Hard X-ray imaging of solar flares by Solar Orbiter STIX

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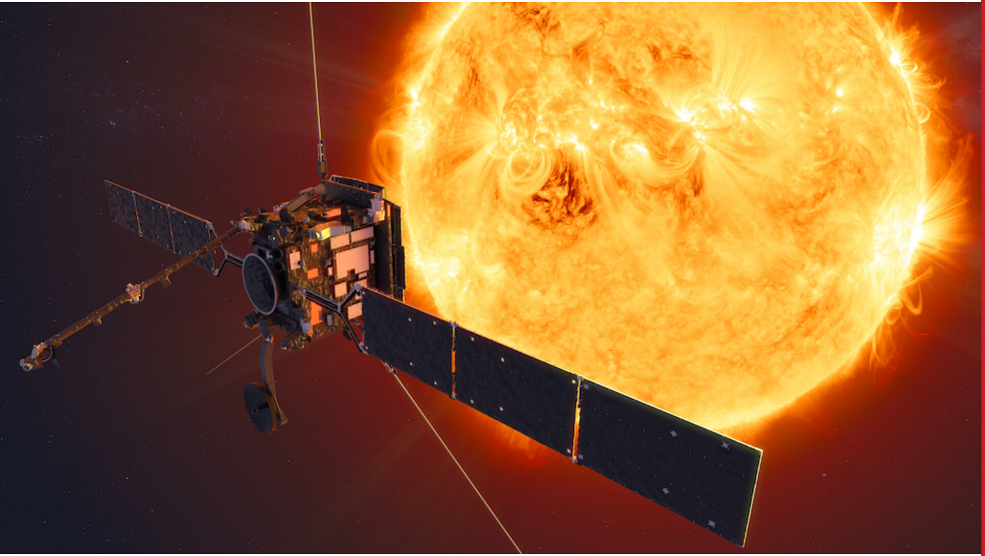
Outline

- The STIX imaging concept
- Overview of the methods for image reconstruction from STIX data
- Results
- Conclusions

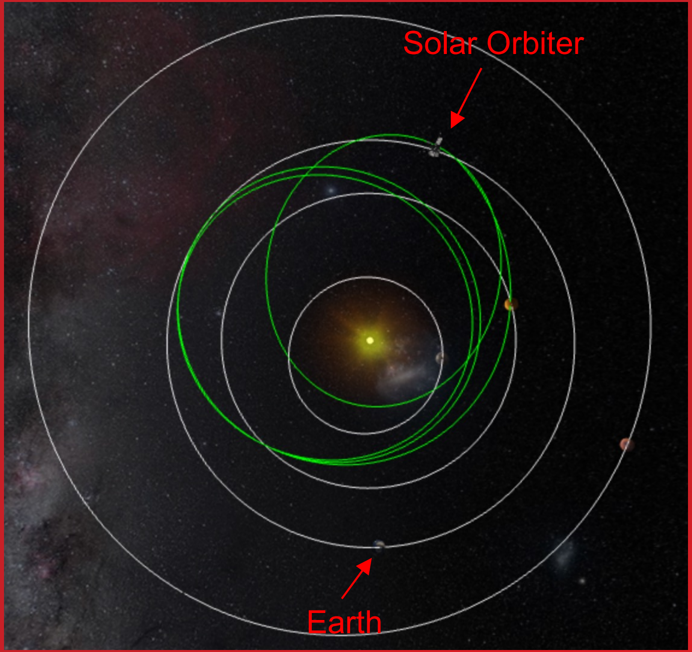
The STIX imaging concept

STIX in Solar Orbiter



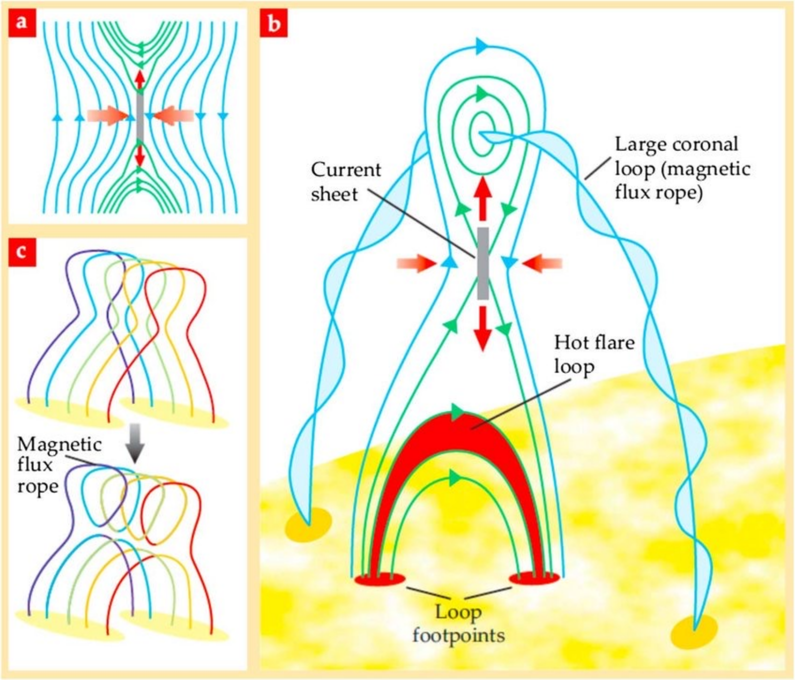
credits: ESA website

Solar Orbiter trajectory



https://solarorbiter.esac.esa.int/where/

The STIX instrument



STIX: Spectrometer/Telescope for Imaging X-rays

Scientific goal: provide information on electrons accelerated during a solar flare and on the plasma temperature

How: by measuring X-ray photons emitted by bremsstrahlung

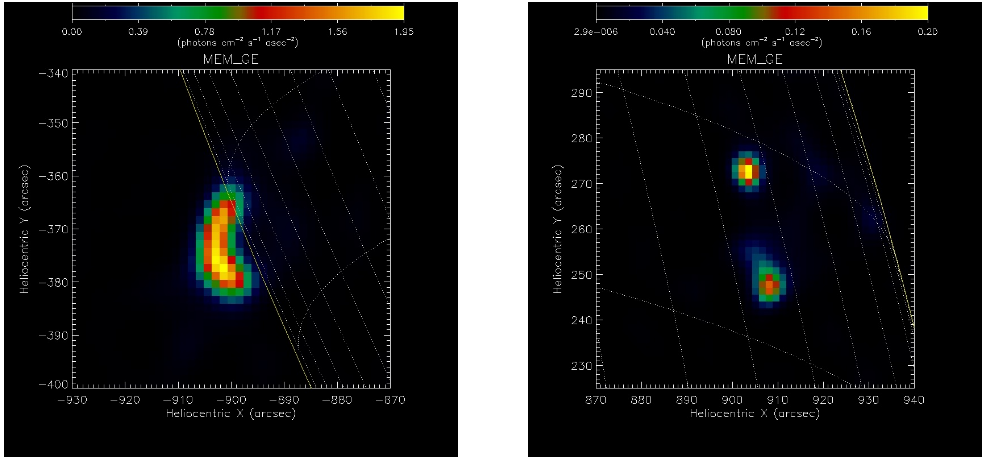
The STIX instrument

STIX imaging objective:

reconstruct the image of the flaring X-ray emission form <u>indirect measurements</u>

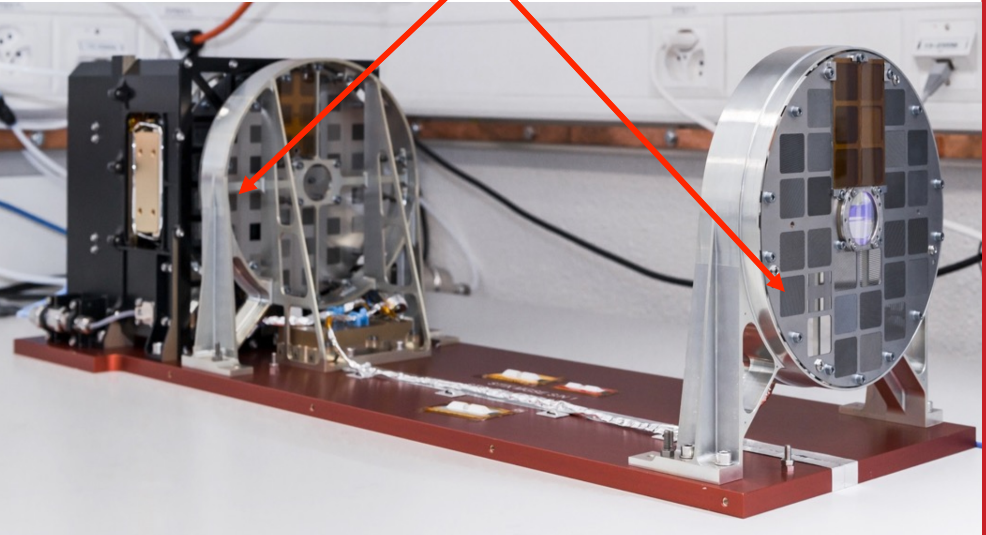
Fourier components of the angular distribution of the X-ray source

Examples from RHESSI data (Lin et al., 2002)



The STIX instrument

Subcollimator = front grid + rear grid + detector

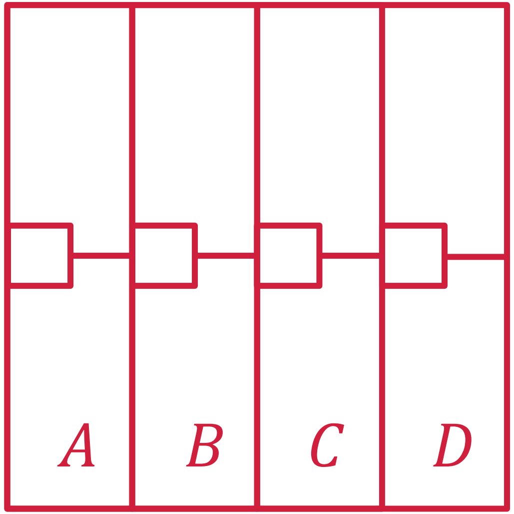


Bigrid imaging system

STIX consists of 32 subcollimators:

- 30 are used for imaging
- Coarse Flare Locator
- Background monitor

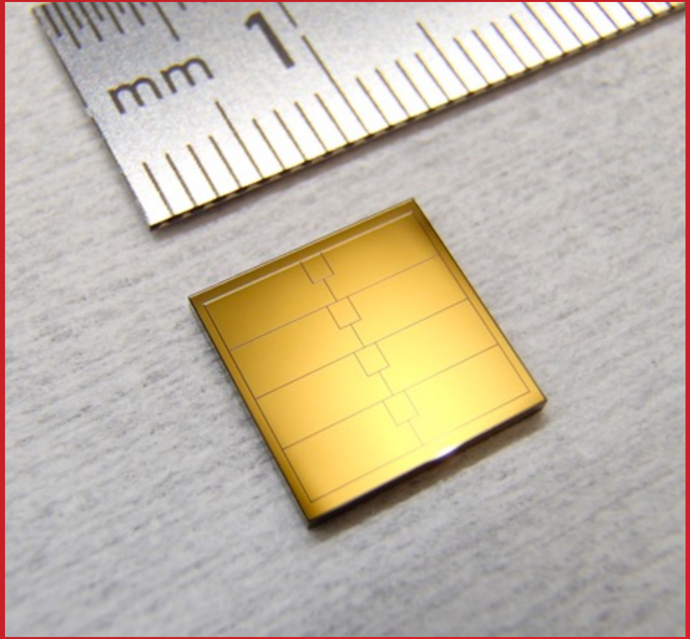
The STIX instrument



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

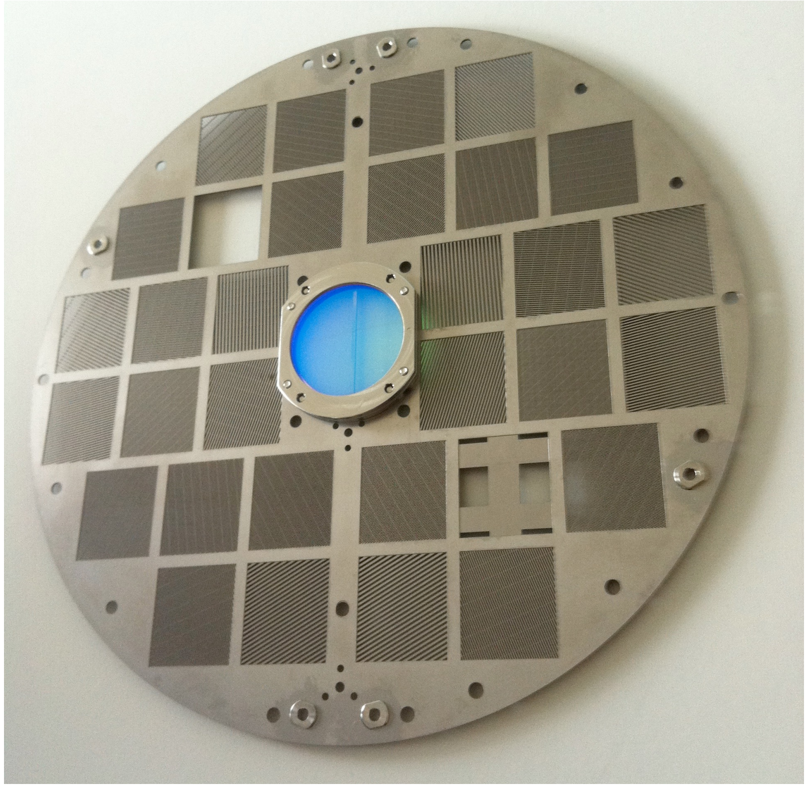
STIX Cadmium-Telluride detector

(Meuris et al. 2015)



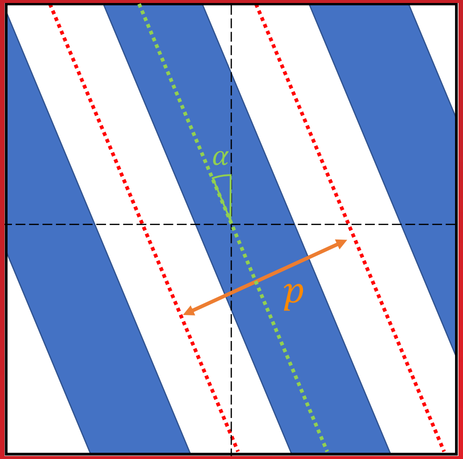
Krucker et al., 2020

The STIX instrument



Grid parameters:

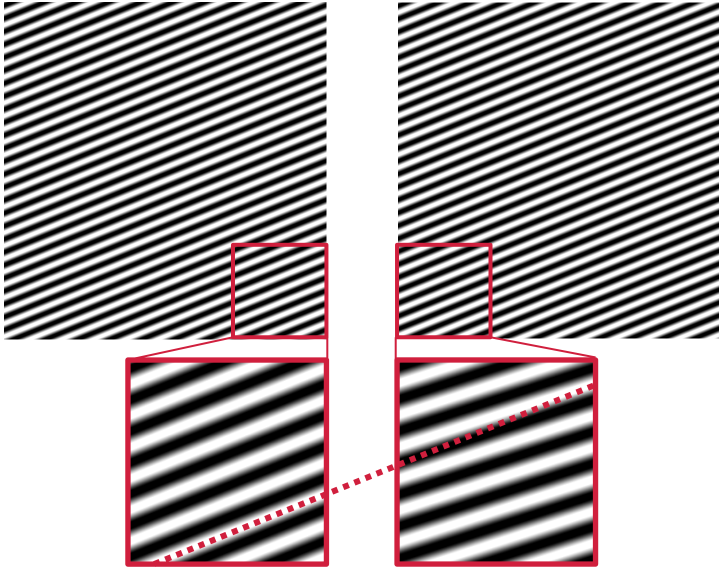
- α: orientation angle
- p: pitch = distance between two consecutive slit centers



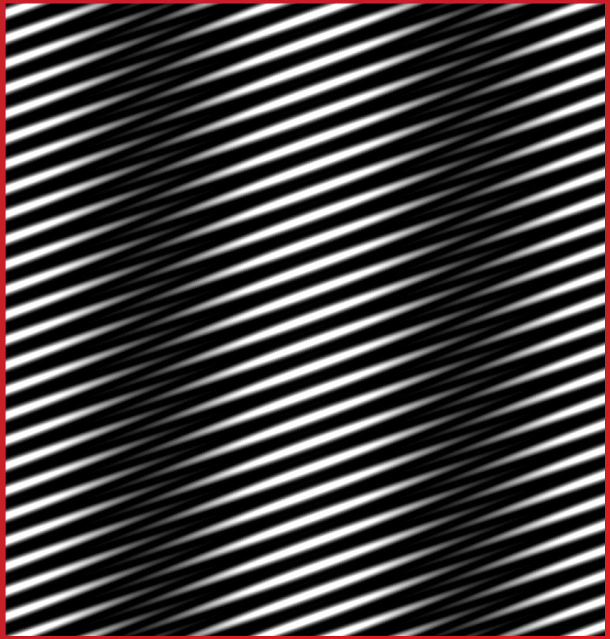
The STIX imaging concept

Front and rear grid have different orientation and pitch

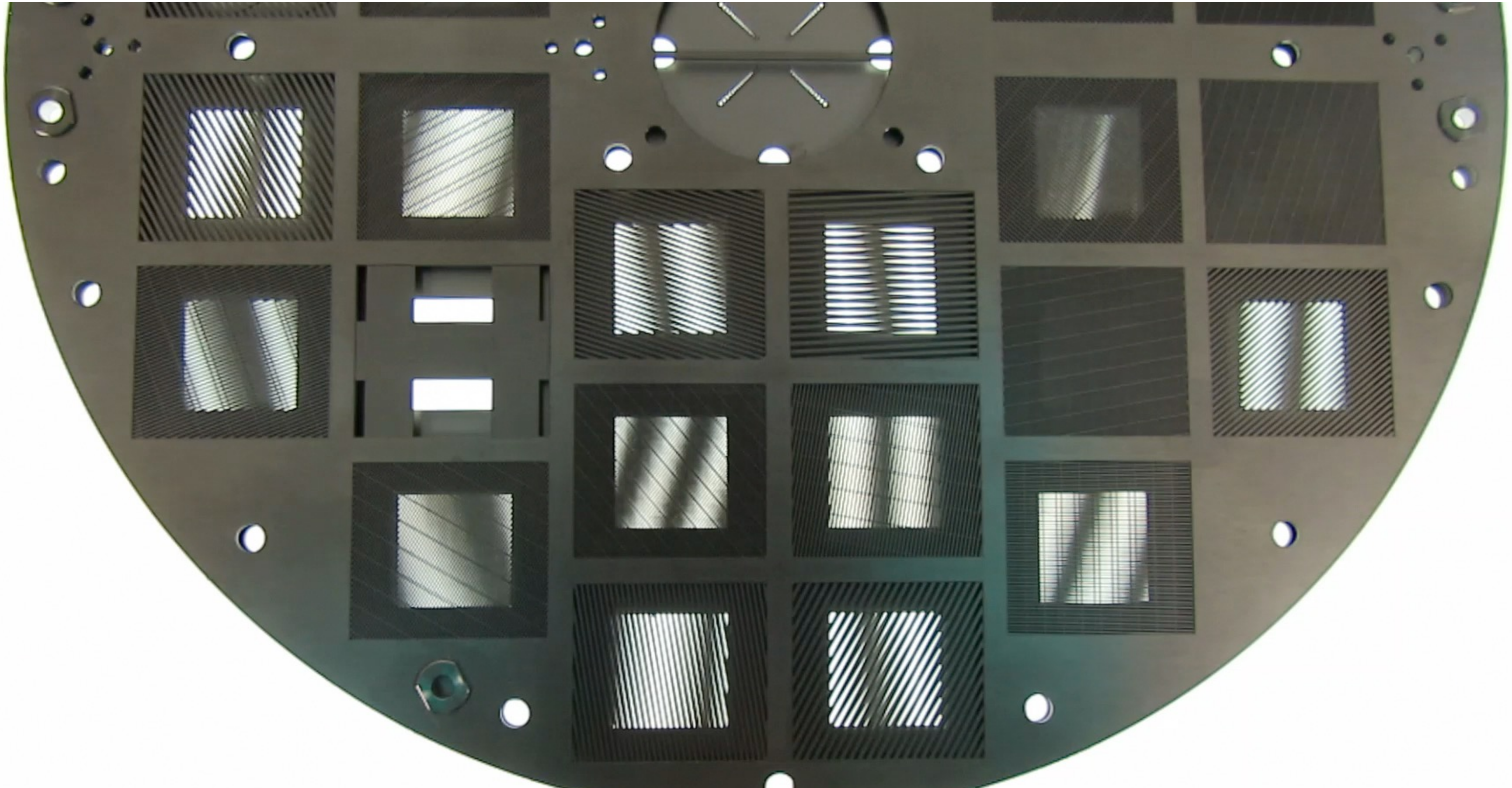
Front grid Rear grid



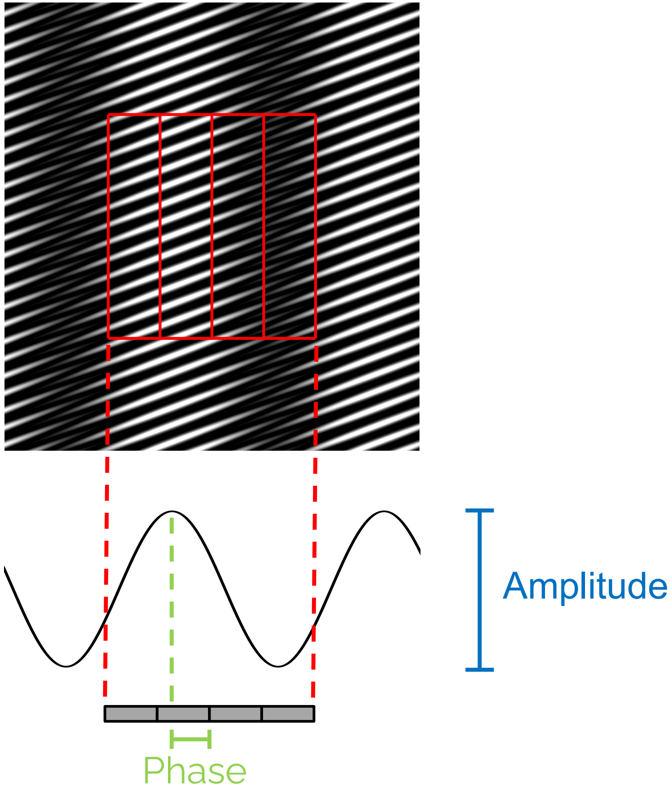
The transmitted X-ray photon flux creates a **Moiré pattern**



The STIX imaging concept



The STIX imaging concept



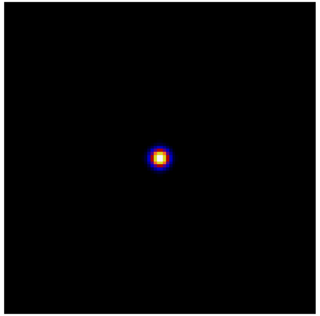
Moiré patterns have:

- period equal to the detector width
- orientation perpendicular to the pixels stripes
- amplitude sensitive to the size of the X-ray source
- phase sensitive to the X-ray source location

The STIX imaging concept

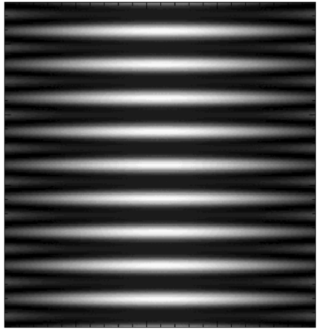
The amplitude of a Moiré pattern is sensitive to the source size

X-ray source

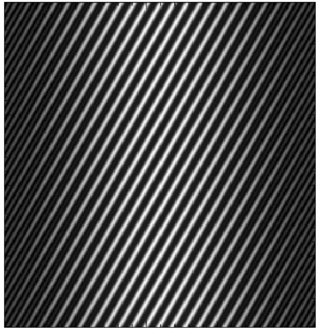


FWHM
from 12 to
120 arcsec

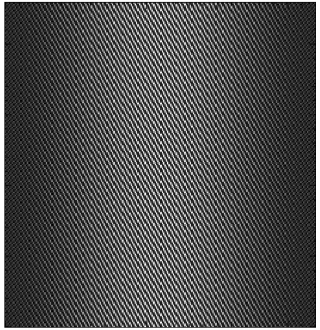
Resolution: 178.6 arcsec



Resolution: 61.0 arcsec

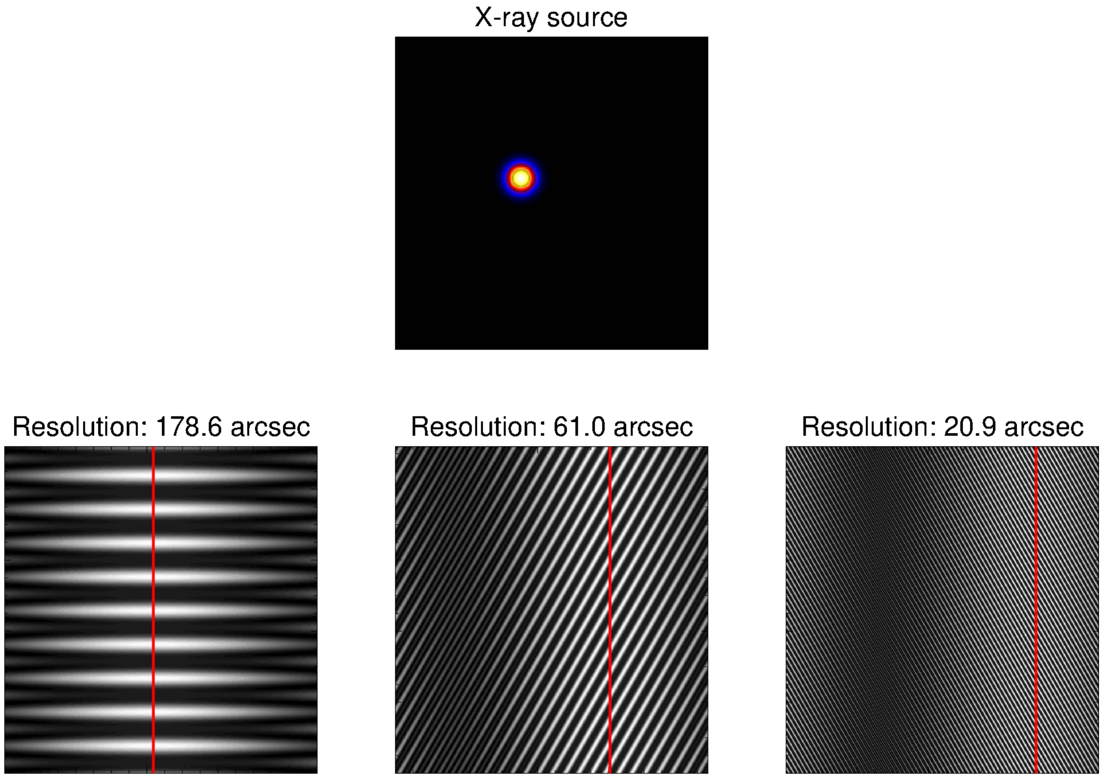


Resolution: 20.9 arcsec

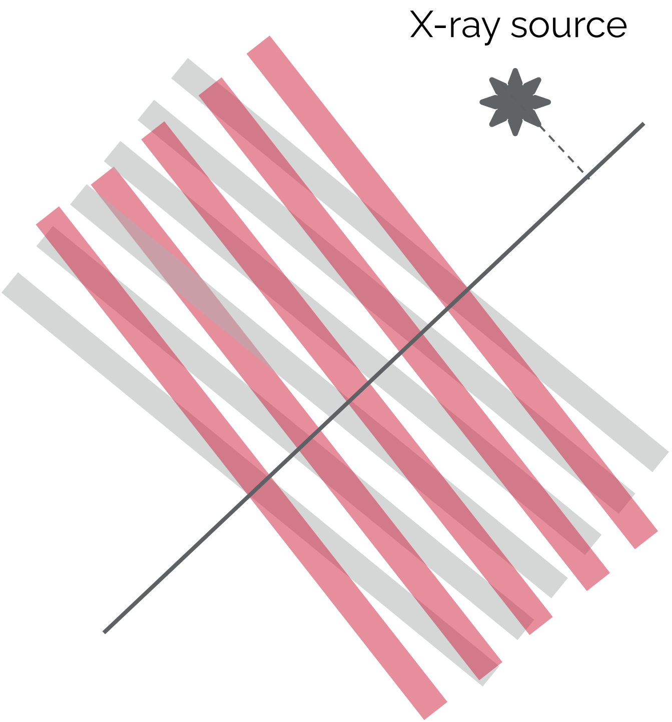


The STIX imaging concept

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



The STIX imaging concept



Moiré patterns in a nutshell:

- sensitive to specific directions (grids' orientation, phase)
- sensitive to specific source sizes (grids' pitch, amplitude)

Each pattern contains information on a bi-dimensional Fourier component **(visibility)** of the hard X-ray flaring source

The STIX imaging concept

$\phi(x, y)$ represents the intensity of the X-ray radiation emitted from (x, y) on the Sun disk

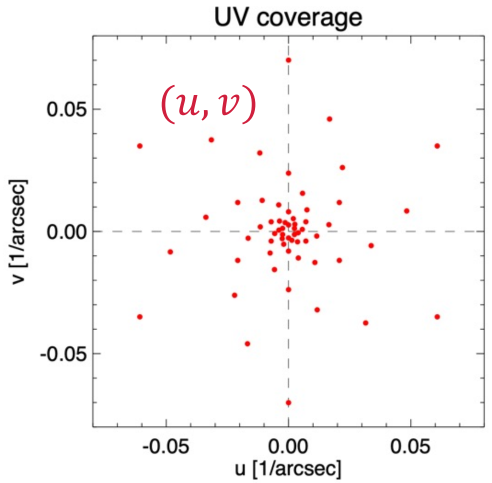
Data measured by STIX: $\mathbf{V} = (V_1, \ldots, V_{30})$, where

$$\boxed{V} = \iint \phi(x, y) \exp(2\pi i(x\boxed{u} + y\boxed{v}))\, dx\, dy$$

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

Determined by count measurements

Krucker et al., 2020



Determined by grids' pitch and orientation

The STIX imaging concept

$\phi(x, y)$ represents the intensity of the X-ray radiation emitted from (x, y) on the Sun disk

Data measured by STIX: $\mathbf{V} = (V_1, \dots, V_{30})$, where

$$V = \iint \phi(x, y) \exp(2\pi i (xu + yv)) \, dx \, dy$$

Image reconstruction problem for STIX: determine ϕ s.t.

$$\boldsymbol{F}\boldsymbol{\phi} = \boldsymbol{V}$$

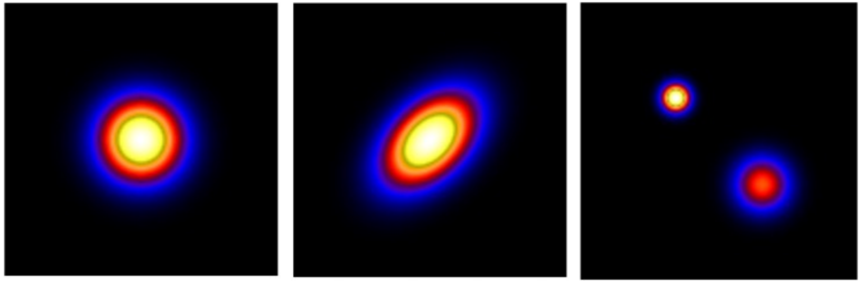
where $\boldsymbol{F}$ is the Fourier transform computed in the STIX frequencies

Imaging methods

Amplitude imaging

(Massa et al., 2021)

Choose a parametric shape ϕ_θ among



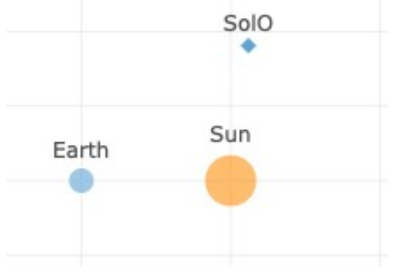
and solve

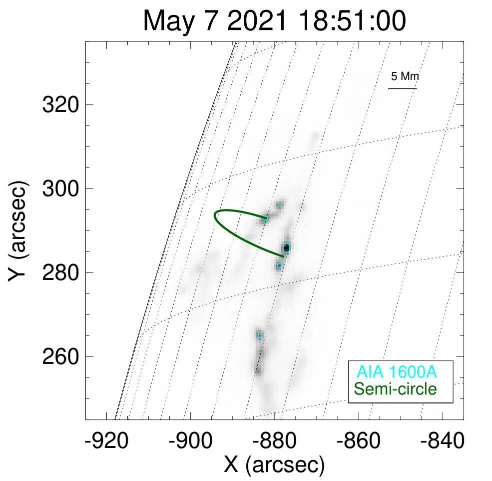
$$\theta^* = \underset{\theta}{\operatorname{argmin}} \sum_i \frac{(|(F\phi_\theta)_i| - |V_i|)^2}{\sigma_i^2}$$

- First attempt to image reconstruction from STIX data
- Solve: $|\boldsymbol{F}\boldsymbol{\phi}| = |\mathbf{V}|$
- Visibility amplitudes
  - Contain information on the source dimension and morphology
  - Do not contain information on the source location
- Parametric approach

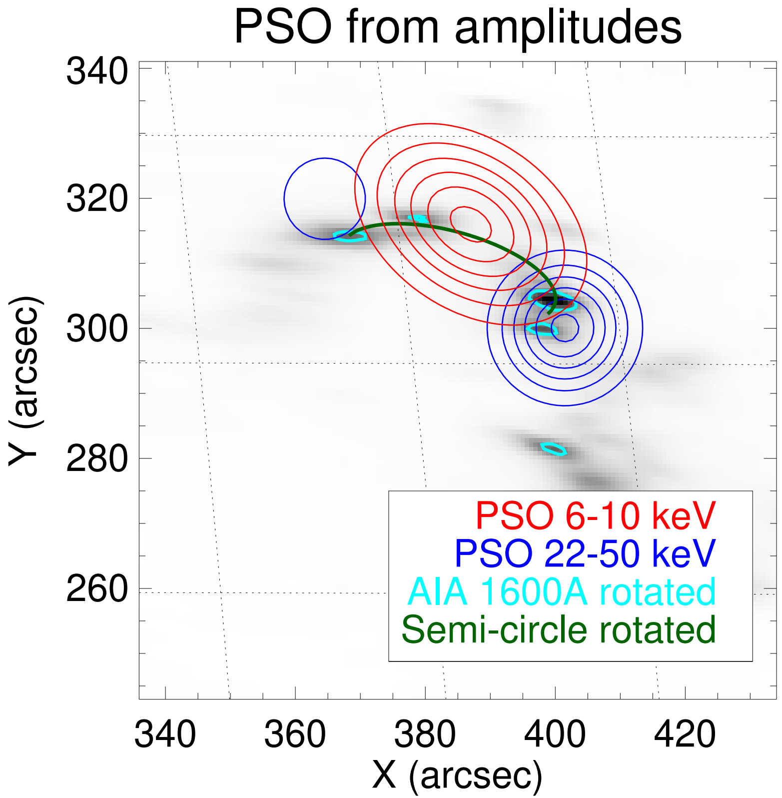
Amplitude imaging (Massa et al., 2021)

May 7 2021 event





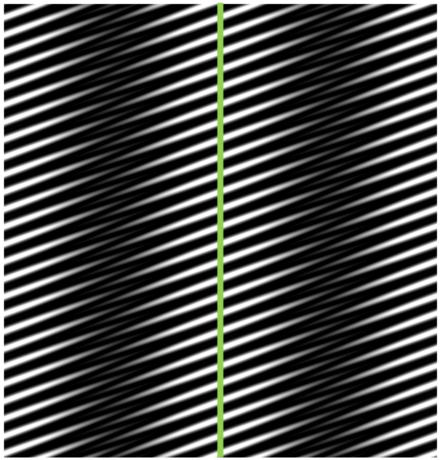
Reprojected AIA map (see Battaglia et al, 2021)

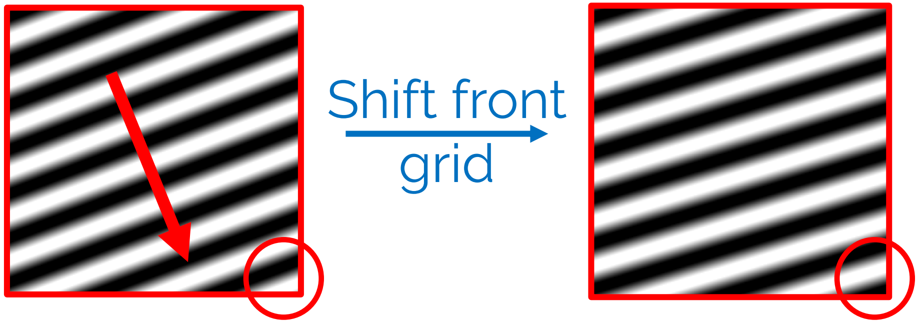


Visibility phase calibration

- Determine the correction factor ϕ_{calib} in $\phi = \operatorname{atan}\left(\frac{D-B}{C-A}\right) + 45° + \phi_{\text{calib}}$
- Check for potential instrument deformations

ϕ_{calib} is determined by the relative position of front and rear grid





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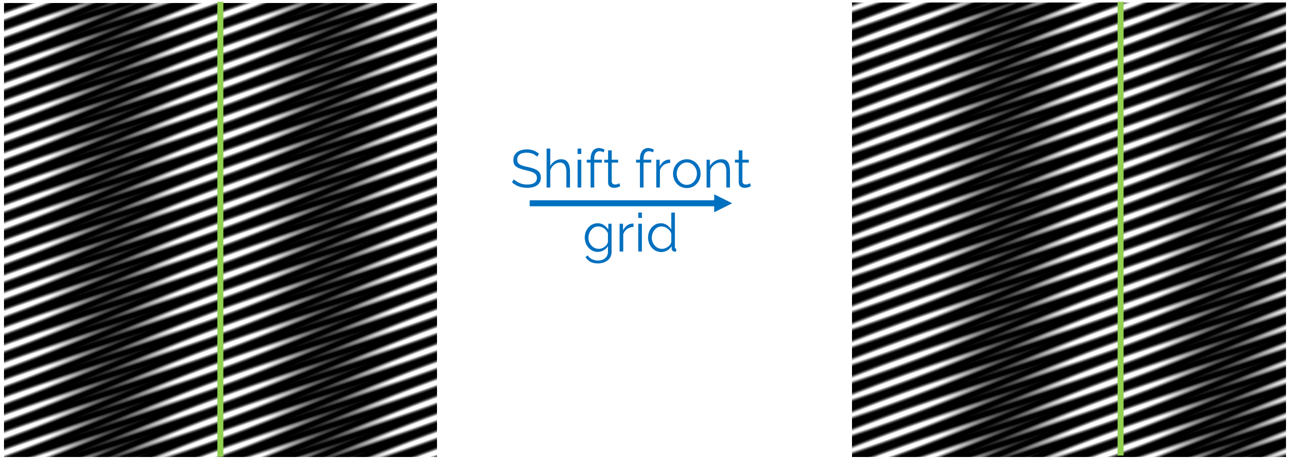

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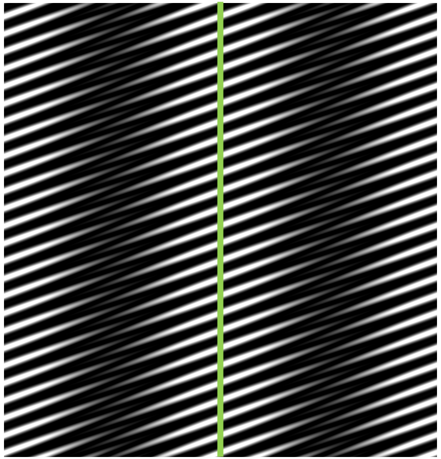
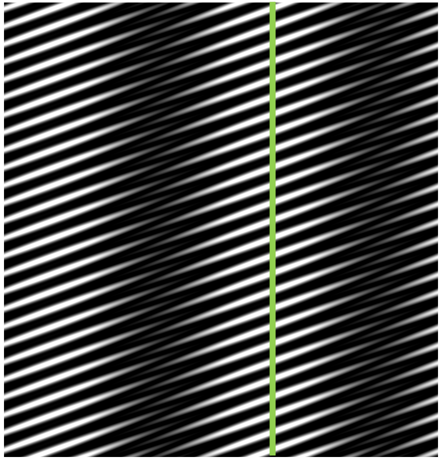


Shift front grid



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)

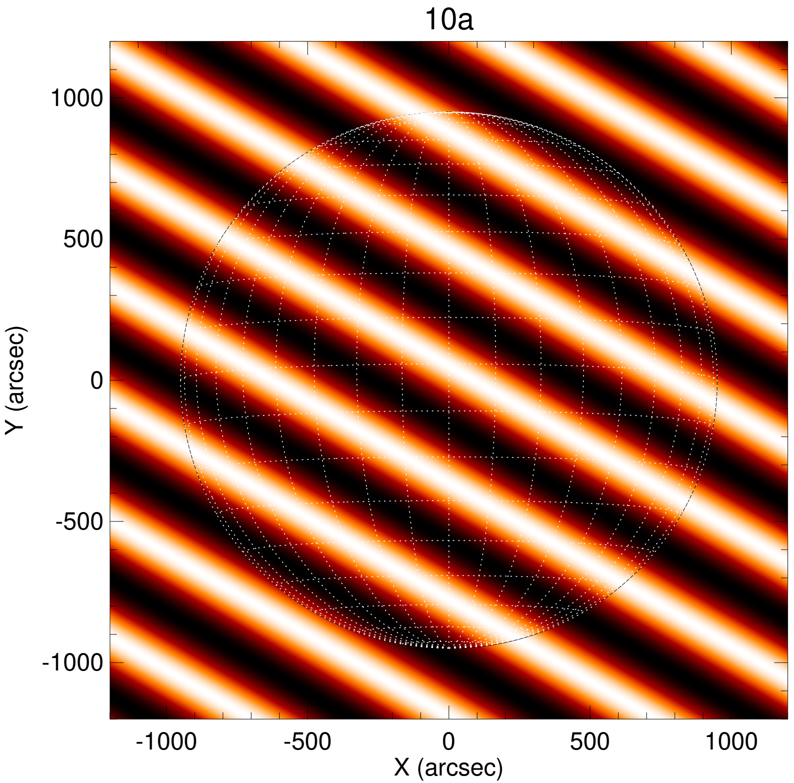
+

Other methods in preparation:

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

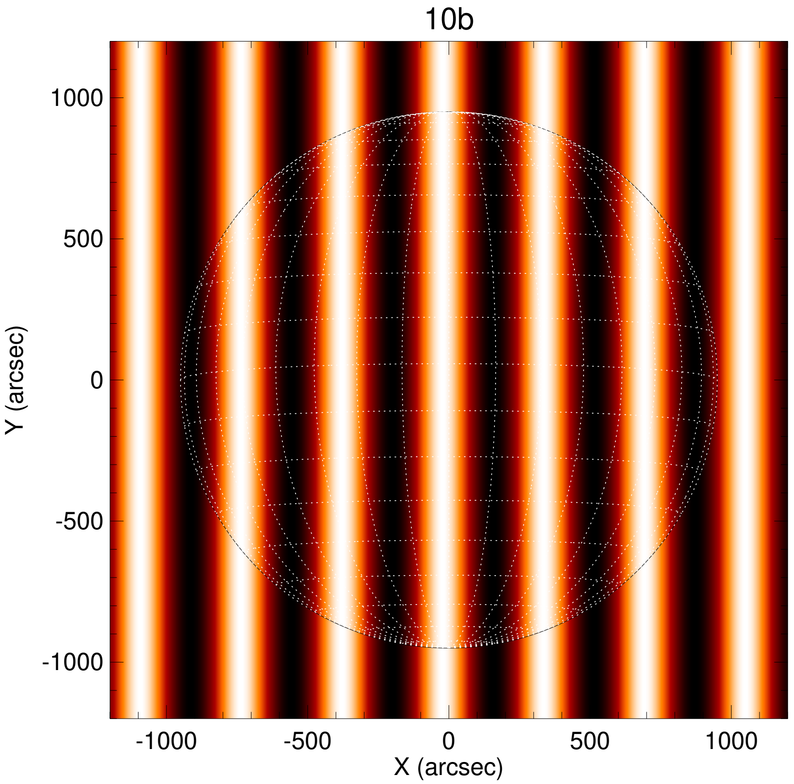
- **The STIX imaging problem has no unique solution**
- Need to develop many different algorithms and compare their results
- RHESSI legacy: we can use the same algorithms

Back-projection



- Direct Fourier inversion
- Basic idea: the back-projection of a single visibility is a sinusoidal wave

Back-projection



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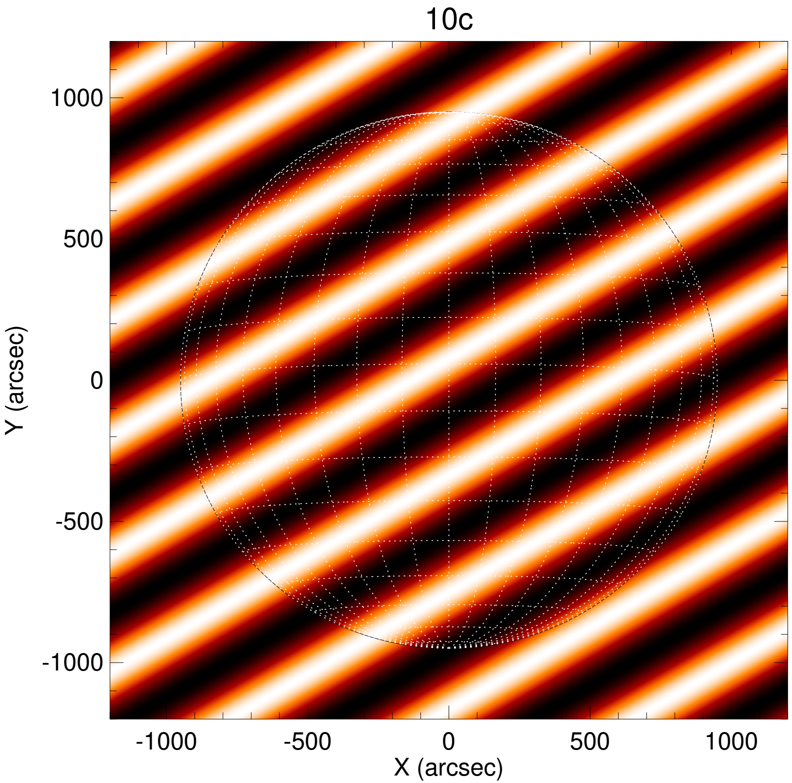
Back-projection



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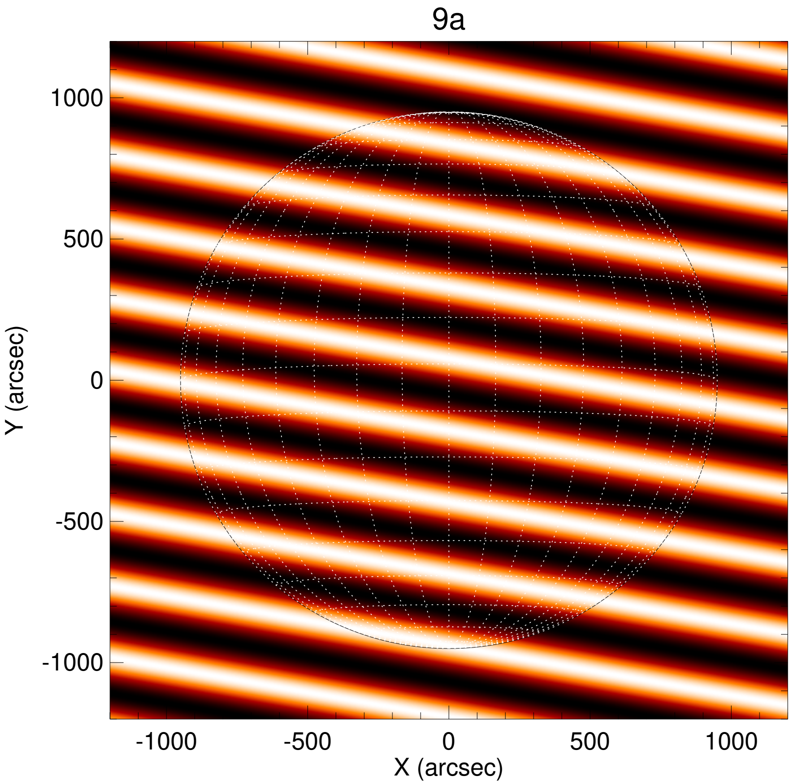
Back-projection



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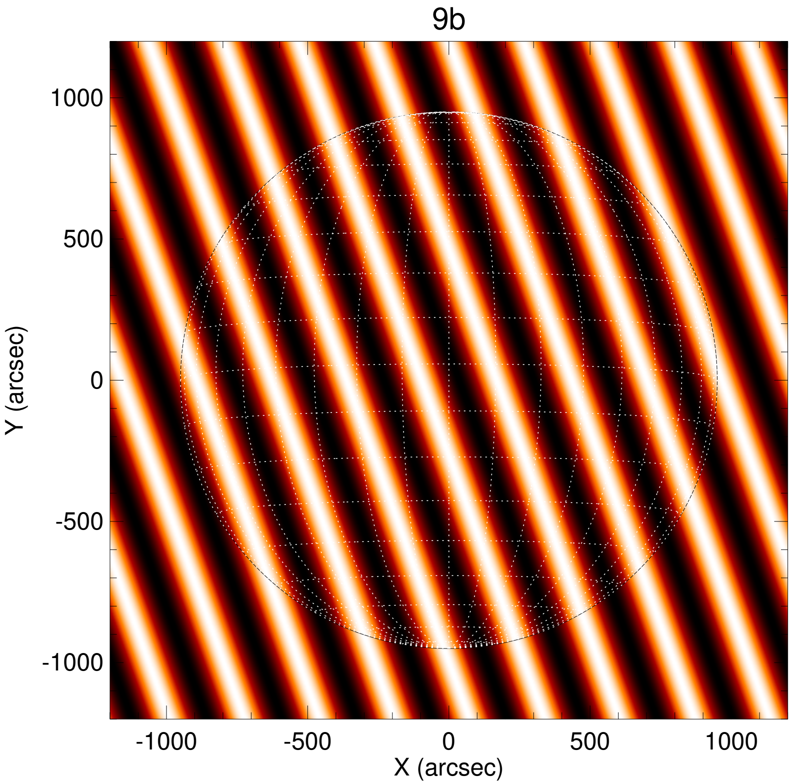

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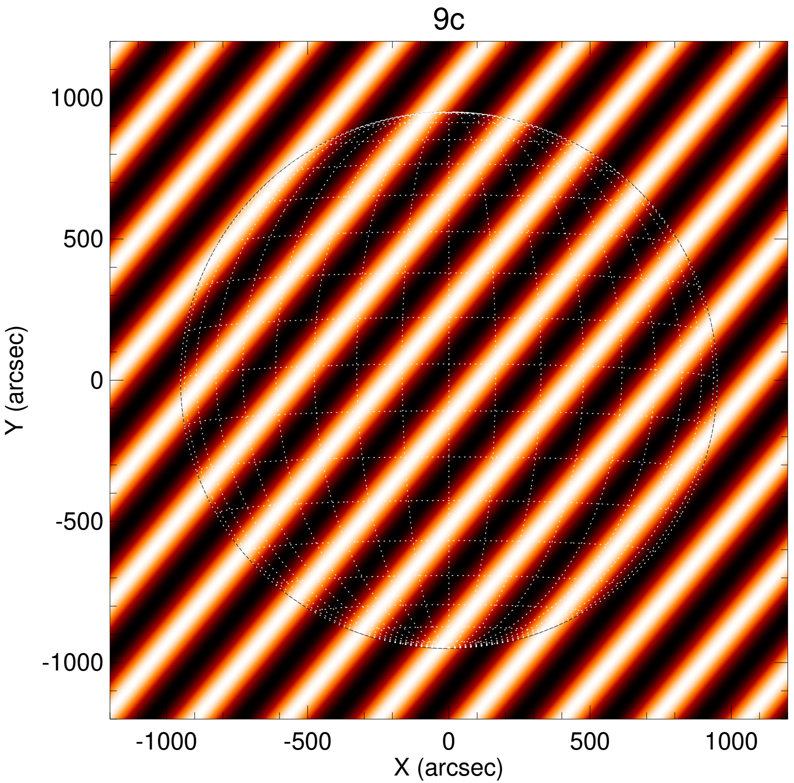
Back-projection



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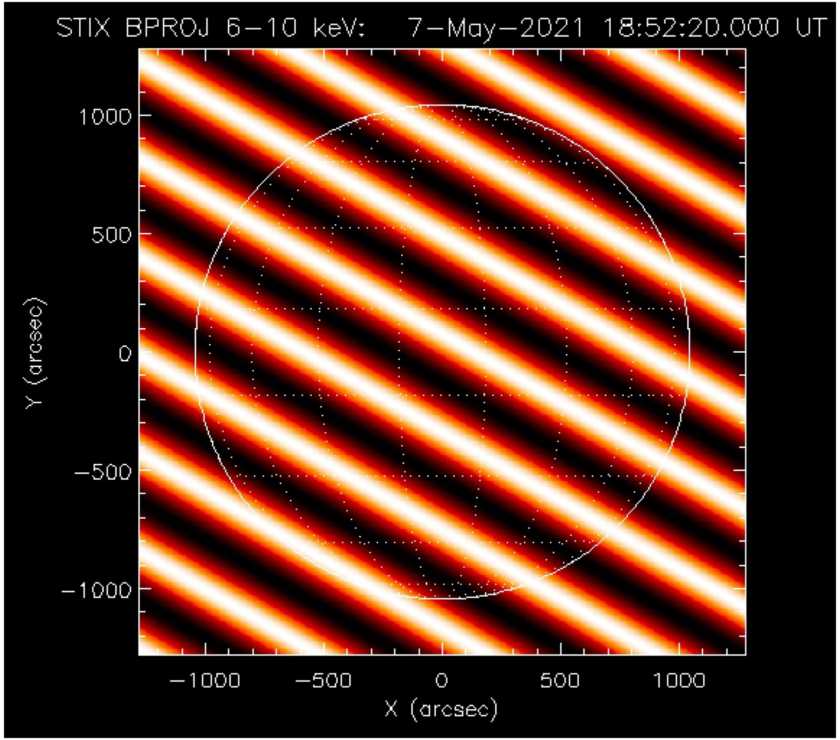
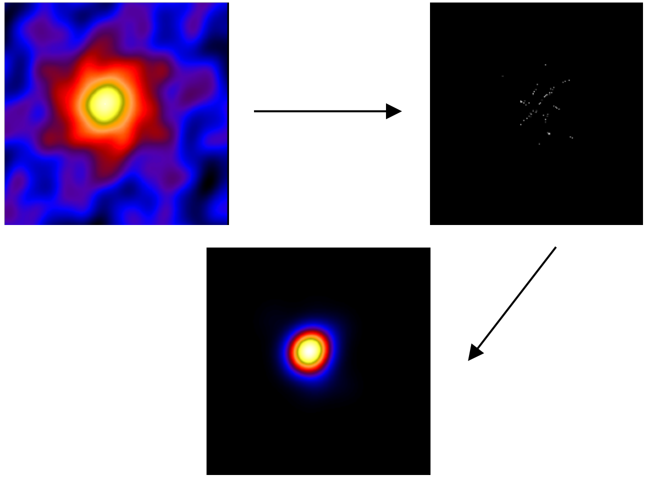


- Direct Fourier inversion
- Basic idea: the back-projection of a single visibility is a sinusoidal wave

Clean

- Deconvolution algorithm
- Starts from Back-projection
- Extracts point sources (Clean components)
- Convolves the Clean components with a gaussian beam



MEM_GE

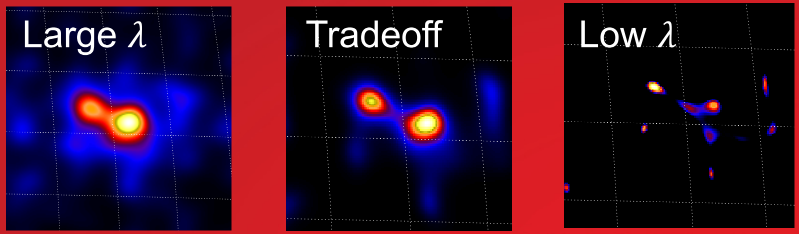
Solves

$$\operatorname*{argmin}_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

where

$$\chi^2(\phi) = \sum_i \frac{|(F\phi)_i - V_i|^2}{\sigma_i^2},$$

$$H(\phi) = \sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)$$



Expectation Maximization

- Same as Richardson-Lucy for image deconvolution
- Image reconstruction directly from counts
- Maximum-likelihood: data are Poisson distributed

VIS_FWDFIT

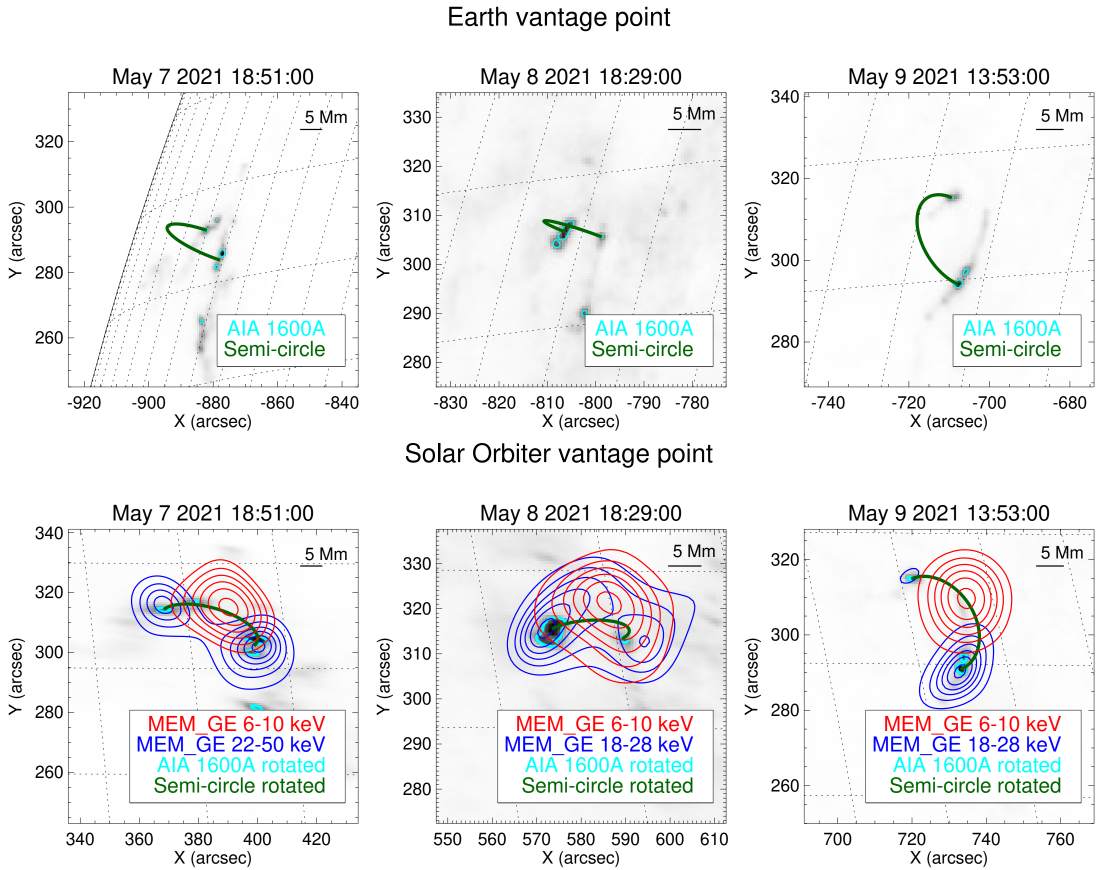
- Parametric imaging
- Choose a parametric shape ϕ_θ among

- Solve

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

Results

First imaging results (Massa et al., 2022)



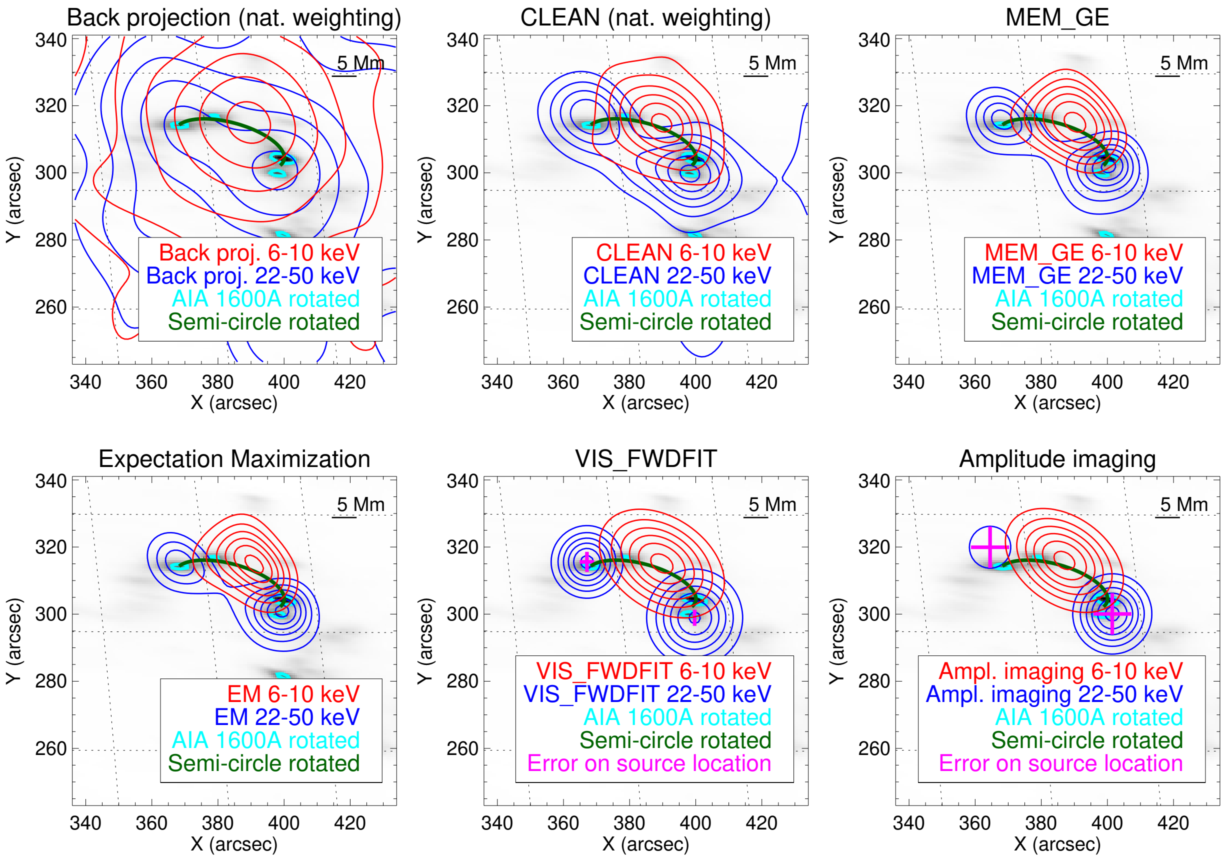
Active region AR2822

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

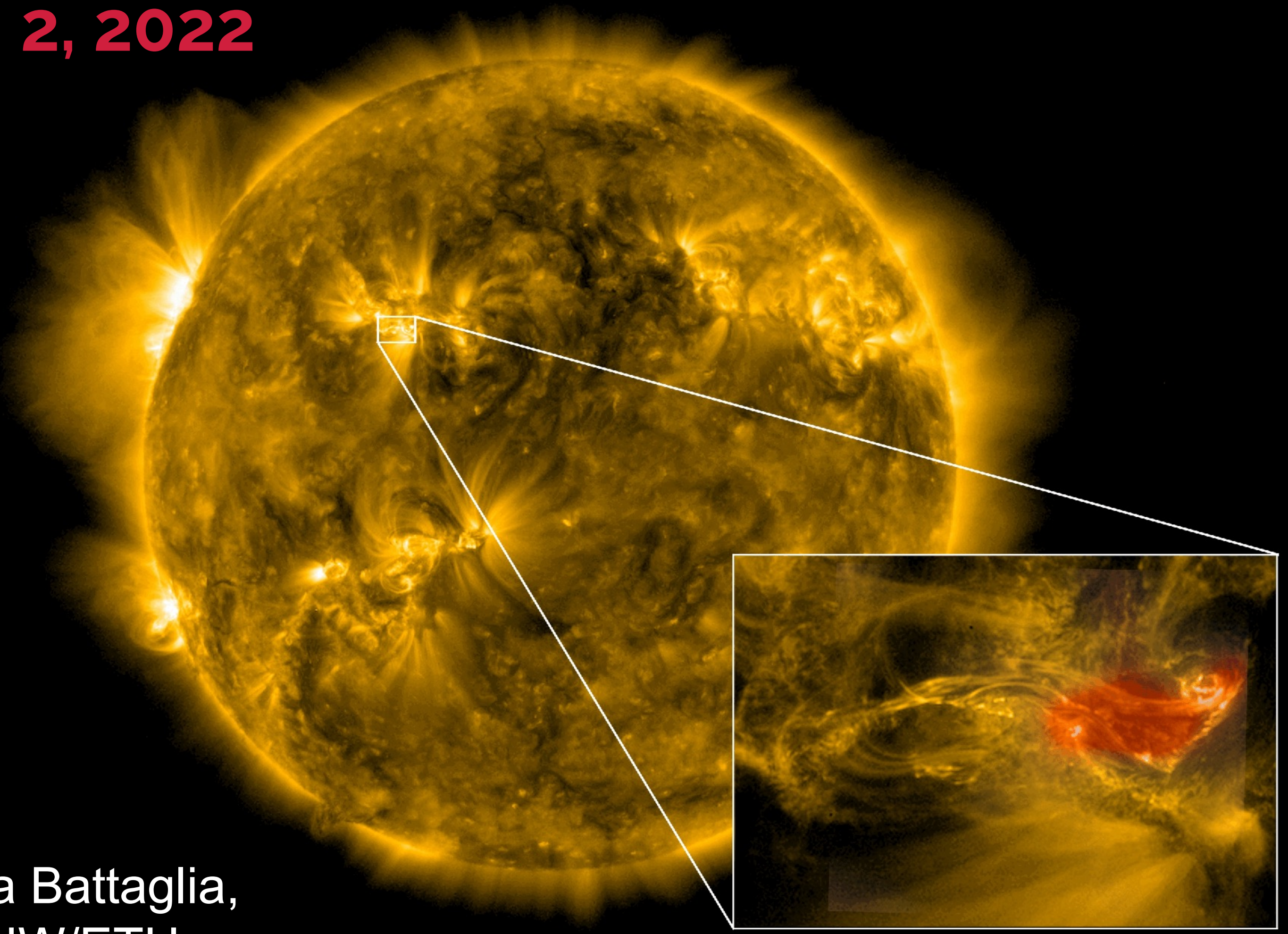
Manual shift STIX reconstructions

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

First imaging results (Massa et al., 2022)

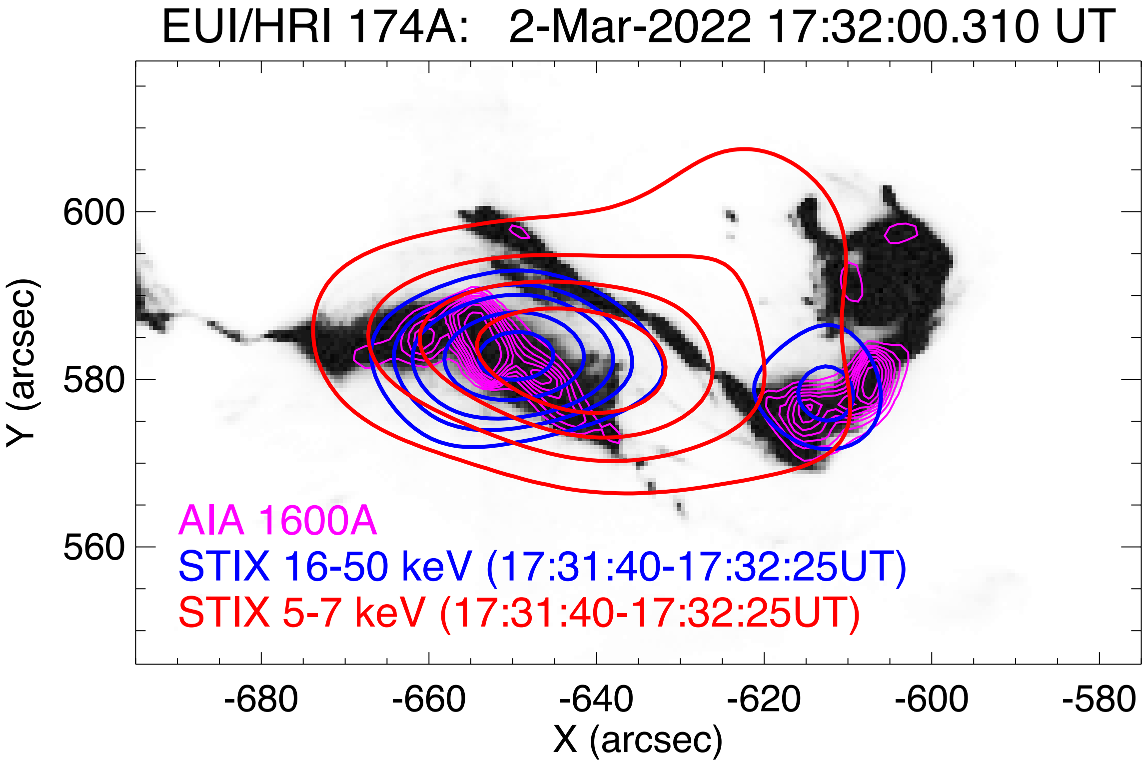


March 2, 2022



Andrea Battaglia,
FHNW/ETH

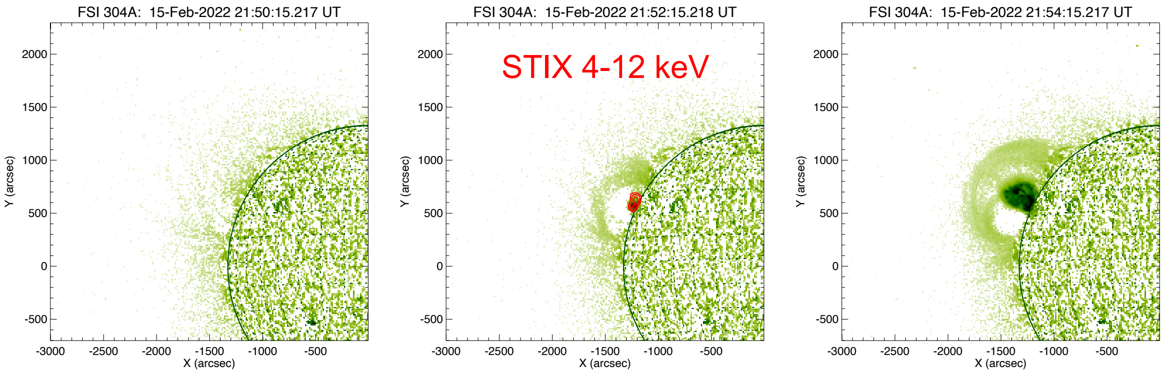
March 2, 2022

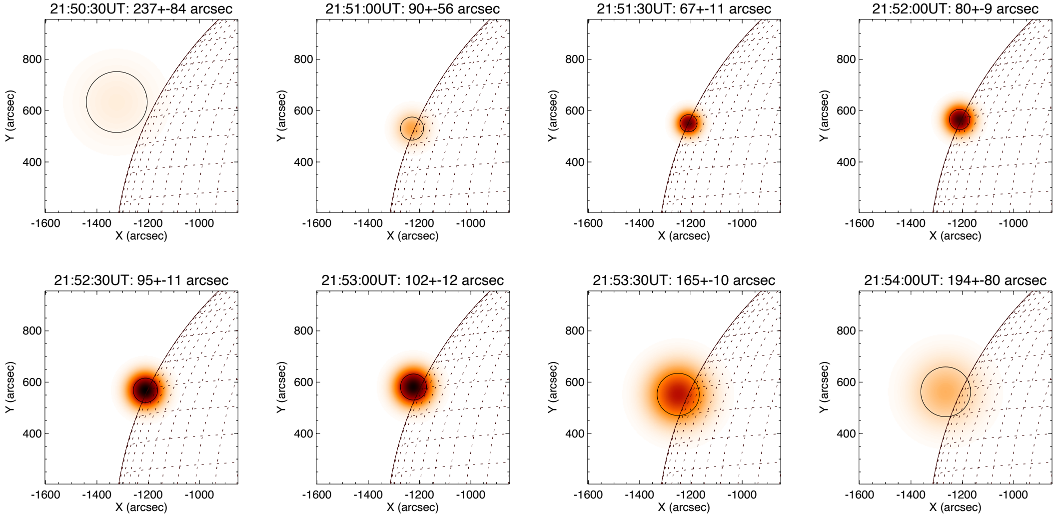


Courtesy of Säm Krucker

February 15, 2022

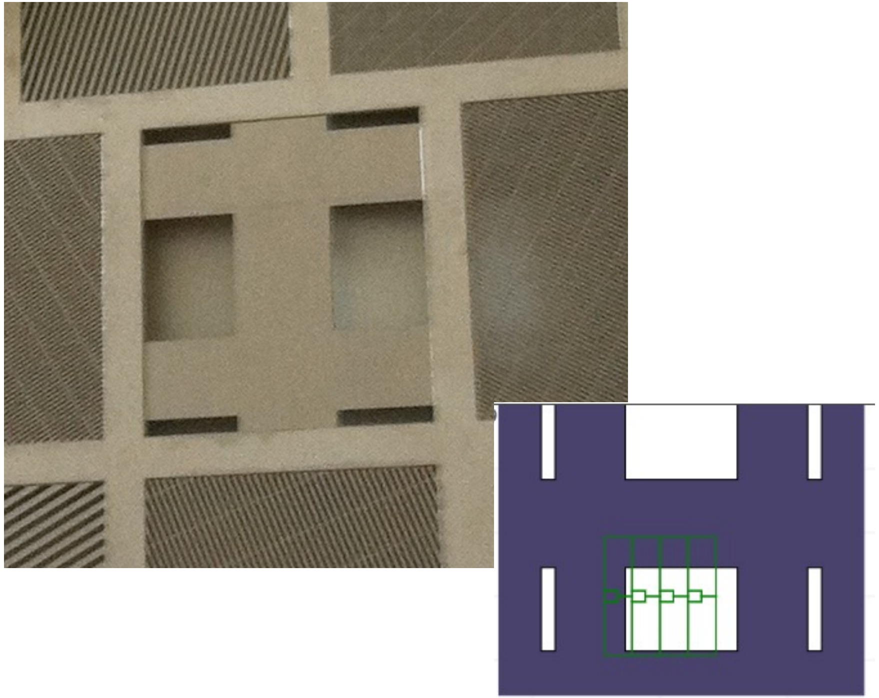
Courtesy of Säm Krucker





- VIS_FWDFIT reconstruction
- After 21:54:00 the source is bigger than the STIX coarsest resolution

STIX-like instrument for SW



STIX Coarse flare locator allows to

- Provide information on flare location (up to ~2 arcmin)
- Measure timing, intensity and spectrum of the X-ray emission

Conclusions

- We described the STIX instrument and the image reconstruction problem
- We showed several imaging techniques both from semi-calibrated and calibrated data
- We presented the first results of STIX imaging and other results combined with EUI

STIX imaging status

- Reached a satisfactory level for scientific data exploitation
- Absolute location of STIX reconstructions to be improved (to reach goal of 4 arcsec precision)
- Calibration of the finest resolution detectors to be investigated
- Second order errors in data calibration to be corrected

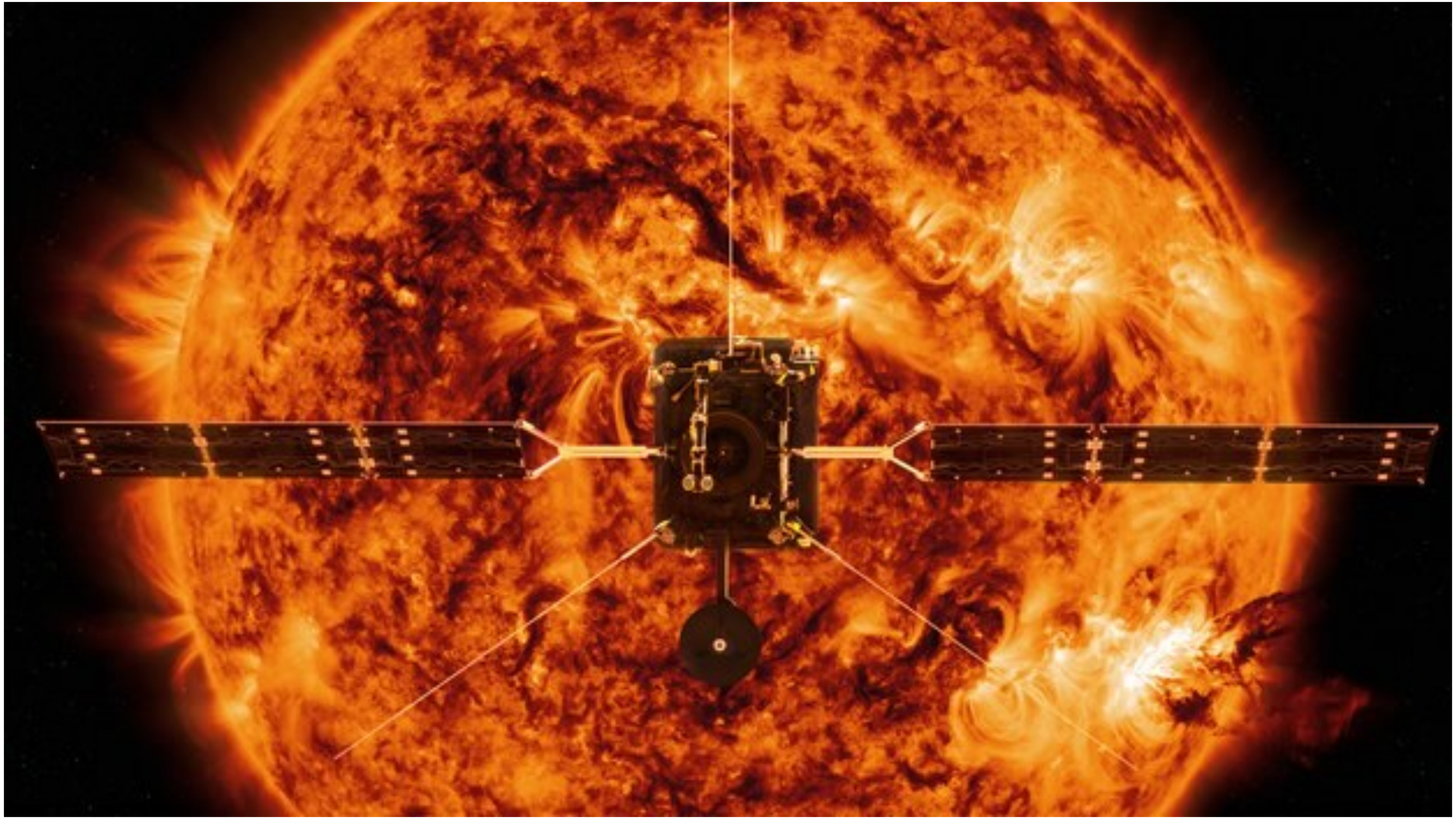
References

- 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

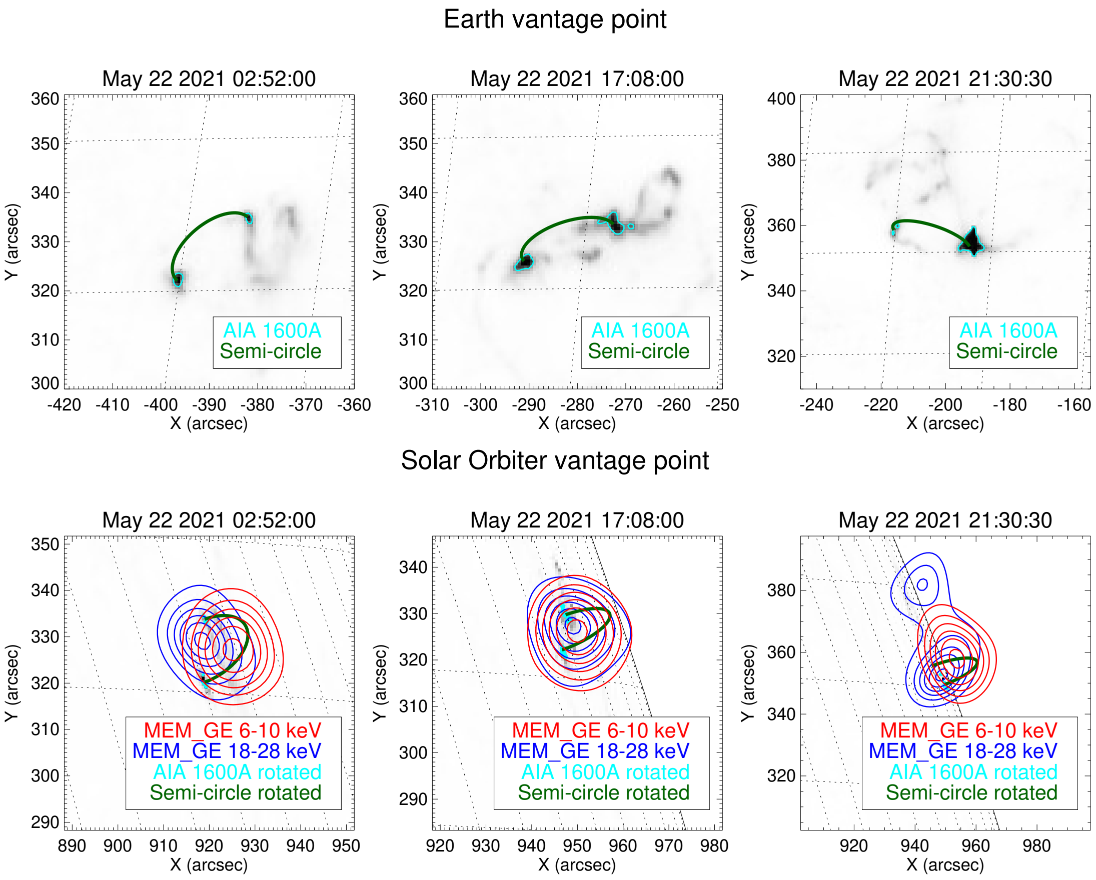
Acknowledgements

- STIX team
- ASI and INAF for the financial contribution to STIX and to the AI-FLARES project

Thank you for the attention!



First imaging results (Massa et al., 2022)



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