Open Source Software for MRI Reconstruction

2026-05-09 – ISMRM26 | Cape Town

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Declaration of Financial Interests or Relationships

Speaker Name: Pierre-Antoine Comby

I have no financial interests or relationships to disclose with regard to the subject matter of this presentation.

Outline

- MRI Reconstruction

1. Landscape of MRI Reconstruction
   Overview of current usage in languages and toolboxes
2. MRI-NUFFT as a case study
3. Beyond toolboxes and software
   Dataset, Benchmarking, Community Initiative

- Good practice to take home

MRI Reconstruction

- Solving an (or many) *ill-posed* **inverse problem**

$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{\varepsilon}$$

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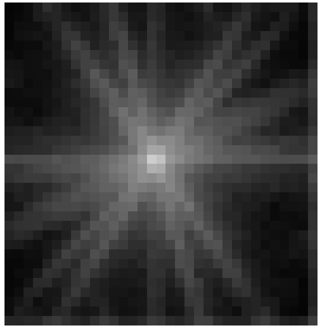
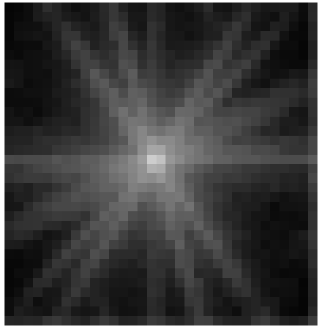
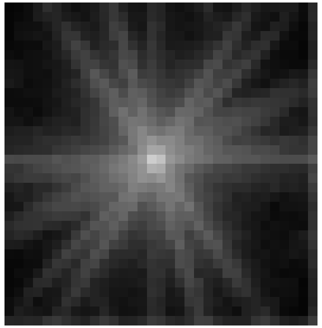


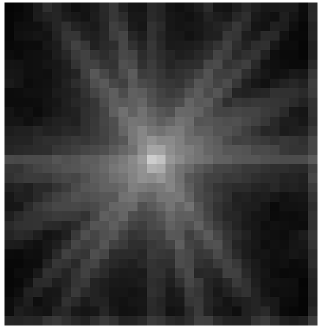
Anatomical MRI



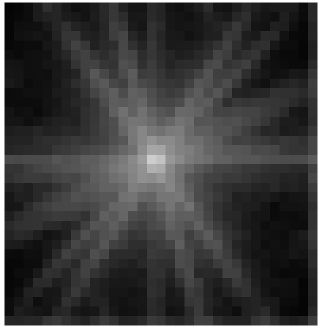
Cardiac /CINE



Quantitative MRI



Diffusion MRI

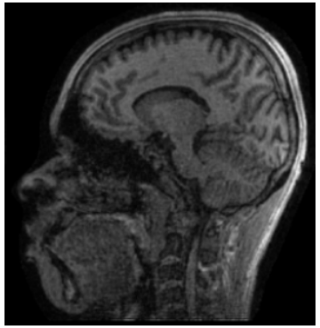


Functional MRI

MRI Reconstruction

- Solving an (or many) *ill-posed* **inverse problem**

$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \varepsilon \quad \Longrightarrow \quad \boldsymbol{x} = \mathcal{M}(\boldsymbol{A}, \boldsymbol{y}, \textit{priors})$$



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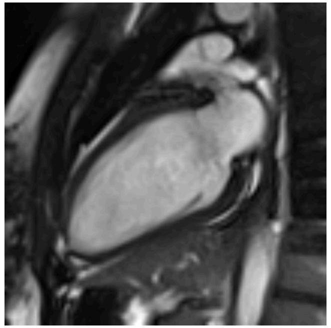

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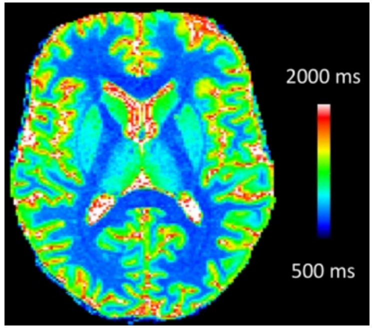

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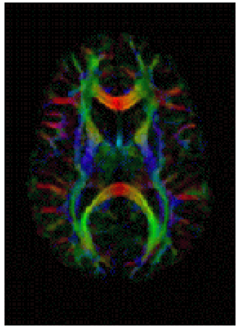

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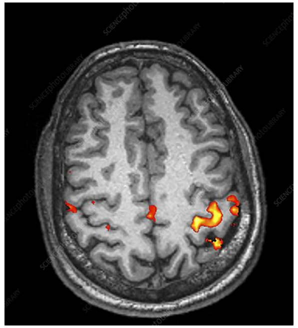

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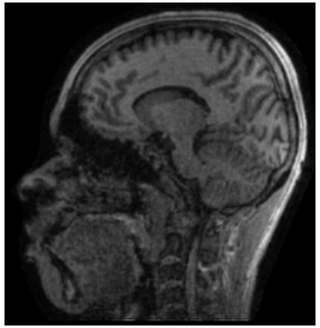

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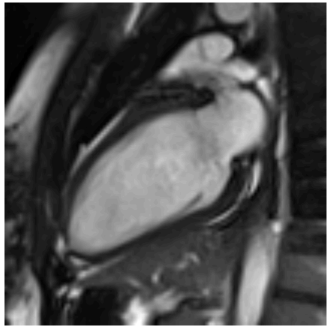

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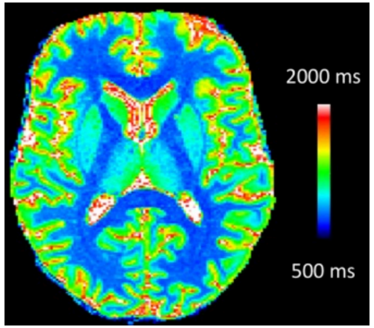

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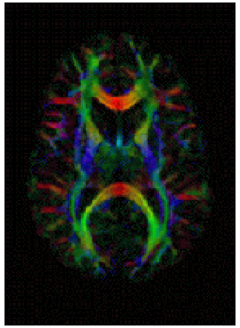

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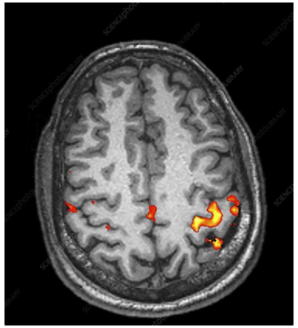

Functional MRI

Common Goal: Solve the inverse problem

Design (Learn ?) and validate $\mathcal{M}$, $\boldsymbol{A}$ and *priors*

Open-source software

- Open source vs free software
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- Licences to (un)protect the code !
- Good license choices
  - MIT, BSD-3-clause, (A)GPL[1]
  - Or whatever your legal departement requires

[1] https://opensource.stackexchange.com/questions/217/what-are-the-essential-differences-between-the-bsd-and-mit-licences

Where do we stand with open-source in MRI ?

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- Reconstruction Software

$\Rightarrow$ This talk !

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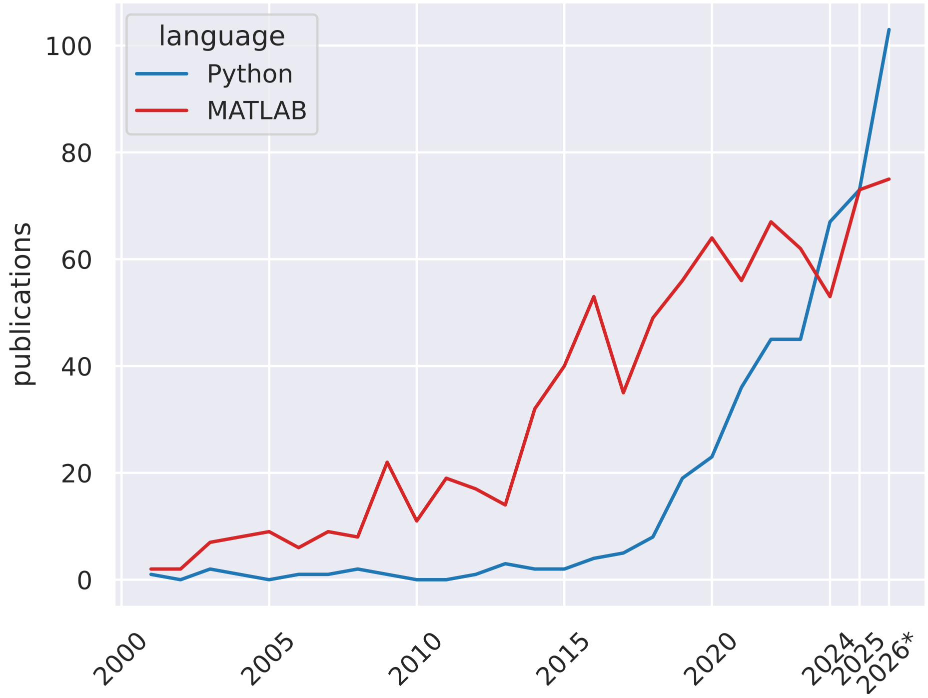
  KomaMRI.jl, Jemris, *SNAKE*, …
- Open-source Hardware
  Low-Field MRIs
- Reconstruction Software
- Analysis
  Nilearn, **f/s/d mriprep**, …

⇒ This talk !

1. MRI Reconstruction software

Software usage in the Literature



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2026: Extrapolated results from Q1

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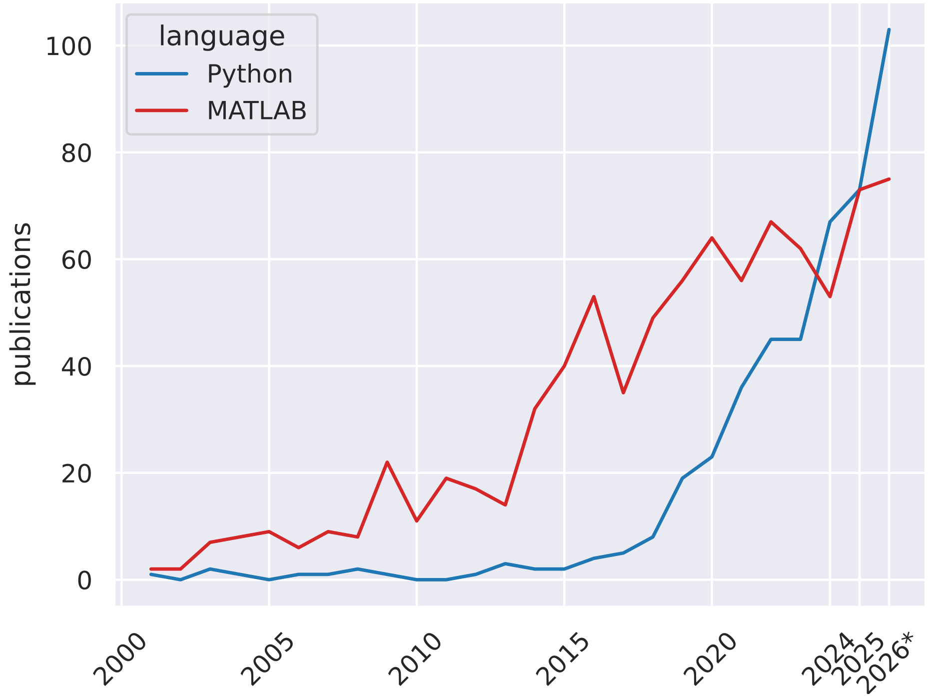

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- Python adoption accelerates, and has stronger ecosystem
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  - PyTorch / JAX for deep learning and GPU based reconstruction
  - 2026 is (finally) the year of Python for MRI ?

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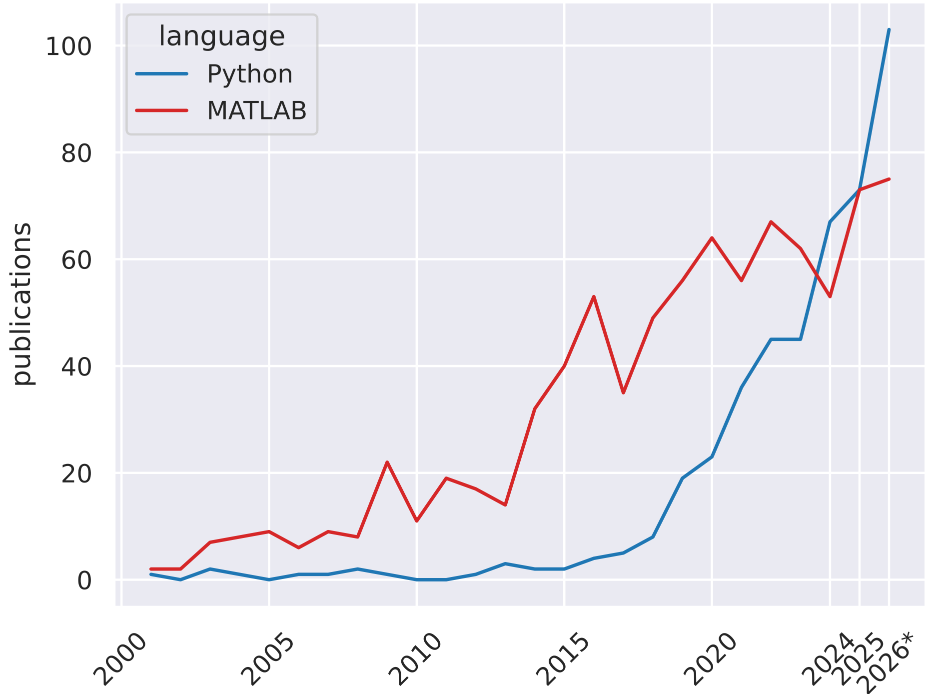

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- Python adoption accelerates, and has stronger ecosystem
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  - PyTorch / JAX for deep learning and GPU based reconstruction
  - 2026 is (finally) the year of Python for MRI ?
- MATLAB is still widely use (legacy code base)
  - But Julia grows !

Open Source Repositories

- $\simeq$ 150 Repos filter with topic `mri` & `mri-reconstruction`

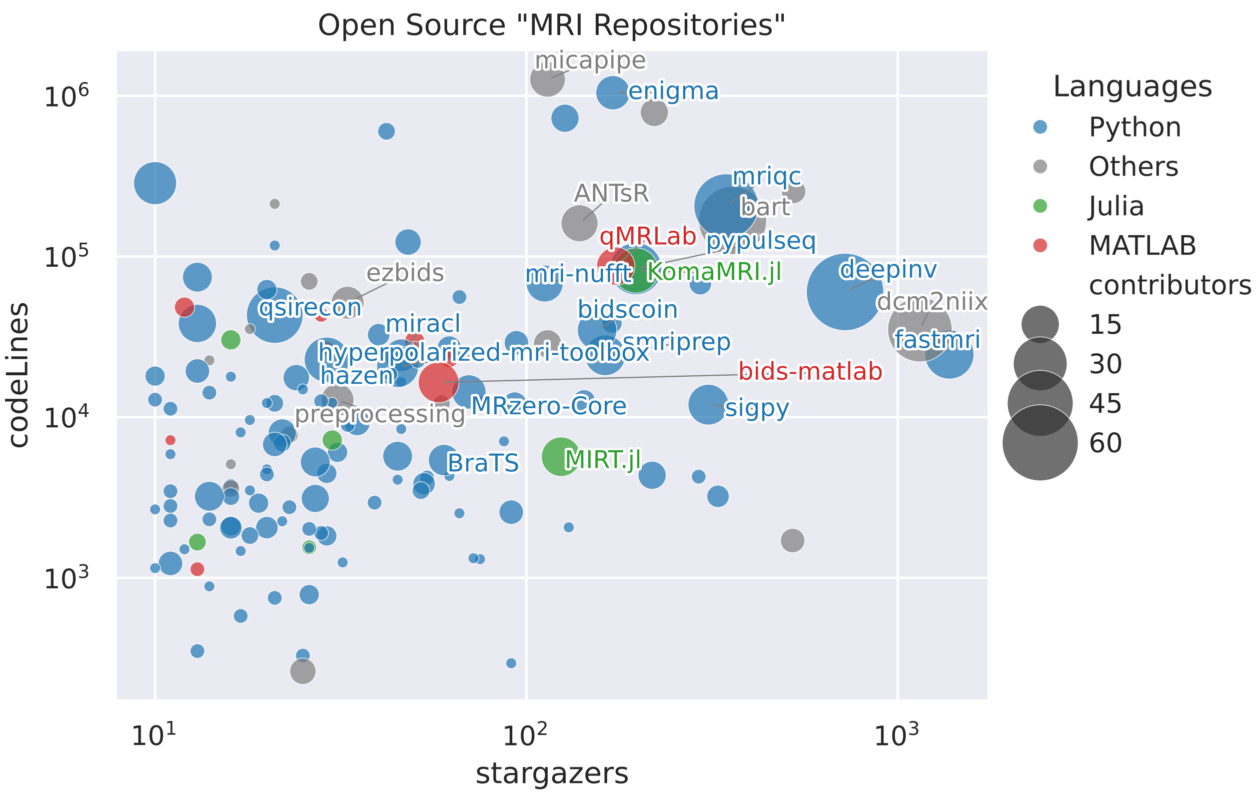

Figure 2: Main GitHub Repositories with 'mri' topic

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- Python/Notebook is the most represented on GitHub
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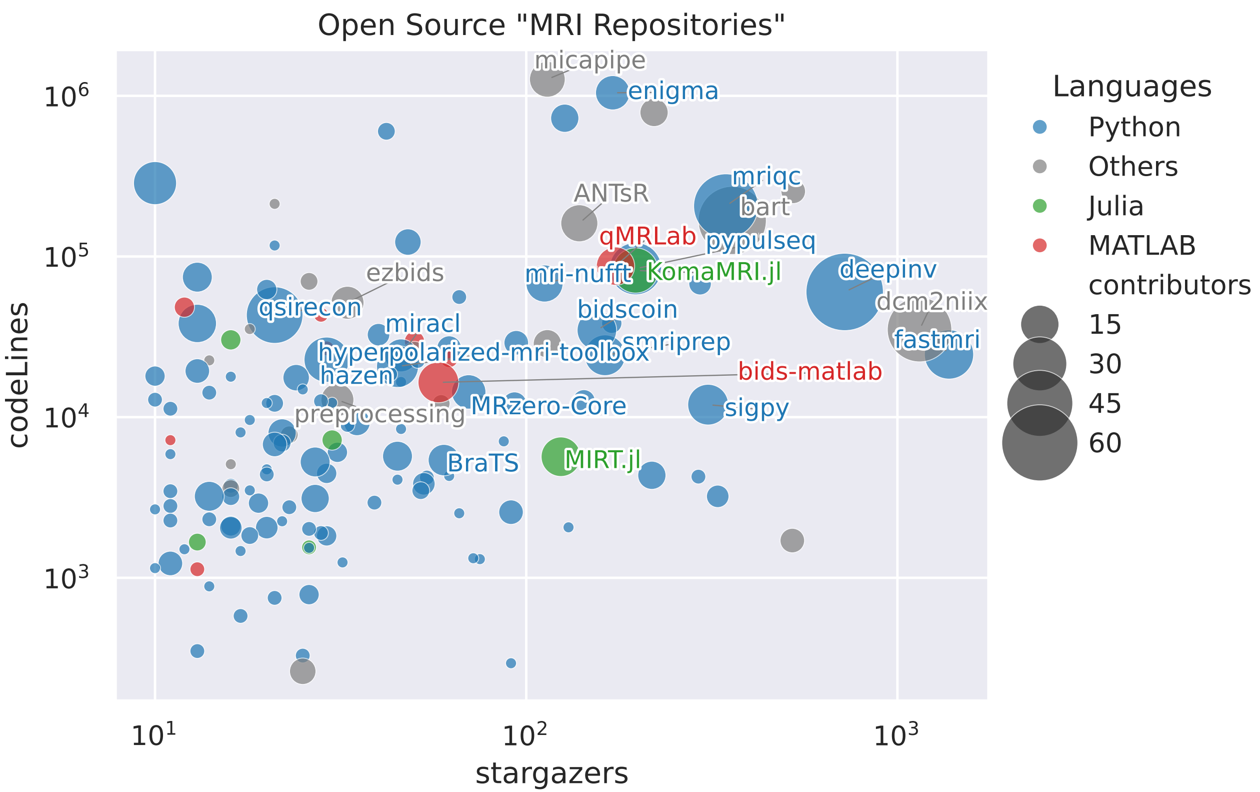

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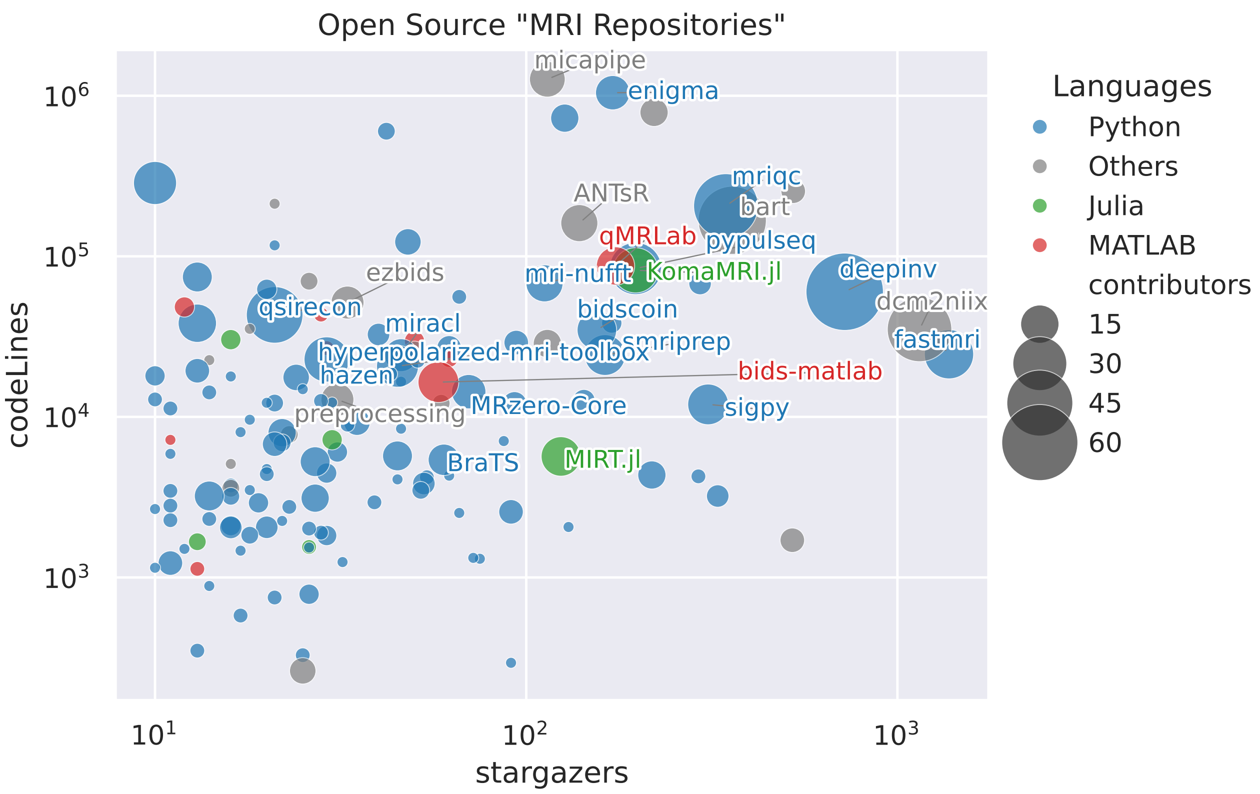

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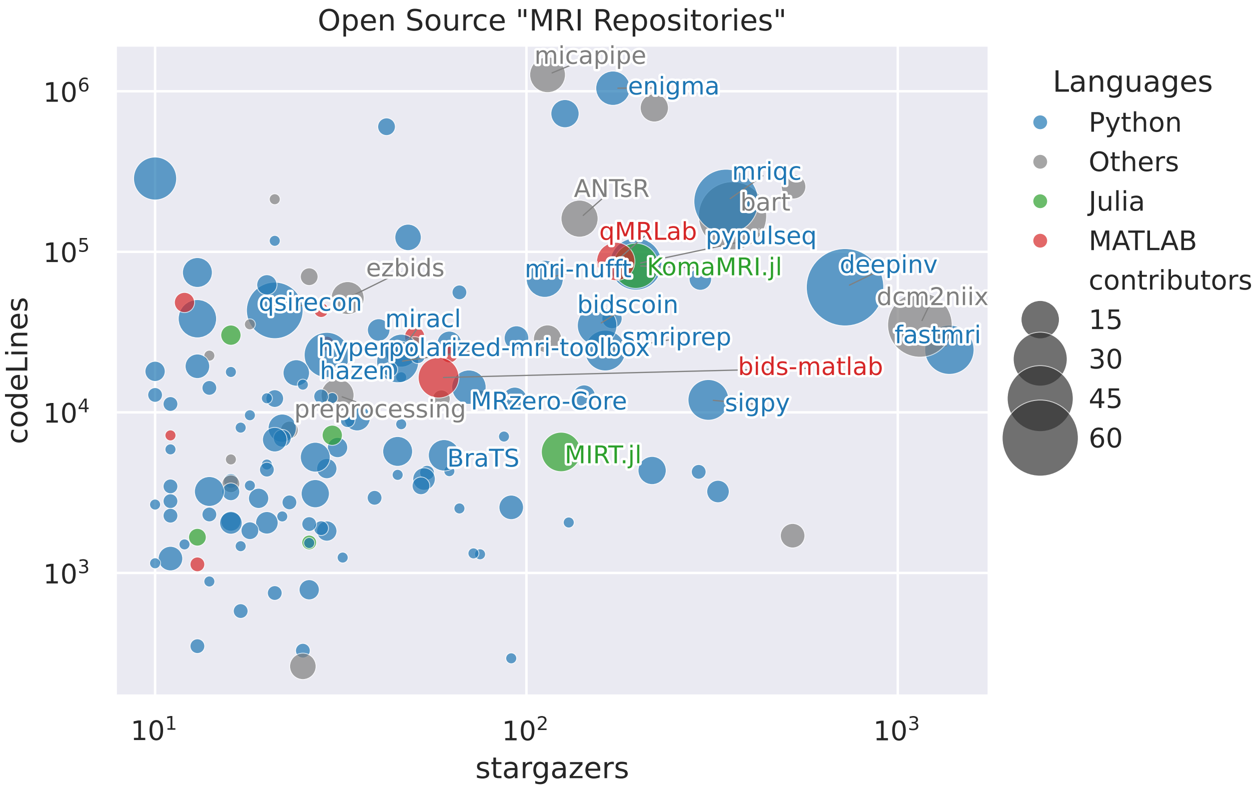
- Only 56% report homepage/ documentation!



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Catch them all !

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Deepinv ⭐726

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DIRECT ⭐301

MIRT ⭐204

SCICO ⭐162

MIRT.jl ⭐124

MRIReco.jl ⭐98

PySAP ⭐48

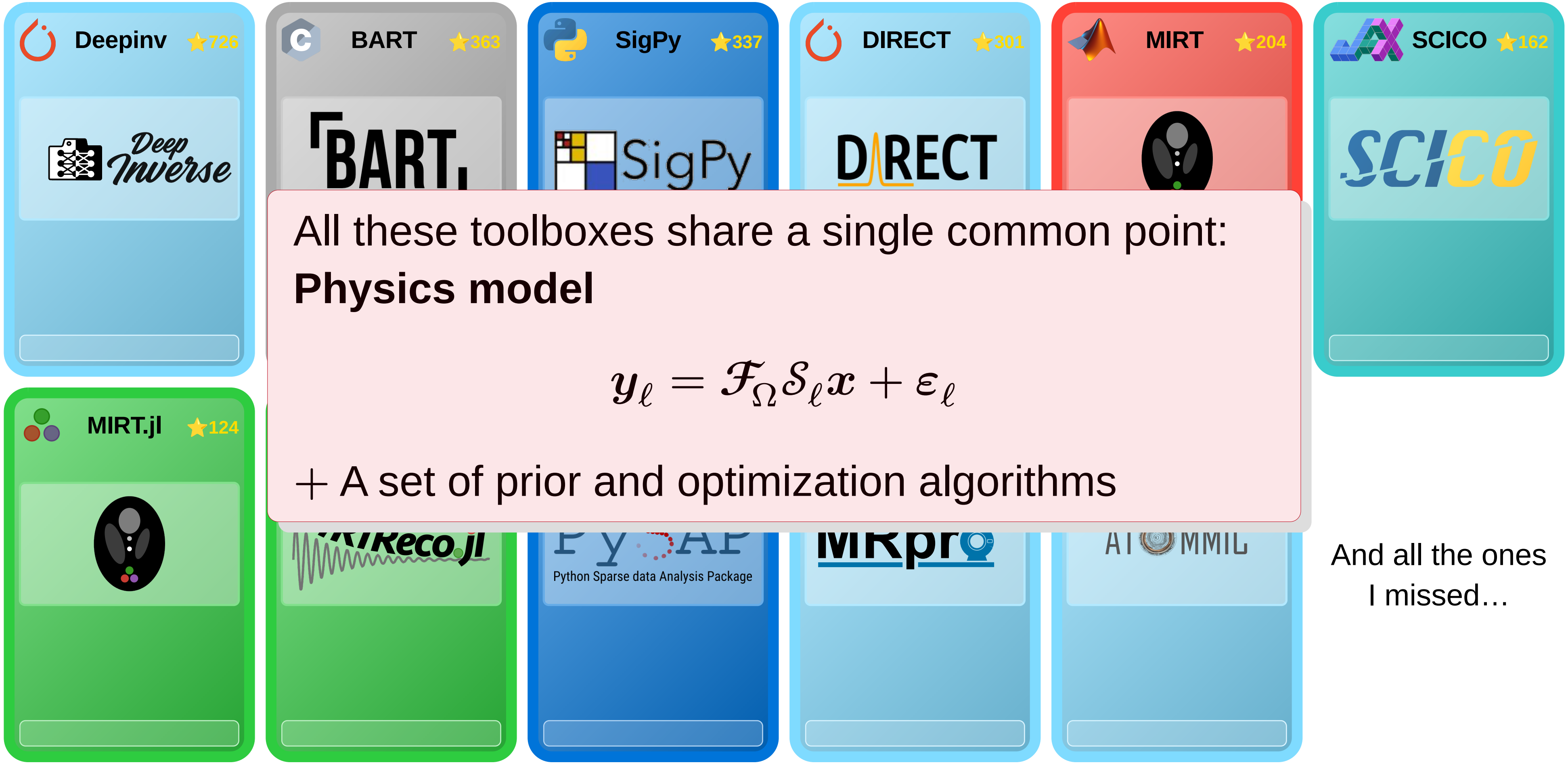
Python Sparse data Analysis Package

MRPro ⭐48

Atommic ⭐23

And all the ones I missed…

Catch them all !



All these toolboxes share a single common point:
Physics model

$$y_\ell = \mathcal{F}_\Omega \mathcal{S}_\ell x + \varepsilon_\ell$$

$+$ A set of prior and optimization algorithms

And all the ones I missed…

2. MRI-NUFFT: Case study

Introducing MRI-NUFFT

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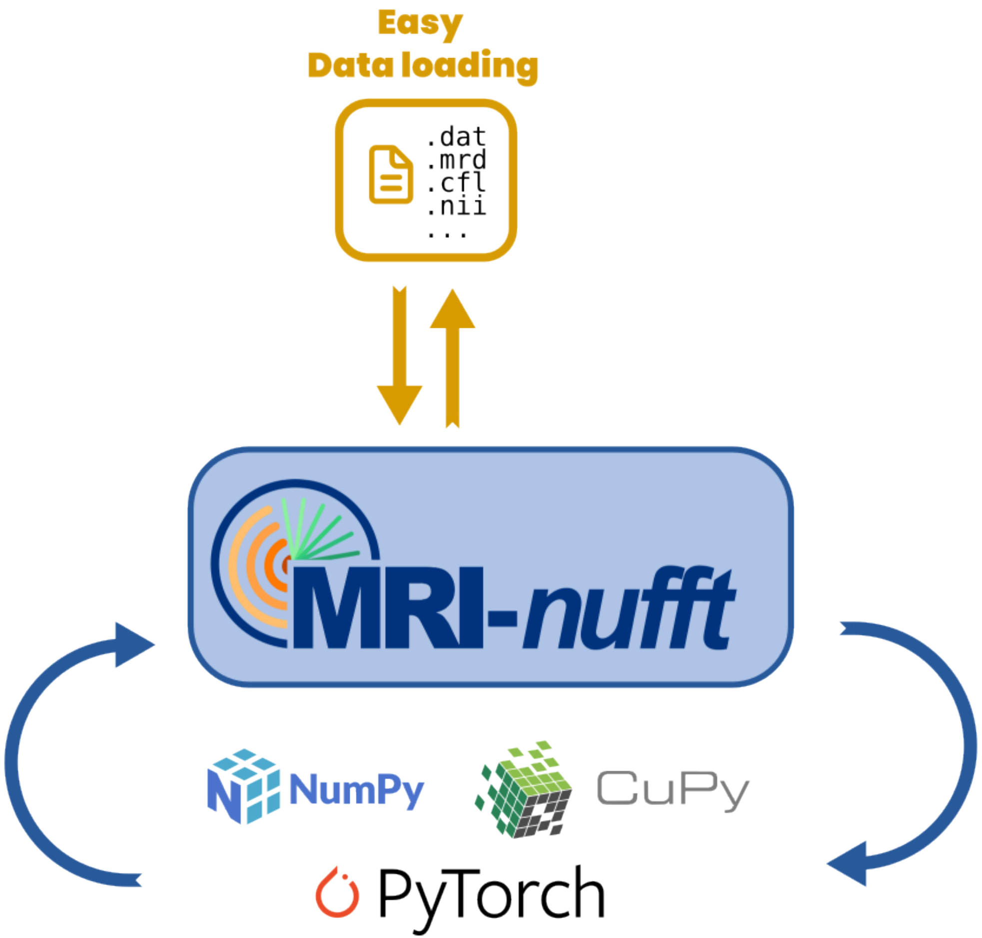
Let's fix this with:

MRI-nufft

What is MRI-NUFFT ?



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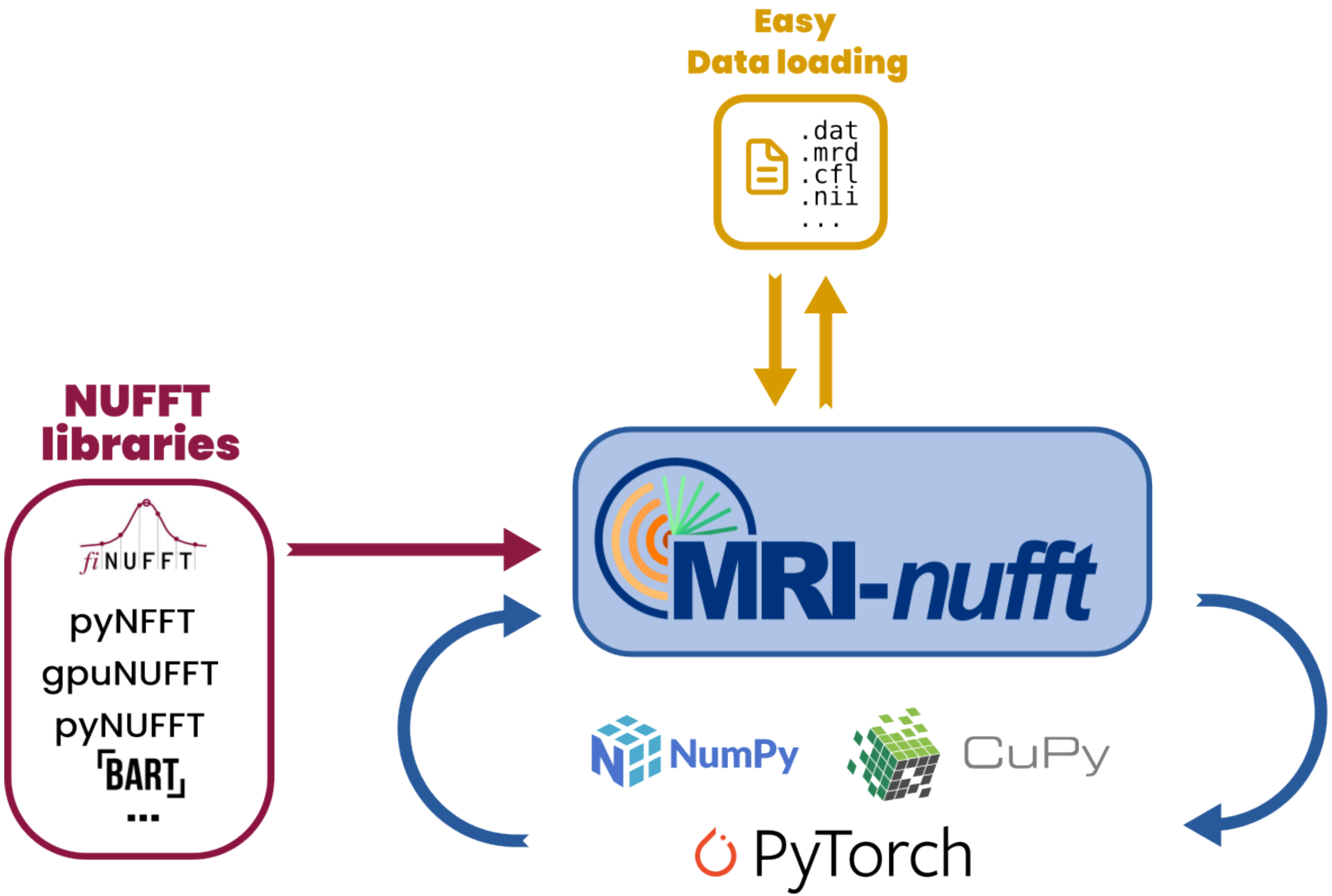

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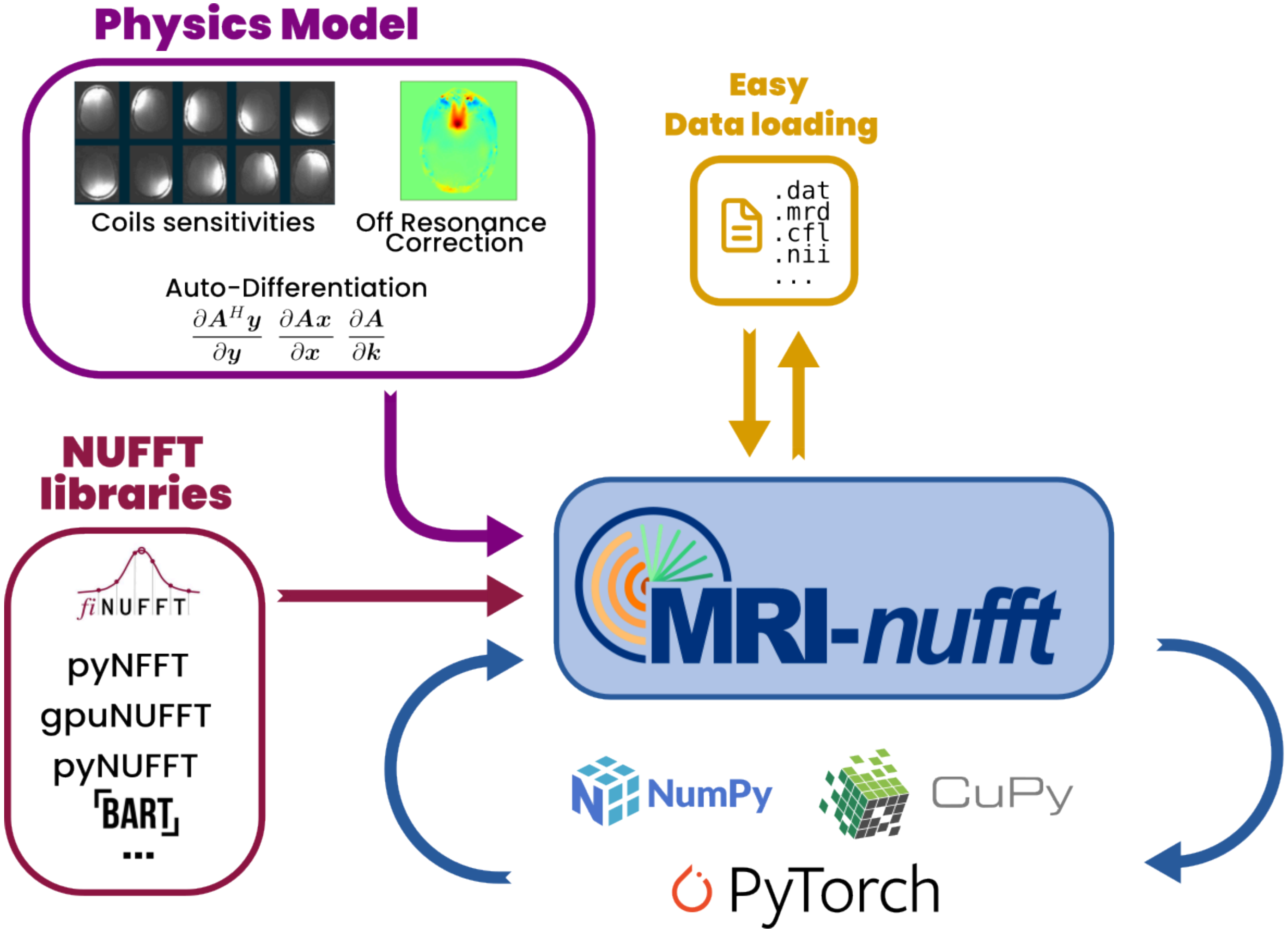
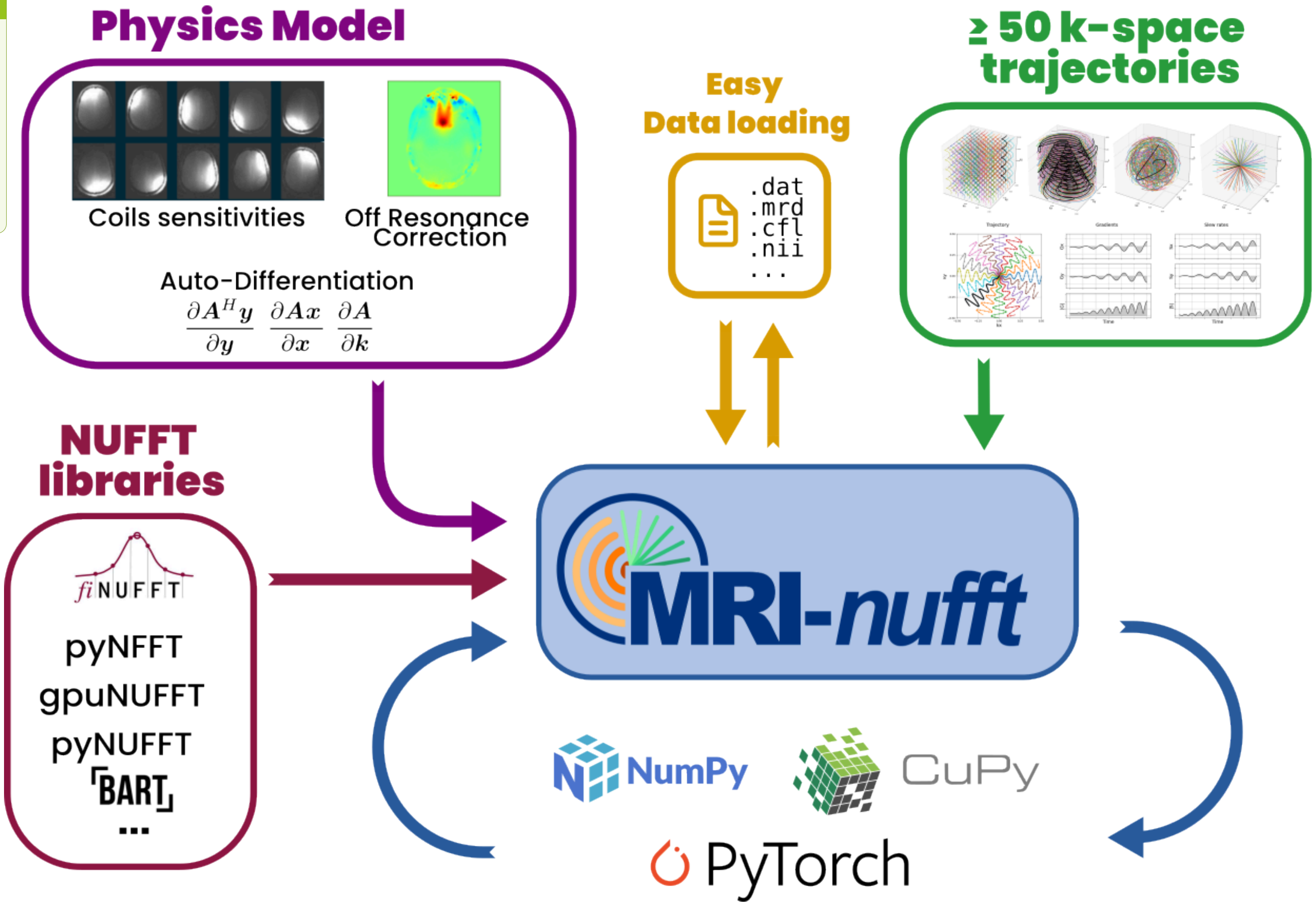


What is MRI-NUFFT ?

Learn more

AI Driven k-space Sampling
Mon. 11/05 7:30-8 AM
Chaithya GR.



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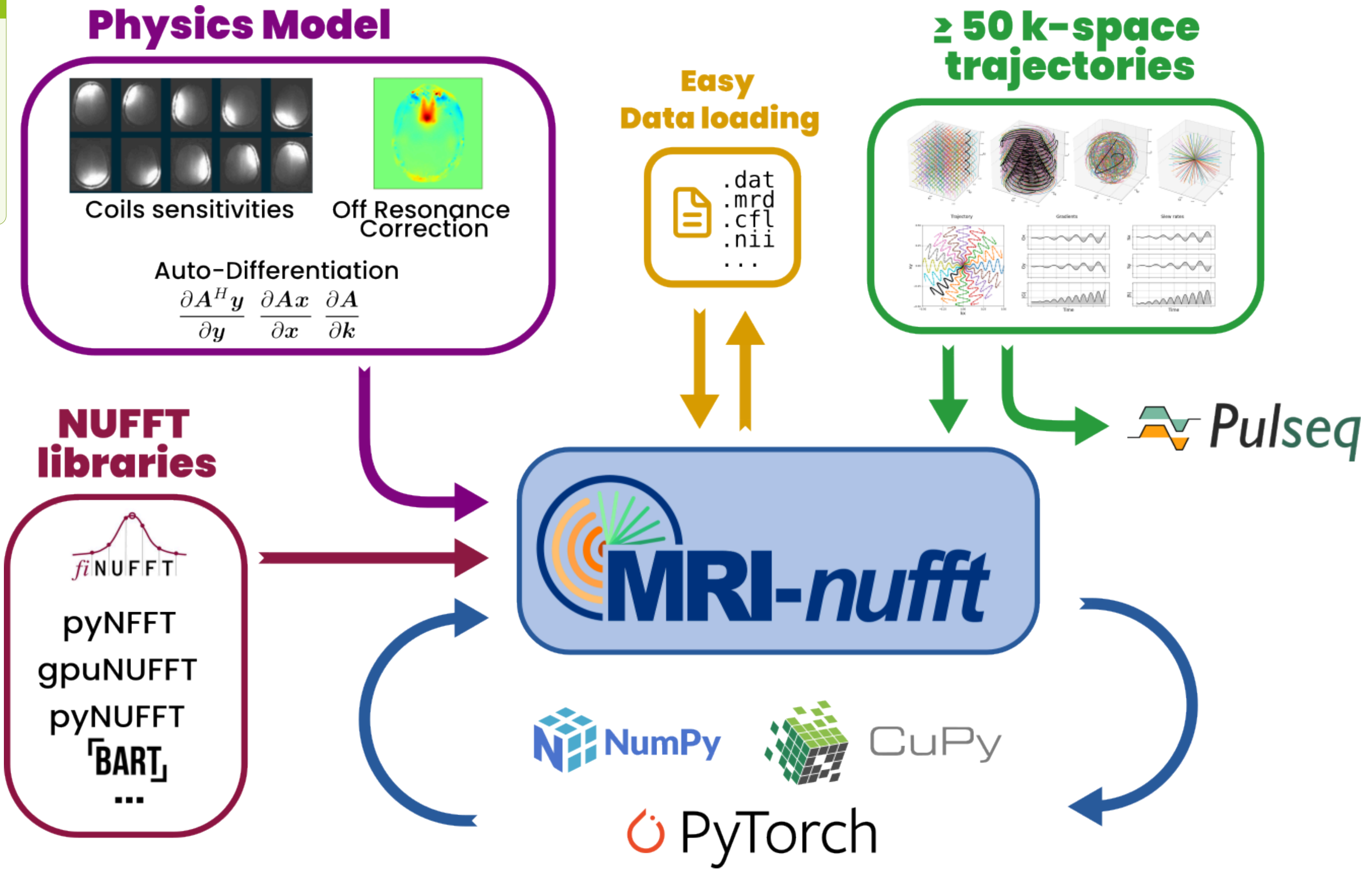

NUFFT for MRI Reconstruction

- Inverse problem formulation for MRI

$$\hat{\boldsymbol{x}} = \arg \min_{\boldsymbol{x} \in \mathbb{C}^N} \frac{1}{2} \sum_{\ell=1}^{L} \|\mathcal{F}_\Omega \mathcal{S}_\ell \boldsymbol{x} - \boldsymbol{y}_\ell\|_2^2 + \lambda g(\boldsymbol{x})$$

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> *… Forward model is for ever"*

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MRI-NUFFT provides *efficient* implementation for the forward model operator:

- based on the NUFFT backend of your choice.
- Handles CPU/GPU transfers and array conversion (`torch/numpy/cupy`)
- `autograd` support $\frac{\partial \boldsymbol{A}\boldsymbol{x}}{\partial \boldsymbol{x}}, \frac{\partial \boldsymbol{A}^H\boldsymbol{y}}{\partial \boldsymbol{y}}, \frac{\partial \boldsymbol{A}_\theta \boldsymbol{x}}{\partial \theta}, \ldots$

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```
from mrinufft import get_operator
nufft = get_operator("cufinufft", samples, shape, smaps=smaps,
density="pipe")
ksp = nufft.op(image)          # y = Ax
adjoint = nufft.adj_op(ksp)    # x = A^H y
pinv = nufft.pinv_solver(ksp) # x = A^† y, using CG
```

Extended Fourier Model

- Multi-coil, subspace representations, …
-

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- Density Compensation (`voronoi`, `pipe`, …)
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- Multi-coil, subspace representations, …
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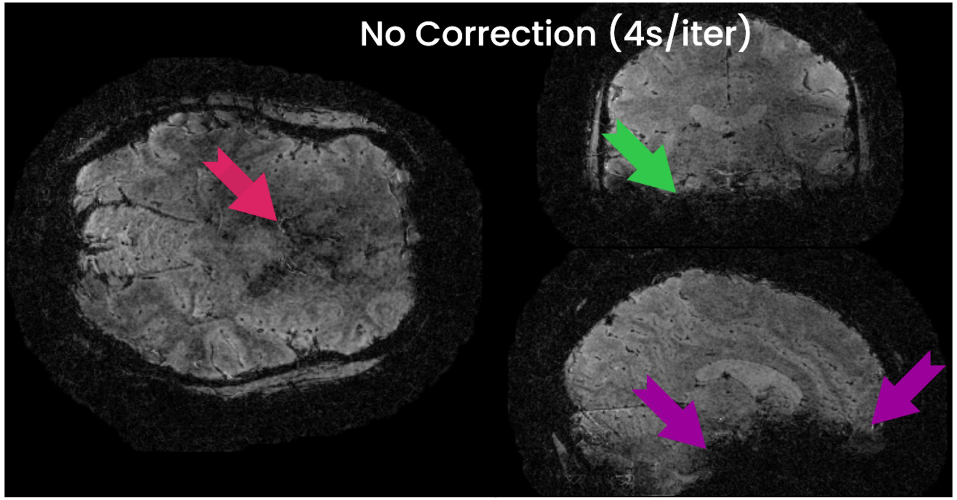
- Off-Resonance

$$\boldsymbol{y}_\ell(t) = \int_{FOV} \boldsymbol{x}(\boldsymbol{r})\mathcal{S}_\ell(\boldsymbol{r})e^{-\Delta\omega(\boldsymbol{r})t}e^{-2i\pi\boldsymbol{k}(t)\cdot\boldsymbol{r}}\mathrm{d}\boldsymbol{r}$$

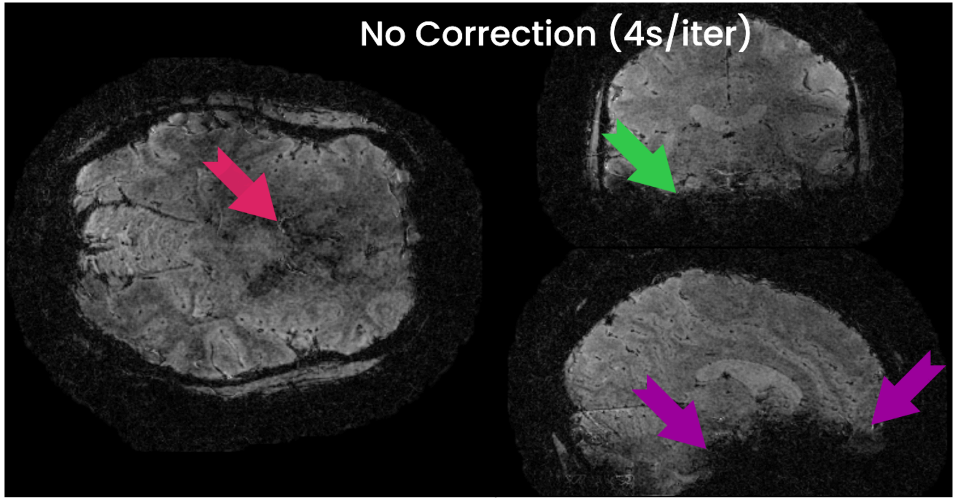


Extended Fourier Model

- Multi-coil, subspace representations, ...
- Density Compensation (`voronoi`, `pipe`, ...)
- Off-Resonance correction via bilinearization (MTI, MFI)

$$\boldsymbol{y}_\ell(t) = \int_{FOV} \boldsymbol{x}(\boldsymbol{r}) \mathcal{S}_\ell(\boldsymbol{r}) e^{-\Delta\omega(\boldsymbol{r})t} e^{-2i\pi \boldsymbol{k}(t)\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r}$$

$$\boldsymbol{y}_\ell \approx \sum_{p=1}^{P} \boldsymbol{b}_p \sum_{\ell=1}^{L} \mathcal{F}_\Omega(\boldsymbol{c}_p \mathcal{S}_\ell \boldsymbol{x})$$



Extended Fourier Model

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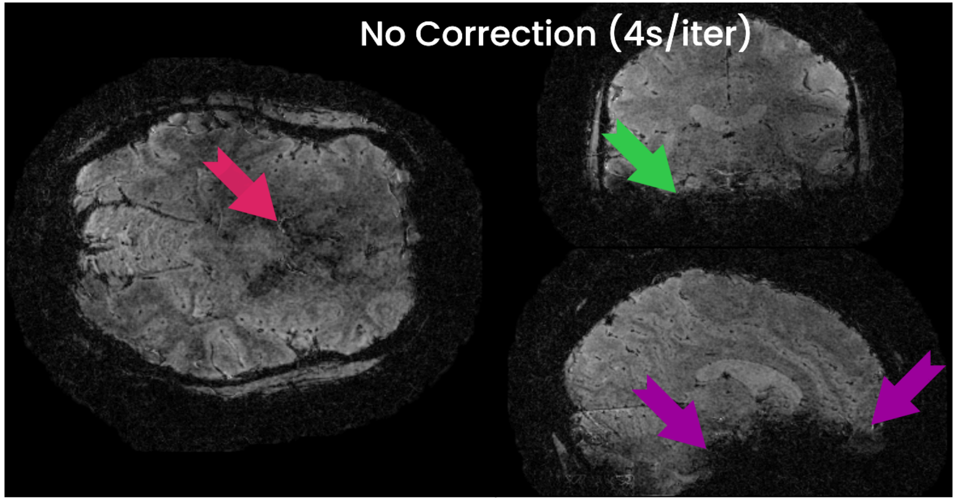
- Off-Resonance correction via bilinearization (MTI, MFI) via bilinearization (MTI, MFI, **SVD**)

$$\boldsymbol{y}_\ell(t) = \int_{FOV} \boldsymbol{x}(\boldsymbol{r})\mathcal{S}_\ell(\boldsymbol{r}) e^{-\Delta\omega(\boldsymbol{r})t} e^{-2i\pi \boldsymbol{k}(t)\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r}$$

$$\min_{\substack{B\in\mathbb{C}^{M\times P}\\ C\in\mathbb{C}^{P\times N}}} \|e^{-\Delta\omega(\boldsymbol{r})t} - BC\|_2^2 \implies \boldsymbol{y}_\ell \approx \sum_{p=1}^{P} \boldsymbol{b}_p \sum_{\ell=1}^{L} \mathcal{F}_\Omega(\boldsymbol{c}_p \mathcal{S}_\ell \boldsymbol{x})$$



Extended Fourier Model

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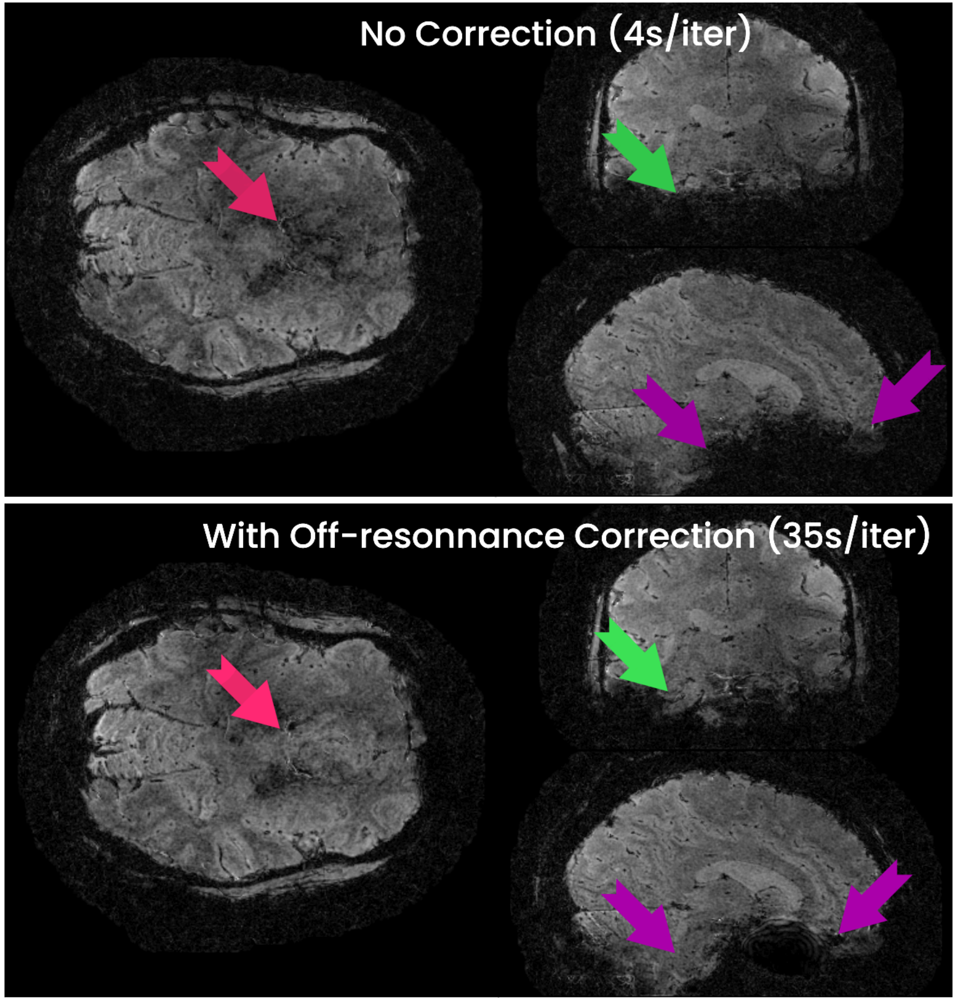
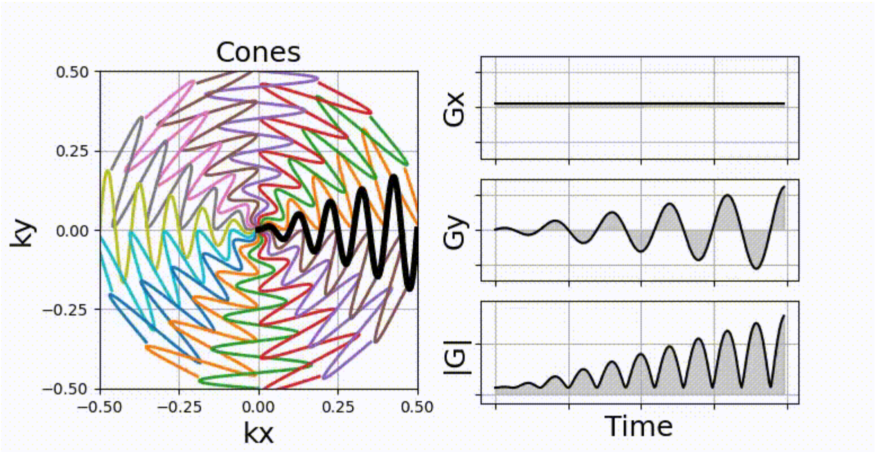
$$\min_{\substack{B\in\mathbb{C}^{M\times P}\\ C\in\mathbb{C}^{P\times N}}} \|e^{-\Delta\omega(\boldsymbol{r})t} - BC\|_2^2 \Longrightarrow \boldsymbol{y}_\ell \approx \sum_{p=1}^{P} b_p \sum_{\ell=1}^{L} \mathcal{F}_\Omega(c_p \mathcal{S}_\ell \boldsymbol{x})$$

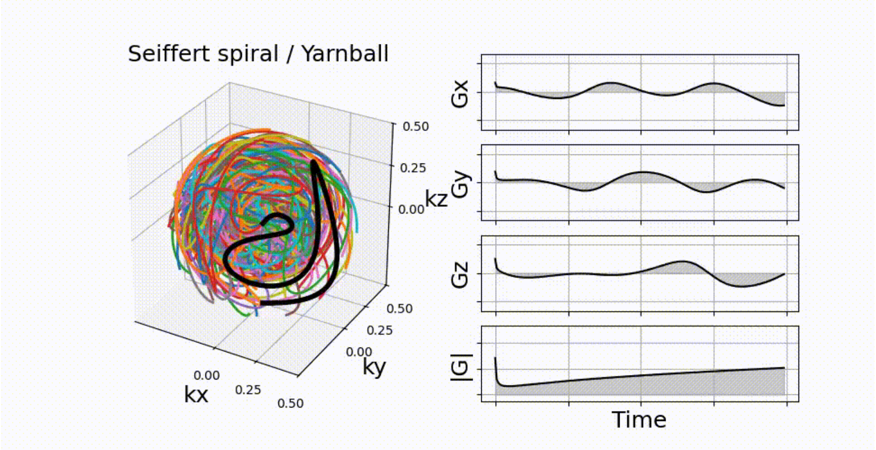
```
nufft_orc = nufft.with_off_resonance_correction(
    field_map=field_map,
    readout_time=readout_time,
    interpolators=20)
adj_orc = nufft_orc.adj_op(ksp) # x = A^H_{Δω} y
pinv_orc = nufft_orc.pinv_solver(ksp) # x = A^†_{Δω} y
```



Trajectories & Gradients

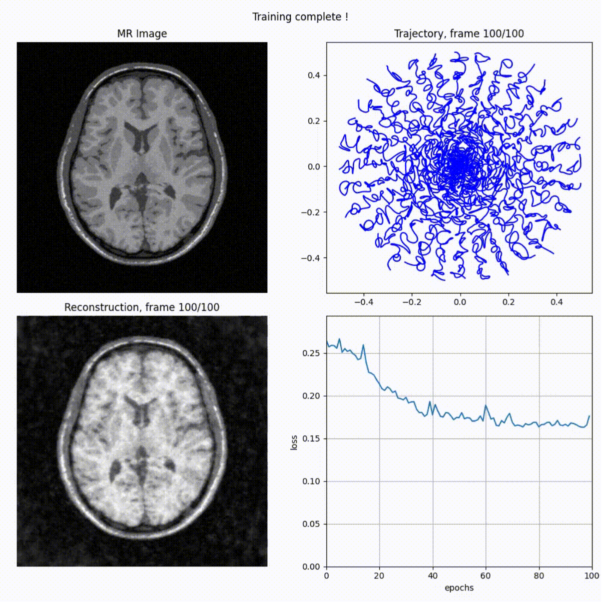
- A large collection of non-Cartesian trajectories
  - 2D and 3D, fully parameterized

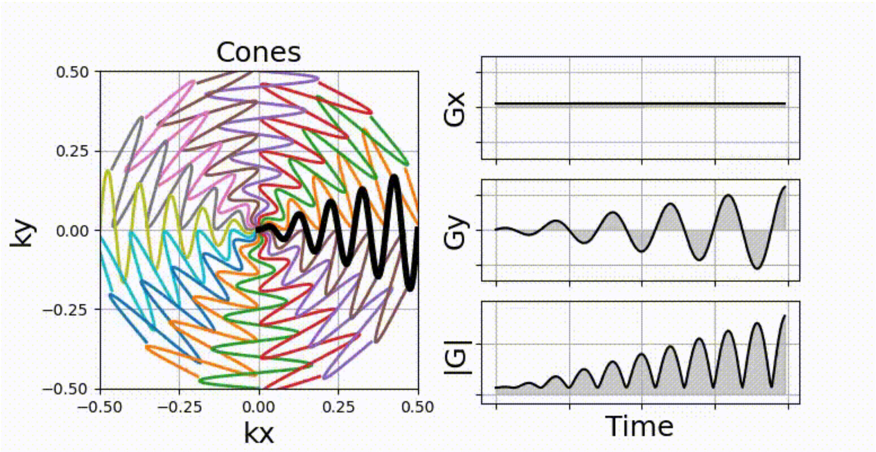


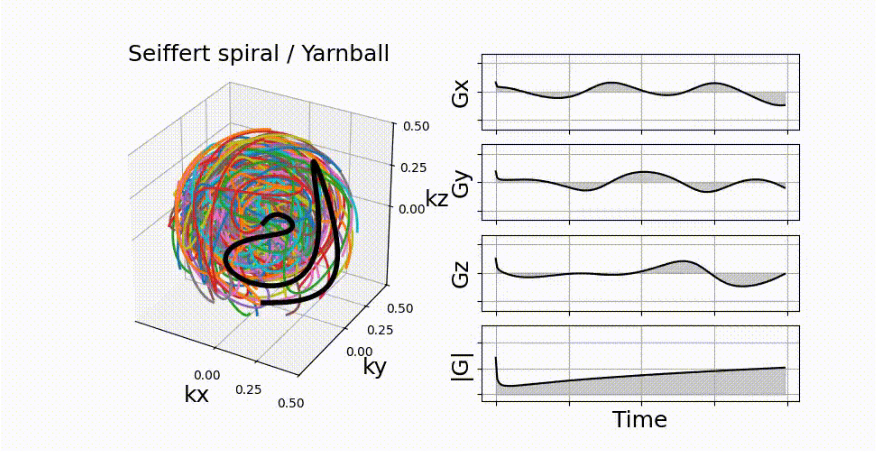


Trajectories & Gradients

- A large collection of non-Cartesian trajectories
  - 2D and 3D, fully parameterized
  - Hardware compliance enforcement.
  - You can even learn trajectories in a deep Learning setting with autodifferentiation !

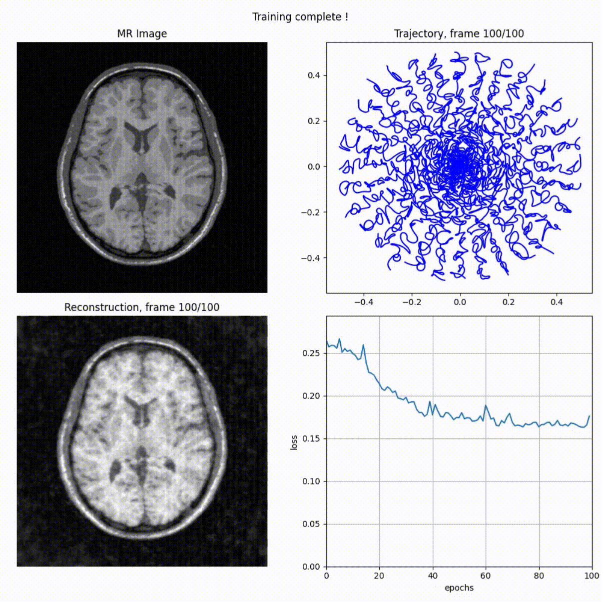






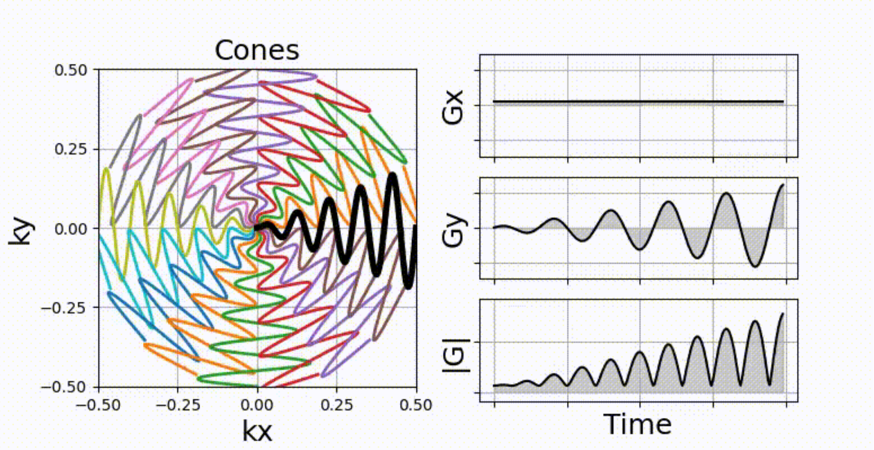
Trajectories & Gradients

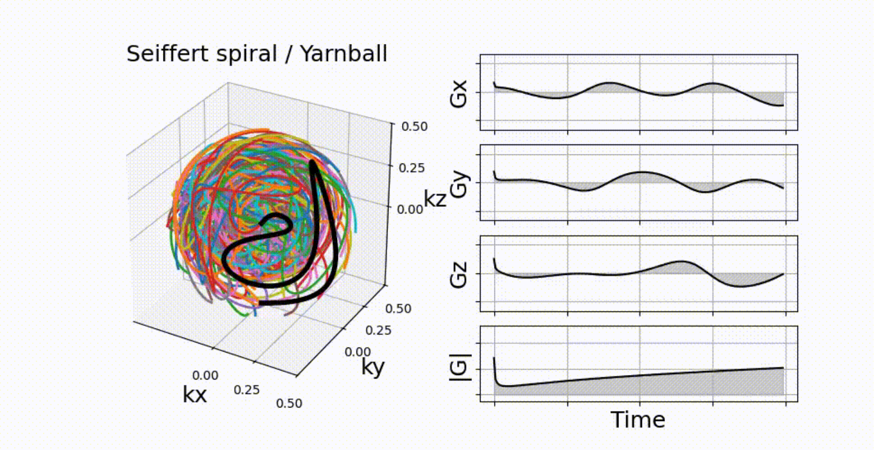
- A large collection of non-Cartesian trajectories
  - 2D and 3D, fully parameterized
  - Hardware compliance enforcement.
  - You can even learn trajectories in a deep Learning setting with autodifferentiation !



Live Demo !

Open in Colab





Integration with other libraries

- $\geq$ 20 Projects depends on MRI-NUFFT[1]
- Integration with external packages

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traj = ...
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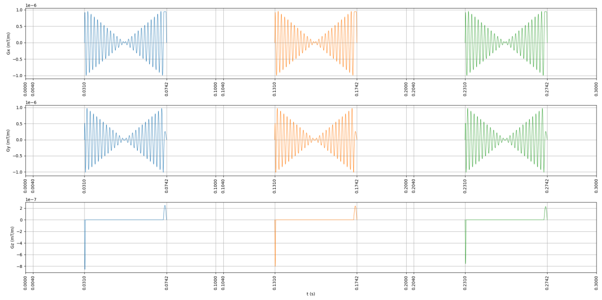

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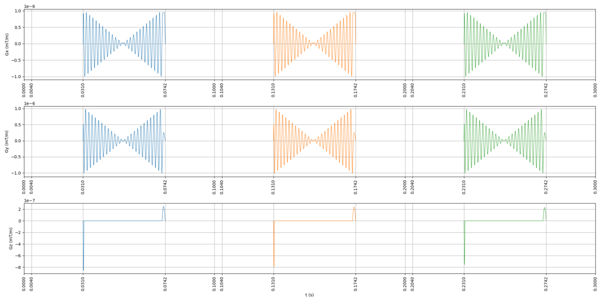

Example for integration with deepinv

```python
from mrinufft import get_operator
from deepinv.optim import WaveletPrior, L2, optim_builder
# MRI-NUFFT setup
fourier_op = get_operator("cufinufft",samples_loc,shape=shape)
y = fourier_op.op(ground_truth) + noise  # y = Ax + ε
```

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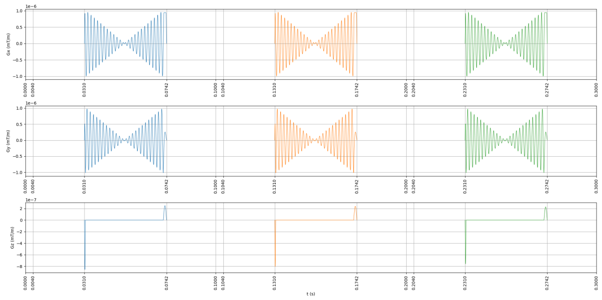

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# DeepInverse setup
physics = fourier_op.make_deepinv_phy()
wavelet = WaveletPrior(wv="sym8", is_complex=True, p=1) # ‖Ψ·‖_1
wavelet_fista = optim_builder(
    iteration="FISTA",
    prior=wavelet, # swap with ANY prior !
    data_fidelity=L2(),
    params_algo={"lambda": 0.1}
)

# Reconstruction
x_pinv   = physics.A_dagger(y) # argmin_x‖ Ax − y ‖_2^2
x_wavelet = wavelet_fista(y, physics) # argmin_x‖ Ax − y ‖_2^2 + λ‖Ψx‖_1^1
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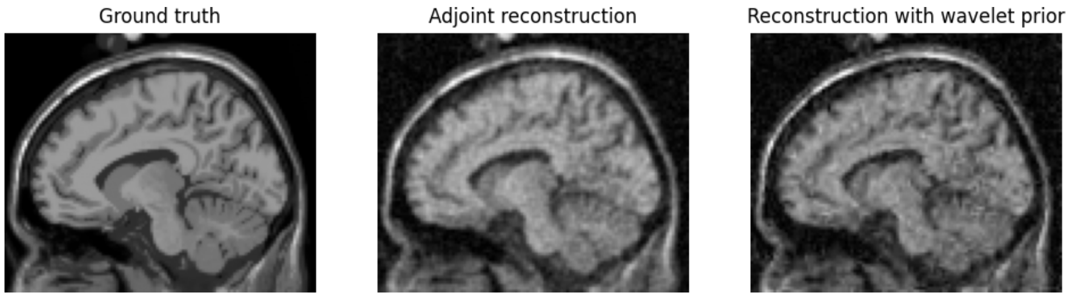

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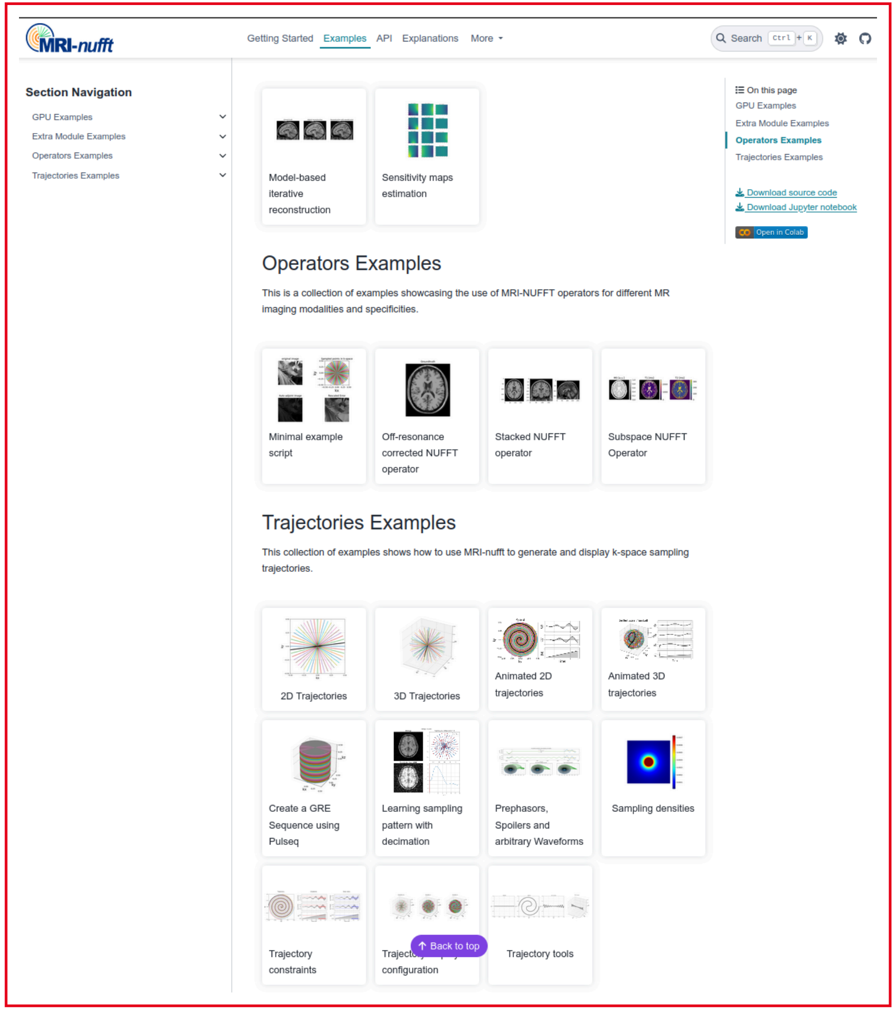
Packaging an Open Source Software

- 📖 Documentation
  - No documentation, no utilization
- ❓ Examples, tutorials
  - Onboarding new-comers Open in Colab



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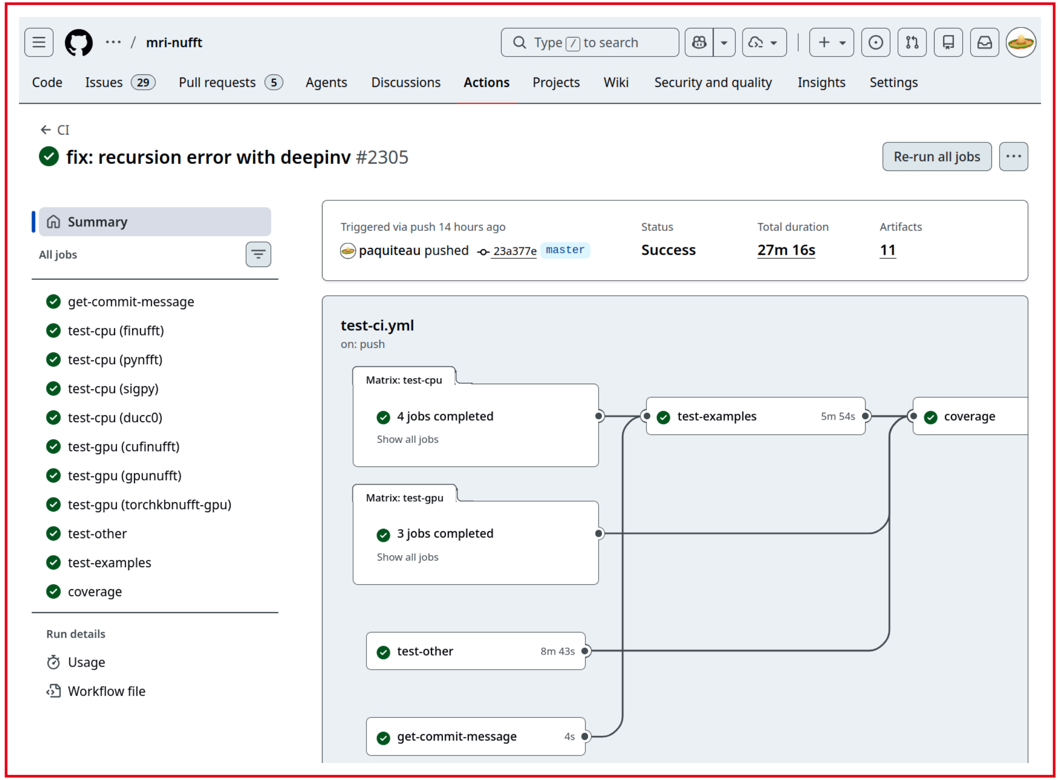

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- 🎁 Python Package:
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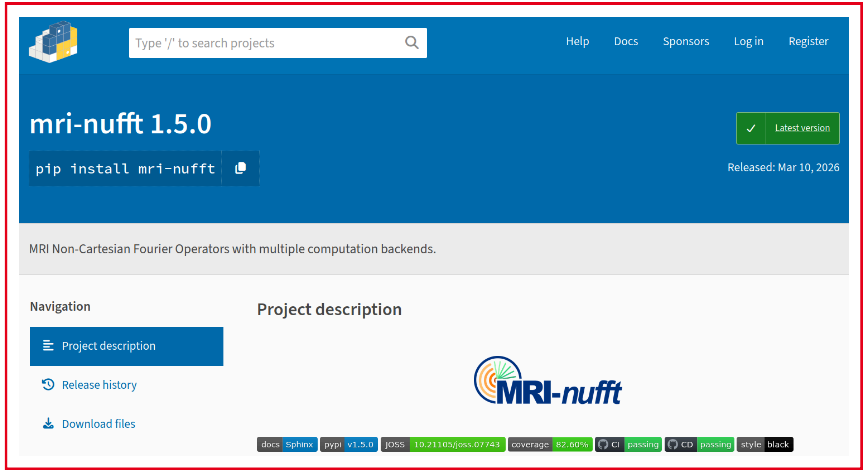

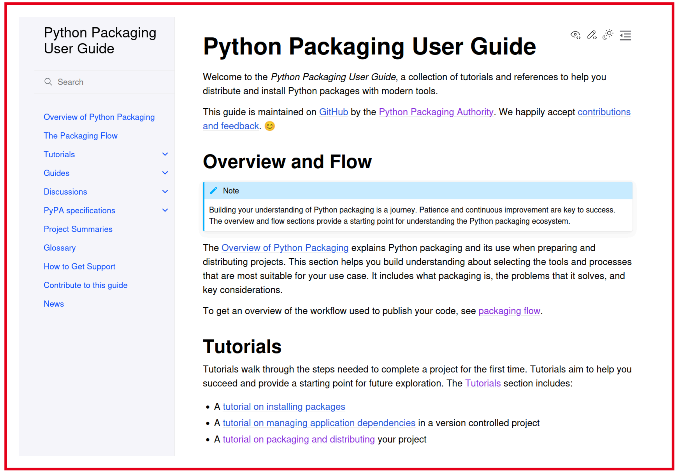

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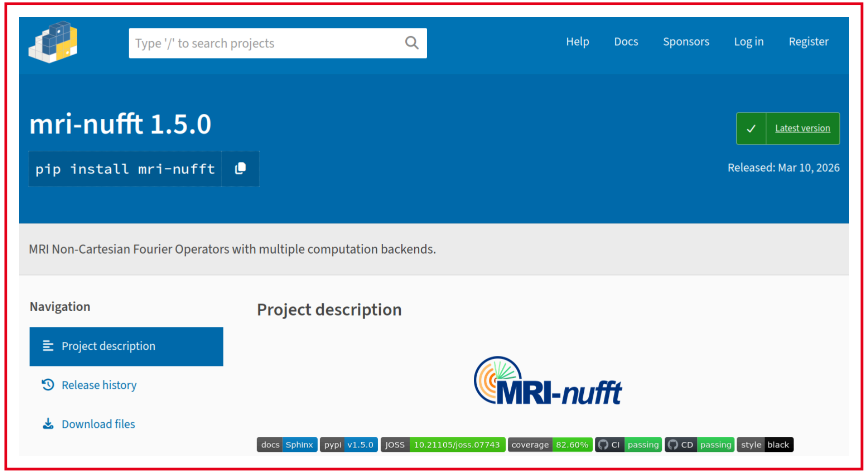

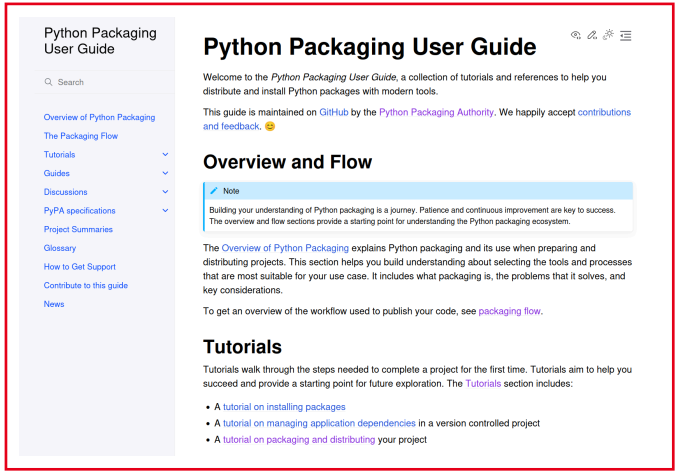

3. Beyond Toolboxes and Packages

Open data for Reproducibility

Dataset for training and validation of reconstruction methods

FastMRI

- Brain, Knee, Prostate, Breast
- stack of 2D images
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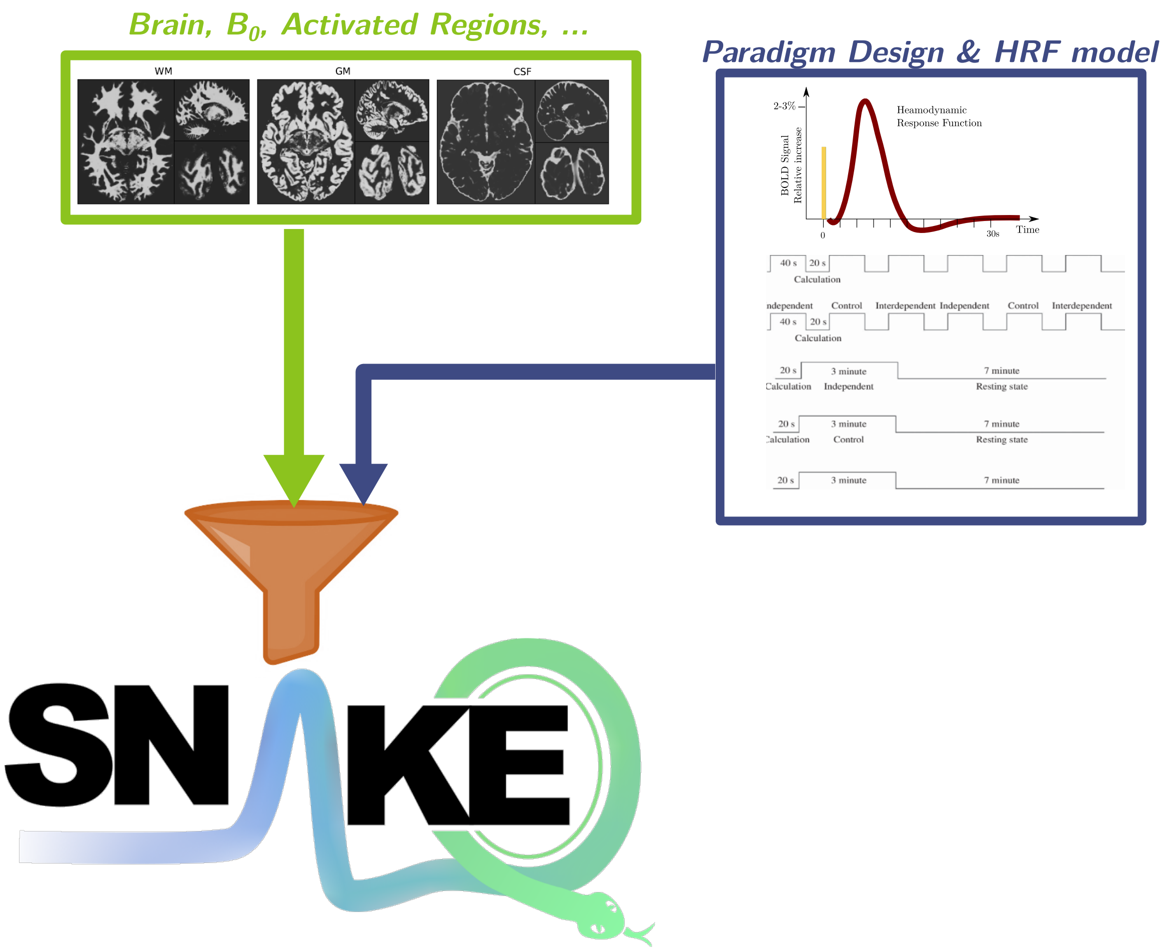
No dataset or Ground-Truth available ?

fMRI, space/time resolution tradeoff

SNAKE fMRI k-space Simulator

Brain, B_0, Activated Regions, ...

SNAKE fMRI k-space Simulator



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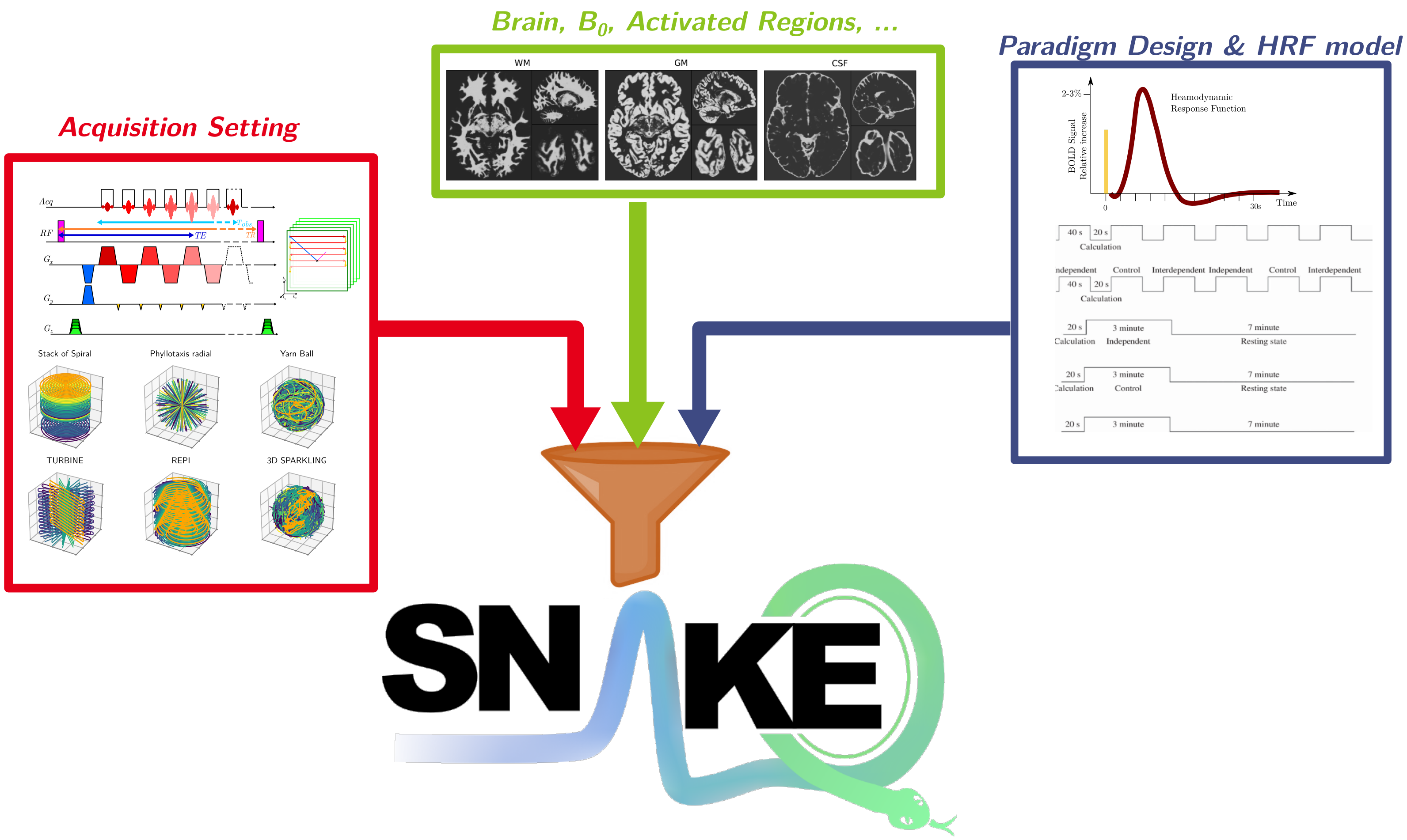

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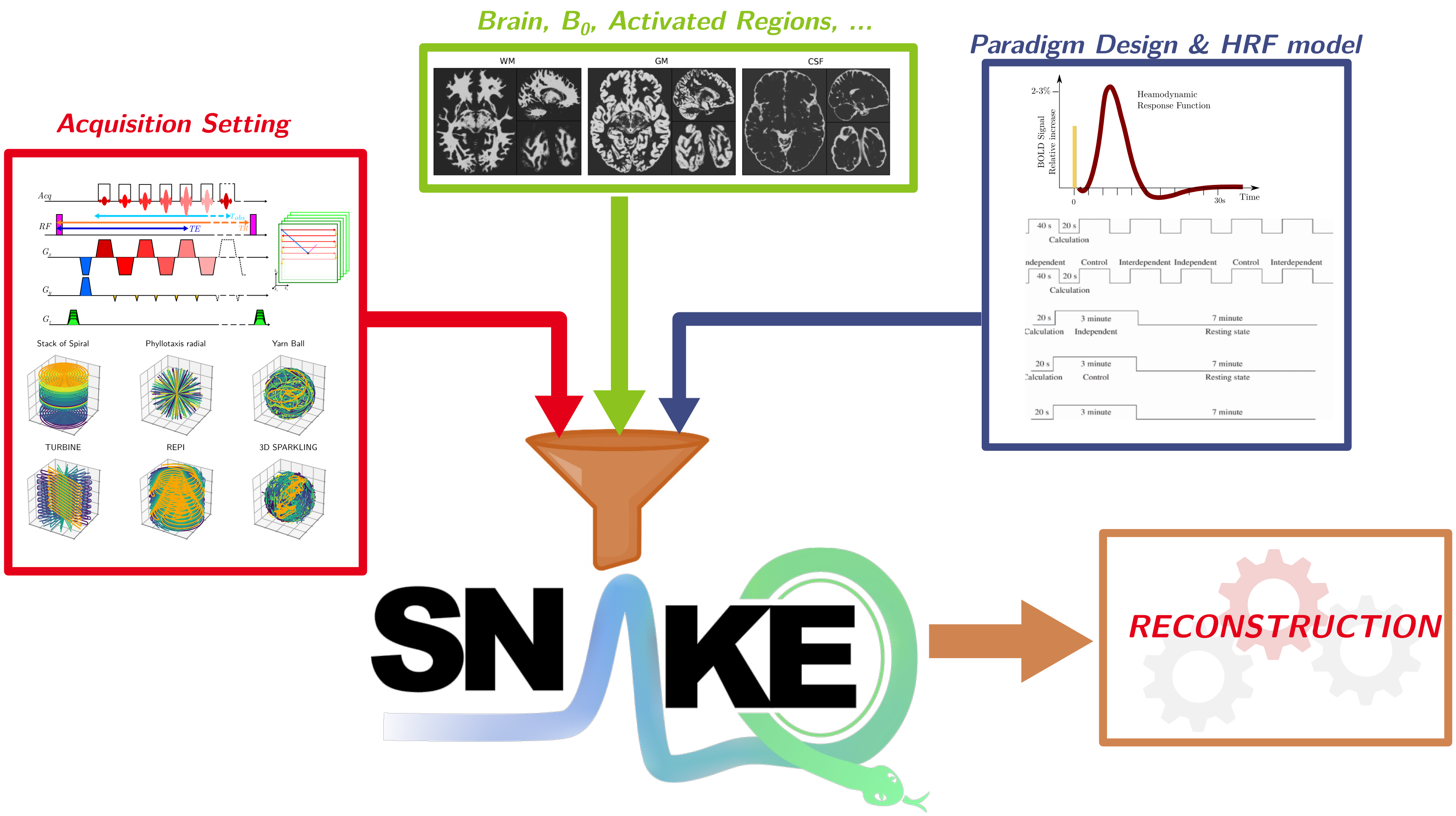

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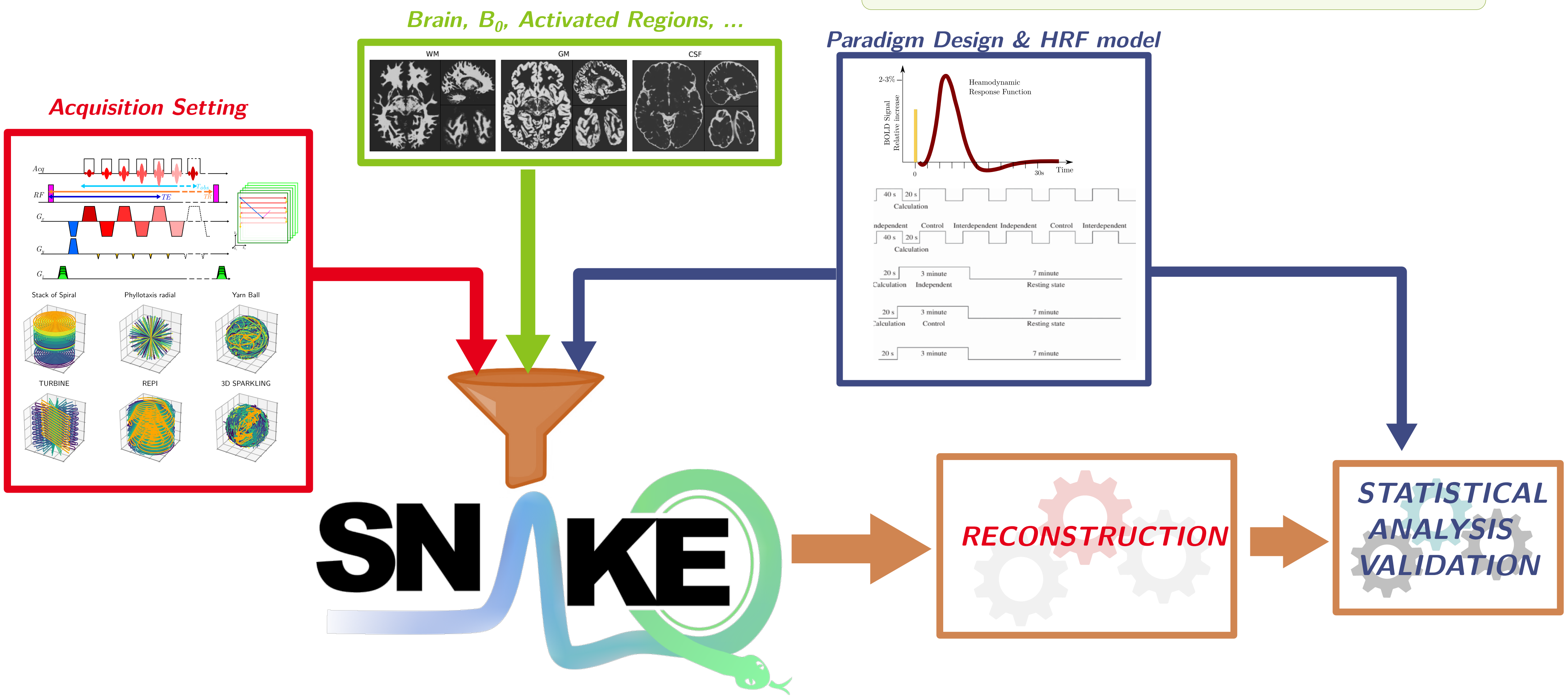
Learn more

Comby et al., Imaging Neuroscience, 2025.



A word about benchmarks

MRM Editorial

MAGNETIC RESONANCE IN MEDICINE | ISMRM | ONE COMMUNITY FOR CLINICIANS AND SCIENTISTS

EDITORIAL | Free Access

The “State of the Art” in MR Image Reconstruction? Knowledge, Culture, and What We Leave Behind in An Era of Big Data and Machine Learning

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First published: 10 April 2026 | https://doi.org/10.1002/mrm.70377 | VIEW METRICS

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State of the art $\neq$ State of the practice

- Make the toolbox usable by non-expert of the k-space.

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Take home messages

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  - Interface between Math, Physics and Computer Science

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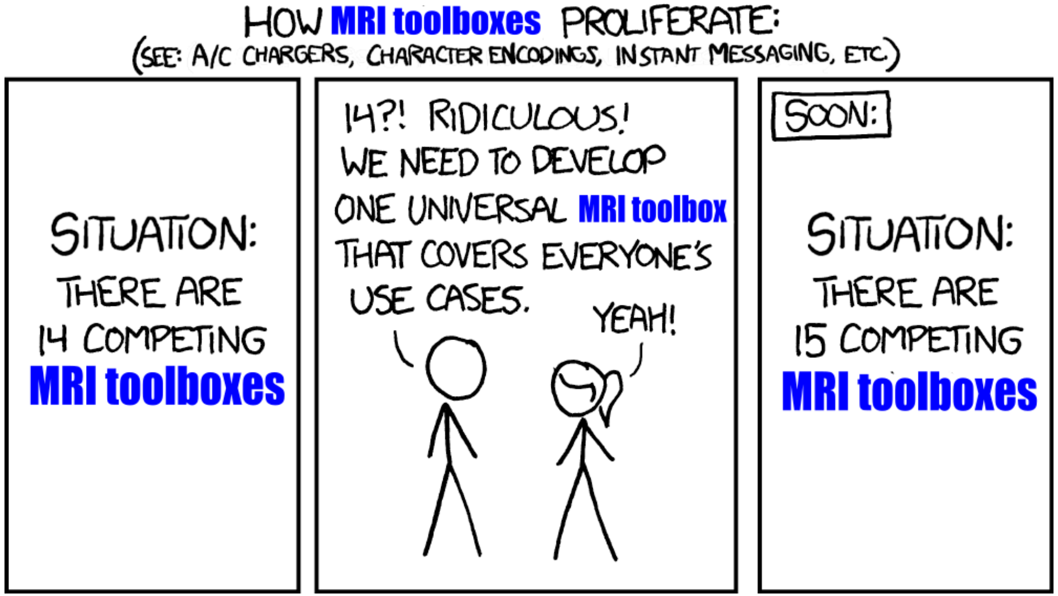

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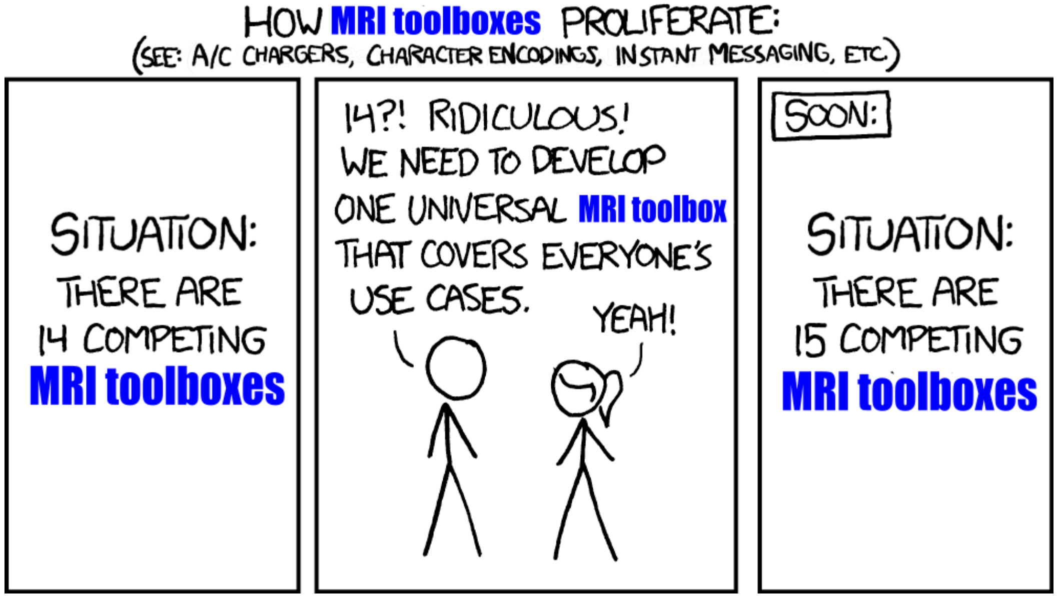

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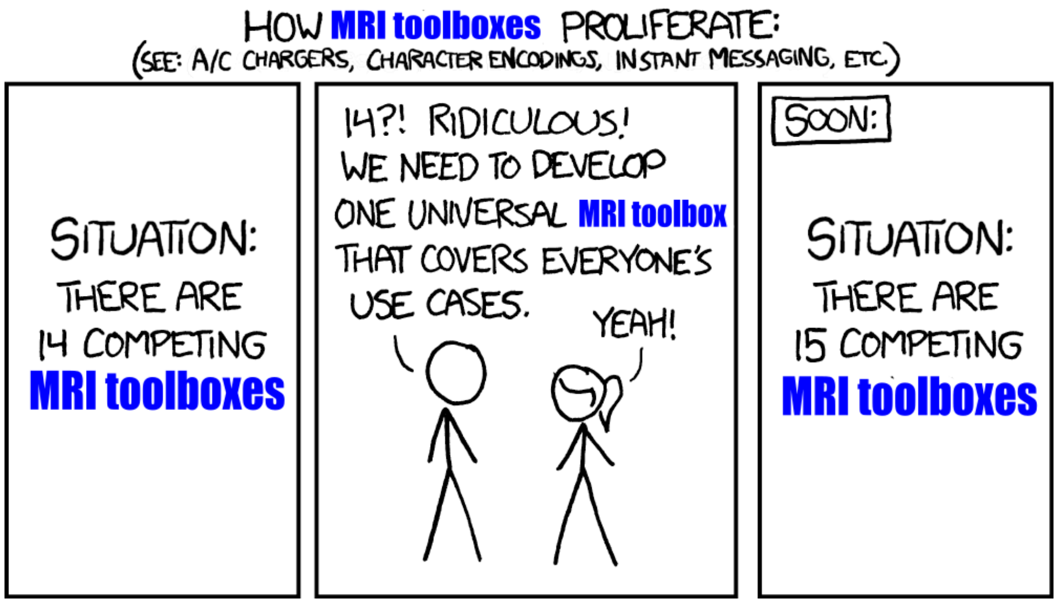
- Contributions are *always* welcomes



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Check out Our *awesome* **open-source** software:

MRI-nufft

SNAKE

Thank you for your attention

pierre-antoine.comby@cea.fr

Neurospin, CEA, Paris-Saclay University