Hard X-ray imaging by Solar Orbiter STIX: challenges, methods and results

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Joint work with: Volpara A., Battaglia A. F., Perracchione E., Garbarino S., Benvenuto F., Massone A. M., Hurford G. J., Krucker S., Piana M. & the STIX team

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STIX imaging

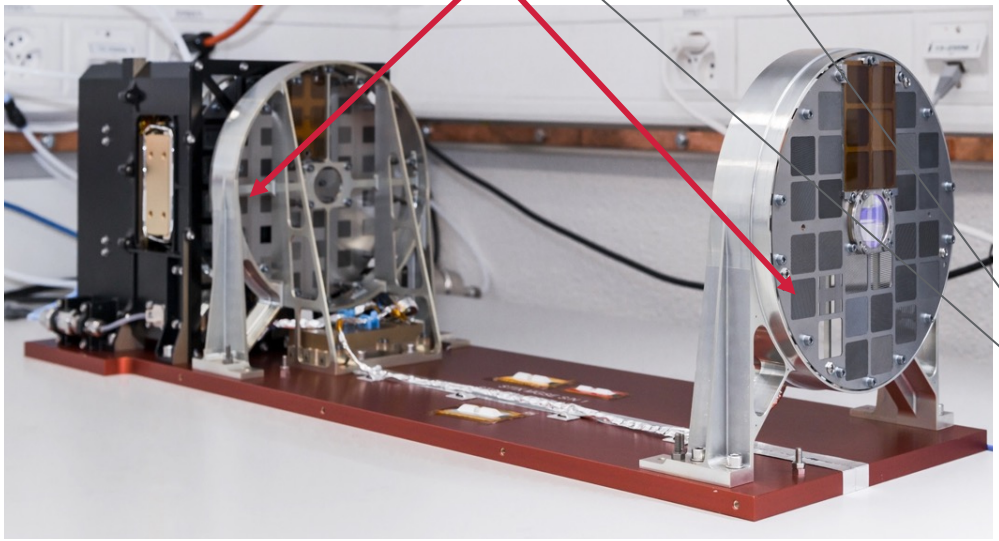
STIX is a **Fourier imager**
(like RHESSI and Yohkoh)

It measures 30 Fourier components of the angular distribution of the flaring X-ray source (named **visibilities**)

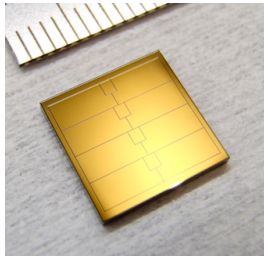
How? It modulates the X-ray radiation by means of a bigrid system

The STIX instrument

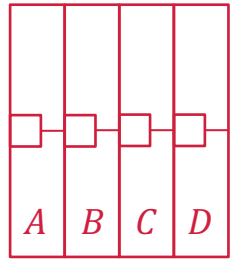
STIX consists of 30 subcollimators:
subcollimator = front grid + rear grid + detector



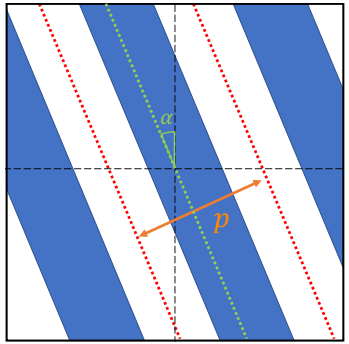
Krucker et al., 2020



Krucker et al., 2020



A, B, C and D: number of counts recorded by the detector pixels

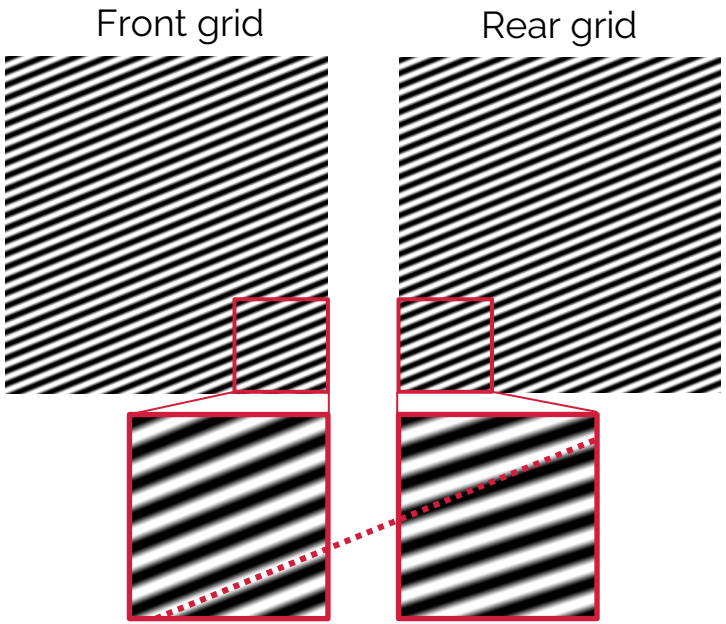


Grid parameters:

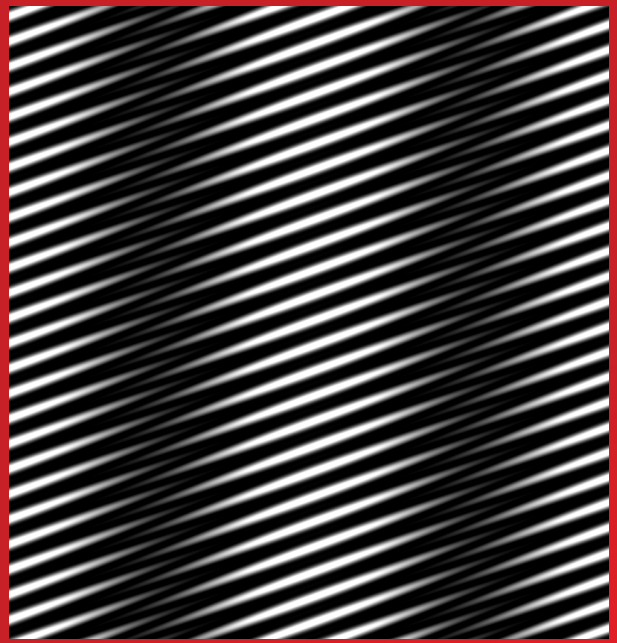
$\boldsymbol{\alpha}$: orientation angle
$\boldsymbol{p}$: pitch = distance between two consecutive slit centers

The STIX imaging concept

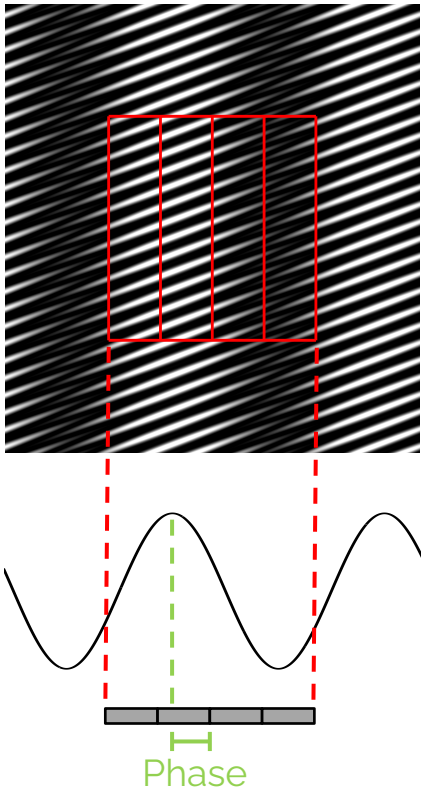
Front and rear grid have different orientation and pitch



The transmitted X-ray photon flux creates a **Moiré pattern**

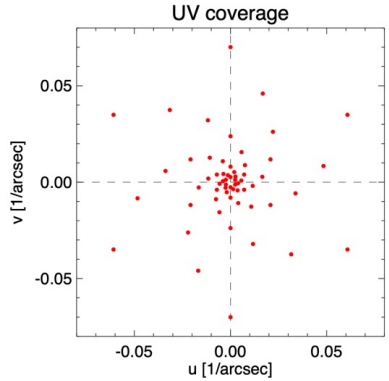


The STIX imaging concept



Amplitude and phase of the pattern corresponds to amplitude and phase of a visibility

The sampling frequencies are determined by the grids' pitch and orientation



Visibility amplitude and phase are derived from count measurements:

- $|V| \propto \sqrt{(C-A)^2 + (D-B)^2}$
- $\phi = \text{atan}\left(\frac{D-B}{C-A}\right) + 45° + \phi_{\text{calib}}$

Image reconstruction problem for STIX:

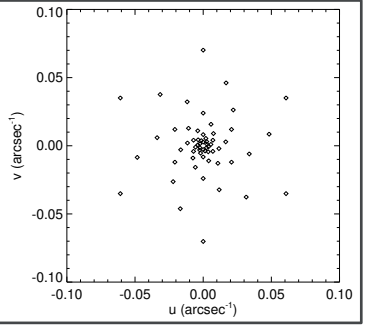
$$\boldsymbol{Fx = V}$$

- $\boldsymbol{F}$ is the Fourier transform computed in the STIX frequencies
- $\boldsymbol{V} = (V_1, \ldots, V_{30})$ is a complex array containing the visibility values

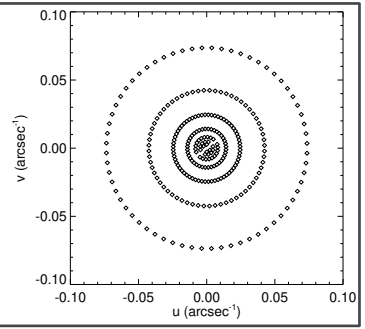
STIX vs RHESSI

RHESSI: Reuven Ramaty High Energy Solar Spectroscopic Imager (Lin et al., 2002)

STIX: 30 subcollimators, each one sampling a visibility through Moiré pattern technology



RHESSI: 9 rotating modulation collimators, each one sampling visibilities on a circle (~10^2 visibilities in total)



	STIX	RHESSI
Orbit	Around the Sun (up to 0.28 AU)	Around the Earth
Finest angular resolution	7.1 arcesc	2.3 arcsec
Time resolution	< 1 sec	~ 2 sec
Energy range	4-150 keV	3 keV to 17 MeV
Energy resolution	1 keV (below 16 keV)	1 keV at 3 keV
Image placement accuracy	4 arcsec	< 1 arcsec

Imaging methods

- Back-projection (Mertz et al., 1986)
- Clean (Högbom, 1974)
- MEM_GE (Massa et al., 2020)
- EM (Massa et al., 2019)
- VIS_FWDFIT (Volpara et al., in preparation)

+

Other methods in preparation:

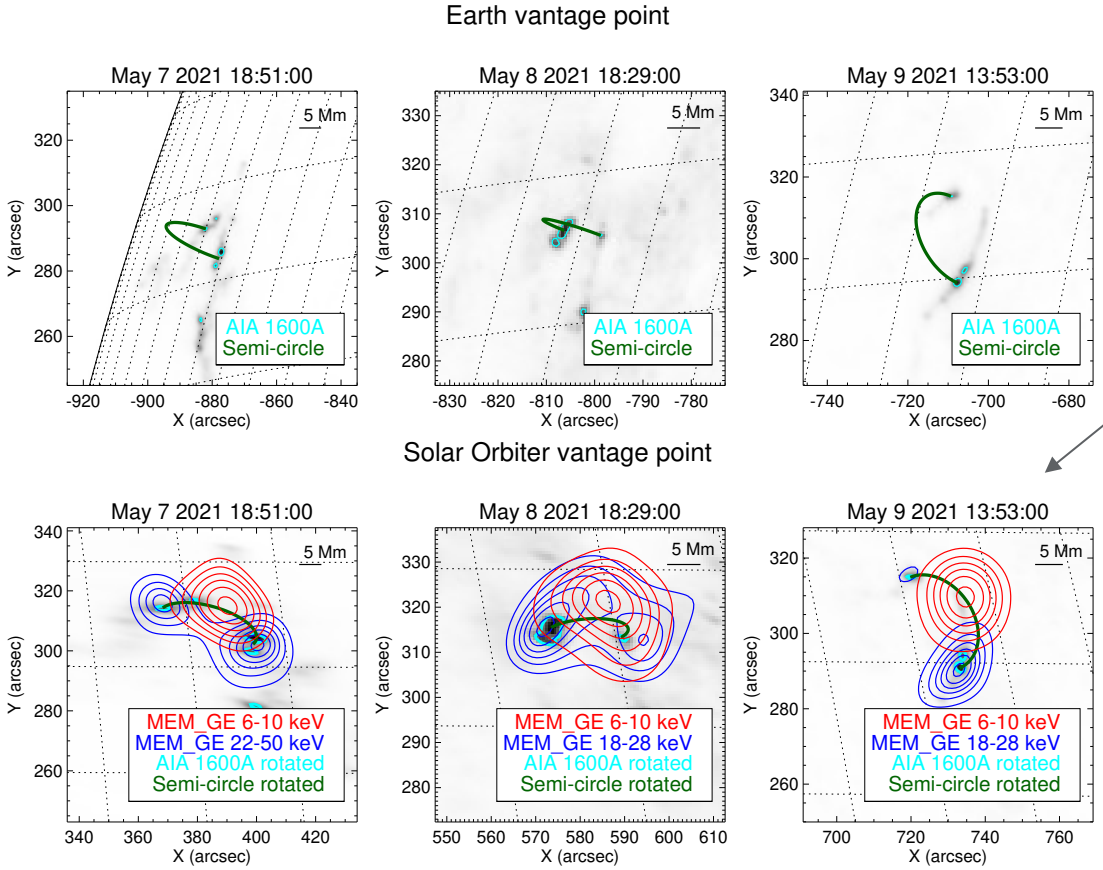
- UV_SMOOTH (Perracchione et al, 2021)
- Sequential Monte Carlo (SMC, Sciacchitano et al., 2018)
- …

- **The STIX imaging problem has no unique solution**
- Need to develop many different algorithms and compare their results

RHESSI legacy: we can use the same algorithms…

…but with caution!

First imaging results (Massa et al., 2022)



Active region AR2822

- May 7: GOES M3.9
- May 8: GOES C8.6
- May 9: GOES C4.0

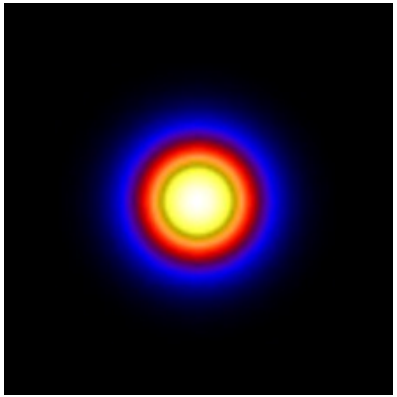
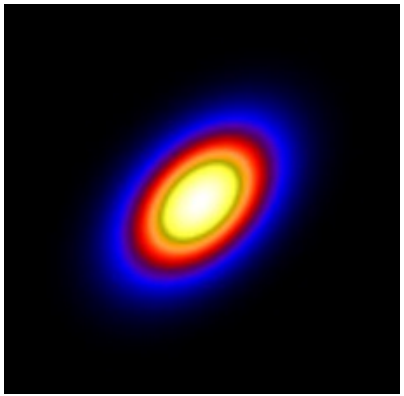
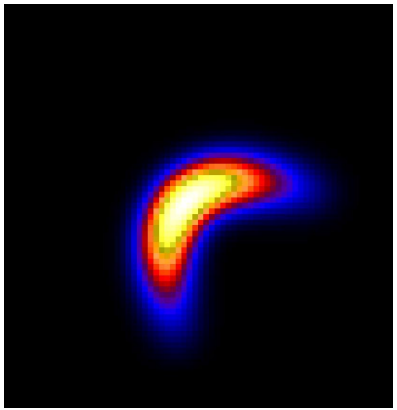
Reprojected AIA images: see Battaglia et al, 2021, for details

Manual shift STIX reconstructions

Event	Δx (arcsec)	Δy (arcsec)
May 7	44	54
May 8	45	57
May 9	47.5	53

VIS_FWDFIT_PSO (Volpara et al., 2022)

- Parametric imaging
- Choose a parametric shape ϕ_θ among

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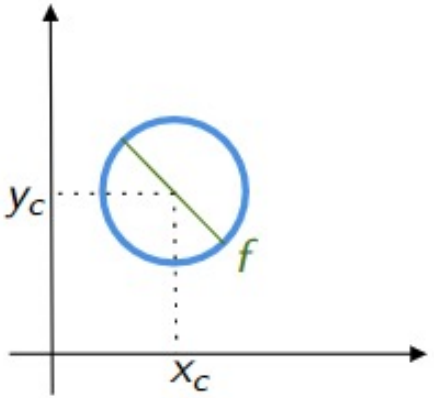

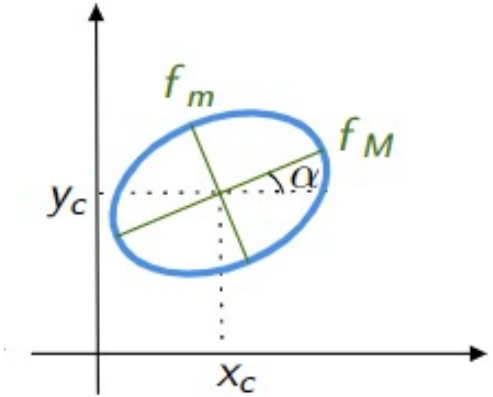

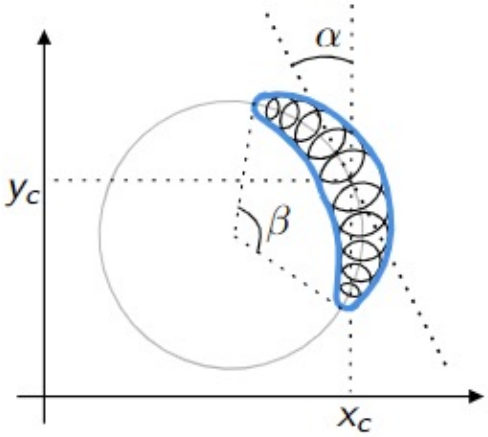

VIS_FWDFIT_PSO (Volpara et al., 2022)

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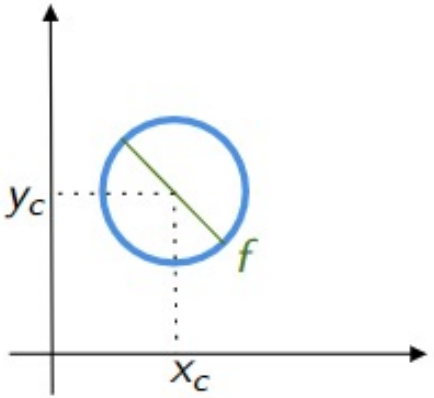
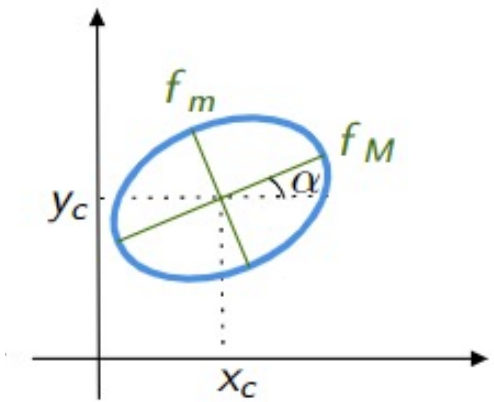
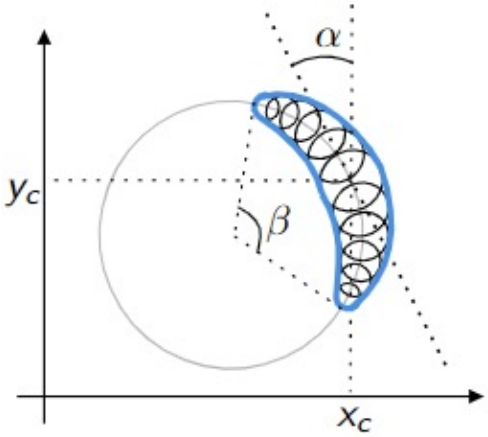




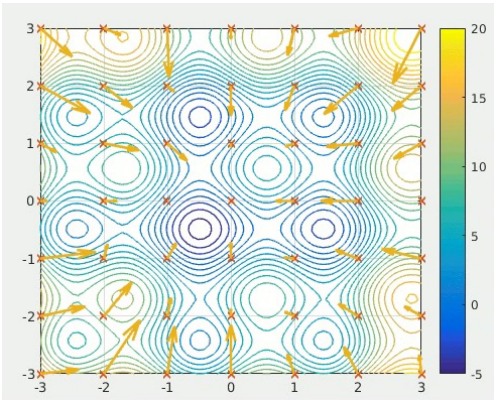


- Solve

$$\theta^* = \underset{\theta}{\operatorname{argmin}} \frac{1}{N_V - N_{\phi_\theta}} \sum_i \frac{|(F\phi_\theta)_i - V_i|^2}{\sigma_i^2}$$

VIS_FWDFIT_PSO (Volpara et al., 2022)

- RHESSI implementation relies on a simplex method for the optimization of parameters
- Sometimes it provides unreliable results with multiple source configuration or with sources not in the center of the FOV
- **New implementation based on Particle Swarm Optimization (PSO)**: stochastic optimization methods inspired by intelligent cooperative behaviour of flocks of birds or schools of fish



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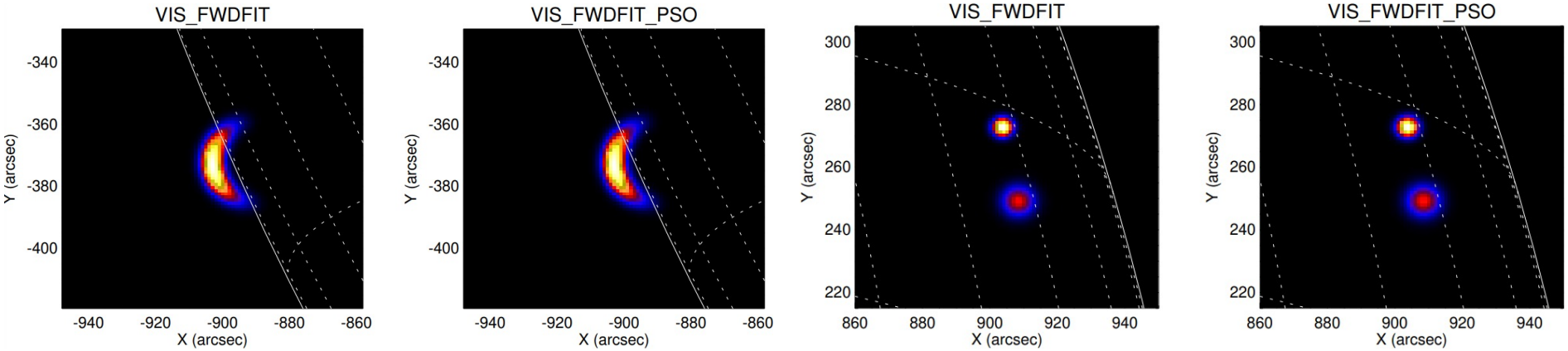
VIS_FWDFIT_PSO (Volpara et al., 2022)

Same results when applied to RHESSI data



February 13, 2002 event

February 20, 2002 event

VIS_FWDFIT_PSO (Volpara et al., 2022)

More robust in the case of STIX data
Test: change FOV center

March 2, 2022 event

Conclusions

We have:

- described the STIX instrument and the STIX imaging concept
- compared the STIX imaging capabilities to the RHESSI ones
- described a new implementation of the forward-fitting method, showing an improvement w.r.t. the RHESSI implementation

The IDL version of the STIX imaging pipeline is ready
(and the Python version will be ready soon)

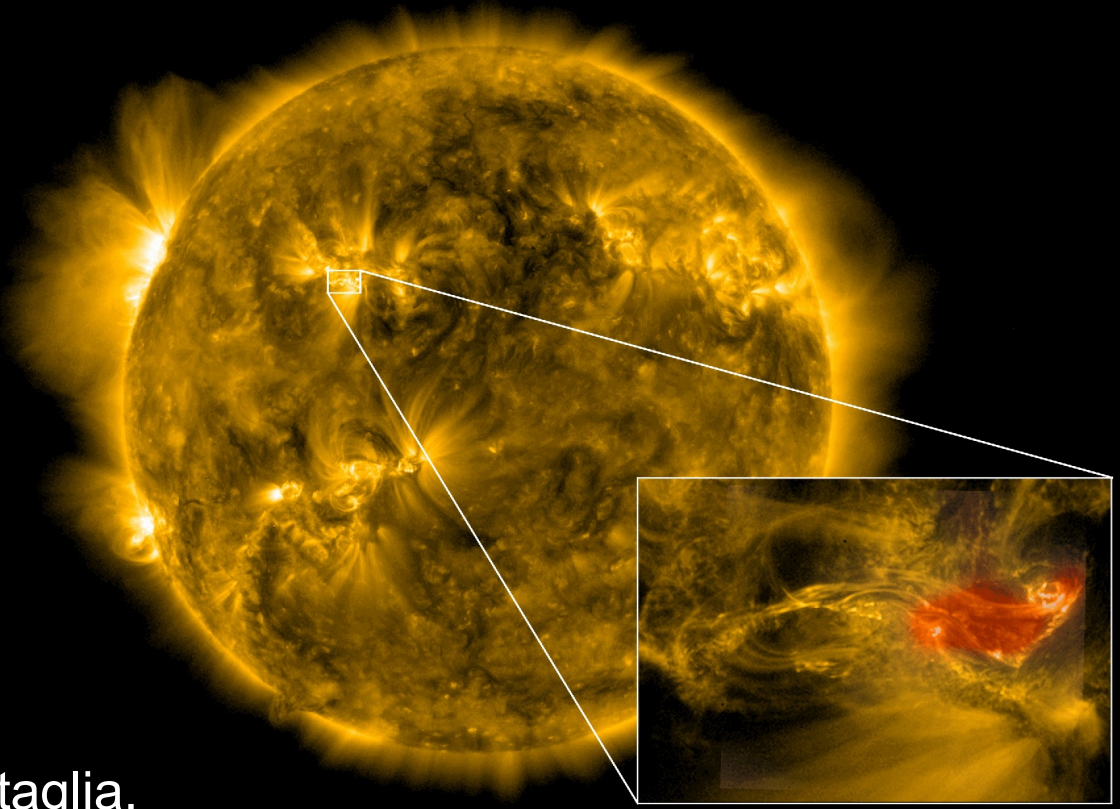
Update SSWIDL and try out a demo at stix/idl/demo/demo_imaging.pro !

If you have problems, contact us or open as issue on the STIX Ground Software GitHub Page (https://github.com/i4Ds/STIX-GSW)

References

- Battaglia et al., *STIX X-ray microflare observations during the Solar Orbiter commissioning phase*, A&A, 2021
- Högbom, *Aperture synthesis with a non-regular distribution of interferometer baselines*, Astronomy and Astrophysics Supplement, 1974
- Hurford et al, *The RHESSI imaging concept*, Solar Physics, 2002
- Krucker et al., *The Spectrometer/Telescope for Imaging X-rays (STIX),* A&A, 2020
- Lin et al. , *The Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI)*, Solar Physics, 2002
- Massa et al., *Count-based imaging model for the Spectrometer/Telescope for Imaging X-rays (STIX) in Solar Orbiter*, A&A, 2019
- Massa et al., *MEM_GE: A New Maximum Entropy Method for Image Reconstruction from Solar X-Ray Visibilities*, APJ, 2020
- Massa et al., *Imaging from STIX visibility amplitudes*, A&A, 2021
- Massa et al., *First hard X-ray imaging results by Solar Orbiter STIX*, accepted for publication in Solar Physics, 2022
- Mertz et al., *Rotational aperture synthesis for x rays*, JOSA A, 1986
- Meuris et al., *Caliste-SO, a CdTe based spectrometer for bright solar event observations in hard X-rays*, Nucl. Instrum. Methods Phys. Res. A, 2015
- Perracchione et al., *Visibility Interpolation in Solar Hard X-Ray Imaging: Application to RHESSI and STIX*, ApJ, 2021
- *Sciacchitano et al ., Identification of Multiple Hard X-Ray Sources in Solar Flares: A Bayesian Analysis of the 2002 February 20 Event, ApJ, 2018*
- *Volpara et al., Forward-fitting STIX visibilities, submitted to A&A*

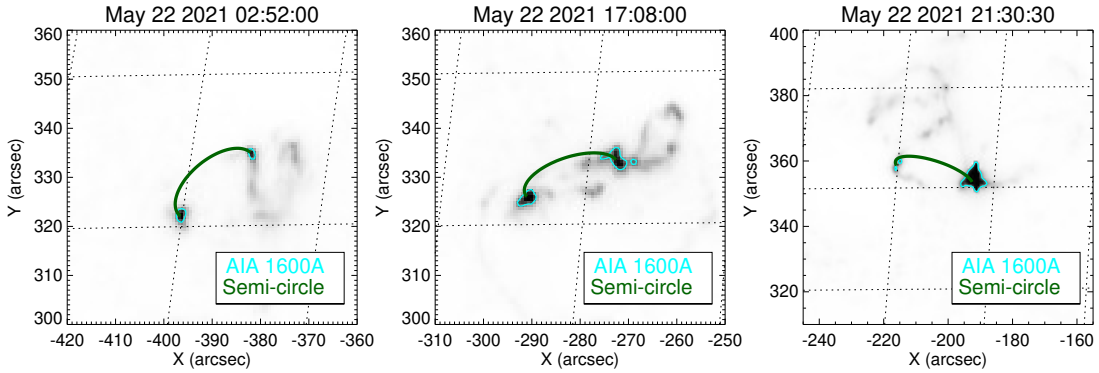
Thank you for the attention!



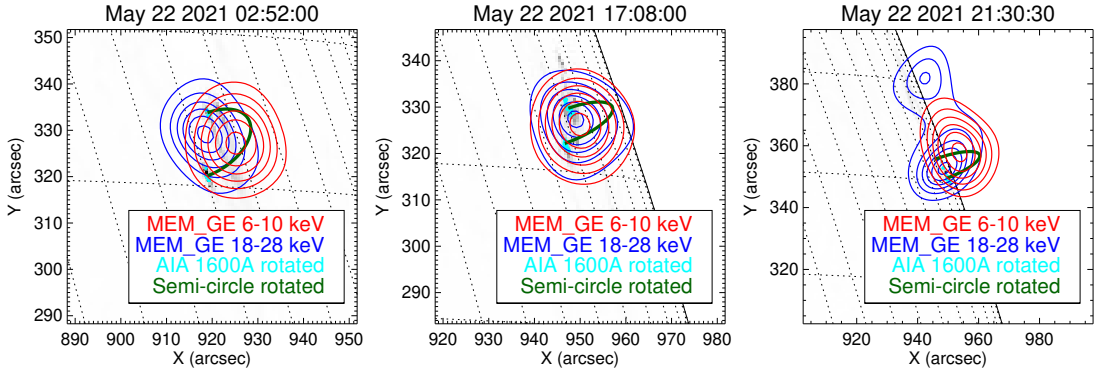
Andrea Battaglia,
FHNW/ETH

First imaging results (Massa et al., 2022)

Earth vantage point



Solar Orbiter vantage point



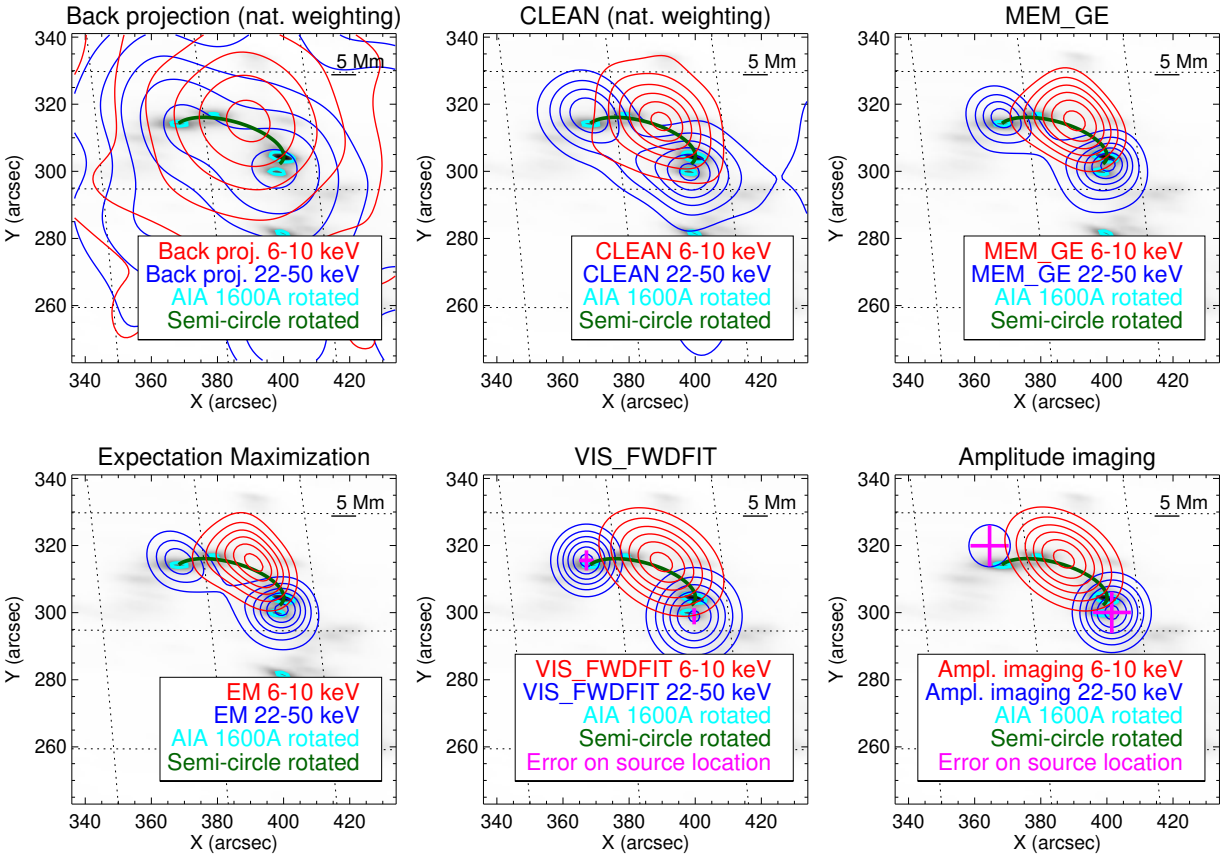
Active region AR2824

- 02:52:00 UT: GOES C6.1
- 17:08:00 UT: GOES M1.1
- 21:30:30 UT: GOES M1.4

Manual shift STIX reconstructions

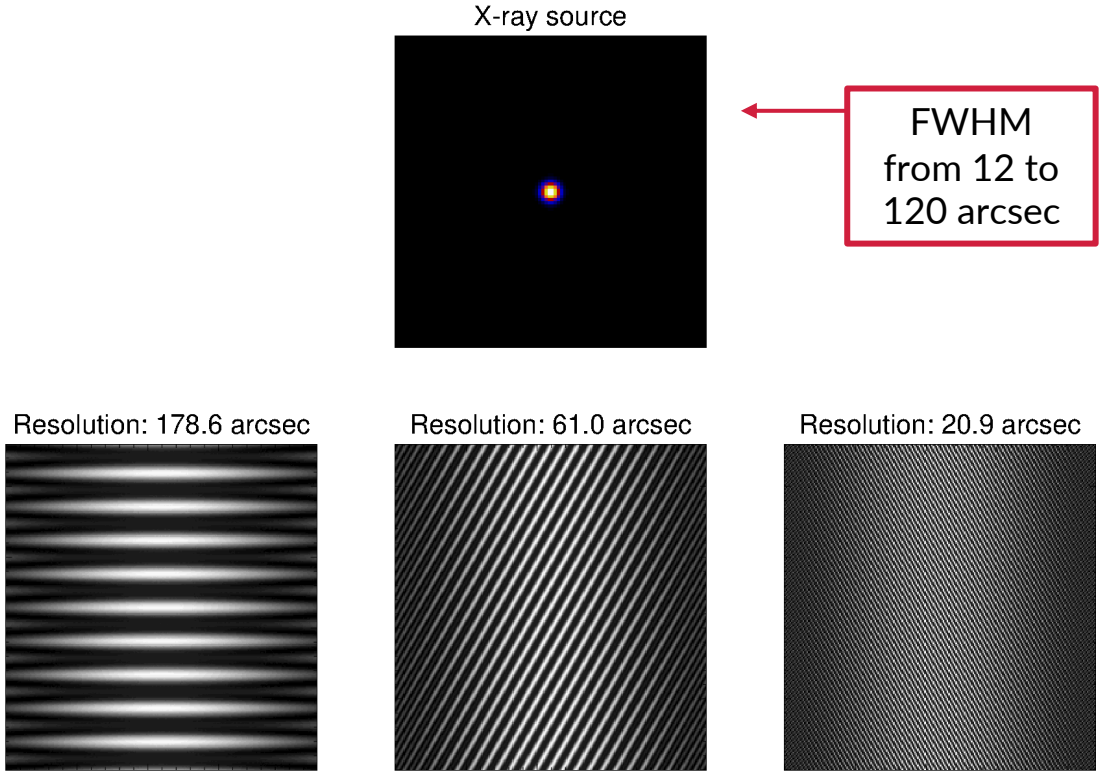
Event	Δx (arcsec)	Δy (arcsec)
02:52	47	55
17:08	47	50
21:30	50	50

First imaging results (Massa et al., 2022)



The STIX imaging concept

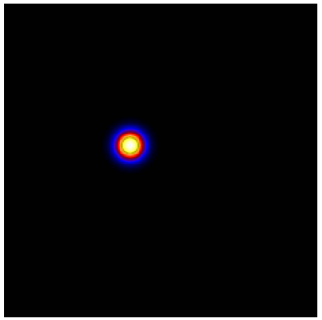
The amplitude of a Moiré pattern is sensitive to the source size



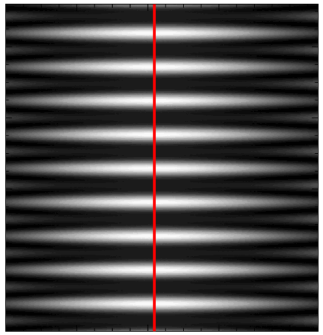
The STIX imaging concept

The phase of a Moiré pattern is sensitive to the source location

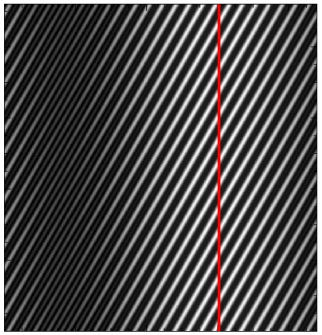
X-ray source



Resolution: 178.6 arcsec



Resolution: 61.0 arcsec



Resolution: 20.9 arcsec