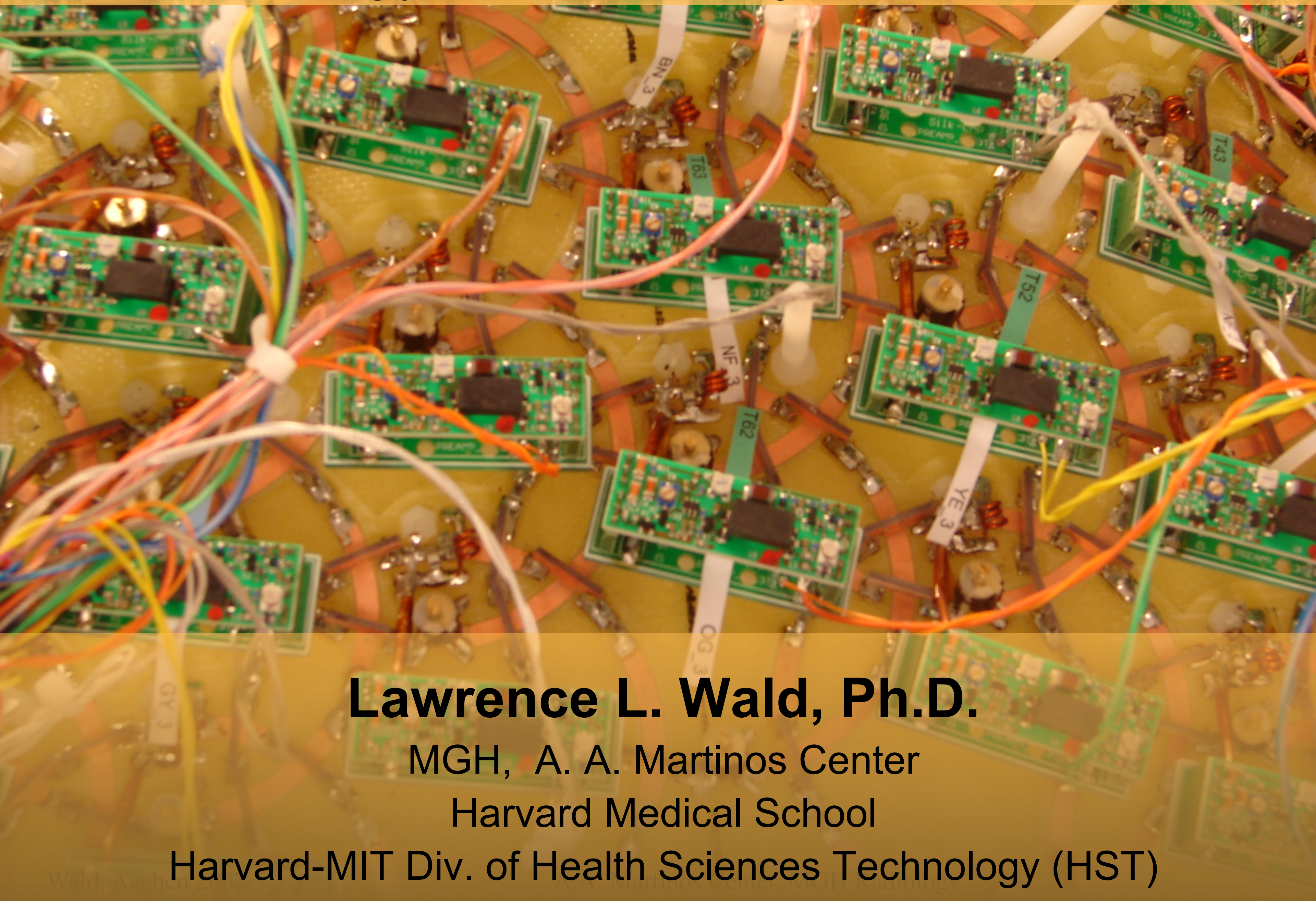
Technology for encoding with detectors



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Outline

1. Coil intro; highly parallel detection, encoding…
   i. Basics of Faraday detection and encoding in MR arrays
   ii. How far can the highly parallel angle take us (modeling).
   iii. Array compression with mode mixing (receive arrays)
   iv. Array compression (transmit arrays).
2. Some coil arrays;
   i. 32-128 channel arrays
   ii. Pediatric arrays
3. Using the coils;
   i. Echo Volume imaging and InI
   ii. Simultaneous multislice imaging.
4. *An application*
   ii. Laminar analysis in cortex

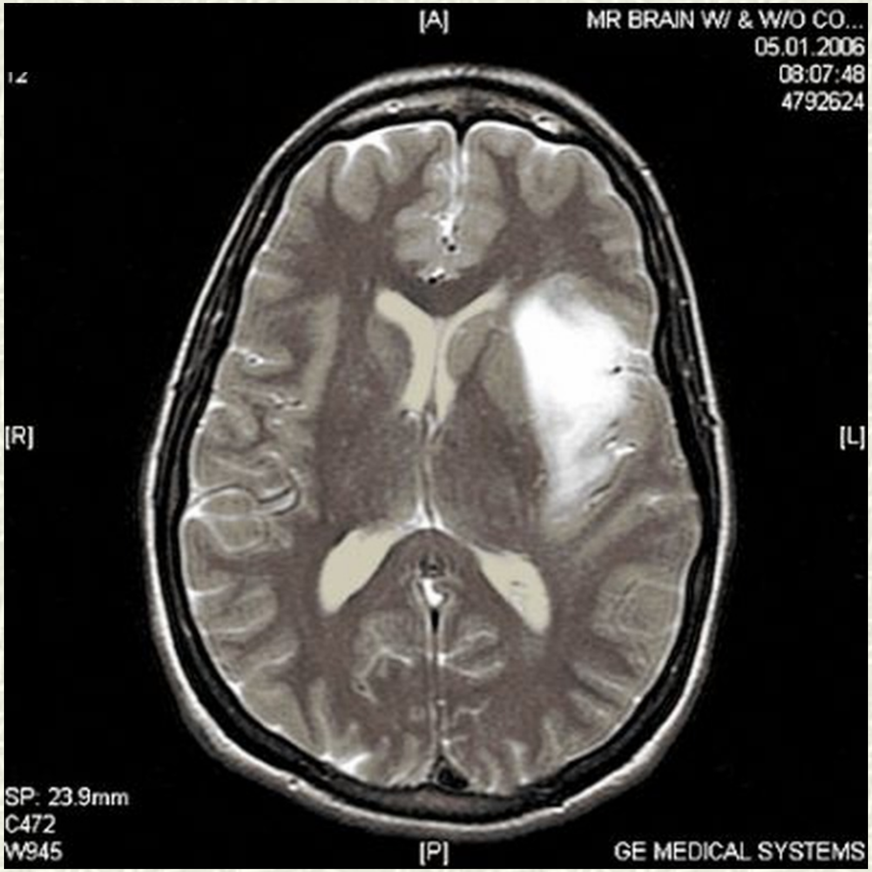
Why work on MRI technology?

Bread and butter of MR industry for 30 years:

Gross pathology, diagnostics and treatment planning…

Next level of brain structure; Laminar and columnar organization needs ~200um <u>isotropic</u> resolution.

>> Both encoding and sensitivity limited



Is there more to see?

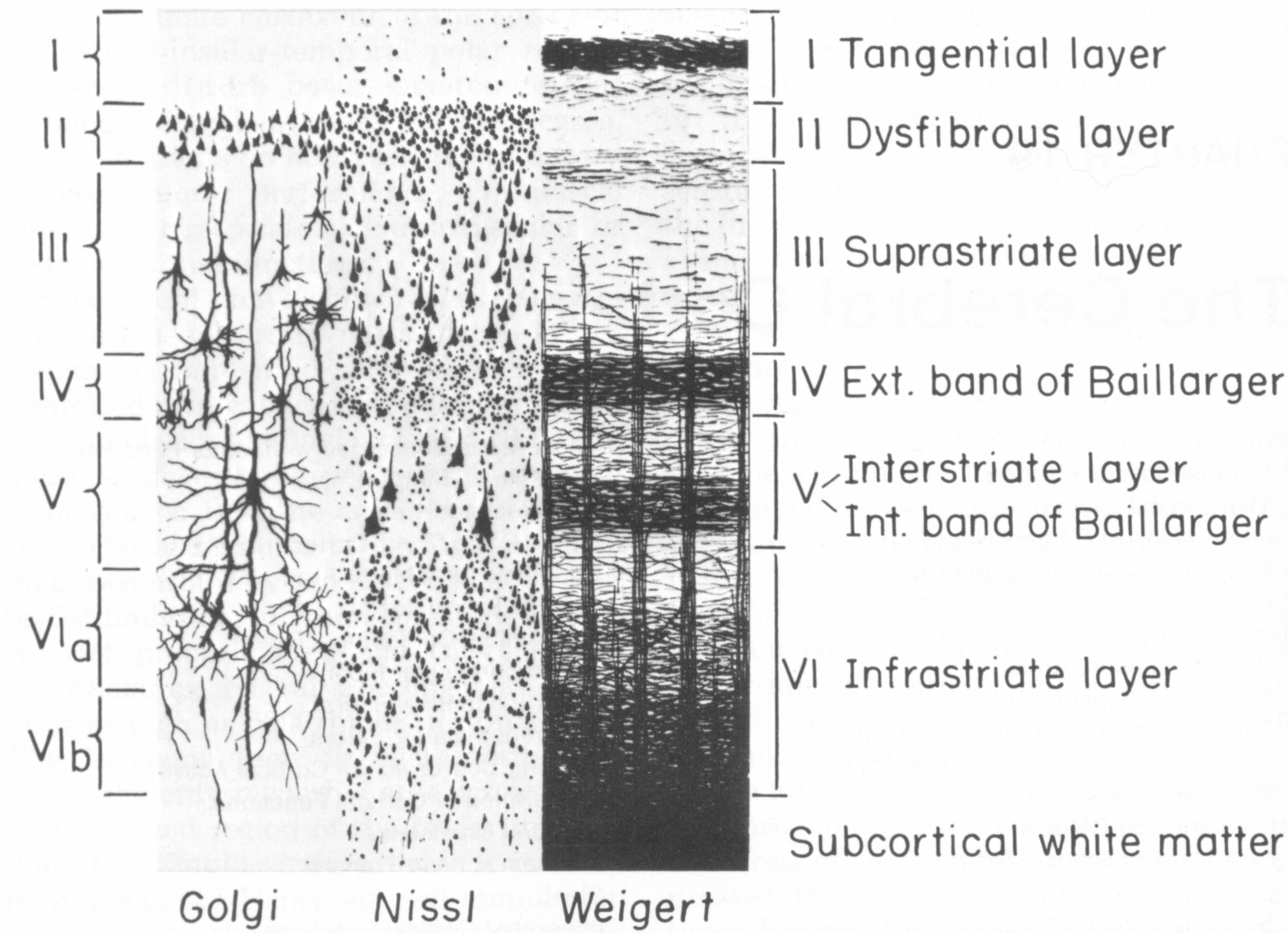
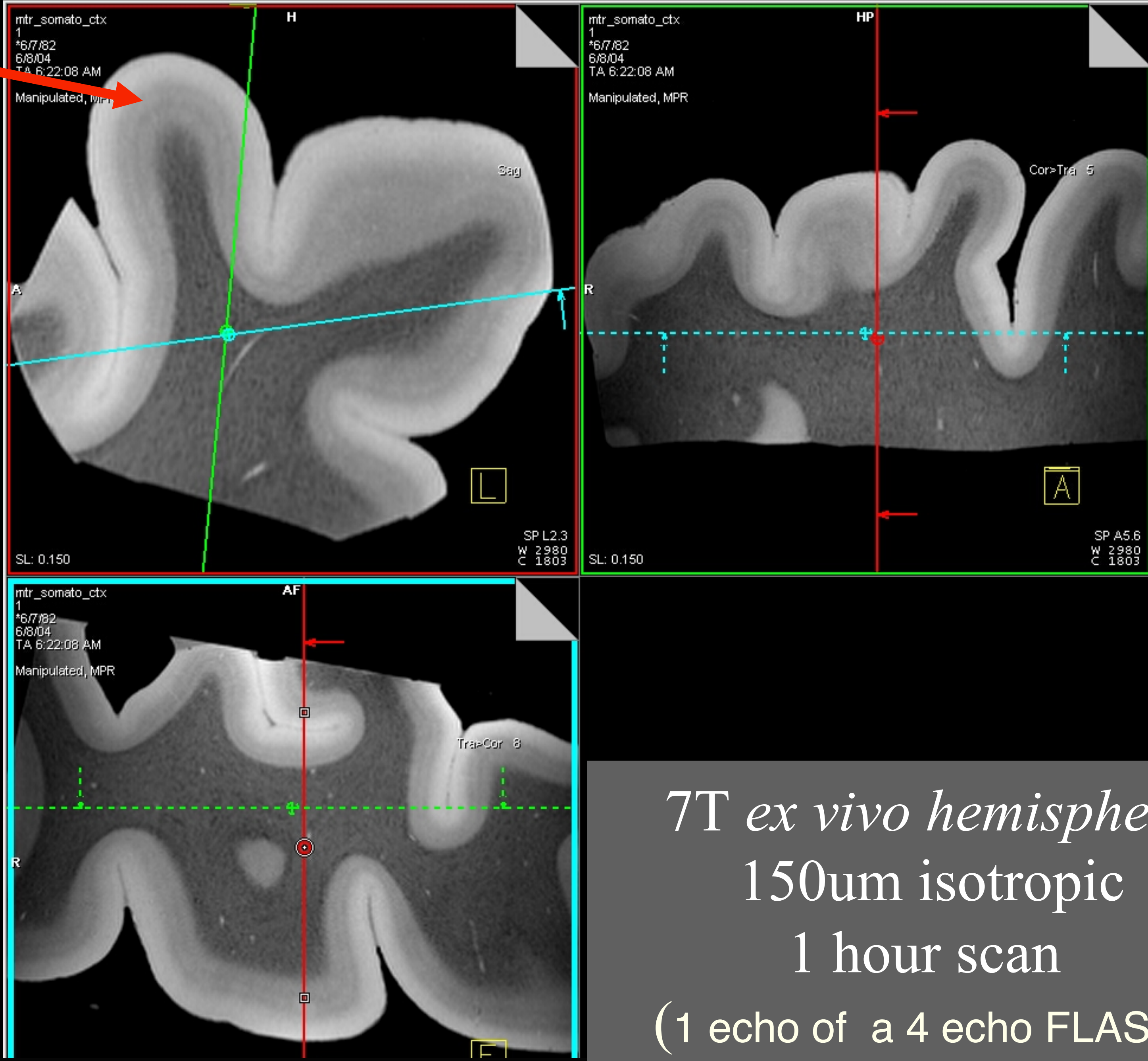


Figure 19-1. The cell layers and fiber arrangement of the human cerebral cortex (semischematic) (after Brodmann (301)).

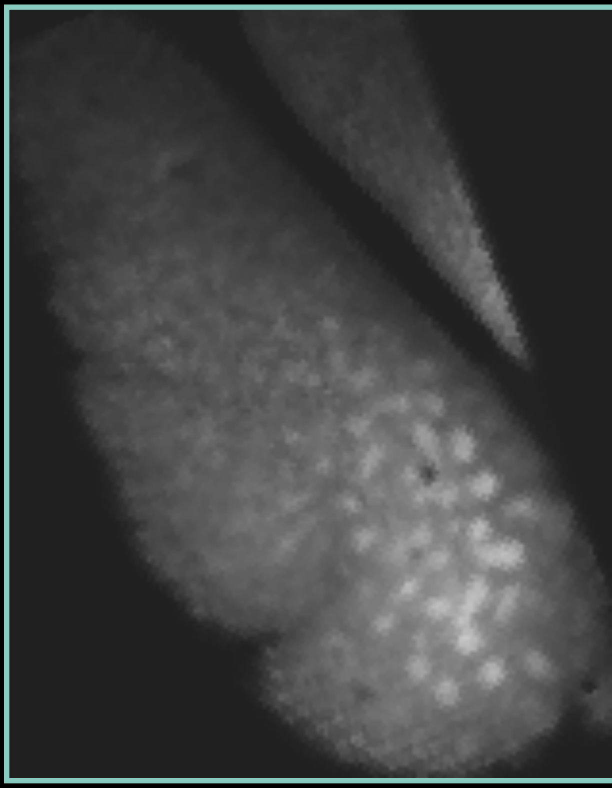


7T *ex vivo hemisphere*
150um isotropic
1 hour scan
(1 echo of a 4 echo FLASH)

Human sensory/motor cortex

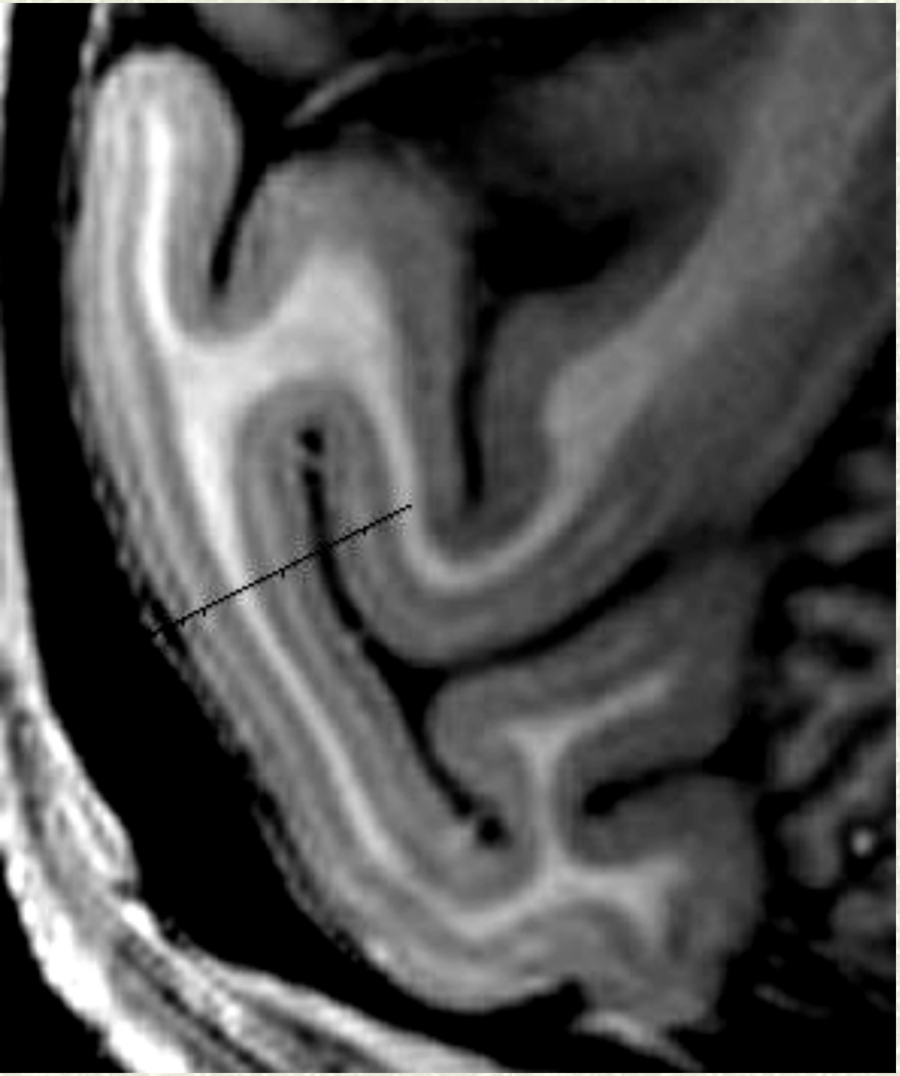
Islands in Endorhinal cortex

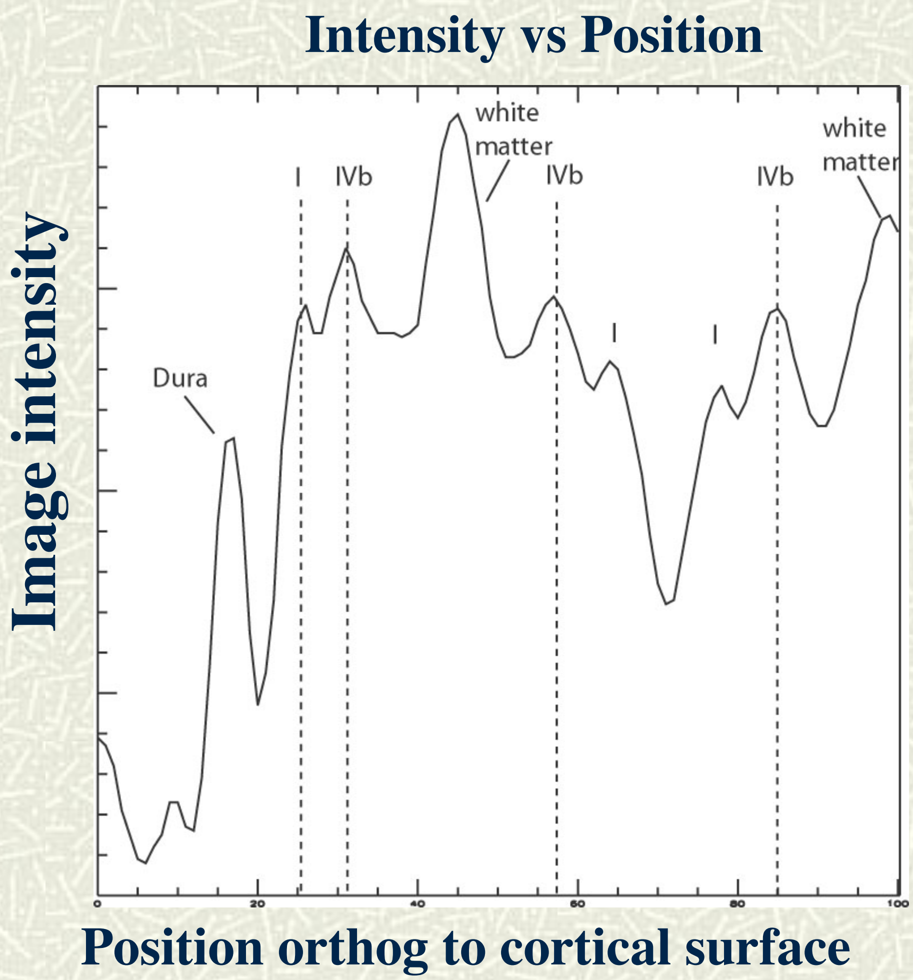
7T *ex vivo*
100um isotropic



B. Fischl
J. Augustinack, MGH

Cortical layers in Monkey V1 at 7T





3D MPRAGE T_1 images   250um x 250um x 750um

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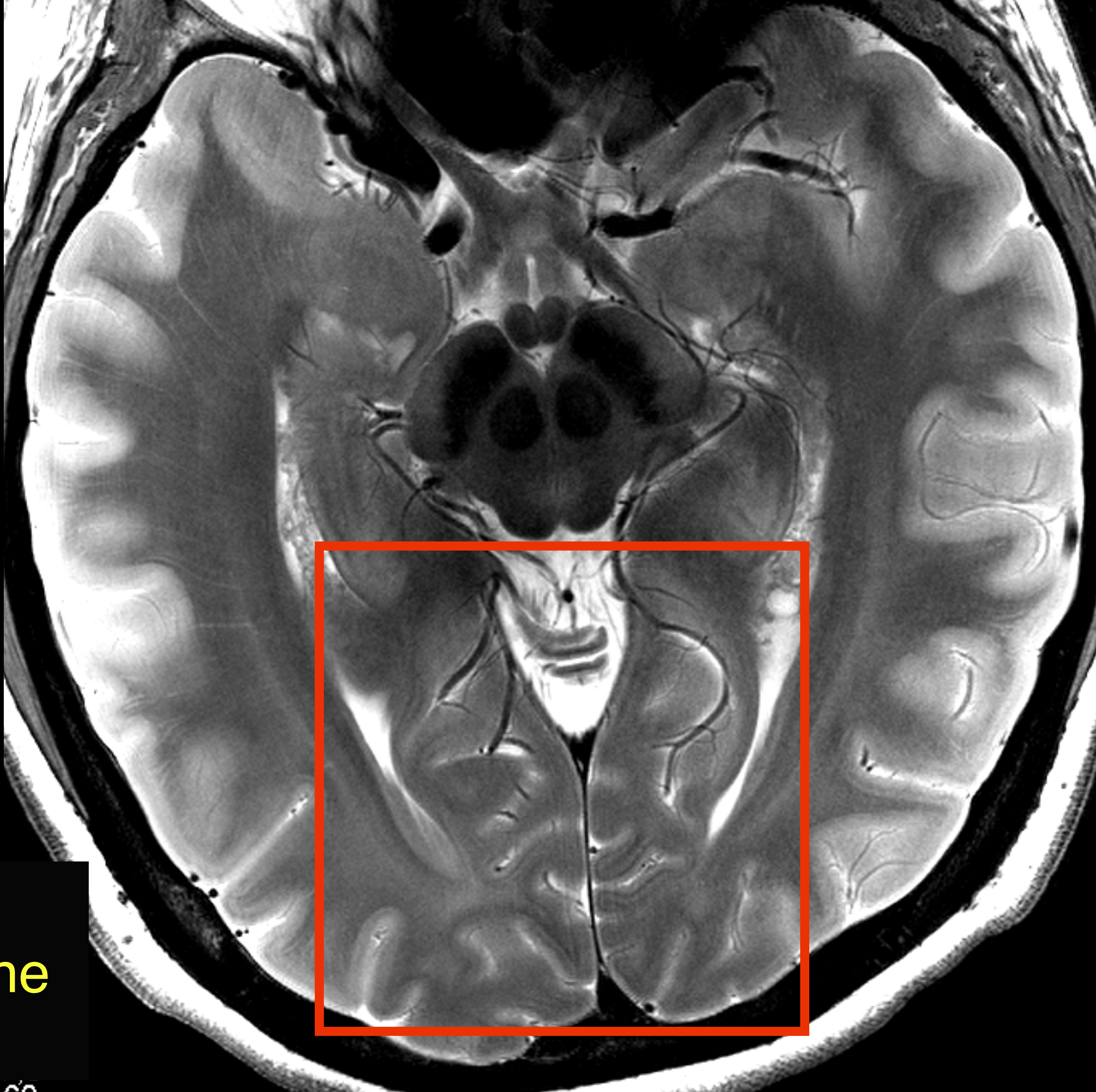
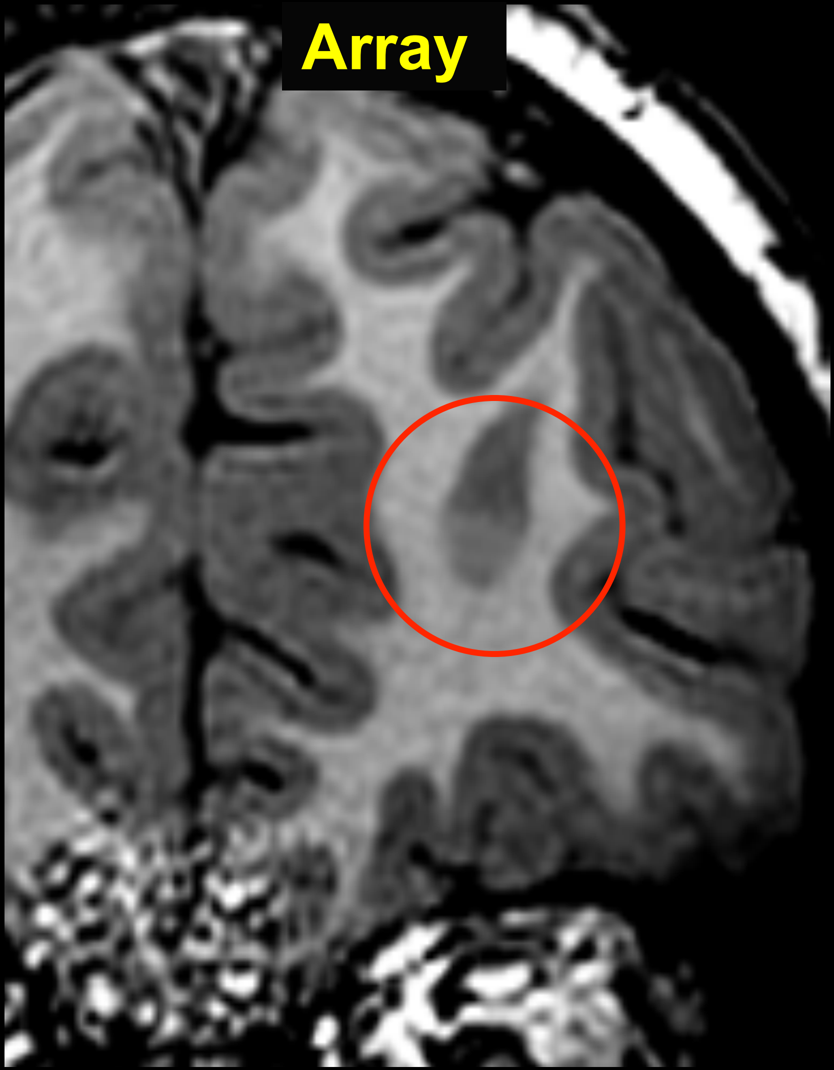


7T array coil
270um inplane
2mm slice

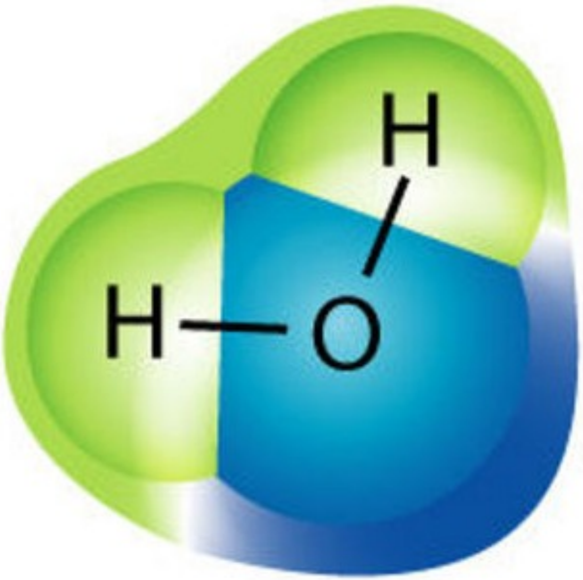
7T array coil
270um inplane
2mm slice

14 yr old: Improved imaging targets surgery



Dozen seizures per day ➡ Seizure free

MRI (short version):
Water magnetism



Is water magnetic? Yes, weakly

Orbital electrons, electron spin:

Diamagnetism; no un-paired e^-,

quenched orbital angular momentum.

Nuclear magnetism:

O^{16} (even number of p and n

> no magnetic moment

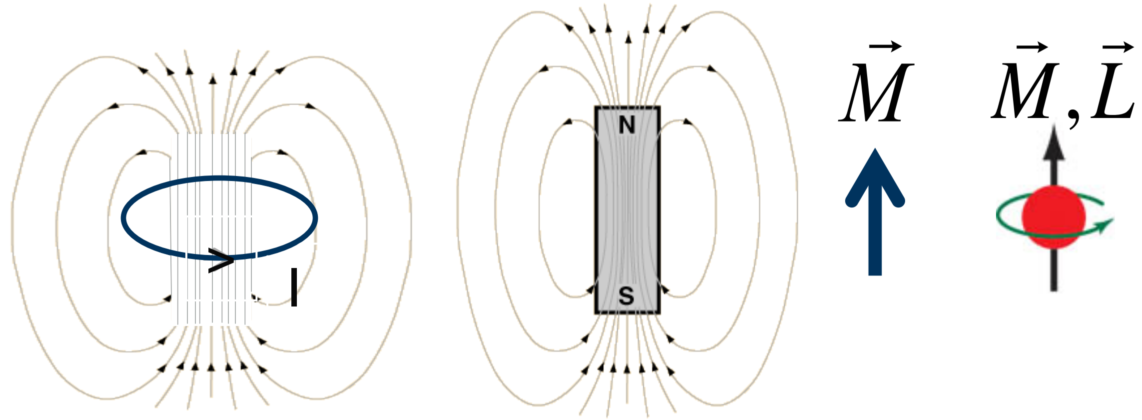
H^1 (proton, spin ½) --->>>

magnetic moment + angular momentum

= Magnetic Resonance

Boltzmann polarization

Magnetic dipole:



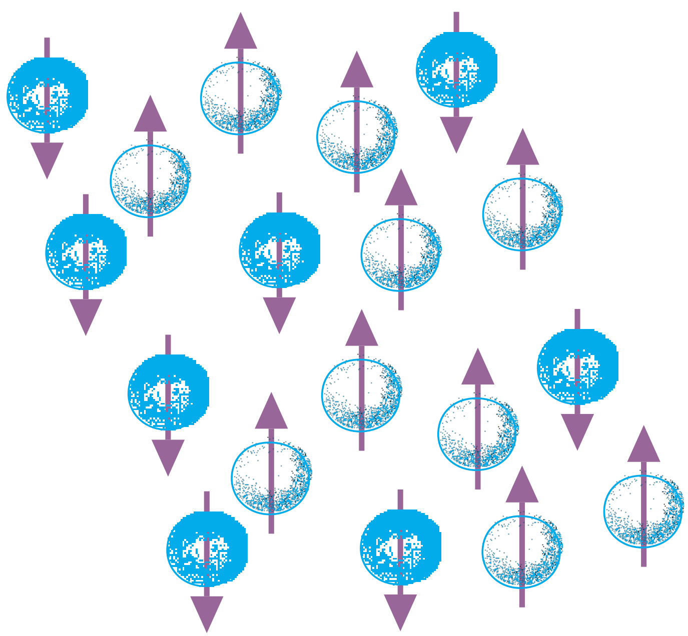


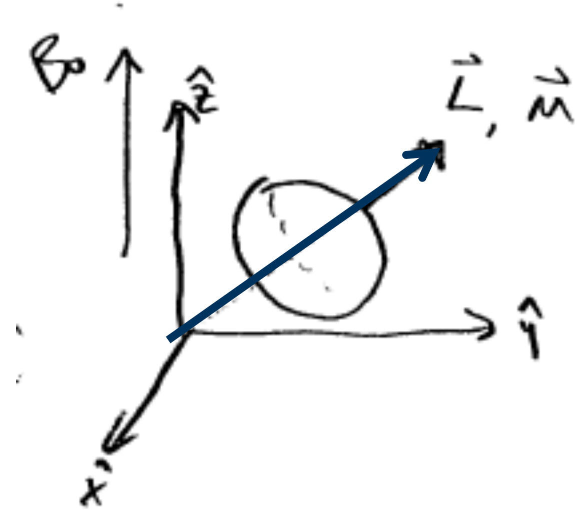
Image distribution of this….

$$= \vec{M}$$

Net alignment:

$$\vec{M} = \sum \vec{m}$$

Energy and Torque on dipole in field

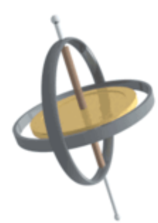


Energy of system (wants to align): $U = -\mathbf{M} \cdot \mathbf{B}$

Torque on M in an applied field; $\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F} = \mathbf{M} \times \mathbf{B}$

Also angular momentum: $\mathbf{M} = \gamma \mathbf{L}$

Torque = dL/dt yields gyroscopic motion: $d\mathbf{M}/dt = \gamma \mathbf{M} \times \mathbf{B}$



Equations of motion for spin in B field

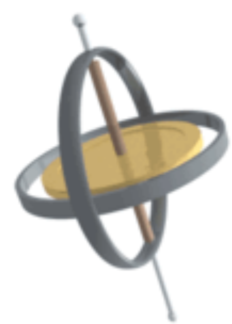
Bloch Eqs. Lab Frame

$$\dot{M} = \gamma \overrightarrow{M} \times \overrightarrow{B}$$

For **B** = $B_0 \hat{z}$ $\quad \dot{M}_z = 0 \quad$ M_z is a constant of motion

$$M_{xy} = M_0 e^{-\gamma B_0 t}$$

M_{xy} rotates cw in xy plane, $\omega_0 = \gamma B_0$



Two components of Magnetization

M_z : Stationary, does not contribute to signal.

Tells you how much is "stored" ready for the next excitation.

M_{xy}: Processes at $\omega = \gamma B_{total}$.

Determines amplitude and phase of detected signal.

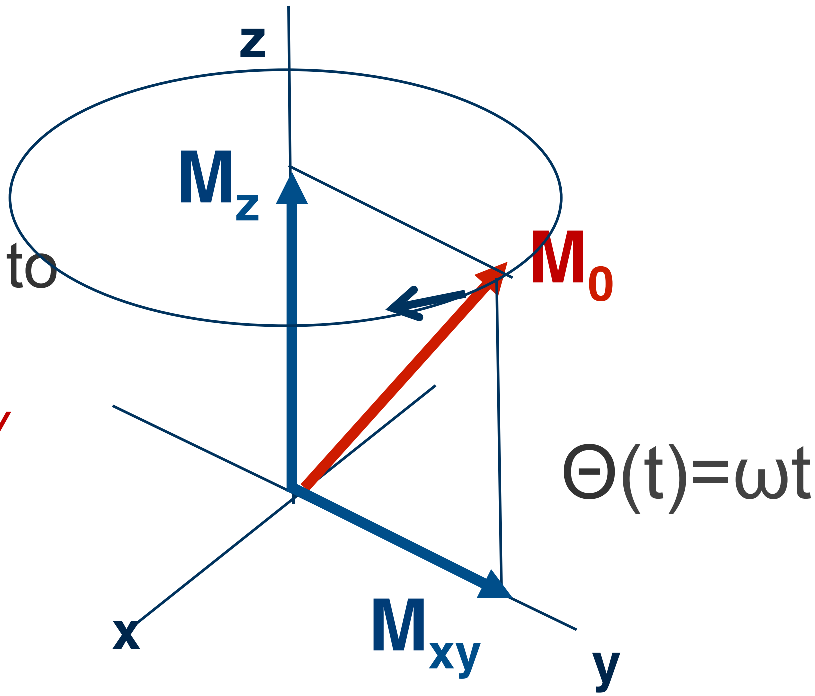
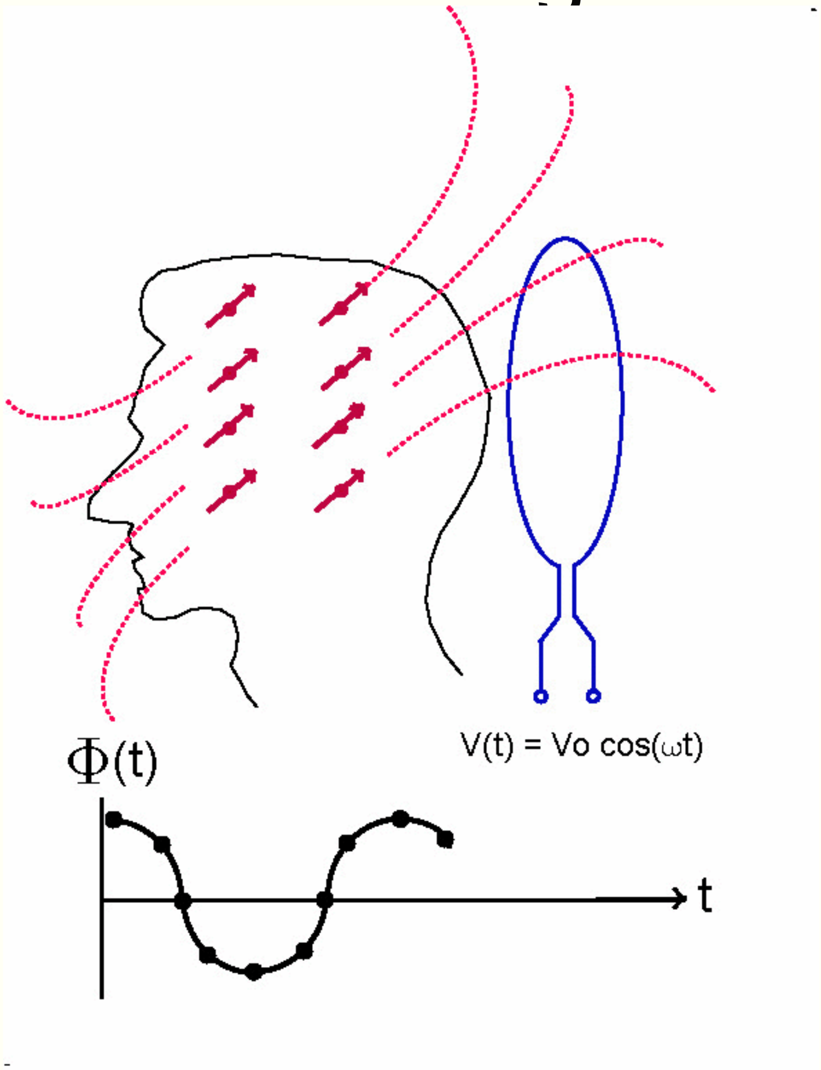


Image encoding: keep track of M_{xy} when a gradient is on…

Faraday detection: Near-field magnetic dipole detectors



$$\Phi(t) \propto M_0 \cos(\omega t)$$

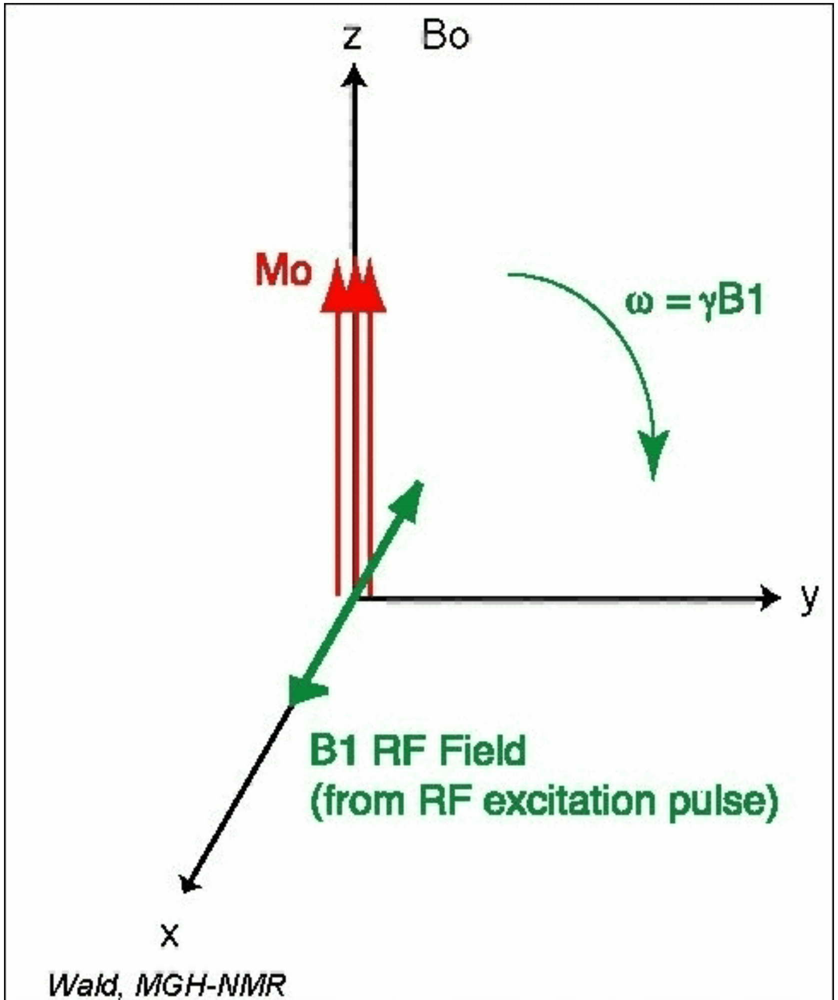
$$V(t) = -\frac{d\Phi(t)}{dt}$$

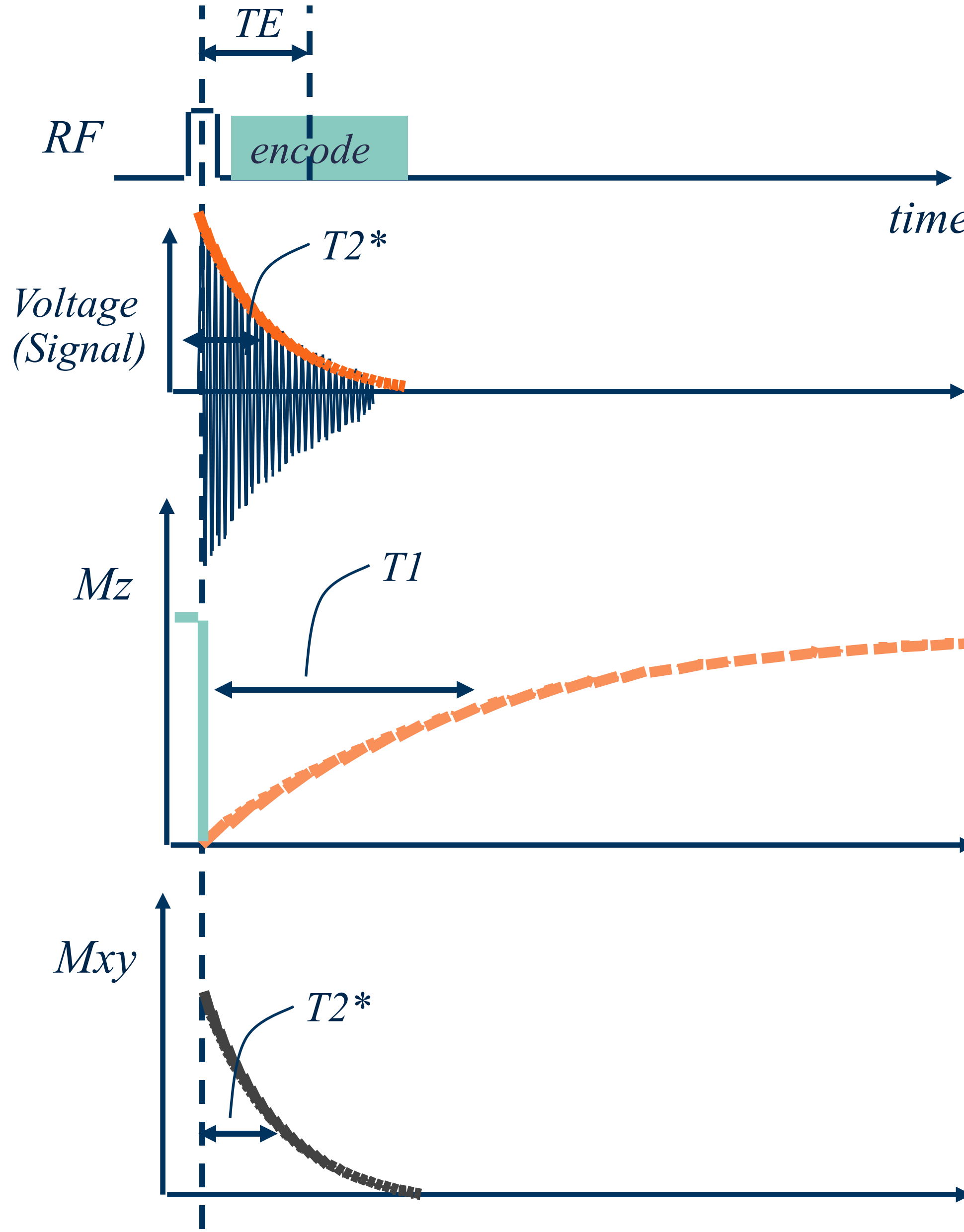
$$V(t) \propto -M_0 \omega \sin(\omega t)$$

$$M_0 \propto B_0 \qquad \omega \propto B_0$$

$$V(t) \propto B_0^{\ 2}$$

Magnetization vector during MR





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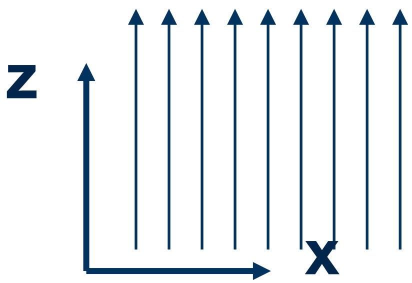
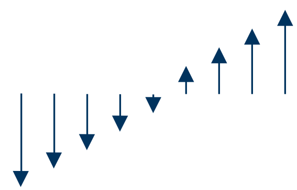
Fourier encoding with applied static field gradients

B_o



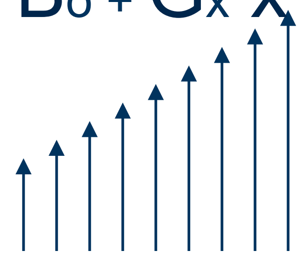
Uniform magnet

$G_x\, x$



Field from gradient coils

$B_o + G_x\, x$



Total field

$$G_x = \partial B_z / \partial x$$

$$\vec{B}(\vec{r}) = (B_0 + \vec{G} \cdot \vec{r})\hat{z}$$

$$\omega_{spins} = \gamma B_0 + \gamma \vec{G} \cdot \vec{r}$$

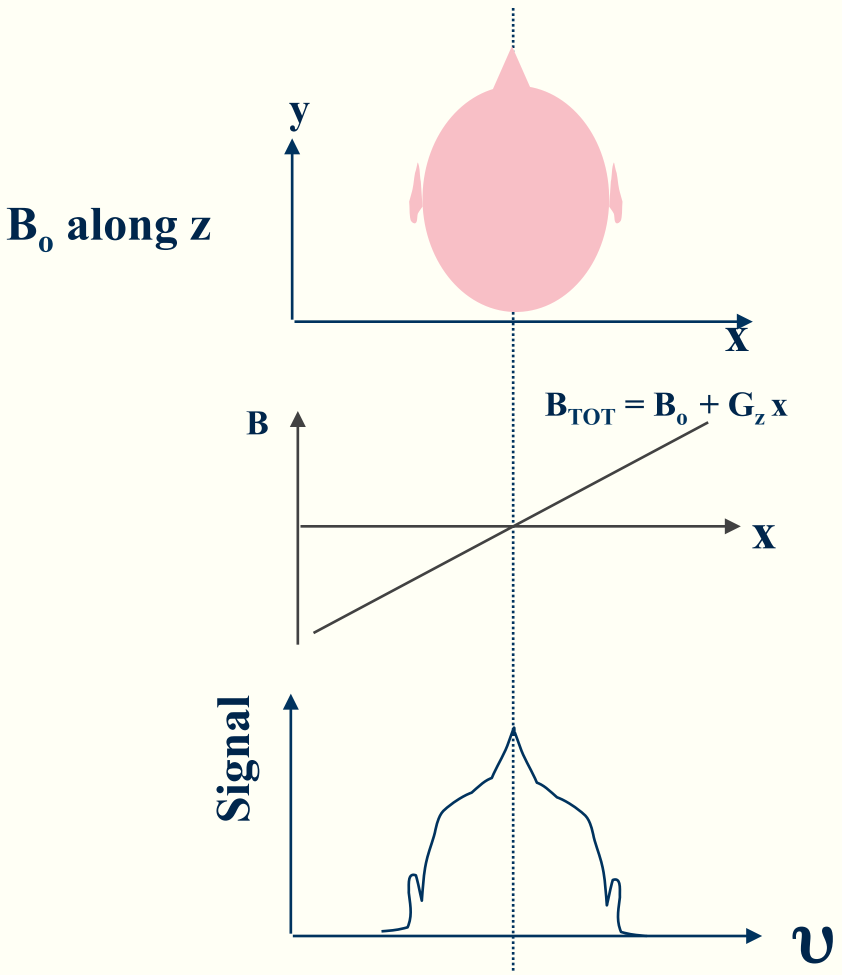
$$M_{xy} = M_0 e^{-\gamma B(\vec{r})t}$$

M_{xy} rotates cw in xy plane,

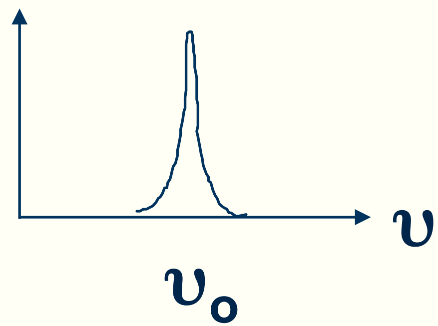
$$\boxed{\omega = \gamma B_0 + \gamma \vec{G} \cdot \vec{r}}$$

Encoding, intuitive picture

"Frequency encoding"



with gradient



without gradient

Equations of motion in gradient field

$$M_{xy} = M_0 e^{-\gamma B_0 + \gamma(\vec{G}(t)\cdot\vec{r})t}$$

M_{xy} rotates cw in xy plane,

View in frame Rotating with spins:

$$M_{xy} = M_0 e^{-\gamma(\vec{G}\cdot\vec{r})t}$$

Use complex notation for xy component:

$$M = M_x + iM_y$$

Be a little more precise about phase:

$$\theta(\vec{r},t) = \int_0^t \omega(t)\, d\tau$$

$$M(\vec{r},t) = M_0(\vec{r})\exp\left(-i\int_0^t (\vec{G}(t)\cdot\vec{r})\, d\tau\right)$$

Equations of motion in gradient field

Bloch Eqs. Rotating frame

$$M(\vec{r},t) = M_0(\vec{r})\exp\left(-i\int_0^t (\vec{G}(t)\cdot\vec{r})\,d\tau\right)$$

Define: $\vec{k}(t) = \frac{1}{2\pi}\int_0^t \vec{G}(t)d\tau$

r has no time depend, can bring it out of the integral…

$$M(\vec{r},\vec{k}) = M_0(\vec{r})\exp(-i\vec{k}\cdot\vec{r})$$

Note, t dependence is in k, <u>which is under user control…</u>

Detection coil integrates signal over space:

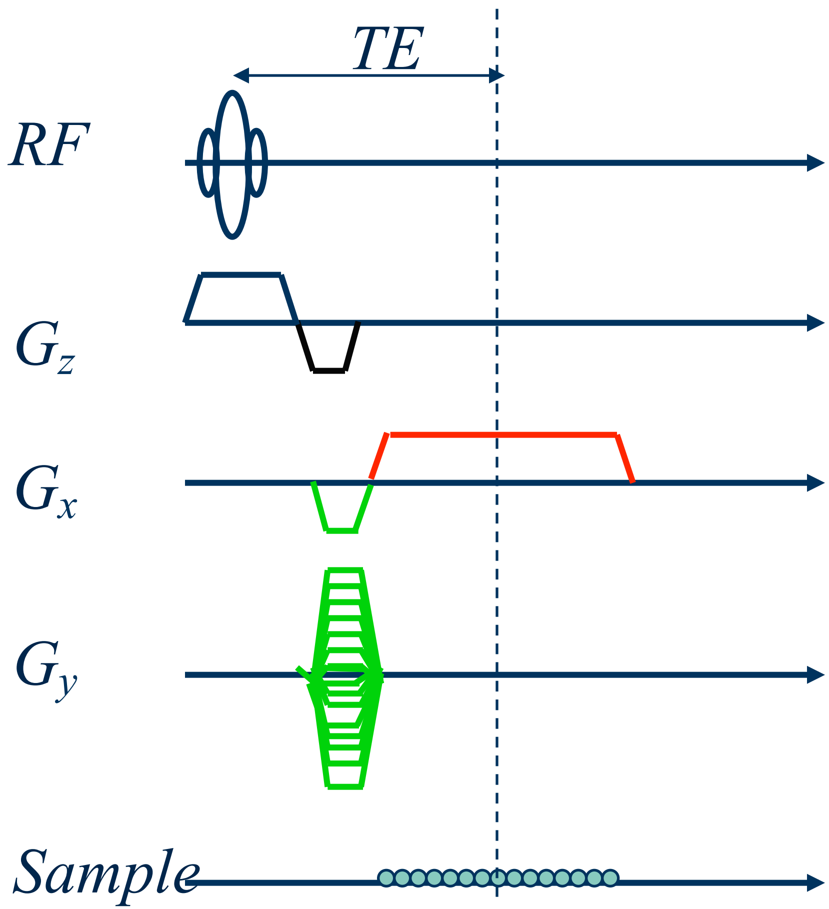
$$S(\vec{k}) = \iiint_{RFcoil} M(\vec{r},\vec{k})\,dr^3$$

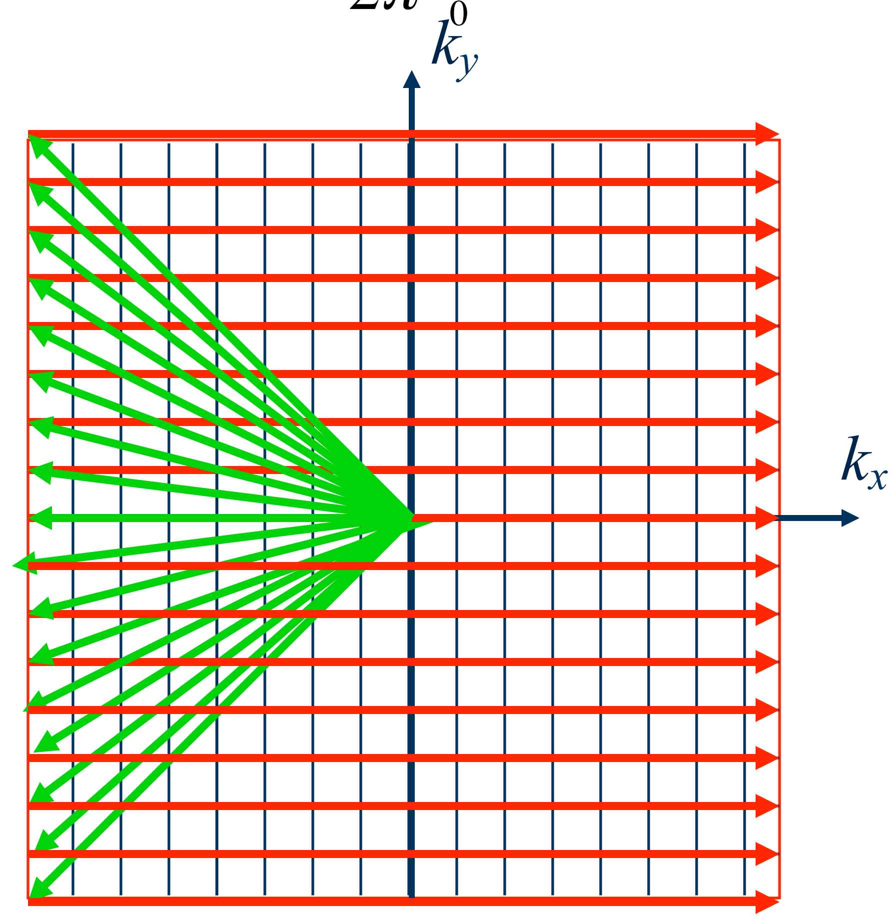
$$S(\vec{k}) = \iiint_{RFcoil} M(\vec{r})\exp(-i\vec{k}\cdot\vec{r})\,dr^3$$

S and M related thru Fourier Integral, measure S(k), compute M(r)…

k(t) is what we control; view the imaging process as a "trip thru k-space"

$$\vec{k}(t) = \frac{1}{2\pi}\int_0^t \vec{G}(t)d\tau$$





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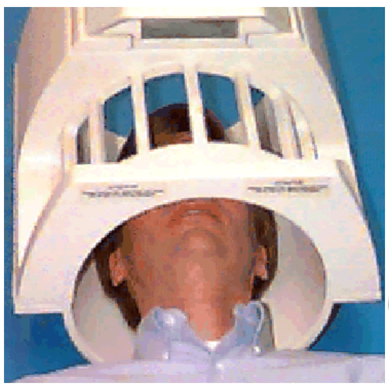
Receive coils over last 15 years

1 channel to many,
loose-fitting to tight-fitting…



1ch quad BC

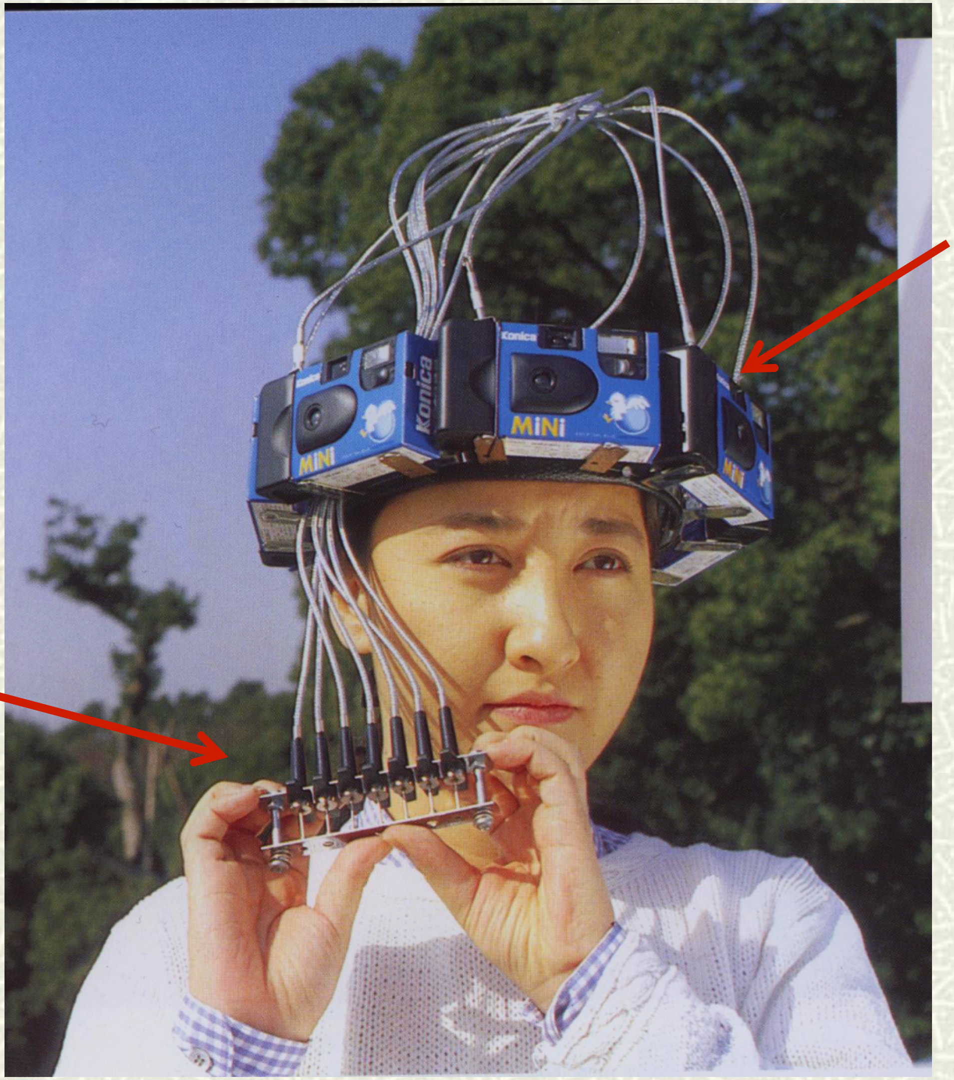
8ch “dome” array

32ch “helmet” array

32ch “helmet” array

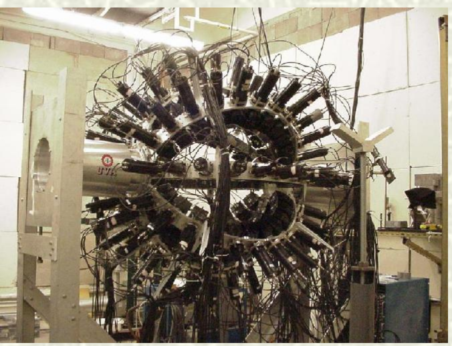
Parallel imaging: it just makes sense.

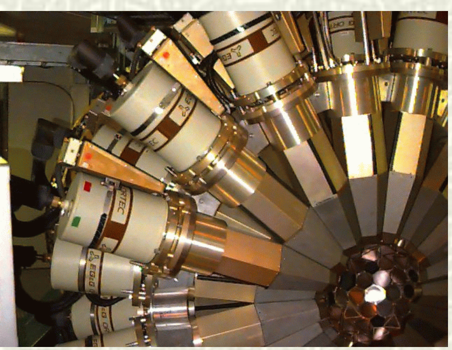
Each detector creates a separate photo (with different spatial information!)

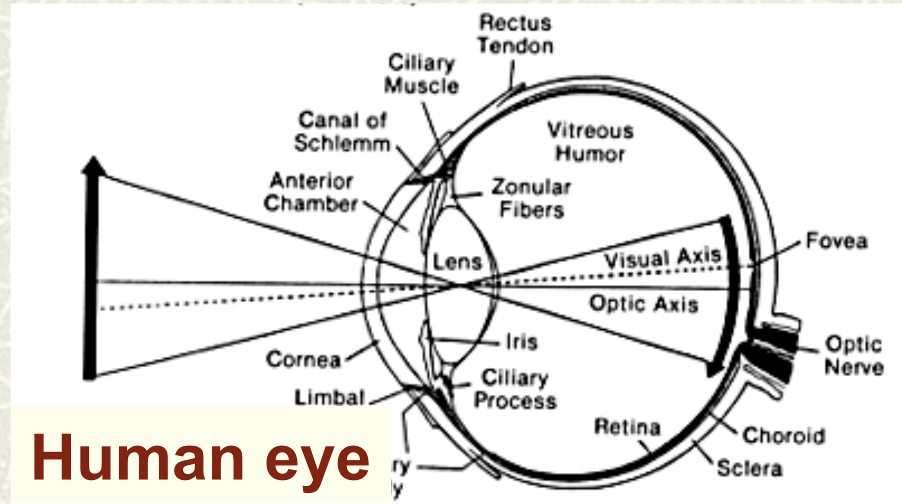


Simultaneous acquisition

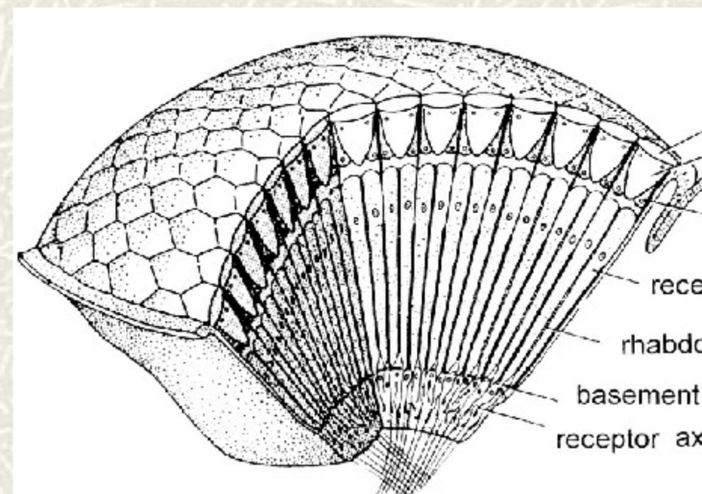
Almost every imager is array-based…



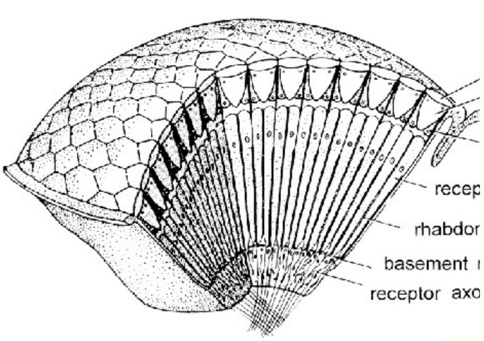




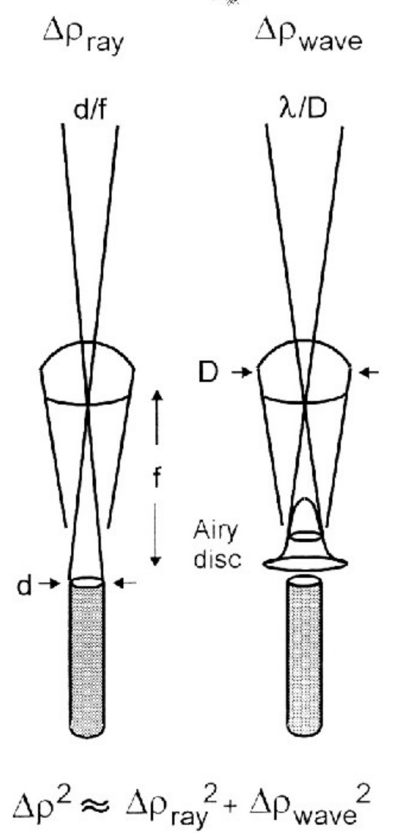
Human eye



compound eye



How many elements does an insect need?



Angular resolution is diffraction limited, ommatidium size needs to be ~30um.

(Feynman Lectures vol. 1)

-> To cover 2π square radians in 3mm dia need: ~50k of them

Far-field array

Aeshna dragonfly; 28,000 ommatidium

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Others?

Creature	# elements
Wood Lice	5
Small flies	~5k
Lobster	~14k
Dragonfly	~30k

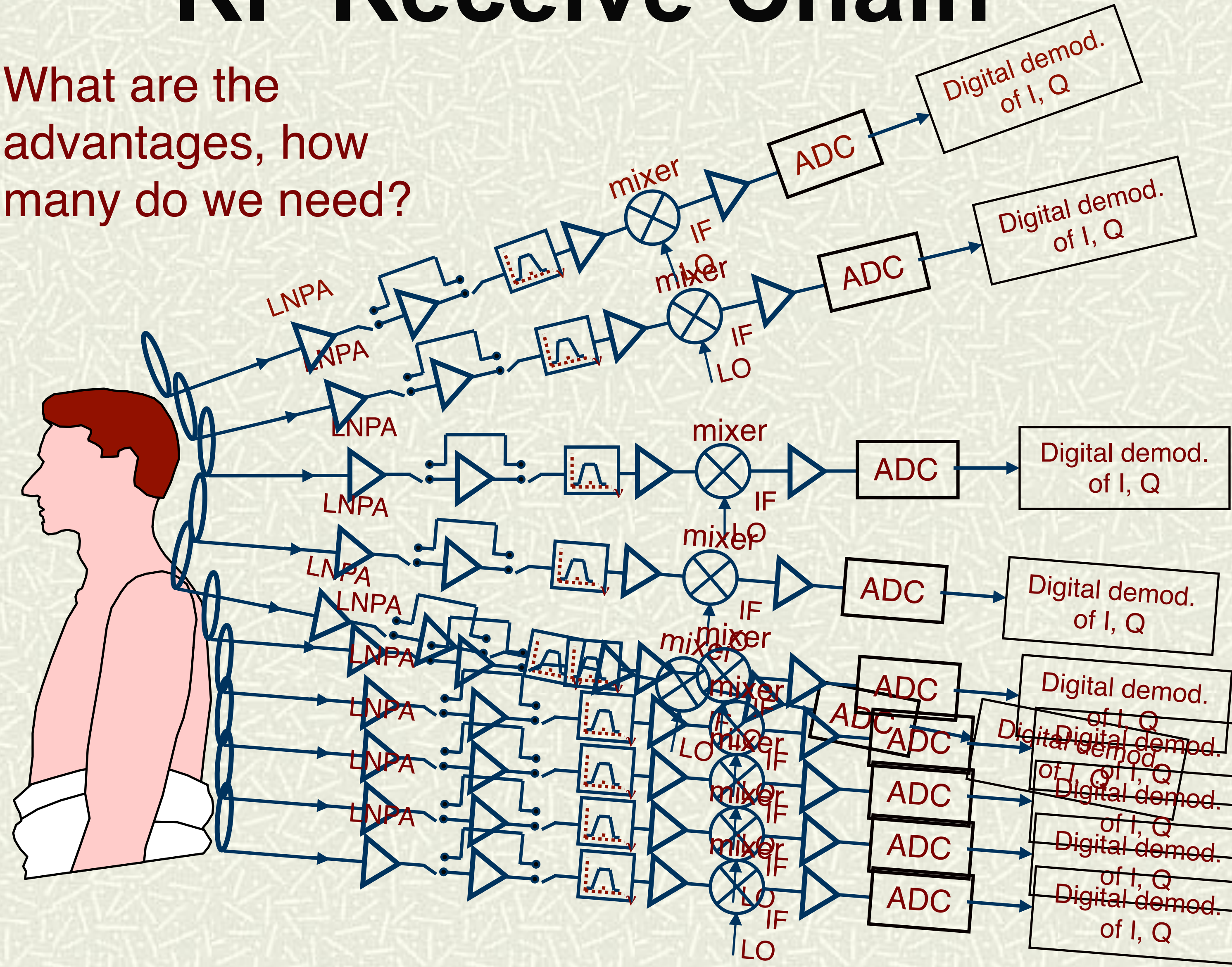
Get MR out of the "wood lice" category!

Strategy

- Coils placed close to head to maximize coupling to brain.
- Entire dome of head covered
- Expand capabilities of scanner (# of receive channels) as needed.
- Solve the coupling issues, loss sources that cut into performance of highly parallel detection.

RF Receive Chain

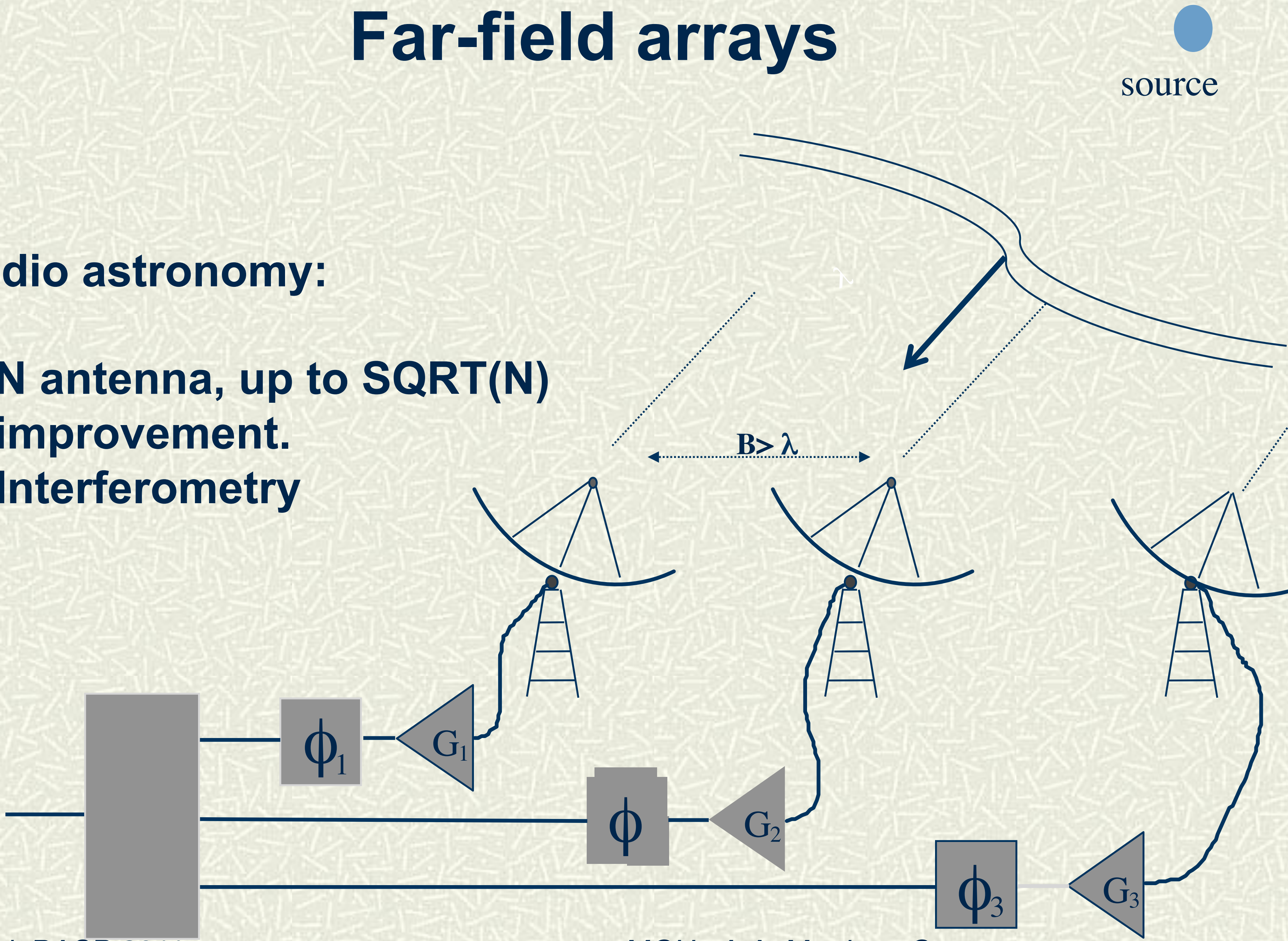
What are the advantages, how many do we need?



Far-field arrays

Radio astronomy:

- **N antenna, up to SQRT(N) improvement.**
- **Interferometry**

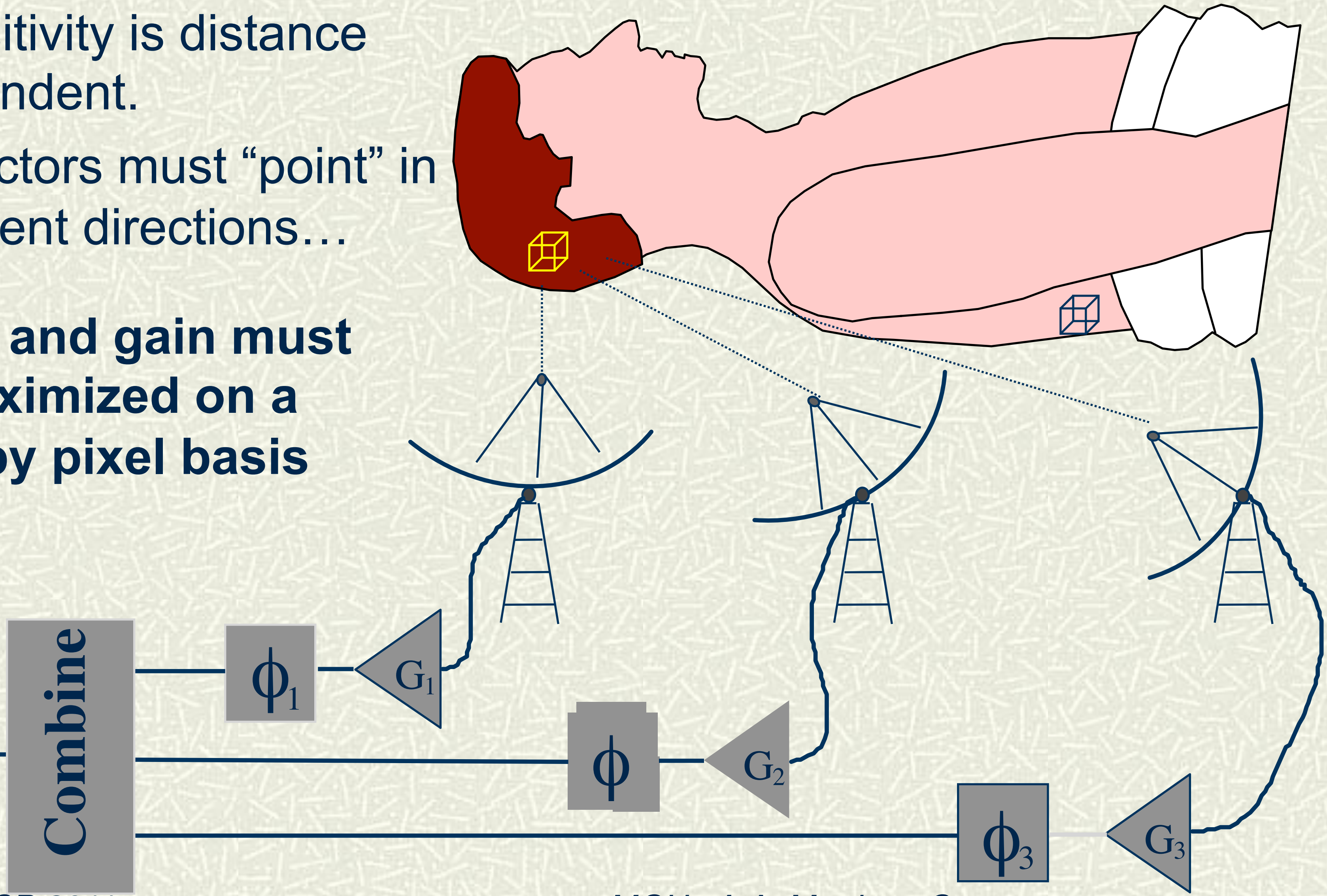


MR arrays are near field arrays

Sensitivity is distance dependent.

Detectors must “point” in different directions…

phase and gain must be maximized on a pixel by pixel basis



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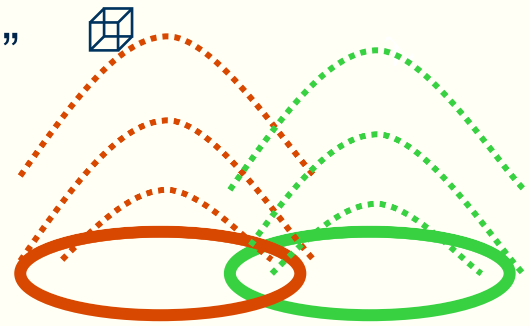
Optimize the combination for each pixel (best done in image space…)

C(x,y,z) is "coil sensitivity map"



$$I = \sum_{coil=1}^{N} w_{coil}(x,y) S_{coil}(x,y) = \mathbf{w}^H \mathbf{S}$$

$$SNR = \frac{\mathbf{w}^H \mathbf{S}}{\sqrt{\mathbf{w}^H \Psi \mathbf{w}}}$$

Optimum weight (least squares sense): $w_i(x,y,z) = C_i(x,y,z)$.

Common simplification: S_i is a good approx. of C_i (assume high SNR, uniform noise in channels.)

"Sum of Squares" recon

$$I^{rSoS} = \sqrt{S^H S} \qquad SNR_0^{rSoS} = \frac{S^H S}{\sqrt{S^H \Psi S}}$$

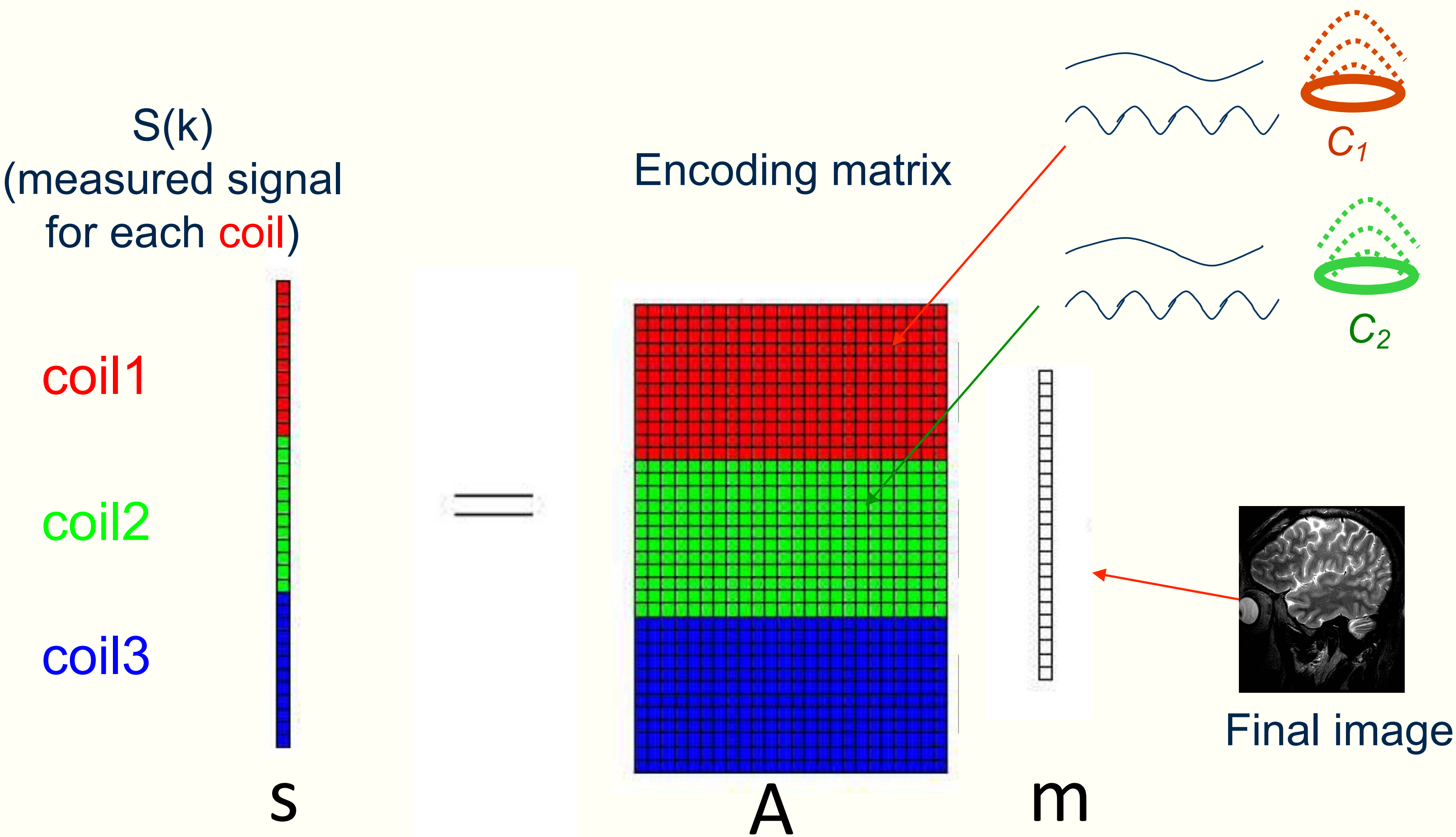
Next best (almost always good enough);

$$I^{cov-rSoS} = \sqrt{\mathbf{S}^H \Psi^{-1} \mathbf{S}} \qquad SNR_0^{cov-rSoS} = \sqrt{\mathbf{S}^H \Psi^{-1} \mathbf{S}}$$

Encoding in MR

$$S(k) = \int_{object} M(x)\, C(x)\, e^{-2\pi ikx}\, dx$$

Ncoil*Npixel → $s = Am$ ← Npixel



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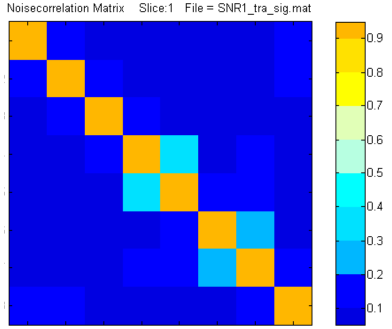
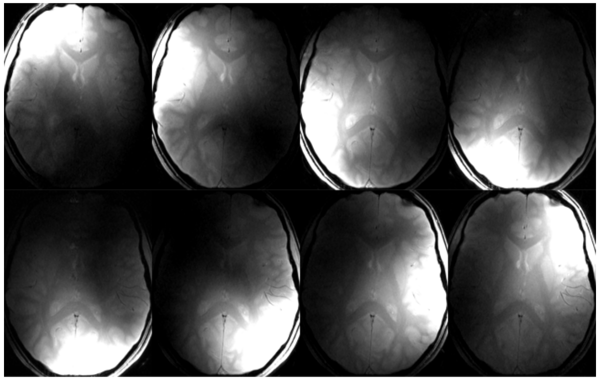
Encoding matrix must be well-conditioned

noise enhancement "G-factor" depends on coil geometry, under-sampling pattern

$$SNR_{accel} = \frac{SNR_{full-k}}{G\sqrt{R}}$$

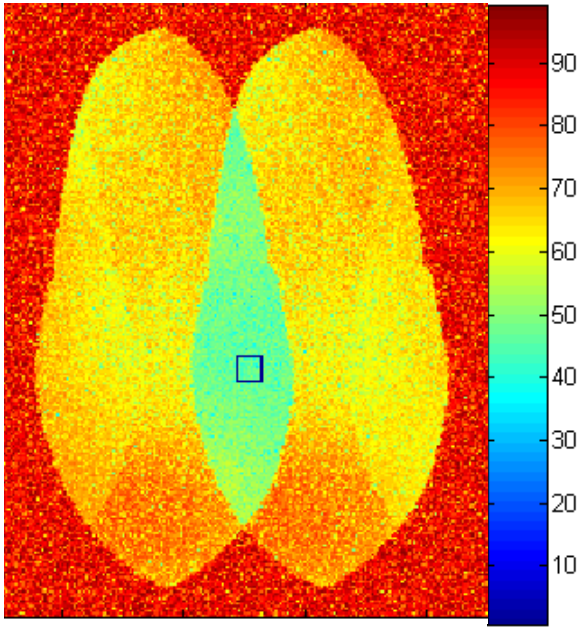


noise correlation matrix



coil sensitivity profiles

map of 1/G



Rate = 4
Gmax=2.17

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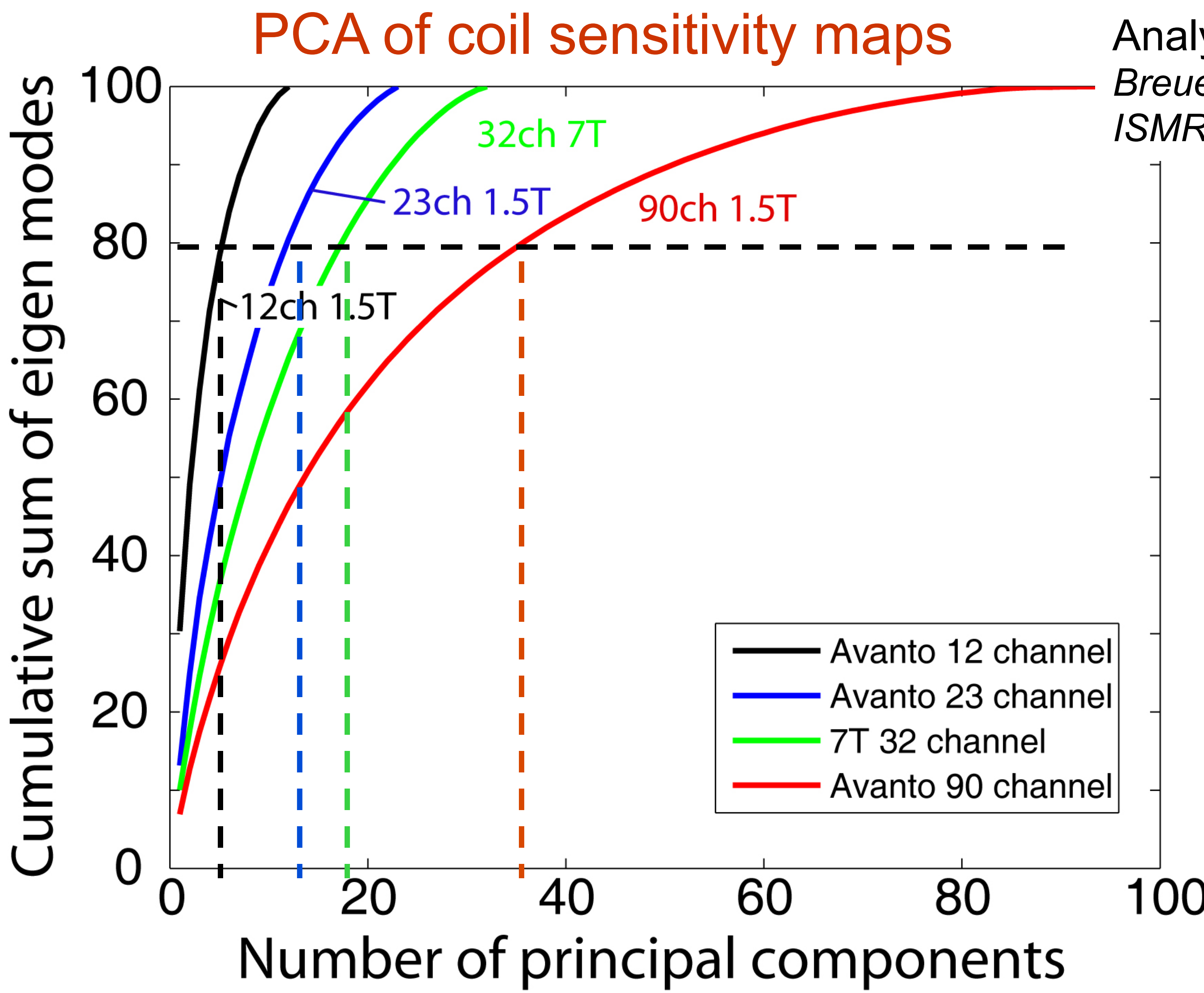
3D encoding power of the array:

 # eigenmodes of the sensitivity maps which contribute 80% of the energy



Analysis following:
Breuer et al.
ISMRM 2005 p2668

Mode Compression: The performance of a 96 ch array on a 32 ch scanner

Basic premise: Spatial modes of the array do not form an orthogonal basis set desirable for parallel imaging.

Use the methods of image compression…

Create linear combinations of the signals which diagonalize the spatial modes. Retain only the modes which contribute the most to SNR / acceleration capabilities.

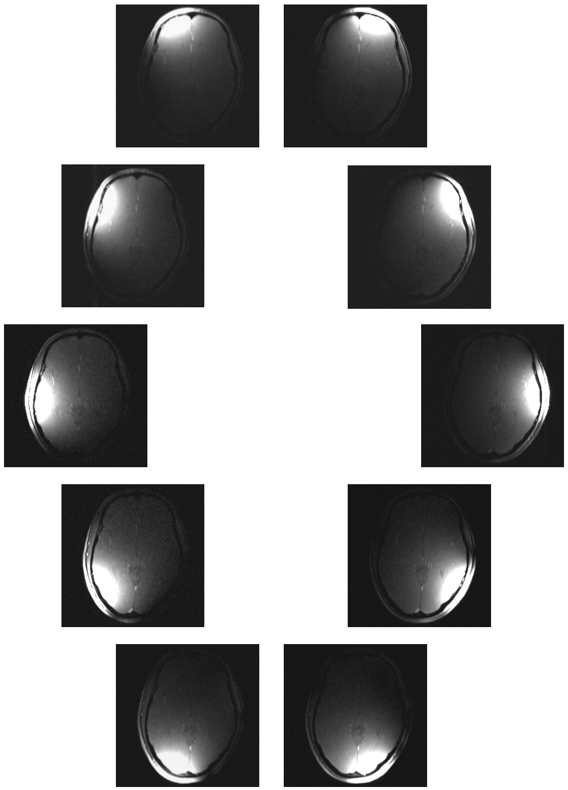
Signal from Coil j

$$M_i(k_x, k_y) = \sum_{j=1}^{N_{coils}} \underbrace{a_{i,j} e^{i\varphi_{i,j}}} S_j(k_x, k_y)$$

Mode i

weights

Mode Compression: Simulation



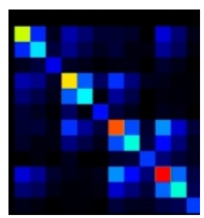
96 channel
coil maps ($S_j(x,y)$)
(only 3rd row from bottom shown)

$$R = S\,S^H$$

Diagonalizing R w/ eigenvector decomposition:

$$R = U\,D\,U^{-1}.$$

Need SNR, not S, so form whitened version of S using noise covariance matrix: ψ

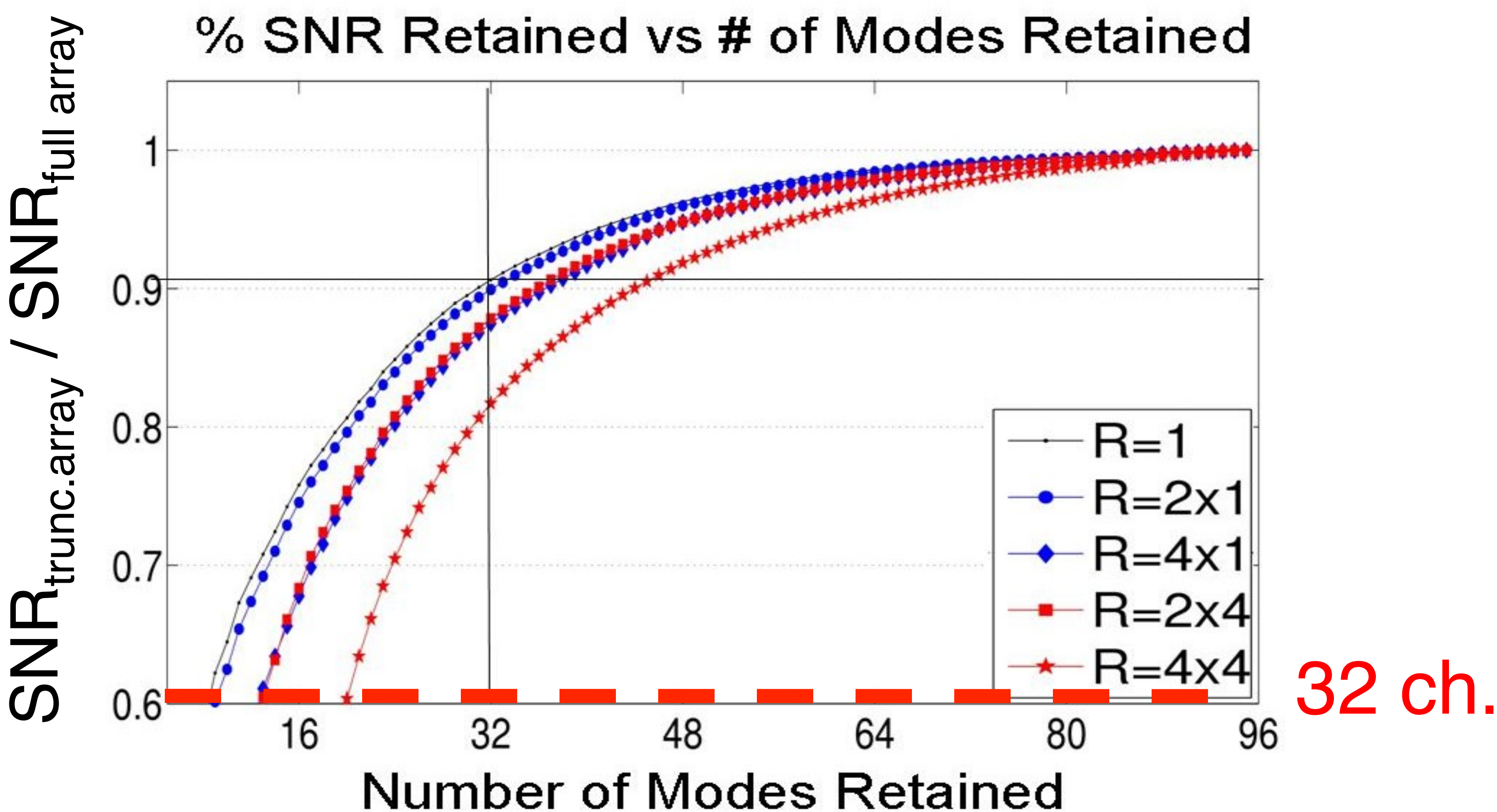


$$W^H W = \psi^{-1} \qquad \tilde{S} = WS$$

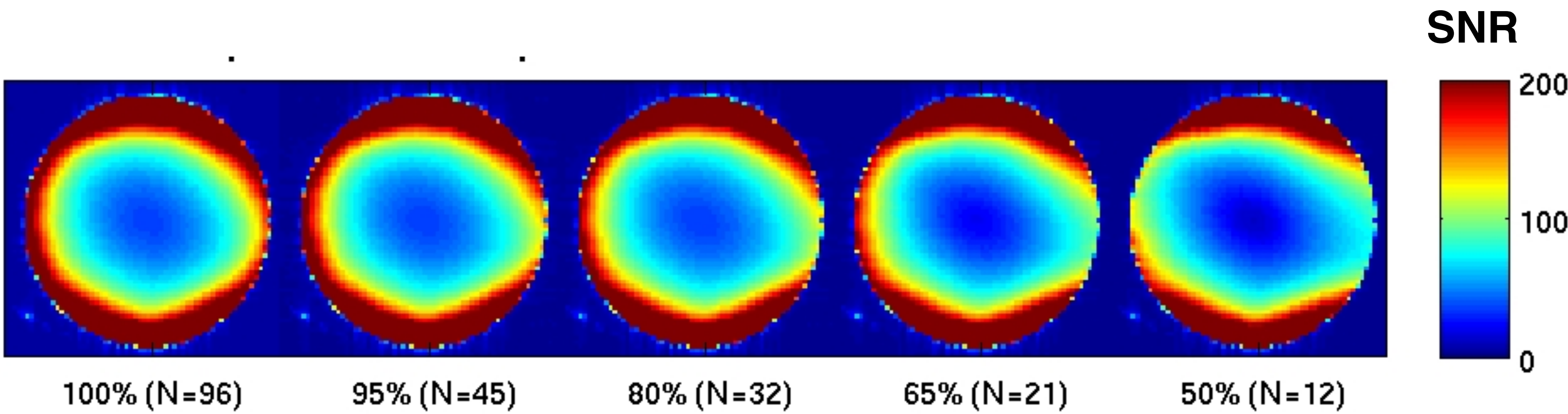
Diagonalize: $\tilde{R} = \tilde{S}\tilde{S}^H$

<u>Truncate</u> mode basis set retaining only most important modes

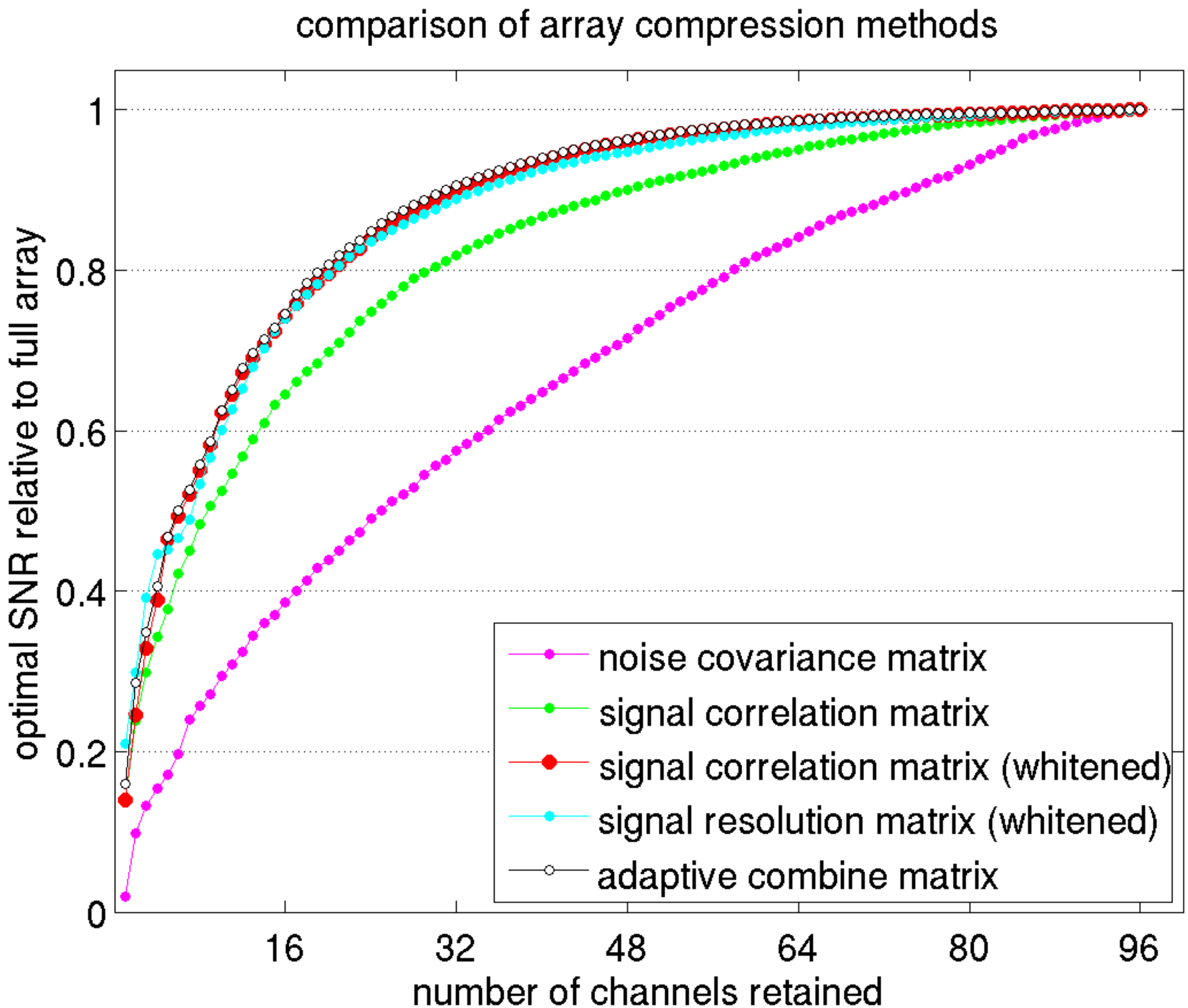
Mode Compression: SNR performance (96→32)



Mode Compression: Distribution of SNR loss in compression of 96ch array

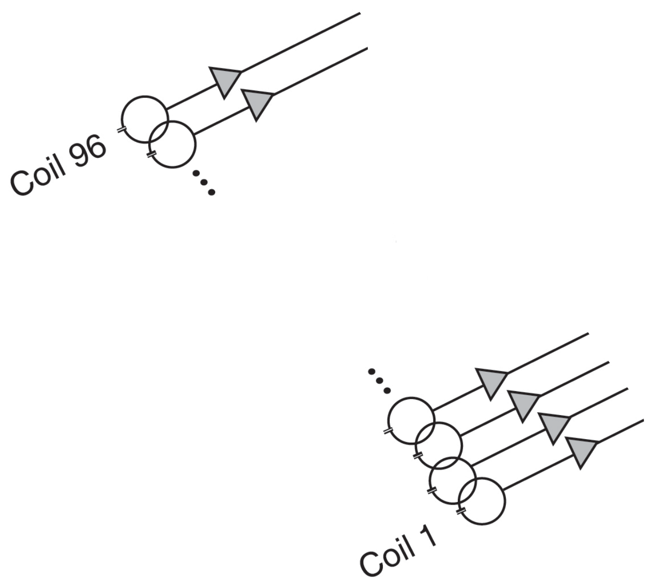


Mode Compression: other methods



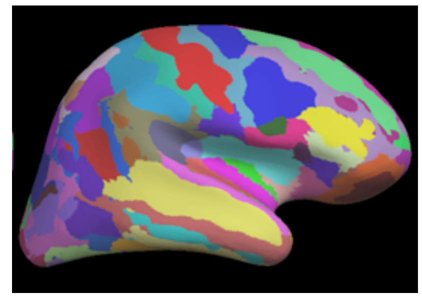
Mode Compression: Hardware construction

$$M_i(k_x,k_y) = \sum_{j=1}^{N_{coils}} a_{i,j} e^{i\varphi_{i,j}} S_j(k_x,k_y)$$



Vision of the future.

1) 256 channel array adaptively compresses to 64 channels.
2) Labeled cortical map is created from 2min 3D scan

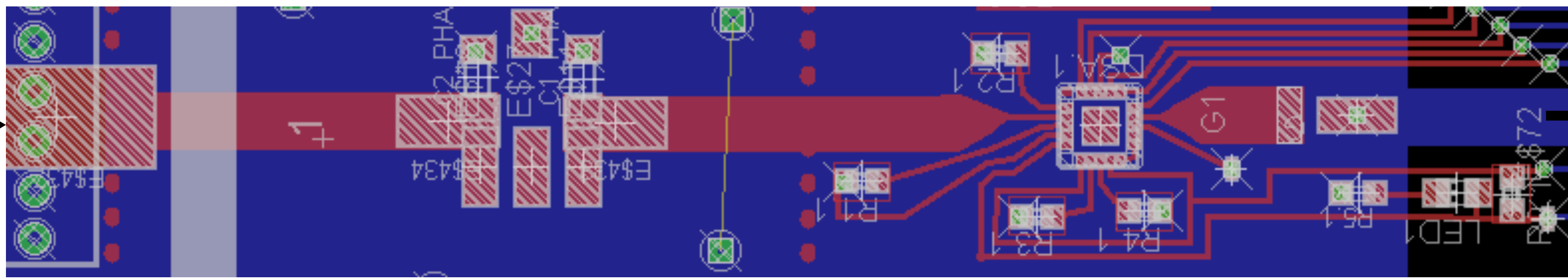


3) User clicks on anatomy (e.g. "Broca's + Wernicke's area") and a particular sequence (e.g. EVI, R=3 x 4)
4) Scanner calculates mode coefficients to optimize Broca's + Wernicke's area SNR, downloads to mode-matrix.
5) User enjoys >2x sensitivity and improved acceleration over 32ch array in language study.

Mode Compression: Hardware construction

Proof-of-principle: 32→16

One matrix connection…



analog signal from splitter board (copy of S_j)

Pi circuit phase shift ($\Phi_{i,j}$)

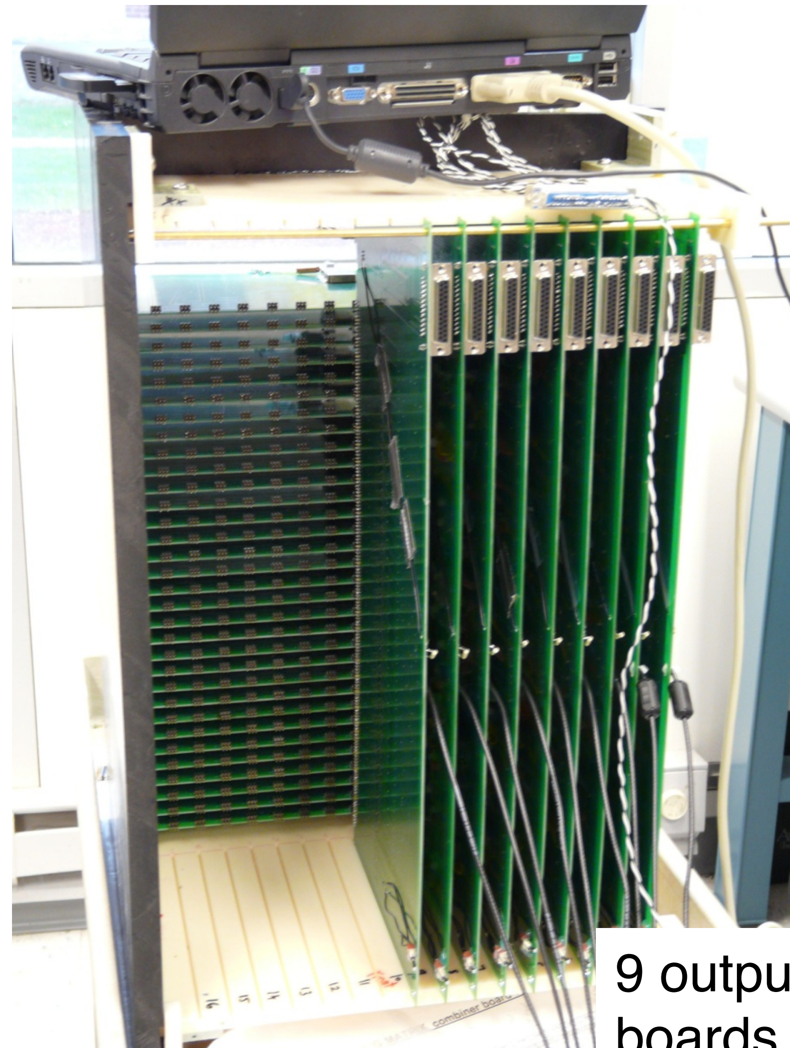
5 bit digital attenuator ($a_{i,j}$)

Output to combiner

Mode Compression: Hardware construction

Proof-of-principle: 32→16

Input S from 32 coils



9 output boards

Mode Compression: Hardware construction

Proof-of-principle: 32→16

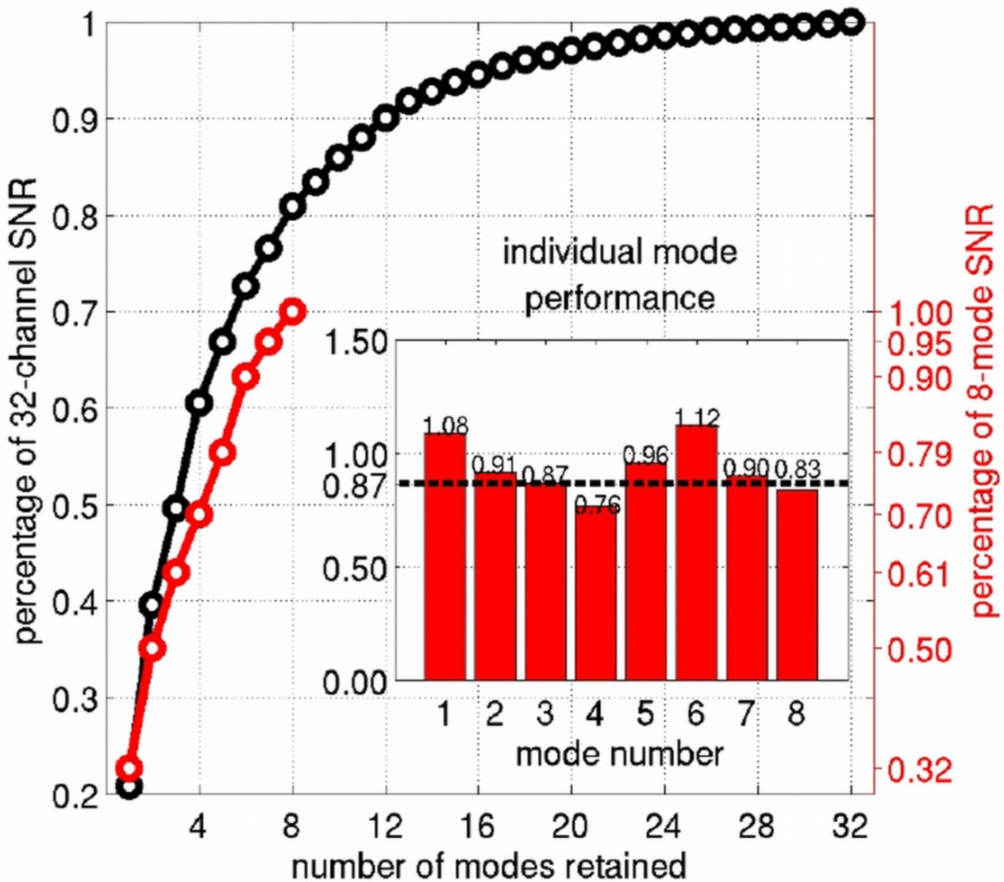


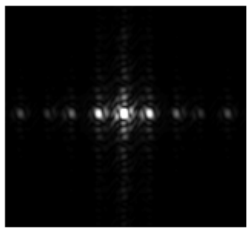
Figure 3: Ideal versus measured SNR compression achieved by 32-to-8 mixing matrix. (Inset) Percentage SNR retained in each individual mode.

Spatially tailored excitation:

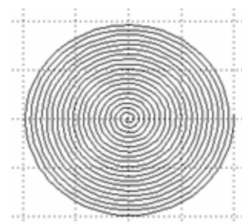
Pauly et al   A k-space analysis of small-tip angle excitation.
J Magn Reson, 1989. 81: p. 43-56.

Spiral Trajectory

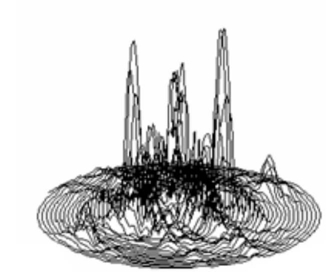
Target m(x,y)



Fourier transform of target

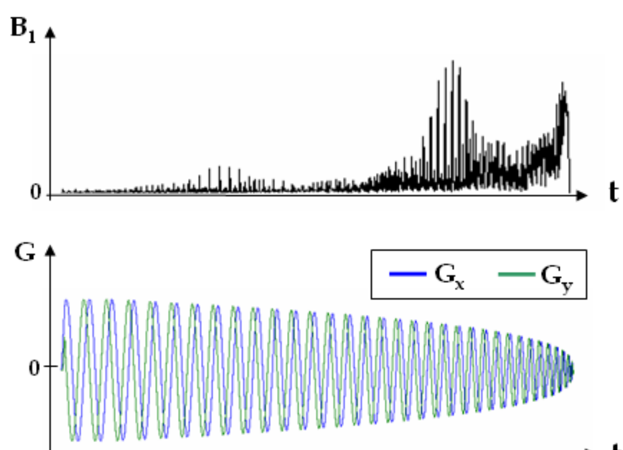


Spiral Trajectory



$B_1(\bar{k})$

Corresponding RF and Gradient pulses



2mm trajectory,
16ms pulse duration.

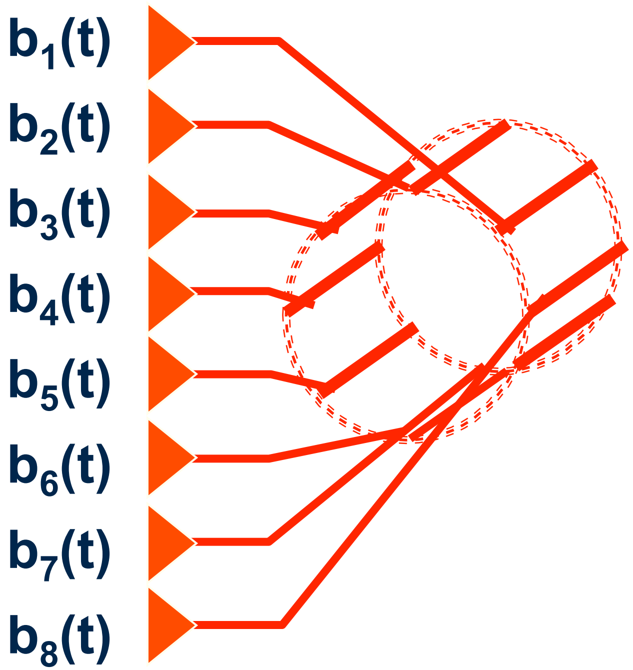
Excited Profile

Add spatial degrees of freedom via Tx array

Parallel Transmit (pTx)

Eight pulse shapes:

Eight:
1) Small signal pulse gen.
2) B_0 eddy current comp.
3) B_1 linearization.
4) Power amplifiers.
5) SAR monitors.

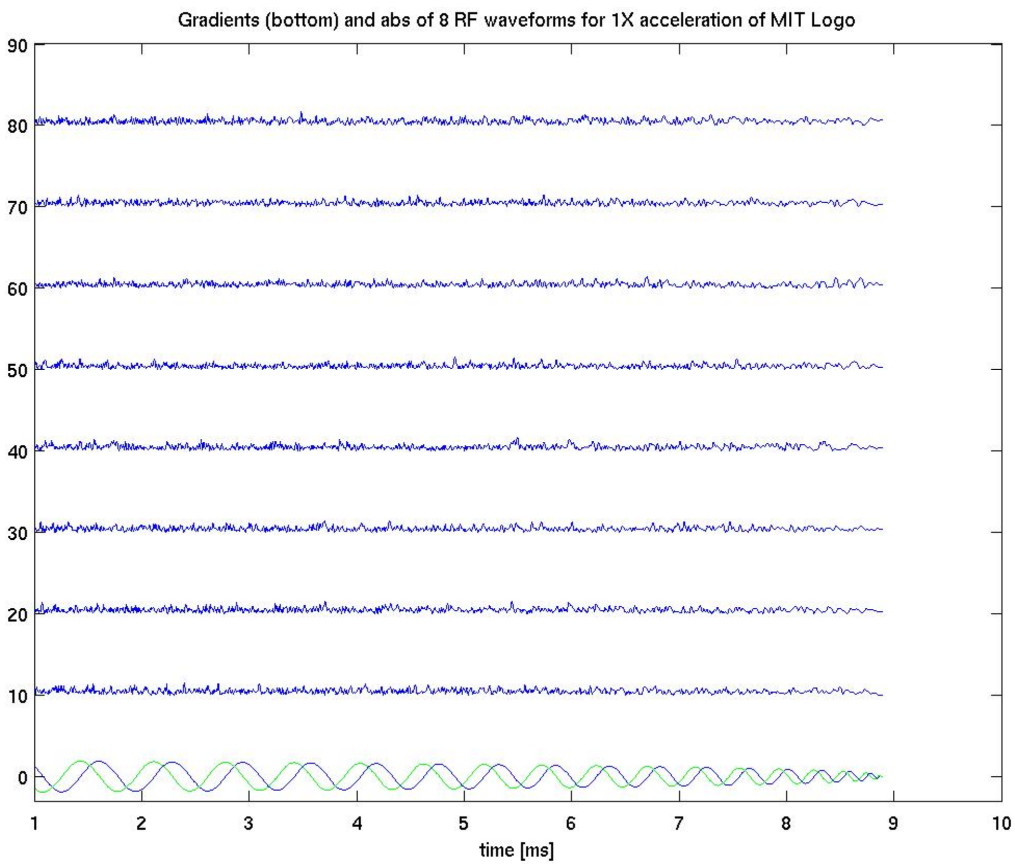


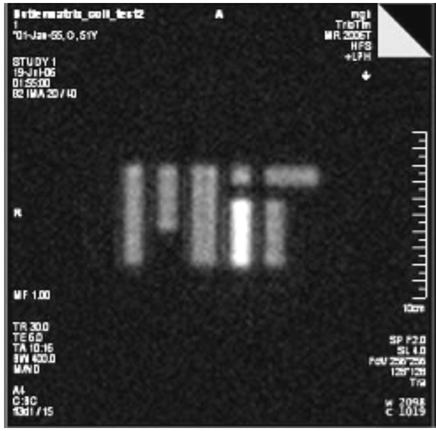
The RF waveform…

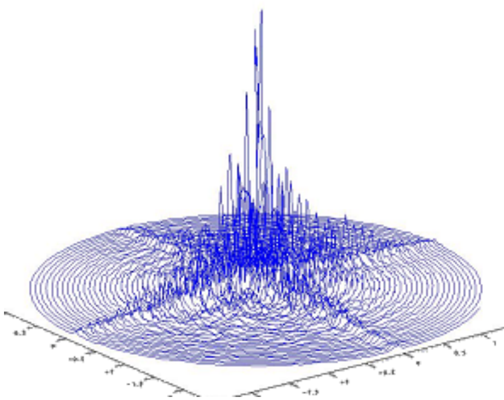
Nyquist sampled

Pulse length = 9ms

RF 1
RF 2
RF 3
RF 4
RF 5
RF 6
RF 7
RF 8
grads

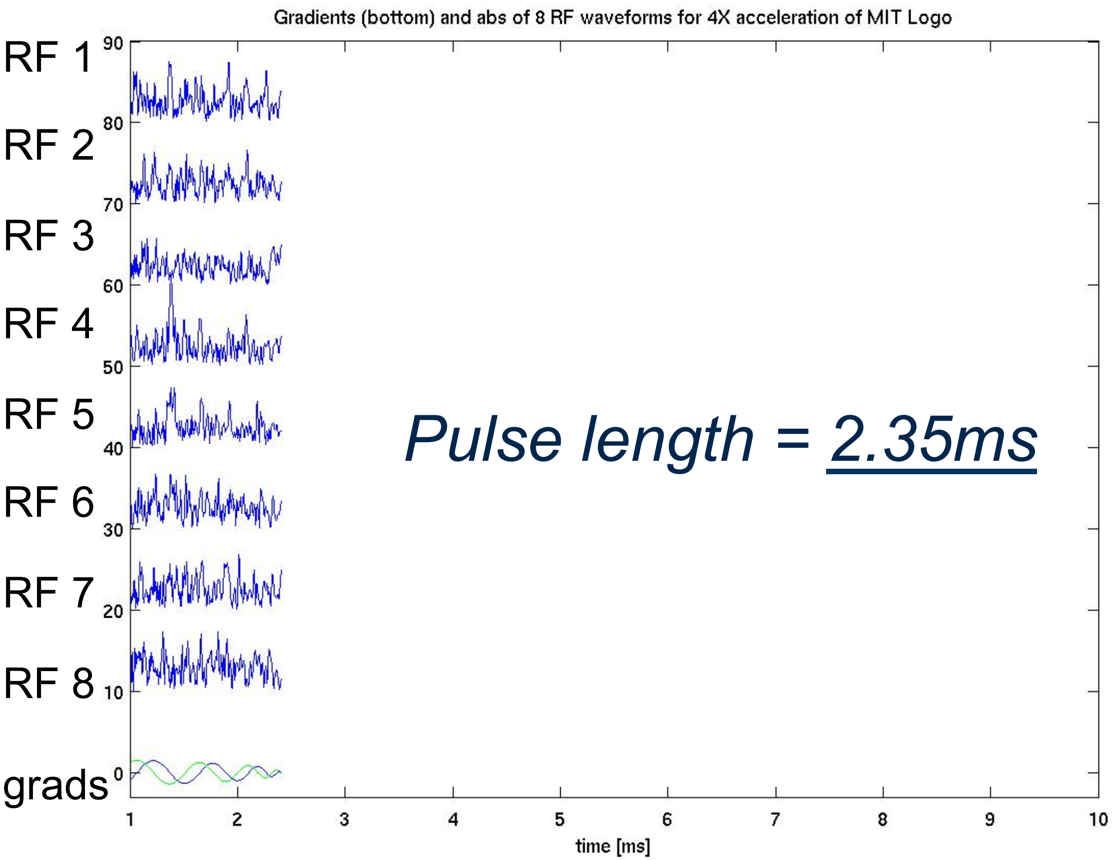


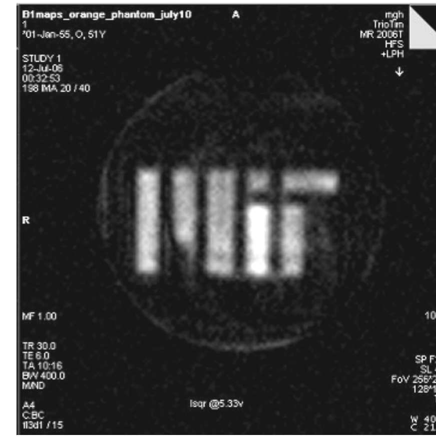


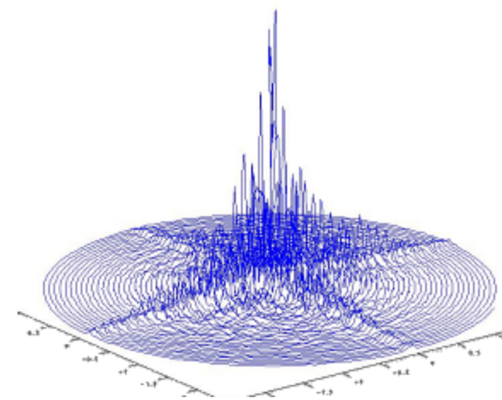


Undersampling the transmit kspace trajectory

4x acceleration







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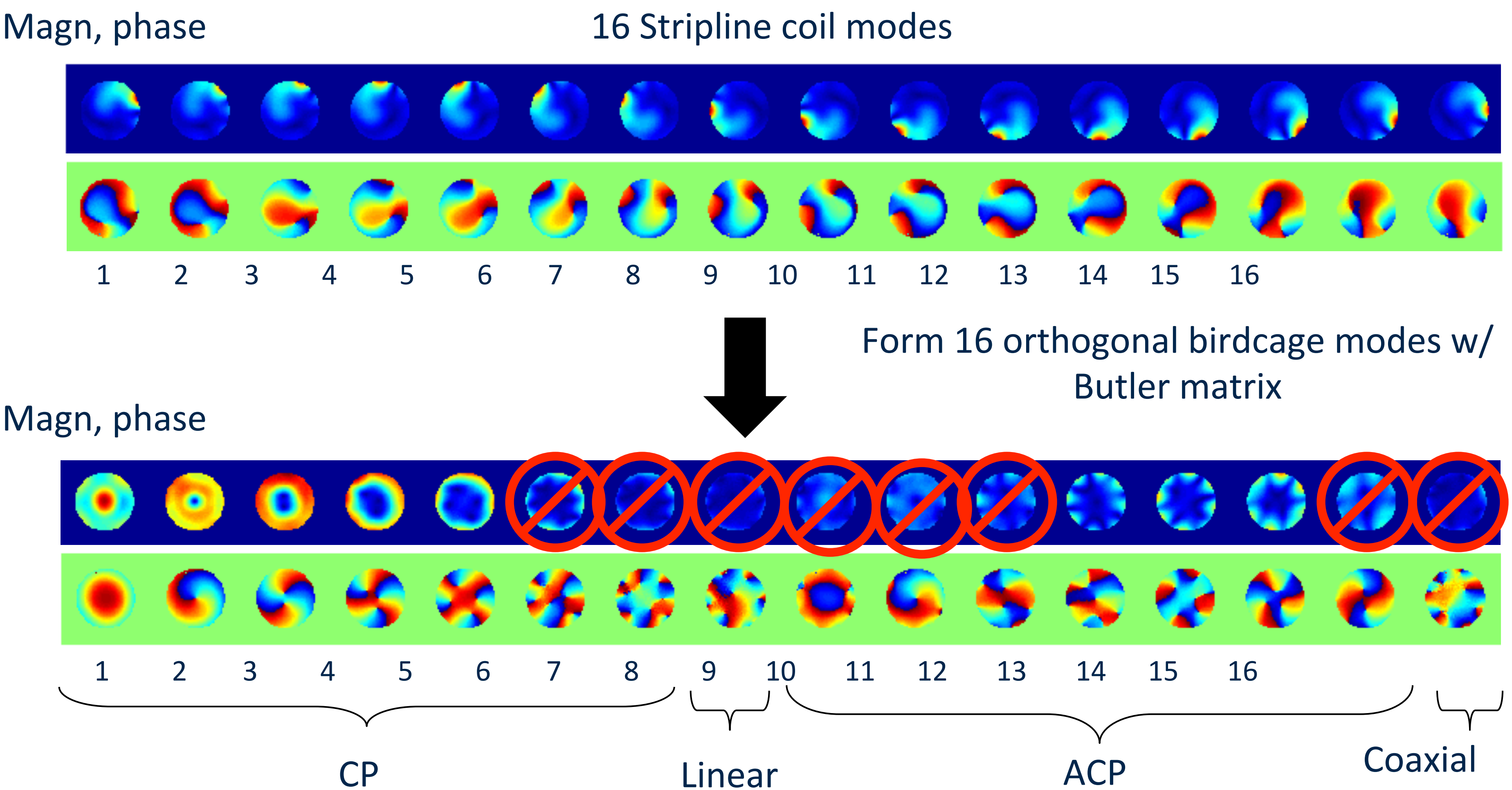
Mode compression in transmit arrays
16ch Tx array at 7T,
strip-line modes and birdcage modes



Wald, BASP 2011

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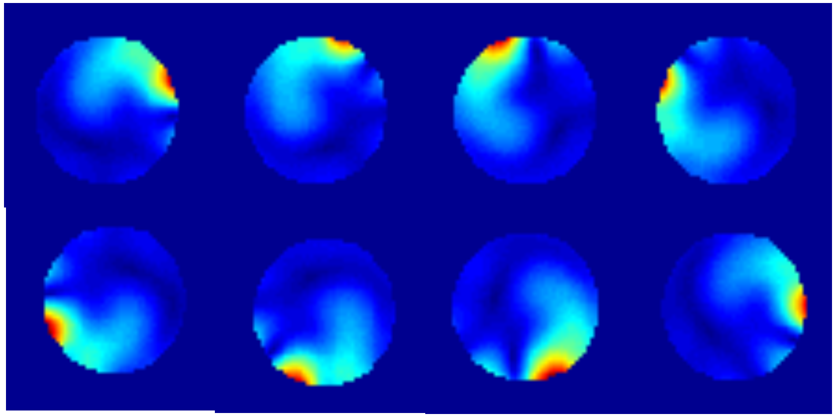
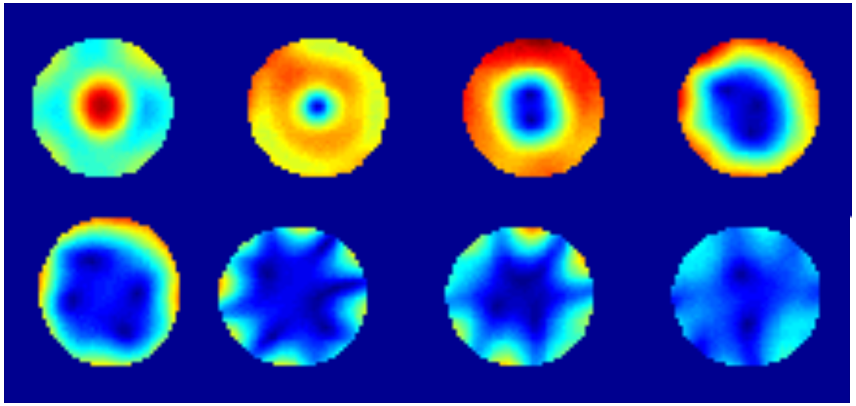
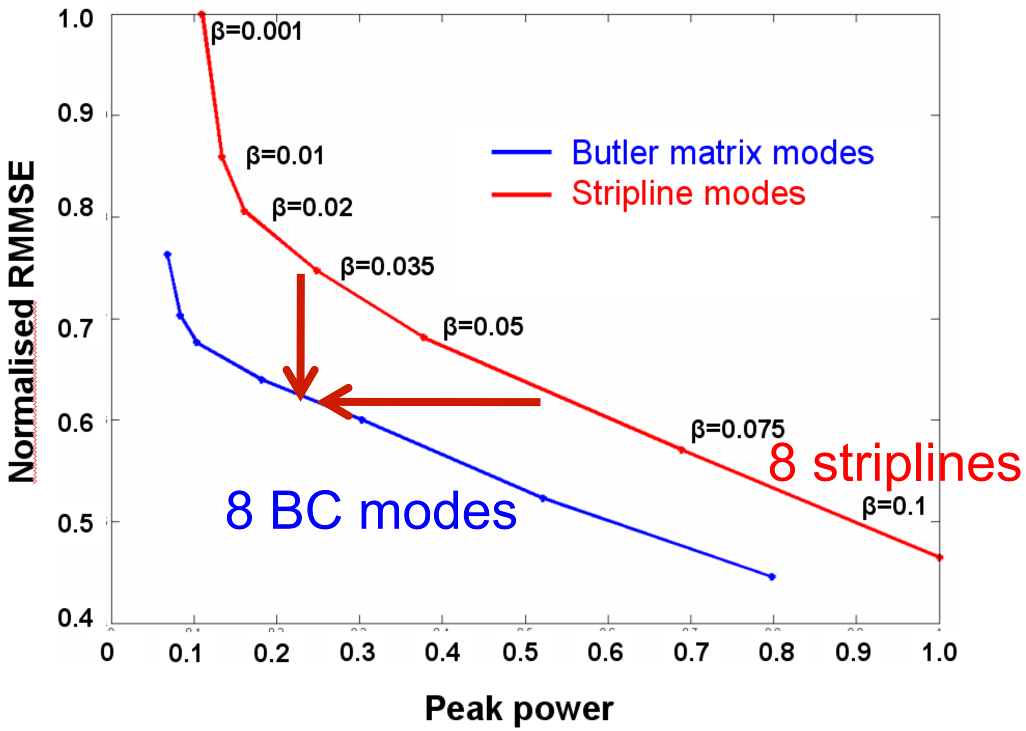
Coil mode compression

8 stripline modes



8 optimal modes of 16 BC modes





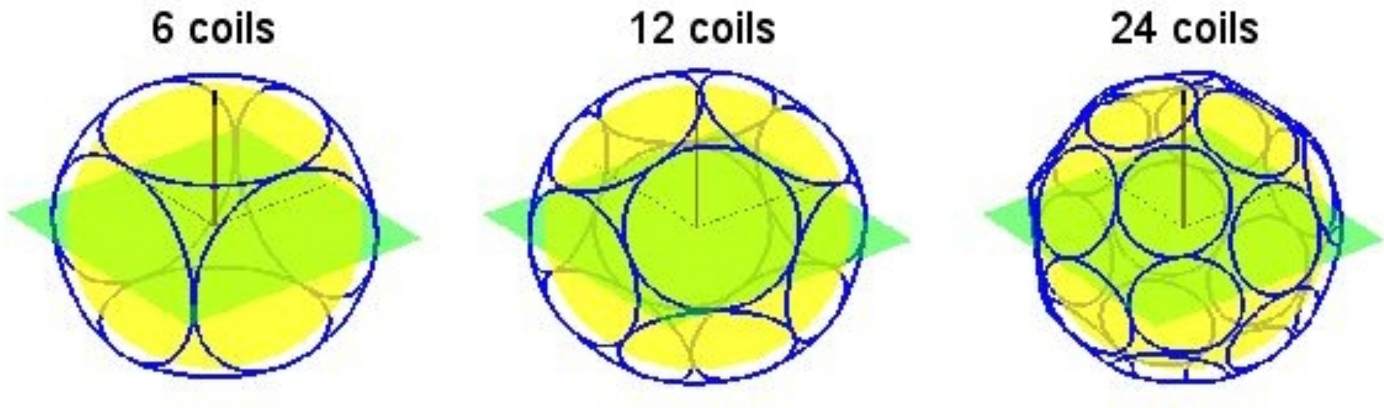
Mode Compression:

Alagappan et al ISMRM 2008, p.618

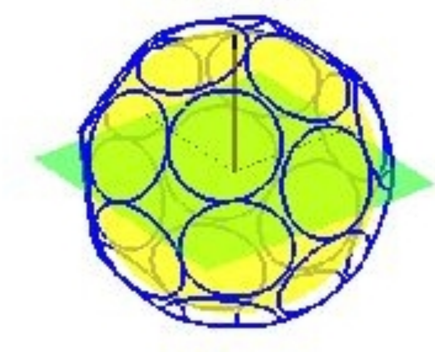
Mode choice based on target:

Zelinski et al ISMRM 2008, p.1302

What does more buy you?
Spherical array model, ETH Group



Approaching Ultimate SNR with Finite Coil Arrays
F. Wiesinger, N. De Zanche, K. P. Pruessmann
Institute for Biomedical Engineering, University Zurich and ETH ,
ISMRM 2005 p672.

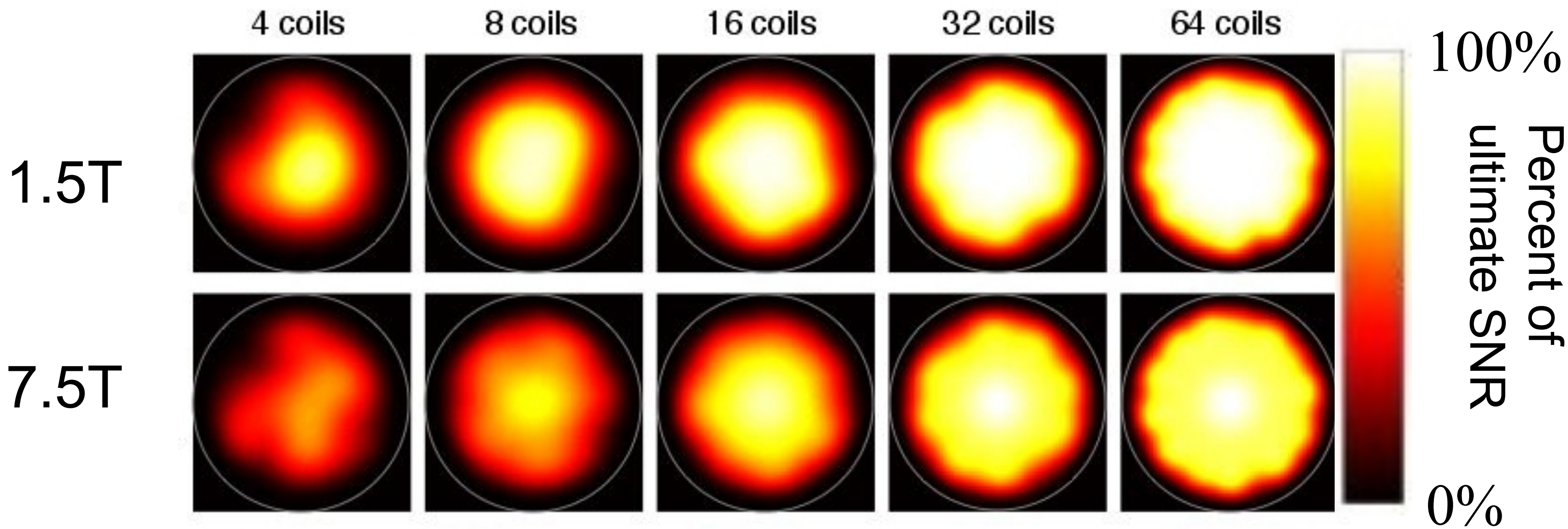


Spherical array model

data courtesy of:

Wiesinger, DeZanche, Pruessman, ETH Zurich

Percent of <u>achievable</u> sensitivity



- Max-out in the center first.
- SNR at periphery ~ linear in # of elements.
- Higher field needs more elements.
- Adding elements only helps if body noise dominated.

Ultimate SNR

What is the maximum SNR you achieve with a coil distribution on a cylinder or sphere?

Roemer, Edelstein, 6th SMRM, p.410, 1987
Reykowski, Ph.D. Thesis, Texas A&M, 1996.
Ocali, Atalar MRM 39 p.462-473,1998
Ohlinger, Grant, Sodikson, MRM 50(5) p1018 2003
Wiesinger, Boesinger, Pruessmann, MRM 52(2) p376 2004

Any coil sensitivity profile:

- must satisfy Maxwell's equations.
- can be expressed as a linear combination of basis functions which:
  1) Are solutions.
  2) Span the space of solutions to Maxwell's Eq.

Ultimate SNR

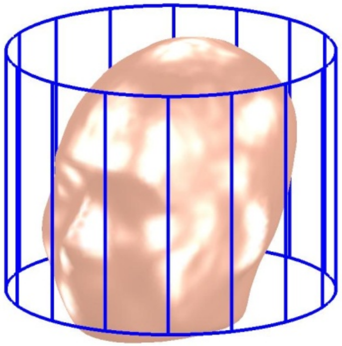
Express an arbitrary sensitivity pattern as the infinite sum over the basis functions and optimize for sensitivity.

Favorite basis functions include:

- plane waves
- spherical harmonics

SNR is intrinsically limited by Maxwell equations.

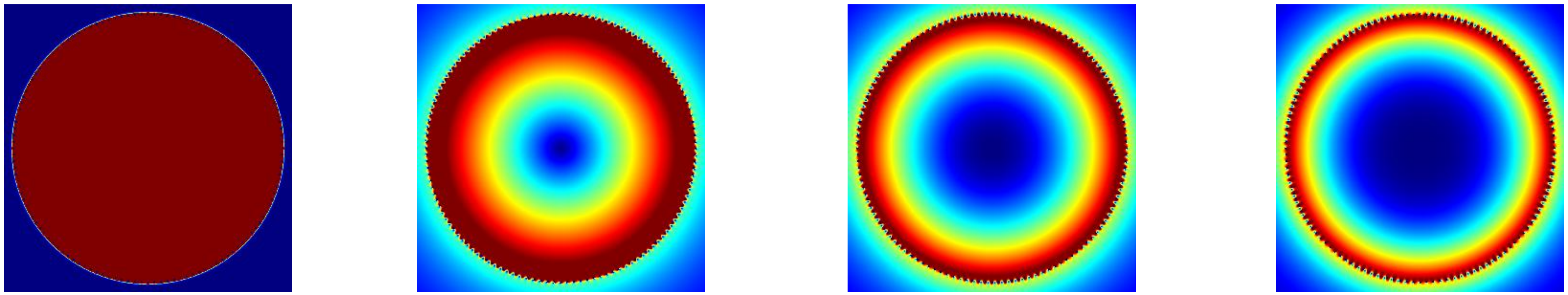
- The ultimate SNR is lower in the center of the object…
- Its likely to be easier to reach the limit at lower field.



Ultimate SNR: birdcage basis

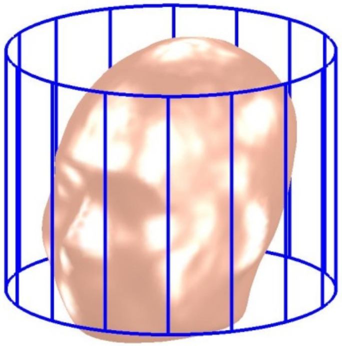
An array built from nesting birdcages each tuned to a different mode, spans the required space.

Birdcage detection profiles:

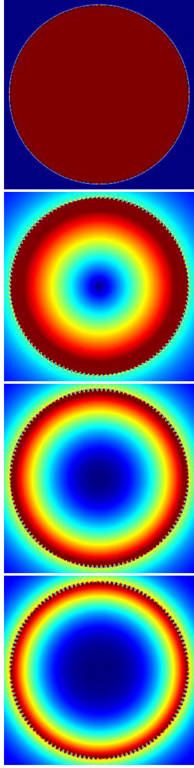


Uniform mode	2nd mode	3rd mode	4th mode…

Common use — No signal from center



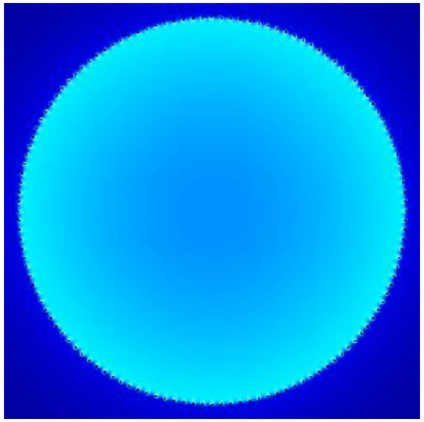
Ultimate SNR



An array built from nesting birdcages...

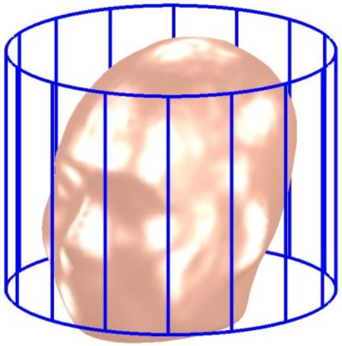
<u>Ultimate SNR for cylinder:</u>

- Is just a standard array combination of these basis functions.
- Needs only one element to achieve in center.
- More elements only add to the periphery

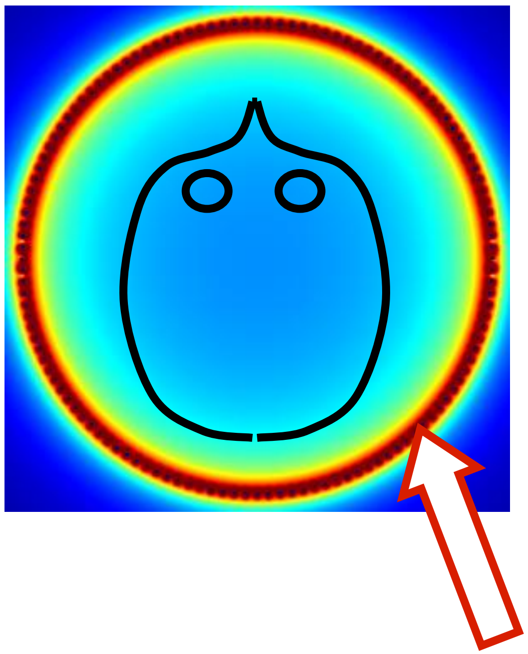


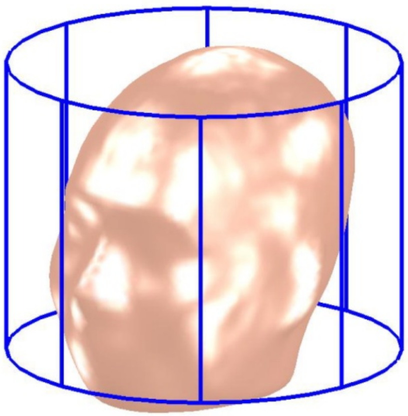
Cumulative combination of 32 lowest modes

Ultimate SNR

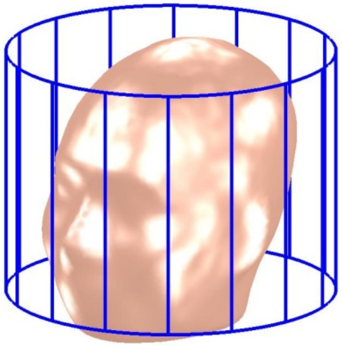


An array built from nesting birdcages...



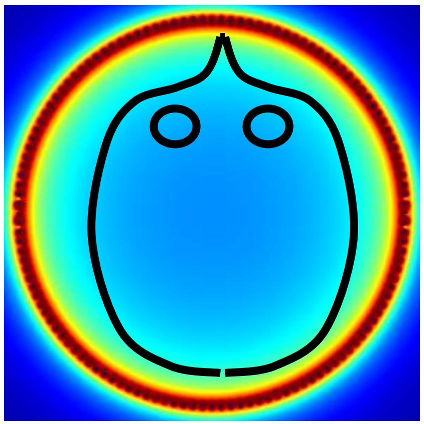


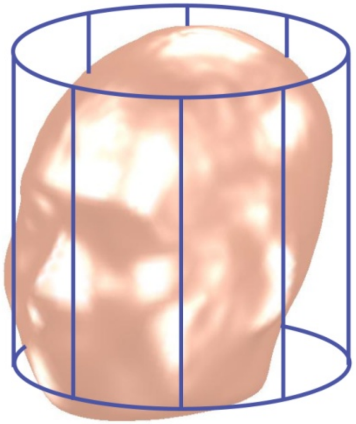
Most of the gain from the higher modes misses the head!



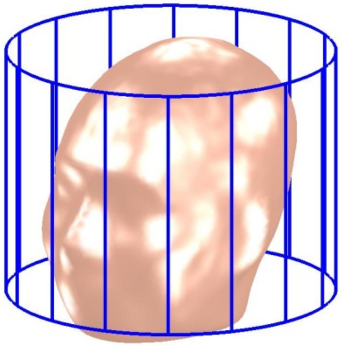
Ultimate SNR

An array built from nesting birdcages...



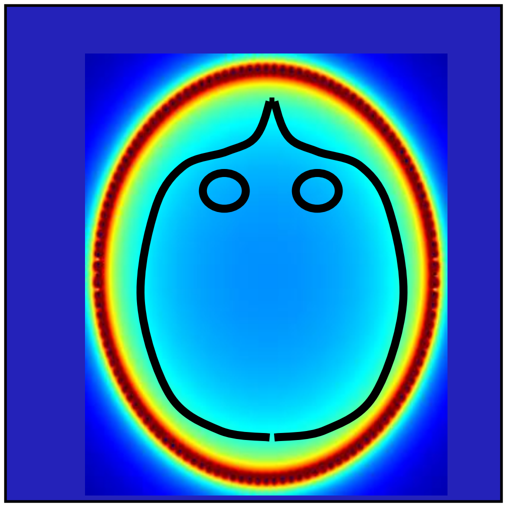


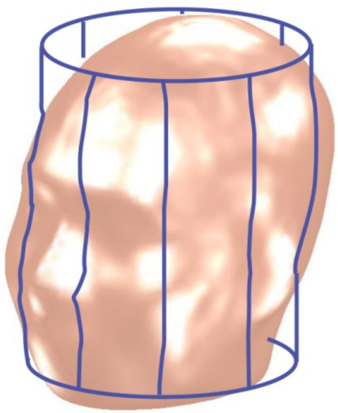
Need to shrink-wrap to head to get benefit of the higher mode array elements



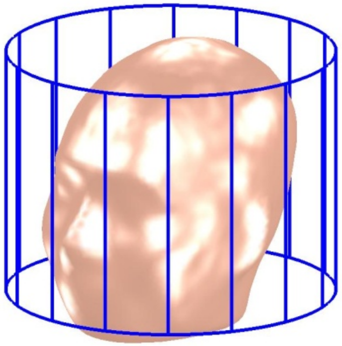
Ultimate SNR

An array built from nesting birdcages...



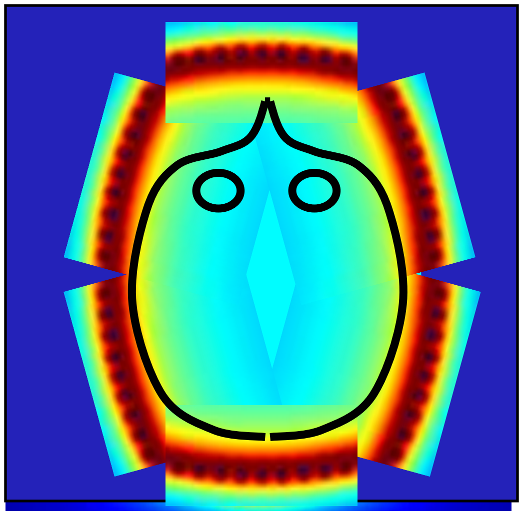


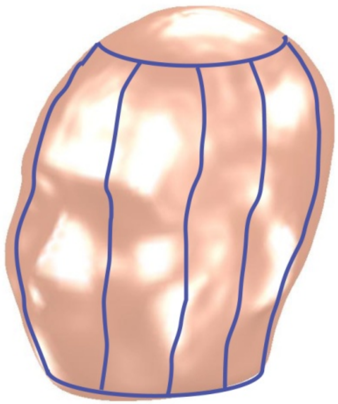
Need to shrink-wrap to head to get benefit of the higher mode array elements



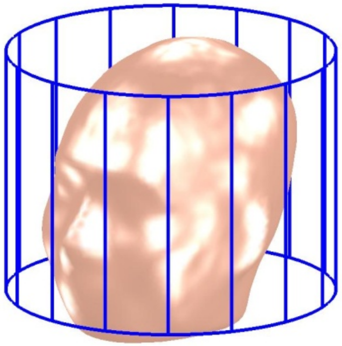
Ultimate SNR

An array built from nesting birdcages...



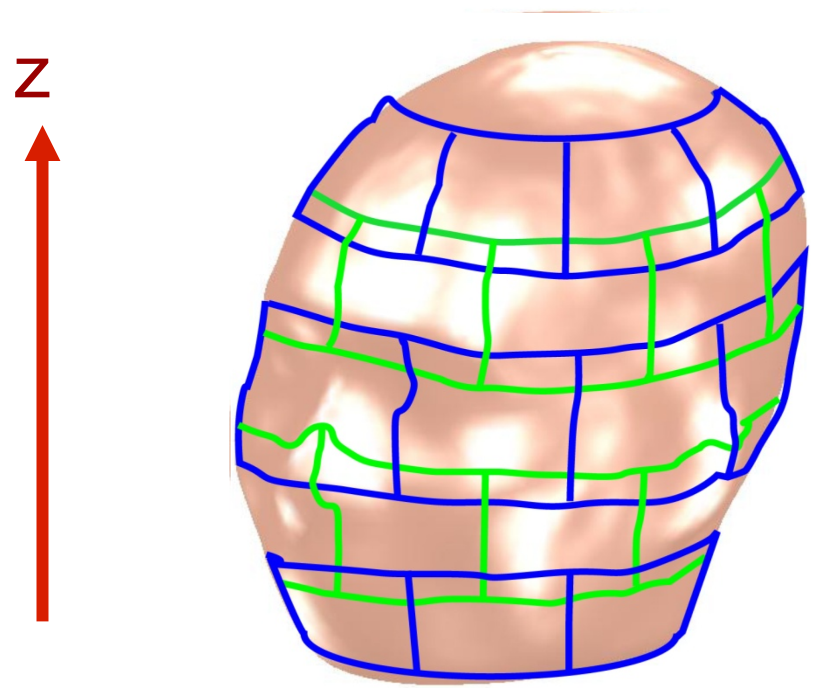


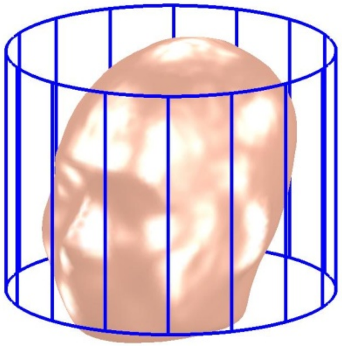
Need to shrink-wrap to head to get benefit of the higher mode array elements



Implementing ultimate SNR

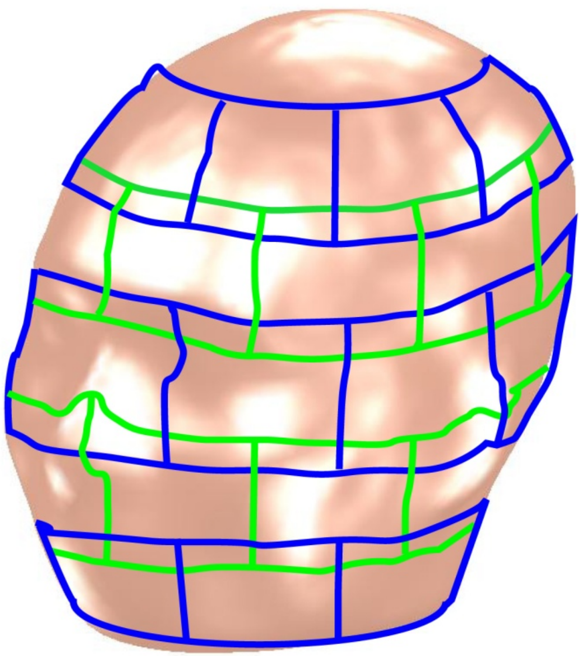
How do we get spatial variations in z for acceleration?





Implementing ultimate SNR

How many elements?



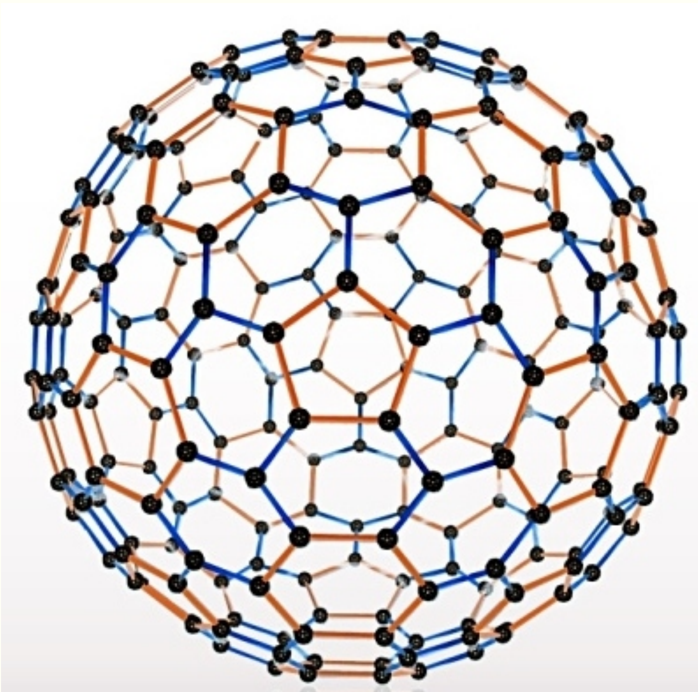
1
2
3
4
5

5 birdcages in z

x 32 modes detected per birdcage

160 Total elements

90 Channel 1.5T Phased Array



C240 Carbon "Buckyball"

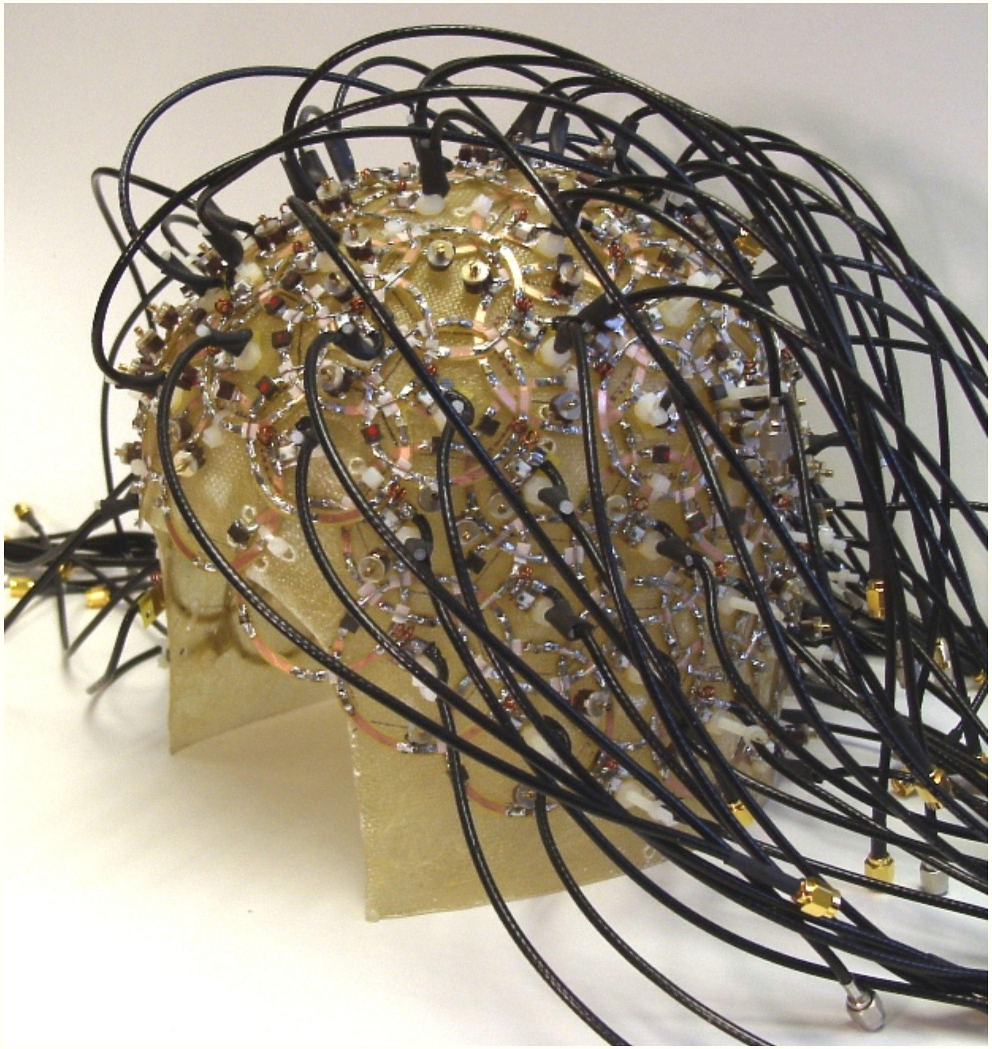
Wald, BASP 2011

MGH, A.A. Martinos Center

90 Channel 1.5T Phased Array

Most coils are 48mm I.D.

Pin diode detuning



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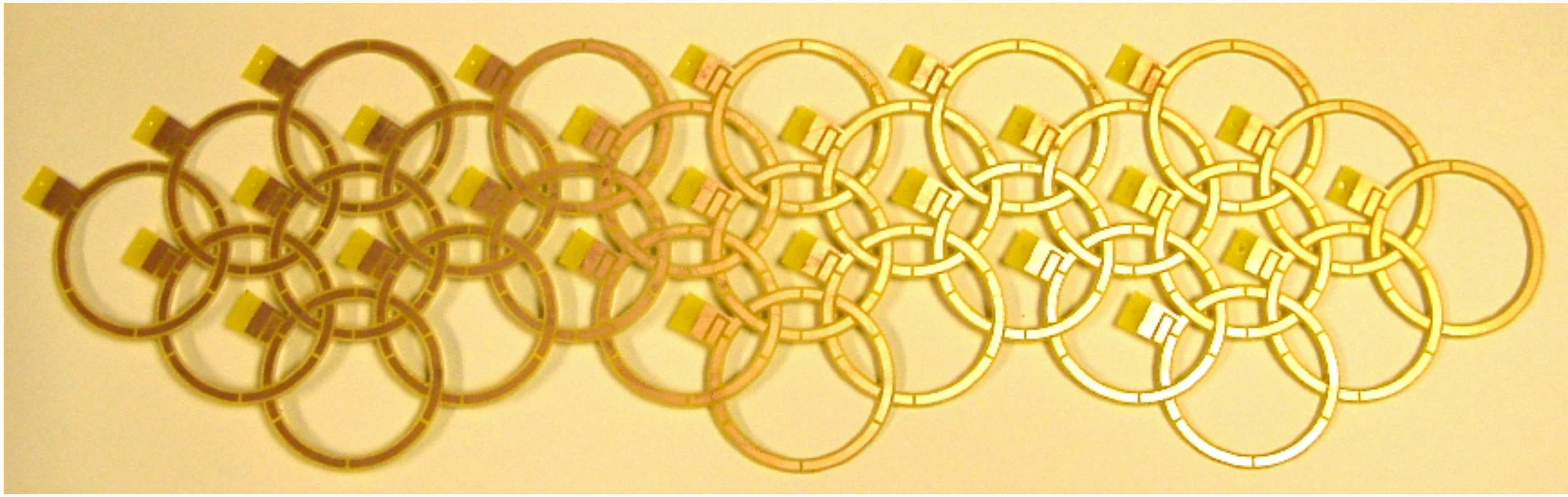
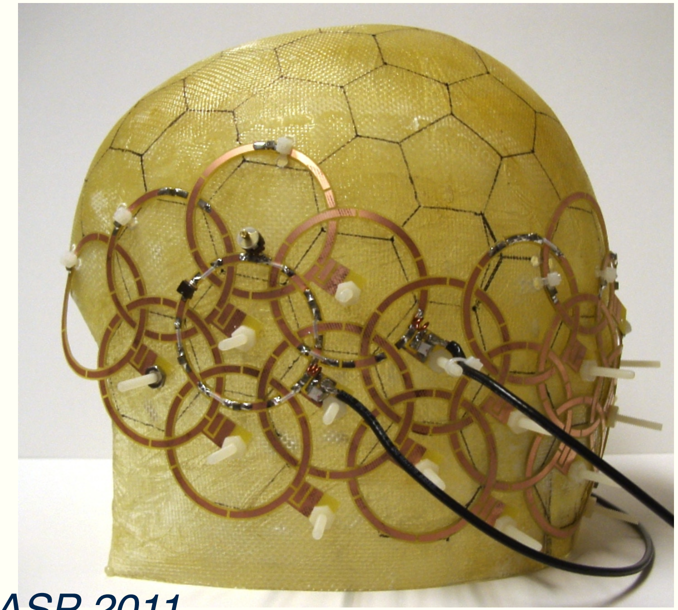
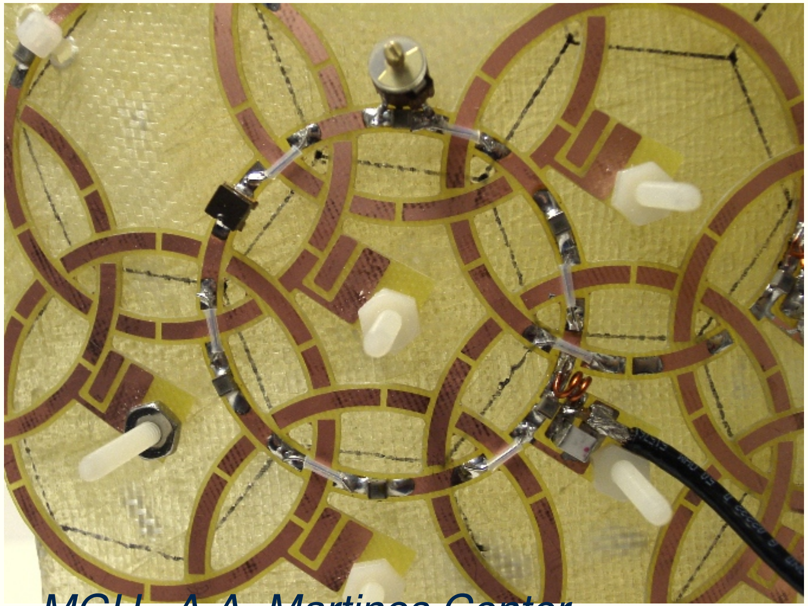
Many Coils From One Piece







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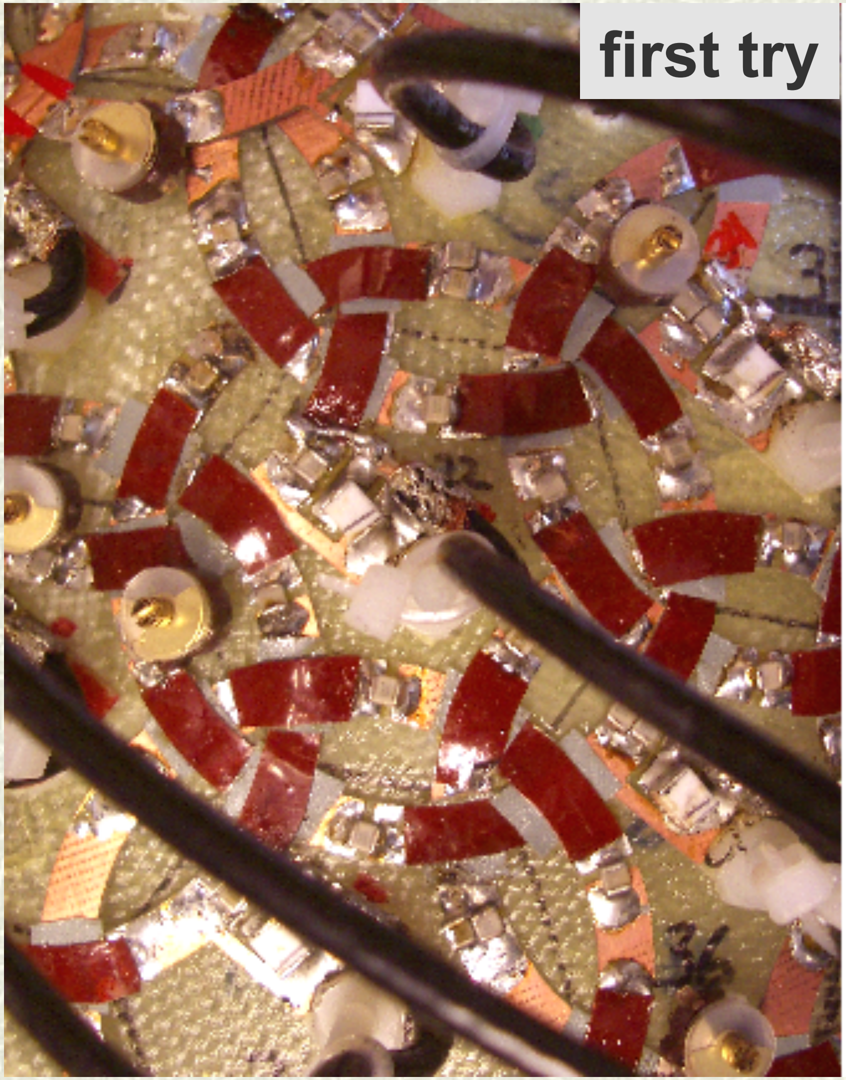
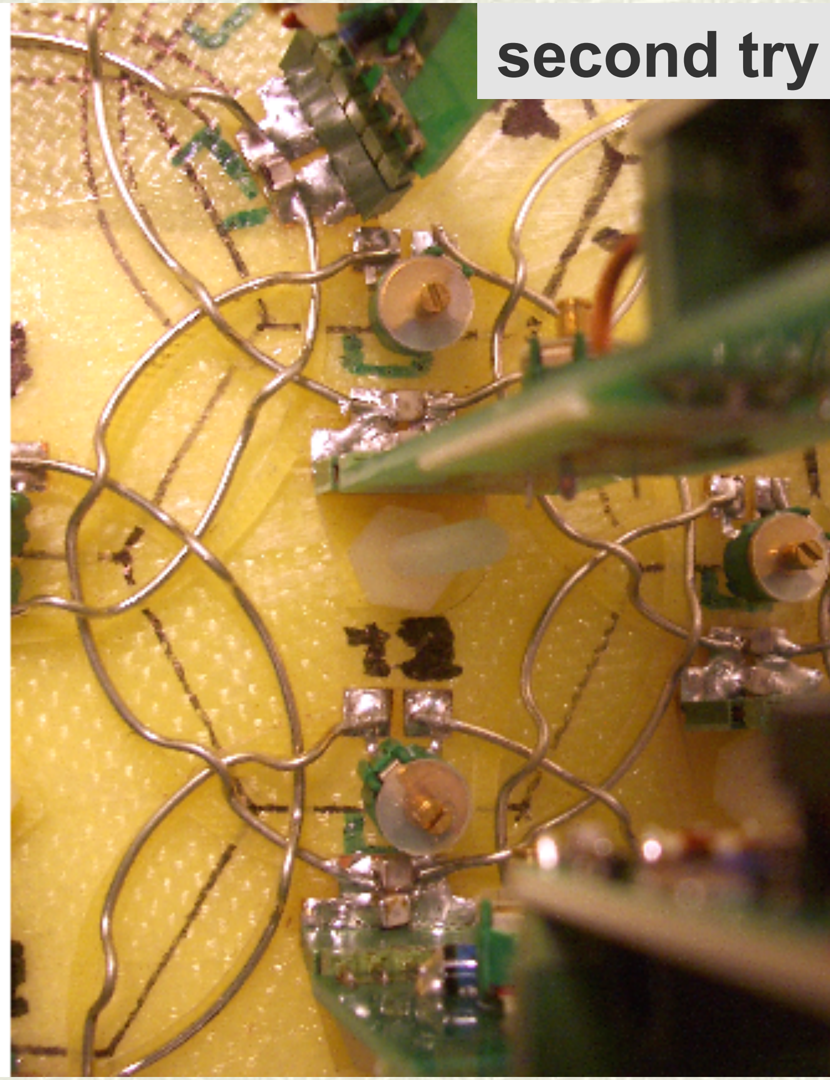
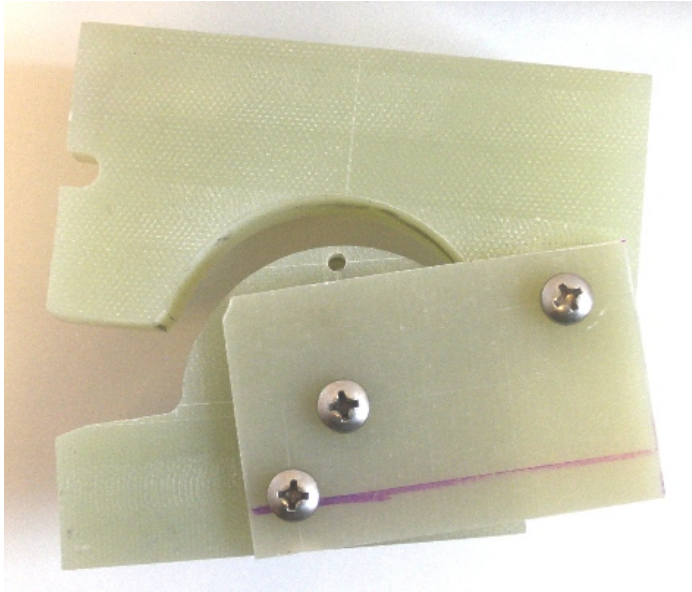
MGH 96 channel 3T





How to Build 96 Wire Coil Elements?

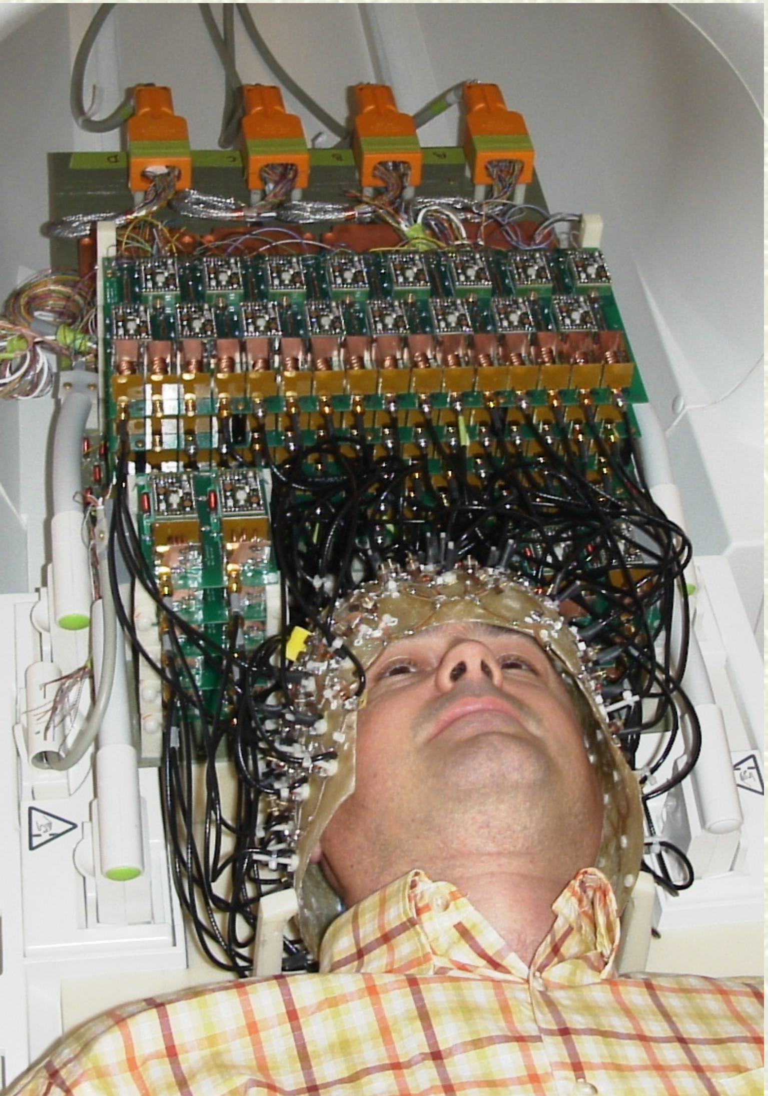
Tools for forming wires

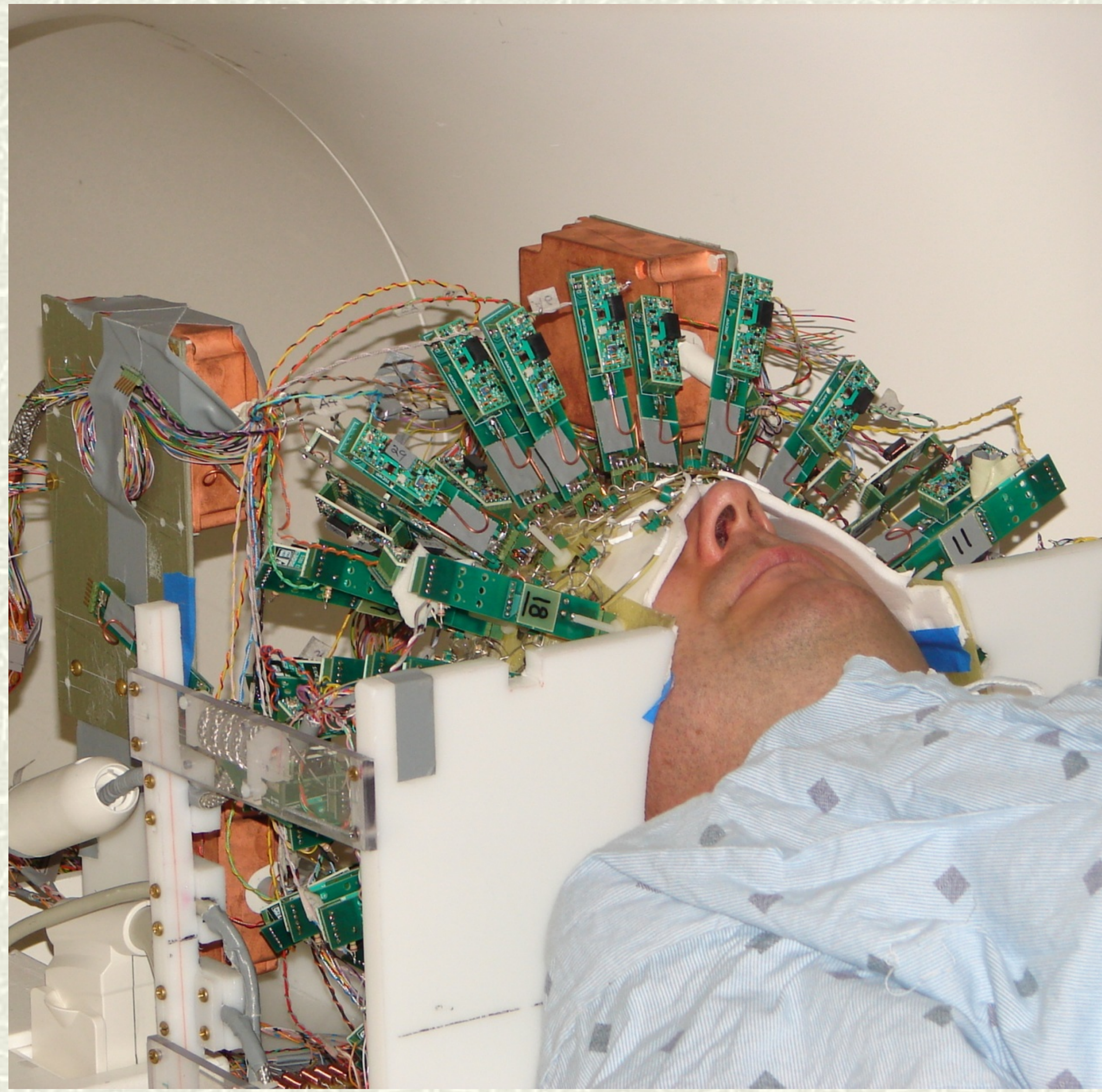


96 Ch 3T
(second try)

90 ch 1.5T

96 ch 3T

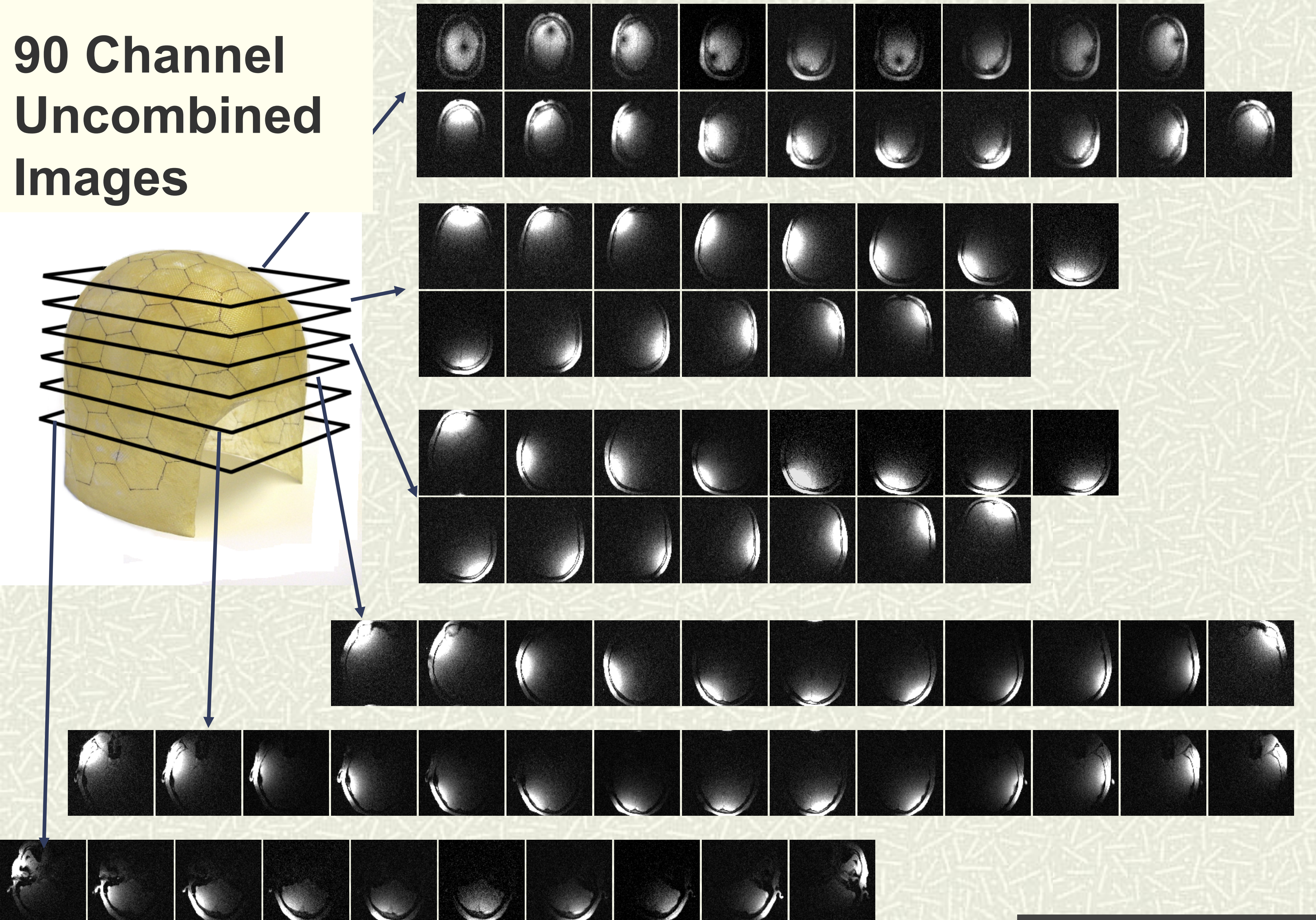




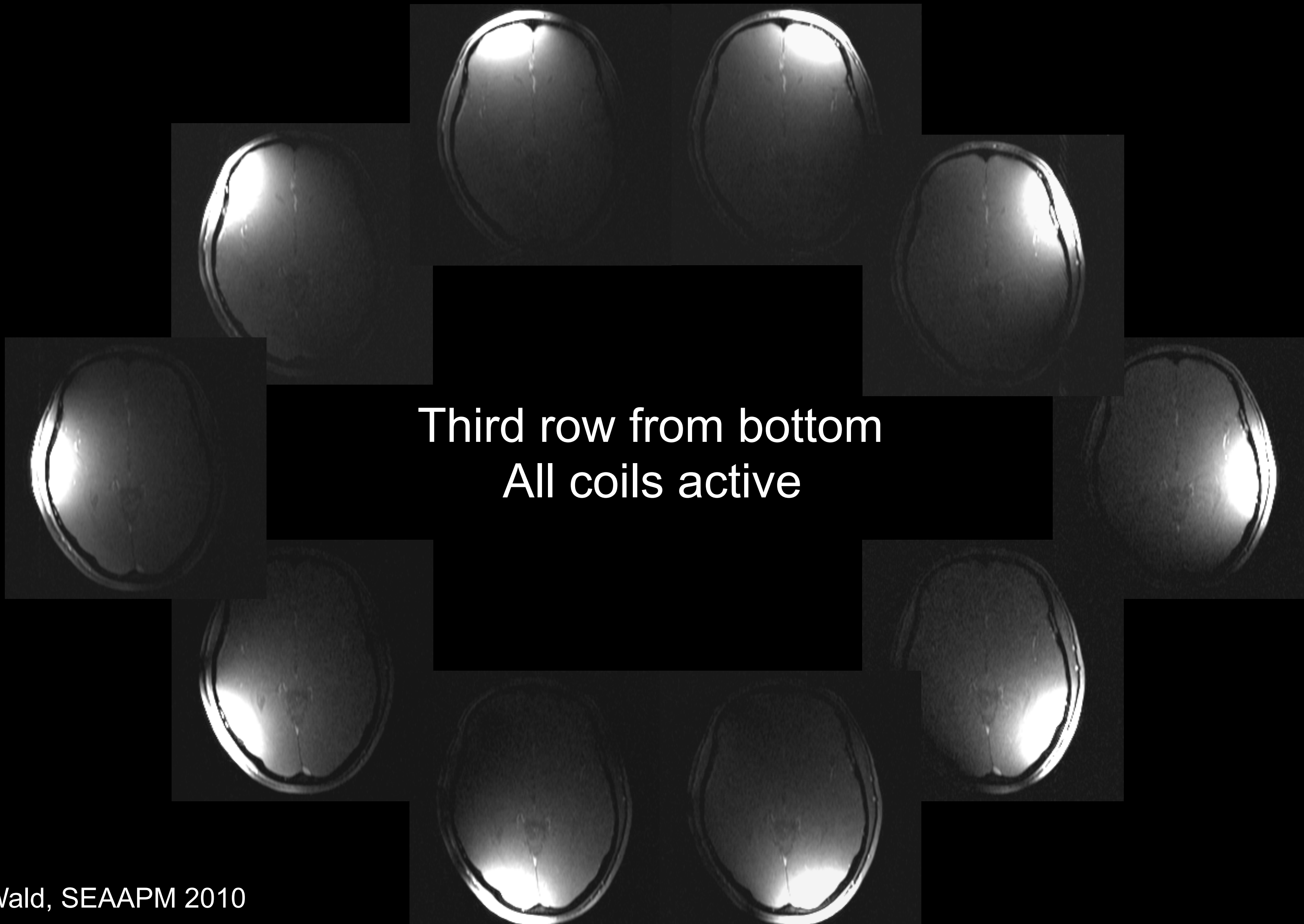
Wald, BASP 2011

MGH, A.A. Martinos Center

90 Channel Uncombined Images

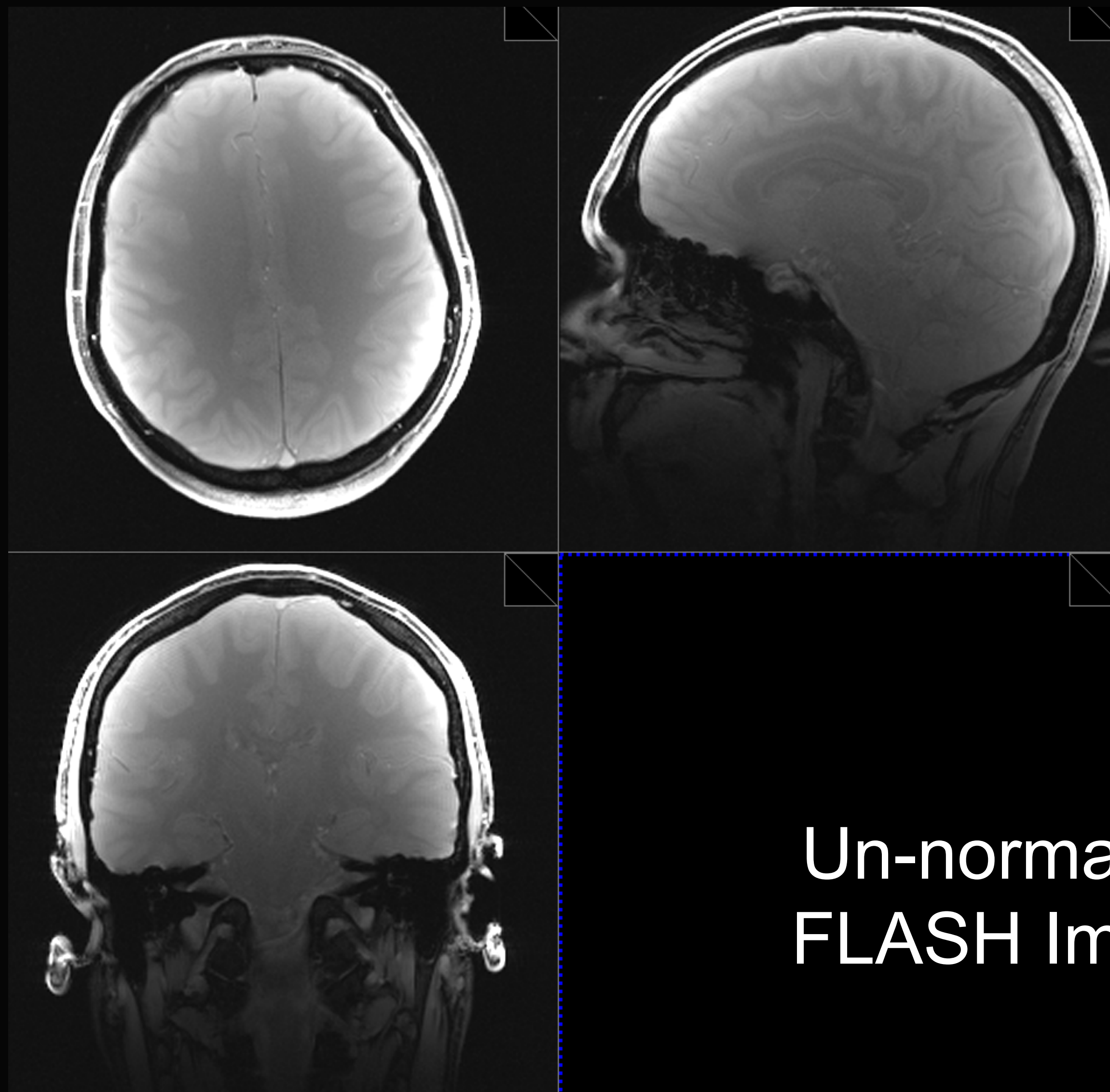


Uncombined Coil Images



Wald, SEAAPM 2010

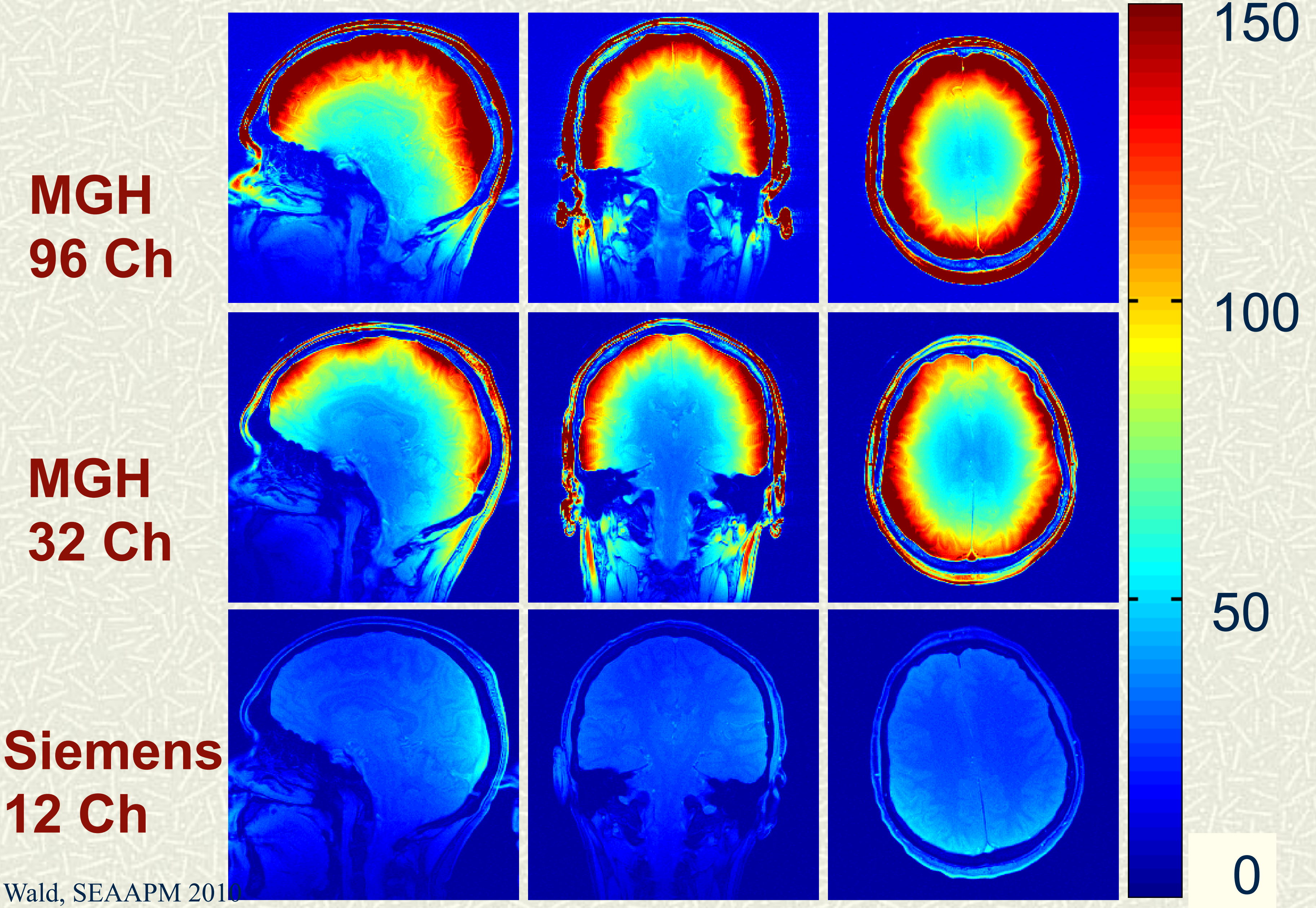
MGH 96 Channel Head Coil for 3T



Un-normalized
FLASH Images

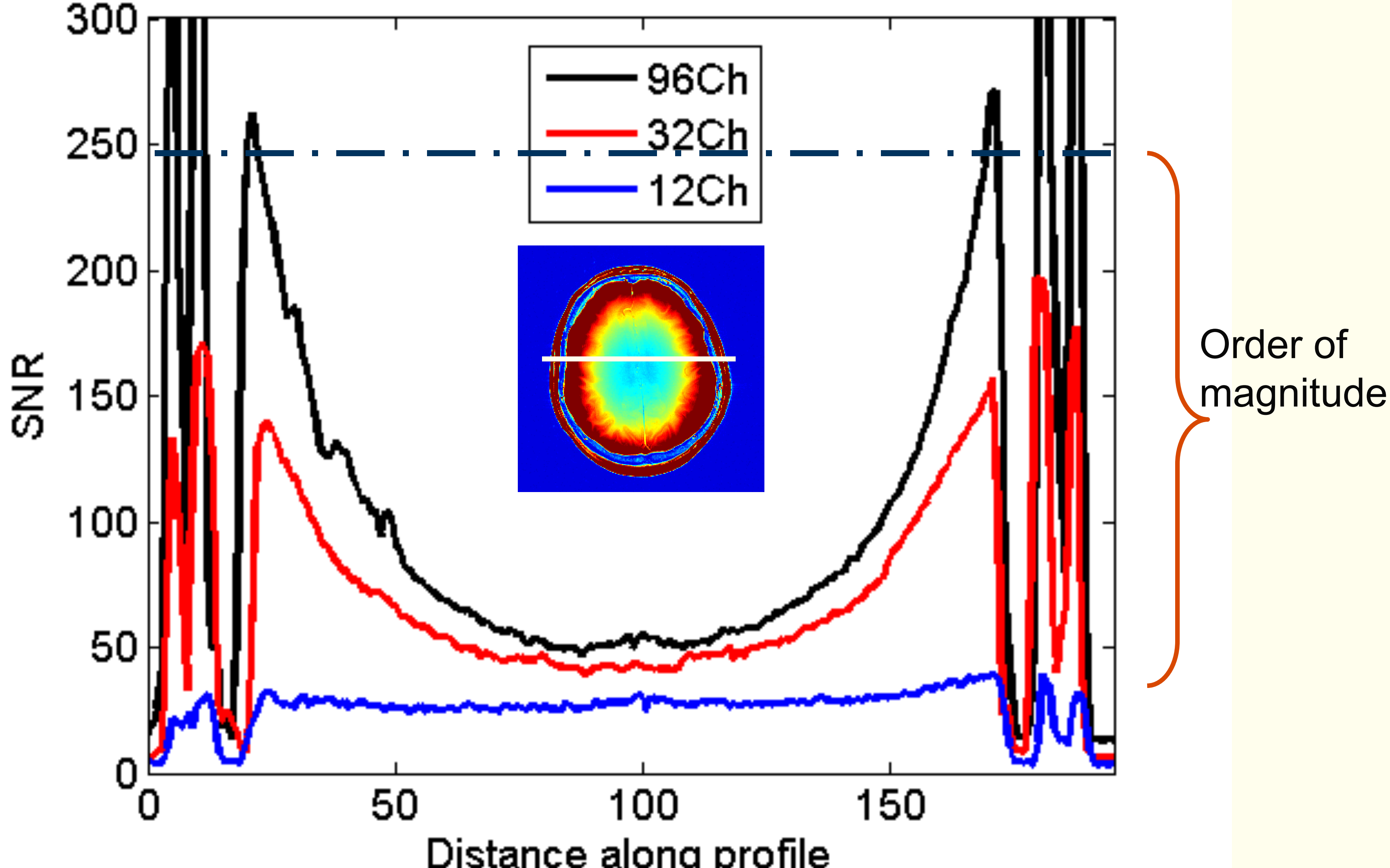
TR / TE / Flip = 200 / 4.07 / 20deg, BW = 200, FoV = 220mm, 256x256

Sensitivity Maps (SNR)



Wald, SEAAPM 2010

Sensitivity Profiles (SNR)



Wald, BASP 2011

MGH, A.A. Martinos Center

Bench-to-bedside translation via industrial partnership

Bench

MGH prototype 32 channel brain array

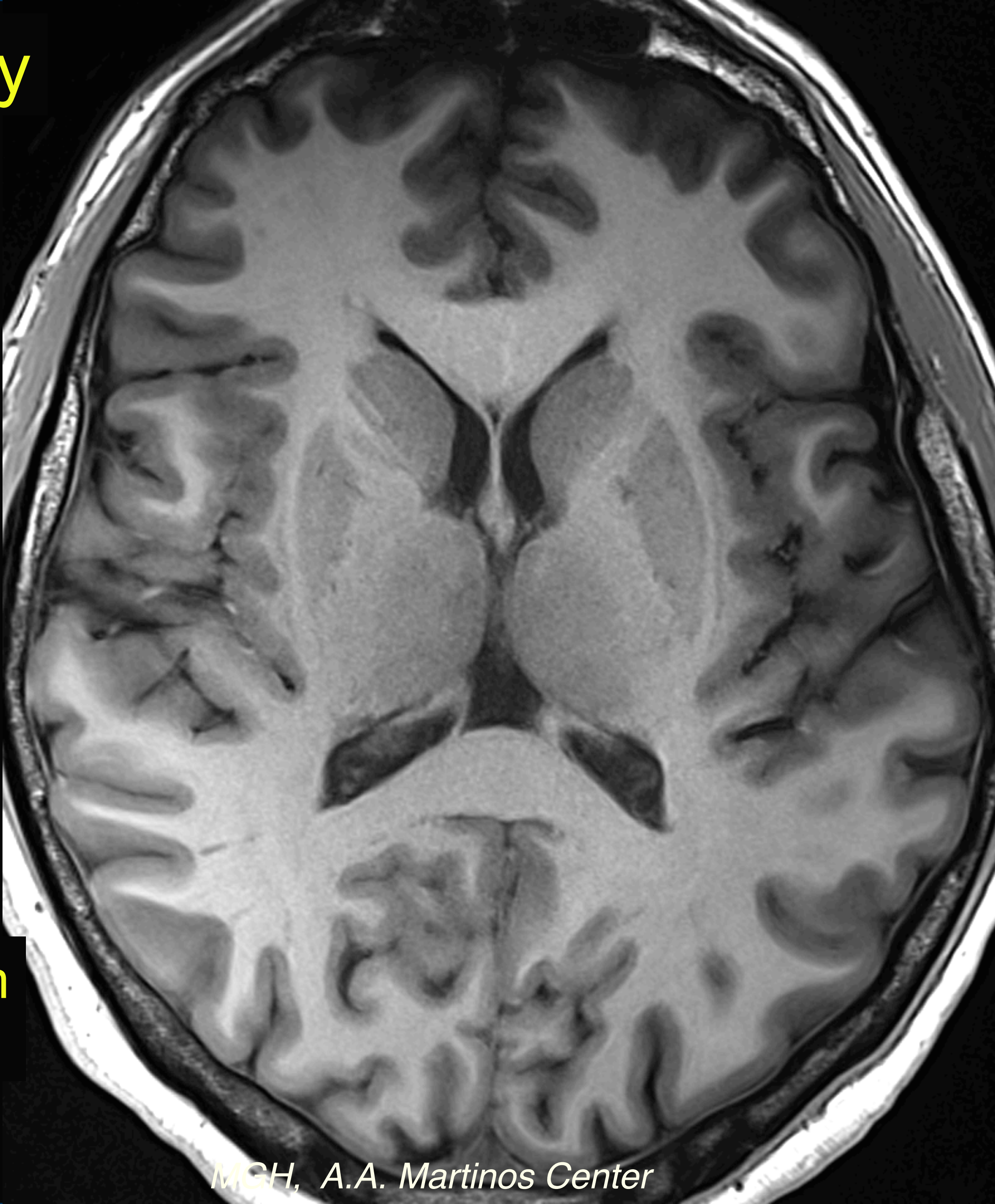
Bedside

Siemens 32 channel brain array

Wald, BASP 2011

MGH, A.A. Martinos Center

3T 32ch MGH array

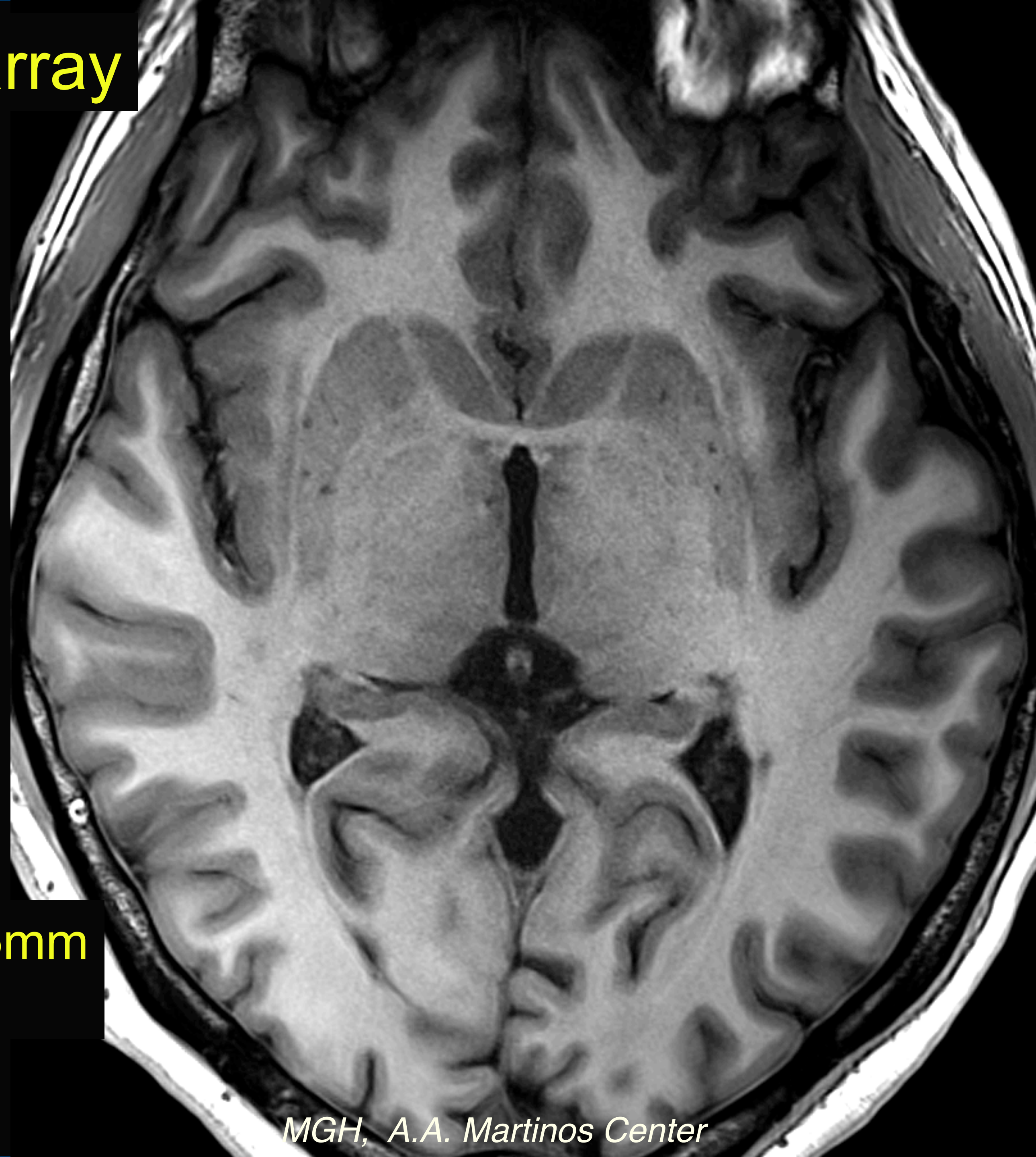


Volume MPRAGE

400um x 400um x 1.5mm
= 240nl

Wald, BASP 2011

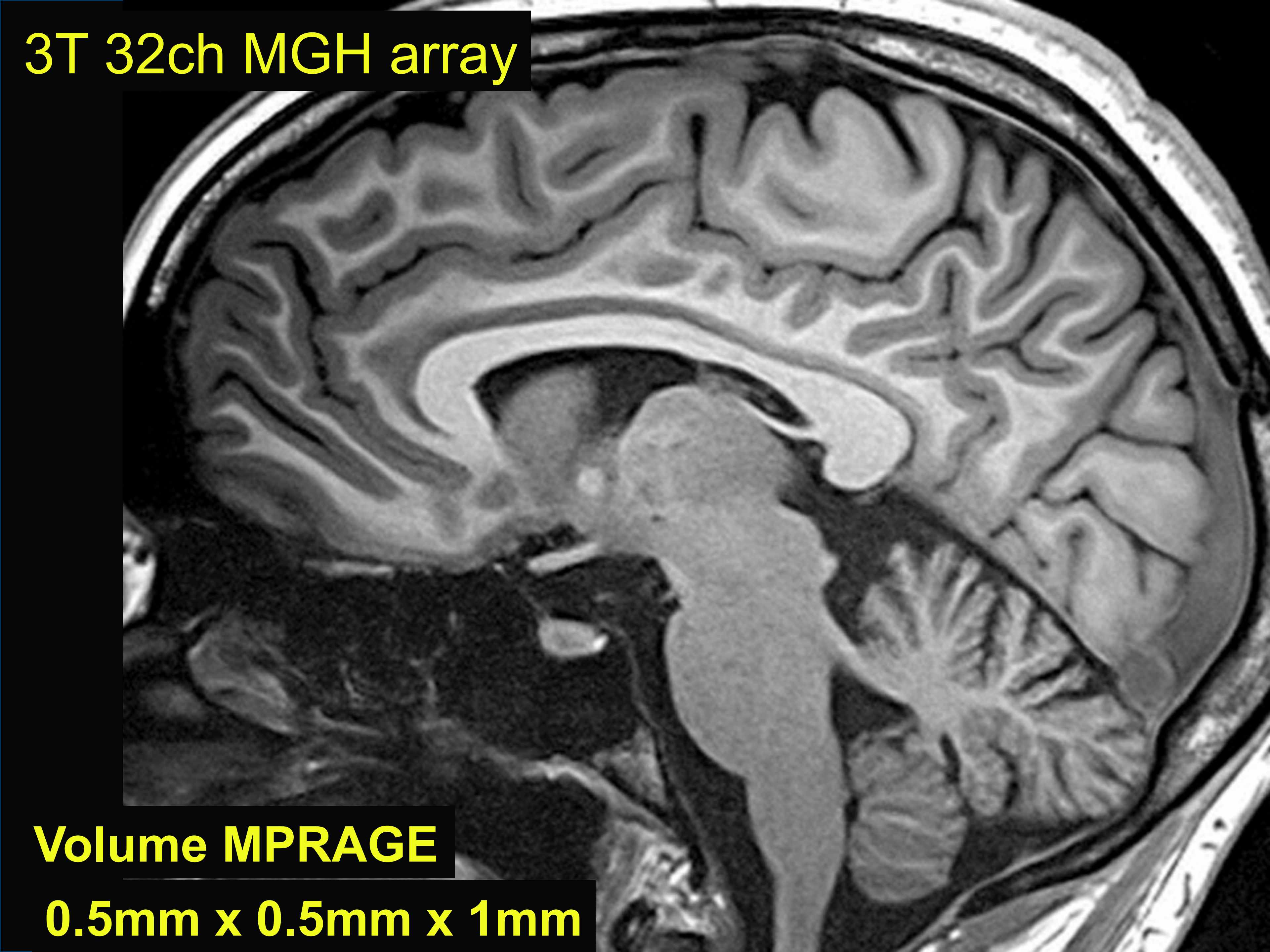
3T 32ch MGH array

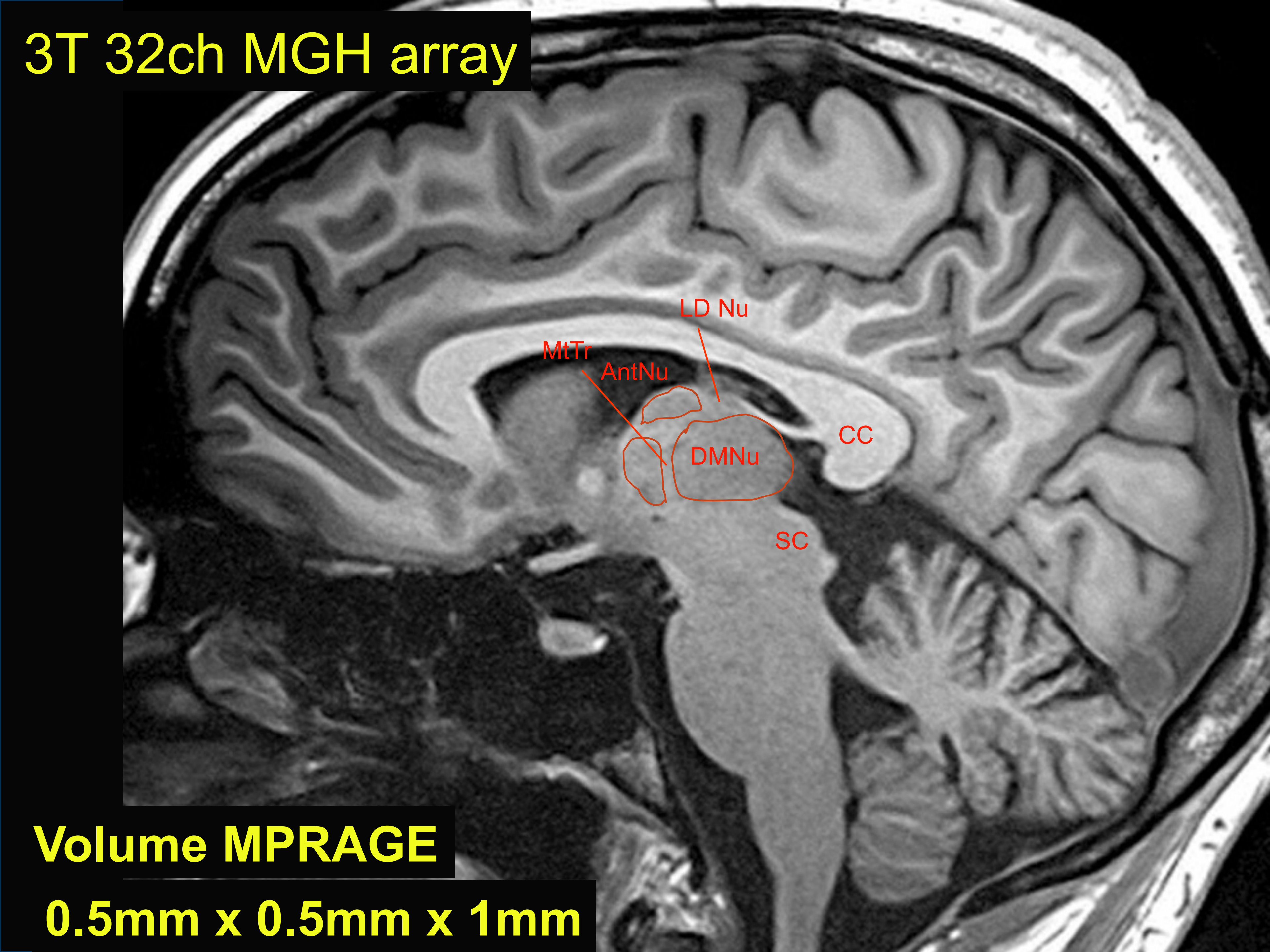


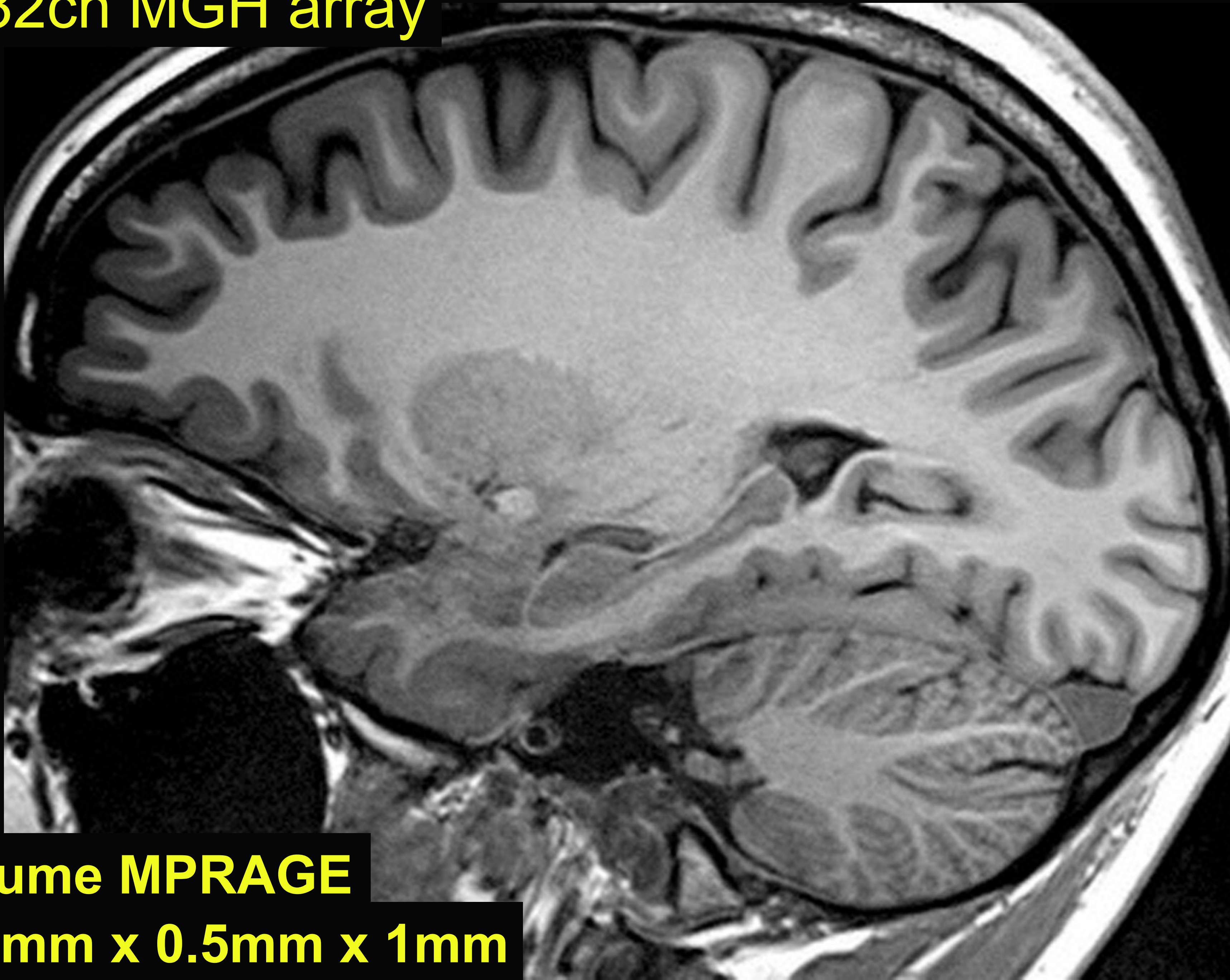
Volume MPRAGE

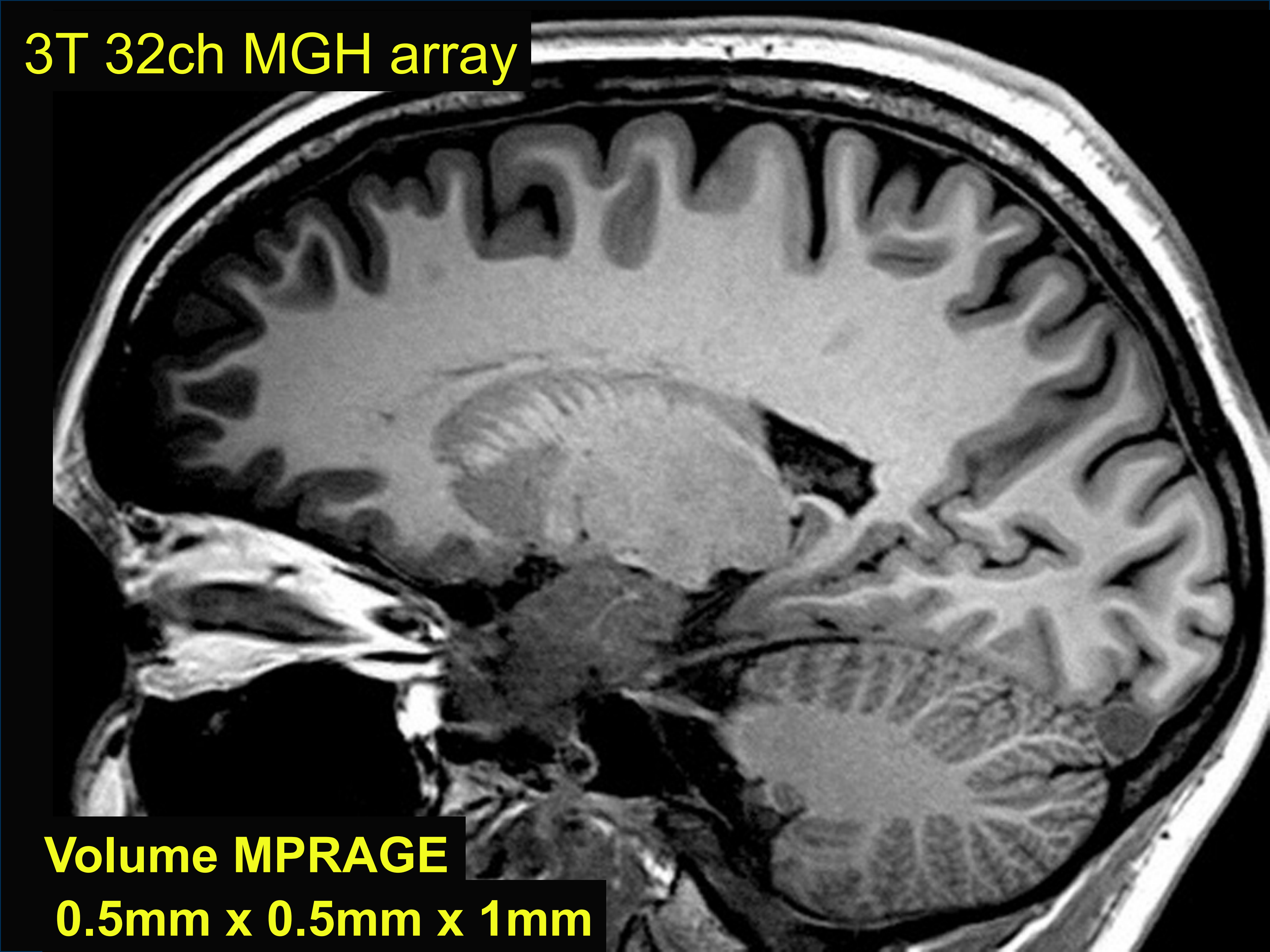
400um x 400um x 1.5mm
= 240nl

Wald, BASP 2011

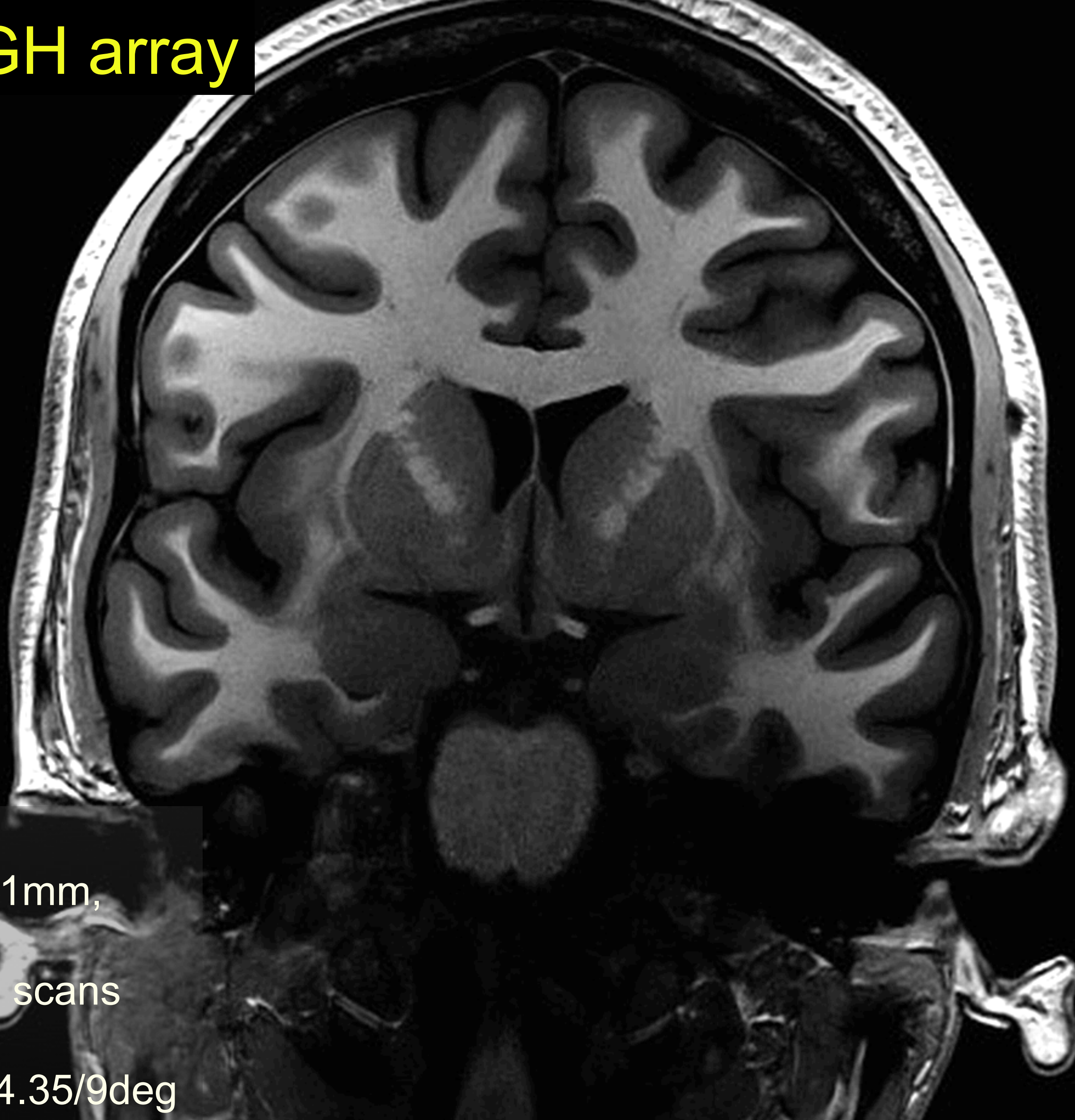

3T 32ch MGH array
Volume MPRAGE
0.5mm x 0.5mm x 1mm


3T 32ch MGH array
LD Nu
MtTr
AntNu
CC
DMNu
SC
Volume MPRAGE
0.5mm x 0.5mm x 1mm


3T 32ch MGH array
Volume MPRAGE
0.5mm x 0.5mm x 1mm

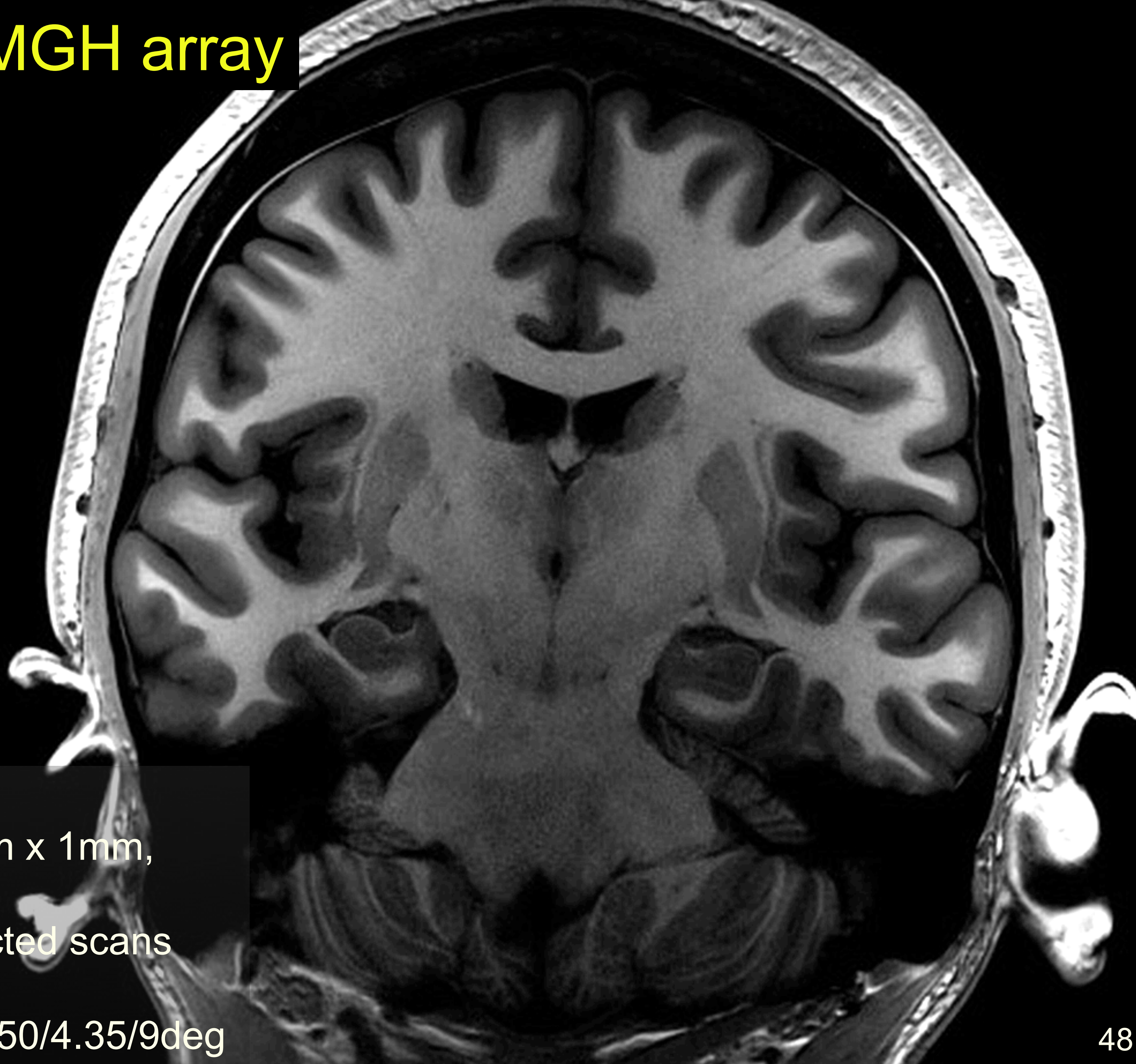

3T 32ch MGH array
Volume MPRAGE
0.5mm x 0.5mm x 1mm

3T 32ch MGH array

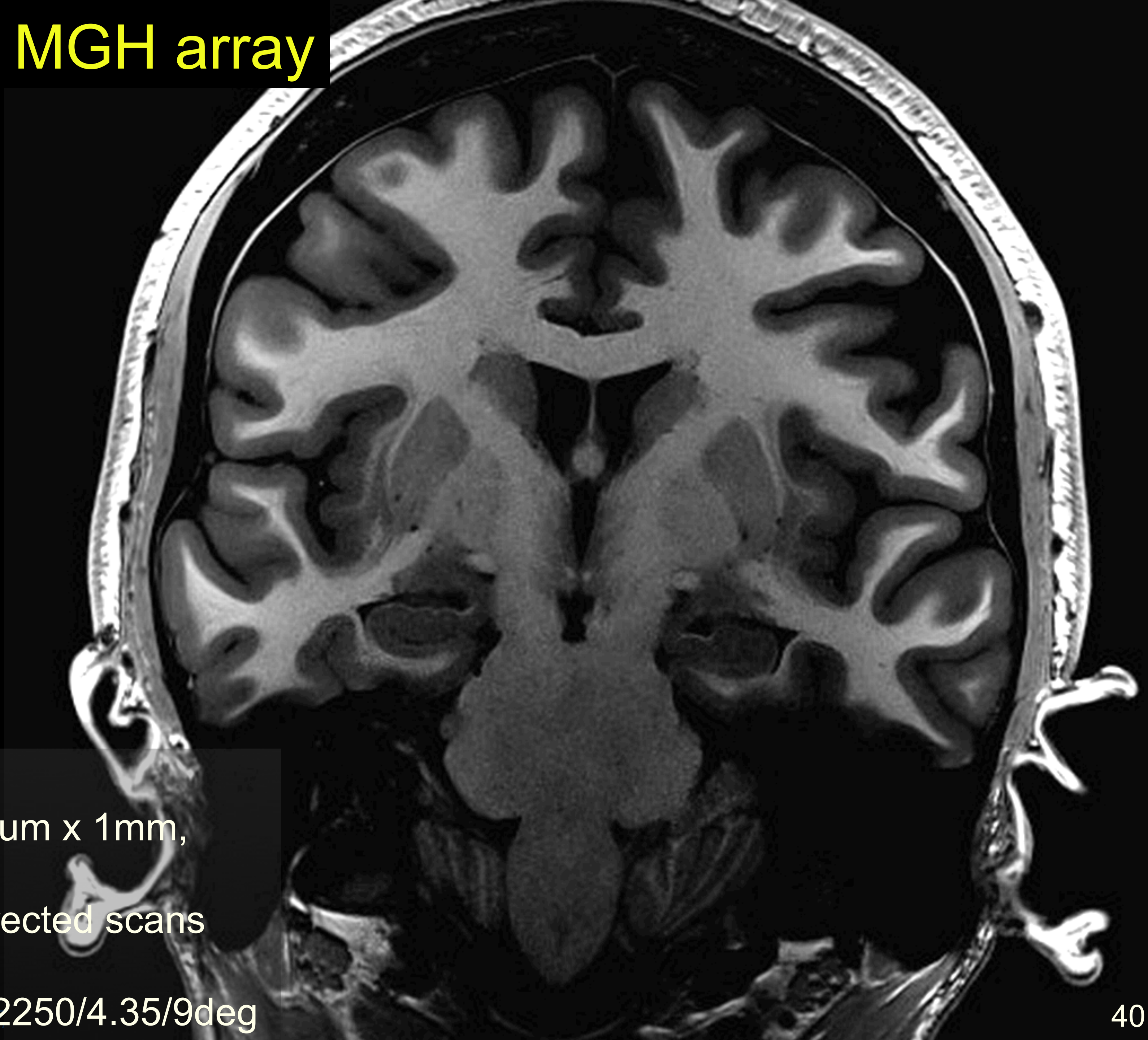


3D MPRAGE
380um x 380um x 1mm,
Resol.=144nl
7 motion corrected scans
TI=900ms,
TR/TE/flip = 2250/4.35/9deg

3T 32ch MGH array

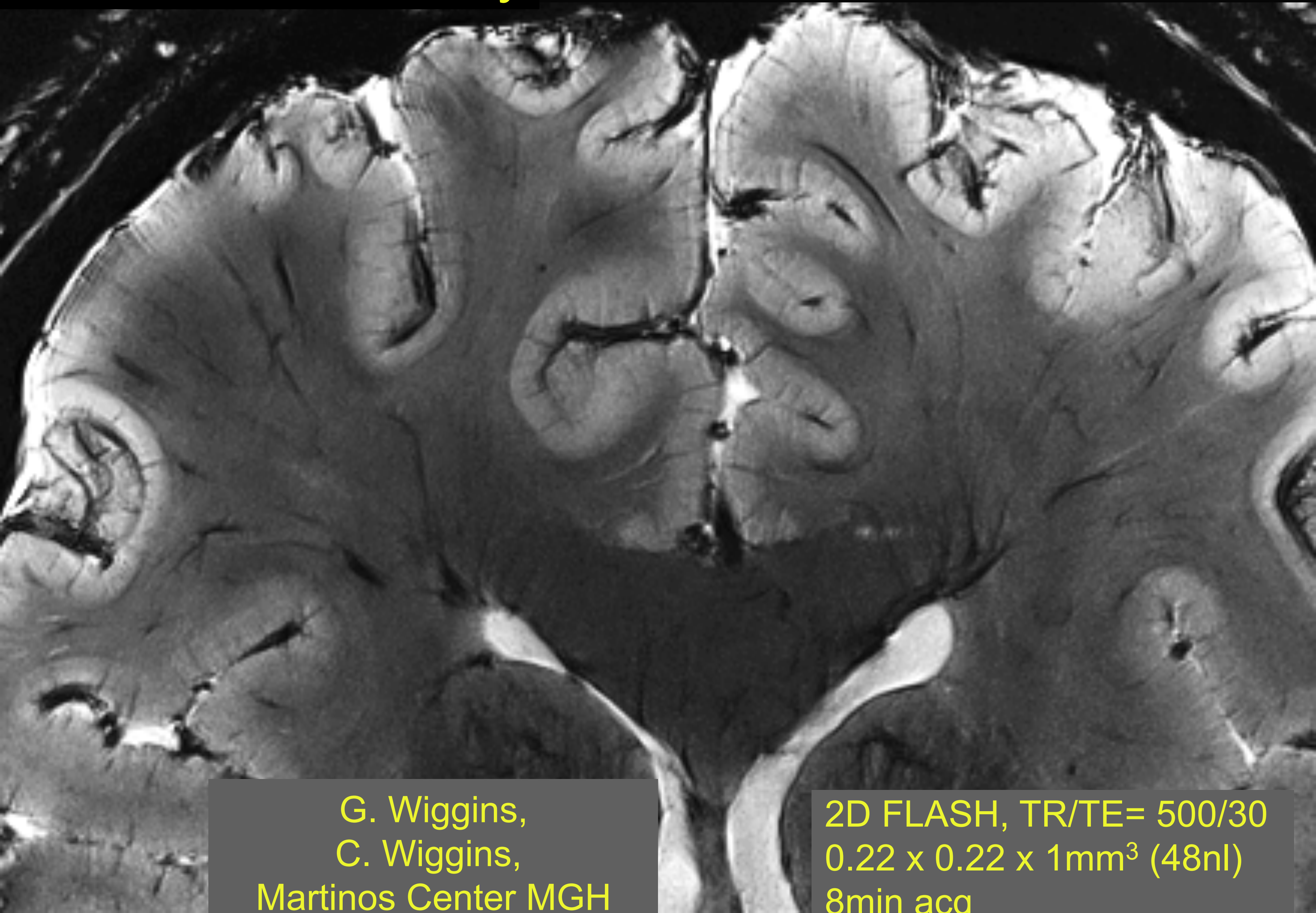


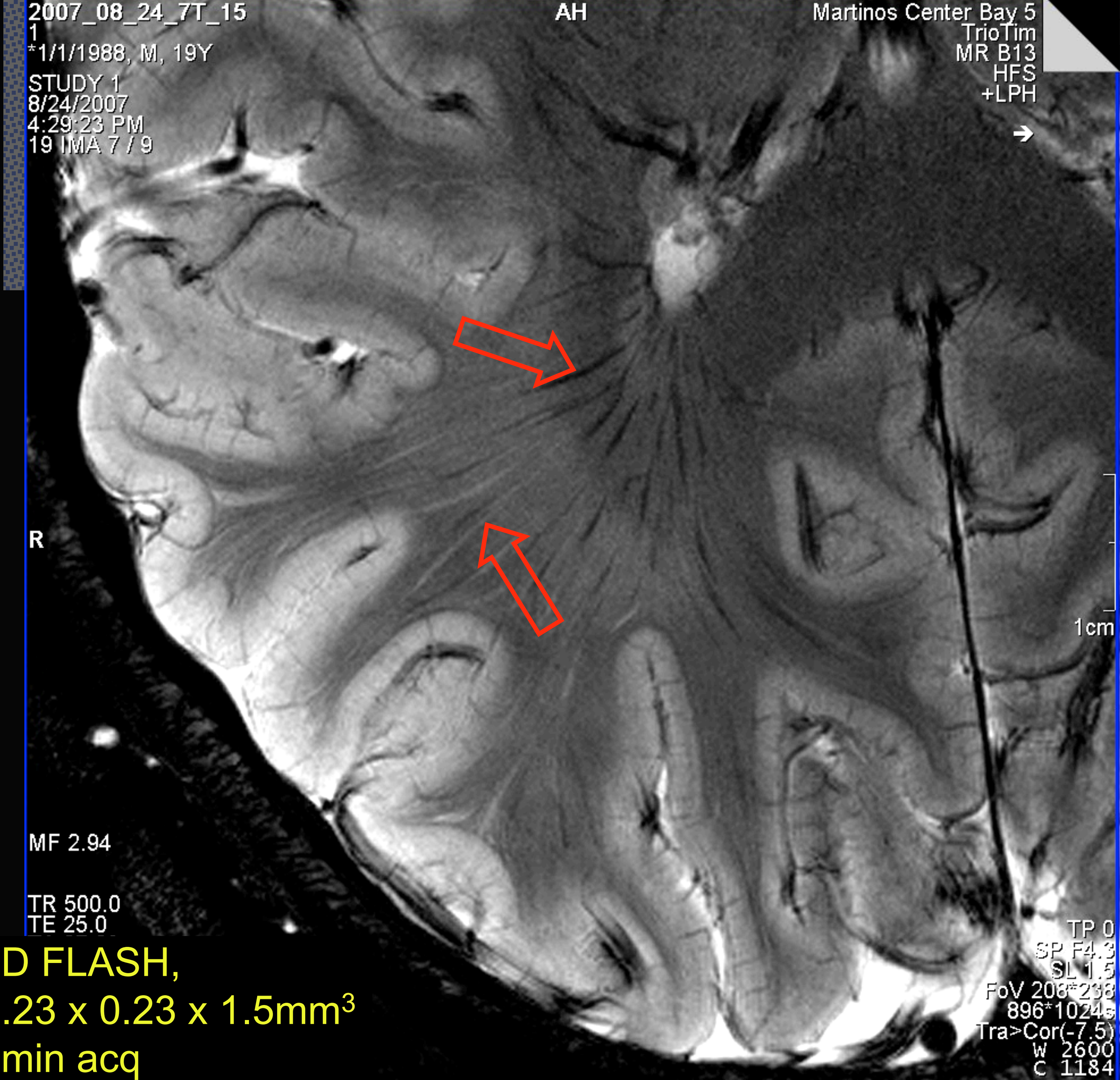
3T 32ch MGH array



3D MPRAGE
380um x 380um x 1mm,
Resol.=144nl
7 motion corrected scans
TI=900ms,
TR/TE/flip = 2250/4.35/9deg

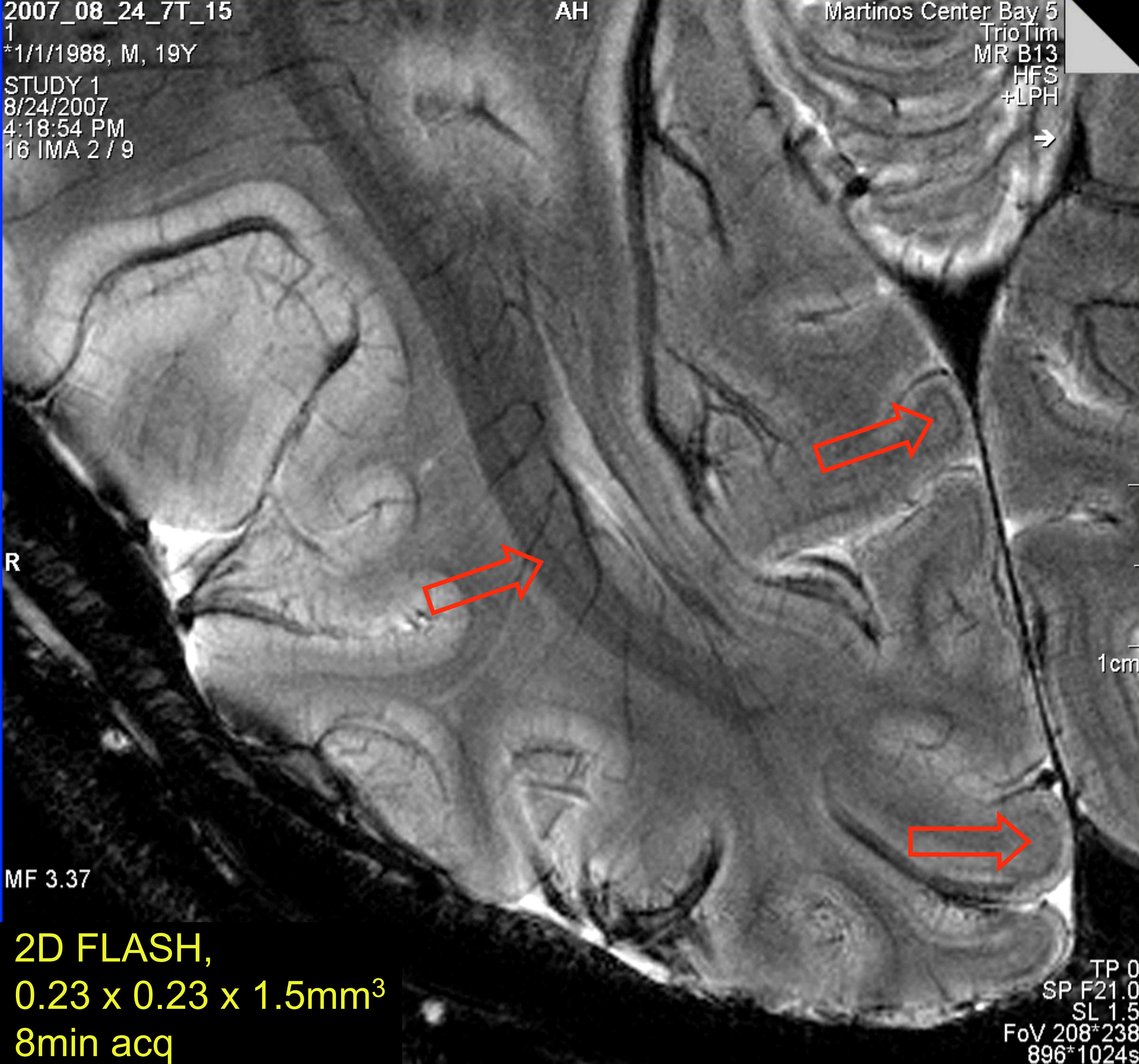
7T 32ch MGH array





7 Tesla
230um

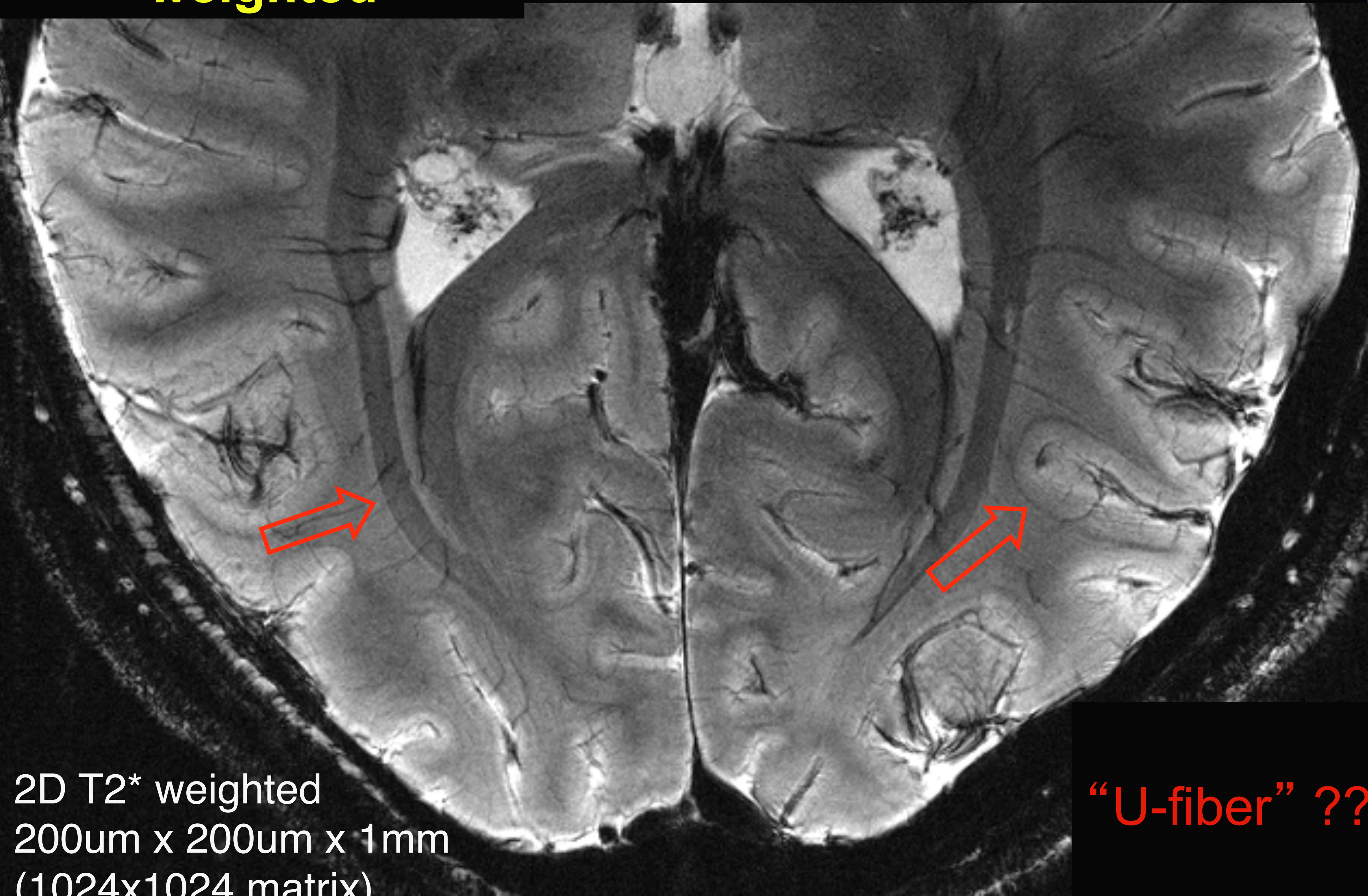
2D FLASH,
$0.23 \times 0.23 \times 1.5mm^3$
8min acq



7 Tesla 230um

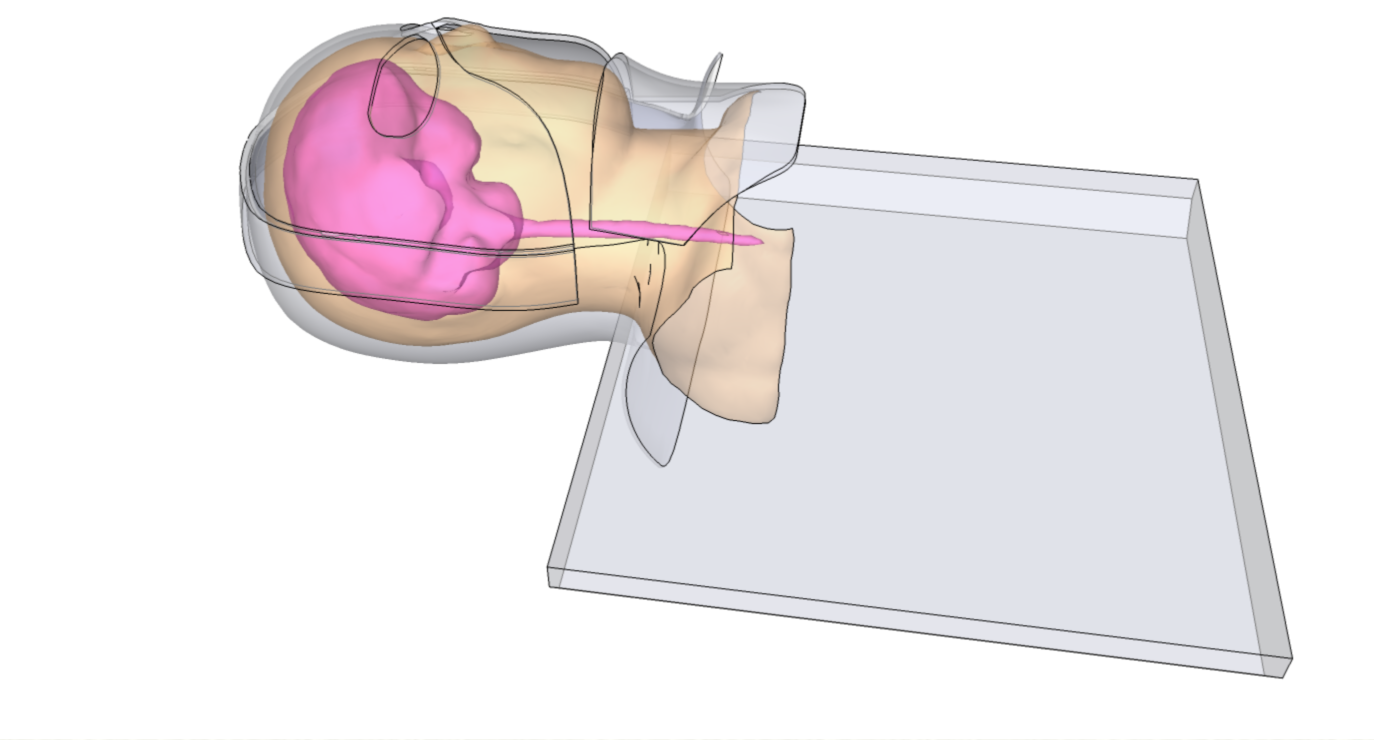
2D FLASH,
0.23 x 0.23 x 1.5mm^3
8min acq

7T Highres T2* weighted



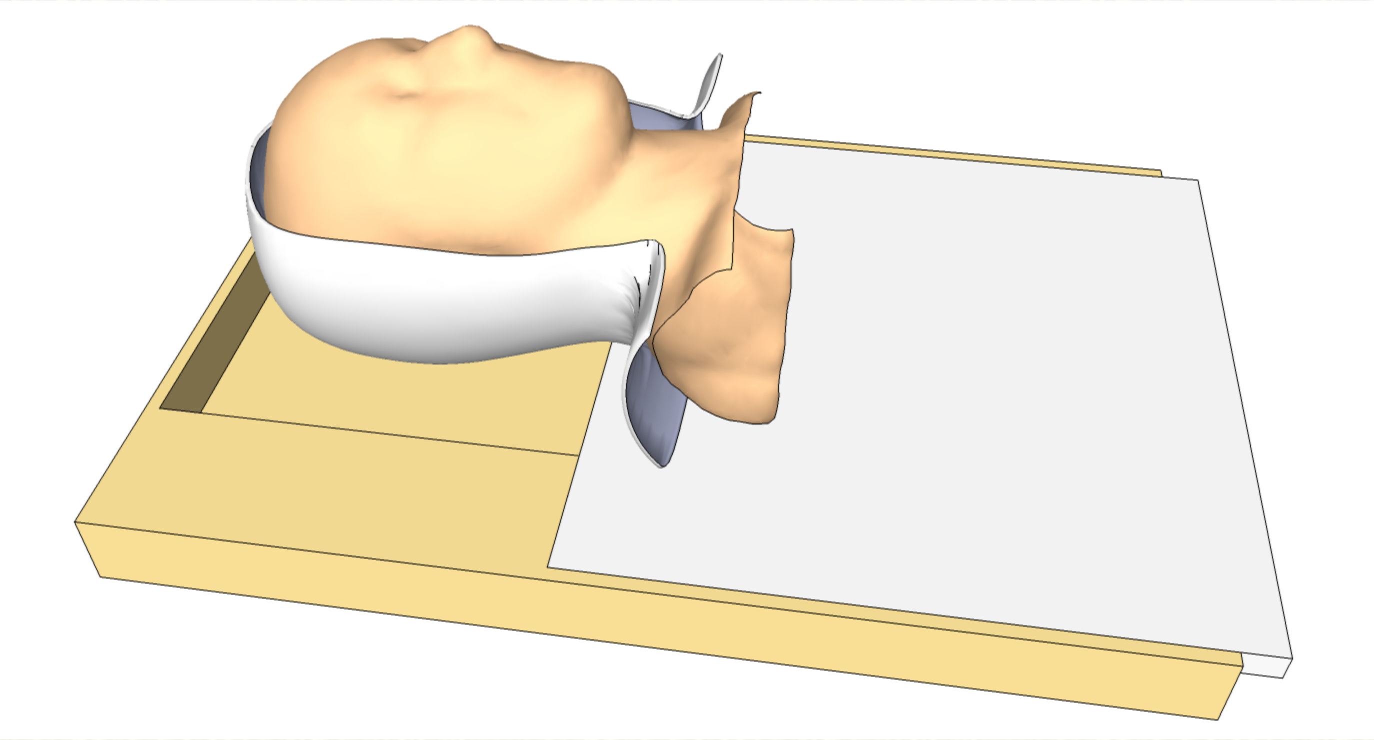
64ch head-neck-Cspine prototype

Build around statistical head-shape from MR images



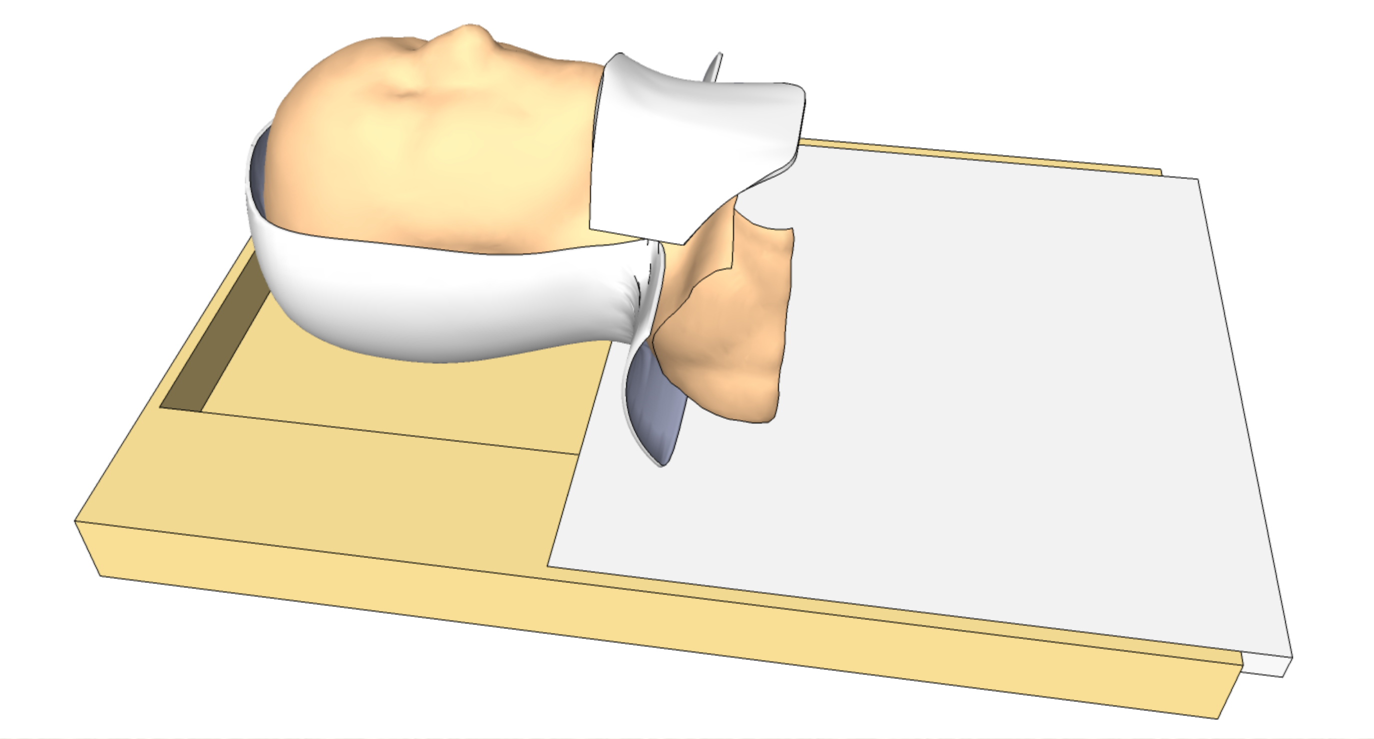
64ch head-neck-Cspine prototype

Build around statistical head-shape from MR images



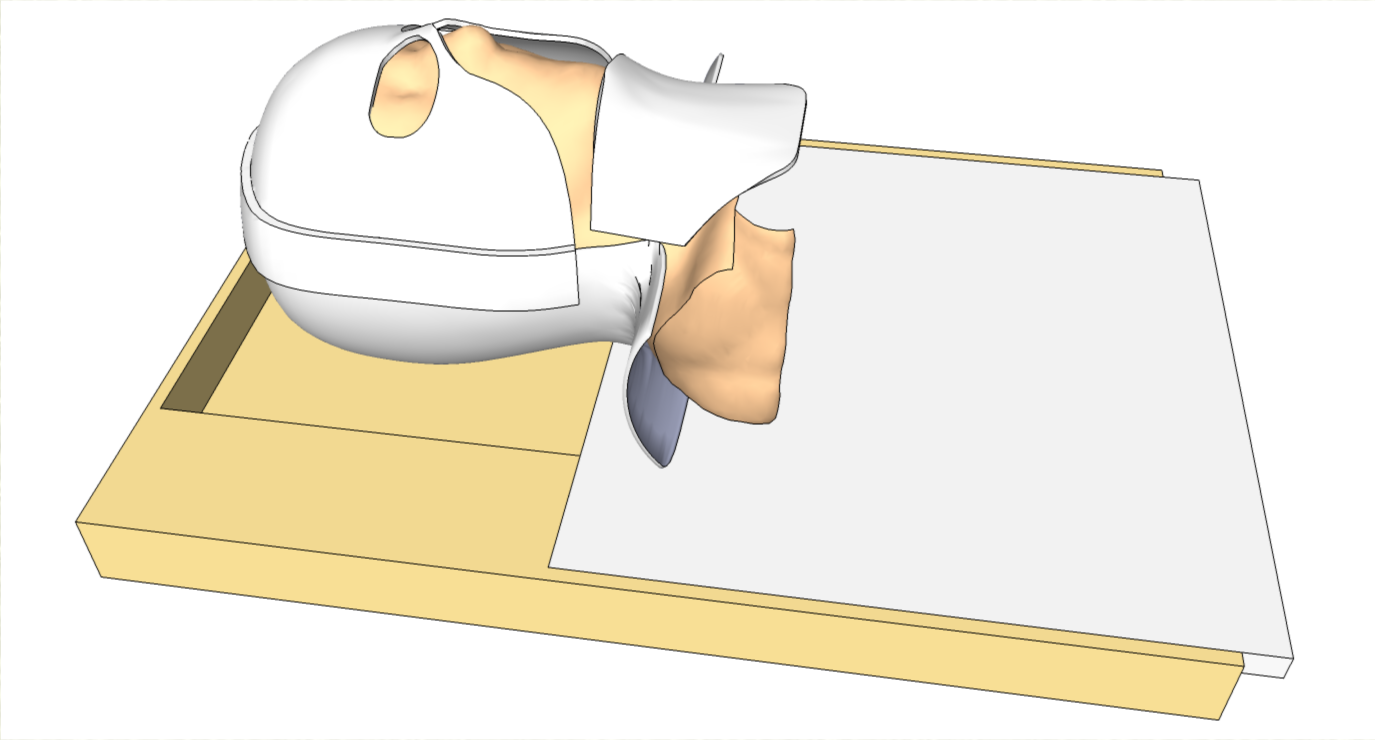
64ch head-neck-Cspine prototype

Build around statistical head-shape from MR images



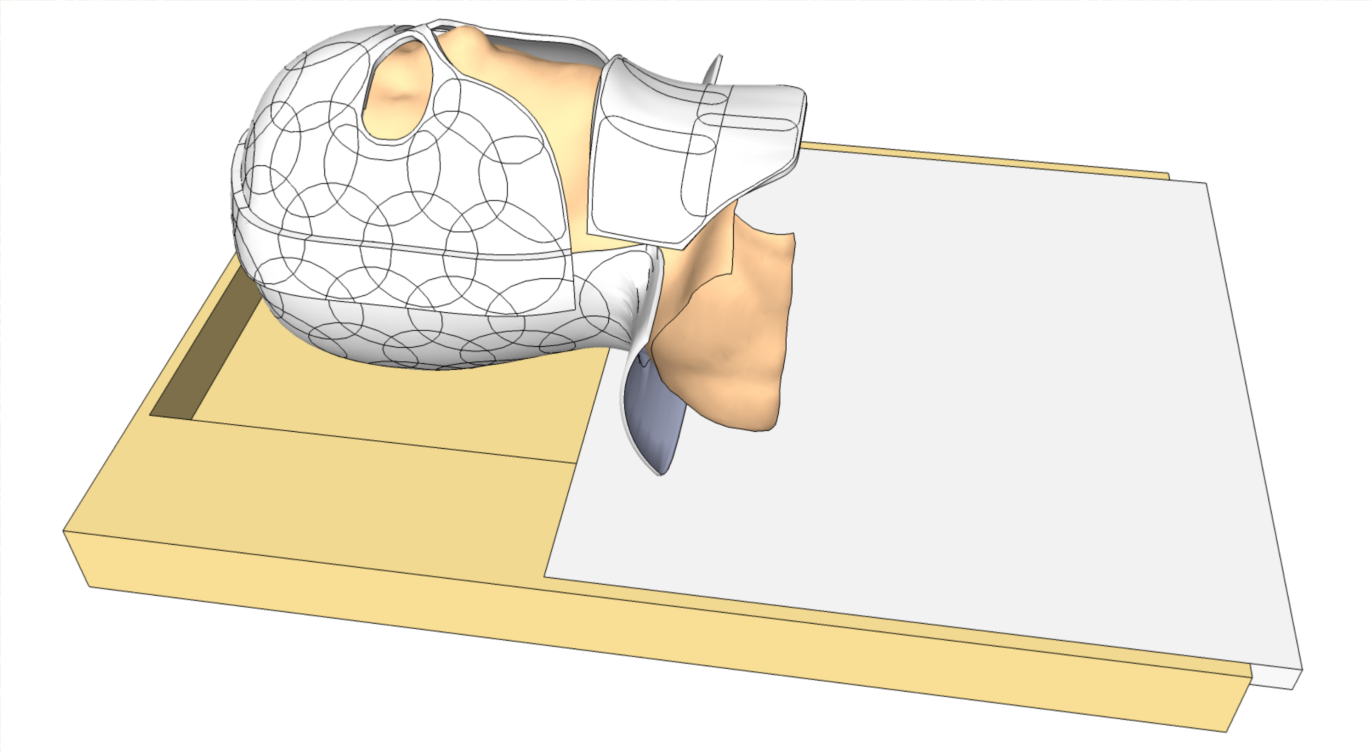
64ch head-neck-Cspine prototype

Build around statistical head-shape from MR images



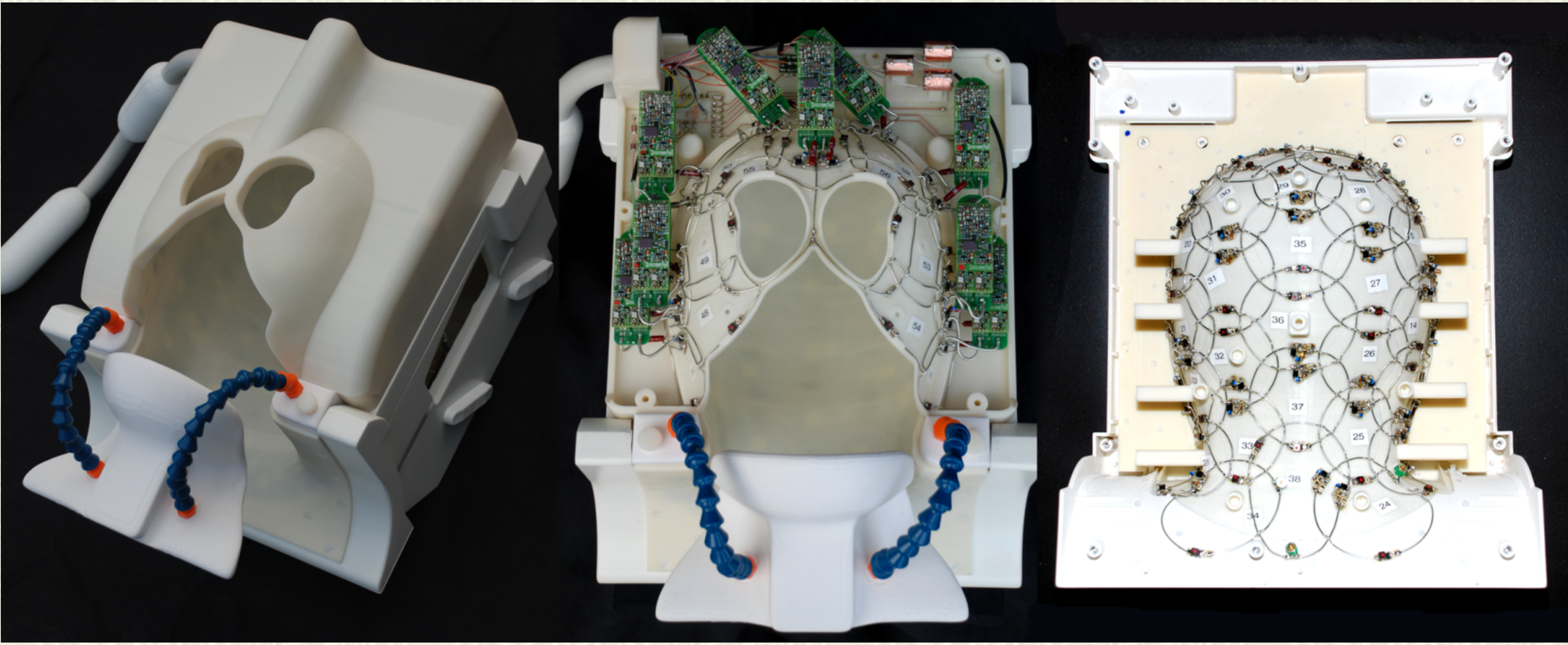
64ch head-neck-Cspine prototype

Build around statistical head-shape from MR images



64ch head-neck-Cspine prototype

Build around statistical head-shape from MR images



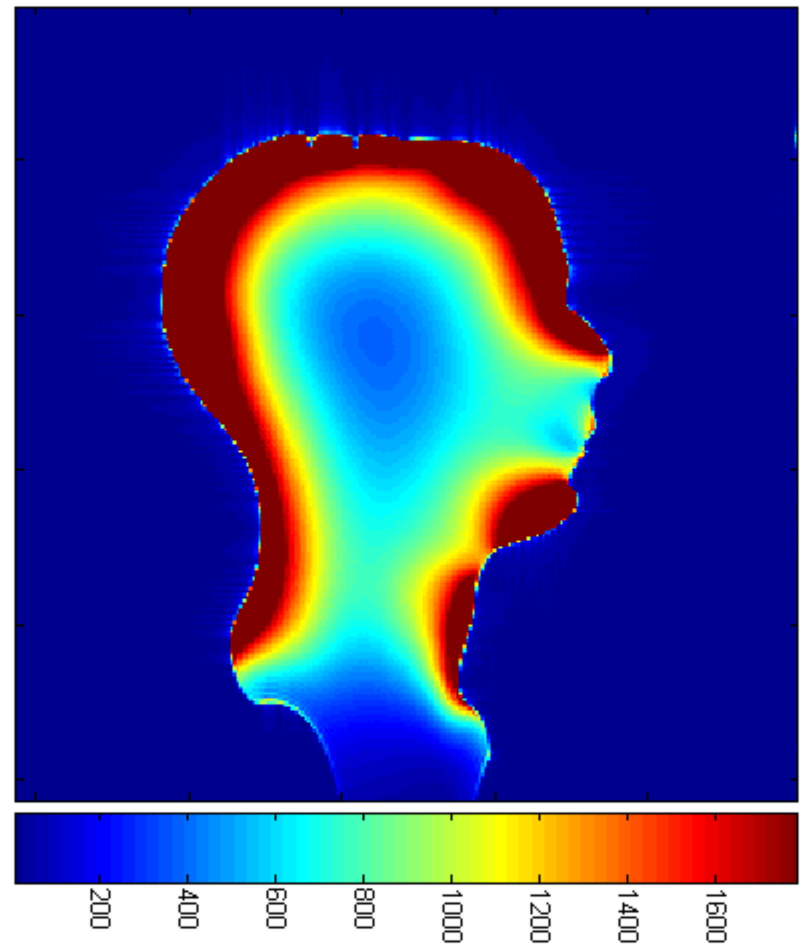
Wald, BASP 2011

MGH, A.A. Martinos Center

Sensitivity comparison

20CH Head-Neck (Siemens)

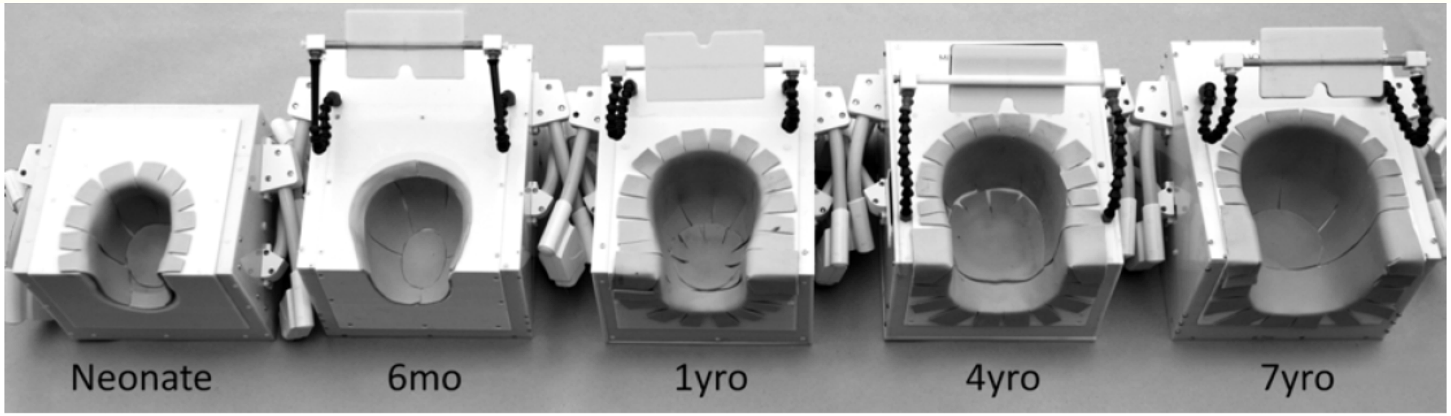
64CH-Head-Neck (MGH)

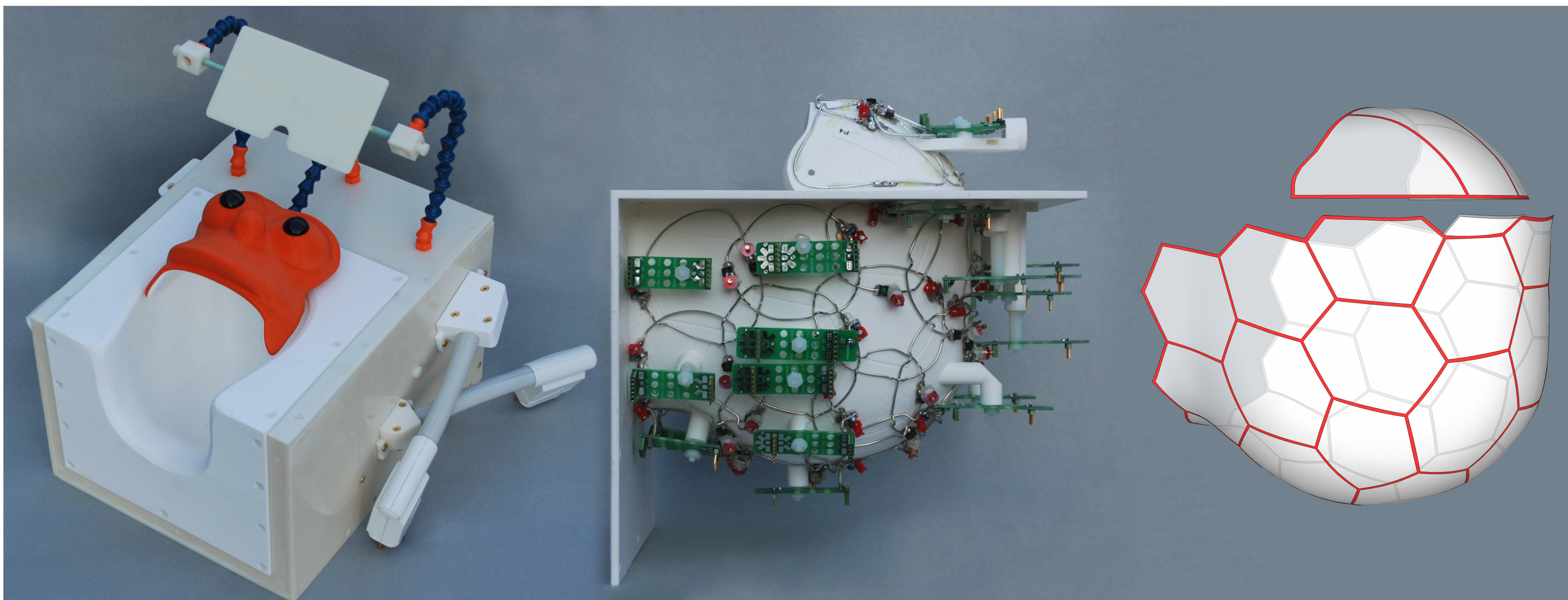


Wald, BASP 2011

MGH, A.A. Martinos Center

SNR in 32ch Pediatric arrays

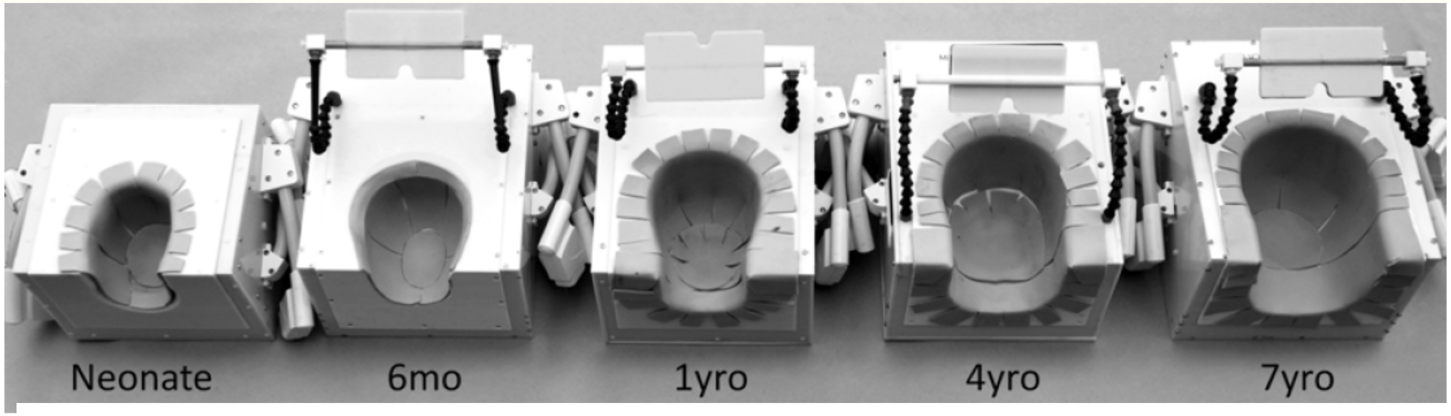


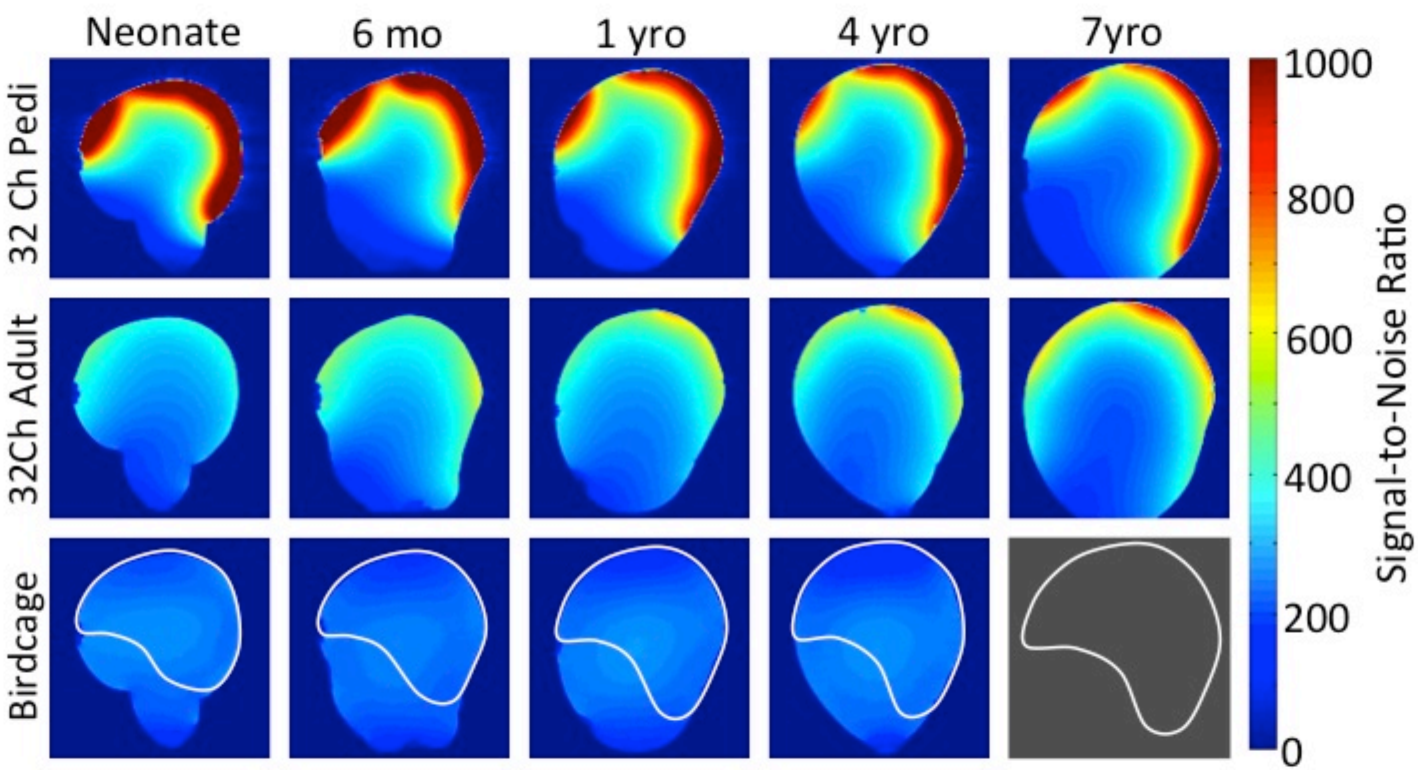


Wald, BASP 2011

MGH, A.A. Martinos Center

SNR in 32ch Pediatric arrays

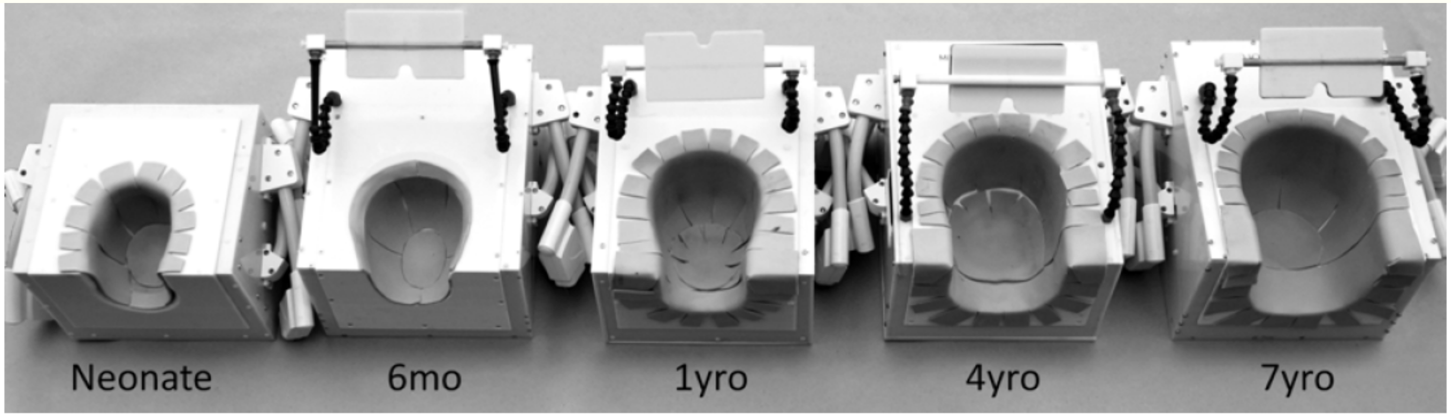


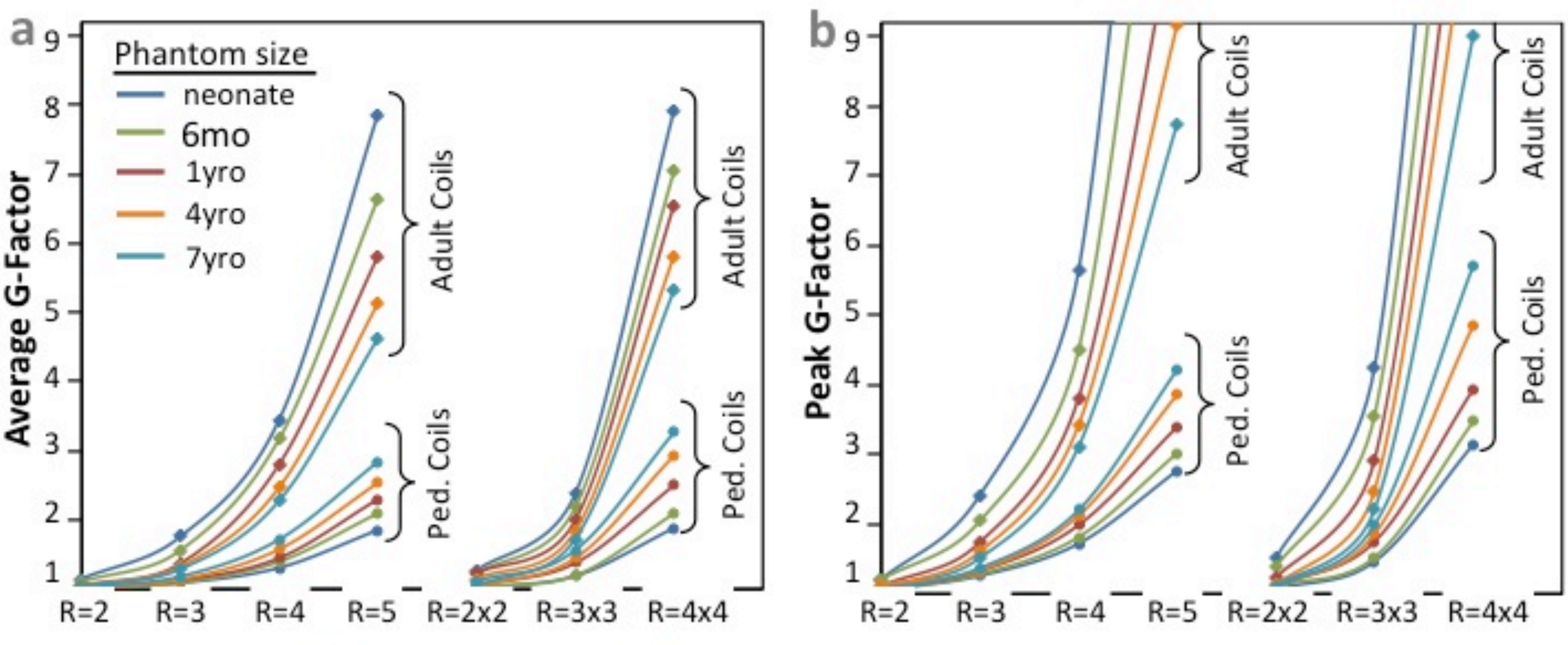


Wald, BASP 2011

MGH, A.A. Martinos Center

G-factor in 32ch Pediatric arrays

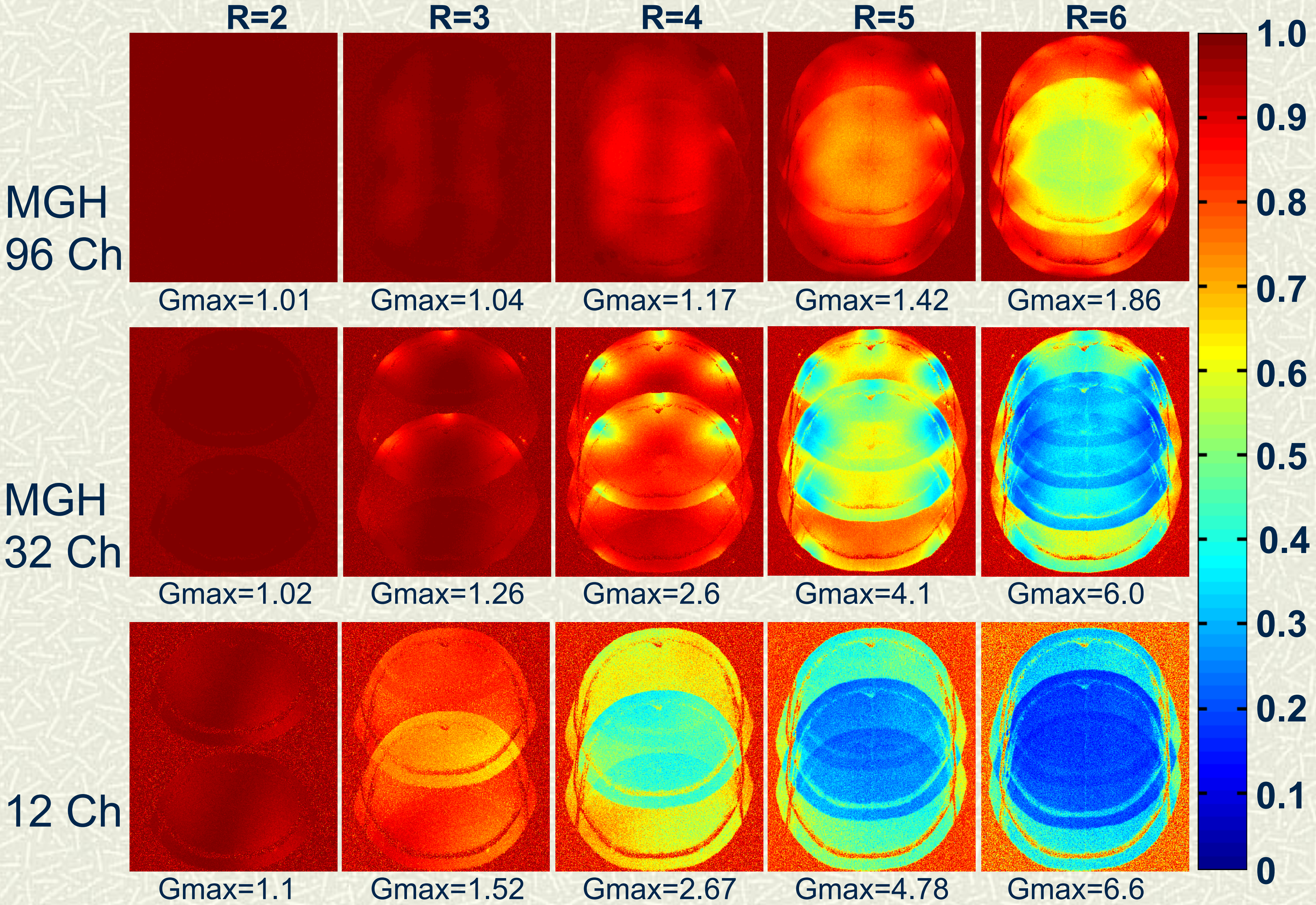




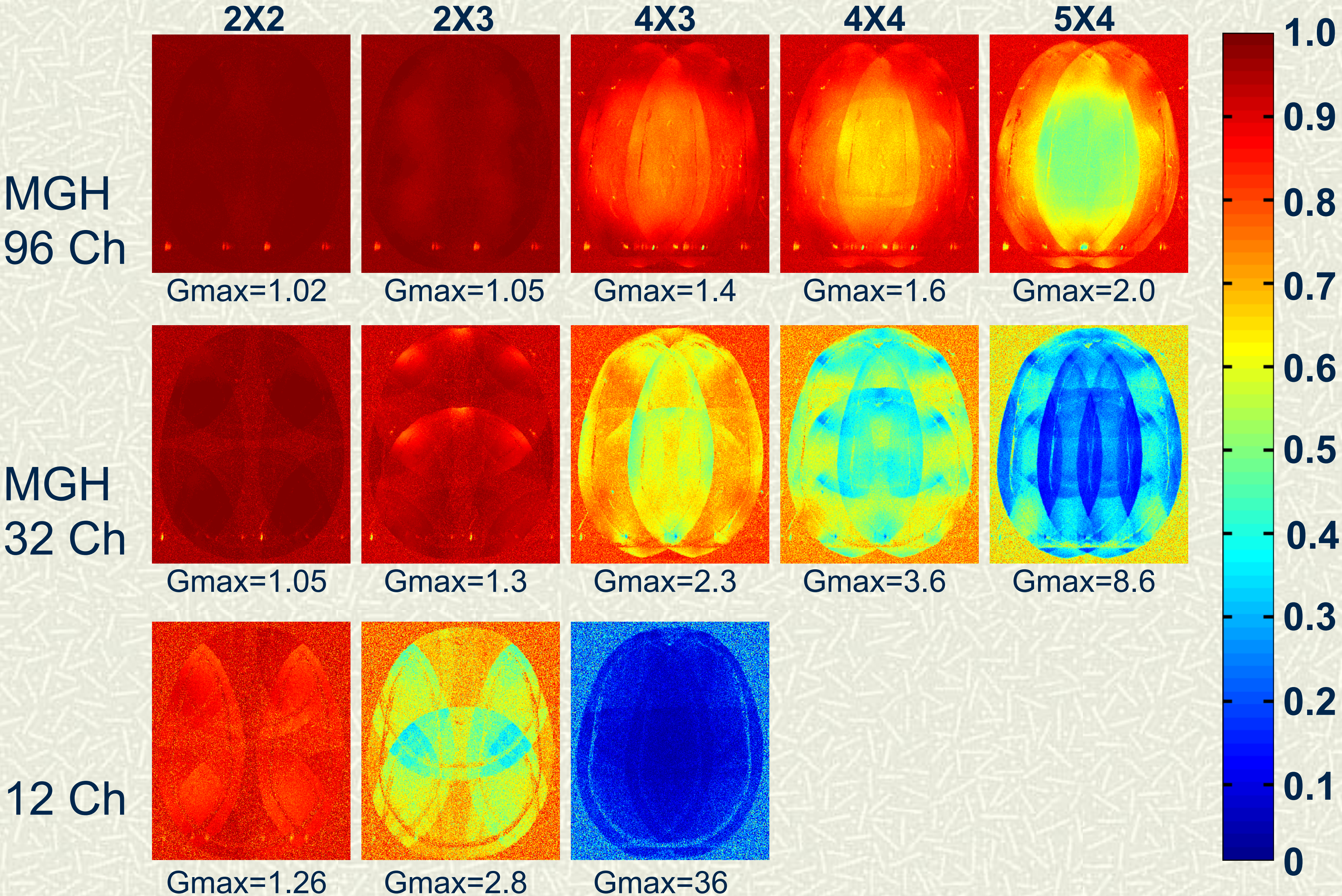
Wald, BASP 2011

MGH, A.A. Martinos Center

1/G-factor Maps, 3 Tesla, adult arrays



1/G-factor, 2D Acceleration



3T 32ch Flash with R=12x

1mm isotropic,
acquisition =
1:20

TR = 12
TE = 4.7
Flip=15
BW = 130
Norm

Courtesy: Mathias Nittka, Siemens Medical Solutions

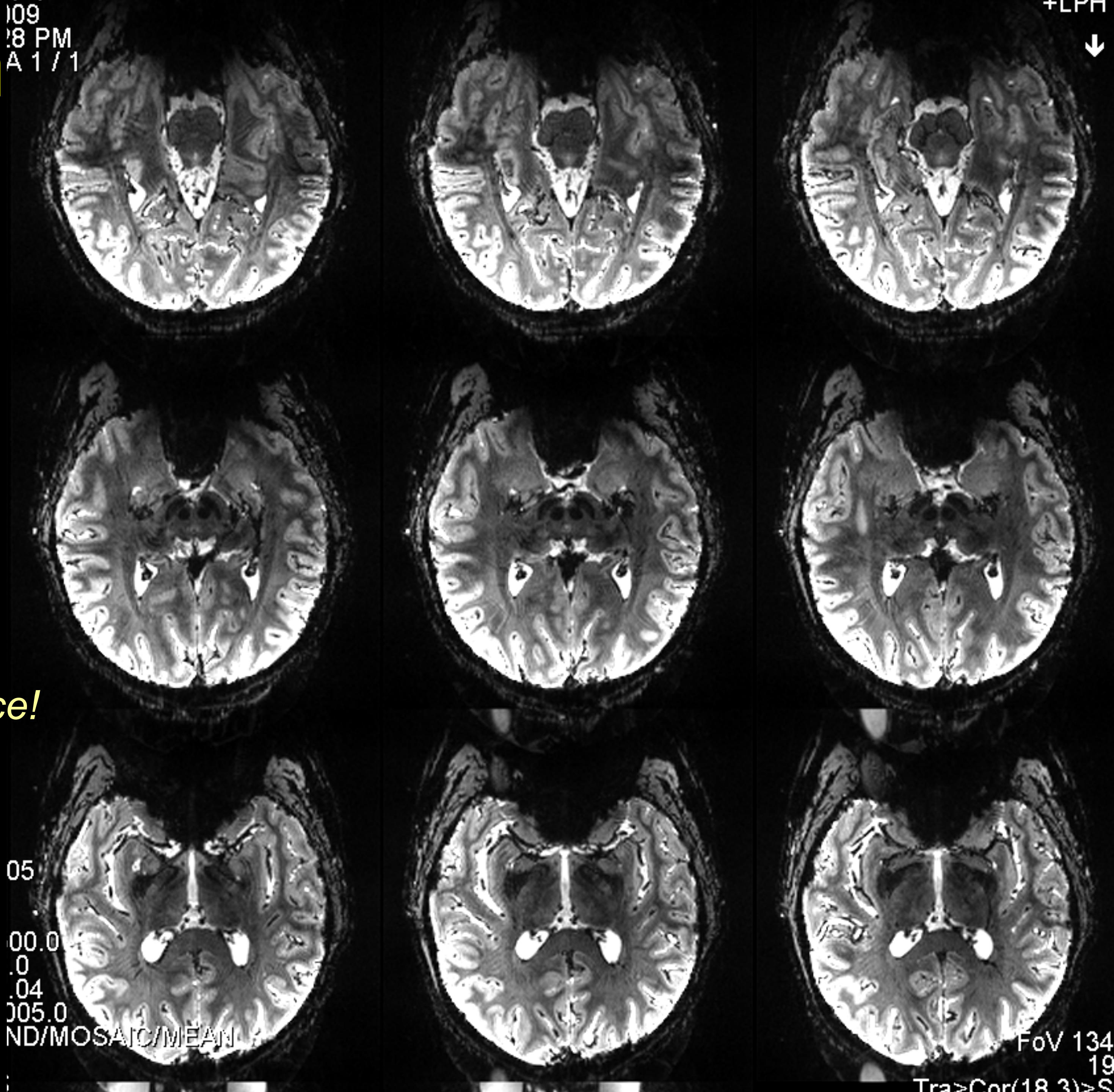
Wald, BASP 2011

MGH, A.A. Martinos Center

0.75mm 7T fMRI

7T
0.75mm isotropic
Single shot EPI
32ch
R=3 Grappa

<100ms per slice!

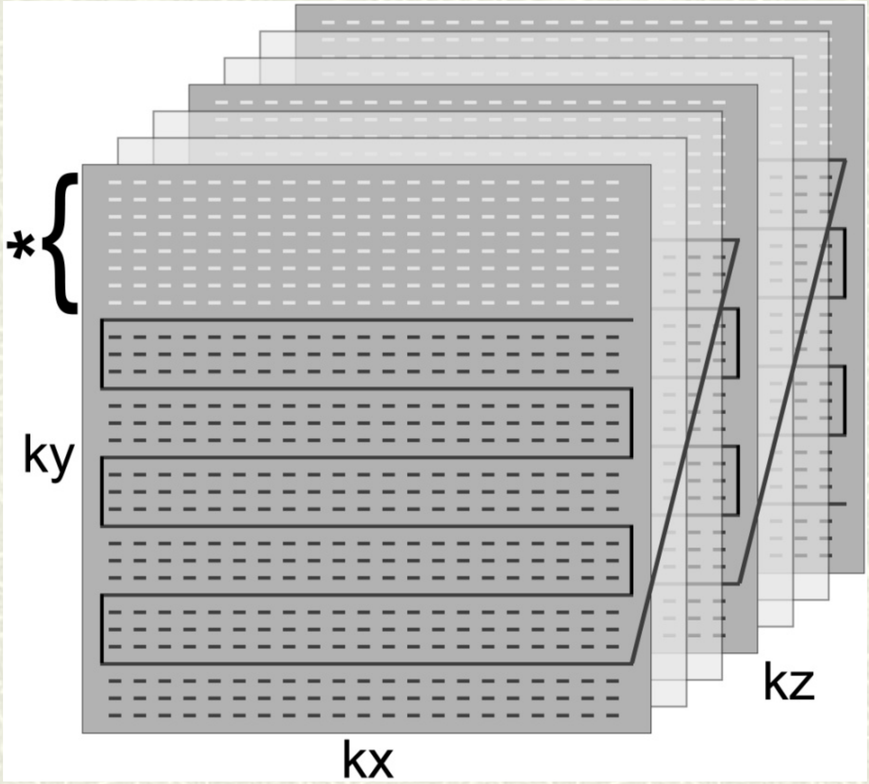


Do something new;
Single Shot Echo-Volumnar Imaging (EVI)

64x64x56 matrix, 3.4mm isotropic resolution, 32 channel coil

16x acceleration + 6/8 PF = 21 fold reduction in distortion

3D EVI
K-space
trajectory

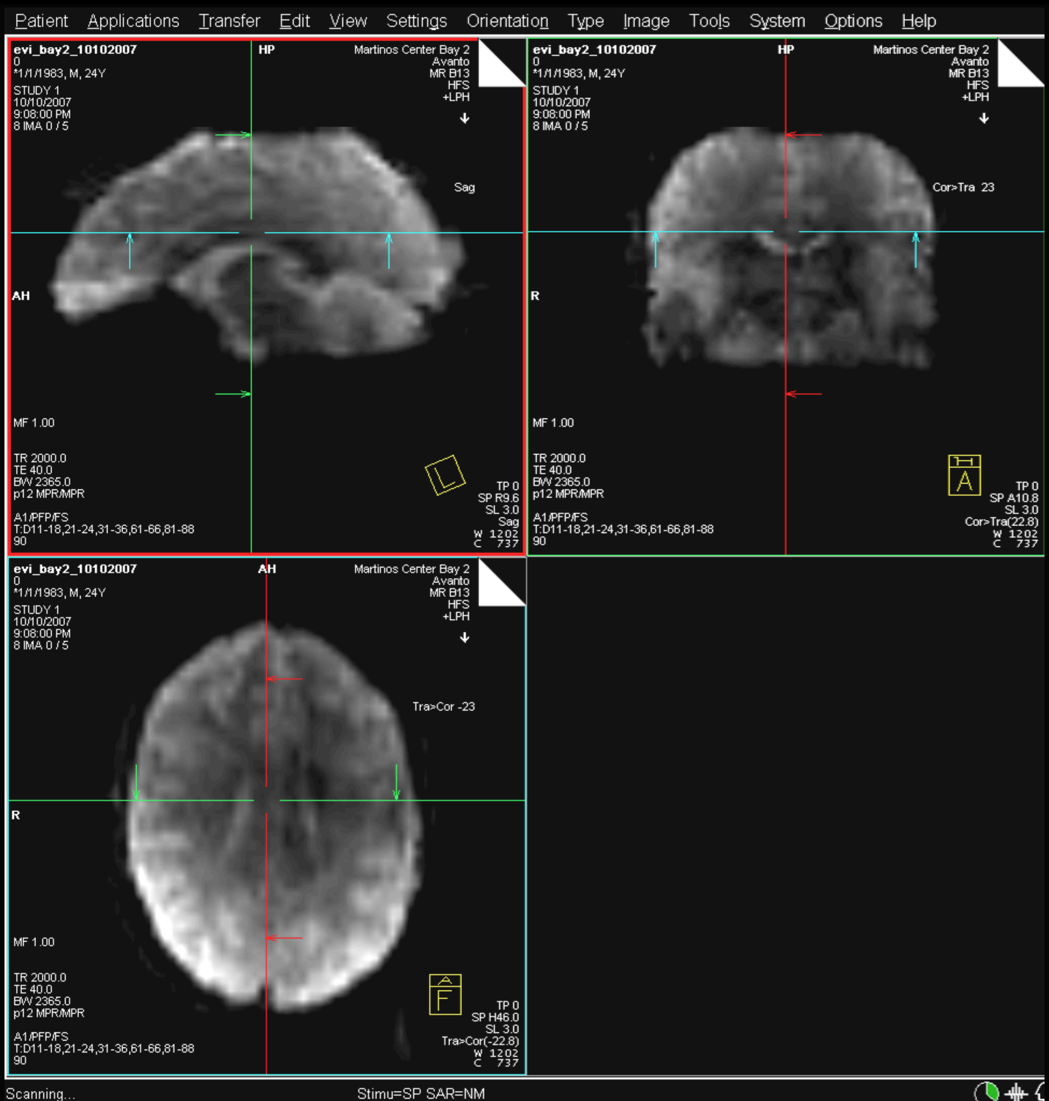


readout ~ 80ms

Whole-head in100ms

EVI: Whole brain imaging at 5 fps

Single shot, 64 x 64 x 48, 3mm isotropic



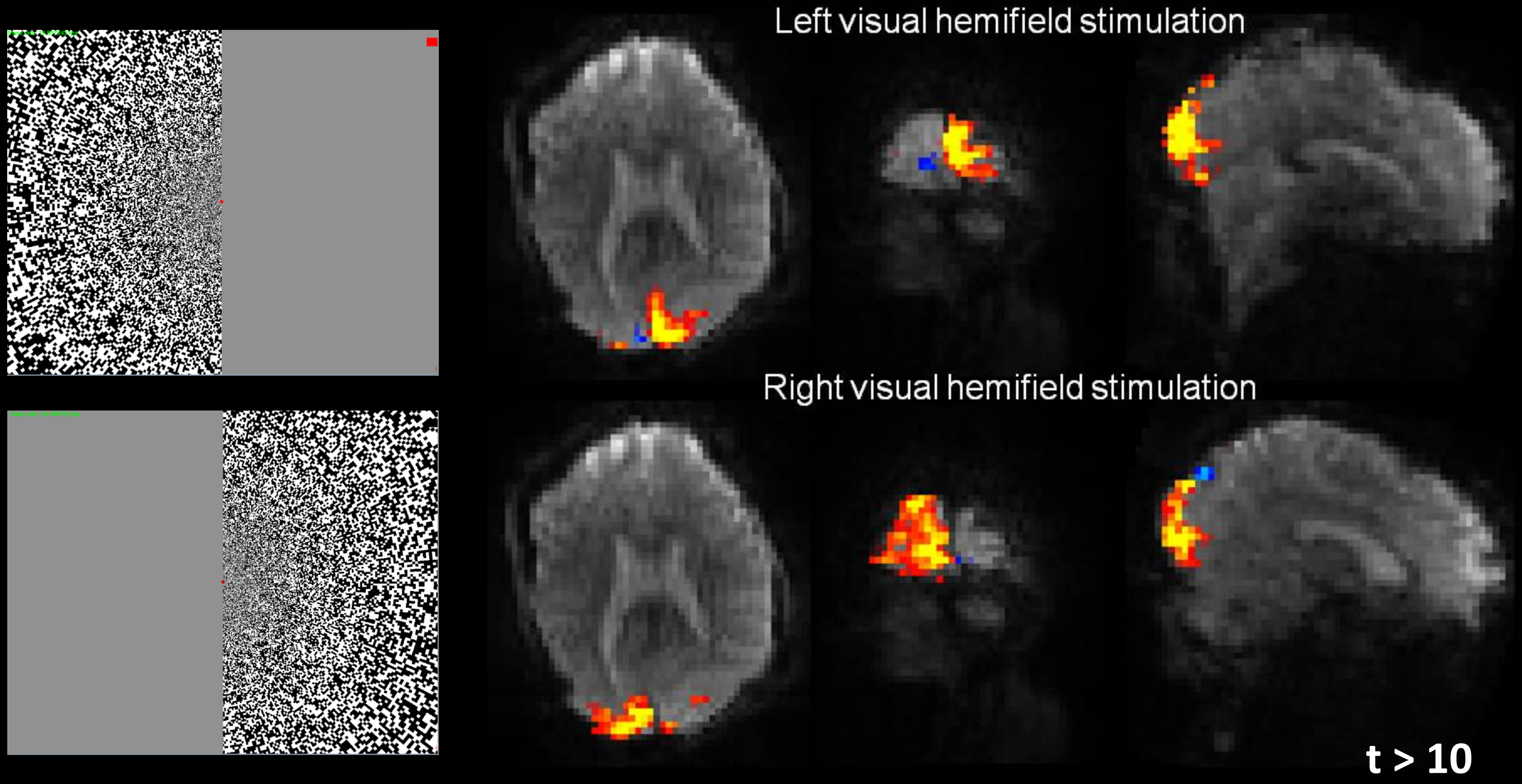
Unaccelerated, would be 3000 lines of PE

R=12, PF=6/8

Whole head w/ 192 lines

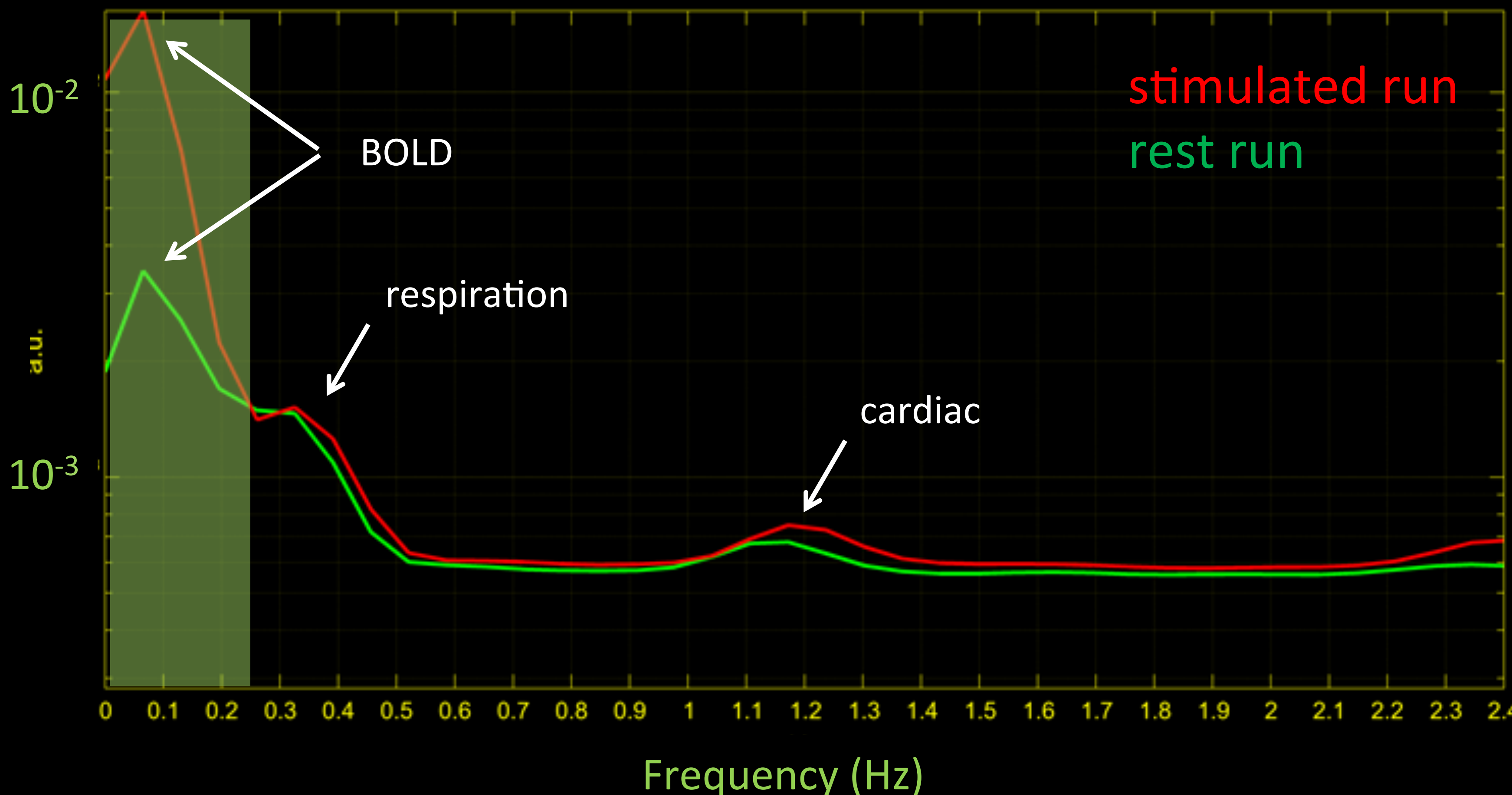
32ch coil, 1.5T
R= 3x4 (12x)
accel

3T fMRI: results hemifield task



- 8 runs of 4 randomized trials each (950 TRs), block design 16s ON/10s OFF
- Basic GLM in MATLAB for fMRI analysis, fixed effects combination of runs
- Expected contralateral activity can be observed

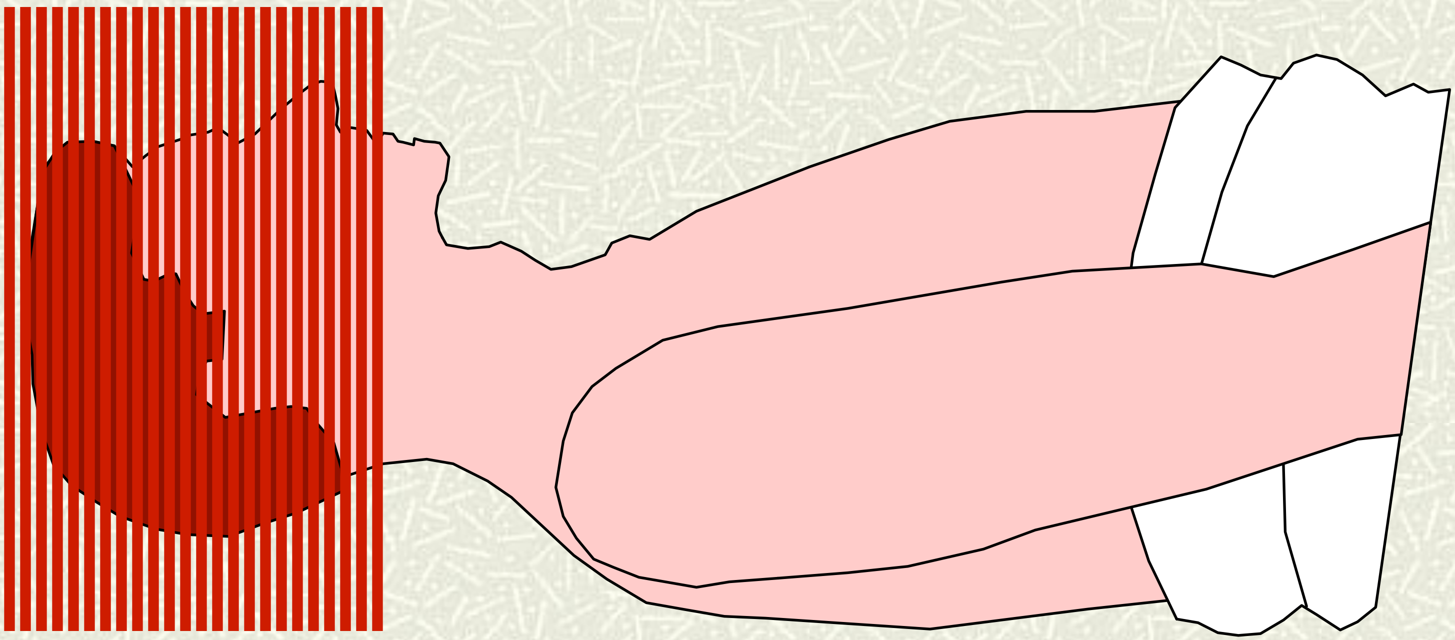
Power Spectral Analysis: V1 voxels



- Selected activated voxels, 64pt Welch Spectrogram.
- Respiraton is biggest interference, but only factor of 2 below resting state BOLD
- BOLD occupies only 1/8 of the frequency band in this acquisition

One more way to accelerate: Simultaneous multi-slice

3 slices acquired simultaneously…

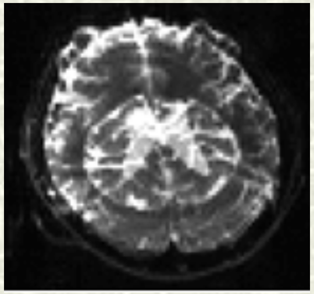


Wald, BASP 2011

Simultaneous multi-slice

Note: encoding is not undersampled, no √R penalty !!

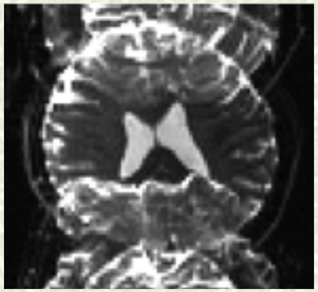
3 EPI slices acquired simultaneously…



Un-alias with parallel imaging…

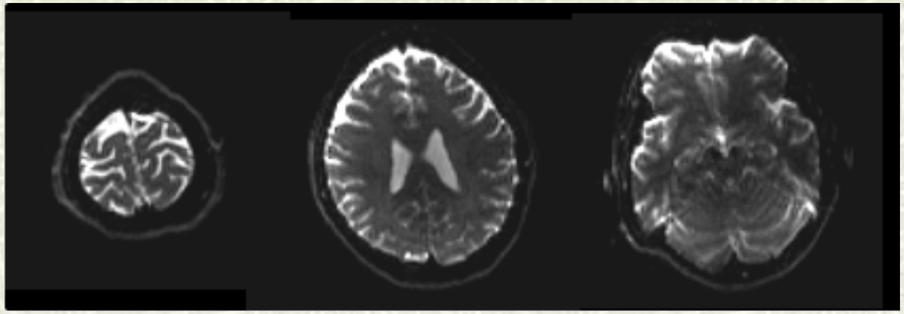
Larkman et al. JMRI 13(2) p313, 2001

Feinberg, et al. PLoS One, 2010



Blip scheme for shifting EPI, then use parallel imaging…

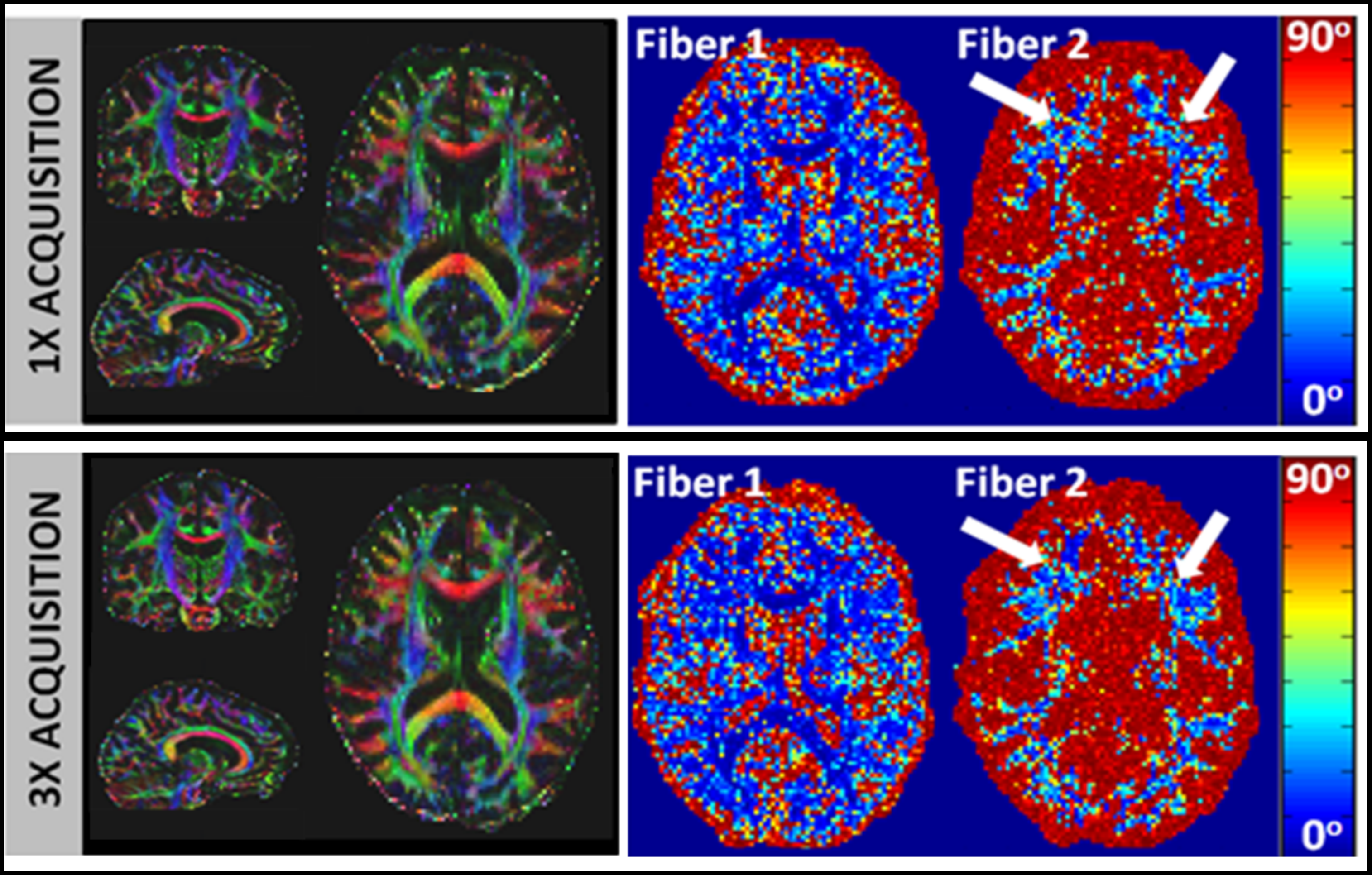
Setsompop et al. ISMRM 2010, p551



Blip scheme reduces g by 2x

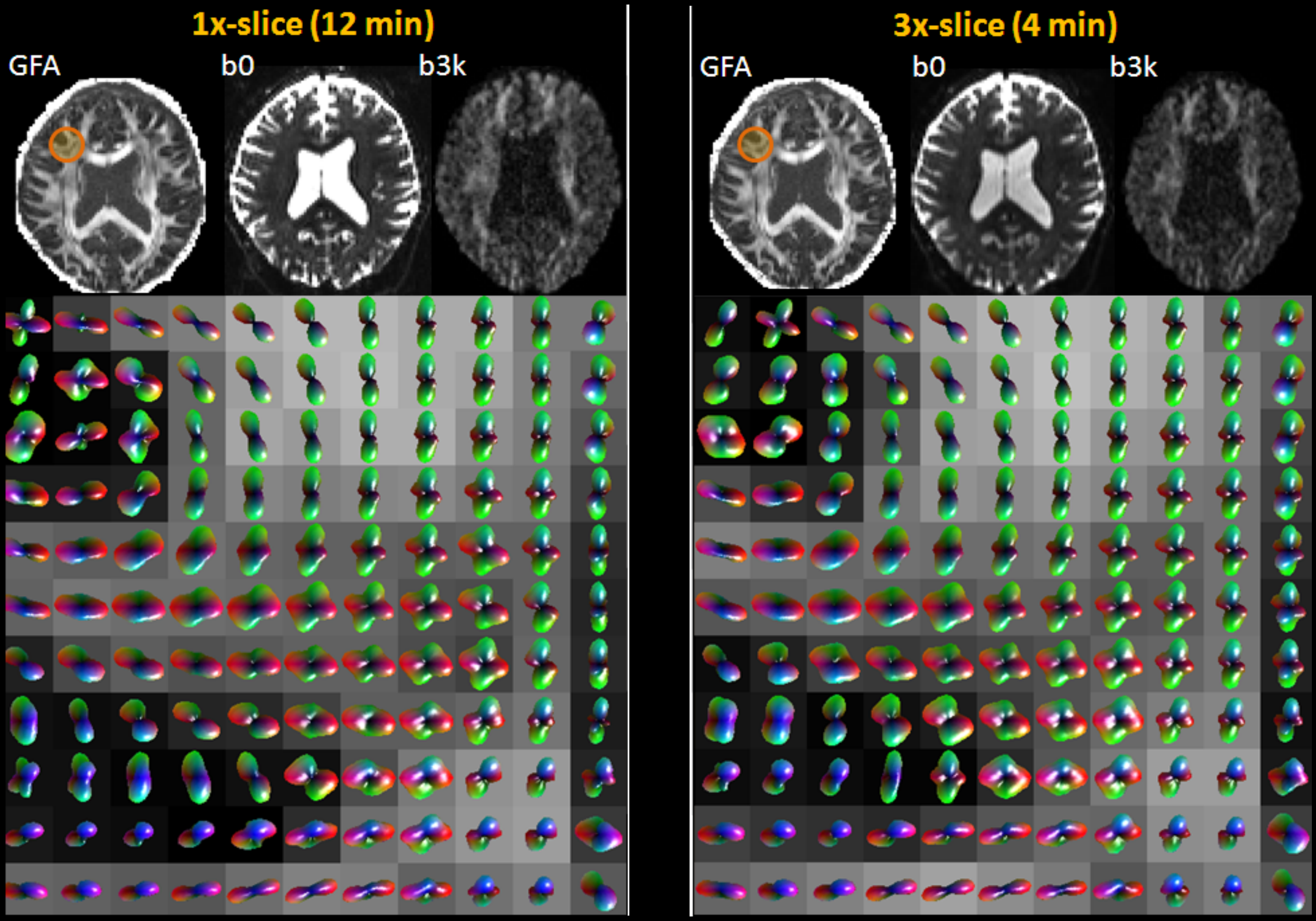
Blipped-CAIPIRIHNA, 3 slice simultaneous

Kawin Setsompop (*ISMRM 2010, p551*)



64 direction Q-ball acquisition FA maps, 95% uncertainty angle for fiber orient. Acquire 3 slices at a time and use multi-channel coils to unravel. No significant SNR penalty (maybe 10% for unaliasing)!

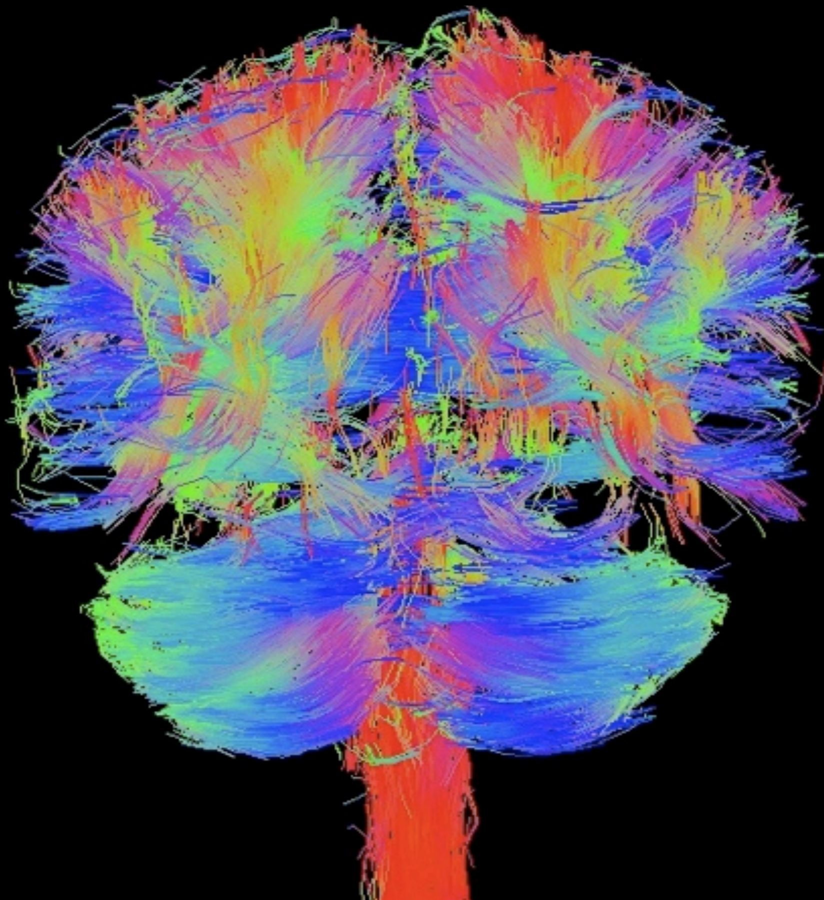
DWI EPI; exactly the same but 3x faster!

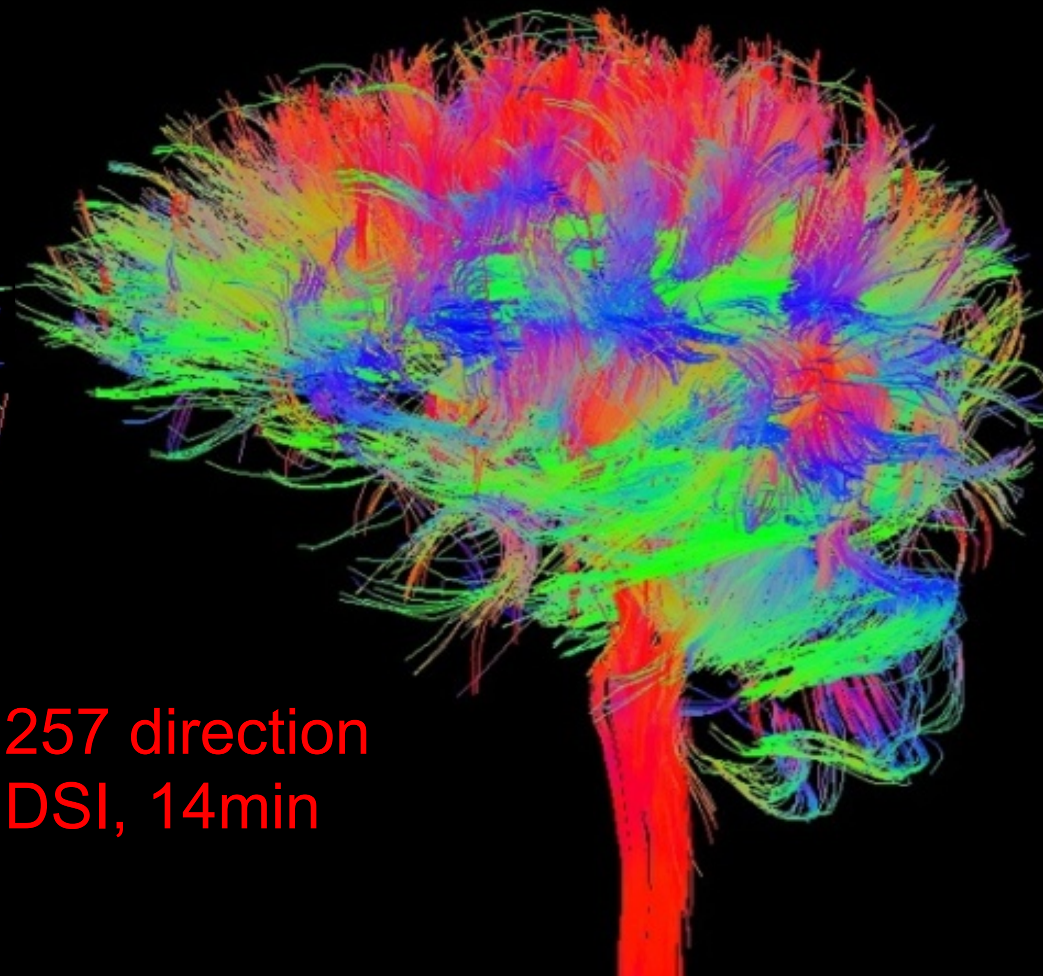


DWI EPI 120 directions, 1mm isotropic whole head

Kawin Setsompop, MGH

Diffusion Spectrum Imaging (DSI) becomes feasible…



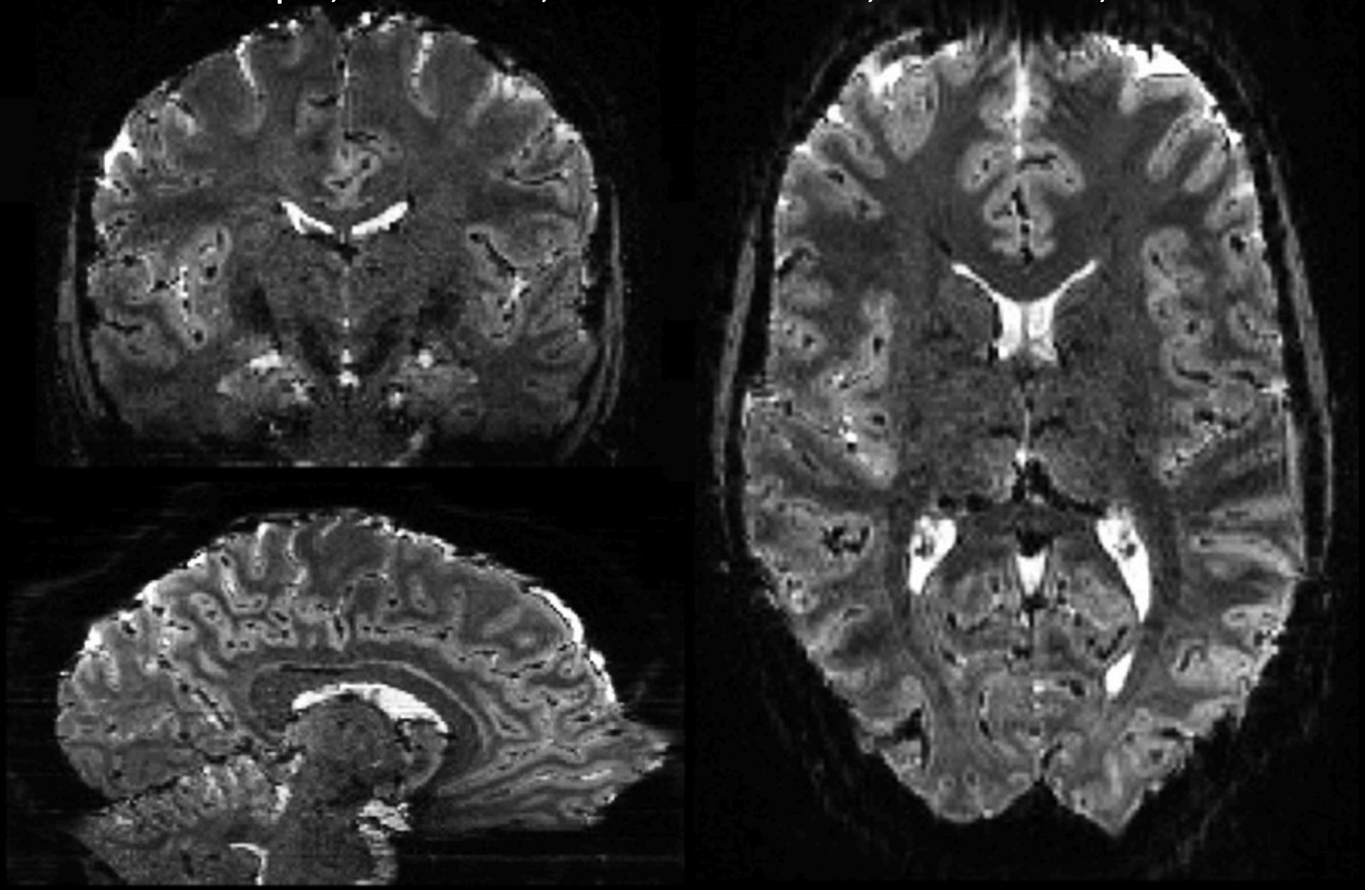


257 direction
DSI, 14min

Kawin Setsompop, MGH

3x simultaneous multi-slice EPI for 7T fMRI

1 mm isotropic, 120 slices, 200x200 matrix, TE = 24 ms, TR = 2.88 s



unfolded images

3-fold multi-slice, *R*=2 in-plane

whole-brain 1 mm iso. in 2.88 s

Kawin Setsompop, MGH

[Setsompop *et al.* 2010 *ISMRM*]

What can we see after all this work?

Laminar specific fMRI in human brain with 7T.

Jon Polimeni, MGH

fMRI at 7T compared to 3T

- 2x the signal to noise (at high resolution)
- 2x the BOLD contrast.

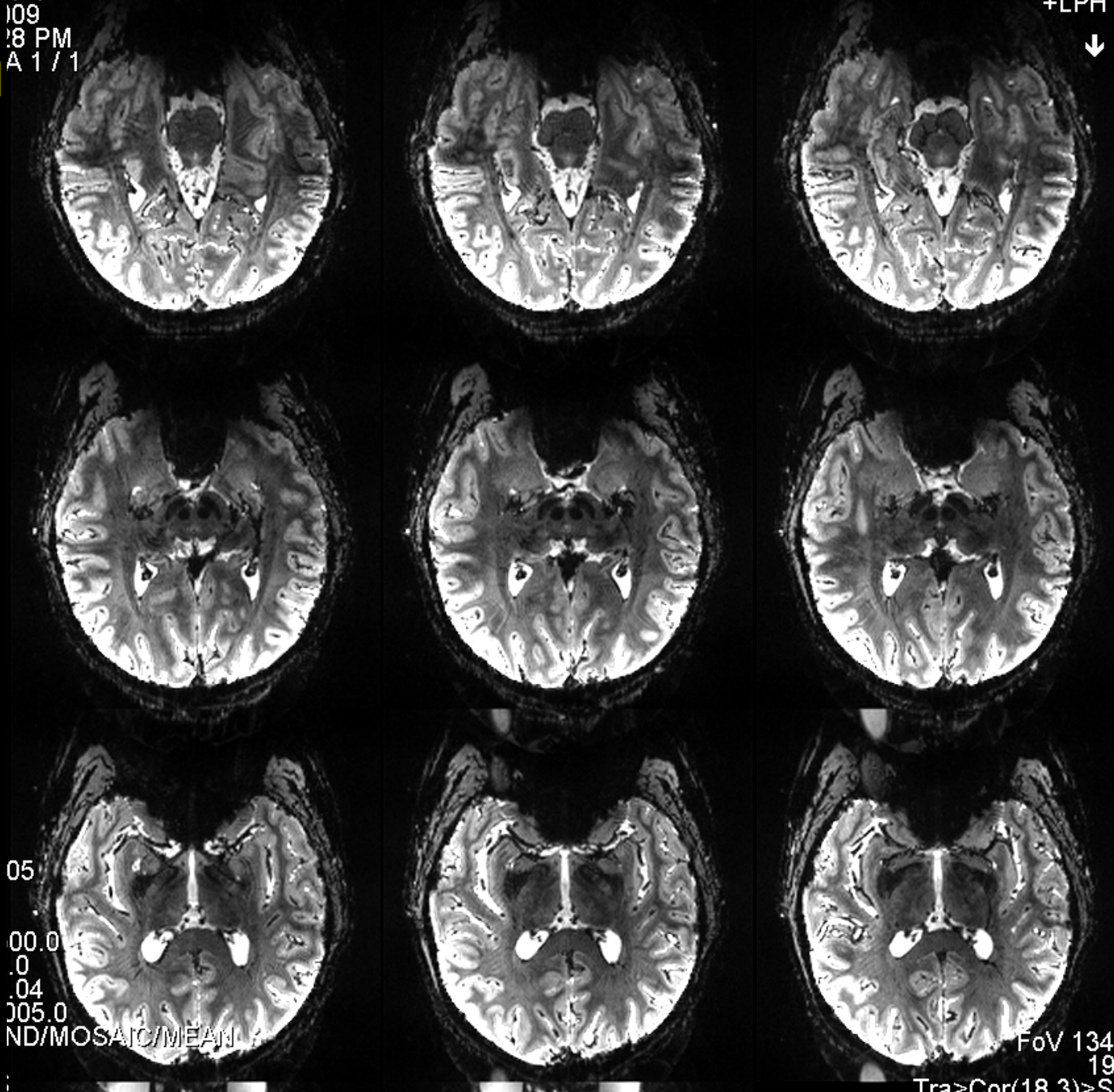
- 4x the Contrast to Noise Ratio

- 20min run at 3T -> 1.25min at 7T
- 16 subjects at 3T -> single subject at 7T

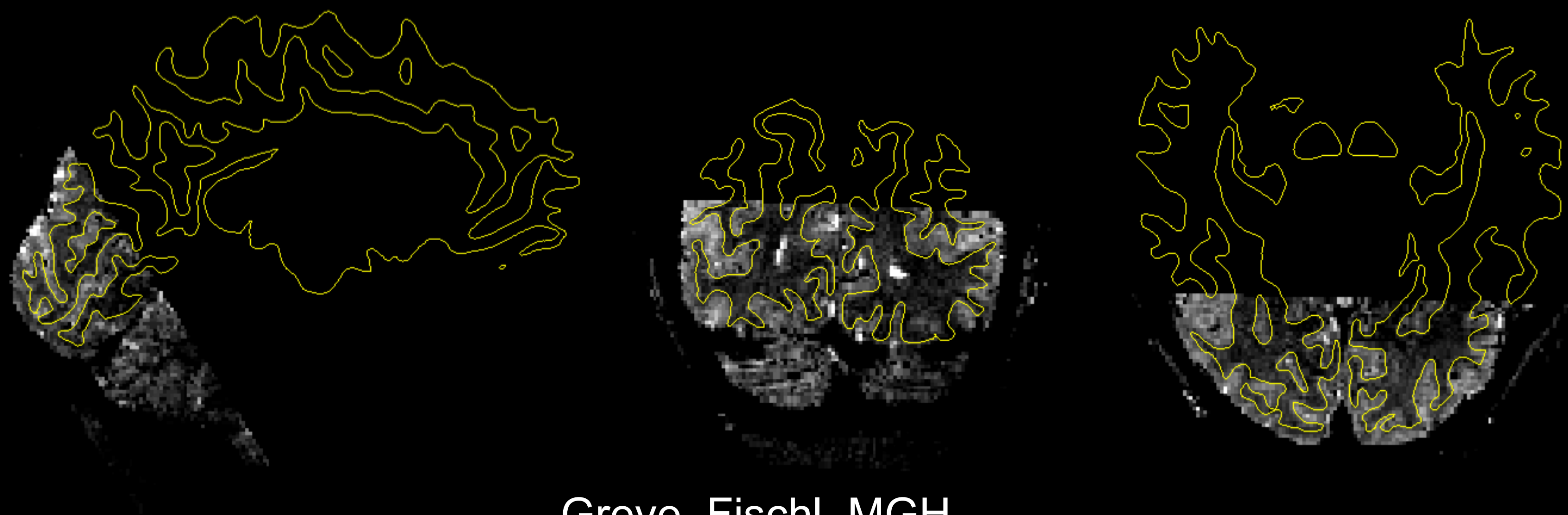
0.75mm 7T

7T
0.75mm isotropic
Single shot EPI
32ch
R=3 Grappa

Average of 10 shots shown



boundary-based registration



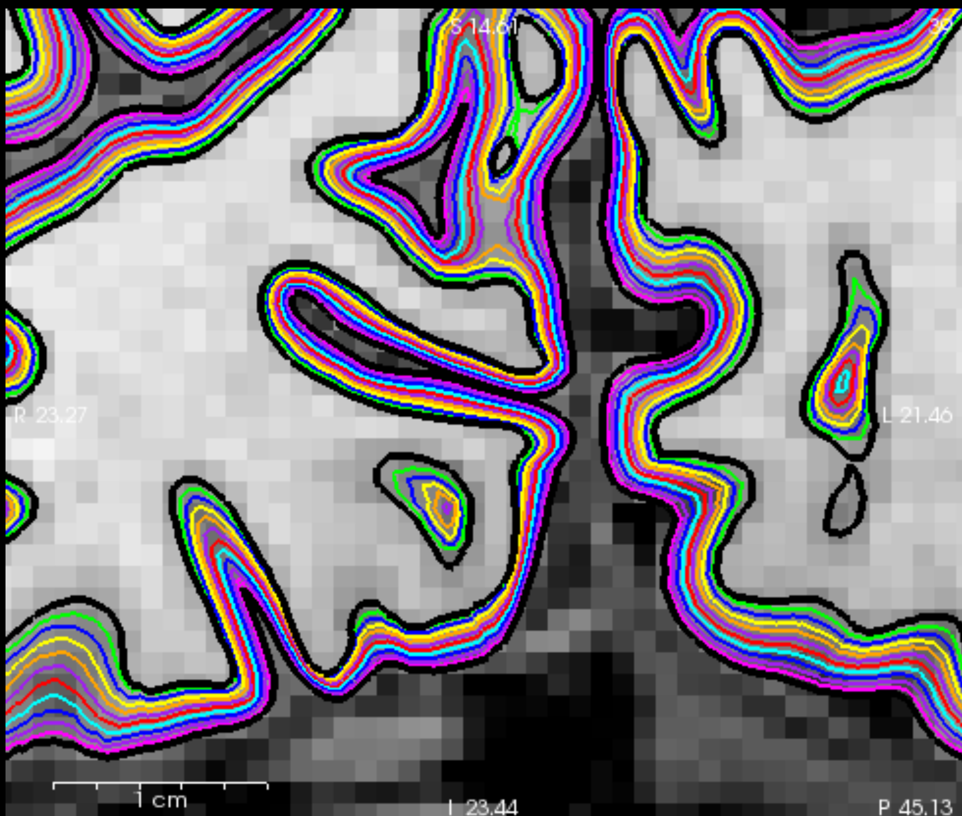
Greve, Fischl, MGH.

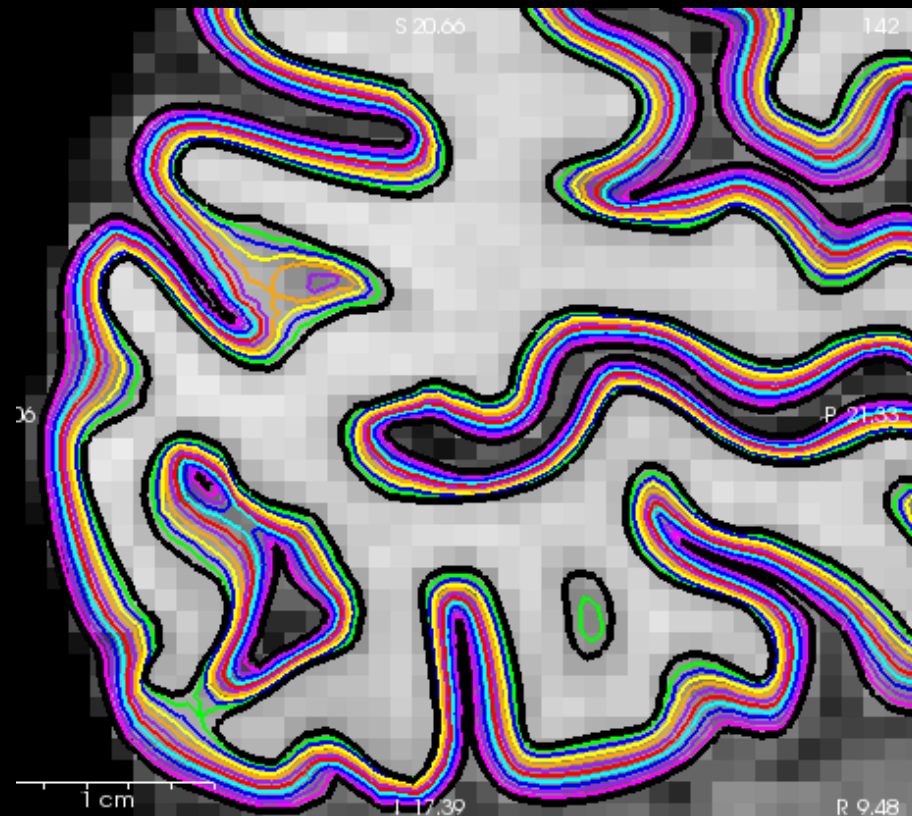
- computes gray-white boundary from EPI data
- calculates rigid transformation that aligns boundary to gray-white surface reconstruction

1mm iso. EPI to 1mm iso. MEMPRAGE!

Interpolate along the path between pial surface vertices and WM surface vertices.

Generate a cortical surface at each depth…

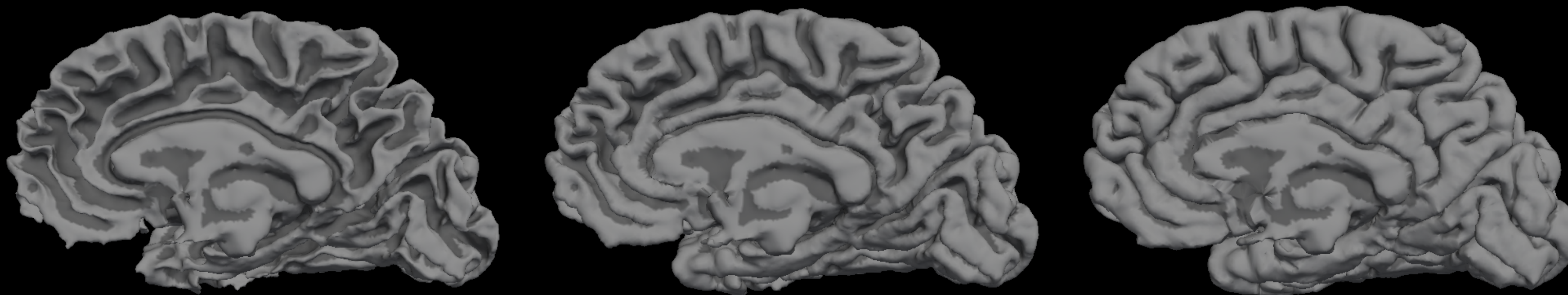




Wald, BASP 2011

MGH, A.A. Martinos Center

Generate surfaces at each depth

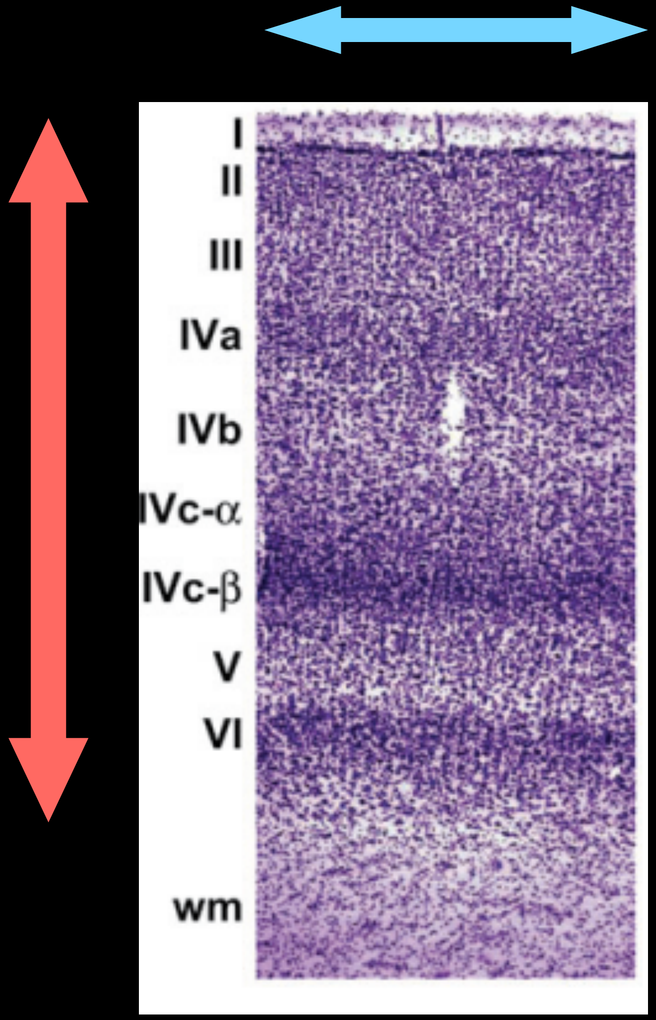


White matter surface   Middle depth surface   Pial

- fMRI analysis on intermediate surfaces:
  - E.g. consider only the activated voxels which intersect a given surface…

targeted sampling of cortical layers

- explore tangential specificity *as function of* layer
- radial specificity – laminar regulation?
- measurement *columnar* and *laminar* features of functional architecture



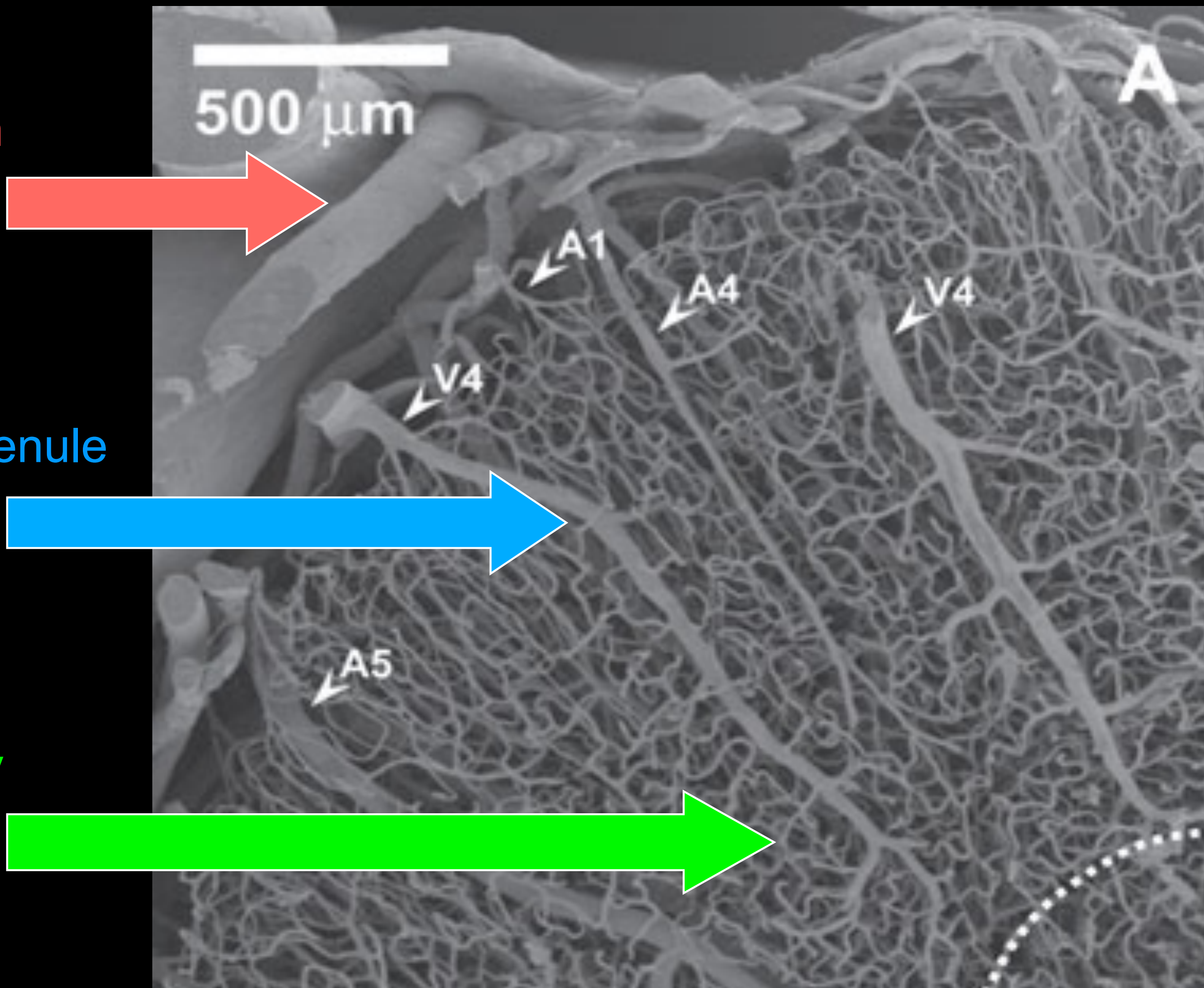
macaque V1, Nissl stain
[Weber *et al.* 2008, *Cereb Cortex*]

spatial scales of vascular anatomy

pial vein

diving venule

capillary

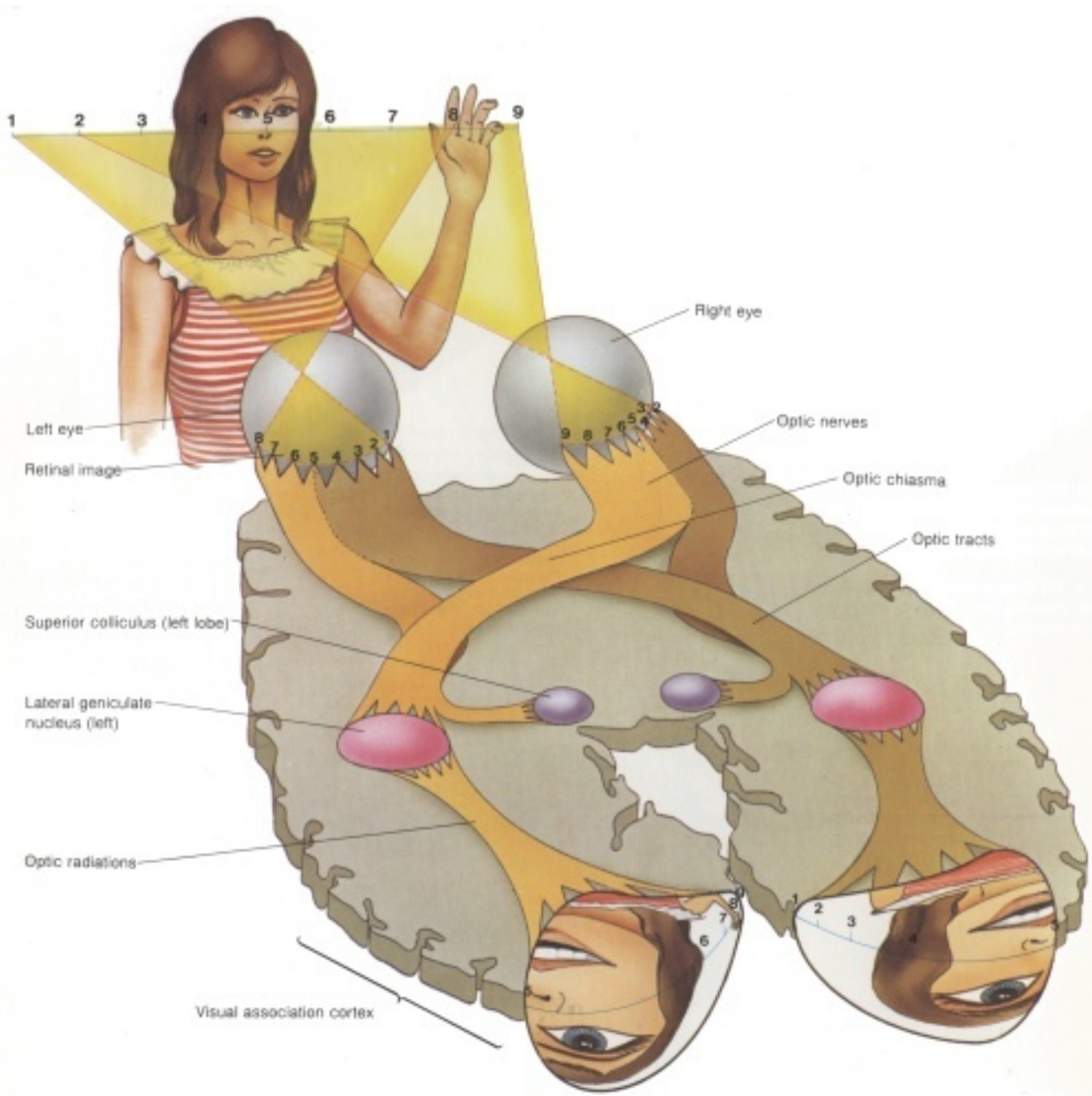


vascular corrosion casts from gyrus of macaque V1

[Weber *et al.* 2008, *Cereb Cortex*]

can exploit *regularity* of vascular organization!

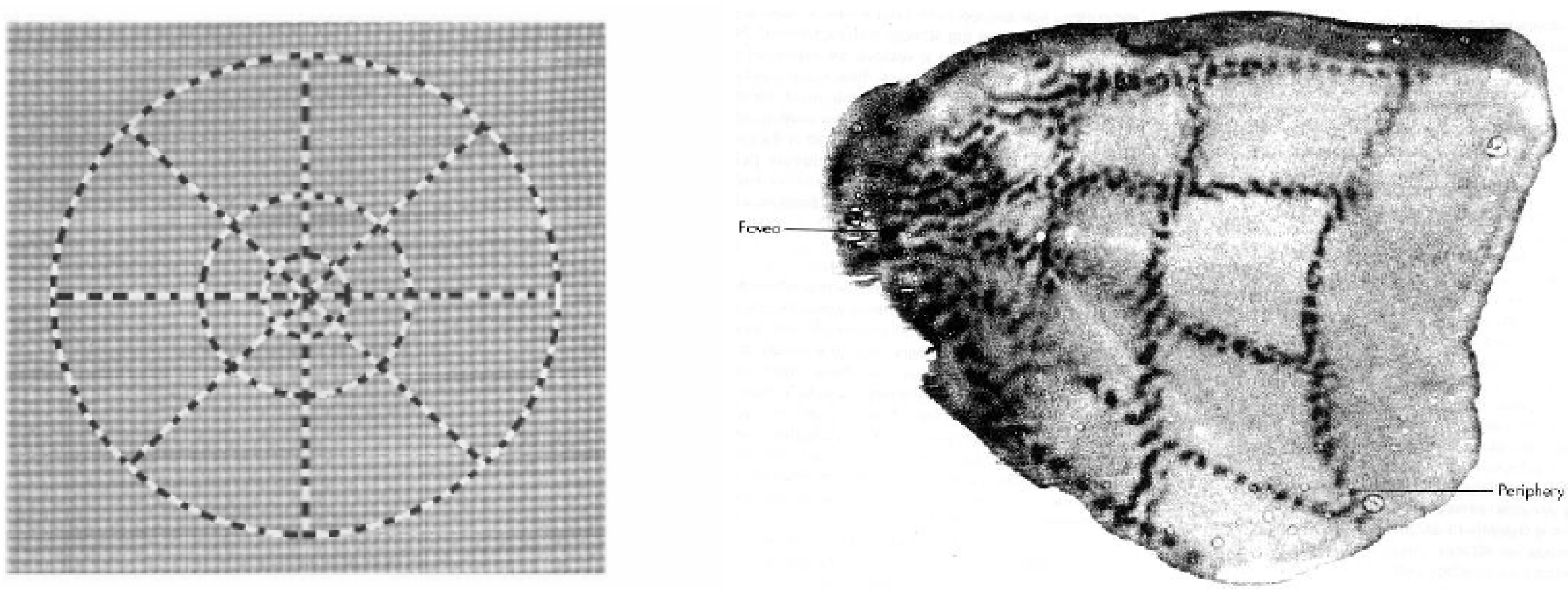
Retinotopy: *nearby* neurons possess receptive fields that are *nearby* in visual field



a **topographic map** of the visual field is laid out on cortical *surface*

[reproduced from Frisby 1980]

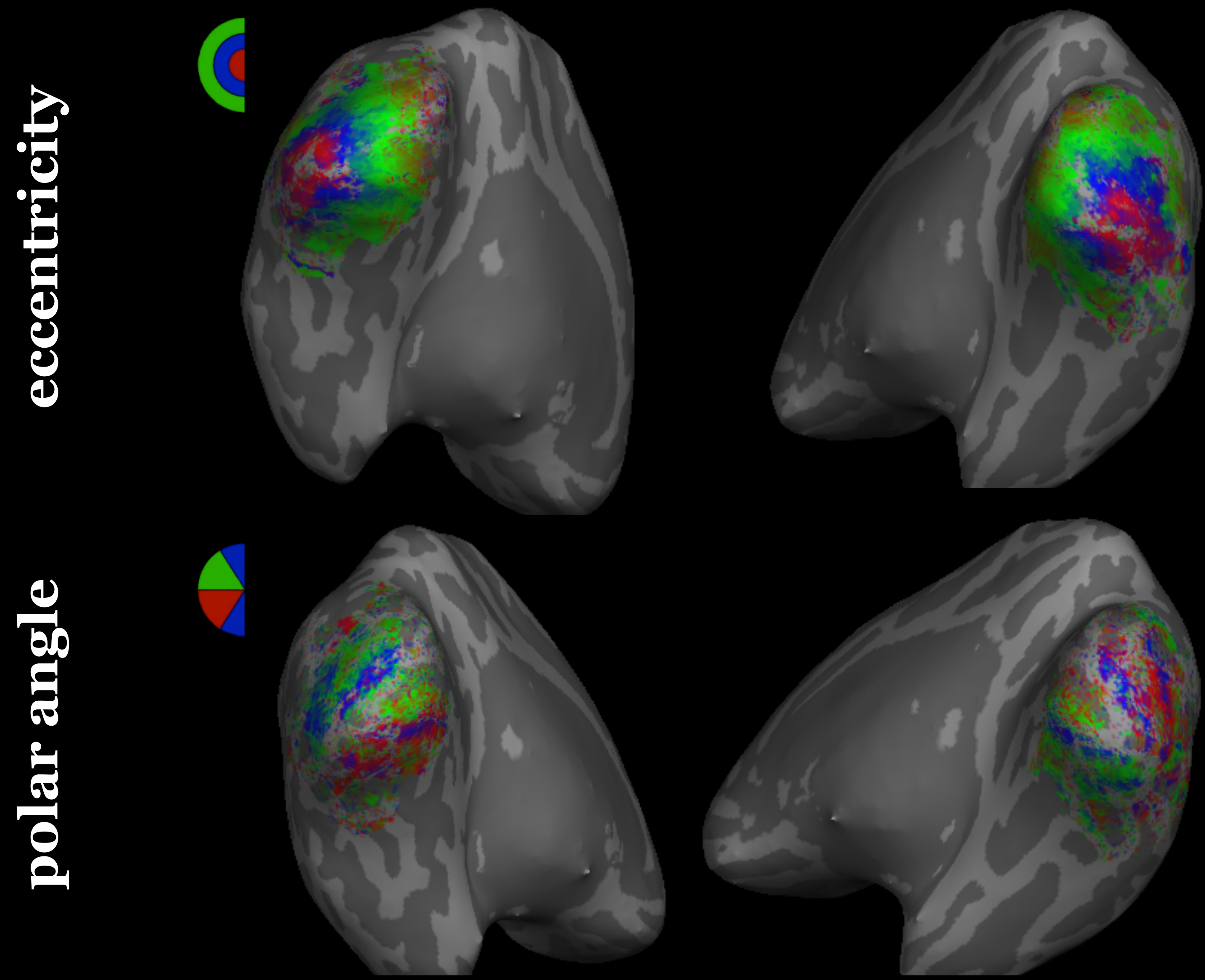
first imaging demonstration: 2DG



(Tootell *et al.*, 1982)

1 mm isotropic fMRI retinotopy, 7T 32ch

Jon Polimeni, MGH.

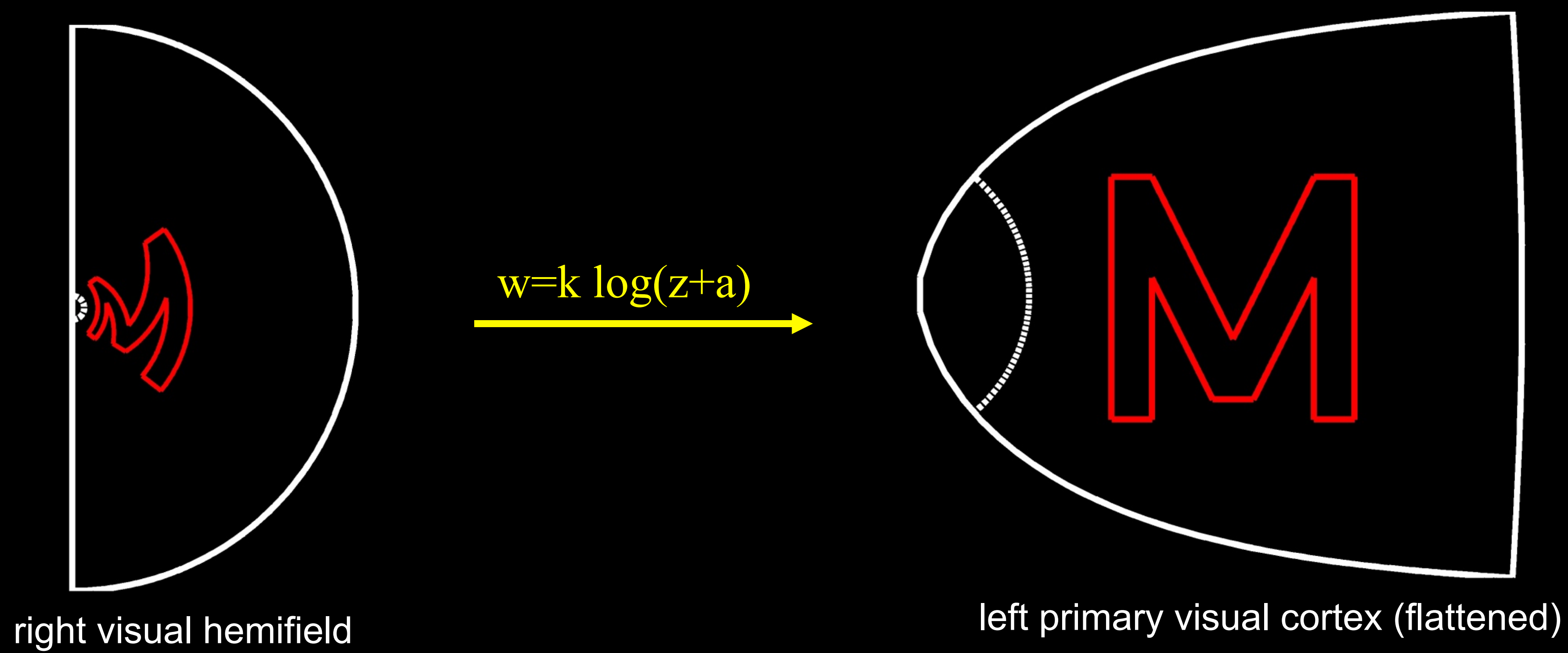


unsmoothed , 20 minutes of scanning total

Resolution Stimulus

goal: \imposed desired activity pattern on V1 surface

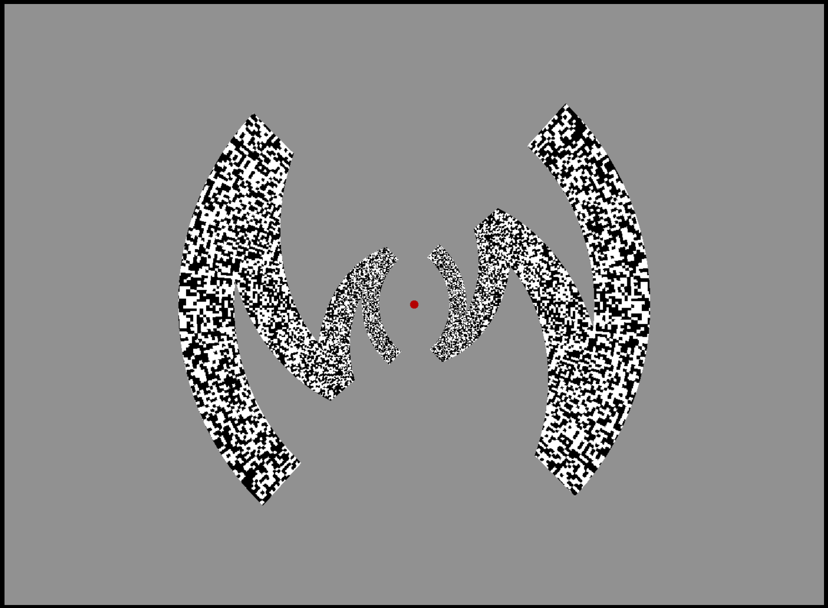
Jon Polimeni, MGH.



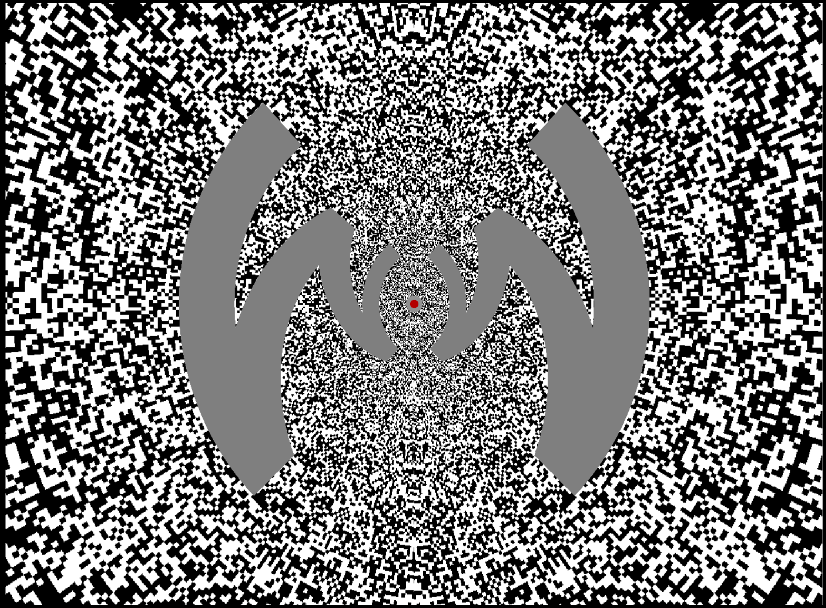
resolution stimulus

Jon Polimeni, MGH.

stimulus condition A

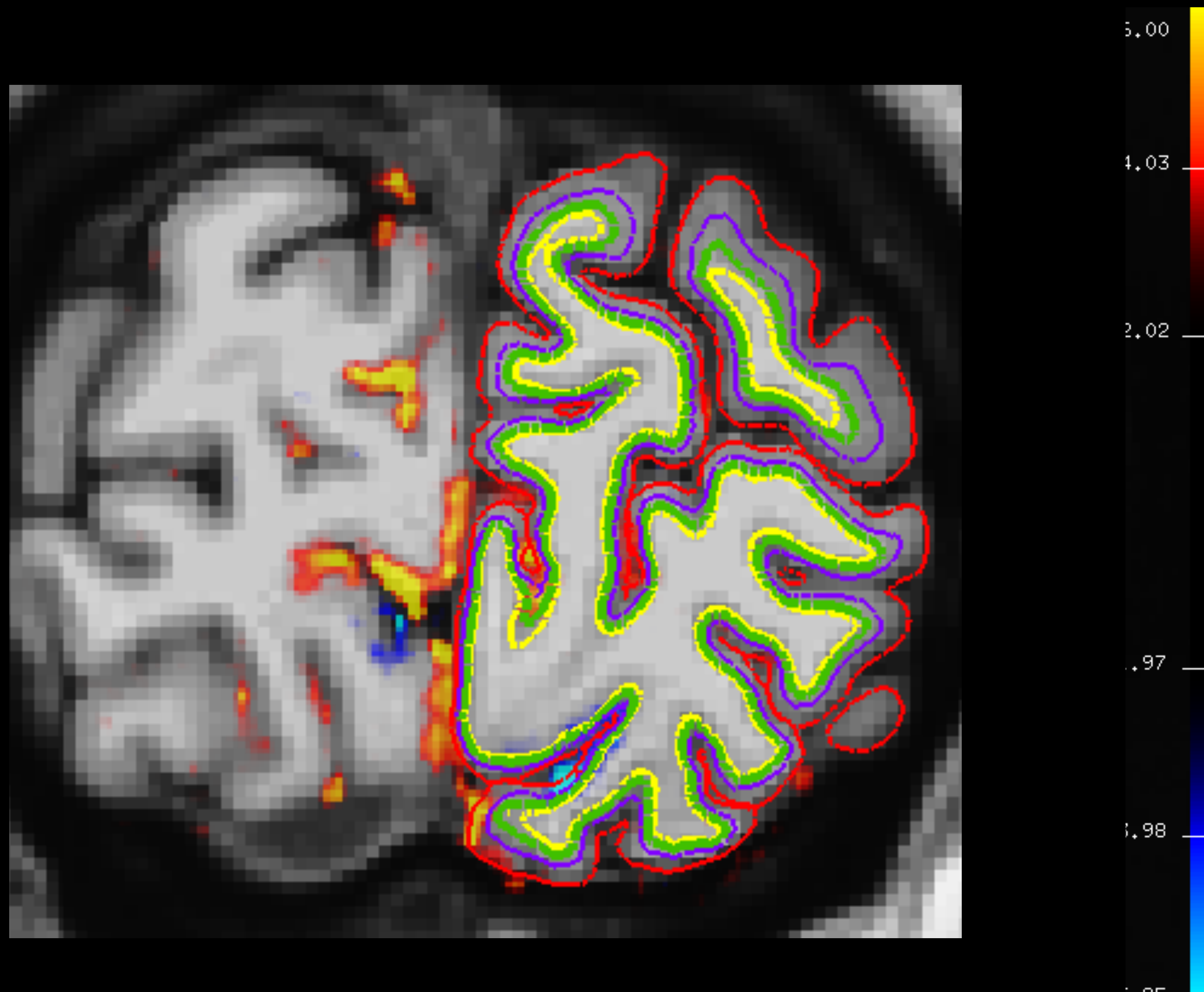


stimulus condition B



- counterphase flickering (8 Hz) scaled spatial noise pattern
- fixation task to minimize blurring due to eye movements
- block design presentation: two stimulus conditions plus rest, 5min total

Here’s the result!



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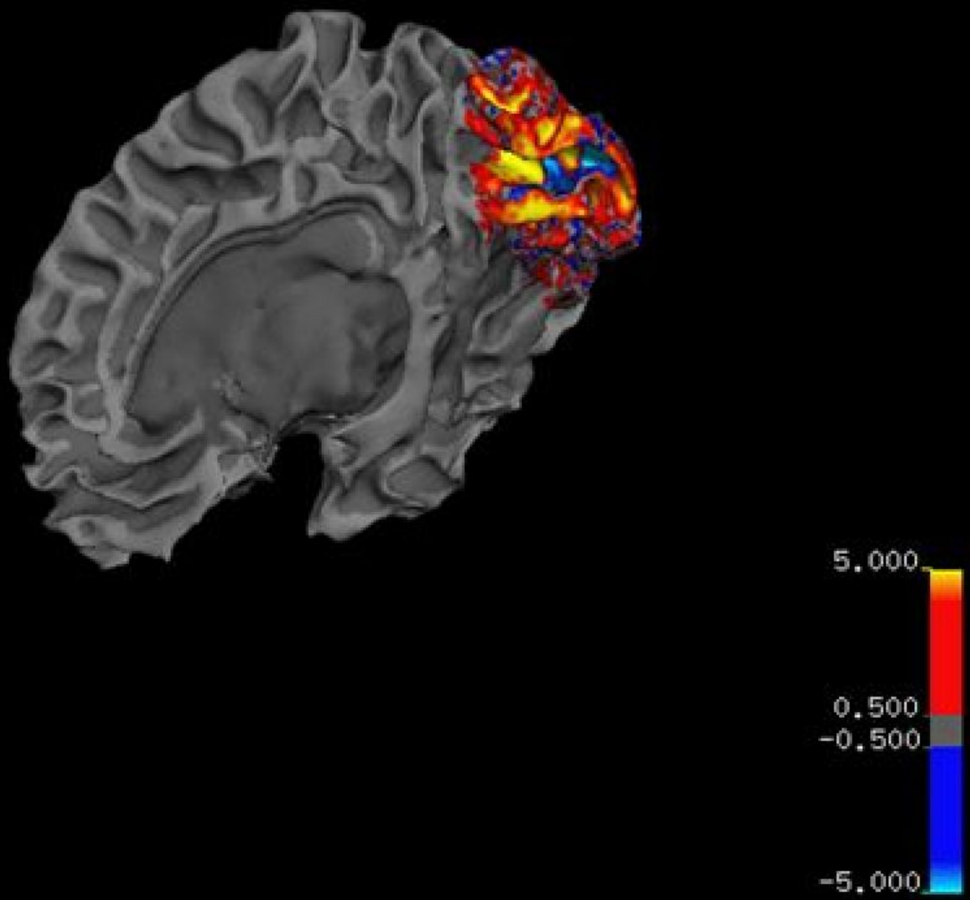
Here it is again…



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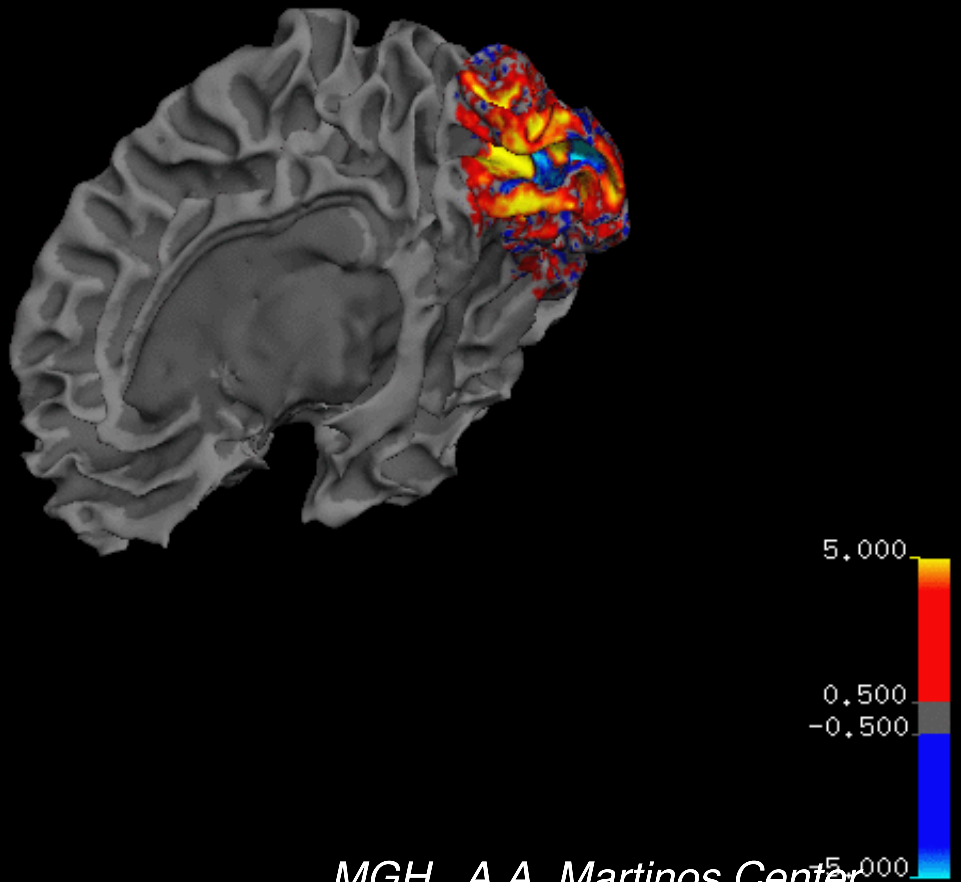
View activation on inflated surface

5 Minute block design



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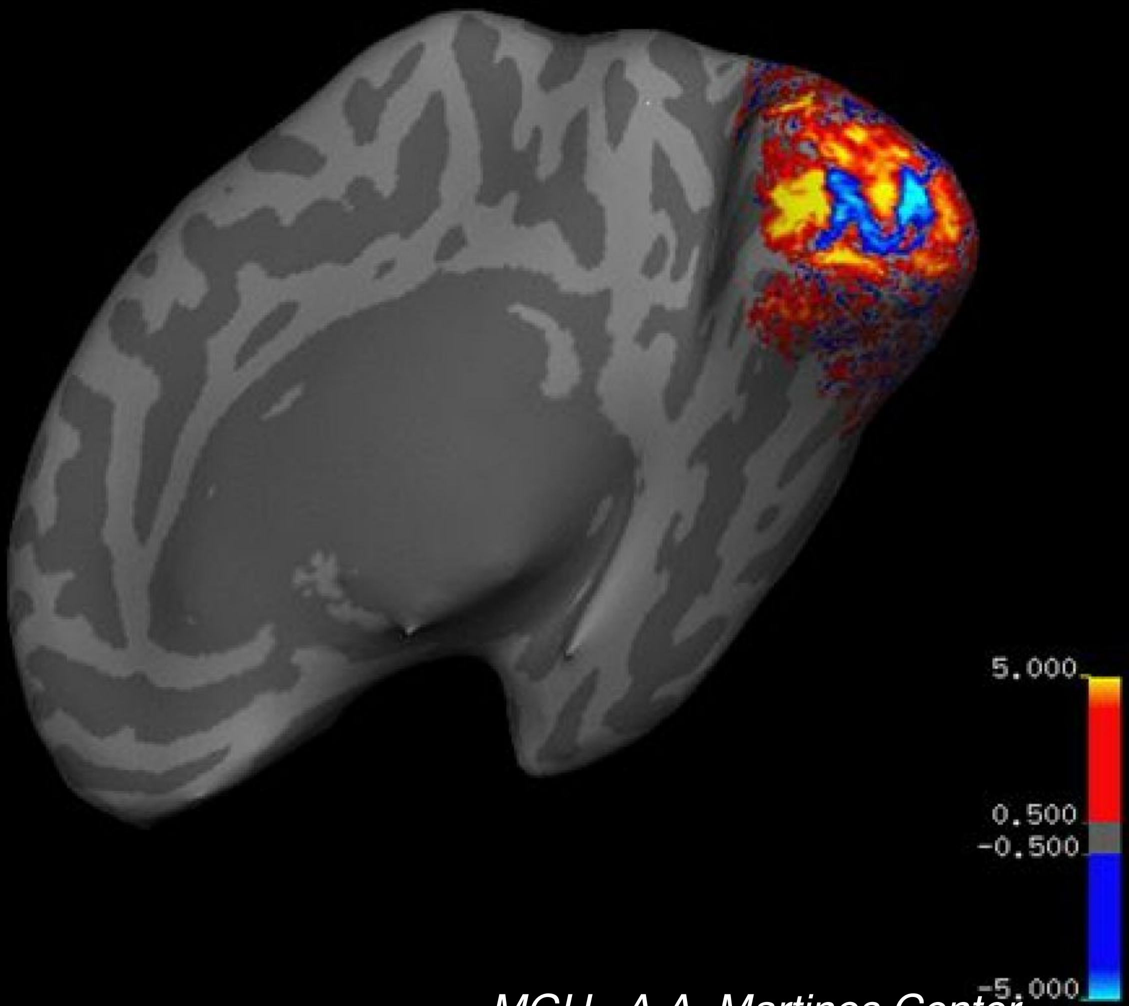
View activation on inflated surface

5 Minute block design



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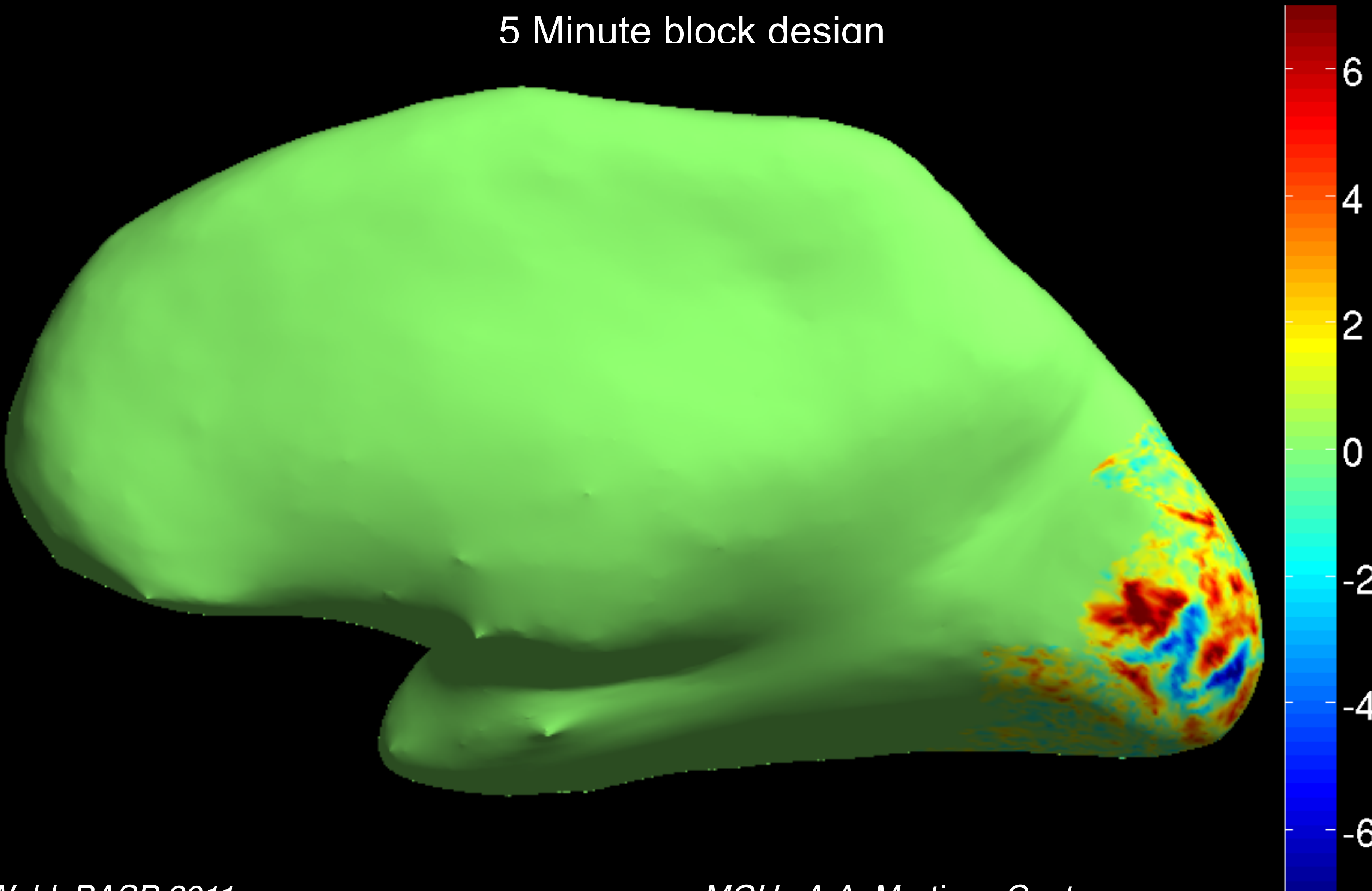
Unsmoothed, unthresholded Z scores

5 Minute block design



View activation pattern from voxels thru each of the many cortical surfaces.

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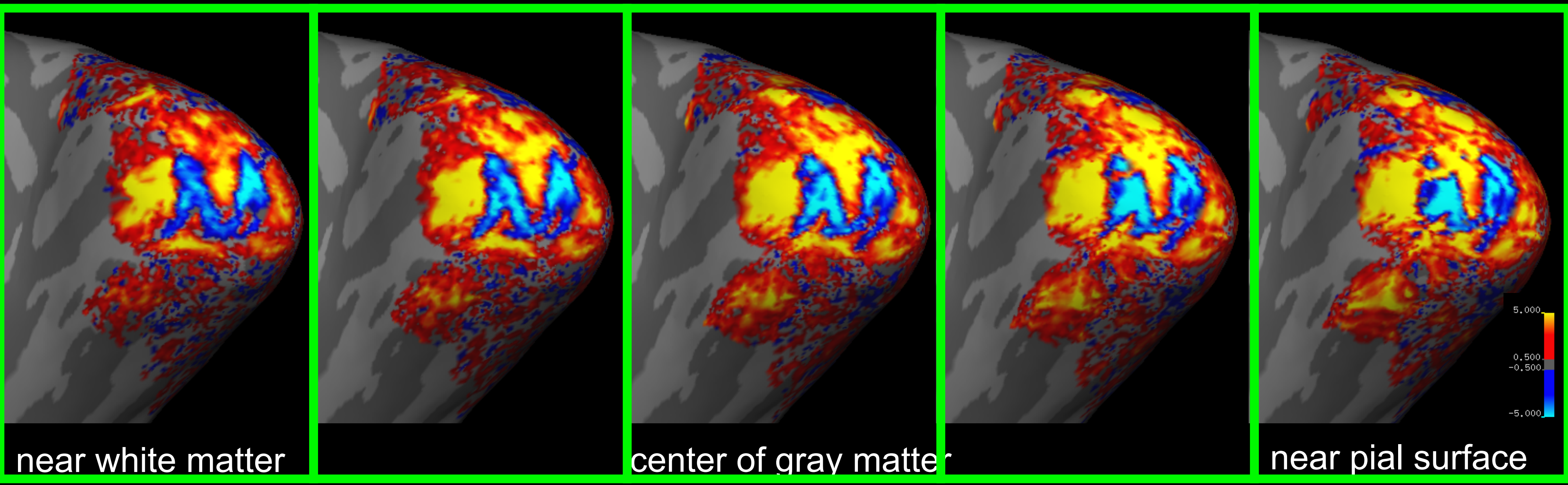
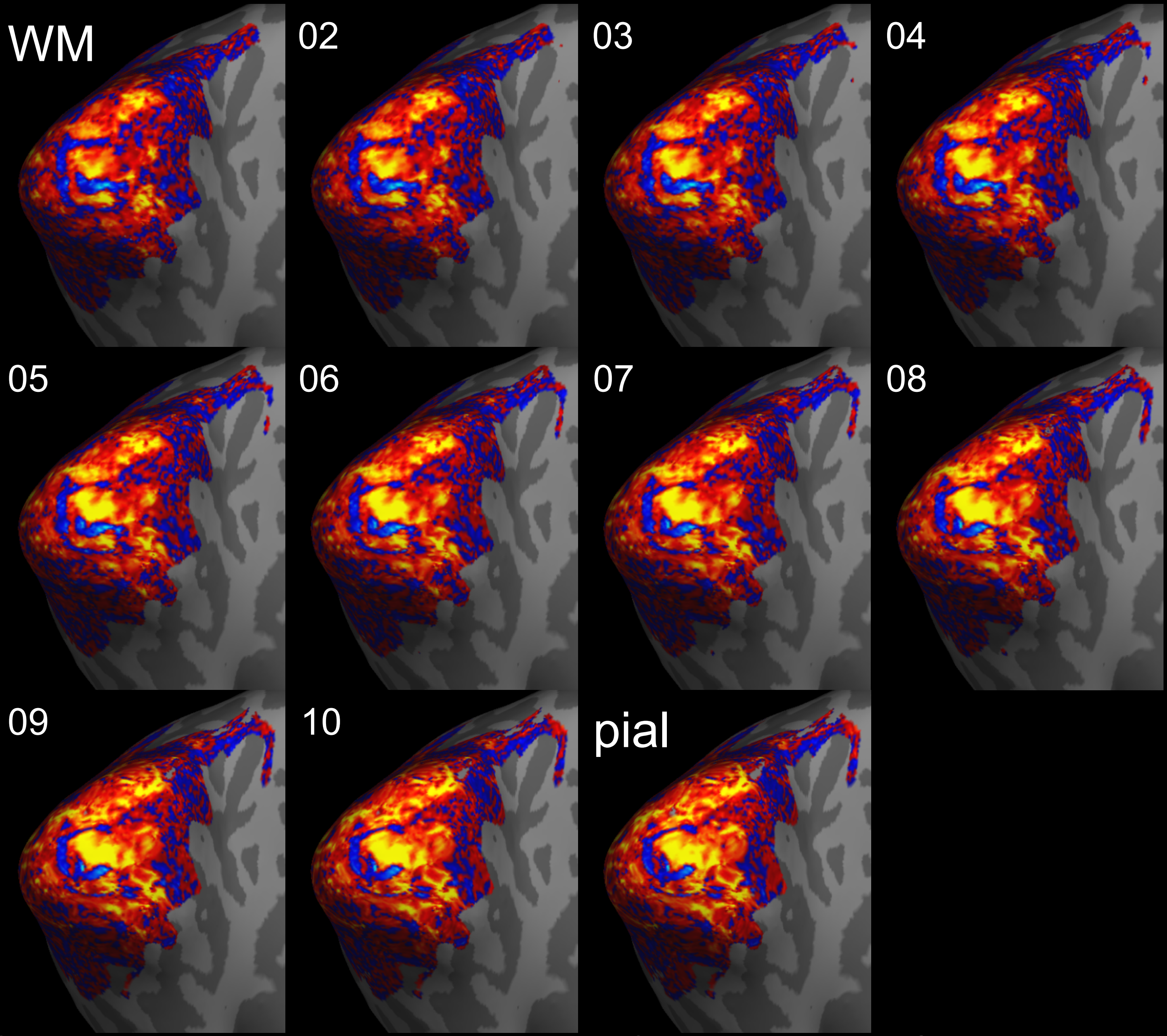
TA: 5 min, 24 sec



Resolution Pattern Degrades with Proximity to Pial Vessels



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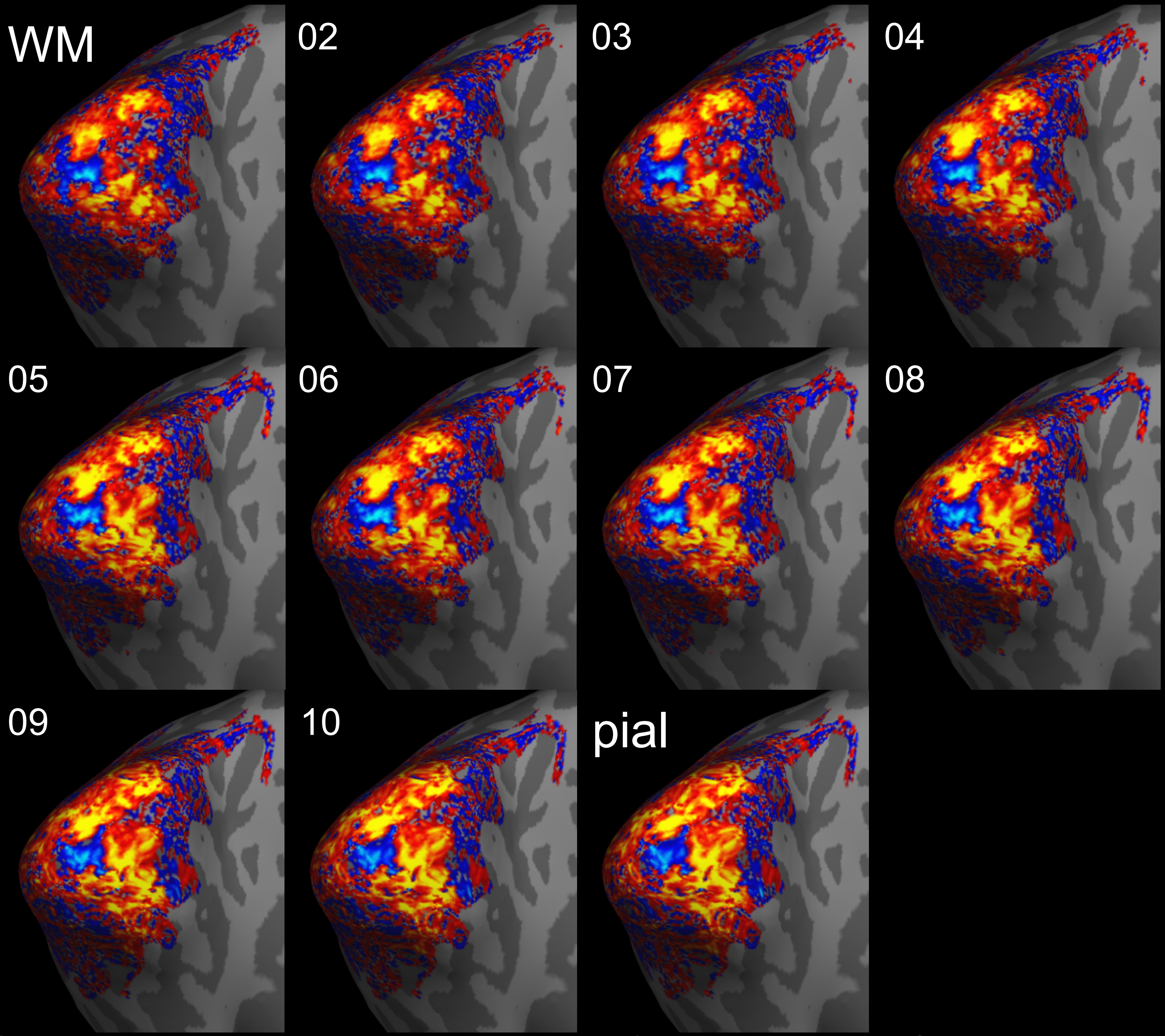

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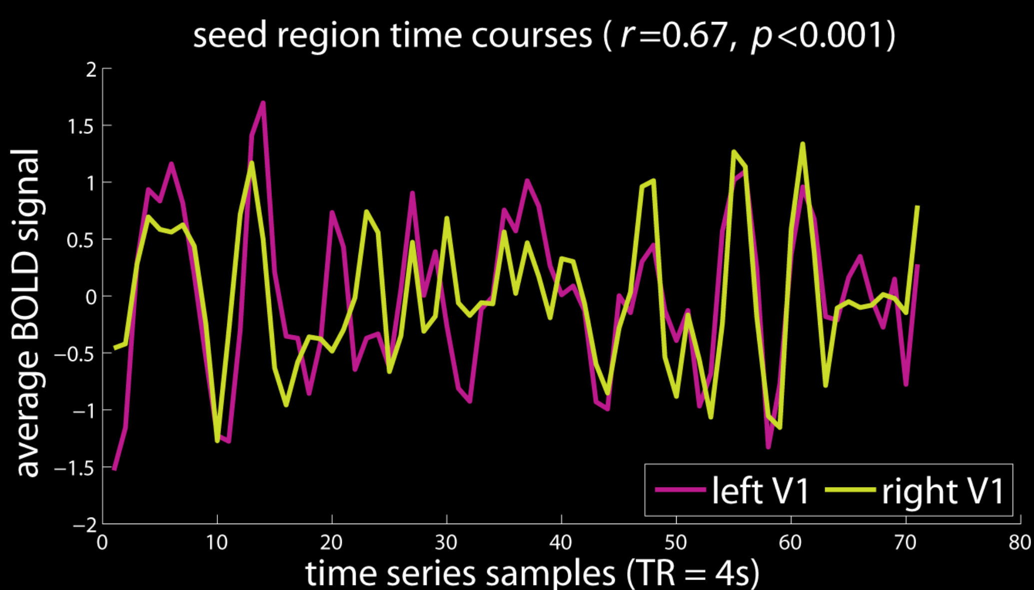
BOLD based connectivity

- Connected brain regions have correlated BOLD time-series in the absence of stimulus. *(Biswal 1995)*
- regress out motion, WM, ventrical, and whole-brain signals
- calculate correlation-coeff. between two regions.



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Laminar-specific connectivity studies

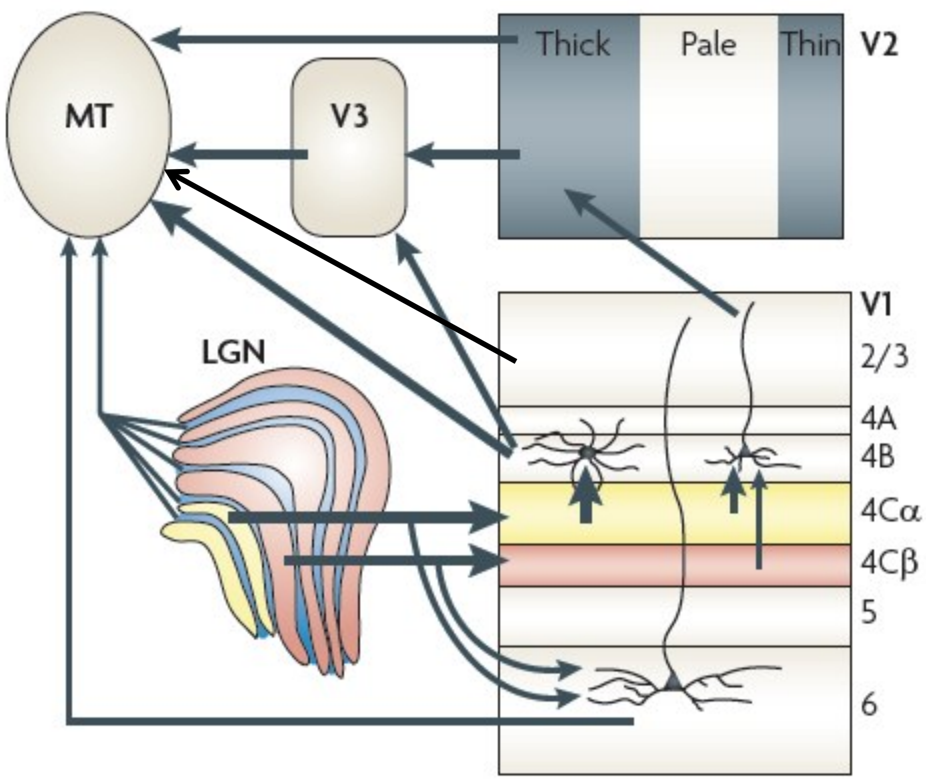
Can we exploit the laminar specific wiring diagram for:

1. Evidence that BOLD has laminar specificity.
2. Determine directionality in cortical networks.

Can you tell which direction the information is flowing?

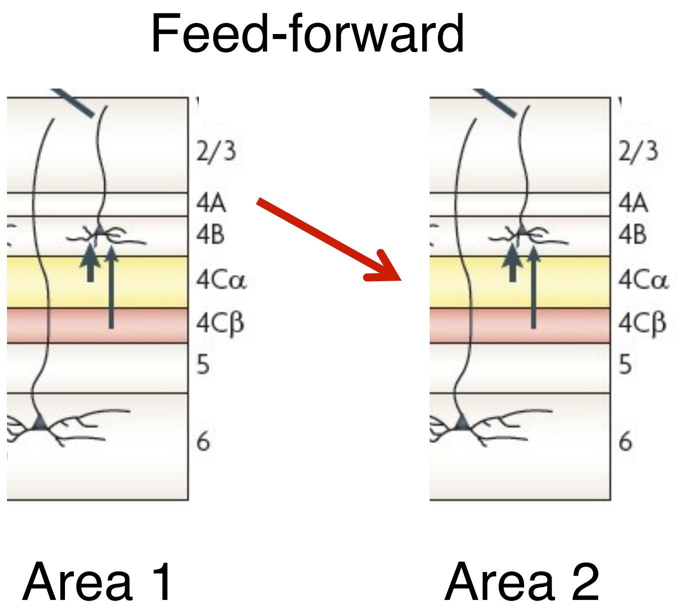
How to test laminar specificity w/ fMRI?

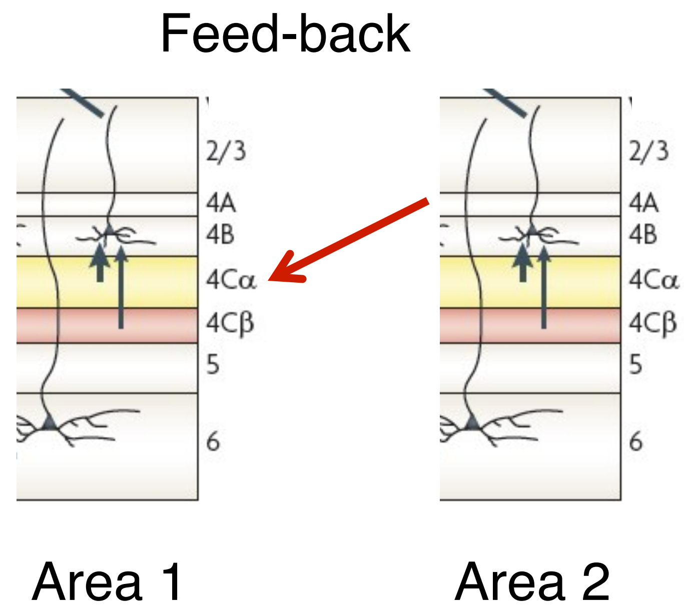
exploit known anatomical connections between V1 and MT; *inputs and output layers are different*

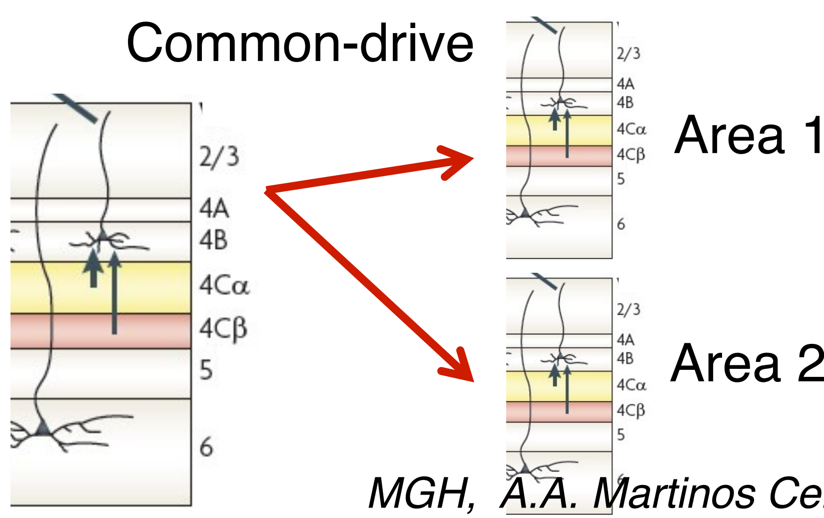


Nassi and Callaway
Nature Reviews: Neuroscience
Vol 10, 2009, p360-372

“Connections” in resting state fMRI







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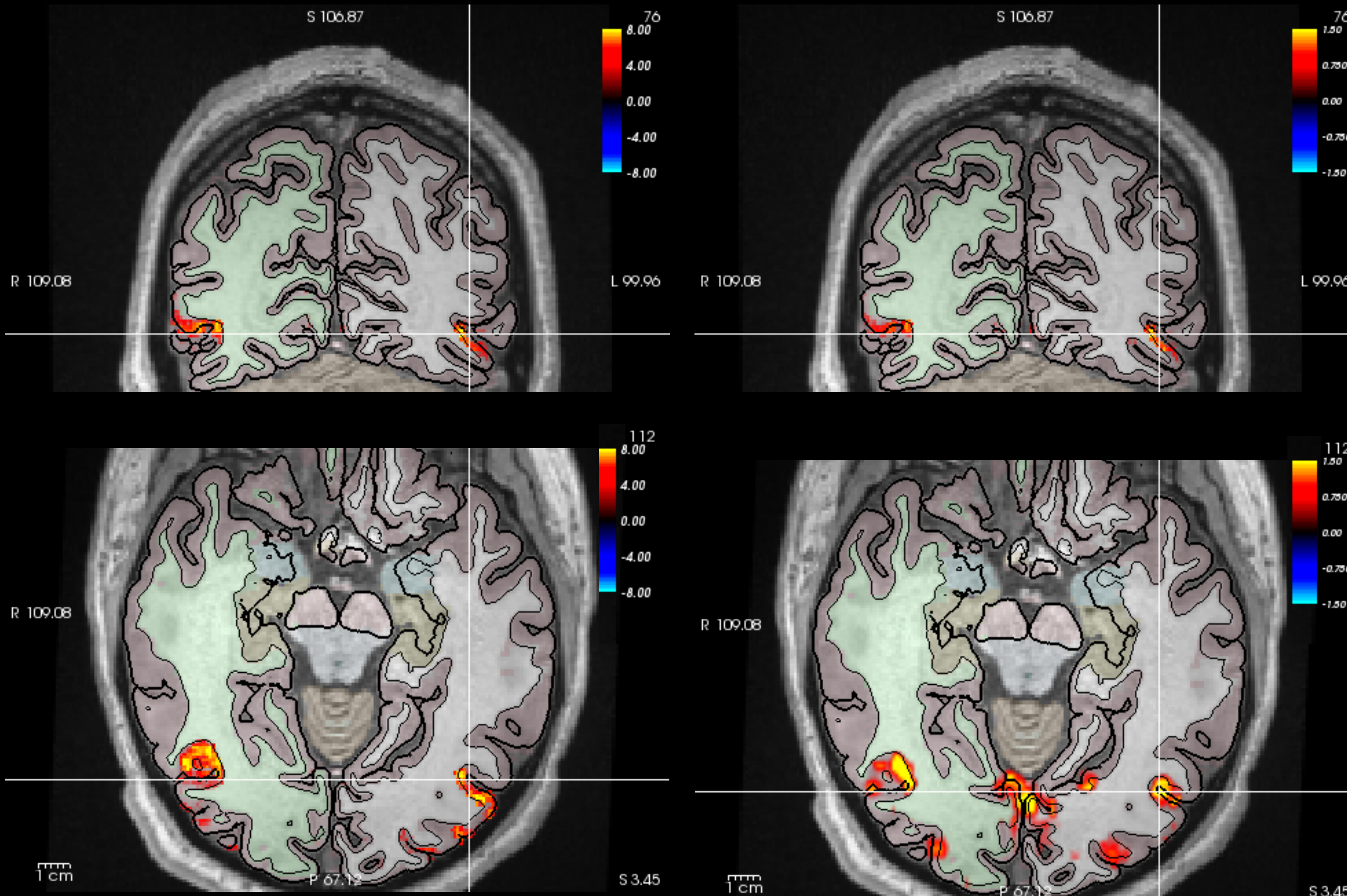
MT functional localizer (LCMS)

correlations from seeding
left hemisphere activation ROI



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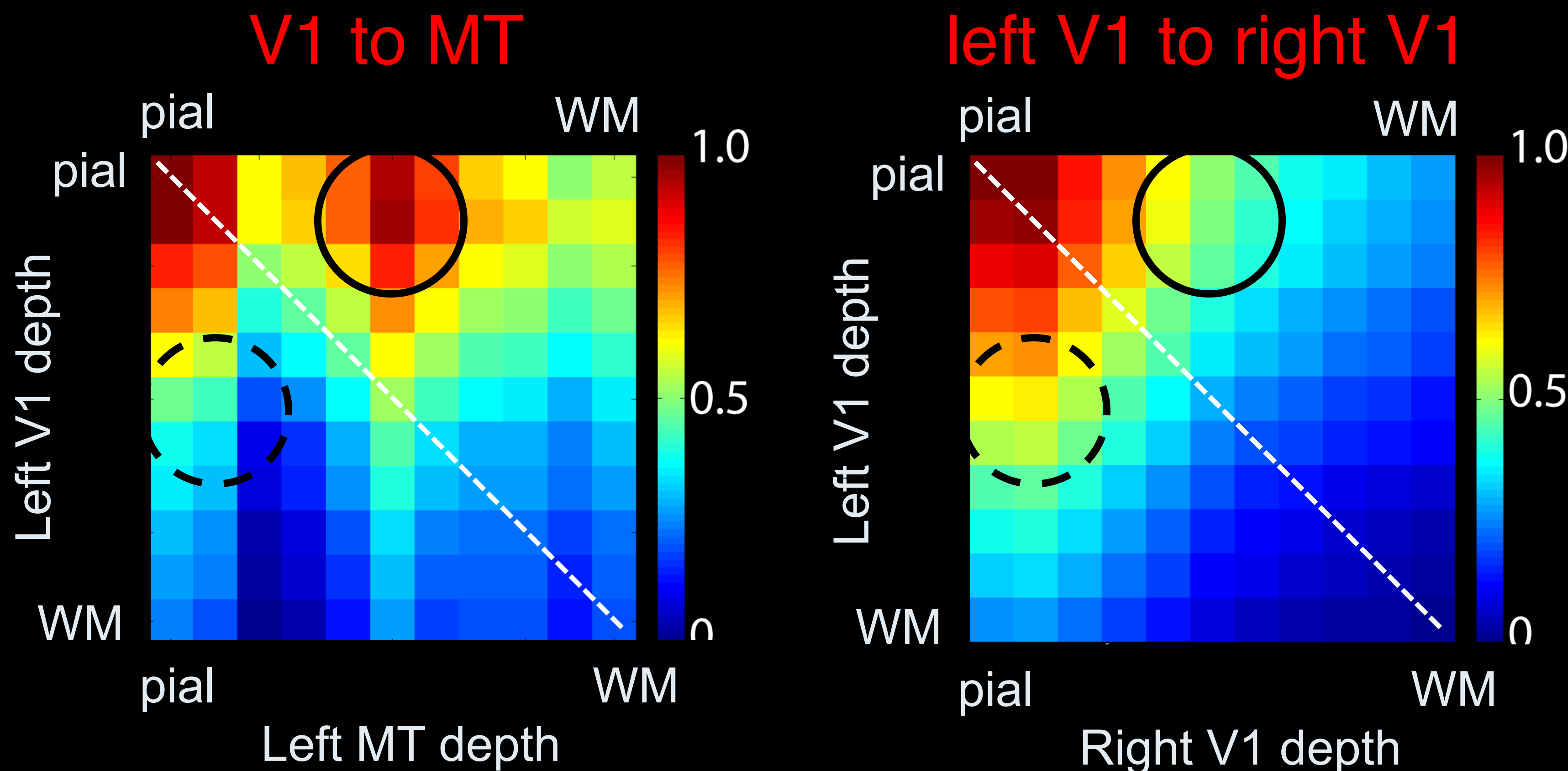
laminar-specific fcMRI

normalized correlation coefficienent

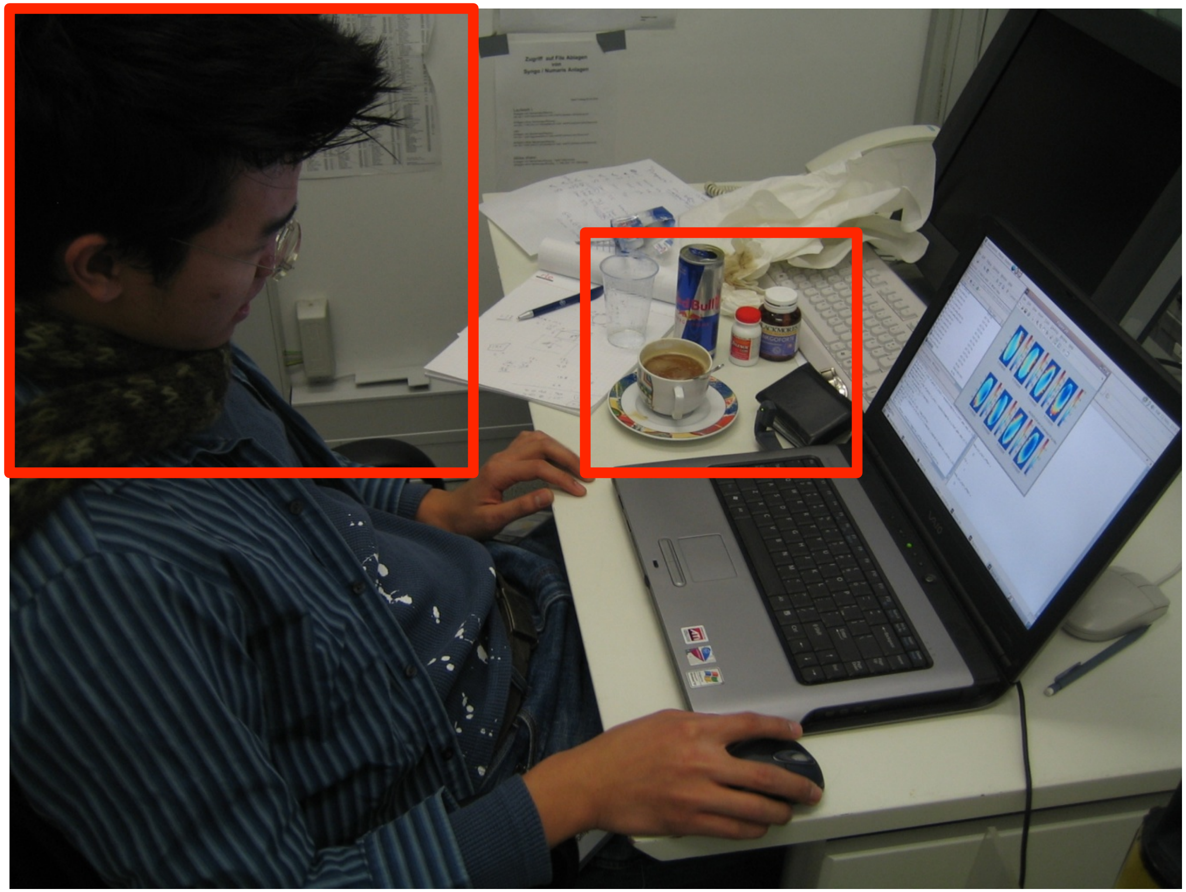


1. blood flow regulation at laminar level.
2. identify common drive situation.
3. infer directionality of connections.

What will advance MR encoding…

MR and signal processing expertise…

Kawin Setsompop, at work at the MR console…



Coffee, Red bull, Tylenol & Ginko Forte

Thank you!

wald@nmr.mgh.harvard.edu

Equations of motion in gradient field

Bloch Eqs. Rotating frame

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \left(\vec{B} - \vec{\omega}_{rot} / \gamma \right) \qquad \vec{B} = (B_0 + \vec{G} \cdot \vec{r})\hat{z}$$

choose rotating frame $\omega_{rot} = \omega_0$
(spins at $\omega=\omega_0$ are stationary…)

$\Delta\omega = \omega_{spins} - \omega_{rot}$
$= \gamma G \cdot R$ when $\omega_{rot} = \omega_0$

$$\left(\vec{B} - \vec{\omega} / \gamma \right) = \gamma \vec{G} \cdot \vec{r} = \Delta\omega$$

$$\begin{pmatrix} \dot{M}_x \\ \dot{M}_y \end{pmatrix} = \begin{pmatrix} 0 & \vec{G} \cdot \vec{r} \\ -\vec{G} \cdot \vec{r} & 0 \end{pmatrix} \begin{pmatrix} M_x \\ M_y \end{pmatrix}$$

complex notation for xy component: $M = M_x + iM_y$

$$M(\vec{r},t) = M_0(\vec{r})\exp\left(-i\int_0^t (\vec{G}(t) \cdot \vec{r})\, d\tau \right)$$