Active detection of sound in the inner ear

QuickTime™ and a
PNG decompressor
are needed to see this pict

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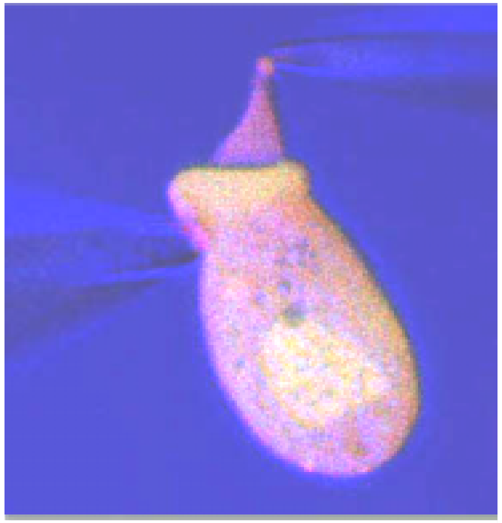
Performance of human ear

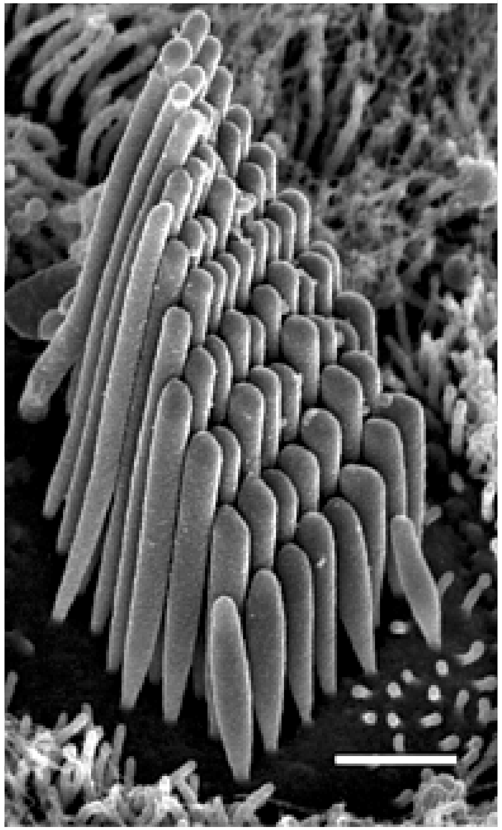
Frequency analysis:	responds selectively to frequencies in range 20–10,000 Hz
Sensitivity:	faintest audible sounds impart no more energy than thermal noise: 4 zJ
Dynamic range:	responds and adapts over 7 orders of magnitude of pressure: 0–140 dB

Detection apparatus

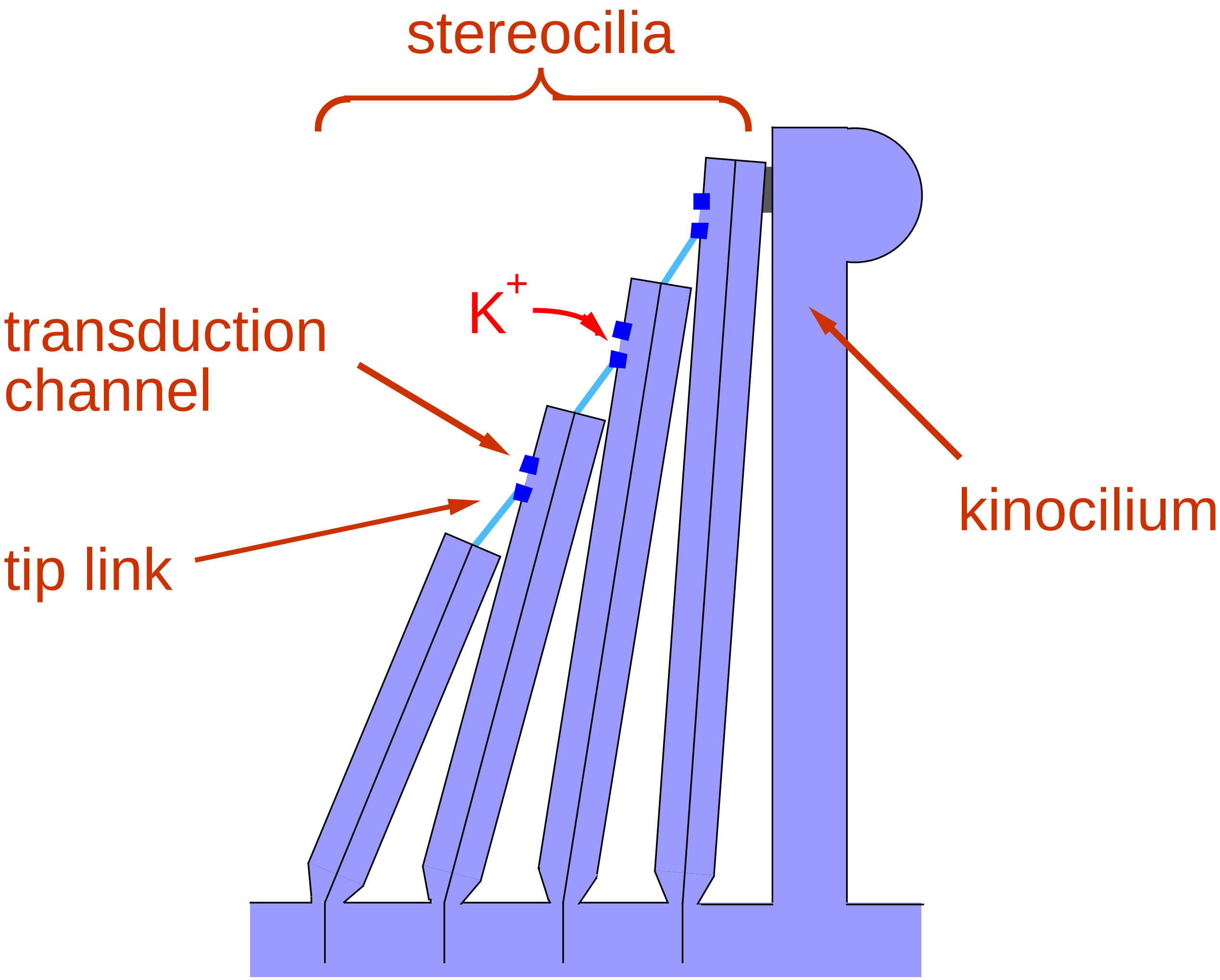
sources: Hudspeth, Hackney



hair cell *(frog)*



hair bundle *(turtle)*

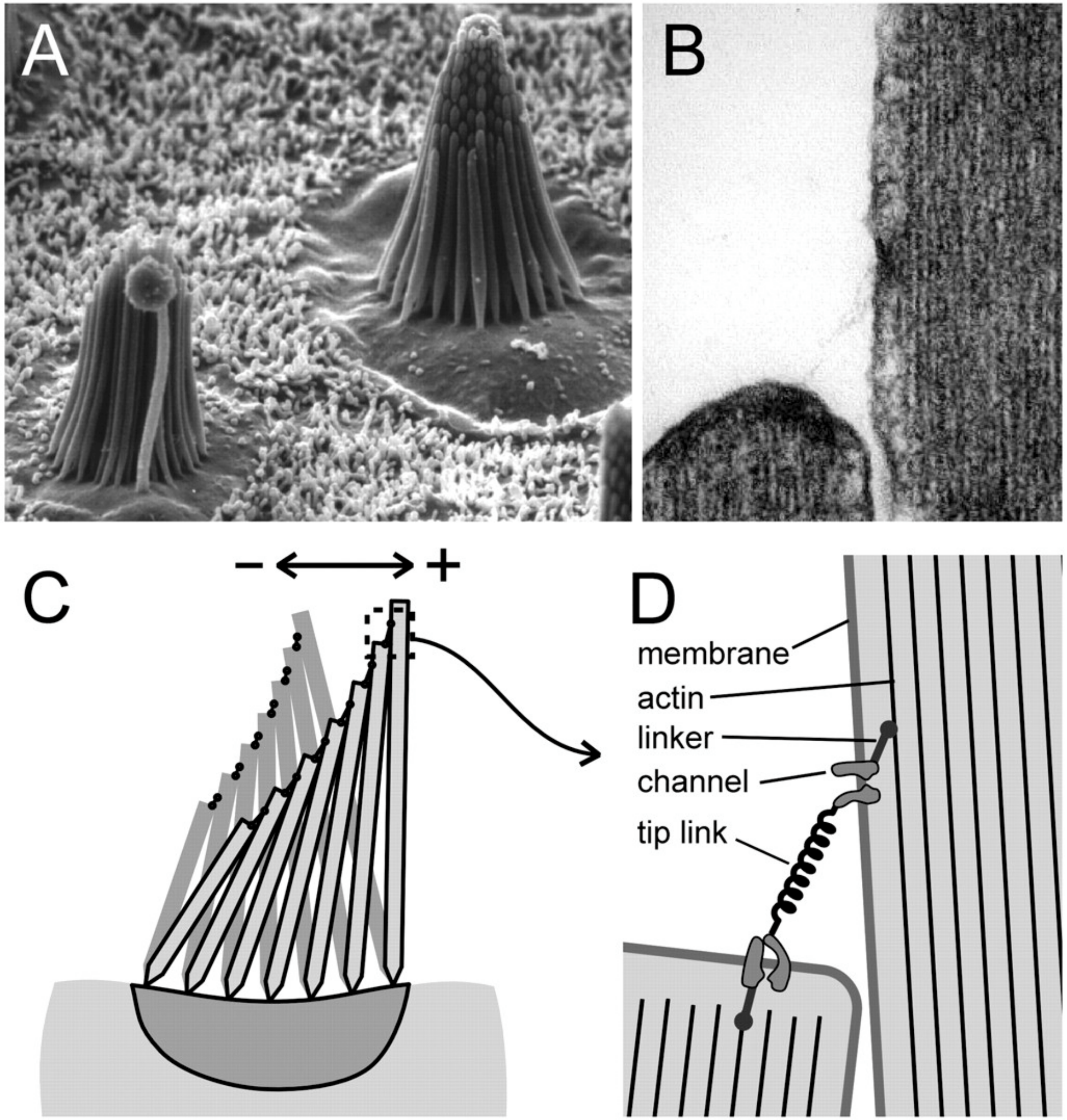


Mechano-chemo-electrical transduction

sources: Corey, Hudspeth

Tension in tip links
pulls open
transduction channels
& admits K^+

which depolarizes the
membrane & opens
voltage-gated channels
to nerve synapse



Spontaneous oscillations in the inner ear

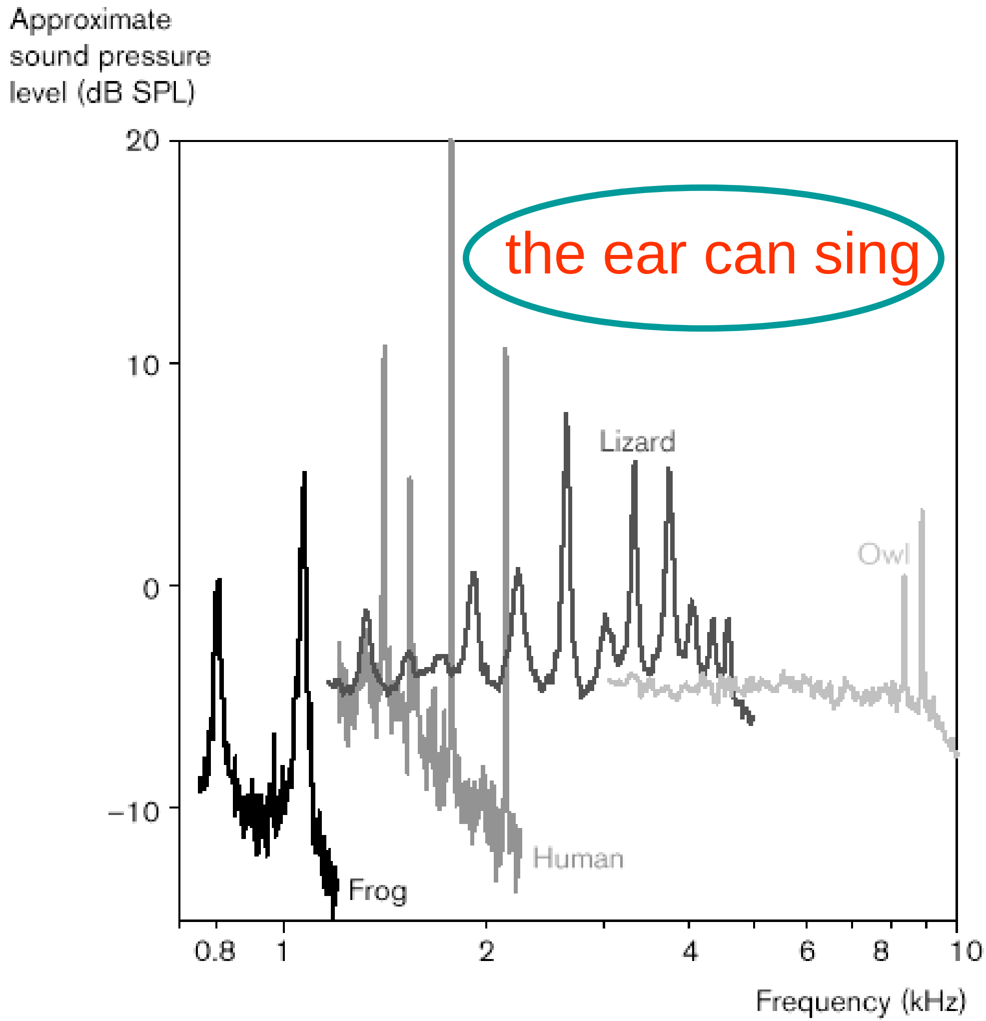
Kemp ‘79

Manley & Koppl ‘98

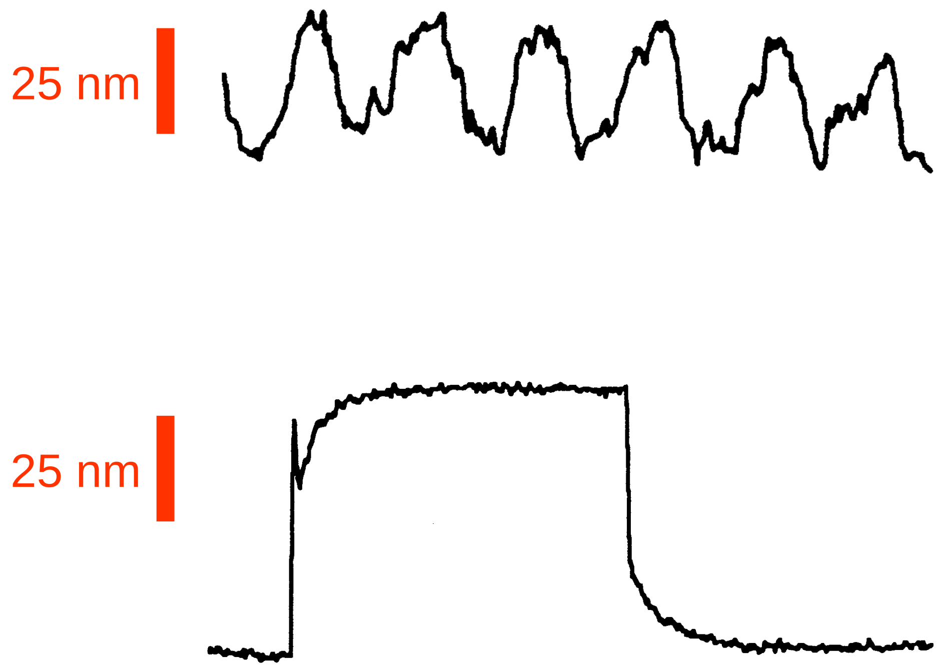
Crawford & Fettiplace ‘86

Howard & Hudspeth ‘87

- Otoacoustic emissions



- Active bundle movements

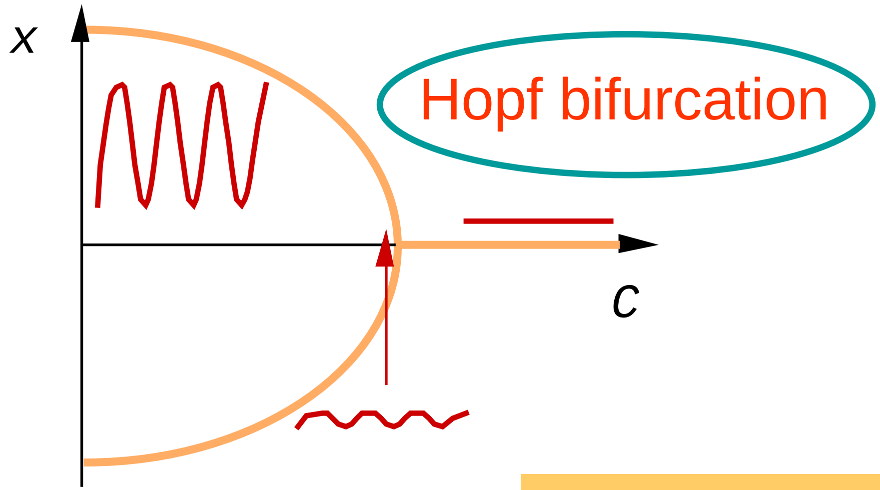


Self-tuned critical oscillators

Camalet, Duke, Jülicher & Prost '00

Active amplifiers: Ear contains a set of nonlinear dynamical systems each of which can generate self-sustained oscillations at a different characteristic frequency

Self-adjustment: Feedback control mechanism maintains each system on the verge of oscillating



→ remarkable response properties at critical point

Hopf resonance

force: $F(t) = \sum_{n=-\infty}^{\infty} F_n e^{in2\pi ft}$

displacement: $x(t) = \sum_{n=-\infty}^{\infty} x_n e^{in2\pi ft}$

$$F_1 \simeq \mathcal{A} x_1 + \mathcal{B}|x_1|^2 x_1 + \ldots$$

control parameter: C

bifurcation point: $\mathcal{A}(f_c, C_c) = 0$

- stimulus at characteristic frequency:

$$|x_1| \simeq \frac{|F_1|^{1/3}}{|\mathcal{B}|^{1/3}}$$

gain diverges
for weak stimuli

Hopf resonance

force: $F(t) = \sum_{n=-\infty}^{\infty} F_n e^{in2\pi ft}$

displacement: $x(t) = \sum_{n=-\infty}^{\infty} x_n e^{in2\pi ft}$

$$F_1 \simeq \mathcal{A} x_1 + \mathcal{B}|x_1|^2 x_1 + \ldots$$

control parameter: C

bifurcation point: $\mathcal{A}(f_c, C_c) = 0$

- stimulus at different frequency: $\mathcal{A}(f, C_c) = \alpha(f - f_c) + \ldots$

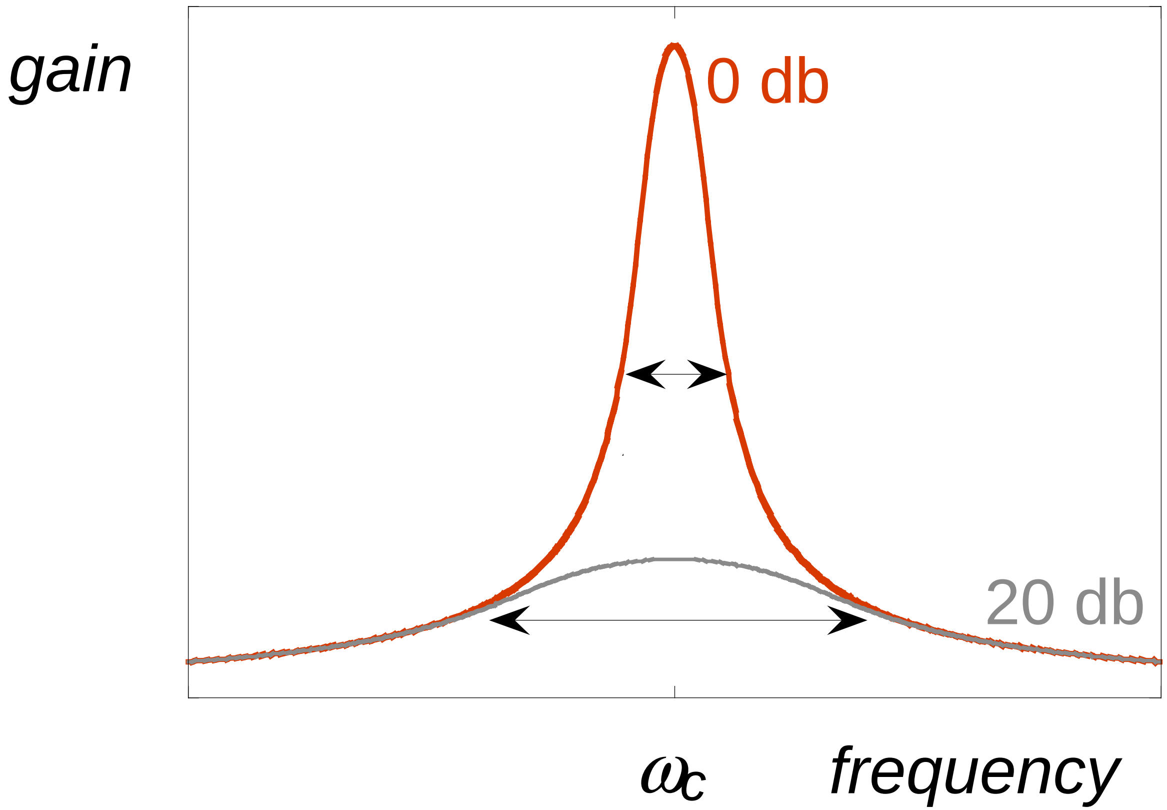
→ if $|f - f_c| \ll$ $\Delta f_a \equiv \frac{|\mathcal{B}|^{1/3}}{|\alpha|} |F_1|^{2/3}$

$$|x_1| \simeq \frac{|F_1|}{|(f - f_c)\alpha|}$$

active bandwidth

critical Hopf resonance
single tone response

Gain and active bandwidth depend on level of stimulus



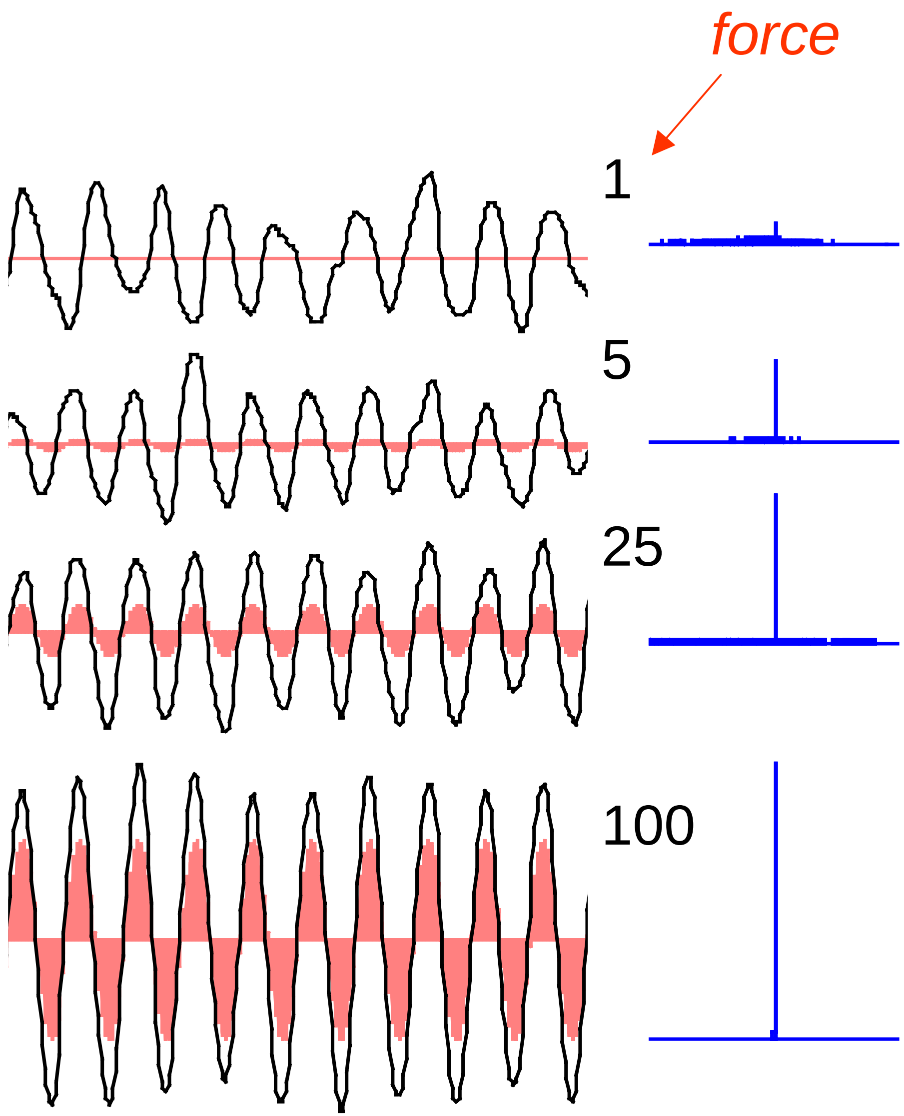
critical Hopf response
effect of noise

Camalet et al. '00

Response to a tone

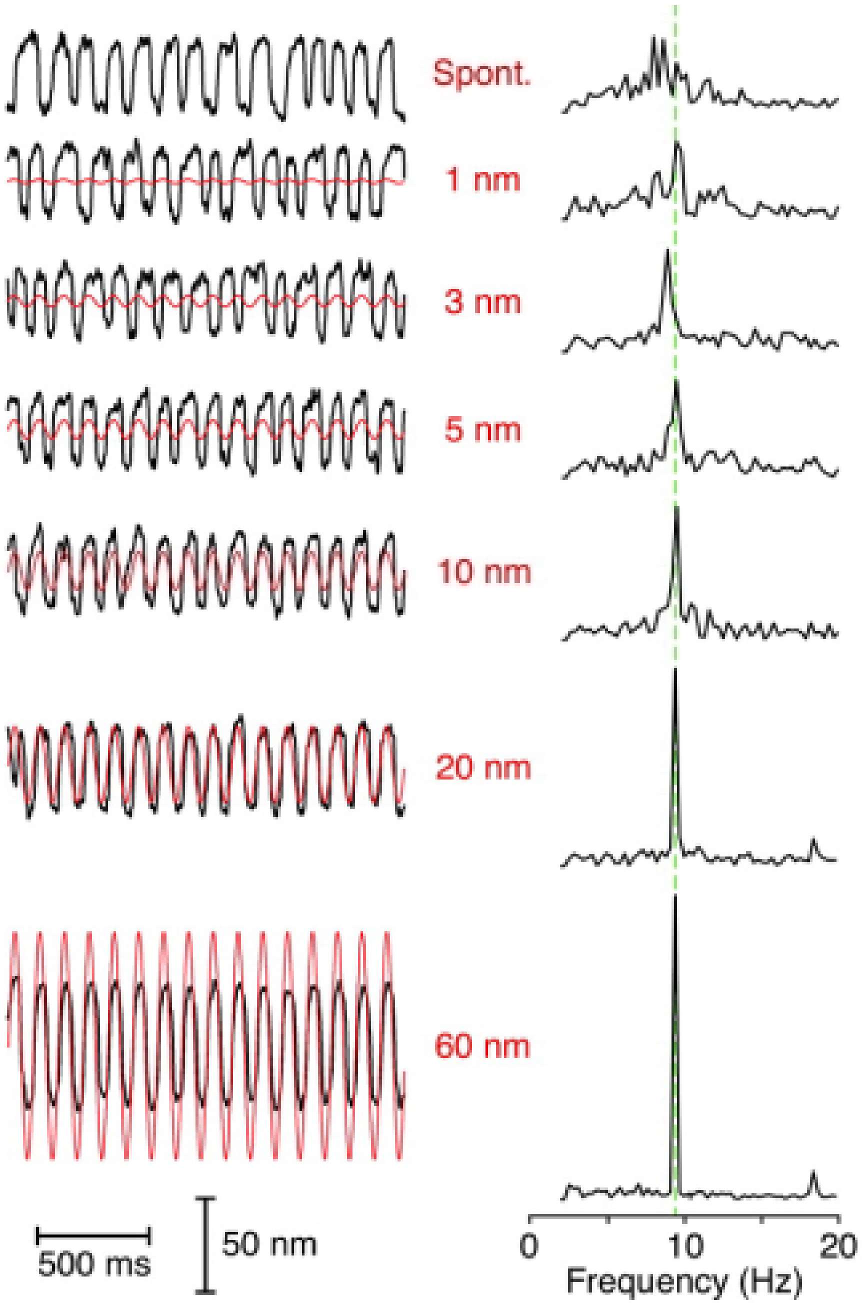
- spontaneous critical oscillations are incoherent

- stimulus at characteristic frequency gives rise to phase-locking



Hair bundle response

Martin & Hudspeth '01



Response of a frog hair bundle forced by a microneedle

Questions

- What is the physical basis of the force-generating dynamical system ?
- How is the self-tuning realised ?

We might expect that different organisms use different apparatus to implement the same general strategy

→ Model for *non-mammalian vertebrates*

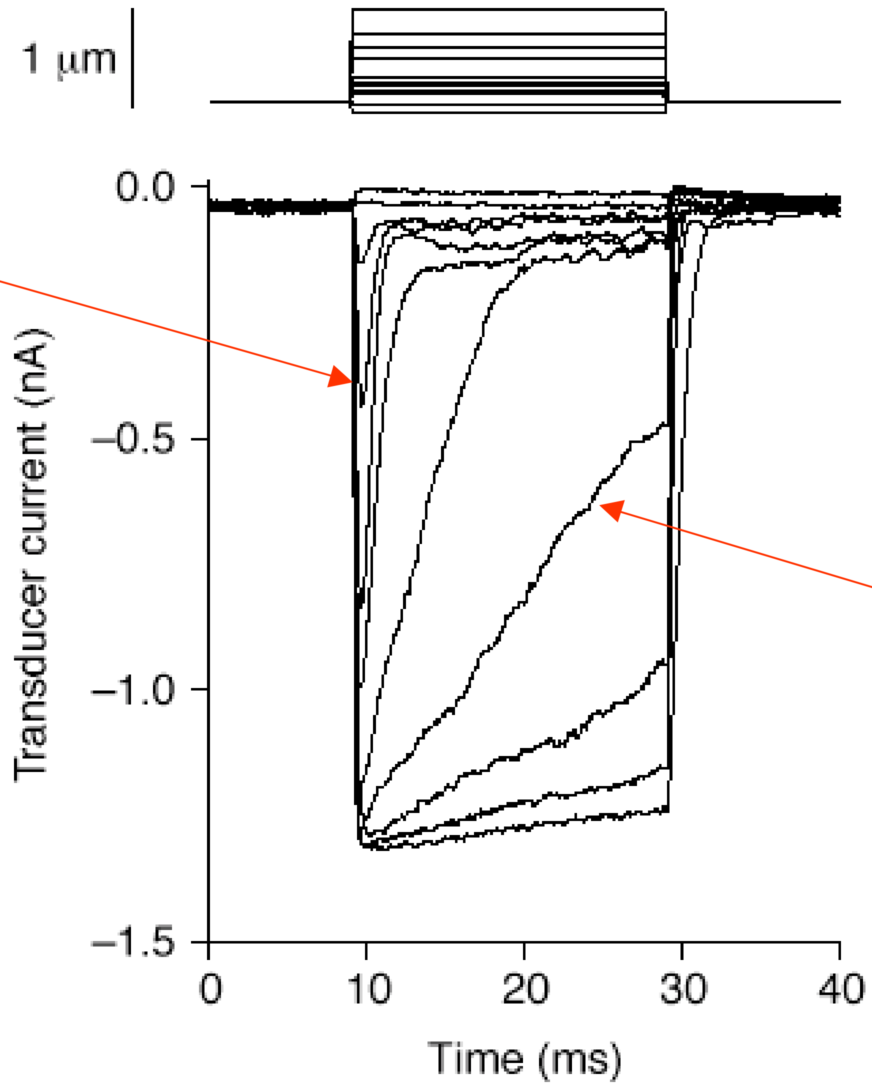
Two adaptation mechanisms

Fettiplace et al. '01

Fast process

Ca^{2+} binding to transduction channel

~ 1 ms



Slow process

movement of myosin-1C motors

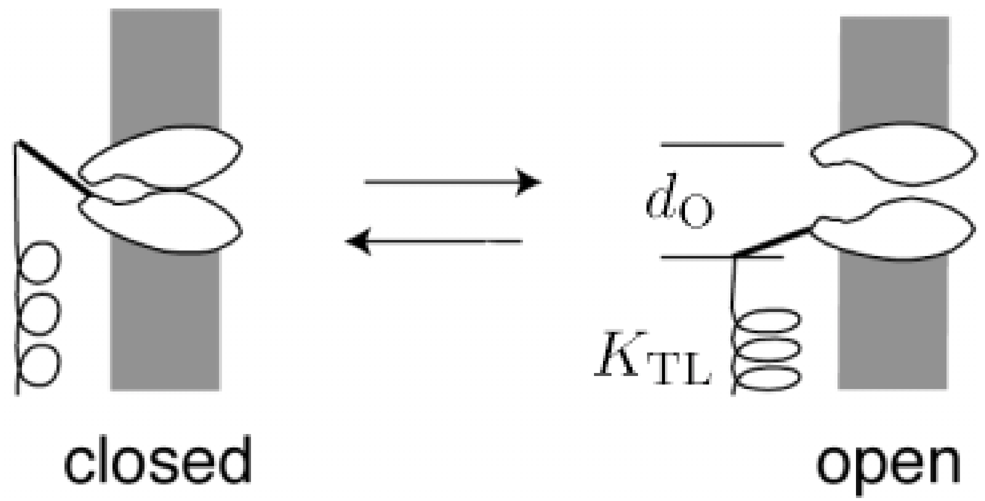
~ 100 ms

Channel gating compliance

Howard & Hudspeth '88; Martin, Mehta & Hudspeth '00

Suppose channel incorporates a lever arm

→ opening of channel can substantially reduce the tension in the tip link



- negative elasticity if $K_{\mathrm{TL}} d_{\mathrm{O}}^2 > 4 k_B T$ $\quad K_{\mathrm{TL}} \approx 0.5\,\mathrm{pN/nm}$

Physical basis of self-tuned critical oscillators

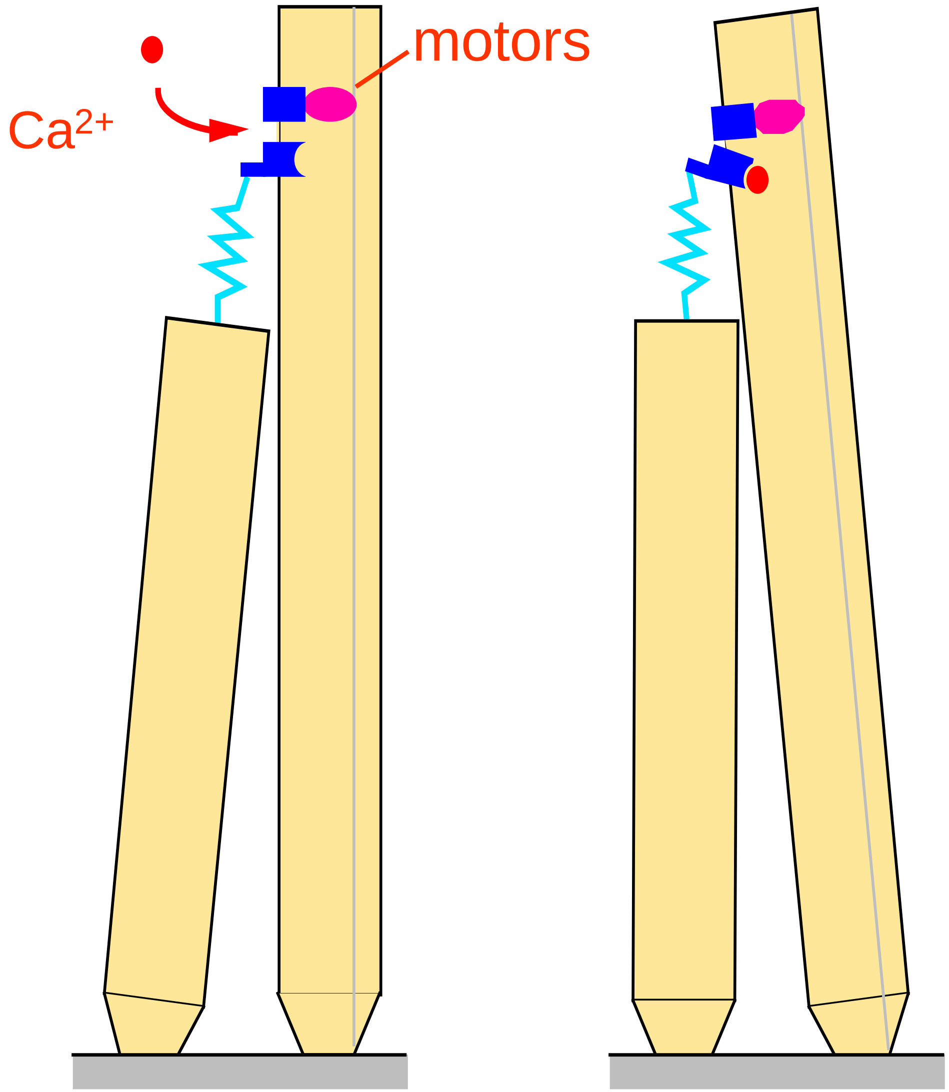
Vilfan & Duke

- Oscillations generated by interaction of Ca^{2+} with transduction channels

frequency $$\omega_c \approx \sqrt{\frac{1}{\tau_{mech}\tau_{ca}}}$$

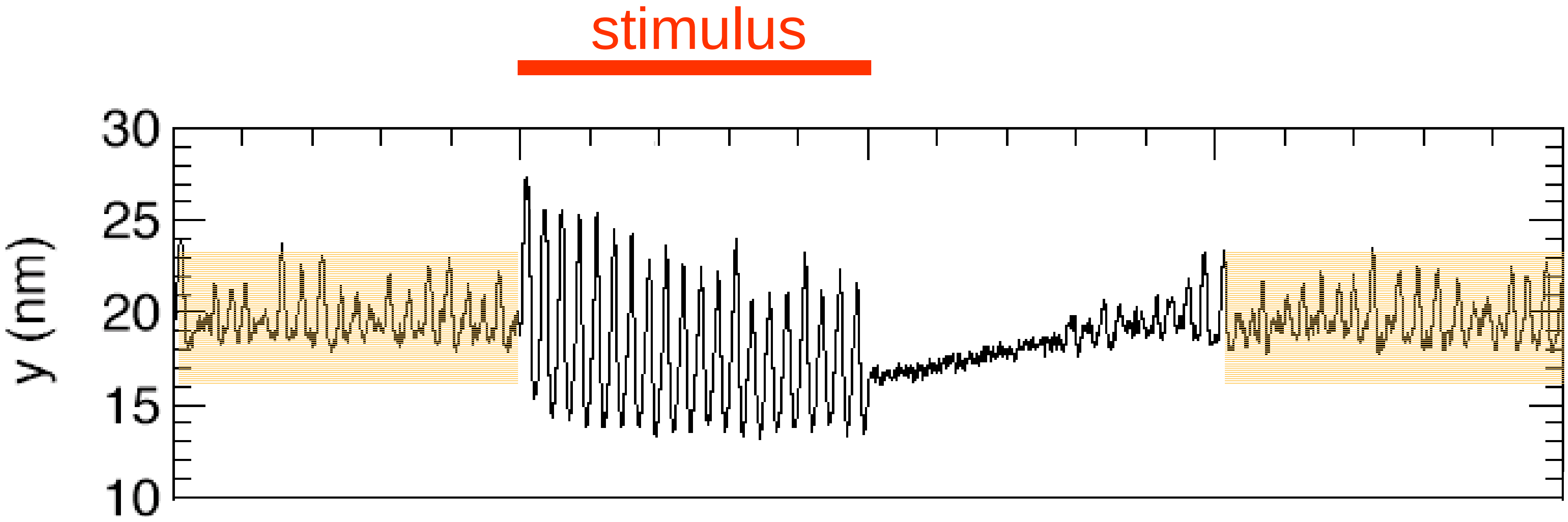
depends on bundle geometry

- Self-tuning accomplished by movement of molecular motors, regulated by Ca^{2+}



hair bundle model

self-tuned critical oscillations



Nonlinearities due to active amplification

Self-tuned Hopf bifurcation is ideal for detecting a single tone …

… but it causes tones of different frequency to interfere

Response to two tones:

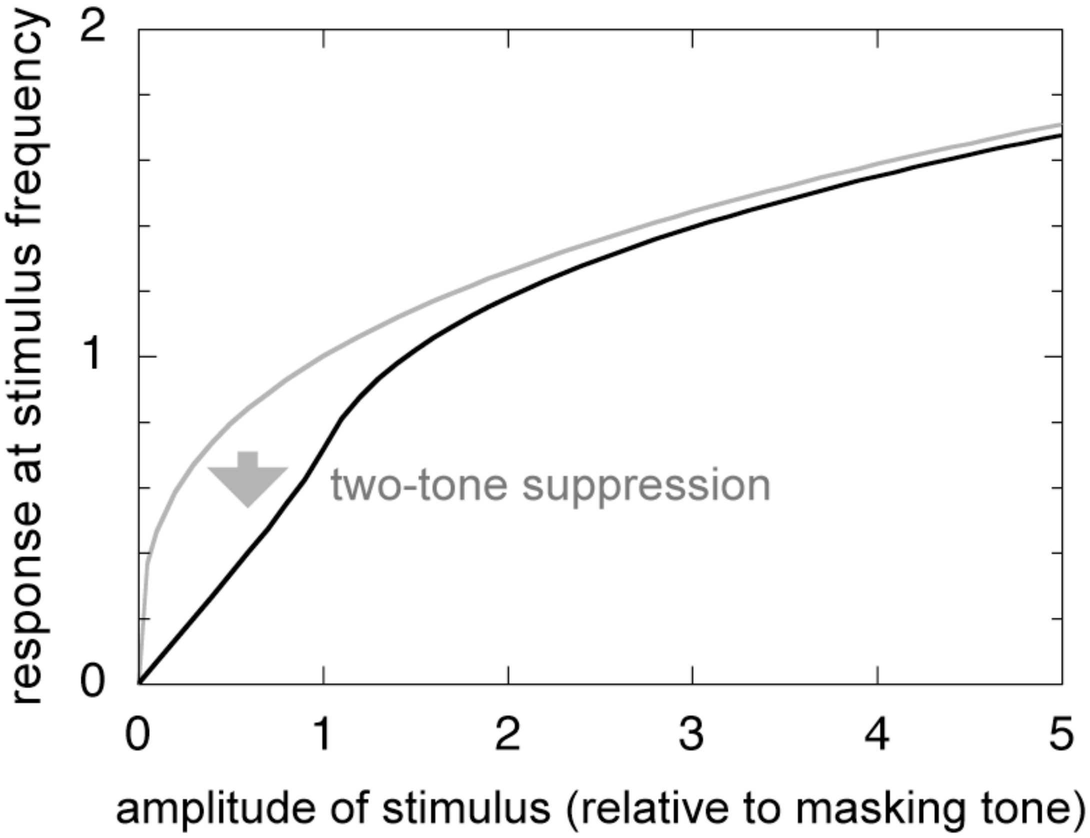
$$F_{f_k} = \mathcal{A}(f_k) X_{f_k} + \sum_{mn} \mathcal{B}(f_k, f_m, f_n) X_{f_k - f_m - f_n} X_{f_m} X_{f_n} + \ldots$$

Two-tone suppression

Presence of second tone can extinguish the nonlinear amplification

$$F_{f_1} = A(f_1)X_{f_1} + B(f_1)|X_{f_1}|^2 X_{f_1} + \bar{B}(f_1, f_2)|X_{f_2}|^2 X_{f_1}$$

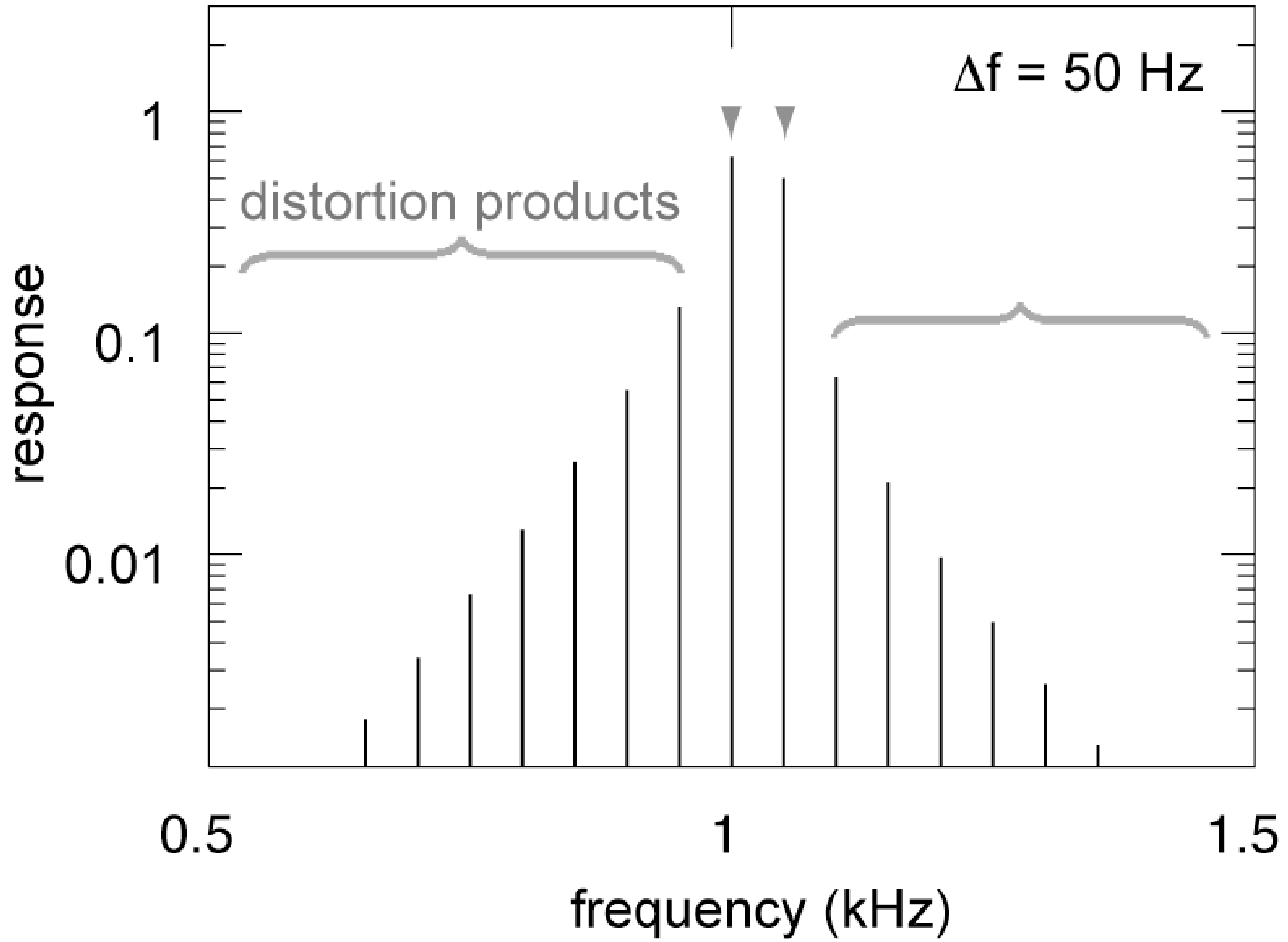
$A(f_1)$ = 0; $\bar{B}(f_1, f_2)$ 0



Distortion products

Julicher, Andor & Duke '01

Nonlinearities create a characteristic spectrum of distortion products



Responses at f_1 and f_2 couple to frequency $2f_1 - f_2$

$$0 = A\, X_{2f_1-f_2} + B\, |X_{2f_1-f_2}|^2 X_{2f_1-f_2} + C\, X_{f_1}^2 X_{f_2}^*$$

... which in turn excites a hierarchy of further distortion products:

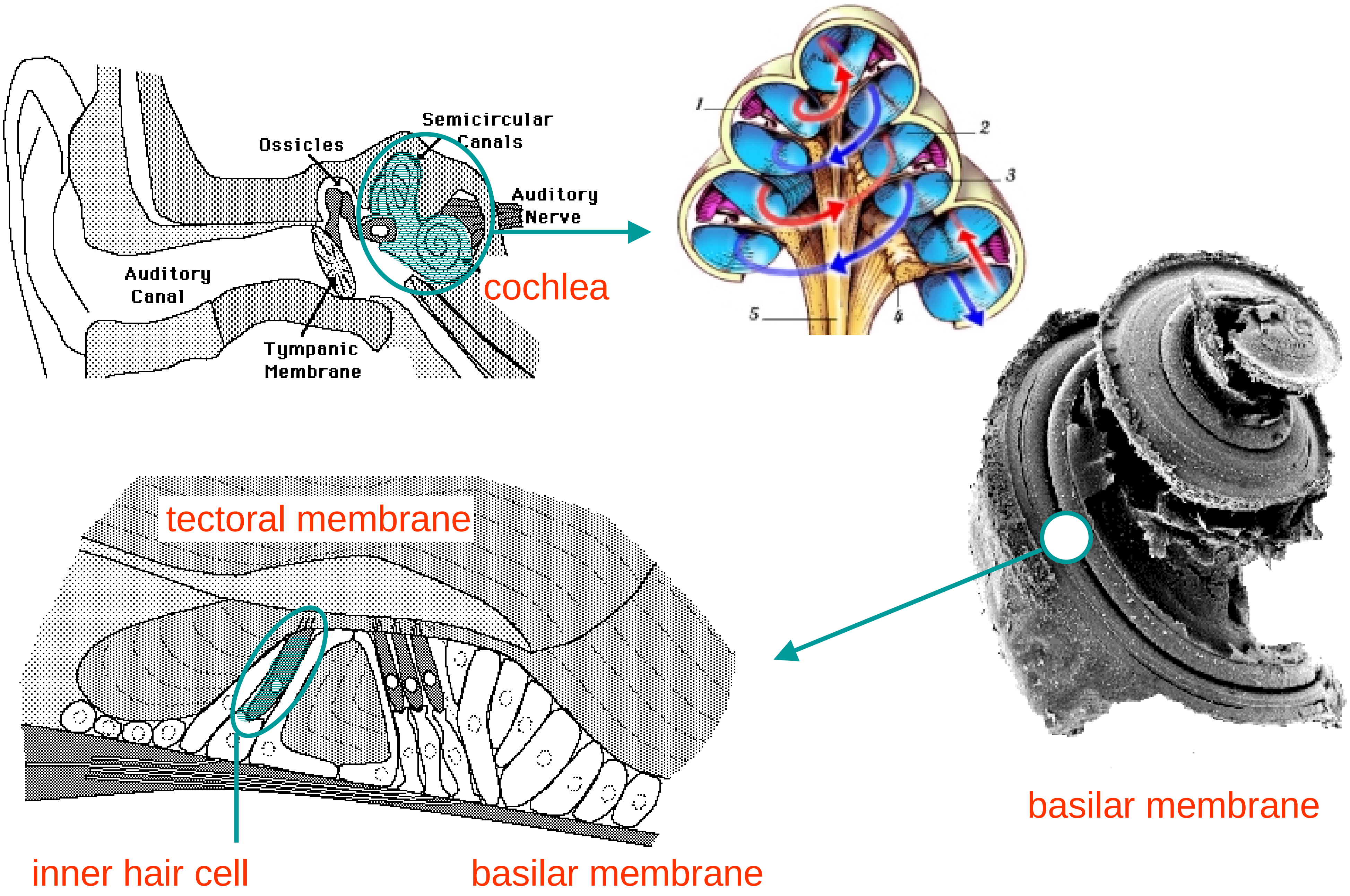
$$f_k = f_1 + (k-1)\,\Delta f$$

Spectrum:

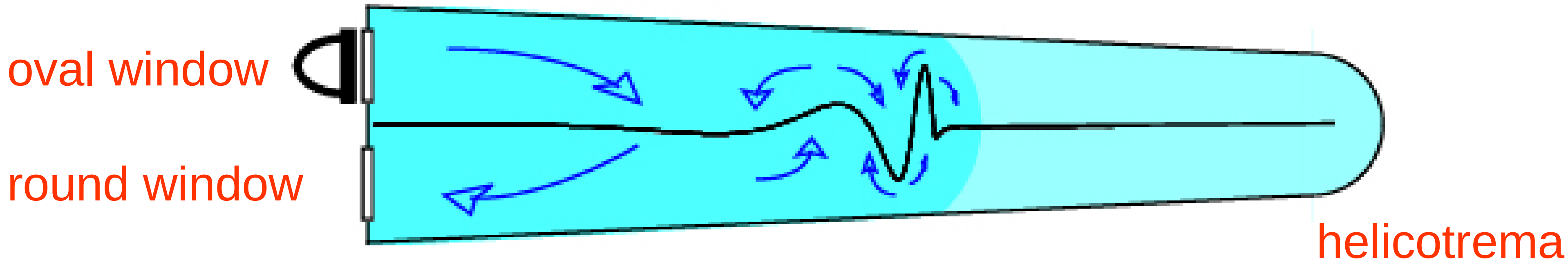
$$|X_{f_k}| \sim \left(\frac{\Delta f}{\Delta f_a}\right)^{-|k-\frac{3}{2}|} , \qquad \Delta f \gg \Delta f_a$$

$$|X_{f_k}| \sim \left|k - \frac{3}{2}\right|^{-4/3} , \qquad \Delta f \ll \Delta f_a$$

Mammalian cochlea



Cochlear travelling wave

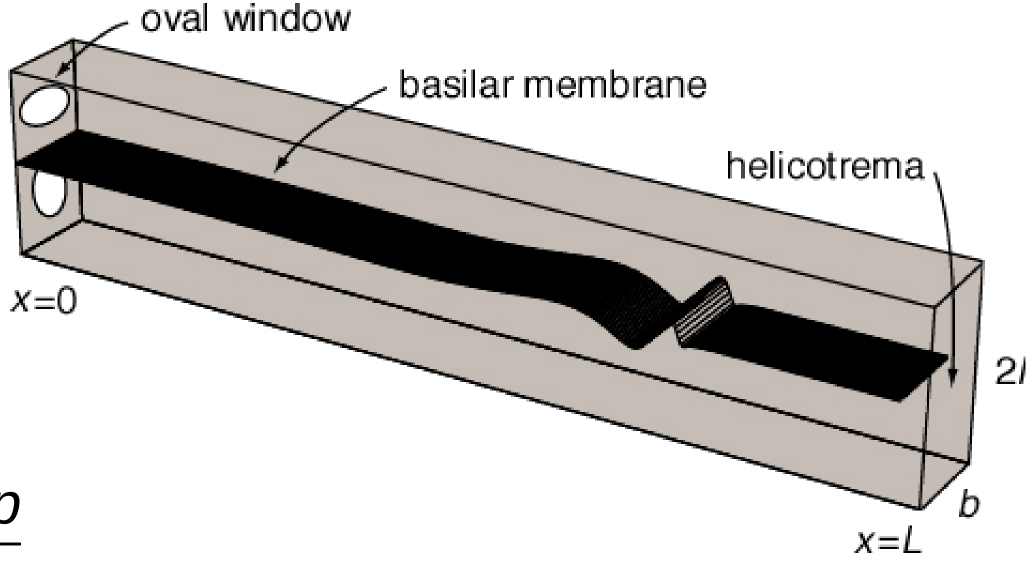


- sound sets fluid into motion
- variation in flow rate is accommodated by movement of membrane
- membrane acceleration is caused by difference in fluid pressure

travelling wave
one-dimensional model

Zwislocki '48

membrane displacement	h
pressure difference	$p = P_1 - P_2$
difference in flows	$j = J_1 - J_2$



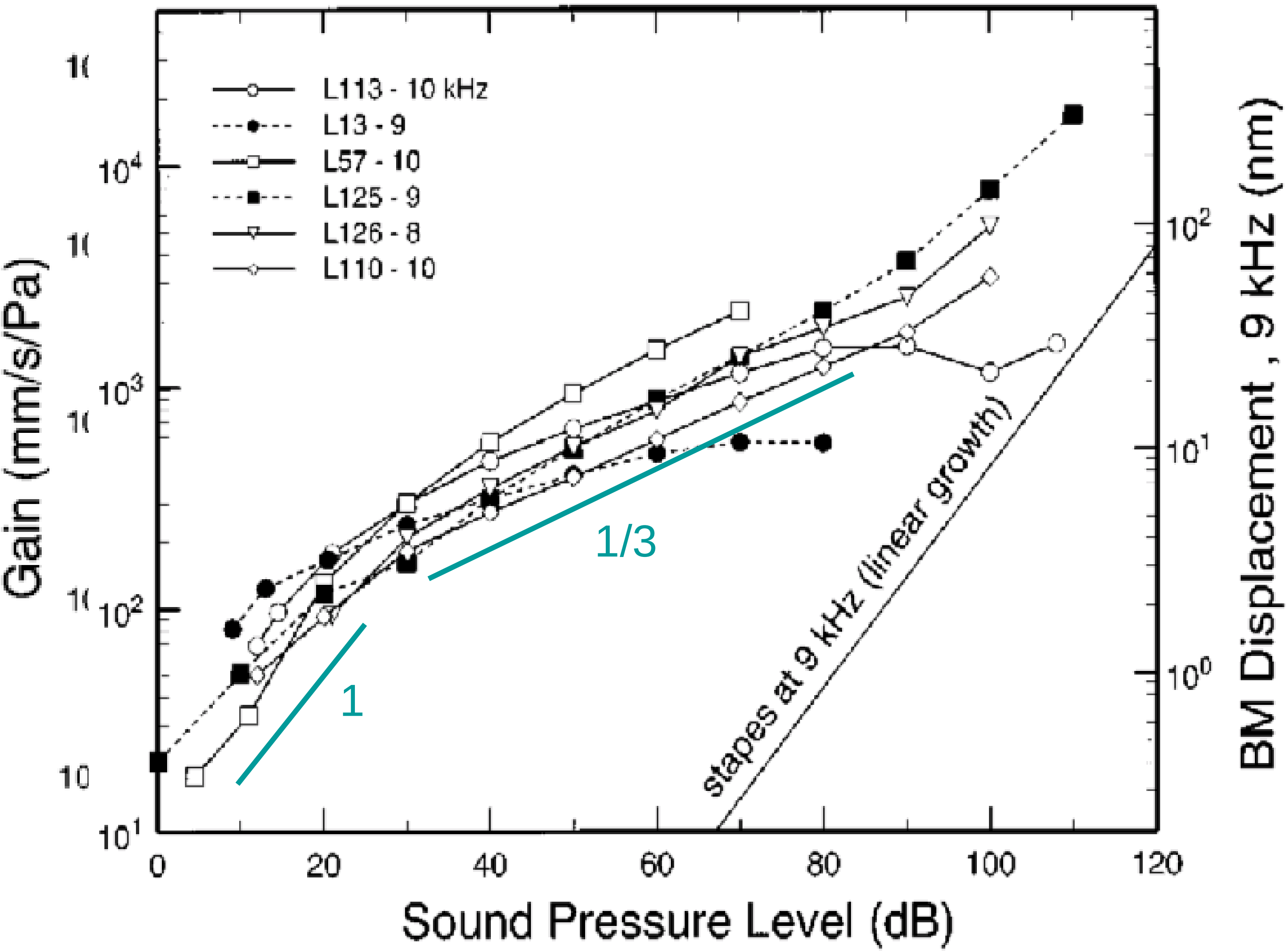
- fluid flow $$\rho \frac{\partial j}{\partial t} = -b\, l \frac{\partial p}{\partial x}$$
- incompressibility $$2b \frac{\partial h}{\partial t} - \frac{\partial j}{\partial x} = 0$$
- membrane response $$p(x,t) = K(x)\, h(x,t)$$

→ wave velocity $$c(x) = \sqrt{\frac{K(x)\, l}{2\rho}}$$

Basilar membrane motion

Rhode '71; Ruggero et al. '97

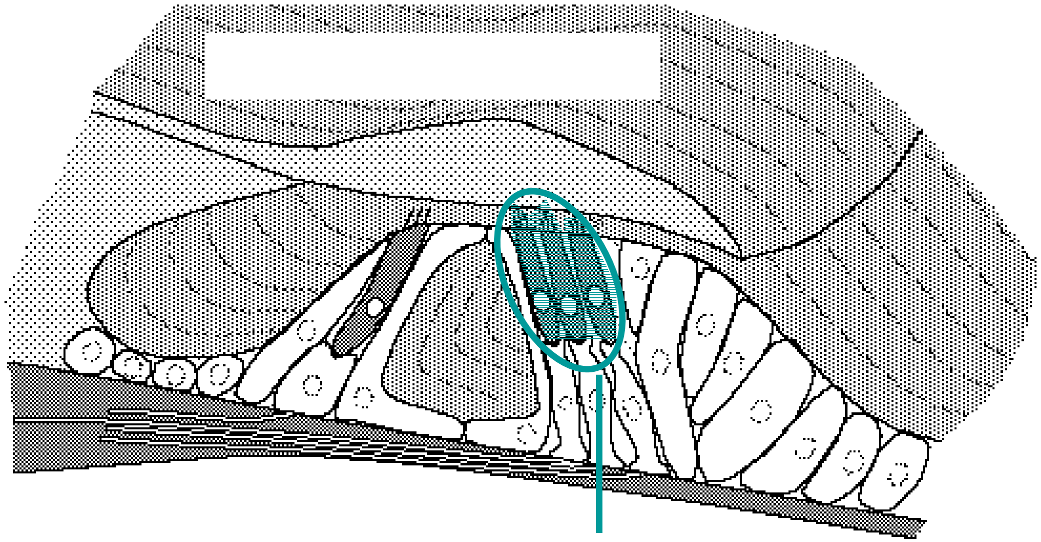
BM response is nonlinear



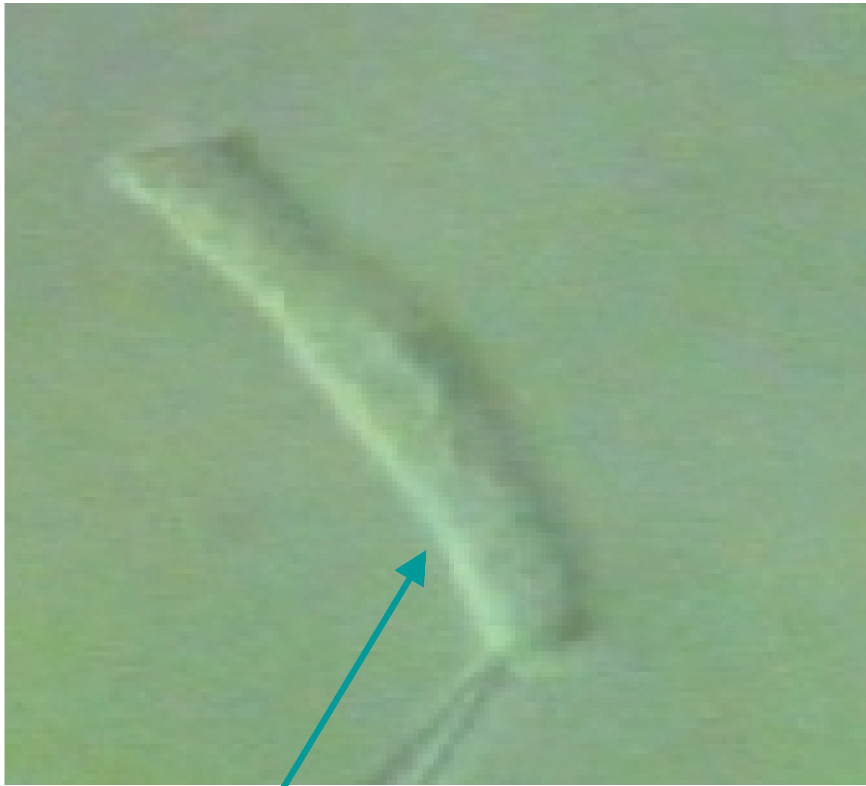
Outer hair cell motor

Brownell '85; Ashmore '87

Outer hair cells are electromotile



outer hair cells



prestin

Dallos *et al.* '99

Active basilar membrane

Duke & Jülicher

Critical oscillators ranged along basilar membrane

characteristic frequencies span audible range: $\omega_c(x) = \omega_0 e^{-x/d}$

→ membrane is an excitable medium with a nonlinear active response

$$\bar{p}(\omega) = A(x,\omega)\bar{h} + B\,|\bar{h}|^2\,\bar{h}$$

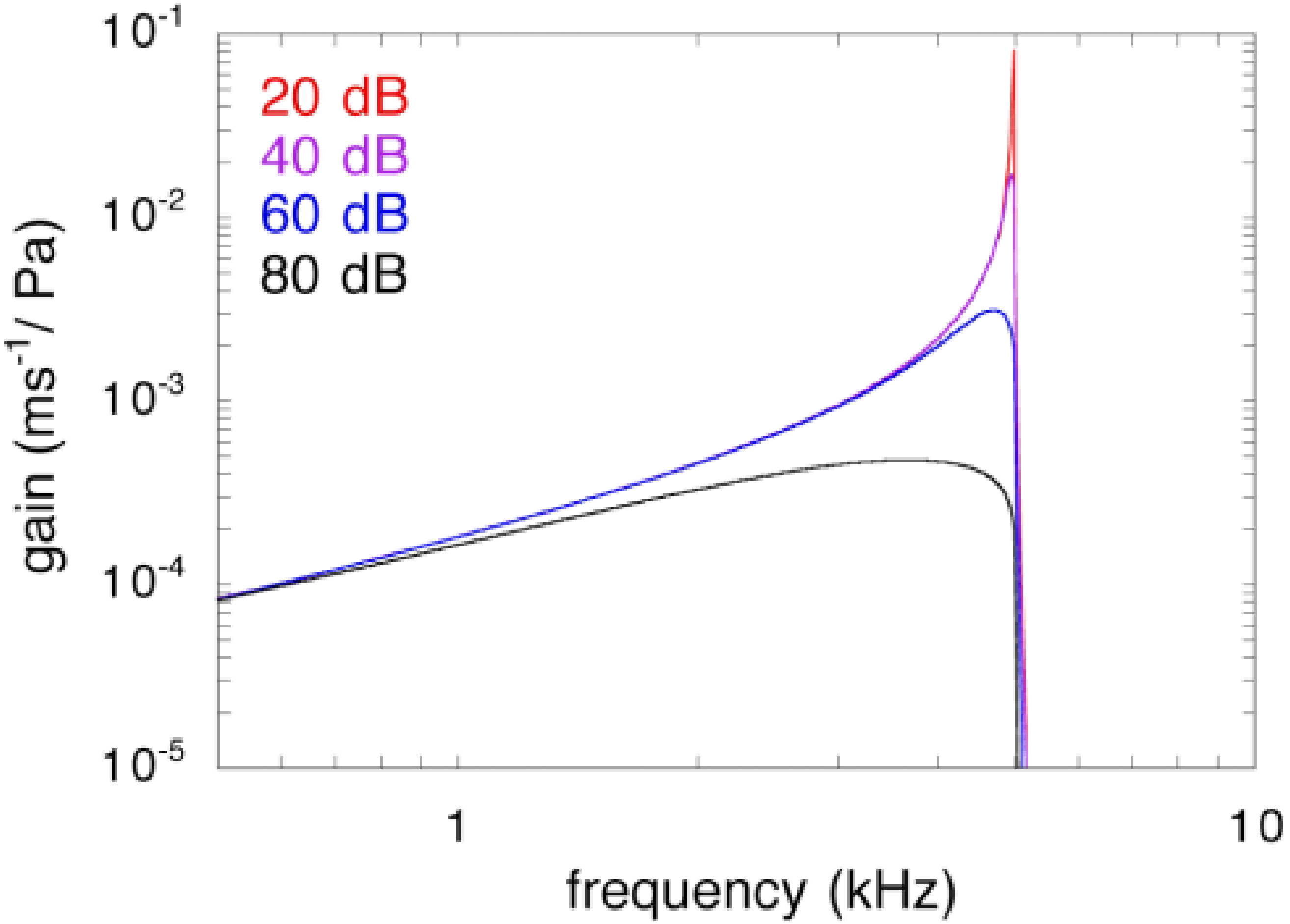
$$A(x,\omega) = \alpha(\omega_c(x) - \omega)$$
$$B = i\beta$$

captures essence of active membrane

$$A(x,\omega_c(x)) = 0$$

$$K(x) = A(x,0) = \alpha\,\omega_c(x)$$

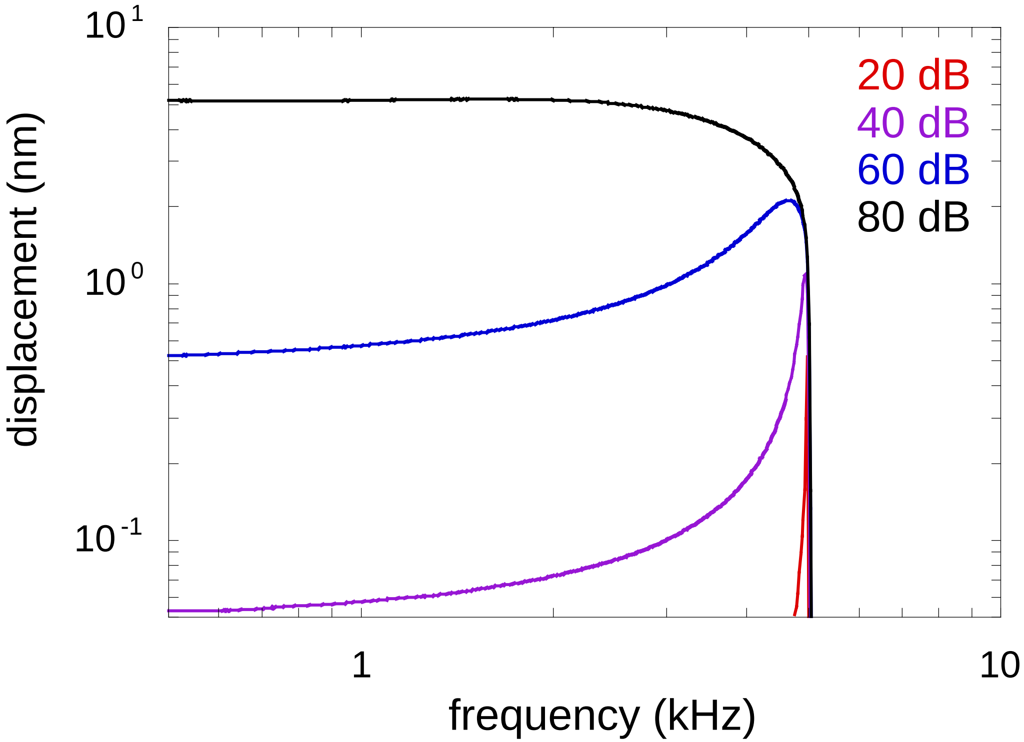
active travelling wave
cochlear tuning curve

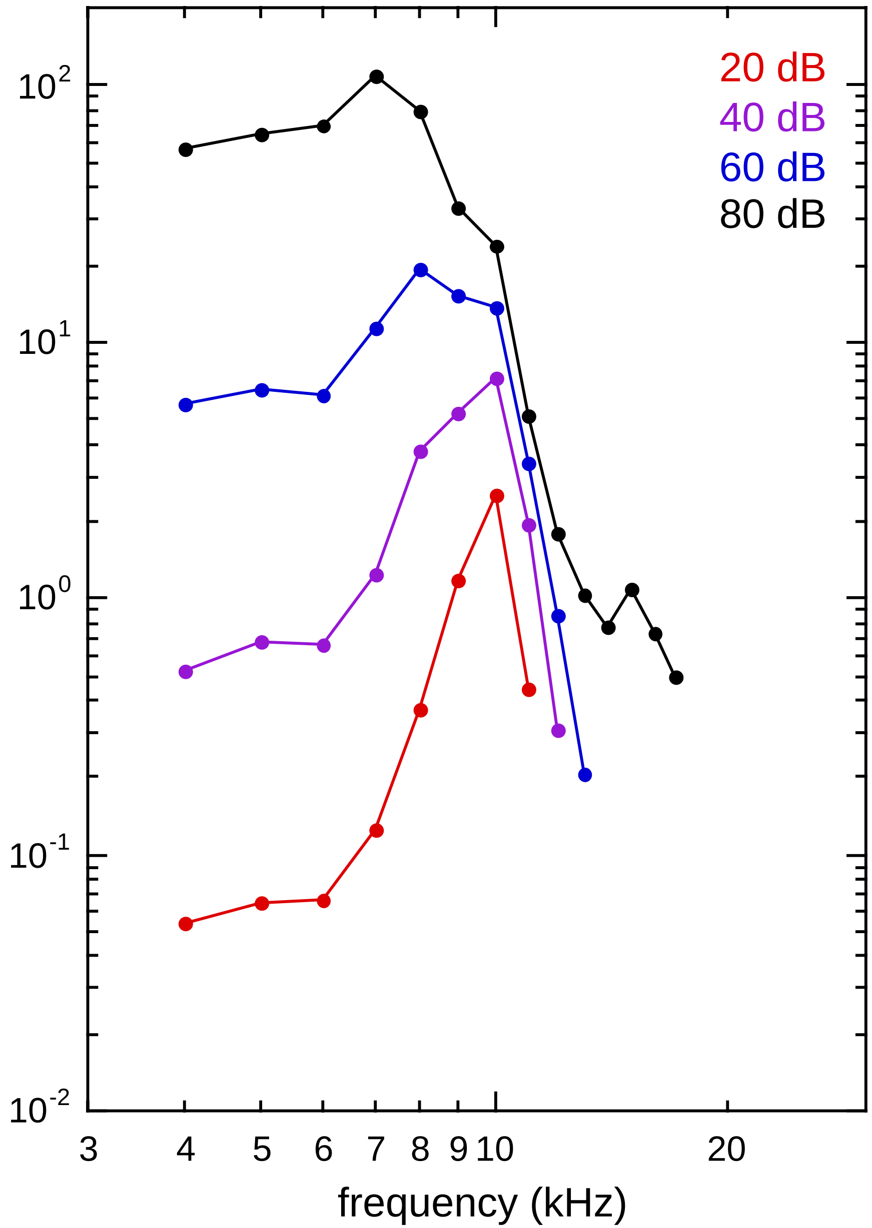


Precipitous fall-off on high frequency side owing to critical-layer absorption

active travelling wave
cochlear tuning curve

Ruggero et al. '97





Summary

- Active amplification by critical oscillators is ideally suited to the ears needs:

  frequency selectivity, exquisite sensitivity, dynamic range

- Spontaneous hair-bundle oscillations may be generated by transduction channels and regulated by molecular motors

- Critical oscillators that pump the basilar membrane give rise to an active travelling wave with a sharp peak

- Many psychoacoustic phenomena may be related to the nonlinearities caused by active amplification