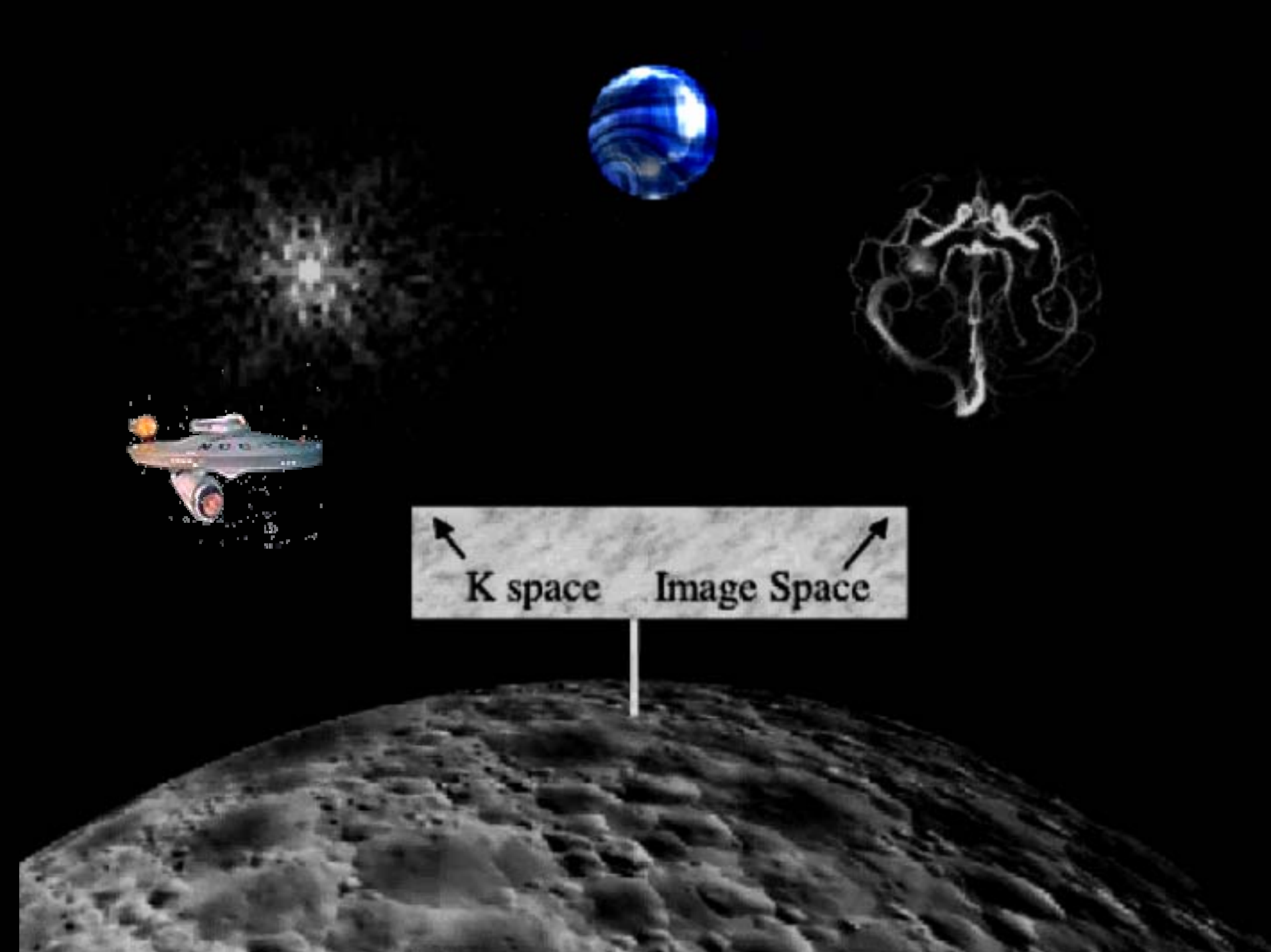
Fast 4D Imaging
Breaking the Speed Limits in MR and CT

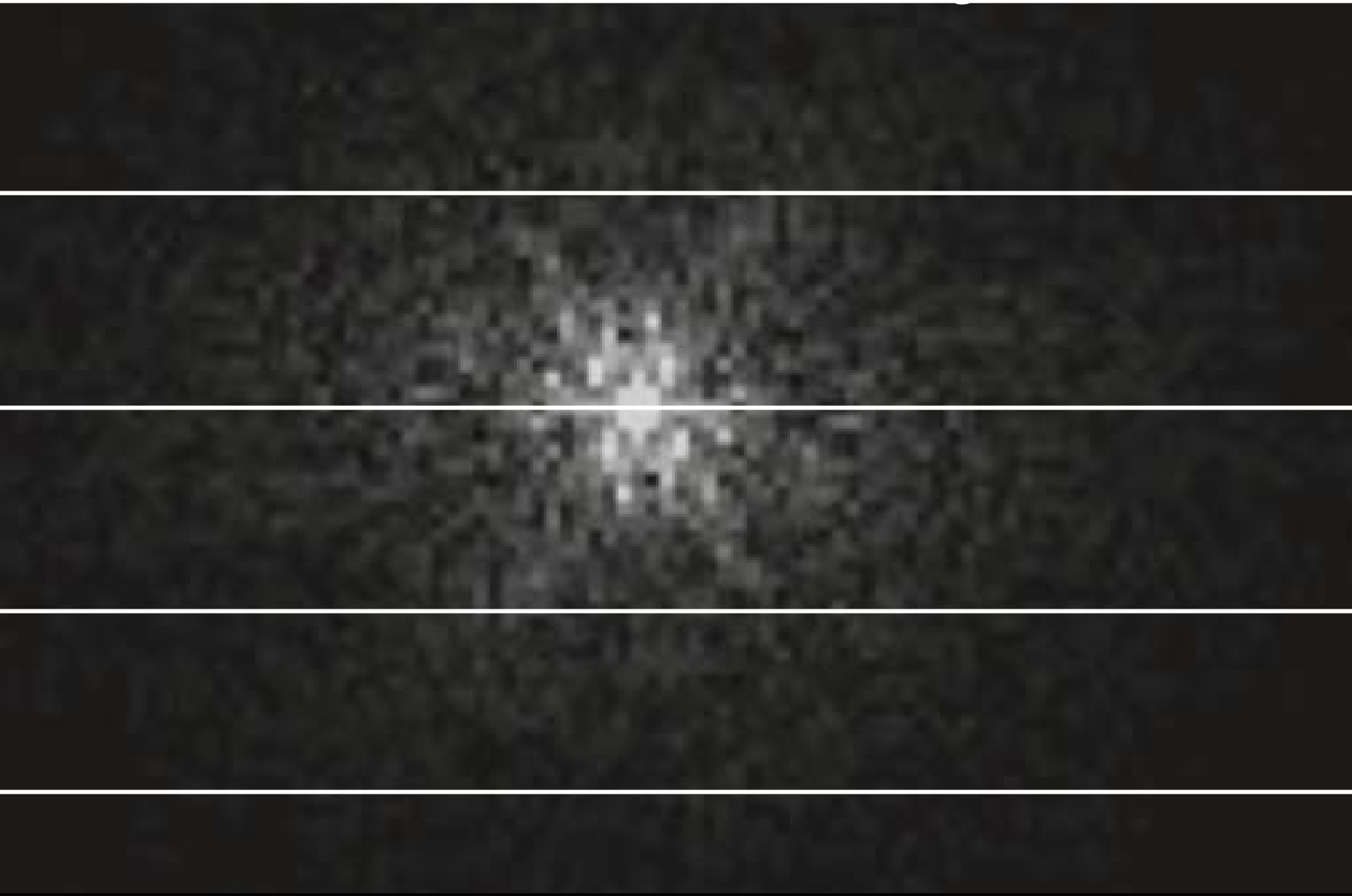
Chuck Mistretta

Departments of Medical Physics, Radiology
And Biomedical Engineering

The University of Wisconsin, Madison


K space
Image Space

Cartesian Phase Encoding



Limitations of Cartesian Acquisitions

For Cartesian acquisition the Nyquist Theorem demands n^3 Fourier samples for an n^3 image matrix.

This imposes a k-space speed limit that dictates that spatial resolution is directly proportional to imaging time.

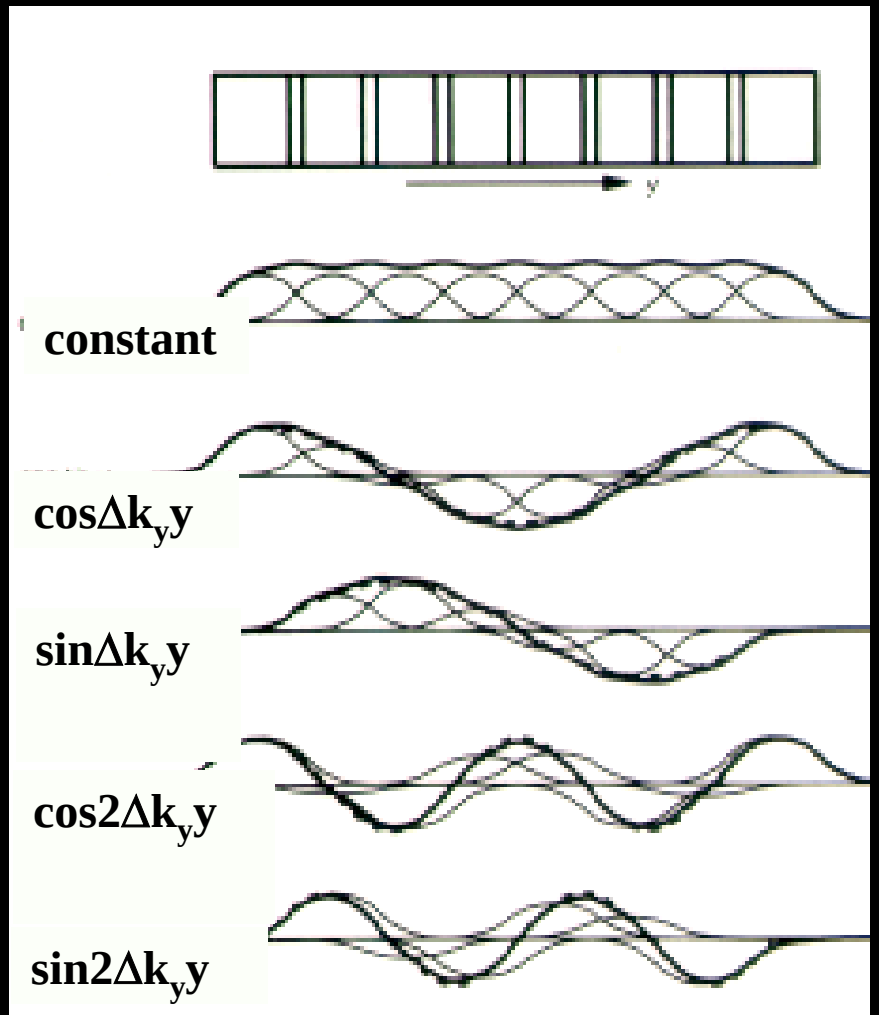
Methods for Breaking The k-space Speed Limit

Parallel Imaging
SMASH
SENSE

Undersampled Projection Imaging

SMASH

SiMultaneous Acquisition of Spatial Harmonics

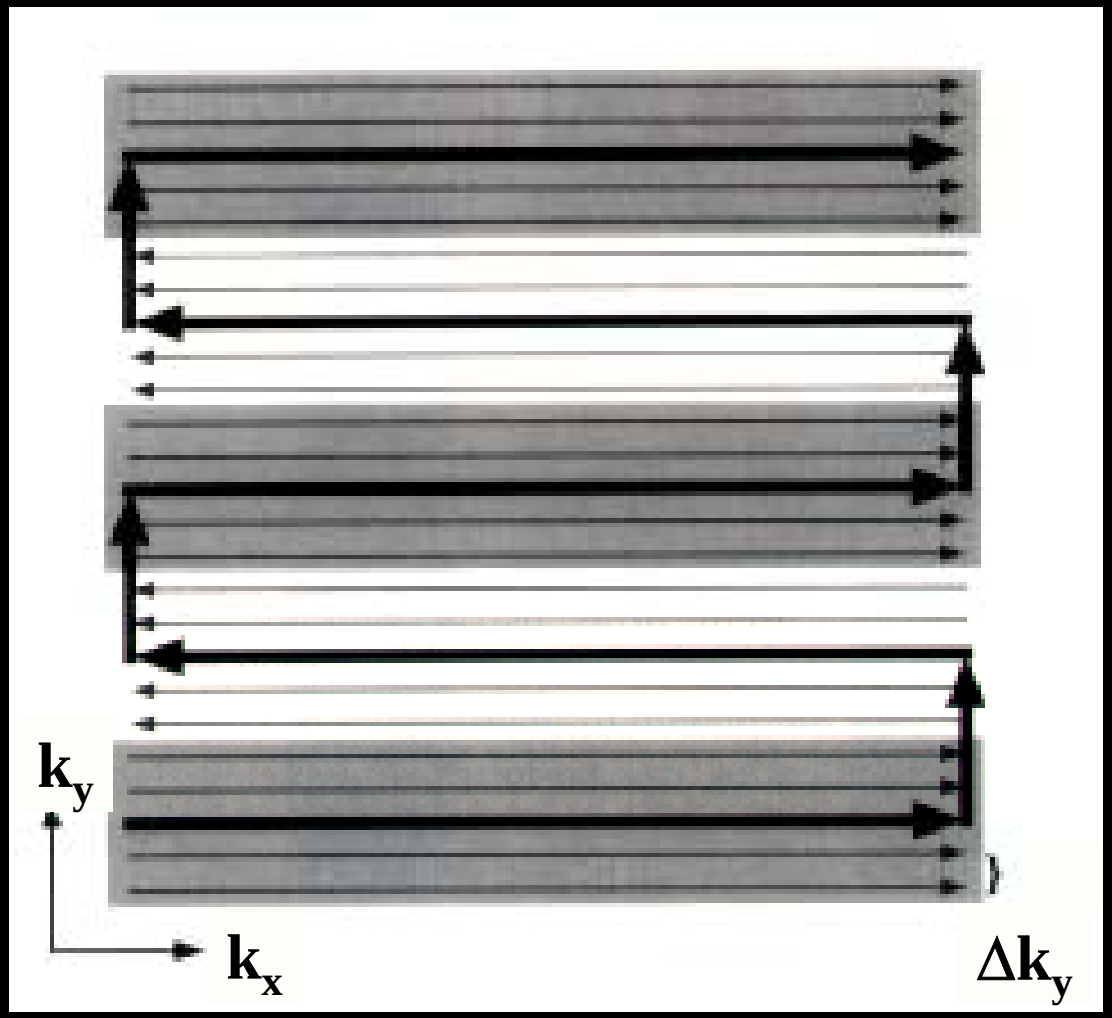


Multiple Coils

Synthesized spatial modulations

Sodickson and Manning
MRM 38:585-590 (1997)

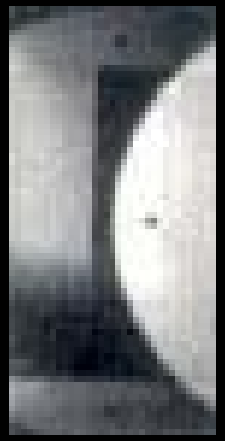
Skipping k-space lines



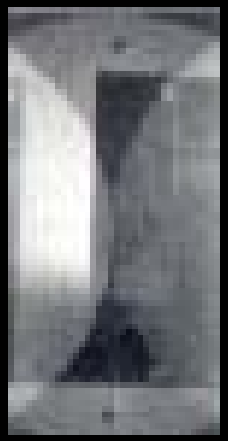
SMASH
Sodickson and Manning
MRM 38:585-590 (1997)

Image Synthesis

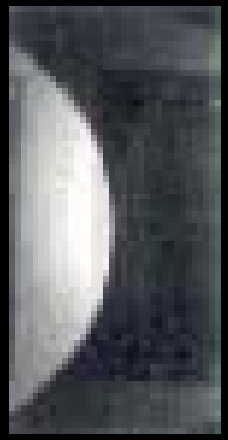
Coil 1



Coil 2



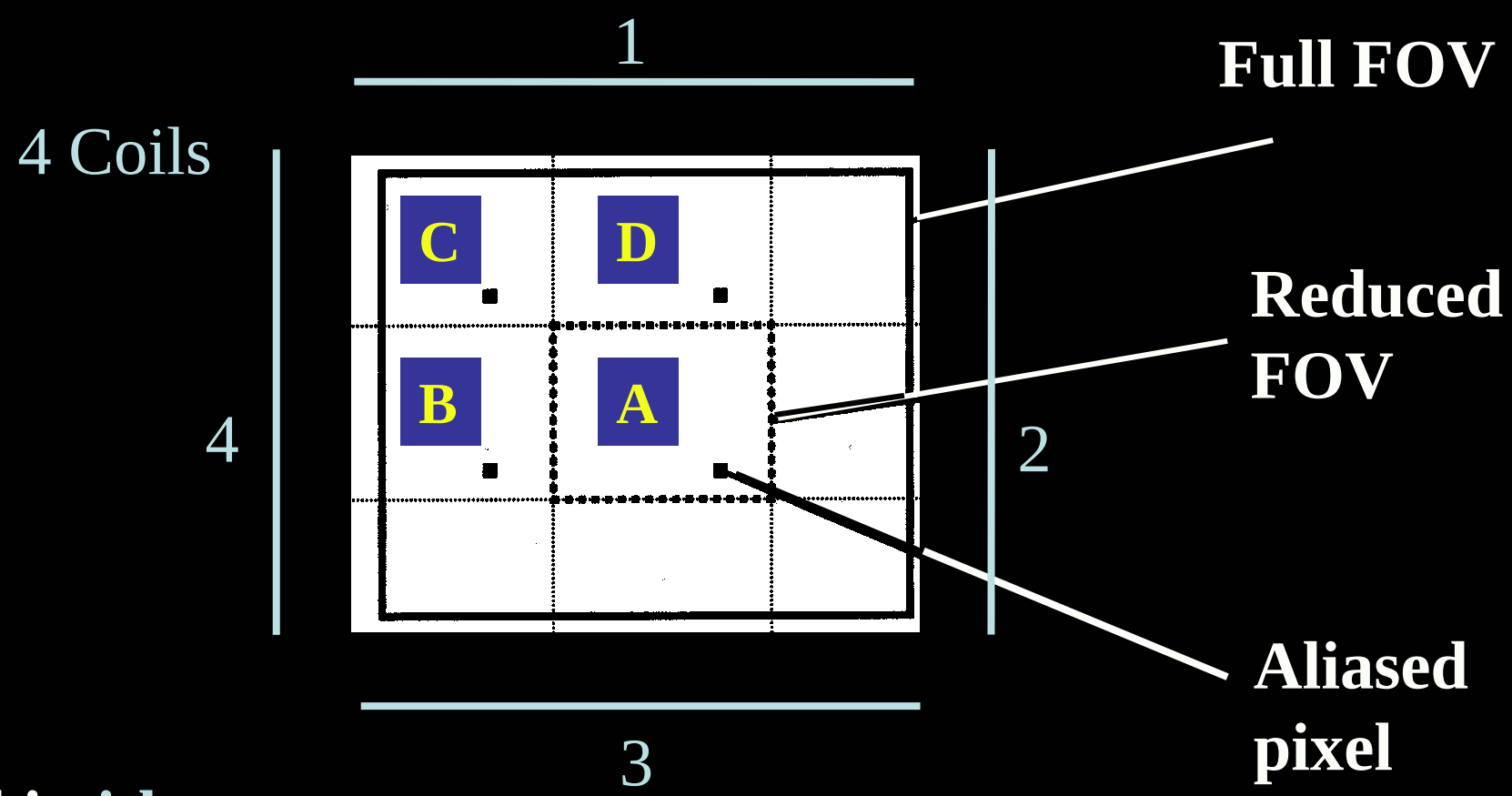
Coil 3



Synthesized Image

SMASH
Sodickson and Manning
MRM 38:585-590 (1997)

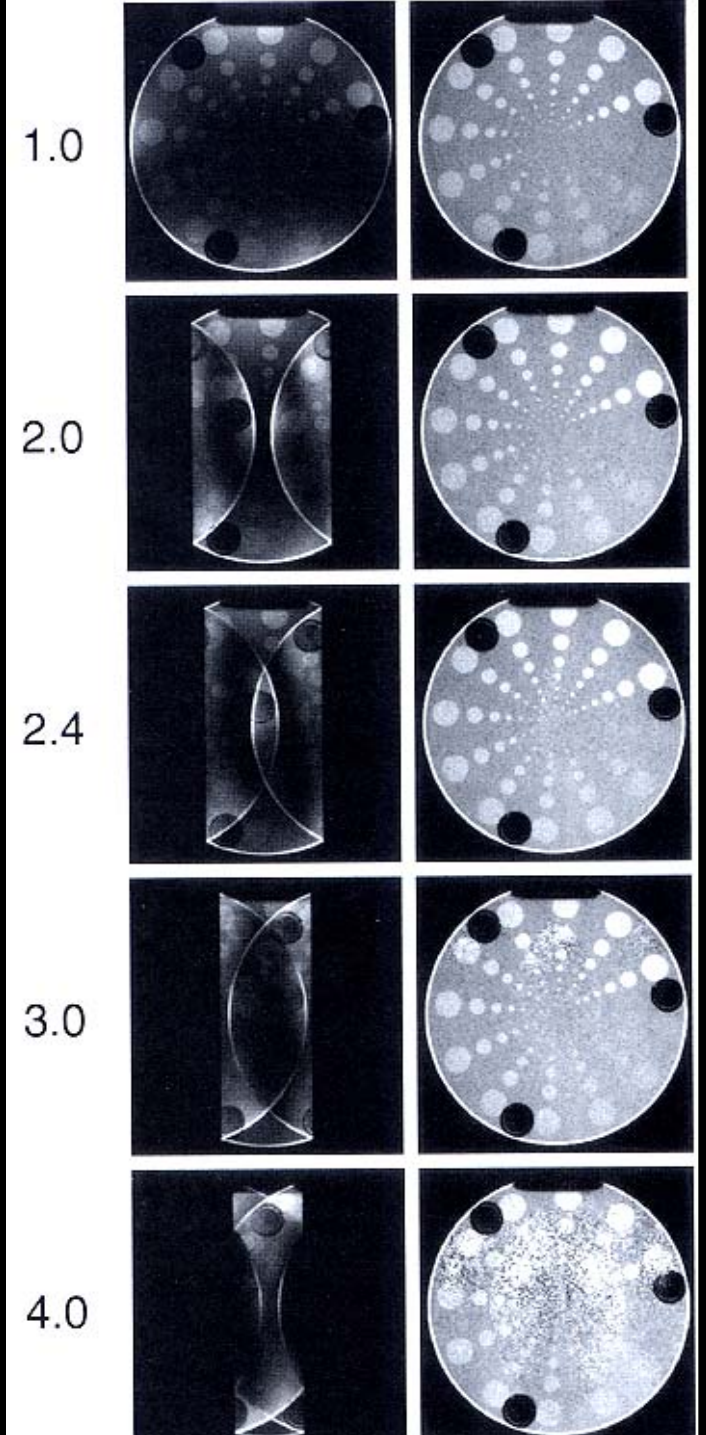
SENSitivity Encoding (SENSE)



Pixel in ith reduced FOV image from overlapping pixels j

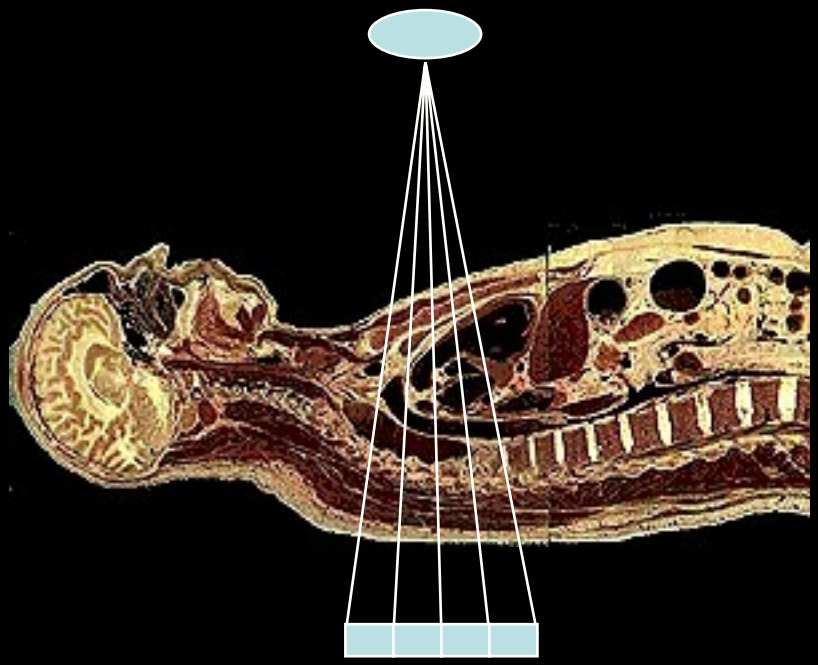
$$P_i = \Sigma\, S_{ij} \bullet P_j$$

SENSE Images



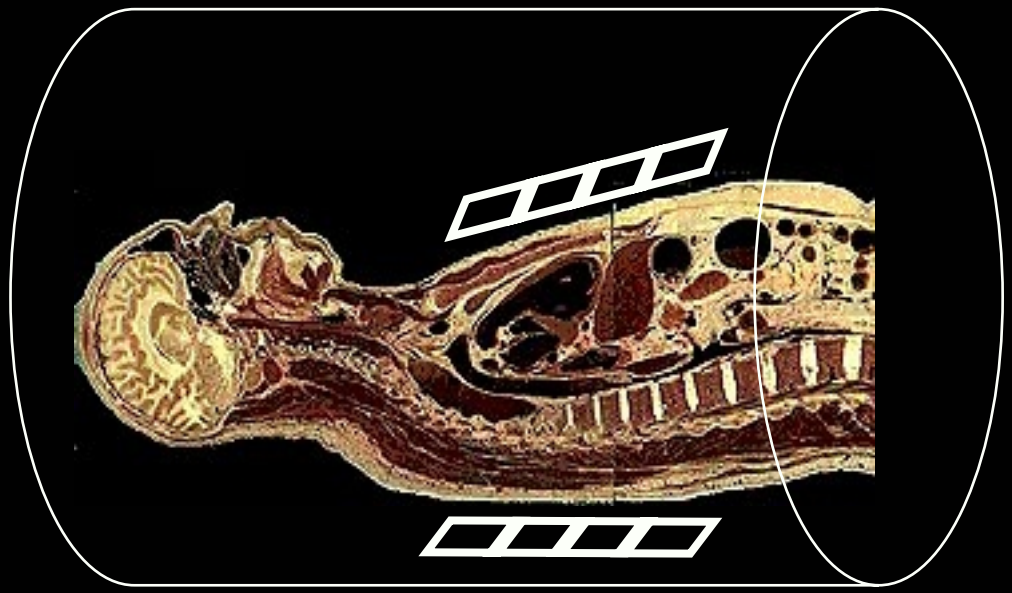
Pruessmann et al.
MRM 42:952-962(1999)

Parallel MRI and Multidetector CT



CT

Multiple image slices at once

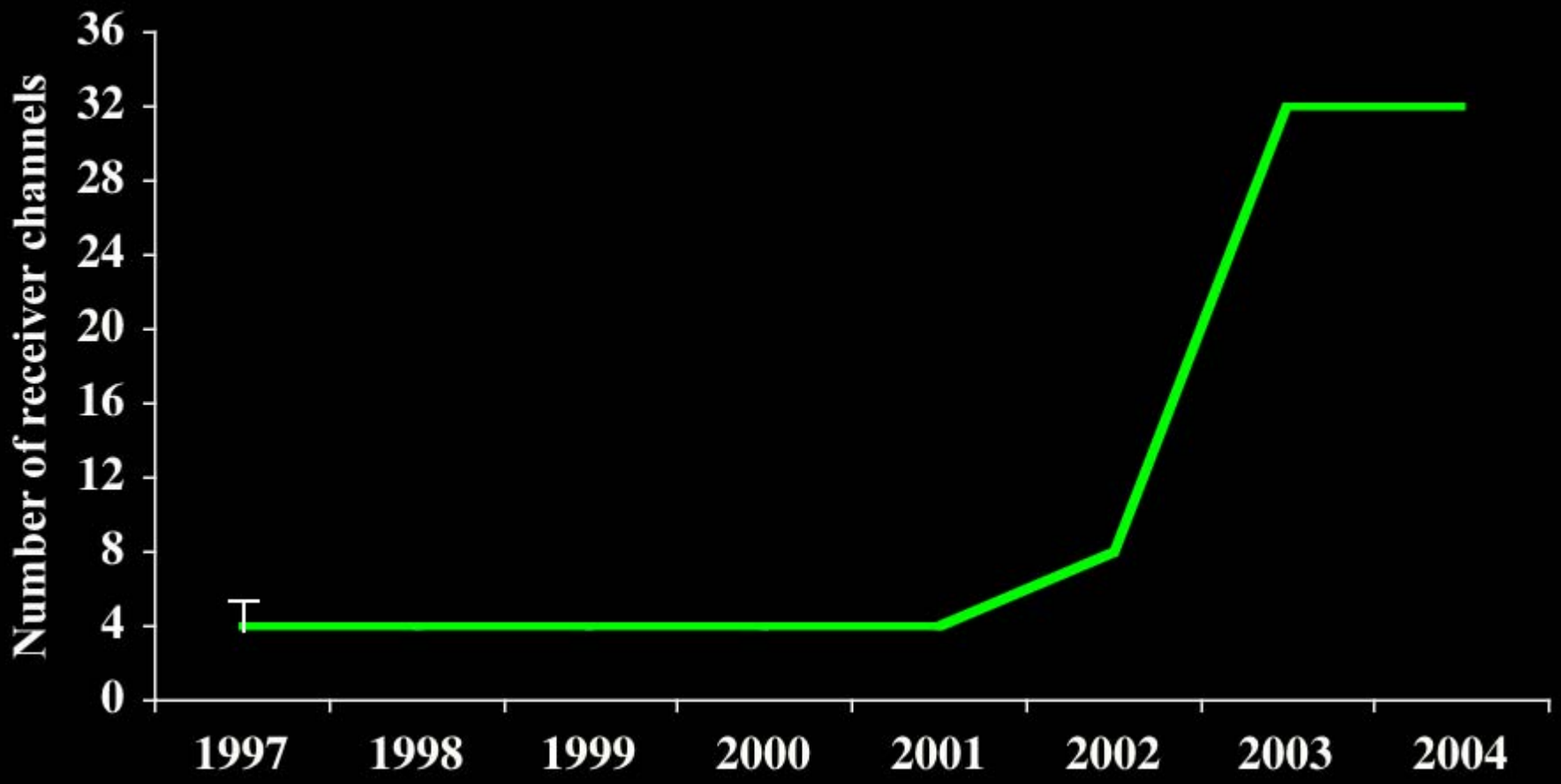


MRI

Multiple k-space “slices” at once

DK Sodickson, MD, PhD

Commercially available receiver channels over time

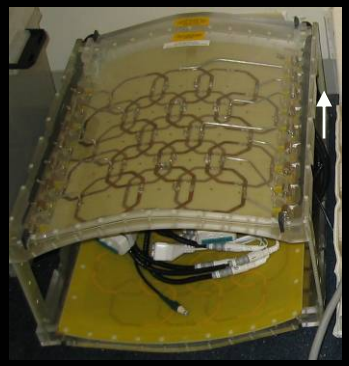


DK Sodickson, MD, PhD

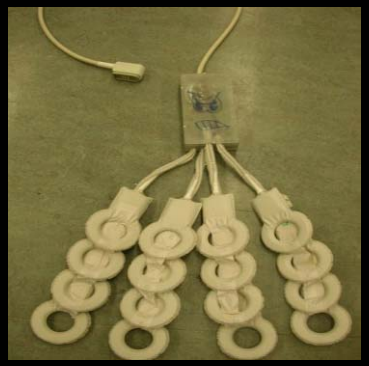
32-element coil arrays: body, cardiac, head…

Zhu et al, MRM 2004; 52: 869

90 element arrays are in the works!
Larry Wald, Graham Wiggins
Massachusetts General Hospital, Boston, MA, USA
ISMRM 2005 #671

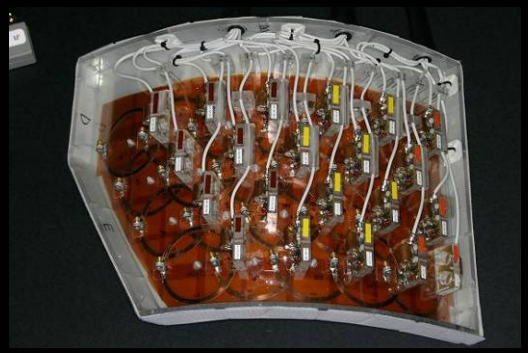


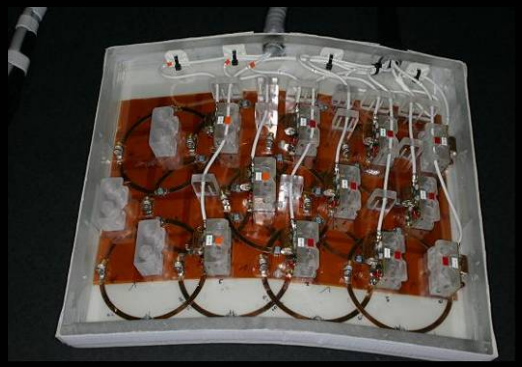
Hardy et al,
MRM 2004; 52:878



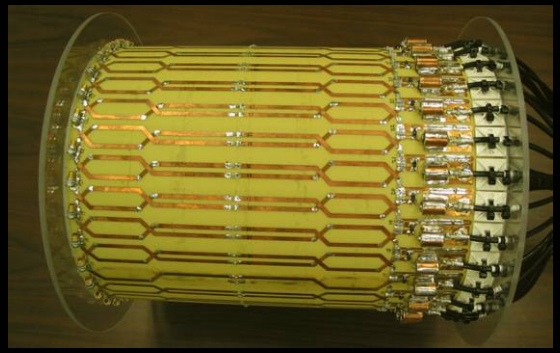
Possanzini et al,
ISMRM 2004, 1609

Spencer et al,
ISMRM 2005, 911

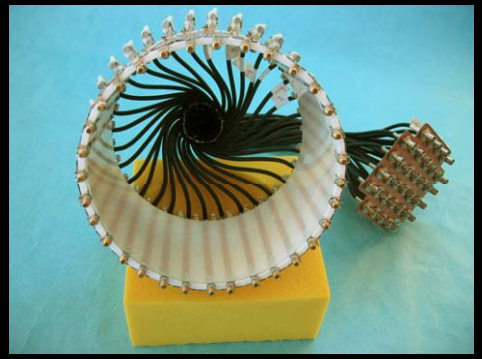




Hardy et al
ISMRM 2005, 951



Cline et al, ISMRM 2004, 2387



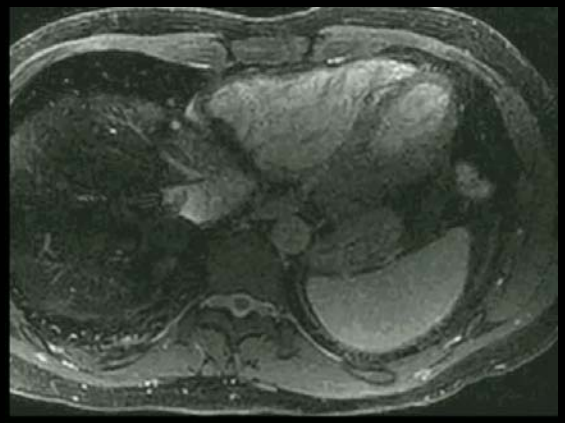
Moeller et al, ISMRM 2004, 2388

DK Sodickson, MD, PhD

Highly Accelerated Coronary MRA

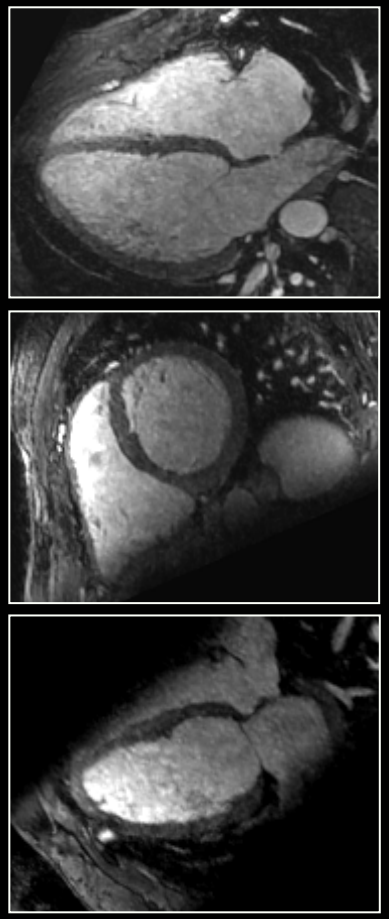
25 sec single breath-hold scan

NO localization
60 axial slices
12 cm S-I coverage

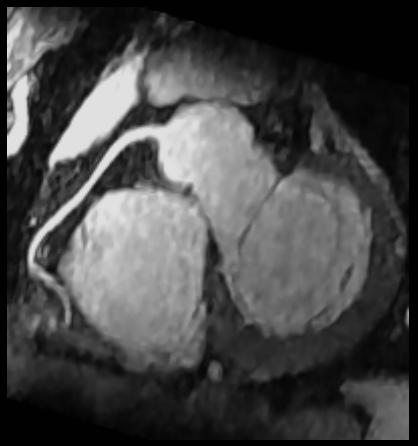


8 fold acceleration
(4 x 2 aliasing)

retrospective reformatting



breath-held CAI with whole-heart coverage



DK Sodickson, MD, PhD

T. Niendorf et. al, SCMR 2005, #168

Rapid volumetric body screening

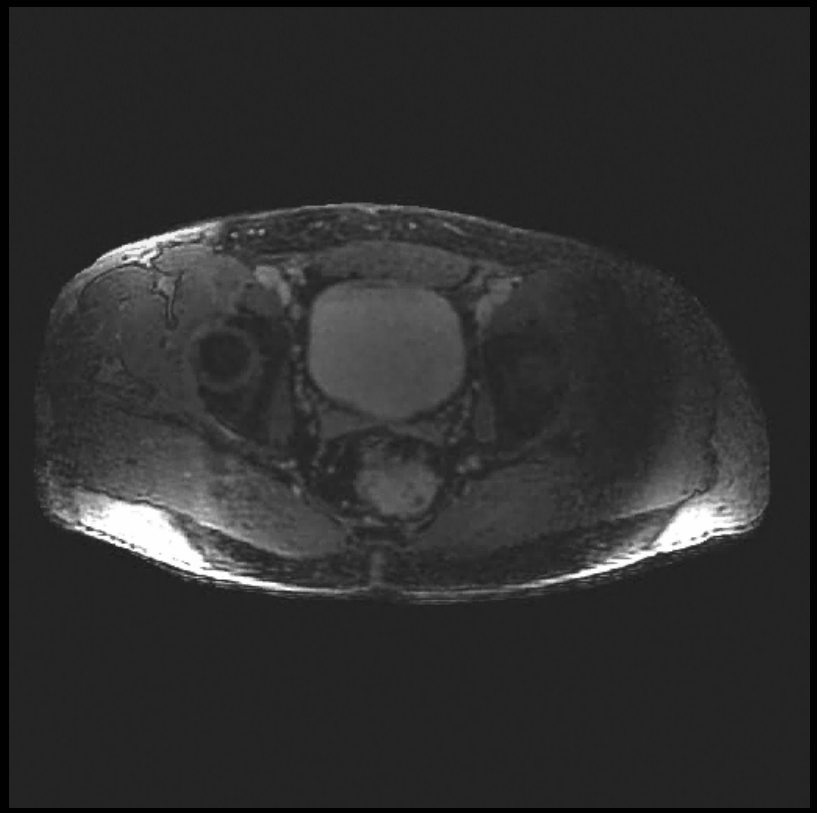
Large volume (44 cm x 44cm x 40cm)
at
clinical resolution (1.7mm x 1.7mm x 2.2mm)

12-fold acceleration (4 x 3 aliasing)

4:24
(264 second)
acquisition

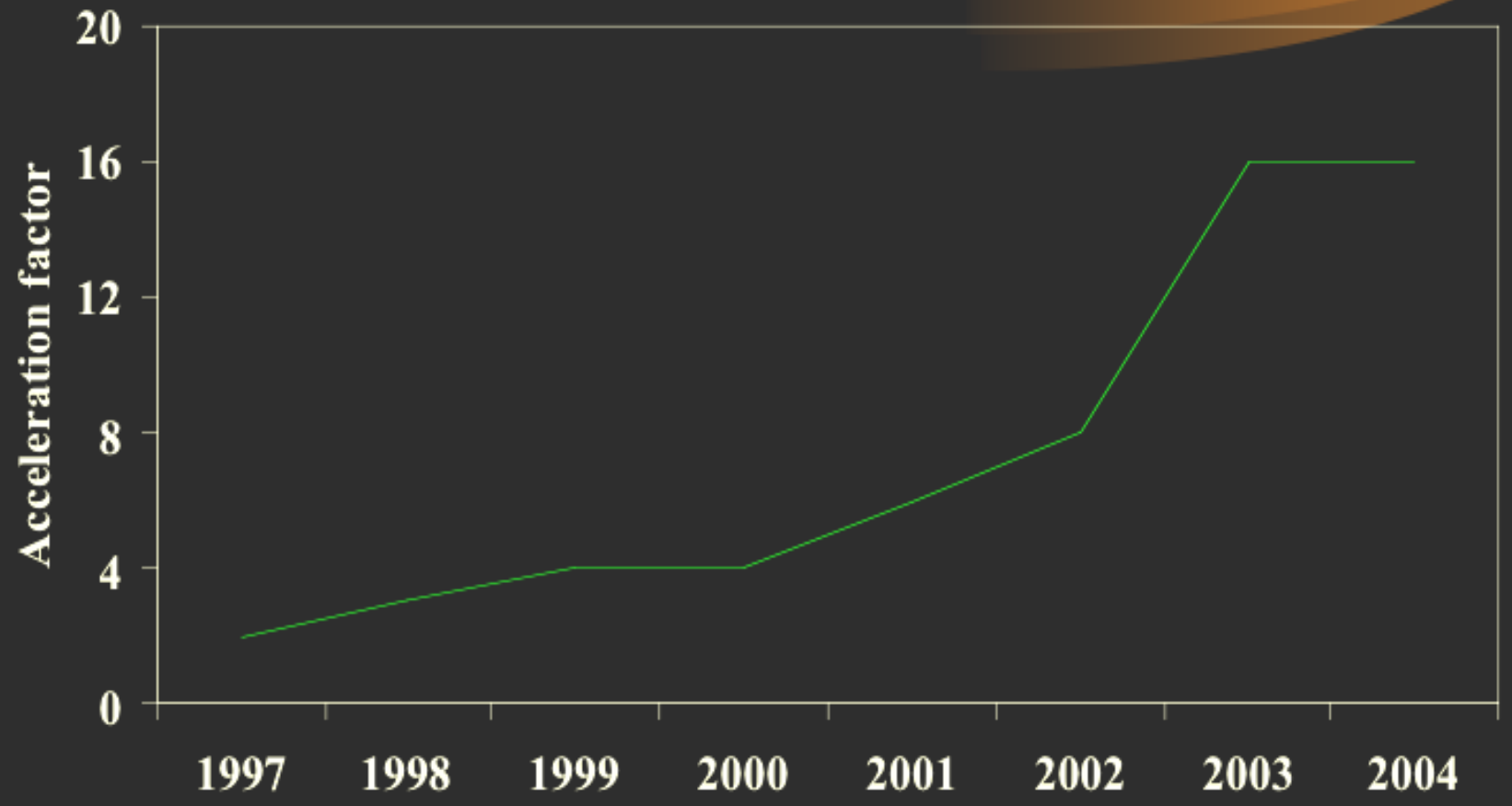
÷12

22 second
breath-hold



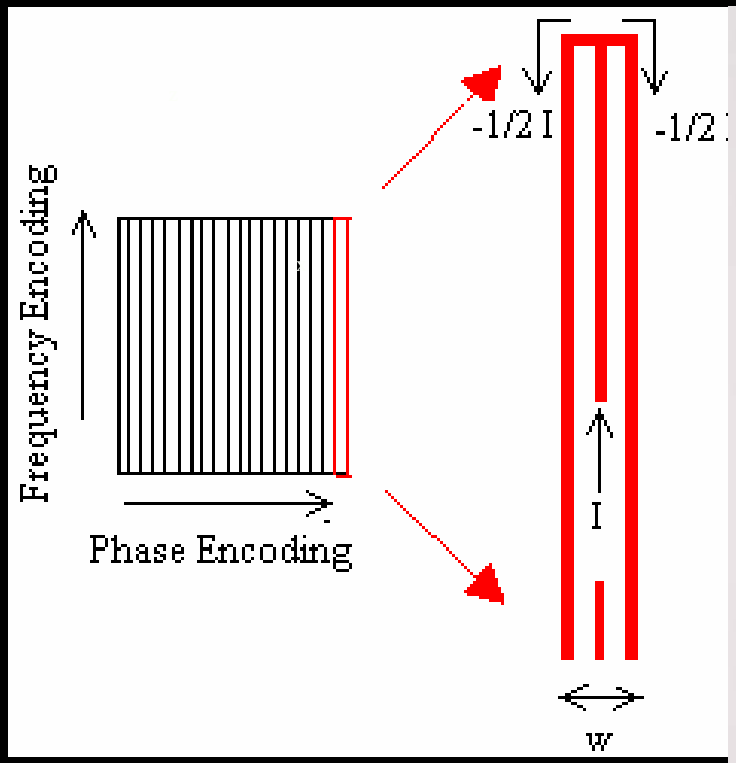
DK Sodickson, MD, PhD

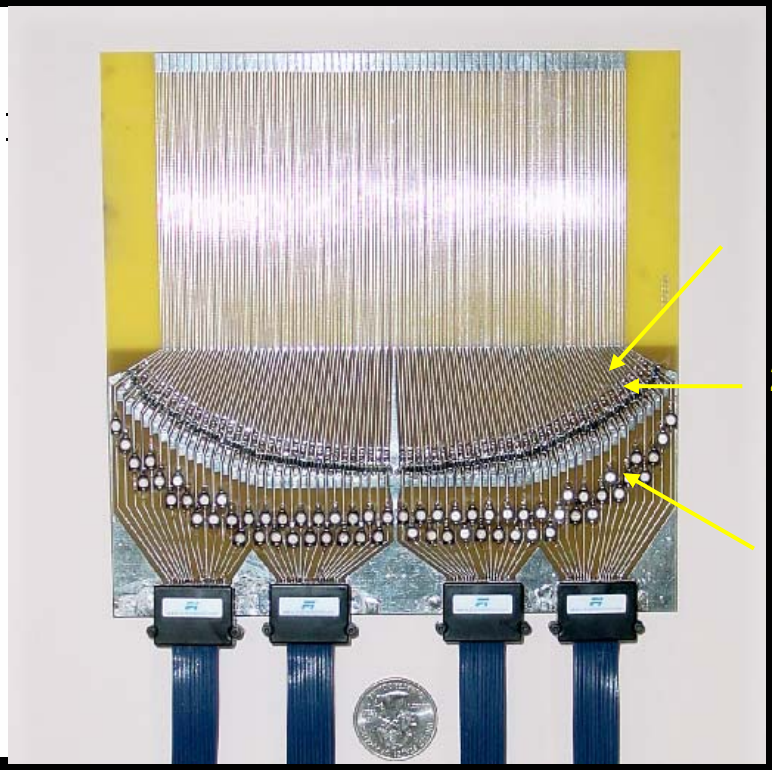
Acceleration over time



Single Echo Acquisition (SEA) MRI

- ***Phase encoding is entirely eliminated and replaced by the spatial localization of long and very narrow coils***





DC Blocking Cap

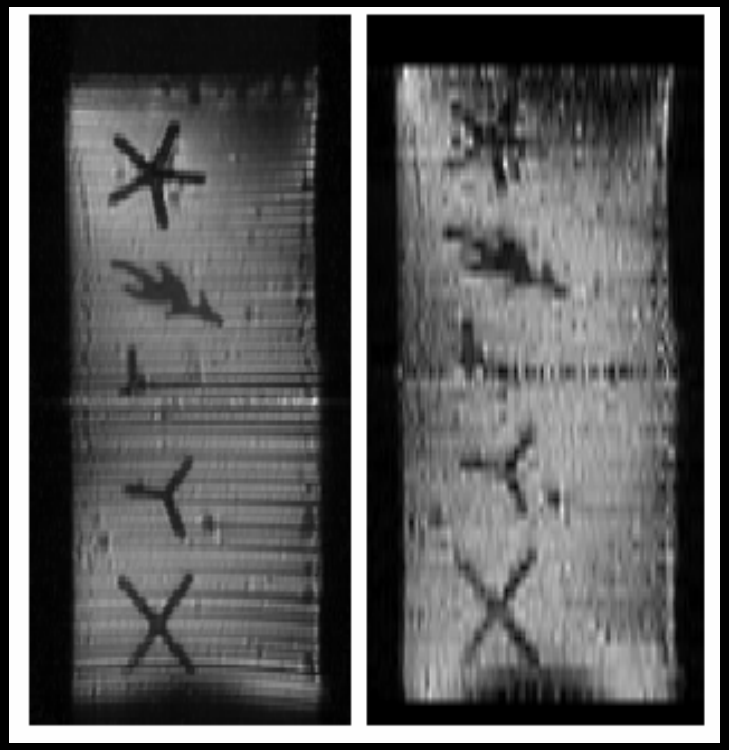
2 x Varactor Diode for tune

Tunable capacitor for match
10k⌖ resistor underneath

McDougall, M.P. and Wright, S.M., Magn. Reson. Med., Aug, 2005

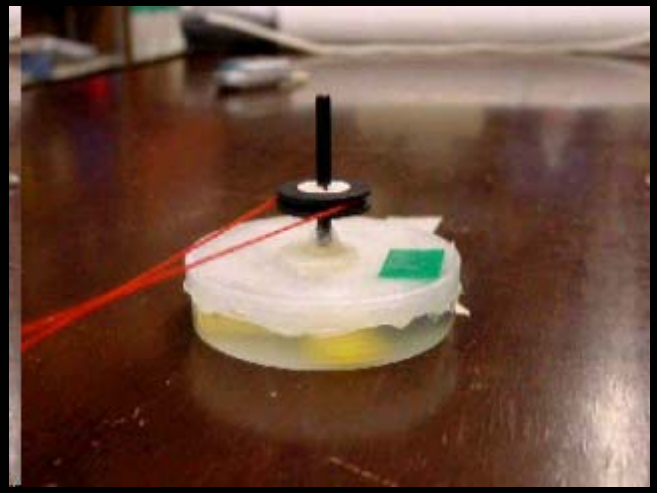
Single Echo Images- First images

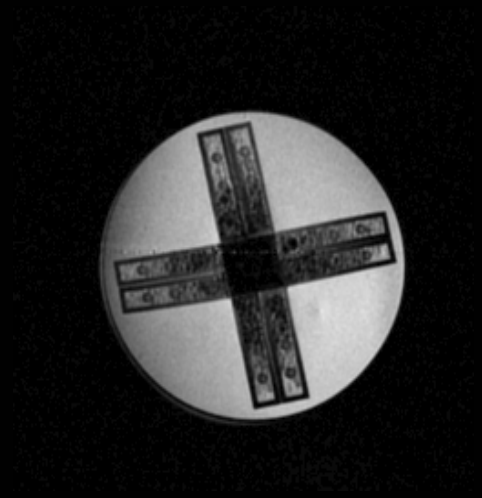
- Standard image on left-
  - 128 acquisitions, 300 msec TR
  - Acq. time: 38 seconds
- Single acquisition image on right-
  - 1 acquisition by 64 elements
  - Acq. time: 20 msec.



Proc. 2nd Joint EMBS/BMES Conference, p. 1181-1182, 2002

Motion imaging



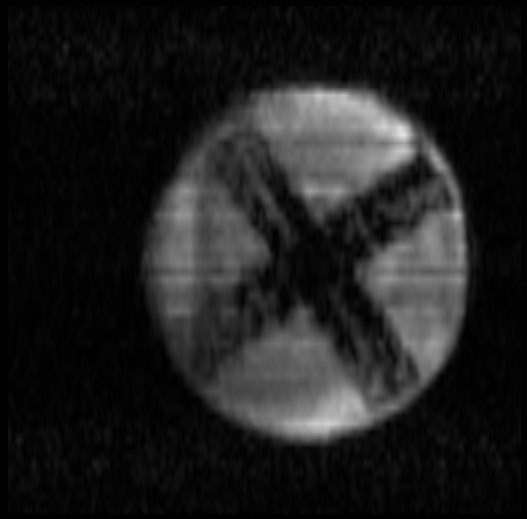


Test phantom

Spin Echo, 256x256 resolution

0 RPM, 100 percent speed

- SEA Imaging is remarkably insensitive to motion artifacts.
  - Each image is created from a single echo.
  - No motion artifacts due to motion in phase encoding gradients



Test phantom

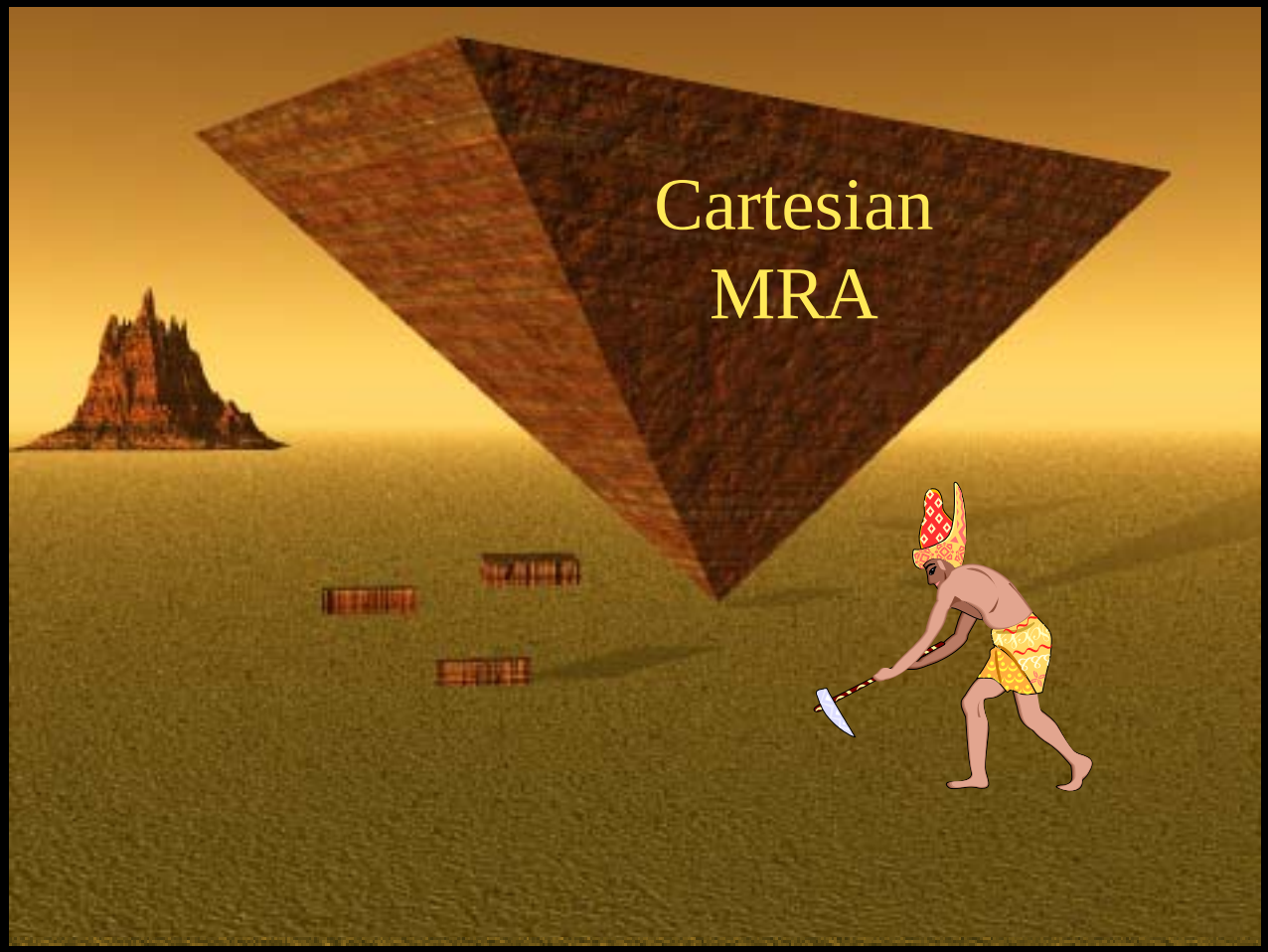
Gradient Echo, 64 x 128 resolution

TR/TE = 8/4 msec.

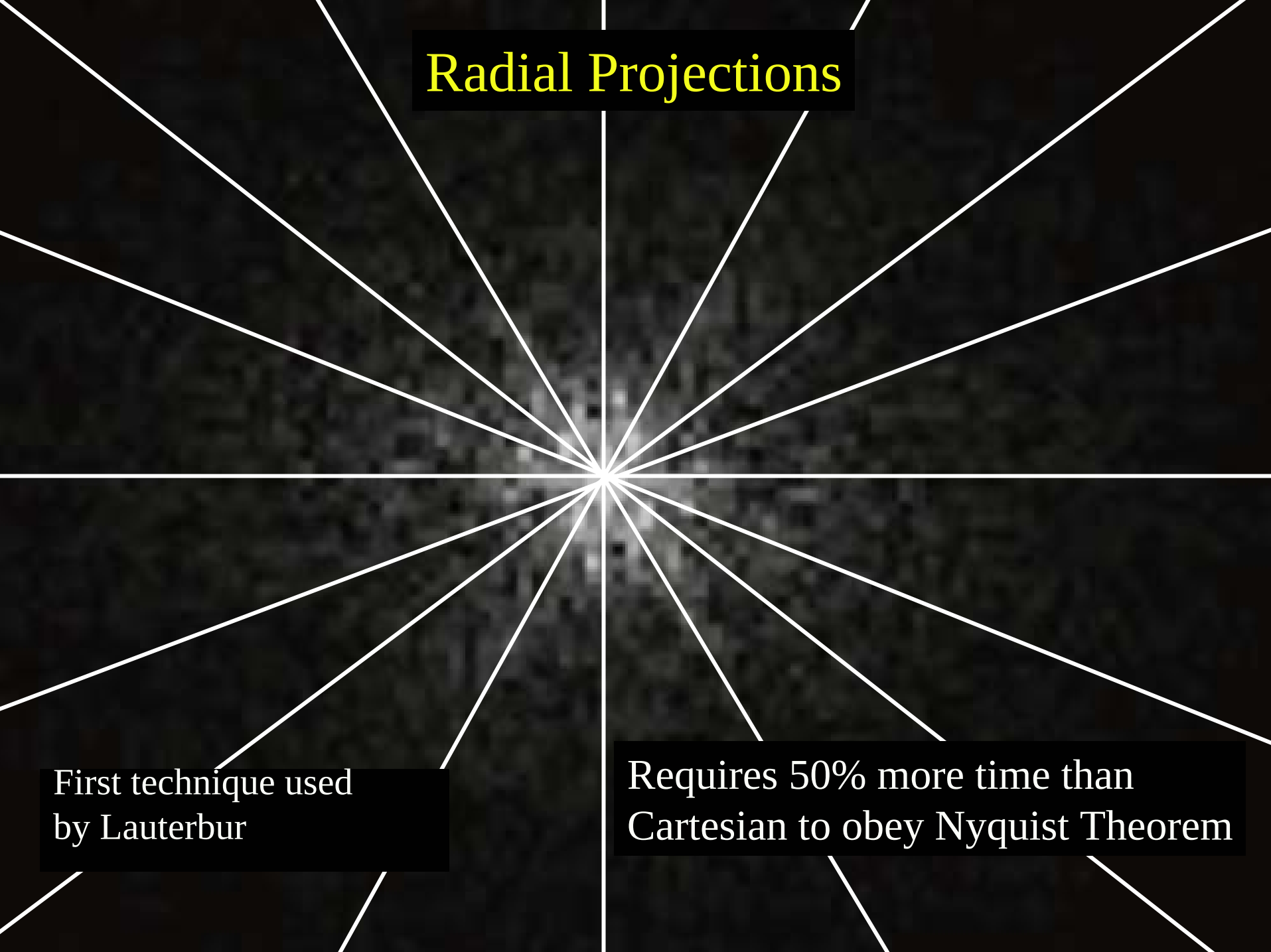
60 RPM, 80 percent display speed.

Ultra-fast Magnetic Resonance Angiography

How would we do MRA if we could start all over?



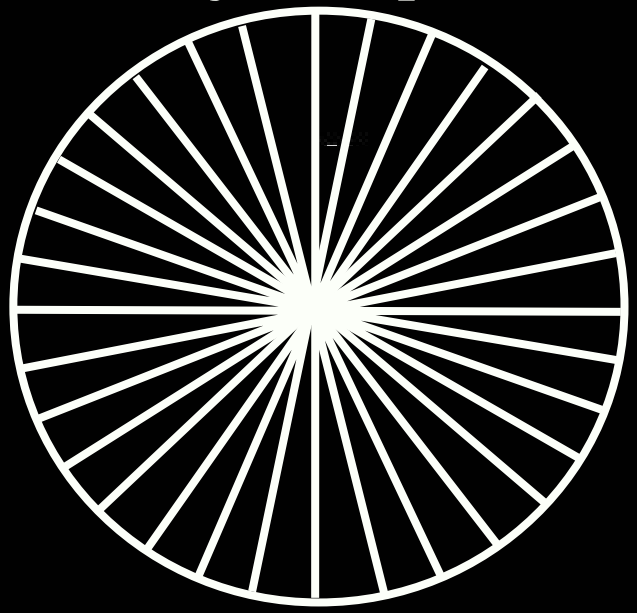
Radial Projections

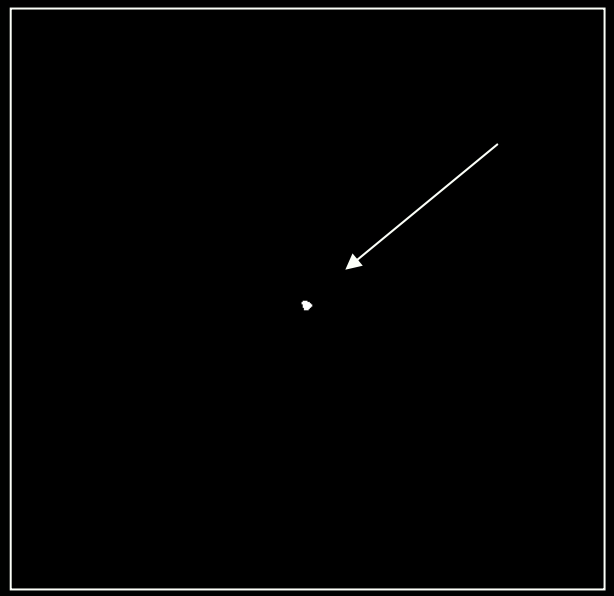


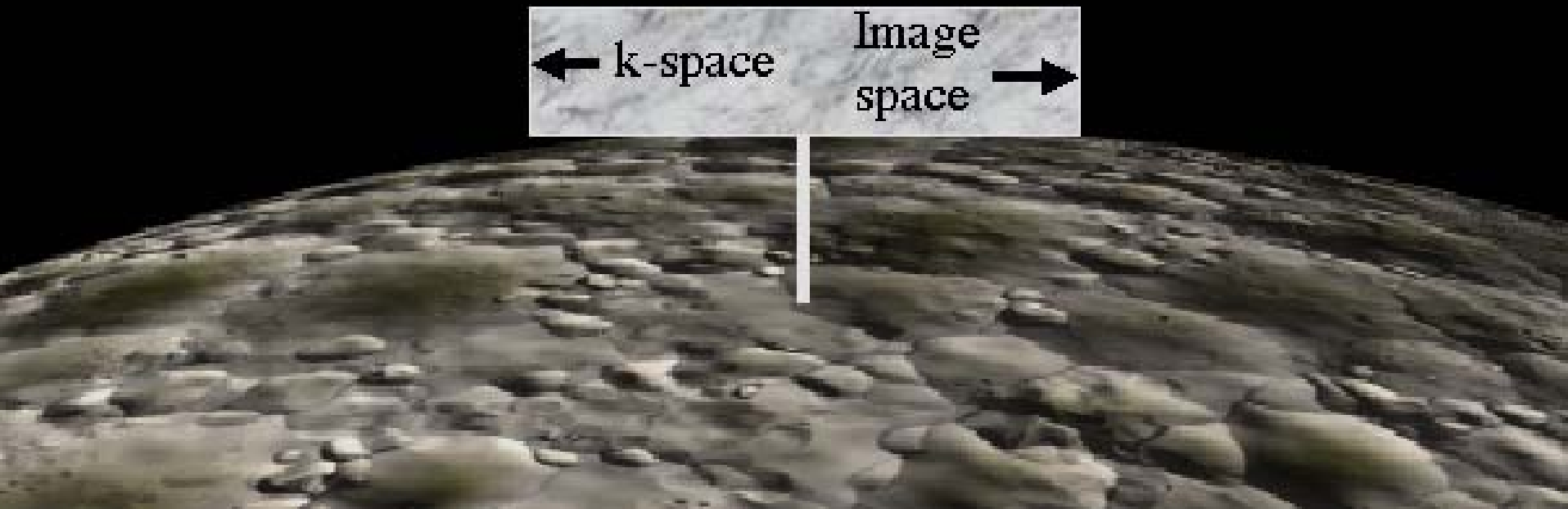
First technique used
by Lauterbur

Requires 50% more time than
Cartesian to obey Nyquist Theorem

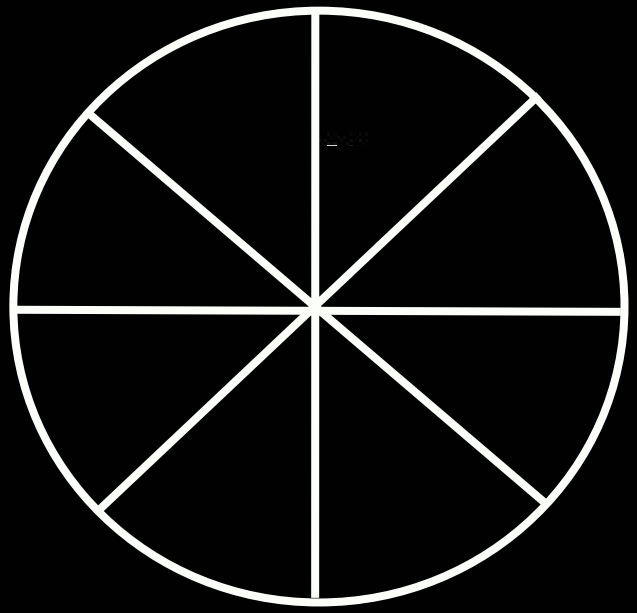
Fully Sampled

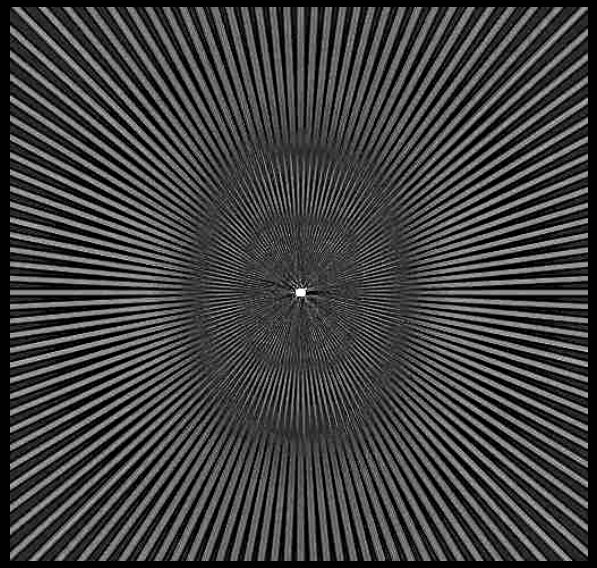




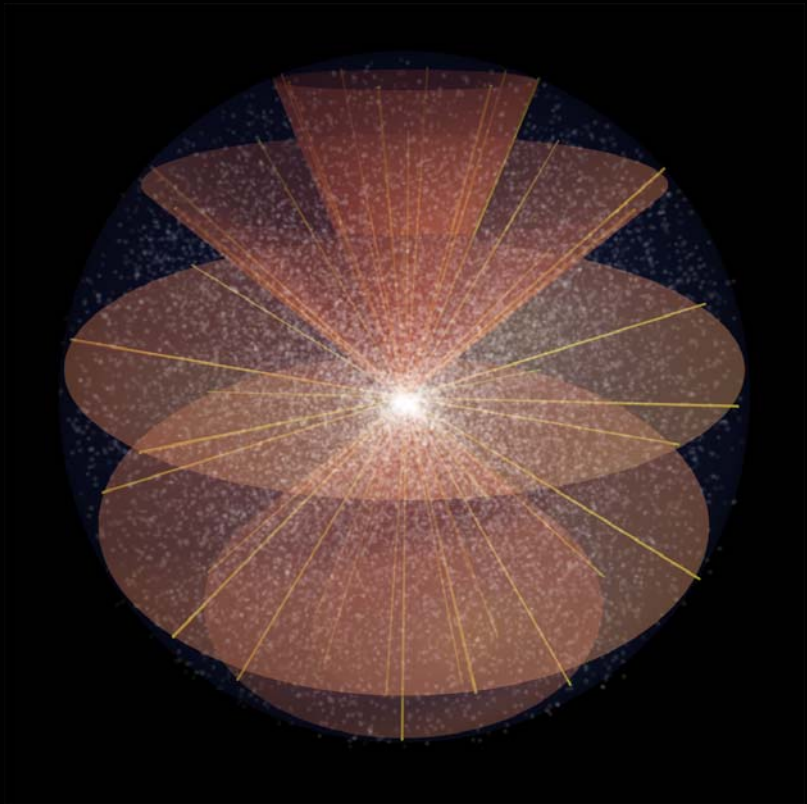


Undersampled

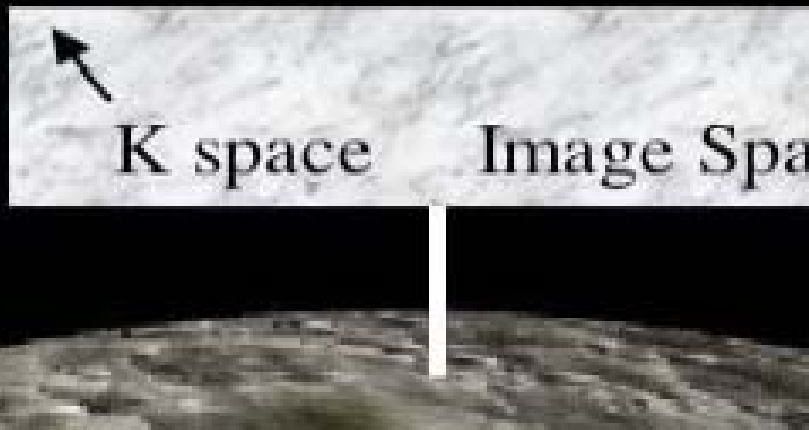




Extension of Undersampled Projection Imaging to 3D

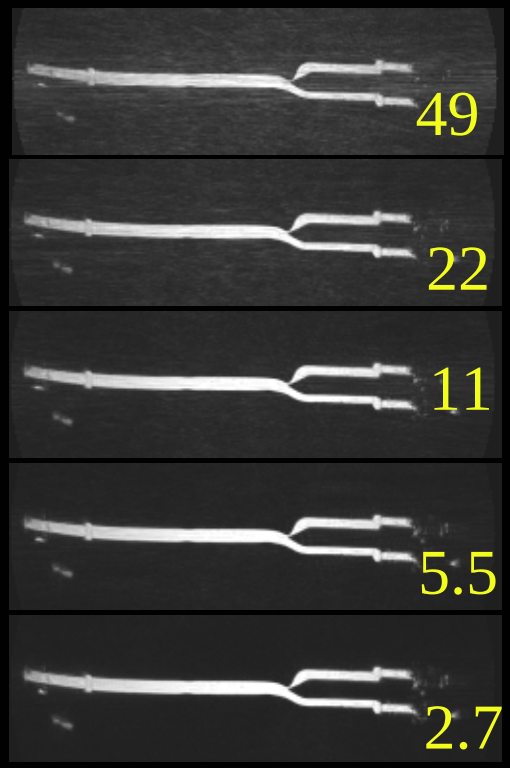


VIPR: Vastly undersampled Isotropic imaging with PRojections



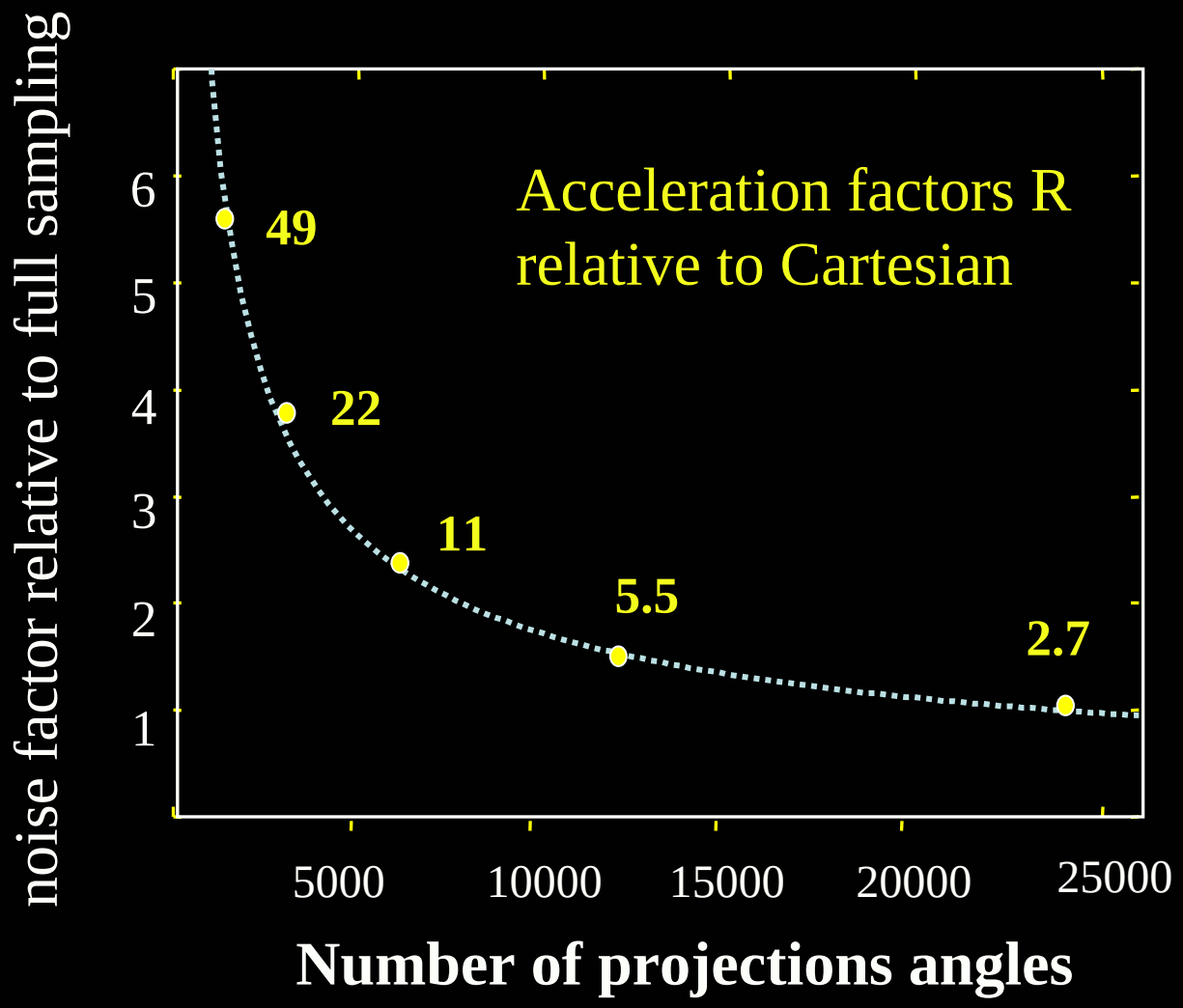
WF Block, AV Barger, TM Grist and CA Mistretta, Radiology 217(P), 311, 2000

Relative VIPR Noise vs Acceleration Factor*



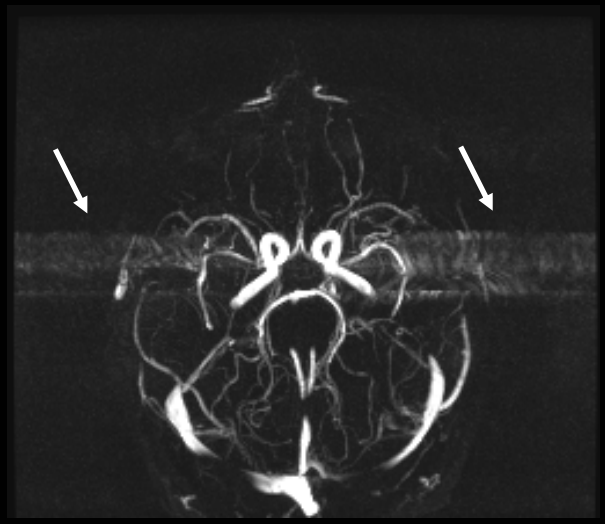
256 x 256 x 256

A. Barger PhD thesis



* Acceleration = ratio (scan speed x voxel resolution x 3D volume)

PC VIPR vs. 3D Cartesian PC: Acceleration factor 61 with contrast



Cartesian 3D PC

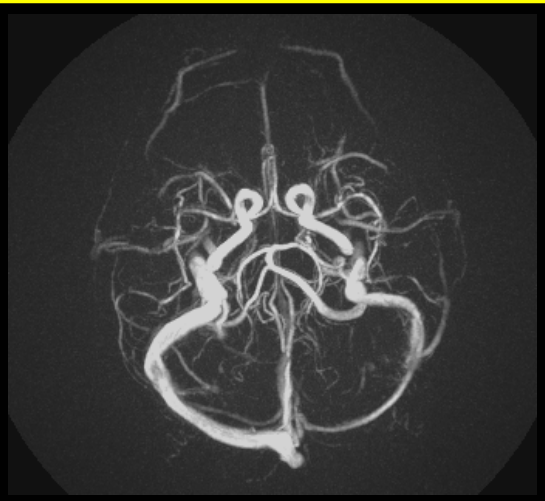
Time: 7:22

S/I Coverage: 4 cm

Through-plane resolution 2mm

In Plane resolution

0.94 x 0.94mm



PC VIPR

Time: 3:50 (2x)

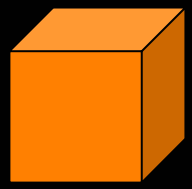
S/I Coverage:18 cm (4.5x)

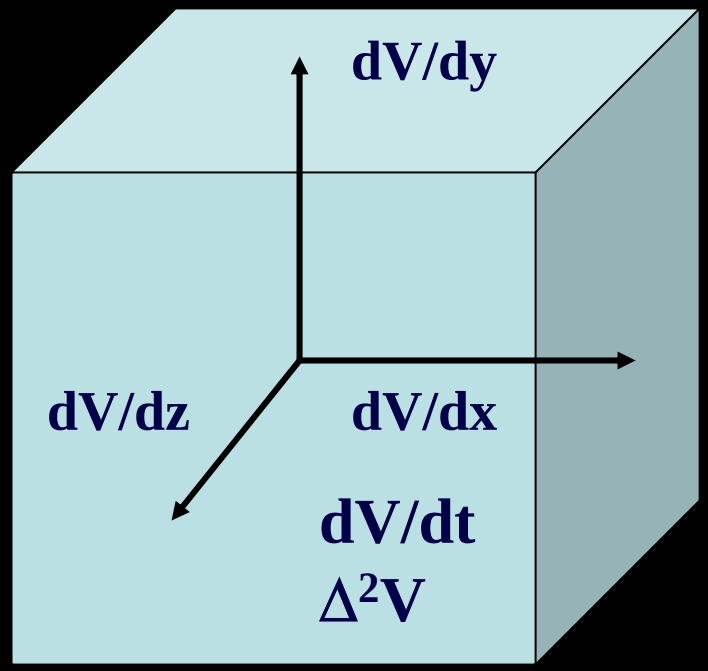
Isotropic resolution

0.63 x 0.63 x 0.63mm (7x)

= 61

Navier Stokes Relative Pressure Calculation





.63 x .63 x .63 = 0.25 mm^3

PC VIPR

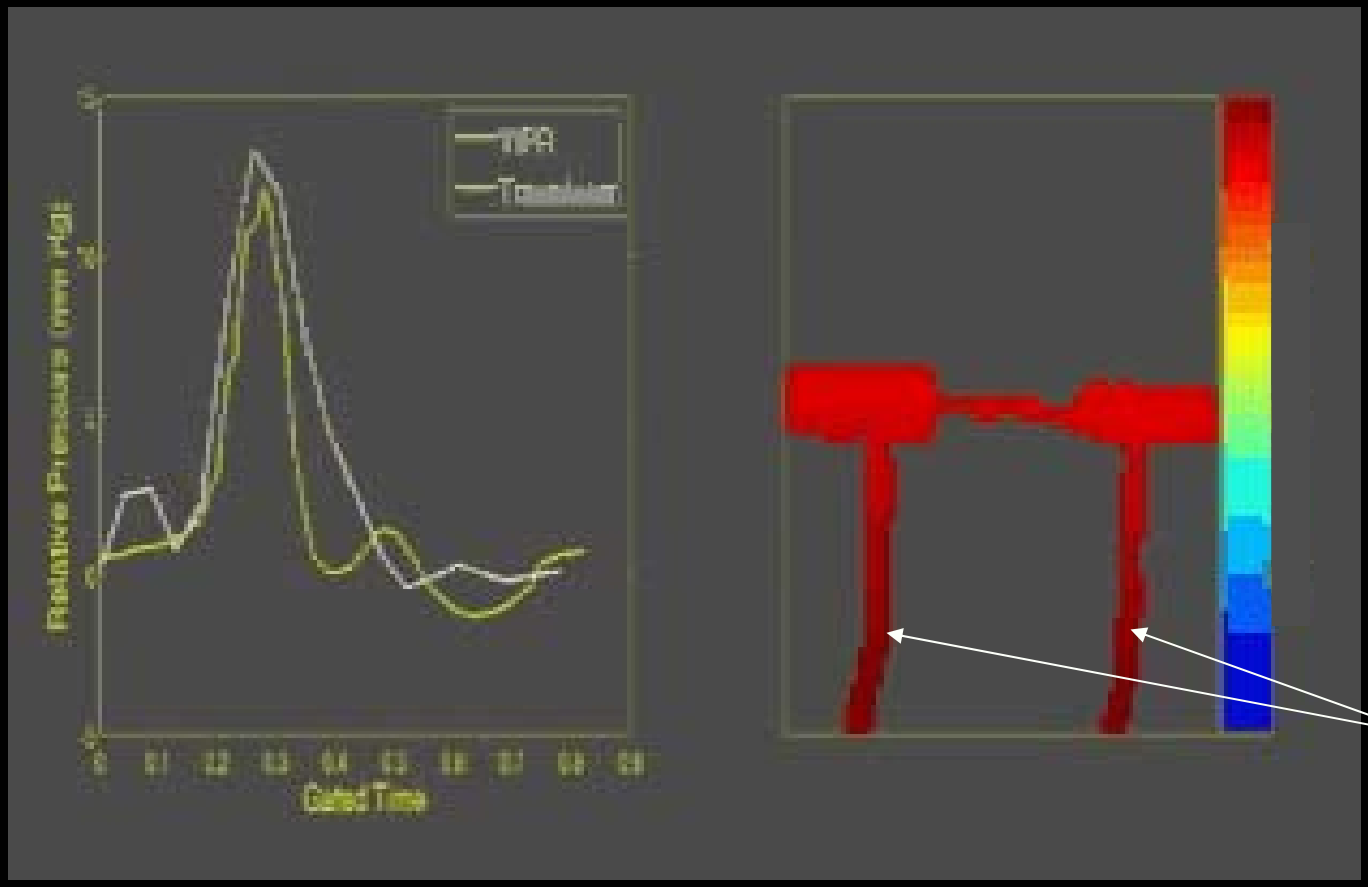
2.5 x 2.5 x 3 = 19 mm^3

3DPC*

76

Tyska et al. JMRI 12:321-329(2000)

In-Vitro Pressure Drop Validation



0

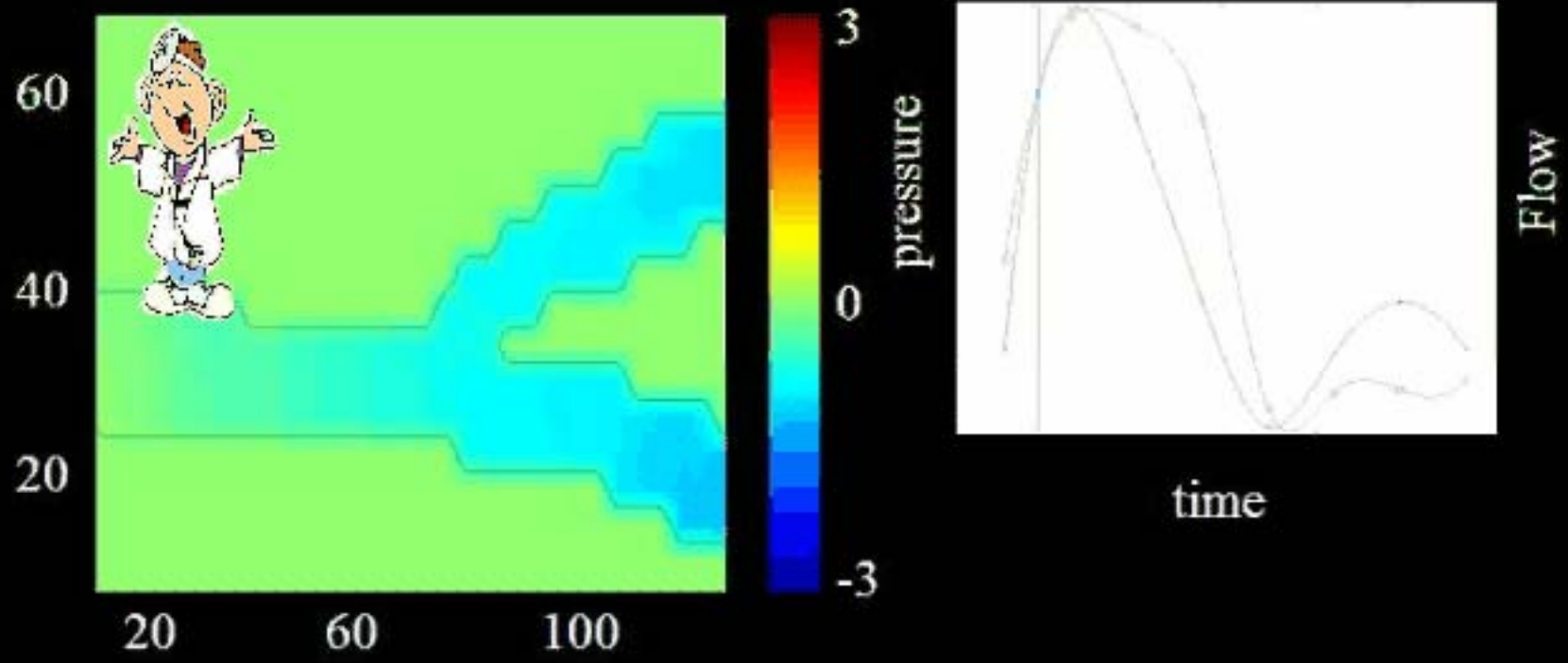
5 mm/Hg

10

Pressure transducers

94% (area) stenosis in 7mm vessel

Pressure relative to input



Preliminary Study by Kevin Johnson

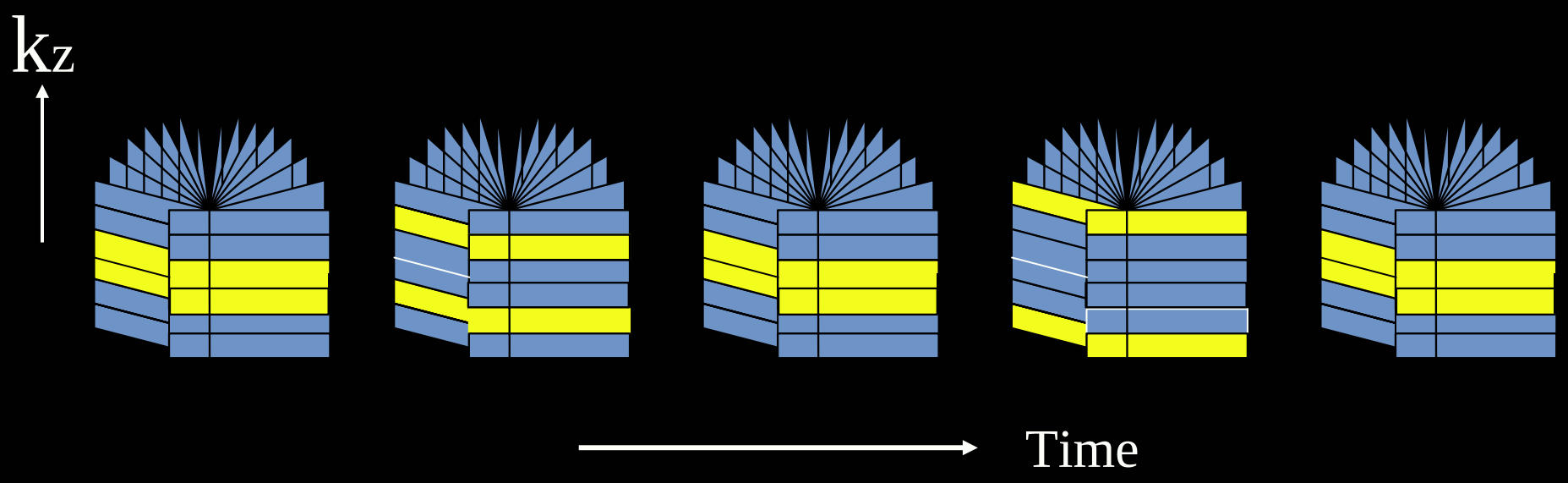
A New Challenge to The Nyquist Theorem

Candès and Romberg (Cal Tech) and Tao (UCLA)have shown that the number of Fourier samples needed to generate an exact reconstruction of an object is not N^3 but instead is about equal to twice the number of occupied pixels in the image.

Iterative reconstruction methods have been used to produce exact reconstructions with angular undersampling factors of ~ 20 in 2D for noise-free images. In our experience the addition of noise degrades performance.

Undersampling in k-space and Time

In PR TRICKS radial undersampling is performed in k_x and k_y while k_z is sparsely sampled in time, producing an undersampling factor of 18



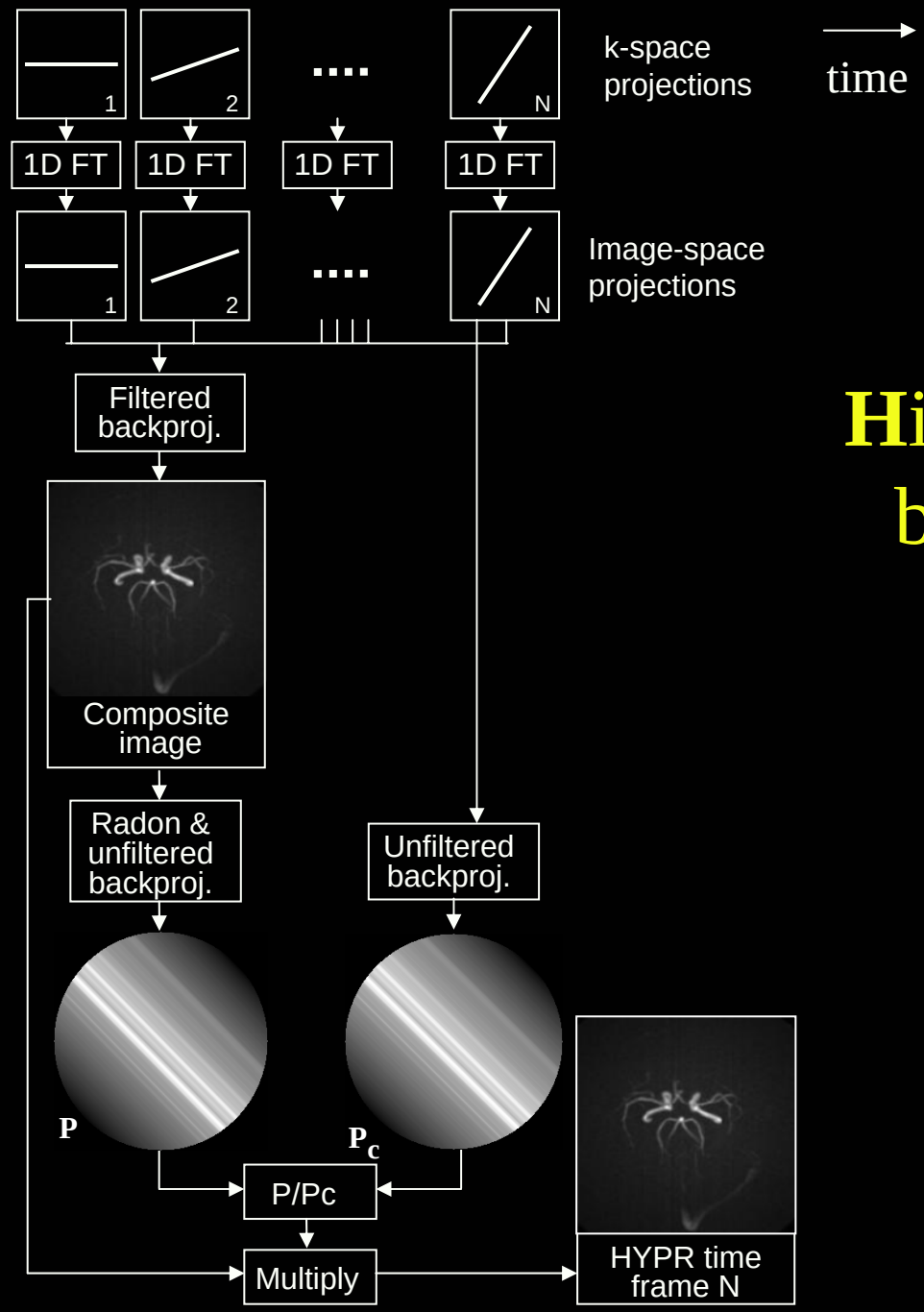
Vigen KK, et.al.

Exploiting the Redundancies in 4D Data

Recently investigators have developed iterative algorithms that use data from an entire time-resolved acquisition to constrain the reconstruction of individual time frames.

Tsao J., Boesinger P. and Pruessman KP, k-t BLAST and k-t Sense: Dynamic MRI with High Frame Rate Exploiting Spatiotemporal Correlations, Magn Reson Med. 2003; 50 (5):1031-43.

Huang Y., Gurr D., and Wright G., Time-Resolved 3D MR Angiography by Interleaved Biplane Projections, Abstract 1707, ISMRM 2005; Miami, Florida.

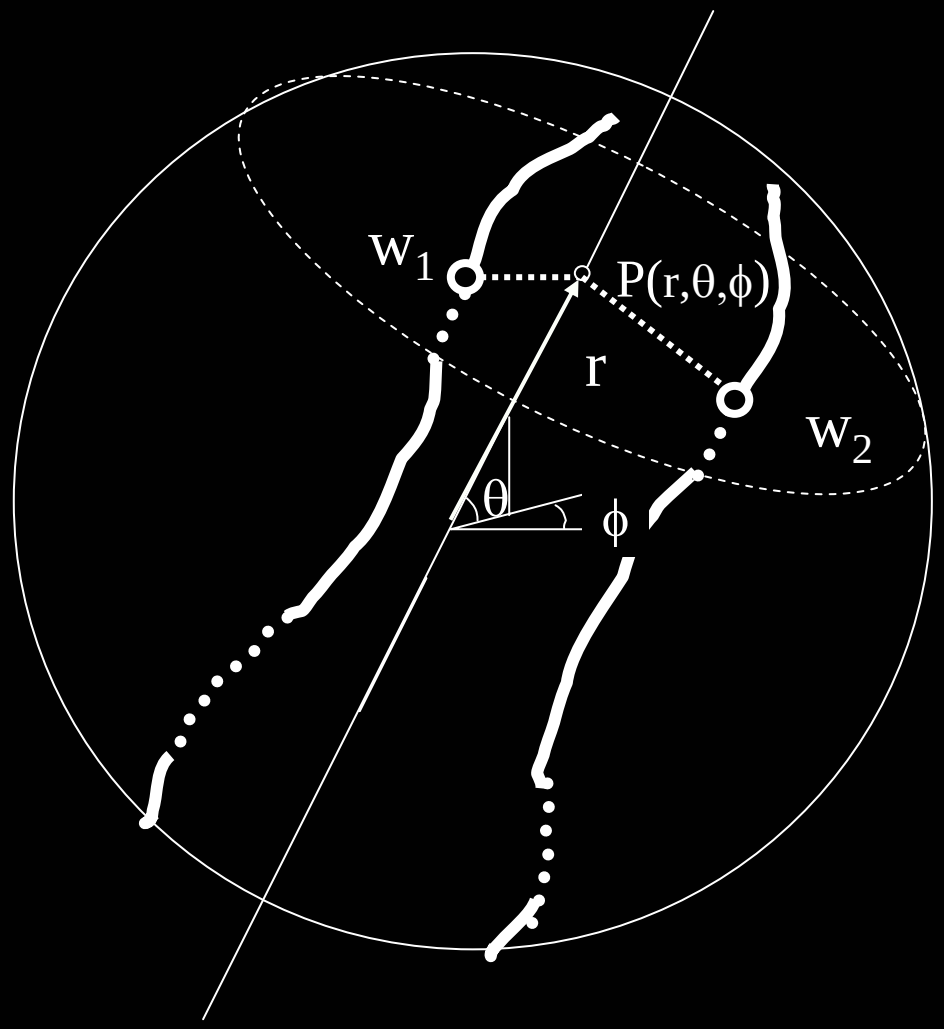


High**Y** constrained back **PR**ojection

HYPR

HYPR VIPR Reconstruction Using Highly Constrained Backprojection

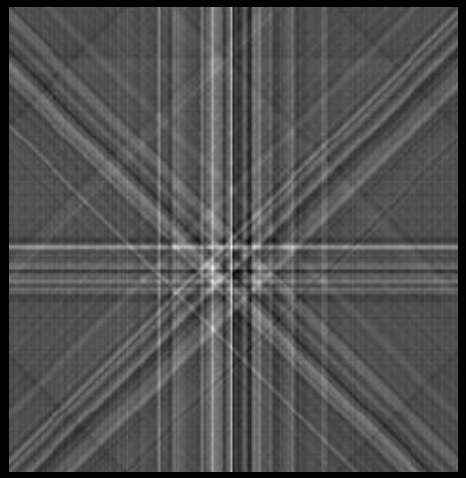
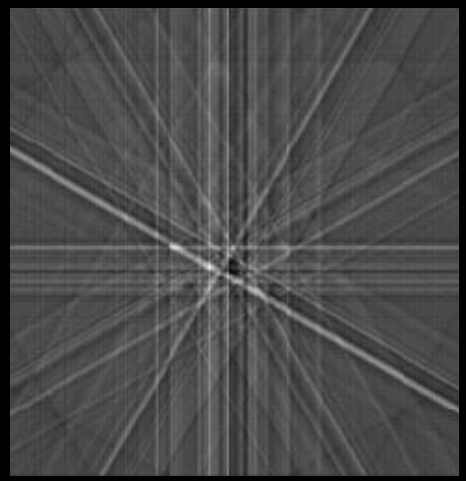
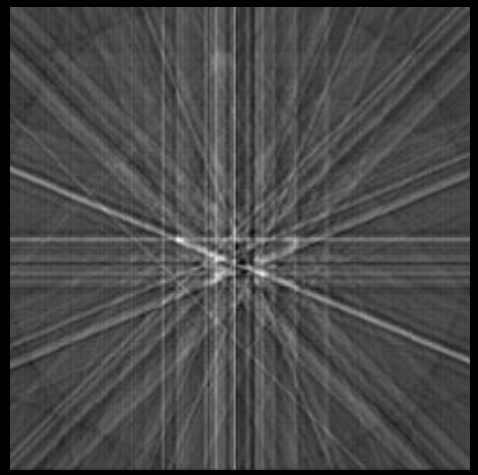
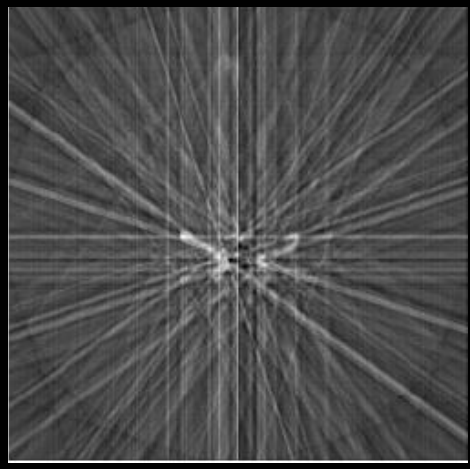
$$S_1 = \frac{w_1}{w_1 + w_2}$$



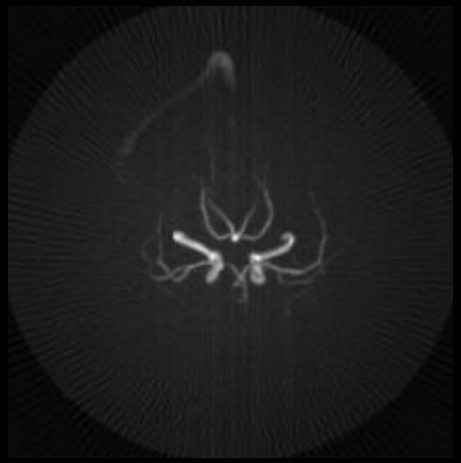
$$S_2 = \frac{w_2}{w_1 + w_2}$$

Comparison of Conventional Filter Back Projection and HYPR

FBP

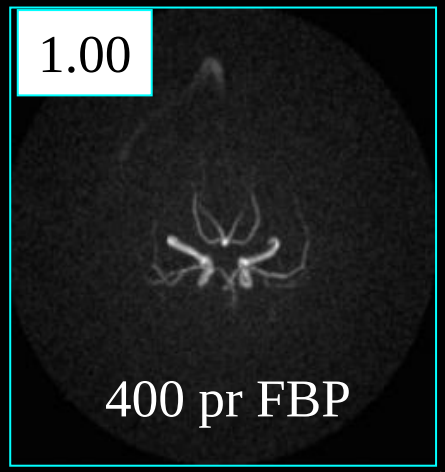





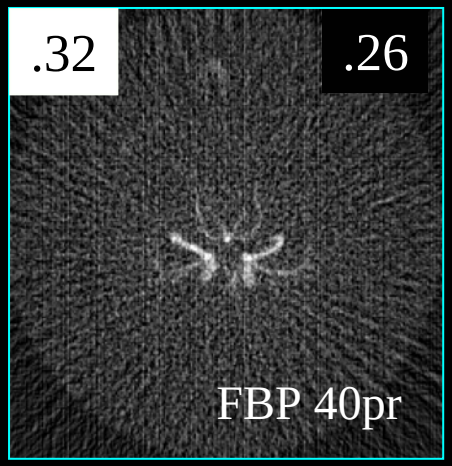
No. of Projections 4 6 8 10

HYPR

HYPR vs Conventional FBP

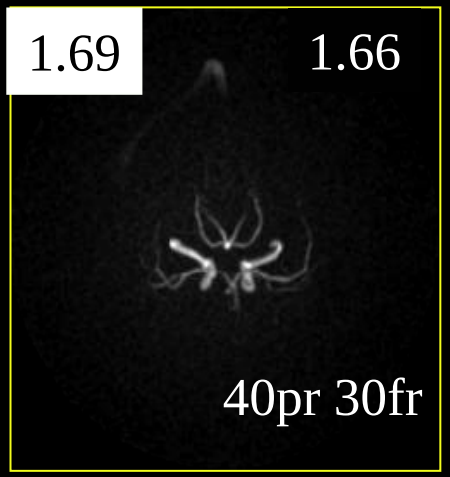




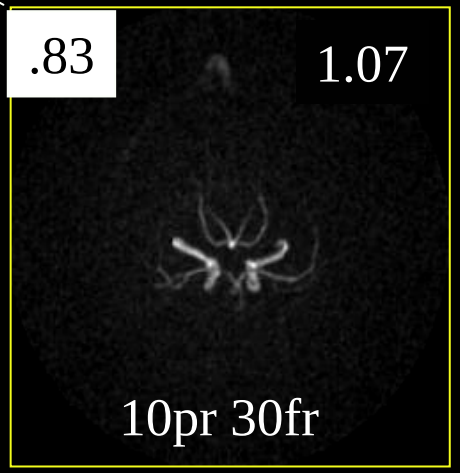
10

Measured Relative CNR

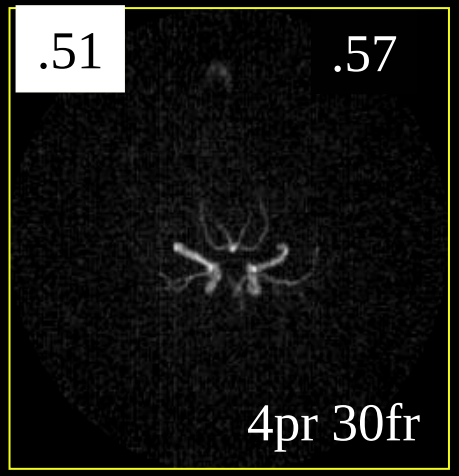
Predicted Relative CNR



10



40



100

◯ = angular undersampling factor

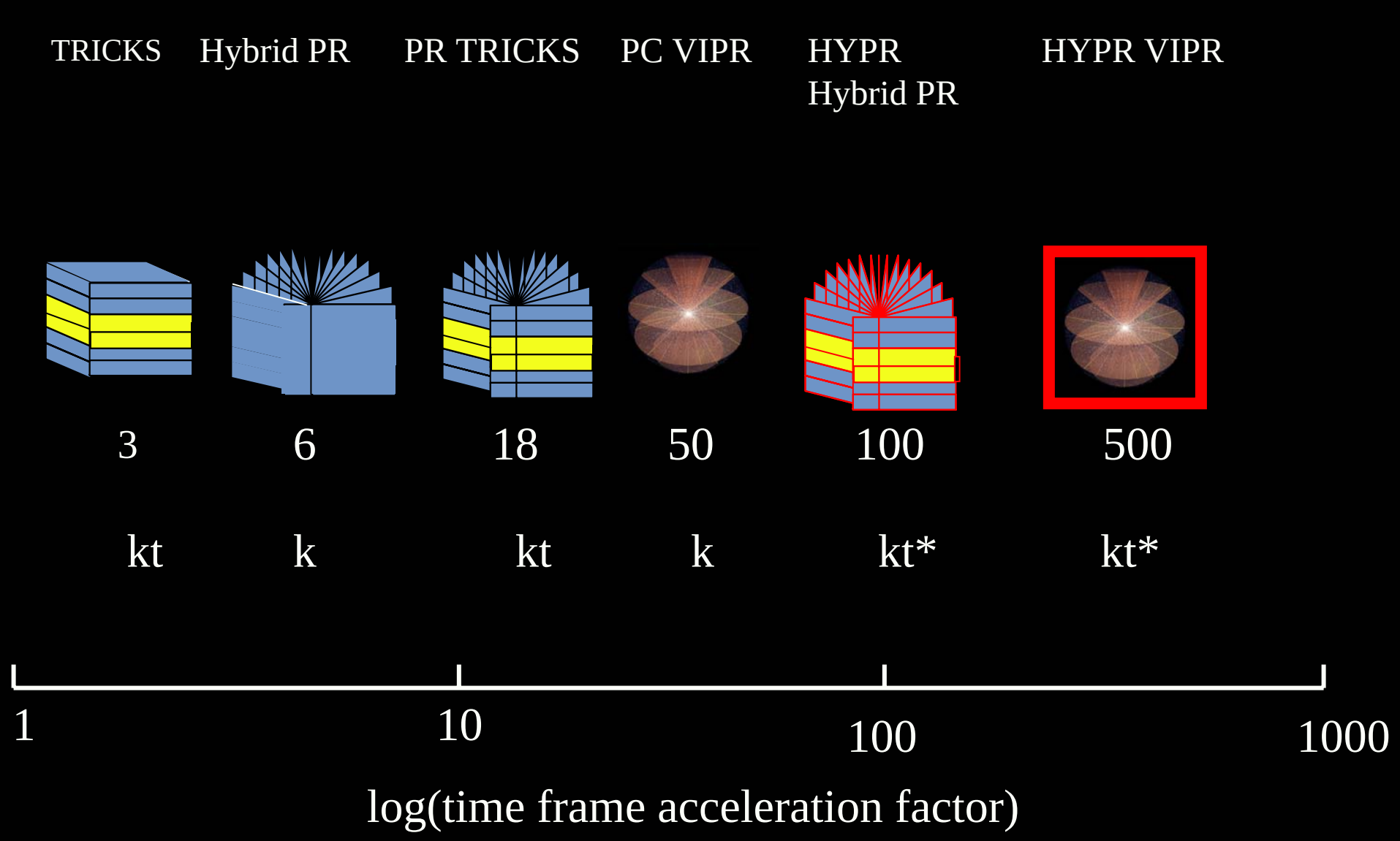
Anticipated HYPR VIPR Parameters for Velocity and Pressure Measurements

256 x256 x256 30 phases/ cardiac cycle

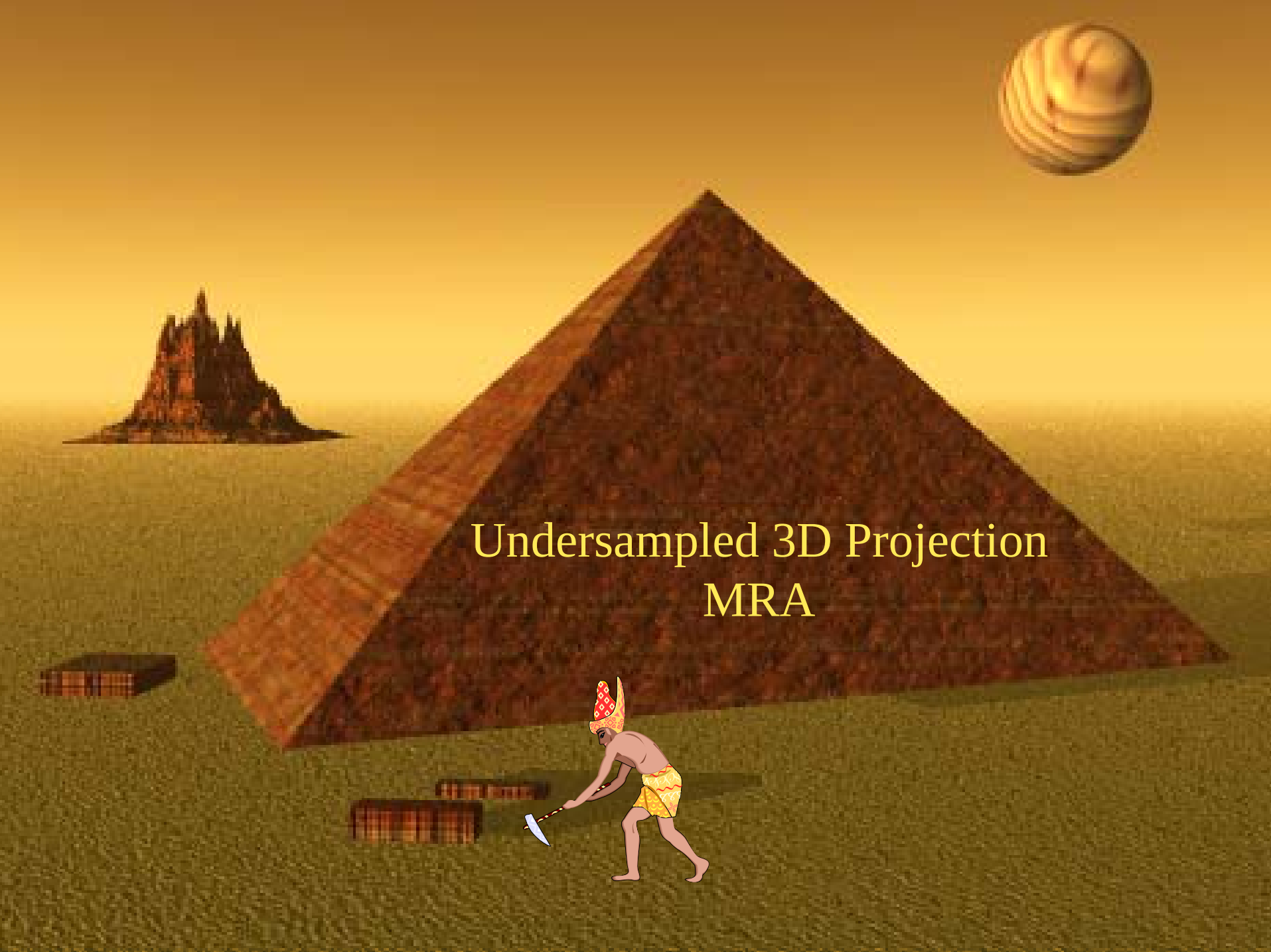
3 minute scan undersampling factor = 500
predicted SNR= 1.7 * present VIPR
that undersamples by 50.

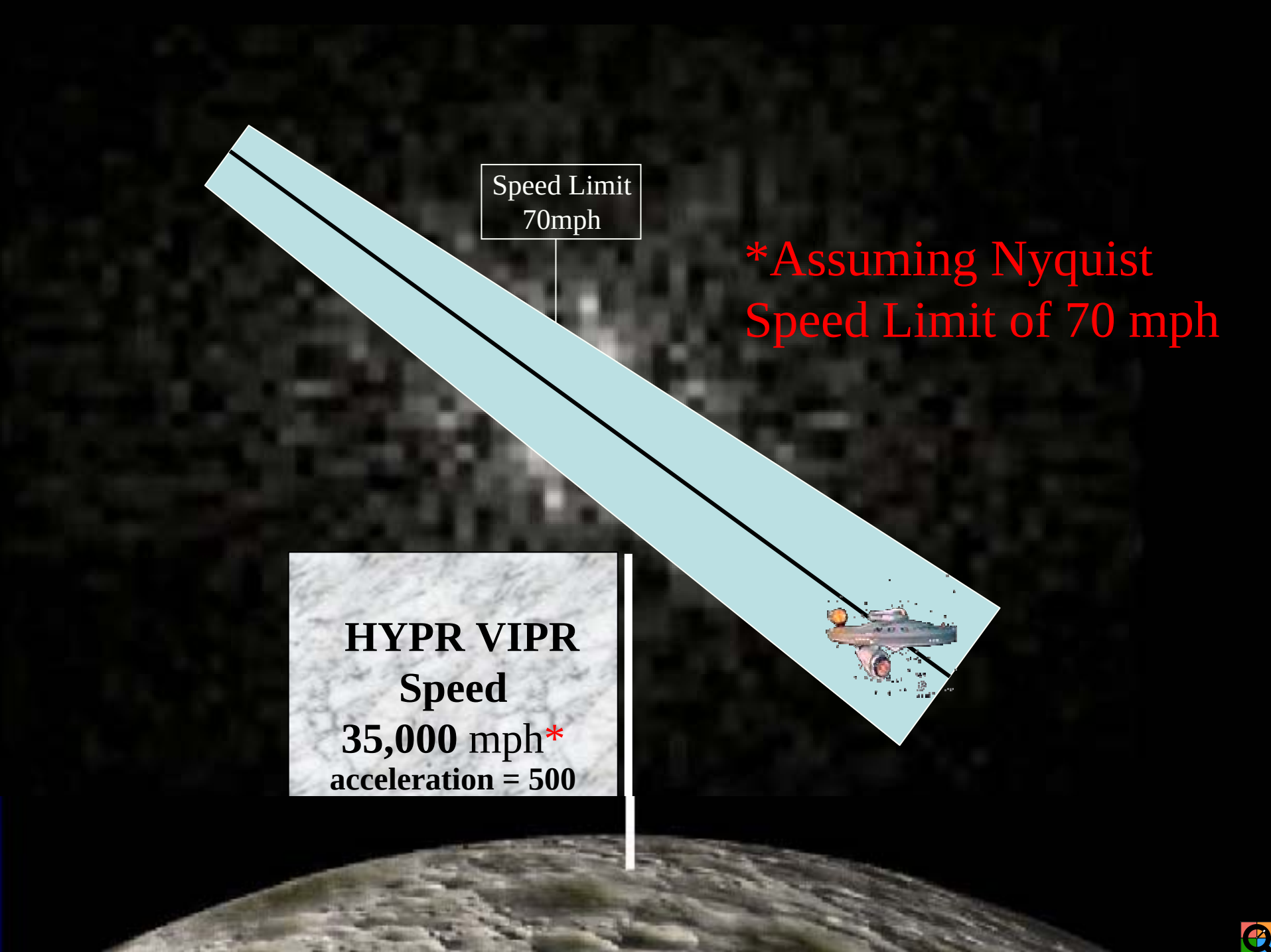
Time for equivalent scan obeying the Nyquist Theorem (k-space speed limit)

23 hour scan

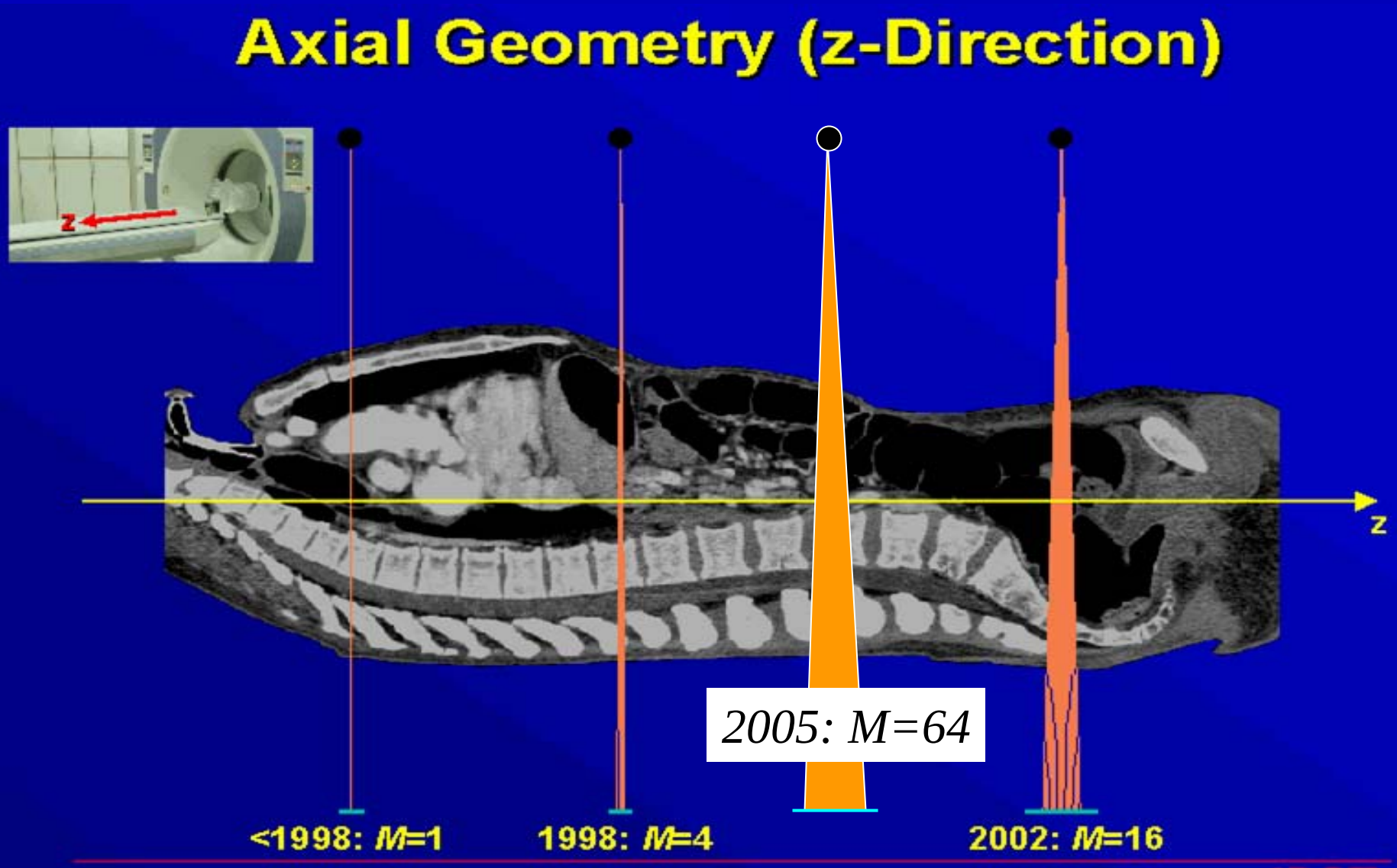


Mistretta, Wieben, et. al., submitted to MRM


Undersampled 3D Projection
MRA


Speed Limit
70mph
*Assuming Nyquist
Speed Limit of 70 mph
HYPR VIPR
Speed
35,000 mph*
acceleration = 500

Multi-Detector CT

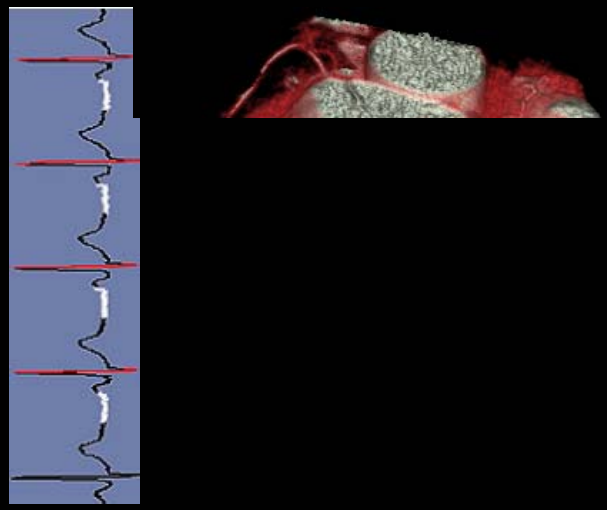


W.Kalender

Coverage Comparison in 5-Heart Beats

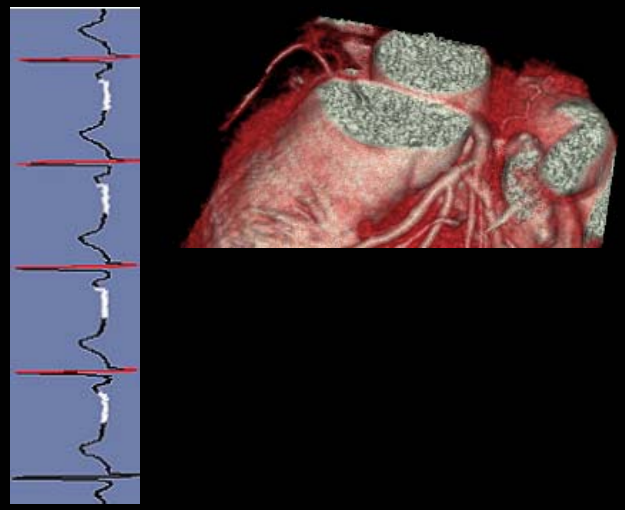
10mm detector
Pitch ~0.25

3cm in 5 sec



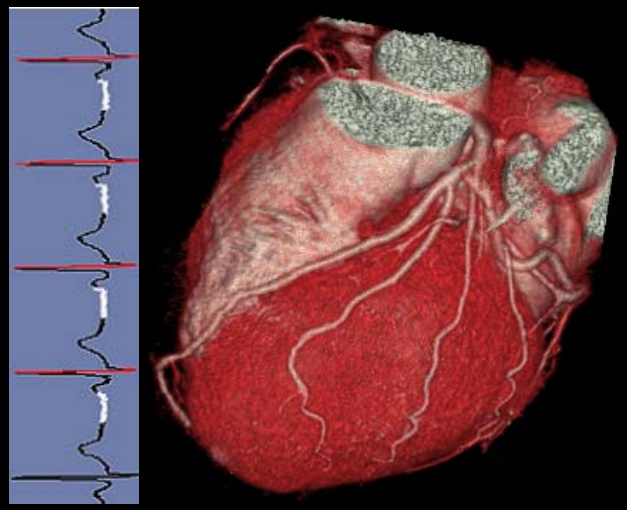
20mm detector
Pitch ~0.25

6.2cm in 5 sec



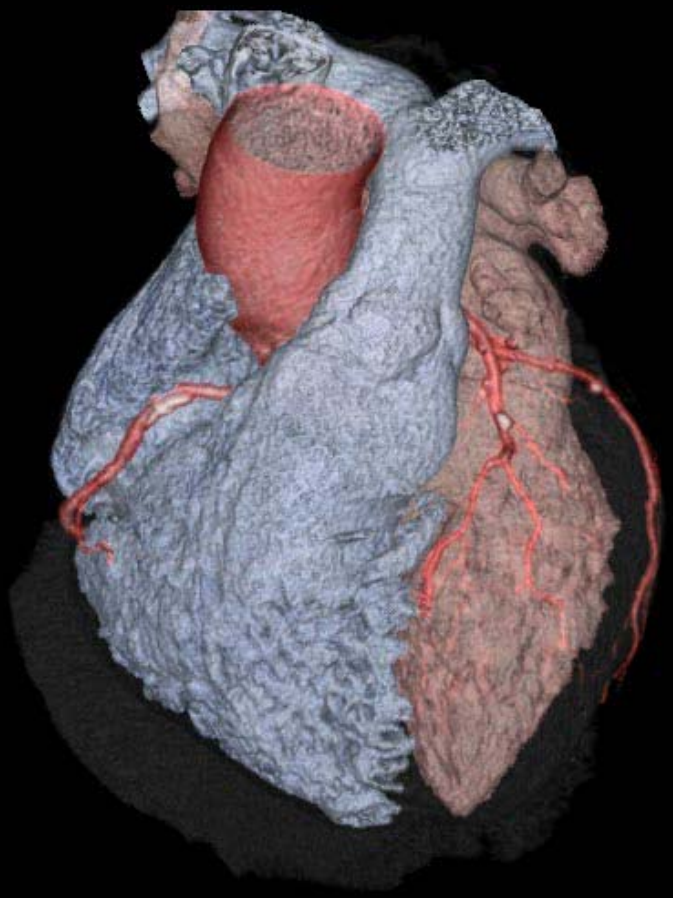
40mm detector
Pitch ~0.25

12.5cm in 5 sec



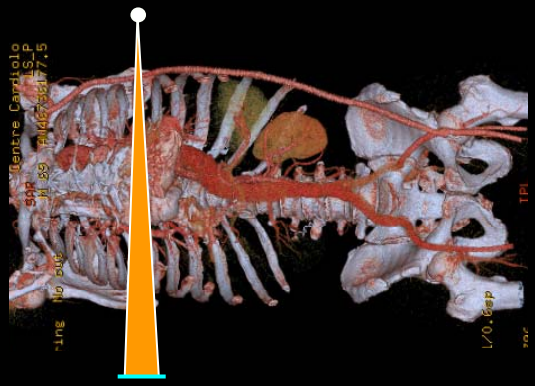
5-Beat Cardiac™ CT

Courtesy of Jiang Hsieh GE Healthcare



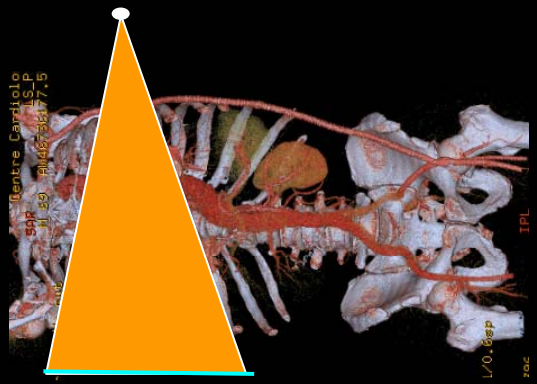
Courtesy W Dennis Foley, MD
Froedtert Memorial Lutheran Hospital
Medical College of Wisconsin

Flat Panel Cone Beam CT



CT detectors

64 slice CT
4mm coverage
~2000 focal spots/s
ΔT (coronaries)~ 150ms



Flat Panel

Flat panel Cone Beam CT
400mm coverage
~30 focal spots/s

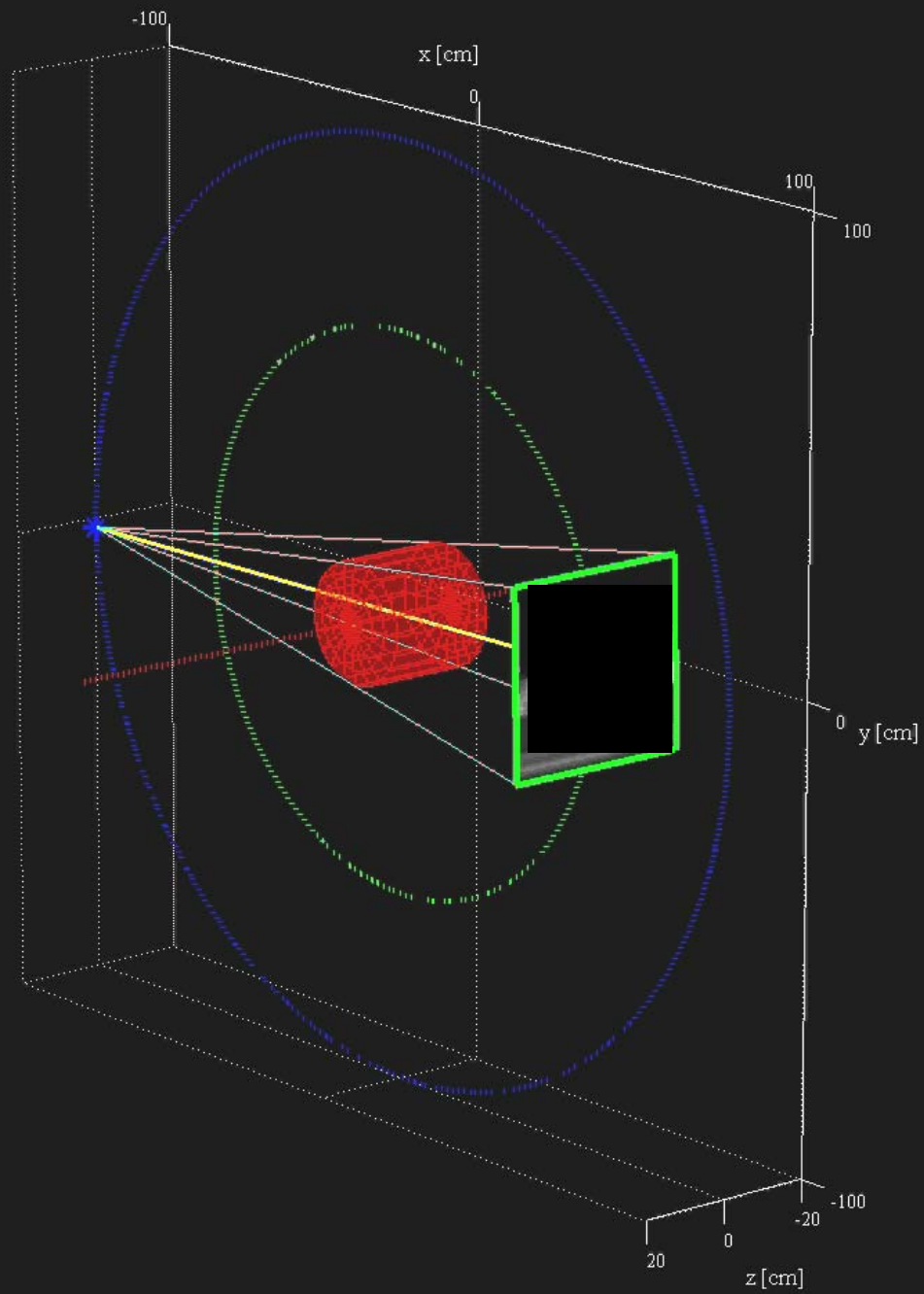
Flat-Panel Cone-Beam CT

300 – 600 projections

through 360°

(512x512x512)

reconstruction



Siewerdsen and Jaffray,
Princess Margaret Hospital,
University of Toronto

Flat-Panel Cone-Beam CT

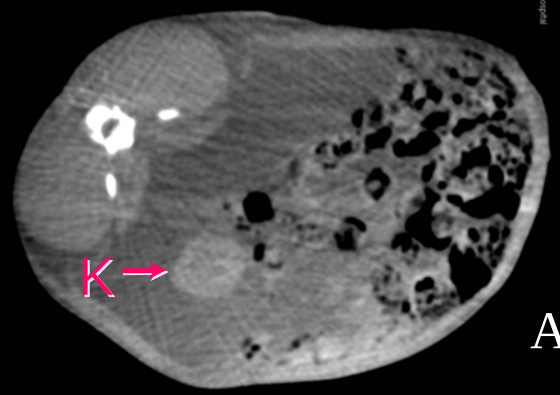
<u>Imaging Technique:</u>

110 kVp

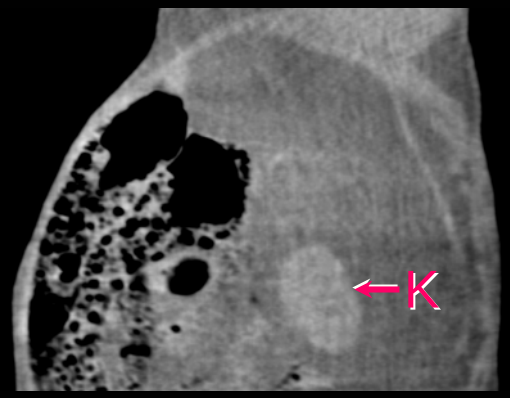
1 mAs / proj (512 x 512 x 384) voxels

N_{proj} = 300 T_{acq} ~ 10 s – 5 min

D_0 ~ 0.5 cGy T_{recon} ~ 12 min



Axial

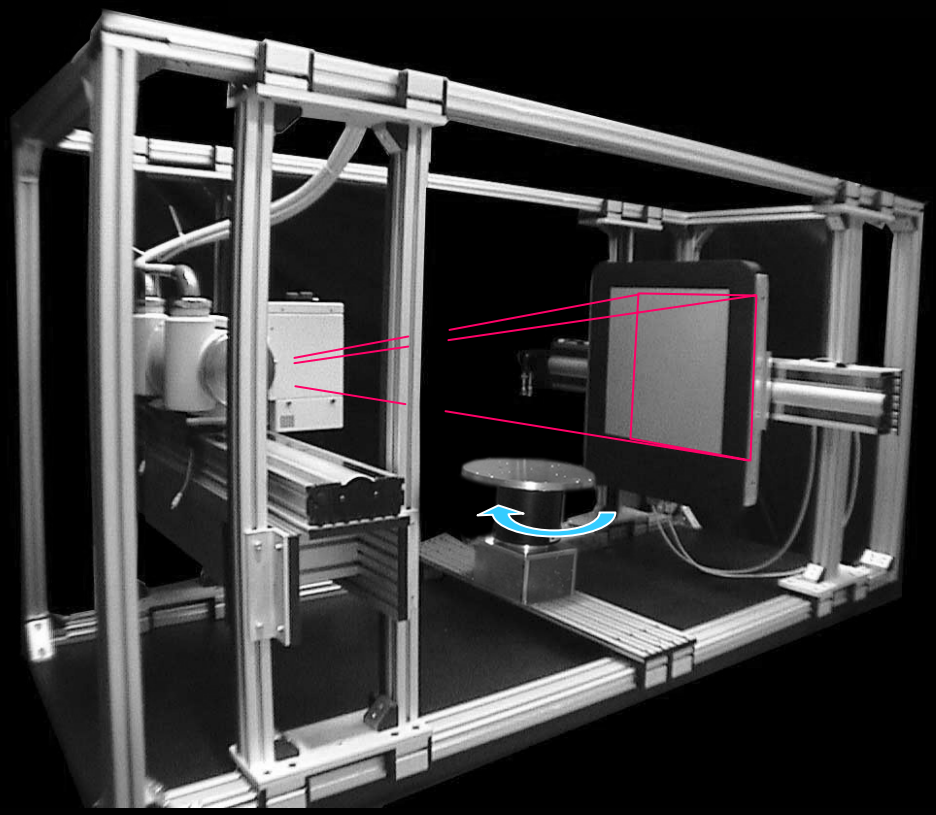


Sagittal

Coronal

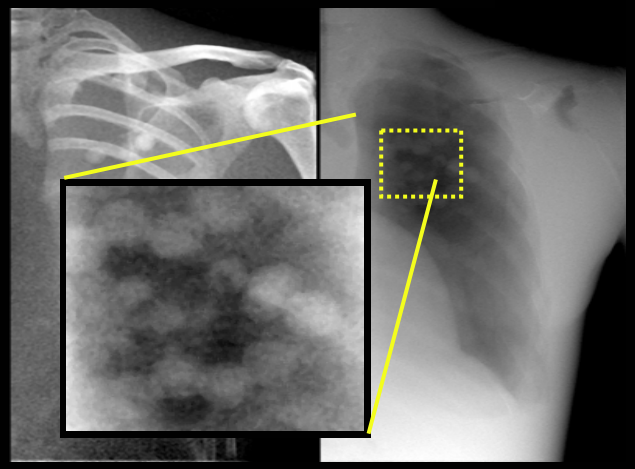
Siewerdsen and Jaffray, Princess Margaret Hospital, University of Toronto

Benchtop platform for advanced applications



Cone-Beam CT

Dual-Energy Imaging

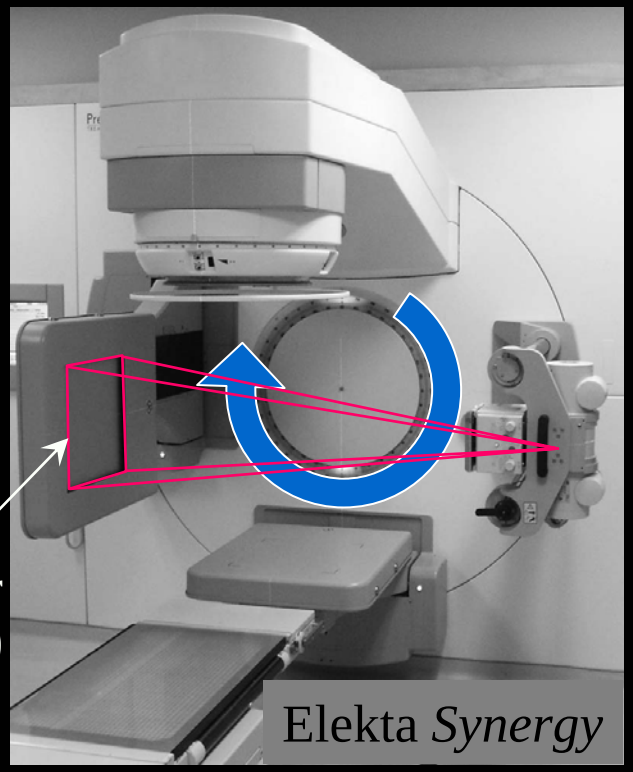


Bone Image Tissue Image

Siewerdsen and Jaffray, Princess Margaret Hospital, University of Toronto

Flat-Panel Cone-Beam CT

- A promising modality for IG procedures
  - Multi-mode Rad / Fluoro / CBCT
  - Open geometry; Mechanically simple



Linac Platform for
IG Radiation Therapy

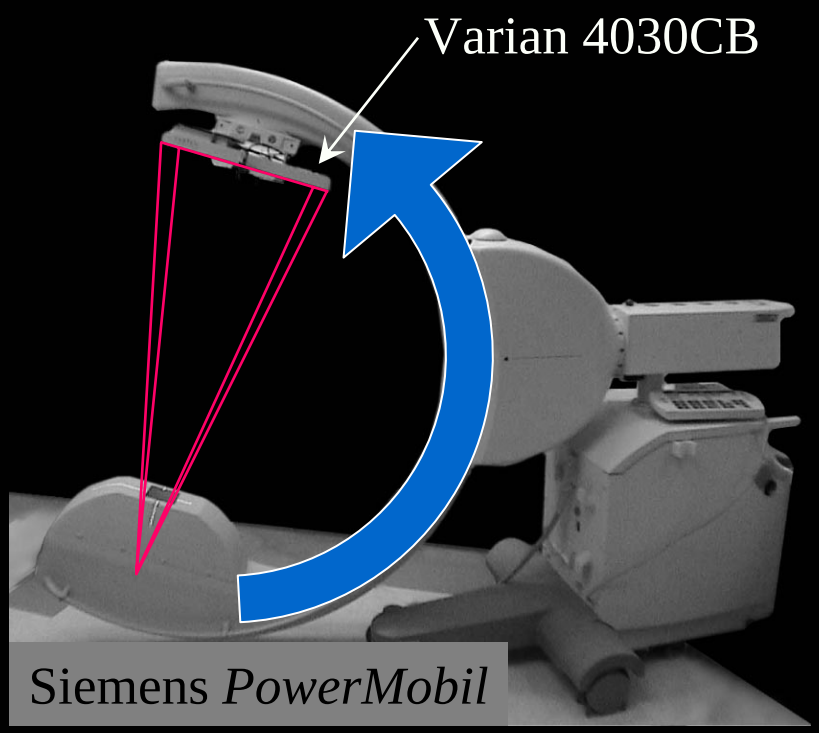
IGRT of
<u>the Prostate:</u>

N_{proj} = 330
T_{acq} = 2 min
512^3 voxels
D_0 = 1.1 cGy

Siewerdsen and Jaffray, Princess Margaret Hospital, University of Toronto

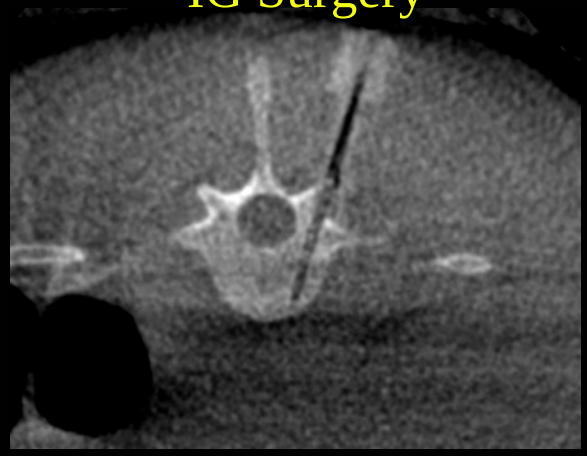
Flat-Panel Cone-Beam CT

- A promising modality for IG procedures
  - Multi-mode Rad / Fluoro / CBCT
  - Open geometry; Mechanically simple



Isocentric C-arm for IG Surgery

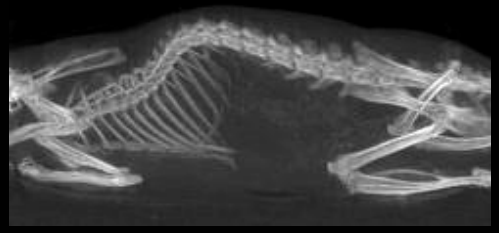
IG Surgery

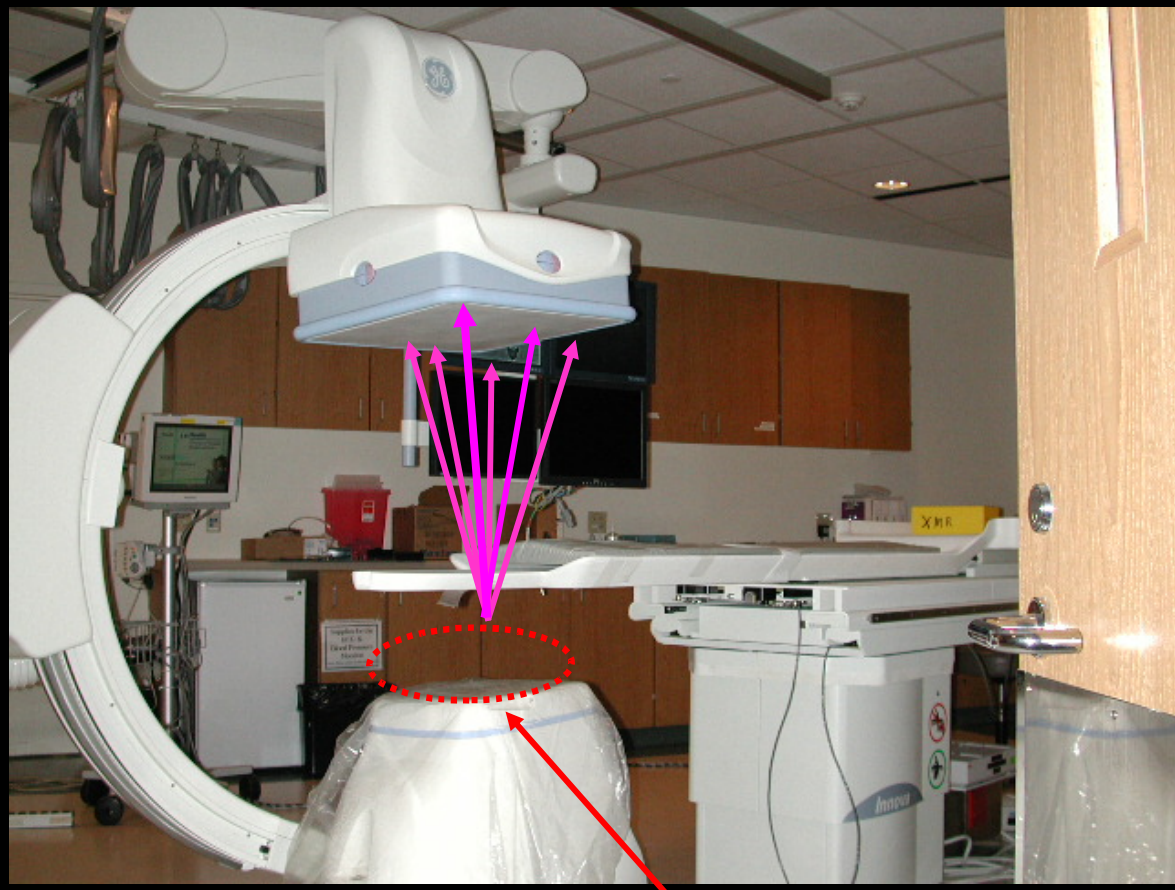


Siewerdsen and Jaffray, Princess Margaret Hospital, University of Toronto

Evaluation of interventional procedures using C-arm based tomosynthetic perfusion imaging

Initial CBCT recons





Chen, et.al

State-of-the-art cone-beam image reconstruction algorithms via filtered backprojection (FBP)

A. Katsevich, SIAM J. APPL. MATH, Vol. 62,2012-2026(2002);

A. Katsevich, Phys. Med. Biol., Vol.47, 2583-2597(2002)

Y. Zou, and X. Pan, Phys. Med. Biol., Vol. 49 ,2717-2731(2004);

E. Sidky, Y. Zou, and X. Pan, Proc. 8th Fully 3D Conference, Salt Lake City,291-294 (2005) .

G.H. Chen, T. Zhuang, B.E. Nett, S. Leng, Proc. 8th Fully 3D Conference, Salt Lake City,295-299 (2005) .

T. Zhuang, B. E. Nett, S. Leng, G. H. Chen, Proc. 8th Fully 3D Conference, Salt Lake City,337-341 (2005) .

J. D. Pack and F. Noo, Proc. 8th Fully 3D Conference, Salt Lake City,287-290 (2005)

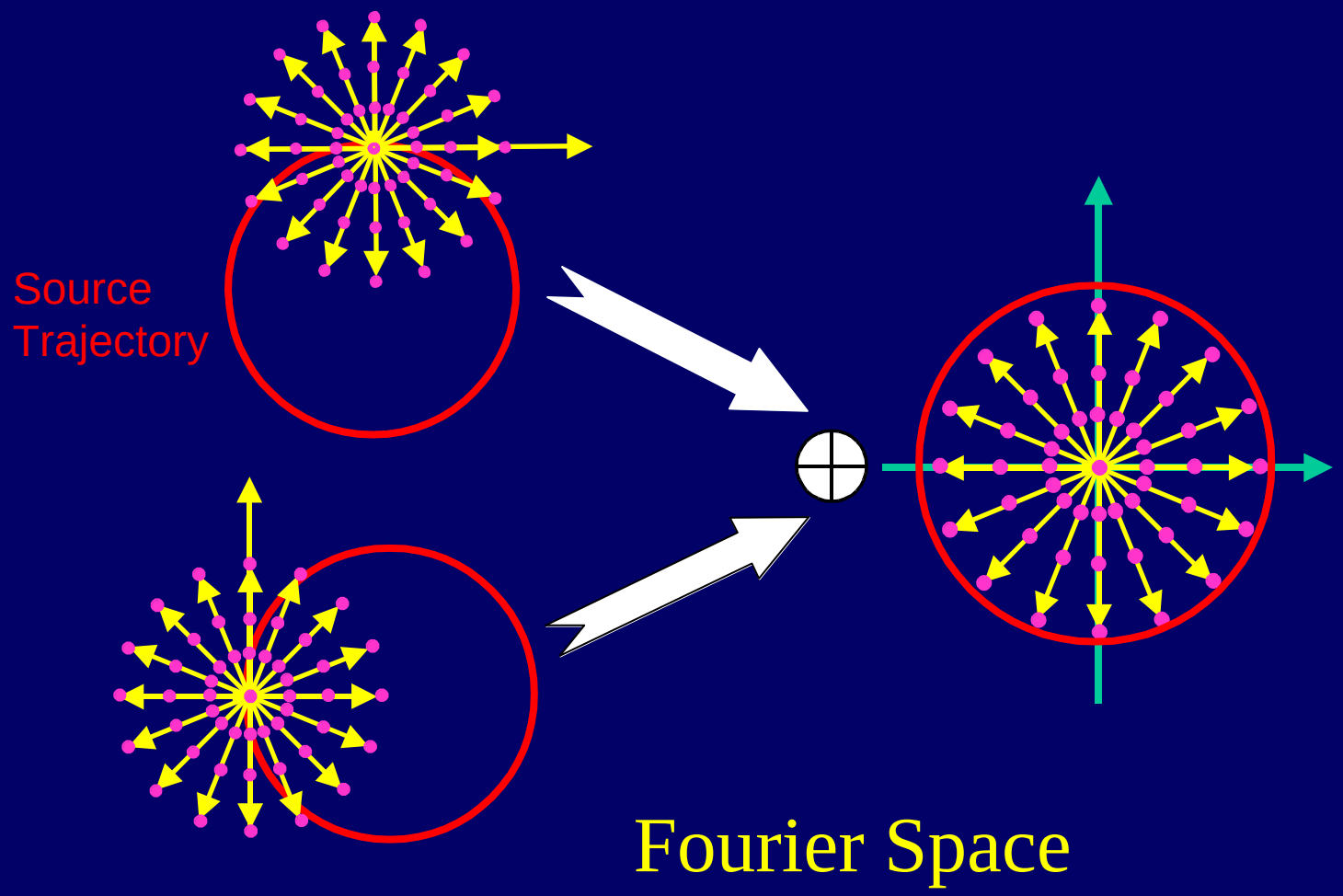
State-of-the-art cone-beam image reconstruction algorithms via filtering the backprojection image of differentiated projection data (FBPD)

1. Zou and Pan, Phys. Med. Biol., Vol. 49: 941-959(2004);

2. Zhuang, Leng, Nett, and Chen, Phys. Med. Biol., Vol.49:5489-5503(2004);

3. Pack, Noo, and Clackdoyle, IEEE Trans. Med. Imaging, Vol.24:70-85 (2005).

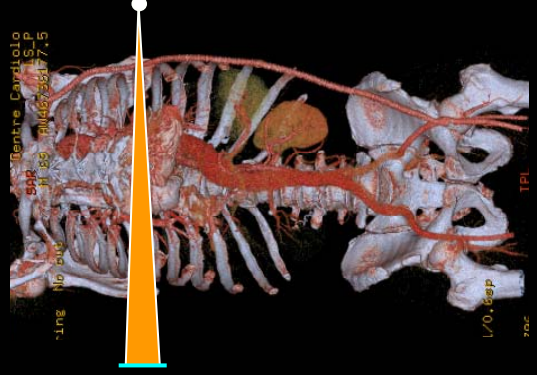
EXTENSION OF CENTRAL SLICE THEOREM TO CONE BEAM GEOMETRY



The Fourier transform of an image object is a weighted sum over the source trajectory of translated Fourier transforms of the 1/r weighted backprojection data.

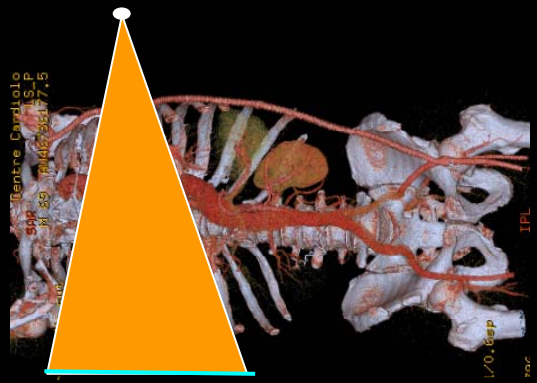
Chen et. Al.

Extension of Undersampled 3D Acquisition to X-Ray CT?



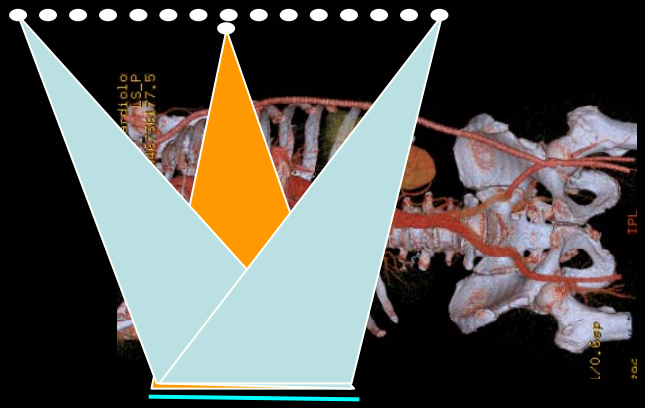
CT detectors

64 slice CT
4mm coverage
~2000 focal spots/s
ΔT (coronaries)~ 150ms



Flat Panel

Flat panel Cone Beam CT
400mm coverage
~30 focal spots/s

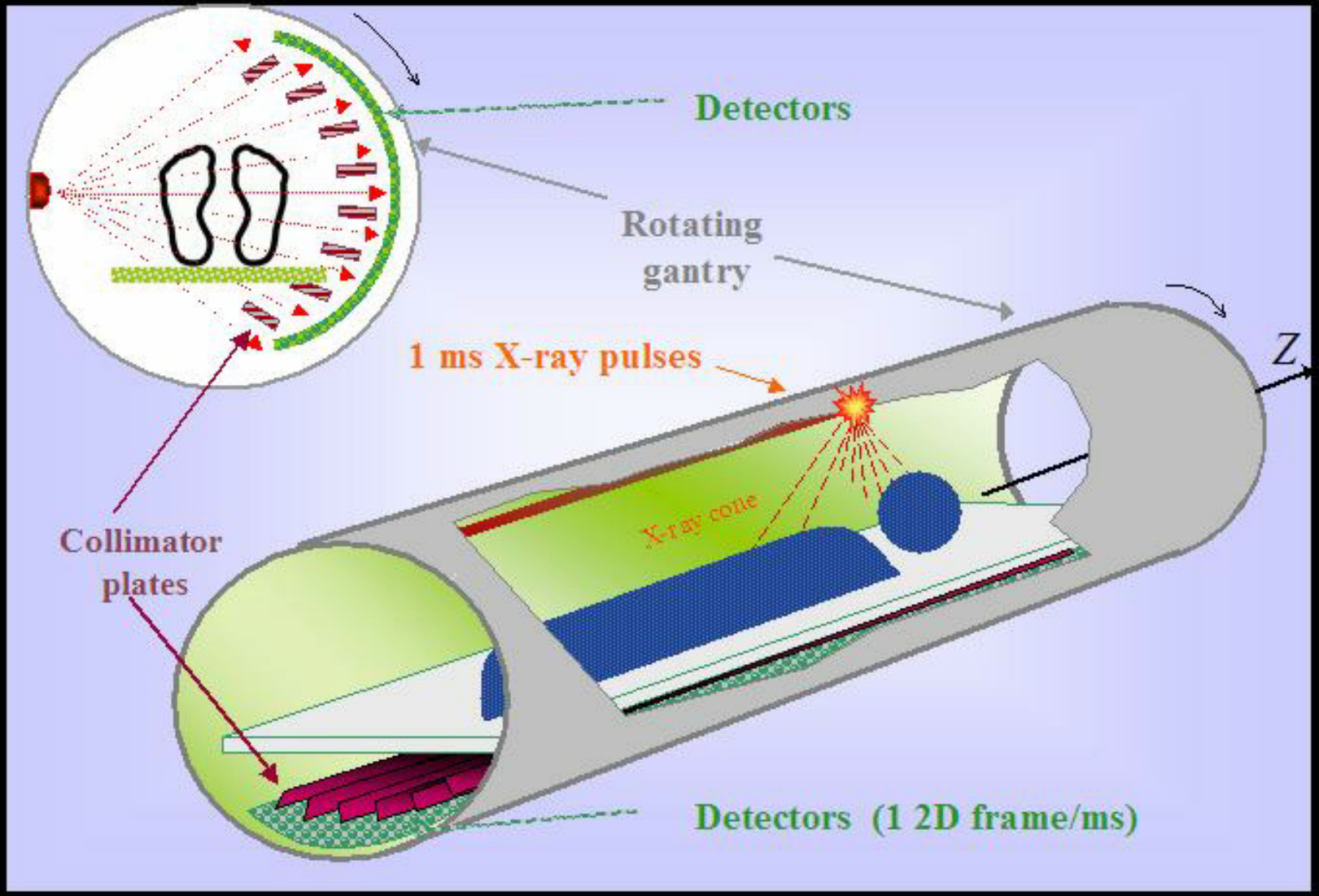


CT detectors

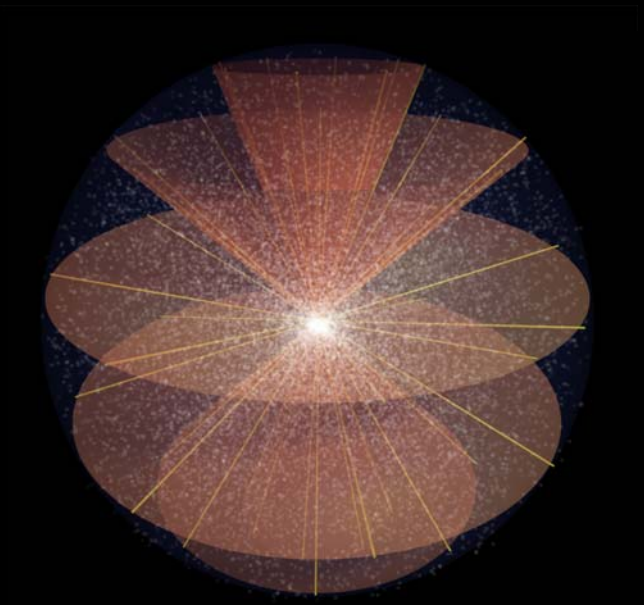
Z scan CT 15 sources
400mm coverage
~2000 focal spots/s
ΔT (coronaries)~ 10-15ms*

Design goal

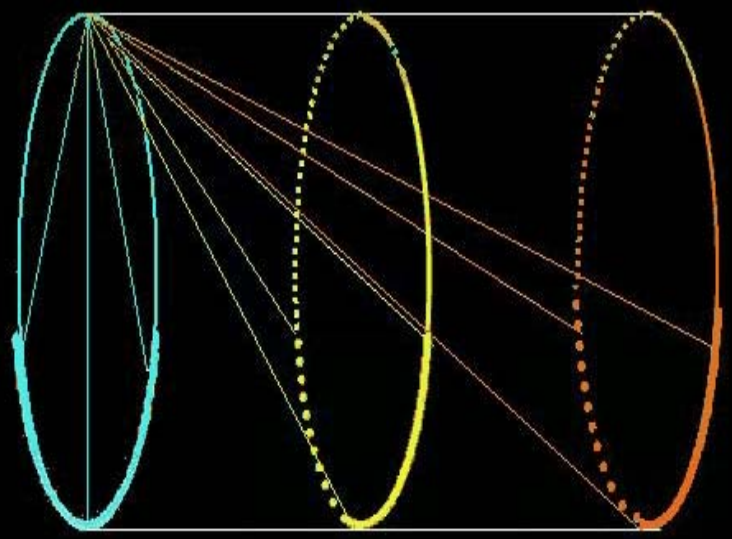
Z-Scan X-Ray CT

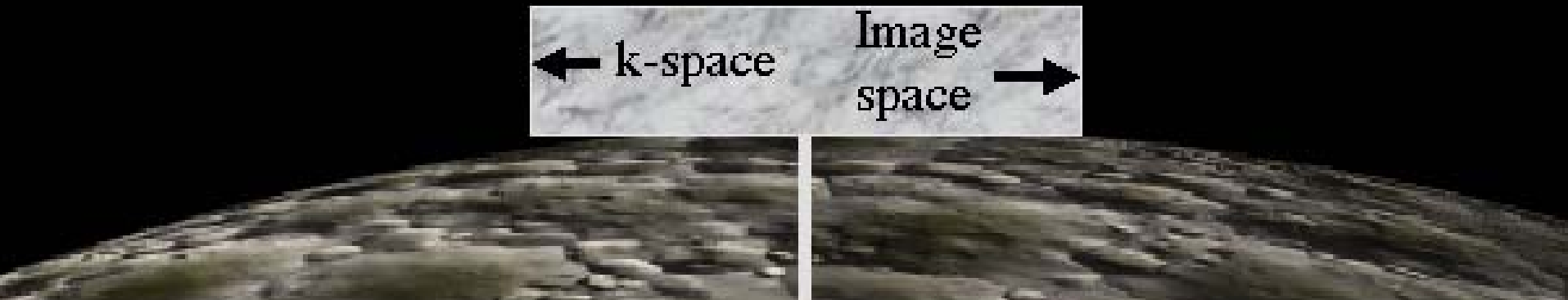


VIPR

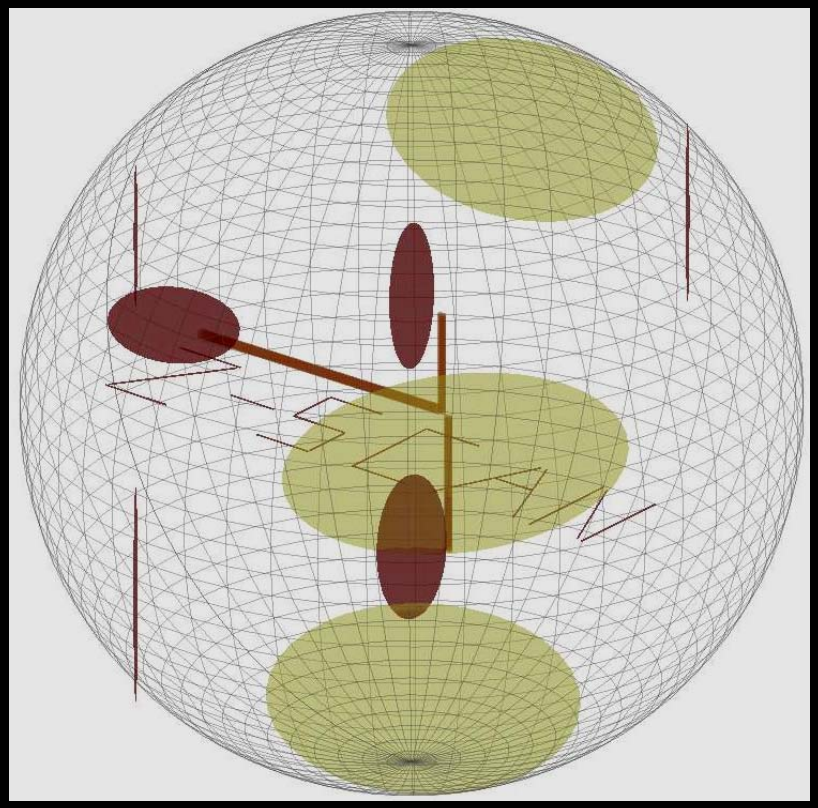


X-ray CT





“Z-Scan”
Simulation Phantom



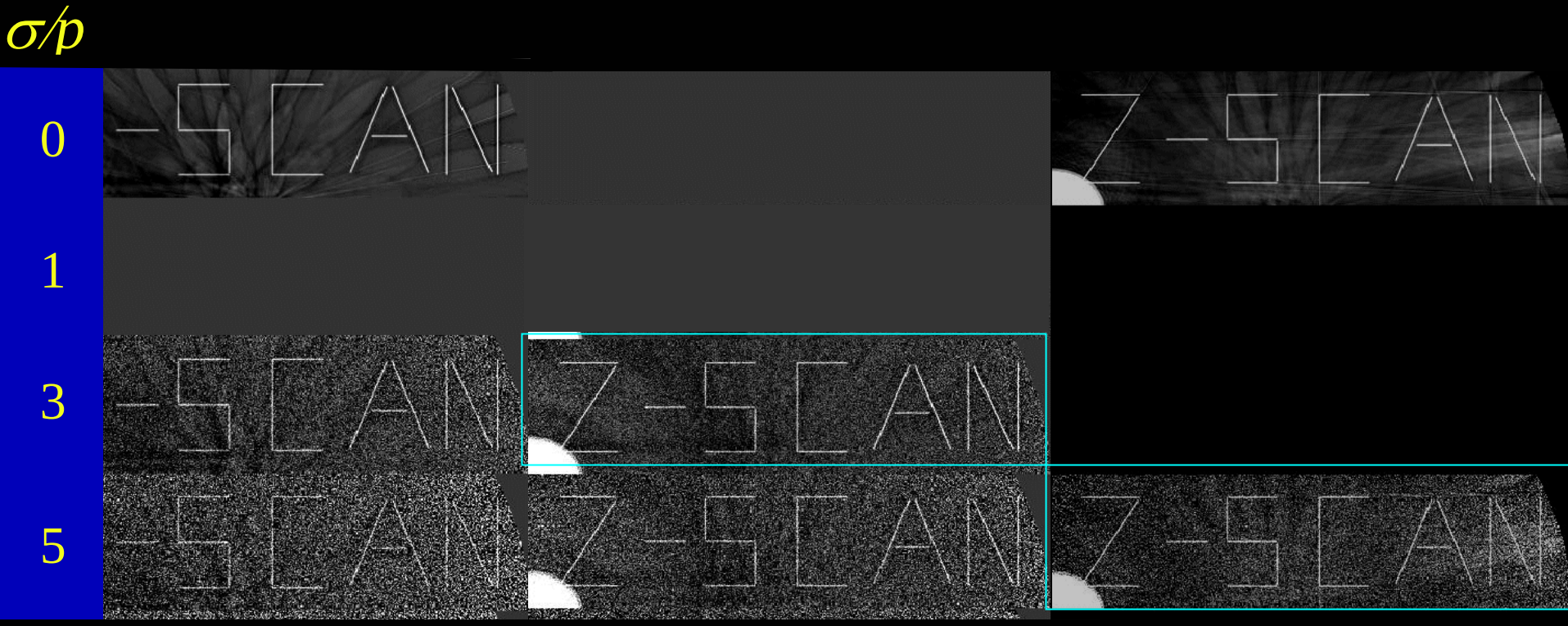
“Z-Scan” signal = attenuation in 1mm vessel following IV iodine

Focal sphere diameter: 600 mm

Gaussian noise added

Noise unit σ = attenuation made by “Z-Scan” feature

Simulated 1mm coronary artery imaged in 10 ms using iv injection and gating



100 **200** **300**

No. of focal spots

*Assuming Nyquist
Speed Limit of 70 mph

Speed Limit
70mph

HYPR VIPR
Speed
35,000 mph*

Zscan CT
Road Under
Construction

With thanks for slides and videos from

Guang-Hong Chen

Brian Nett

Jeff Siewerdsen

Dan Sodickson

Steve Wright

Ruola Ning

Jiang Hsieh

Dennis Foley

Willi Kalender