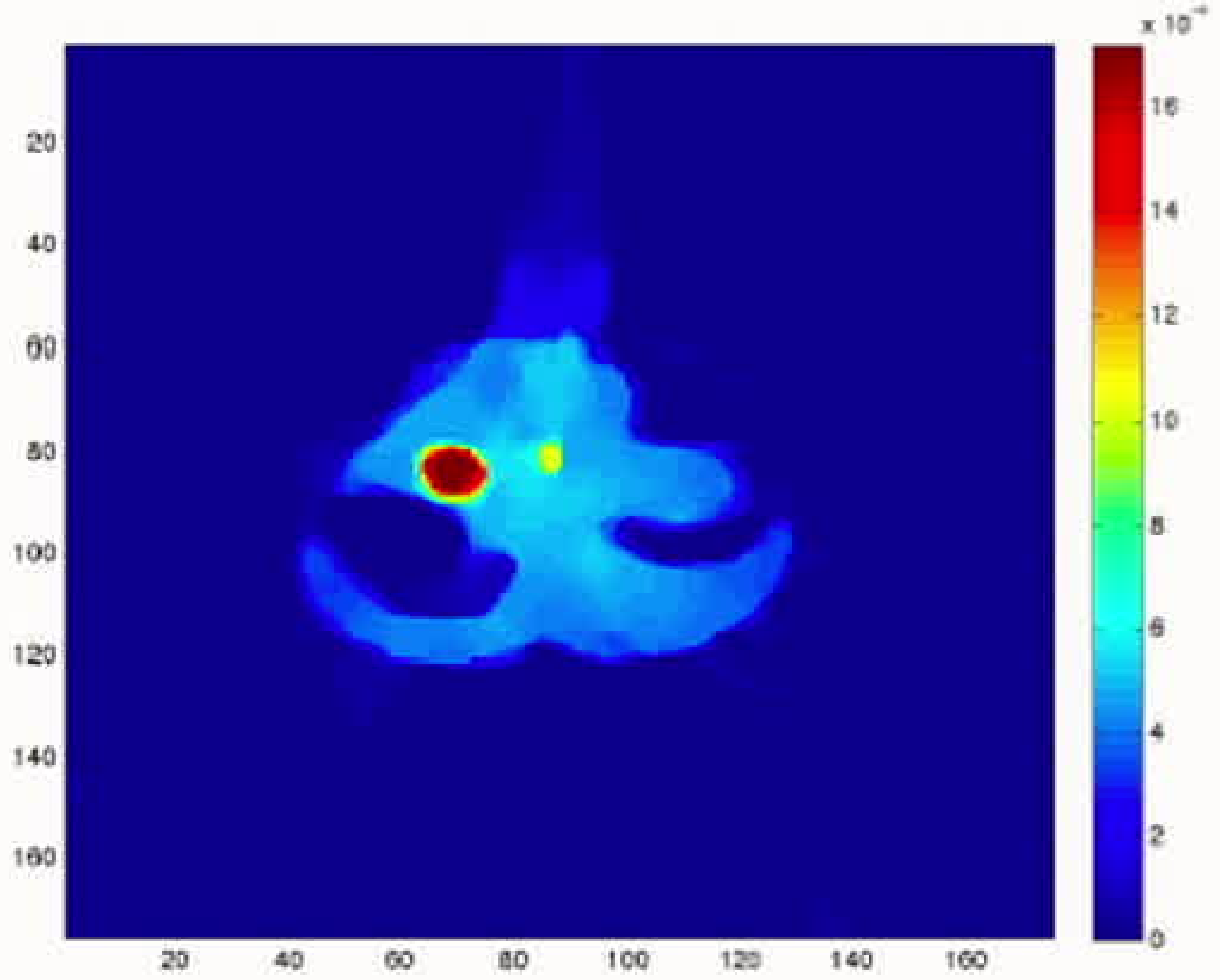
Outline

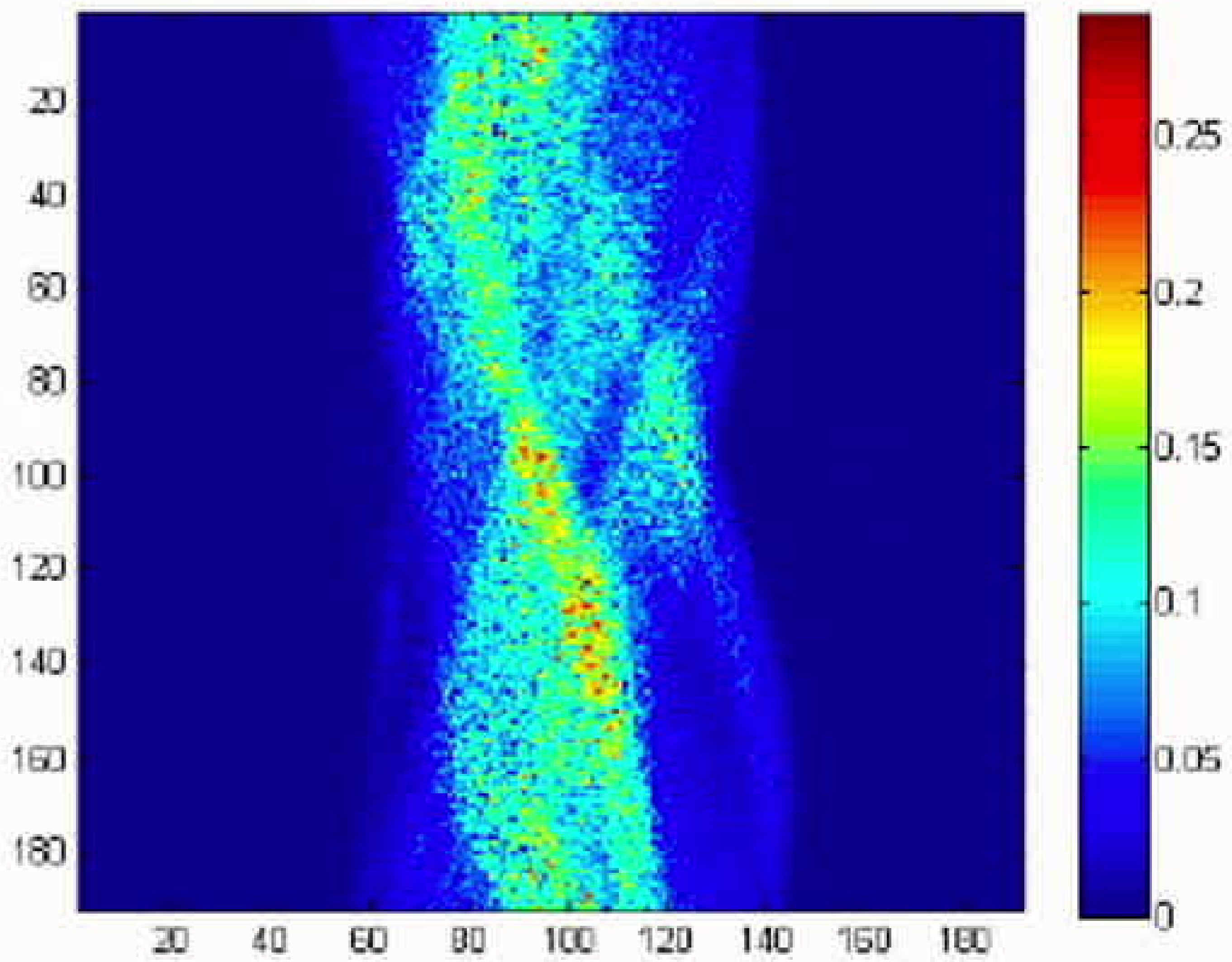
What is an inverse imaging problem?

Forward problem: knowing physical quantity compute the measurements
Inverse problem: measuring the datum compute the physical quantity.

Physical quantity
(trazer accumulation)



Measurements
(sinogram)

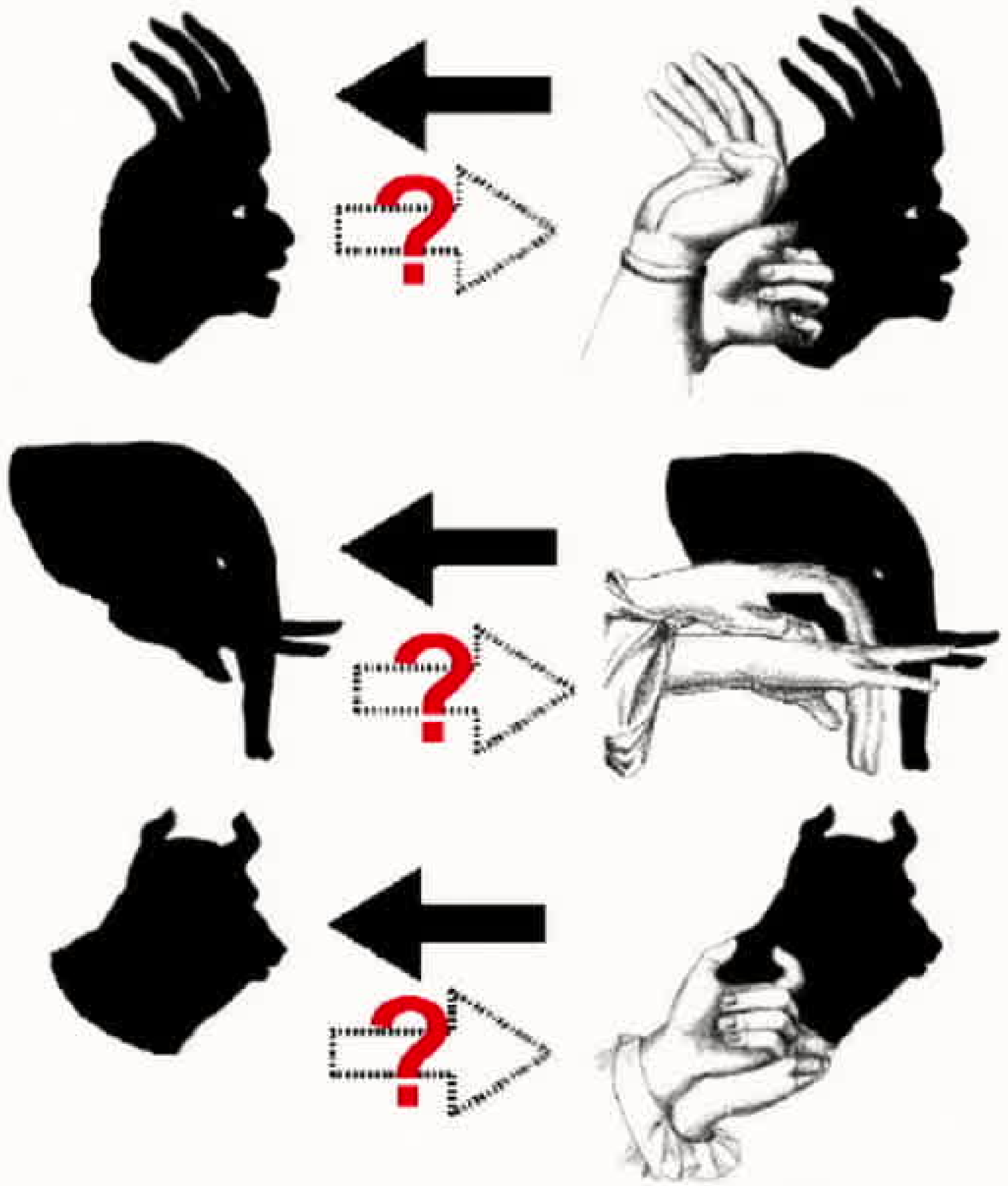


Mathematically: compute $u \in X$ from $Y \ni f = T(u) + n$, X, Y normed vector spaces.

Ill-posedness

Reasons: unbounded or discontinuous inverse (examples are compact forward operators with infinite range), underdetermined data (subsampling), noise, . . .

Consequences: instabilities (solution is not continuously dependent on input data), non-uniqueness, . . .



The variational approach

General task: **restore u** from an **observed datum f** where

$$f = \underbrace{T(u)}_{\text{forward model}} + \underbrace{n}_{\text{noise}}.$$

Variational approach: Compute u as a minimizer of

$$\mathcal{J}(u) = \alpha \underbrace{R(u)}_{\text{regularization}} + \underbrace{D(T(u), f)}_{\text{data fidelity}} \to \min_{u \in X},$$

where

- $R(u)$ is a prior/regularizer that models a-priori information on u weighted by positive α, e.g., $R(u) = \|\nabla u\|_1$ (in infinite dimensions $|Du|(\Omega)$)
- $D(\cdot, \cdot)$ is a distance function, e.g. $D(Tu, g) = \|Tu - f\|_2^2$ and B suitable Banach space, e.g., $X = BV(\Omega)$.

Engl, Hanke, Neubauer '96; Rudin, Osher, Fatemi, Physica D '92; Natterer, Wübbeling '01; Candes, Romberg, Tao, IEEE Trans Inf Theory '06; Kaltenbacher, Neubauer, Scherzer '08; Schuster, Kaltenbacher, Hofmann, Kazimierski '12

What is the right sparsity?

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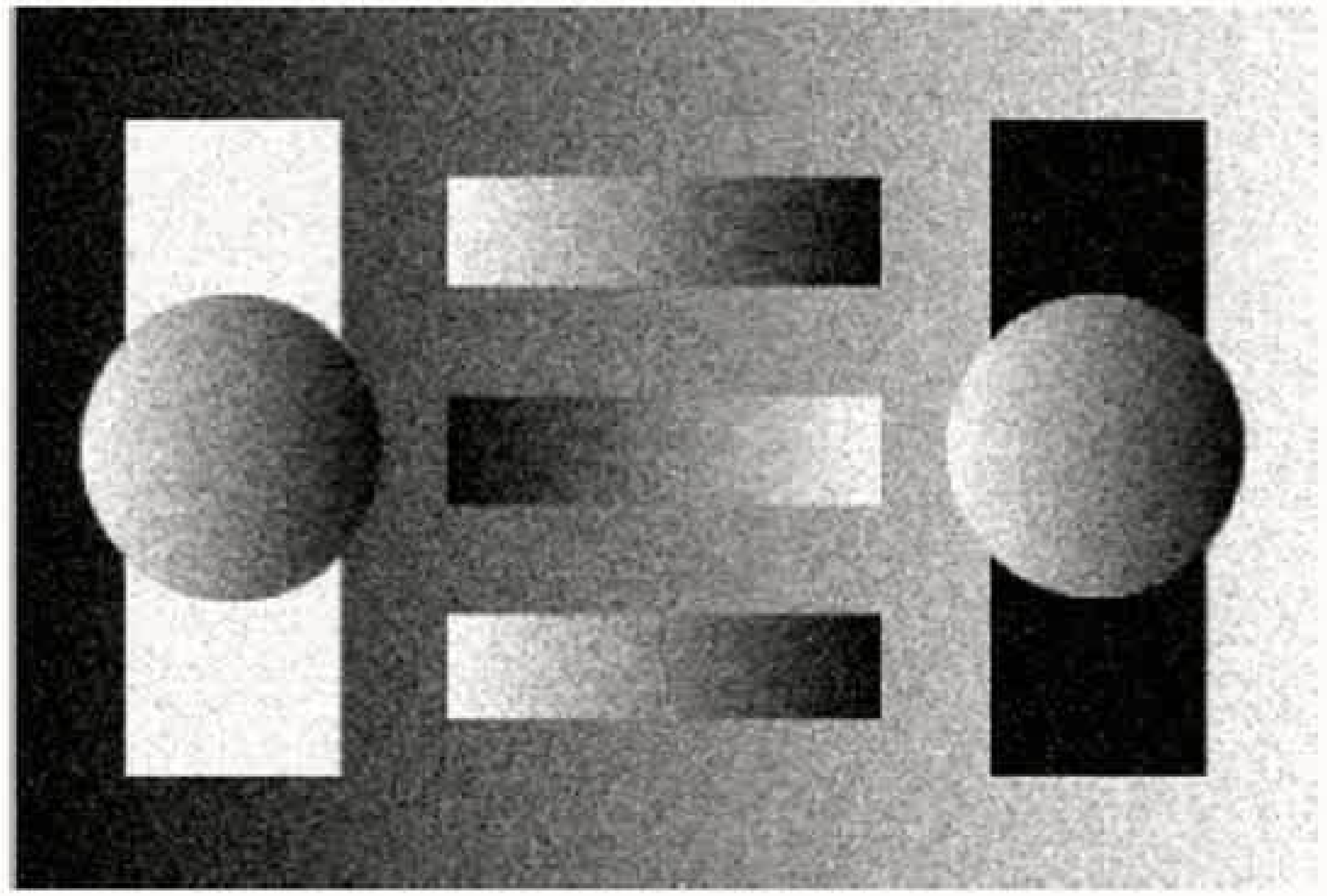
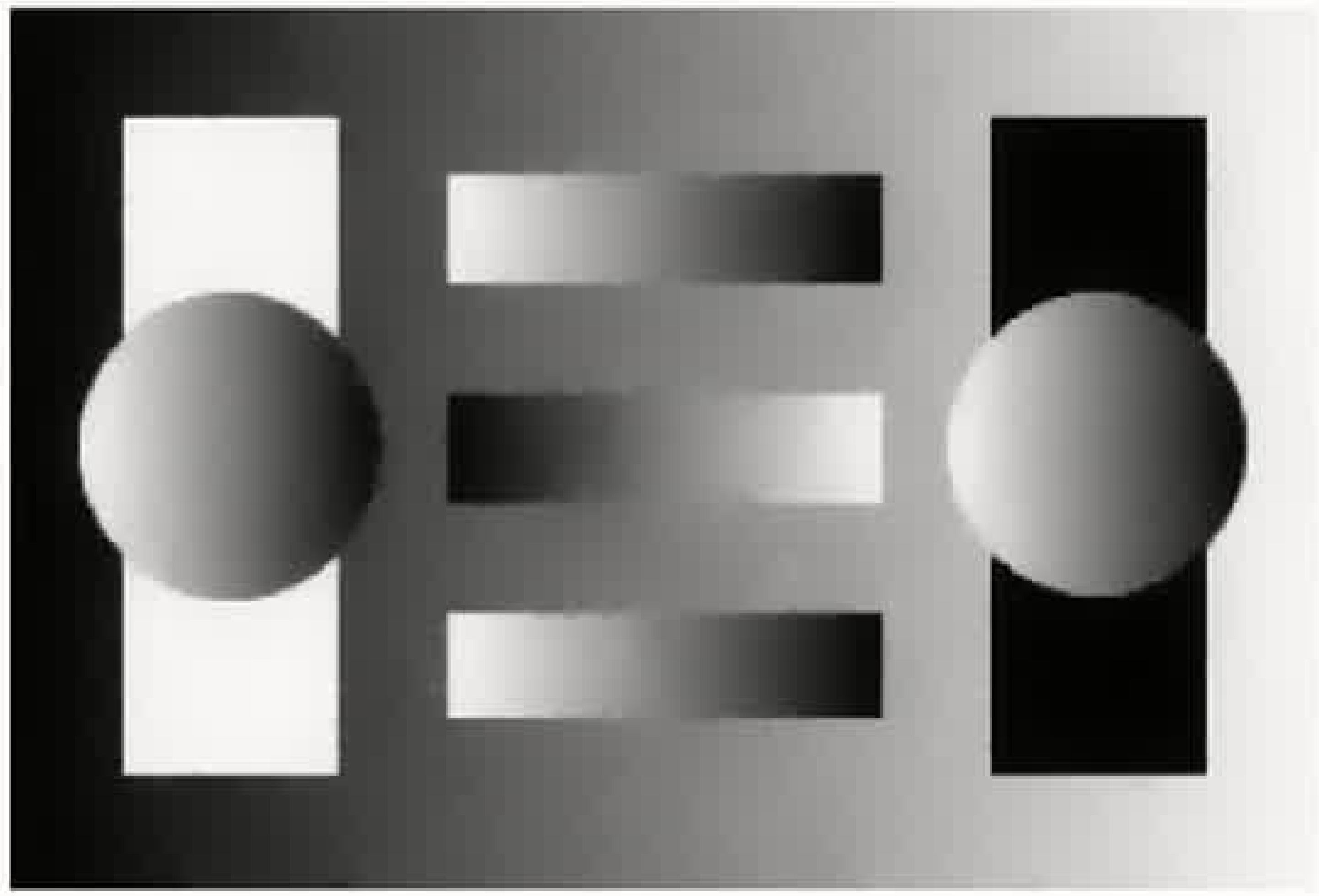
$$\min_u \left\{ \min_w \{\alpha_1 \|\nabla u - w\|_1 + \alpha_2 \|Ew\|\} + \|u - f\|_2^2 \right\}$$



Noisy image



TGV^2 denoised image

Image courtesy of K. Papafitsoros

References: Rudin, Osher, Fatemi '92; Hinterberger, Scherzer, Computing '06; Bredies, Kunisch, Pock, SIAM Imaging '10; Papafitsoros, CBS, J. Math. Imaging & Vision, '13 ...

Deep image processing

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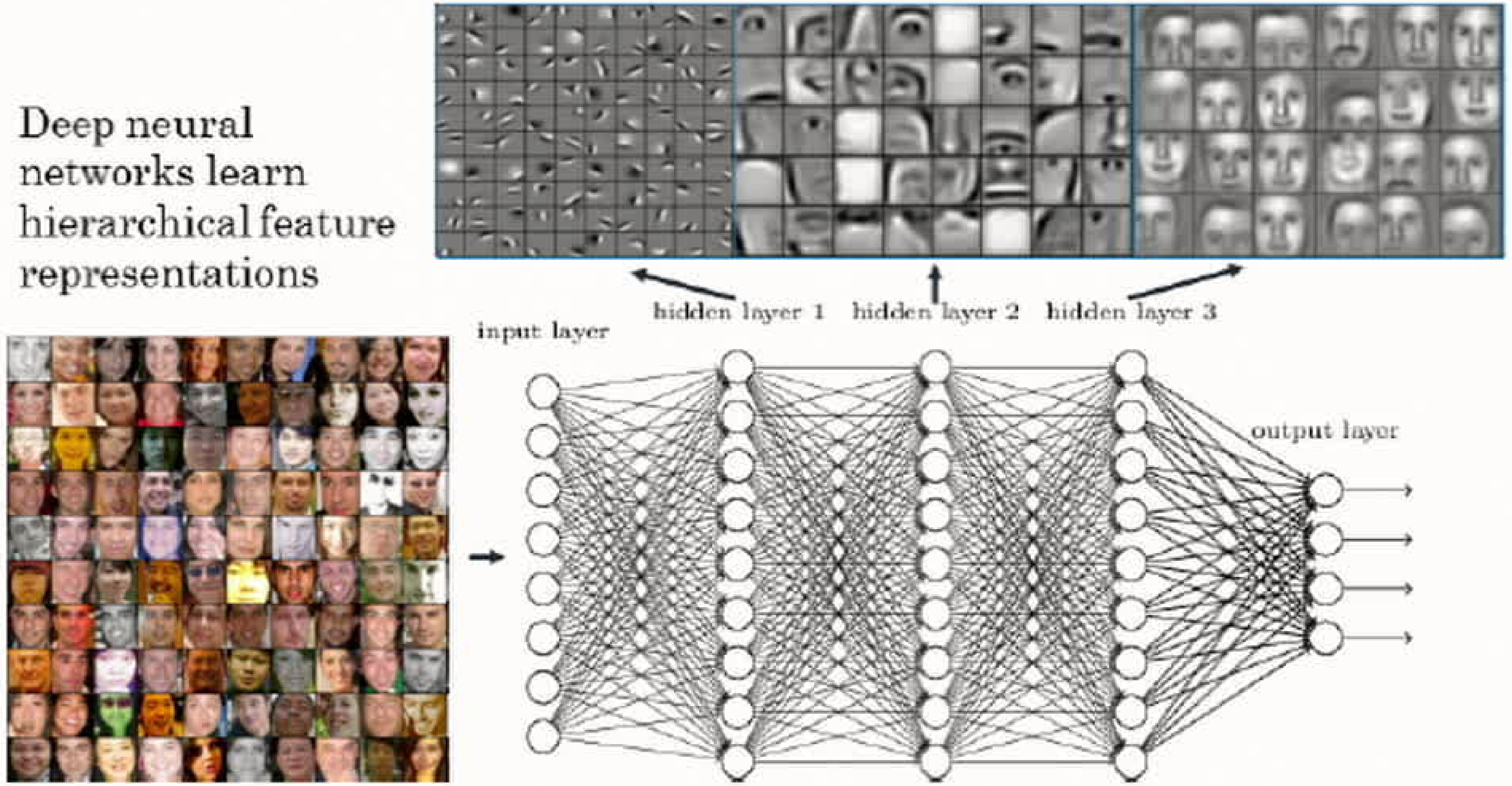

Picture from strong analytics. LeCun, Y., Bengio, Y., & Hinton, G. (2015). Deep learning. Nature, 521(7553), 436-444.

Basic model for deep learning

$$\min_{\Theta} F(u_\Theta^K) \quad \text{s.t.} \quad \begin{aligned} & u^0 \in \mathbb{R}^n \\ & u^1 = \psi(A_\Theta^0 u^0 + b_\Theta^0) \\ & \vdots \\ & u^k = \psi(A_\Theta^{k-1} u^{k-1} + b_\Theta^{k-1}) \\ & \vdots \\ & u_\Theta^K = \psi(A_\Theta^{K-1} u^{K-1} + b_\Theta^{K-1}) \end{aligned}$$

Learning from examples

Deep learning for inverse imaging

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Main existing approaches

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Recent reviews: McCann, Jin, Unser, IEEE Signal Processing Magazine, 34(6), 85-95, '17; Arridge, Maass, Öktem, CBS, Acta Numerica '19

Fully learned model

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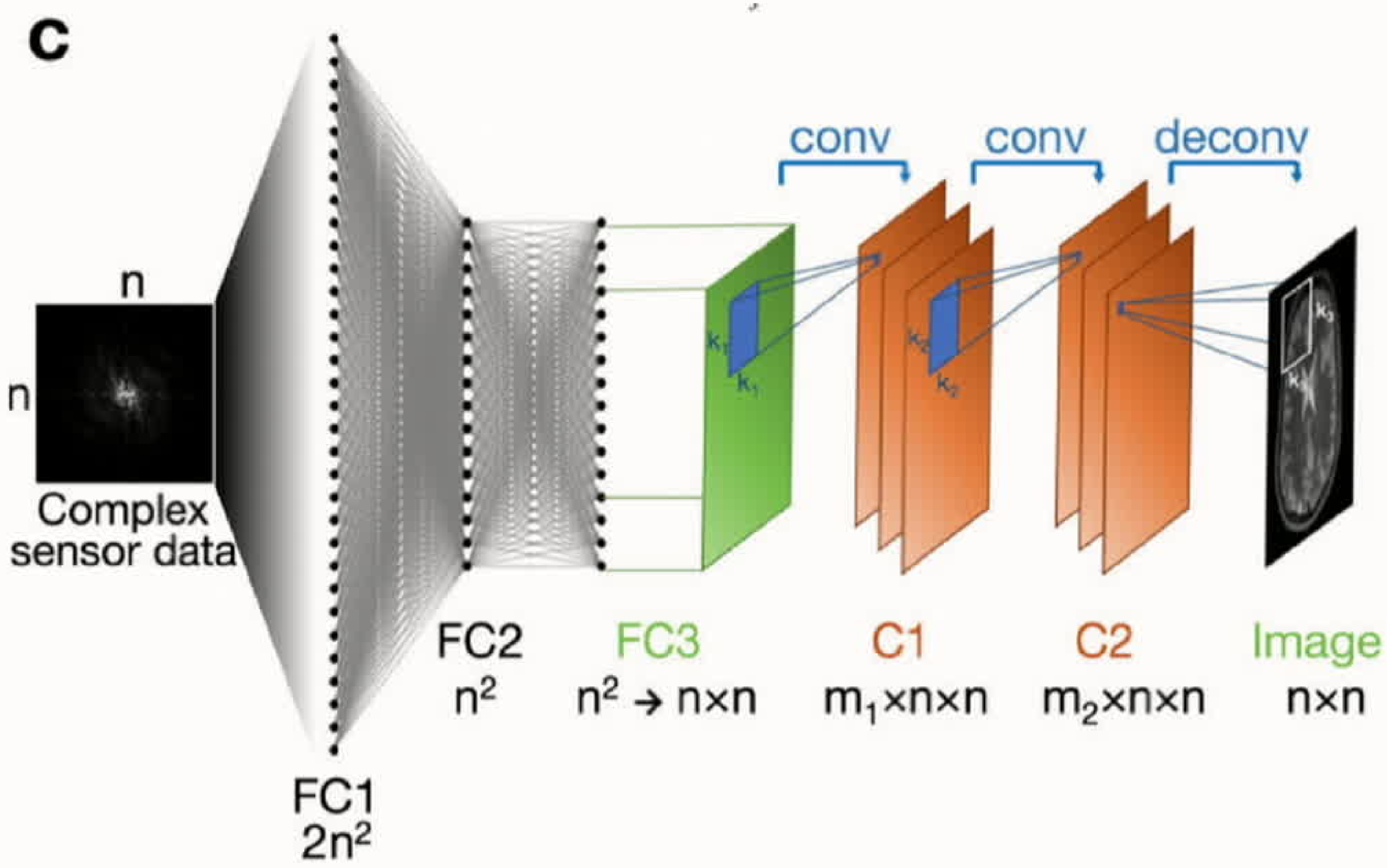

Training with dataset of 50,000 brain images.

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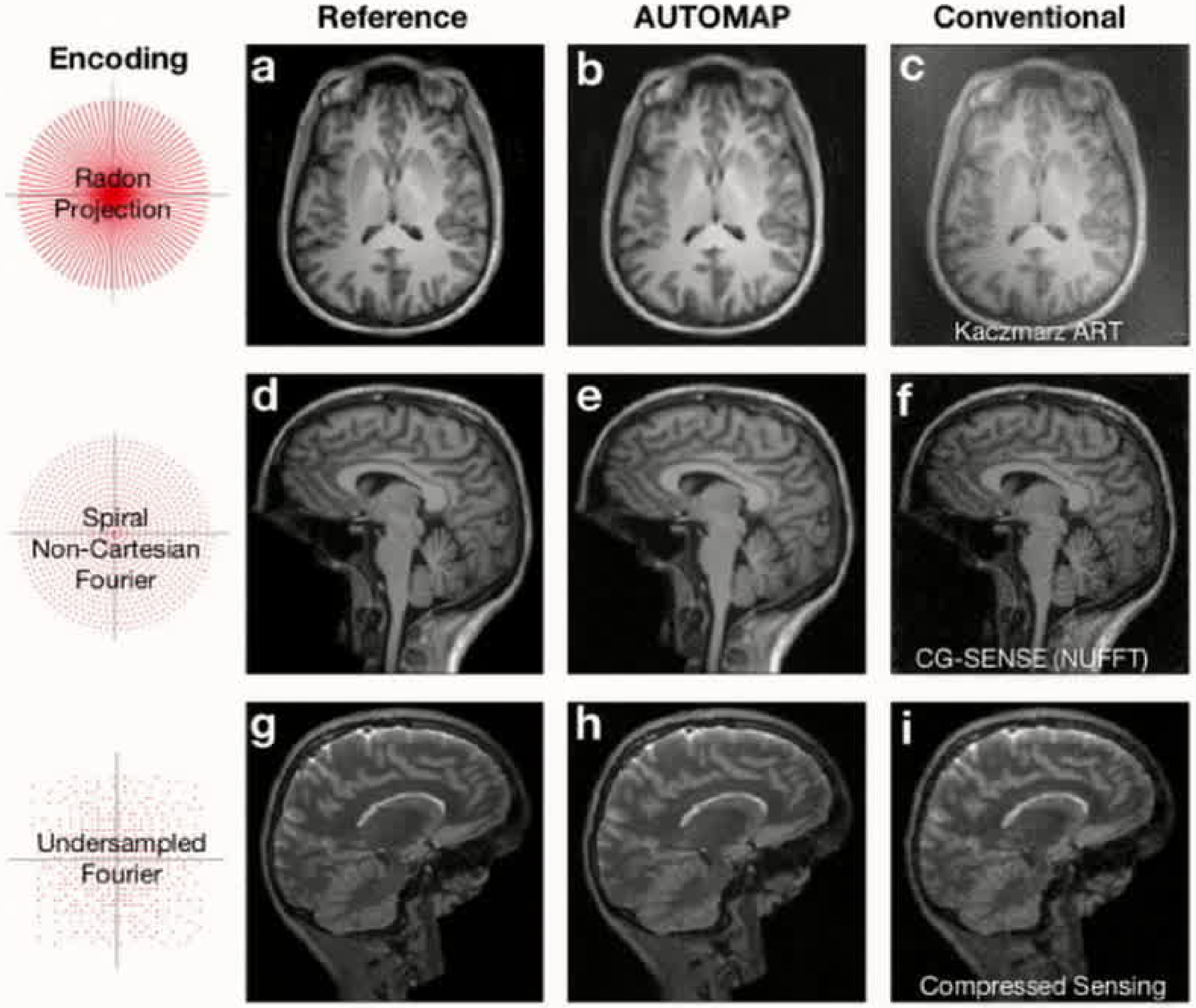

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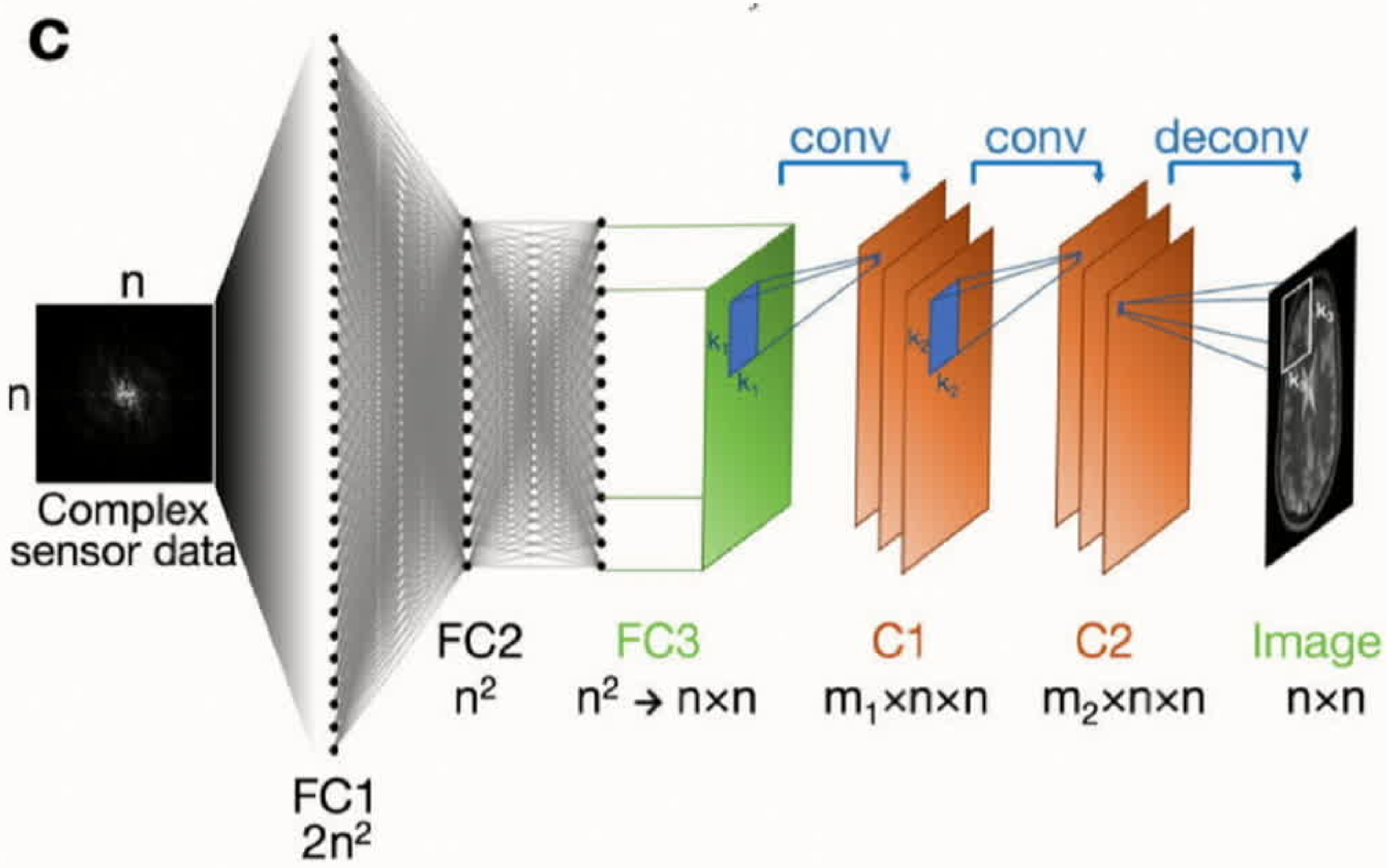

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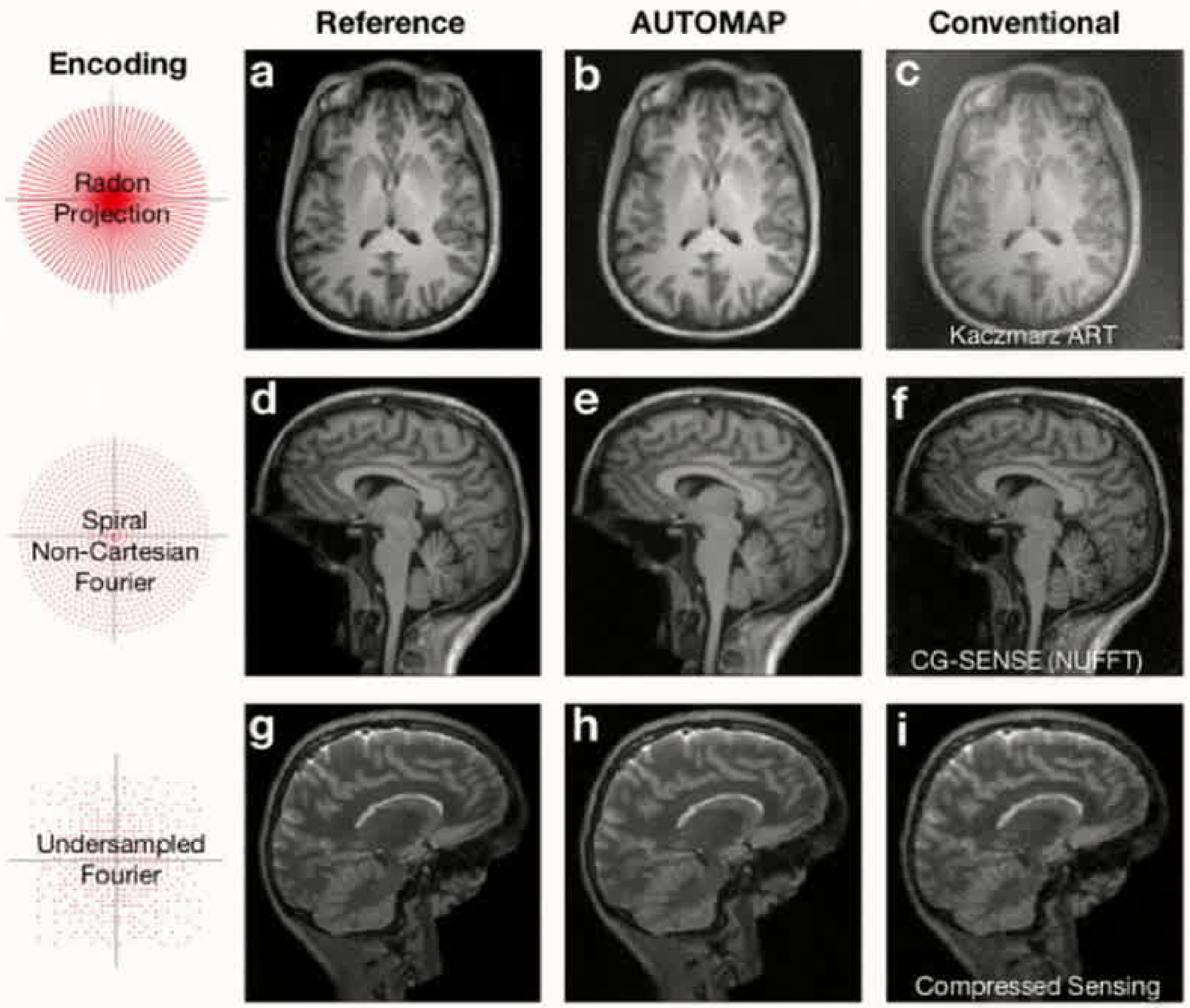

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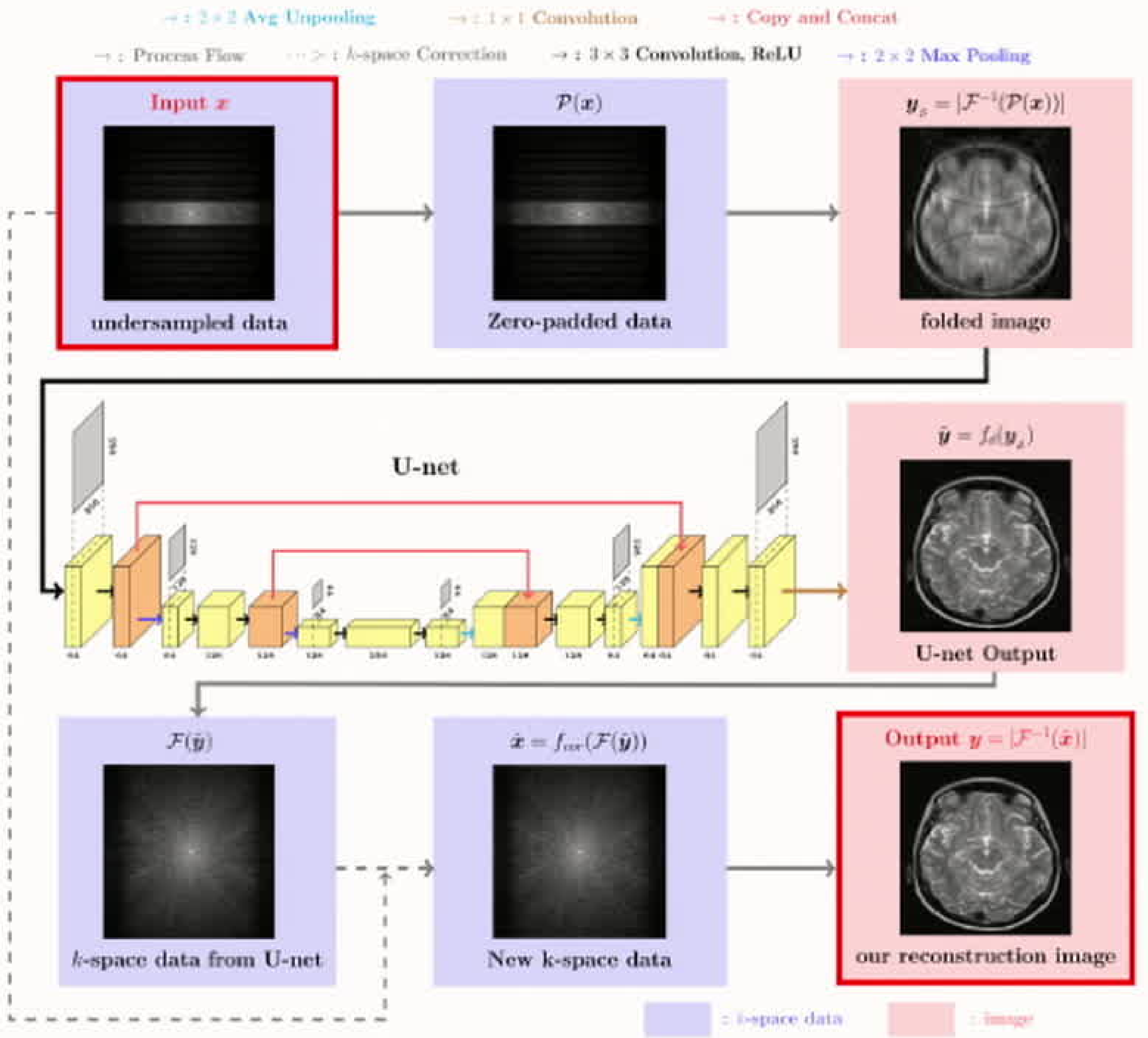

Chang Min Hyun et al 2018 Phys. Med. Biol. 63 135007. From Jin Keun Seo's group.

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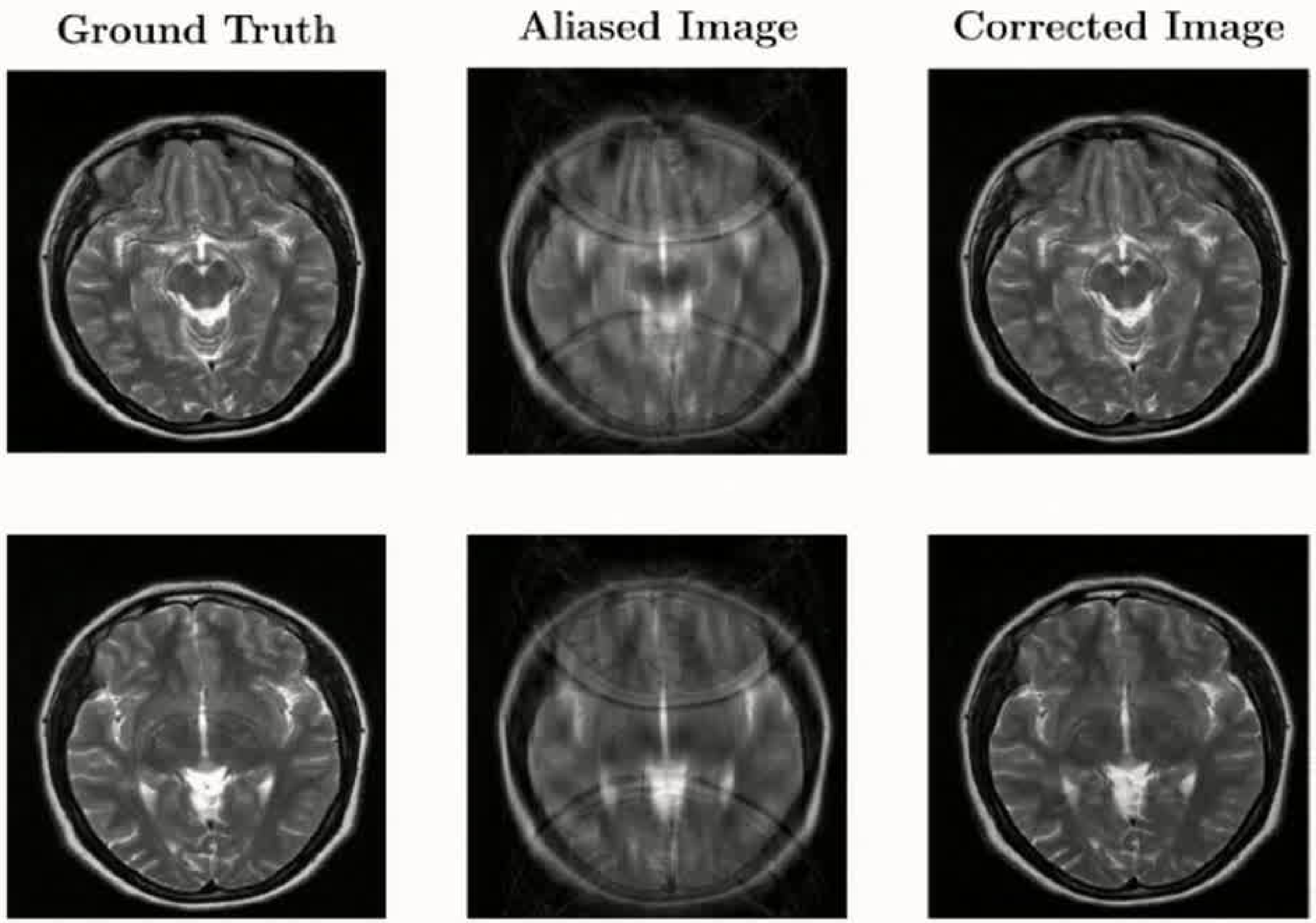

Reconstruction from only 29% of Fourier samples. Trained on 1400 images.

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Learned iterative reconstruction

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Learning to reconstruct

- Variational regularization:
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- Data in $\rightarrow$ reconstruction out

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\end{aligned}
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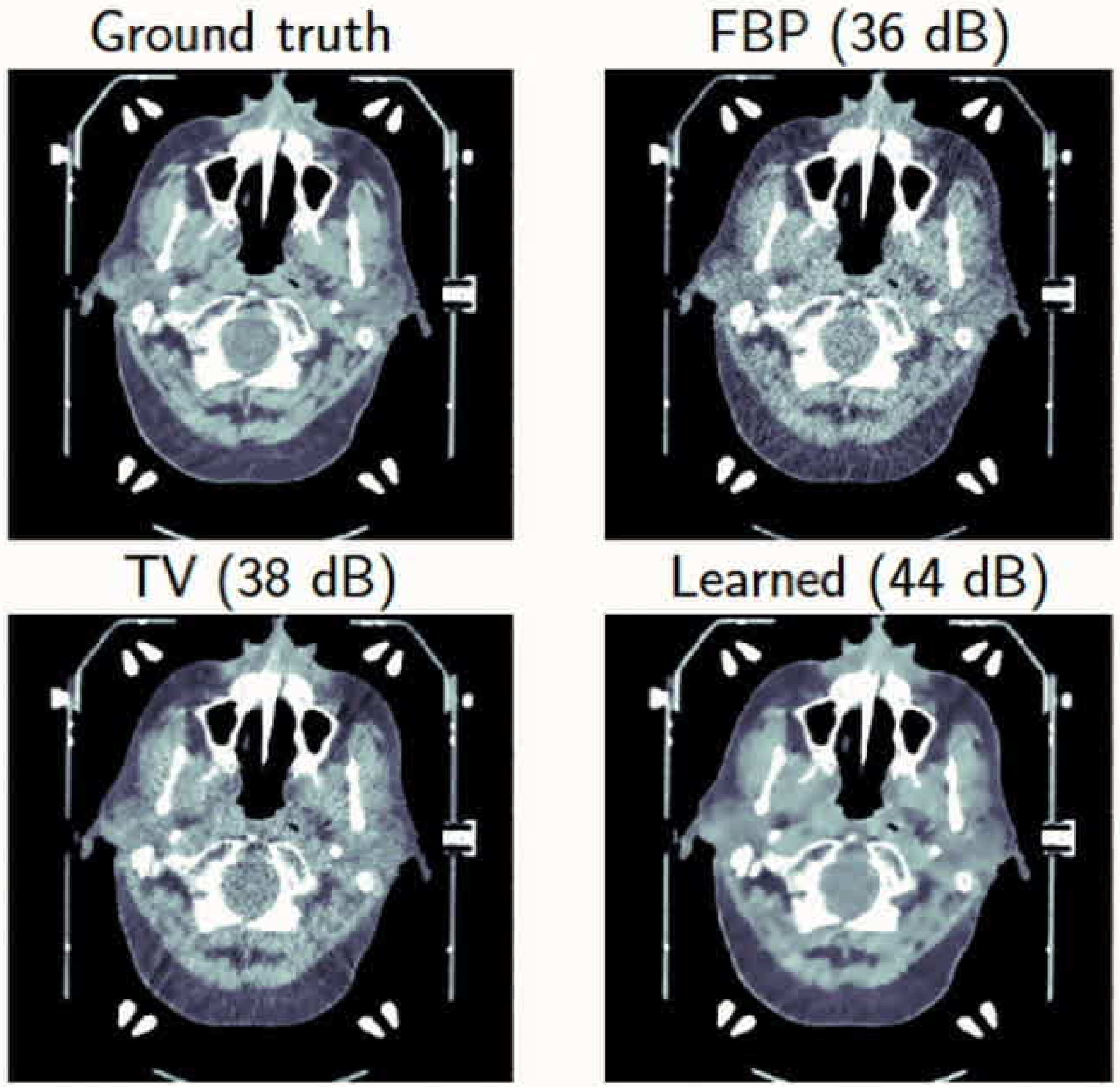

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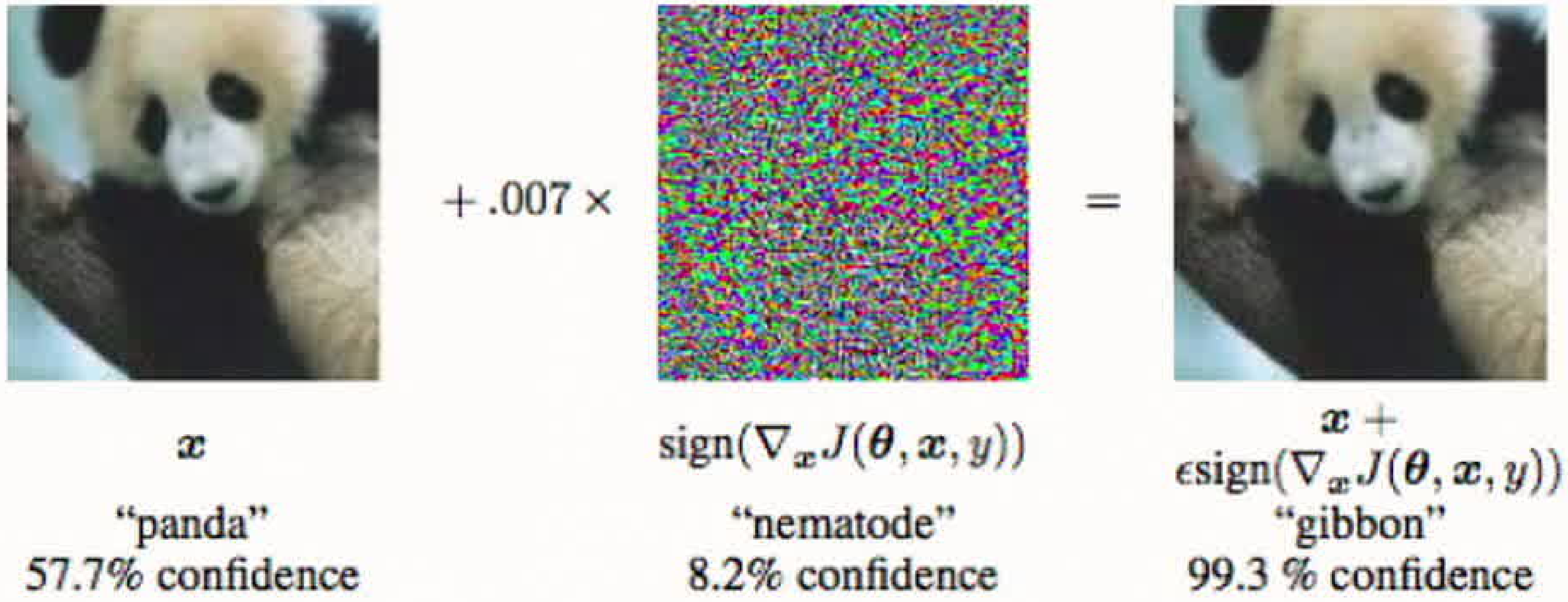
Deep Fool



Perturbed examples - visually indistinguishable but they break network performance.

Goodfellow I, Shlens J, Szegedy C., CoRR 2015; Nguyen A, Yosinski J, Clune J. In Computer Vision and Pattern Recognition (CVPR '15), IEEE, 2015; Szegedy, Zaremba, Sutskever, Bruna, Erhan, Goodfellow, Fergus, arXiv:1312.6199; Antun, Renna, Poon, Adcock, Hansen, arXiv:1902.05300
How to stabilise? Haber, Ruthotto, Inverse Problems '17; Chaudhari, Oberman, Osher, Soatto, Carlier, Research in the Mathematical Sciences, '18

Outline

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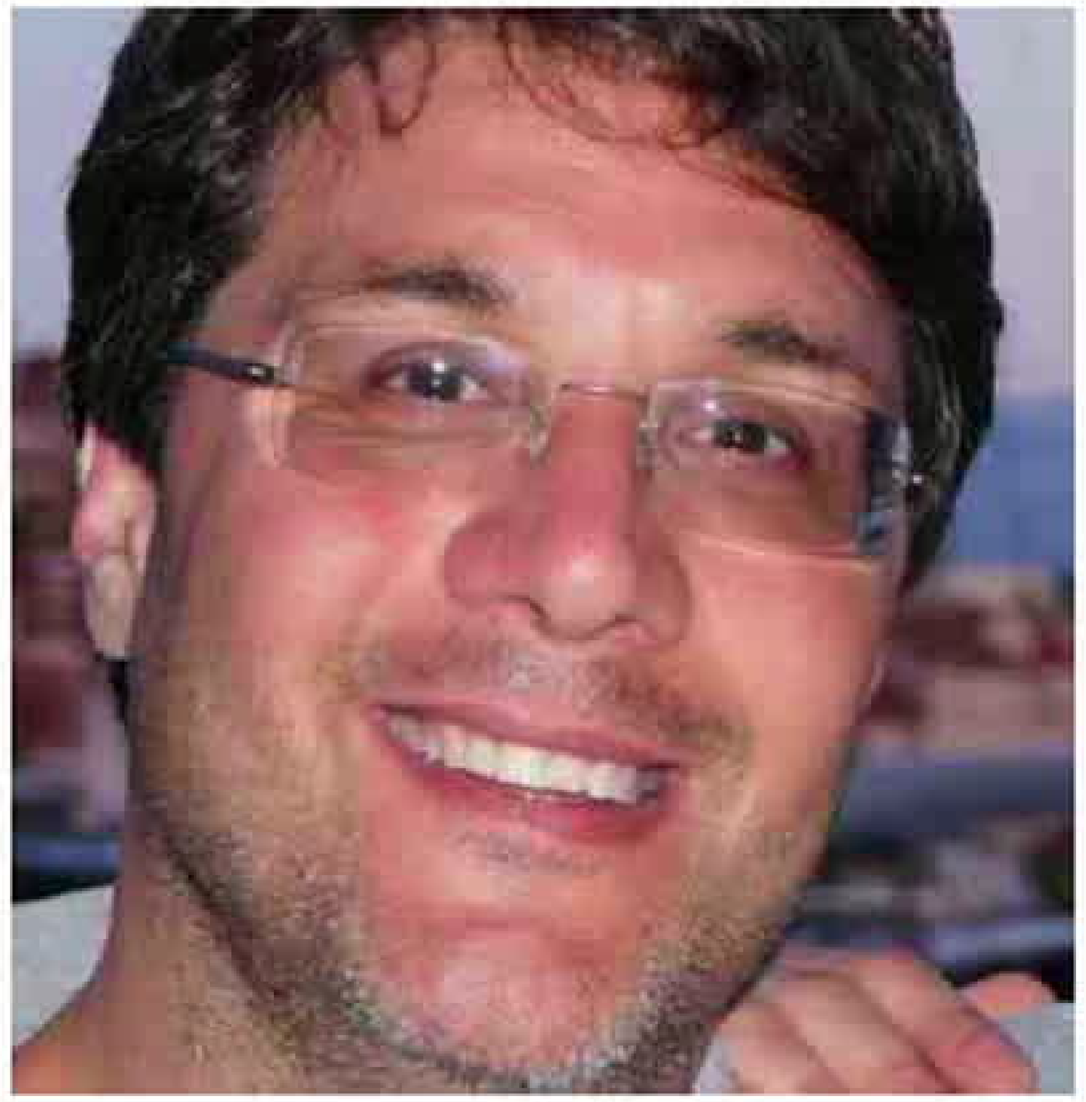
Deep neural networks as regularizers

Joint work with Sebastian Lunz and Ozan Öktem



S. Lunz, O. Öktem, CBS, Adversarial Regularizers in Inverse Problems, in NeurIPS 2018

Conclusion

Philosophy: learning structured but adaptive imaging models with guarantees

See also forthcoming Acta Numerica 2019.

And several minisymposia this week, e.g. **MS35, MS54, MS108, MS109, MS110, MS113, MS133, MS141-143, MS146, . . . , MS266, . . .**

Cambridge Image Analysis

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- Dr Angelica Aviles-Rivero
- Dr Noemie Debroux
- Dr Yury Korolev
- Dr Lukas Lang
- Dr Pan Liu
- Dr Jingwei Liang
- Dr Matt Thorpe
- Thomas Buddenkotte
- Veronica Corona
- Tamara Grossmann
- Sebastian Lunz
- Lisa Kreusser
- Simone Parisotto
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- Rob Tovey
- Jon Williams

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Sponsored by EPSRC, London Mathematical Society, The Leverhulme Trust, Alan Turing Institute, Horizon2020, and The Royal Society.

Wanted: image processing researcher

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Researcher for project *Scalable image enhancement for light-sheet microscopy: space varying deconvolution and image fusion*. Collaboration between CAIC, CIA, LMB, SLCU.

Limit of tenure is 2 years. Start date: June 2019
More details: `http://www.jobs.cam.ac.uk/job/20474/` or email `cbs31@cam.ac.uk`

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Email: cbs31@cam.ac.uk

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Variational regularisation

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Consider the inverse problem associated to operator $T : X \to Y$, X and Y Banach spaces

$$y = Tx + n$$

Variational regularisation model under Gaussian white noise model is given by

$$\arg\min_x \|Tx - y\|_2^2 + \lambda R(x)$$

Aim: parametrise regulariser and optimise it over appropriate 'data'.

Engl, Hanke, Neubauer '96; Natterer, Wübbeling '01; Kaltenbacher, Neubauer, Scherzer '08; Schuster, Kaltenbacher, Hofmann, Kazimierski '12

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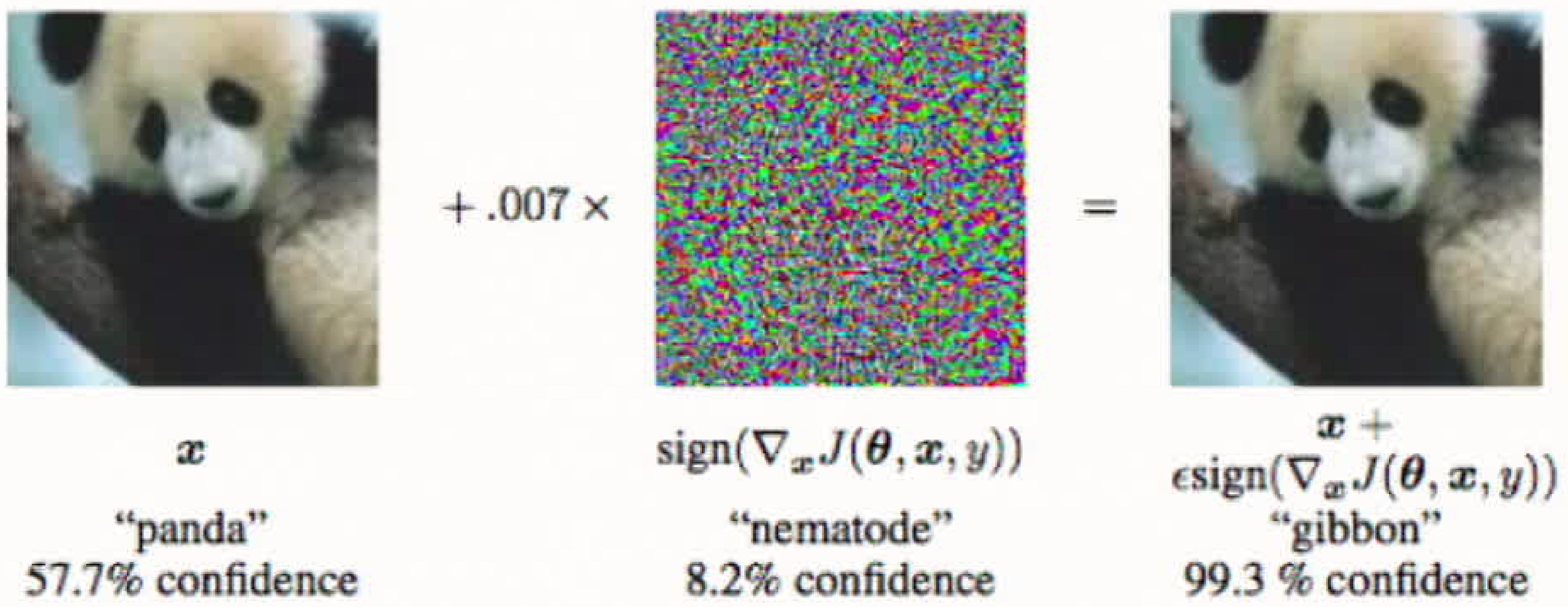

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Learned iterative reconstruction

Learning to reconstruct

- Variational regularization: Iterative schemes
- Learned operators
- Data in $\rightarrow$ reconstruction out

Algorithm 1 Learned Gradient

1: **for** $i = 1, \ldots$ **do**
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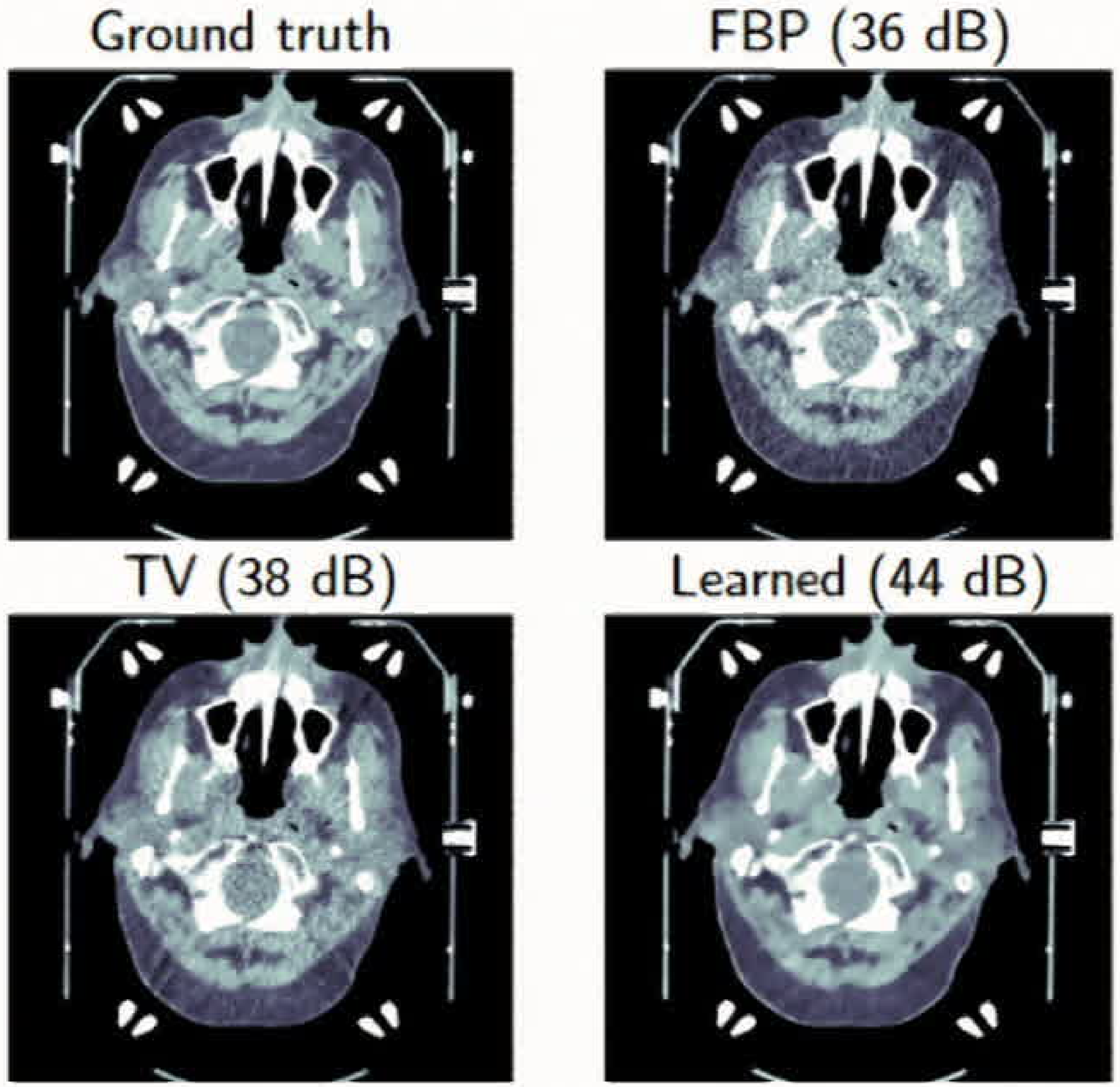

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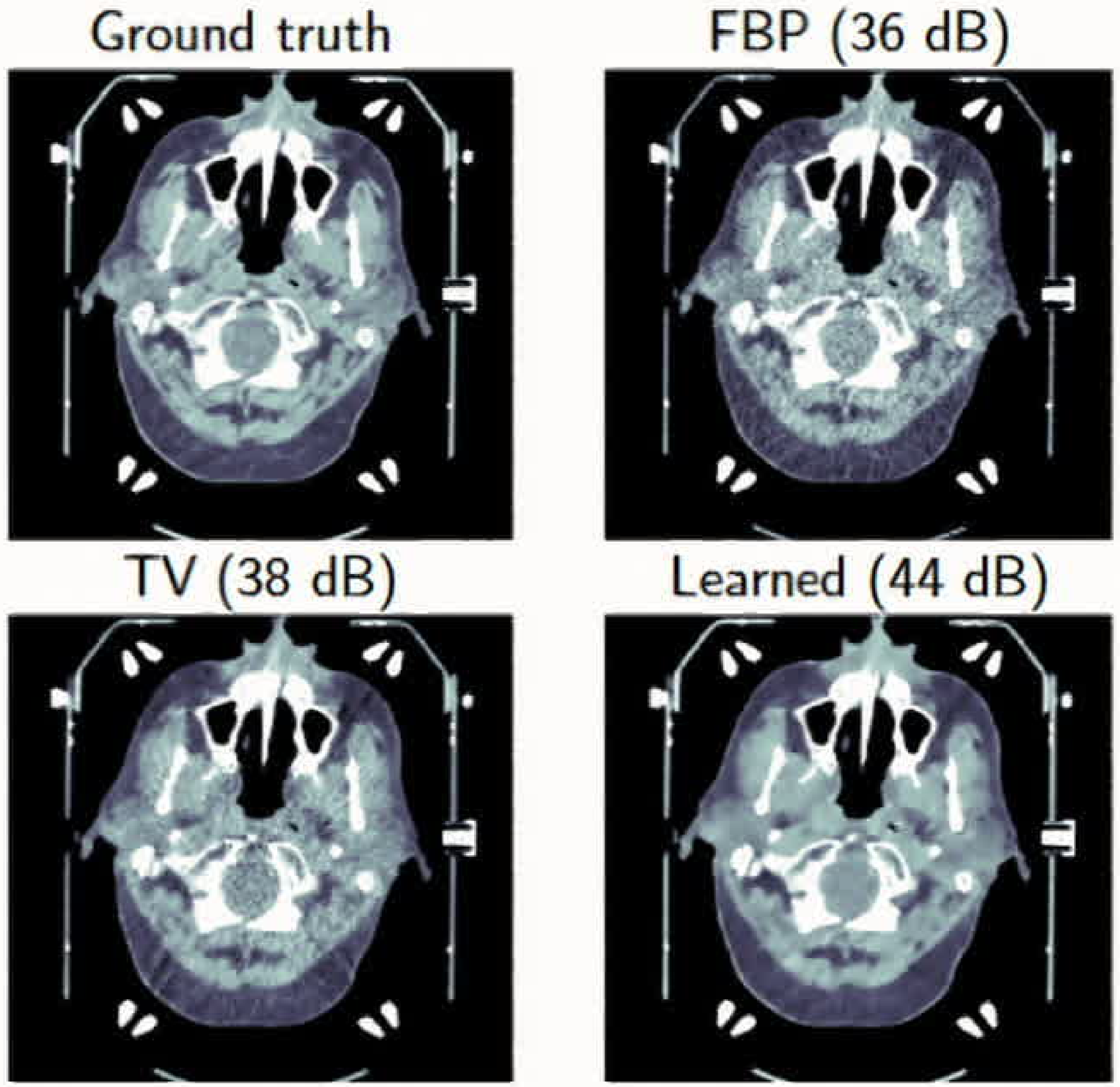

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Learned post processing

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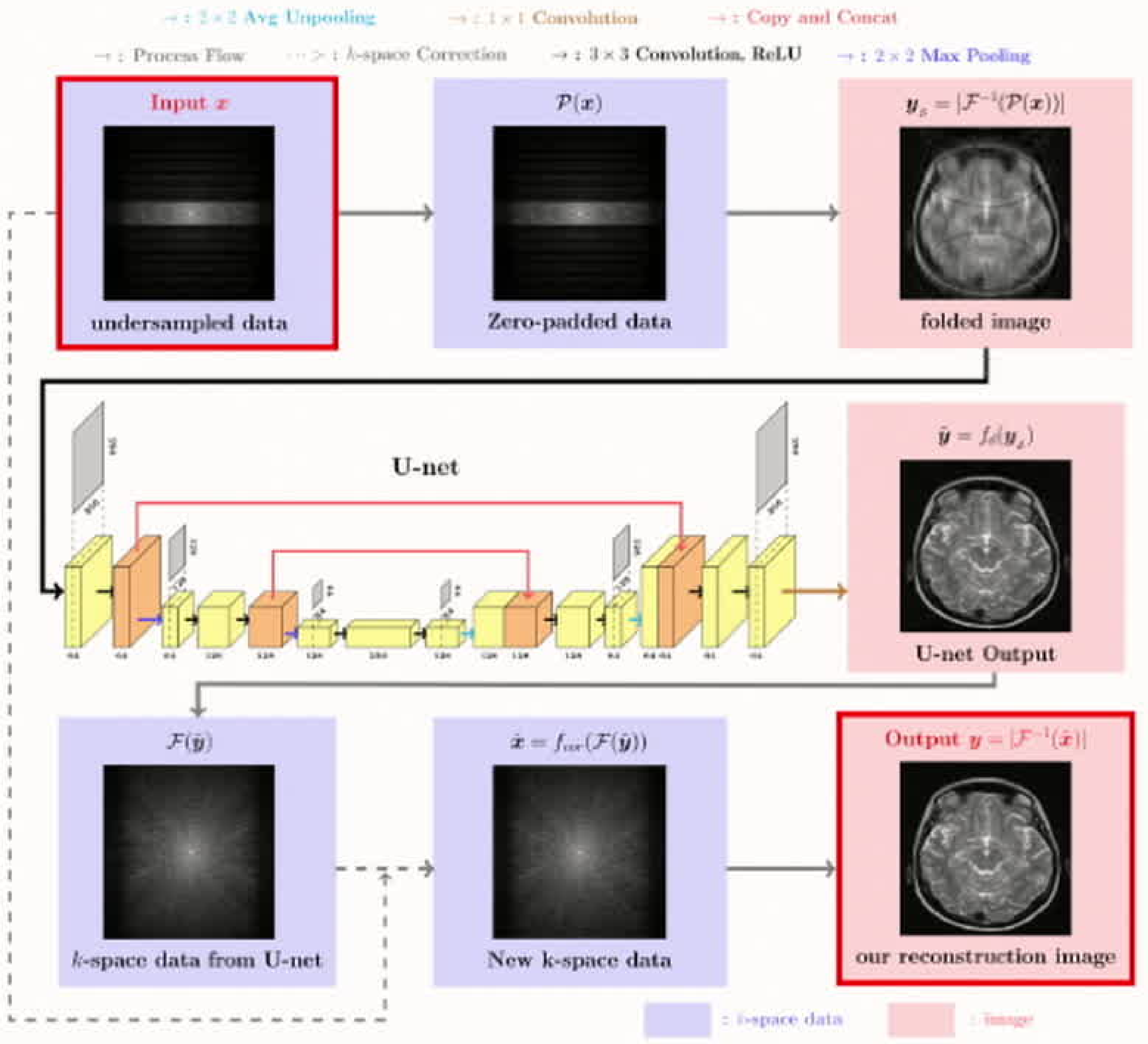

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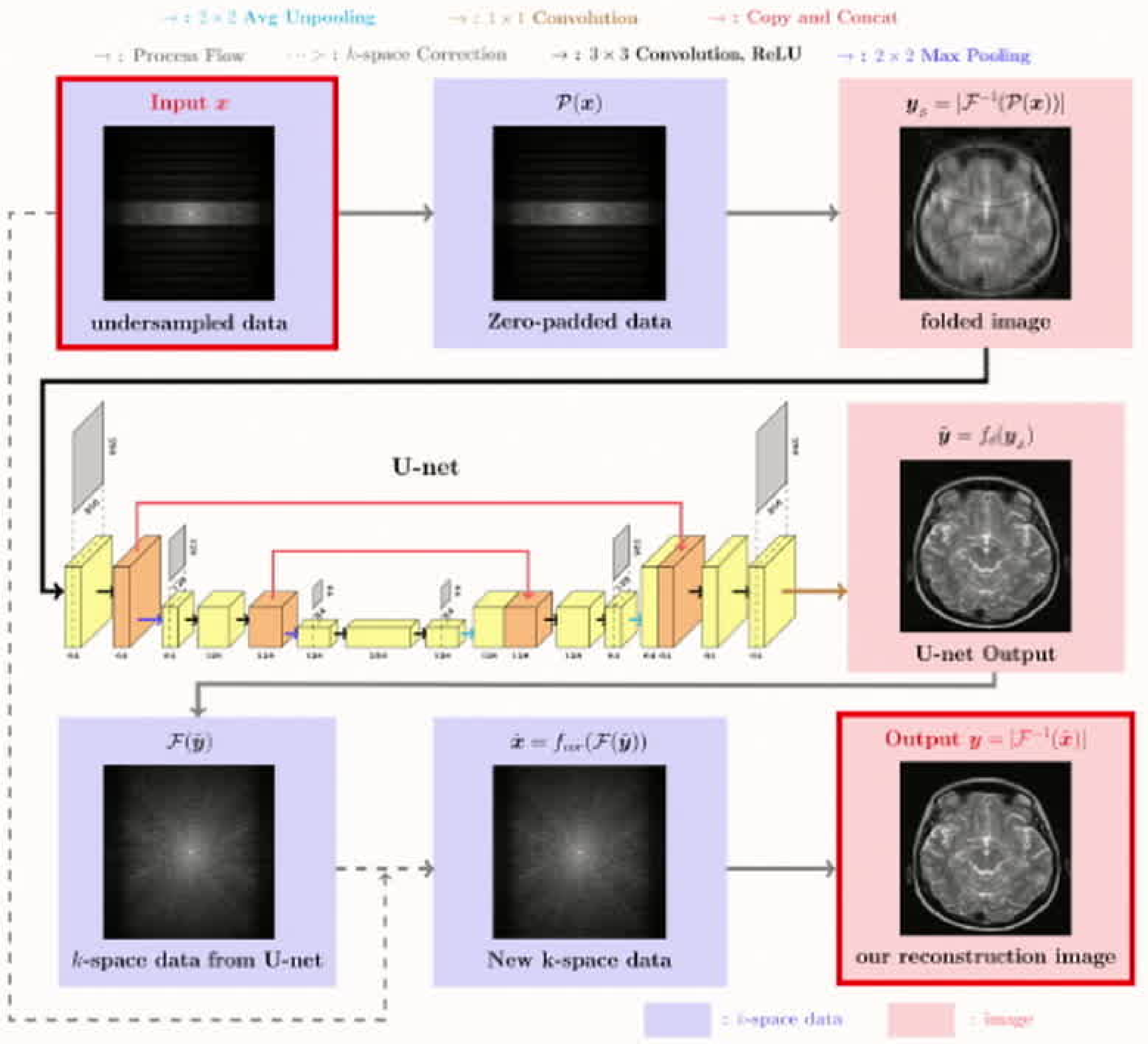

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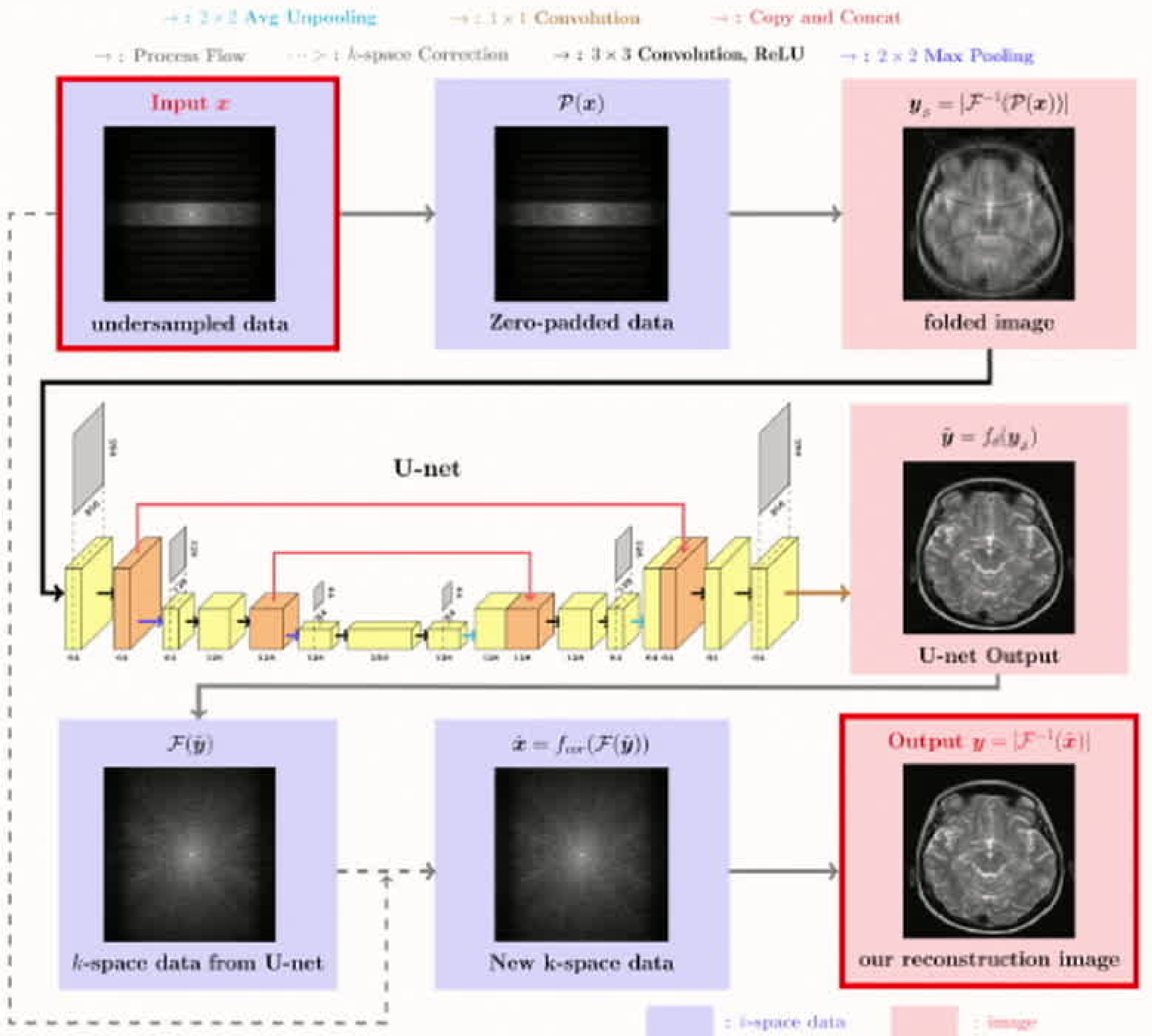

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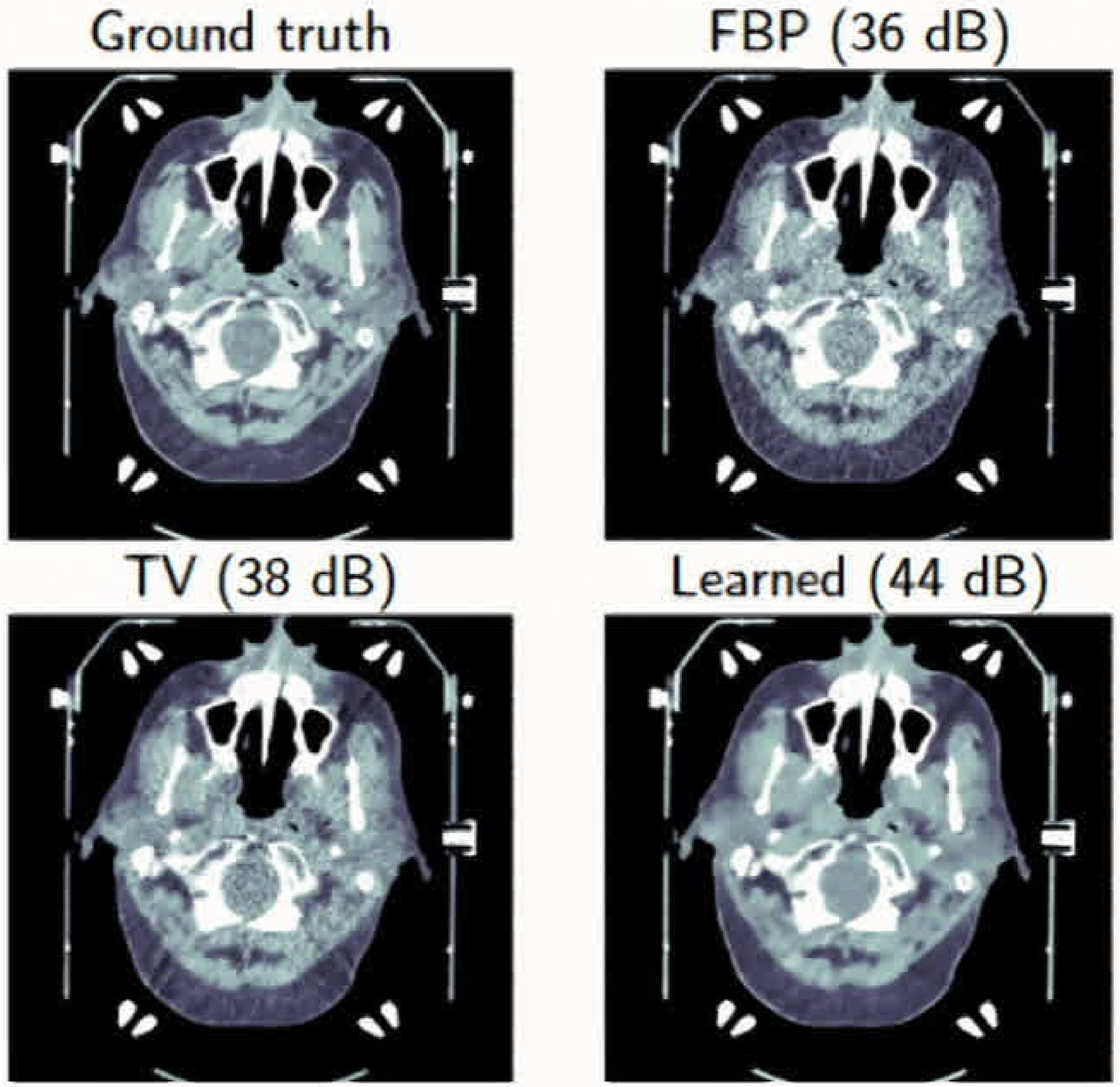

J. Adler and O. Öktem, *Solving ill-posed inverse problems using iterative deep neural networks*, Inverse Problems '17. See also M. Unser et al. 2017; Hammernick et al. 2018; J. Adler, S. Lunz, O. Verdier, CBS, O. Öktem 2018

Deep learning for inverse imaging

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Main existing approaches

- Fully Learned Models Zhu, Bo, Liu, Cauley, Rosen, Rosen, Nature '18.
- Learned Post Processing Jin, McCann, Froustey, Unser, IEEE Transactions on Image Processing, '17; Kang, Min, Ye, Medical Physics '17.
- Learned Iterative Schemes Yang, Sun, Li, Xu, In Advances in Neural Information Processing Systems '16; Meinhardt, Moeller Hazirbas, Cremers, ICCV '17; Putzky, Welling, ArXiv 1706.04008; Adler, Öktem, Inverse Problems '17; Adler, Öktem, IEEE transactions on medical imaging '18; Hammernik, Klatzer, Kobler, Recht, Sodickson, Pock, Knoll; Magnetic resonance in medicine, '18; Adler, Lunz, Verdier, CBS, Öktem, In NIPS 2018 meets medical imaging, ArXiv 1809.00948; Hauptmann, Lucka, Betcke, Huynh, Adler, Cox, Beard, Ourselin, Arridge, IEEE Transactions on Medical Imaging, 2019.
- Learning the regulariser Li, Schwab, Antholzer, Haltmeier, '18; Lunz, Öktem, CBS, NeurIPS '18; Ye, Ravishankar, Long, Fessler, IEEE Transactions on Medical Imaging '18.

Recent reviews: McCann, Jin, Unser, IEEE Signal Processing Magazine, 34(6), 85-95, '17; Arridge, Maass, Öktem, CBS, Acta Numerica '19

Outline

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1. Knowledge-driven inversion
2. Data-driven inversion
3. Deeply learned inversion
   - Learning a regularizer

CT reconstruction on LIDC data

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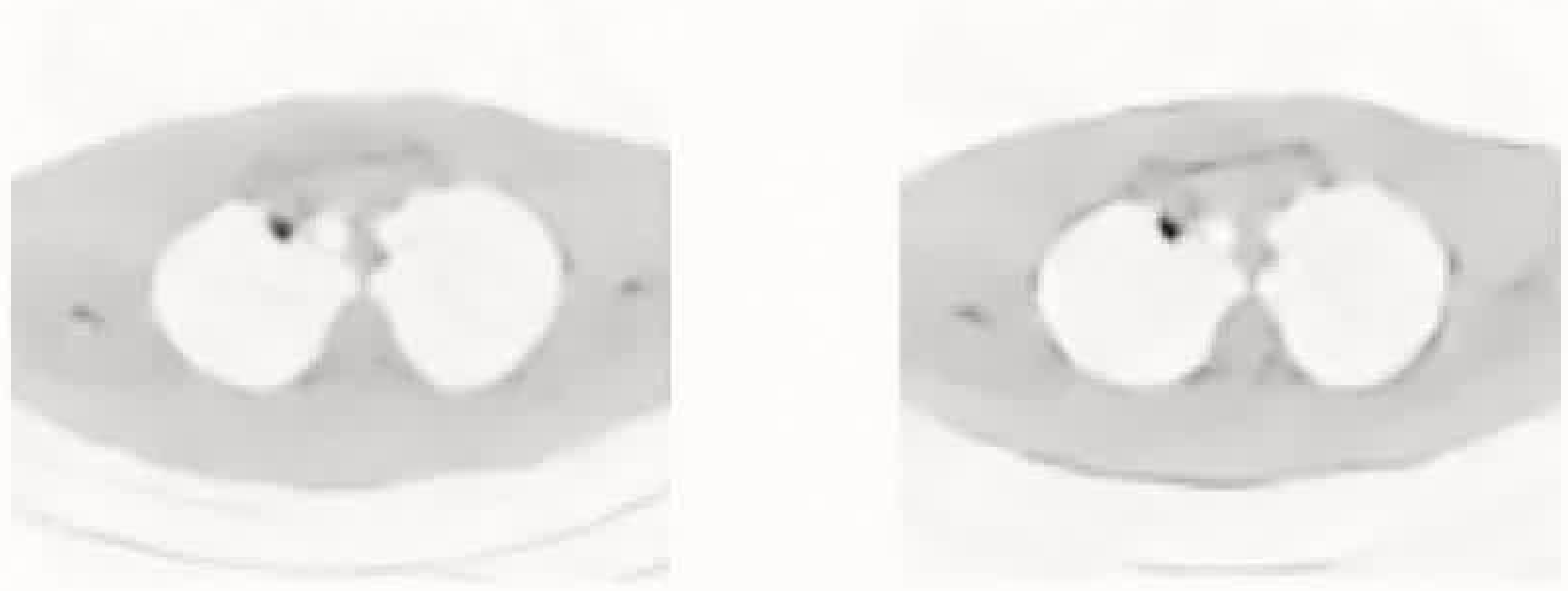

(a) Post-Processing (b) Adversarial Reg.

Figure: Reconstruction from simulated CT measurements on LIDC