Scanning at High Fields... 7T and Beyond

José P. Marques, Rolf Gruetter

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3.0

Structural imaging

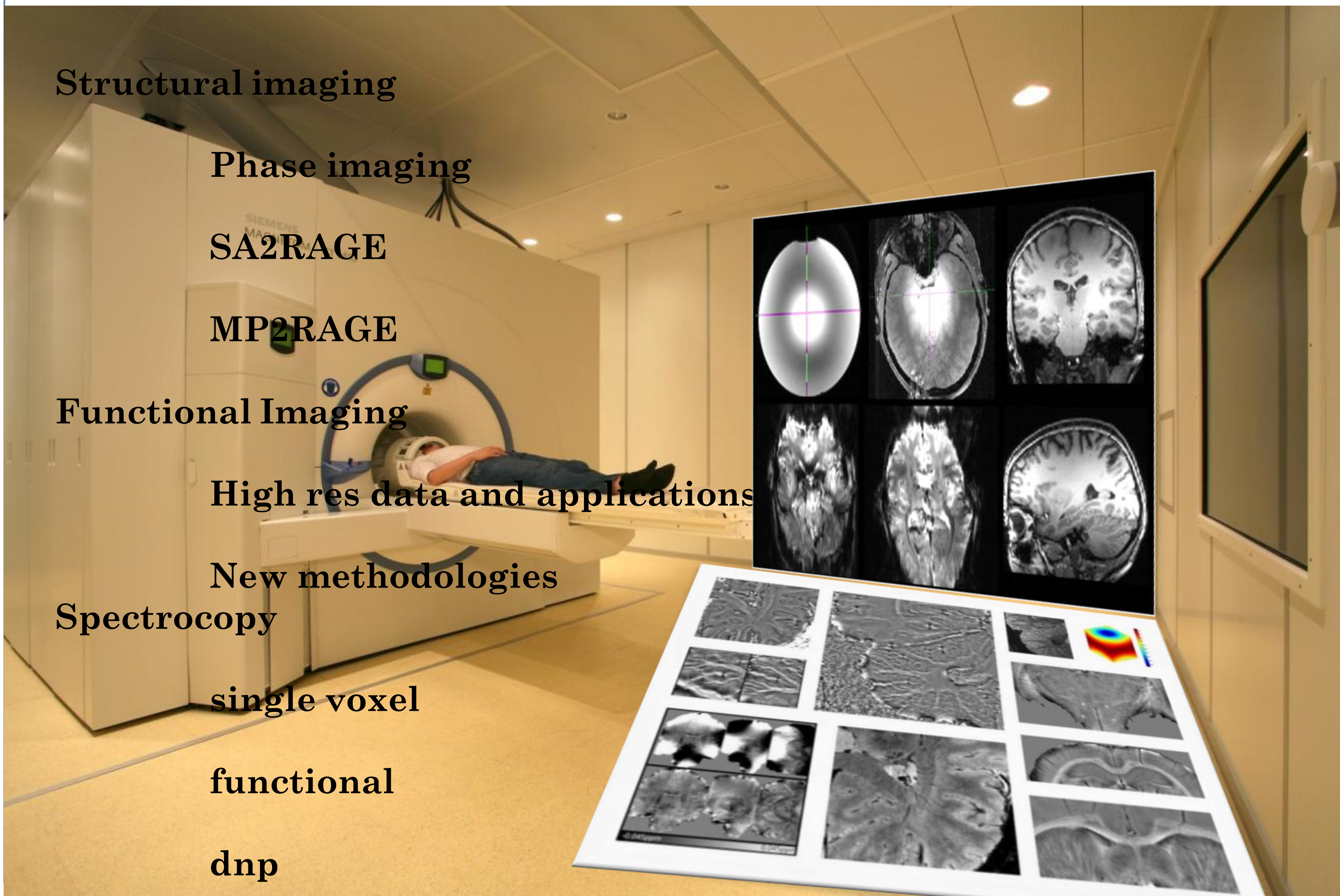
- Phase imaging
- SA2RAGE
- MP2RAGE

Functional Imaging

- High res data and applications
- New methodologies

Spectrocopy

- single voxel
- functional
- dnp



-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

Revisiting the pros and cons of 7T

PROS	**CHALLENGES**
Higher SNR $\propto B_0^{1-1.5}$	
Increased susceptibility related contrast	More susceptibility induced distortion (specially in EPI)
Useful for T_1 contrast and perfusion	Longer T_1 (slower imaging)
	B_1 inhomogeneity, high SAR
Increased T_2^* /BOLD contrast	Shorter T_2^* (less time to image)
Increase in BOLD specificity	

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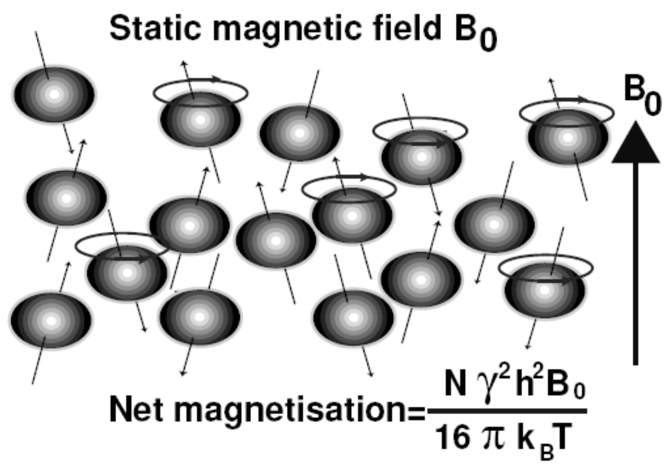

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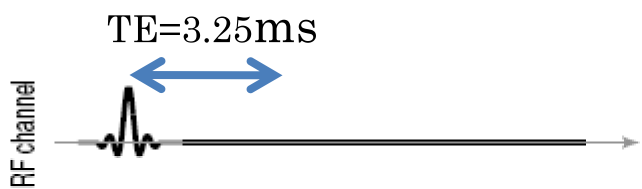
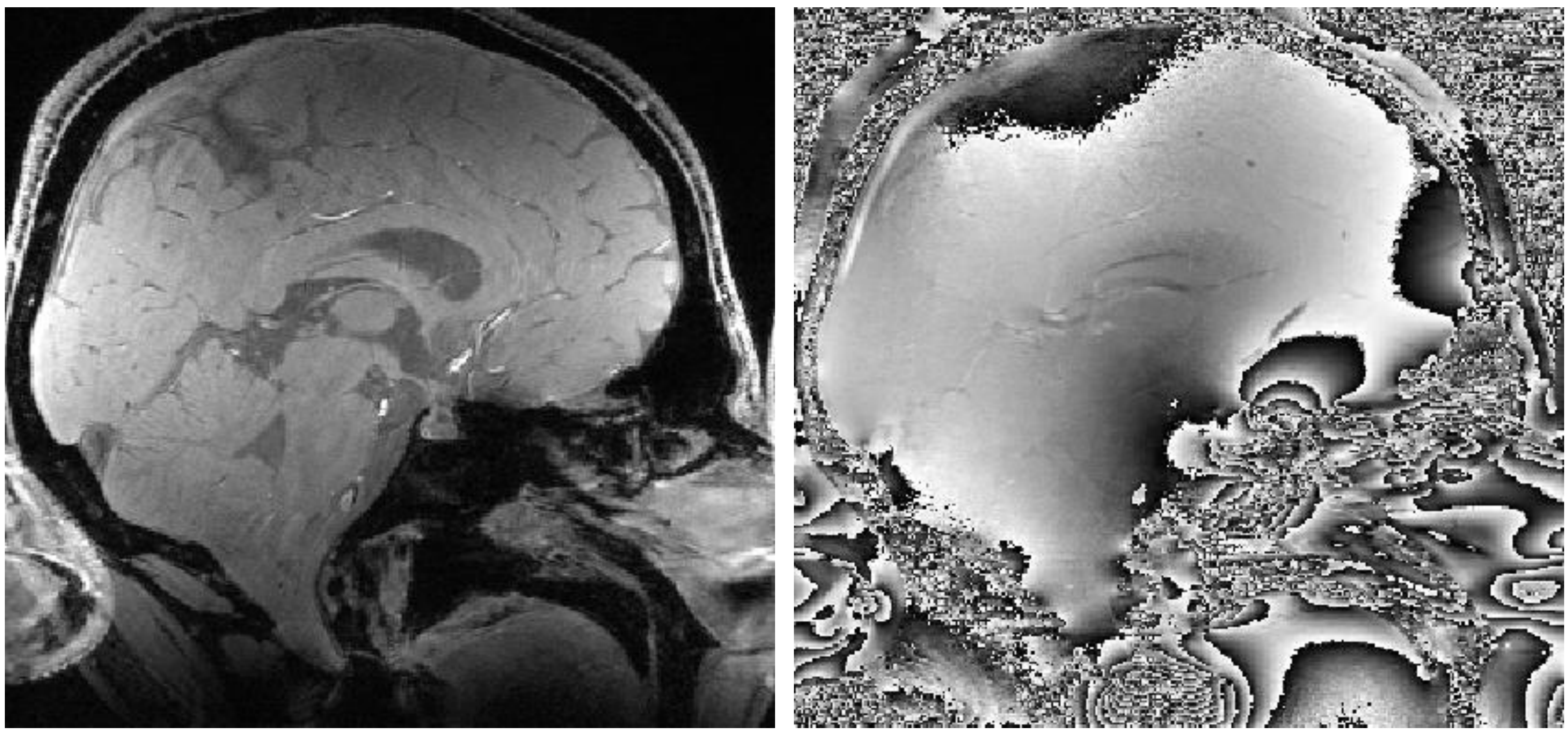
The **magnetic susceptibility**, χ, induced magnetization, M, of a material in response to an applied magnetic field, H, is characterized

$$\vec{M} = \chi \vec{H}$$

Susceptibility related contrast



$$M^{+}(TE) = m_0 e^{-TE/T_2^*} e^{-i\Delta\omega TE} = m_0 e^{-TE/T_2^*} e^{-i\gamma\Delta B_0 TE}$$



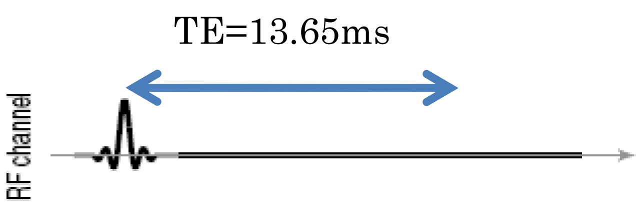
$$\vec{B} = \mu_0 (1+\chi)\vec{H}$$

Susceptibility related contrast

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging



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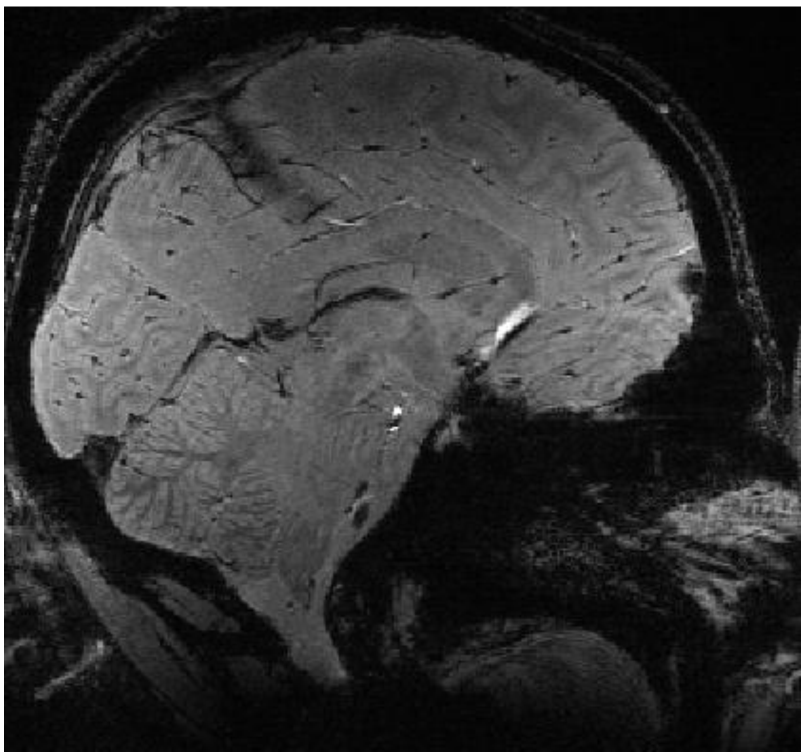

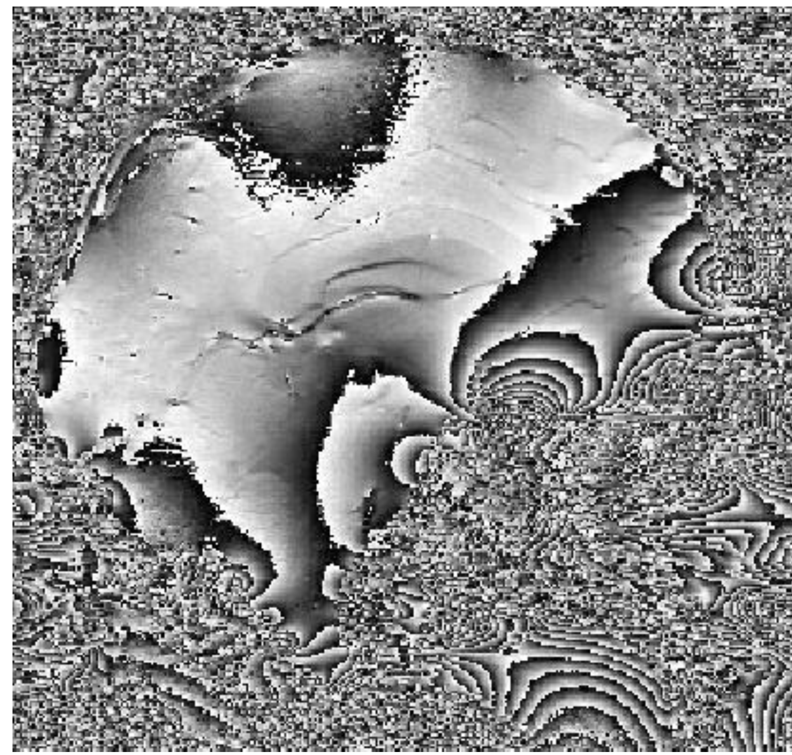

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Susceptibility related contrast

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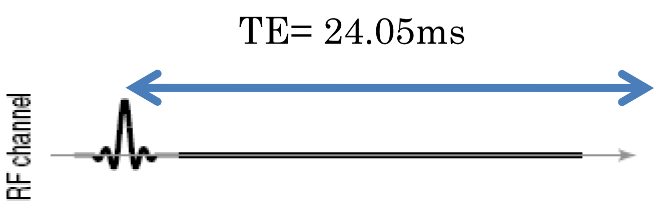

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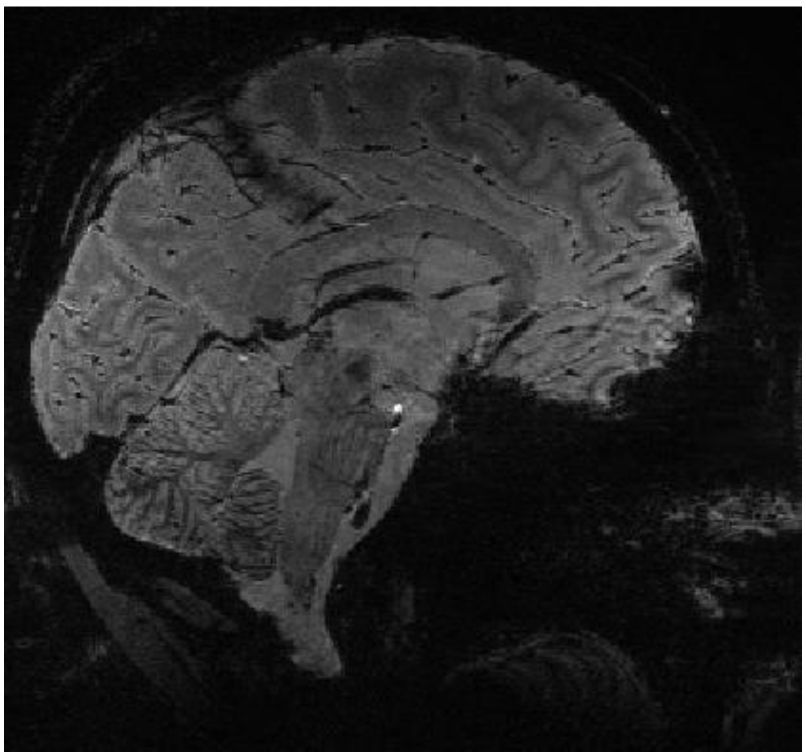
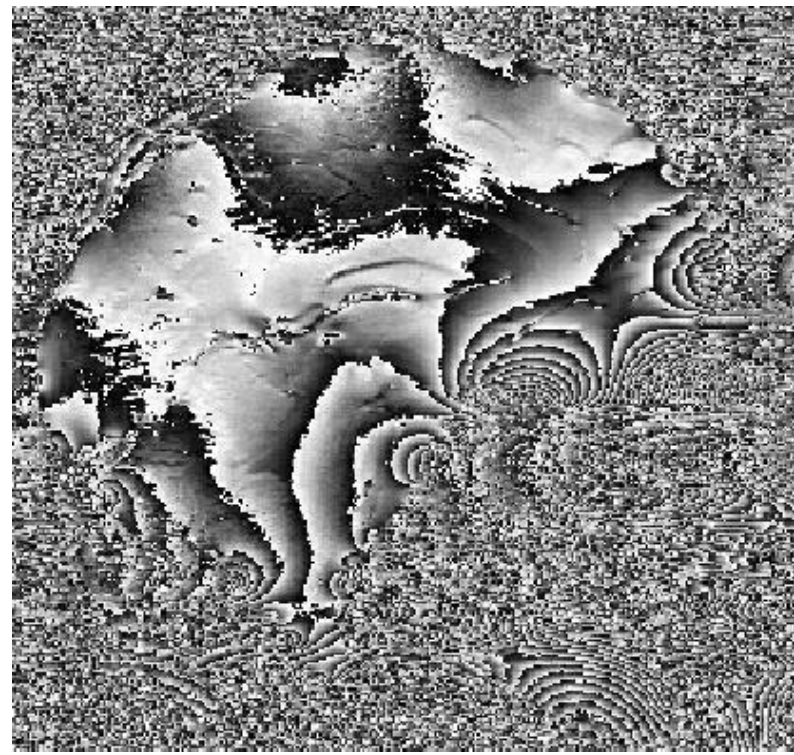
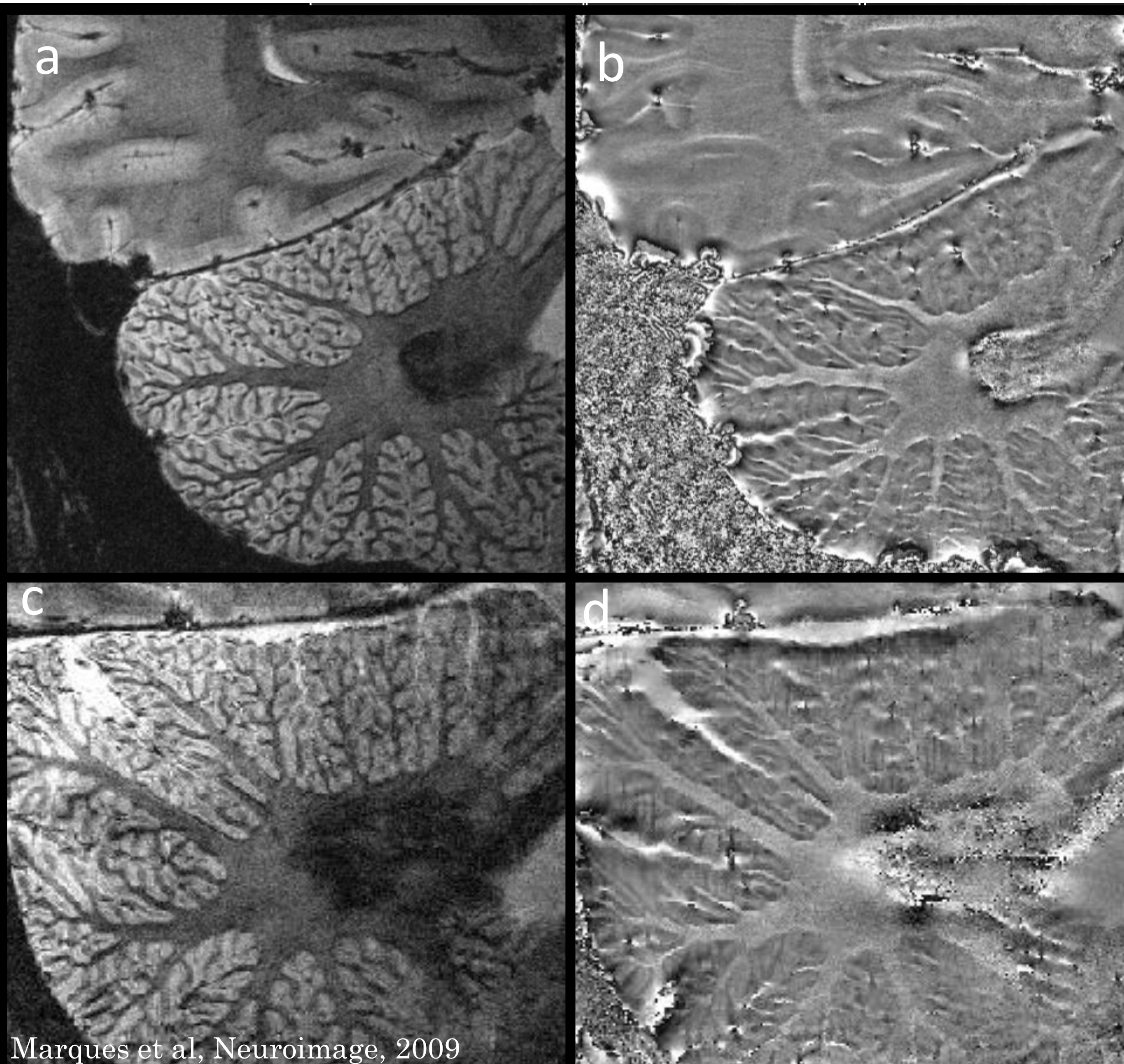




$$\vec{B} = \mu_0 (1+\chi)\vec{H}$$

T_2^* weighted and Phase contrast



T2*-weighted oblique sagittal multi-slice gradient echo (GRE)

TE 25 ms
TR 980 ms,
flip angle 65°,
bandwidth 30 kHz,

Matrix 960×960,
Slice thickness
1 mm-0.8 mm

FOV 115×115 mm
(i.e. in-plane resolution =
120×120 μm)

Marques et al,
Radiology, 2010

T_2^* weighted and Phase contrast

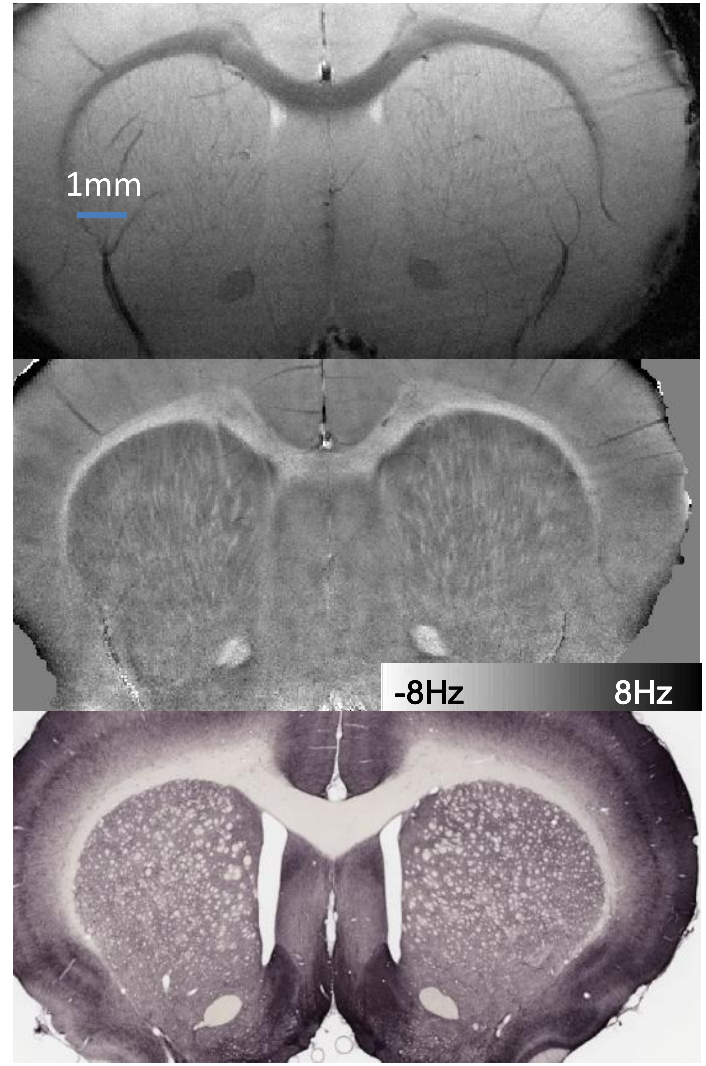
T_2^* weighted and Phase contrast

Magnitude GRE

33x33x500 μm^3, 70 min

Phase imaging

KChIP1



histochemistry: www.brainmaps.org

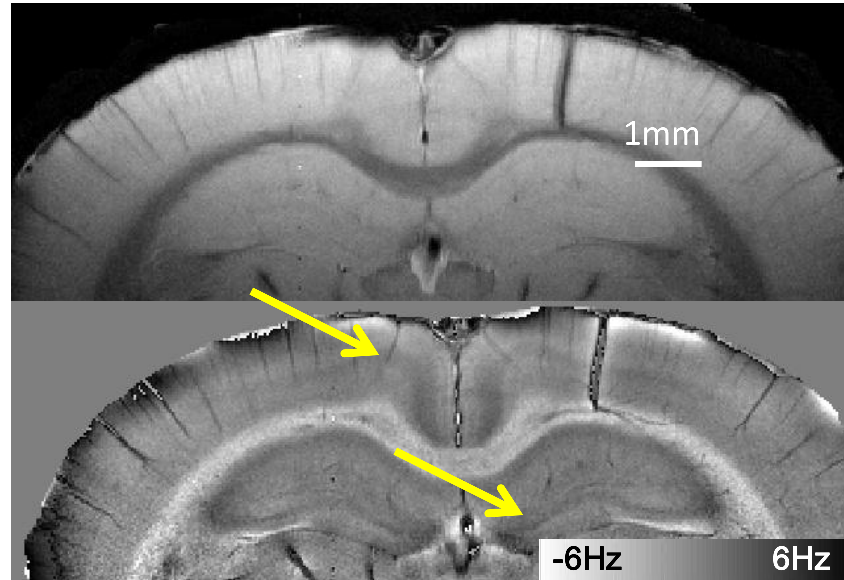
Marques et al, Neuroimage, 2009

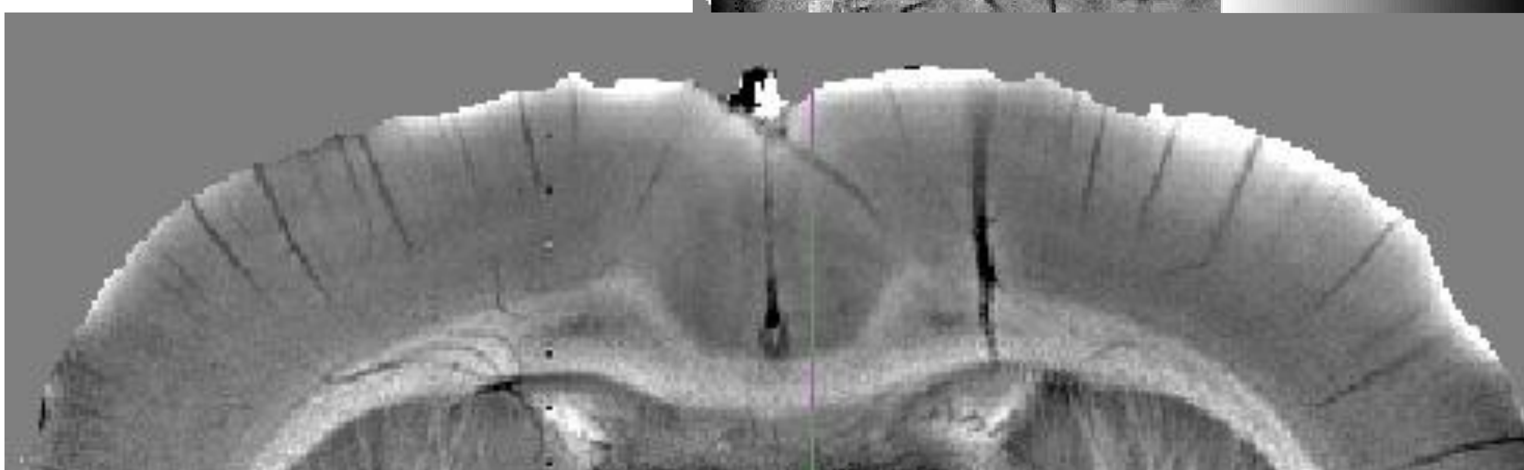
T_2^* weighted and Phase contrast

Magnitude GRE

39x39x400 μm³, 68 min

Phase imaging





Marques et al, Neuroimage, 2009

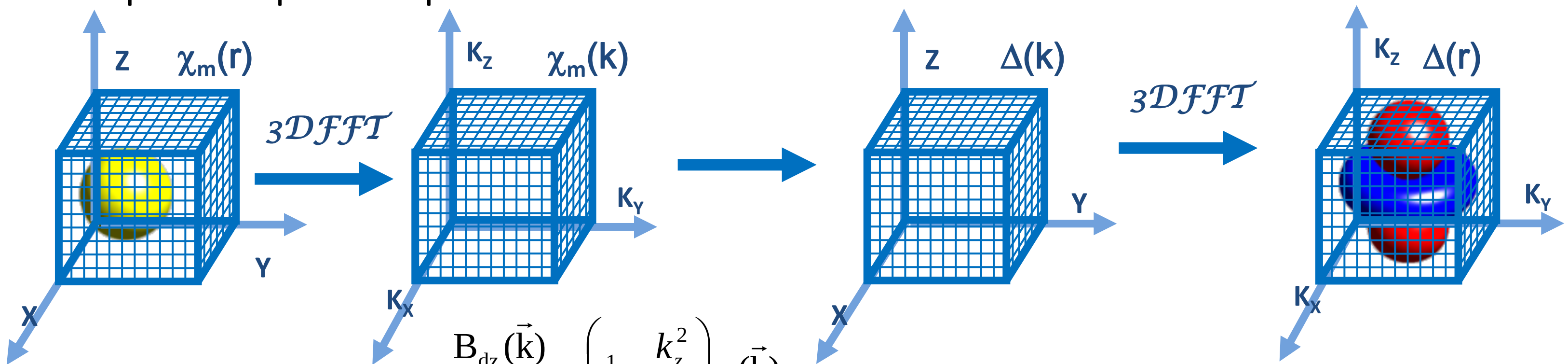
from a susceptibility distribution to a field perturbation

-Structural imaging

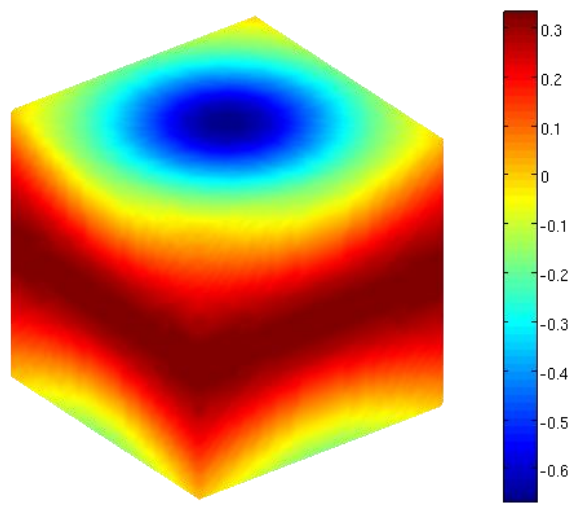
-Functional imaging

- Spectroscpy and metabolic imaging

the simple example of a sphere…



$$\frac{B_{dz}(\vec{k})}{B_0} = \left(\frac{1}{3} - \frac{k_z^2}{k^2}\right)\chi(\vec{k})$$



Salomir *et al,* Conc. Magn. Reson B. 19, 2003; Marques and Bowtell, Conc. Magn. Res. B, 25, 2005

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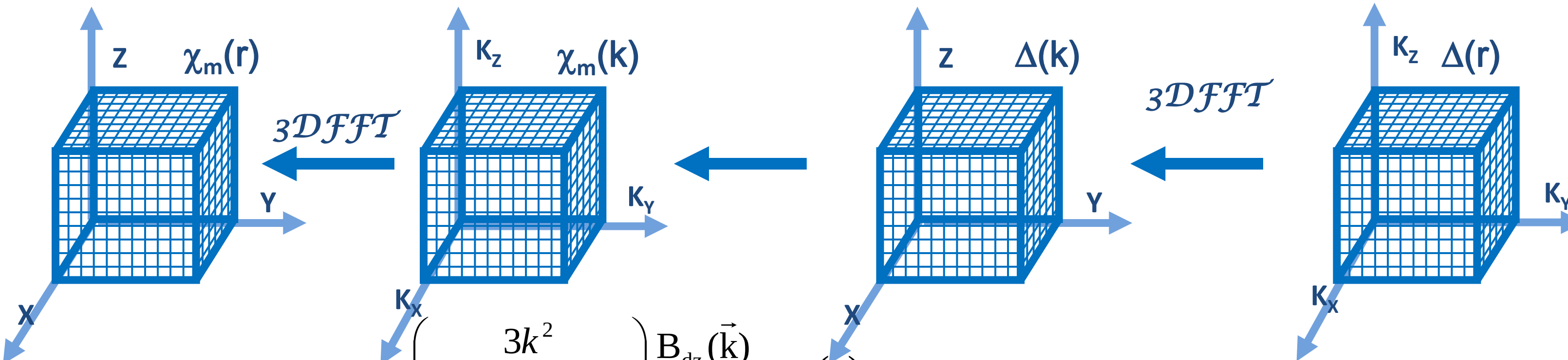
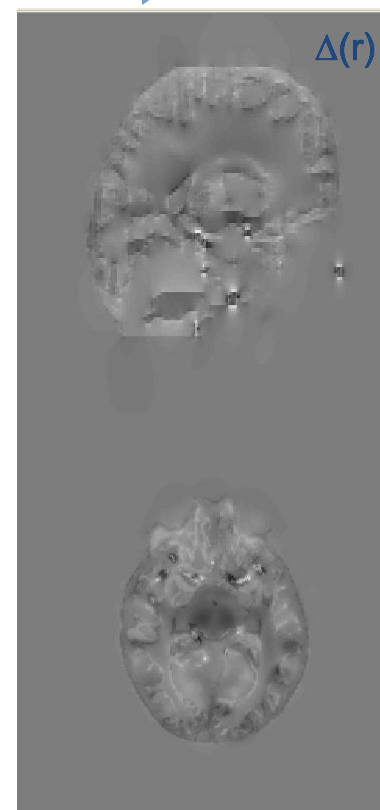


$$\left(\frac{3k^2}{k_x^2+k_y^2-2k_z^2}\right)\frac{B_{dz}(\vec{k})}{B_0} = \chi(\vec{k})$$

The flaws in the plan:

- have you really measured a field?
- field measured is not B_{dz}, but M B_{dz} ;
- dominating effects are those due to susceptibility of air/tisue boundaries…
- the inverse problem is ill-conditioned;



More on the ill conditioning

-Structural imaging

-Functional imaging

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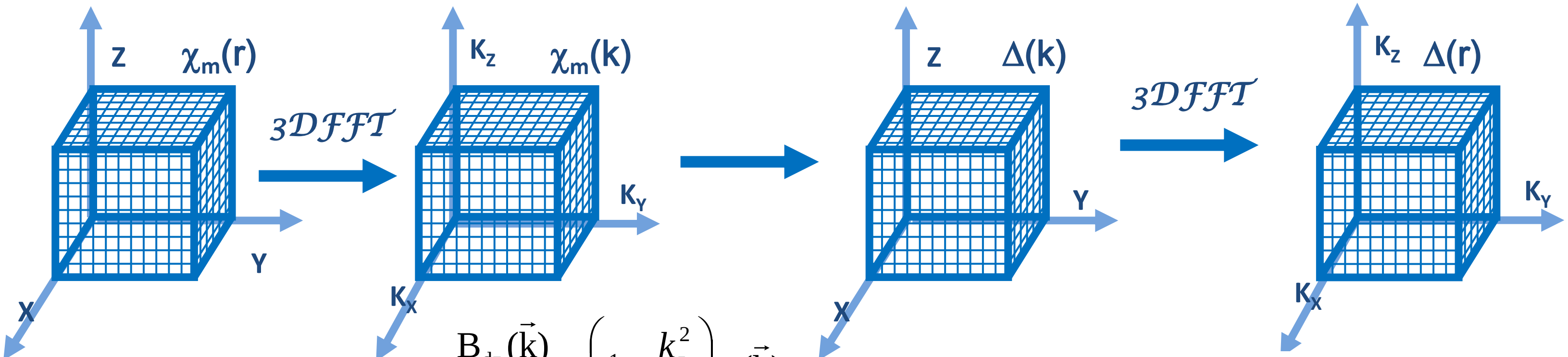
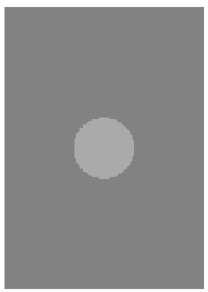
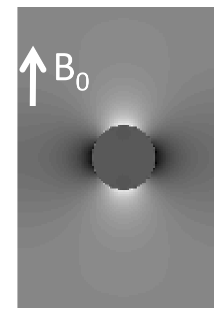
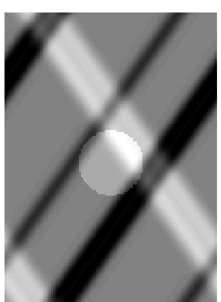


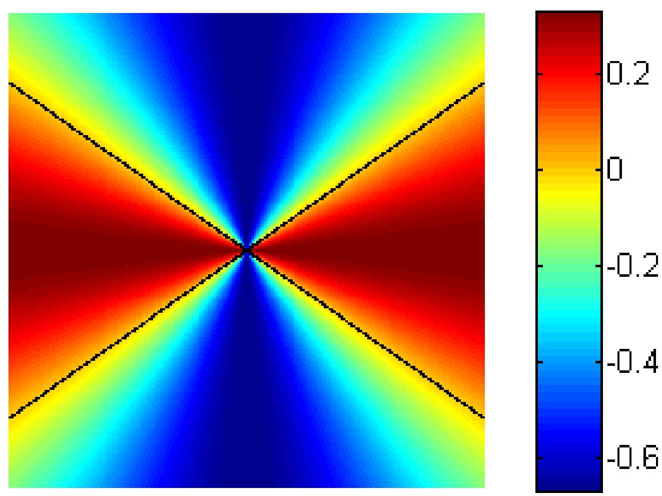
$$\frac{B_{dz}(\vec{k})}{B_0} = \left(\frac{1}{3} - \frac{k_z^2}{k^2}\right)\chi(\vec{k})$$

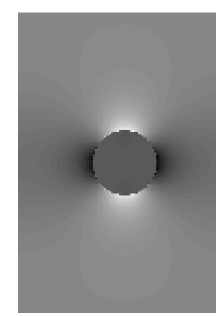
$$\Delta(\vec{k}) = C(\vec{k})\chi(\vec{k})$$







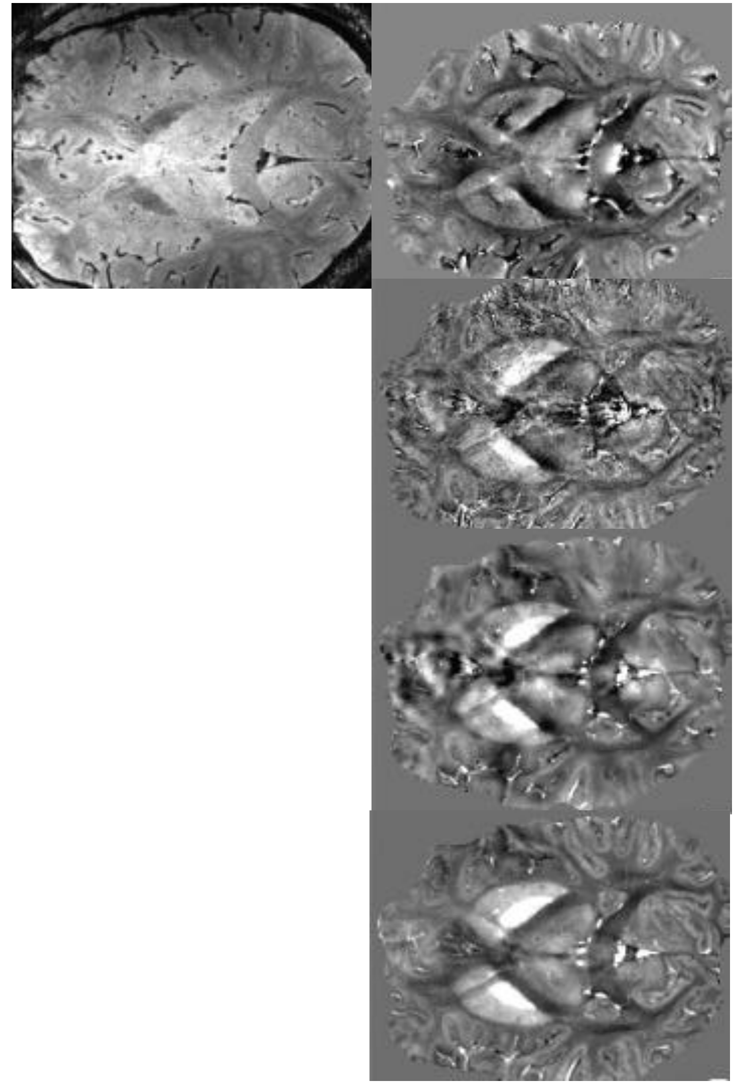




from a field perturbation to a susceptibility distribution

4 classes of options:

- piece-wise constant
  - Weisskoff et al, MRM, 1992
  - Neelavalli et al, JMRI, 2009
  - Rochefort et al, MRM, 2008
- single orientation thresholded
  - Shmueli et al ,MRM, 2009
  - Wharton et al, MRM, 2010
- single orientation regularized
  - Kressler et al ,IEEE TMI, 2009
  - Rochefort et al, MRM, 2010
- multiple orientations
  - Marques et al, Concepts, 2005
  - Liu et al, MRM, 2009
  - Wharton et al, MRM, 2010



S. Wharton et al, Neuroimage, 2010

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

But,

and what is contributing to this susceptibility?

do we really know the forward problem?

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RF transmit field inhomogeneity

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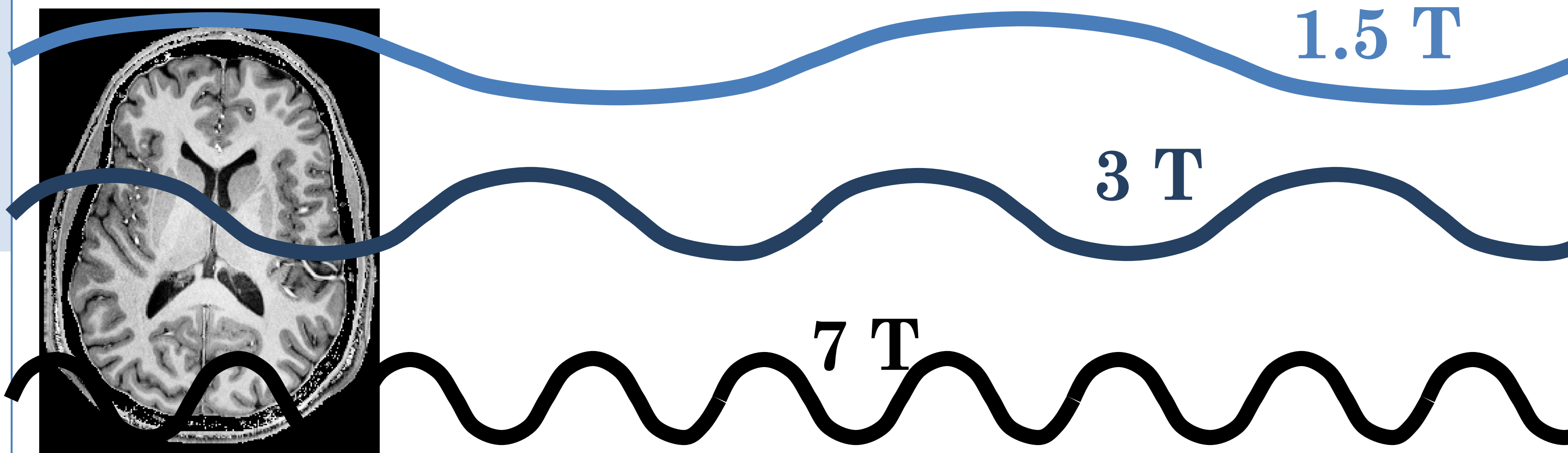
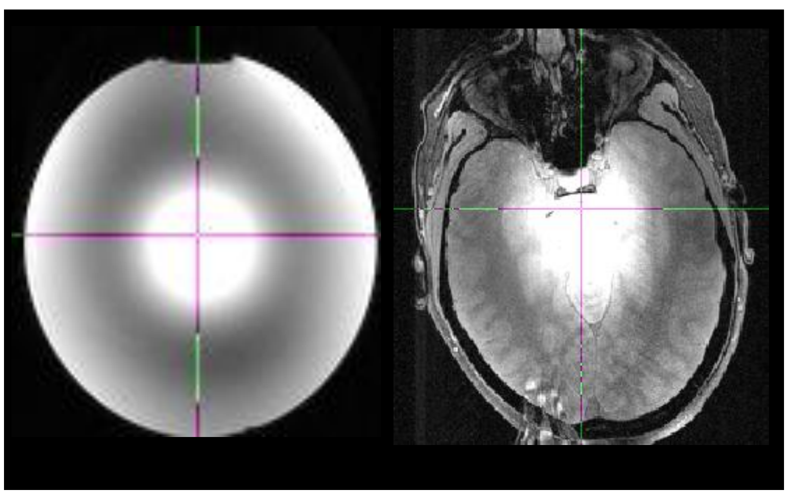


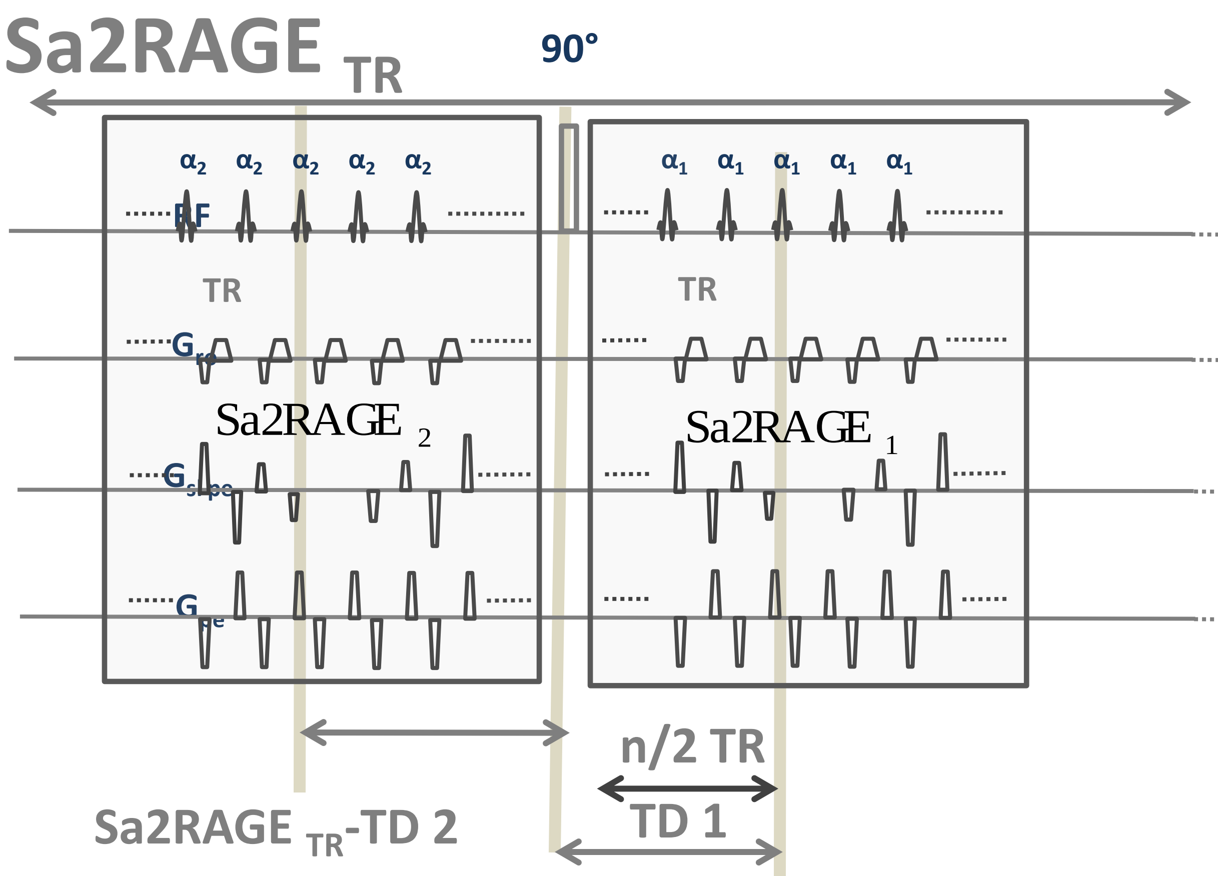


$$\omega \propto B_0$$

$$\lambda \propto \frac{1}{B_0}$$

$$SAR \propto \omega^2$$

Sa2RAGE: B1 mapping



low SAR, 3D, fast, phase sensitive and **accurate**

$Sa2RAGE_{TR}$ =2 secs

TR_{GRE}=3ms

TD_1=0.1s

TD_1=1.6s

α_1, α_2=5,13^0

matrix 64x64x16

Total time 32 secs

F. Eggenschwiller et al, MRM, in press

-Structural imaging

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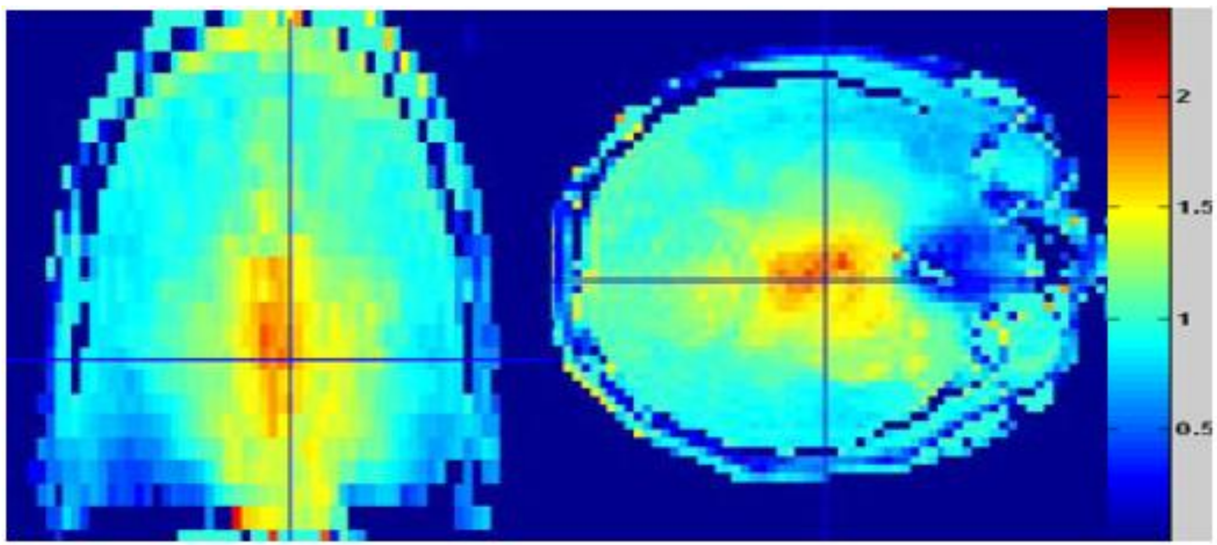
- Spectroscpy and metabolic imaging

Sa2RAGE: B1 mapping

Human studies, T_1 independence



low SAR, 3D, fast, phase sensitive and **accurate**

F. Eggenschwiller et al, MRM, in press

$Sa2RAGE_{TR}$ =2 secs

TR_{GRE}=3ms

TD_1=0.1s
TD_1=1.6s

α_1, α_2=5,13^0

matrix 64x64x24

Total time 48 secs

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

measuring is the first step to correcting.

but wouldn’t it be great if there was no need to correct it?

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T_1 weighted - MP2RAGE

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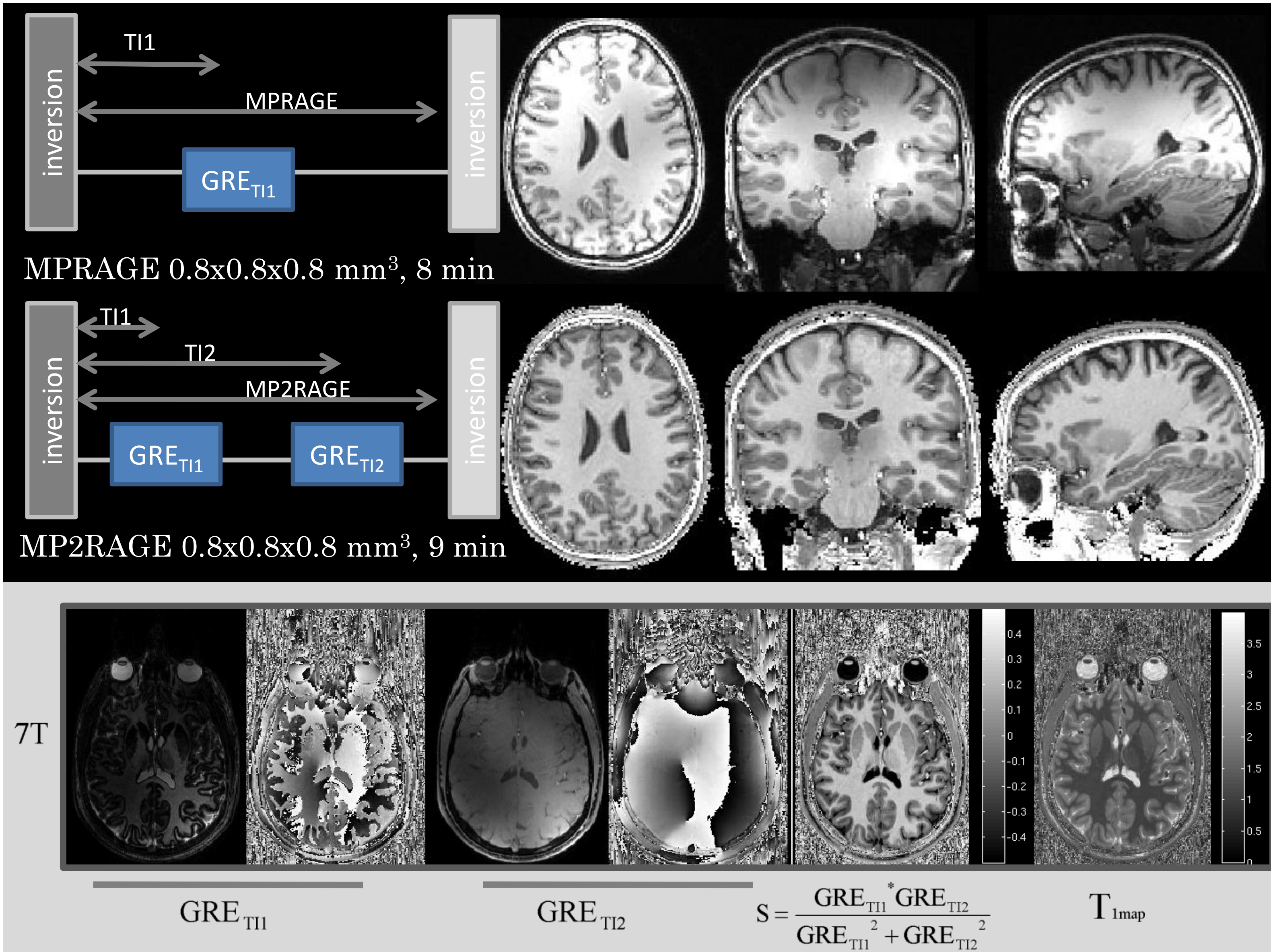

Marques JP, Kober T et al, Neuroimage, 2010

T_1 weighted - MP2RAGE @7T

-Structural imaging

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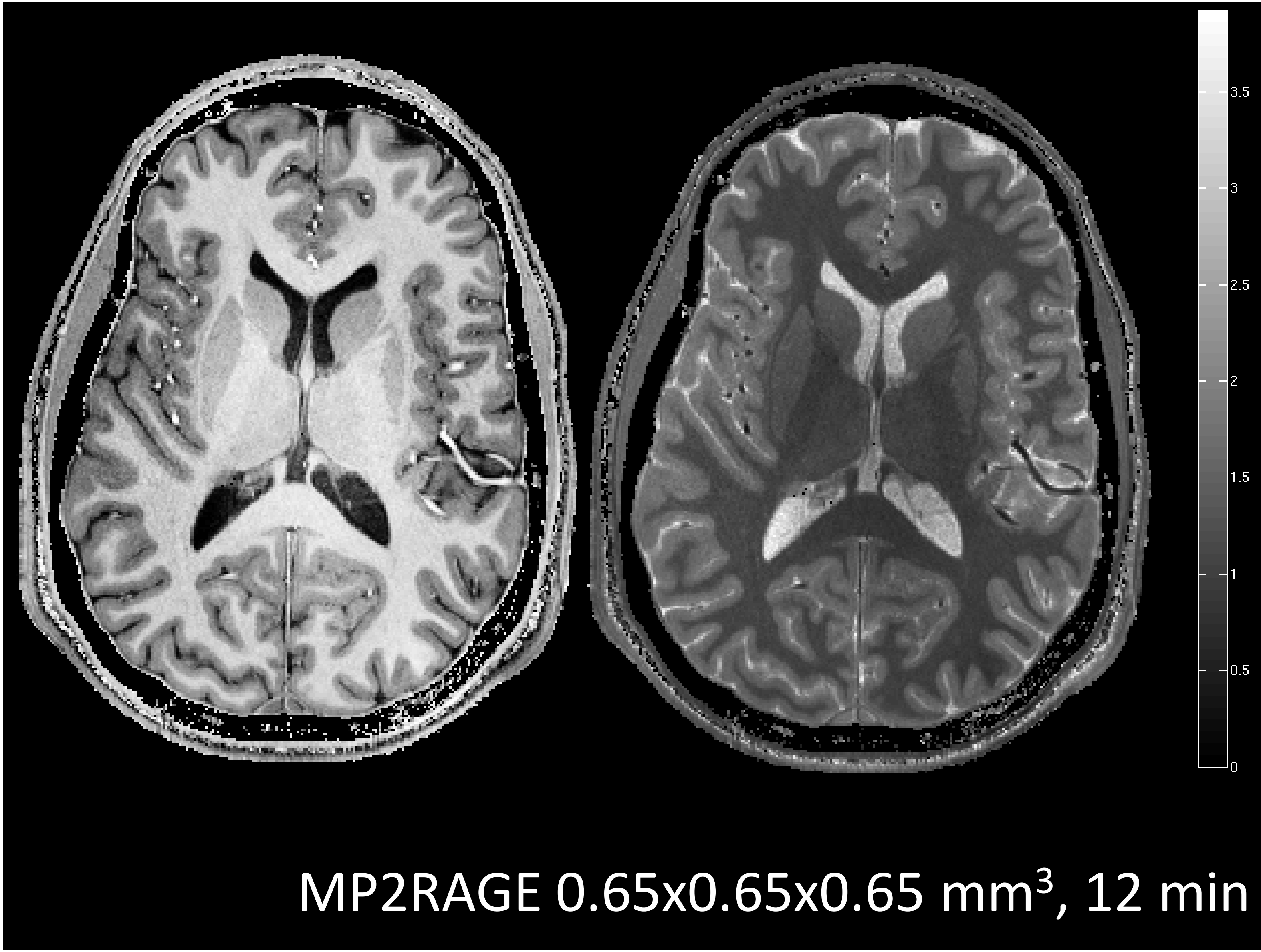

-Structural imaging

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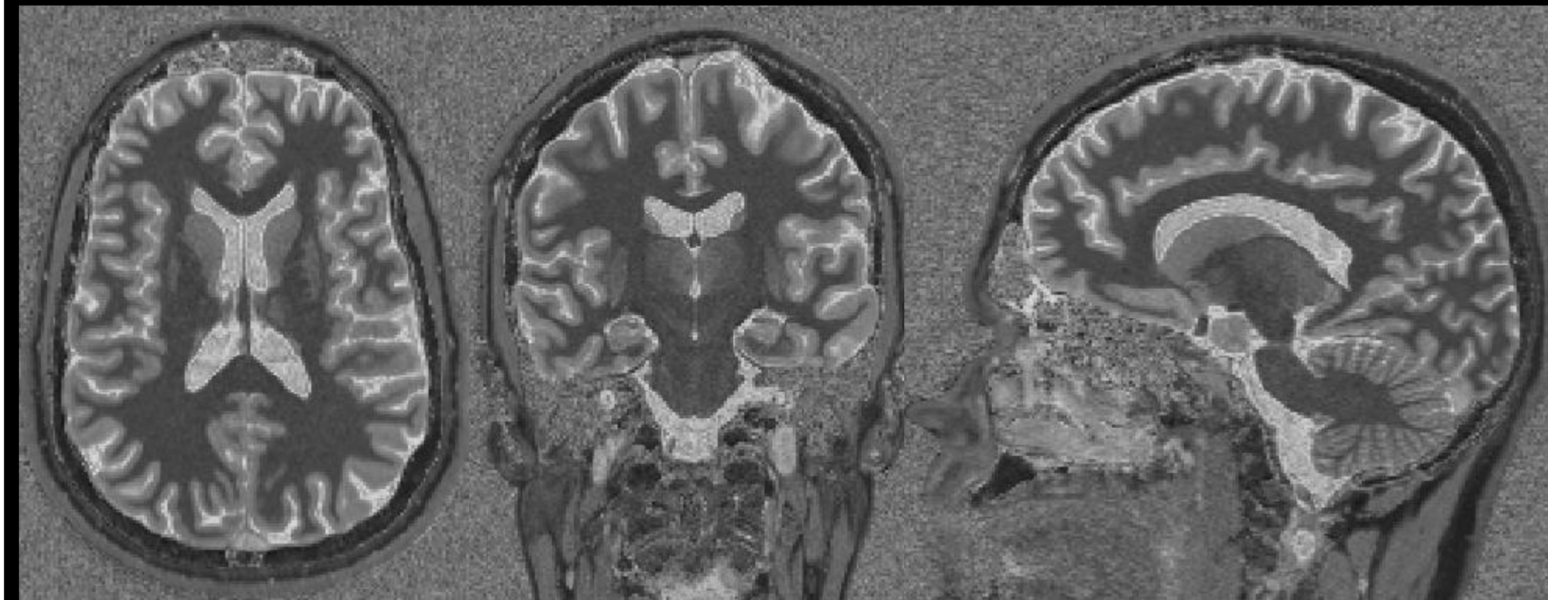
technology going down the field

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

Applications @ 3T - T_1 maps



study	Magnetic Field	T_1(s) White Matter	Putamen	Nucleus caudate	Gray Matter	Method
Wansapura	3T	0.79±0.01			1.28±0.02	Saturation recovery, seven TR's, single slice, 3mm
Lu	3T	0.76±0.05	1.10±0.04	1.25±0.06	1.16±0.11	Inversion recovery, 10 TI's, single slice, single slice, 6mm
Wright	3T	0.84±0.05	1.33±0.07	1.39±0.05	1.61±0.10	MPRAGE, 8 TI's, 20 slices, 15mm
this study	3T	0.81±0.03	1.13±0.07	1.25±0.07	1.35±0.05	MP2RAGE, 160 slice, 1mm

MP2RAGE 1x1x1 mm^3, 8 min

Marques JP, Kober T et al, Neuroimage, 2010

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compressed sensing

-Structural imaging

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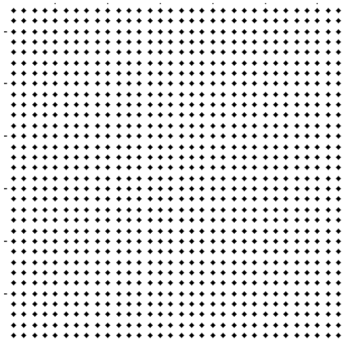

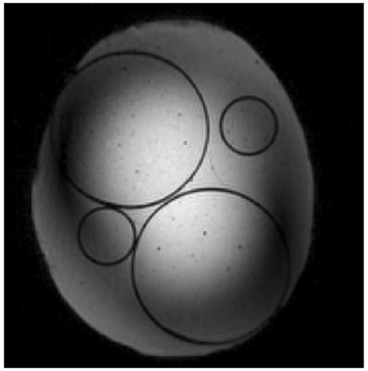

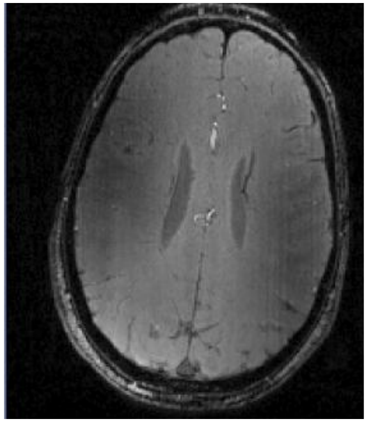

Puy G, IEEE TMI, 2011 submitted; collaboration with Yves Wiaux from the CIBM signal processing core

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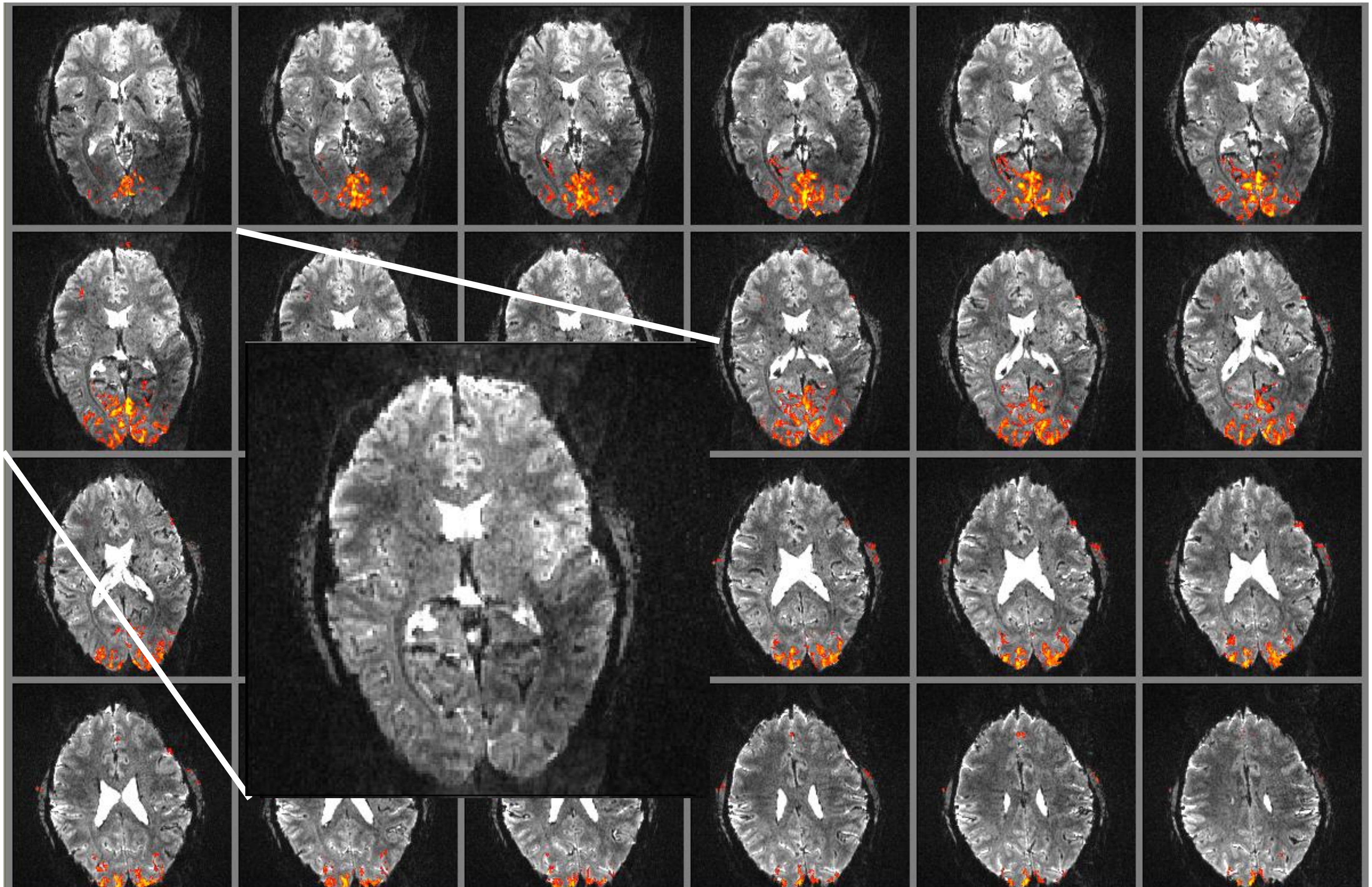
Whole Brain Coverage fMRI

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging



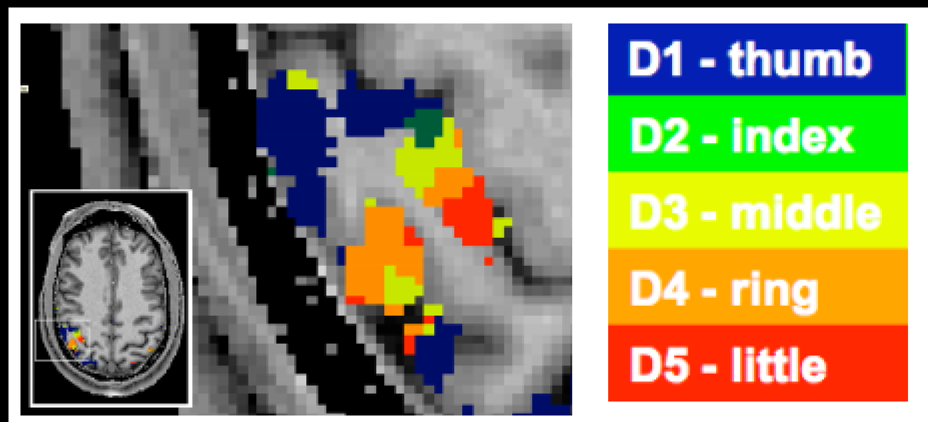
192 x 192 matrix, TE = 29 ms, speed-up factor 2, 6/8 k-space sampling, BW 1132 Hz/pixel, visual task, total acquisition time: 3 min 20 secs

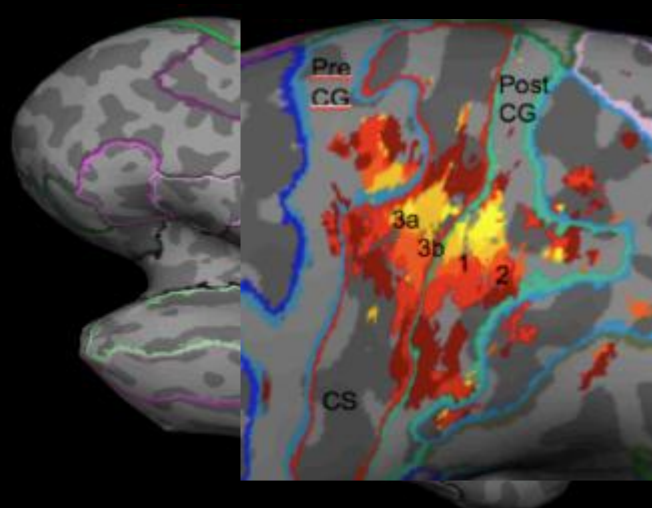
Somatotopy

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging





Manual stroking
D1, D3, D5, D2, D4
Act 20s – rest 10s Tacq 20 minutes.

Scan parameters:

Transverse oblique planes
FOV = 160 mm
Res= 1.3 x 1.3 x 1.3 mm,

TE / TR =
25 ms / 2.5 s

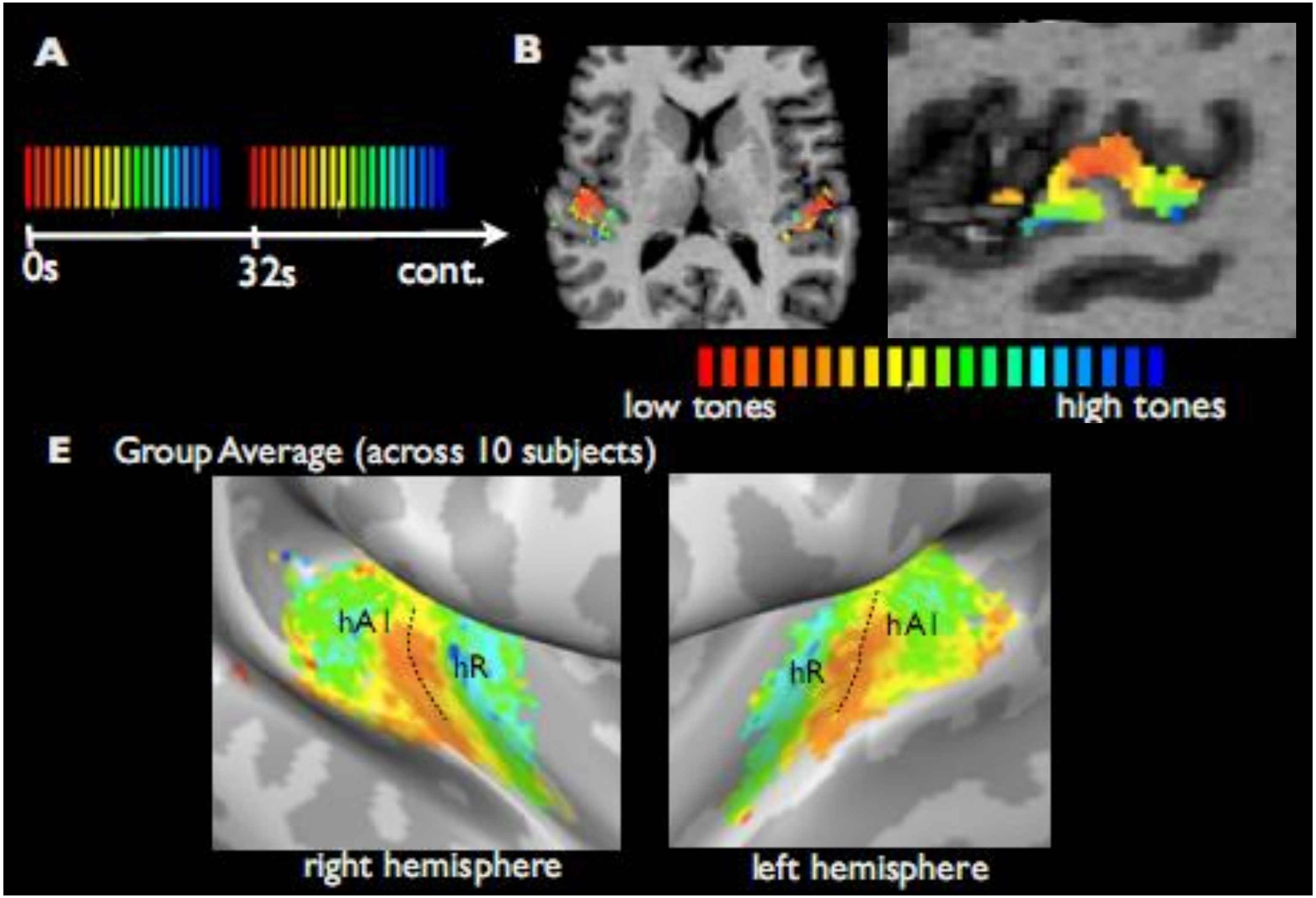
GRAPPA = 2 was used to optimise TE

Examples - tonotopy

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging



Da Costa S et al, Journal of Neuroscience, in press many slices - long acquisition times

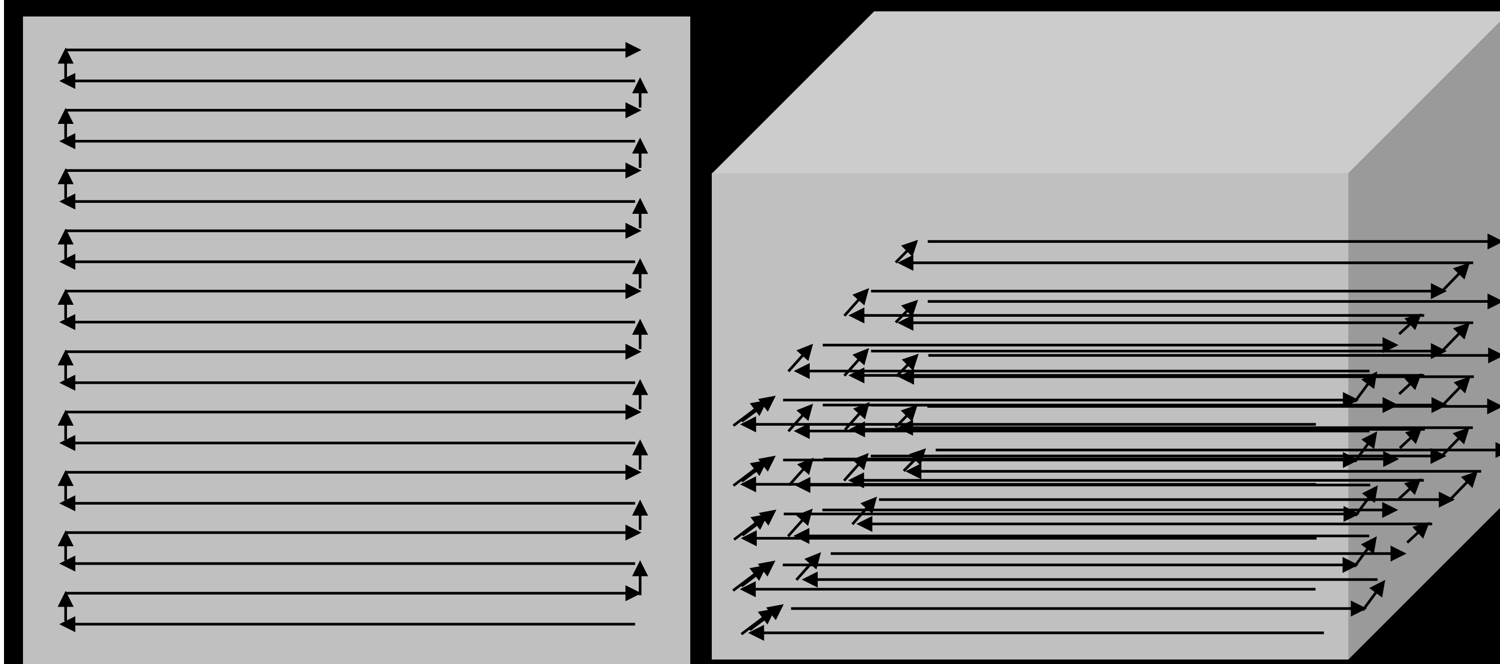
New k-space trajectories

'normal' multi-slice EPI:

2-dimensional k-space

segmented EVI:

3-dimensional k-space



van der Zwaag W. et al, Proc. ISMRM, 1550, 2009
Poser B, Neuroimage, 2010

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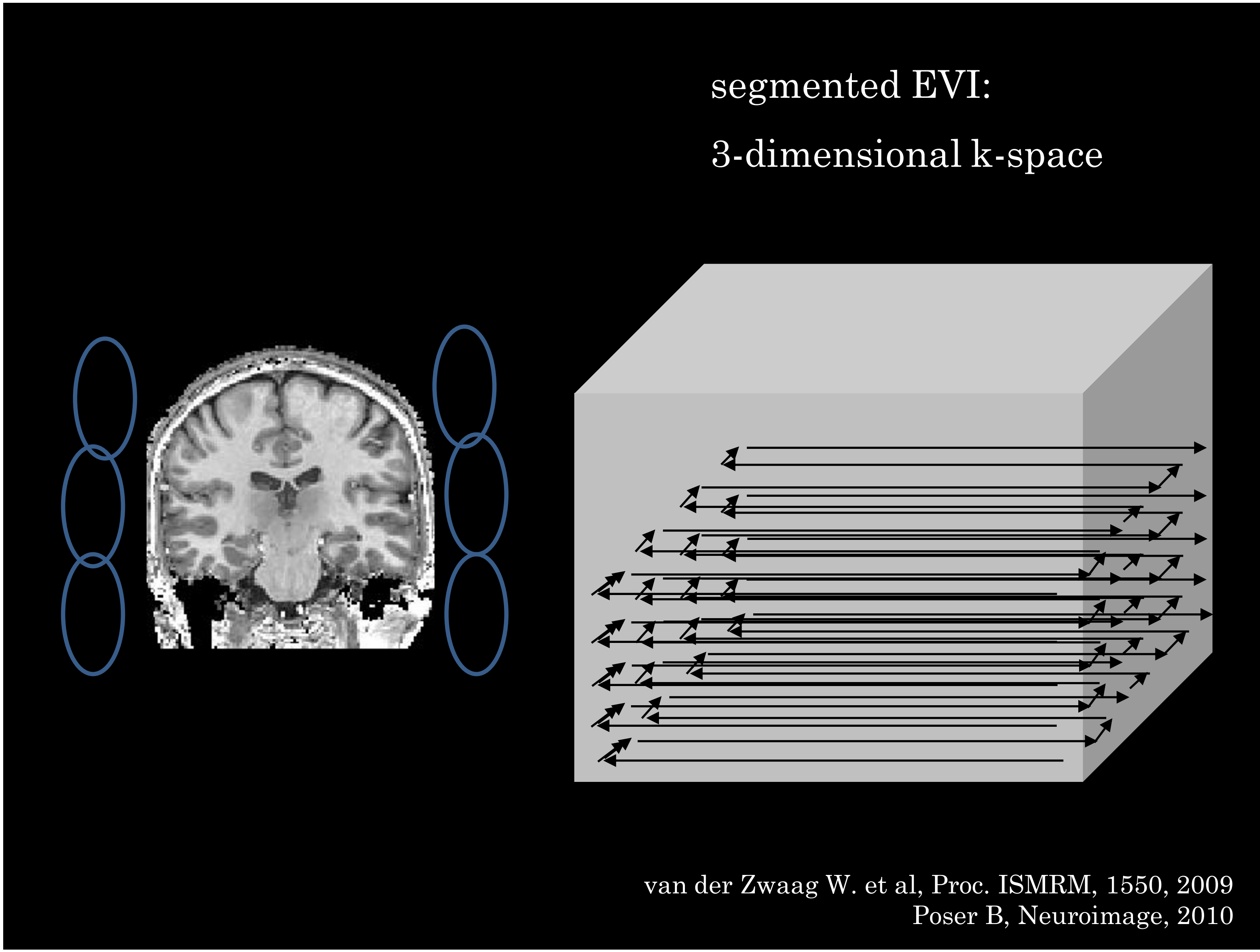

New k-space trajectories

-Structural imaging

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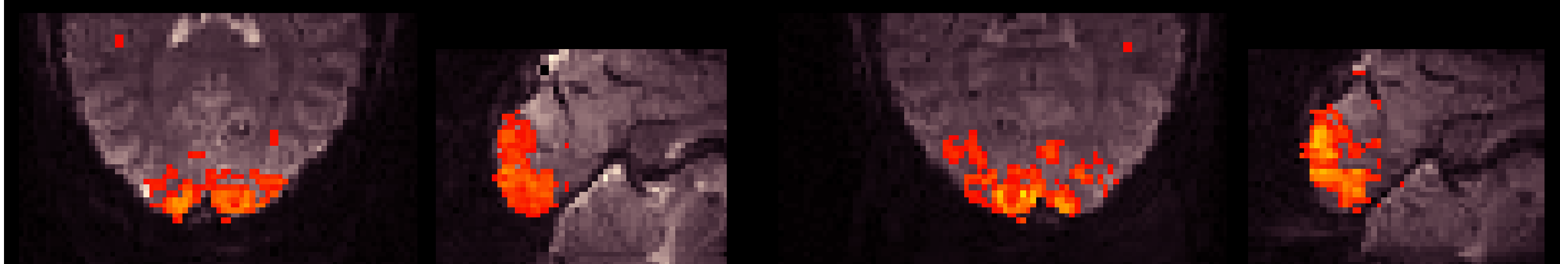
'normal' multi-slice EPI:

2-dimensional k-space

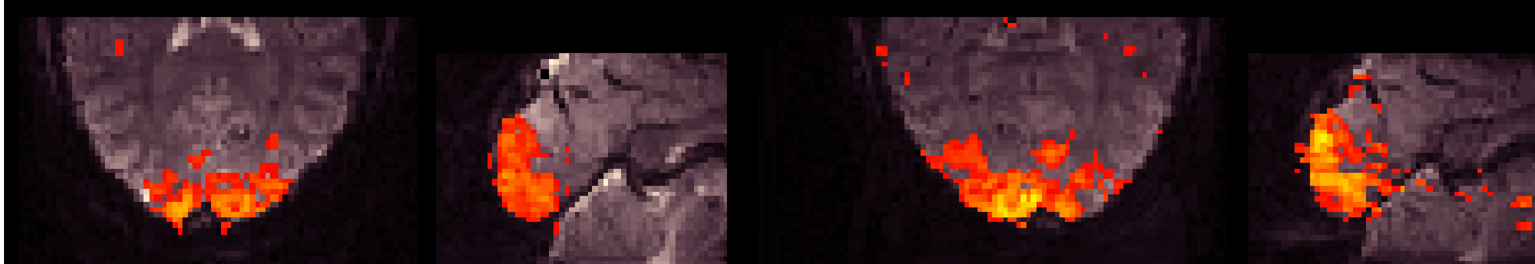
segmented EVI:

3-dimensional k-space

With no physiological noise correction



With physiological noise correction



Jorge J. et al Neuroimage, revision

-Structural imaging

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- Spectroscpy and metabolic imaging

going beyond water

-Structural imaging

-Functional imaging

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Useful for T_1 contrast and perfusion	Longer T_1 (slower imaging)
	B_1 inhomogeneity, high SAR
Increased T_2^* /BOLD contrast	Shorter T_2^* (less time to image)
Increase in BOLD specificity	
Increased spectral separation	

spectroscopy @ 3T

-Structural imaging

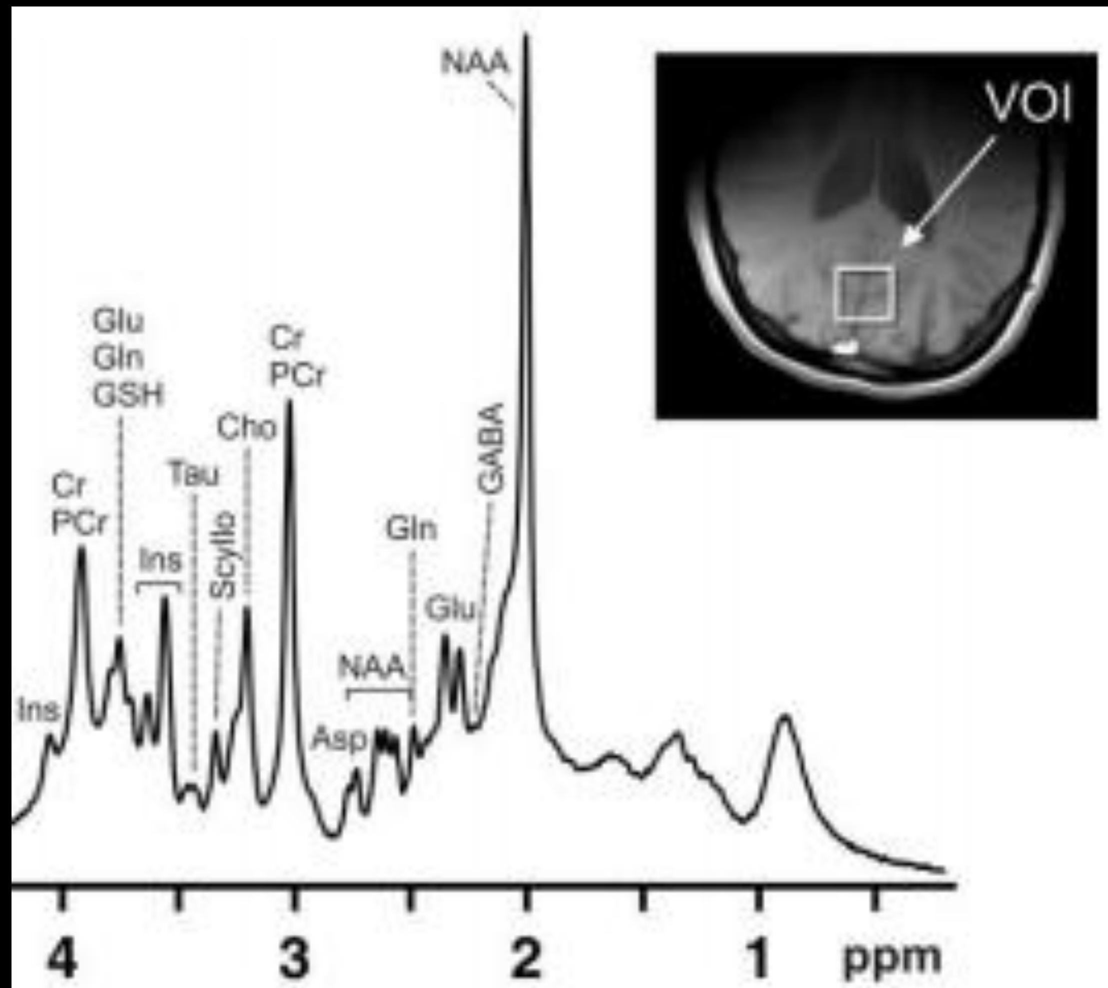
-Functional imaging

- Spectroscpy and metabolic imaging

1H NMR

SPECIAL
TR/TE
4000 ms/6 ms,

128 averages



Mekle R. et al, MRM, 2009

Spectroscopy @ 7T

-Structural imaging

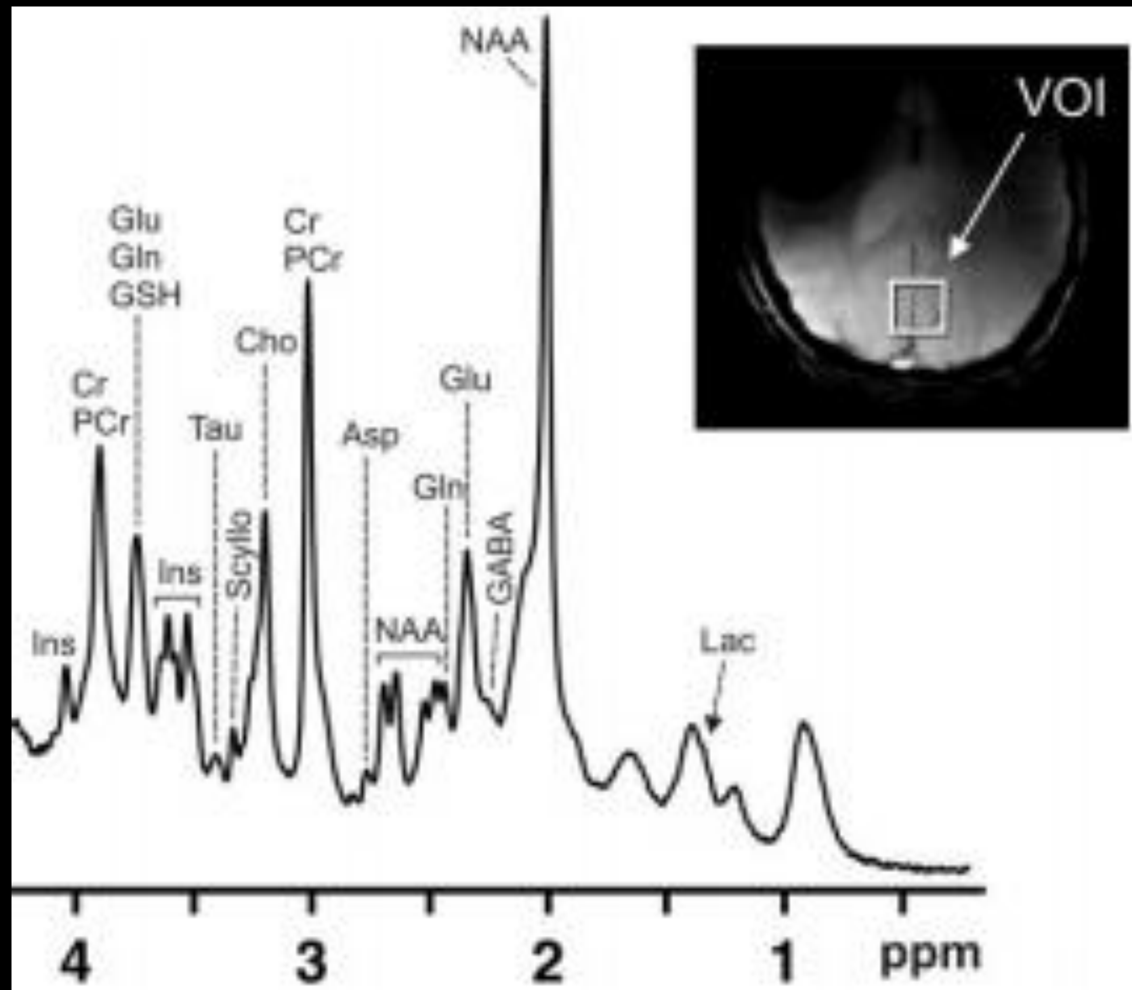
-Functional imaging

- Spectroscpy and metabolic imaging

1H NMR

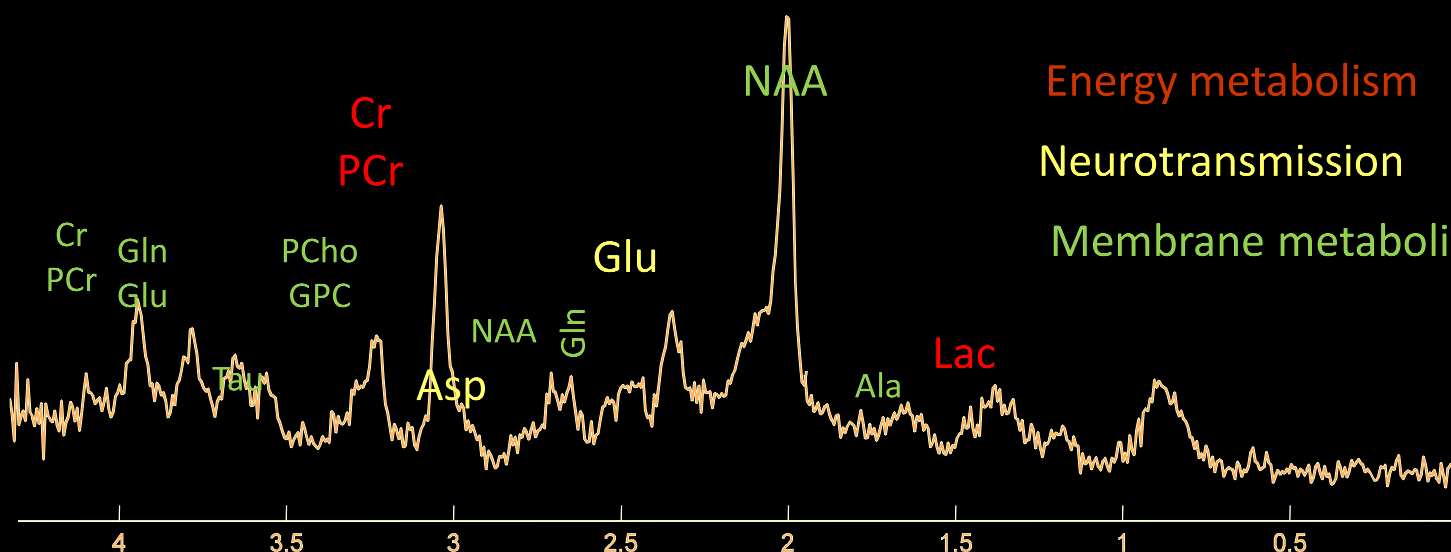
SPECIAL
TR/TE
4000 ms/6 ms,

64 averages



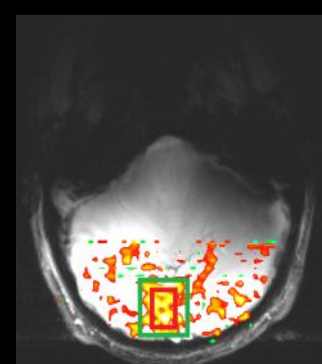
Mekle R. et al, MRM, 2009

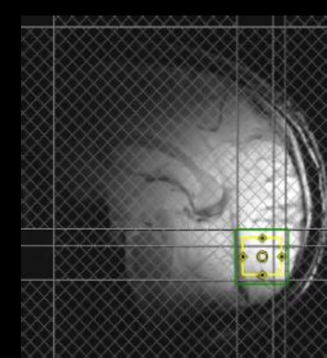
Functional spectroscopy @7T



fMRI localizer (EPI, 10s ON, 20s OFF, TA=2.5min)

VOI=20*22*20mm^3, OVS bands





Schaller B. et al. Proc ISMRM, 2011

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

Functional spectroscopy @7T

Changes:

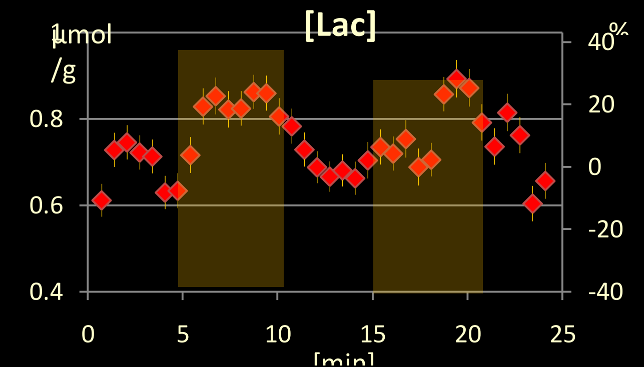
[Lac]: 0.14±0.02μmol/g ($p<0.001$)

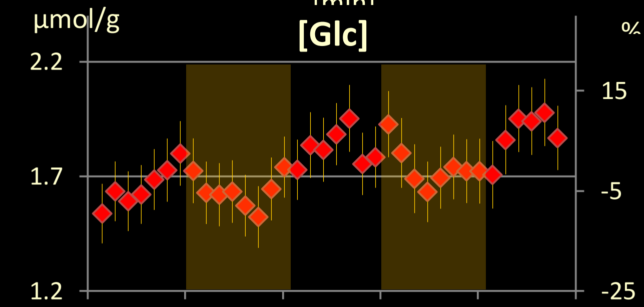
[Glc]: -0.21±0.06μmol/g ($p<0.03$)

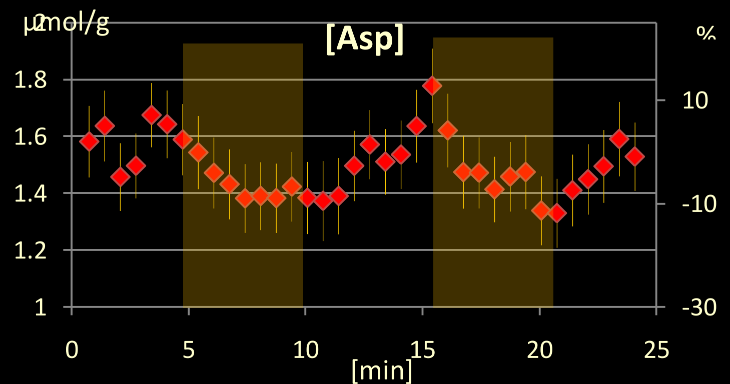
[Glu]: 0.31±0.01μmol/g ($p<0.003$)

[Asp]: -0.10±0.05μmol/g ($p<0.09$)

[Lac], [Glc], [Glu] and [Asp] changes imply the predominance of oxidative metabolism during neuronal activation *in vivo*





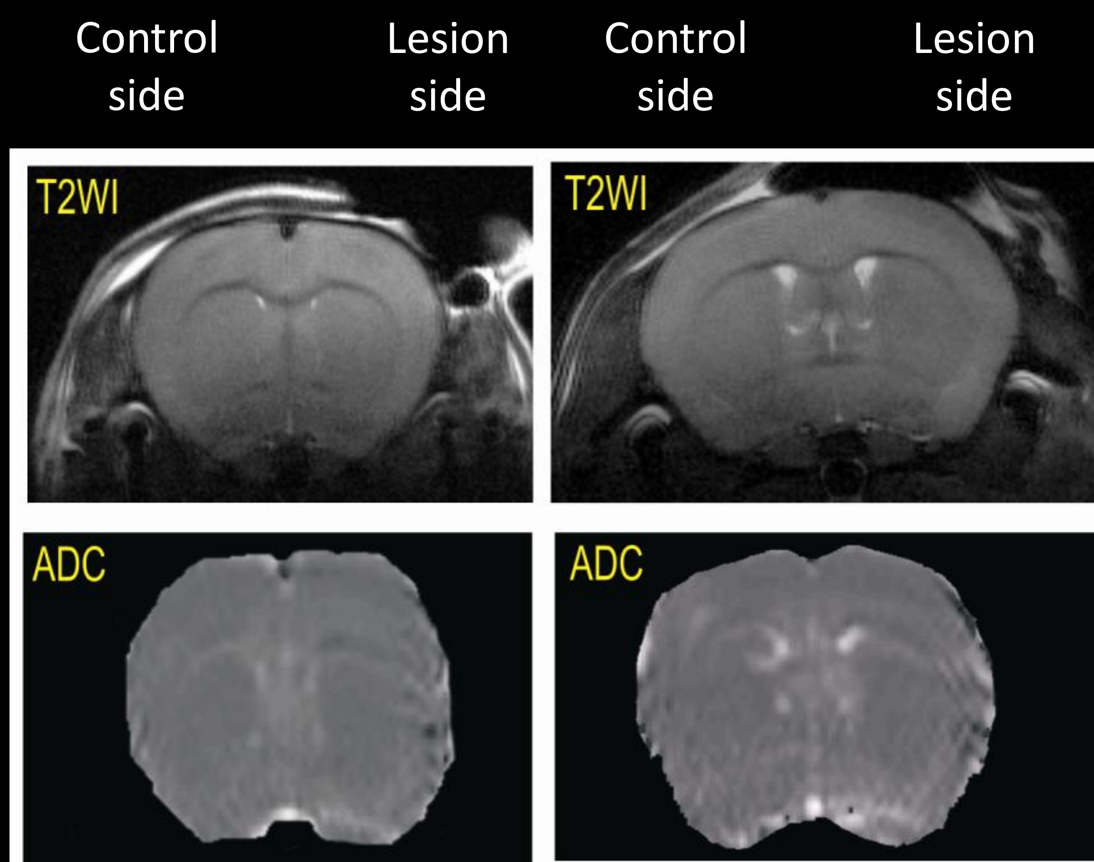


Spectroscopy @ 14 T
3h after induced 10min ischemia

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging



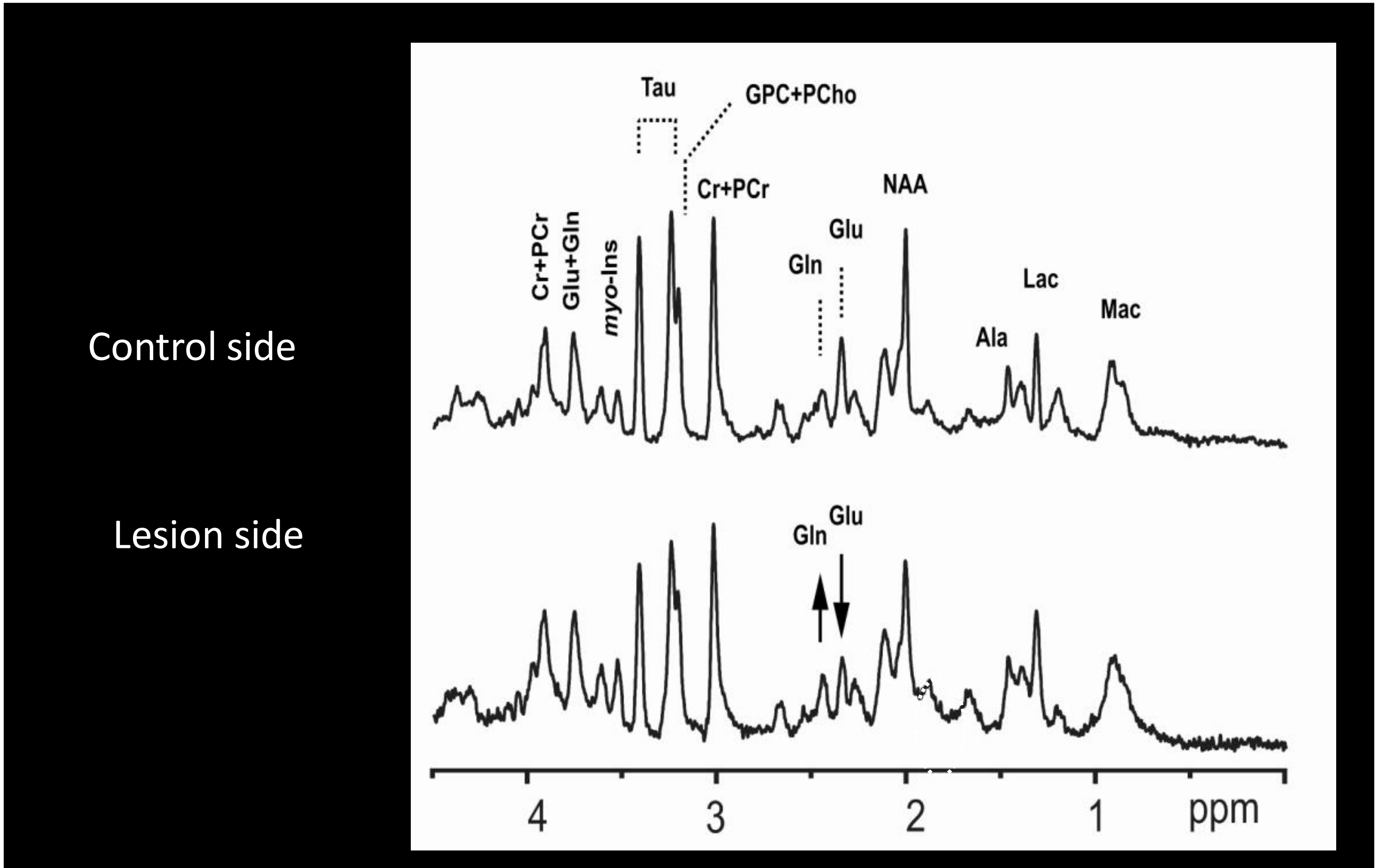
Berthet, Lei, Hirt et al. Stroke, 2011

Spectroscopy @ 14 T
3h after induced 10min ischemia

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging



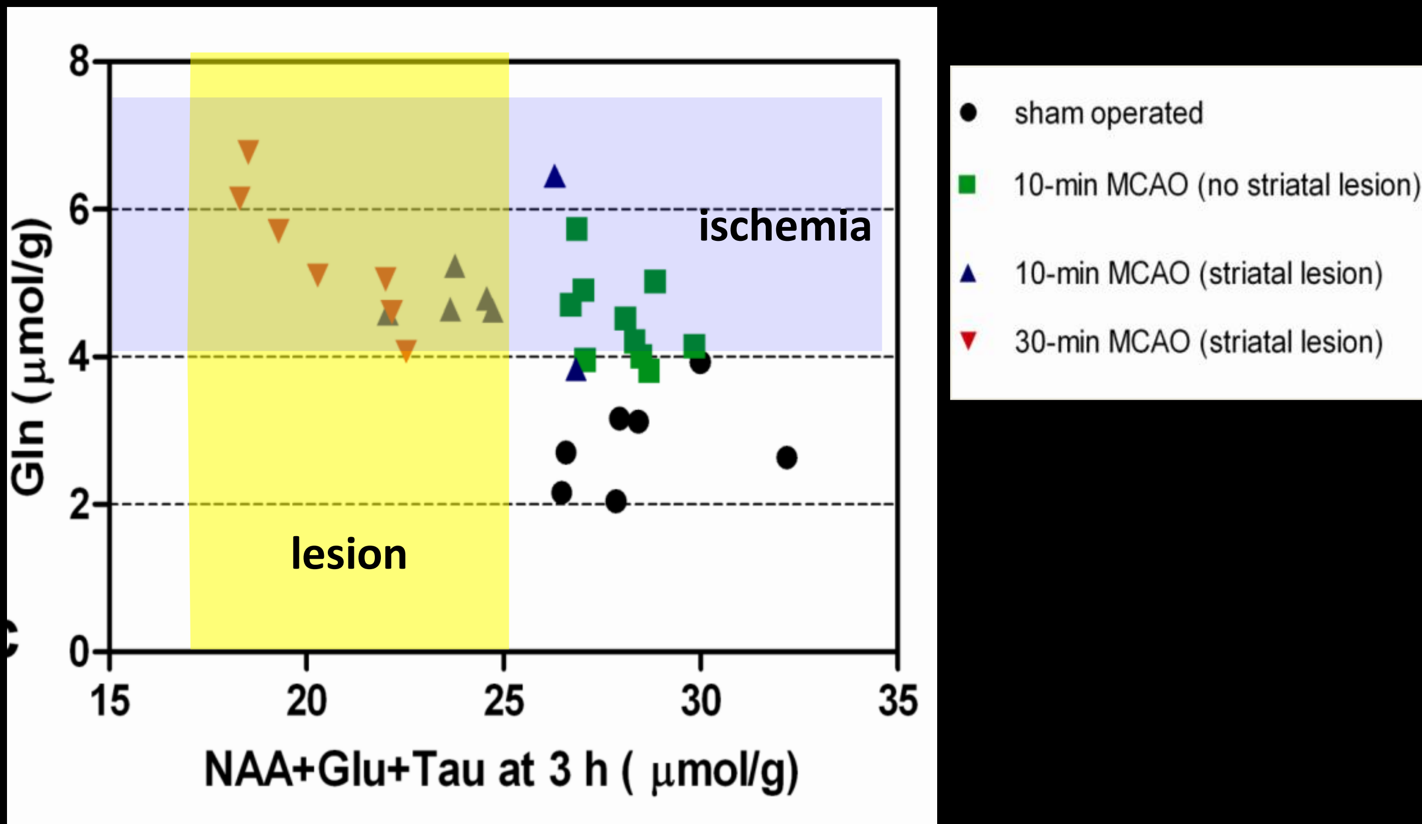
Berthet, Lei, Hirt et al. Stroke, 2011

Spectroscopy @ 14 T
3h after induced 10min ischemia

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging



Berthet, Lei, Hirt et al. Stroke, 2011

can we not go beyond the single voxel?

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

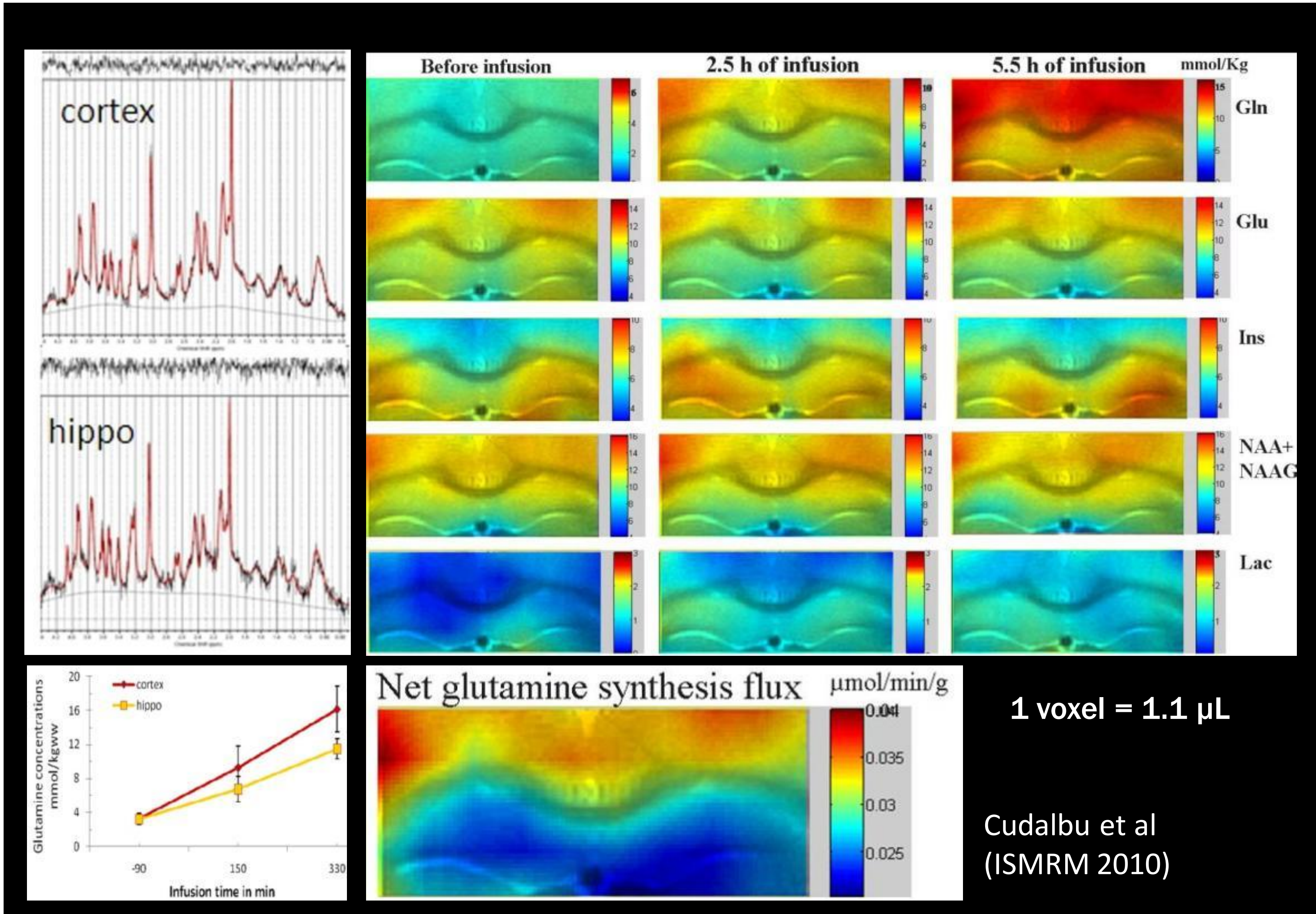
yes we can!

Metabolic imaging - net glutamine synthesis rates *in vivo*

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

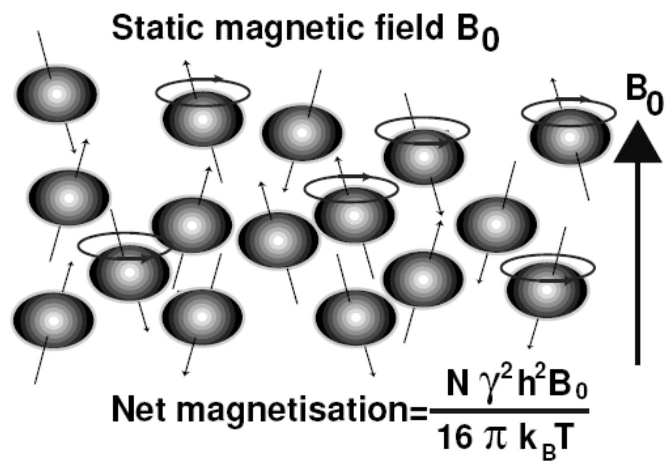


maybe there is some space for acceleration…

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging



Dynamic nuclear polarization: 10000 fold enhanced NMR

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

Enhance NMR magnetization @ 1K

Heat to 300K in 5 seconds

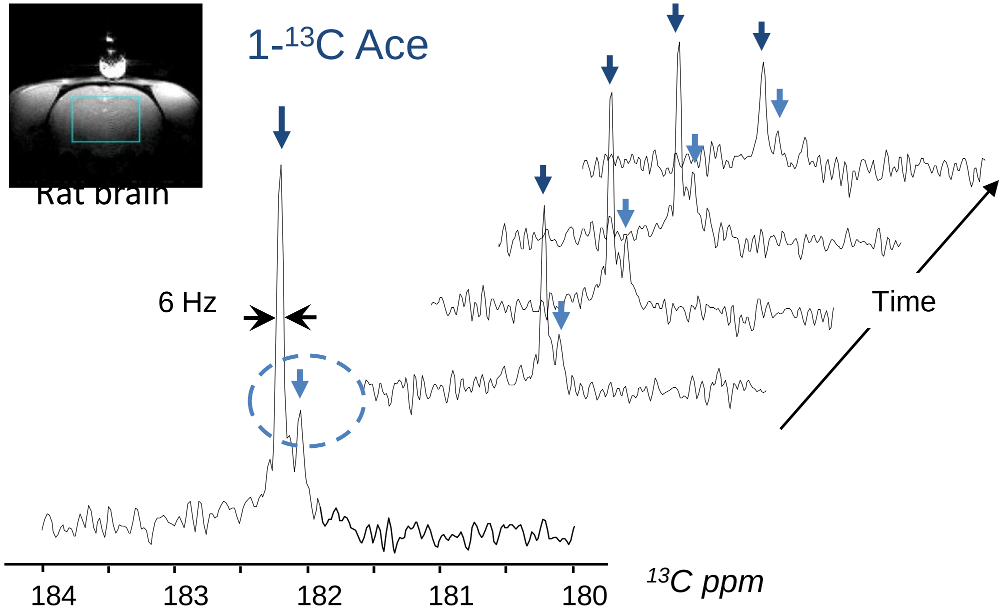
Transfer, inject and enjoy!

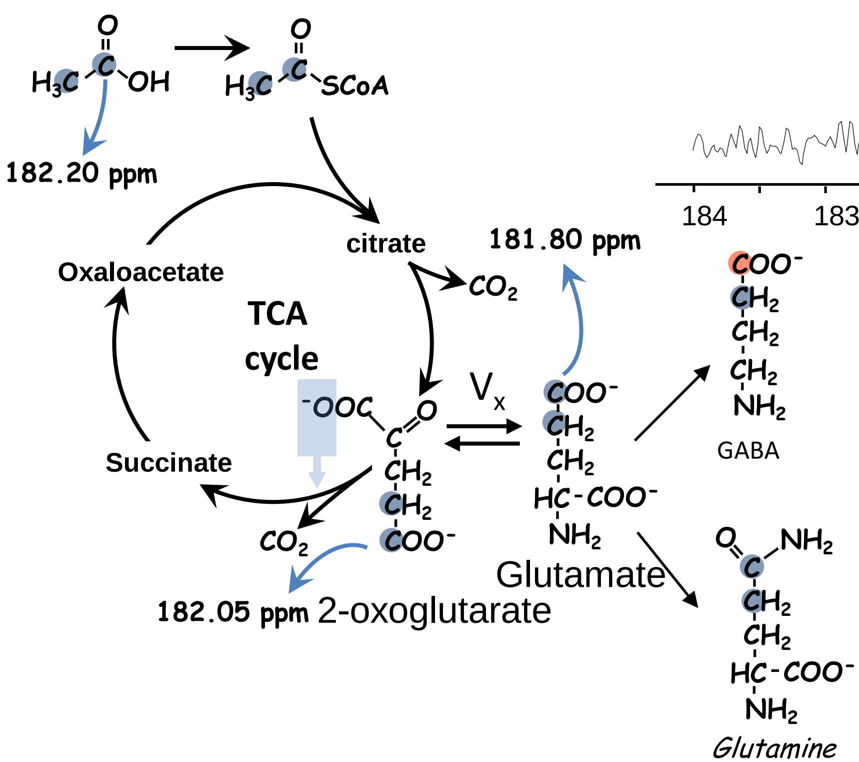
separator/infusion pump located inside the imager
(A. Comment & J.J. van der Klink, patent pending)

Comment et al., *Conc Magn Reson.* (2008)

In vivo Localized ^{13}C NMR after infusion of hyperpolarized ^{13}C acetate

DNP combined with high field & high order shimming → high resolution *in vivo* spectra





Krebs cycle 2OxoGlutarate intermediate detected:

- Mobile enough, low concentration
- Glutamate – 2OG exchange V_x not extremely fast

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

Once you see it, it is gone.

Faster encoding is essential.

Conclusions…

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

High field scanners bring us improved SNR and CNR which can be traded by increased resolution or to look at less concentrated metabolites…

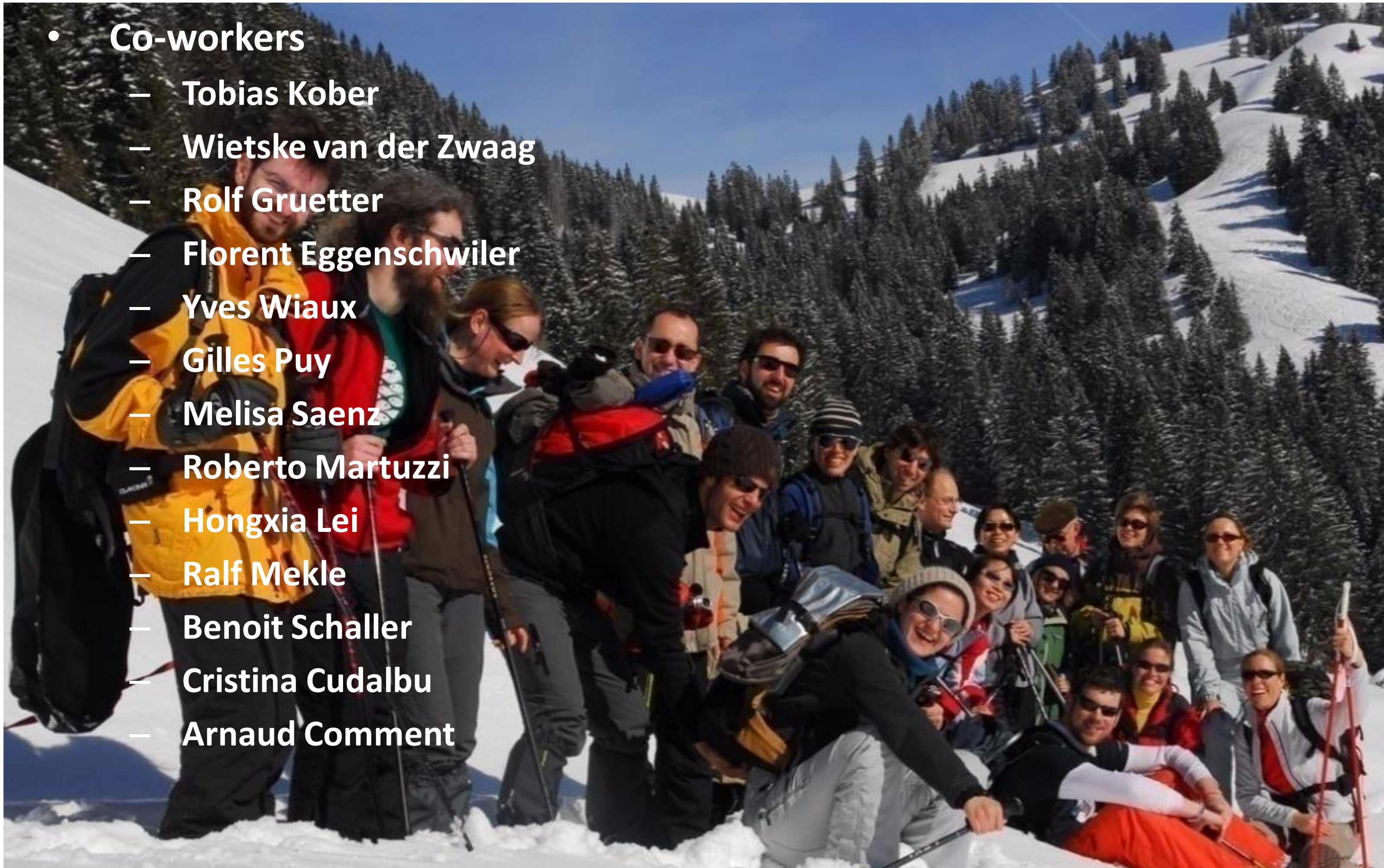
There is still MR physics to be worked out.. But it might be better/faster worked out when using more sophistcated signal processing tools.

-Structural imaging

-Functional imaging

- Spectroscpy and metabolic imaging

Acknowledgements



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  - Cristina Cudalbu
  - Arnaud Comment

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You, for your attention…