Ultra-High Field Magnetic Resonance Imaging: HiMR

MARIE CURIE INITIAL TRAINING NETWORK

Detecting brain function with high-field MRI

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Seminar Sept 2014

Università di Pisa

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Outline

1. MR physics: introduction
2. Functional MRI

   - Physical and physiological and changes during an fMRI experiment

3. Advantages and pitfalls of using High-field fMRI

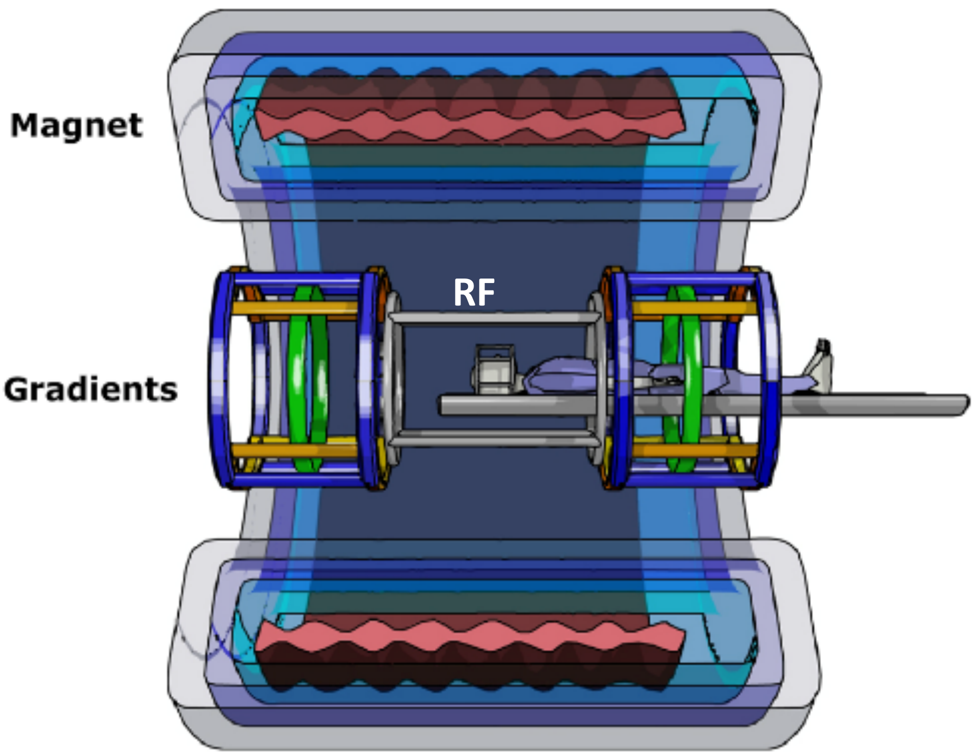
4. Physiology of the center of vision
5. Road to Mapping the Orientation Columns in V1:

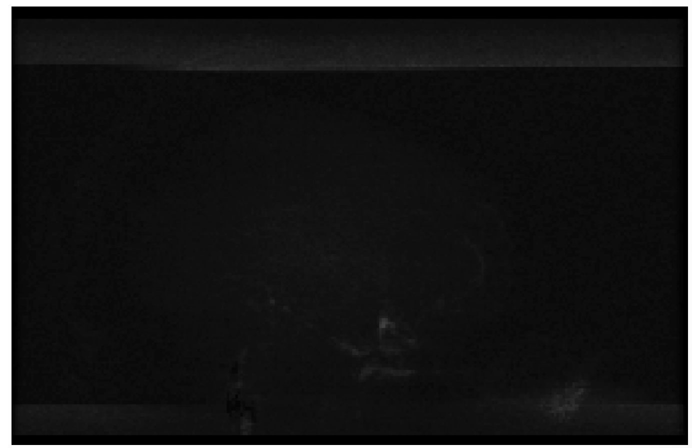
   - The 7T experience

1. Final Remarks
2. Acknowledgements

The MR signal

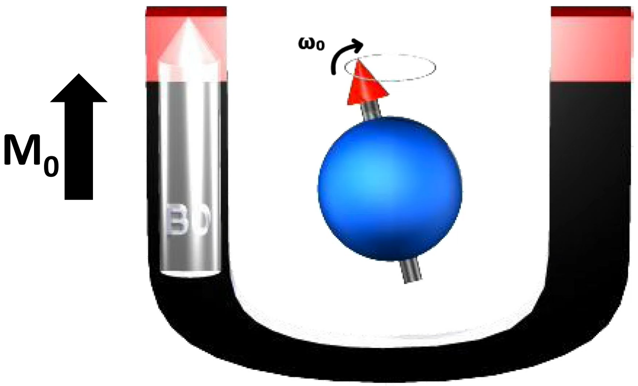
A correct manipulation of magnetic fields and radio waves allows acquisition of detailed images of tissue and organs of the human body.





Whole brain structural scan 1mm isotropic resolution

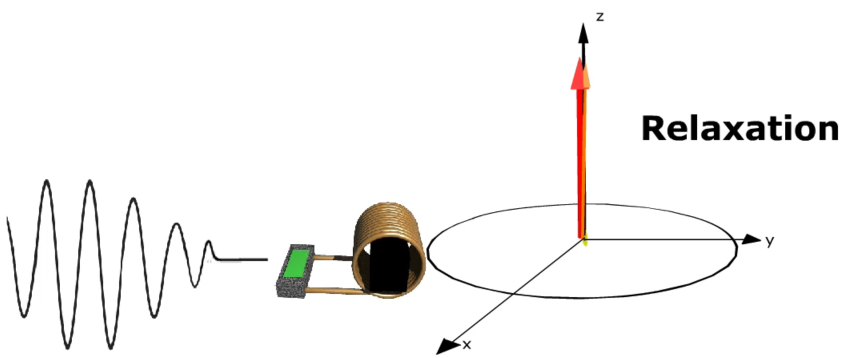
The MR signal



Hydrogen protons in a strong magnetic field precess at a certain frequency (ω_0):

$$\omega_0 = \gamma B_0$$

- The MR signal is a measure of the magnetization vector after a perturbation has occurred



- Once the RF transmitter is turned off, **relaxation** happens:
  - longitudinal magnetization recovers;
  - transverse magnetization decays;

Longitudinal magnetization:

$$M_z(t) = M_{z,\mathrm{eq}}\left(1 - e^{-t/T_1}\right)$$

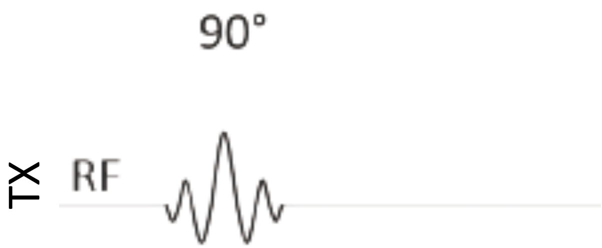
Transverse magnetization:

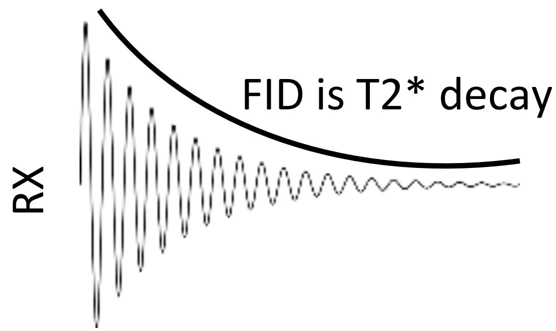
$$M_{xy}(t) = M_{xy}(0)e^{-t/T_2}$$

Spin signal to tissue contrast

Coils can receive the signal in the transverse plane due to variations of transverse magnetization vector. So if:

1st we apply a simple 90º RF pulse



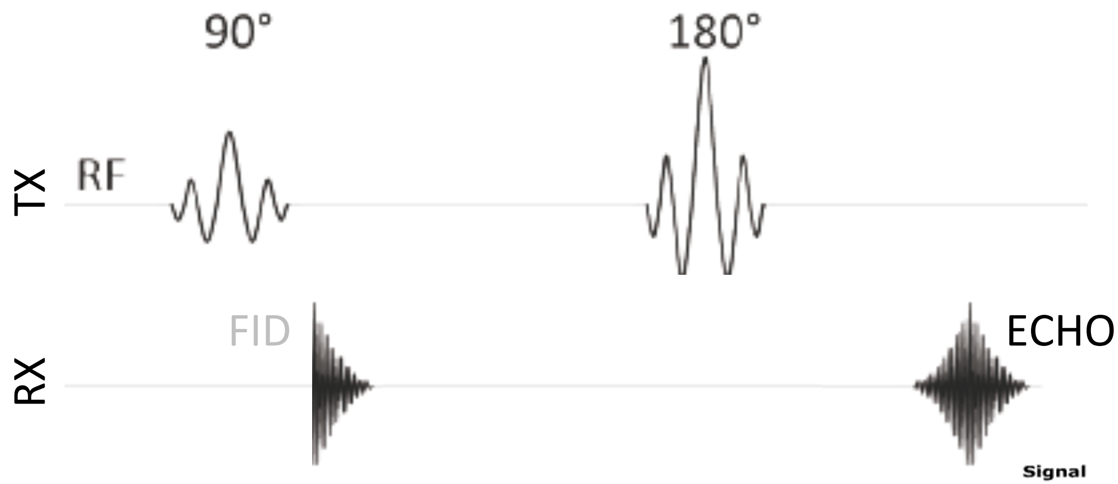


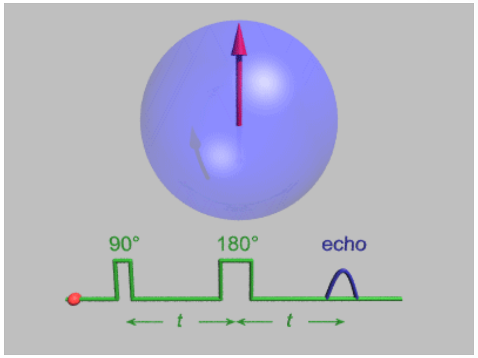
T2* decay depends on:

A. tissue specific spin-spin relaxation (random interactions between spins) responsible for **pure T2 decay**;
B. static **inhomogeneities** in magnetic fields which accelerate spins dephasing.

Spin signal to tissue contrast

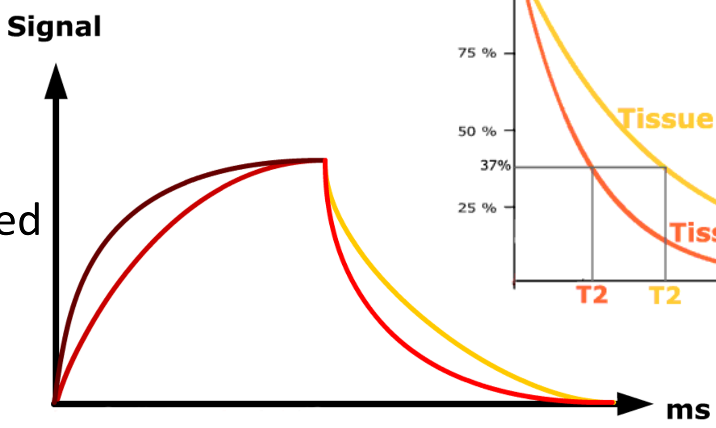
2nd After some time *t* apply another pulse of 180º (i.e. Refocusing Pulse):

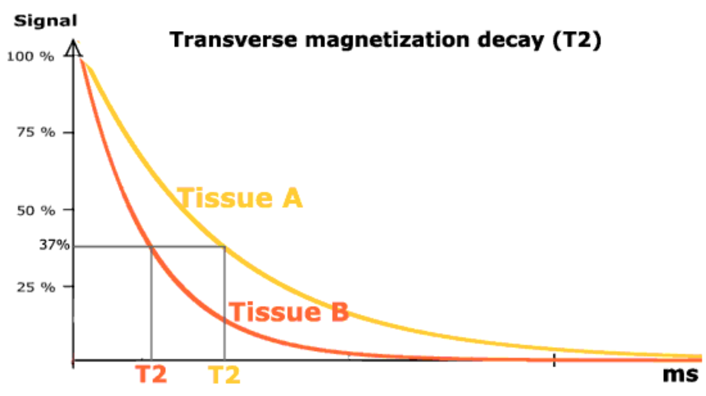




What signal do we get?

- Depends on **when** we acquire the echo (called echo time, **TE**).





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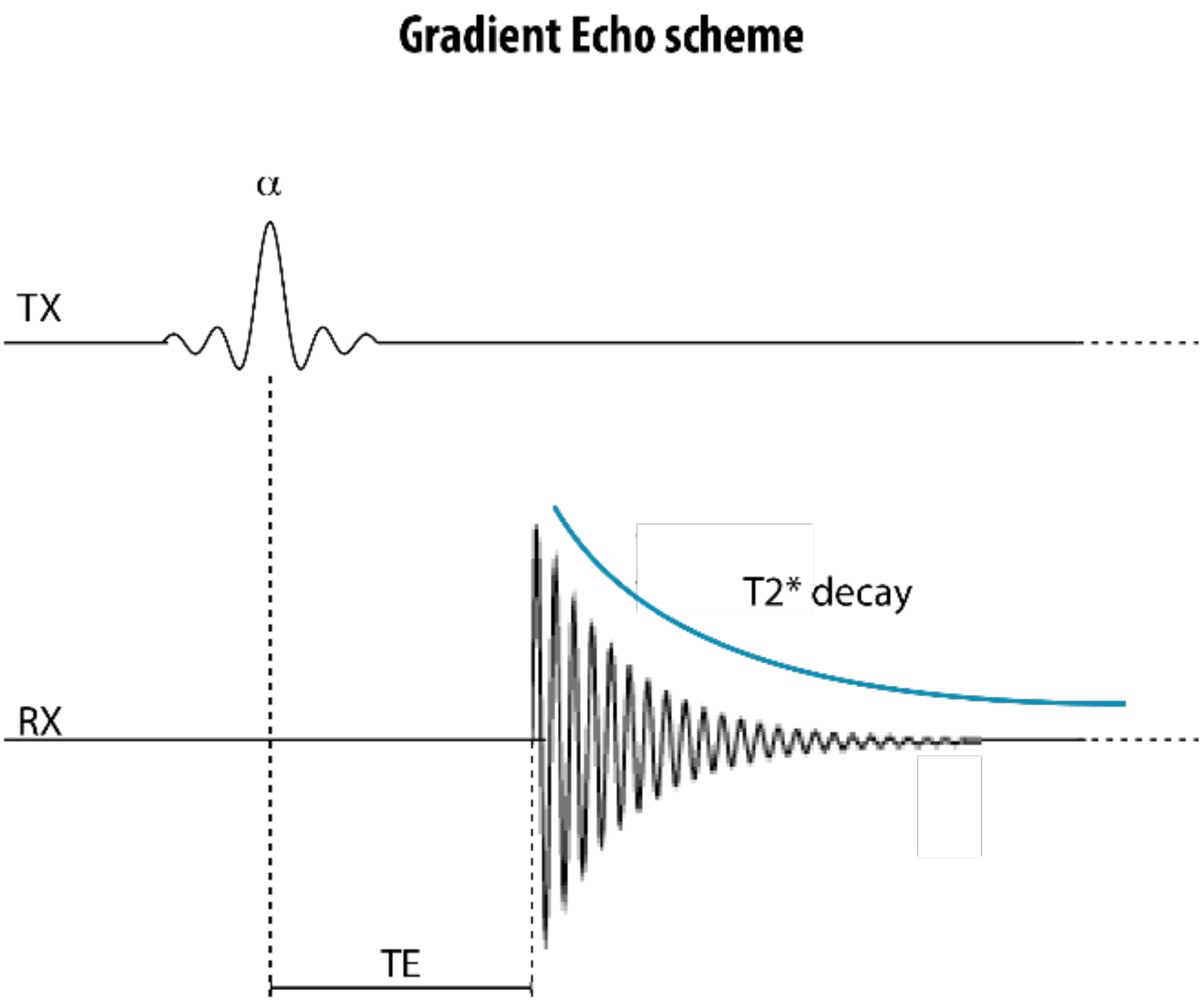
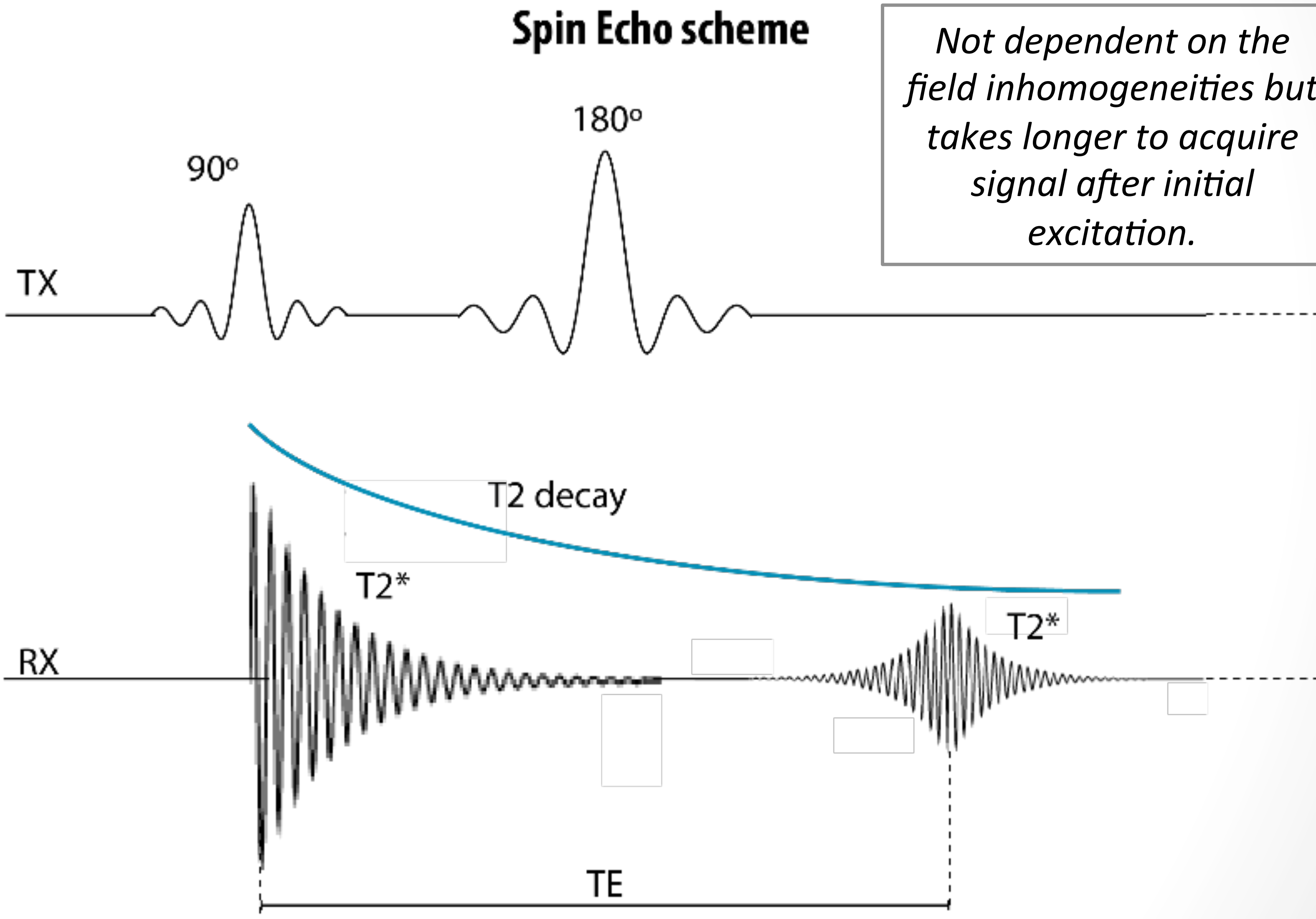
Gradient Echo and Spin Echo



Gradient Echo and Spin Echo



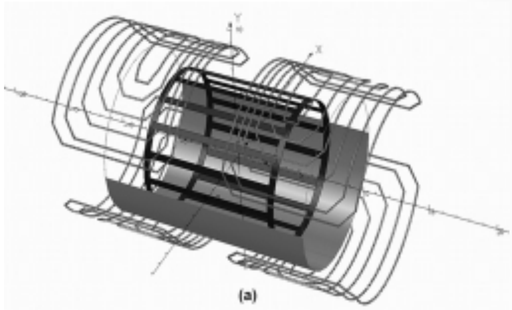
Not dependent on the field inhomogeneities but takes longer to acquire signal after initial excitation.

Spatial encoding in MRI

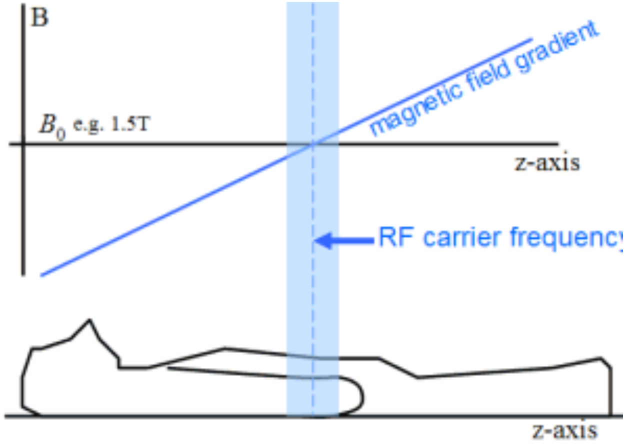
Selecting the slice plane and spatial encoding of each voxel involves the use of magnetic field gradients.

- Spatial encoding is accomplished by amplitude, direction and duration modulation of gradients in the 3 spatial directions:

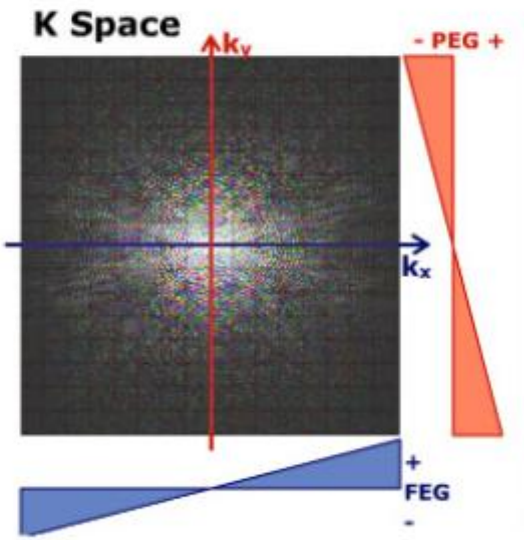
$$\vec{B} = (B_0 + G_x x + G_y y + G_z z)\hat{z}$$



Typical gradient layout plates



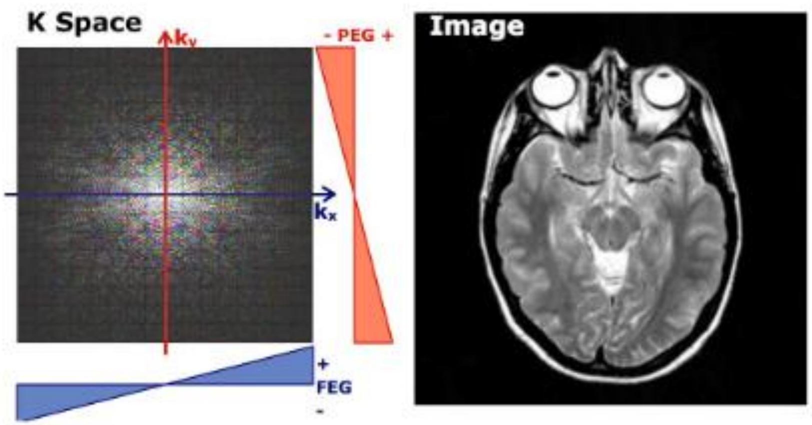
Slice selection magnetic field gradient on the z axis



Phase and frequency encoding gradients fill in k-space

From Magnetization to Image

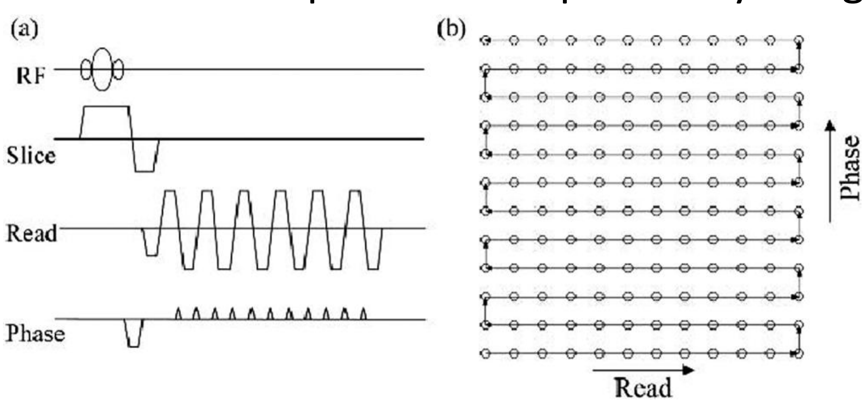
The readout MR signal is a mix of RF waves with different amplitudes, frequencies and phases, containing spatial information.



$$S(k) \propto \int_{-\infty}^{+\infty} \rho(r)\, e^{ikr}\, dr$$

- 2D-FFT techniques allow image reconstruction, i.e. from k-space to image space.

- Dedicated sequences are specifically designed for diverse purposes:

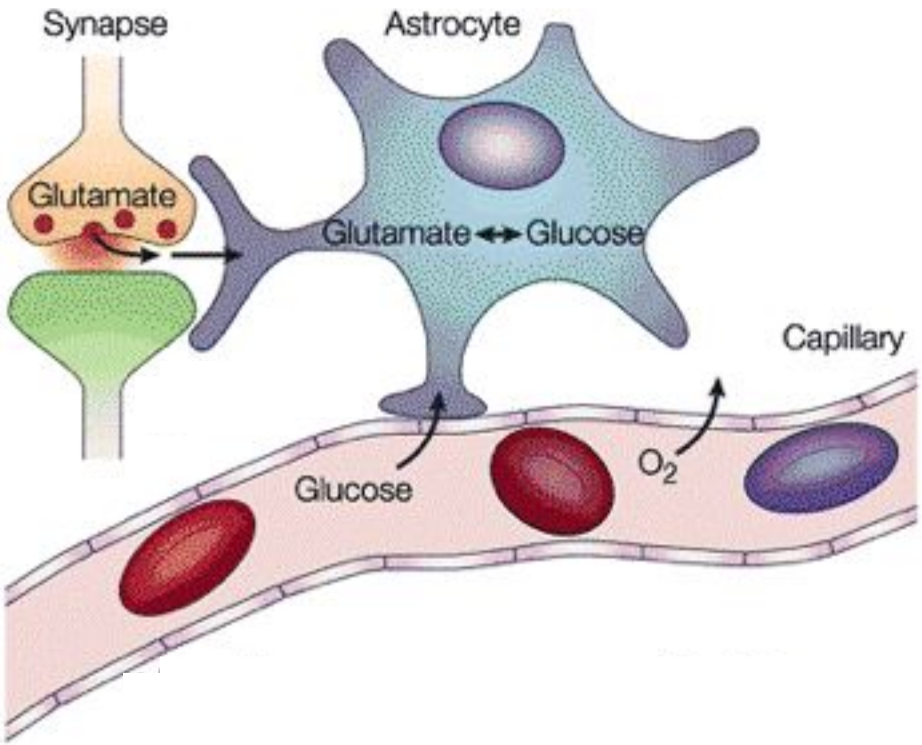


- Modify the contrast;
- Accelerate acquisition;
- Reduce artifacts.

Gradient Echo Echo Planar Imaging (GRE-EPI) sequence design

Measure brain function with MR

Physiology of the Brain: A higher cell activity demands for increased energy metabolism; translates in the form of higher glucose and O2 intake.

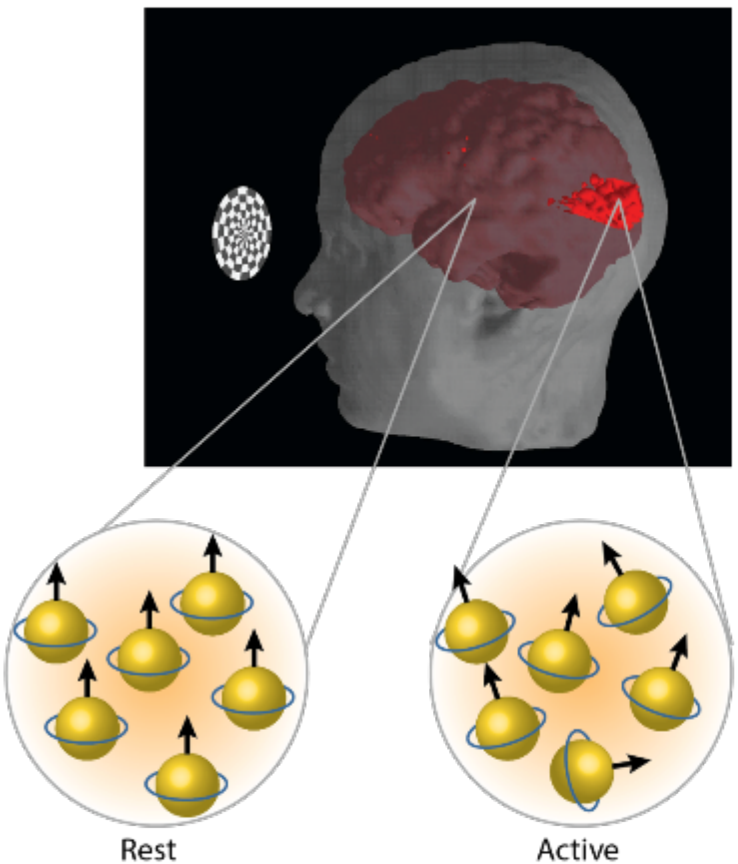


Assumption:

increased blood flow in Grey Matter (*cell bodies*) follows from increased synaptic activity.

Measure brain function with MR

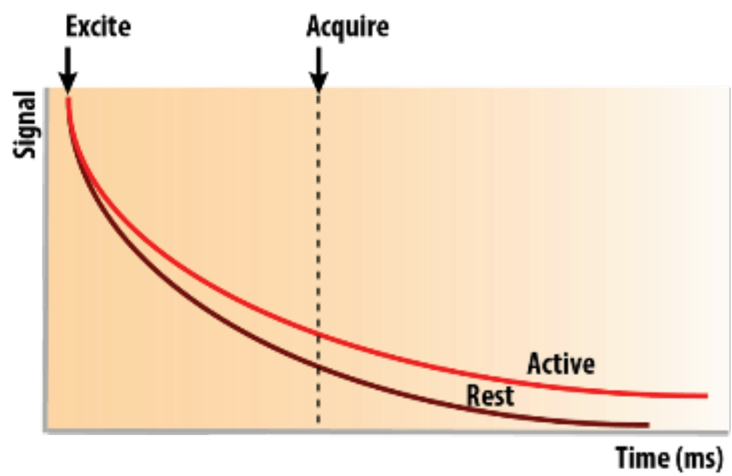
Physics of MR: Deoxyhemoglobin (dHb) is paramagnetic, and oxyhemoglobin (Hb) non-magnetic.



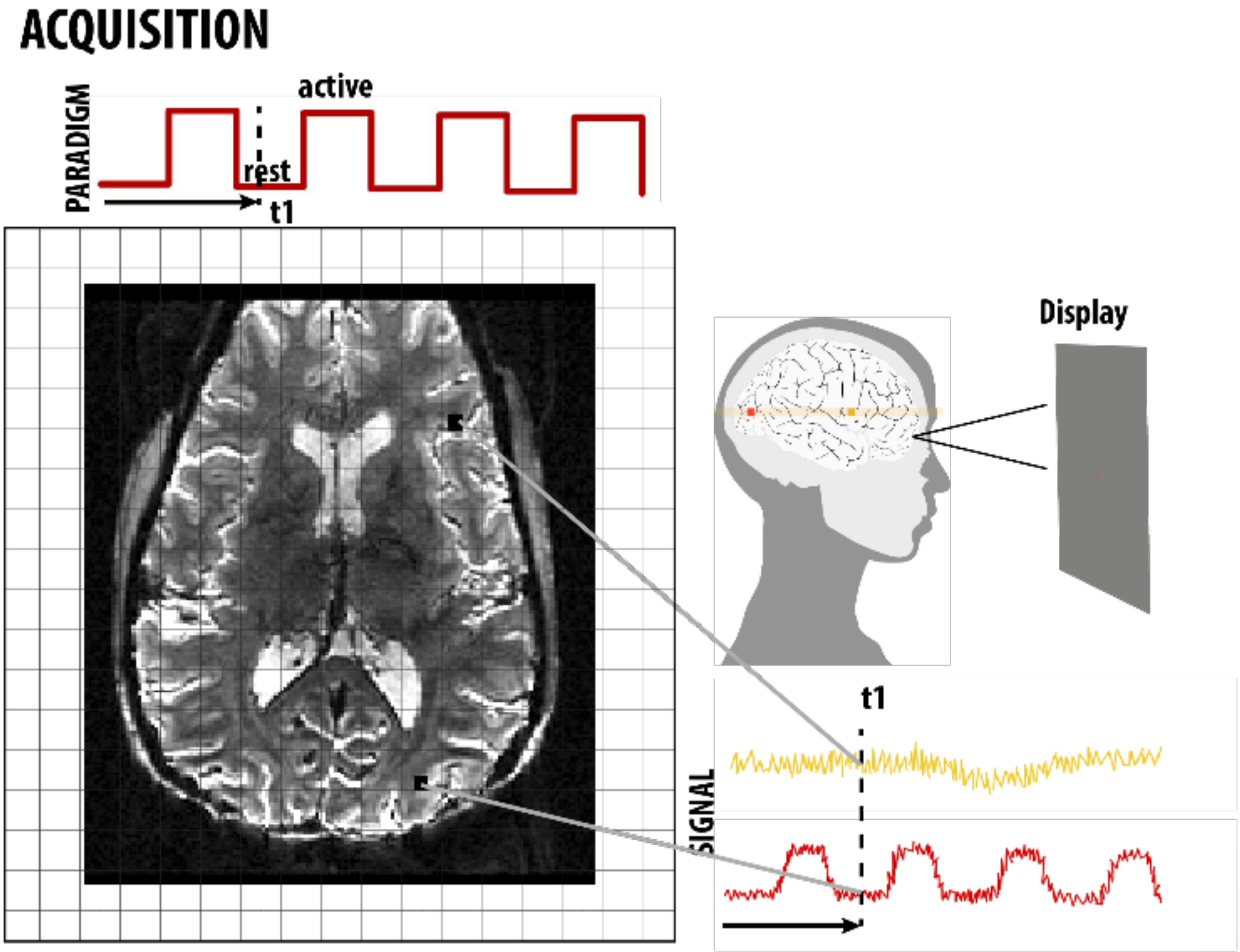
1. Fluctuations of dHb/Hb induce local magnetic susceptibility changes: $\Delta\chi$

2. Induces a dynamic change of the local T2*

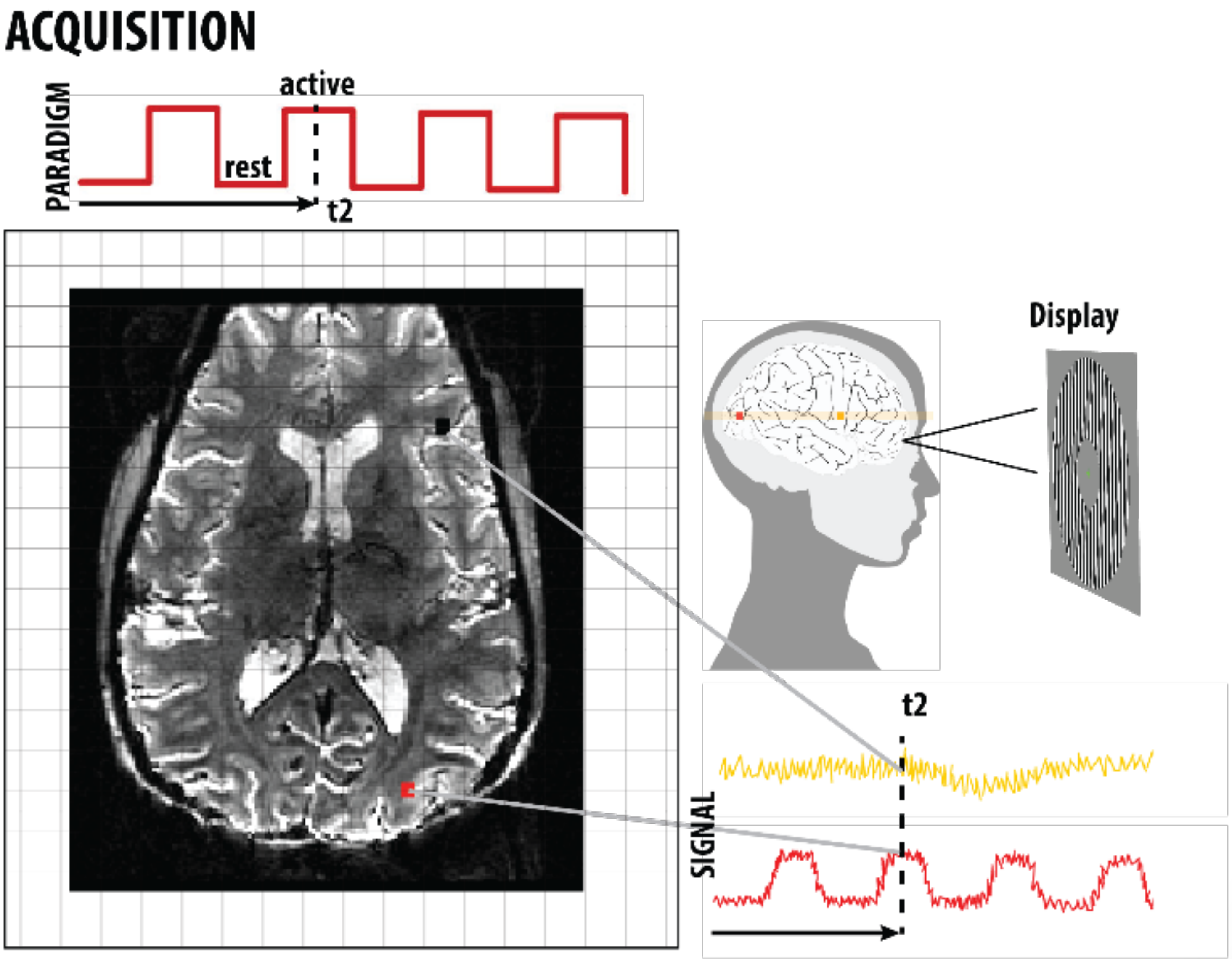
3. detectable signal changes **= *BOLD imaging***



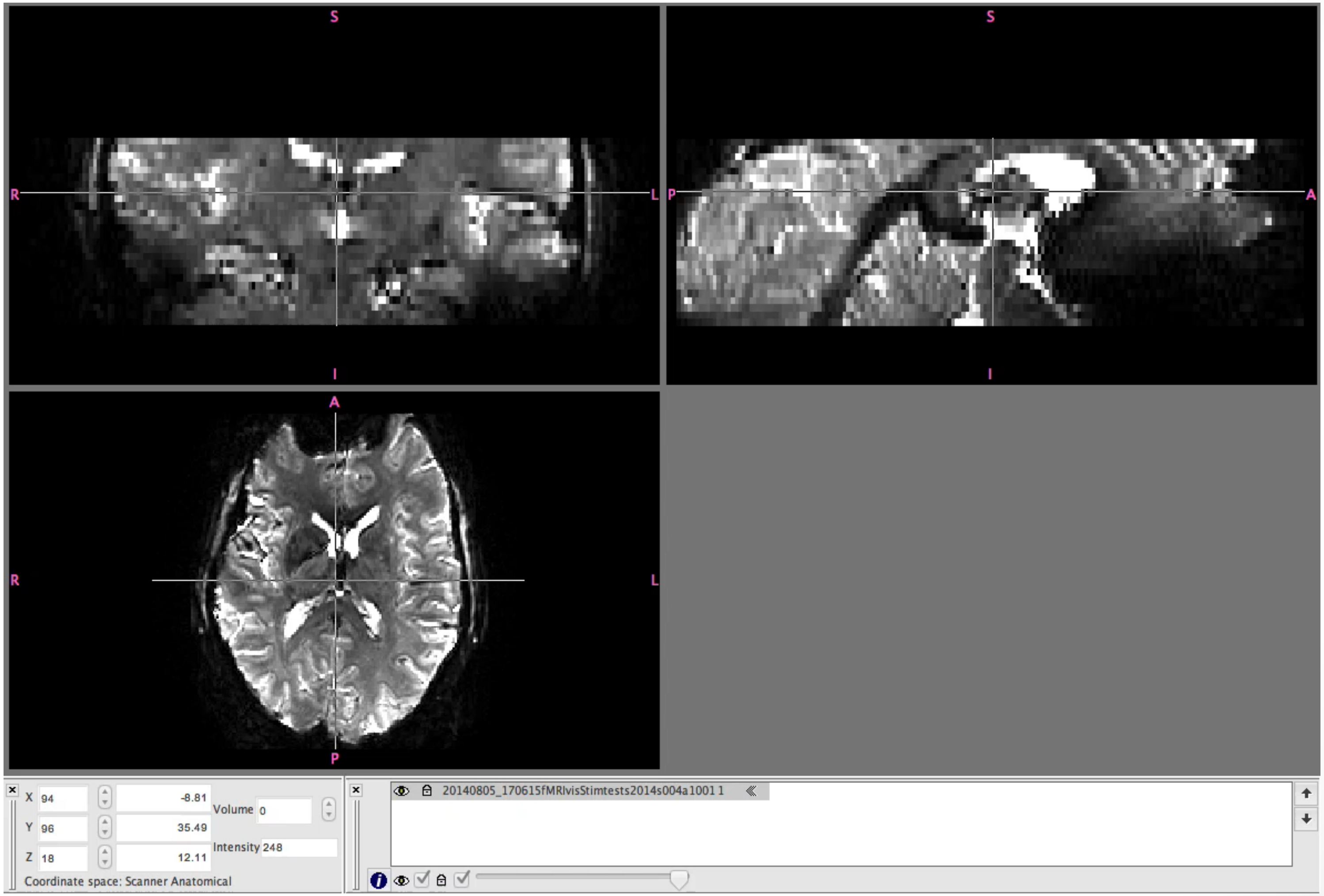
Typical fMRI experiment



Typical fMRI experiment



Typical fMRI experiment



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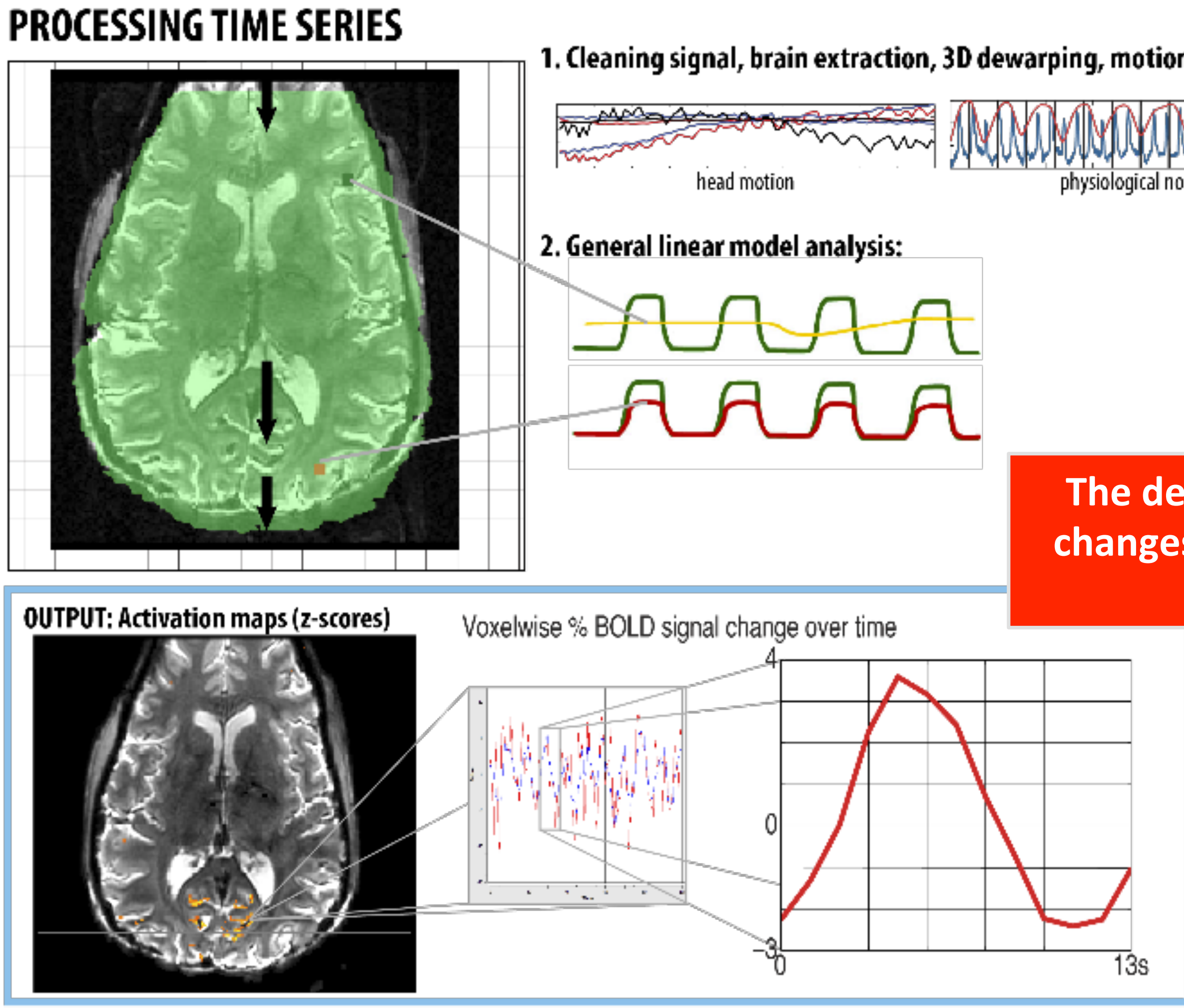
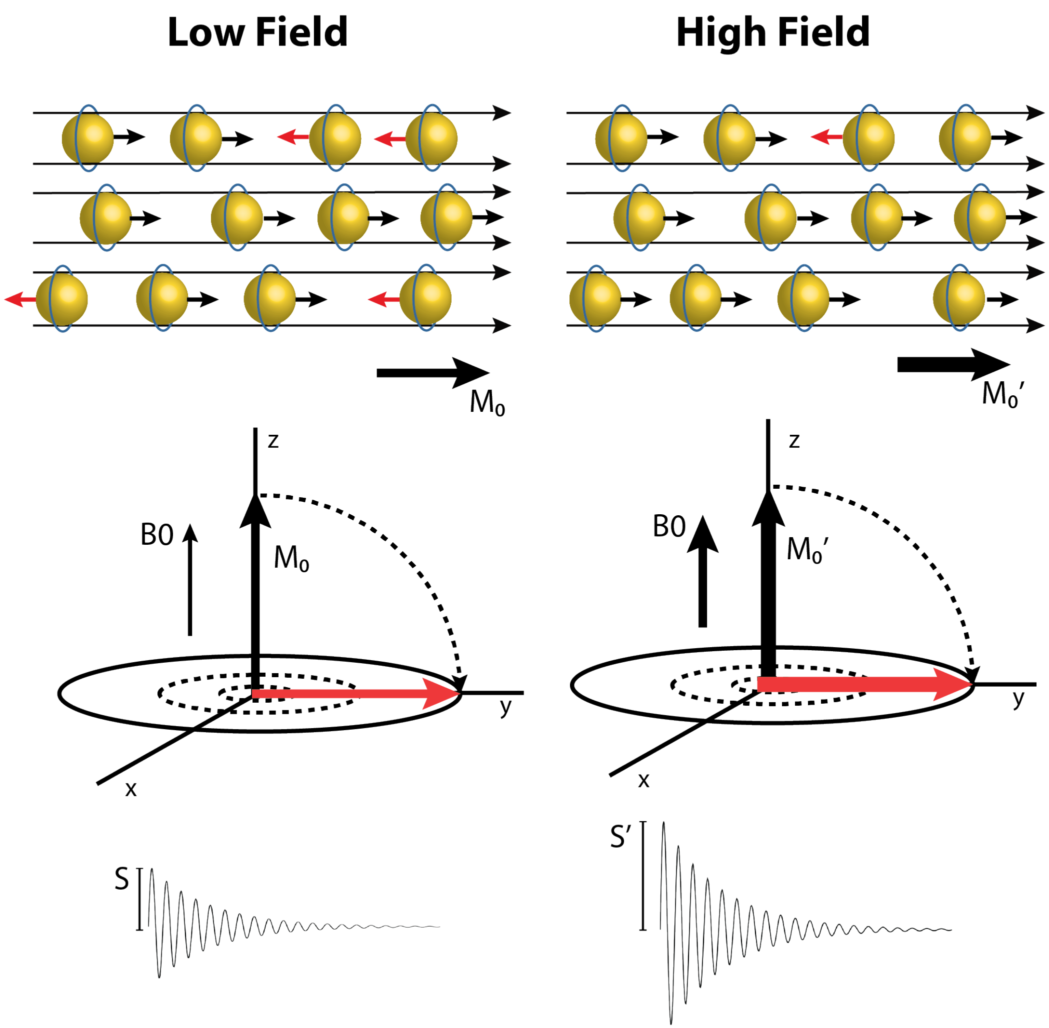
Typical fMRI experiment



The detectable signal changes are very small (~3%)

High-field fMRI: advantages

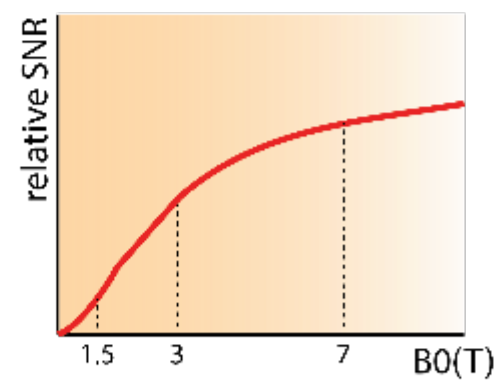


Signal dependency:

$$\frac{N_{up}}{N_{down}} = e^{-\Delta E/kT} = e^{-h\nu/kT}$$

$$S \propto {B_0}^2$$

Signal-to-Noise (SNR) dependency:



High-field fMRI: advantages

$$\mathrm{SNR} \propto \left[\text{Voxel Volume}\right] * \sqrt{\text{Total Data Acquisition Time}}$$

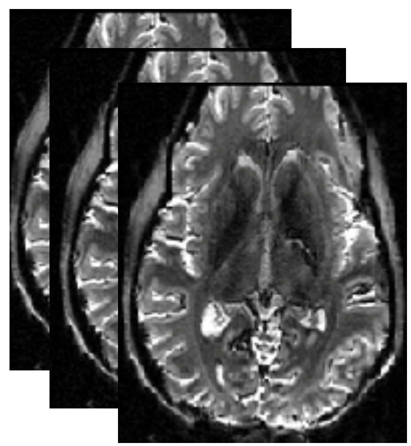
Spatial **Temporal**

Low fields (up to 3T)

Low spatial resolutions (until ~ 3mm^3)

1 volume in every 2 seconds

High fields (4T, 7T,…)

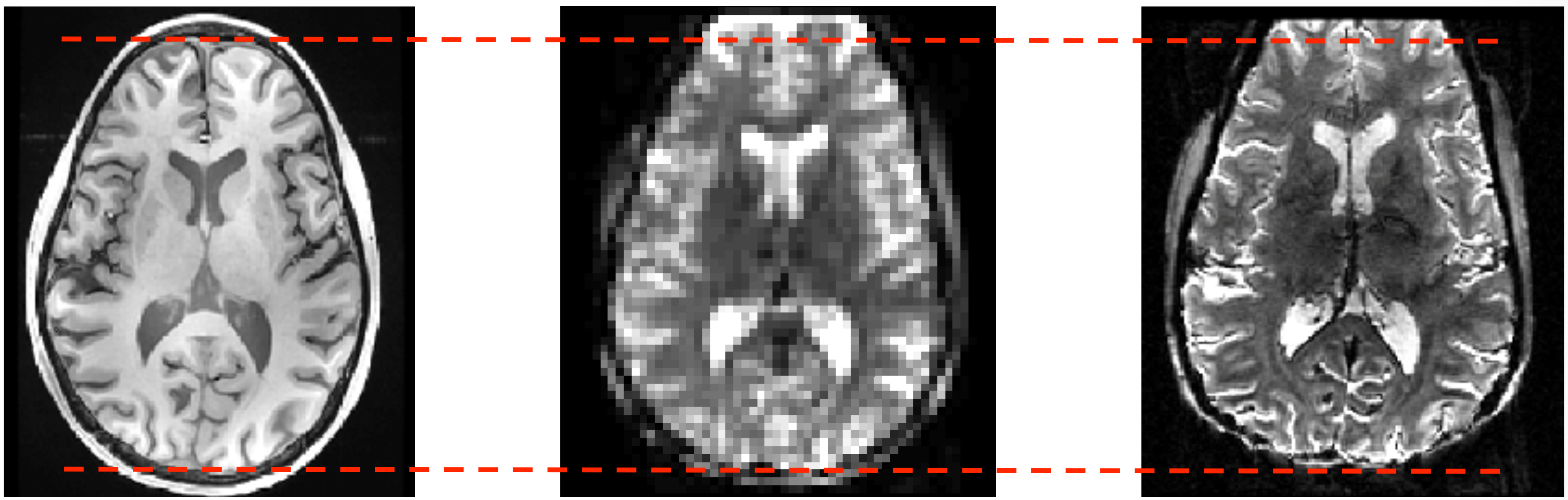


Higher spatial resolutions (sub-mm scale)

1 volume in every 2 seconds

High-field fMRI: advantages… and pitfalls

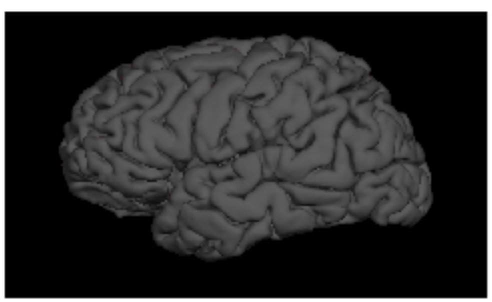
Structural ($1mm^3$) Functional ($3mm^3$) Functional ($1mm^3$)

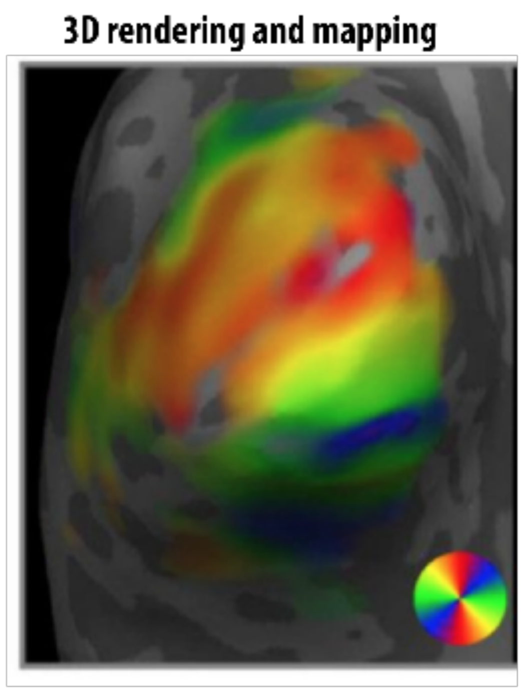


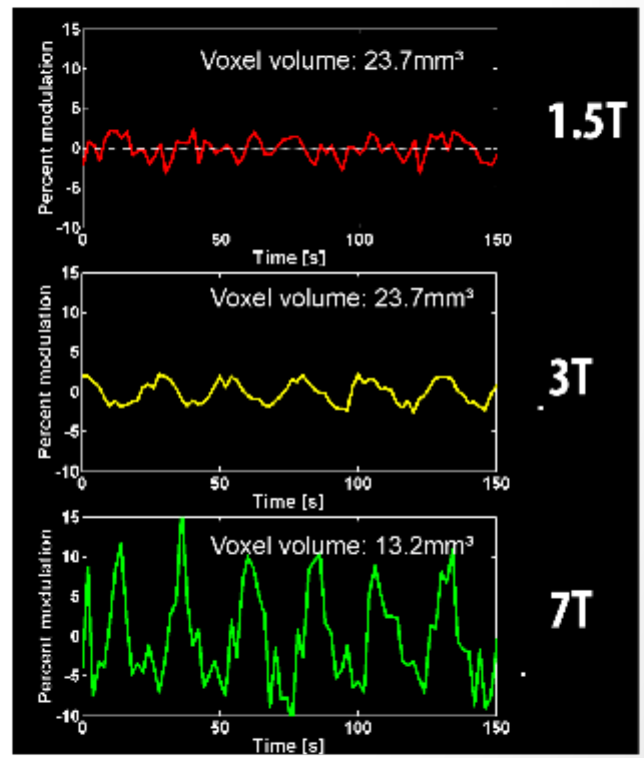
- **Field inhomogeneities** (RF transmission and detection, dielectric effects, fast gradient switching create implications on image quality, i.e., image distortions, ghosting, etc);
- **More RF power deposition** (implications to thermal noise and heating);
- **Physiological fluctuations** (cardiac, respiratory and patient motion).

Detecting brain function at high field MRI

What can we learn with brain data?
"Brain data provide a physical grounding that constrains the myriad otherwise-*plausible* models of cognition." *Kosslyn, S. M. (1994).*



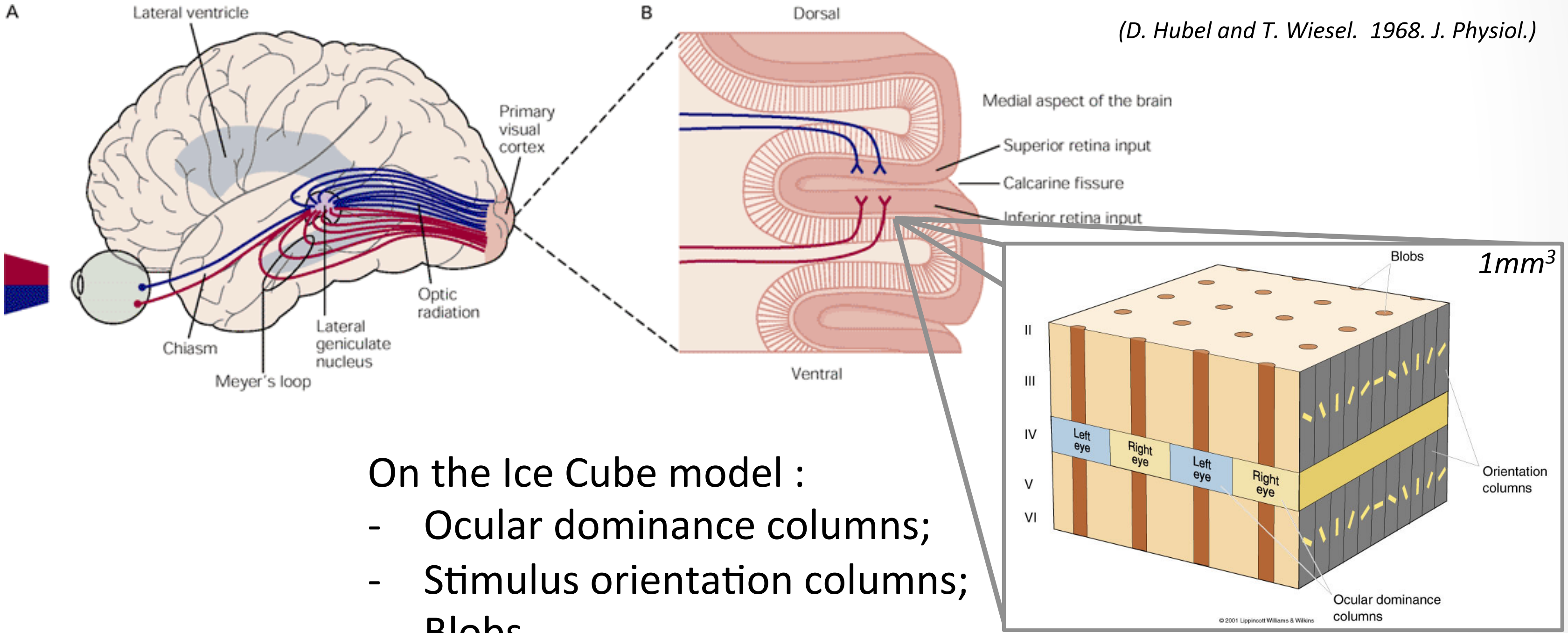




Physiology of the visual cortex

The center of vision is considered a very complex circuitry system: contains large asymmetries, anisotropies and substantial inter-individual variability.

Primary visual cortex (V1) the cortical representation extremely orderly but very small.



(D. Hubel and T. Wiesel. 1968. J. Physiol.)

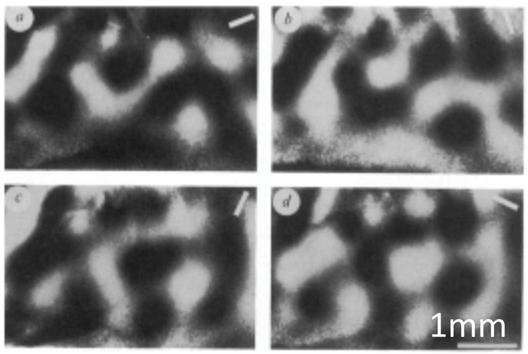
On the Ice Cube model :

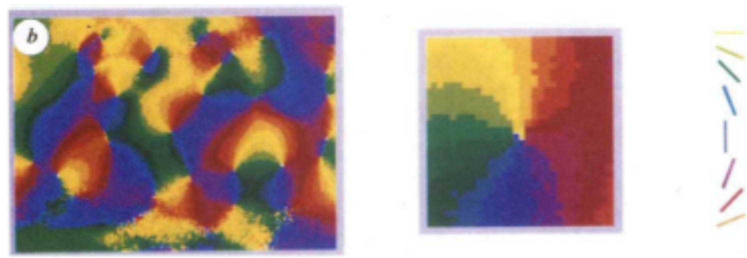
- Ocular dominance columns;
- Stimulus orientation columns;
- Blobs.

The coarse spatial resolutions of fMRI studies so far have limited the specificity of this technique.

Mapping Orientation Columns (OCs)

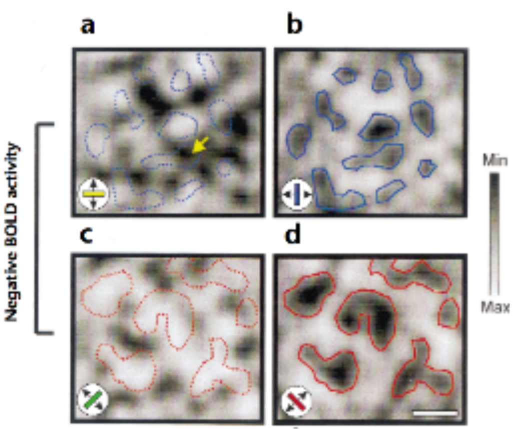
- Previous studies on orientation columns used 2-DG or optical imaging methods on mammals. *(Lowel et al. 1987. J. Comp. Neurol.; Bonhoeffer et al. 1991. Nature)*

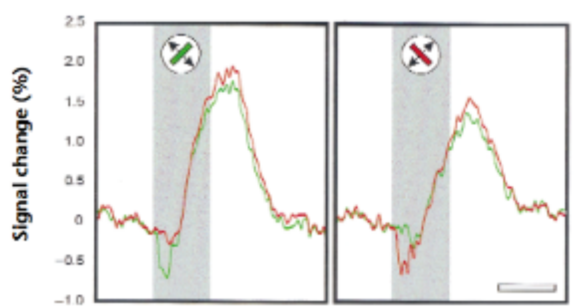




Optical Imaging in cat's brain area 18: Clear orientation selectivity with pinwheel-like centers.

- Non-invasive fMRI was recently performed at the columnar level at sub-millimeter in-plane resolutions. *(Kim et al. 2000. Nature.)*

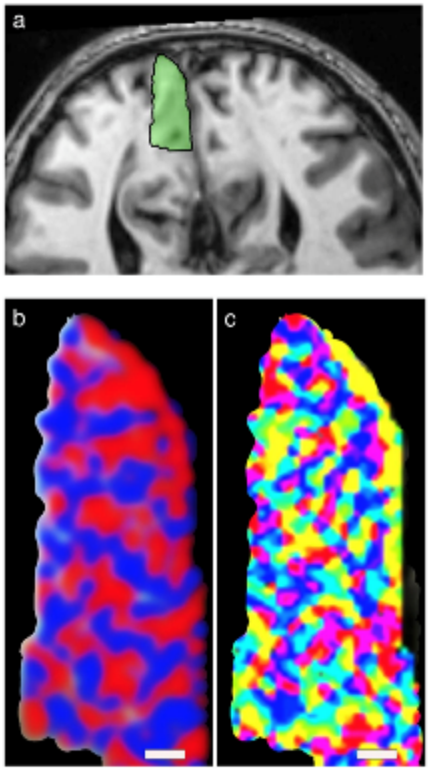




Stimulus-selective responses based on negative BOLD signals were reflected at the columnar scale in the cat's area 18.

Mapping OCs: 7T experience

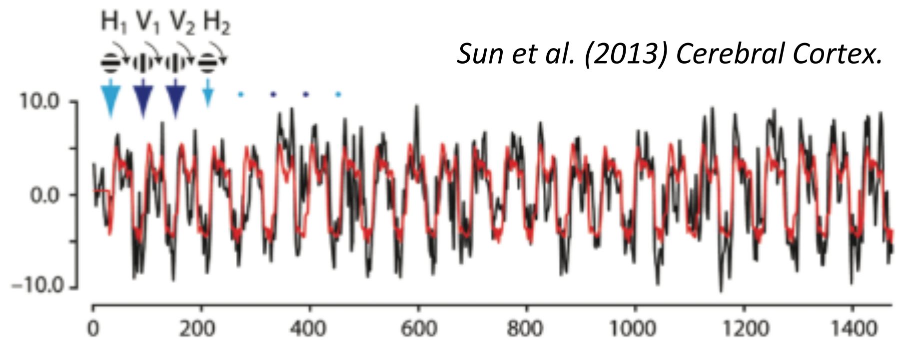
Major challenge is to obtain significant signal changes at the finest resolution and short acquisition time.



Yacoub et al. (2008) PNAS.

Recent approaches used a SE-EPI sequence in a 7T scanner showing increased specificity in detecting orientation columns and pinwheels compared to GRE-EPI sequence.

Major criticism to imaging + reconstruction of data and over interpretation of results.



Sun et al. (2013) Cerebral Cortex.

Other approaches used a GRE-EPI sequence at $0.75mm^2$ in-plane resolution (4T scanner).

Orientation-tuning to obliqueness lower than cardinal, but still not statistically significant.

Possible advantages with the higher signal change at 7T?

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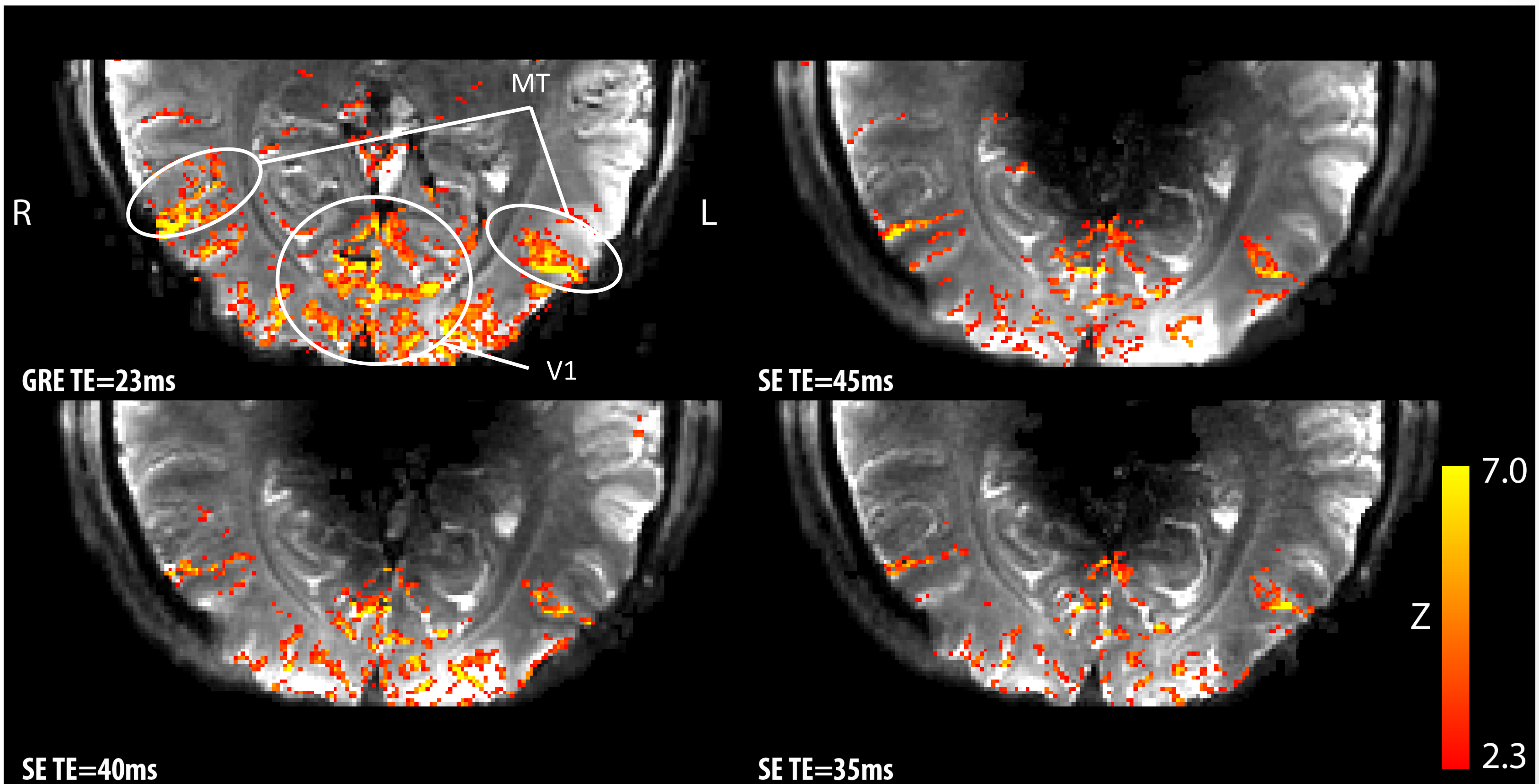
Mapping OCs: 7T Experience

Comparison of different acquisition approaches: SE vs GRE sequence design (1x1x2mm resolution)

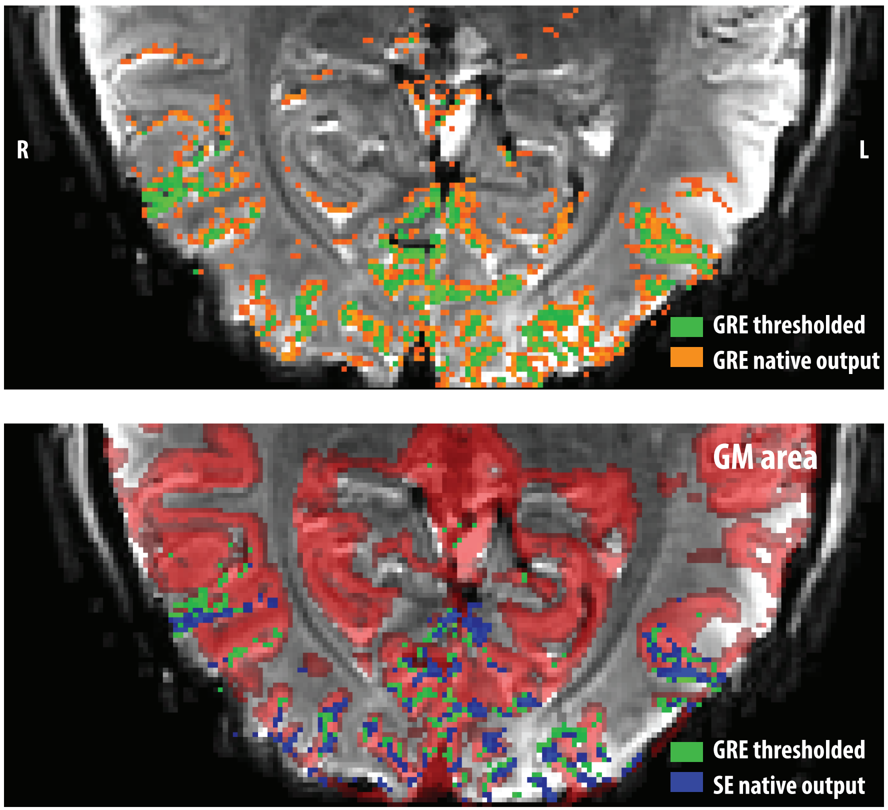
- **Spiral vs Blank block paradigm** Localizes activations primarily in MT and V1 areas.



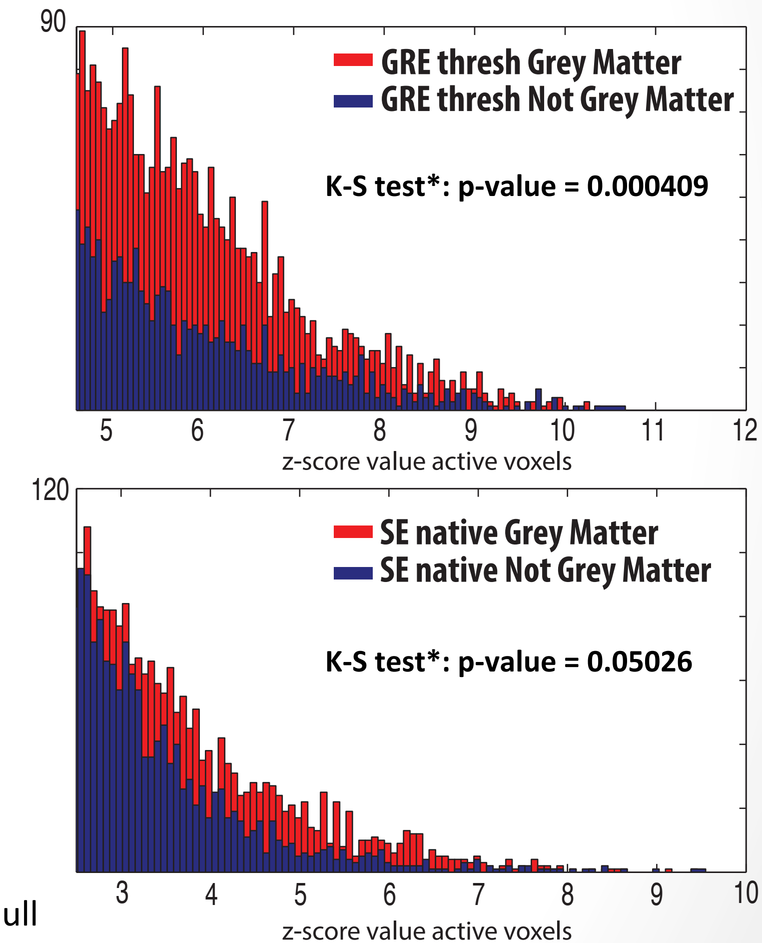
Mapping OCs: 7T Experience

Thresholding on highly active clusters on a GRE acquisition, we were able to isolate the true positive activations with a higher sensitivity than in a SE-based sequence.

Z-score Maps: comparison between GRE and SE activations



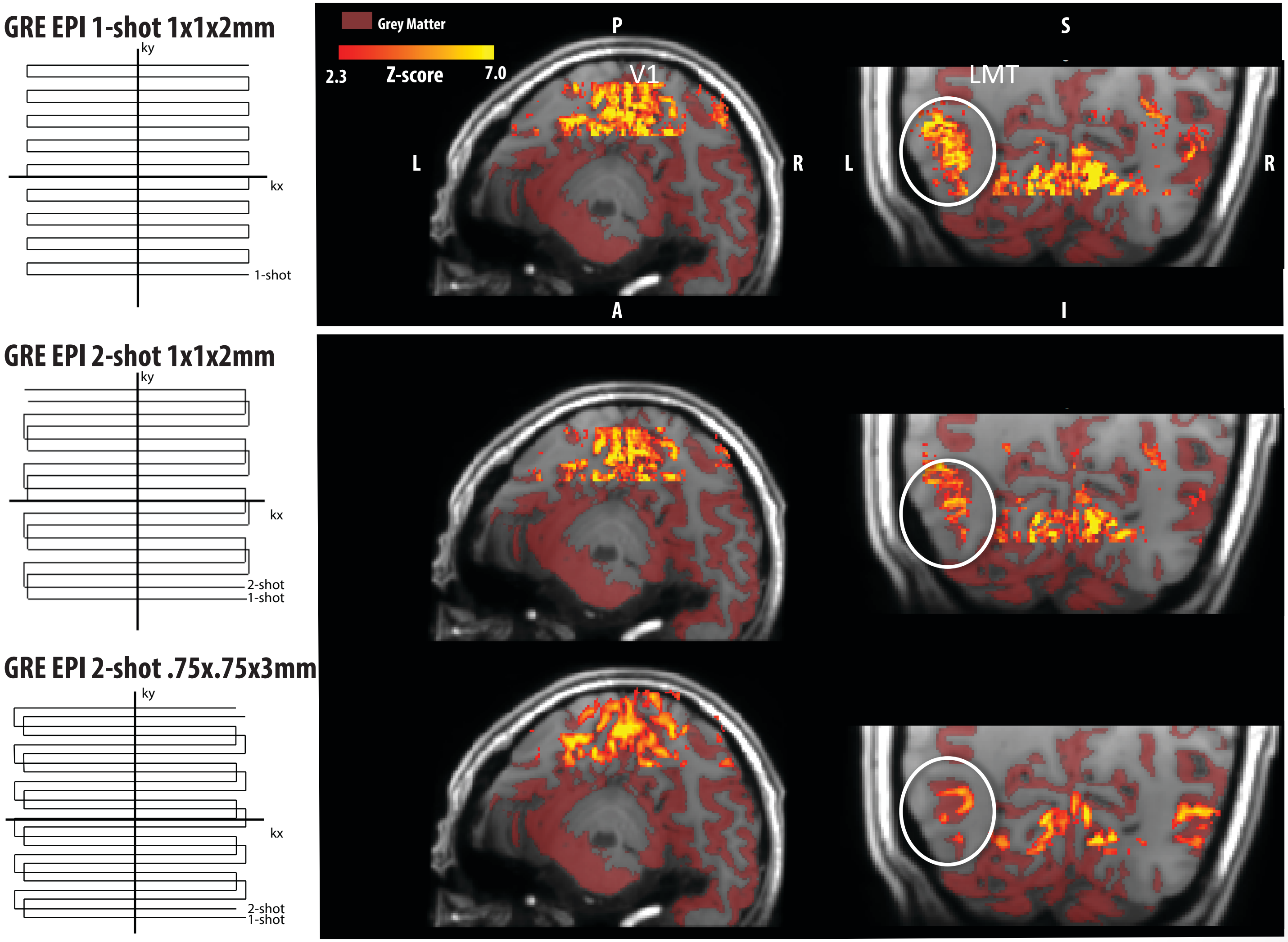
histogram distribution of z-scores



Kolmogorov-Smirnov test: statistic is calculated under the null hypothesis that samples are drawn from the same distribution

Mapping OCs: 7T Experience

Comparison of different acquisition approaches:
GRE sequence design (1-shot vs 2-shot; 1mm2 vs 0.75mm2 resolution)



Mapping OCs: 7T Experience

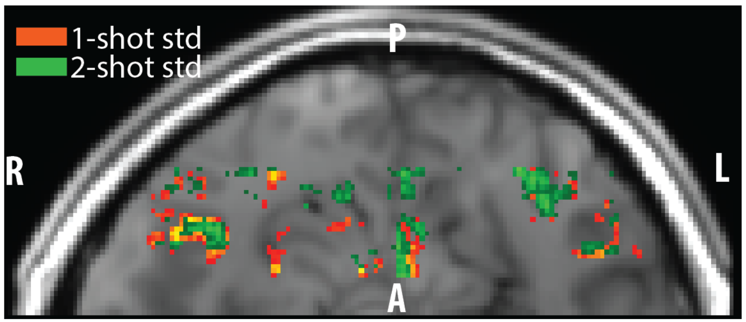
Direct comparison possible between 1-shot vs 2-shot technique:

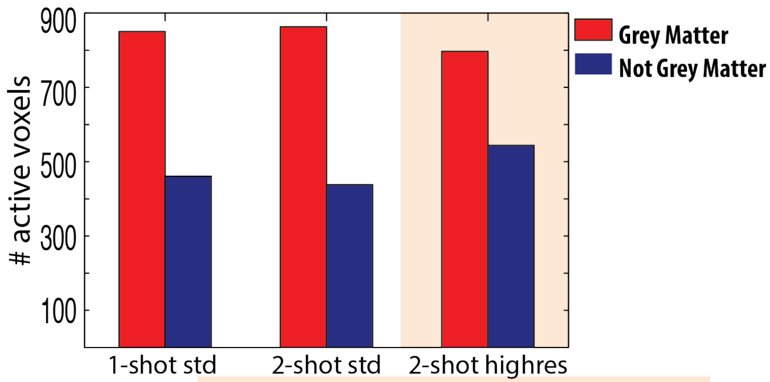
- **BOLD activations are weaker, but trend maintained.**

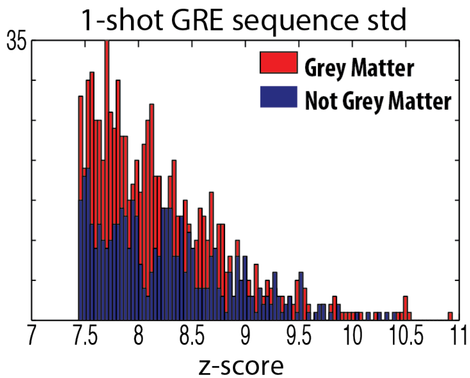
2-shot standard (std) vs high-resolution (highres):

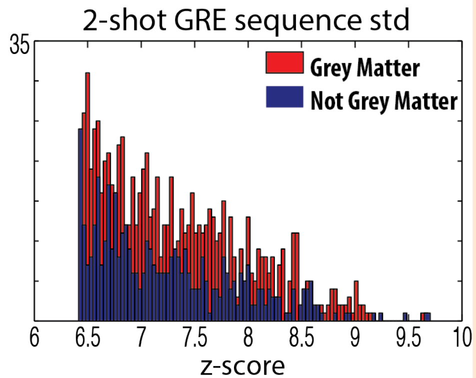
- **Comparison must be made with care since resolution varies.**

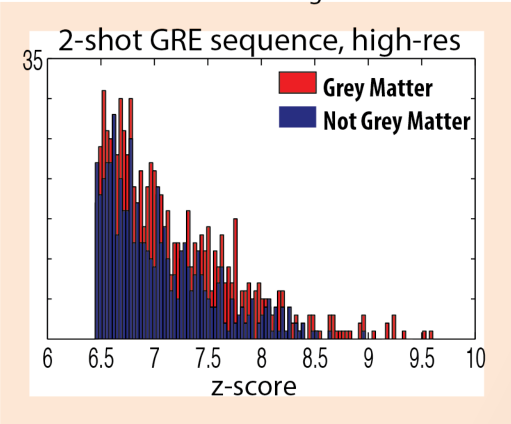
Distribution of 2E3 highest z-scores









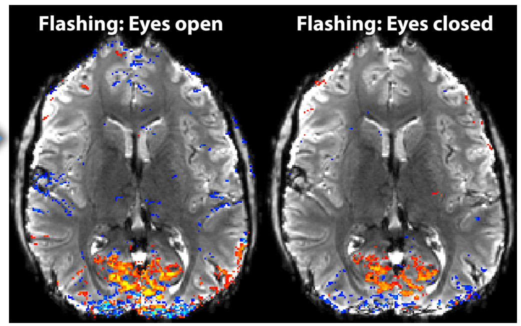


Final Remarks

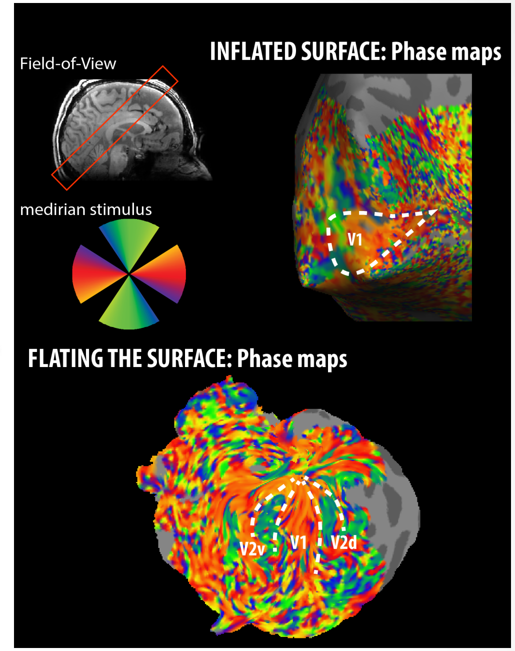
Road to high-resolution fMRI on cortical columns..

Acquisitions at $3mm^2$

Acquisitions at $1mm^2$



Acquisitions at $0.75mm^2$



Still to overcome…

- Image distortions in the occipital lobe due to the field inhomogeneities;
- Physiological artifact time course influences are observed but still very difficult to avoid;
- Head movement in general can decrease SNR and is more problematic at smaller voxel sizes;
- Compromise of small acquisition slab for higher resolution enables correct co-registration to structural.

Acknowledgements

IMAGO7 and Department of Physics

Michela Tosetti

Mauro Costagli

Alberto del Guerra

Mark Symms

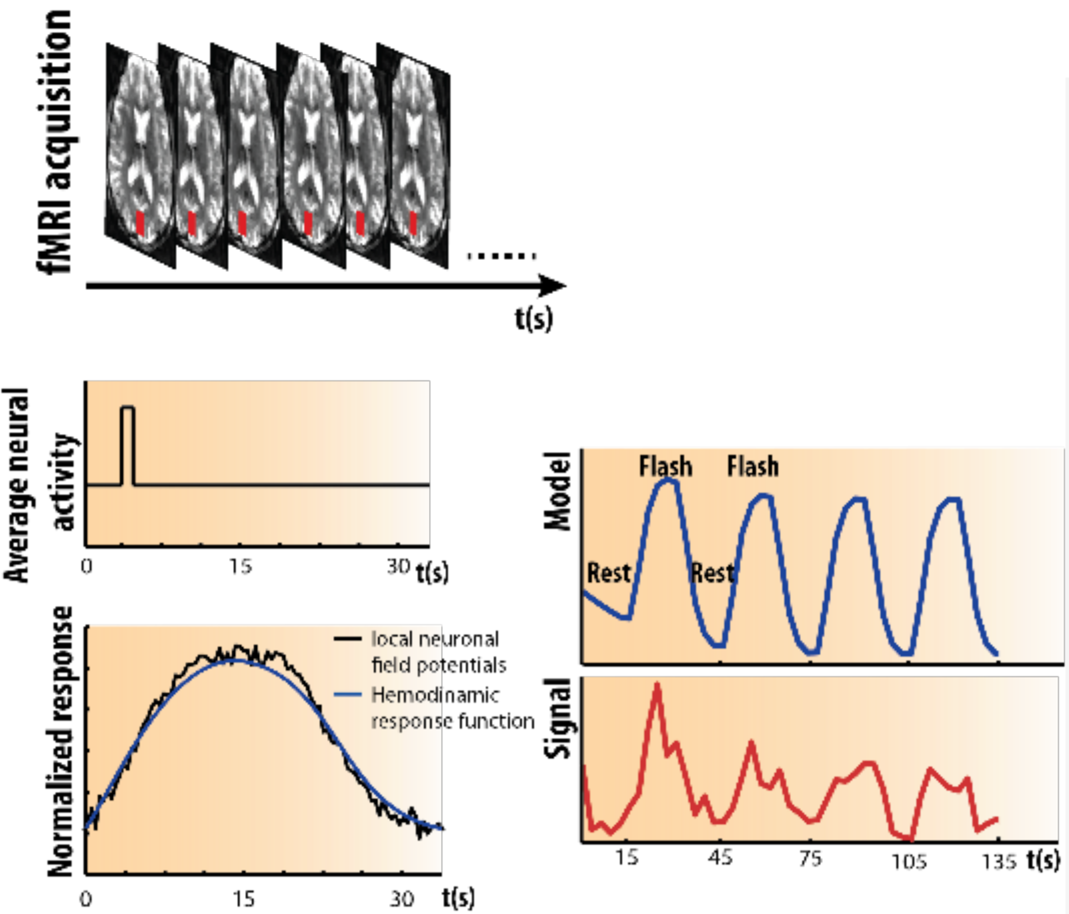
Laura Biagi

HiMR group (Marie Curie training network)

Pisa Vision Lab group

Functional MRI: basis of signal

functional MRI



1. **Neuron dimensions: .004mm up to .1 mm**
   Conventional resolutions around half a centimeter range;

2. **Hemodynamic responses are sluggish**
   Changes observed only ~2*s* after onset of stimulus and reaches maximum 4-8s after;

3. **Ideally we model and fMRI response as a smooth function**
   Magnitude signal changes are very small (0.5 to 3% at 1.5T) and messy.