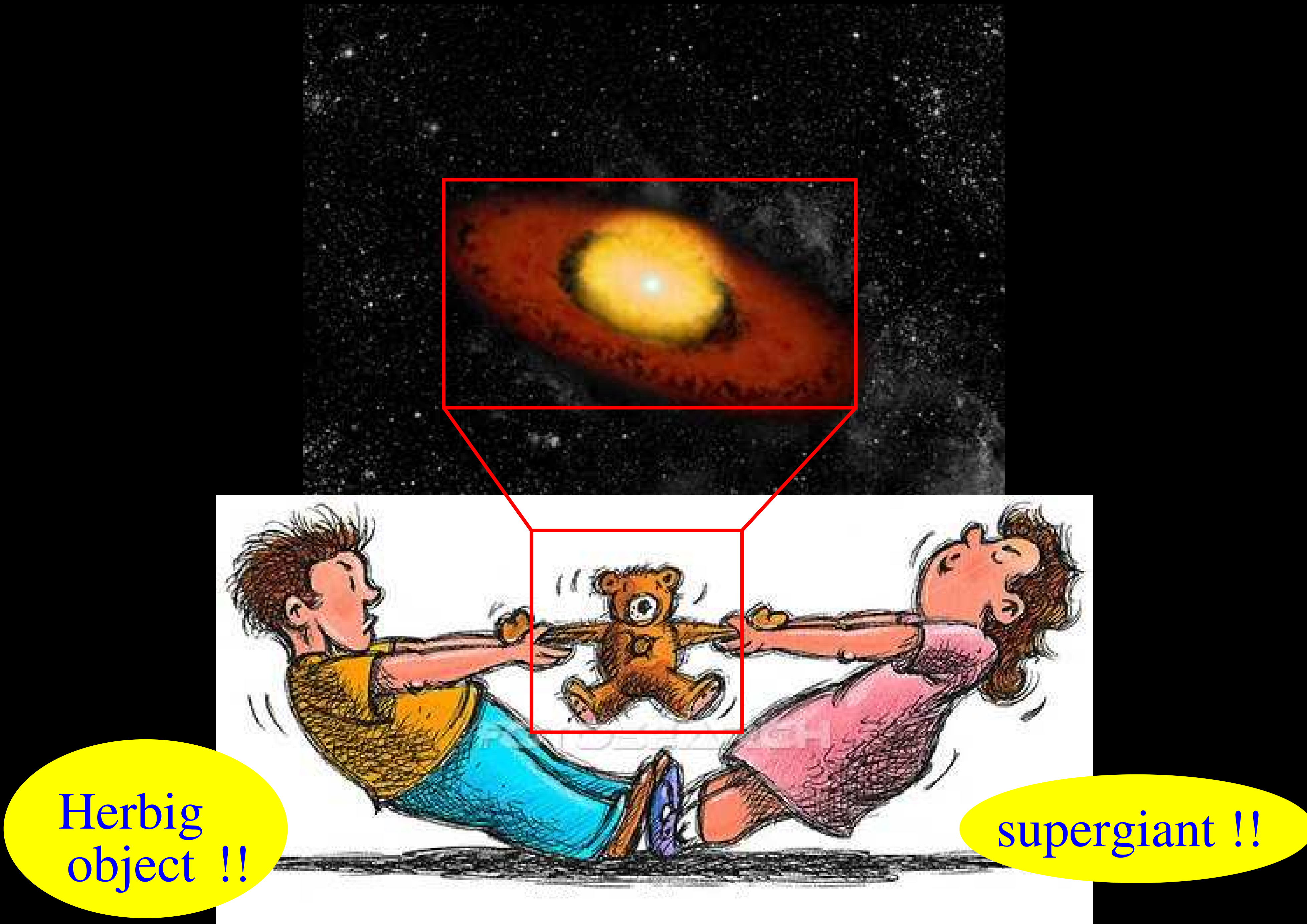
Herbig object !!
supergiant !!

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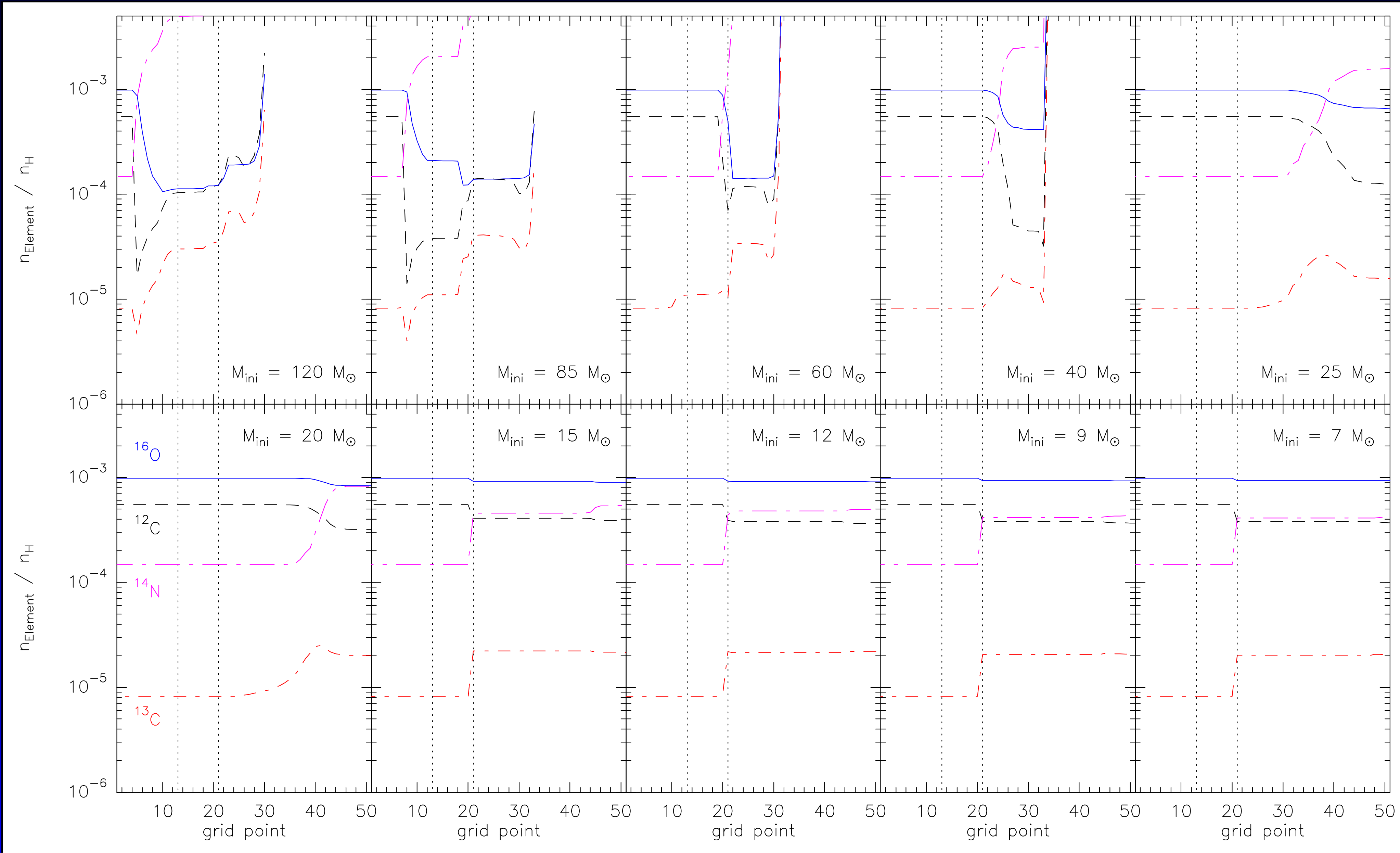
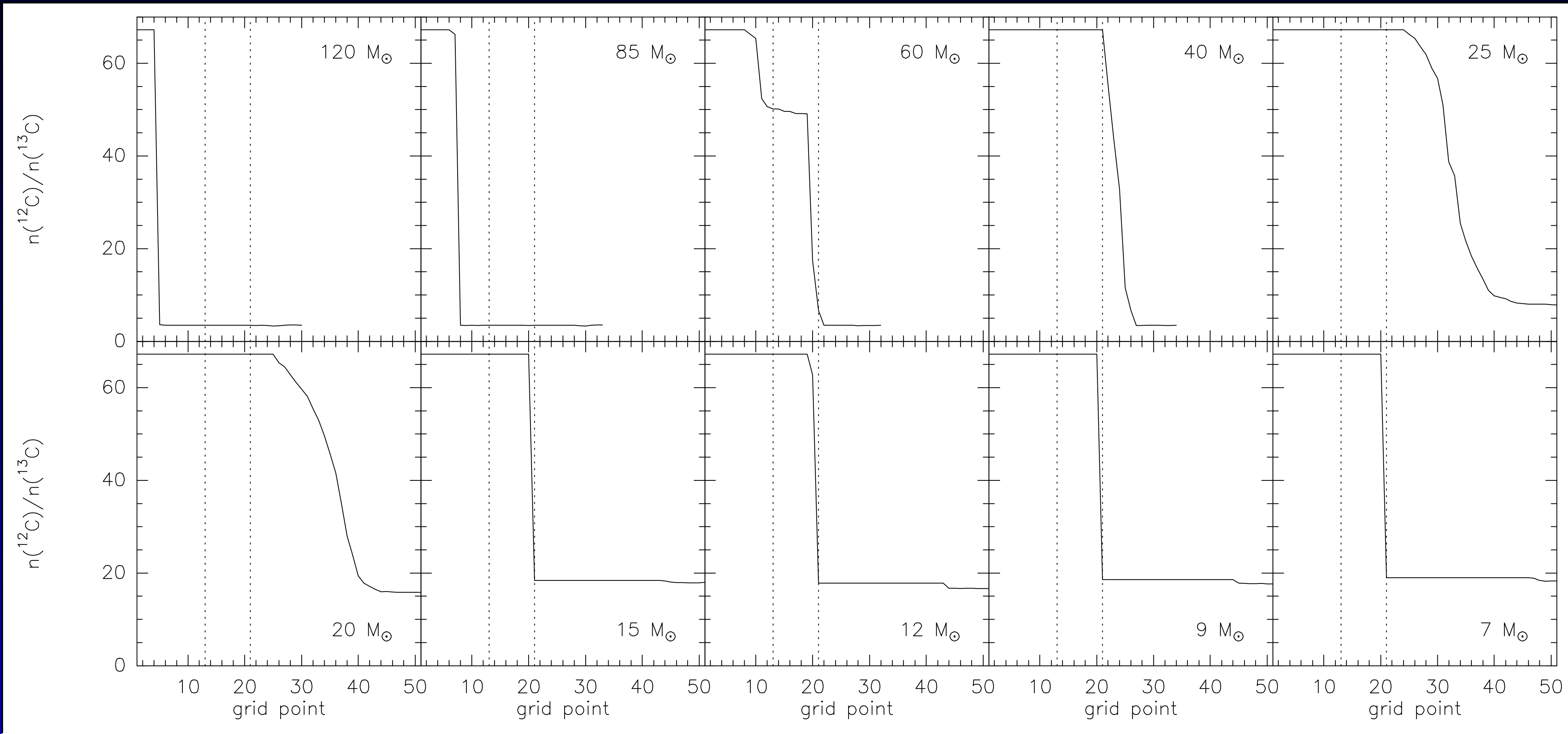
Composition of disk material as tracer of the evolutionary phase !!

Change in surface composition during stellar evolution (based on evolutionary models of Schaller et al. 1992)



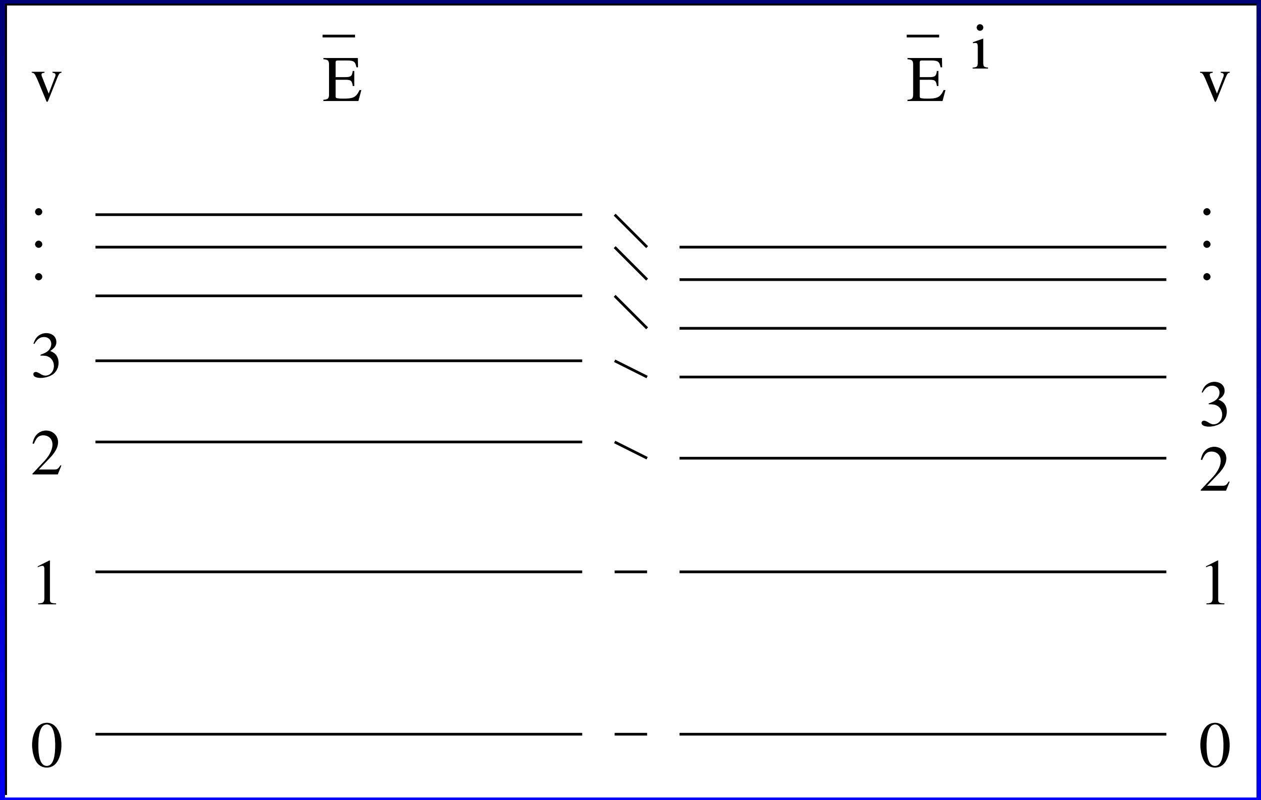
Change in $^{12}C/^{13}C$ ratio during stellar evolution



consequently : $N_{^{13}\mathrm{CO}} = \frac{N_{^{13}\mathrm{CO}}}{N_{^{12}\mathrm{CO}}} N_{^{12}\mathrm{CO}} = \frac{n_{^{13}\mathrm{CO}}}{n_{^{12}\mathrm{CO}}} N_{^{12}\mathrm{CO}} = \frac{N_{^{12}\mathrm{CO}}}{n_{^{12}\mathrm{C}}/n_{^{13}\mathrm{C}}}$

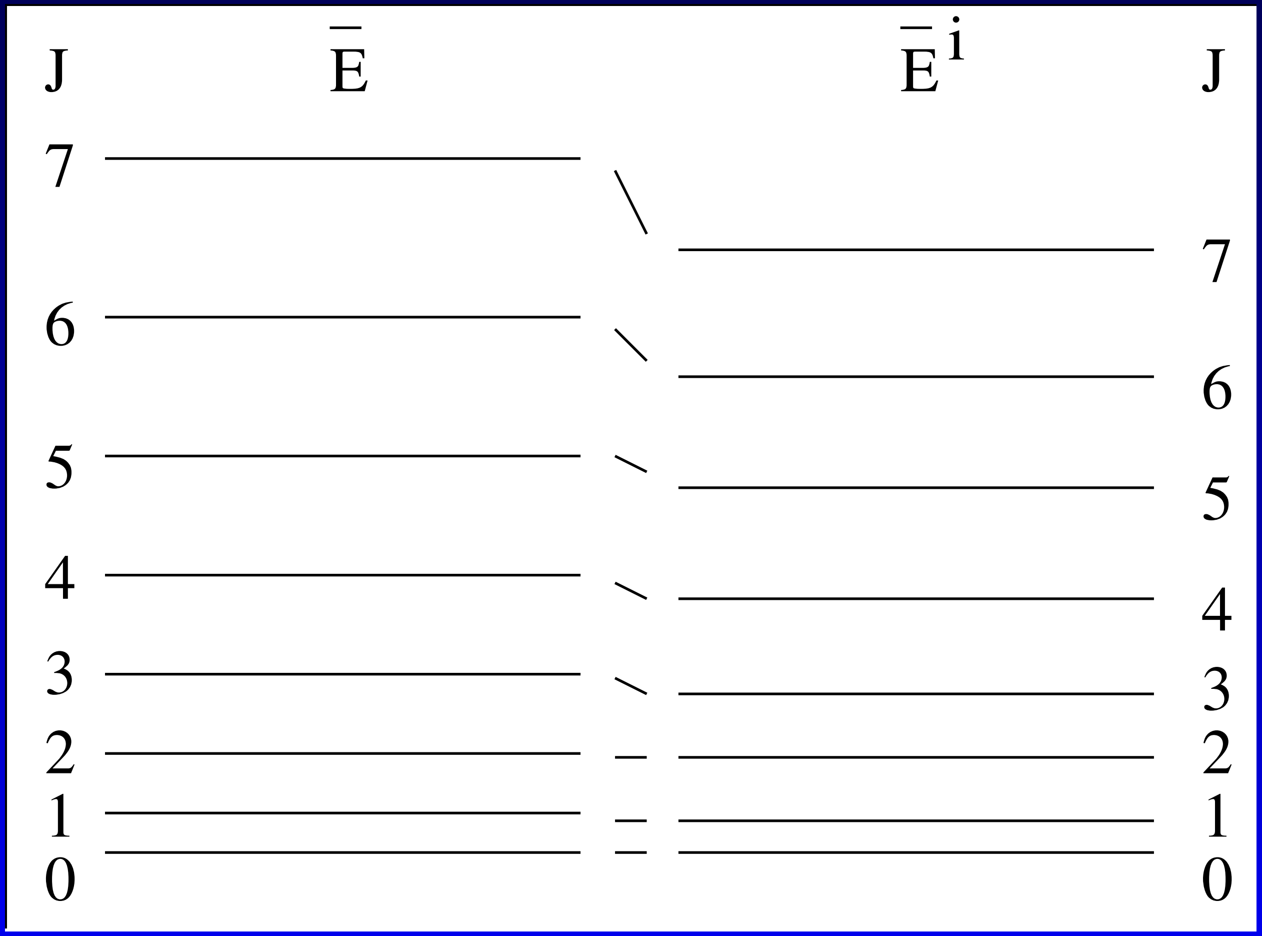
Vib-rot bands of the CO isotopes

- Vibrational frequency depends only on reduced mass, μ
- Ratio of vibrational frequencies is $\frac{\nu^i}{\nu} = \sqrt{\frac{\mu}{\mu^i}}$
- Heavier isotope (i) has lower frequency, (reduced energy levels)

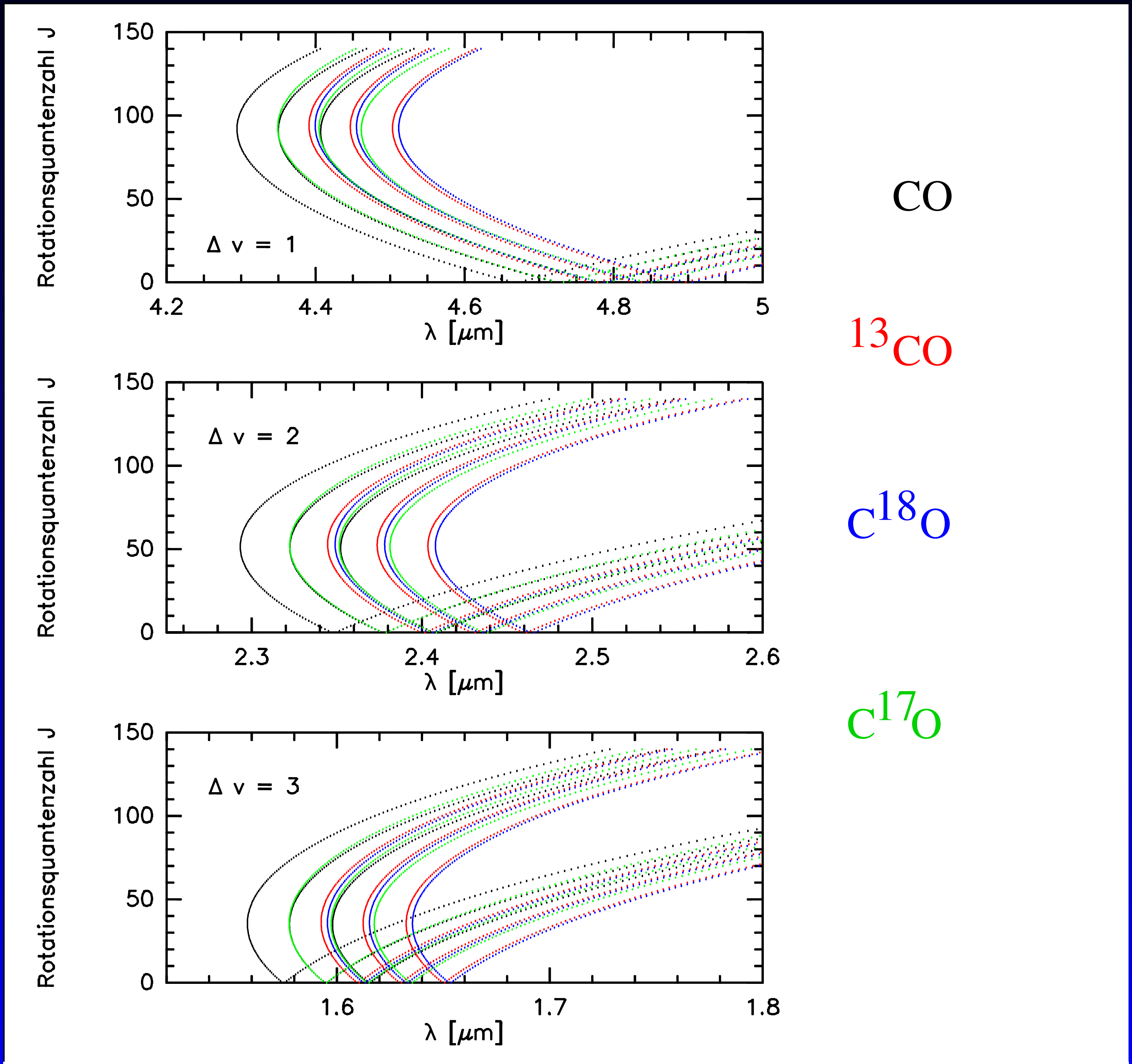


Vib-rot bands of the CO isotopes

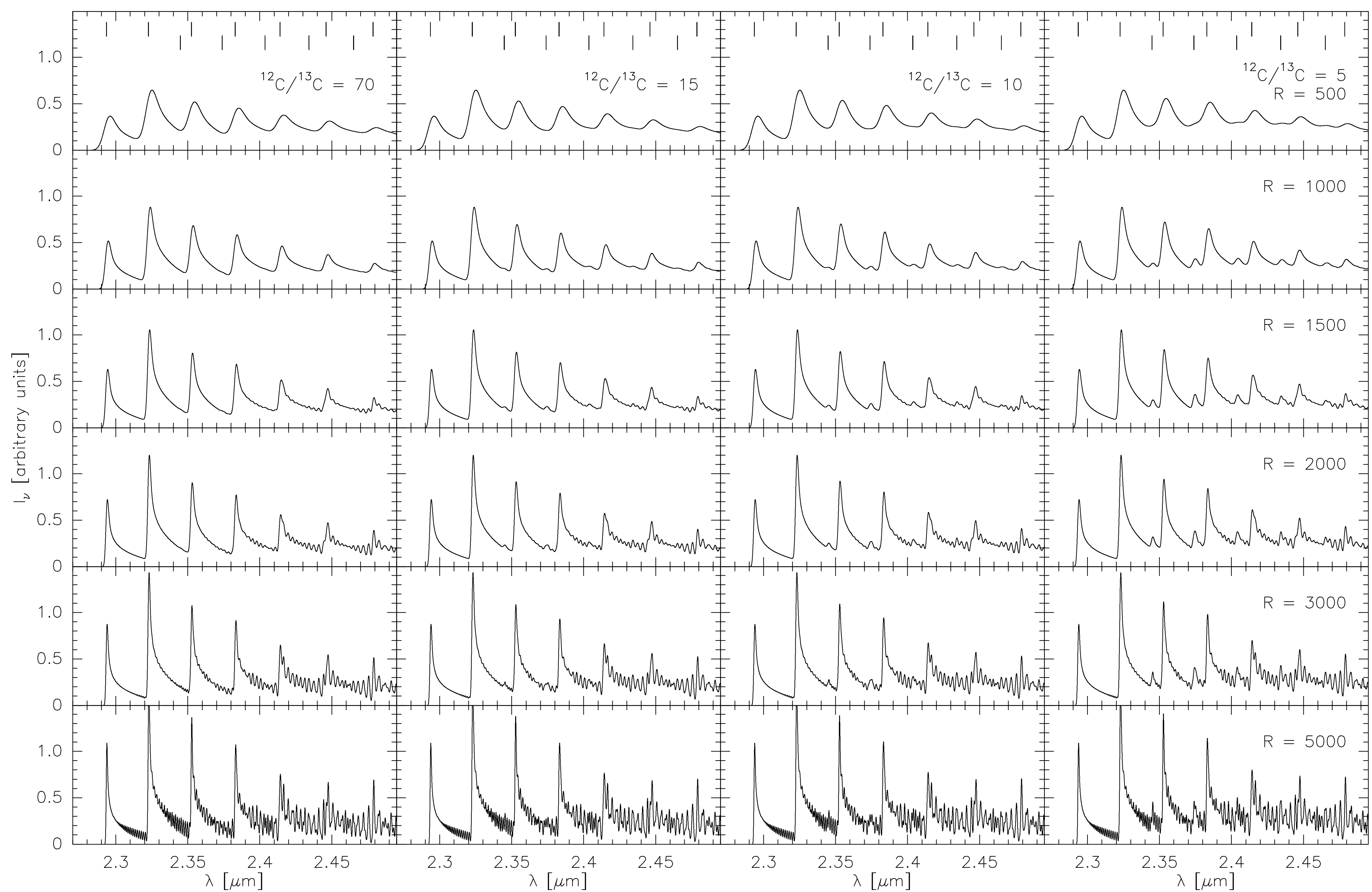
- Larger mass $\longrightarrow$ larger moment of inertia
- Rotational energy levels are also reduced !



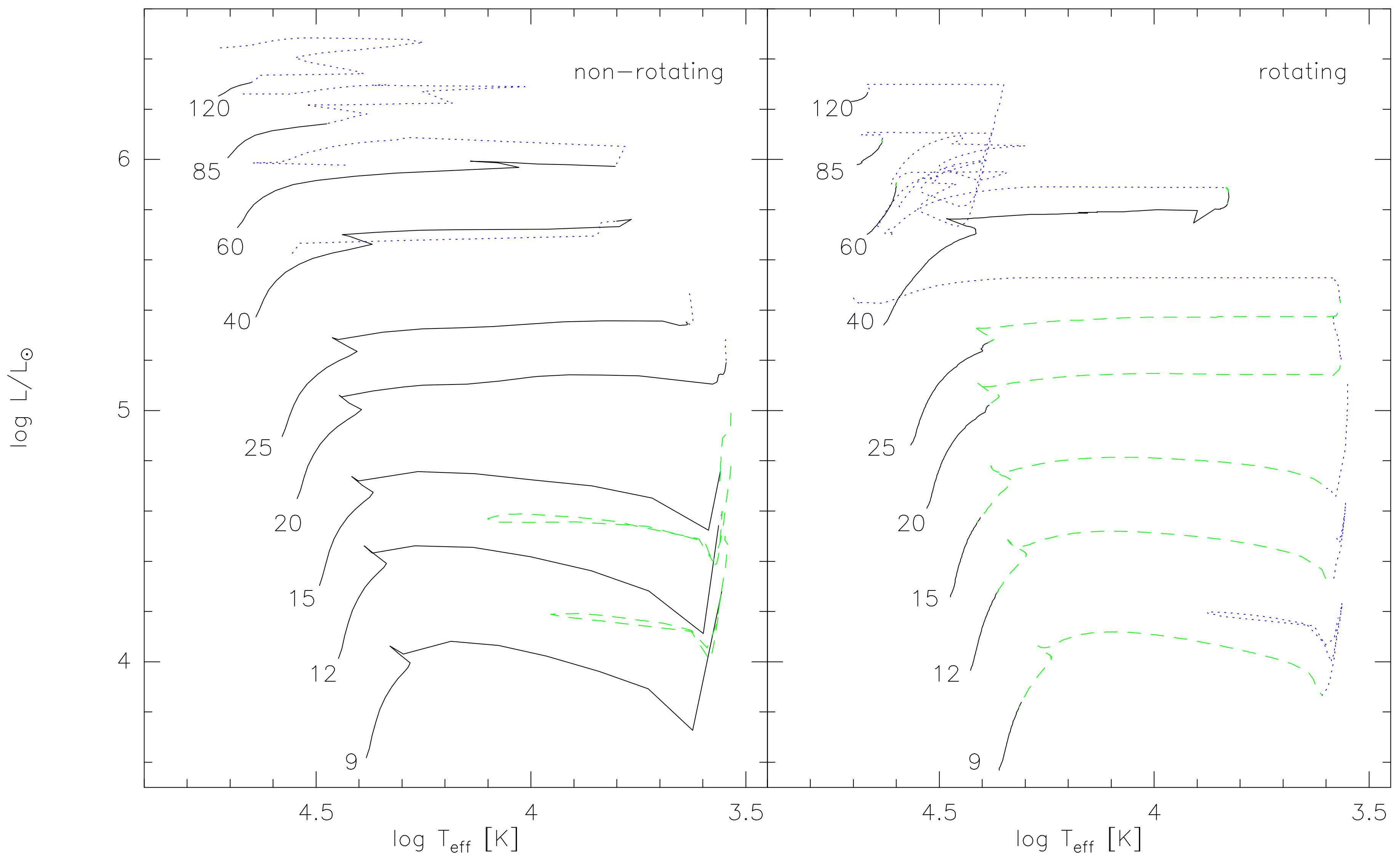
Reduction of energy = increase in wavelength !!



Appearance of the ^{13}CO bands (Kraus 2009)



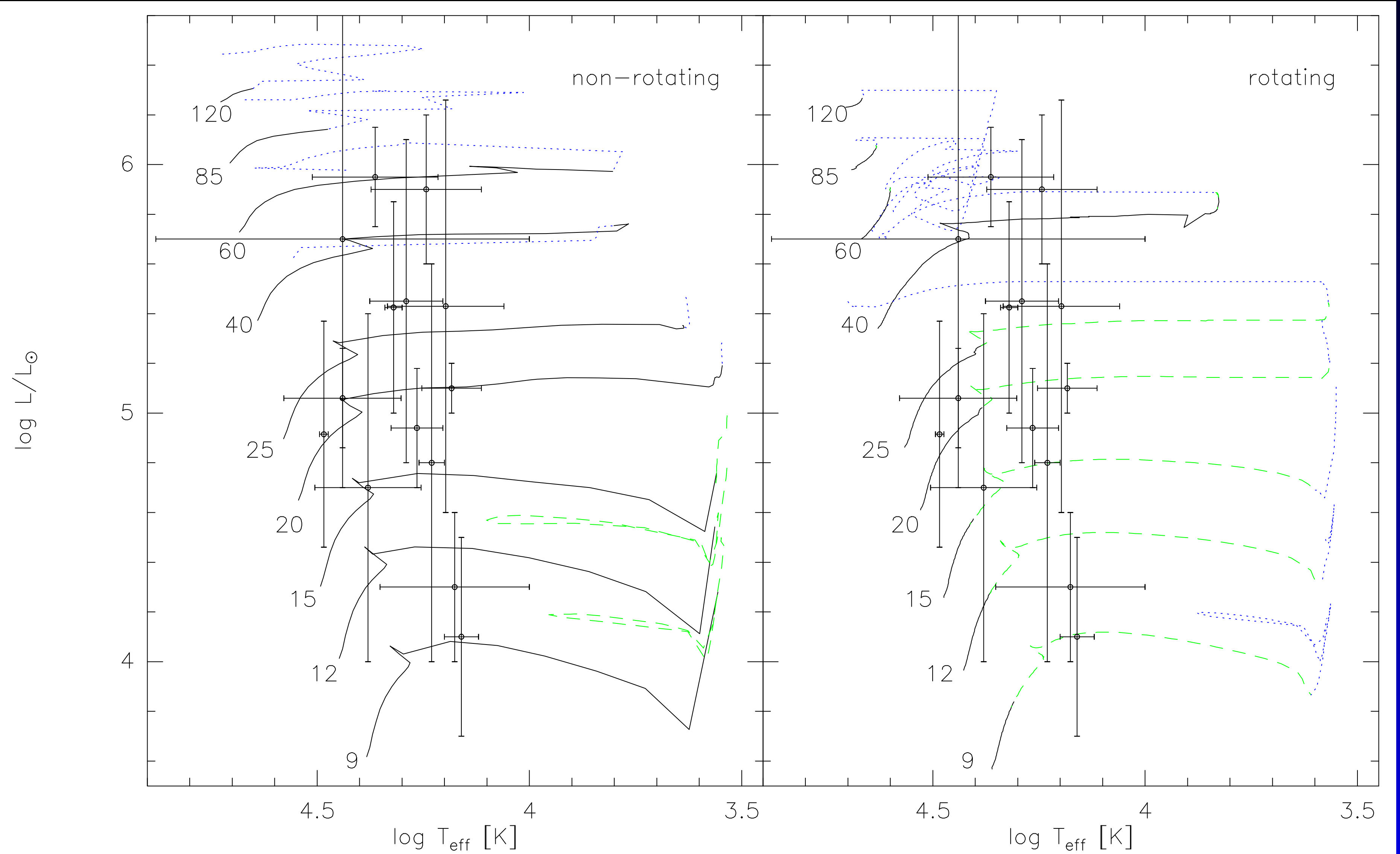
Ranges of low $^{12}C/^{13}C$ over the HRD



$20 > {}^{12}C/{}^{13}C > 15$

$^{12}C/^{13}C < 15$

Positions of the B[e] supergiant candidates



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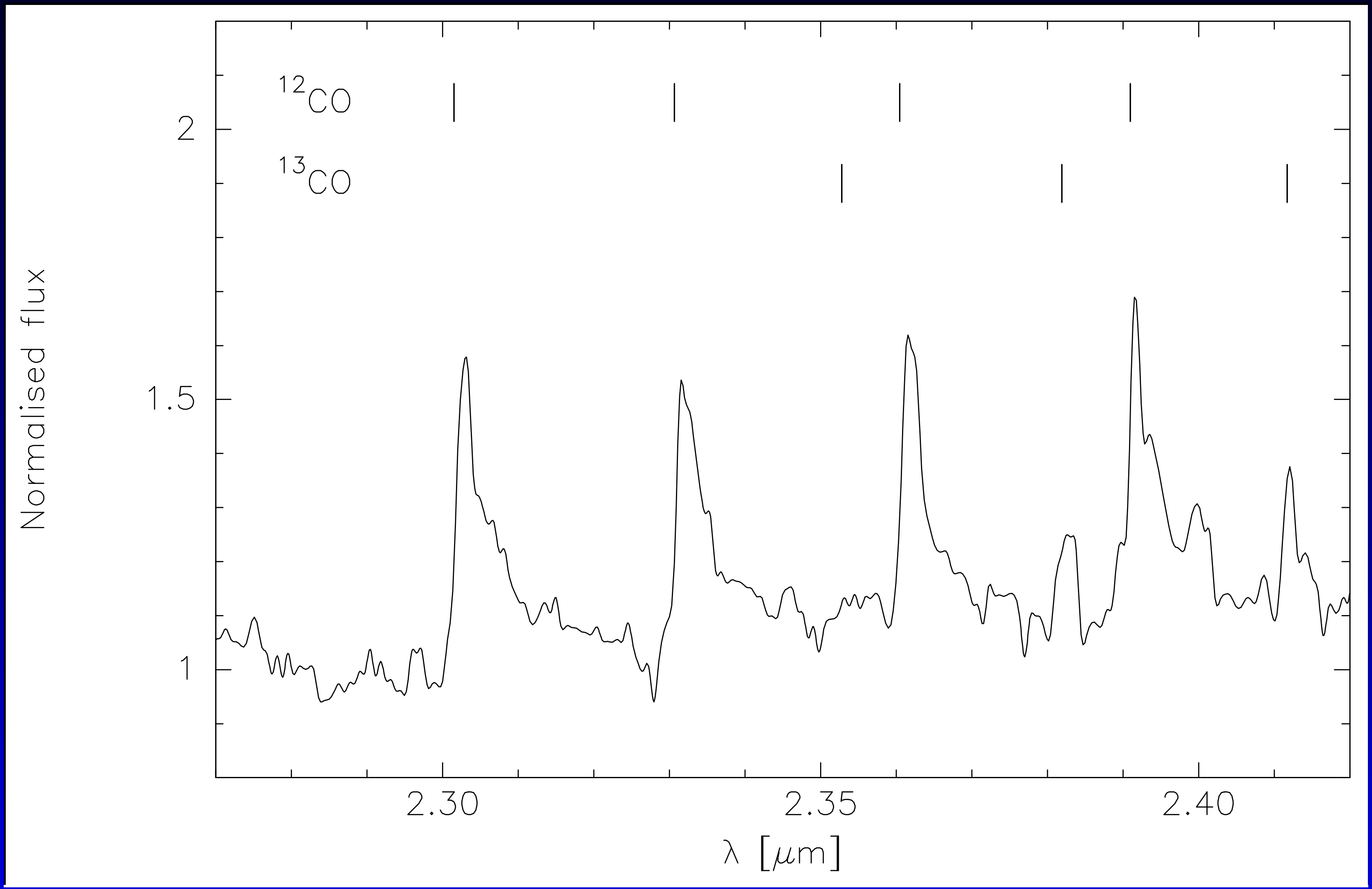
${}^{12}C/{}^{13}C < 15$

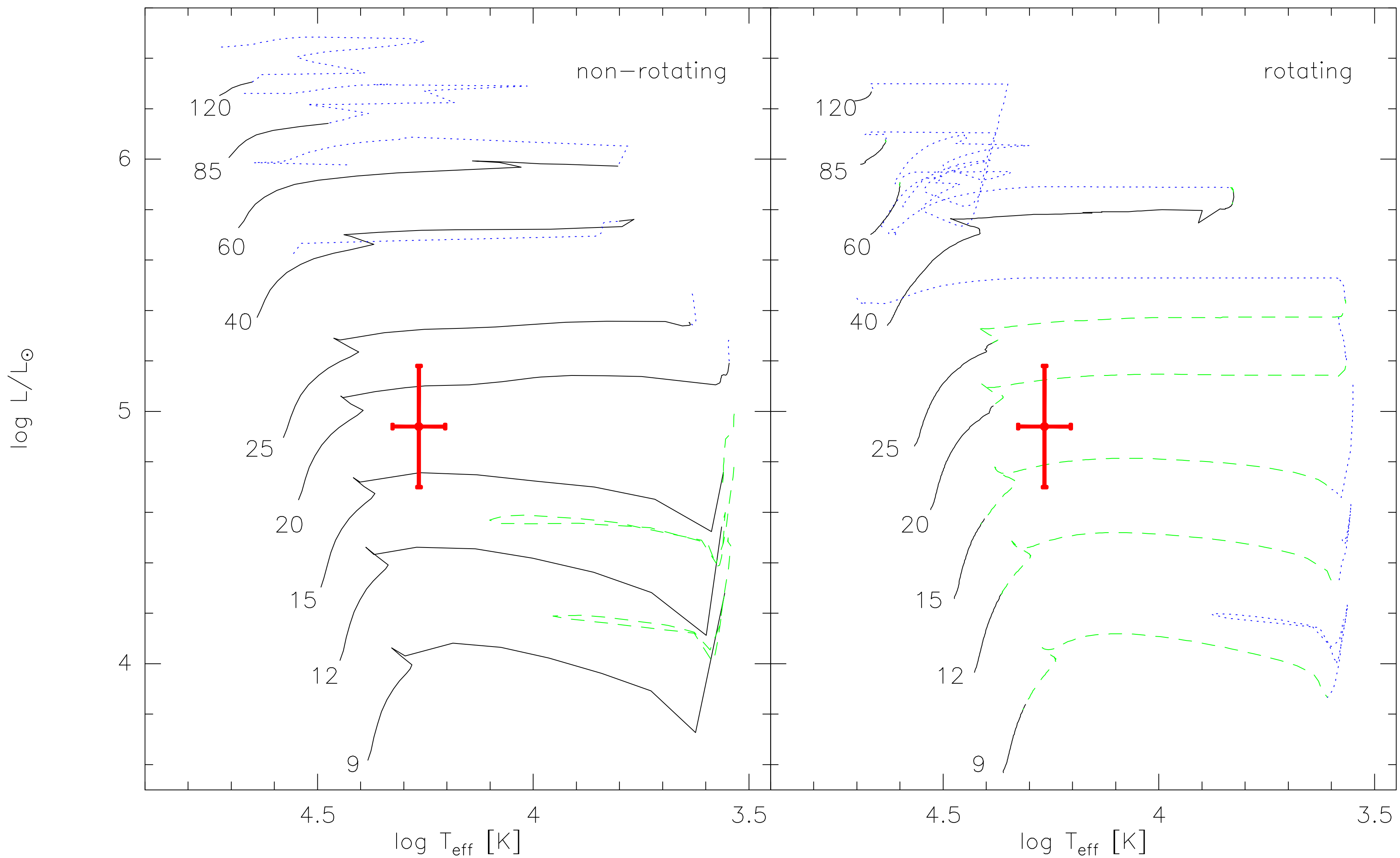
Spectrum of the B[e] star GG Car



Tentative conclusions: $^{12}C/^{13}C < 10$, $T_{CO} = 3000 - 4000$ K

(Domiciano de Souza et al. in prep.)

GG Car in the HRD



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Conclusions & Outlook

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- High-resolution observation will allow us to discriminate whether the CSM of the supergiants is Keplerian rotating or outflowing.

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- ^{13}CO bands are ideal tracers for processed circumstellar material.
- High-quality data at medium resolution are needed to detect ^{13}CO as the *the first and unambigous* distinction characteristics between pre- and post-main sequence stars.