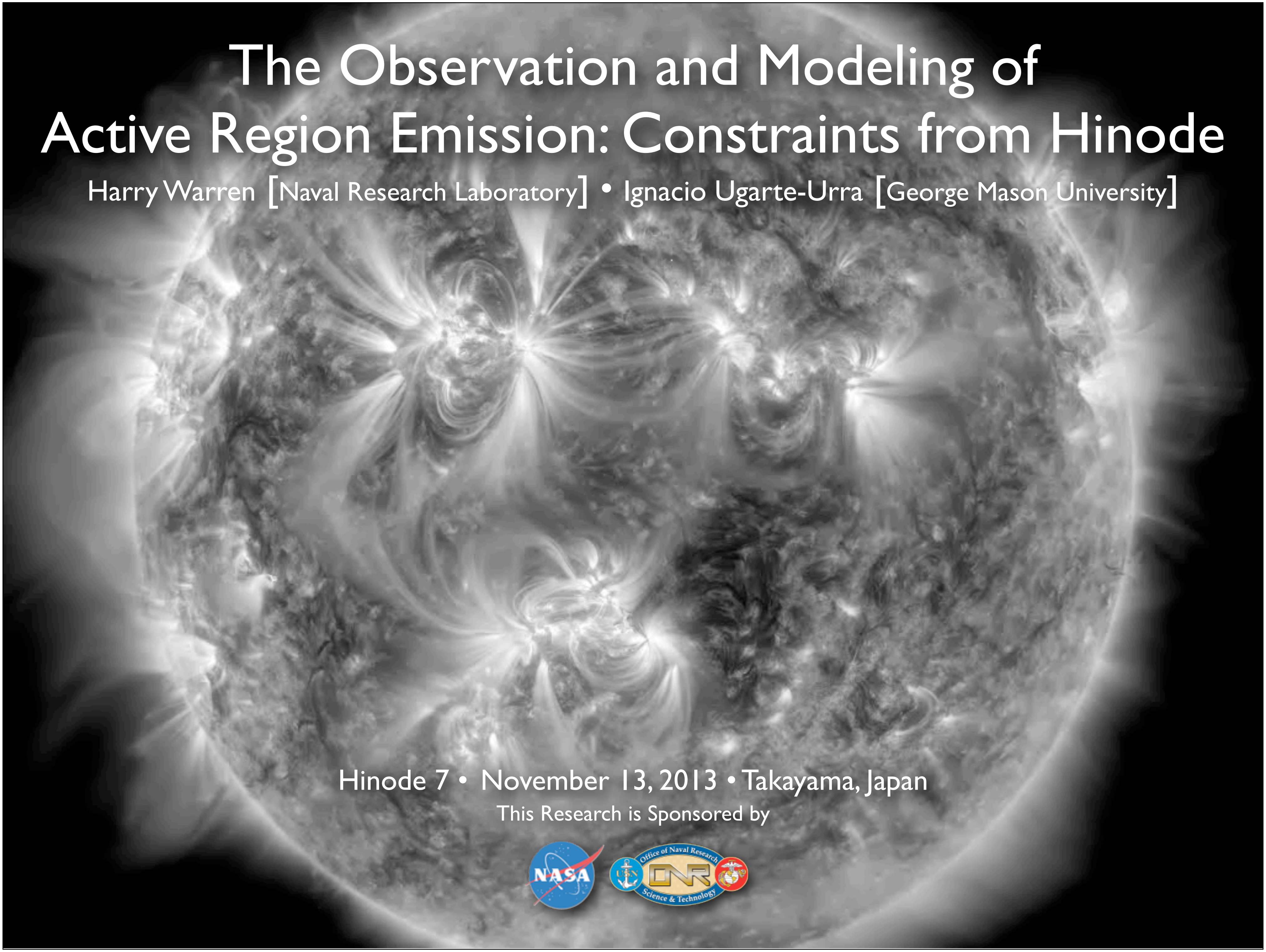
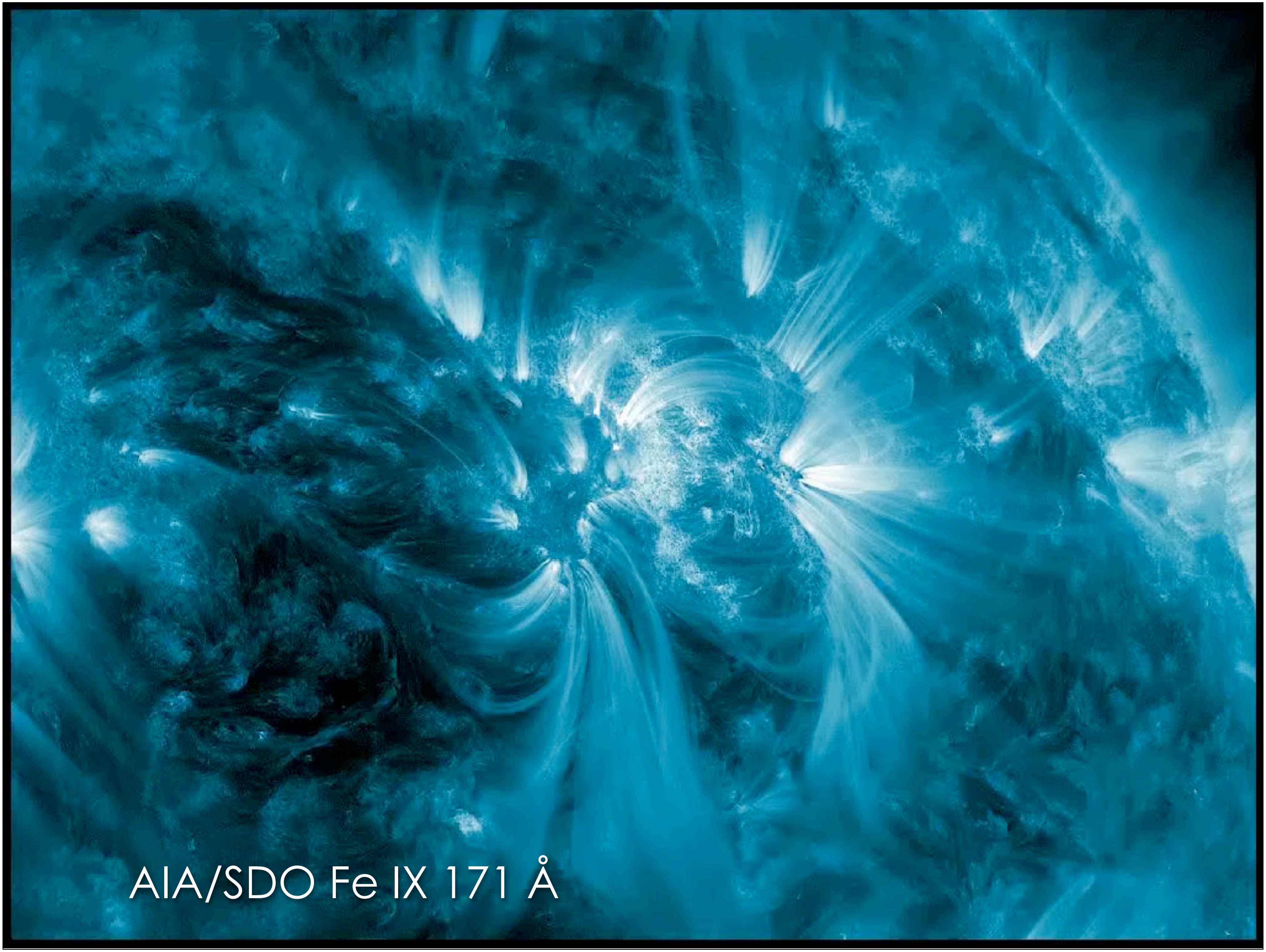


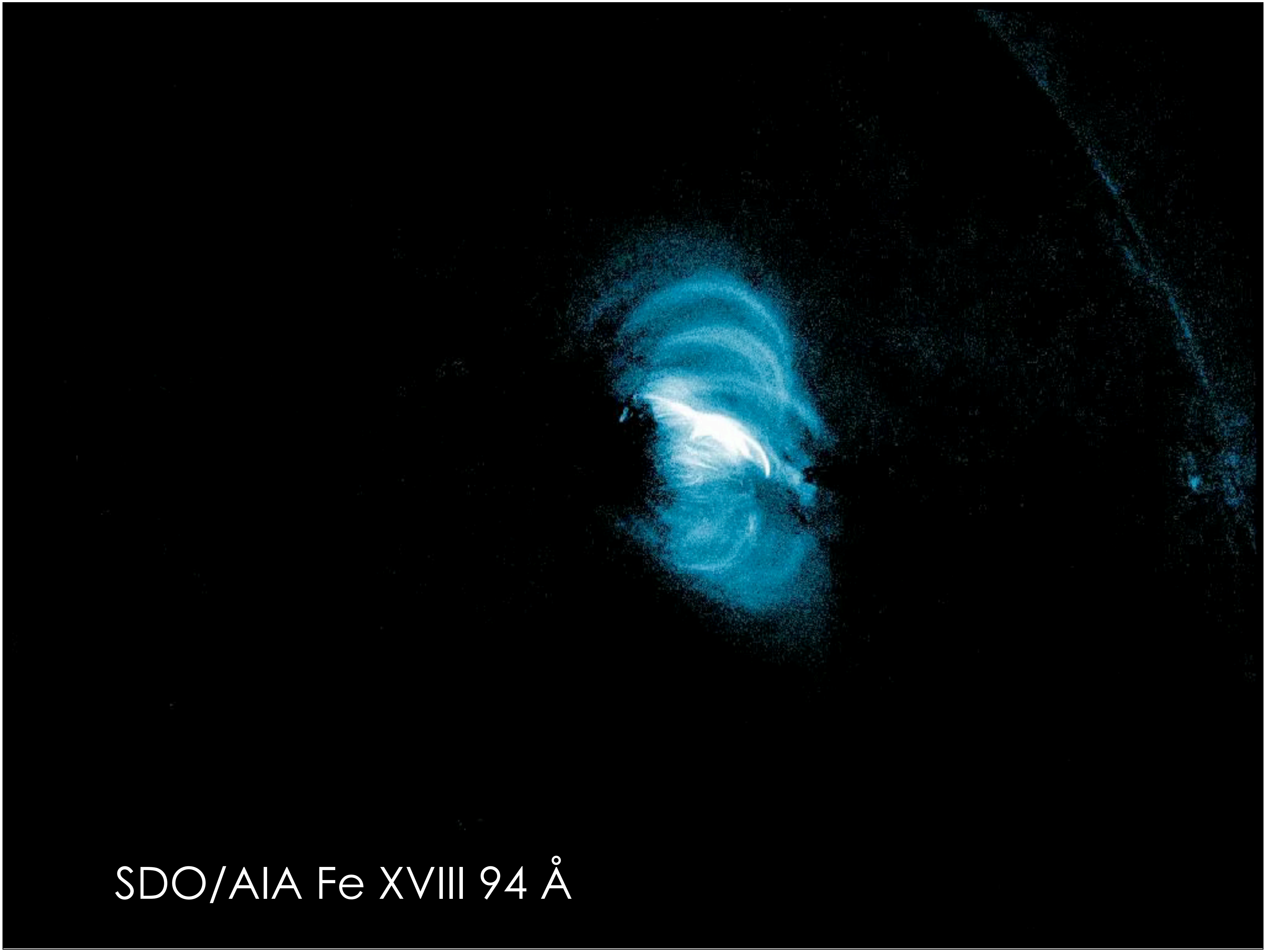
The Observation and Modeling of Active Region Emission: Constraints from Hinode

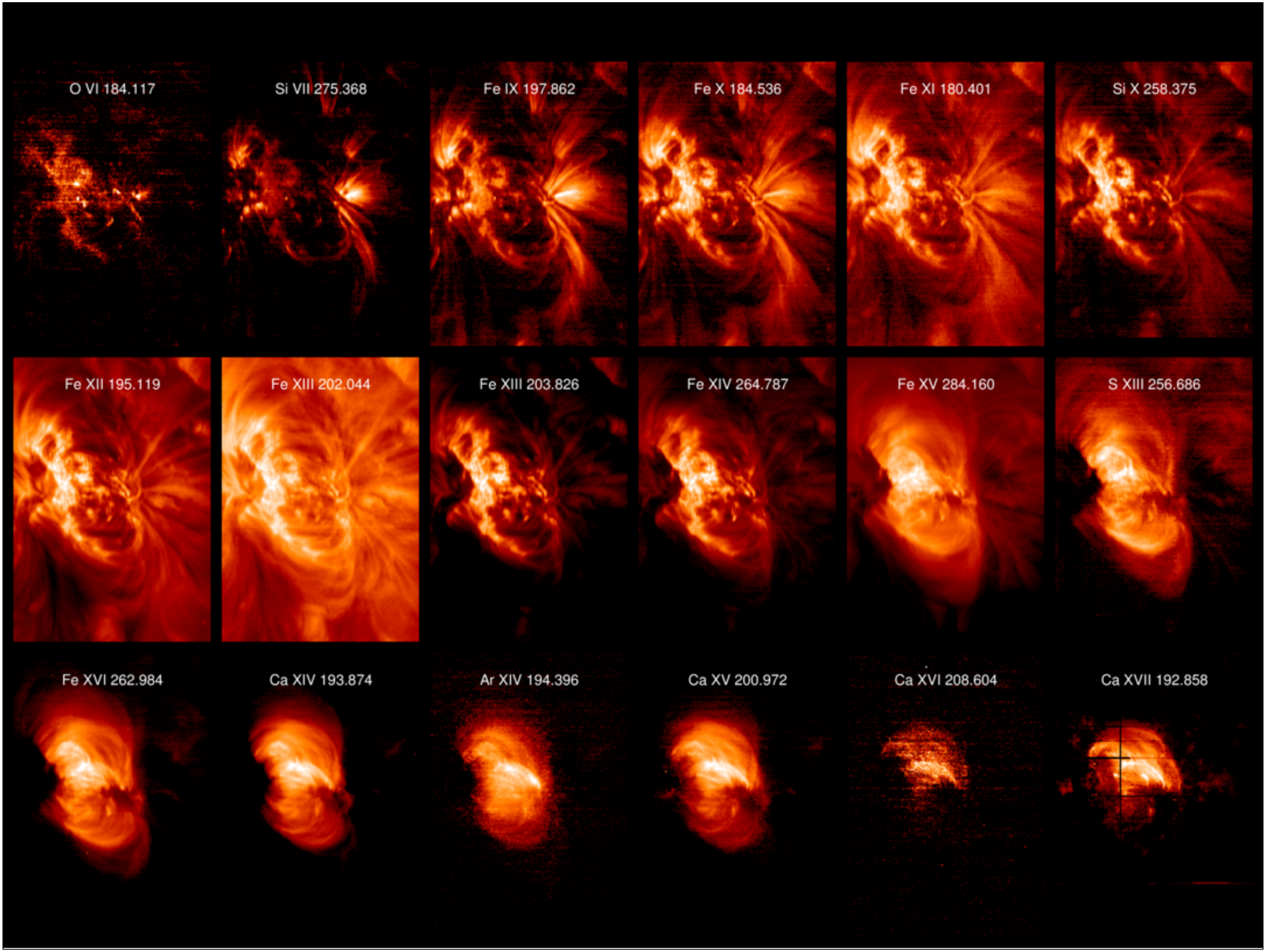
Harry Warren [Naval Research Laboratory] • Ignacio Ugarte-Urra [George Mason University]

Hinode 7 • November 13, 2013 • Takayama, Japan

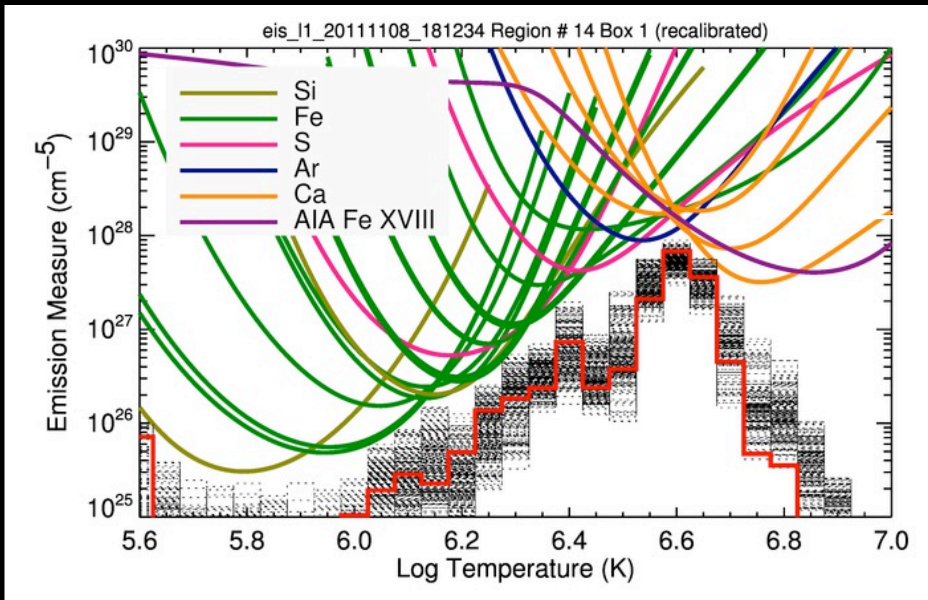
This Research is Sponsored by

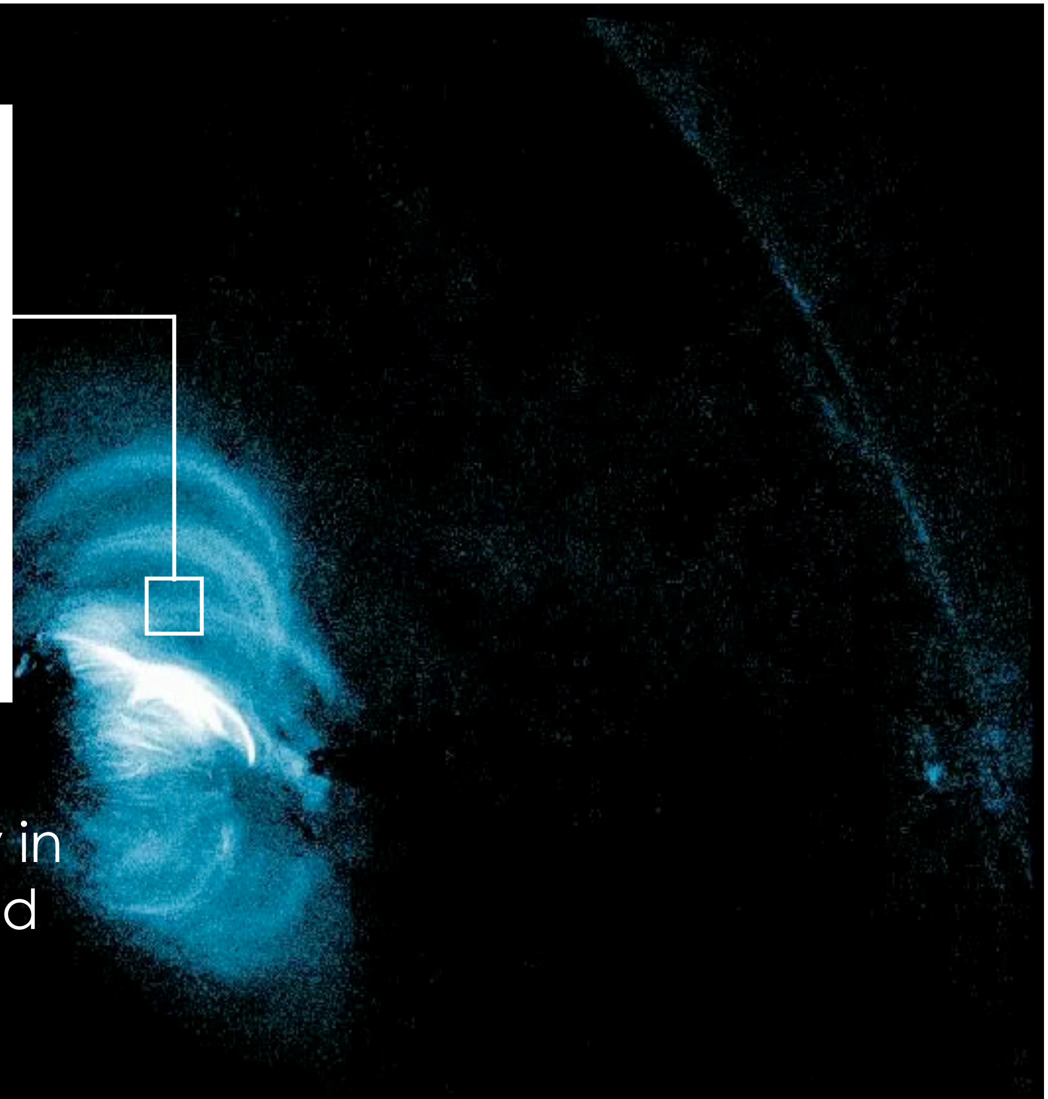

AIA/SDO Fe IX 171 Å


SDO/AIA Fe XVIII 94 Å



O VI 184.117
Si VII 275.368
Fe IX 197.862
Fe X 184.536
Fe XI 180.401
Si X 258.375
Fe XII 195.119
Fe XIII 202.044
Fe XIII 203.826
Fe XIV 264.787
Fe XV 284.160
S XIII 256.686
Fe XVI 262.984
Ca XIV 193.874
Ar XIV 194.396
Ca XV 200.972
Ca XVI 208.604
Ca XVII 192.858

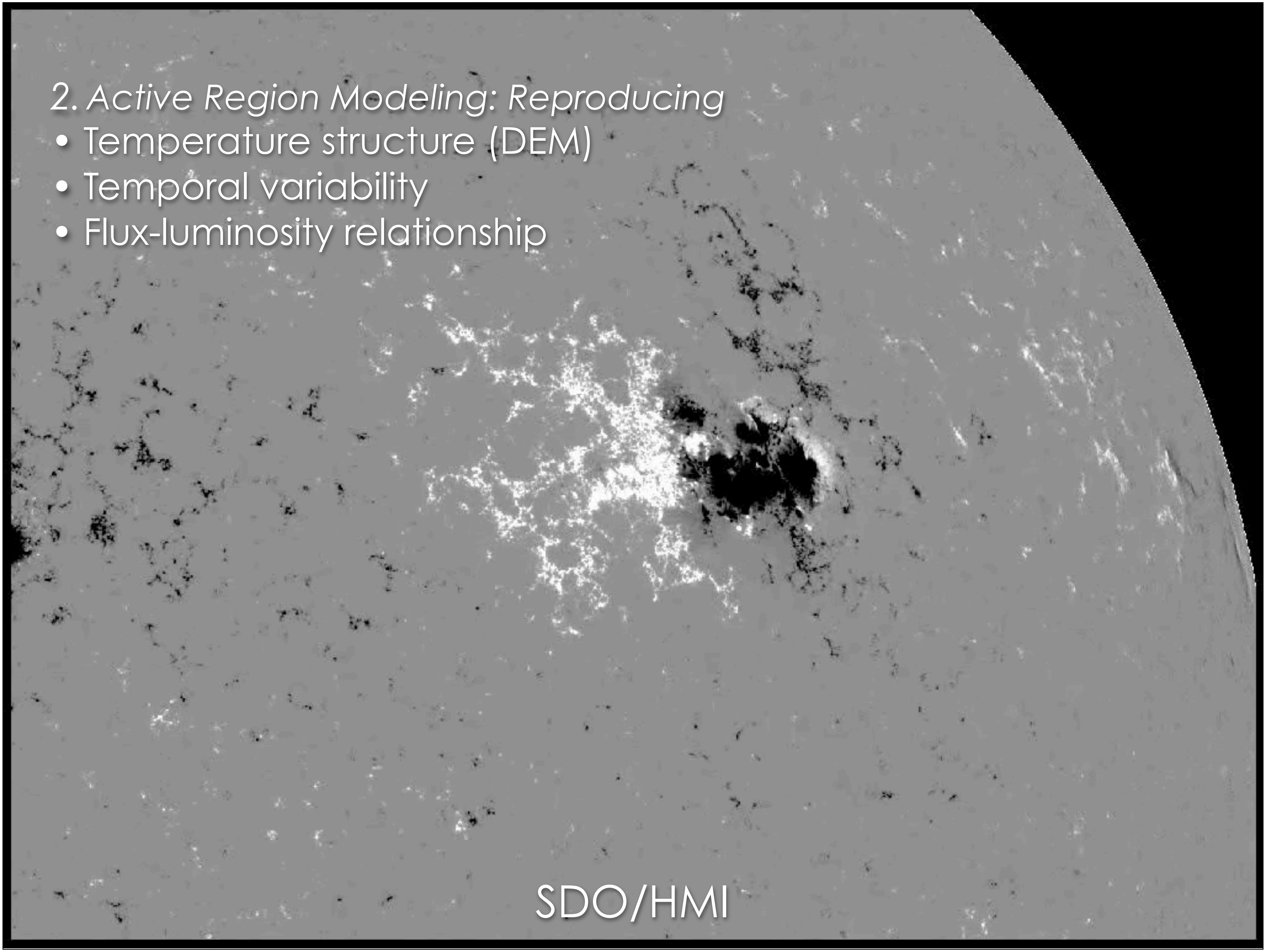




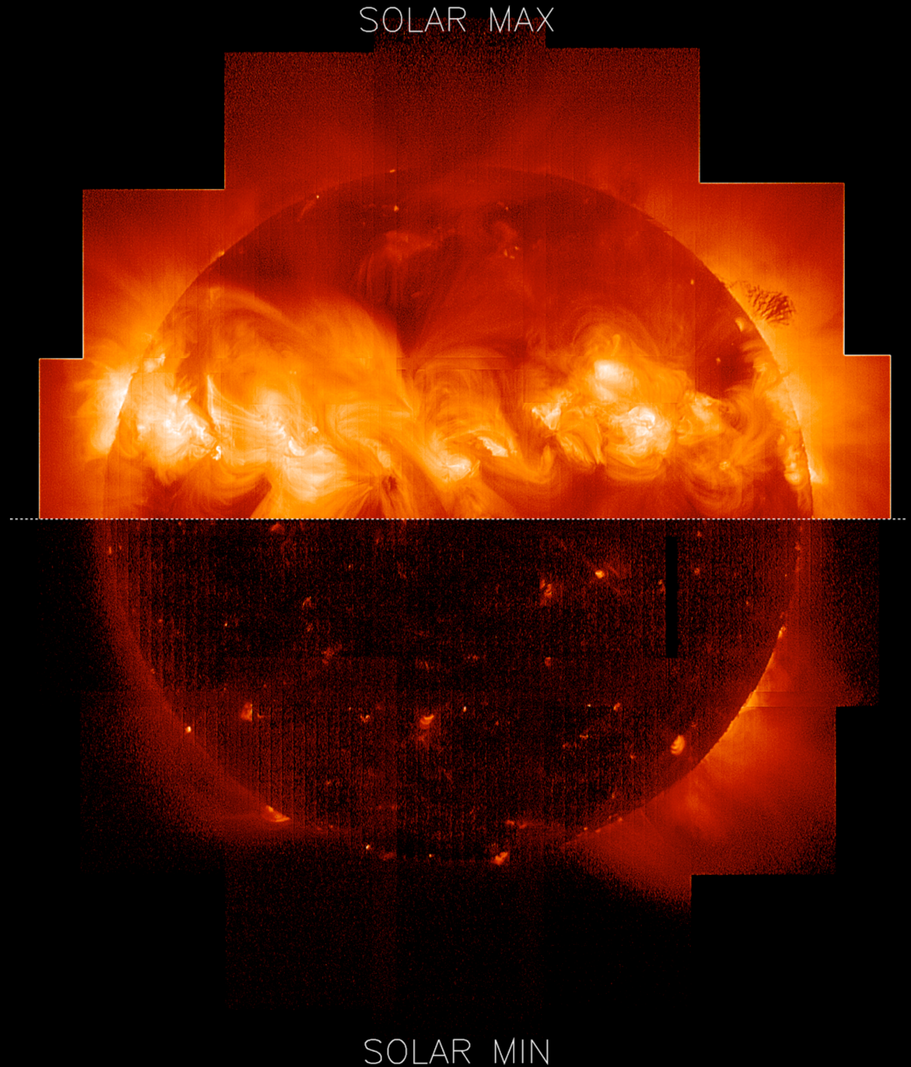
- Guennou et al. 2013 - uncertainty in the atomic data is underestimated
  see poster S3 P25

1. *The application of sparse Bayesian inference to the DEM problem*

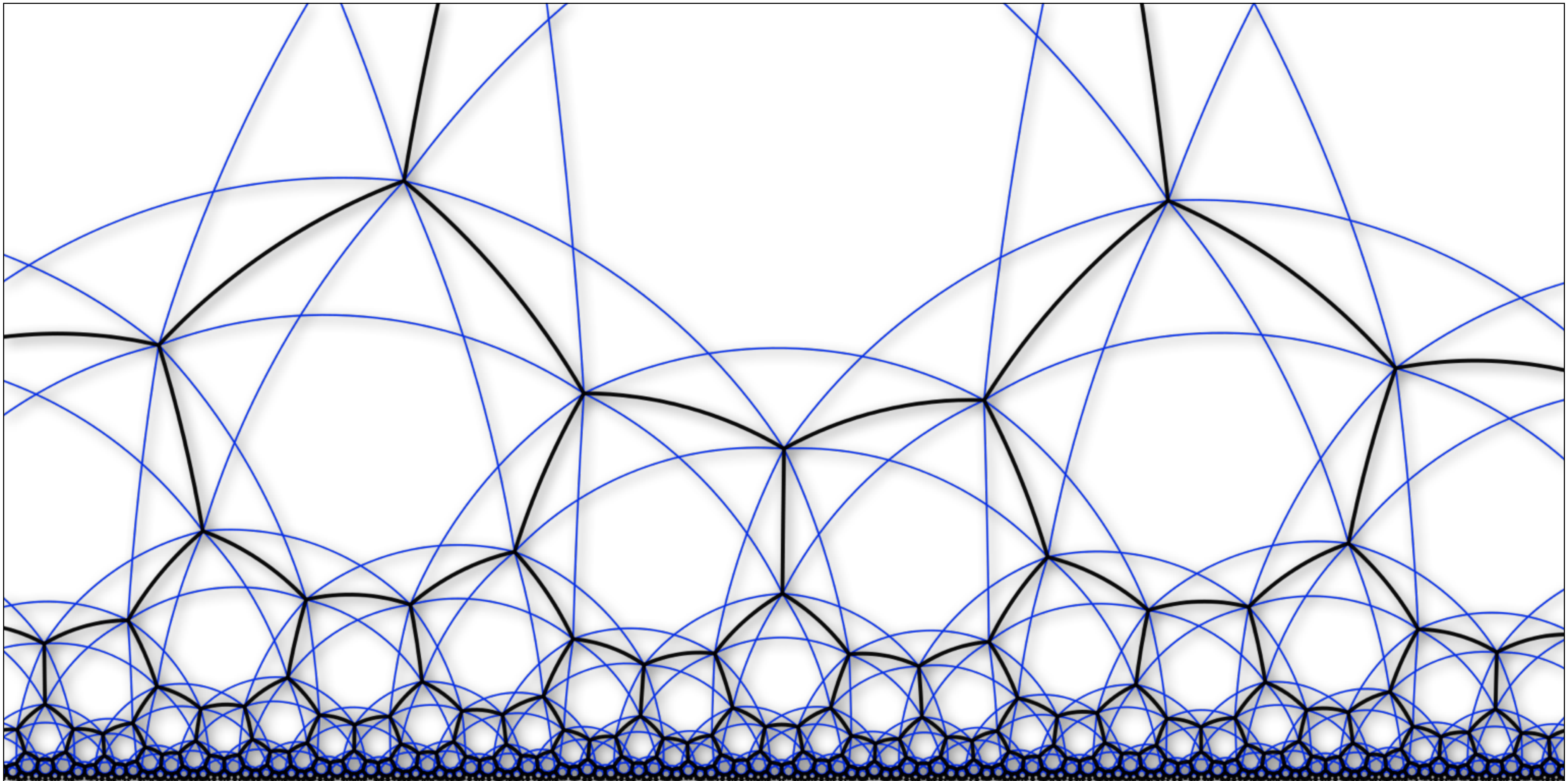
SDO/AIA Fe XVIII 94 Å


2. Active Region Modeling: Reproducing
• Temperature structure (DEM)
• Temporal variability
• Flux-luminosity relationship
SDO/HMI

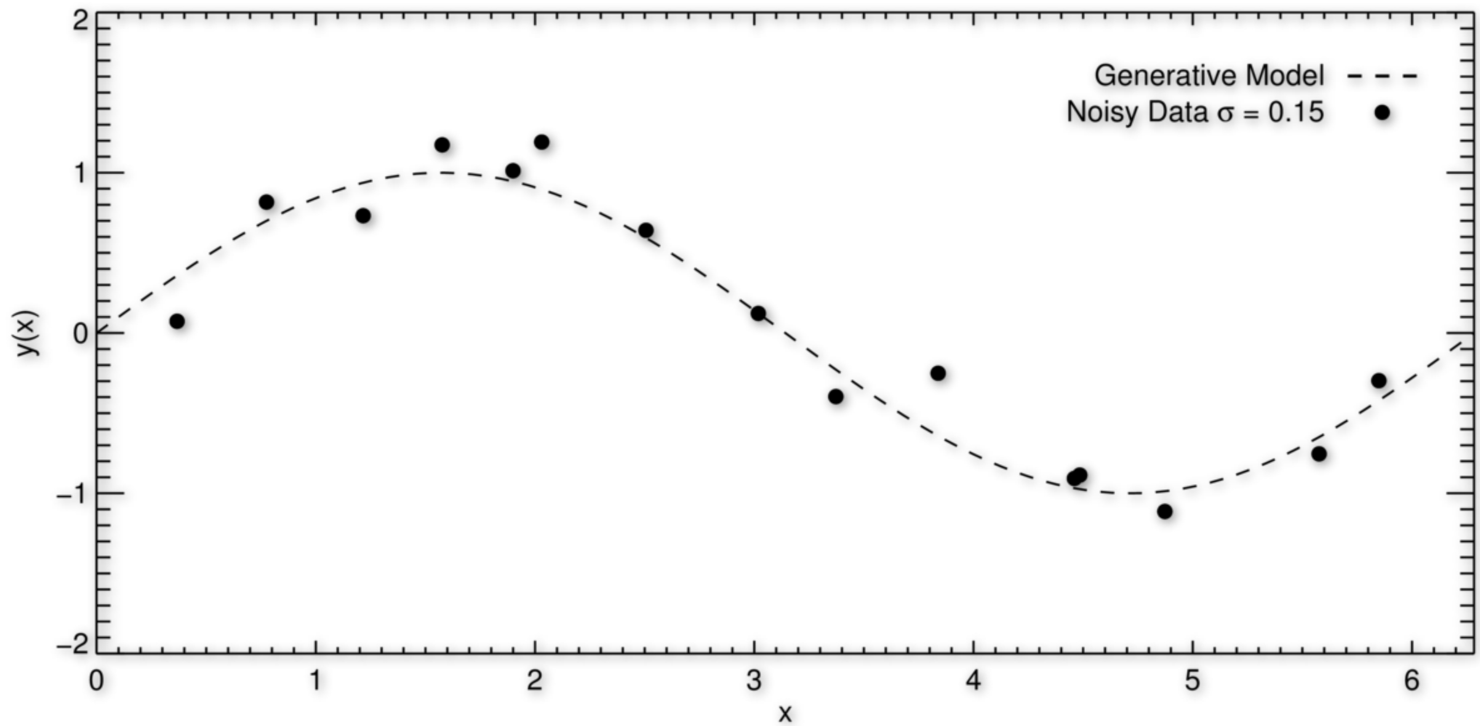
3. HOP 130, Atomic Physics, and the EIS Calibration



EIS Fe XV 284.16 Å



Sparse Bayesian Inference and the Temperature Structure of the Solar Corona

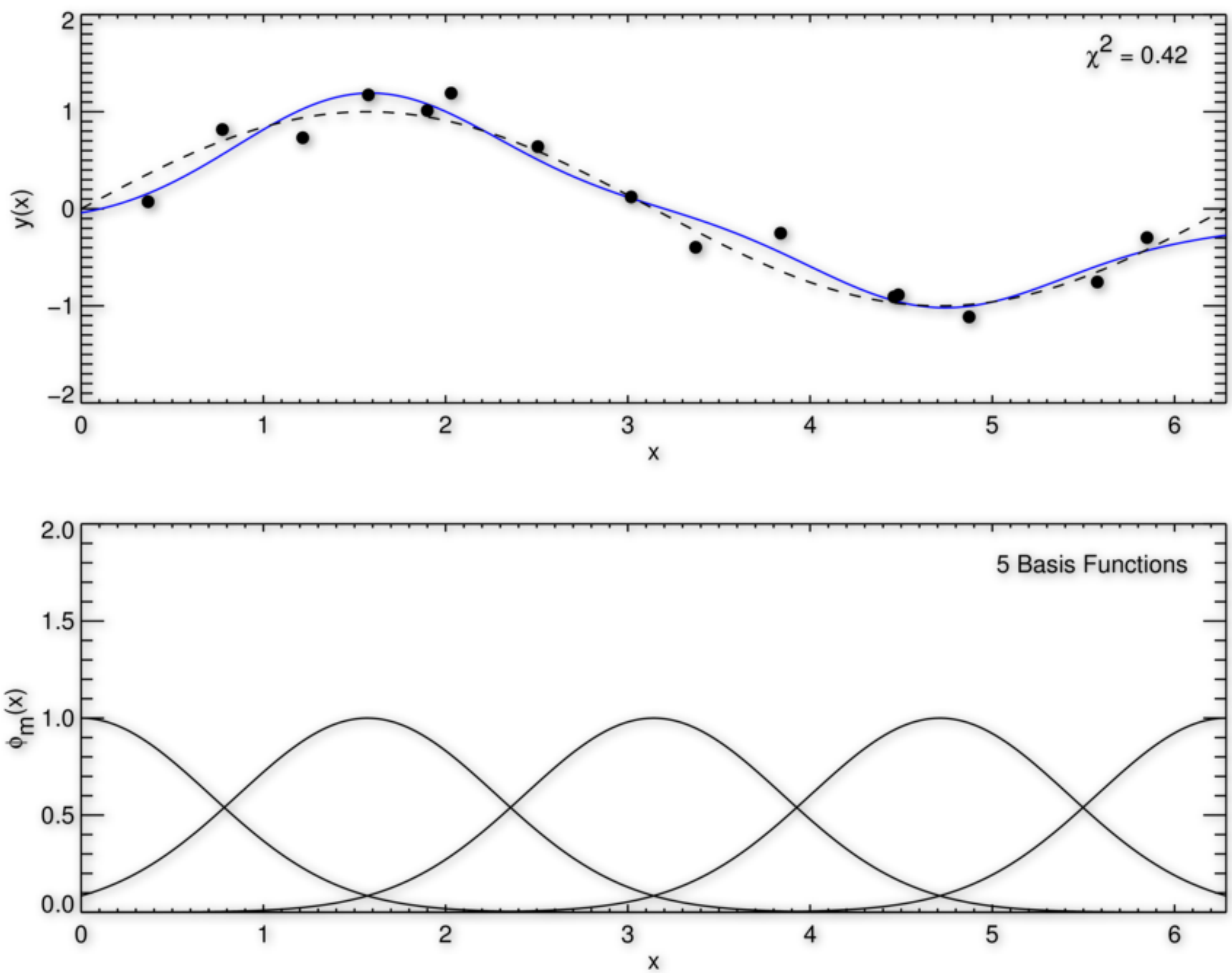


$$y(x) = \sum_{m=1}^{M} w_m \phi_m(x)$$

$$\phi_m(x) = \exp\left[-\frac{(x - x_m)^2}{r^2}\right]$$

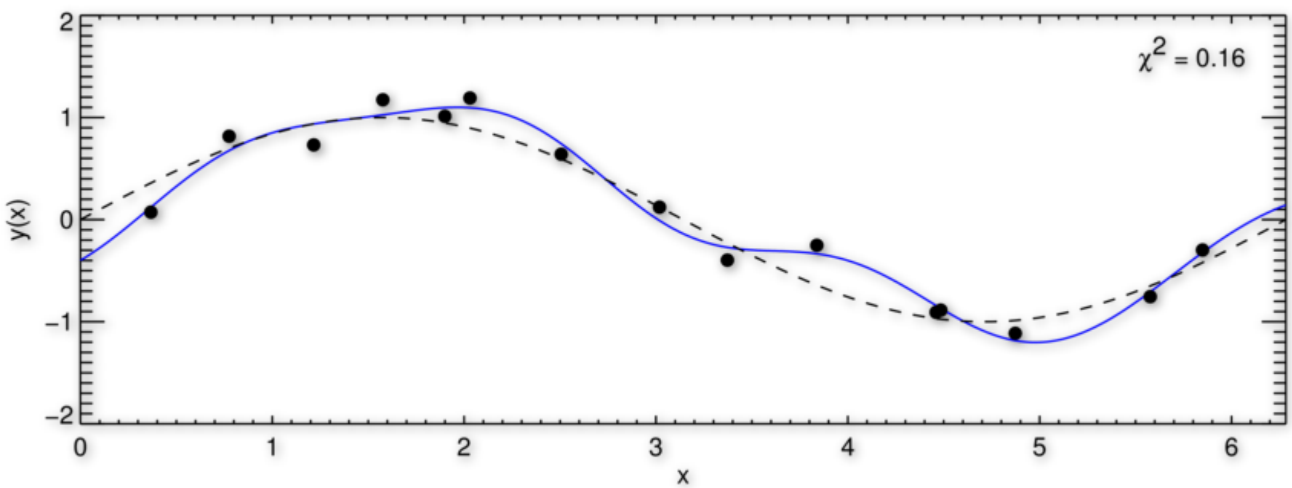
Least Squares Solution

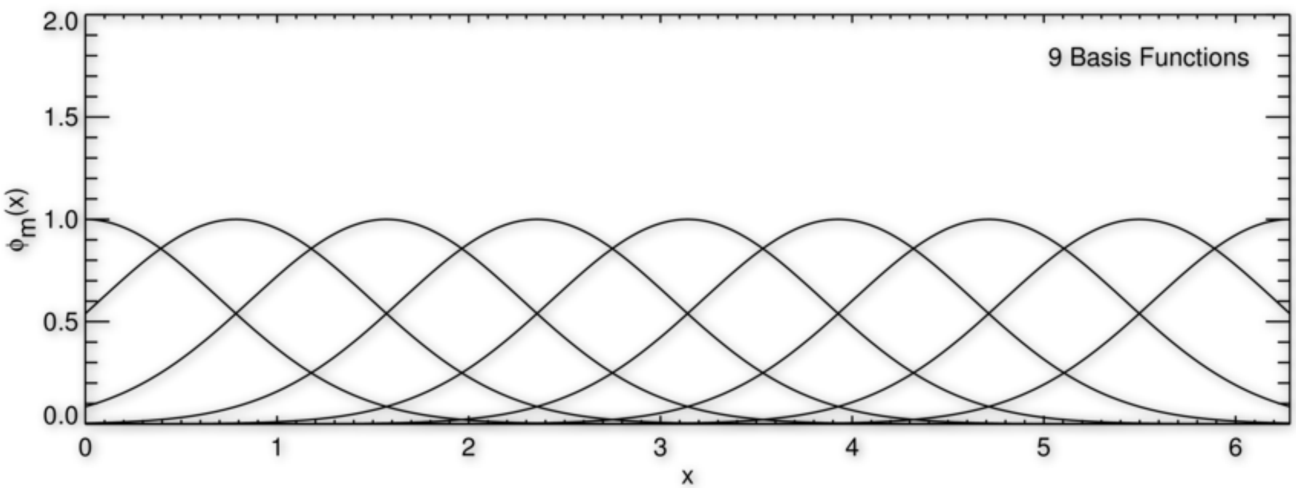
$$\mathbf{w} = (\mathbf{\Phi}^{\mathrm{T}}\mathbf{\Phi})^{-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{y}$$



Least Squares Solution

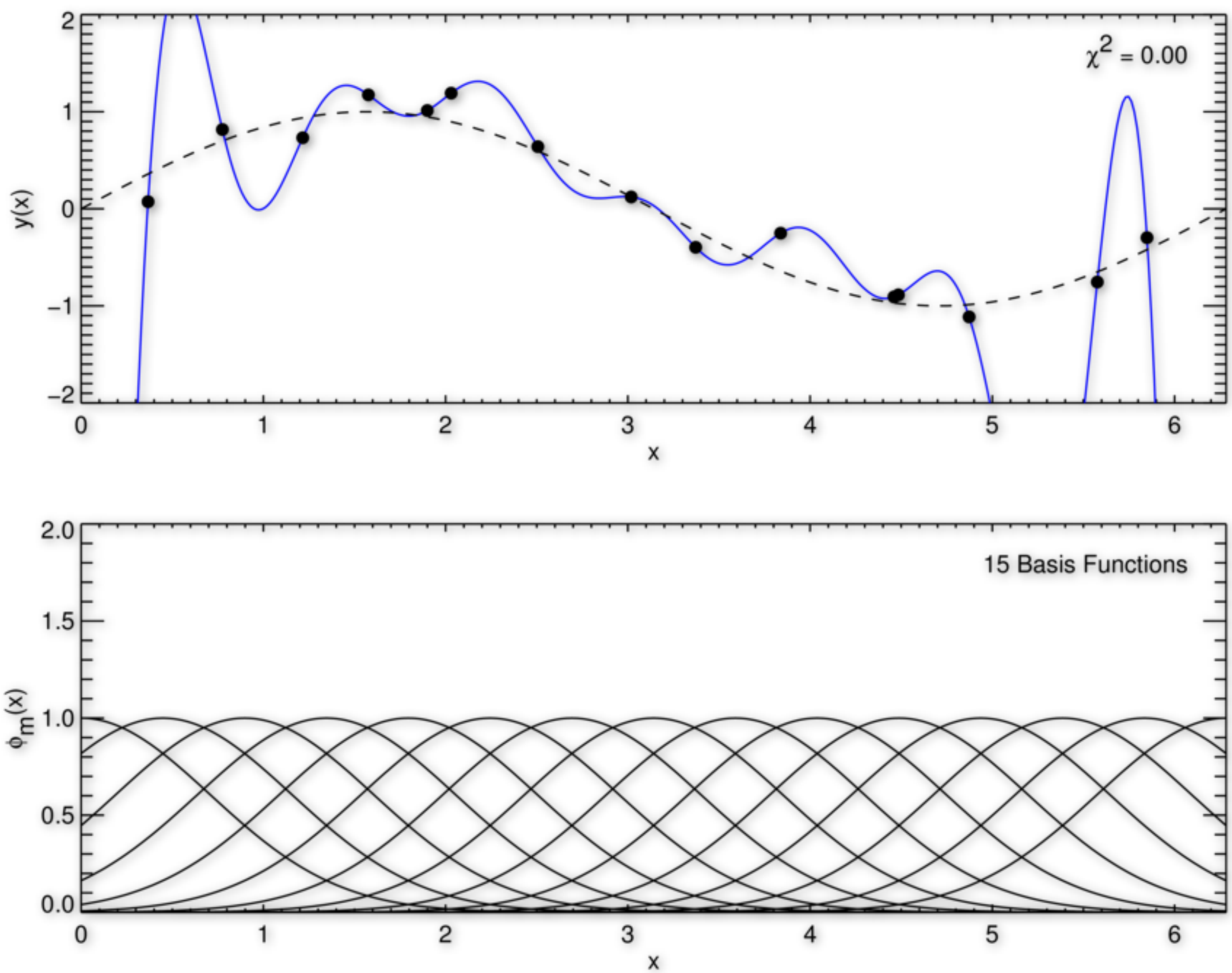
$$\mathbf{w} = (\mathbf{\Phi}^{\mathrm{T}}\mathbf{\Phi})^{-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{y}$$





Least Squares Solution

$$\mathbf{w} = (\mathbf{\Phi}^{\mathrm{T}}\mathbf{\Phi})^{-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{y}$$



A "SuperSet" of Least Squares: Bayesian Inference

Bayes' Theorem

likelihood prior

posterior

$$P(\mathcal{M} \mid \mathcal{D}) = \frac{P(\mathcal{D} \mid \mathcal{M})P(\mathcal{M})}{P(\mathcal{D})}$$

evidence

Sparse Bayesian Inference: The Relevance Vector Machine [RVM]

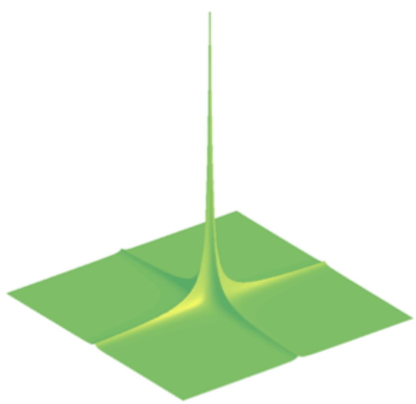
Michael Tipping, Microsoft Research
Journal of Machine Learning Research (2001)

$$P(\mathcal{M} \mid \mathcal{D}) = \frac{P(\mathcal{D} \mid \mathcal{M}) P(\mathcal{M})}{P(\mathcal{D})}$$

"hierarchical prior"

$$p(\mathbf{w} \mid \alpha) = \prod_{m=1}^{M} \sqrt{\frac{\alpha_m}{2\pi}} \exp\left[-\frac{1}{2}\alpha_m w_m^2\right]$$

$$p(w_m) =$$



Student-t distribution

After much gnashing of teeth
a Quasi-Analytic Solution

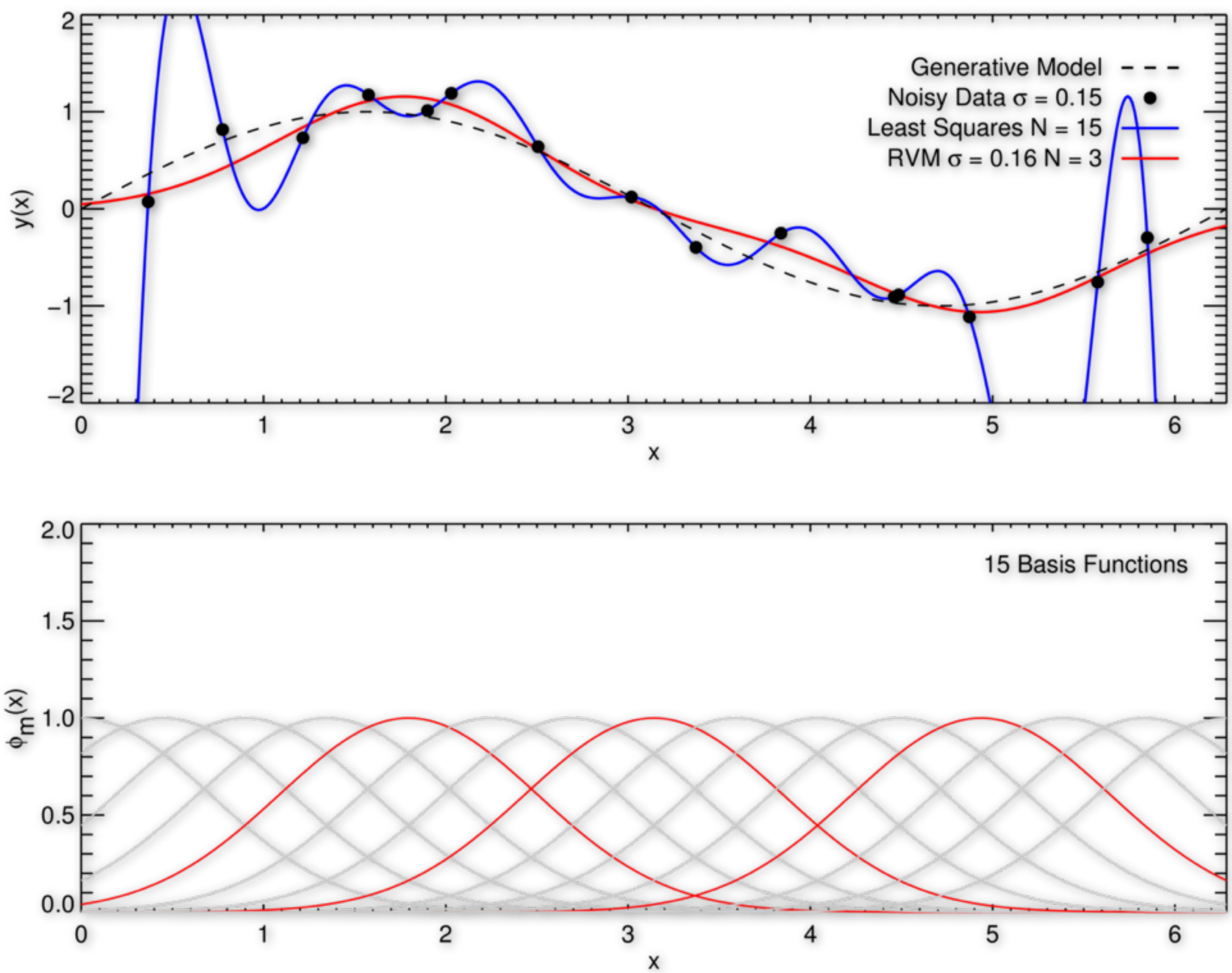
$$\mathbf{w} = \sigma^{-2}(\sigma^{-2}\mathbf{\Phi}^{\mathrm{T}}\mathbf{\Phi} + \mathbf{A})^{-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{y} = \sigma^{-2}\mathbf{\Sigma}\mathbf{\Phi}^{\mathrm{T}}\mathbf{y}$$

solve by iteration

$$\alpha_i^{new} = \frac{1 - \alpha_i \Sigma_{ii}}{w_i^2}$$

$$\sigma^{new} = \frac{\|\mathbf{y} - \mathbf{\Phi}\mathbf{w}\|}{\sqrt{N - c}}$$

RVM vs Least Squares
Magic!



Positivity: A Fly in the Ointment!

Positivity is not built in. How do we do the DEM problem?

$$I_n = \int \epsilon_n(T)\xi(T)\, dT$$

$$\xi(T) = \sum_{m=1}^{M} w_m \phi_m(T)$$

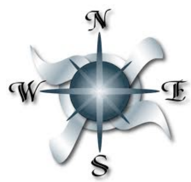
a simple solution

$$\xi(T) = \sum_{m=1}^{M} 10^{w_m} \phi_m(T) > 0$$

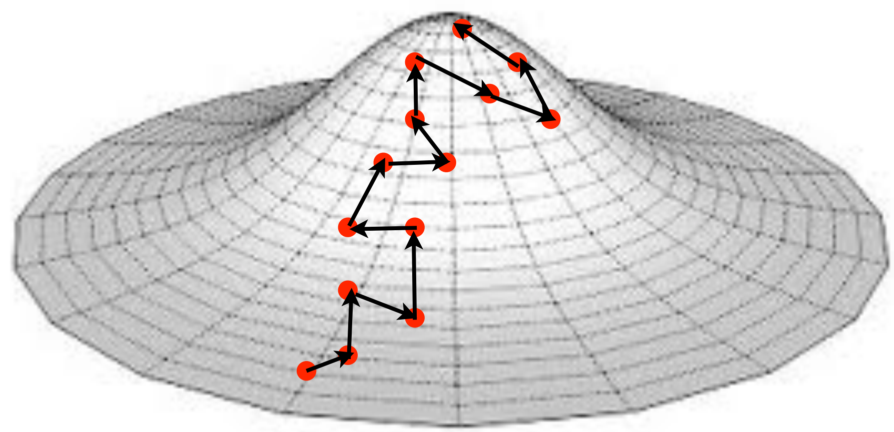
but this breaks Tipping's iterative scheme

Exploring the Posterior:
Markov Chain Monte Carlo and Metropolis-Hastings

we need to *explore* the posterior



move to where the posterior is
highest,
but not always



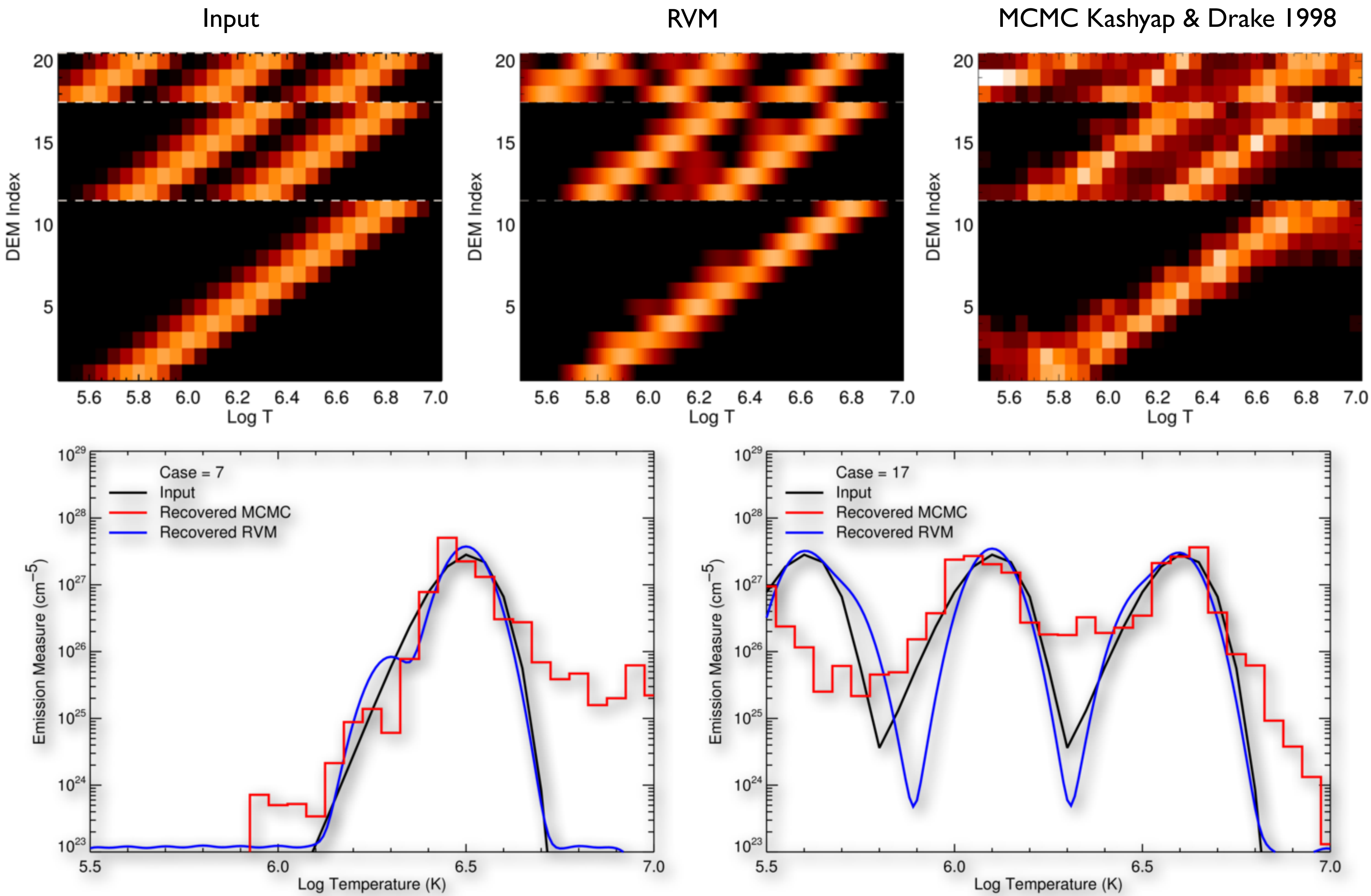
The Metropolis-Hastings Algorithm

$$\text{consider } \mathbf{w} \to \mathbf{w}'$$

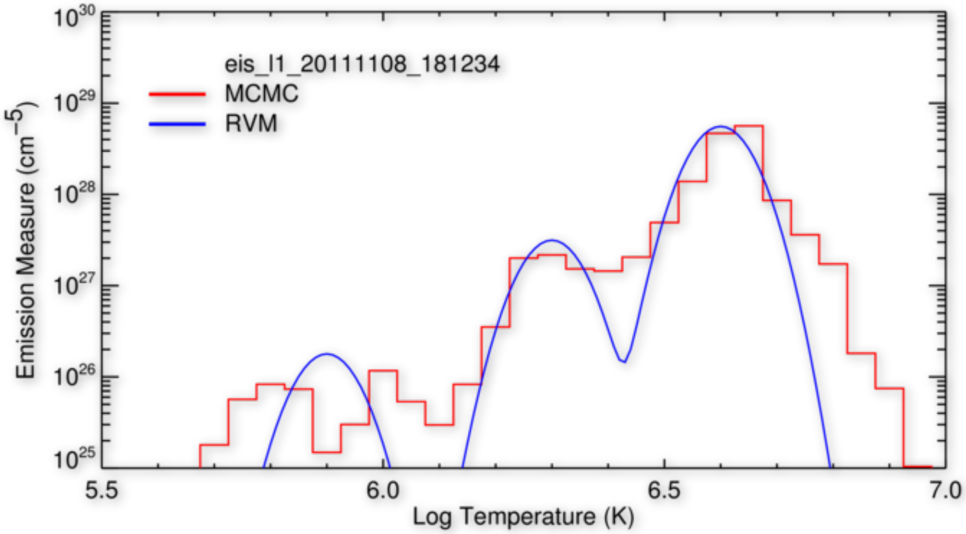
$$\text{accept if: } P(D \mid \mathbf{w}') > P(D \mid \mathbf{w})$$

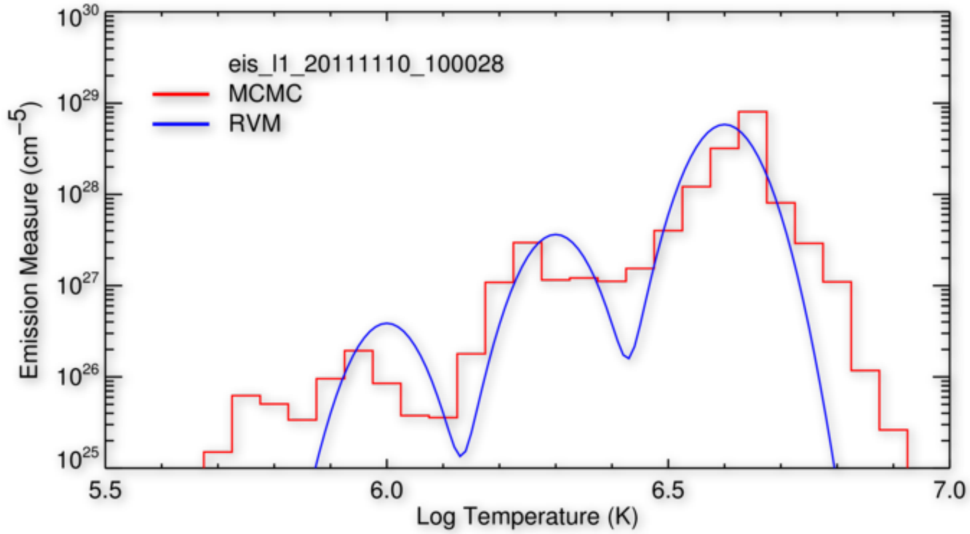
$$\text{or if: } u < P(D \mid \mathbf{w}')/P(D \mid \mathbf{w}) \; u \in [0,1]$$

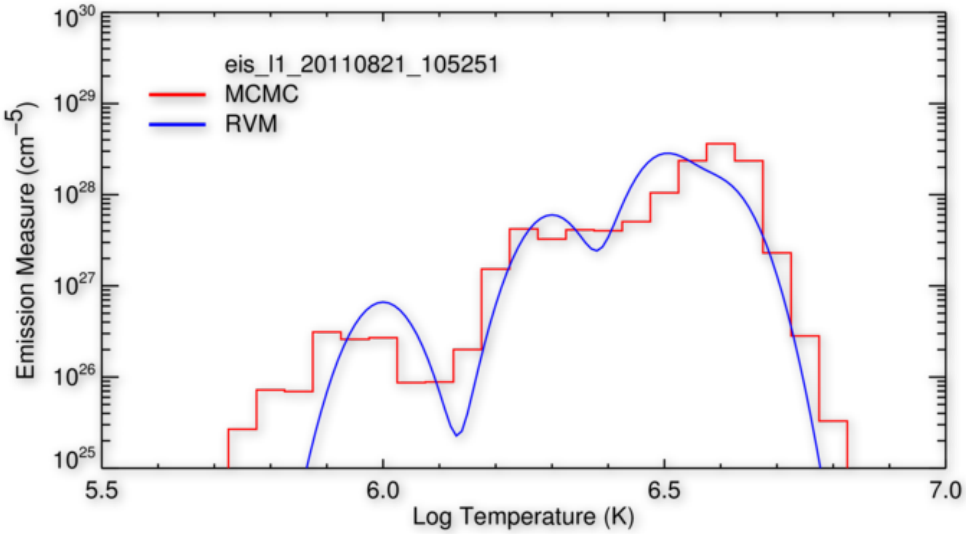
The DEM "Library"



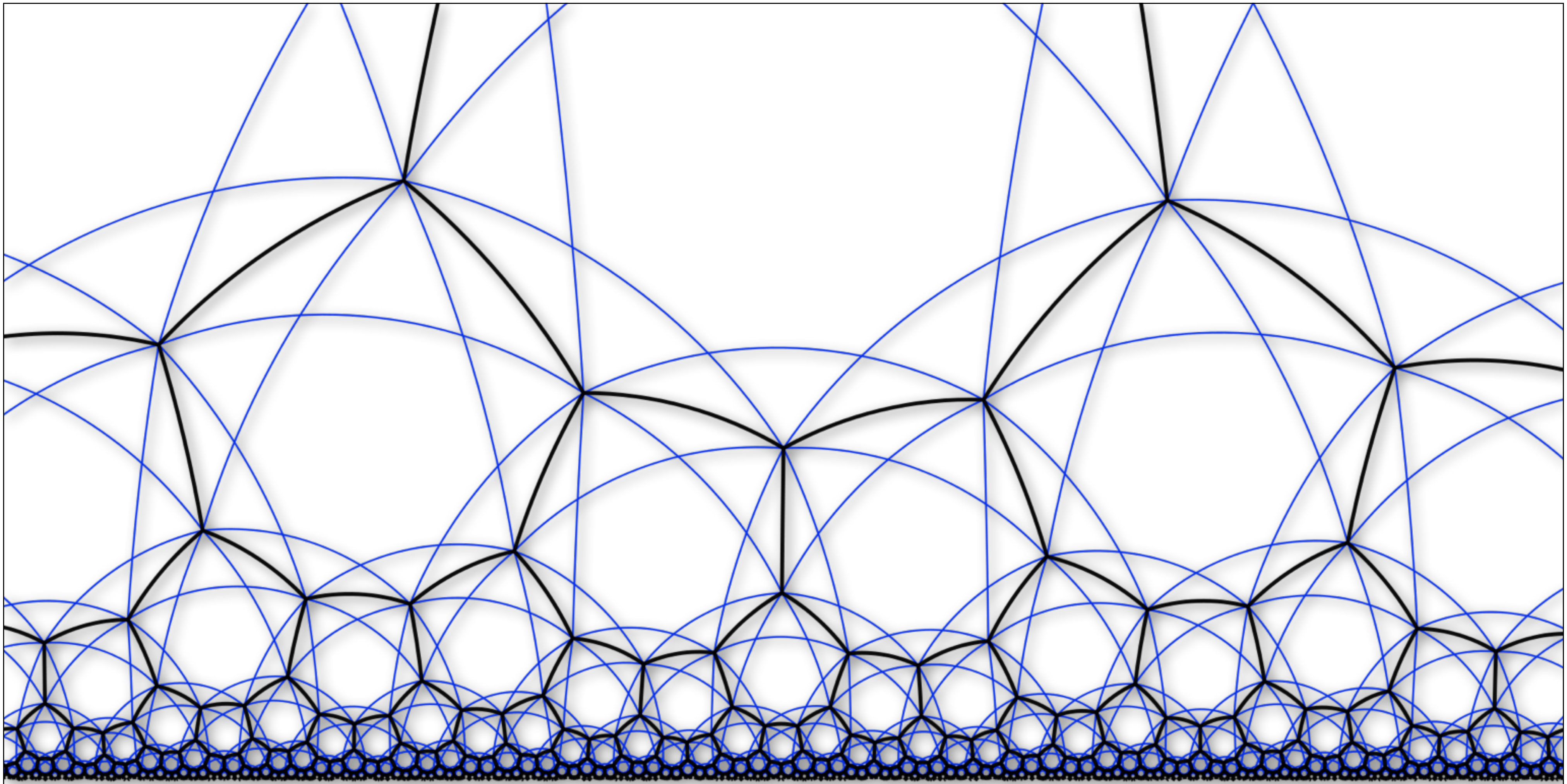
Application to Observations



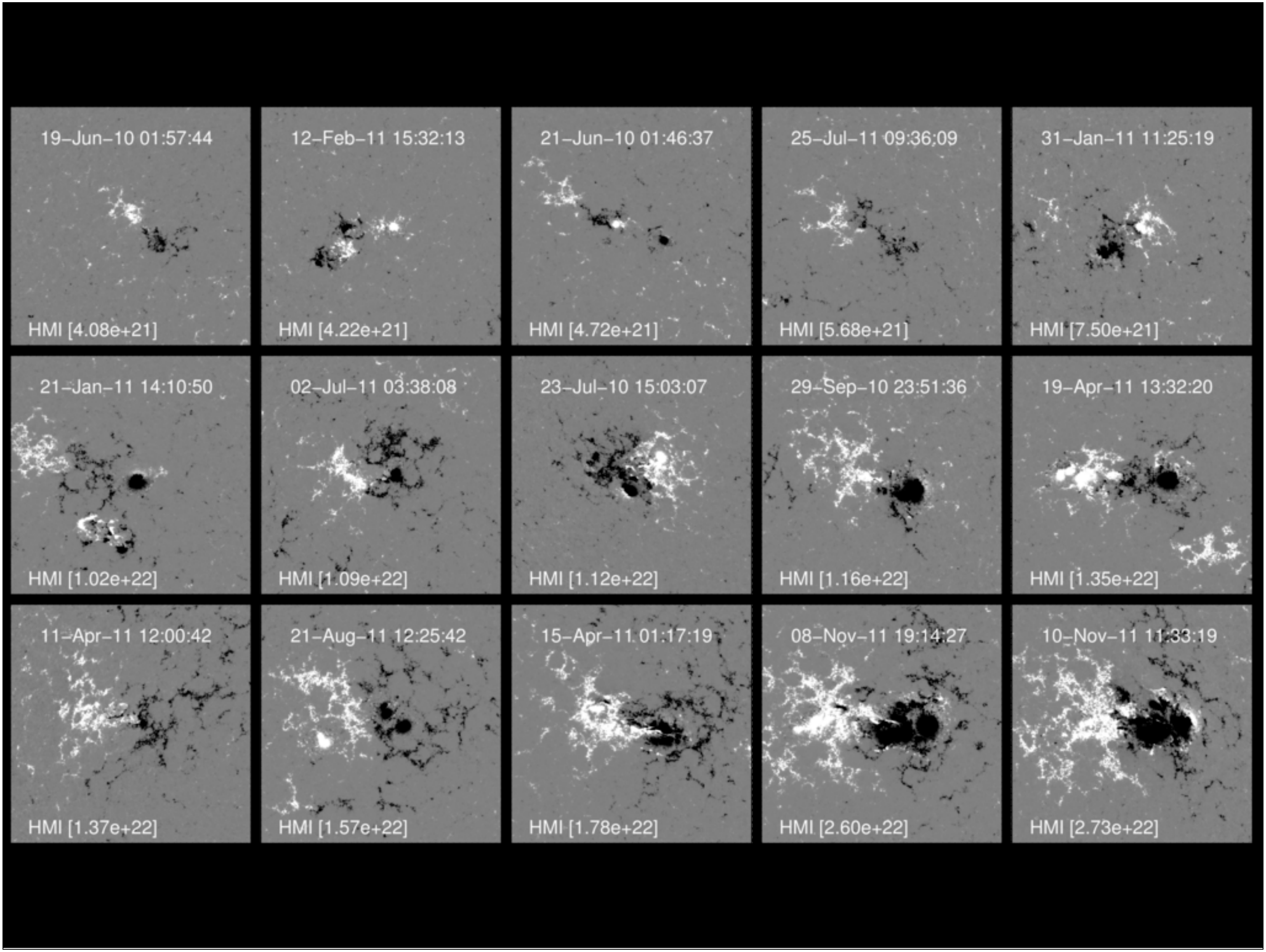


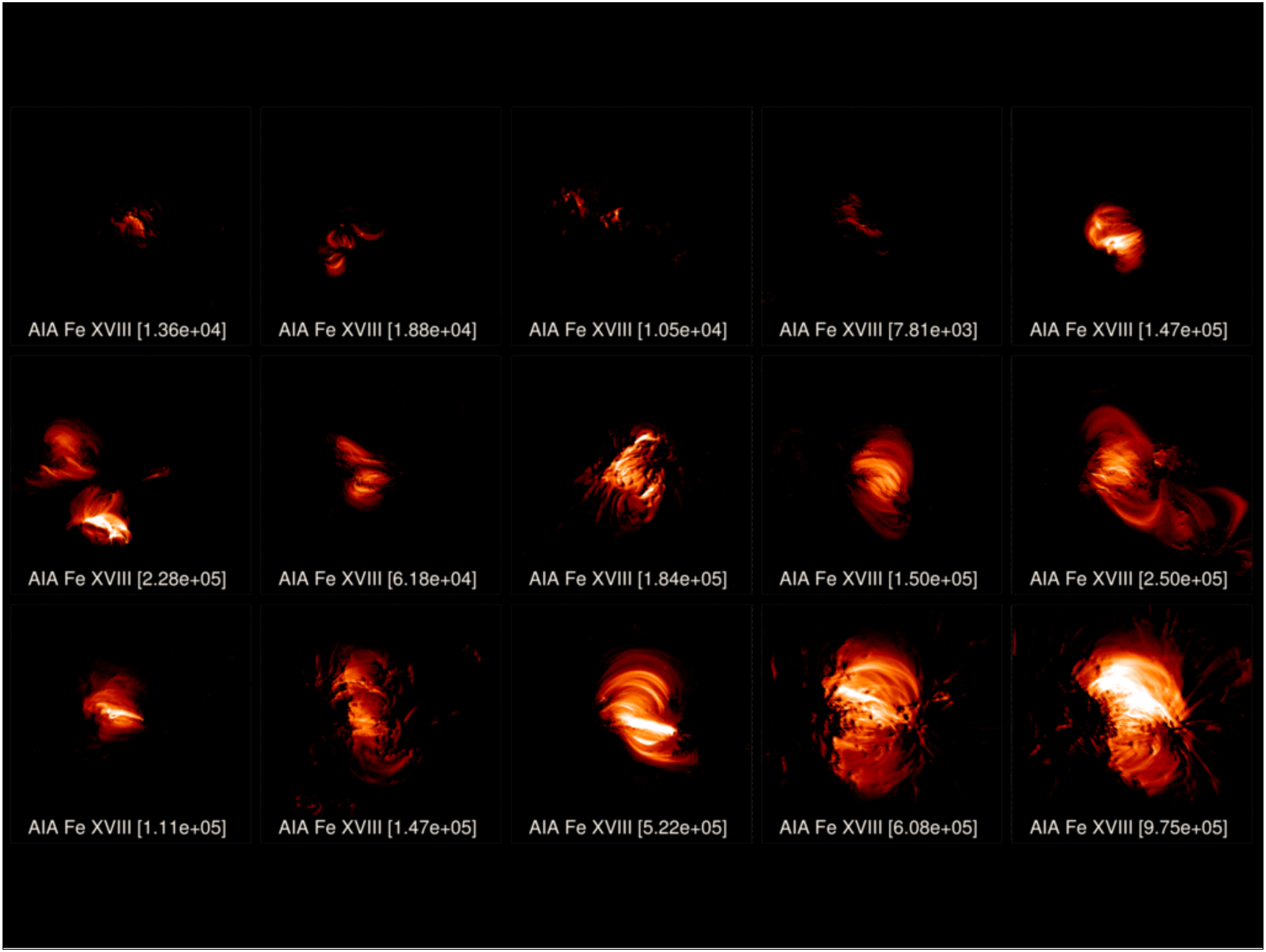


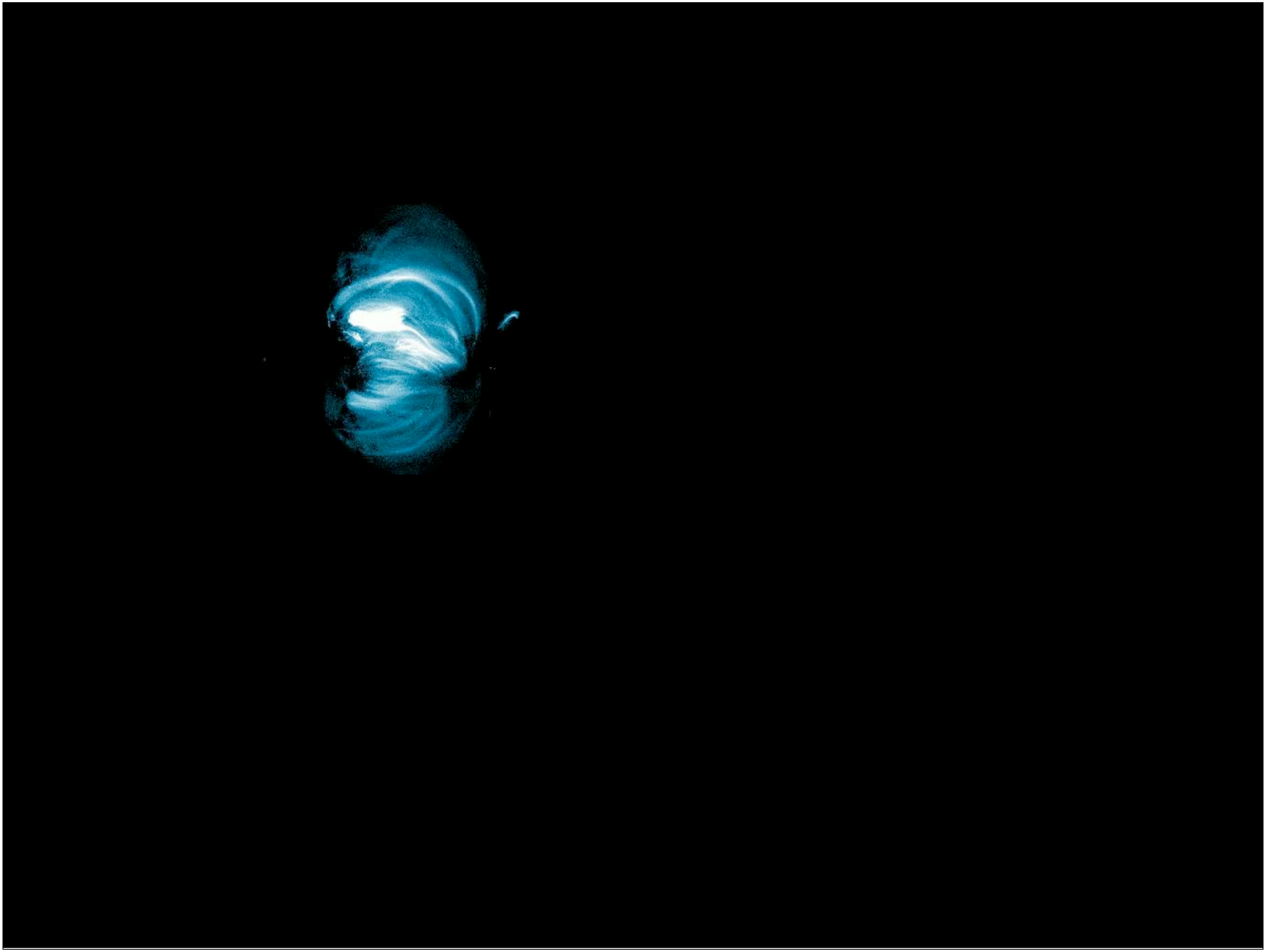
- Similar to previous results
- Slow! For speed see Hannah & Kontar (2012)
- Doesn't address errors in atomic data
- BUT, we know how to balance uncertainty and complexity

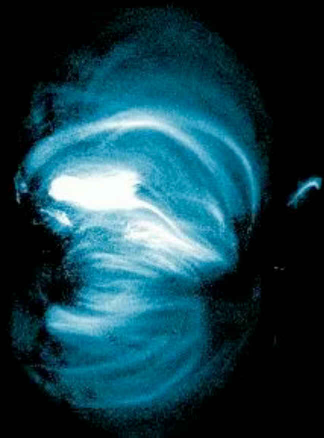


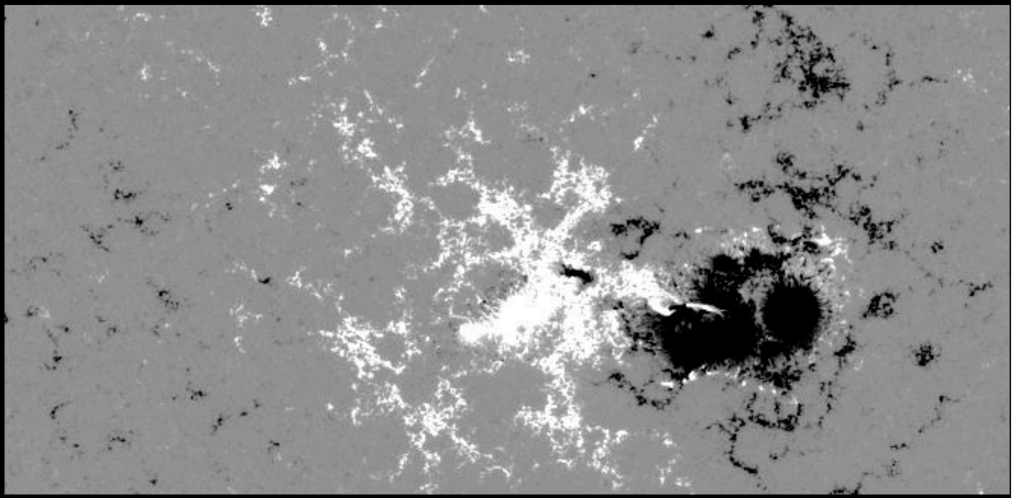
Modeling Solar Active Regions

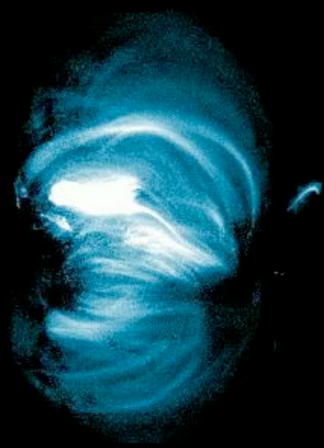

19-Jun-10 01:57:44
HMI [4.08e+21]
12-Feb-11 15:32:13
HMI [4.22e+21]
21-Jun-10 01:46:37
HMI [4.72e+21]
25-Jul-11 09:36:09
HMI [5.68e+21]
31-Jan-11 11:25:19
HMI [7.50e+21]
21-Jan-11 14:10:50
HMI [1.02e+22]
02-Jul-11 03:38:08
HMI [1.09e+22]
23-Jul-10 15:03:07
HMI [1.12e+22]
29-Sep-10 23:51:36
HMI [1.16e+22]
19-Apr-11 13:32:20
HMI [1.35e+22]
11-Apr-11 12:00:42
HMI [1.37e+22]
21-Aug-11 12:25:42
HMI [1.57e+22]
15-Apr-11 01:17:19
HMI [1.78e+22]
08-Nov-11 19:14:27
HMI [2.60e+22]
10-Nov-11 11:33:19
HMI [2.73e+22]

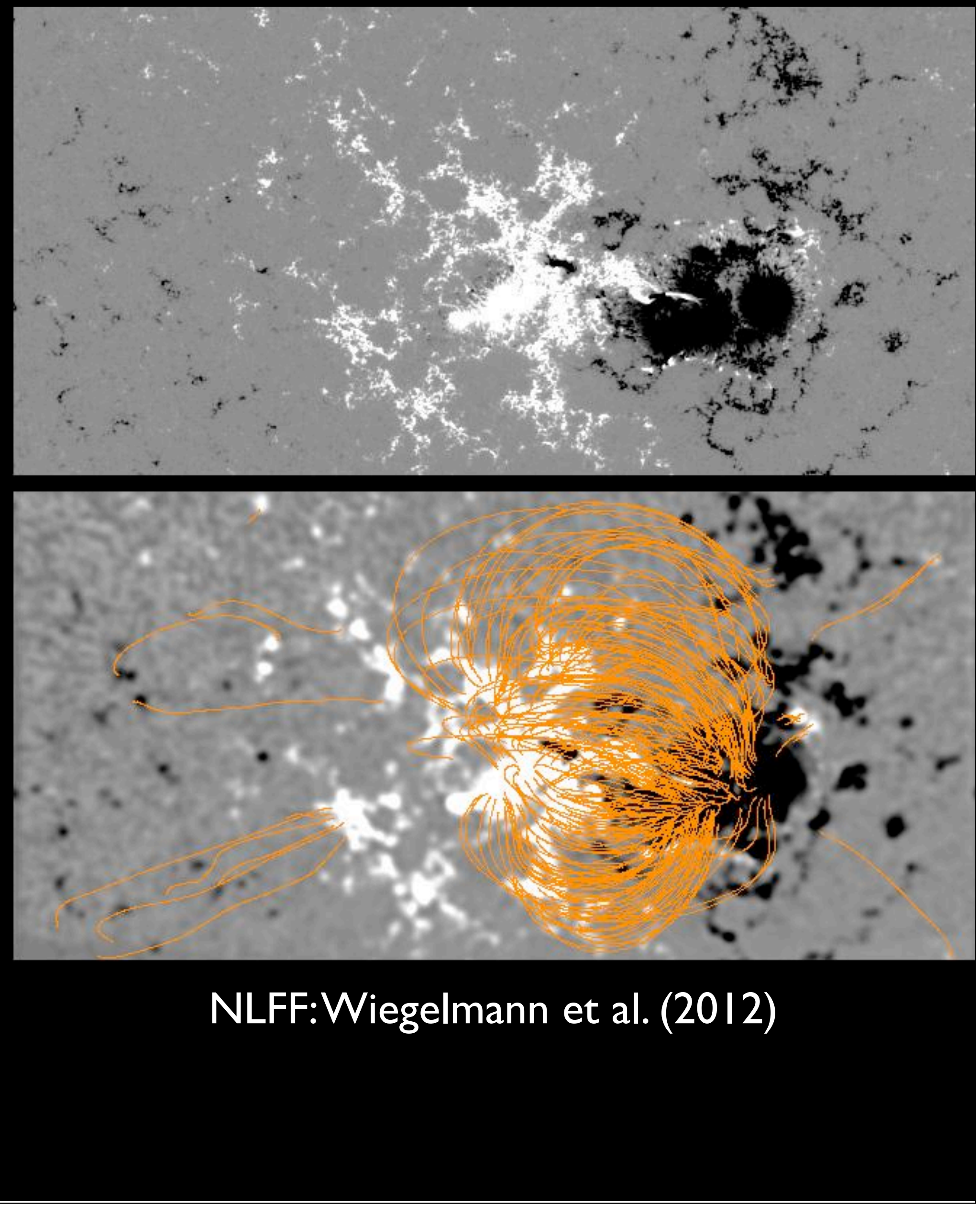

AIA Fe XVIII [1.36e+04]
AIA Fe XVIII [1.88e+04]
AIA Fe XVIII [1.05e+04]
AIA Fe XVIII [7.81e+03]
AIA Fe XVIII [1.47e+05]
AIA Fe XVIII [2.28e+05]
AIA Fe XVIII [6.18e+04]
AIA Fe XVIII [1.84e+05]
AIA Fe XVIII [1.50e+05]
AIA Fe XVIII [2.50e+05]
AIA Fe XVIII [1.11e+05]
AIA Fe XVIII [1.47e+05]
AIA Fe XVIII [5.22e+05]
AIA Fe XVIII [6.08e+05]
AIA Fe XVIII [9.75e+05]



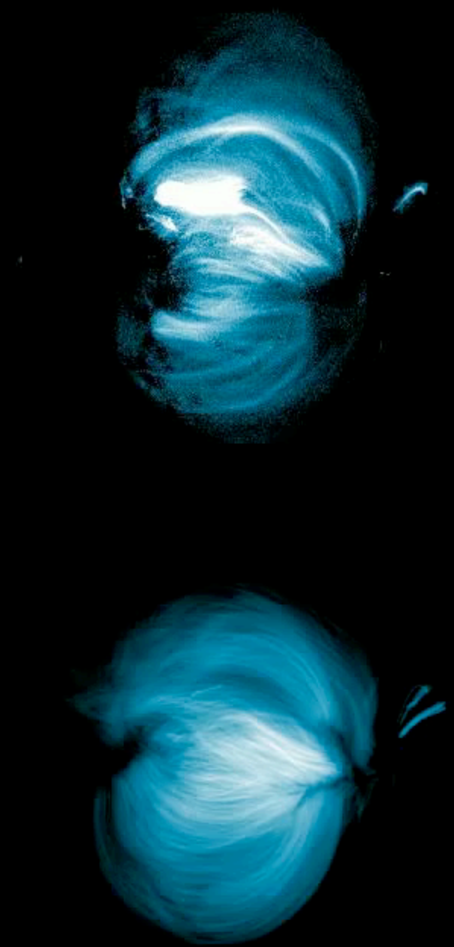




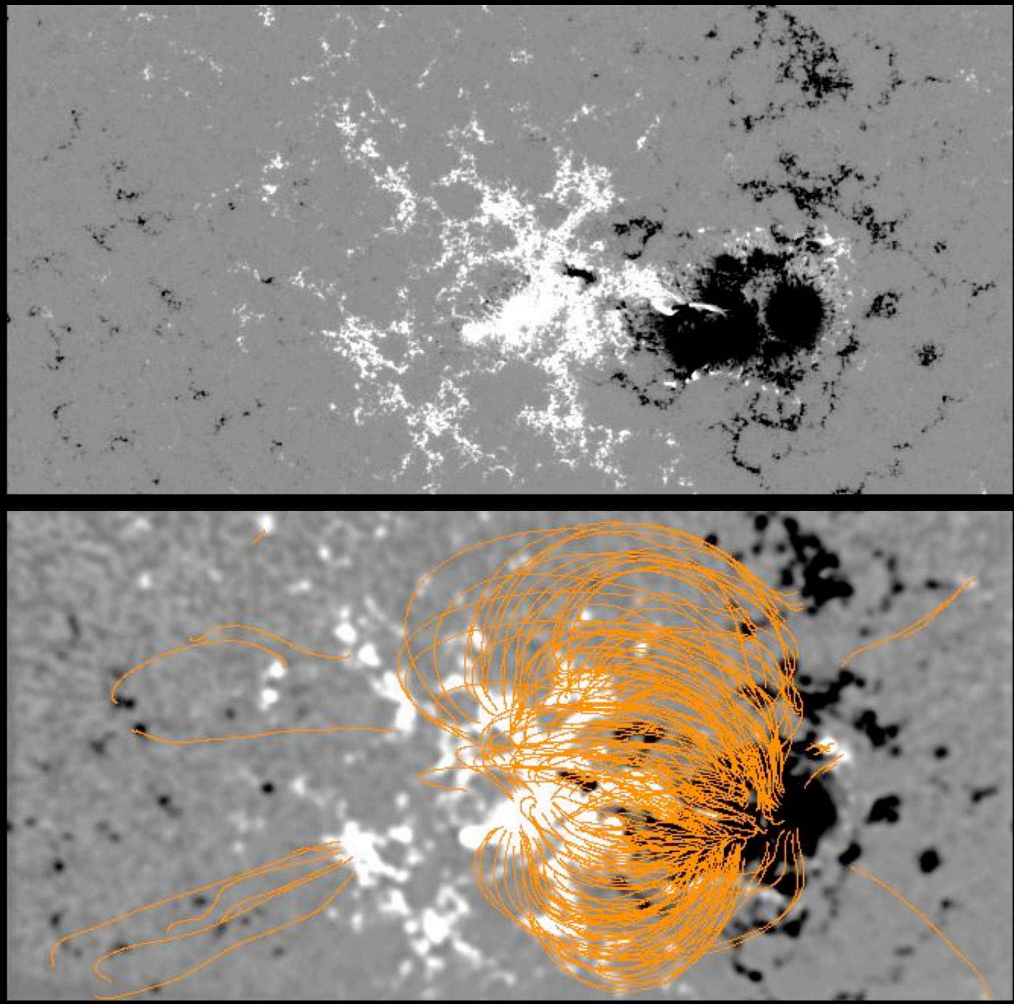




NLFF: Wiegelmann et al. (2012)



EBTELv2: Cargill et al. (2012)



NLFF: Wiegelmann et al. (2012)

Steady

$$\epsilon_E = \epsilon_0 \left(\frac{\bar{B}}{\bar{B}_0} \right)^\alpha \left(\frac{L_0}{L} \right)^\beta$$

$$\alpha = \beta = 1$$

Schrijver et al., 2004; Lundquist et al., 2008; Warren & Winebarger 2006, 2007; Winebarger et al., 2008, 2011;

Steady

$$\epsilon_E = \epsilon_0 \left(\frac{\bar{B}}{\bar{B}_0} \right)^{\alpha} \left(\frac{L_0}{L} \right)^{\beta}$$

$$\alpha = \beta = 1$$

Schrijver et al., 2004; Lundquist et al., 2008; Warren & Winebarger 2006, 2007; Winebarger et al., 2008, 2011;

Impulsive

magnitude of heating event

duration of heating event

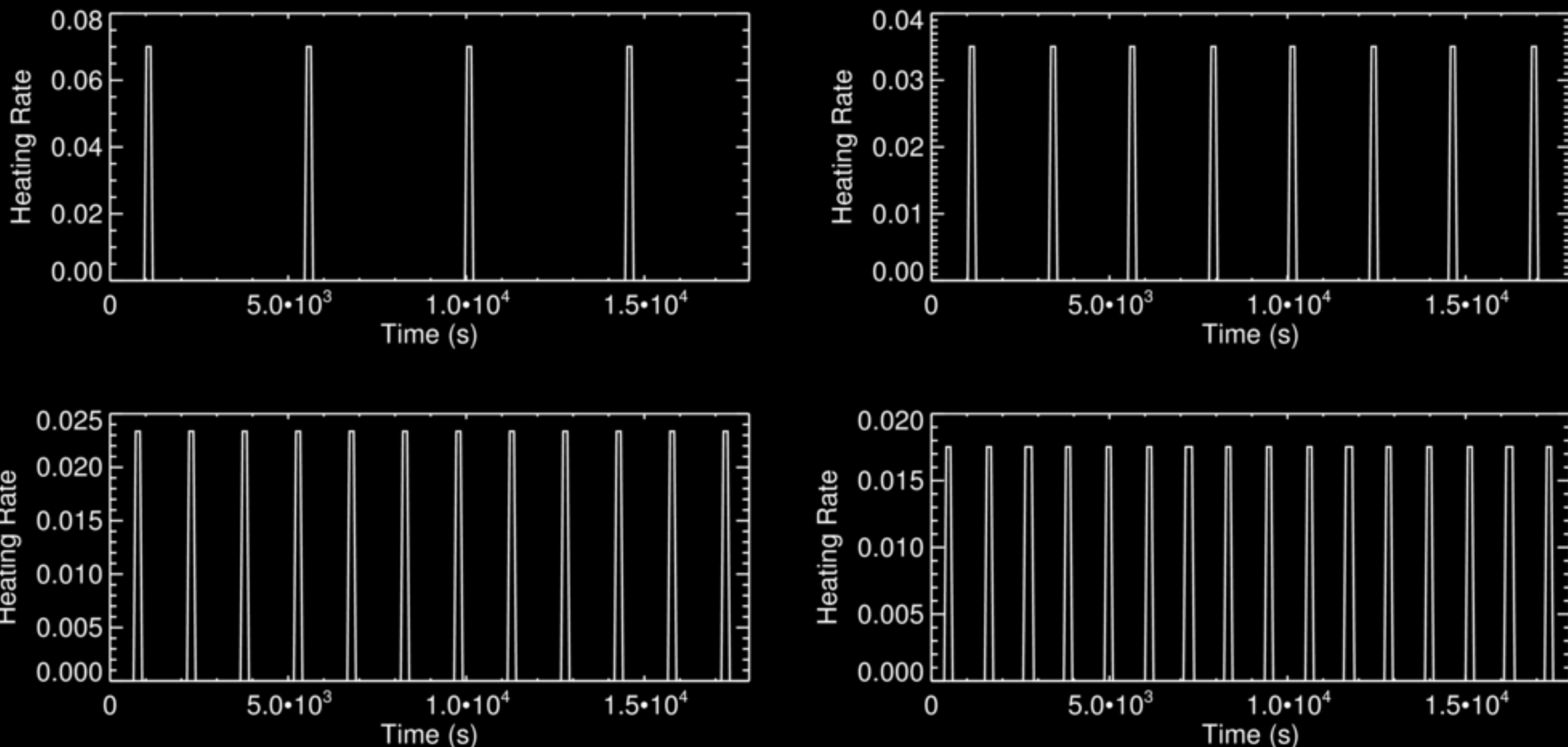
$$\epsilon_E = \epsilon_D \frac{\delta}{\tau}$$

magnitude of equilibrium heating

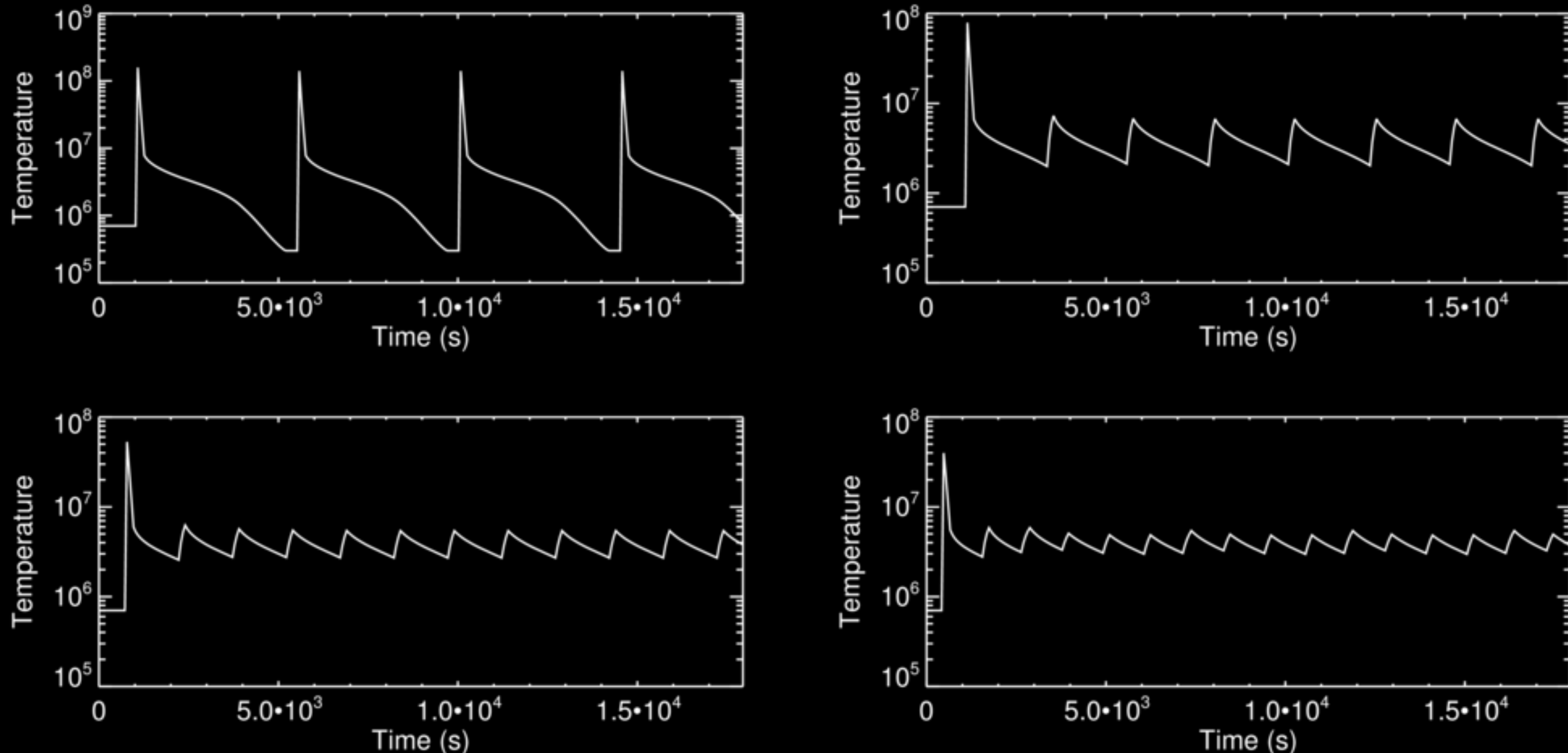
time between heating events

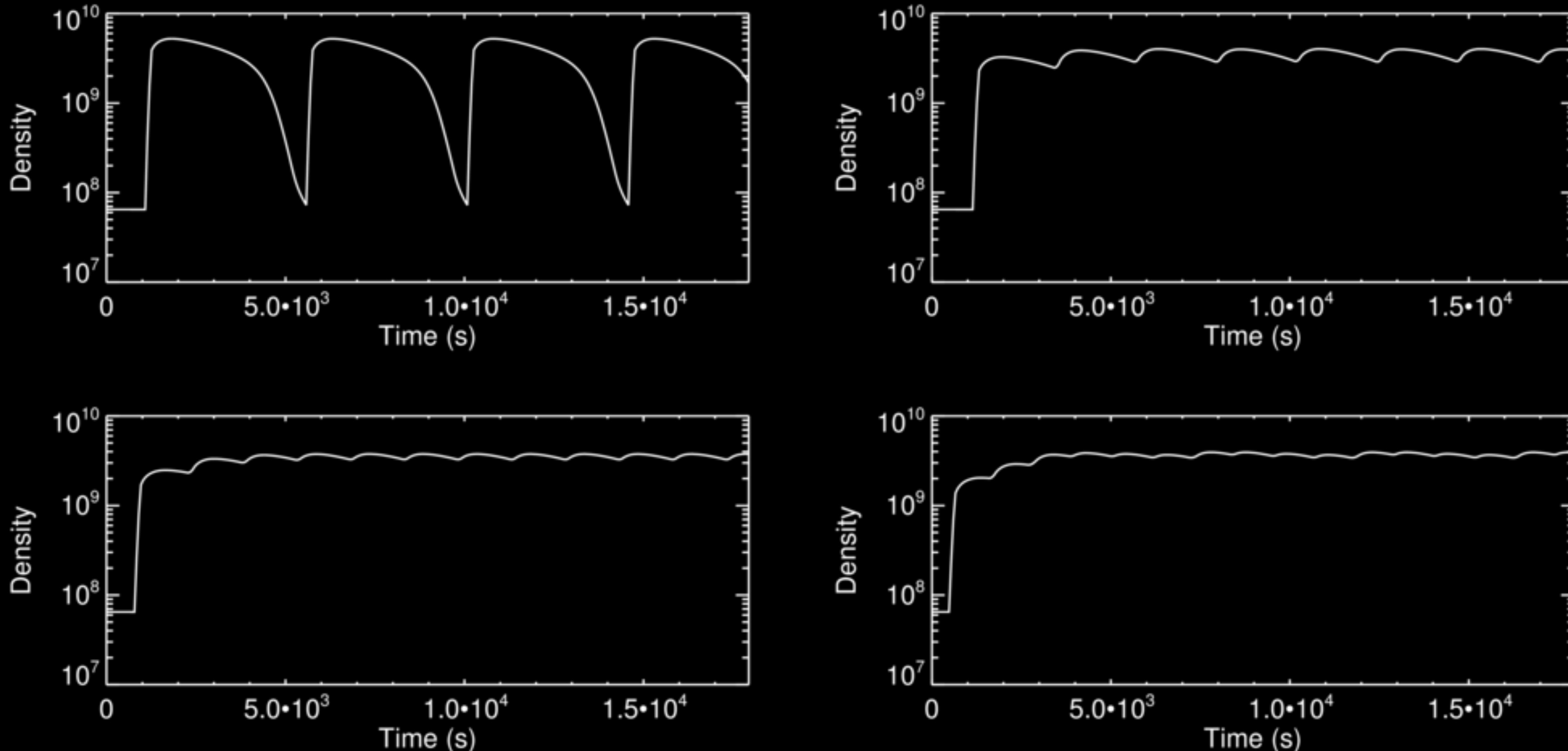
$\tau \sim \tau_{cool} \rightarrow$ impulsive heating

$\tau \ll \tau_{cool} \rightarrow$ equilibrium

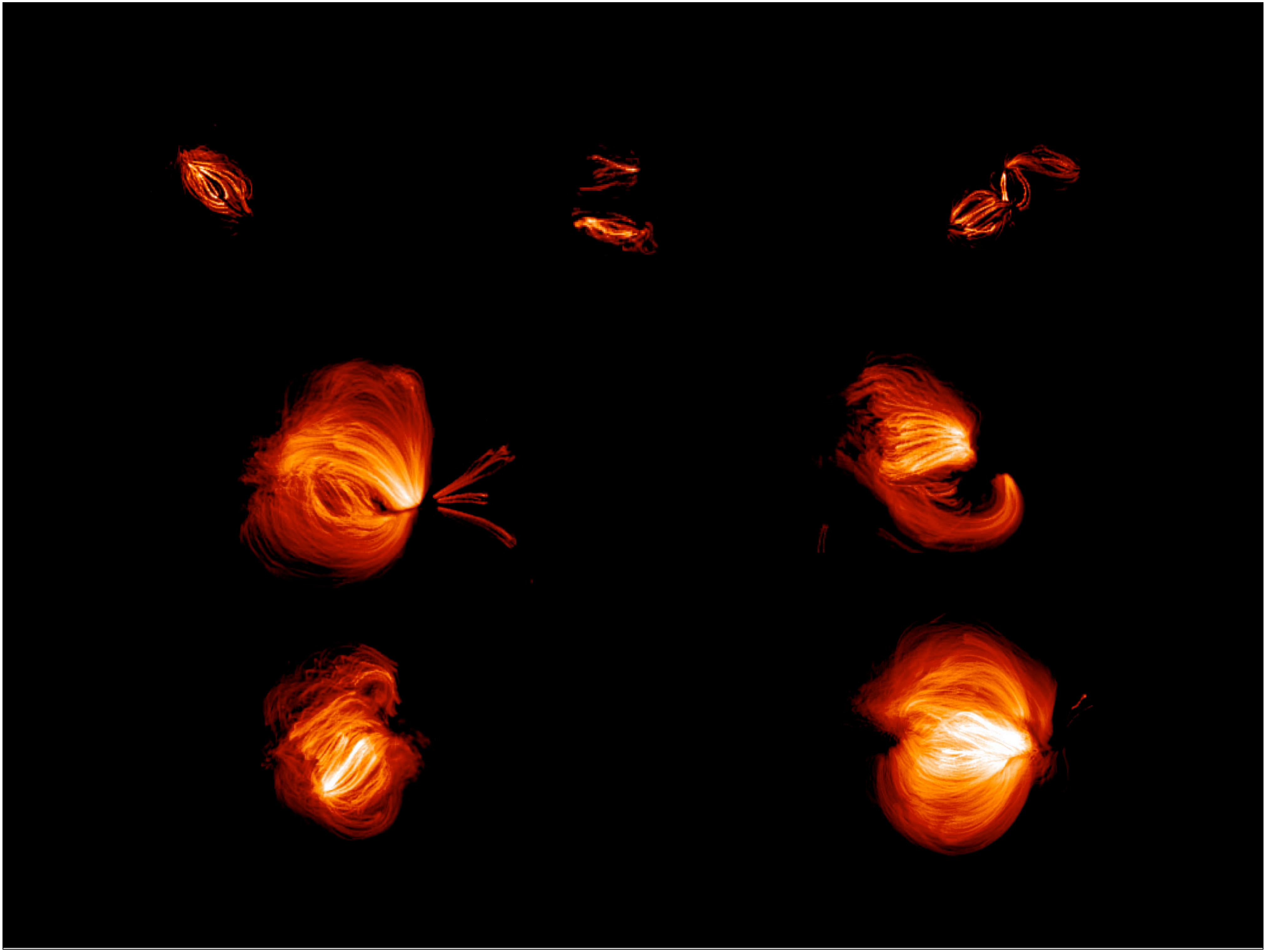


Heating Rate
0.08
0.06
0.04
0.02
0.00
0
5.0•10^3
1.0•10^4
1.5•10^4
Time (s)
Heating Rate
0.04
0.03
0.02
0.01
0.00
0
5.0•10^3
1.0•10^4
1.5•10^4
Time (s)
Heating Rate
0.025
0.020
0.015
0.010
0.005
0.000
0
5.0•10^3
1.0•10^4
1.5•10^4
Time (s)
Heating Rate
0.020
0.015
0.010
0.005
0.000
0
5.0•10^3
1.0•10^4
1.5•10^4
Time (s)

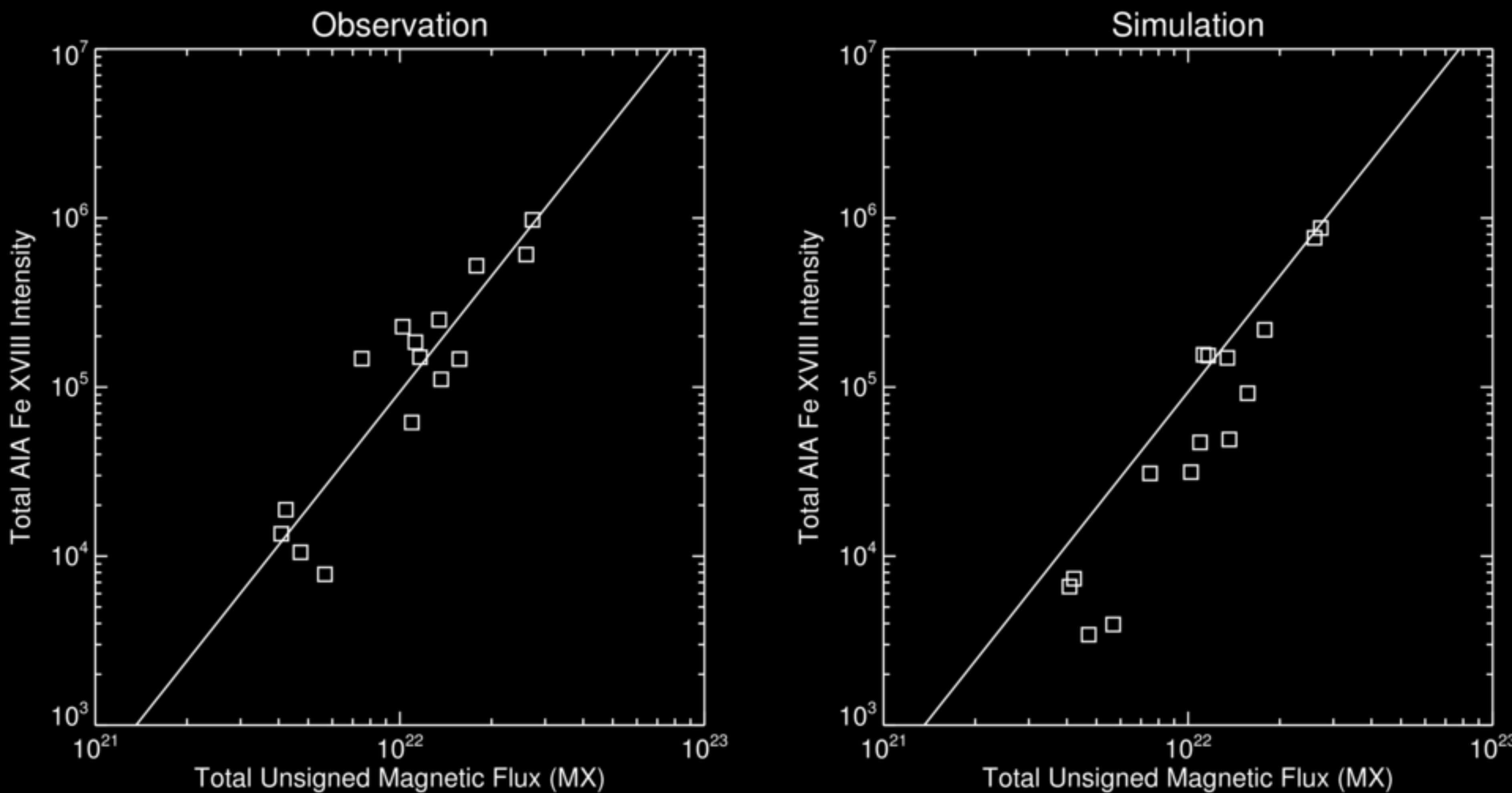

Temperature
Time (s)
0
5.0•10^3
1.0•10^4
1.5•10^4
10^5
10^6
10^7
10^8
10^9



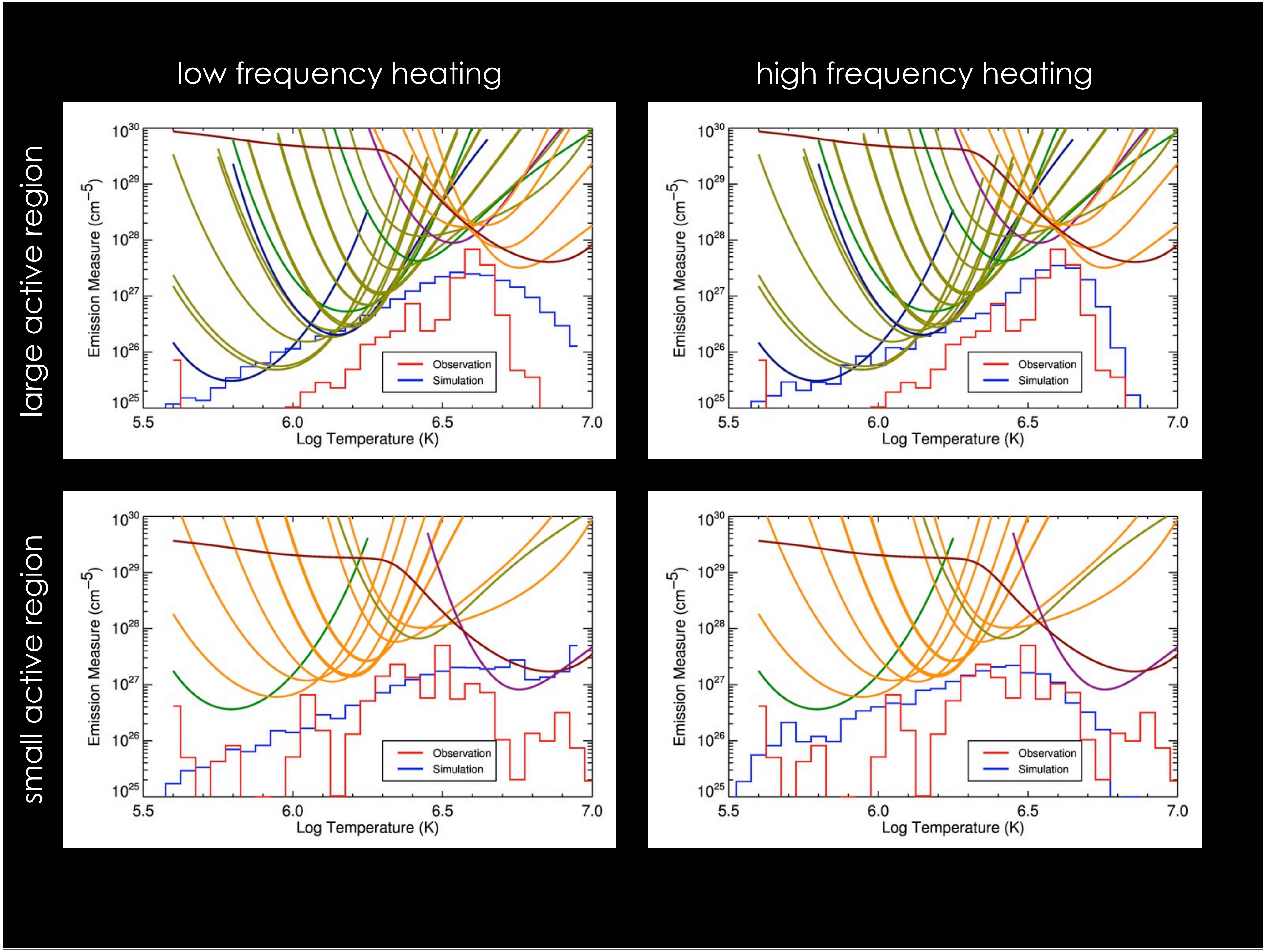
10^10
10^9
10^8
10^7
Density
0
5.0•10^3
1.0•10^4
1.5•10^4
Time (s)



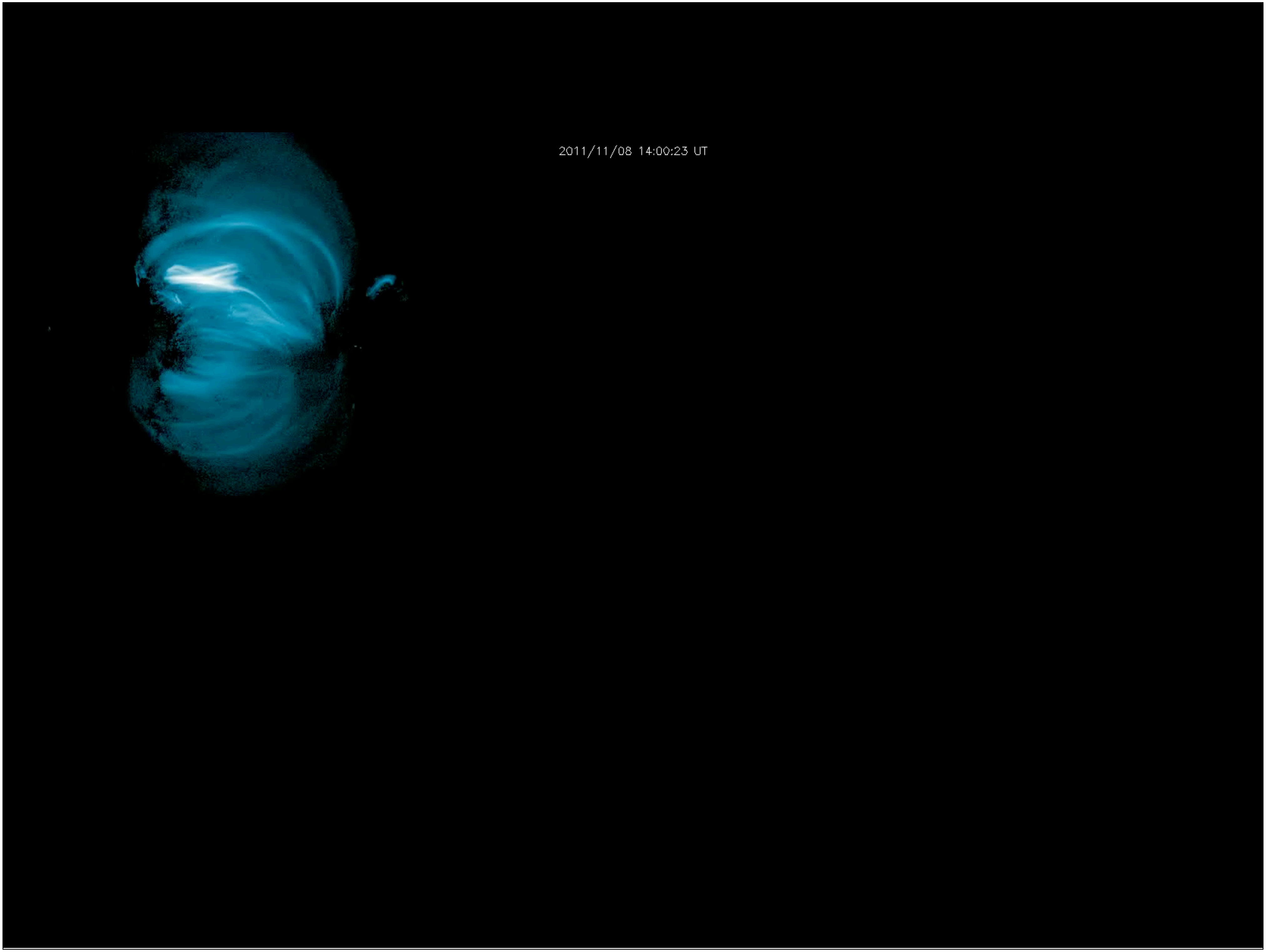
The Flux-Luminosity Relationship

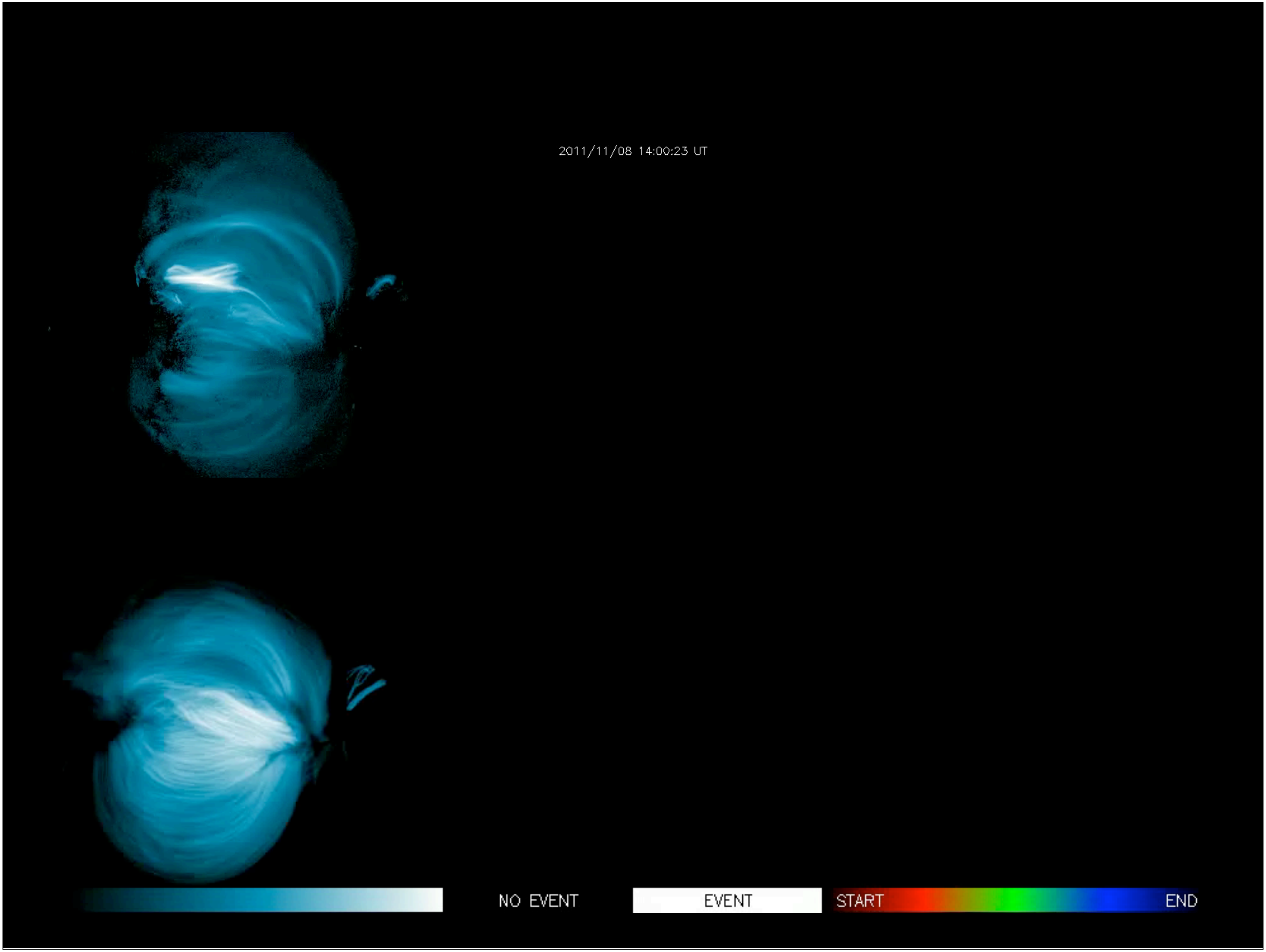


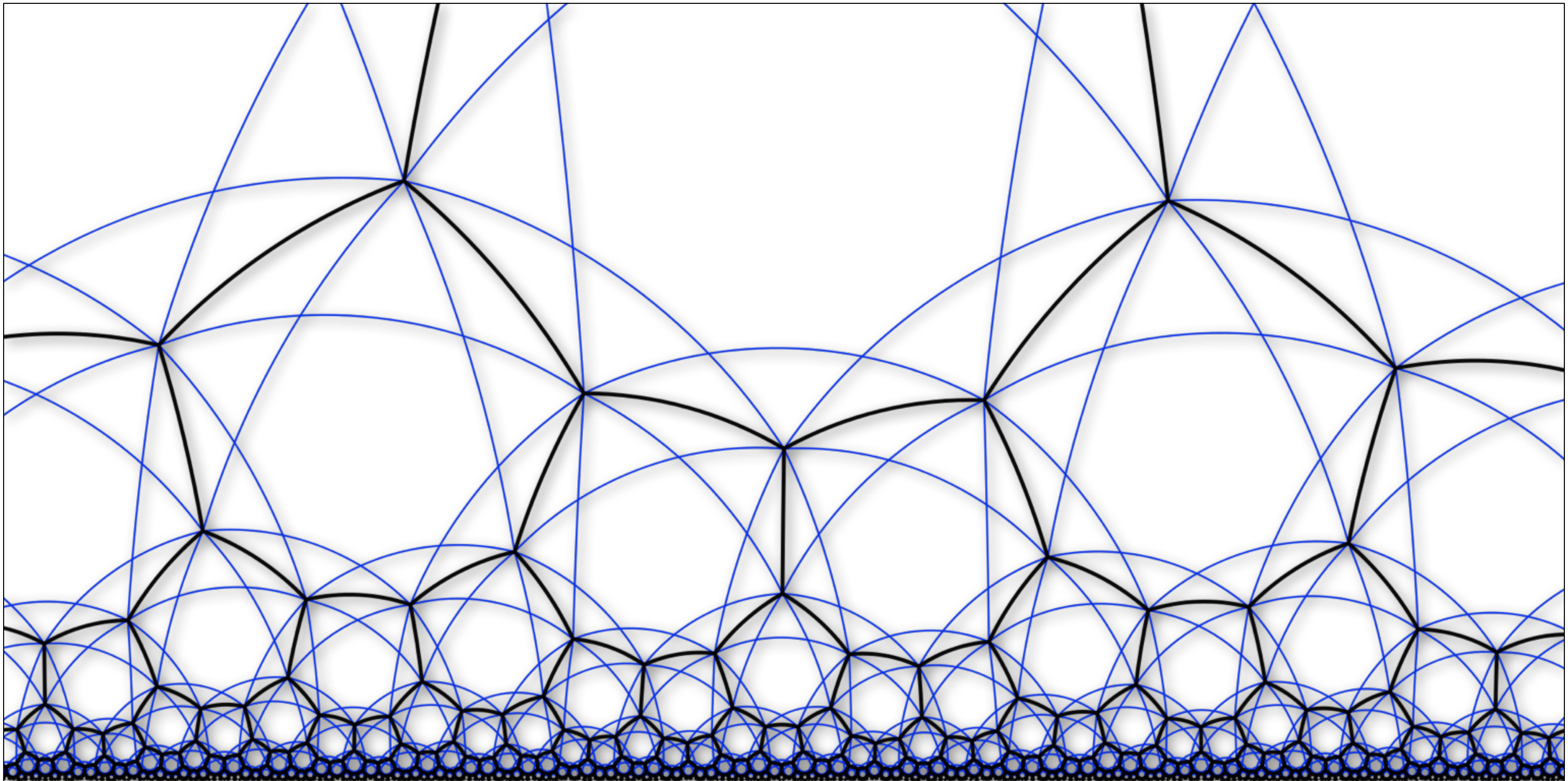
Reproduced for all heating scenarios. B/L works!



low frequency heating
high frequency heating
large active region
small active region
Emission Measure (cm^{-5})
Log Temperature (K)
Observation
Simulation
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{30}
5.5
6.0
6.5
7.0

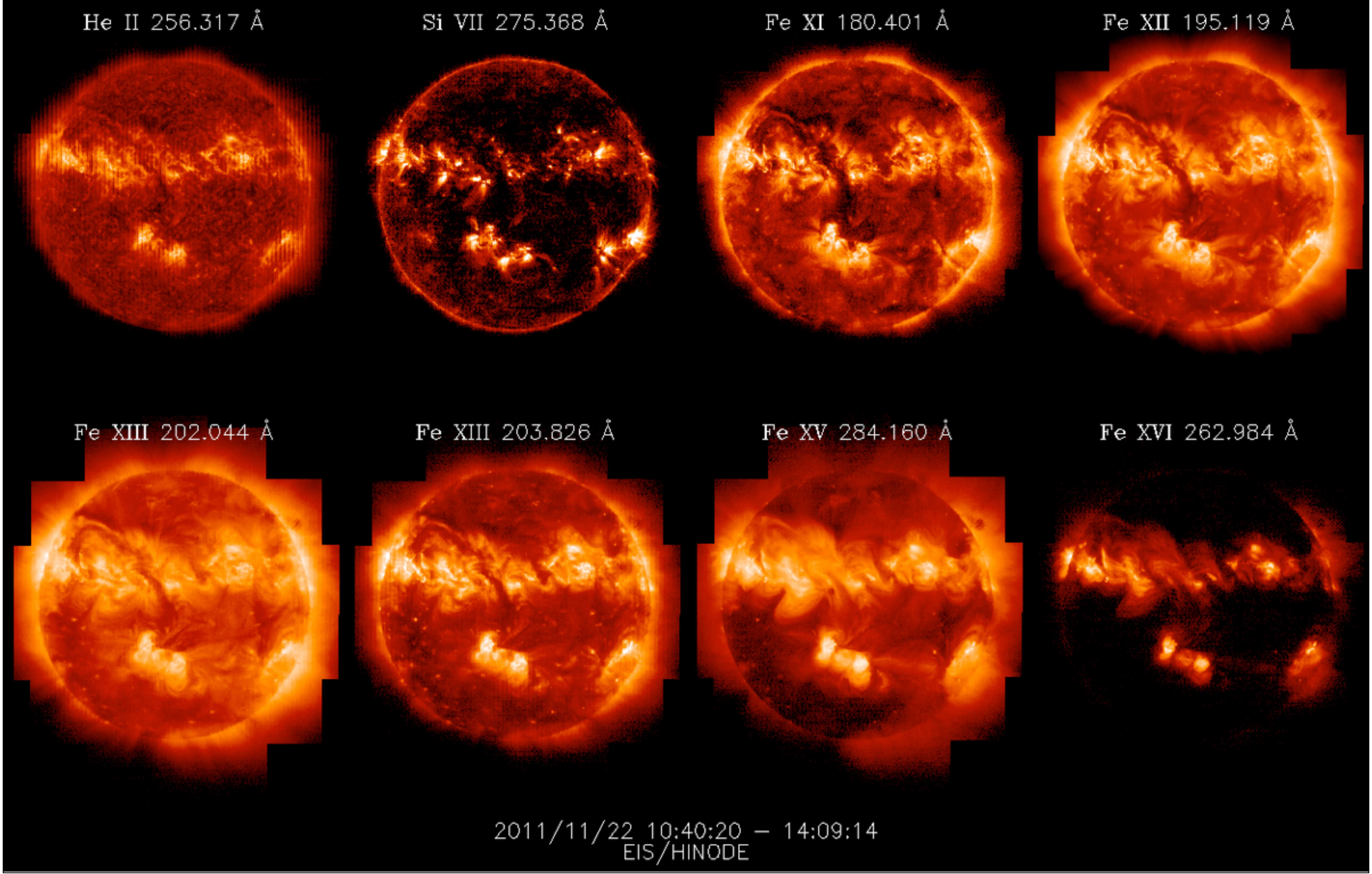

2011/11/08 14:00:23 UT


2011/11/08 14:00:23 UT
NO EVENT
EVENT
START
END

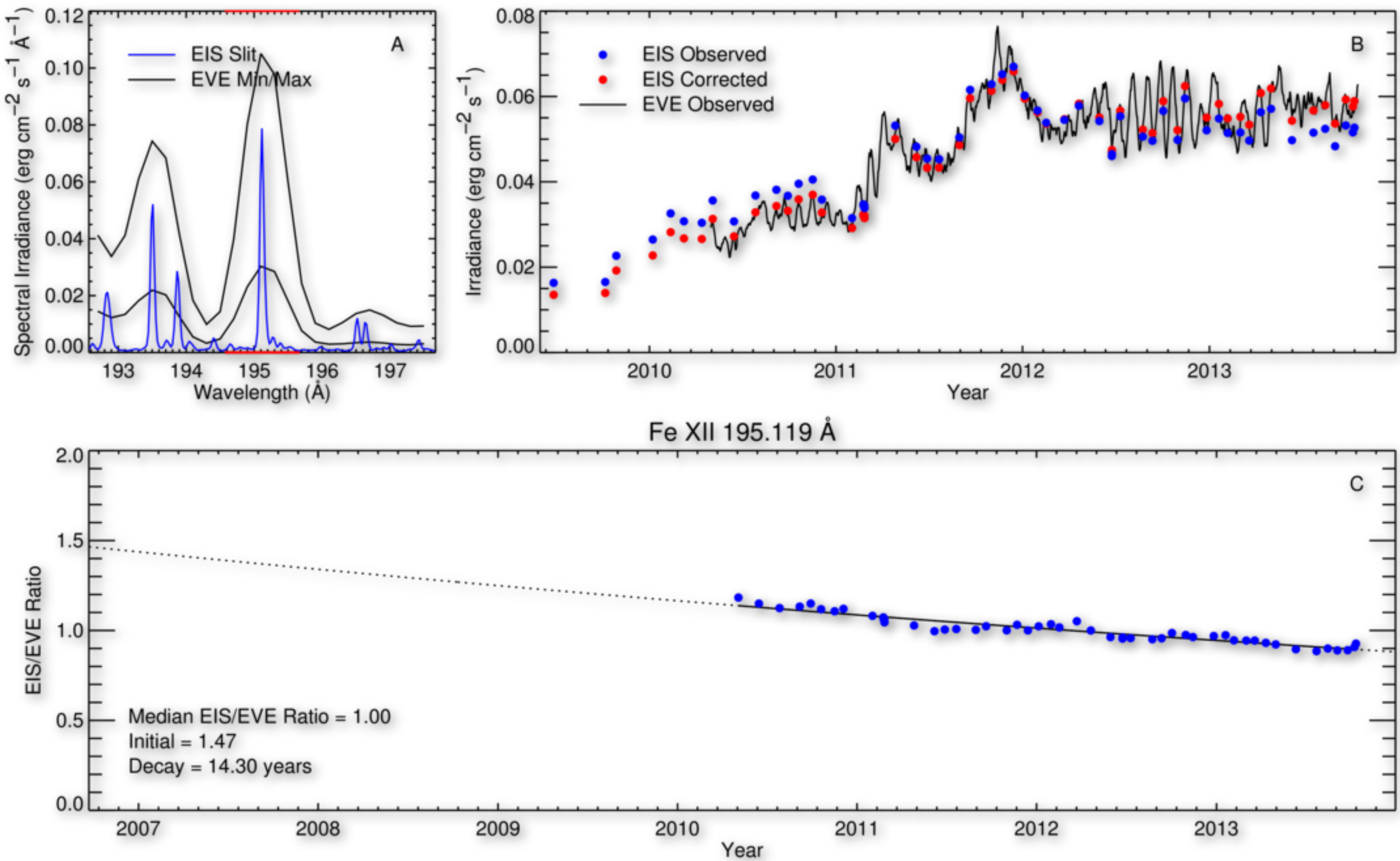


The EIS Calibration

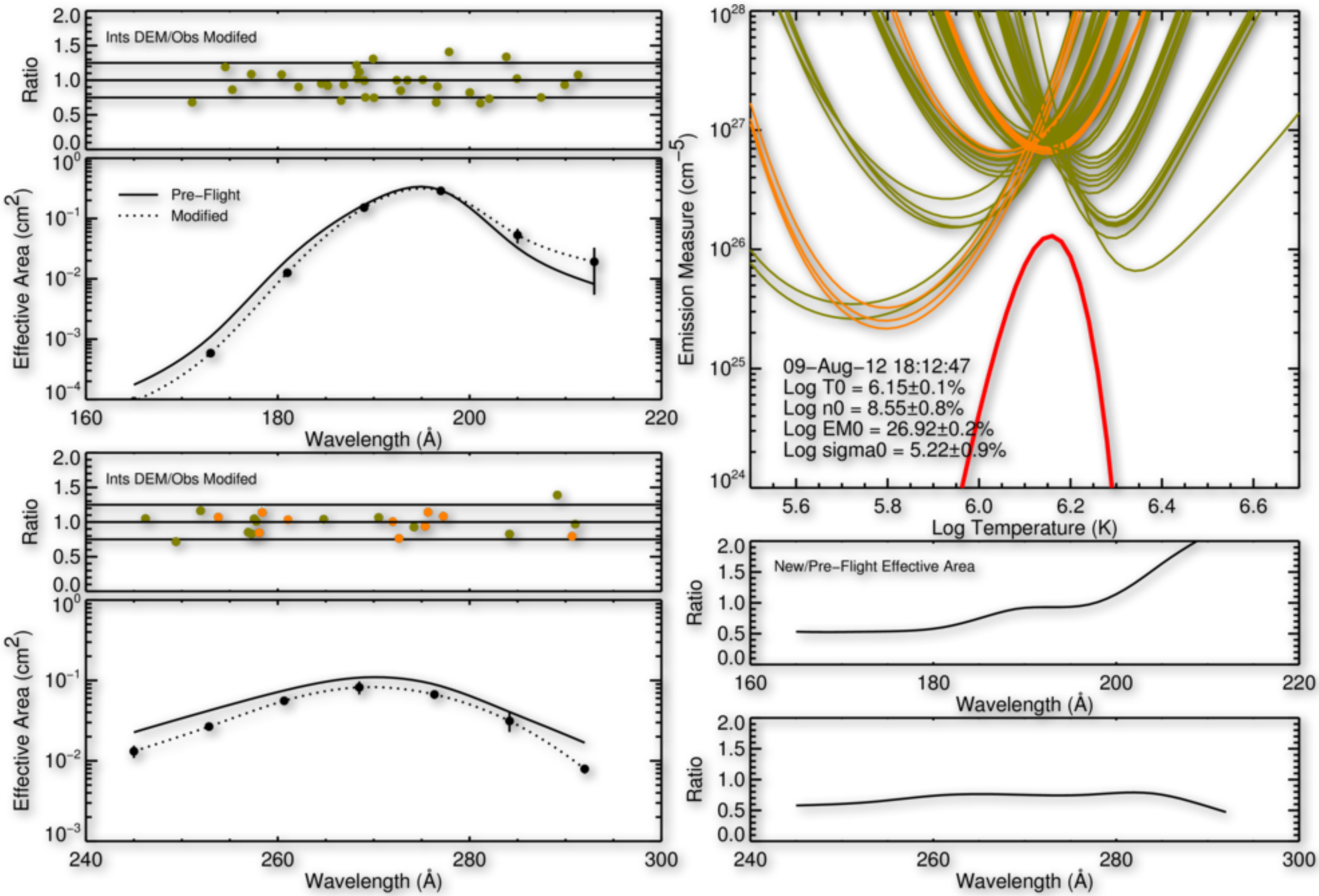
Example HOP 130 EIS Data



EIS and EVE Irradiance Data

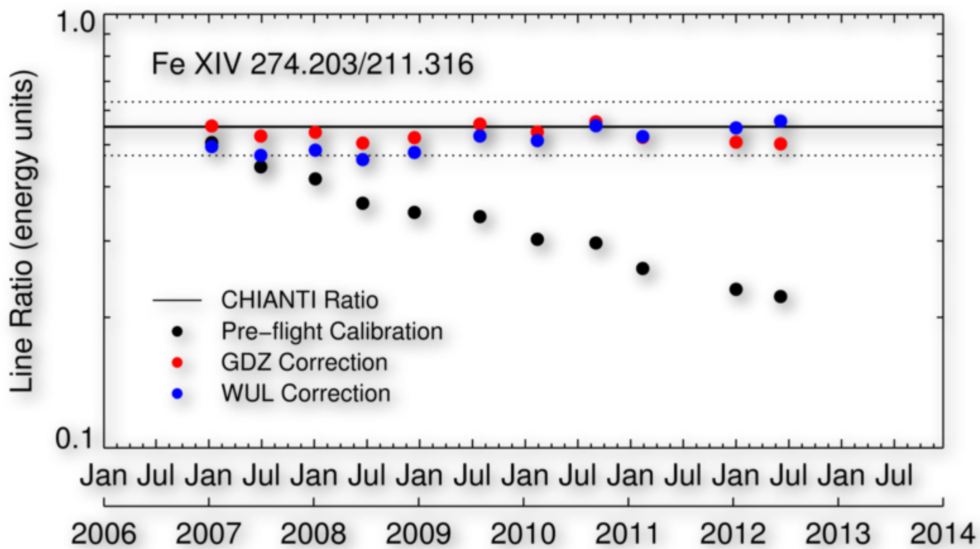


Inferring the EIS Effective Areas

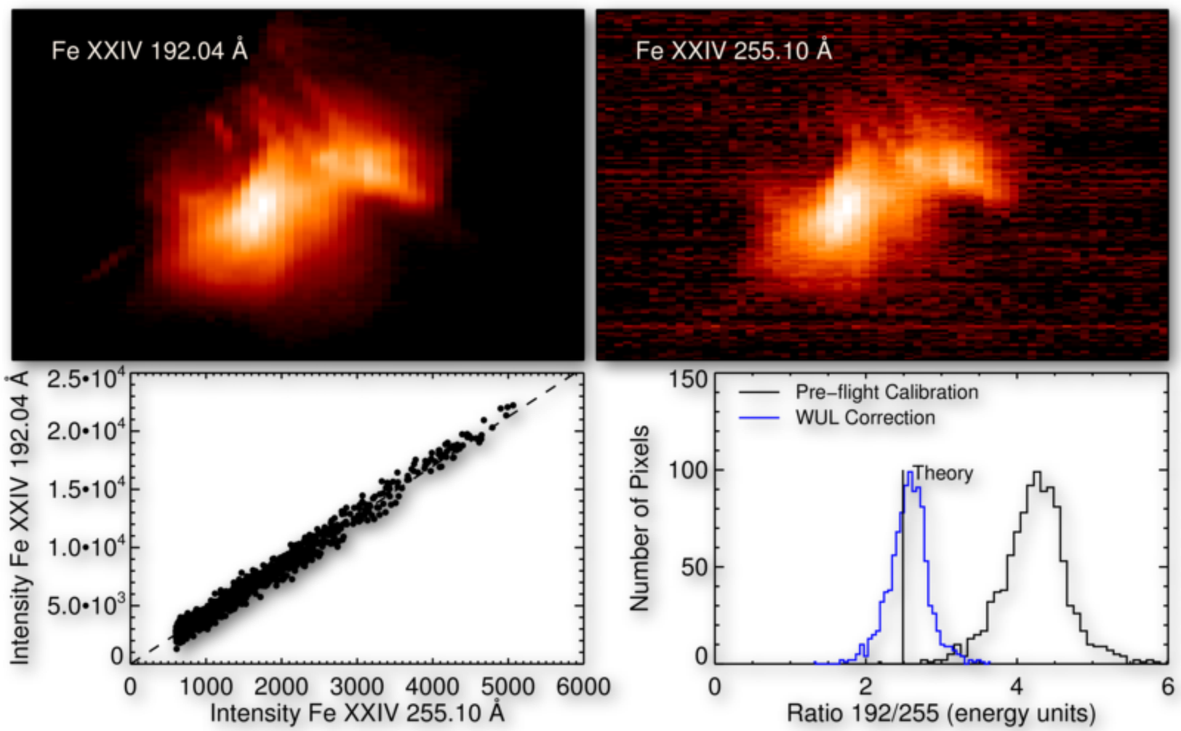


Checking the Revised Effective Areas

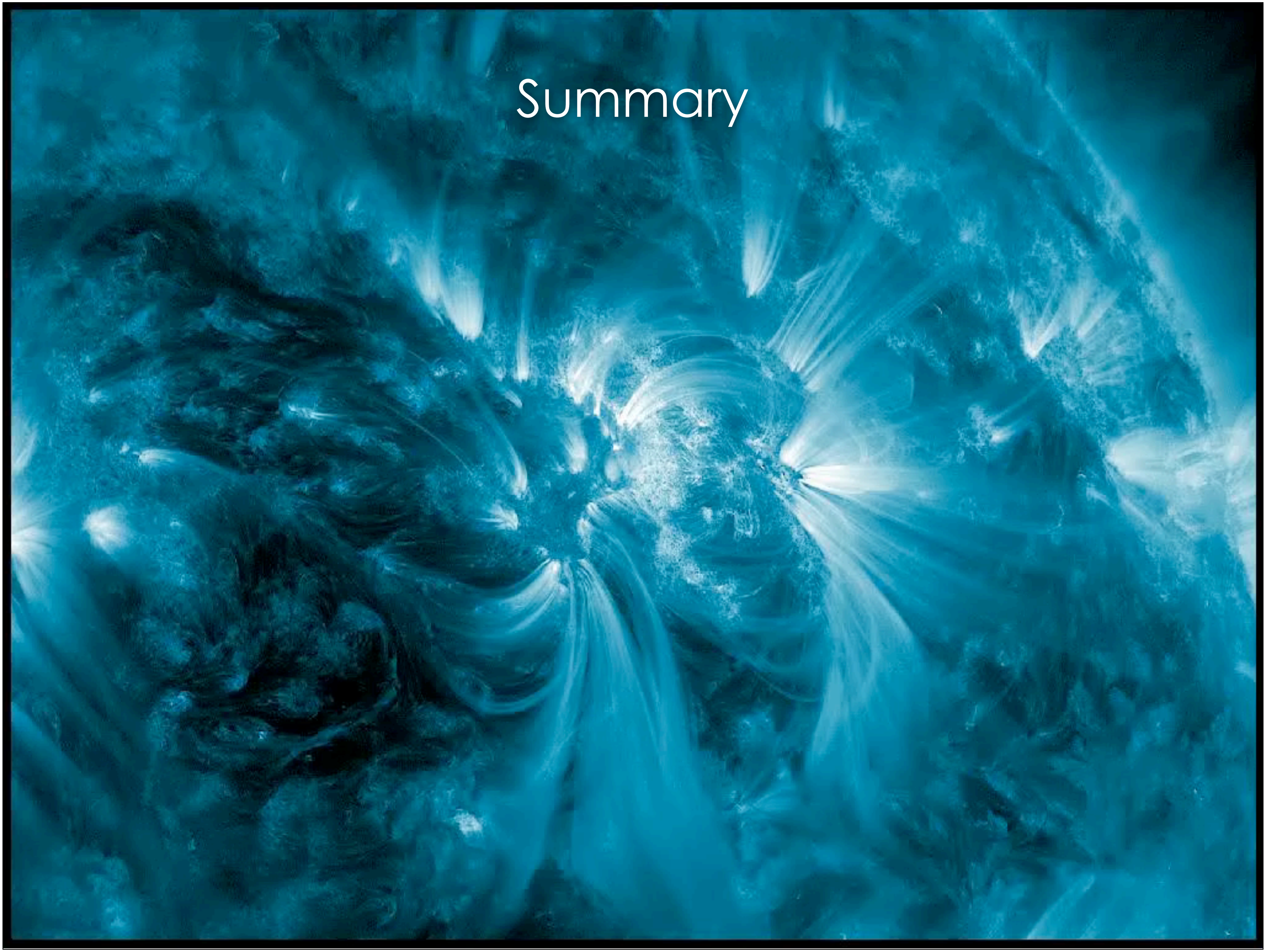
Fe XIV Ratio



Fe XXIV Ratio



Summary



Summary

- EIS Calibration
  - see the EIS wiki and routines in ssw
  - see Del Zanna A&A (2013), Warren et al. astro-ph (2013)

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- Active Region Modeling
  - Work in progress
  - Need to reproduce DEM, flux-luminosity, variability
  - High frequency heating is “winning” . . . ?

Summary

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- Active Region Modeling
  - Work in progress
  - Need to reproduce DEM, flux-luminosity, variability
  - High frequency heating is "winning" . . . ?
- Sparse Bayesian Inference
  - Promising!
  - Errors in the atomic data need to be addressed
  - Not magic! - Still limitations to DEM (e.g., Testa et al 2012)