



University
of Glasgow

Introduction to RHESSI X-ray Imaging

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PART I (Lecture):

What are we going to image ?

- Basics of solar flares
- Geometry of solar flares

How are we going to image with RHESSI?

- Imaging HXRs
- RHESSI Imaging concept

a) Modulated light curves

b) X-ray visibilities

From modulated counts (visibilities) to X-ray images (making an image)

- Back Projection
- Clean
- MEM (NJIT flavour)
- Pixon
- Forward Fit

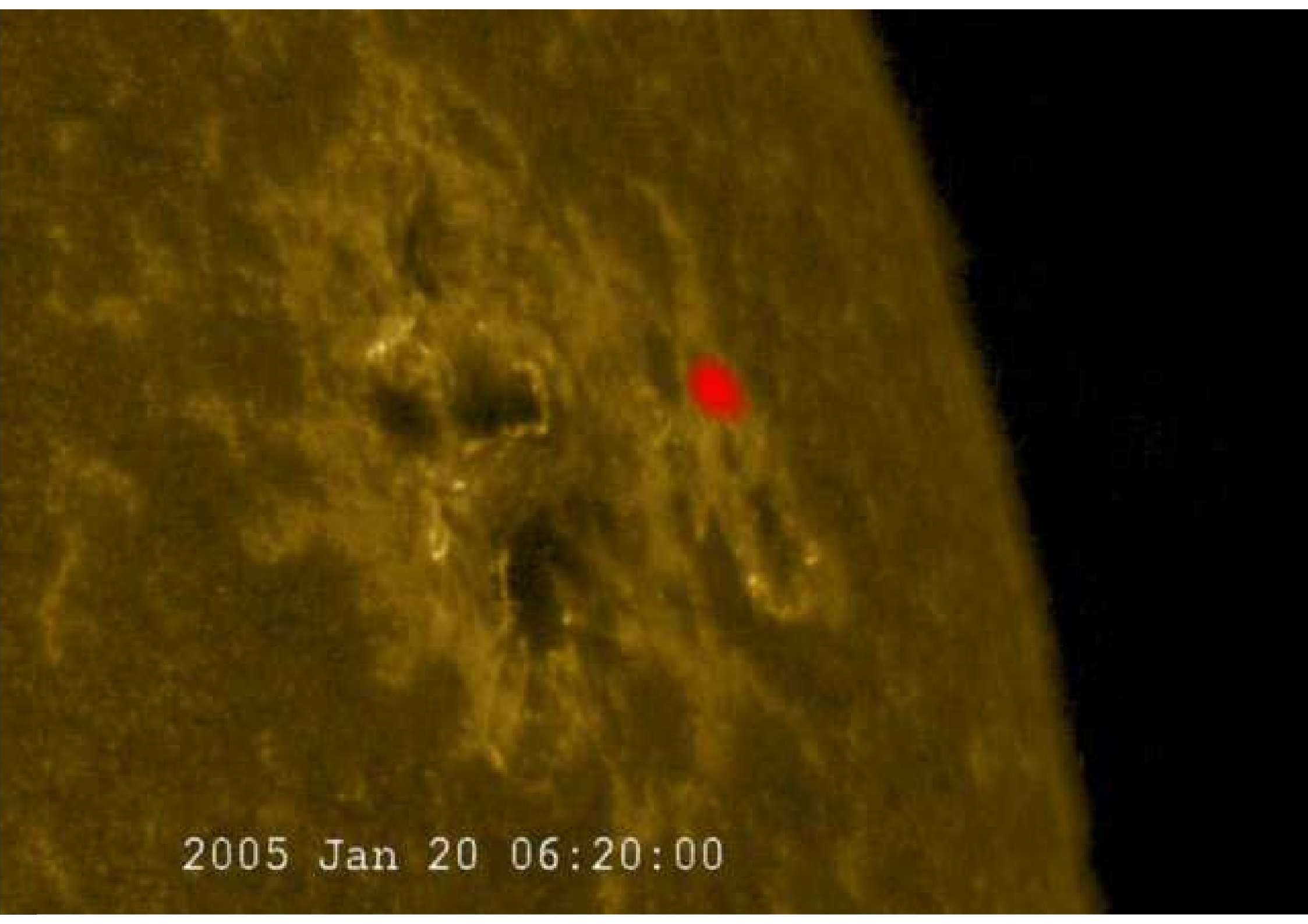
PART II (Tutorial):

RHESSI imaging software: basic parameters

Making an image using various algorithms

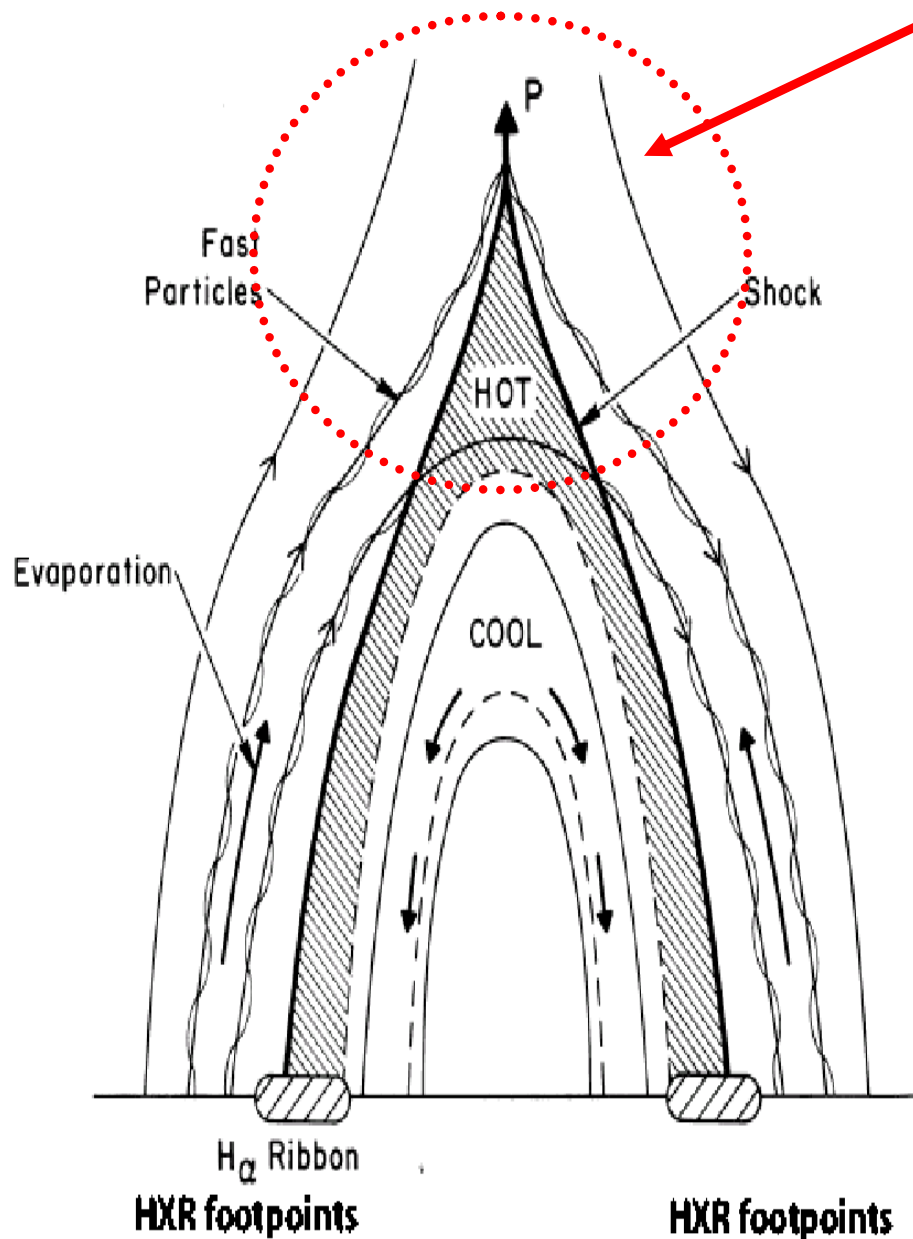
- Graphical User Interface (GUI)
- Command line

Combining RHESSI with other instruments



2005 Jan 20 06:20:00

Energy release/acceleration



Solar corona $T \sim 10^6 \text{ K} \Rightarrow 0.1 \text{ keV per particle}$

Flaring region $T \sim 4 \times 10^7 \text{ K} \Rightarrow 3 \text{ keV per particle}$

Flare volume $10^{27} \text{ cm}^3 \Rightarrow (10^4 \text{ km})^3$

Plasma density 10^{10} cm^{-3}

Photons up to $> 100 \text{ MeV}$

Number of energetic electrons 10^{36} per second

Electron energies $> 10 \text{ MeV}$

Proton energies $> 100 \text{ MeV}$

Large solar flare releases about 10^{32} ergs
(about half energy in energetic electrons)

1 megaton of TNT is equal to about 4×10^{22} ergs.

Observed X-rays

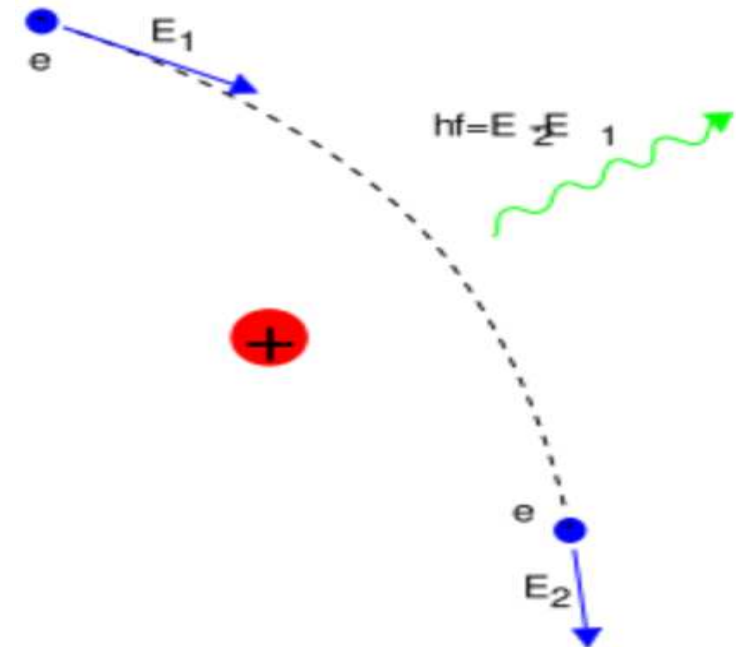
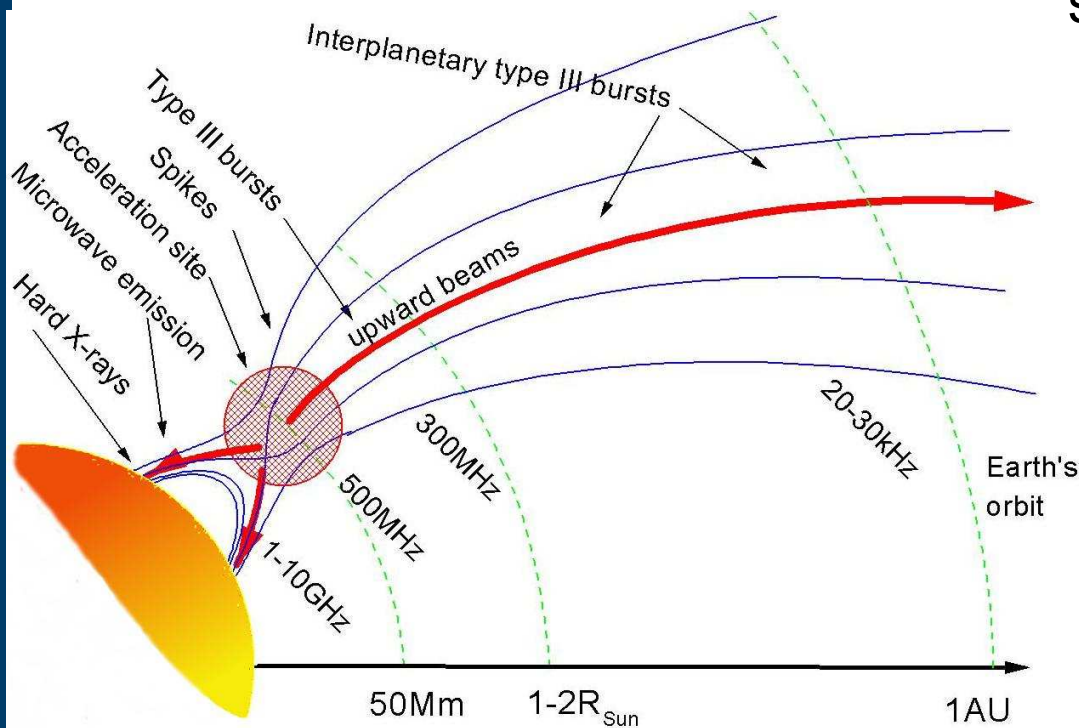
Unknown electron distribution

Emission cross-sections

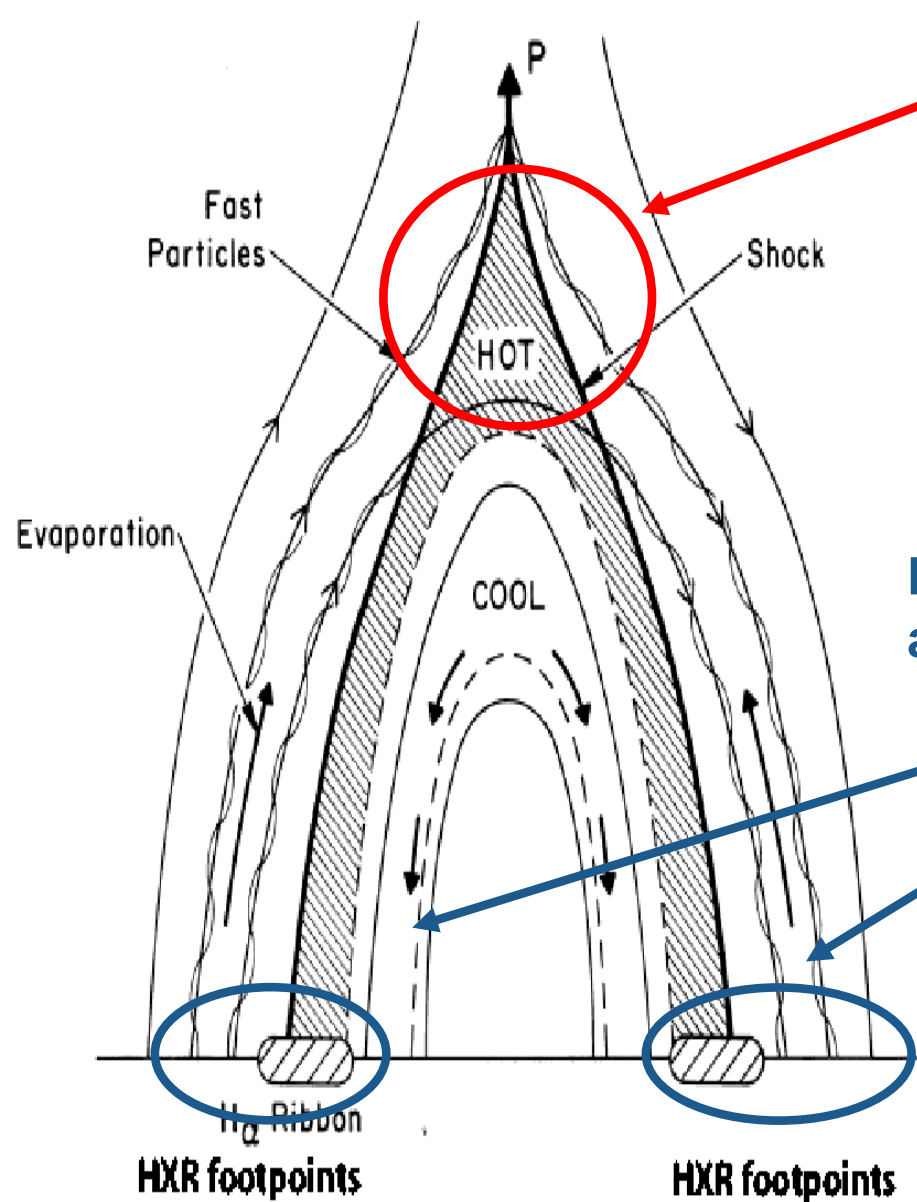
$$I(\epsilon, \Omega, t) = \int_{\ell} \int_{\Omega'} \int_{\epsilon}^{\infty} n(\mathbf{r}) \bar{F}(E, \Omega', \mathbf{r}, t) Q(\Omega, \Omega', \epsilon, E) dE d\Omega' d\ell,$$

Thin-target case: For the electron spectrum $F(E) \sim E^{-\delta}$,

Electron-ion bremsstrahlung (free-free emission)

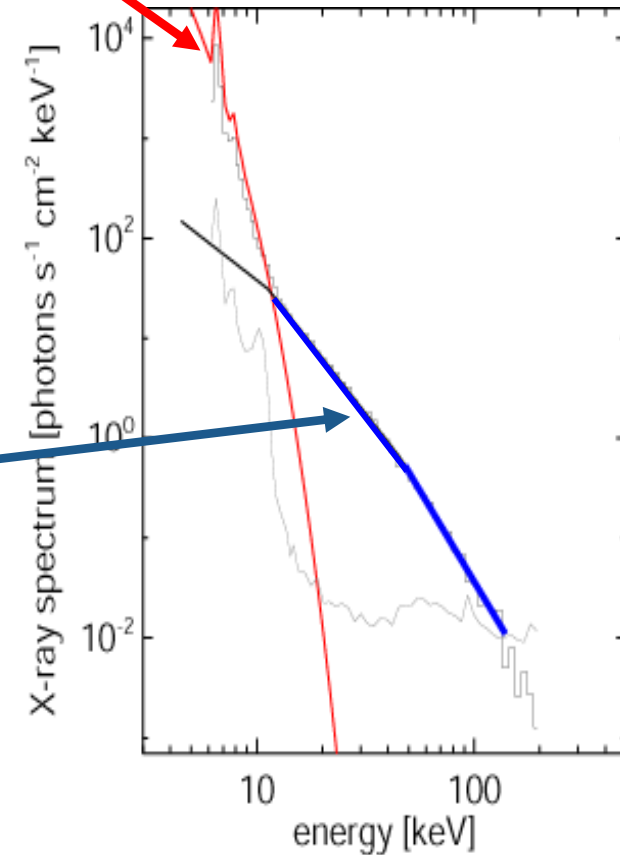


Dominant process for energies $\sim 10 - 400$ keV
 the photon spectrum is $I(\epsilon) \sim \epsilon^{-\delta-1}$



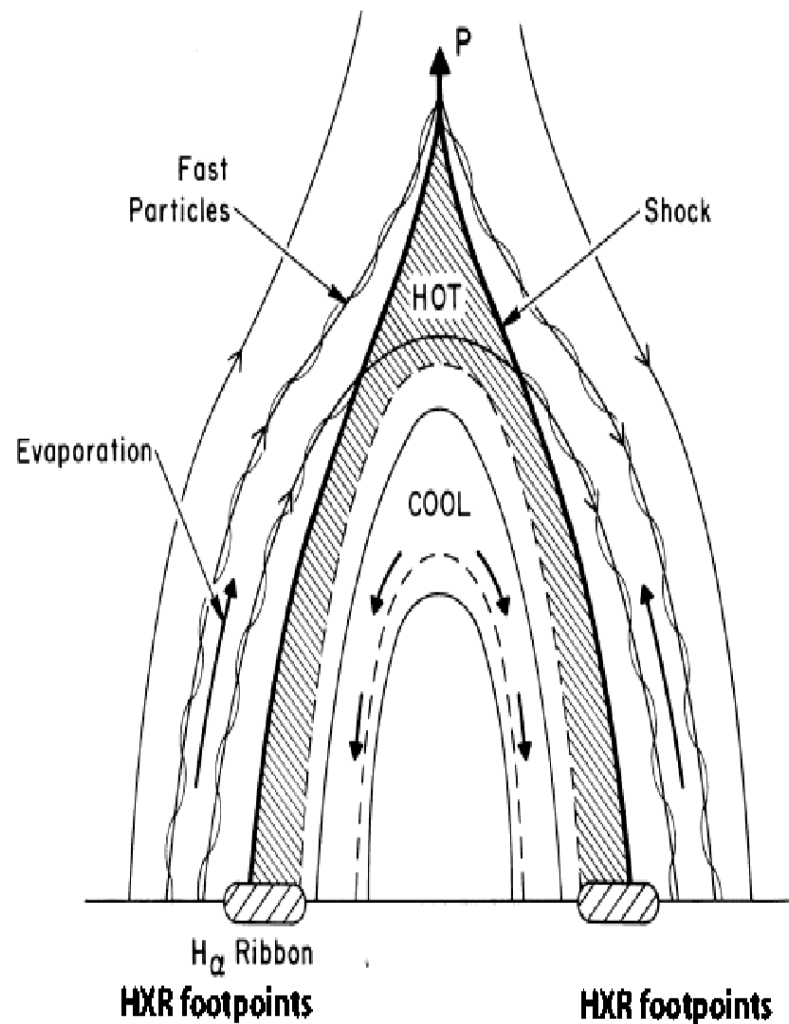
Soft X-ray emission up to ~10 - 20 keV

Hard X-ray sources above ~20 keV

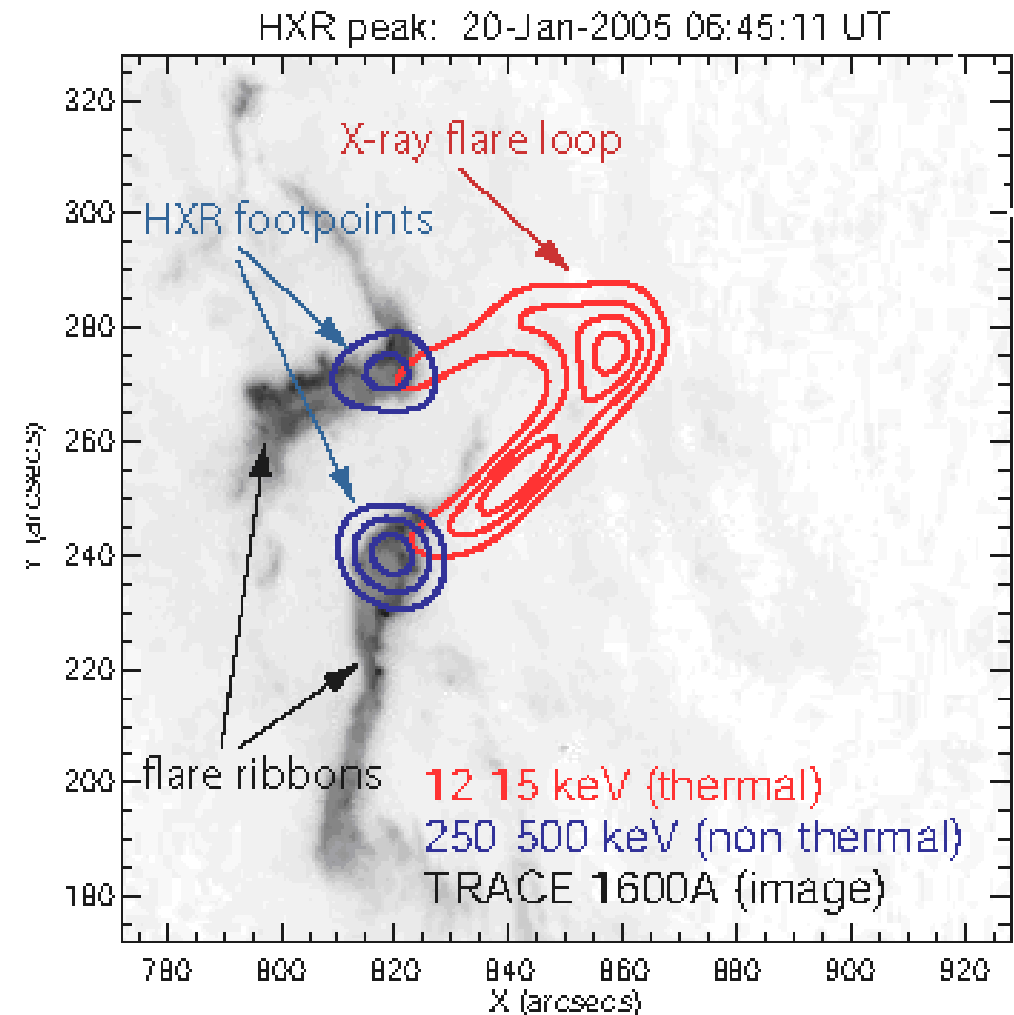


RHESSI spectrum (see Hannah Lecture)

'Standard' flare model picture in 2D (Shibata, 1996)

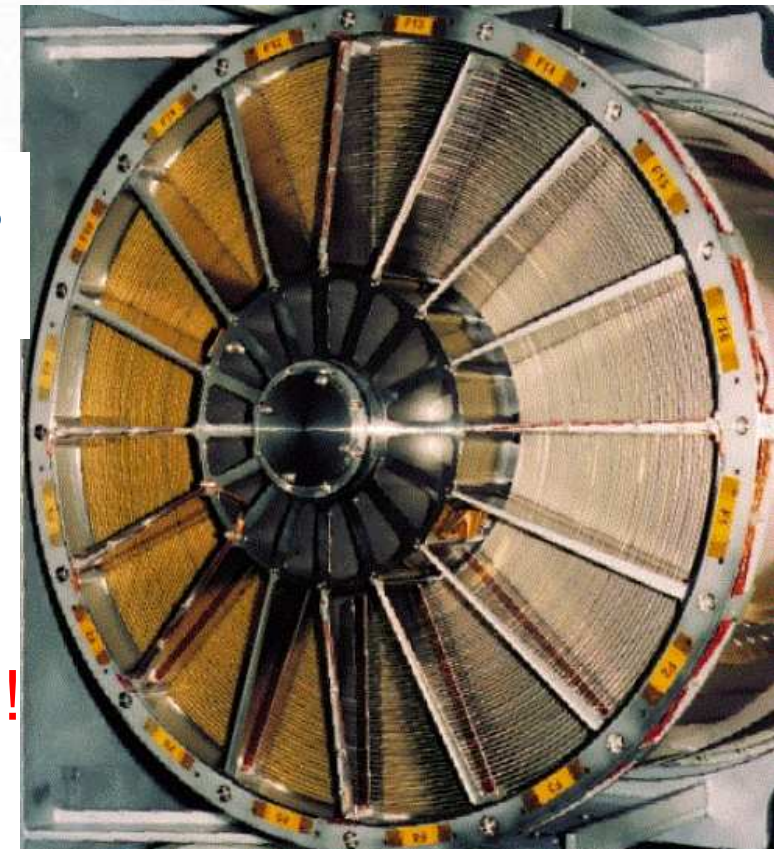
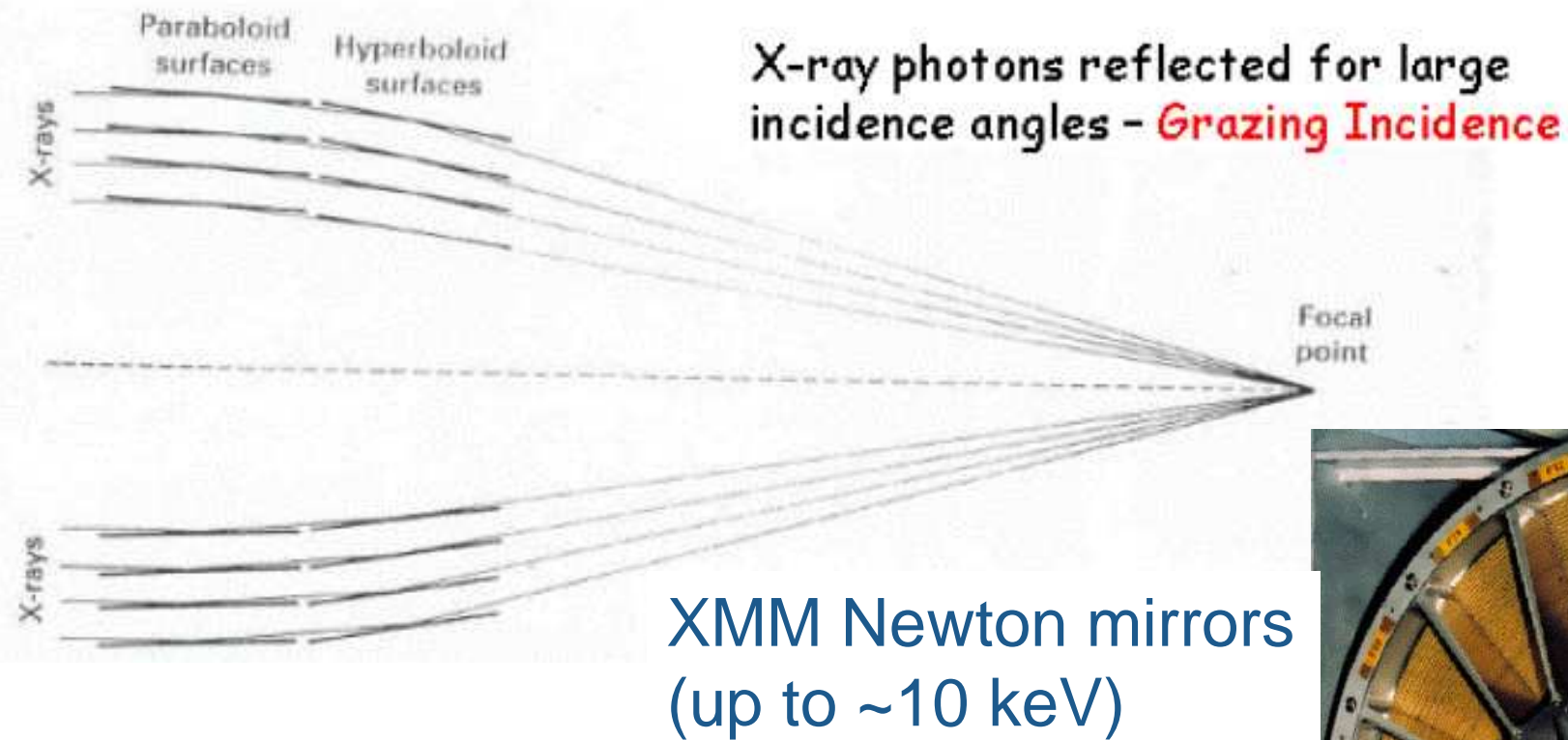


Standard flare model picture (Shibata, 1996)



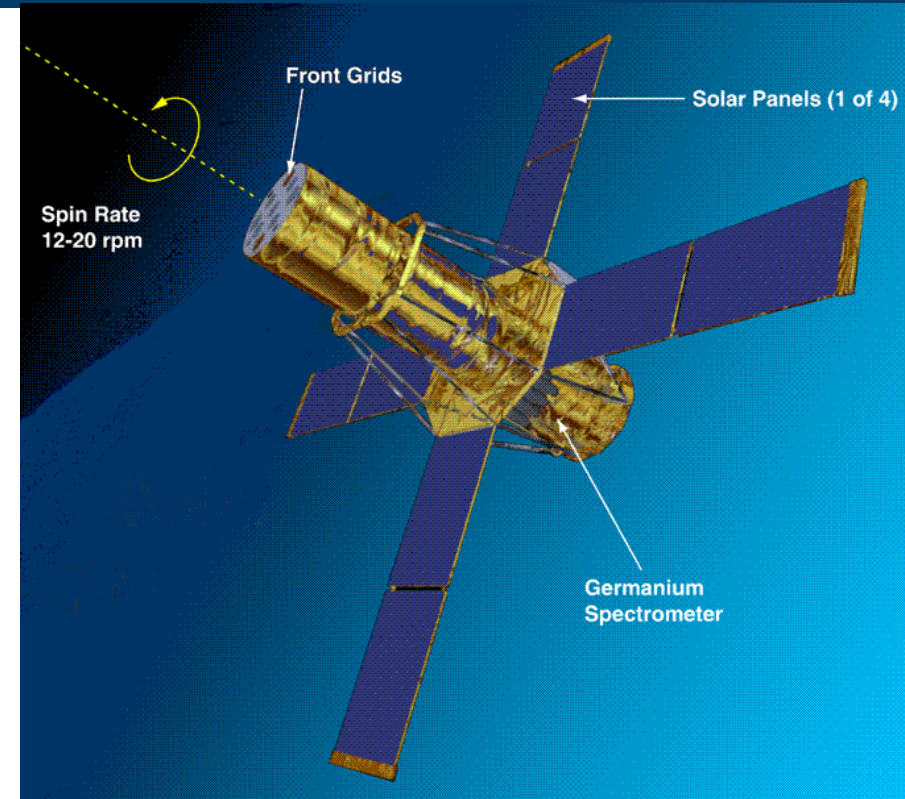
Krucker et al, 2007

Grazing Incidence optics:



Works OK but only up to < a few tens of keV !

Ramaty High Energy Solar Spectroscopic Imager

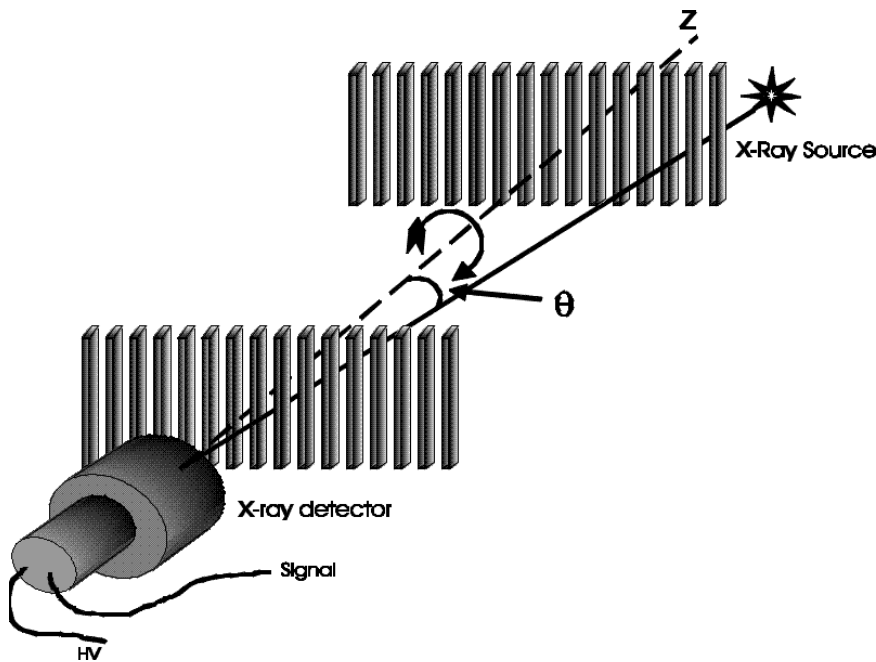


RHESSI is designed to investigate particle acceleration and energy release in solar flares through imaging and spectroscopy of hard X-ray and gamma-rays in the range from 3 keV up to 17 MeV (*Lin et al 2002*).

Spectroscopy: 9 Ge detectors with energy resolution around 1 keV (*Hannah, Lecture on Wed*);

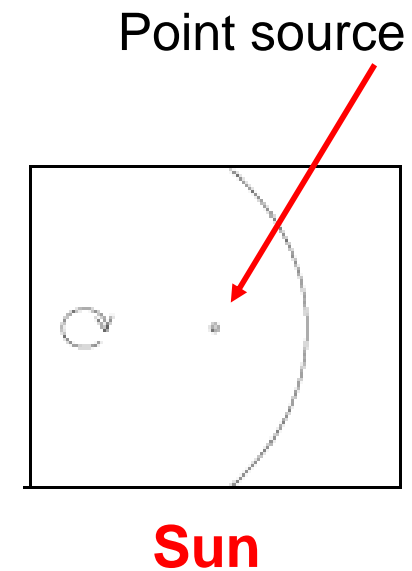
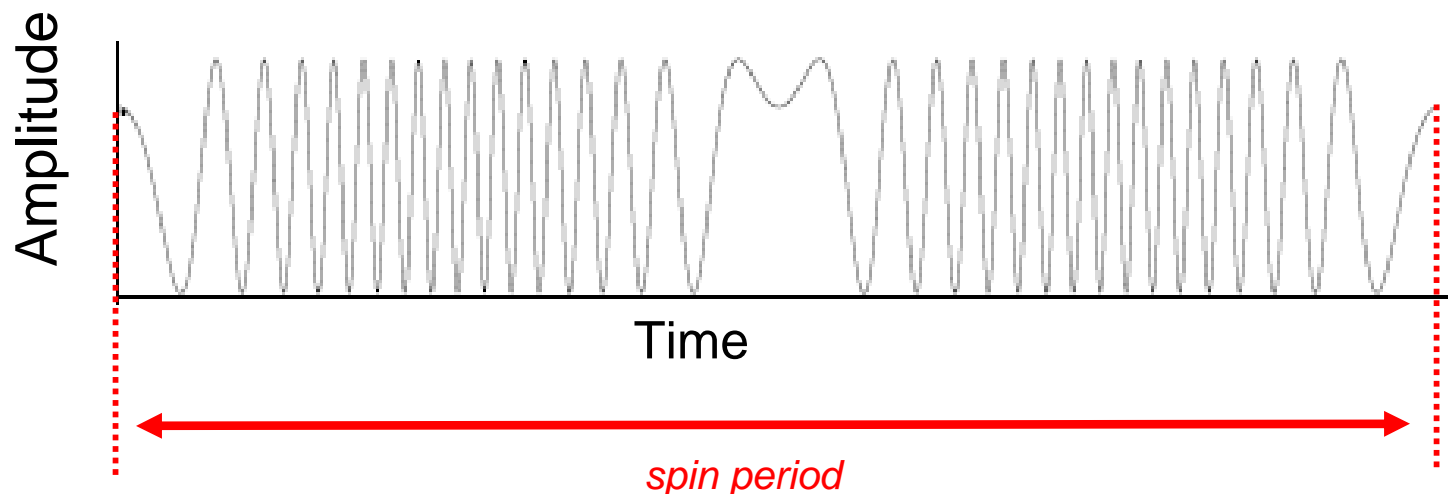
Imaging: rotating modulating collimators allowing angular resolution down to 2.3 arcsec;

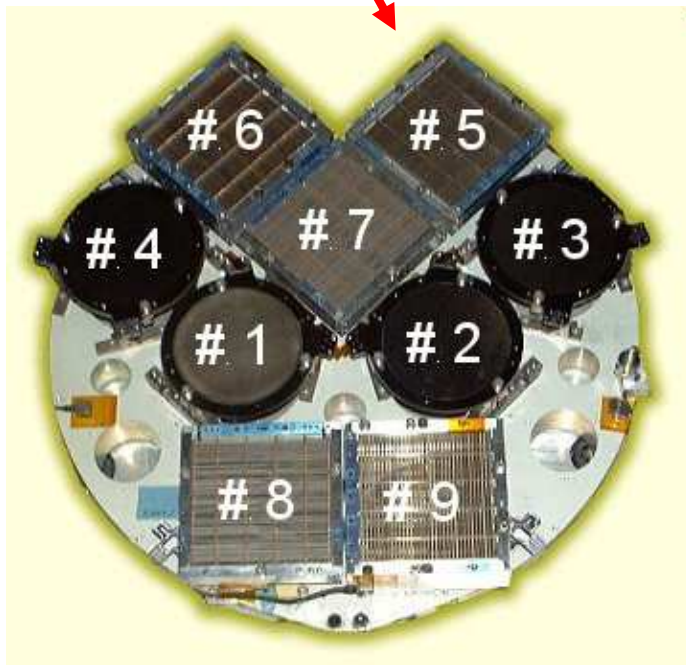
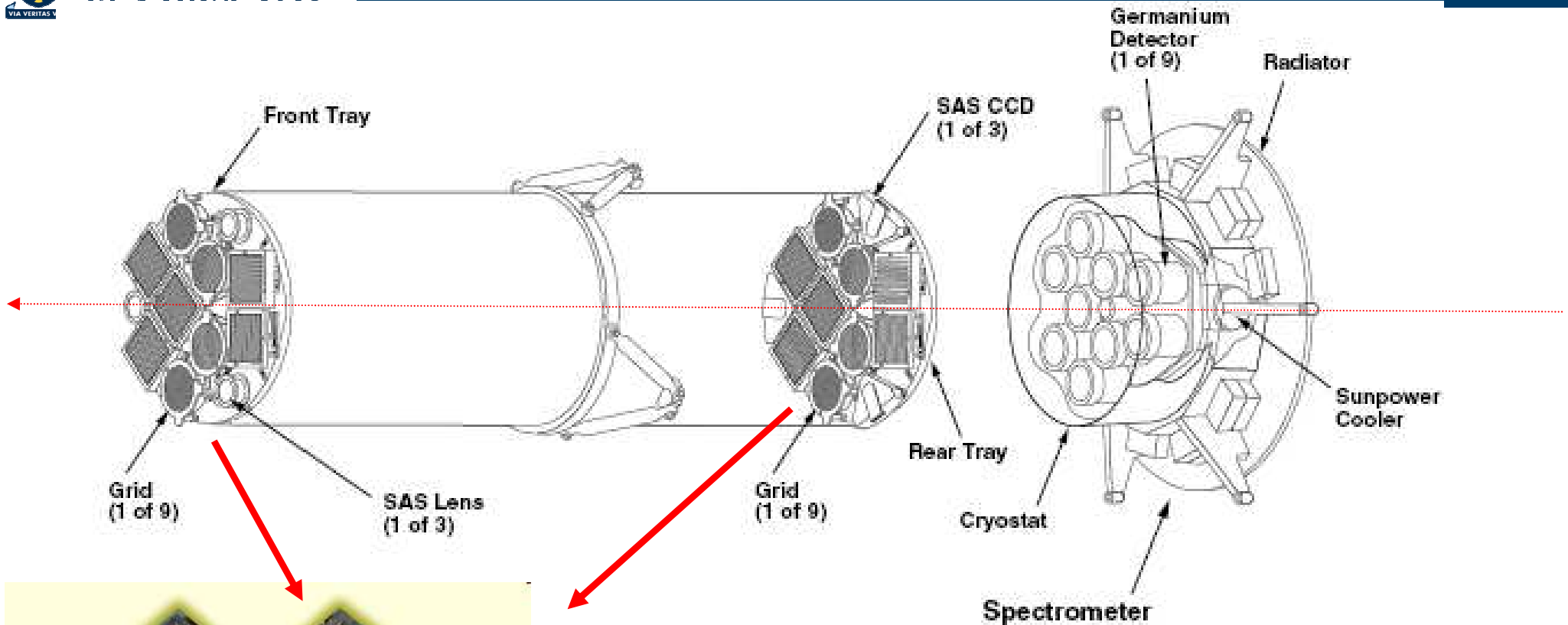
Imaging spectroscopy: simultaneous images in various energy ranges



RHESSI detectors look at the source through a pair of grids called **Rotating Modulating Collimator (RMC)**

Spacecraft spins about once every ~ 4 sec => *artificial modulation of incoming X-ray flux*





RHESSI has 9 RMCs for 9 detectors

Slats/Slits spacing growing with detector
(RMC) number
 \Rightarrow angular resolution from $\sim 2.3''$ (RMC #1)
 to $180''$ (RMC #9)

Modulation profiles for various ideal sources for a grid of pitch P with equal slits and slats

Point source

Half flux from the point source => note half amplitude

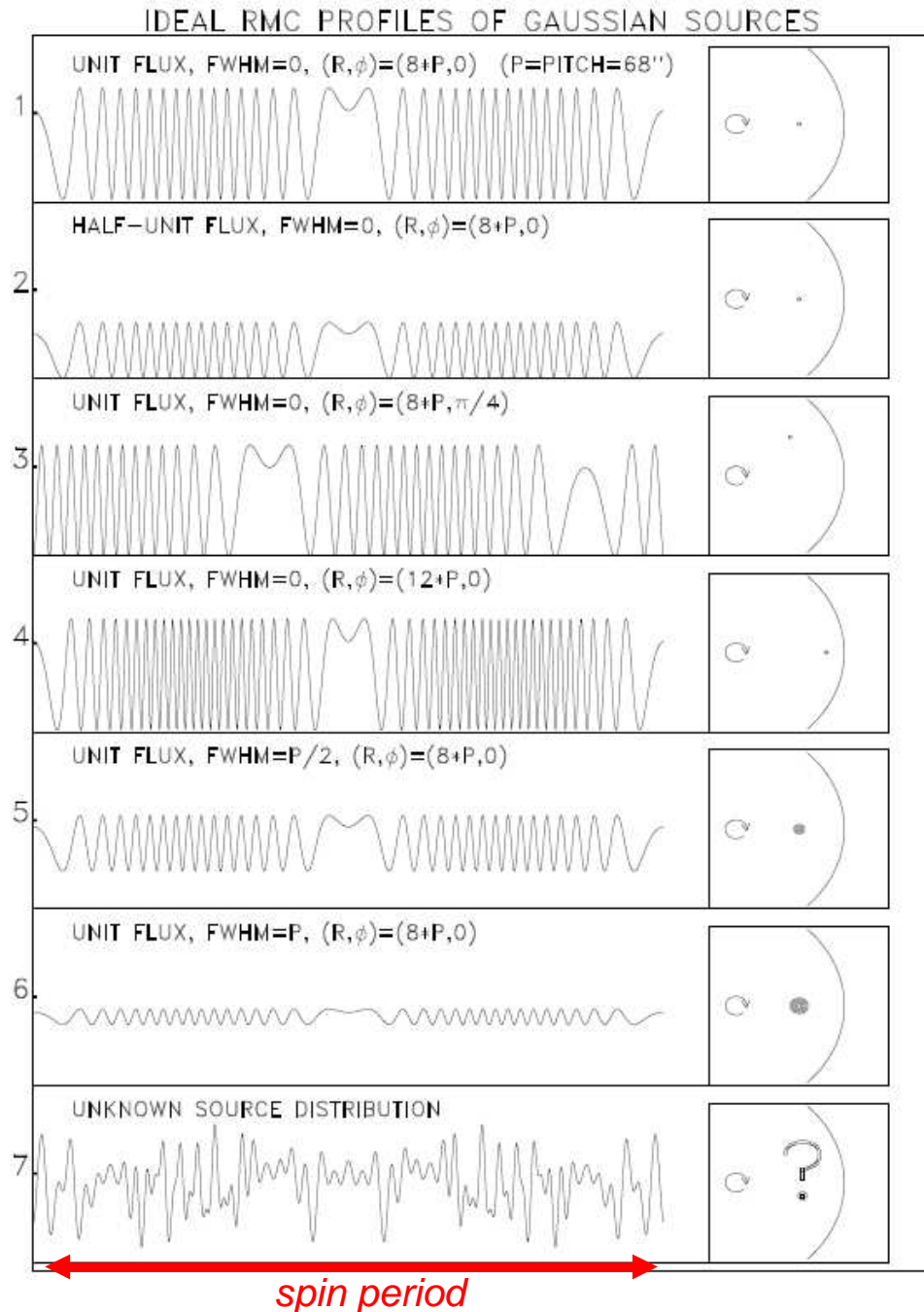
45 degrees angle => note change of phase

Source further from the axis => note change of modulation frequency

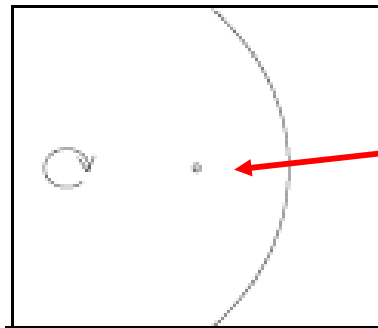
Source size= $P/2$ => note change of the amplitude

Source size= P => note change of modulation depth (no modulation for source size $\gg P$)

***Modulation encodes spatial source information:
Phase of the modulation => position angle
Distance from the centre => modulation frequency
Amplitude => source size***



Sun



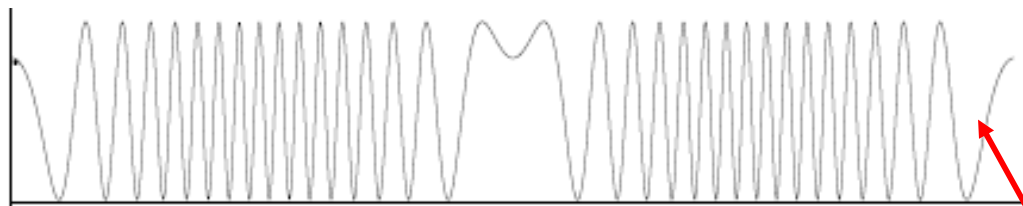
Point source

Incoming **photon flux** from **pixel m** of the source

Time interval = observation time – dead time

Detector area

$$C_i = A \sum_m P_{im} F_m \Delta t_i$$



Modulated Lightcurve

Probability to find a photon from **m -th pixel** in **i -th time bin** (basically the response of the instrument)

To find an image is to find the solution:

$$I_m = \frac{1}{A} \sum_{i=1}^N [C_i / \Delta t_i] \hat{P}_{im},$$

Photons (counts) in i -th time bin

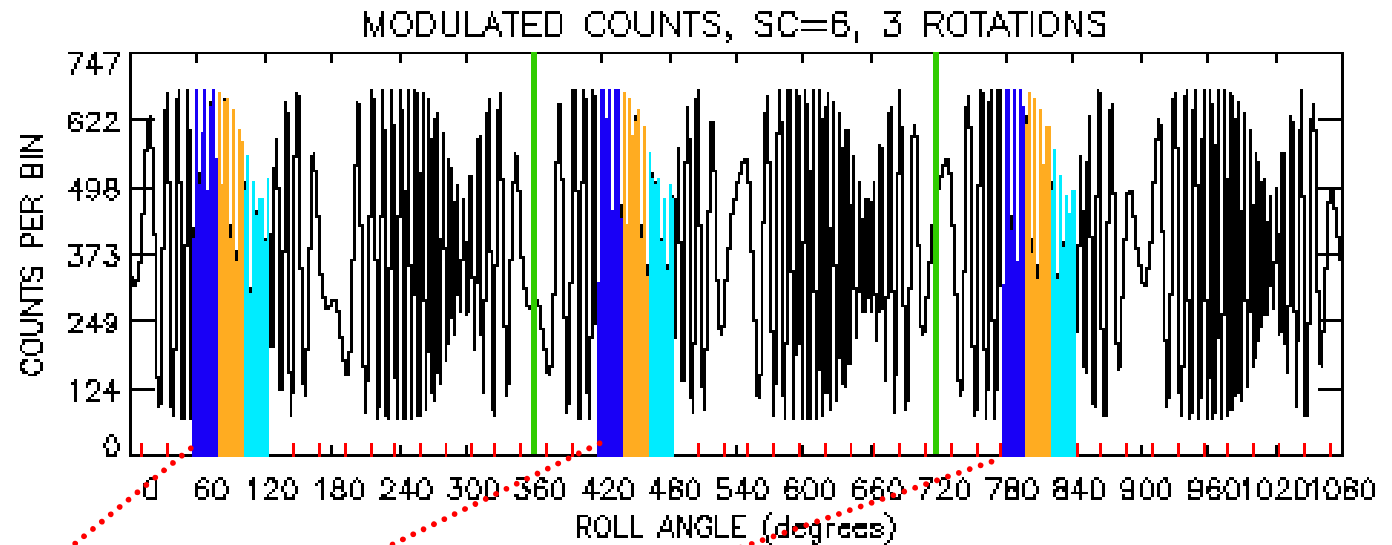


Who is this person ?



Fourier, Joseph, Baron
(From *Britannica.com*)

Stacking
(sum one roll bin over a few periods in)

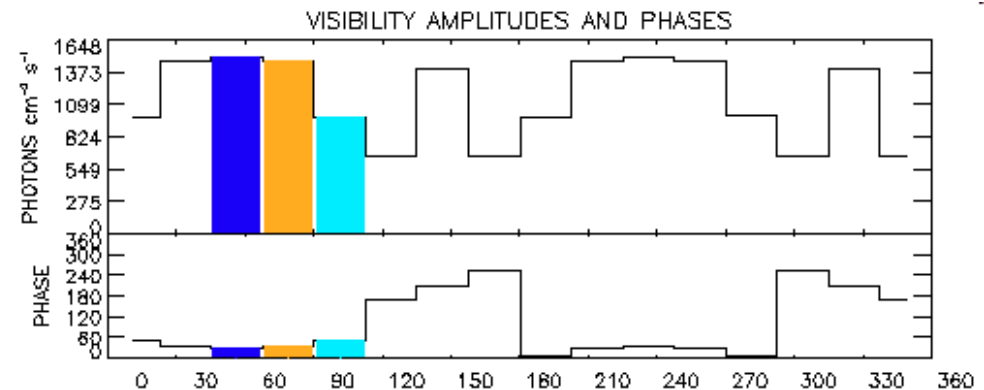
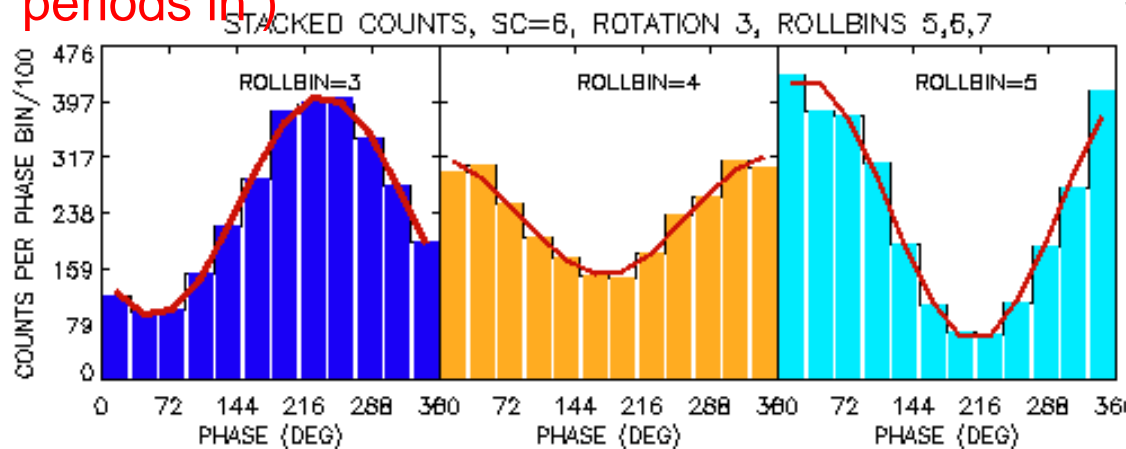


RHESSI Modulation profile over three periods from (*Schmahl and Hurford*)
(http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&article_id=39)

Each period is split into **roll bins** (here it is 16)

Stacking increasing signal-to-noise ratio and helps to calculate **mean amplitude and phase**

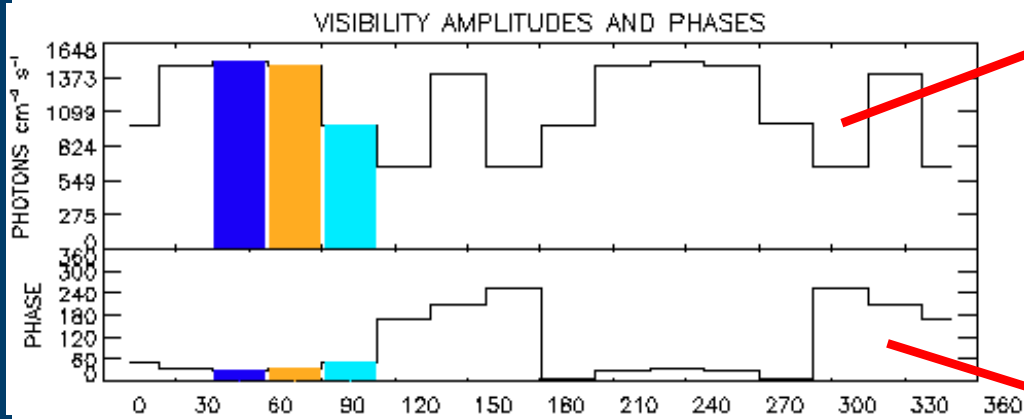
=> **X-ray Visibilities!**



X-ray Visibilities are two dimensional spatial Fourier components of X-ray source

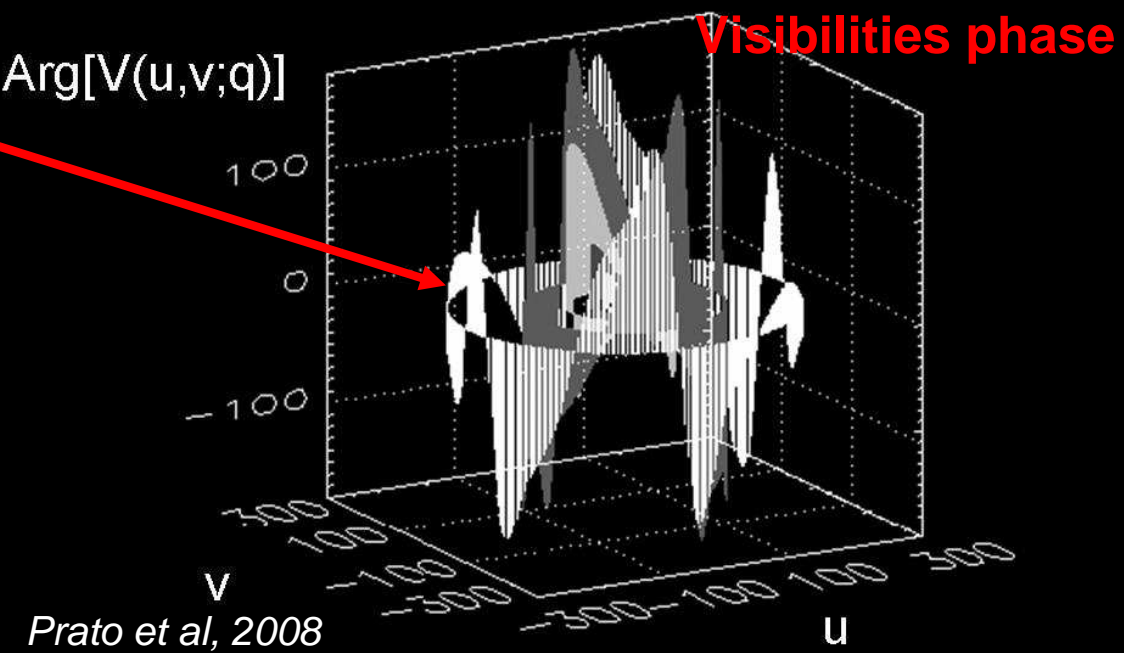
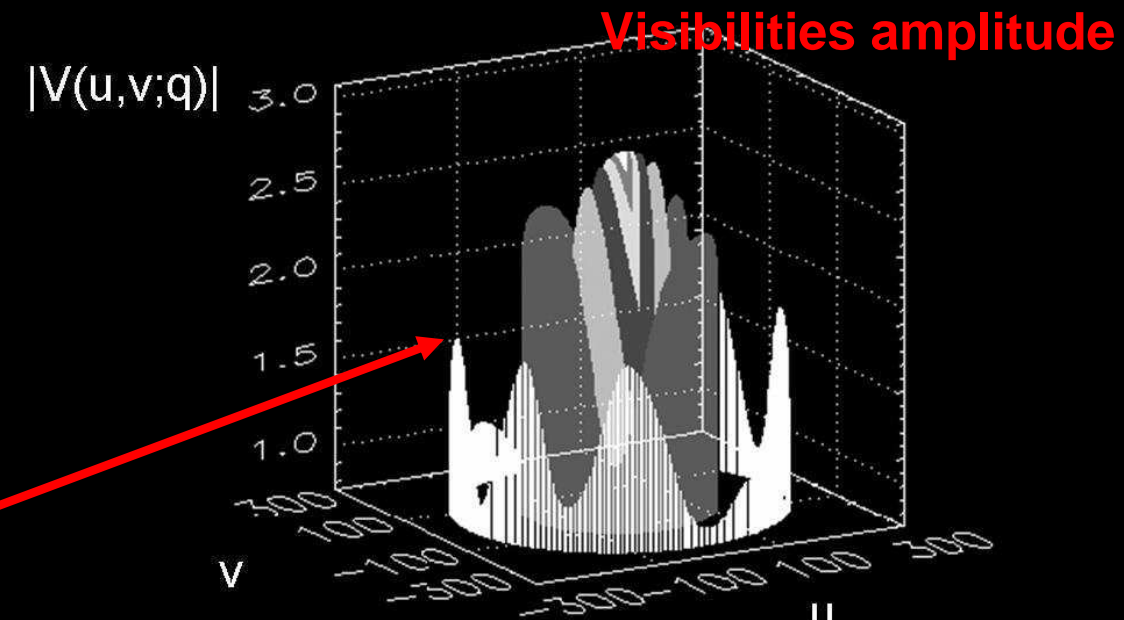
$$V(u, v; q) dq = \int_x \int_y \int_{\epsilon=q}^{\infty} D(q, \epsilon) I(x, y; \epsilon) e^{2\pi i(ux+vy)} d\epsilon dx dy$$

Visibilities amplitude



Visibilities phase

Note 9 circles (nine RMCs) in U,V (spatial frequencies) plane



The fundamental problem of RHESSEI imaging is to find the spatial photon distribution knowing **the modulated time profile** or **visibilities** (**solve an inverse problem!** ;():

$$I_m = \frac{1}{A} \sum_{i=1}^N [C_i / \Delta t_i] \hat{P}_{im},$$

To accomplish this task various imaging algorithms to solve this inverse problem exist:

Back Projection

CLEAN

Maximum Entropy Method MEM based (e.g. MEM NJIT)

PIXON

Forward Fit

Interpolated (smooth) FFT

...

You method could be here!



Back projection (Mertz, Nakano, and Kilner, 1986) is the most basic method of image reconstruction (roughly 2D Fourier transforms (Kilner and Nakano, 1989)), leads to so-called 'dirty map' or 'dirty image'.

$$I_m = \frac{1}{A} \sum_{i=1}^N [C_i / \Delta t_i] \hat{P}_{im},$$

$$\tilde{P}_{im} = P_{im} - \langle P_m \rangle \quad \hat{P}_{im} = \tilde{P}_{im} / \langle \tilde{P}_m^2 \rangle.$$

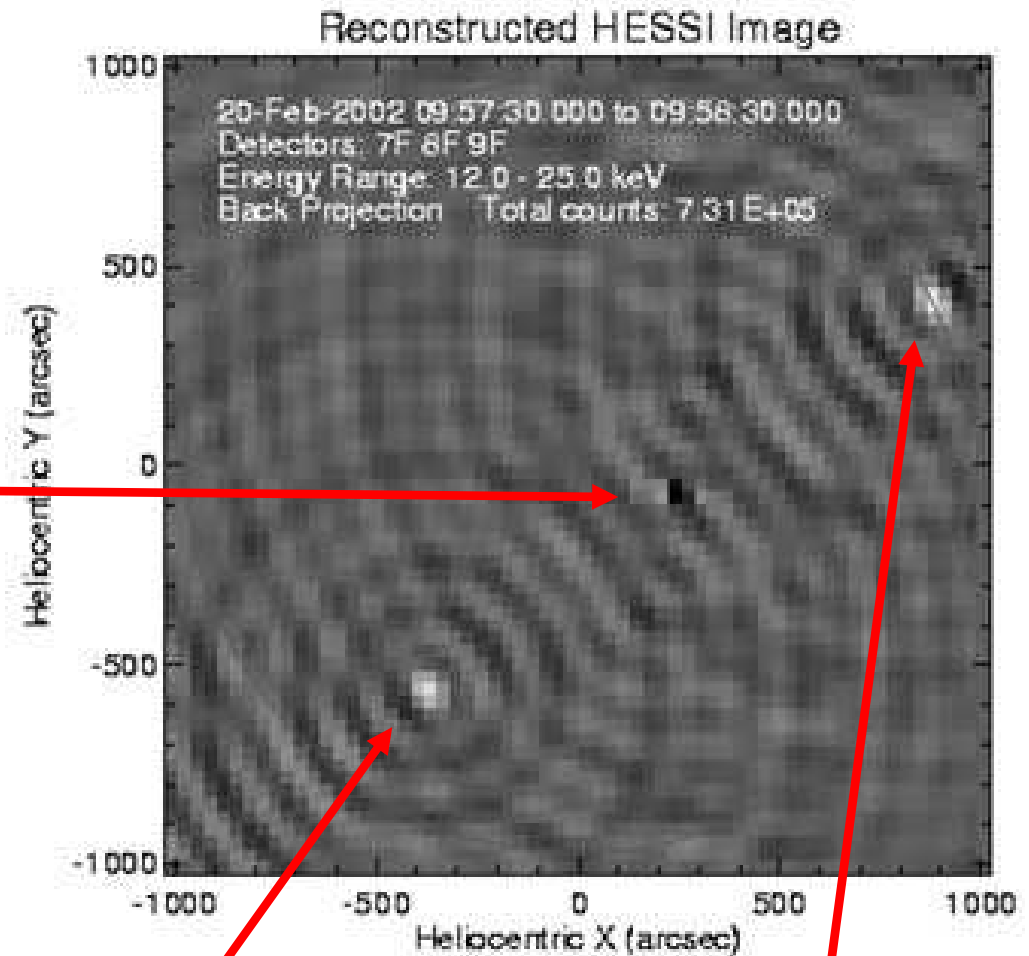
Advantages:

- Very fast
- Linear and simple

Disadvantages:

- poor quality images
- no reliable source sizes

spin axis



Mirror image

Flare

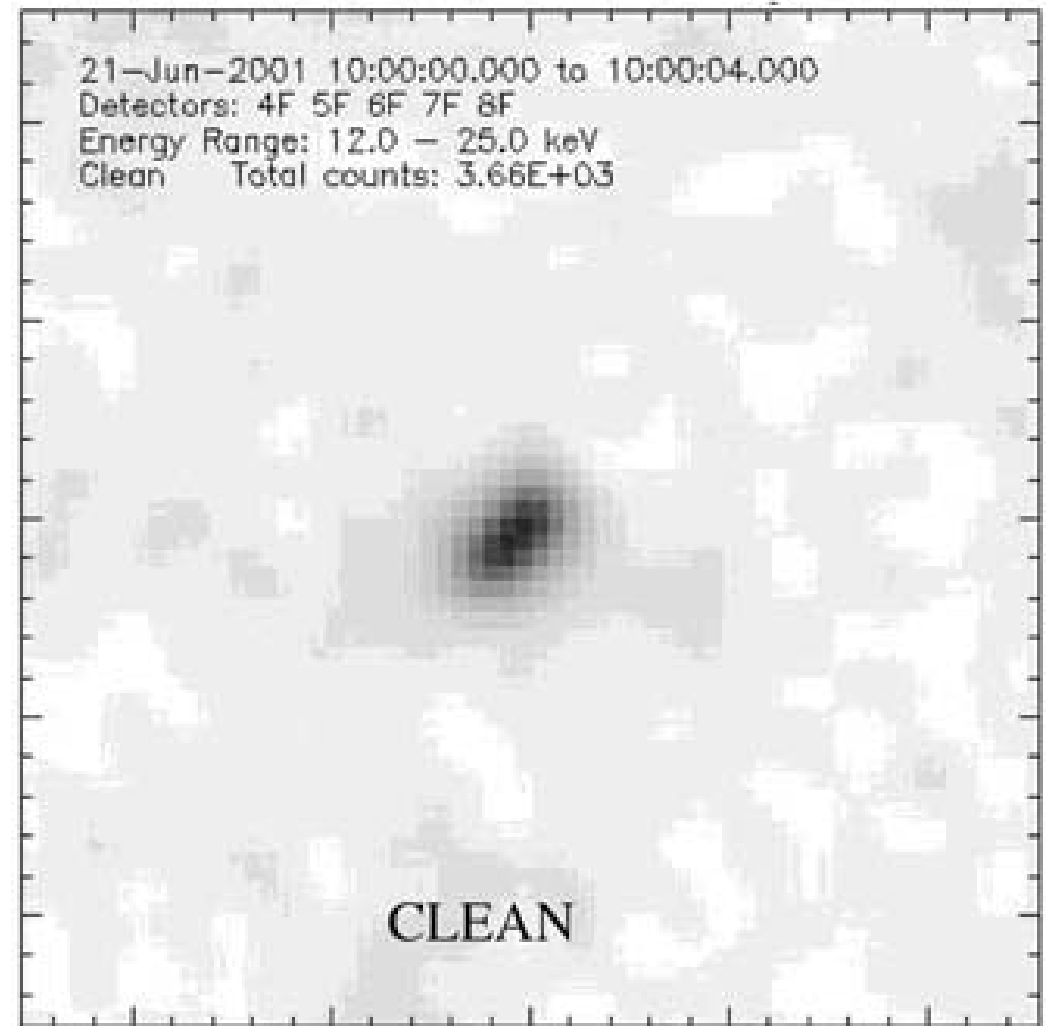
Clean assumes that the image is a superposition of point sources convolved with **Point Spread Function (PSF)** and iteratively cleans the initial back-projected image until either negative residuals or max number of iterations Högbom (1974).

Advantages:

- Relatively fast
- Positive fluxes

Disadvantages:

- Nonlinear
- Overestimates source sizes
- Likely to misinterpret extended sources



Maximum Entropy Methods (MEM) algorithm looks for the map that is both consistent with the data and contains the least information about the source (i.e. maximum entropy). (Hurford et al, 2002)

$$\chi^2 = \sum_i \frac{(C_i - \mathcal{E}_i)^2}{\sigma_i^2}, \quad \mathcal{H} = - \sum_m F_m \log F_m,$$

consistency with
data

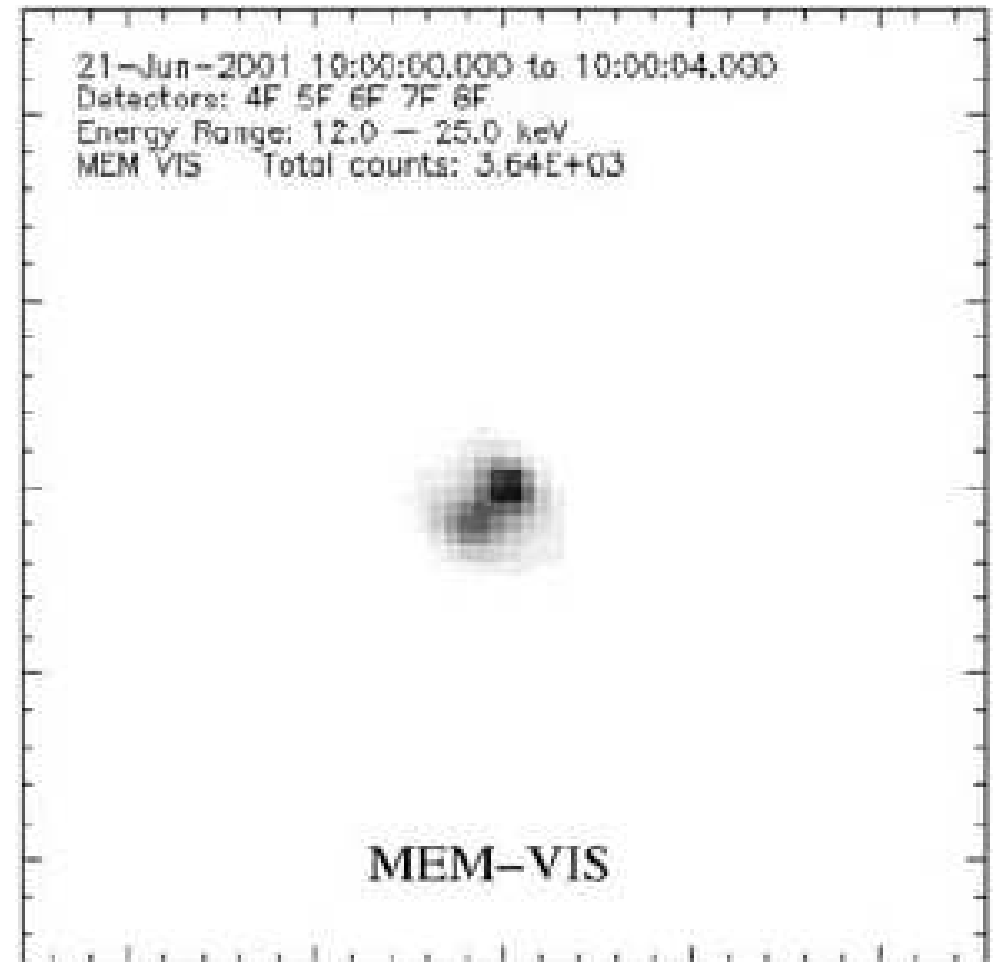
Maximising entropy

Advantages:

- Relatively fast
- Positive fluxes

Disadvantages:

- Nonlinear
- Underestimates source sizes



Hurford et al, 2002

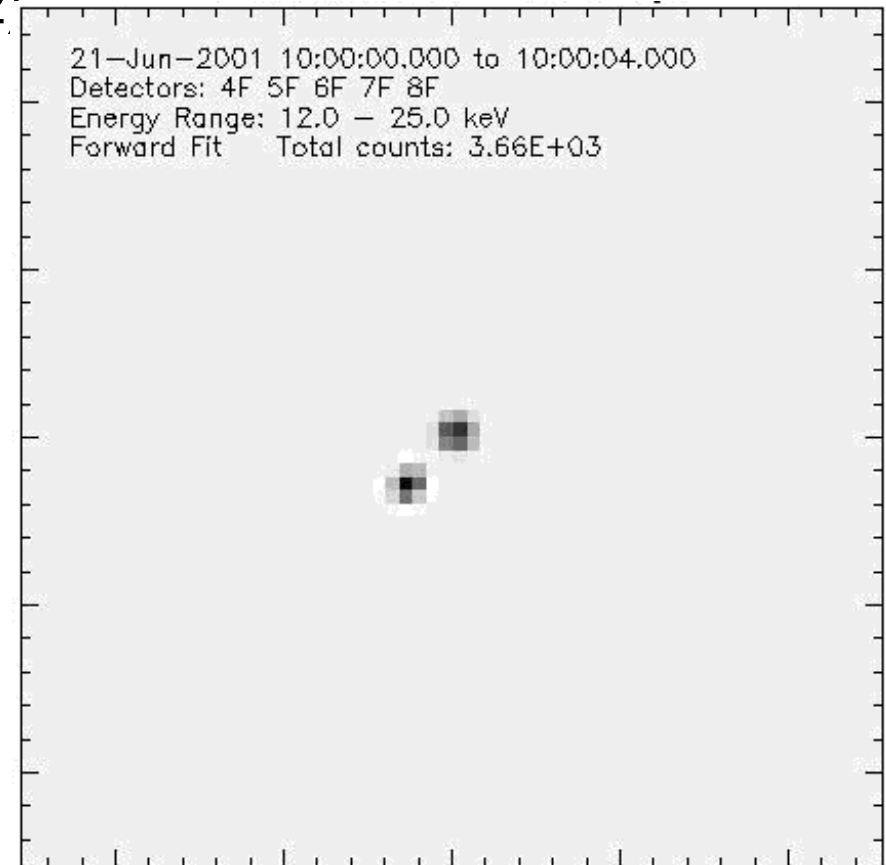
Forward Fit assumes that the source can be presented as a prescribed functional form with a number of free parameters (for example, two circular Gaussian sources) and looks for the parameters which produce a map that is consistent with the data. (Aschwanden et al, 2002; Hurford et al, 2002)

Advantages:

- Fast
- Positive fluxes
- Source sizes and errors on parameters

Disadvantages:

- Does not work well for complex sources



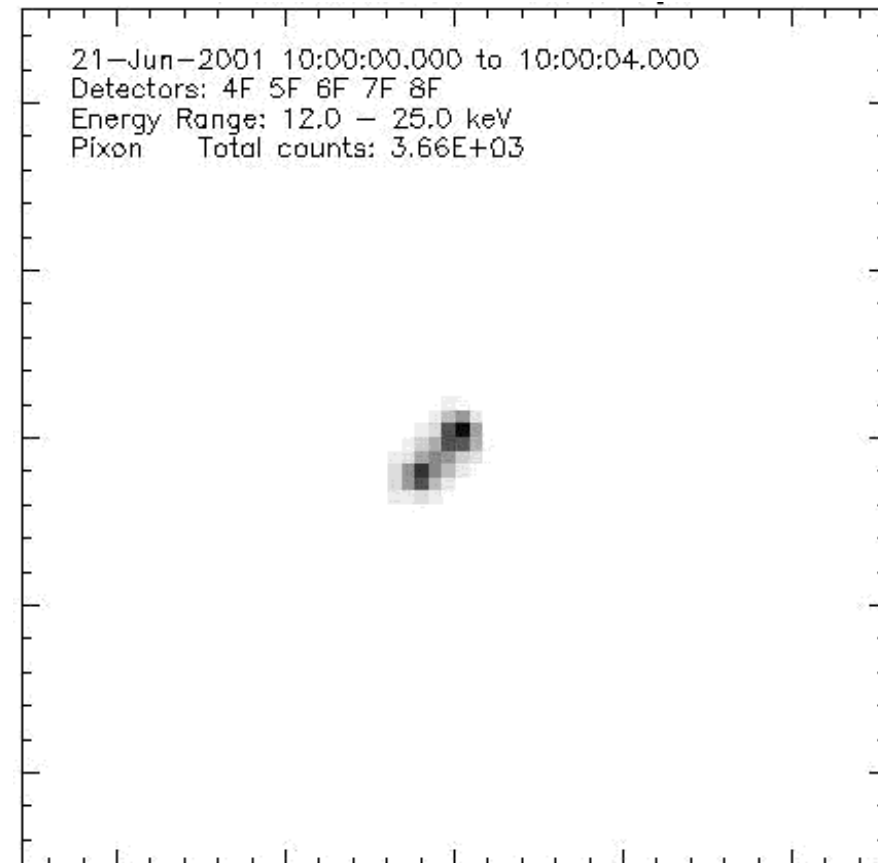
Pixon looks for **the simplest model** for the image that is consistent with the data (suitable CHI2) (Puetter, 1995; Metcalf *et al.*, 1996). Pixon simultaneously minimises smooths the image *locally* (*minimisation of independent patches*) and simultaneously consistent with the data.

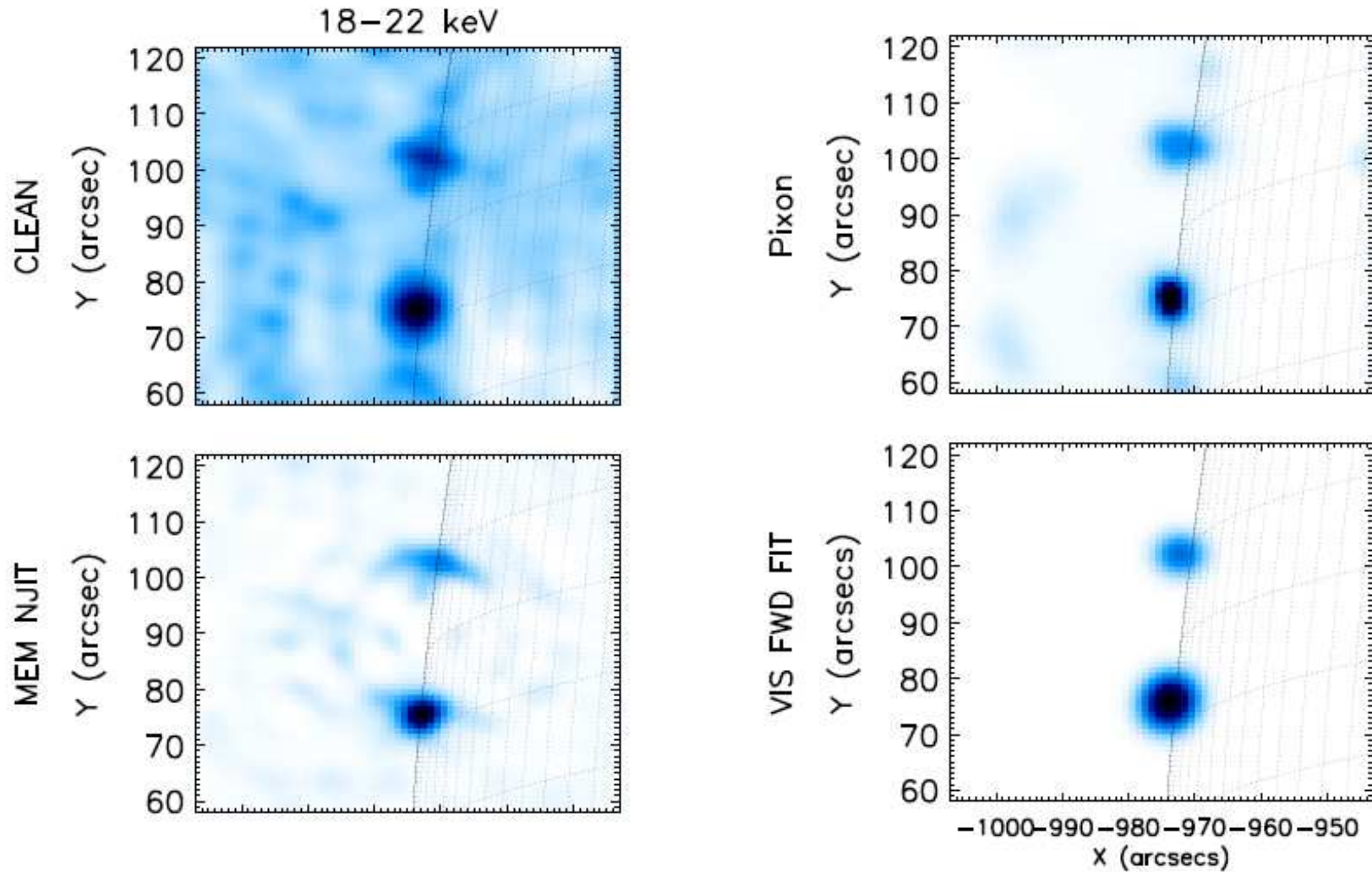
Advantages:

- Photometric accuracy
- no spurious features

Disadvantages:

- Very slow (too orders of magnitude)





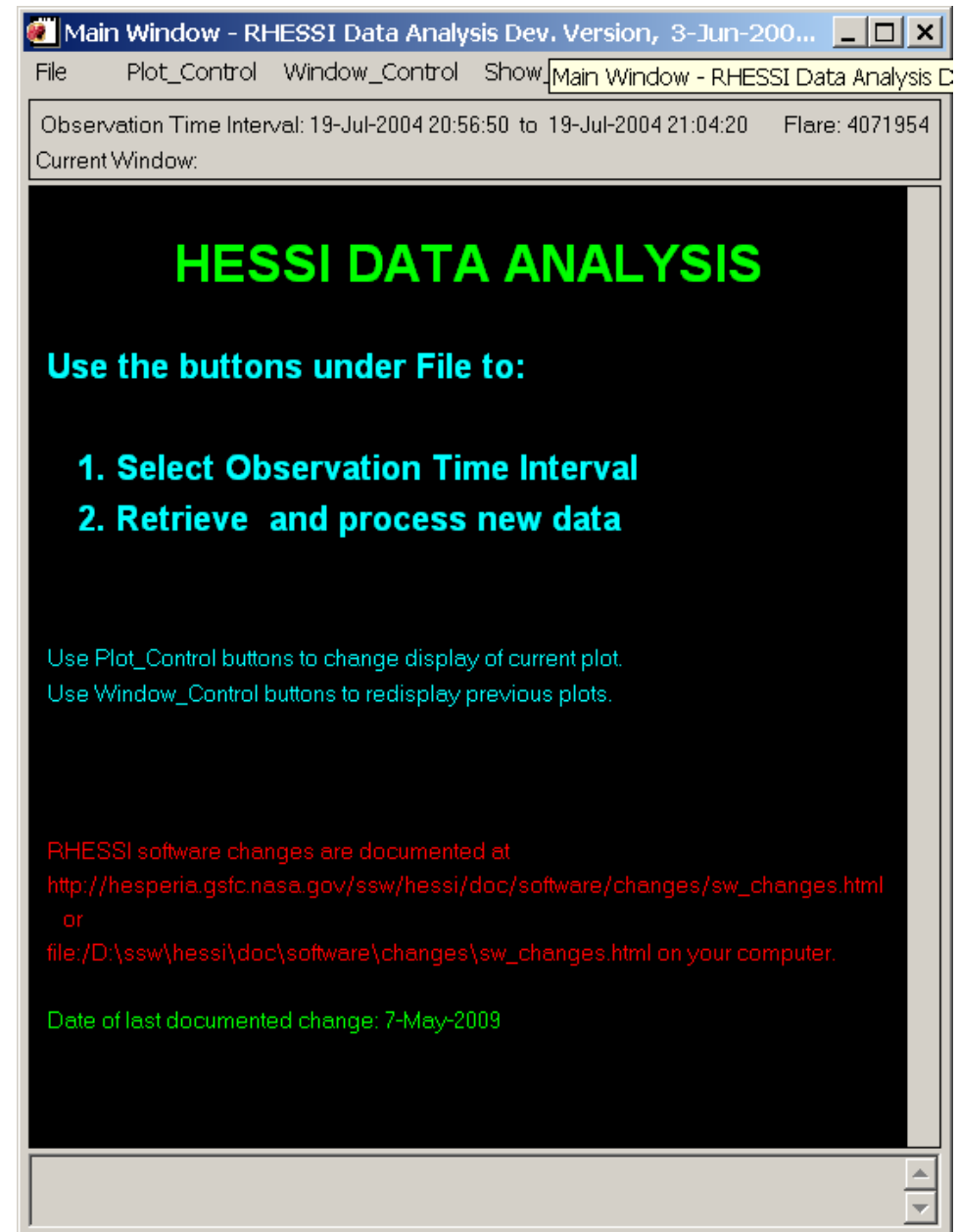
1) Start GUI interface

IDL>hessi

2) You will see this

3) Let us select a flare

January 06, 2004 ~06:20 UT



1) Select time interval

Obs Time Interval Selection - RHESSI Data Analysis Dev. Version, 4-Jun-20...

Observation Time Interval Obs Time Interval Selection - RHESSI D

Set Obs Time Interval in Main GUI Window and Imaging, Spectrum and Lightcurve Objects by:
 Selecting time explicitly in time widgets, or choosing
 a flare, or plotting obs summ data for time interval and zooming in on plot

Start... 6-Jan-2004 06:00:00.000 Reset Duration (s): 3600.000
 End... 6-Jan-2004 07:00:00.000 Reset

Set times to start/end of flare: 4010604 Flare Selection...

Flare 4010604: 6-Jan-2004 06:13:12.000 to 06:31:28.000 Peak: 06:25:30.000, 2288.00 c/s

Expand Times by 2 minutes before 2 minutes after flare

Select Data To Plot: Count Rate Show Flags: S, N, F, FDn, RDn, An Change

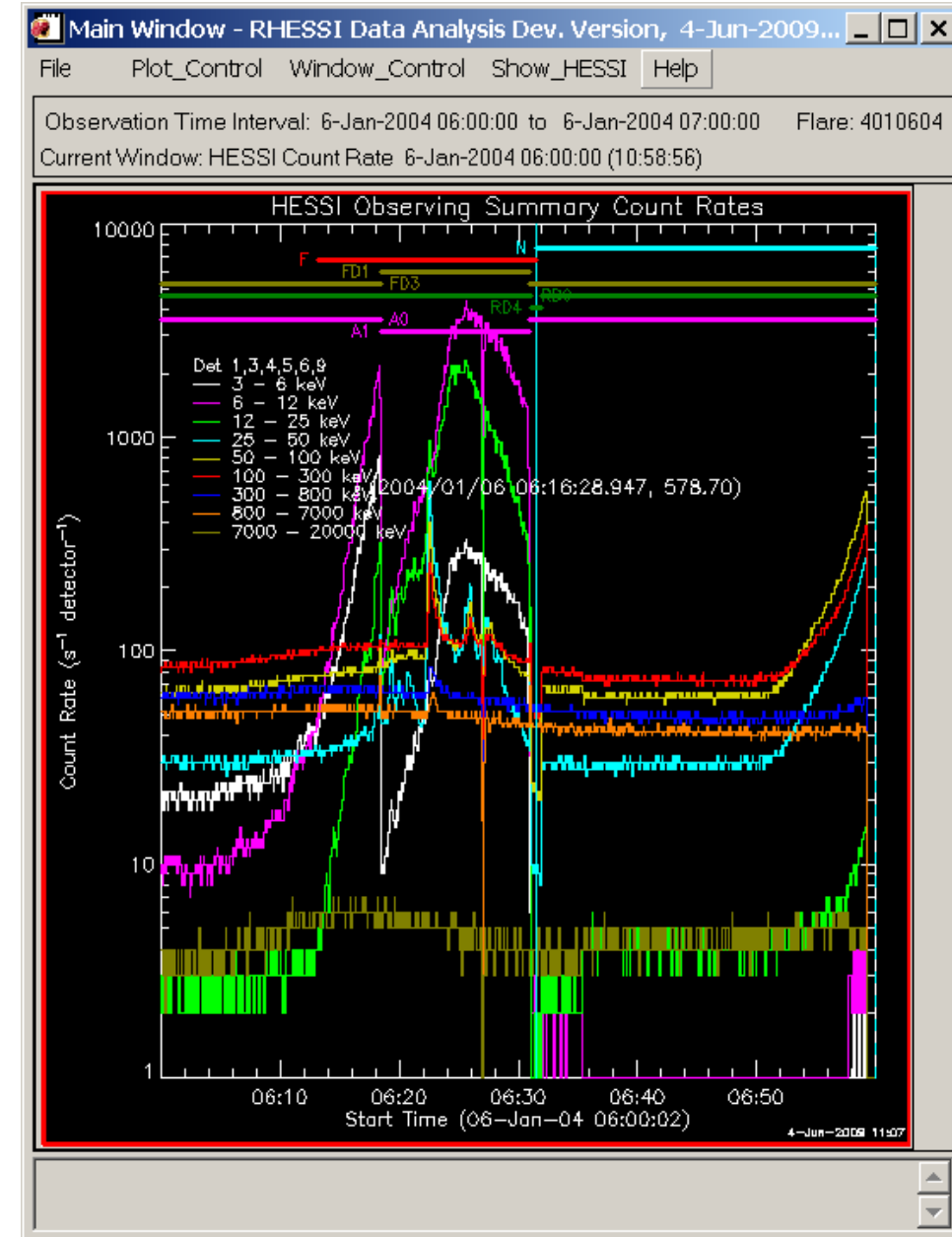
Plot Observing Summary Data

Set Obs Time Set Obs Time to Plot Limits

Help Cancel (Undo any Set Obs Time) Just Close Set Obs Time and Close

2) Plot observing summary data

3) Set obs time & close



In the main window select
File -> Retrieve/Process data -> Imaging

- 1) Select time interval
- 2) Select energy range
- 3) Select detectors
- 4) Select image details:
size, pixel size, xy offset
- 5) Select image algorithm
- 6) Do not mess with this
(unless you know what you are doing)
- 7) Choose output

Imaging - RHESSI Data Analysis Dev. Version, 4-Jun-2009 11:16

IMAGING (* - changing these parameters forces reprocessing and takes longer)

Select Input: Raw Data 6-Jan-2004 06:00:00.000 to 07:00:00.000 Change...

Selected Time Range: 6-Jan-2004 06:00:00 to 6-Jan-2004 07:00:00
Flare 4010604: 6-Jan-2004 06:13:12.000 to 06:31:28.000 Peak: 06:25:30.000, 2288.00 c/s

*1 Image Time Interval: 6-Jan-2004 06:25:30.000 to 06:25:34.000 Change... 4s at peak

*1 Energy Band (keV): 12.0 to 25.0 Change... Binning Code: None Show Binning Codes

Collimators and Detector Front/Rear Segments Selected:
1FR, 2FR, 3FR, 4FR, 5FR, 6FR, 7FR, 8FR, 9FR Change...

Automatic Time Bin Calculation: Enabled Digital Quality: 0.95

Pixel Size (arcsec): 4.0 x 4.0 Image Dimensions (pixels): 64 x 64
Offset of Map Center from Sun Center (arcsec): X: -973.36 Y: 74.63 Change...
Image Size = 256 x 256 arcsec X range = -1101 to -845 arcsec Y range = -53 to 203 arcsec

* Image Algorithm: Back Projection Set parameters... Set visibility params... Mark clean boxes...

Flatfield: Enabled Modpat_skip: 1 Phase Stacker: Disabled Cull: Enabled (Fraction: 0.50)
Weighting: Natural Tapering Width (arcsec): 0.00 Local Average: Disabled Change...
Variable Flux Correction: Enabled Decimation Correction: Front Rate-based BProj: Enabled

Send Image(s) to: GUI FITS File Show: Progress Bar Verbose Images

Make/Plot Image(s) Write FITS File Display -> Movie Write Script ->

Refresh Reset to Defaults Set Params Manually Help Close

Selecting time interval....

1) Define time interval here

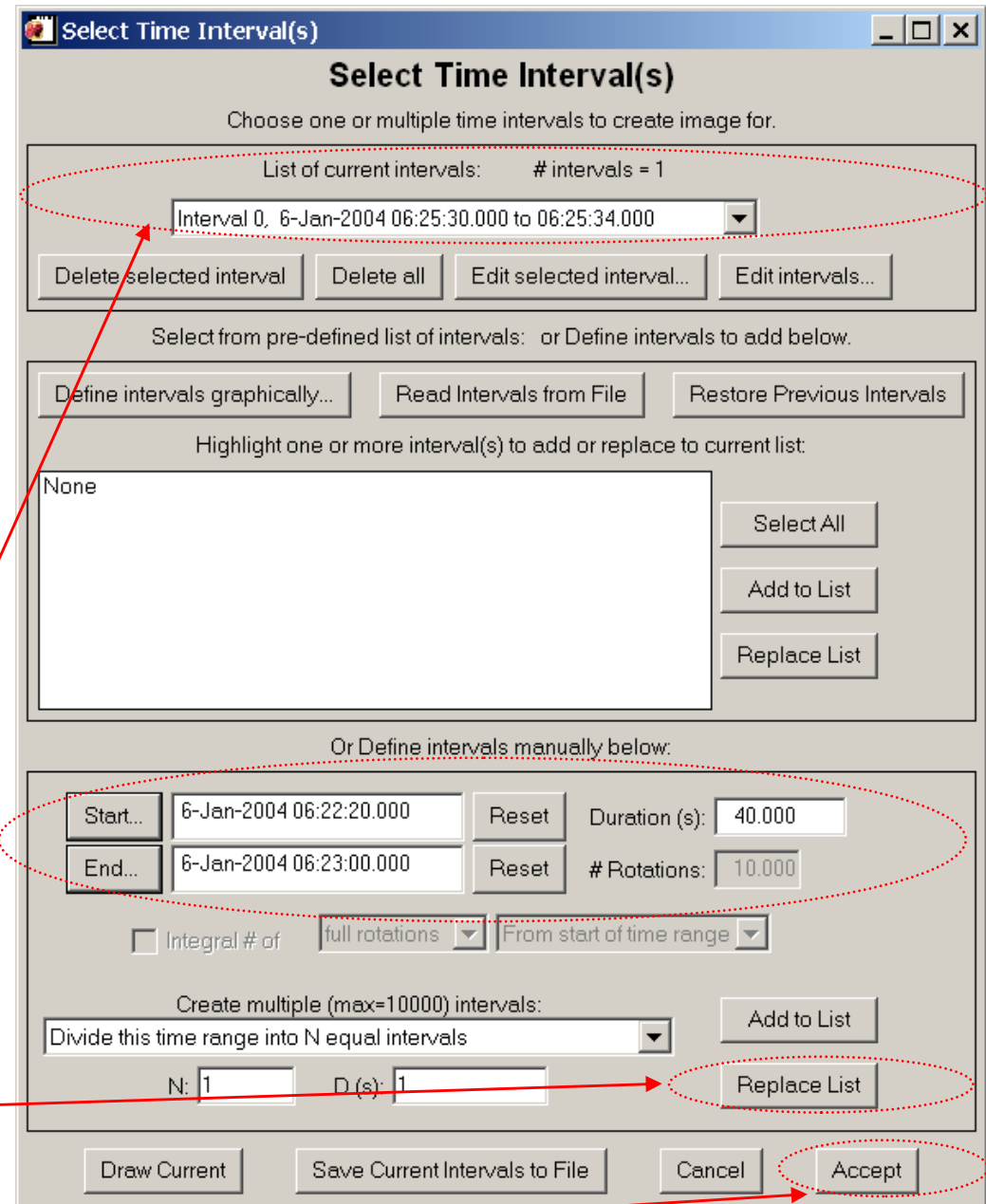
Good practice:

a) Time interval is a multiple of spin period (or a half)

b) The weaker the flare the longer the time (20-40 seconds => good images for a medium class flare)

2) **Always press replace list**
(note the change at the top)

3) Press accept



Selecting energy interval....

1) Define energy range here

Good practice:

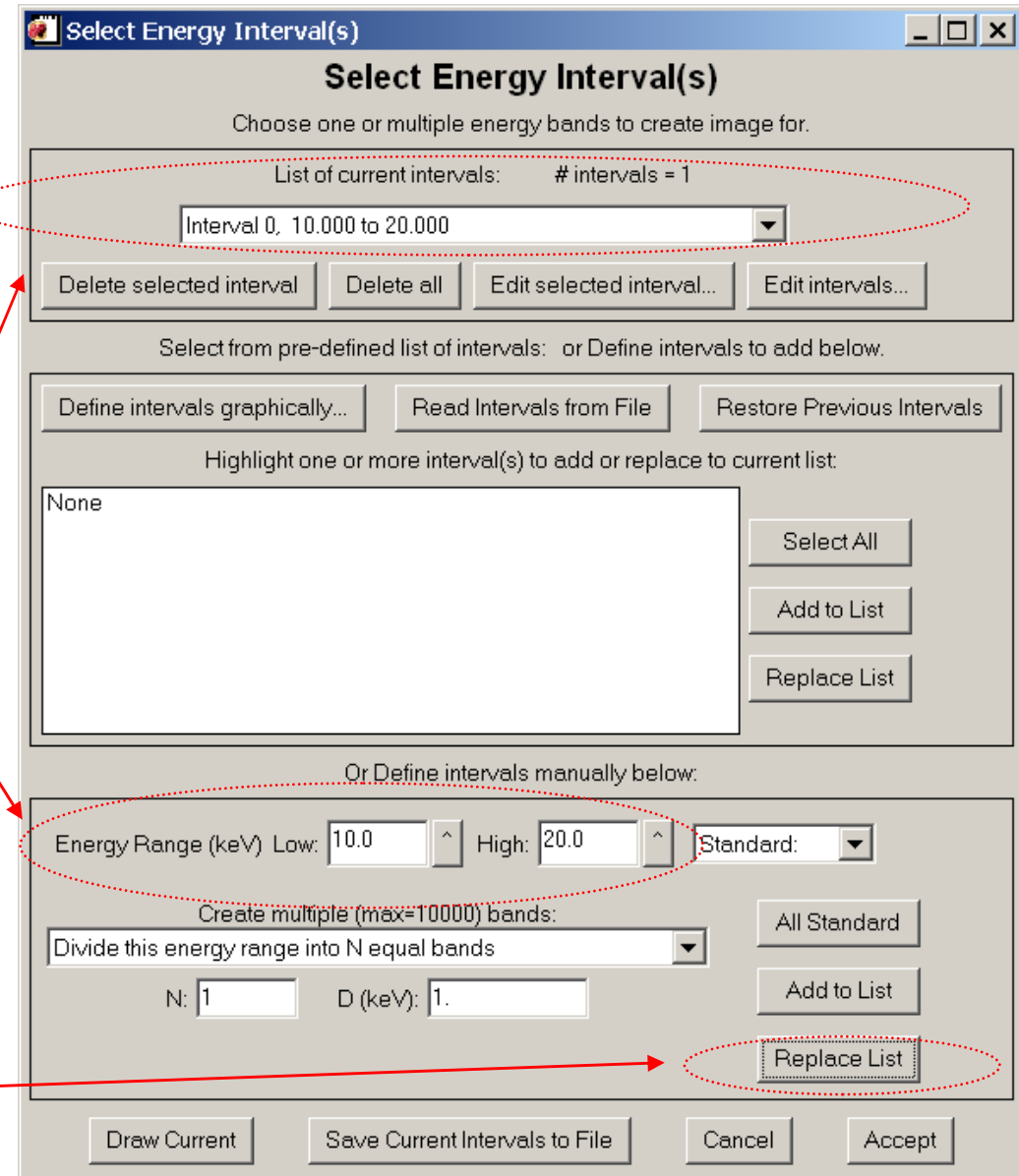
a) Time interval is more than a few keV

b) The weaker the flare the longer the energy range (5-20 of keV is OK)

c) The higher the energy the longer the energy range (recall X-ray spectrum) (~100 of keV at 200 keV)

2) **Always press replace list**
(note the change at the top)

3) Press accept



Select Energy Interval(s)

Choose one or multiple energy bands to create image for.

List of current intervals: # intervals = 1

Interval 0, 10.000 to 20.000

Delete selected interval Delete all Edit selected interval... Edit intervals...

Select from pre-defined list of intervals: or Define intervals to add below.

Define intervals graphically... Read Intervals from File Restore Previous Intervals

Highlight one or more interval(s) to add or replace to current list:

None

Select All

Add to List

Replace List

Or Define intervals manually below:

Energy Range (keV) Low: 10.0 High: 20.0 Standard:

Create multiple (max=10000) bands:

Divide this energy range into N equal bands

N: 1 D (keV): 1.

All Standard

Add to List

Replace List

Draw Current Save Current Intervals to File Cancel Accept

Selecting Collimators/Detectors ...

1) Define RMC here

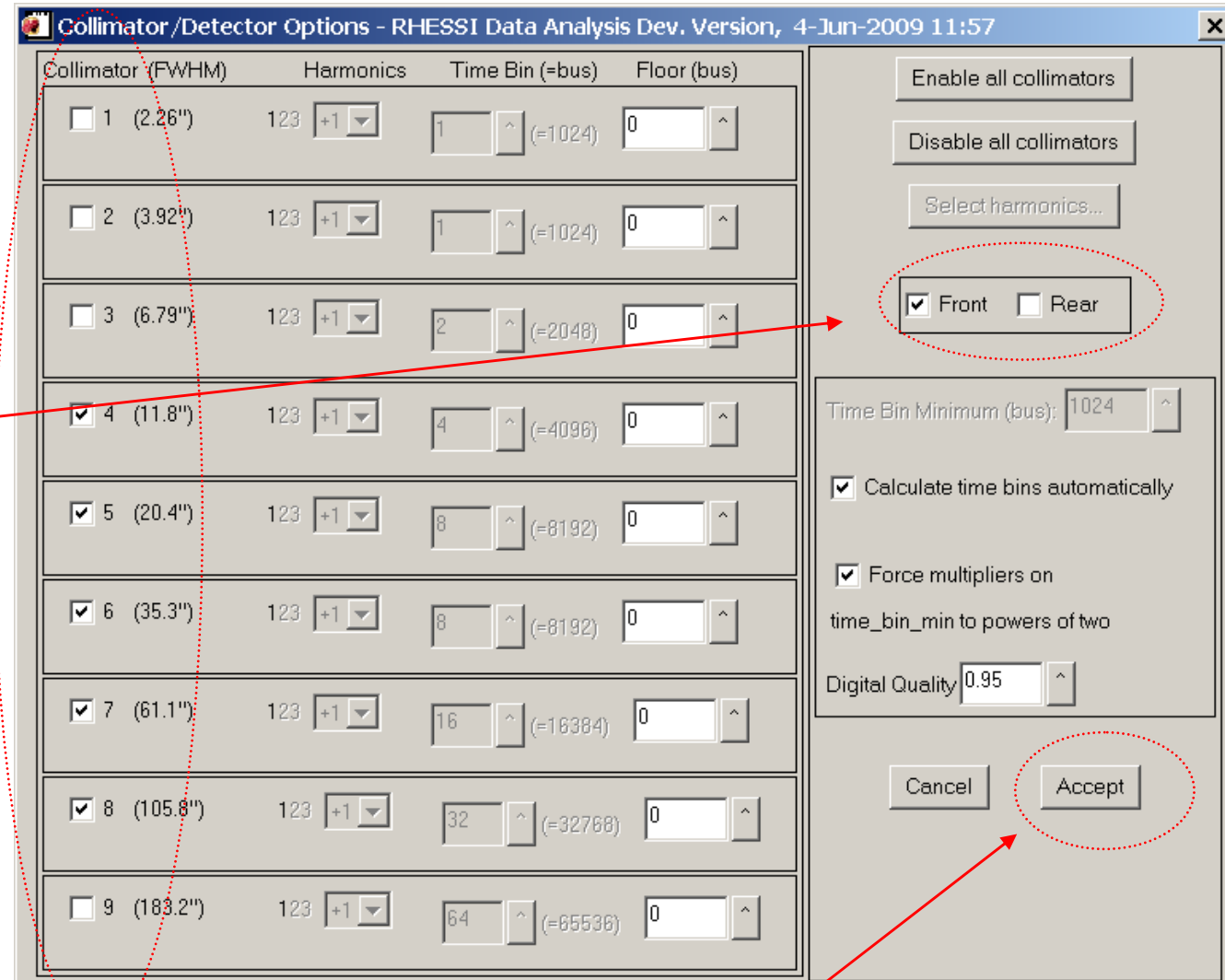
Good practice:

a) **Front** for energies $< \sim 300$ keV, **Rear** for higher energies (Det#1 up to 100 keV)

b) Det #3-8 is a common choice

c) Det#2 above 20-25 keV only

d) Det#9 for scales $> \sim 180''$



Collimator (FWHM)	Harmonics	Time Bin (=bus)	Floor (bus)
<input type="checkbox"/> 1 (2.26")	123 +1	1 (=1024)	0
<input type="checkbox"/> 2 (3.92")	123 +1	1 (=1024)	0
<input type="checkbox"/> 3 (6.79")	123 +1	2 (=2048)	0
<input checked="" type="checkbox"/> 4 (11.8")	123 +1	4 (=4096)	0
<input checked="" type="checkbox"/> 5 (20.4")	123 +1	8 (=8192)	0
<input checked="" type="checkbox"/> 6 (35.3")	123 +1	8 (=8192)	0
<input checked="" type="checkbox"/> 7 (61.1")	123 +1	16 (=16384)	0
<input checked="" type="checkbox"/> 8 (105.8")	123 +1	32 (=32768)	0
<input type="checkbox"/> 9 (183.2")	123 +1	64 (=65536)	0

Enable all collimators
Disable all collimators
Select harmonics...

Front Rear

Time Bin Minimum (bus): 1024

Calculate time bins automatically

Force multipliers on time_bin_min to powers of two

Digital Quality 0.95

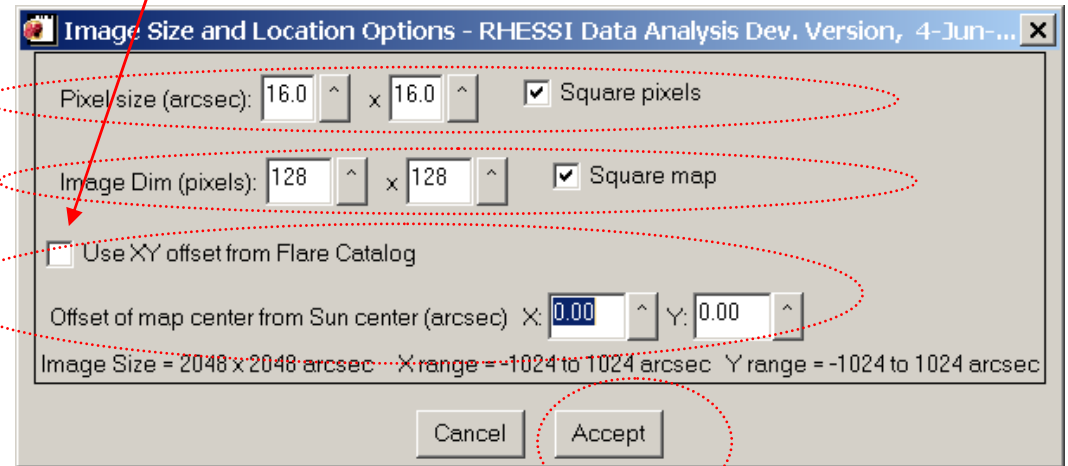
Cancel Accept

2) Press accept

Selecting Collimators/Detectors ...

It is not bad idea to use XYoffset from flare catalog (put tick if you want it)

- 1) Define pixel size
- 2) Define image size
- 3) Set the centre of the image as offset from the Sun centre



Good practice:

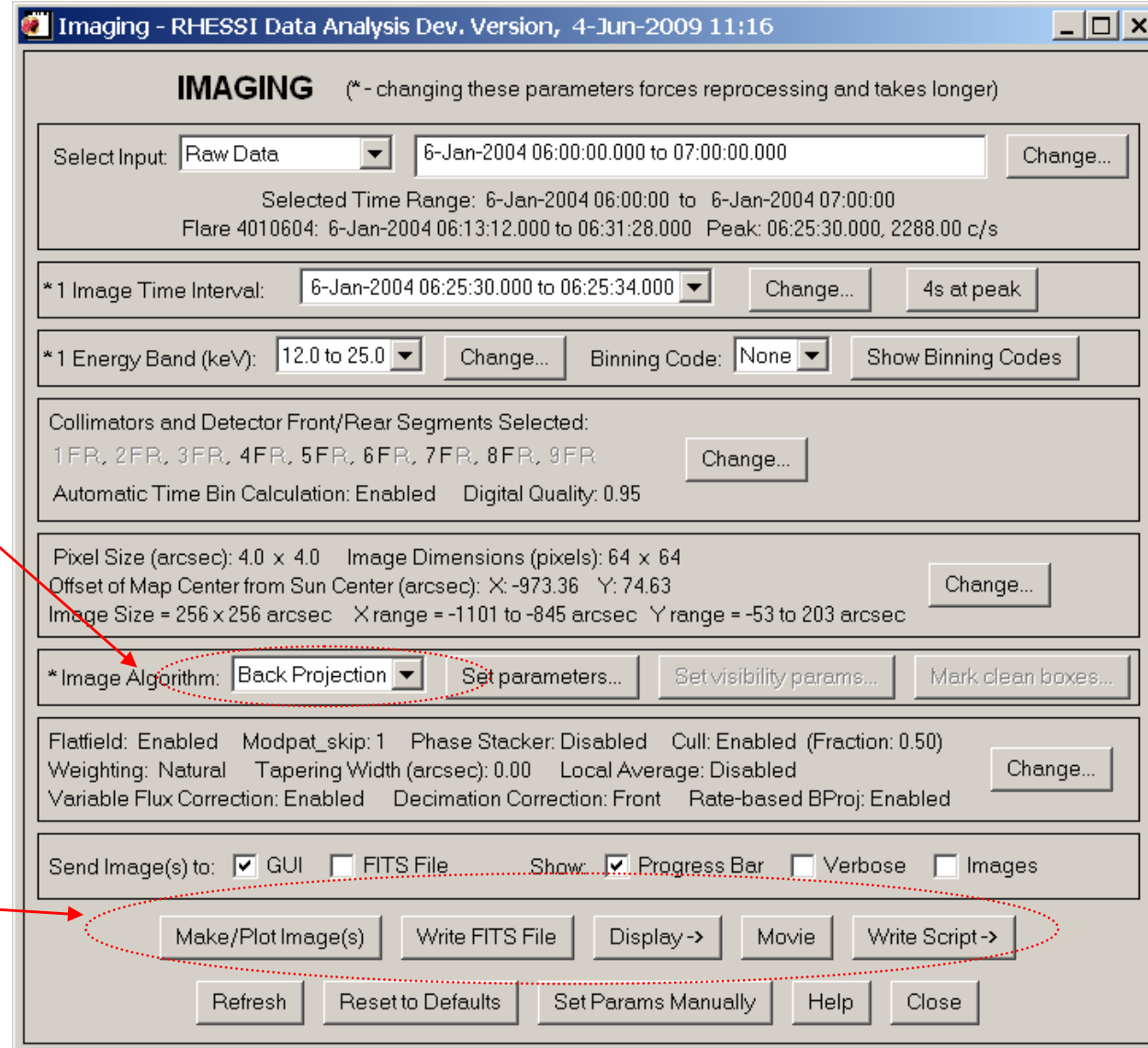
- a) Pixel size less than RMC FWHM
- b) Use small image size
~64x64 or 32x32 (especially with Pixon)
- c) Keep in mind where the spin axis is

- 4) As usual press 'accept' when finished

Finally ...

1) Choose algorithm

2) Output type
(save as image as a file or display in the main window)



IMAGING (* - changing these parameters forces reprocessing and takes longer)

Select Input: Raw Data 6-Jan-2004 06:00:00.000 to 07:00:00.000 Change...

Selected Time Range: 6-Jan-2004 06:00:00 to 6-Jan-2004 07:00:00
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Automatic Time Bin Calculation: Enabled Digital Quality: 0.95

Pixel Size (arcsec): 4.0 x 4.0 Image Dimensions (pixels): 64 x 64
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* Image Algorithm: Back Projection Set parameters... Set visibility params... Mark clean boxes...

Flatfield: Enabled Modpat_skip: 1 Phase Stacker: Disabled Cull: Enabled (Fraction: 0.50)
Weighting: Natural Tapering Width (arcsec): 0.00 Local Average: Disabled Change...
Variable Flux Correction: Enabled Decimation Correction: Front Rate-based BProj: Enabled

Send Image(s) to: GUI FITS File Show: Progress Bar Verbose Images

Make/Plot Image(s) Write FITS File Display -> Movie Write Script ->

Refresh Reset to Defaults Set Params Manually Help Close

Use synoptic data ... (almost all main solar data are accessible !!!)

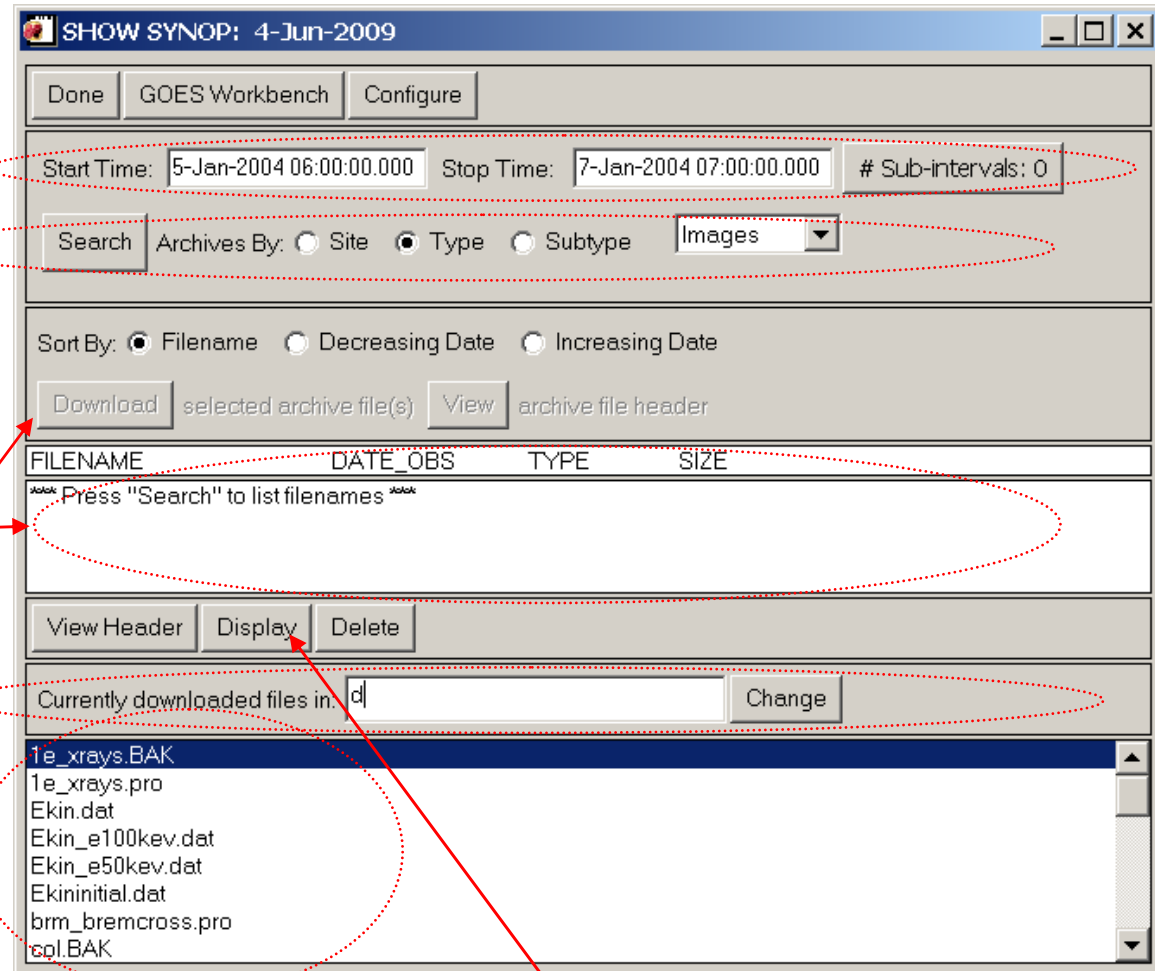
1) Choose the time range

2) Choose type of data
and press **'search'**

Search results will appear here

3) Set your local folder

4) Download the data



SHOW SYNOP: 4-Jun-2009

Done GOES Workbench Configure

Start Time: 5-Jan-2004 06:00:00.000 Stop Time: 7-Jan-2004 07:00:00.000 # Sub-intervals: 0

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- 1e_xrays.pro
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- Ekin_e100kev.dat
- Ekin_e50kev.dat
- Ekininitial.dat
- brm_bremcross.pro
- col.BAK

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4) Plot the data


```
obj = hsi_image()           <= Defining imaging object anything instead of 'obj'  
obj-> set, det_index_mask= [0, 0, 1, 1, 1, 1, 1, 1, 0]   <= Detectors used #3-8  
obj-> set, im_energy_binning= [10.0, 20.0]   <= Energy range used from 10 to 20 keV  
obj-> set, im_time_interval= ' 6-Jan-2004 '+'[06:22:20', '06:23:00']   <= time interval  
obj-> set, image_algorithm= 'Back Projection'   <= image algorithm; could be Clean, Pixon, etc  
  
obj-> set, image_dim= [128, 128]   <= image size in pixels  
obj-> set, pixel_size= [32., 32.]   <= pixel size in arcseconds  
obj-> set, use_flare_xyoffset= 0   <= if set to 1 uses catalog data, if set to 0 not  
obj-> set, xyoffset= [0.0, 0.0]   <= sets image centre coordinates  
  
data = obj-> getdata()   ; retrieve the last image made  
  
obj-> plot   ; plot the last image  
obj-> plotman   ; plot the last image in plotman
```

```
obj = hsi_image()
obj-> set, det_index_mask= [0, 1, 1, 1, 1, 1, 1, 0, 0]
obj-> set, im_time_interval= '6-Jan-2004 '+'[06:22:20', '06:23:00']
obj-> set, im_energy_binning=[25.,35.]

obj-> set, image_algorithm= 'VIS FWDFIT'           <=visibilities forward fit to be used
obj-> set, xyoffset=[-970,73]                     <= centre of the map
obj-> set, use_phz_stacker= 1                       <= stacking into roll bins
;obj-> set,PHZ_radius=10.                          <= automatic choice of roll bins based on the characteristic scale 10"
obj-> set,image_dim=[64,64]
obj-> set,pixel_size=[1.0,1.0]
obj-> set, vf_multi=1                              <= two sources

obj-> set,phz_n_roll_bins_control=[20,38,20,20,12,12,12,12,20] <= manual choice of roll bins
;sets the number of roll bins per detector

; useful controls when calculating the visibilities
obj-> set, vis_edit=1, vis_combine=1
;remove outliers and combine conjugates
```

```
our_fit=obj ->get(/vf_srcout)  
;gets visibilities parameters
```

<= gets parameters out of object

```
fit_err=obj ->get(/vf_sigma)  
;gets visibilities parameter errors
```

<= errors on the fit parameters

;you can set some initial parameters for you visibility structure

```
our_fit.srcctype=['ellipse', 'ellipse']
```

<= two ellipse fit

```
our_fit.srcflux=[11,9]
```

<= fluxes per ellipse

```
our_fit.srcfwhm=[7,6]
```

<=FWHMs of the sources

```
our_fit.eccen=[0.7,0.7]
```

<= ellipse eccentricities

<= two source sizes per

```
our_fit.srcpa=[175,-178]
```

<= position angles

```
our_fit.srcx=[907,904]
```

<= x coordinates of the ellipse/circle centre

```
our_fit.srcy=[248,272]
```

<= y coordinates of the ellipse/circle centre

```
obj -> set, vf_srcin=our_fit  
; sets out fit params
```

<= setting parameters as initial guess for forward fit

```
obj-> plot  
obj->plotman
```

<= plotting the output map (image)

These lecture notes and example IDL scripts:

<http://www.astro.gla.ac.uk/users/eduard/sodas>

RHESSI imaging overview (good collection):

<http://hesperia.gsfc.nasa.gov/hessi/instrumentation.htm>

RHESSI imaging tutorials (from first steps to advanced level):

<http://hesperia.gsfc.nasa.gov/rhessidatcenter/imaging/overview.html>

Description of all RHESSI imaging software parameters:

http://hesperia.gsfc.nasa.gov/ssw/hessi/doc/hsi_params_all.htm