STIX imaging
State-of-the-art and algorithms under construction

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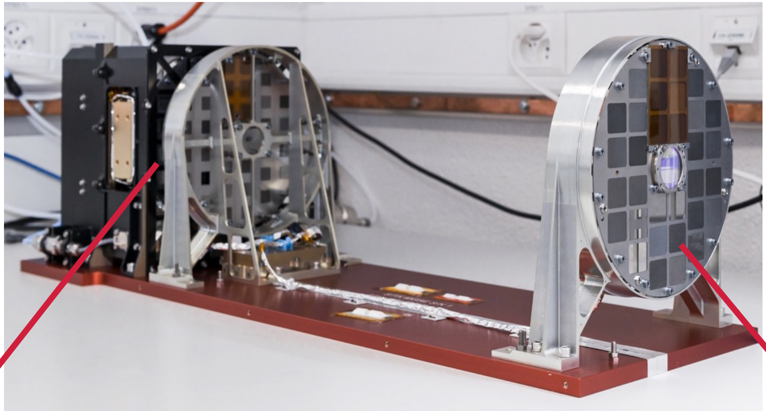
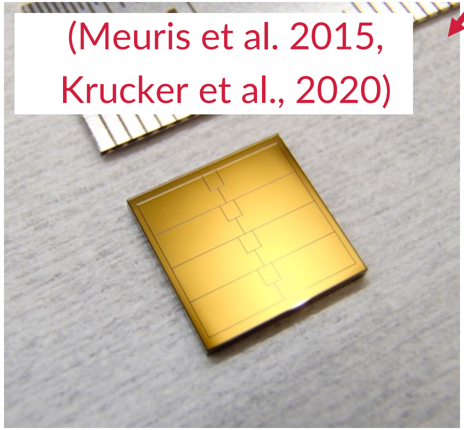
Joint work with: Volpara A., Battaglia A. F., Perracchione E., Garbarino S., Benvenuto F., Massone A. M., Hurford G. J., Piana M., Krucker S. & the STIX team

April 11, 2023 – STIX team meeting

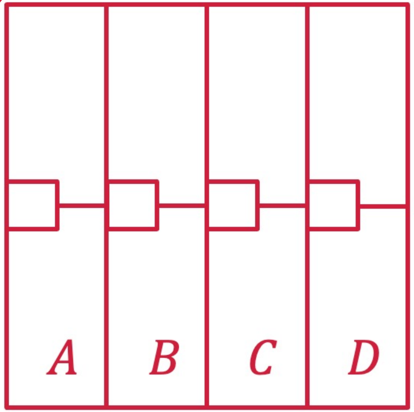
The STIX imaging concept

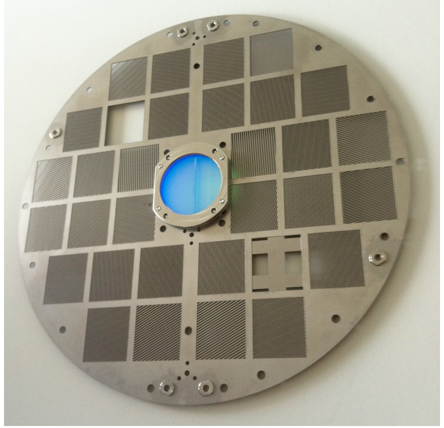


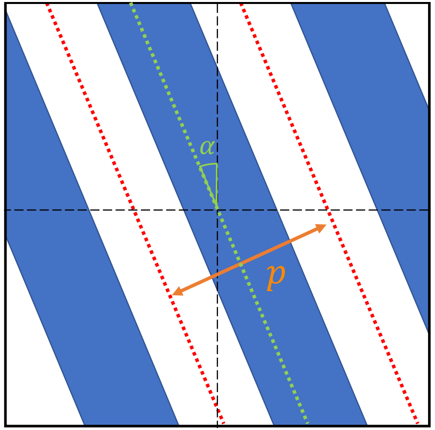
Window parameters:
α: orientation angle
p: pitch = distance between two consecutive slit centers



(Meuris et al. 2015, Krucker et al., 2020)







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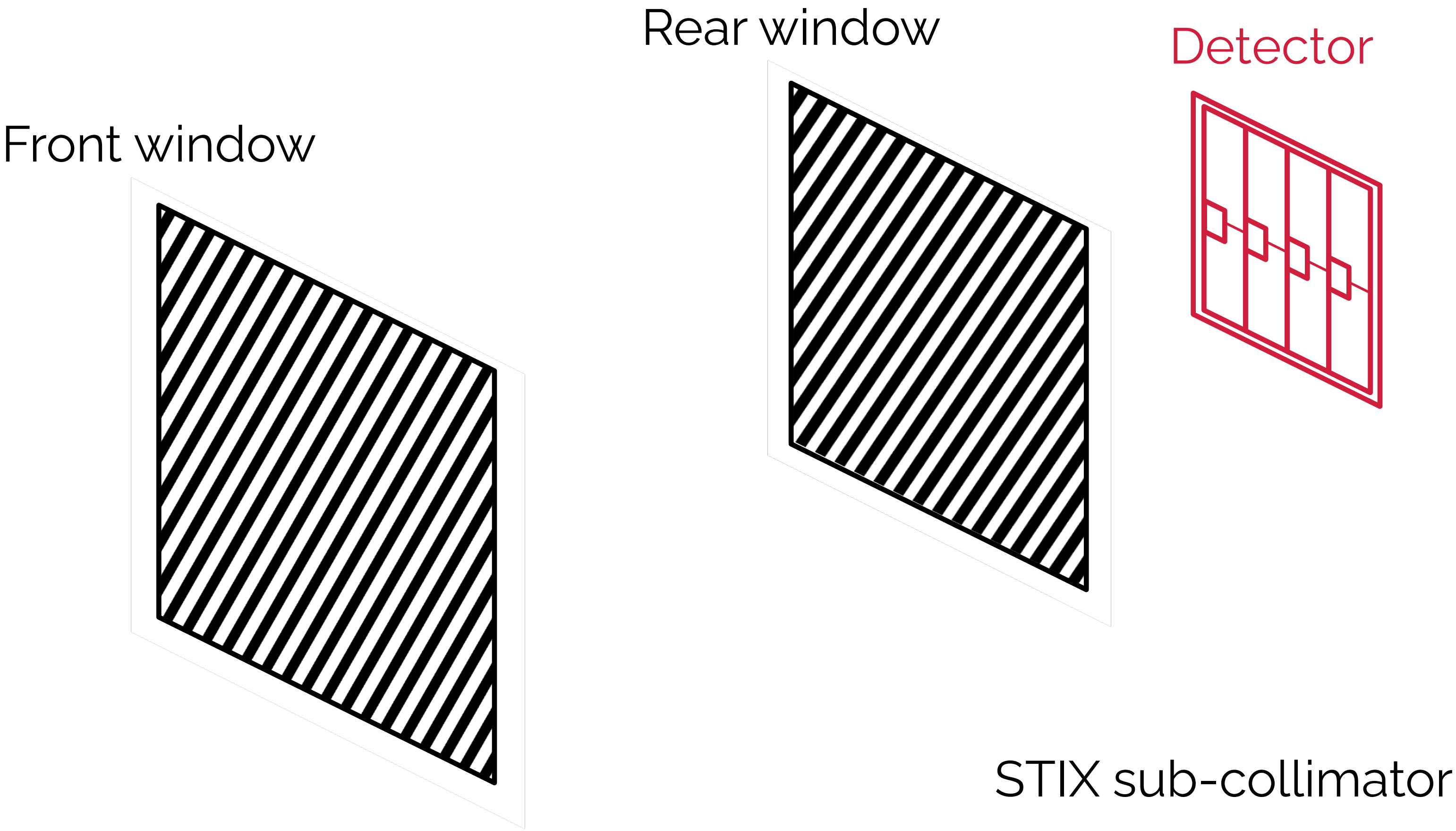

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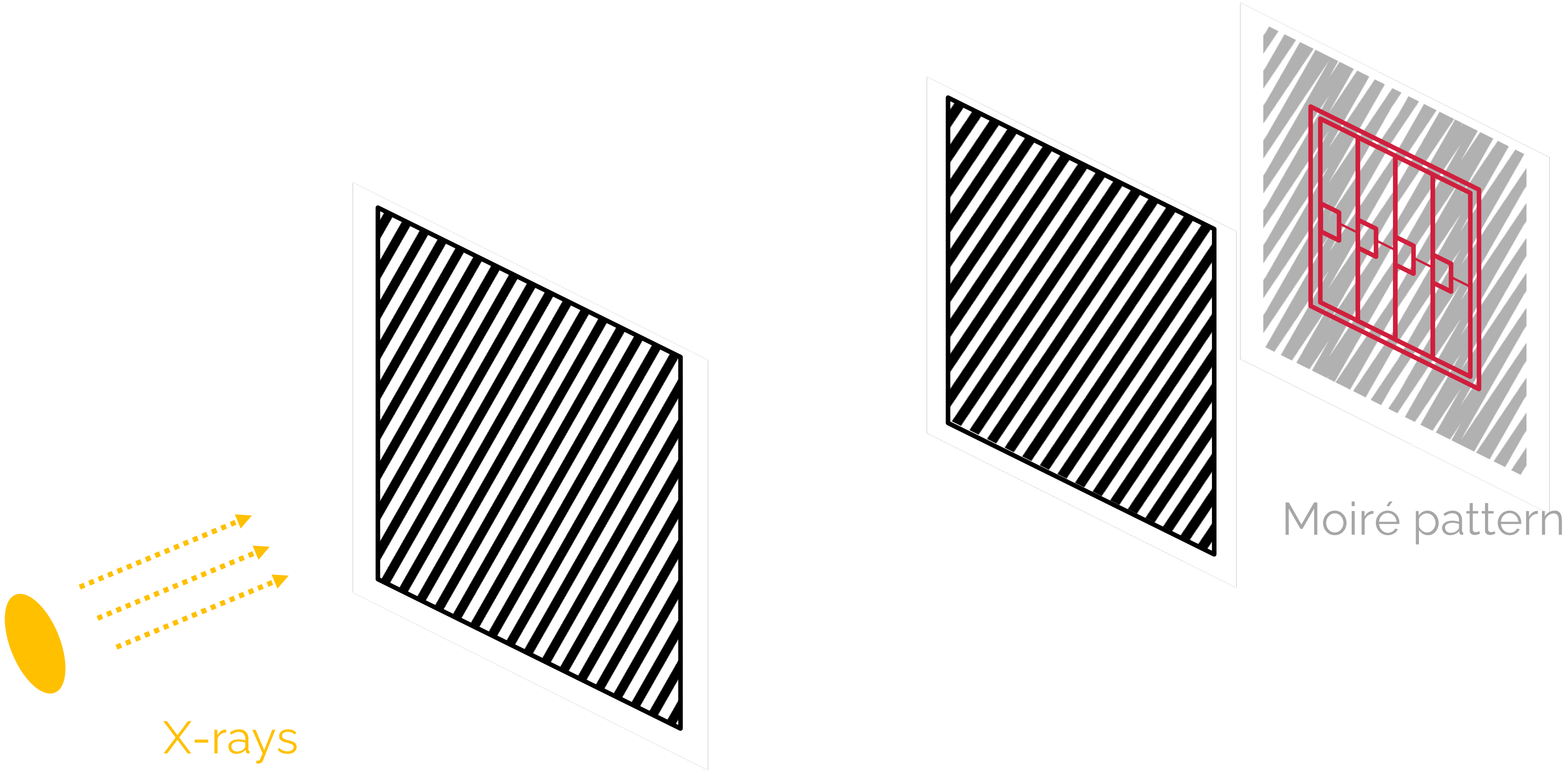

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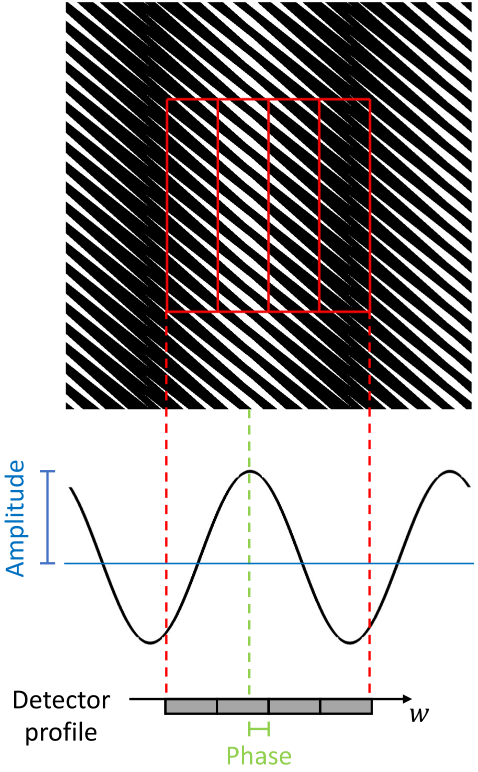


Moiré patterns have:

- period equal to the detector width
- fringes parallel to the pixel stripes

Amplitude and phase of a pattern

⇩

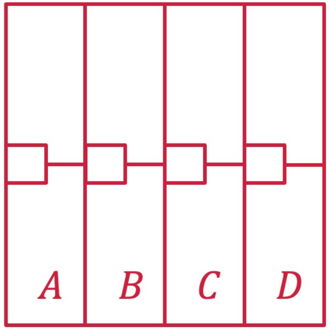
Amplitude and phase of a Fourier component (**visibility**) of the X-ray source

The STIX imaging concept

Massa et al., arxiv, 2023

Amplitude and phase of the visibilities are determined from count measurements:

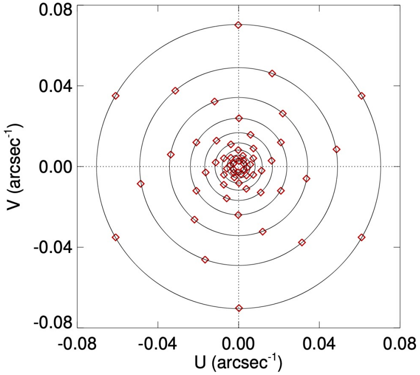
- $|V| \propto \sqrt{(C-A)^2 + (D-B)^2}$
- $\phi = \mathrm{atan}\left(\frac{D-B}{C-A}\right) + 45° + \phi_{\mathrm{calib}}$



The (u, v) point is determined by hardware parameters of the sub-collimator

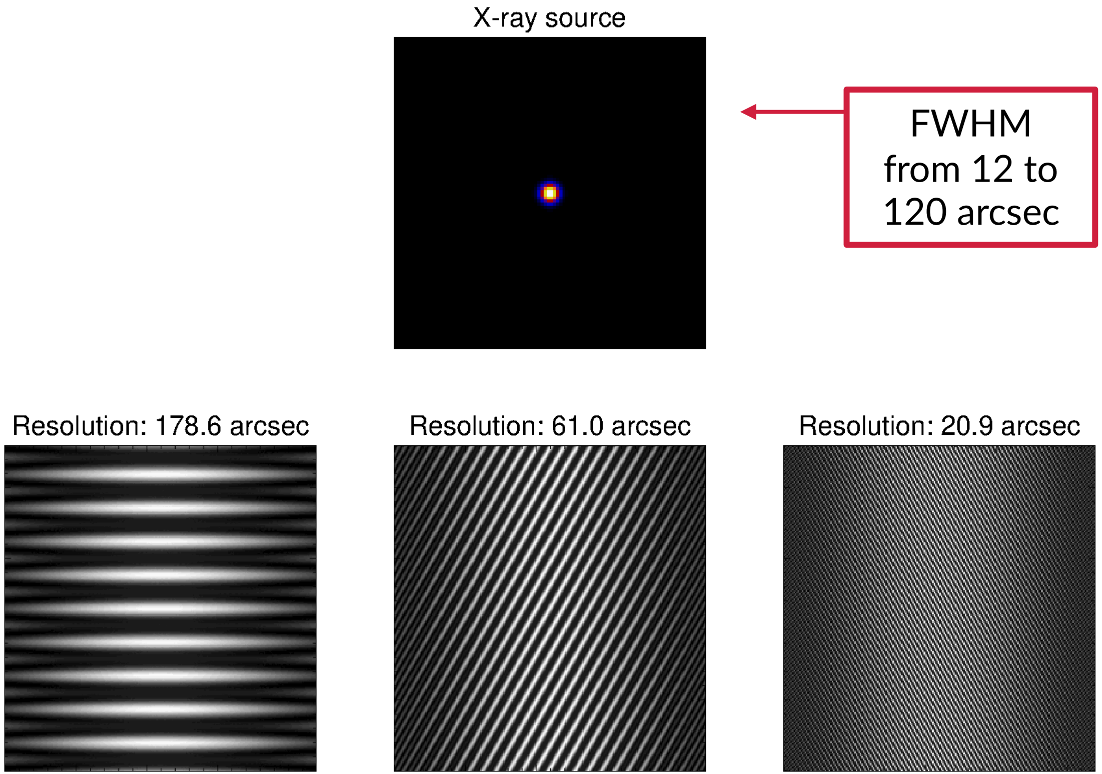
$$(u, v) = \frac{d_{\mathrm{sep}} + d_{\mathrm{det}}}{p_f} \boldsymbol{k}_f - \frac{d_{\mathrm{det}}}{p_r} \boldsymbol{k}_r$$

where $\boldsymbol{k}_{f/r} = (\cos(\alpha_{f/r}), \sin(\alpha_{f/r}))$



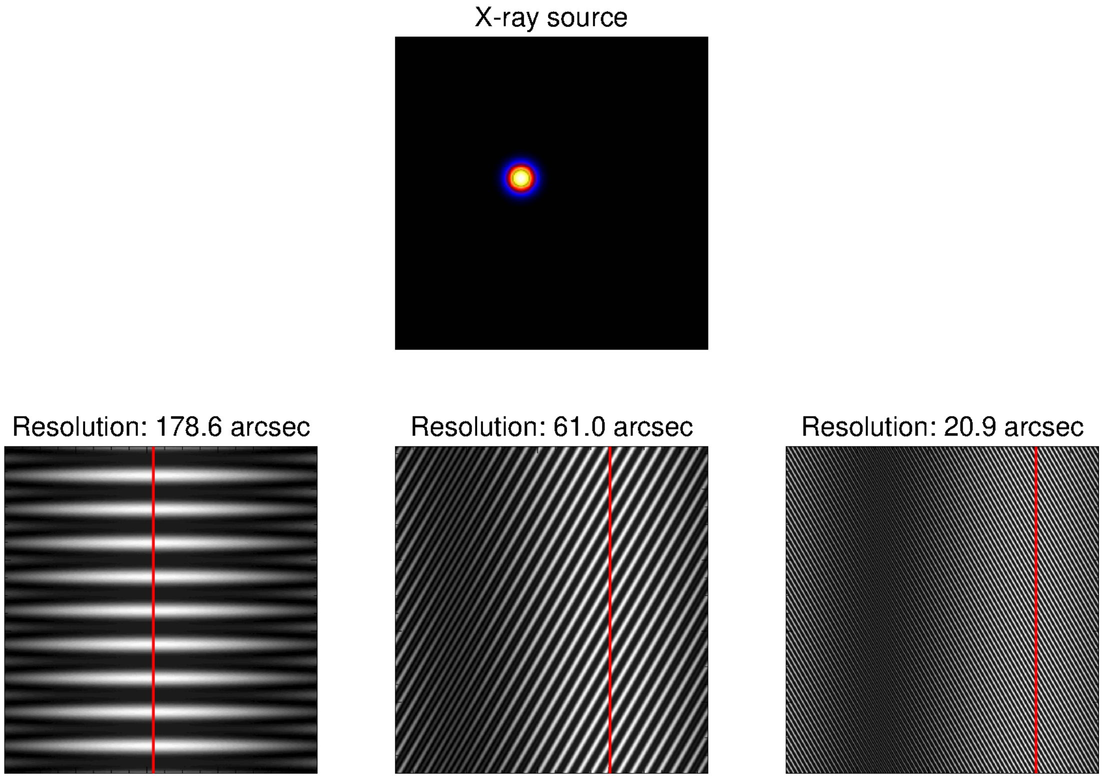
The STIX imaging concept

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



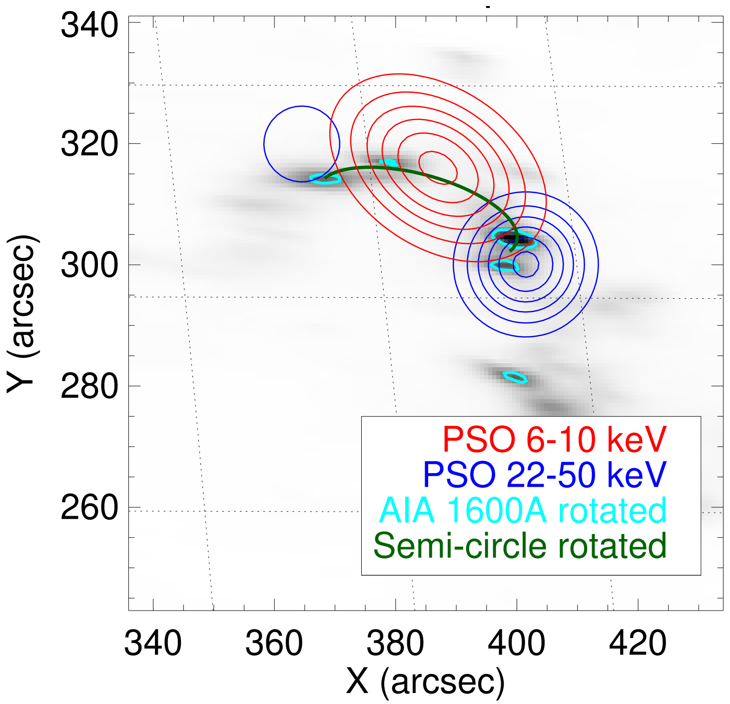
Imaging methods

The past...

Imaging from visibility amplitudes (Massa et al., 2021):

- Information on the source morphology
- No information on the source location

We adopted a parametric approach similar to VIS_FWDFIT



...the present...

Currently in the IDL STIX Ground software:

- Back-projection (Mertz et al., 1986)
- Clean (Högbom, 1974)
- MEM_GE (Massa et al., 2020)
- EM (Massa et al., 2019)
- VIS_FWDFIT_PSO (Volpara et al., 2022)

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RHESSI legacy

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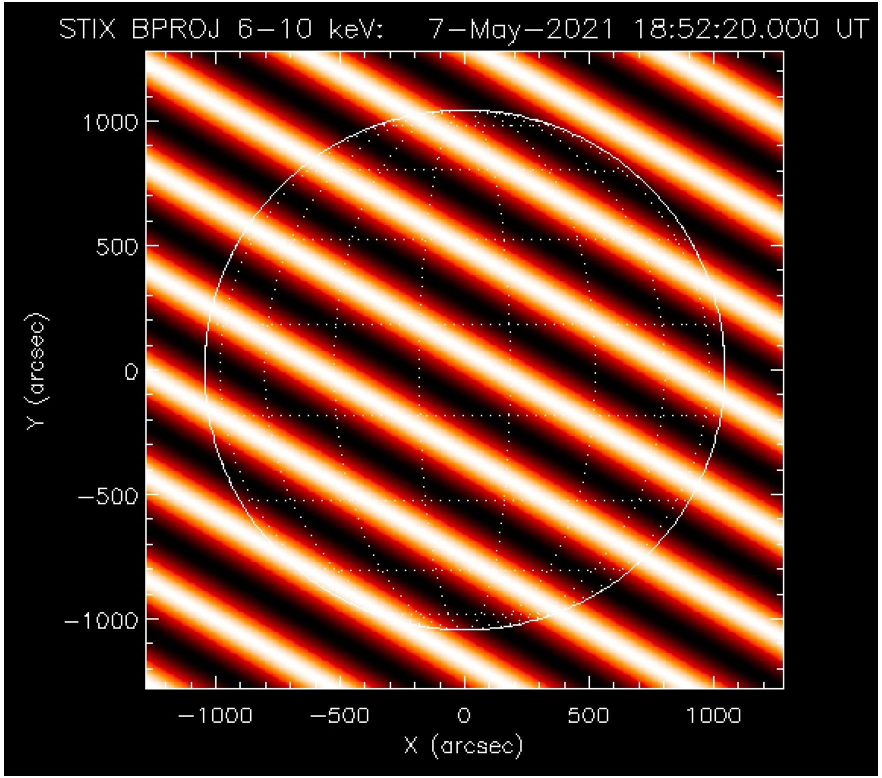
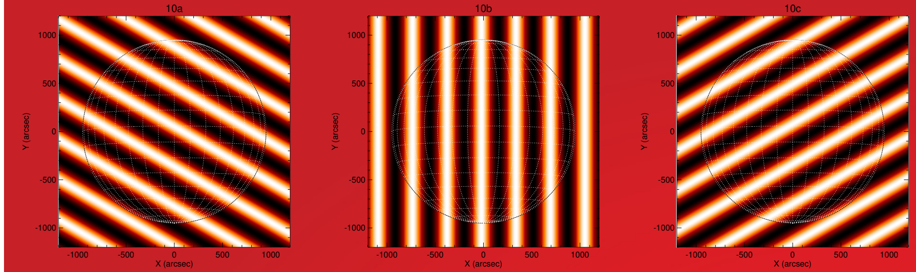
Developed for STIX

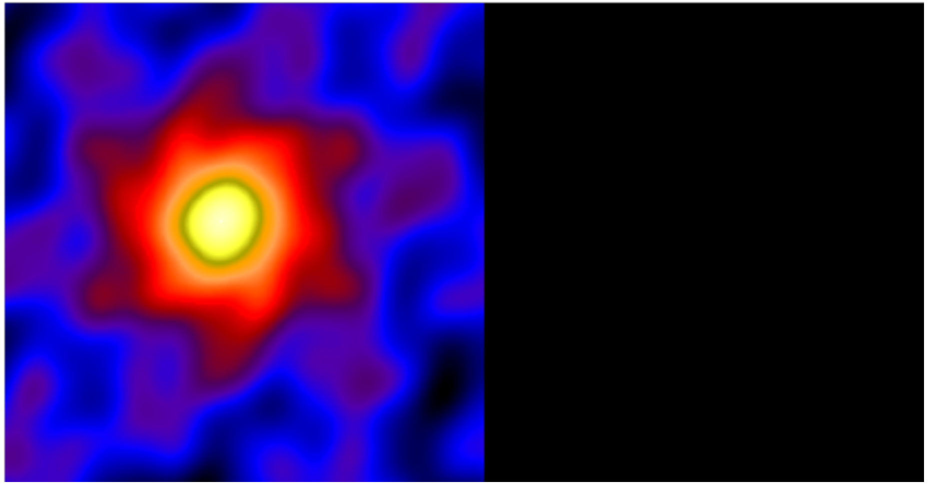
Back-projection



- Direct Fourier inversion
- Idea: the Back Projection of a single visibility is a sinusoidal wave



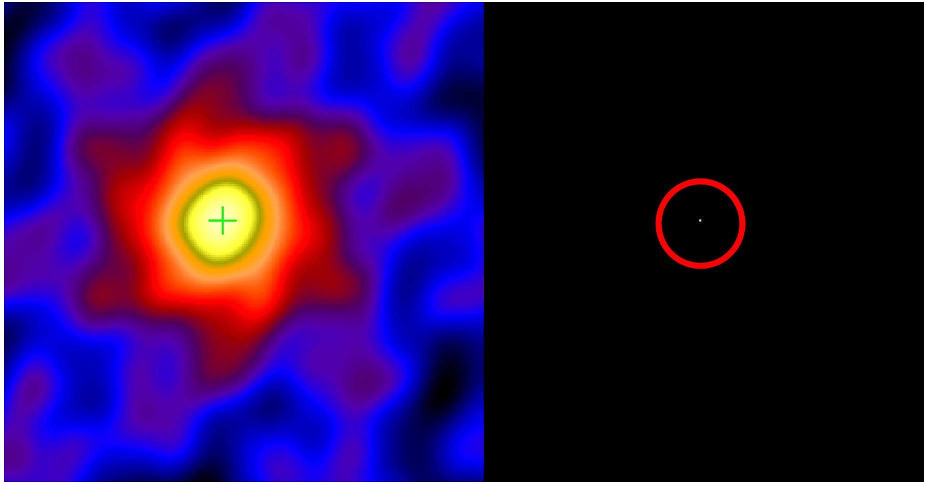
Clean



Iterative method:

- Creates two maps: **dirty map** (back projection) and **clean components (cc) map** (zero map)

Clean



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- Creates two maps: **dirty map** (back projection) and **clean components (cc) map** (zero map)
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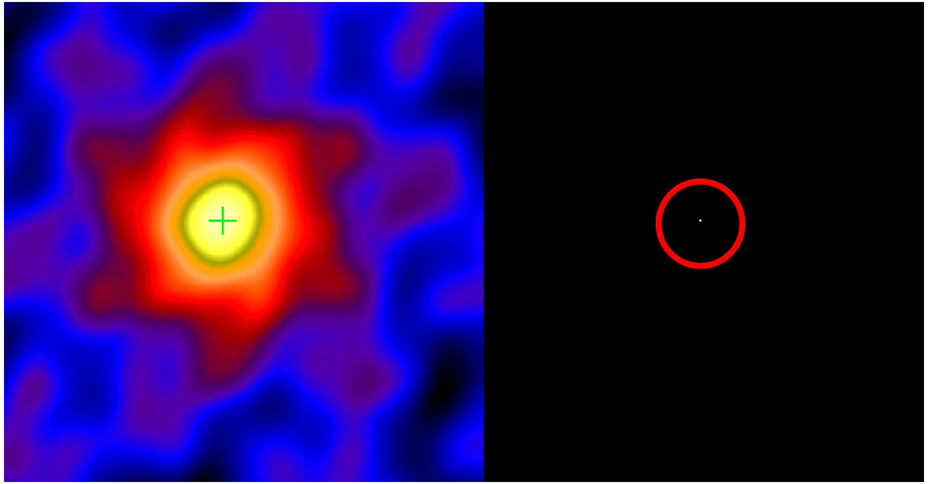

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- Creates two maps: **dirty map** (back projection) and **clean components (cc) map** (zero map)
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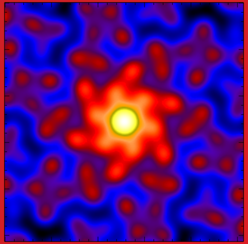

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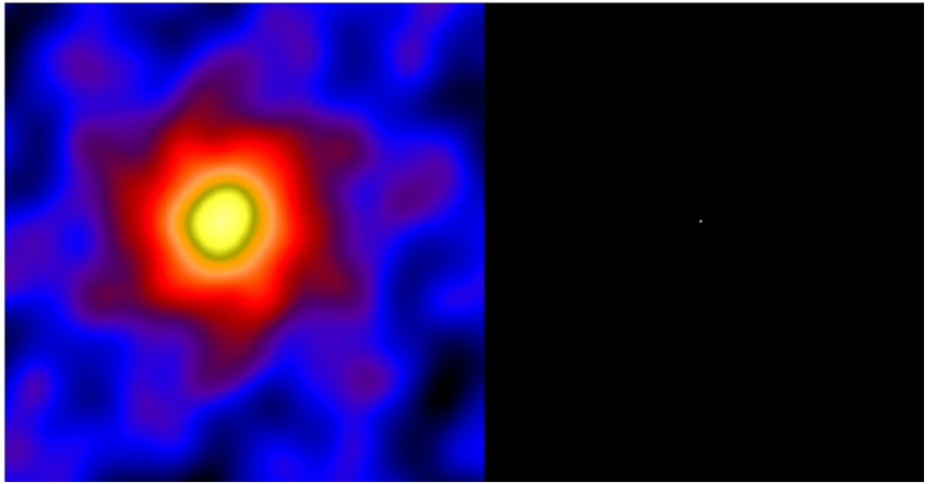

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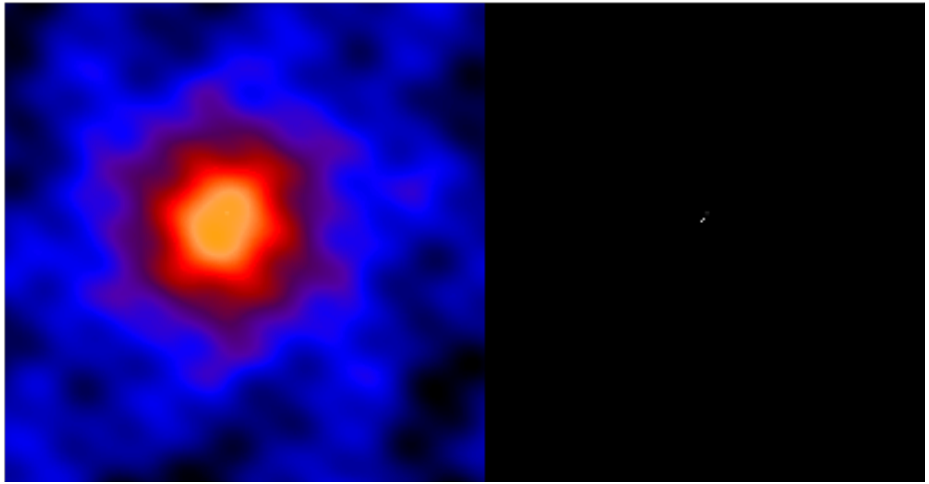

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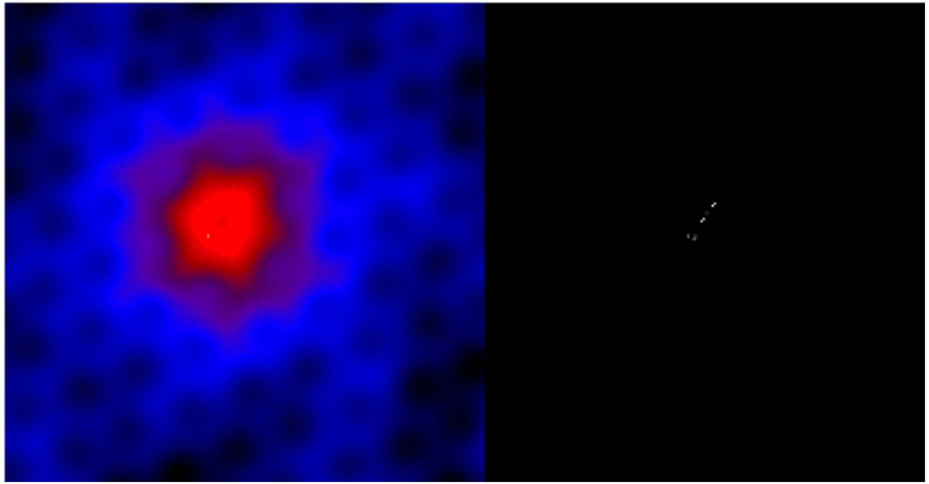

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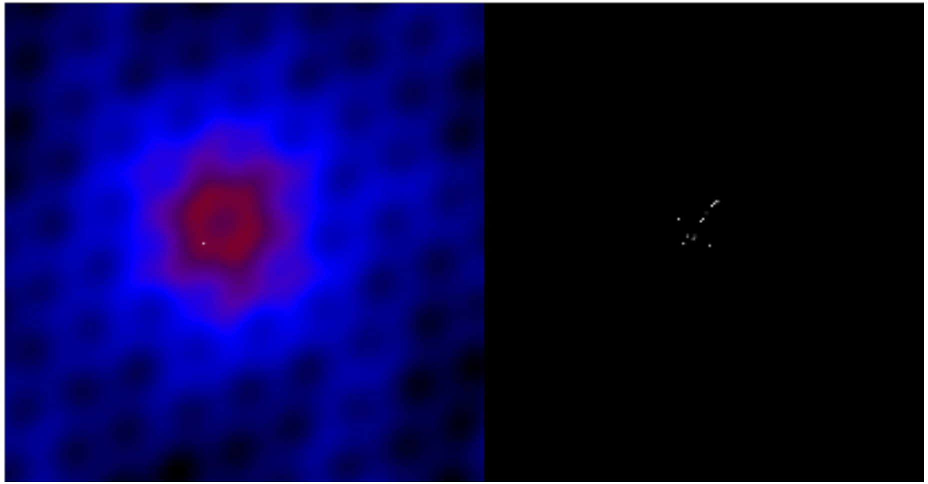

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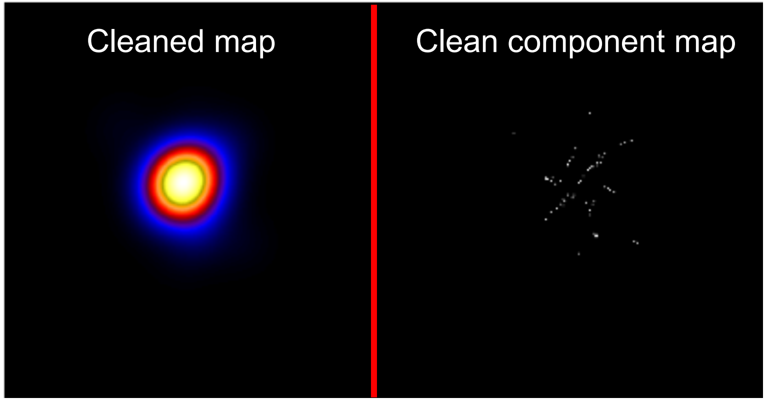
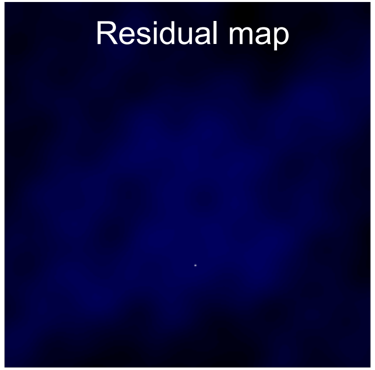
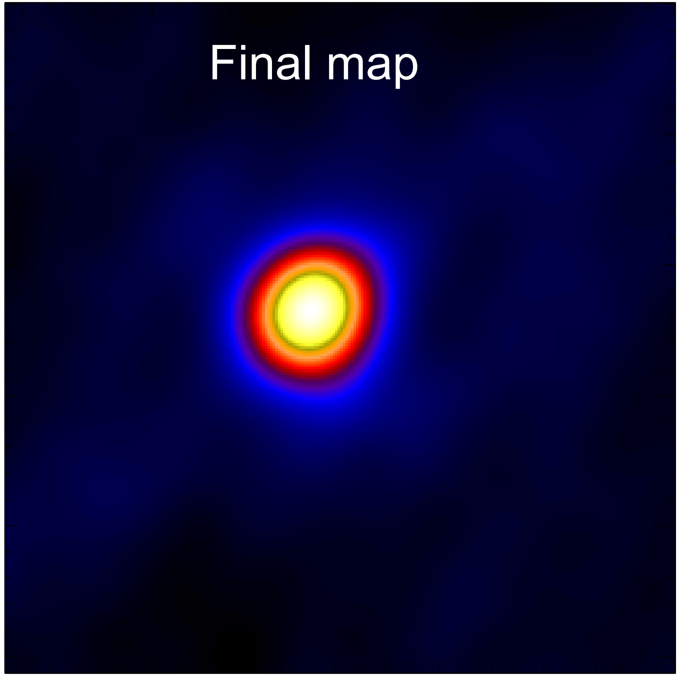




Final step: convolution with clean beam and residuals

Clean



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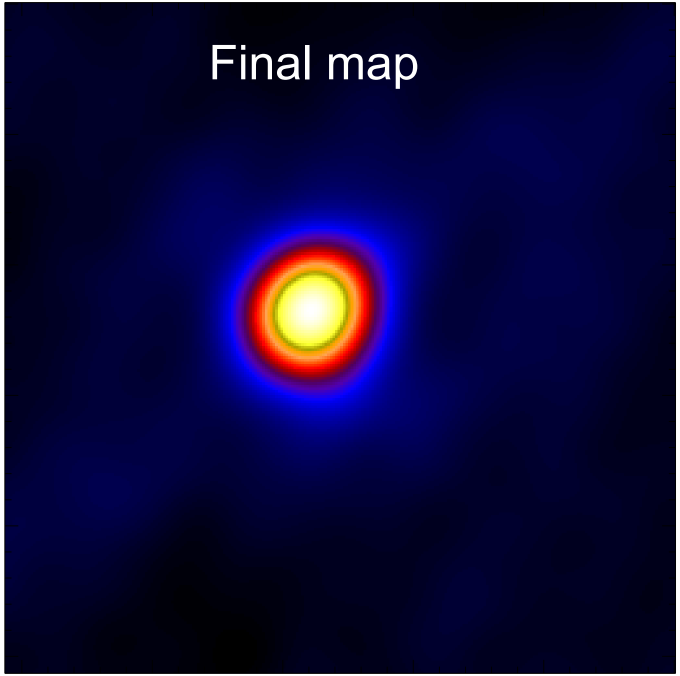


Final step: convolution with clean beam and residuals

Selection of the beam width is no more an issue in the multiscale version

MEM_GE & EM

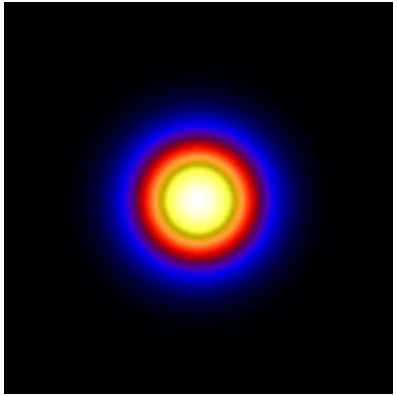
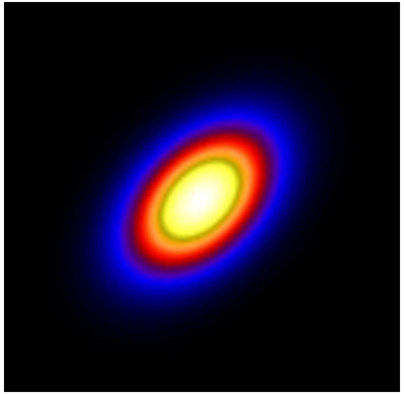
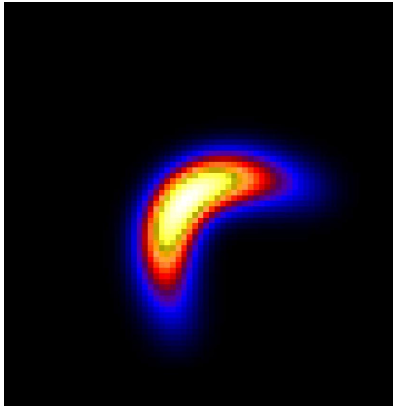
MEM_GE determines the solution such that:

- Minimizes the χ^2 between observed and predicted visibilities
- Maximizes the entropy
- Has a total flux equal to an a-priori estimate and positive entries

Expectation maximization (EM):
- Maximum likelihood approach from counts assuming Poisson noise on the counts
- Positivity constraint on the solution

VIS_FWDFIT_PSO

- Parametric imaging
- Choose a parametric shape ϕ_θ among

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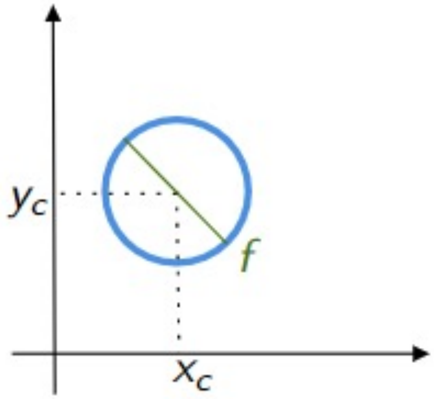

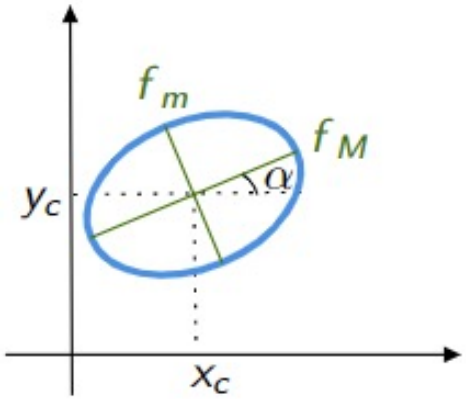

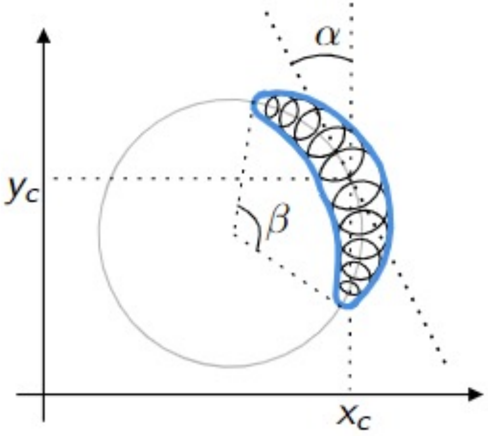

VIS_FWDFIT_PSO

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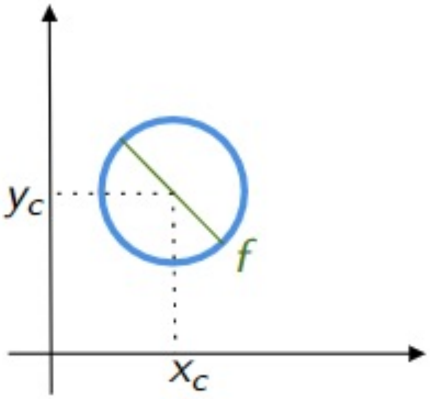
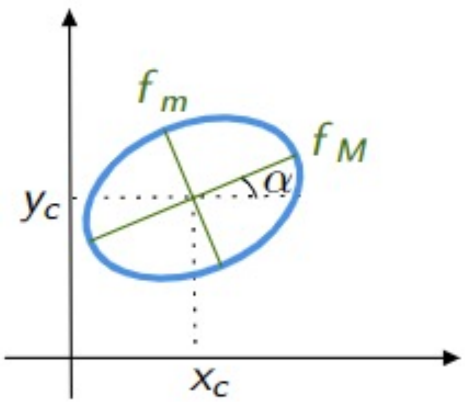
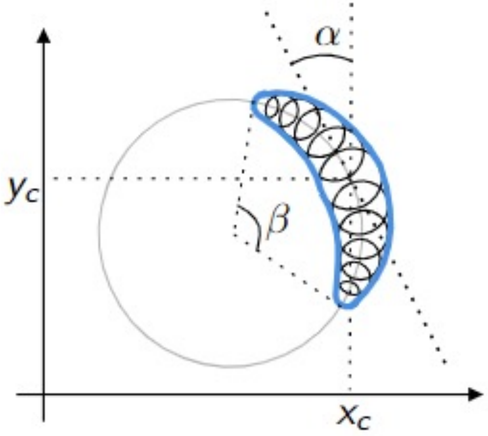






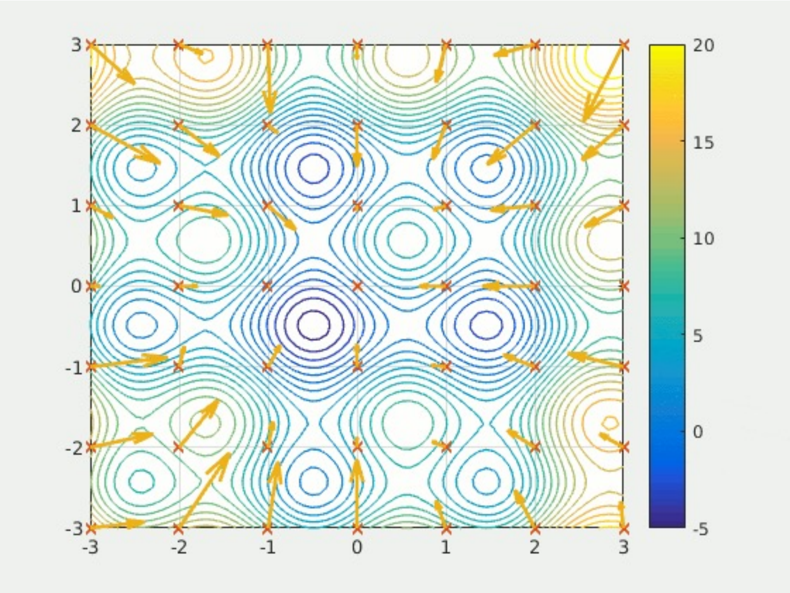
- Solve

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

VIS_FWDFIT_PSO

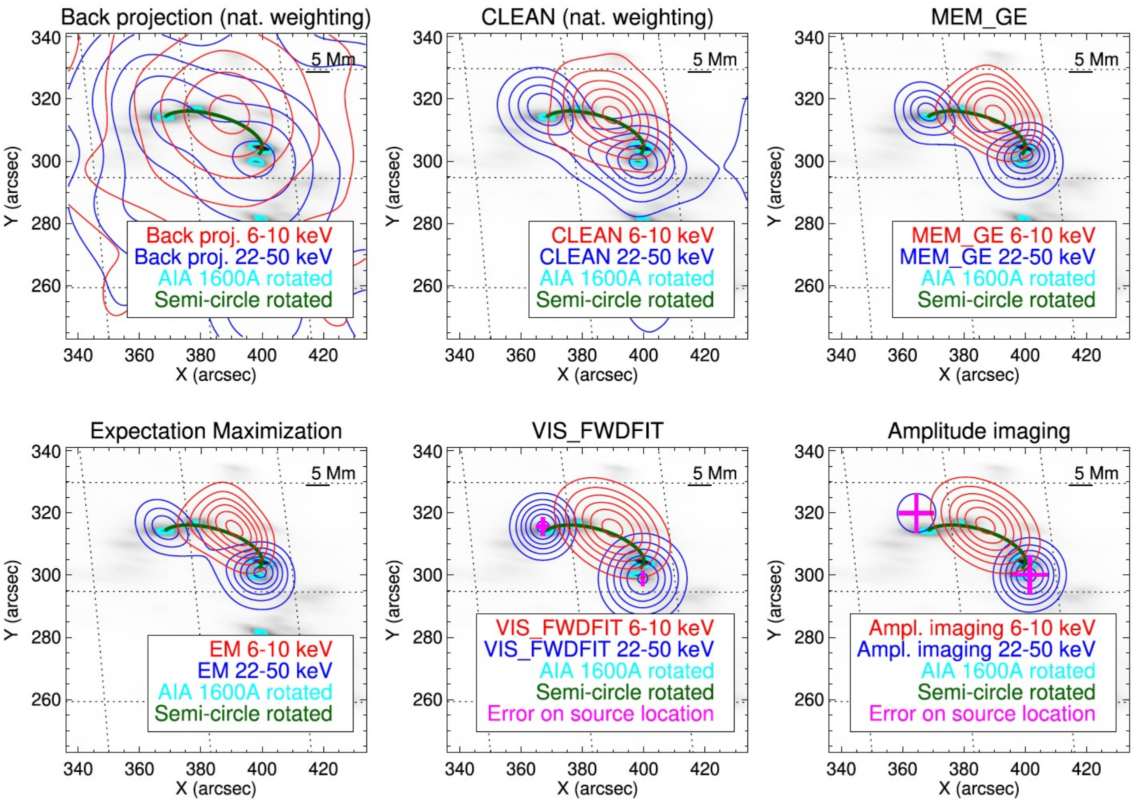
- **Uncertainty on the parameters**: 20 reconstructions from visibilities perturbed with Gaussian noise and computation of the standard deviation

- **New optimization method:** based on Particle Swarm Optimization (PSO, Eberhart et al., 1995)



Comparison

Massa et al., 2022



...and the future

- UV-SMOOTH (Perracchione et al, 2021): interpolation of the visibilities in the (u, v)-plane and inversion

- Sequential Monte-Carlo (SMC; Schiacchitano et al., 2019):
  - bayesian parametric approach
  - automatic estimate of the number of sources
  - probability distribution on the parameters

- Neural network approach (in preparation):
  - combines features of VIS_FWDFIT and SMC
  - fast: to be used for statistical studies on the entire database

- Multiscale Clean and electron maps

STIX imaging status

- Calibration of the finest resolution detectors (1 a,b,c and 2 a,b,c) will be released by this summer

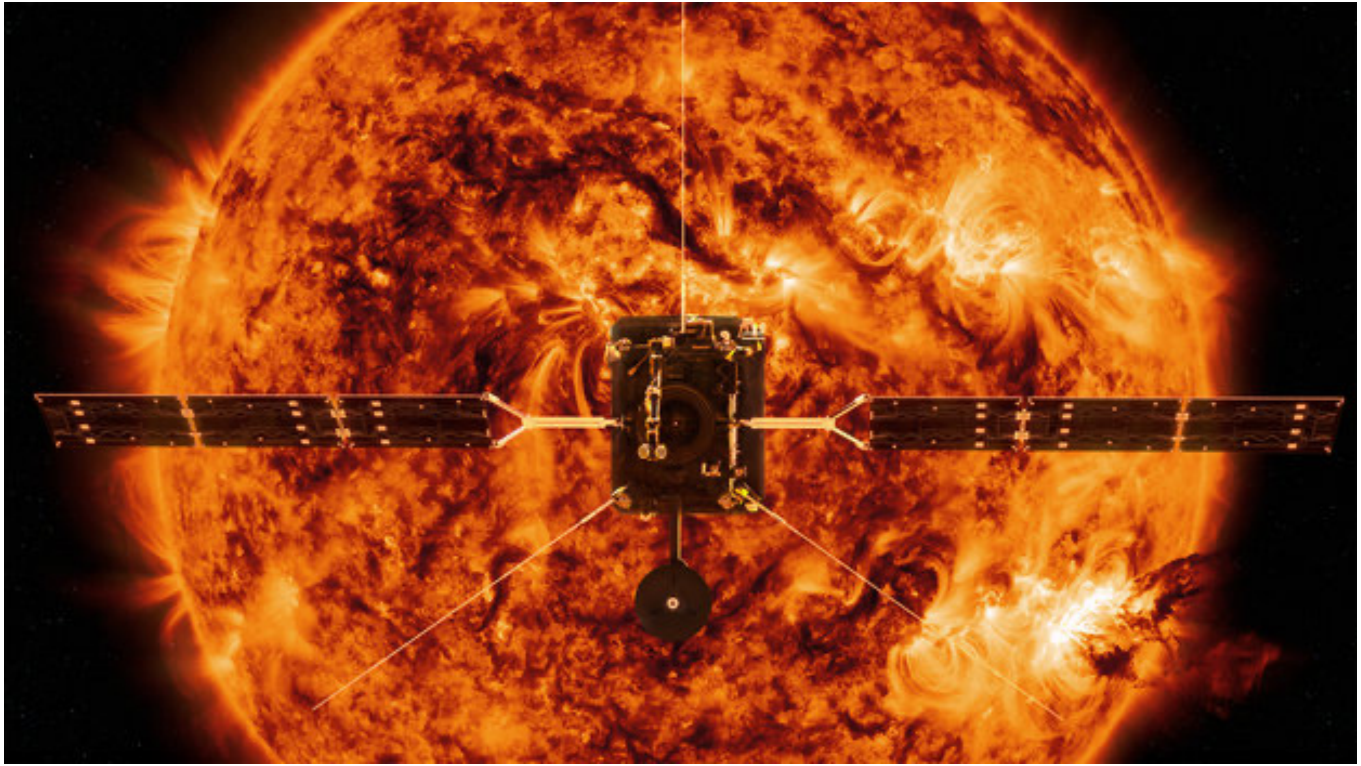
- Correction of second order errors in data calibration is under investigation

- We have refined nominal values for grid to grid separation and rear grid to detector separation: small changes in the absolute location of STIX reconstructions

References

- Högbom, *Aperture synthesis with a non-regular distribution of interferometer baselines*, Astronomy and Astrophysics Supplement, 1974
- Krucker et al., *The Spectrometer/Telescope for Imaging X-rays (STIX),* A&A, 2020
- 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
- Volpara et al., *Forward-fitting STIX visibilities,* A&A, 2022

Thanks for the attention!



MEM_GE

Solves the maximum-entropy regularized problem:

$$\arg\min_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

$$\text{with} \sum_j \phi_j = f$$

where

$$\chi^2(\phi) = \sum_i \frac{|(\mathcal{F}\phi)_i - V_i|^2}{\sigma_i^2} \qquad H(\phi) = -\sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)$$

MEM_GE

Solves the maximum-entropy regularized problem:

$$\arg\min_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

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where

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

Data fitting

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

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Regularization

MEM_GE

Solves the maximum-entropy regularized problem:

$$\arg\min_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

$$\text{with} \sum_j \phi_j = f$$

Regularization parameter

where

$$\chi^2(\phi) = \sum_i \frac{|(\mathcal{F}\phi)_i - V_i|^2}{\sigma_i^2} \qquad H(\phi) = -\sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)$$

MEM_GE

Solves the maximum-entropy regularized problem:

Positivity constraint

$$\underset{\boxed{\phi \geq 0}}{\arg\min}\, \chi^2(\phi) - \lambda H(\phi)$$

$$\text{with} \sum_j \phi_j = f$$

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MEM_GE

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Flux constraint

where

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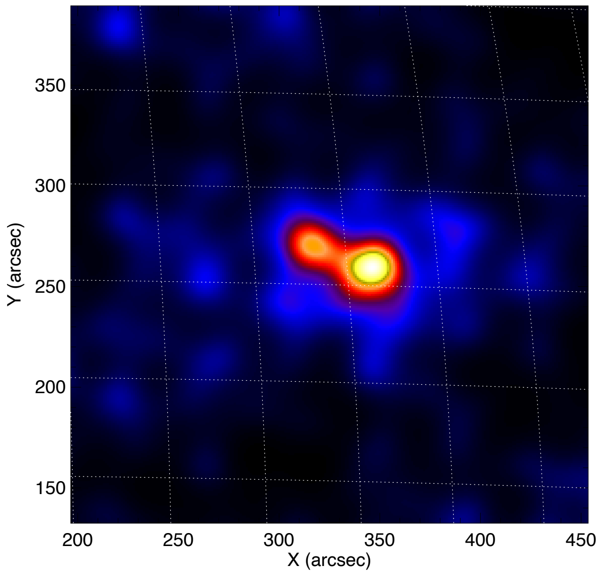
MEM_GE

λ finds tradeoff between data fitting and regularization:

Large λ



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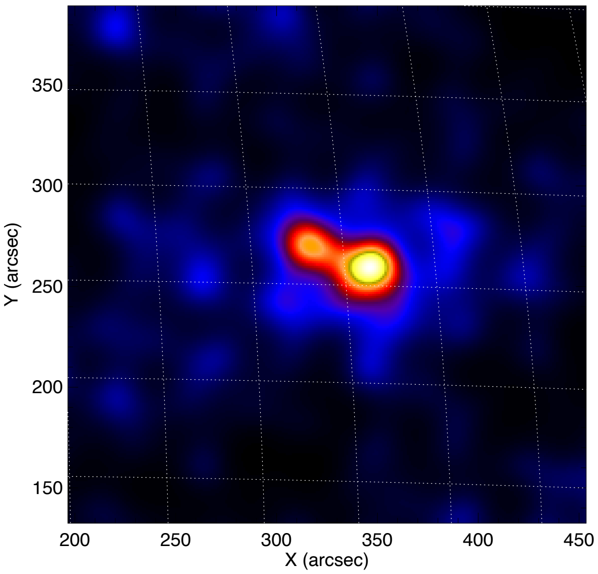
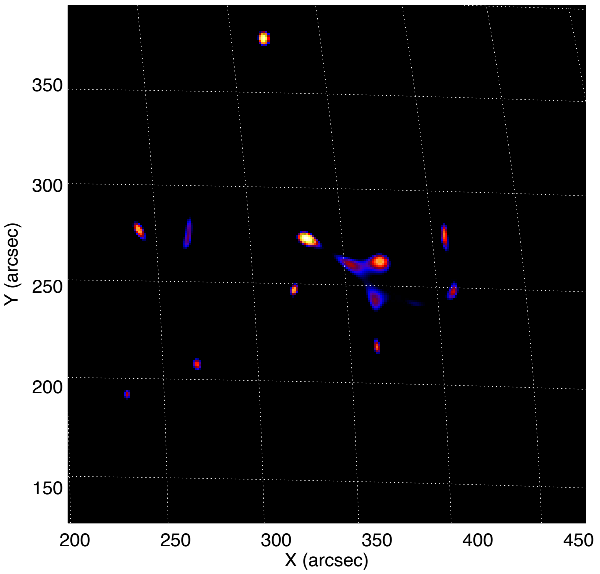


Low λ



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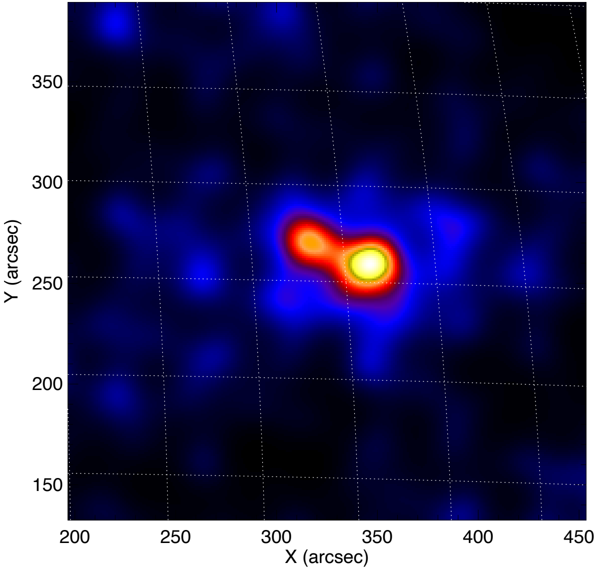
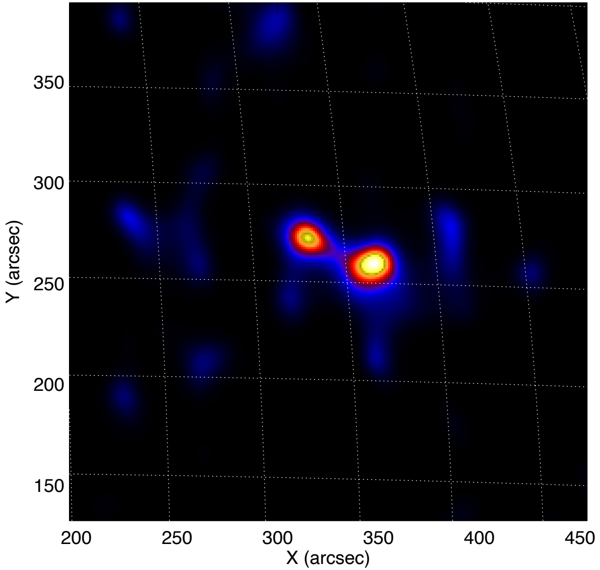


Tradeoff



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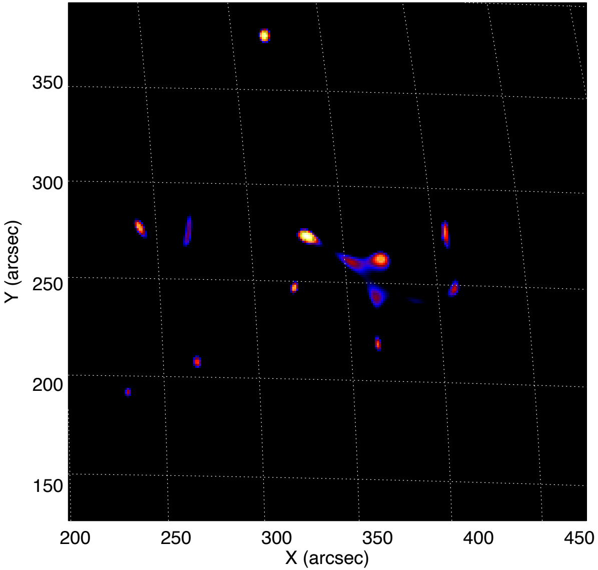

Expectation Maximization

- Count based method which solves

$$M\phi = \mathbf{C}$$

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Matrix modeling the grids' transmission

Expectation Maximization

- Count based method which solves

$$M\phi = \mathbf{C}$$

Array containing the measured counts

Expectation Maximization

- Count based method which solves

$$M\phi = \mathbf{C}$$

- Maximum likelihood approach:

$$\arg\max_{\phi \geq 0} P(\mathbf{C}|\phi)$$

Expectation Maximization

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- Same as Richardson-Lucy:

$$\phi_{k+1} = \frac{\phi_k}{M^T 1} M^T \left(\frac{\mathbf{C}}{M\phi_k} \right)$$