What can we learn from medical imaging techniques ?

Urvashi Rau - NRAO [Friday Lunch Talk at NRAO-Charlottesville - 13 Dec 2024]

MRI and RI have very similar indirect-imaging problems

⇒ Different Physics, but similar ‘Measurement Equations’

⇒ Similar signal extraction and reconstruction problem.

NRAO : Cells-to-Galaxies initiative

- Algorithm R&D Group (S.Bhatnagar) + Technology-transfer office (J.Pixton) in 2019
- Hosted : Online Lecture Series (2020) + In-person Workshops (2019, 2021)
- Participated :
    - From Innovation to Implementation in Imaging : i2i workshop (2023)
    - International Society for Magnetic Resonance in Medicine : ISMRM (2024)

Outline

Data Acquisition

– Sampling the spatial FFT of the image

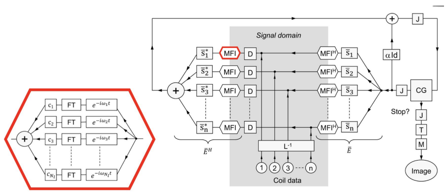
– Increasing field-of-view and SNR

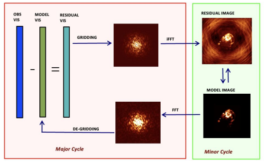
Signal Reconstruction

– Classical methods

– AI and ML methods

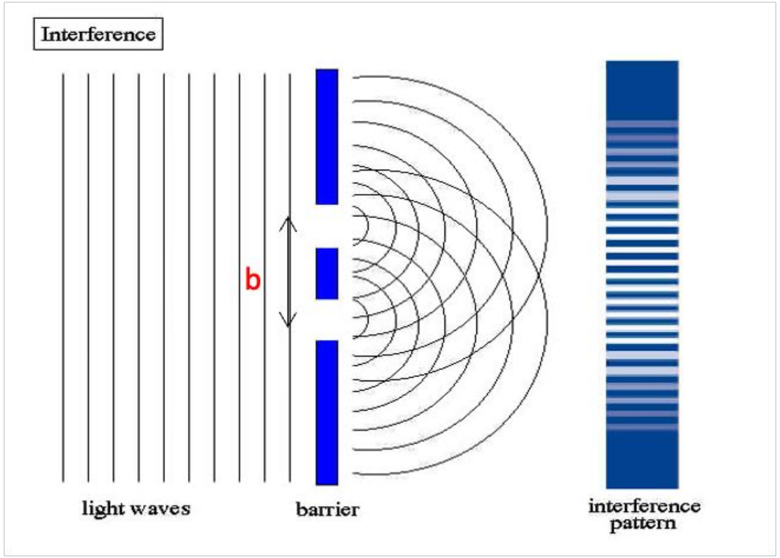
– Relation to the state of the art in Radio Interferometry algorithms

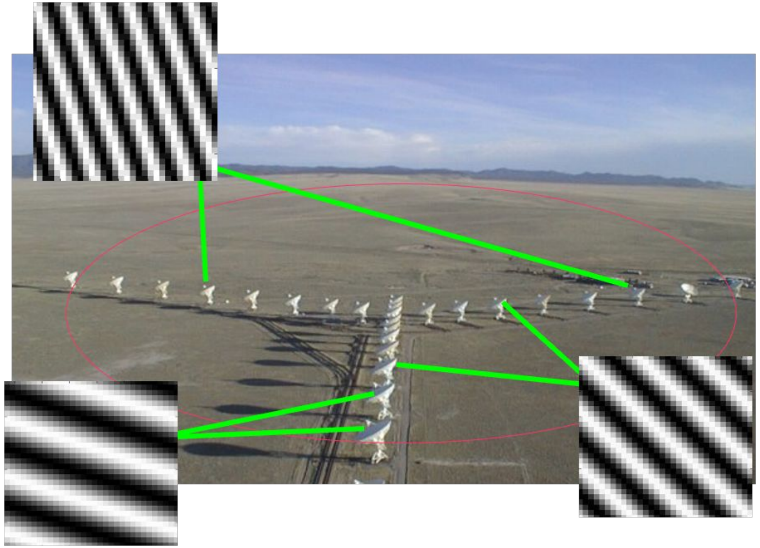




Dynamics between “Algorithm R&D” -> “Production Development” -> “User needs”

Physics of RI Data Acquisition - Signal + Sampling

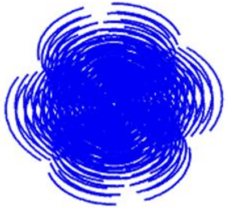




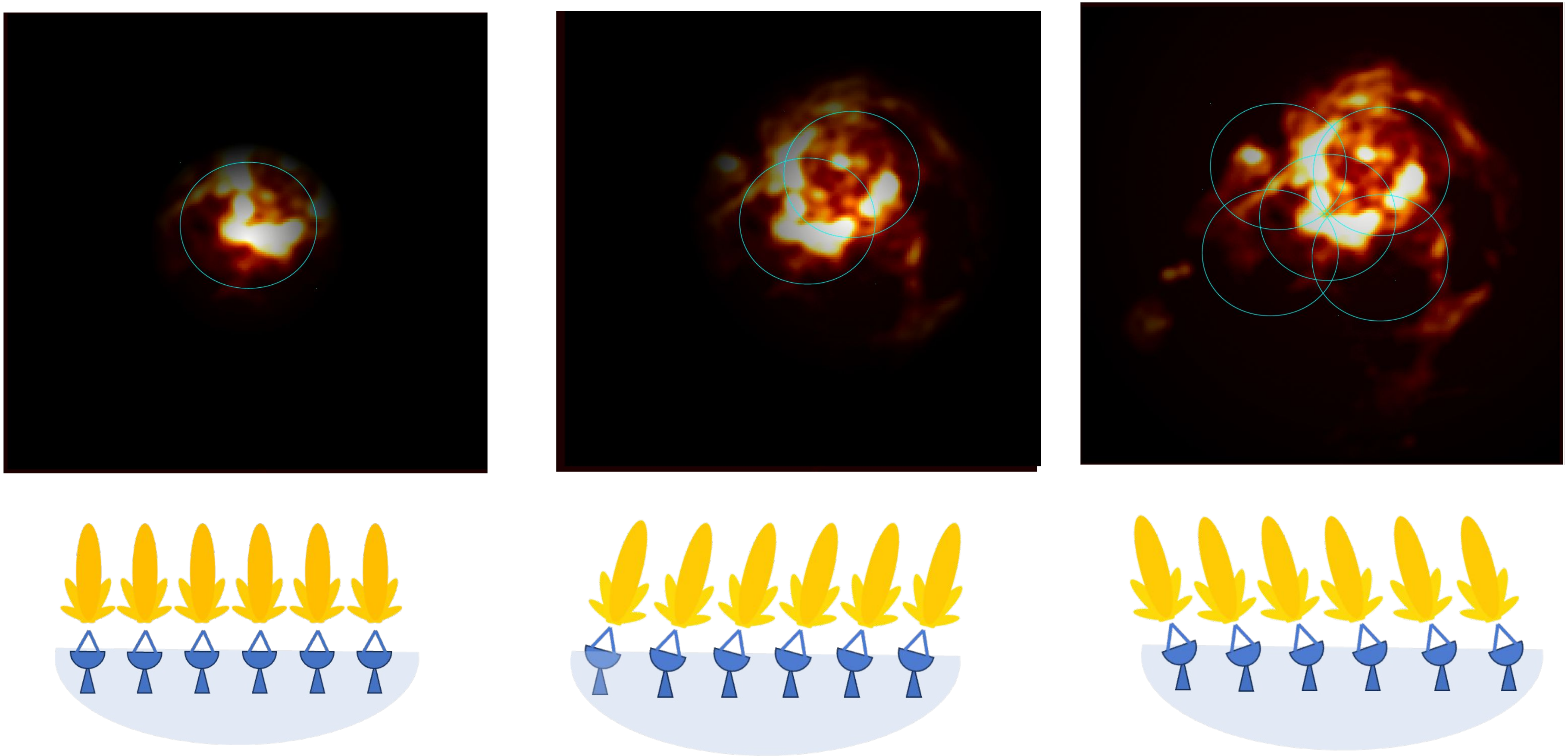
Each pair of ‘slits’ sees one Fourier term ====> 2D Fourier Series + Transform

Measure the spatial coherence of the E-field at each pair of detectors….

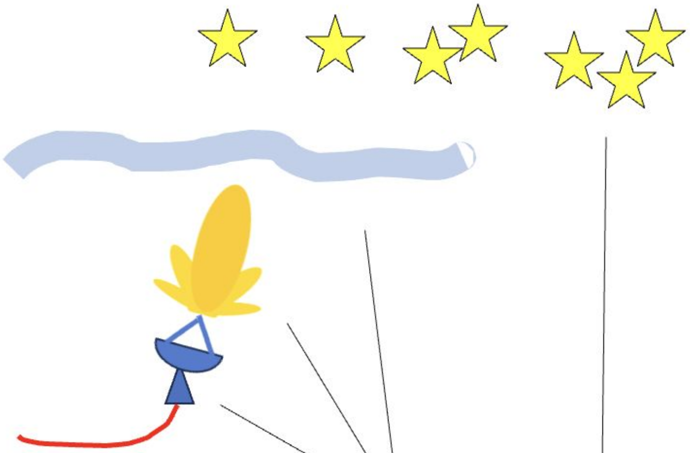
⇒ Parameters : ‘amp’, ‘phase’, ‘fringe wavelength’, ‘fringe orientation’

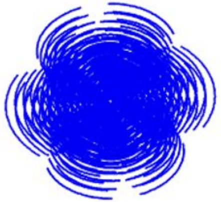


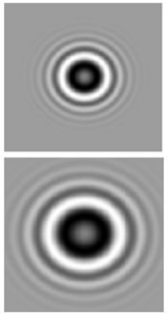
Physics of RI Data Acquisition - Mosaics



Physics of RI Data Acquisition - Measurement Equation







$$V_{b,c,t} = \int M_c(\vec{r}, b, t)\, I^{sky}(\vec{r})\, e^{i\vec{k}_b\cdot\vec{r}}\, e^{i\Delta\phi(\vec{r})}\, d^3r$$

antenna
sensitivity

sky
brightness

k-space trajectory

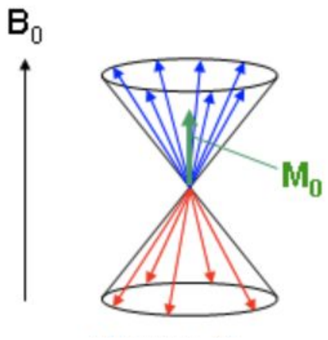
3D -> 2D
projection effects

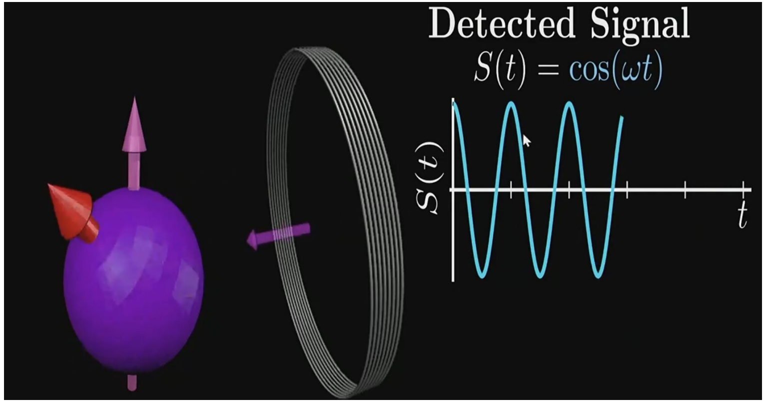
Physics of MRI data acquisition - Magnetization + NMR

B_0 ⇒ Constant B field ⇒ Alignment of proton spin axis

RF pulses along the X-Y plane are used to 'excite' protons and perturb the M vector

- When RF pulse is turned off, spins continue to precess about Z while they 'relax'
- NMR signal is detected via Faraday induction (Coils placed around X-Y)





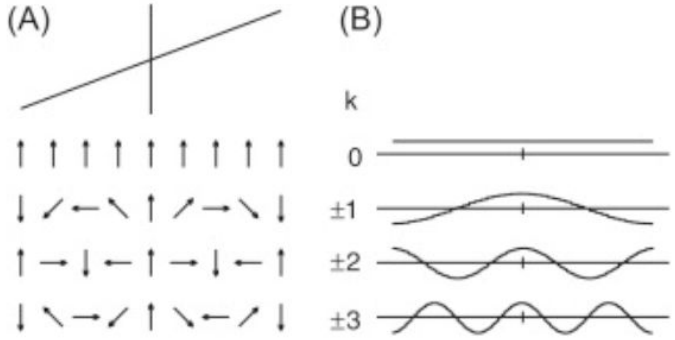
Physics of MRI data acquisition - Spatial Encoding

Slice selection :

B_z is a gradient along Z. Use RF frequency to ‘pick’ a slice to excite, along that linear B_z.

2D spatial frequency

B_x,y are also gradients



Measured signal amplitude is the “sum” of spatially varying magnetization amplitudes.

Fourier Components + Freedom to choose spatial frequencies to measure.

Physics of MRI data acquisition - Spatial Encoding

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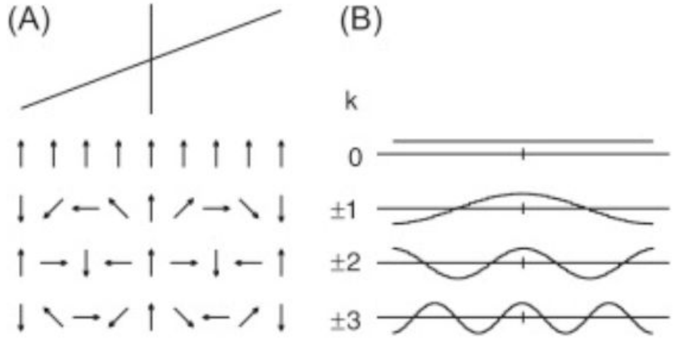
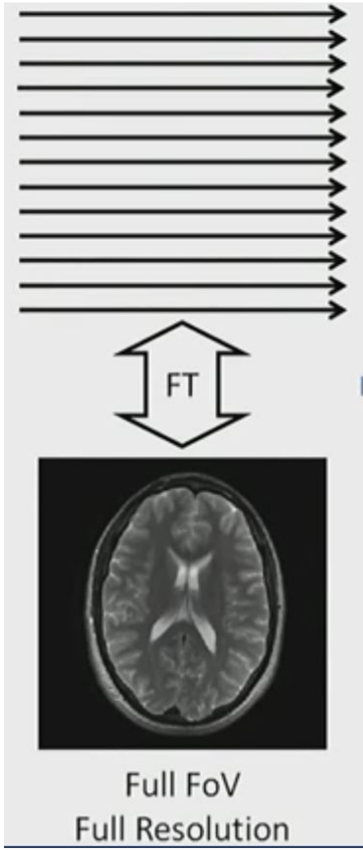


Fourier Components + Freedom to choose spatial frequencies to measure.



Data acquisition constraints

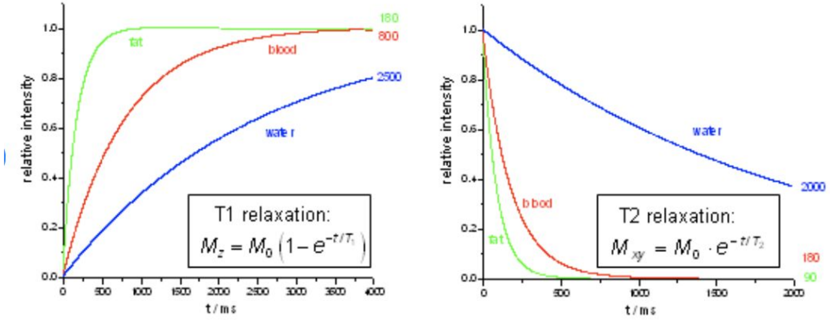
Relaxation Timescales

T1 : The flipped magnetization vector moved back to B_z

⇒ Loss of spatial isolation

T2 : Alignment along X-Y becomes incoherent

⇒ decreasing signal amplitude



Need to take measurements in-between these timescales….

Different tissues respond differently ⇒ Contrast Enhancement ⇒ Scheduling problem.

An complex art form

ML/AI R&D here too

Data acquisition constraints

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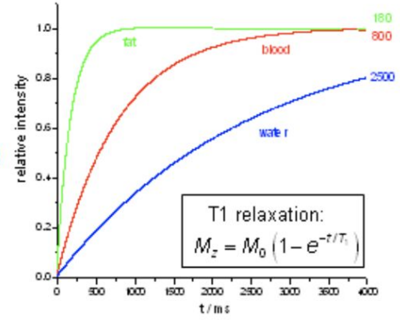
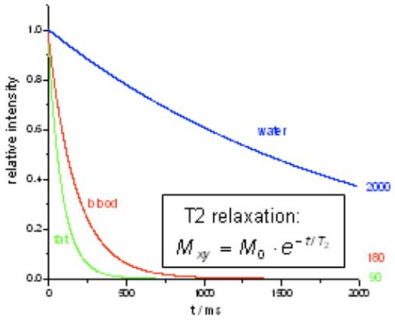




Need to take measurements in-between these timescales….

Different tissues respond differently ⇒ Contrast Enhancement ⇒ Scheduling problem.

An complex art form

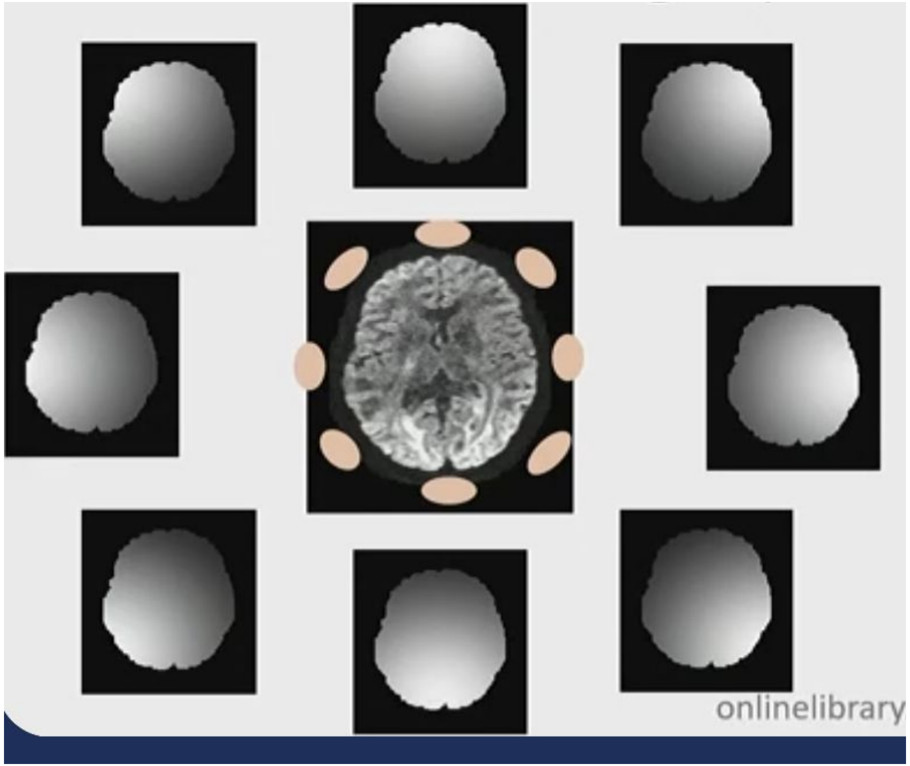
ML/AI R&D here too

Also….. Instrument Noise, Body Noise,

Movement artifacts,

Limits to B-field strength

Parallel Imaging (a.k.a. mosaics)



Simultaneous Data Acquisition using multiple receive coils.

"Coil Sensitivity Patterns"

[[Primary Beams]]

Significant spatial overlap….

⇒ Improved sensitivity

⇒ Wider field of view.

Physics of MRI Data Acquisition - Measurement Equation

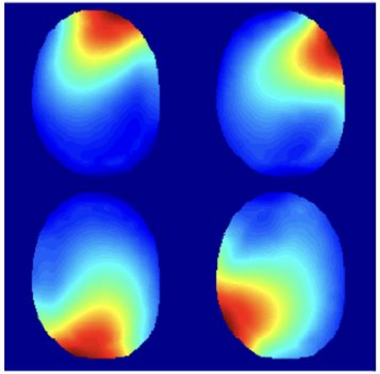
coil sensitivity

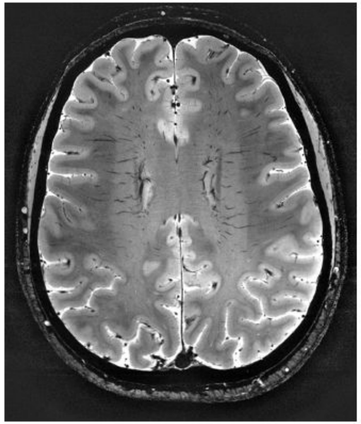
magnetization

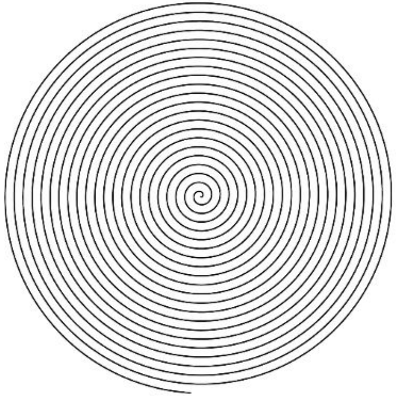
k-space trajectory

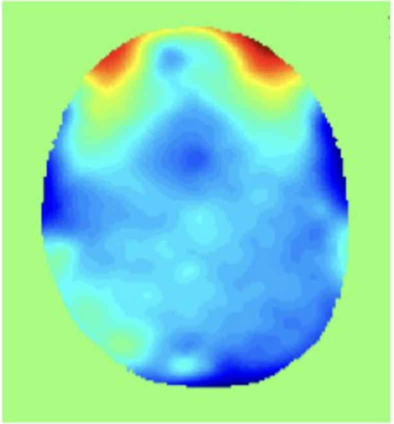
magnetic field perturbation

$$m_{c,t} = \int s_c(\vec{r})\, \rho(\vec{r})\, e^{i\vec{k}(t)\cdot\vec{r}}\, e^{i\Delta\phi(\vec{r},t)}\, d^3r$$









Measurement Equations have the same structure

coil sensitivity

magnetization

k-space trajectory

magnetic field perturbation

$$m_{c,t} = \int s_c(\vec{r})\, \rho(\vec{r})\, e^{i\vec{k}(t)\cdot\vec{r}}\, e^{i\Delta\phi(\vec{r},t)}\, d^3r$$

$$V_{b,c,t} = \int M_c(\vec{r}, b, t)\, I^{sky}(\vec{r})\, e^{i\vec{k}_b\cdot\vec{r}}\, e^{i\Delta\phi(\vec{r})}\, d^3r$$

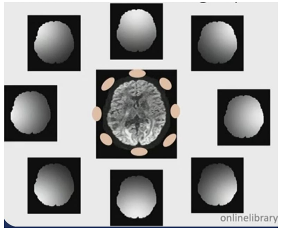
antenna sensitivity

sky brightness

k-space trajectory

3D -> 2D projection effects

Parallel Imaging



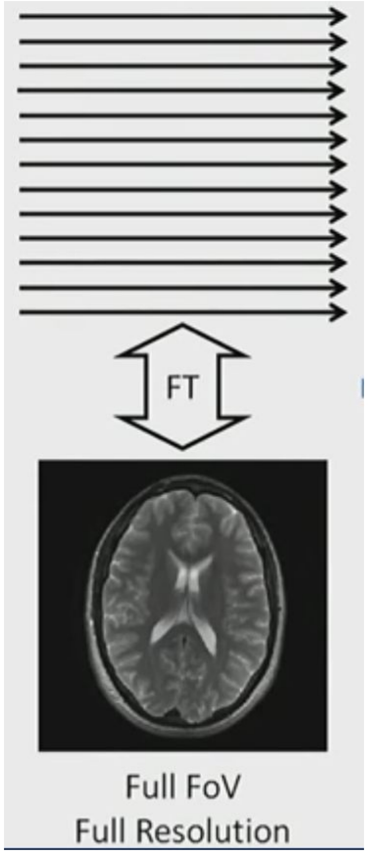
GRAPPA [[A-Projection]]

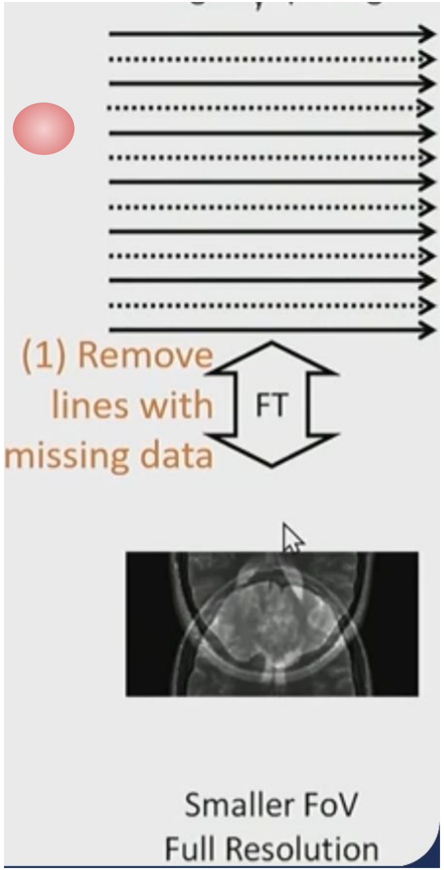
- K-Space Convolution with a kernel = F(C) =

  measured near K=0

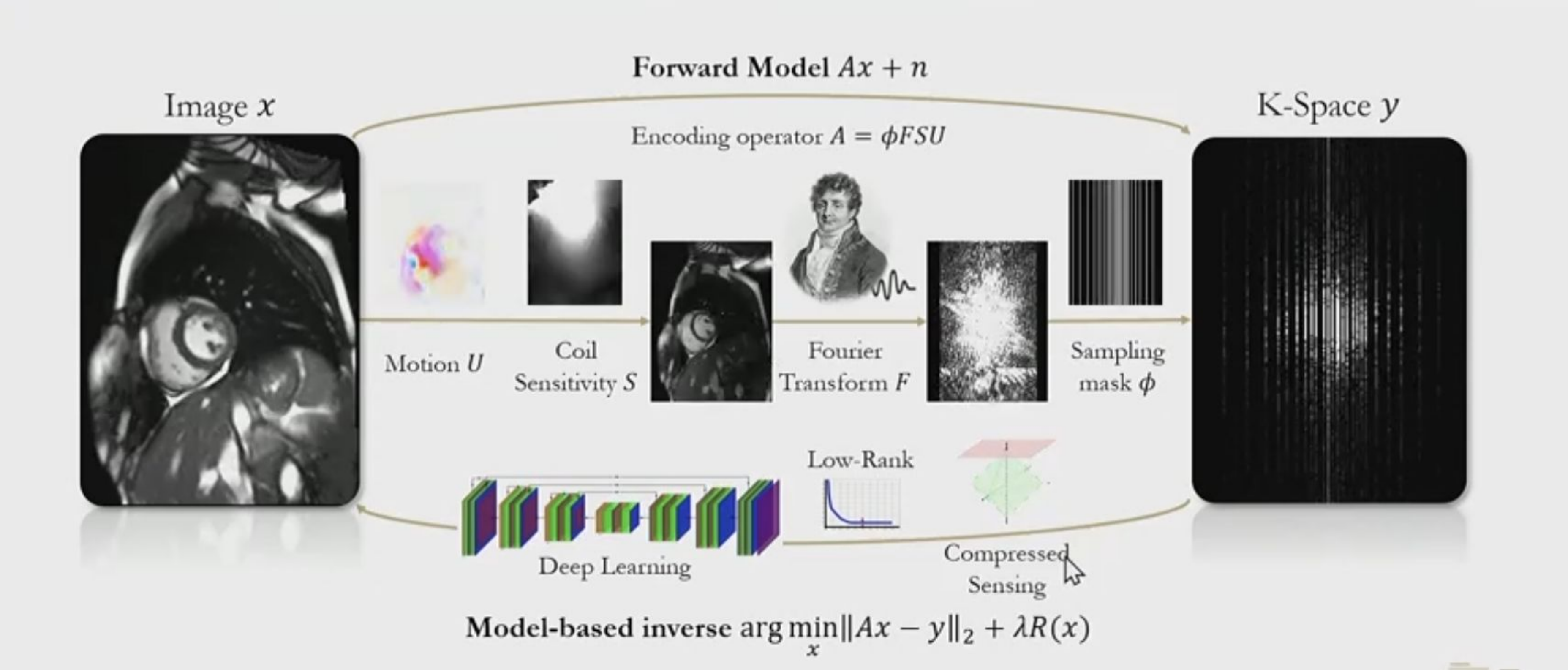
SENSE [[Linear Mosaic]]

- Undo linear combination of I x C in the image domain





Compressed Sensing (+ reconstruction)



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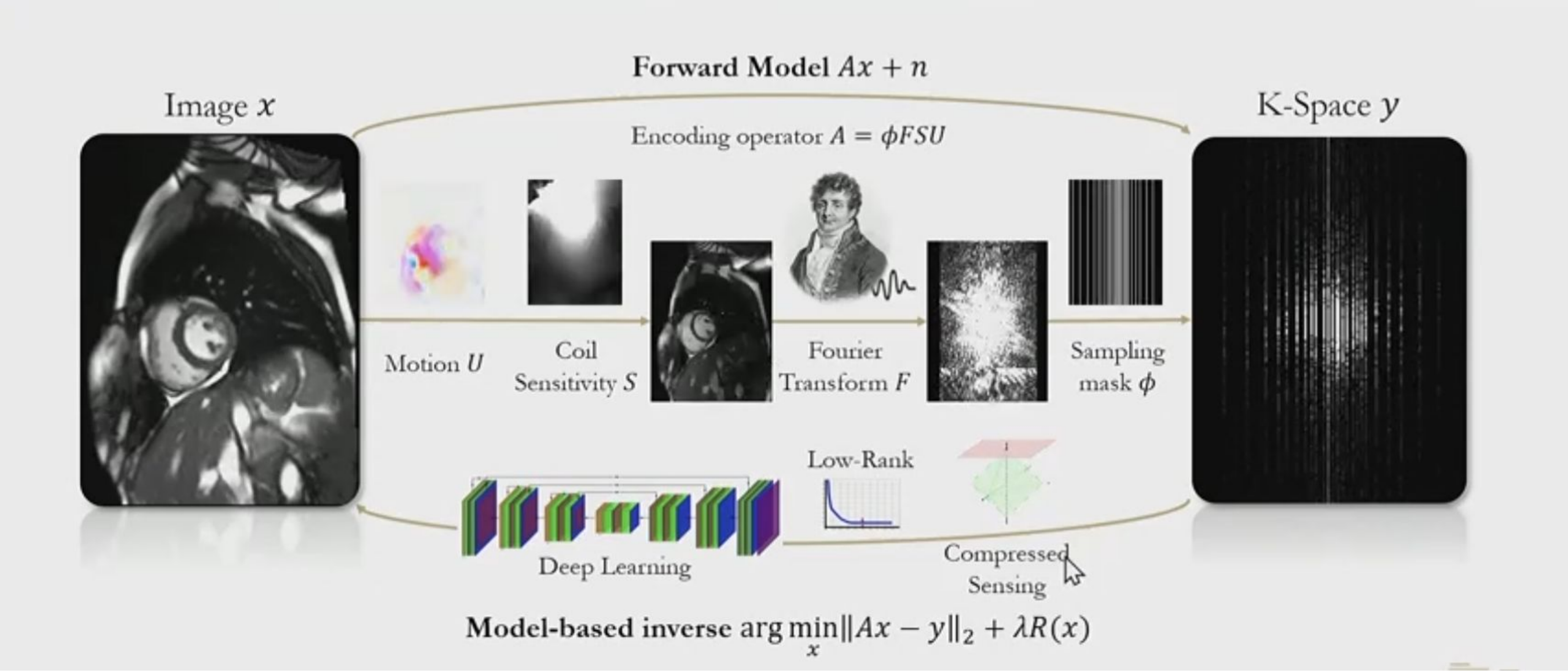
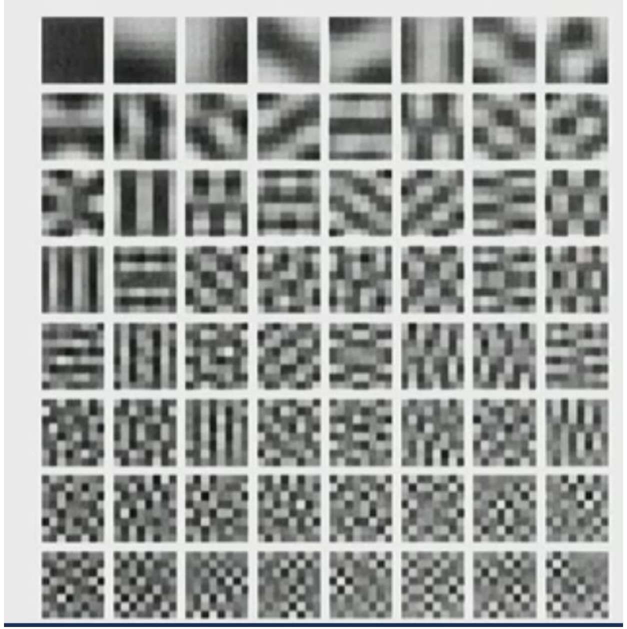


[[Major and minor Cycles + Plug’n’play different ‘minor cycle’ algorithms]]

Image Reconstruction – Dictionary methods

$$\min_{\mathbf{x}} \frac{1}{2}||\mathbf{y} - \mathbf{A}\mathbf{x}||_2^2 + Q(\mathbf{x})$$



Bayesian view + Priors

– Likelihood term (Chi-Sq) , nu-FFT, Prior terms

– Image = linear combination of patches

– L1 regularization to get sparsity

(i.e. find the min number of unique patches that represent the structure)

[[Sky Model : Points, List of multiscale Paraboloids, Wavelets, etc…]]

Image Reconstruction – Dictionary methods

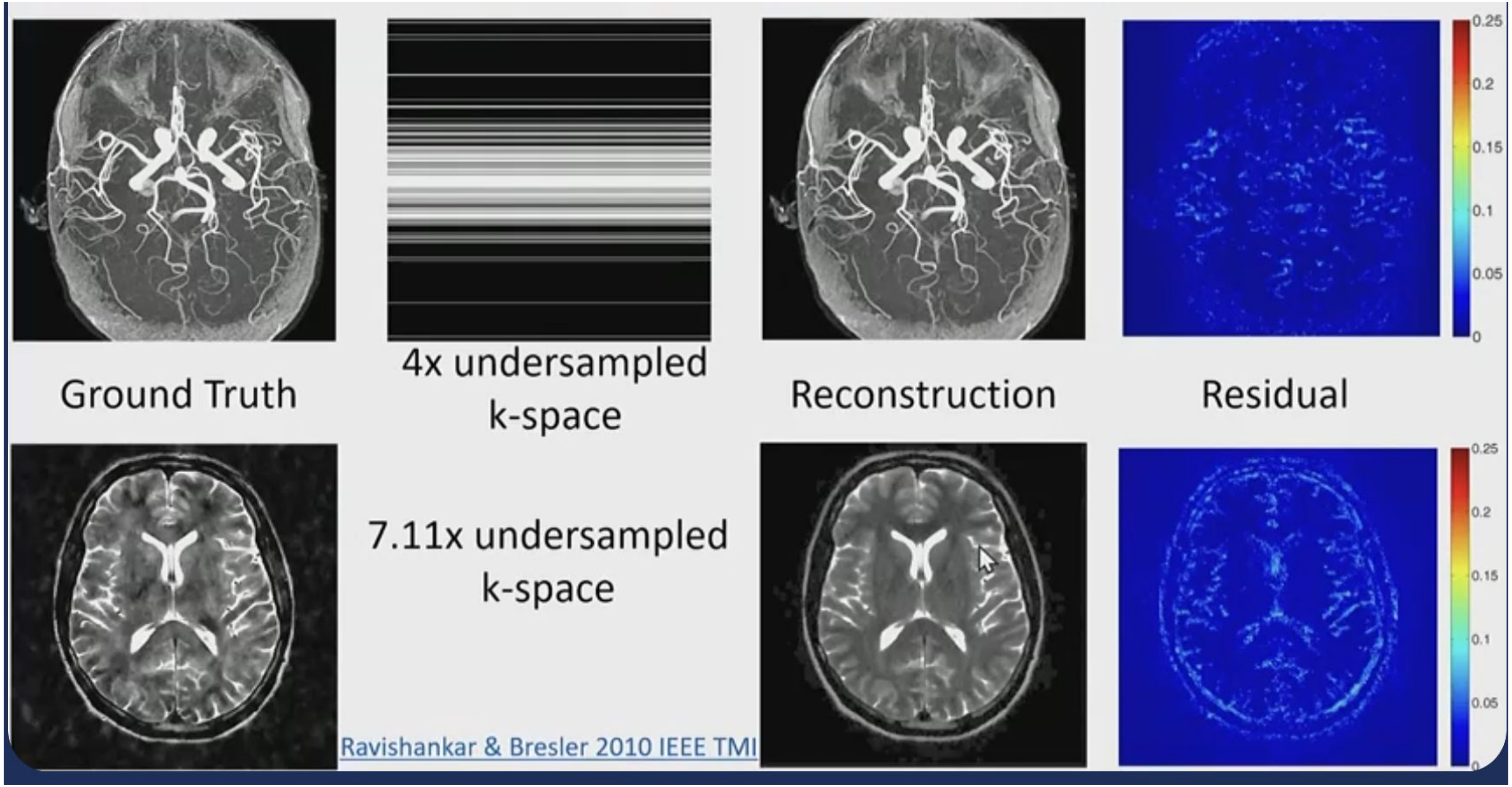
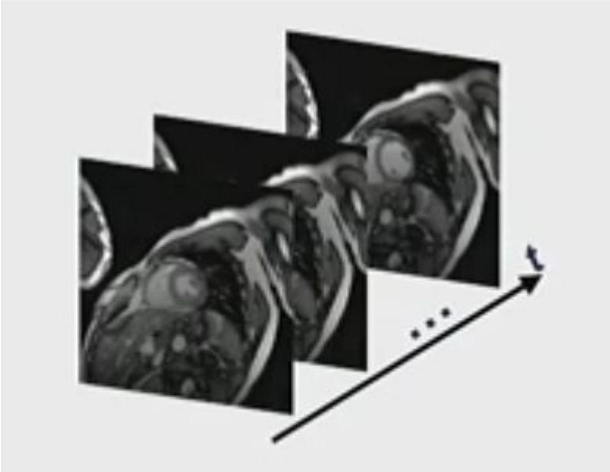


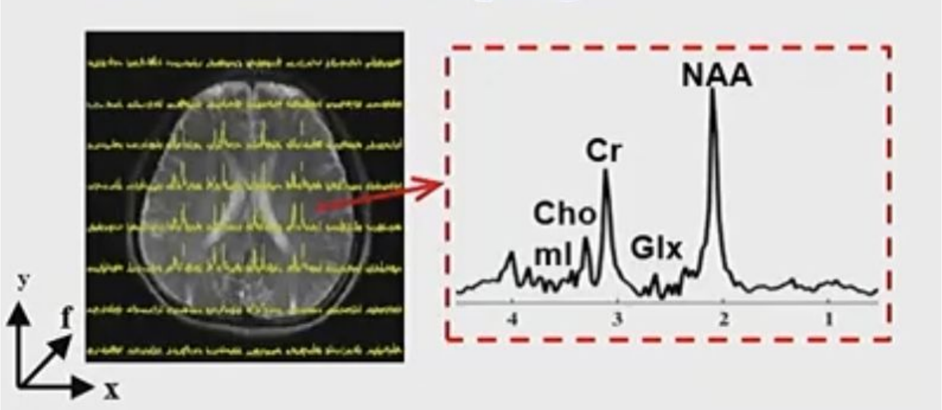
Image Reconstruction - Low Rank Models

Joint Reconstructions across axes with slow variability

(Linear combination models, with partial separability.)

[[MT-MFS, TV-MT-MFS , etc…]]





SPICE : A joint modeling approach for Spectral Lines

Low-rank on Spatial axes

[[??]]

Image Reconstruction - Machine Learning

Started in 2016…… by 2024, the ISMRM needed a “non-AI methods” session….

Supervised Learning

- Use labeled data : Partially sampled k-space + Truth images
- Learn “ Transforms “

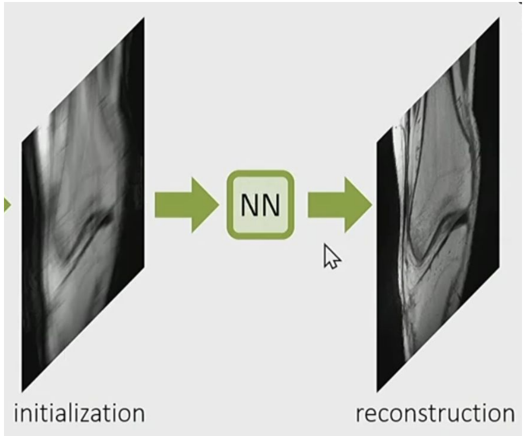
Unsupervised learning

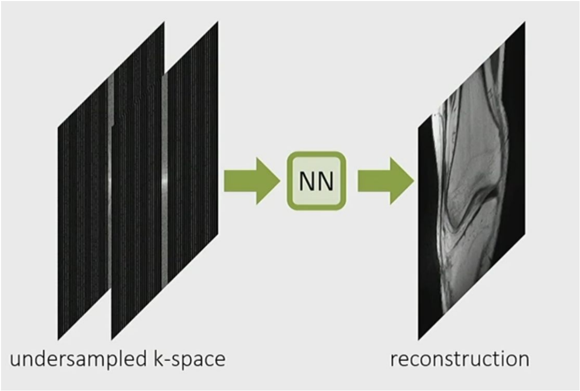
- Use unlabeled data : Discover patterns
- Learn “ Probabilities of features “ : Generative Modeling…

Image Reconstruction - Supervised Learning

Image Denoising & Super-Resolution

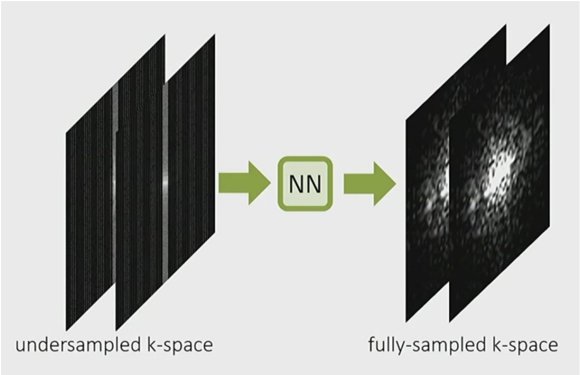
⇒ Learn "dirty to clean" transform for some range of PSF shapes





K-Space to Image

⇒ Learn the FT and some image shapes



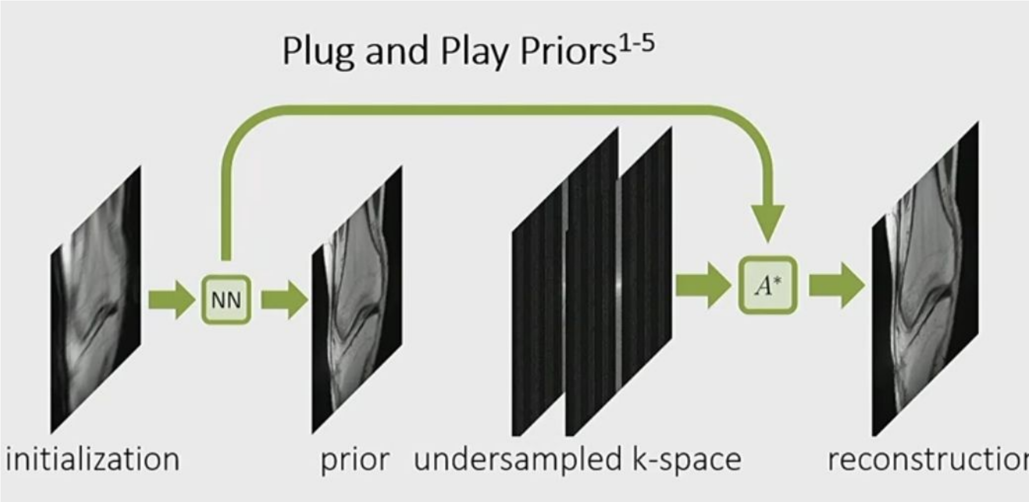
K-Space Interpolation

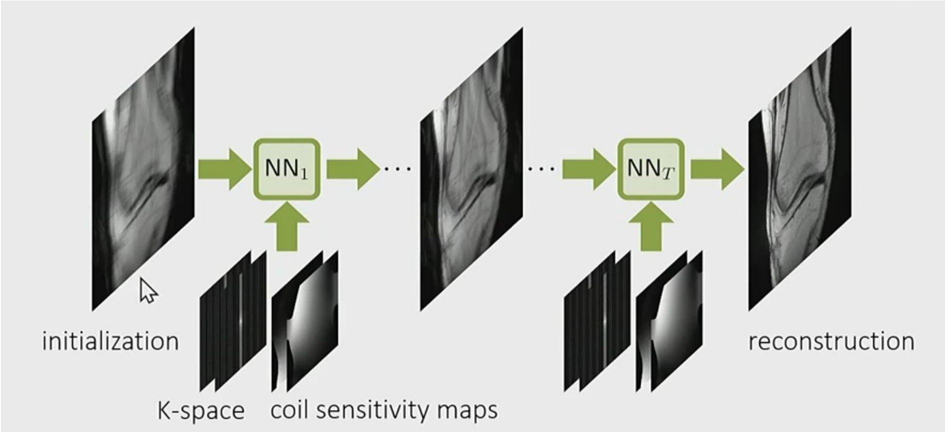
⇒ Learn interpolation rules

Image Reconstruction - Supervised Learning

Plug and Play methods

⇒ Denoising/superresolution as a ‘minor cycle’ algorithm.





Physics-based models

⇒ Use (or solve for and use) instrumental terms as part of imaging

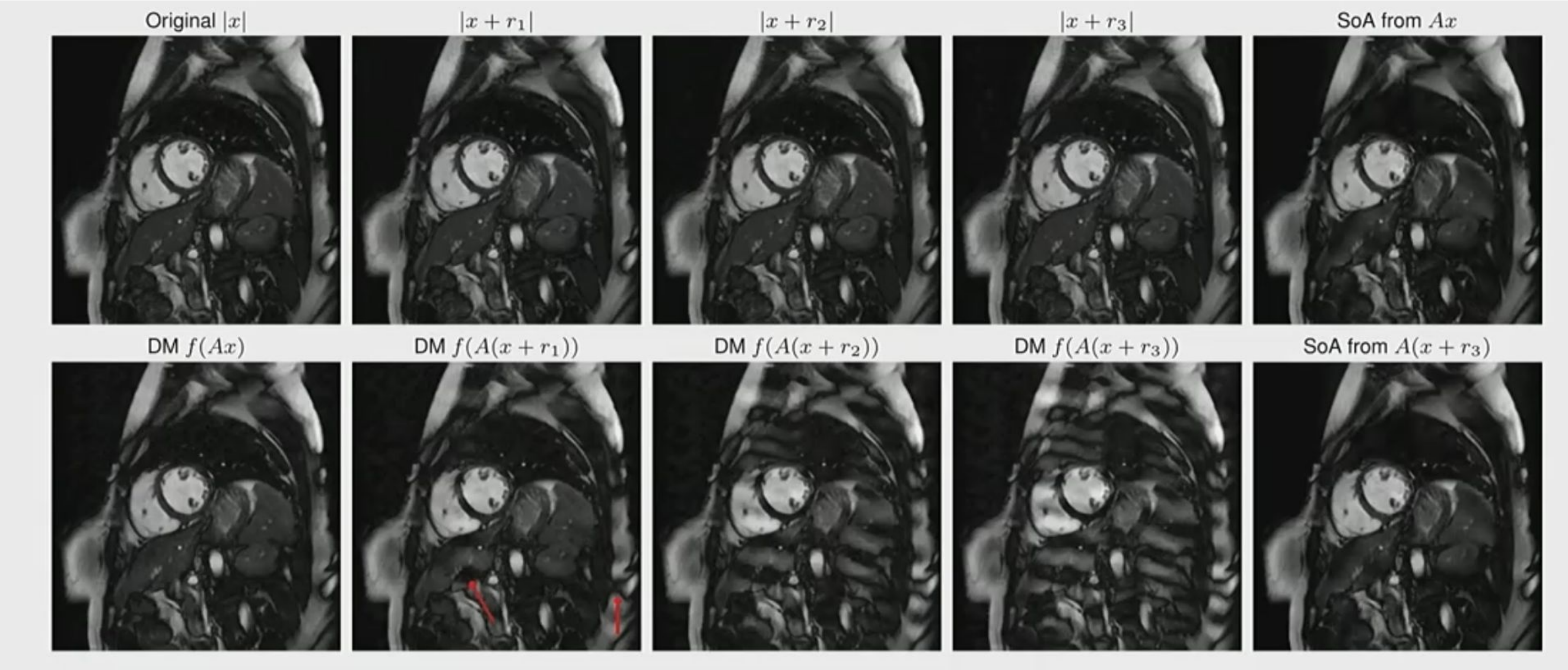
(e.g. pbcor, mosaic, etc..)

ML - Image Reconstruction Errors – Some are easy to hack

Increase data noise ——--->

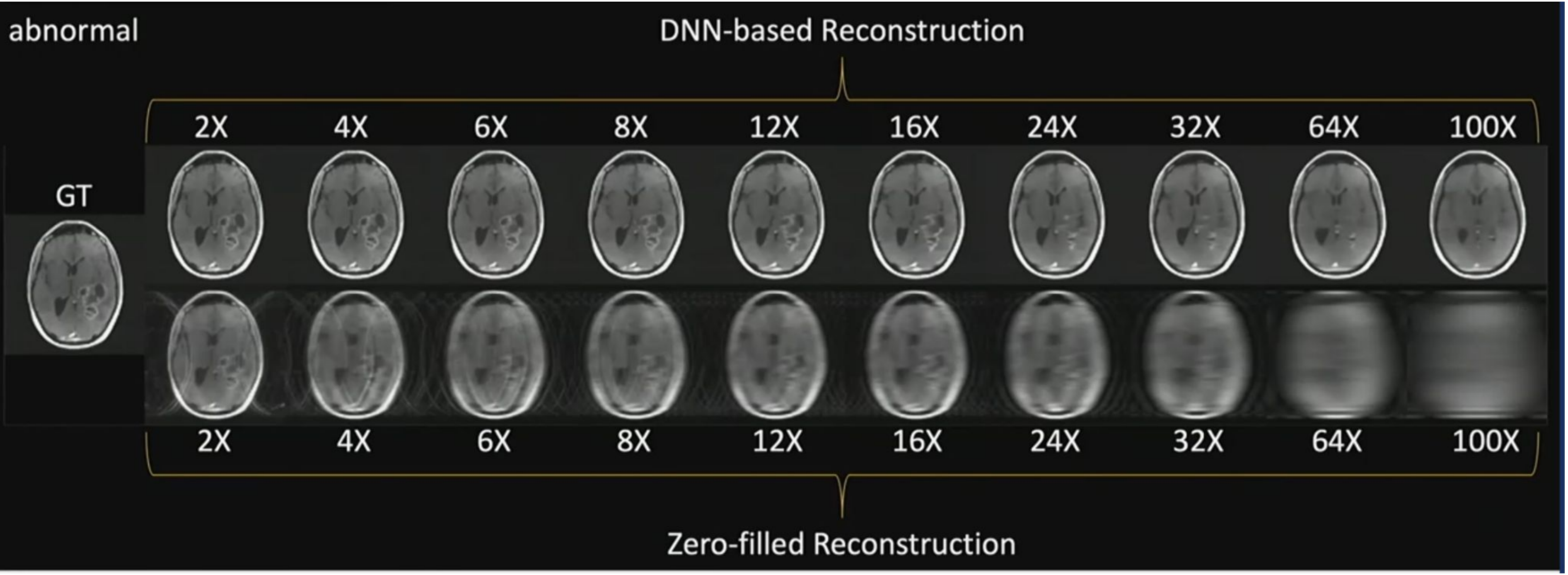
Classical

Deep Learning



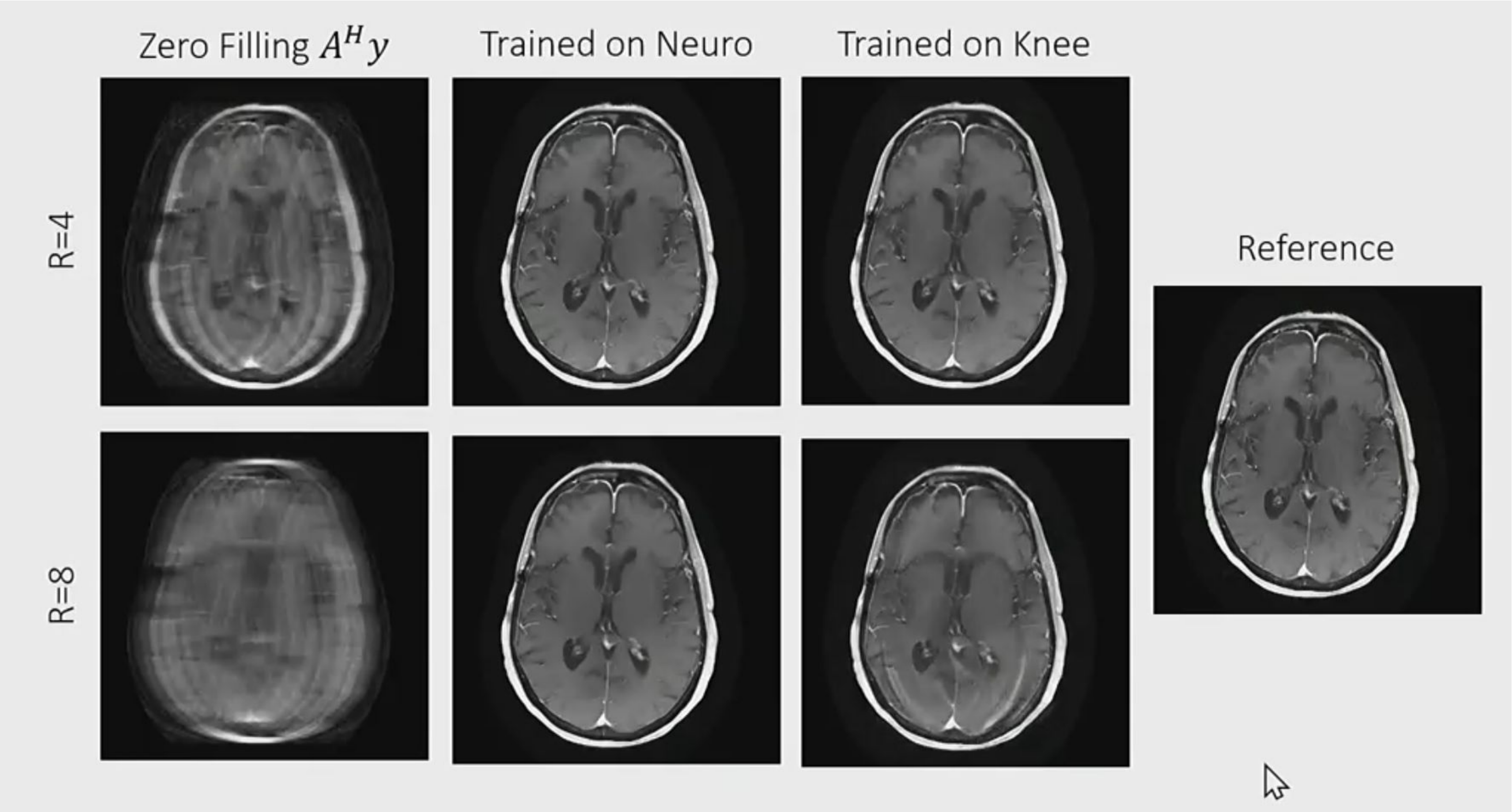
ML - Image Reconstruction Errors – Overconfidence

Sparser K-space sampling —-->



ML - Image Reconstruction Errors – Hallucination

Sparser K-space



Lessons from 8 years of exploration with ML/AI (video)

Classic Methods,

Plug-n-play / Unrolled,

Generative Modeling

⇩

→ Where are they useful ?

→ Where do they tend to fail ?

Speed, Accuracy, Generalizability, Training Cost,

Robustness, Uncertainty estimation   —-> Which are easier to take to production?

What is the Radio Interferometry landscape ?

Classical methods

Sky model (points, paraboloids, smooth spectra. L2 min with regularization (CLEAN, MS/MT, ASP, MORESANE). (Bayesian) bias terms and (sparsity-L1) priors (MEM, RESOLVE, MPOL,SARA, PURIFY). Direct modeling and MCMC (e.g. EHT algorithms, SMILI)

Plug'n'play deconv and gridders. Low-rank models and Joint Recons. Solving for DD instrumental terms.

Machine learning exploration - early steps…

Several attempts at using CNNs/DNNs for image-domain super-resolution and denoising.

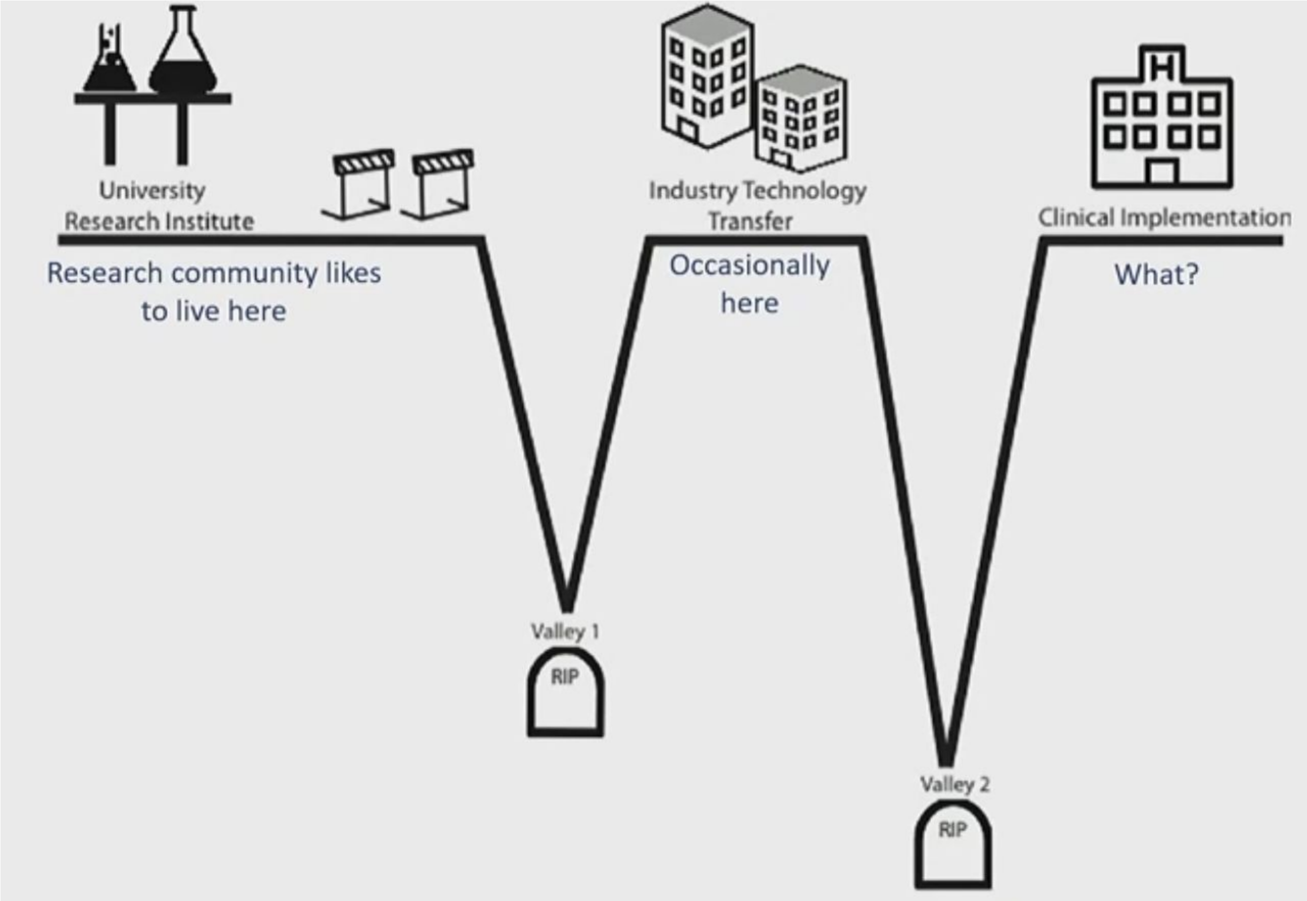
POLISH : Applying denoising/superresolution algorithms to deconvolve a range of PSFs (scaling, rotation, shift, random phase distortion (cal errors). Image domain only.

DEEP-FOCUS : Auto-encoder with a 'meta learner' that optimizes across NN architectures for ALMA reconstructions. Image domain only.

AIRI - Use a 'DNN-based denoiser" as a 'minor cycle' of standard image reconstruction. (plug'n'play class of algos with major/minor cycles)

Others….. NN+Bayesian, , Low-rank learner, Learn uv-interpolation , image compression, transient detection

Algorithm R&D —> Production Development —> Clinical Users



Algorithm R&D —> Production Development —> Clinical Users

A very familiar dynamic …

- Very few R&D results actually make it into production.
  - Compressed Sensing and Parallel Imaging (in the past 15yrs)
- Clinical scientists (at companies) choose what goes to production.
  - Constraints : Cost-vs-benefit + Generalizability/Robustness requirements
- Clinical users still have unmet needs.

The ISMRM had talks that tried to address this — "Solve the right problems"

⇒ Better connect R&D efforts + Production Metrics + User Needs

⇒ Algorithms need to be robust

References

- Accessible MRI (low-field + portable) - Andrew Webb (plenary) : Drivers of Innovation

- Lessons learnt from 8yrs of ML/AI algorithm R&D in medical imaging

- Ethics in medical imaging with AI (plenary) : Biases, Uncertainties, etc…

- Inner Space to Outer Space (plenary) : Connection with Radio Interferometry
    - https://public.nrao.edu/news/invisible-realms-revealed/

- MR-Physics 1 & MR-Physics 2 + D.Sodickson's lecture from C2G
- Image Recon - Classical + Machine Learning : Abstracts + Session Recording

- Cells to Galaxies / I2i Workshop series
- ISMRM (Singapore - May 2024, Hawaii - May 2025)

(Acknowledgement : All images/figures were taken from the above ISMRM videos or publicly available tutorials.)