New Methods for Denoising MEG data

and

Attending (at) a Cocktail Party

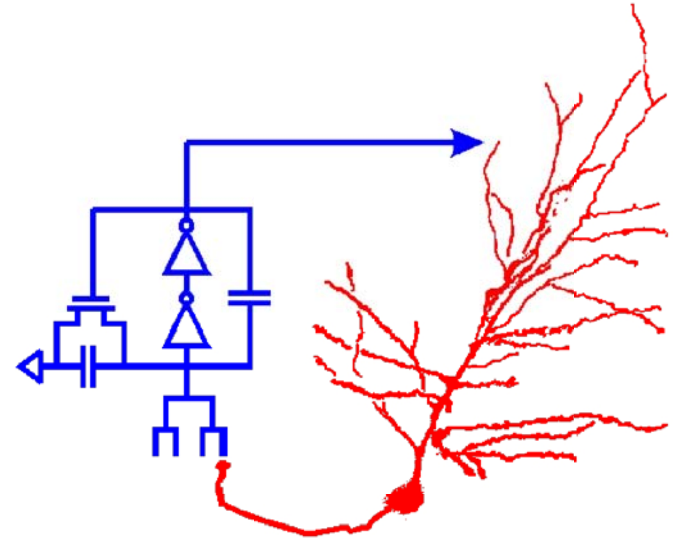
Jonathan Z. Simon

Neuroscience and Cognitive Sciences / Biology / Electrical & Computer Engineering

University of Maryland, College Park

N.Y.U. Workshop   January 24, 2009

Computational Sensorimotor Systems Laboratory & Friends



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Ray Shantanu

Supported by

NIH: NIDCD, NIBIB, NIA

Outline

- Brief Introduction to MEG
- Denoising MEG Data
  - Environmental Noise Reduction
    TSPCA = *Time Shifted Principle Component Analysis*
  - Sensor Noise Reduction
    SNS = *Sensor Noise Suppression*
  - Physiological Noise Reduction
    DSS = *Denoising Source Separation*
- Attention and Auditory Streams
  - MEG in the Frequency Domain
  - Neural & Behavioral Correlates of Auditory Attention

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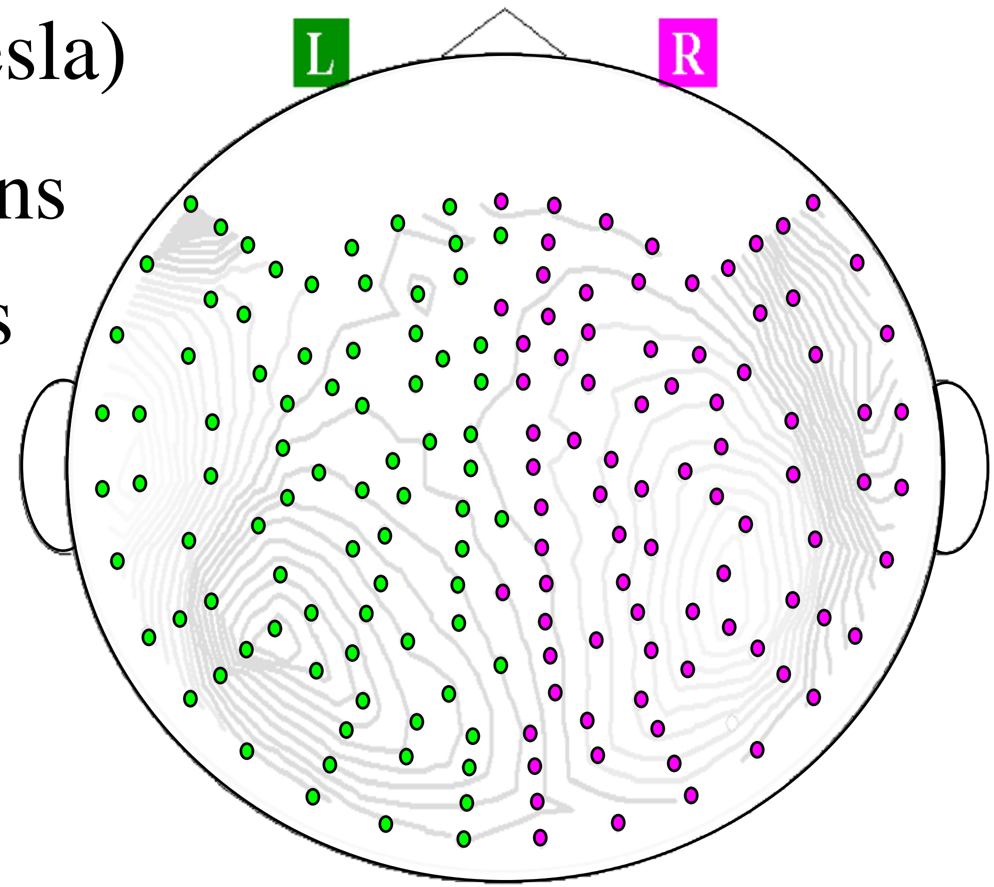
Magnetoencephalography (MEG)

- 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 Imaging

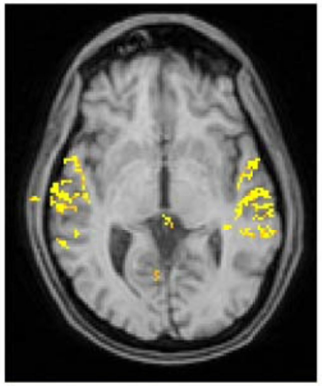
Non-invasive recording from human brain (Functional brain imaging)

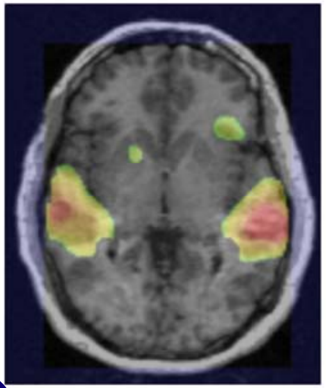
Hemodynamic techniques

Functional magnetic resonance imaging fMRI

Positron emission tomography PET

Excellent *spatial resolution* (~1-2 mm)
Poor temporal resolution (~1 s)





PET, EEG require across-subject averaging

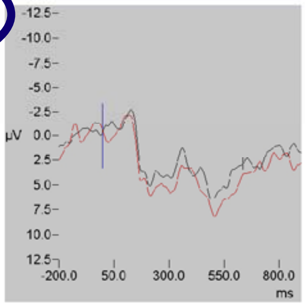
fMRI and MEG can capture effects in single subjects

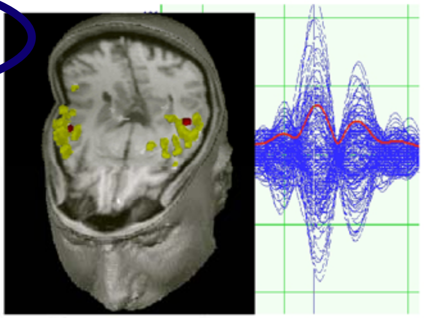
Electromagnetic techniques

Electroencephalography EEG

Magnetoencephalography MEG

Poor spatial resolution (~1 cm)
Excellent *temporal resolution* (~1 ms)





Primary Neural Current

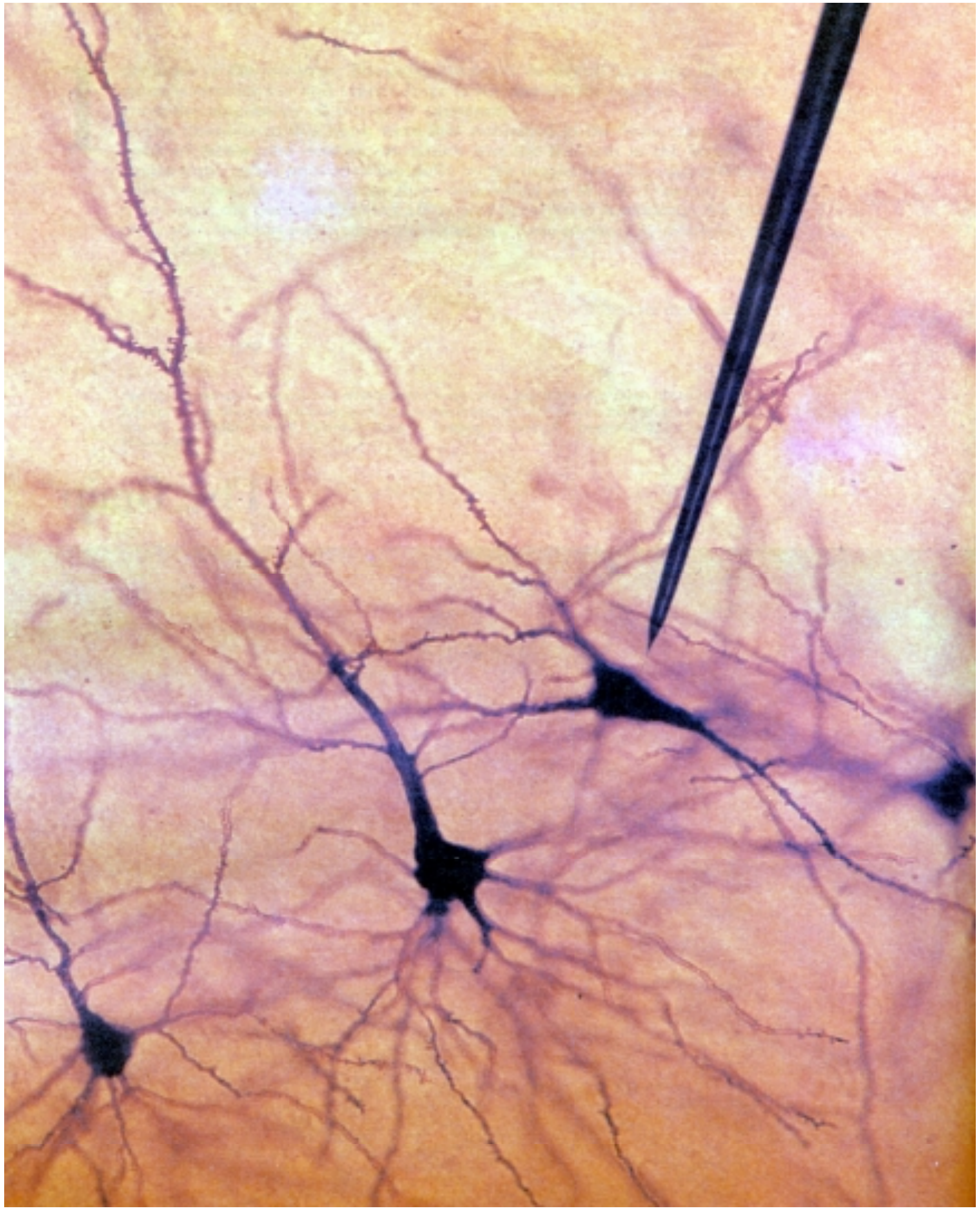
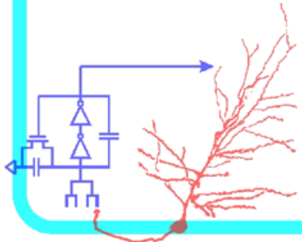
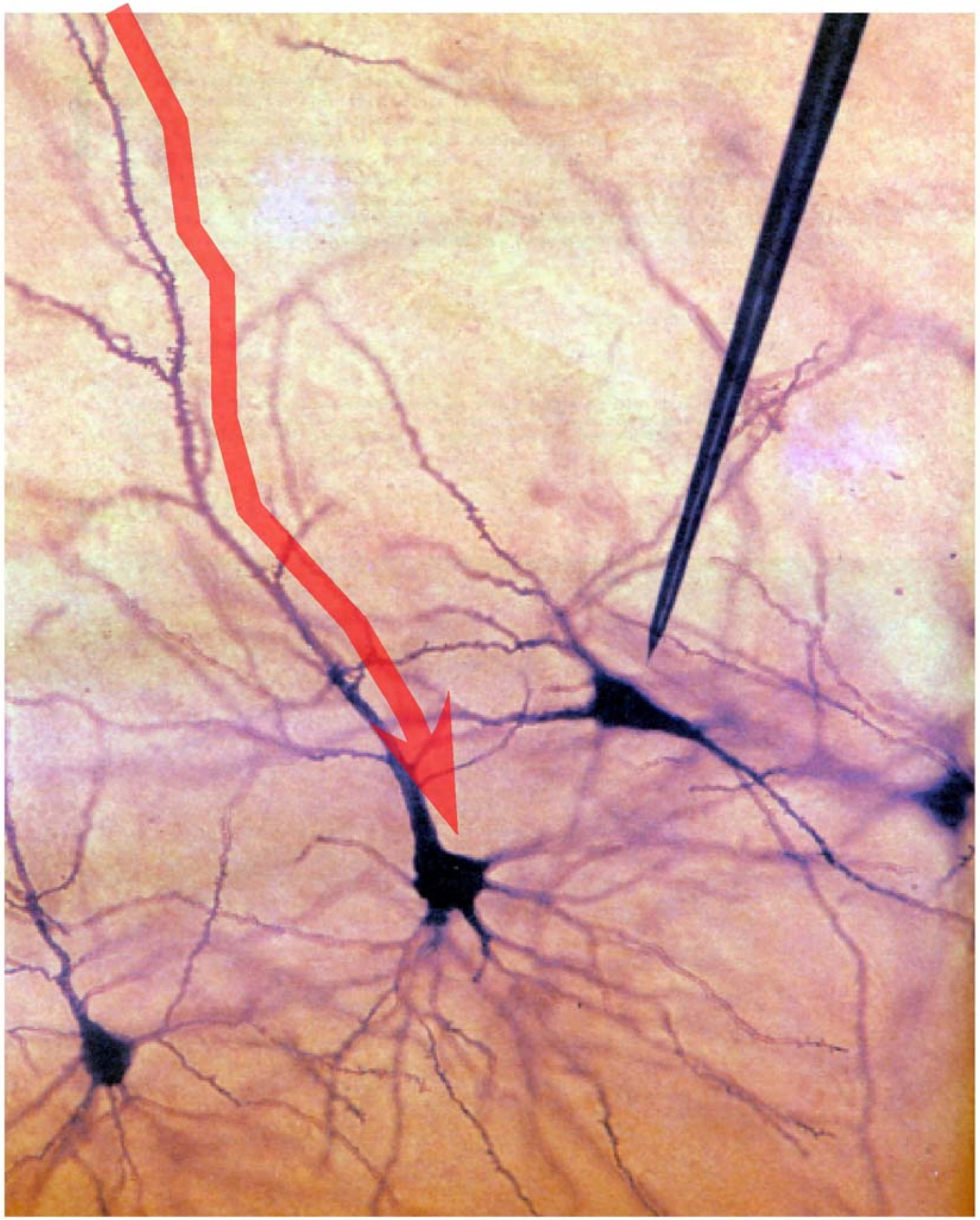


Photo by Fritz Goro



Primary Neural Current



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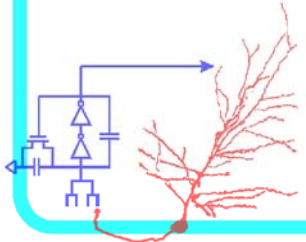
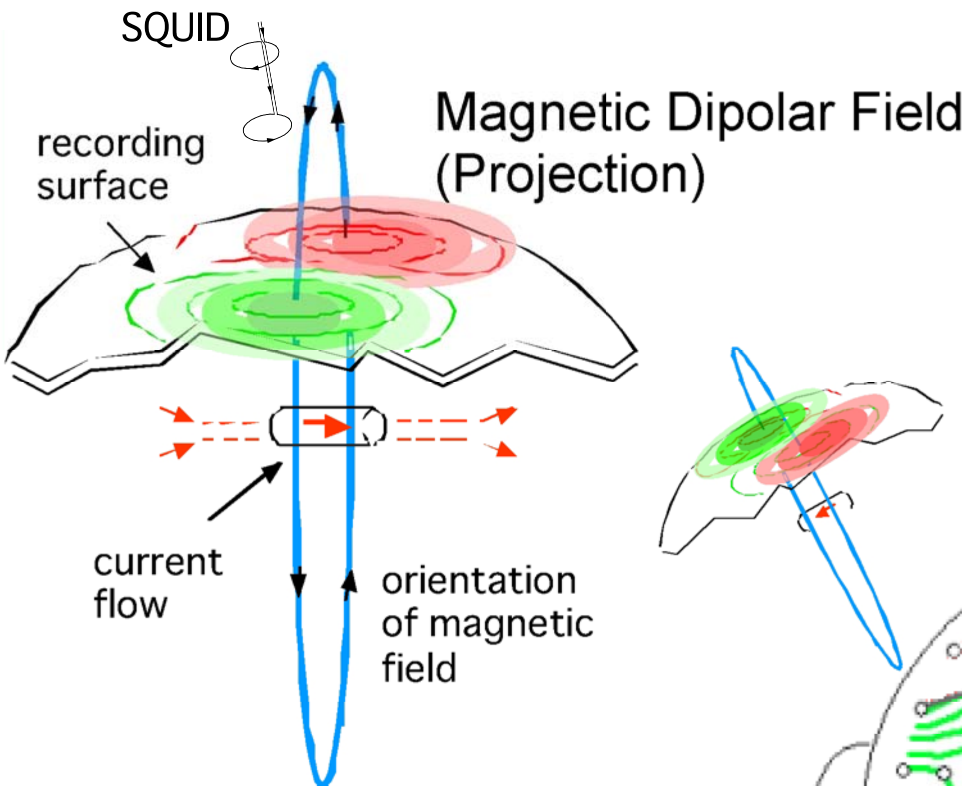
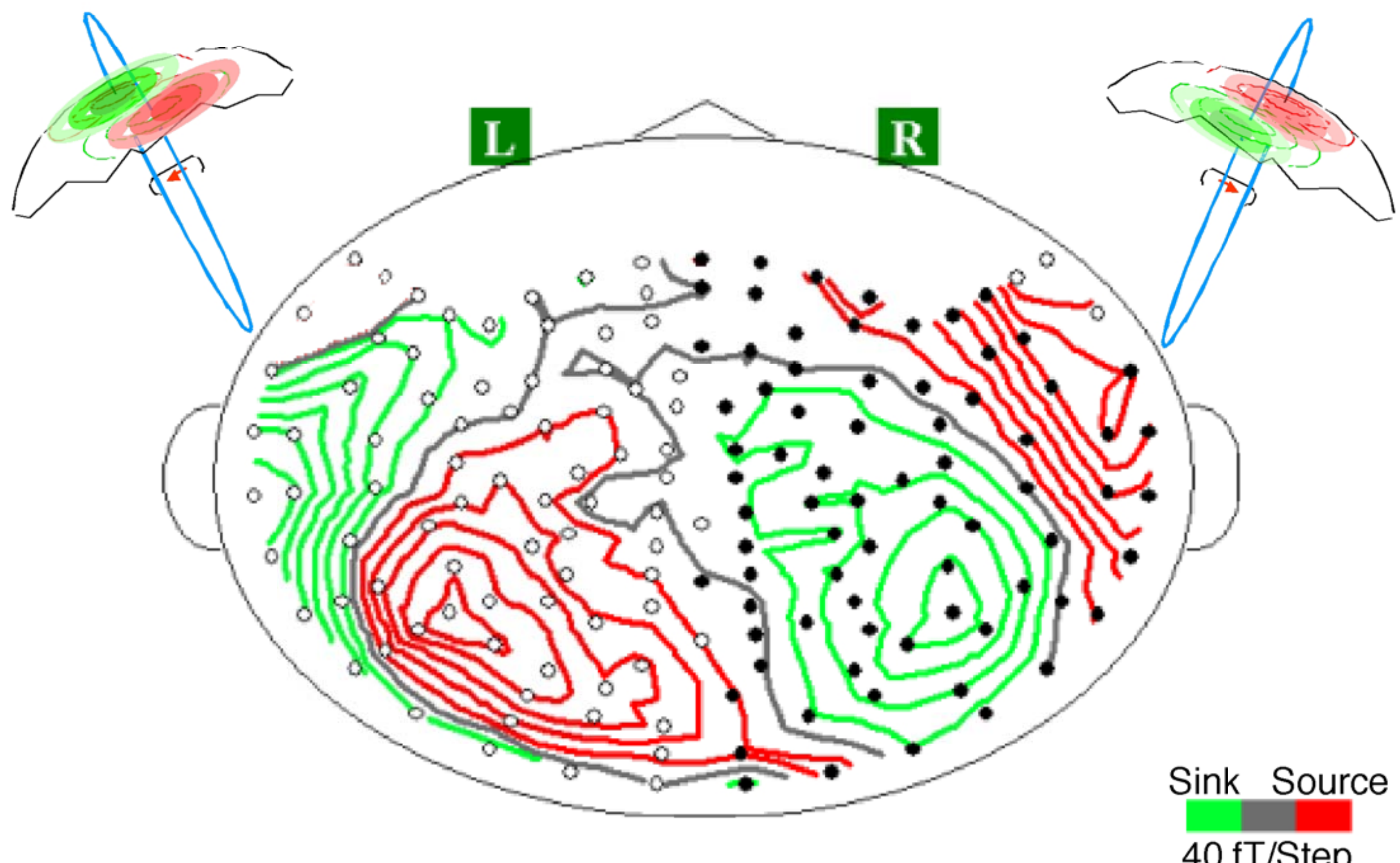


MEG Measures Neural Currents



- Direct electrophysiological measurement
  - not hemodynamic
  - real-time
- No unique solution for distributed source



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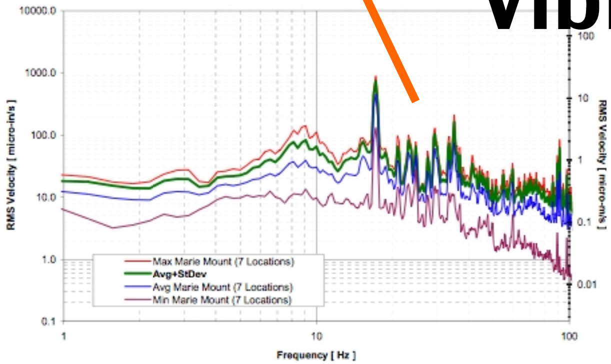
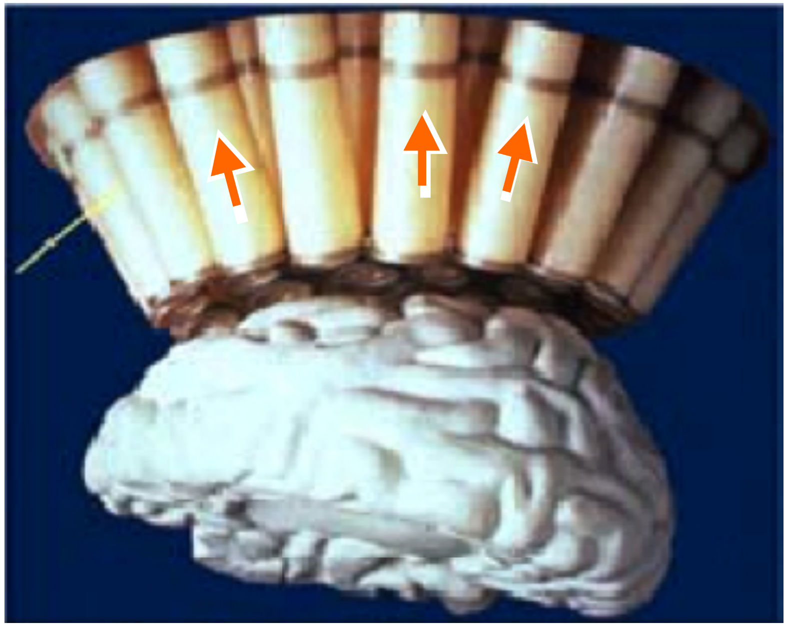
Environmental Noise

Electromagnetic

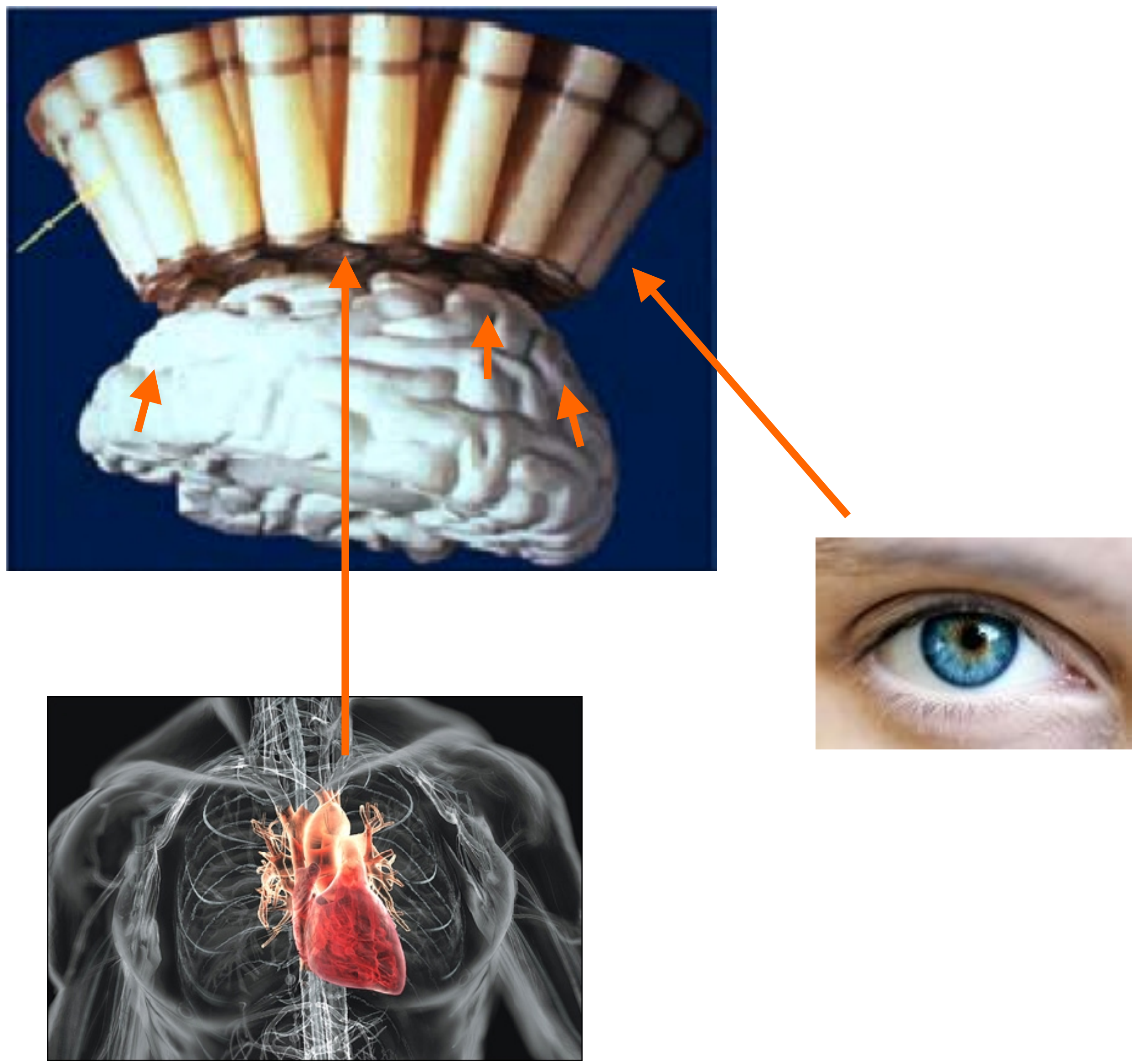
Vibrational



Sensor Noise



Physiological Noise



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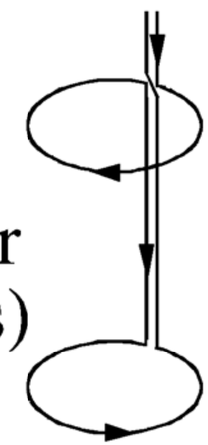
External Noise Reduction Aids

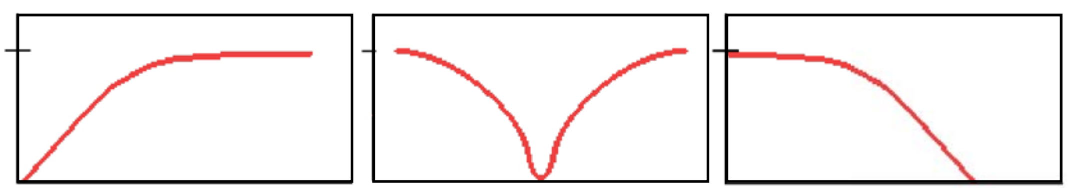
Magnetically shielded room

Magnetic/electromagnetic sheilding

Gradiometers (sensitive to near sources)



Gradiometer

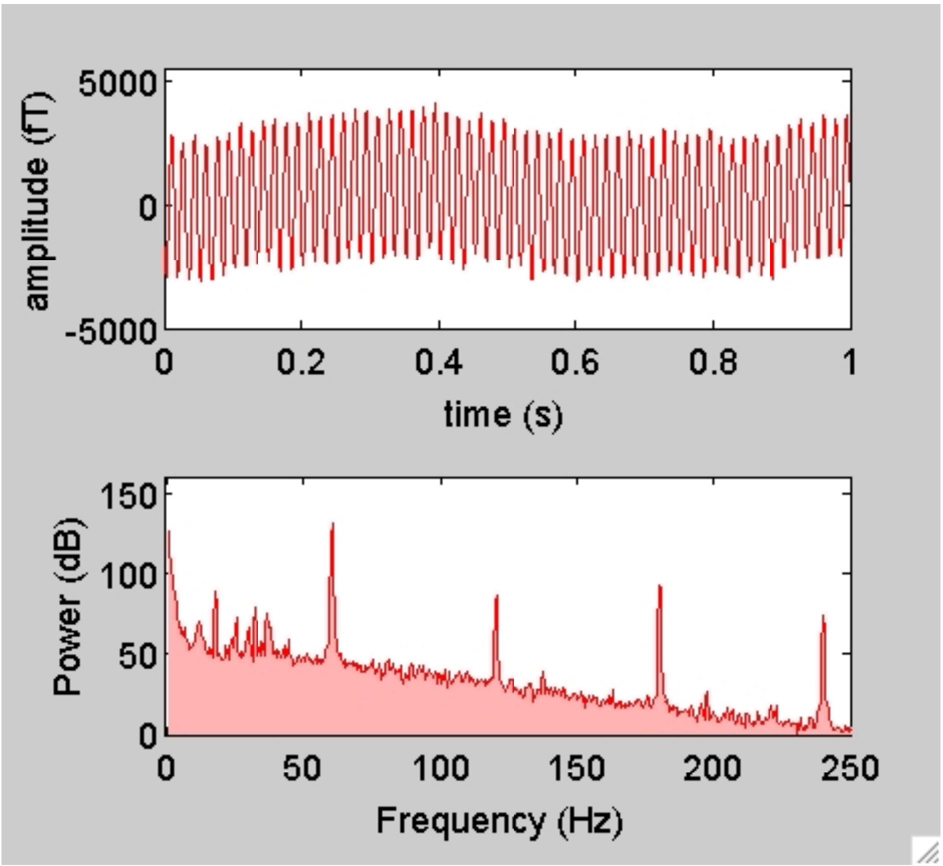


Spectrally Selective Filters

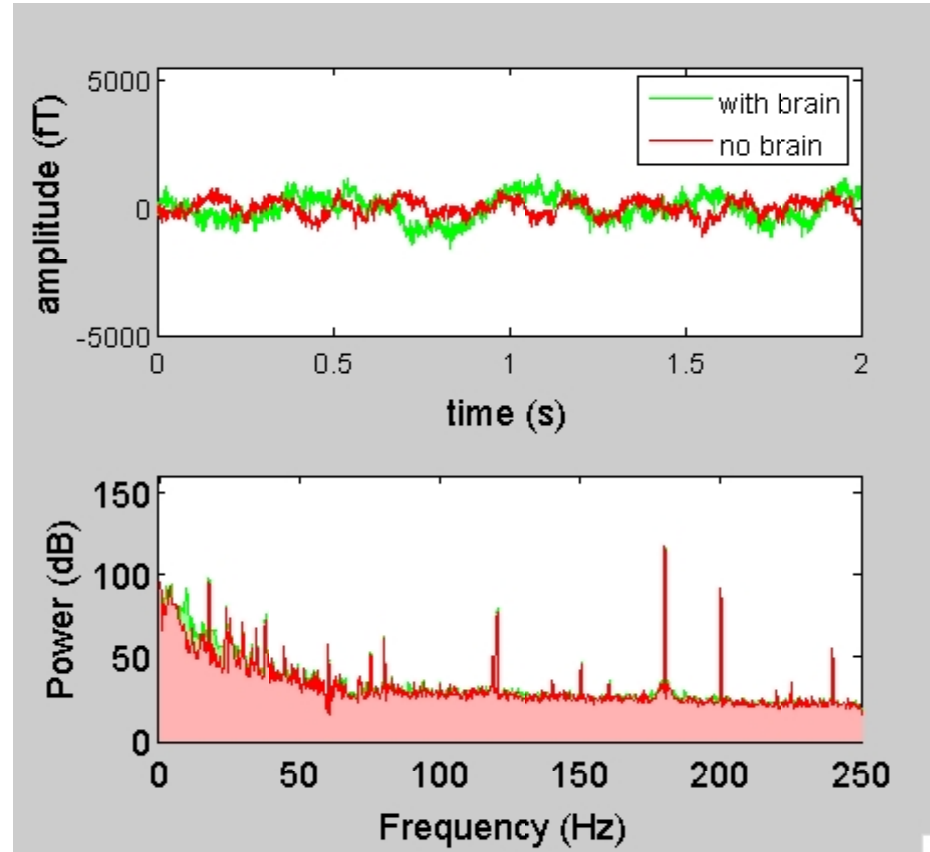
Spectral filtering (high-pass, notch, low-pass)

Effects of Filtering

Raw:



HPF 1 Hz, Notch 60 Hz:



After filtering, typically ~90% of MEG power is still environmental noise.

Filtering also adds distortions (group delay, phase shift, etc.).

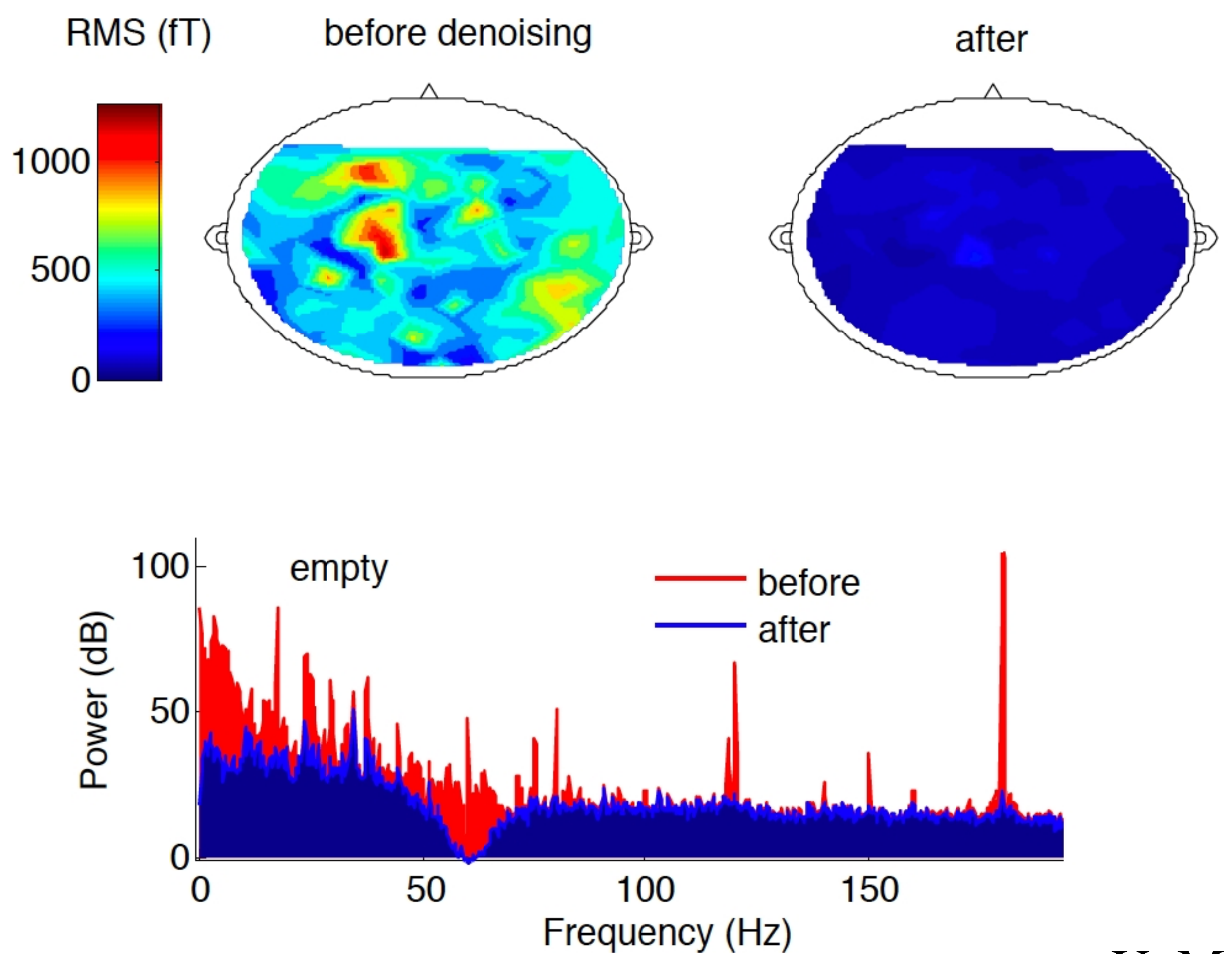
TSPCA

- Time Shifted Principle Component Analysis
- Target: Environmental Noise
- Requirement: Reference channels

in colloboration with Alain de Cheveigné

TSPCA Example

Empty Chamber



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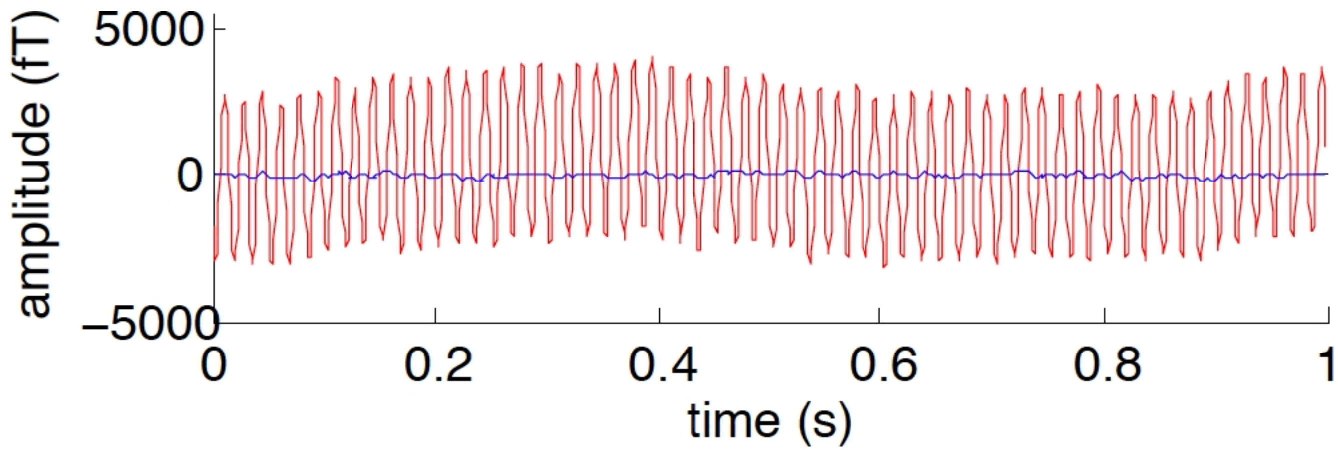
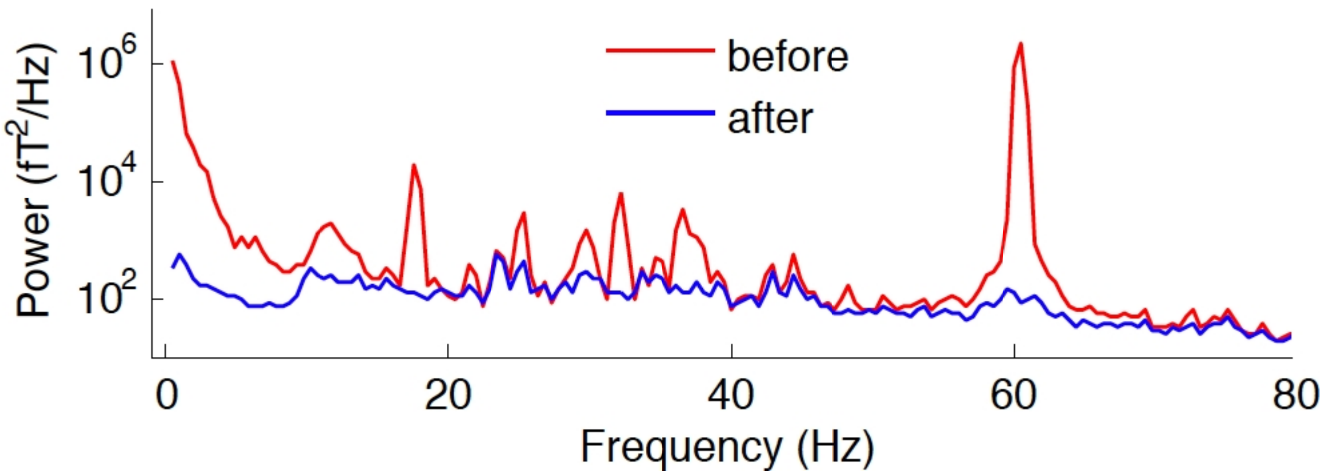
TSPCA Example

Without Notch & HP hardware filters





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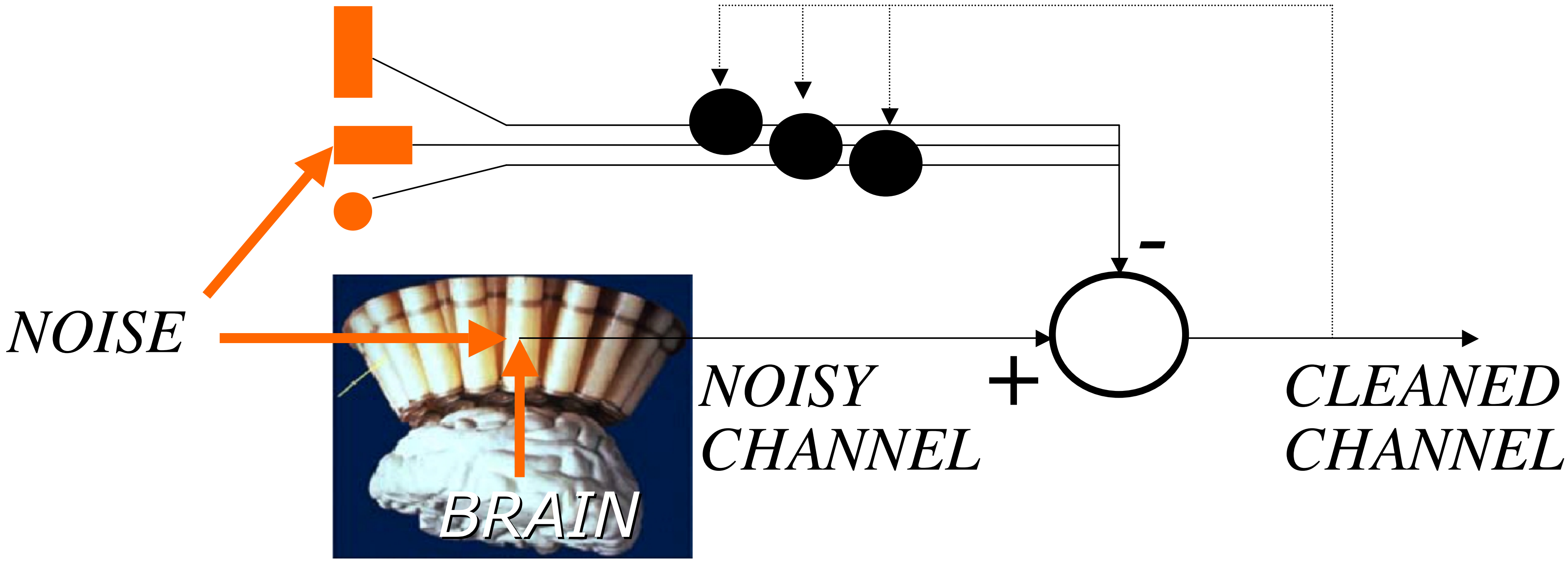
TSPCA: How it works

First, understand classic Scalar Regression methods (e.g. CALM)



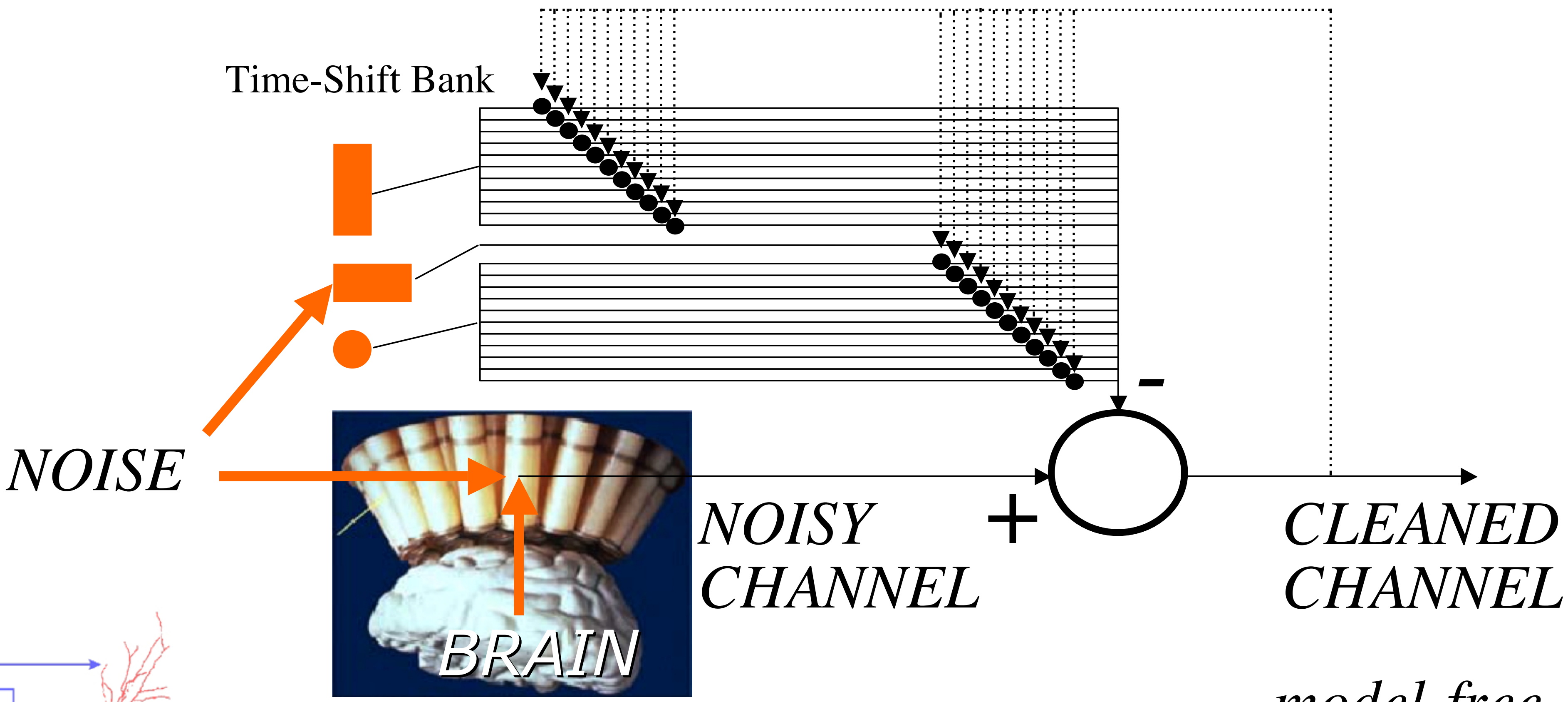
When scalar regression may fail since:

- Noise in Reference may be *filtered* w.r.t. Brain channel
- Noise in Reference may be *time-shifted* w.r.t. Brain channel
- May be *more* independent noise sources than References

TSPCA: How it works

Generalize Scalar Regression:

- Include Multiple Time-Shifted versions of References
- Linear combinations of Time-Shifts are Filters
- Increases *effective* number of References



model-free

TSPCA: How it works

DELAY

$$\hat{s}_k(t) = s_k(t) - \sum_{j=1}^{J}\sum_{\tau=1}^{N}\alpha_{kj\tau}r_j\left(t + \tau - \frac{N}{2}\right)$$

BRAIN CHANNEL

REFERENCE CHANNELS

Example:
100 Taps (individual time delays)
3 Reference sensors → 300 coefficients/Brain Sensor
157 Brain sensors → 47100 coefficients Total

c.f. Scalar Regression: $\hat{s}_k(t) = s_k(t) - \sum_{j=1}^{J}\alpha_{kj}r_j(t)$

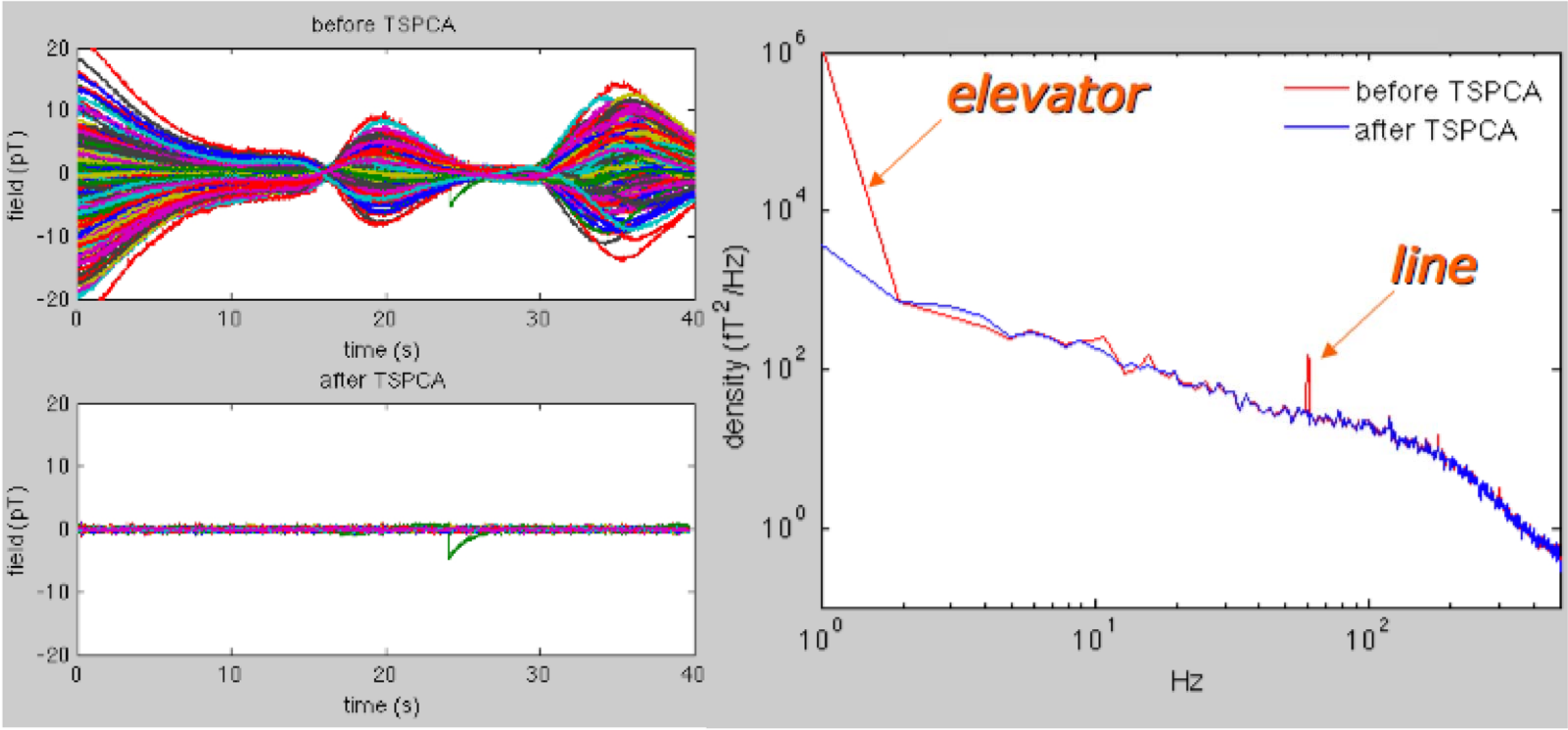
TSPCA: How it works

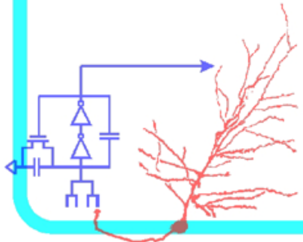
Algorithm:

1. Time-shift 3 reference signals by up to ±N/2 samples (➔ 3N time-shifted signals)
2. Orthogonalize the 3N shifted signals to obtain an orthogonal basis (PCA)
3. Project each brain channel on this basis
4. Subtract projection to obtain clean channel...

... et voilà!

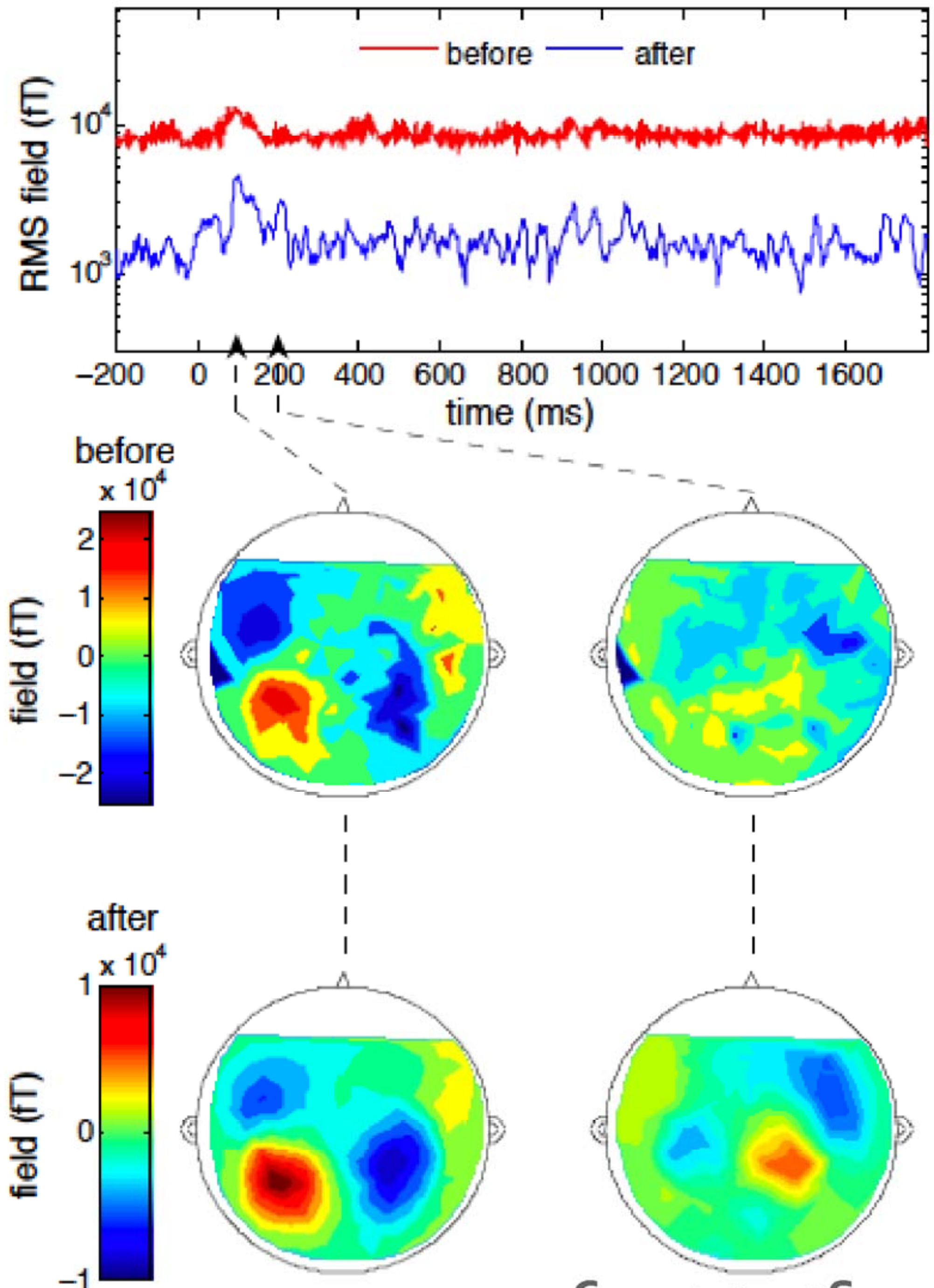
TSPCA Example





ATR MEG
(Advanced Telecommunications Research, Kyoto)

TSPCA Example



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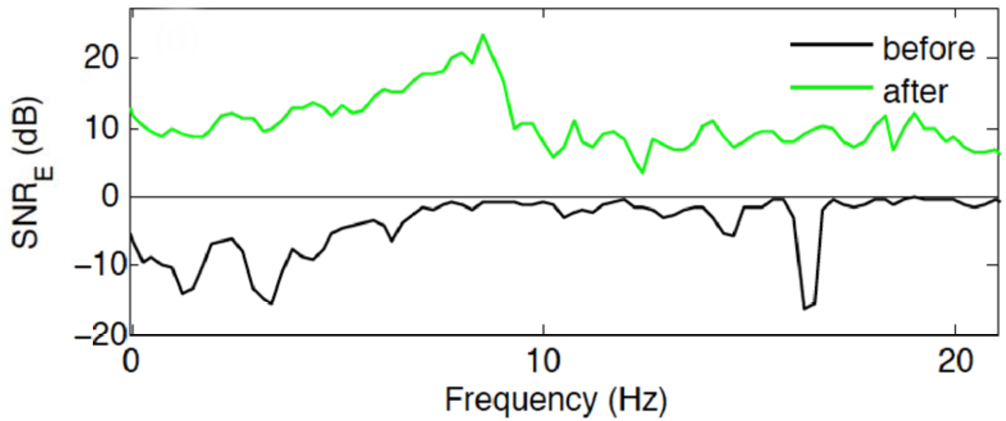
TSPCA Summary

- TSPCA removes ~98% of noise power, SNR increase > 10 dB for low frequencies



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

- No Target Distortion: only Reference channels filtered;
- Tested on wide range of systems
- Single Parameter to choose: N = (# of taps), not sensitive
  Caveats: For small durations, N cannot be too large
  Large N increases processsing time $O(N^2)$
- Can turn off High Pass filter (possibly Notch filter too)
  Caveat: If turn off Notch, beware of large amplitudes due to 60 Hz (clipping, finite # of bits)

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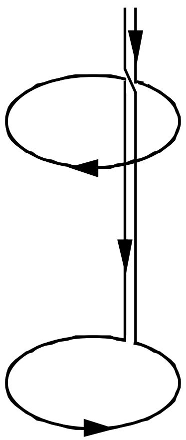
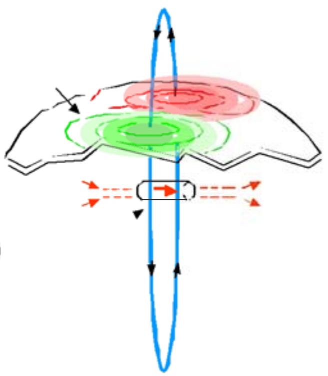
SNS

- Sensor Noise Supression
- Target: Sensor Noise

Transducer Noise (SQUID)

Electronics Noise (FLL, amplifier, A/D)

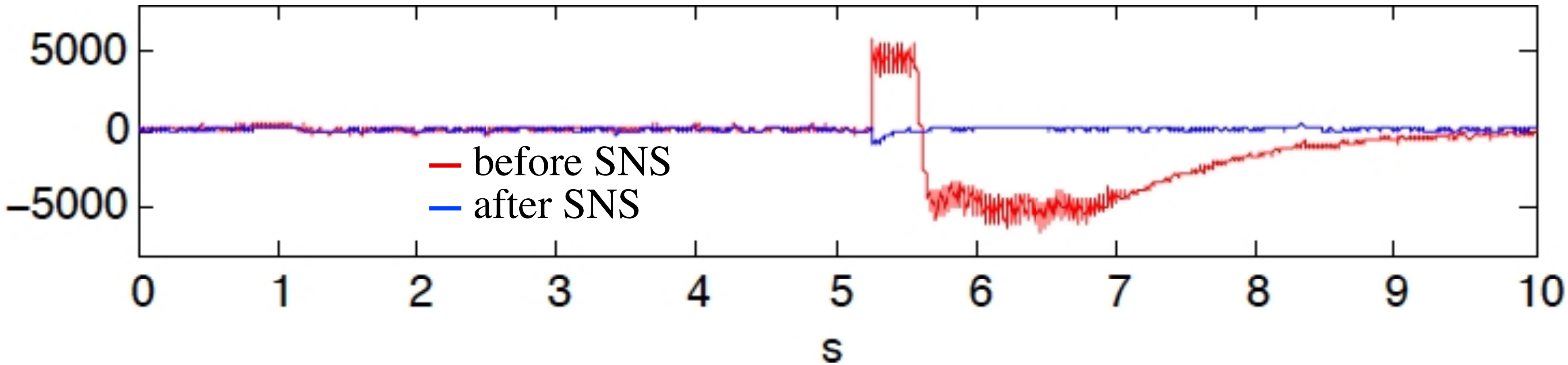




in colloboration with Alain de Cheveigné

SNS Example

Glitch Removal



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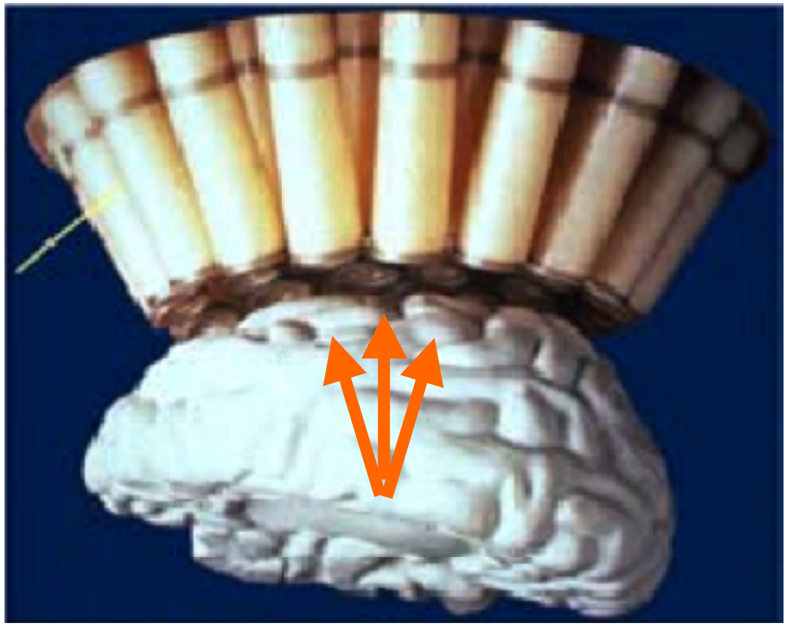


Assumption: Every neural source is picked up by multiple sensors

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

Requires spatially dense sensors

Otherwise model-free

SNS: How it works

Algorithm:

1. Project each channel on subspace formed by *other* channels.

2. Replace channel by projection.

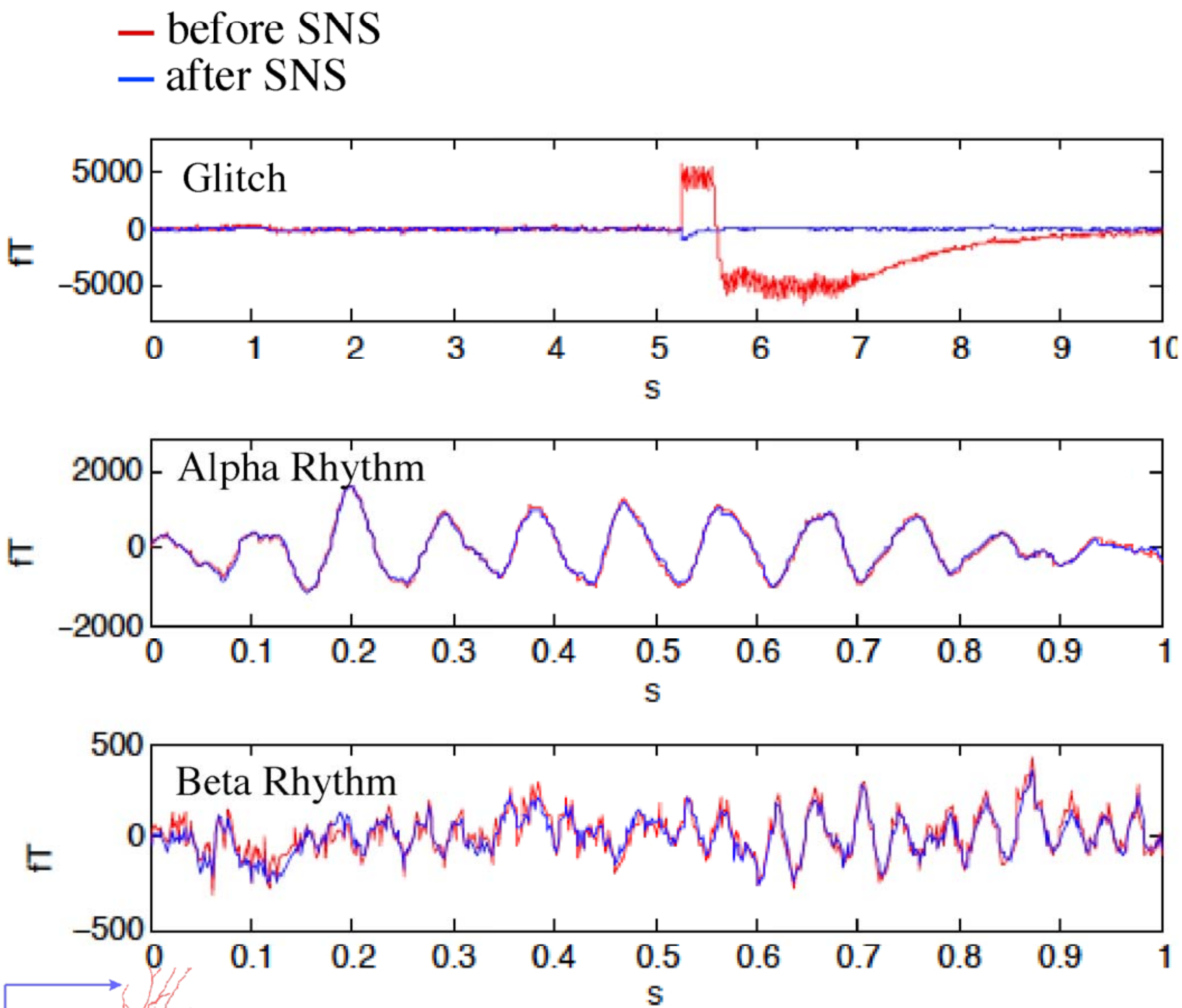
... et voilà!

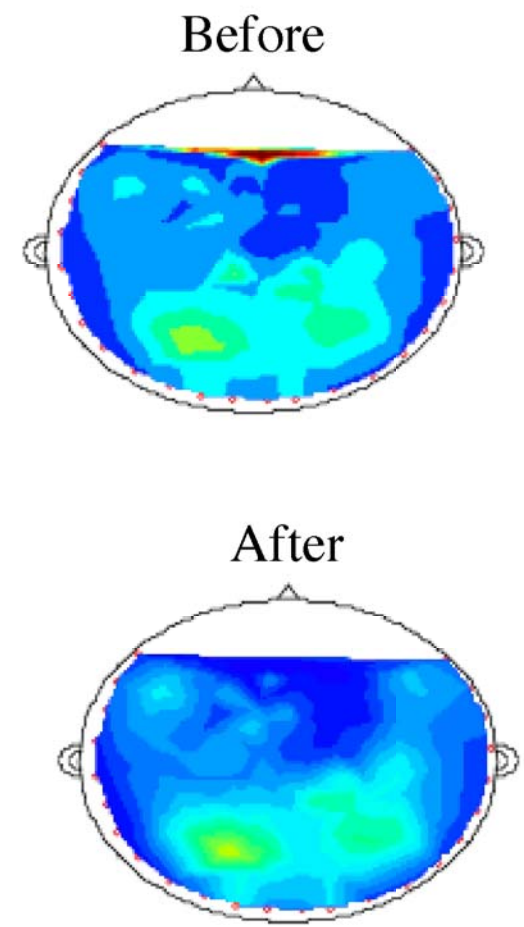
$$\hat{S} = AS$$

where $diag(A) = 0$

SNS Example

Neural Responses Unaffected





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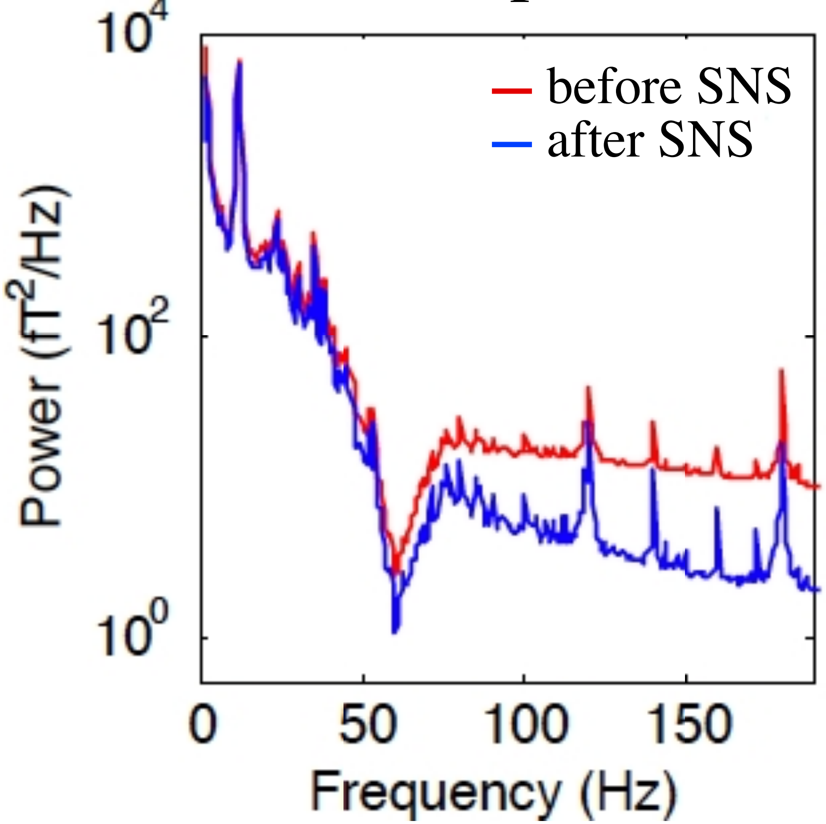
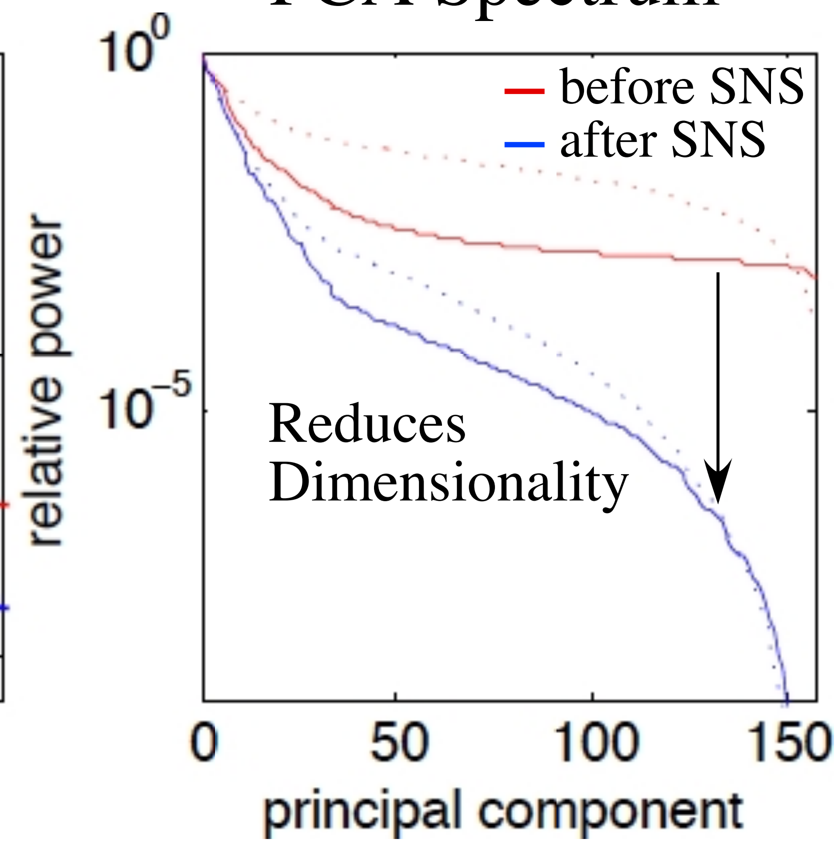
SNS Example

Power and PCA Spectra

Power Spectrum



PCA Spectrum



Removes spurious sensor-specific dimensions

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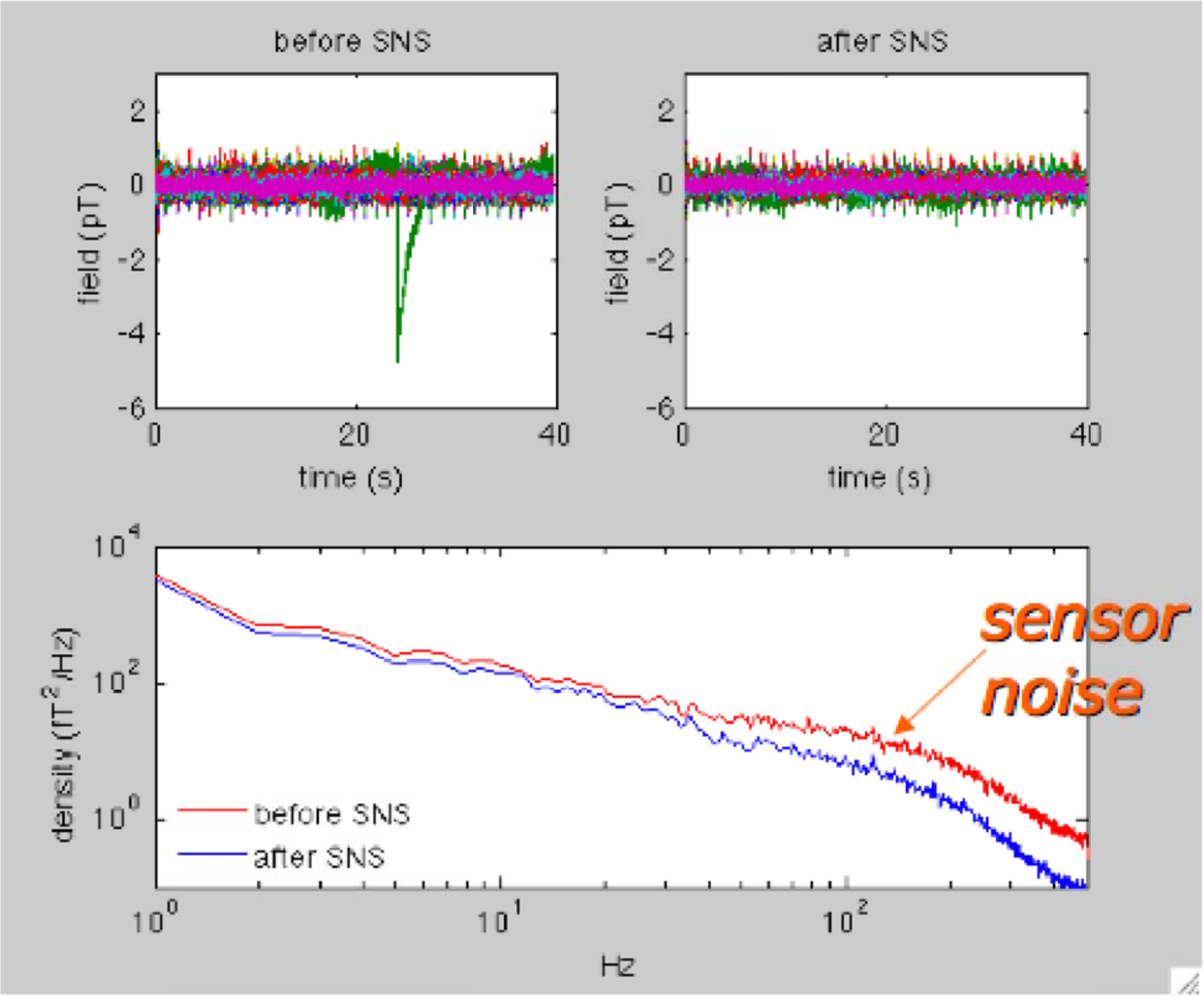
SNS Example

Glitch Removal



ATR MEG

SNS Summary

- Removes Sensor Noise
  - Glitches
  - 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)

TSPCA + SNS

- Both “user friendly”
  - Can be implemented without parameter fiddling
  - Robust even in poor SNR situations (no false minima)

- Implemented in Matlab for KIT “sqd” files
  - 700MB = 7 minutes on fast desktop computer (2008)
  - Only needs to be run once per file
  - Transparent—output is also sqd file (not Matlab file).

http://www.isr.umd.edu/Labs/CSSL/simonlab/resources/

code by Ray Shantanu & Dan Hertz

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DSS

- Denoising Source Separation
- Target: Physiological Noise
- *Requirements*:
  - Neural sources of signal-of-interest must be *spatially distinct* from noise sources
    (overlap is OK)
  - Time courses must be distinguishable
    (correlation is OK)
  - A *stimulus-based* criterion exists to say what is signal-of-interest vs. noise

DSS developed by Särelä & Valpola (2005)
Applications in colloboration with Alain de Cheveigné

DSS: How it works

DSS produces a *set of spatial filters*

$$\hat{s}_{k'}(t) = \sum_{k=1}^{K} a_{kk'} s_k(t)$$

such that:

- The DSS components, $\hat{s}_{k'}(t)$, are orthogonal
- Waveforms sum to original waveform
- Powers sum to original power ("partition of power")
- $\hat{s}_{k}{}'(t)$ ordered by decreasing quality: $\hat{s}_1(t)$, $\hat{s}_2(t)$
- Spatial filters ordered by decreasing quality: a_{k1}, a_{k2}, etc.

DSS: How it works

Algorithm:

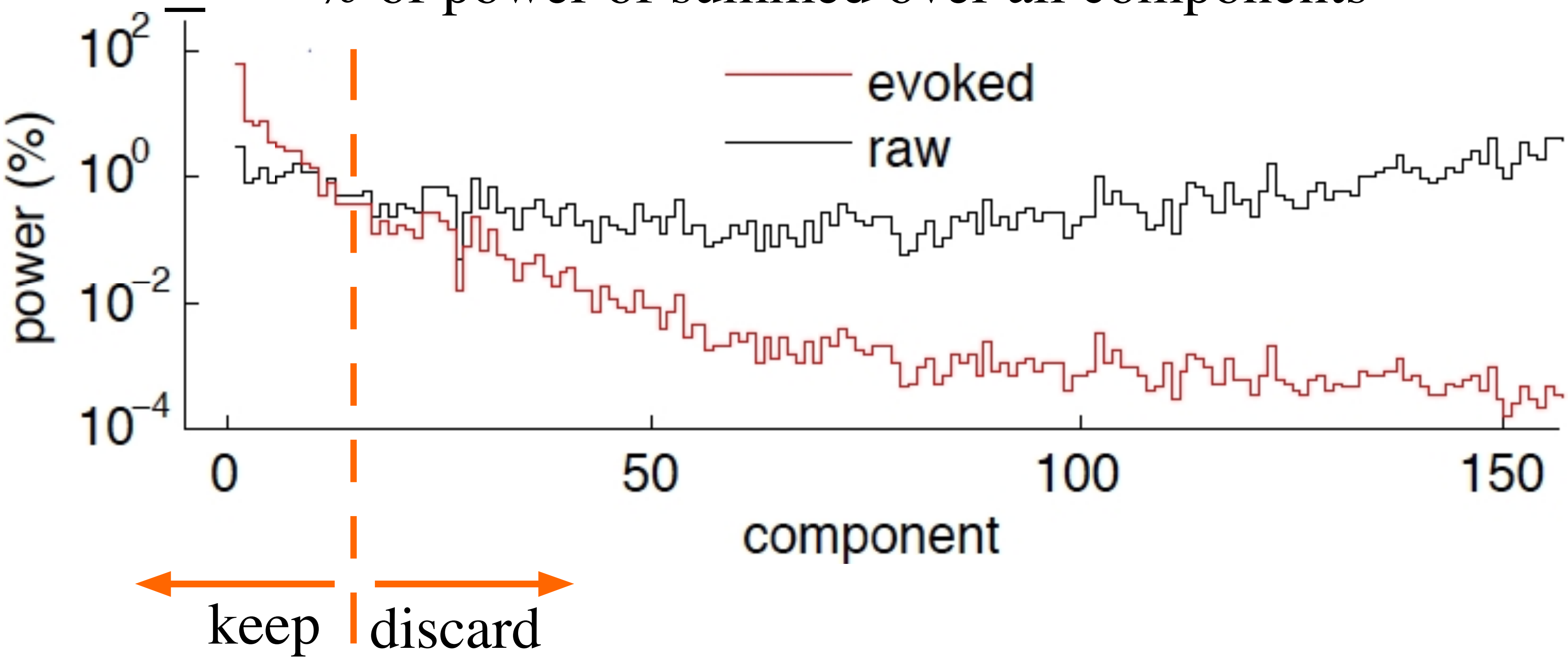
1. Normalize sensor signals & apply PCA to (spatially whiten).
2. Apply Bias (here: *average over trials*)
   to enhance good directions.
3. Apply PCA to align/order according to maximum bias.
   and retain this transform as a rotation matrix.
4. Apply rotation matrix from previous step to <u>Step 1</u> data(!).
5. Select best components, discard others (“denoising step”).
6. Project back to sensor space.

... et voilà!

DSS: How it works

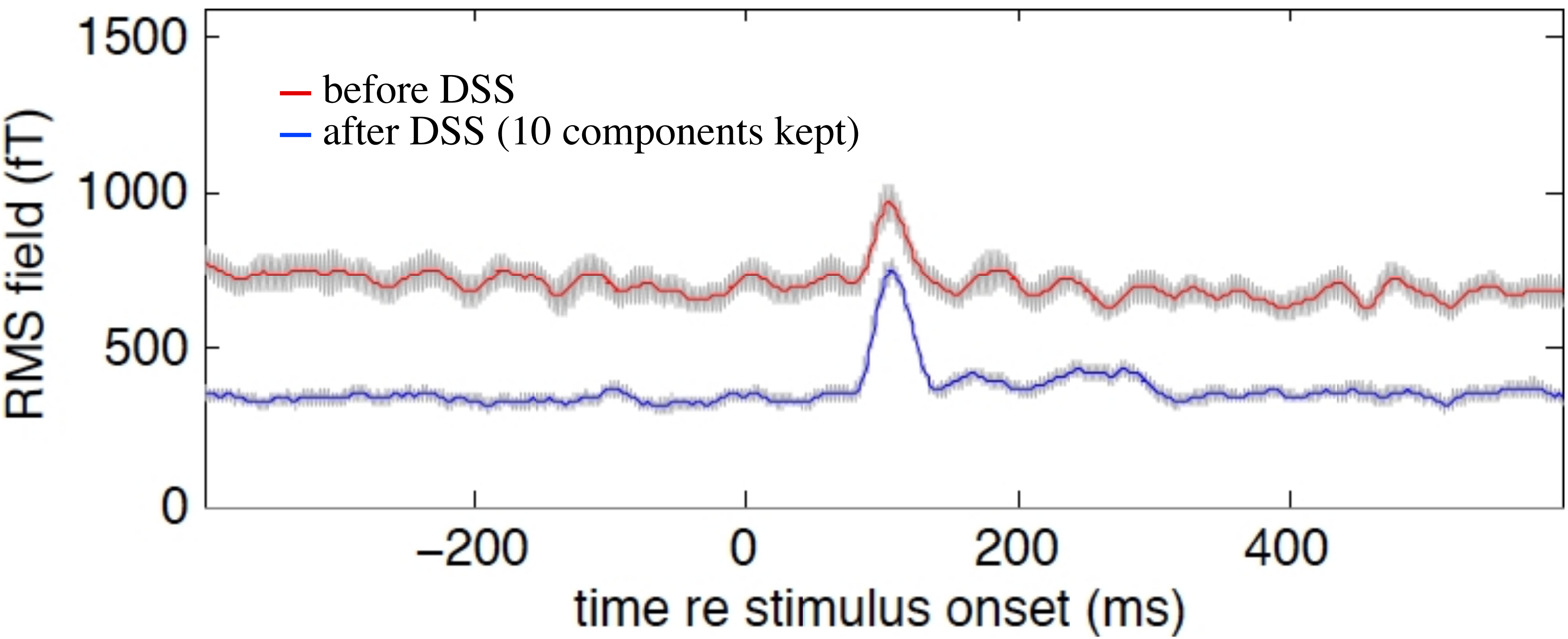
“Select best components, discard others”

% of power of summed over all components

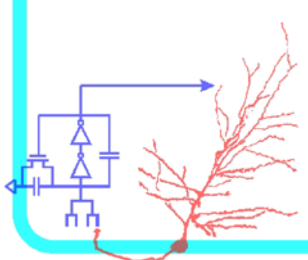


DSS Example

RMS (over all channels) of response to auditory stimulus



gray band = ± 2 SD (via bootstrap)



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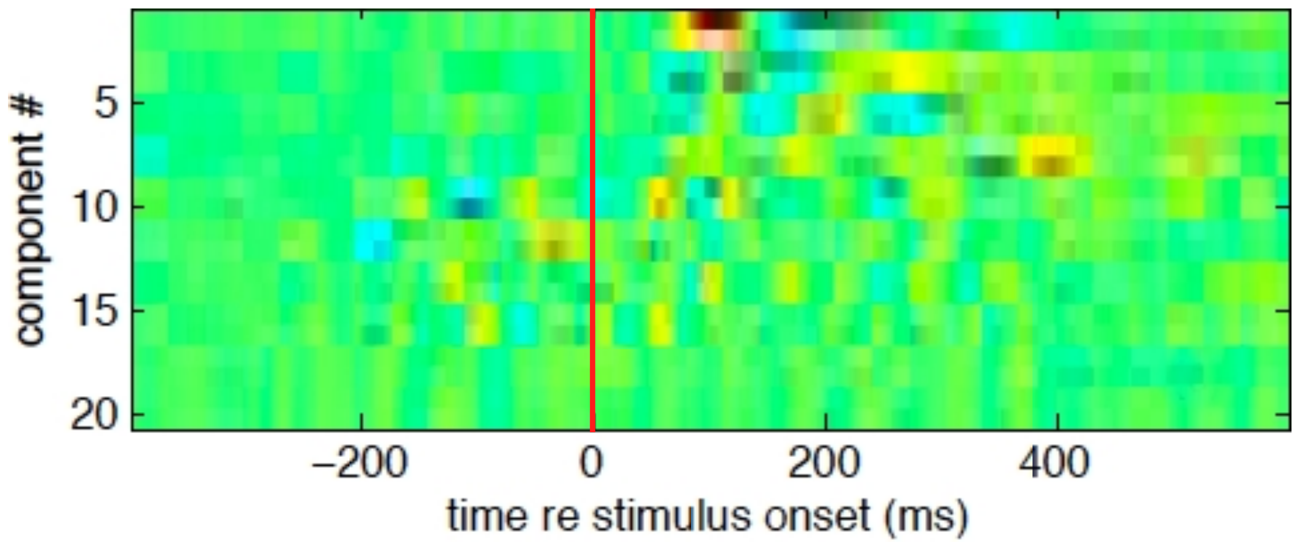
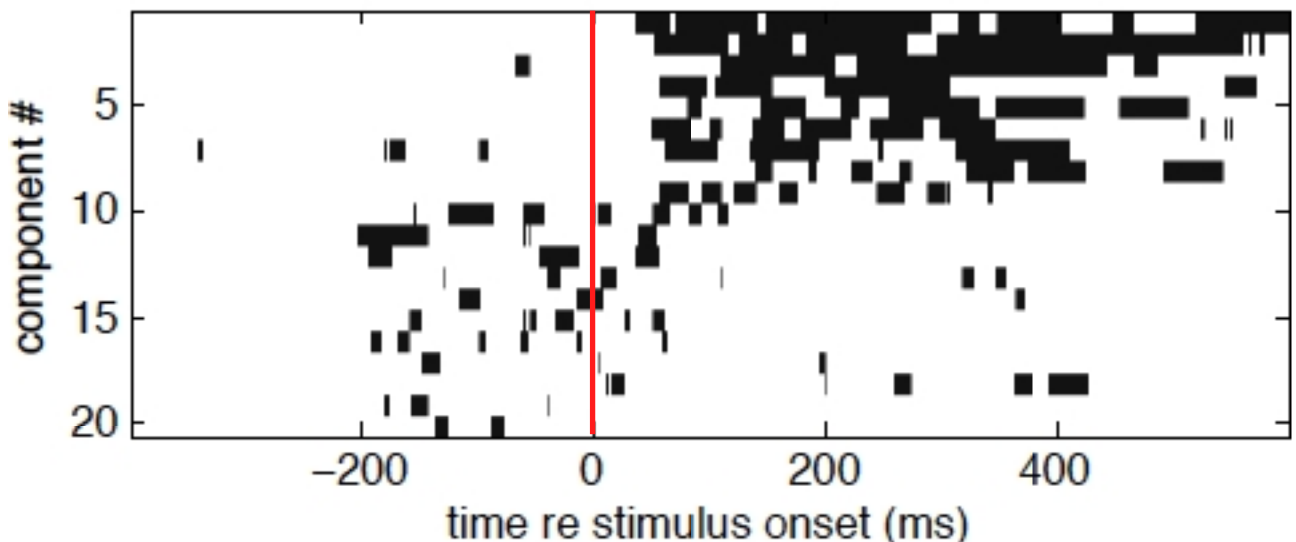
DSS Example



20 first (best) DSS components



Reliability map (4 SD threshold)

auditory stimulus, 100 repetitions

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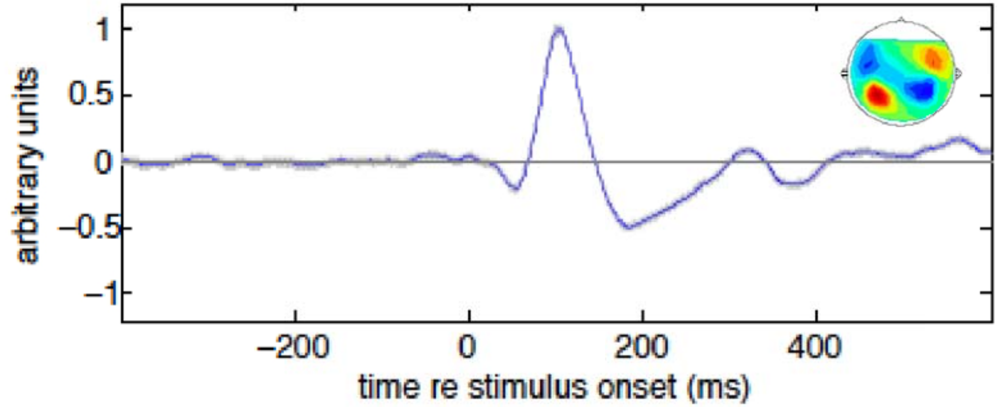
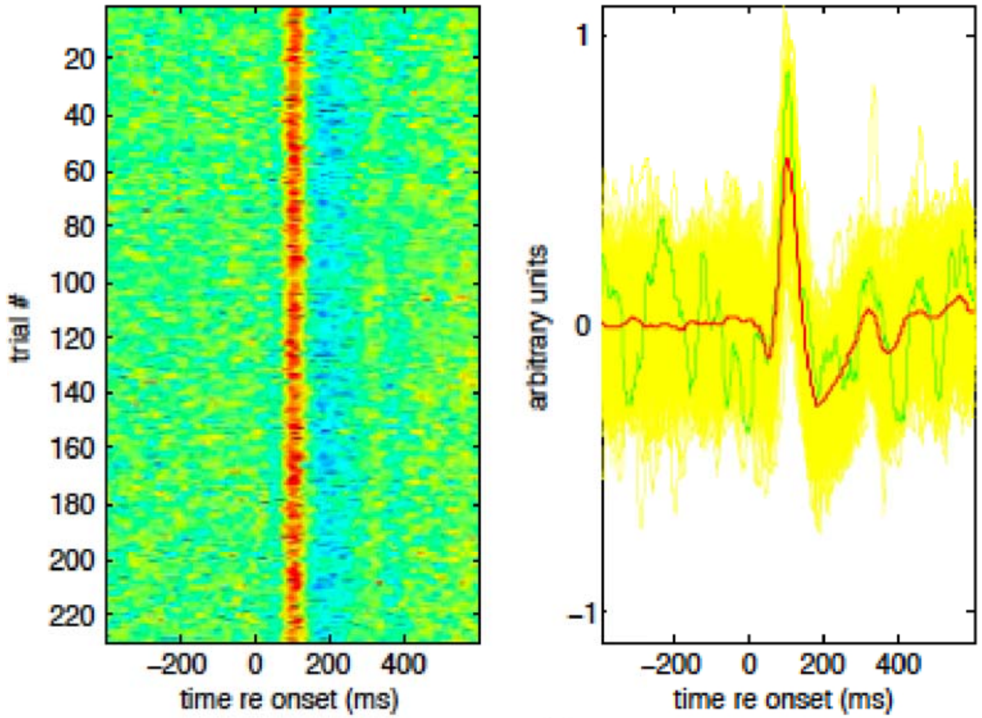
DSS Example

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

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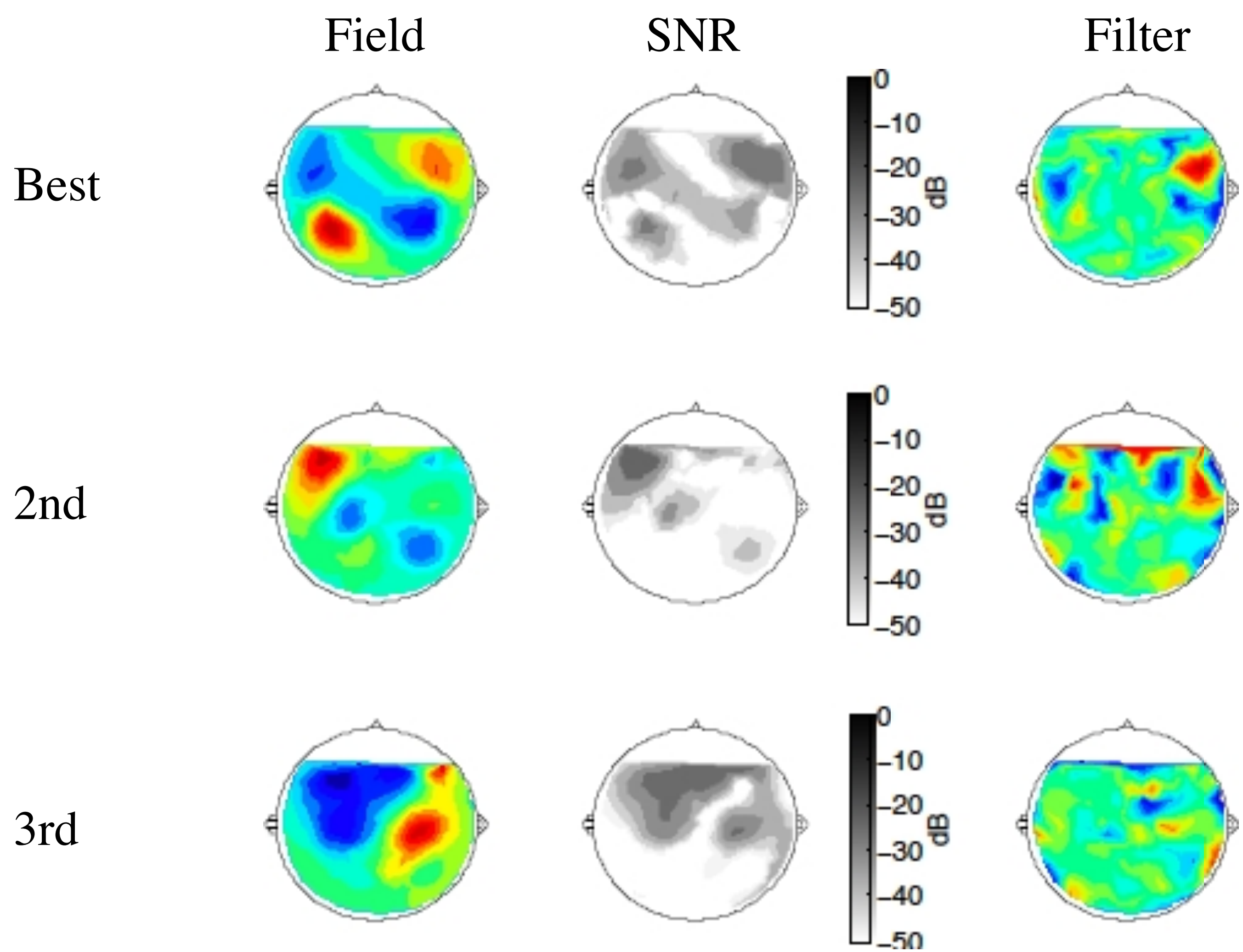
DSS Example 4

Spatial Properties of top 3 DSS filters



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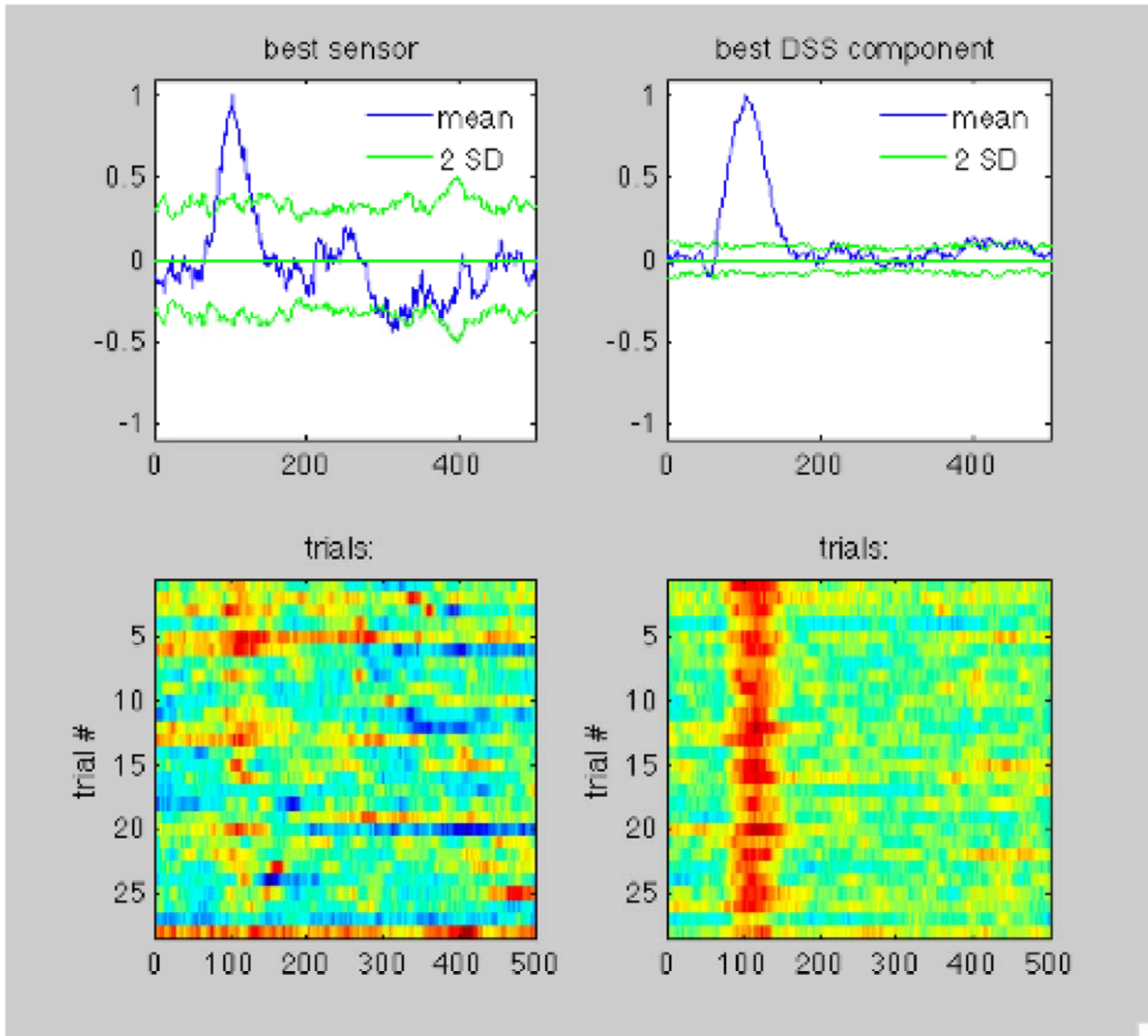
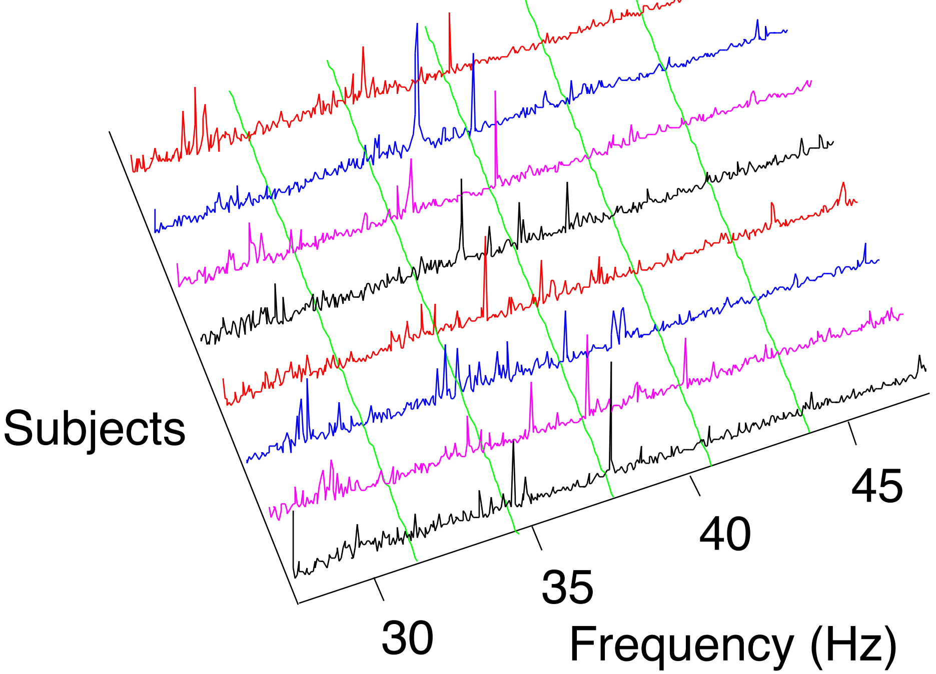
DSS Example

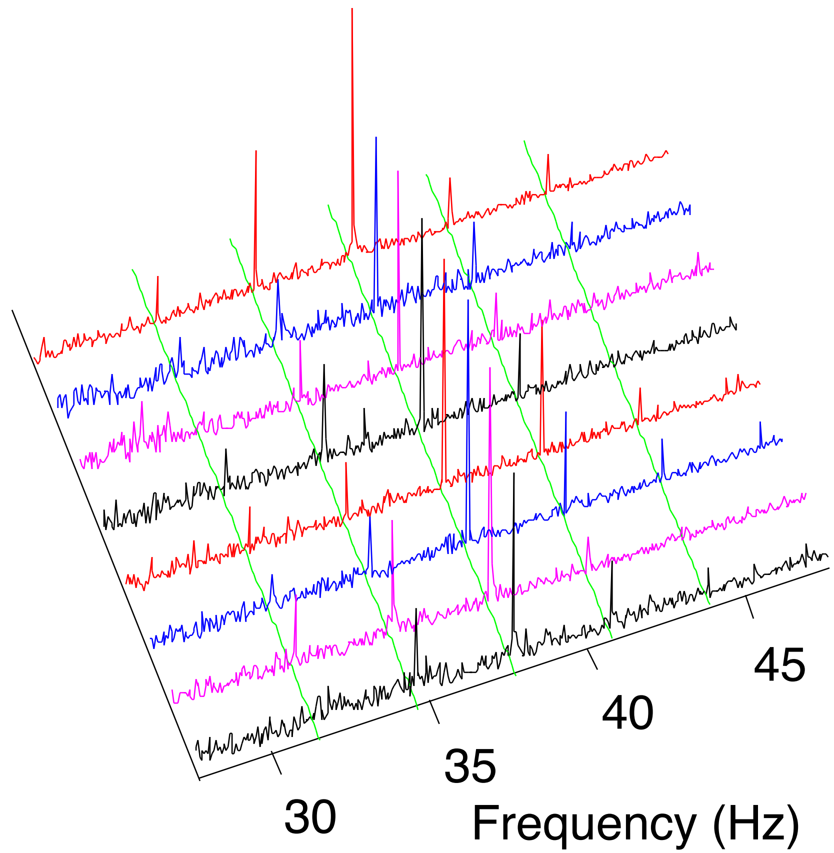
DSS as replacement for “best sensor” or “best 20” (etc.) sensors



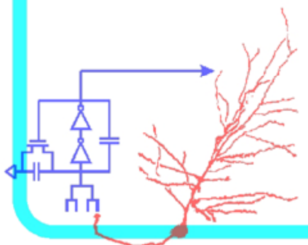
DSS Example

Spectra of MEG Steady State Response (to dual modulation)



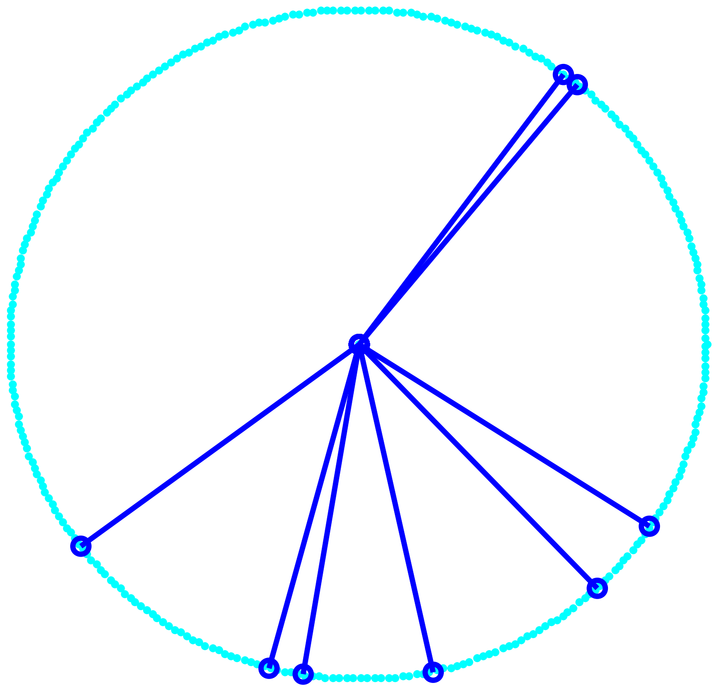


U. Maryland/KIT, courtesy of Nai Ding

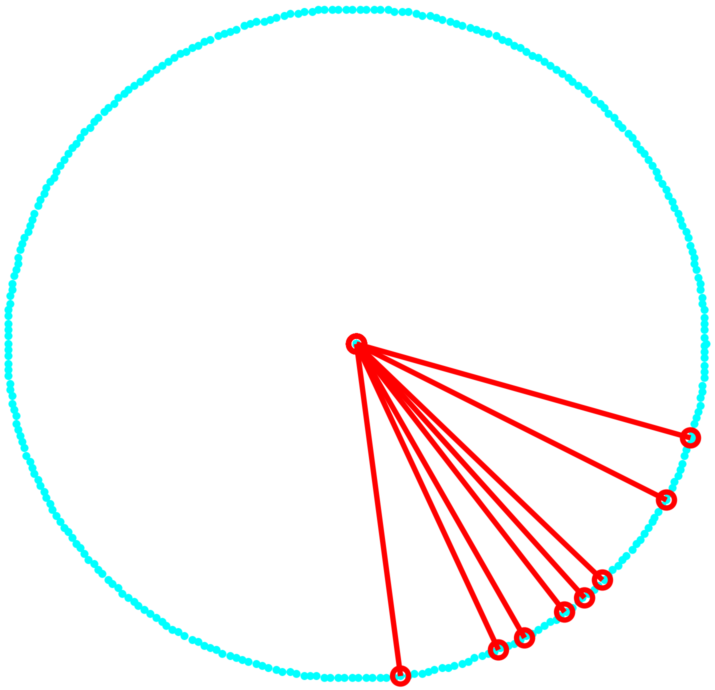


DSS Example

Phase coding parameter α (by subject)



Before DSS (20 Best Channels)



First DSS component

U. Maryland/KIT, courtesy of Nai Ding

Computational Sensorimotor Systems Laboratory

DSS Summary

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

Denoising Summary

- Denoising tools presented here are:
  - Effective: reduce noise & preserve signals of interest
  - Complementary with existing analysis tools
  - Available in Matlab
- For users:
  - Increase your MEG signal quality
  - Relax hardware filtering & loss of neural signal
    - retain slow changes
    - retain frequencies near 60 Hz
    - no filter-based distortion
- Additional applications:
  - BMI/BCI?
  - Non-shielded (portable) MEG?

Thank You


HELLO NEW MEMBERS
At the monthly meeting of Squidheads Anonymous

References & Links

de Cheveigné, A. and Simon, J. Z. (2007). "*Denoising based on Time-Shift PCA*." Journal of Neuroscience Methods 165: 297-305.

de Cheveigné, A. and Simon, J. Z. (2008). "*Sensor Noise Suppression*." Journal of Neuroscience Methods 168: 195-202.

de Cheveigné, A. and Simon, J. Z. (2008). "*Denoising based on spatial filtering*." Journal of Neuroscience Methods 171: 331-339.

http://www.isr.umd.edu/Labs/CSSL/simonlab/resources/