STEREO/SECCHI Simulations of CMEs and Flares Using TRACE images

Markus J. Aschwanden
James Lemen, Nariaki Nitta, Tom Metcalf, Jean-Pierre Wuelser
(Lockheed Martin Solar Astrophysics Laboratory)
& David Alexander (Rice University)

2004 AGU Fall Meeting, San Francisco, 3-5 Nov 2004

Special Session SH08 – Preparing for the Solar STEREO Mission :
The 3D, Time-dependent Heliosphere from Models and Observations

Content of talk :
STEREO/SECCHI 3D Analysis Tasks:

1) Coronal magnetic field
   - Fingerprinting methods (Strous; Lee & Gary)
   - Nonlinear force-free modeling (Wiegelmann)
2) Coronal Loops
   - Disentangling of loop strands
   - Stereoscopic geometry and time-tracking
   - 3D detection of loop oscillation modes
3) Filaments/Prominences/Fluxropes
   - Measurements of twist and helicity
4) Postflare loop systems
   - Stereoscopic tracking of spatio-temporal evolution
5) CME tracking
   - 2-LOS back-projection

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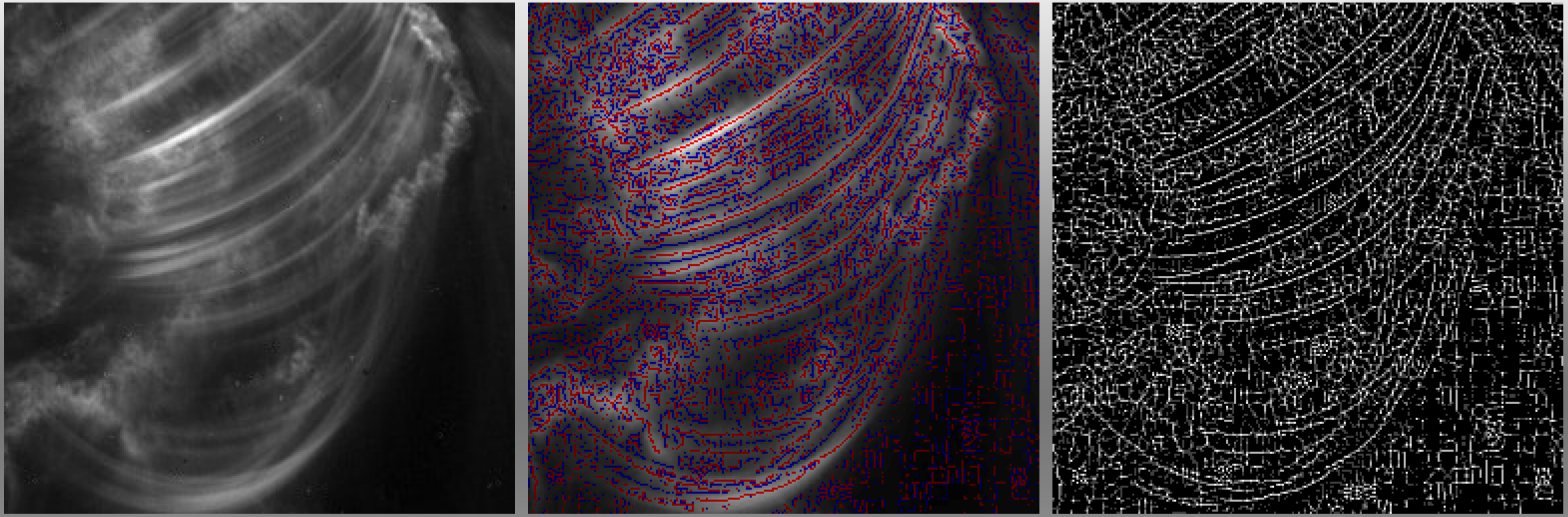
Fingerprinting (automated detection) of curvi-linear structures



Louis Strous (2002) http:/www.lmsal.com/~aschwand/stereo/2000easton/cdaw.html

-Strous detects curvi-linear segments from brightness gradients in 3x3 neighborhood areas

-Problems: incompleteness of coronal loops

no discrimination between noisy pixels and loops

combination of curvi-linear segments to full loops

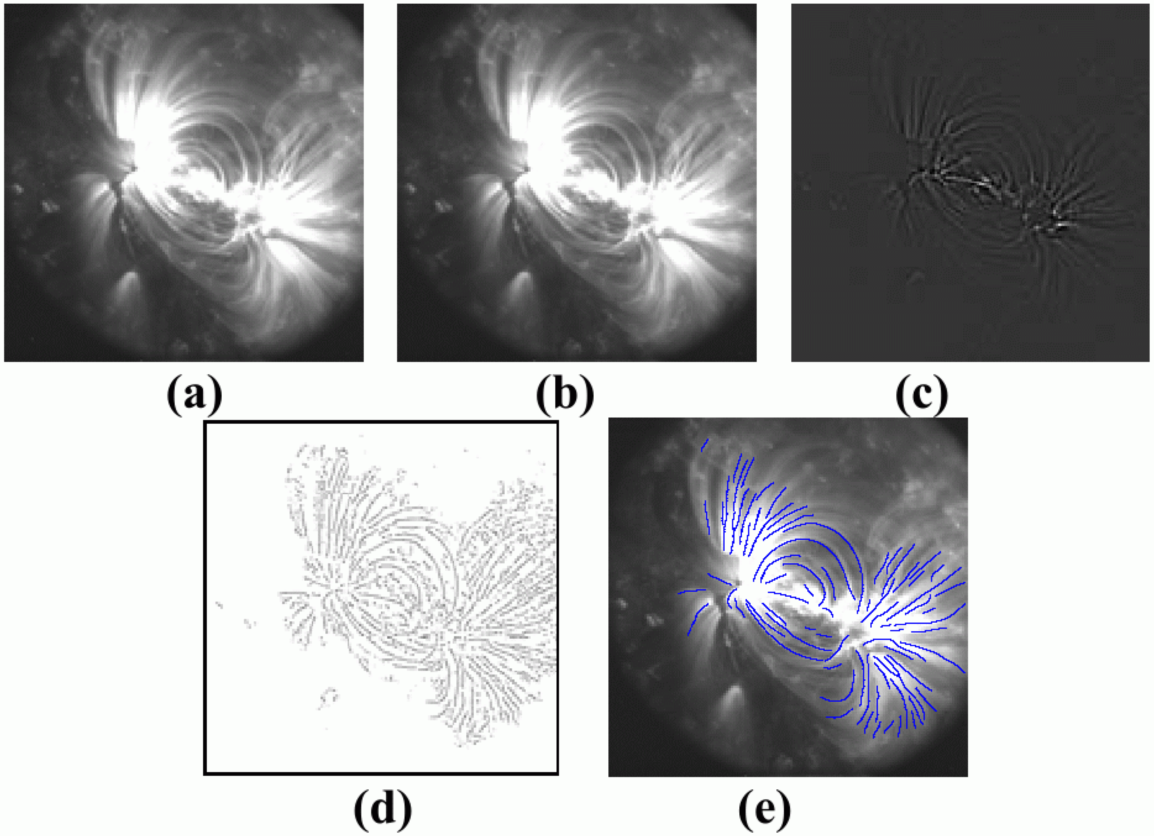


Fig. 1. (a) Coronal image, (b) Median filtered image, (c) Contrast enhanced version of unsharp masked image, (d) Curve features after thresholdings (e) Detected loops.

Lee, Newman & Gary improve detection of coronal loops with "Oriented connectivity Method" (OCM):

- -median filtering
- -contrast enhancement
- -unsharp mask
- -detection threshold
- -directional connectivity
- -potential field guidance

Lee, Newman, & Gary (2004), 17th Internat. Conf. On Pattern Recognition, Cambridge UK, 23-26 Aug 2004

Methods: MM =Manual Method
SMM=Semi-Manual Method
OCM=Oriented Connectivity Method

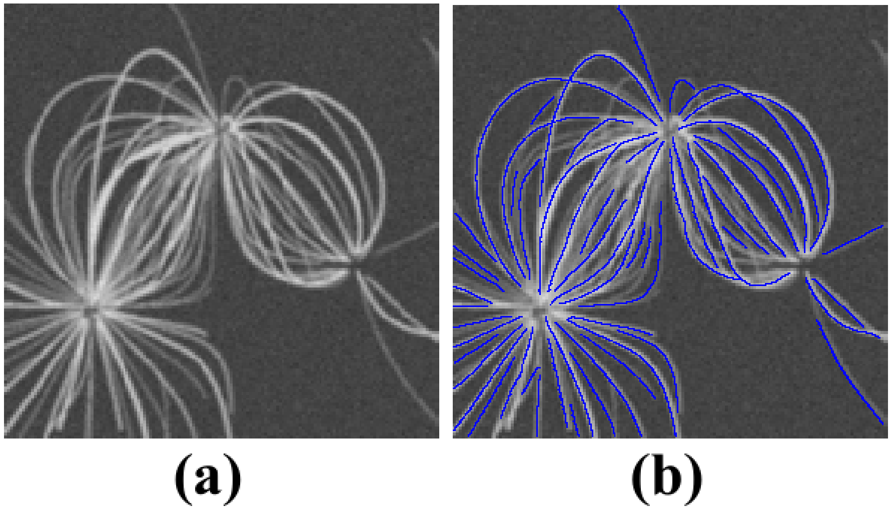


Fig. 2. (a) Synthetic image, (b) Detected loops

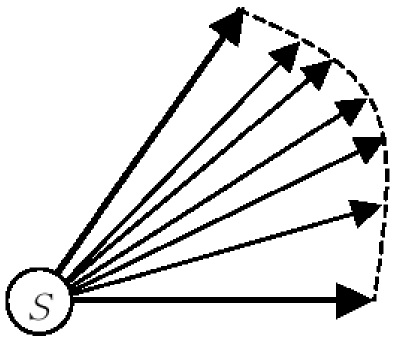
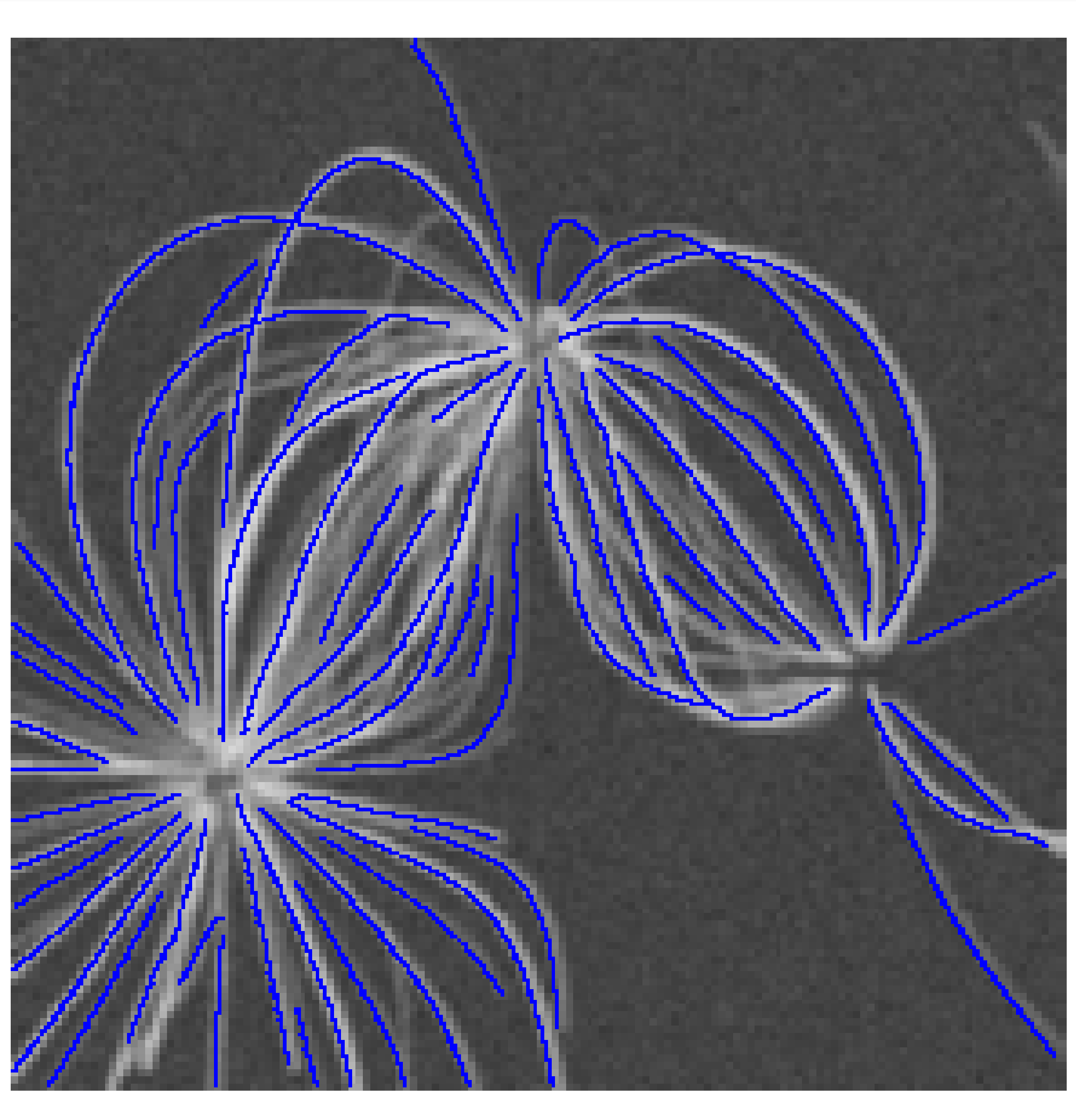


Fig. 3. Search Region about S

Table 1. Errors (GPE) on synthetic image (in pixels)

Method	Max	Min	Mean	Std Dev
MM	3.61	0.00	0.66	0.63
SMM	3.51	0.00	0.58	0.40
OCM	3.00	0.00	0.57	0.37

Lee, Newman, & Gary (2004)

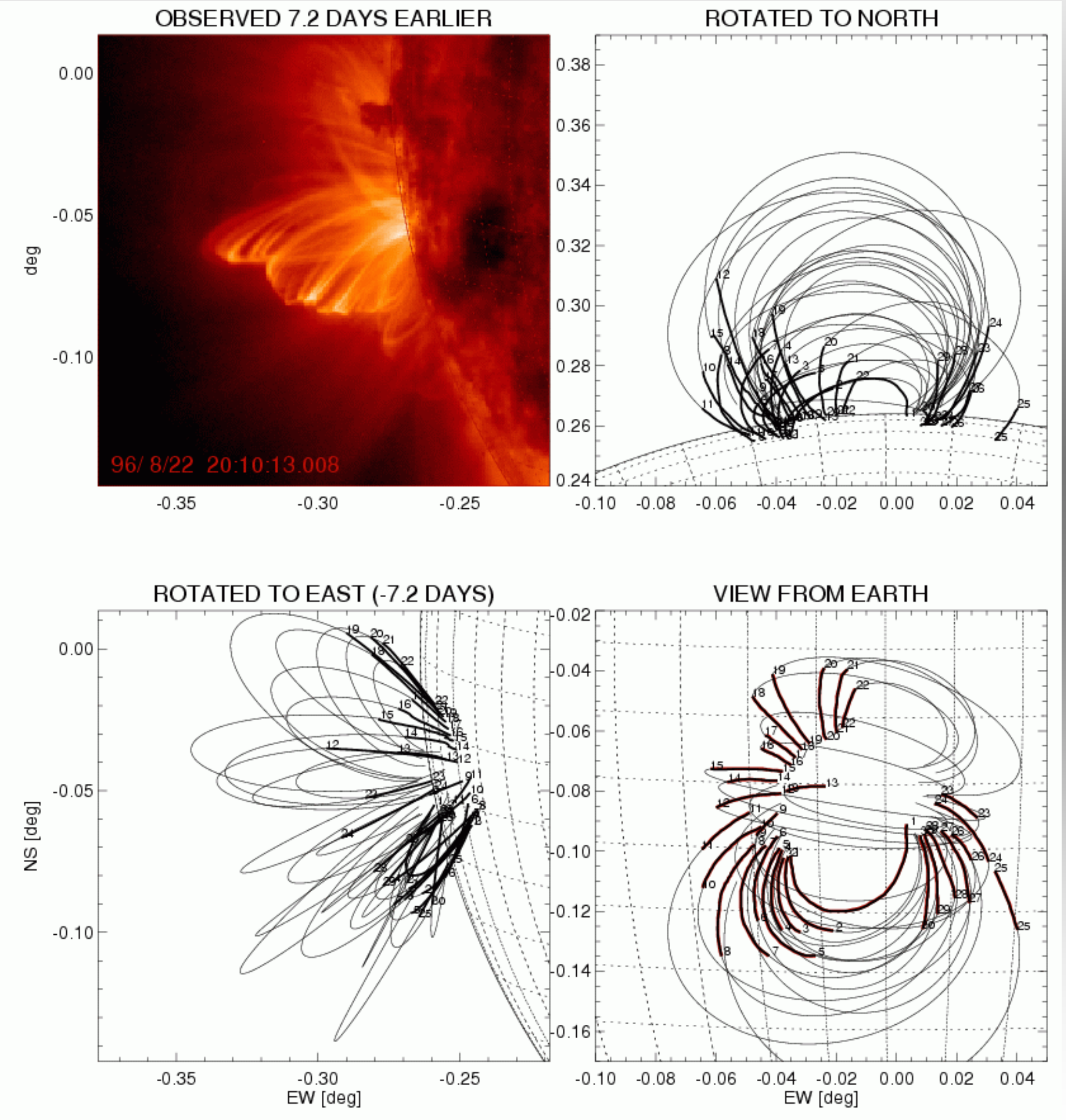


Simulation results:
-OCM renders most
 of the loop structures

Remaining problems:
-crossing loops
-misconnections
-ambiguous connections
-faint loops
-crowded regions

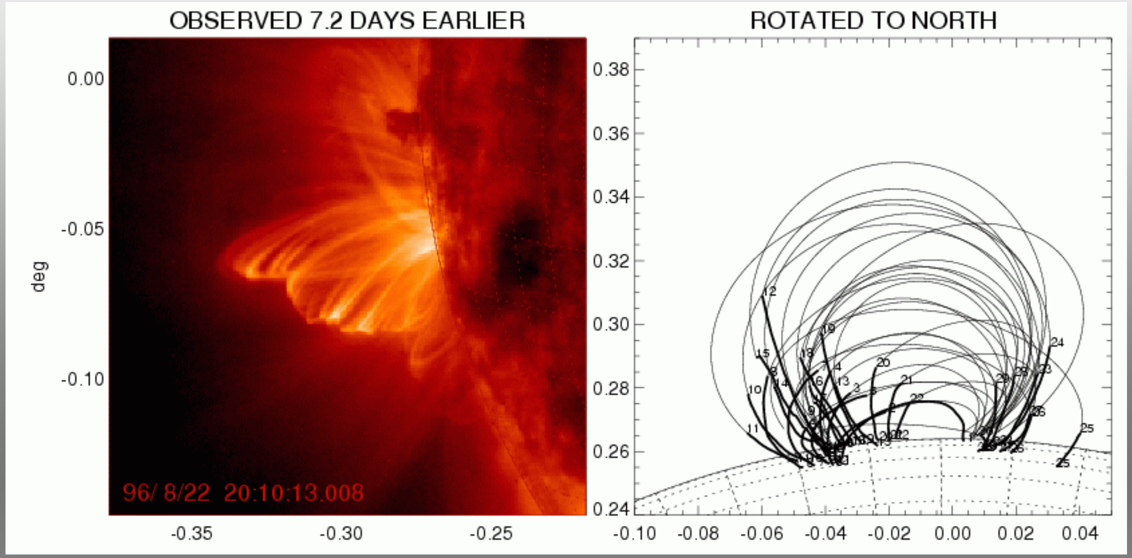
Lee, Newman, & Gary (2004)

3D-Reconstruction of Coronal Magnetic Field

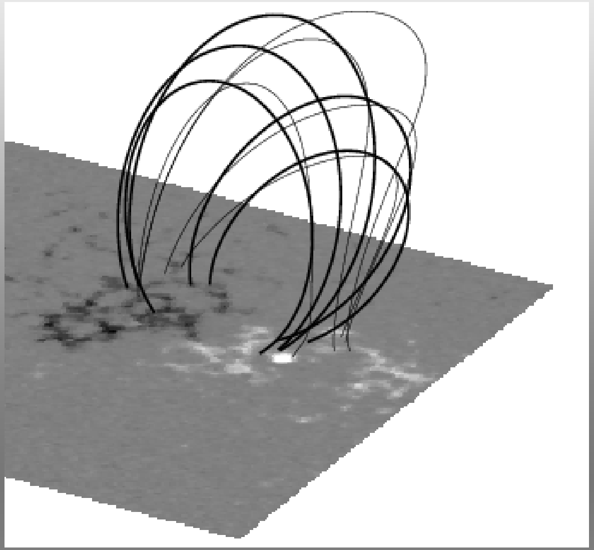


Full testing of theoretical magnetic field extrapolation models with EUV-traced loops requires 3D reconstruction of loop coordinates [x(s), y(s), z(s)]

→
(1) Solar-rotation dynamic stereoscopy
(2) Two-spacecraft stereoscopy

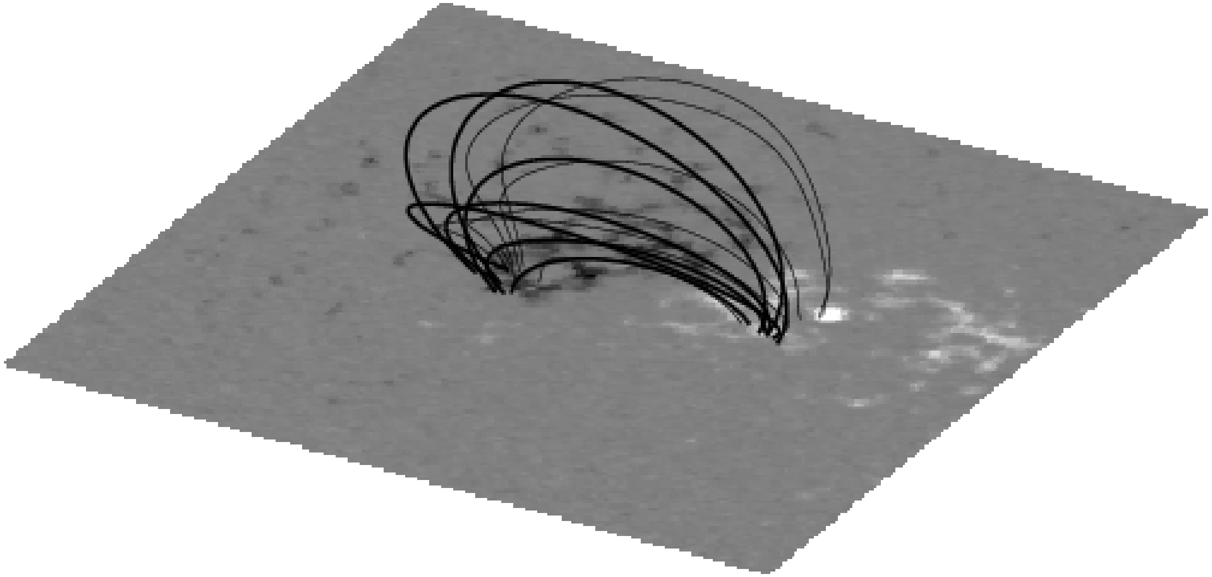


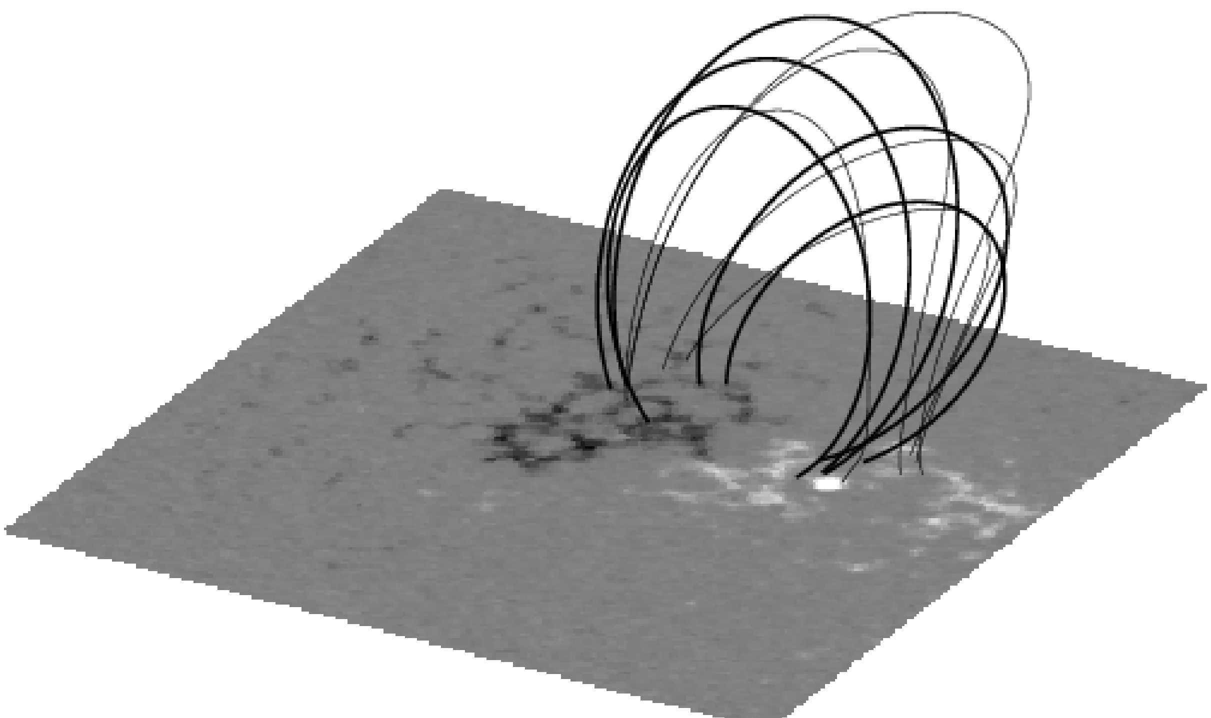
Aschwanden et al. (1999)


Wiegelmann & Neukirch (2002)

-Tests of theoretical (potential field, linear force-free, and nonlinear force-free) magnetic field extrapolation by comparison with observed EUV loops (projected in 2D)

-3D reconstruction of EUV loop coordinates with “dynamic solar-rotation stereoscopy” or “two-spacecraft observations”



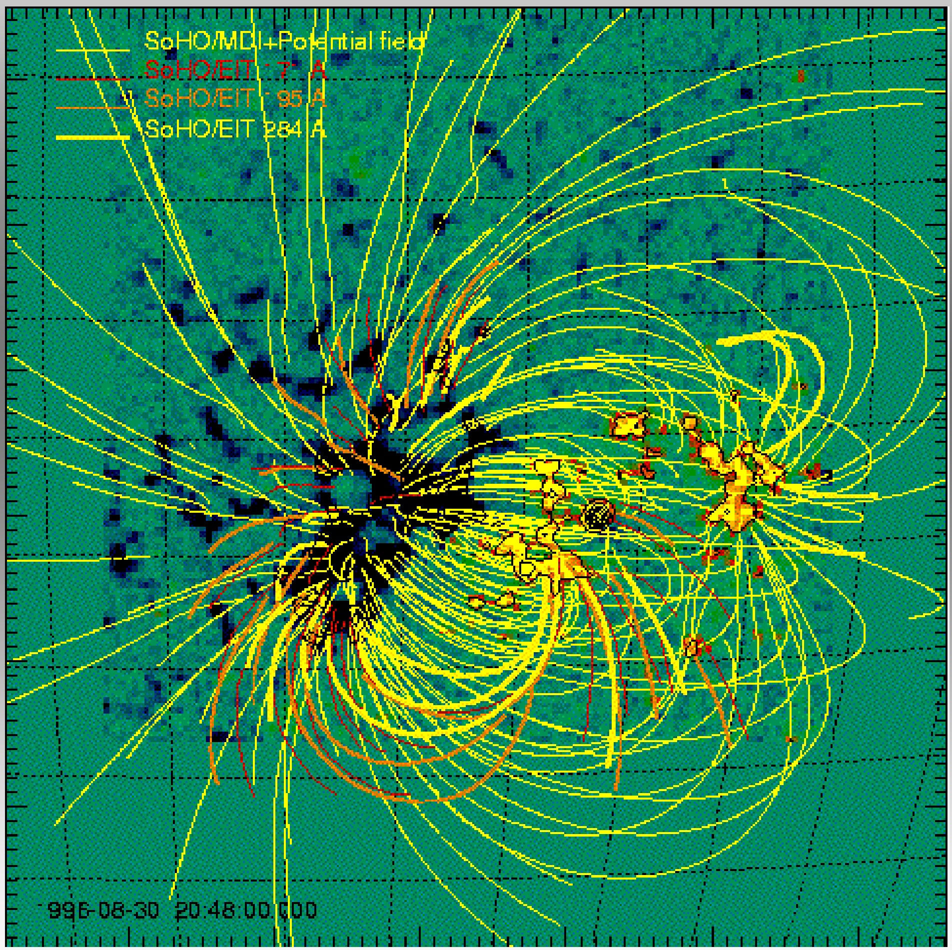


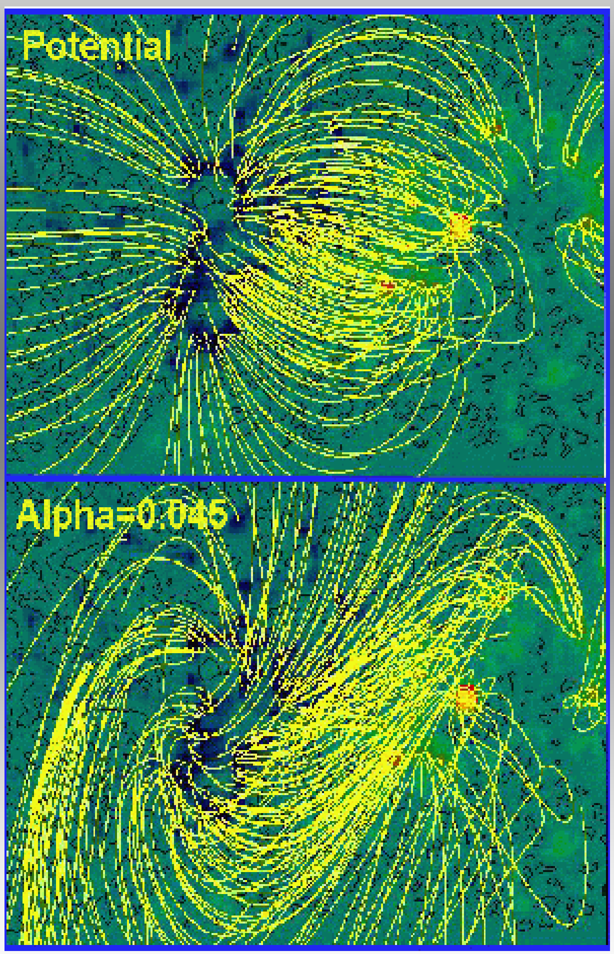
Wiegelmann & Neukirch (2002)

Matching/Fitting of EUV tracings and extrapolated field lines allows to constrain free parameters:

Alpha of nonlinear force-free field model.

Automated detection of coronal loop structures to test theoretical models of magnetic field extrapolations (potential field, constant-alpha, …)





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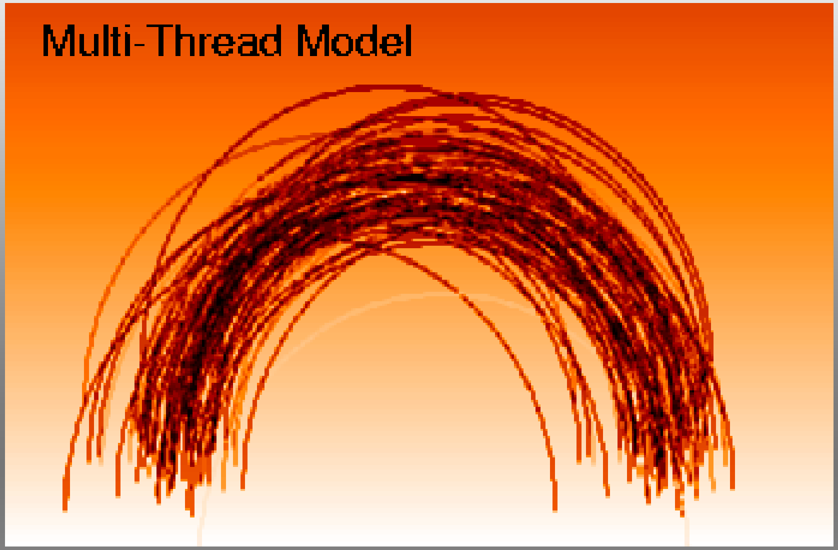
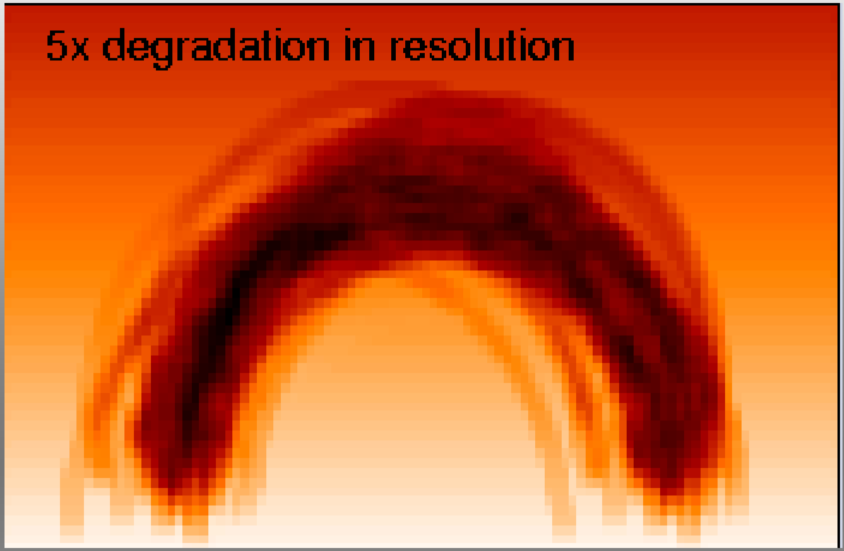
Disentangling of coronal loop strands





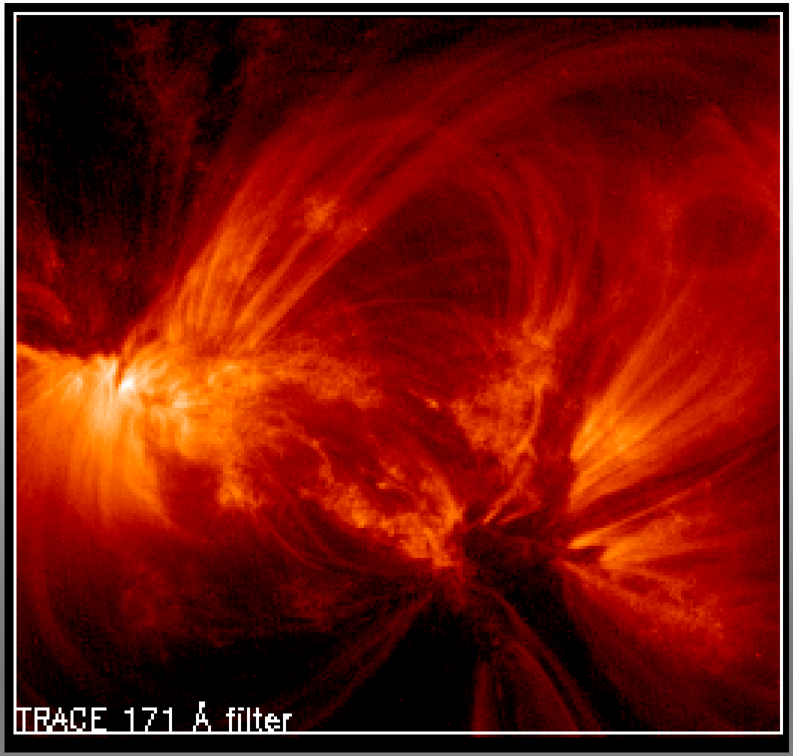
Problems:

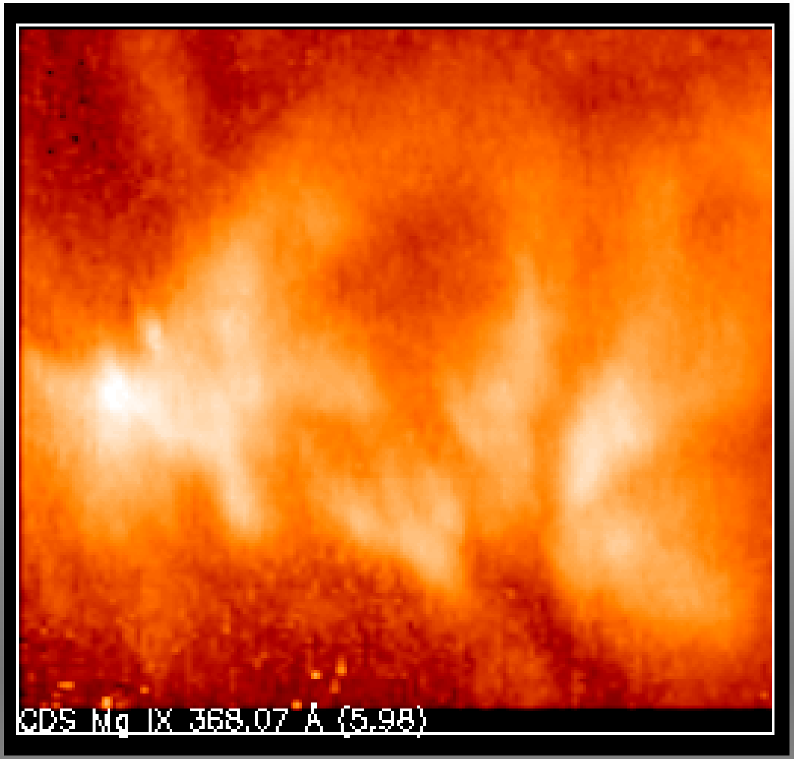
-Isolated loops don't exist

-Every background consists of loops itself

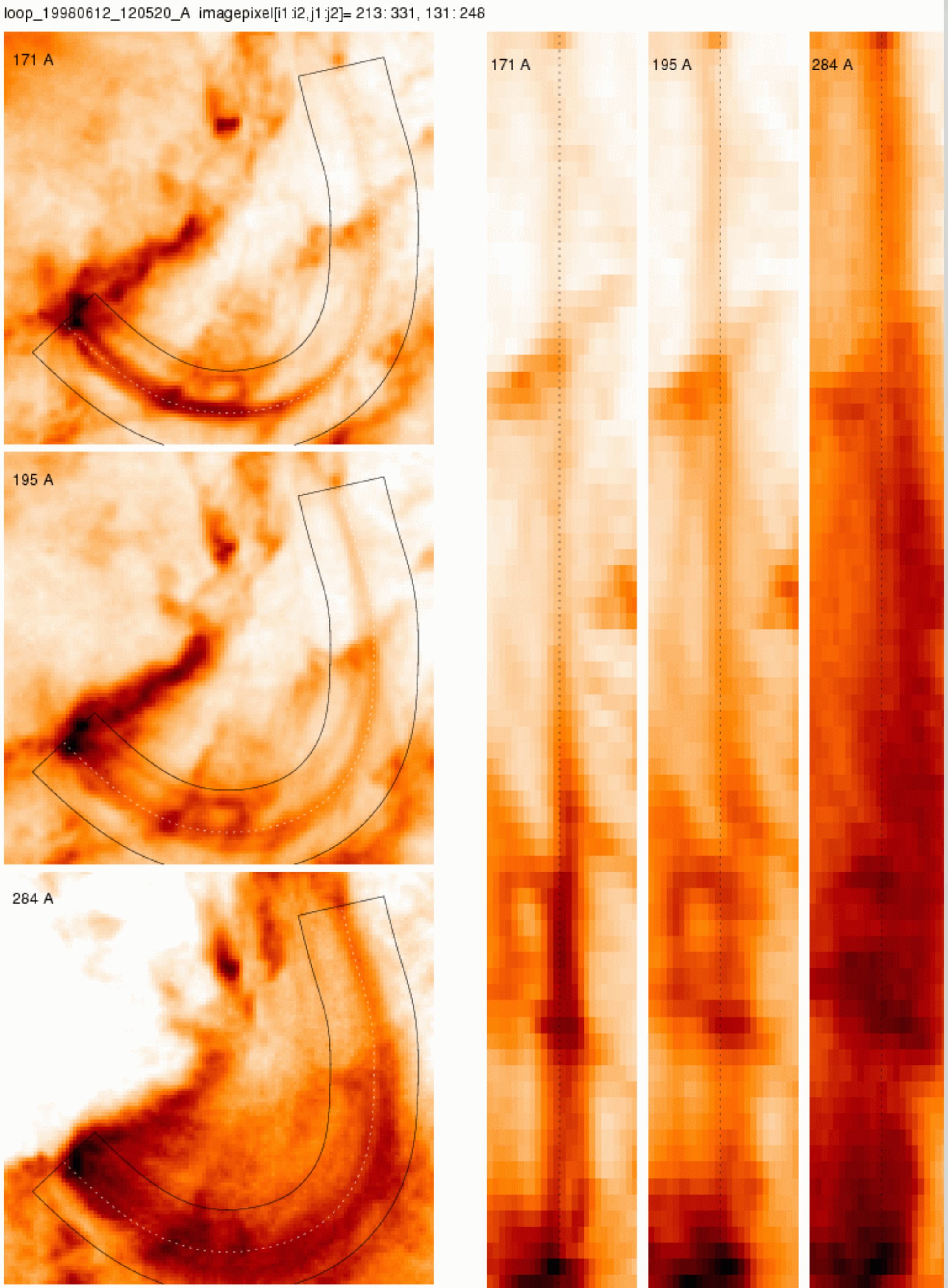
-Disentangling of nested loop strands often impossible due to lack of 3D information and insufficient resolution

-Background is often ill-defined because it requires modeling of background loops ad infinitum





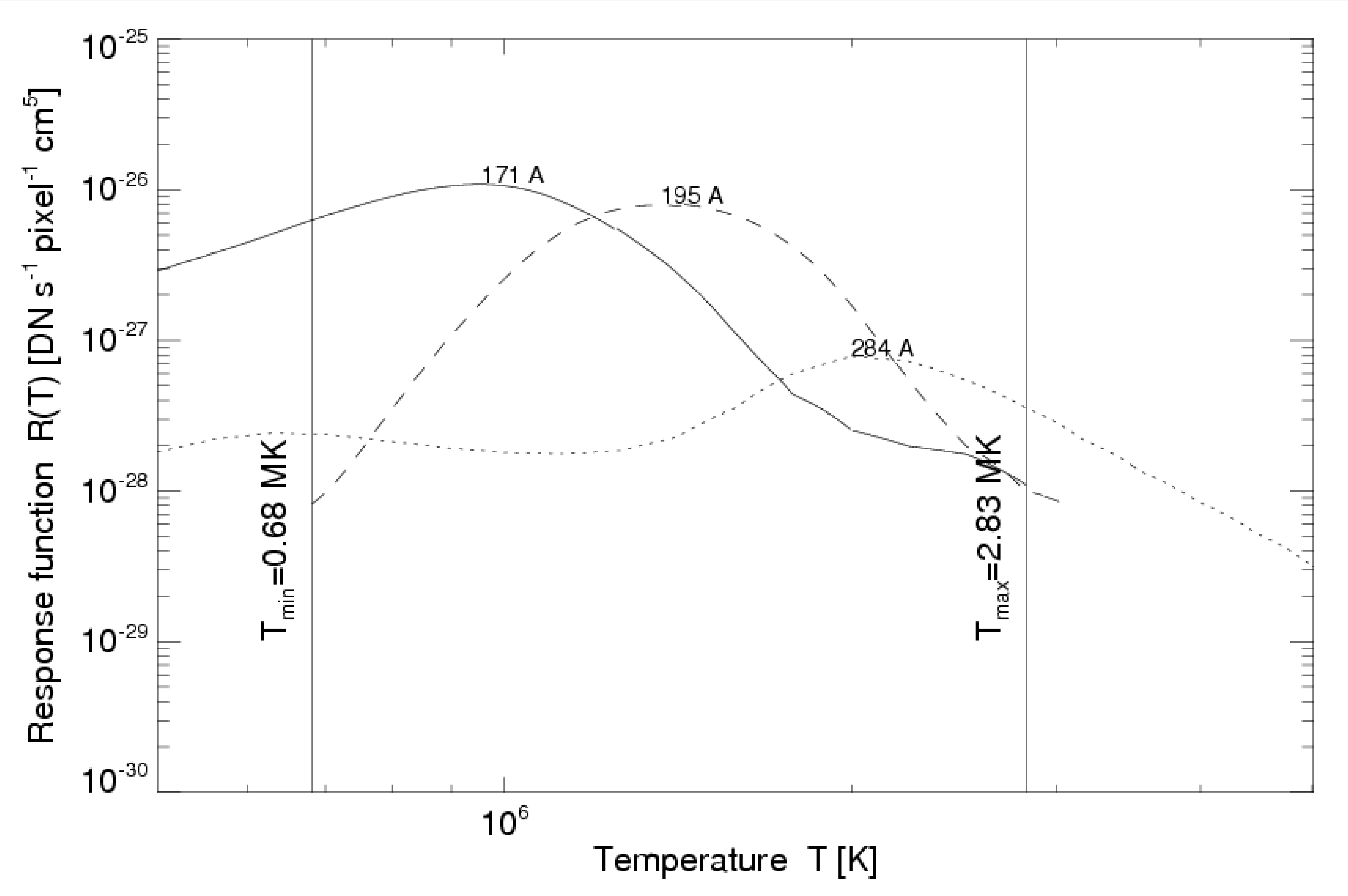
Each loop strand represents an "isolated mini-atmosphere" and has its own hydrodynamic structure T(s), n_e(s).
If we don't resolve a bundle of loop strands (e.g. in CDS image) we cannot model it as a single fluxtube with a 1-dimensional hydrodynamic model (it would be rather a statistical average).
→Need to separate curvi-linear coordinates of loop strands in images with sufficient spatial resolution (e.g., TRACE)



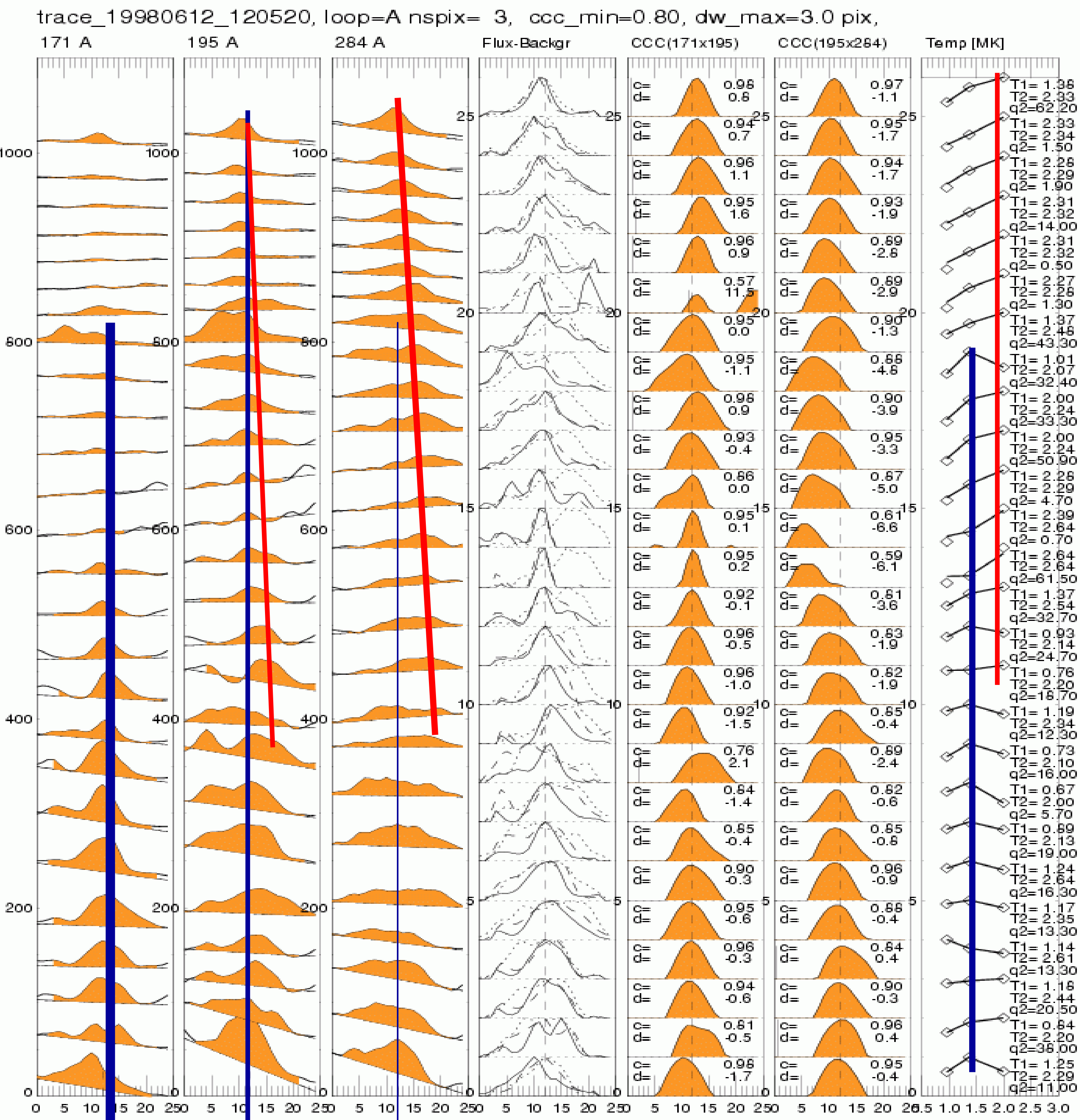
Loop detection in triple-filter TRACE data (171 A, 195 A, 284 A) 1998-Jun-12 1205:20 UT

- Manual tracing (10 pts)
- spline interpolation x(s),y(s)
- 1D stretching with bilinear interpolation

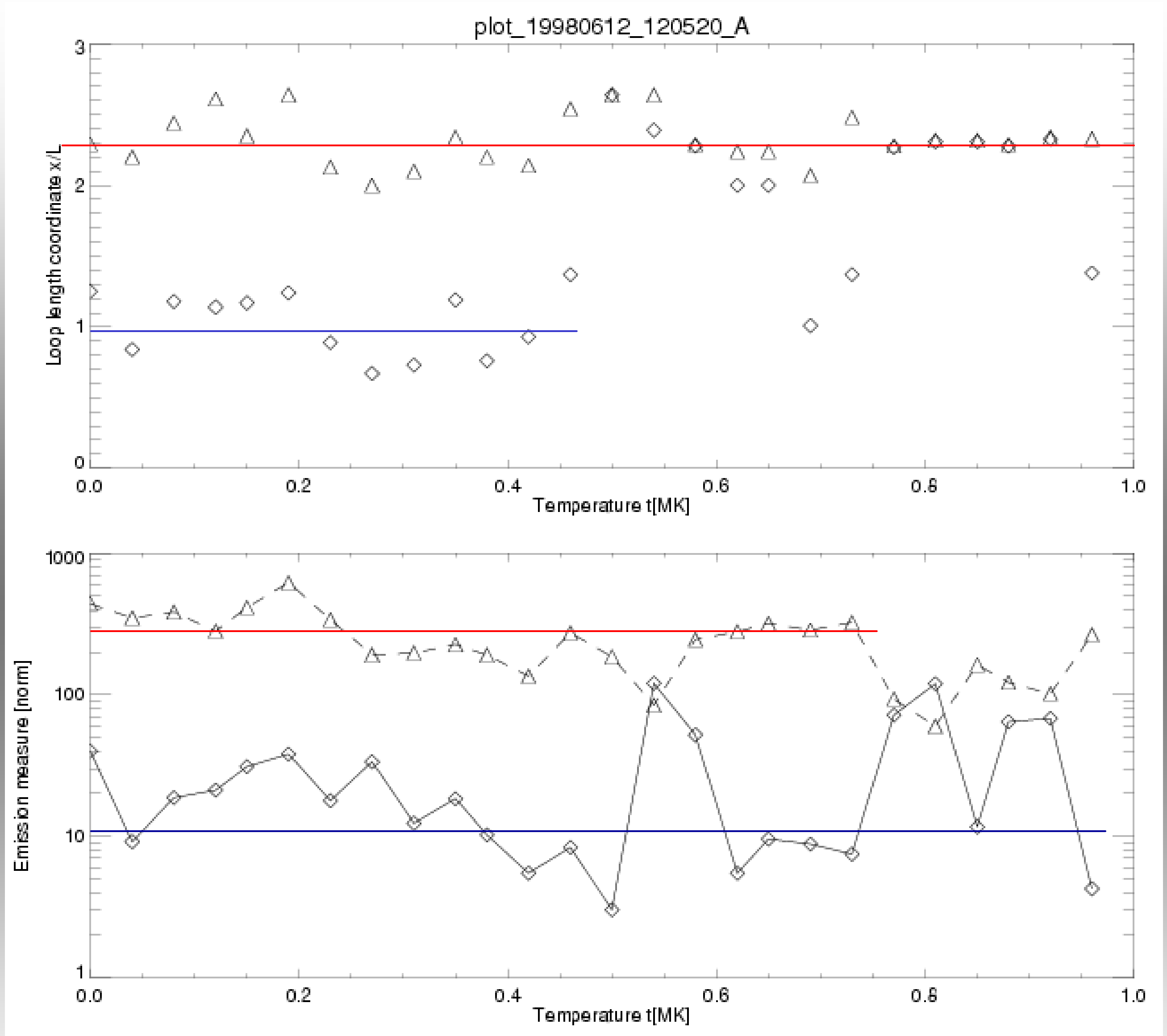
- multiple strands visible
- spatial offsets of loop centroids in 3 filters
- background loops
- background moss



Forward-modeling of model (T,EM) x Response → Obs.fluxes



- -background estimate from 4^{th}-order polynomial fit to loop profile
- -multiple loop strands with different temperatures
- -Triple-filter fluxes can be fitted with 2-component model (T,n_e)



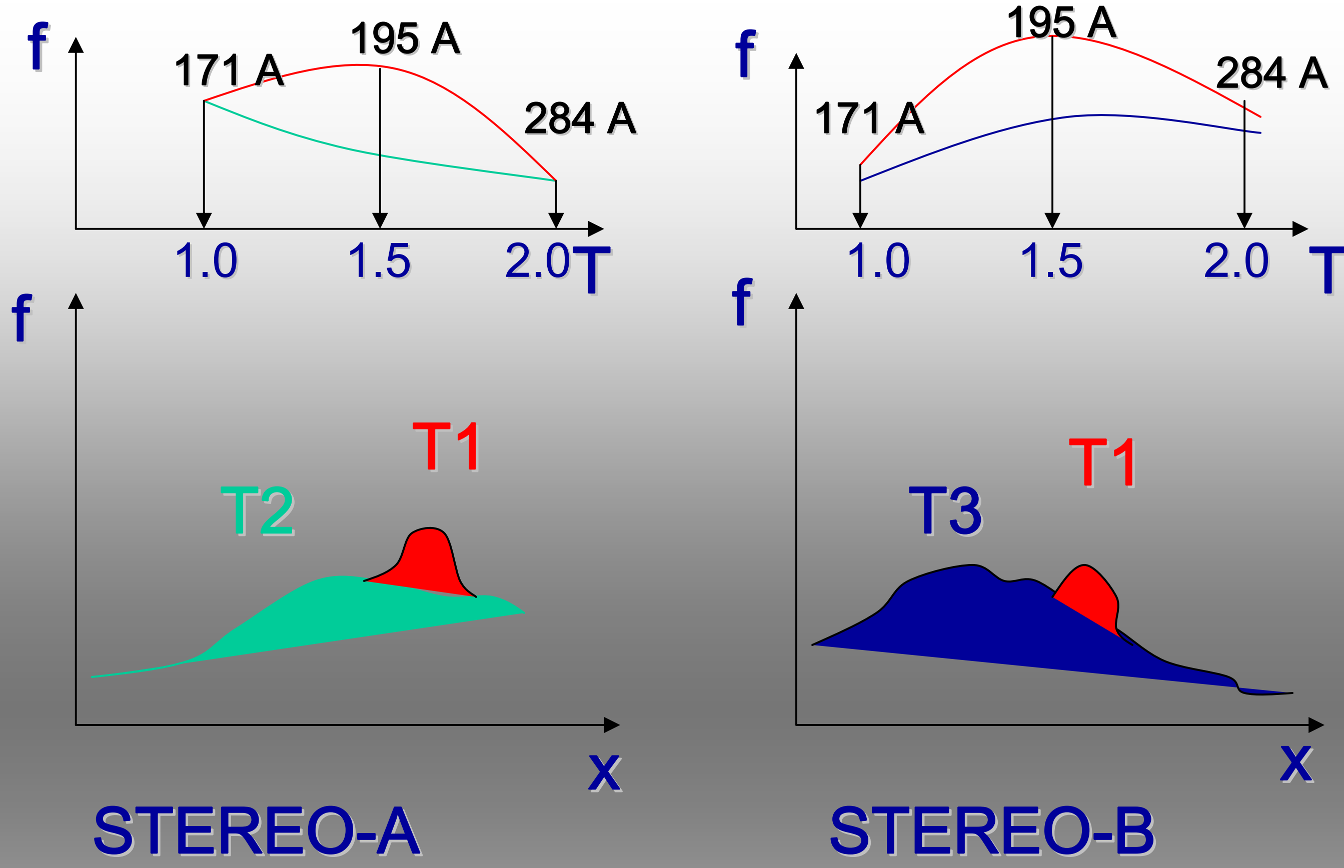
T1=2.25 MK

T2=0.95 MK

EM2=3*10^29 [cm-5]

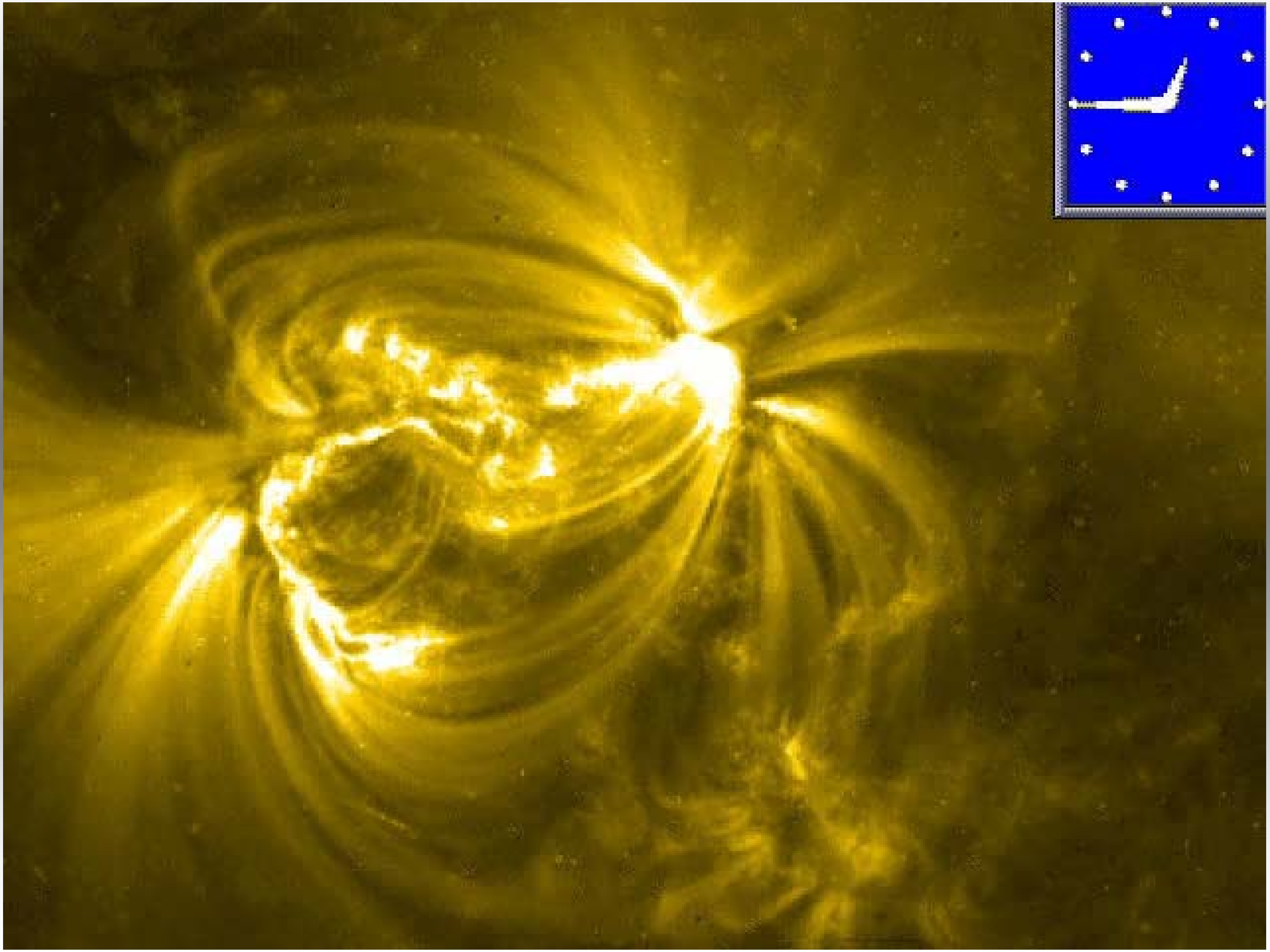
EM1=1*10^28 [cm-5]

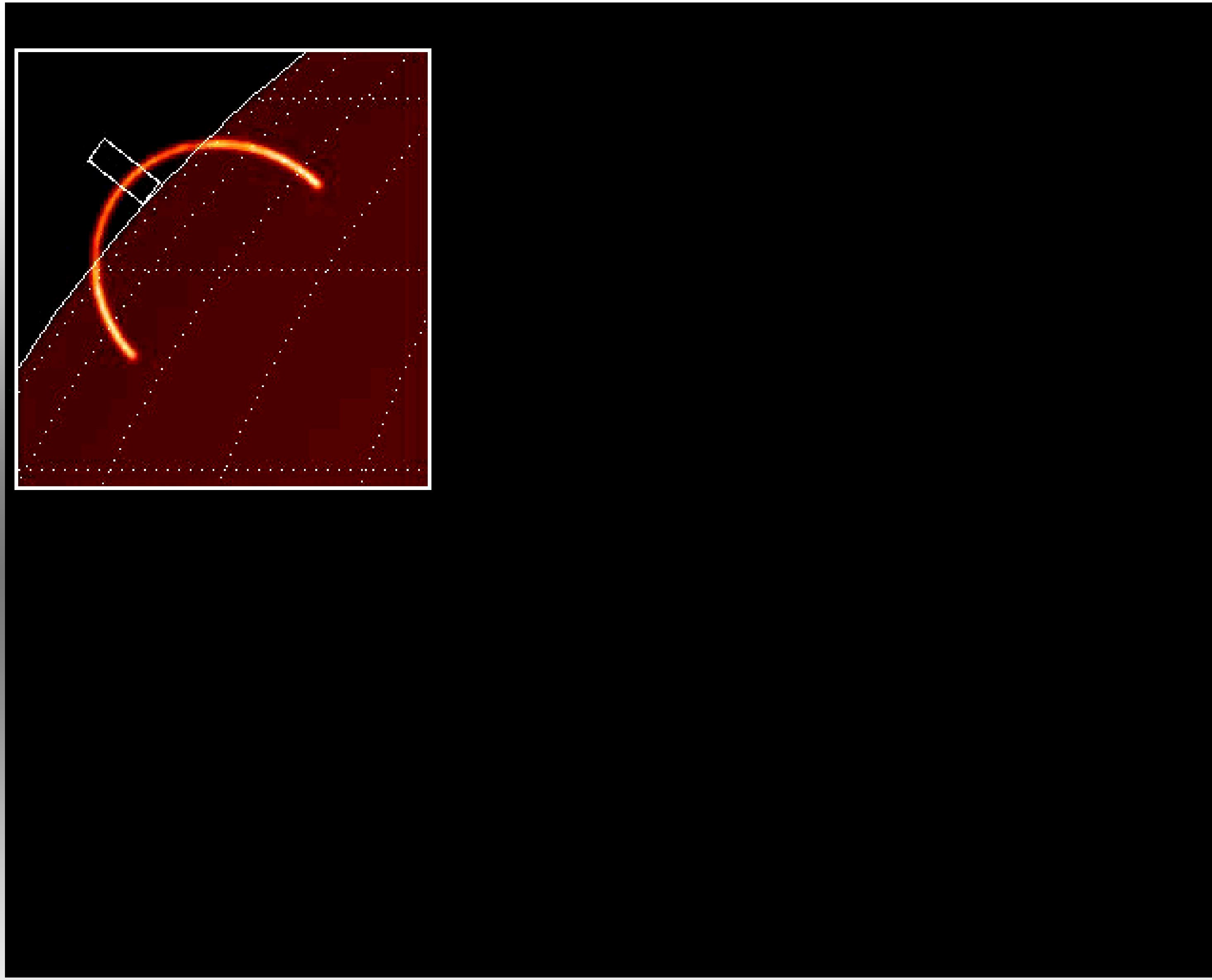
Results of 2-loopstrand forward-modeling to fluxes:
[T1(s),EM1(s);(T2(s),EM2(s)] → F_171(s), F_195(s), F_284(s)



Two views from two different spacecraft will allow the subtraction of two independent background flux profiles f(T2[x]), f(T3[x]) and provides a consistency check for the uncontaminated background-subtracted flux f(T1[x]) of a selected loop.

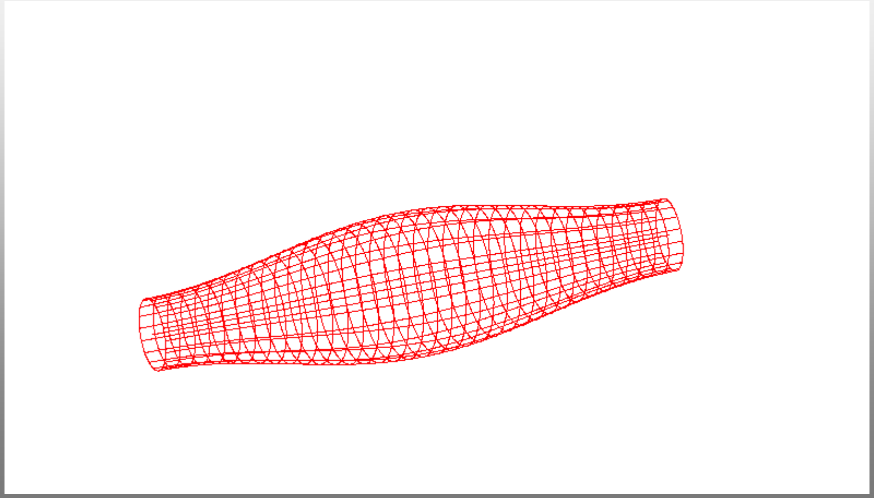
3D coordinates of oscillating loops [x(t), y(t), z(t)]



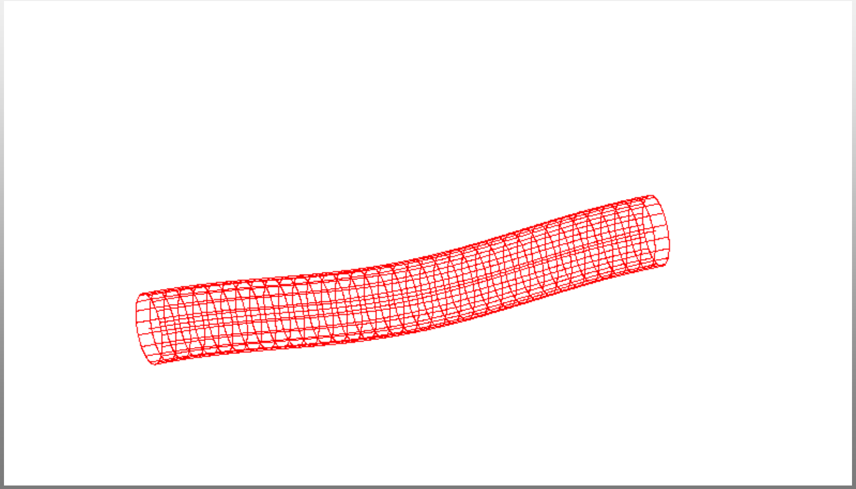


Two views from two STEREO spacecraft provide complete 3D coordinates of loop oscillations, [x(t),y(t),z(t)], [v_x(t),v_y(t),v_z(t)] and allows decomposition of multiple wave modes.

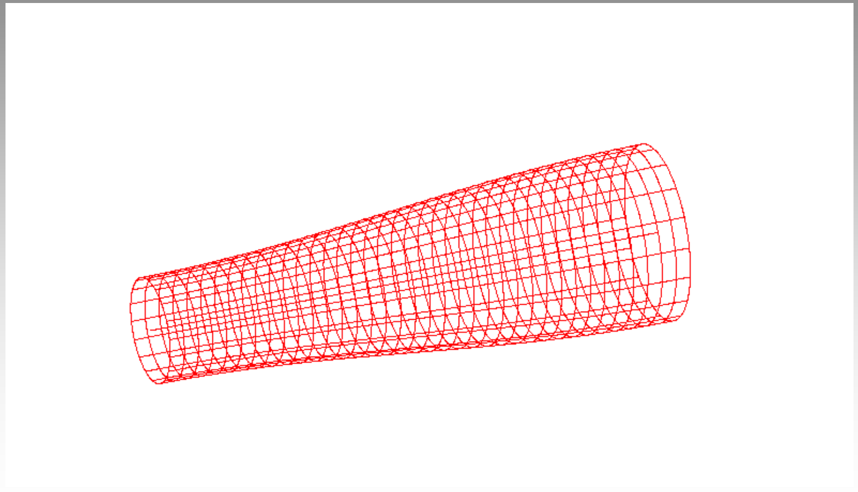
MHD fast sausage mode



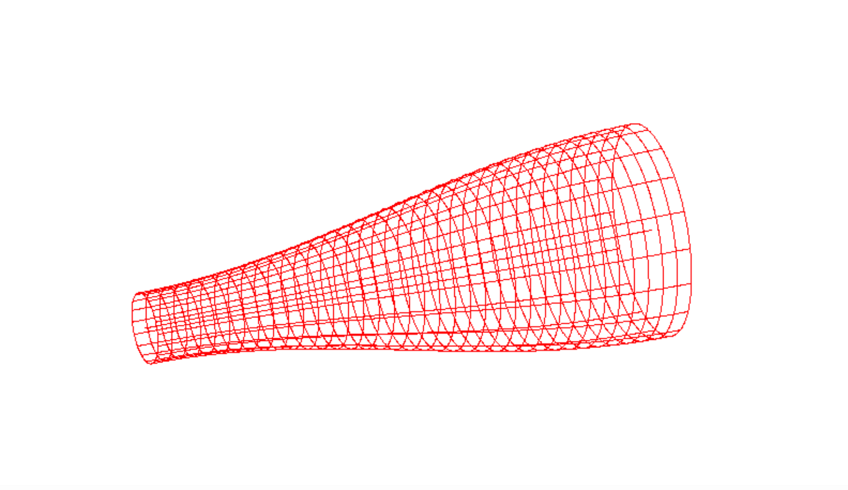
MHD fast kink mode



MHD slow (acoustic) mode



Impulsively generated (propagating) wave



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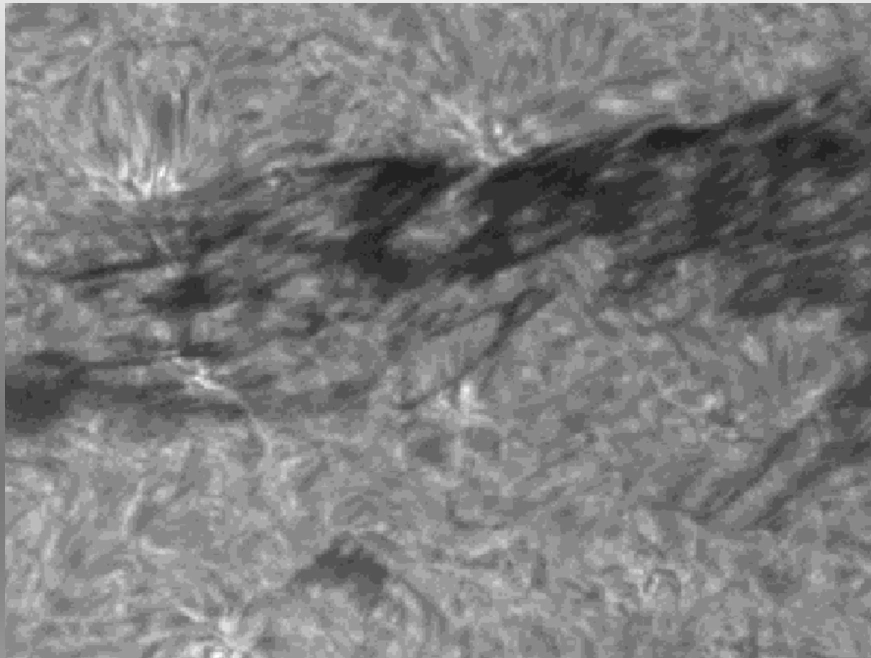
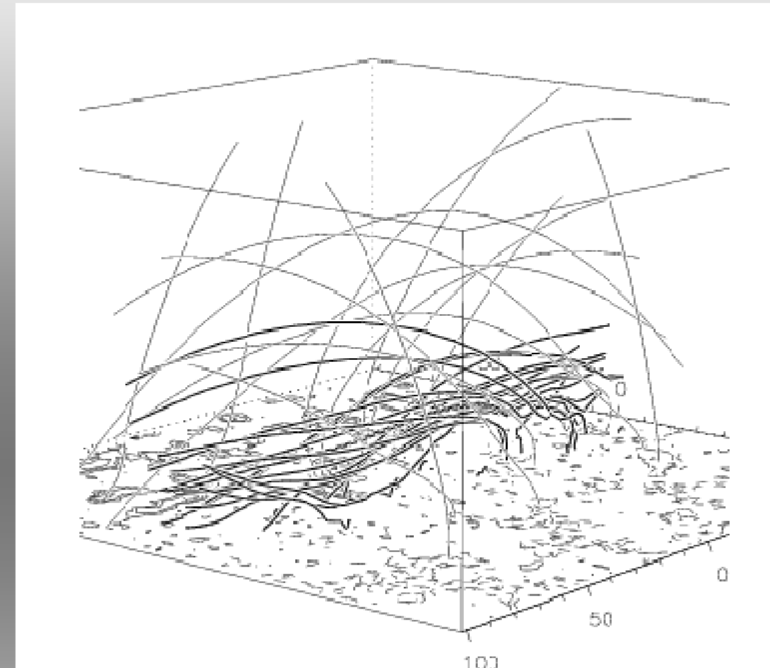
3D geometry of filaments



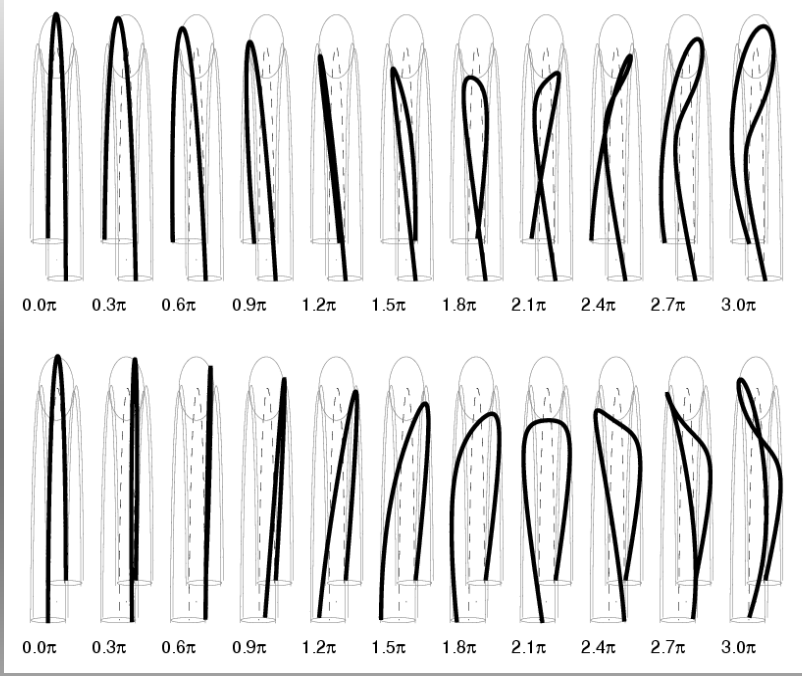
Envold (2001)



Aulanier & Schmieder (2002)

- -Geometry and multi-threat structure of filaments (helicity, chirality, handedness → conservation, fluxropes)
- -Spatio-temporal evolution and hydrodynamic balance
- -Stability conditions for quiescent filaments
- -Hydrodynamic instability and magnetic instability of erupting filaments leading to flares and CMEs

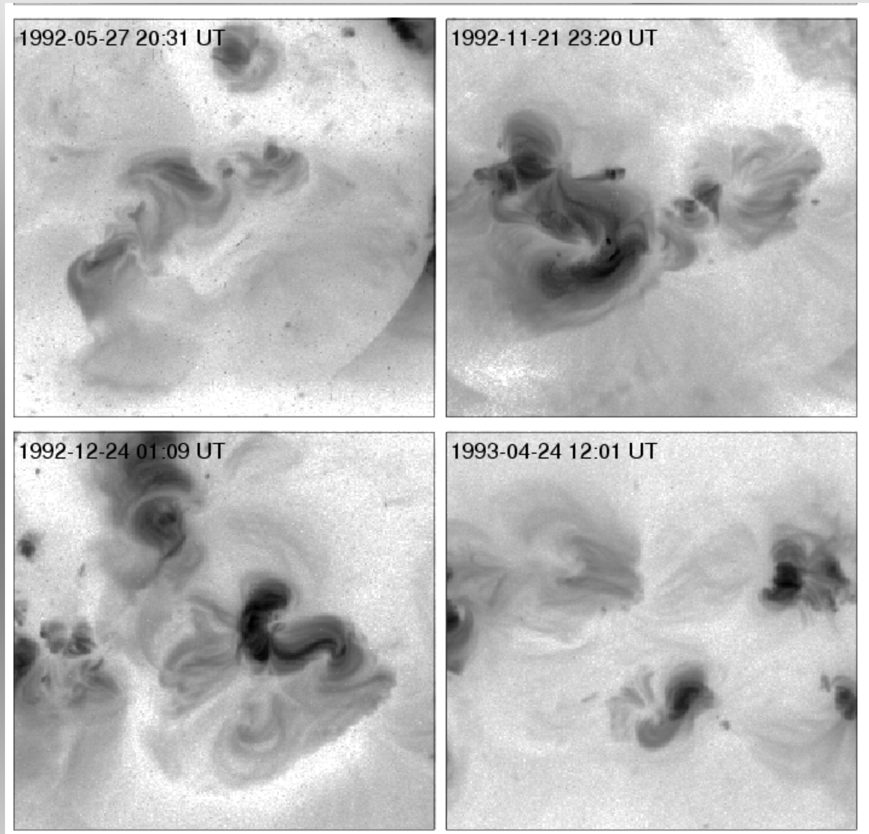
Measuring the twist of magnetic field lines

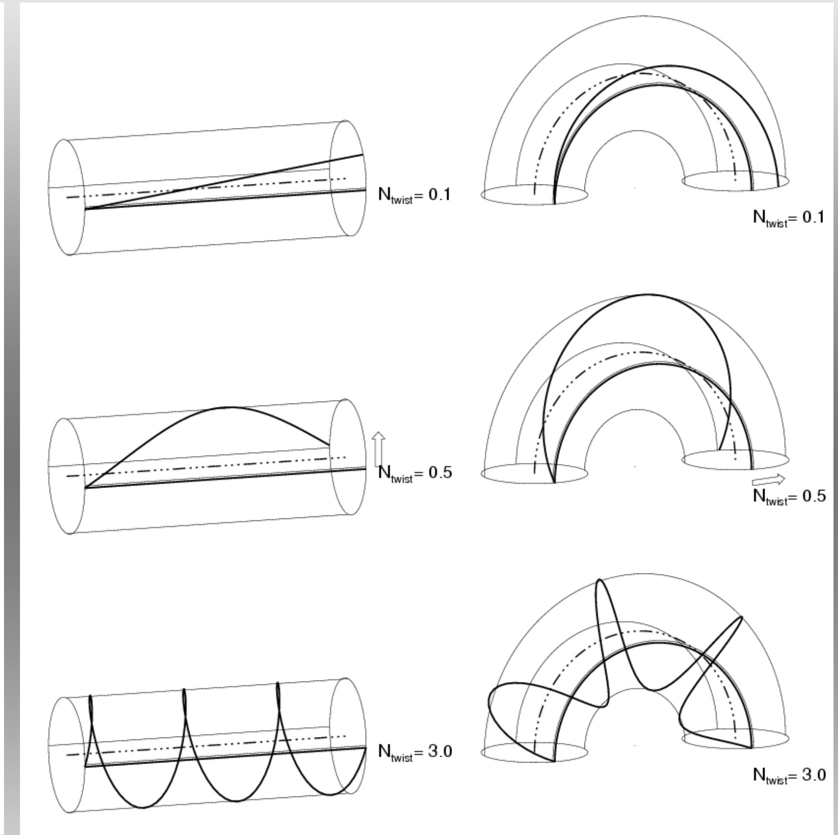


Aschwanden (2004)

- -Measuring the number of turns in twisted loops
- -Testing the kink-instability criterion for stable/erupting loops
- -Monitoring the evolution of magnetic relaxation (untwisting) between preflare and postflare loops

Measuring the twist of magnetic field lines



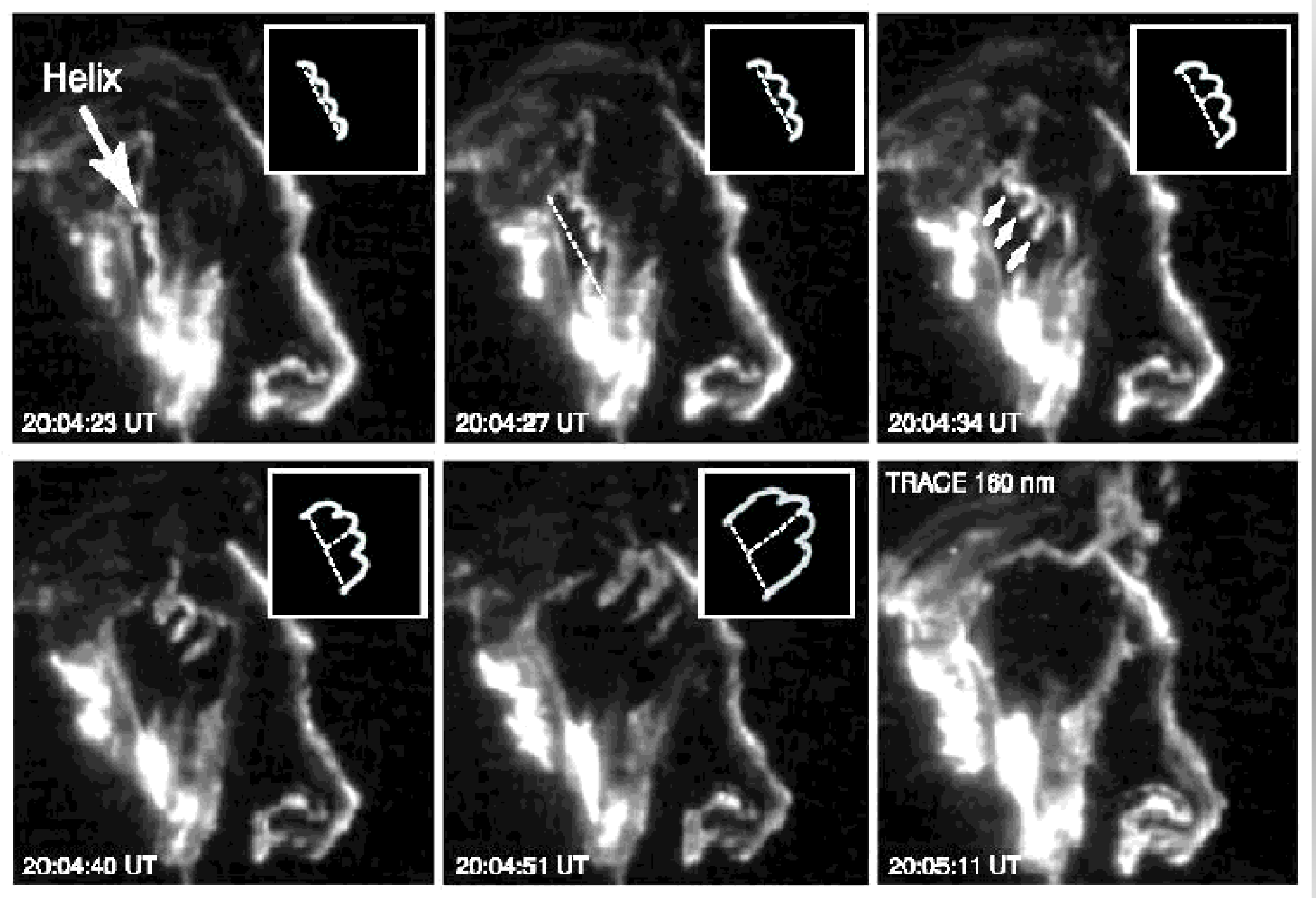


Aschwanden (2004)

-Measuring number of turns in (twisted) sigmoids before and after eruption

-Test of kink-instability criterion as trigger of flares/CMEs

Measuring the twist of erupting fluxropes

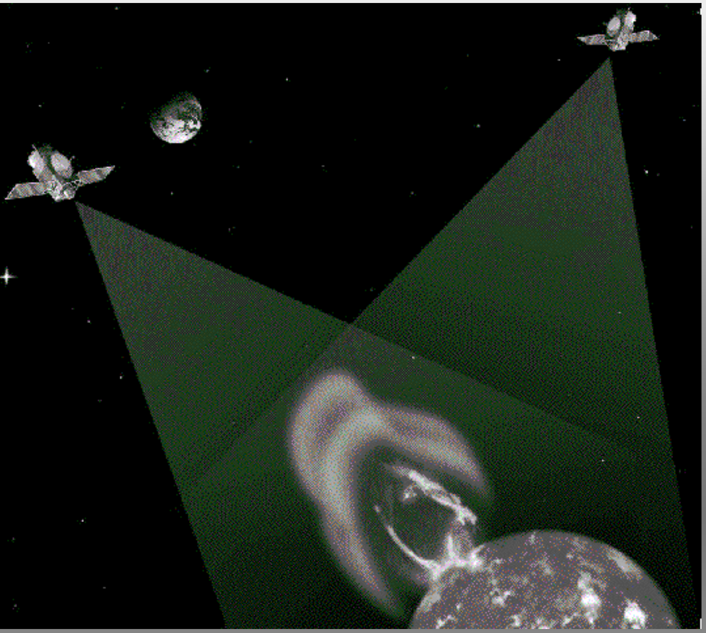


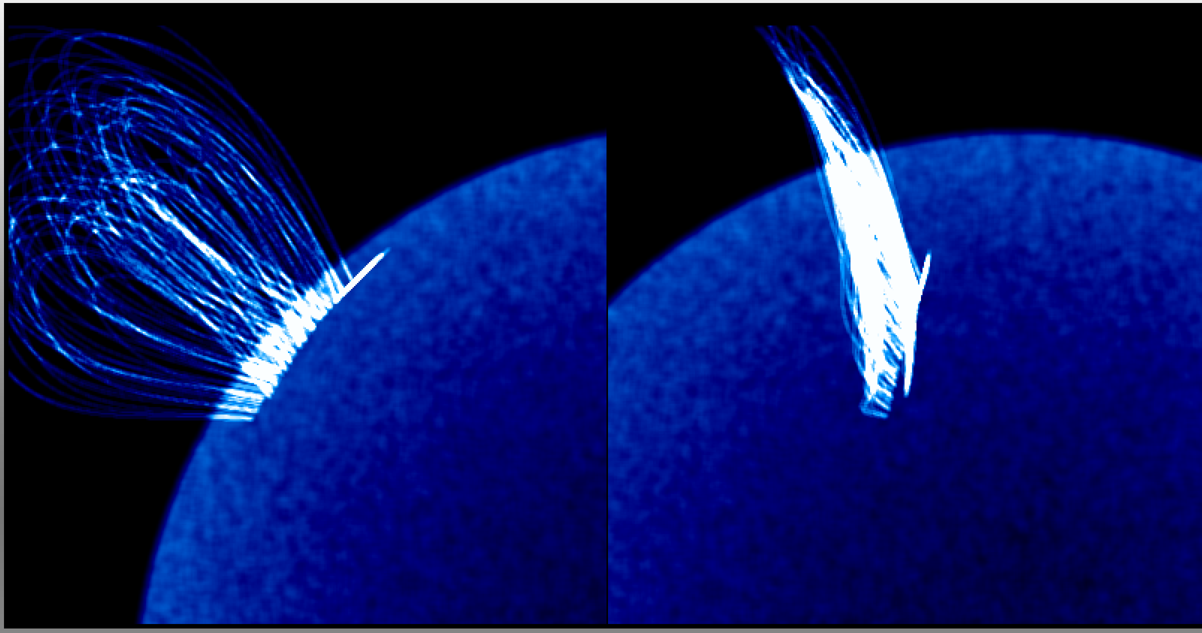
Gary & Moore (2004)

-Measuring number of turns in erupting fluxropes

-Test of kink-instability criterion as trigger of flares/CMEs

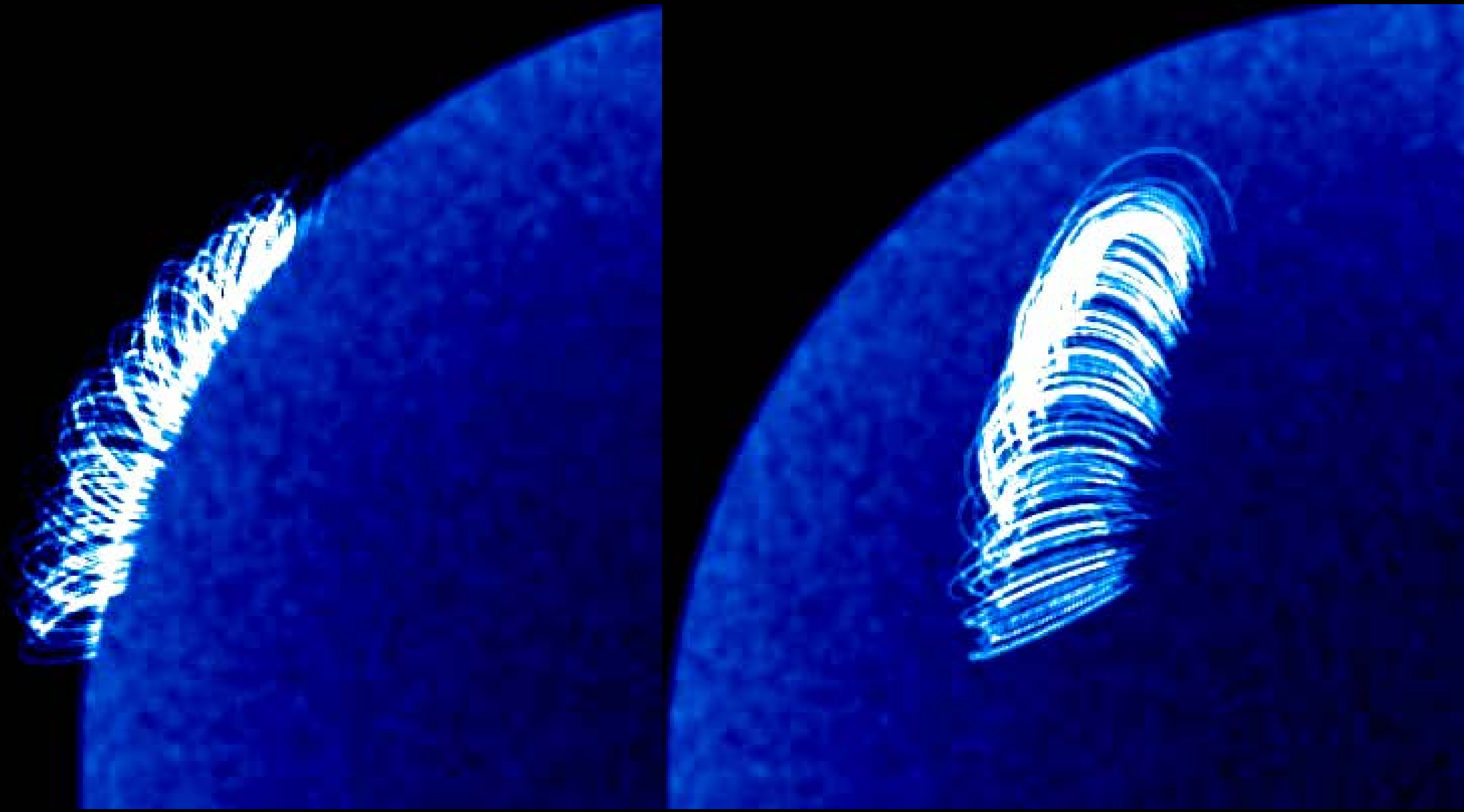
Stereoscopic view of an erupting filament





-Identification of a common feature from two views is difficult for nested structures (loop arcades, active region loops)

-Stereoscopic 3D-reconstruction is least ambiguous for small stereo-angles, but 3D accuracy is best for large stereo-angles: optimum at angles of ~10-30 deg.



Animation of stereoscopic view (with a separation angle of 45 deg) of an erupting filament and associated flare loop arcade

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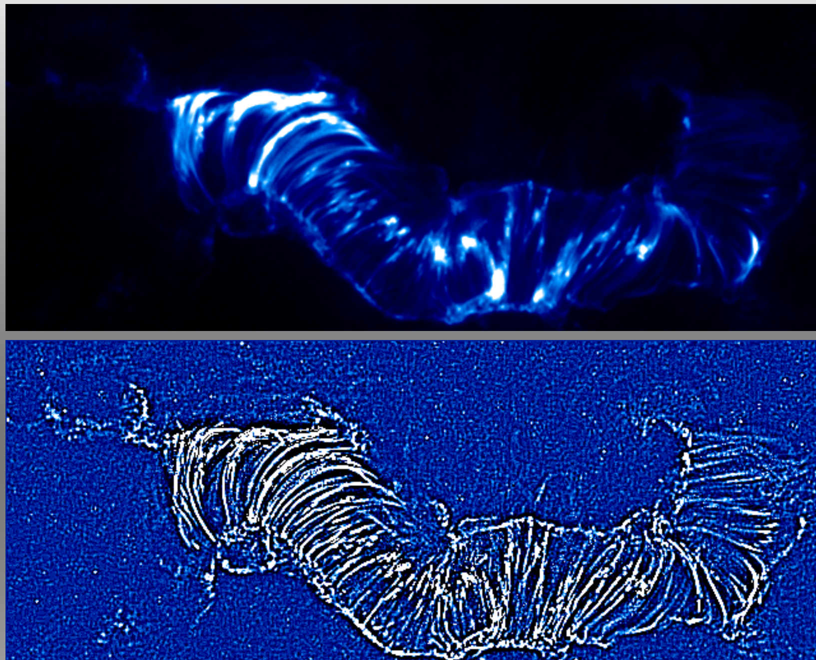
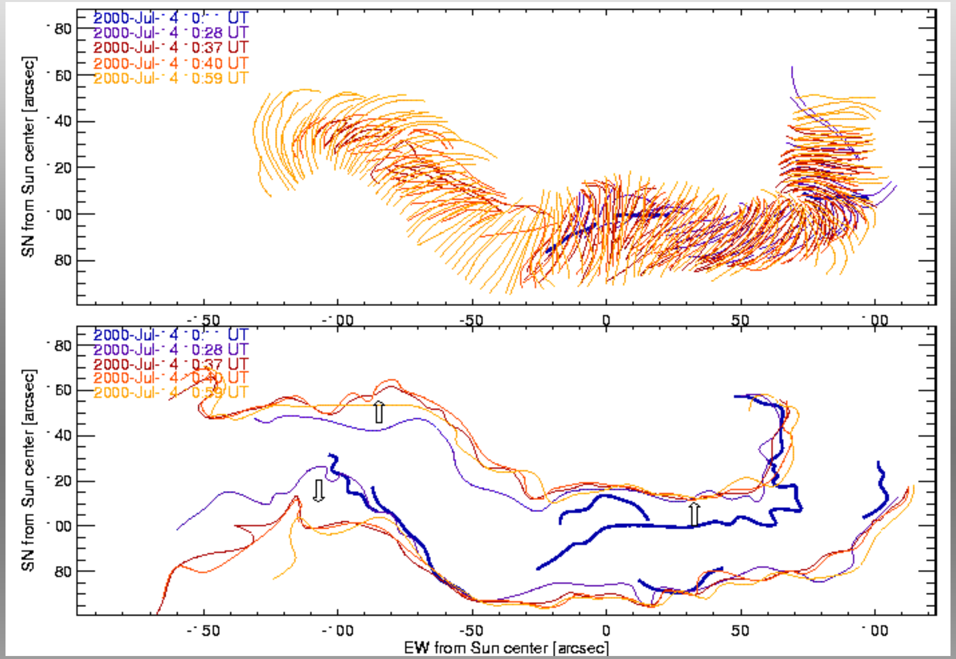
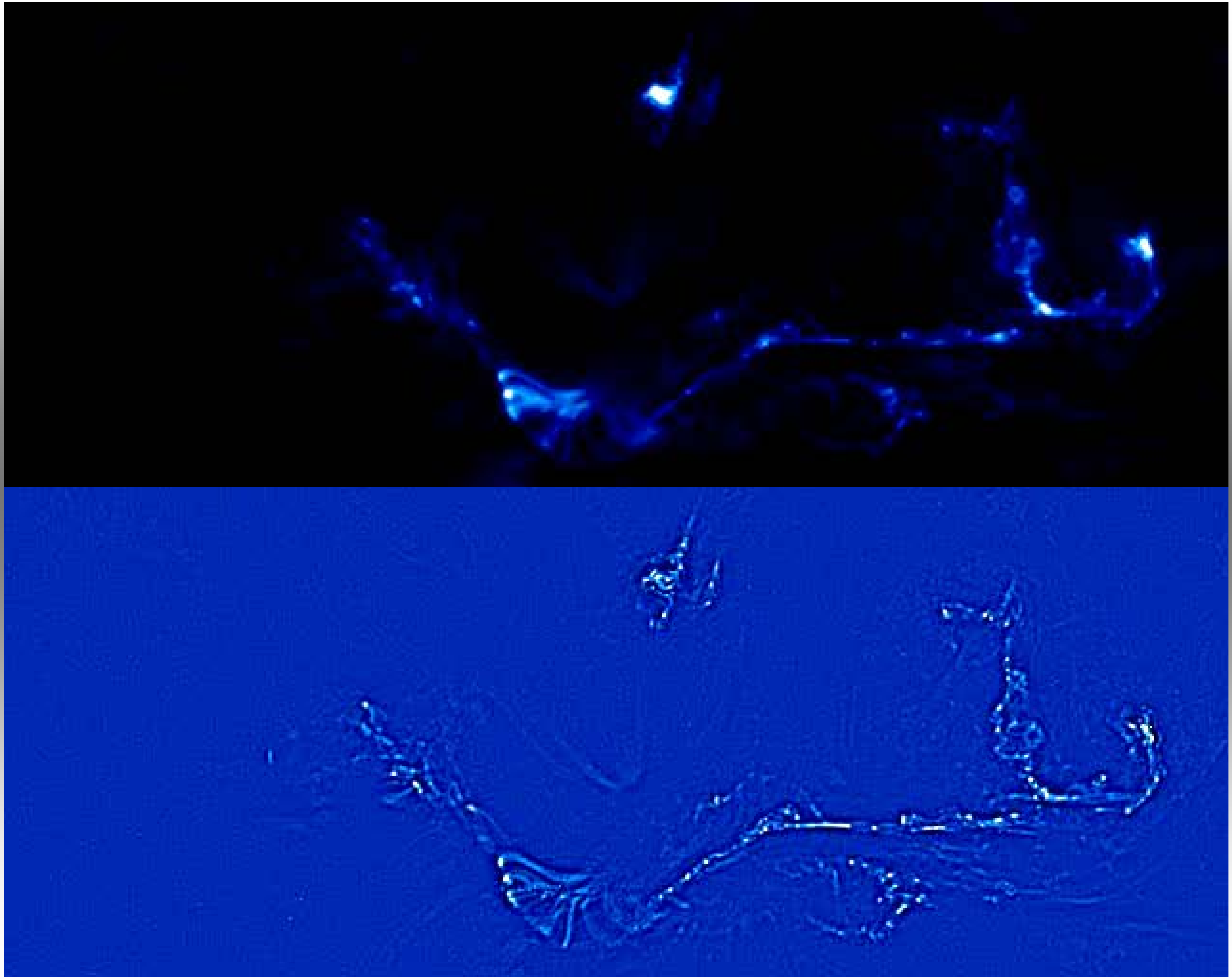
Spatio-temporal evolution of flare loop systems

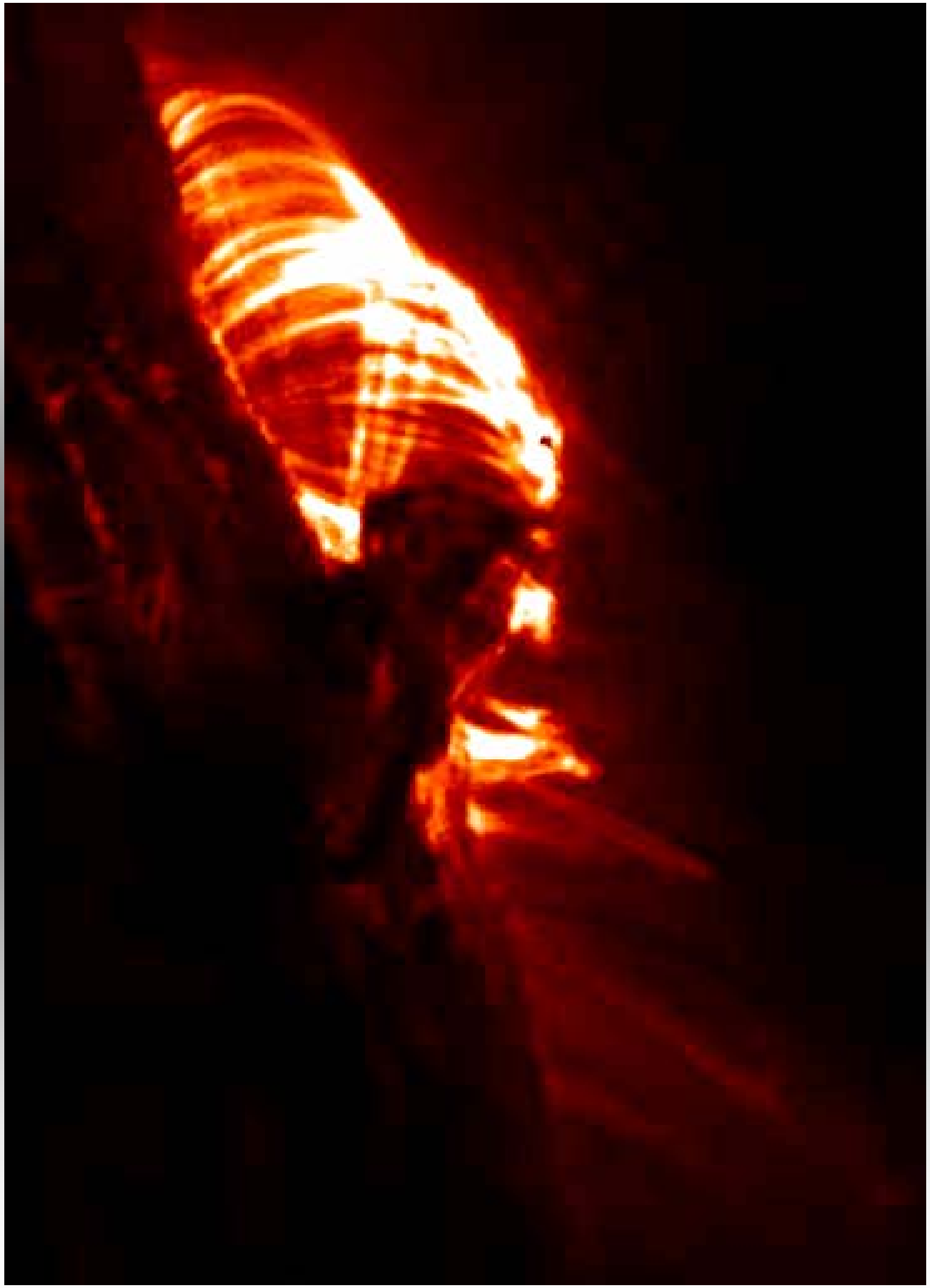




Aschwanden (2002)

- Spatio-temporal fragmentation of magnetic reconnection
- Hydrodynamics, heating, cooling of 100’s of flare arcade loops
- Footpoint (double) ribbon separation and X-point height h(s)
- Shear vs. height relation of reconnecting field lines

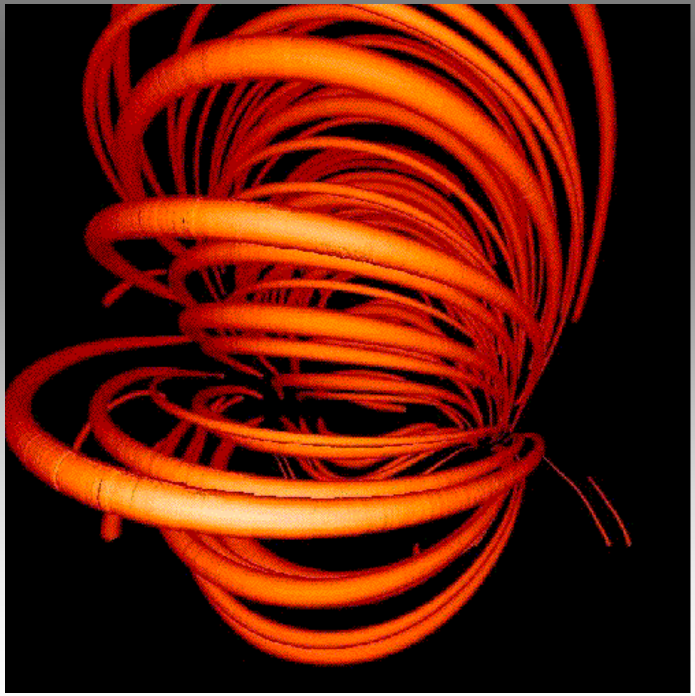


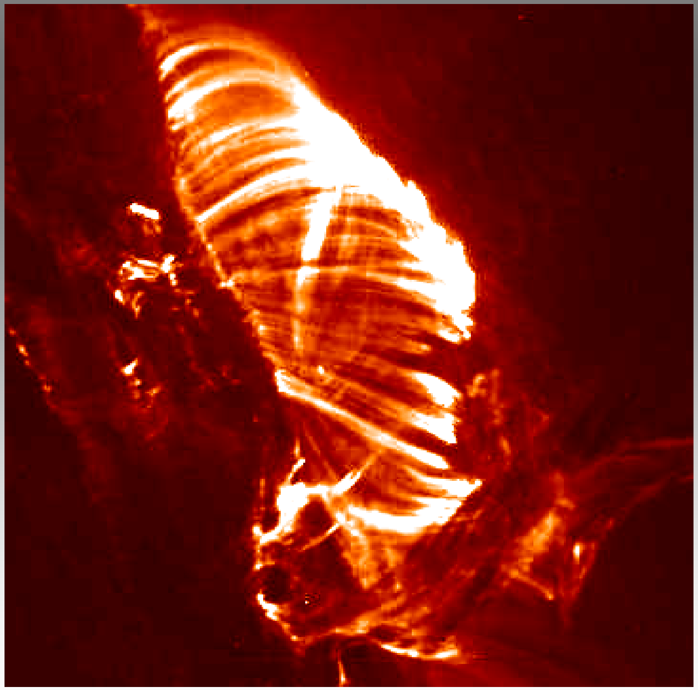


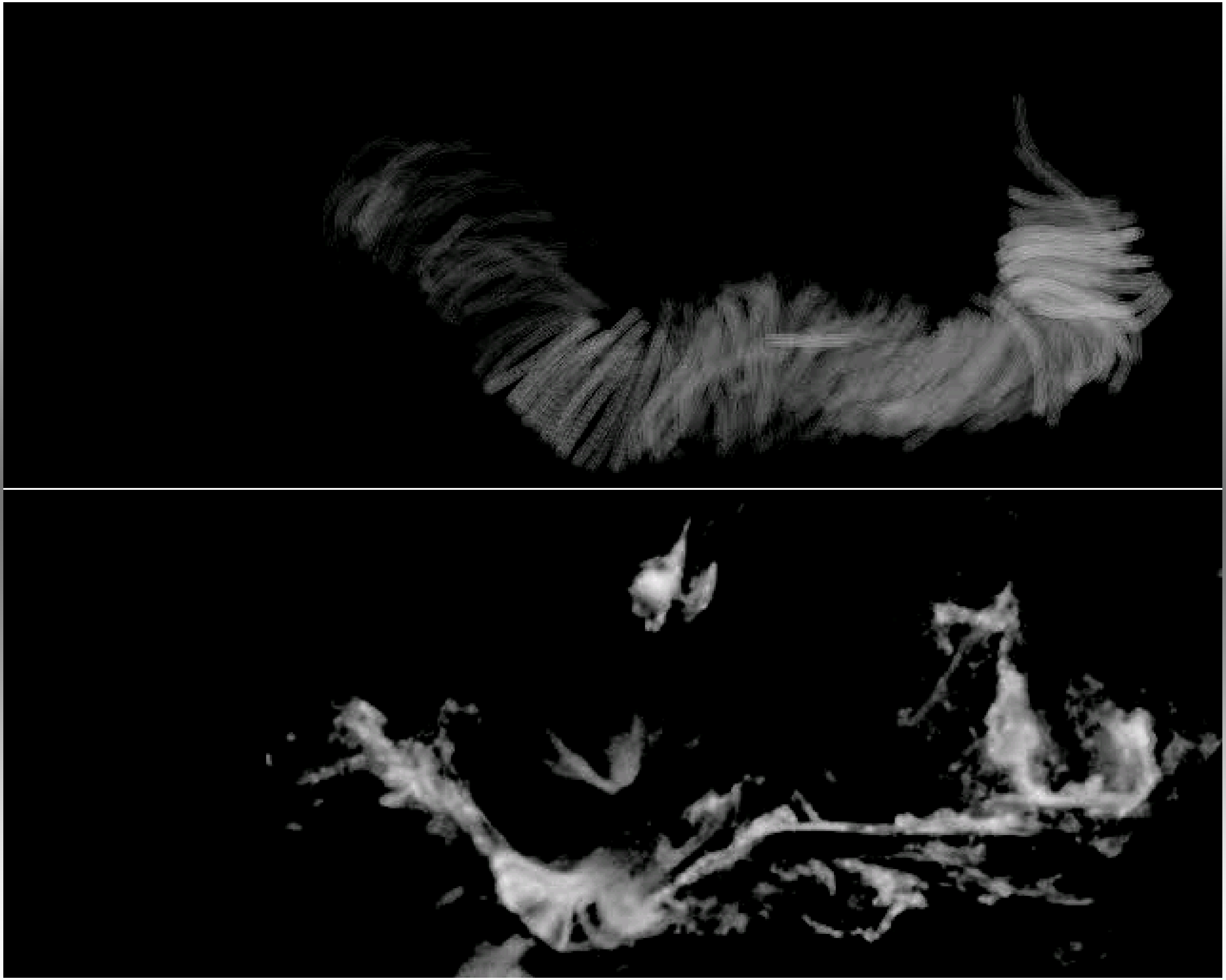
Side view of filament eruption and expanding postflare arcade

→Increasing footpoint separation and apparent expansion of postflare loop arcade indicates rise of reconnection X-points according to the Kopp-Pneuman model.

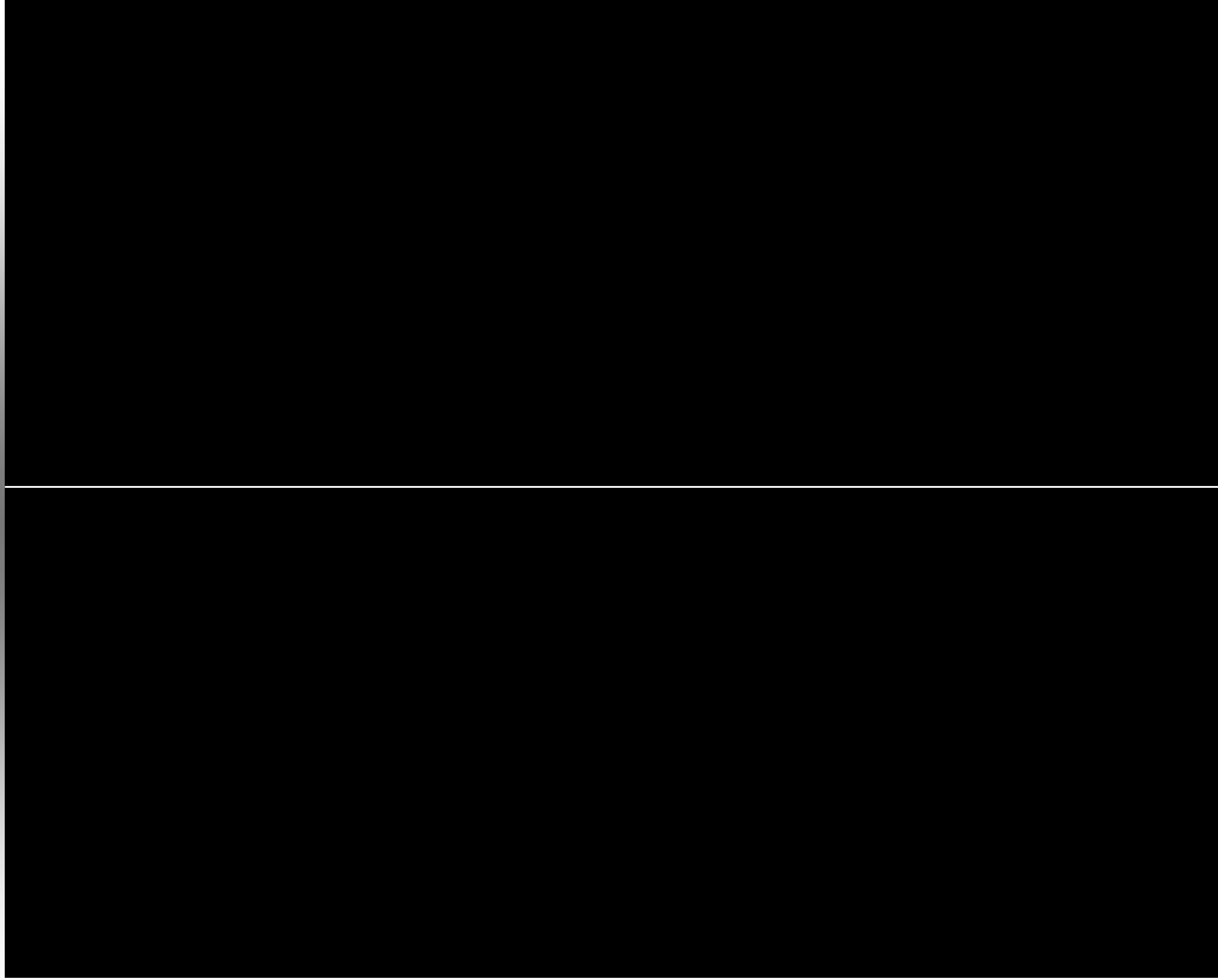
Hydrodynamic modeling of the evolution of a flare loop system requires modeling of the density $n(s,t)$ and temperature $T(s,t)$ in a time-dependent multi-loop system, convolution with the filter response functions and forward-fitting to multi-filter data in soft X-ray and EUV images.



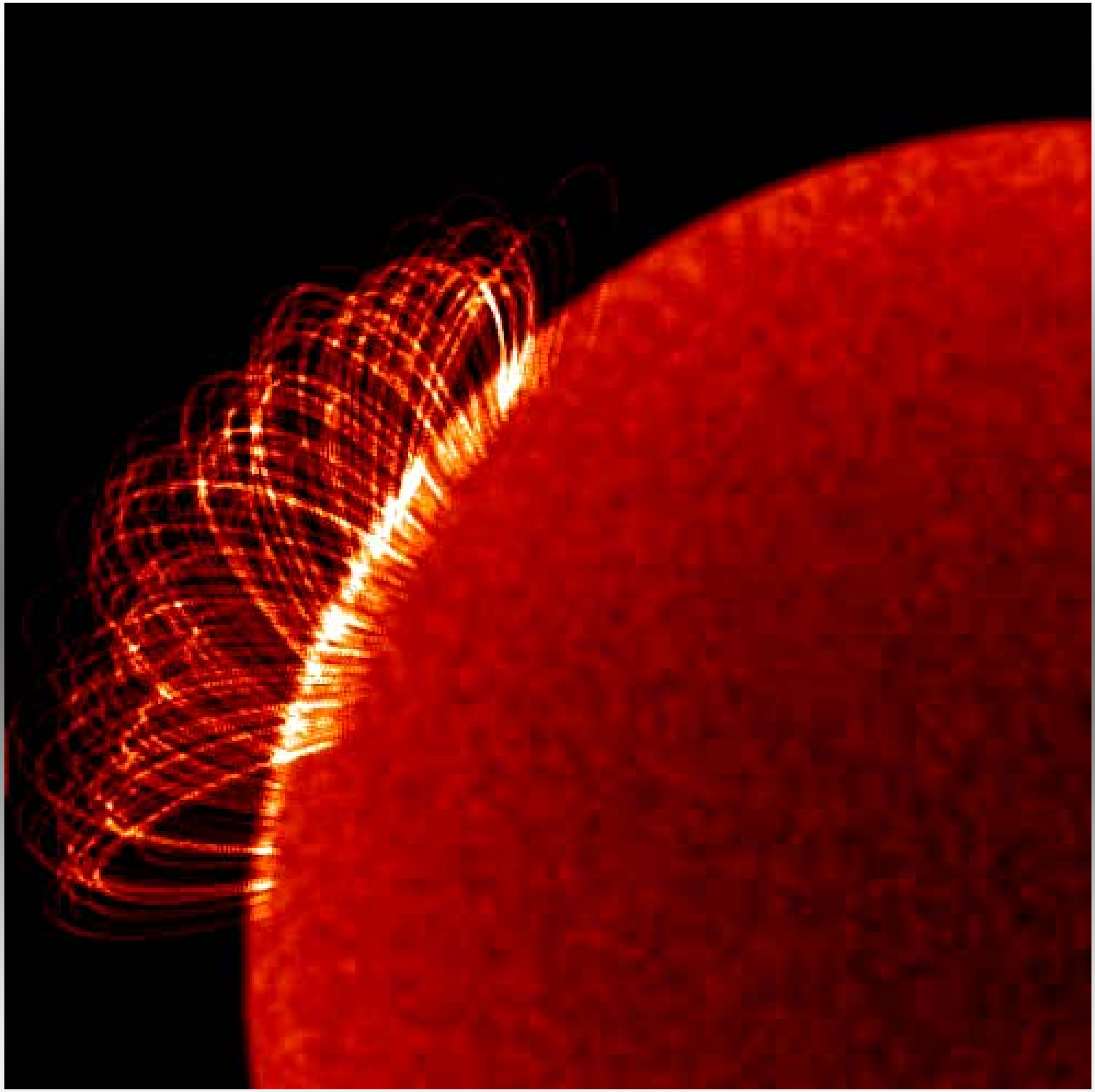




Forward-fit model of cooling (post-reconnection) flare loop arcade



Forward-fit model of relaxing (post-reconnection) flare loops



Stereoscopic views allows for modeling constraints from 2 projections

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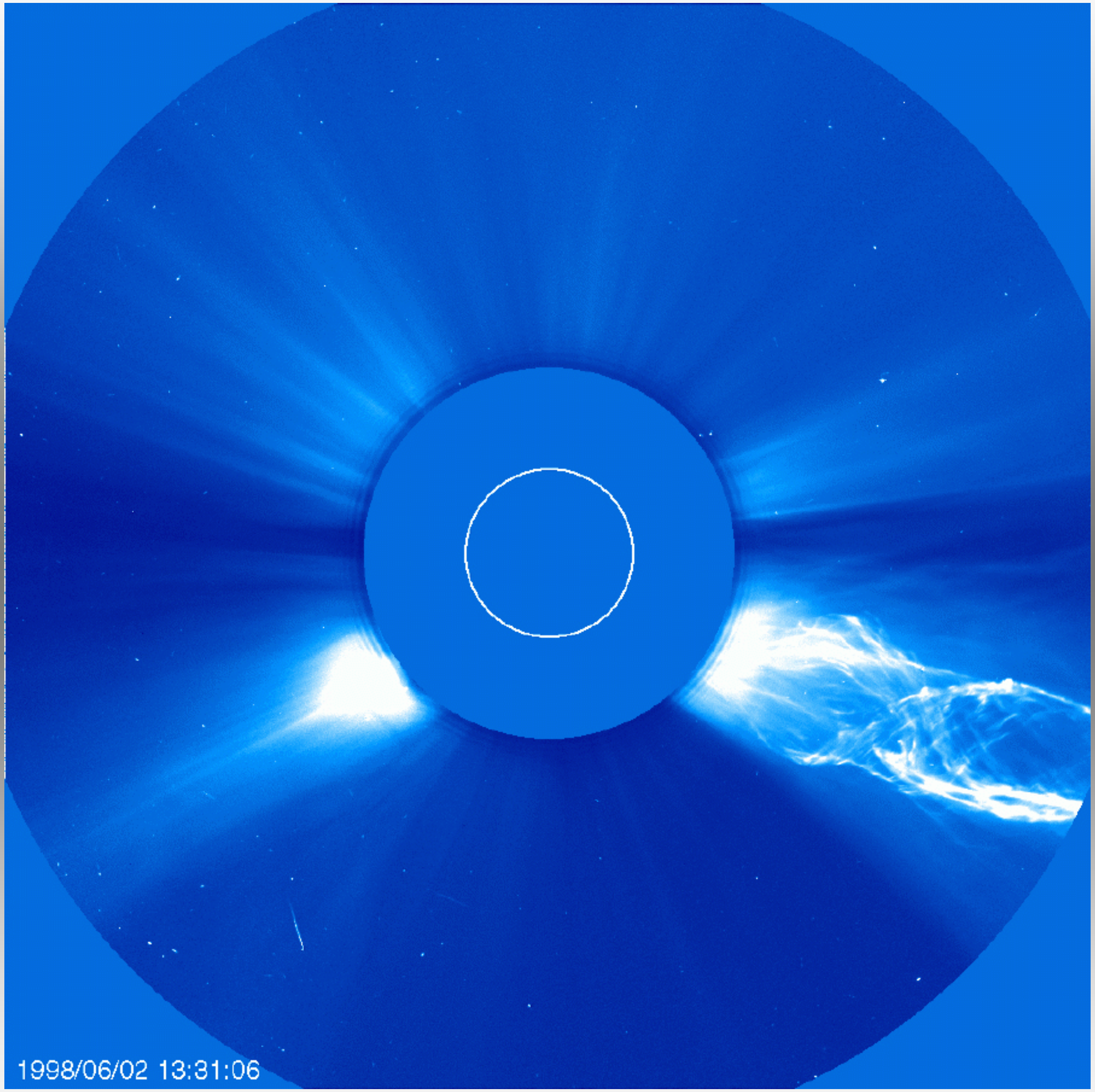
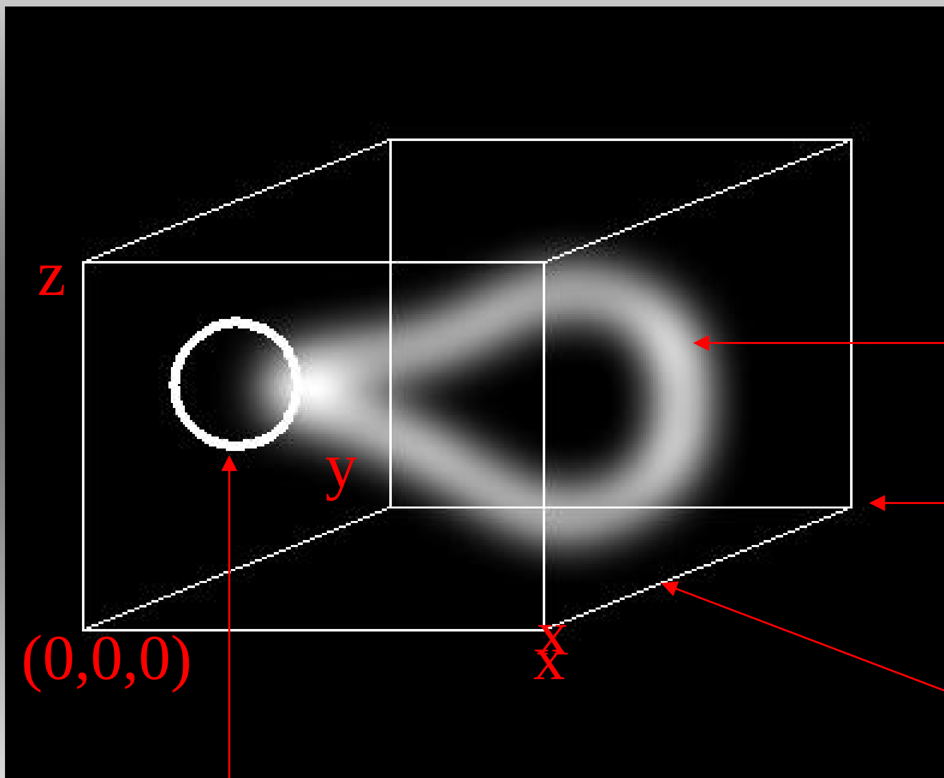
Observation of CME Structure with LASCO/SoHO



How can spatio-temporal complexity be modeled or quantified in terms of 3D models ?

3D Reconstruction from 2 STEREO images
(either from EUVI or white-light coronagraphs)

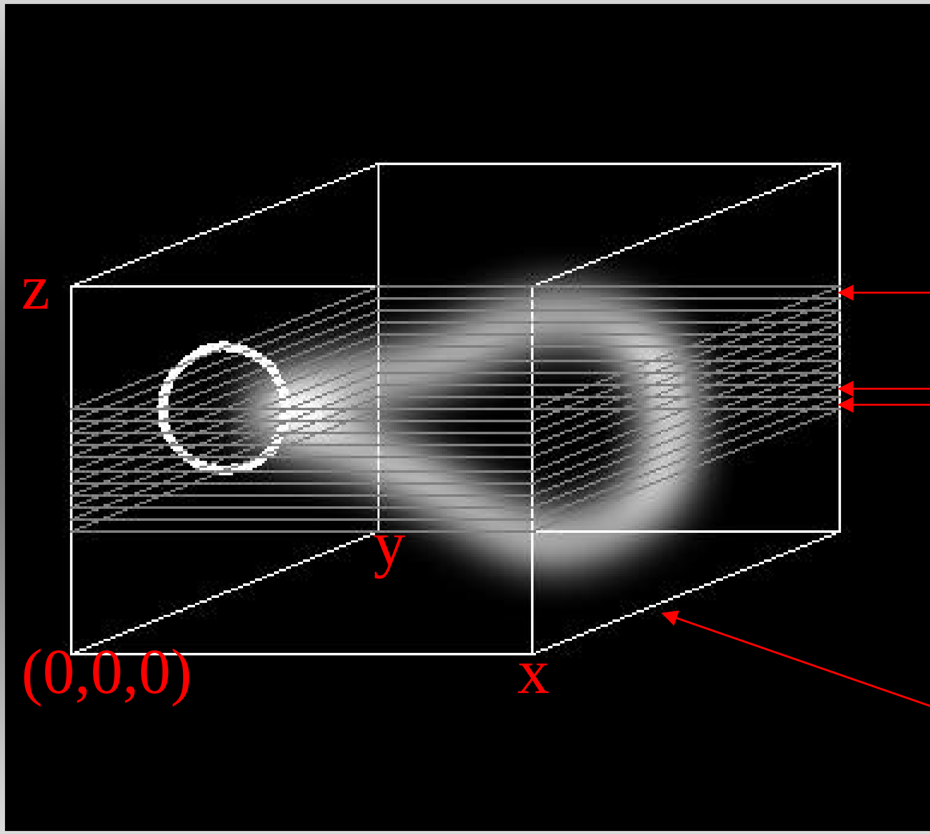


CME

3D Reconstruction Volume

x-y plane coplanar with STEREO spacecraft A and B

Sun



Independent reconstruction planes of 3D volume:

f(x,y,z=z_n)

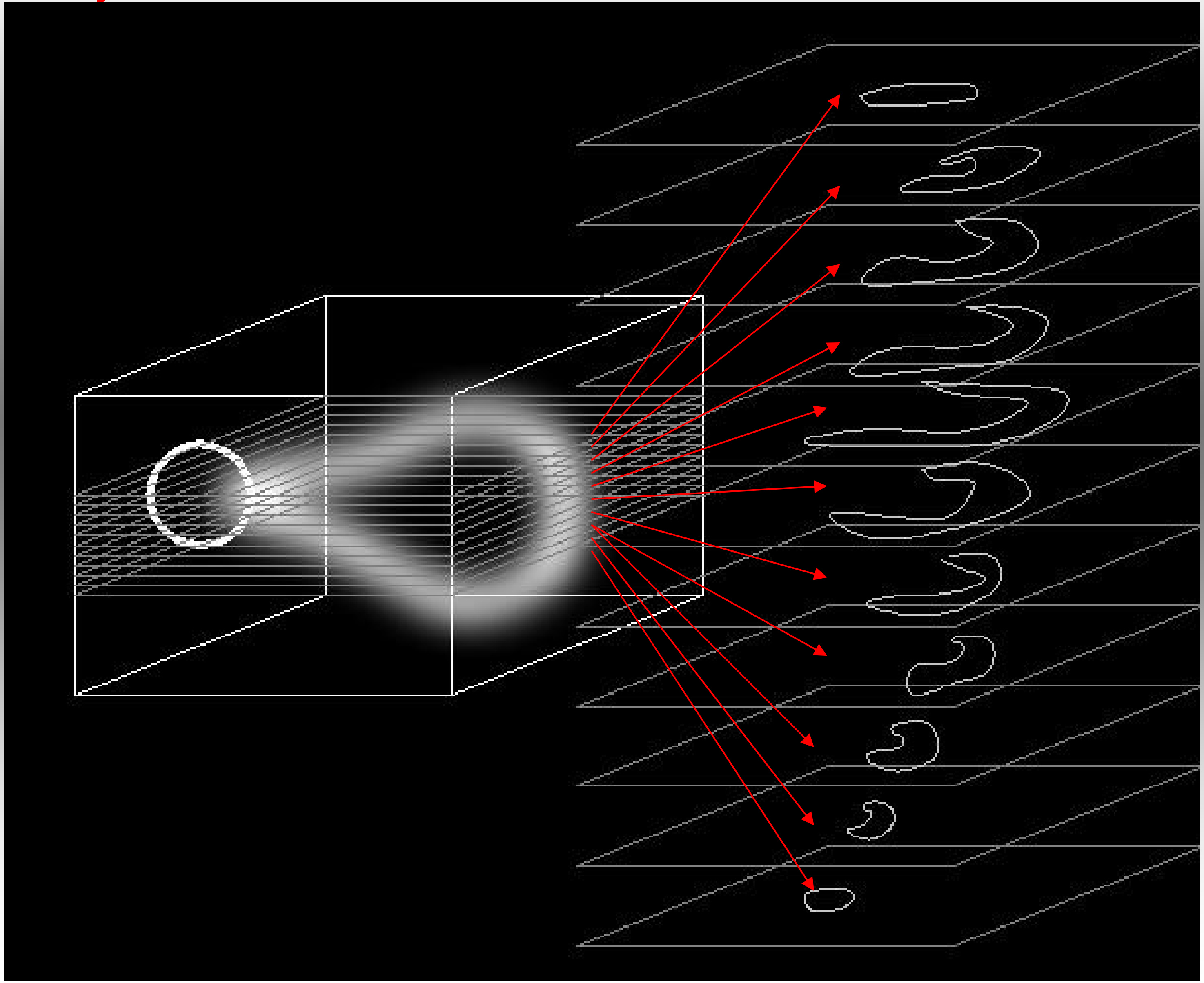
f(x,y,z=z_2)

f(x,y,z=z_1)

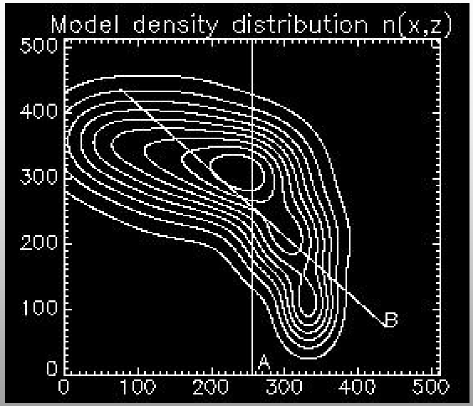
X-y plane coplanar with STEREO spacecraft A and B

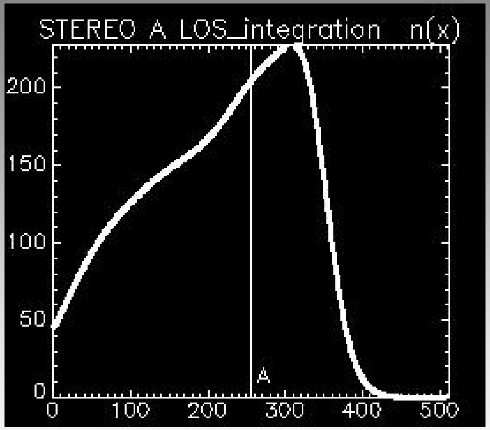
Slices with independent 2D reconstructions :

- Adjacent solutions can be used as additional constraints

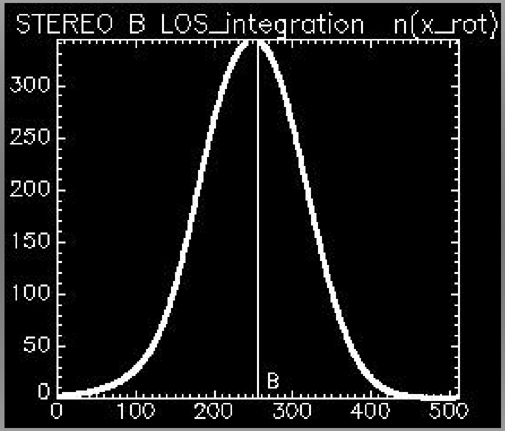


2D Slices of reconstruction from 2 views



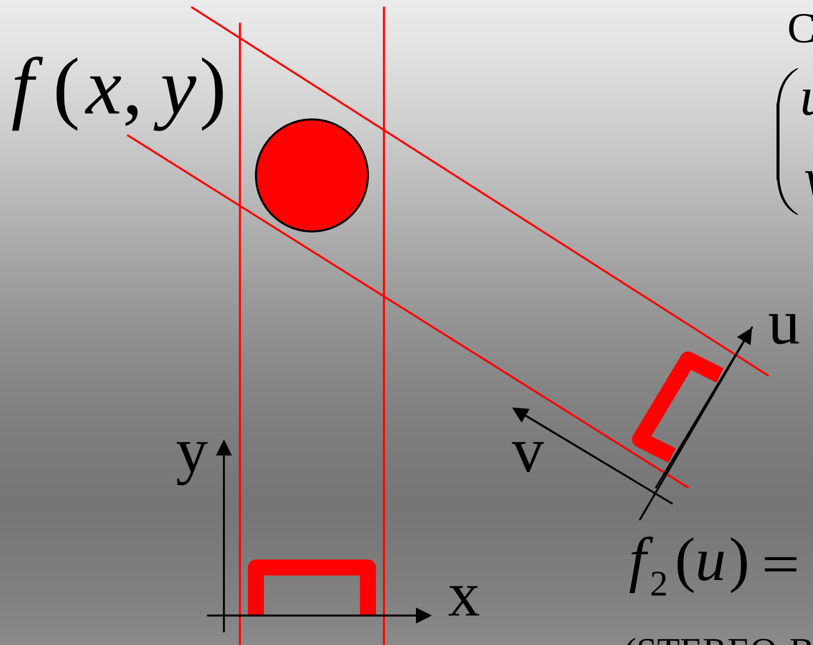


STEREO-A



STEREO-B

Is 2D reconstruction from two projections unique ?



Coordinate rotation $(x,y) \rightarrow (u,v)$:

$$\begin{pmatrix} u-u_0 \\ v-v_0 \end{pmatrix} = \begin{pmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{pmatrix} \begin{pmatrix} x-x_0 \\ y-y_0 \end{pmatrix}$$

$$f_2(u) = \int f(u[x,y], v[x,y])\,dv$$

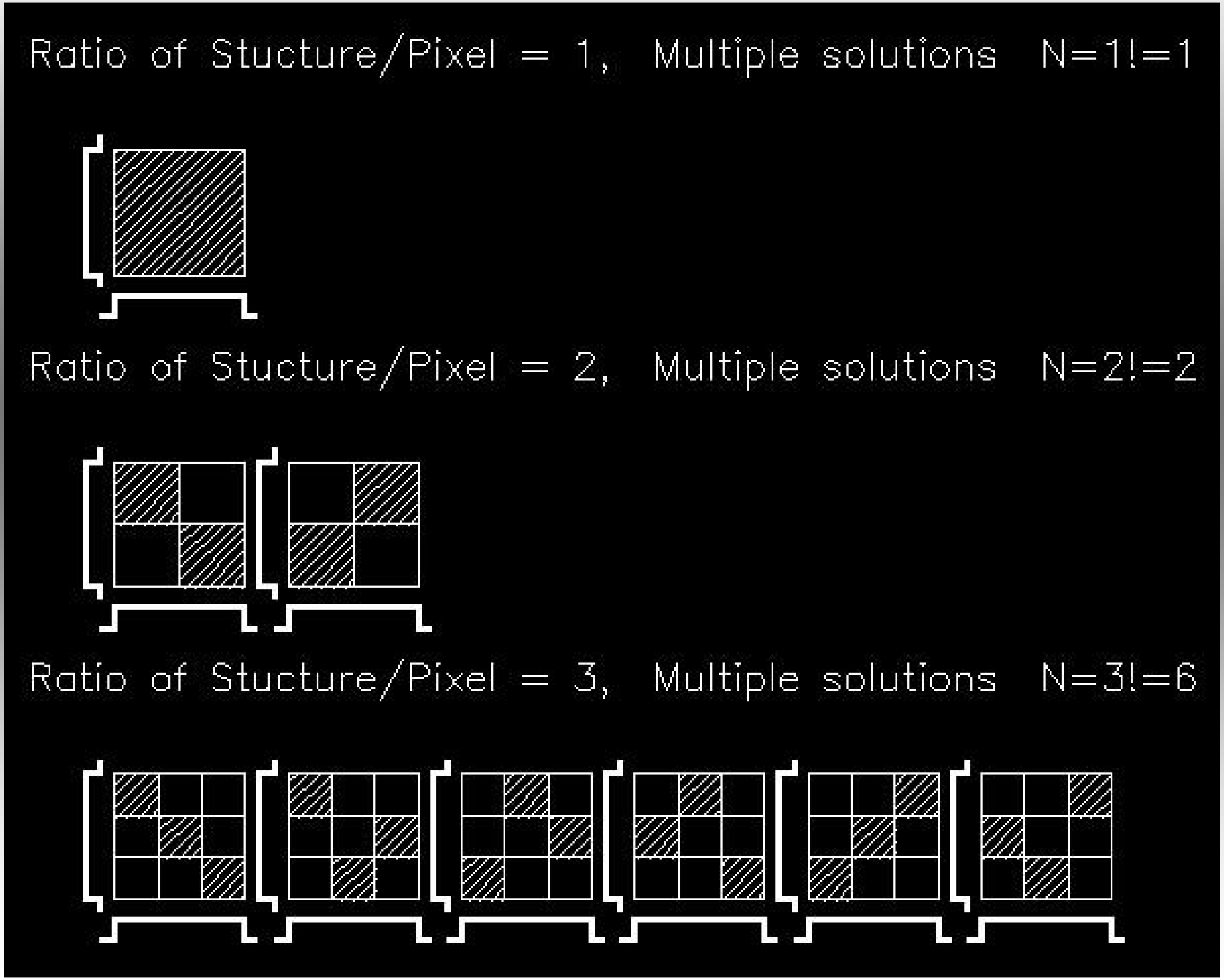
(STEREO-B)

$$f_1(x) = \int f(x,y)\,dy$$

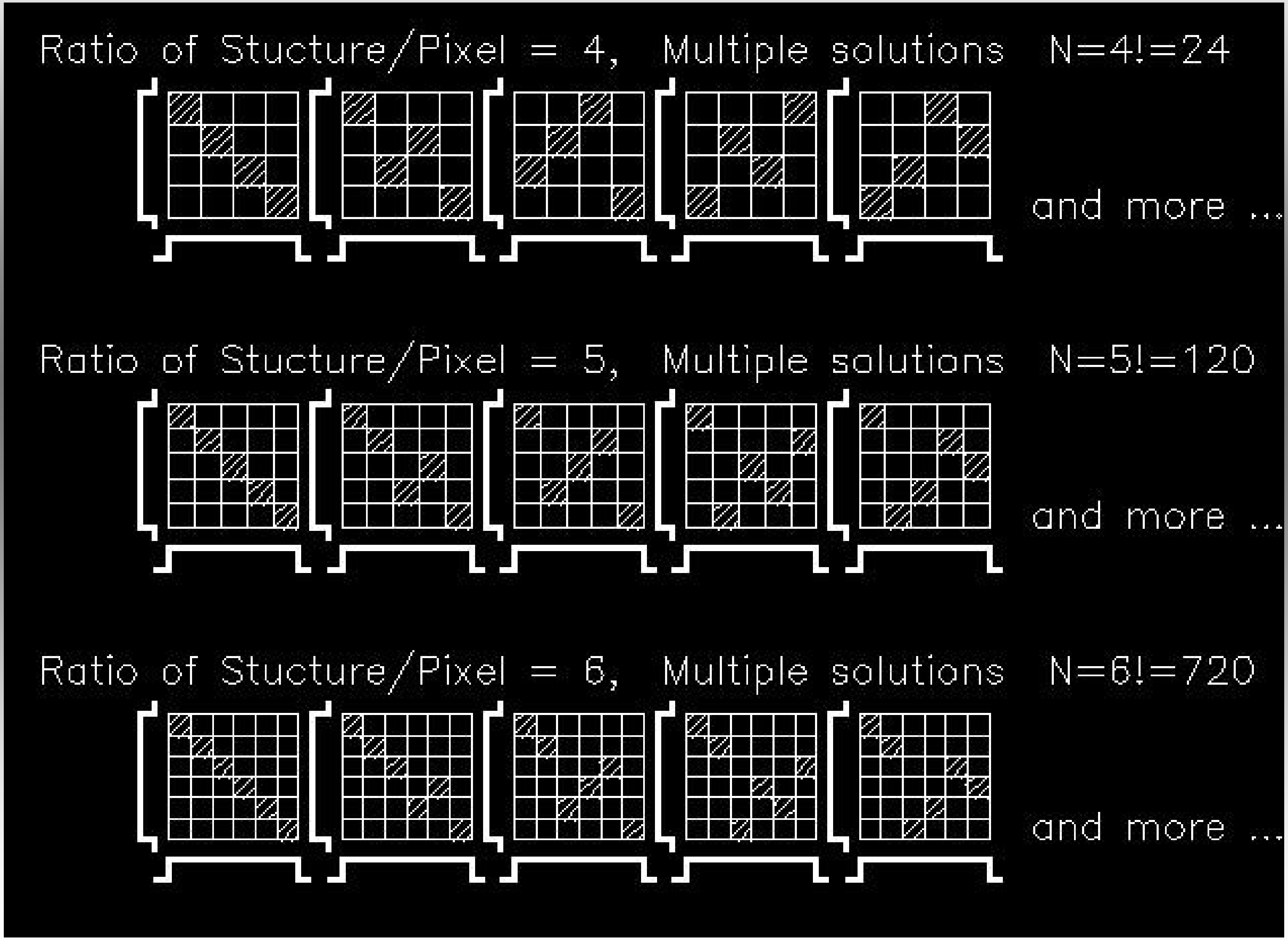
(STEREO-A)

$$\left.\begin{aligned} f_1(x) &= \int f(x,y)\,dy \\ f_2(u) &= \int f(u[x,y], v[x,y])\,dv \end{aligned}\right\} \xrightarrow{\text{INVERSION}} f(x,y)$$

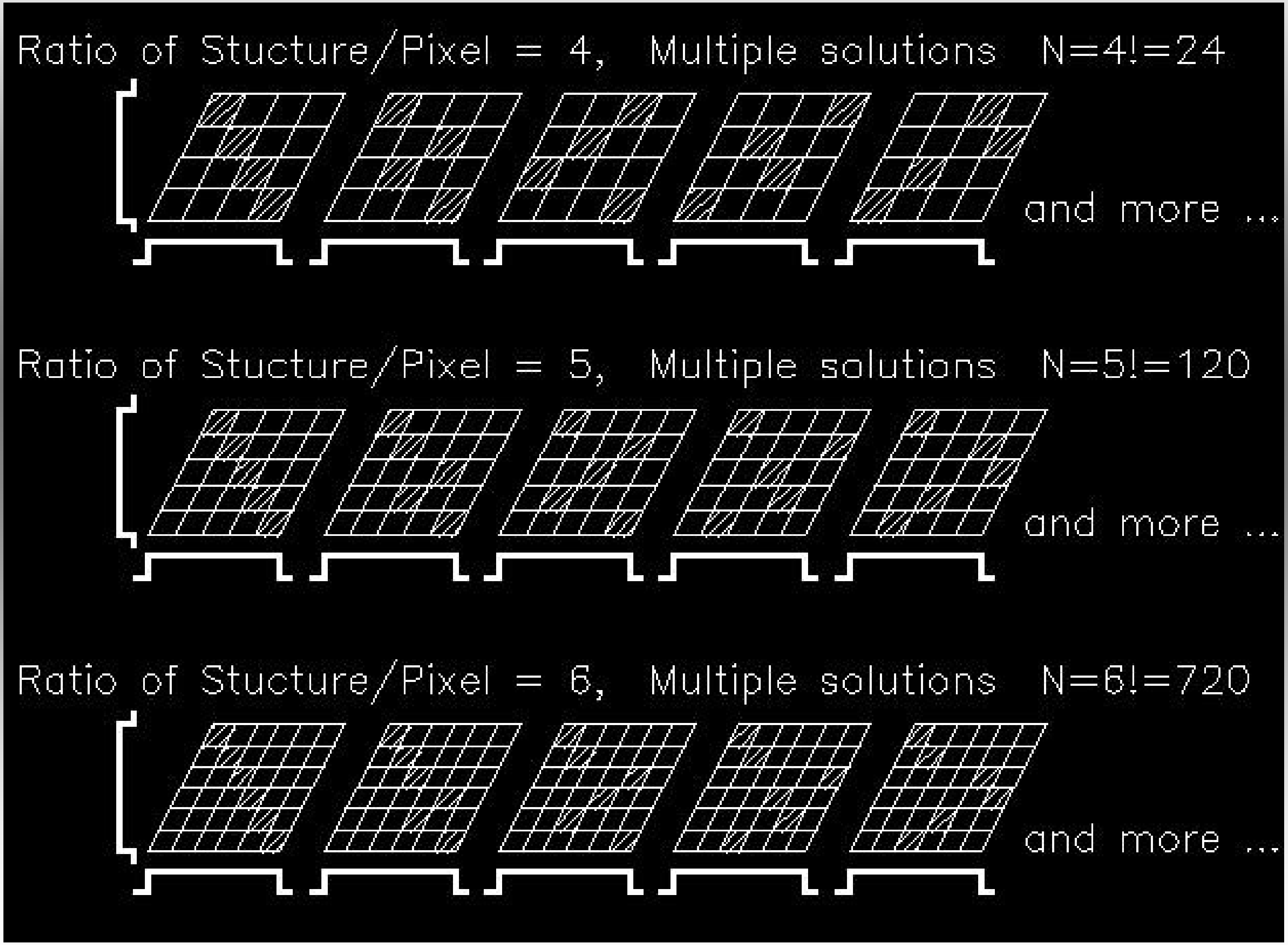
The number of ambiguous 2D distributions scales with N=n!, where n is the ratio of structure/pixel

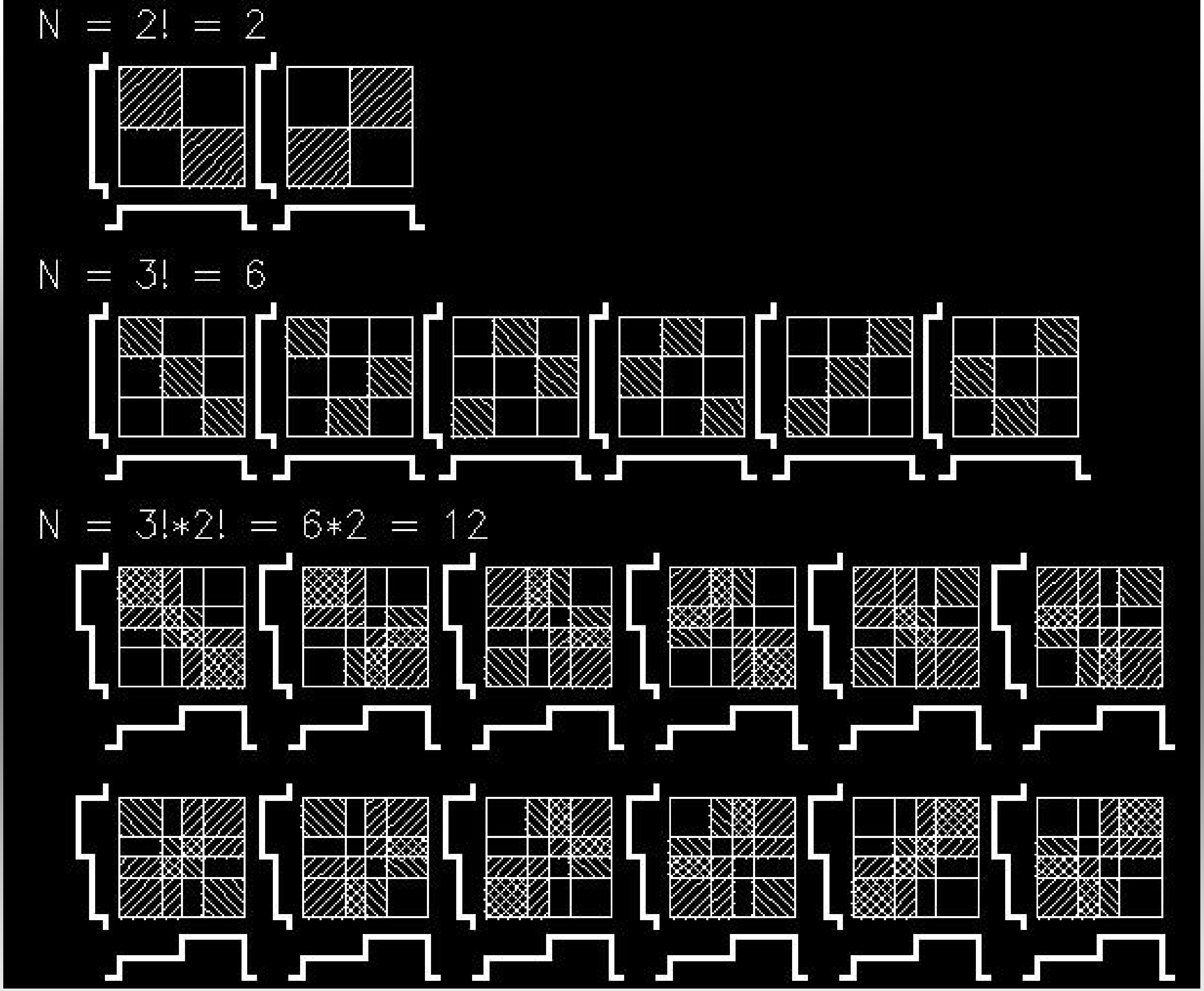


Ambiguity in reconstruction of flat 2D distribution: N=n!



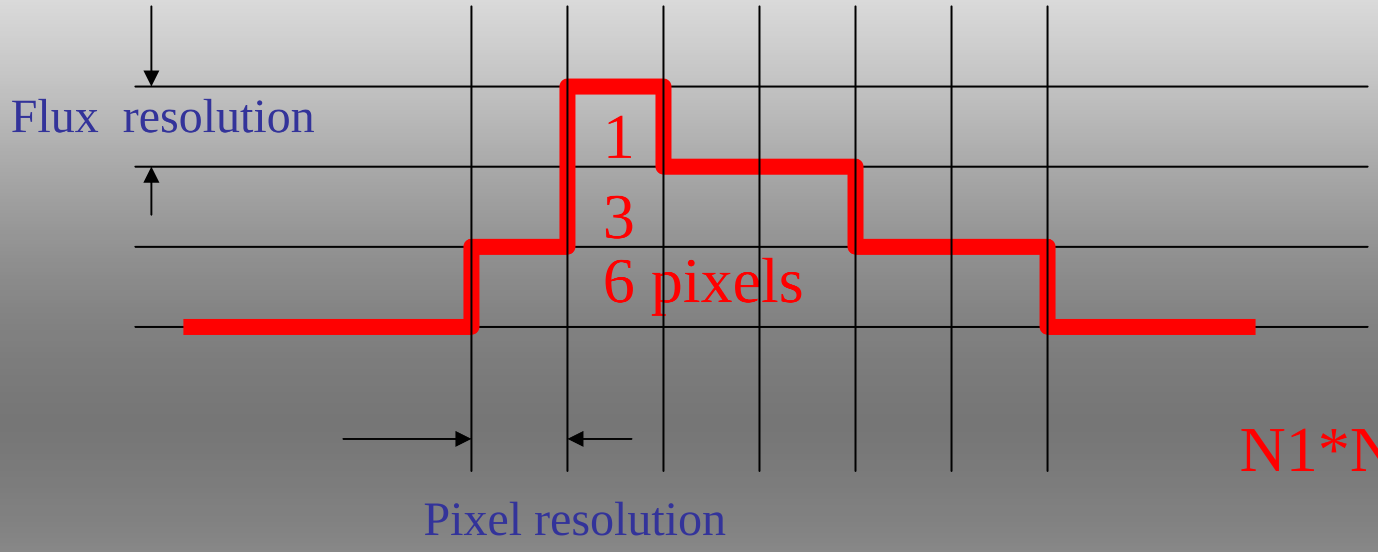
Ambiguities in 2D reconstruction of flat distributions: N=n! for non-orthogonal stereo-angles





Non-flat distributions can be decomposed into flat sub-distributions. Ambiguities in reconstruction N=n1!*n2!*…

Flux profile of one STEREO slice:



N3=1!=1
N2=3!=6
N1=6!=720

N1*N2*N3=4320

Ambiguities in reconstructing 2D distributions from pairs of arbitrary 2D projections:

$$N_{amb} = \prod_{i=1}^{n\_flux} n_i!$$

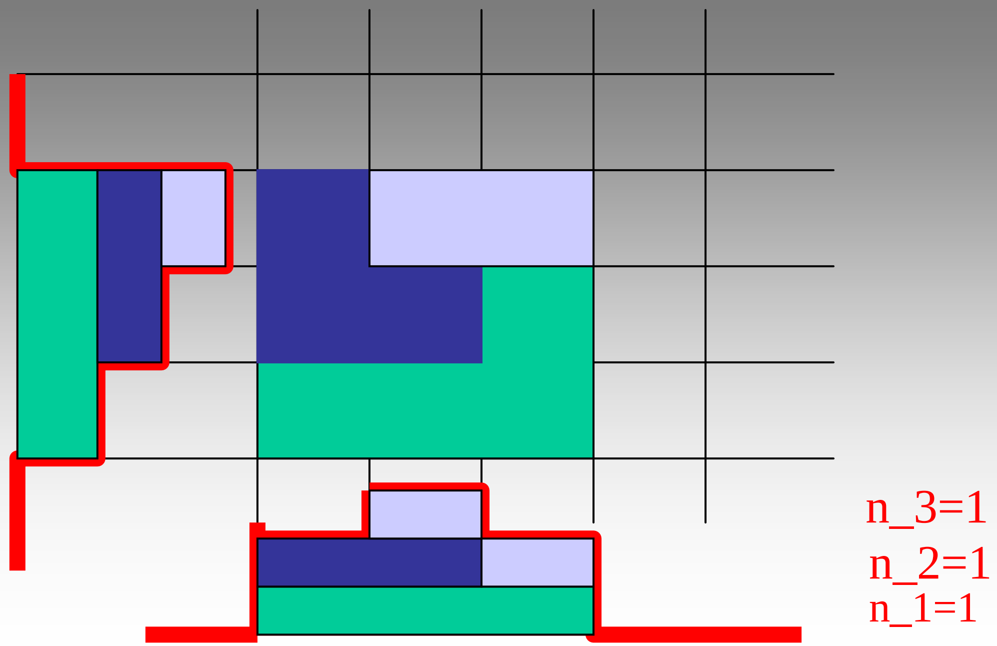
n_flux = max(flux)/dflux (flux resolution)
n_i   = structure width/pixel (spatial resolution)

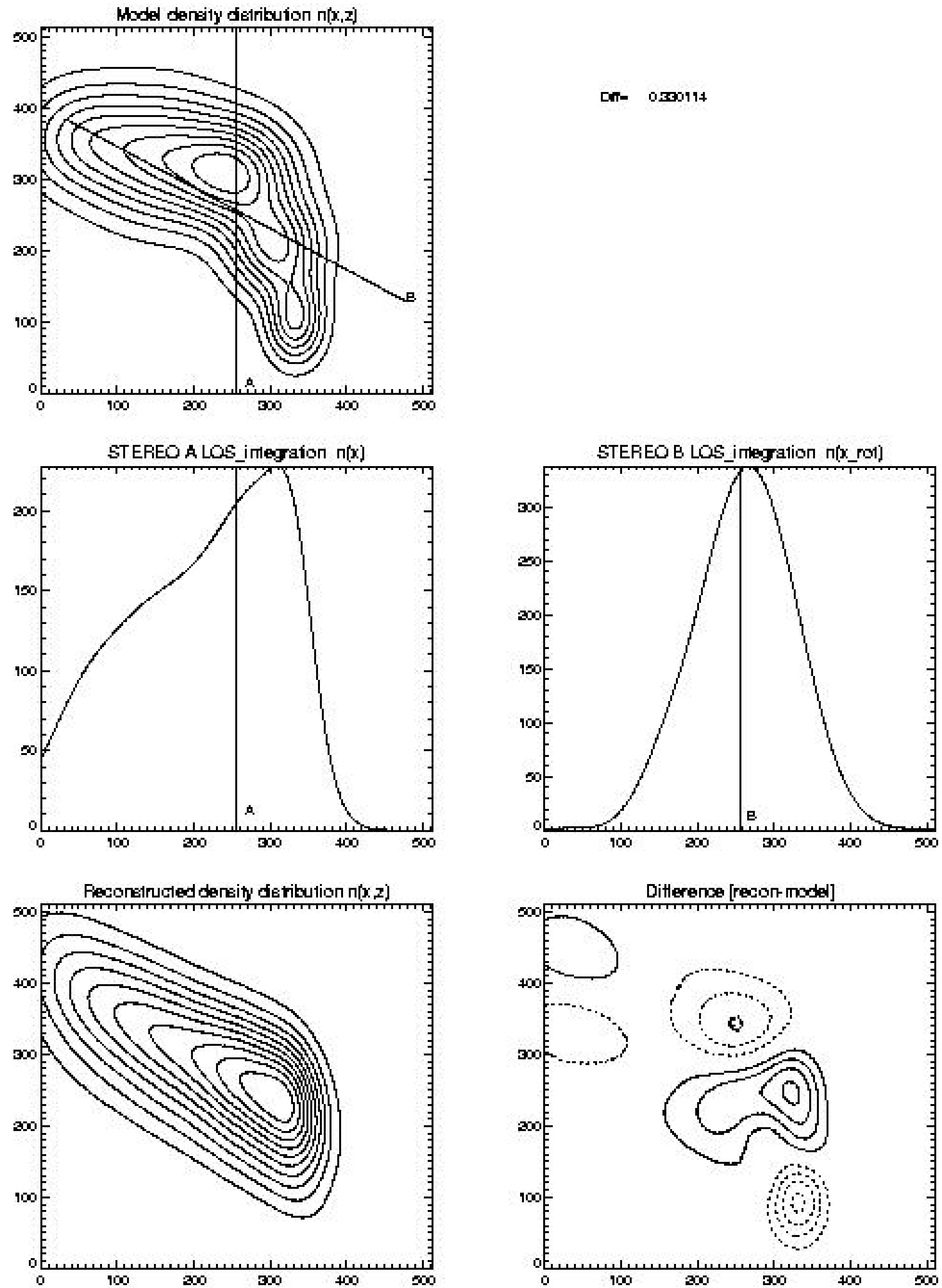
Strategies: BACK-PROJECTION METHOD

1) Unique solution can be obtained if no finestructure is recovered:

$$n\_1 = n\_2 = n\_3 = \ldots. = 1$$

$$N\_amb = 1$$

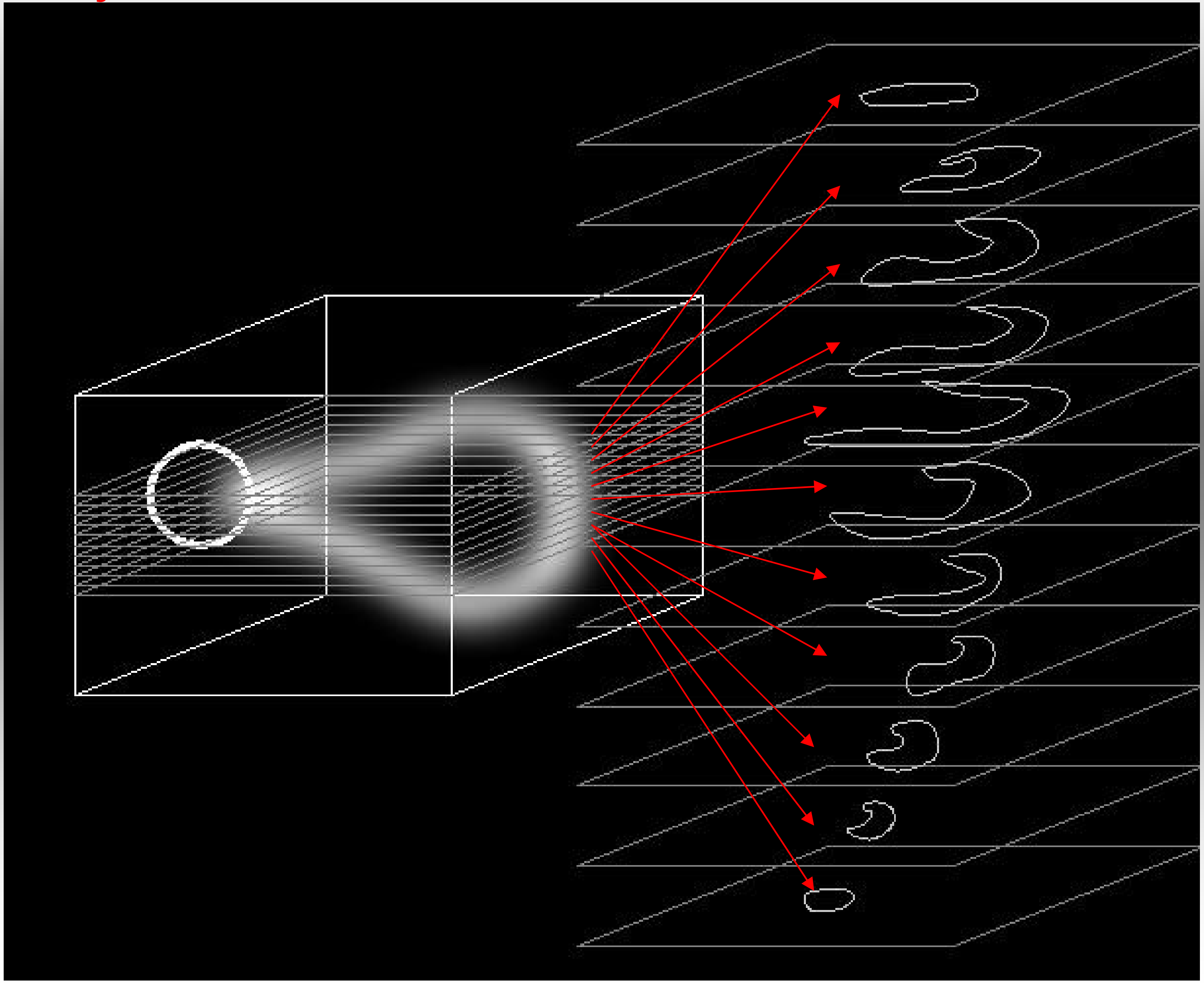




Model density distribution n(x,z)
Diff= 0.330114
STEREO A LOS_integration n(x)
STEREO B LOS_integration n(x_rot)
Reconstructed density distribution n(x,z)
Difference [recon-model]
A
B

Strategy 2:

- Adjacent solutions can be used as additional constraints



First-Proxi Reconstruction Algorithm :

1) 3D density reconstruction can be broken down into slices of 2D reconstructions with a back-projection method.
2) Backprojection method can be much faster than other methods (pixon, etc.)
3) Backprojection gives one possible result, but there is no unambiguous solution using a pair of projections.
4) The number of ambiguous solutions scales with

$$N_{amb} = \prod_{i=1}^{n\_flux} n_i!$$

where n_i=structure size/pixel is the spatial resolution of structures
And n_flux=max(flux)/dflux is the flux resolution.

5) Additional constraints can be imposed from adjacent slices of the STEREO reconstruction.

6) Disentangled linear features (loops, filaments, flux ropes) can be reconstructed almost unambiguously with two views, but the finestructure of extended sources (CME shells) is highly ambiguous to reconstruct.

Conclusions :
STEREO/SECCHI 3D Analysis Tasks:

1) Coronal magnetic field : 2D projections can be automatically mapped with fingerprinting methods and be used to test theoretical models (e.g. nonlinear force-free field models)
2) Coronal Loops : Hydrodynamic modeling requires disentangling of loop strands with multi-temperature filters and stereoscopic determination of geometry. Stereoscopic 3D coordinates can disentangle multiple loop oscillation modes.
3) Filaments/Prominences/Fluxropes
   Measurements of twist and helicity enabled with stereoscopy.
4) Postflare loop systems
   Stereoscopic tracking of spatio-temporal evolution may provide insights into hydrodynamics and reconnection dynamics.
5) CME tracking
   3D reconstruction of CME structures (e.g. via back-projection) from 2 or 3 line-of-sights) is ambiguous and challenging. Additional a-priori constraints are required (e.g. max.entropy).

http://www.lmsal.com/~aschwand/