UC | Chile

LIBRE hub

Latam Hub for Bioimaging through Open Hardware

Chan Zuckerberg Initiative

MRI simulation

Carlos Castillo Passi

UC | Chile

LIBRE hub

Latam Hub for Bioimaging through Open Hardware

Chan Zuckerberg Initiative

What is MRI

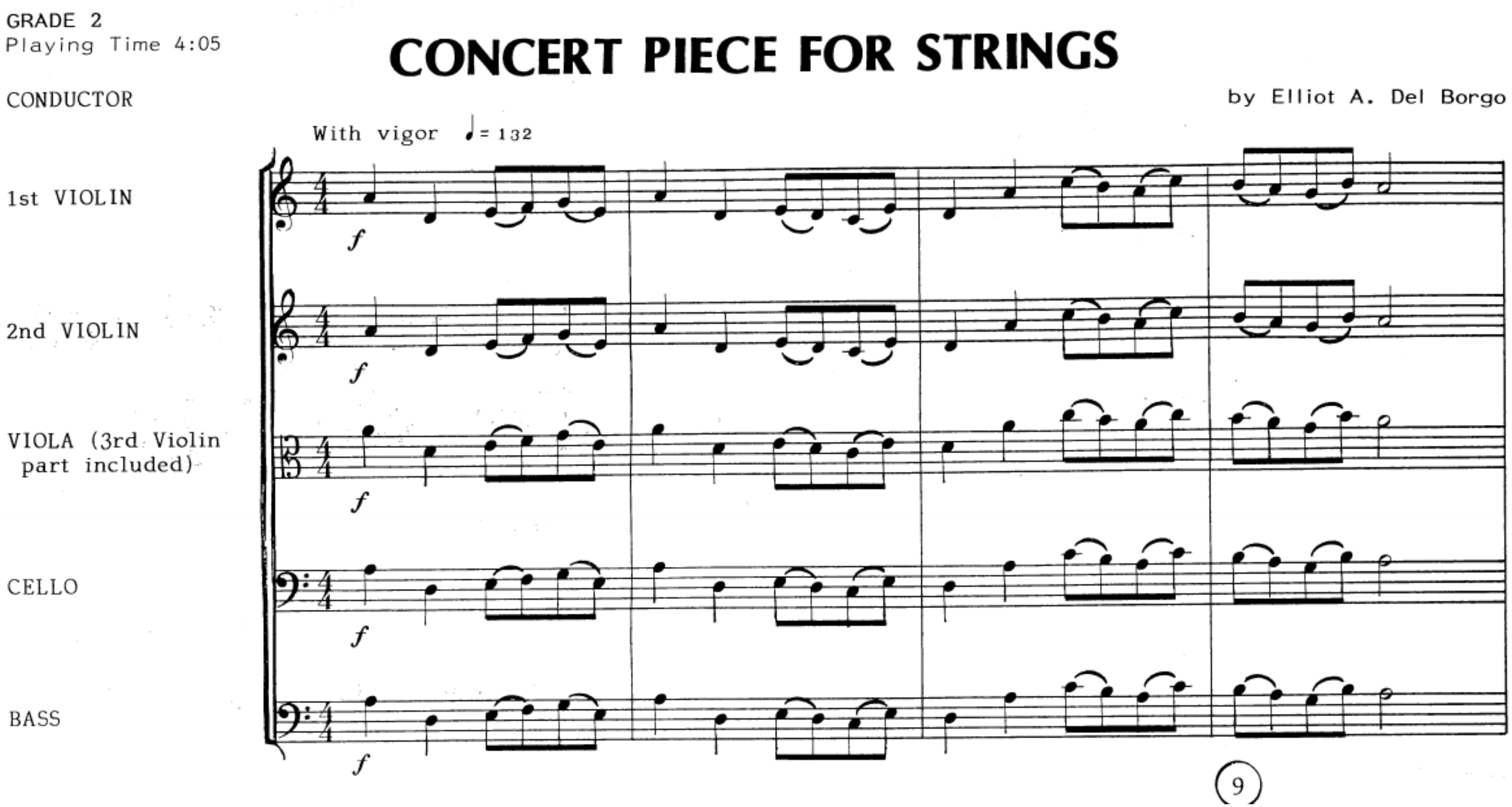
UC | Chile

LIBRE hub

Latam Hub for Bioimaging through Open Hardware

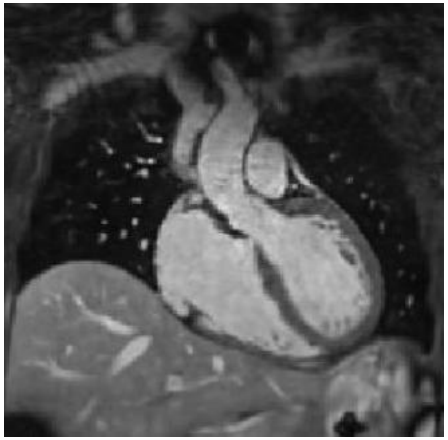
Chan Zuckerberg Initiative

How does MRI work?



How does MRI work?

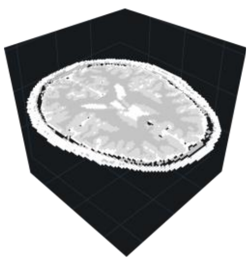
Sequence **Scanner** **Image**



Virtual MRI experiment

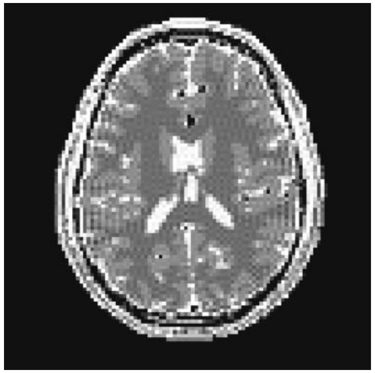
Phantom

$M_0, T_1, T_2, \ldots$



Scanner

Image



Sequence

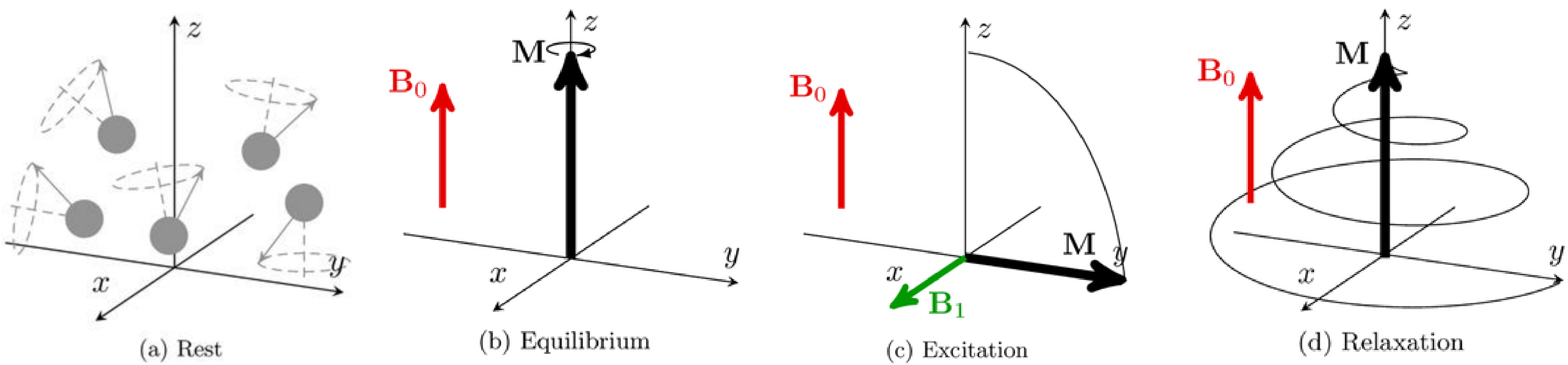
B

t

We have indirect measurements of the object

Bloch equation:

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = \gamma \boldsymbol{M} \times \boldsymbol{B} + \frac{(M_0 - M_z)\hat{\boldsymbol{z}}}{T_1} - \frac{M_x \hat{\boldsymbol{x}} + M_y \hat{\boldsymbol{y}}}{T_2}$$

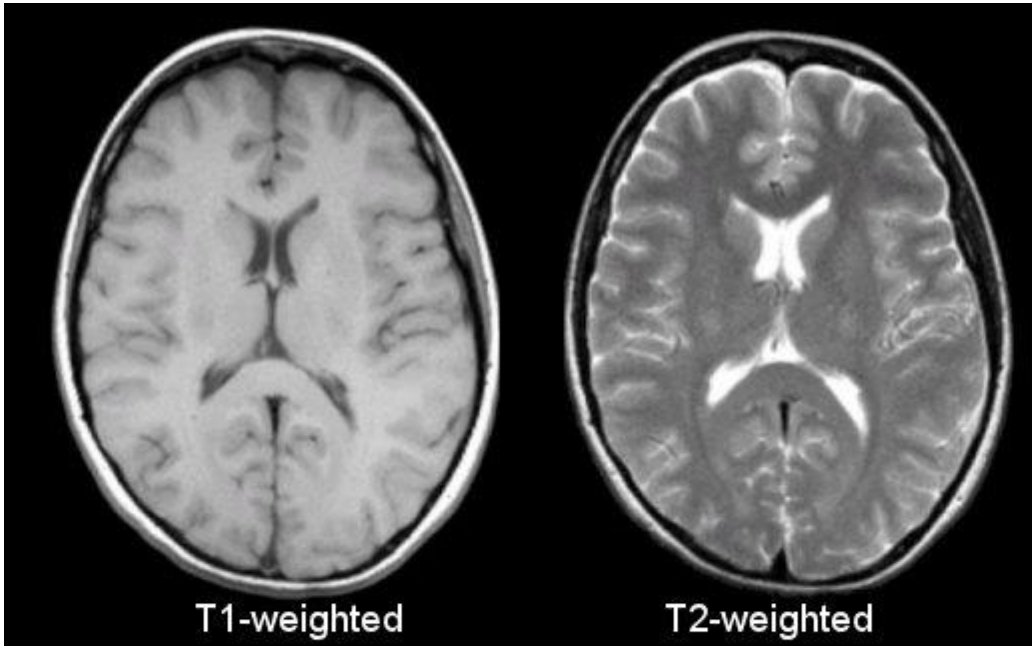


Numerical simulation of time-resolved 3D phase-contrast magnetic resonance imaging. Thomas Puiseux, et al. PlosOne.

Difference in magnetic prop. generate contrast

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = \gamma \boldsymbol{M} \times \boldsymbol{B} + \frac{(M_0 - M_z)\hat{\boldsymbol{z}}}{T_1} - \frac{M_x \hat{\boldsymbol{x}} + M_y \hat{\boldsymbol{y}}}{T_2}$$

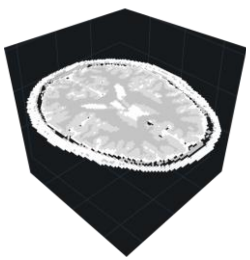
Sequence #1 **Sequence #2**



MRI simulation

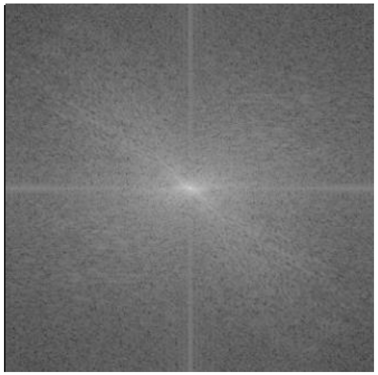
Phantom

$M_0, T_1, T_2, \ldots$



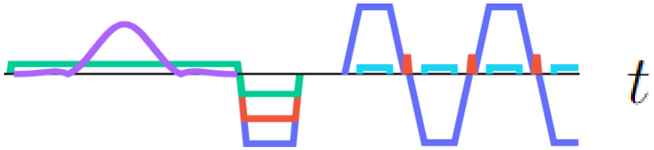
Scanner

Data



Sequence

B



Simulation: Forward problem

Non-linear
Encoding op.

Data

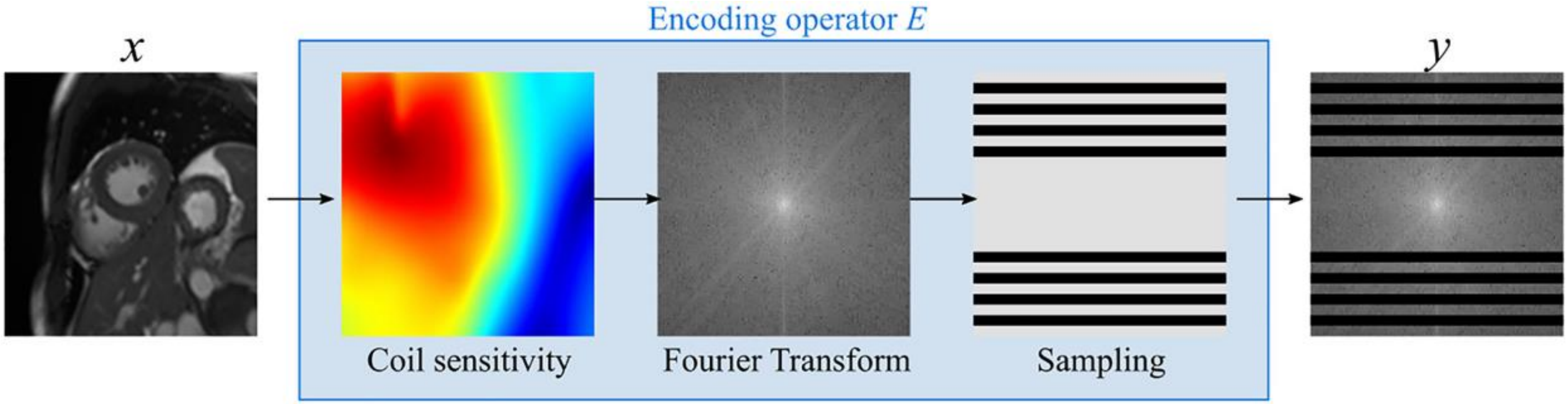
$$\boldsymbol{E}(\boldsymbol{x}) = \boldsymbol{y}$$

Image or
Quantitative maps

Reconstruction: Inverse problem

A **simplification** of the MRI system is used to enable **rapid reconstruction**

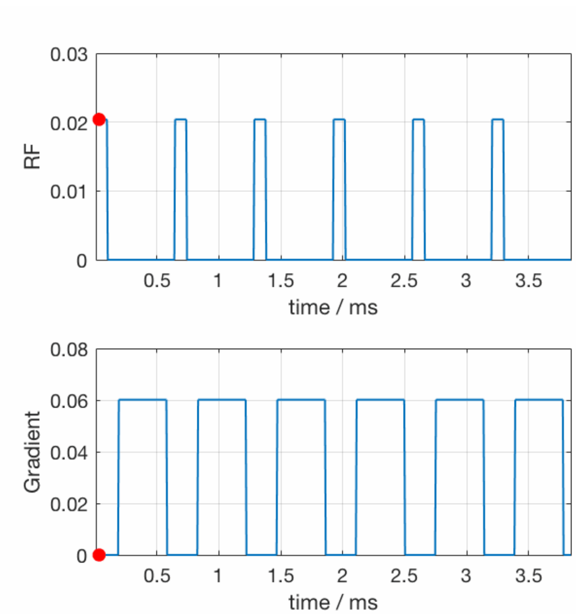
$$\boldsymbol{E}(\boldsymbol{x}) \approx \mathbf{E}\,\boldsymbol{x} \Rightarrow \min_{\boldsymbol{x}} \frac{1}{2}\|\mathbf{E}\boldsymbol{x} - \boldsymbol{y}\|_2^2 + \lambda R(\boldsymbol{x})$$

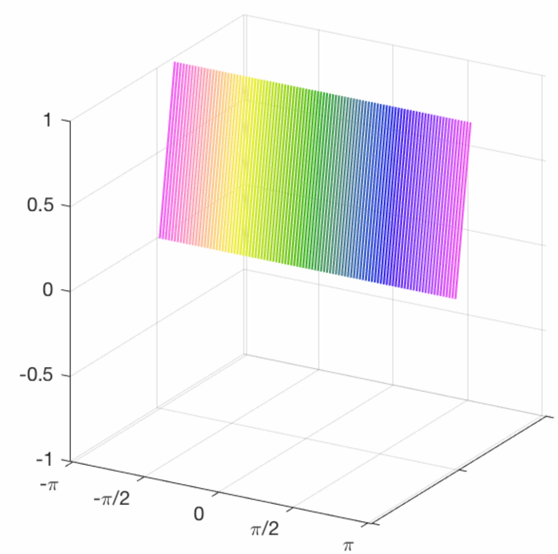


Camila Munoz, et al. Latest Advances in Image Acceleration: All Dimensions are Fair Game. MRM.

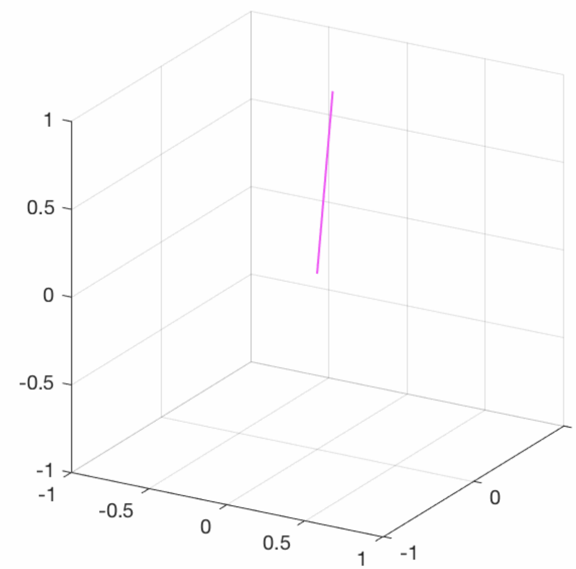
Simulation methods: Bloch

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = \gamma \boldsymbol{M} \times \boldsymbol{B} + \frac{(M_0 - M_z)\hat{\boldsymbol{z}}}{T_1} - \frac{M_x\hat{\boldsymbol{x}} + M_y\hat{\boldsymbol{y}}}{T_2}$$





Spins along the x-axis

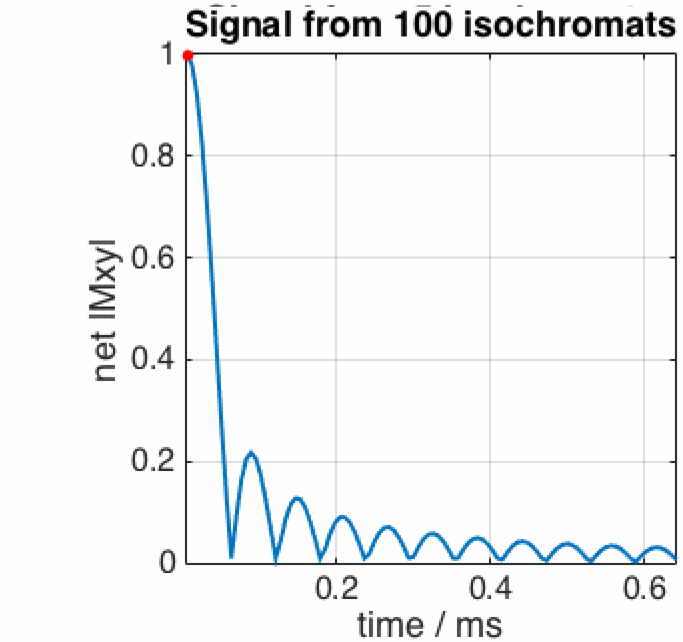


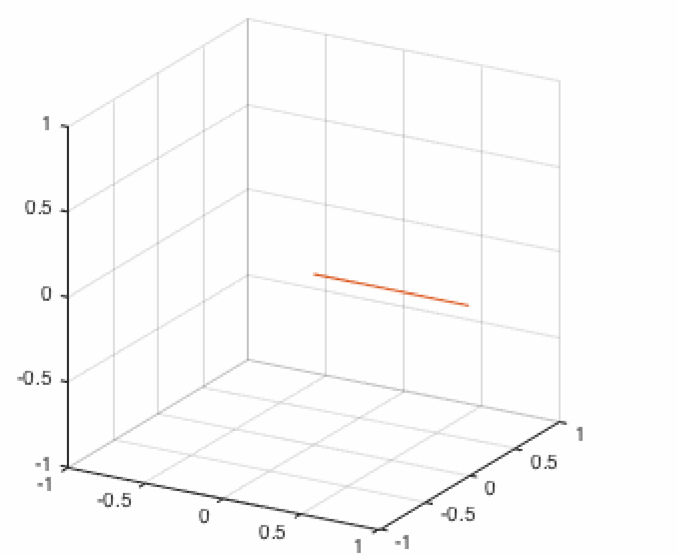
Spins on top of each other

Shaihan Malik. https://mriphysics.github.io/teaching-mri-intro.html

Isochromat: Spins that precess at different frequencies

- Effect of a big gradient on a spin ensemble with a low number of isochromats



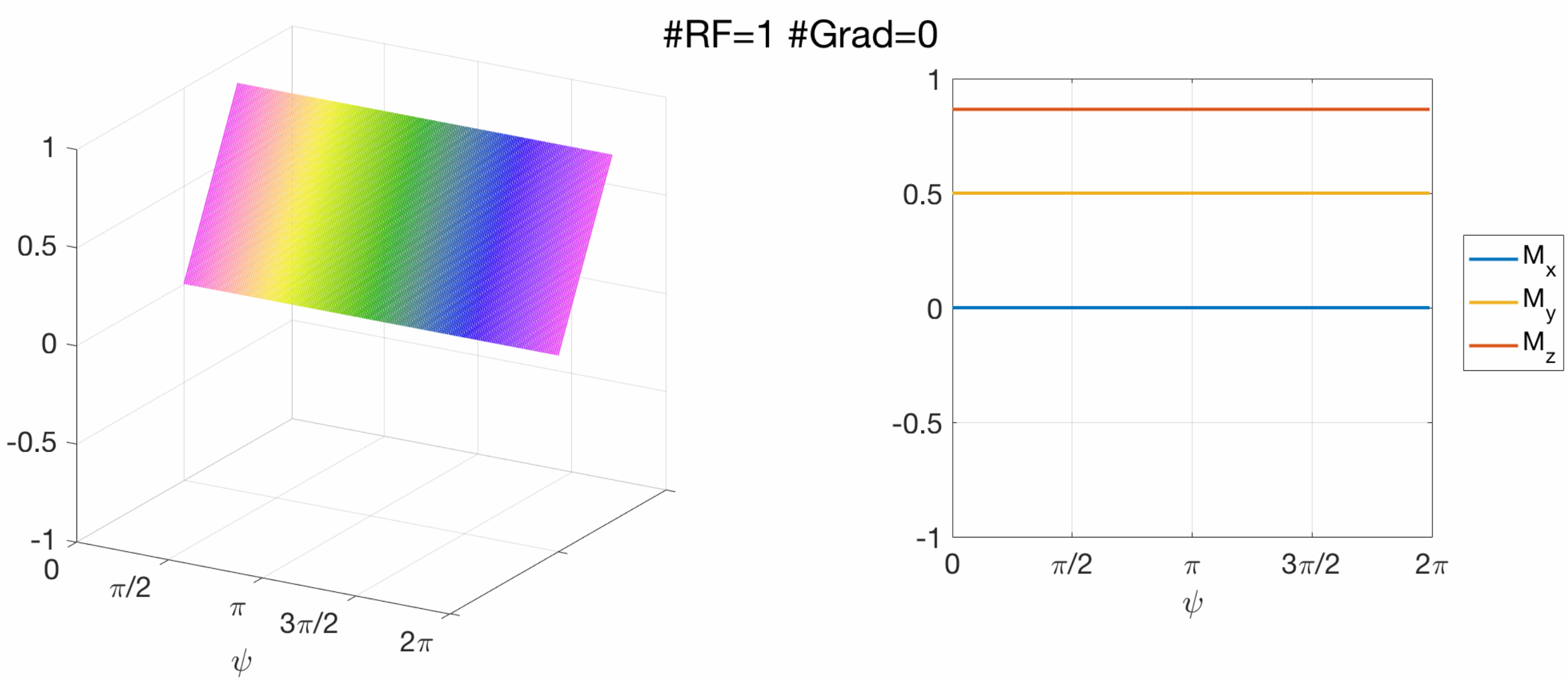


Not realistic spurious echoes

Shaihan Malik. https://mriphysics.github.io/teaching-mri-intro.html

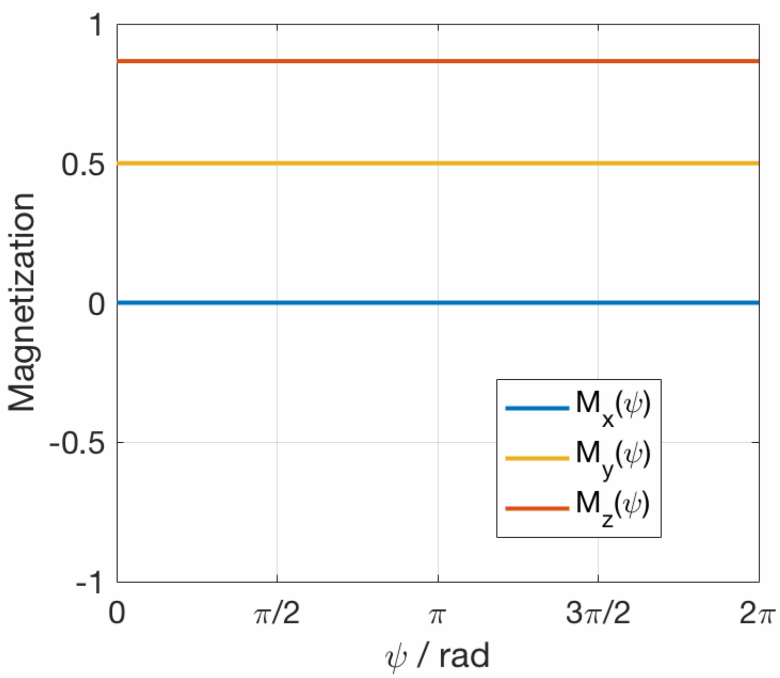
Simulation method: EPG

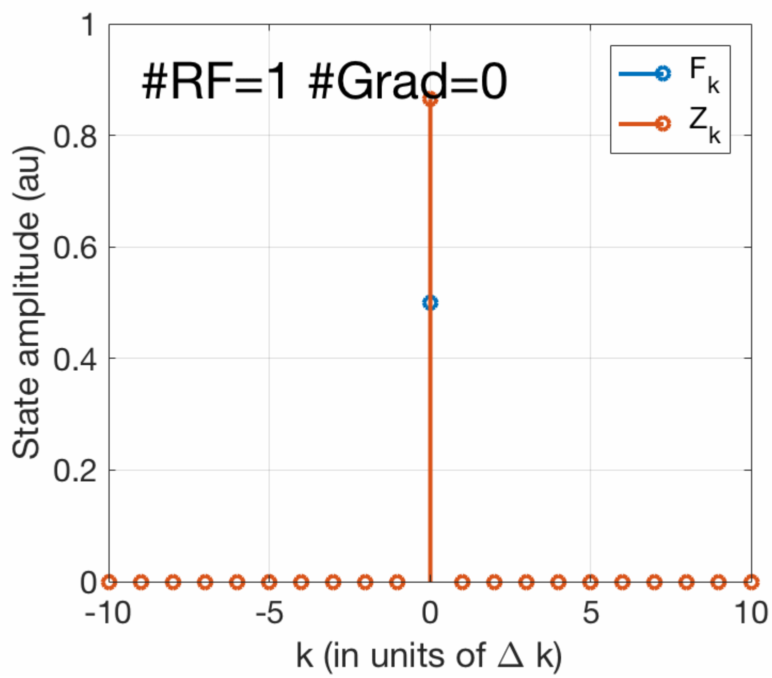
- Let’s look at the previous example in another way



Simulation method: EPG

- Let’s look at the previous example in another way





Instead of 100 isochromats
we can use just a few Fourier components!

Shaihan Malik. https://mriphysics.github.io/teaching-mri-intro.html

Operator splitting method

- How do you deal with **relaxation**?

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = \gamma \boldsymbol{M} \times \boldsymbol{B} + \frac{(M_0 - M_z)\hat{\boldsymbol{z}}}{T_1} - \frac{M_x\hat{\boldsymbol{x}} + M_y\hat{\boldsymbol{y}}}{T_2}$$

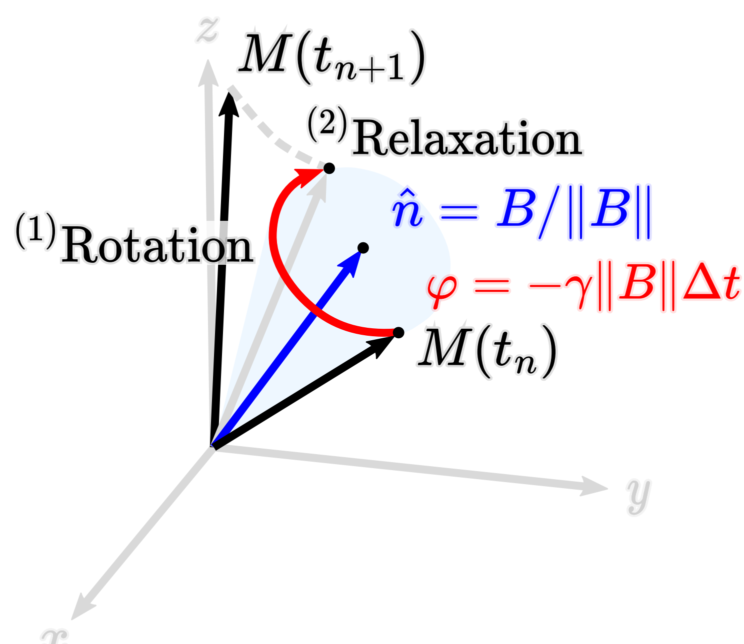
Precession Relaxation

No general solution

$$\frac{\mathrm{d}\boldsymbol{M}^{(1)}}{\mathrm{d}t} = \begin{bmatrix} 0 & \gamma B_z & -\gamma B_y \\ -\gamma B_z & 0 & \gamma B_x \\ \gamma B_y & -\gamma B_x & 0 \end{bmatrix} \boldsymbol{M}^{(1)}, \qquad (3)$$

with initial condition $\boldsymbol{M}^{(1)}(t_n) = \boldsymbol{M}(t_n)$, and the relaxation is described by

$$\frac{\mathrm{d}\boldsymbol{M}^{(2)}}{\mathrm{d}t} = \begin{bmatrix} -\frac{1}{T_2} & 0 & 0 \\ 0 & -\frac{1}{T_2} & 0 \\ 0 & 0 & -\frac{1}{T_1} \end{bmatrix} \boldsymbol{M}^{(2)} + \begin{bmatrix} 0 \\ 0 \\ \frac{M_0}{T_1} \end{bmatrix}, \qquad (4)$$



Carlos Castillo-Passi. KomaMRI.jl: An open-source framework for general MRI simulations with GPU acceleration (2023). MRM

UC | Chile

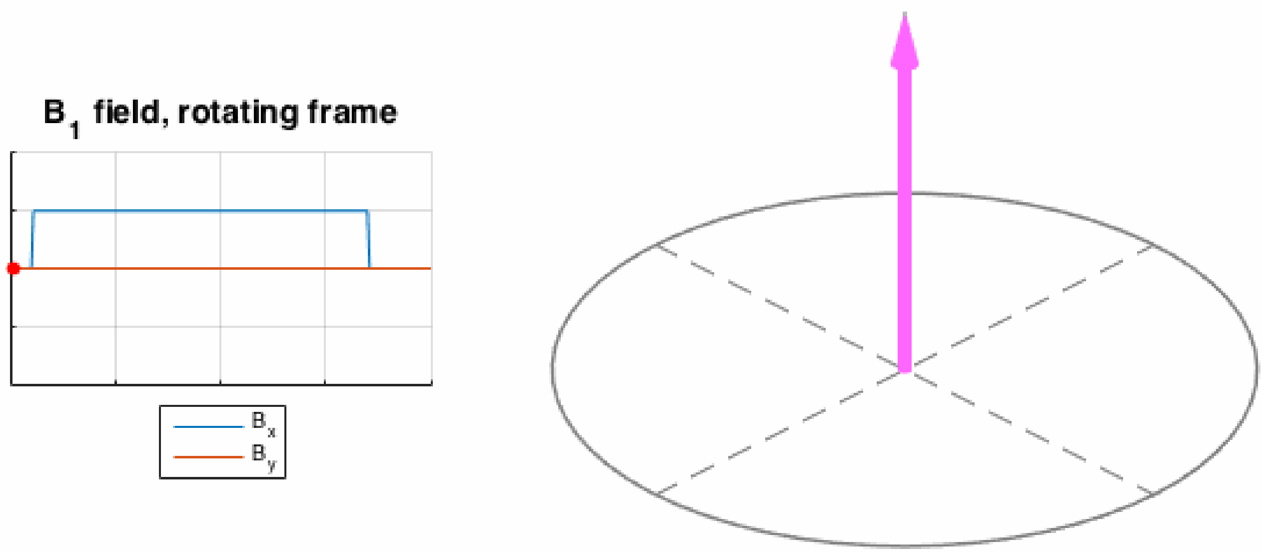
LIBRE hub

Latam Hub for Bioimaging through Open Hardware

Chan Zuckerberg Initiative

Simulation examples

- Slice selectivity



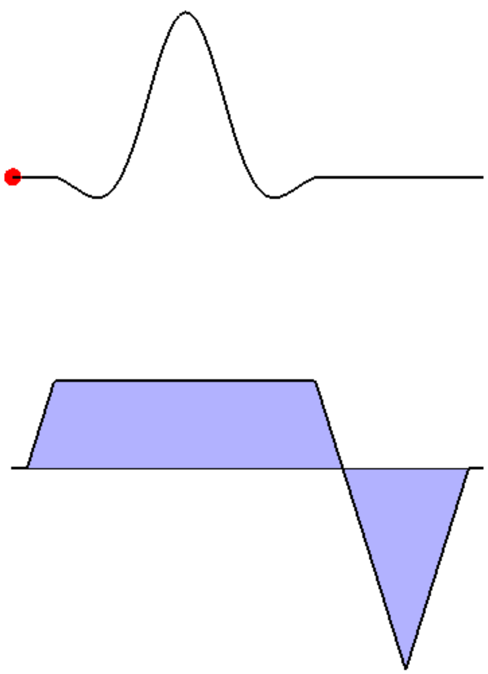
UC | Chile

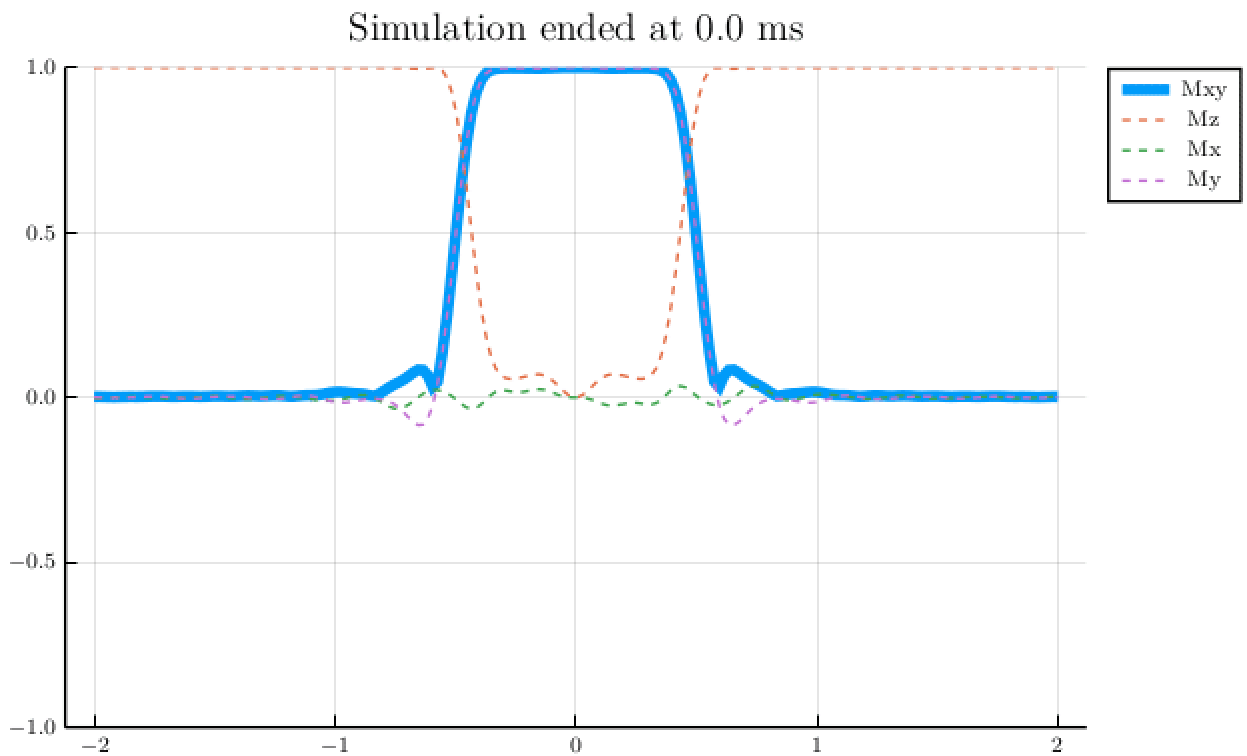
LIBRE hub
Latam Hub for Bioimaging through Open Hardware

Chan Zuckerberg Initiative

Simulation examples

- Slice selectivity

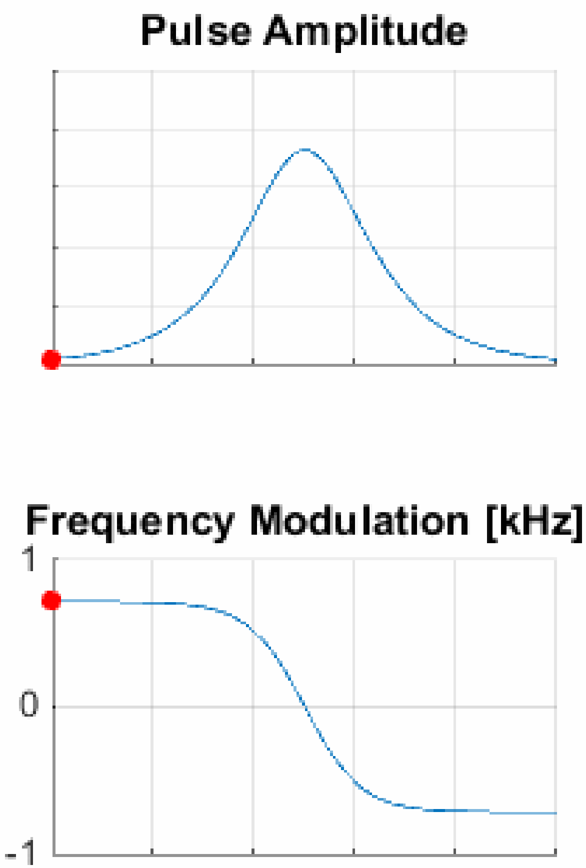


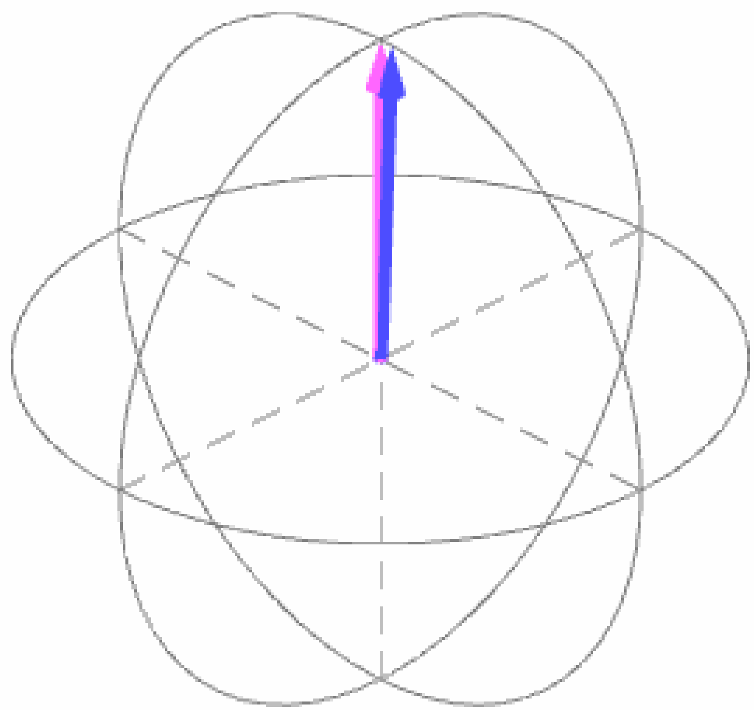


z

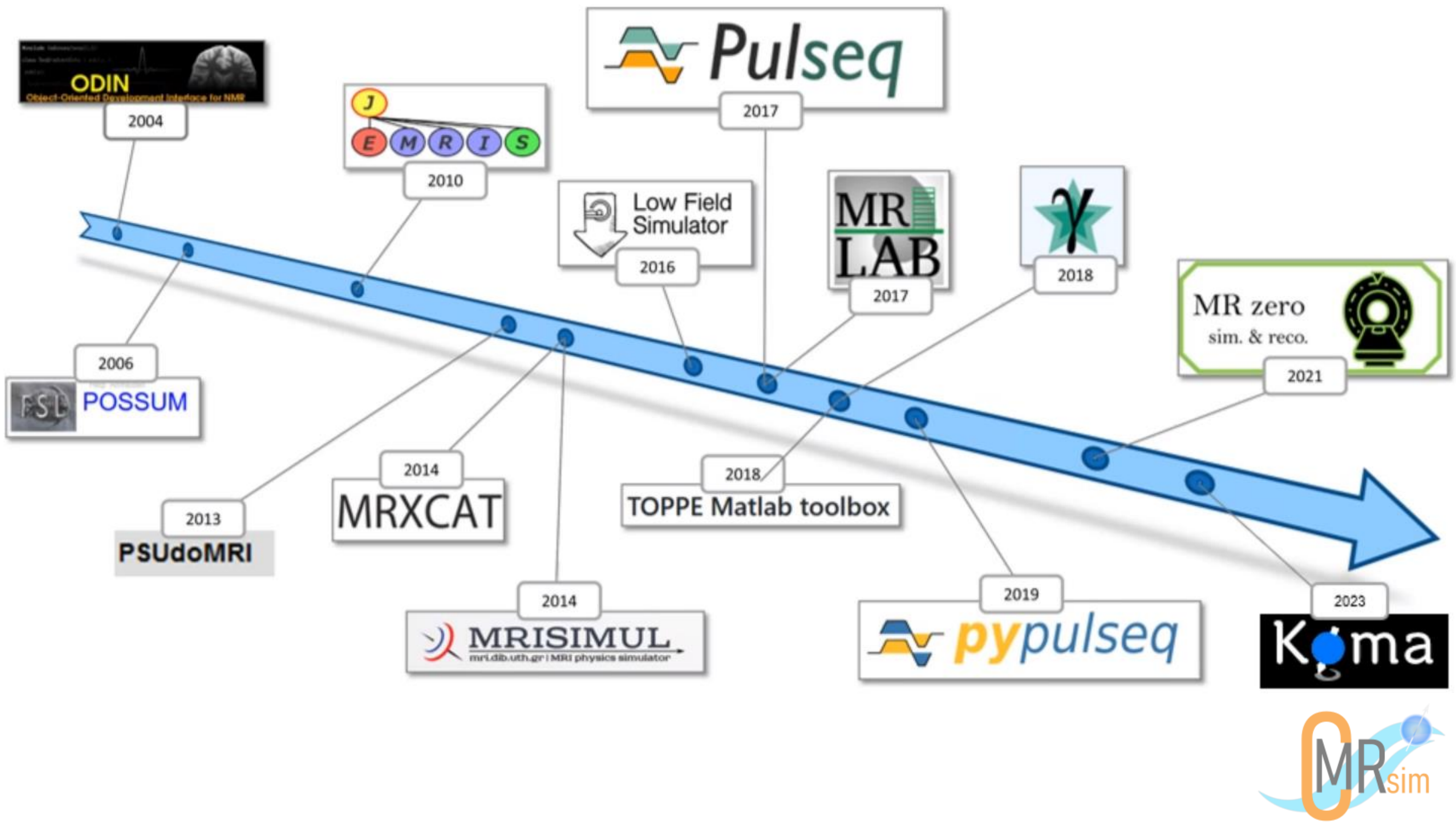
Simulation examples

- Adiabatic RF pulses





MRI simulation landscape



Jonathan Weine, et al. Poster #2393. ISMRM 2023, Toronto, Canada.

UC | Chile

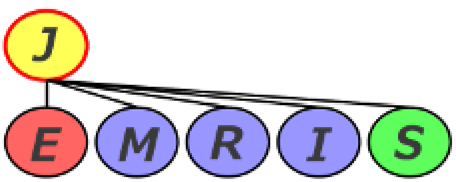
LIBRE hub

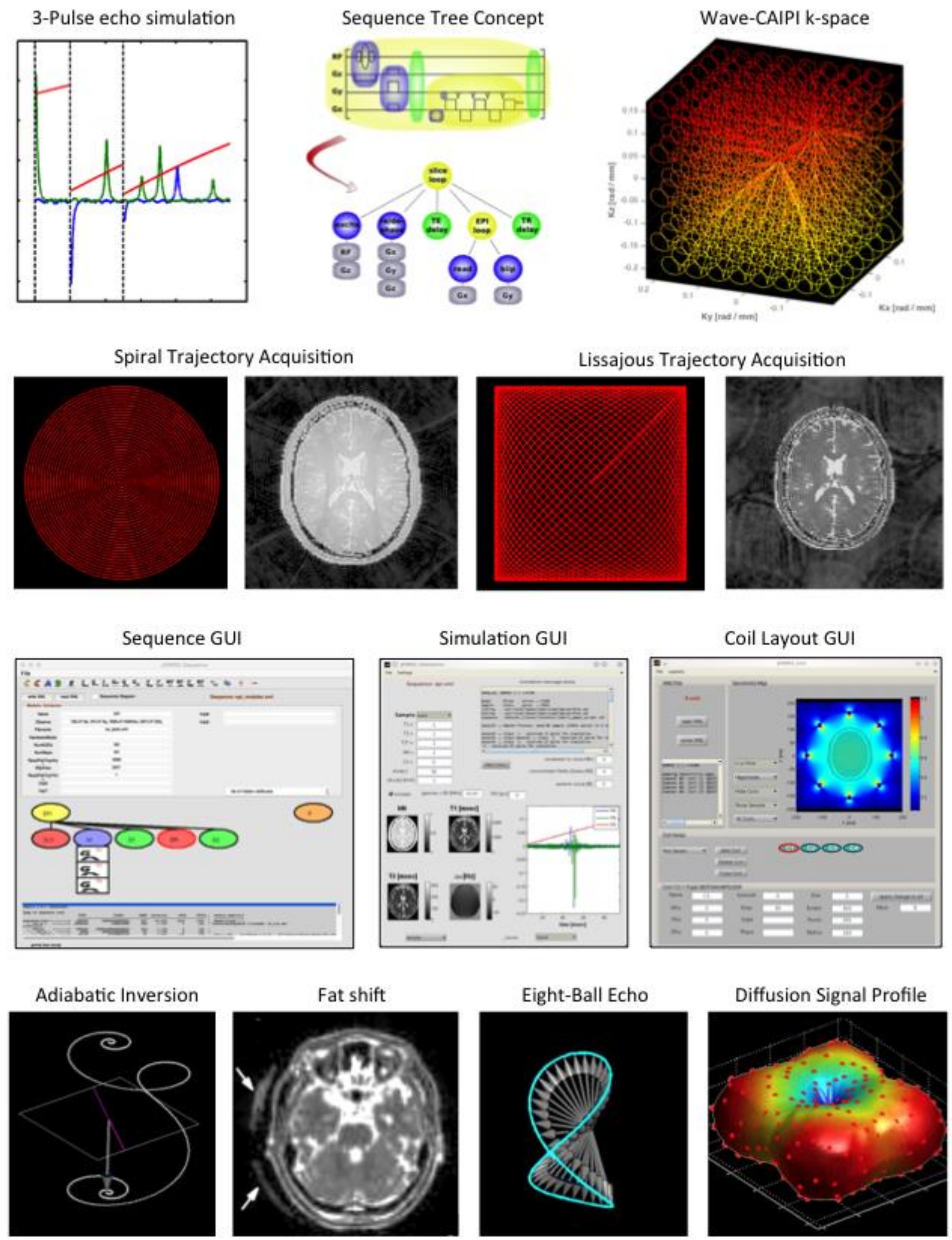
Latam Hub for Bioimaging through Open Hardware

Chan Zuckerberg Initiative

JEMRIS (2010)

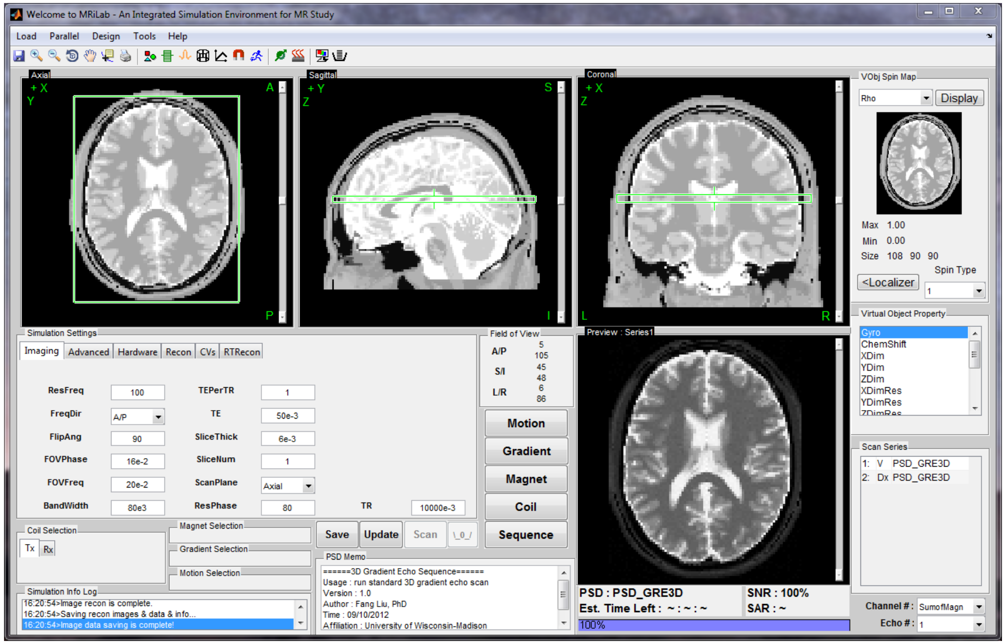
- MATLAB GUI
- CPU Multithreading
- C++





MRiLab (2017)

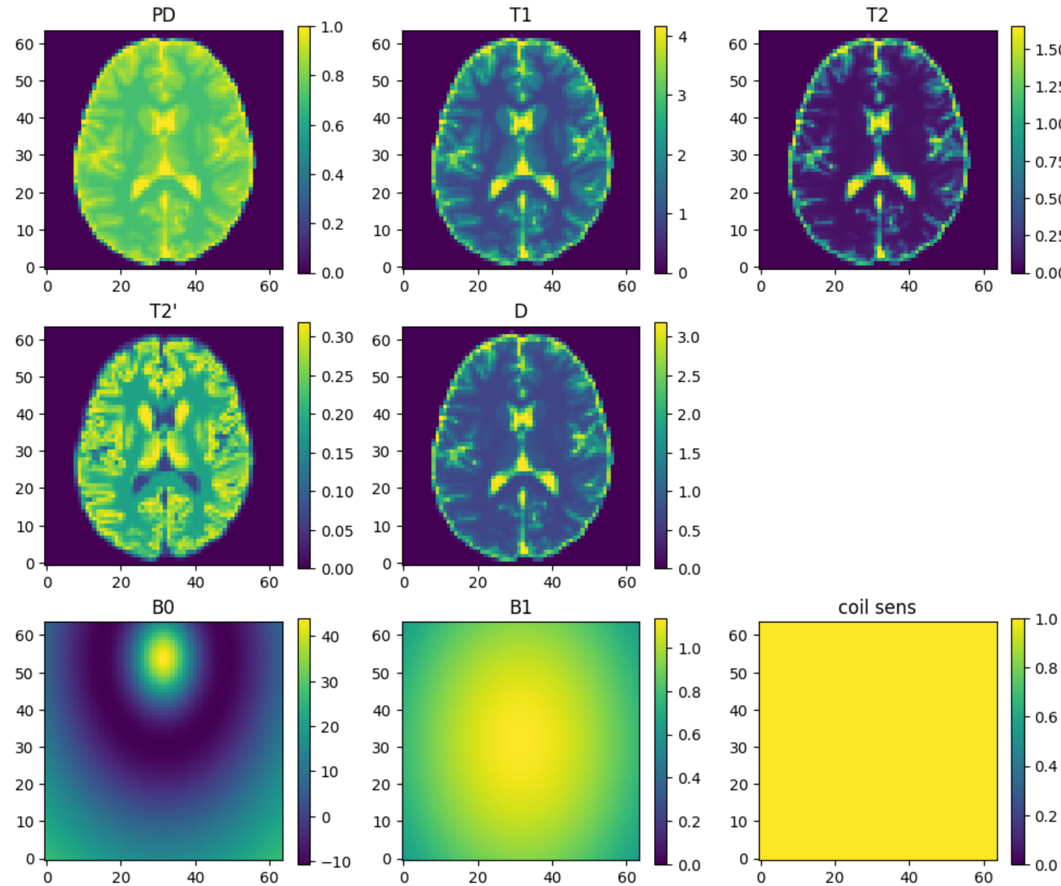
- MATLAB GUI
- CPU Multithreading
- GPU acceleration
- C++ and CUDA



MR LAB

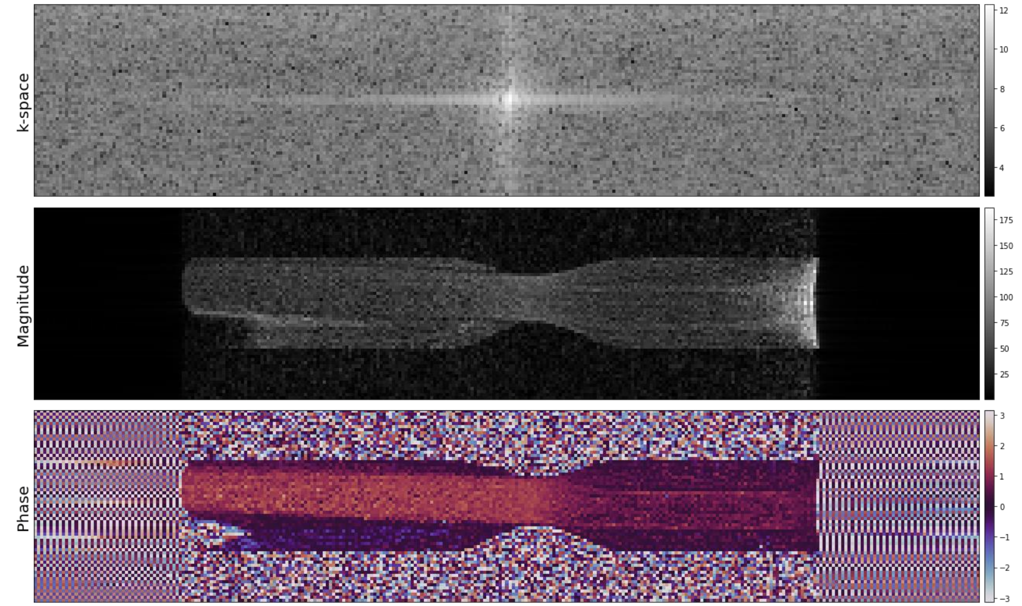
MRZero (2021)

- No GUI
- GPU acceleration
- Pure Python
- Pulseq compatible
- PyTorch based



CMRsim (2023)

- No GUI
- GPU acceleration
- Pure Python
- TensorFlow2 based



CMRsim

UC | Chile

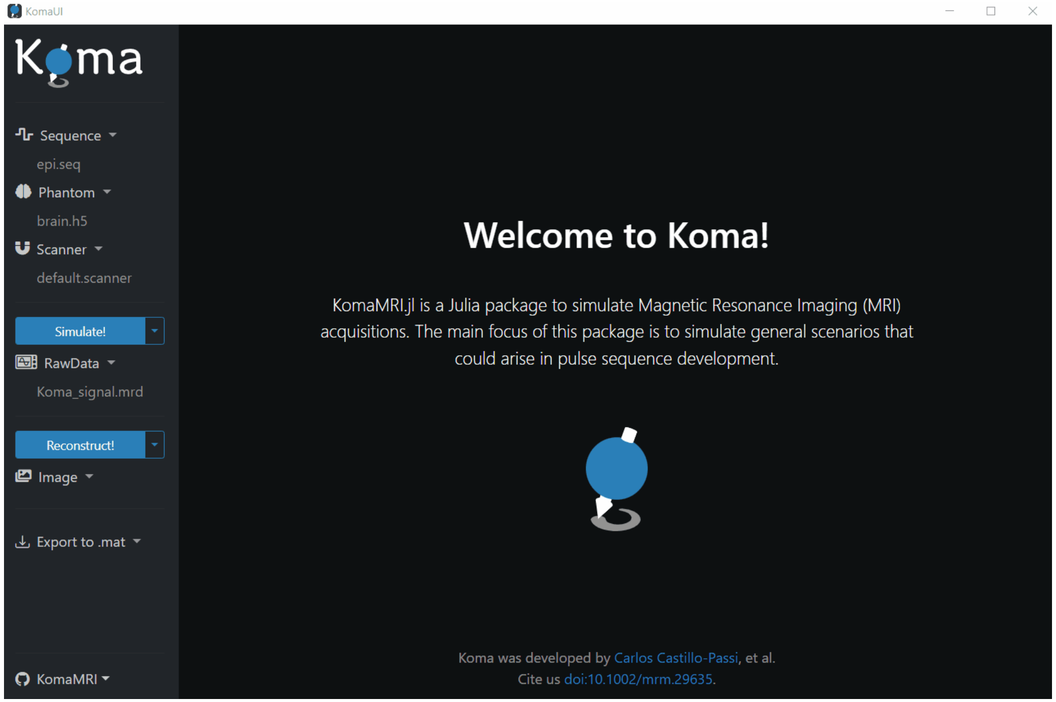
LIBRE hub

Latam Hub for Bioimaging through Open Hardware

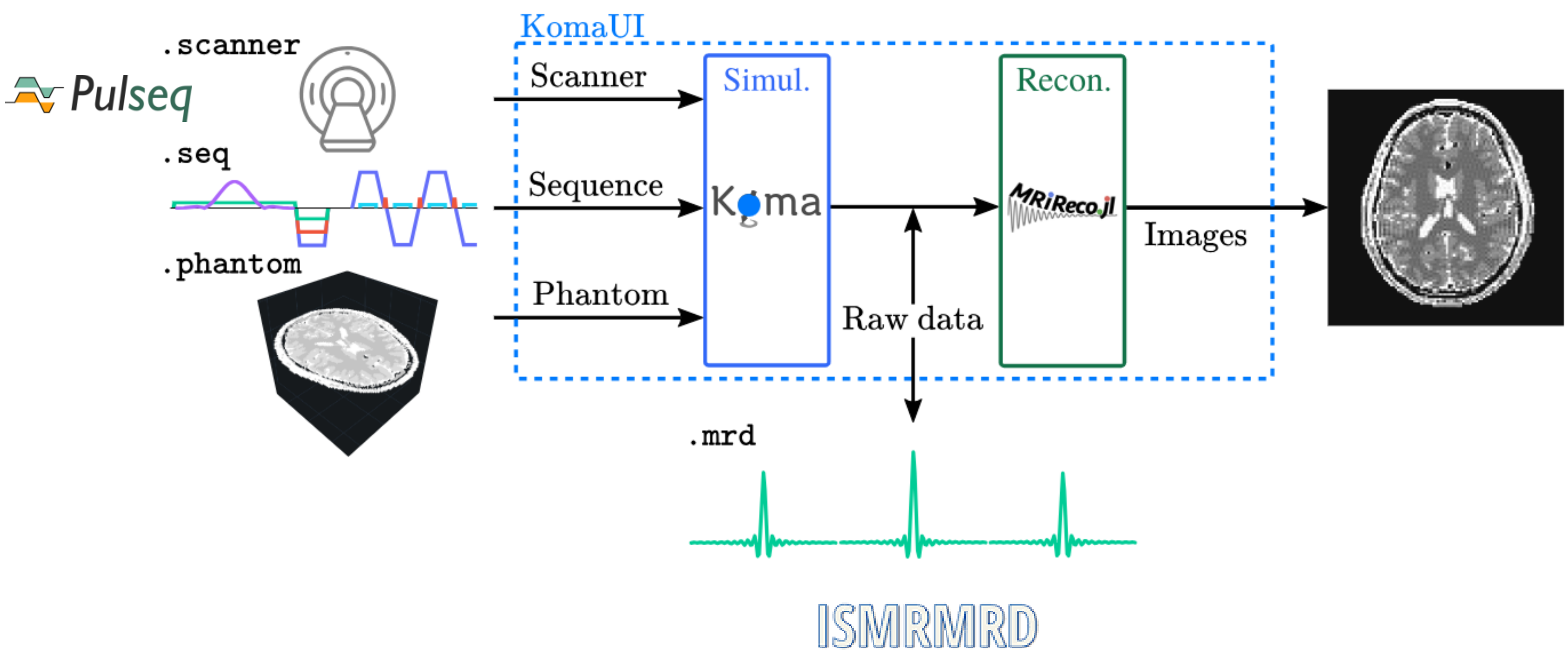
Chan Zuckerberg Initiative

KomaMRI (2023)

- Web GUI
- CPU Multithreading
- GPU acceleration
- Pure Julia
- Pulseq compatible

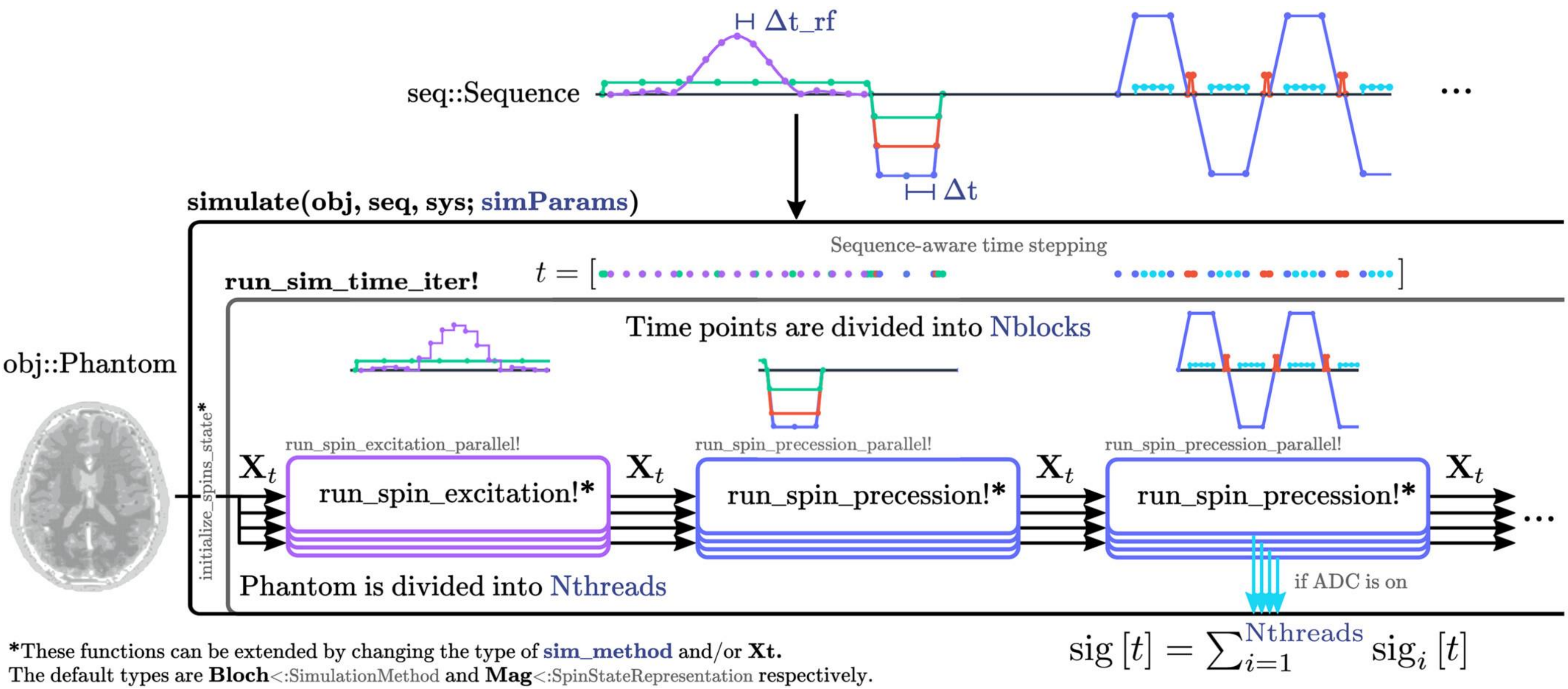


KomaMRI.jl



Carlos Castillo-Passi, KomaMRI.jl: An open-source framework for general MRI simulations with GPU acceleration. MRM.

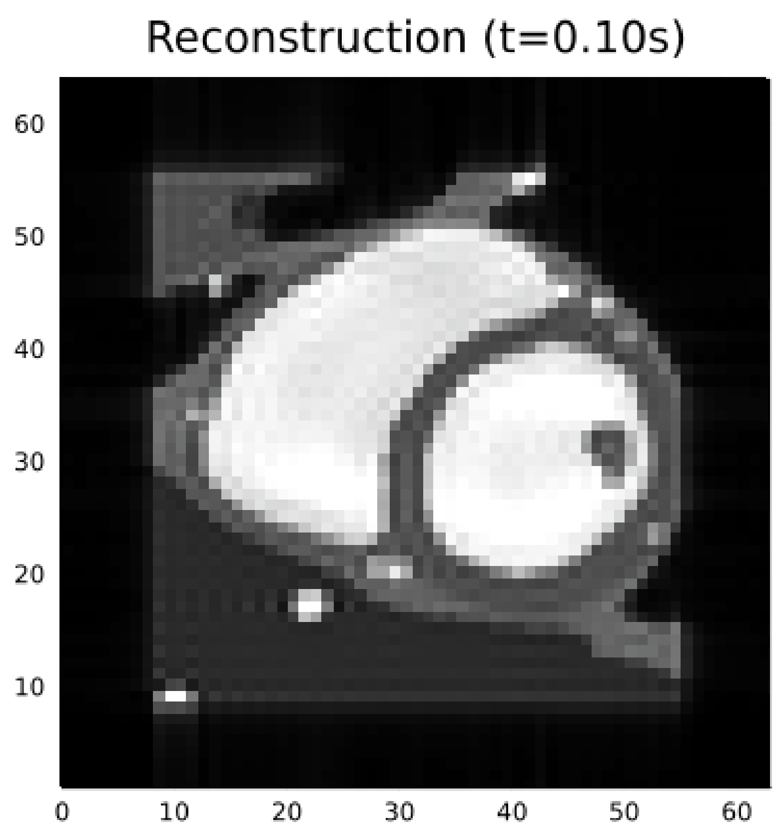
Parallelization and extensibility

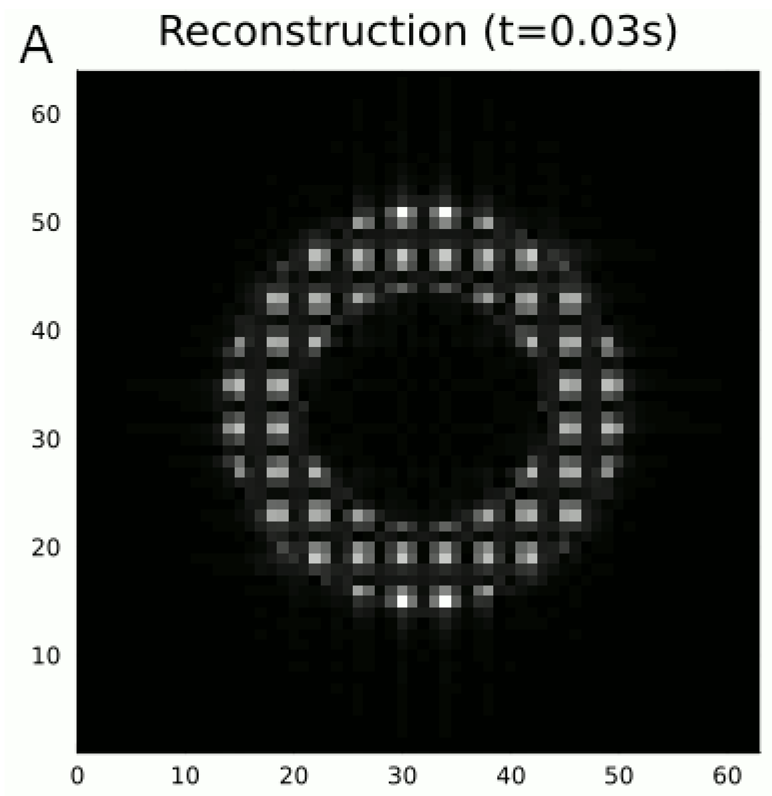


Carlos Castillo-Passi, KomaMRI.jl: An open-source framework for general MRI simulations with GPU acceleration. MRM.

A KomaMRI Phantom Extension for Integrated Dynamic Imaging

Pablo Villacorta Aylagas, Carlos Castillo-Passi, Rosa María Menchón-Lara, Pablo Irarrazaval, Carlos Alberola-López



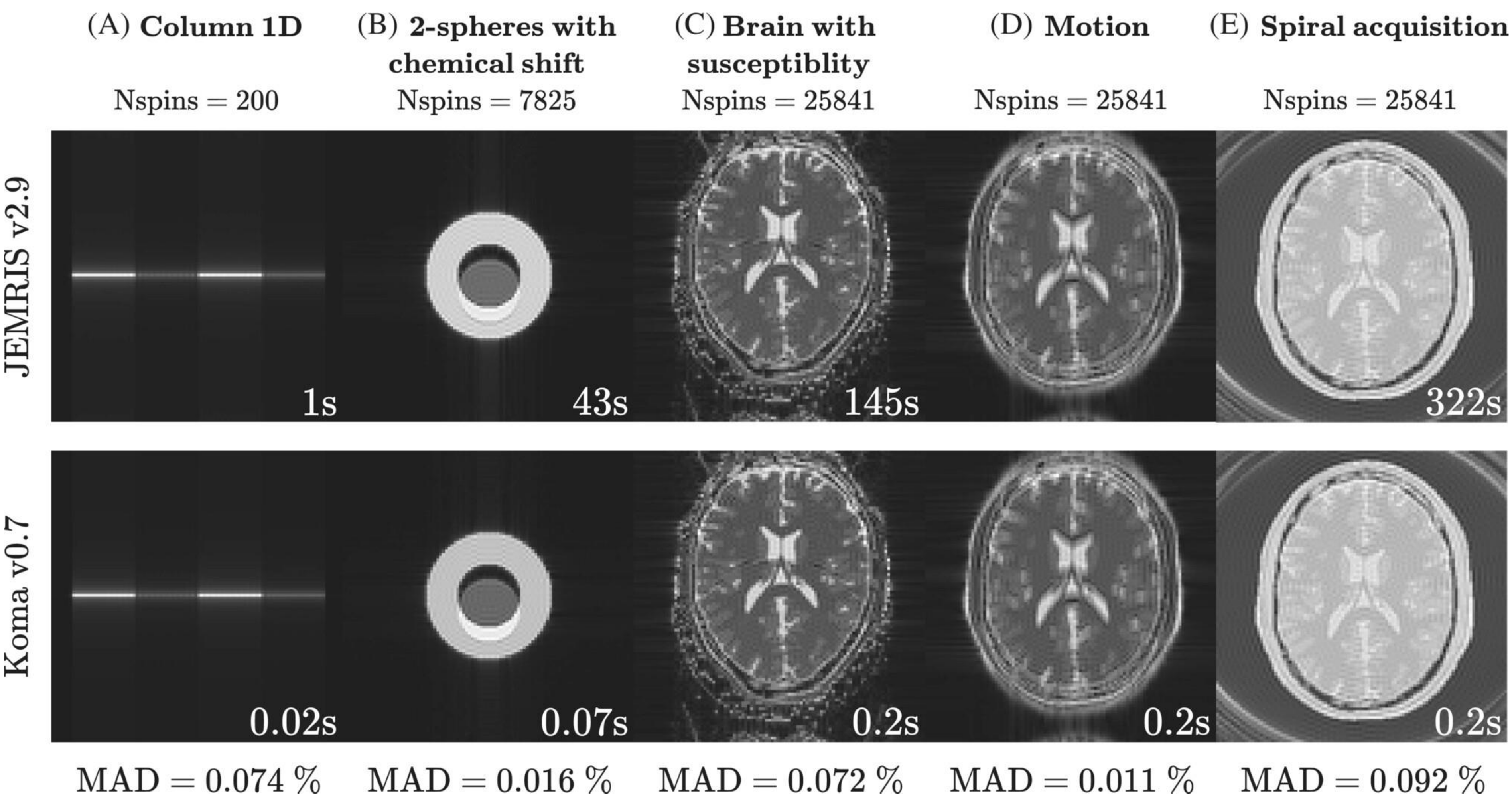


Speed: Comparing simulation speed

	CPU	GPU	
Name	Intel i7-1165G7	GTX 1650 Ti	RTX 2080 Ti
JEMRIS	≈ 7 min	-	-
MRiLab	**1.56 s ± 0.07 s**	0.84 s ± 0.02 s	0.91 s ± 0.02 s
Koma	1.82 s ± 0.17 s	**0.32 s ± 0.02 s**	**0.15 s ± 0.01 s**

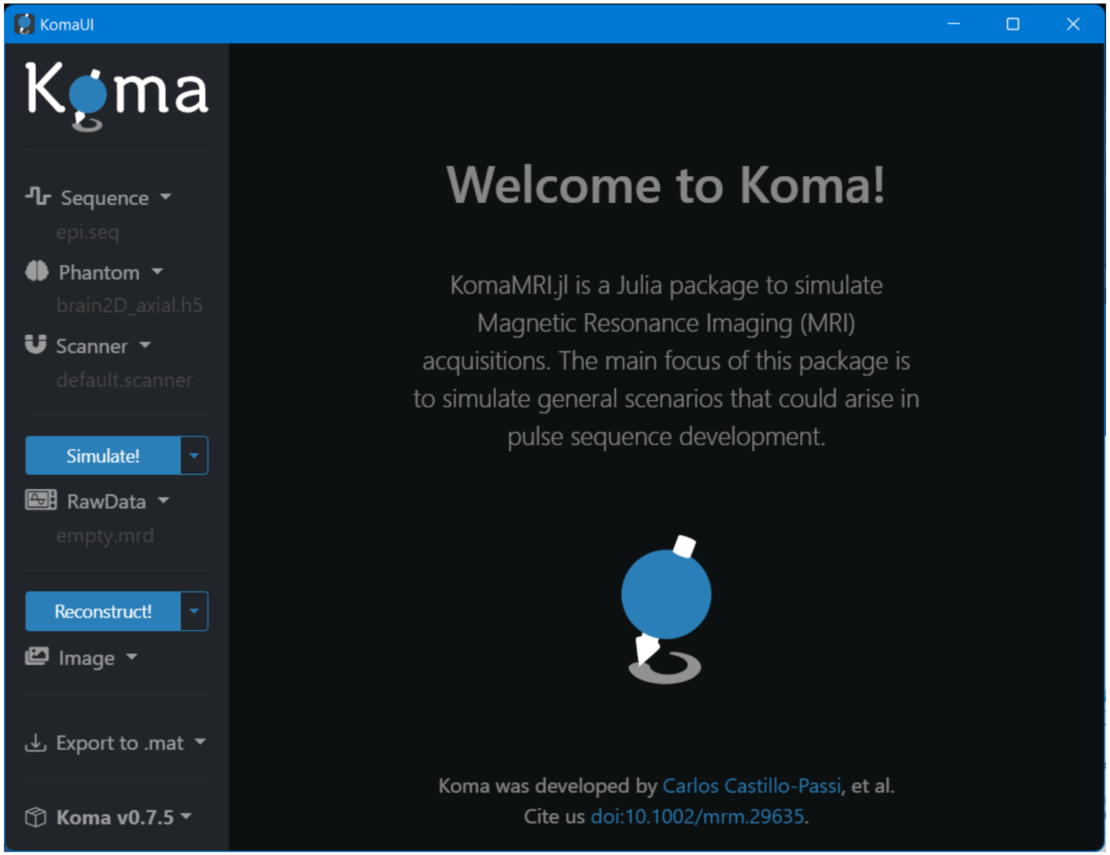
Carlos Castillo-Passi, KomaMRI.jl: An open-source framework for general MRI simulations with GPU acceleration. MRM.

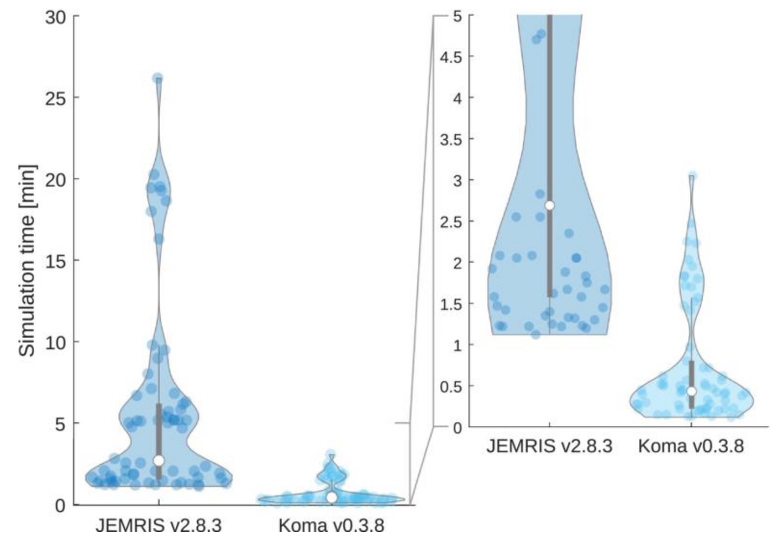
Acc: Comparing simulation accuracy with JEMRIS



Carlos Castillo-Passi, KomaMRI.jl: An open-source framework for general MRI simulations with GPU acceleration. MRM.

Easy-to-use: Students’ experience (beta testers)





User experience

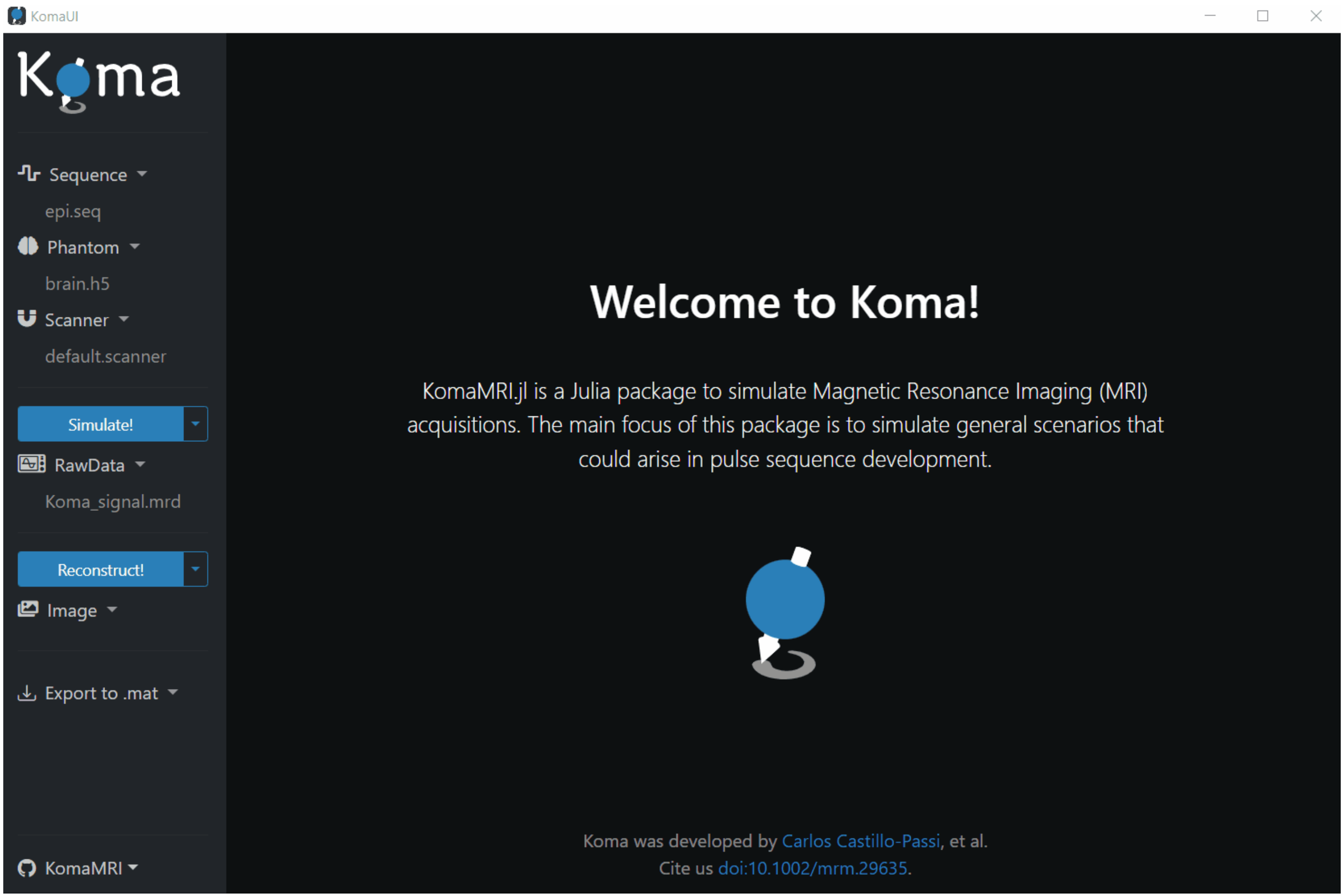
Students reported no problem installing Julia (mean 4.7/5), Koma (mean 4.2/5), JEMRIS (mean 3.8/5), and MRiLab (mean 4.3/5). Regarding the time taken to install each simulator, most of the students were able to install Koma (mean 13.2 min), JEMRIS (mean 33.8 min), and MRiLab (mean 16.9 min) in less than 40 min.

Their first simulation took them more time in JEMRIS (mean 19 min) and MRiLab (mean 13.9 min) than in Koma (mean 5.7 min). 31% of the students could not simulate on MRiLab (six students using Mac OS), so we decided to only use Koma and JEMRIS for the rest of the activities.

Blink.jl + PlotlyJS.jl powered

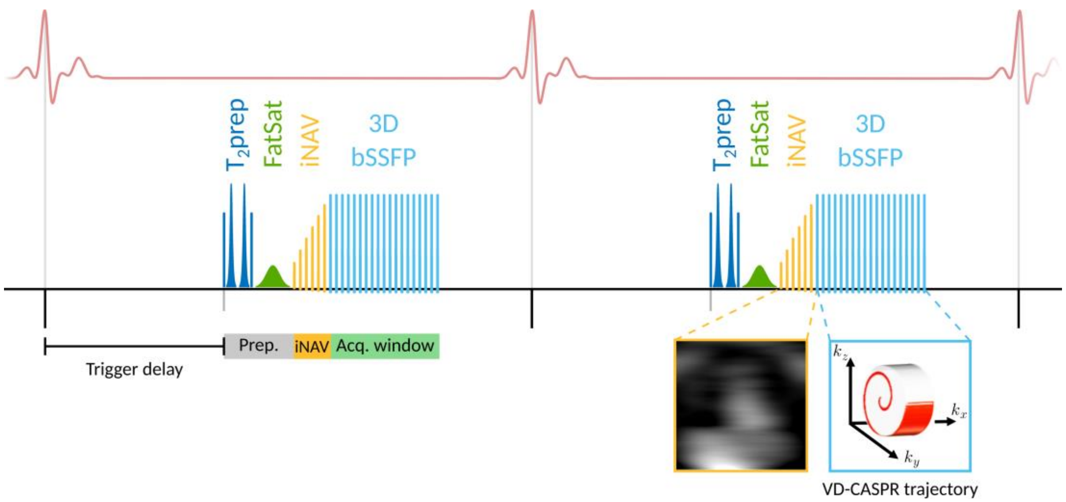
You can export your sequence to an interactive HTML! :)

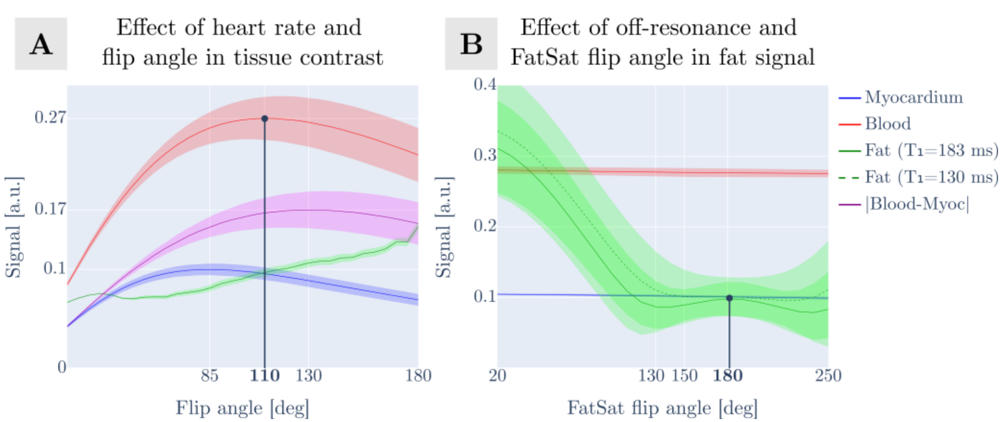
Using KomaMRI's GUI

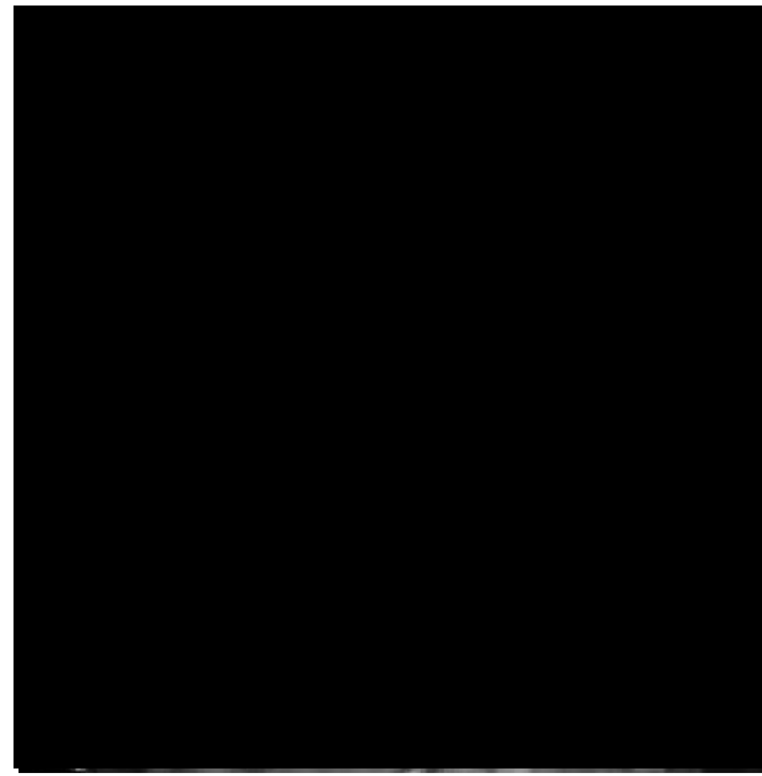


Whole-Heart Cardiovascular MRA with iNAV-based Non-Rigid Motion-Corrected Reconstruction at 0.55T

Carlos Castillo-Passi, Michael Crabb, Camila Munoz, Karl P. Kunze, Radhouene Neji,
Pablo Irarrazaval, René M. Botnar, and Claudia Prieto

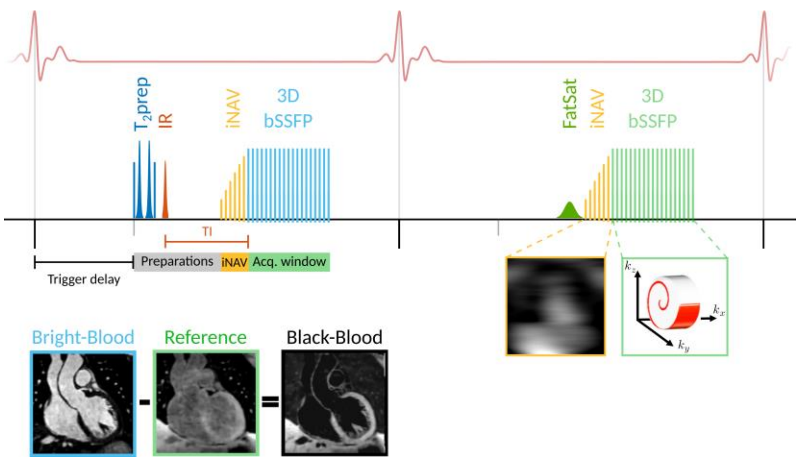


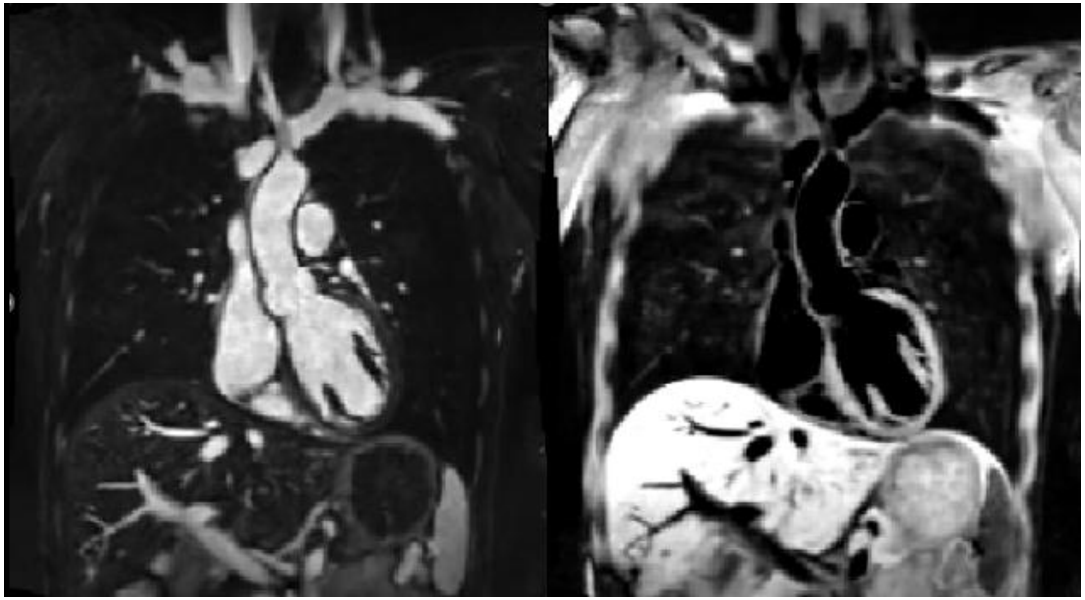




Simultaneous iNAV-based 3D Whole-Heart Bright-Blood and Black-Blood Imaging at 0.55T

Carlos Castillo-Passi, Karl P. Kunze, Michael Crabb, Camila Munoz, Radhouene Neji,
Pablo Irarrazaval, René M. Botnar, and Claudia Prieto





UC | Chile

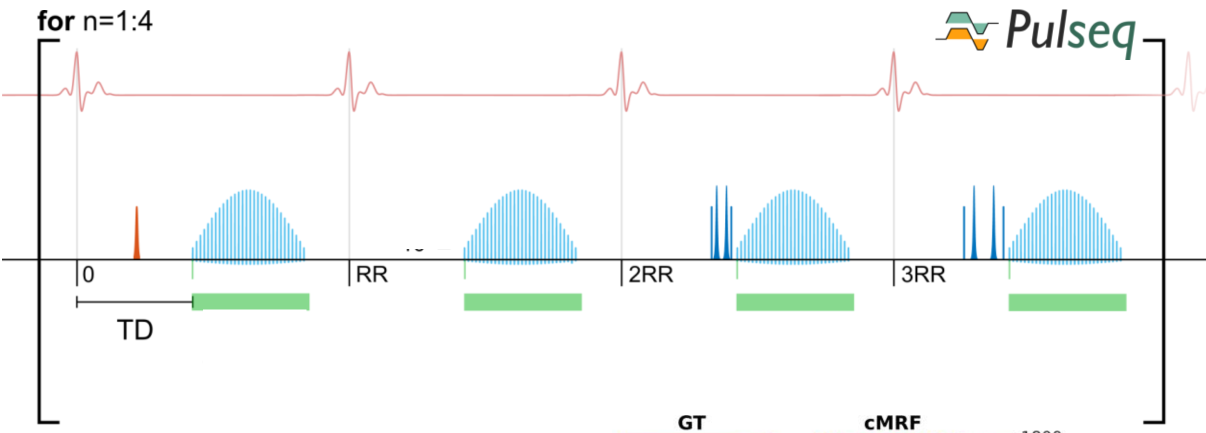
LIBRE hub

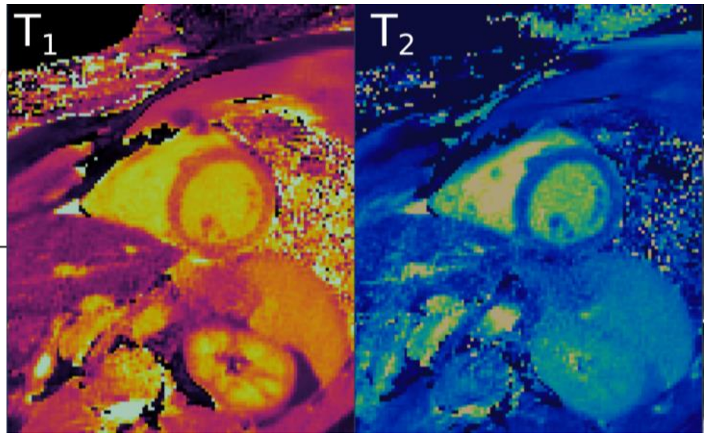
Latam Hub for Bioimaging through Open Hardware

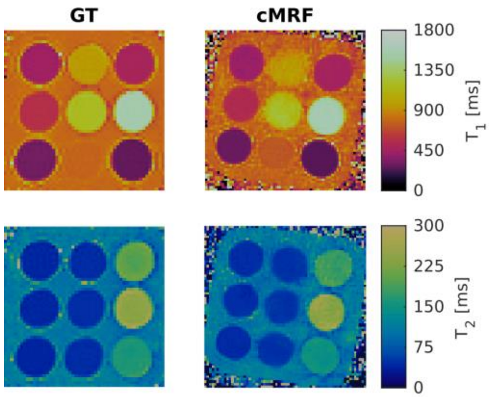
Chan Zuckerberg Initiative

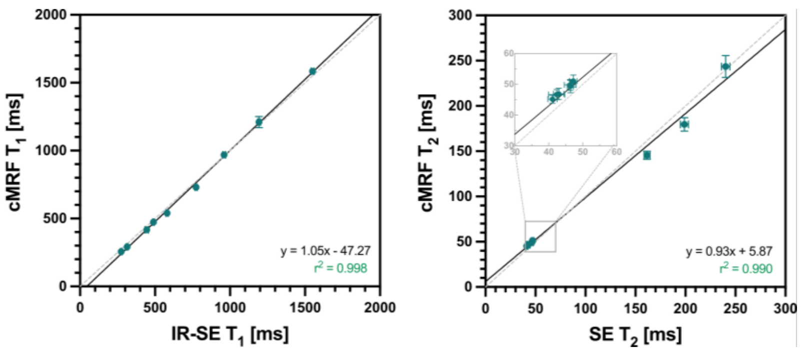
Cardiac Magnetic Resonance Fingerprinting for Simultaneous T1 and T2 Mapping at 0.55T

Carlos Castillo-Passi, Carlos Velasco, Donovan Tripp, Karl P. Kunze, Radhouene Neji,
Pablo Irarrazaval , René M. Botnar, and Claudia Prieto









Cardiac Magnetic Resonance Fingerprinting for Simultaneous T1 and T2 Mapping at 0.55T

Carlos Castillo-Passi, Carlos Velasco, Donovan Tripp, Karl P. Kunze, Radhouene Neji, Pablo Irarrazaval, René M. Botnar, and Claudia Prieto