A computational model for solar flares: kinectics and microwave/X-ray emission

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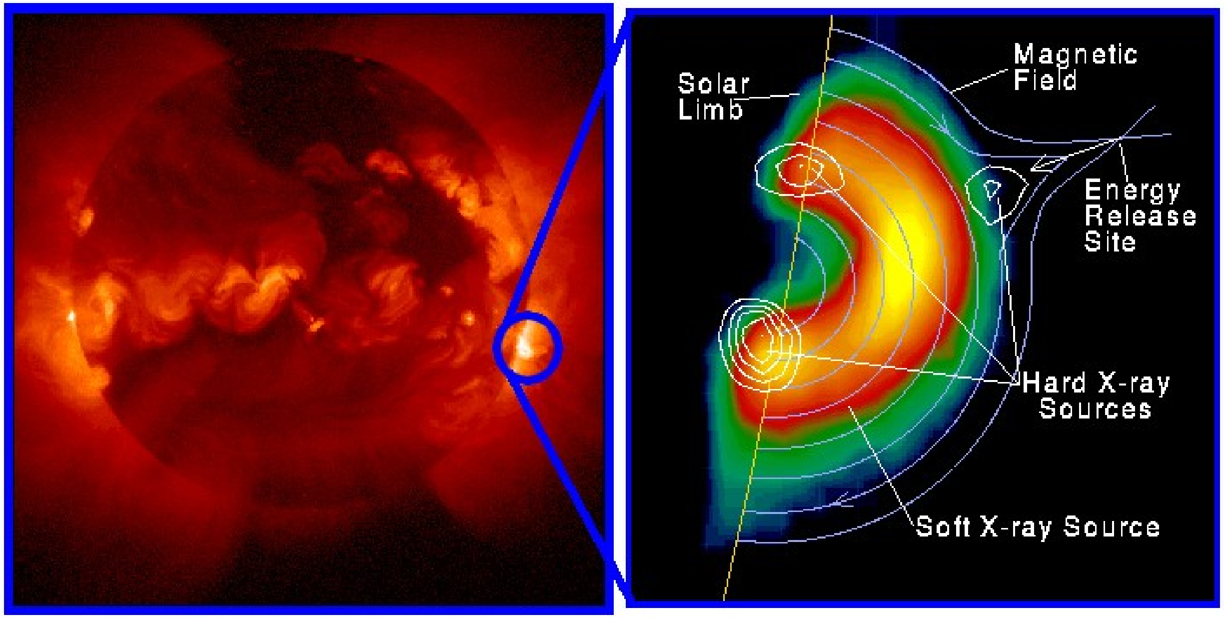
I Workshop de Computação Científica em Astronomia
02-05 de Junho de 2011

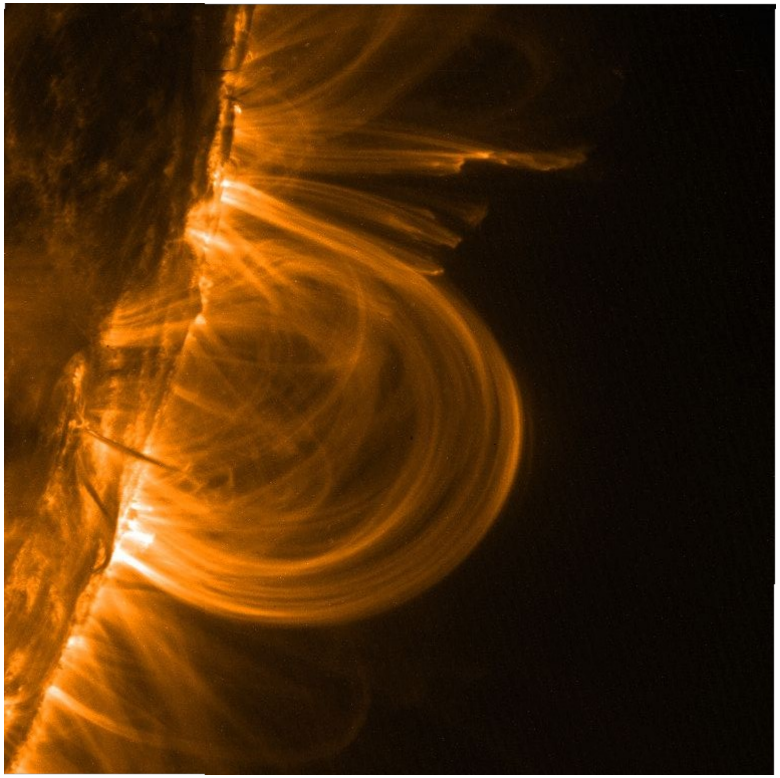
FAPESP Proc. no. 2008/09339-2 and 2009/18386-7

Solar activity and solar flares

Solar activity cycle: 11 years
Solar flares:
- release of magnetic energy → heating and acceleration of particles
- production of electromagnetic waves: radio to gamma rays
- acelerated electrons trapped in magnetic fields → microwave and X-rays
- occurr in active regions (above sunspots) → magnetic loops

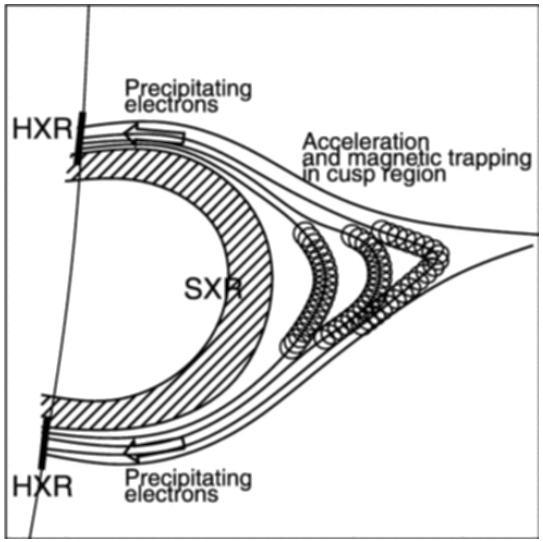


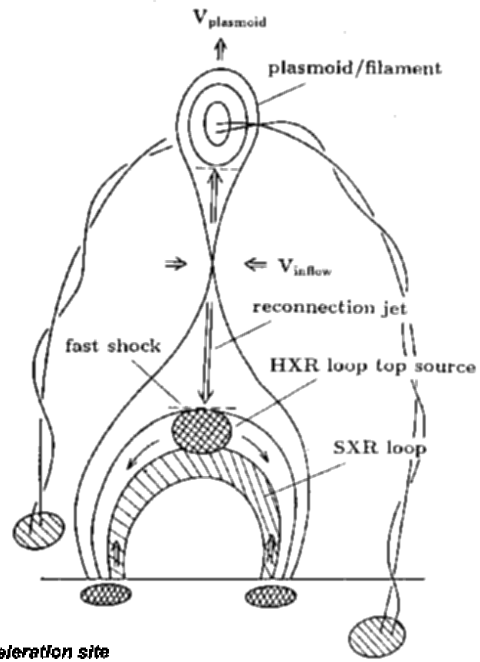
Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

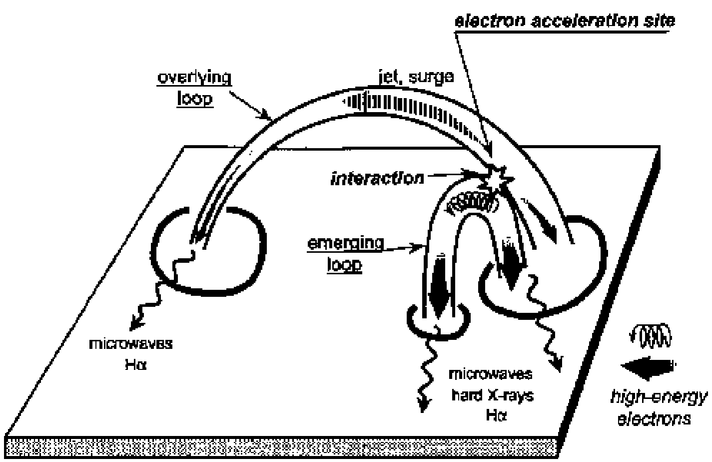


Flare models

Qualitative models (cartoons)

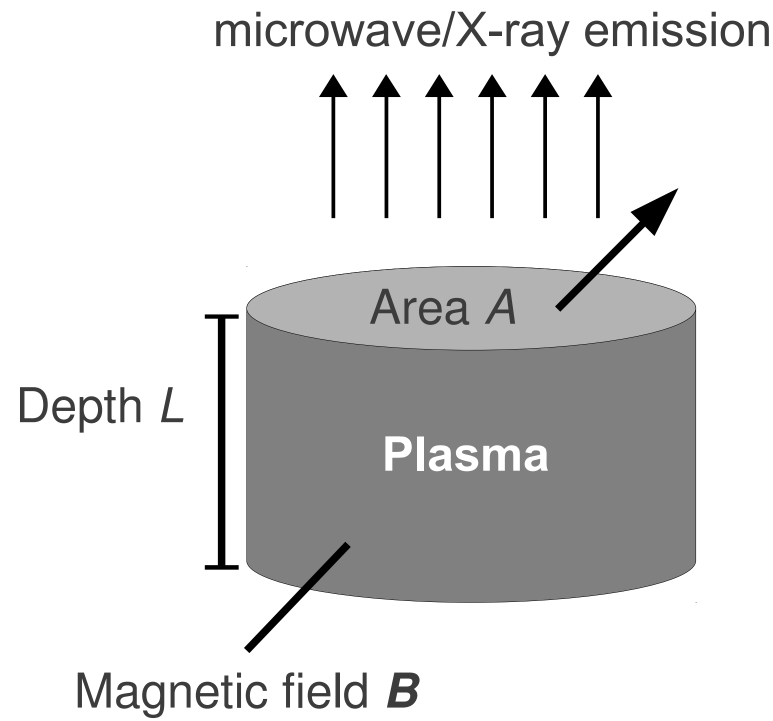






Quantitative model

Homogeneous source model



Plasma density: homogeneous
Plasma temperature: isothermal
Accelerated electron density: homogeneous

Cartoons: **http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/**

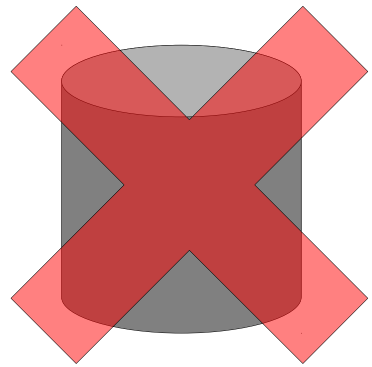
Model improvement

Solar flares are not static!
+ dynamics of the accelerated electrons

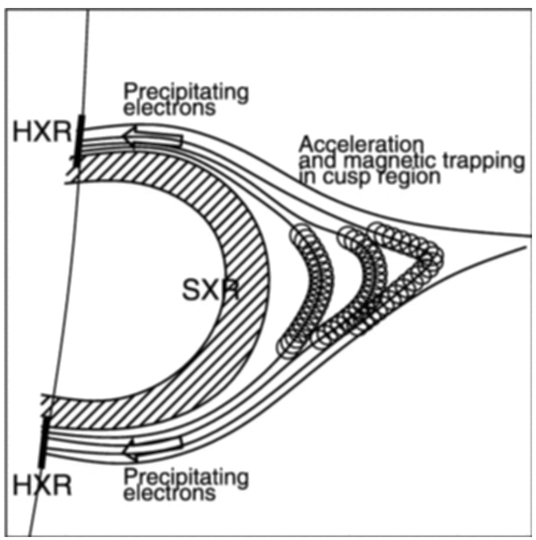
Getting rid of the cillinder/sphere/cube models:
+ 3D modeling of the source
geometry, magnetic field, plasma density

Microwave and X-rays emission from electrons
+ 3D radiative transfer

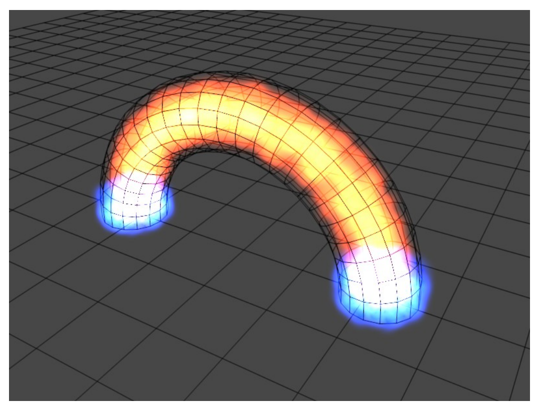
Model improvement



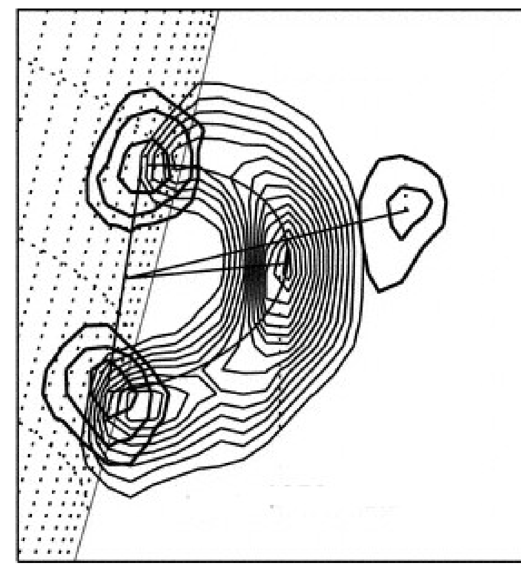
cartoons



computer models



observations

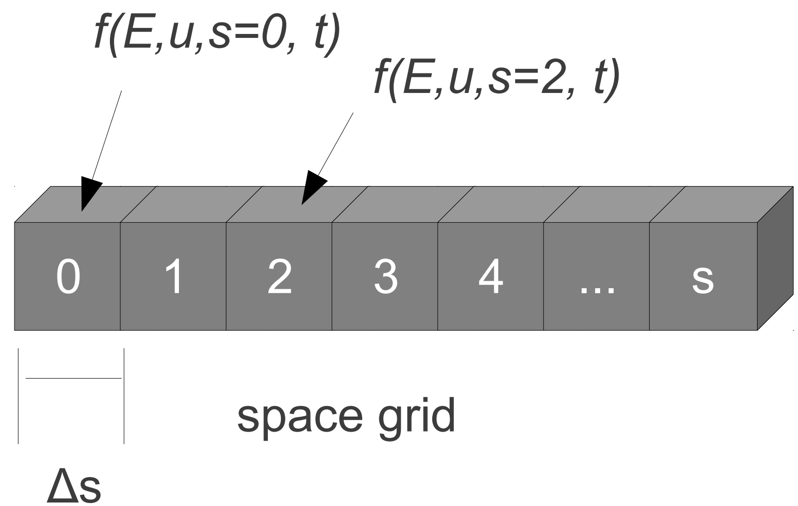


Electron dynamics

$$\frac{\partial f}{\partial t} = -\mu c\beta \frac{\partial f}{\partial s} - \frac{\partial}{\partial \mu}\dot{\mu} f - \frac{\partial}{\partial E}\dot{E} f + \frac{\partial}{\partial \mu}\left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right) + S(E, \mu, s, t)$$

Fokker-Planck equation

1. Electrons' movement
2. Magnetic trapping
3. Energy loss (Coulomb collisions)
4. Pitch-angle diffusion (Coulomb collisions)
5. Source function (injection)



Numerical solution of
the Fokker-Planck equation
Hamilton et al., 1990, *ApJ*

Finite differences methods
grid: f(E, u, s) advancing in time

FORTRAN code

Magnetic field and plasma density defined as functions of position:
B(s)
N(s)

Microwave and X-rays emission

Microwave
Gyrosynchrotron radiation of electron distribution *f(E,u)*

Ramaty, 1969, *ApJ*
IDL and C code

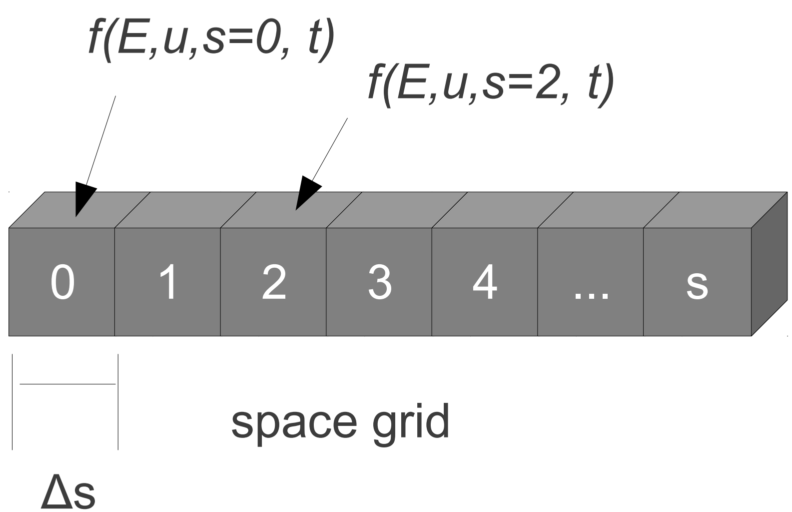
X-rays
Thin and thick-target bremsstrahlung of electron distribution *f(E)*

Brown, 1971, *ApJ*
FORTRAN codes

Numerical integration
Equations (and numerical codes) defined for **uniform/homogeneous** sources

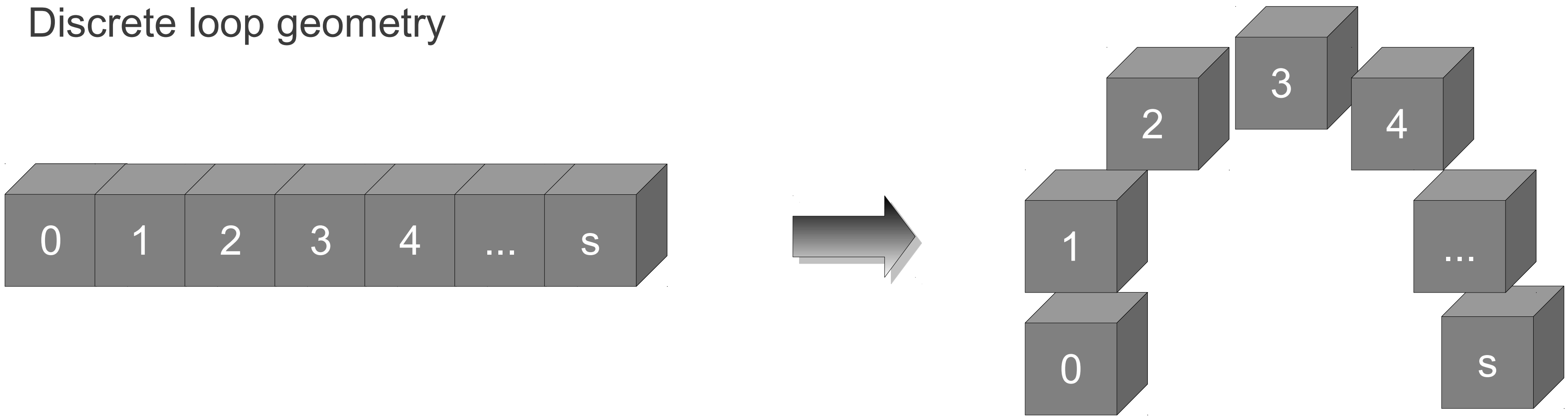
From the Fokker-Planck code:
discrete space → homogeneous cell

So microwave and X-rays codes can be used.



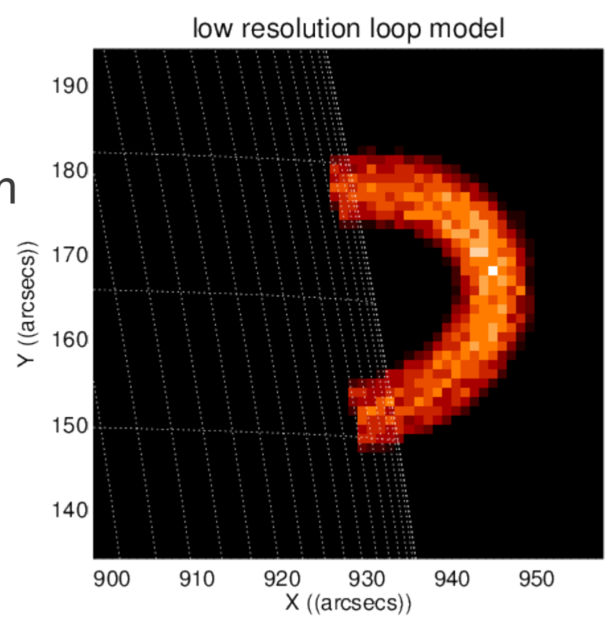
Geometric model

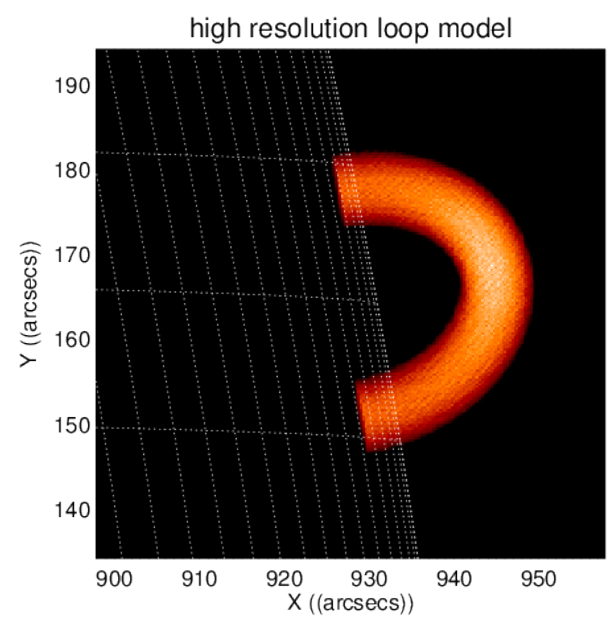
Discrete loop geometry



3D voxel filled volume

Each section of the loop
Corresponds to a cell from
Fokker-Planck result





Source model

Magnetic field

Spatial variation

+ electron trapping

+ microwave emission

Background plasma

Homogeneous density and isothermal

Loop geometry

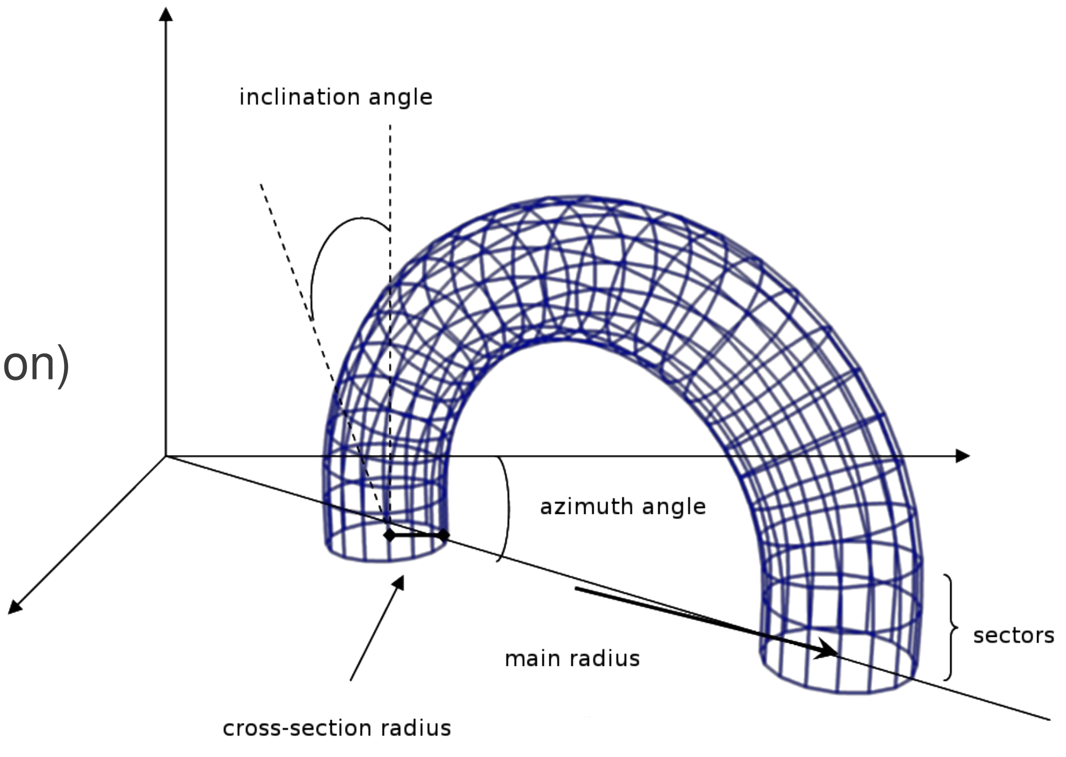
Loop main radius

Cross-section radius

Heliographic position (lat. and lon.)

Loop orientation (inclination and rotation)

Loop geometry: definitions

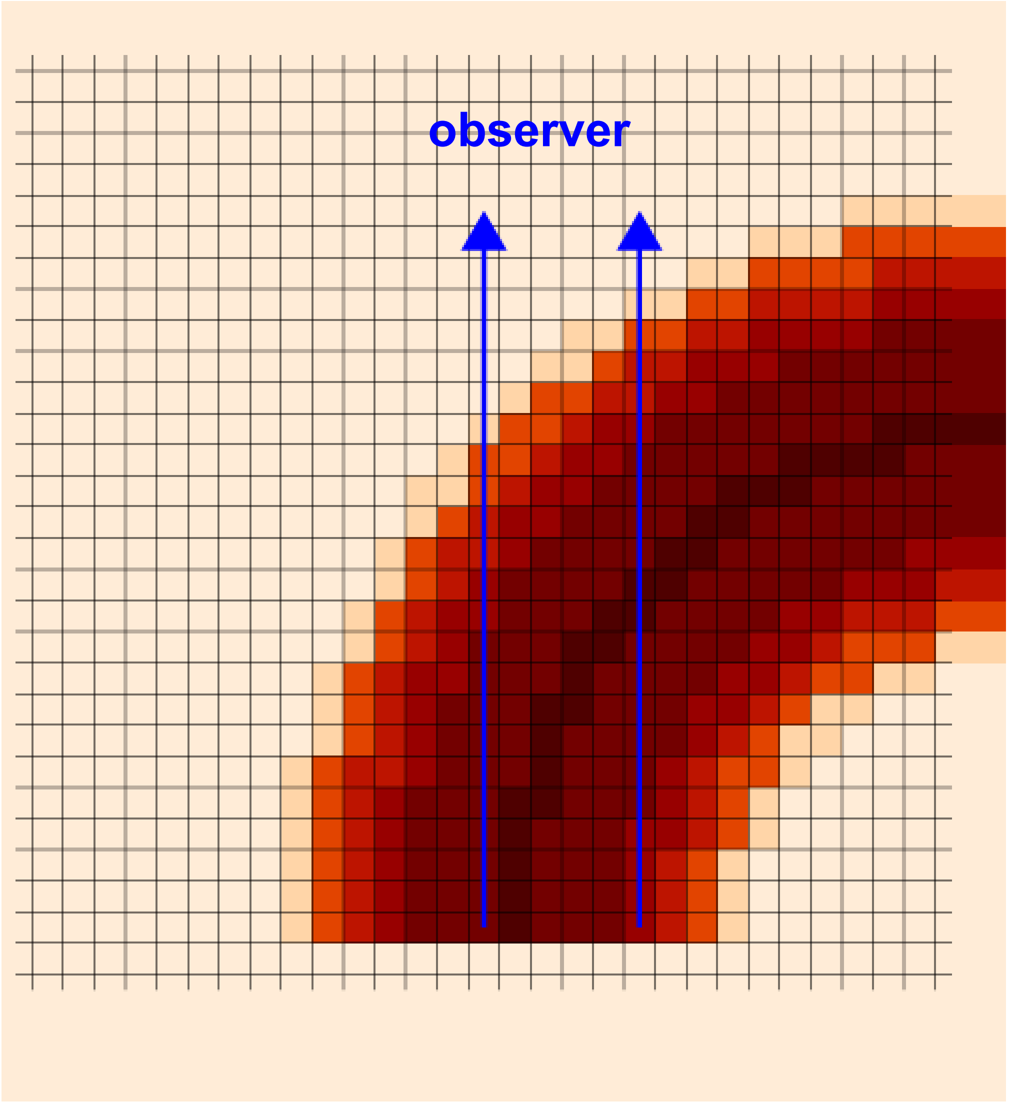


3D radiative transfer

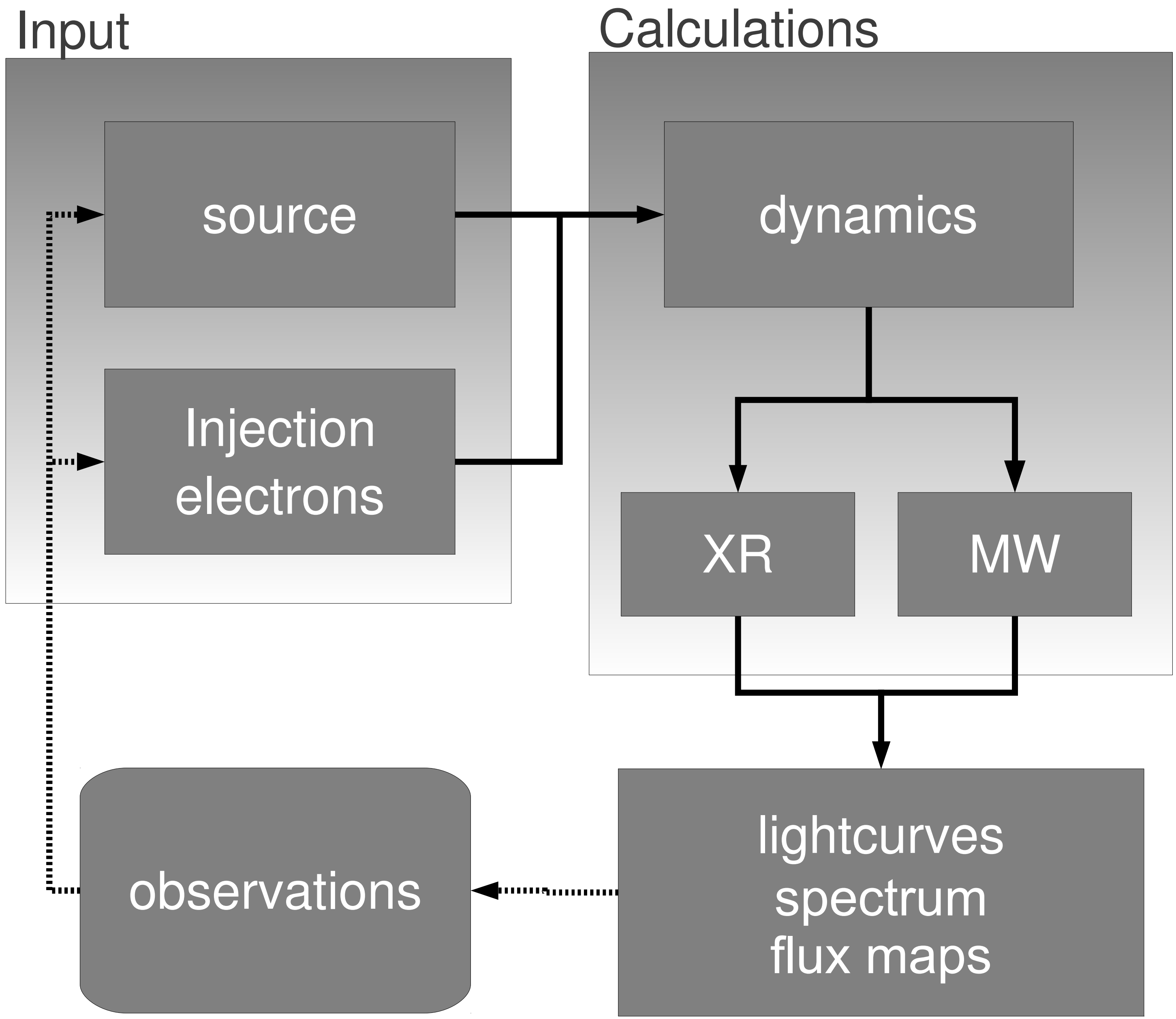
Homogeneous voxels
Refraction index ~ 1

Solution of the radiative transfer equation for a homogeneous region:

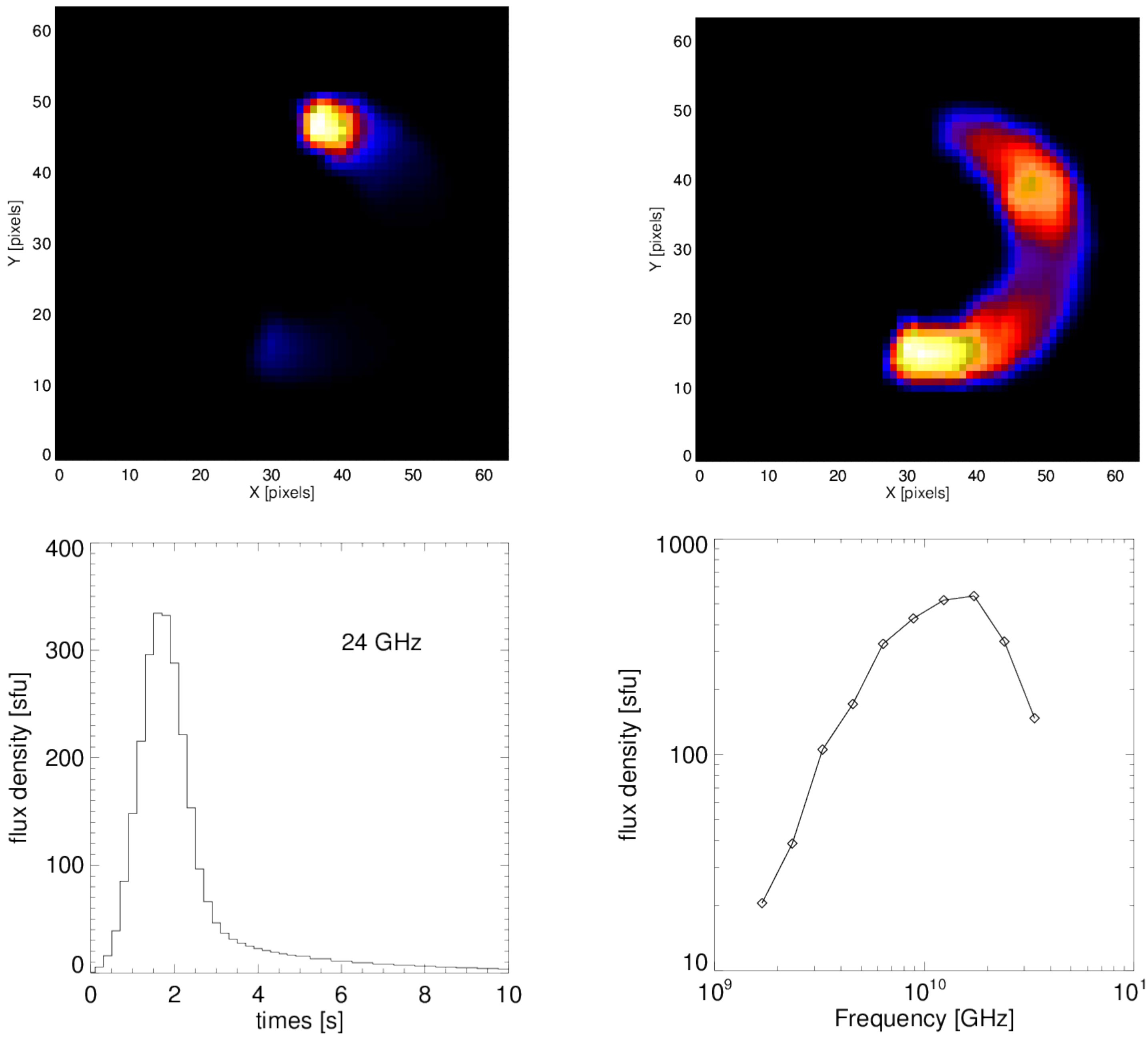
$$I_1 = \frac{j_1}{k_1}\left(1 - e^{-k_1 L}\right) + I_0 e^{-k_1 L}$$



Computational flowchart



Model output



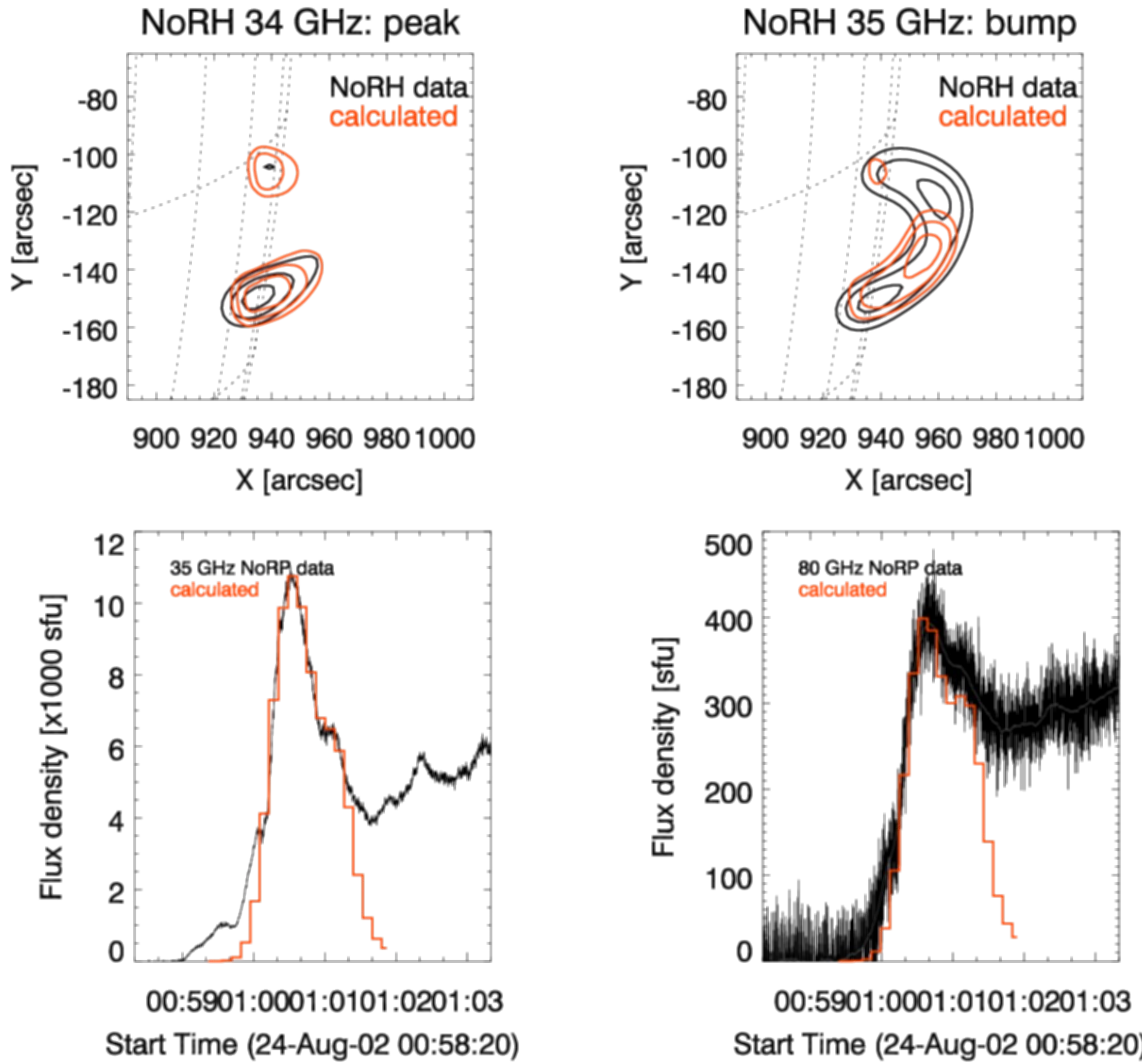
Using the model: 2002 August 24 flare

GOES X3.1
~30 min (radio)
No X-rays observations (RHESSI)
Loop structure seen in NoRH

Two injections
main and 'bump'
Beam and Pancake

Good fittings
lightcurves, spectrum and main footpoint sources

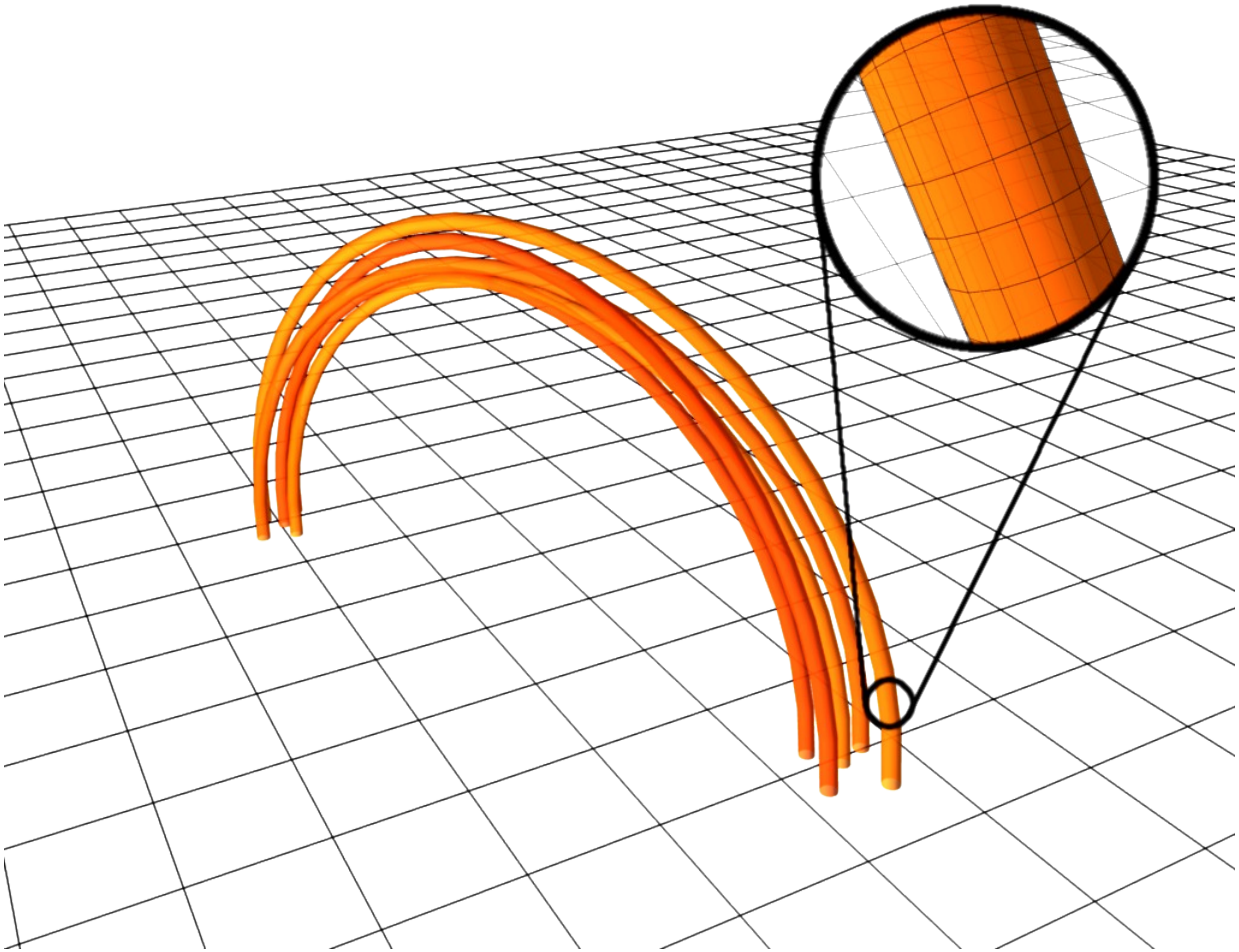
Looptop 'bump' source
Improvement of
loop model and/or physical model
- B field asymmetry
- complex loop geometry
- other diffusion processes



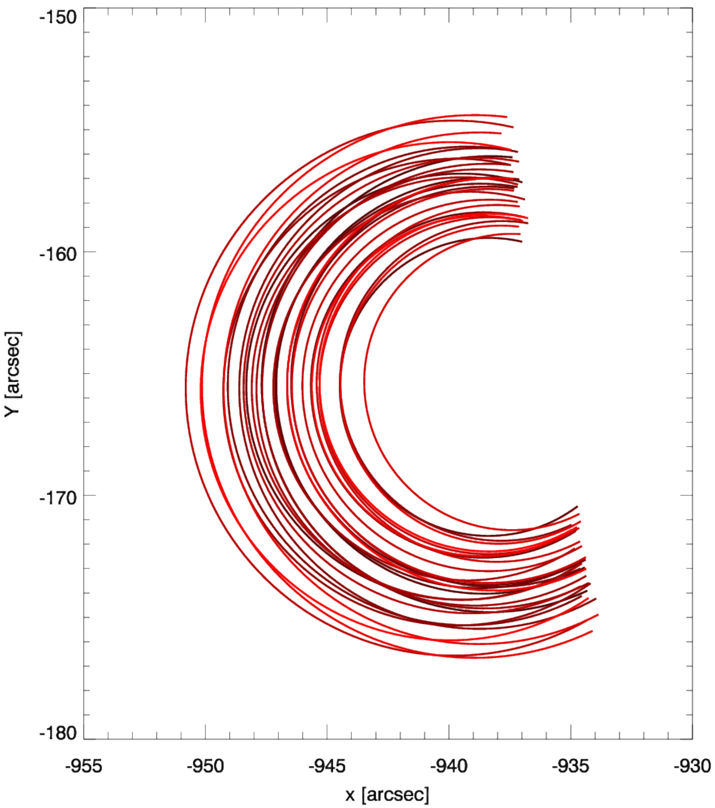
Multi-thread model

Multiple loop structure
Allows more possibilities

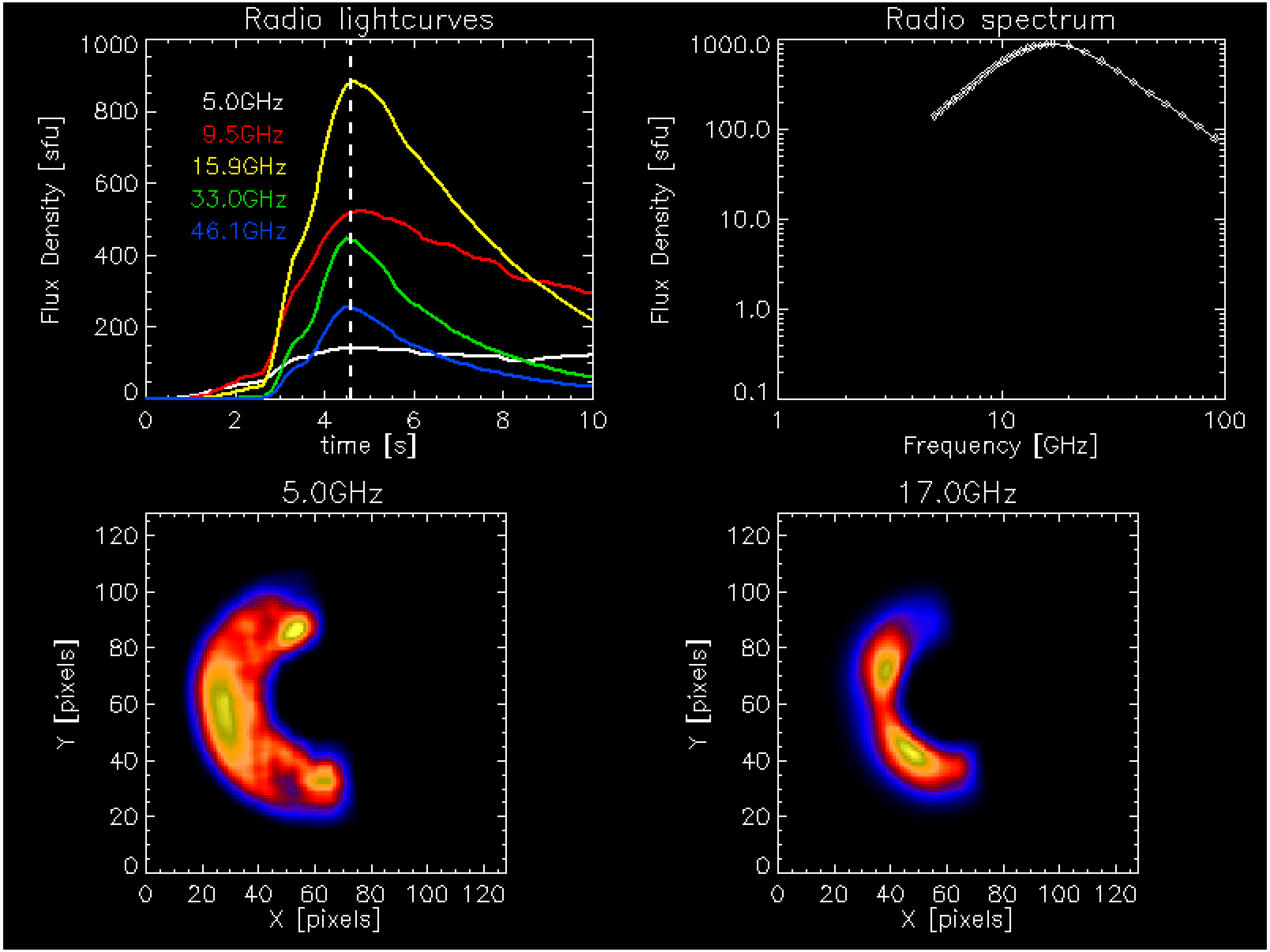
Needs more computational resources



30 loops
Random parameters (within limits)

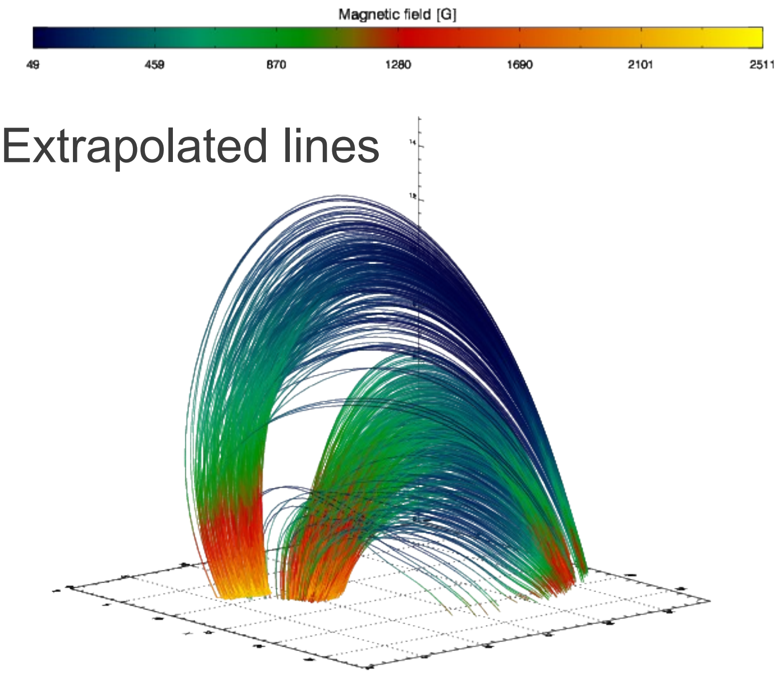


Multi-thread model



Force-free field extrapolations

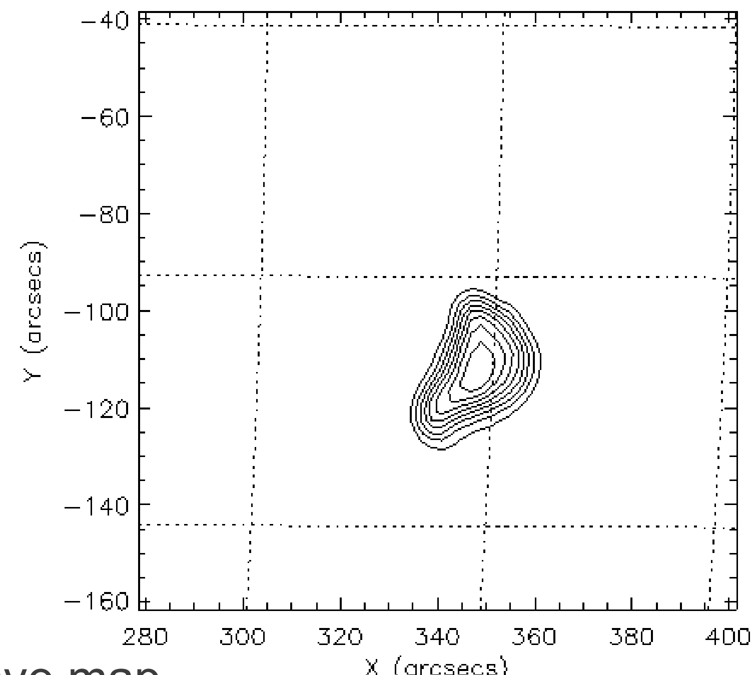
Extrapolated lines

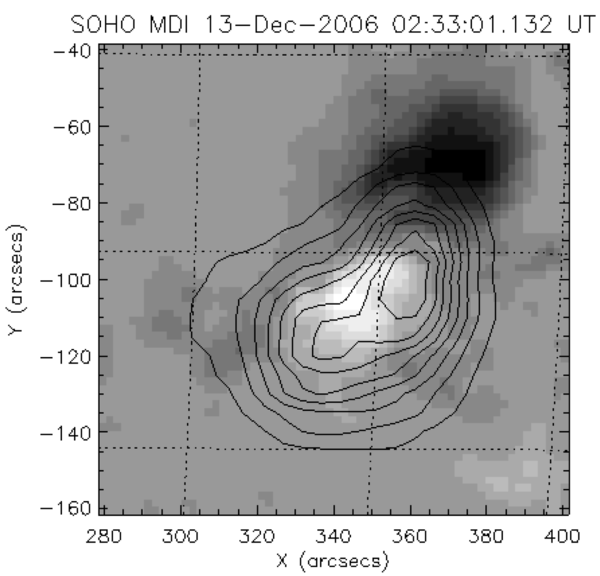


Observational images (NoRH, RHESSI)
Magnetograms: force-free field extrapolations
Extrapolated field lines as the field model

(PhD student Tereza Satiko, DAS/INPE)

Calculated microwave map

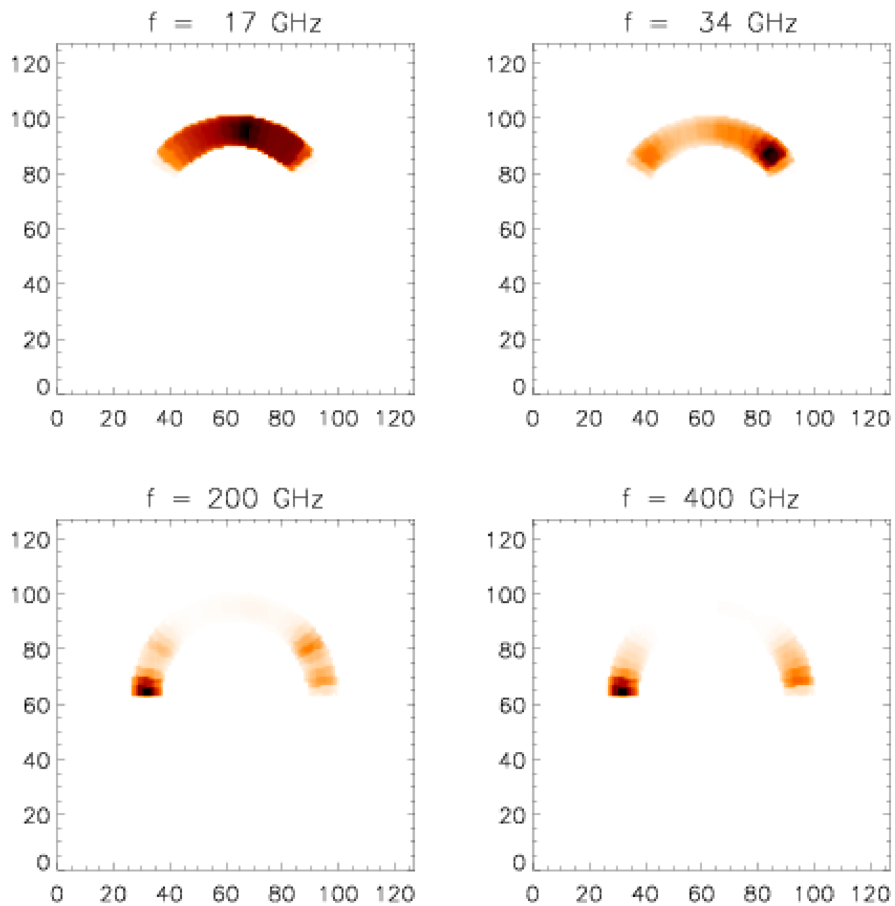


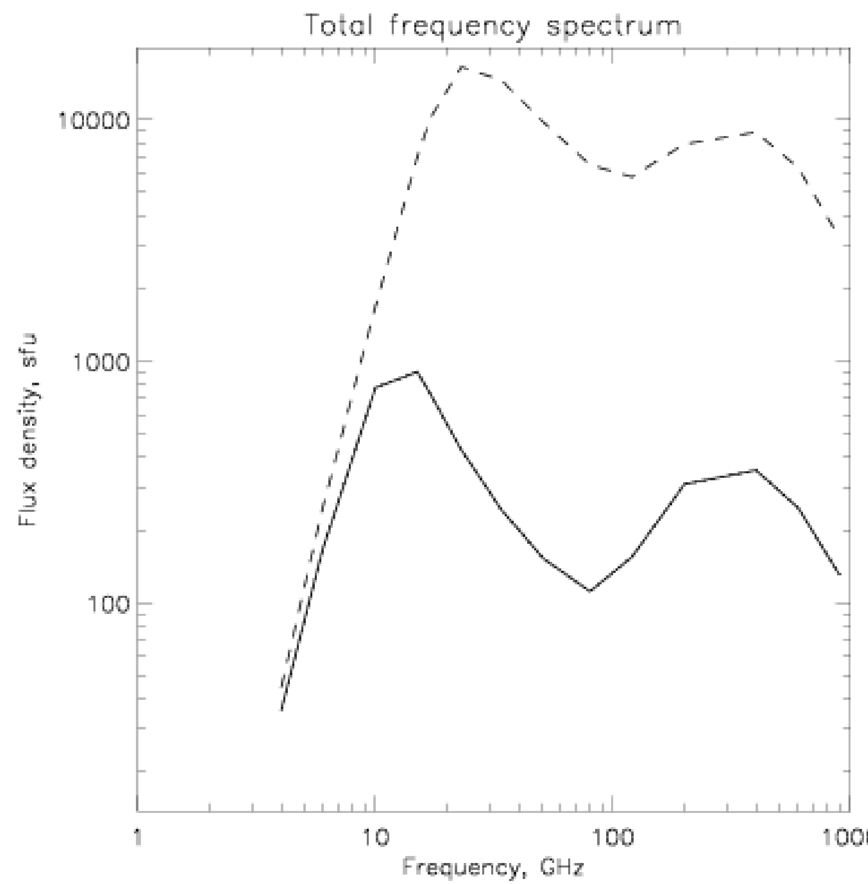


Observed microwave map

Sub-THz spectral component

Increasing spectral component observed above 100 GHz (Solar Submillimeter Telescope)
Several emission mechanisms proposed (e.g. Fleishman and Kontar, 2010)
We found an explanation with our model:
Sub-THz flare emission: an evidence for relativistic electron beams
in the dense chromosphere (Melnikov, Costa, Simões)





Future development

Flare model

Chromospheric evaporation, plasma heating (e.g. Liu et al, 2009, *ApJ*)
Return current (ohmic losses) (e.g. Karlický and Kasparová, 2009, *A&A*)
Strong diffusion (electron-whistler) (e.g. Bespalov et al, 1991, *ApJ*)
Self-interaction of fast electrons (e.g. Galloway et al, 2010, *A&A*)
Electron-electron bremsstrahlung (Kontar et al, 2007, *ApJ*)
Langmuir waves (Hannah and Kontar, 2011, *A&A*)
Acceleration models (stochastic, betatron, etc.)

Computational method

High Performance Computing (HPC):
- Parallel processing (MPI/OpenMP)
    - Cluster: 4U x 2 AMD Magny-Cours (12 cores) = 96 CPUs + 48 GB RAM
- GPU processing (CUDA)
    - Nvidia Tesla C2050: 448 CUDA cores + 3GB DDR3

FAPESP Proc. no. 2009/18386-7 (Dr. Giménez de Castro – CRAAM)