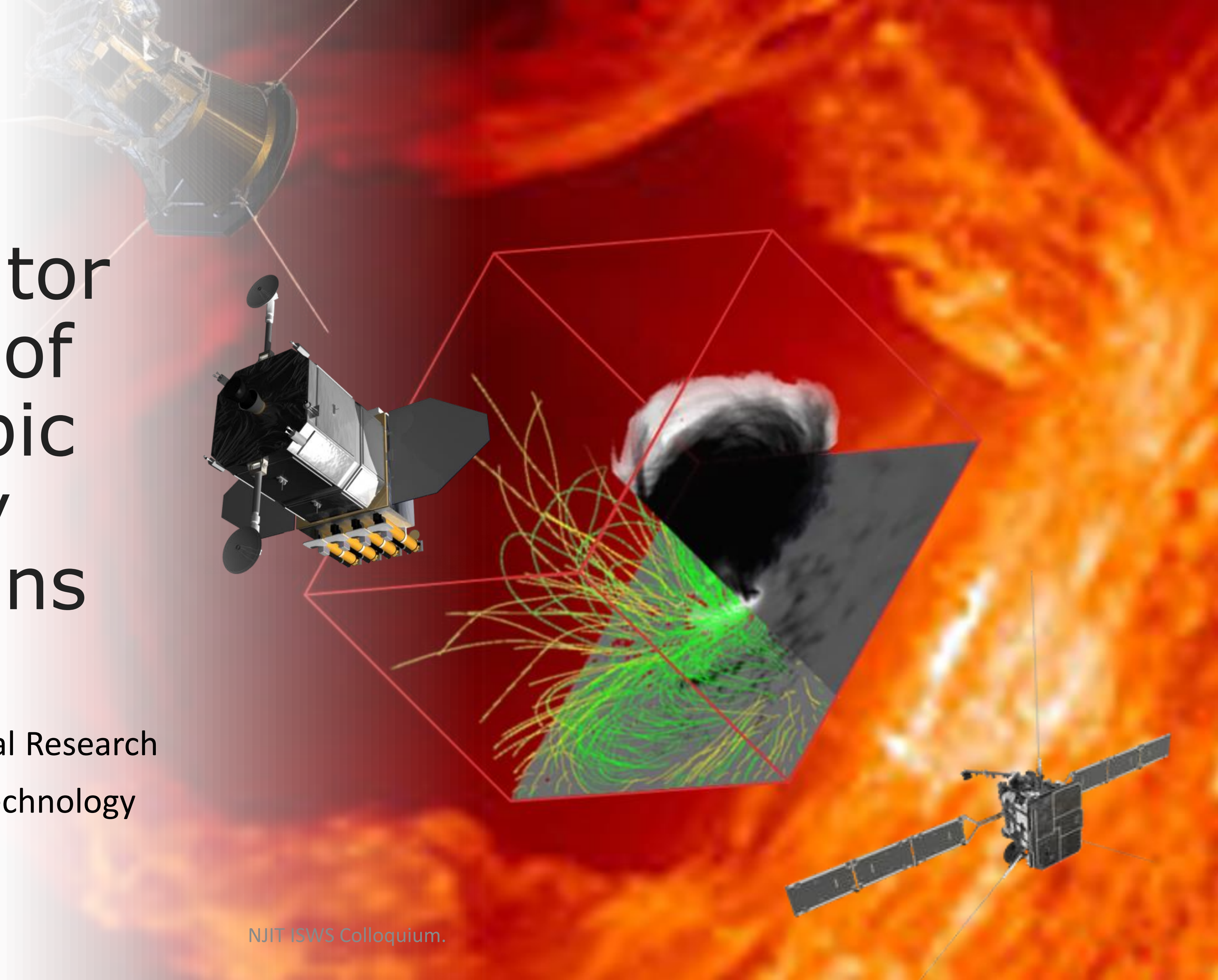
GX Simulator in the era of stereoscopic hard X-ray observations

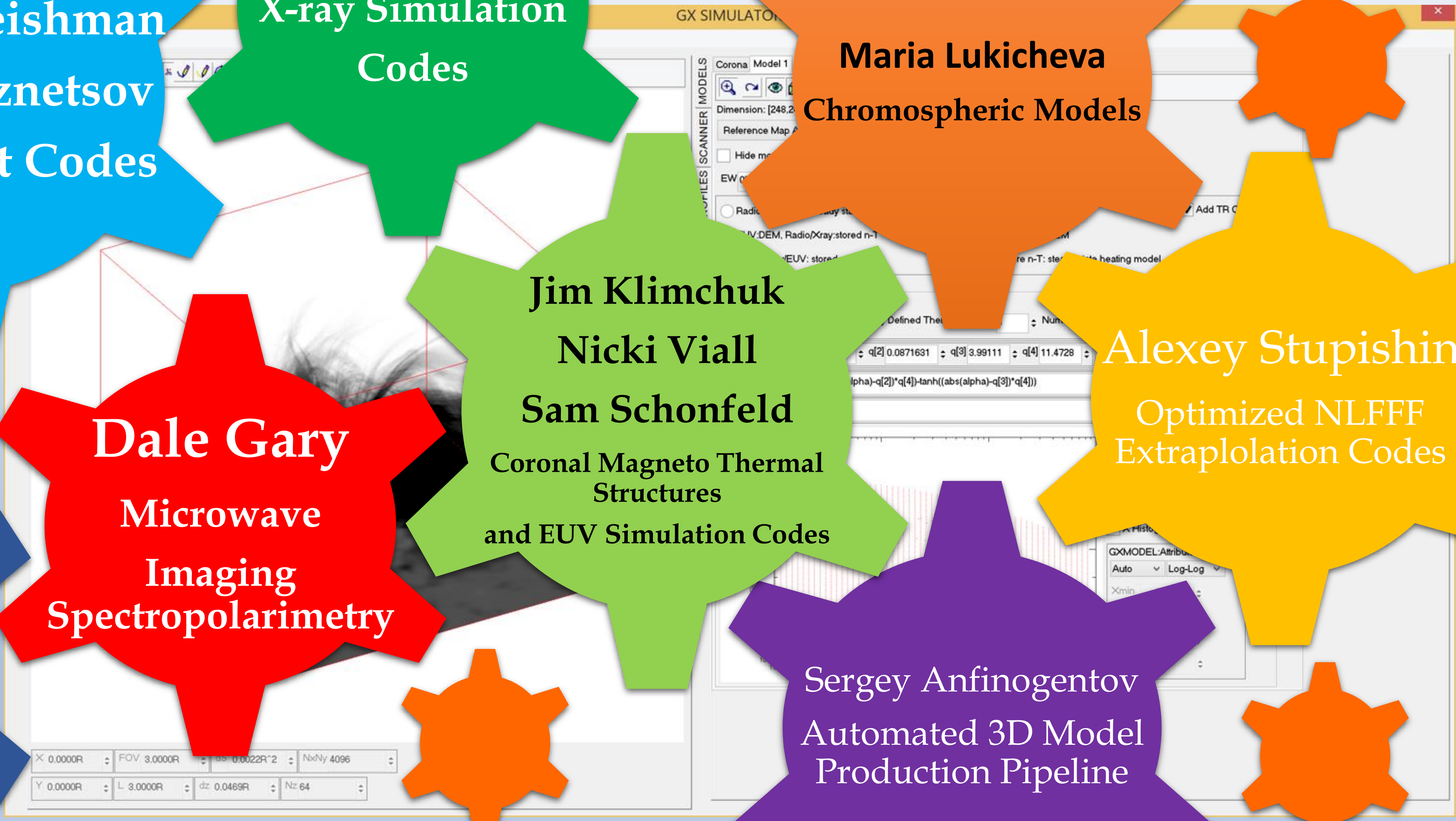


Gelu M. Nita

Center for Solar-Terrestrial Research

New Jersey Institute of Technology

Product of decade-long Teamwork



Gregory Fleishman
Alexey Kuznetsov
GS/GR Fast Codes

Eduard Kontar
X-ray Simulation Codes

Maria Lukicheva
Chromospheric Models

Jim Klimchuk
Nicki Viall
Sam Schonfeld
Coronal Magneto Thermal Structures and EUV Simulation Codes

Alexey Stupishin
Optimized NLFFF Extraplolation Codes

Dale Gary
Microwave Imaging Spectropolarimetry

Gelu Nita
Architecture and Developement

Sergey Anfinogentov
Automated 3D Model Production Pipeline

GX Simulator Framework

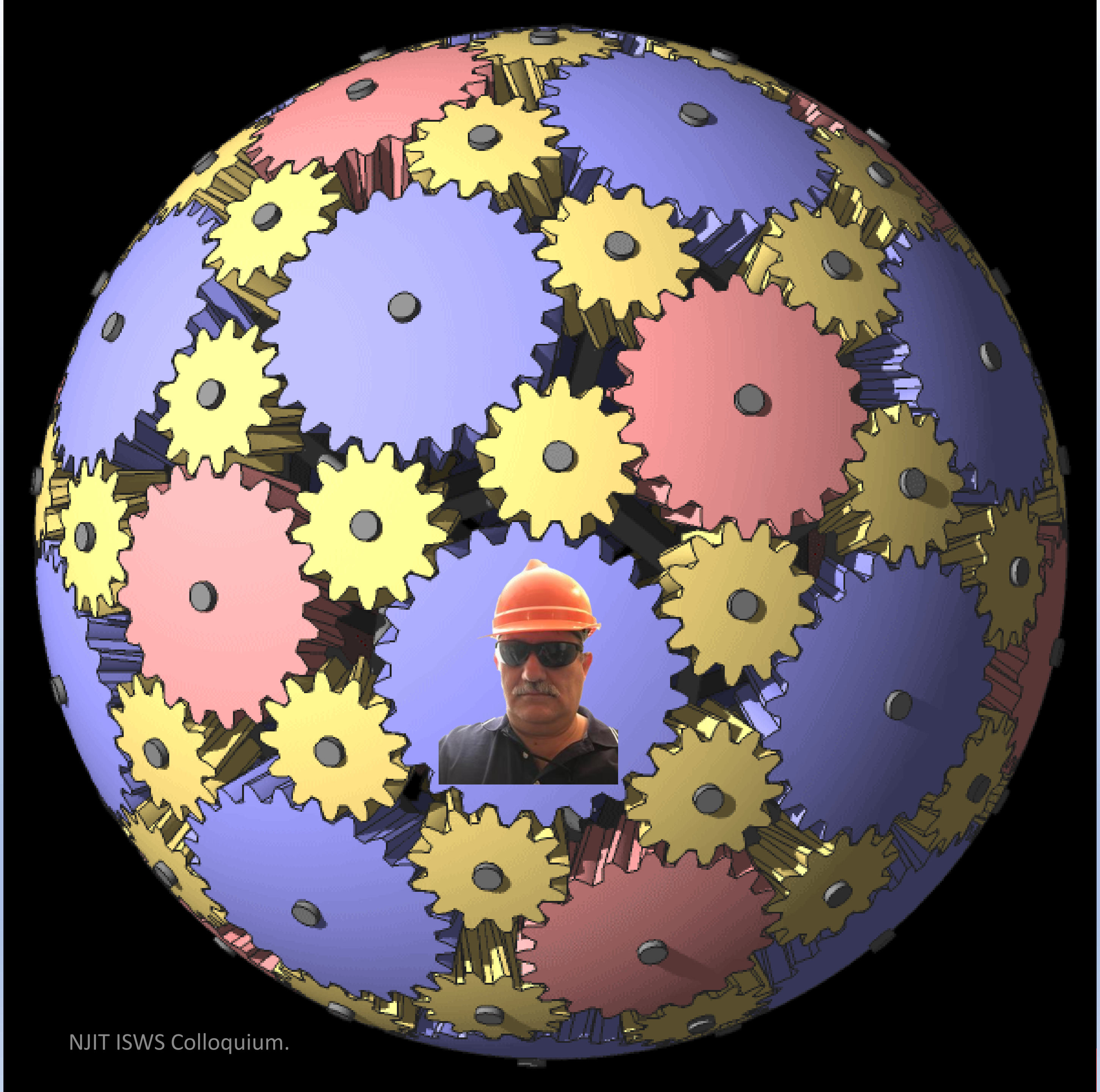
Puts together different observational inputs, theoretical methods, simulations and modeling, to create data-constrained modeling of a 3D volume of interest

IDL/SSW Package

https://github.com/Gelu-Nita/GX_SIMULATOR/

Nita et al. 2023, ApjS

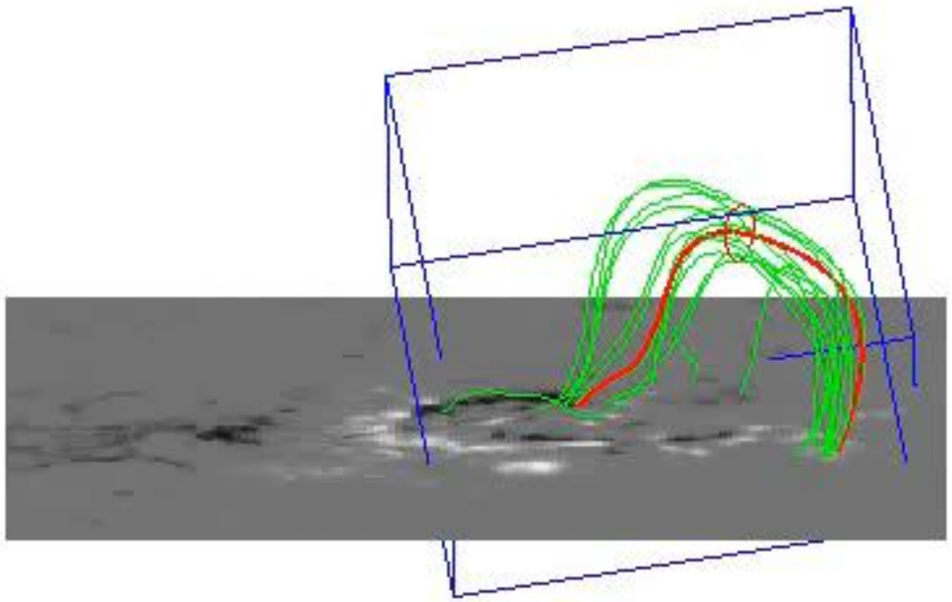
https://doi.org/10.3847/1538-4365/acd343



- Magnetic Flux Tube
- Temperature Distribution
- Thermal Electrons Density Distribution
- Nonthermal Electrons Density, Energy, and Pitch Angle Distributions

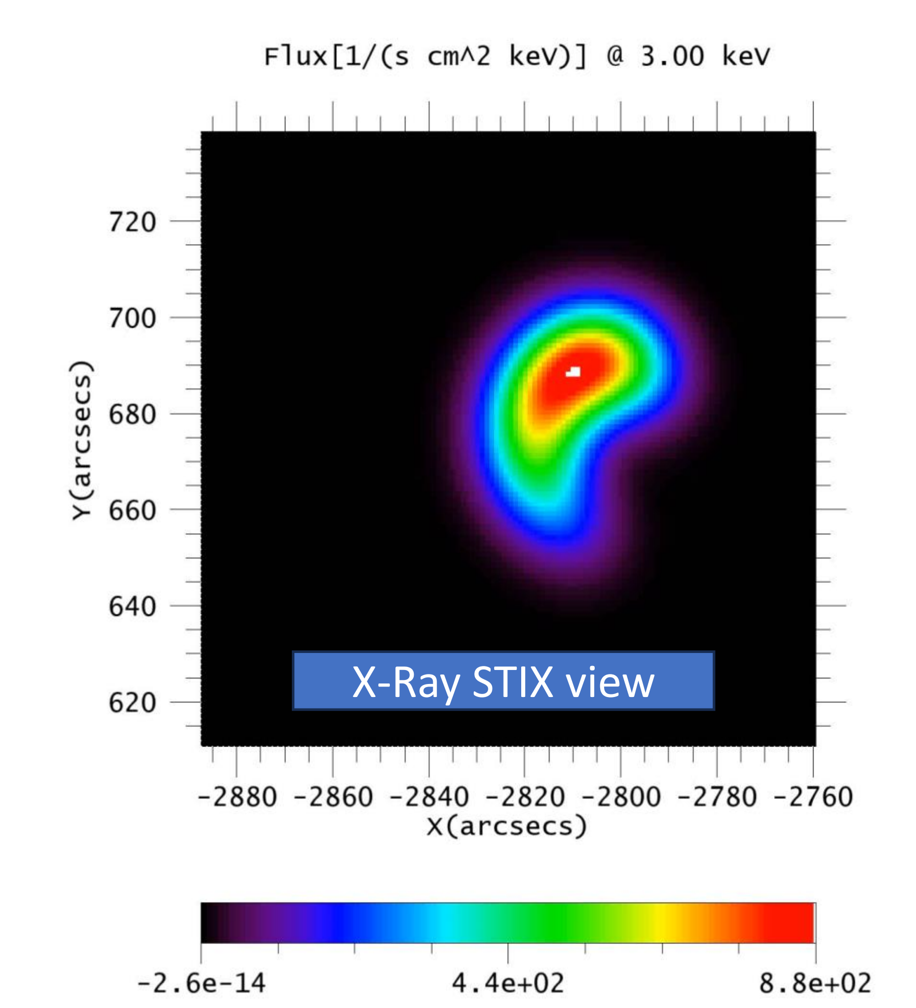
What GX Simulator can do?:

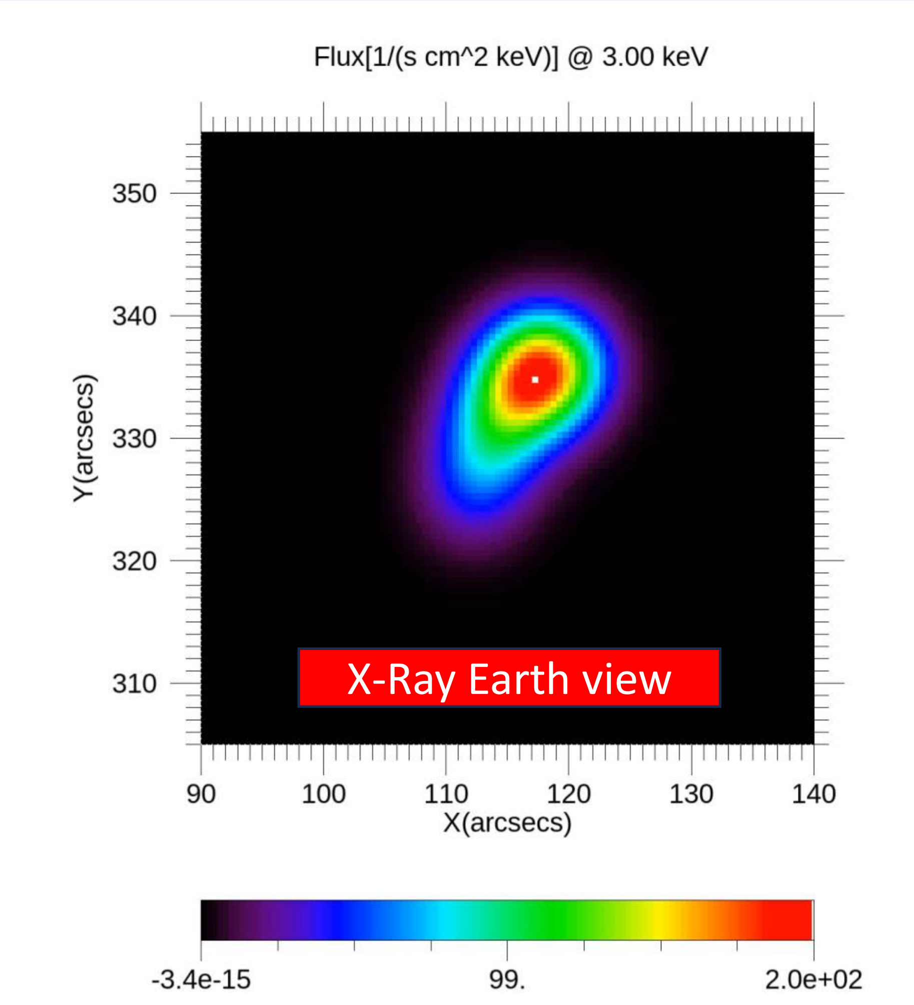
Build a 3D magneto-plasma model and used it to generate synthetic Microwave, X-ray, and EUV Images as seen from Earth and Spacecraft vantage points



Synthetic X-ray Images from STIX and Earth views, generated from the same 3D magneto-plasma model

- GX Simulator 3D Model tuned to match integrated FOV parameters derived from OSPEX STIX analysis
- Multi energy synthetic X-ray images generated from both STIX and Earth perspectives:
- No hard X-ray imaging data from Earth's perspective to compare with
- X-ray spectroscopy data available from both STIX and Earth perspectives (Fermi, Konus Wind),
- Thermal X-ray imaging data available from both perspectives (STIX and Hinode/XRT)



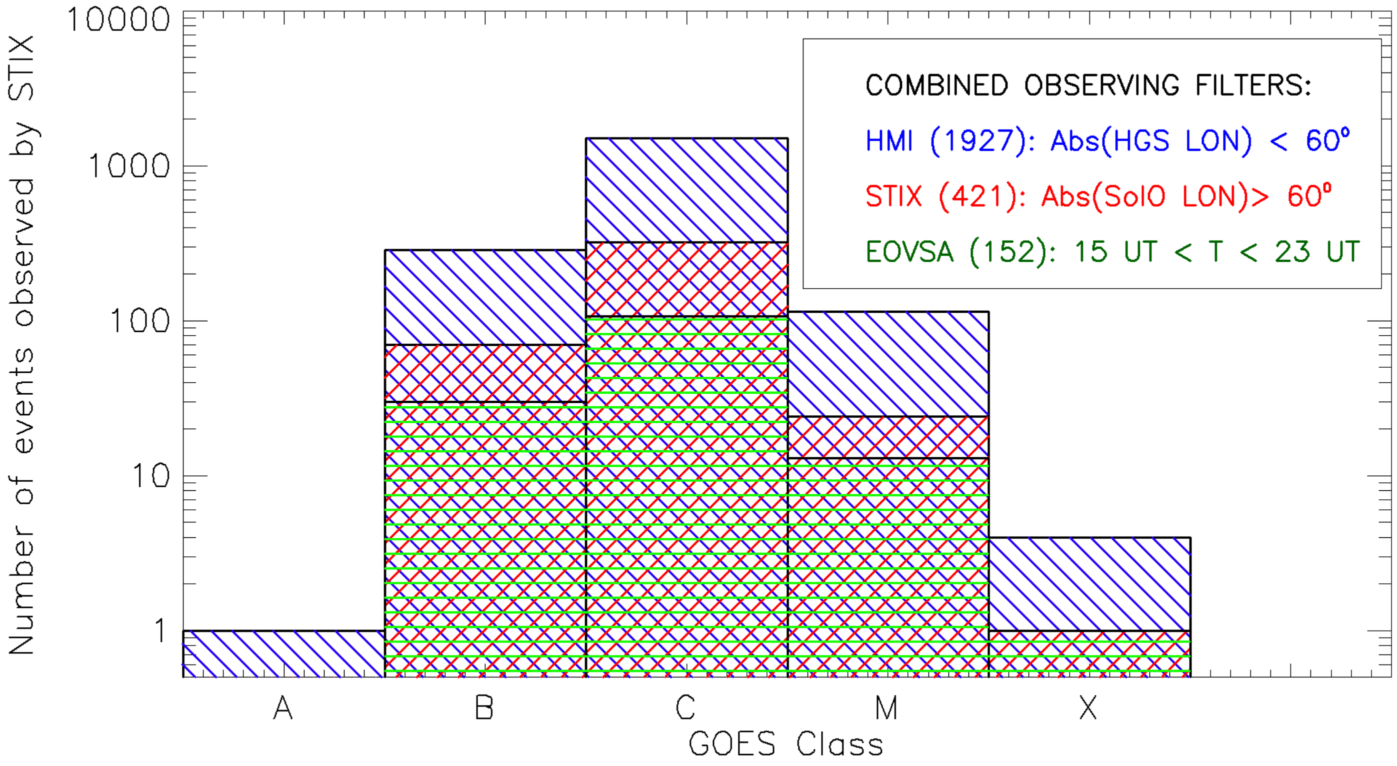


Outline of this presentation

- The anisotropy of energetic electrons accelerated and propagating in the flaring solar atmosphere is a central question in solar flare physics.
- Stereoscopic observations of solar flare hard X-ray emissions simultaneously from two spacecraft (e.g., Earth-orbiting and Solar Orbiter) offer a unique diagnostic opportunity to investigate Hard X-ray anisotropy, albedo, and electron anisotropy in solar flares.
- However, detailed simulations of Hard X-ray emission also require data-constrained 3D modeling of the magnetic field structure and plasma properties. Currently, this is feasible only for solar active regions observed by SDO/HMI reasonably close to the disk center.
- In this presentation, I will introduce an upgraded version of the GX Simulator IDL package. This enhanced tool allows for the modeling of magnetic field geometry and emissions across multiple wavelengths from various observation angles.
- Furthermore, I will share preliminary findings from a study involving X-ray data collected from nearly 90-degree-separated perspectives by STIX/SolO and Fermi/GBM.
- These results will be complemented by observations from microwave imaging spectroscopy provided by the Expanded Owens Valley Solar Array (EOVSA).

STIX EVENTS DATABASE

A total of 6429 observed between 2021-02-14T01:41:06.670 UT and 2023-04 30T15:06:45.205 UT

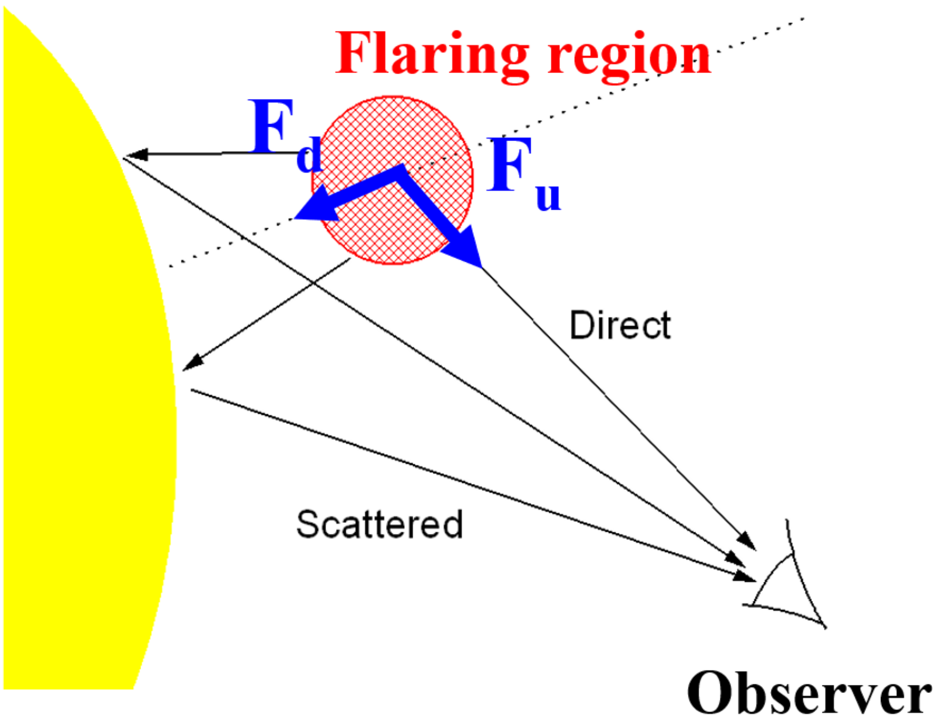


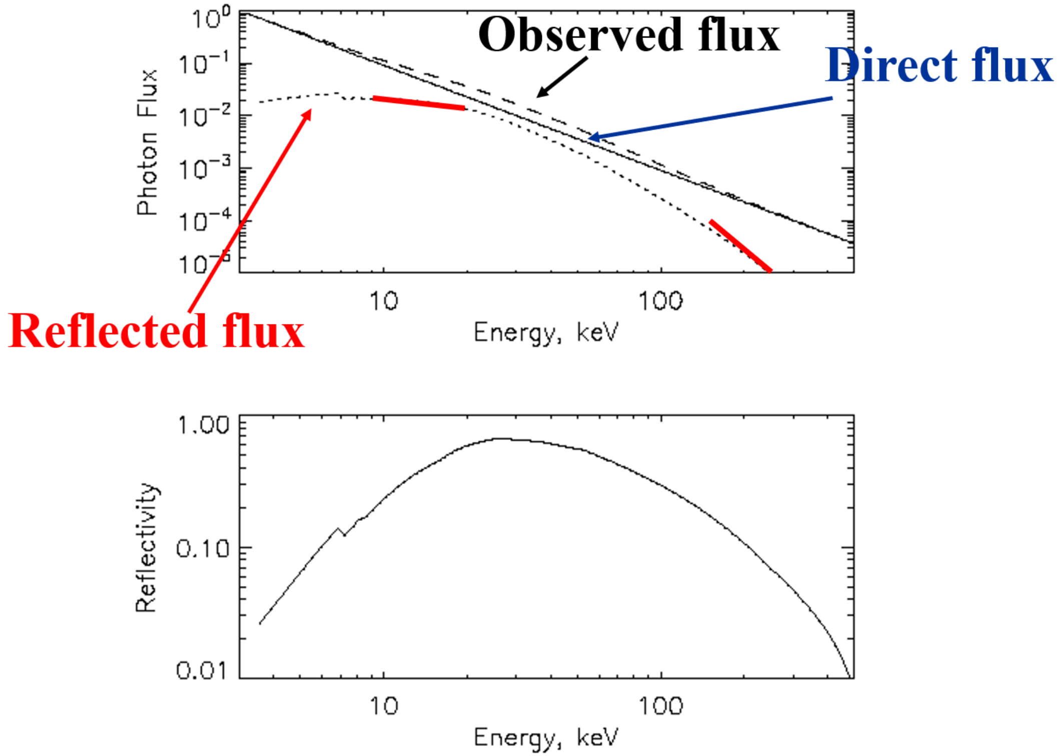
Distributions of STIX solar flare events in respect to their GOES class, filtered by a set of cumulatively applied selection criteria related to the SDO/HMI perspective, SolO/STIX perspective, and EOVSA observing time window

Credits: Laura Hayes & Hannah Collier

Overall source-observer geometry: Direct and Compton scattered photons

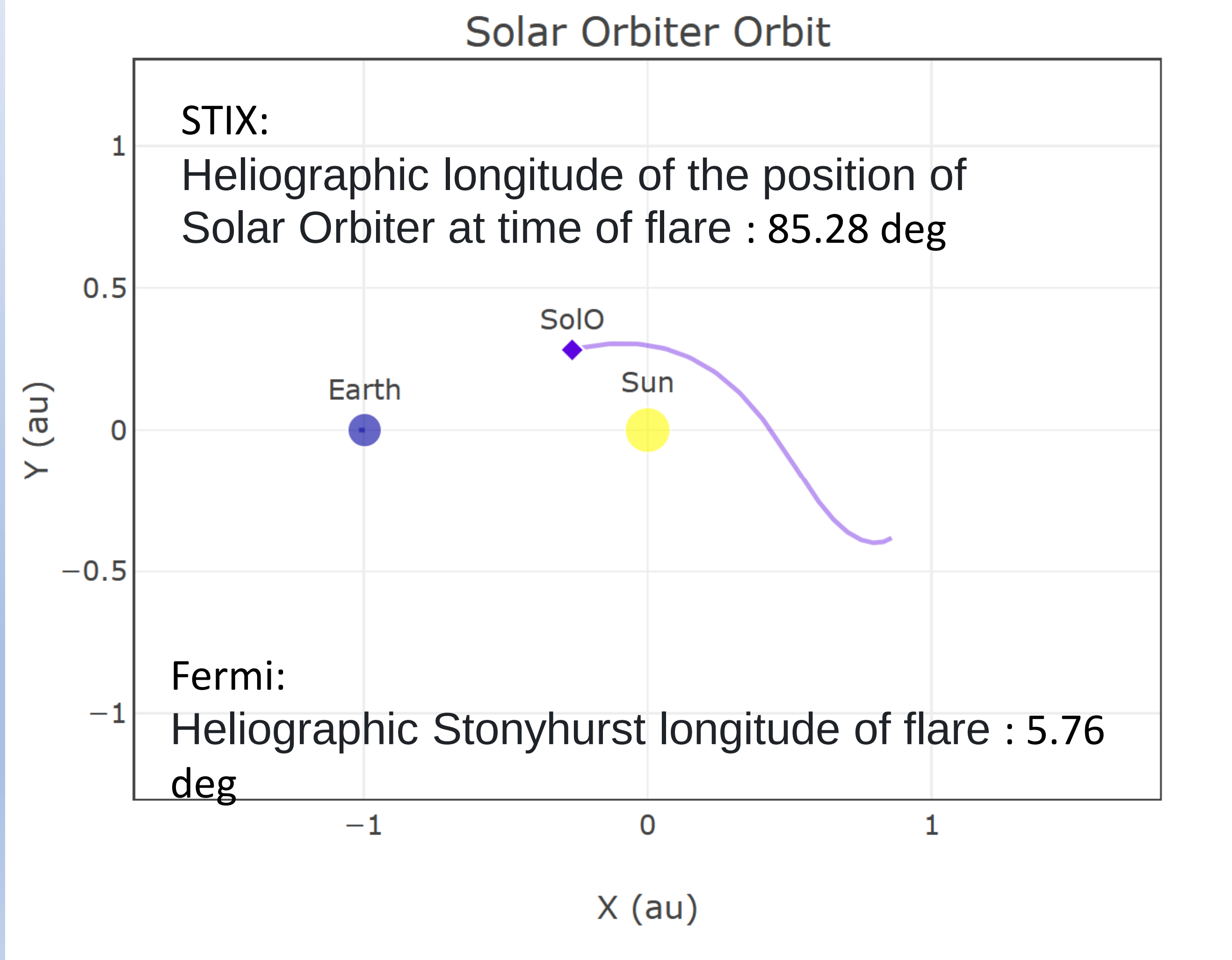
- The reflected flux **mainly** contribution depends on the source-observer geometry and on the alpha=Direct/Downward flux ratio.
  - Alpha=1 means isotropic emission
  - Alpha<1 results in more albedo contribution.





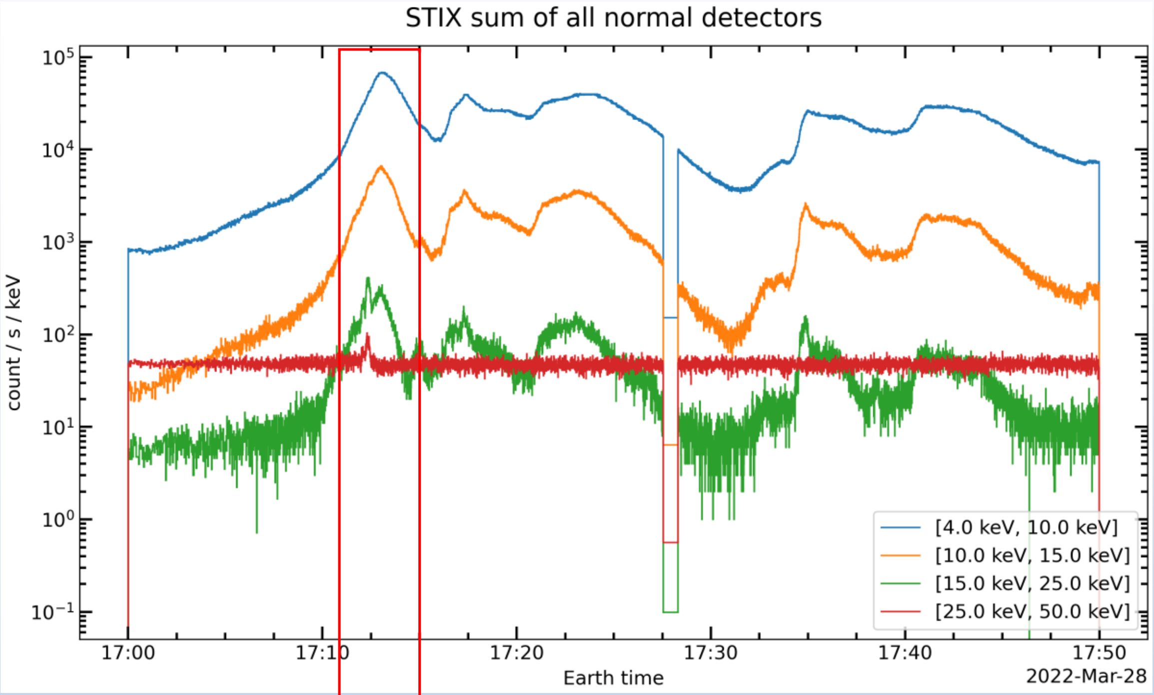
Credits: Eduard Kontar

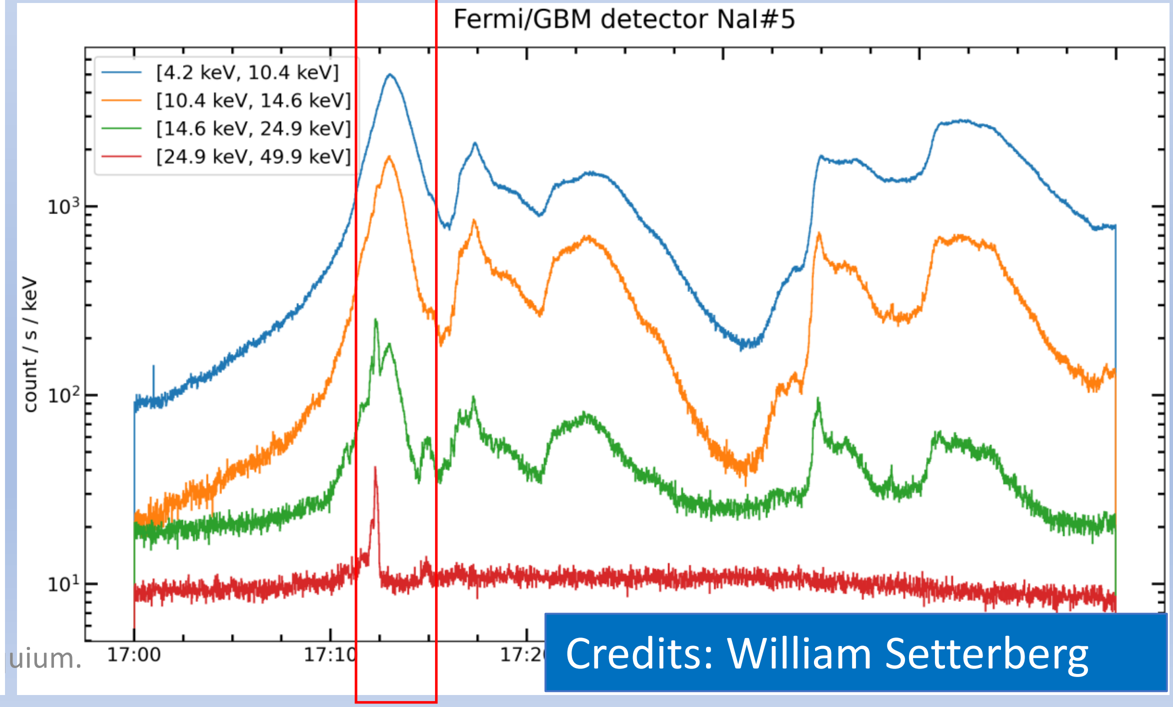
STIX and Fermi:
28-Mar-2022 17:11:11 UT
GOES M1.0 Solar Flare



STIX:
Heliographic longitude of the position of Solar Orbiter at time of flare : 85.28 deg

Fermi:
Heliographic Stonyhurst longitude of flare : 5.76 deg

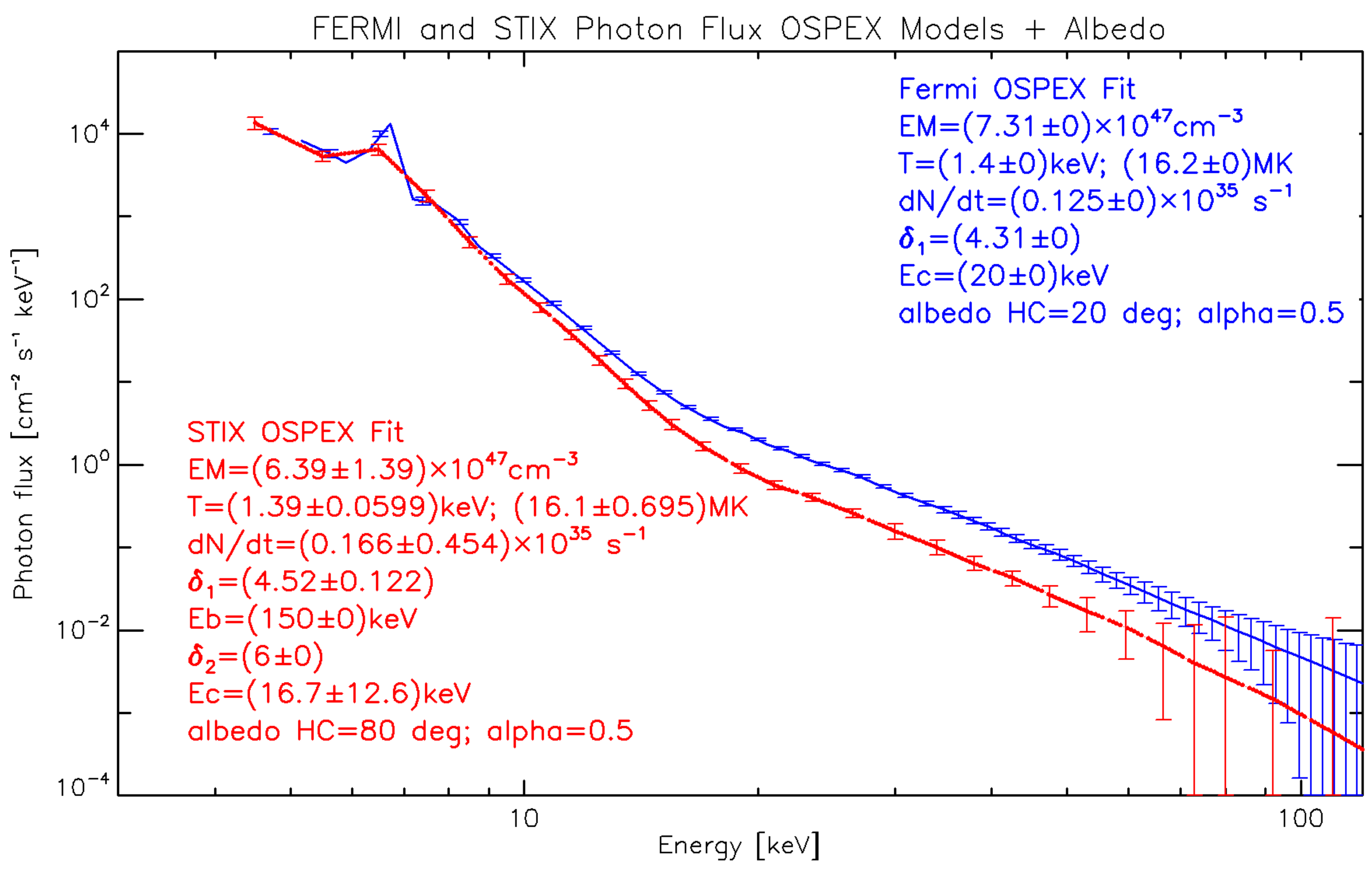




Credits: William Setterberg

STIX vs Fermi OSPEX fits

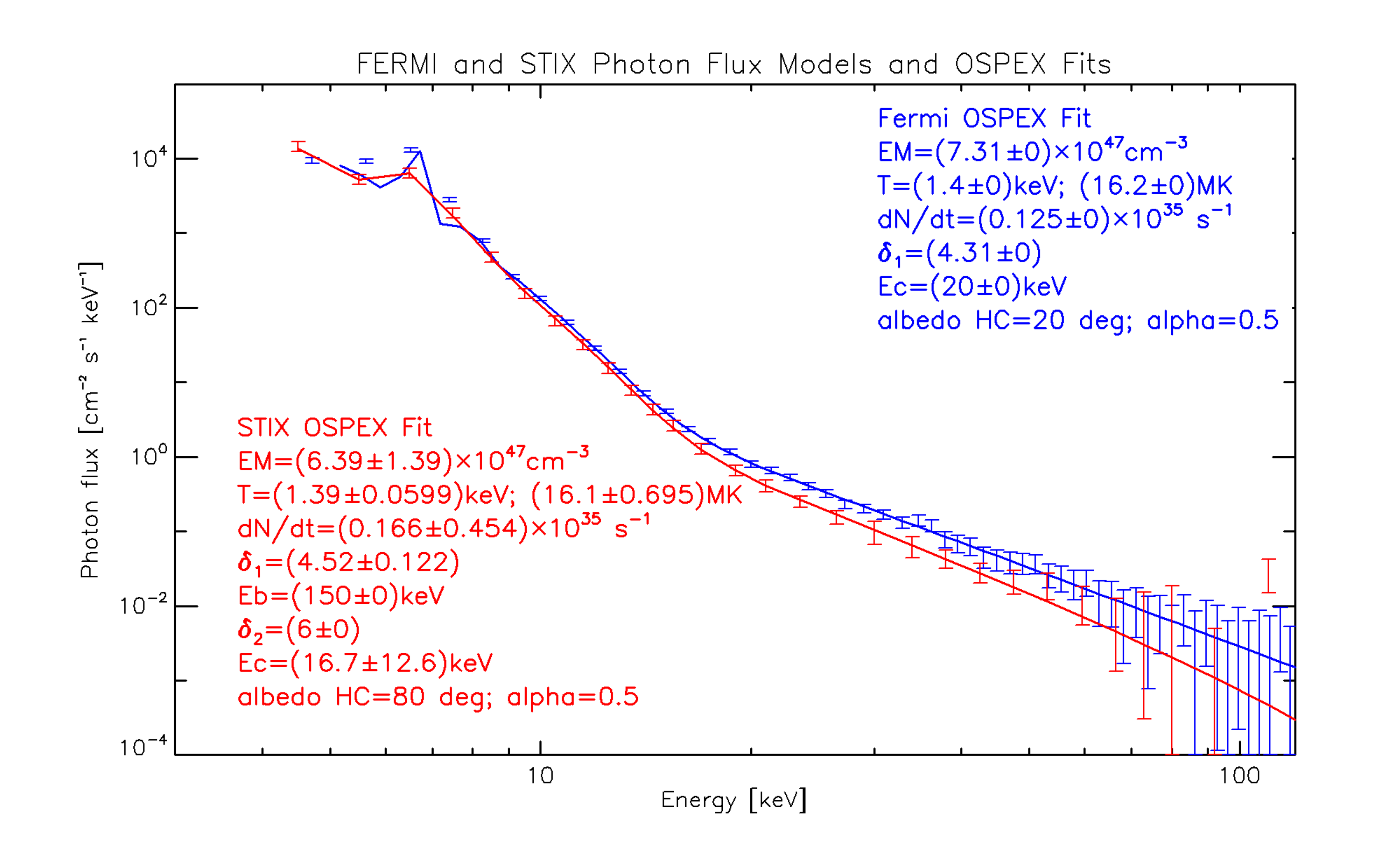
- The nonthermal dominated part of the STIX and FERMI photon flux model data disagree by more that their combined 3-sigma uncertainties.
- Possible reasons of disagreement:
  - **Calibration**
  - **Limb occultation** of one of the footpoints or an additional source seen by FERMI (near-disk center LOS) and not-seen by STIX (near-limb LOS)
  - **Different albedo contribution**
    - **Source-observer geometry**
    - **alpha=Direct/Downward Flux Ratio**
  - **Other possible directivity-related effects**
    - **3D distribution of particles**
    - **Distribution over pitch angle**



Credits: Natasha Jeffrey and Eduard Kontar

STIX vs Fermi OSPEX fits

- The nonthermal dominated part of the STIX and FERMI **source** photon flux model still disagree by more that their combined 3-sigma uncertainties after the albedo model is subtracted.
- Albedo contributions are different due to different source-observer geometry, but this cannot be the reason for the discrepancy seen here because the OSPEX model photon fluxes shown in the figure do not include the albedo components
- Possible reasons of disagreement:
  - The assumed **alpha** parameter might need to be adjusted
  - **Other directivity-related effects?**
    - **Spatially resolved observations from different vantage points may help disentangle all contributing factors**

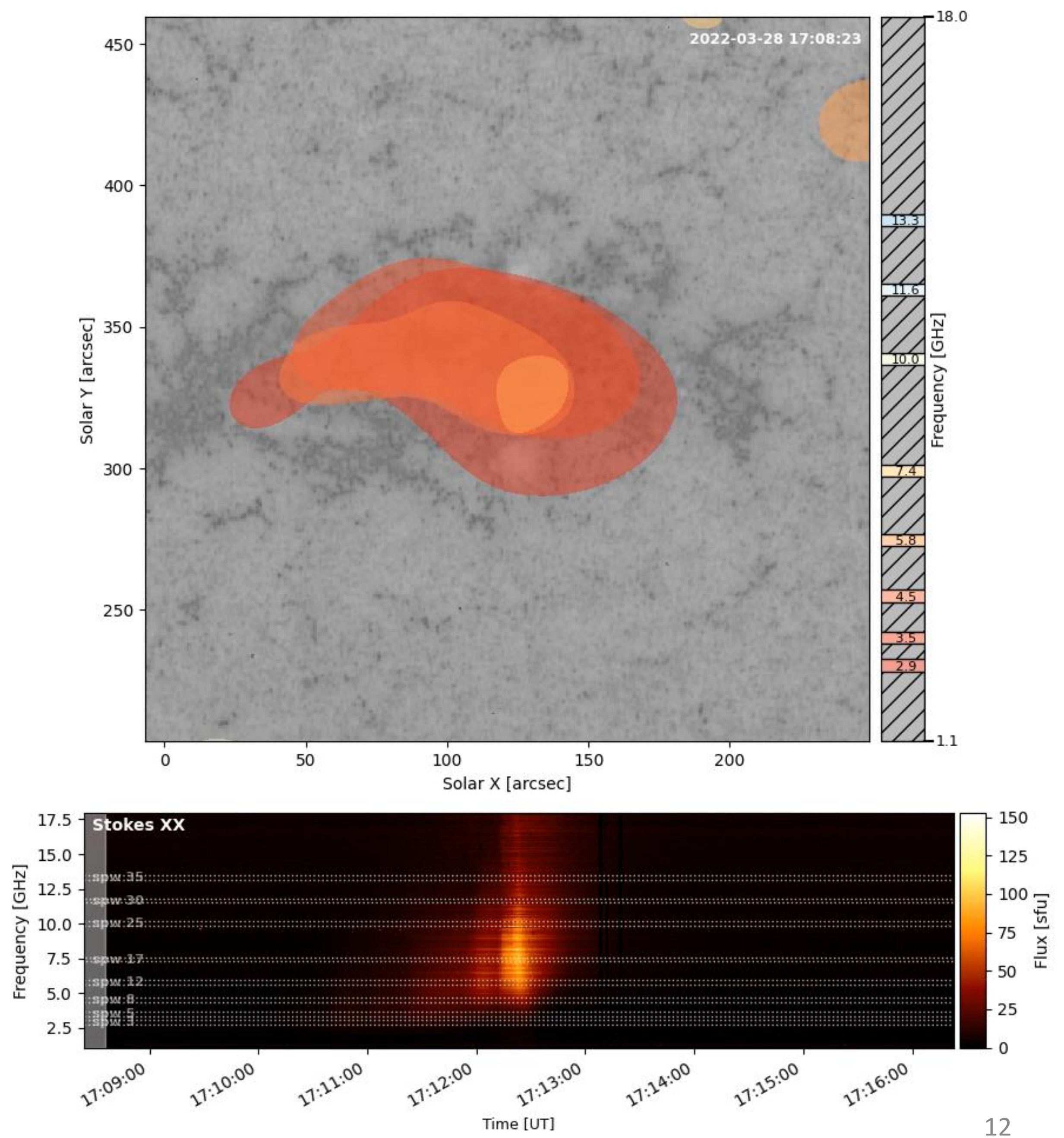


Credits: Natasha Jeffrey and Eduard Kontar

EOVSA Microwave Imaging Data
28-Mar-2022 17:11:11 UT
GOES M1.0 Solar Flare

EOVSA provides multi-frequency evolving microwave maps a tens of frequencies in the 1-!8 GHz range with a time resolution that can be as high as one frame per second.

The movie shown the time interval containing the the 28-Mar-2022 17:11:11 UT peak (8 frequencies, frequency-dependent spatial resolution, and 12 seconds time resolution)

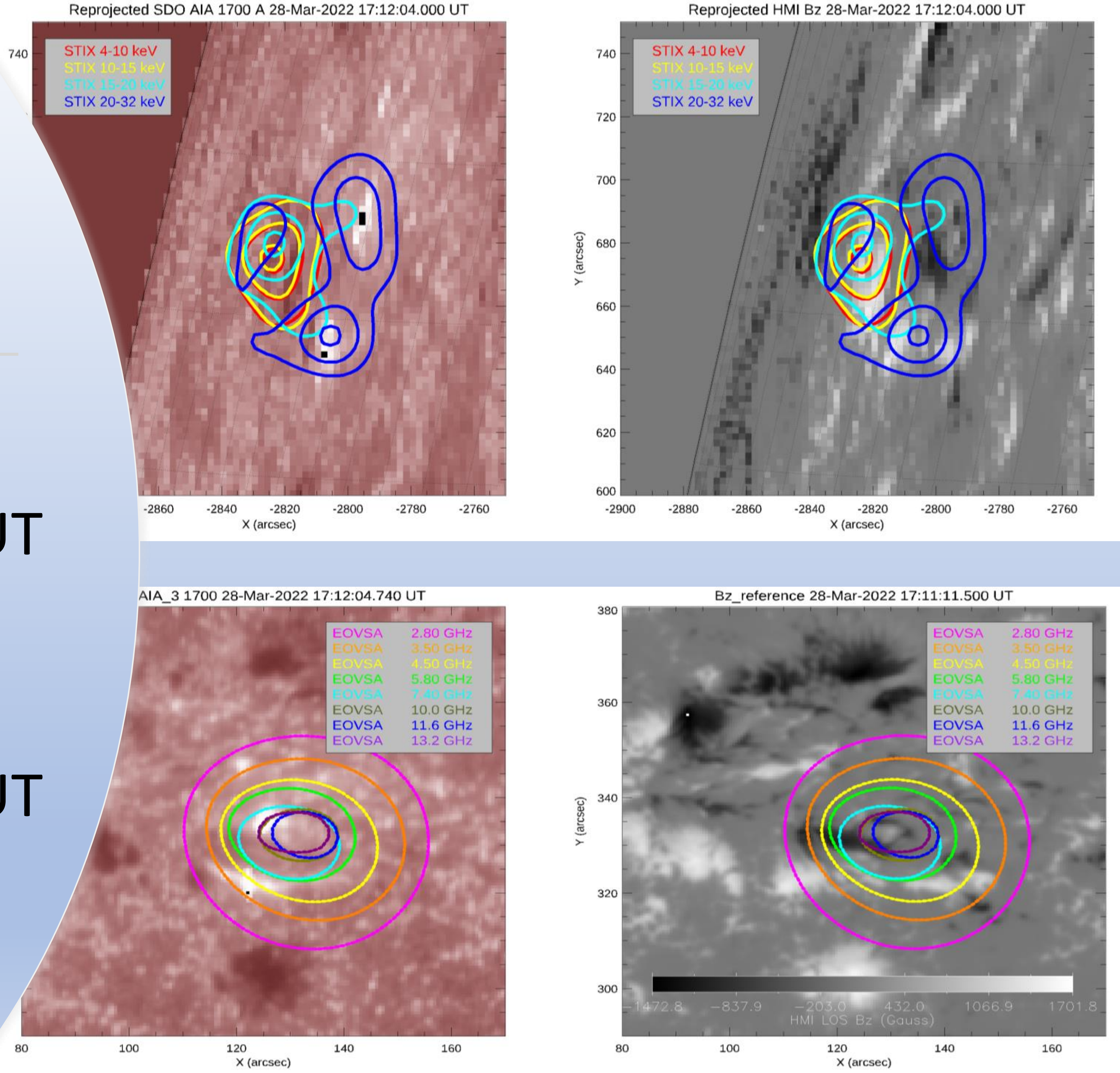


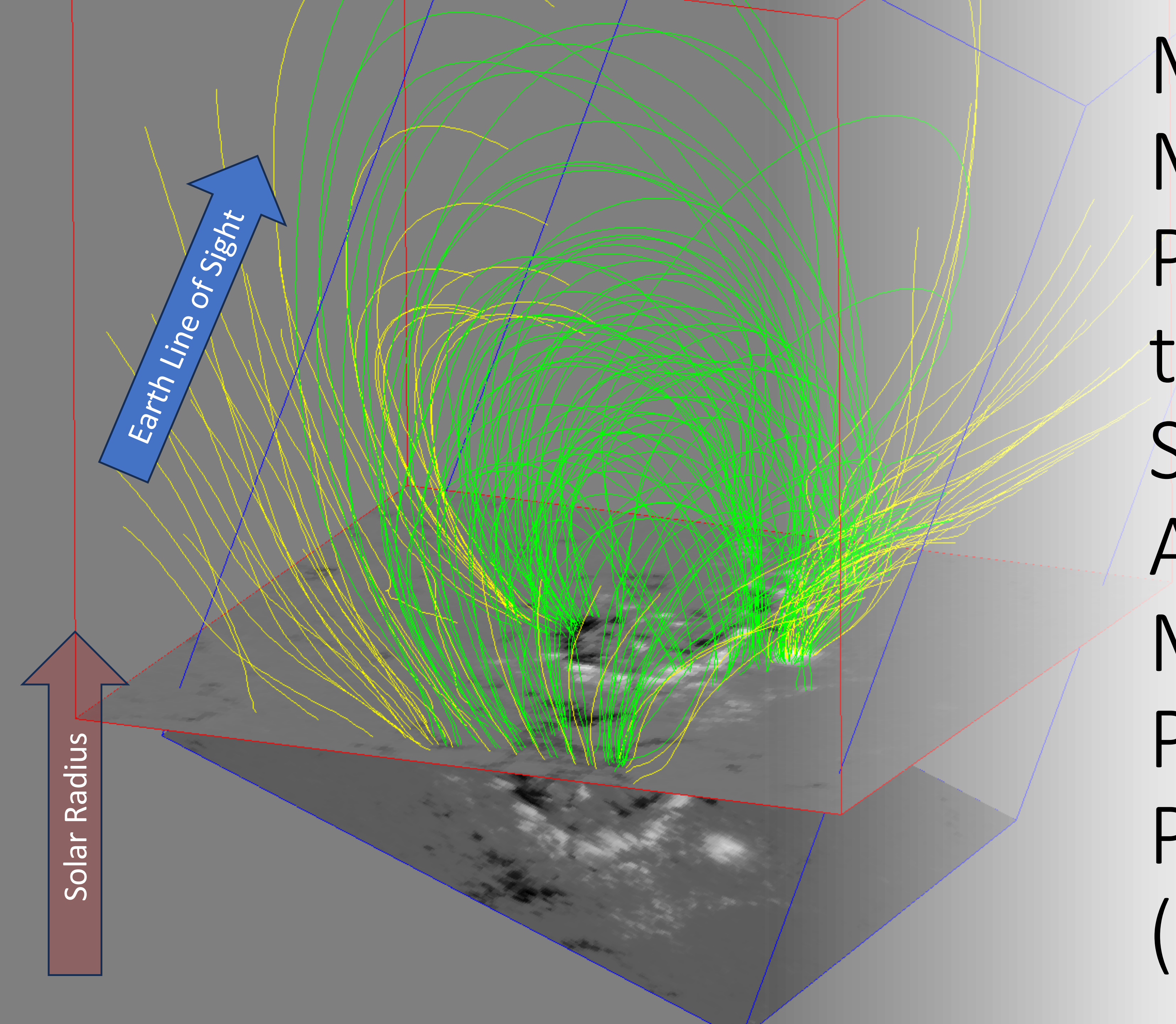
Credits: Surajit Mondal

STIX, SDO and EOVSA imaging data

- SolO:
  - 28-Mar-2022 17:06:20 UT
- SDO & Earth:
  - 28-Mar-2022 17:11:11 UT

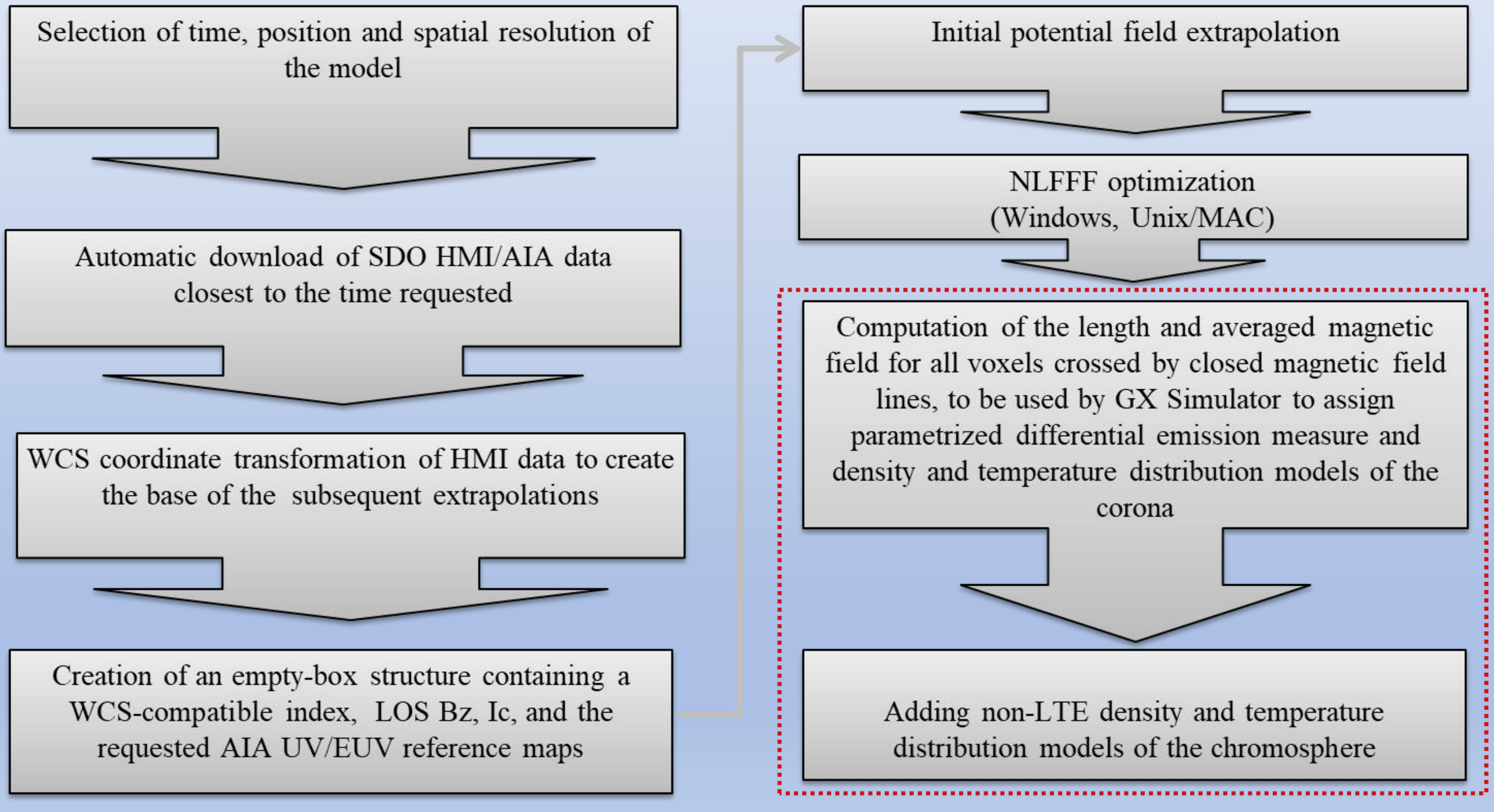
Credits: Laura Hayes and Surajit Mondal



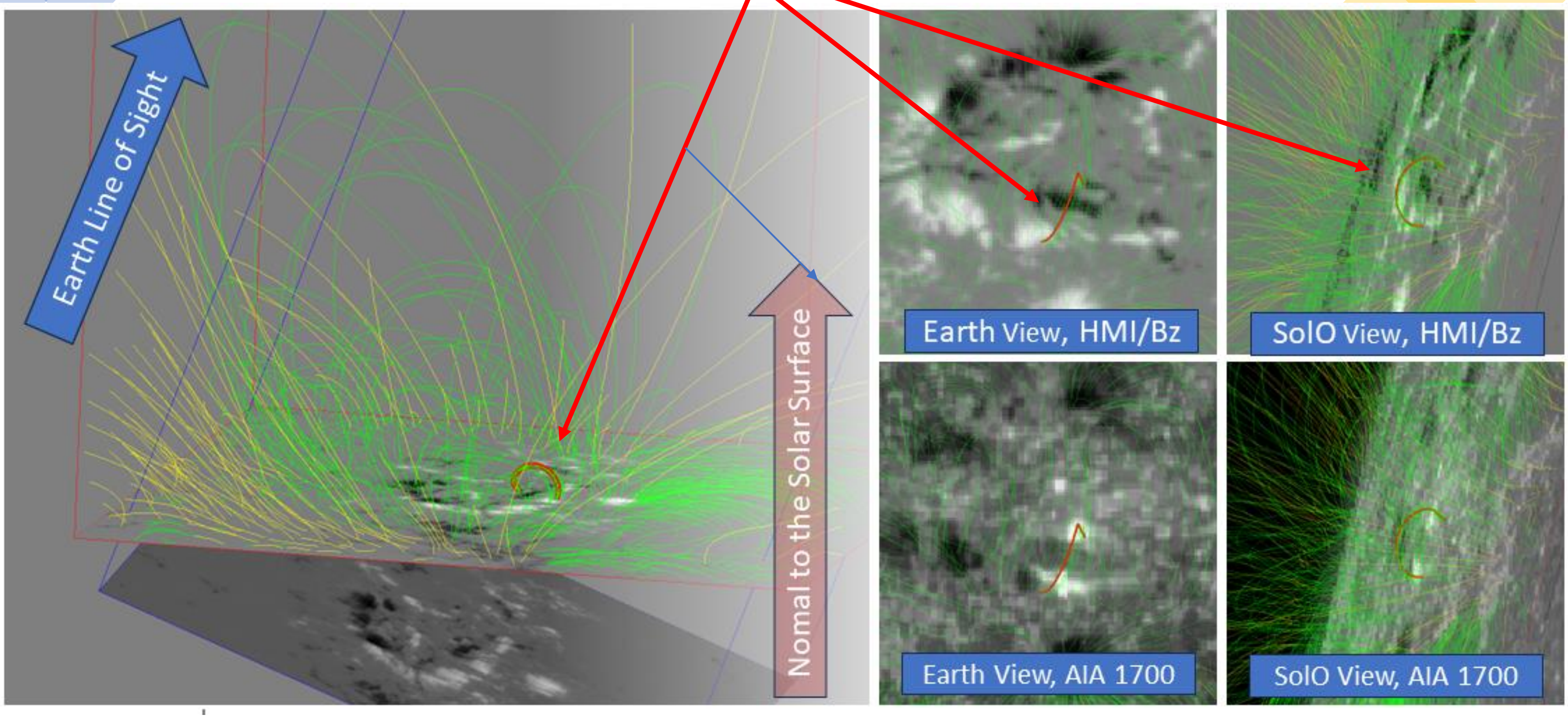


Magnetic field Model Produced by the GX Simulator Automatic Model Production Pipeline (AMPP)

GX Simulator Automatic Model Production Pipeline (AMPP)

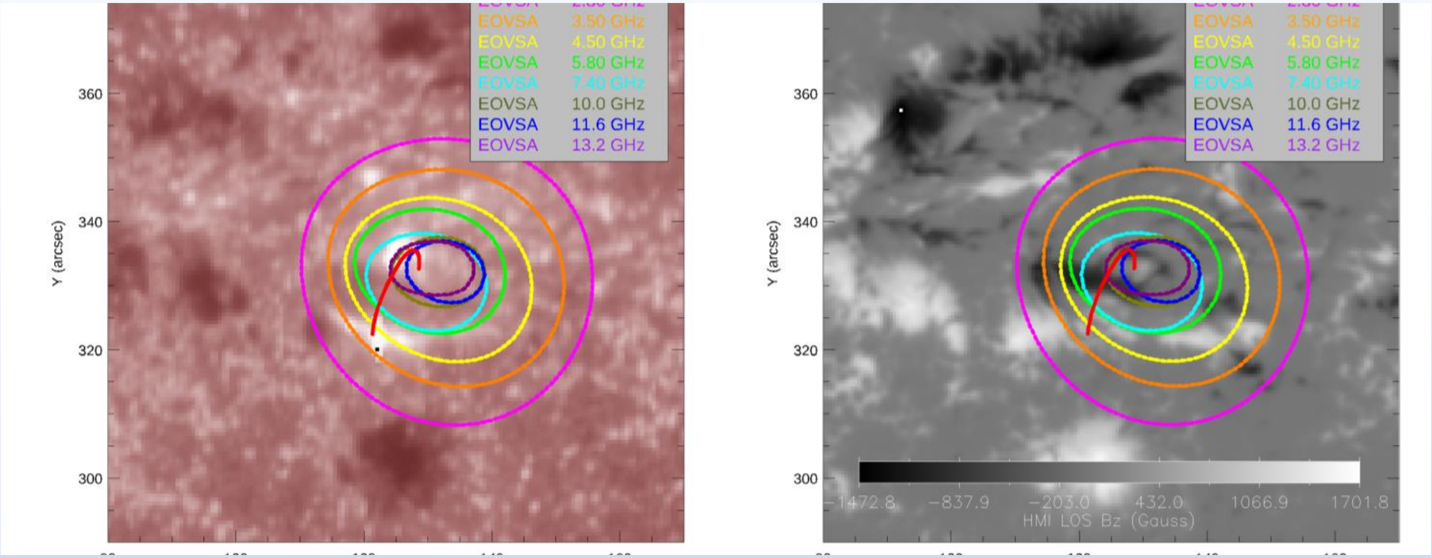


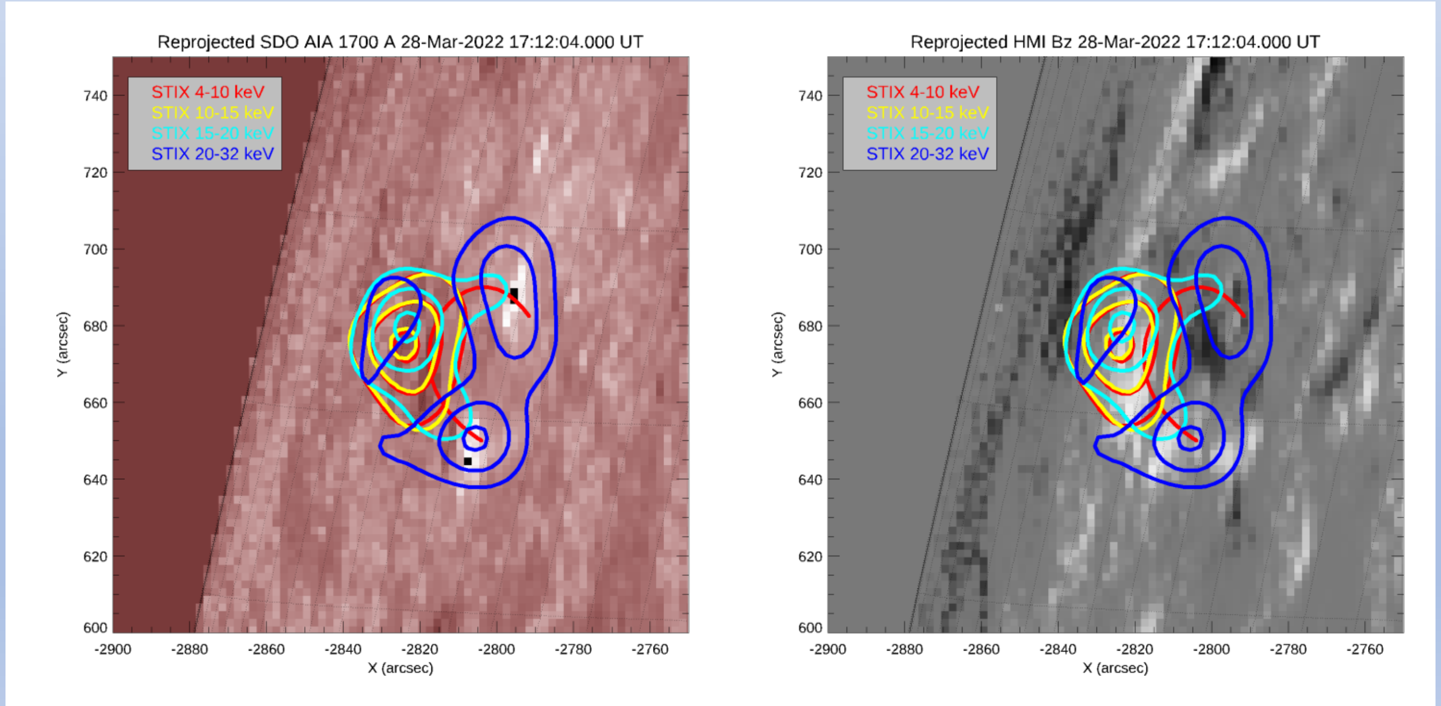
Selected Magnetic Field Line



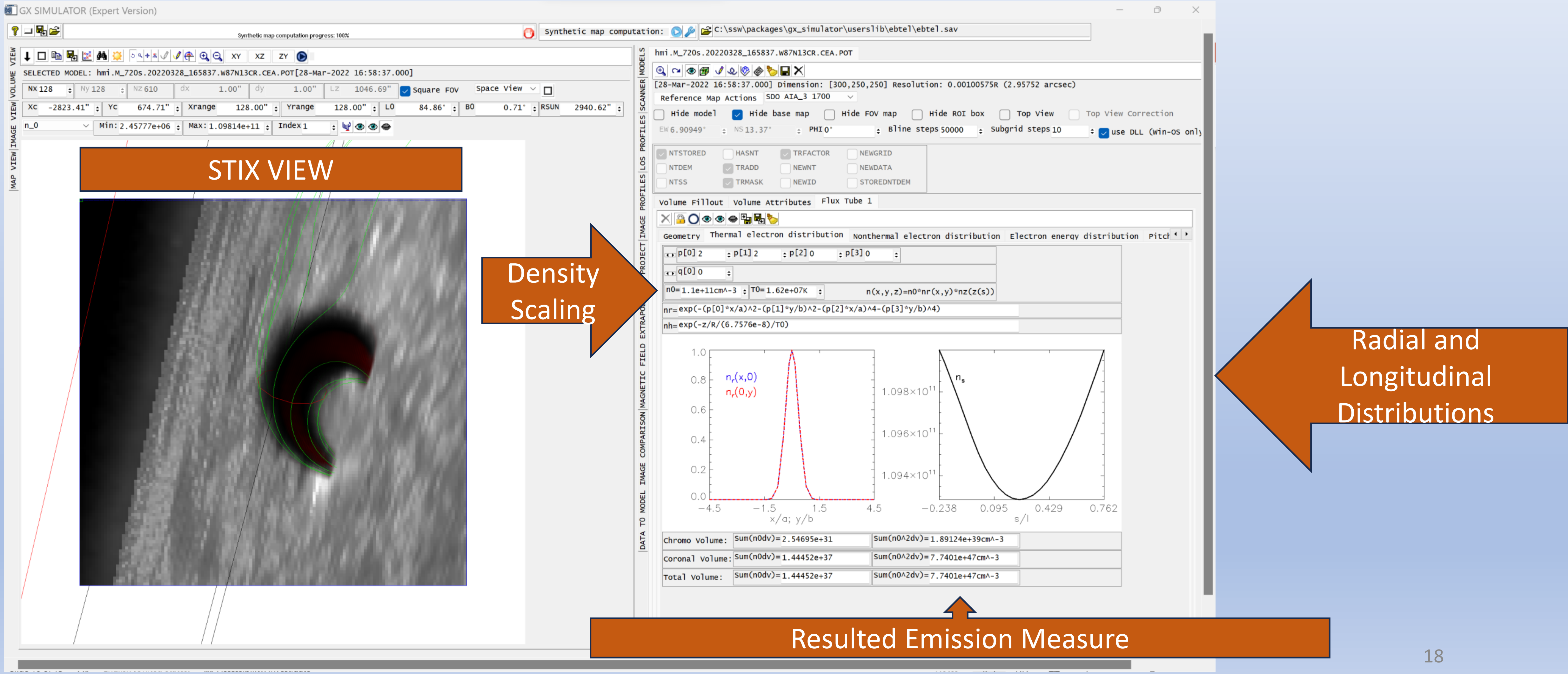
STIX, SDO and EOVSA imaging data+3D Magnetic Field Model

- SolO:
  - 28-Mar-2022 17:06:20 UT
- SDO & Earth:
  - 28-Mar-2022 17:11:11 UT
- Magnetic field line selected as flaring loop central line as suggested by all available imaging data

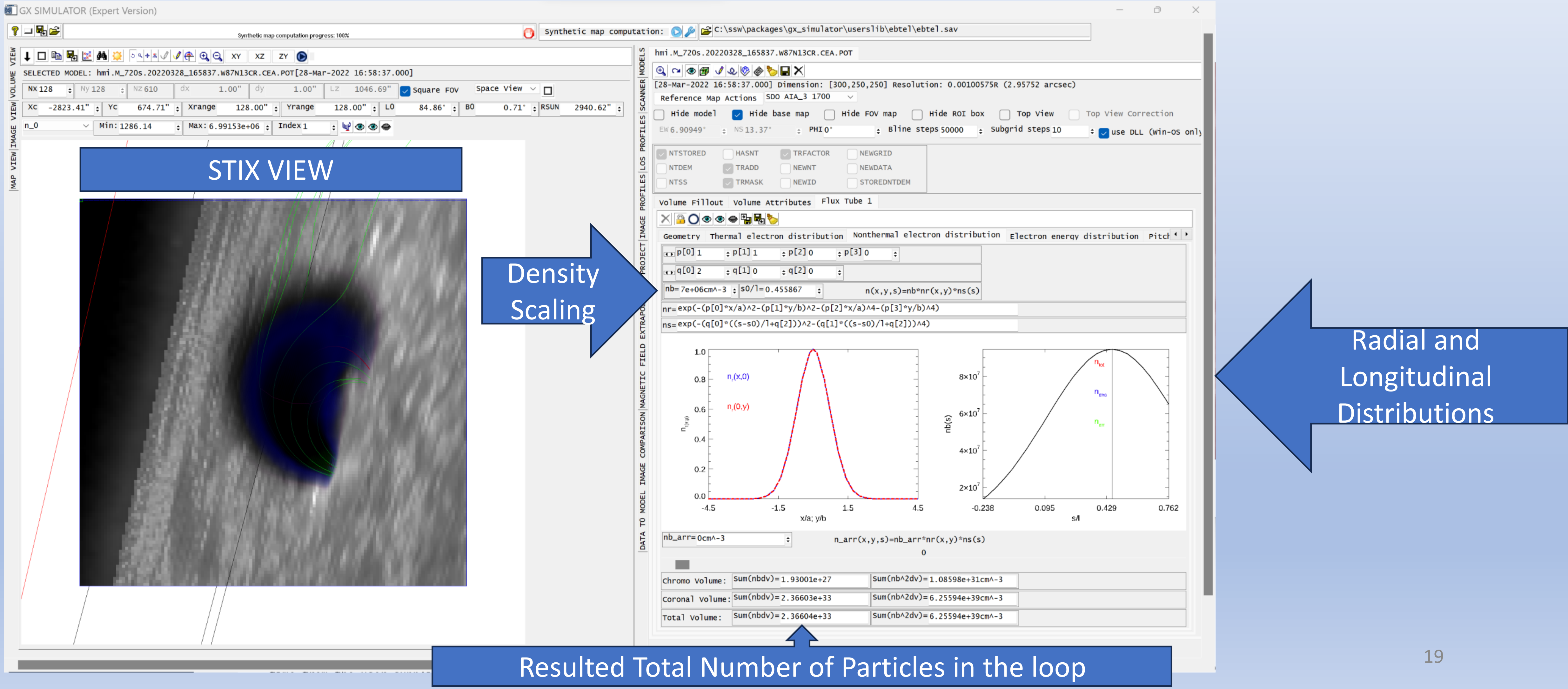




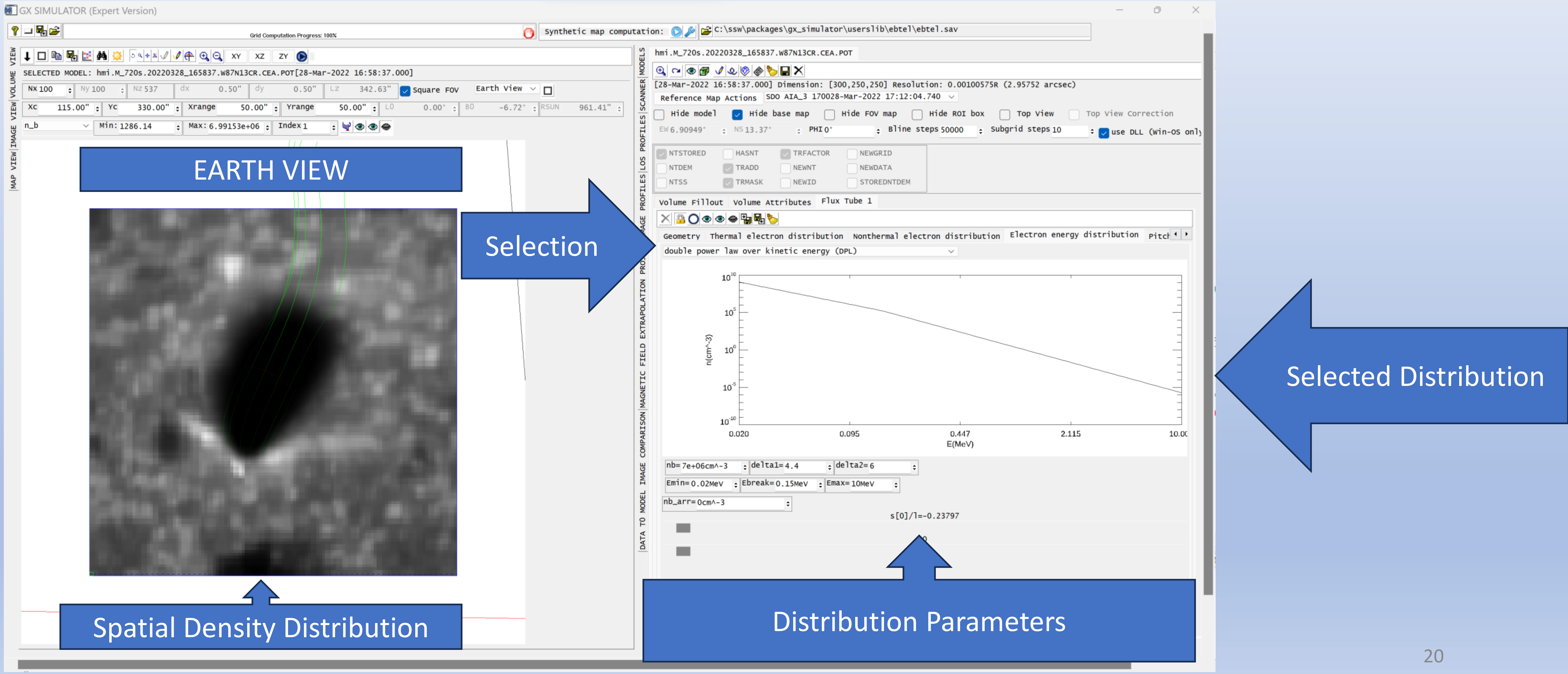
Magnetic Fluxtubes: Tools for Interactive Adjustment of the Thermal Electrons Spatial Distribution



Magnetic Fluxtubes : Tools for Interactive Adjustment of the Non-Thermal Electrons Spatial Distribution



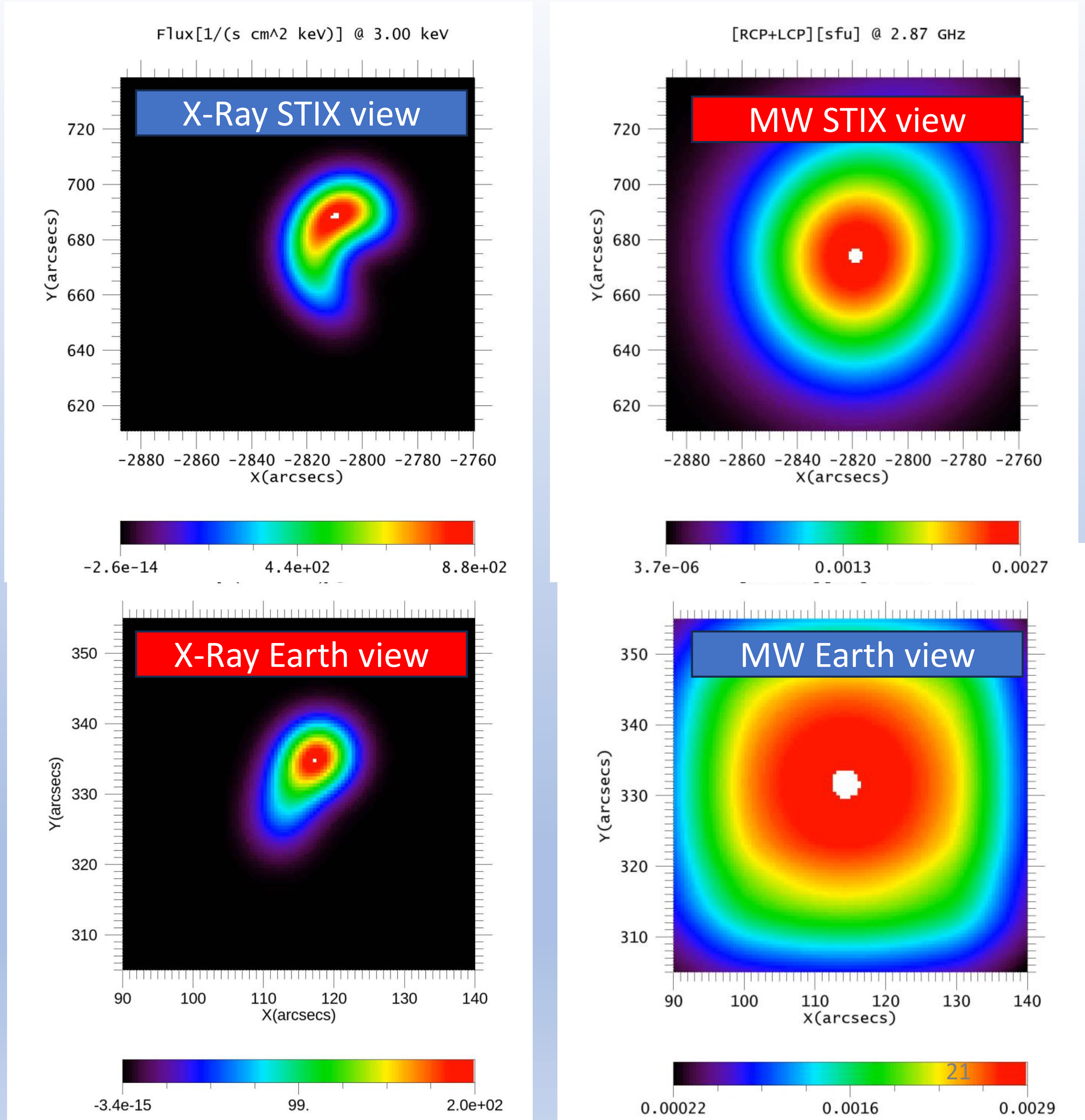
Magnetic Fluxtubes : Tools for Interactive Adjustment of the Non-Thermal Electrons Distribution over Energy



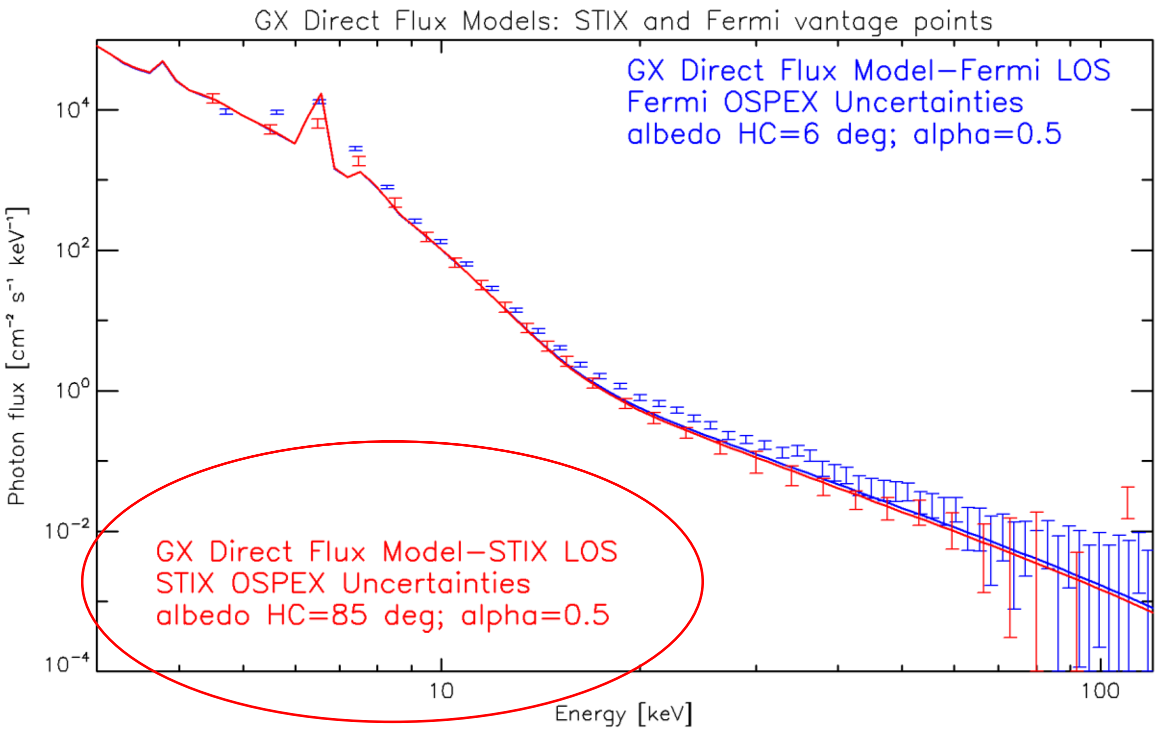
GX Simulator Synthetic Images from STIX and Fermi views

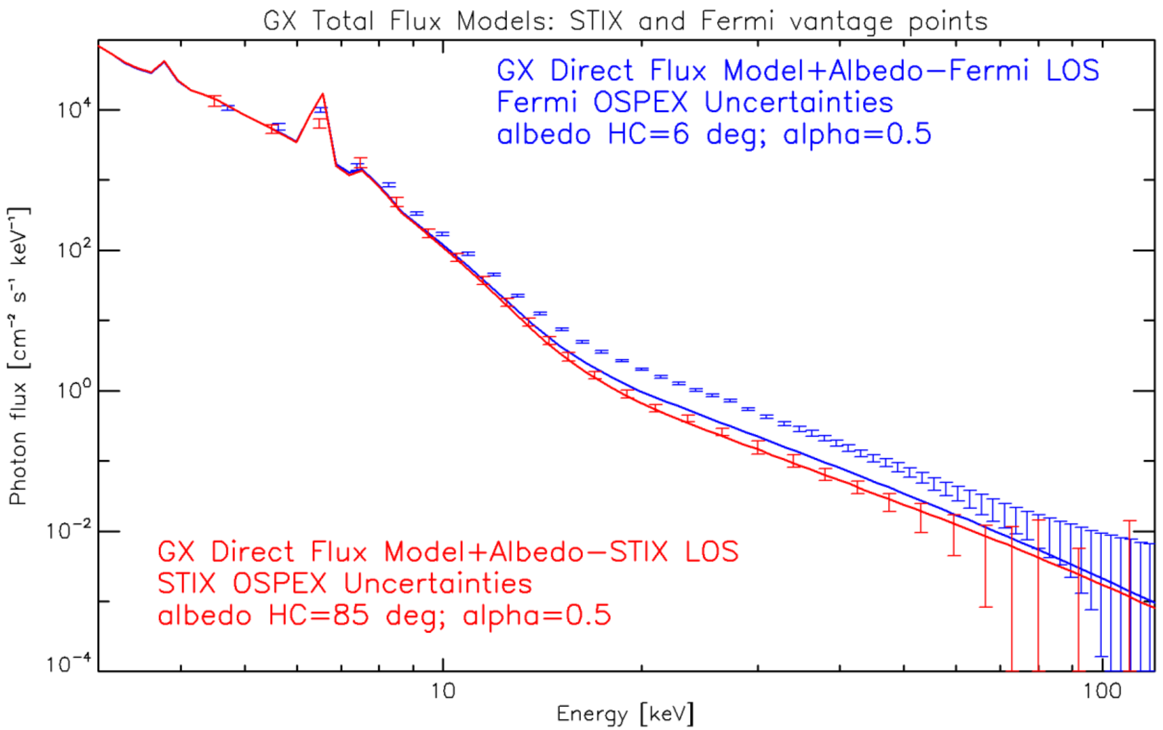
- GX Simulator 3D Model tuned to match integrated FOV parameters derived from OSPEX STIX analysis

- Synthetic X-ray images generated from STIX and Fermi perspectives:
  - 100 energy channels from 3-300 keV
- Synthetic MW images generated from STIX and EOVSA perspectives:
  - 42 frequencies from 2.87 to 16.19 GHz (EOVSA covers the 1-18 GHz range)
- No hard X-ray imaging data from Earth perspective and no MW imaging data from STIX perspective to compare with



Quantitative Model-to-Data Comparison of FOV-integrated X-ray Photon Spectra (STIX model tuning)

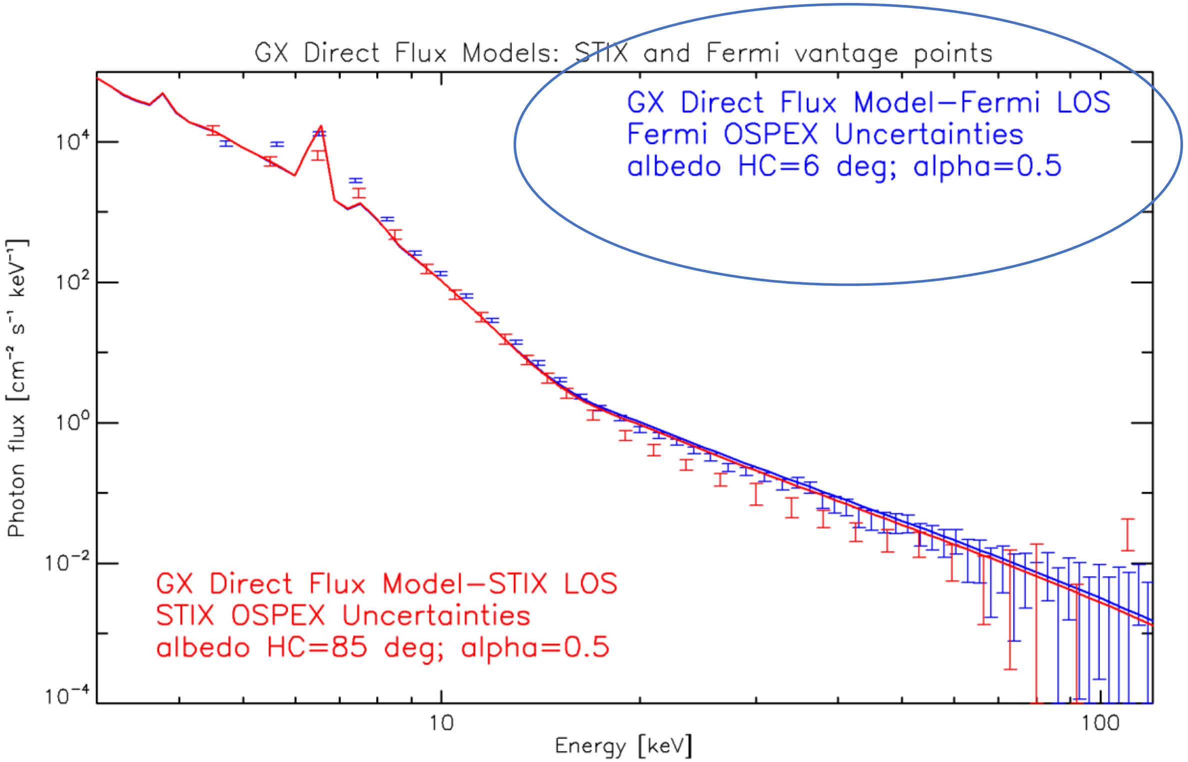


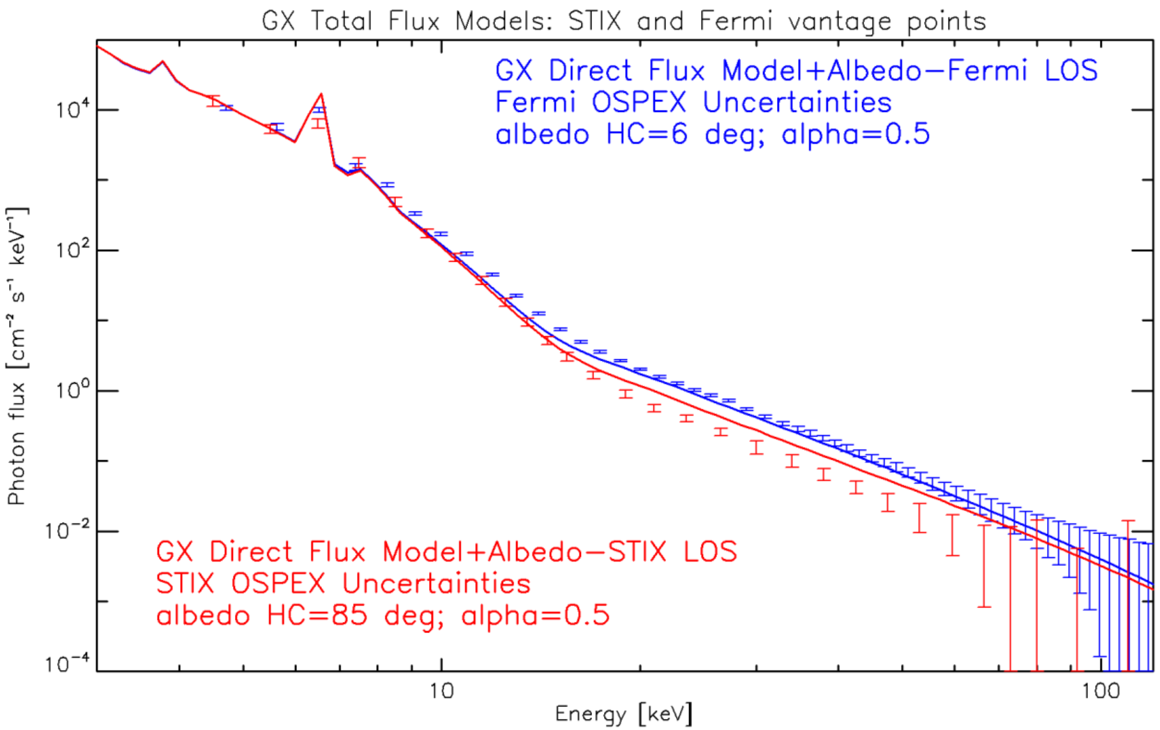


Only the GX STIX-view direct photon flux spectrum has been tunned to match the OSPEX STIX model spectrum

The STIX-tuned model underestimates the FERMI albedo

Quantitative Model-to-Data Comparison of FOV-integrated X-ray Photon Spectra (Fermi model tuning)



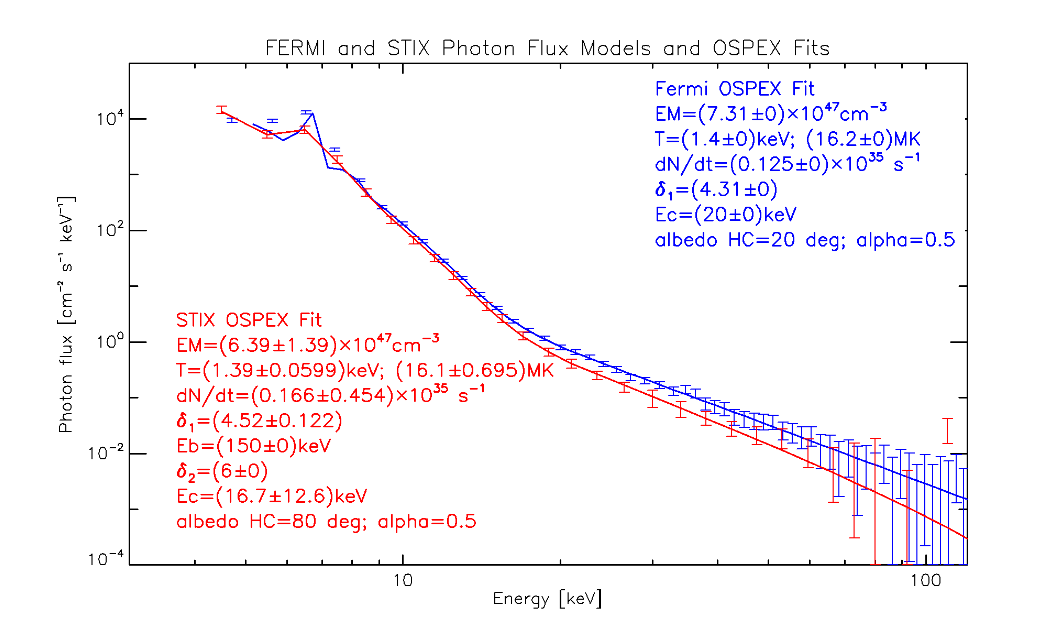


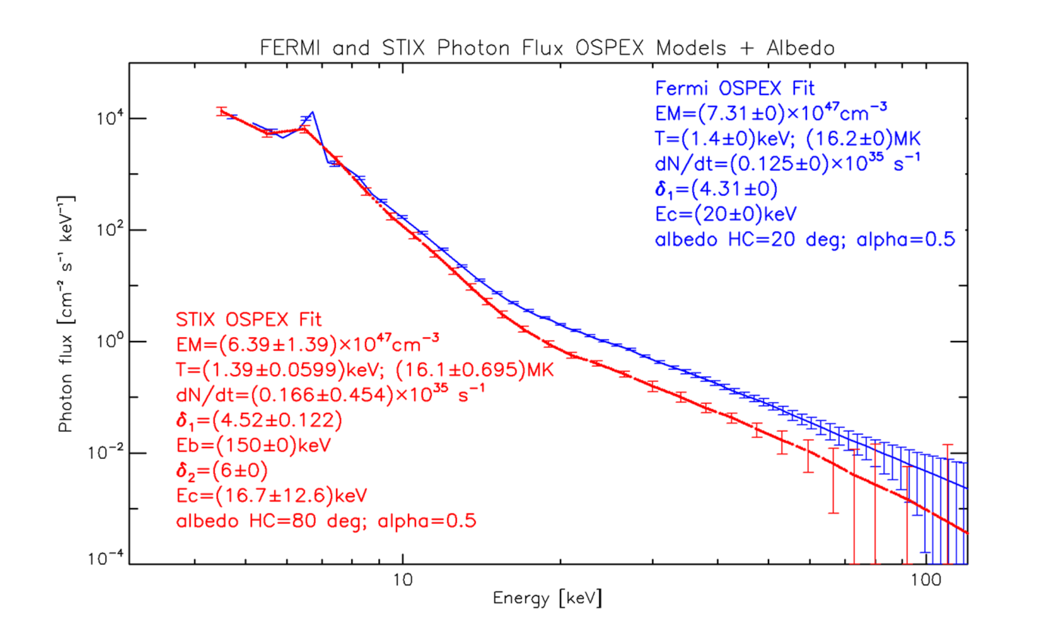
Only the GX Fermi-view direct photon flux spectrum has been tunned to match the OSPEX Fermi model spectrum

The FERMI albedo contribution is also relatively well matched, but the STIX OSPEX direct and total photon fluxes are overestimated

Challenge: Could the same GX Model be tunned to satisfy both STIX and FERMI OSPEX fits?

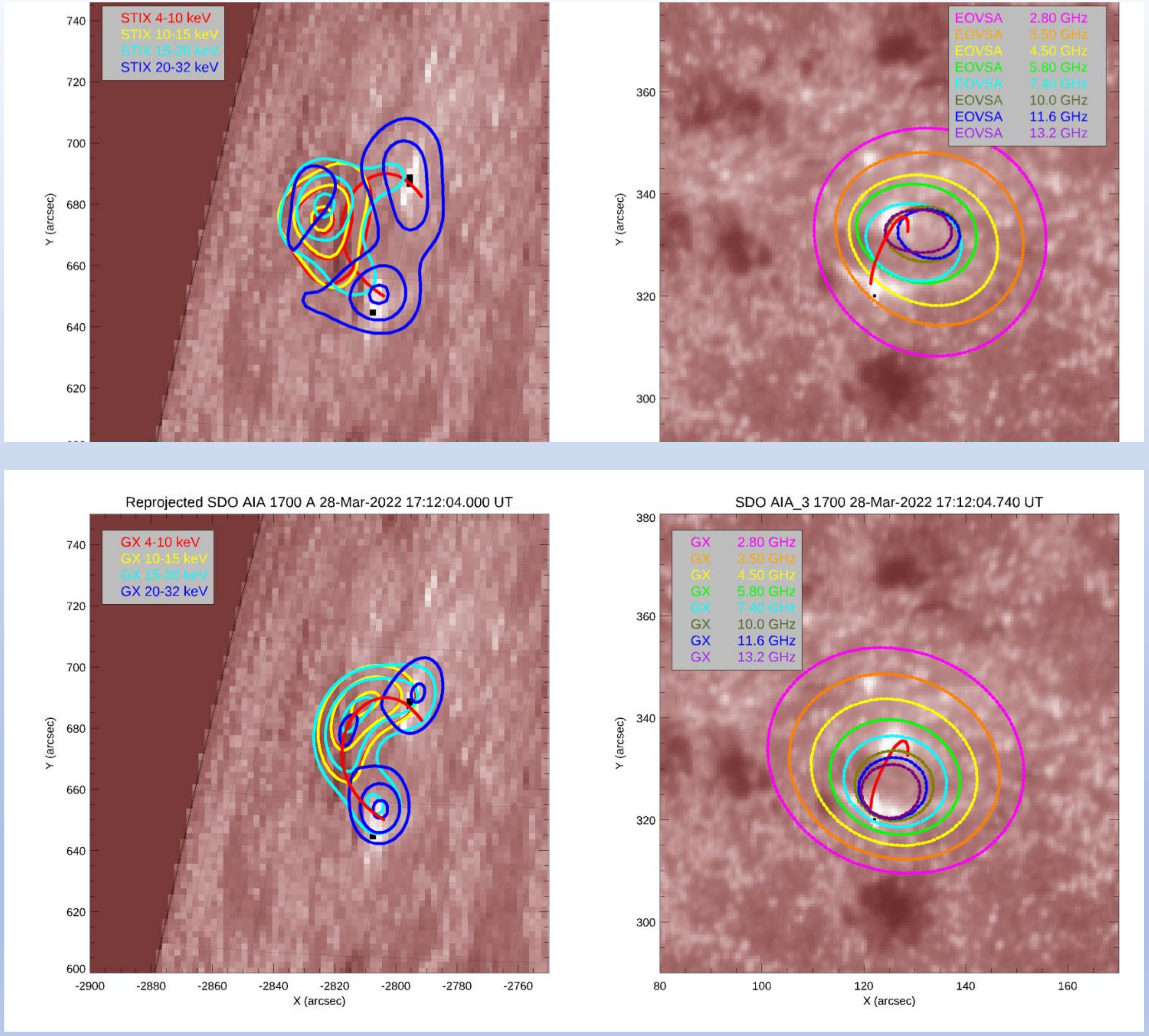
- The GX Simulator X-ray thick target +albedo computation routine is based on the same backbone computations used by the OSPEX software. Thus, if the FOV-integrated properties of a GX 3D Model exactly match the OSPEX parameters the OSPEX model spectra should be also matched within the same uncertainty range.
- Therefore, if, after the estimated albedo contribution is subtracted, the STIX and Fermi spectra disagree more tan their combined uncertainties, then, no singe GX Model tunned to match one or the other could satisfy both.
- Nevertheless, in this case, when the Direct Flux photon spectra are marginally close, a GX Model satisfying marginally close both observational constrains could be eventually found
- However, matching the FOV integrated constraints is not guaranteed to provide a full representation of the 3D reality
- The real challenge is to also satisfy all available observational imaging data constraints





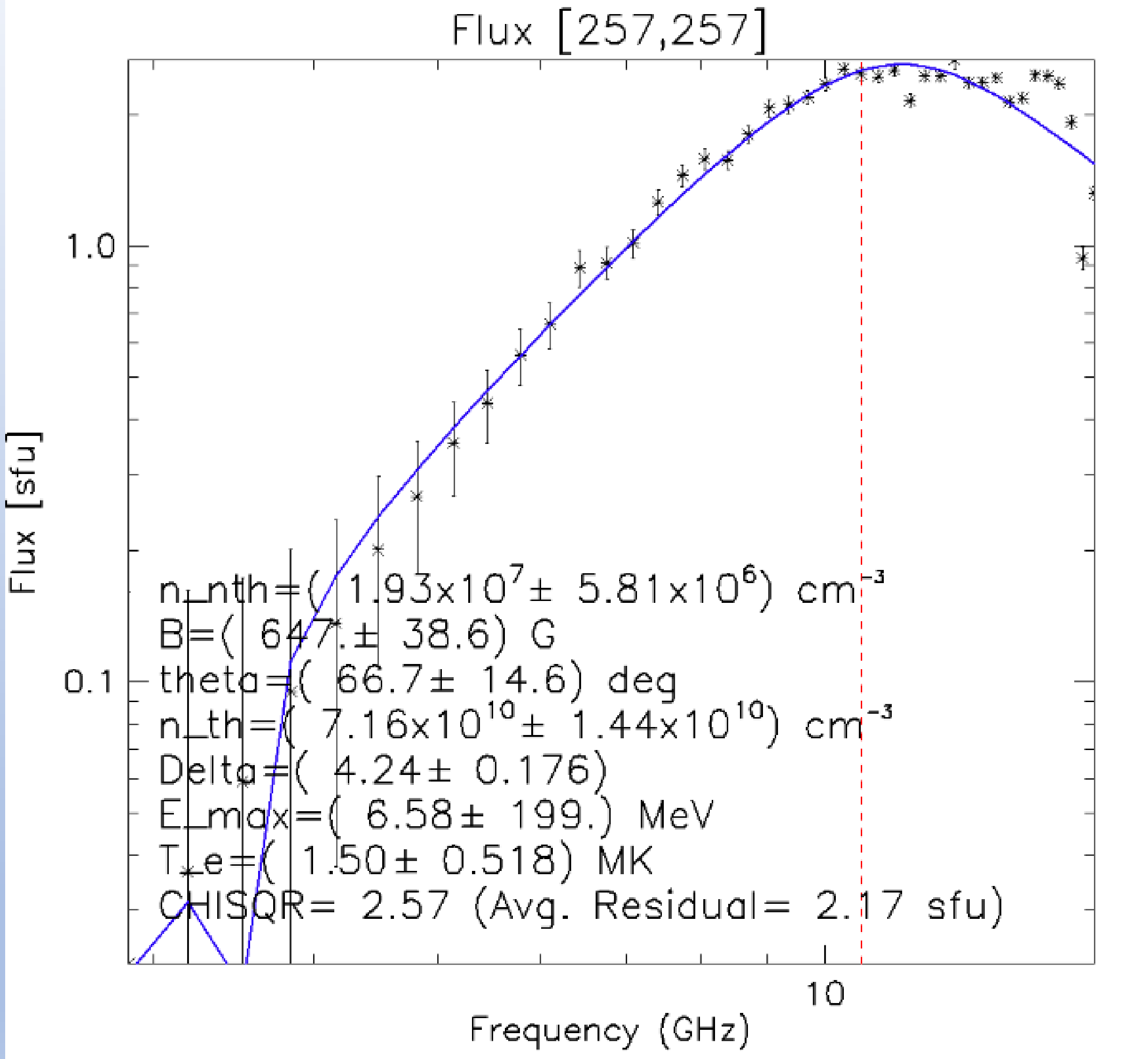
Data to Model Image Comparison

- Overall good alignment between the synthetic X-ray and microwave source locations relative to the STIX contours, respectively.
- Nevertheless, the morphology of the modeled images (shapes of the contours) does not exhibit perfect agreement with the observed images
- The contours of the modelled microwave images do not agree particularly well in shape and location, which indicates that, at least, the modeled spatial distribution of the emitting particles needs more adjustments
- One may attempt to perform such adjustments from scratch, but guidance from imaging spectroscopy observation having sufficient spatial resolution may prove to be very useful

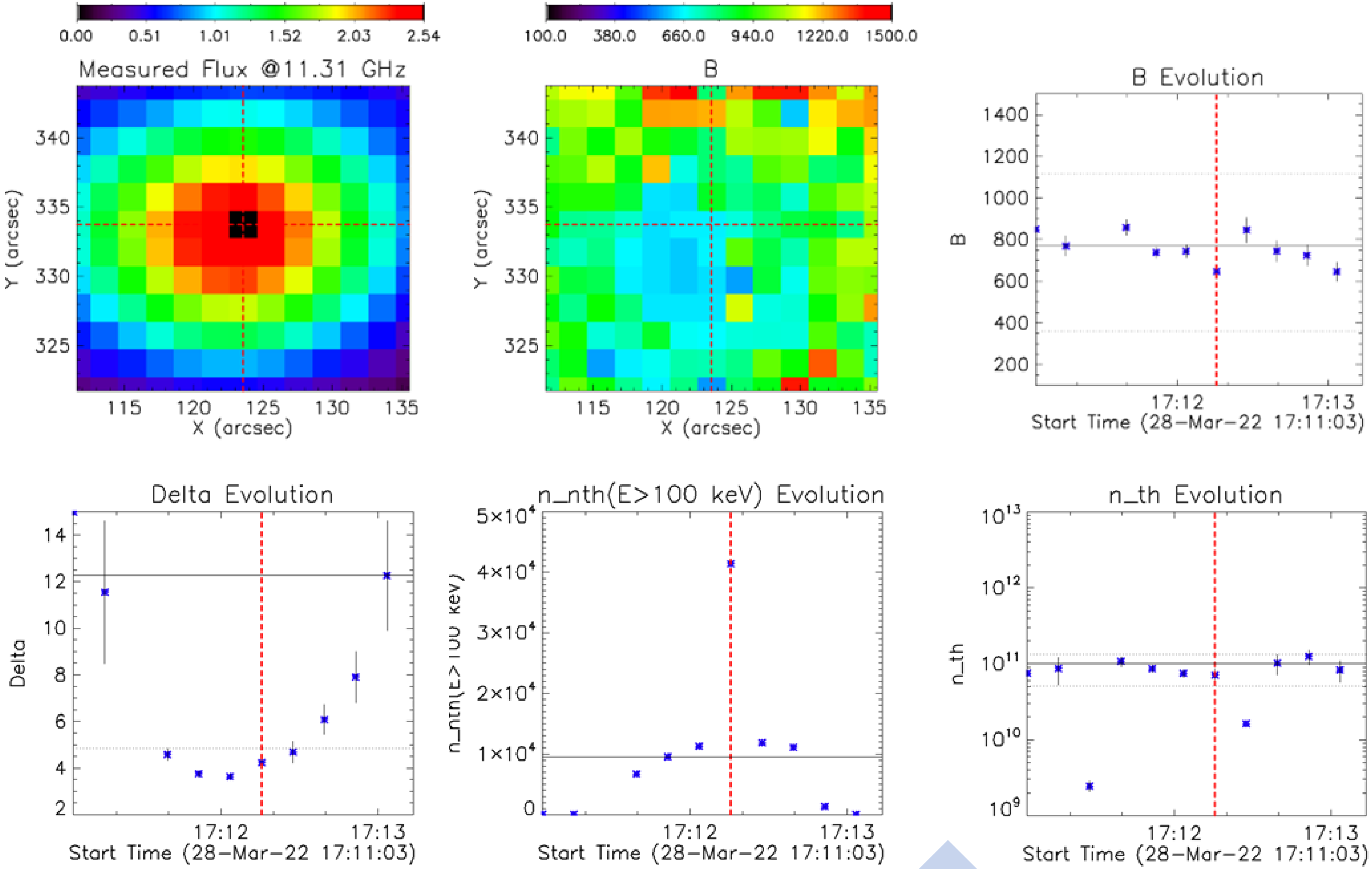


EOVSA MW Imaging Spectroscopy Modeling Constraints (I)

- EOVSA multi-frequency MW maps may provide LOS spectra for each pixel of the FOV
- Provided that some data quality requirements are met, each such spectra may be fitted using GSFIT SSW IDL application to obtain spatially resolved source parameters.
- When obtained from top-- or almost top--view perspective, the spatially resolved spectra corresponding to each pixel of the field of view encode the contribution from an unresolved microwave source volume crossed by the line of sight.
- Although such LOS ambiguity might not be fully compliant with the uniform source assumption under which the GSFIT parameters are obtained, the inferred 2D parameter represent averaged properties along each LOS path weighed by the distribution of the non-thermal electrons, thus they may provide valid modeling constrains on their spatial distribution
- Ideally, a GX 3D model forward-fitted based on these data would be capable of generating LOS MW spectra in very good agreement with the observations.



EOVSA MW Time-Evolving Imaging Spectroscopy Modeling Constraints (II)



More work to be done: GX Simulator Forward Fitting of the MW Imaging Spectroscopy and X-ray Imaging and Spectroscopy Constraints

- The GX Simulator MW rendering codes provide the choice of a variety of adjustable analytical distributions of the non-thermal electrons over energy and pitch angle, as well as numerically defined particle distributions as a function of time and position along a flaring loop, based for example on 1D Fokker-Planck simulations.
- The GSFIT parameter maps may be used to guide the choice of the particle distributions most suitable for iterative fine tuning of the 3D GX models
- When the particularities of a selected event deem necessary the use of the most advanced options provided by the MW codes, GX Simulator can also employ a version of the X-ray radiation rendering routine, which, likewise, allows the use of numerically defined distributions.

Acknowledgments:

Many thanks to **Natasha Jeffrey**, **Laura Hayes**, **Eduard Kontar**, **Surajit Mondal**, **Daniel Ryan**, and **William Setterberg** for their valuable contributions, which enriched the materials used in this presentation. Although not all their contributed materials could be displayed here, their support was invaluable.

Special thanks to the **GX Simulator Team** for their support and assistance throughout the years.

Thanks to the audience for their attention!