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ILLINOIS
UNIVERSITY**

**A LOW-DOSE, ACCURATE MEDICAL
IMAGING METHOD FOR PROTON THERAPY:
PROTON COMPUTED TOMOGRAPHY**

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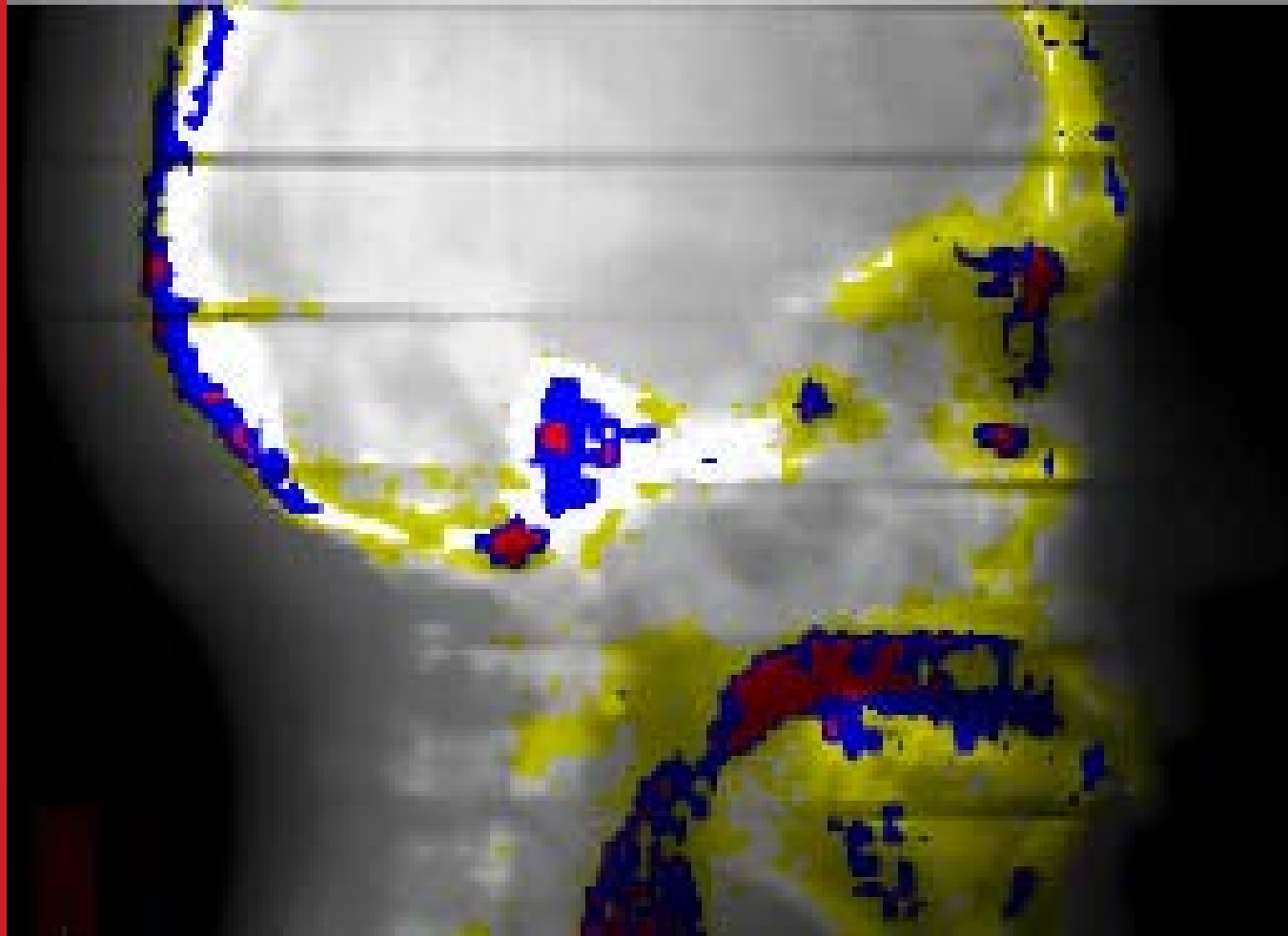
OUTLINE

- The main idea
- A little history
- The fundamentals
- Current status
- Summary

THE MAIN IDEA

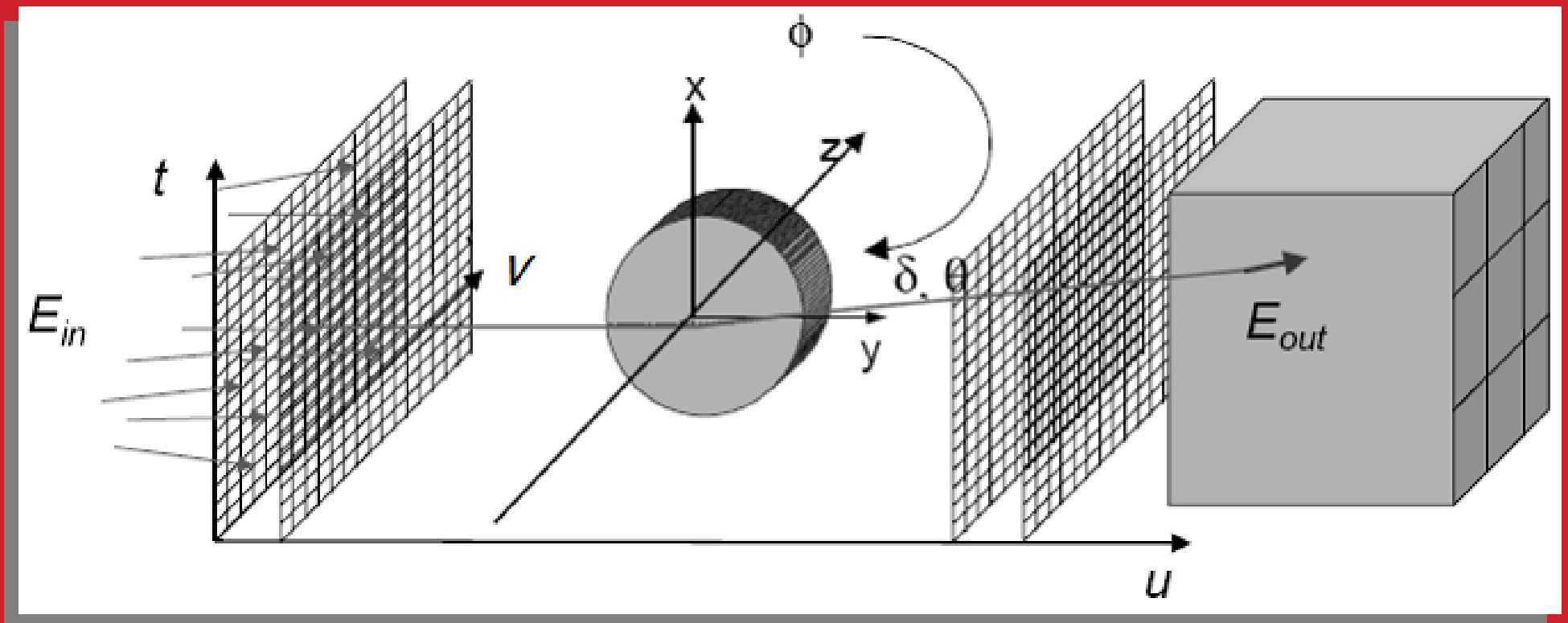
- For proton therapy, one positions the Bragg peak onto the tumor
- For pCT, raise the initial energy so protons traverse the object to be imaged
- Measure the phase space data of each proton individually
- Use this data to construct the electron density map of the object traversed by protons
- Use the resulting electron density map for diagnosis, proton therapy treatment plan, adaptive treatment, positioning verification, etc.

MOTIVATION: RANGE UNCERTAINTIES



Schneider U. (1994), "Proton radiography as a tool for quality control in proton therapy," Med Phys. 22, 353.

OVERVIEW



ADVANTAGES AND BENEFITS

- Practically *eliminates range uncertainties*, therefore allowing *very accurate and precise proton treatment plans*
- Provides *fast patient positioning verification* and *adaptive treatments*, if necessary
- Achieves a *reduced dose necessary for imaging* relative to XCT
- Provides a *quantification of the range uncertainties* as a function of tumor site, type, etc. that will be *useful to any proton therapy facility* in operation that lacks a pCT system.

HISTORY OF PCT (1)



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Representation of a Function by Its Line Integrals, with Some Radiological Applications

A. M. CORMACK

Physics Department, Tufts University, Medford, Massachusetts

(Received 28 January 1963; in final form 26 April 1963)

A method is given of finding a real function in a finite region of a plane given its line integrals along all straight lines intersecting the region. The solution found is applicable to three problems of interest for precise radiology and radiotherapy: (1) the determination of a variable x-ray absorption coefficient in two dimensions; (2) the determination of the distribution of positron annihilations when there is an inhomogeneous distribution of the positron emitter in matter; and (3) the determination of a variable density of matter with constant chemical composition, using the energy loss of charged particles in the matter.

virtually no ionization beyond the end of the range. Both of these of importance in therapy as was pointed out by R. R. Wilson (16) and as has been shown by treatments of a number of different conditions at Uppsala, Harvard and Berkeley. In fact, protons are far superior to X-rays for the treatment of some conditions. So one can envisage a large metropolitan area as having a 250 MeV proton accelerator with a number of different ports, say ten, at which patients could be treated simultaneously (17). If one of these ports was devoted to proton tomography, the marginal cost of such tomography would not be great. In exploring these possibilities it is essential that diagnostic radiologists and therapeutic radiologists work together.

HISTORY OF PCT (2)

- In the late 1970s, Ken Hanson (LANL) and Kramer et al. (ANL) experimentally explored the advantages of pCT and proton radiography
- They pointed out the dose reduction w.r.t. XCT and the problem of limited spatial resolution due to proton scattering
- In the 1990s Ron Martin (ANL) proposed building a proton CT system using a scanning beam proton gantry
- During the 1990s Uwe Schneider (PSI) further developed the idea of proton radiography as a tool for quality control in proton therapy
- In the late 1990s Piotr Zygmanski (MGH) Harvard Cyclotron tested a cone beam CT system with protons
- pCT Collaboration (2003-)

THE FUNDAMENTALS (1)

The Bethe-Bloch formula gives the mean energy loss rate of protons in a medium

$$-\frac{dE(\vec{r})}{dl} = \eta_e(\vec{r}) F(I(\vec{r}), E(\vec{r}))$$

$$F(I(\vec{r}), E(\vec{r})) = K \frac{1}{\beta^2(E)} \left[\ln \left(\frac{2m_e c^2}{I(\vec{r})} \frac{\beta^2(E)}{1 - \beta^2(E)} \right) - \beta^2(E) \right]$$

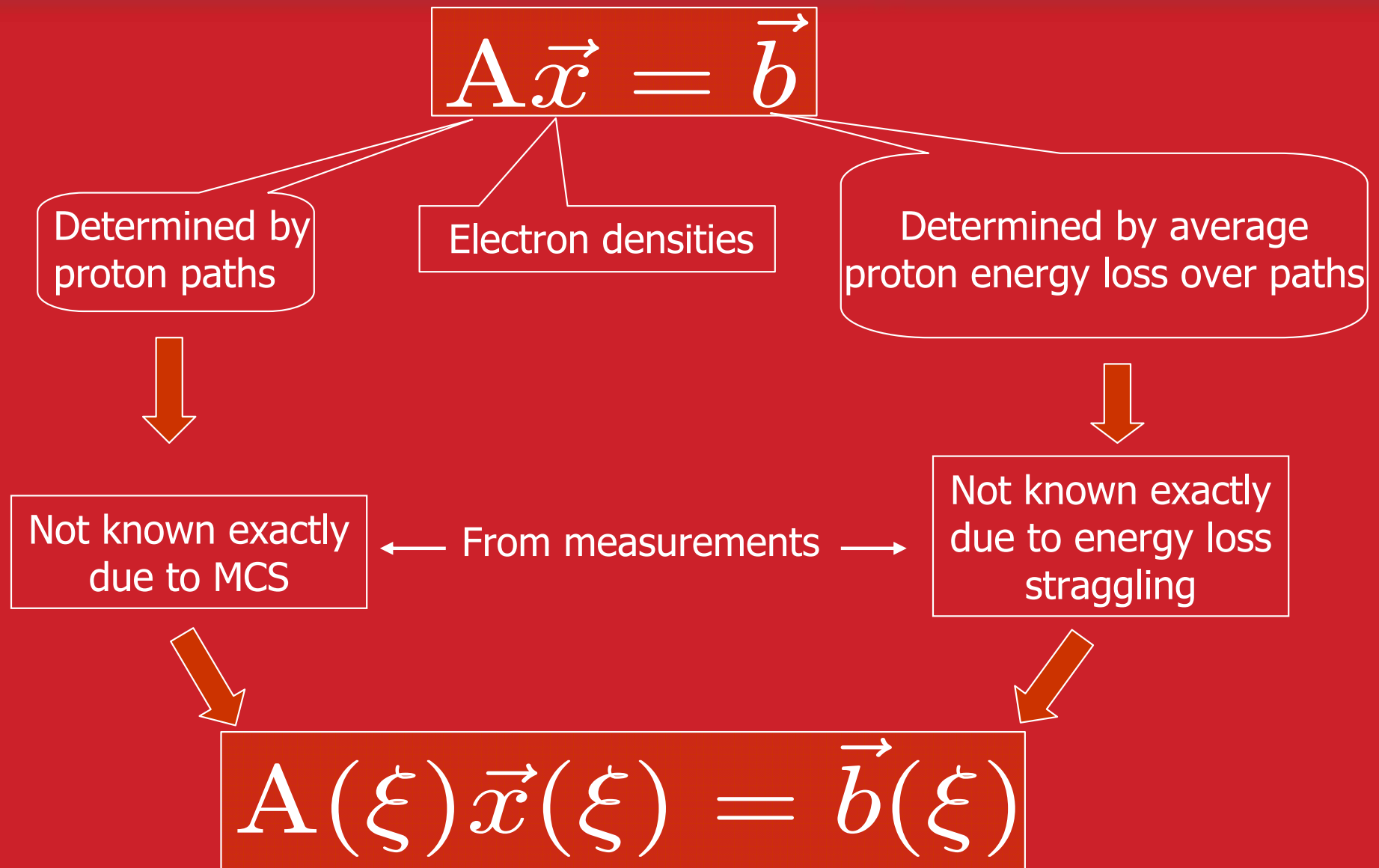
$$\int_0^L \eta_e(\vec{r}) dl = - \int_{E_0}^{E(L)} \frac{dE}{F(I(\vec{r}), E(\vec{r}))}$$

$$I(\vec{r}) \mapsto I_{water} \quad \Rightarrow \text{rhs is a numerical integration} \Rightarrow b_i, i = \overline{1, m}.$$

Discretize $\eta_e(\vec{r})$ over some basis functions (typically voxels) $\Rightarrow x_i, i = \overline{1, n}$.
Each proton will determine a linear equation in the variables x_i

$$\boxed{A\vec{x} = \vec{b}}$$

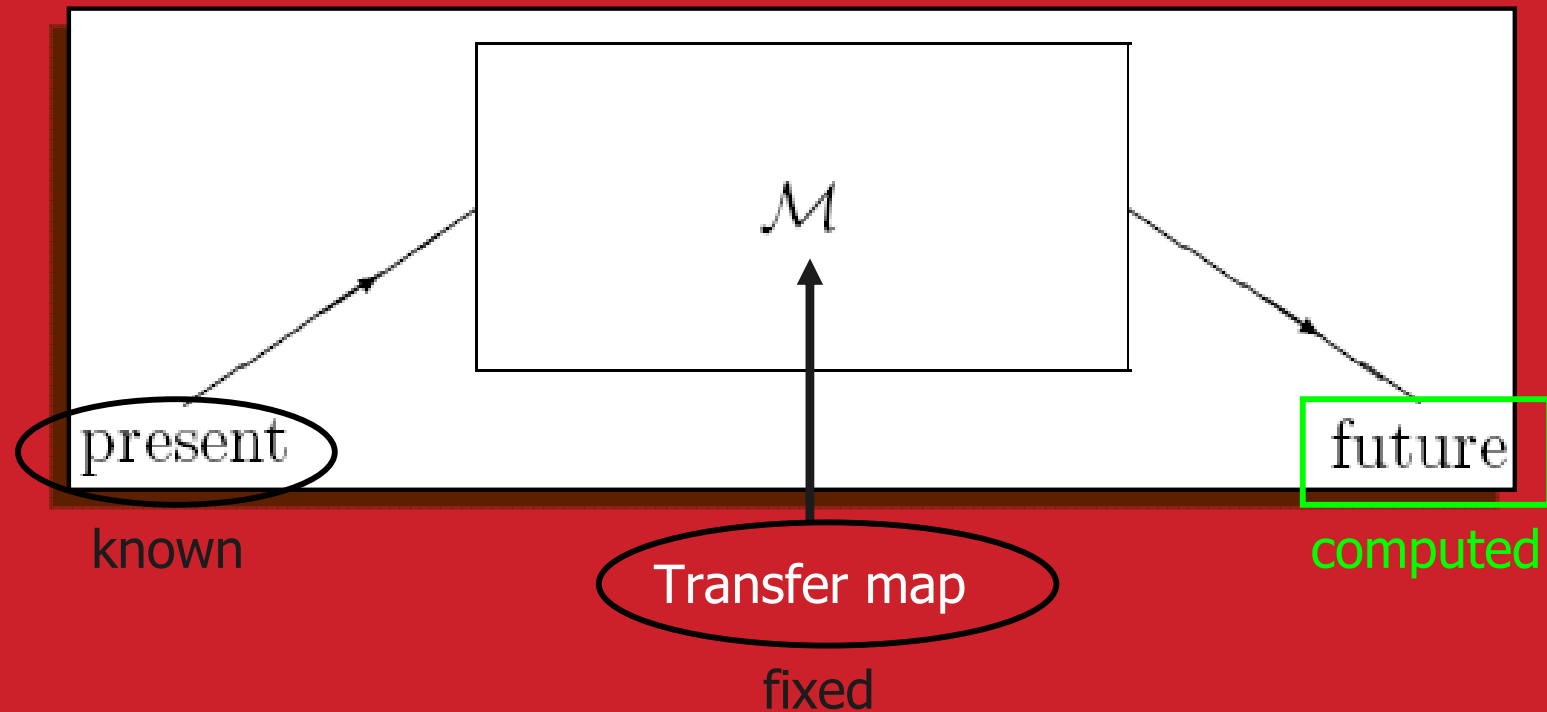
THE FUNDAMENTALS (2)



Random realization with ξ drawn from a probability distribution

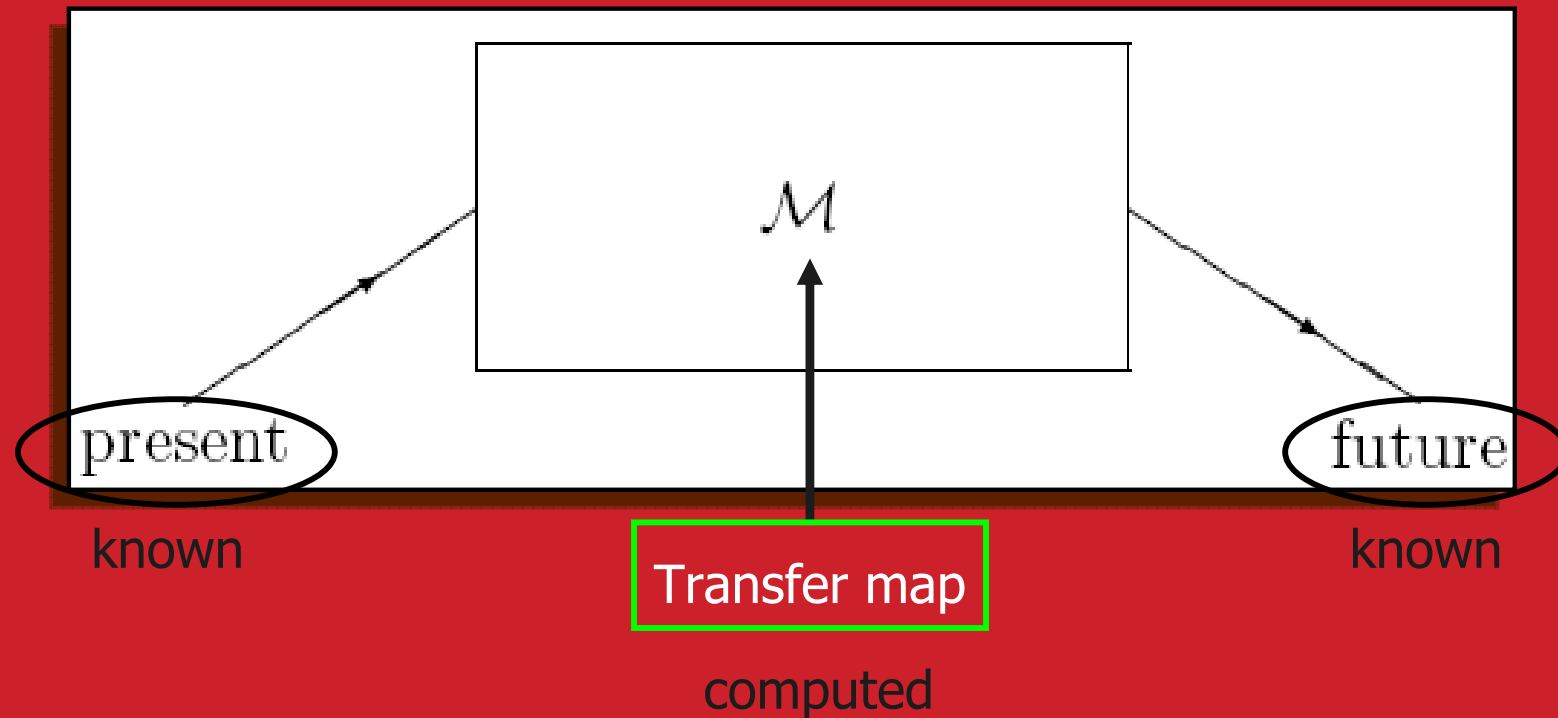
THE MOST LIKELY PATH

Deterministic systems



THE MOST LIKELY PATH

Stochastic systems



SPATIAL RESOLUTION (1)

A measure of our ability to predict each individual proton's trajectory inside the object to be imaged is the spatial resolution

Multiple Coulomb Scattering (MCS)

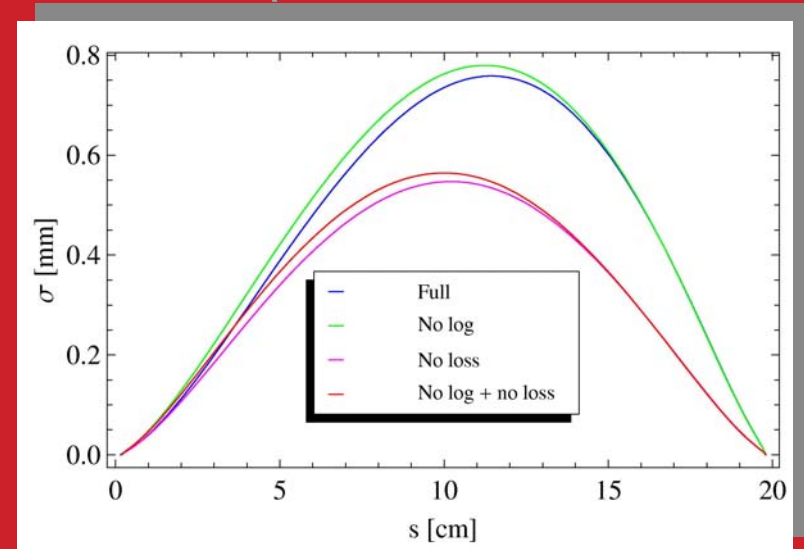
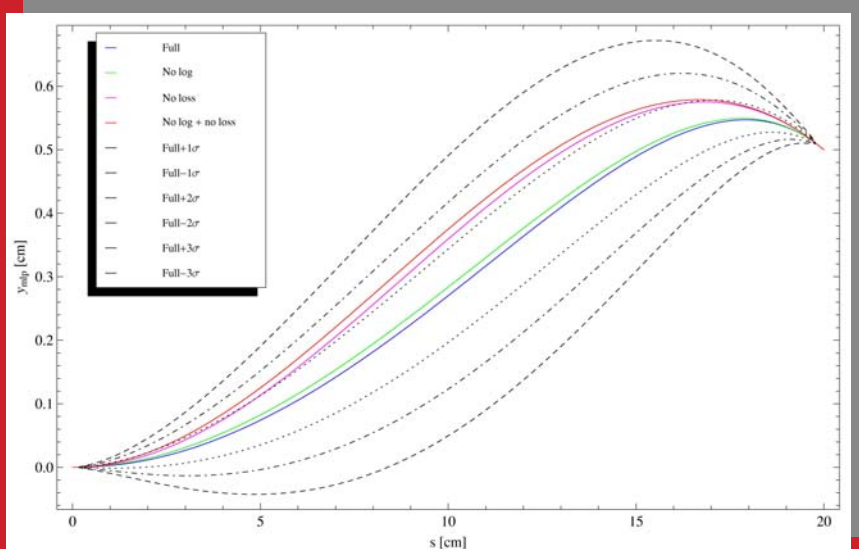
$$\sigma(l, E) = \frac{13.6 \frac{\text{MeV}}{c}}{\beta(E) p(E)} \sqrt{\frac{l}{X}} \left[1 + 0.038 \ln \left(\frac{l}{X} \right) \right]$$

Example: 200 MeV protons in 20cm of water have
 $\sigma = 39 \text{ mrad} \rightarrow \sigma_{\text{lat}} = 3.5 \text{ mm}$



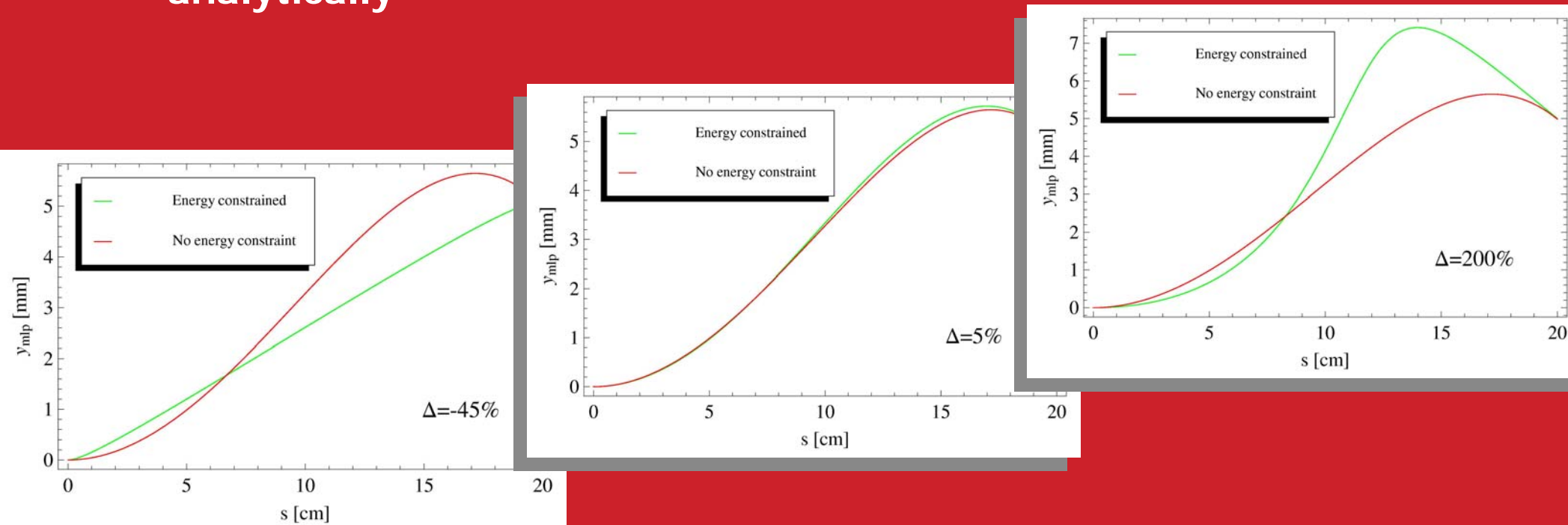
Use constraints to reduce uncertainty: position, direction, energy

The Most Likely Path (MLP)



SPATIAL RESOLUTION (2)

- Developed new formalism to include energy as a constraint
- Equivalently, it fixes the trajectory length
- Example: 2 protons, with exactly the same incoming energy, position, direction, and outgoing position and direction – but different outgoing energy
- Previous MLP formalism gives the same MLP, new one is different due to the different path lengths
- Also implies improved spatial resolution – difficult to compute analytically



ELECTRON DENSITY RESOLUTION (1)

$$A(\xi) \vec{x}(\xi) = \vec{b}(\xi)$$

A measure of our ability to predict \vec{x} from the random vector $\vec{x}(\xi)$ is the electron density resolution

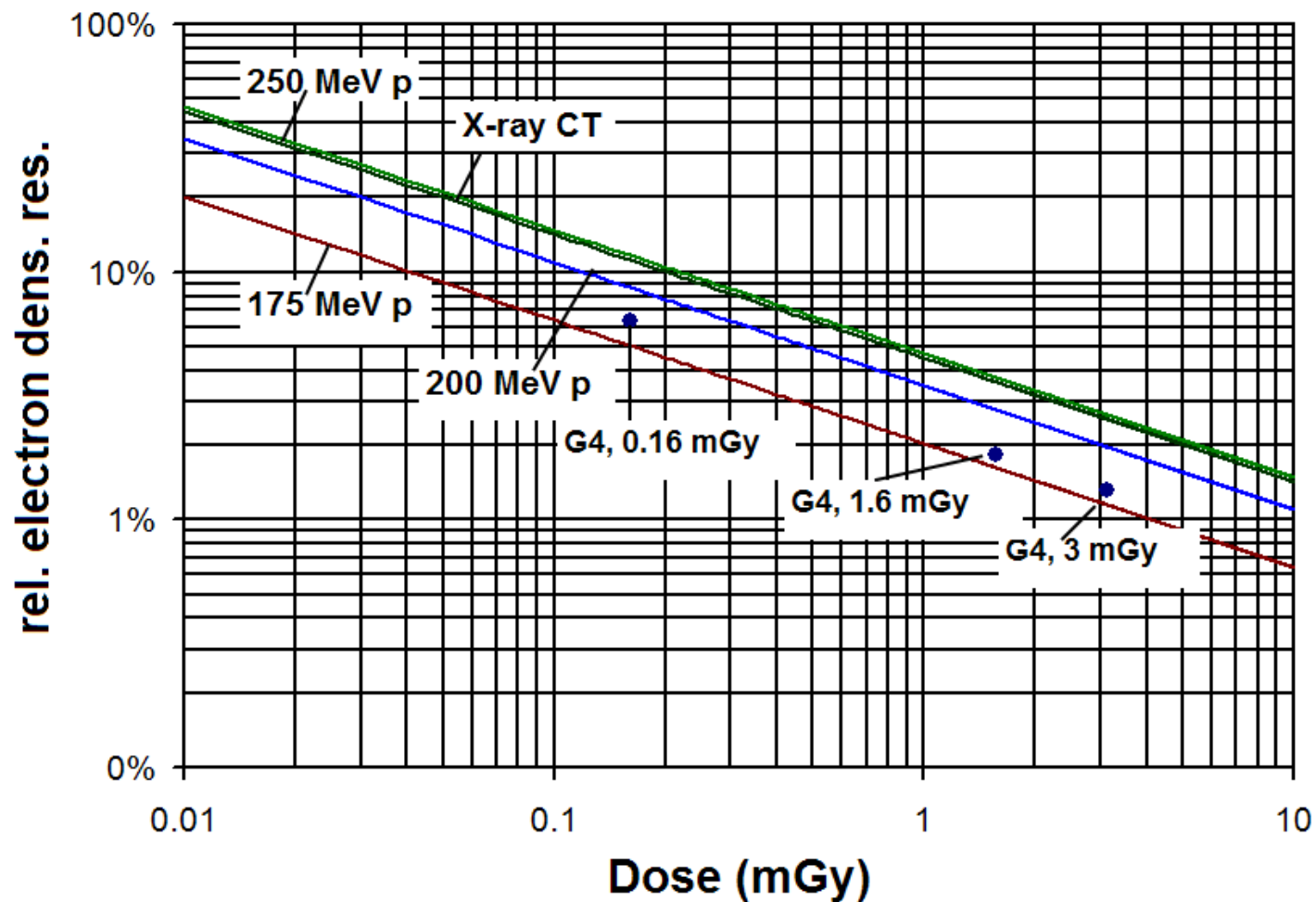
Definition:

$$\sigma_x = \sqrt{\frac{\sum_{i=0}^n \sigma_{x_i}^2(\xi)}{n}}$$



$$\sigma_x = g \frac{\sigma_{\langle E_{out} \rangle} k_A}{v F (\langle E_{out} \rangle) \sqrt{m_v}}$$

ELECTRON DENSITY RESOLUTION (2)



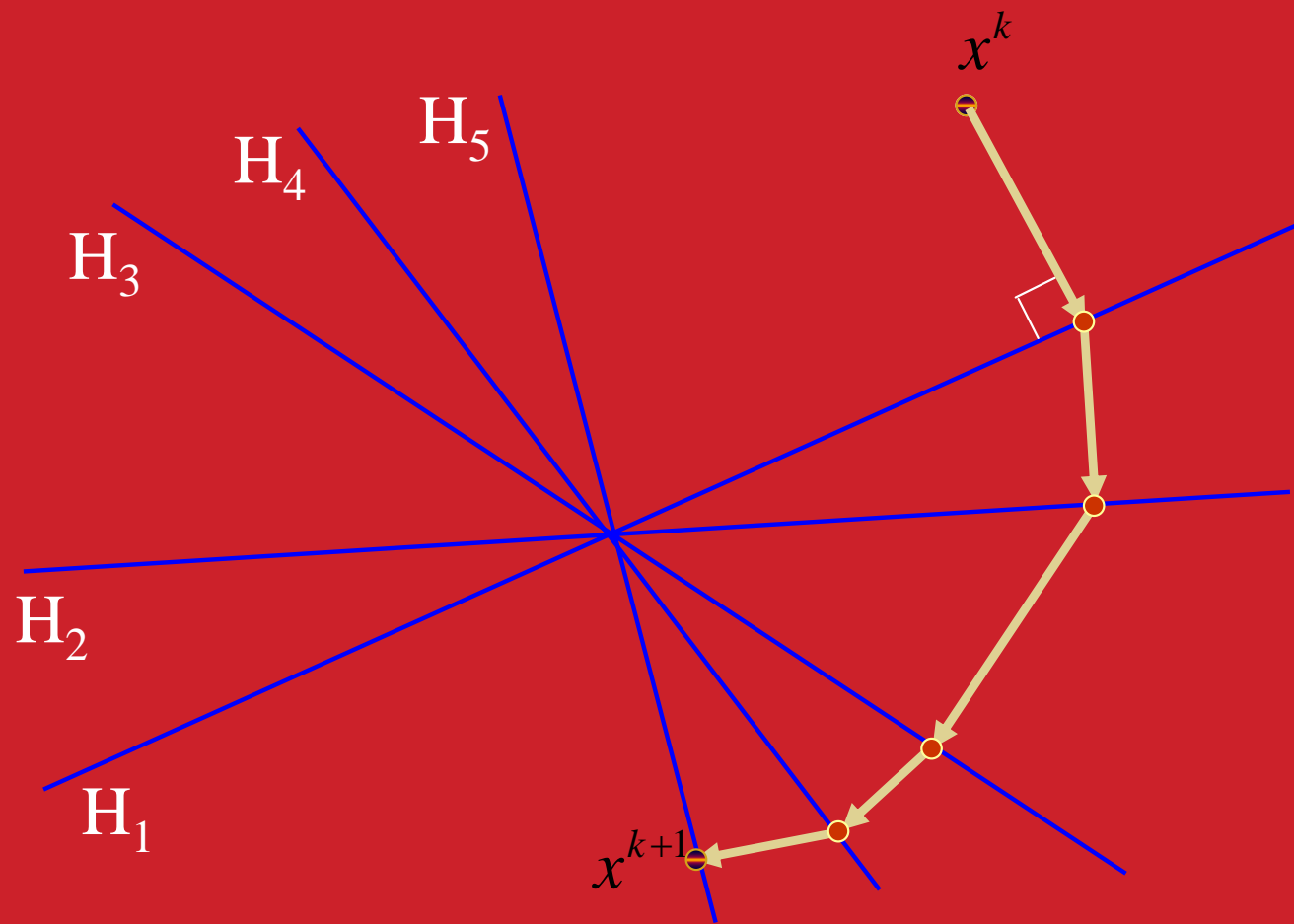
RECONSTRUCTION METHODS

Projection Methods

Basic property: To reach any goal that is related to the whole family of sets by performing projections onto the individual sets.

Basic ability: To handle huge-size problems whose dimensions are beyond the capabilities of current, more sophisticated, methods.

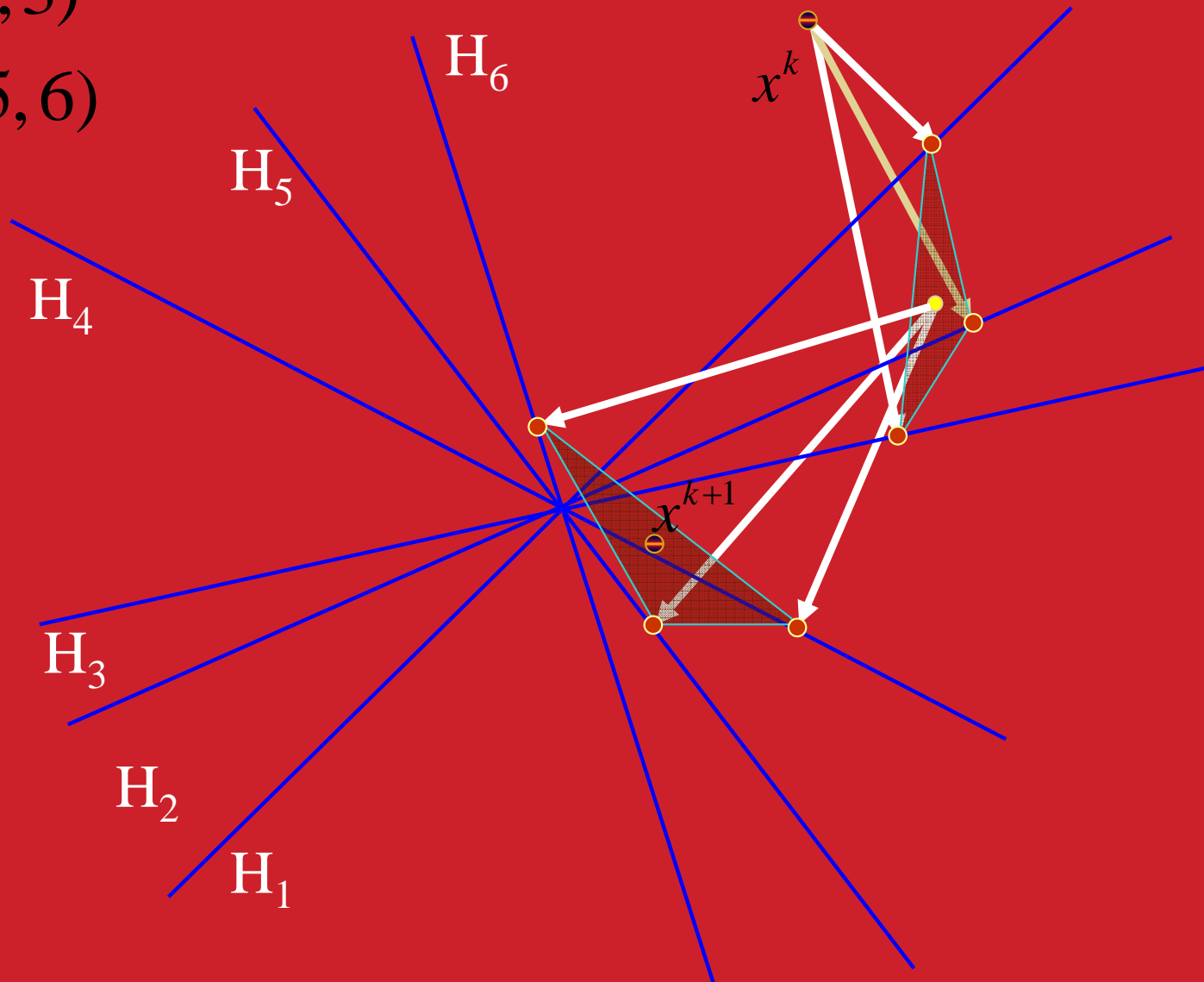
ALGEBRAIC RECONSTRUCTION TECHNIQUE



BLOCK ITERATIVE PROJECTION

$$B_1 = (1, 2, 3)$$

$$B_2 = (4, 5, 6)$$

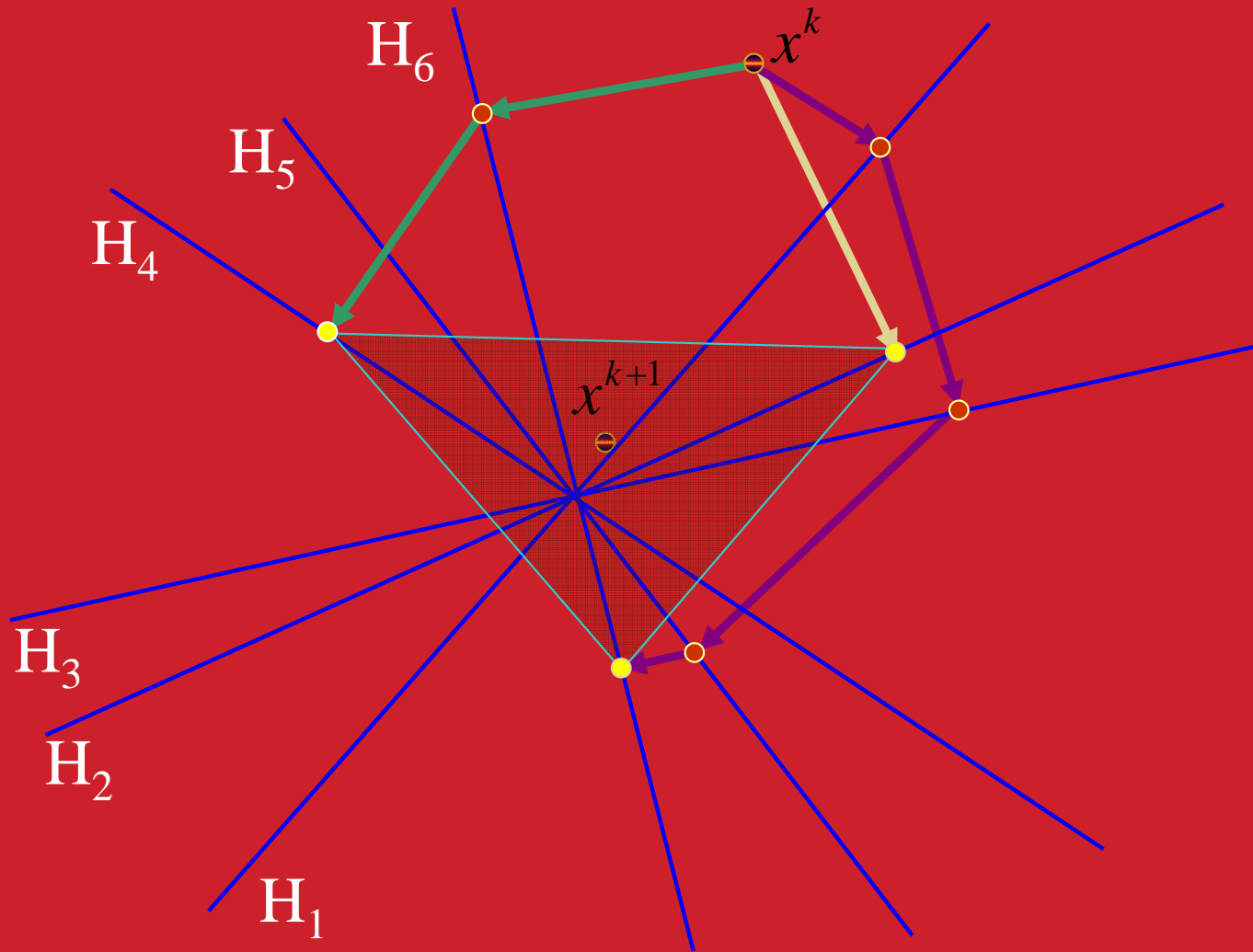


STRING AVERAGING

$$I_1 = (1, 3, 5, 6)$$

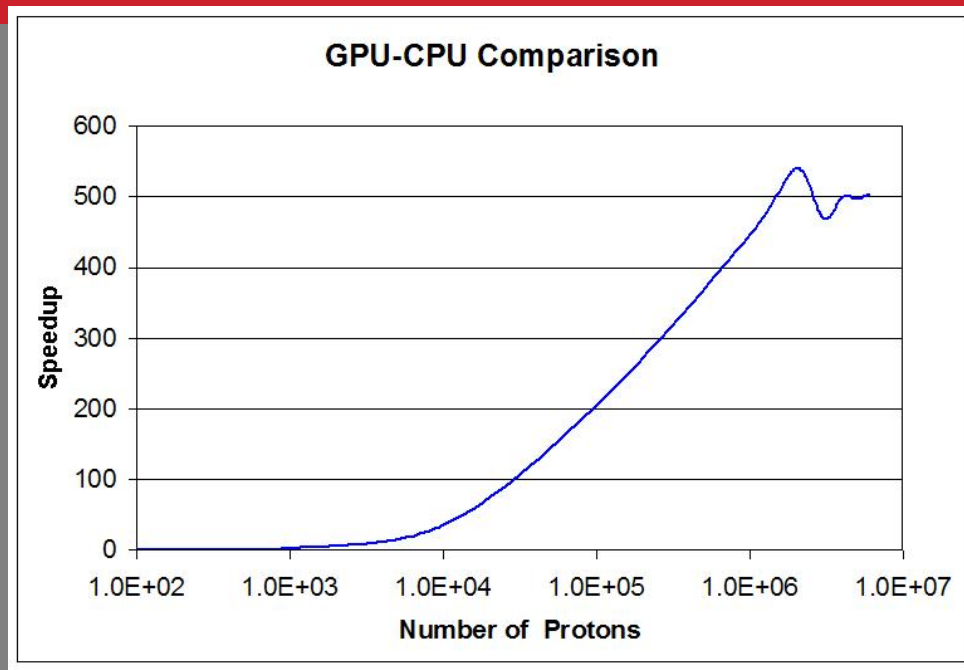
$$I_2 = (2)$$

$$I_3 = (6, 4)$$



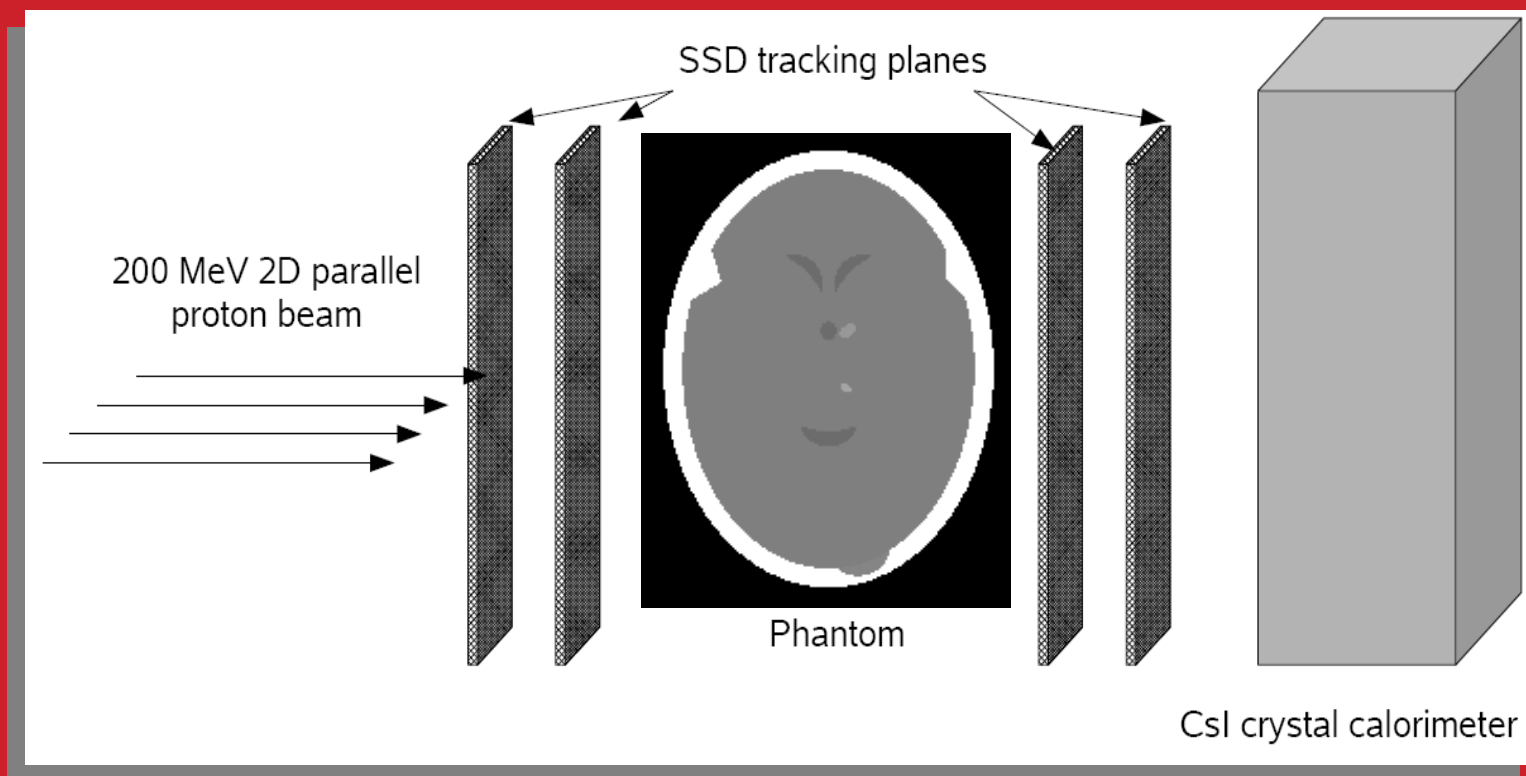
HARDWARE IMPLEMENTATION

- Desktop/laptop
- Compute Clusters
- GP-GPU
- GP-GPU clusters
- Hybrid: multi-core CPUs + GP-GPUs (clusters)

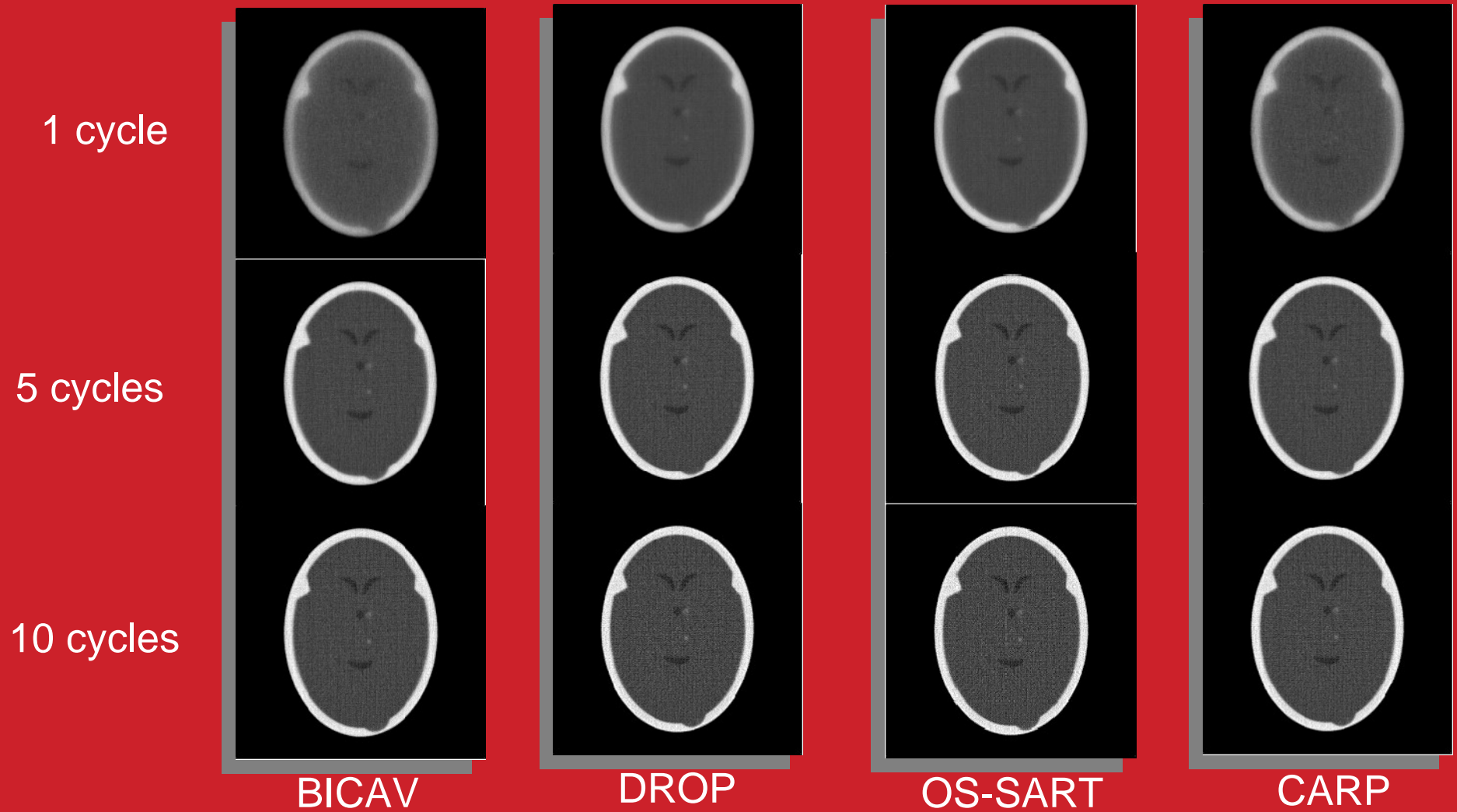


Speedup of the rel. electron density calculation when performed with a NVIDIA GTX280 GPU relative to a Intel Q6600 quad core CPU (Scott McAllister, Master's Thesis, Cal State SB, 2009)

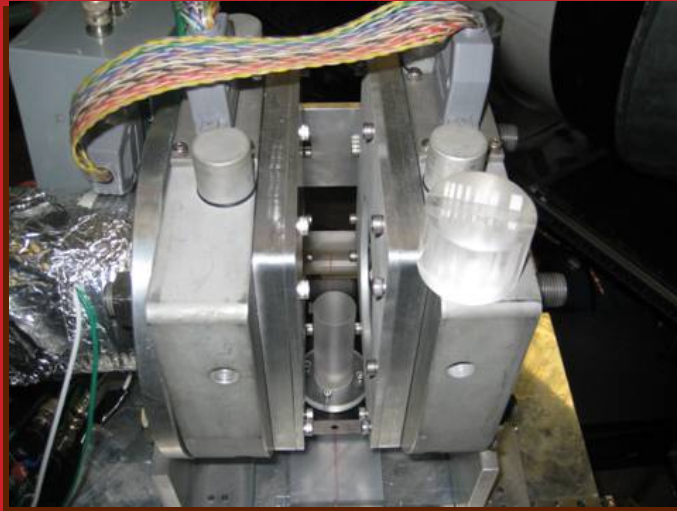
GEANT4 SIMULATIONS



RECONSTRUCTION RESULTS FROM SIMULATIONS



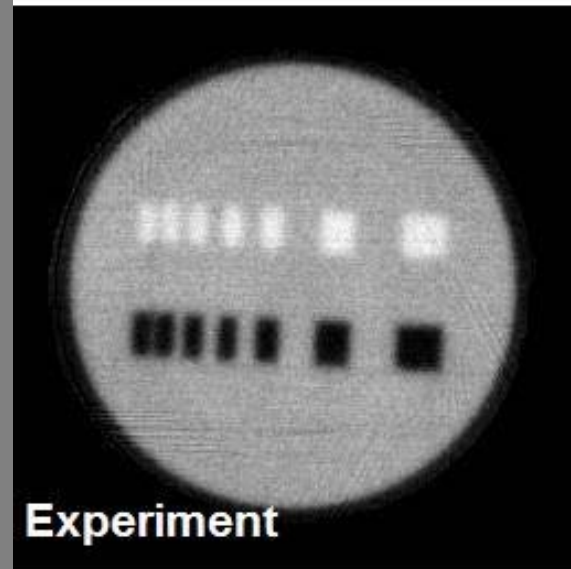
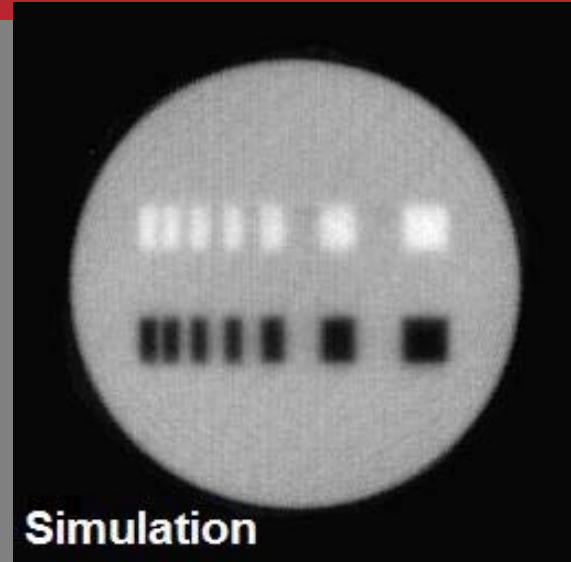
RECONSTRUCTION RESULTS FROM REAL DATA



pCT prototype

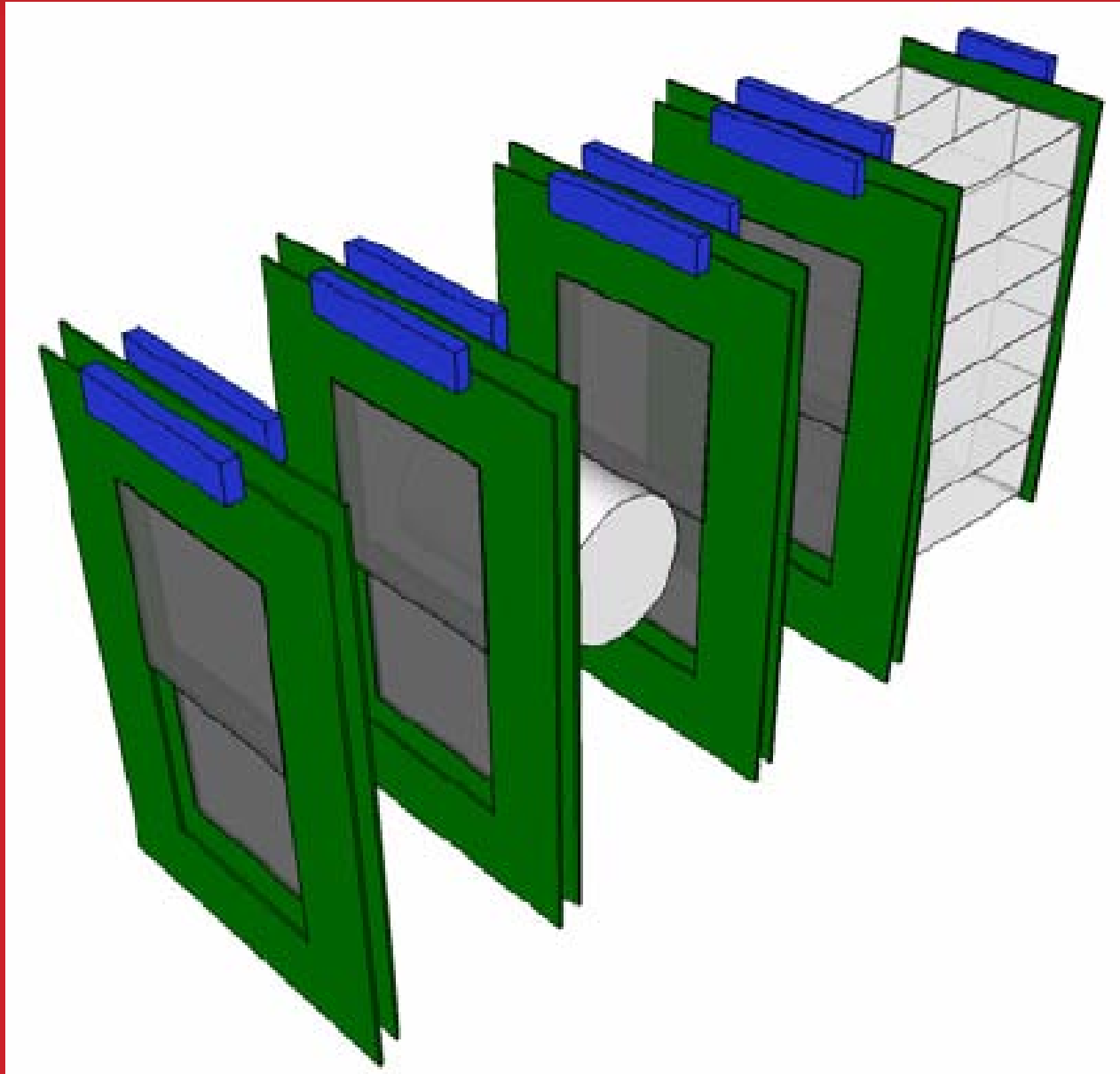


pCT phantom

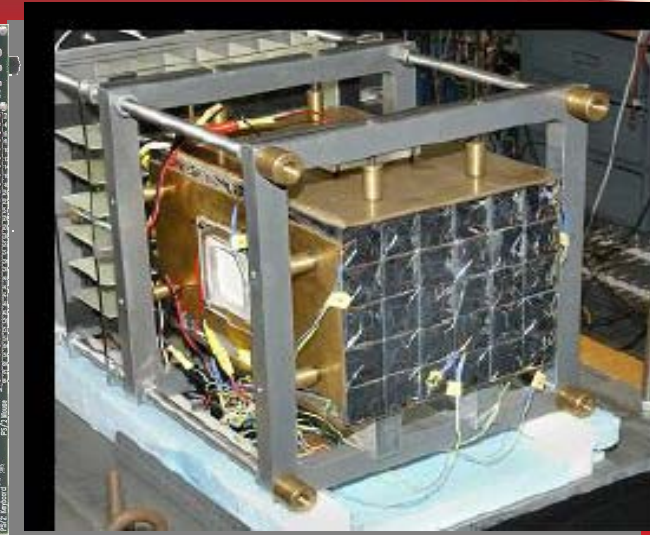
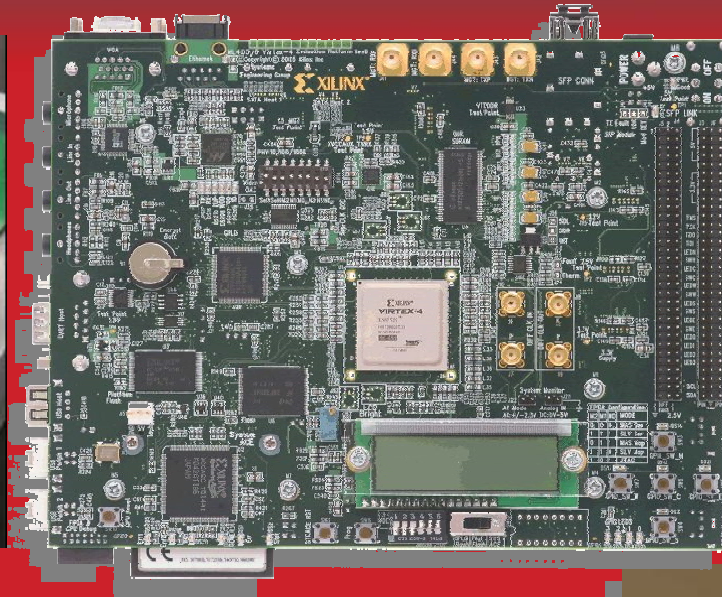
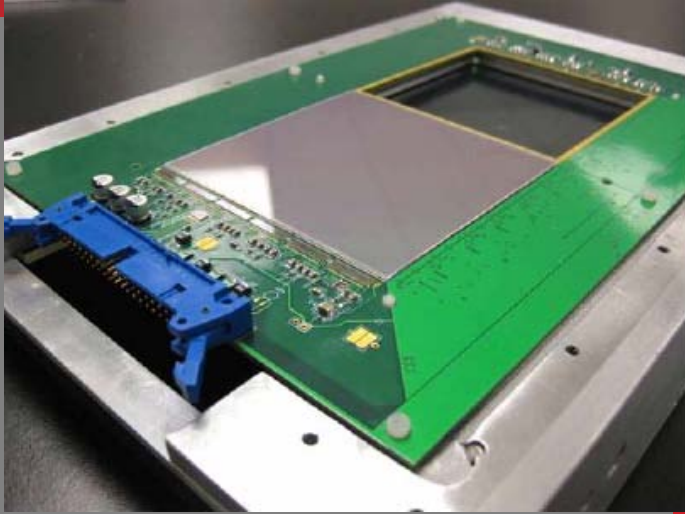


THE PCT SYSTEM PROTOTYPE SCHEMATIC

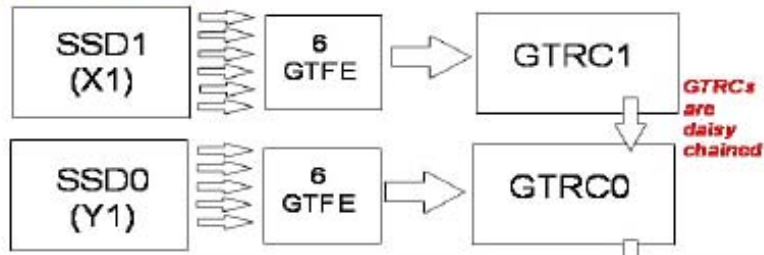
Ready by early 2010



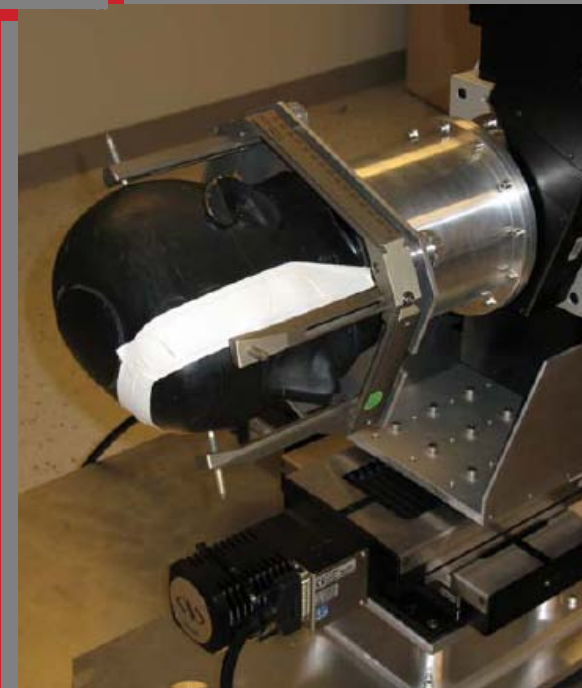
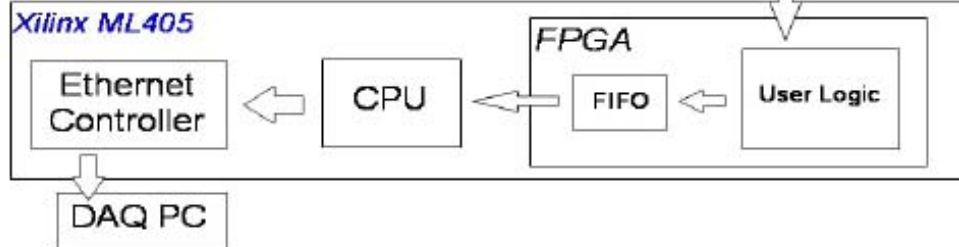
SYSTEM COMPONENTS



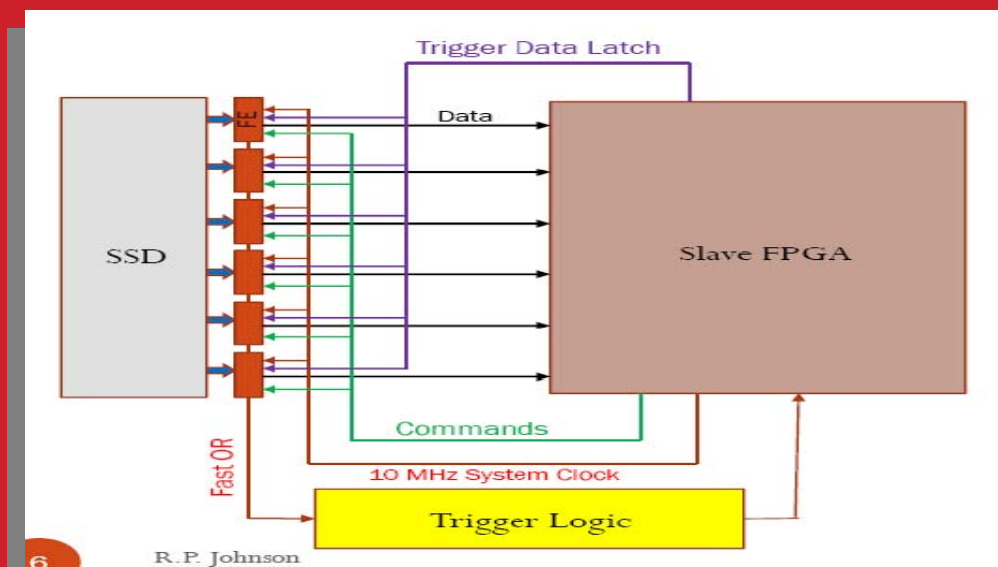
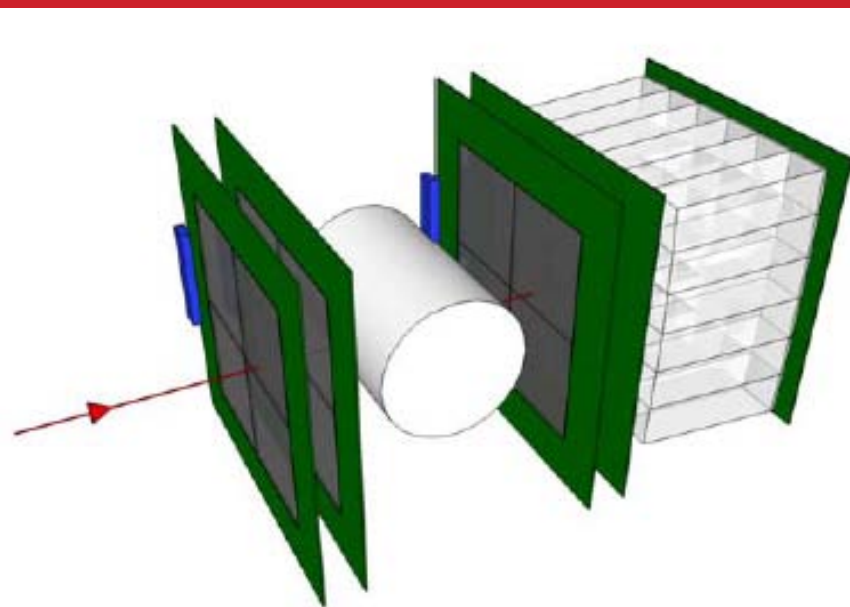
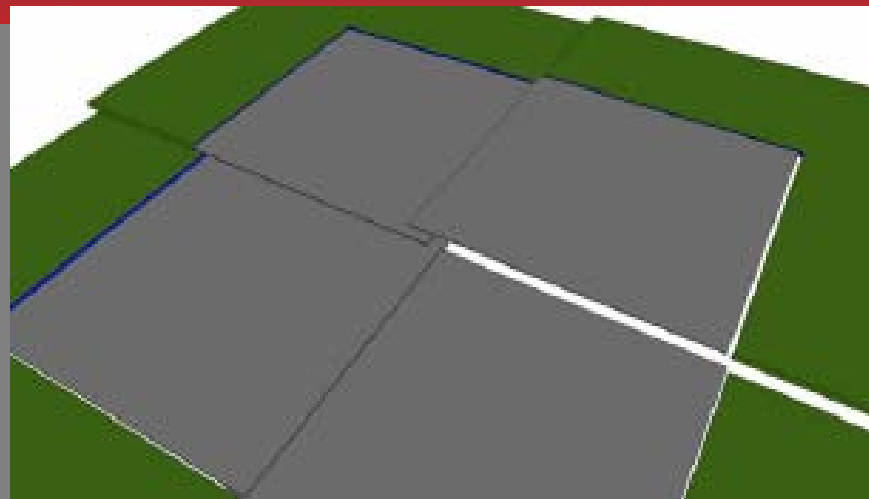
pCT Detector Board



Xilinx ML405



NEXT PHASE



SUMMARY

- pCT is a new medical imaging method that will greatly benefit proton therapy in general and will offer a low-dose diagnostic imaging modality
- The project is truly interdisciplinary involving physics, mathematics, computer science and engineering
- The NIU-LLUMC-SCIPP Collaboration is well underway; the first pCT prototype system capable of imaging head-sized objects will be ready by early 2010
- Further work is necessary towards a fully clinical operation-ready pCT system