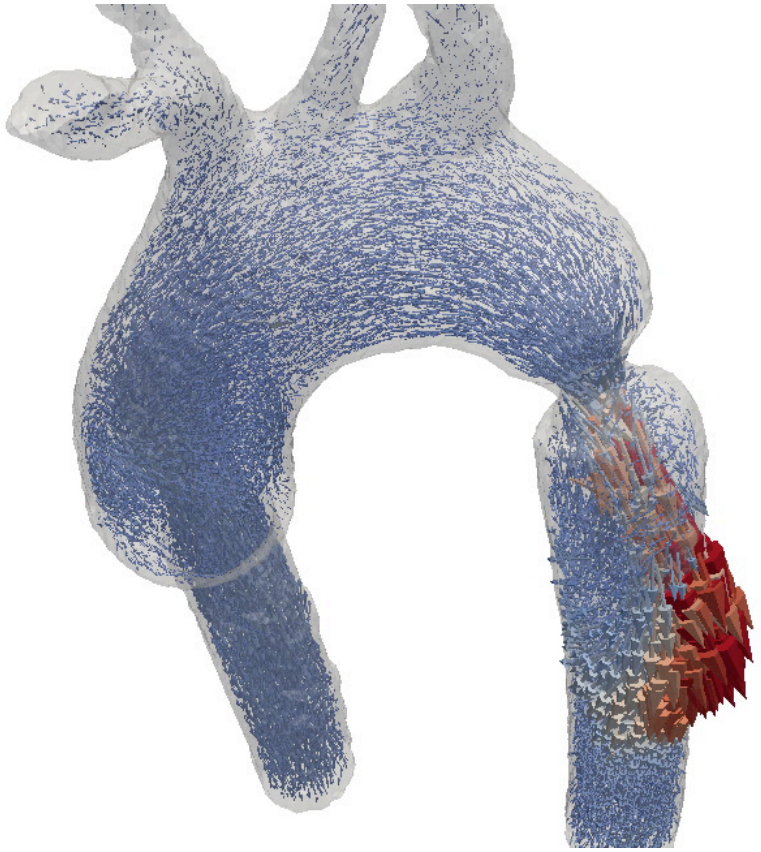
Quantifying and improving the quality of 4D flow



Cristóbal Bertoglio

rijksuniversiteit groningen

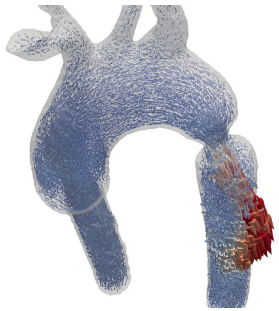
erc

Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

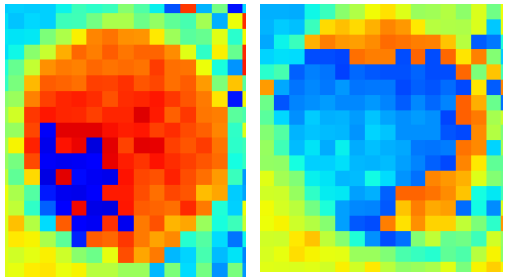
www.math.rug.nl/~bertoglio

Outline of this talk

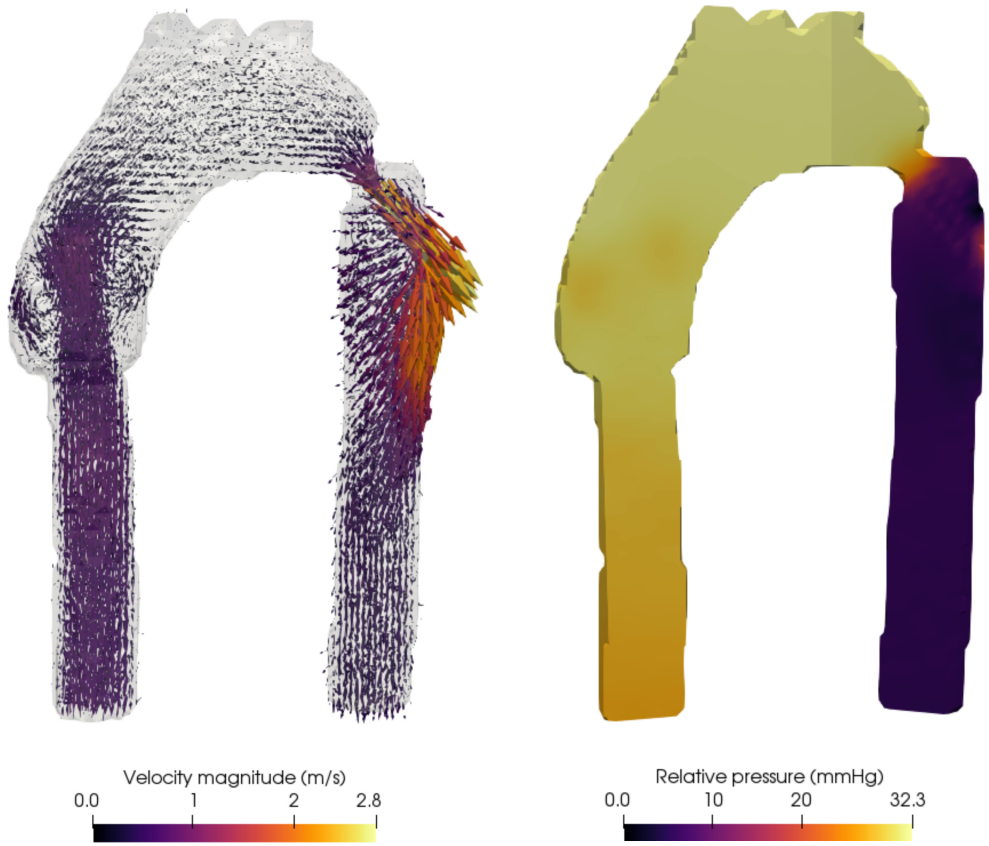
1. Pressure maps from 4D flow



2. Dual/Multi VENC reconstructions



Relative pressure maps from 4D flow



Relative pressure maps from 4D flow

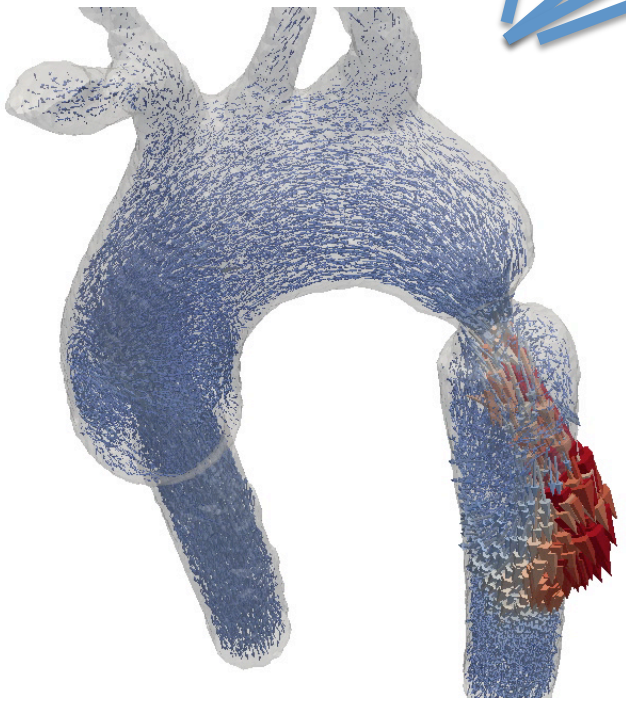
Navier-Stokes Equations:

$$\rho_{\mathrm{f}} \frac{\partial \boldsymbol{u}_{\mathrm{f}}}{\partial t} + \rho_{\mathrm{f}} (\boldsymbol{u}_{\mathrm{f}} \cdot \boldsymbol{\nabla}) \boldsymbol{u}_{\mathrm{f}} - \mu \Delta \boldsymbol{u}_{\mathrm{f}} + \boldsymbol{\nabla} p = \boldsymbol{0},$$

?

INSTANTANEOUS PRESSURE GRADIENT! (**NOT** PEAK-TO-PEAK)

4D Flow



IDEA: solve for pressure with velocities in right-hand-side

Ebbers++'01, Donati++'15
Svihlova++'15, Bertoglio++'18

- Spatial resolution: 1.0-3.0 mm3
- Temporal resolution: 20-60 ms
- Ideal noise around 10-20% of max. velocity

Relative pressure estimation methods

Until 2014: solve Laplace equation for the pressure (PPE)

Ebbers++ '01, Krittian++'12

$$\Delta p = -\boldsymbol{\nabla} \cdot (\rho \partial_t \boldsymbol{u} - \rho(\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} + \mu \Delta \boldsymbol{u})$$

Pressure is now ``too regular" (hence, may be underestimated)

2015-18: other methods, but best performing is

"Stokes estimator" (STE) *Svihlova++'15*

$$-\Delta \boldsymbol{w} + \boldsymbol{\nabla} p = -\rho \partial_t \boldsymbol{u} - \rho(\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} + \mu \Delta \boldsymbol{u}$$

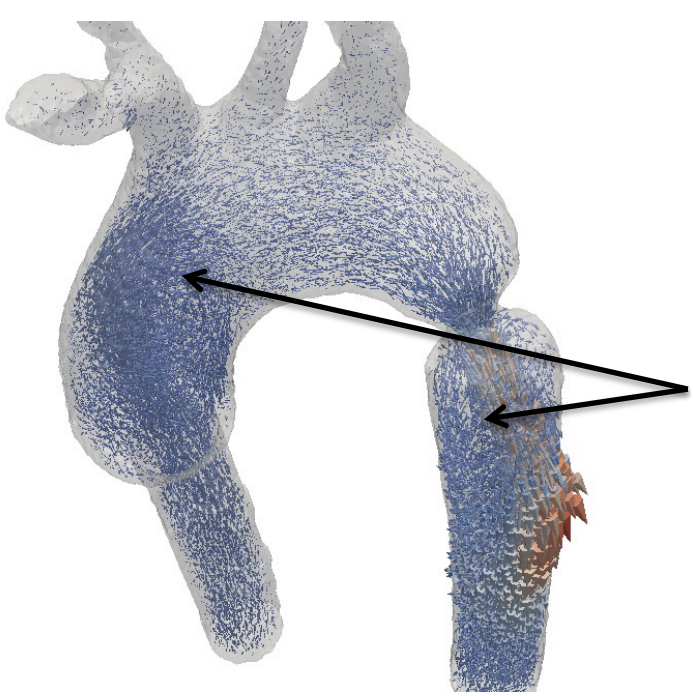
$$\boldsymbol{\nabla} \cdot \boldsymbol{w} = 0$$

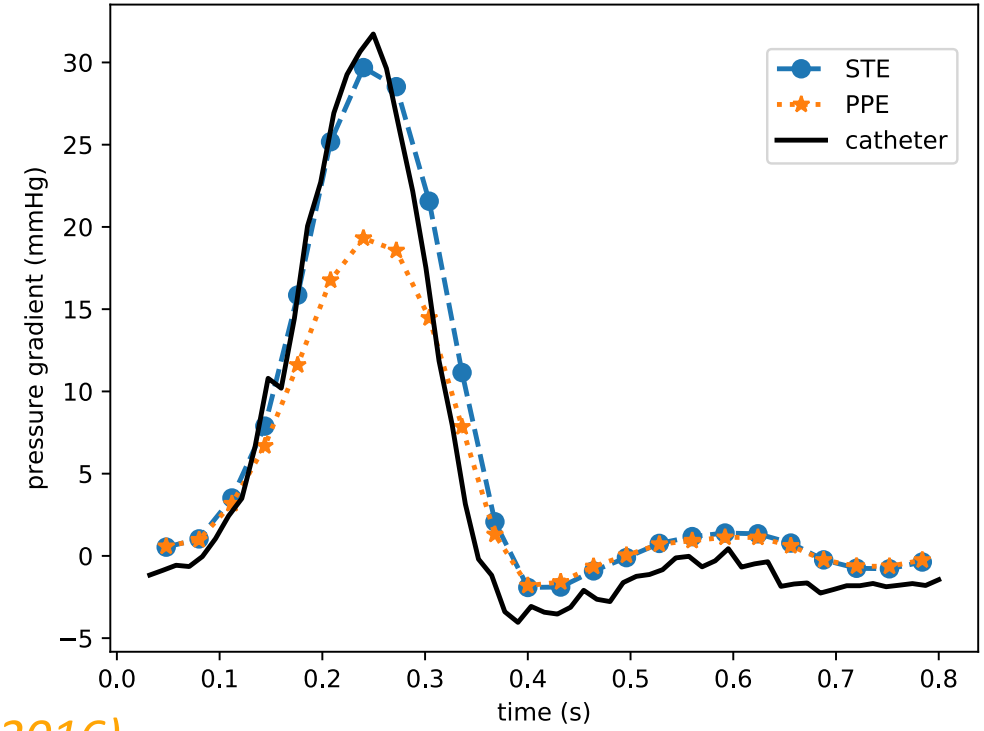
$$\boldsymbol{w} = \boldsymbol{0} \quad \text{on} \quad \partial\Omega$$

Problem consistent with Navier-Stokes *Araya, Bertoglio, Cárcamo (preprint soon)*

➔ *Convergence analysis, cost/effective discretization*

Experimental validation

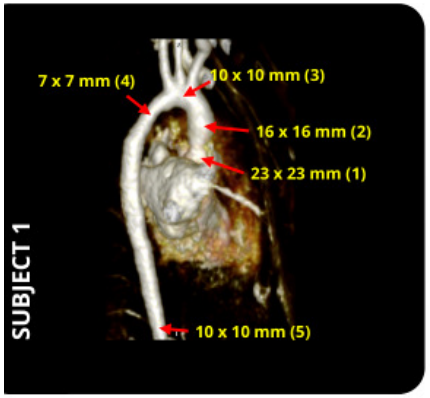


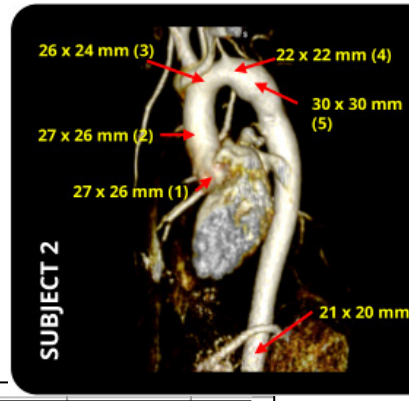


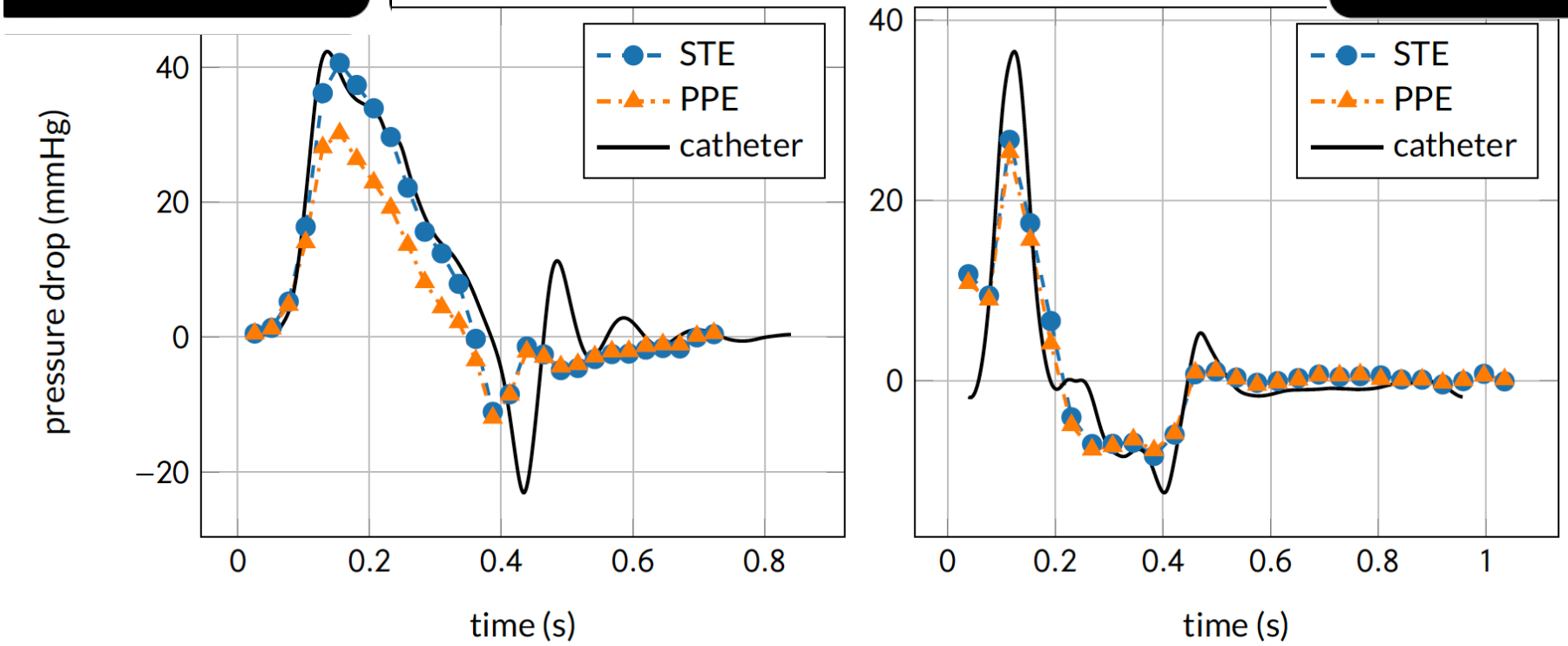
Experiments from PUC (Urbina++ 2016)

Nolte++ ***Validation of 4D flow based relative pressure maps in the aorta***
(under review, preprint available)

Patient validation







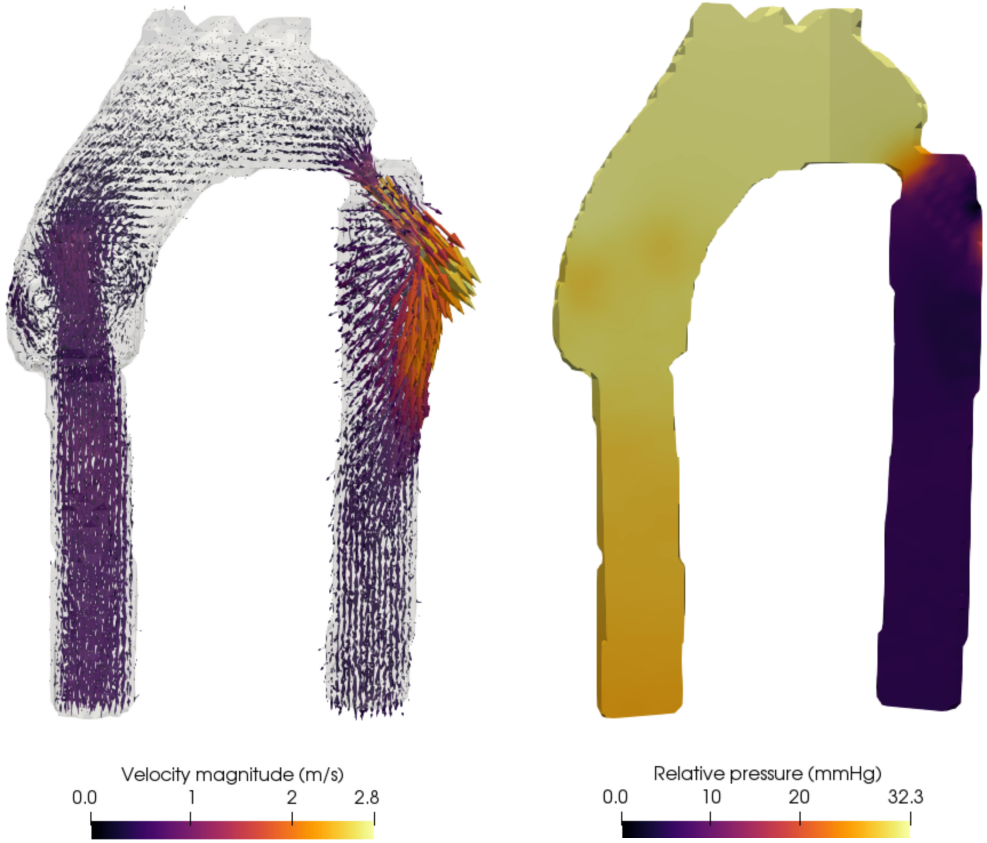
Peak-to-peak: 20 *mmHg*

Peak-to-peak: 2 *mmHg*

Nolte++ ***Validation of 4D flow based relative pressure maps in the aorta***
(under review, preprint available)

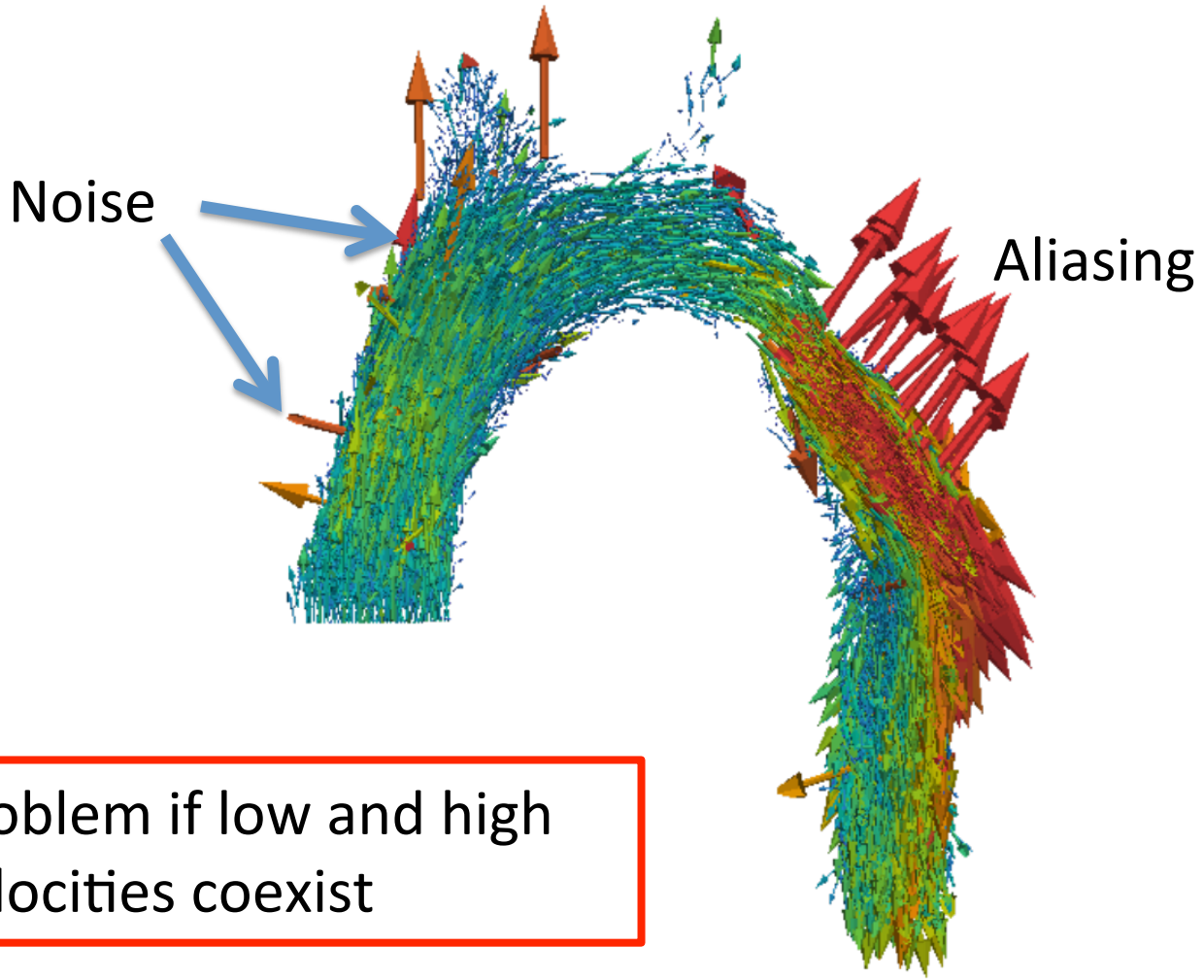
Clinical potential of pressure maps

*+ **Pressure maps***
(“catheterize afterwards”)
*+ **Low gradient** problems*
(viscous dominated)
*+ **Few seconds** for clinically relevant resolutions*
*+ **Challenge**: peak-to-peak from minimal cath?*



Nolte++ ***Validation of 4D flow based relative pressure maps in the aorta***
(under review, preprint available)

Dual/Multi-VENC reconstructions

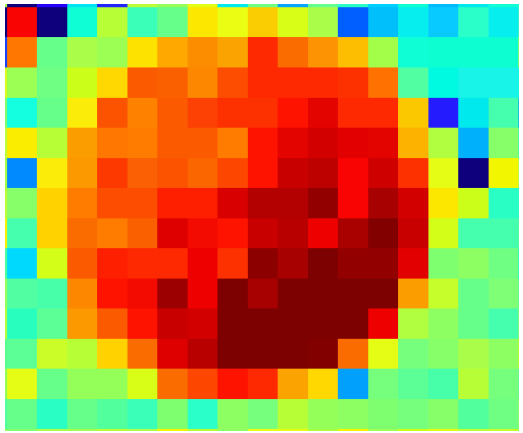


Problem if low and high velocities coexist

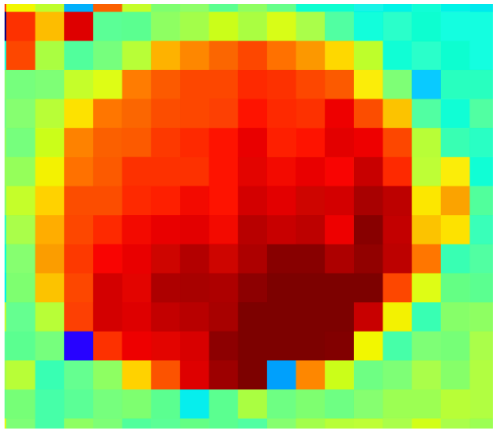
The problems of phase-contrast MRI

Problem: **noise** in velocity grows with $venc$

Example with volunteer data (ascending aorta)



$venc = 225$



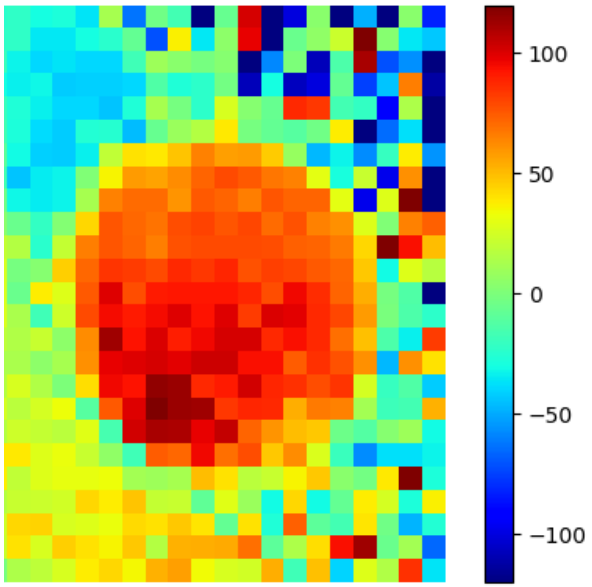
$venc = 100$

$$u = \frac{\varphi^{G_1} - \varphi^{G_2}}{\pi} venc(G_1, G_2)$$

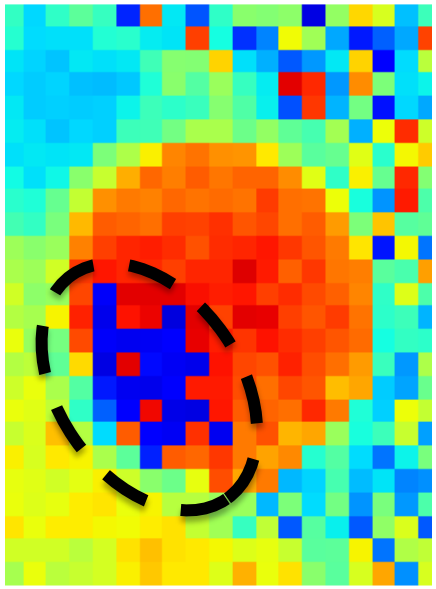
The problems of phase-contrast MRI

But! Aliasing when $venc <$ true velocity

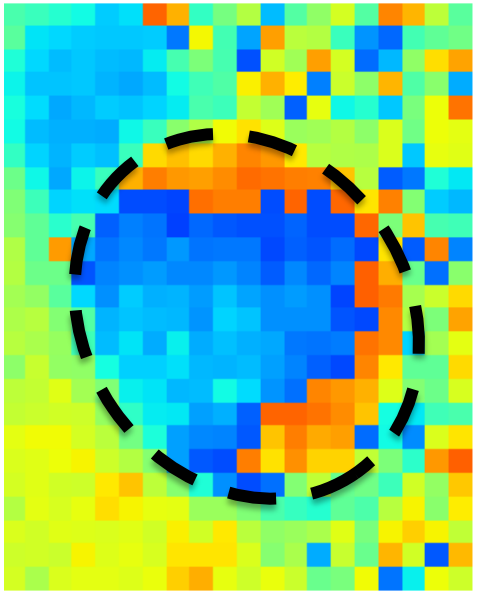
Example with volunteer data (ascending aorta)



$venc = 150$



$venc = 100$



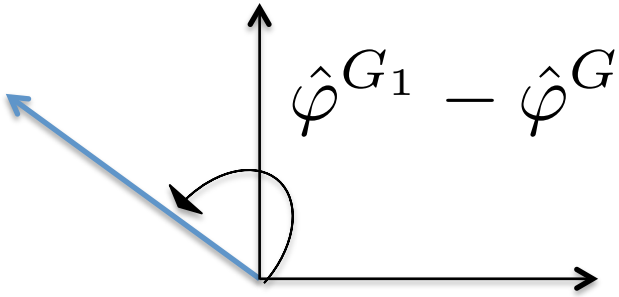
$venc = 75$

Phase aliasing

$$\hat{u}_k = \frac{\hat{\varphi}^{G_1} - \hat{\varphi}^{G_2} + 2\pi k}{\pi} venc_{1,2}$$

$$k \in \mathbb{Z}$$

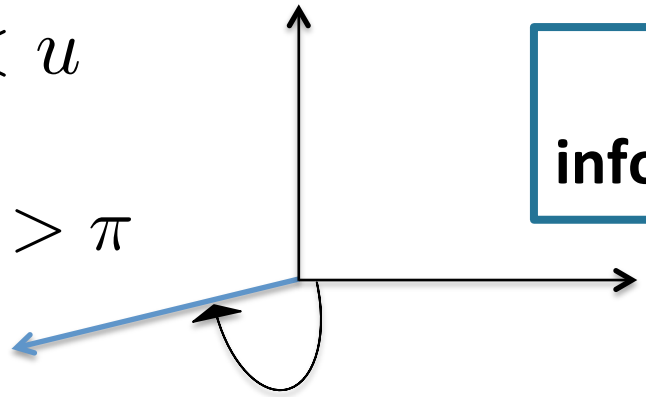
- If $venc_{1,2} > u$ then $\hat{u}_{k=0}$ is the correct solution!



$$\hat{\varphi}^{G_1} - \hat{\varphi}^{G_2} < \pi$$

- If $venc_{1,2} < u$

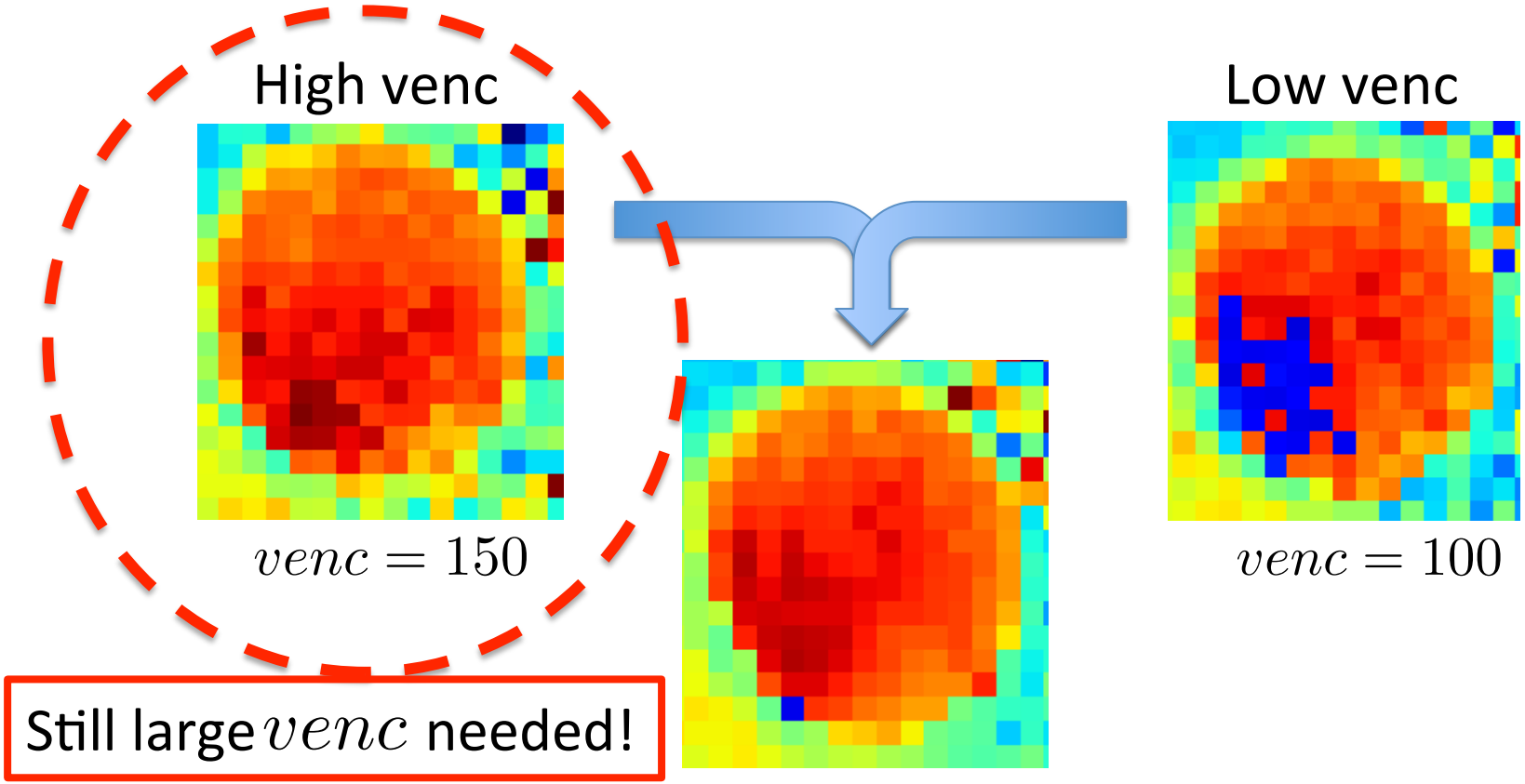
$$\hat{\varphi}^{G_1} - \hat{\varphi}^{G_2} > \pi$$



We need **more information** for finding *k*

Standard *dual-venc* reconstruction (SDV)

Goal: Improve velocity/noise with additional measurement

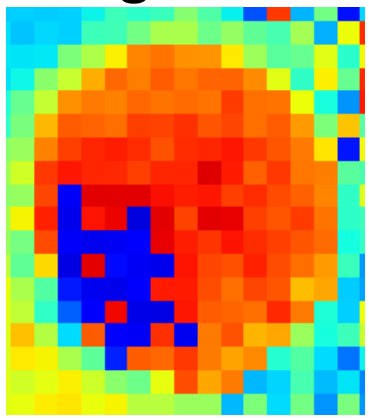


Dual-venc *Lee et al 1995, Schnell et al 2017*

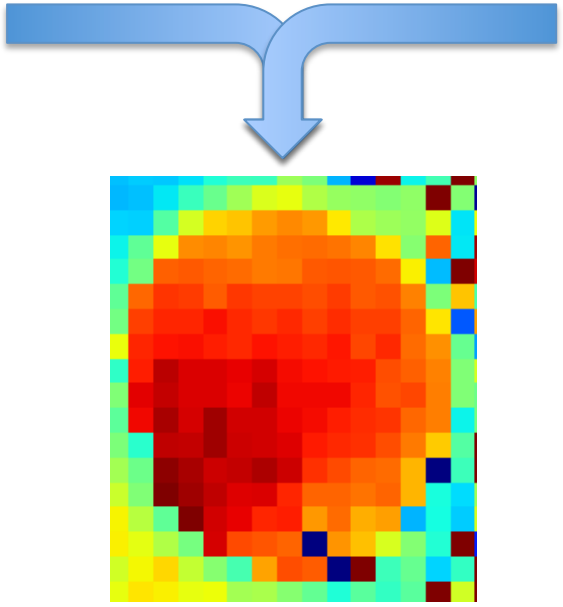
Optimal *dual-venc* reconstruction (ODV)

Aliasing-free estimation when $venc < u$

High venc

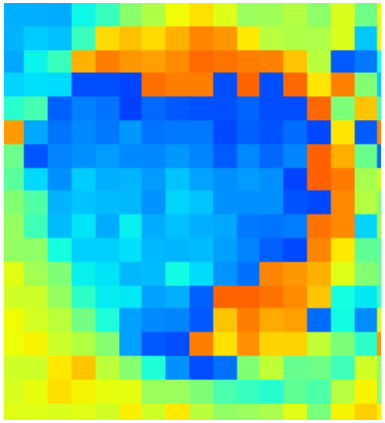


$venc = 100$



Dual-venc

Low venc



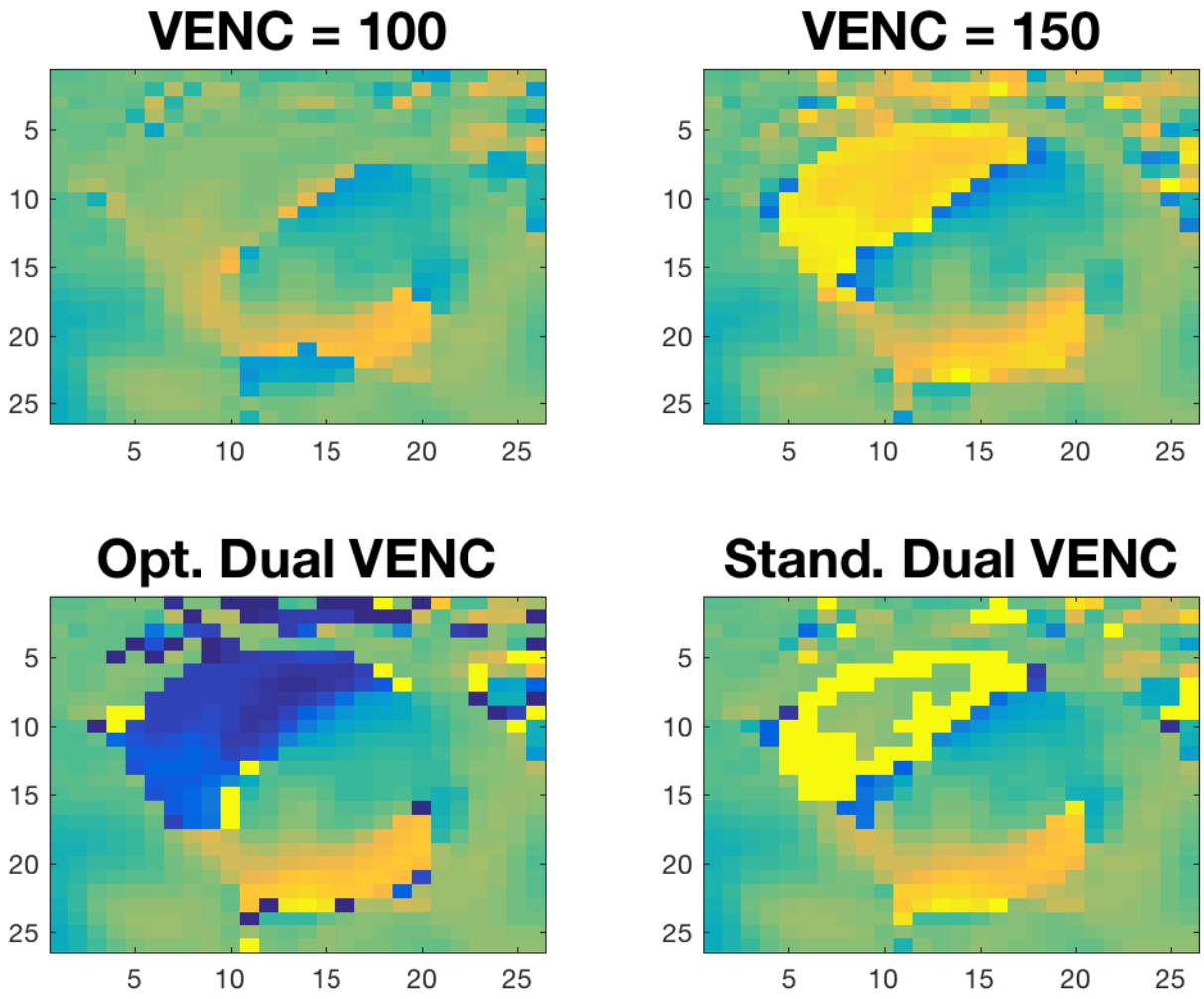
$venc = 75$

Optimal Dual-VENC (ODV) unwrapping in Phase-Contrast MRI

H. Carrillo, A. Osses, S. Uribe, C. Bertoglio. IEEE Trans. Medical Imaging, 2019

Example in pulmonary artery

With Tineke Willems (Groningen Medical Center)



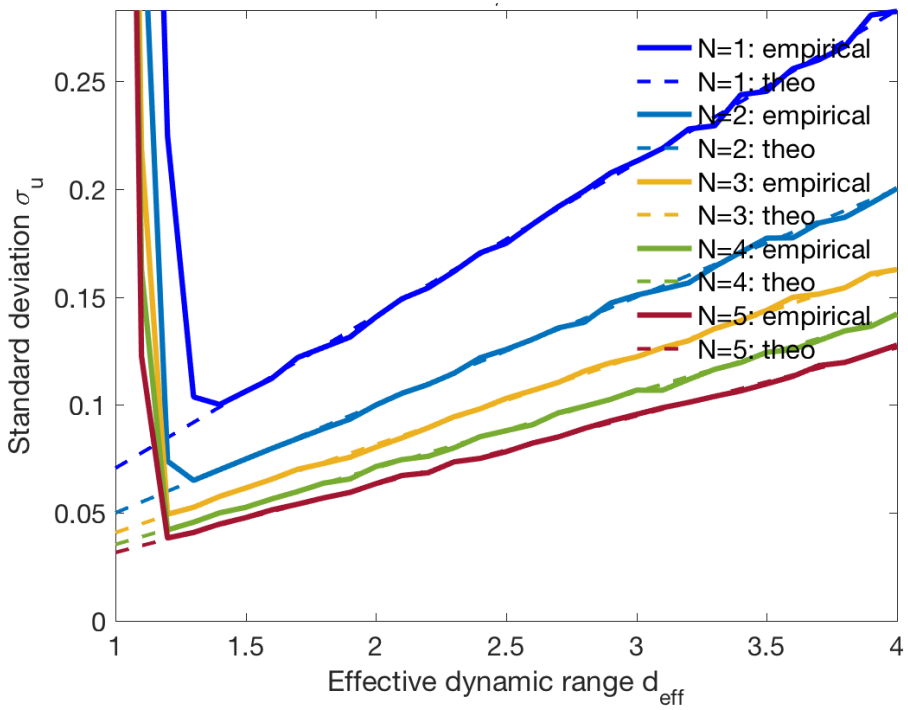
Clinical potential of dual/multi-VENC

+ Straightforward extension to multi-VENC

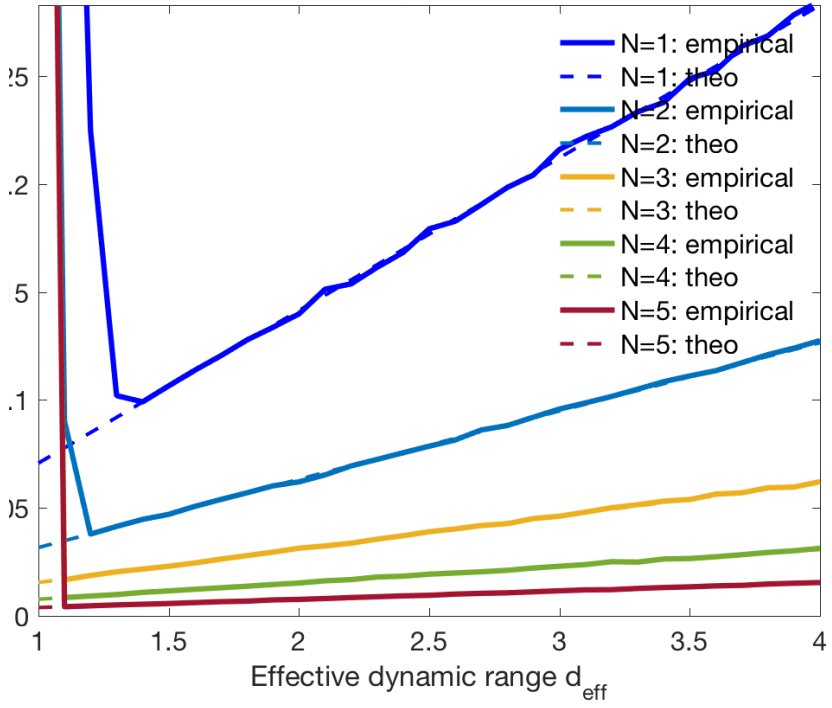
***Optimal multiple motion encoding (OMME) in Phase-Contrast MRI** (under review)*

***+ Efficient VNR improvements + robustness** (shorter examinations?)*

Standard averaging



Multi-VENC



***Ongoing:** "clever" extension to 4D flow*

Thanks! Questions?

c.a.bertoglio@rug.nl

www.math.rug.nl/~bertoglio

rijksuniversiteit
groningen