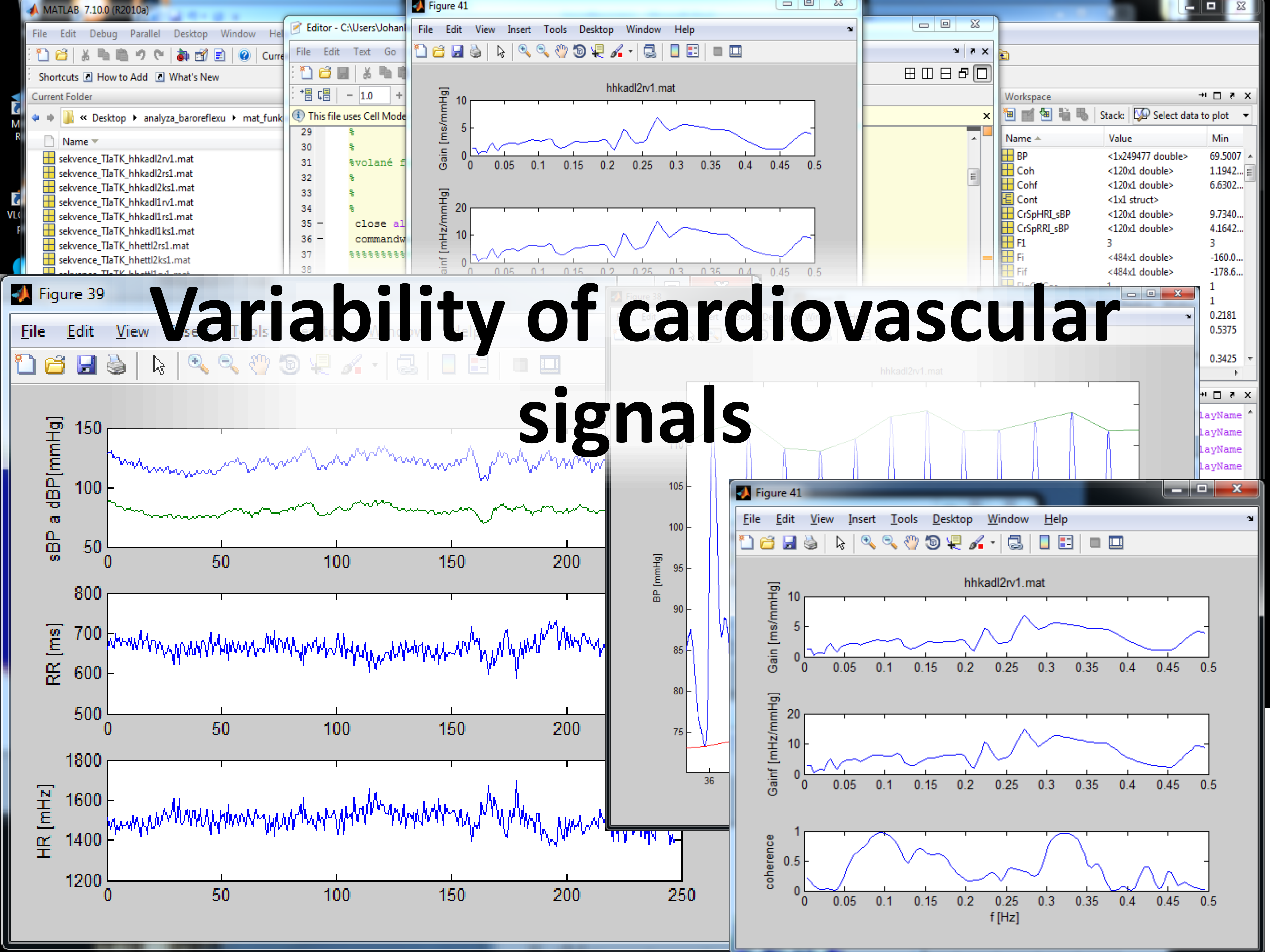
Variability of cardiovascular signals



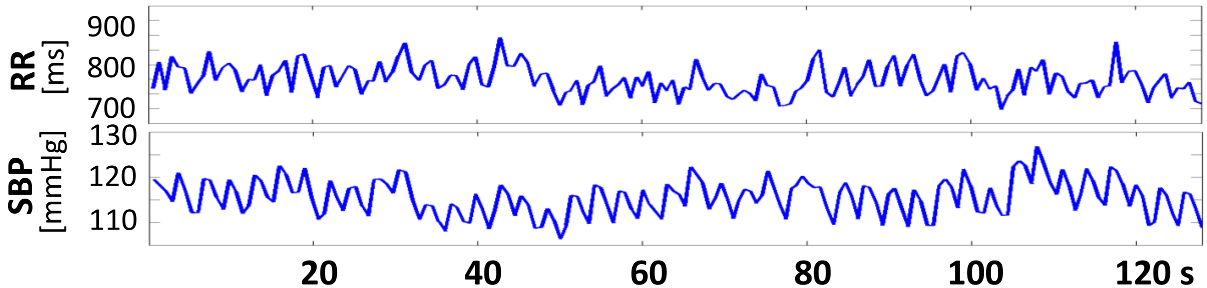
Cardiovascular signal variability

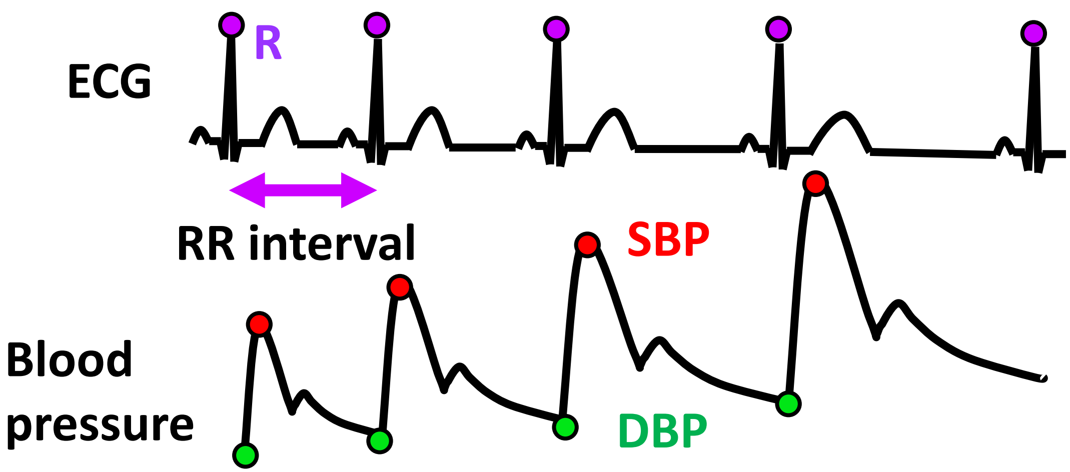
- **Cardiovascular signals (C-V signals)**
  - Easy to measure
    - EGG: RR intervals, heart rate - HR (1/RR)
    - Blood pressure: systolic (SBP), diastolic (DBP), mean (MAP), pulse pressure (PP)
  - Difficult to measure directly (bioimpedance method), can be evaluated indirectly from blood pressure wave (Windkessel model)
    - Stroke volume (SV), cardiac output (CO), total peripheral resistance (TPR)
  - Very difficult to measure directly (invasive measurement)
    - Blood flow and pressure in various places of vessels

Signal: time series

Beat to beat (for example 5 minutes)

- RR interval: 805, 820, 815, 817, 822, 816,….. ms
- Hear rate: 70, 73, 68, 65, 67, 71,….. bpm
- Systolic blood pressure: 115, 117, 120, 116, 121, 119,….. mmHg

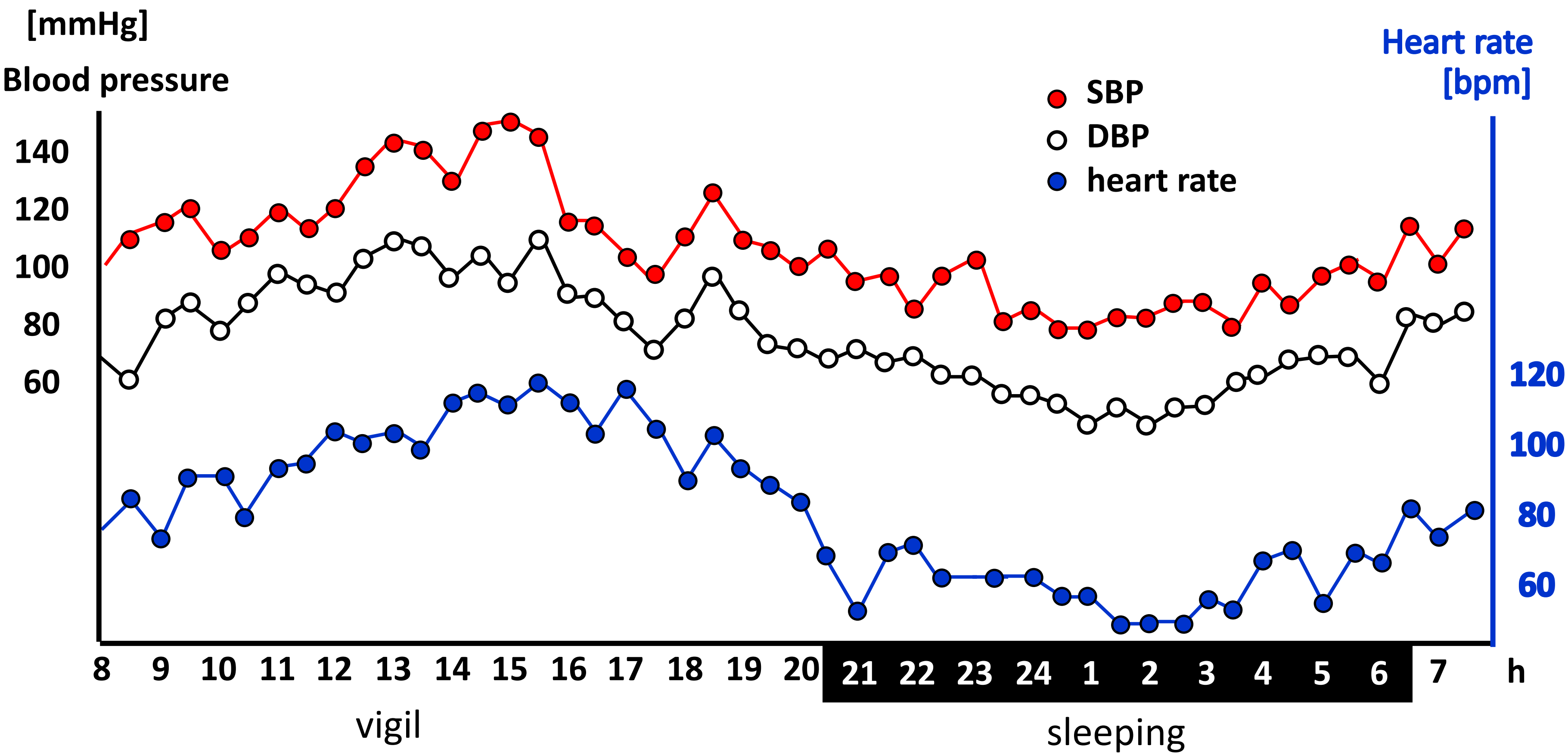




Signal: time series

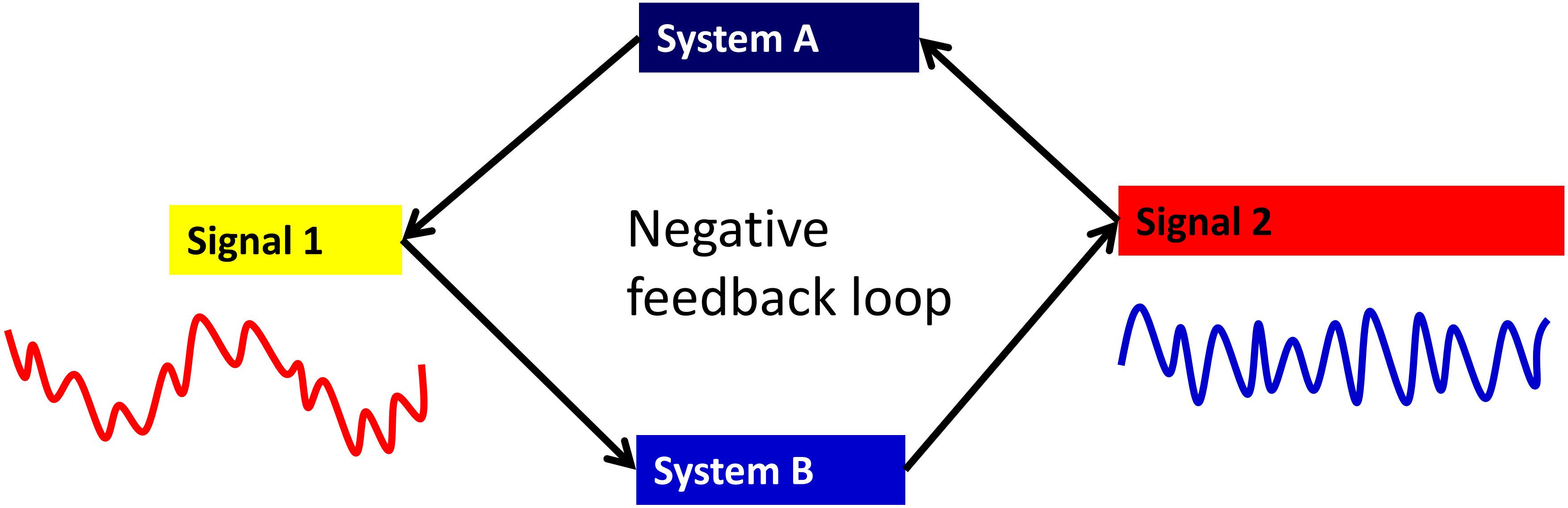
Every 15 minutes

- 24-hour blood pressure measurement, ECG Holter



Variability of cardiovascular signals

- Cardiovascular system is regulated by negative feedback
- Negative feedback forms oscillations in the signals – the longer feedback loop, the slower oscillations
- Analysis of oscillations in the C-V signals contains information about regulatory mechanism



Brief introduction in theory of systems

$$A(z) = \begin{pmatrix} A_{11}(z) & A_{12}(z) \\ A_{21}(z) & A_{22}(z) \end{pmatrix} = \sum_{k=0}^{p} A_k z^{-k}$$

$$= \begin{pmatrix} a_{11,1}z^{-1} + a_{11,2}z^{-2} + \cdots + a_{11,n}z^{-p} & a_{12,1}z^{-1} + a_{12,2}z^{-2} + \cdots + a_{12,n}z^{-p} \\ a_{21,0} + a_{21,1}z^{-1} + a_{21,2}z^{-2} + \cdots + a_{21,n}z^{-p} & a_{22,1}z^{-1} + a_{22,2}z^{-2} + \cdots + a_{22,n}z^{-p} \end{pmatrix}$$

$$H(f) = (I - A(z))^{-1} = \begin{pmatrix} H_{11}(f) & H_{12}(f) \\ H_{21}(f) & H_{22}(f) \end{pmatrix}$$

$$S(f) = H(z) \cdot \Lambda \cdot H'(z^{-1}) = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix},$$

$$\Lambda = \begin{pmatrix} \lambda_1^2 & 0 \\ 0 & \lambda_2^2 \end{pmatrix}$$

$$S_{11}(f) = |\Delta(z)|^2 \cdot [|1 - A_{22}(z)|^2 \lambda_1^2 + |A_{12}(z)|^2 \lambda_2^2],$$
$$S_{22}(f) = |\Delta(z)|^2 \cdot [|A_{21}(z)|^2 \lambda_1^2 + |1 - A_{11}(z)|^2 \lambda_2^2]$$
$$S_{12}(f) = |\Delta(z)|^2 \cdot [(1 - A_{22}(z))A_{21}(z^{-1})\lambda_1^2 + (1 - A_{11}(z^{-1}))A_{12}(z)\lambda_2^2],$$

kde $\Delta(z) = \left((1 - A_{11}(z))(1 - A_{22}(z)) - A_{12}(z)A_{21}(z)\right)^{-1}$.

Brief introduction in theory of systems

$-k$

$_{1,n}z^{-p} \qquad a_{12,1}z^{-1} + a_{12,2}z^{-2} + \cdots + a_{12,n}z^{-p} \Big)$

$- a_{21,n}z^{-p} \quad a_{22,1}z^{-1} + a_{22,2}z^{-2} + \cdots + a_{22,n}z^{-p} \Big)$

$)^{-1} = \begin{pmatrix} H_{11}(f) & H_{12}(f) \\ H_{21}(f) & H_{22}(f) \end{pmatrix}$

$S \qquad \Big),$

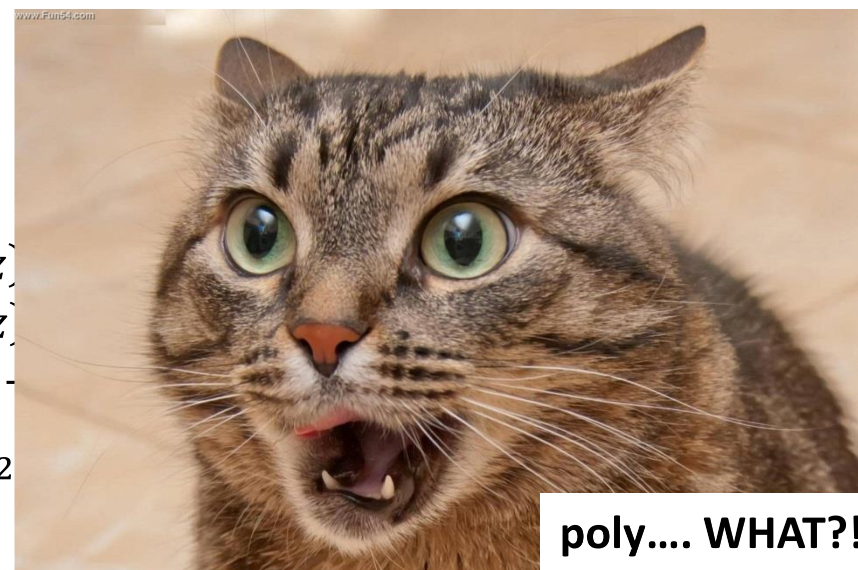
$\Lambda = \begin{pmatrix} \lambda_1^2 & 0 \\ 0 & \lambda_2^2 \end{pmatrix}$

$S_{11}(f) = |\Delta(z)|^2 \cdot [|1 - A_{22}(z)|^2 \lambda_1^2 + |A_{12}(z)$

$S_{22}(f) = |\Delta(z)|^2 \cdot [|A_{21}(z)|^2 \lambda_1^2 + |1 - A_{11}(z)$

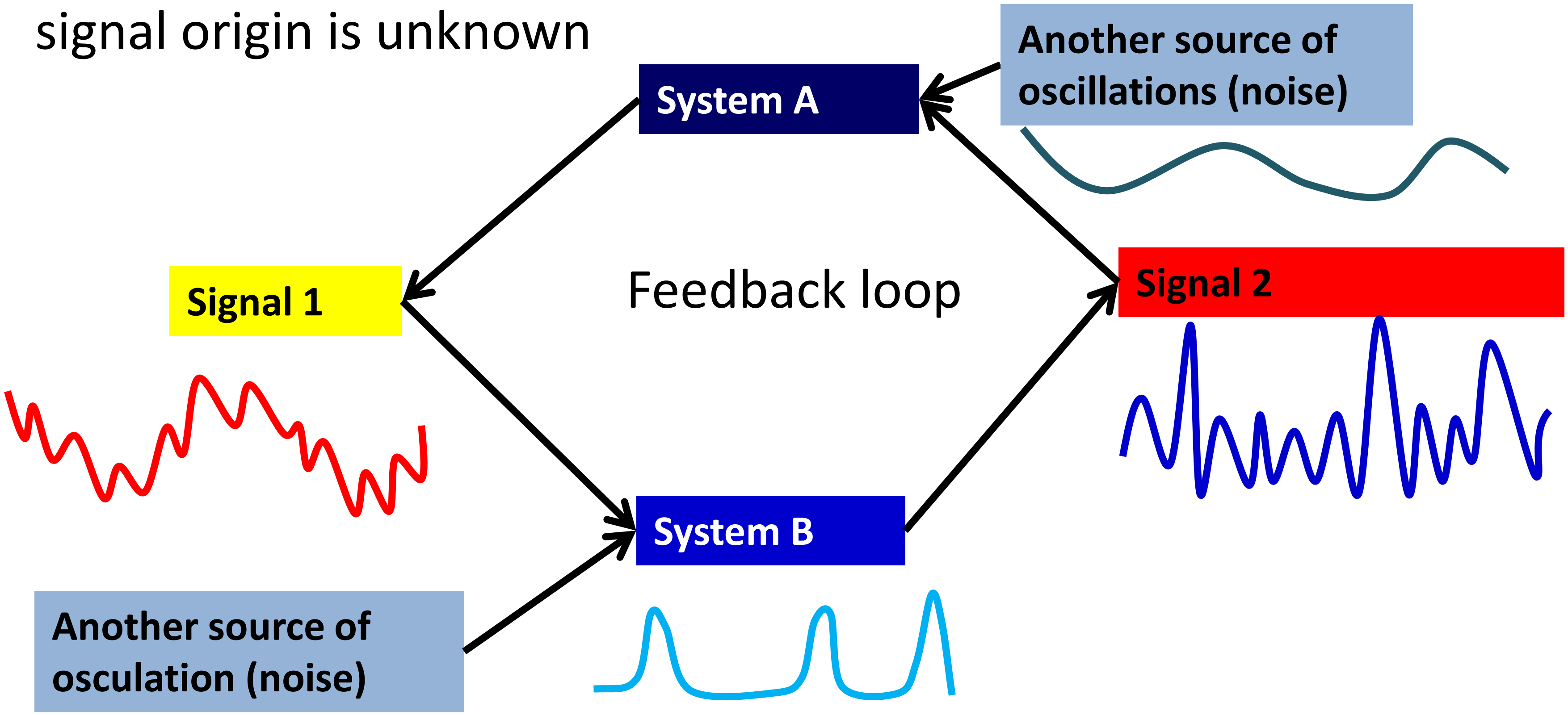
$S_{12}(f) = |\Delta(z)|^2 \cdot [(1 - A_{22}(z))A_{21}(z^{-1})\lambda_1^2 -$

kde $\Delta(z) = \big((1 - A_{11}(z))(1 - A_{22}(z)) - A_{12}$

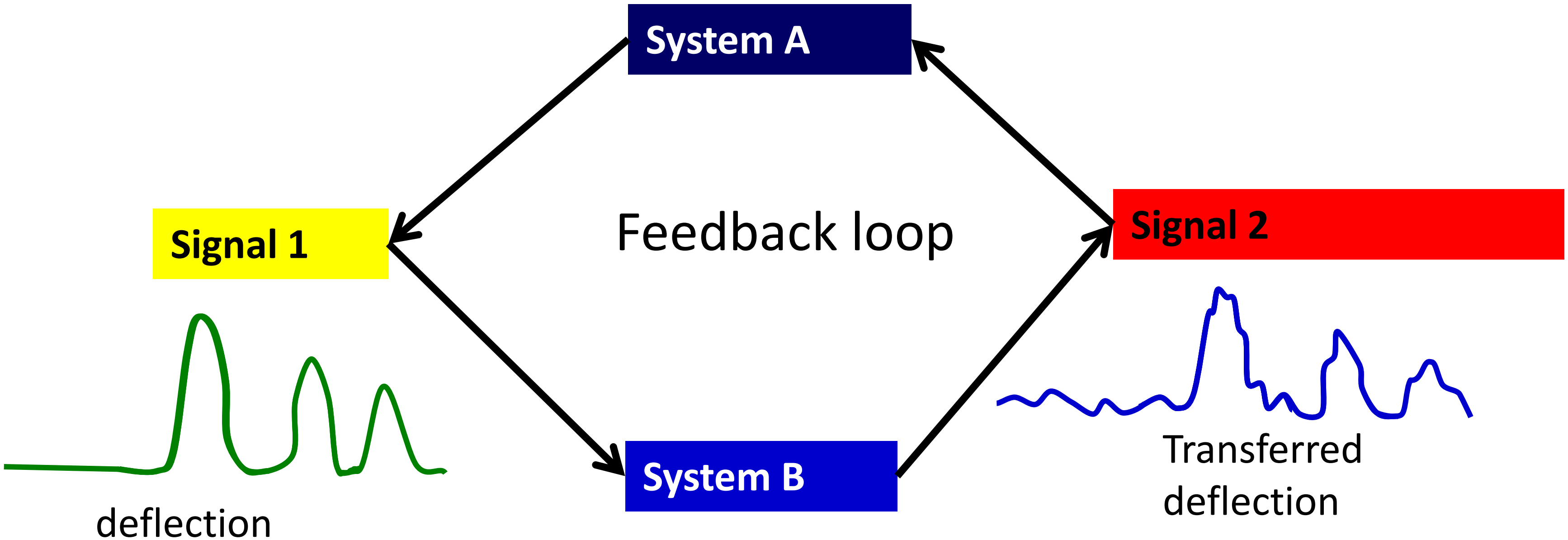


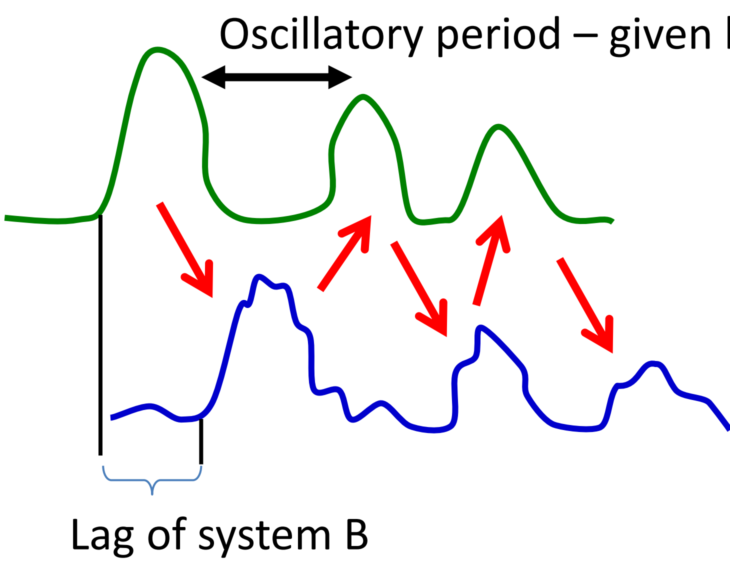
Brief introduction in theory of systems

- Biological systems are complex – more than one input, system setting and outputs can change
- System transforms input signal into output signal – analysis of input/output signals helps to understand the sys
- noise: another input signal – we do not care about signal and/or signal origin is unknown



Source of oscillations

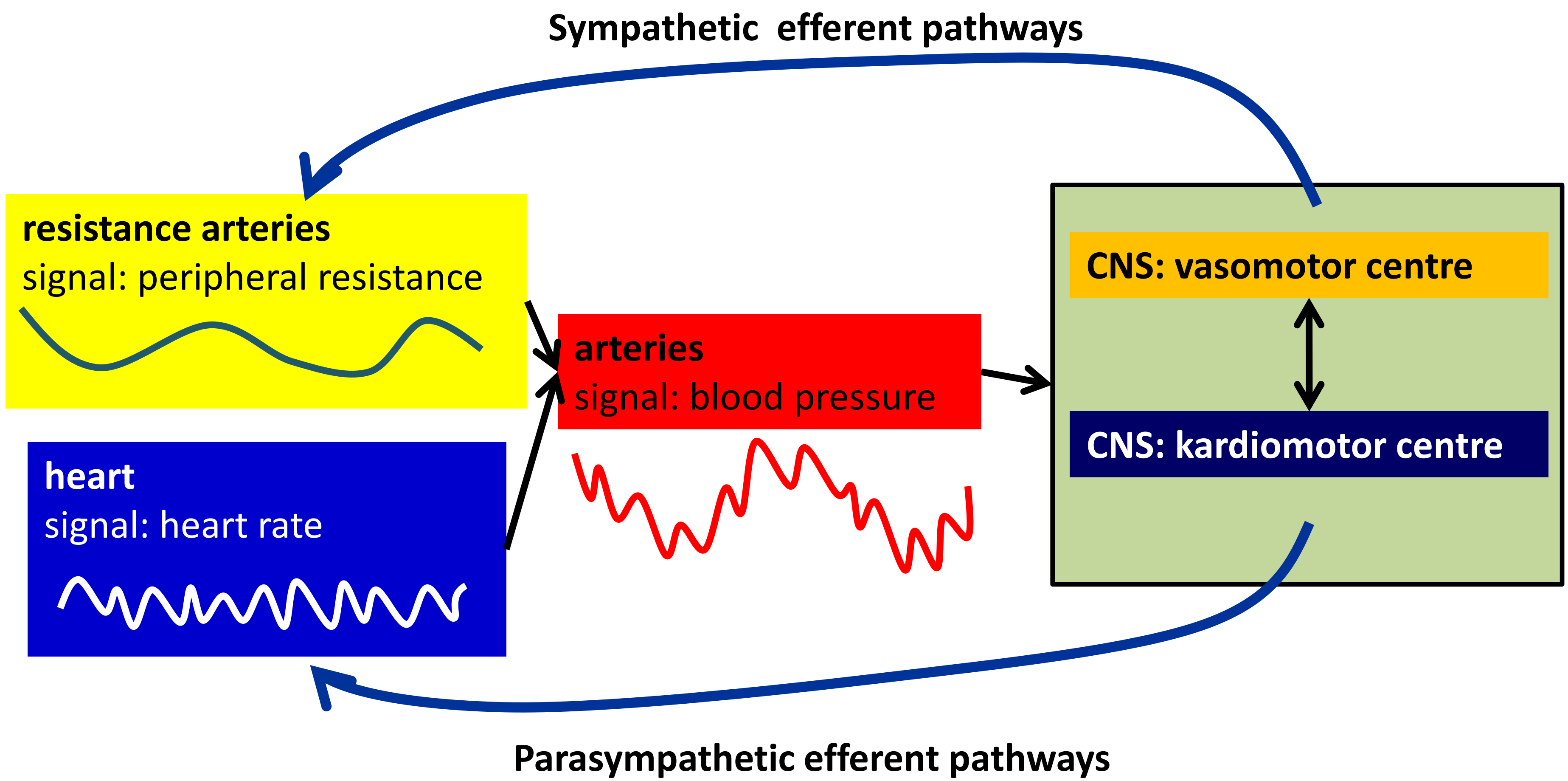




Frequency of oscillation = 1/period

→ **frequency (spectral) analysis contain** information about system

Feedback loop - baroreflex



Methods of the variability assessment

methods

Time-domain methods

- Statistic methods
- Geometric methods

Frequency-domain methods

Non-linear methods

(index of ireversibility, entropy based indices, symbolic analysis…)

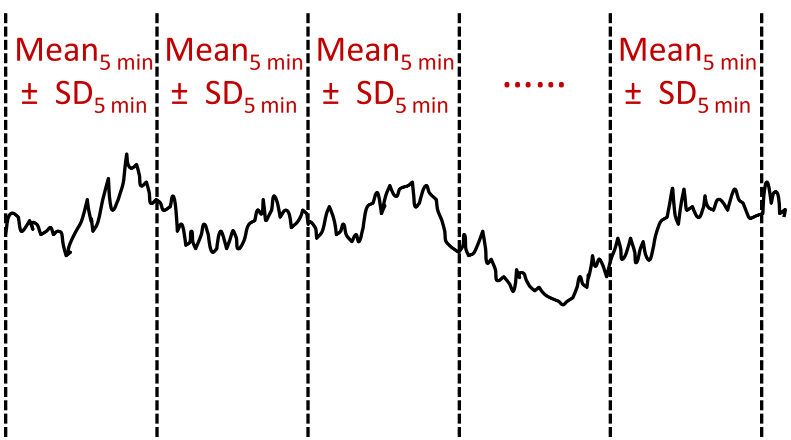
Statistic methods

(Variations on Standard Deviation)

24-hour record of RR intervals

$Mean_{24\text{-}h} \pm SD_{24\text{-}h}$

24-hour record of RR intervals divided into 5-min segments ($Mean_{5\ min} \pm SD_{5\ min}$)



$SD_{24\text{-}h}$ counted from all RR-intervals in 24 hours — **SDRR**

$SD_{24\text{-}h}$ counted from all normal RR-intervals in 24 hours — **SDNN**

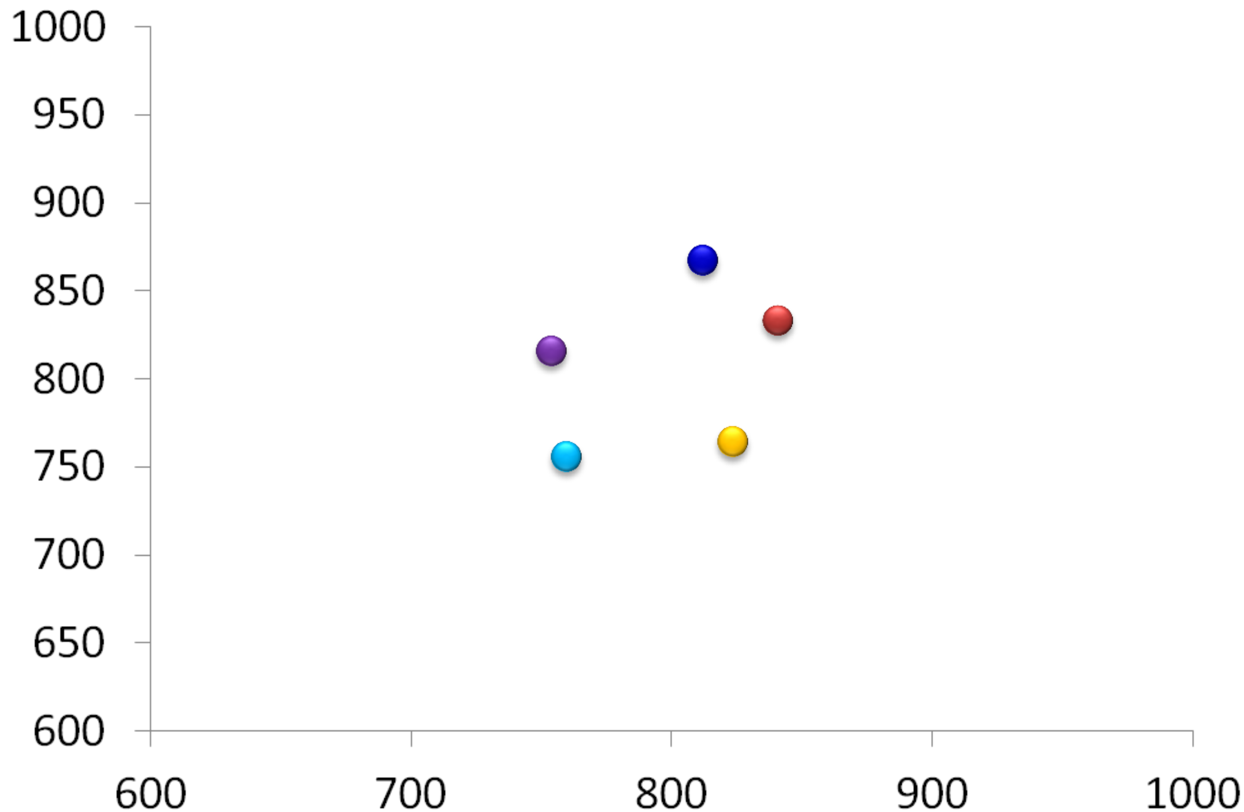
SD counted from all $Mean_{5\ min}$ — **SDANN**

SD counted from all $SD_{5\ min}$ — **SDANNIDX**

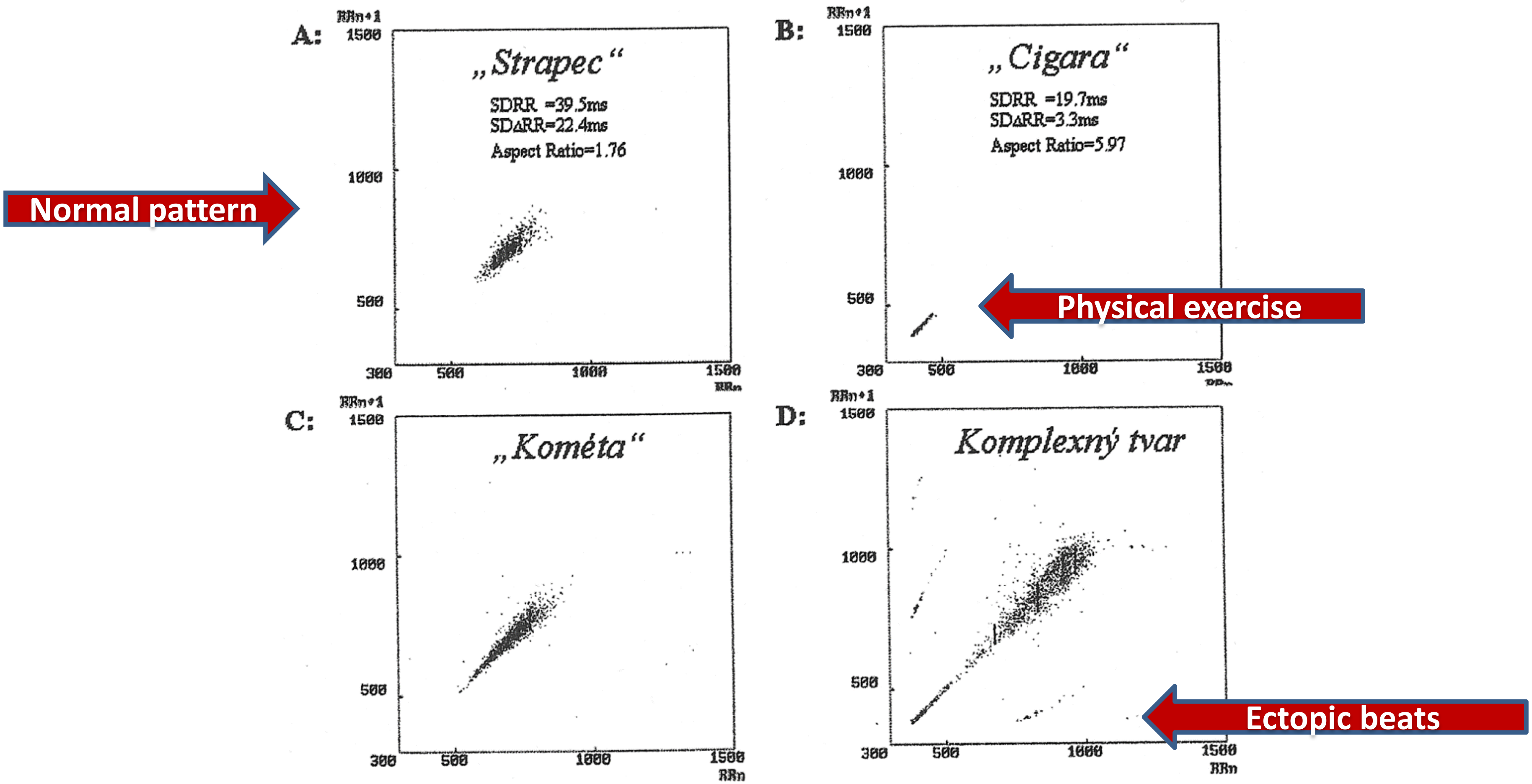
Geometric methods

RR (ms)

840 x
828 y x
760 y x
756 y x
808 y x
856 y
768
780
808
756
708
728
756
732
708



Geometric methods

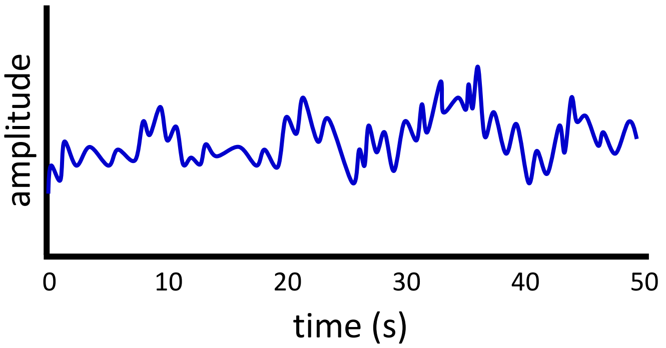


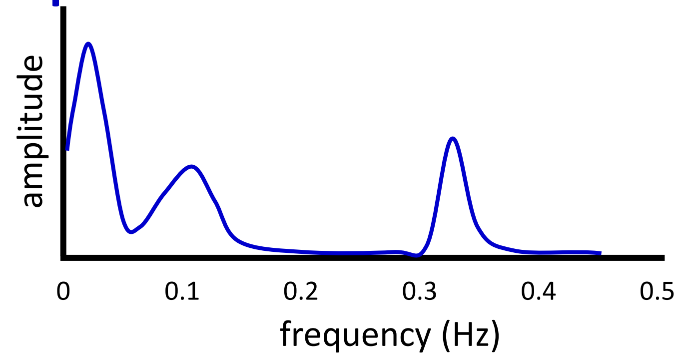
Frequency domain methods – spectral analysis

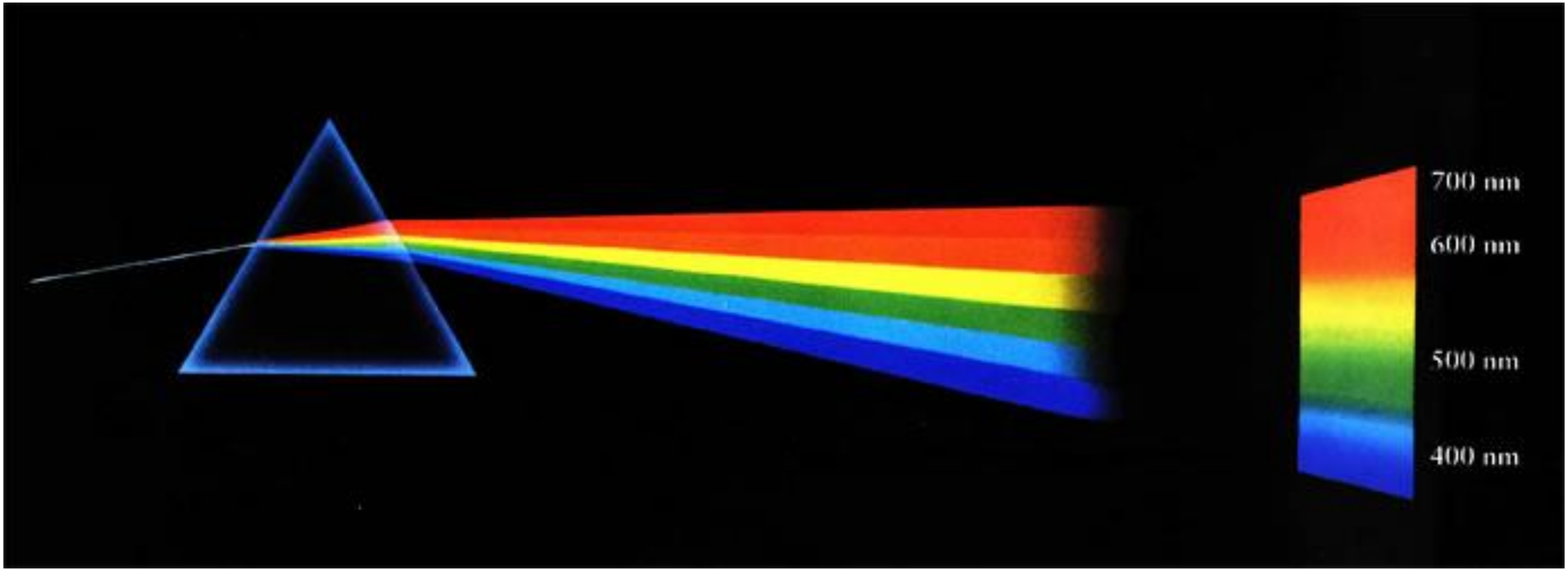
Time series
Signal in time domain

Spectrum
Signal in frequency domain

Signal is decomposed in individual frequencies





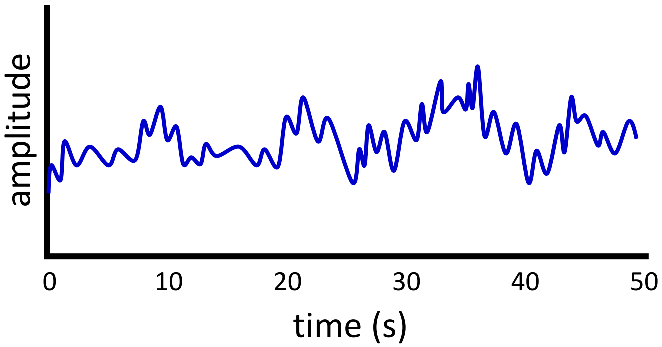


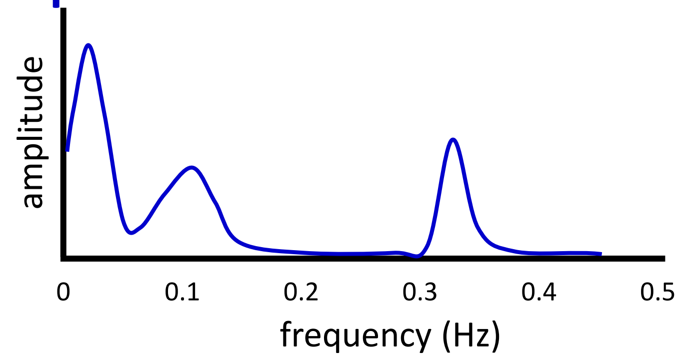
Frequency domain methods – spectral analysis

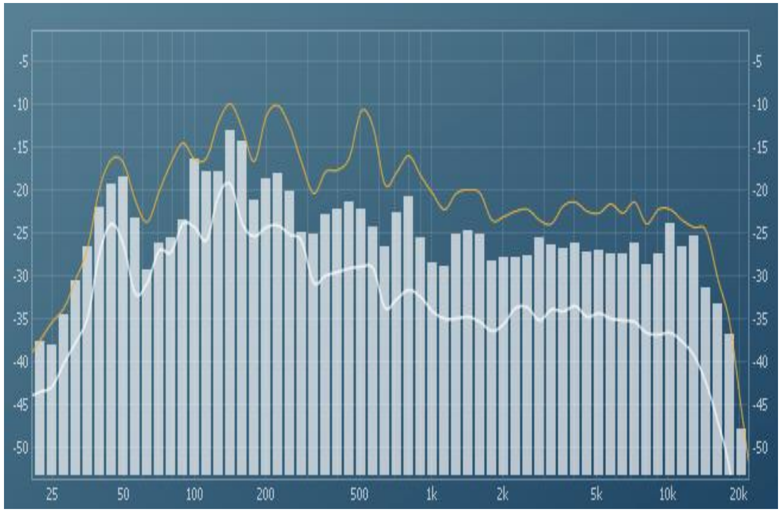
Time series
Signal in time domain

Spectrum
Signal in frequency domain

Signal is decomposed in individual frequencies



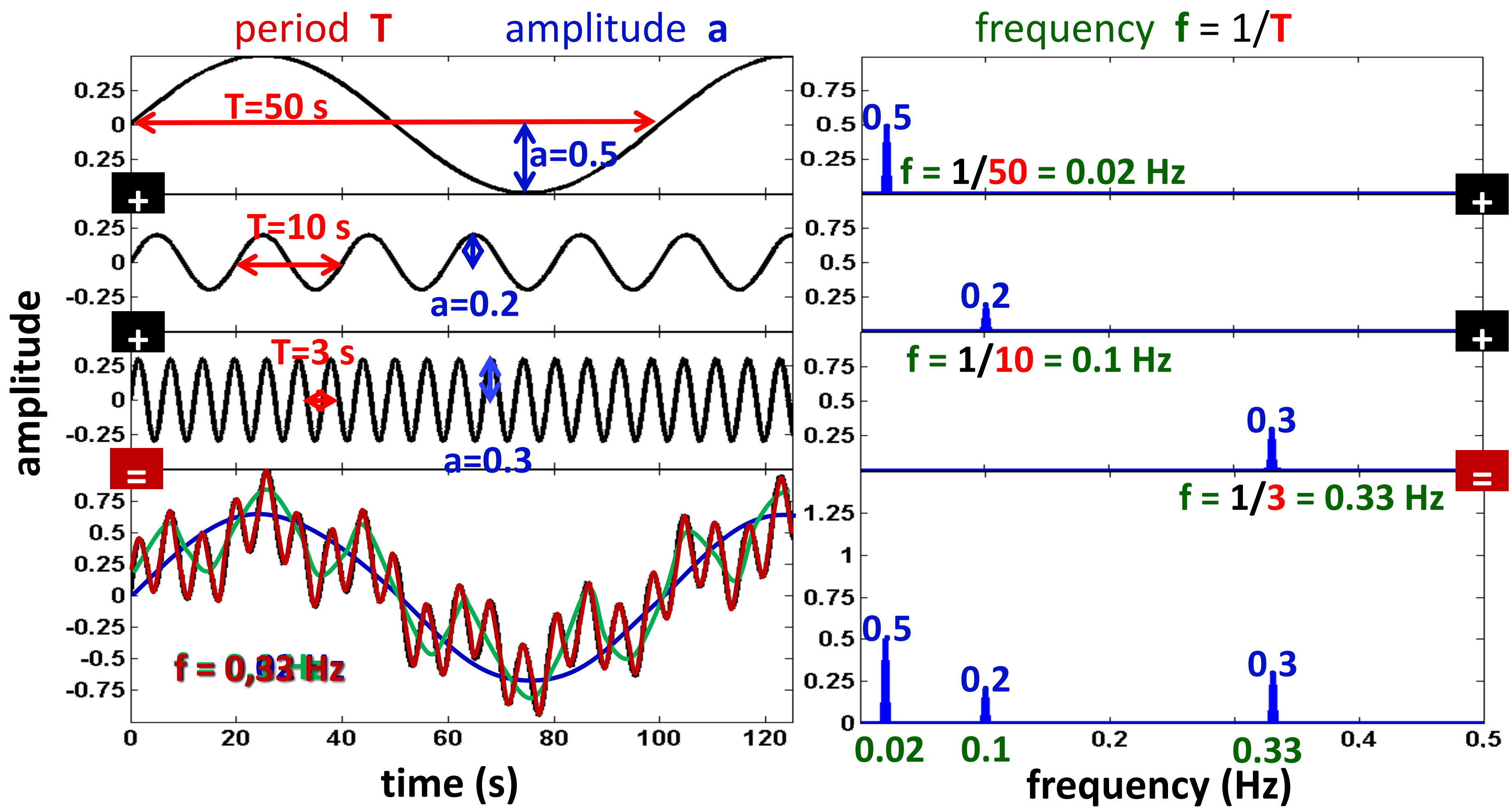




How the spectrum is formed?

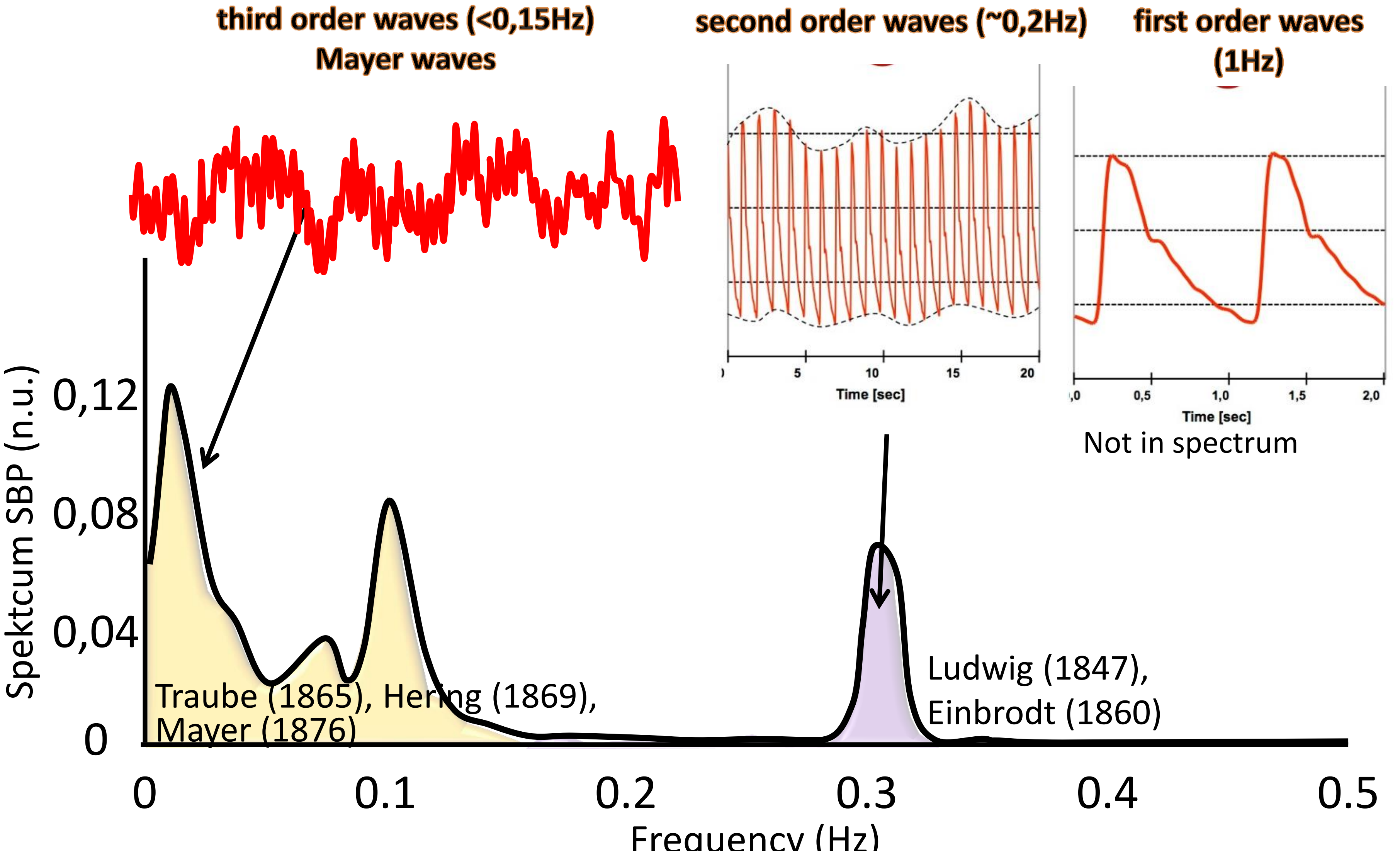
Time domain

Spectrum
Frequency domain



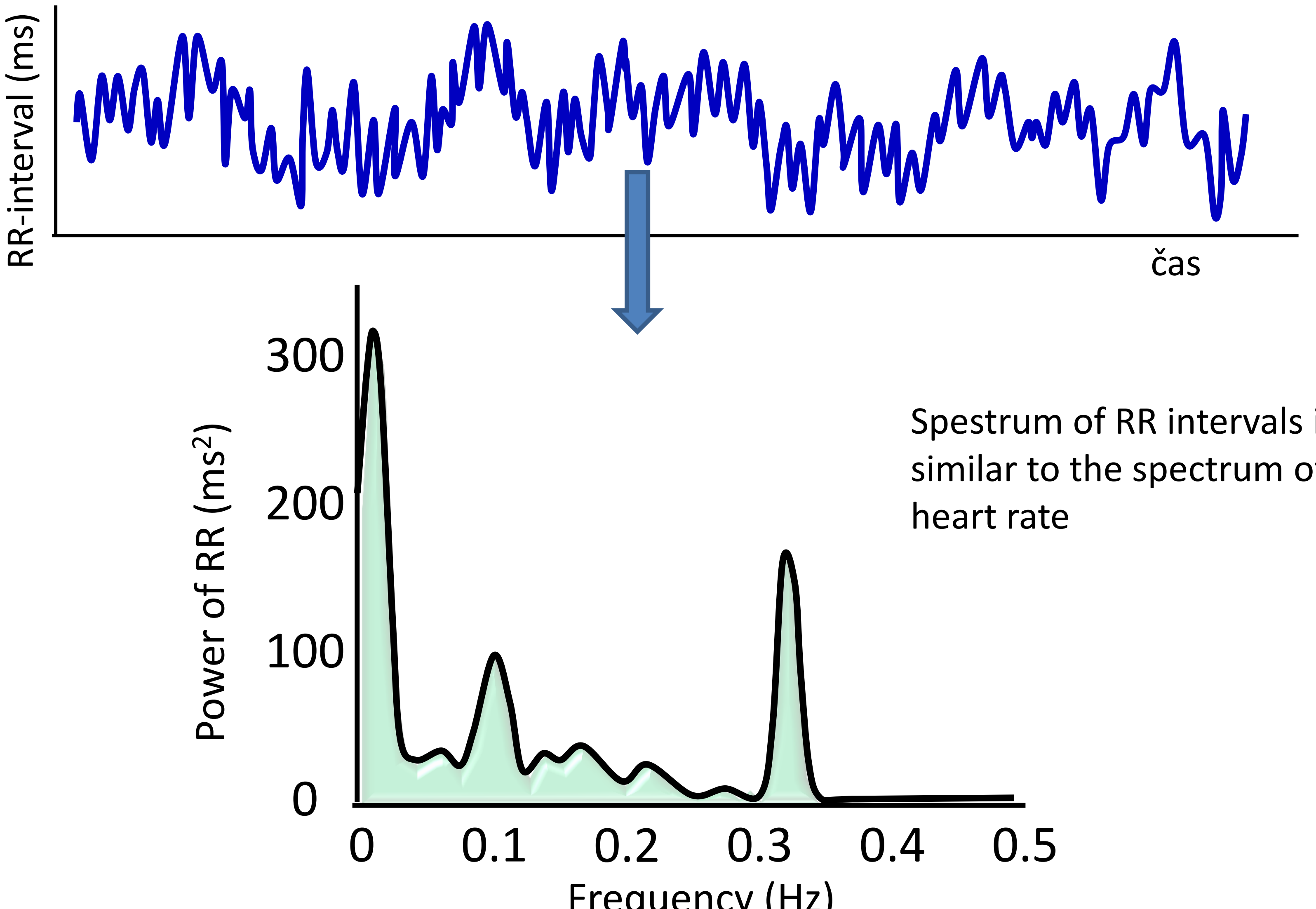
Blood pressure variability – spectrum of SBP

Signal: beat-to beat series of systolic blood pressure (5 minutes)



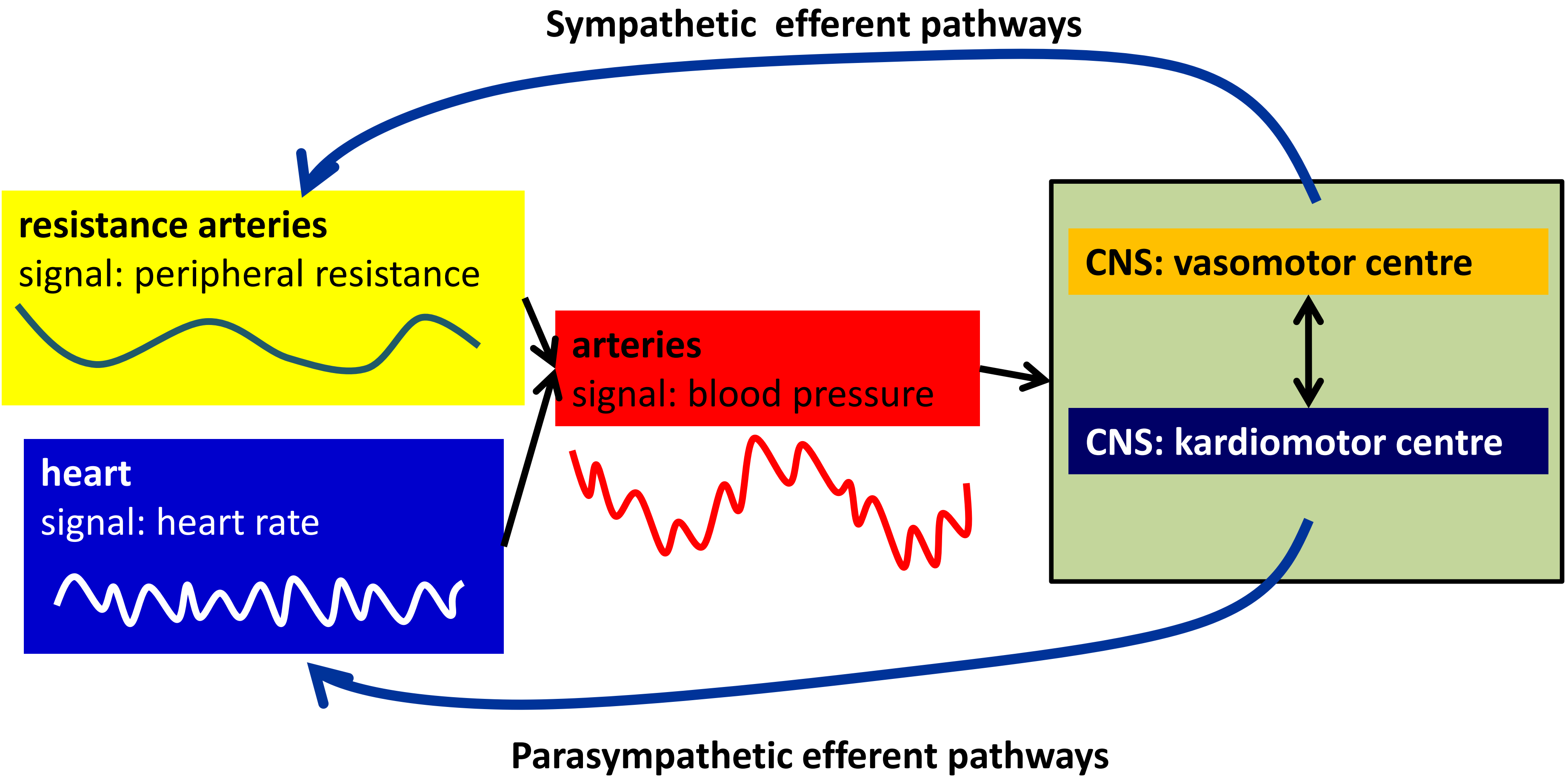
Heart rate variability (HRV)

Signal: beat-to-beat RR-intervals (5 min)



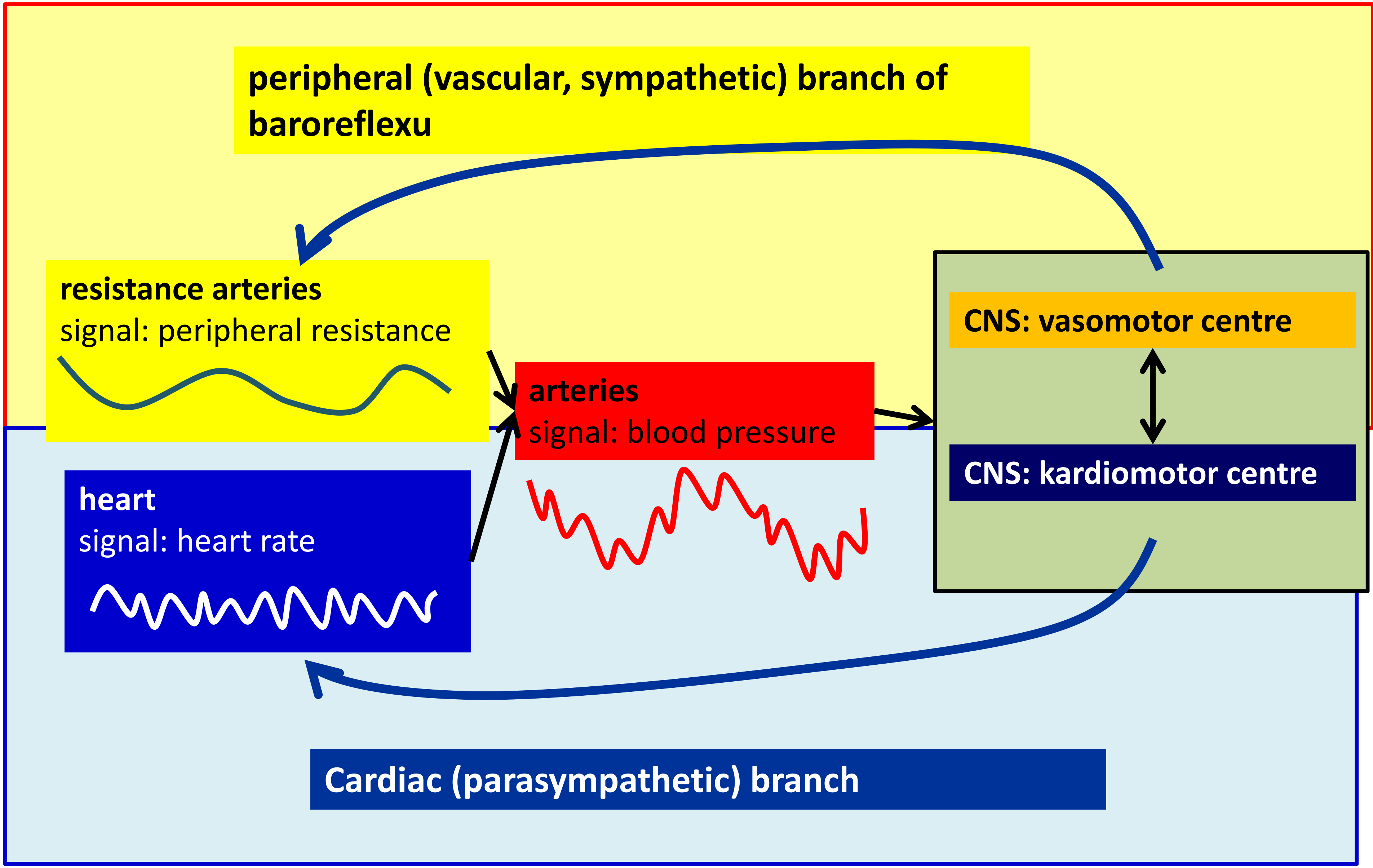
Spestrum of RR intervals is similar to the spectrum of heart rate

Baroreflex

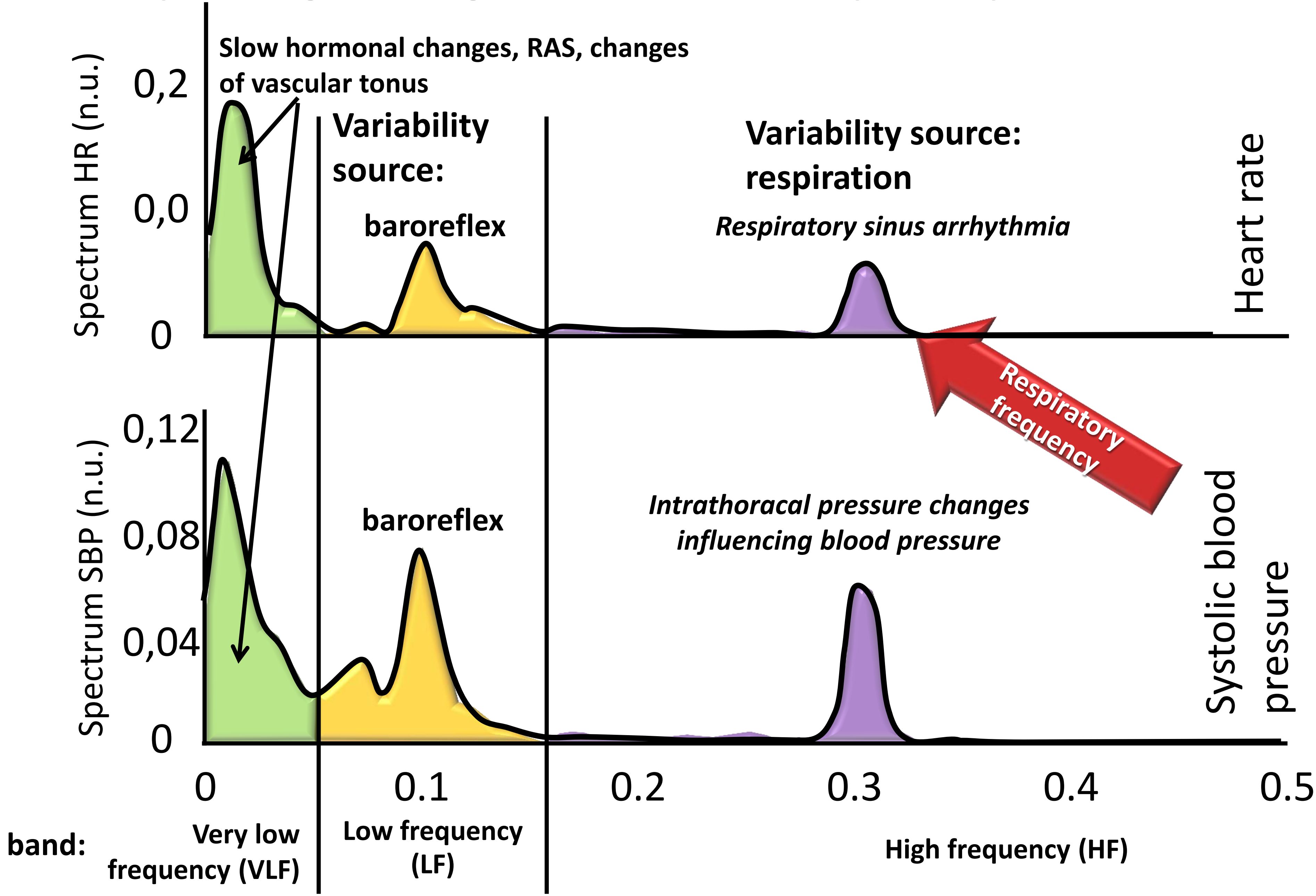


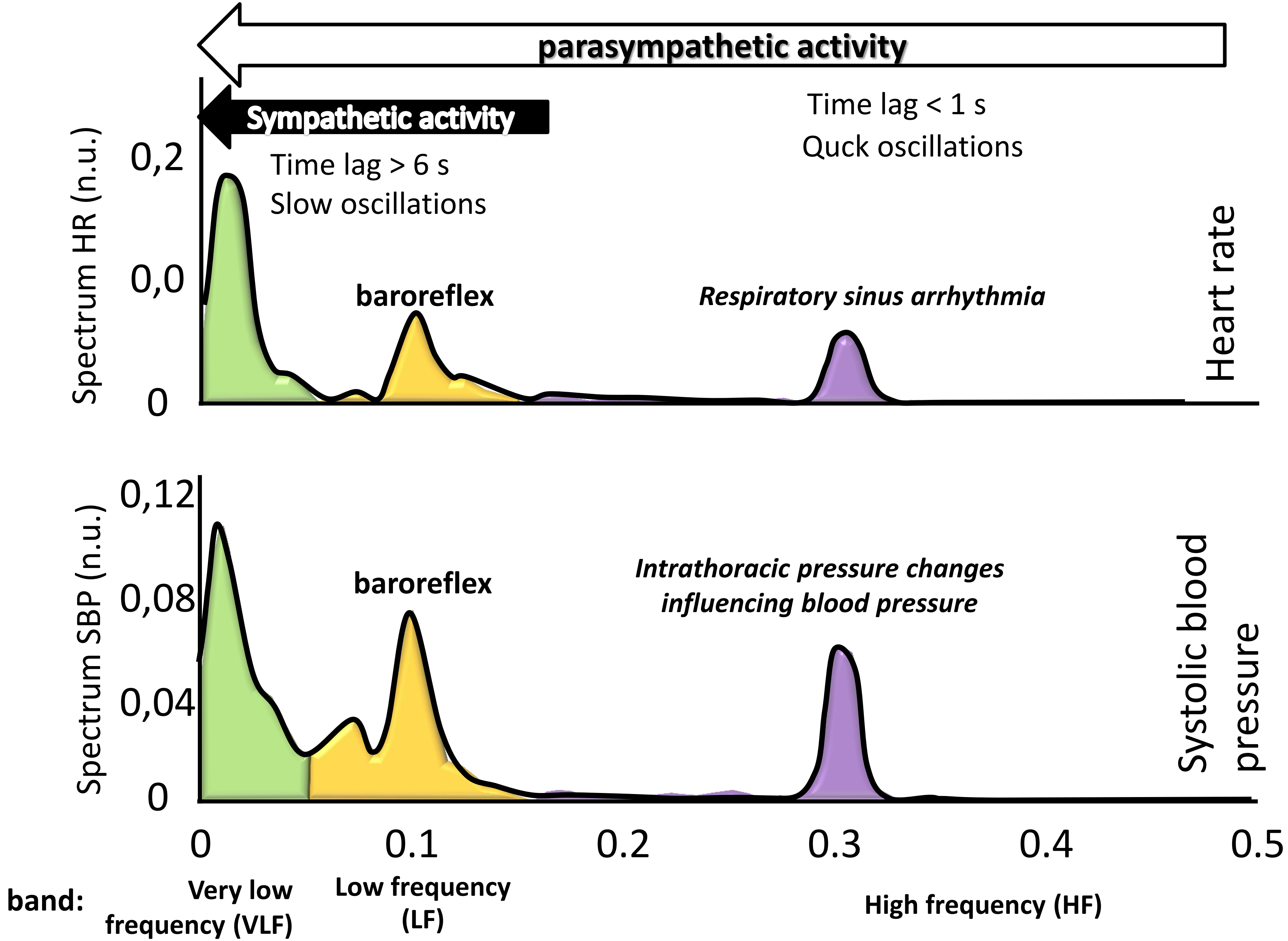
Sympathetic efferent pathways
resistance arteries
signal: peripheral resistance
arteries
signal: blood pressure
CNS: vasomotor centre
CNS: kardiomotor centre
heart
signal: heart rate
Parasympathetic efferent pathways

Baroreflex

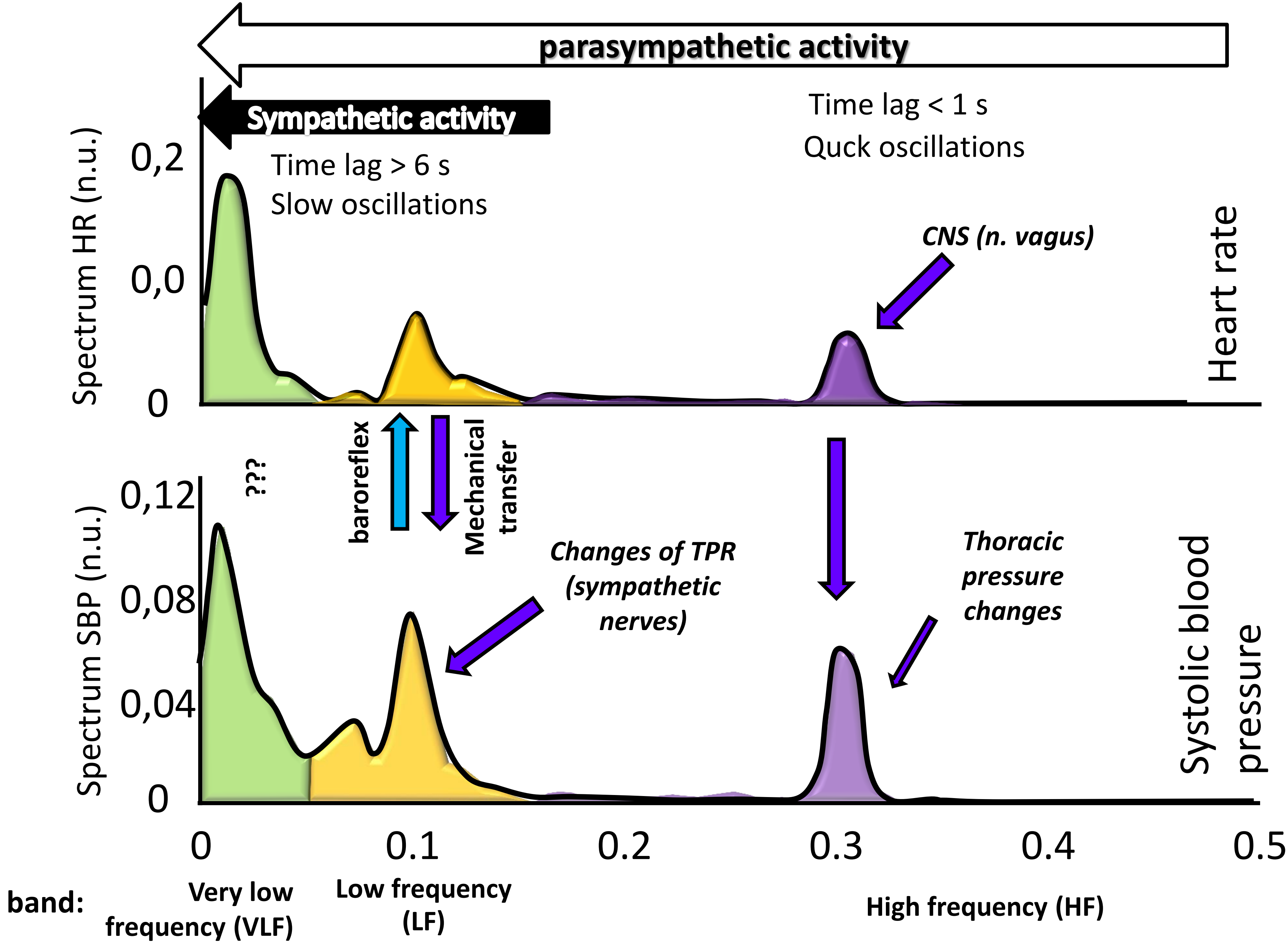

peripheral (vascular, sympathetic) branch of baroreflexu
resistance arteries
signal: peripheral resistance
arteries
signal: blood pressure
CNS: vasomotor centre
CNS: kardiomotor centre
heart
signal: heart rate
Cardiac (parasympathetic) branch

Physiological significance – frequency bands



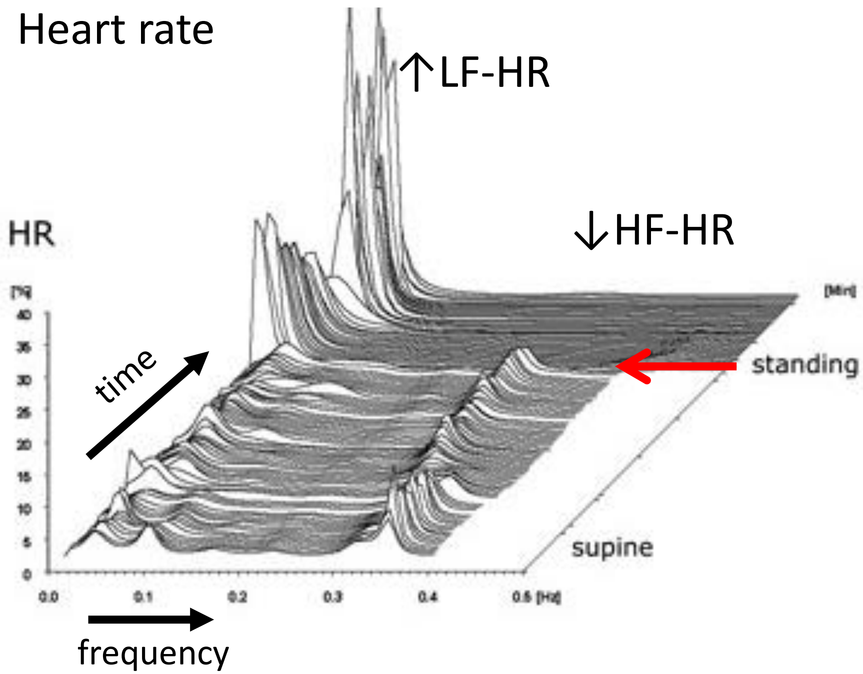


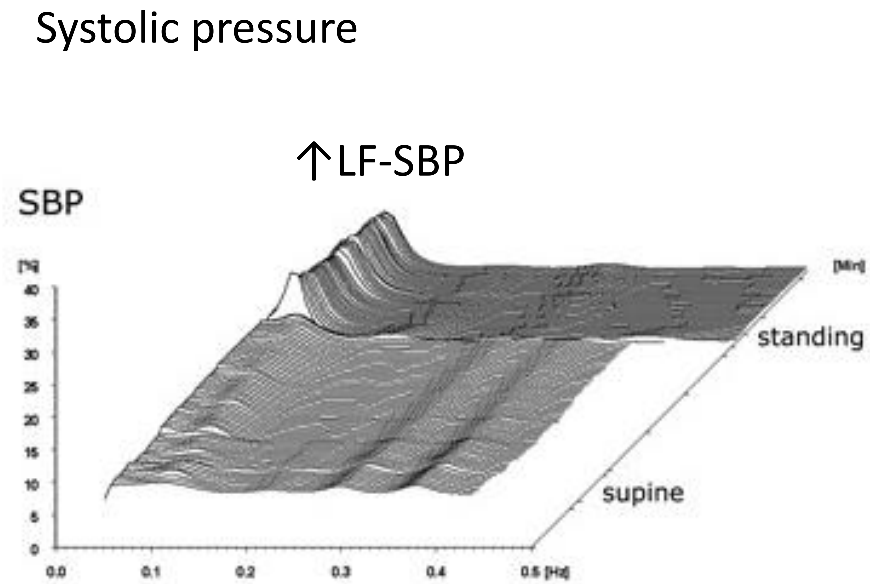
parasympathetic activity
Sympathetic activity
Time lag > 6 s
Slow oscillations
Time lag < 1 s
Quck oscillations
Spectrum HR (n.u.)
0,2
0,0
0
baroreflex
Respiratory sinus arrhythmia
Heart rate
Spectrum SBP (n.u.)
0,12
0,08
0,04
0
baroreflex
Intrathoracic pressure changes
influencing blood pressure
Systolic blood
pressure
0
0.1
0.2
0.3
0.4
0.5
band:
Very low
frequency (VLF)
Low frequency
(LF)
High frequency (HF)


parasympathetic activity
Sympathetic activity
Time lag > 6 s
Slow oscillations
Time lag < 1 s
Quck oscillations
CNS (n. vagus)
Heart rate
Spectrum HR (n.u.)
0,2
0,0
0
baroreflex
Mechanical transfer
???
Spectrum SBP (n.u.)
0,12
0,08
0,04
0
Changes of TPR (sympathetic nerves)
Thoracic pressure changes
Systolic blood pressure
0
0.1
0.2
0.3
0.4
0.5
band:
Very low frequency (VLF)
Low frequency (LF)
High frequency (HF)

Variability changes: orthostatic challenge

Sympatho-vagal ratio LF-HR/HF-HR



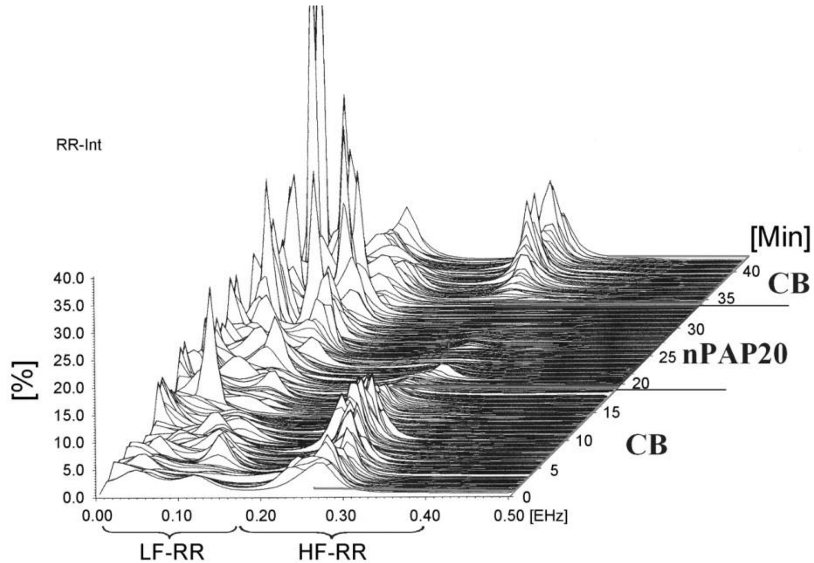


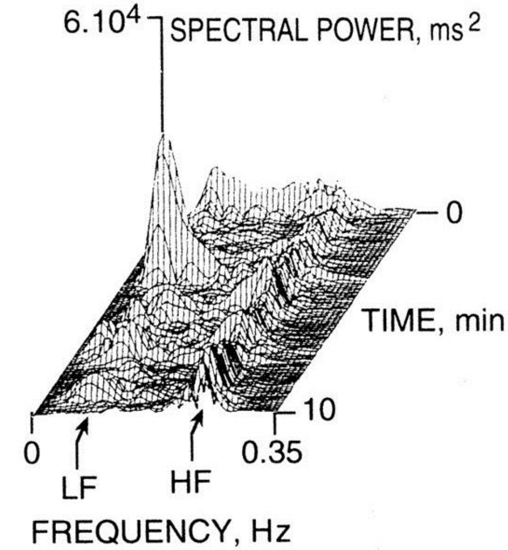
Orthostatic challenge:

- Increase of sympathetic activity → increase of low frequency HR and SBP variability (LF-HR, LF-SBP)
- Decrease of parasympathetic activity → decrease of variability in respiratory frequency (HF-HR)

⟹ **analysis of autonomic nervous system function**

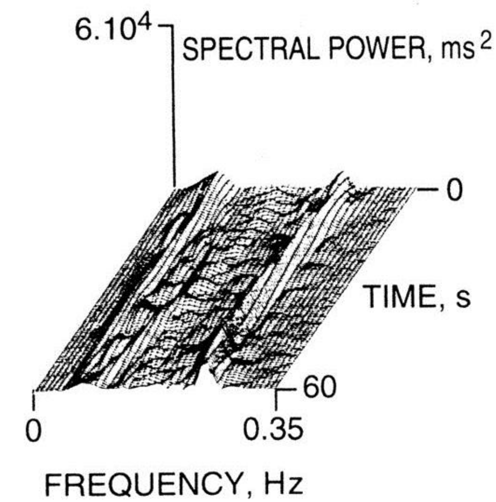
Heart rate variability (HRV) changes



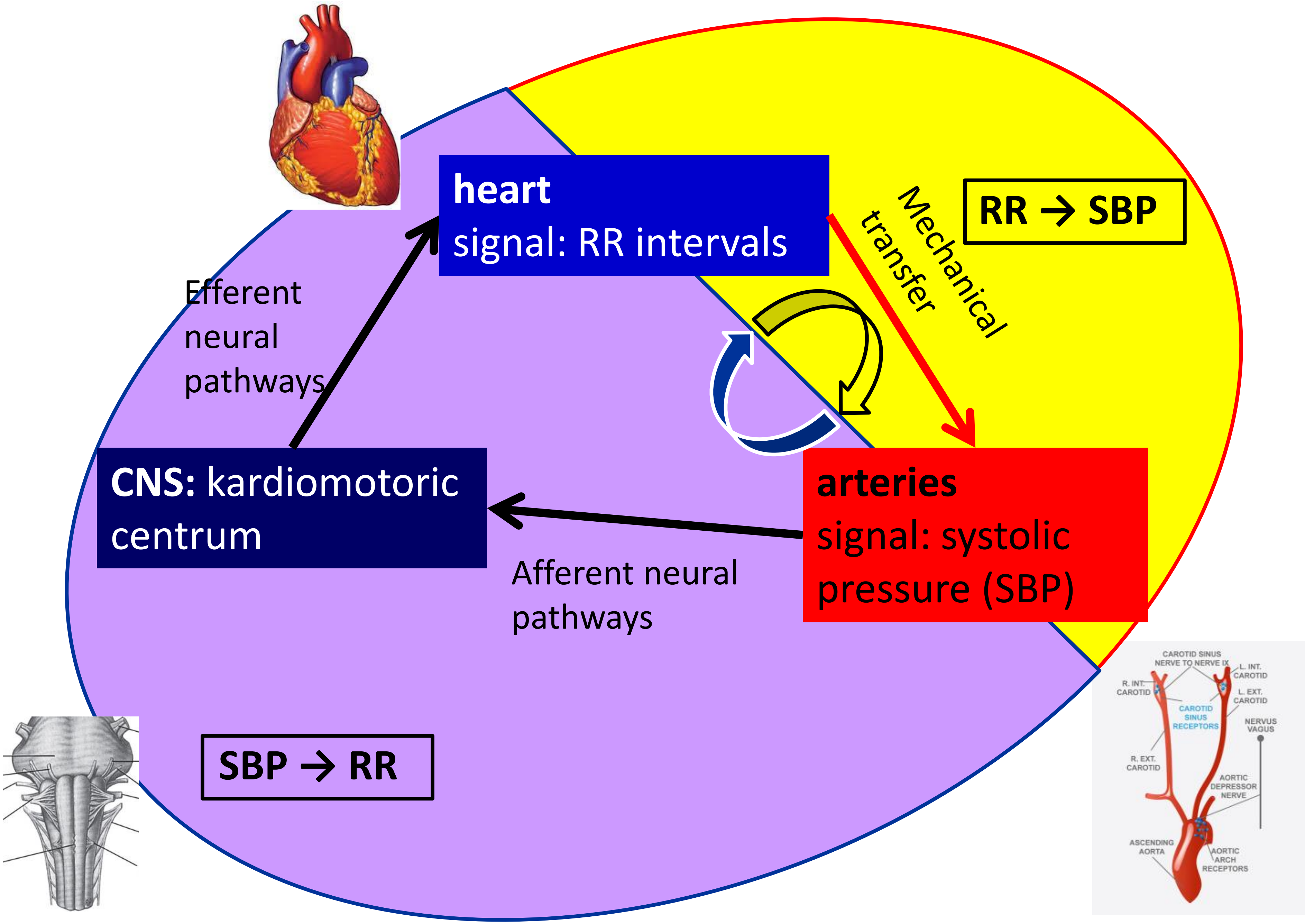


HRV in respiratory frequency decreases in stress situations (↑sympathetic activity)

- Physiologically – sport, mental stress
- Pathologically – diabetes, hear failure
- Transplanted heart
- **Predictor of the cardiovascular risk**

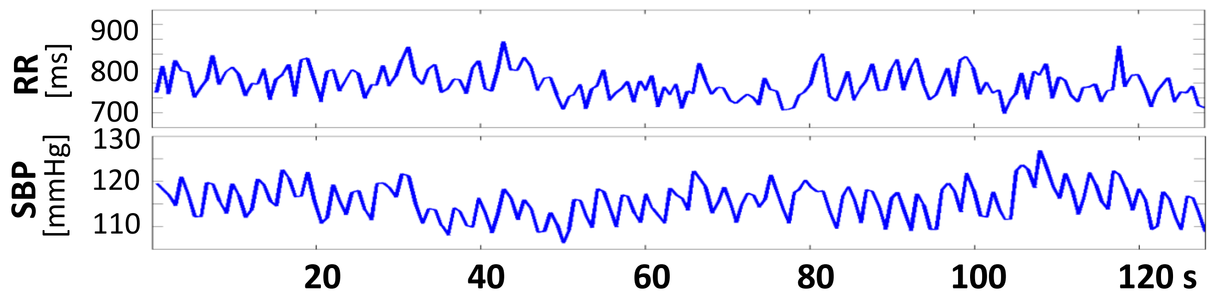


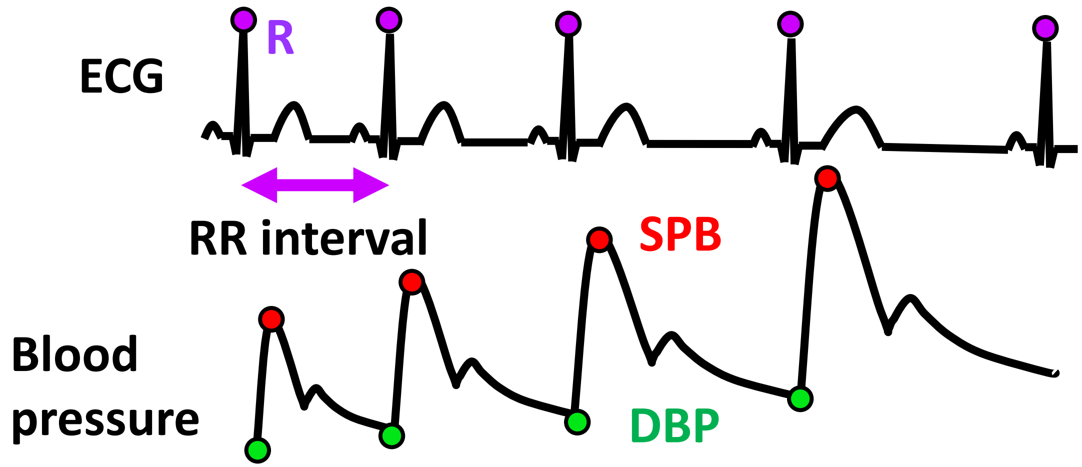
Evaluation of baroreflex function



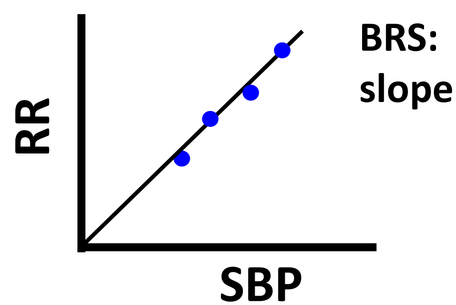
Baroreflex sensitivity (BRS)

Cardiac baroreflex can be evaluted by analysis of SBP- HR interaction





BRS: change of cardiac cycle caused by change of SBP by 1 mmHg [ms/mmHg]



Baroreflex sensitivity

Laboratory methods:

- Phenylephrin application (standard)
- neck suction
- Valsalva manoeuvre

Spontaneous methods:

in time domain: sequence analysis

in spectral domain: cross-spectral analysis, α-index

Bolus injections of vasoactive drugs