SECCHI 3D Reconstruction Efforts at NRL

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With inputs from:
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Outline

- **Currently pursuing three approaches for 3D reconstructions of CMEs and coronal structures (plumes, streamers, etc).**
  - **Parametric modeling (RayTrace)**

    Thernisien, Howard
  - **Tomographic modeling (Pixon)**

    Cook, Newmark, Reiser
  - **Hybrid Approach (Pixon w/ ARM)**

    Reiser

RayTrace

- **Models the brightness (total and polarized) produced by Thomson electron scattering from an arbitrary electron density distribution.**
- **The input electron density distribution can be either a 3D data cube or an analytic description.**
- **The output is a 2D image that simulates the observation in a white light coronagraph (user-defined).**
- **The observer location, image spatial resolution, the orientation of the density model and the instrumental vignetting function are arbitrary.**
- **Key contacts:**
  Thernisien (raytrace), Patel (GUI), Howard, Vourlidas.

RayTrace Frontend

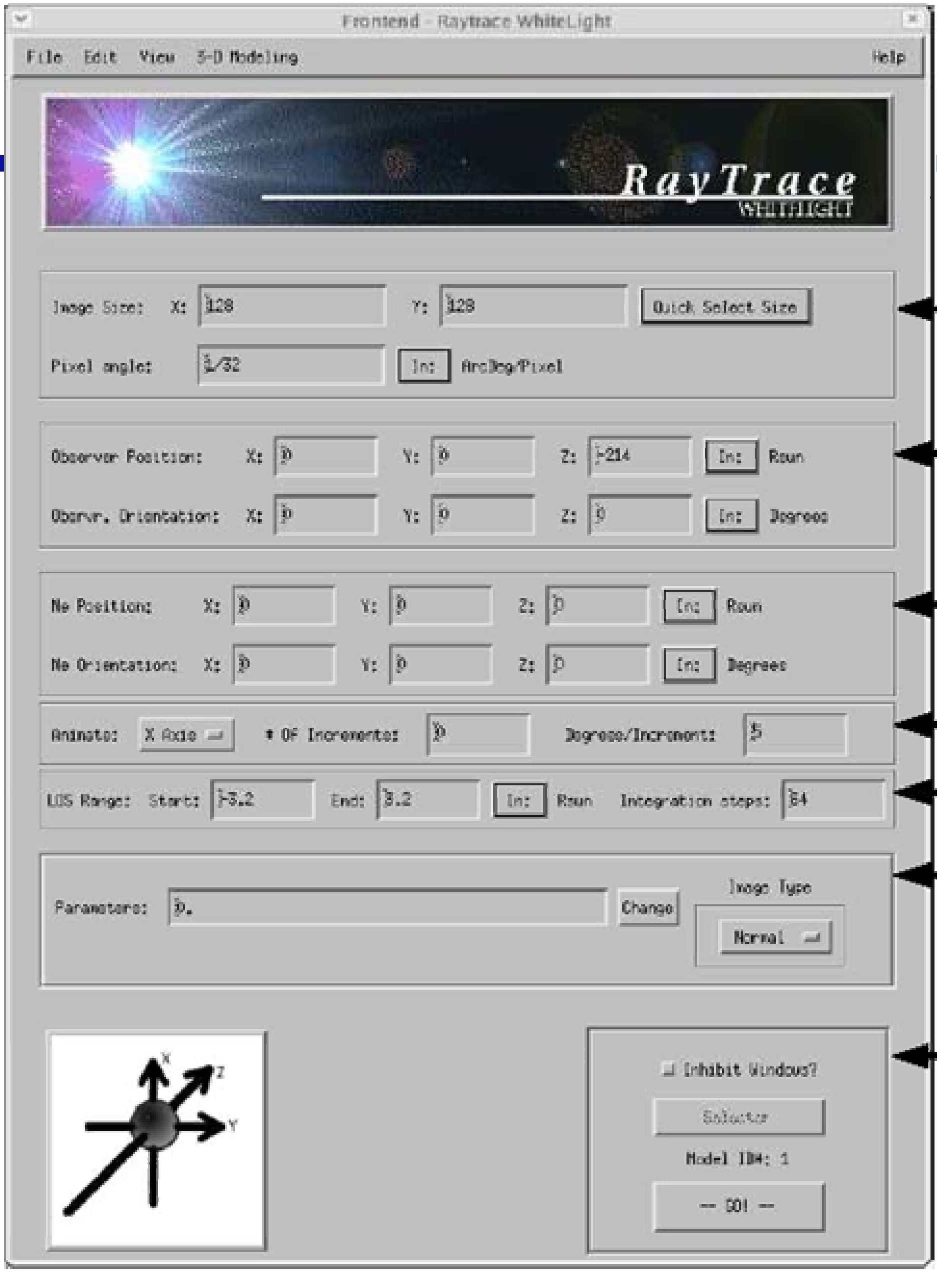


Image Resolution

Observer Position

Electron Density Position

Movie Making

LOS Integration Step

Model Parameters

Start Raytracing and Display

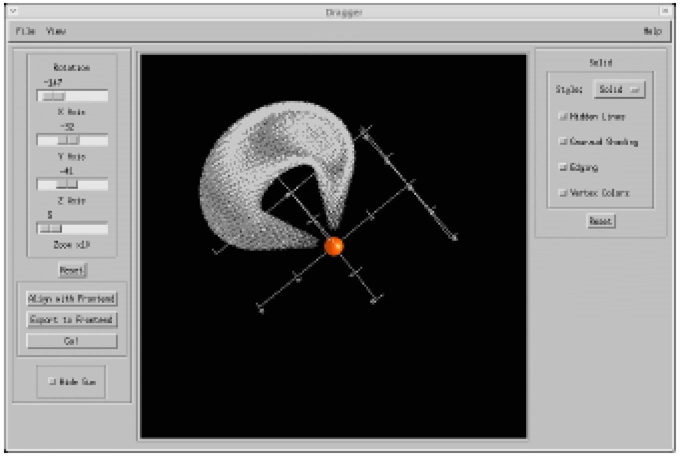
From Thernisien et al. 2004

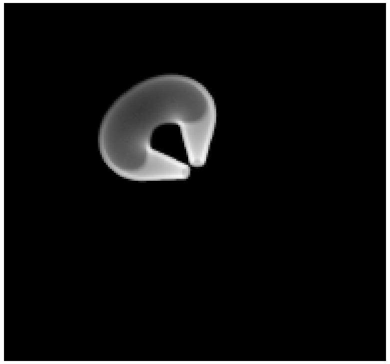
RayTrace Visualization

- **Example of a fluxrope visualization in RayTrace.**

Electron Density Positioning

- Positioning with trackball
- Data image background can be used in order to match structure position





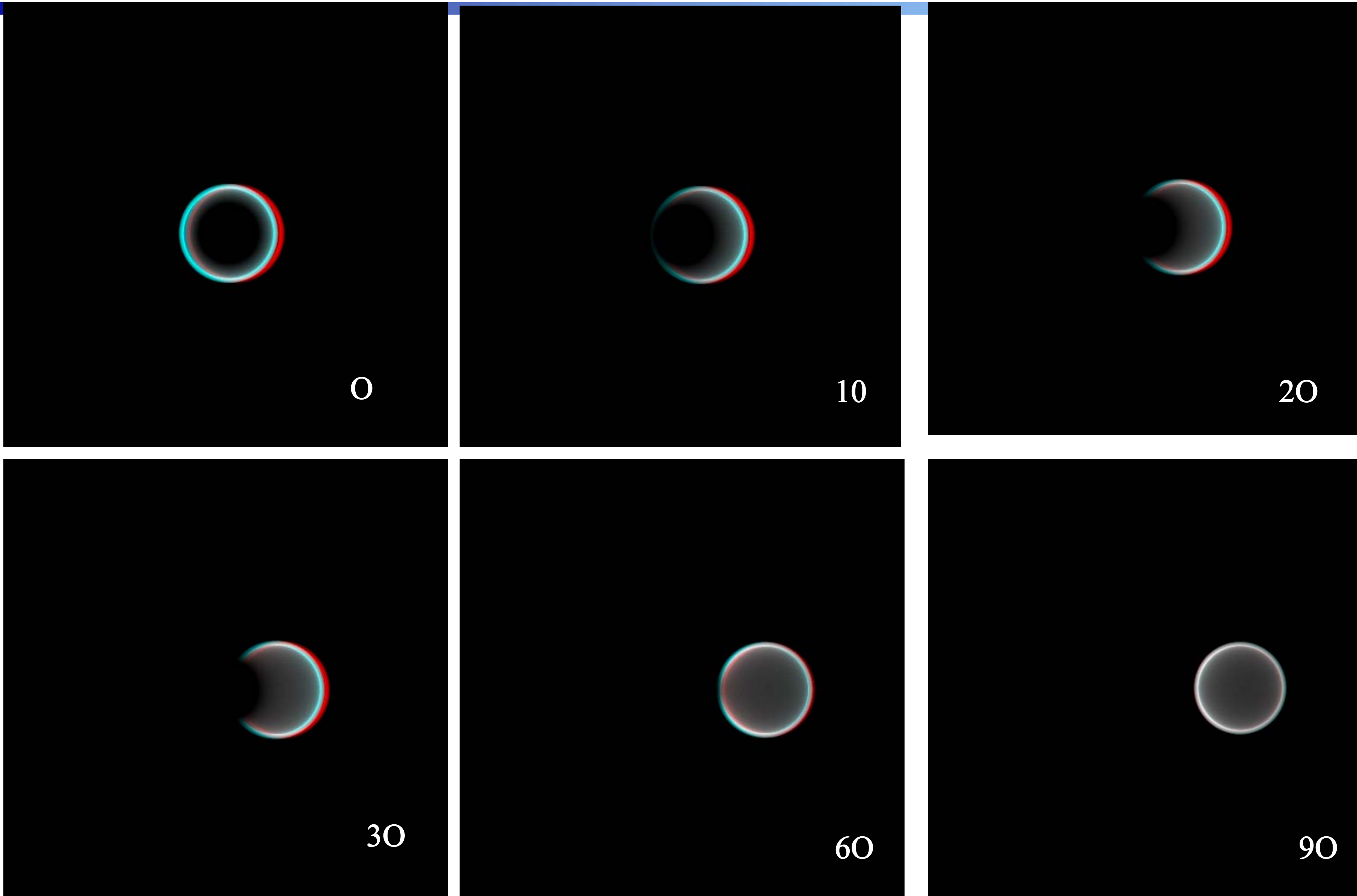
CME model positioned with GUI and corresponding LASCO/C3 simulation.

From Thernisien et al. 2004

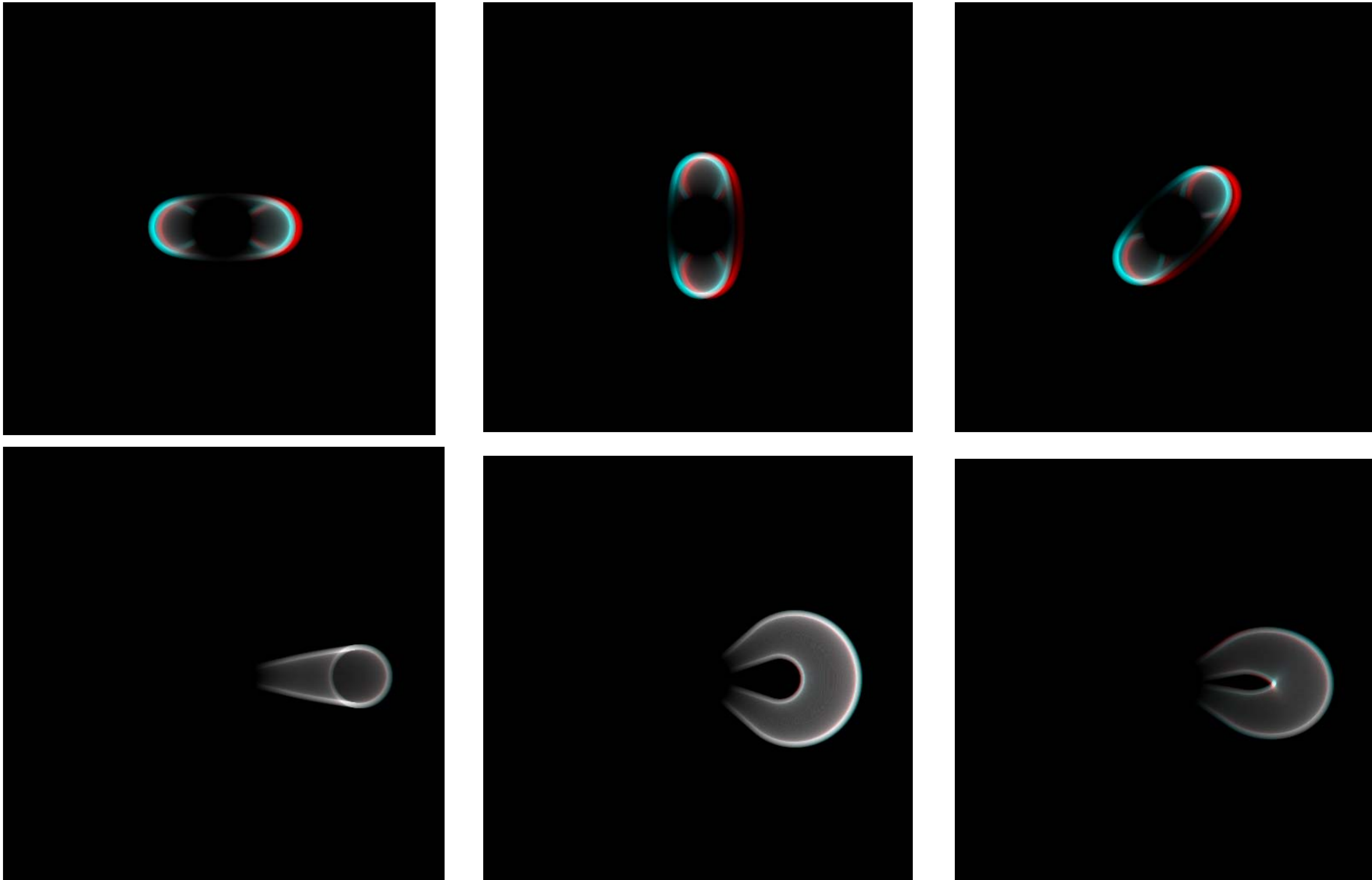
CME Models Currently Implemented

- "2D" Loop
- Spherical shell
- Cylindrical shell
- "Ice Cream Cone"
- Graduated cylindrical shell (GCS)
  - Since the GCS model is a reasonable simulation of a flux-rope CME, we have used it to investigate the appearance of a CME as a function of STEREO separation angle.
  - Parameters are
    - The angular size in the two directions
    - Thickness of the shell
    - The height of the leading edge
    - The orientation of the structure in the corona
    - The radial electron density distribution

Spherical Shell



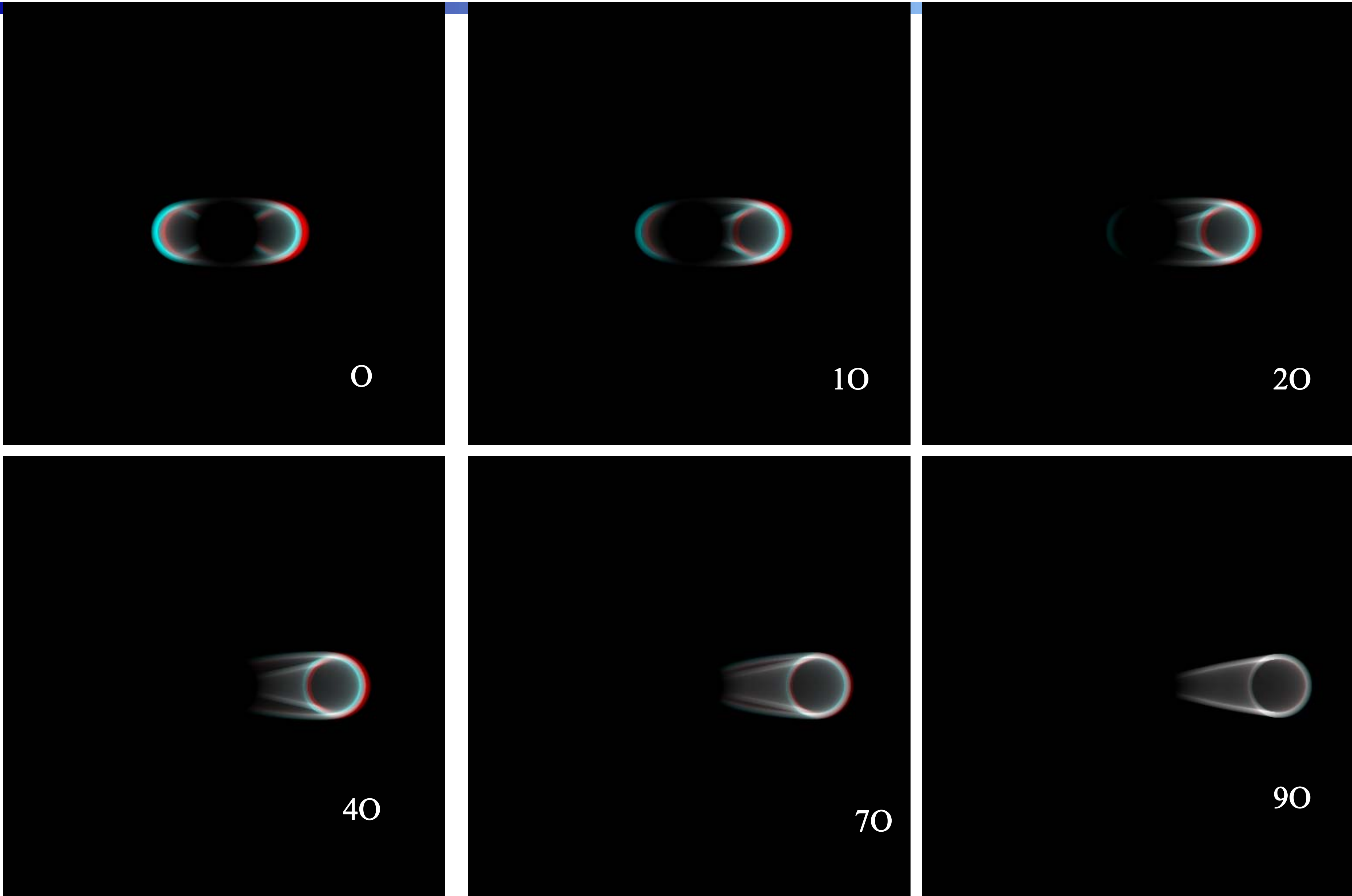
“Flux Rope” Calculated in 3 Orientations



“Horizontal” Flux Rope

- We present views of the horizontal flux rope as a function of angle from the observer’s viewpoint
  – A halo CME is 0 degrees
  – A limb CME is 90 degrees
- The SECCHI COR2 vignetting function as been applied

Horizontal “Flux Rope”



RayTrace Summary

- **We have simulated the effect of the STEREO orbit separation on the appearance and the ability to reconstruct the 3D geometry**
- **Spherical Shell, Loop, Cone and Graduated Cylinder give recognizable differences**
- **Stereo separation angles of <20 degrees show little to no stereo effect.**
- **Polarized Brightness (pB) images have little effect on CMEs at the limb, but considerable effect at large angles from the plane of the sky.**
- **Complementary to 3D inversion and MHD techniques.**
- **Could provide constraints to the MHD models.**

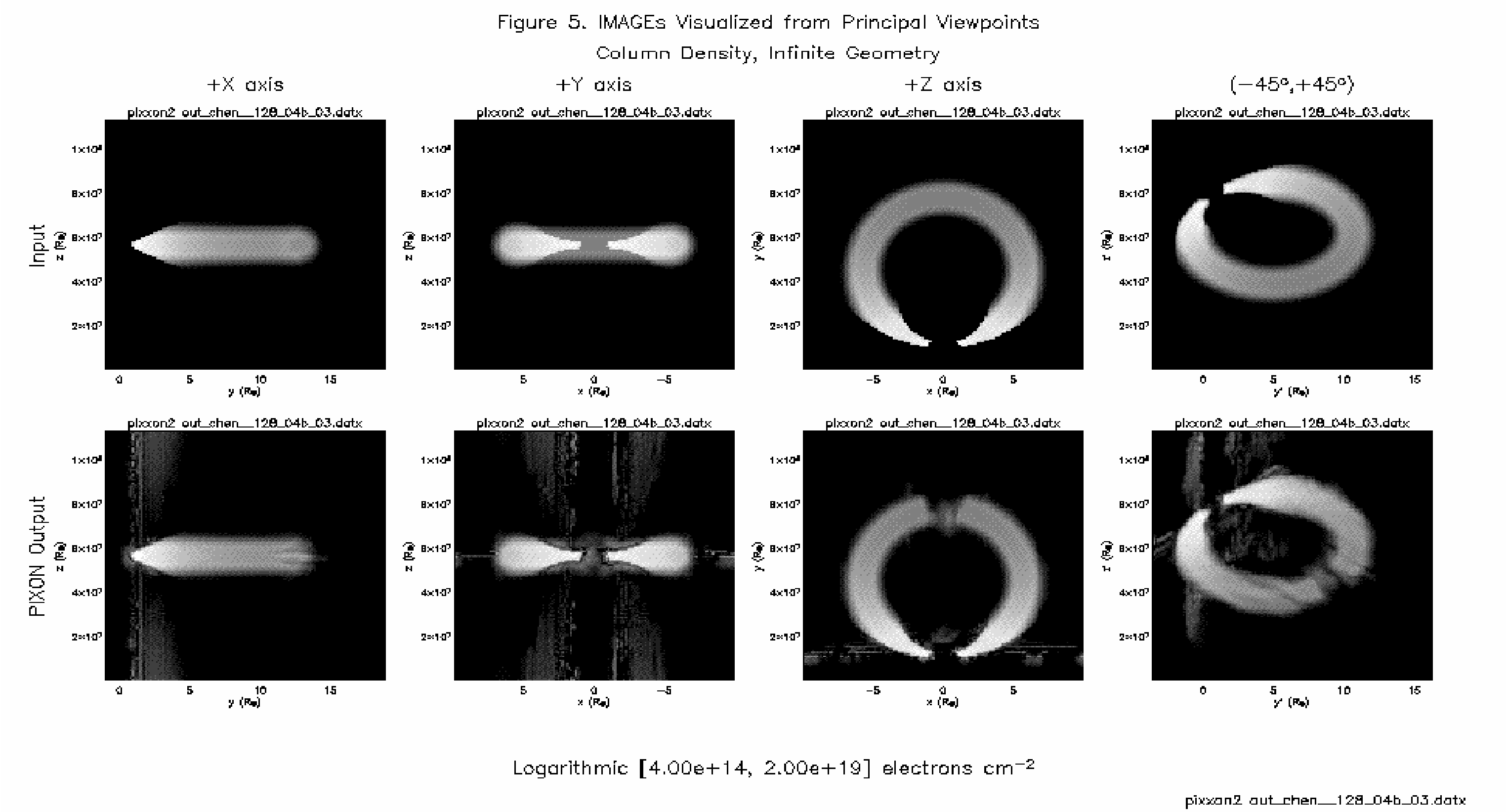
Tomographic Modeling

- **Strategy:**
  - **Apply 3D tomographic electron density reconstruction techniques to solar features (mainly CMEs).**
  - **Utilize B, pB, temporal evolution from 2/3 vantage points.**
  - **Construct (time dependent) 3D electron density distribution.**
- **Focus:**
  - **Use theoretical CME models and existing LASCO observations to identify the range of conditions and features where reconstruction techniques will be applicable.**
- **Goal:**
  - **Provide a practical tool that will achieve ~daily CME 3D electron density models during the STEREO mission.**
- **Key contacts:**
  - **J. Newmark, J. Cook, P. Reiser**

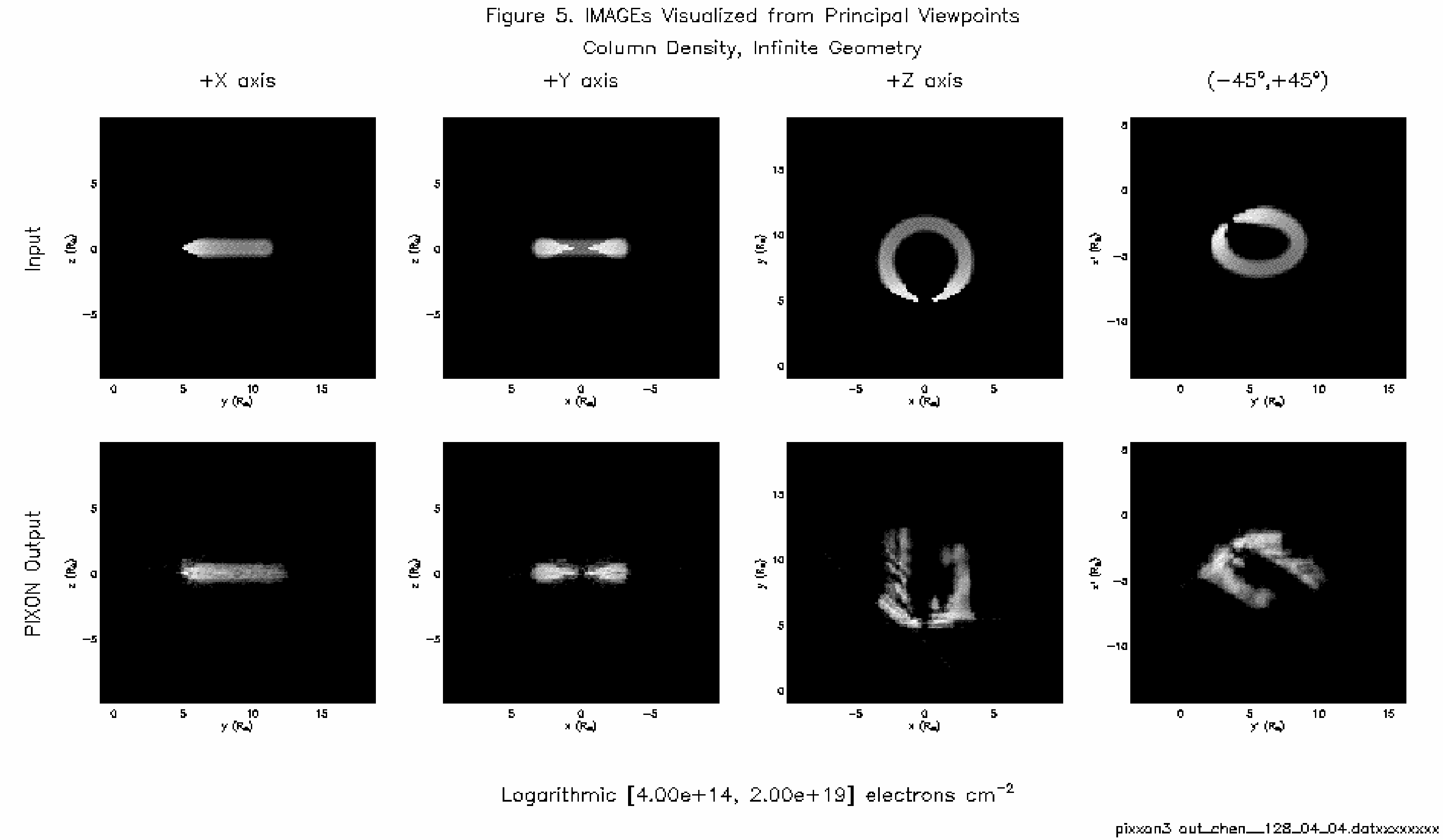
Key Aspects

- **Renderer:**
  - **Physics (Thomson scattering), tangential and radial pB, total B, finite viewer geometry, optically thin plasma.**
- **Reconstruction Algorithm:**
  - **PIXON (Pixon LLC), Pina, Puetter, Yahil (1993, 1995) - non-parametric, locally adaptive, iterative image reconstruction.**
  - **Chosen for speed (<10^9 voxels): small number of iterations, intelligent guidance to declining complexity per iteration. Sample times: 32^3 <15 min, 64^3 ~1 hr, 128^3 ~6 hrs (1 GHz PC).**
  - **Minimum complexity: With this underdetermined problem, we make minimal assumptions in order to progress. Another possibility is forward modeling**
- **Visualization:**
  - **3D electron density distribution, time dependent (movies), multiple instrument, multiple spacecraft, physics MHD models.**

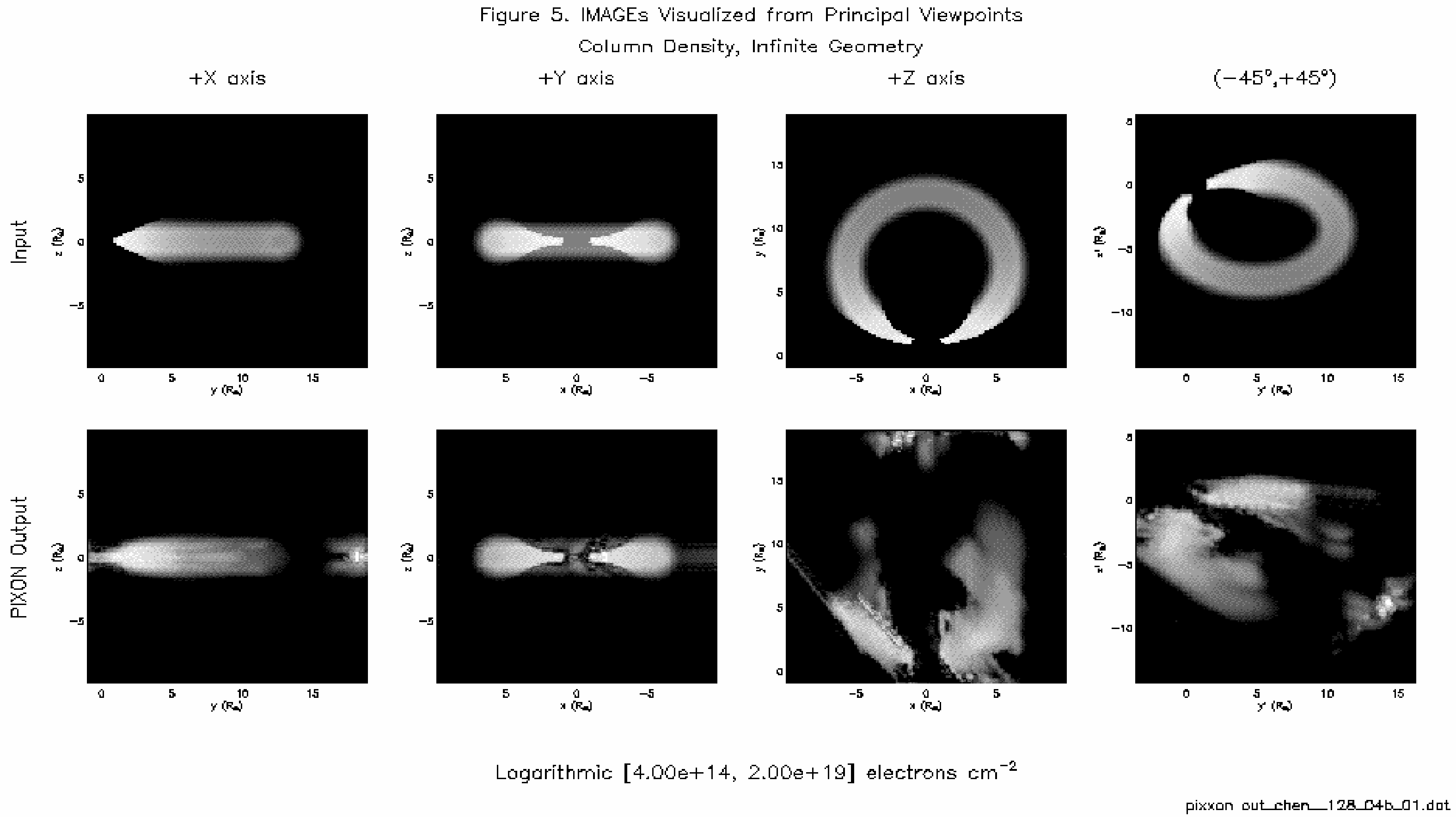
3D Reconstruction: CME model (J. Chen)
Three Orthogonal Viewpoints



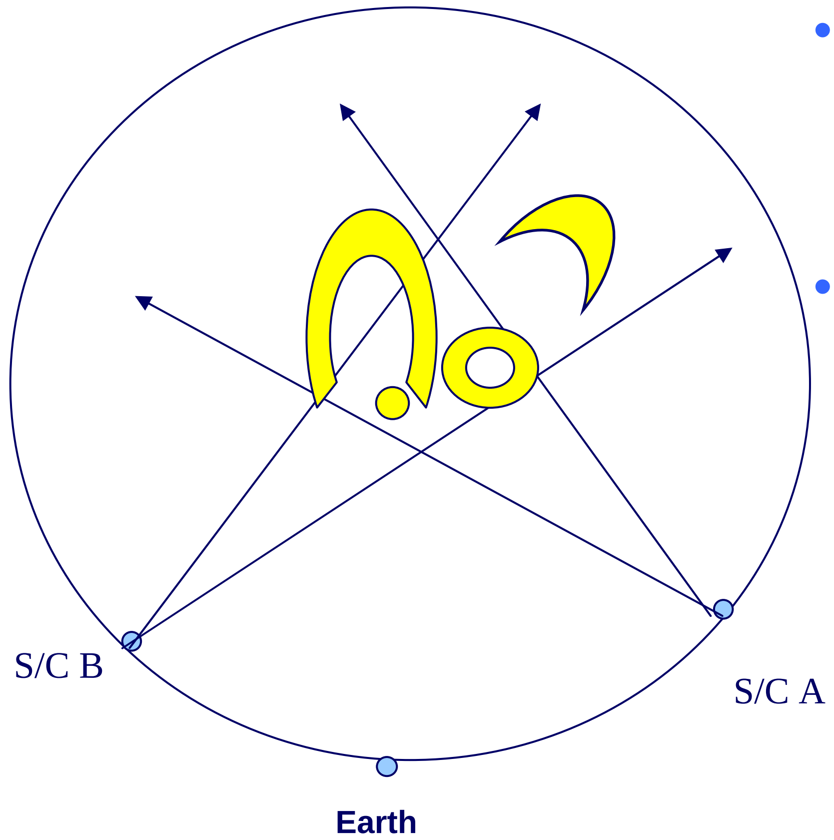
3D Reconstruction: CME model (J. Chen)
Three Ecliptic Viewpoints



3D Reconstruction: CME model (J. Chen)
Two Viewpoints



Limitations



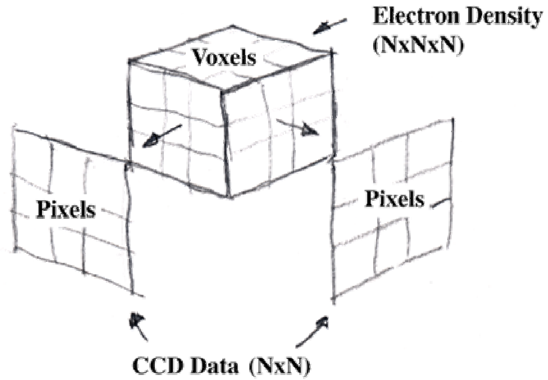
- **Limited viewpoints, underdetermined solution. Introduction of third vantage point helps with some objects.**
- **Limited overlap region of multiple viewpoints. Objects outside one field of view. Intensity contributions from seen by only one telescope.**

Hybrid (ARM) Modeling

- Recently we started exploring a 3rd approach to electron density reconstruction.
  - Namely, to incorporate a priori knowledge to the tomograhic method (Additional Regularization Method (ARM)).
  - For example, we "know"
    - that electrons should be distributed smoothly along LOS,
    - that the emission should be positive,
    - that the large scale envelope of the CME should be symmetric.

- Paul Reiser tested the effect of several constraints on synthetic data

A Priori Knowledge



$$\text{MINIMIZE} \quad P(I) = \chi^2$$

where χ^2 (chi-squared) is given by

$$\chi^2 = \sum_{all\ pixels} \left(\frac{Rendered\ data - Measured\ data}{Error} \right)^2$$

When χ^2 is about equal to $2N^2$ (i.e. about one per pixel) then the fit is "close enough".

But

- **Problem is underdetermined ($2N^2$ equations, N^3 unknowns)**
- **Solutions are noisy**

Let's add two constraints:

1. Electron Density Distribution is Smooth

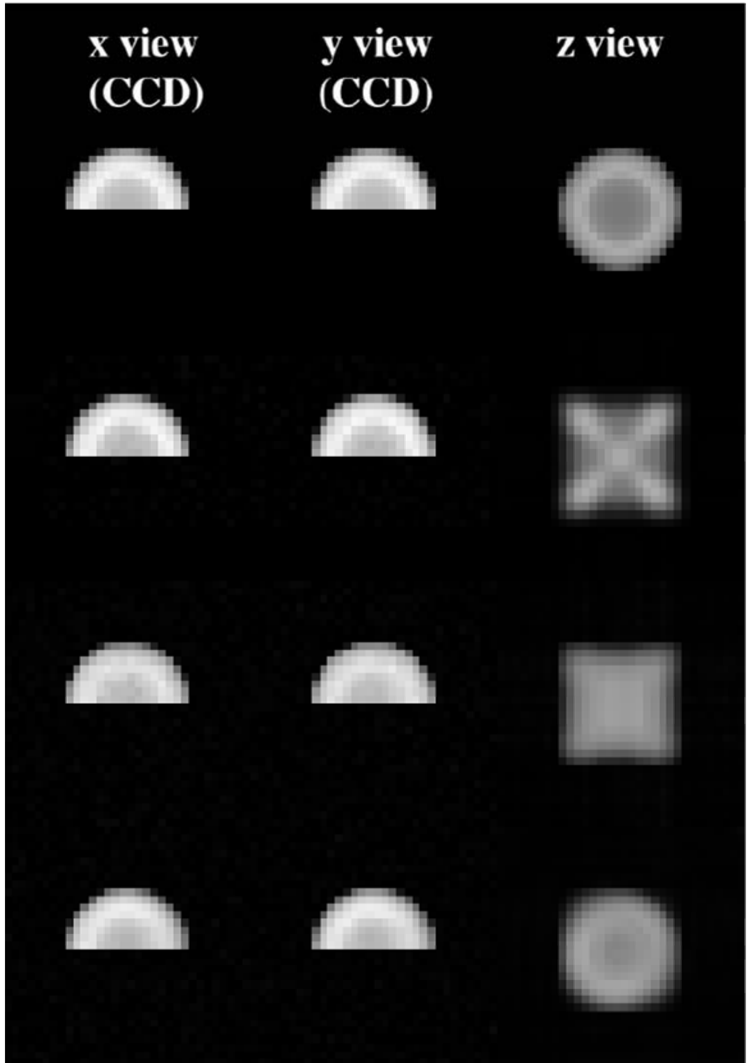
$$\text{MINIMIZE} \quad P(I) = \chi^2 + \lambda_s P_s(I) \qquad \text{Eq. 2}$$

where λ_s is an adjustable parameter and $P_s(I)$ is a **Penalty function** which increases as electron density smoothness decreases.

2. Axial Symmetry

$$\text{MINIMIZE} \quad P(I) = \chi^2 + \lambda_s P_s(I) + \lambda_\phi \sum_{all\ voxels} \left(\frac{\partial I}{\partial \phi} \right)^2$$

Hybrid Modeling w/ Axial Symmetry



"True" density

PIXON reconstruction

Tikhonov reconstruction

Tikhonov reconstruction
with axial regularization

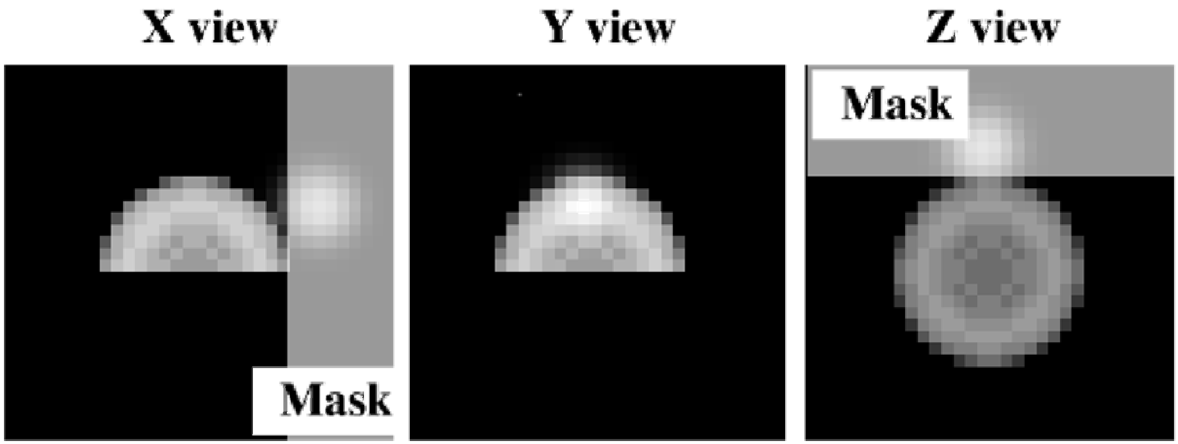
Another Example - Unmatched Scenes

What to do when one viewpoint contains additional structure?

Apply axial symmetry regularization only in the voxels shown here.

MINIMIZE

$$P(I) = \chi^2 + \lambda_s P_s(I) + \lambda_\phi \sum_{shell\ voxels} \left(\frac{\partial I}{\partial \phi}\right)^2$$



Unmatched Scenes- ARM Result

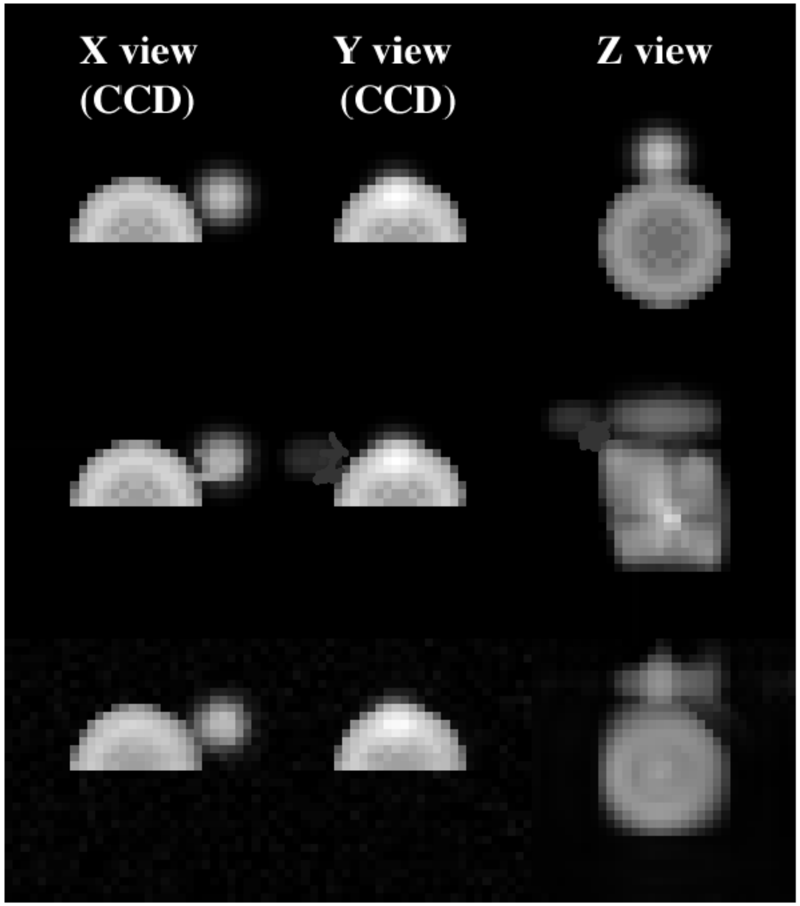


Figure 6: Half shell with blob

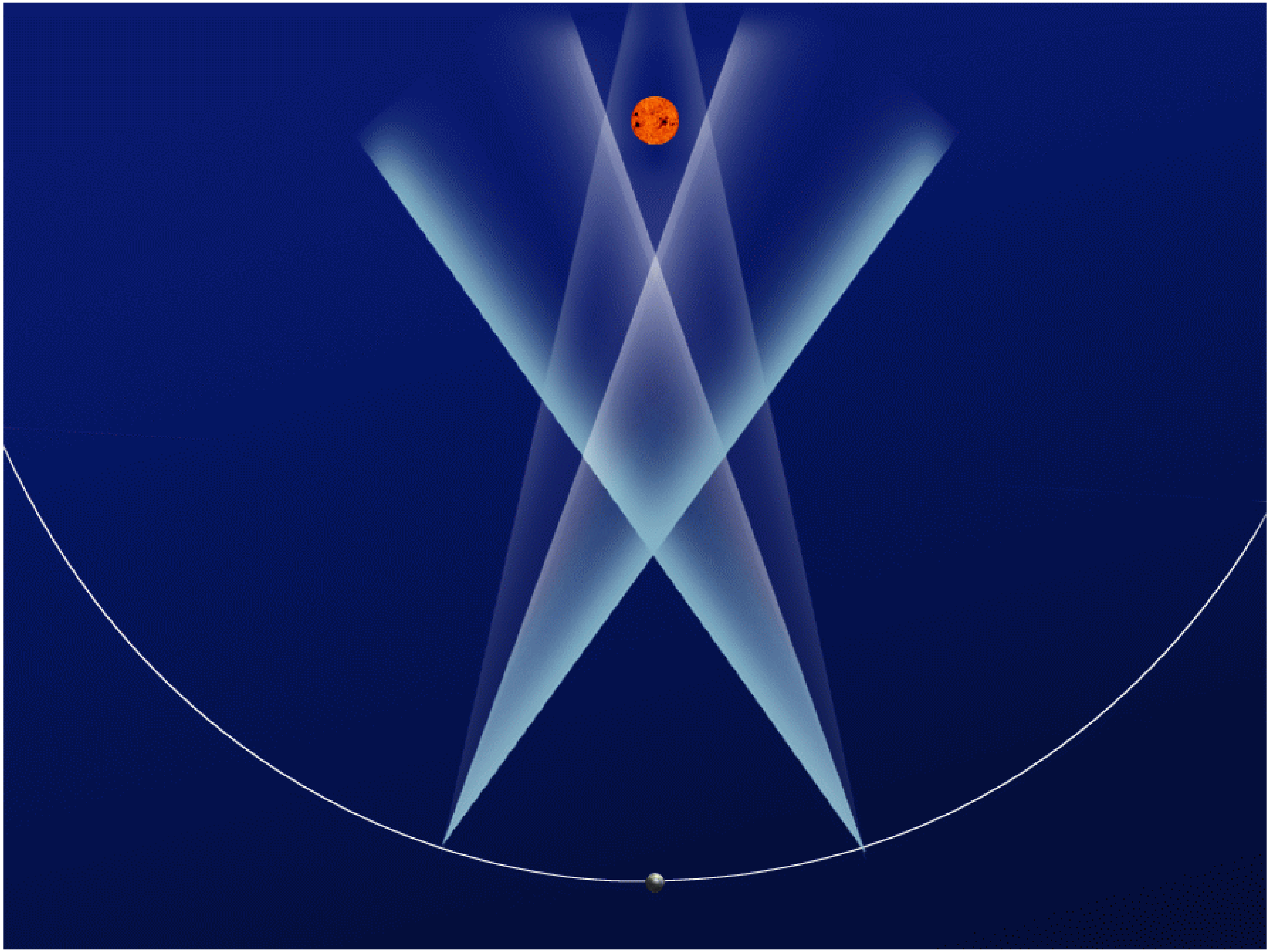
Conclusions

- Useful 3D reconstructions are achievable!
- Parametric modeling is easy to implement, fast, and intuitive. It can be directly linked to MHD models. Unlikely to match observations in detail.
- Tomographic techniques achieve better agreement with observations. Time-consuming, error analysis is difficult/complex.
- Incorporation of a priori knowledge in tomographic reconstruction shows great promise. Minimization subject to "magic" selection of parameters (different for each reconstruction). Still time-consuming
- Tomographic reconstructions are significantly improved with the addition of a third viewpoint (LASCO continuing operation is extremely important).
- Application to SECCHI will require substantial effort and collaboration; we appreciate all help on scientific preparations.
- Web Site: http://stereo.nrl.navy.mil/ (follow link to 3D R&V). This contains past presentations and all necessary details to test reconstruction methods on our sample problems.

Backup

Backup Slides

Views From STEREO-A and -B



SECCHI Telescopes

- The SECCHI suite consists of 5 telescopes to observe CMEs from their birth at the solar surface through the corona and into the inner heliosphere

Telescope	EUVI	COR1	COR2	HI-1	HI-2
FOV (Rsun)	disk -1.7	1.3 - 4	2.5 - 15	12 - 85	66 - 318
Pixel Size (arcsec)	1.7 arc sec	1.3 - 8	2.5 - 15	70	243
Bandpass	Fe IX 17.1 nm	White Light	White Light	White Light	White Light
	Fe XII 19.5 nm				
	Fe XV 28.4 nm				
	He II 30.4 nm				

Science - Examples

- Geometric figures - uniform density, no background
- Polar Plumes - hydrostatic equilibrium solution of density vs. height, tube expansion, statistics.
- Equatorial streamers - projection of current sheets, effect of AR's, compare to 3D reconstruction using tie points (Liewer 2001), density enhancements vs. folds.
- CME's – Use models to prepare for SECCHI, effect of viewpoint angles, velocity, polarization, structure evolution, etc. CME models include time dependence
  - J. Chen – CME, no background
  - P. Liewer – CME + background – not yet studied
  - Z. Mikic – CME, K corona evolution
  - S.T. Wu – CME - not yet studied
- Questions: How to isolate CME? Assume subtraction of F+minimum K corona, but how to handle time dependent K corona? Why we want to: decrease complexity, eliminate structures of equal or greater brightness

3-D Reconstruction Using the Pixon Method

- The problem is to invert the integral equation with noise:

$$D_n(\mathbf{x}) = \int \mathbf{d}^3\mathbf{r} H_n(\mathbf{x},\mathbf{r}) n(\mathbf{r}) + N_n(\mathbf{x})$$

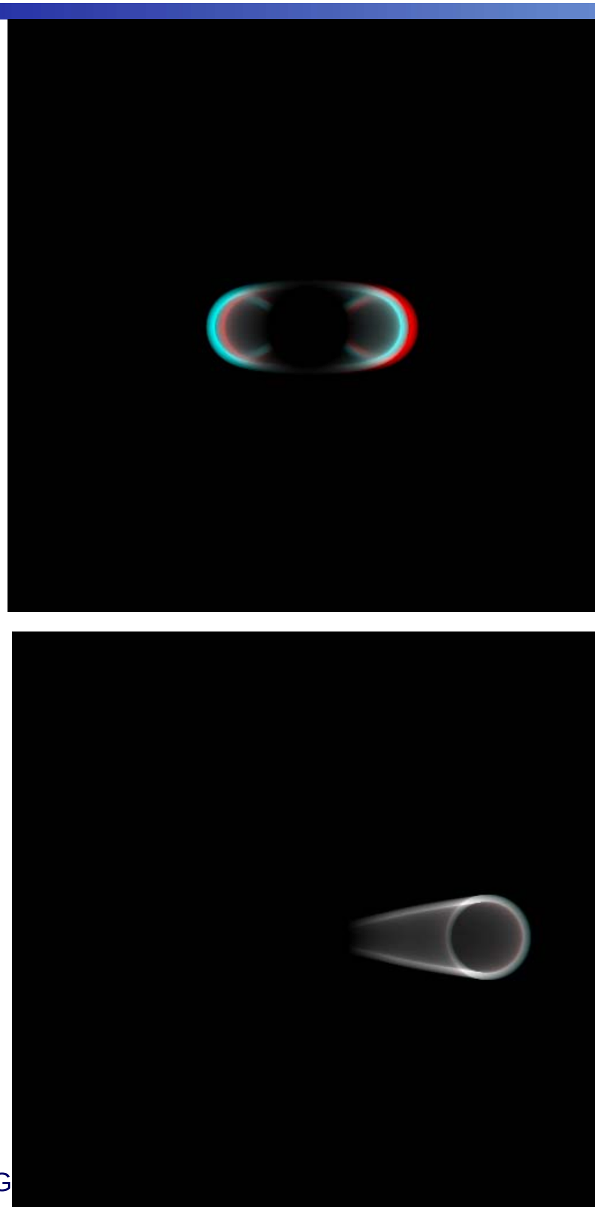
- But there are many more model voxels than data pixels.
- And the reconstruction significantly amplifies the noise.
- All reconstruction methods try to overcome these problems by restricting the model; they differ in how they do that.
- A good first restriction is non-negative n(r).

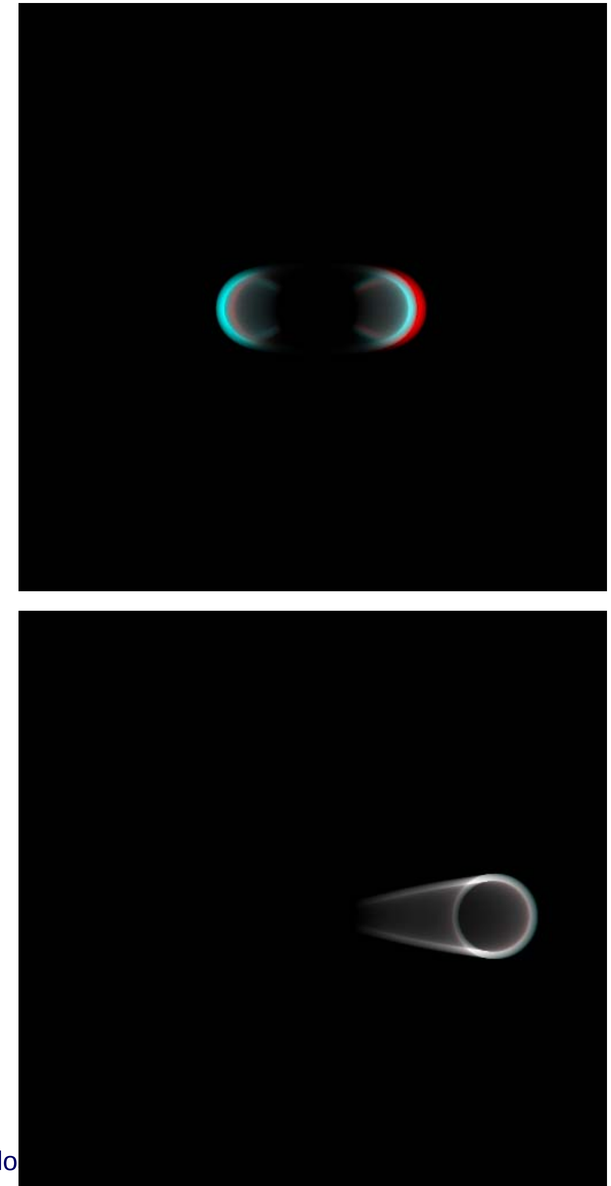
  $\Rightarrow$ Non-Negative Least-Squares (NNLS) fit.
- Minimum complexity (Ockham's razor): restrict n(r) by minimizing the number of parameters used to define it.
- The number of possible parameter combinations is large.

  $\Rightarrow$ An exhaustive parameter search is not possible.
- The Pixon method is an efficient iterative procedure that approximates minimum complexity by finding the smoothest solution that fits the data (details: Puetter and Yahil 1999).
- New modification: Adaptive (Hierarchical) Gridding

“Flux Rope” Calculated in Total B and pB

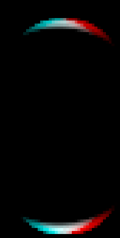
B

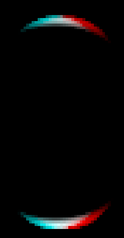




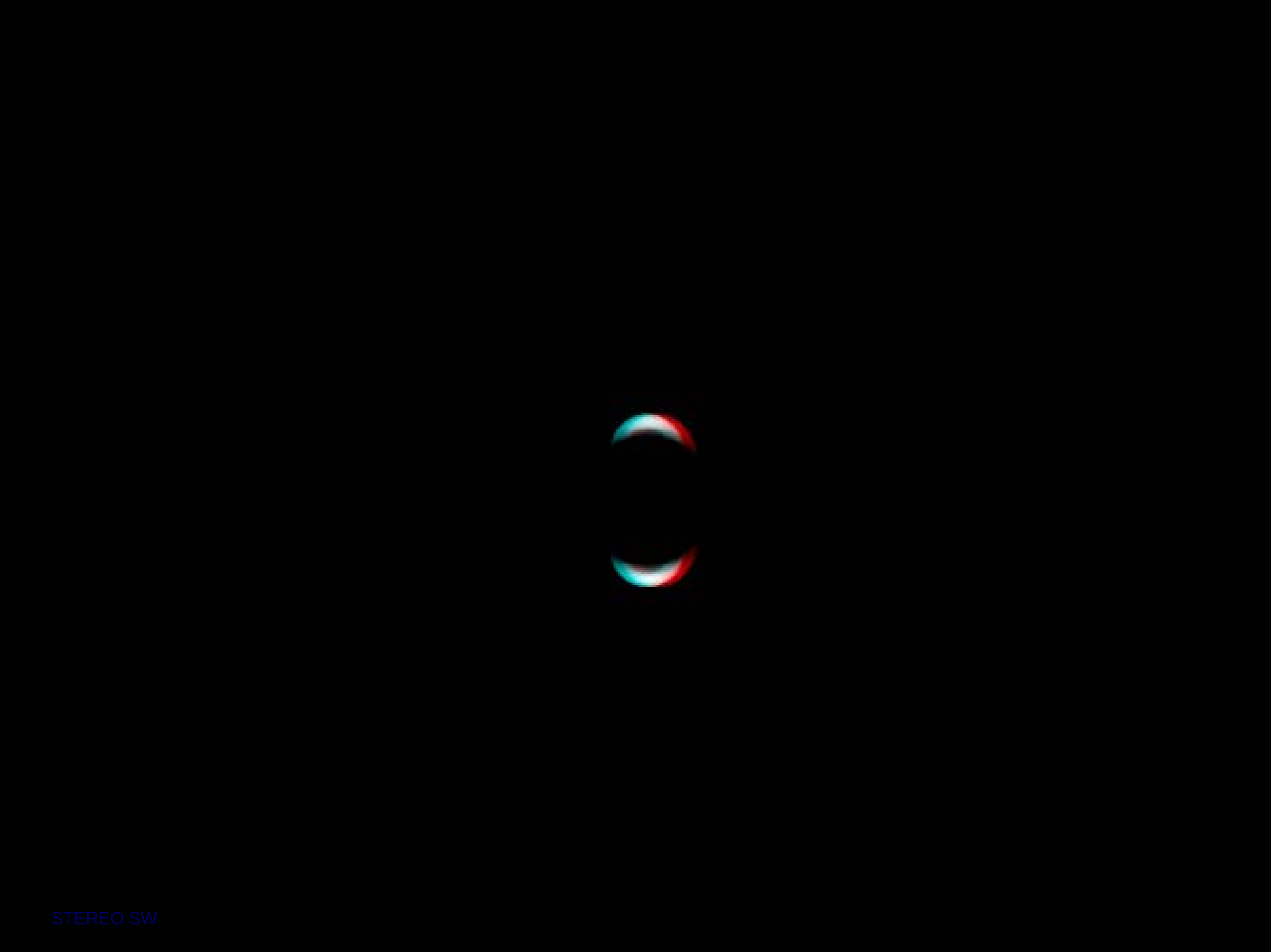
pB

Evolution of Vertical “Flux Rope” as a Halo



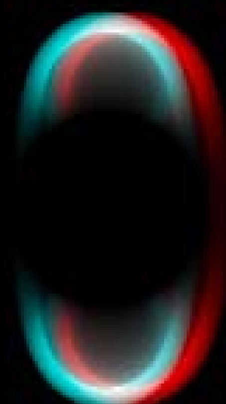


STEREO S

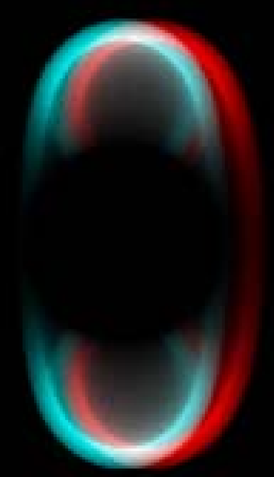

STEREO SW

STEREO SW

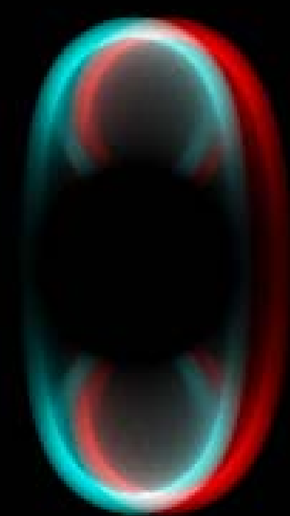
STEREO SW



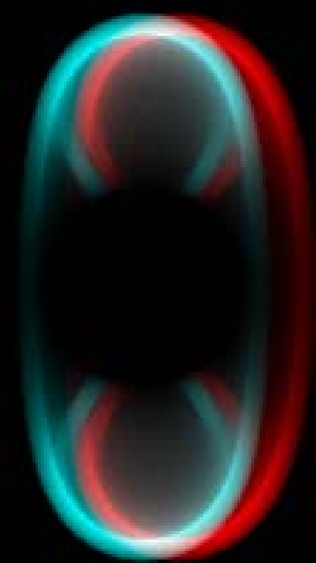
STEREO SW



STEREO SW



STEREO SW



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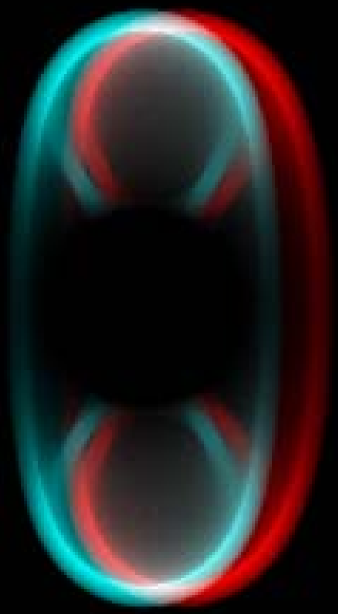
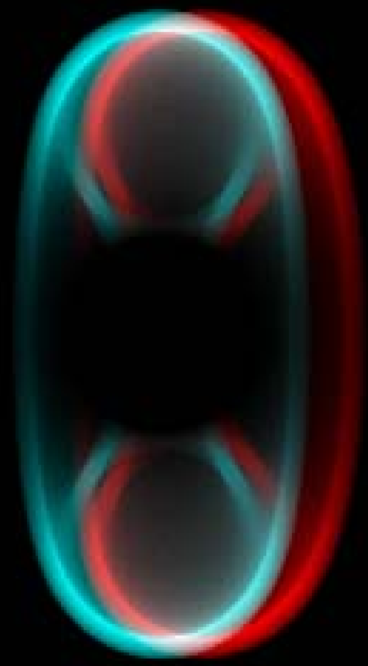


STEREO SW



STEREO SW

STEREO SW