Applications from Magnetoencephalography: *Neural Detection of Attended Voices* and *Signal Enhancement*

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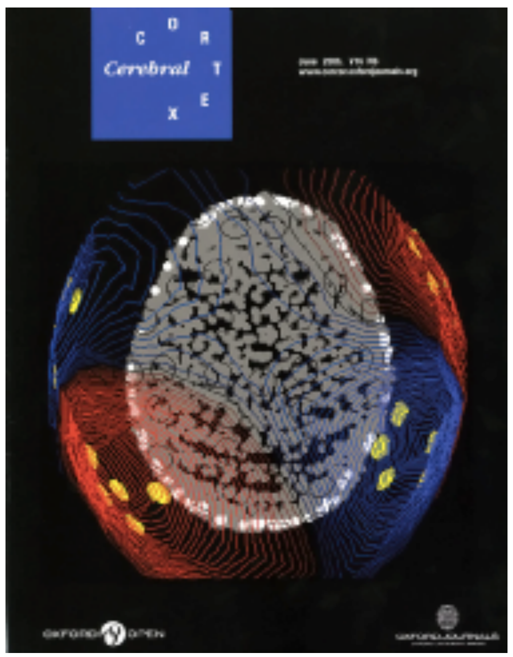
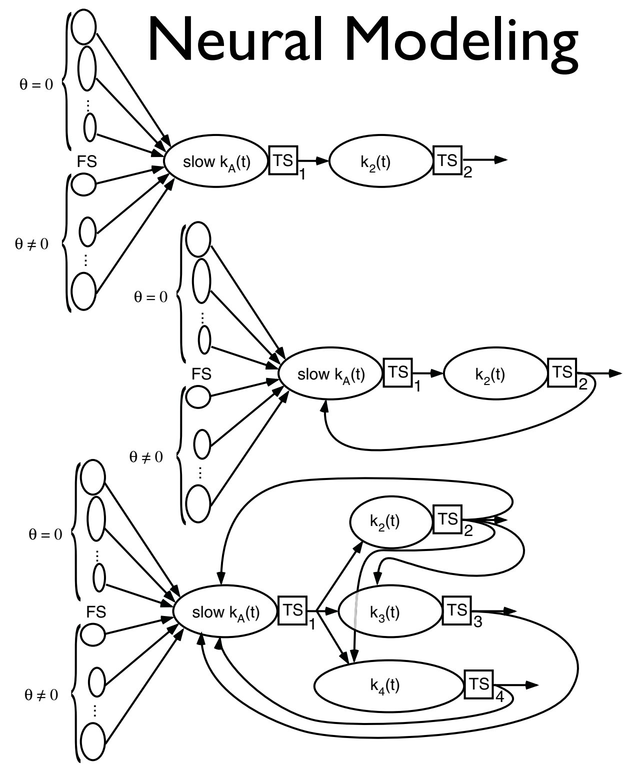
Neural processing of speech and complex auditory scenes

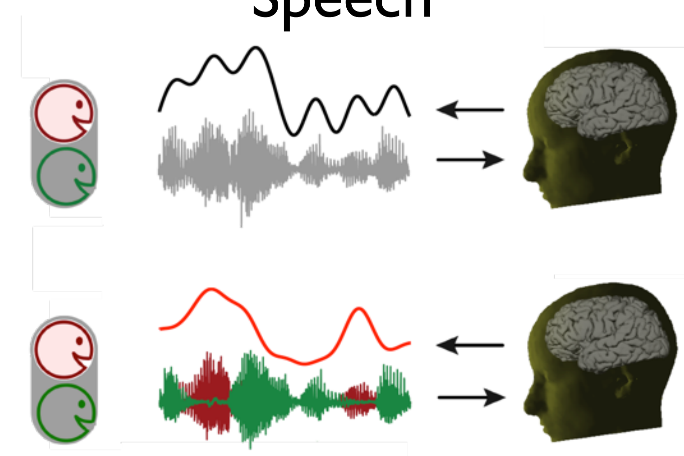
Magnetoencephalography



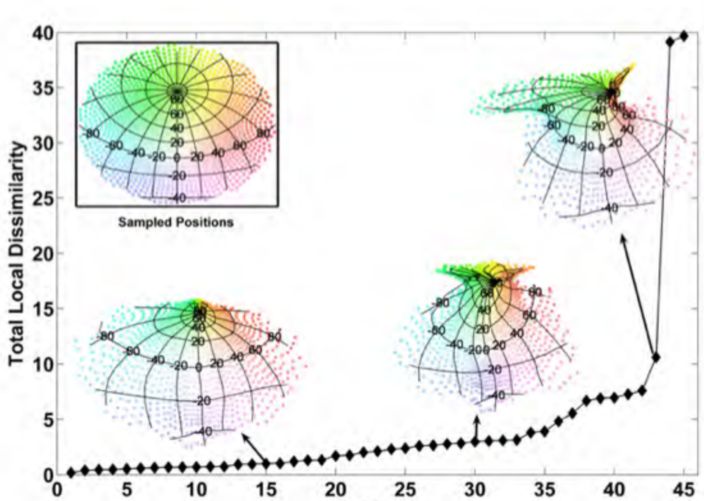
Neural Modeling



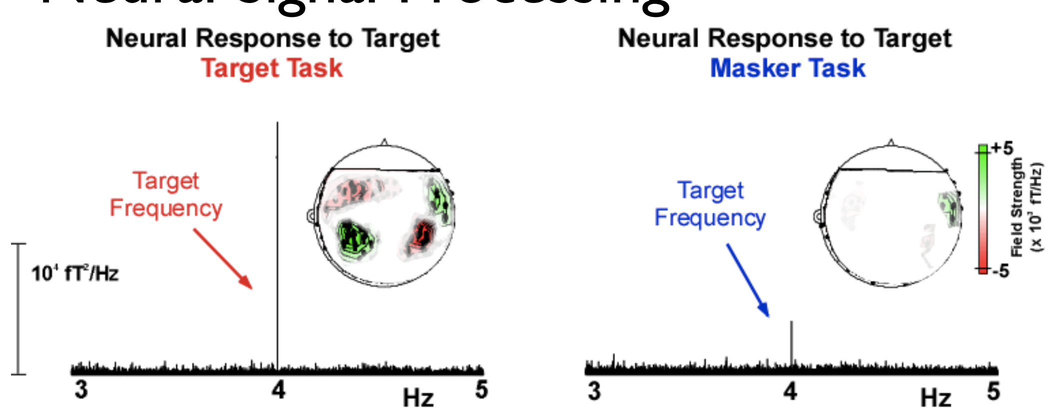
Neural Un-Mixing of Speech



Neurally Inspired Algorithms



Neural Signal Processing



Advanced Neuroimaging

Outline

- Magnetoencephalography (MEG) - Brief introduction
- Neural Detection of Attended Voices
- Signal Enhancement / Noise Reduction

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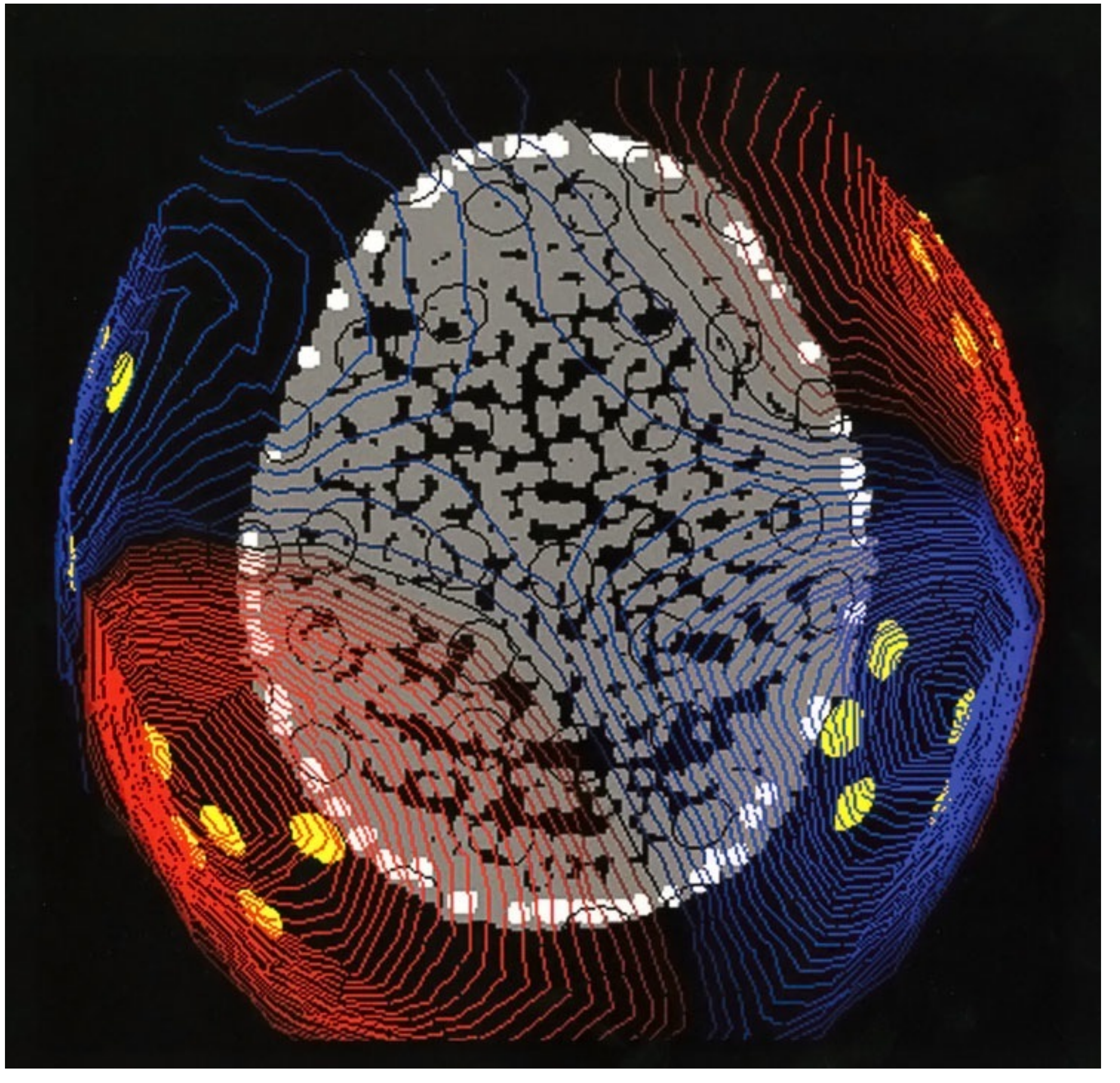
Magnetoencephalography

- Non-invasive, Passive, Silent Neural Recordings
- Simultaneous Whole-Head Recording (~200 sensors)
- Sensitivity
  - high: ~100 fT (10^{-13} Tesla)
  - low: ~10^4 – ~10^6 neurons
- Temporal Resolution: ~1 ms
- Spatial Resolution
  - coarse: ~1 cm
  - ambiguous

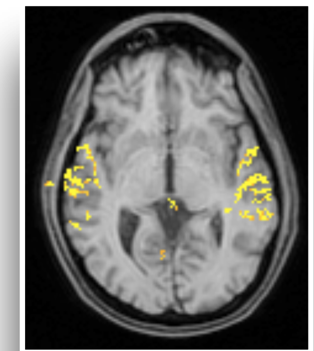


Functional Brain Scanning

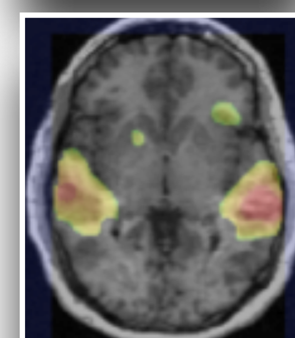
Functional Brain Scanning
= Non-invasive recording from human brain

Hemodynamic techniques

fMRI
functional magnetic resonance imaging



PET
positron emission tomography



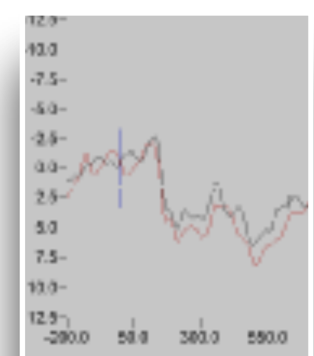
Excellent Spatial Resolution (~1 mm)

Poor Temporal Resolution (~1 s)

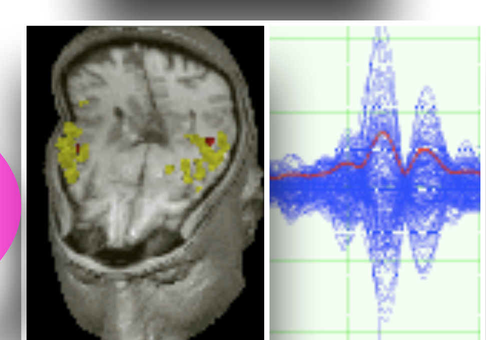
fMRI & MEG can capture effects in single subjects

Electromagnetic techniques

EEG
electroencephalography



MEG
magnetoencephalography



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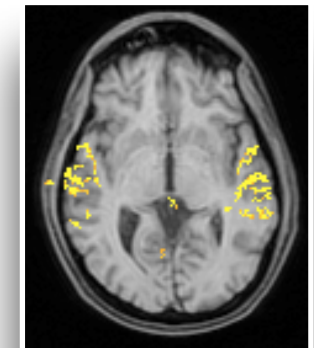

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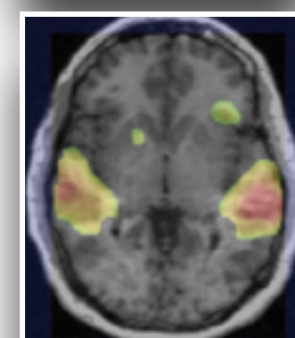

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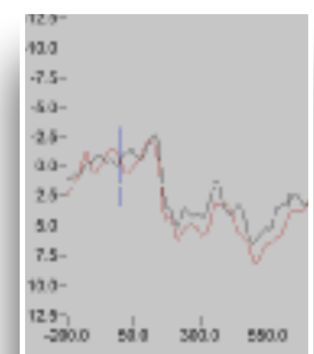
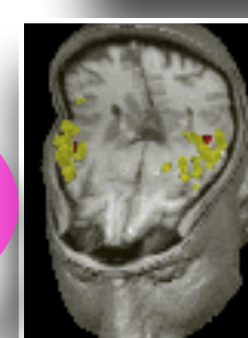
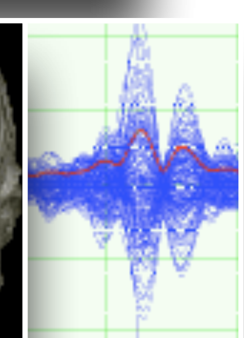


MEG
magnetoencephalography





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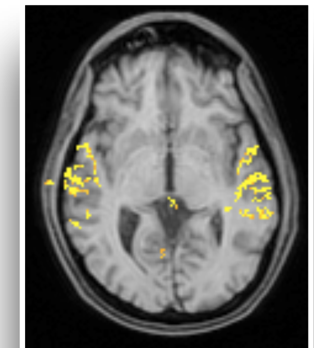

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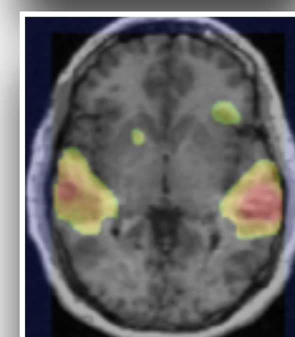

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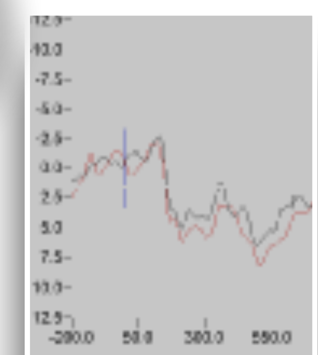
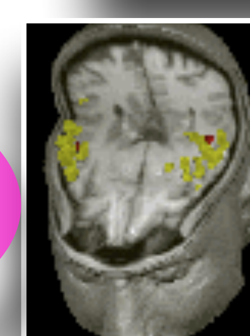
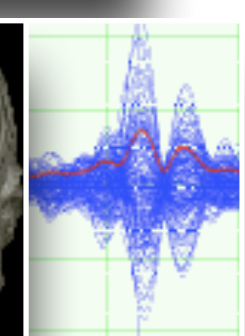


MEG
magnetoencephalography



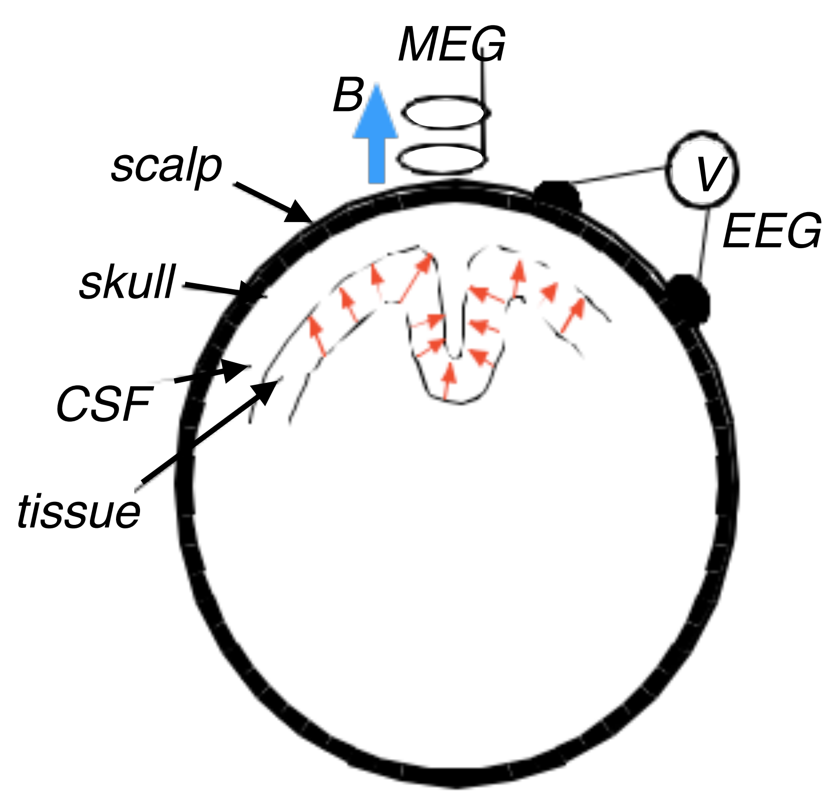


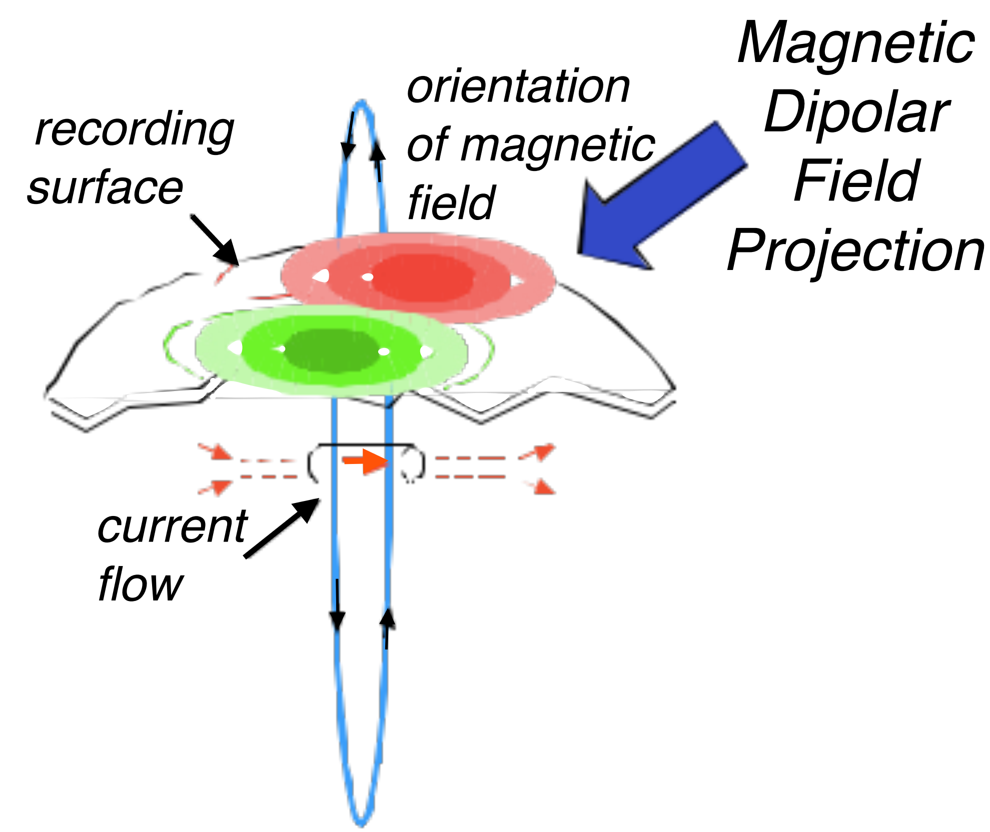
Limited Spatial Resolution (~1 cm)

Excellent Temporal Resolution (~1 ms)

Neural Signals & MEG

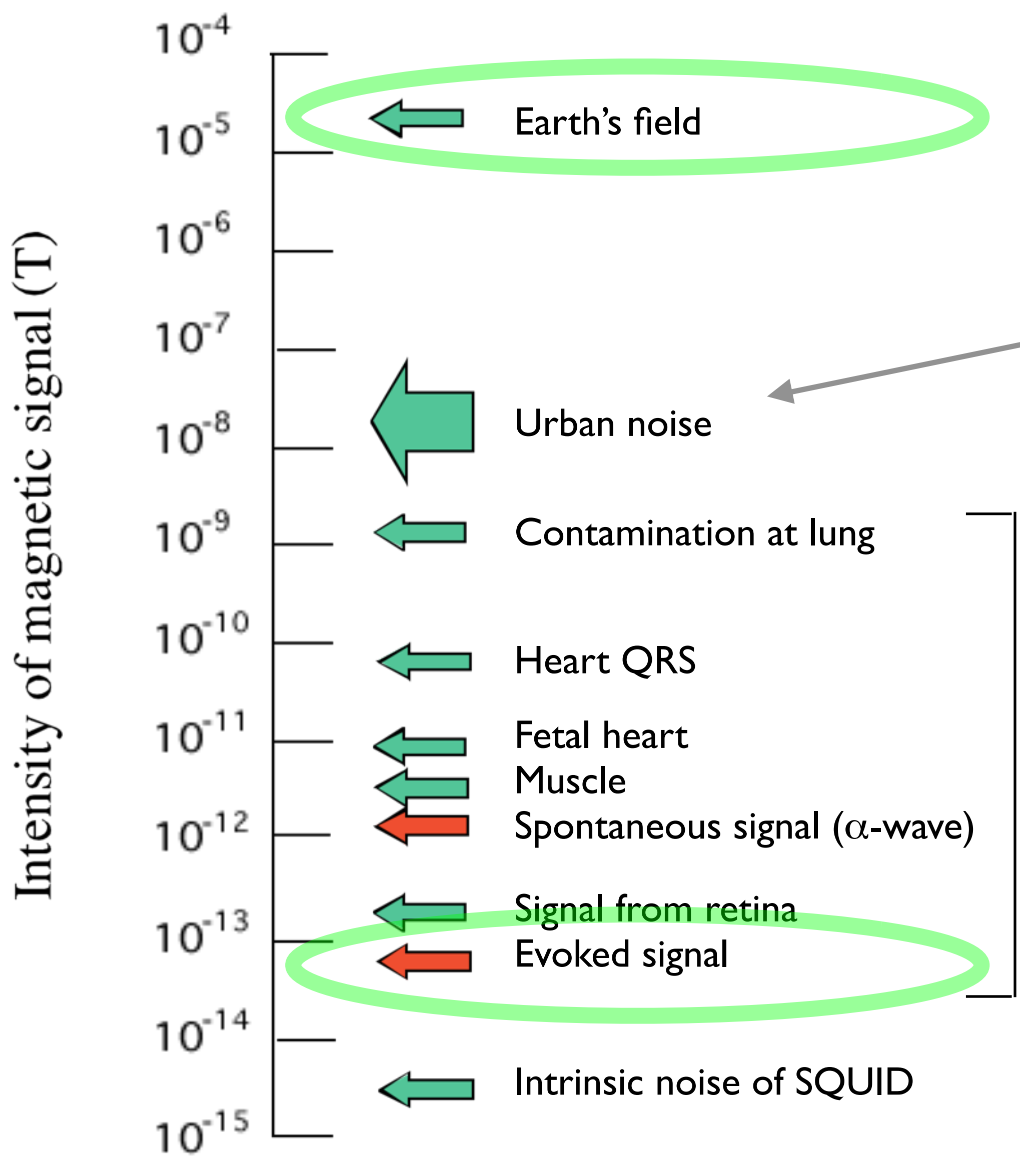
Photo by Fritz Goro

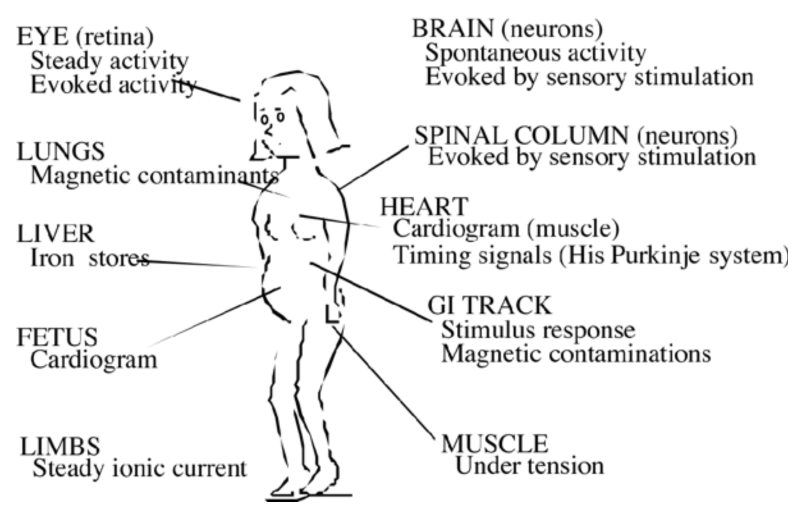




- Direct electrophysiological measurement
  - not hemodynamic
  - real-time
- No unique solution for distributed source
- Measures spatially synchronized cortical activity
- Fine temporal resolution (~ 1 ms)
- Moderate spatial resolution (~ 1 cm)

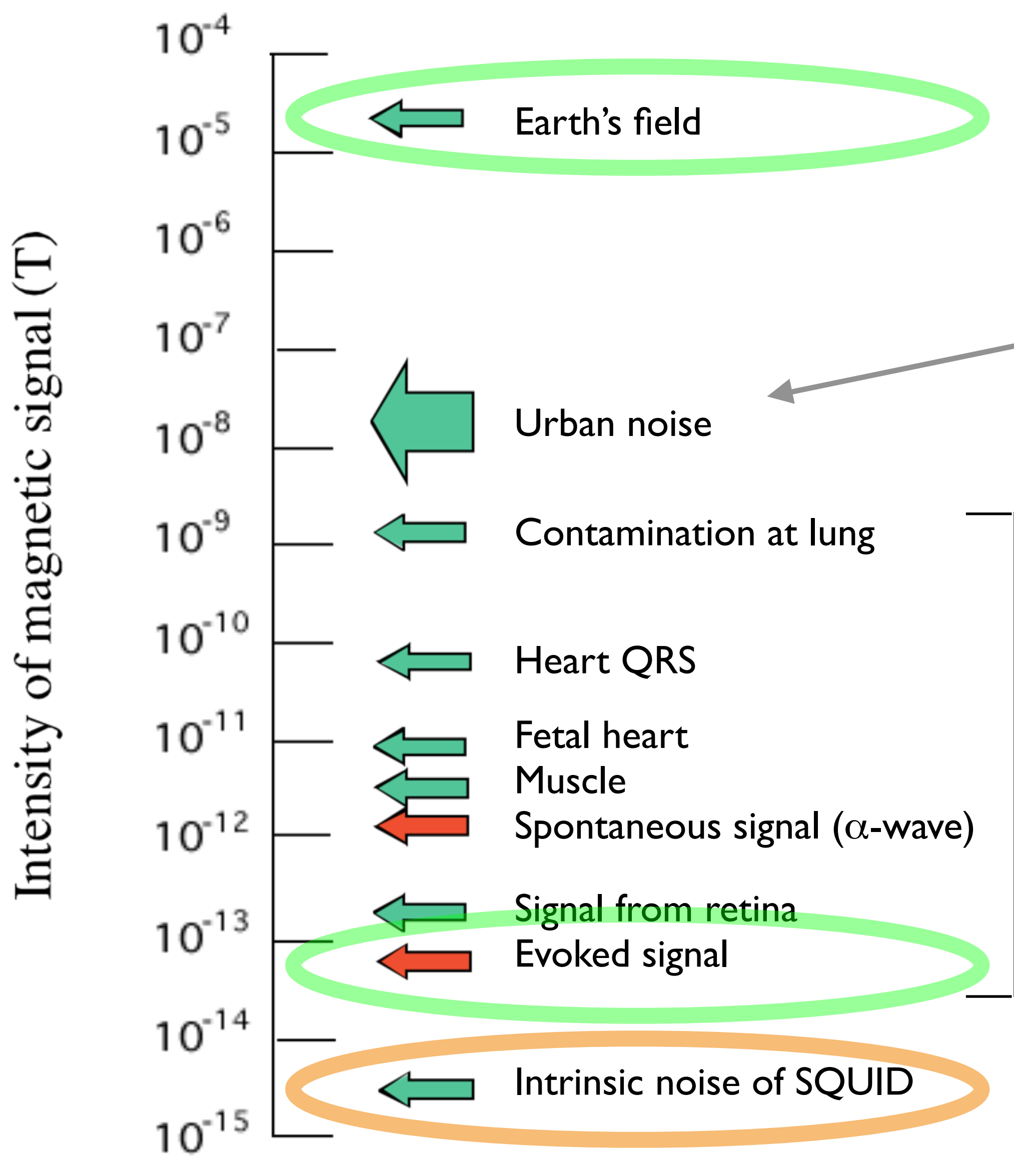
Magnetic Field Strengths

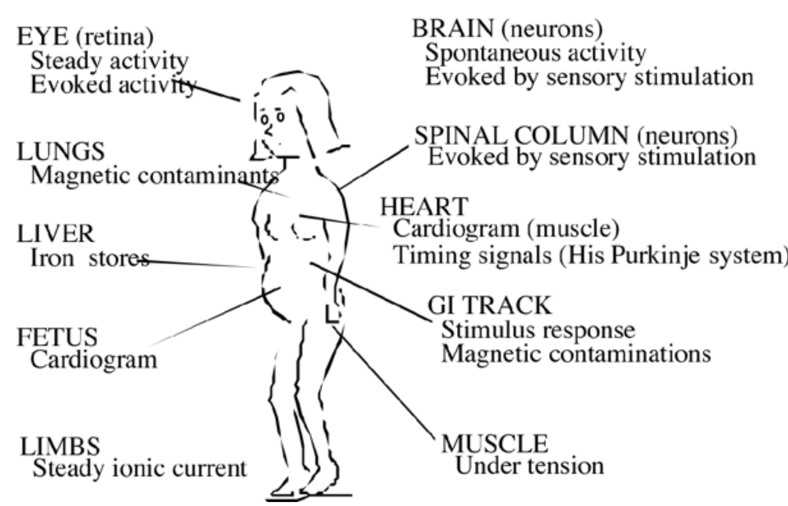




Biomagnetic Signals

Magnetic Field Strengths

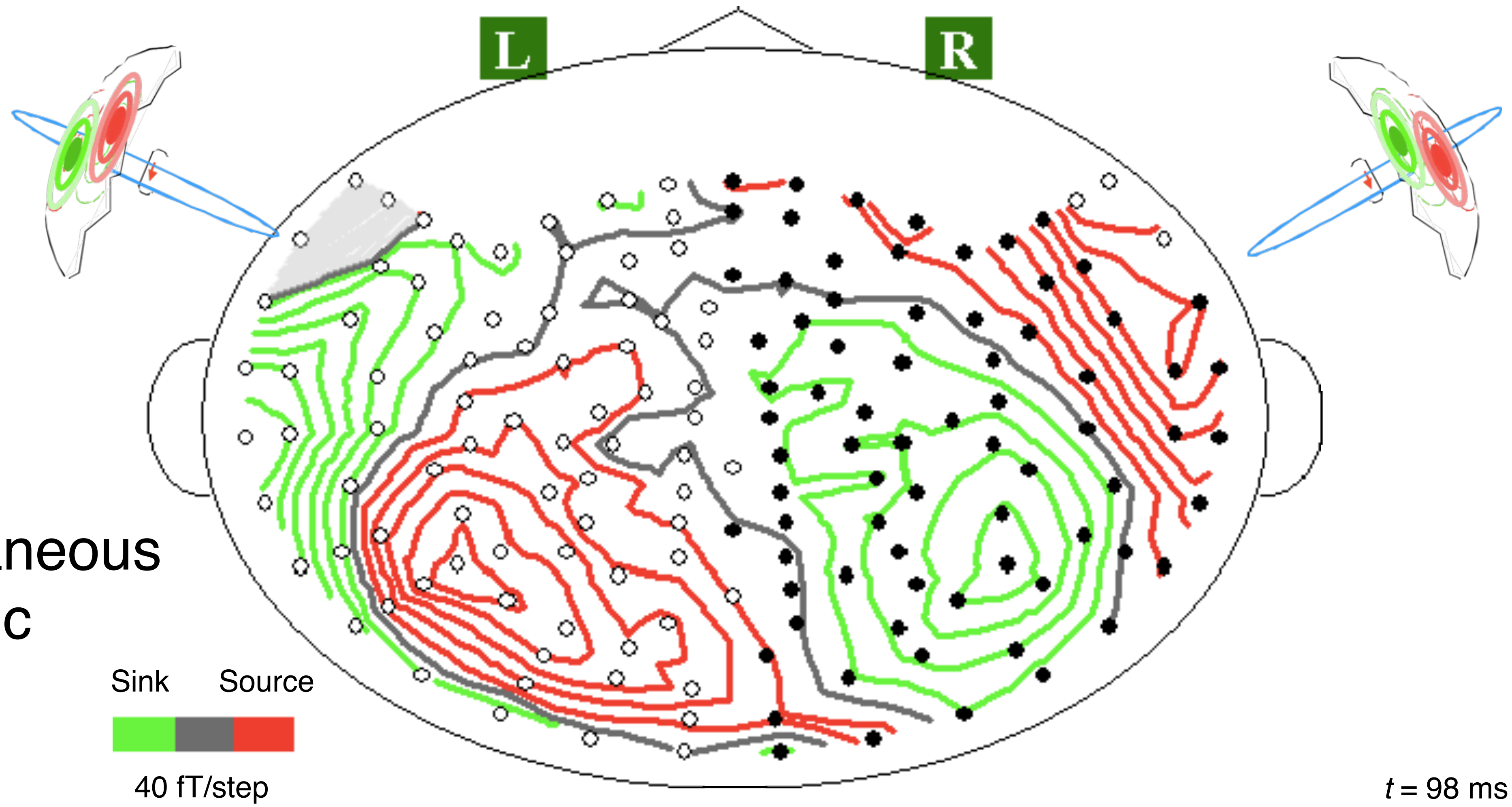




Biomagnetic Signals

MEG Auditory Field

Flattened Isofield Contour Map

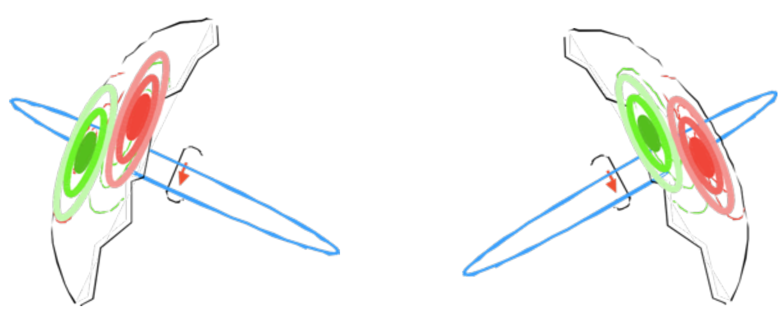


Instantaneous Magnetic Field

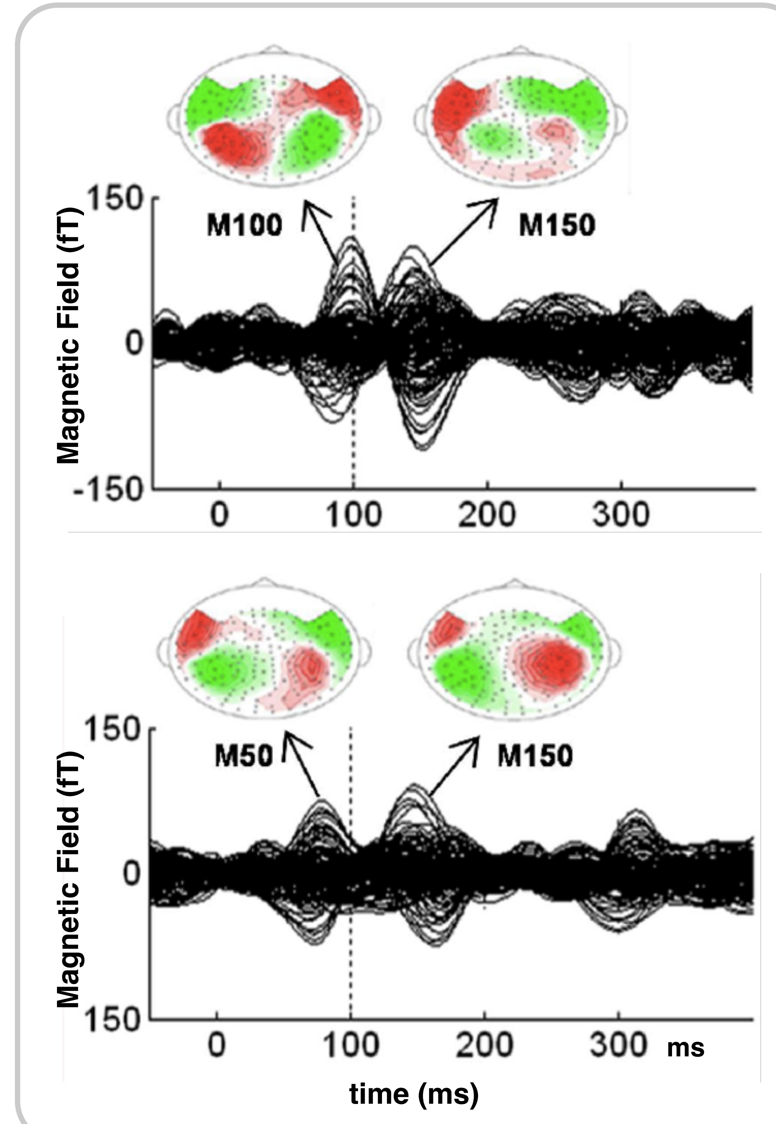
Time Course of MEG Responses

Auditory Evoked Responses

- MEG Response Patterns Time-Locked to Stimulus Events
- Robust
- Strongly Lateralized



Pure Tone



Broadband Noise

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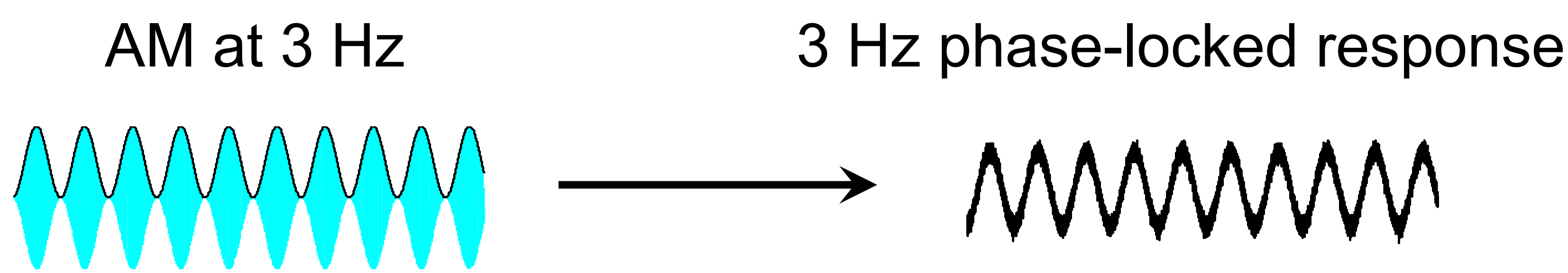
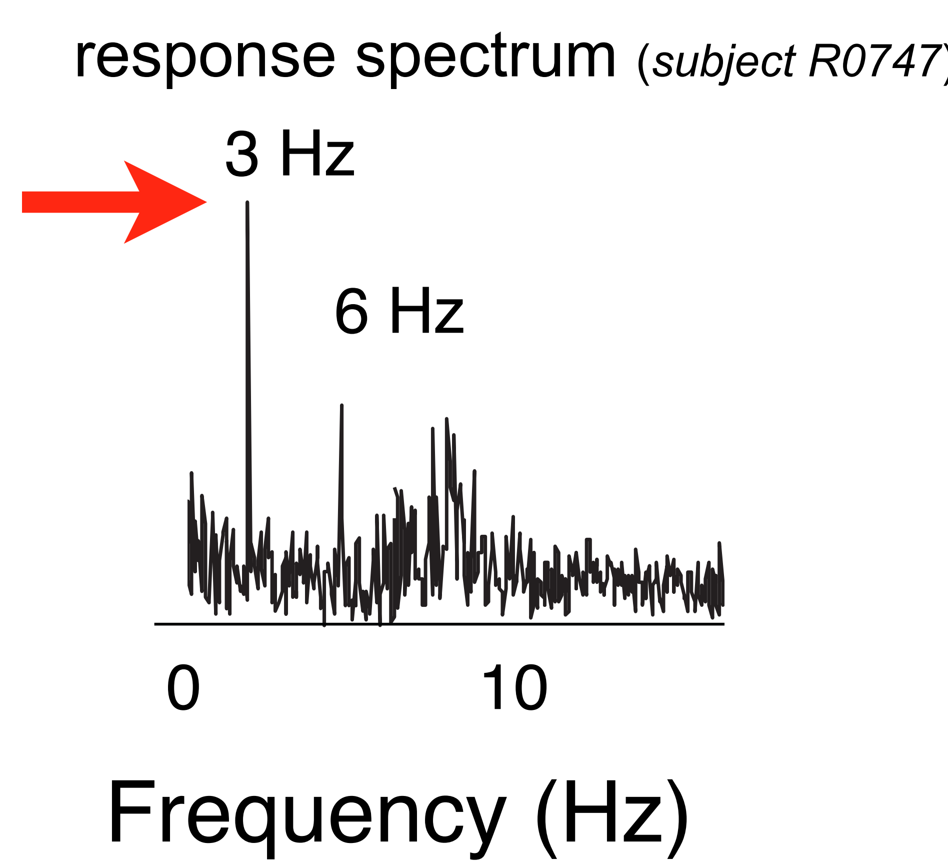
Phase-Locking in MEG to Slow Acoustic Modulations

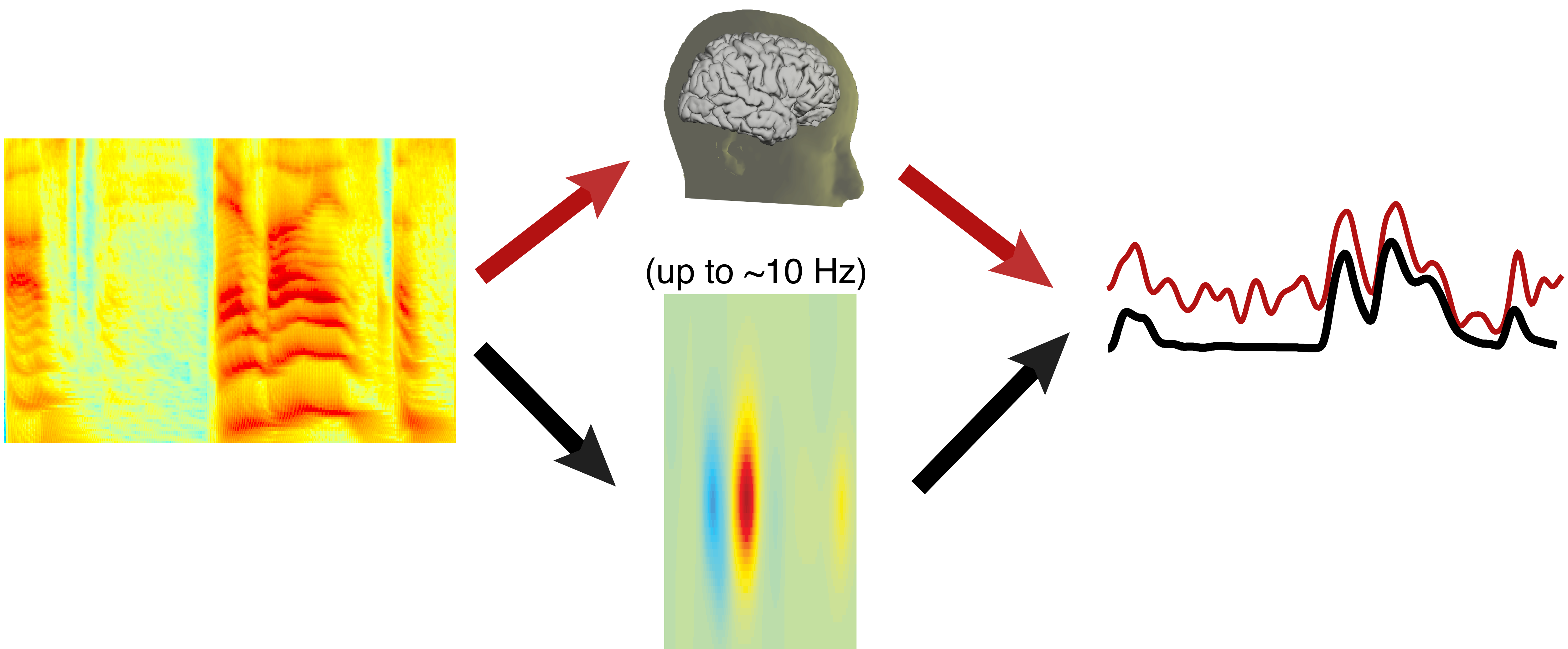


MEG activity is precisely phase-locked to temporal modulations of sound



Ding & Simon, J Neurophysiol (2009)
Wang et al., J Neurophysiol (2012)

MEG Responses Predicted by STRF Model

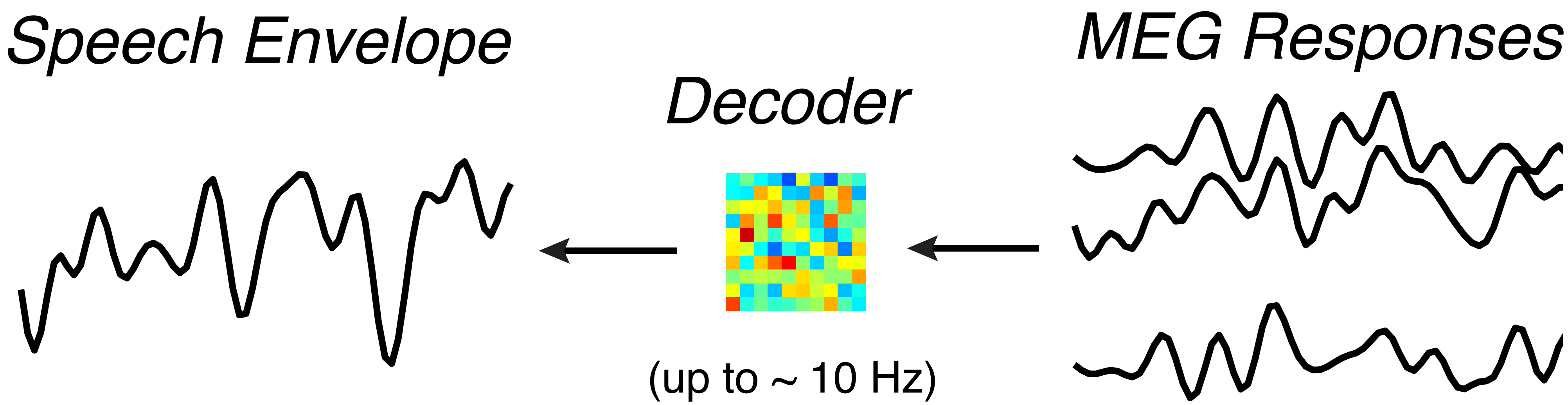


Linear Kernel = STRF

Ding & Simon, J Neurophysiol (2012)

"Spectro-Temporal Response Function"

Neural Reconstruction of Speech Envelope



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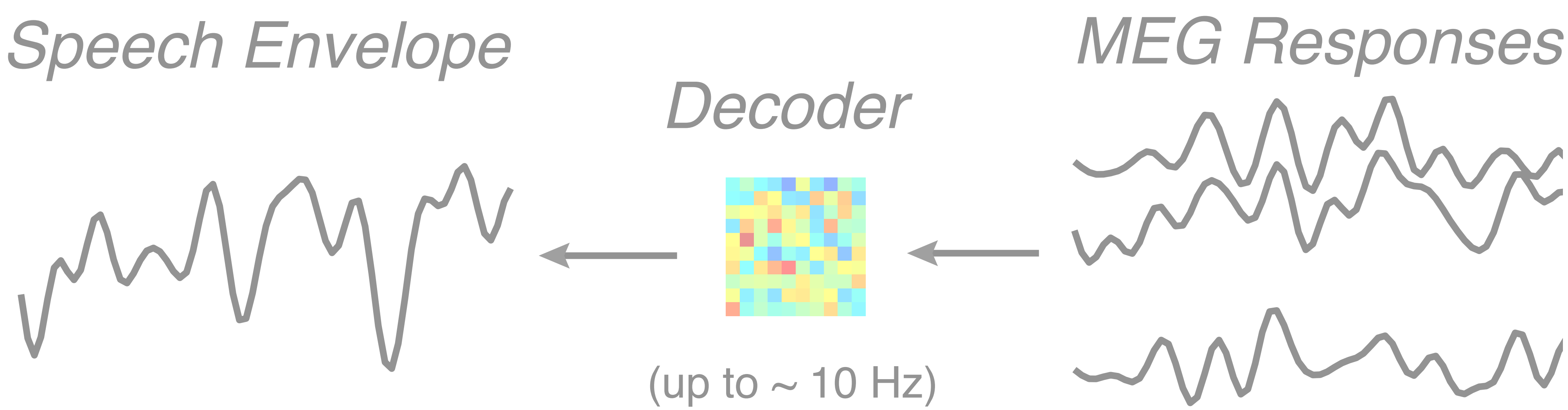
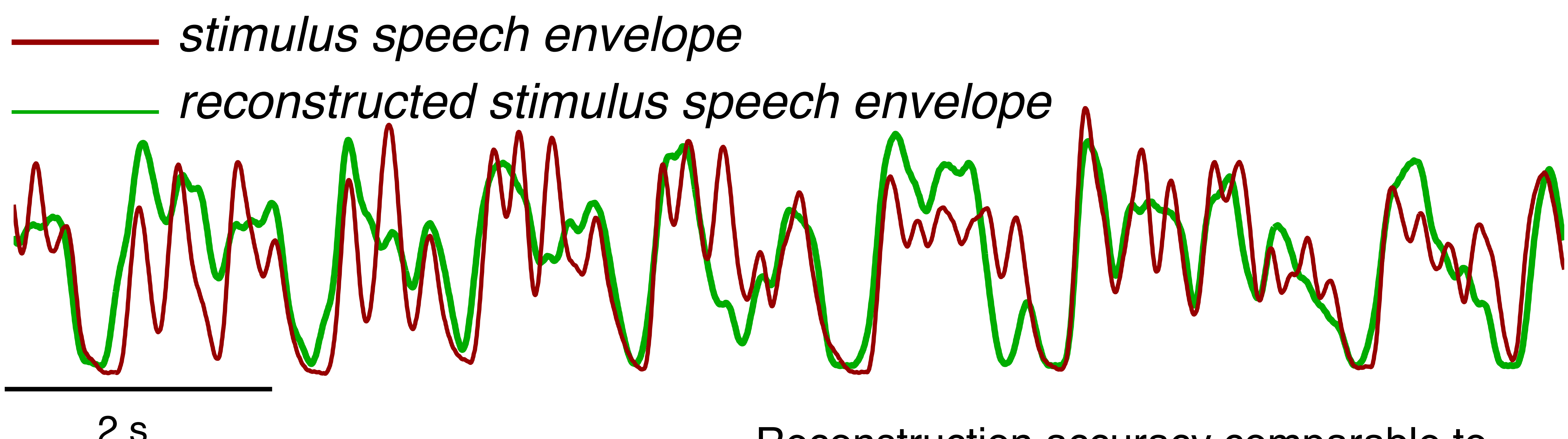
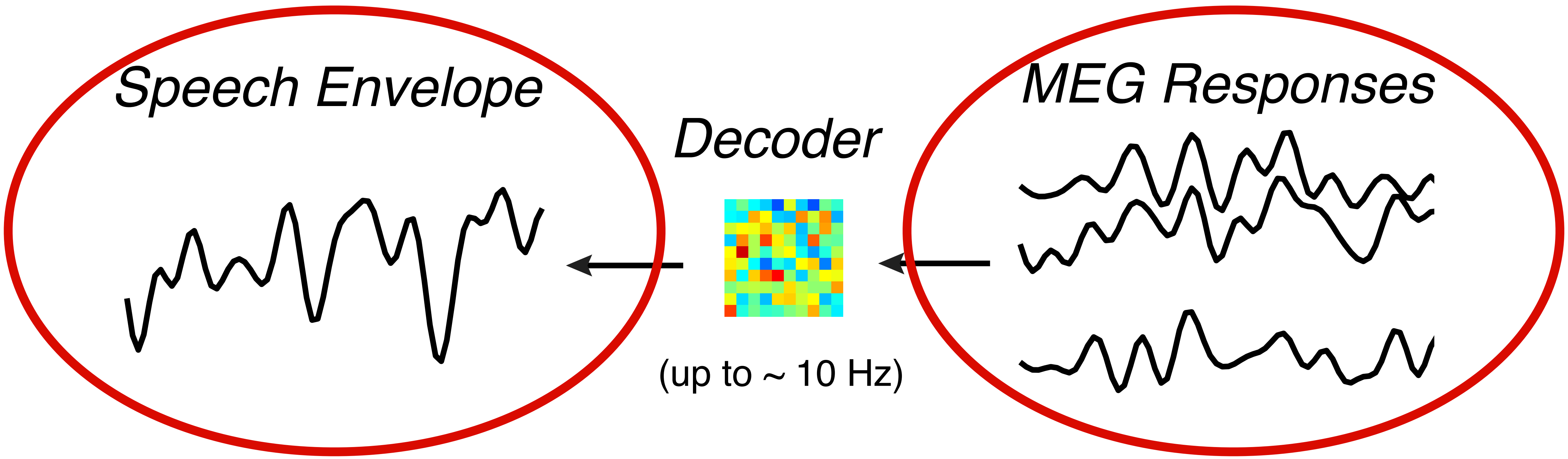


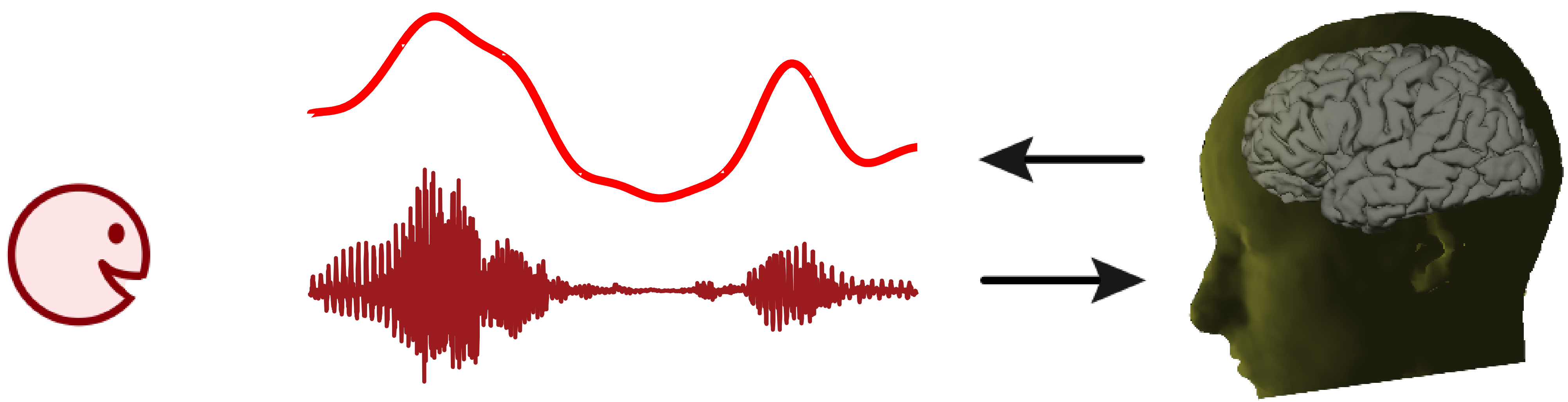


Reconstruction accuracy comparable to single unit & ECoG recordings

Ding & Simon, J Neurophysiol (2012)
Zion-Golumbic et al., Neuron (2013)


Speech Envelope
Decoder
(up to ~ 10 Hz)
MEG Responses

Selective Neural Encoding



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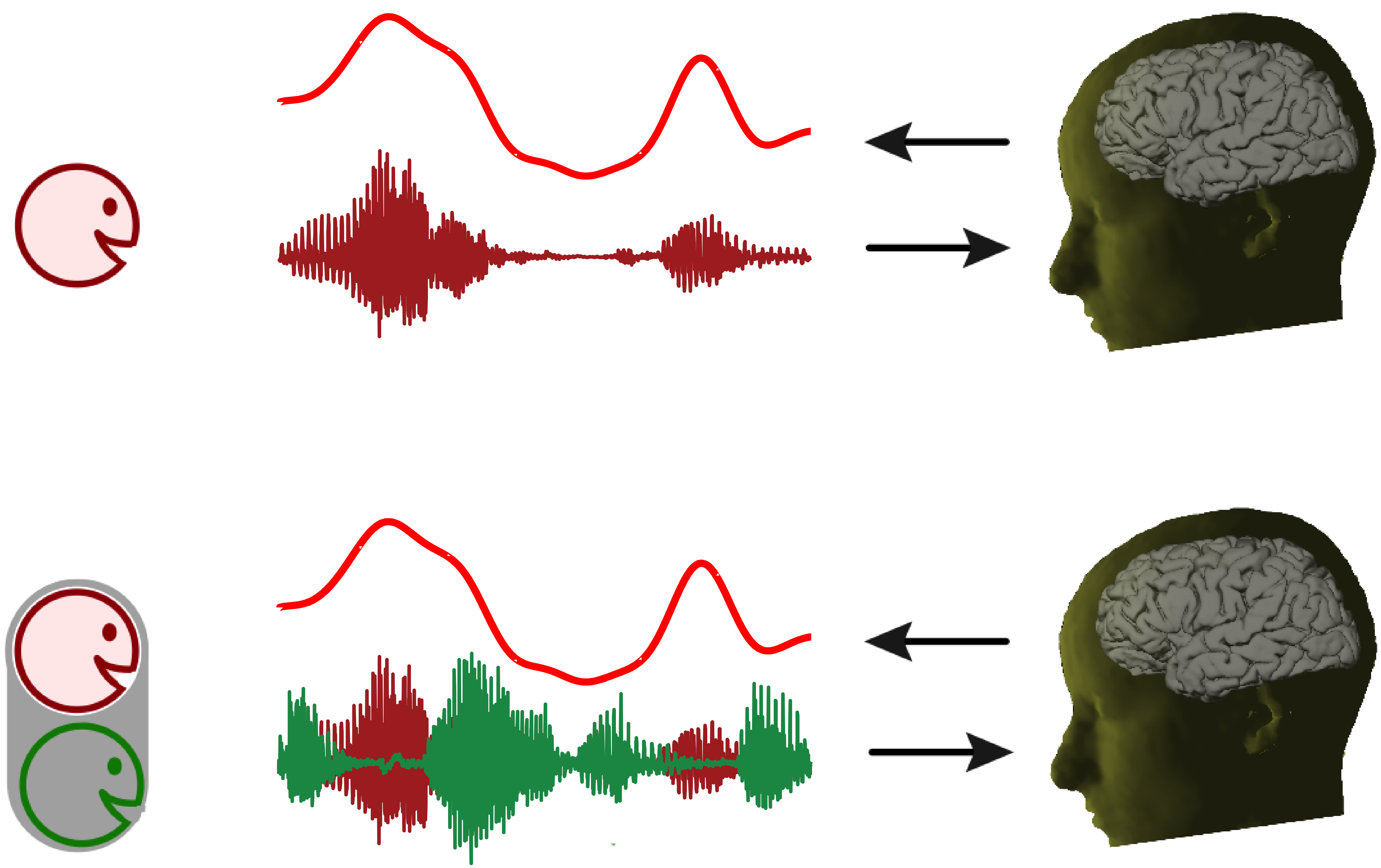

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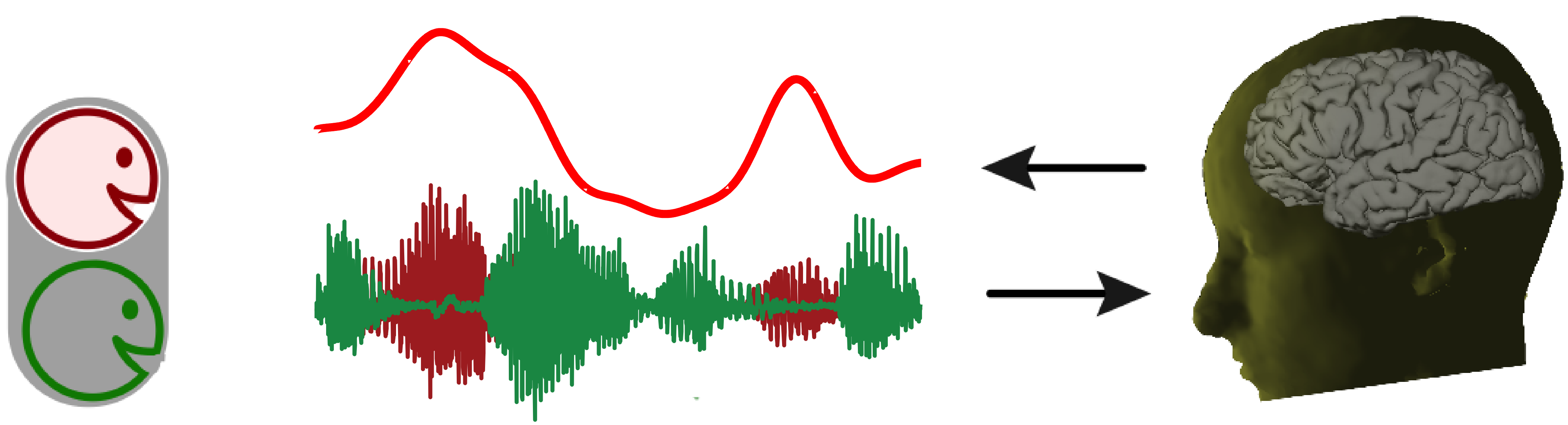
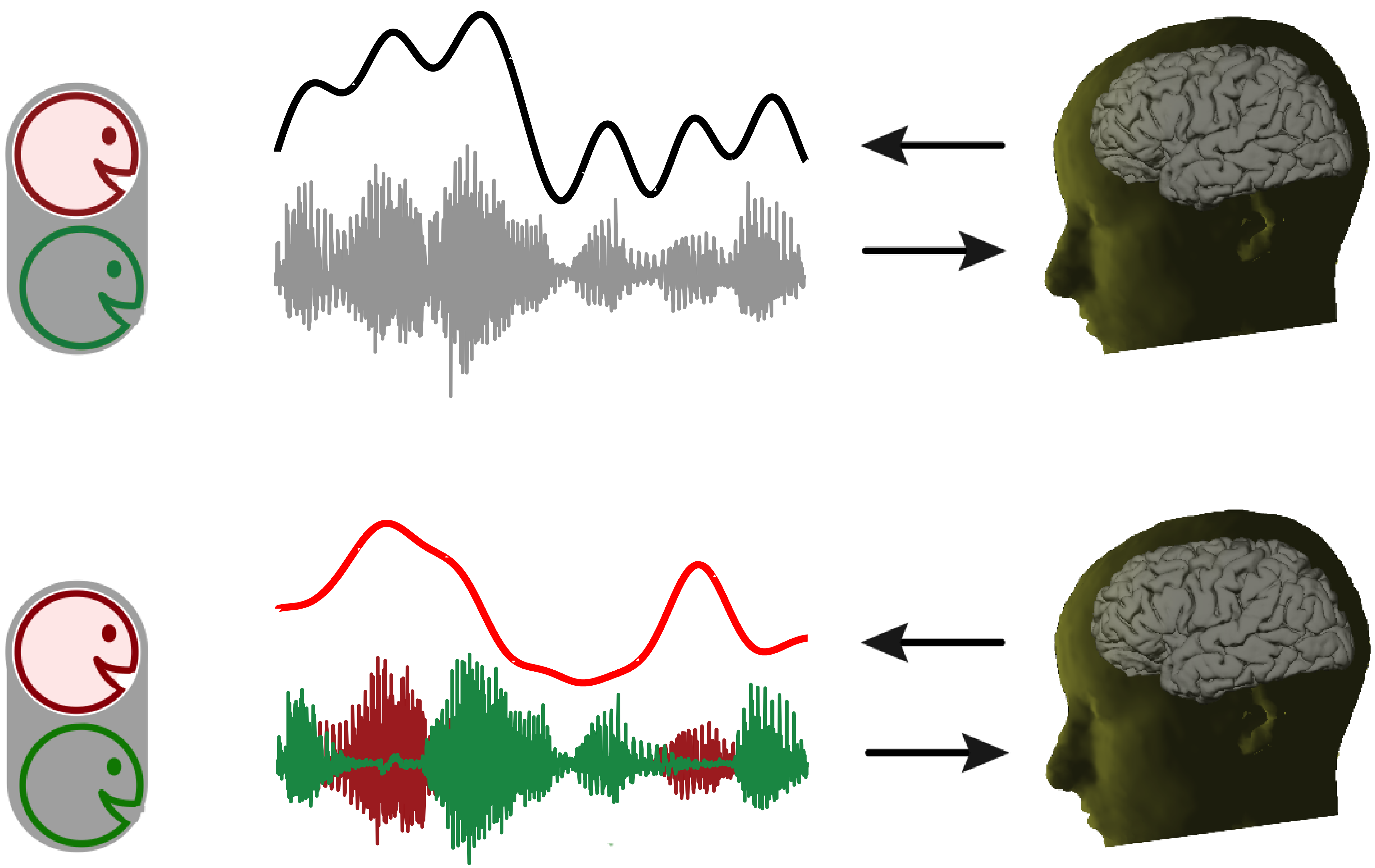


Unselective vs. Selective Neural Encoding



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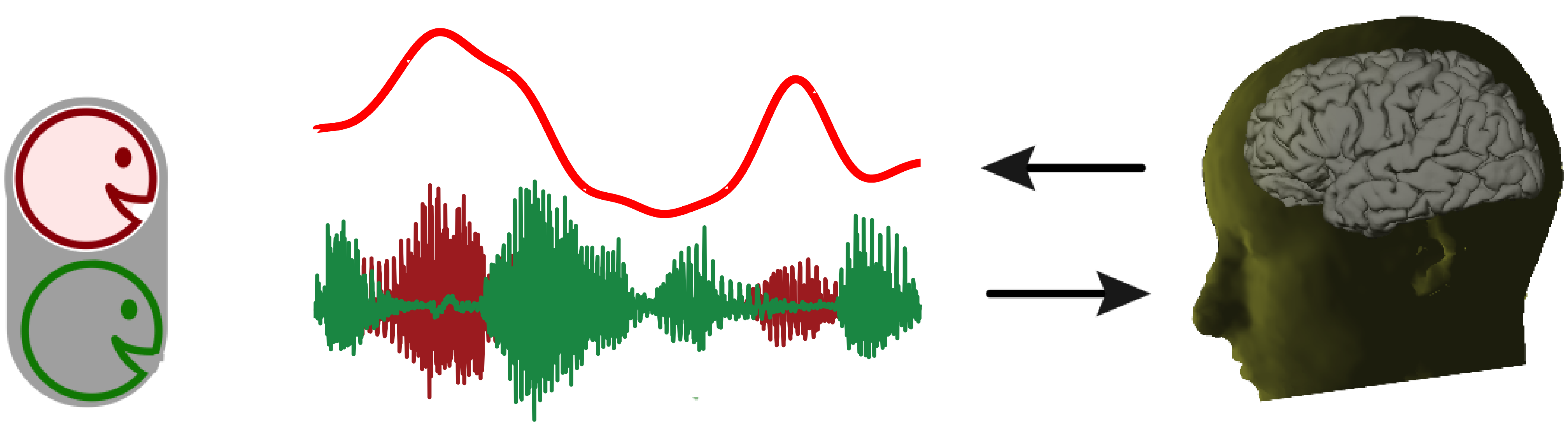

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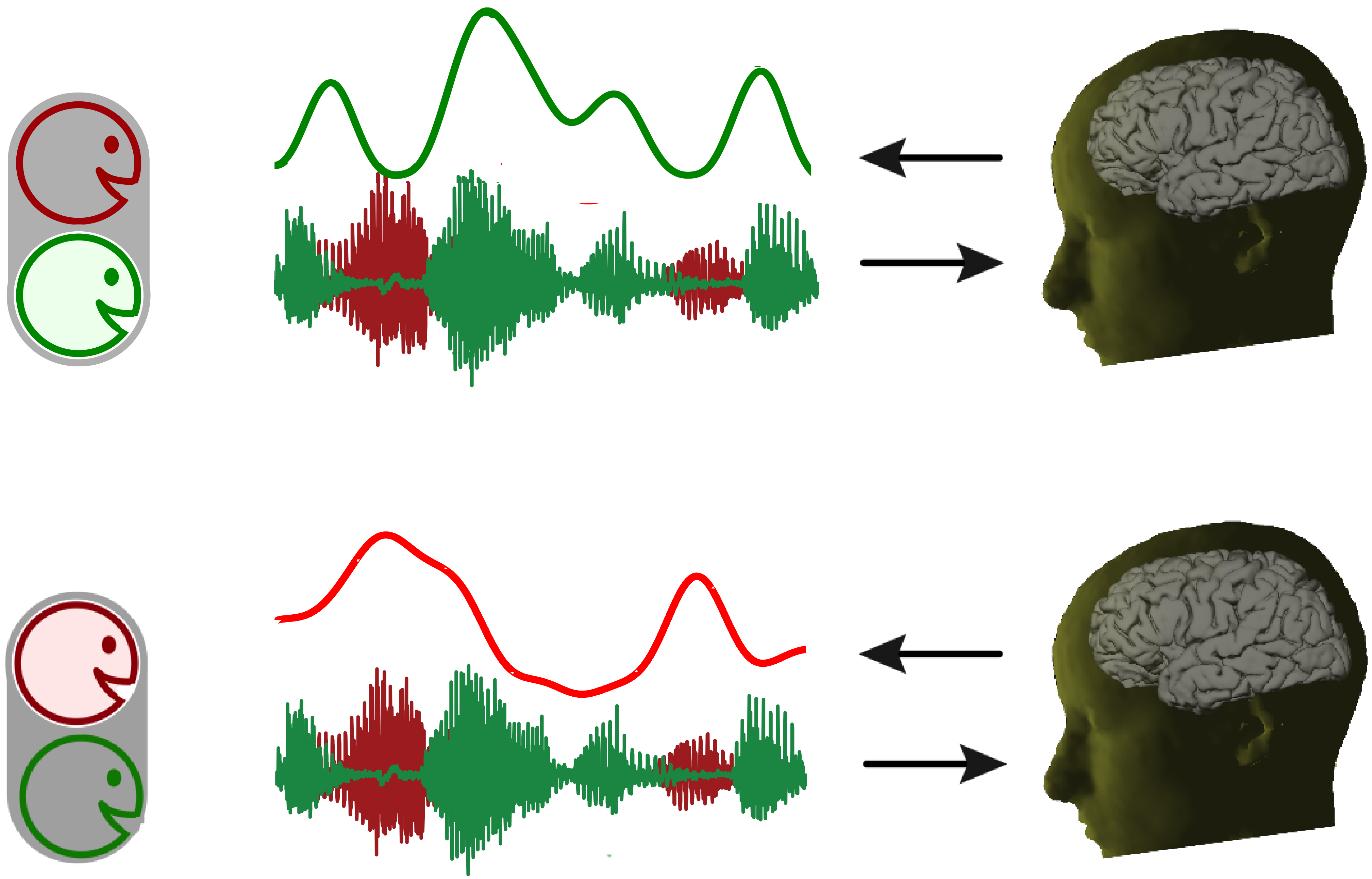
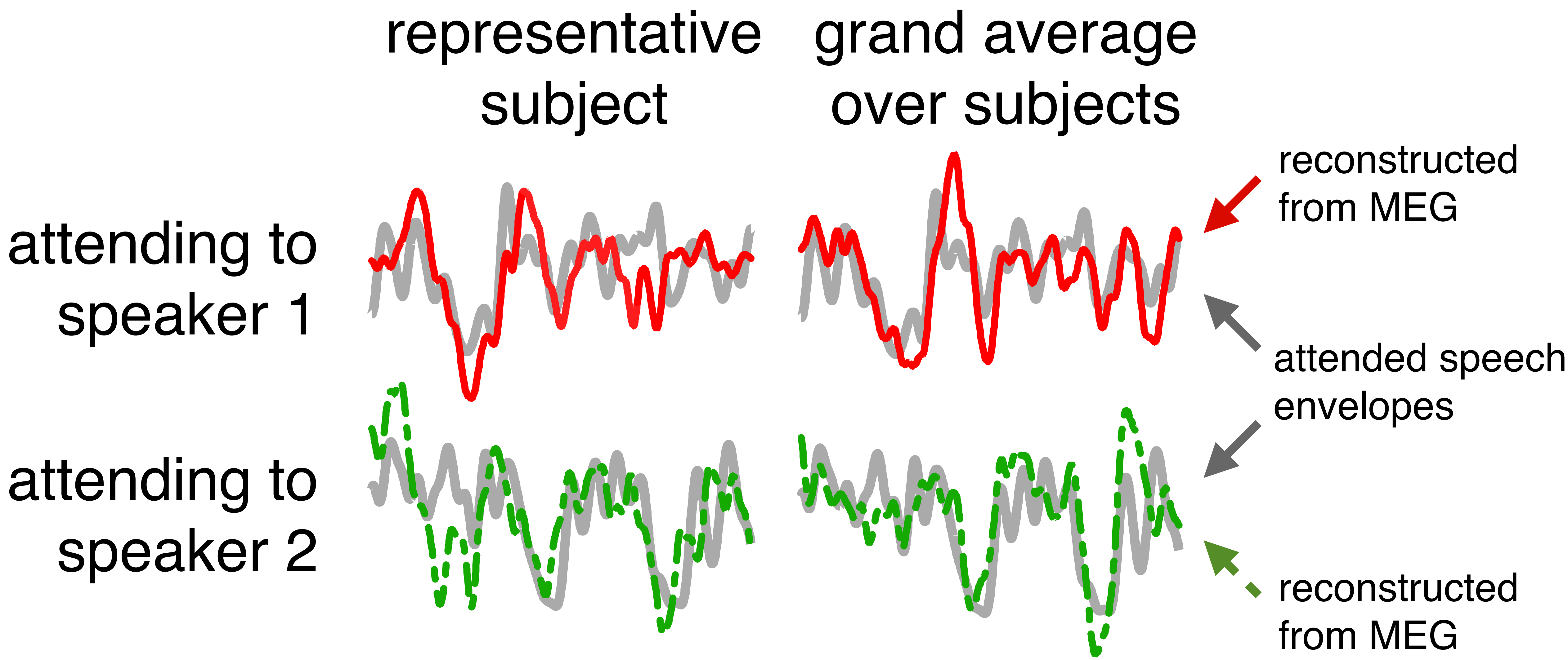


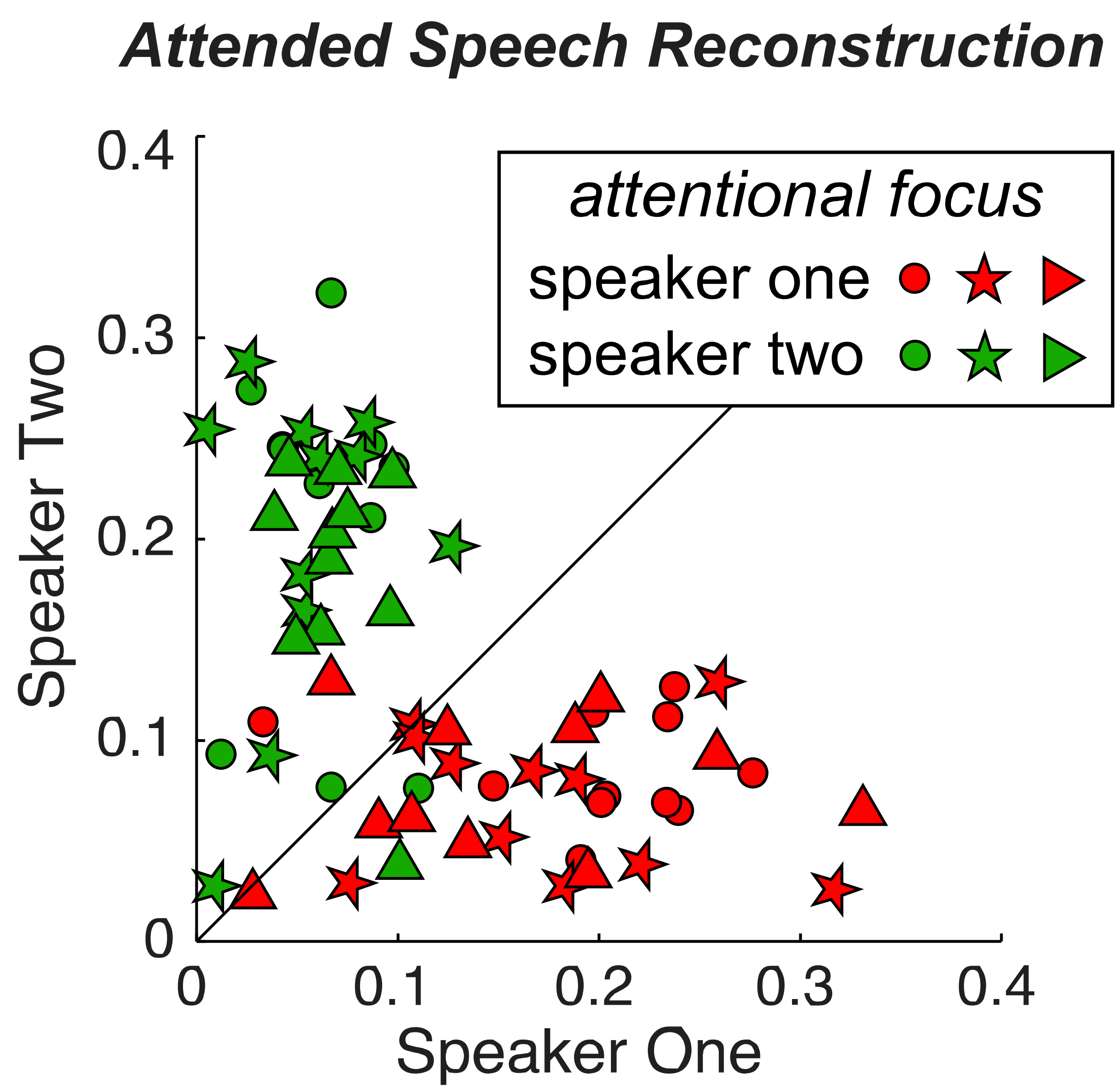
Speech Reconstruction Results



Identical Stimuli!

Ding & Simon, PNAS (2012)

Single Trial Speech Reconstruction



Ding & Simon, PNAS (2012)

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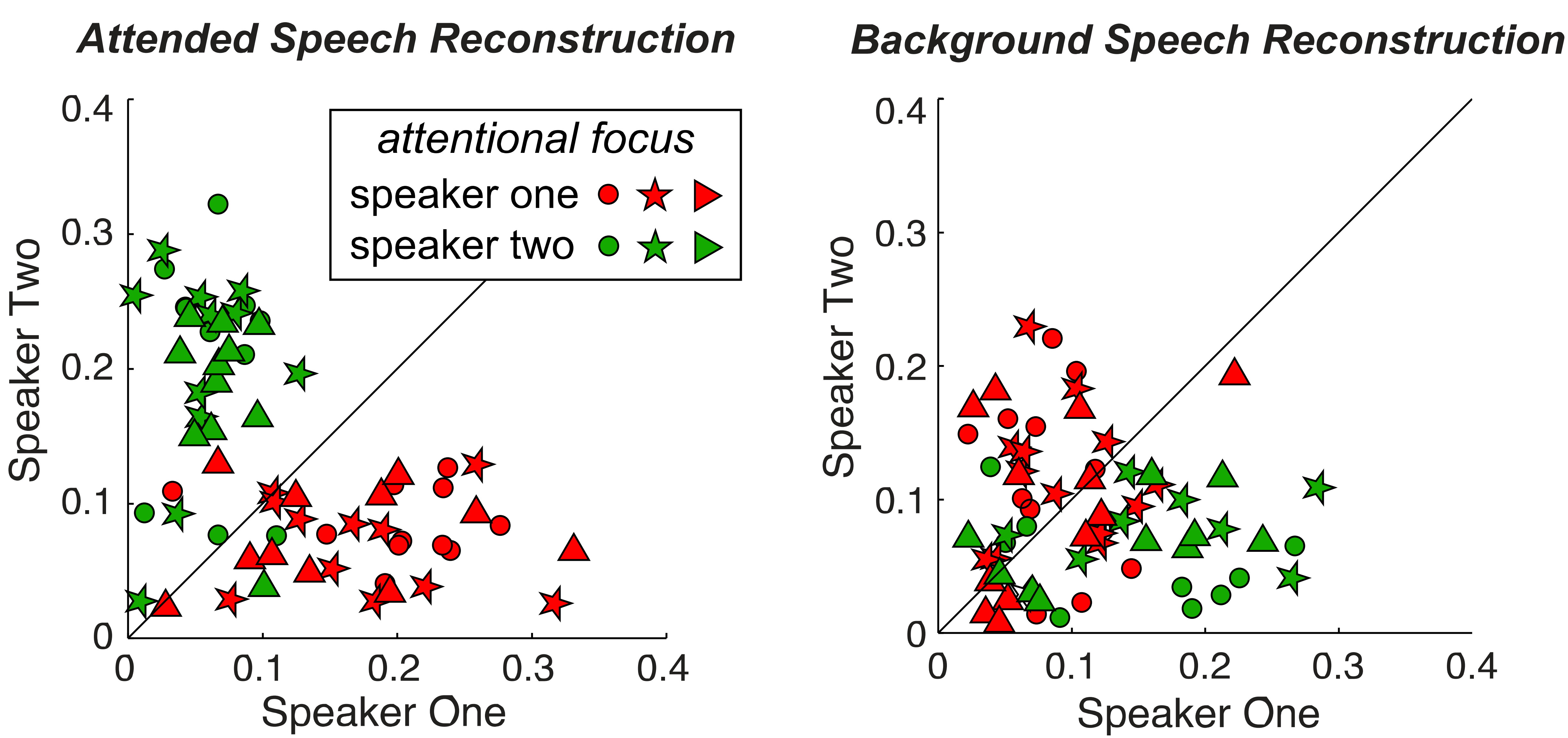

Neural Detection of Attended Voice: Summary

- Can tell *which voice* a listener is attending to
- Can even track *speech envelope* of that voice
- Since attention can be manipulated (familiar vs. unfamiliar speaker, familiar vs. unfamiliar language, familiar vs. unfamiliar verbal content):

Access to familiarity of voice / speech content

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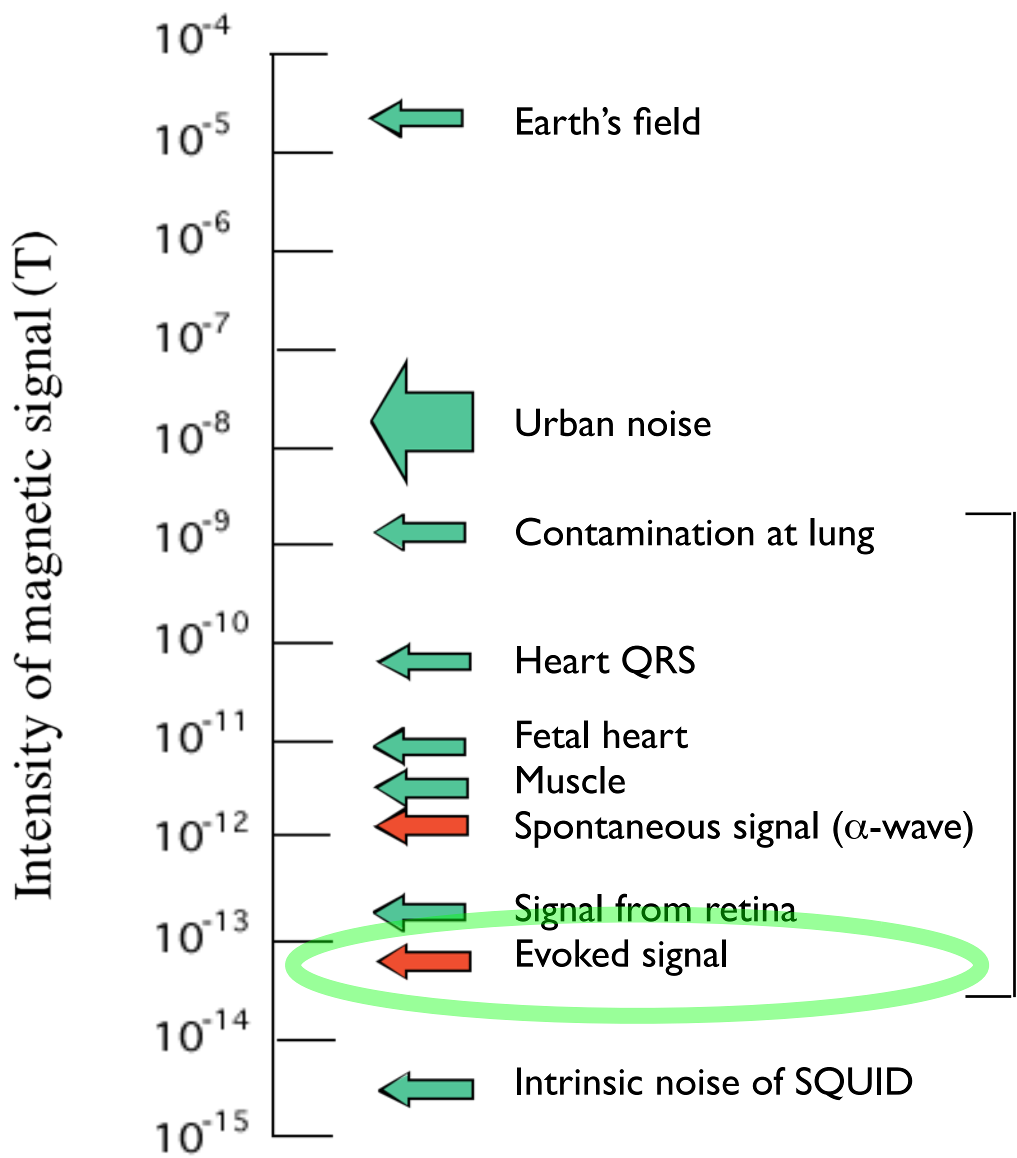

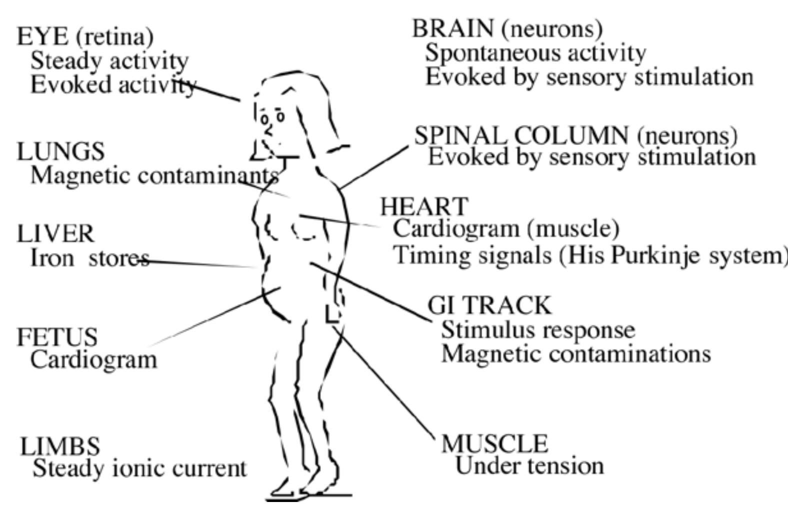

Biomagnetic Signals

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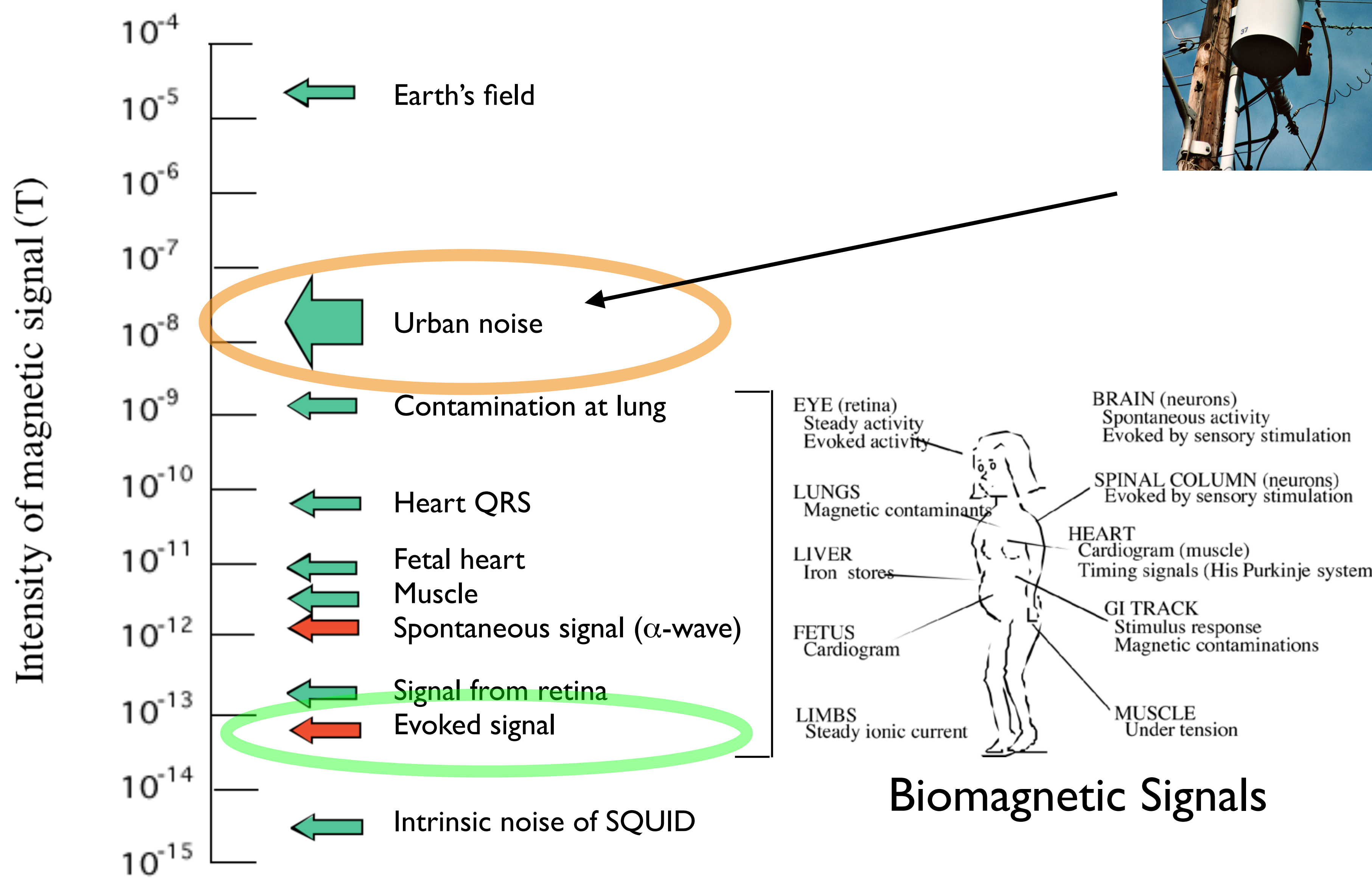

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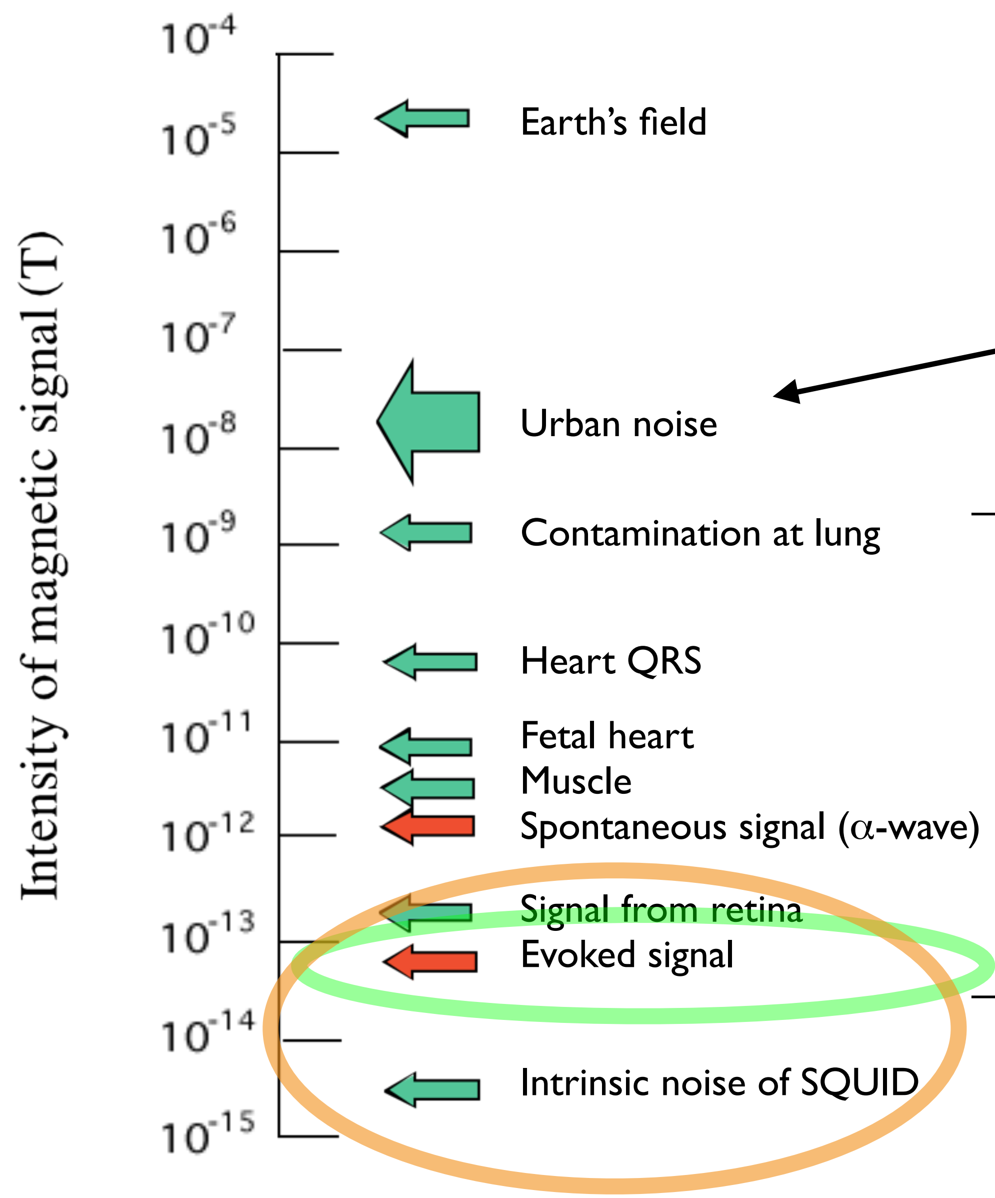

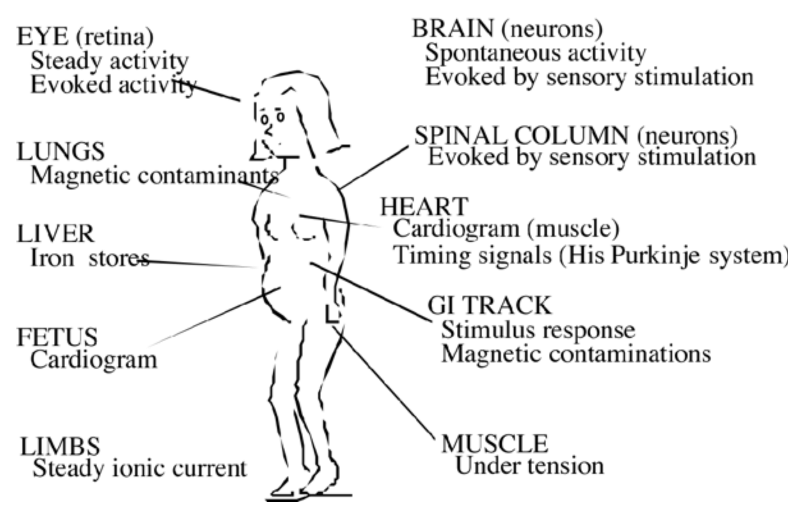

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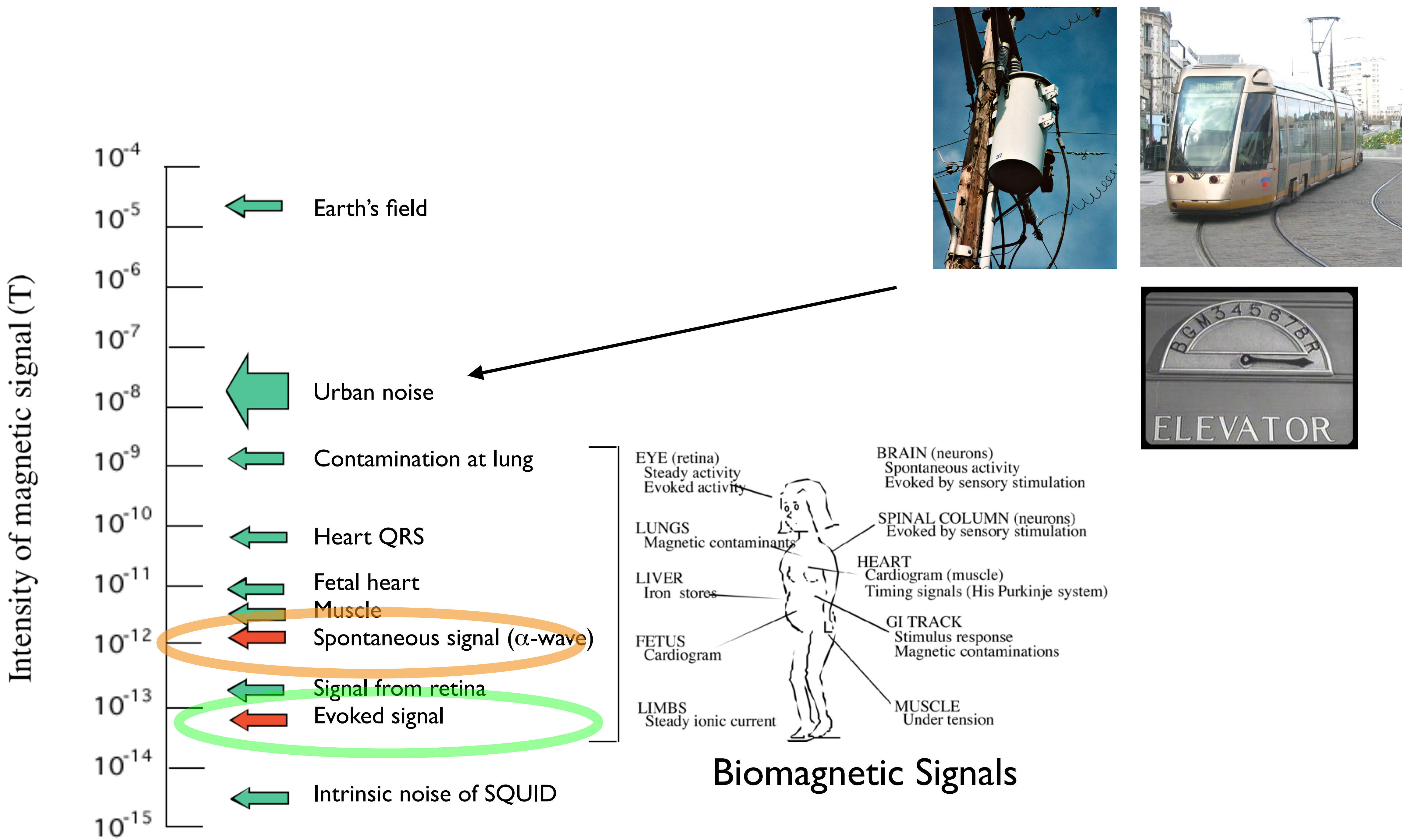
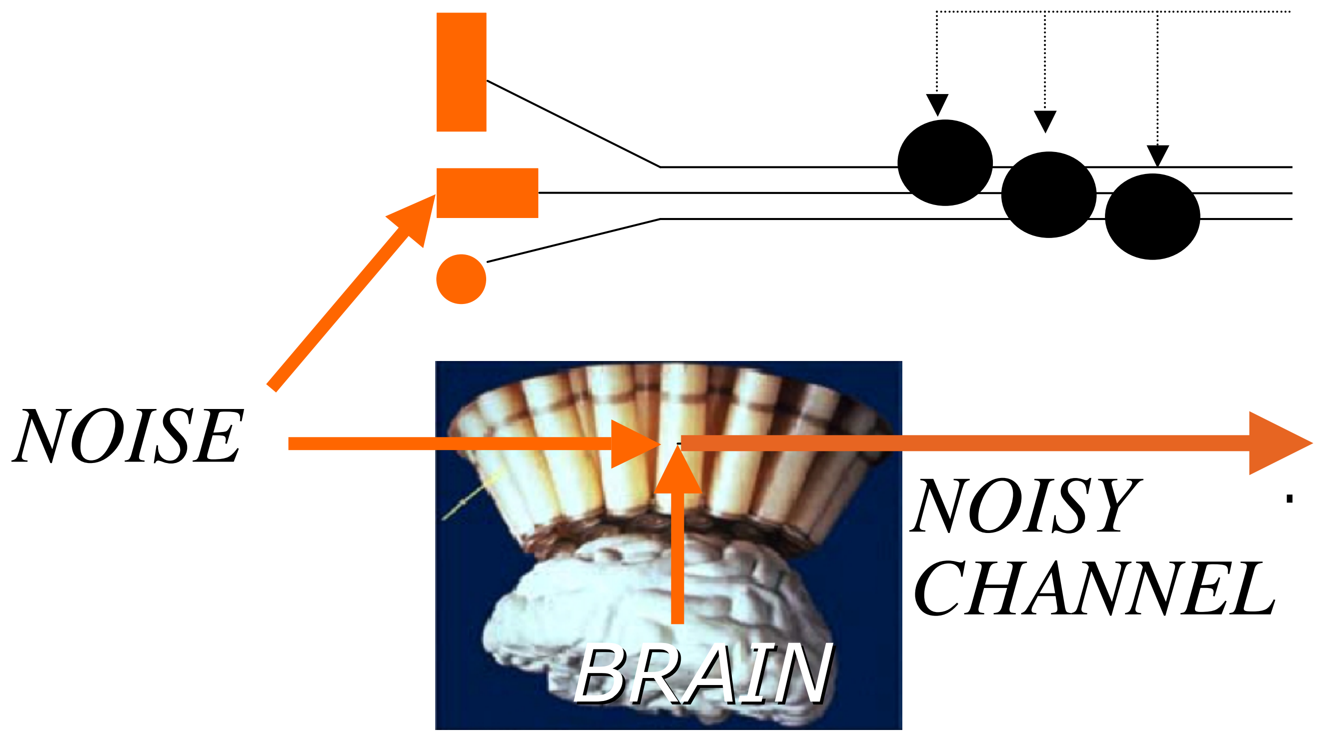


External Noise

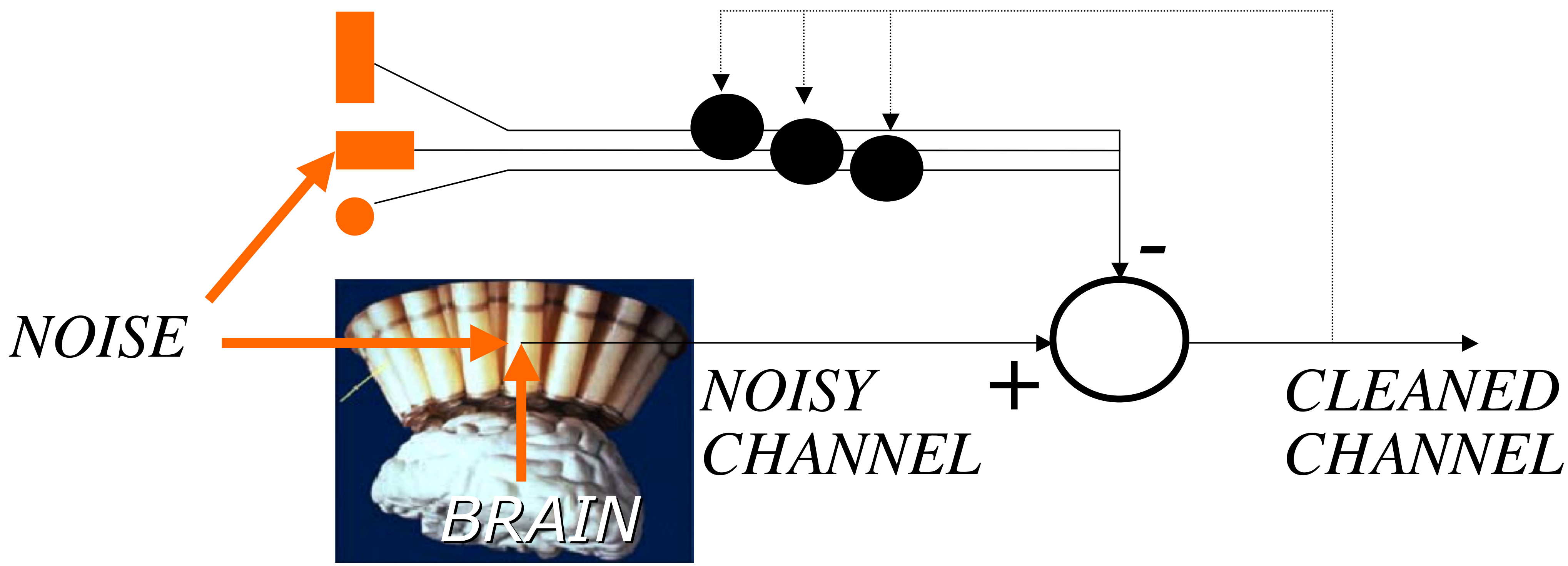
External Noise

Can be estimated using Reference Channels



External Noise Removal: 1

c.f. Classic Scalar Regression



External Noise Removal: I

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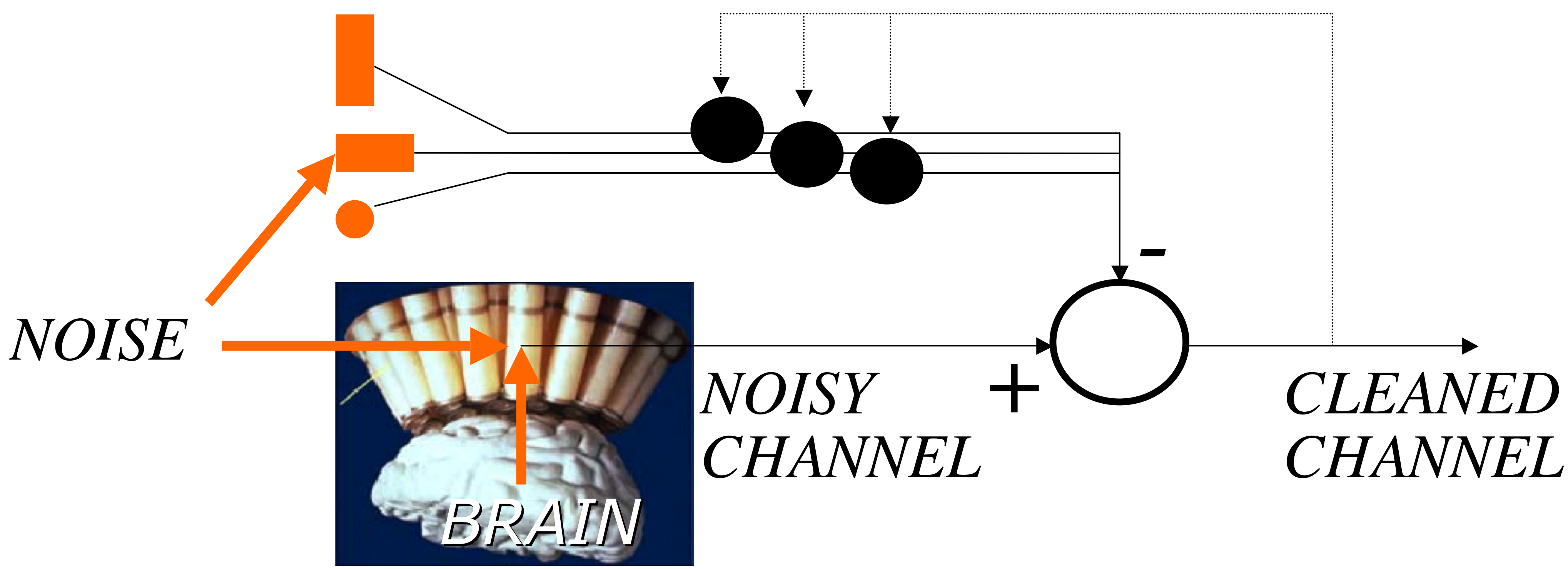
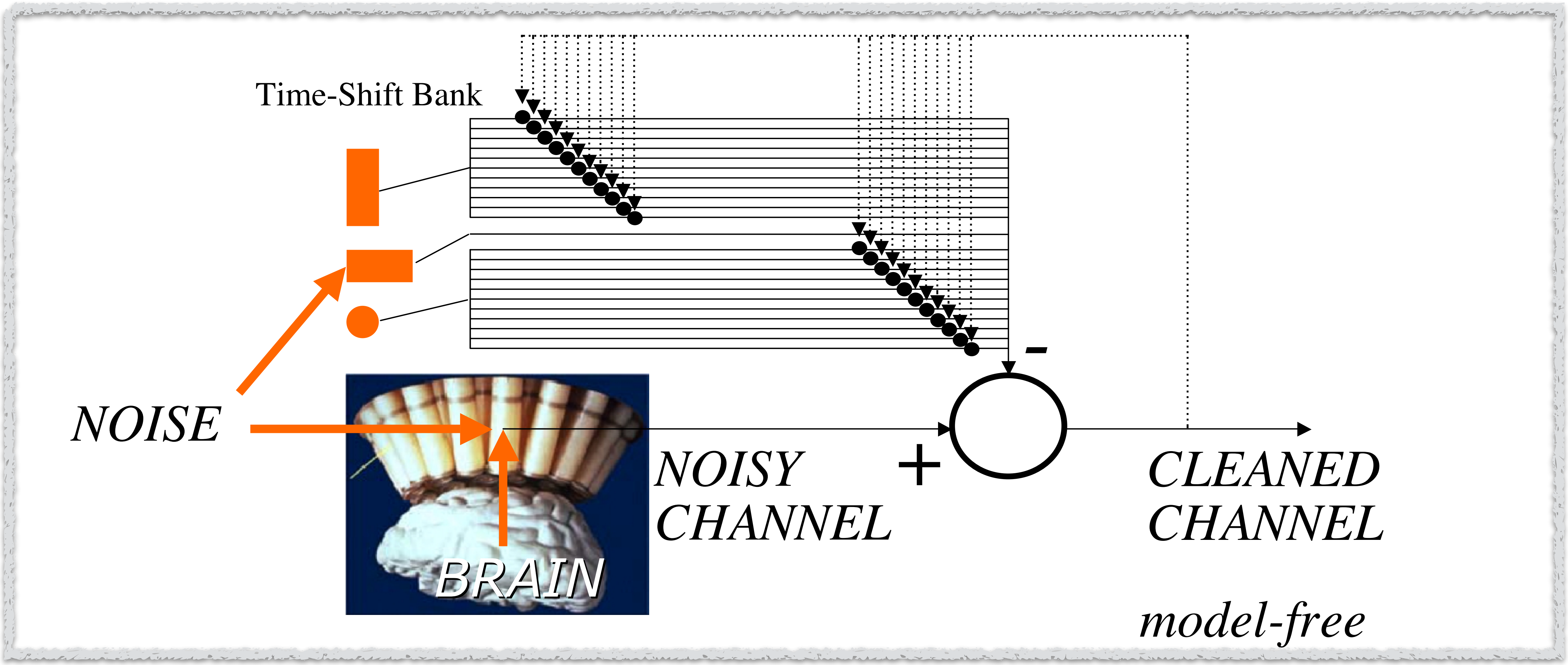


But scalar regression fails when:

- Noise Reference is *filtered* with respect to Noisy channel
- Noise Reference is *time-shifted* with respect to Noisy channel
- More independent Noise sources than Reference channels

External Noise Reduction: TSPCA

Time-Shift Principle Component Analysis



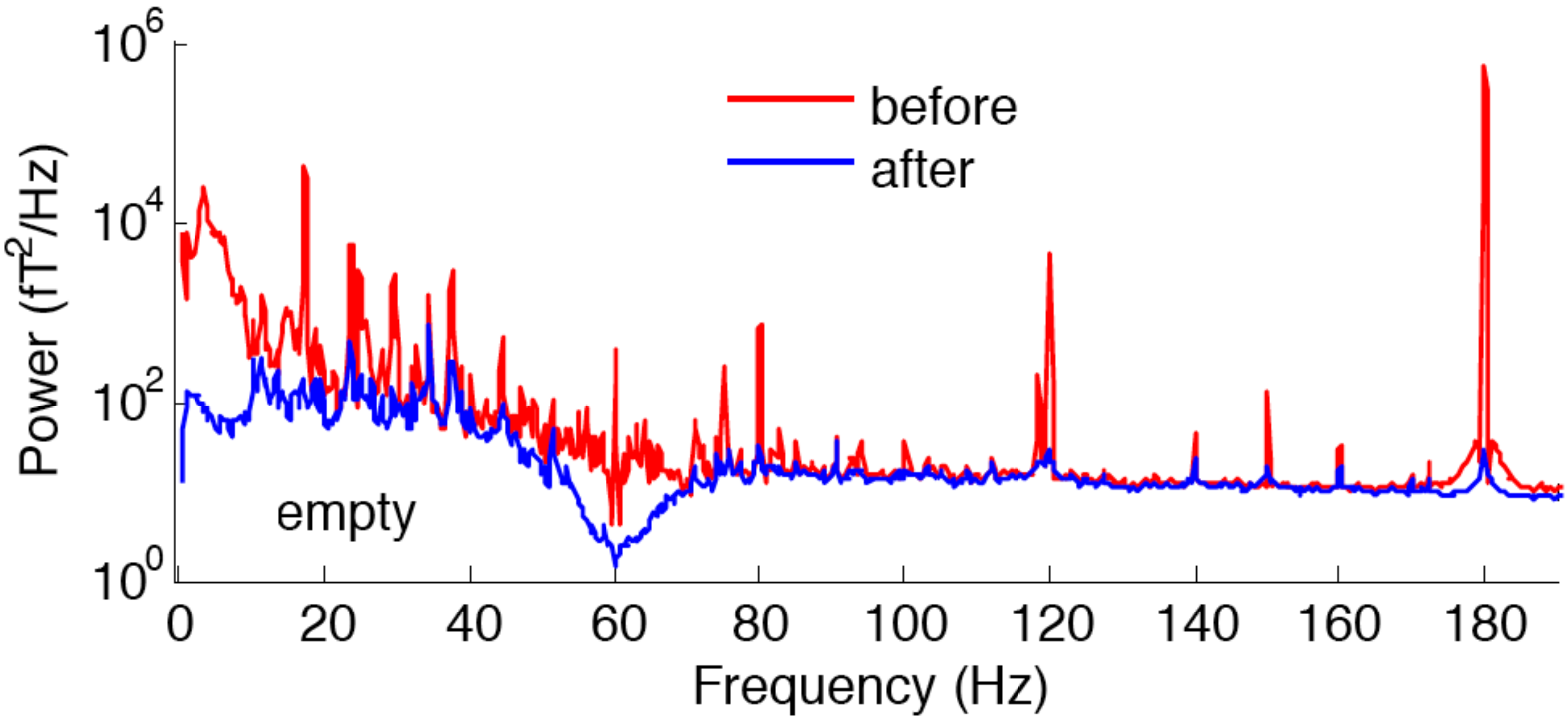
Generalizes Scalar Regression:

- Include Multiple Time-Shifted versions of References
- Linear Combinations (PCA) of Time-Shifts are Filters
- Increases *effective* number of References

de Cheveigné and Simon, J. Neurosci. Methods (2007)

External Noise Reduction: TSPCA

Signal cleaned using TSPCA and 3 Reference channels



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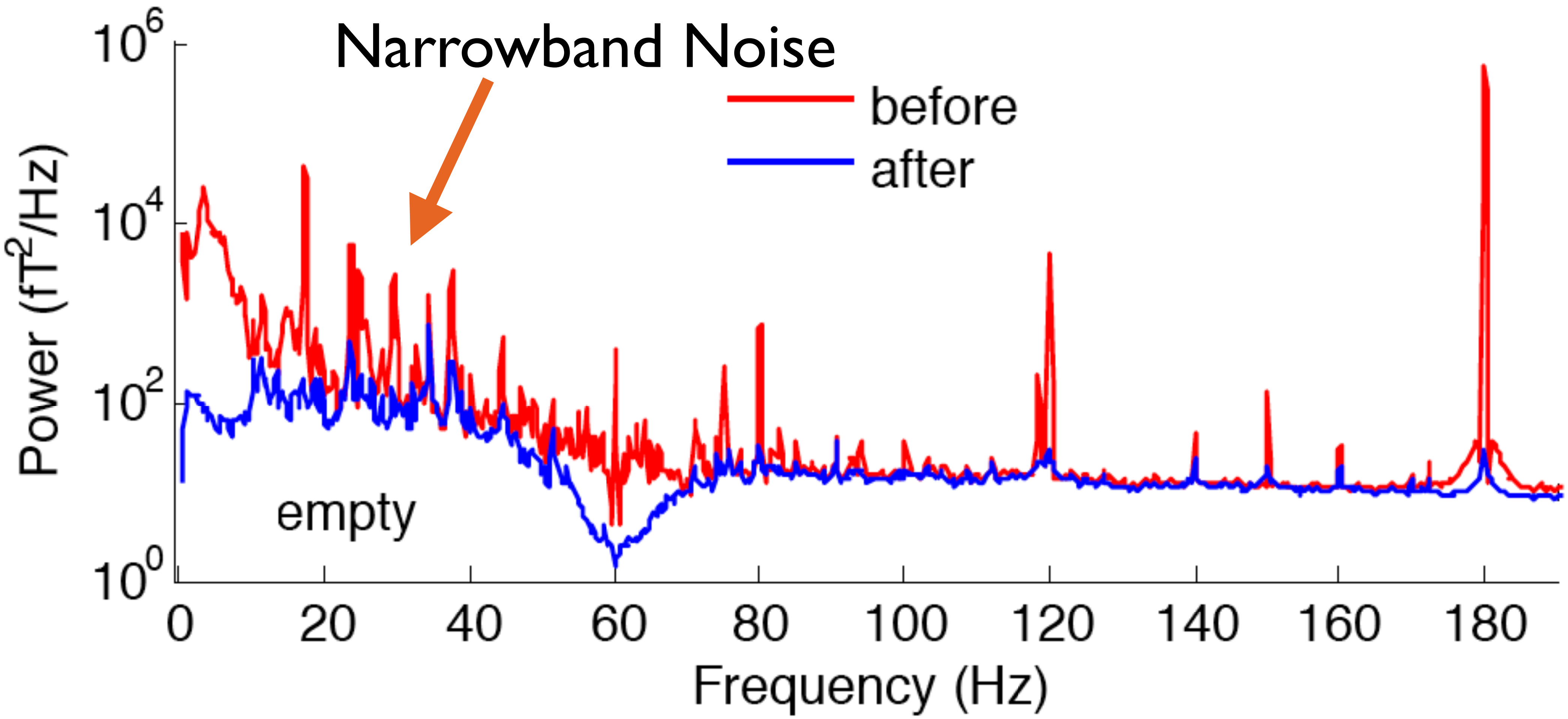

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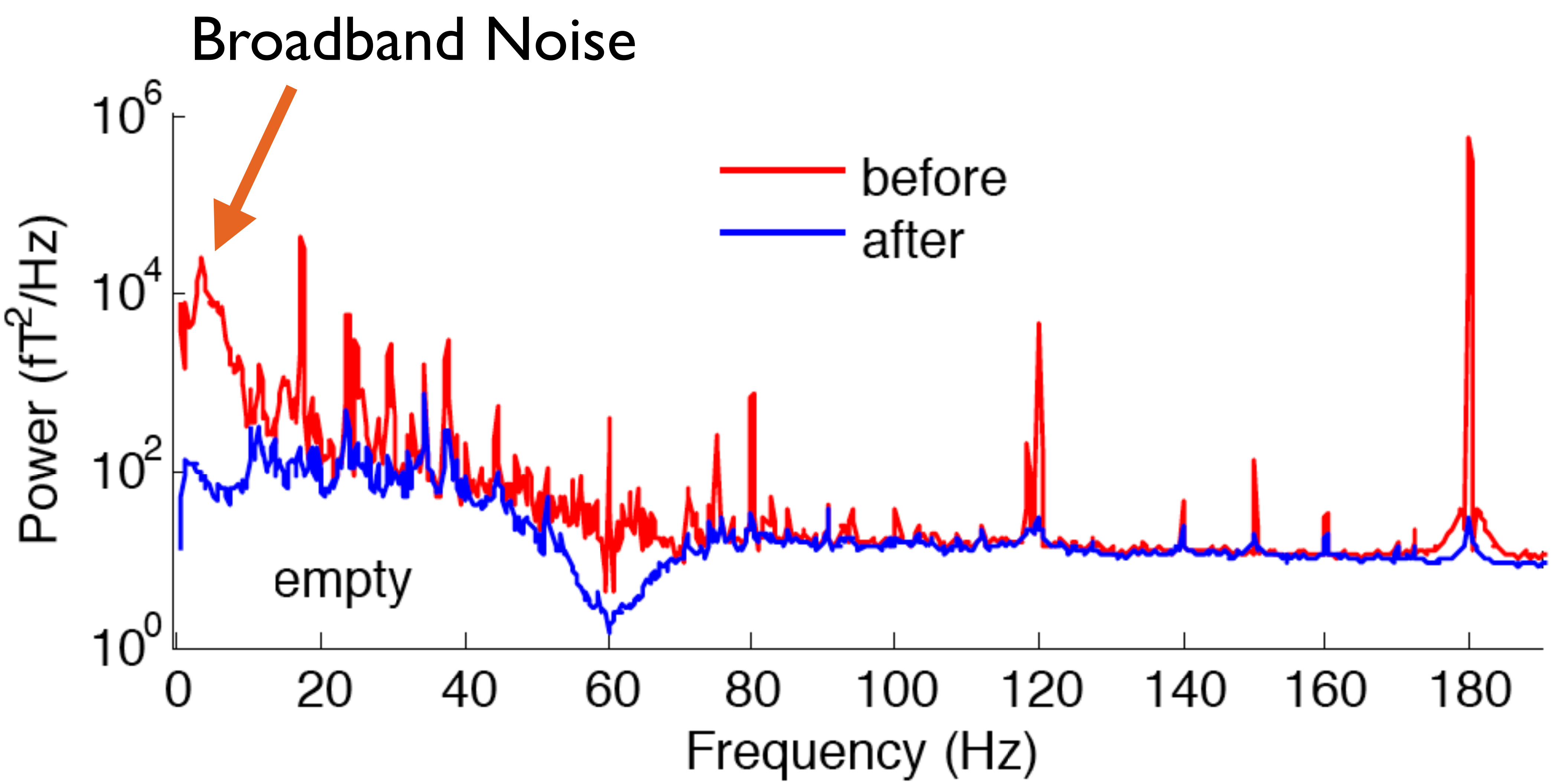

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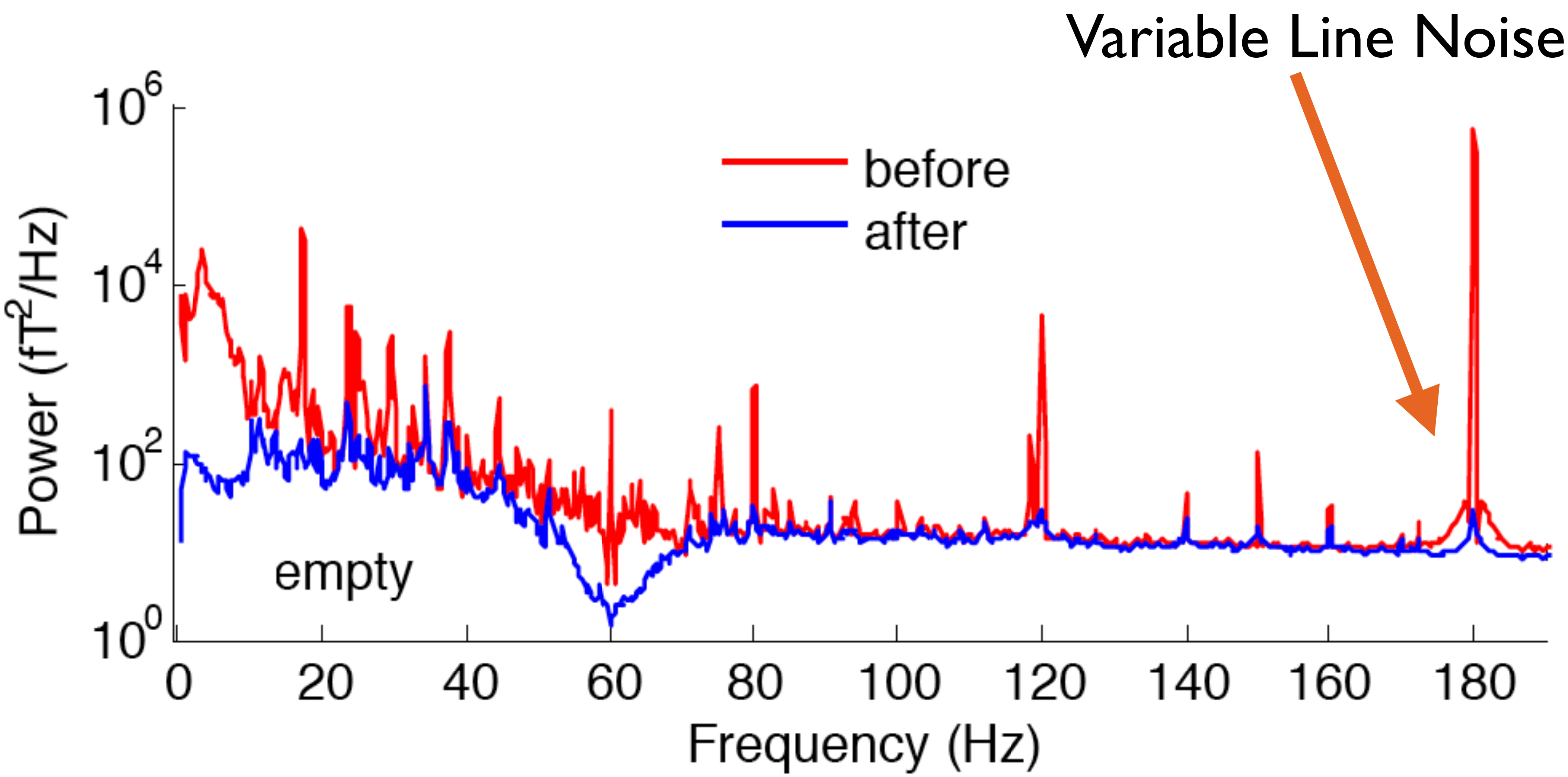
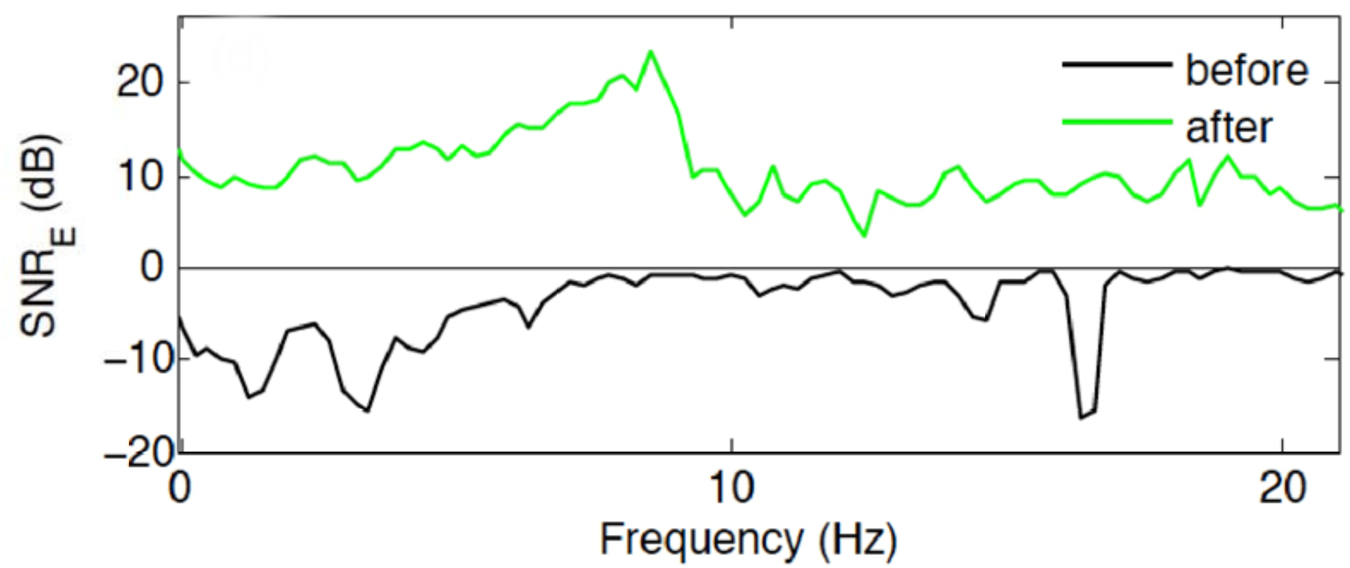


de Cheveigné and Simon, J. Neurosci. Methods (2007)

TSPCA Summary

- TSPCA removes ~98% of noise power
- SNR increase > 10 dB at noisiest frequencies



SNR_E: ratio of Signal other than Environmental Noise to Environmental Noise

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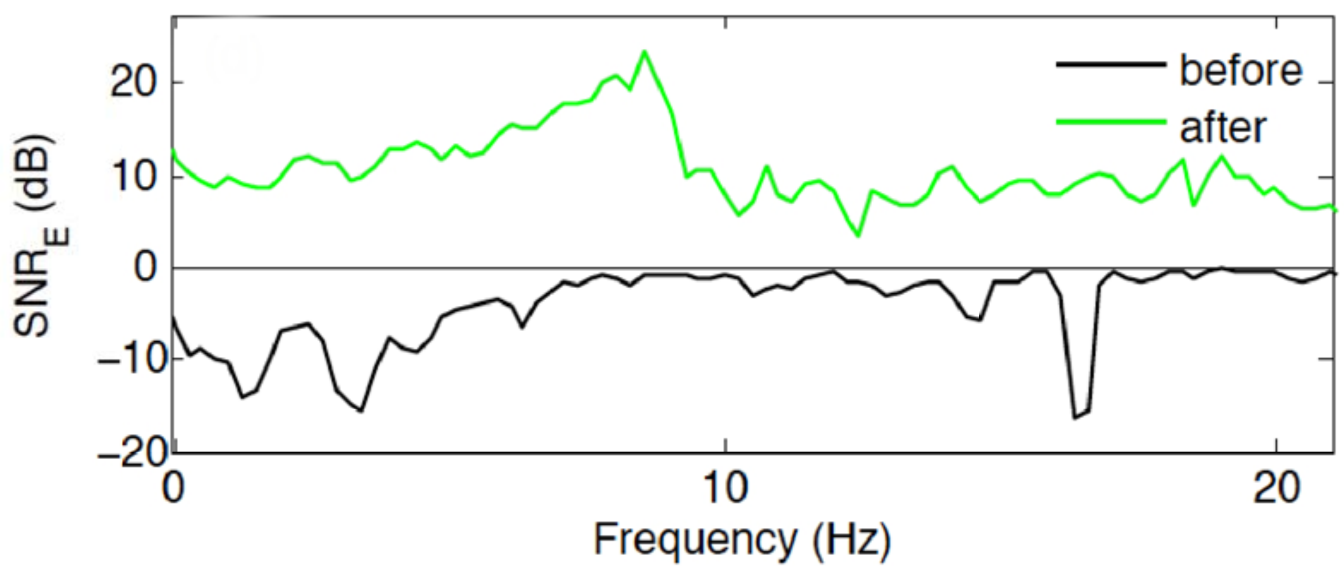
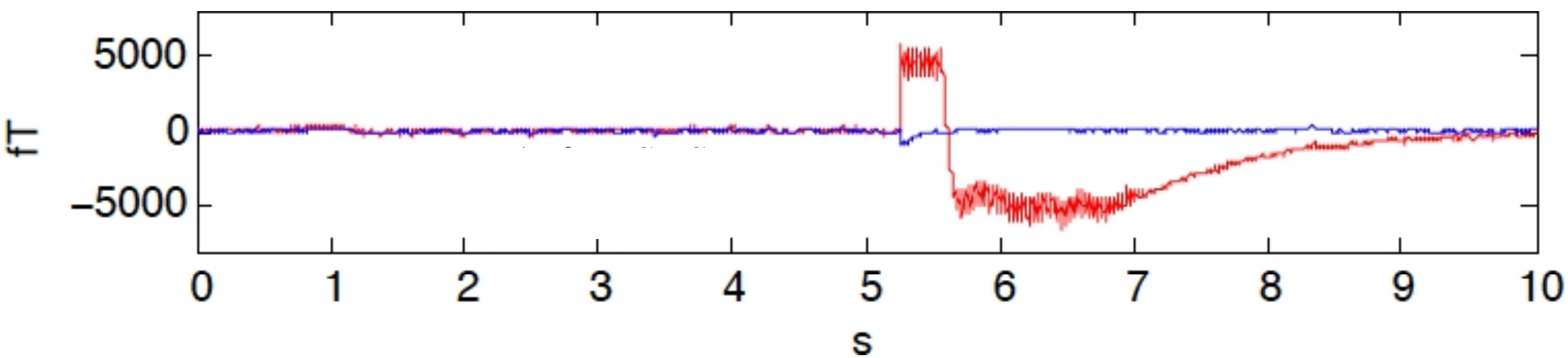


SNR_E: ratio of Signal other than Environmental Noise to Environmental Noise

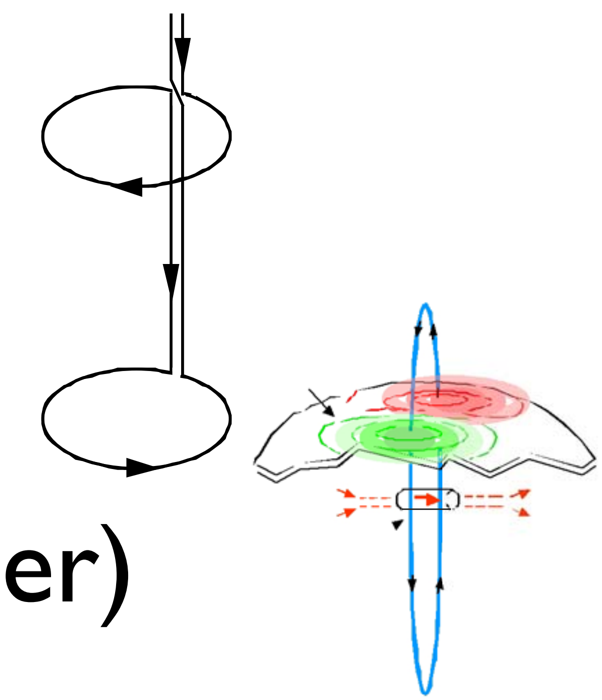
- No Target Distortion: only Reference channels are filtered
- Tested on wide range of systems
- User Friendly: Single Parameter to be chosen in advance:
  N = (# of taps), not algorithm sensitive
- Caveats: For small duration signals, N cannot be to large
  Processing time $O(N^2)$

Sensor Noise



Sensor Noise Reduction: SNS

Sensor Noise Suppression



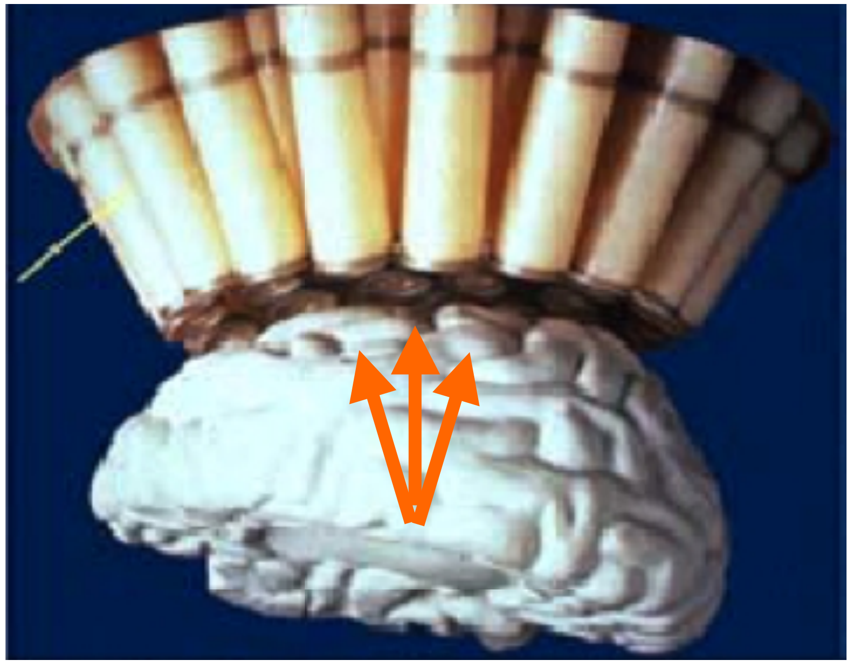
Targets Sensor Noise, including:

Transducer Noise (e.g., SQUID)

Electronics Noise (e.g., FLL, amplifier)

de Cheveigné and Simon, J. Neurosci. Methods (2008a)

SNS Methodology



Assumption: Every neural source is picked up by multiple sensors

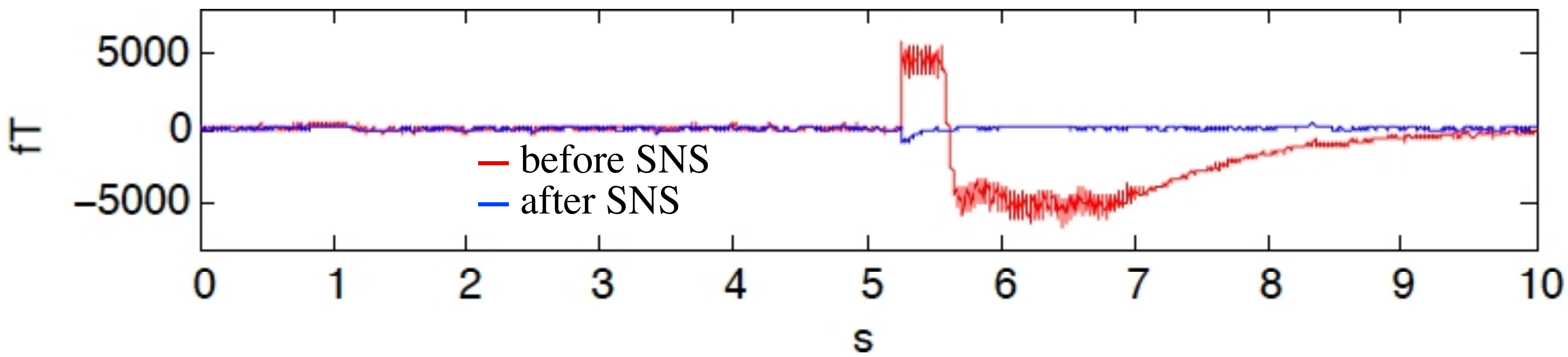
Consequence: Any component observed on only one sensor is **artifactual**.

Requires spatially dense sensors

Otherwise model-free

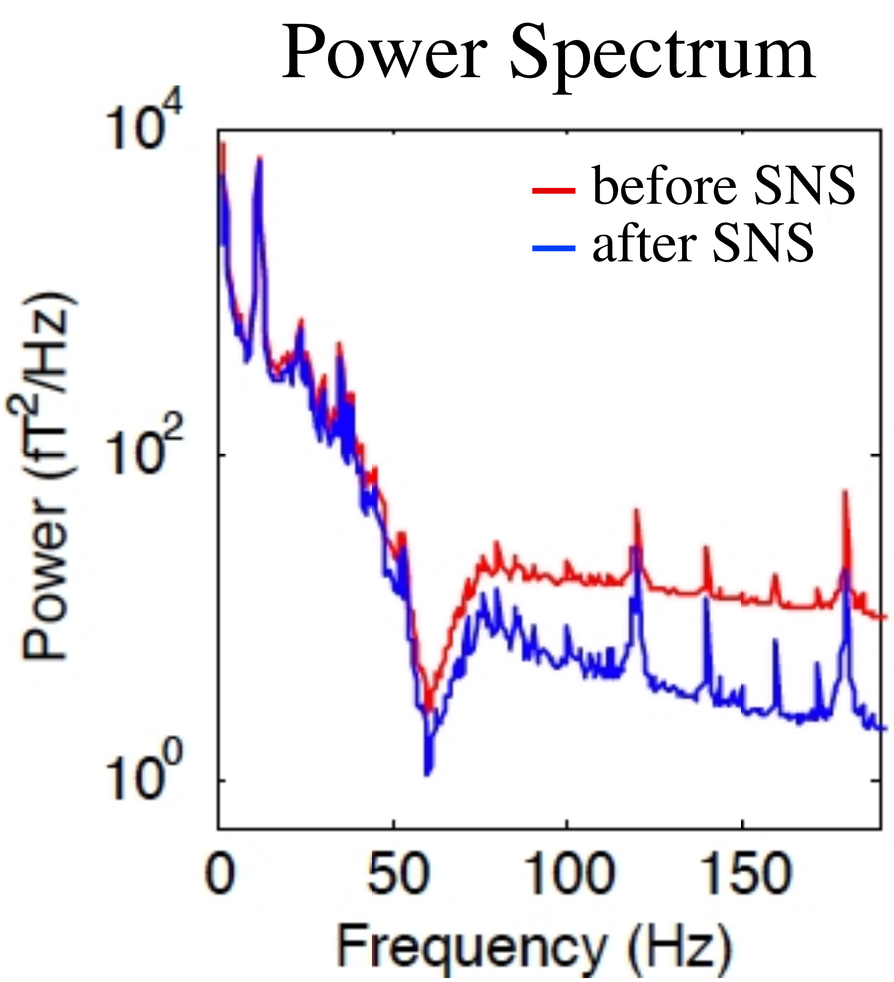
SNS Example

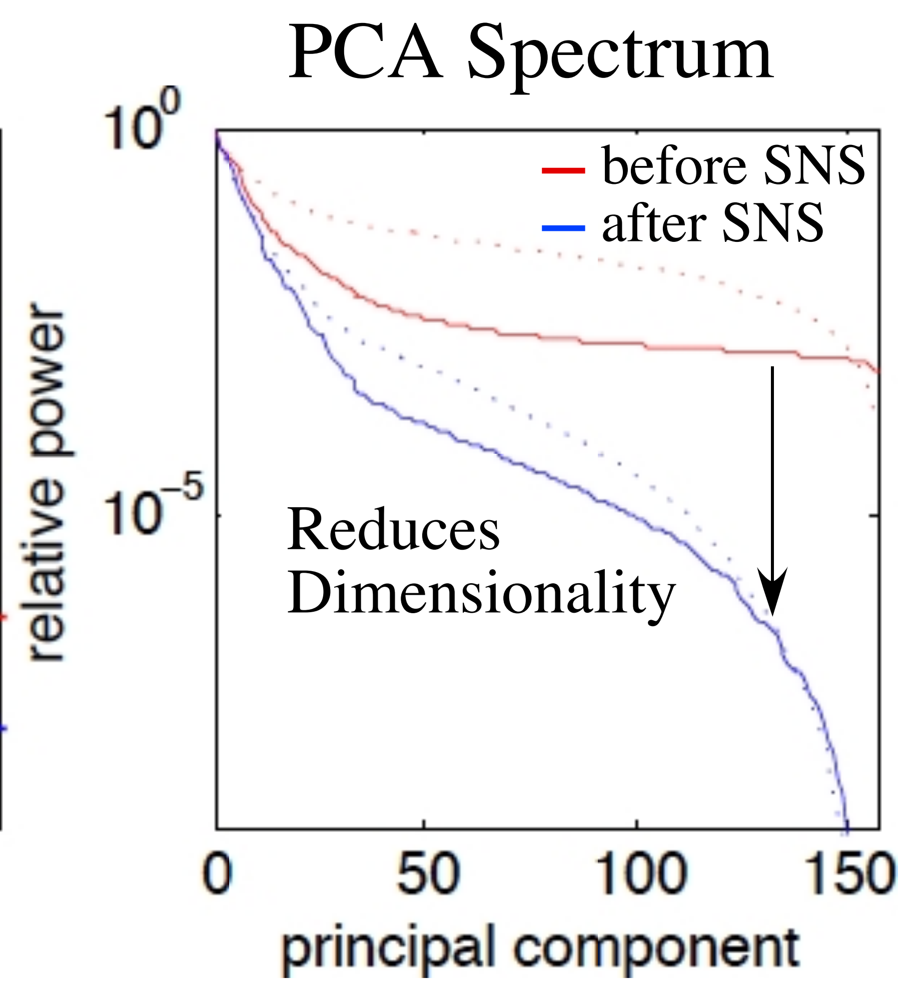
"Glitch" Removal



SNS Example

Power and PCA Spectra





Removes spurious sensor-specific signal dimensions

SNS Summary

- Removes Sensor Noise Glitches
- Esp. high frequency noise
- No Target Distortion (unless target loads only 1 sensor)
- Allows:
  - Cleaner Data
  - More usable epochs (no need to discard glitches)
  - Reduction of spurious dimensionality (e.g., for PCA, ICA)

Strongly-Mixed-Noise Reduction

Neural Signal-of-Interest vs. Neural Noise

- Neural sources of Signal-of-Interest may overlap with Neural Noise
- Time courses of Signal-of-Interest may correlate with Neural Noise
- But still separable if there exists a Stimulus-Based Criterion to distinguish between them

Strongly-Mixed-Noise Reduction: DSS

Denoising Source Separation

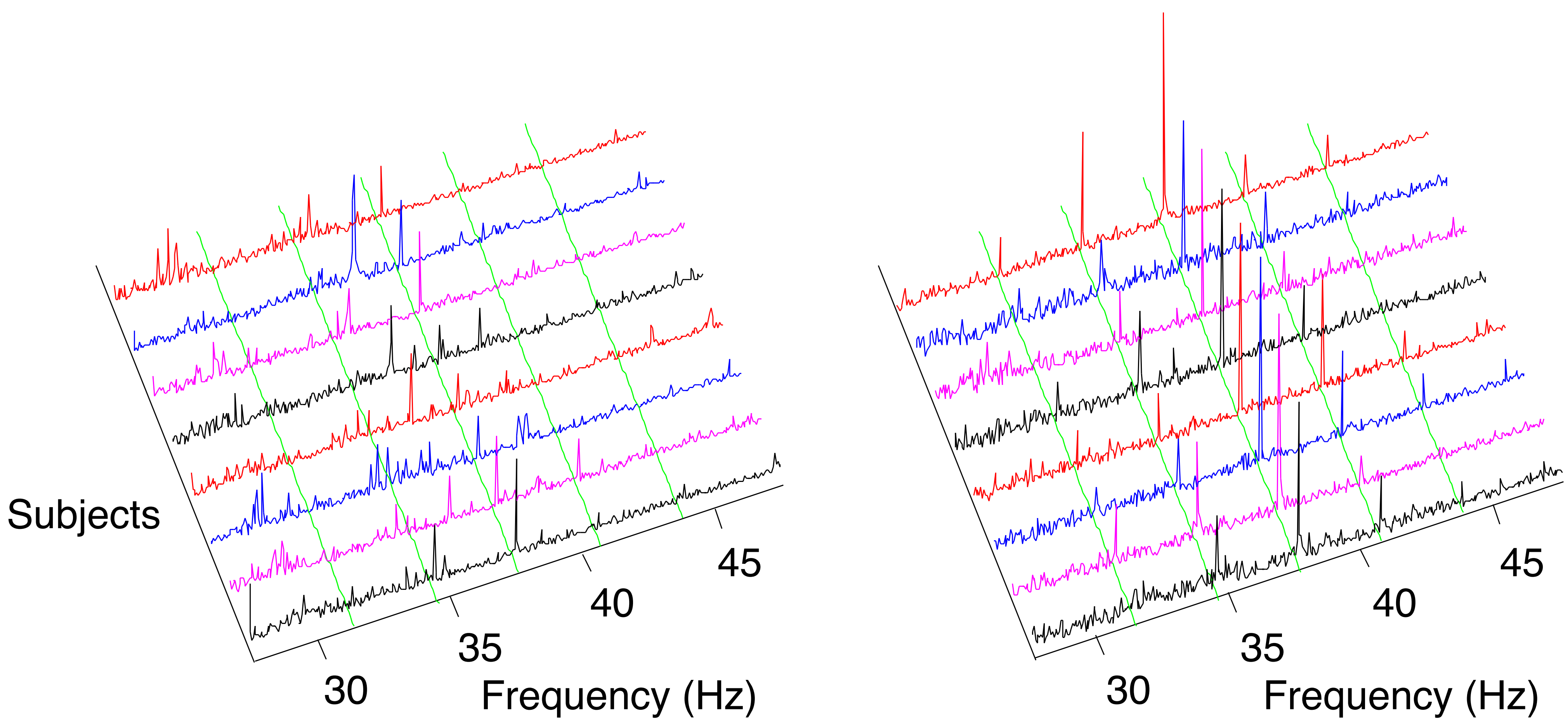
- Algorithm creates *Spatial Filters* based Stimulus-Based separation criterion (generates Separated Components)
- Neural sources of Signal-of-Interest must be spatially distinct from Neural Noise (overlap OK)
- Time courses of Signal-of-Interest must be distinguishable from Neural Noise (correlation OK)

Särelä and Valpola, J. Mach. Learn. Res. (2005)
de Cheveigné and Simon, J. Neurosci. Methods (2008b)

DSS Example

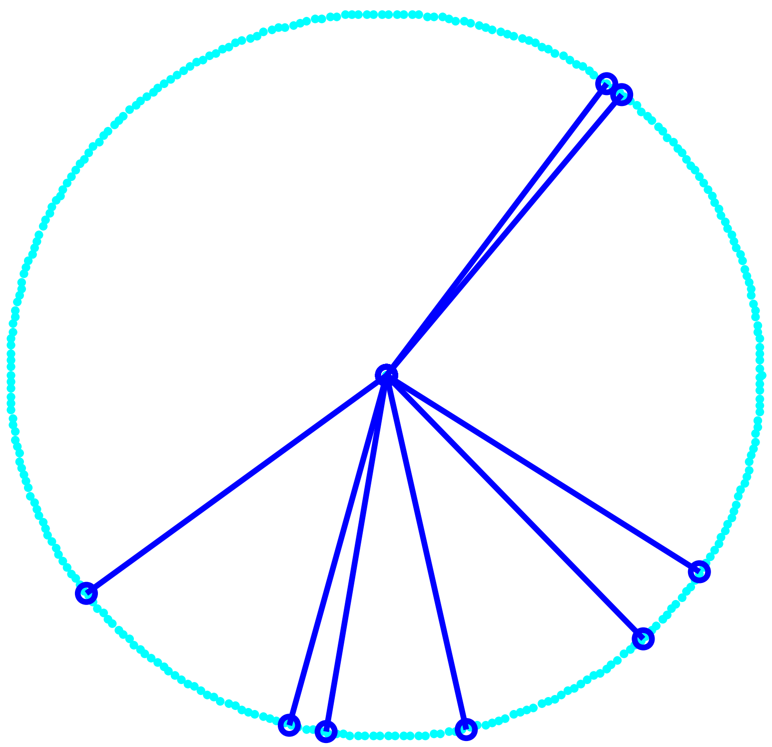
Spectra of MEG Steady State Response (to dual modulation)

Before DSS (20 Best Channels) *First DSS component*

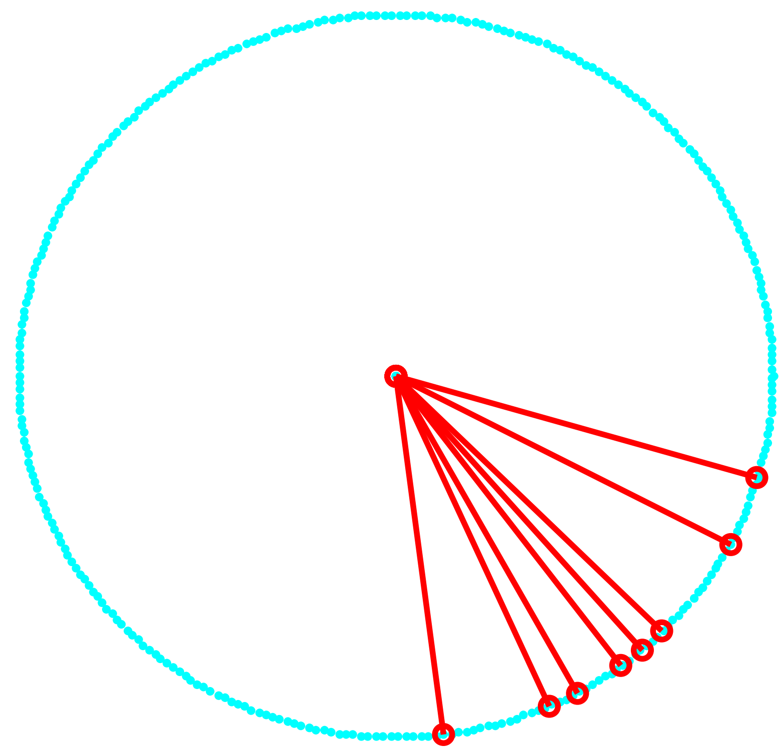


DSS Example

Phase coding parameter α (by subject)



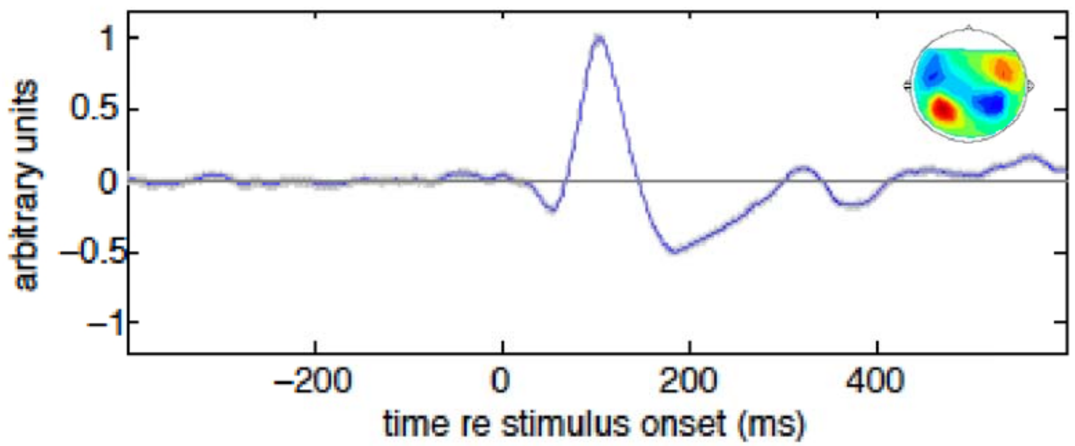
Before DSS (20 Best Channels)



First DSS component

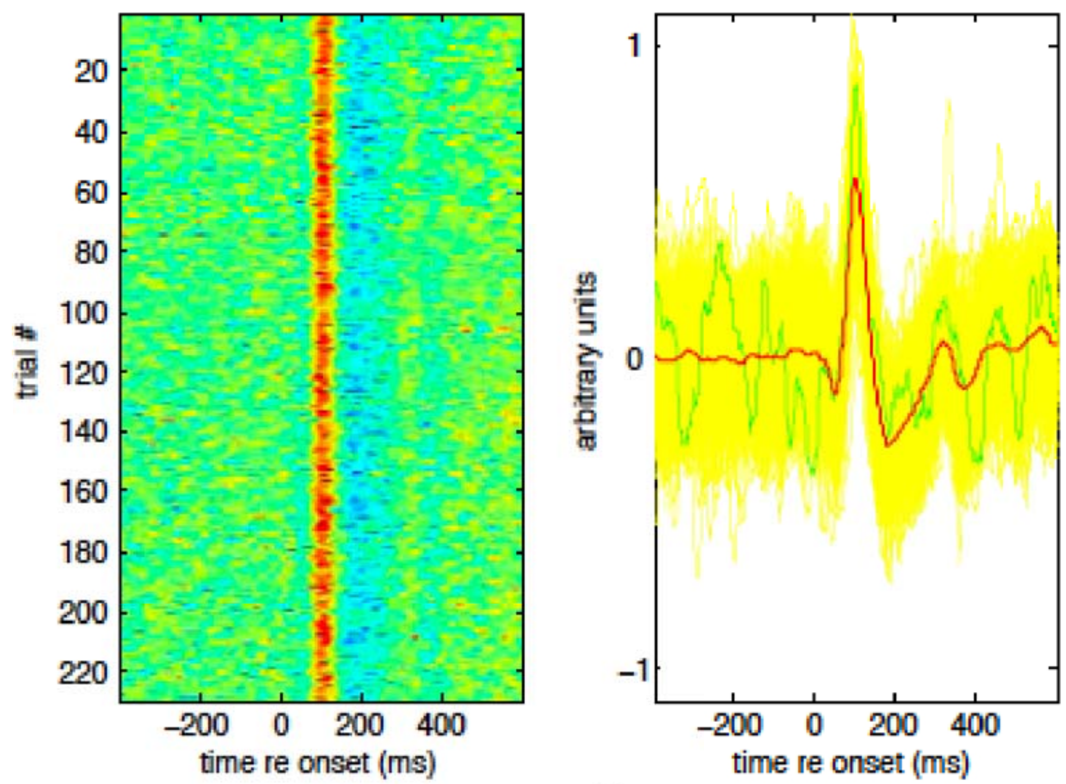
DSS Example

Best Component:



= output of Spatial Filter with the most reproducible linear combination of sensors

Single trials passed through spatial filter of best component



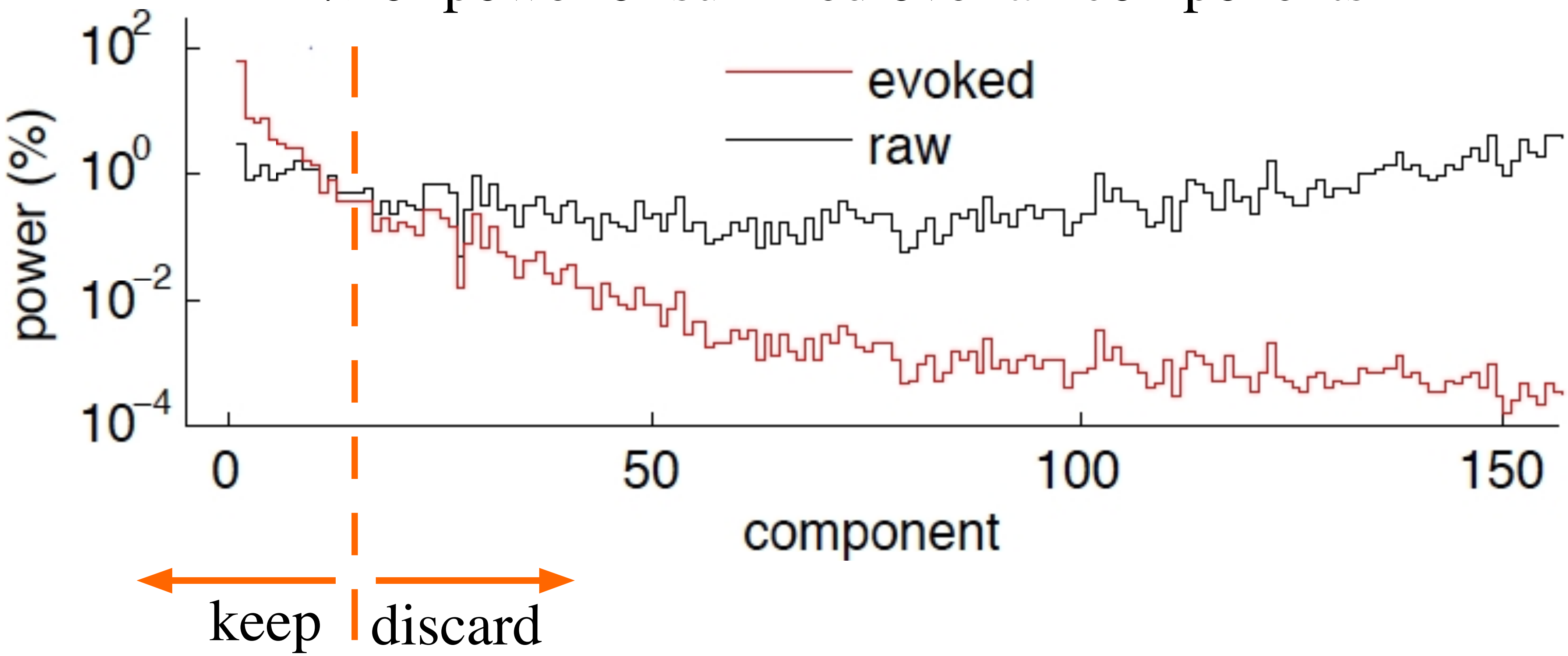
red: average

yellow & green: individual trials

DSS: How it Helps

“Select best components, discard others”

% of power of summed over all components



DSS Summary

- Removes Noise deeply mixed with Signal
- Complementary with:
  - Other denoising algorithms (TSPCA, SNS)
  - Standard analysis tools (beamforming, dipole source analysis, etc.)
- Flexible: case-dependent bias criteria can be used:
  Bandpassed evoked response (e.g. theta, gamma)
  Any stimulus-dependent representation of response
- Caveats:
  Bias should be robust, so temporarily remove outliers (e.g. ~20% of trials), but OK to use in end
- When SNR is poor (weaker evoked response), may fail, or give component-of-interest as 2nd component.

Denoising Summary

- Different noise sources are best removed using different methods
- Each denoising step decreases dimensionality of signal space, increasing the power of the next step
- TSPCA: Removes External noise represented (imperfectly) in Reference Channels (*user friendly)*
- SNS: Removes Sensor noise uncorrelated with other channels (*user friendly*)
- DSS: Removes more "entrenched" noise (*tunable)*

Summary

- Magnetoencephalography: powerful, sensitive
- Sensitivity allows neural tracking of speech, attended vs. unattended, and all it entails
- Sensitivity includes sensitivity to noise, which must then be removed.
  - Powerful Noise Removal techniques

Thank You

Comparison with EEG

- High temporal resolution
- Inexpensive, Room temperature
- Slow, careful set-up
- Electric fields strongly distorted
  - Brain = *inhomogeneous*, *anisotropic*, dielectric
  - Poor spatial neural reconstruction unless very carefully modeling of currents and entire head
  - Inverse problem: worse? better?
- Many more neural sources
- Complementary with MEG