Per quanto concerne i moderatori, relatori, formatori, tutor, docenti è richiesta dall'Accordo Stato-Regioni vigente apposita dichiarazione esplicita dell'interessato, di trasparenza delle fonti di finanziamento e dei rapporti con soggetti portatori di interessi commerciali relativi agli ultimi due anni dalla data dell'evento.
La documentazione deve essere disponibile presso il Provider e conservata per almeno 5 anni.

Dichiarazione sul Conflitto di Interessi

Il sottoscritto MAURO COSTAGLI in qualità di:

☐ responsabile scientifico ☐ moderatore ☐ docente ☒ relatore ☐ tutor

dell'evento "X CONGRESSO AIRMM - RISONANZA MAGNETICA IN MEDICINA 2019: DALLA RICERCA TECNOLOGICA AVANZATA ALLA PRATICA CLINICA"
Milano, 28-29 marzo 2019

da tenersi per conto di **Biomedia srl Provider n. 148,**

ai sensi dell'Accordo Stato-Regione in materia di formazione continua nel settore "Salute" (Formazione ECM) vigente,

Dichiara

☒ che negli ultimi due anni NON ha avuto rapporti anche di finanziamento con soggetti portatori di interessi commerciali in campo sanitario

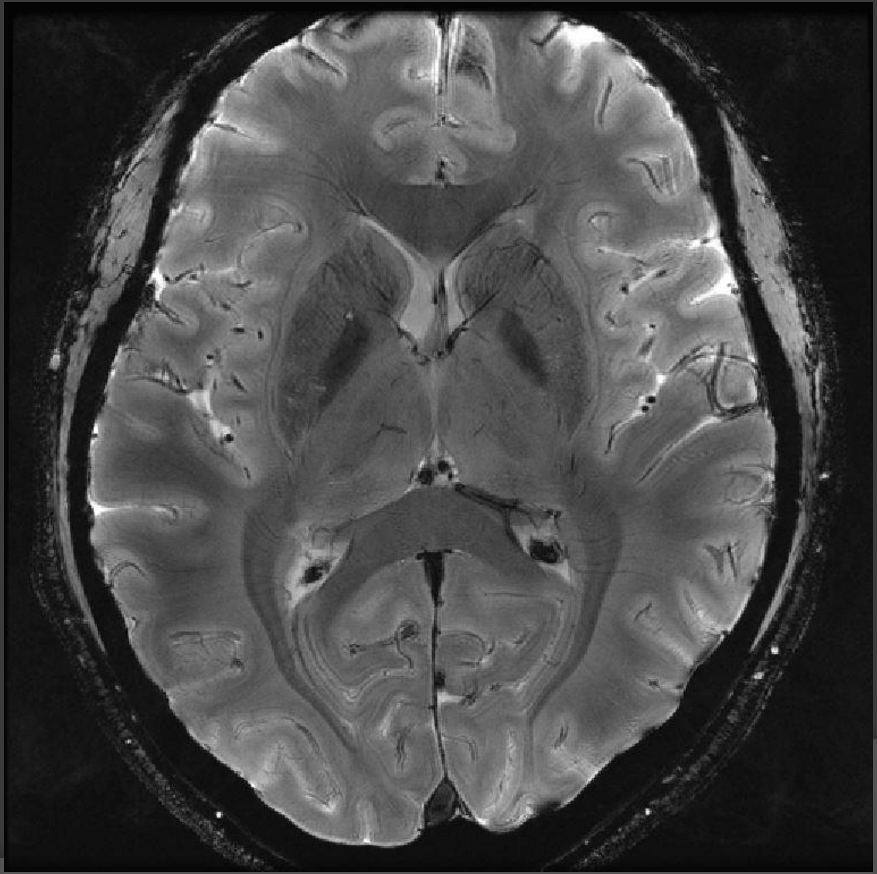
From qualitative T2*-weighting to

QUANTITATIVE SUSCEPTIBILITY MAPPING:

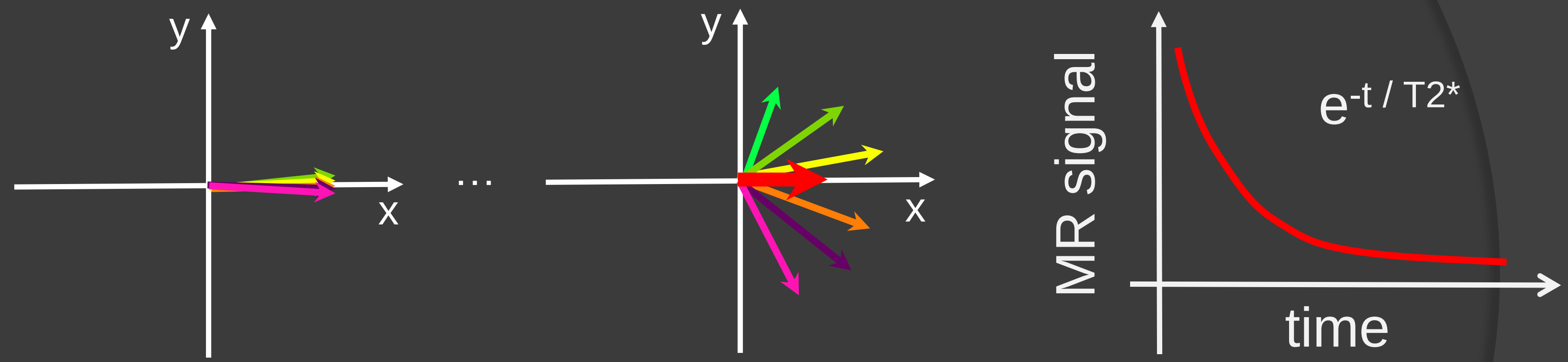
Mechanisms & Methods

Mauro Costagli
Staff researcher at IMAGO7 and IRCCS Stella Maris, Pisa
mcostagli@imago7.eu / www.maurocostagli.info

- Gradient-recalled echo (GRE) imaging



- T2*-weighted MR signal after RF pulse:



$$R2^* = \frac{1}{T2^*} = \frac{1}{T2} + \tfrac{1}{2}\,\gamma\,\Delta B_{inhomog}$$

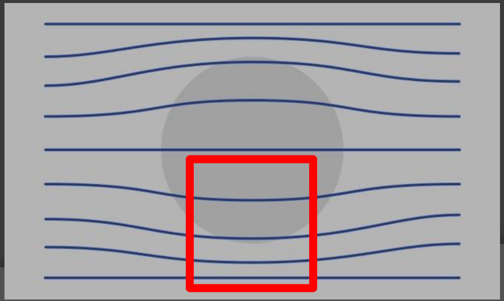
T2* MR signal and magnetic susceptibility:

$$R2^* = \frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{2}\gamma\,\Delta B_{inhomog}$$

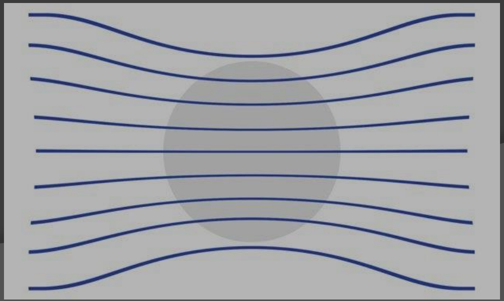
Magnetic susceptibility χ: magnetic response of a substance when it is placed in an external magnetic field. In an object within a uniform external magnetic field, the induced magnetization (owing to its χ) distorts the magnetic field outside the object.

Diamagnetic : $\chi<0$

(e.g. calcium phosphates, proteins and lipids associated with myelin)

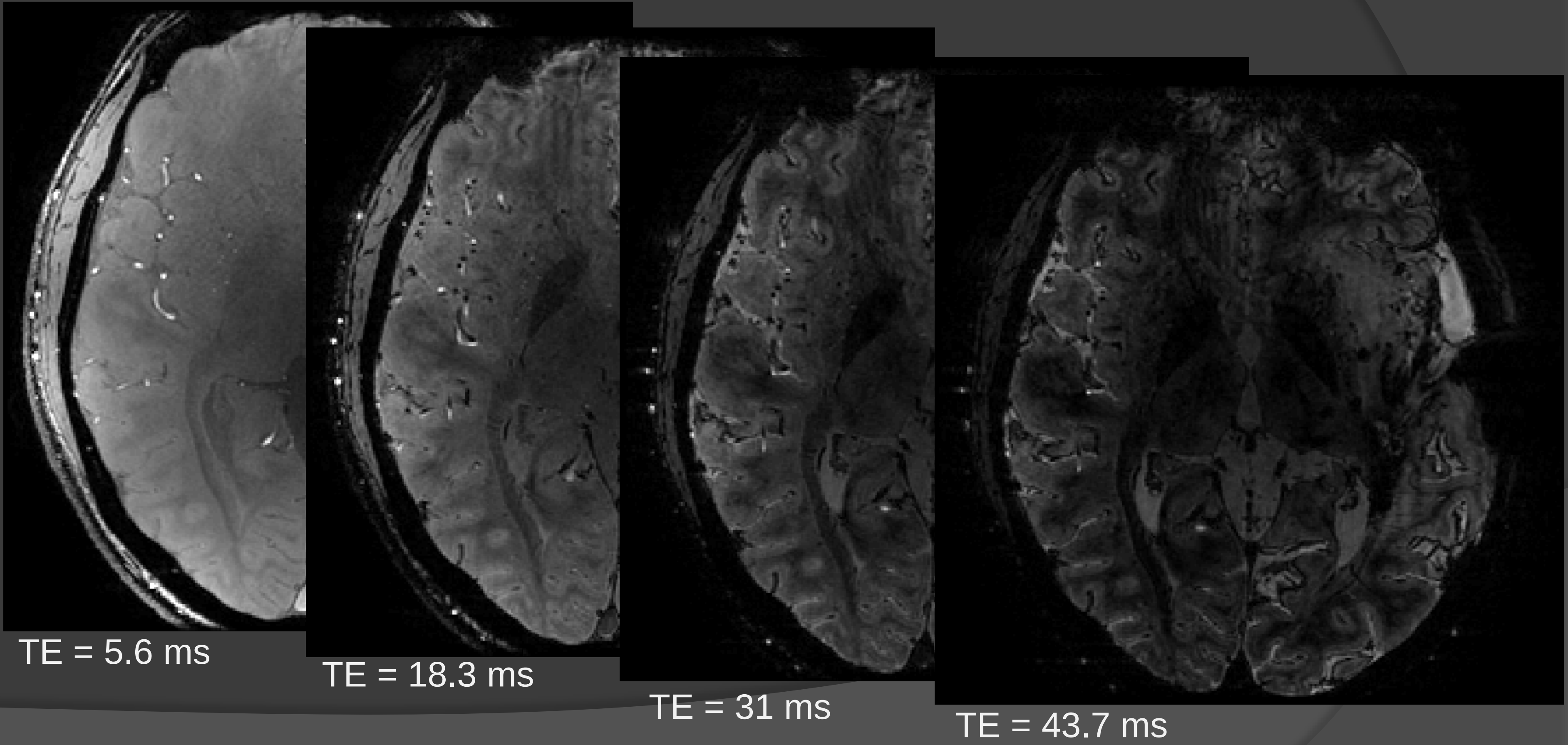


Paramagnetic : $\chi>0$

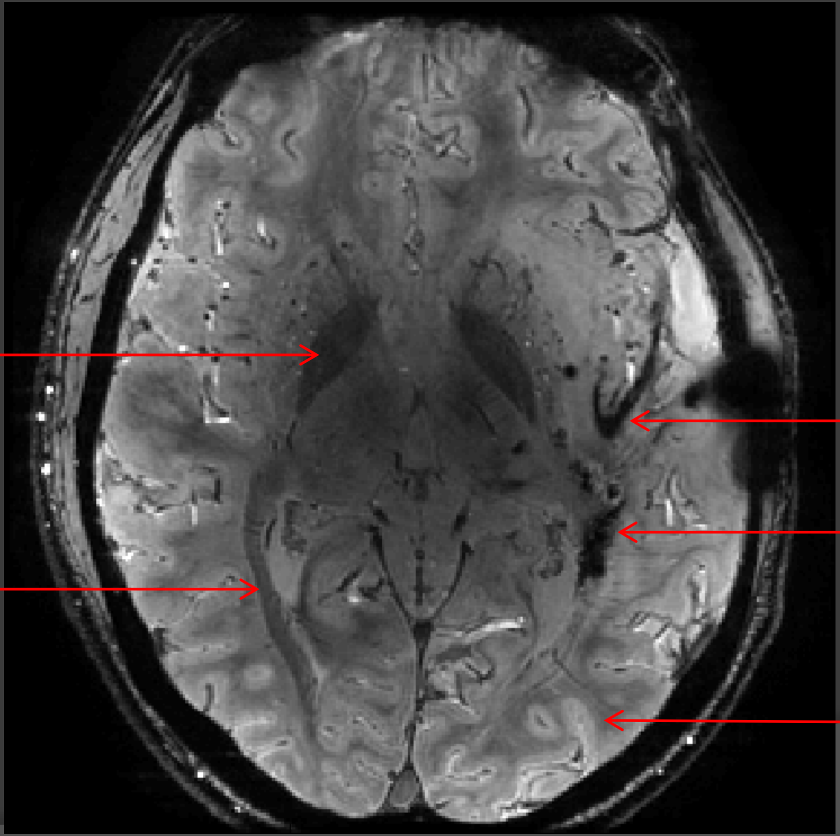


(e.g. iron-based tissues, deoxy-genated blood, proteins like ferritin and hemosiderin)

3D multi-echo GRE imaging: TC & SNR

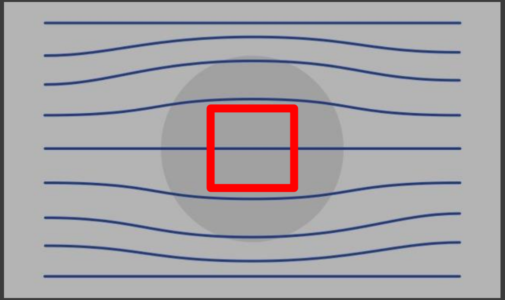


- Average of T2*w signal from all echoes:



Magnetic susceptibility and MR signal phase:

Diamagnetic : χ<0

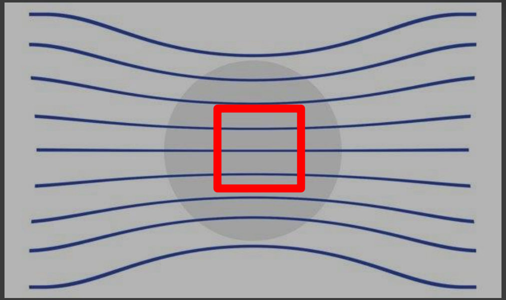


e.g. calcium phosphates, proteins and lipids associated with myelin

angular frequency:

$$\omega = \gamma B_0$$

Paramagnetic : χ>0

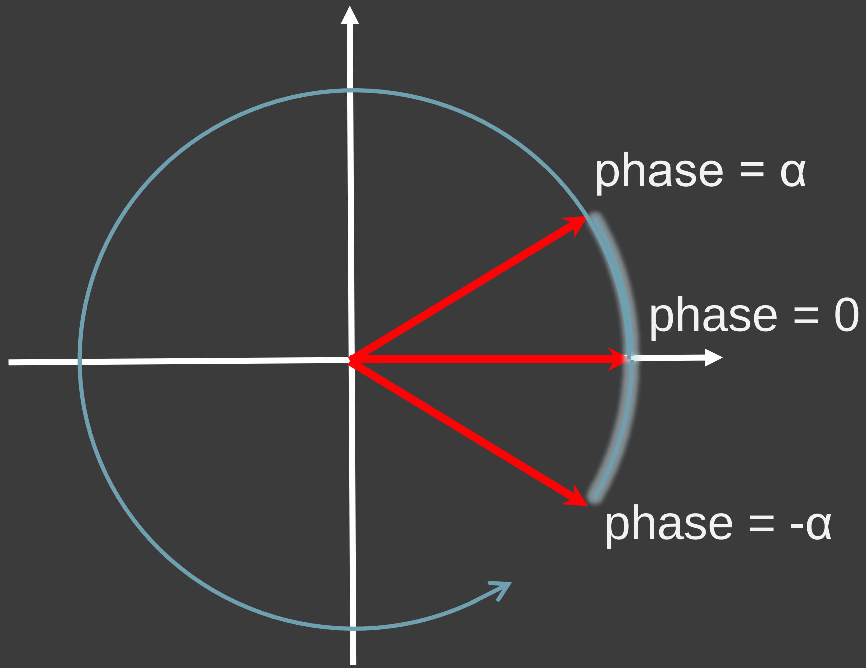


e.g. iron-based tissues, deoxygenated blood, proteins like ferritin and hemosiderin

B_0 inhomogeneities lead to <u>local changes</u> in MR <u>phase images</u>.

- Magnetic susceptibility and MR signal phase:

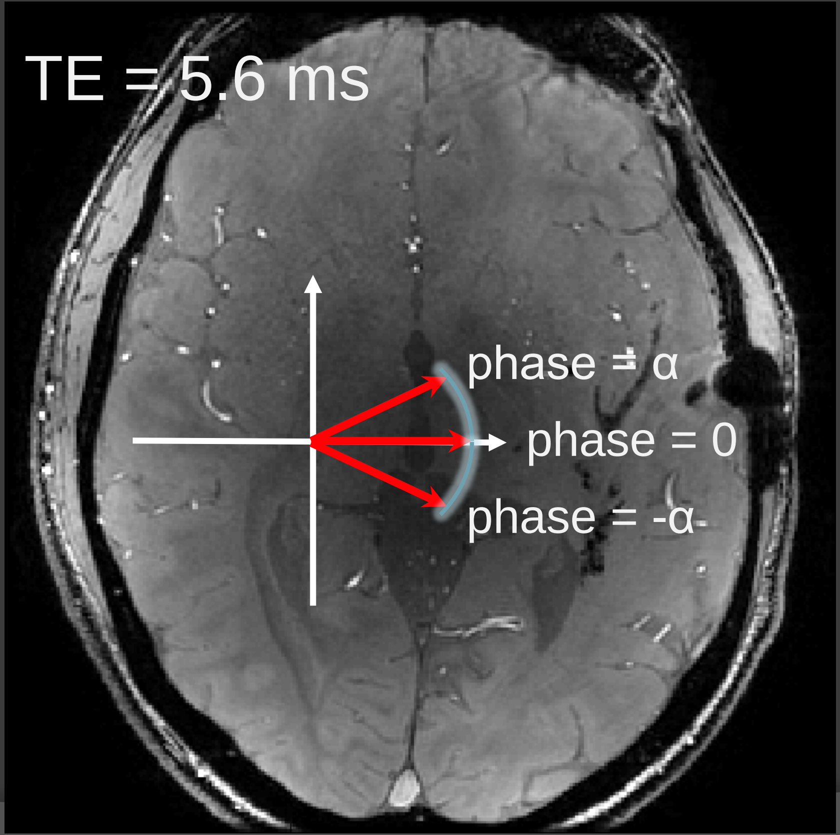
$$\omega = \gamma B_0$$

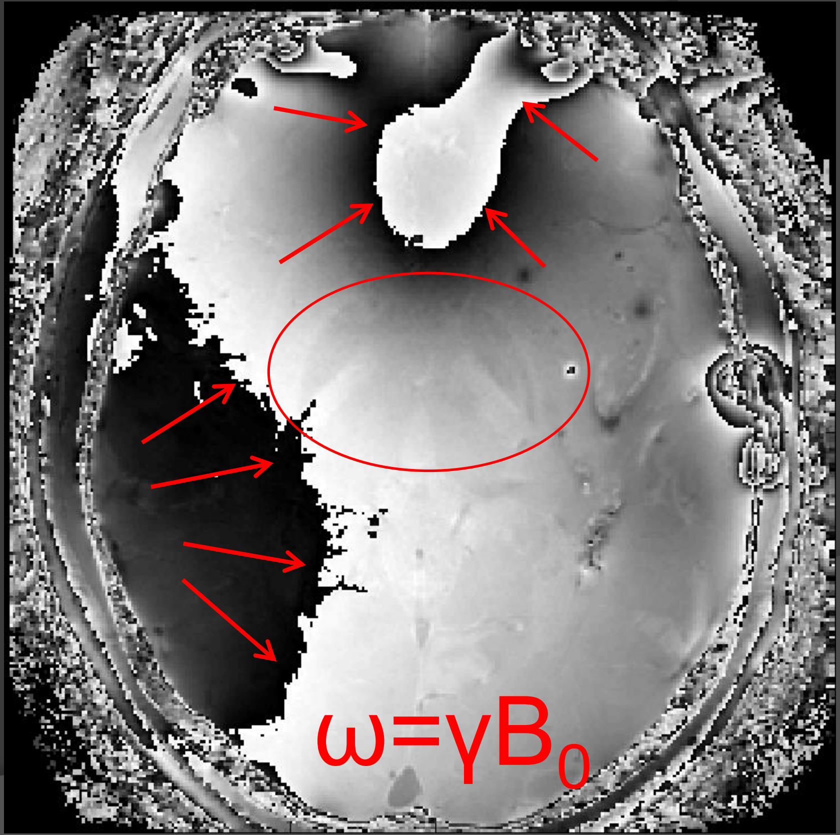


Phase imaging is used <u>best at high field</u>

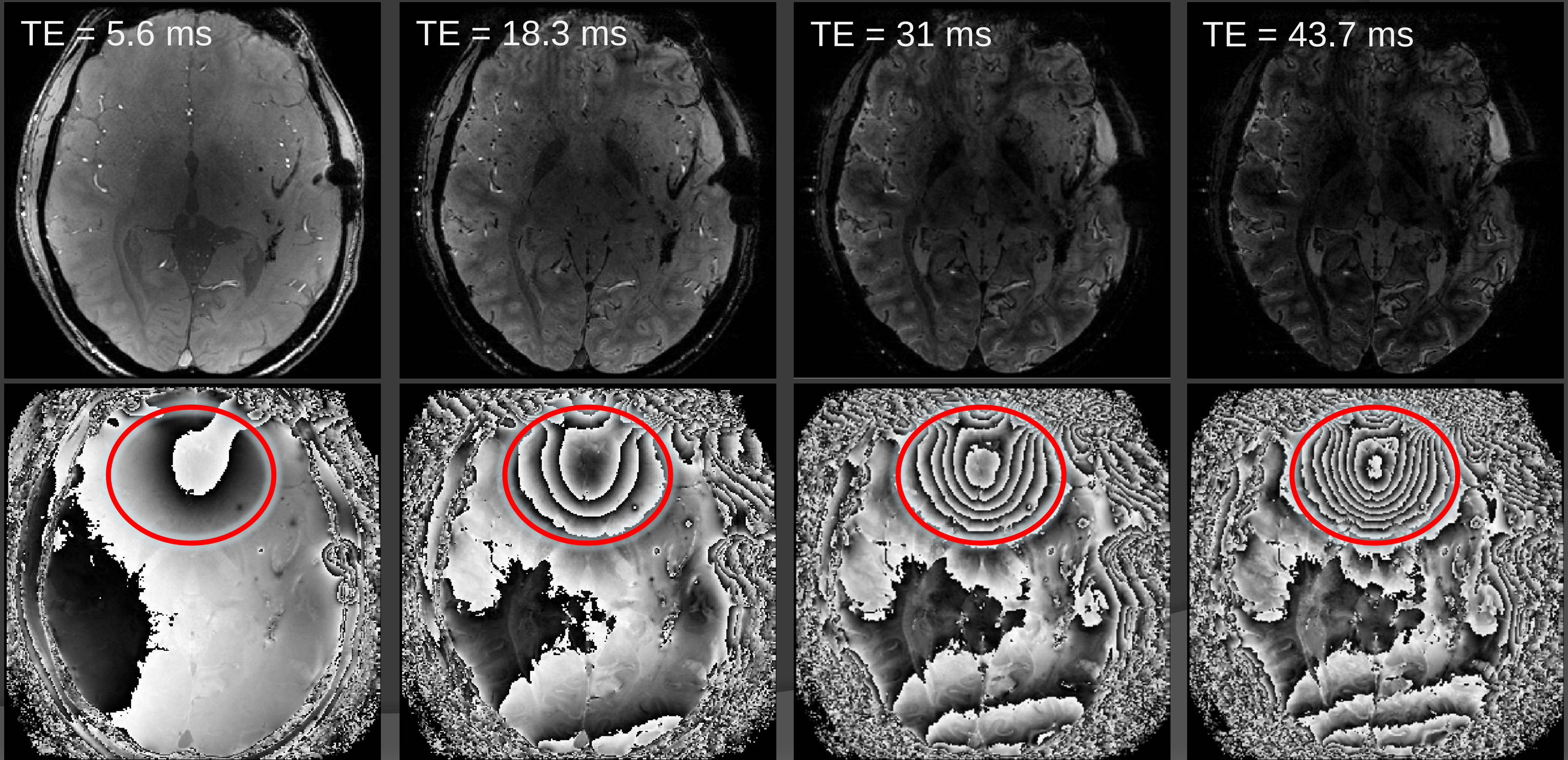
where large phase differences can be obtained with short TE.

Phase-based imaging:



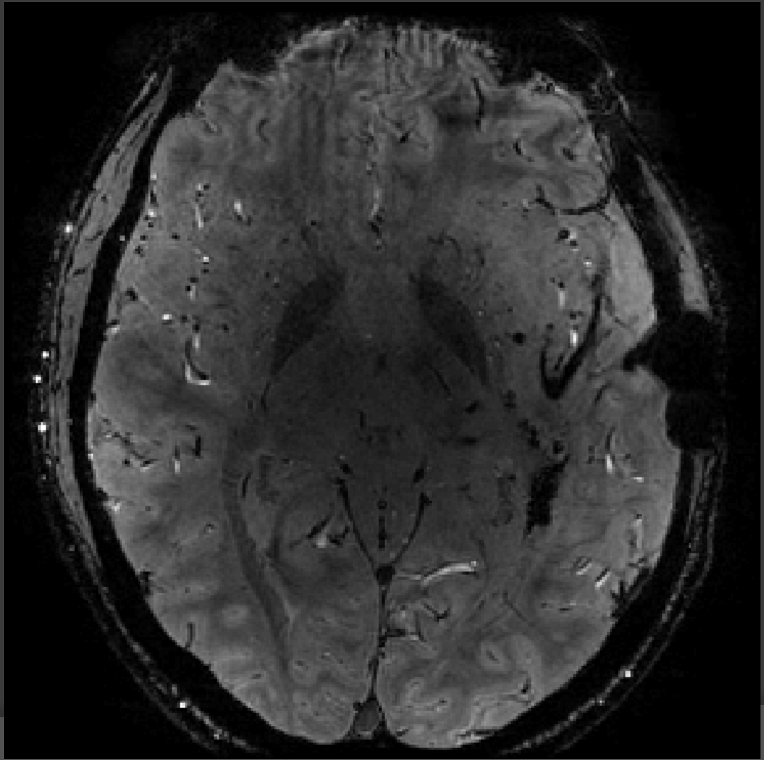


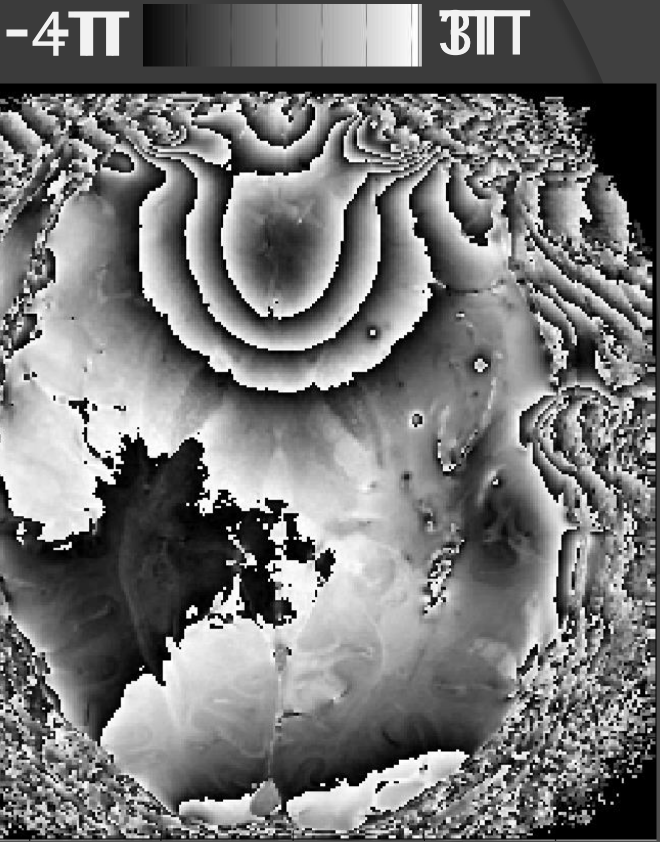
Phase contrast increases with TE



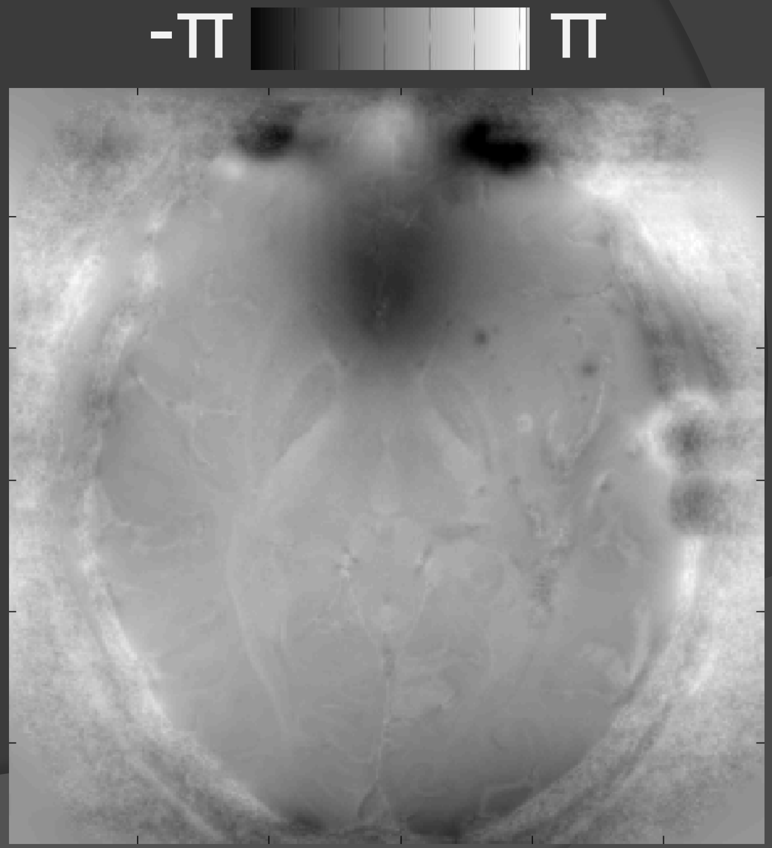
Signal processing: phase unwrapping

TE = 18.3 ms



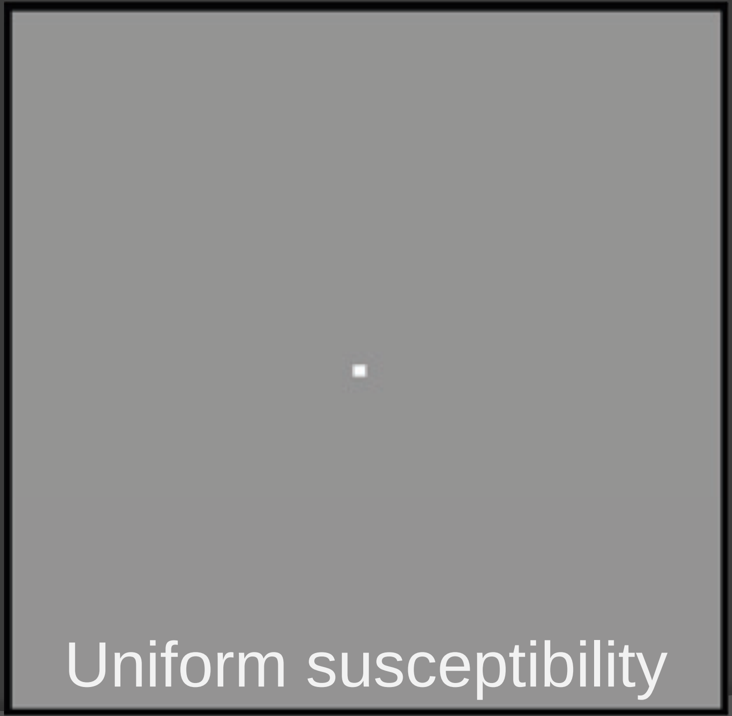


Signal processing: background field removal



- The relationship between phase signal and magnetic susceptibility

$\omega = \gamma B_0$

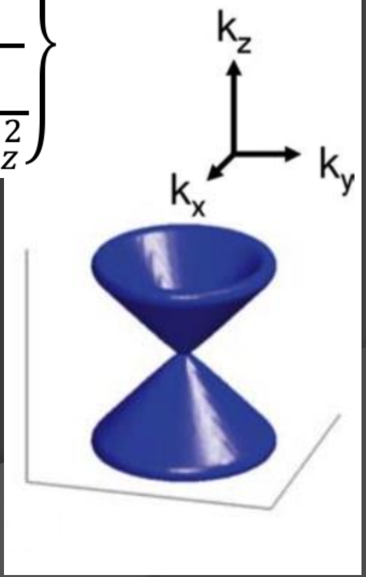


Uniform susceptibility distribution

Non-local field perturbation

- The relationship between phase signal and magnetic susceptibility

$$\chi(x,y,z) = \mathcal{F}^{-1}\left\{\mathcal{F}\left[\frac{\varphi(x,y,z)}{-\gamma \cdot \mathrm{B}_0 \cdot TE}\right] \cdot \frac{1}{\frac{1}{3} - \frac{k_z^2}{k_x^2 + k_y^2 + k_z^2}}\right\}$$



Divisions by zero: ill-conditioned problem.

- COSMOS
(calculation of susceptibility through multiple orientation sampling, Liu et al., 2009)

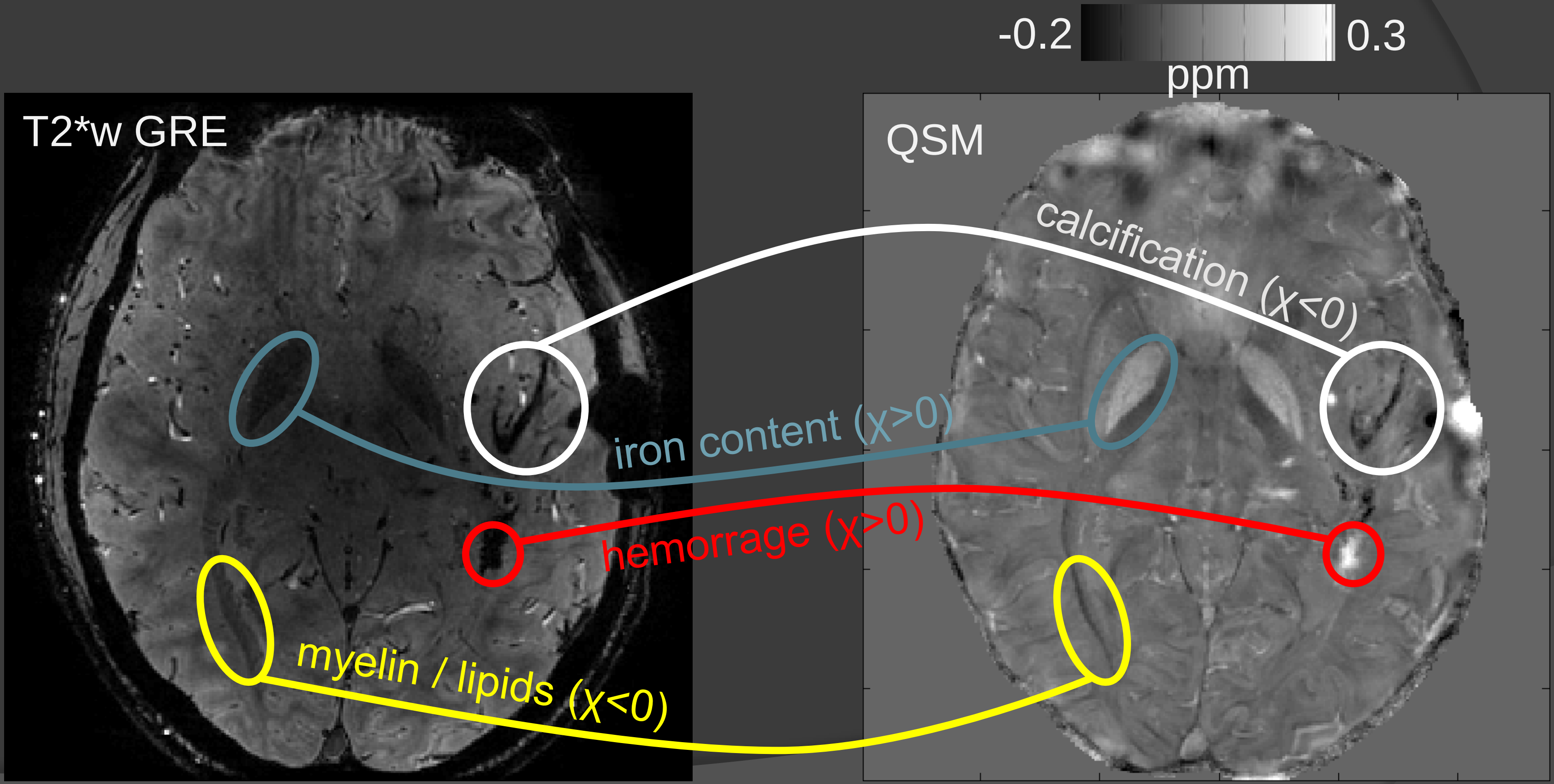
Wharton et al., Magnetic Resonance in Medicine 2010

QSM – single orientation methods

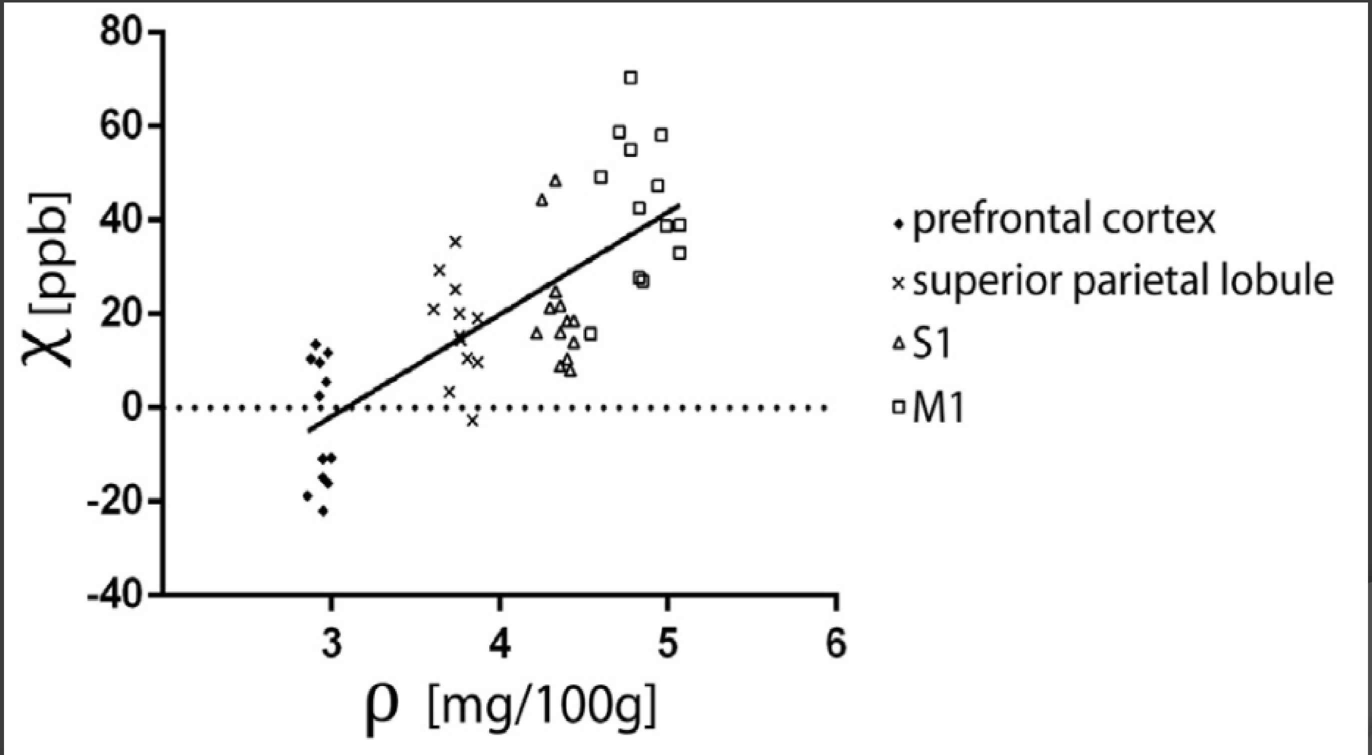
$$\chi(x,y,z) = \mathcal{F}^{-1}\left\{\mathcal{F}\left[\frac{\varphi(x,y,z)}{-\gamma\cdot \mathrm{B}_0\cdot TE}\right]\cdot\frac{1}{\frac{1}{3}-\frac{k_z^2}{k_x^2+k_y^2+k_z^2}}\right\}$$

- Thresholded k-space division (Shmueli et al., MRM 2009)
- Morphology-enabled dipole inversion (Liu et al., Neuroimage 2012)
- Closed-form L2-regularized inversion (Bilgic et al., JMRI 2014)
- Total generalized variation (Langkammer et al., NeuroImage 2015)
- iterative LSQR (Li et al., NeuroImage 2015)
- Multi-scale dipole inversion (Acosta-Cabronero et al., 2018)
- ...

Quantitative Susceptibilty Mapping (QSM)



- QSM – correlation between QSM and estimated iron concentration



Costagli et al., NeuroImage: Clinical 2016

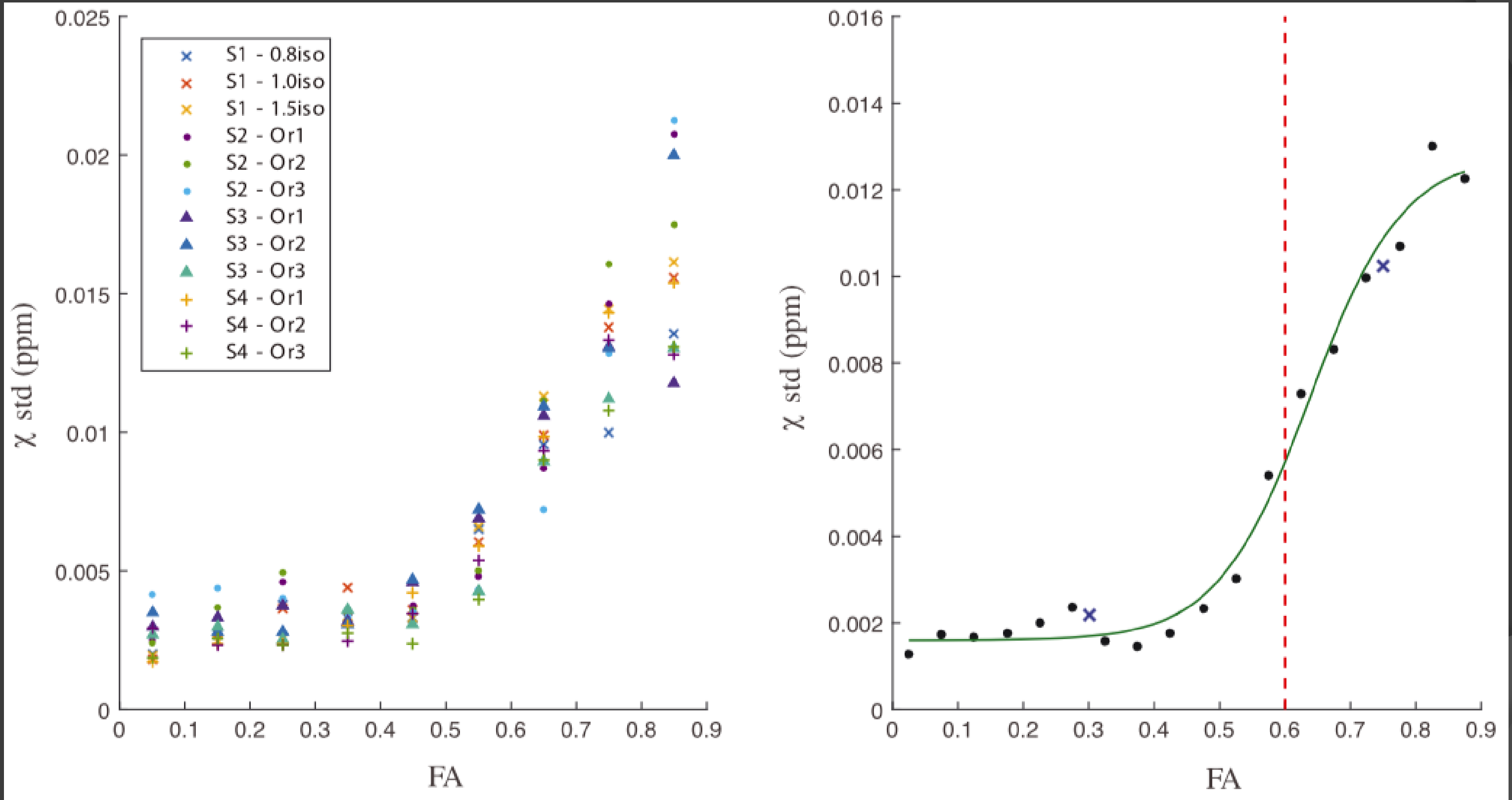
QSM – single orientation methods

$$\chi(x,y,z) = \mathcal{F}^{-1}\left\{\mathcal{F}\left[\frac{\varphi(x,y,z)}{-\gamma \cdot \mathrm{B}_0 \cdot TE}\right] \cdot \frac{1}{\frac{1}{3} - \frac{k_z^2}{k_x^2 + k_y^2 + k_z^2}}\right\}$$

Intrinsic limitations:

- Magnetic susceptibility is a tensor, yet single-orientation techniques produce a scalar value
  - ➢ Susceptibility Tensor Imaging (Liu et al., Magnetic Resonance in Medicine, 2010)
  - ➢ Acquisition of a large number of datasets (~12) with patient's head positioned in different orientations with respect to B_0

QSM – dependence on tissue orientation

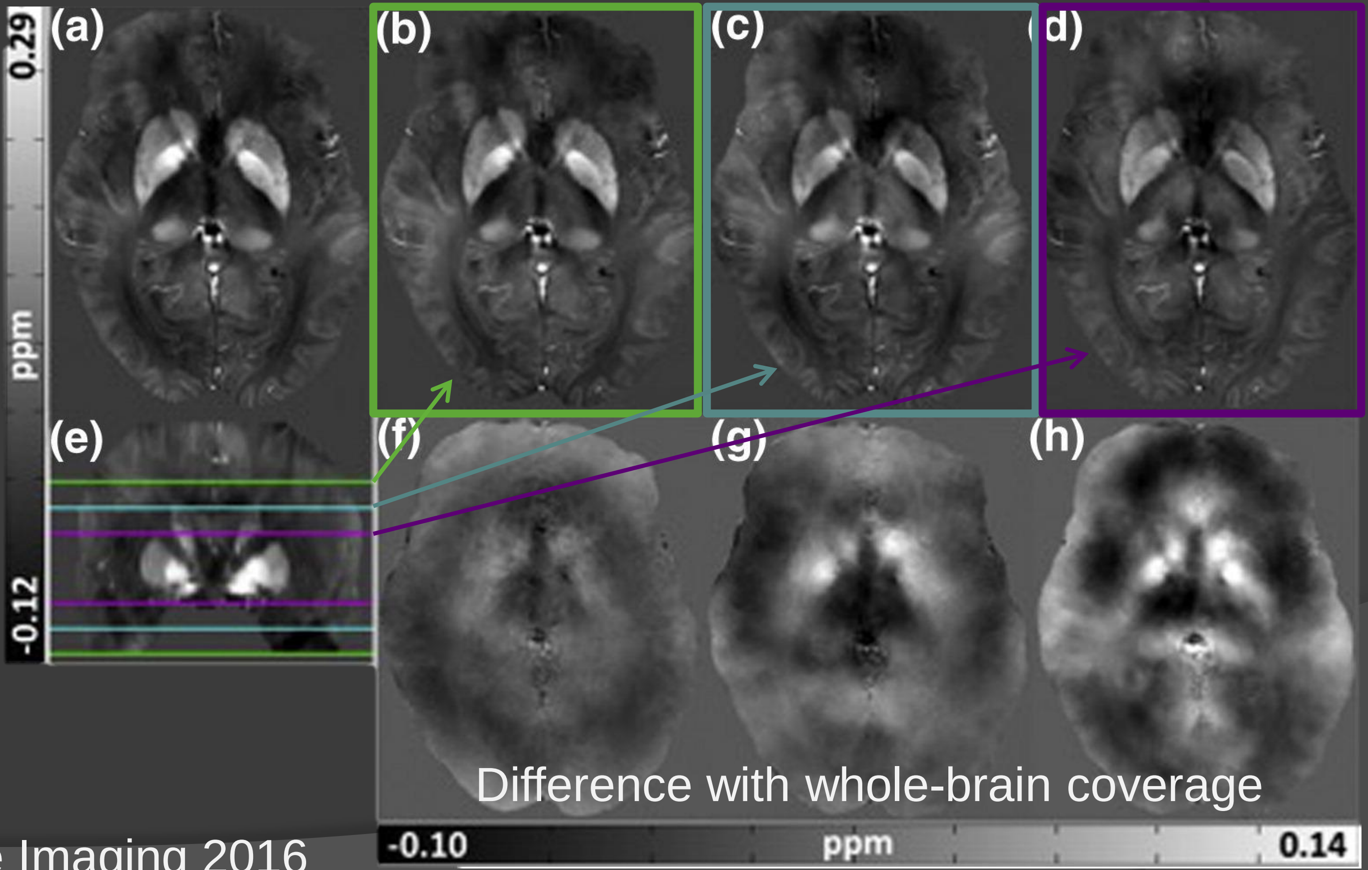


Lancione et al., NMR in Biomedicine 2017

Quantitative yet “relative” susceptibility mapping

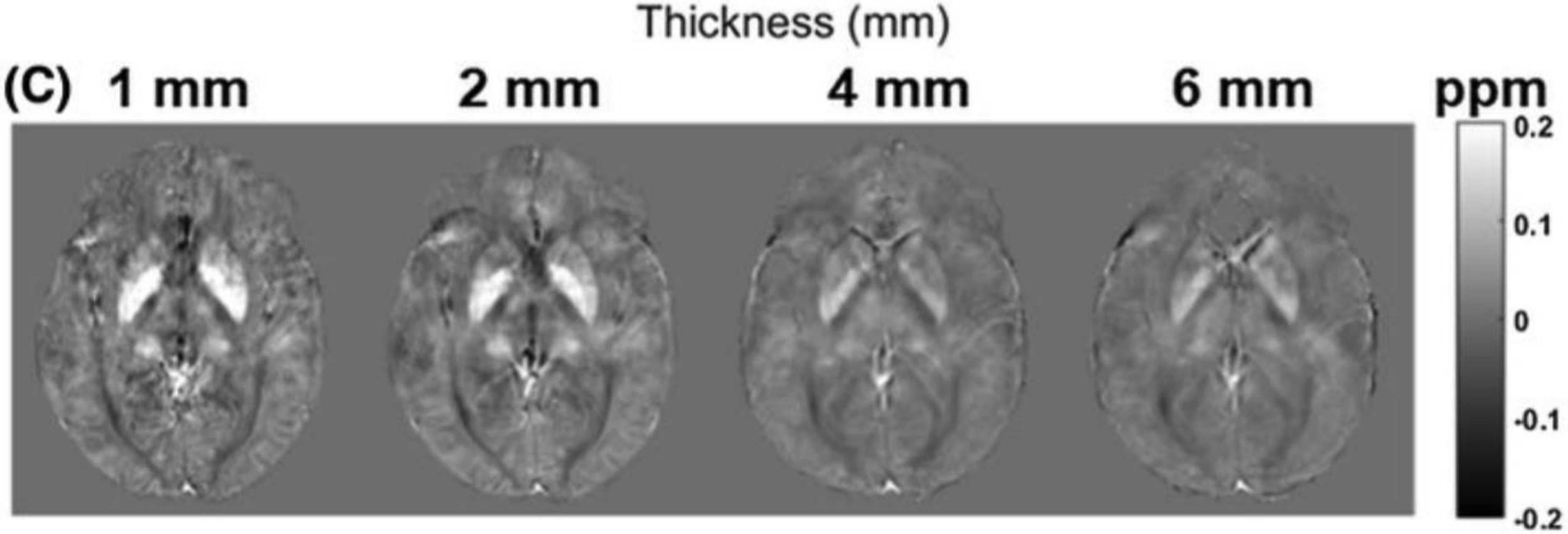
- QSM values are usually expressed in ppb or ppm with respect to a “reference” which, by default, is the mean magnetic susceptibility inside the imaged volume
- alternatively, QSM can be expressed in ppb with respect to a reference region that must be
  1. invariant in the study population (e.g. spared by pathology)
  2. homogeneous (e.g. the ventricles, but the choroid plexus must be carefully avoided)
  3. with either little susceptibility anisotropy (e.g. avoid major and coherent white matter fiber bundles) or with minimal orientation variability (e.g. splenium of the corpus callosum)

QSM – dependence on coverage



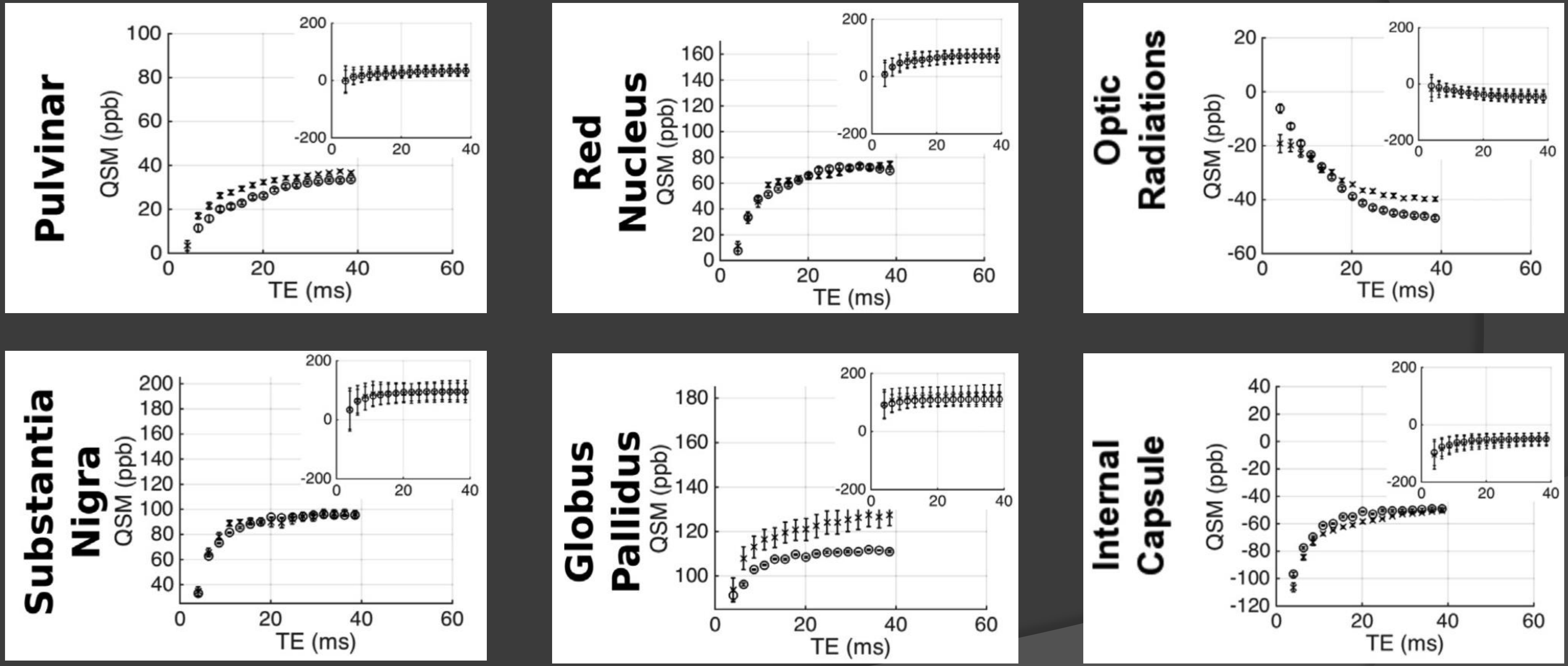
Elkady et al.,
Magnetic Resonance Imaging 2016

QSM – dependence on voxel size



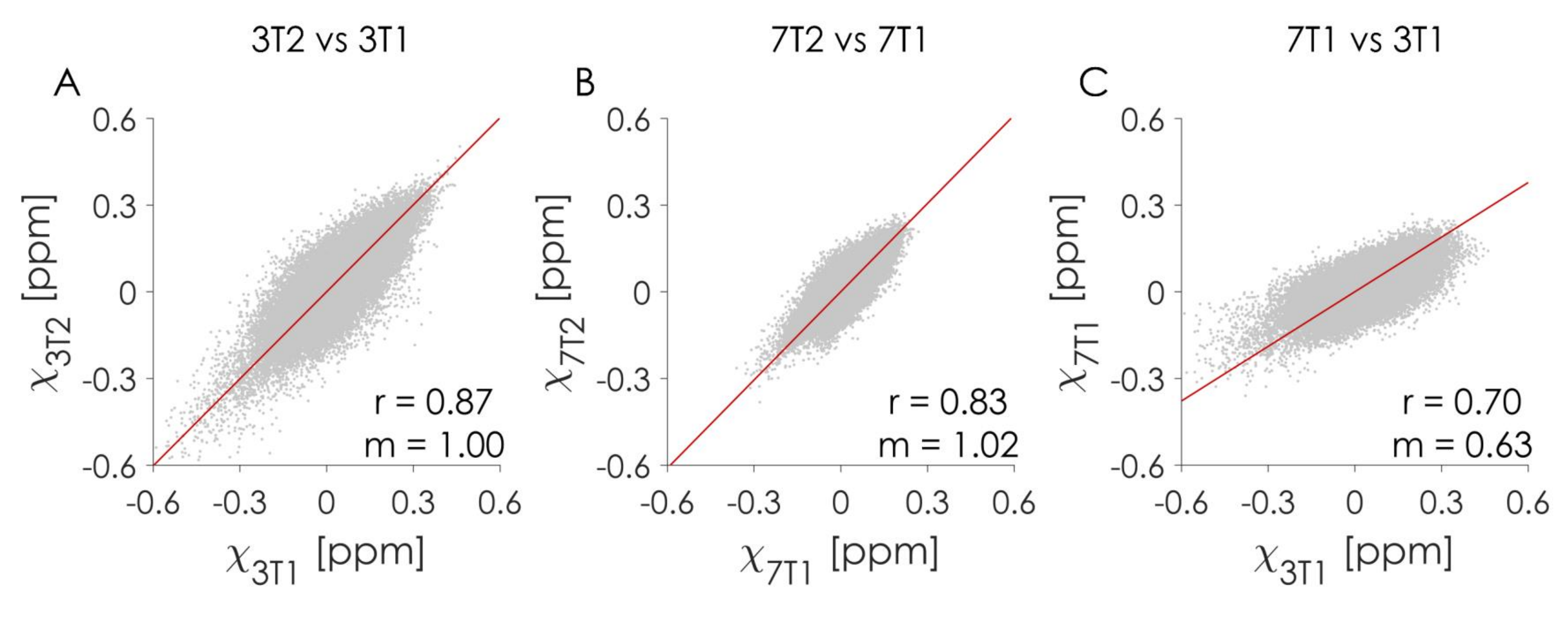
Karsa et al., Magnetic Resonance in Medicine 2018

QSM – dependence on TE



Cronin et al., NeuroImage 2017

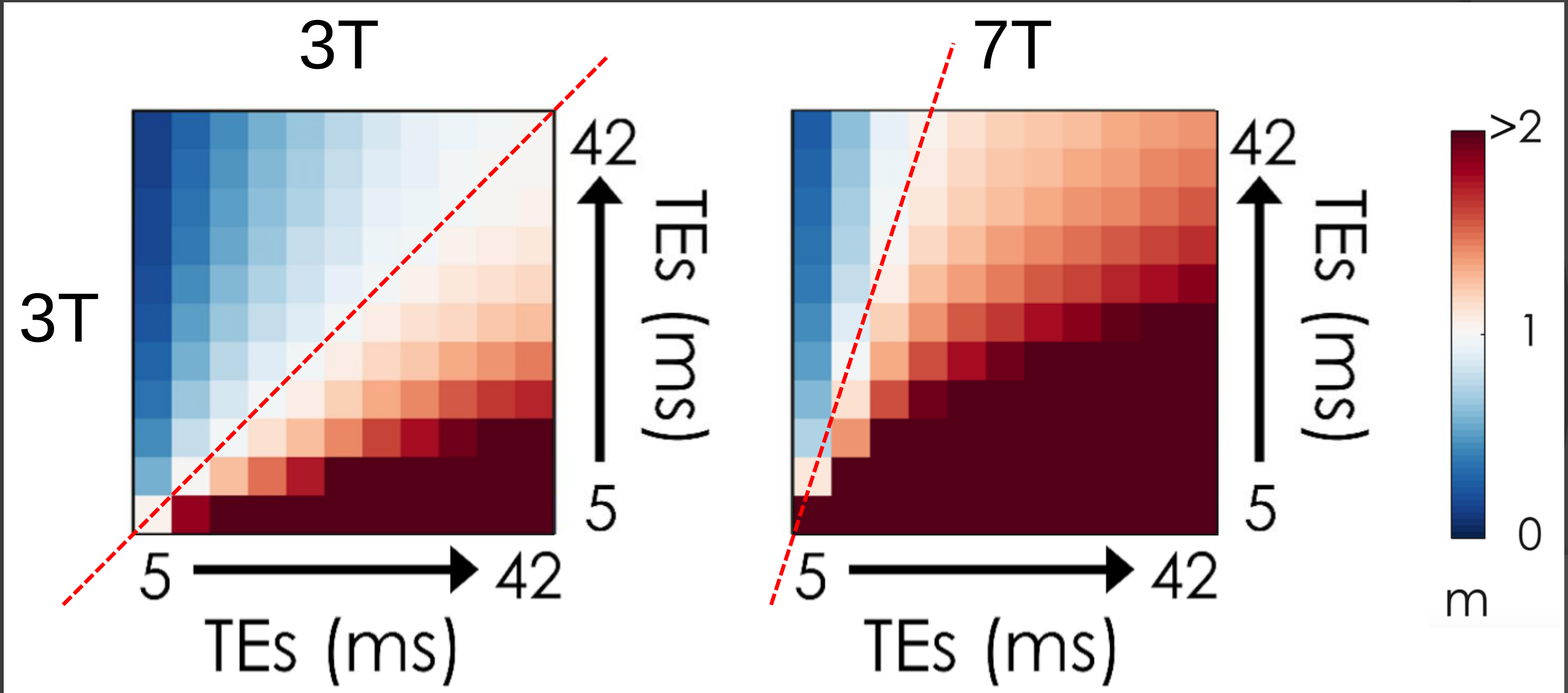
QSM – dependence on TE and B_0



whole-brain datasets, voxelwise comparisons

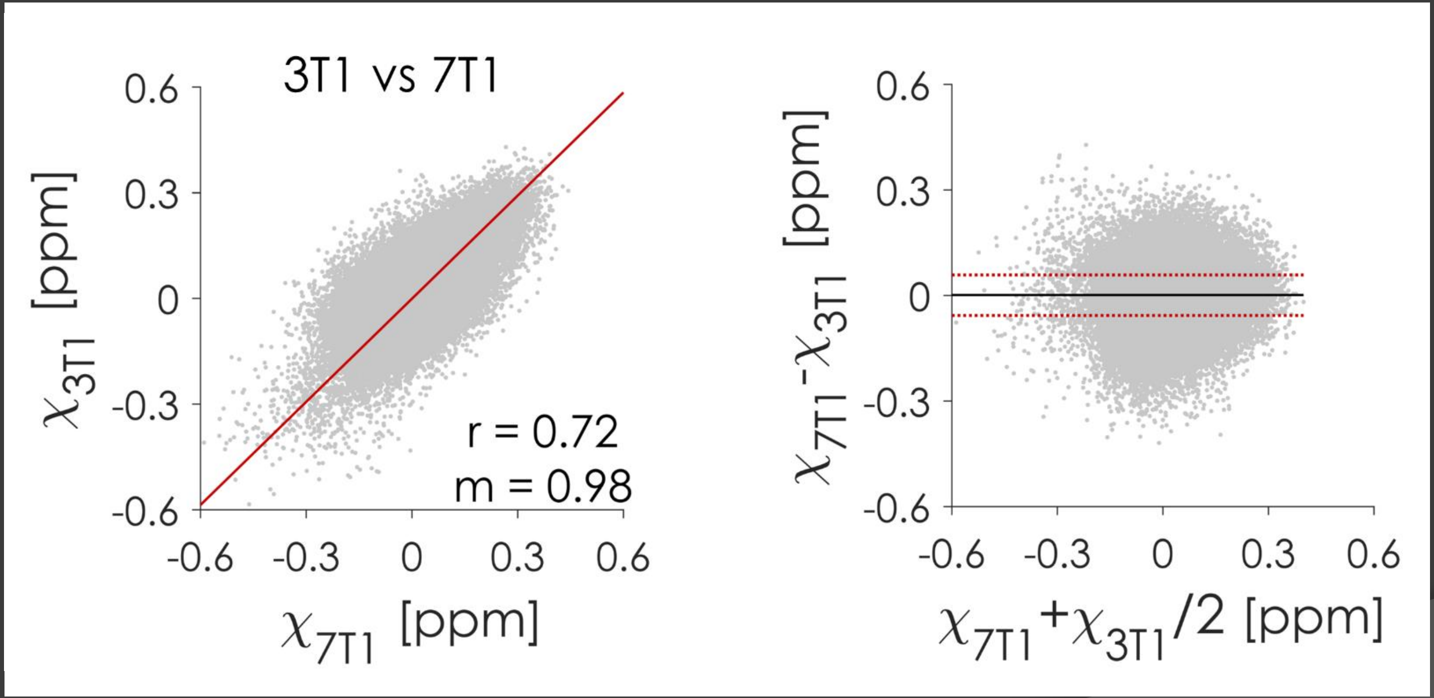
Lancione et al., ISMRM 2019

QSM – dependence on TE and B_0



Lancione et al., ISMRM 2019

QSM – dependence on TE and B_0



Lancione et al., ISMRM 2019

Keep in mind…

- Magnetic susceptibility is a tensor, yet single-orientation QSM techniques produce a scalar value. Suitable for isotropic tissues.
  - For anisotropic tissues, the measured scalar value depends on tissue orientation
- Phase-to-Susceptibility remapping is an ill-posed problem with divisions-by-zero:
  - Different algorithms may produce different χ maps
- QSM output depends also on scanning parameters:
  - coverage, voxel size, TE, B_0
- Excellent reproducibility can be achieved, even across scanners operating at different fields, provided that scanning protocols are accurately set.

Potential for clinical neurology and neuroscience

- QSM enables to **quantitatively** measure variations in content of brain iron, myelin phospholipids, calcium, oxygen saturation levels in venous blood…
- Main applications:
  - aging
  - neurodegeneration (AD, PD, HD, brain iron accumulation, ALS / neuromuscular)
  - demyelinating disease
  - traumatic brain injury
  - drug addiction
  - cerebral metabolic rates of oxygen extraction
  - fMRI applications
  - …