THE UNIVERSITY OF QUEENSLAND
AUSTRALIA
CREATE CHANGE

Emerging Quantitative Contrasts: Quantitative Susceptibility Mapping (QSM)

Theory & Methods

Steffen Bollmann

Research Fellow - School of Information Technology and Electrical Engineering
Affiliate Fellow – Centre for Advanced Imaging
CI - Centre for Innovation in Biomedical Imaging Technology
The University of Queensland, Australia

Centre for Innovation in Biomedical Imaging Technology
An ARC Industrial Transformation Training Centre

Declaration of Financial Interests or Relationships

Speaker Name: Steffen Bollmann

I have the following financial interest or relationship(s) to disclose with regard to the subject matter of this presentation:

- Grant/research support: Siemens Healthineers
- Other: Patent Applications on Deep Learning QSM (US 2019/0204401 A1) and Masking for QSM (US 2019/0302200 A1)

QSM-Acronym soup: Ingredient list

COMPOSER - Combining phase images from array coils using a short echo time reference scan

COSMOS - Calculation of susceptibility through multiple orientation sampling

EPI – Echo Planar Imaging

FINE - Fidelity imposed network edit

GRE – GRadient Echo

mIP – minimum Intensity Projection

LBV - Laplacian boundary value background field removal

MEDI – Morphology Enabled Dipole Inversion

ppm – parts per million

PRELUDE – Phase Region Expanding Labeler for Unwrapping Discrete Estimates

QSM – Quantitative Susceptibility Mapping

SEGUE - A Speedy rEgion-Growing Algorithm for Unwrapping Estimated Phase

SENSE - Sensitivity encoding

SHARP - sophisticated harmonic artifact reduction for phase data

SHARQnet - Sophisticated Harmonic Artifact Reduction in Quantitative Susceptibility Mapping using a Deep Convolutional Neural Network

SS – Single Step

STI – Susceptibility Tensor Imaging

SVD – Singular Value Decomposition

SWI – Susceptibility Weighted Imaging

TA – Acquisition Time

TR – Repetition Time

TE – Echo Time

TFI – Total Field Inversion

TGV – Total Generalized Variation

TKD – Truncated K-Space Division

V-SHARP - variable-radius sophisticated harmonic artifact reduction for phase data

https://www.chefkoch.de/rezepte/2166951347805623/Buchstabensuppe-mit-frischem-Gemuese.html

Full Reference List

Abdul-Rahman et al. AO 2007: 'Fast and Robust Three-Dimensional Best Path Phase Unwrapping Algorithm'. *Applied Optics* 46, no. 26 (10 September 2007): 6623–35. https://doi.org/10.1364/AO.46.006623.

Bernstein et al. MRM 1994: 'Reconstructions of Phase Contrast, Phased Array Multicoil Data'. *Magnetic Resonance in Medicine* 32, no. 3 (1994): 330–34.

Bollmann et al. Z Med Phys 2019: 'SHARQnet – Sophisticated Harmonic Artifact Reduction in Quantitative Susceptibility Mapping Using a Deep Convolutional Neural Network'. *Zeitschrift Für Medizinische Physik*, 14 February 2019. https://doi.org/10.1016/j.zemedi.2019.01.001.

Bollmann et al. NI 2019: 'DeepQSM - Using Deep Learning to Solve the Dipole Inversion for Quantitative Susceptibility Mapping'. *NeuroImage* 195 (15 July 2019): 373–83. https://doi.org/10.1016/j.neuroimage.2019.03.060.

Chatnuntawech et al. NMR Biomed 2017: 'Single-Step Quantitative Susceptibility Mapping with Variational Penalties: Single-Step Qsm with Variational Penalties'. *NMR in Biomedicine* 30, no. 4 (April 2017): e3570. https://doi.org/10.1002/nbm.3570.

Deistung et al. PLoS ONE 2013: 'Quantitative Susceptibility Mapping Differentiates between Blood Depositions and Calcifications in Patients with Glioblastoma'. *PLoS ONE* 8, no. 3 (21 March 2013): e57924. https://doi.org/10.1371/journal.pone.0057924.

Deistung et al. NMR Biomed 2017: 'Overview of Quantitative Susceptibility Mapping: Overview of Quantitative Susceptibility Mapping'. *NMR in Biomedicine* 30, no. 4 (April 2017): e3569. https://doi.org/10.1002/nbm.3569.

Dymerska et al. MRM 2021: 'Phase Unwrapping with a Rapid Opensource Minimum Spanning Tree Algorithm (ROMEO)'. *Magnetic Resonance in Medicine* n/a, no. n/a. Accessed 2 November 2020. https://doi.org/10.1002/mrm.28563.

Eckstein et al MRM 2018: 'Computationally Efficient Combination of Multi-Channel Phase Data From Multi-Echo Acquisitions (ASPIRE)'. *Magnetic Resonance in Medicine* 79, no. 6 (2018): 2996–3006. https://doi.org/10.1002/mrm.26963.

Haacke et al. MRM 2004: 'Susceptibility Weighted Imaging (SWI)'. *Magnetic Resonance in Medicine* 52, no. 3 (1 September 2004): 612–18. https://doi.org/10.1002/mrm.20198.

Full Reference List

Haacke et al. MRI 2014: 'Quantitative Susceptibility Mapping: Current Status and Future Directions'. *Magnetic Resonance Imaging*, 2014. https://doi.org/10.1016/j.mri.2014.09.004.

Hammond et al. NI 2008: 'Development of a Robust Method for Generating 7.0 T Multichannel Phase Images of the Brain with Application to Normal Volunteers and Patients with Neurological Diseases'. *NeuroImage* 39, no. 4 (15 February 2008): 1682–92. https://doi.org/10.1016/j.neuroimage.2007.10.037.

Jenkinson MRM 2003: 'Fast, Automated, N-Dimensional Phase-Unwrapping Algorithm'. *Magnetic Resonance in Medicine* 49, no. 1 (2003): 193–97. https://doi.org/10.1002/mrm.10354.

Yoon et al. NI 2018: 'Quantitative Susceptibility Mapping Using Deep Neural Network: QSMnet'. *NeuroImage* 179 (1 October 2018): 199–206. https://doi.org/10.1016/j.neuroimage.2018.06.030.

Jung et al. NMR Biomed 2020: 'Overview of Quantitative Susceptibility Mapping Using Deep Learning: Current Status, Challenges and Opportunities'. *NMR in Biomedicine*, 23 March 2020, e4292. https://doi.org/10.1002/nbm.4292.

Karsa et al. TMI 2019: 'SEGUE: A Speedy REgion-Growing Algorithm for Unwrapping Estimated Phase'. *IEEE Transactions on Medical Imaging* 38, no. 6 (June 2019): 1347–57. https://doi.org/10.1109/TMI.2018.2884093.

Khabipova et al. NI 2015:'A Modulated Closed Form Solution for Quantitative Susceptibility Mapping — A Thorough Evaluation and Comparison to Iterative Methods Based on Edge Prior Knowledge'. *NeuroImage* 107 (15 February 2015): 163–74. https://doi.org/10.1016/j.neuroimage.2014.11.038.

Lai et al. ArXiv 2020:'Learned Proximal Networks for Quantitative Susceptibility Mapping'. *ArXiv:2008.05024 [Cs, Eess]*, 11 August 2020. http://arxiv.org/abs/2008.05024.

Langkammer et al. NI 2015 'Fast Quantitative Susceptibility Mapping Using 3D EPI and Total Generalized Variation'. *NeuroImage* 111 (1 May 2015): 622–30. https://doi.org/10.1016/j.neuroimage.2015.02.041.

Langkammer et al. MRM 2018: 'Quantitative Susceptibility Mapping: Report from the 2016 Reconstruction Challenge: QSM Reconstruction Challenge 2016'. *Magnetic Resonance in Medicine* 79, no. 3 (March 2018): 1661–73. https://doi.org/10.1002/mrm.26830.

Li et al. NI 2011: 'Quantitative Susceptibility Mapping of Human Brain Reflects Spatial Variation in Tissue Composition'. *NeuroImage* 55, no. 4 (15 April 2011): 1645–56. https://doi.org/10.1016/j.neuroimage.2010.11.088.

Full Reference List

Li et al. NI 2015: 'A Method for Estimating and Removing Streaking Artifacts in Quantitative Susceptibility Mapping'. *NeuroImage* 108 (March 2015): 111–22. https://doi.org/10.1016/j.neuroimage.2014.12.043.

Liu et al. MRM 2009: 'Calculation of Susceptibility through Multiple Orientation Sampling (COSMOS): A Method for Conditioning the Inverse Problem from Measured Magnetic Field Map to Susceptibility Source Image in MRI'. *Magnetic Resonance in Medicine* 61, no. 1 (1 January 2009): 196–204. https://doi.org/10.1002/mrm.21828.

Liu MRM 2010: 'Susceptibility Tensor Imaging'. *Magnetic Resonance in Medicine : Official Journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine* 63, no. 6 (June 2010): 1471–77. https://doi.org/10.1002/mrm.22482. https://doi.org/10.1002/mrm.22482.

Liu et al. MRM 2013: 'Nonlinear Formulation of the Magnetic Field to Source Relationship for Robust Quantitative Susceptibility Mapping'. *Magnetic Resonance in Medicine* 69, no. 2 (1 February 2013): 467–76. https://doi.org/10.1002/mrm.24272.

Liu et al. MRM 2017: 'Preconditioned Total Field Inversion (TFI) Method for Quantitative Susceptibility Mapping: QSM Using Preconditioned Total Field Inversion'. *Magnetic Resonance in Medicine* 78, no. 1 (July 2017): 303–15. https://doi.org/10.1002/mrm.26331.

Marques et al. MRM 2021: 'QSM Reconstruction Challenge 2.0: A Realistic in Silico Head Phantom for MRI Data Simulation and Evaluation of Susceptibility Mapping Procedures'. *Magnetic Resonance in Medicine*, 26 February 2021. https://doi.org/10.1002/mrm.28716.

Parker et al. MRM 2014: 'Phase Reconstruction from Multiple Coil Data Using a Virtual Reference Coil'. *Magnetic Resonance in Medicine* 72, no. 2 (1 August 2014): 563–69. https://doi.org/10.1002/mrm.24932.

Robinson et al. NMR Biomed 2017: 'An Illustrated Comparison of Processing Methods for MR Phase Imaging and QSM: Combining Array Coil Signals and Phase Unwrapping: Phase Image Combination and Unwrapping'. *NMR in Biomedicine* 30, no. 4 (April 2017): e3601. https://doi.org/10.1002/nbm.3601.

Robinson et al. MRM 2017: 'Combining Phase Images from Array Coils Using a Short Echo Time Reference Scan (COMPOSER)'. *Magnetic Resonance in Medicine* 77, no. 1 (January 2017): 318–27. https://doi.org/10.1002/mrm.26093.

Roemer et al MRM 1990: 'The NMR Phased Array'. *Magnetic Resonance in Medicine* 16, no. 2 (1990): 192–225. https://doi.org/10.1002/mrm.1910160203.

Schenck et al. MP 1996: 'The Role of Magnetic Susceptibility in Magnetic Resonance Imaging: MRI Magnetic Compatibility of the First and Second Kinds'. *Medical Physics* 23, no. 6 (1 June 1996): 815–50. https://doi.org/10.1118/1.597854.

Shmueli et al. MRM 2009: 'Magnetic Susceptibility Mapping of Brain Tissue in Vivo Using MRI Phase Data'. *Magnetic Resonance in Medicine* 62, no. 6 (1 December 2009): 1510–22. https://doi.org/10.1002/mrm.22135.

Full Reference List

Schofield et al. Opt. Lett. 2003: 'Fast Phase Unwrapping Algorithm for Interferometric Applications'. *Optics Letters* 28, no. 14 (15 July 2003): 1194–96. https://doi.org/10.1364/OL.28.001194.

Schweser et al. NI 2011: 'Quantitative Imaging of Intrinsic Magnetic Tissue Properties Using MRI Signal Phase: An Approach to in Vivo Brain Iron Metabolism?' *NeuroImage* 54, no. 4 (14 February 2011): 2789–2807. https://doi.org/10.1016/j.neuroimage.2010.10.070.

Schweser et al. Z Med Phys 2016: 'Foundations of MRI Phase Imaging and Processing for Quantitative Susceptibility Mapping (QSM)'. *Zeitschrift Für Medizinische Physik* 26, no. 1 (March 2016): 6–34. https://doi.org/10.1016/j.zemedi.2015.10.002.

Schweser et al. NMR Biomed 2017: 'An Illustrated Comparison of Processing Methods for Phase MRI and QSM: Removal of Background Field Contributions from Sources Outside the Region of Interest: Background Field Elimination'. *NMR in Biomedicine* 30, no. 4 (April 2017): e3604. https://doi.org/10.1002/nbm.3604.

Stüber et al. IJoMS 2016: 'Iron in Multiple Sclerosis and Its Noninvasive Imaging with Quantitative Susceptibility Mapping'. *International Journal of Molecular Sciences* 17, no. 1 (14 January 2016): 100. https://doi.org/10.3390/ijms17010100.

Sun et al. MRM 2014: 'Background Field Removal Using Spherical Mean Value Filtering and Tikhonov Regularization'. *Magnetic Resonance in Medicine* 71, no. 3 (1 March 2014): 1151–57. https://doi.org/10.1002/mrm.24765.

Walsh et al. MRM 2000: 'Adaptive Reconstruction of Phased Array MR Imagery'. *Magnetic Resonance in Medicine* 43, no. 5 (1 May 2000): 682–90. https://doi.org/10.1002/(SICI)1522-2594(200005)43:5<682::AID-MRM10>3.0.CO;2-G.

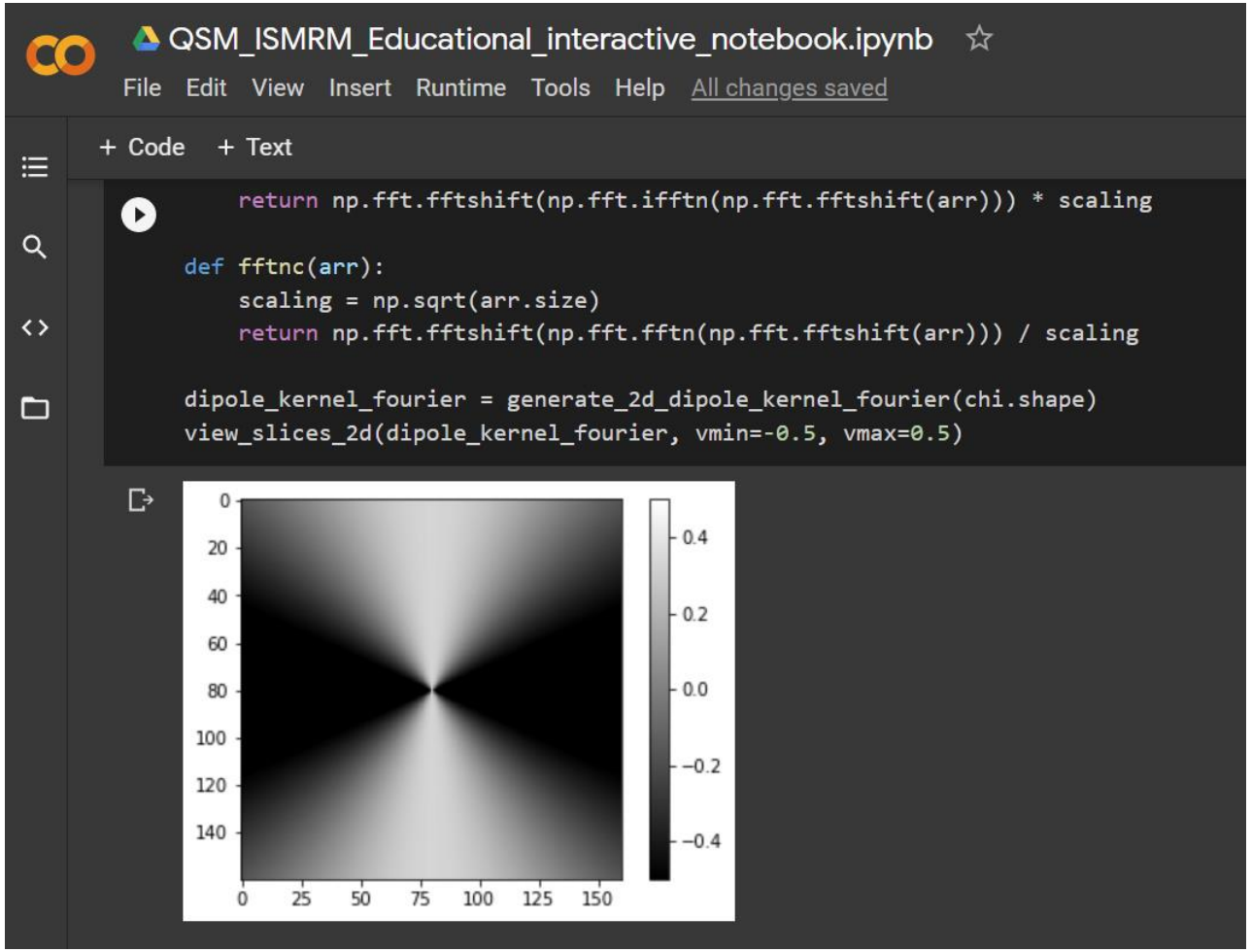
Wei et al. NI 2019: 'Learning-Based Single-Step Quantitative Susceptibility Mapping Reconstruction without Brain Extraction'. *NeuroImage* 202 (15 November 2019): 116064. https://doi.org/10.1016/j.neuroimage.2019.116064.

Zhang et al. NI 2020: 'Fidelity Imposed Network Edit (FINE) for Solving Ill-Posed Image Reconstruction'. *NeuroImage*, 22 January 2020, 116579. https://doi.org/10.1016/j.neuroimage.2020.116579.

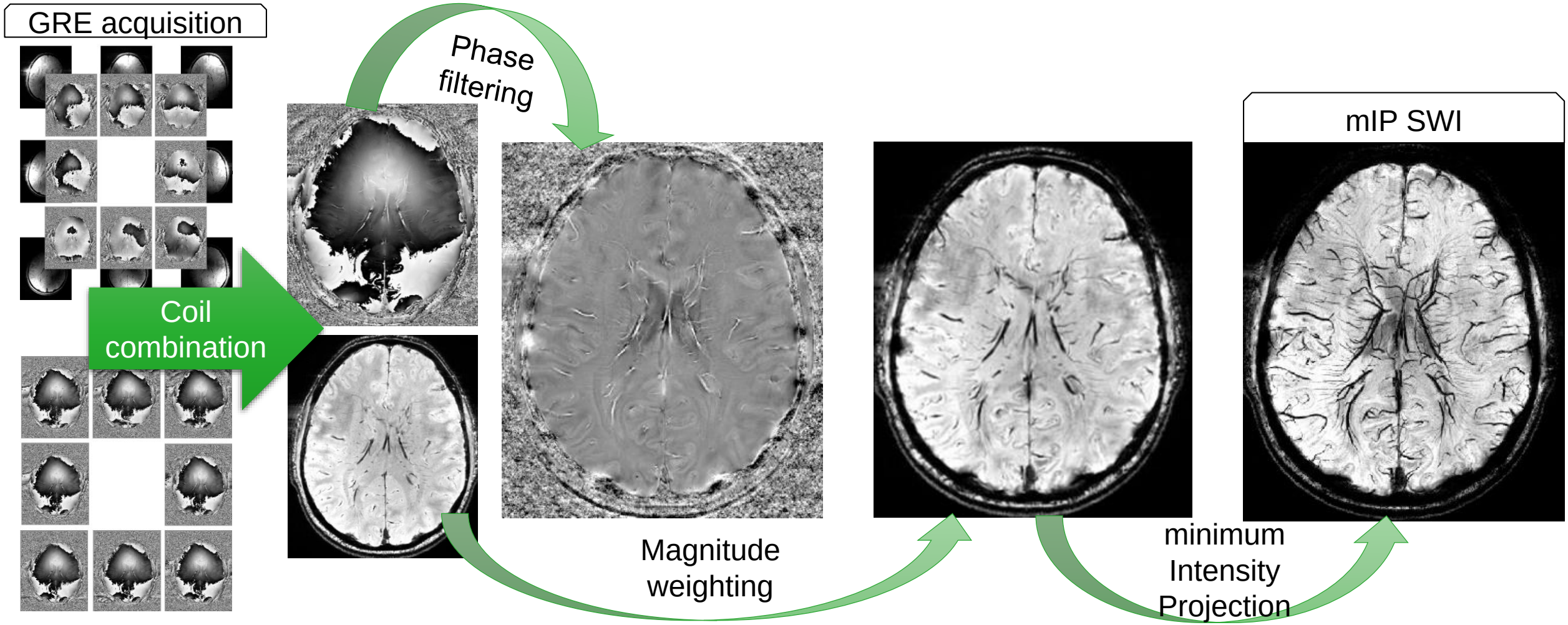
Zhou et al. NMR Biomed 2014: 'Background Field Removal by Solving the Laplacian Boundary Value Problem'. *NMR in Biomedicine* 27, no. 3 (March 2014): 312–19. https://doi.org/10.1002/nbm.3064.

Interactive Computational Notebook to learn about QSM

- http://bit.ly/ISMRM-QSM-2021



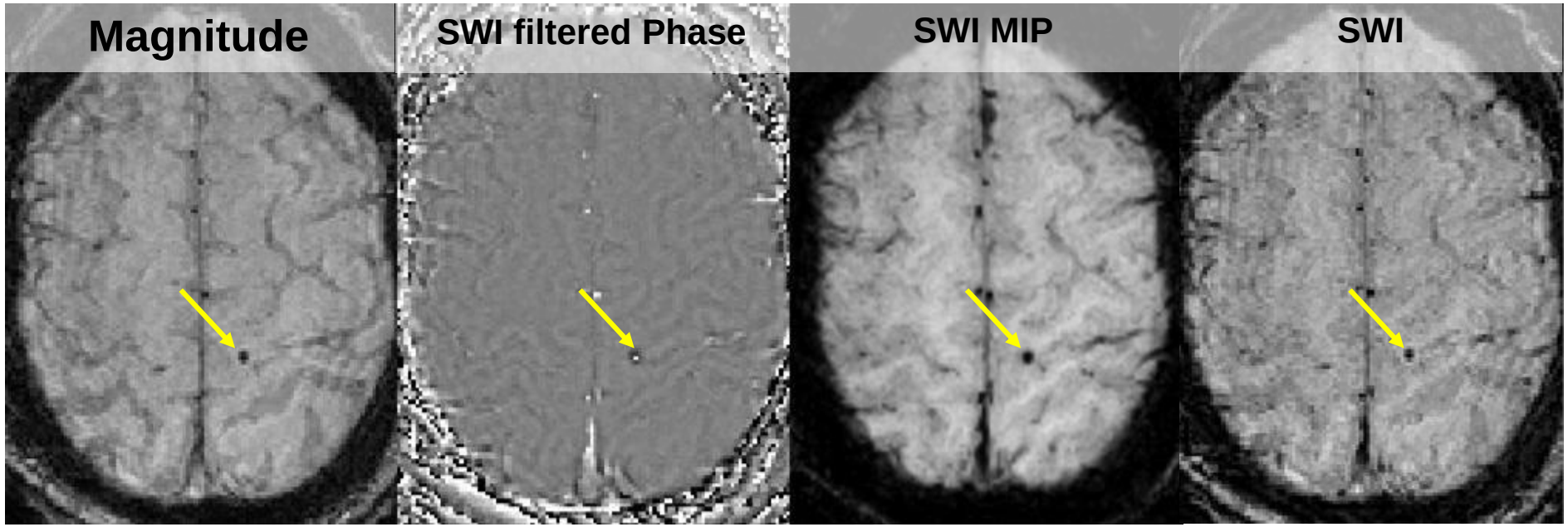
From Susceptibility Weighted Imaging (SWI) …



Haacke et al. MRM 2004

Why bother with QSM?

- Is this lesion calcified or haemorrhaging?

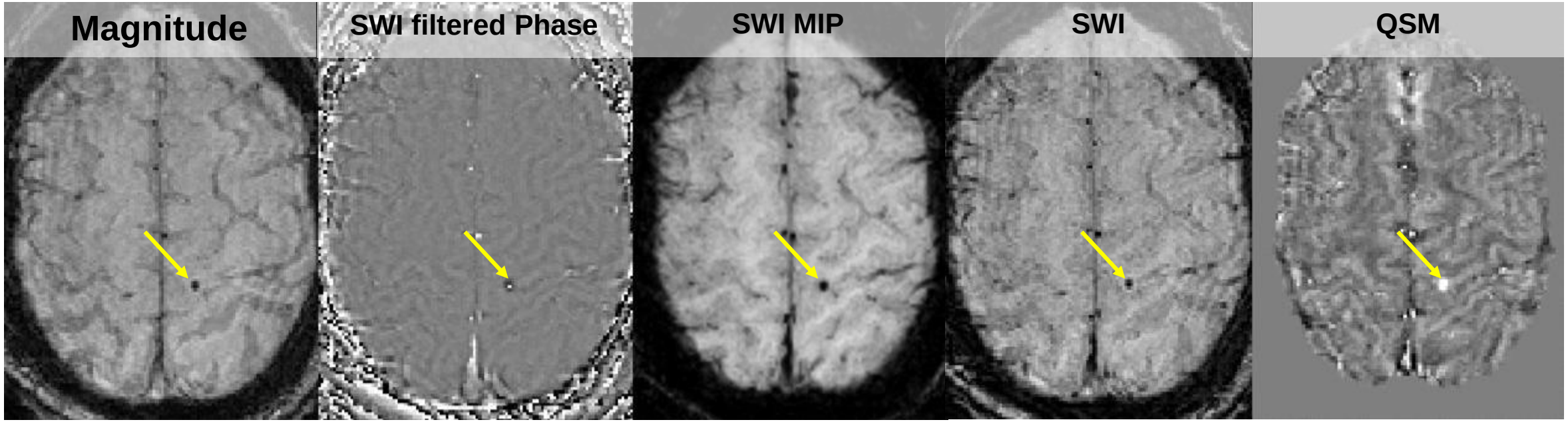


Images courtesy of Fatima Nasrallah and Abdalla Mohamed with support from Kieran O'Brien & Ashley Stewart

Why bother with QSM?

	SWI Magnitude	SWI Filtered Phase	QSM
Calcification	Hypointense (-)	Ambiguous	Hypointense (-)
Blood products	Hypointense (-)	Ambiguous	Hyperintense (+)

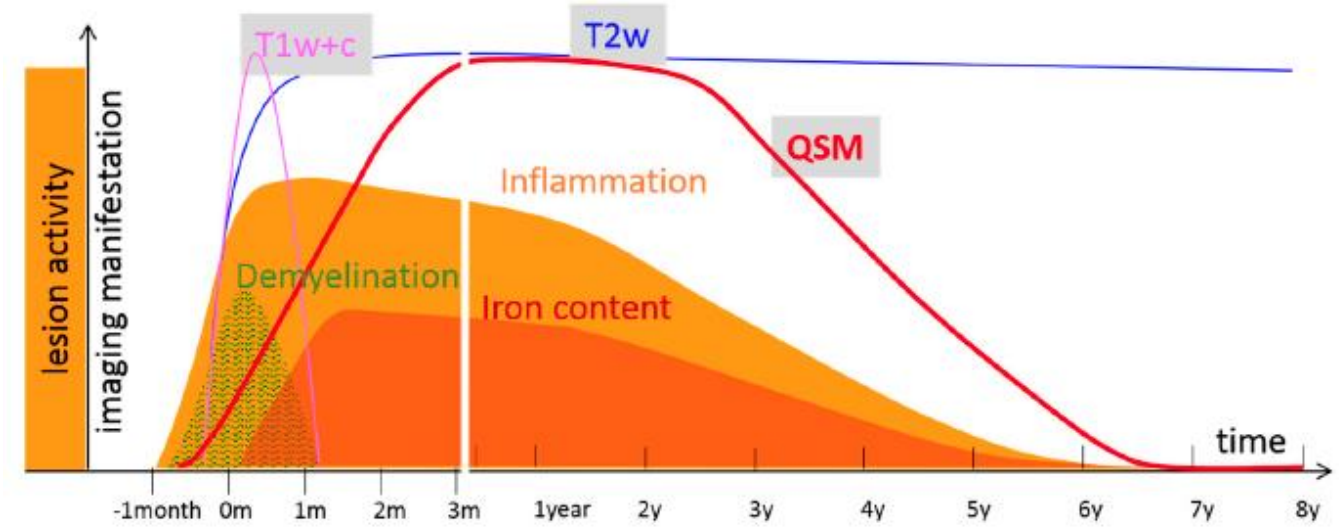
QSM differentiates between blood products (Hyperintense) and calcifications (Hypointense).



Images courtesy of Fatima Nasrallah and Abdalla Mohamed with support from Kieran O'Brien & Ashley Stewart

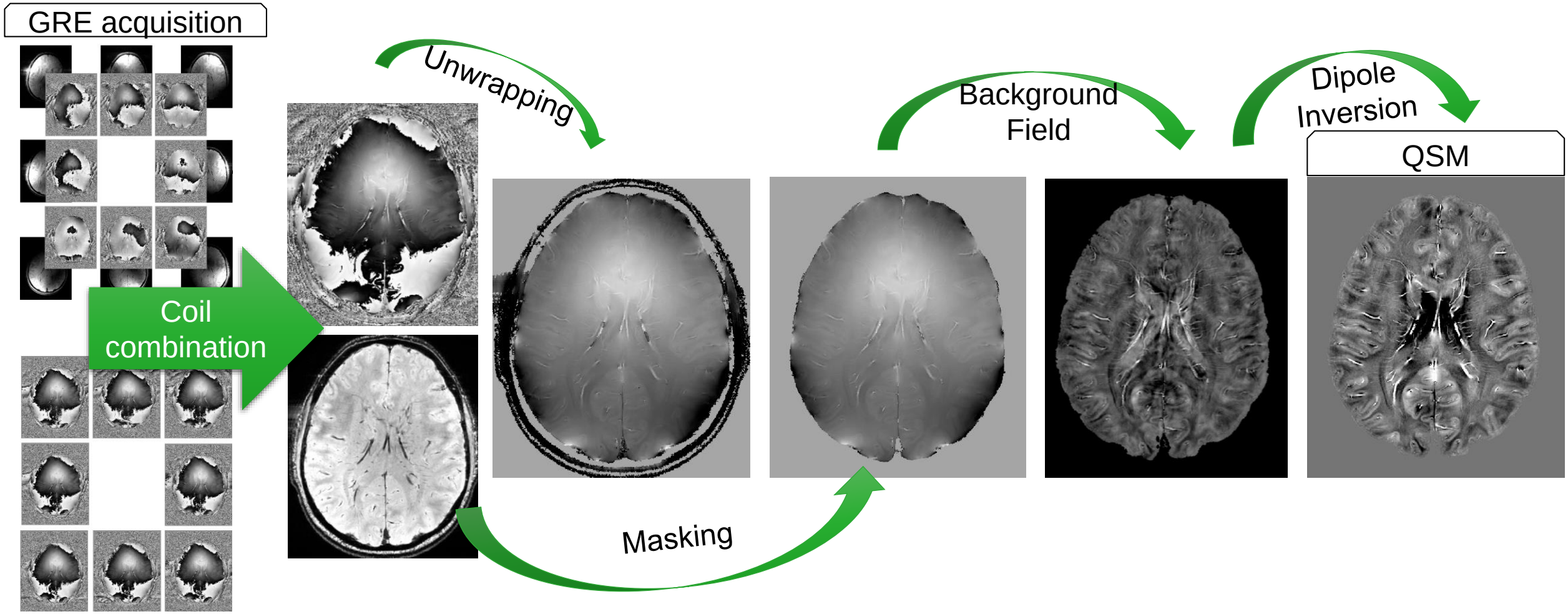
Why bother with QSM?

- QSM is sensitive to bio-metals - e.g. iron in Multiple Sclerosis:
  - iron accumulates after demyelination in microglia
  - slow iron-depletion from normal appearing white matter



Stüber et al. IJoMS 2016

… to Quantitative Susceptibility Mapping (QSM)

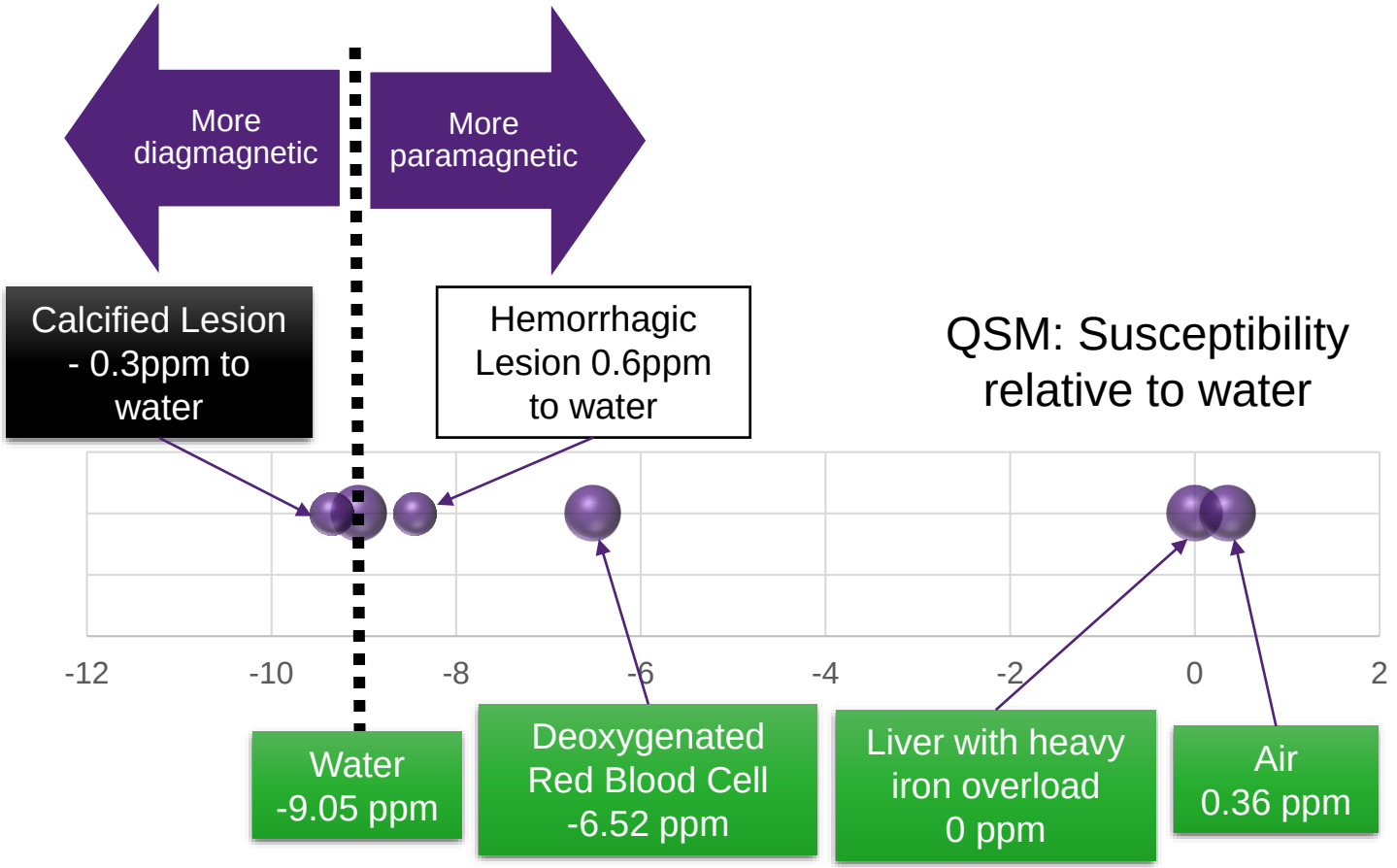


Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

What is magnetic susceptibility?

$$M = \chi H$$

the degree (χ) that a material can be magnetised (M) by an external magnetic field (H).



absolute susceptibility in ppm

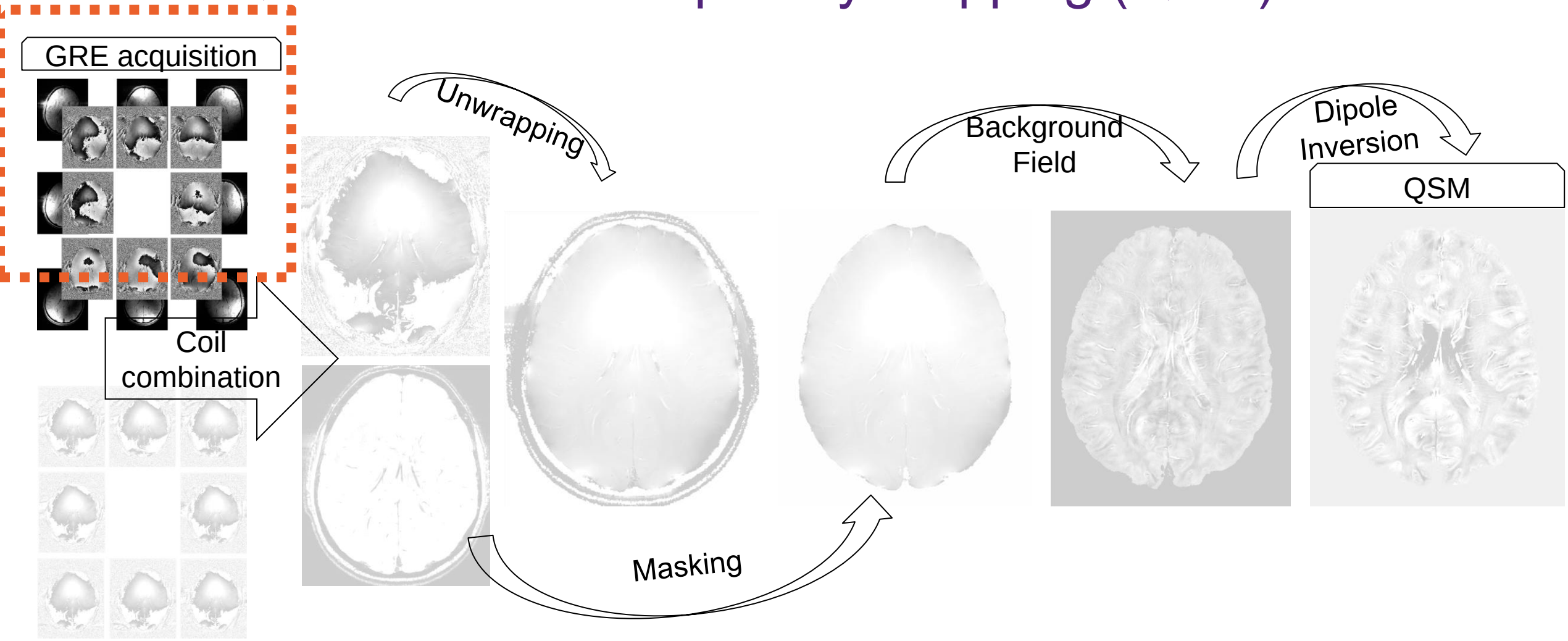
Schenck et al. MP 1996

Calcium deposits

Deistung et al. PLoS ONE 2013

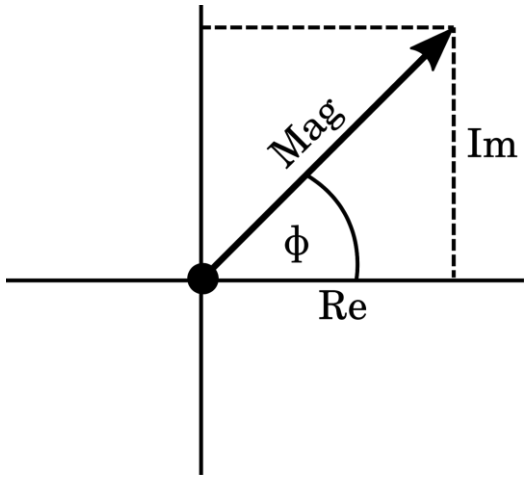
Blood products

… to Quantitative Susceptibility Mapping (QSM)



Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

Image acquisition

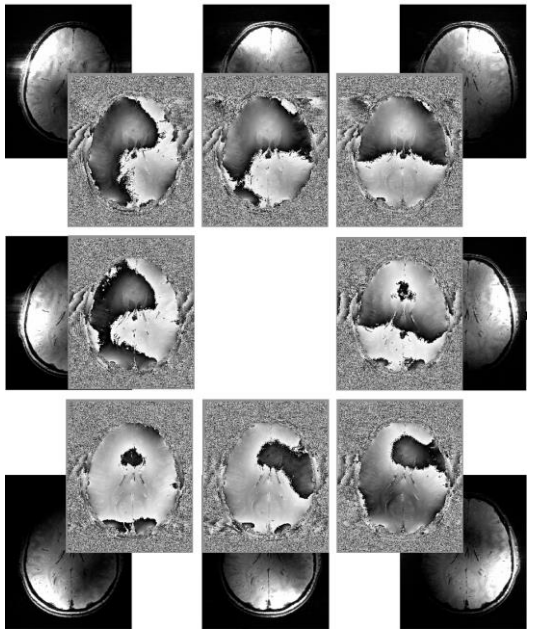


Complex MRI Signal

Magnetic field inhomogeneities cause **dephasing** due to:

- Imperfect static magnetic field
- **Object susceptibility**

We need the signal phase of a gradient echo scan



Sequence considerations for QSM

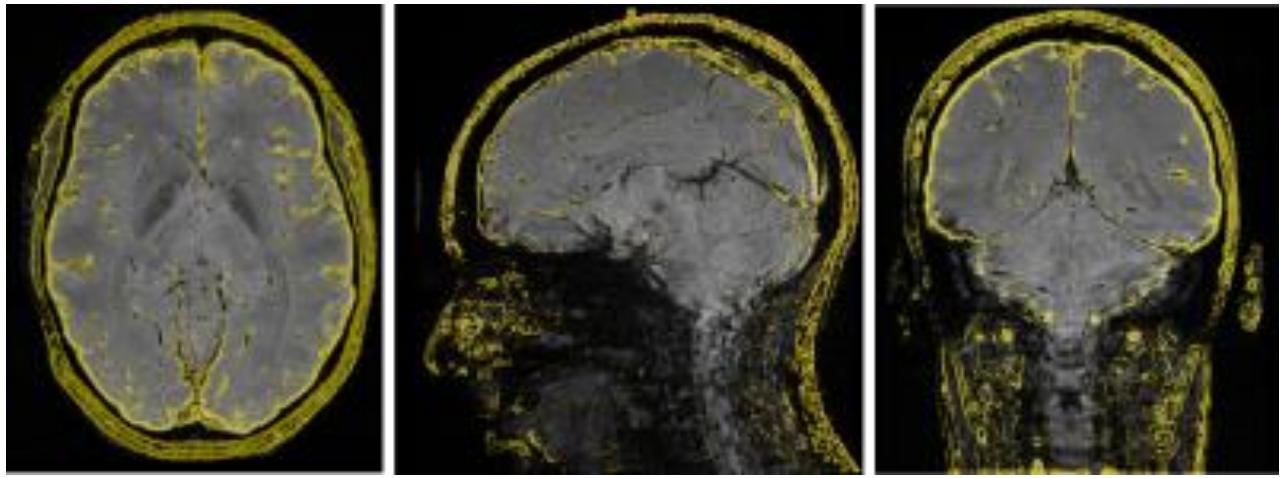
- GRE sequence (e.g. single echo GRE, multi-echo GRE, EPI, Wave-CAIPI GRE)
- Isotropic acquisition ideal for inverse solution
- High-resolution (e.g. 1mm or sub-millimetre)
- Multi-echo is efficient and can compensate signal loss + T2* fit possible, but not absolutely necessary
- flow compensation is a good idea, especially for first echo

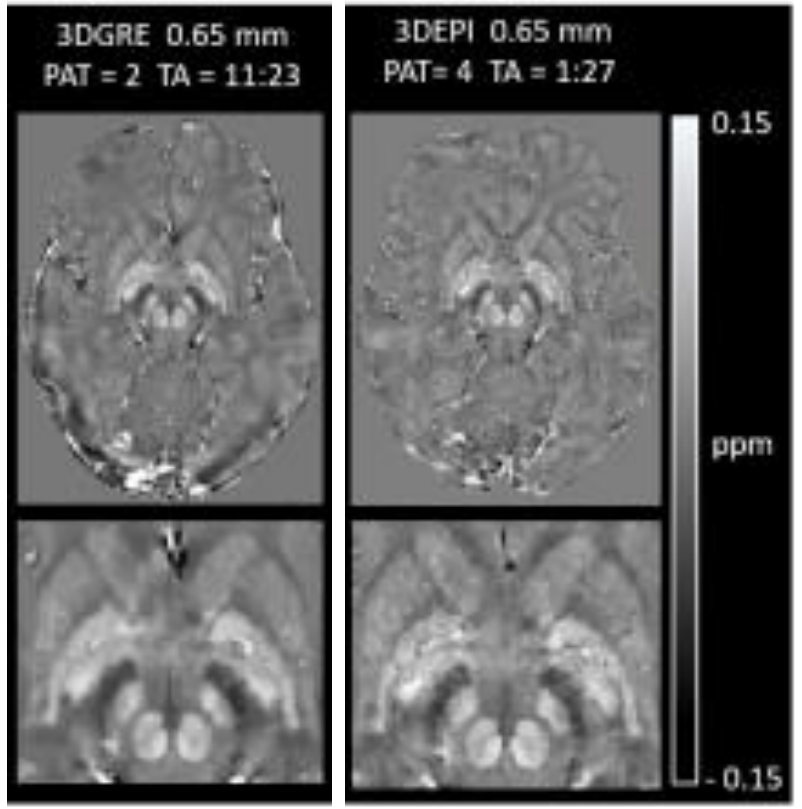
Examples

Sequence	Resolution	TE (ms)	TR (ms)	Acceleration	TA (min:sec)
3D GRE @ 3T	0.8x0.8x0.8	5, 10, 15, 20, 25	31	GRAPPA 1x2	9:20
3D GRE @ 3T	1x1x1	20	25	GRAPPA 1x3	4:52
3D EPI @ 3T	0.8x0.8x0.8	31	56	CAIPI 1x2	1:56

Submillimeter, Sub-Minute Quantitative Susceptibility Mapping using a Multi-Shot 3D-EPI with 2D CAIPIRINHA Acceleration

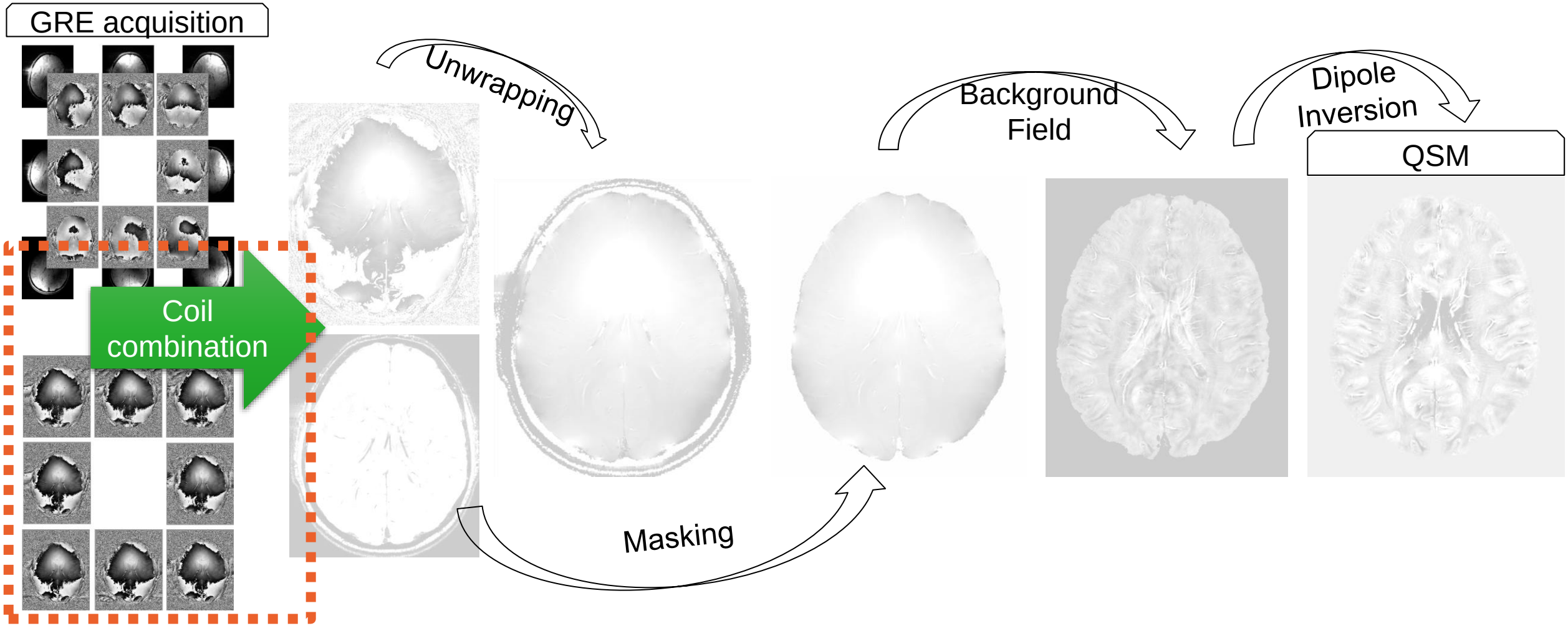
Monique Tourell[1,2], Jin Jin[2,3], Ashley Stewart[1,2], Saskia Bollmann[1], Steffen Bollmann[1,2,4], Simon Robinson[1,5,6], Kieran O'Brien[2,3], and Markus Barth[1,2,4]





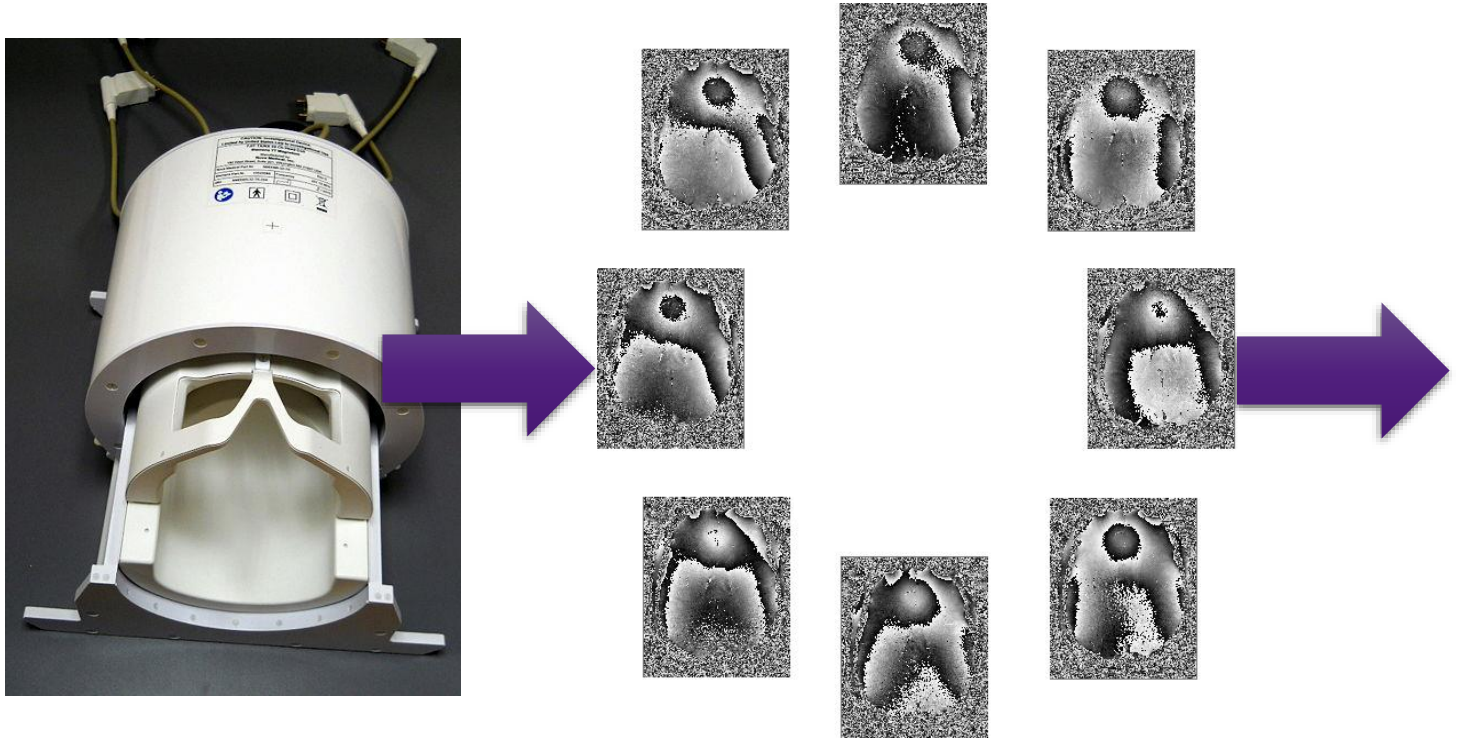
0.65mm 3D EPI with minimal distortion compared to standard GRE (yellow outline)

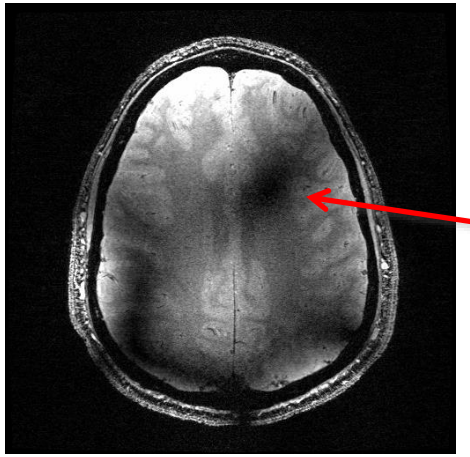
… to Quantitative Susceptibility Mapping (QSM)



Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

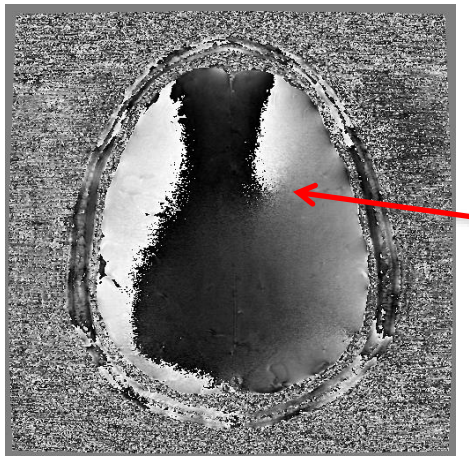
Coil combination via complex sum (no phase correction)





$$M_{comb} = \left| \sum_c M_c e^{-i\varphi^c} \right|$$

Zero signal in magnitude



$$\varphi_{comb} = \angle \sum_c M_c e^{-i\varphi^c}$$

Open-ended fringe line

No simple solution

Each RF coil element has its own spatial varying phase offset

$$\varphi^C(TE) = \varphi_0^C + \gamma \Delta B \cdot TE$$

φ_0^C

Unique to each channels

- Delays in RF chain (scalar)
- Imposed phase shifts (scalar)
- Coil sensitivity (3D)

Same for all channels

- Transmit phase B_1^+ / ETP (3D)
- Readout gradient – ADC mistiming (1D)
- Eddy current effects

+ (wrongly, any non-linear ΔB effects)

$\varphi^C(TE)$ = coil phase at TE,
φ_0^C = coil phase at time 0 (a.k.a phase offset or initial phase)
γ = gyromagnetic ratio
ΔB = deviation from B_0
TE = echo time

Phase combination approaches

1 echo, No reference scan	• Scalar phase matching [1] • Adaptive combine [2] • Virtual Reference Coil [3]
1 echo, Reference scan	• Roemer/SENSE [4] • COMPOSER [5]
Multiple echoes	• SVD [6] • Solve for ΔB_0 via phase difference [7] • Solve for φ_0^C: ASPIRE [8]

[1] Hammond et al. NI 2008
[2] Walsh et al. MRM 2000
[3] Parker et al. MRM 2014

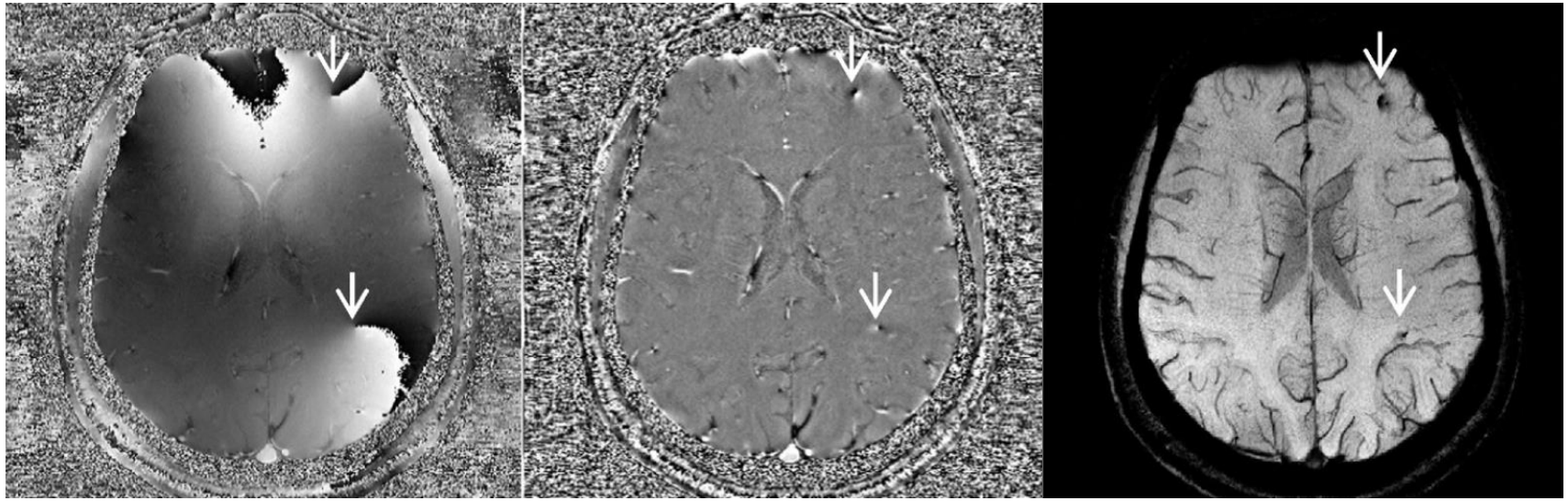
[4] Roemer et al. NI 1990
[5] Robinson et al. MRM 2017

Review: Robinson et al. NMR Biomed 2017

[6] Khabipova et al. NI 2015
[7] Bernstein et al. MRM 1994
[8] Eckstein et al. MRM 2018

Coil combination considerations for QSM

- check for phase combination artifacts and signal cancellations:

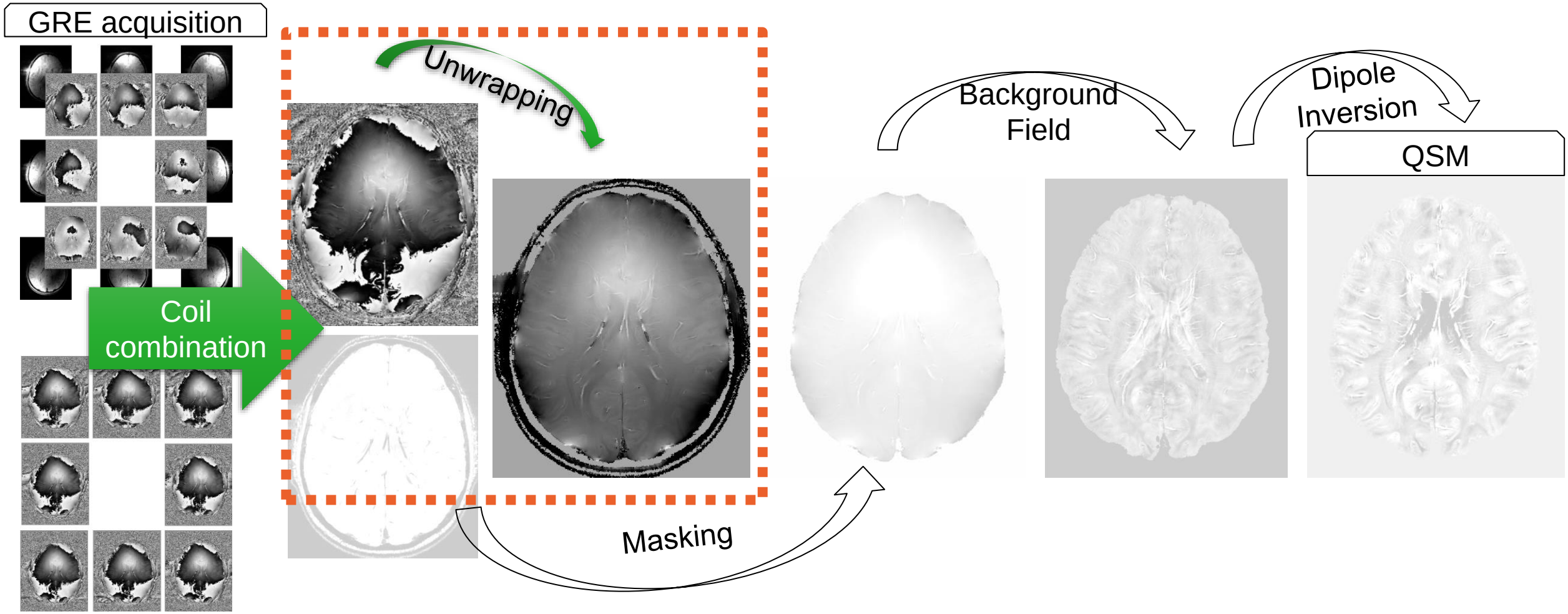


Haacke et al.
MRI
2014

ask local support for phase optimal combination method, but to get started:

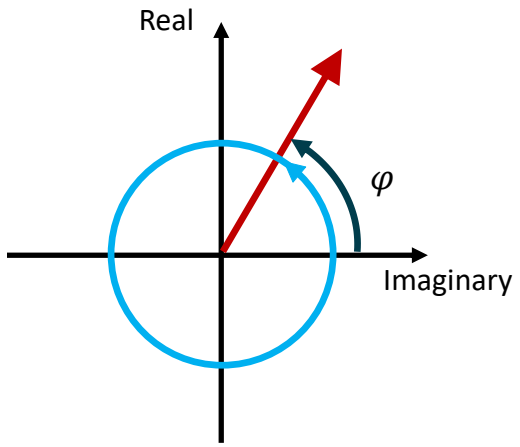
- less of a problem on coils with few channels (e.g. Bruker animal systems)
- SENSE works well (e.g. Philips/GE)
- Siemens: ASPIRE C2P from Simon Robinson available for VB17, VE11, VE12U
- adaptive combine works well, not yet out of the box for systems older than VD or VE12U

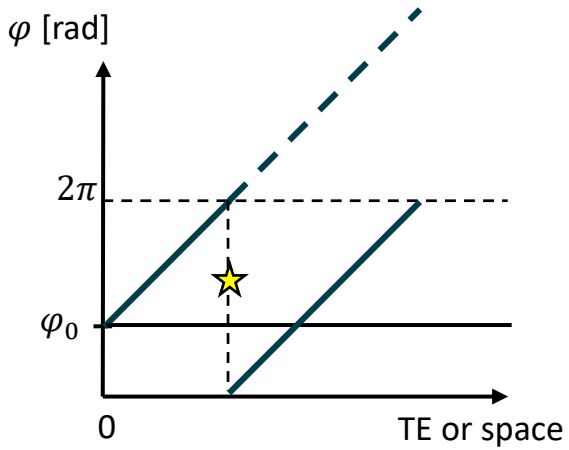
… to Quantitative Susceptibility Mapping (QSM)



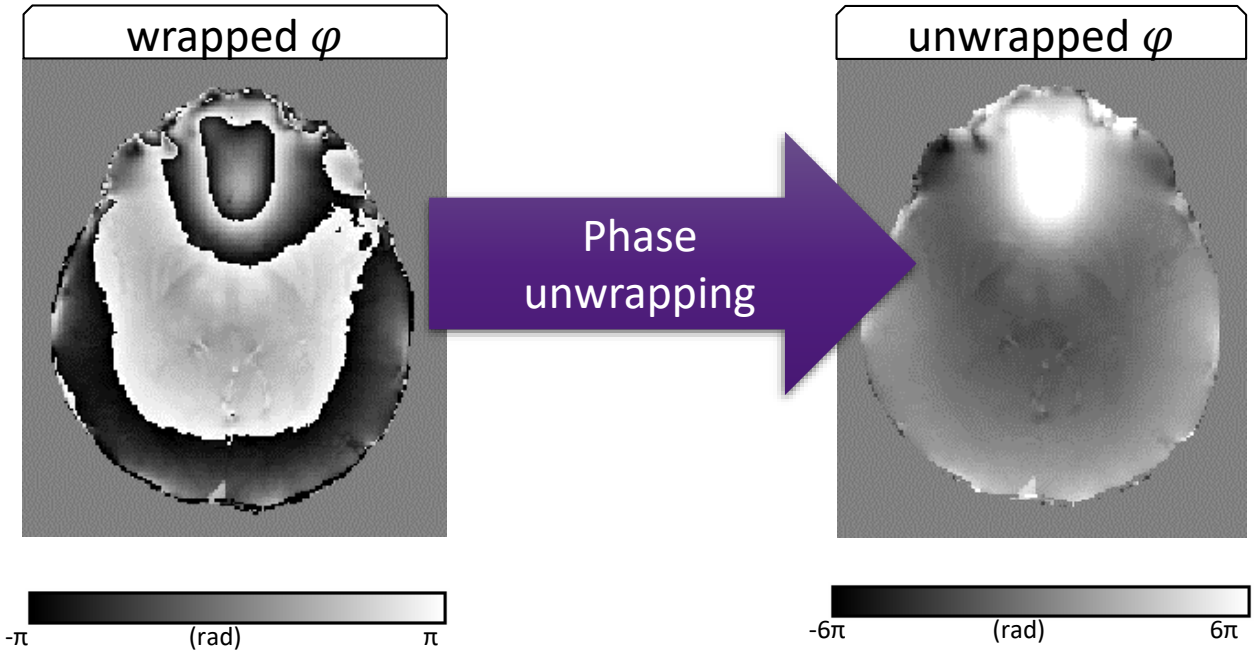
Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

Phase unwrapping problem





$$\varphi(r) = \varphi_w(r) + 2\pi n(r)$$



Unwrapping techniques

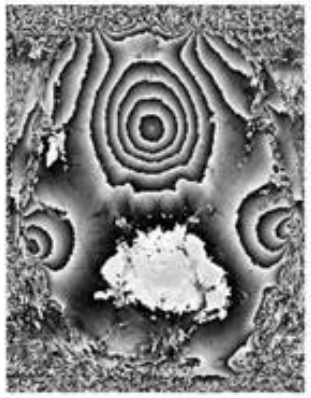
- Laplacian
- Region-growing
- Path Based

Unwrapping techniques

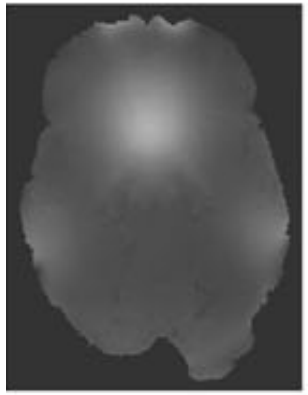
Laplacian

- differentiable operator applied to the unwrapped phase can produce the same result on the wrapped phase -> Laplacian (Schofield and Zhu, Opt. Lett. 2003)
- + fast & robust
- - introduces background phase

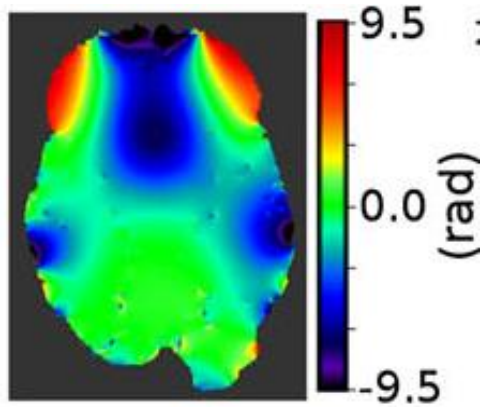
Wrapped Phase



Laplacian-unwrapped phase



Difference from true phase



Unwrapping techniques

Laplacian

- differentiable operator applied to the unwrapped phase can produce the same result on the wrapped phase -> Laplacian (Schofield and Zhu, Opt. Lett. 2003)
- + fast & robust
- - introduces background phase

Region-growing

- Identify discontinuities between regions
- PRELUDE (Jenkinson MRM 2003) can take a while to compute for highly wrapped data
- SEGUE (Karsa et al. TMI 2019) similar accuracy to PRELUDE, but faster

Unwrapping techniques

Laplacian

- differentiable operator applied to the unwrapped phase can produce the same result on the wrapped phase -> Laplacian (Schofield and Zhu, Opt. Lett. 2003)
- + fast & robust
- - introduces background phase

Region-growing

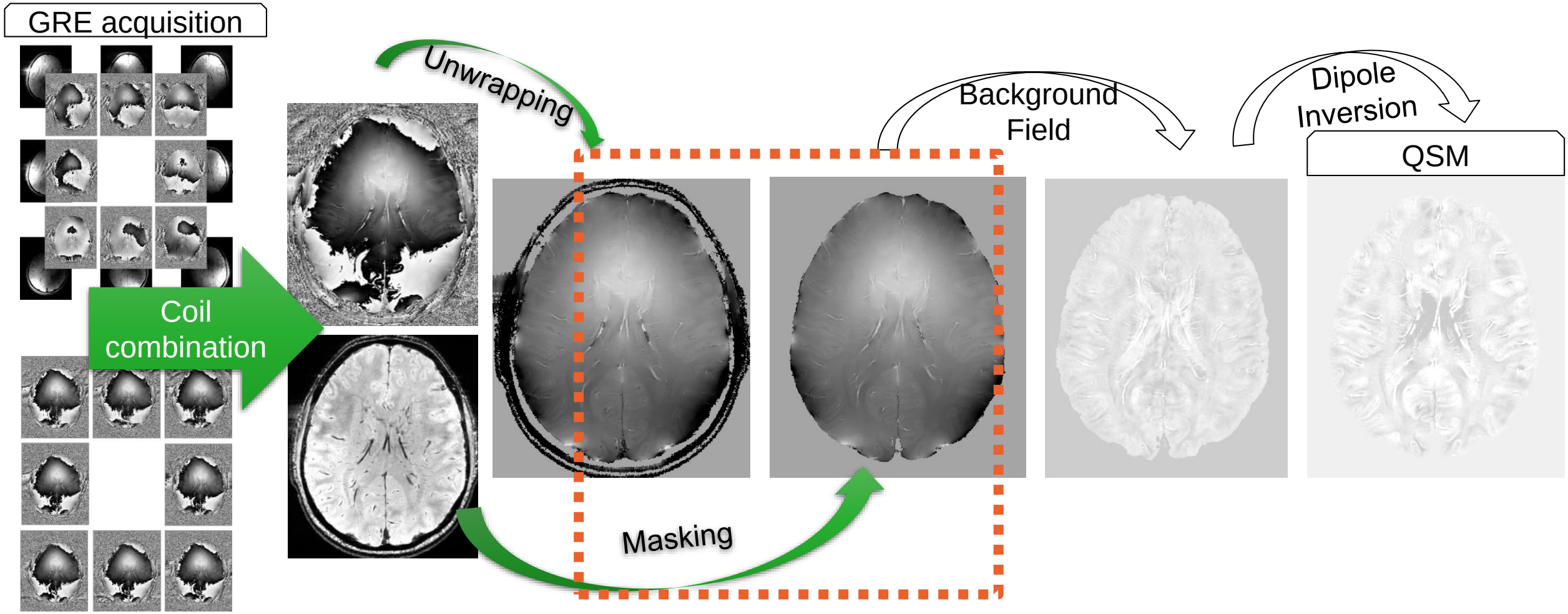
- Identify discontinuities between regions
- PRELUDE (Jenkinson MRM 2003) can take a while to compute for highly wrapped data
- SEGUE (Karsa et al. TMI 2019) similar accuracy to PRELUDE, but faster

Path Based

- 3D voxel-by-voxel unwrapping guided by the quality of voxel connections
- BEST PATH (Abdul-Rahman et al. AO 2007)
- ROMEO (Dymerska et al. MRM 2021)

Review: Robinson et al., NMR Biomed 2017

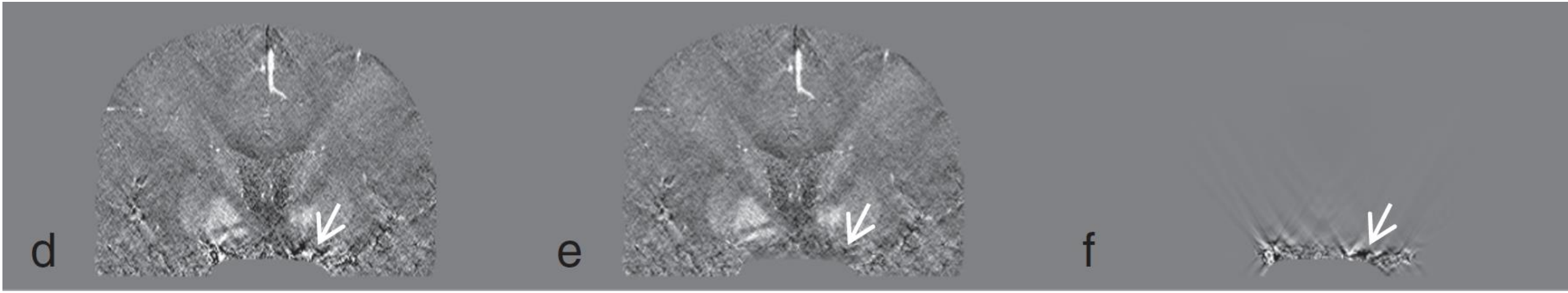
… to Quantitative Susceptibility Mapping (QSM)



Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

Why do we need to mask the object of interest?

- required for most background field correction algorithms to define inside/outside object of interest
- including unreliable phase values in the dipole inversion results in artifacts

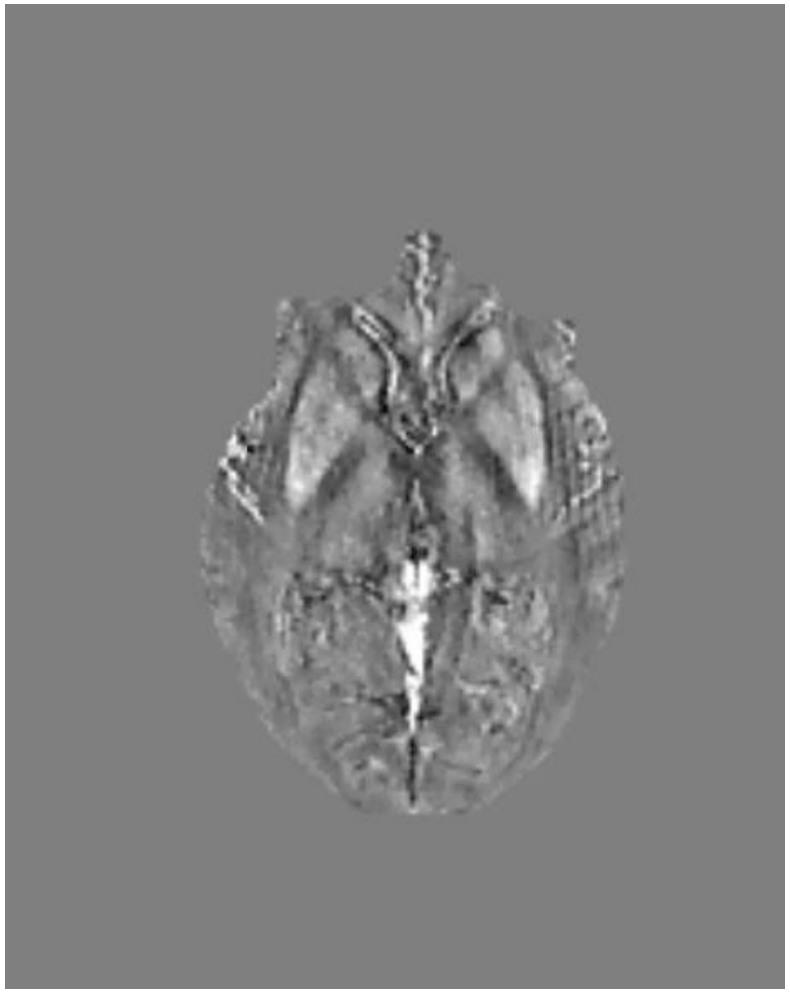


Haacke et al. MRI 2014

Why do we need to mask the object of interest?

- tradeoff between artifacts and

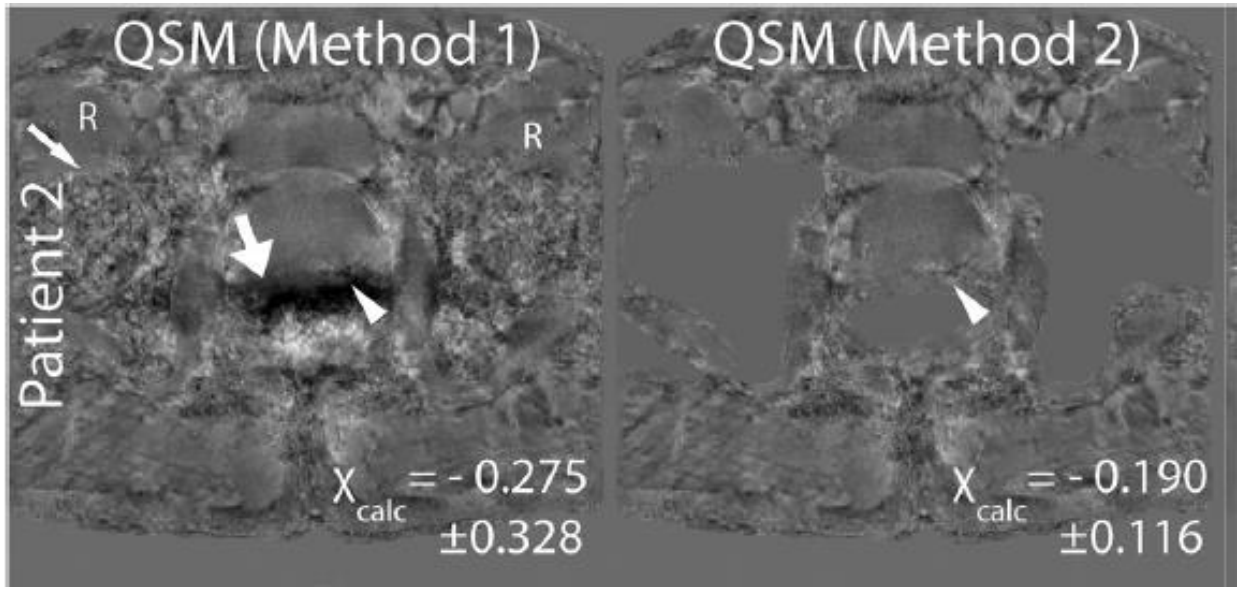
  masking out regions of interest



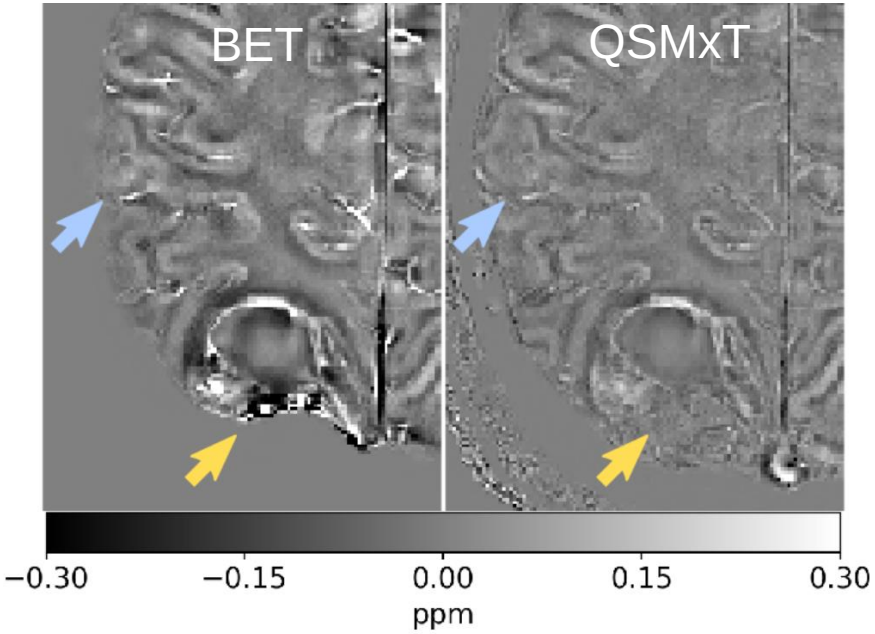
So, masking isn't trivial?

- most QSM toolkits do not bring a masking procedure ☹
- commonly used for brain data: BET (Smith et al, HBM 2002)

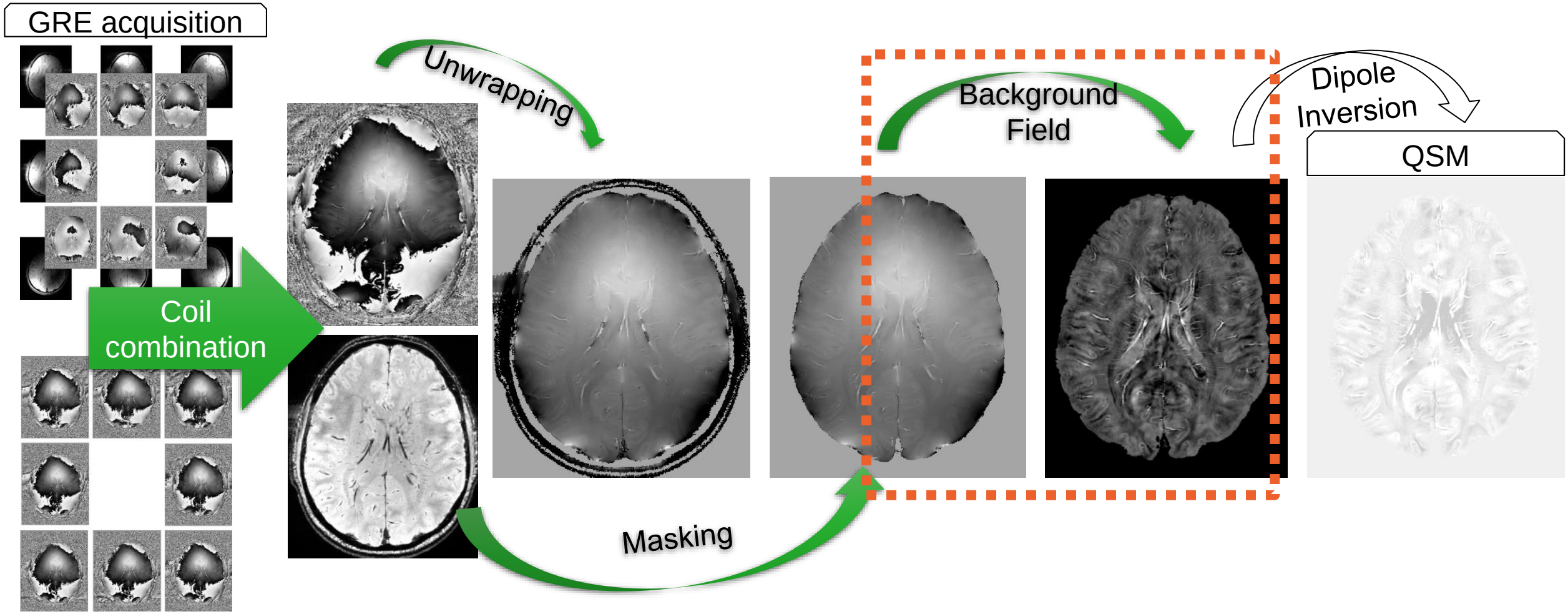
dedicated methods crucial for e.g. abdominal QSM
(Straub et al., Tomography 2017)



improved masking for QSM
(Stewart et al., ISMRM 2021, #0725, #3971)



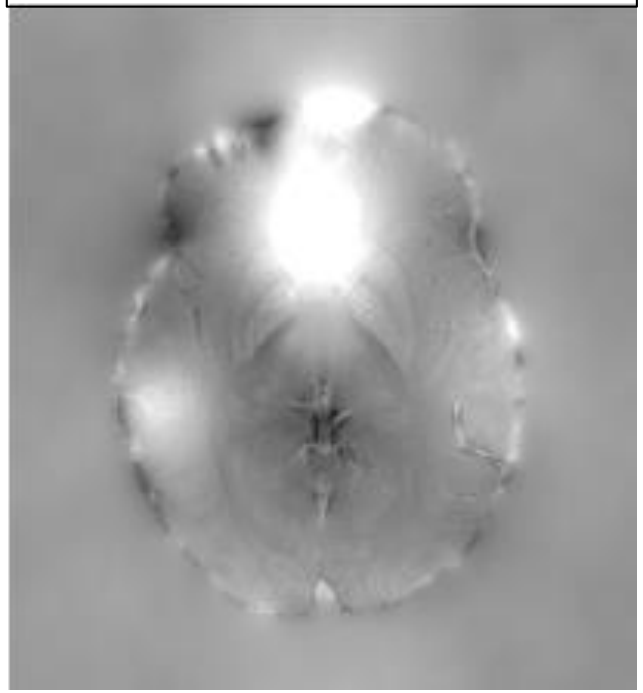
… to Quantitative Susceptibility Mapping (QSM)



Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

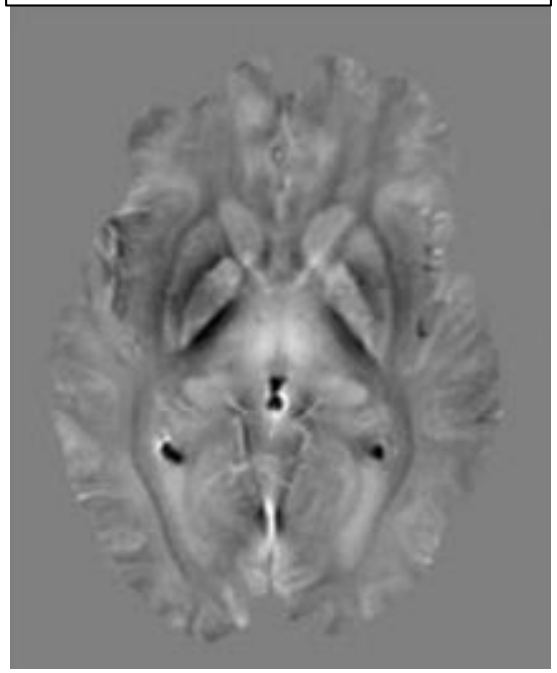
Background Field Removal

Unwrapped masked phase



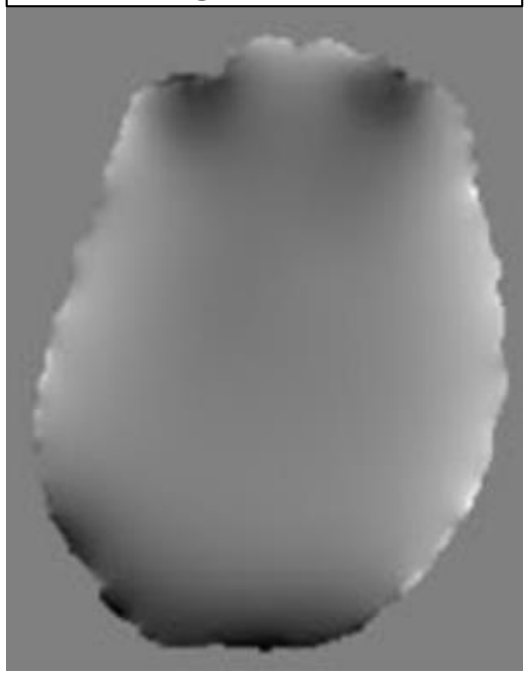
=

Internal tissue field



+

background field



Susceptibility difference between tissue and air

Shim coil fields

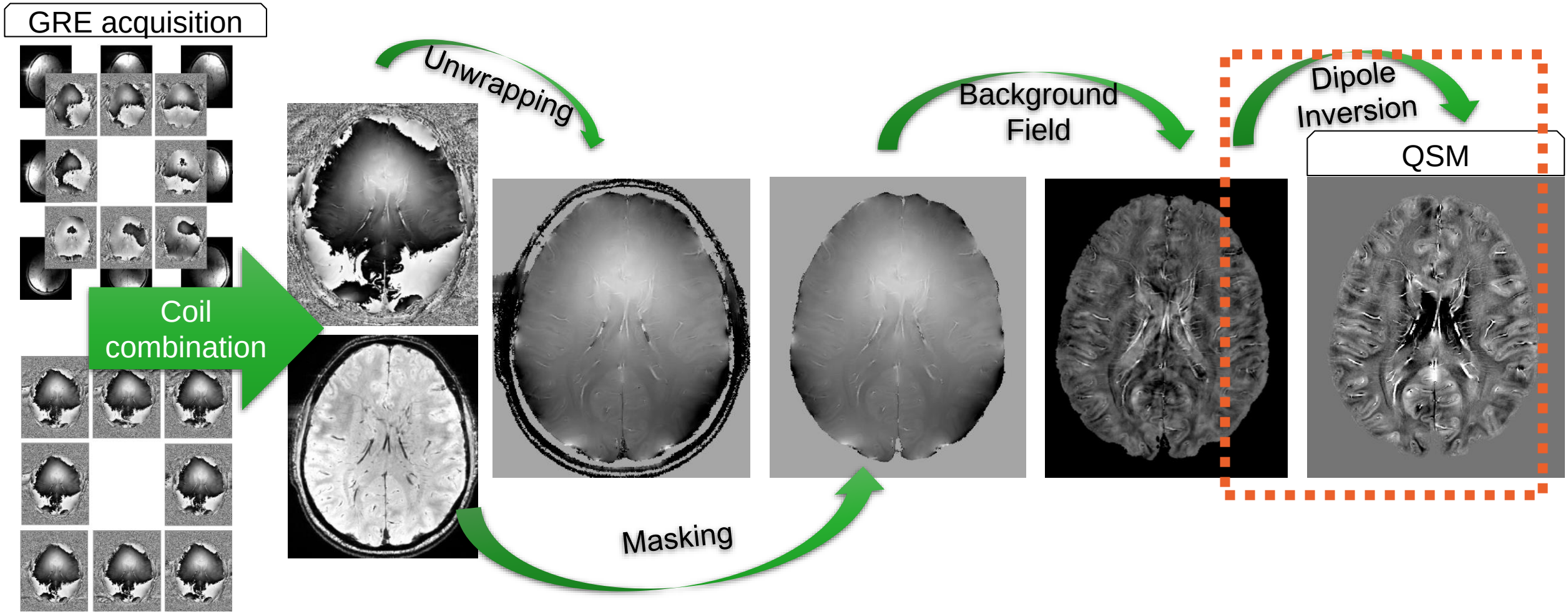
Static field inhomogeneities

Background field correction methods & assumptions

no sources close to boundaries	• SHARP (Schweser et al. NI 2011) • V-SHARP (Li et al. NI 2011)
no harmonic internal and boundary fields	• LBV (Zhou et al. NMR Biomed 2014)
no implicit boundary assumption	• RESHARP (Sun et al. MRM 2014) • SHARQnet (Bollmann et al. Z Med Phys 2018)

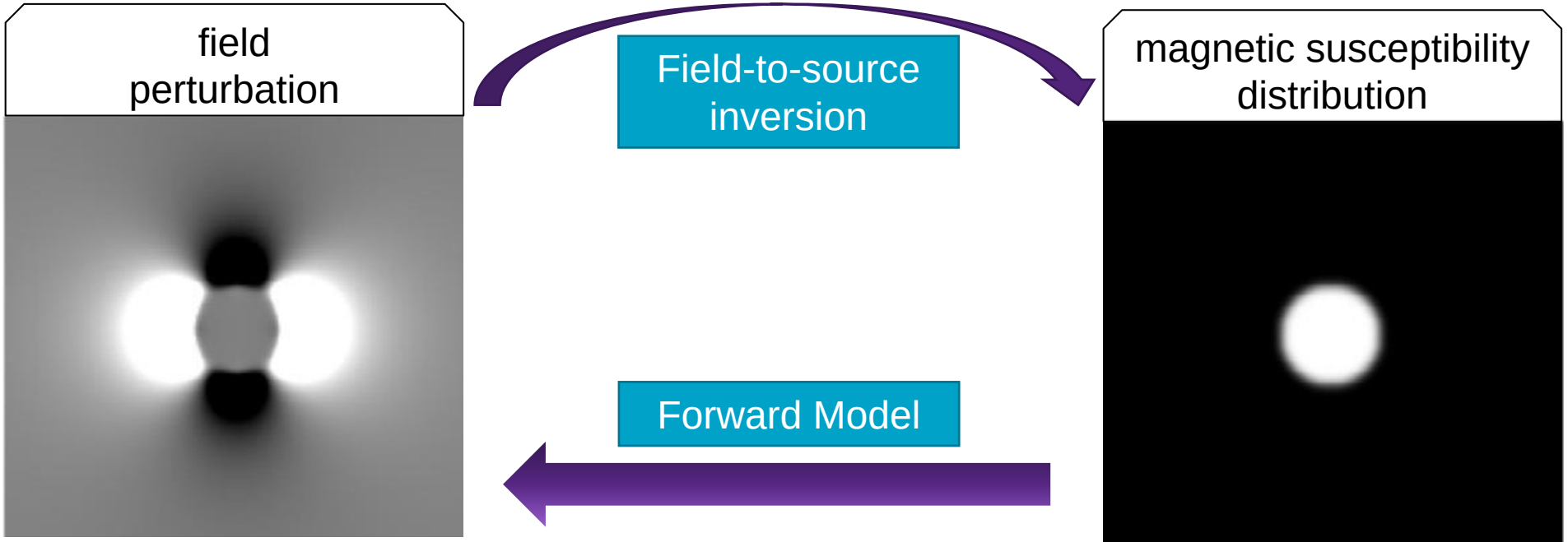
Review: Schweser et al. NMR Biomed 2017

… to Quantitative Susceptibility Mapping (QSM)



Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

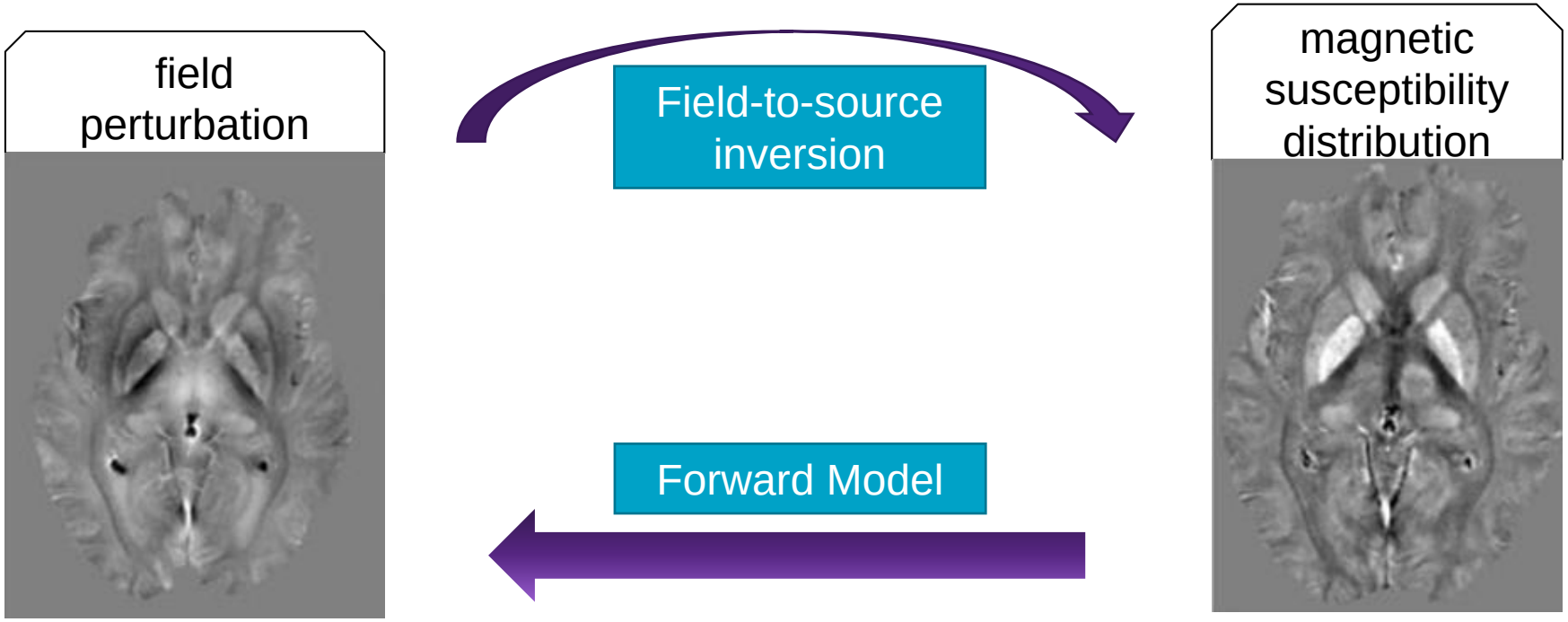
QSM Dipole inversion



$$\Delta B_{\text{int}}(\vec{r}) = B_0 \cdot \int_{-\infty}^{\infty} \tilde{\chi}(\vec{r'}) \cdot d_z(\vec{r} - \vec{r'}) d^3\vec{r'}$$

Review: Deistung et al. NMR Biomed 2017; Schweser et al. Z Med Phys 2016

QSM Dipole inversion



$$\Delta B_{\text{int}}(\vec{r}) = B_0 \cdot \int_{-\infty}^{\infty} \tilde{\chi}(\vec{r'}) \cdot d_z(\vec{r} - \vec{r'}) d^3\vec{r'}$$

Review: Deistung et al. NMR Biomed 2017; Schweser et al. Z Med Phys 2016

Dipole inversion methods & assumptions

multiple orientations

- COSMOS (Liu et al. MRM 2009)
- STI (Liu MRM 2010)
- analytical solutions, but not practical

inverse filtering

iterative methods

agnostic deep learning

hybrid methods

Reviews: Schweser et al. NMR Biomed 2017; Jung et al. NMR Biomed 2020

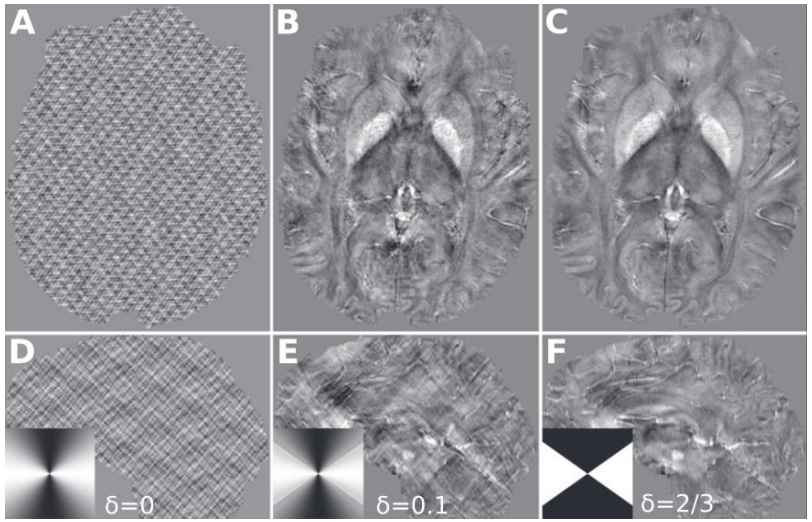
Dipole inversion methods & assumptions

multiple orientations

- COSMOS (Liu et al. MRM 2009)
- STI (Liu MRM 2010)
- analytical solutions, but not practical

inverse filtering

- TKD (Shmueli et al. MRM 2009)
- fast, but need parameter tweaking



TKD: effect of various threshold choices
(Deistung et al. NMR Biomed 2017)

Reviews: Schweser et al. NMR Biomed 2017; Jung et al. NMR Biomed 2020

Dipole inversion methods & assumptions

multiple orientations
- COSMOS (Liu et al. MRM 2009)
- STI (Liu MRM 2010)
- analytical solutions, but not practical

inverse filtering
- TKD (Shmueli et al. MRM 2009)
- fast, but need parameter tweaking

iterative methods
- LSQR (Li et al. NI 2015)
- MEDI (Liu et al. MRM 2013)
- slow, need parameter tweaking

Error function

Regularisation term

$$\tilde{\chi}(\vec{r}) = \arg\min_{\tilde{\chi}} \left\| \frac{\Delta B_{\text{int}}}{B_0} - d_z \circledast \tilde{\chi} \right\|_2^2 + \alpha \cdot R(\tilde{\chi})$$

Measured tissue perturbation

Estimated tissue perturbation (forward model)

Reviews: Schweser et al. NMR Biomed 2017; Jung et al. NMR Biomed 2020

Dipole inversion methods & assumptions

multiple orientations	• COSMOS (Liu et al. MRM 2009) • STI (Liu MRM 2010) • analytical solutions, but not practical
inverse filtering	• TKD (Shmueli et al. MRM 2009) • fast, but need parameter tweaking
iterative methods	• LSQR (Li et al. NI 2015) • MEDI (Liu et al. MRM 2013) • slow, need parameter tweaking
agnostic deep learning	• QSMnet (Yoon et al. NI 2018) • DeepQSM (Bollmann et al. NI 2019) • fast, but fragile

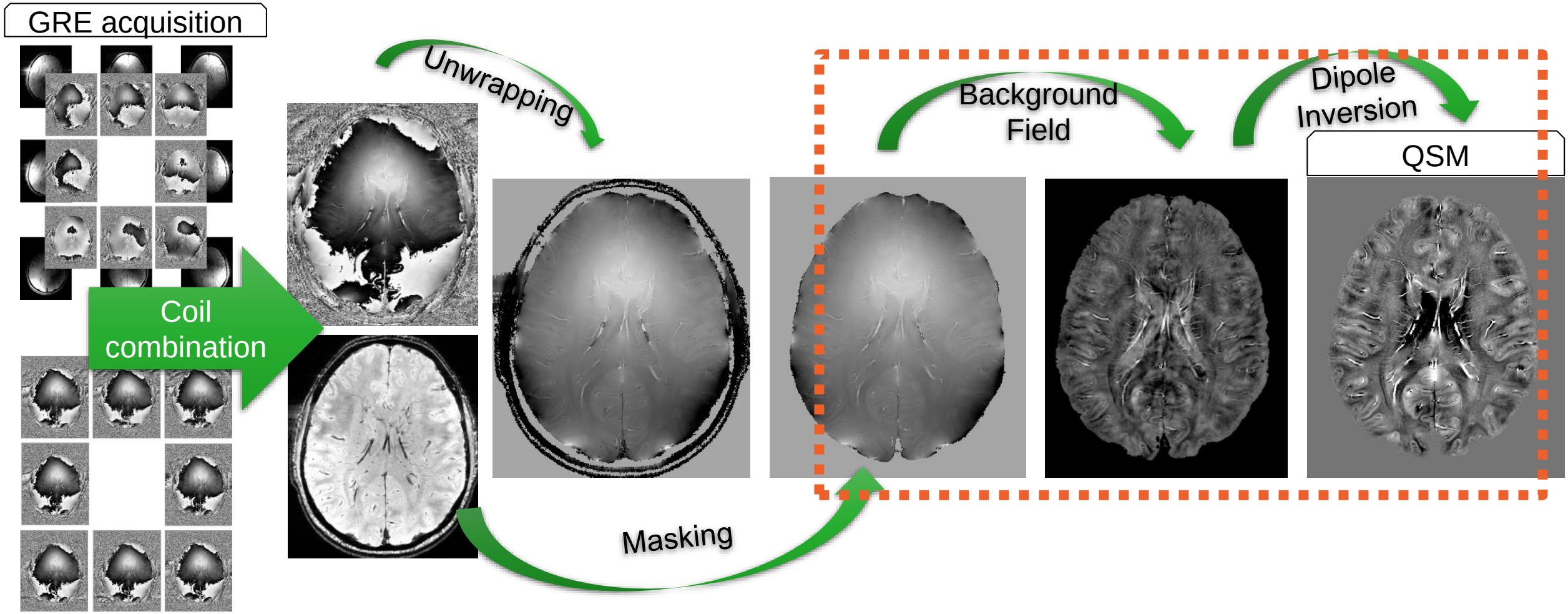
Reviews: Schweser et al. NMR Biomed 2017; Jung et al. NMR Biomed 2020

Dipole inversion methods & assumptions

multiple orientations	• COSMOS (Liu et al. MRM 2009) • STI (Liu MRM 2010) • analytical solutions, but not practical
inverse filtering	• TKD (Shmueli et al. MRM 2009) • fast, but need parameter tweaking
iterative methods	• LSQR (Li et al. NI 2015) • MEDI (Liu et al. MRM 2013) • slow, need parameter tweaking
agnostic deep learning	• QSMnet (Yoon et al. NI 2018) • DeepQSM (Bollmann et al. NI 2019) • fast, but fragile
hybrid methods	• FINE (Zhang et al. NI 2020) • Variational Networks (Lai et al. arXiv 2020) • Deep learning priors + data consistency constraints

Reviews: Schweser et al. NMR Biomed 2017; Jung et al. NMR Biomed 2020

… to Quantitative Susceptibility Mapping (QSM)



Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

Combined approaches (Background field + Dipole inversion)

iterative methods

- TGV-QSM (Langkammer et al. NI 2015)
- SS-QSM (Chatnuntawech et al. NMR Biomed 2017)
- TFI (Liu et al. MRM 2017)

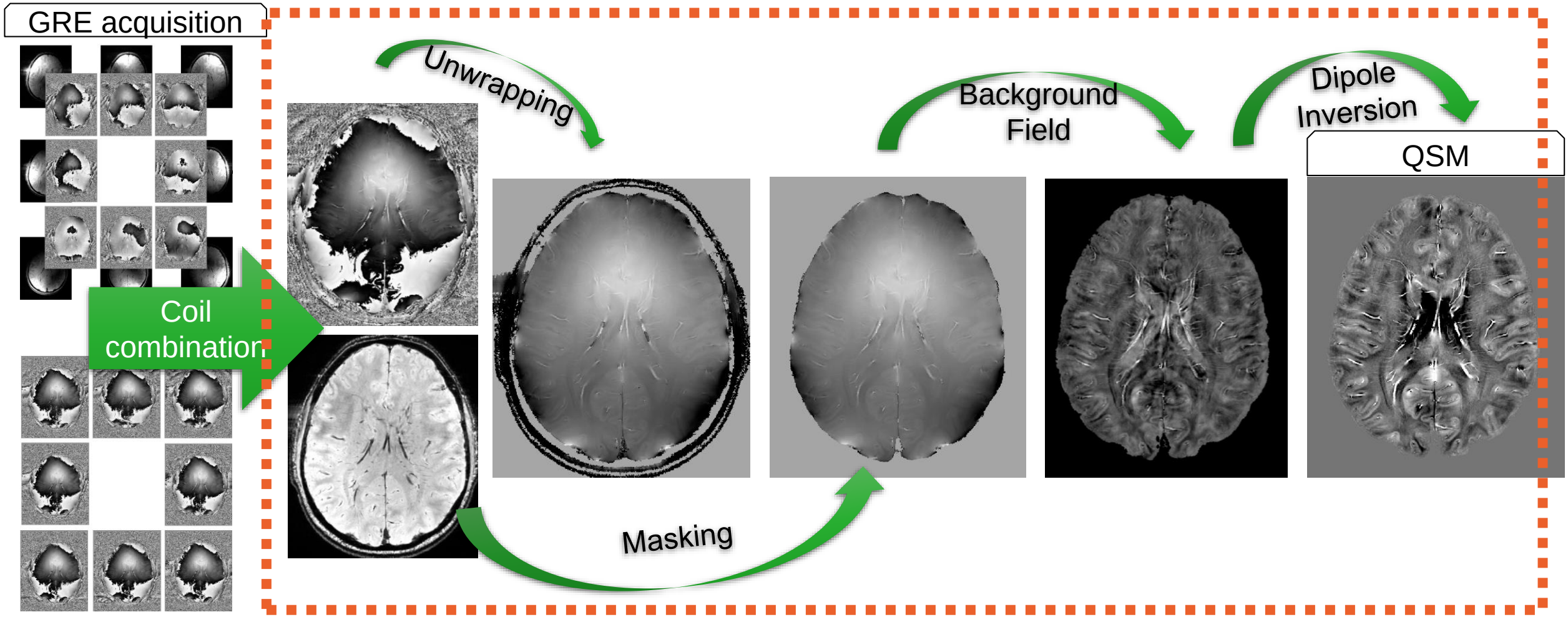
agnostic deep learning

- AutoQSM (Wei et al. NI 2019)

hybrid methods

- NeXtQSM (Cognolato et al. ISMRM 2021, Submission 122)

QSM – The big picture



Thank you for slides and material: Simon Robinson, Ashley Stewart, Markus Barth, Francesco Cognolato

Some Processing Packages for QSM

STI Suite (Matlab) - https://people.eecs.berkeley.edu/~chunlei.liu/software.html

- Laplacian Phase Unwrapping, Background field correction (vSHARP, iHARPERELLA)
- Dipole inversion (iLSRQ + STAR QSM)

MEDI toolkit (Matlab) - http://pre.weill.cornell.edu/mri/pages/qsm.html

- from DICOM to QSM using MEDI framework

FANSI Toolbox (Matlab) - https://gitlab.com/cmilovic/FANSI-toolbox

- various unwrapping, background field and Dipole inversion methods

SEPIA (Matlab) - https://github.com/kschan0214/sepia

- GUI for MEDI, STI Suite, FANSI, SEGUE, NDI

QSMxT (Python) - https://github.com/QSMxT

- DICOM/BIDS, robust masking, NiPype + TGV QSM, integrated anatomical segmentation, optimized for high throughput processing on HPCs

Referencing in QSM

QSM values are relative to the water centre frequency of the scan-session

-> consider re-referencing for group studies?

The ideal reference tissue is a debated topic.

Challenges:

- The tissue should have very low inter-subject variance in age and pathology
- The tissue should be easy to segment
- Quantification should be reliable

Reference region candidates:

- Cerebrospinal fluid in the ventricles
- Whole-brain average susceptibility
- Red nucleus
- Cortical gray matter
- Superior frontal white matter
- Splenium of the corpus callosum
- Other white matter structures

Straub et al. MRM 2016

QSM - The bigger picture ….

- Why are there so many methods to compute QSM and which of them is correct?
  - COSMOS?
  - STI33?
  - The winners of the reconstruction challenges?

Quantitative Susceptibility Mapping: Report from the 2016 Reconstruction Challenge

Christian Langkammer,[1] Ferdinand Schweser,[2,3]* Kari
Christian Kames,[5] Xu Li,[6,7] Li Guo,[8] Carlos Milovic,[9,10] J
Hongjiang Wei,[12] Kristian Bredies,[13] Sagar Buch,[14] Yihao C
Jakob Meineke,[16] Alexander Rauscher,[5] José P. Marques,[17]

QSM reconstruction challenge 2.0: A realistic in silico head phantom for MRI data simulation and evaluation of susceptibility mapping procedures

José P. Marques[1] | Jakob Meineke[2] | Carlos Milovic[3,4,5] | Berkin Bilgic[6,7,8] |
Kwok-Shing Chan[1] | Renaud Hedouin[1,9] | Wietske van der Zwaag[10] |
Christian Langkammer[11] | Ferdinand Schweser[12,13]

QSM - The bigger picture ….

- Why are there so many methods to compute QSM and which of them is correct?

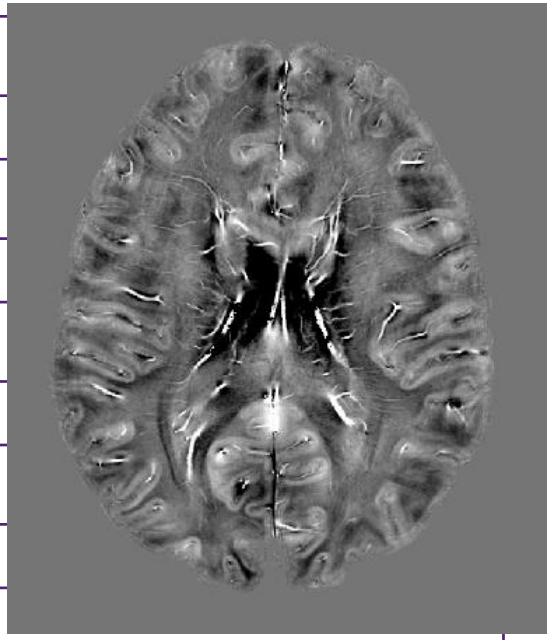
... all models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind....

George Box & Norman Draper, *Empirical Model-Building and Response Surfaces, 1987*

https://en.wikipedia.org/wiki/All_models_are_wrong

How could a useful QSM method look like?

- Fast, robust, no-parameter tweaking (deep learning + data consistency?)
- sensitive to clinical questions?
- developed in an open & high performance language (Julia?)
- automatic and robust masking in brain, joints, body, animal models?
- from DICOMS to results without conversion hassles?
- integrated in the scanner platforms?
- integrated referencing and segmentation to extract values from regions of interest?



Thank you

s.bollmann@uq.edu.au

www.mri.sbollmann.net

@sbollmann_MRI

github.com/sbollmannmri

EMTP Hub

Website of the EMTP ISMRM study group

https://www.emtphub.org/