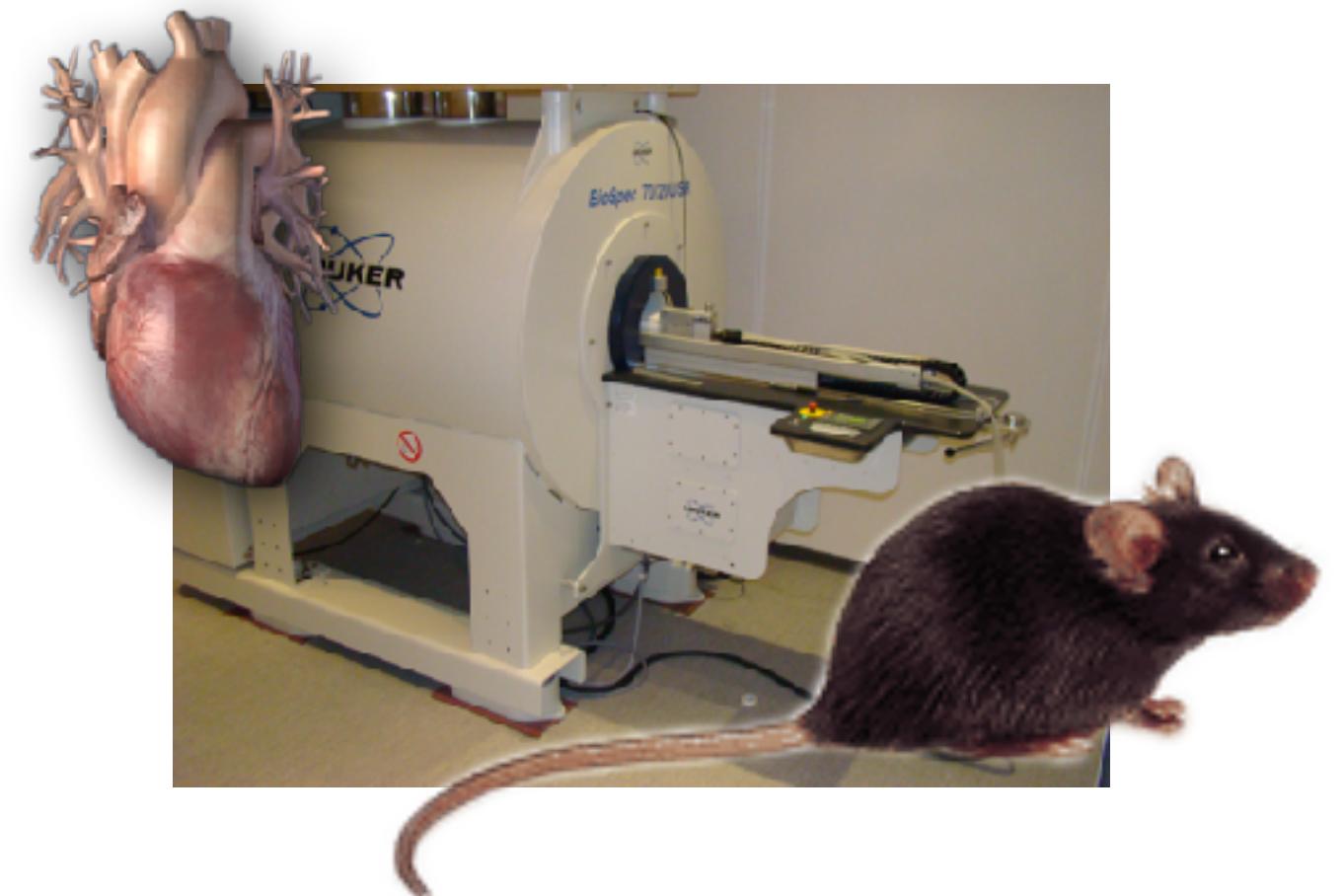


Nouvelles stratégies d'acquisitions non cartésiennes pour l'IRM cardiovasculaire du petit animal.



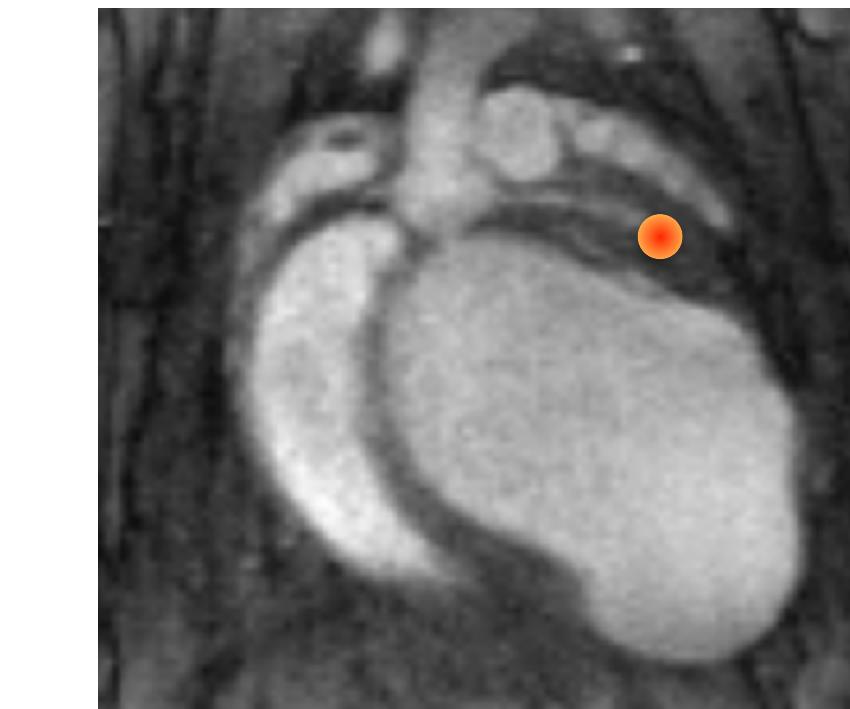
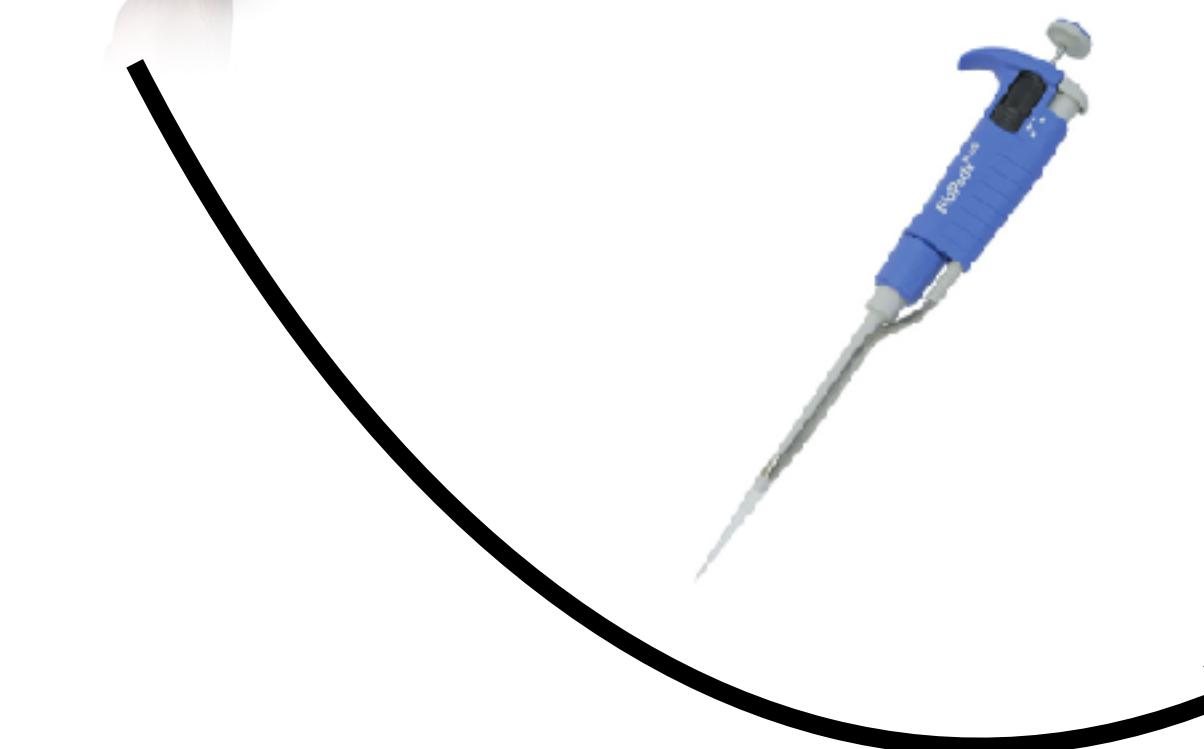
Aurélien Trotier

Directeur de thèse : Dr Sylvain MIRAU

**Centre de Résonance Magnétique des Systèmes Biologiques
UMR 5536 CNRS / Université de Bordeaux**



micro-chirurgie



Infarctus du myocarde

Besoins spécifiques :

Informations anatomiques

Informations fonctionnelles

Modification du génotype



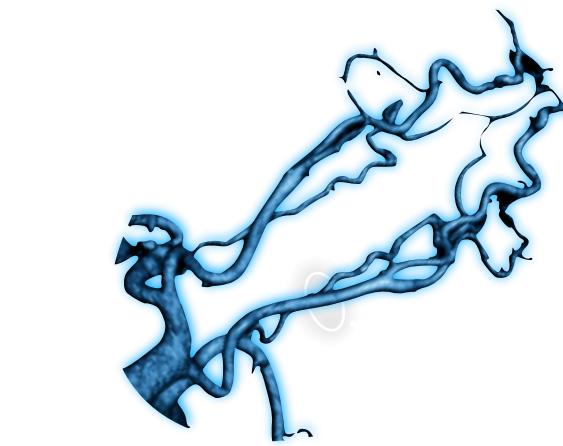
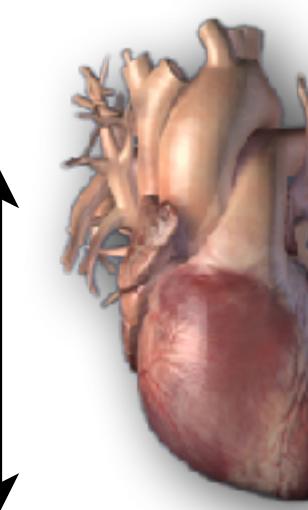
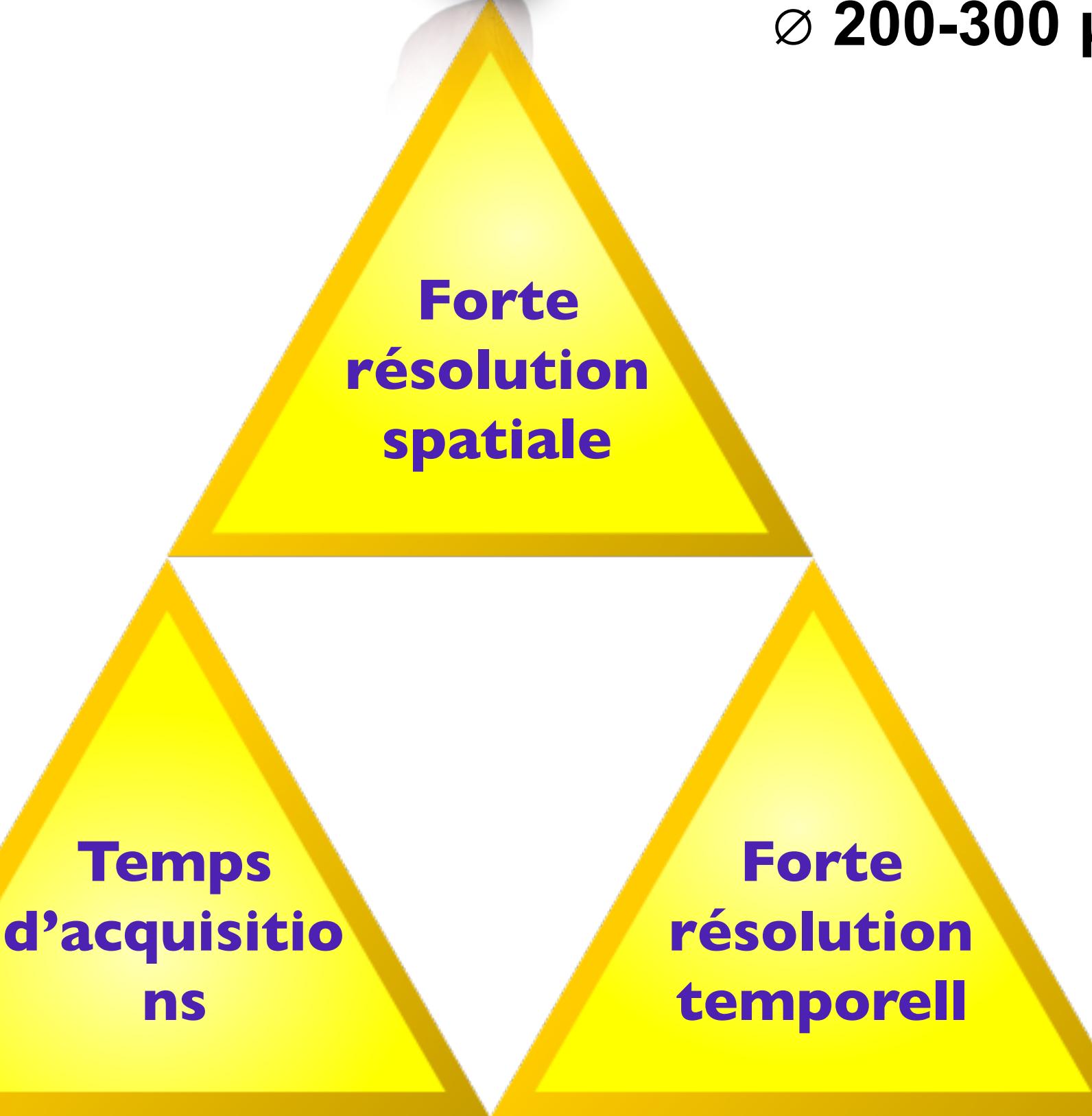
Hypertension pulmonaire



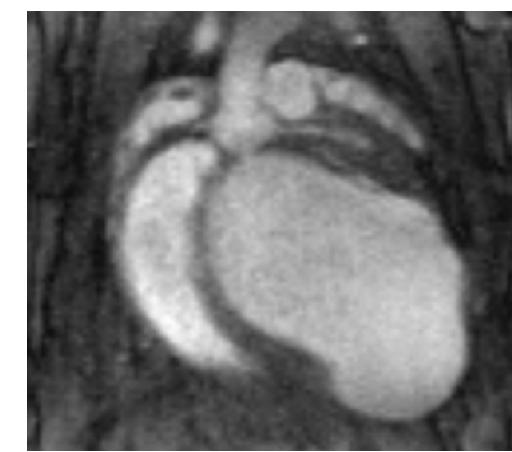
Non-invasive
→ Suivi longitudinal



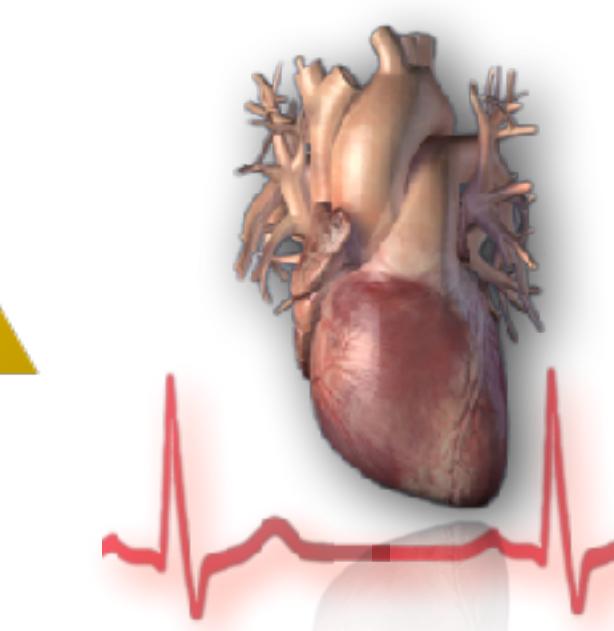
10 mm



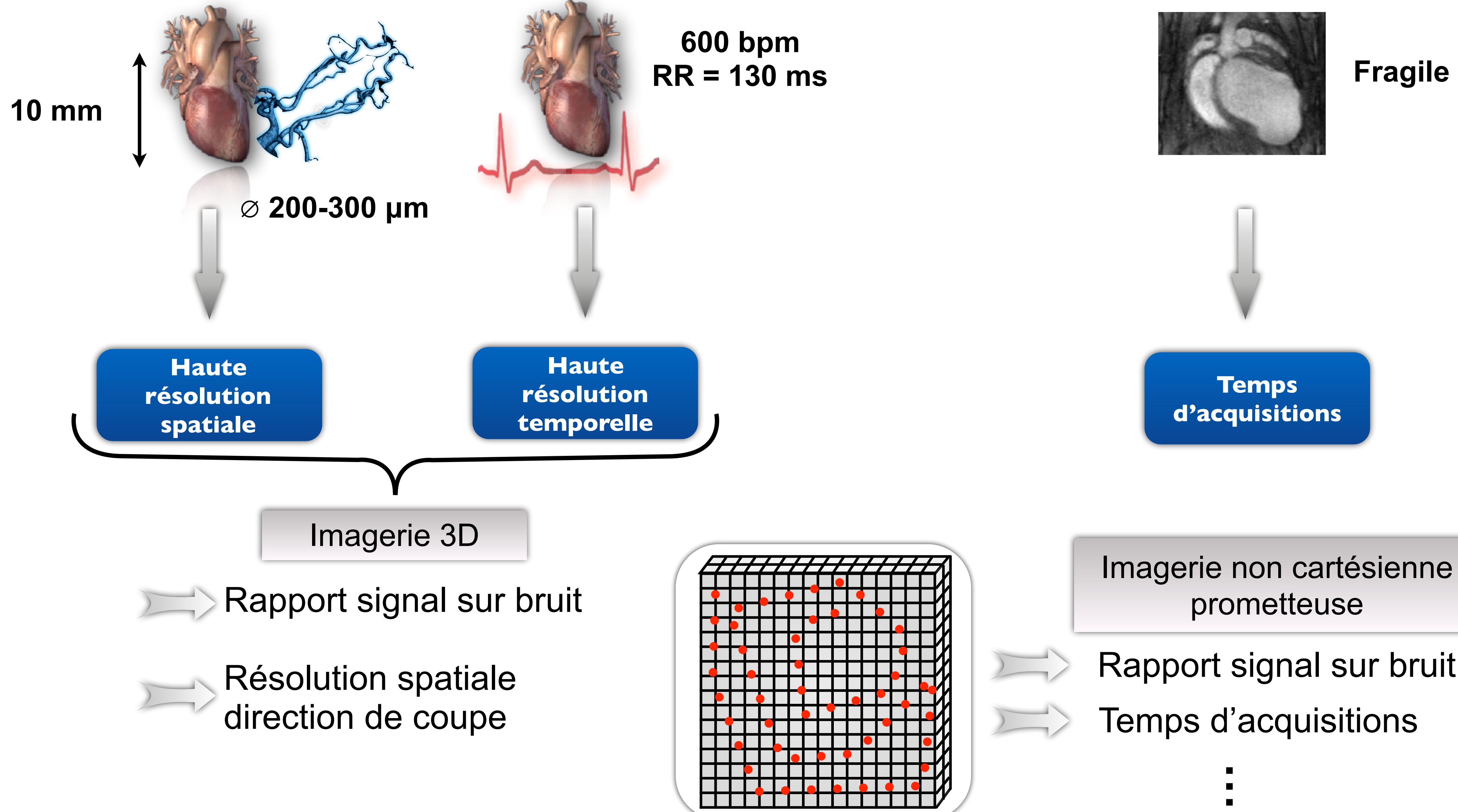
Ø 200-300 µm



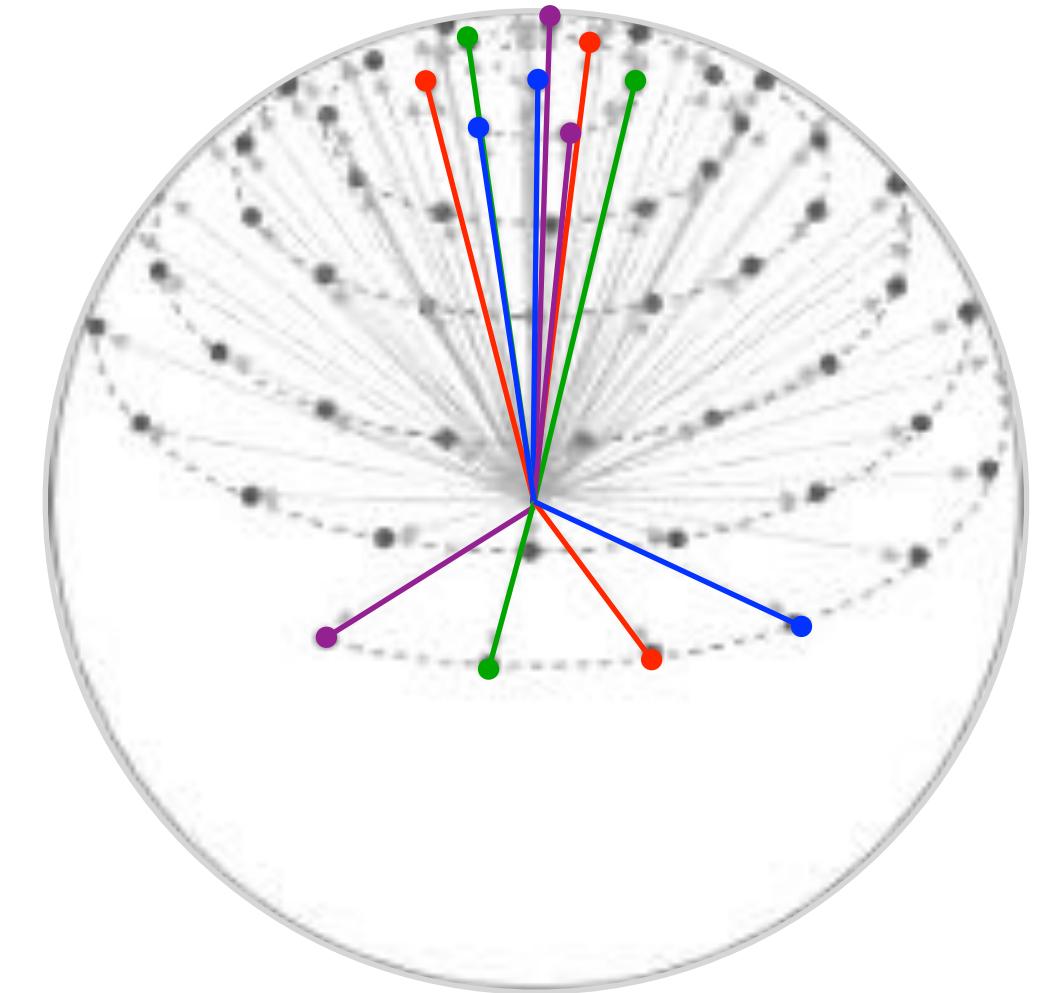
Fragile



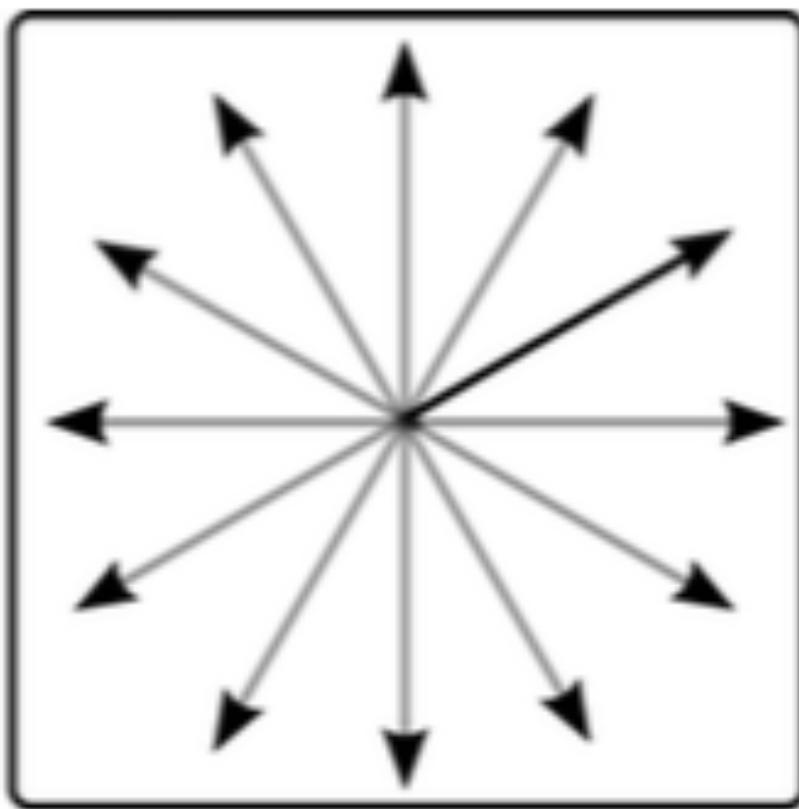
600 bpm
RR = 130 ms



Introduction à l'imagerie radiale



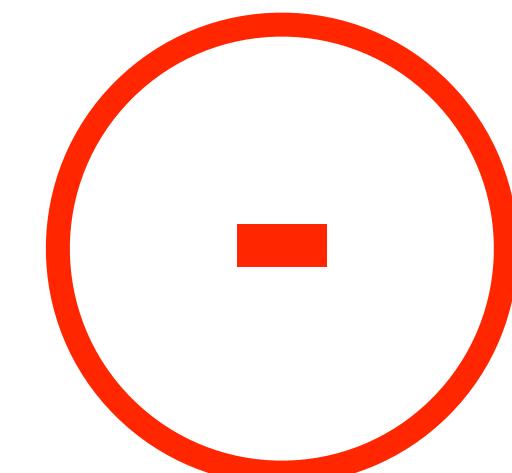
Trajectoires



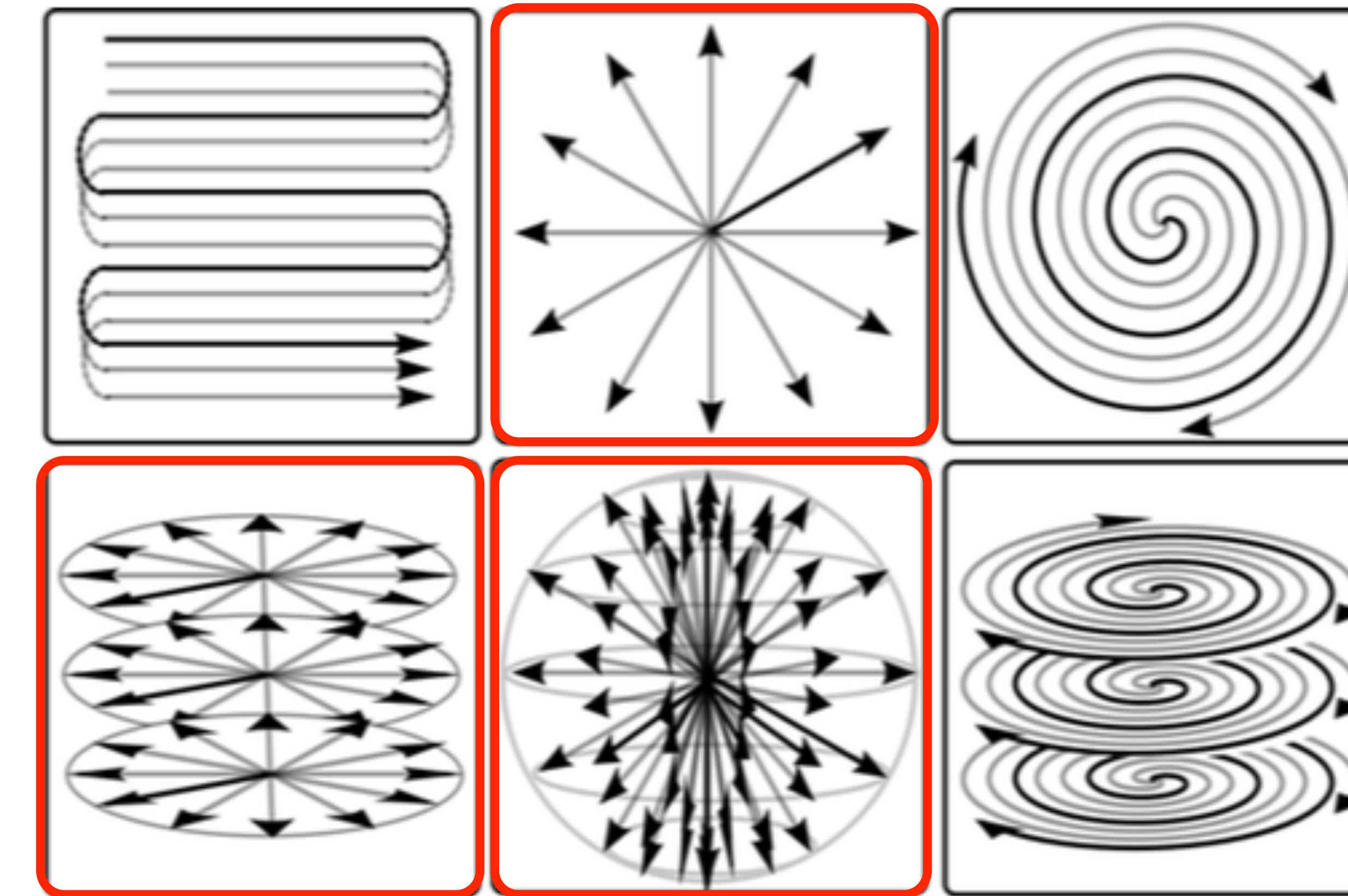
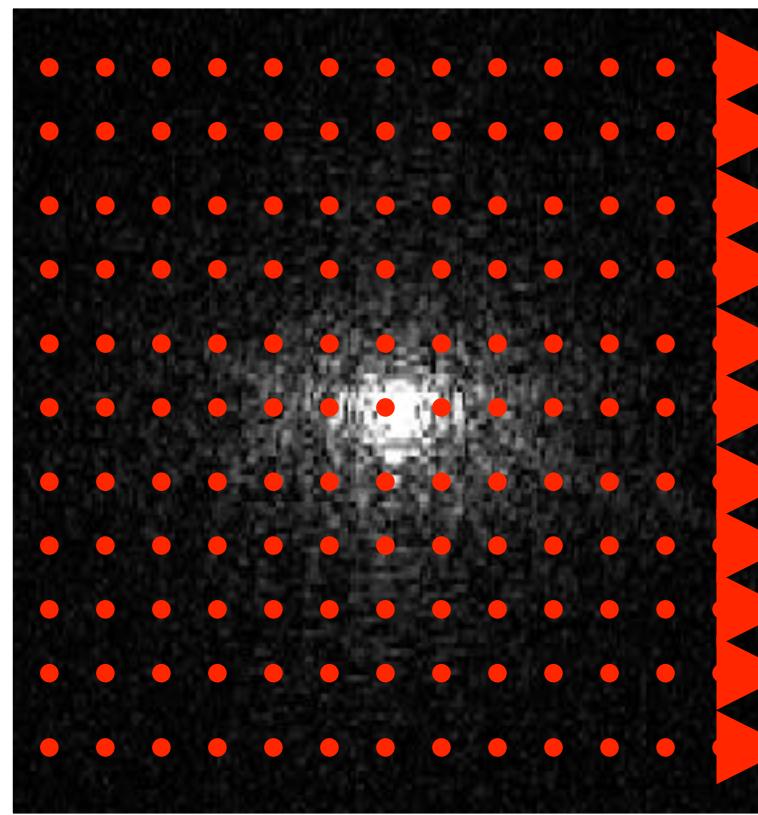
Avantages



Inconvénients



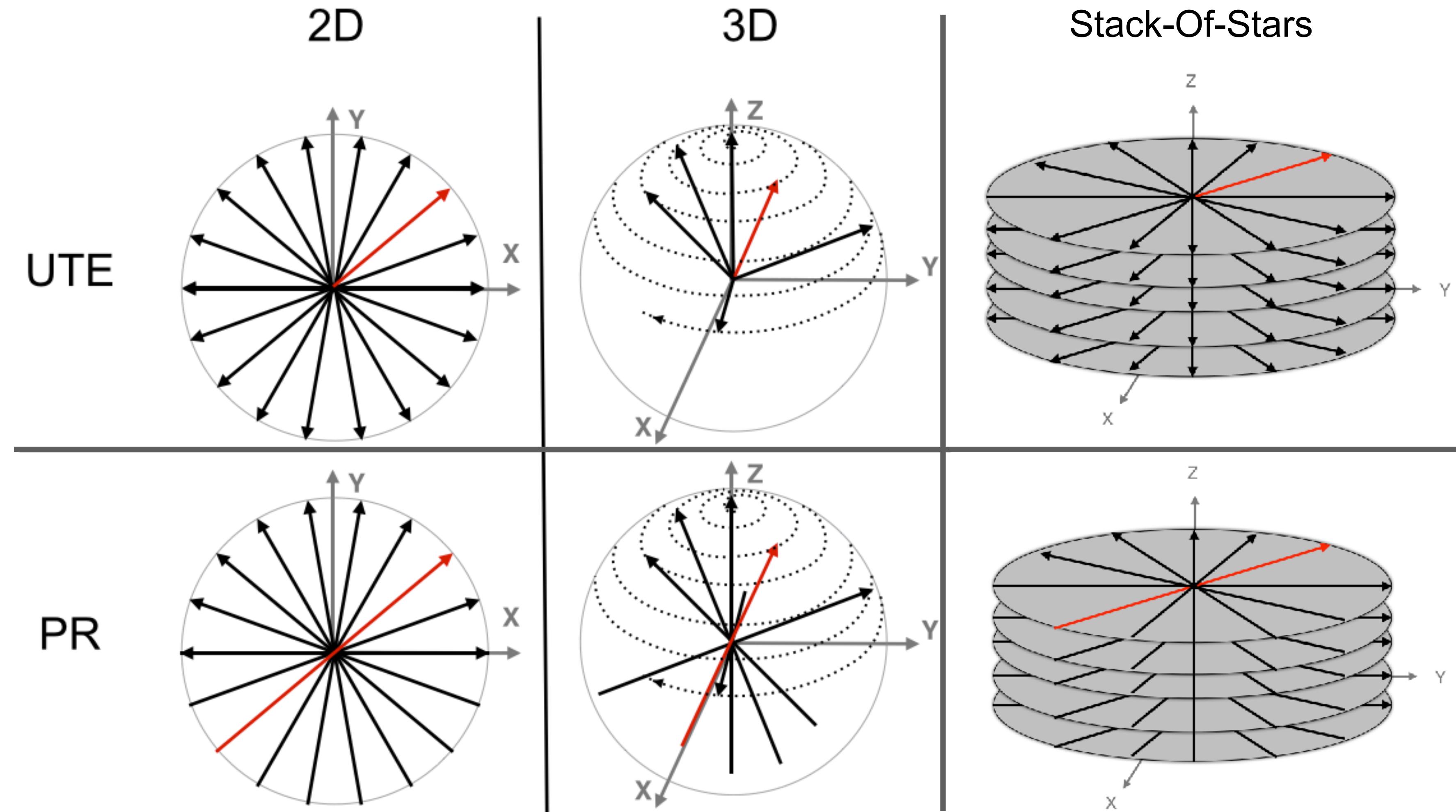
Trajectoires non cartésiennes



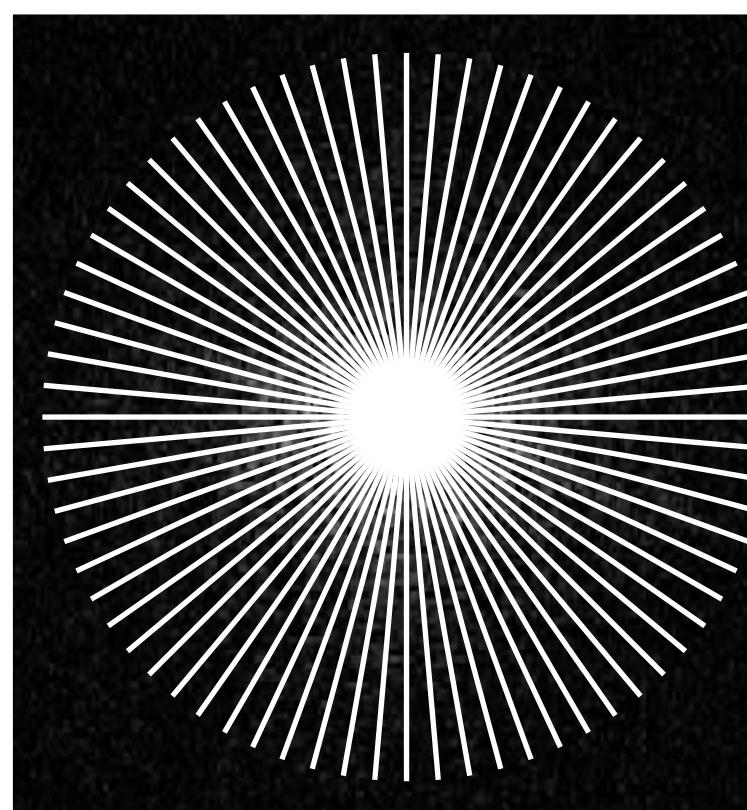
Trajectoires radiales :

- Première trajectoire utilisée par Lauterbur
- Abandon au profit des trajectoires cartésiennes
- Propriétés intéressantes pour l'imagerie cardiaque

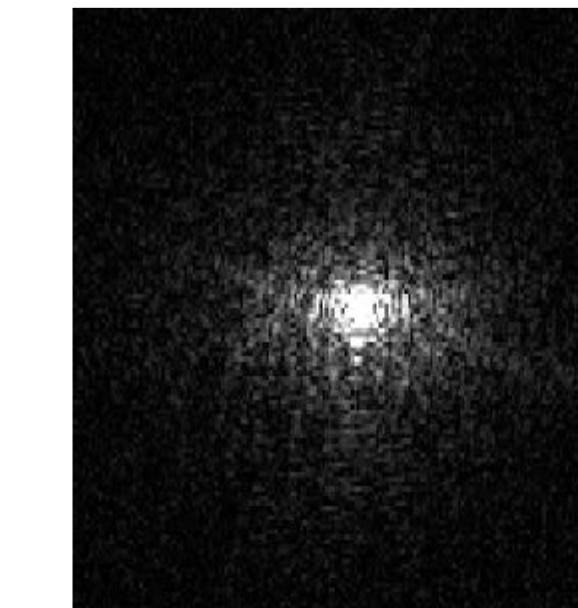
(1) Lustig, 2009



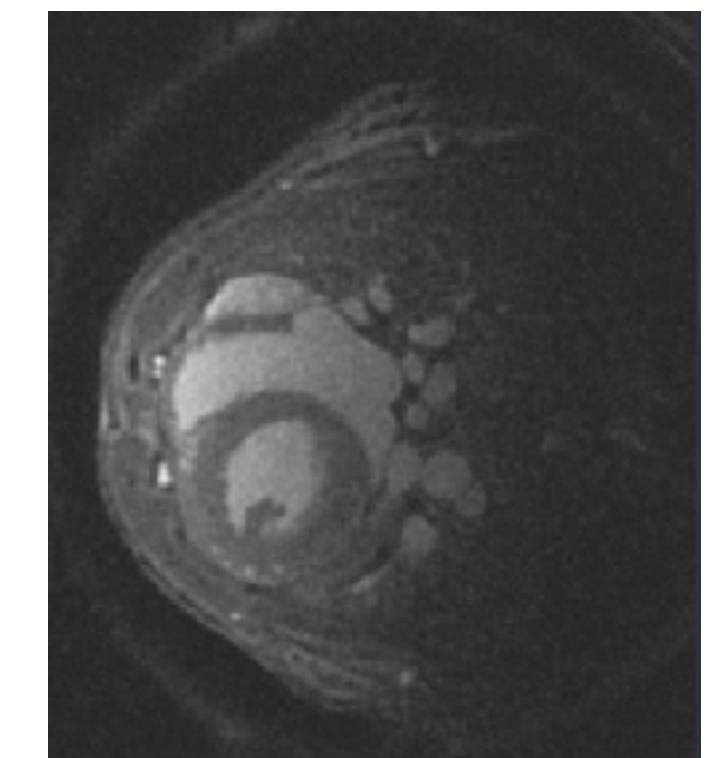
Propriétés des trajectoires radiales



Espace de Fourier
complet



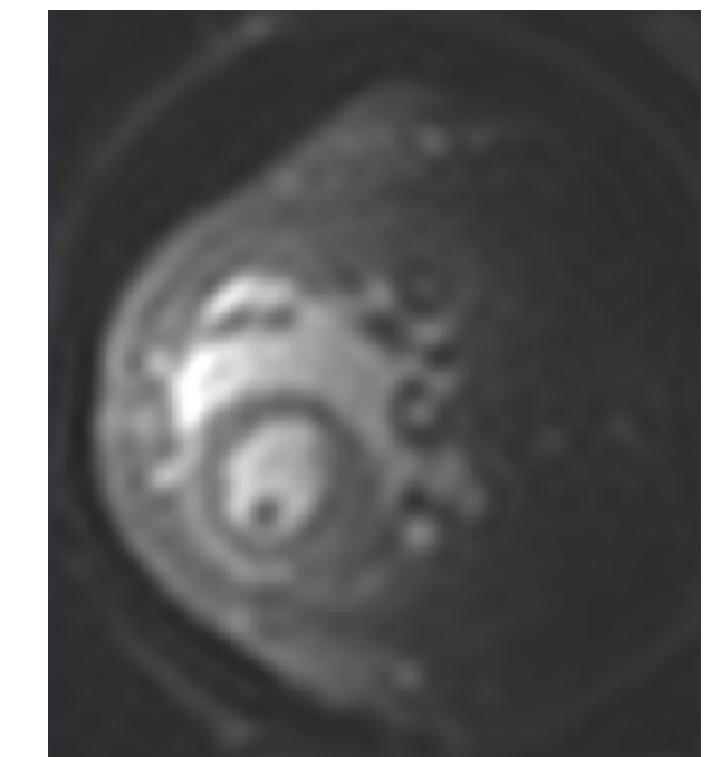
FFT



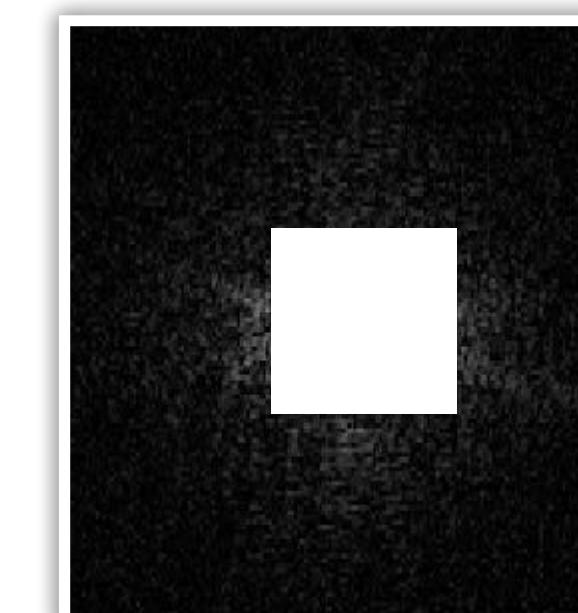
Basses fréquences



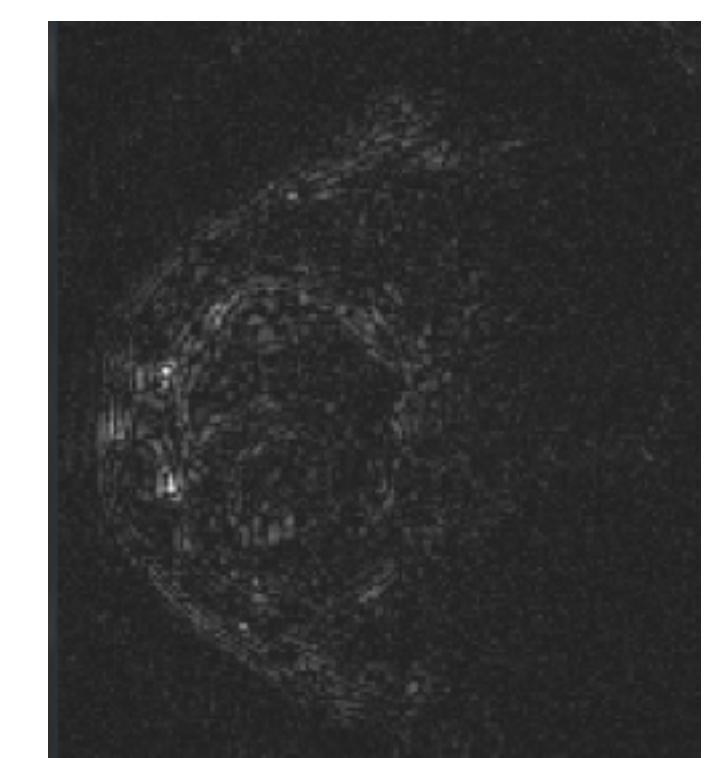
FFT



Hautes fréquences



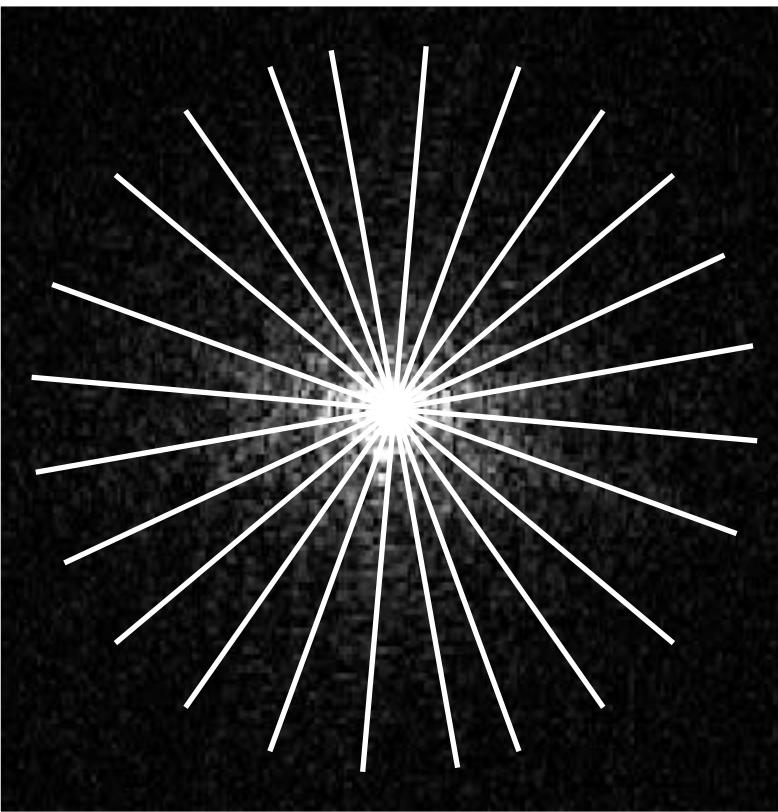
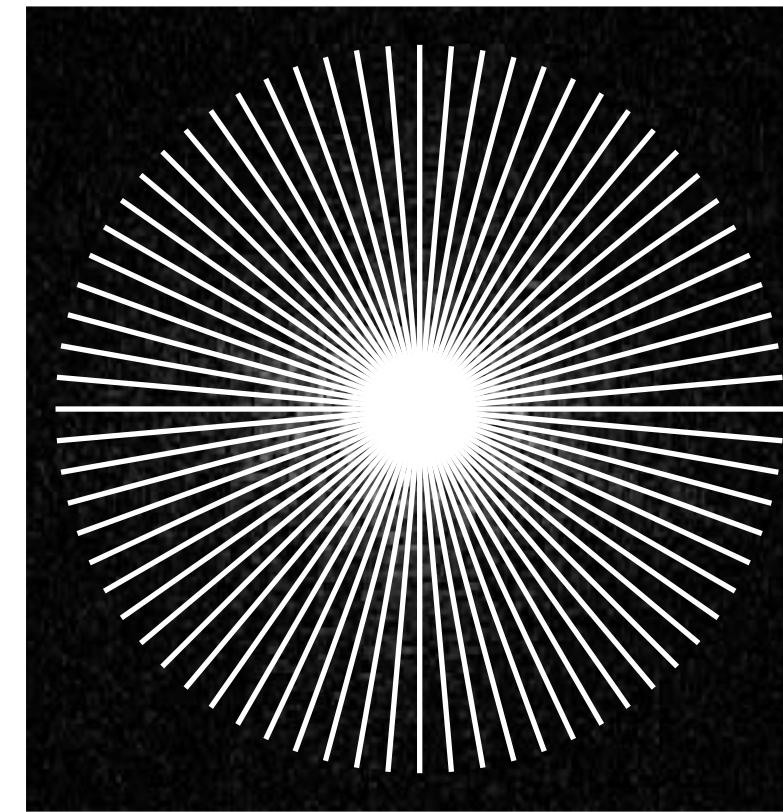
FFT



Signal et
contraste

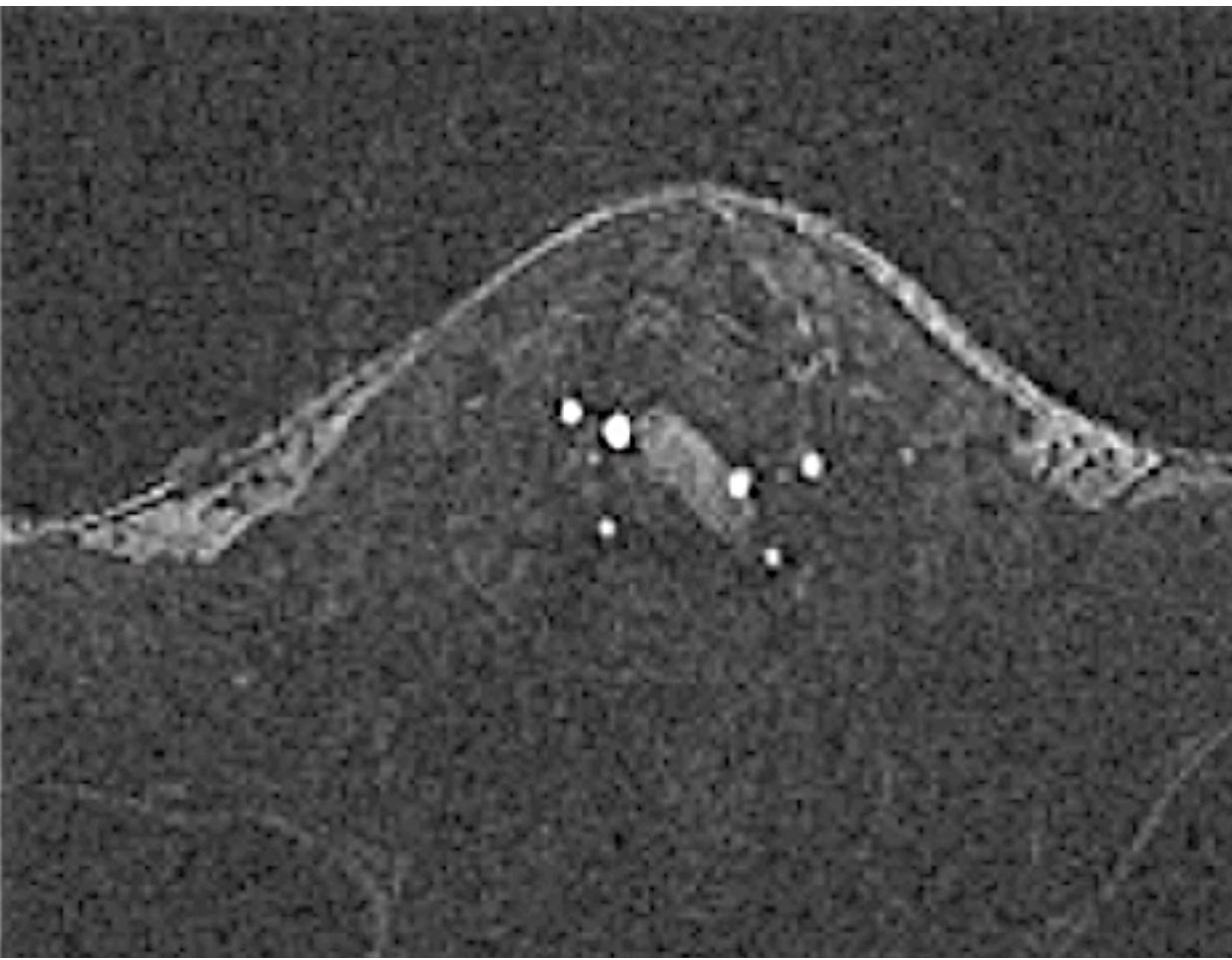
Détails et
bruit

Sous-échantillonnage

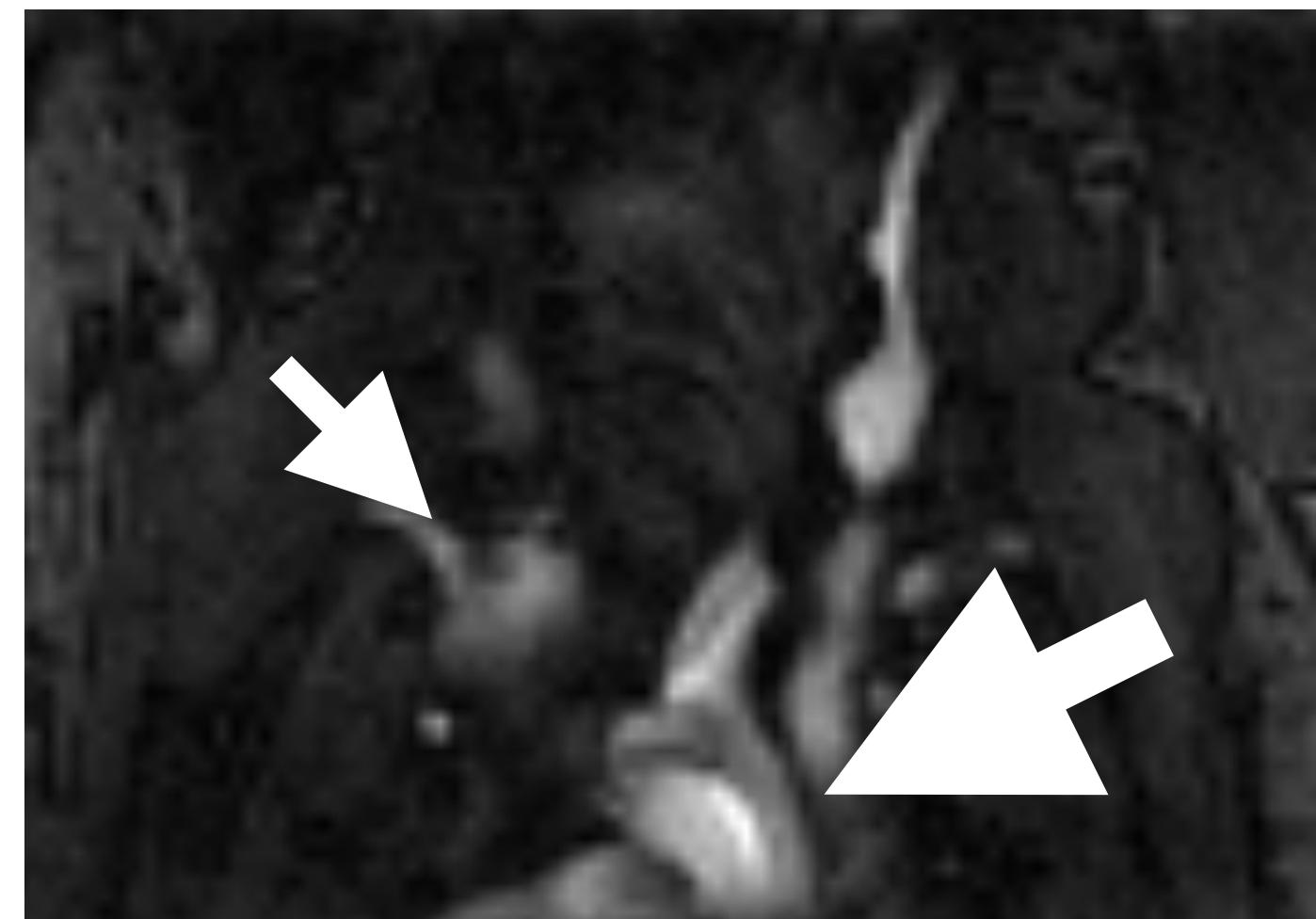


Mouvements et flux

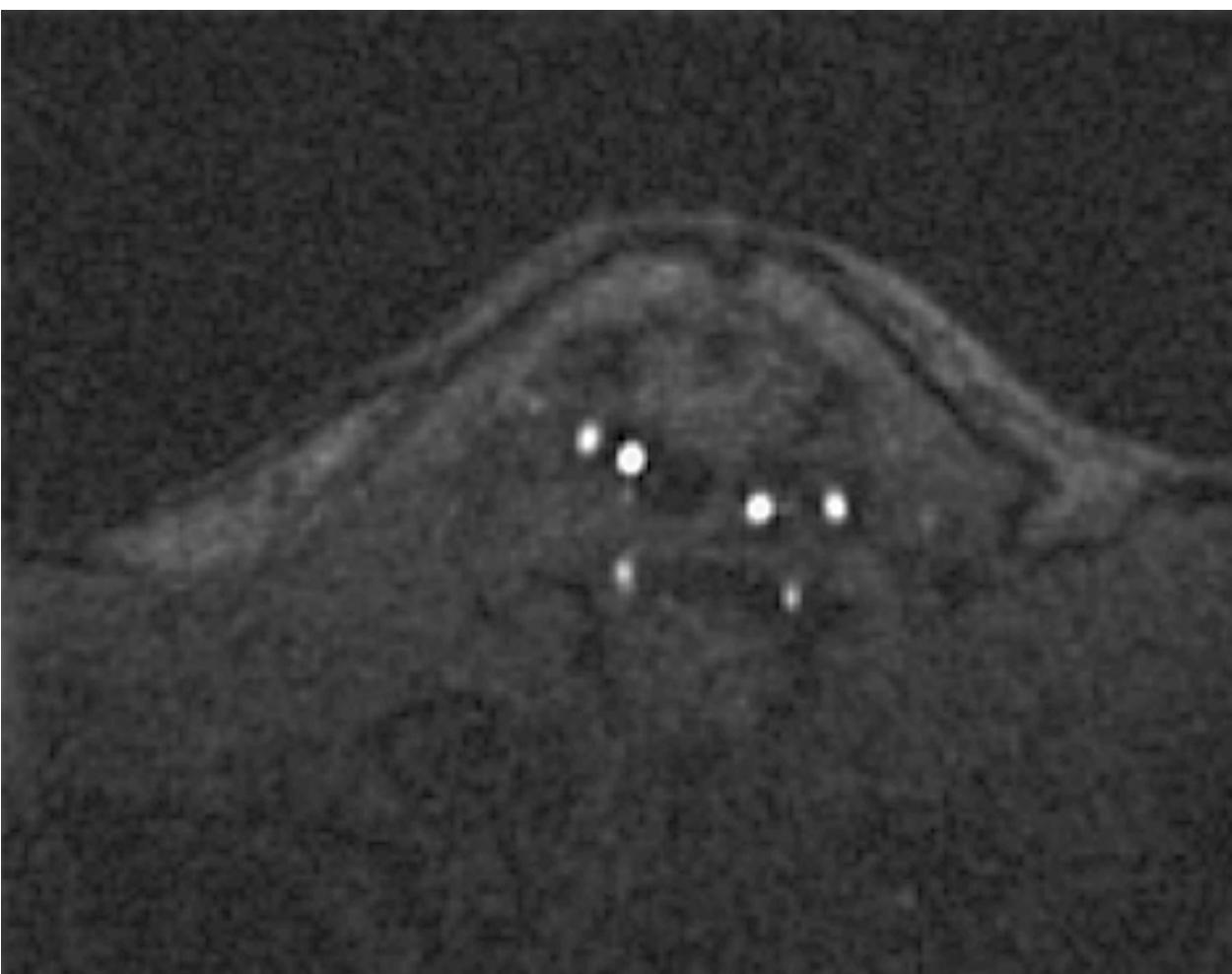
**Acquisition
cartésienne**



**Acquisition
cartésienne**



**Acquisition
radiale PR**



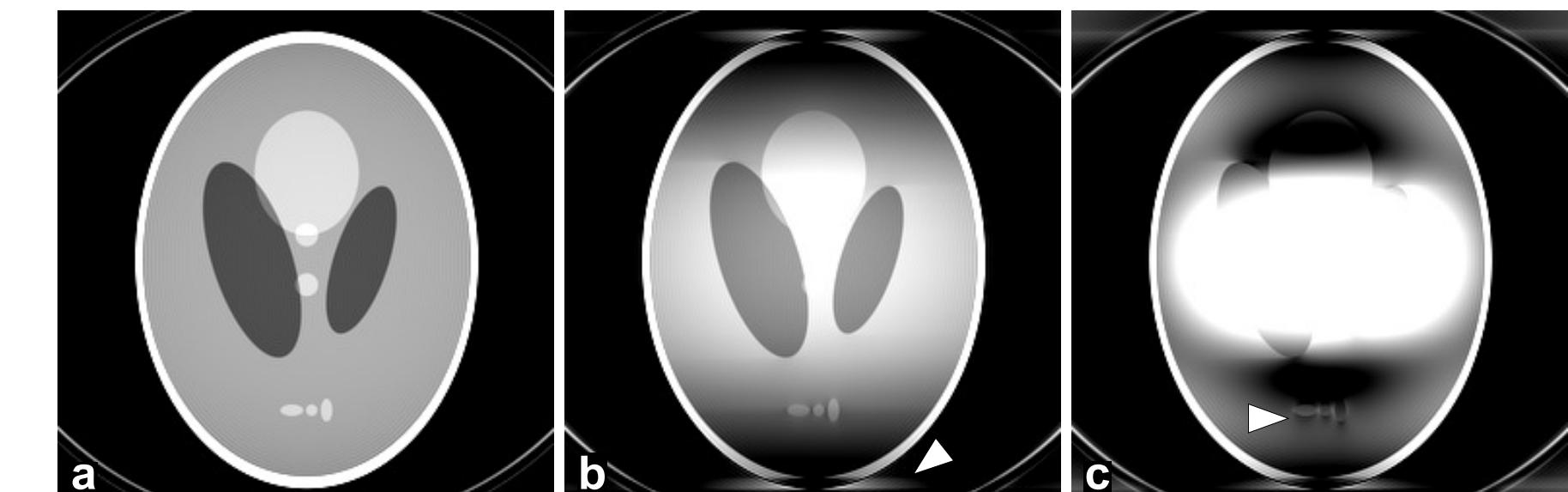
**Acquisition
Stack-Of-Star UTE**



Désavantages

Déviation des gradients :

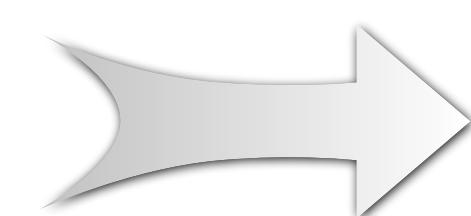
- Courants de Foucault
- Délais de montées



Idéale

Faible

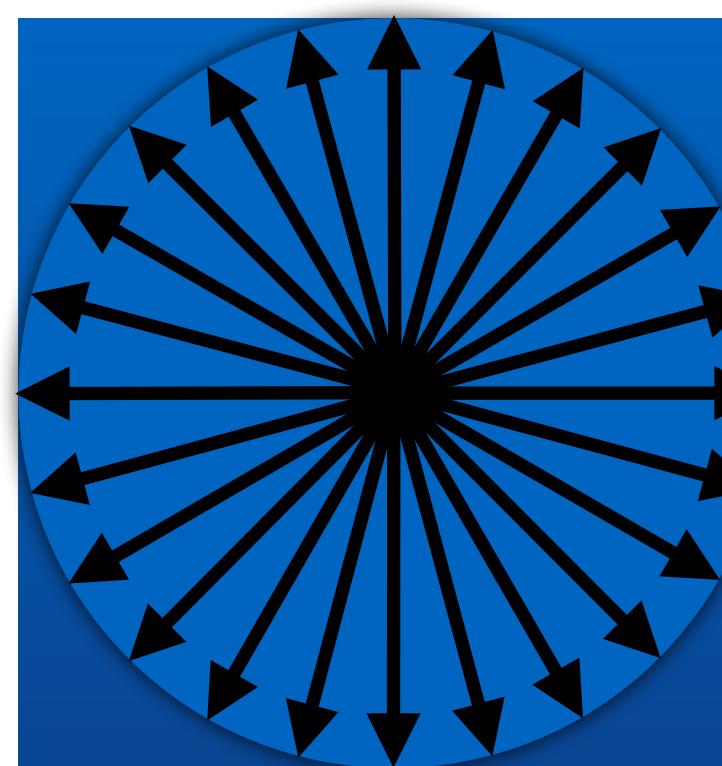
Elevée



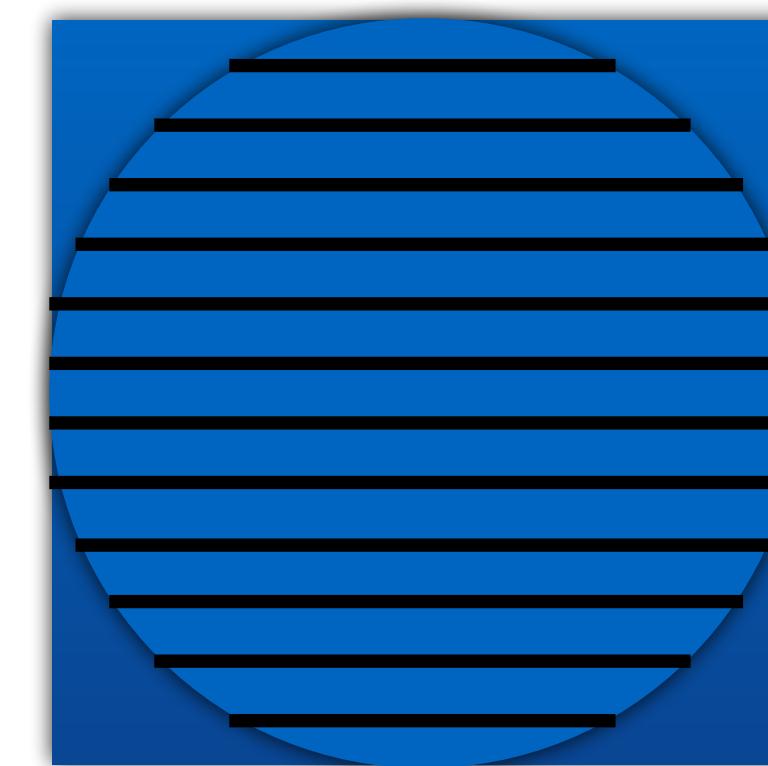
Mesure de
trajectoire

Reconstruction (particulièrement en 3D) :

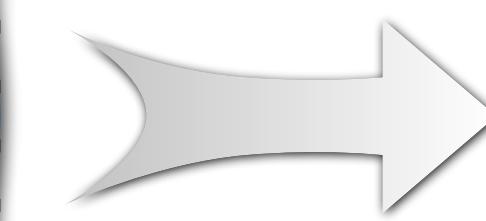
- Durée
- Combinaison avec méthodes de reconstruction parallèle



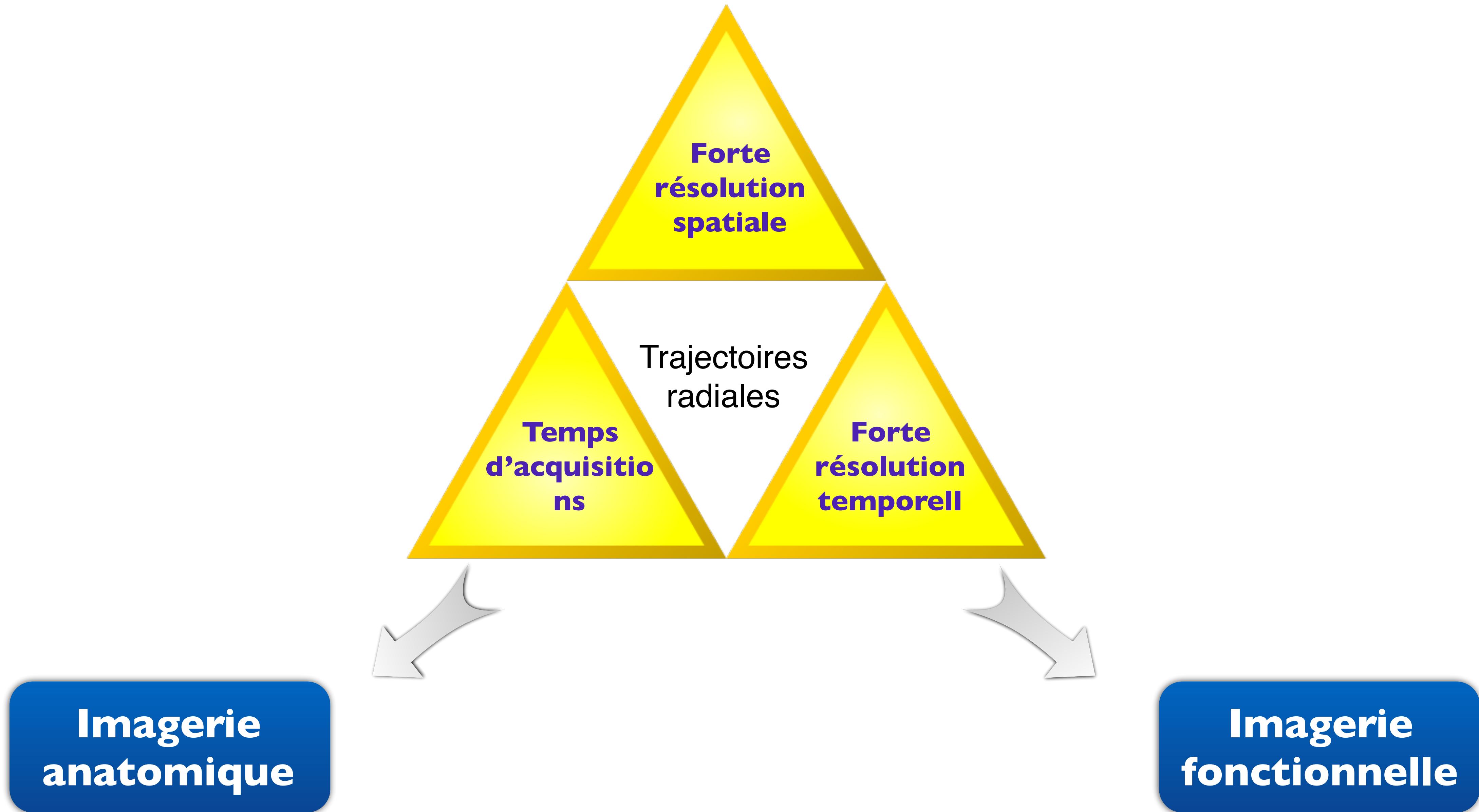
Regridding



FFT



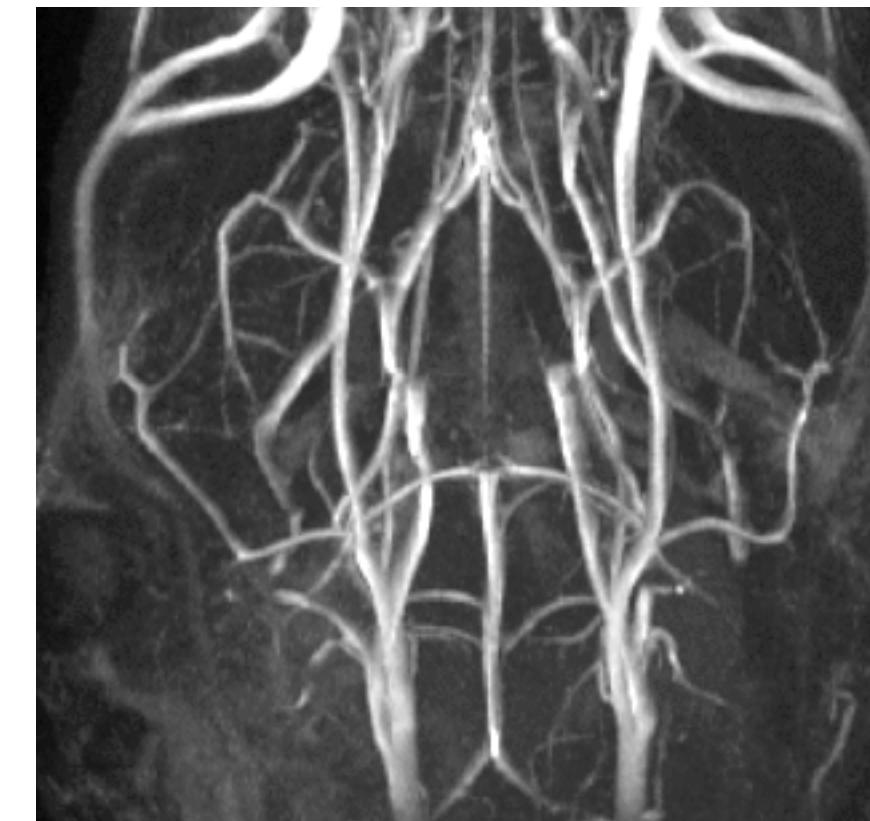
Imagerie cardio-vasculaire chez le petit animal



Angiographie dynamique avec une séquence radiale à encodage pseudo-aléatoire par un double angle d'or ciné.

Etat de l'art au sein du laboratoire

Angiographie 3D anatomique



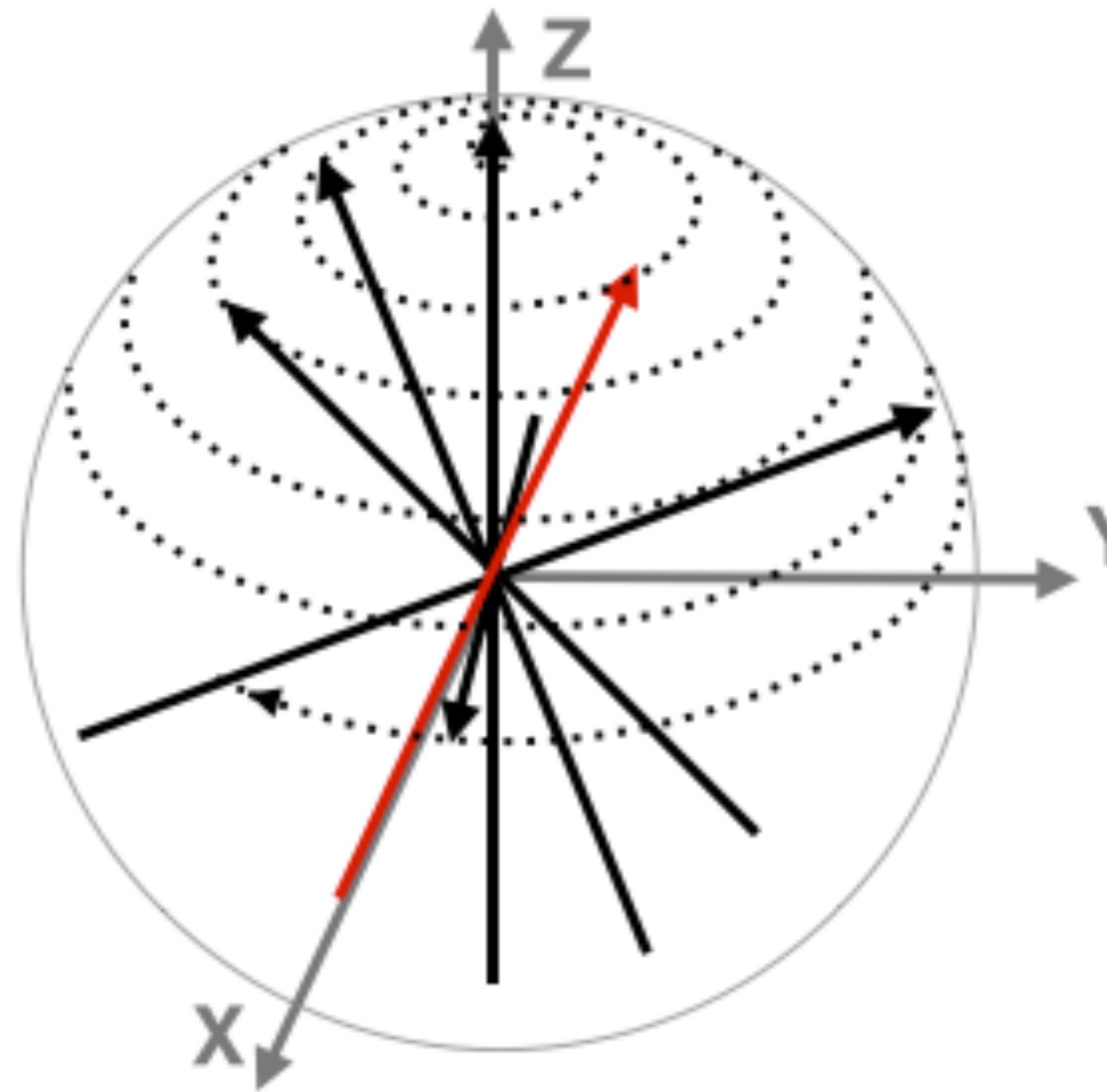
Résolution : 89 µm

Angiographie 3D résolue dans le temps



Résolution : 155 x 195 x 280

Temps d'acquisitions élevés



Développement des trajectoires radiales :

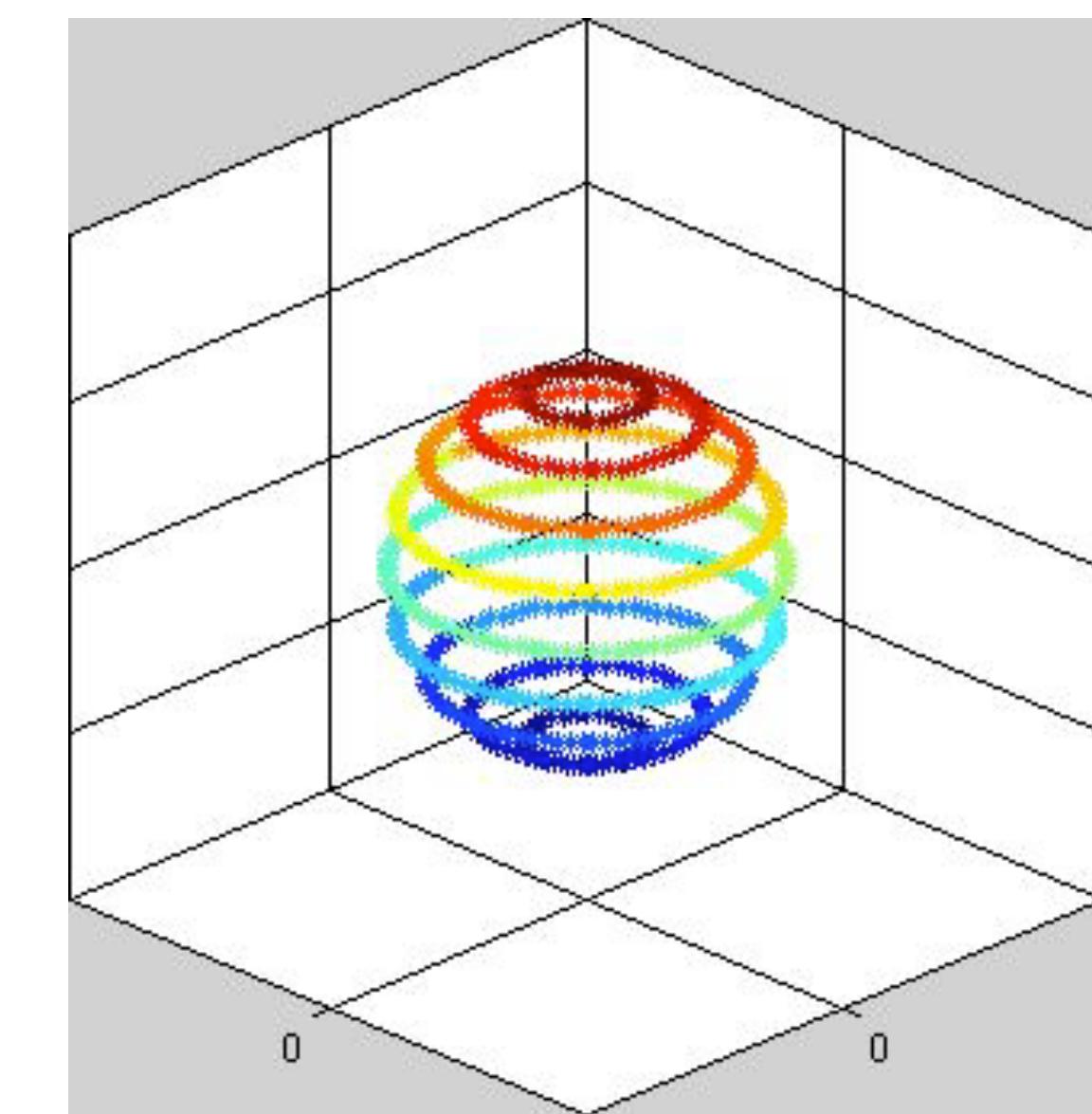
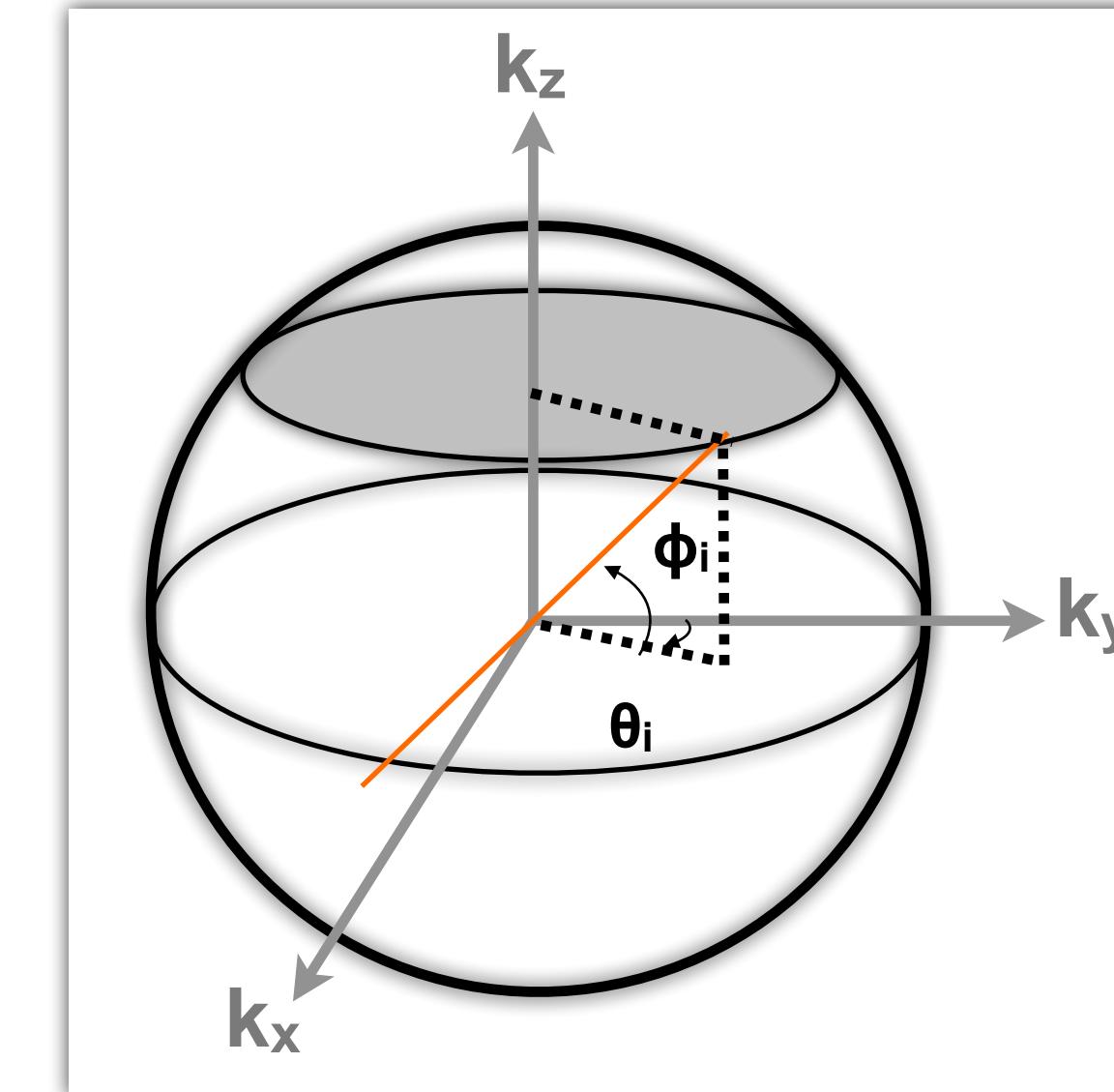
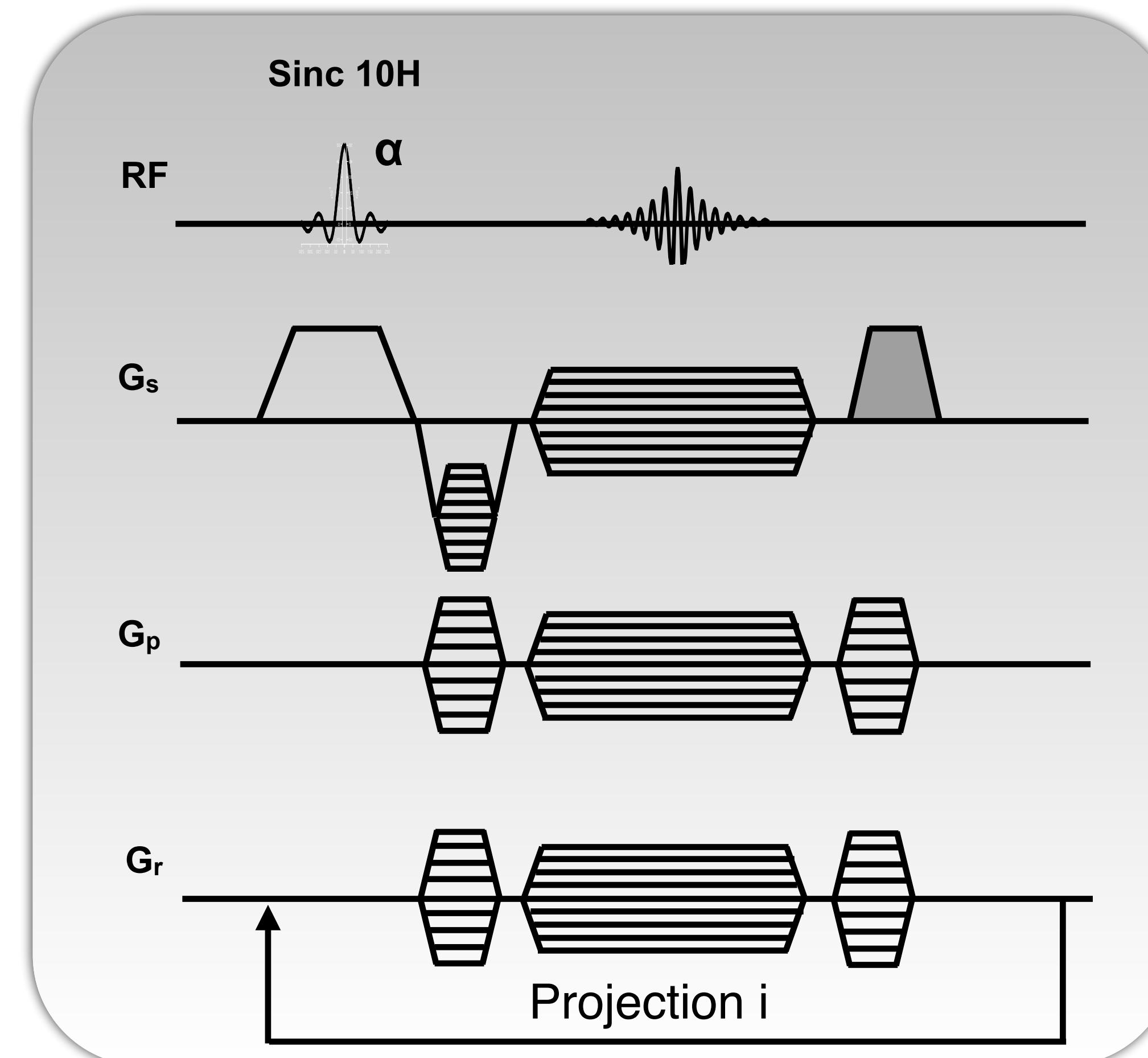
- Séquences
- Mesures de trajectoires
- Reconstructions

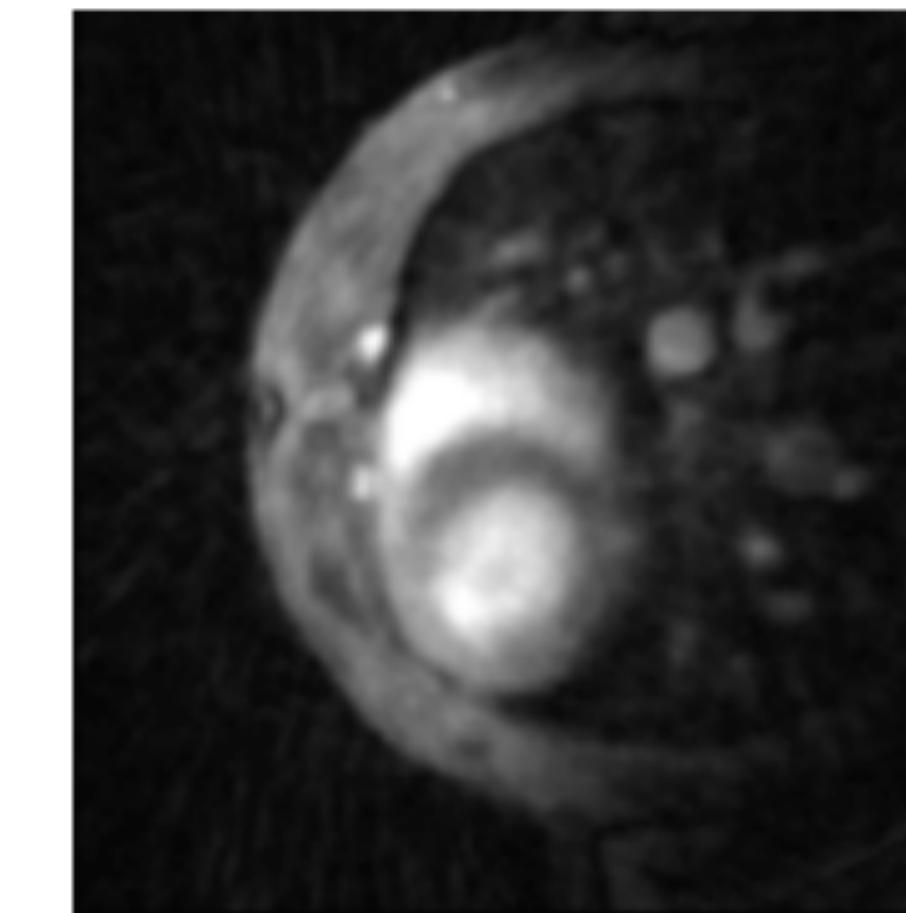
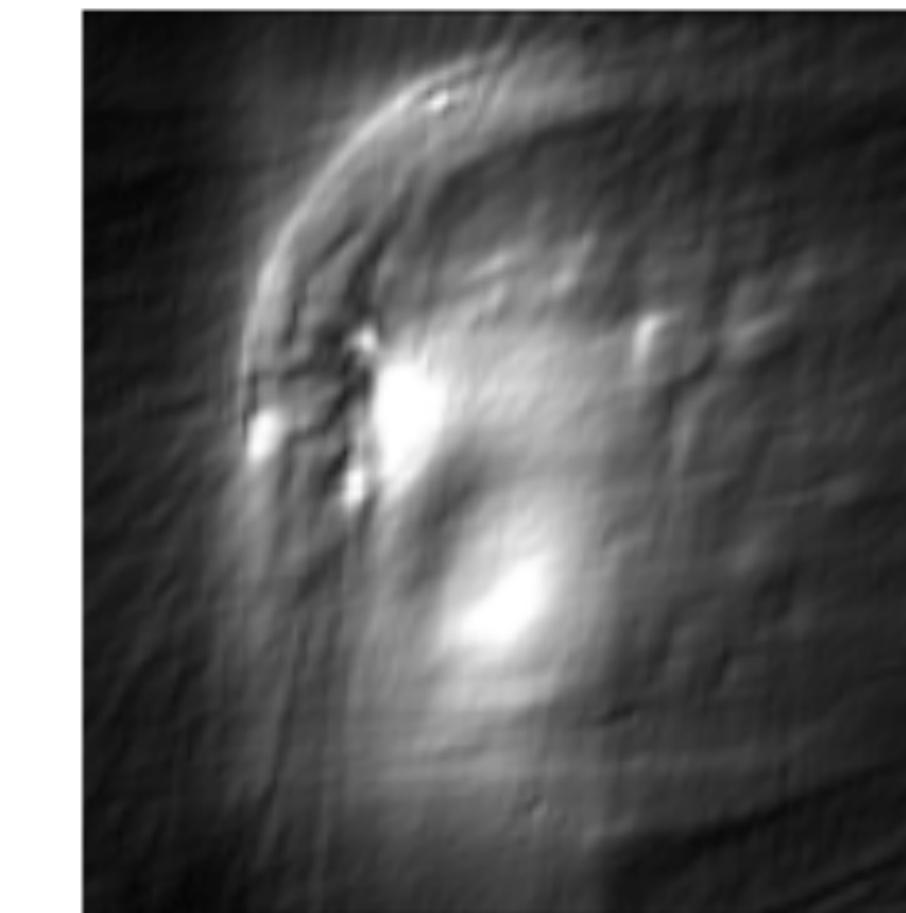
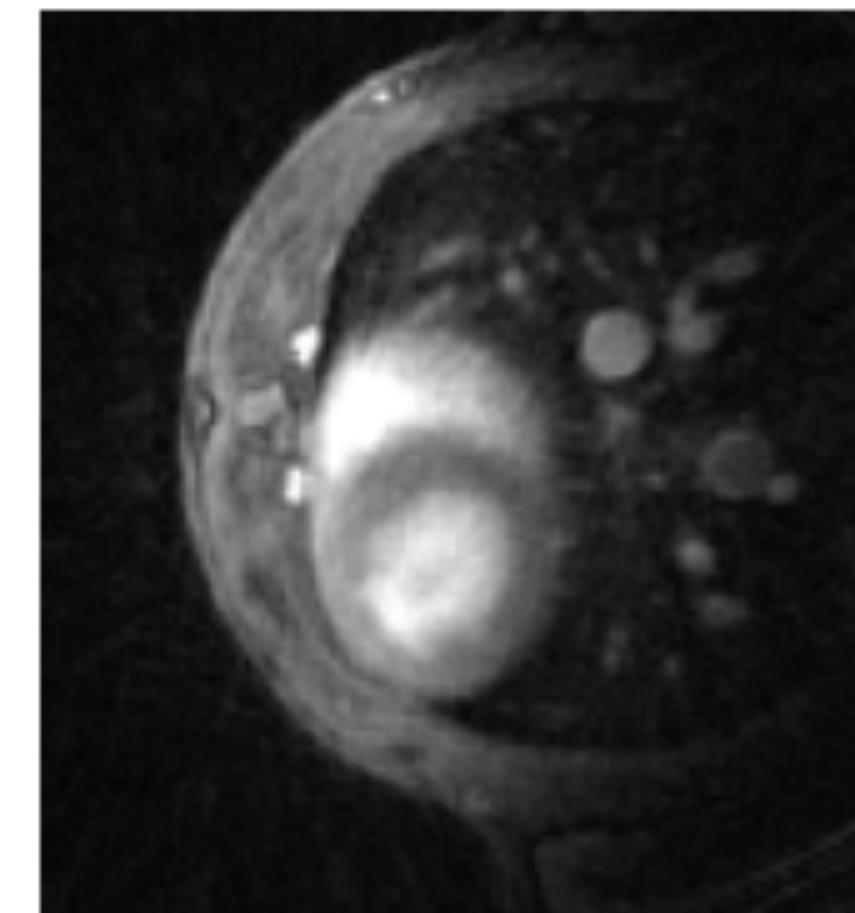
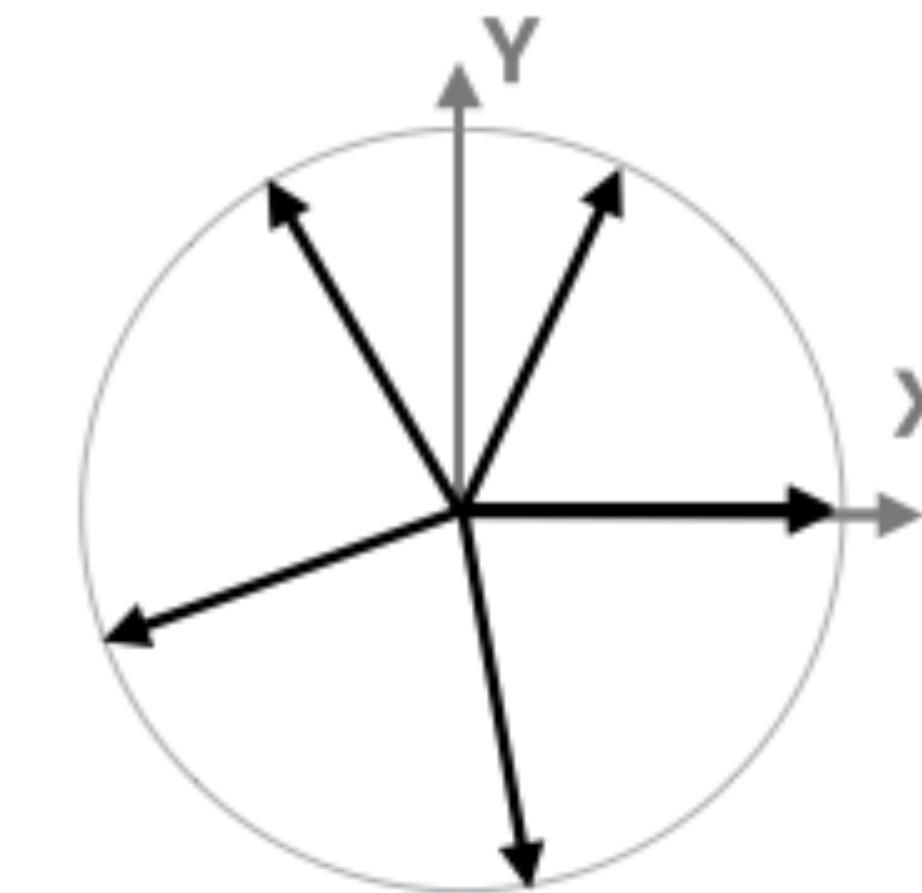
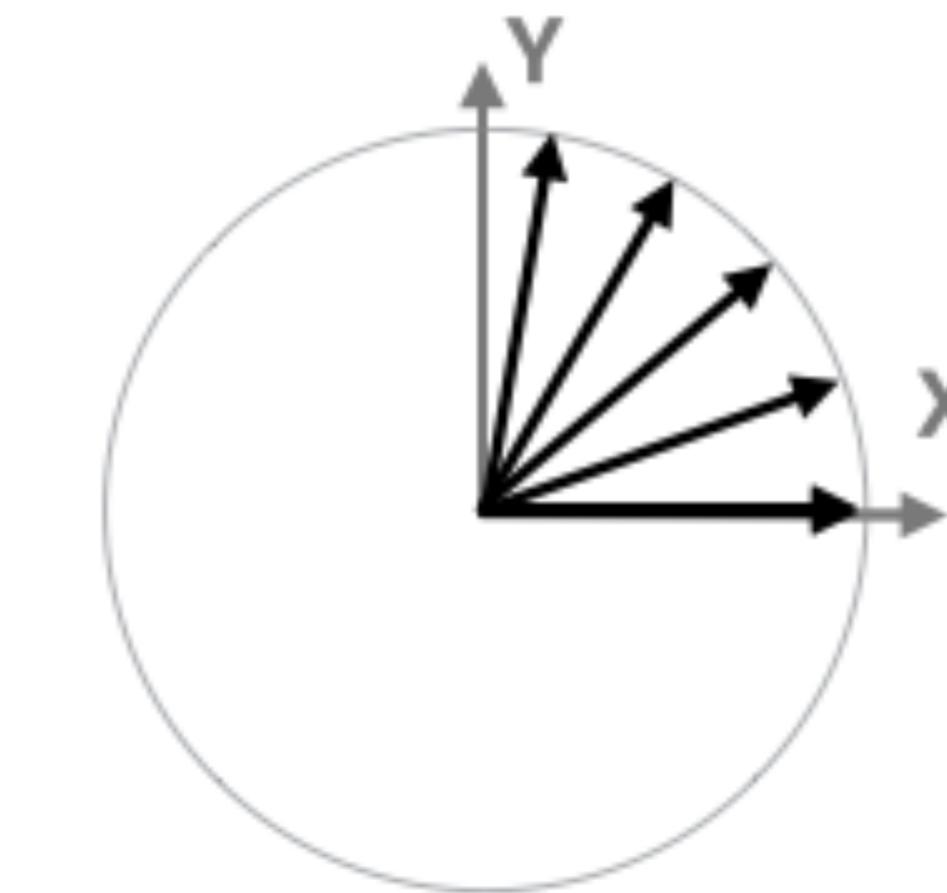
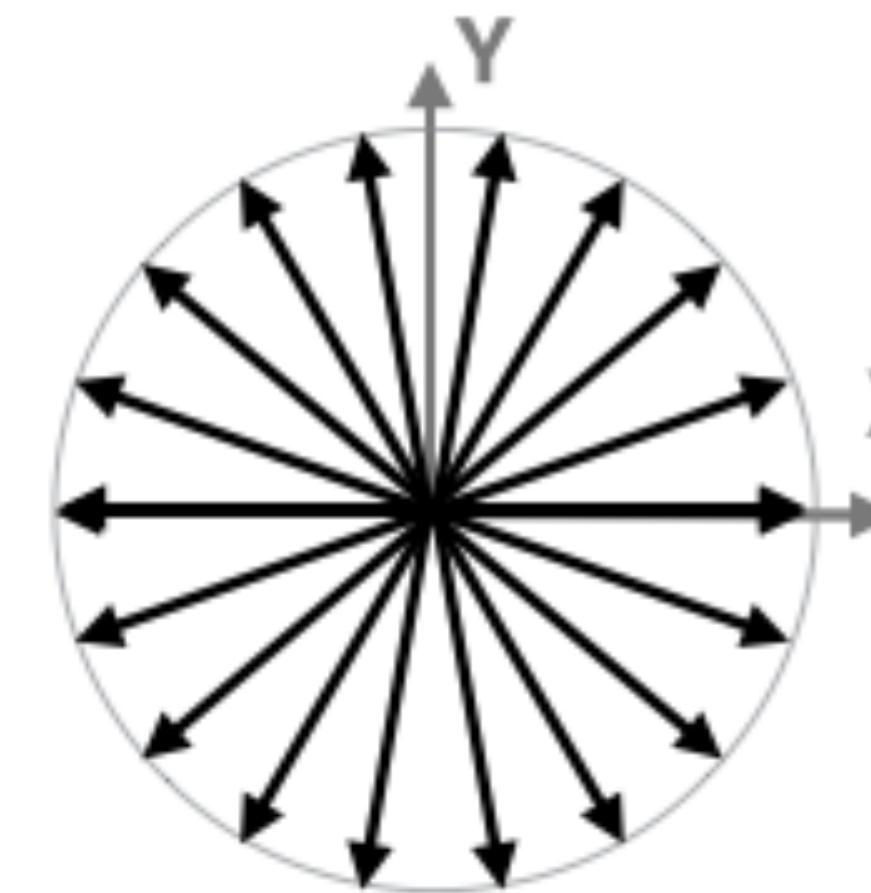
Séquence innovante pour la mesure de flux :

- Résolution temporelle
- Résolution spatiale
- Rapide
- Robuste
- Flexible

Séquence d'angiographie radiale

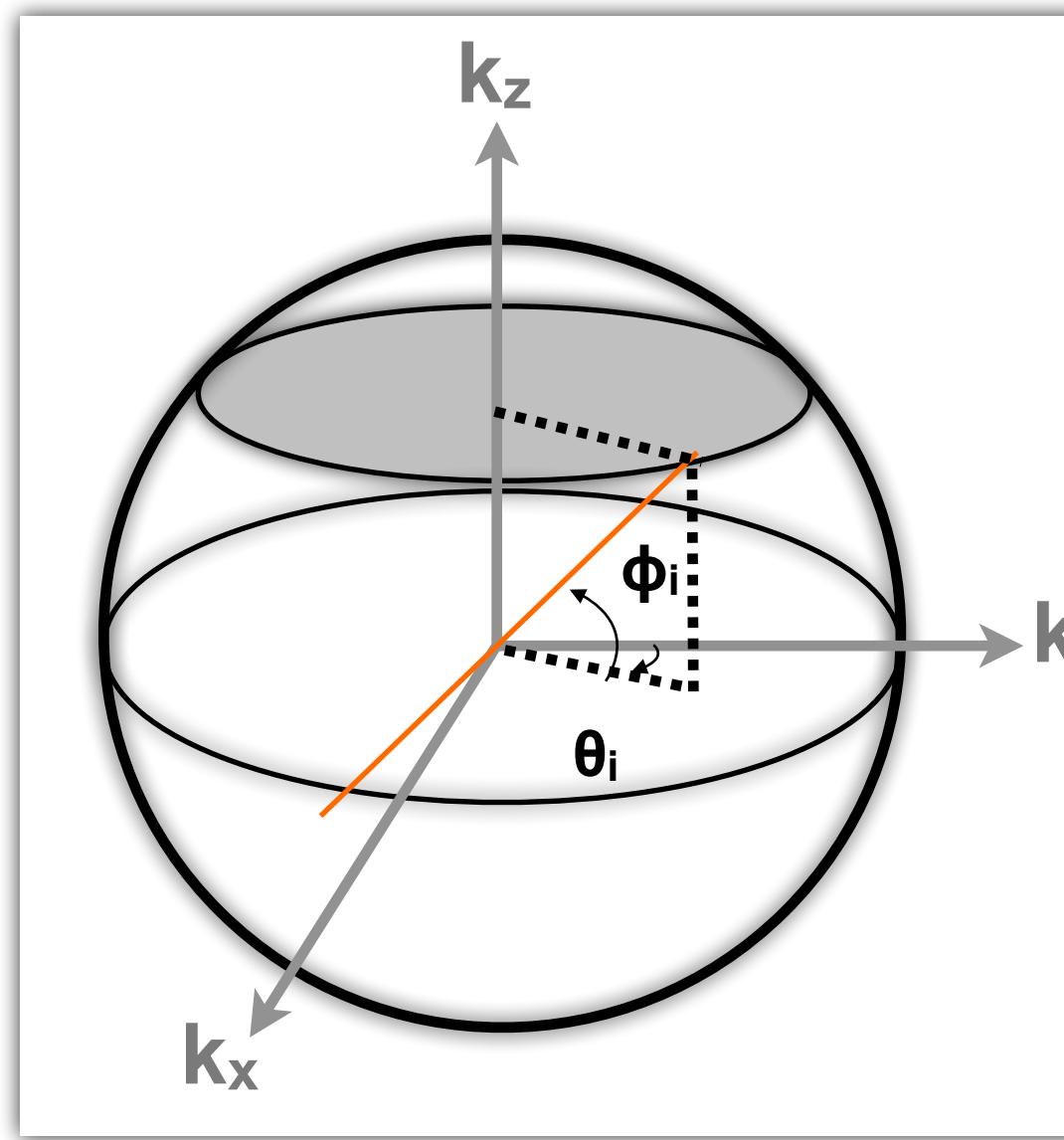
Séquence d'écho de gradient





- Arrêt de la séquence
- Reconstruction rétrospective

Répartition selon l'angle d'or 3D



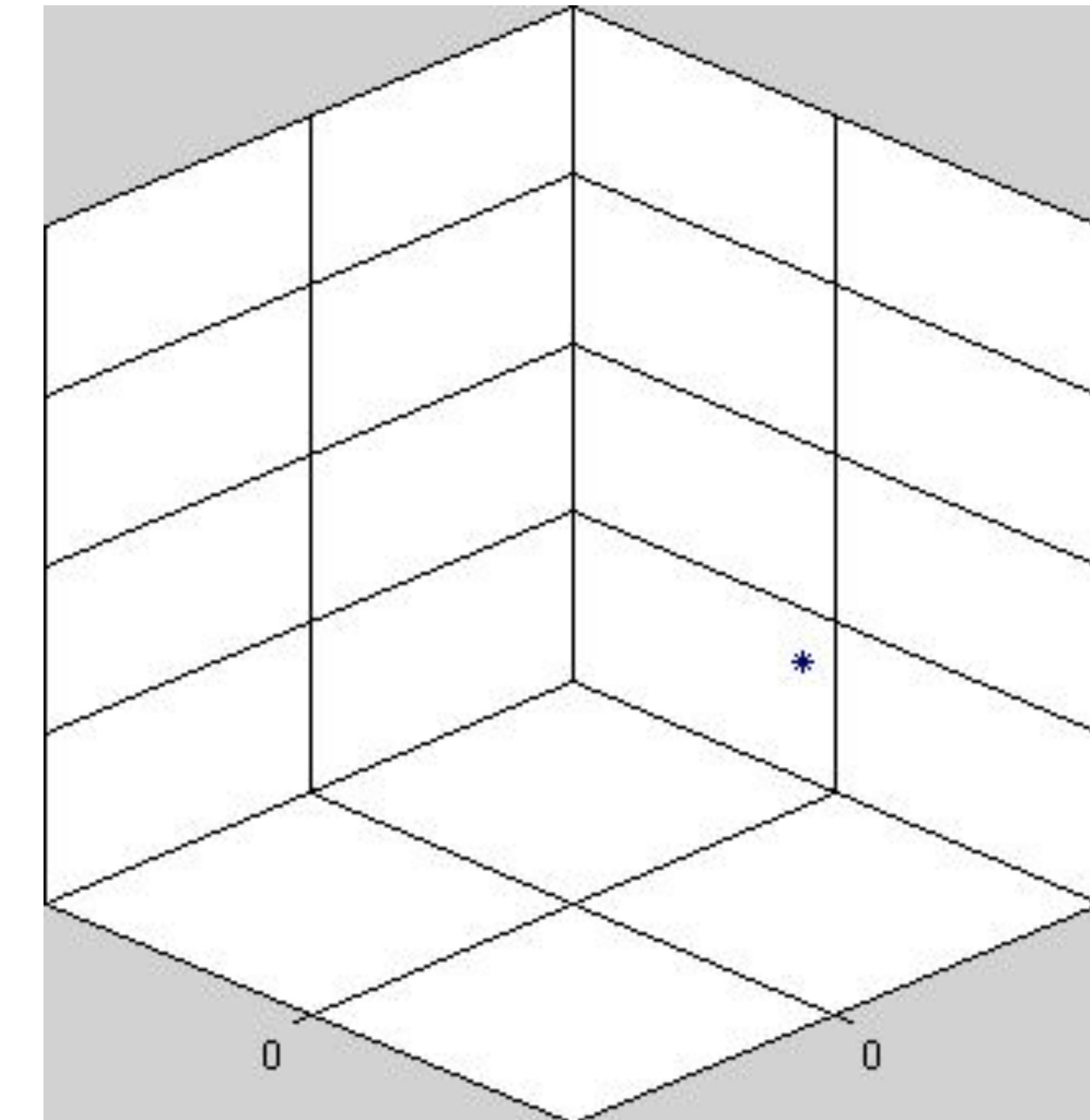
$$\phi_i = 2\pi \times (\langle u_1 \times i \rangle)$$
$$\theta_i = \arccos(\langle u_2 \times i \rangle)$$

avec

$$u_1 = 0.4656 \text{ rad}$$

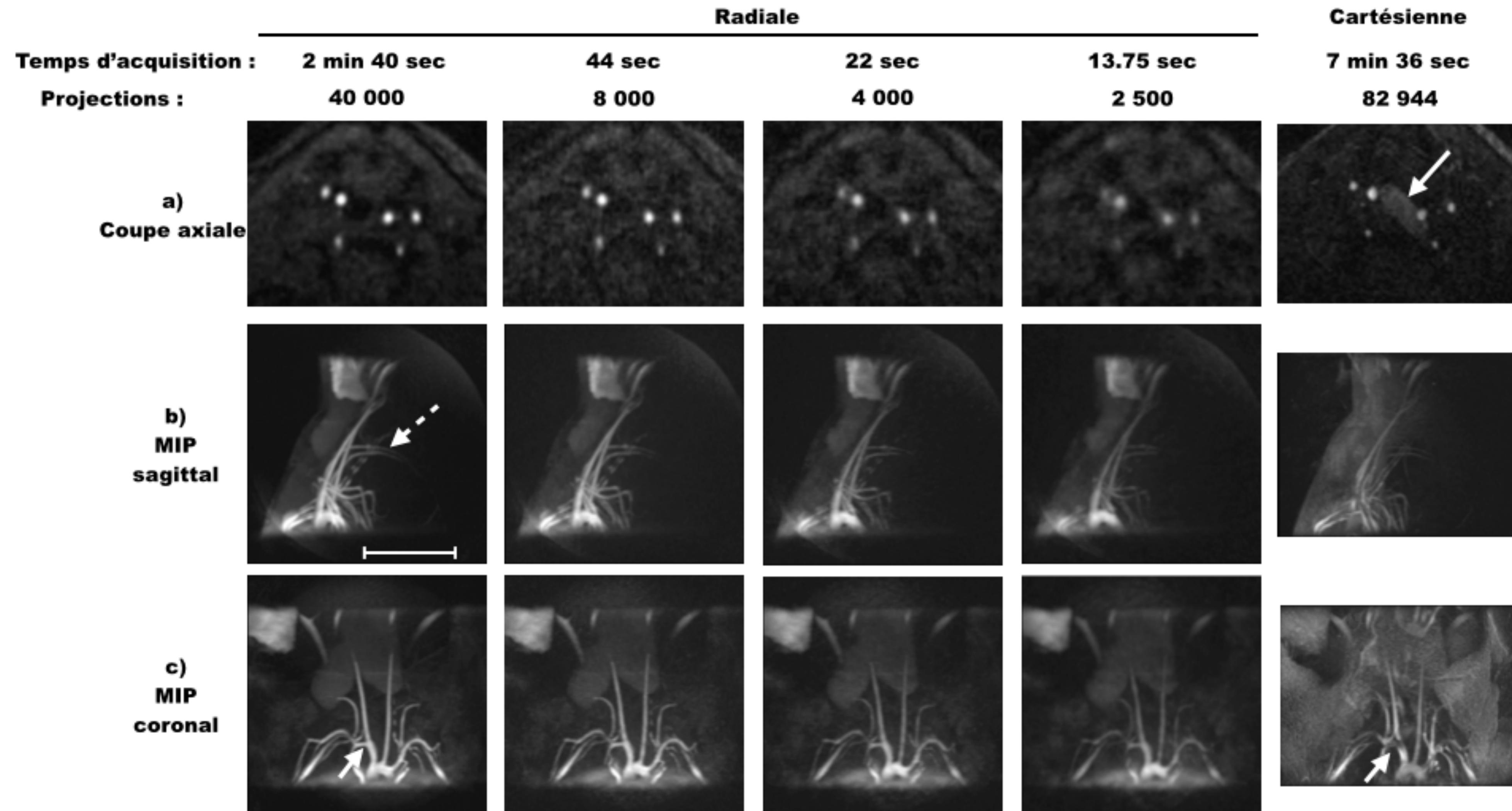
$$u_2 = 0.6823 \text{ rad}$$

L'angle d'or 3D a été décrit par Chan et al en 2009

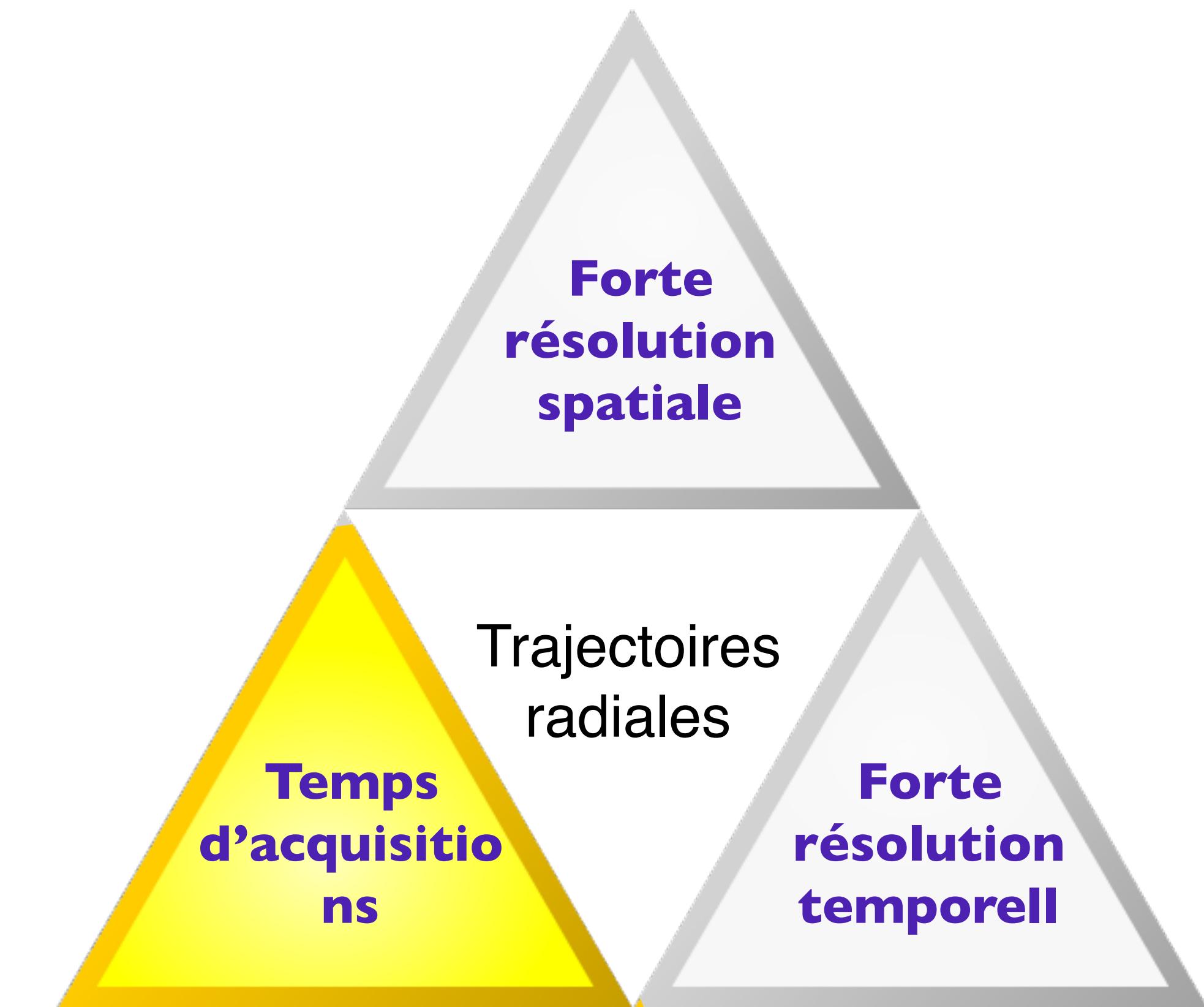


Implémentation trajectoire avec une répartition uniforme au cours du temps

Angiographie anatomique avec l'angle d'or 3D

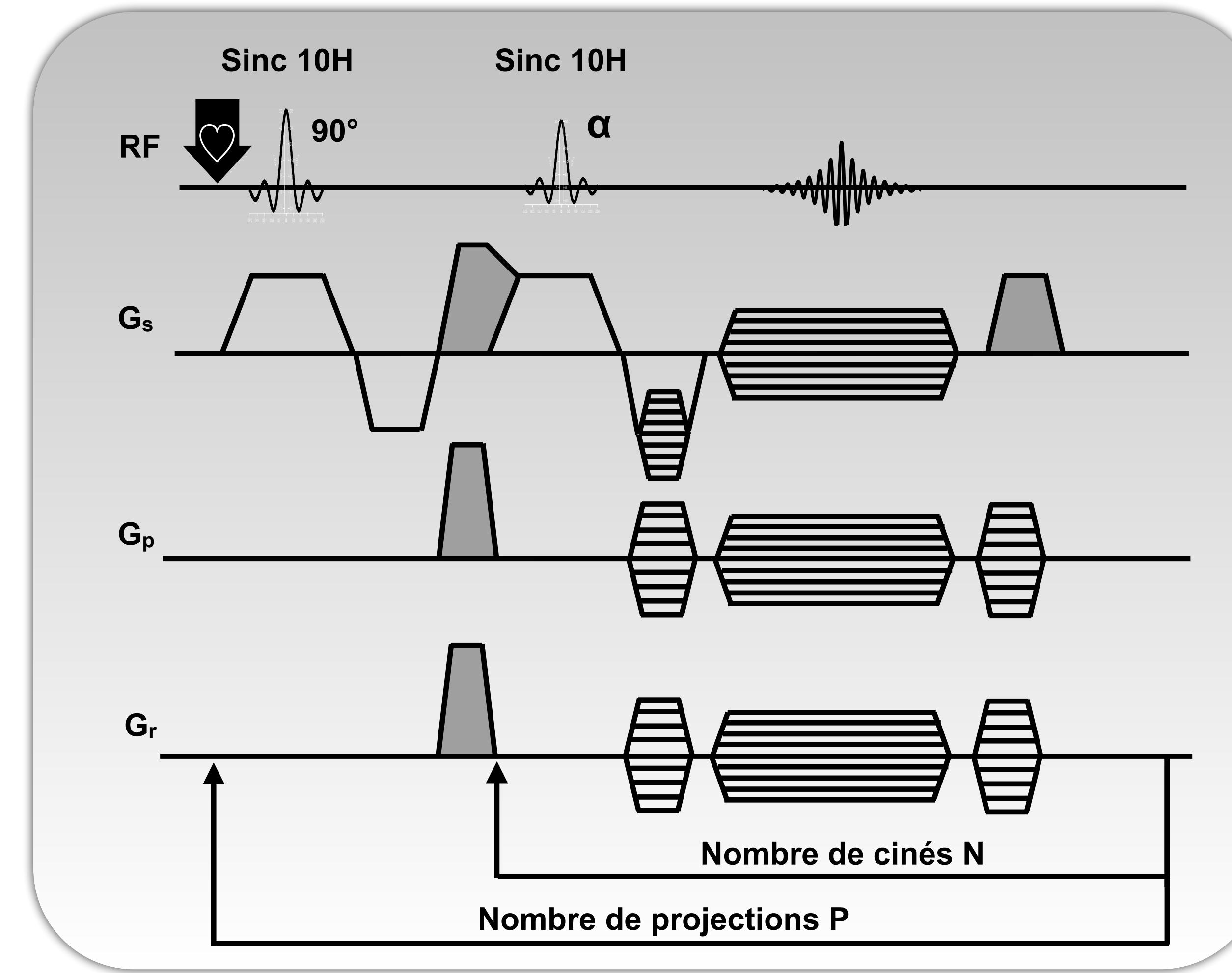


- Robuste aux mouvements
- Accélération par sous-échantillonnage

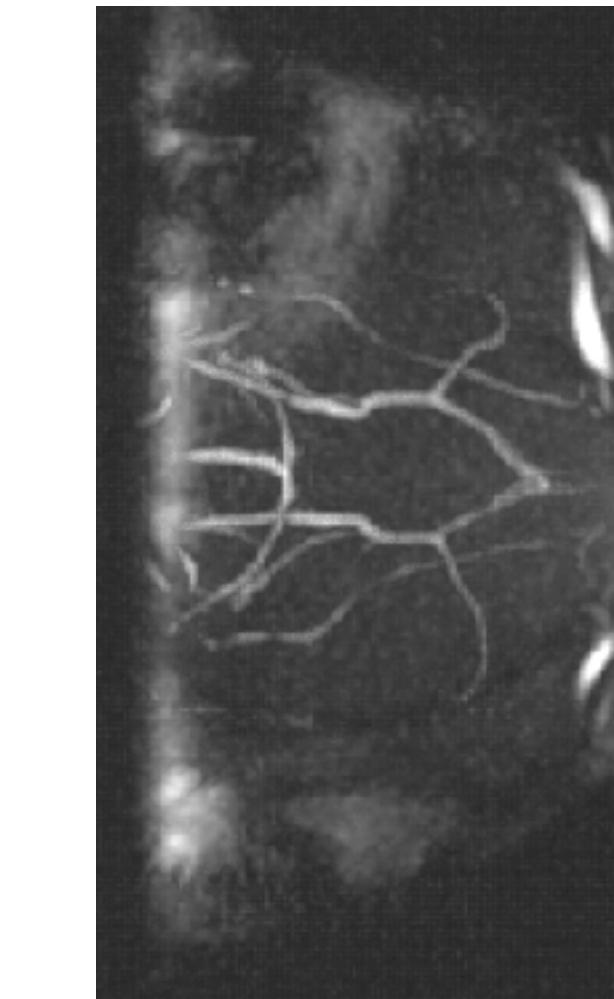


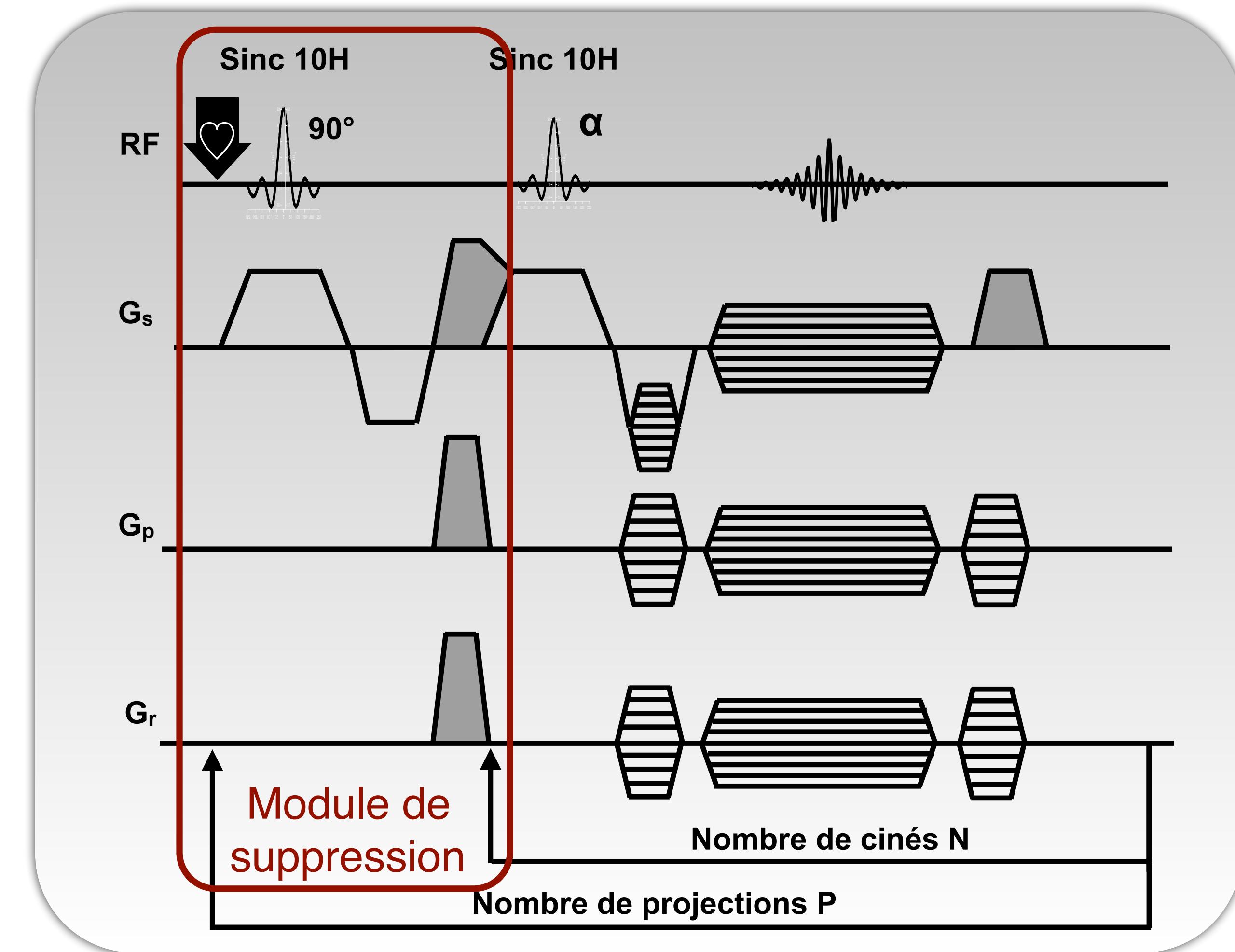
- Sous-échantillonnage important

Application à l'angiographie dynamique



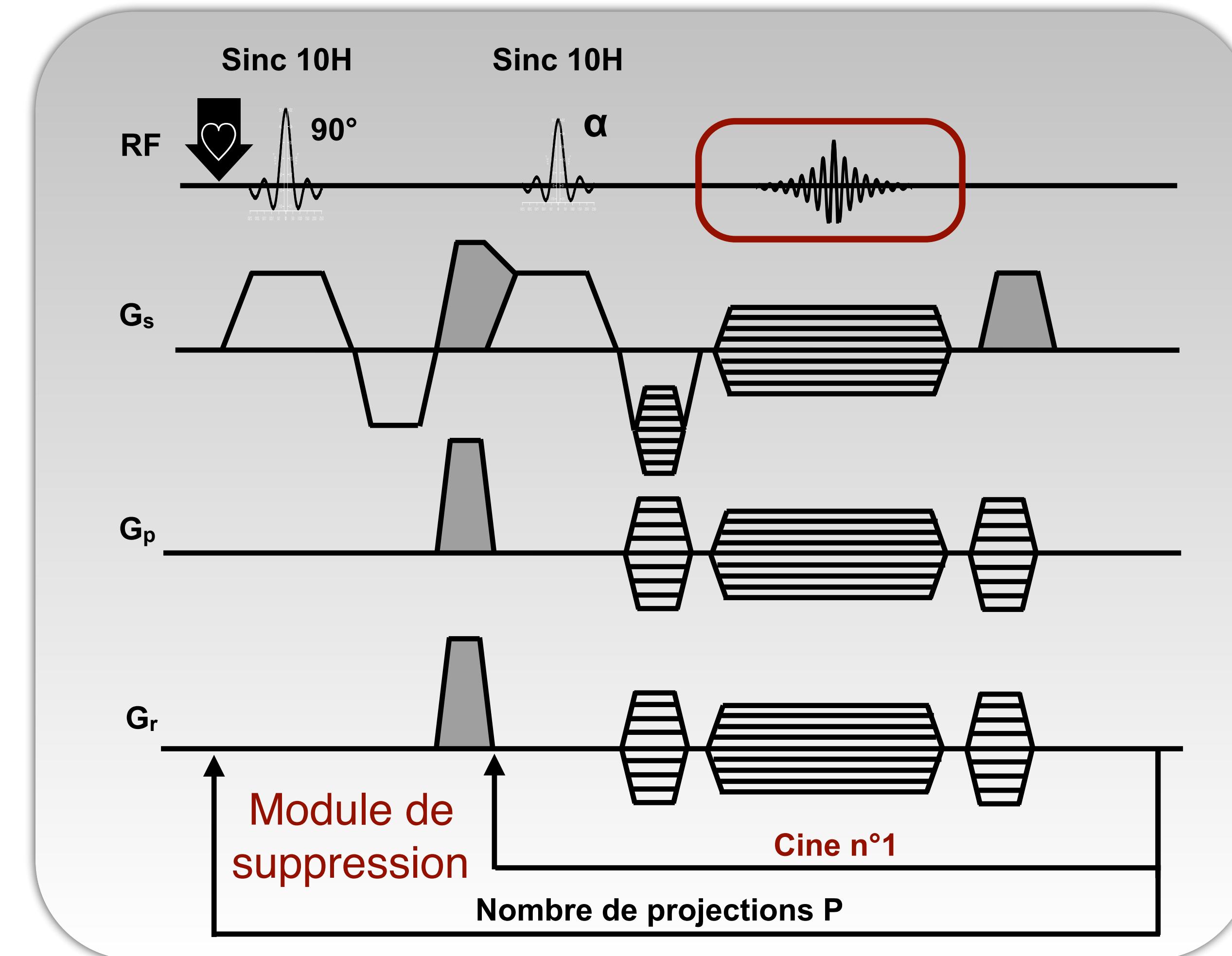
Avant suppression





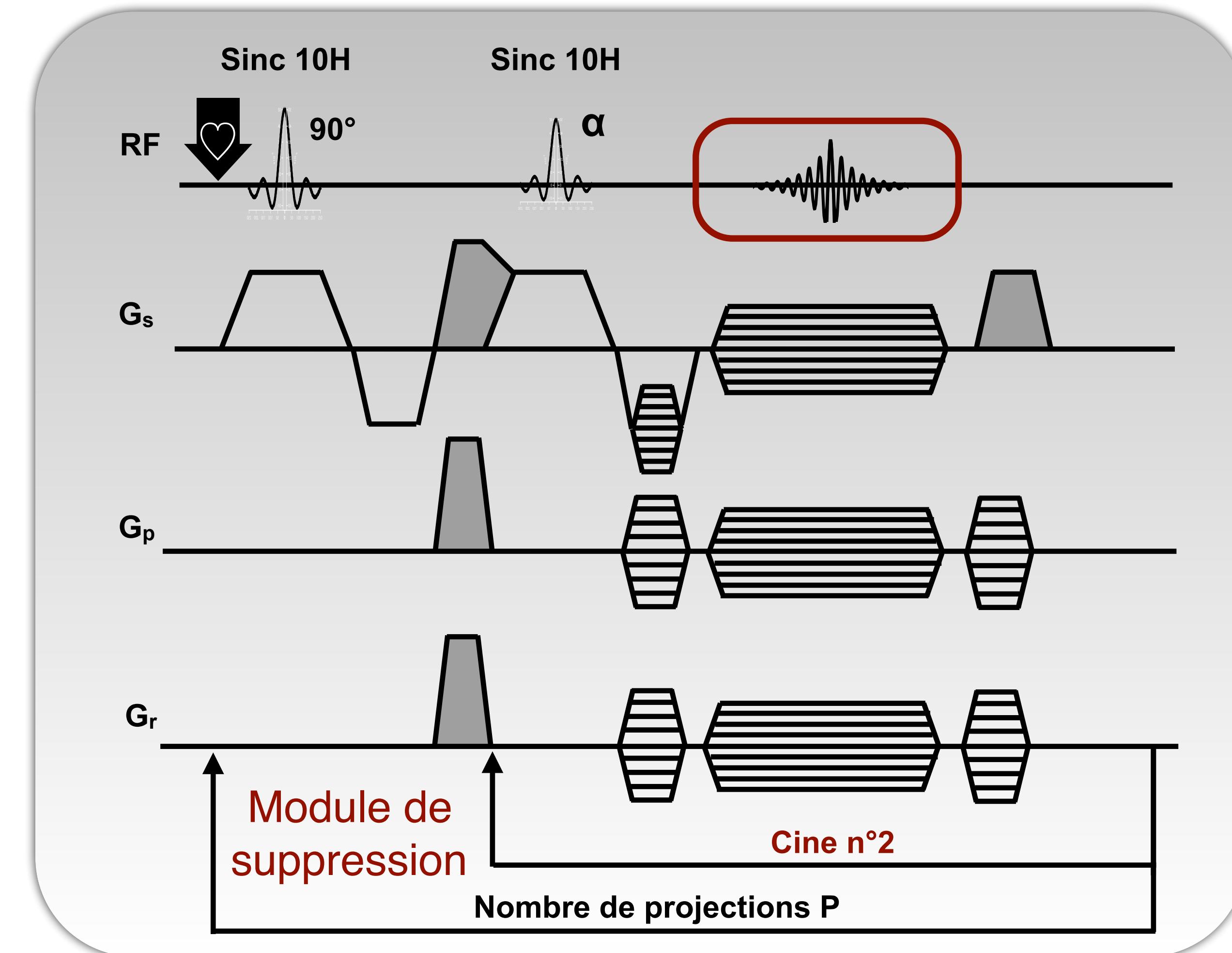
Après suppression





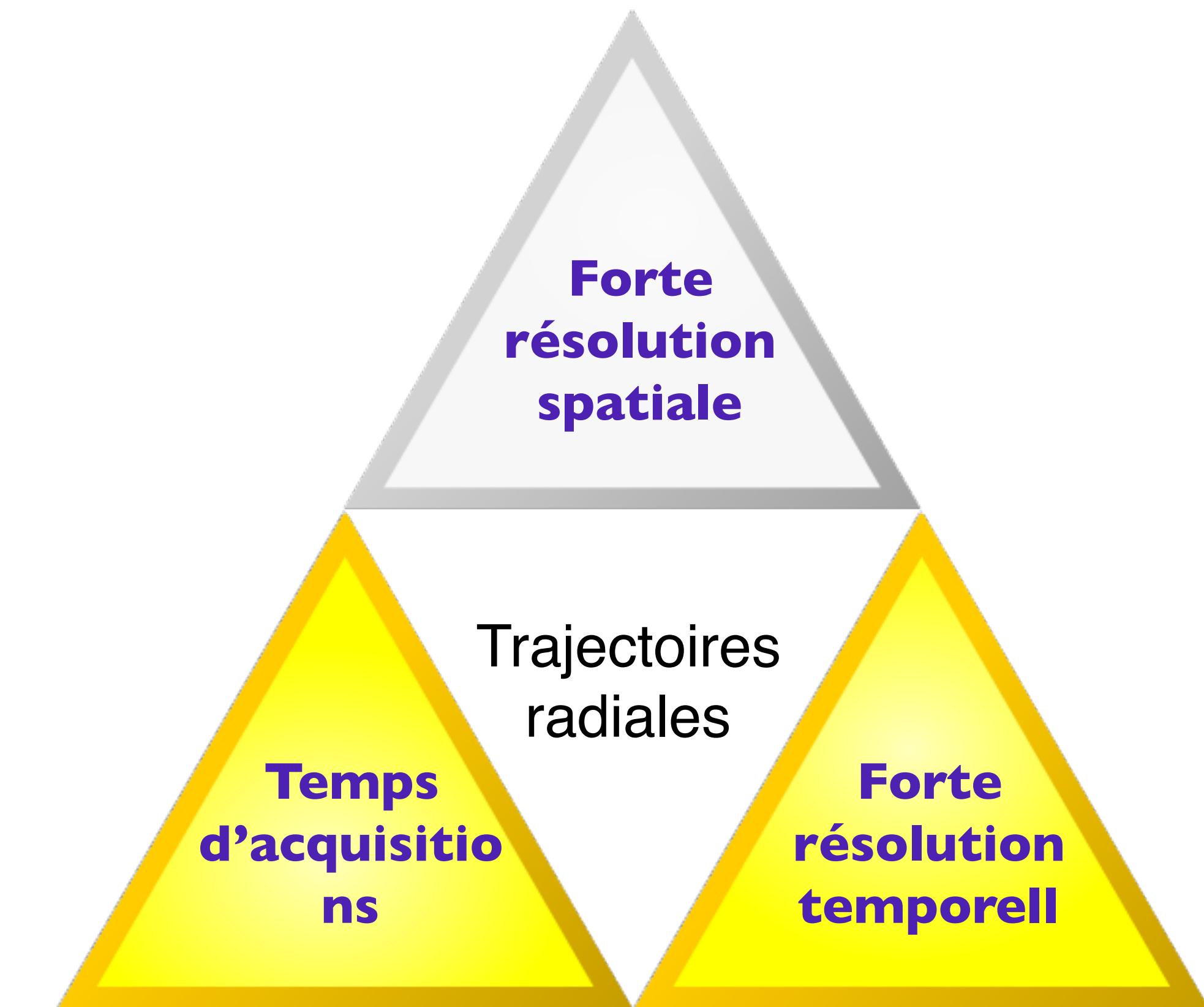
1er écho après suppression





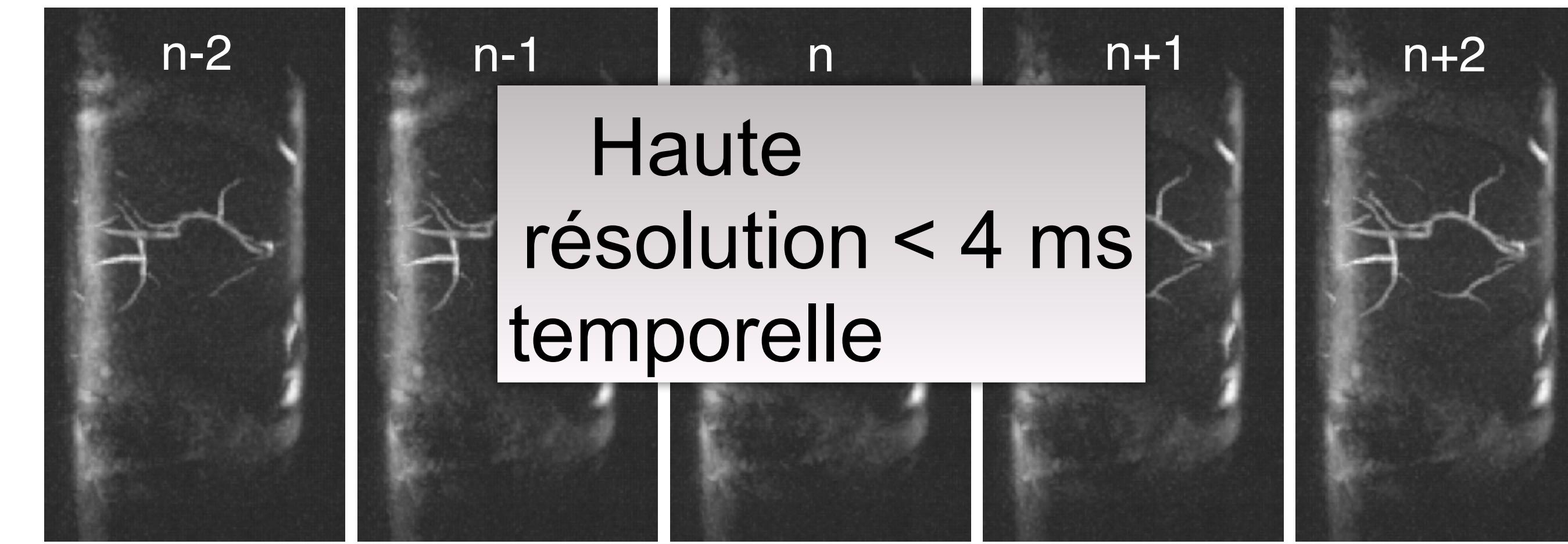
2ème écho après suppression





- Sous-échantillonnage > 10
- Résolution temporelle = TR < 4 ms

Augmentation de la résolution spatiale



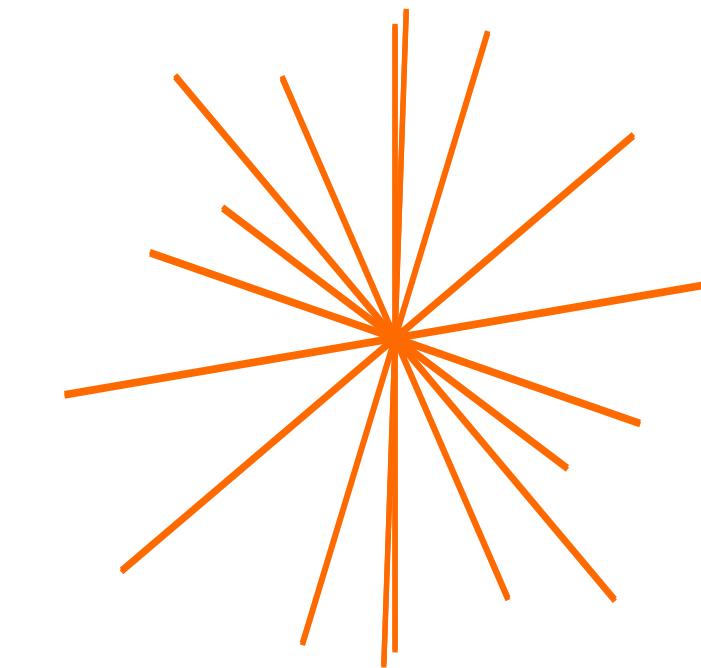
iFFT



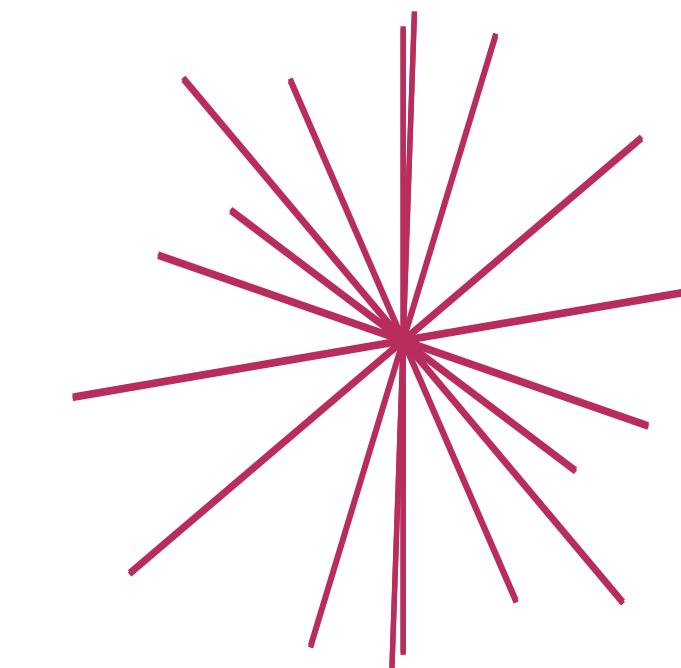
Combinaison des données des espaces de Fourier

Augmentation de la résolution spatiale

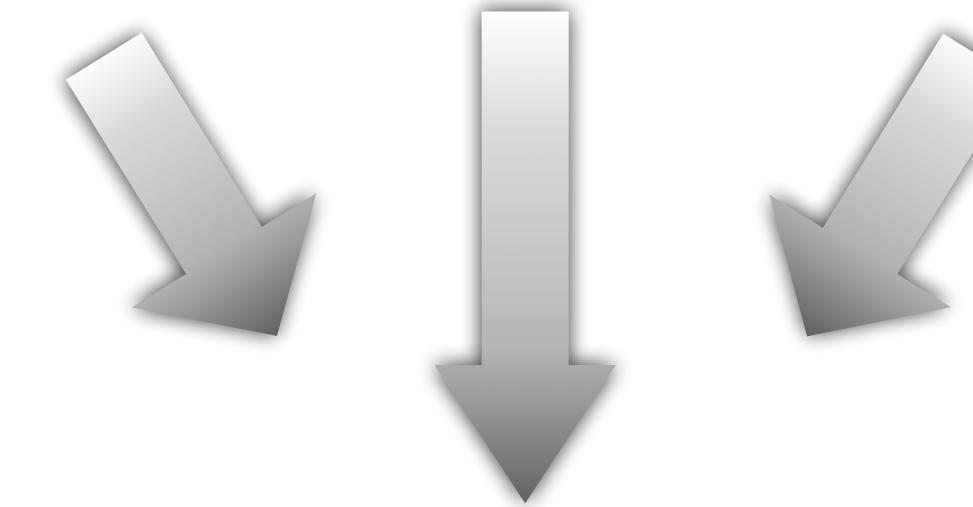
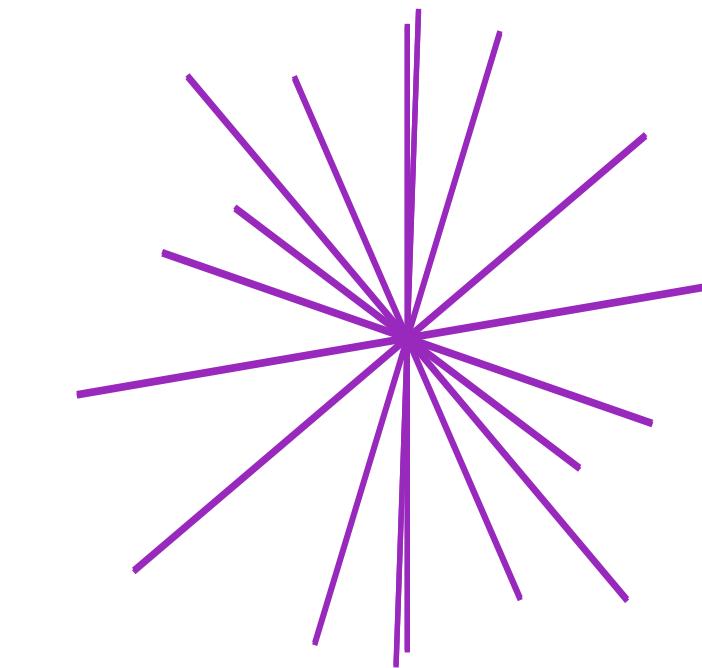
Cine 1



Cine 2

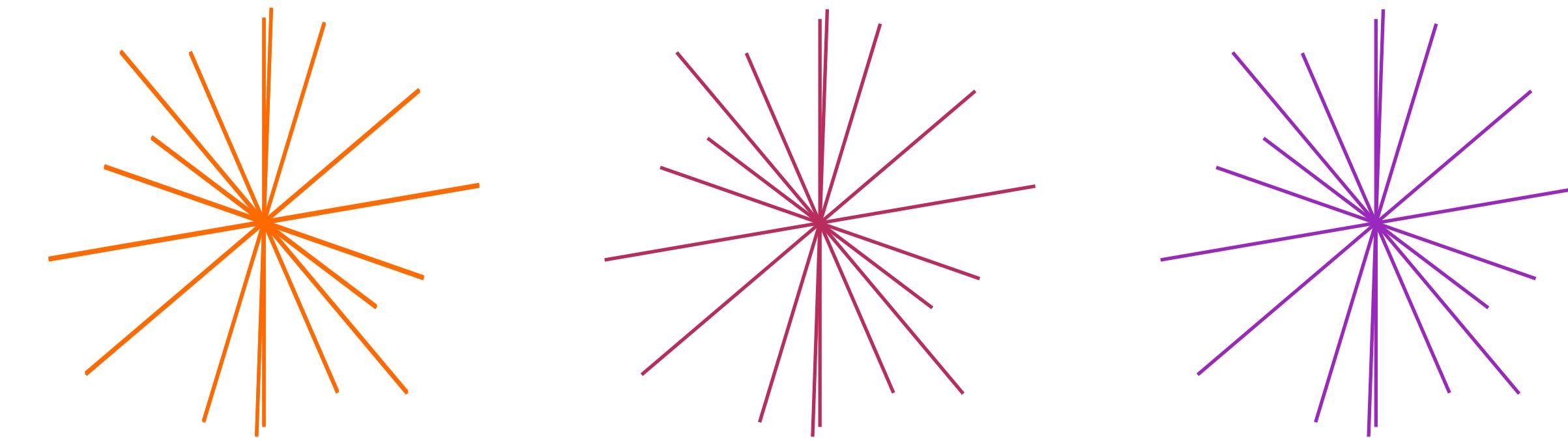


Cine 3

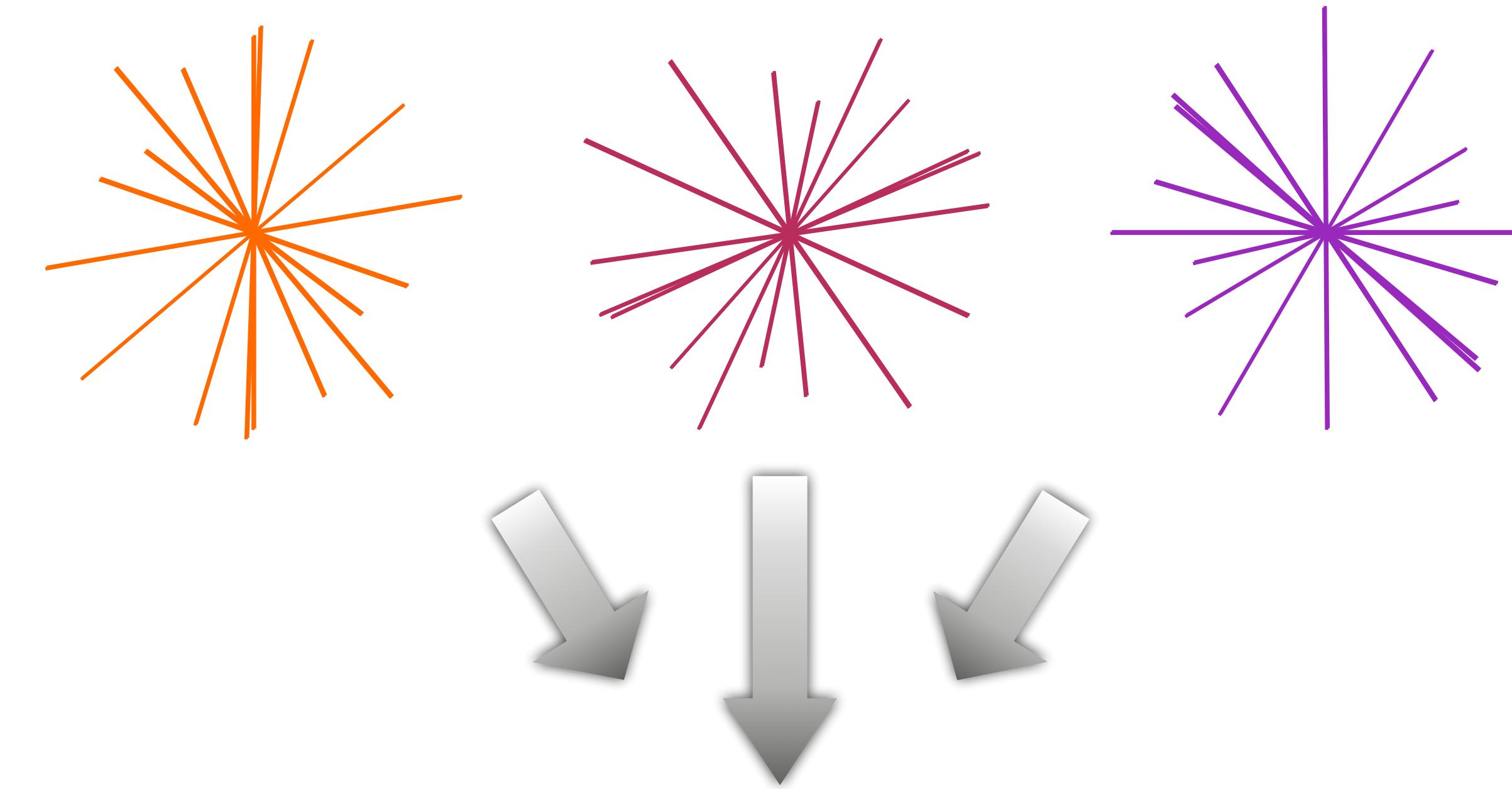


Meilleur SSB mais pas la résolution spatiale

Augmentation de la résolution spatiale

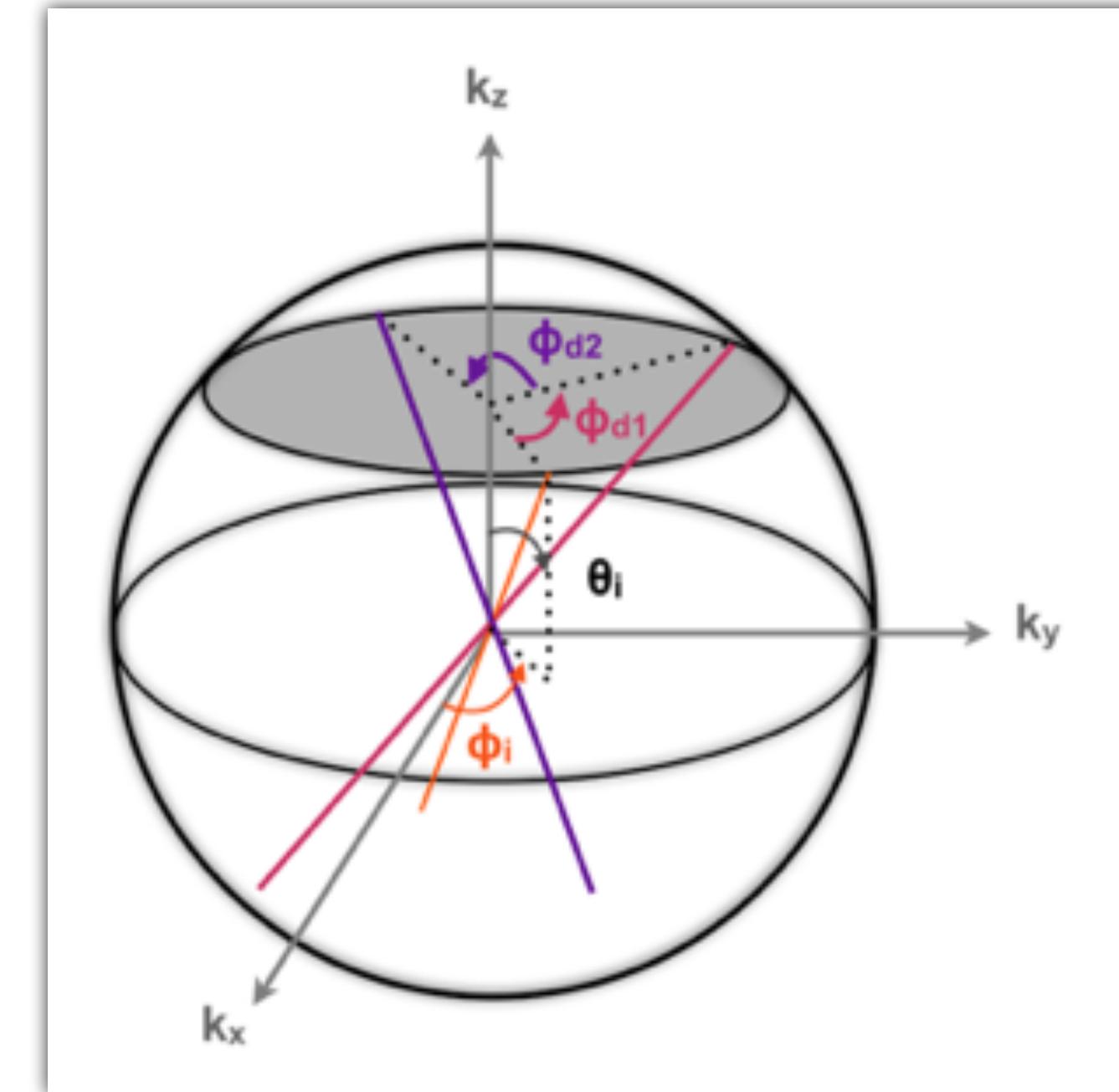


Augmentation de la résolution spatiale



Meilleure
résolution
spatiale Fourier

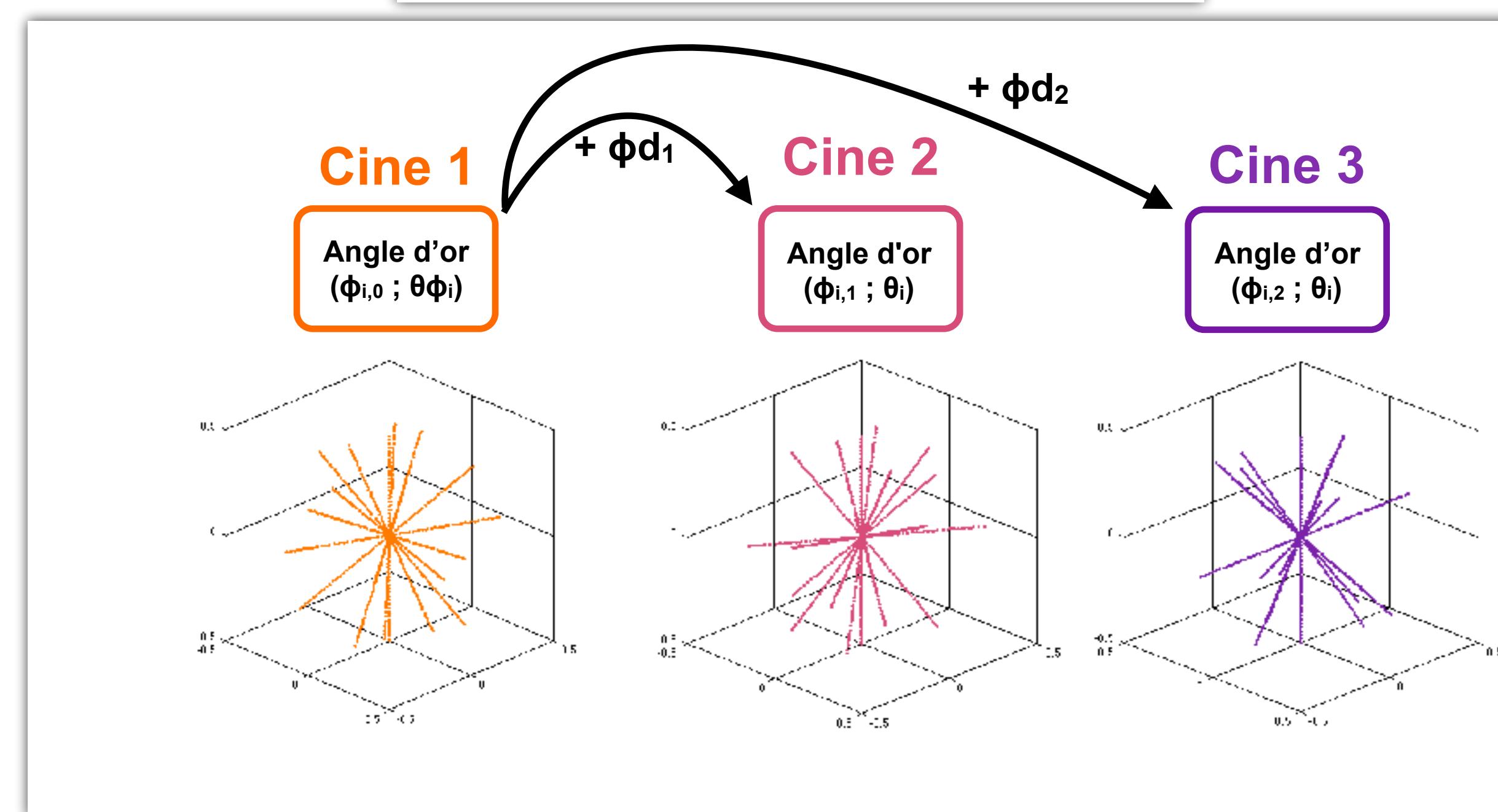
2ème angle d'or



Rotation autour de l'axe Z

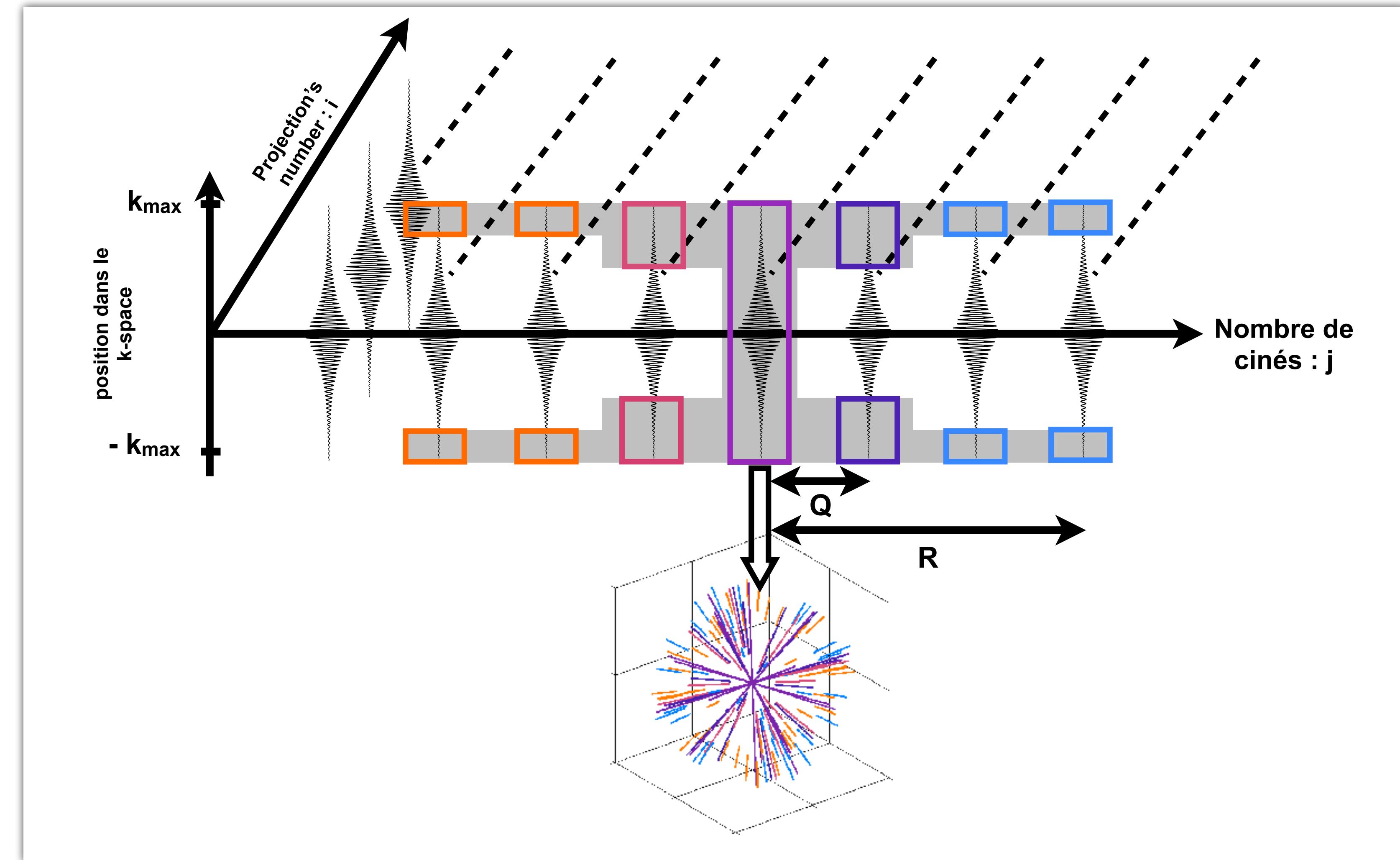
$$\phi_{dj} = 2\pi \times (\langle u_2 \times j \rangle)$$

$$u_2 = 0.6823 \text{ rad}$$

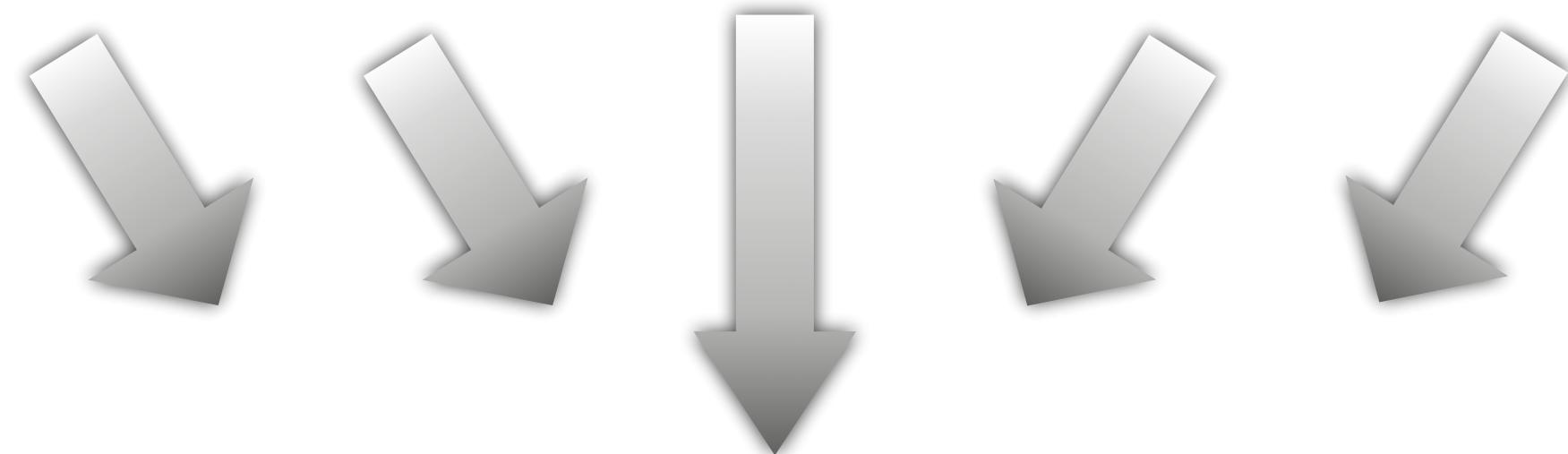
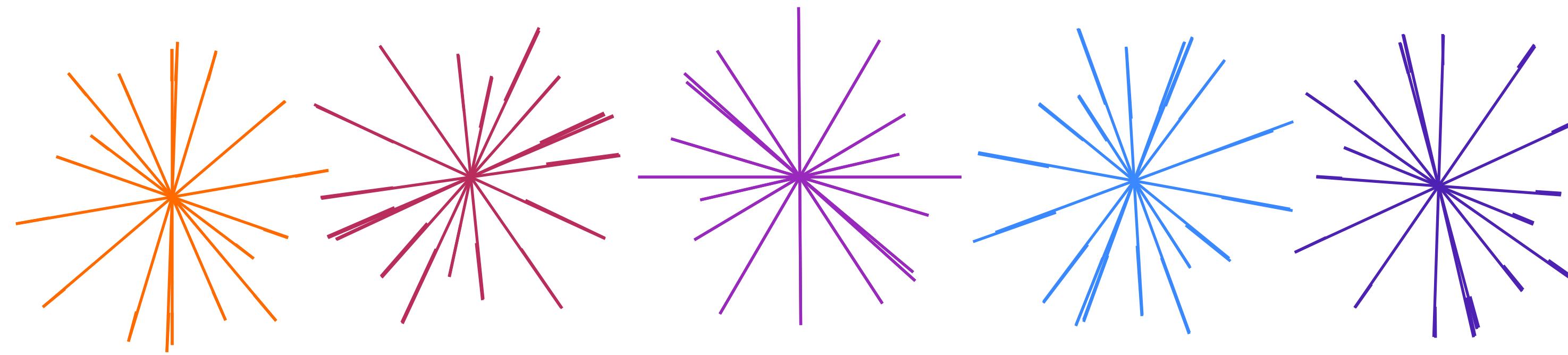
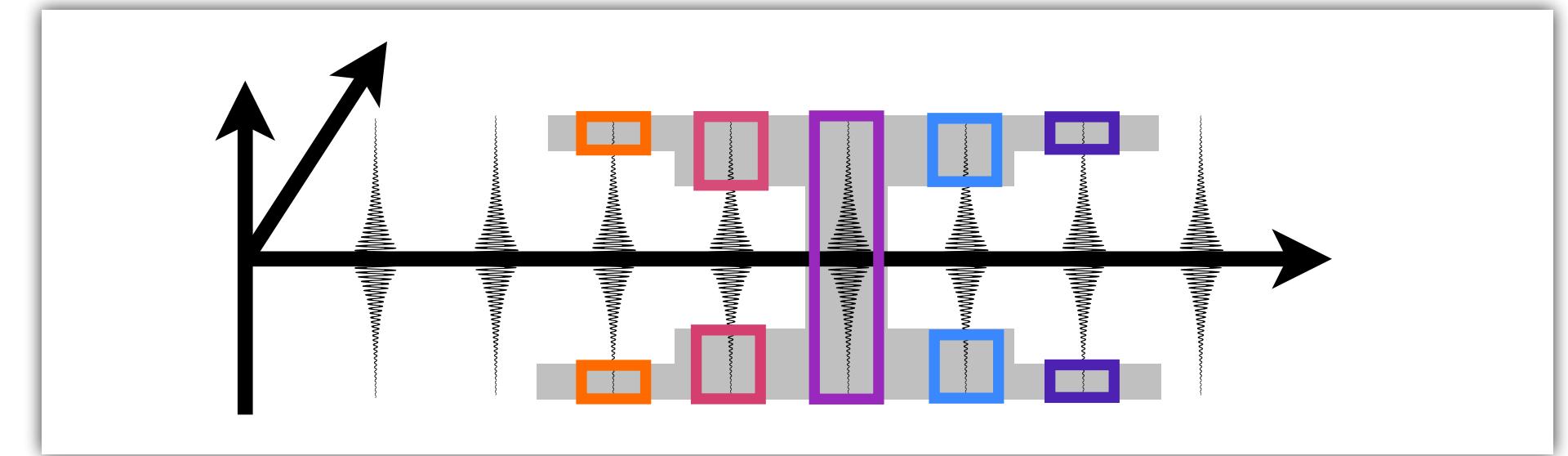


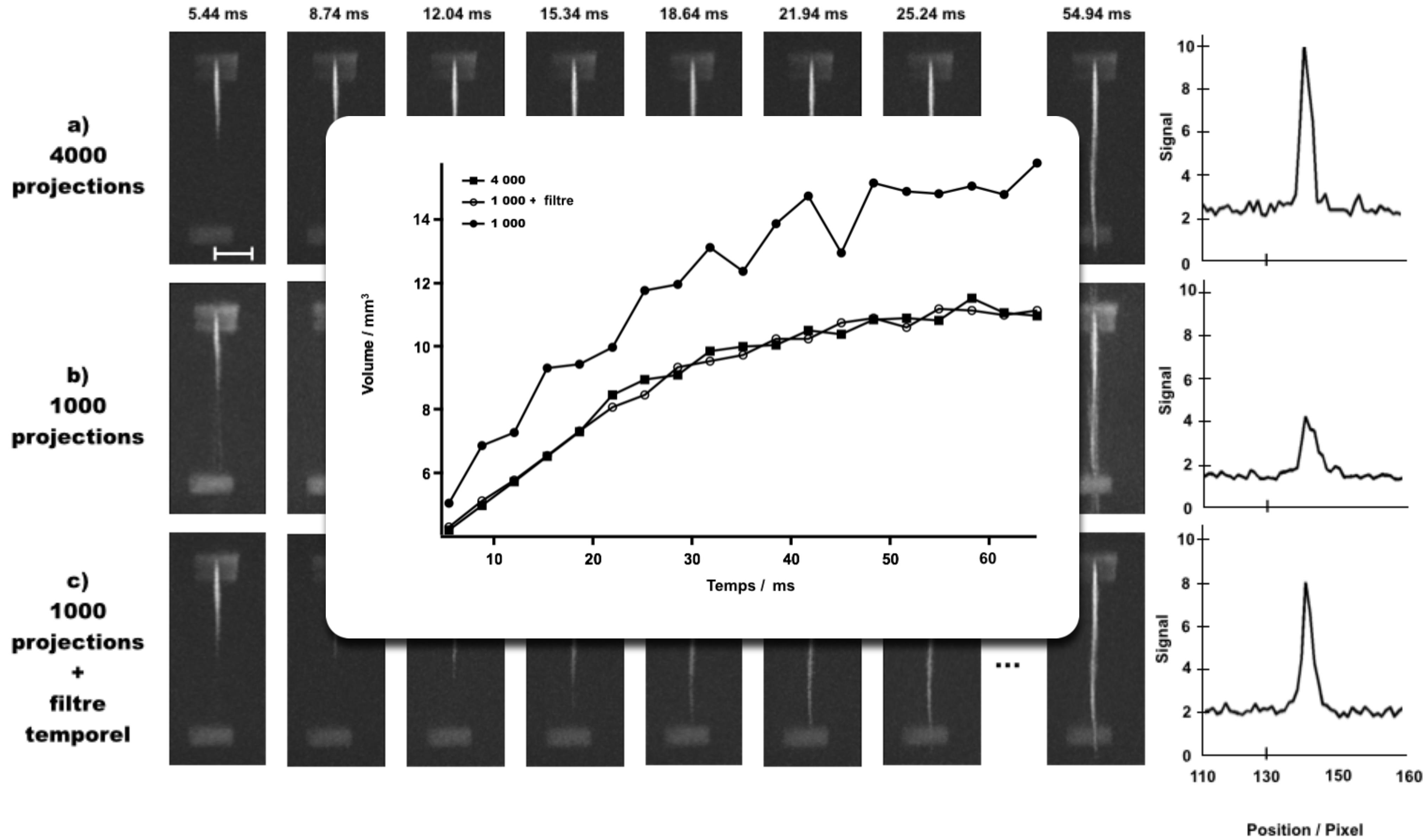
Trajectoires
différentes mais
semblables

Filtre temporel



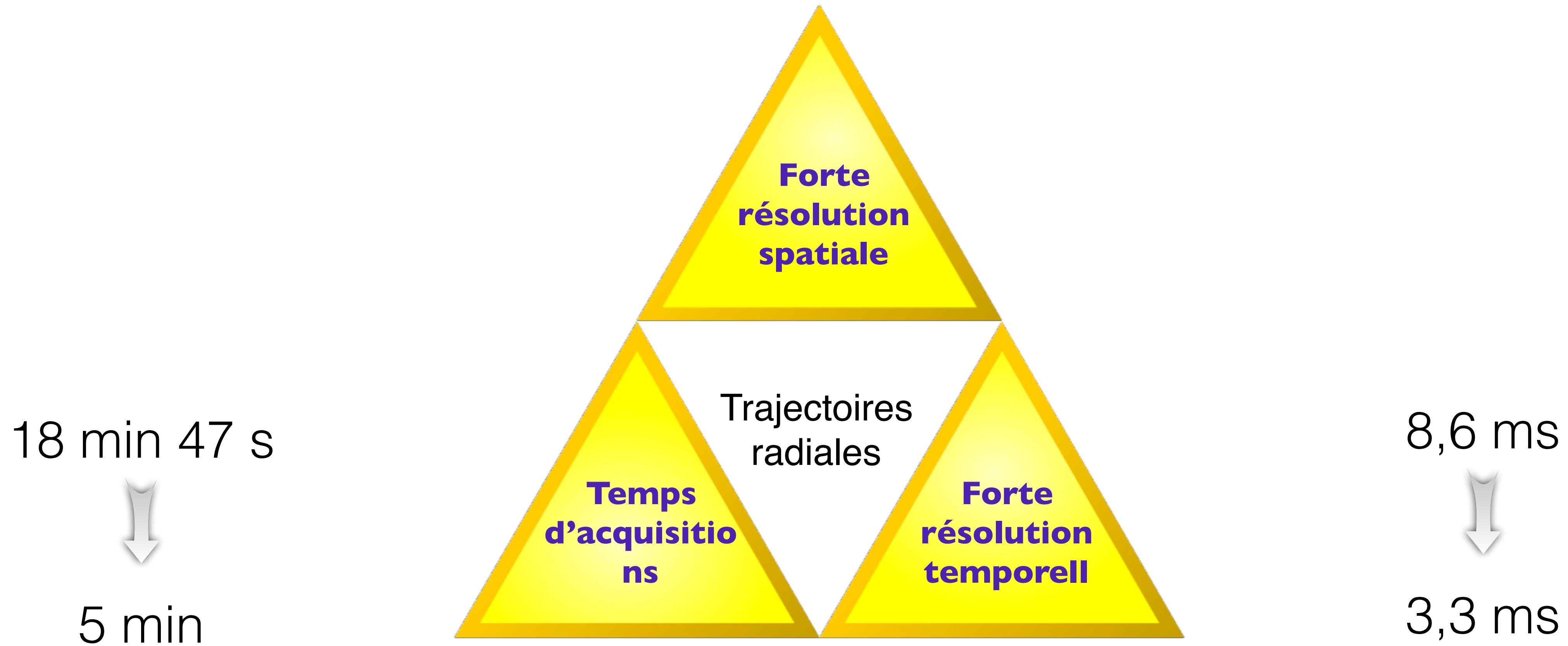
Filtre temporel





Objectif de la thèse

155 x 195 x 280 µm → 130 x 130 x 130 µm

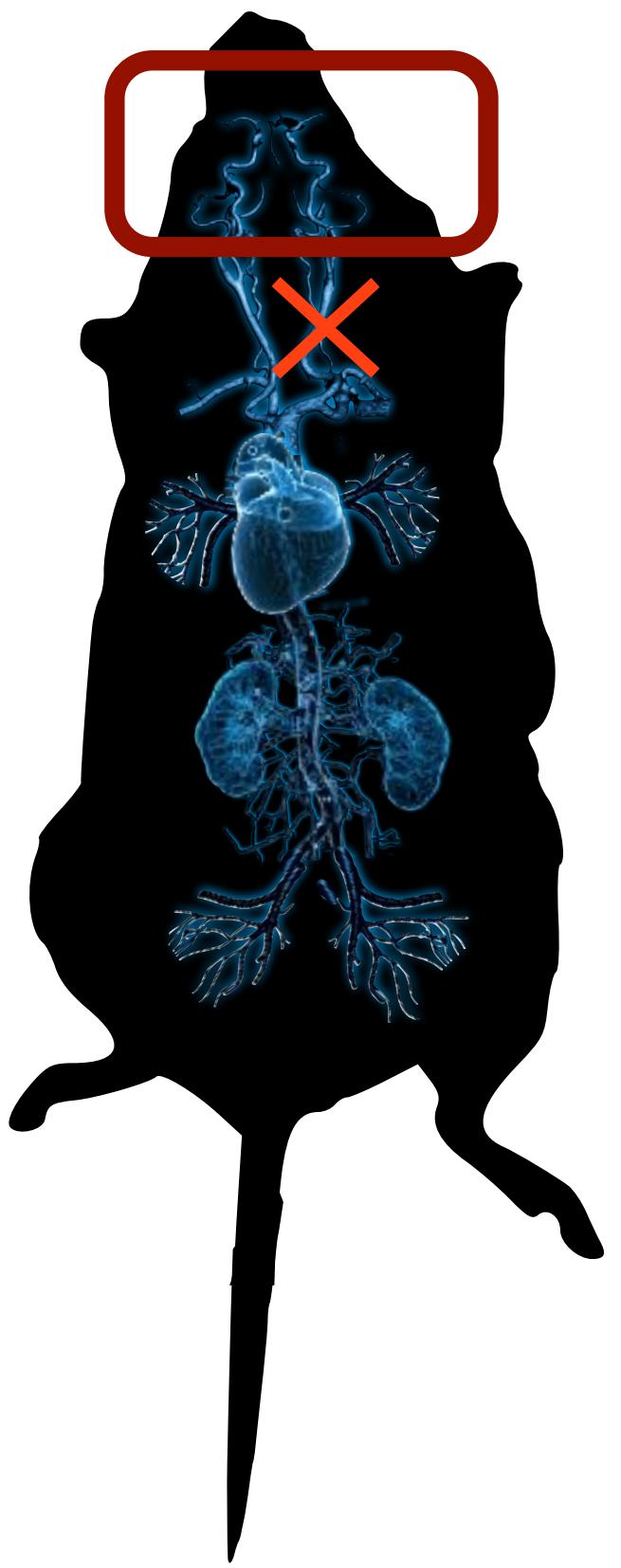
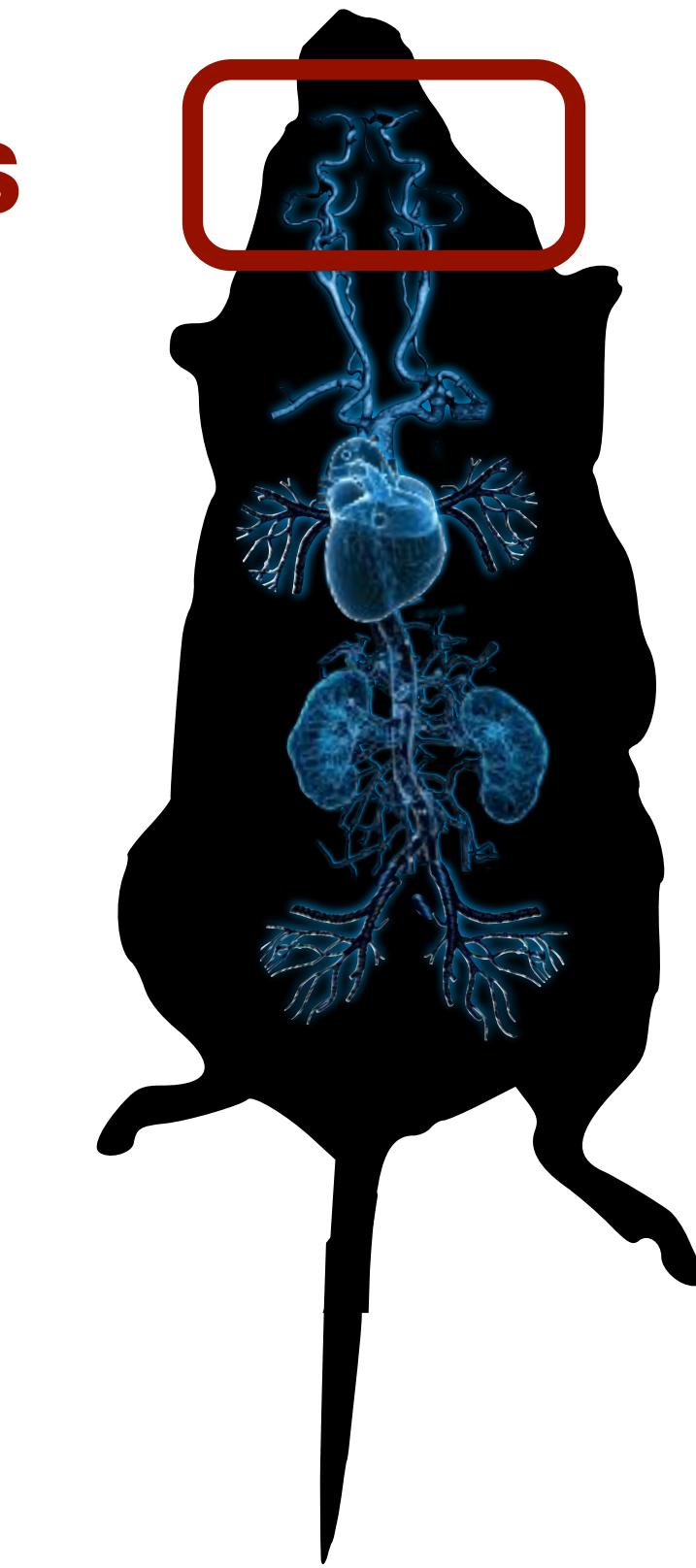


- Sous-échantillonnage > 10
- Résolution temporelle = TR < 4 ms
- Résolution spatiale augmentée

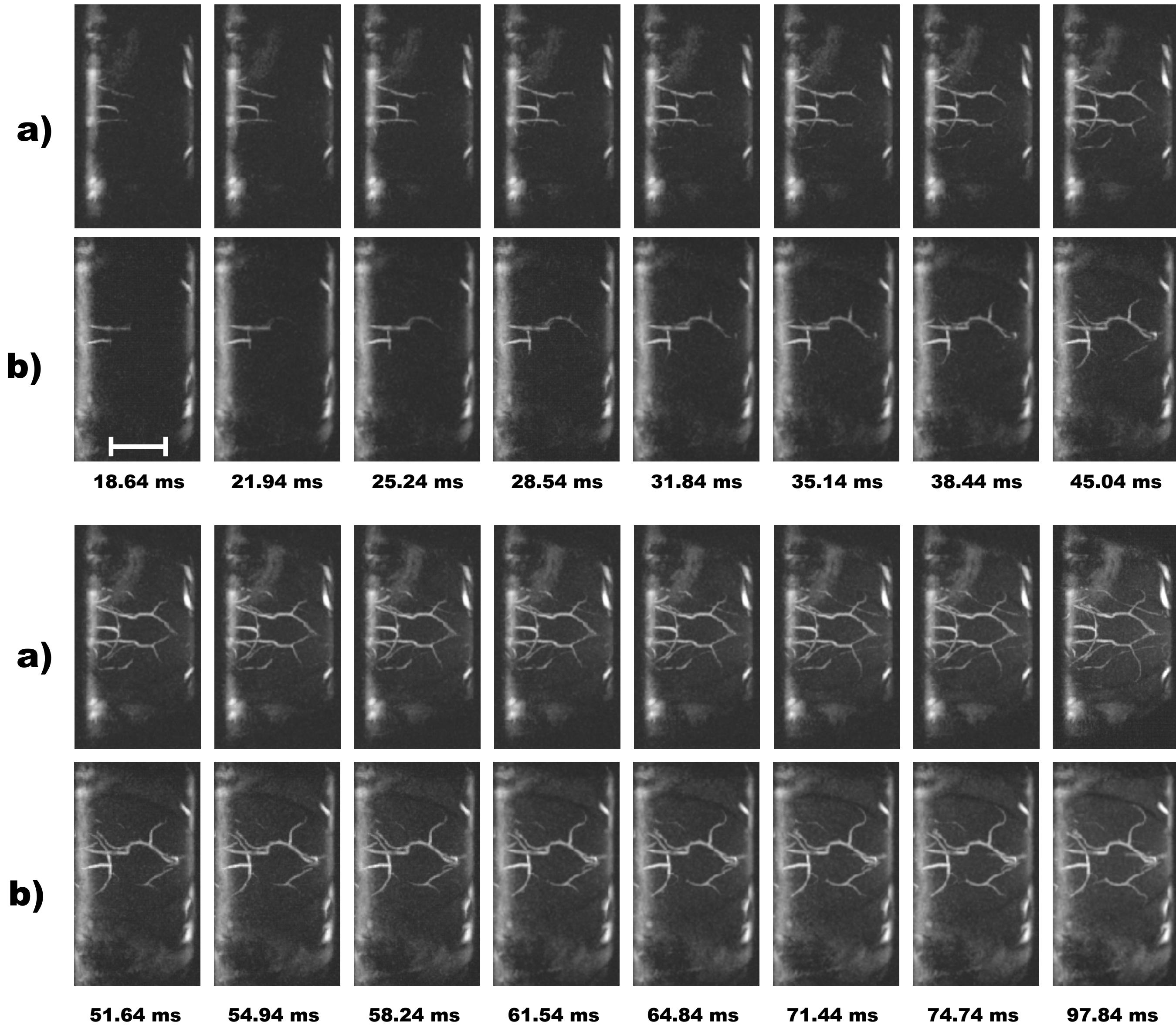
Souris saine

Souris avec une
ligature de la carotide

Polygone de Willis

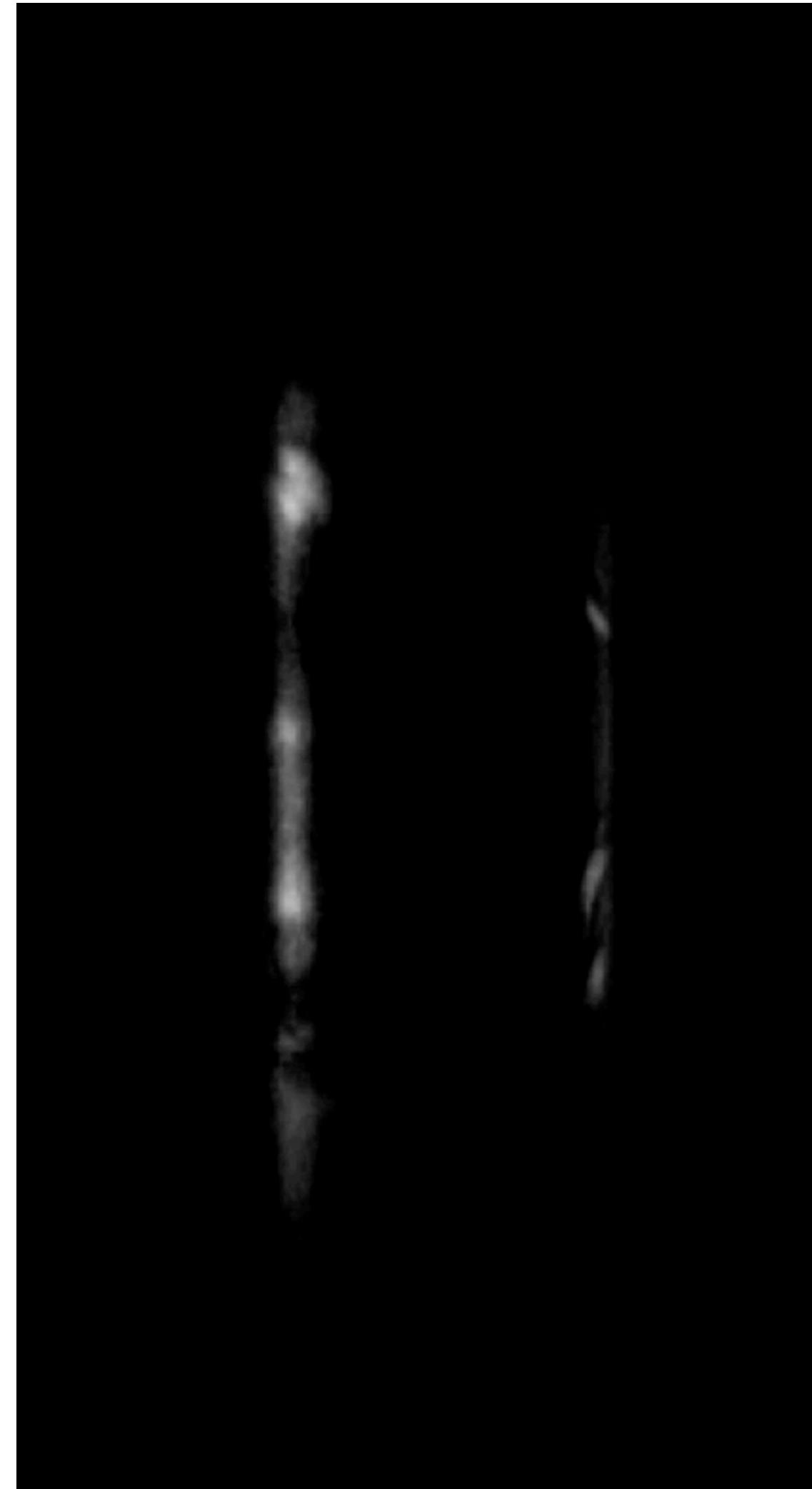


Angiographie sur le cerveau

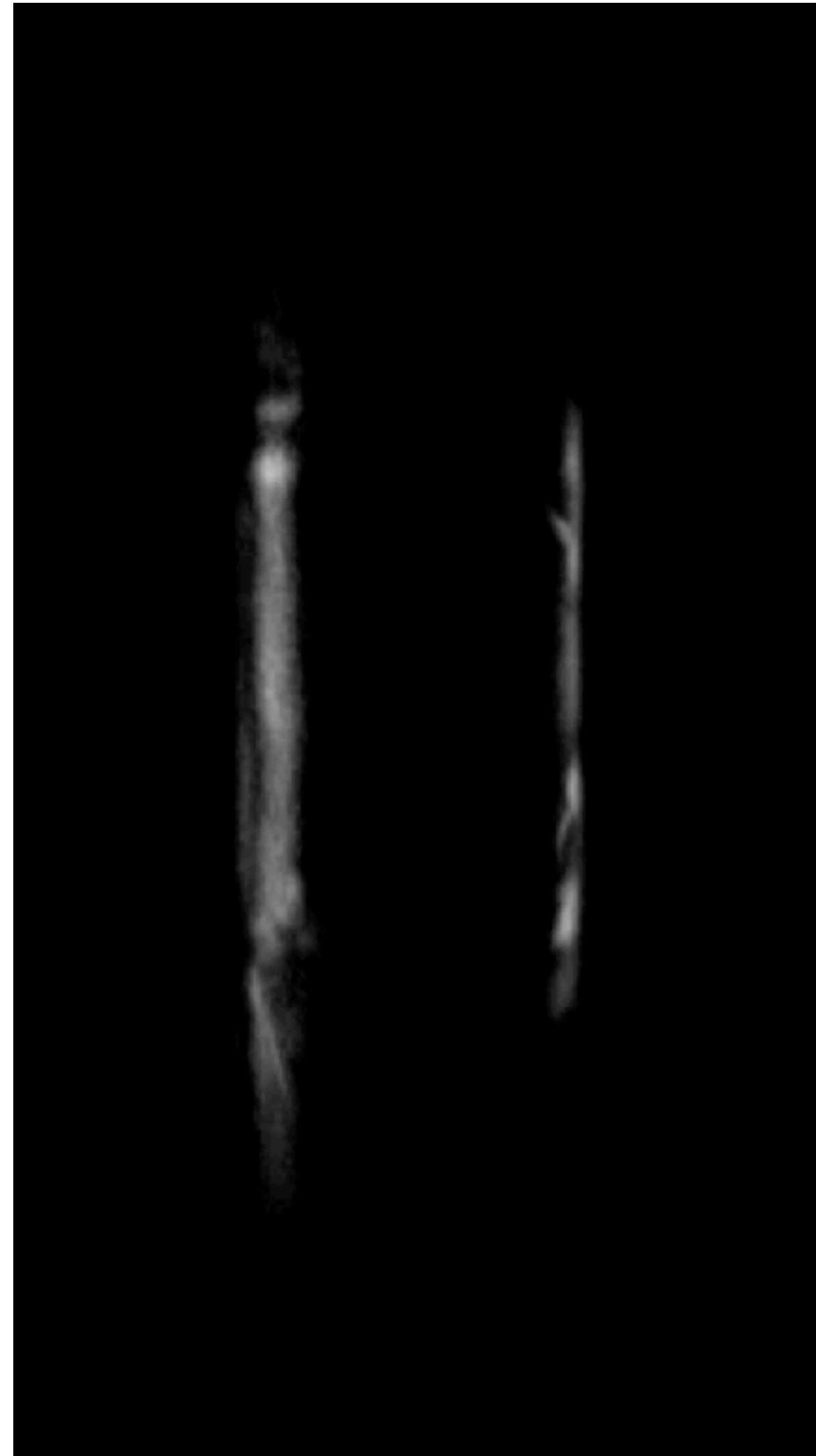


Images cinés : 30
TR : 3,3 ms
Matrice : 192/192/192
FOV : 20×20×20 mm³
TA : 5 min
Res spatiale : (130 µm)³
Projections : 2500
Filtre temporel (R=3, Q=1)

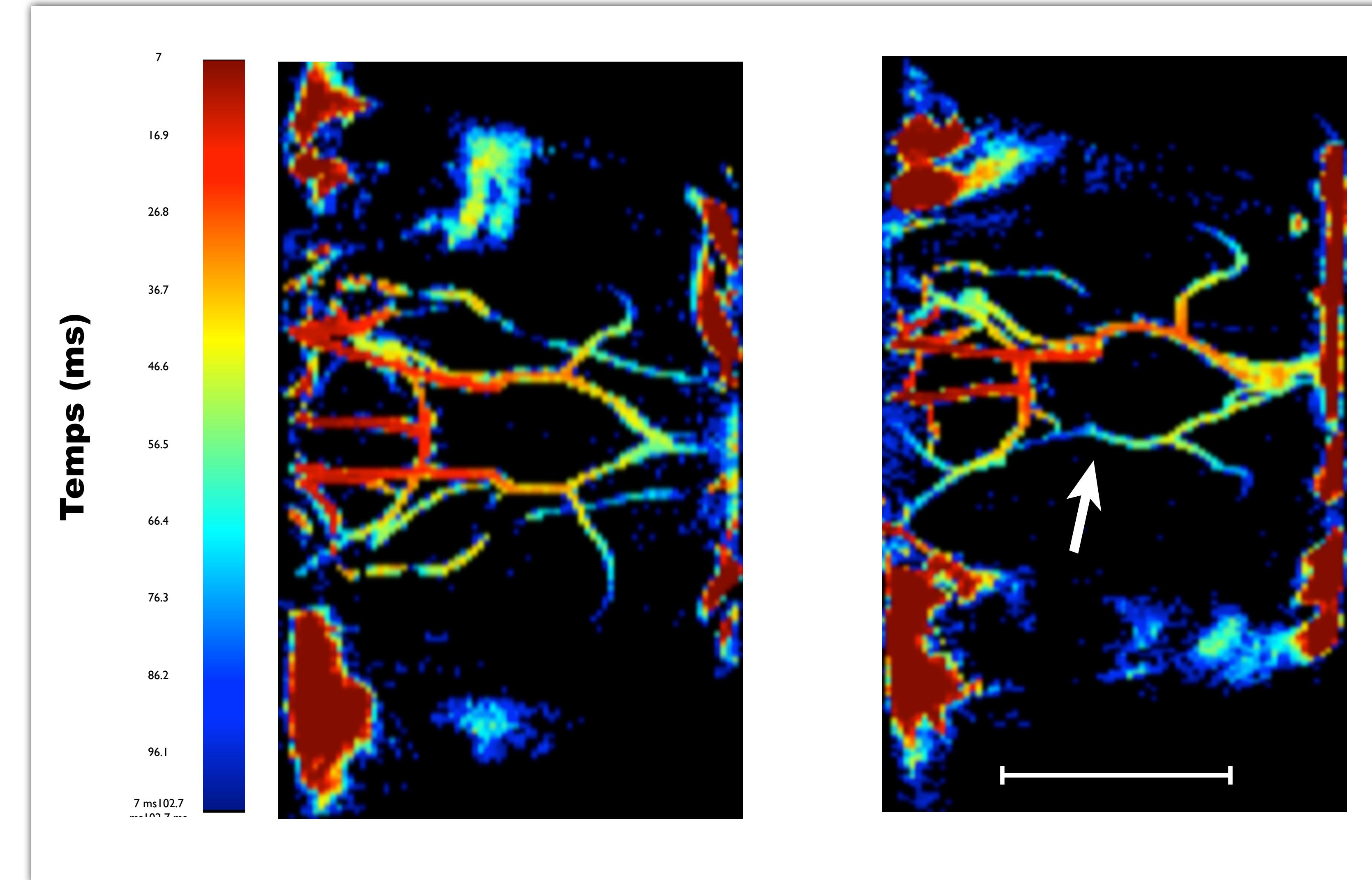
Angiographie sur le cerveau



**Images cinés : 30
TE/TR : 1,5/3,3 ms
Matrice : 192/192/192
FOV : 20×20×20 mm³
TA : 5 min
Res spatiale : (130 µm)³
Projections : 2500
Filtre temporel (R=3, Q=1)
BW = 200 kHz
Epaisseur de coupe = 10 mm**



Carte : Temps d'arrivée du sang dans les artères



Nouvelle séquence radiale d'ARM dynamique

- Implémentation d'une trajectoire basée sur l'angle d'or 3D
- Imagerie anatomique rapide, robuste et flexible chez la souris
- Imagerie de flux sur un modèle de ligature des carotides

Publié en 2014 dans MRM. DOI: 10.1002/mrm.25201

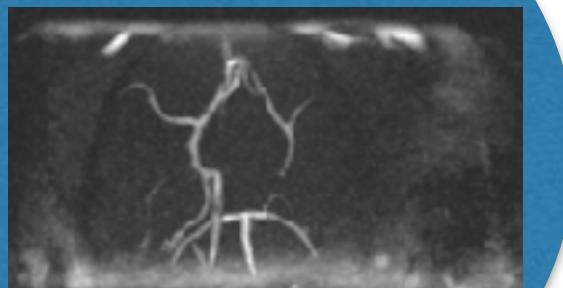
Résolution temporelle : < 4 ms

Temps d'acquisitions :
5 minutes

Résolution spatiale : <
(130 µm)³

Limitations

- Effet temps de vol dépendant de la vitesse du flux
- Sélection de coupe limite le champ de vue utile



Perspectives

- Transfert clinique avec une séquence Stack-Of-Stars permettant de limiter le champ de vue inutile
- Utilisation de méthode de type HYPR (HighLY constrained back-PRojection)

Nouvelle séquence radiale d'ARM dynamique

- Implémentation d'une trajectoire basée sur l'angle d'or 3D
- Imagerie anatomique rapide, robuste et flexible chez la souris
- Imagerie de flux sur un modèle de ligature des carotides

Publié en 2014 dans MRM. DOI: 10.1002/mrm.25201

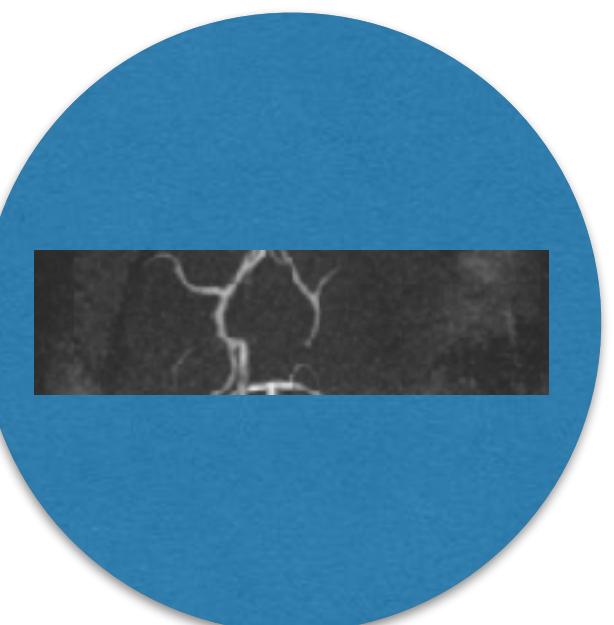
Résolution temporelle : < 4 ms

Temps d'acquisitions :
5 minutes

Résolution spatiale : <
(130 µm)³

Limitations

- Effet temps de vol dépendant de la vitesse du flux
- Sélection de coupe limite le champ de vue utile



Perspectives

- Transfert clinique avec une séquence Stack-Of-Stars permettant de limiter le champ de vue inutile
- Utilisation de méthode de type HYPR (HighLY constrained back-PRojection)

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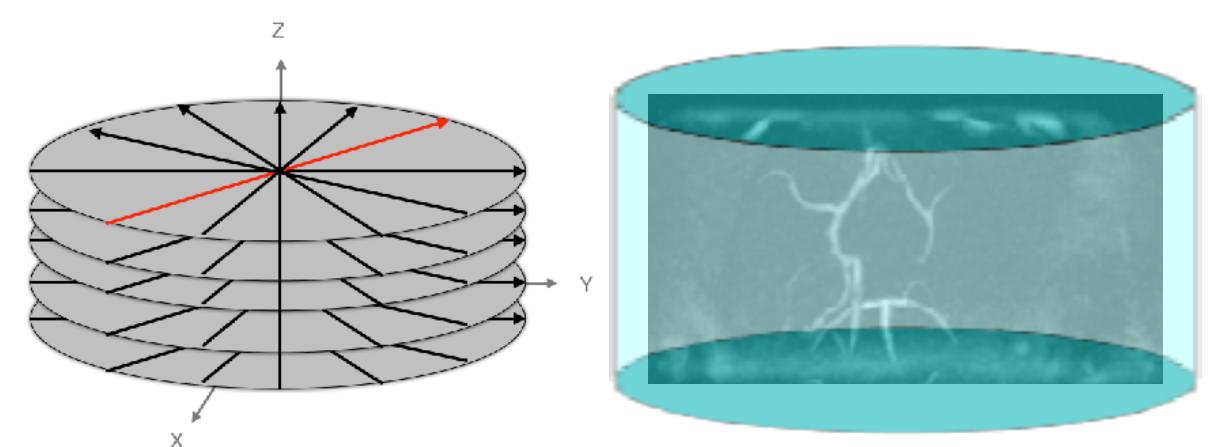
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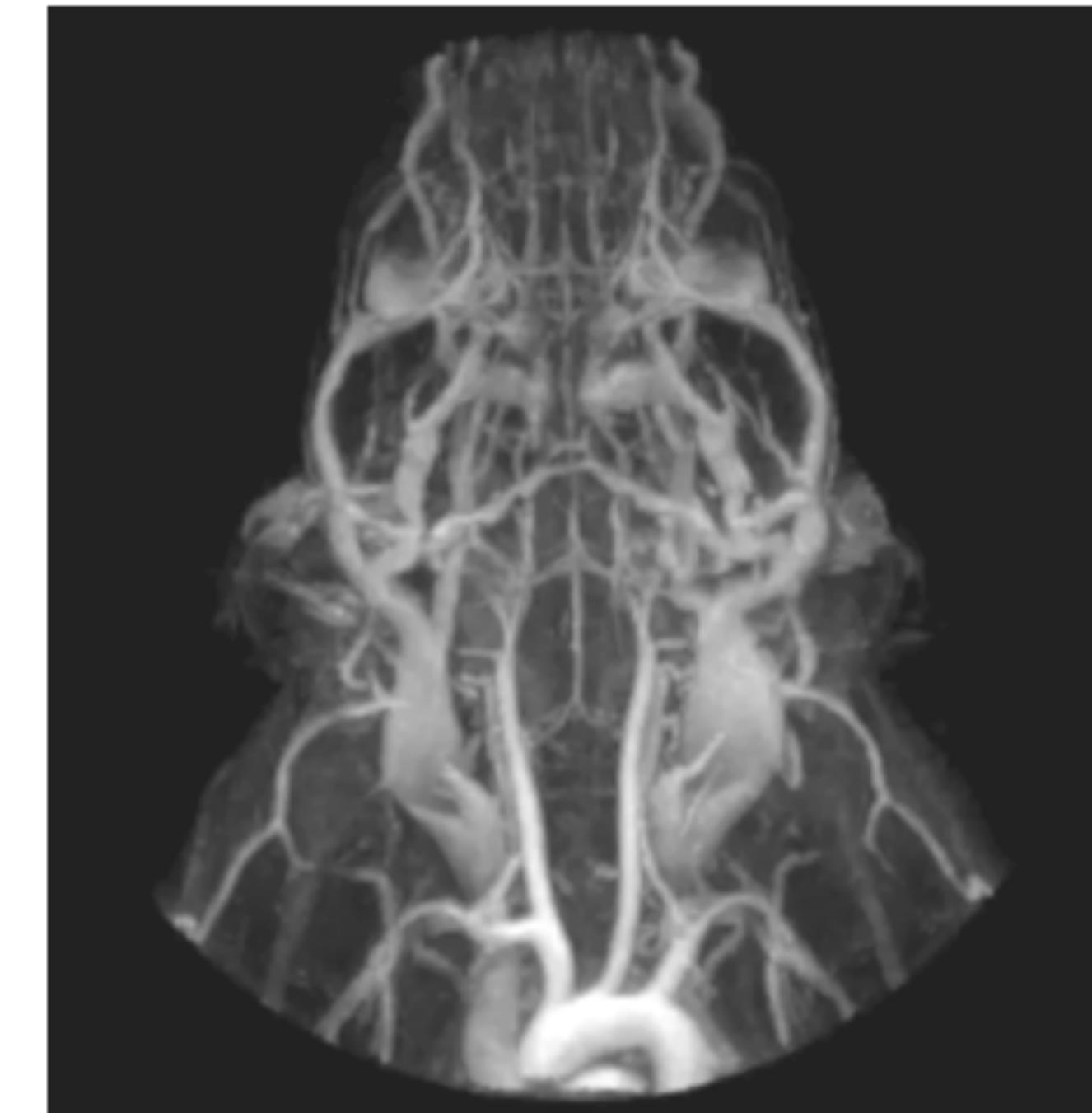
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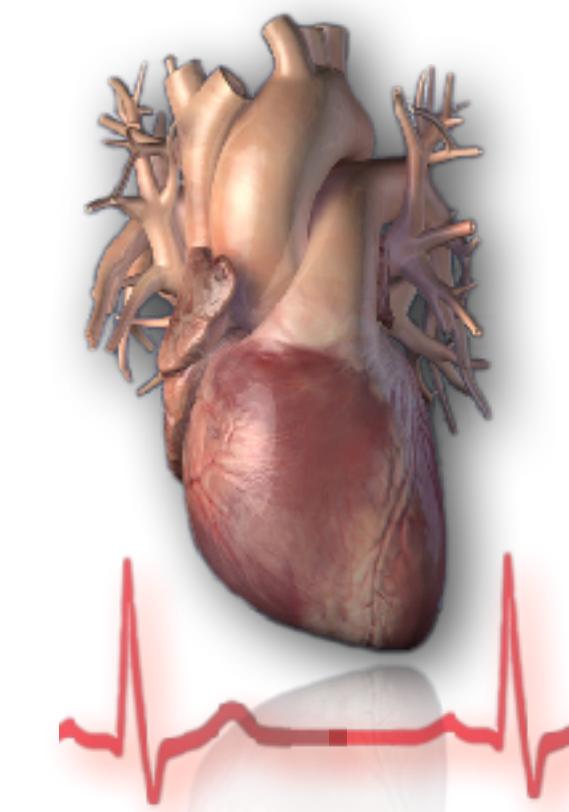
Perspectives

- Transfert clinique avec une séquence Stack-Of-Stars permettant de limiter le champ de vue inutile
- Utilisation de méthode de type HYPR (HighLY constrained back-PRojection)

Imagerie cardiovasculaire 4D sang blanc associant
l'injection de nanoparticules de fer à une séquence à
temps d'écho ultracourt



Imagerie cardiaque



~~3D TOF~~



2D



Faible résolution
spatiale
Faible SSB



Agents de contraste
à base de
gadolinium



Diffuse rapidement en dehors
du système vasculaire

Imagerie cardiaque 3D chez le petit animal

Alternative : Nanoparticules de fer (USPIOs)



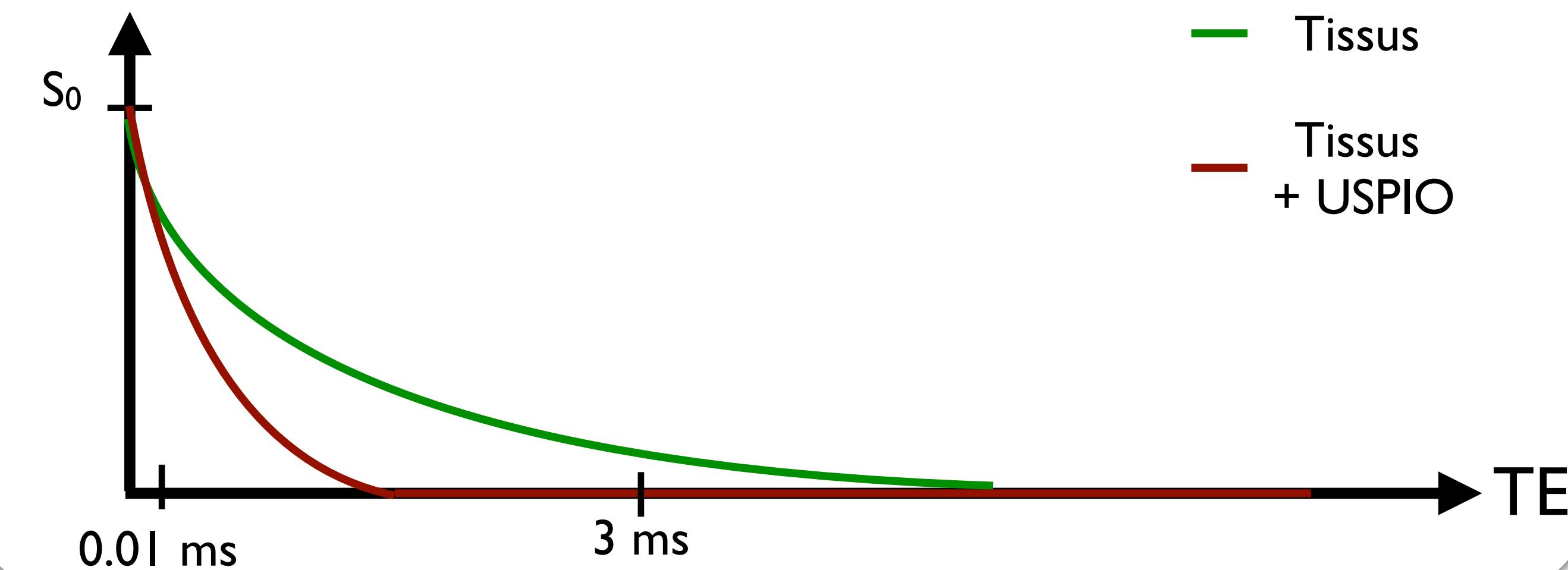
Avantages :

- Longue rémanence vasculaire
- Approuvé par la FDA pour injection chez l'humain (ferumoxytol/endorem...)

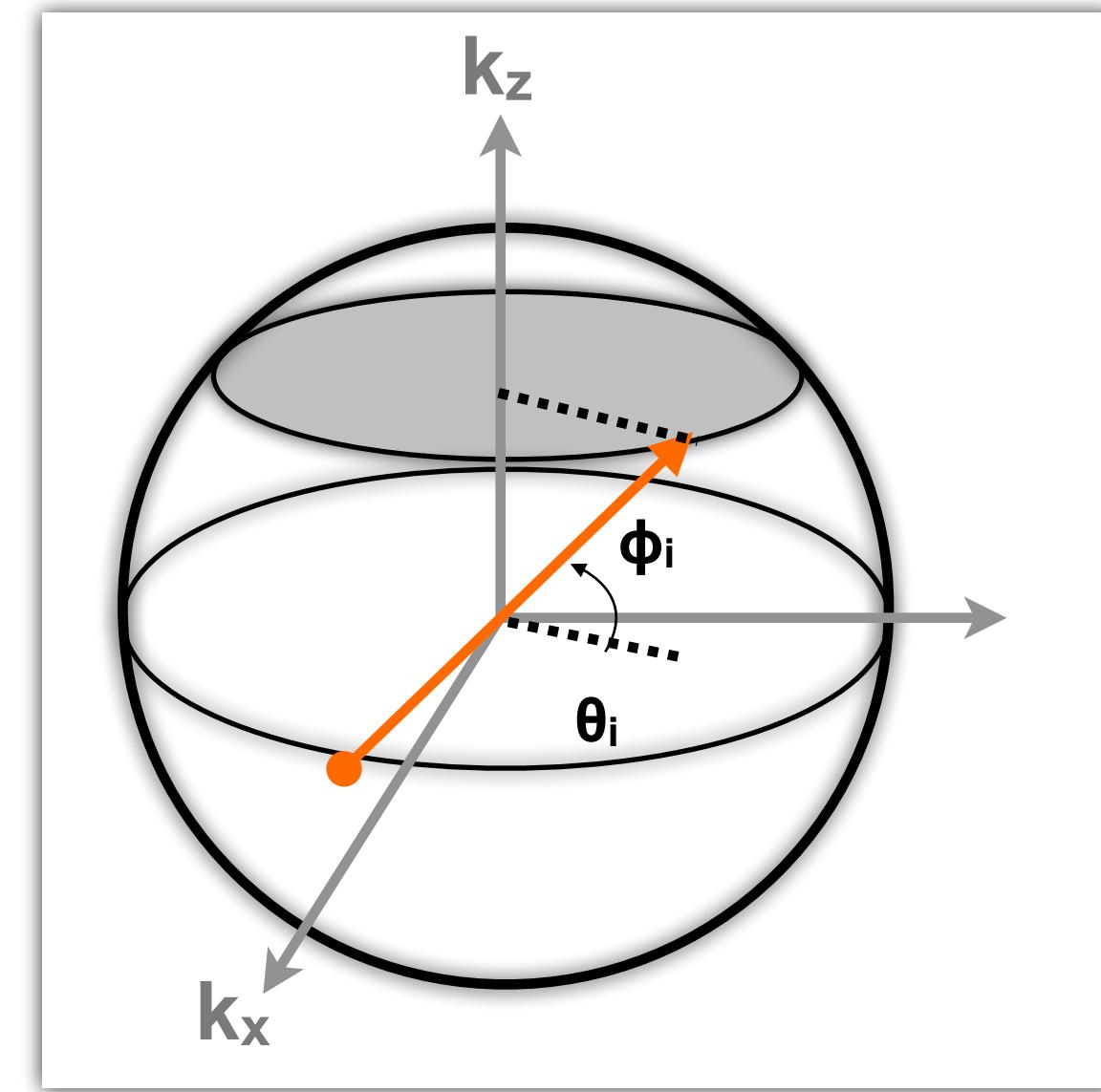
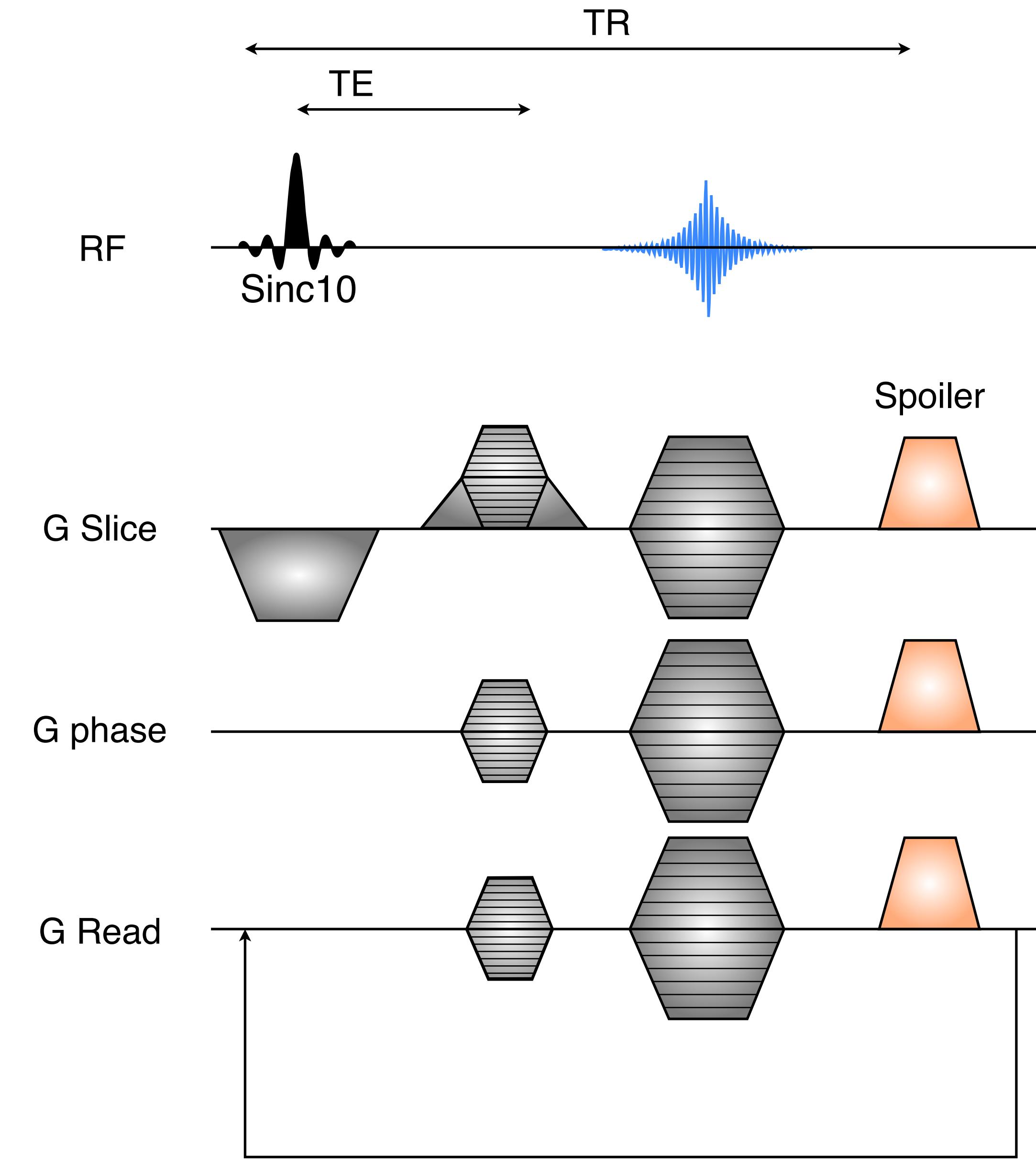
Inconvénients :

- Fort effet T2*

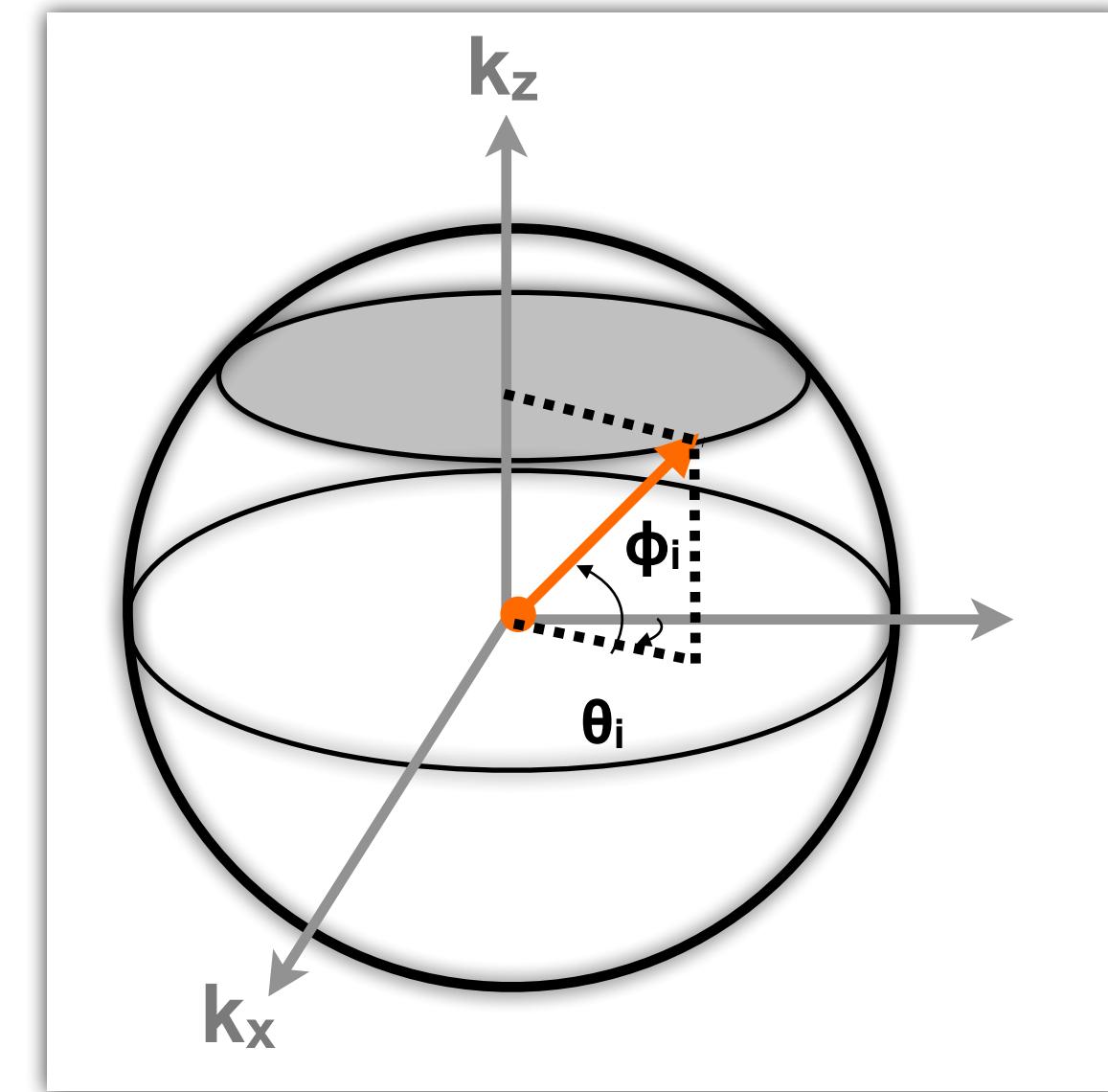
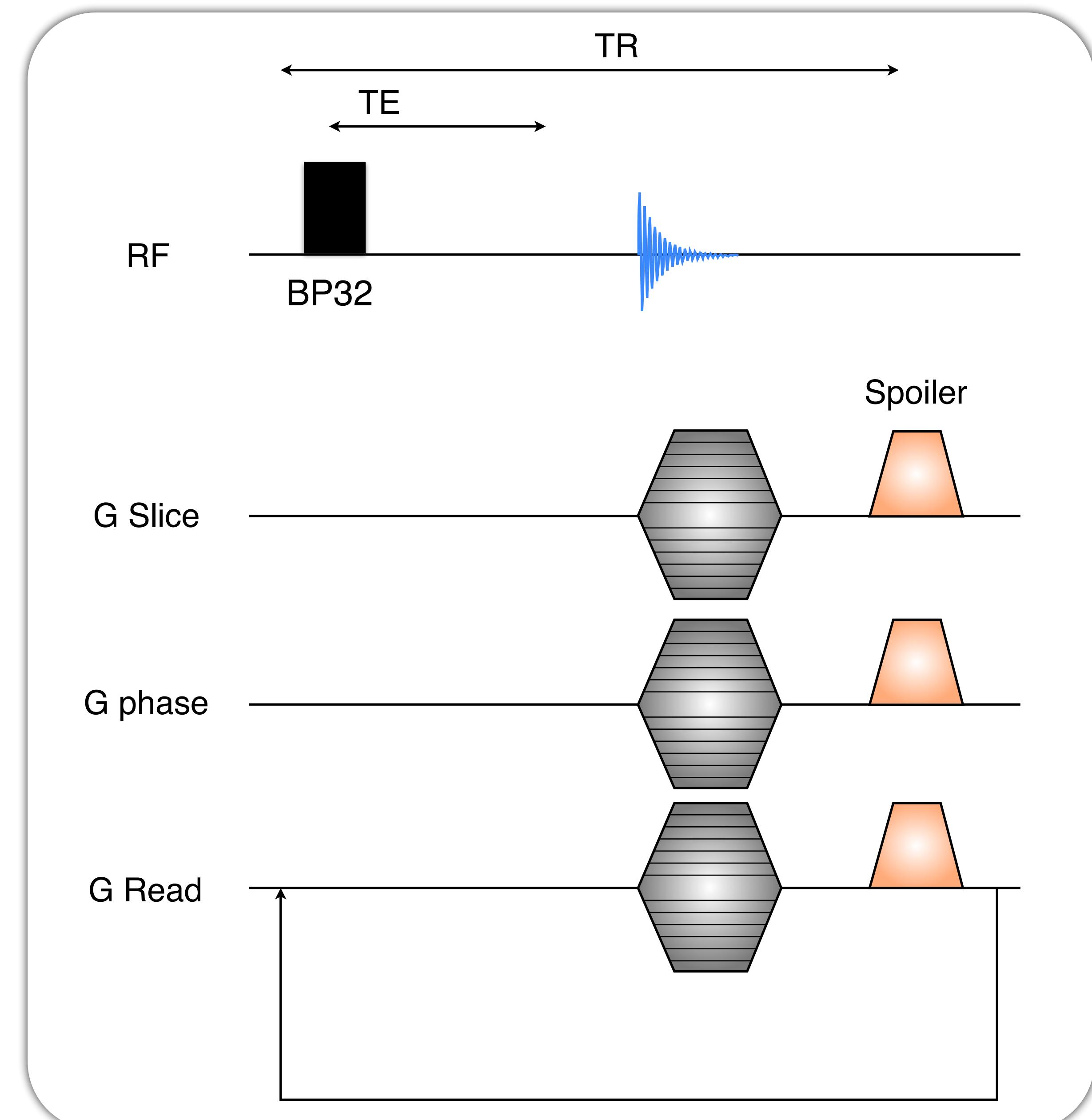
Signal



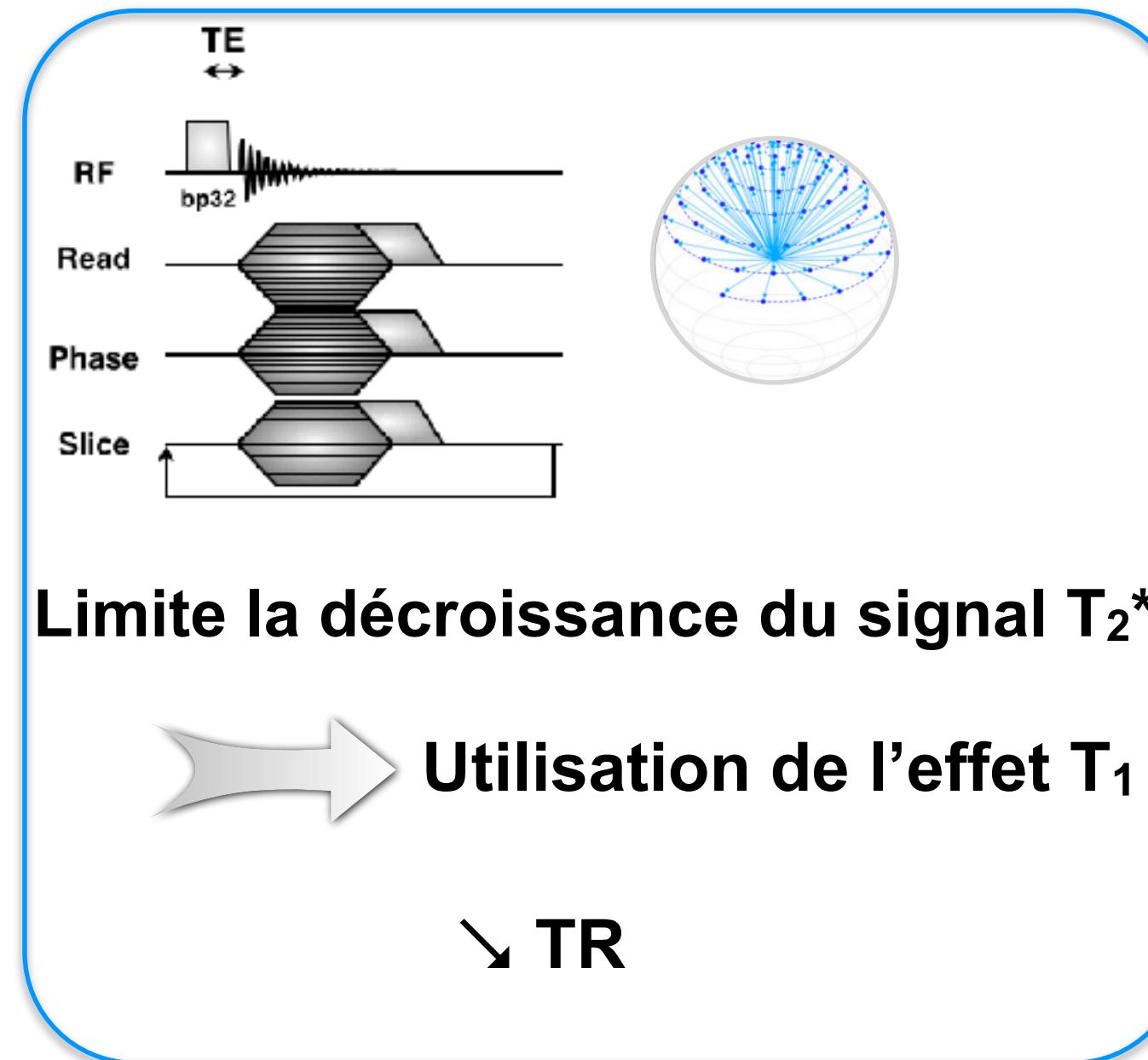
Trajectoire radiale PR vers UTE



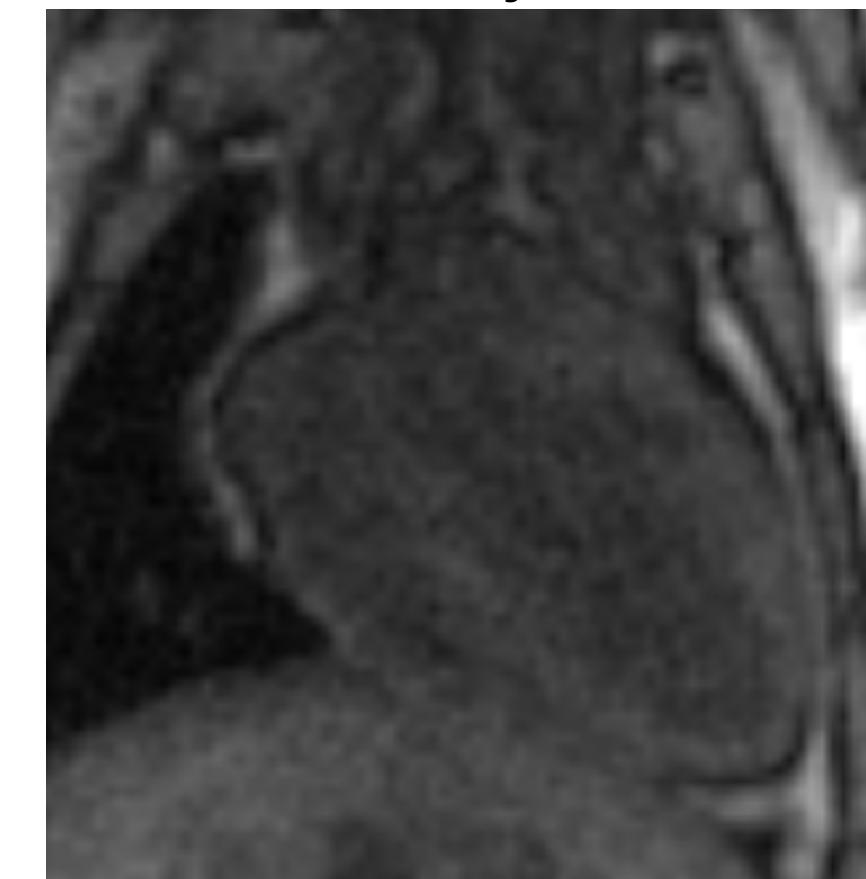
Trajectoire radiale PR vers UTE



3D UTE

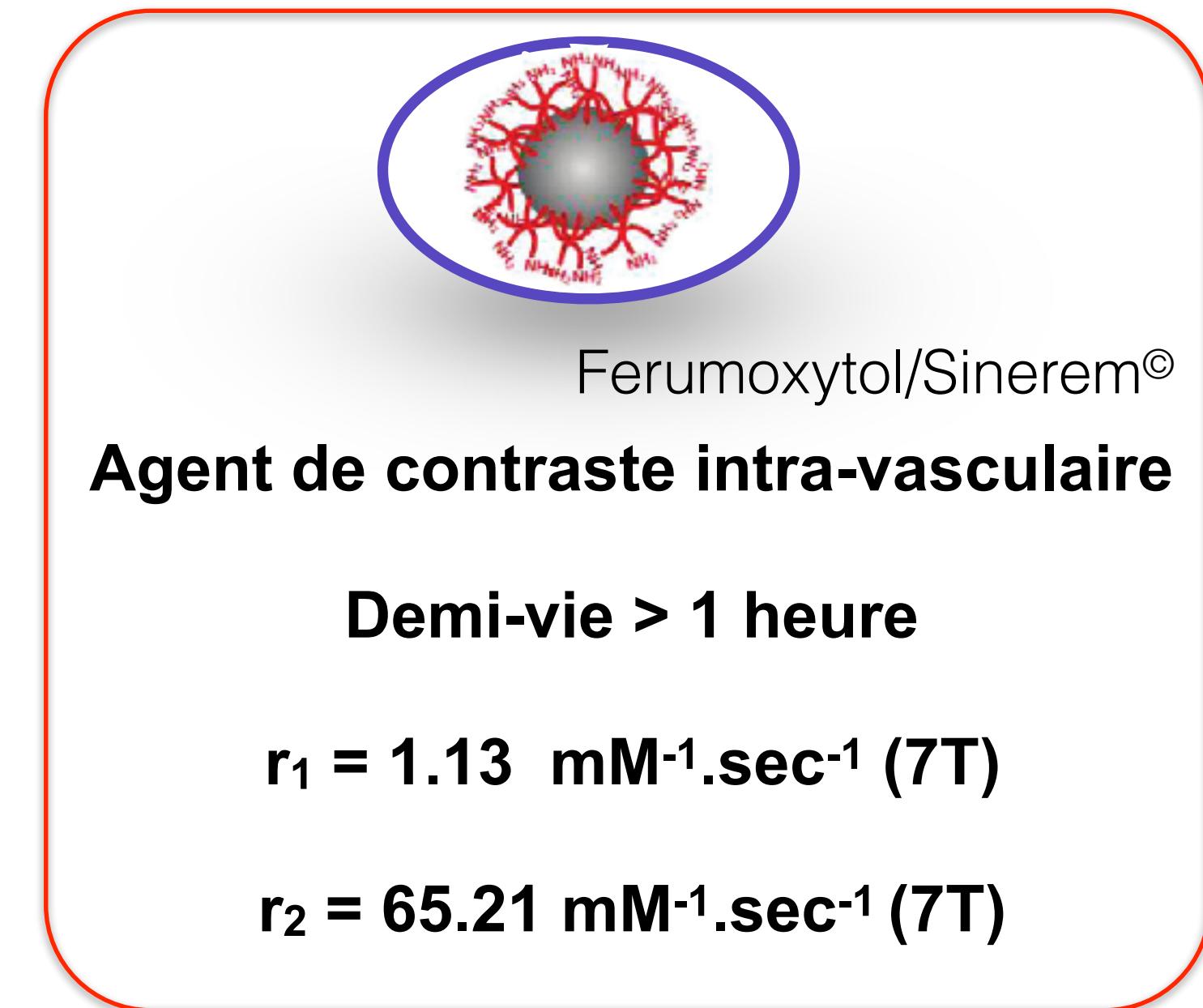


Avant injection

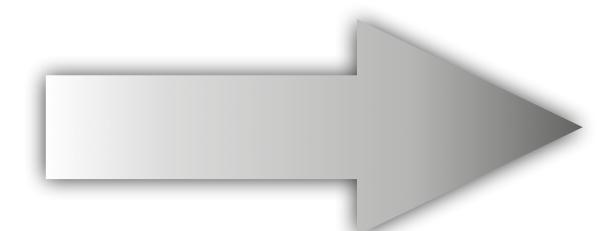
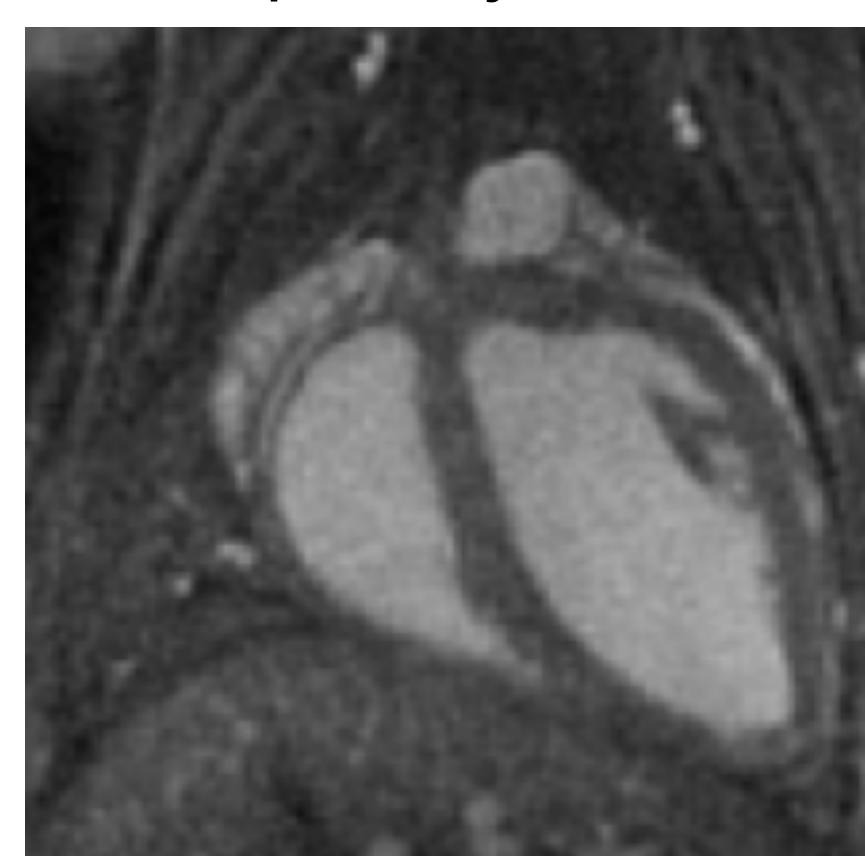


+

USPIO

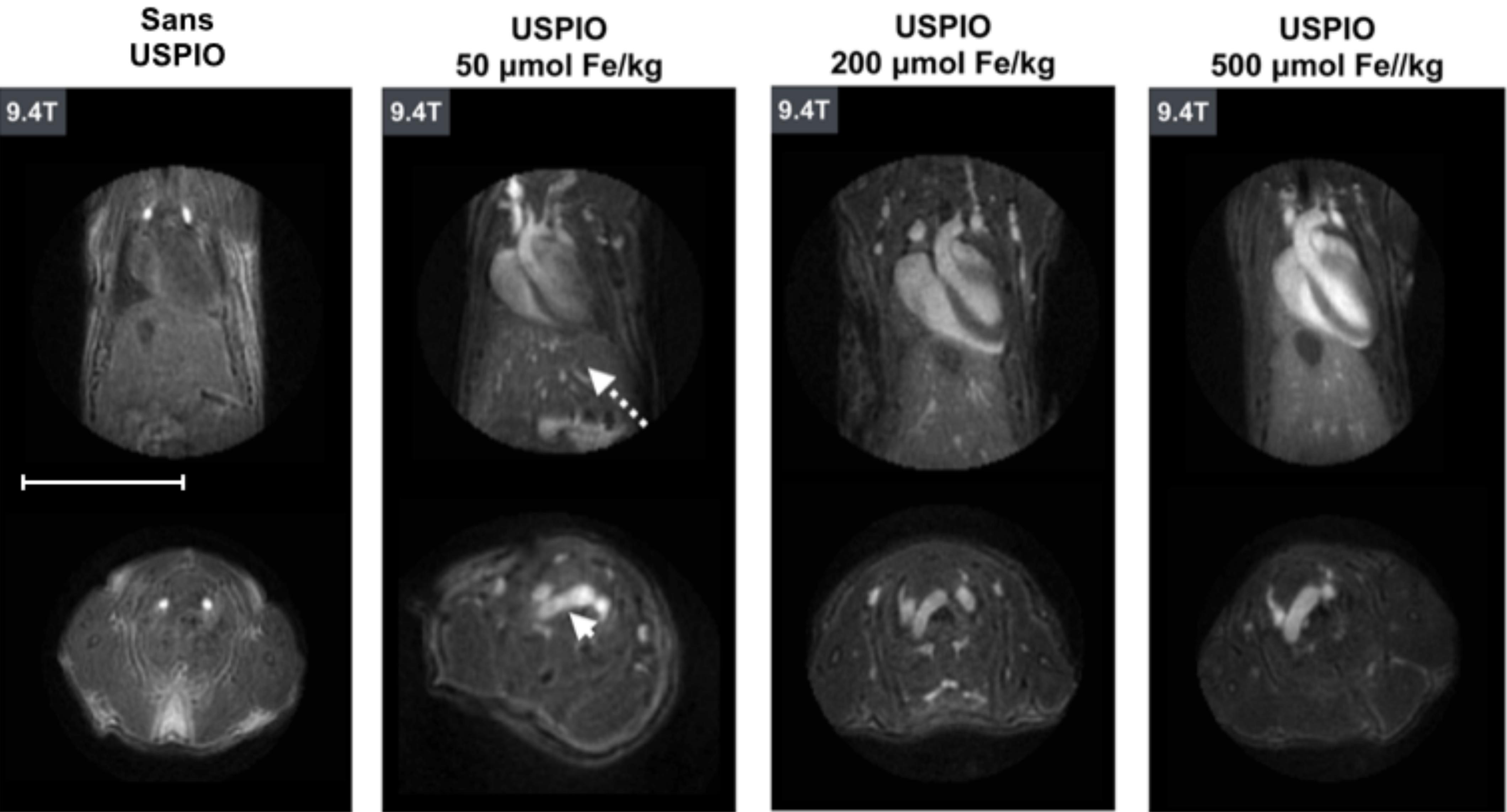


Après injection

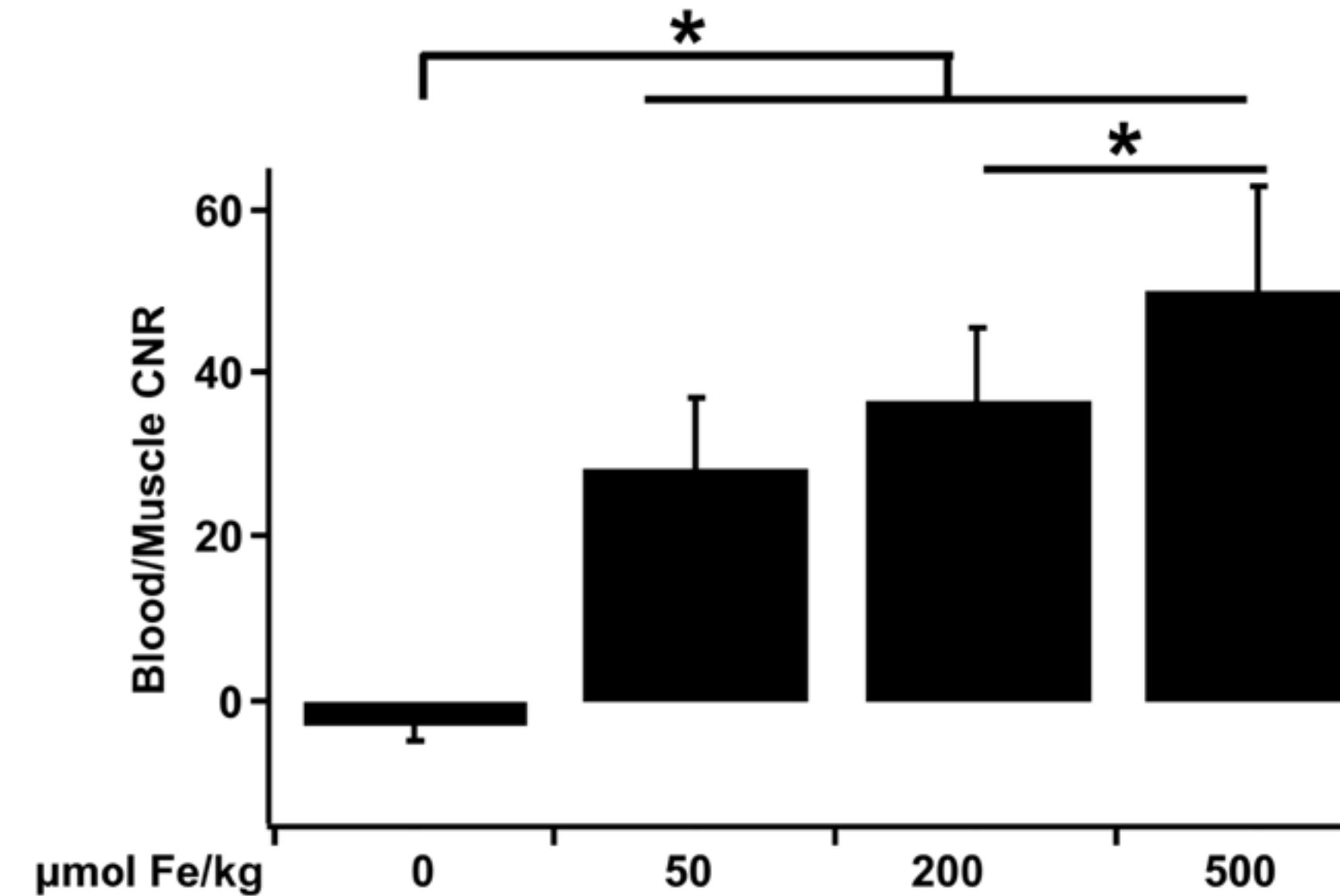


Contraste positif pendant plus d'une heure

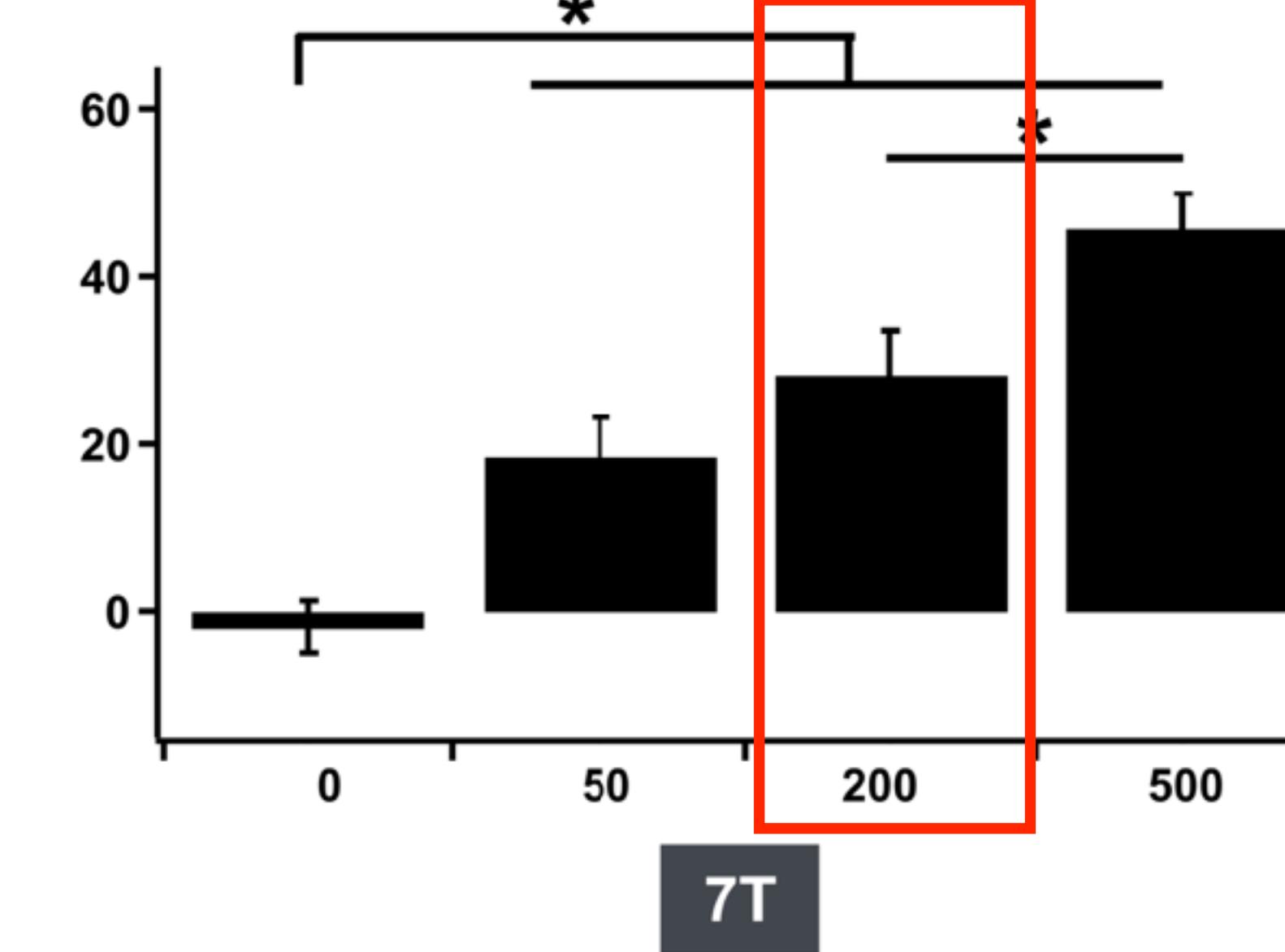
Effets de la concentration



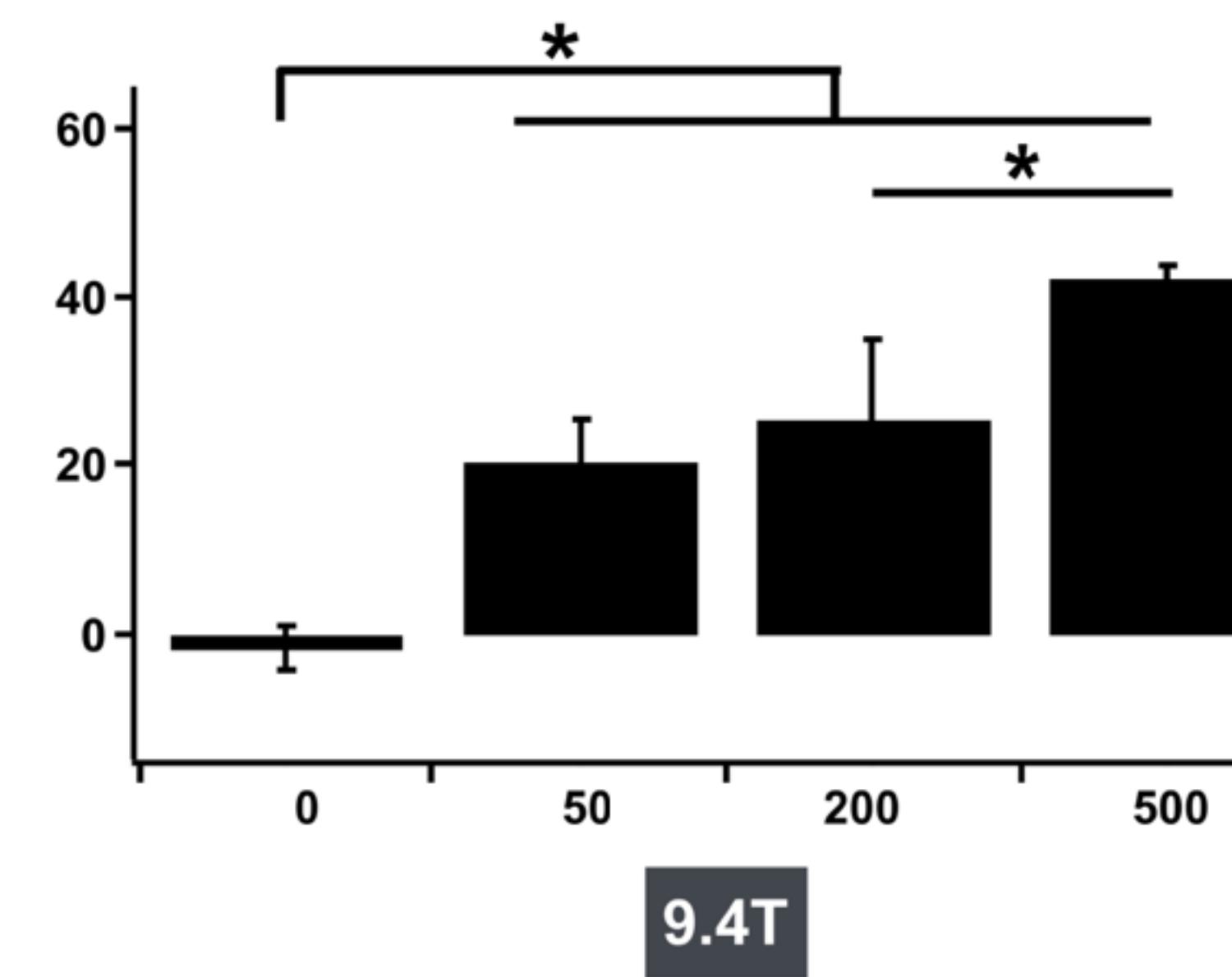
Concentration/champs magnétiques



4.7T



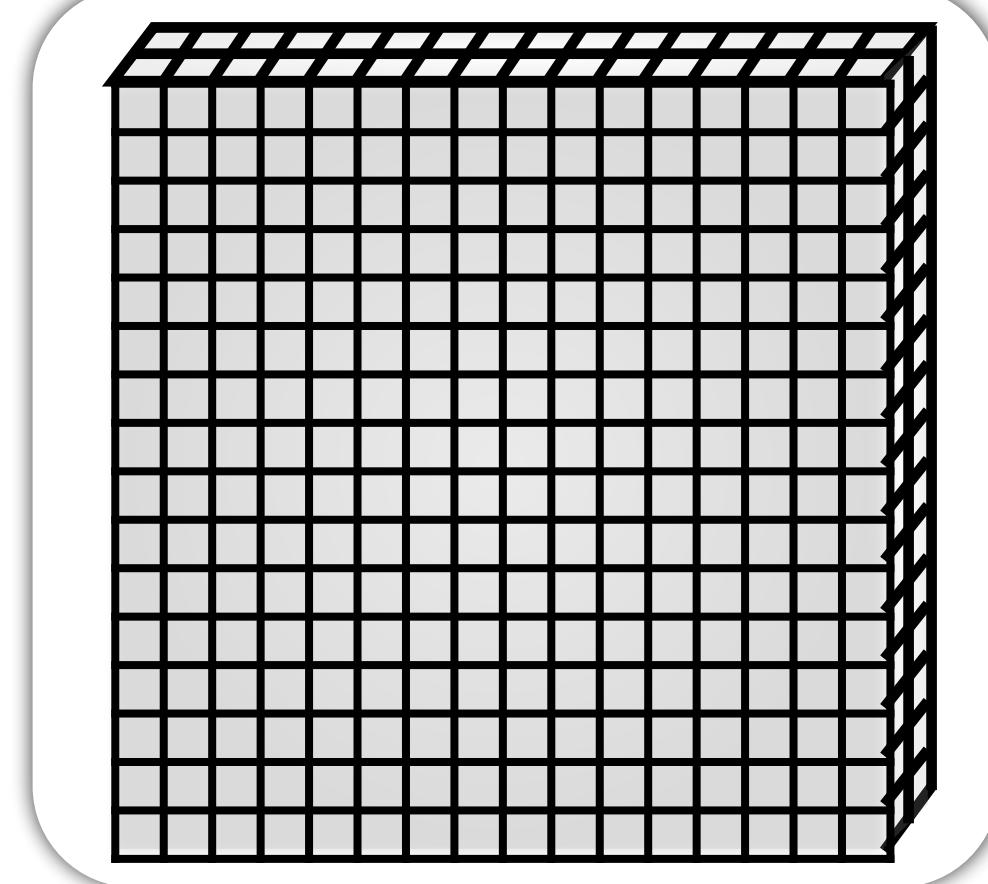
7T



9.4T

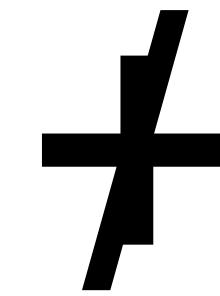
Imagerie cardiovasculaire
anatomique sang blanc

3D

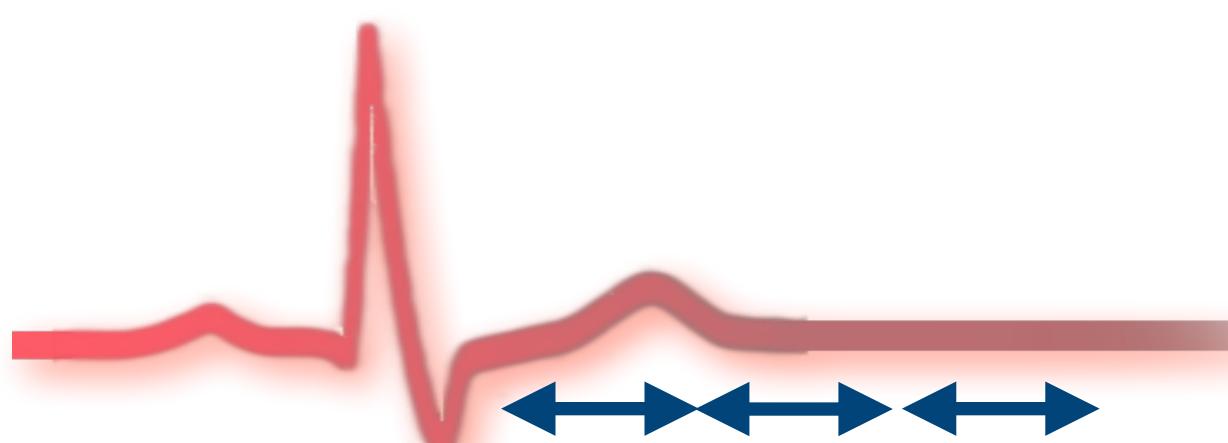


Résolution
spatiale

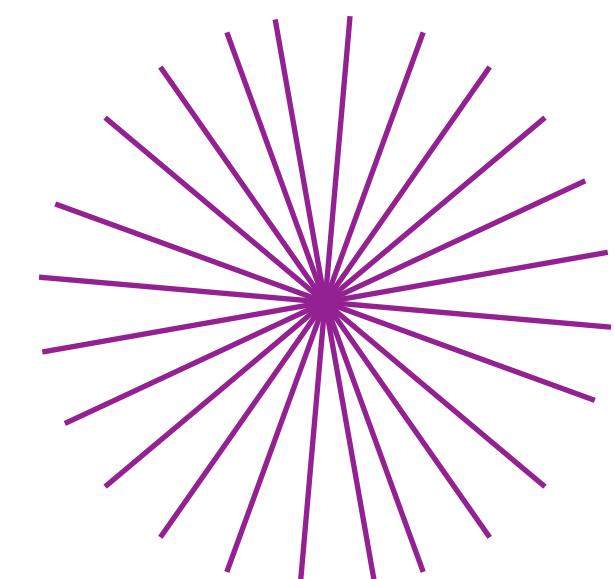
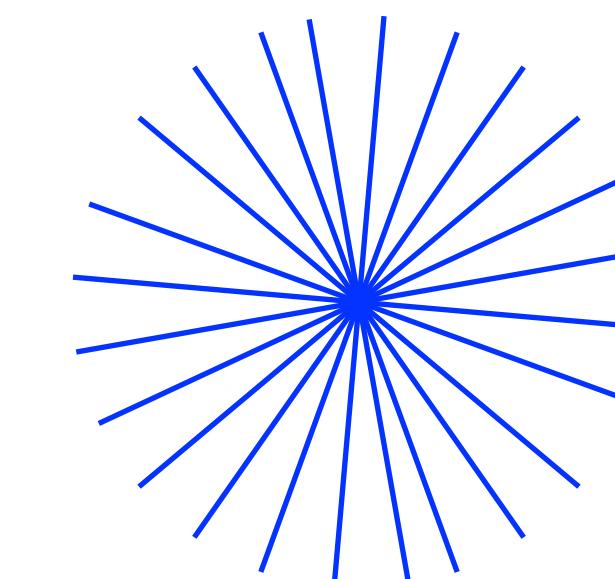
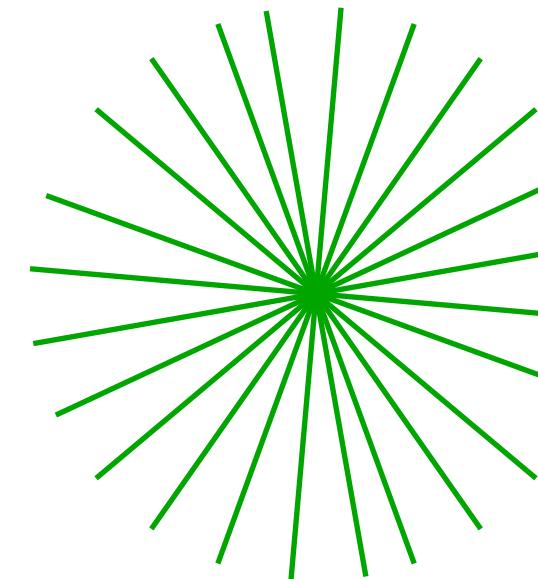
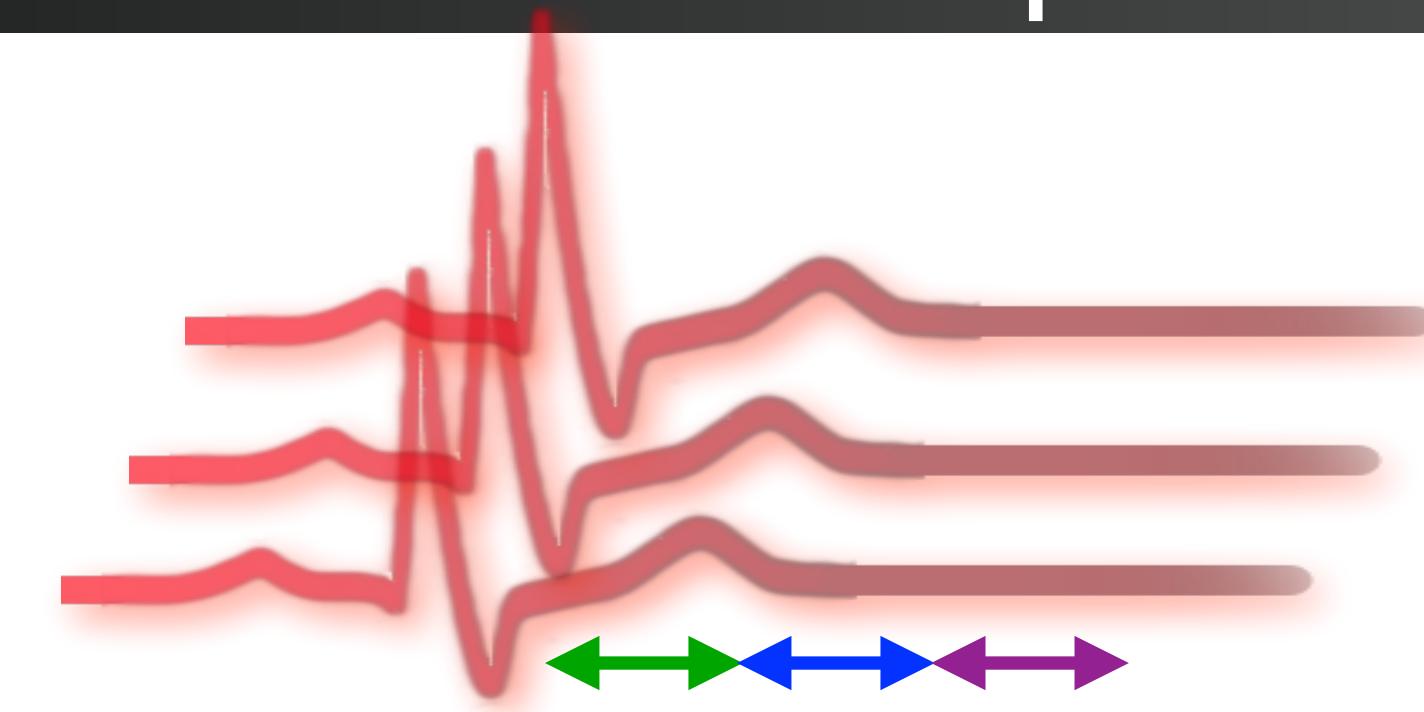
Signal

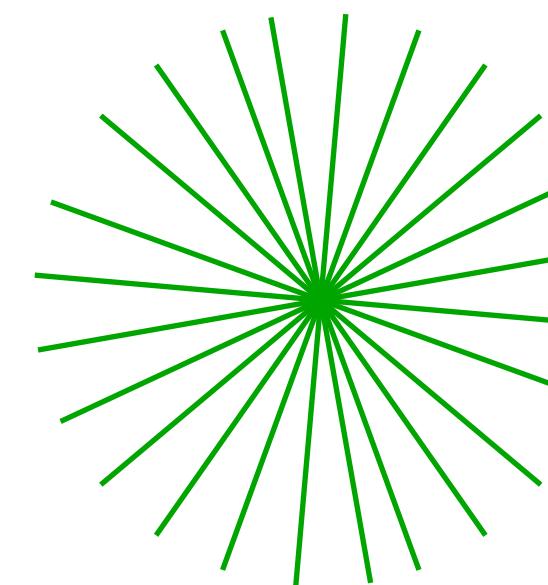


Résolue dans le temps

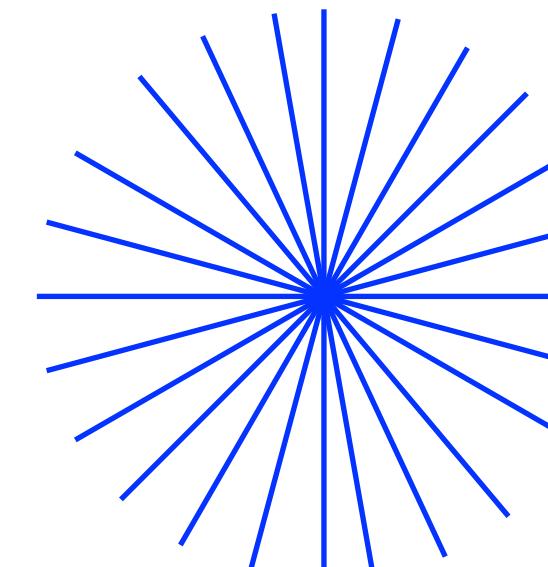


Résolution
temporelle

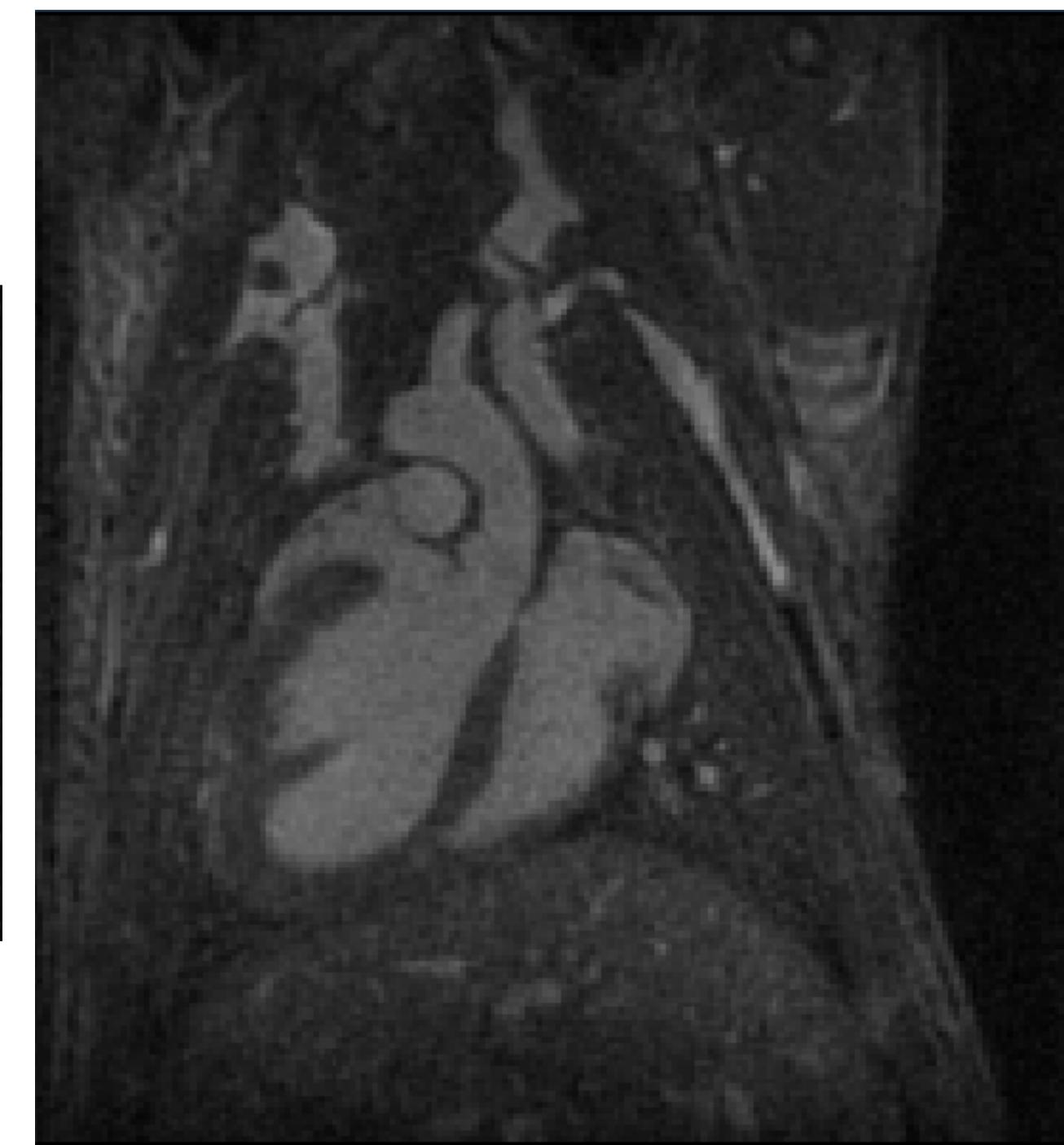
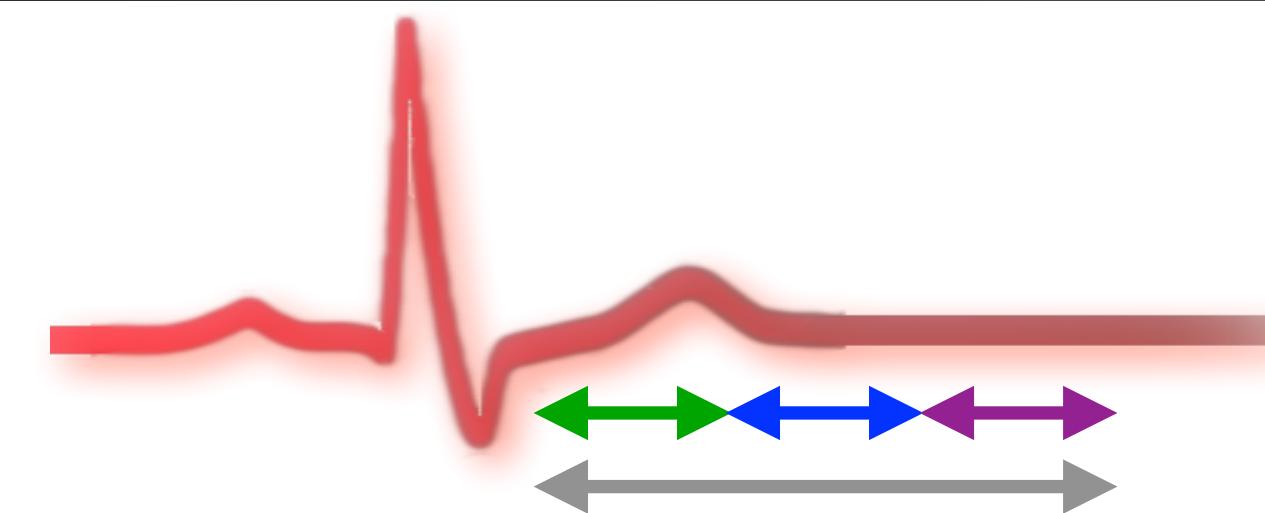
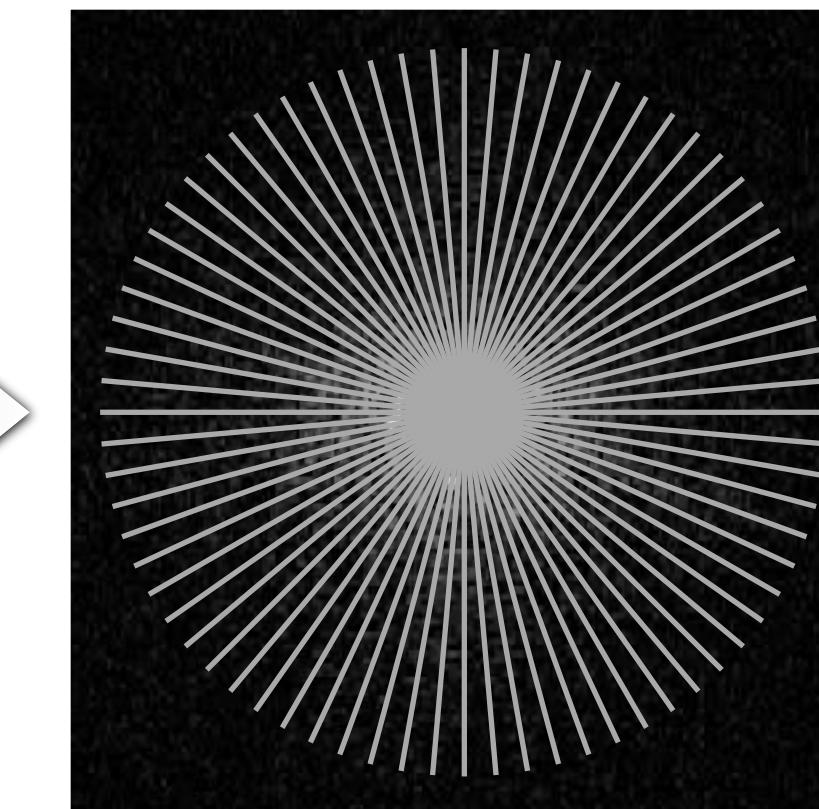
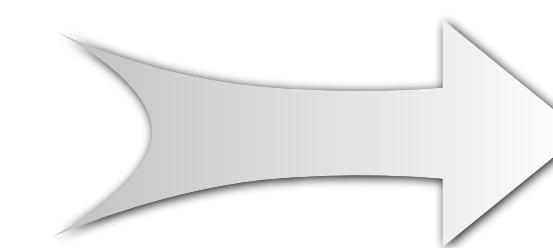
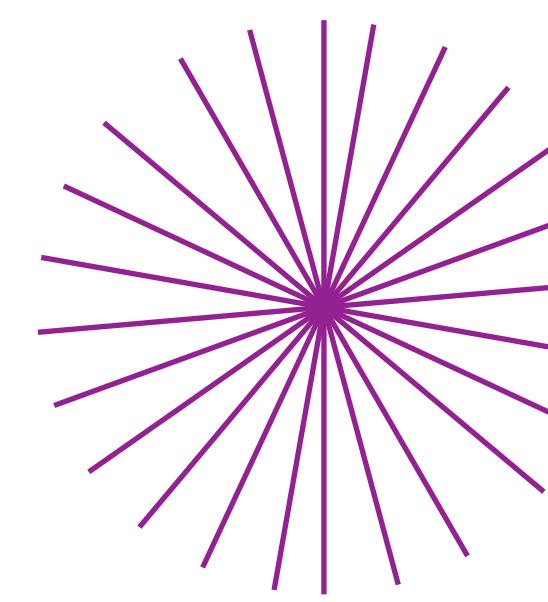




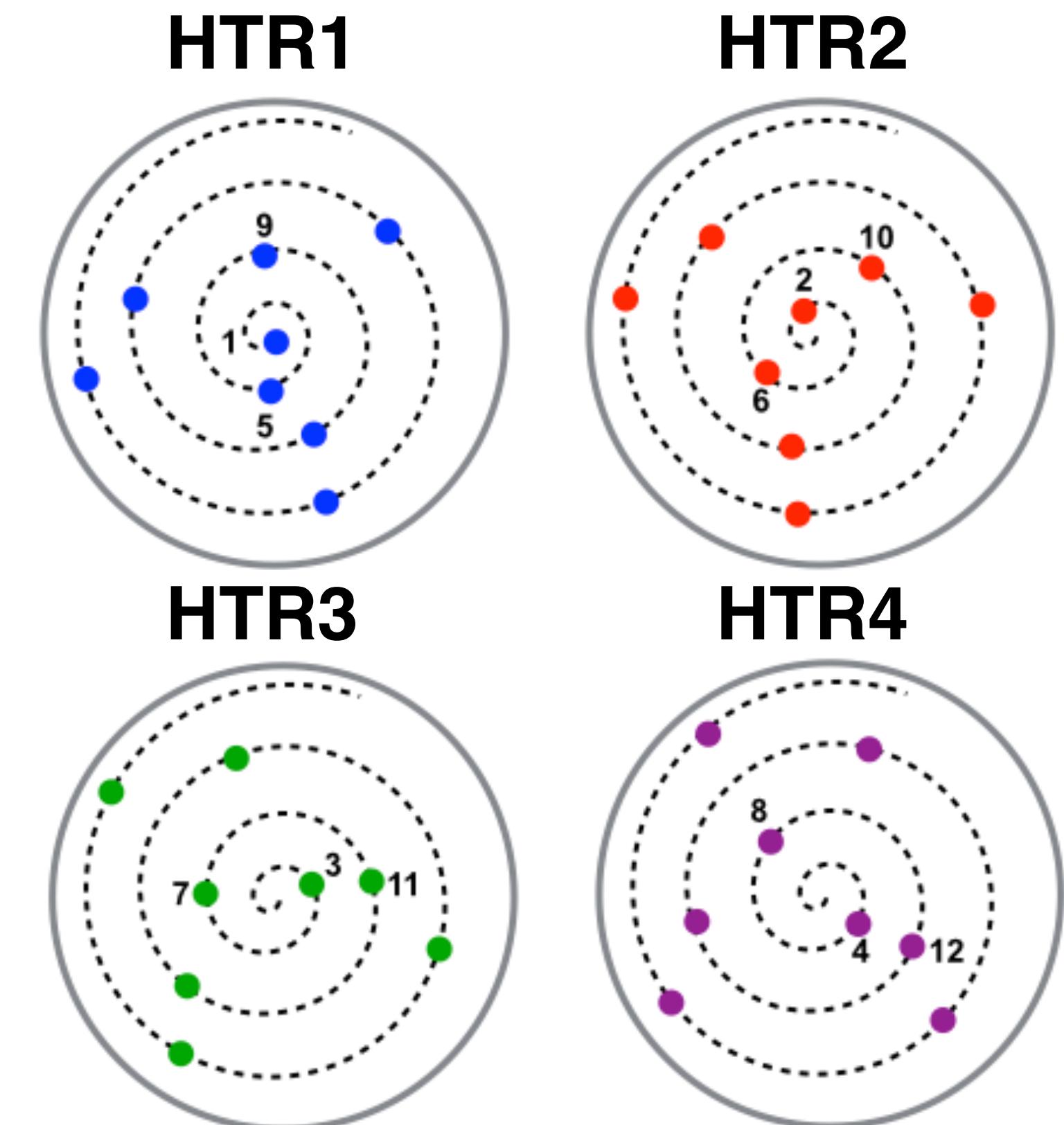
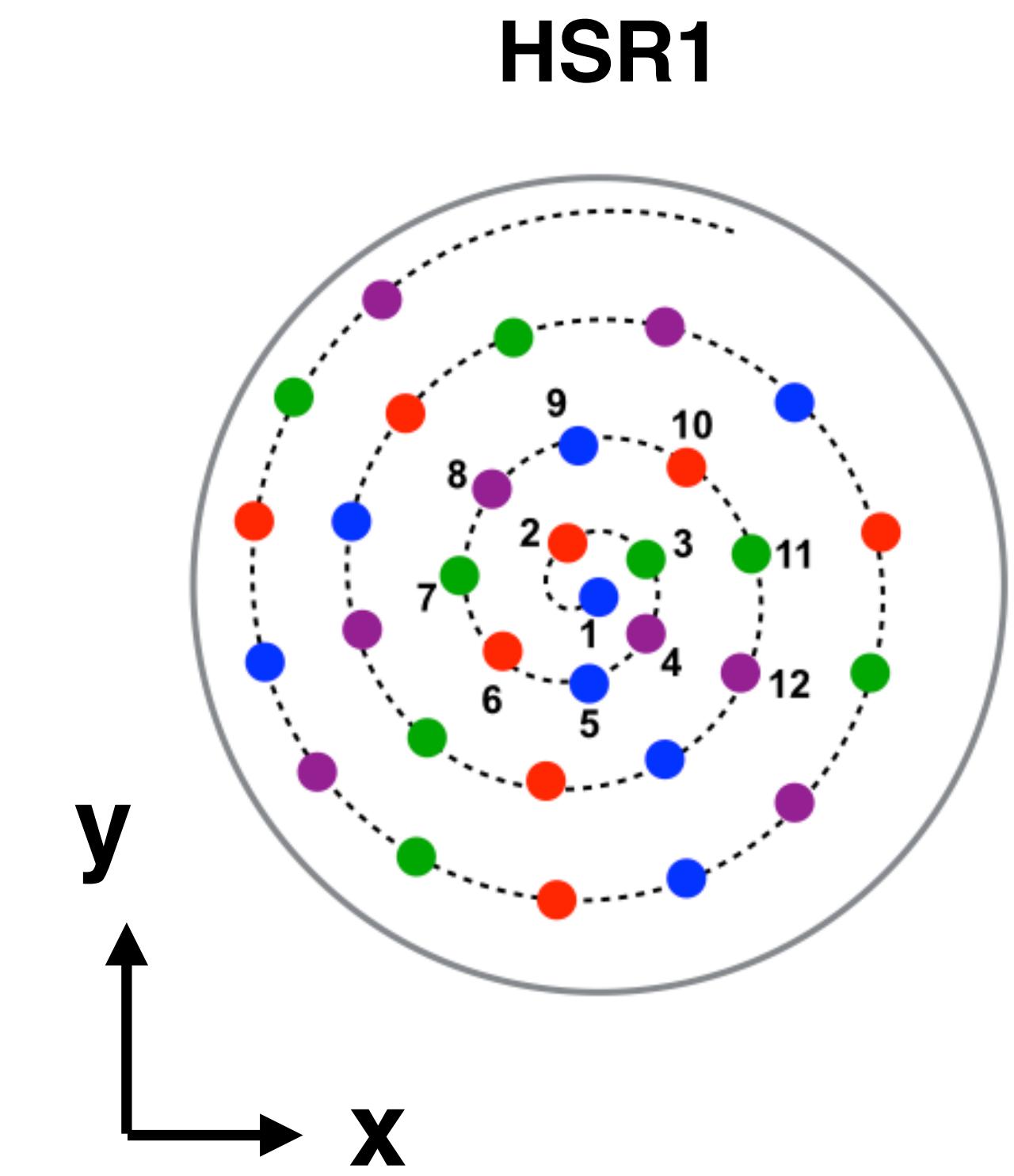
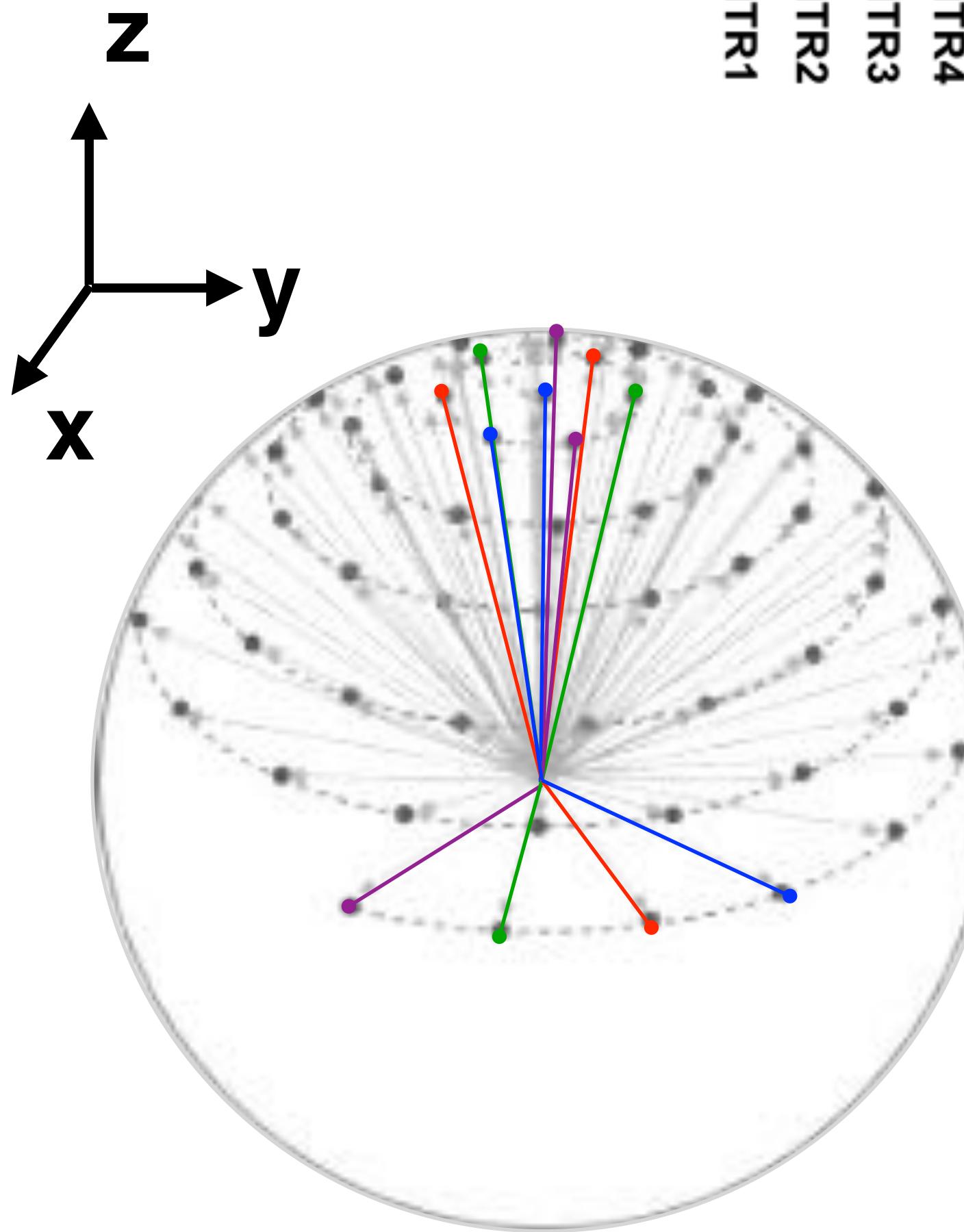
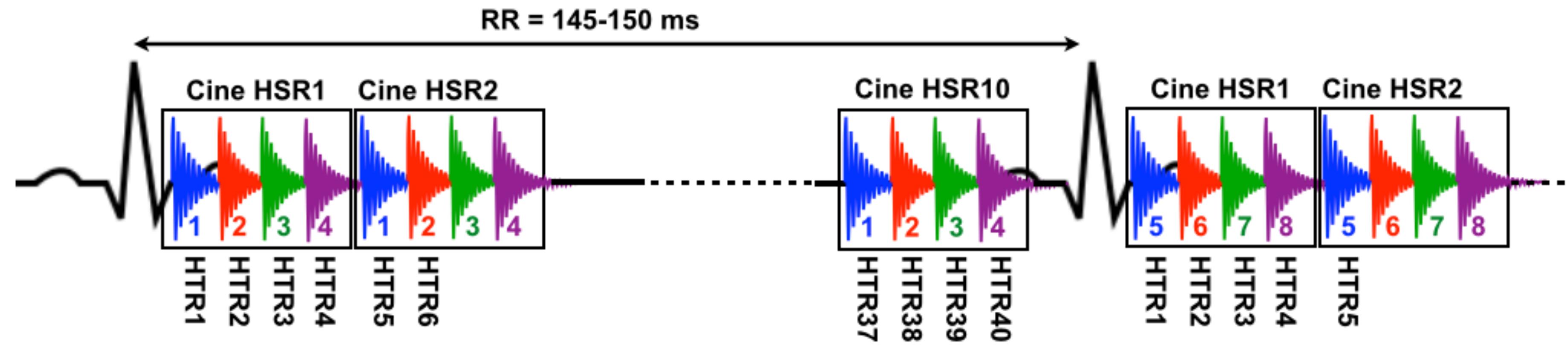
+

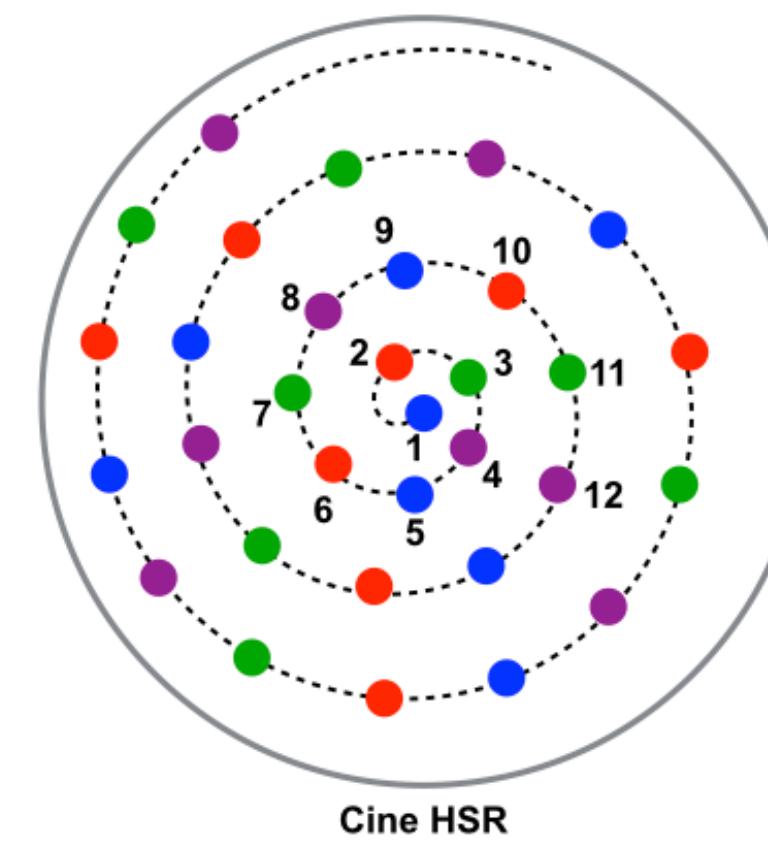
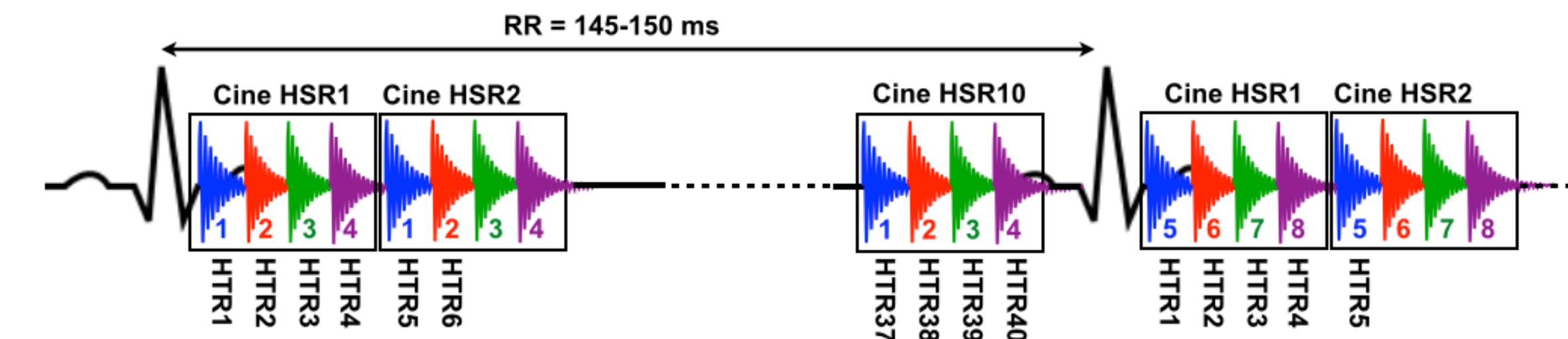


+

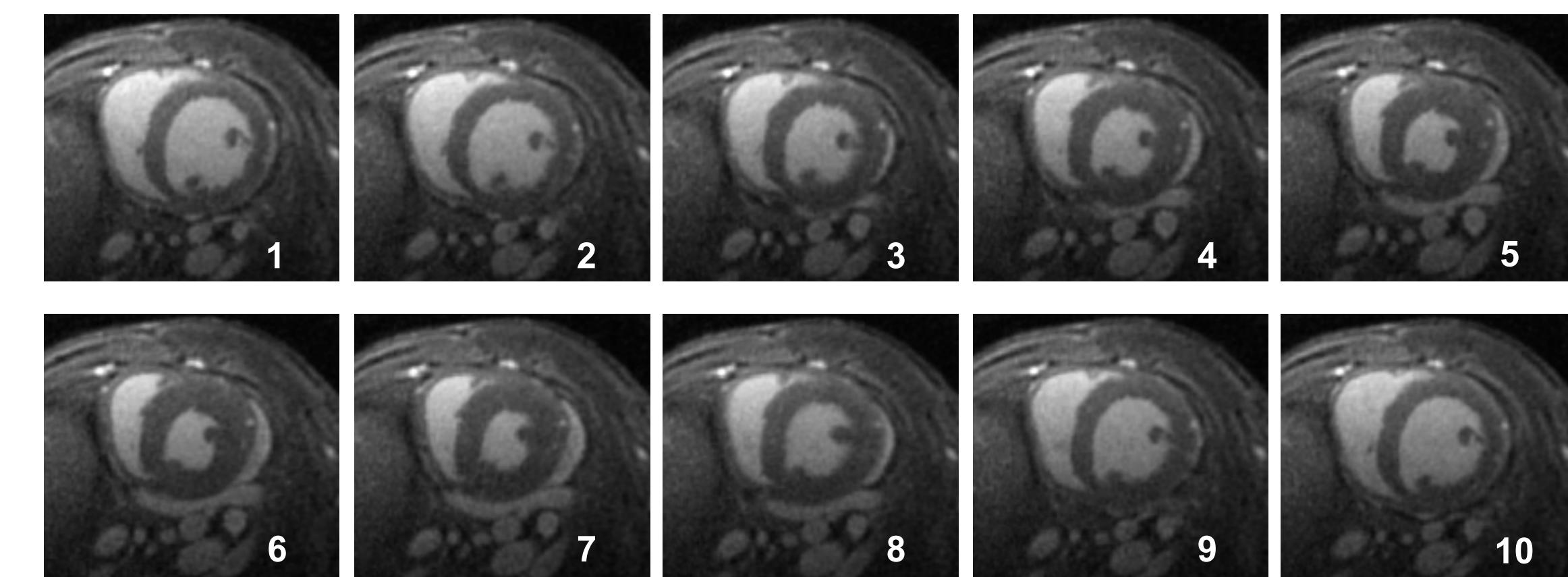
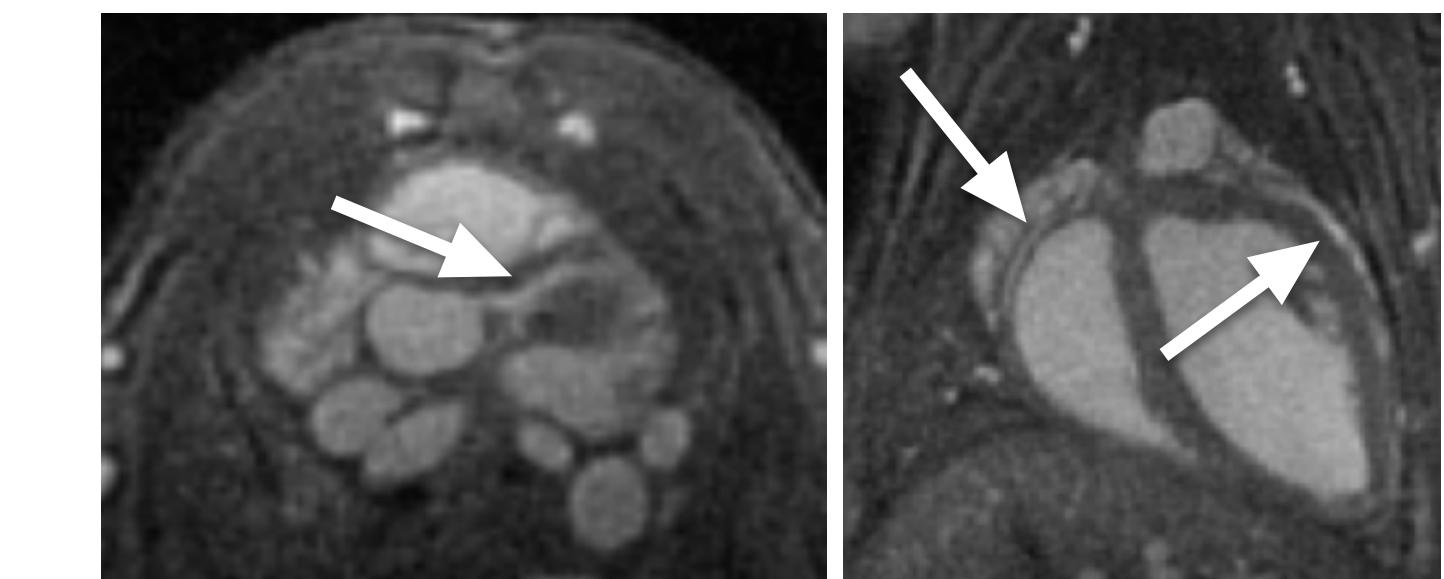


Séquence 4D

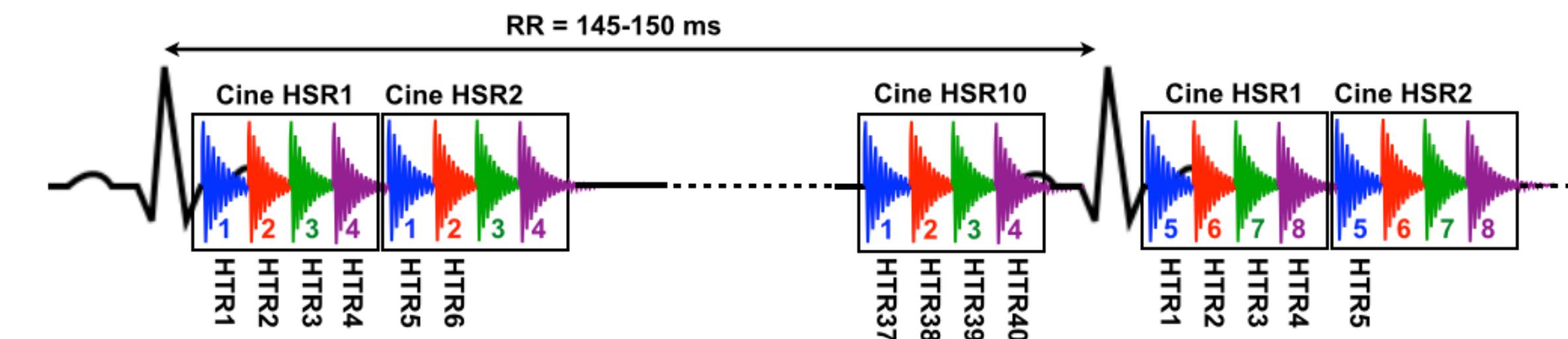




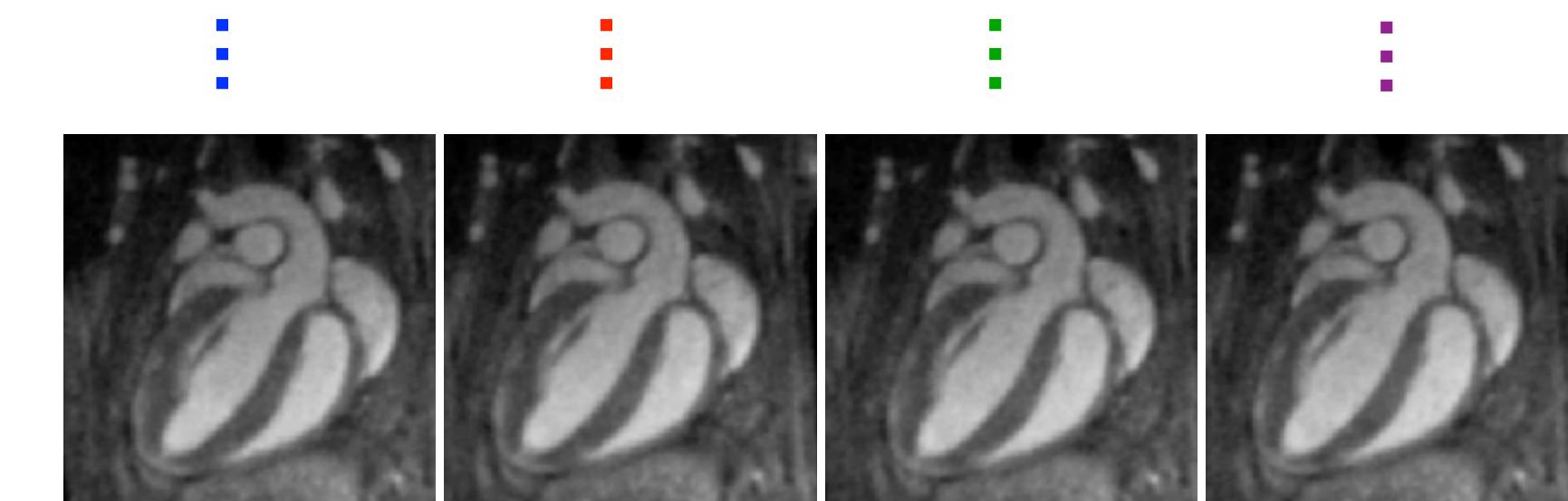
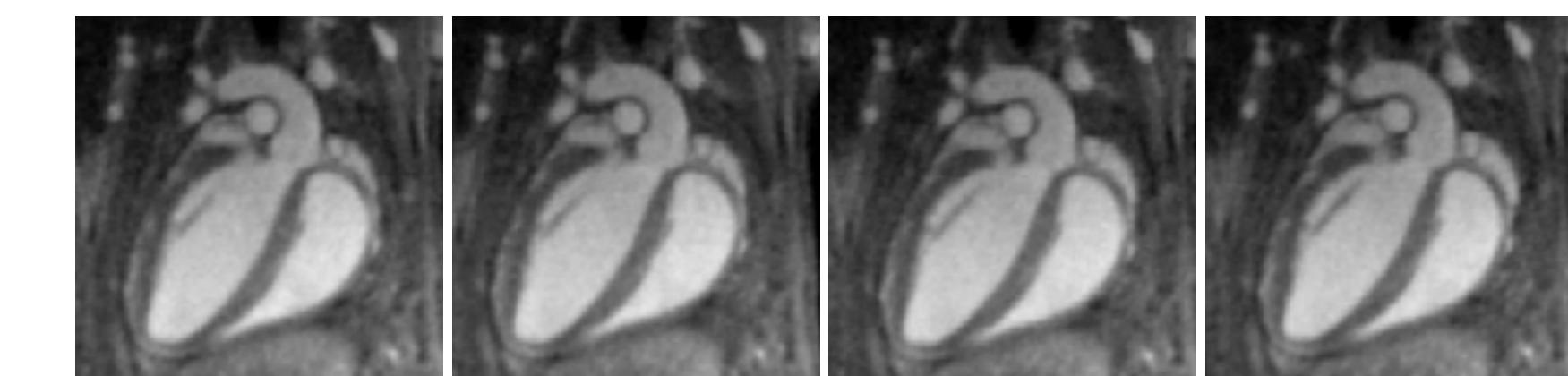
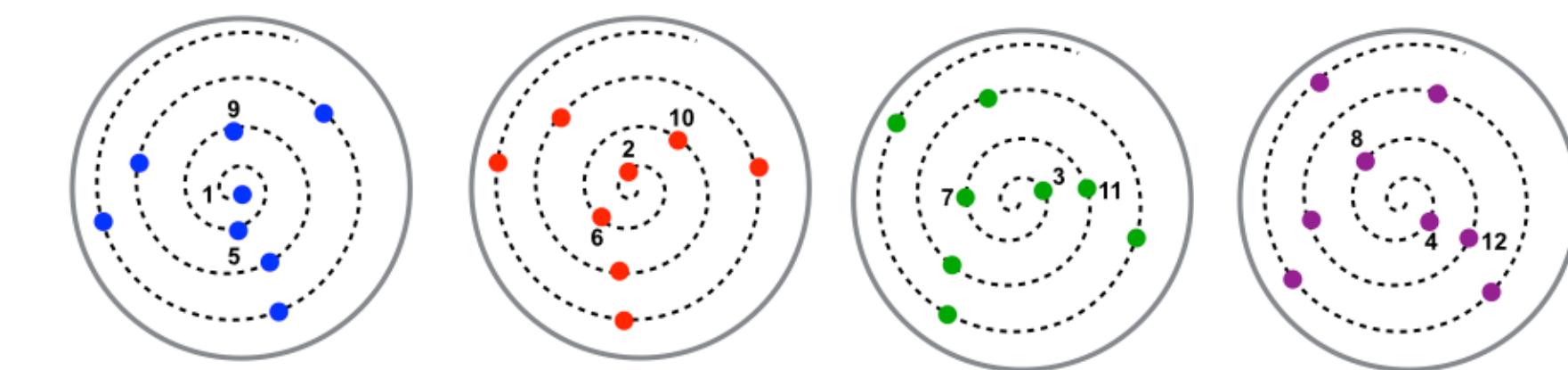
Forte résolution spatiale



10 cine images- (104 μm)³

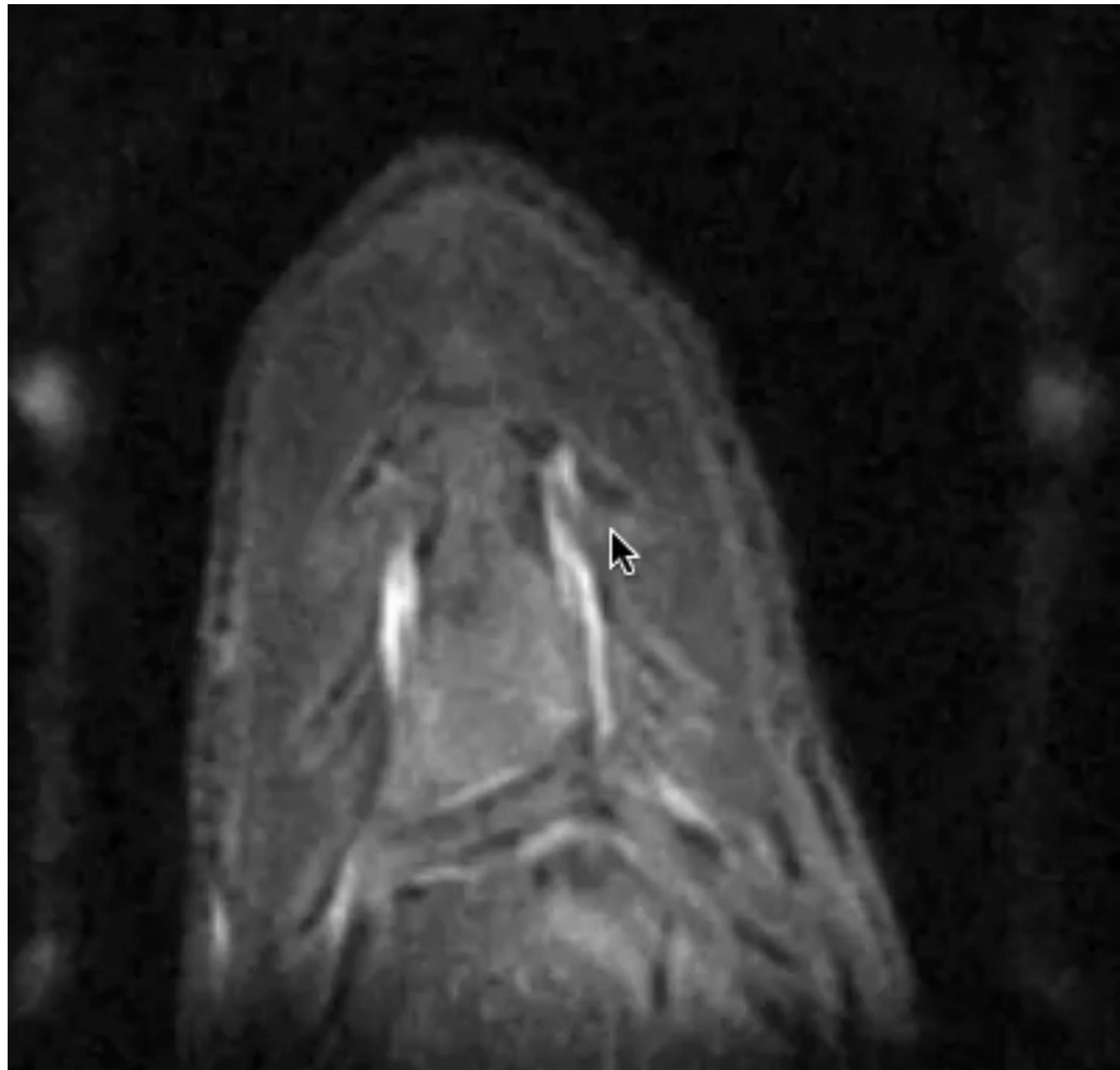


Forte résolution temporelle



40 images cinés

Haute résolution spatiale

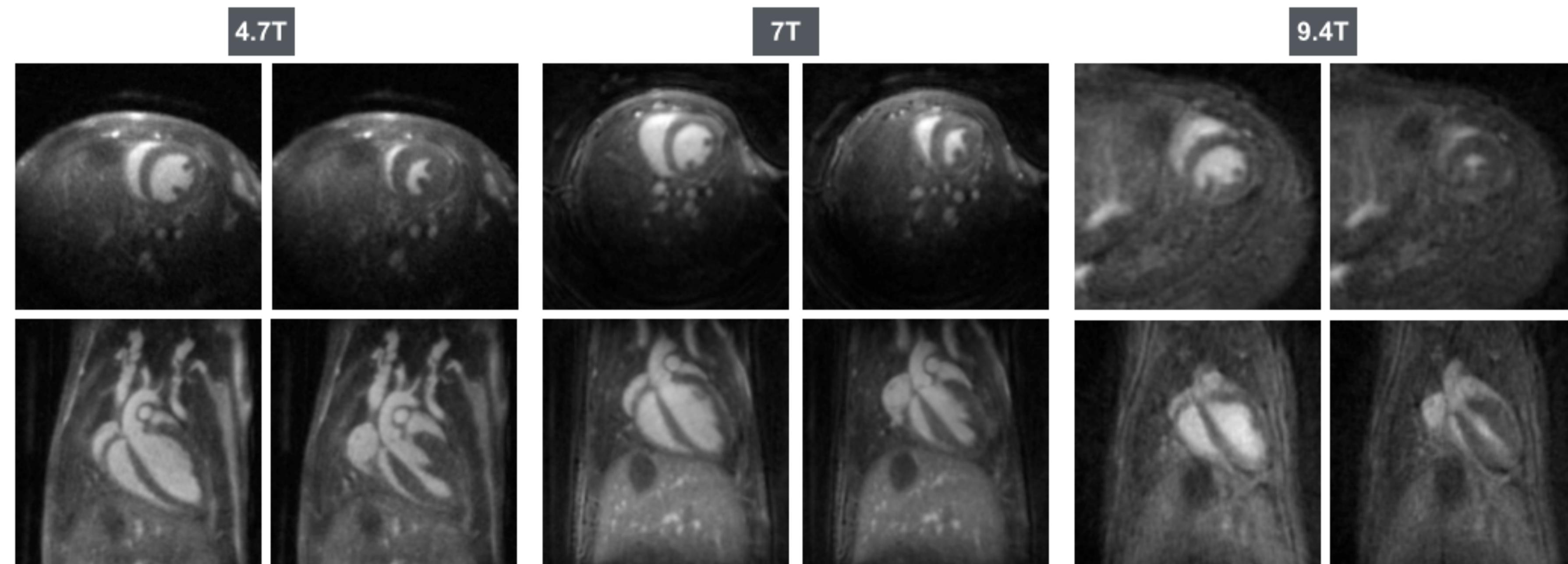


FA : 15°
TE/TR : 0,031/3,5 ms
BP : 100kHz
Matrice : 192/192/192
FOV : 20×20×20 (mm)³
TA : ± 30 min
Projection : 50240
Polar Undersampling : 2,3
N FIDs = 5
RR = 380

Haute résolution temporelle



Avantage de la séquence UTE : Pas d'artefacts de flux



TA : ± 12 min
Cine = 10
FOV = $20 \times 20 \times 20$ (mm)³
matrix = $128 \times 128 \times 128$
Projection = 18144
156 μm isotrope

UTE + USPIO

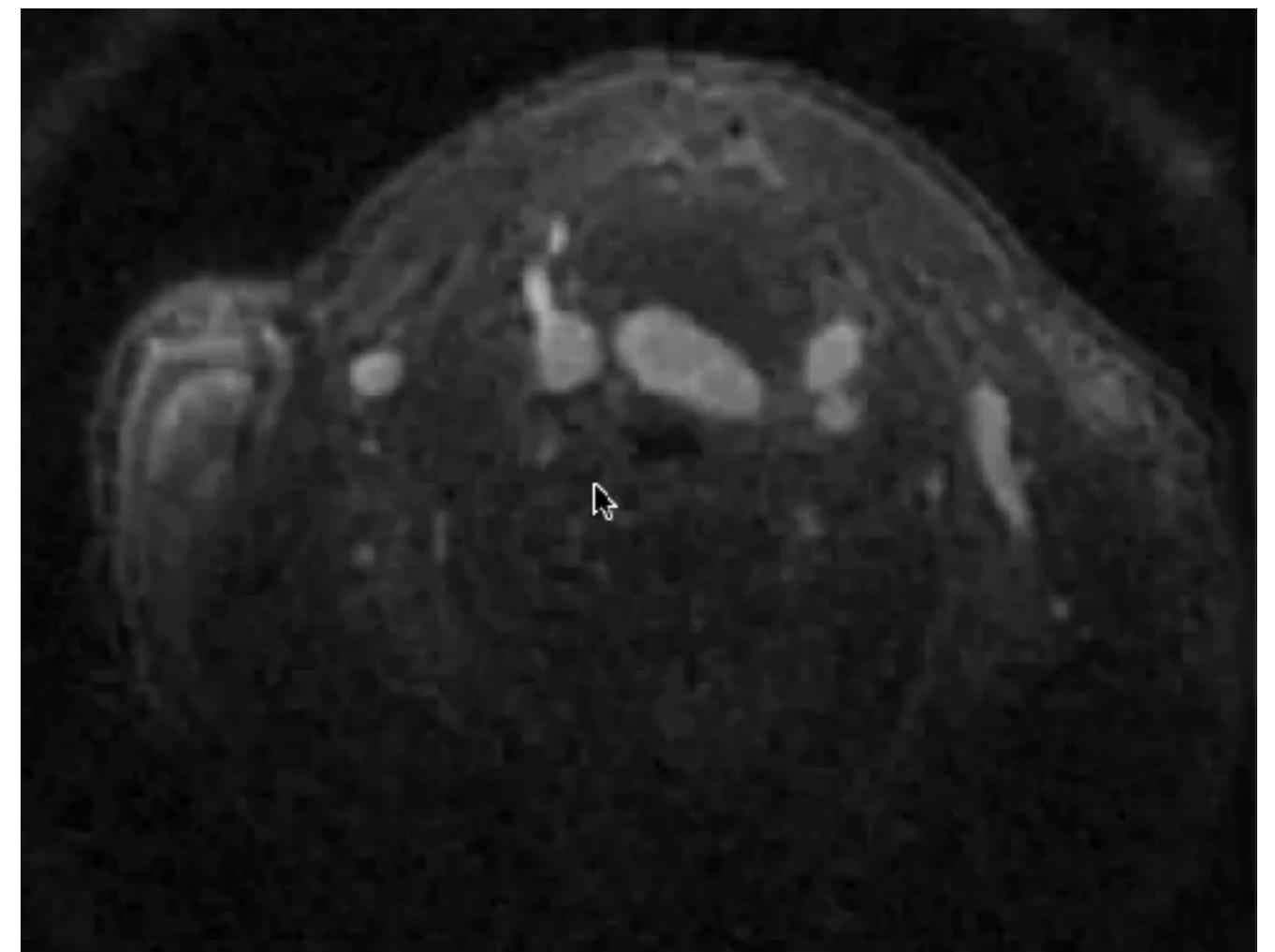
- Fort SSB et CSB entre le sang et le myocarde
- Temps de demi-vie > 1 heure

Concentrations :

- 50 µmol Fe/kg Doses cliniques
- 100 µmol Fe/kg
- 200 µmol Fe/kg
- 500 µmol Fe/kg Doses ciblages cellules

Champs magnétiques :

- 4.7 T
- 7 T
- 9.4 T

**Limitations**

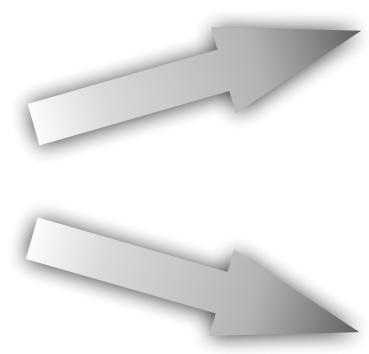
- Avertissement de la FDA dans le cas d'Injection en tant que supplément fer
- Difficilement accessible

Perspectives

- Injection en tant qu'agent de contraste chez l'enfant (Han et al. MRM 2015)
- Possibilité d'utilisation en tant qu'agent de premier passage avec une séquence UTE

Nouvelle séquence : Imagerie cardiaque résolue dans le temps

- Méthode flexible : une acquisition pour plusieurs analyses
- Imagerie de tout le système cardiovasculaire
- Méthodes robustes : pas d'artefact de flux durant la phase systolique



Forte résolution spatiale:
Imagerie des coronaires

Forte résolution temporelle
Arythmie de contraction

Publié début 2015 dans JCMR. DOI: 10.1186/s12968-015-0167-4

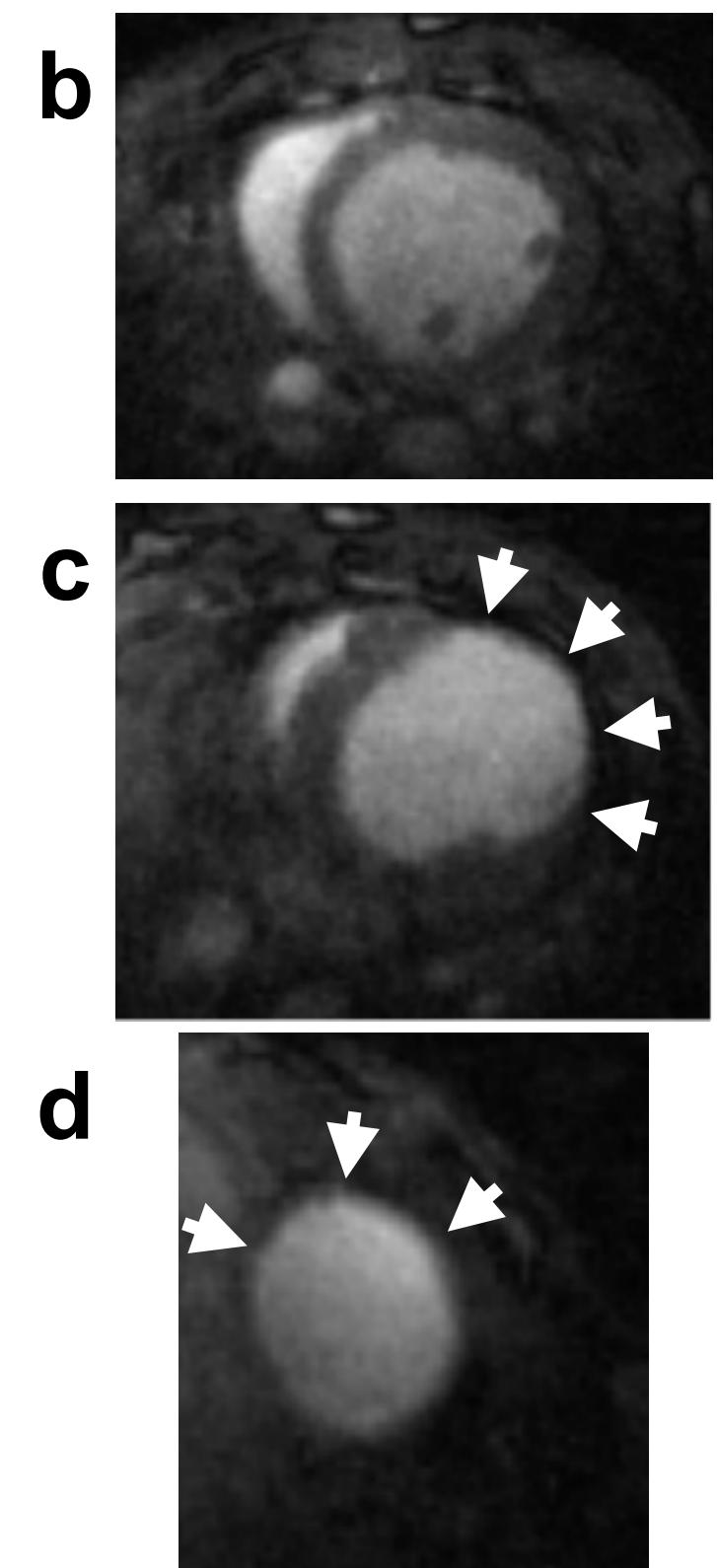
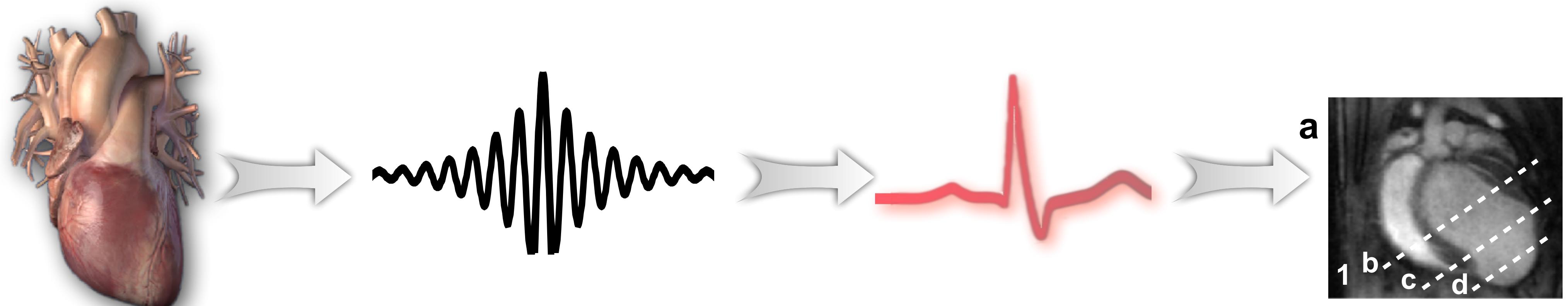
Limitations

- Synchronisation sur ECG
- Durée d'acquisition importante pour les très hautes résolutions spatiales

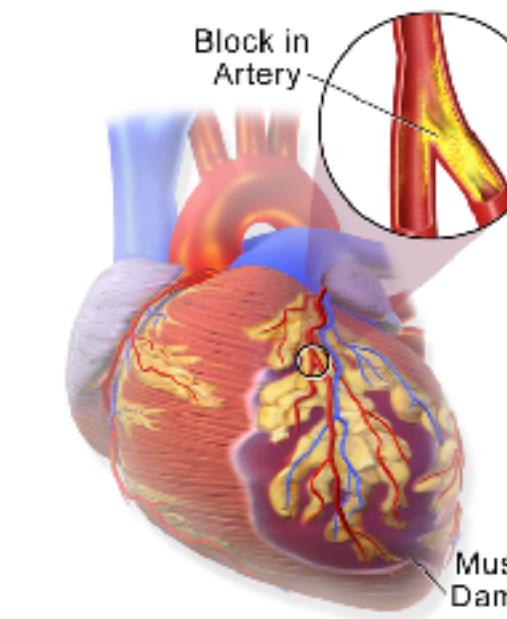
Perspectives

- Application chez l'homme

Imagerie 3D auto-synchronisée sur le rythme cardiaque
basée sur une séquence Stack-Of-Stars UTE



Infarctus du myocarde



Troubles de la conduction
électrique

Gradient intense

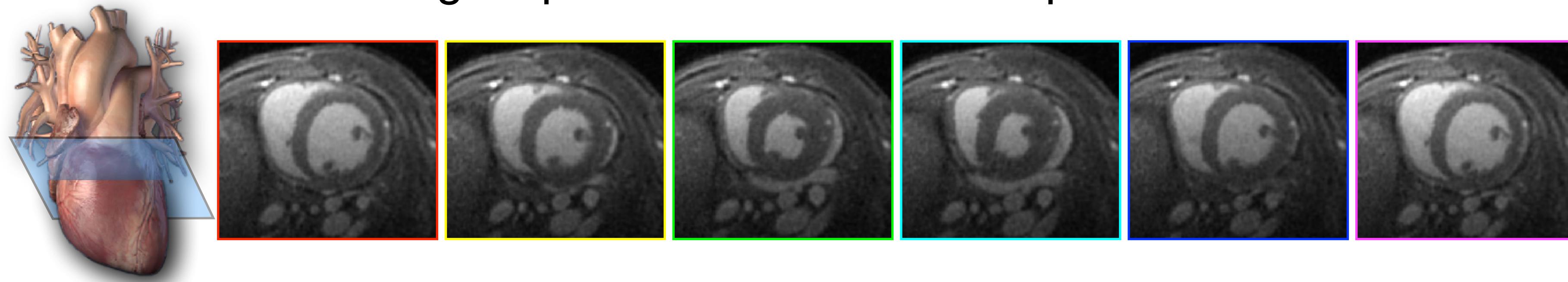


Signal ECG
perturbé

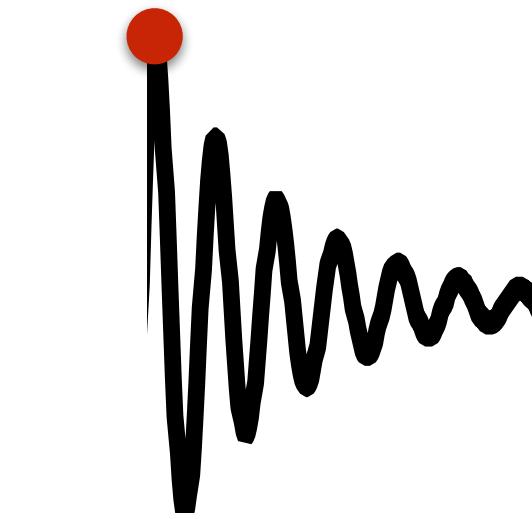
Développement méthode 3D résolue
dans le temps sans capteur ECG

Signal auto-synchronisé

En 2D : Signal provenant de l'effet temps-de vol

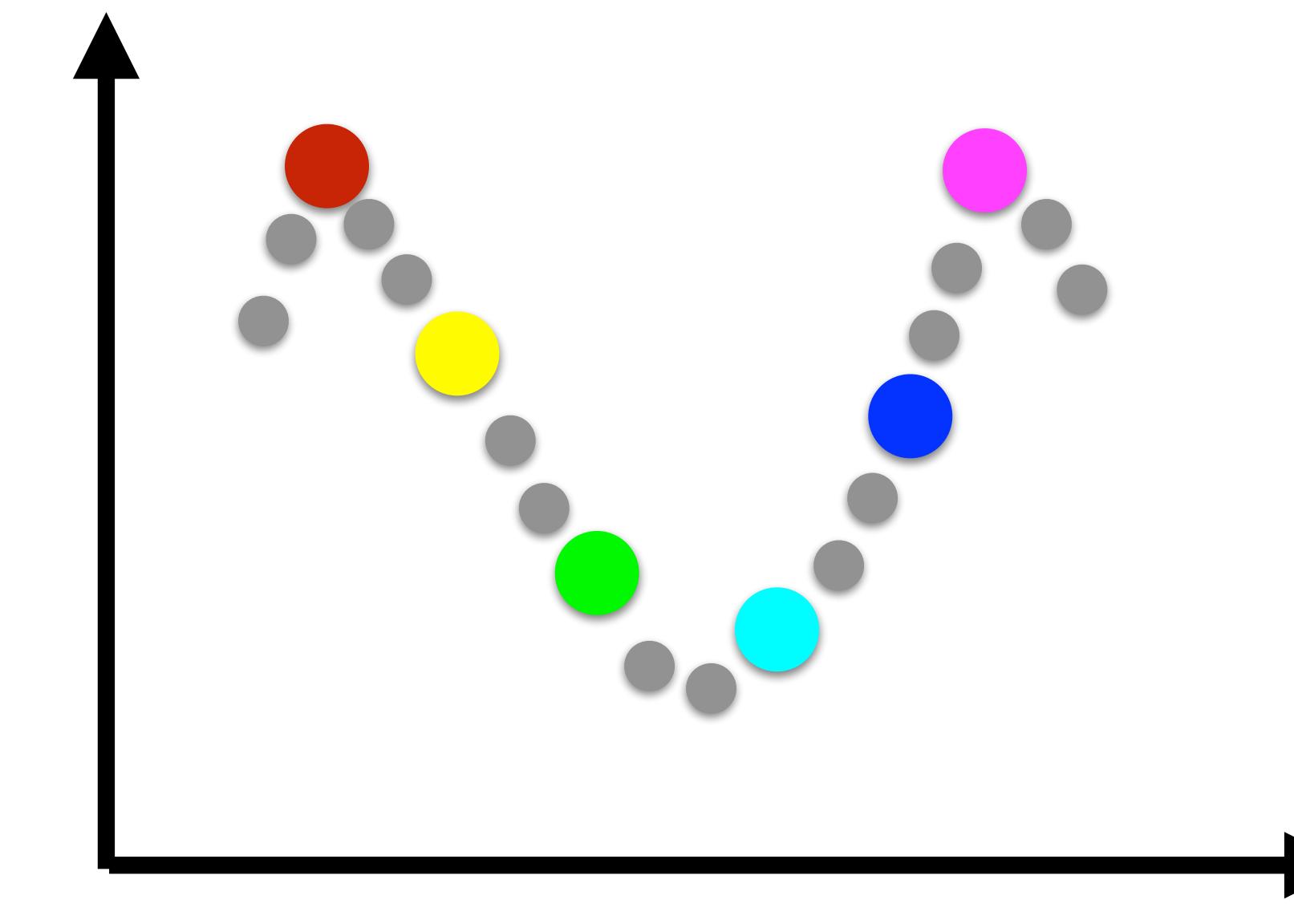


Intensité du premier point



Signal IRM
navigateur

Intensité / U.A.

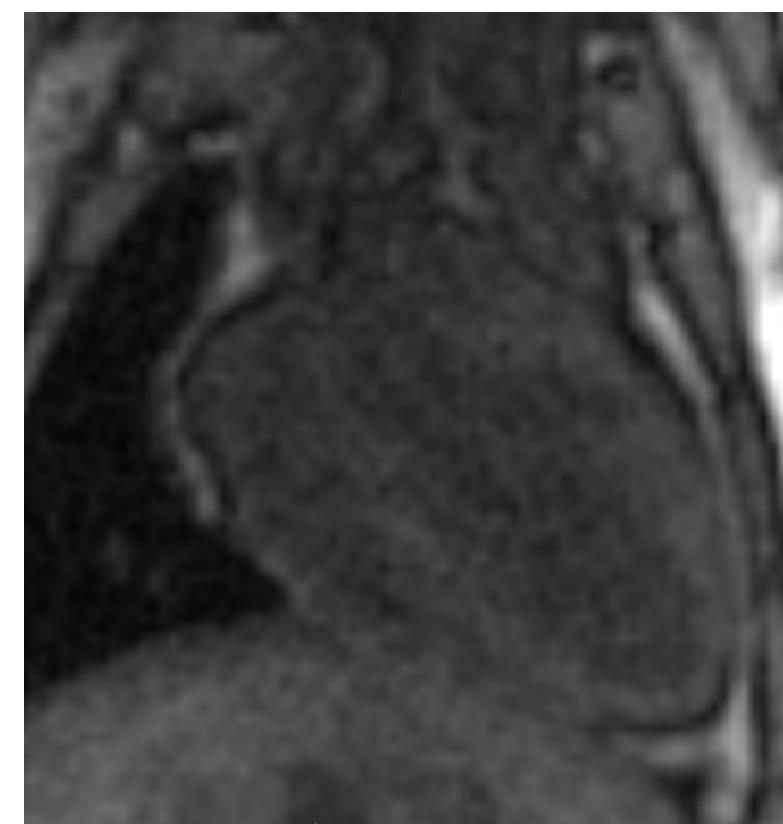
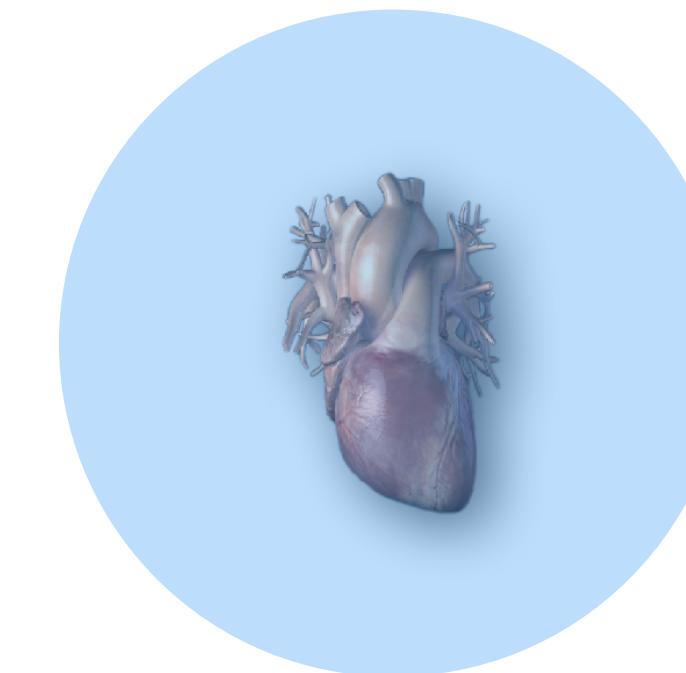


Temps / ms

Sans gradient l'intensité du signal RMN dépend de la position dans le cycle cardiaque

UTE + Auto-synchronisation

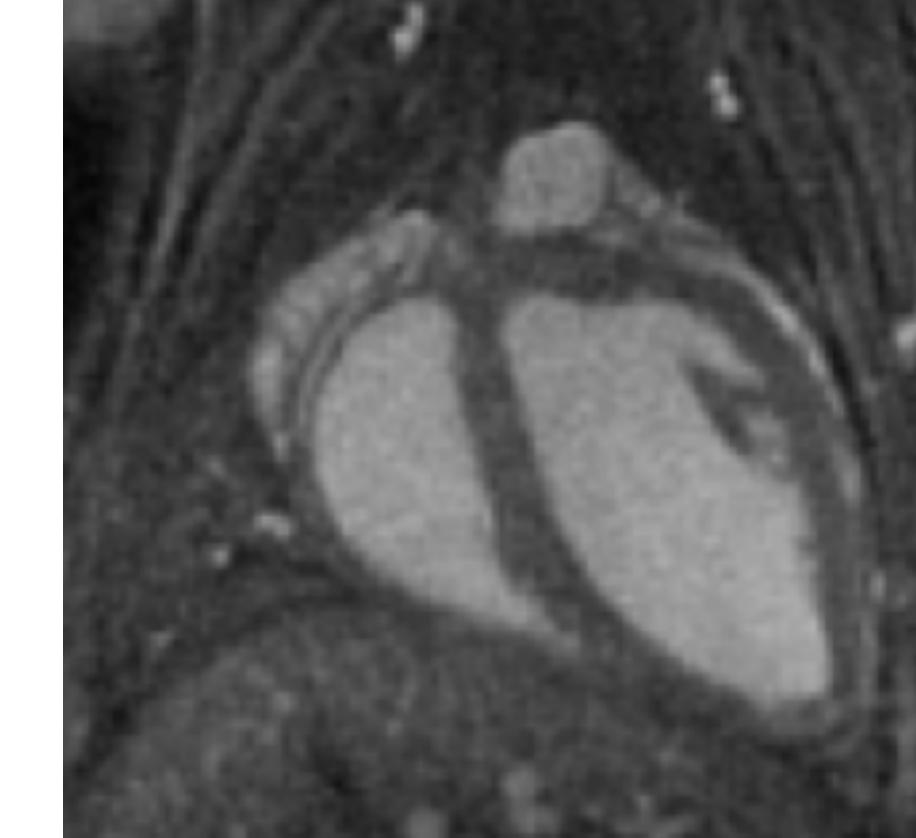
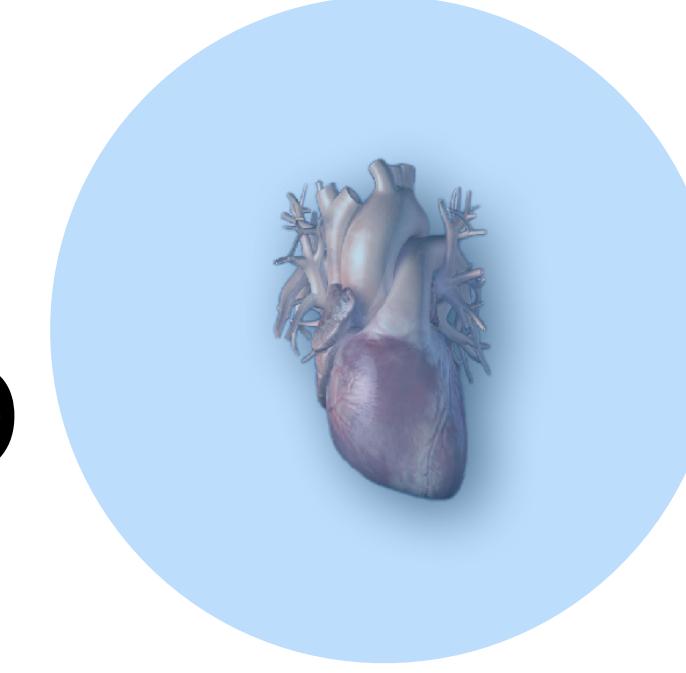
3D



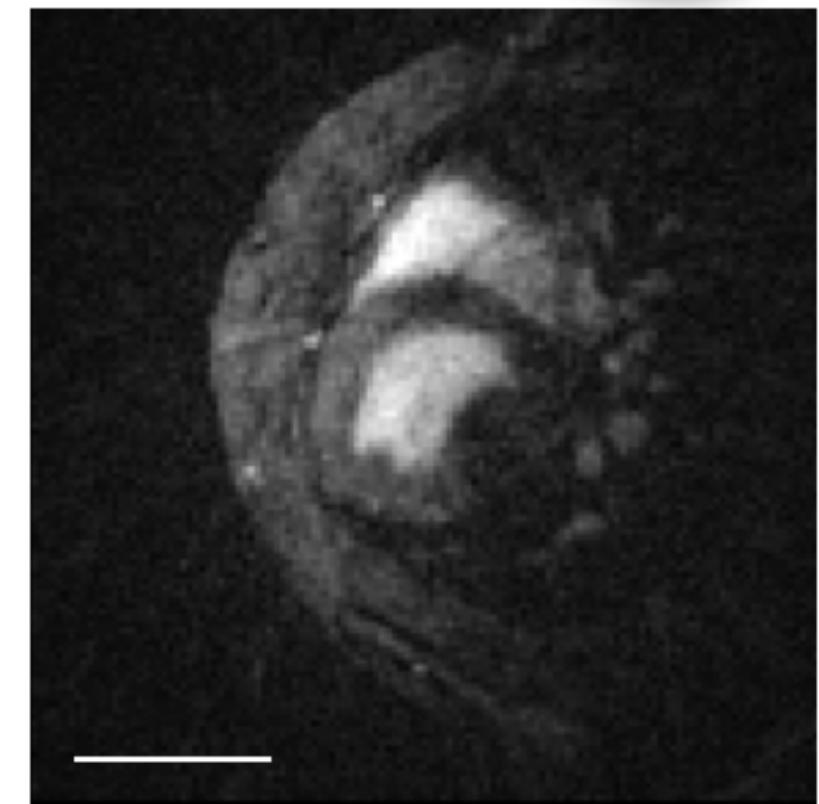
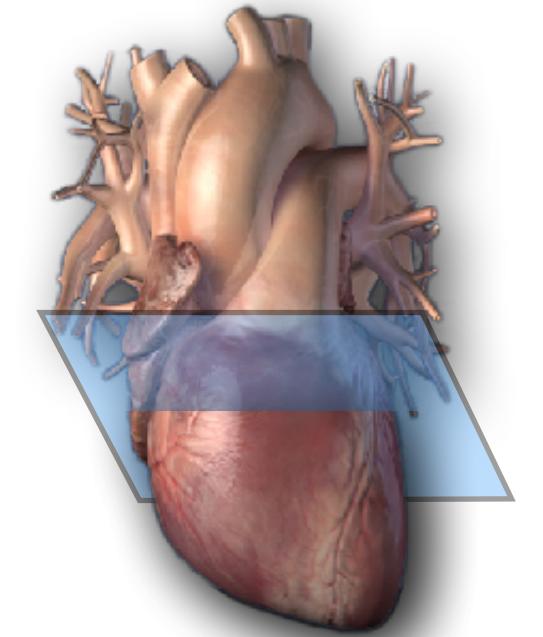
**Pas de
contraste**



**Pas de signal
d'auto-
synchronisation**

3D
USPIO

**Pas de signal
d'auto-
synchronisation**

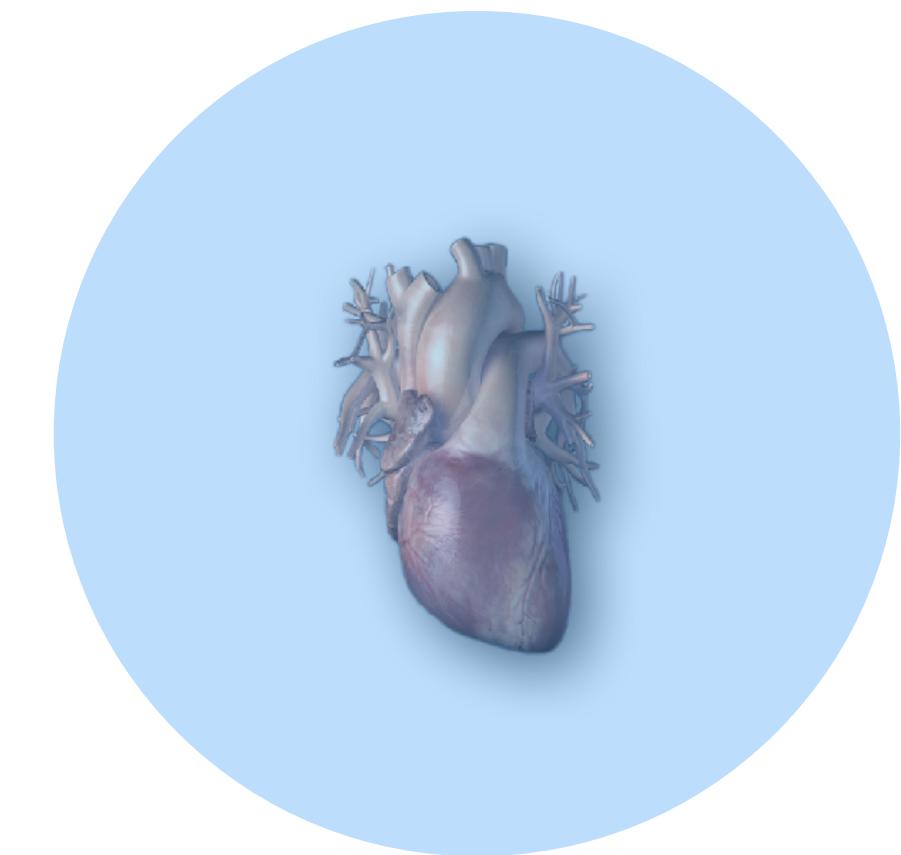
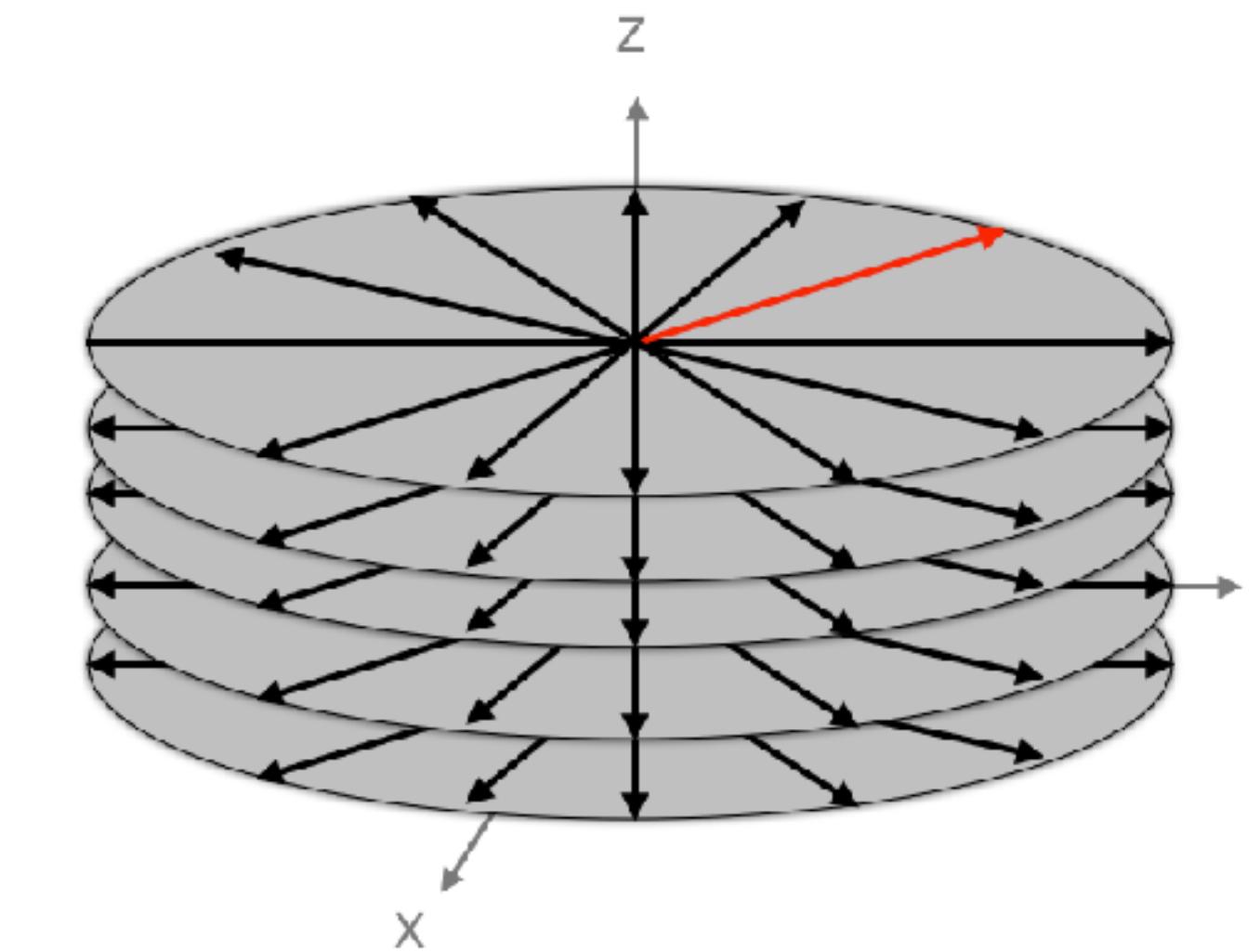
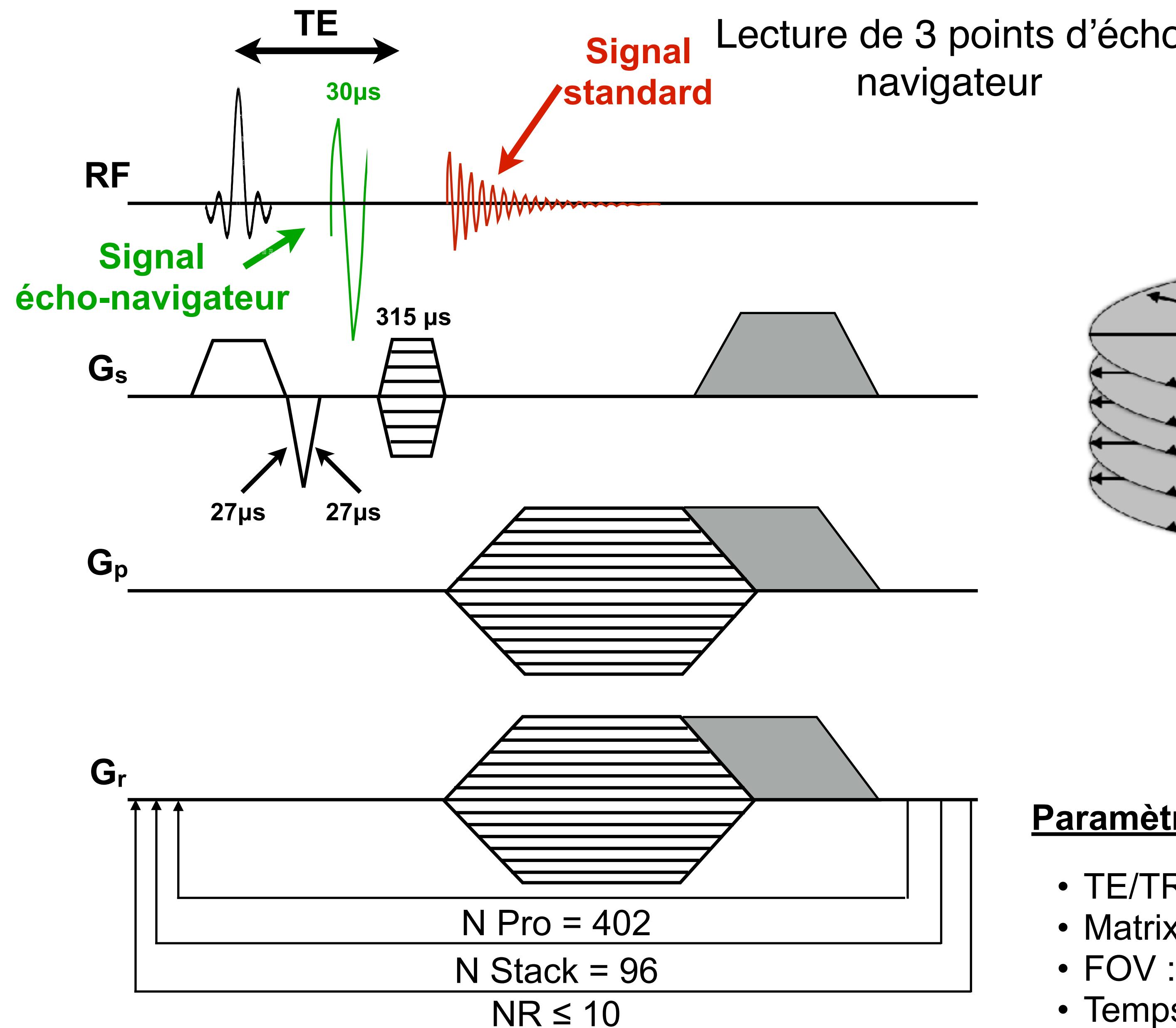
2D
TOF

a)

UTE 2D

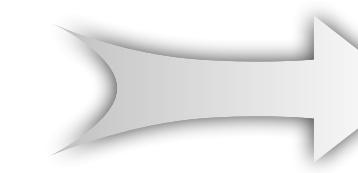


Séquence SOS-UTE auto-synchronisée



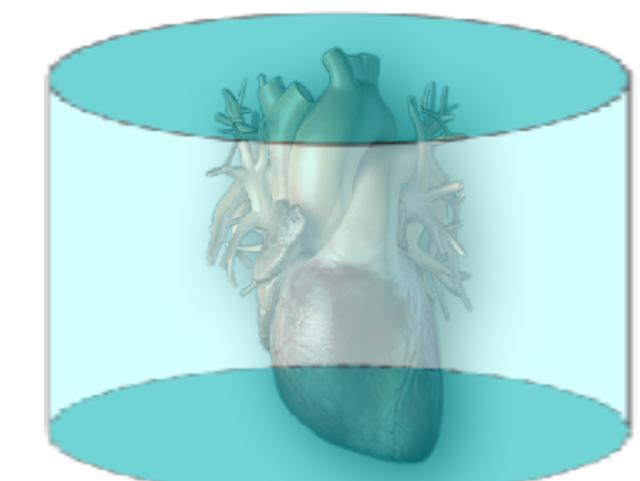
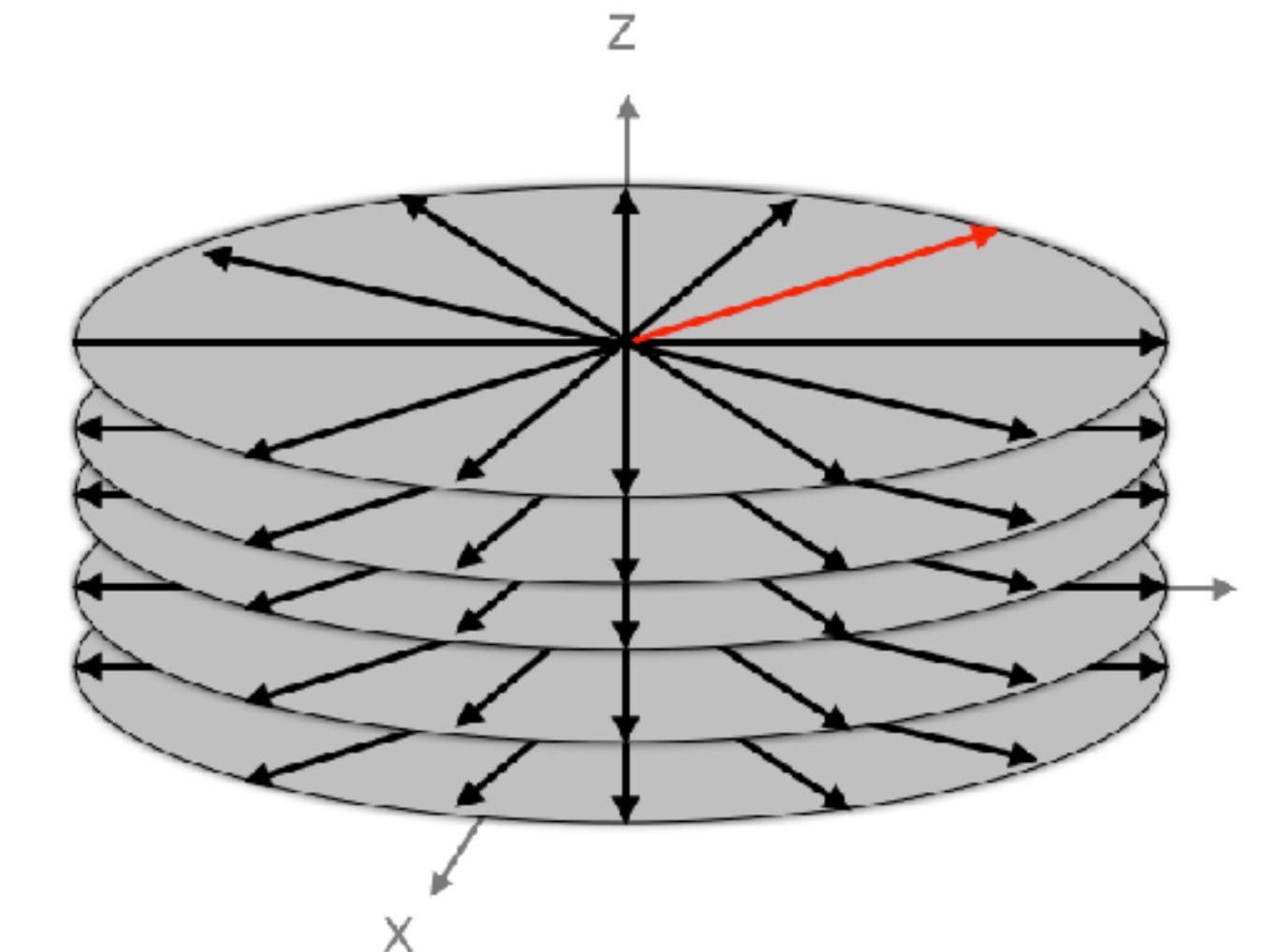
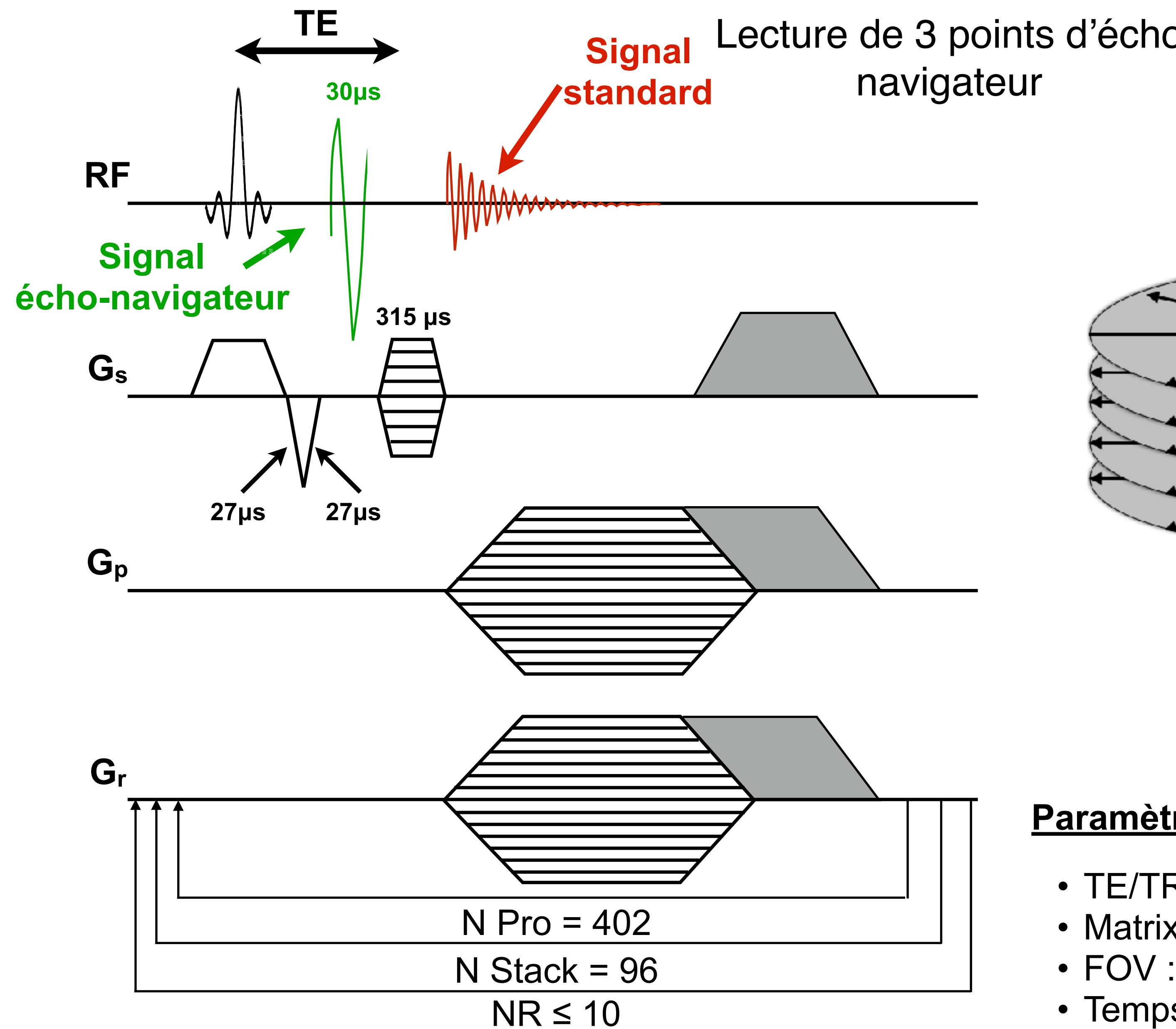
Paramètres :

- TE/TR : 0.52/4 ms
- Matrix : 128 × 128 × 96
- FOV : 20 × 20 × 15 mm
- Temps d'acquisition = 25 min



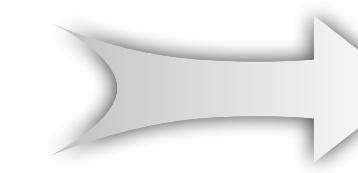
Résolution
spatiale
isotrope :
156 µm

Séquence SOS-UTE auto-synchronisée

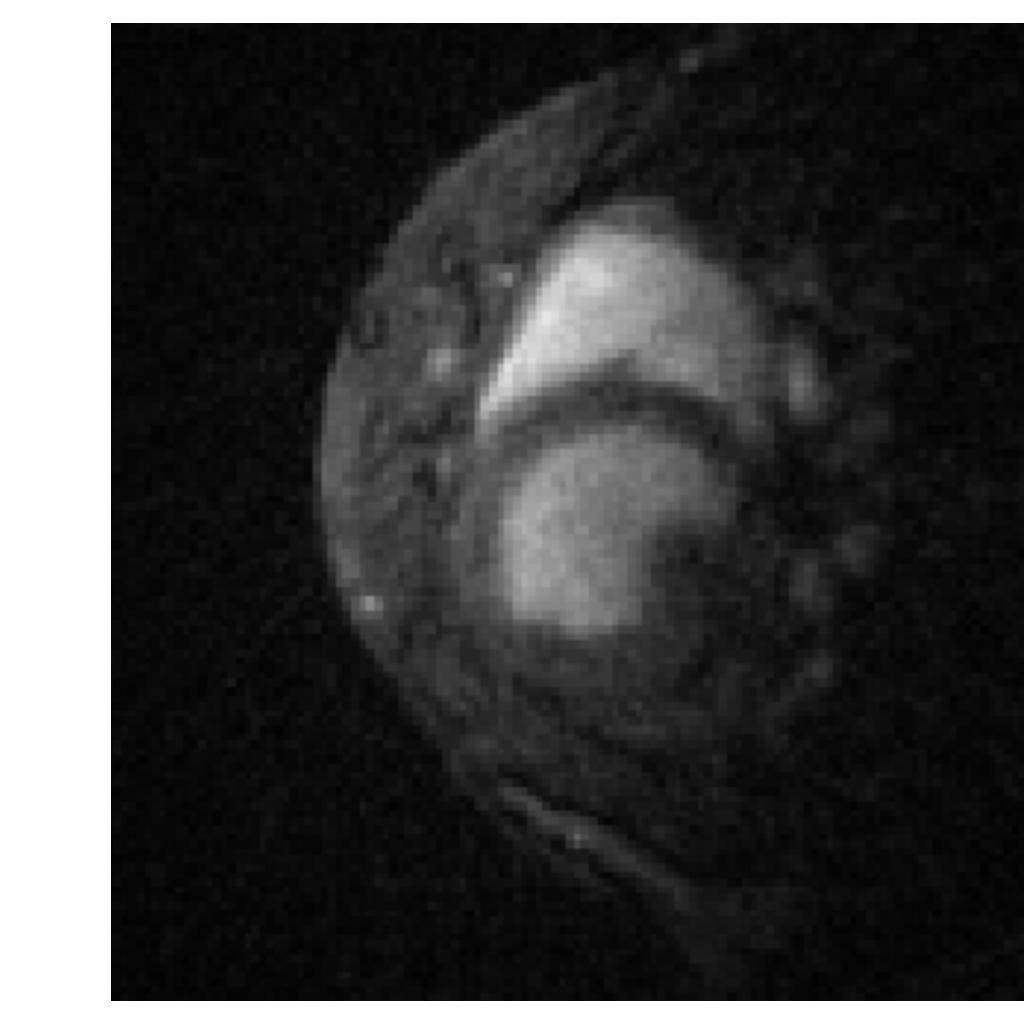
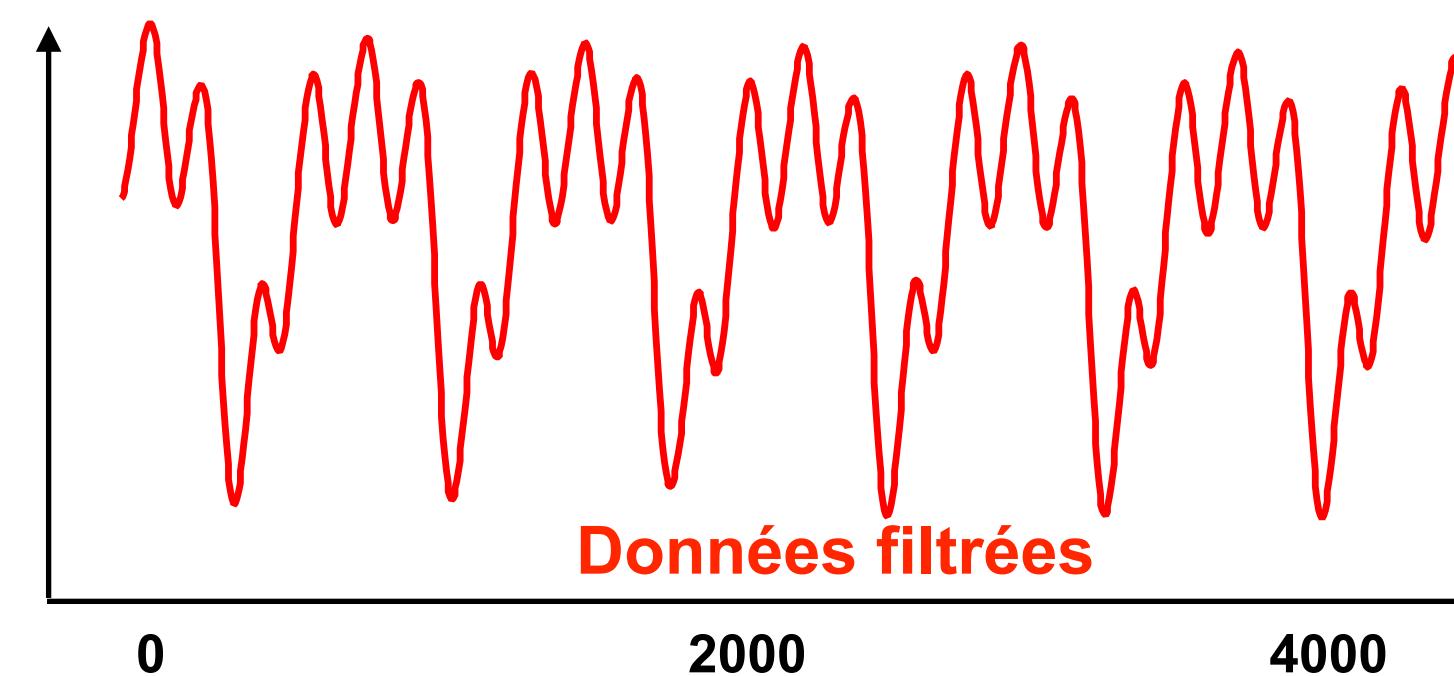
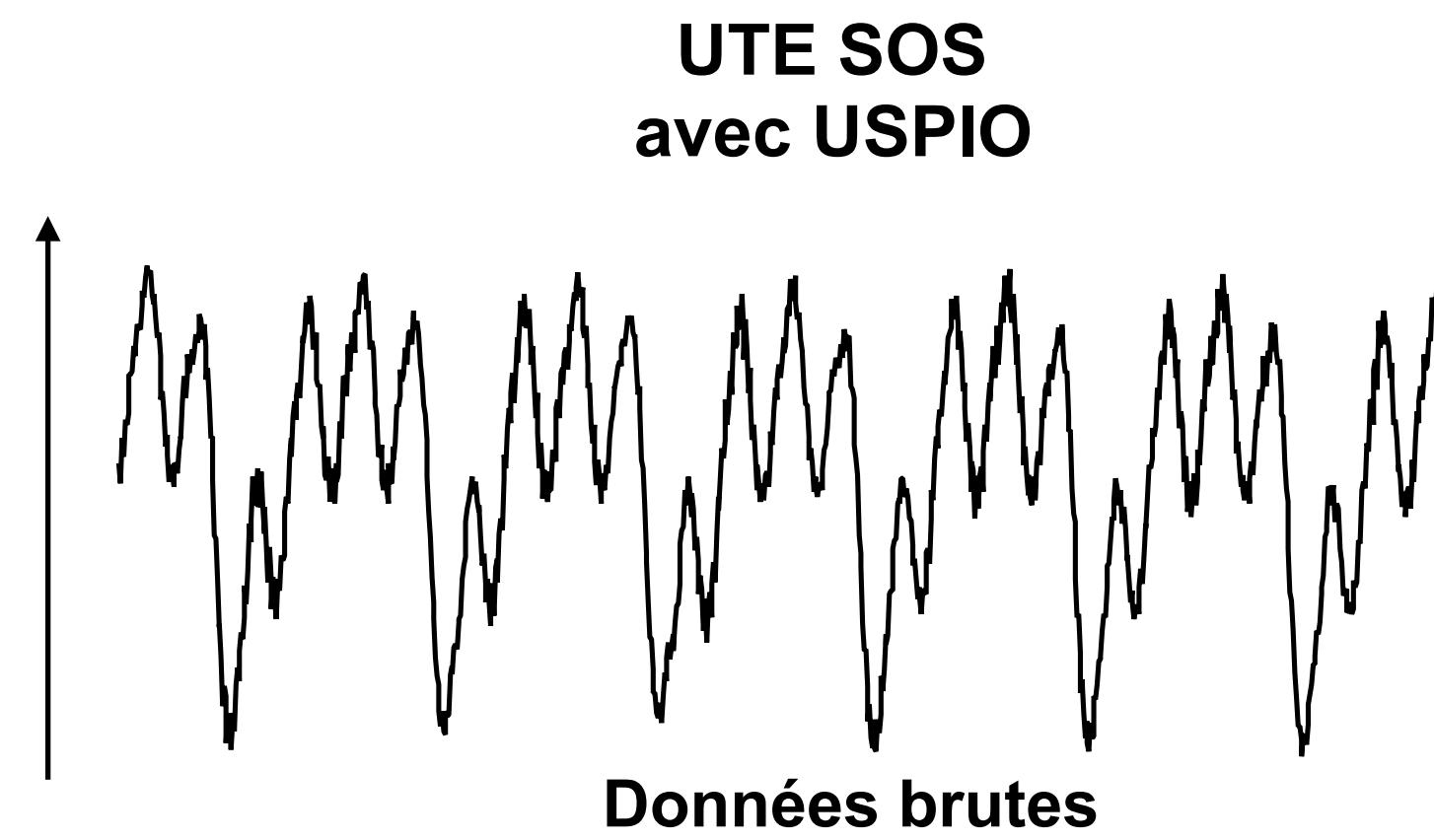
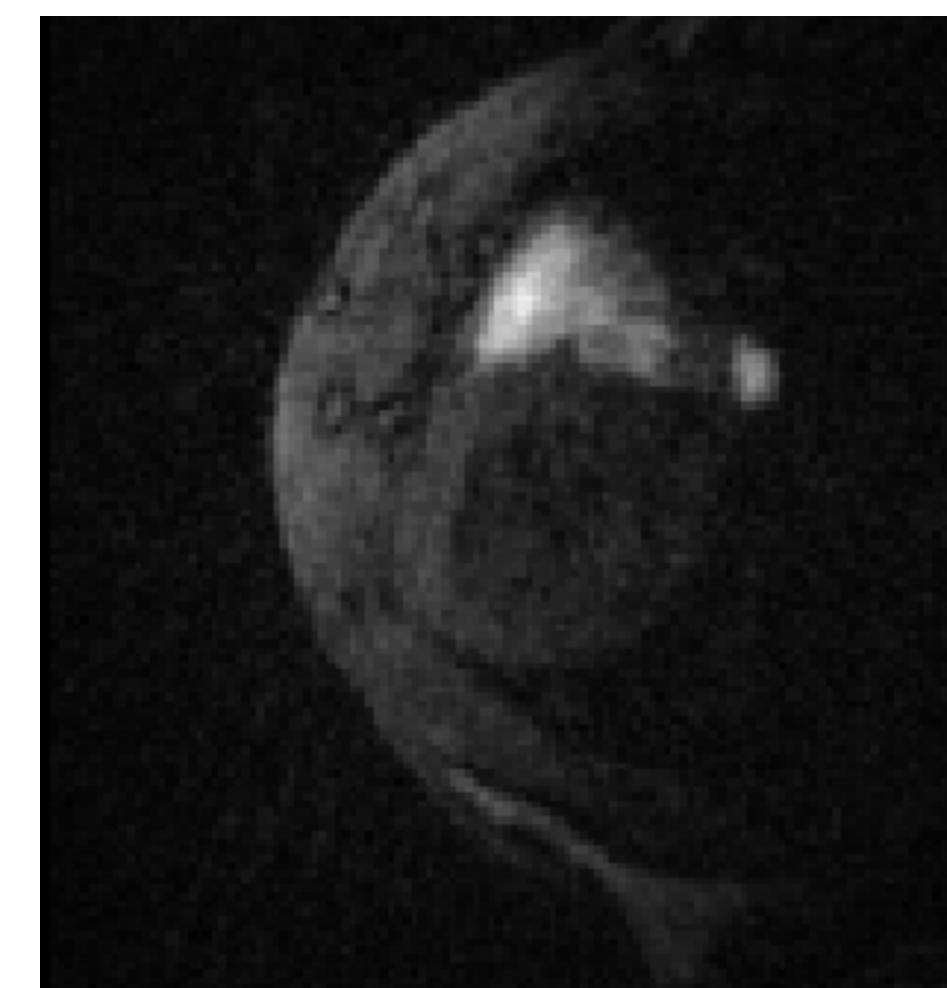
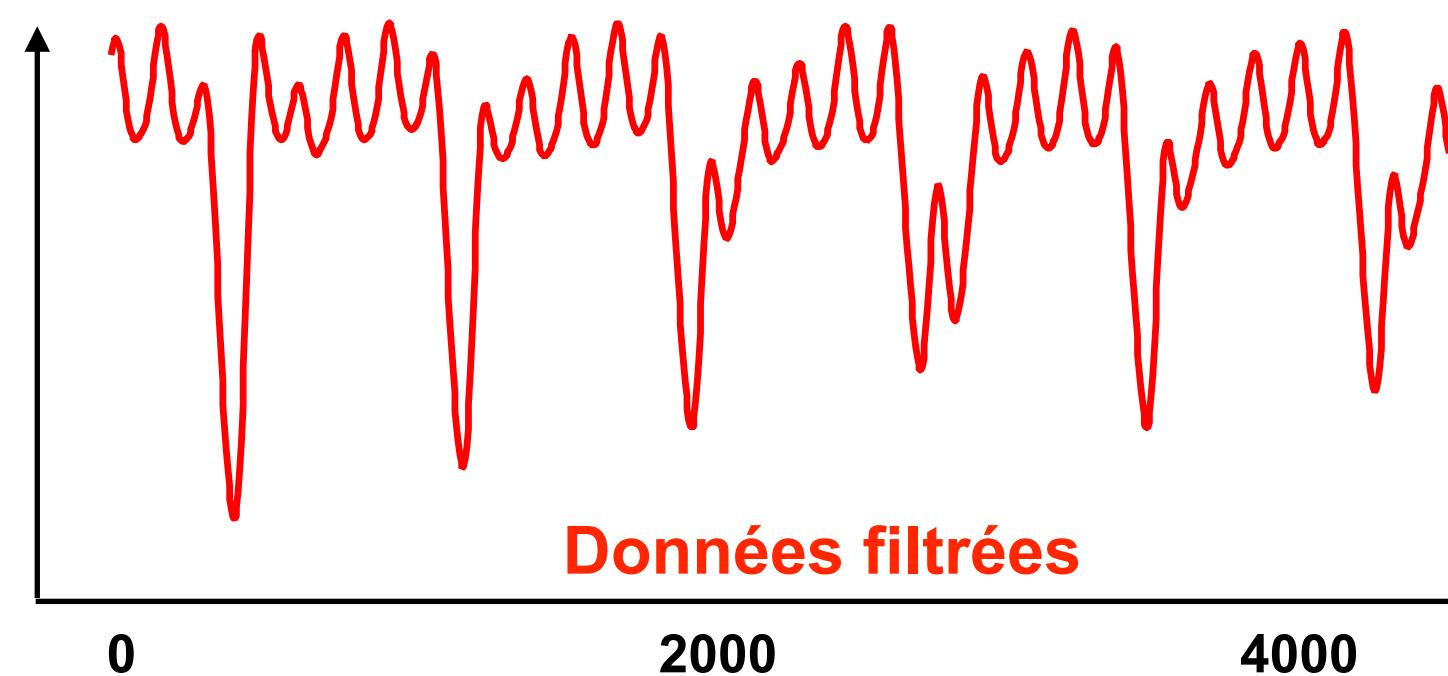
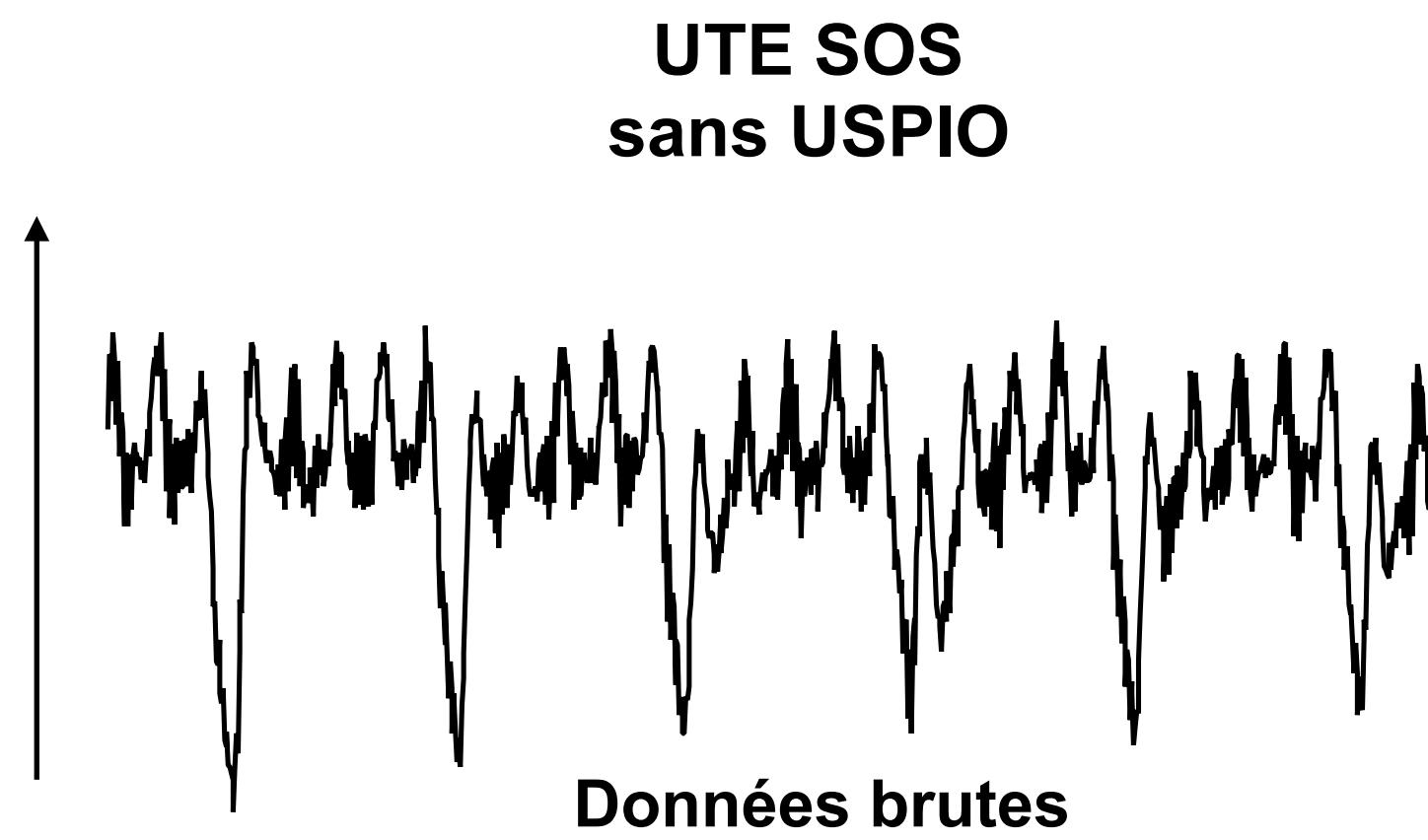


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- FOV : $20 \times 20 \times 15$ mm
- Temps d'acquisition = 25 min

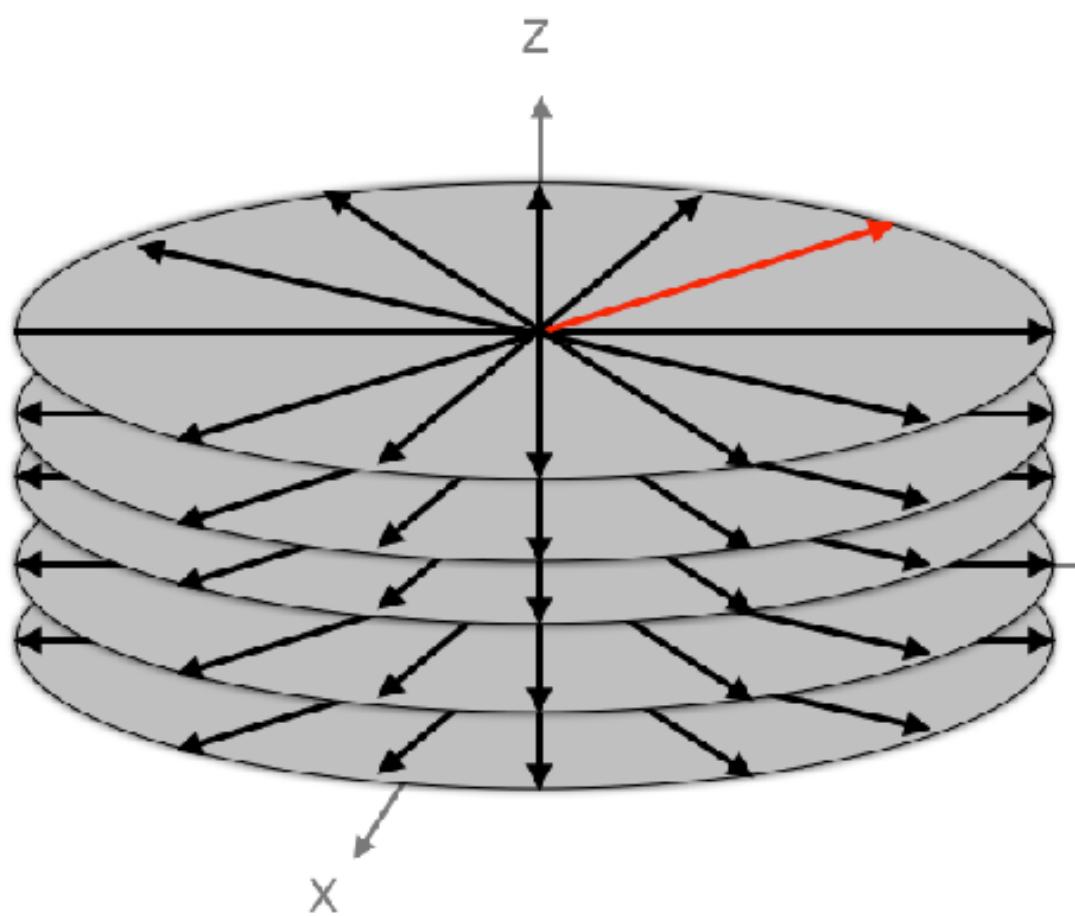


Résolution
spatiale
isotrope :
 $156\mu m$



Augmentation SSB et CSB

Augmentation du signal
d'auto-synchronisation

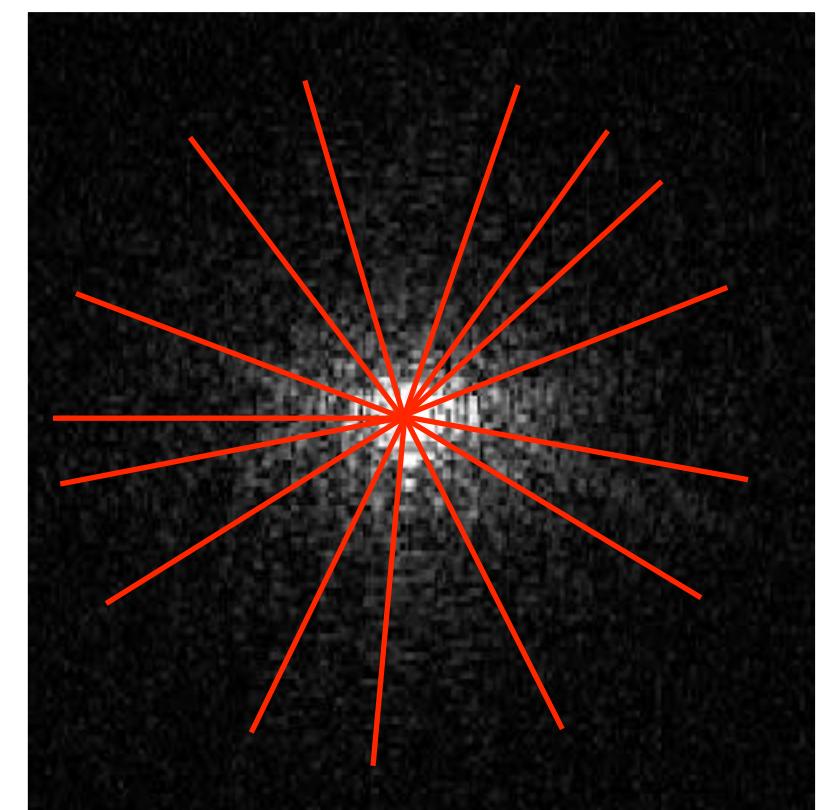
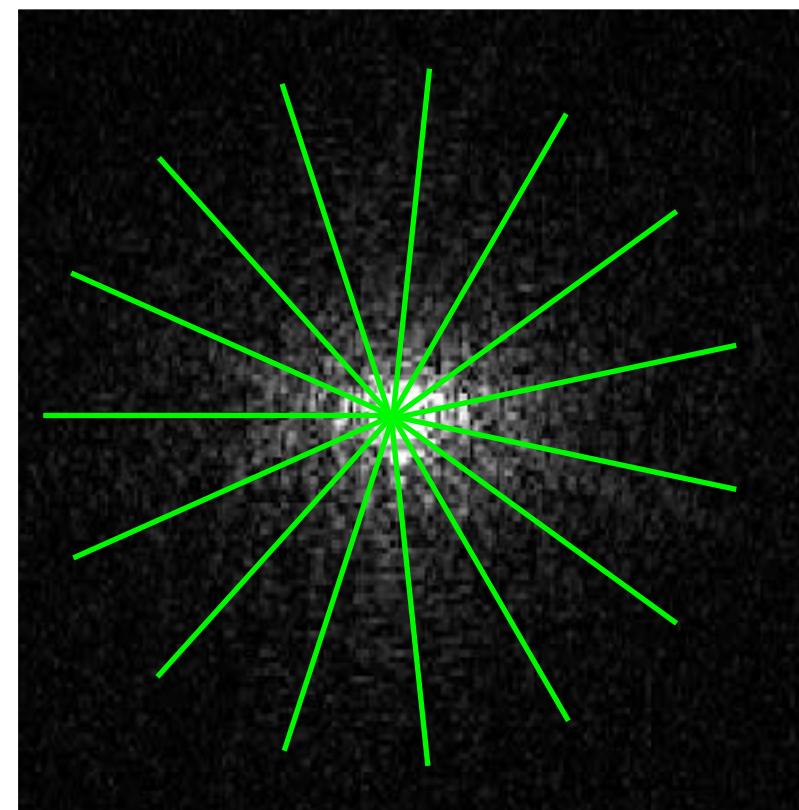


Répartition des projections :

Standard : $\theta = j \times 360/N_{\text{Pro}}$

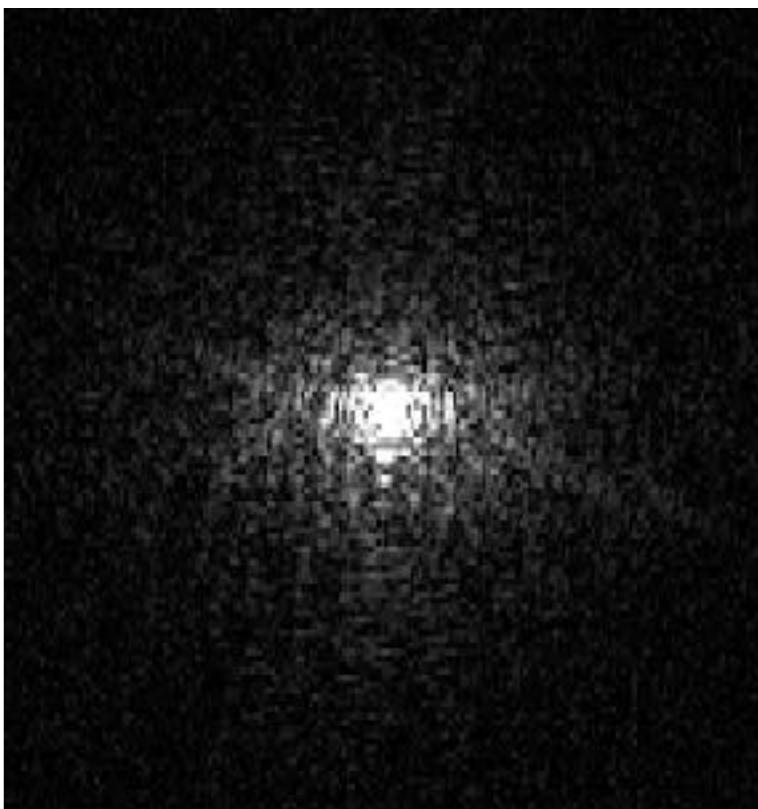
Angle d'or : $\theta = \text{mod}(222,48^\circ \times j, 360)$

$j = 1 : N_{\text{Pro}}$

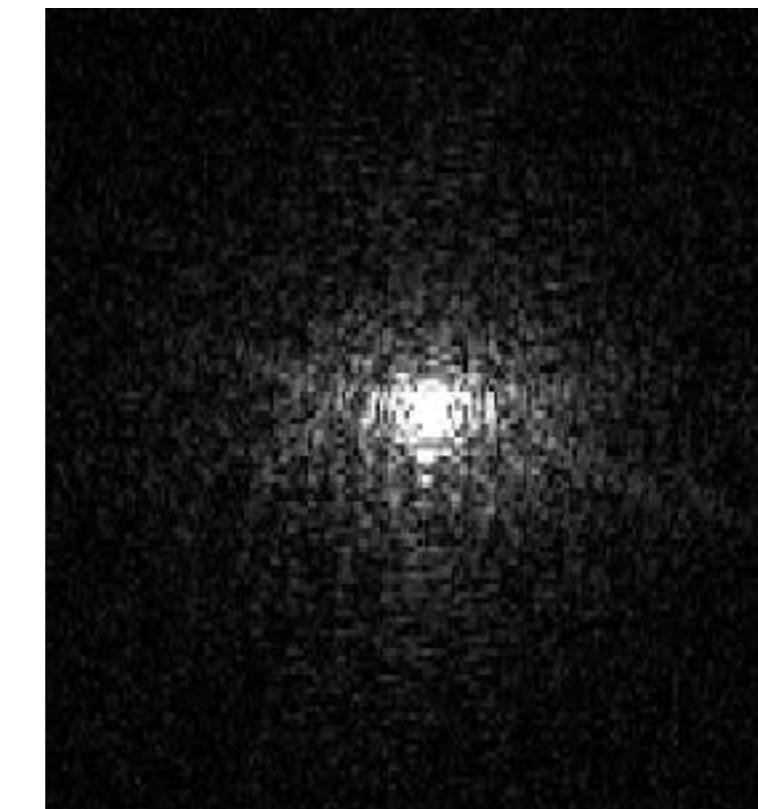


Reconstruction rétrospective :

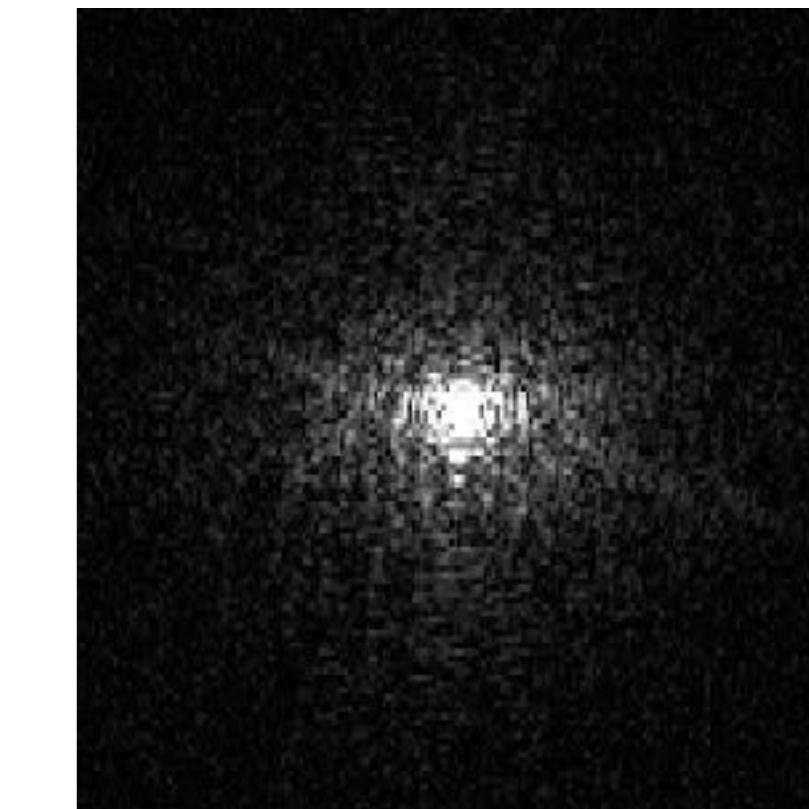
Ciné 1



Ciné 2



Ciné 3

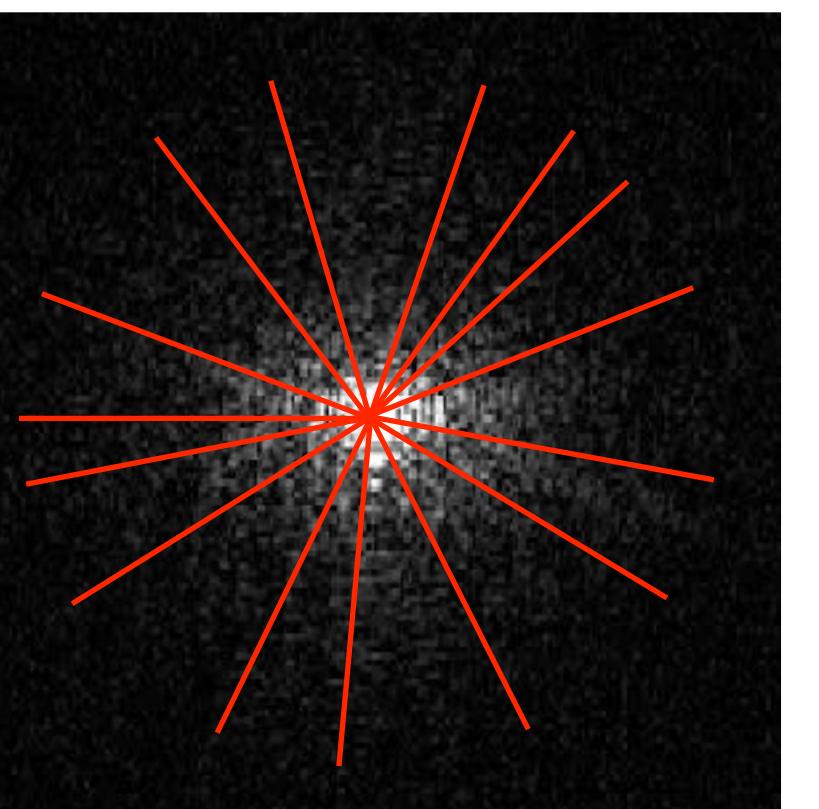
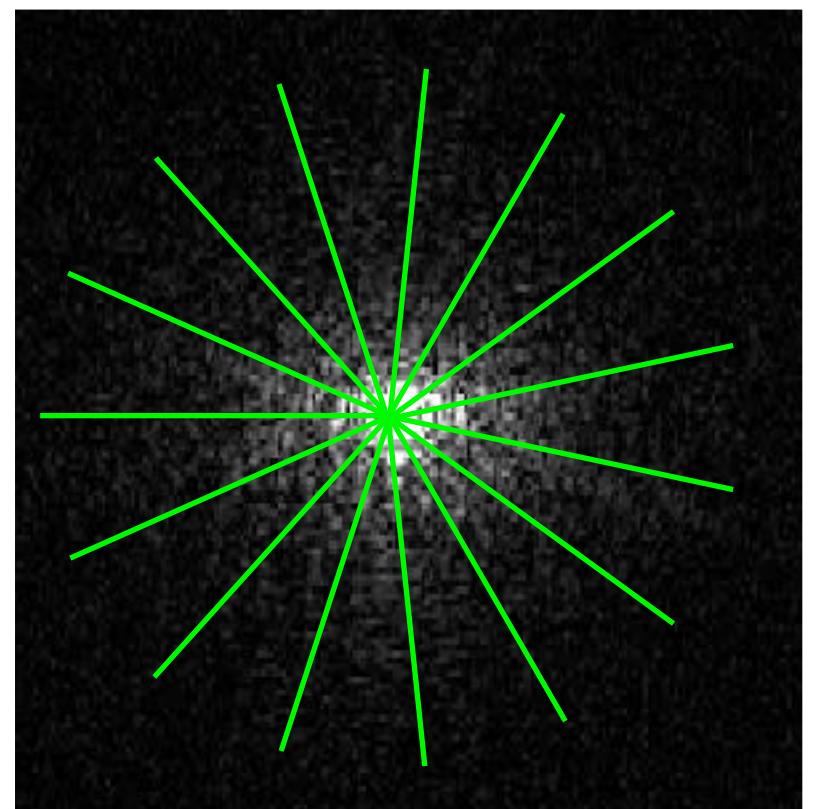


Répartition des projections :

Standard : $\theta = j \times 360/N_{\text{Pro}}$

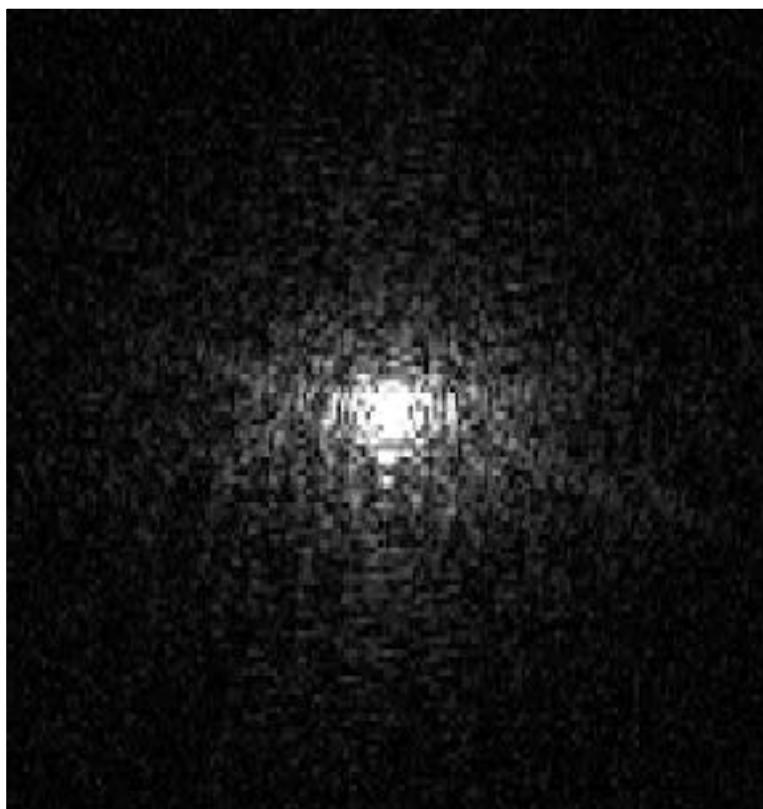
Angle d'or : $\theta = \text{mod}(222,48^\circ \times j, 360)$

$j = 1 : N_{\text{Pro}}$

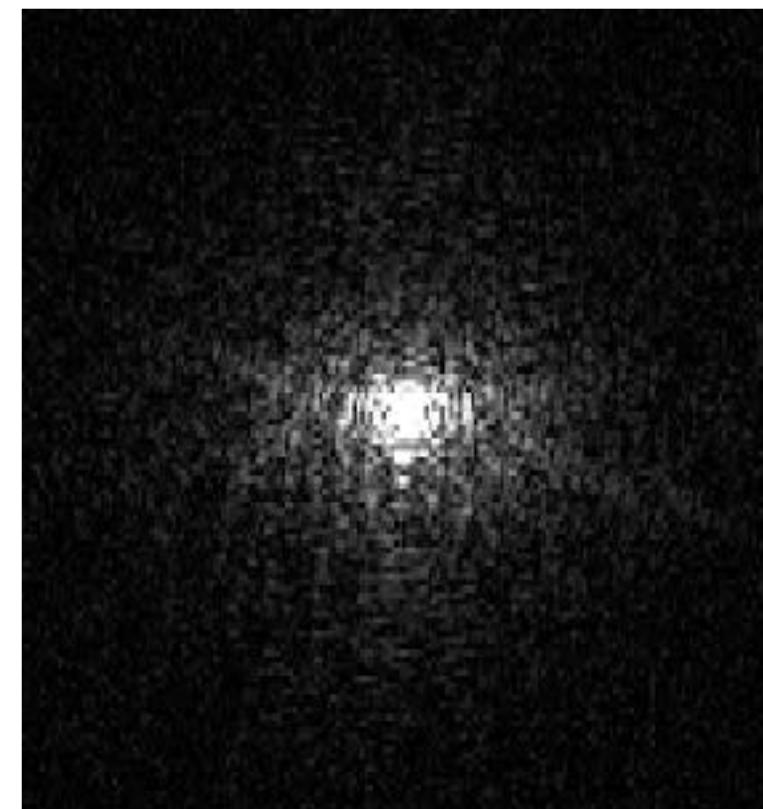


Reconstruction rétrospective :

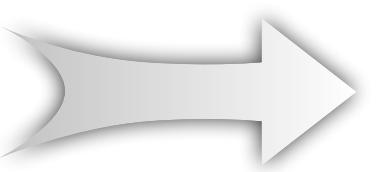
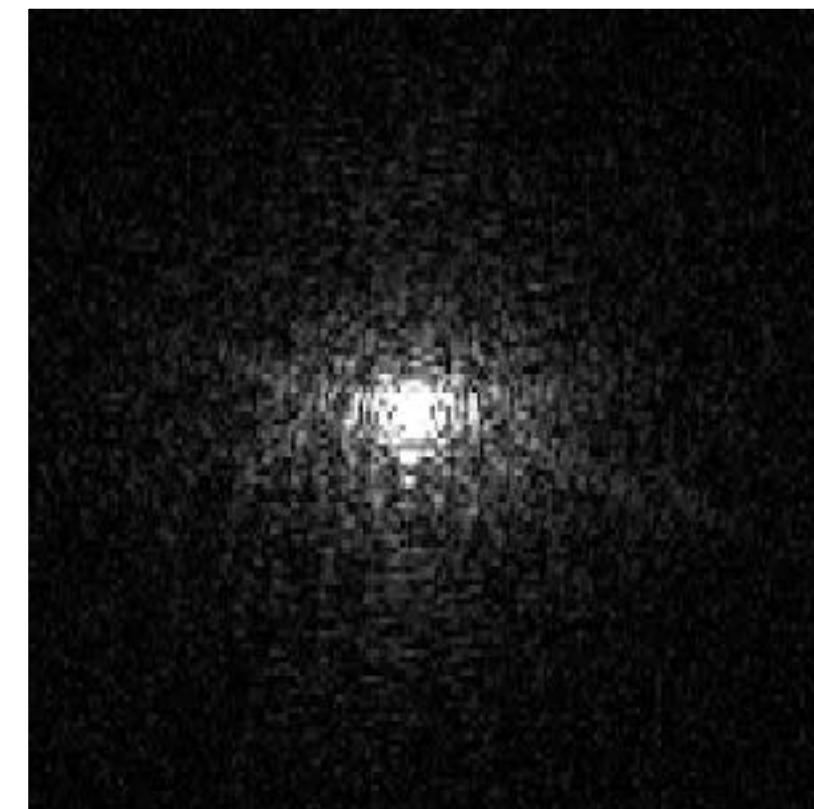
Ciné 1



Ciné 2

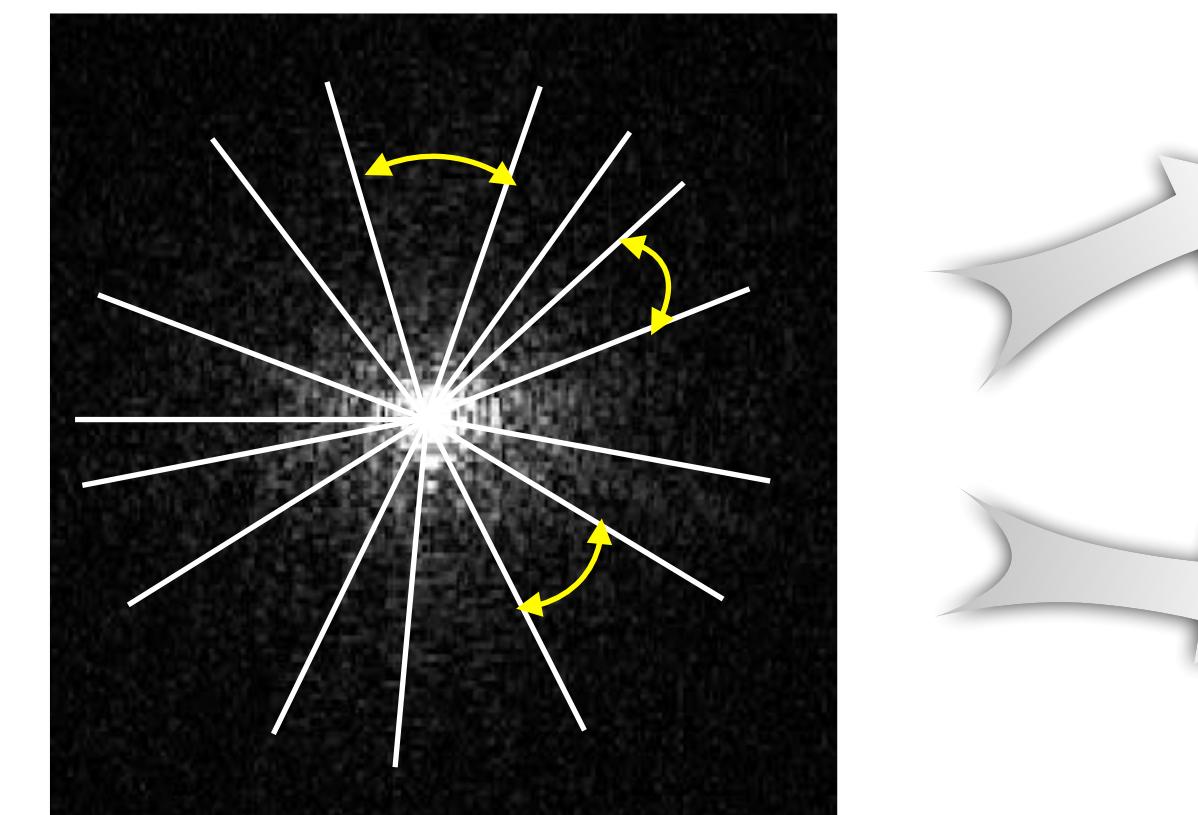


Ciné 3



Meilleure répartition après
N répétitions ?

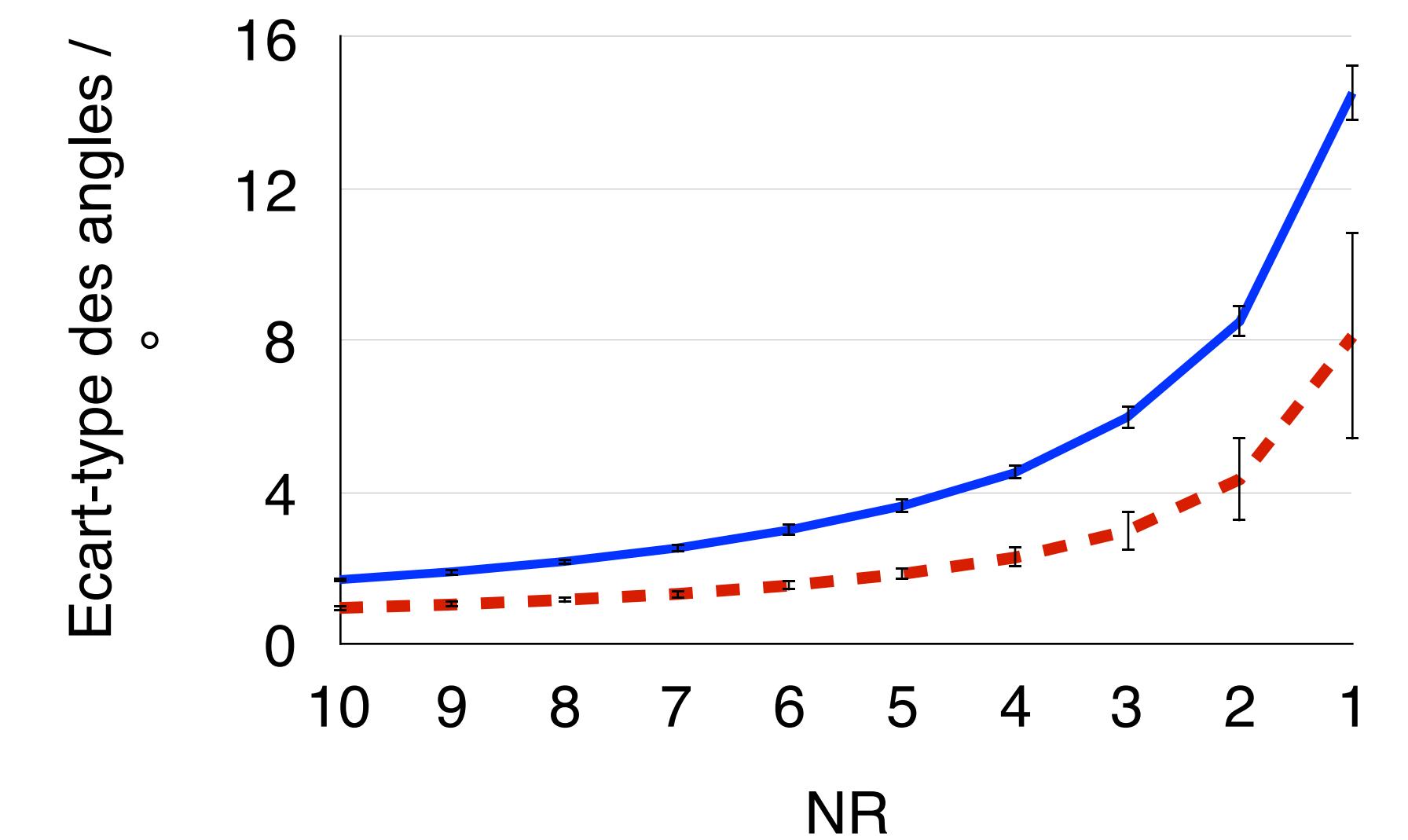
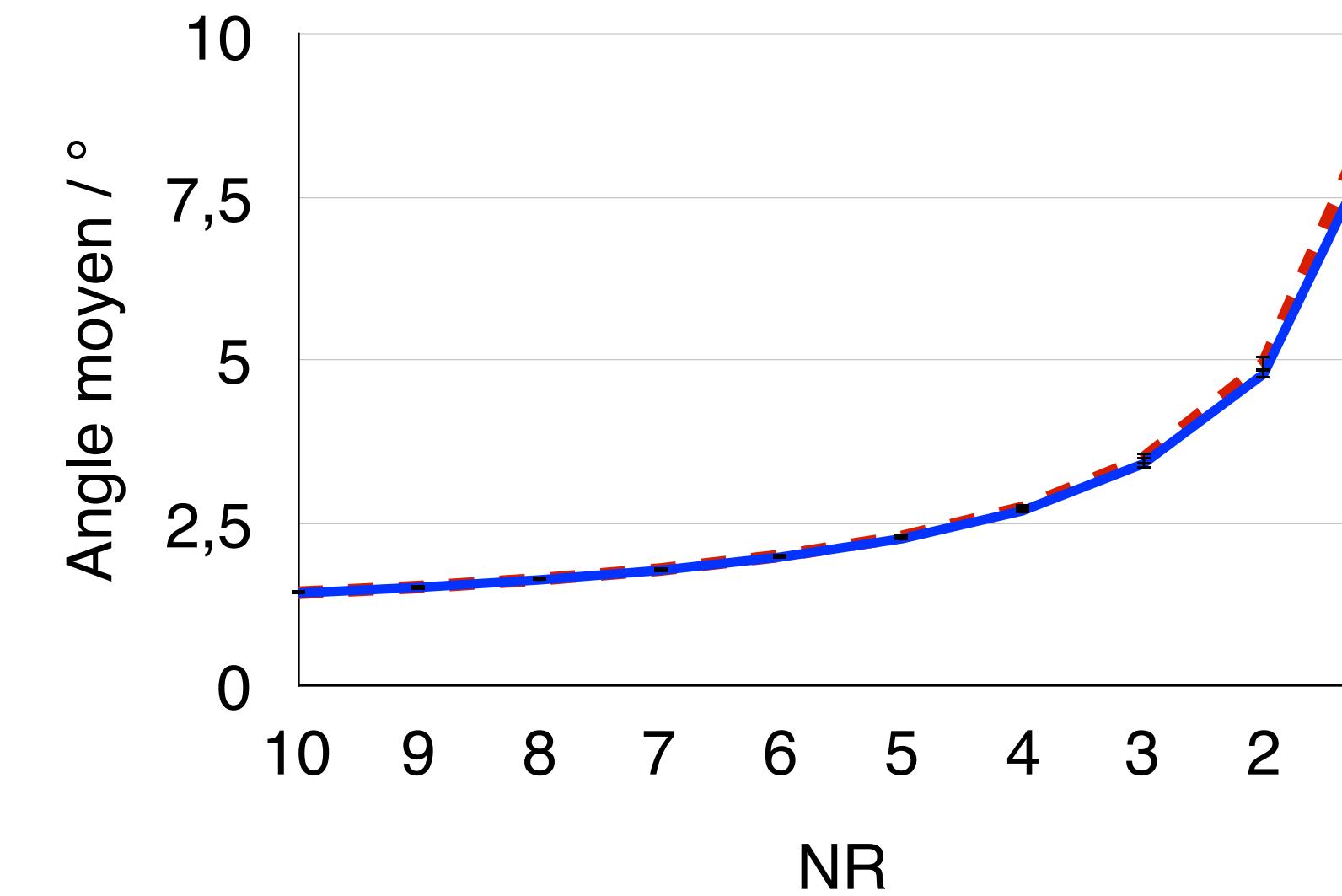
Evaluation de l'effet de l'angle d'or



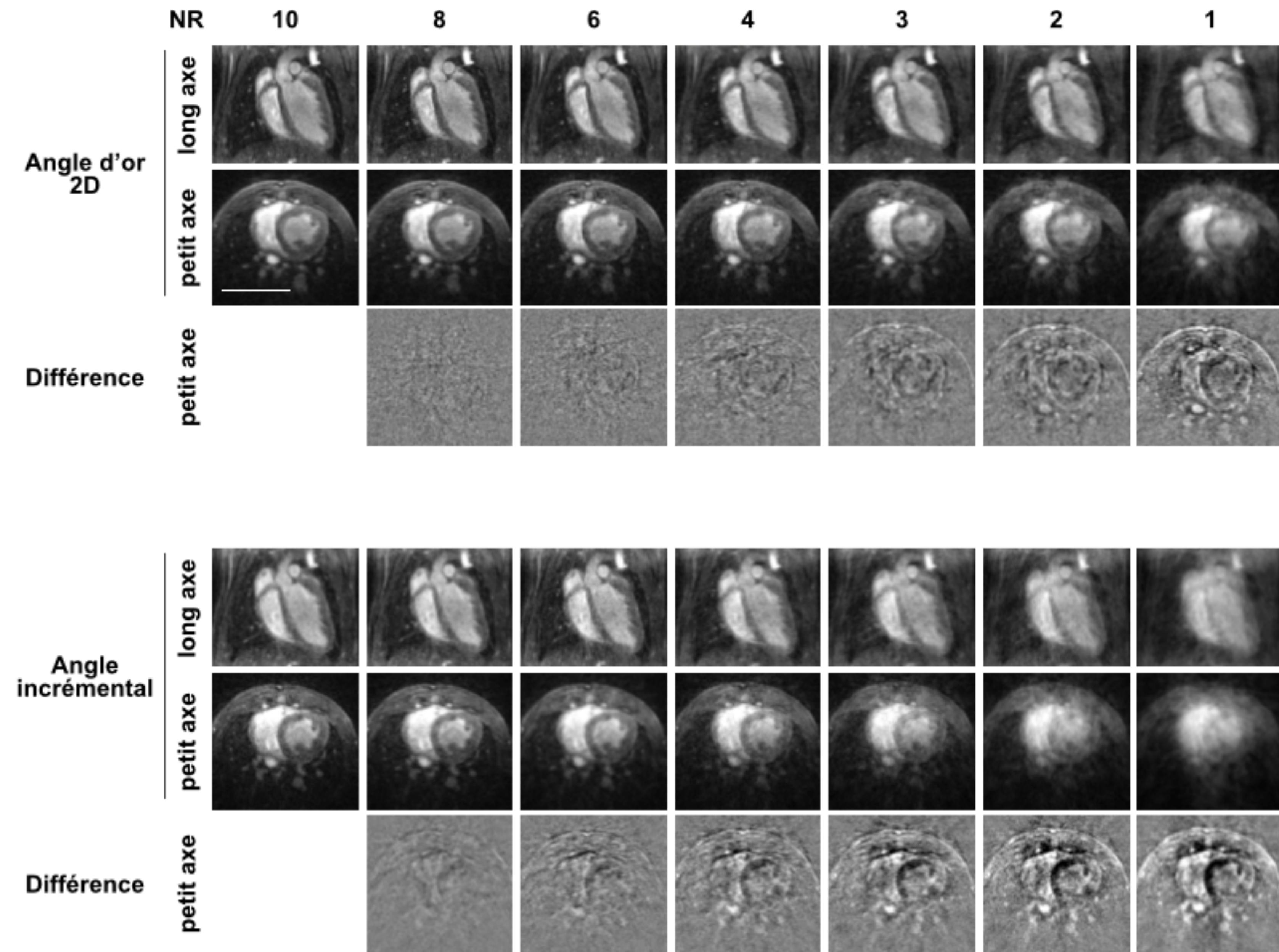
Valeur moyenne
des angles entre les
projections

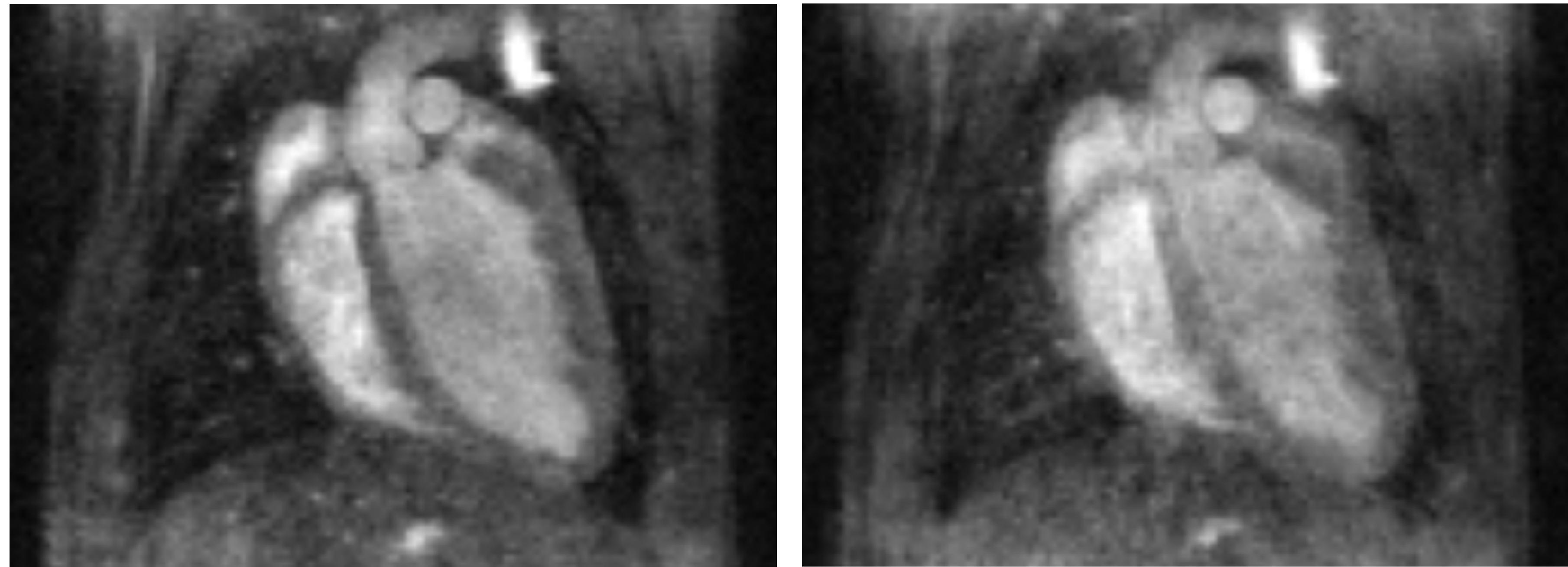
Ecart-type

Etudes à partir des données réelles :



Répartition plus homogène avec l'angle d'or





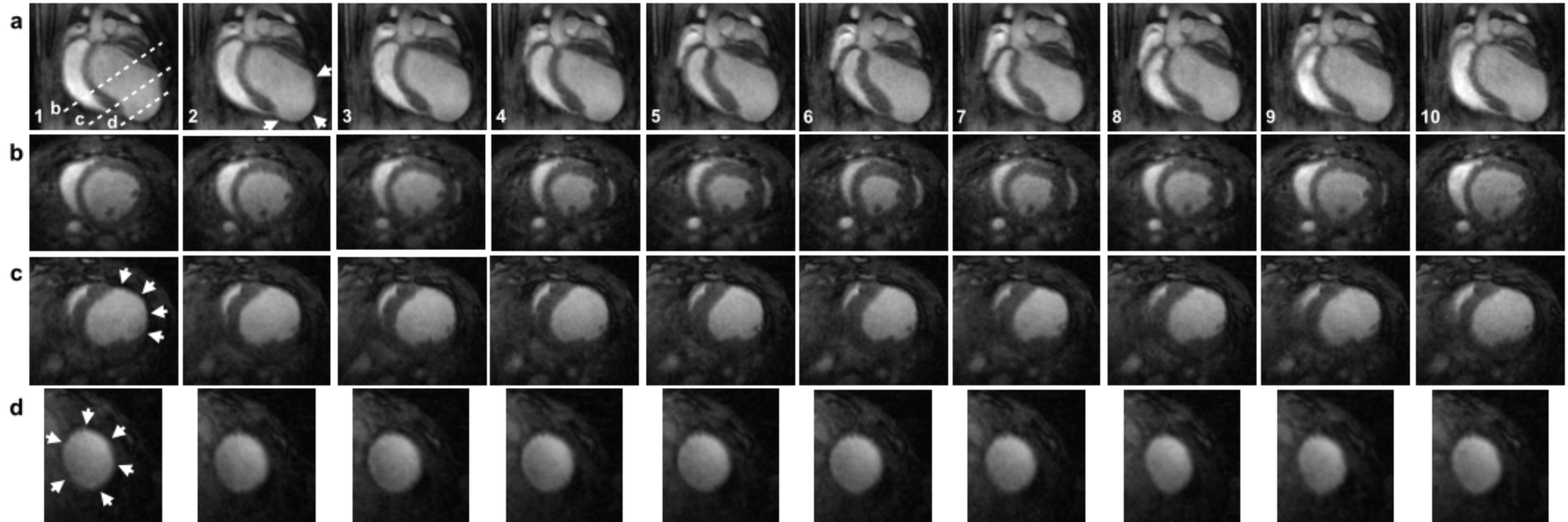
CSB (sang-myocarde)	NR = 10	NR = 8	NR = 6	NR = 4	NR = 3	NR = 2	NR = 1
Angle incrémental	14.0 ± 0.9	10.6 ± 1.2	9.6 ± 1.8	7.5 ± 1.9	3.2 ± 1.7	5.5 ± 1.6	1.8 ± 1.9
Angle d'or 2D	15.3 ± 1.0	13.0 ± 0.9	10.6 ± 1.2	8.9 ± 1.5	9.0 ± 1.0	9.8 ± 1.9	8.1 ± 1.8

Réduction du temps d'acquisition
possible avec l'angle d'or

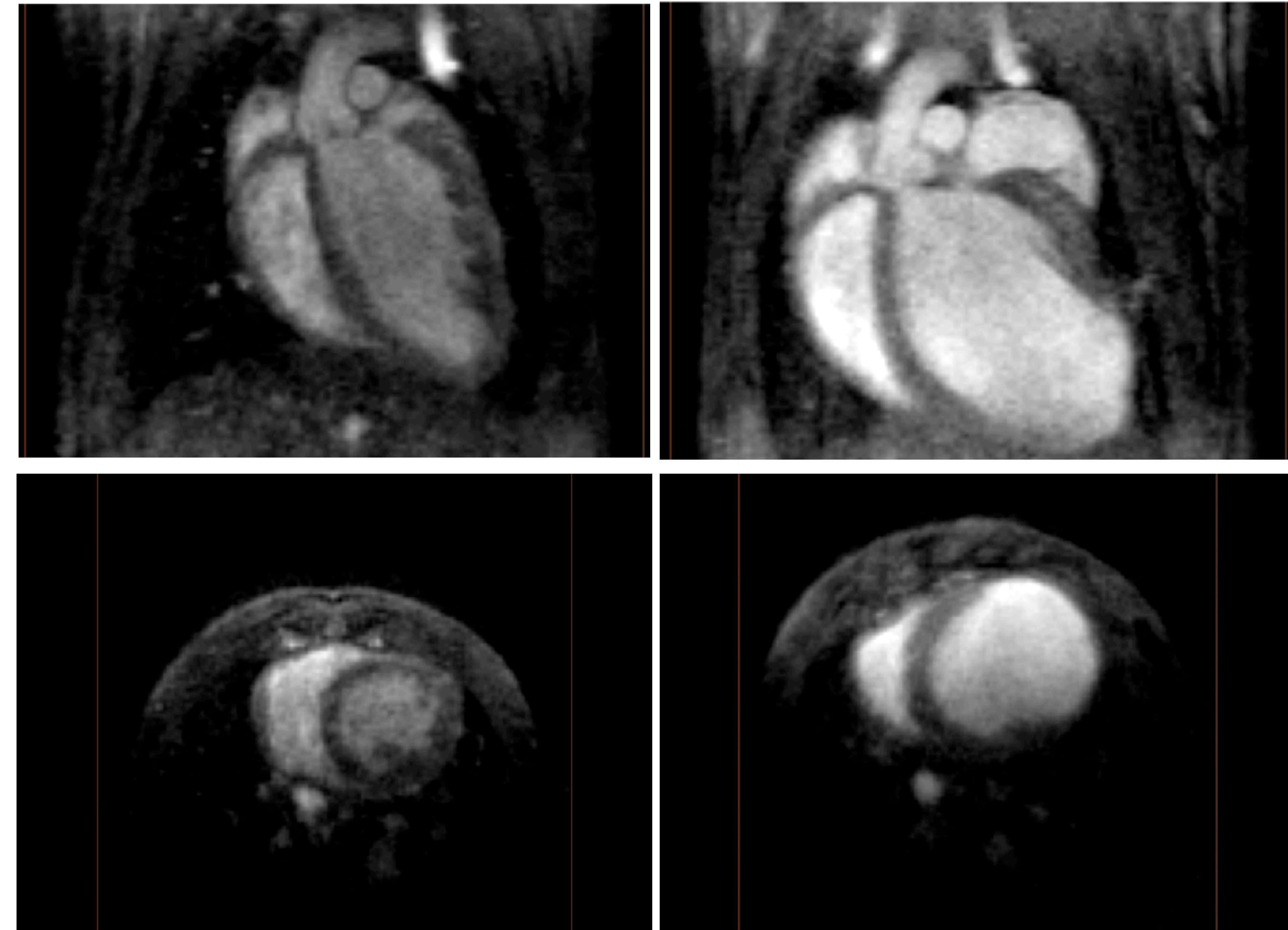
Infarctus aiguë du myocarde

NCine = 10

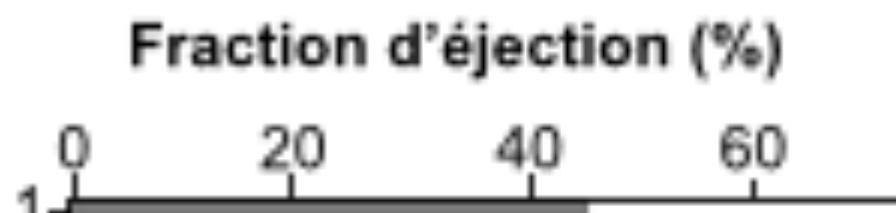
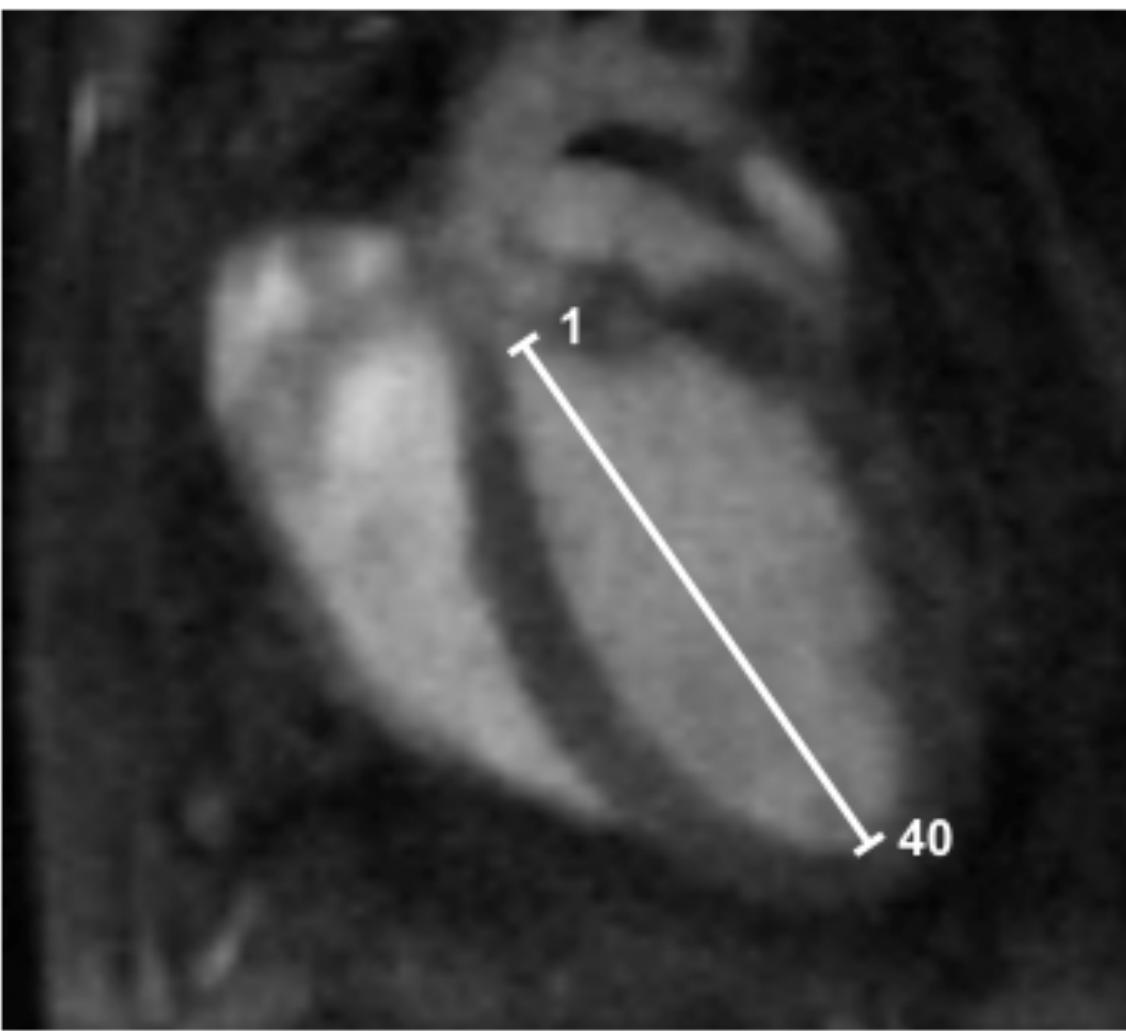
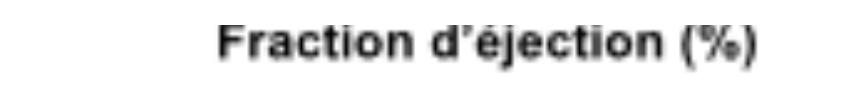
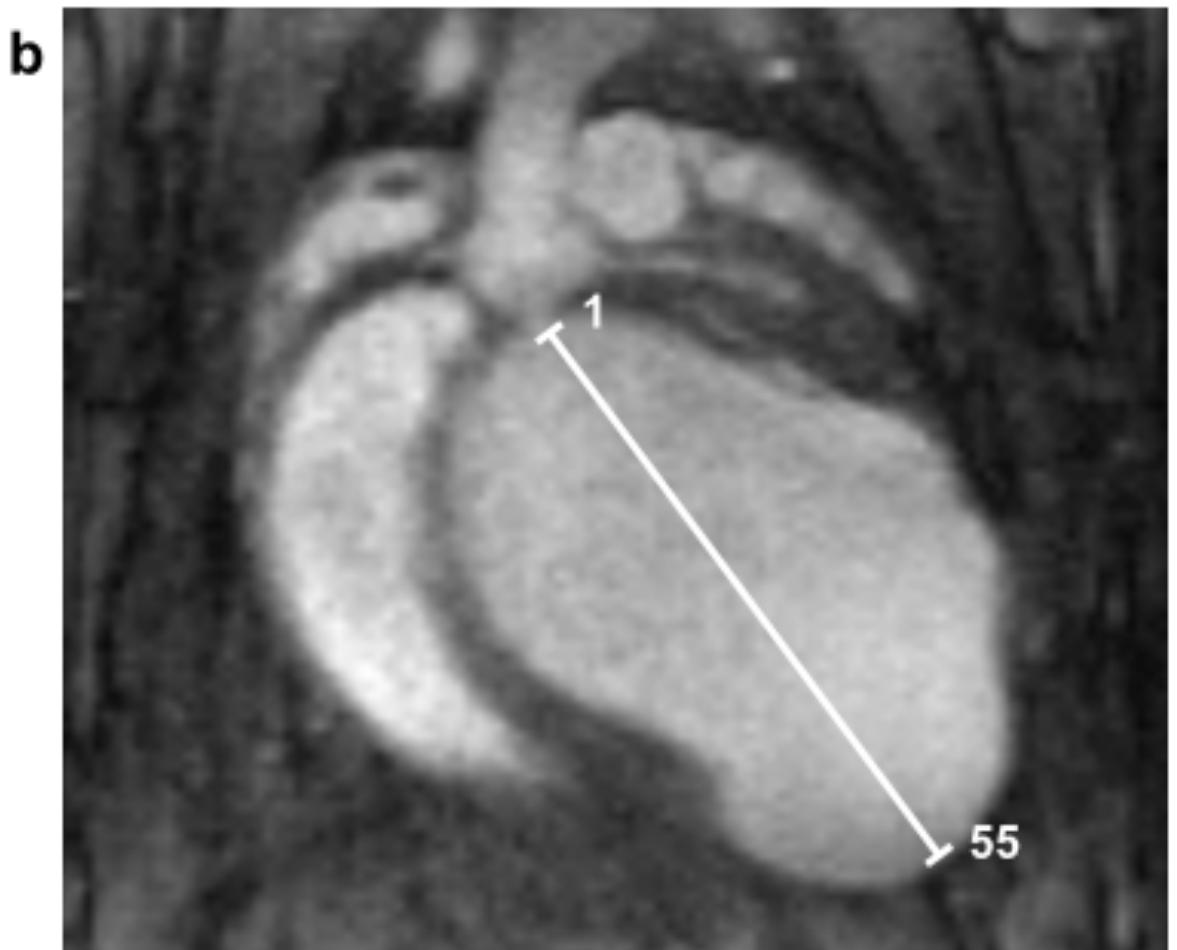
Temps acquisition = 15 min



Visualisation de zone avec une contraction
du myocarde pratiquement nulle



	FE (%)	VD (μL)	VS (μL)
Souris saines	67.7 ± 4.4	42.1 ± 7.1	13.7 ± 3.8
Souris pathologiques	20.7 ± 4.7	147.1 ± 19.2	116.1 ± 15.4

a**b**

Quantification précise en fonction de la position
dans le cœur

**Nouvelle séquence auto-synchronisée
basée sur l'angle d'or**

- Hautes résolutions spatiale et temporelle 3D
- Pas d'électrode ECG : mise en place simplifiée
- Choix a posteriori du nombre d'images à reconstruire
- Temps d'acquisitions réduits

Accepté dans JMRI en Novembre 2015

Limitations

- Sélection manuelle de l'antenne pour extraire le signal d'auto-synchronisation
- Signal d'auto-synchronisation variable en fonction de la position du cœur

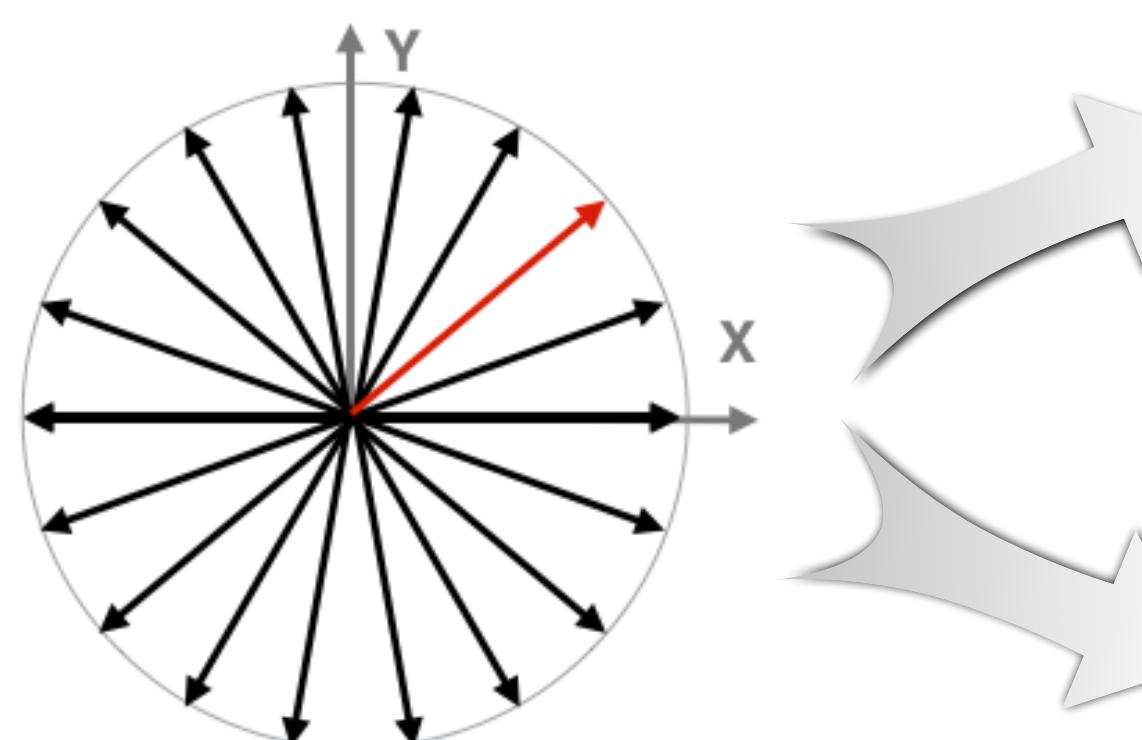
Perspectives

- Amélioration de l'extraction du signal d'auto-synchronisation : Convolution filtre / corrélation entre canaux
- Ajout de filtre temporel de reconstruction

Conclusion générale

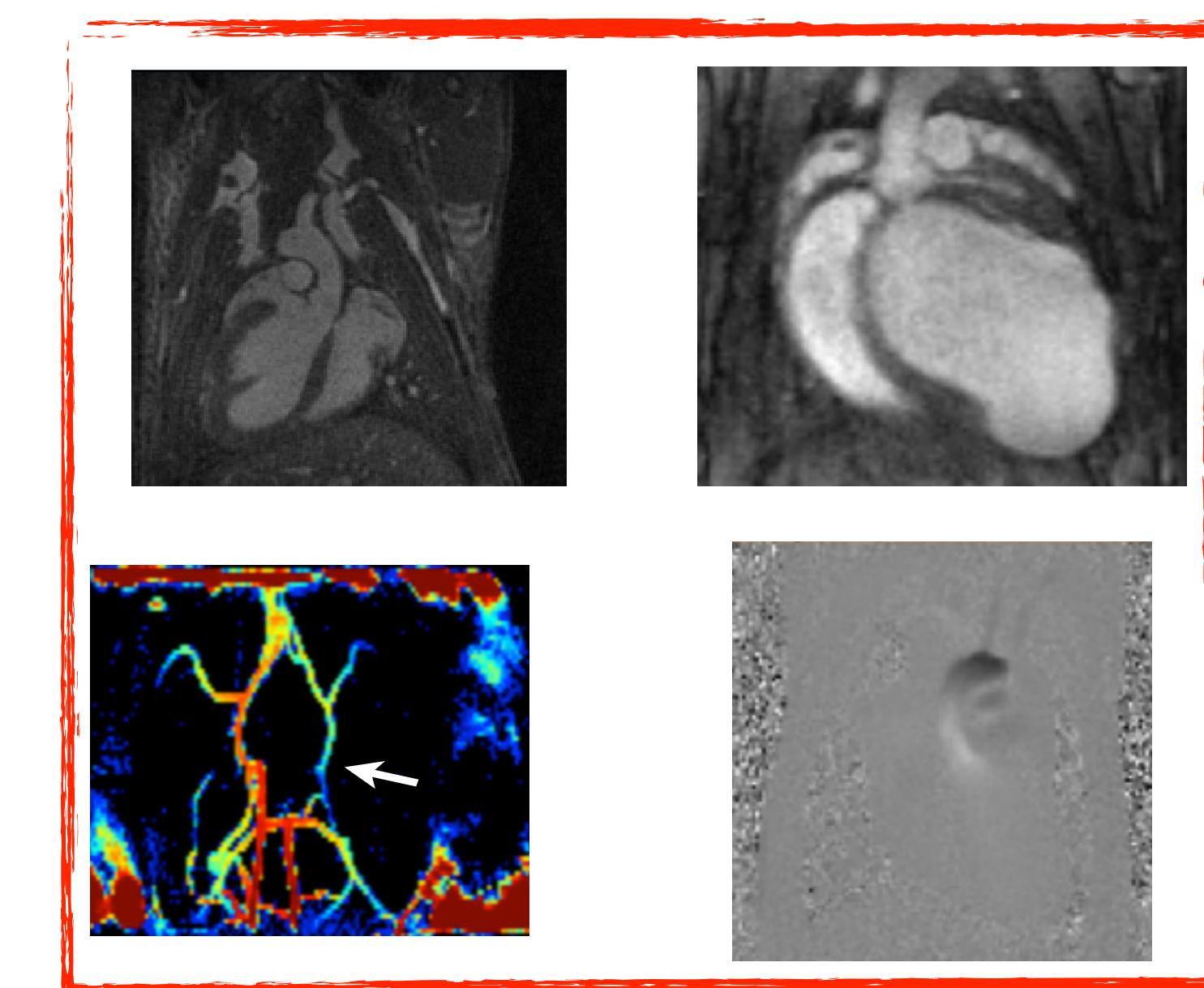
Trajectoires radiales

- Flexibilité de la trajectoire : passage au centre de l'espace de Fourier à chaque lecture
- Peu sensible aux artefacts de mouvements et flux (particulièrement UTE)
- Limitation de la décroissance du signal provoquée par le T₂* pour les séquences UTE



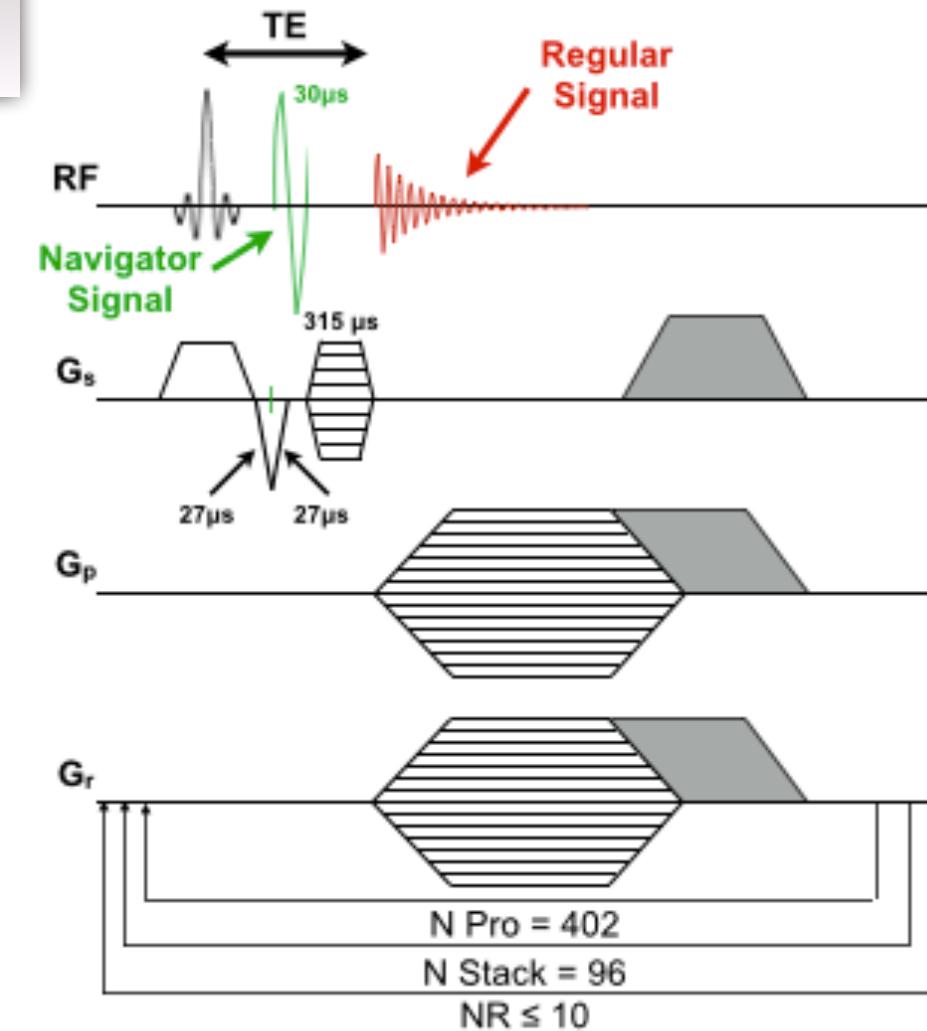
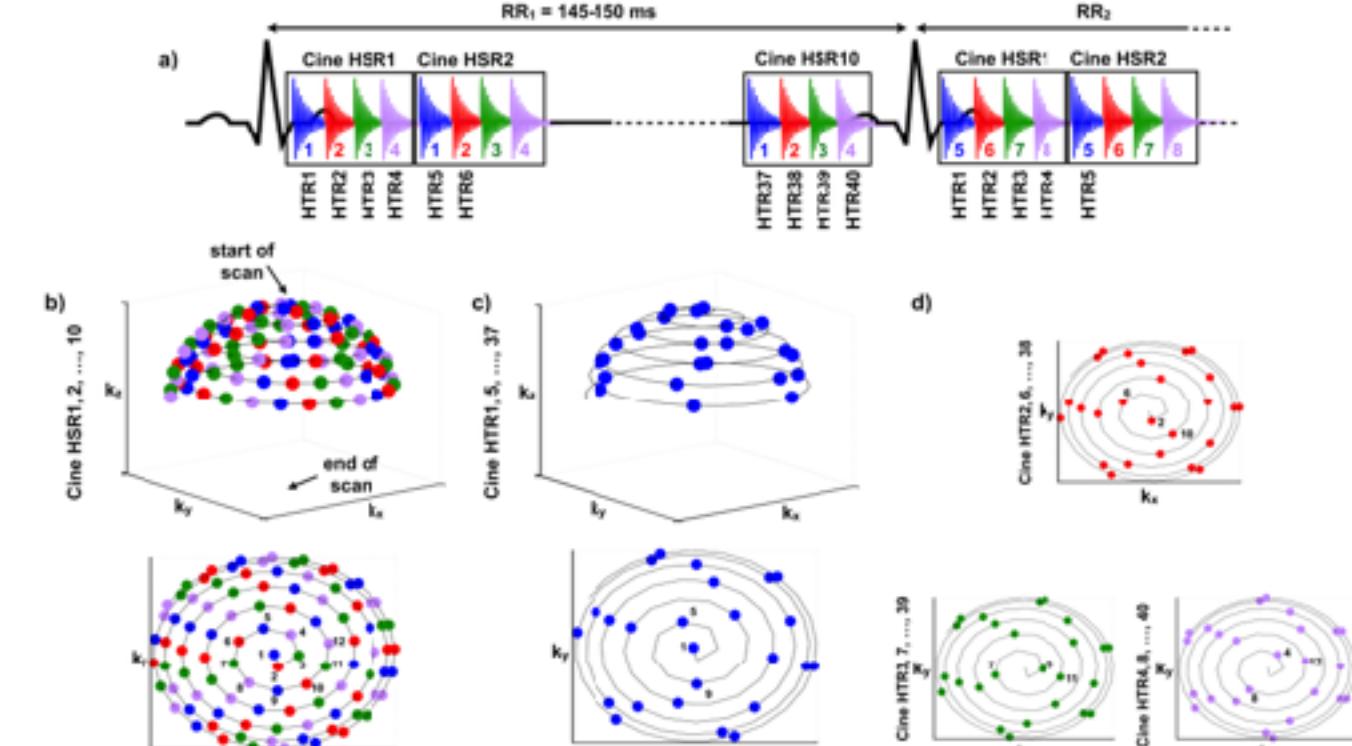
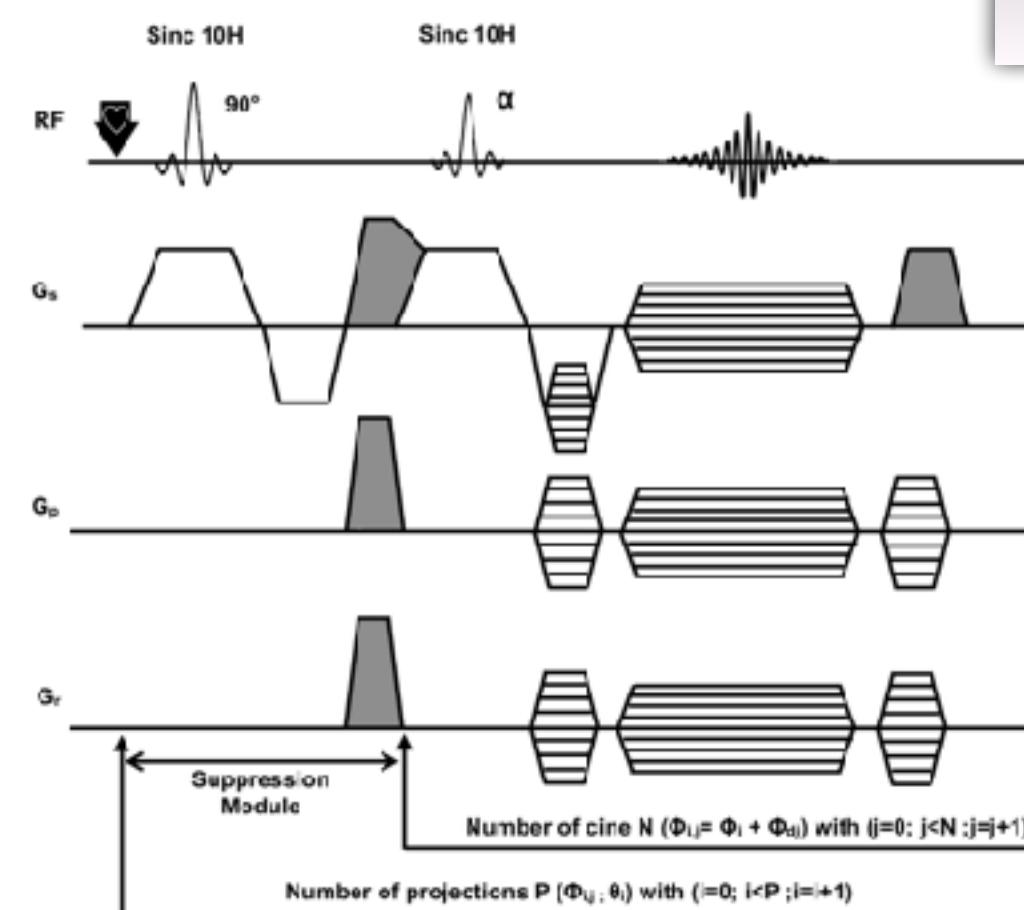
Imagerie
anatomique

Imagerie
fonctionnelle



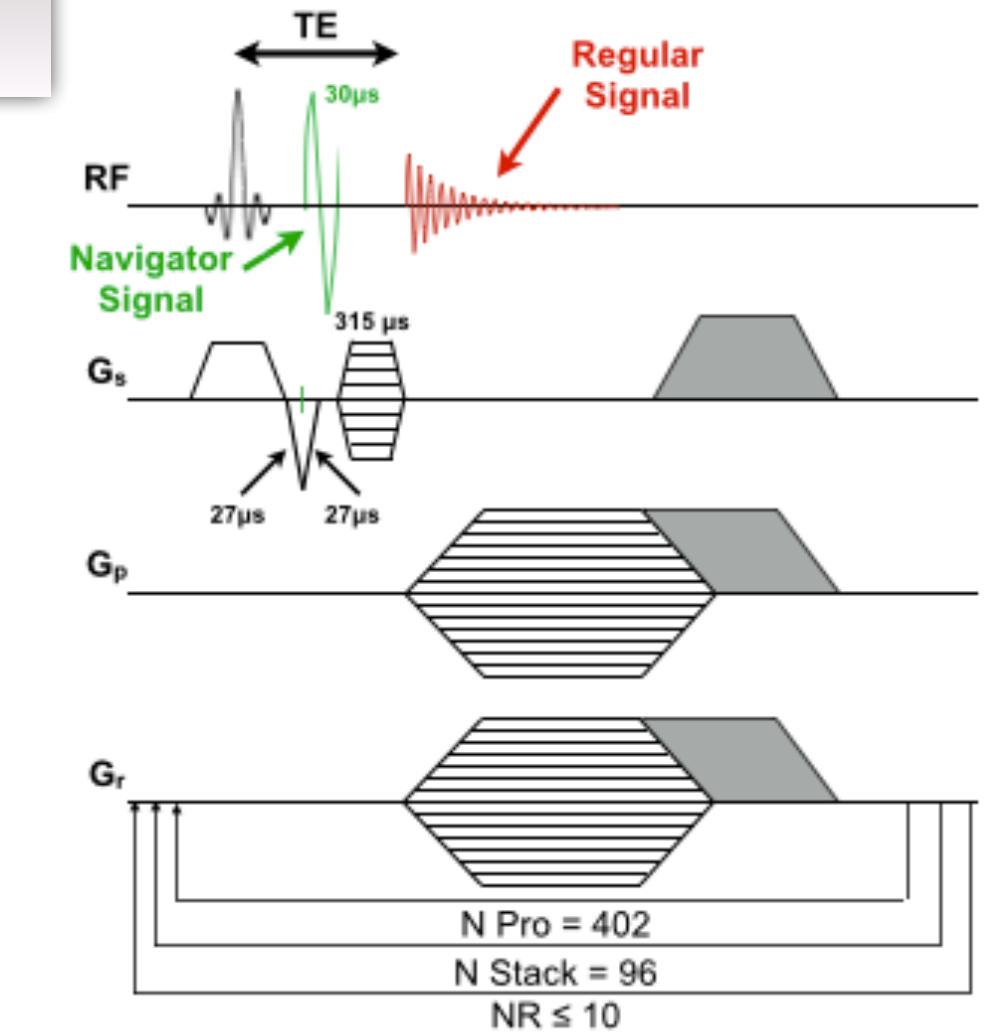
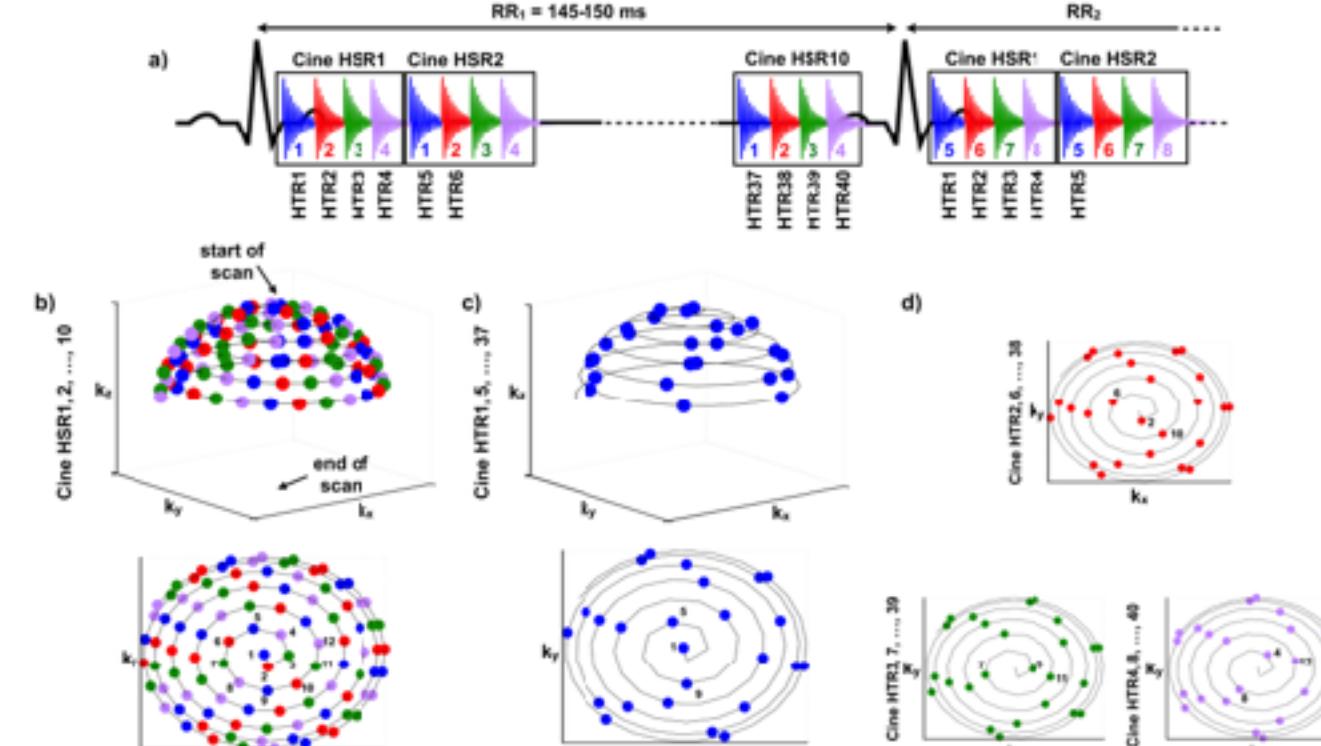
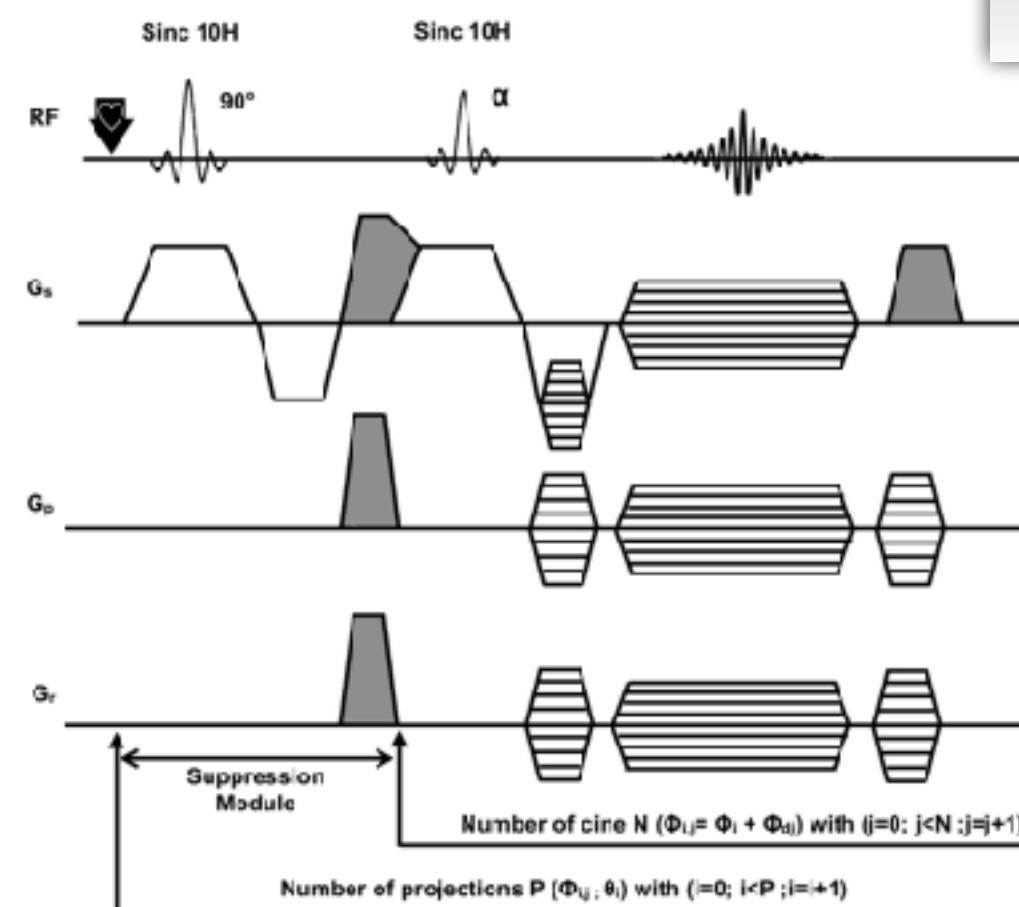
Méthodes complémentaires :
type d'études/pathologies

Schémas d'acquisitions innovants

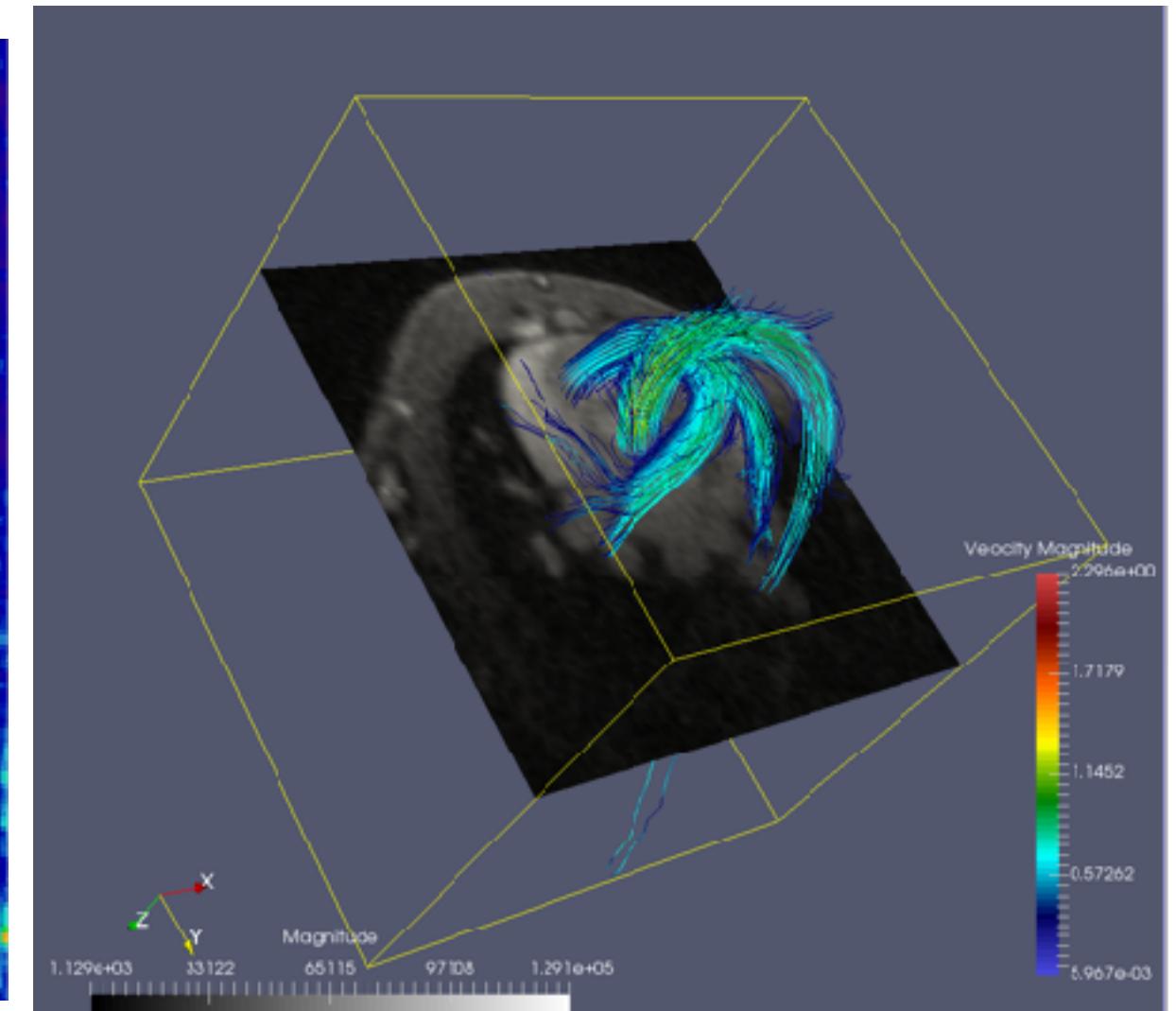
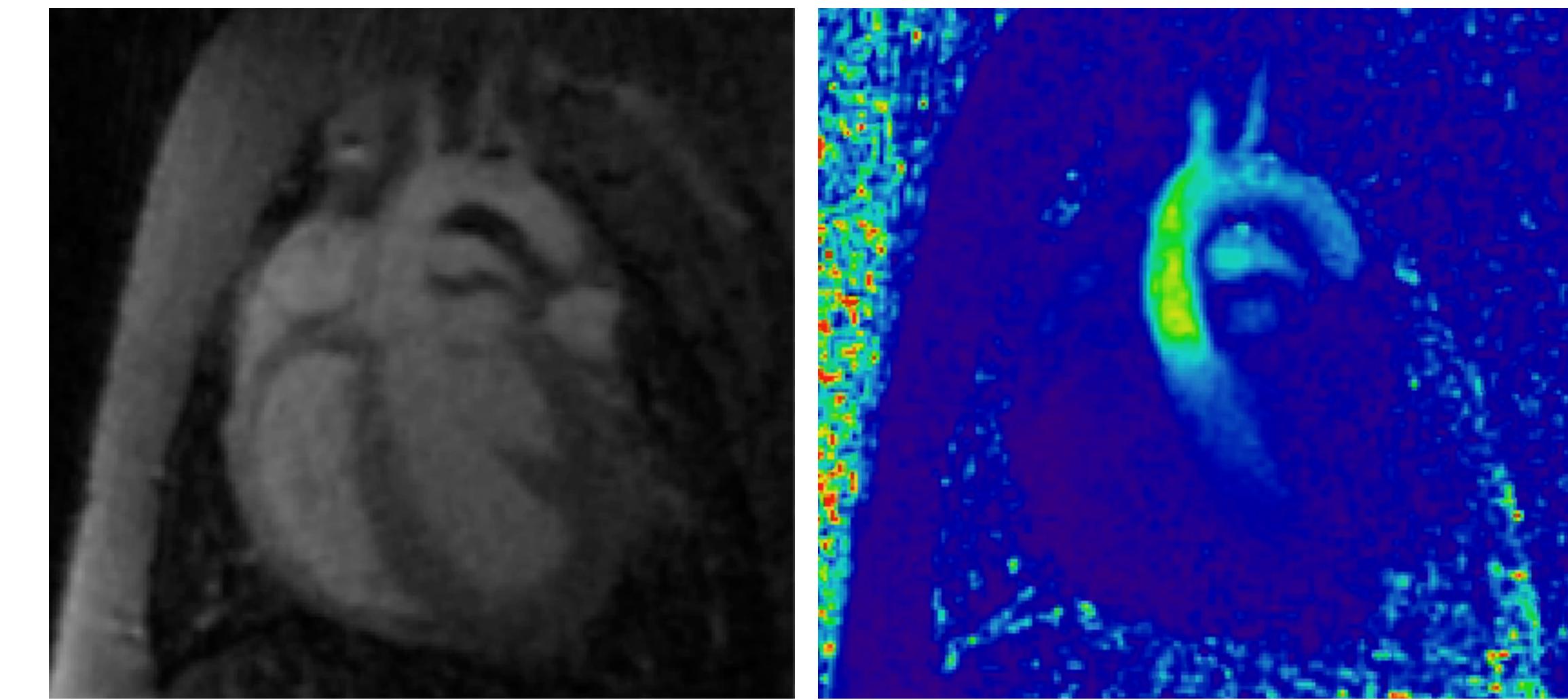
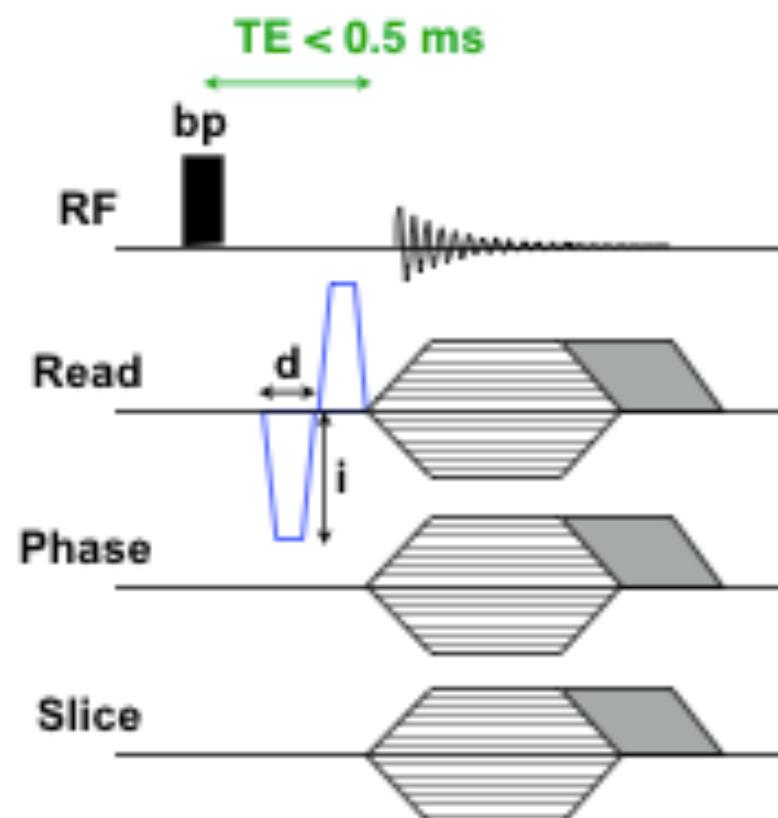


Conclusion générale

Schémas d'acquisitions innovants



Mesure de flux 4D UTE



Articles acceptés**Communications****Article en relation avec cette thèse :**

1. Trotier AJ, Lefrançois W, Ribot EJ, Thiaudiere E, Franconi J, Miraux S. Time-resolved TOF MR angiography in mice using a prospective 3D radial double golden angle approach. *Magn Reson Med* 2015 ;73 :984-94.
2. Trotier AJ, Lefrançois W, Van Renterghem K, Franconi J, Thiaudière E, Miraux S. Positive contrast high-resolution 3D-cine imaging of the cardiovascular system in small animals using a UTE sequence and iron nanoparticles at 4.7, 7 and 9.4 T. *Journal of Cardiovascular Magnetic Resonance* 2015 ;17 :1-10.
3. Trotier AJ, Castets CR, Lefrançois W, Ribot EJ, Franconi J, Thiaudière E, Miraux S. USPIO-enhanced 4D self-gated golden angle cardiac MRI based on a Stack-Of-Stars UTE sequence : Application on mice with acute myocardial infarction. Accepté dans Journal of Magnetic Resonance Imaging.

Articles en collaboration :

1. Hannecart A, Stanicki D, Vander Elst L, Muller RN, Lecommandoux S, Thévenot J, Bonduelle C, Trotier A, Massot P, Miraux S, Sandre O, Laurent S. Nano-thermometers with thermo-sensitive polymer grafted USPIOS behaving as positive contrast agents in low-field MRI. *Nanoscale* 2015 ;7 :3754-67.
2. Ribot EJ, Duriez TJ, Trotier AJ, Thiaudiere E, Franconi J, Miraux S. (2014) Self-gated bSSFP sequences to detect iron-labeled cancer cells and/or metastases in vivo in mouse liver at 7 Tesla. *J. Magn. Reson. Imaging*, 41 : 1413–1421. doi : 10.1002/jmri.24688
3. Castets CR, Ribot EJ, Lefrançois W, Trotier AJ, Thiaudiere E, Franconi J, Miraux S. Fast and robust 3D T1 mapping using spiral encoding and steady RF excitation at 7T : application to cardiac manganese enhanced MRI (MEMRI) in mice. *NMR Biomed.*, 28, 881–889. doi : 10.1002/nbm.3327.
4. Ribot EJ, Wecker D, Trotier AJ, Dallaudiere B, Lefrançois W, Thiaudière E, Franconi J, Miraux S. Imaging and bSSFP Banding Artifact Correction in Humans and Small Animals at 3T and 7T, Respectively. Zhang H, ed. *PLoS ONE*. 2015;10(10):e0139249. doi:10.1371/journal.pone.0139249.
5. Ribot EJ, Trotier AJ, Castets CR, Dallaudiere B, Thiaudière E, Franconi J, Miraux S. Free-breathing 3D diffusion MRI for high-resolution hepatic metastasis characterization in small animals. *Clinical & Experimental Metastasis*, 2015, p. 1-12.





Adaptation des séquences

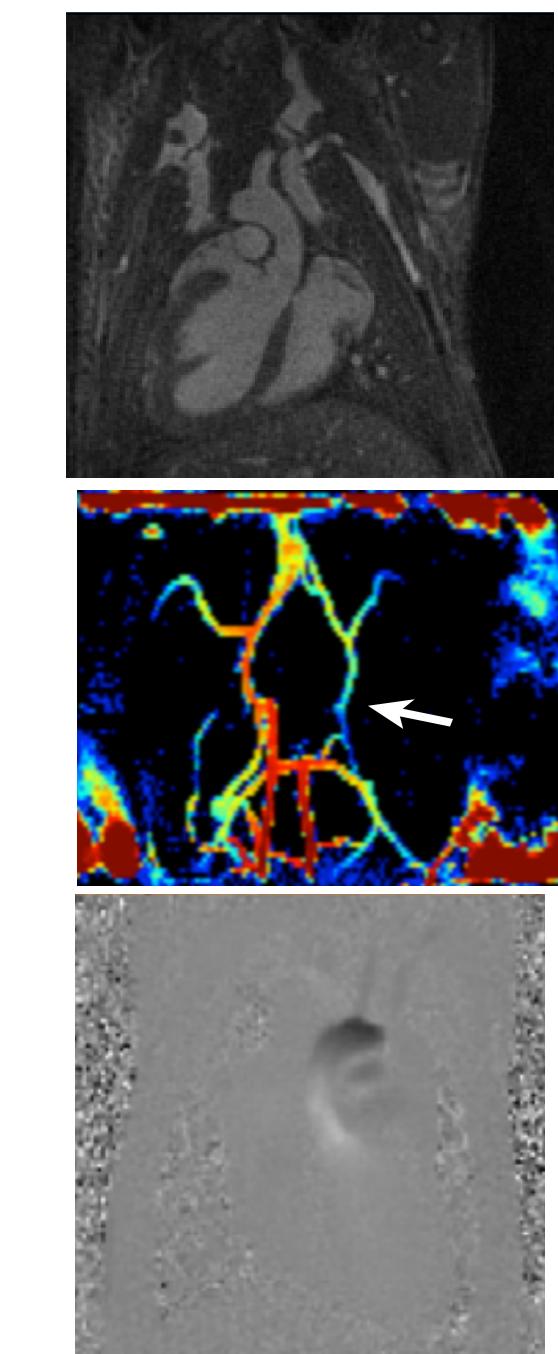
Temps d'acquisitions

- Imagerie parallèle
- Reconstruction « compressed sensing »

Mouvements respiratoires

- Reconstruction rétrospective
- Quantification et correction

Projets en cours



Séquence UTE développée sur un imageur clinique :
Application prochaine sur un cochon

Développement d'une version Stack-Of-Stars
pour application sur le polygone de Willis chez
des volontaires sains

Développement d'une méthode de mesure de
flux Stack-Of-Stars UTE sans injection

Merci de votre attention

Rermerciements

Team MIRAUx



- Emeline
- Neha *
- William
- Charles
- Sylvain



Tout le



bien encadré par
Jean-Michel

Les
retraités

mais pas
totalement

Les
personnes
qui ont
déménagés
mais pas
totalement

MA
FAMILLE

Agathe

Mes
amis

* Malgré ses déclarations durant ses remerciements de thèse ;)

université
de BORDEAUX



TRAIL-newFISP

Questions