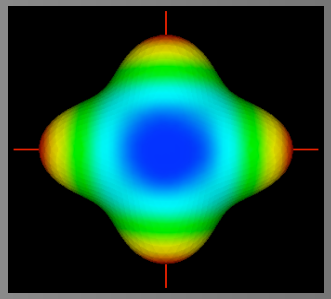
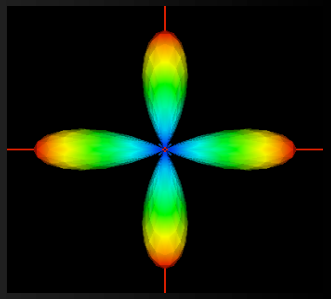
Testing classical single-shell HARDI techniques



Maxime Descoteaux &
Michael Paquette

Sherbrooke Connectivity Imaging Lab,
Computer Science department,
Université de Sherbrooke

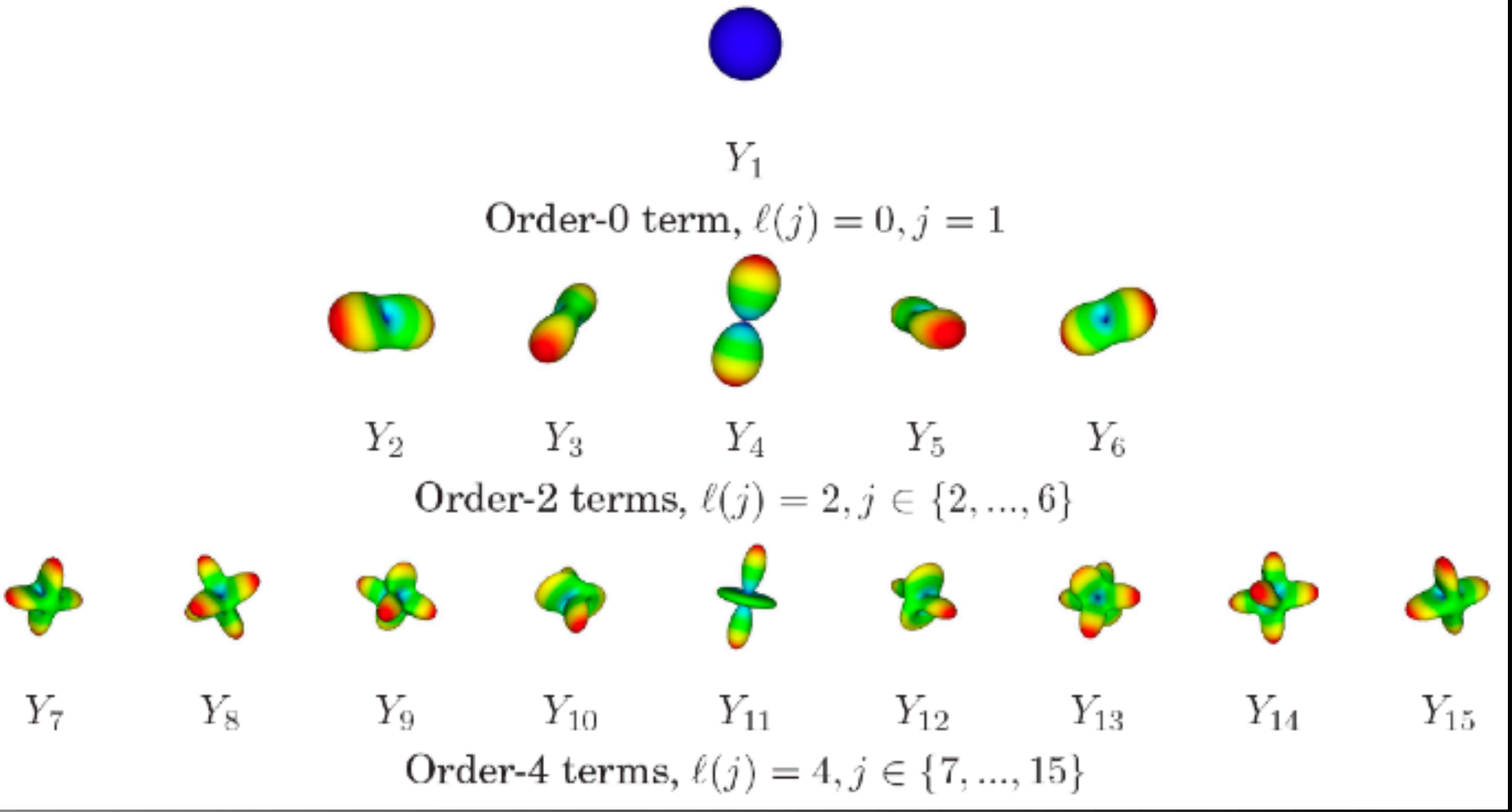


UNIVERSITÉ DE SHERBROOKE

Techniques tested

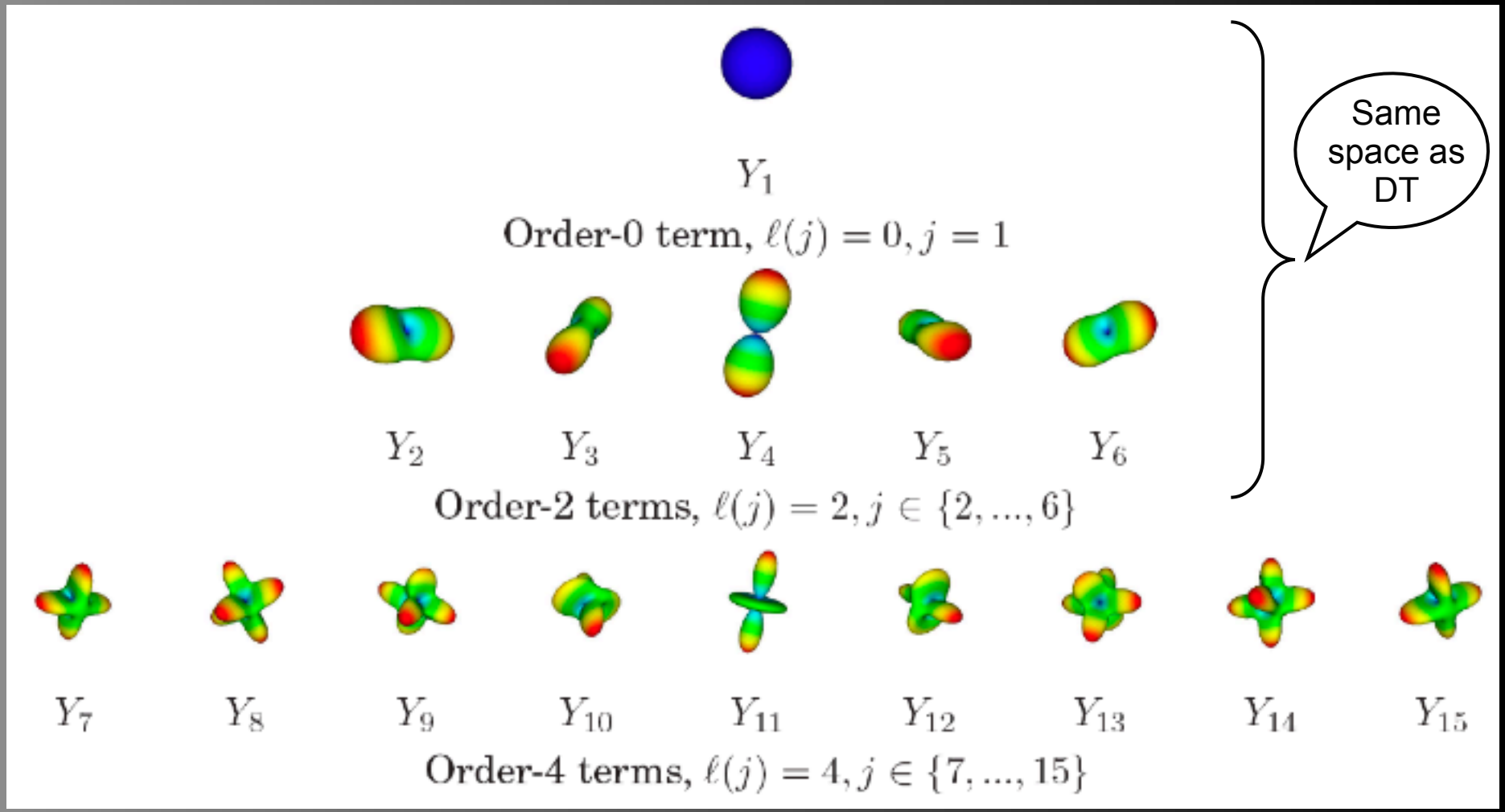
- a-qbi (analytical QBI)
- csa-qbi (normalized QBI)
- swt (spherical wavelet transform)
- odf deconvolution
- *mrtrix* deconvolution
- DSI with parameter-tuning
  (zero-padding, Hanning filtering, integration)

Spherical harmonics



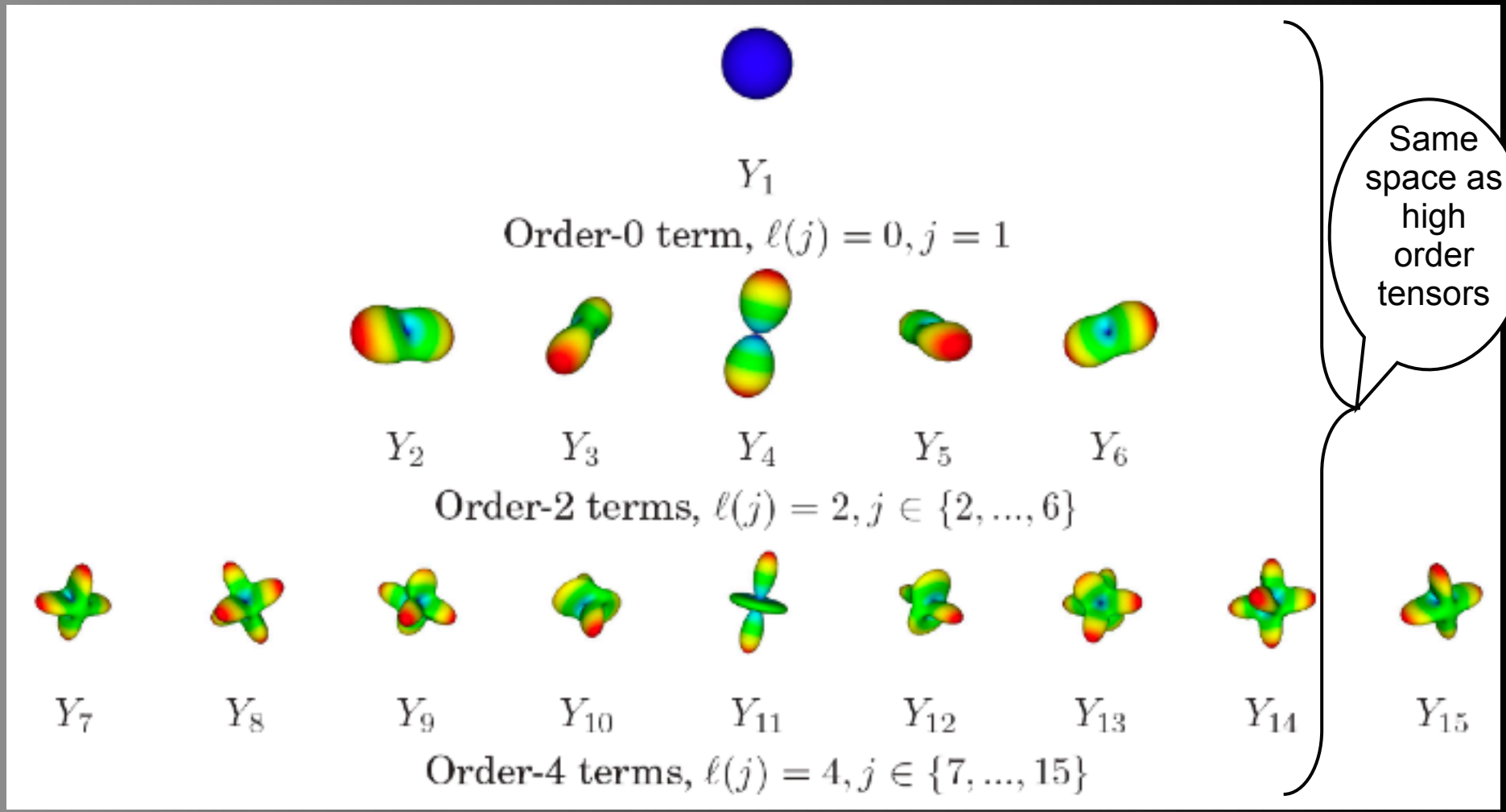
[Descoteaux et al. MRM 06]

Spherical harmonics



[Descoteaux et al. MRM 06]

Spherical harmonics



[Descoteaux et al. MRM 06]

Spherical harmonics

- Order used in the ISBI contest 4, 6, 8, & 10
- Leading to R = 15, 28, 45, & 66 coefficients

$$S(\theta_i, \phi_i) = \sum_{j=1}^{R} c_j Y_j(\theta_i, \phi_i)$$

[Descoteaux et al. MRM 06]

Spherical harmonics

- Order used in the ISBI contest 4, 6, 8, & 10
- Leading to R = 15, 28, 45, & 66 coefficients

$$S(\theta_i, \phi_i) = \sum_{j=1}^{R} c_j Y_j(\theta_i, \phi_i)$$

- In matrix form, S = C*B

  S : discrete HARDI data 1 x N

  C : SH coefficients 1 x R = (1/2)(order + 1)(order + 2)

  B : discrete SH, $Y_j(\phi,\theta)$ N x R

  (N diffusion encoding gradients and R SH basis elements)

[Descoteaux et al. MRM 06]

Laplace-Beltrami regularization

- Minimize
  $(CB - S)^T(CB - S) + \lambda C^T L C$

=>

$C = (B^T B + \lambda L)^{-1} B^T S$

$\lambda = 0$

[Anderson MRM 05]

L := Identity matrix

[Hess et al MRM 06]

L := Laplace-Beltrami matrix

[Descoteaux et al MRM 06
MRM 07]

Laplace-Beltrami regularization

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$\lambda = 0$

[Anderson MRM 05]

L := Identity matrix

[Hess et al MRM 06]

L := Laplace-Beltrami matrix

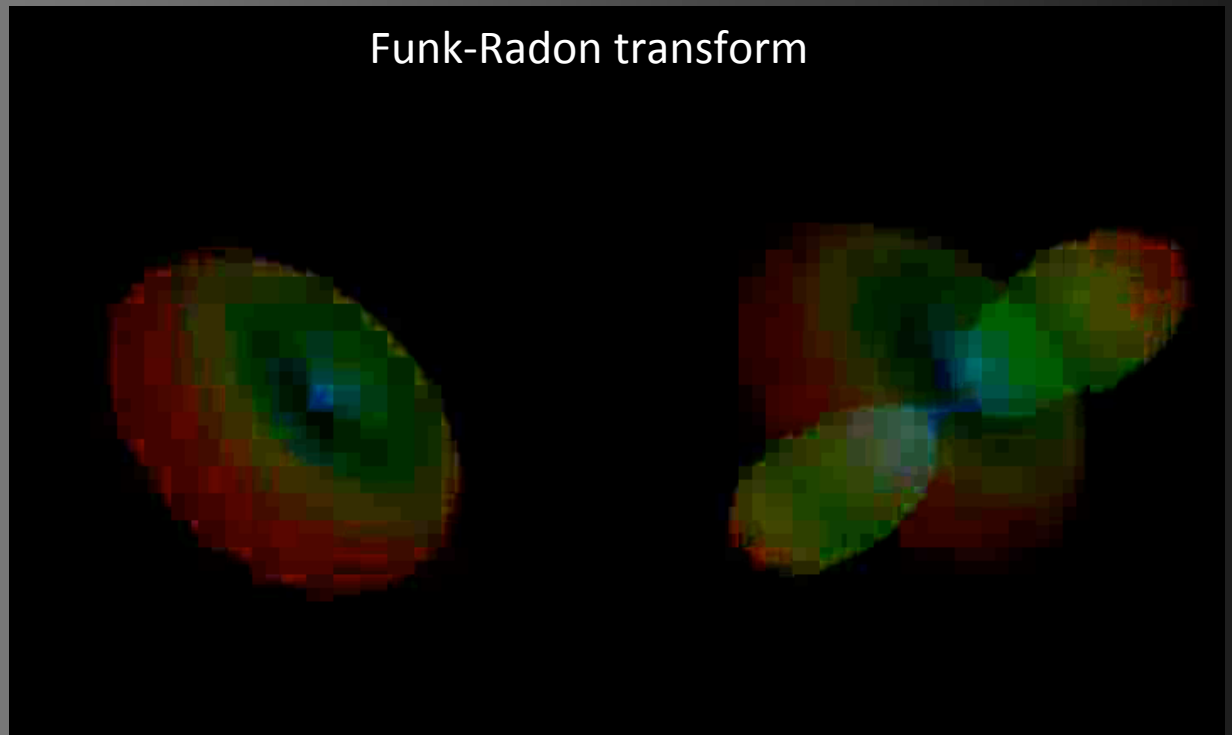
[Descoteaux et al MRM 06 MRM 07]

$$\mathbf{L} = \begin{pmatrix} \ddots & & \\ & \ell_j^2(\ell_j+1)^2 & \\ & & \ddots \end{pmatrix} = \begin{pmatrix} 0 & & & \\ & 4 & & \\ & & \ddots & \\ & & & 36 \\ & & & & \ddots \end{pmatrix} \quad \text{vs} \quad \mathbf{I} = \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & \ddots & \\ & & & & 1 \end{pmatrix}$$

Analytical q-ball (a-qbi)

- Smooth approximation of the ODF through the Funk-Radon transform

$$\Psi(\theta, \phi) = \int_0^\infty P(r, \theta, \phi) dr$$



a-QBI

$$\mathcal{G}[S](\mathbf{u}) = \sum_{j=1}^{R} 2\pi P_{\ell_j}(0) c_j Y_j(\mathbf{u})$$

[Descoteaux et al. MRM 07]

a-QBI

$$\mathcal{G}[S](\mathbf{u}) = \sum_{j=1}^{R} 2\pi P_{\ell_j}(0) c_j Y_j(\mathbf{u})$$

[Descoteaux et al. MRM 07]

a-QBI

$$\mathcal{G}[S](\mathbf{u}) = \sum_{j=1}^{R} 2\pi P_{\ell_j}(0) c_j Y_j(\mathbf{u})$$

$$\mathbf{C}' = \begin{pmatrix} \ddots & & \\ & 2\pi(-1)^{\ell_j/2}\frac{1\cdot 3\cdot 5\cdots(\ell_j-1)}{2\cdot 4\cdot 6\cdots\ell_j} & \\ & & \ddots \end{pmatrix} \begin{pmatrix} \vdots \\ c_j \\ \vdots \end{pmatrix}$$

[Descoteaux et al. MRM 07]

a-QBI

$$\mathcal{G}[S](\mathbf{u}) = \sum_{j=1}^{R} 2\pi P_{\ell_j}(0) c_j Y_j(\mathbf{u})$$

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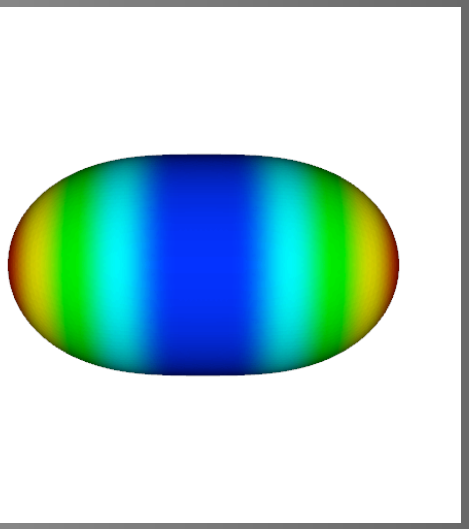
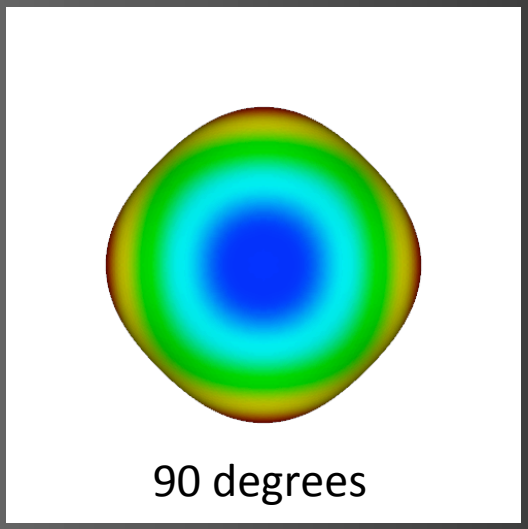
$$\mathbf{\Psi} = \mathbf{P}(\mathbf{B}^T\mathbf{B} + \lambda\mathbf{L})^{-1}\mathbf{B}^T\mathbf{S}$$

lambda = 0.006 [Descoteaux et al. MRM 07]

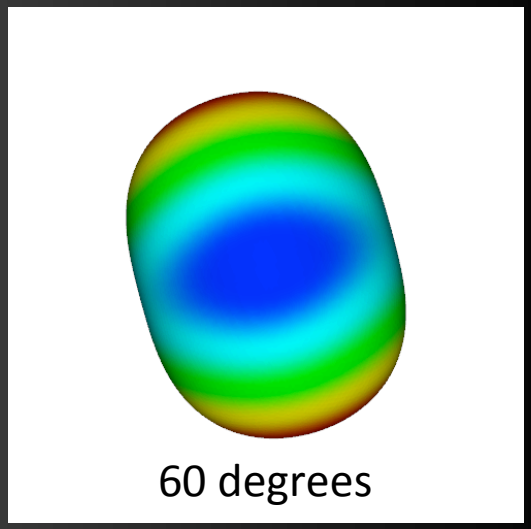
a-QBI limitations

- a-qbi ODFs are not properly normalized!





90 degrees



60 degrees

Constant solid angle (csa-qbi)

$$\Psi(\theta,\phi) = \int_{r=0}^{\infty} P(r,\theta,\phi) r^2 dr$$

$$\Psi(\theta,\phi) = \sum_{j=1}^{\infty} c_j^* Y_j(\theta,\phi)$$

[Aganj et al. 2010, Tristan-Vega et al 2010]

Constant solid angle (csa-qbi)

$$\Psi(\theta,\phi) = \int_{r=0}^{\infty} P(r,\theta,\phi) r^2 dr$$

$$\Psi(\theta,\phi) = \sum_{j=1}^{\infty} c_j^* Y_j(\theta,\phi)$$

$$\mathbf{\Psi} = \frac{1}{16\pi^2}\mathbf{B}^T\mathbf{P}(\mathbf{B}^T\mathbf{B} + \lambda\mathbf{L})^{-1}\mathbf{B}^T log(\mathbf{D}) + \frac{1}{4\pi}$$

$\mathbf{D} = -\log(\mathbf{S})$

[Aganj et al. 2010, Tristan-Vega et al 2010]

lambda = 0.006

Spherical wavelet transform

[Kezele, Descoteaux et al. 2011]

Spherical wavelet transform

- Decompose the ODF in a low frequency and high frequency spherical harmonics part
  ODF = ODF_lowfreq + ODF_highfreq

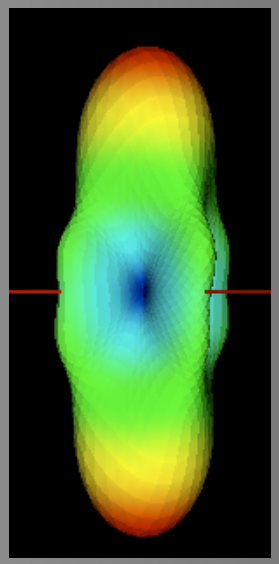
[Kezele, Descoteaux et al. 2011]

Spherical wavelet transform

- Decompose the ODF in a low frequency and high frequency spherical harmonics part
  ODF = ODF_lowfreq + ODF_highfreq
- Use only the *ODF_highfreq* part of the ODF

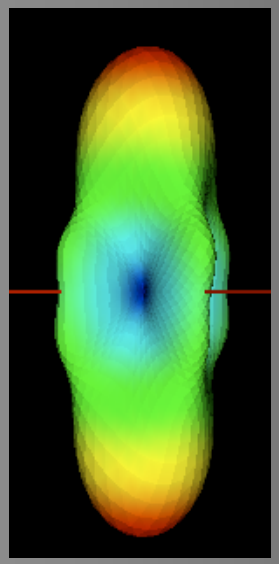
[Kezele, Descoteaux et al. 2011]

Spherical deconvolution



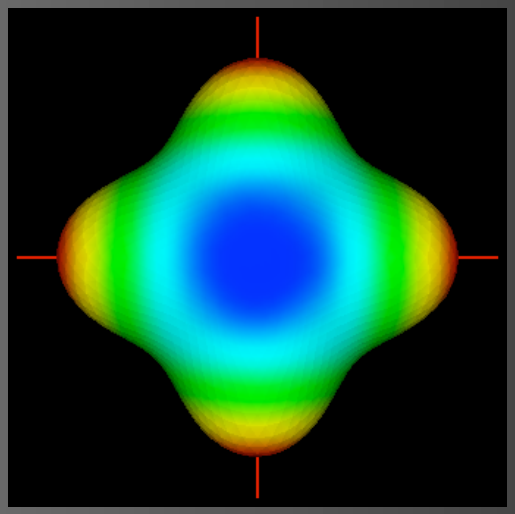
HARDI Signal

Spherical deconvolution



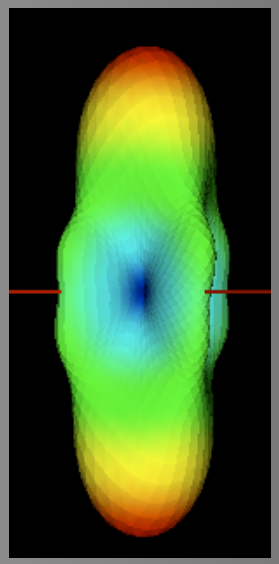
HARDI Signal

Analytical QBI



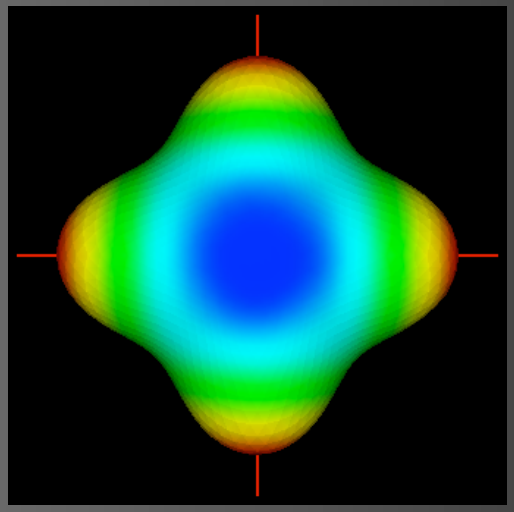
Diffusion ODF

Spherical deconvolution



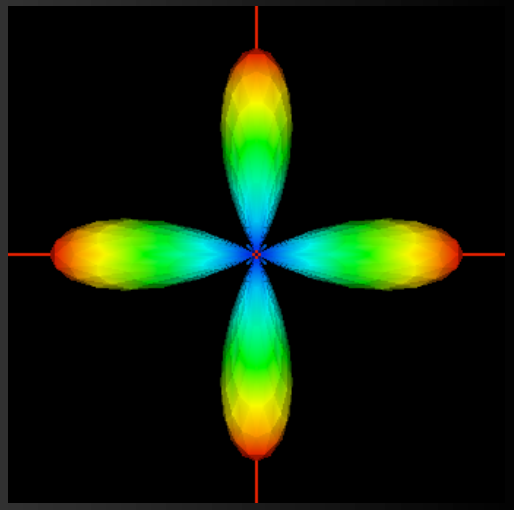
HARDI Signal

Analytical QBI



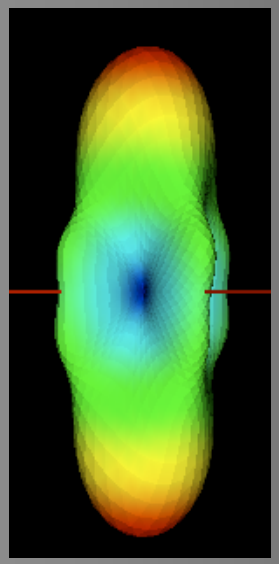
Diffusion ODF

Deconvolution



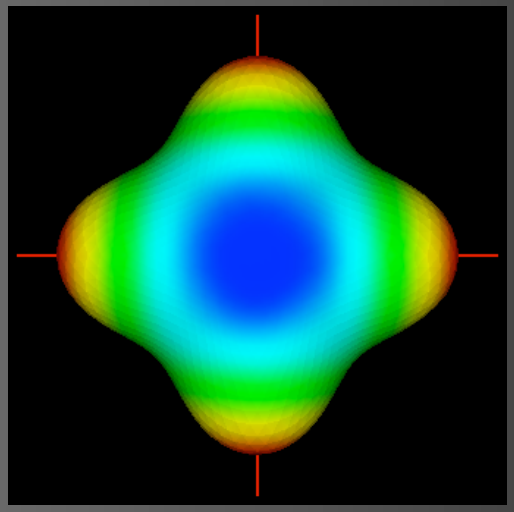
Fiber ODF

Spherical deconvolution



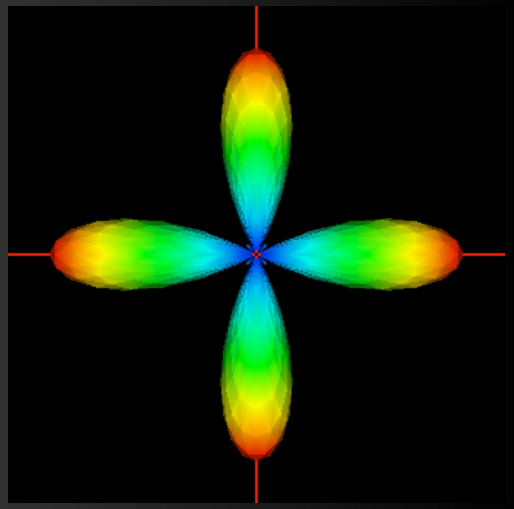
HARDI Signal

Analytical QBI



Diffusion ODF

Deconvolution



Fiber ODF

Deconvolution

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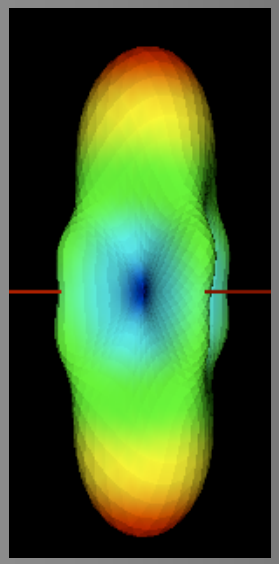
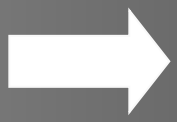
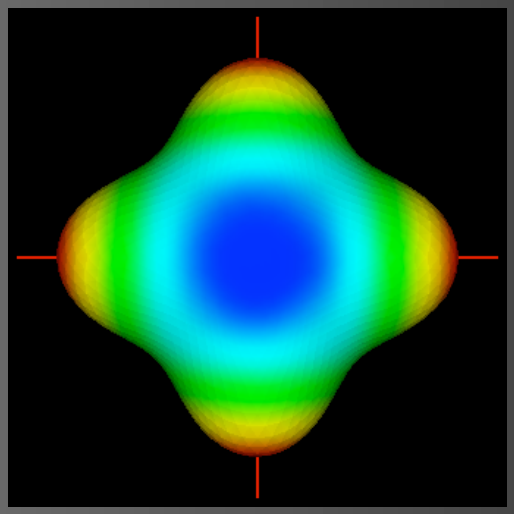


HARDI Signal

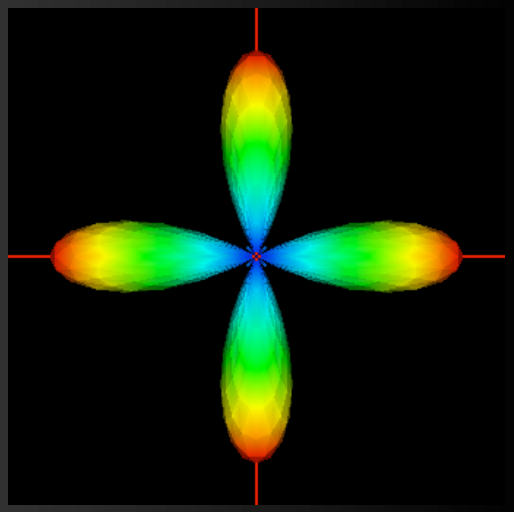
Analytical QBI





Diffusion ODF

Deconvolution

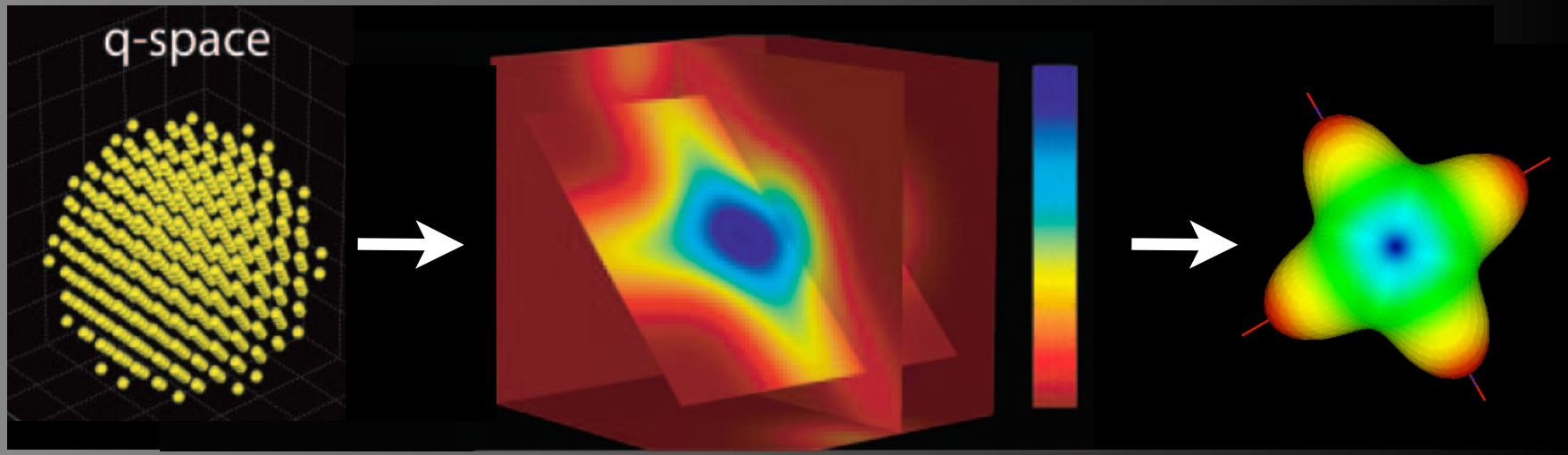


Fiber ODF

- Constrained regularization needed!
- fODF implementation of [Descoteaux et al 2009]
- FOD implementation of mrtrix [Tournier et al 2007, 2012]

Diffusion spectrum imaging (DSI)

1) Zero padding 2) Hanning filtering
3) ODF integration



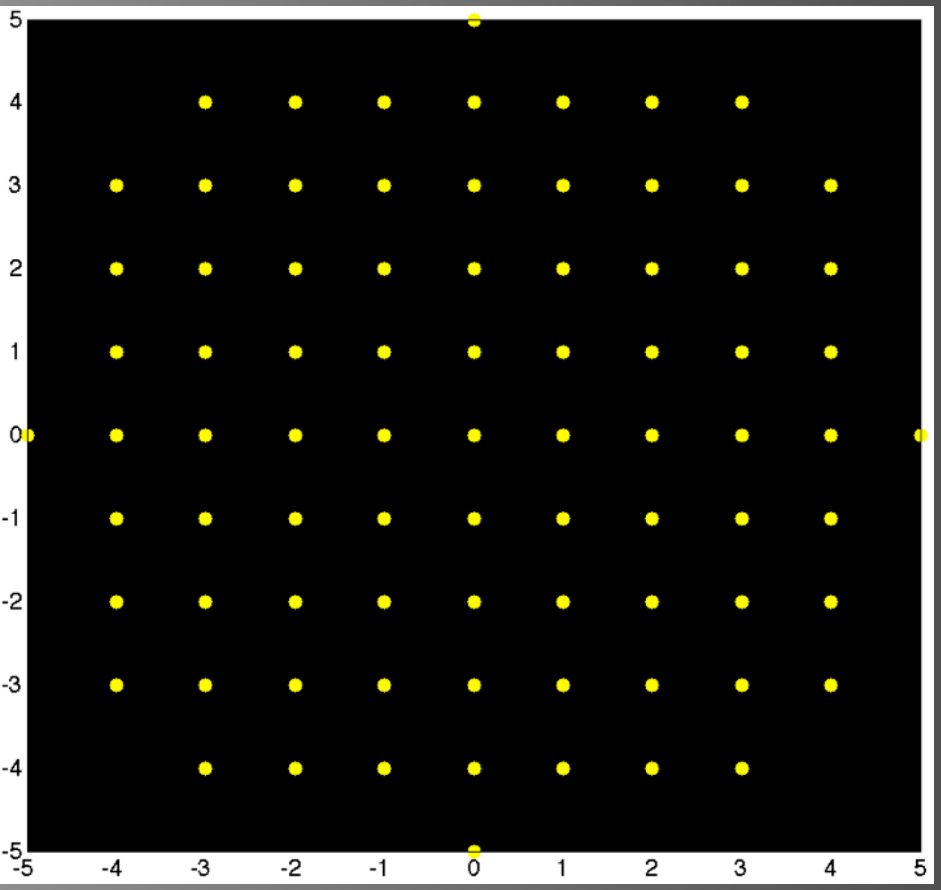
Measured signal

Diffusion propagator

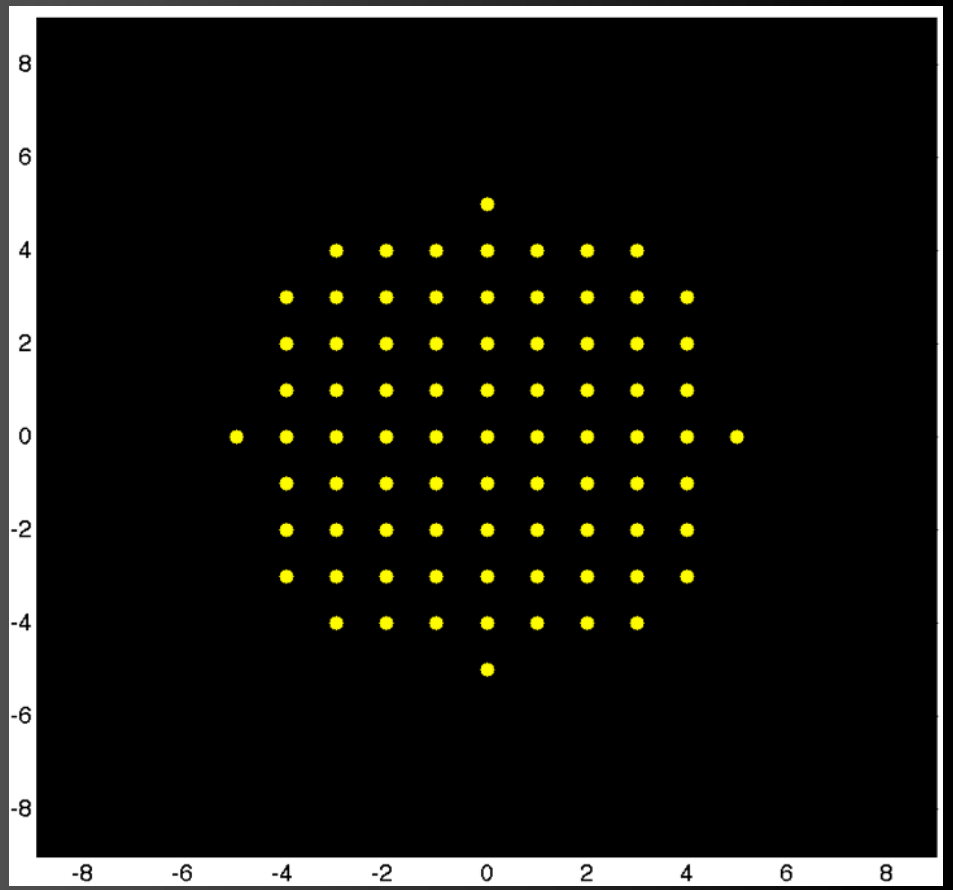
Diffusion ODF

[Wedeen et al. MRM 05]

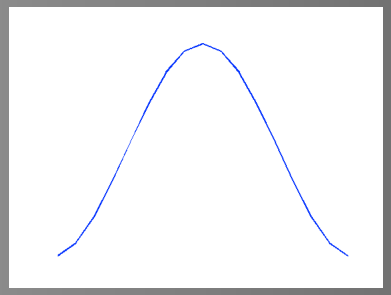
Zero padding



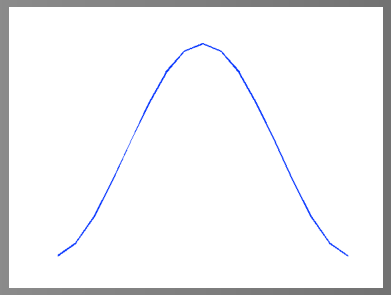
11x11x11
Original q-space grid



19x19x19
Zero-padded q-space grid

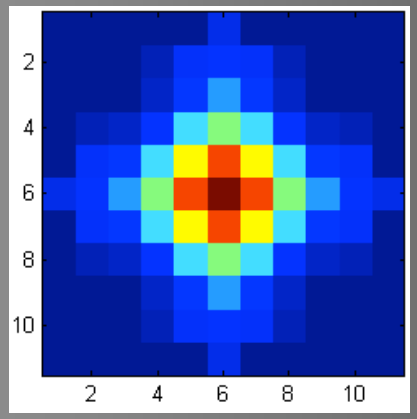


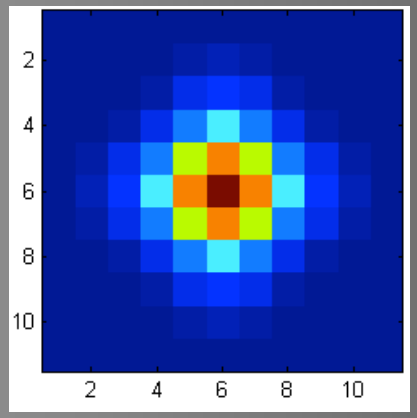
Hanning filtering



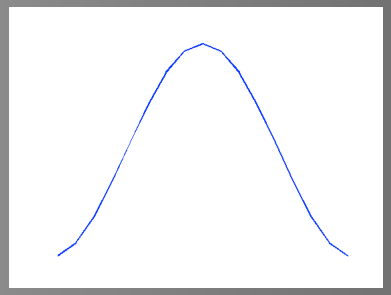
Hanning filtering

Noiseless signal



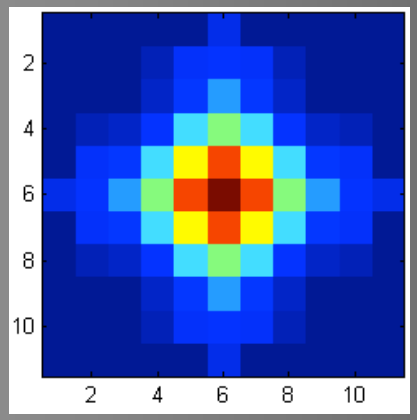


Noiseless signal filtered

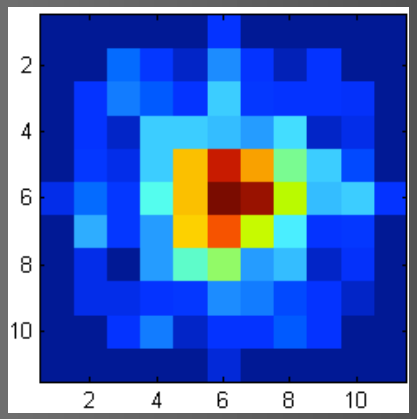


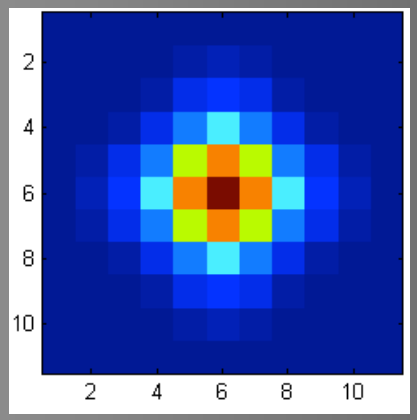
Hanning filtering

Noiseless signal

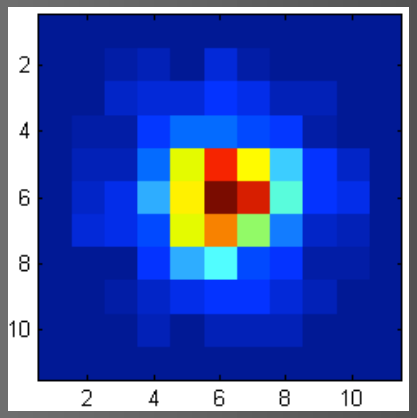


Noisy signal

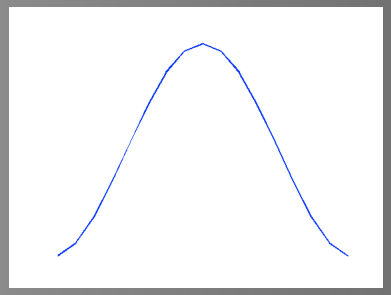




Noiseless signal filtered

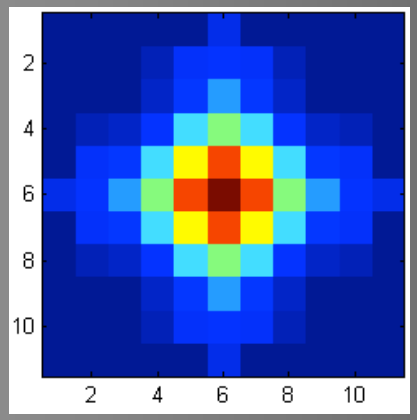


Noisy signal filtered

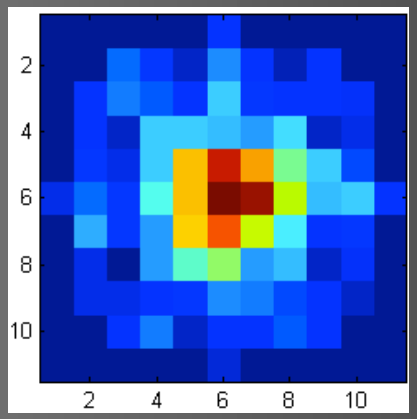


Hanning filtering

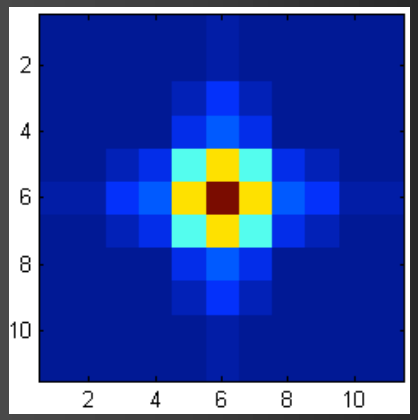
Noiseless signal



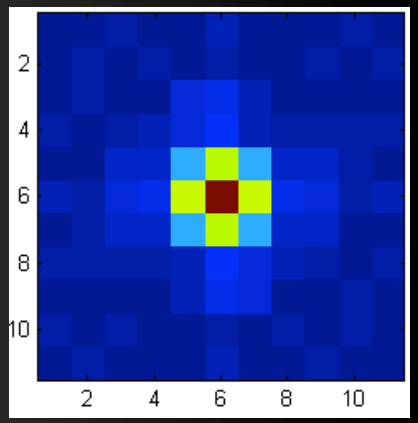
Noisy signal

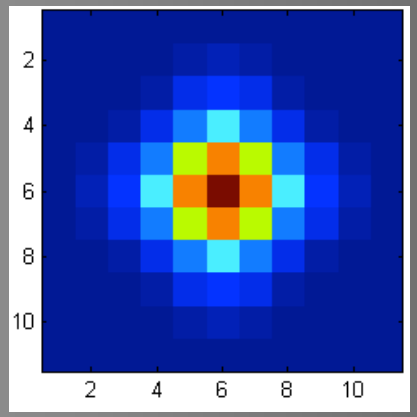


Noiseless PDF

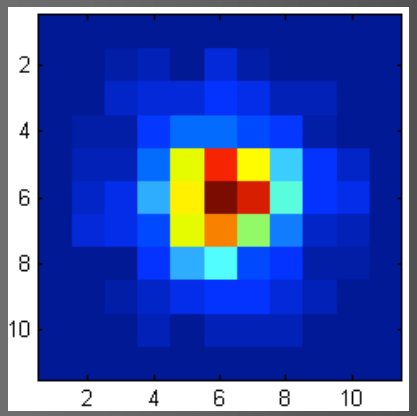


Noisy PDF

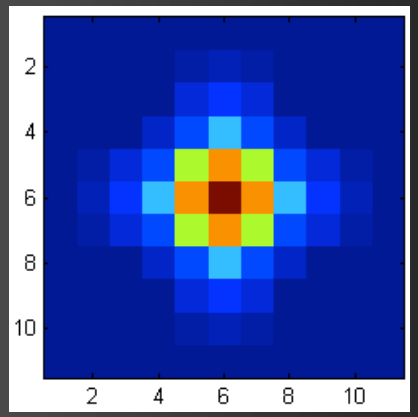




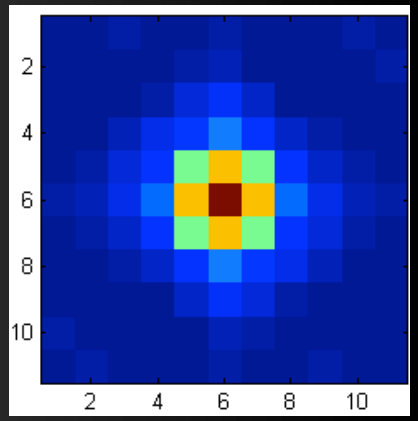
Noiseless signal filtered



Noisy signal filtered



Noiseless PDF filtered



Noisy filtered PDF

ODF integration

$$\Psi(\theta,\phi) = \int_0^\infty P(r,\theta,\phi) r^2 dr$$

ODF integration

- In theory,

$$\Psi(\theta,\phi) = \int_0^\infty P(r,\theta,\phi) r^2 dr$$

ODF integration

- In theory,

$$\Psi(\theta,\phi) = \int_0^\infty P(r,\theta,\phi) r^2 dr$$

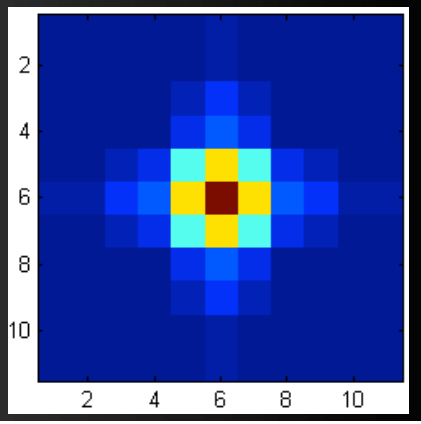
- In practice,

$$\Psi(\theta,\phi) = \int_a^b P(r,\theta,\phi) r^2 dr$$

ODF integration

- In theory,

$$\Psi(\theta,\phi) = \int_0^\infty P(r,\theta,\phi) r^2 dr$$



- In practice,

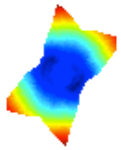
$$\Psi(\theta,\phi) = \int_a^b P(r,\theta,\phi) r^2 dr \quad \rightarrow \quad \Psi(\theta,\phi) = \sum_{r=a}^{b} P(r,\theta,\phi) r^2$$

r increments of 0.1

DSI, SNR 10

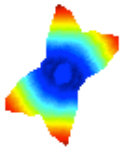
DSI, SNR 10

Noiseless



Noiseless, truncated

Noiseless, zeropadded



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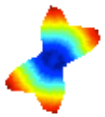
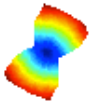


Noiseless, Hanning

Noiseless, Hanning, truncated

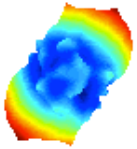


Noiseless, Hanning, zeropadded

Noiseless, Hanning, zeropadded, truncated

DSI, SNR 10

Noisy



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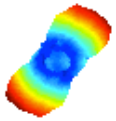
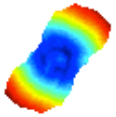


Noisy, zeropadded

Noisy, zeropadded, truncated



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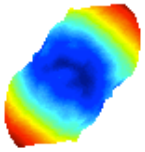

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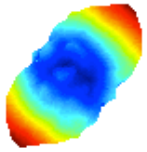
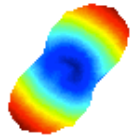


Noisy, Hanning, zeropadded, truncated



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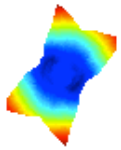

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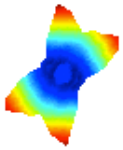

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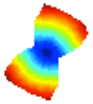

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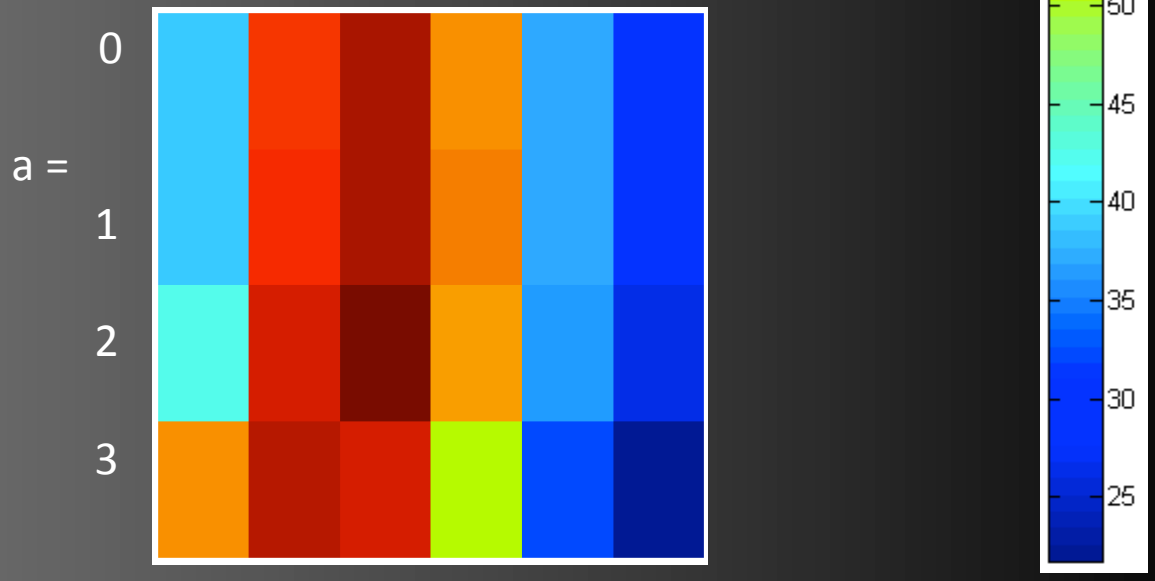

Experiments

- N = 30, 45, 60, 75, 90, 105 & 120 measurements
- b = 700, 1000, 1500, 2000, 2500, 3000, & 3500 s/mm2
- SNRs 5, 10, 15, 20, 25, 30, 35, 40

- Report % of success to detect peaks

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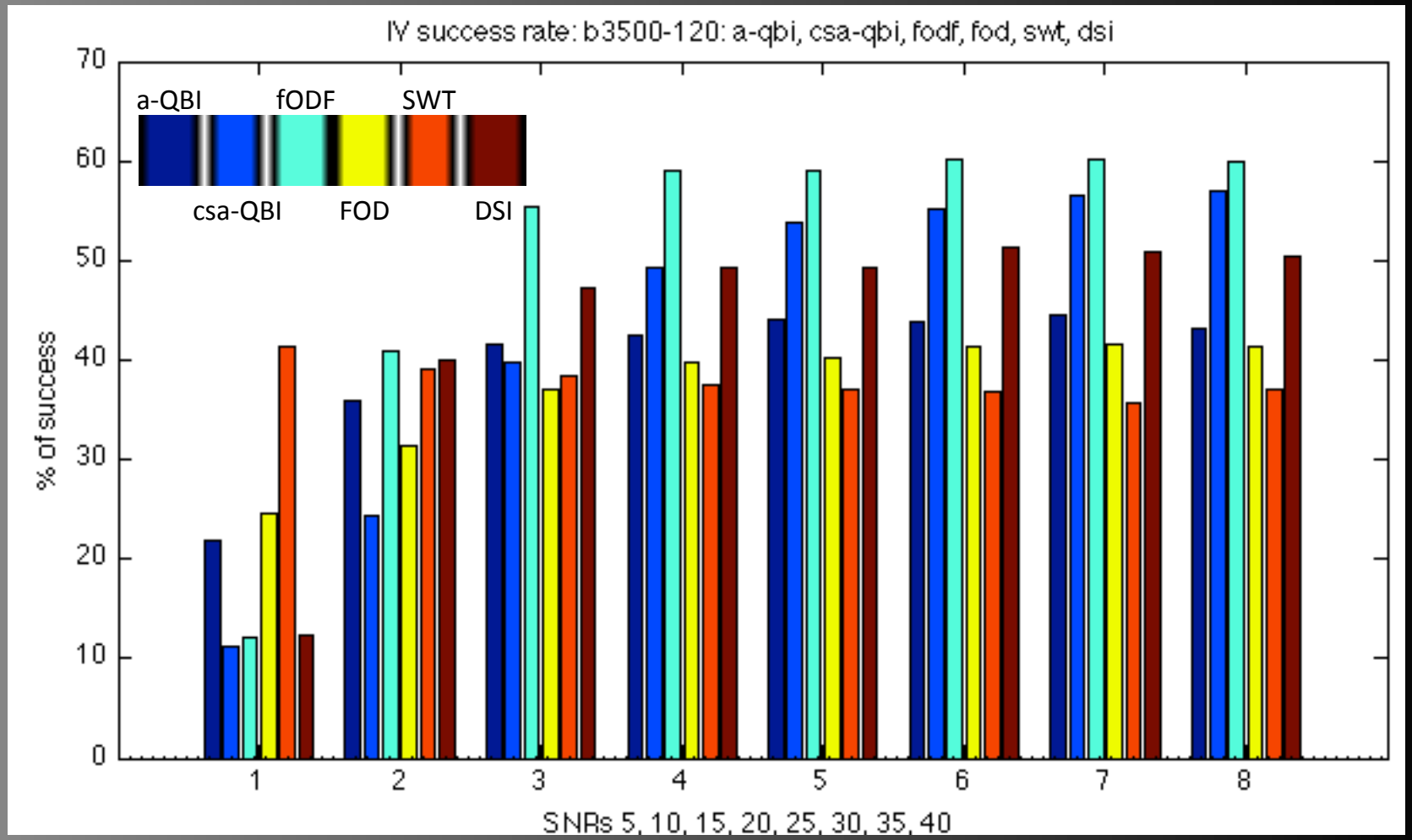
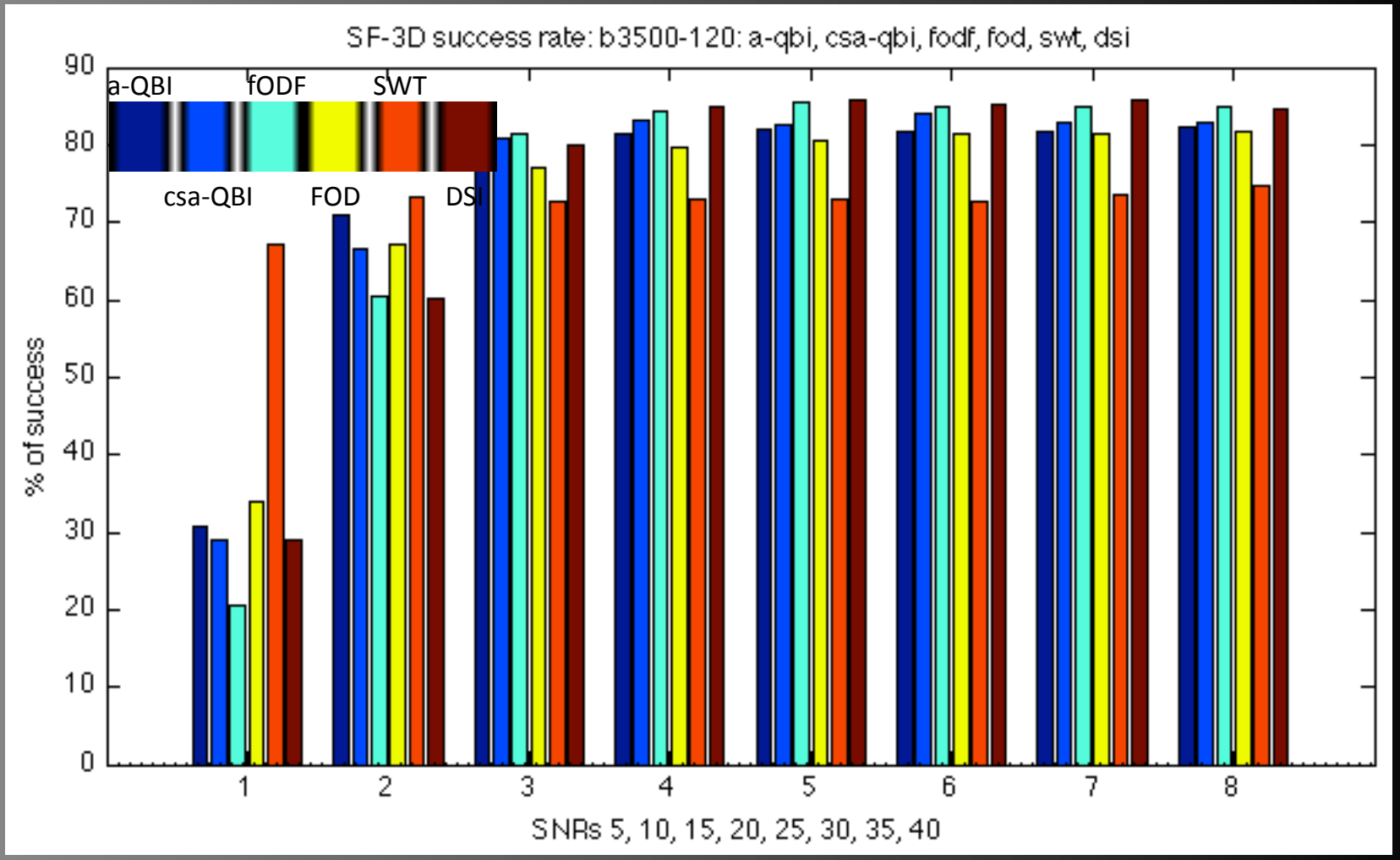
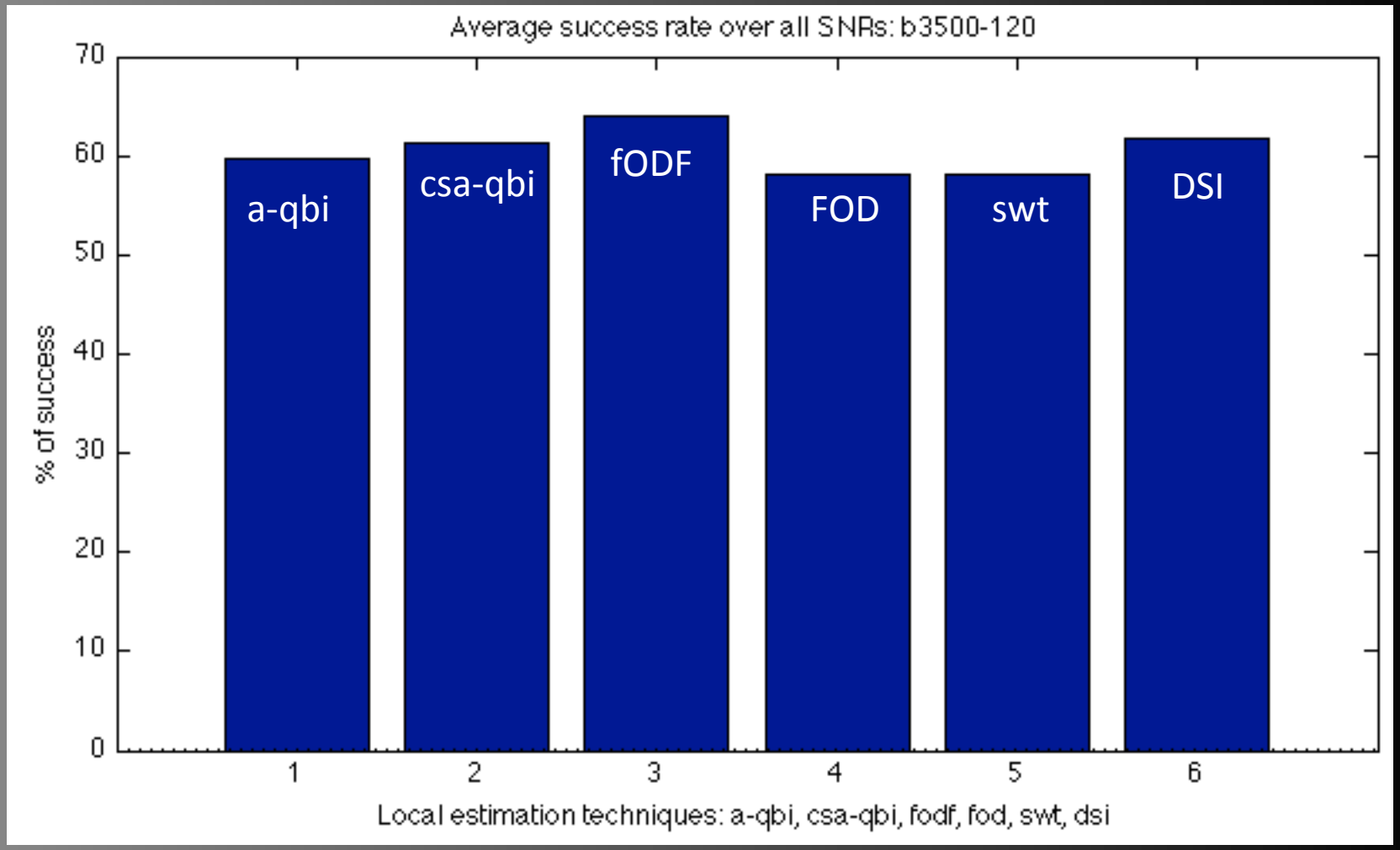
- On average, over all phantoms, all SNRs best, on average of 60%, was **fODF of order 6**, and **DSI equally as good as csa-QBI**


IV success rate: b3500-120: a-qbi, csa-qbi, fodf, fod, swt, dsi
a-QBI
fODF
SWT
csa-QBI
FOD
DSI
% of success
0
10
20
30
40
50
60
70
1
2
3
4
5
6
7
8
SNRs 5, 10, 15, 20, 25, 30, 35, 40


SF-3D success rate: b3500-120: a-qbi, csa-qbi, fodf, fod, swt, dsi
a-QBI
fODF
SWT
csa-QBI
FOD
DSI
% of success
0
10
20
30
40
50
60
70
80
90
1
2
3
4
5
6
7
8
SNRs 5, 10, 15, 20, 25, 30, 35, 40



Recall that this highlights “best of” DSI results

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  - 60 measurements & b = 3000 s/mm2, similar results as before
- For lower b-values, such as 60 measurements & b = 1500 s/mm2, “best of” DSI is better than HARDI techniques
- The “standard” DSI technique as in [Wedeen et al 2005] and used in all connectomics papers [Hagmann et al 2007,2008], **performs terribly bad!**

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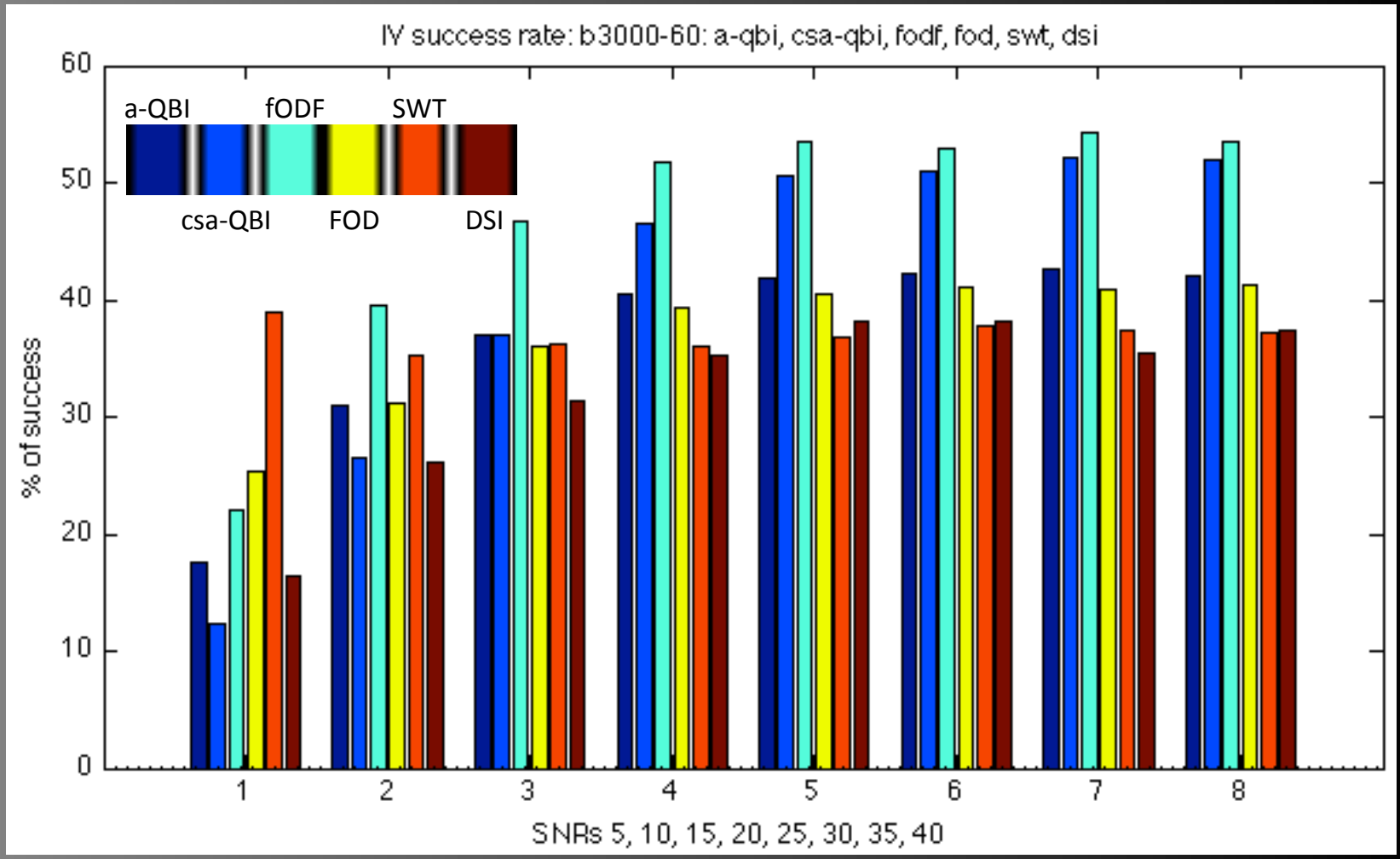

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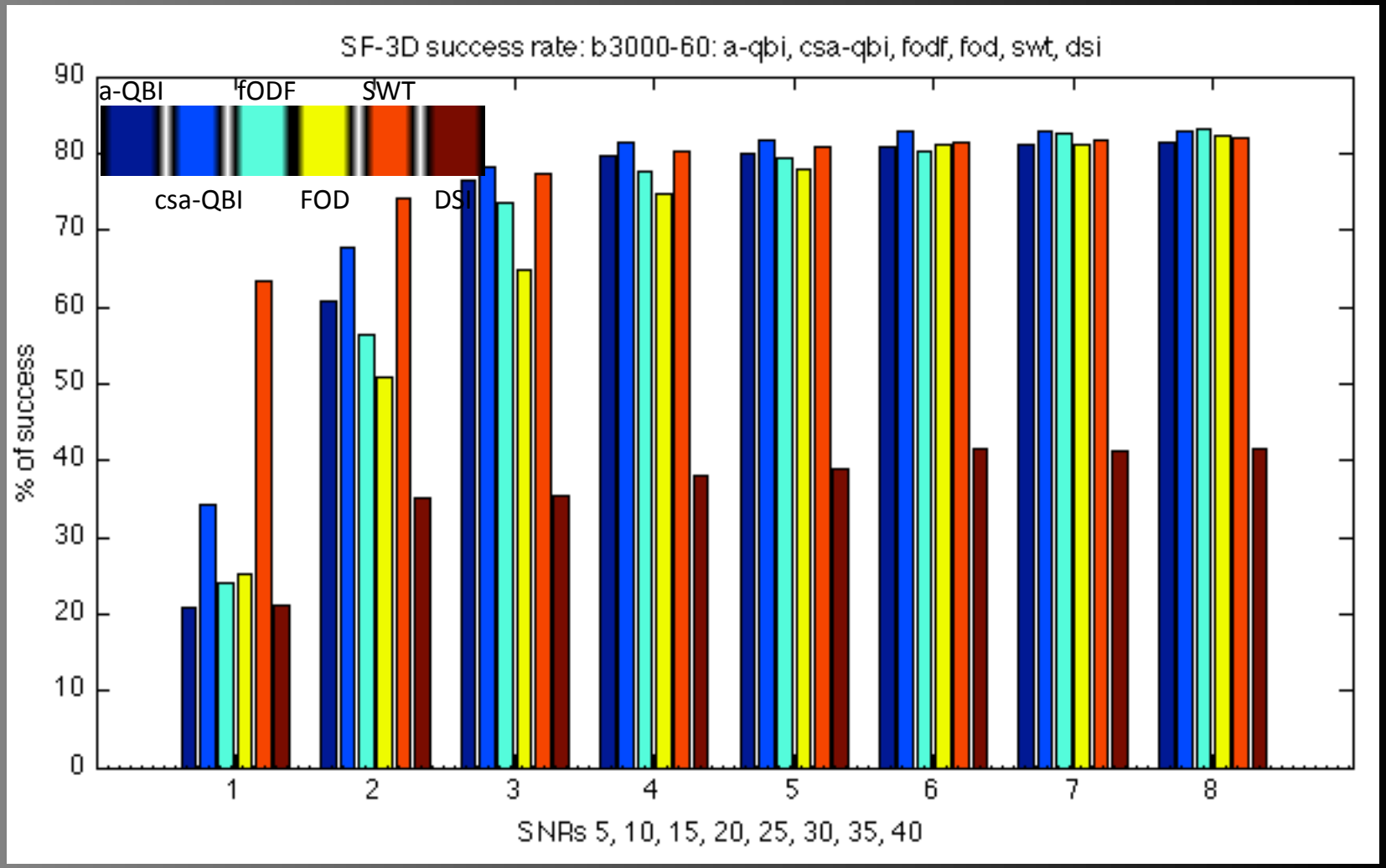

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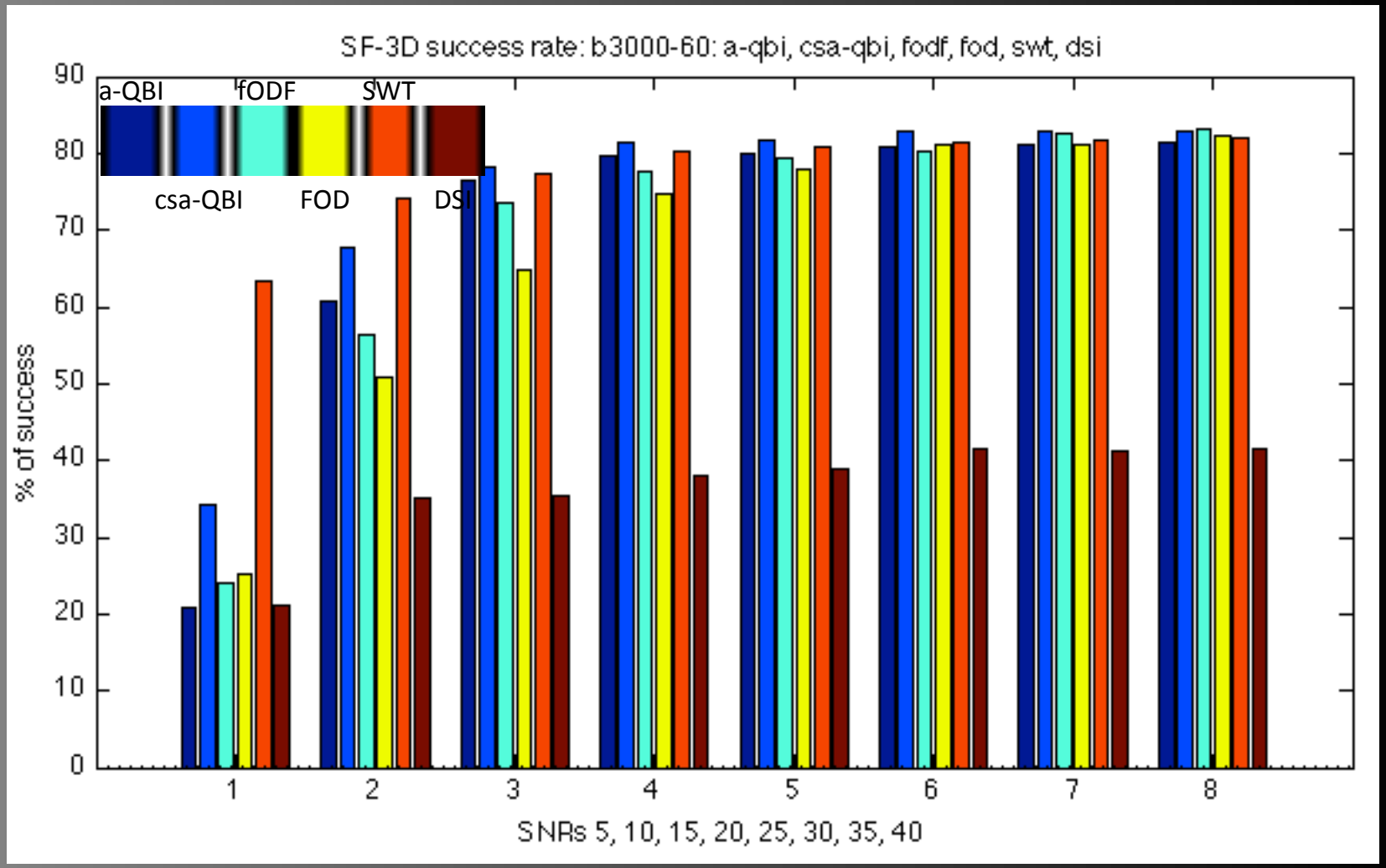

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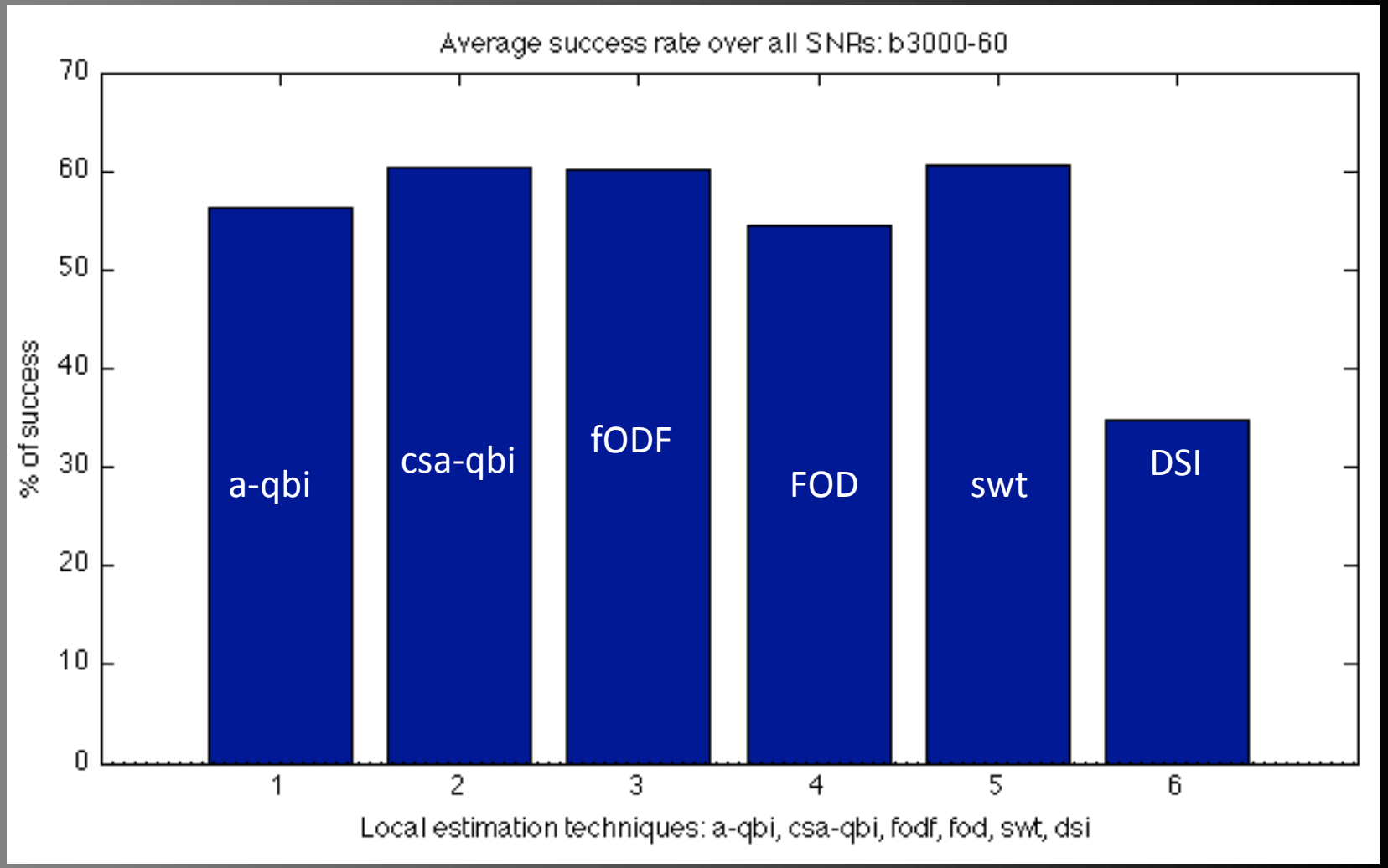

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- Time is **really** an issue in the clinic
  - We truly have at most 5 to 10 minutes (rs-fMRI is done in 3 minutes!)
  - If we can do HARDI at the price of DTI, we are in business