THE ROLE OF MICROMECHANICS IN EXPLAINING TWO TONE SUPPRESSION AND THE UPWARD SPREAD OF MASKING

Jont B. Allen and Deep Sen
Speech Processing Software and Technology
AT&T Research Labs, Florham Park, NJ
http://auditorymodels.org/jba/PAPERS/Titisee/

July 27, 2002

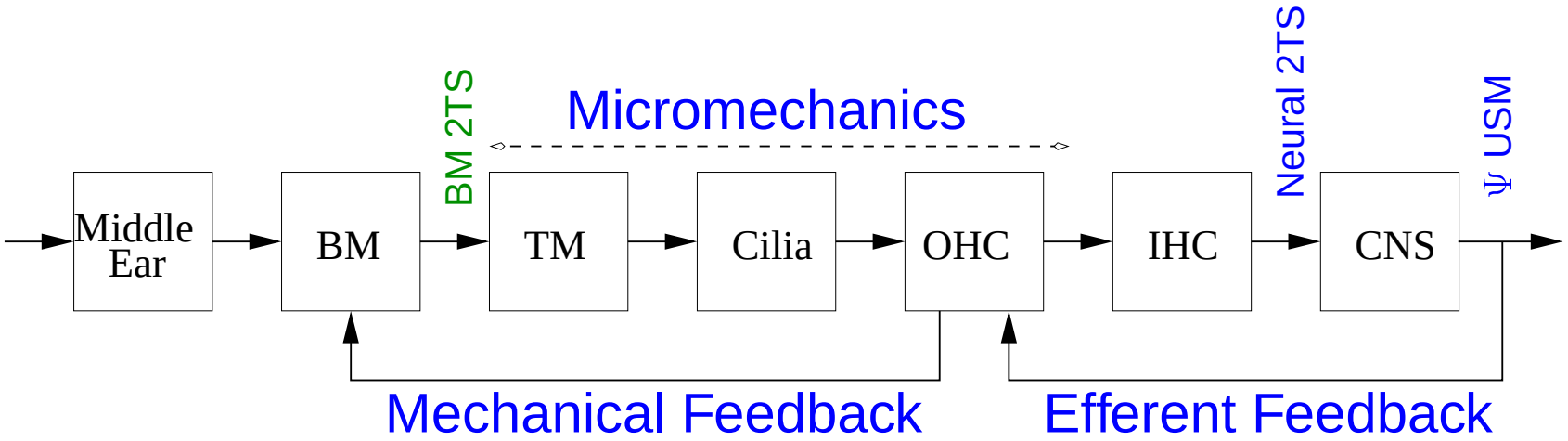
Abstract

When a low frequency tone is above about 65 dB SPL, it is excitatory in the base of the cochlea. This leads to a dramatic elevation in the iso-response psychophysical and neural thresholds of a higher frequency probe tone. When measured psychophysically this effect is called the "upward spread of masking" (USM). USM was first characterized by Fletcher (1923) (and later by Wegel and Lane, 1924). The USM suppression threshold is between 55 and 65 dB SPL (it is nearly independent of probe frequency). The USM "iso-response suppressed-probe response slope" (IR-SP) is approximately 2.4 dB/dB for high frequency ($f_P > 2kHz$) probes. The related "iso-suppressor suppressd-response slope," (IS-SR) of -1.4 dB/dB, is defined as the slope of suppression of the probe relative to the suppressor level. This slope is 1 dB/dB less because of the linear growth of the excitory suppressor at the high frequency probes place. When measured neurally, this same cochlear nonlinear effect is called two-tone suppression (2TS). It was first measured by Anderson, Kiang and Moxin and Sachs and Abbas. As with the USM, the neural iso-response 2TS threshold is also about 65 dB SPL, and the iso-rate suppression slope is close to 2.4 dB/dB. *Thus neural 2TS and USM are two different, yet identical, measures of the same cochlear suppression effect.*

When 2TS is measured on the basilar membrane (BM), the results are very different. Unlike the neural 2TS, the suppressor threshold level is always much greater than the probe level at the probe's place. For BM-2TS, the Fourier response of the low frequency BM suppression threshold is above 80 dB SPL, which is at least 25-35 dB higher than the Fourier component of the high frequency probe tone. The iso-suppessor BM 2TS "suppressed slope" is -1 dB/dB. The discrepancy between -1.4 dB/dB for the neural 2TS suppressed slope, and -1 dB/dB BM SS is key. A slope of -1 is the expected result for a saturating nonlinearity. Thus the disagreement between the BM and haircell 2TS are in sharp disagreement, in threshold, slope, and frequency response.

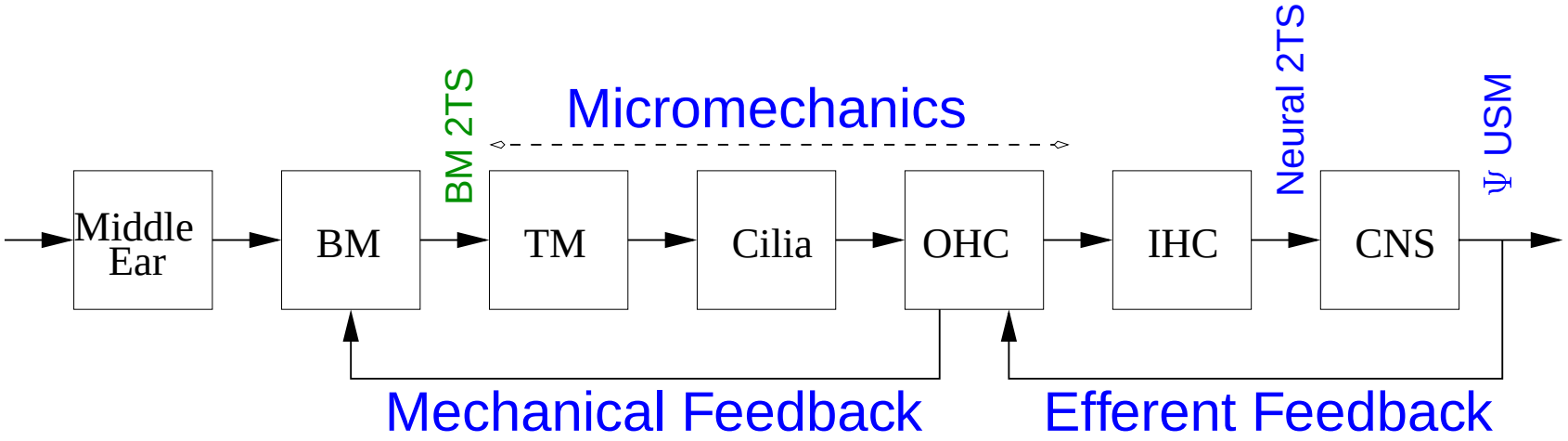
DEFINITIONS

- Three important measures of cochlear nonlinearity are:
  - Basilar membrane 2 tone suppression: BM 2TS
  - Neural 2 tone suppression: Neural 2TS
  - Psychophysical upward spread of masking: Ψ–USM



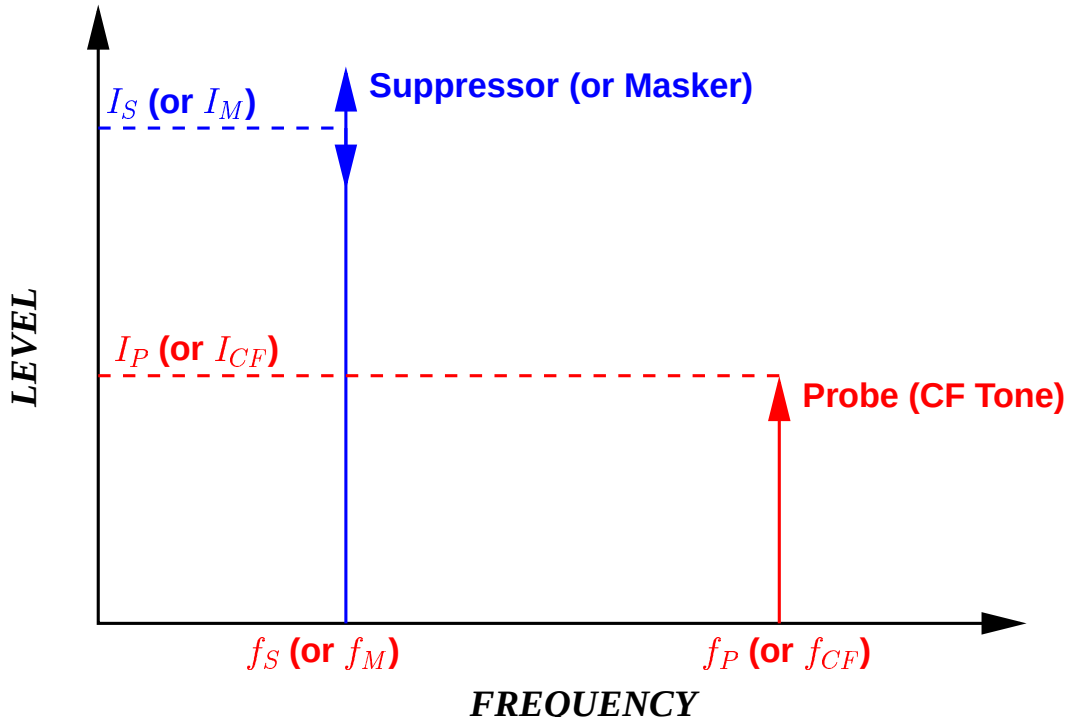
OVERVIEW

- What we want to show:
  - Neural 2TS $\equiv$ Ψ–USM
    These are similar measures of the same underlying cochlear nonlinear suppression effect
  - BM 2TS $\not\equiv$ neural 2TS
    These are not similar
- Micromechanics must account for the difference



STIMULUS DEFINITIONS

- Part I: Ψ–USM $\equiv$ Neural 2TS
  - Two–tone stimulus where $f_S < f_P$ ("low-side" suppression)



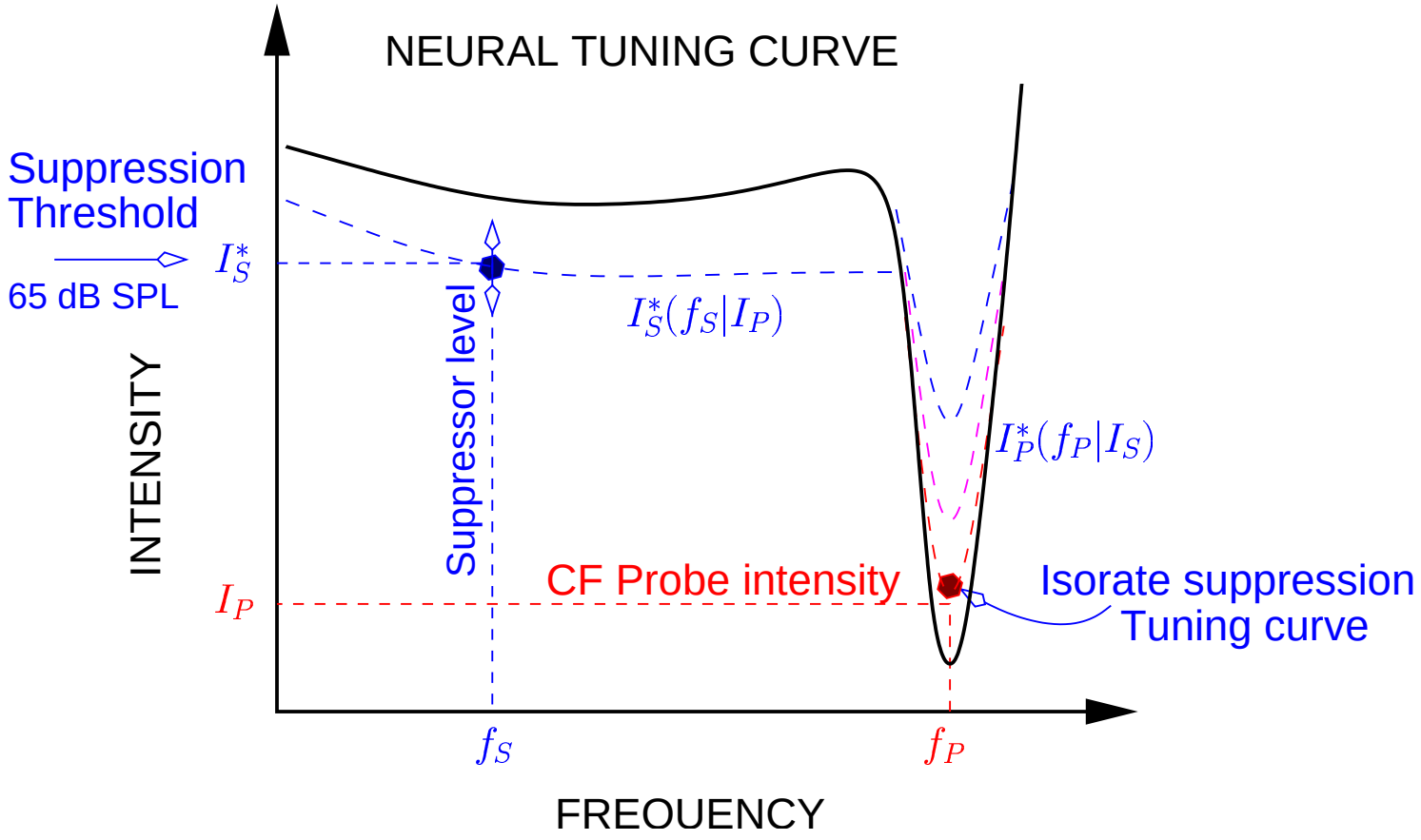
- Unifi ed terminology

  I_S suppressor is also called I_M masker in Ψ–USM

  I_P probe is also called I_{CF} characteristic frequency in 2TS

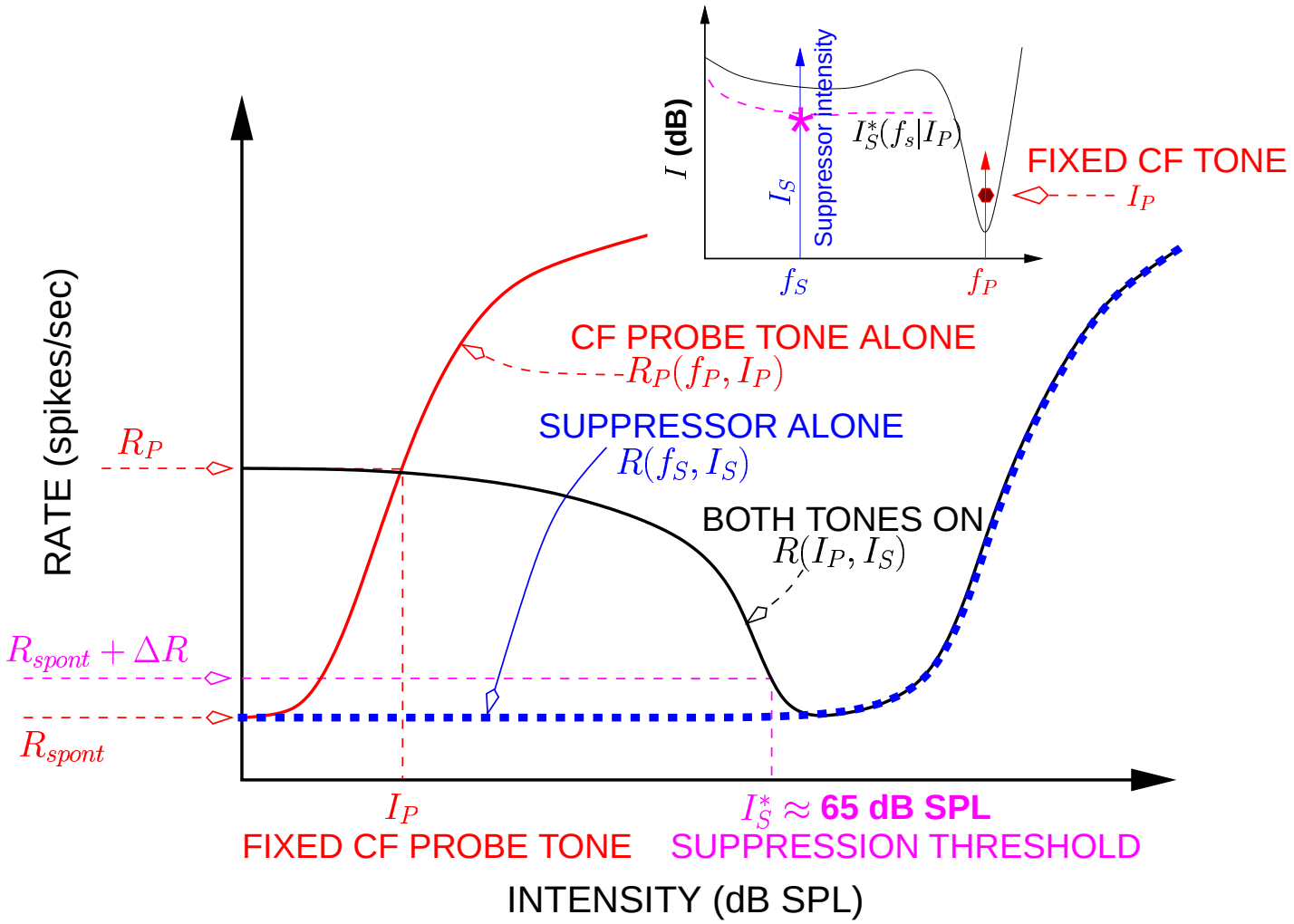
NEURAL TWO TONE SUPPRESSION

- How is neural iso-rate 2TS measured?
- Two methods:
  - Suppressor rate functions with fi xed CF probe [$I_S^*(f_s|I_P)$]
  - FTC's with fi xed suppressor [$I_P^*(f_p|I_S)$]



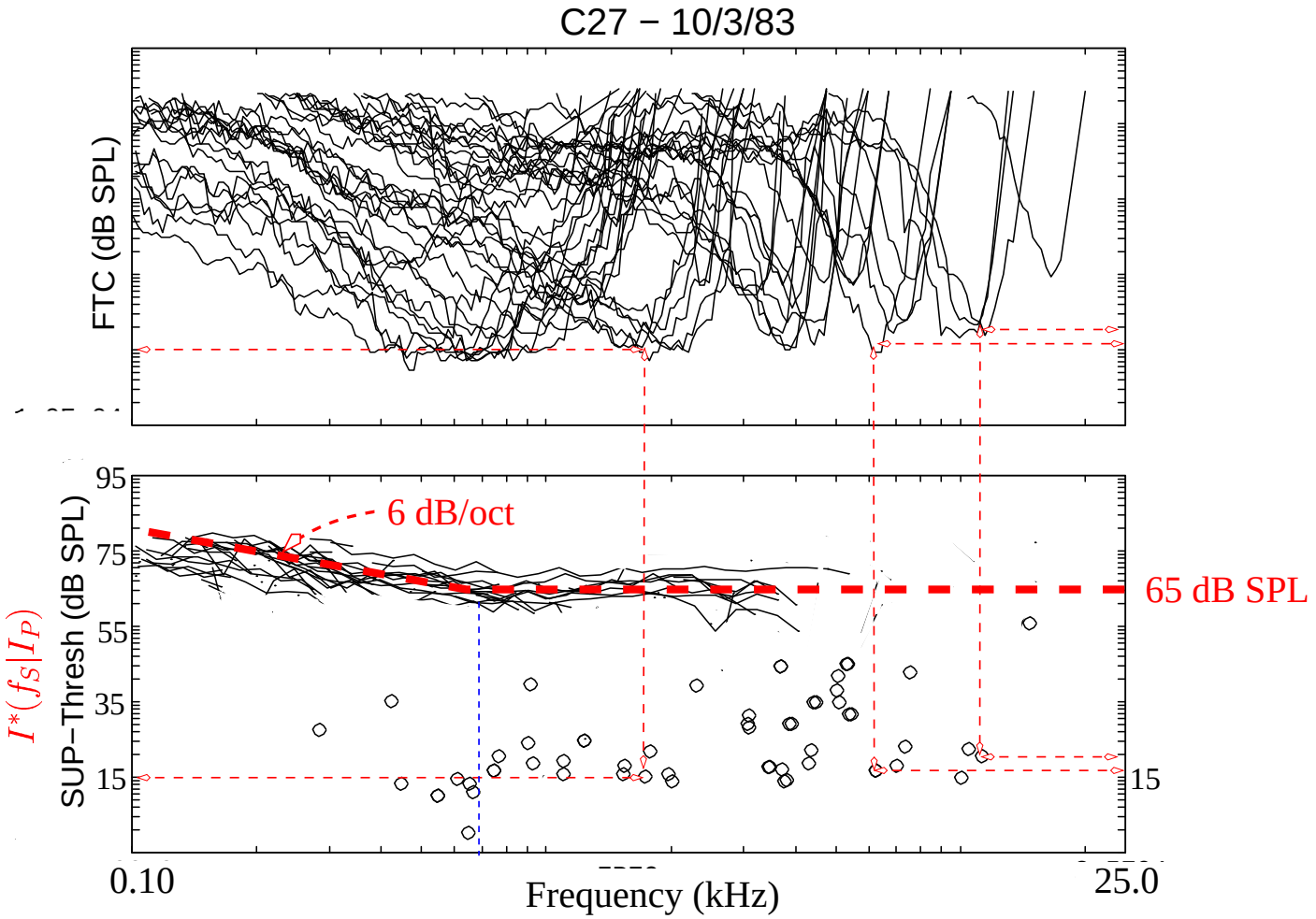
DEFINITION OF $I_S^*(f_S|I_P)$

- Iso–rate suppression criteria ($f_S < f_P$)



SUPPRESSION THRESHOLD DATA

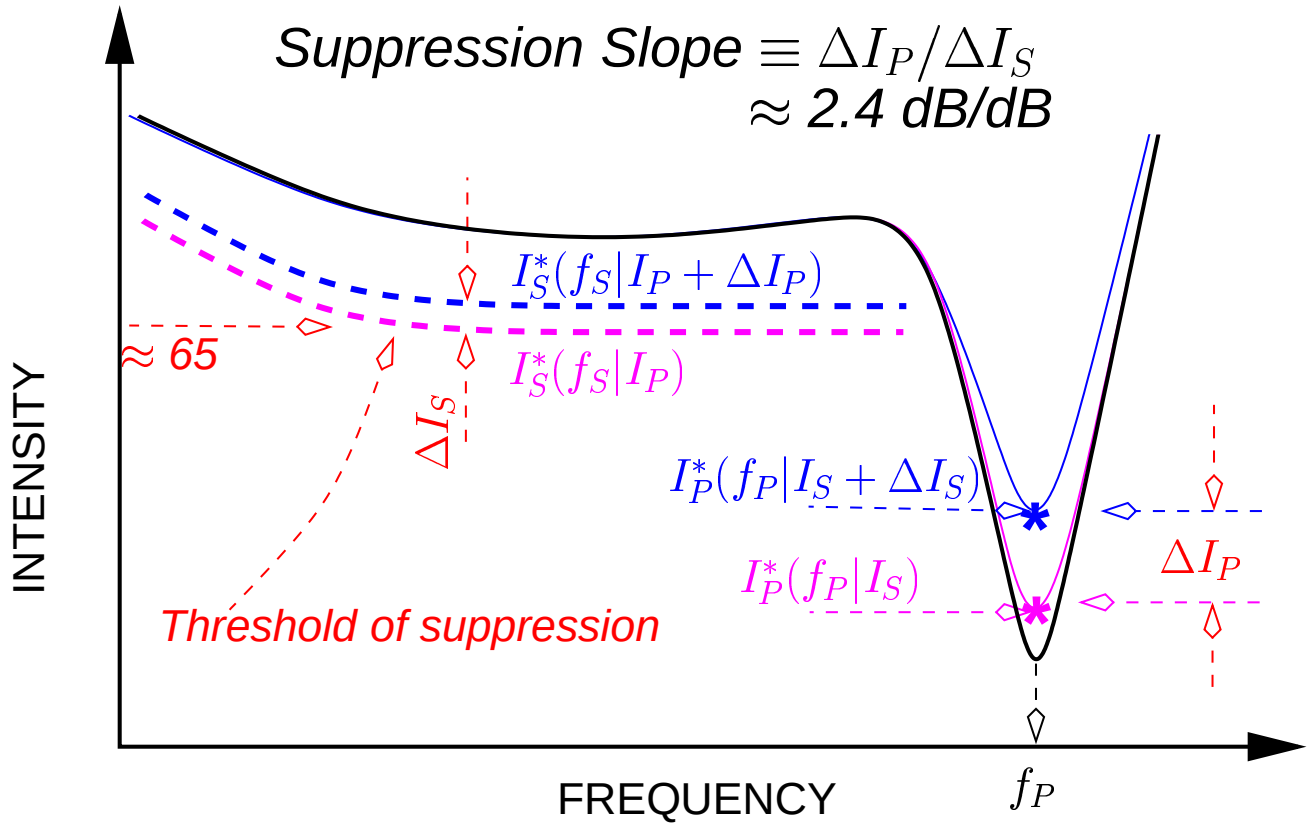
- 2TS thresholds from Fahey and Allen (1985)
  - Mean suppression threshold is 65 dB SPL $\pm$ 5 dB (0.6 – 4.0 kHz)
  - $I^*(f_S)$ follows the middle ear frequency response



SLOPE OF SUPPRESSION (DB/DB)

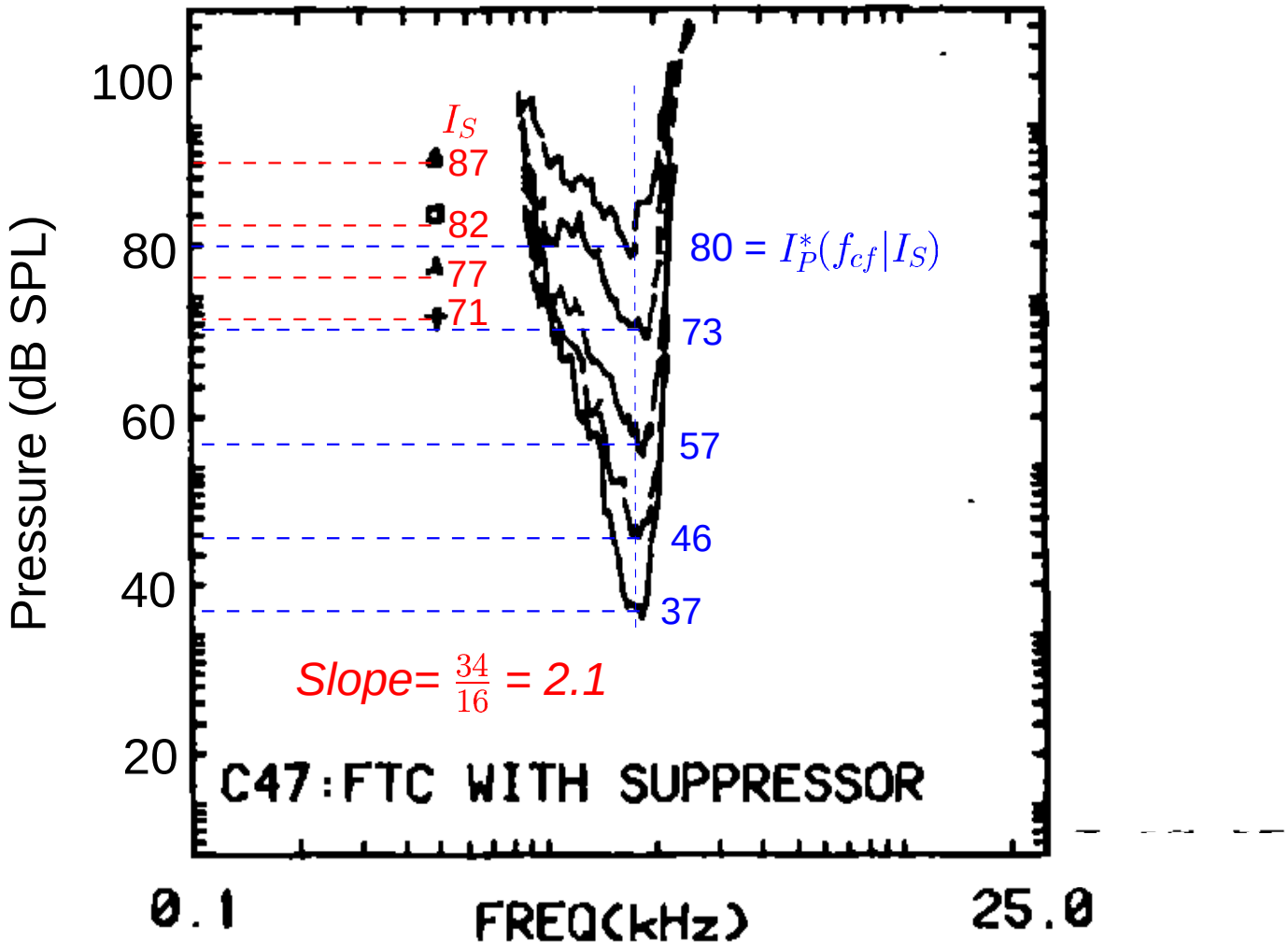
- Rate of suppression:

  CF shift vs. Suppressor intensity



SUPPRESSION THRESHOLD DATA

- $I_P^*(f_P|I_S)$ from Fahey and Allen (1985)

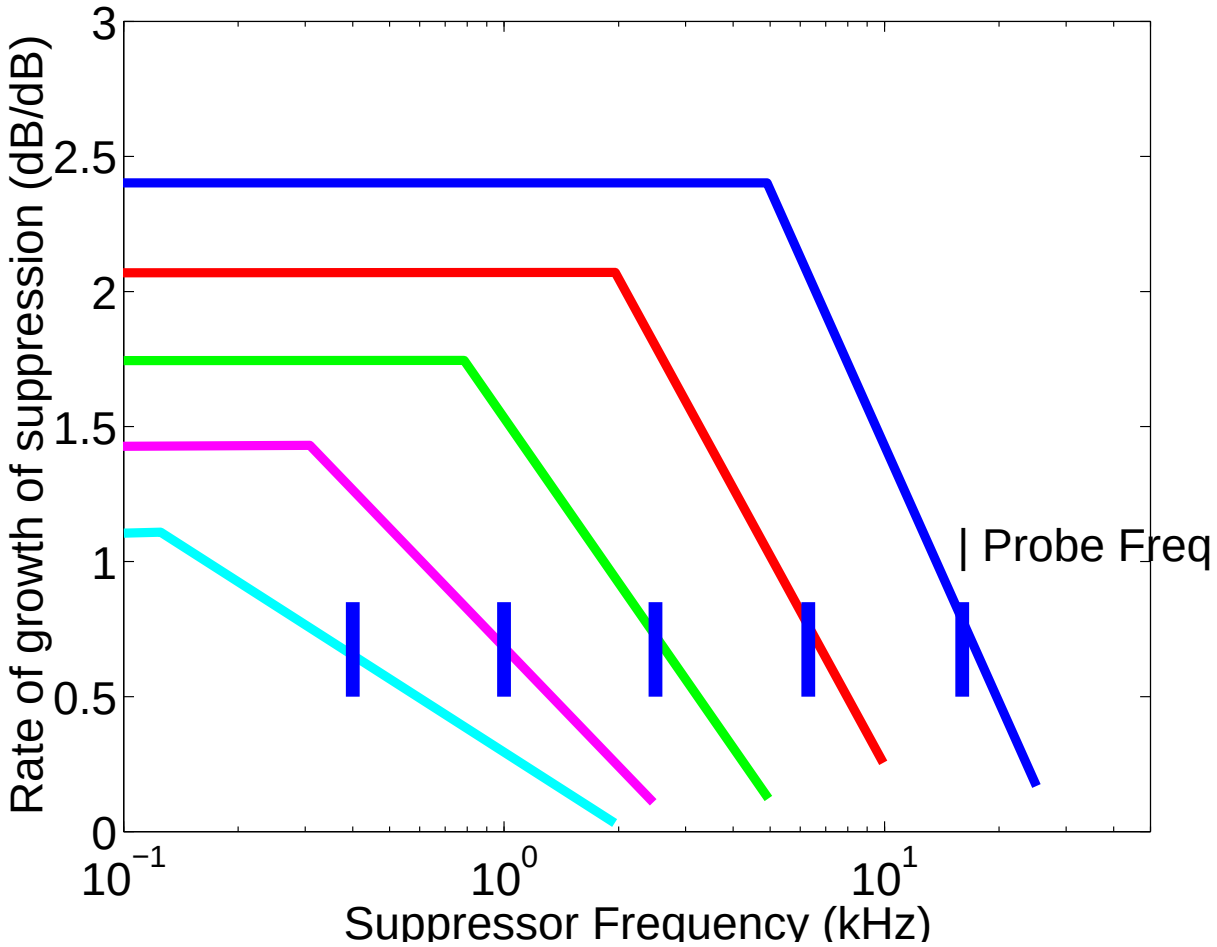


NOTE: CF does not shift down in frequency

Bandwidth nearly constant with level

SUPPRESSION SLOPES FROM DELGUTTE (1990)

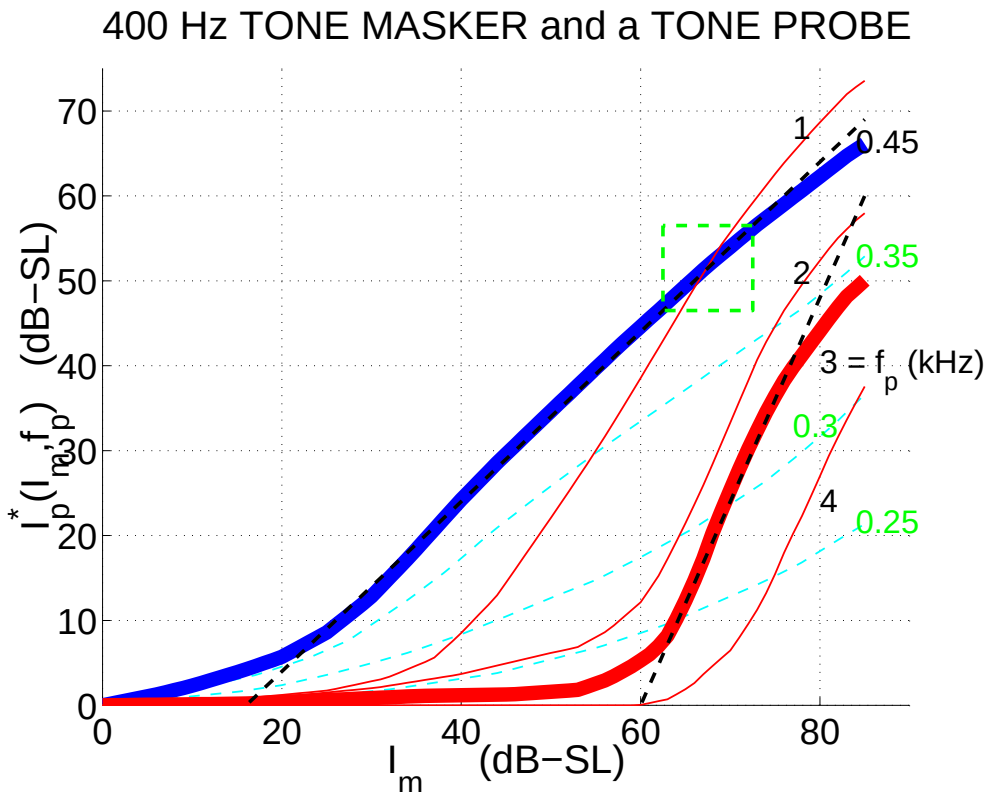
- Compression slope $\frac{\Delta I_P}{\Delta I_S}$ approach 2.5 dB/dB
- The vertical bar marks the probe tone frequency



UPWARD SPREAD OF MASKING

- Data from Fletcher 1923 and Wegel and Lane 1924

  Ψ–USM threshold ≈55-65 dB SPL
  Iso-rate suppression slope: ≈2.4 dB/dB



- Slope of dashed line on the 3 kHz curve is 2.4 dB/dB:

  Ψ–USM ≡ Neural–2TS!

CONCLUSIONS

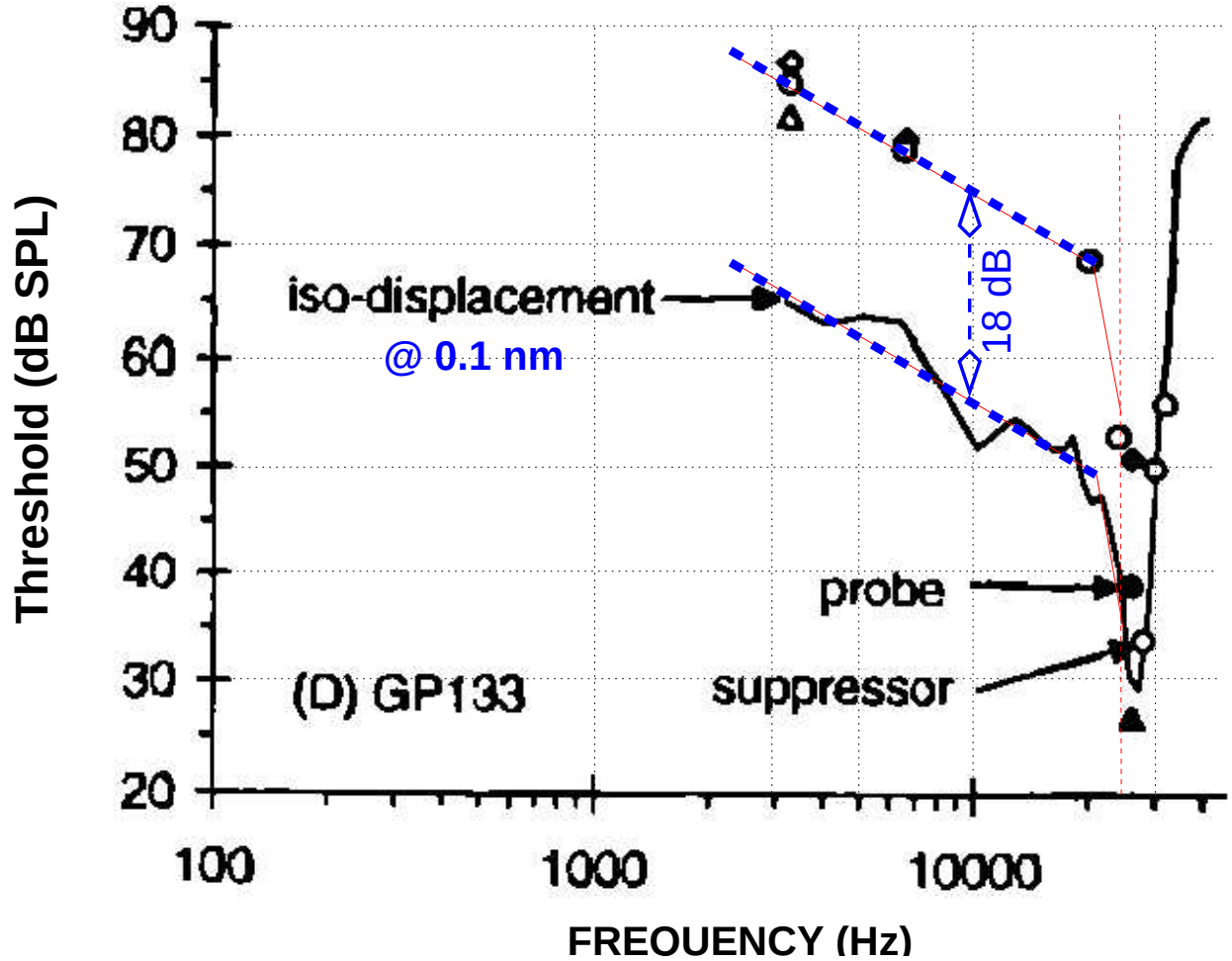
- Slope and threshold of “Low-side” suppressors are nearly identical for Ψ–USM and low-side neural 2TS:

$$\Psi\text{–USM} \equiv \text{Neural–2TS!}$$

- Next: BM 2TS ...

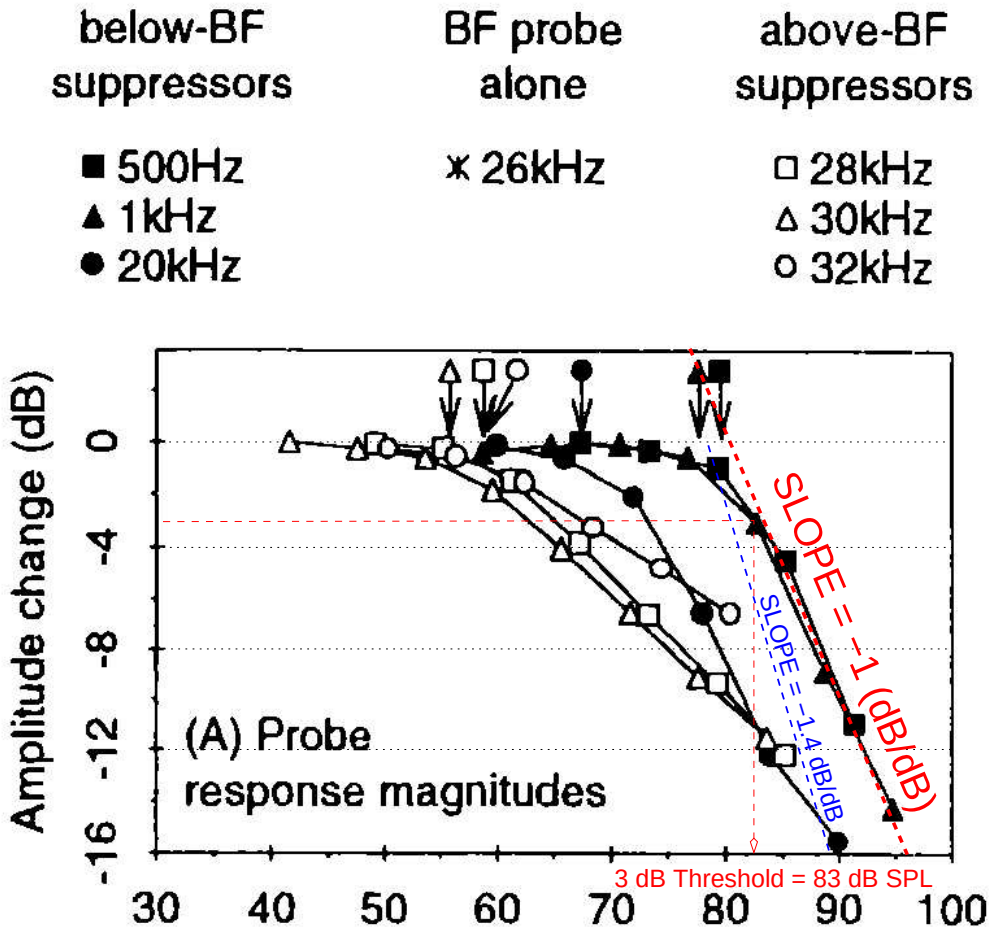
BASILAR MEMBRANE 2TS

- Cooper (1996) Suppression Tuning curves
  - Suppression thresholds are above 80 dB SPL



BASILAR MEMBRANE 2TS

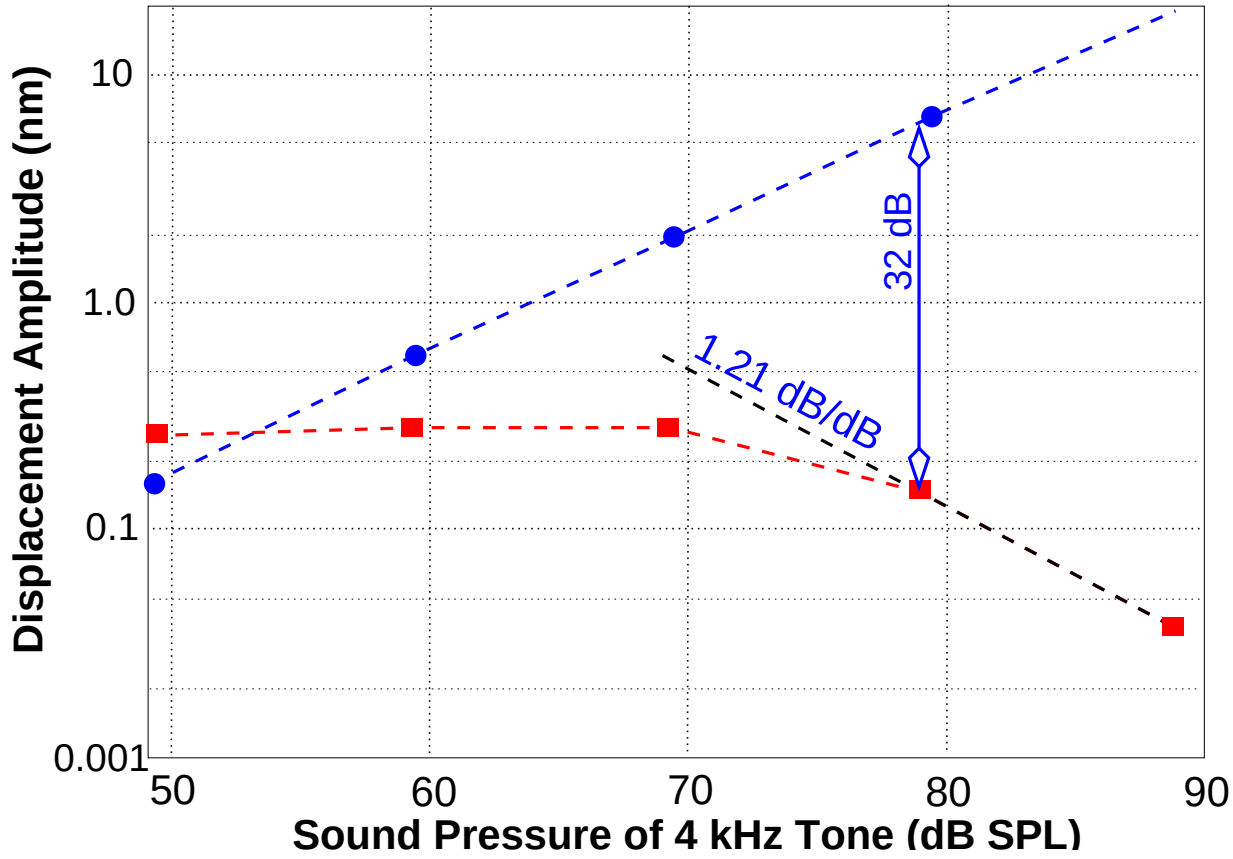
- Cooper (1996) Fig. 1 IO curves
  - Suppression slope ≈ -1 dB/dB
  - Suppression threshold ≈ 80-90 dB SPL



BASILAR MEMBRANE 2TS

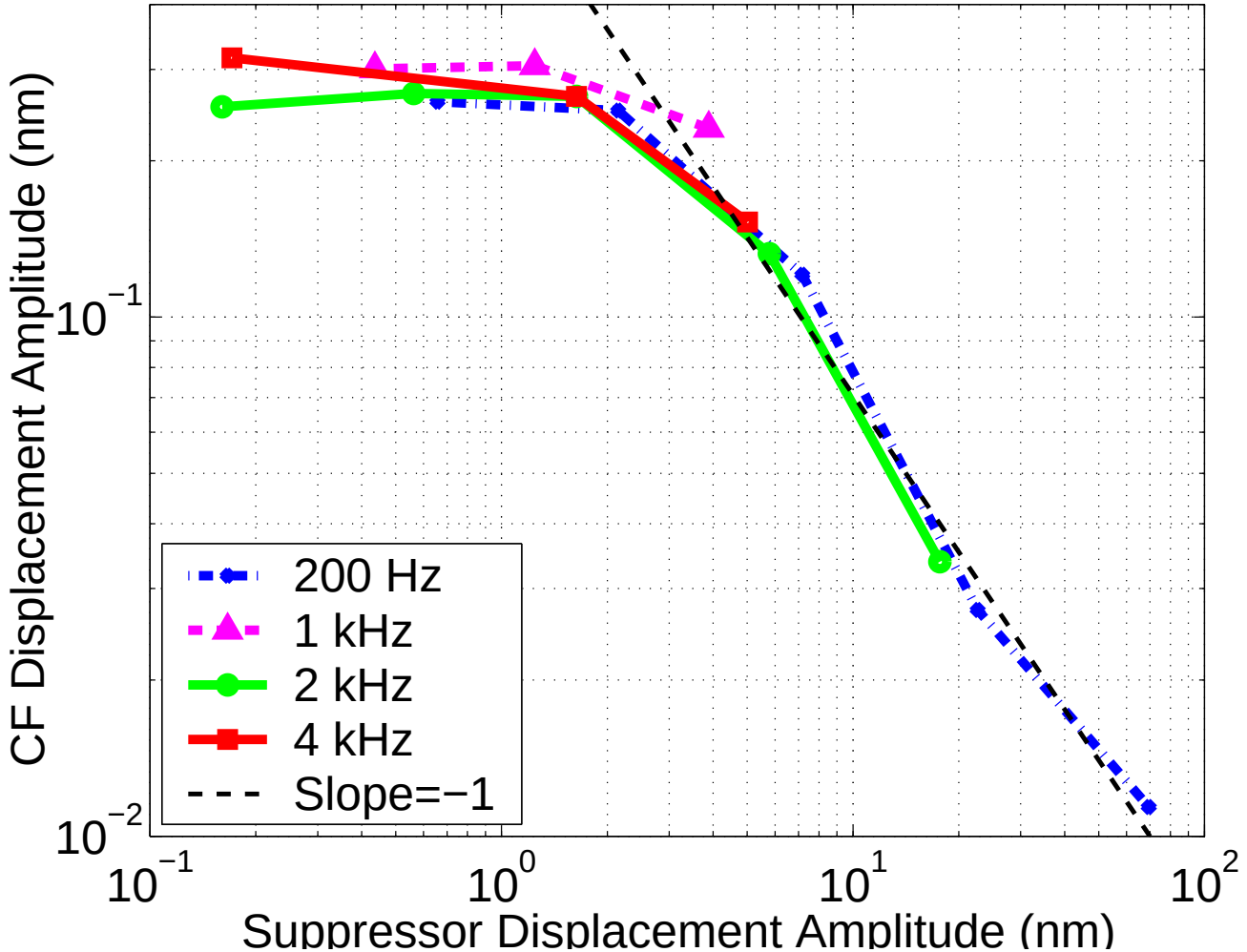
- Geisler and Nuttall (1997)

  Threshold ≈ 79 dB SPL
  Suppressor is ≈ 32 dB larger than probe at threshold
  Displacement not velocity is the relevant variable



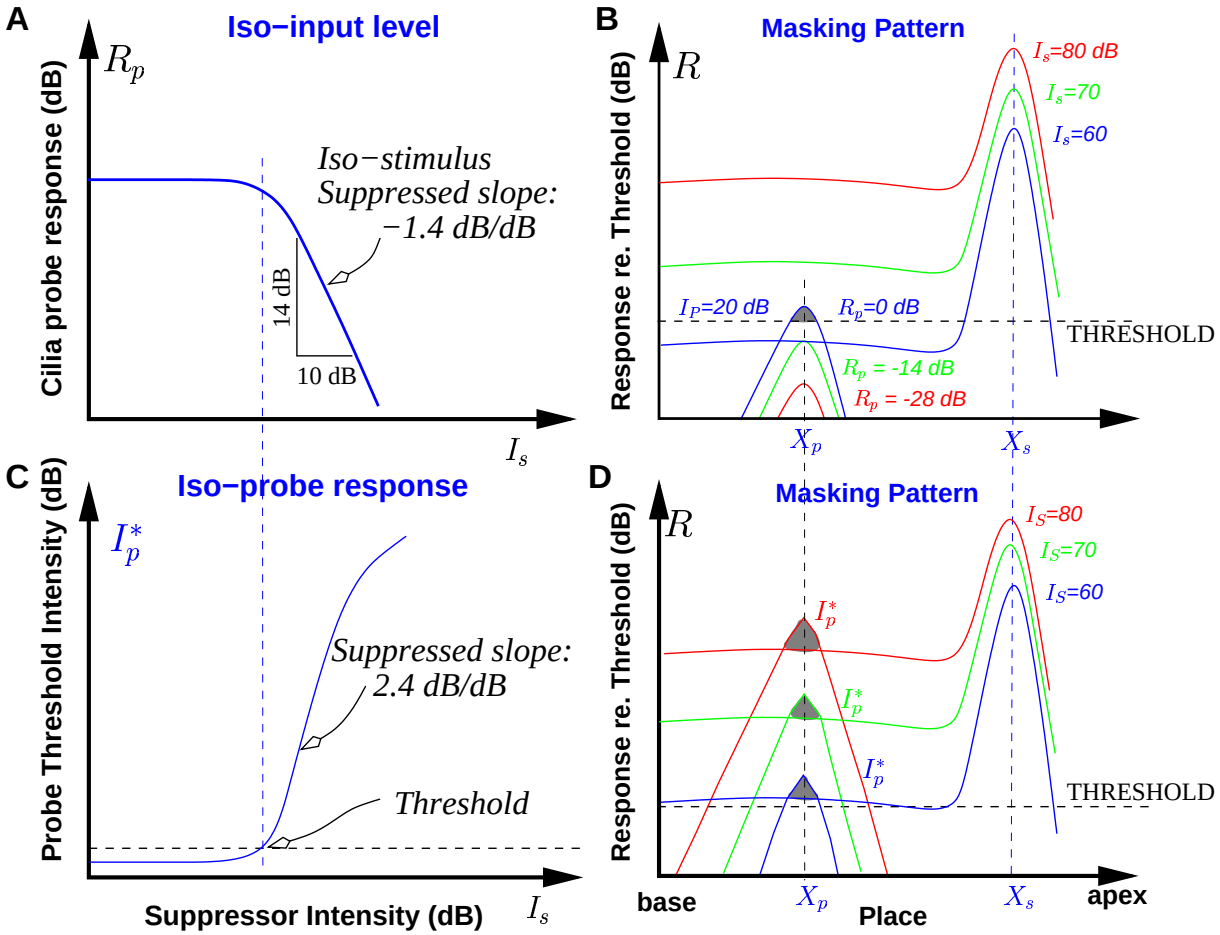
BASILAR MEMBRANE 2TS

- Geisler and Nuttall BM Suppression slope = -1 dB/dB



SUMMARY

- What's going on at the cilia level?



Due to the linear growth of I_S in the base, an iso-response slope of 2.4 dB/dB threshold corresponds to a suppressed slope of -1.4 dB/dB

CONCLUSIONS

- Psychophysical–USM and Neural–2TS are the same
  - Threshold: 65 dB SPL
    Suppression begins at excitation threshold
    Tuned like the middle ear
  - Suppressed slope: -1.4 dB/dB
- Neural and BM 2TS sharply differ
  - BM Threshold $>$ 80 dB SPL
    Tuned like the BM
  - BM Slope: -1 dB/dB

  $\Rightarrow$ BM and neural 2TS require different models
- Neural CF does not shift with suppression
- FTC Bandwidth is $\approx$ constant as a function I_S^*

BM 2TS MODEL

- A saturating nonlinearity gives a slope of -1
- Above 80 dB SPL the haircell begins to saturate

  $\Rightarrow$ Haircell saturation explains BM 2TS

NEURAL 2TS MODEL

- Haircell saturation cannot explain Neural–2TS/Ψ–USM
- Requires a base-stop fi lter private to each place
  - Base stop fi lter required
  - Filter must modify threshold slope
- This fi lter must be in the micromechanics
  Note: Every model of Neural–2TS has a high-pass fi lter between the BM and the IHC cilia!