Combining Active Region Observations and Models to Confront Coronal Heating Theories

Amy R. Winebarger

NASA MSFC

Everything we discuss at the Loops Workshop

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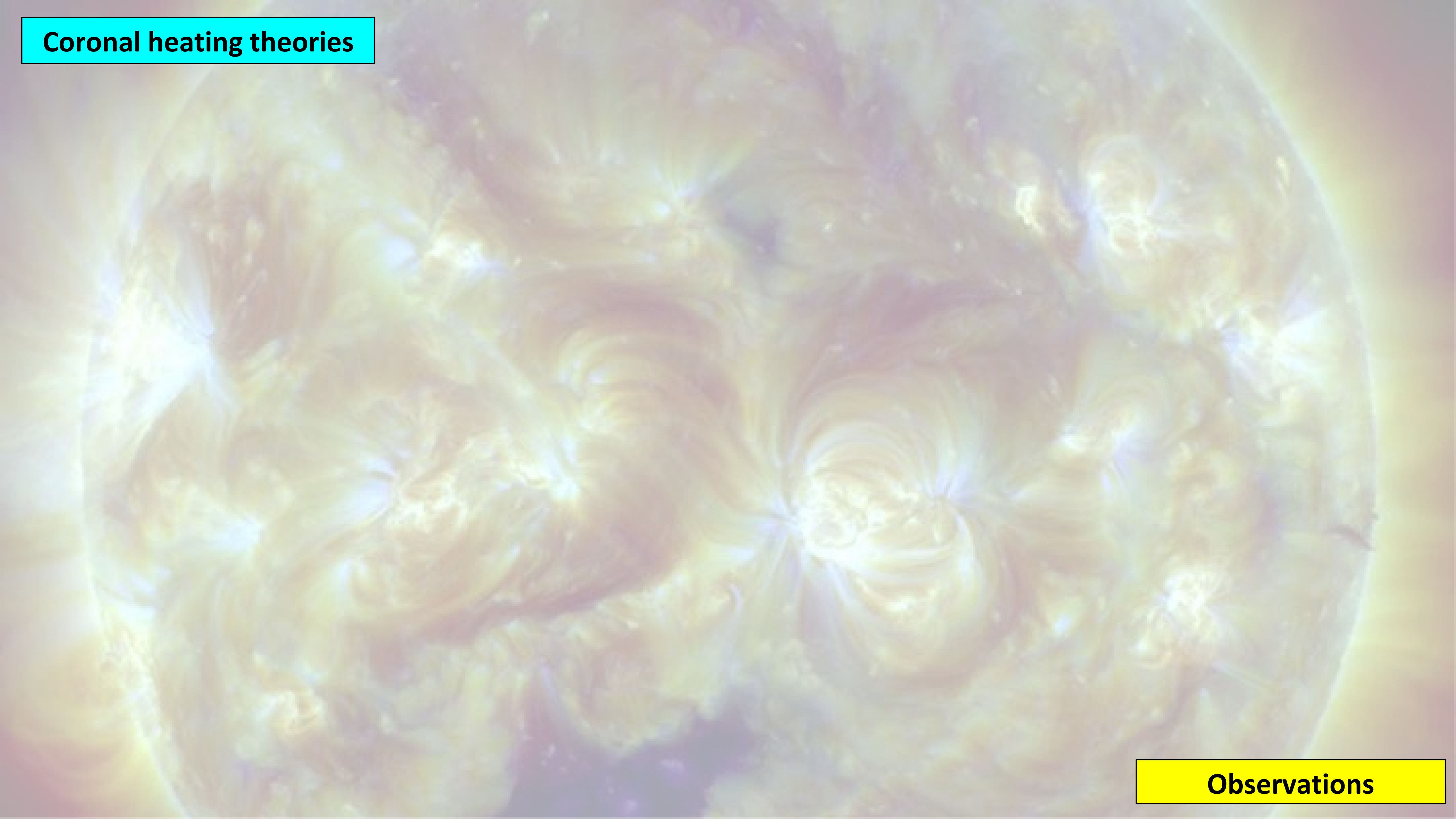
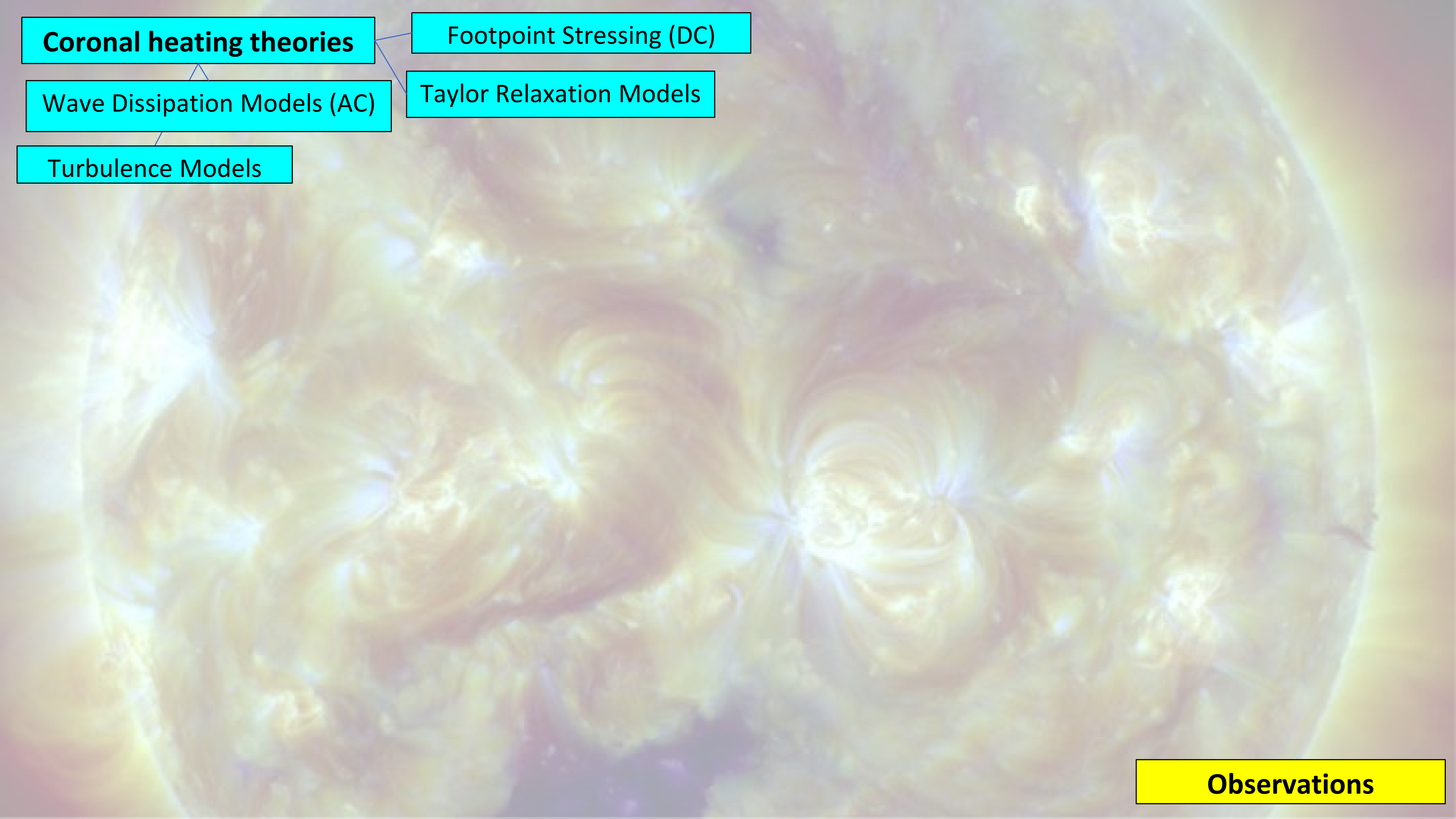
Outline

- Mind map of the problem (and solutions!)
- Four examples of progress
  - Hot plasma observation
  - Time lag maps
  - Pulsing Loops
  - Footpoint evolution

Coronal heating theories



Observations


Coronal heating theories
Footpoint Stressing (DC)
Taylor Relaxation Models
Wave Dissipation Models (AC)
Turbulence Models
Observations

Coronal heating theories

Footpoint Stressing (DC)

Taylor Relaxation Models

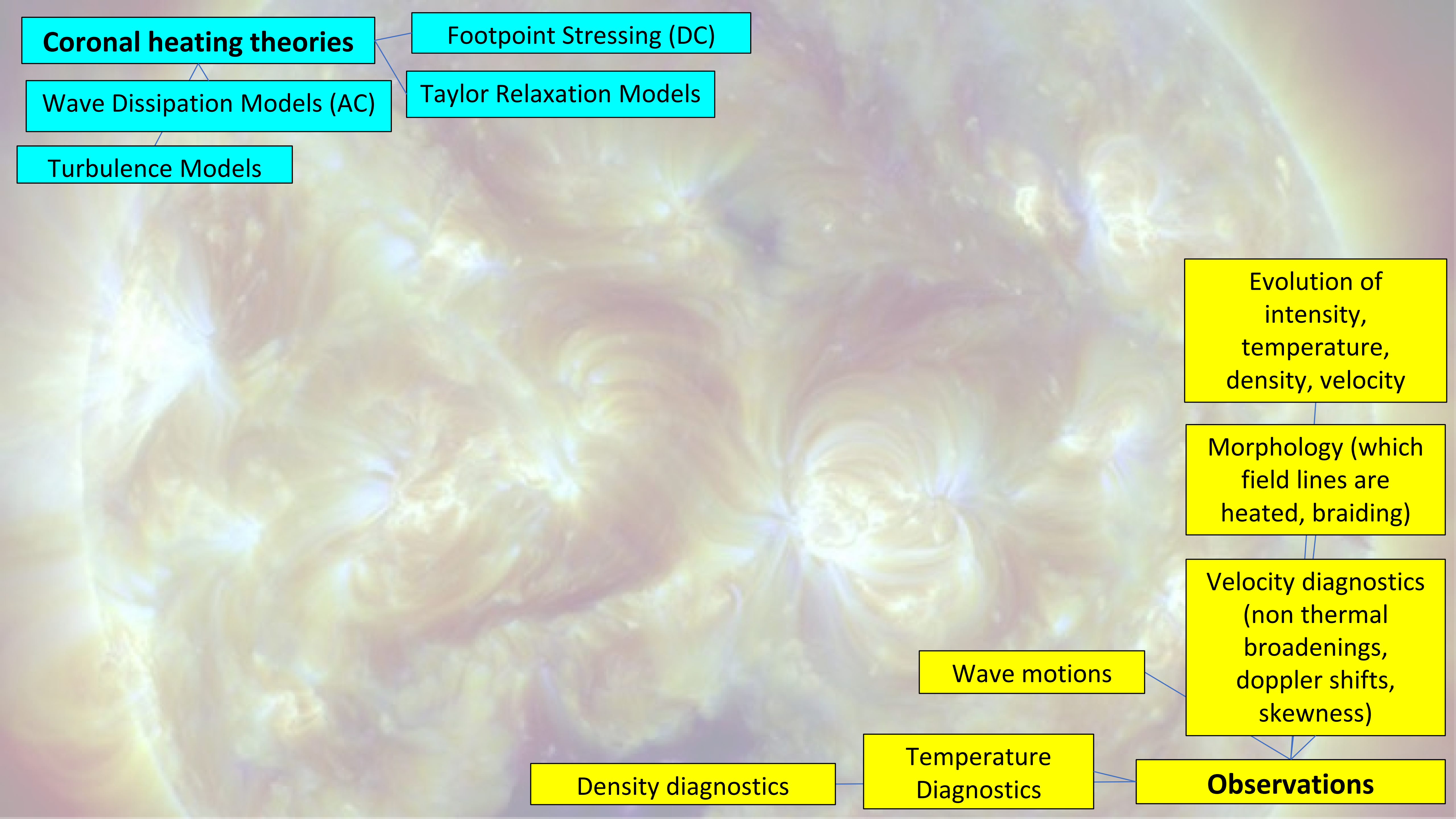
Wave Dissipation Models (AC)

Turbulence Models

Model description	Efficiency ($\mathcal{E}$)	Example reference
Wave Dissipation (AC) Models		
Alfvén-wave collisional damping	$\Lambda^1 \Theta^2 Re^{-1}$	Osterbrock (1961)
Resonant absorption	$\Lambda^1 \Theta^1$	Ruderman et al. (1997)
Phase mixing	$\Lambda^1 \Theta^{4/3} Re^{-1/3}$	Roberts (2000)
Surface-wave damping	$\Lambda^{1/2} \Theta^{3/2} (\Sigma/Re)^{1/2}$	Hollweg (1985)
Fast-mode shock train	$\Lambda^2 \Theta^3$	Hollweg (1985)
Switch-on MHD shock train	$\Lambda^3 \Theta^4$	Hollweg (1985)
Turbulence Models		
Kolmogorov-Obukhov cascade	$\Lambda^1 \Theta^2$	Hollweg (1986)
Iroshnikov-Kraichnan cascade	$\Lambda^2 \Theta^3$	Chae et al. (2002)
Hybrid triple-correlation cascade	$\Lambda^1 \Theta^3 (1+\Theta)^{-1}$	Zhou & Matthaeus (1990)
Reflection-driven cascade	$\Lambda^1 \Theta^2 (f_+^2 f_- + f_-^2 f_+)$	Hossain et al. (1995)
2D boundary-driven cascade	$\Lambda^{2/3} \Theta^{1/3}$	Heyvaerts & Priest (1992)
Line-tied reduced MHD cascade	$\Lambda^1 \Theta^{1/2}$	Dmitruk & Gómez (1999)
Footpoint Stressing (DC) Models		
Current-layer random walk	Λ^1	Sturrock & Uchida (1981)
Current-layer shearing	$\Lambda^1 (1+\Theta^2)^{1/2} (1+\Lambda^2)^{-1/2}$	Galsgaard & Nordlund (1996)
Braided discontinuities	$\Lambda^2 \Theta^1$	Parker (1983)
Flux cancellation	$\Lambda^1 \Theta^1 (\phi^{8/3} - \phi^{4/3})$	Priest et al. (2018)
Taylor Relaxation Models		
Tearing-mode reconnection	$\Lambda^1 \Theta^1 (1-\alpha L)^{-5/2}$	Browning & Priest (1986)
Hyperdiffusive reconnection	$\Lambda^1 \Theta^{-1} (\alpha L)^2$	van Ballegooijen & Cranmer (2008)
Non-ideal/slipping reconnection	$\Theta^{-1} (\alpha L)^1$	Yang et al. (2018)

Cranmer and Winebarger, 2019, ARAA, 57:1-30

Observations



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Temperature Diagnostics
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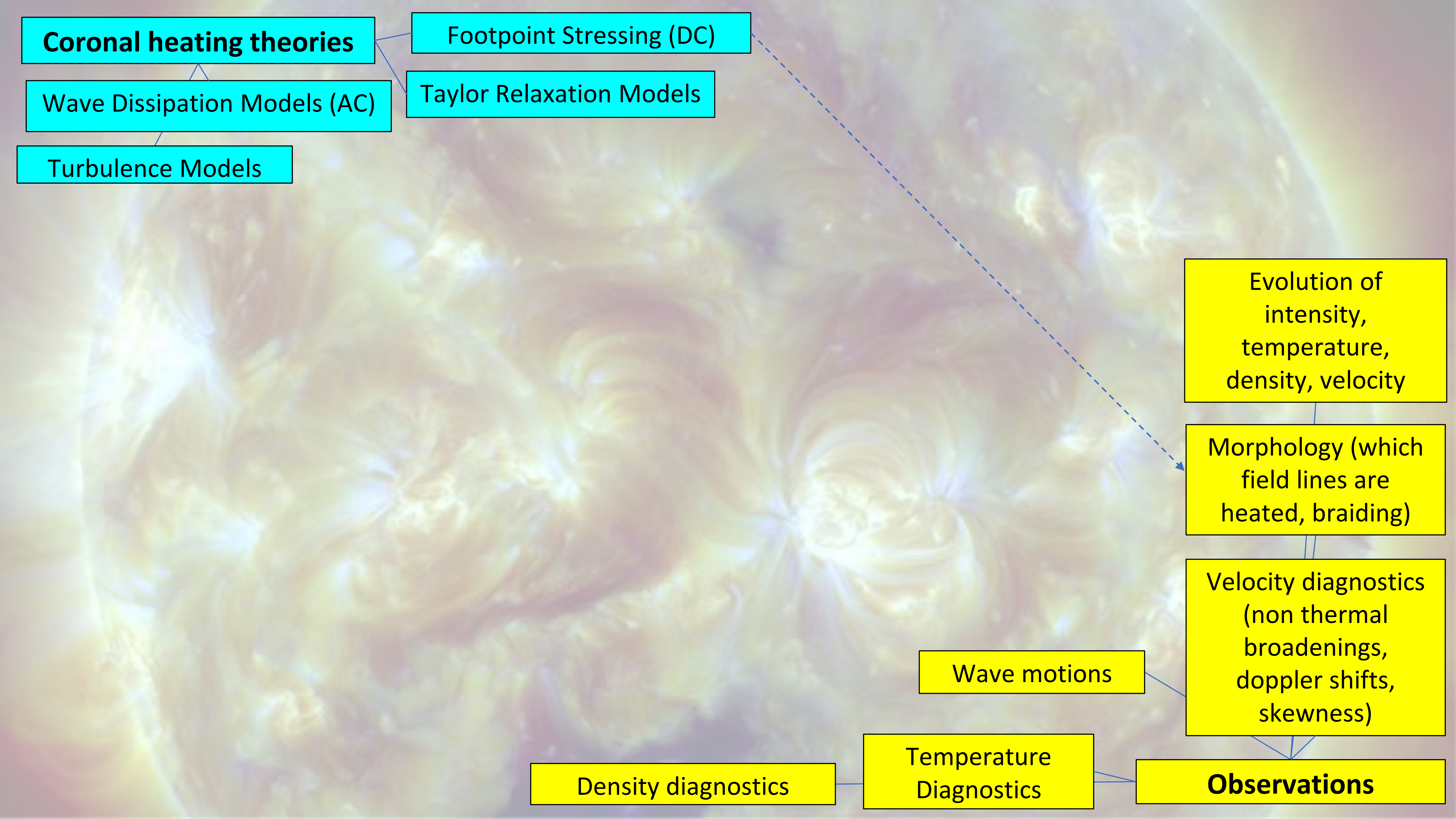
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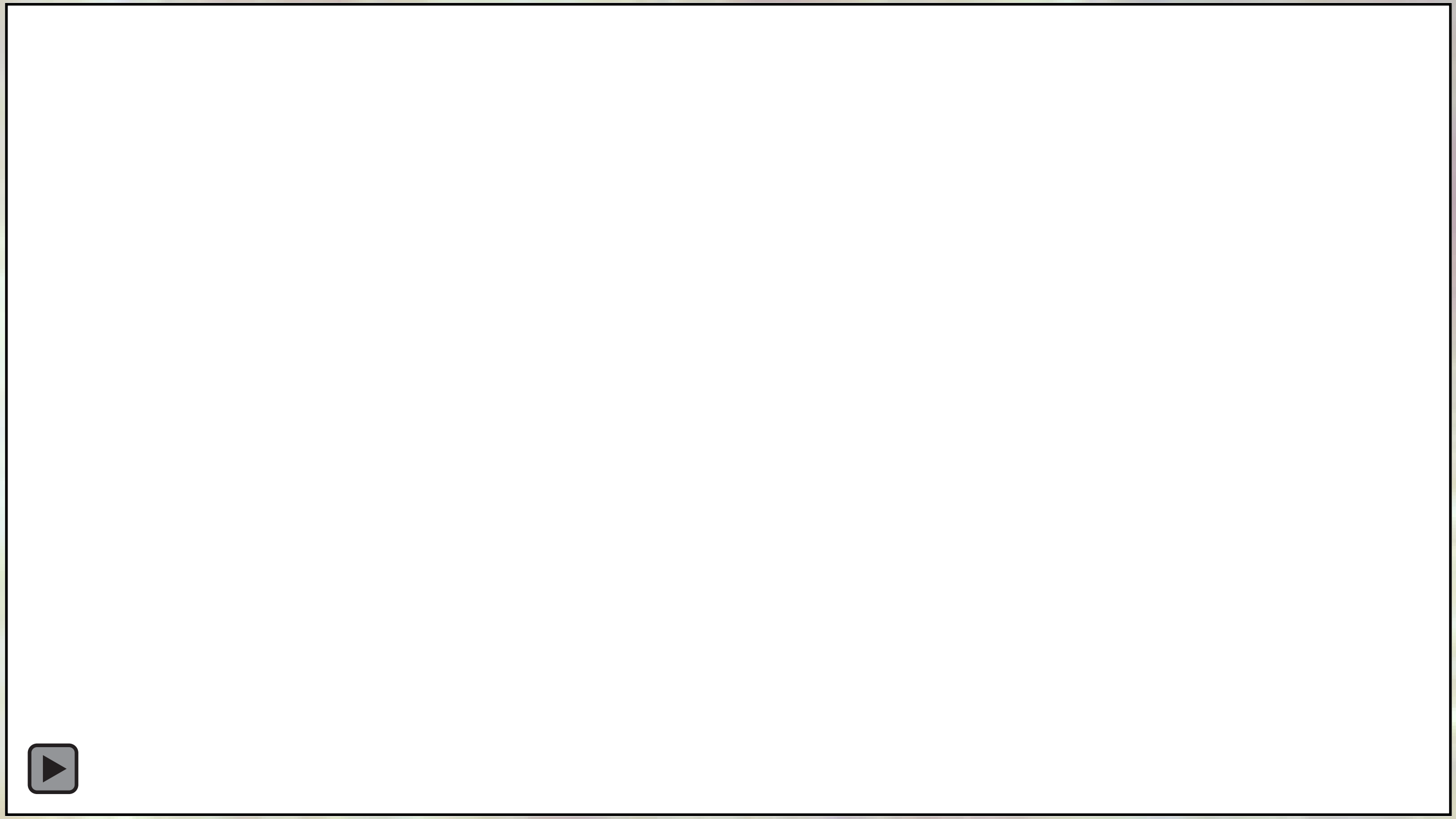

Cirtain, et al., 2013, Nature, 493, 501

Evolution of intensity, temperature, density, velocity

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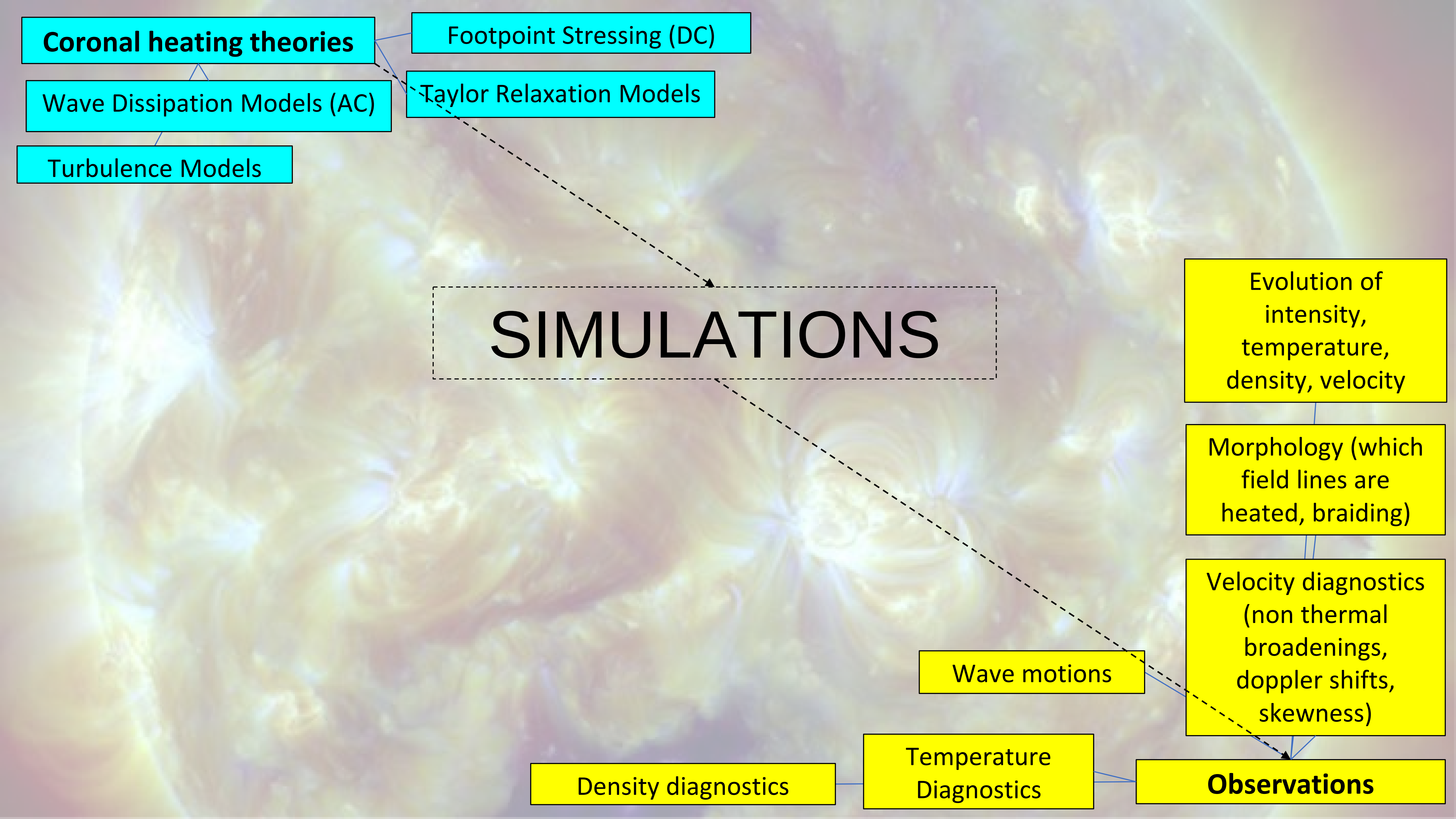
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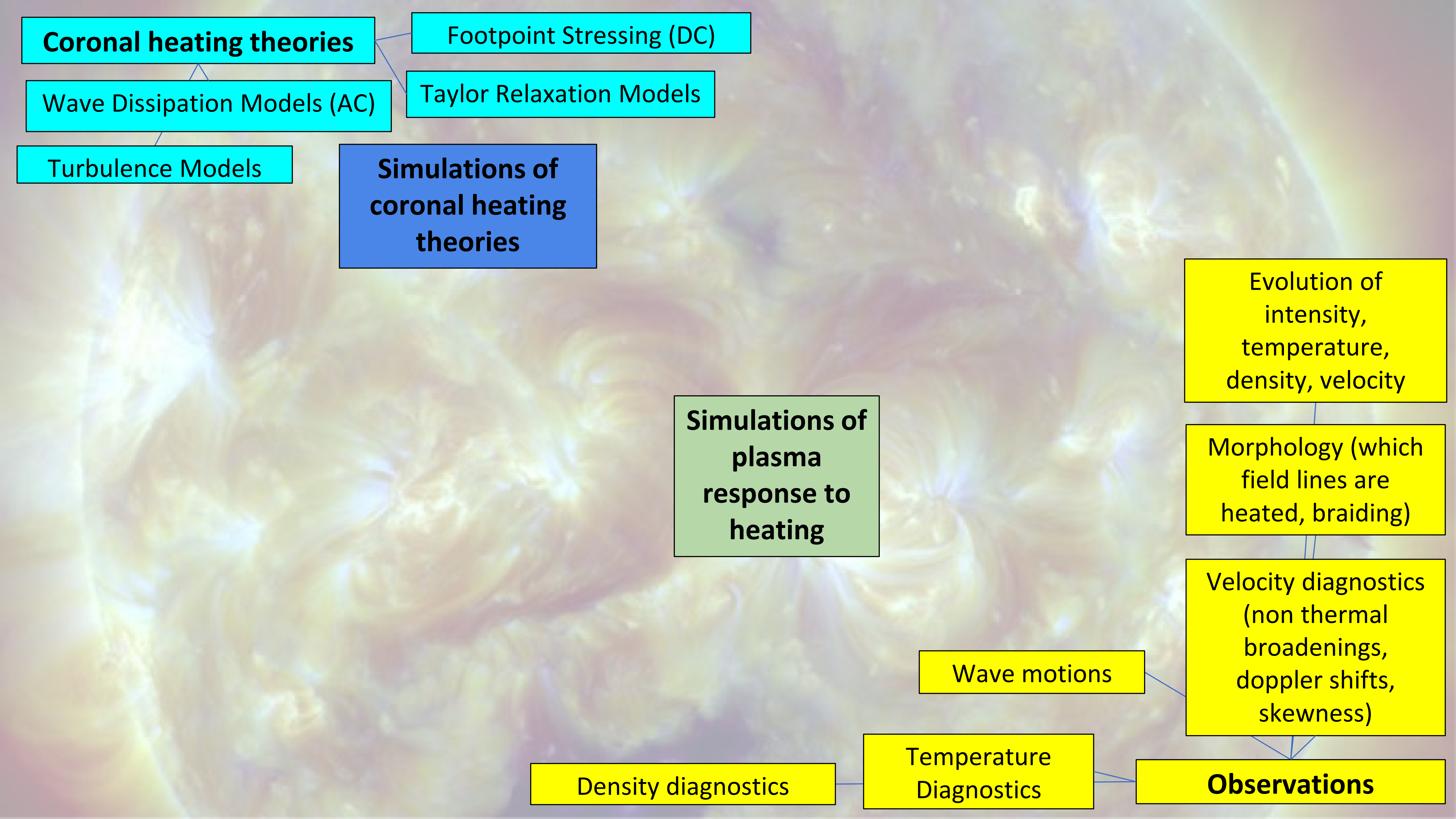
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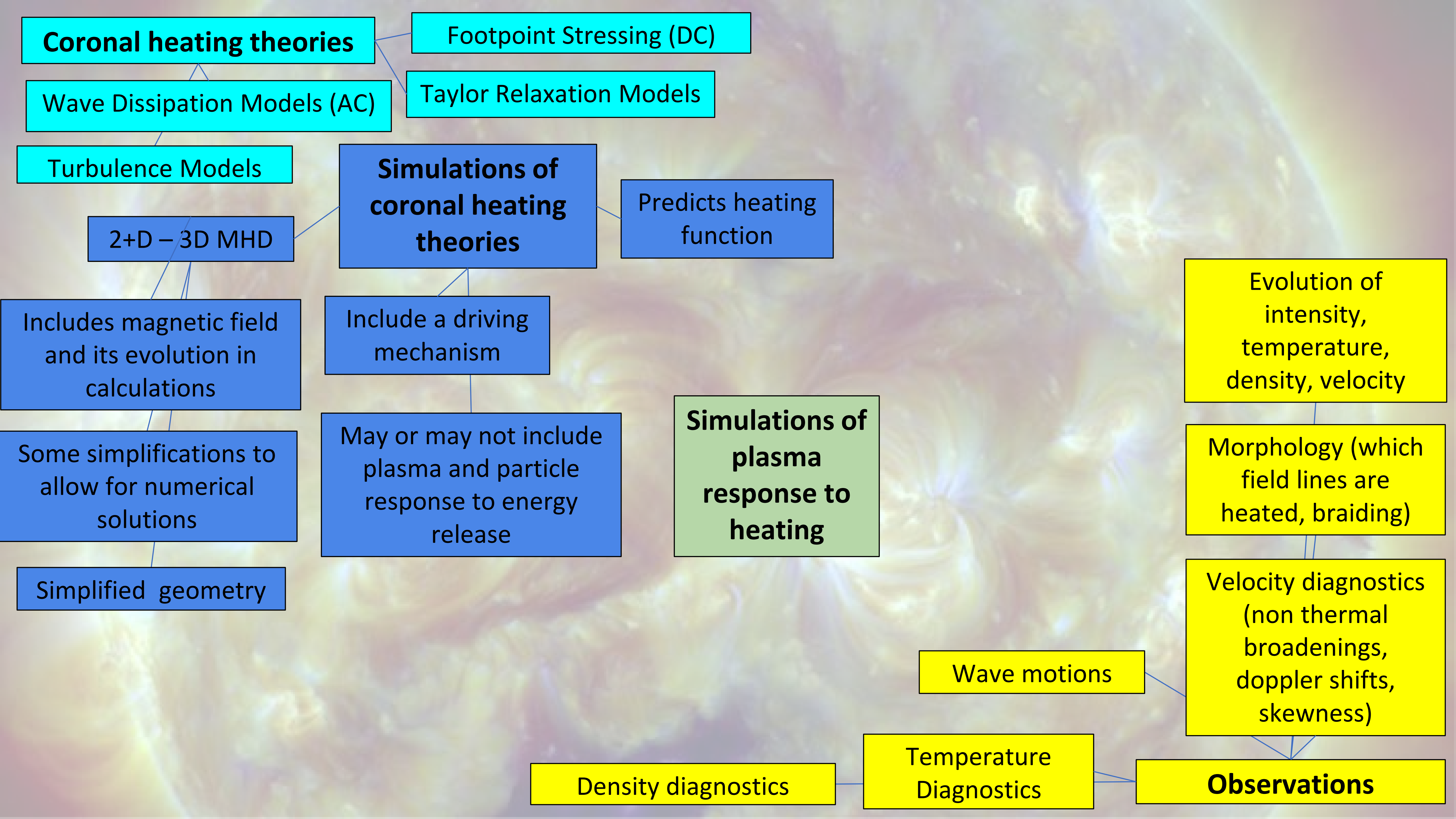
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Some simplifications to allow for numerical solutions
Simplified geometry
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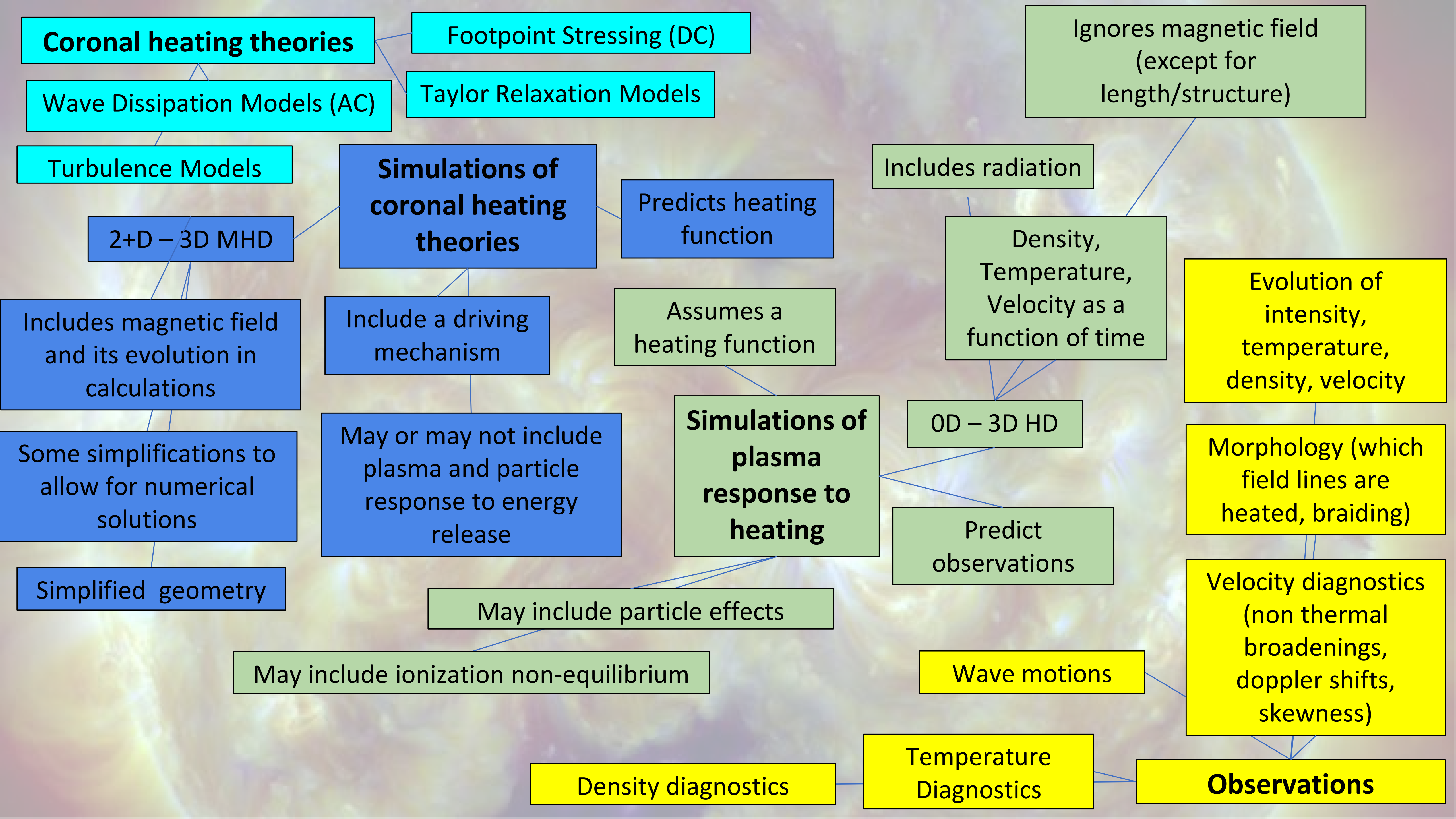

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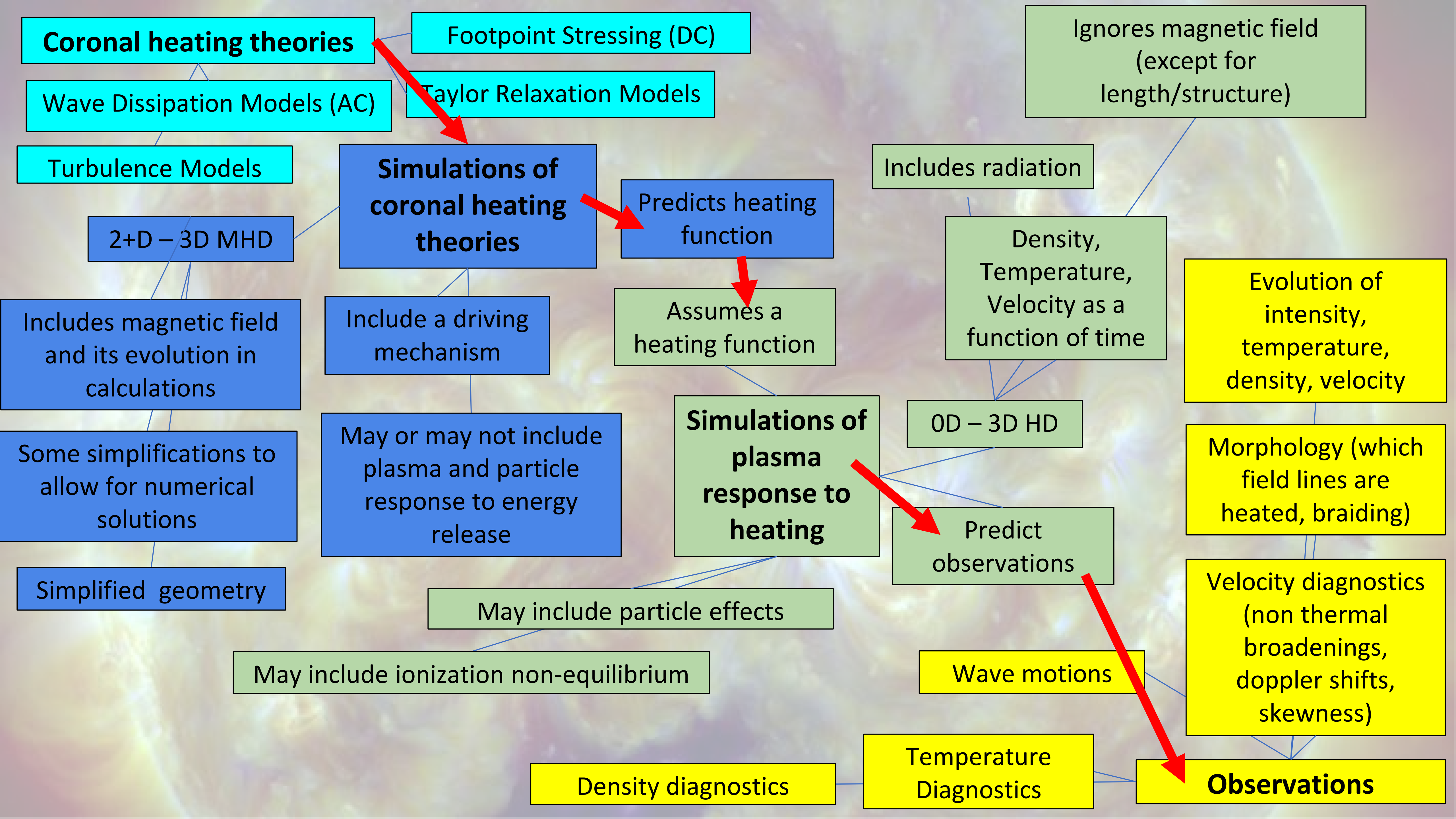
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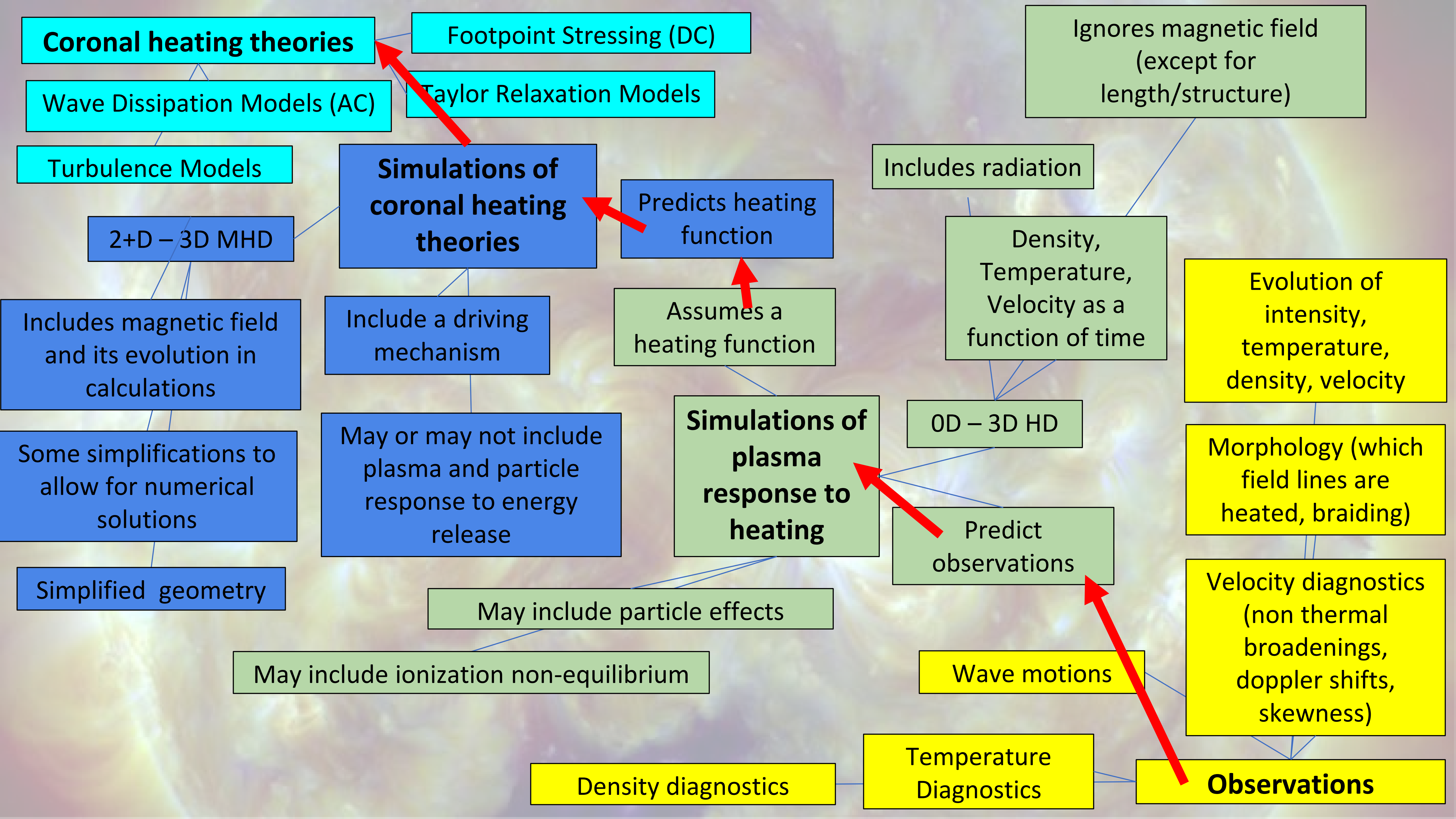
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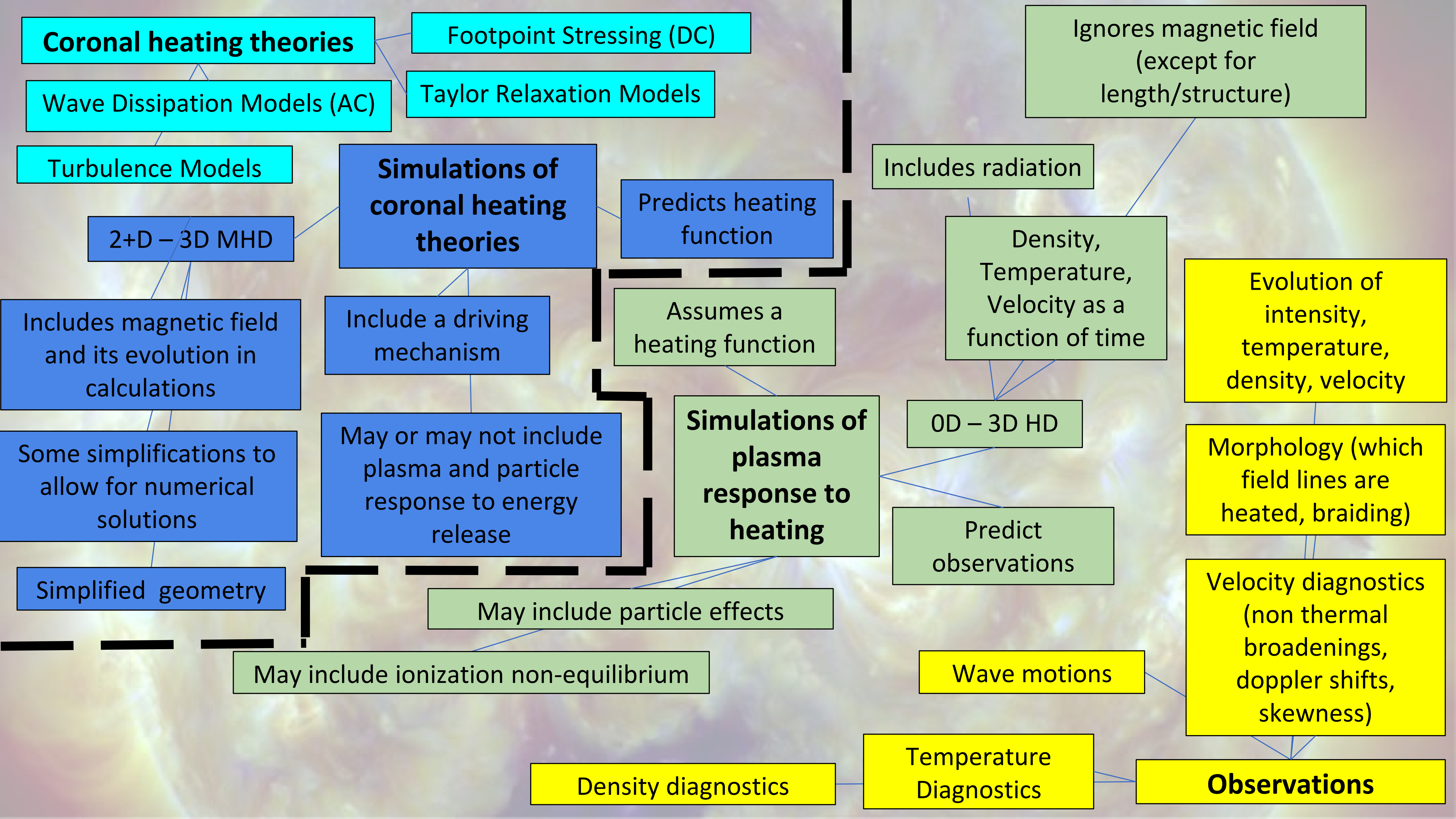
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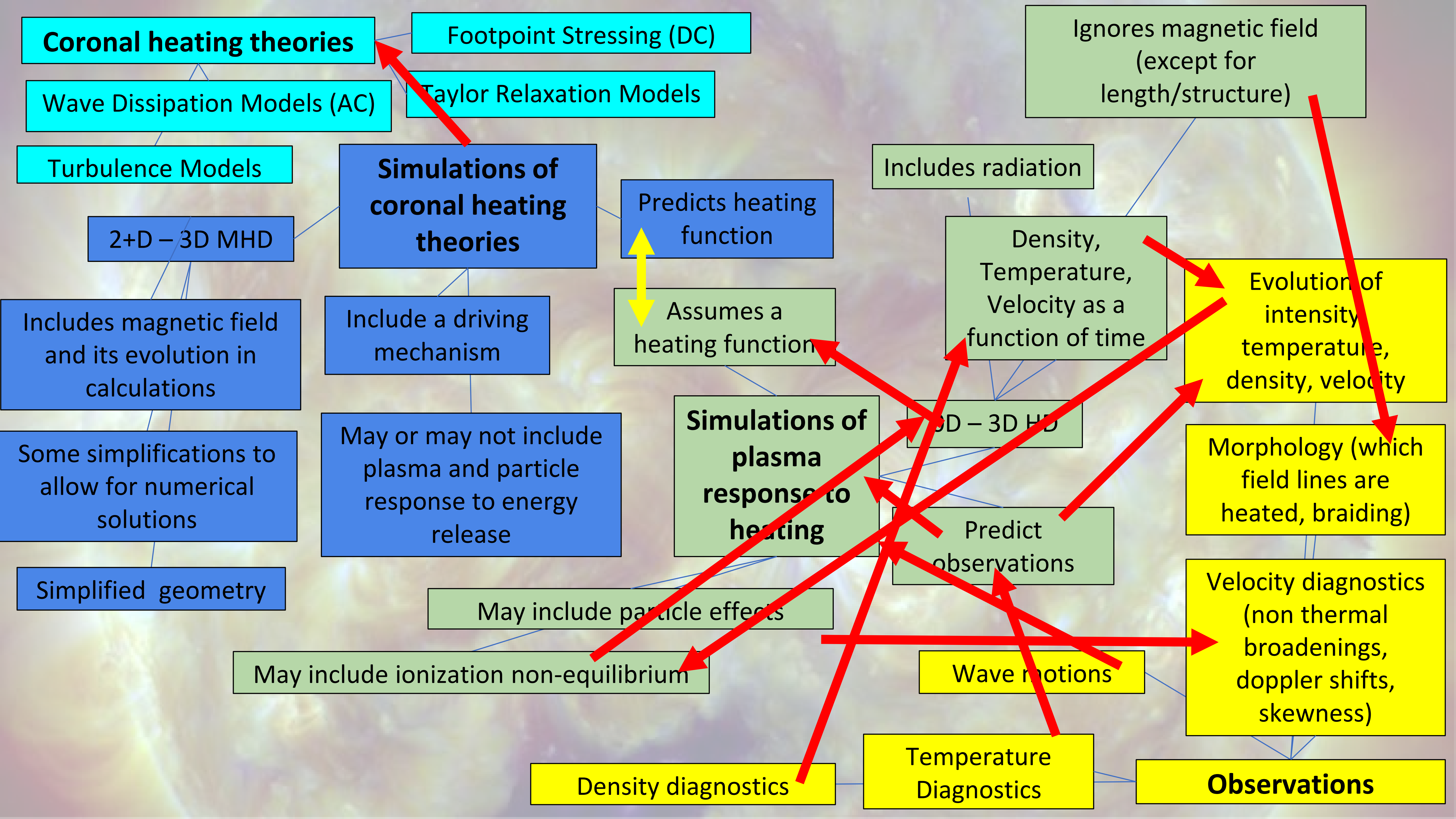
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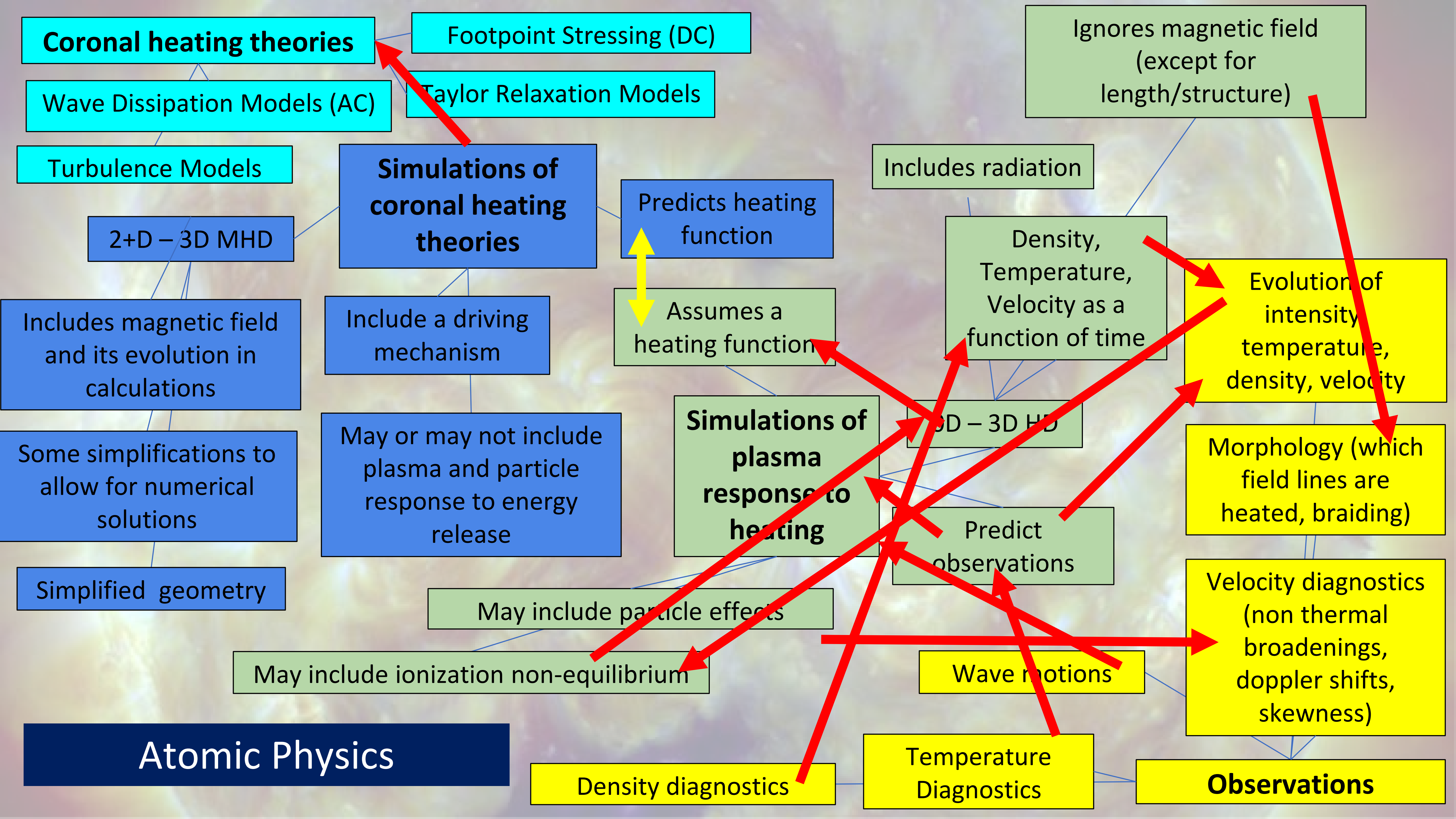
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Take away from mind map

- Progress is happening, but it is “random walk” instead of linear.
- The link between different simulations needs improvement.

The rest of this talk

- Highlight recent work on plasma simulations and observations

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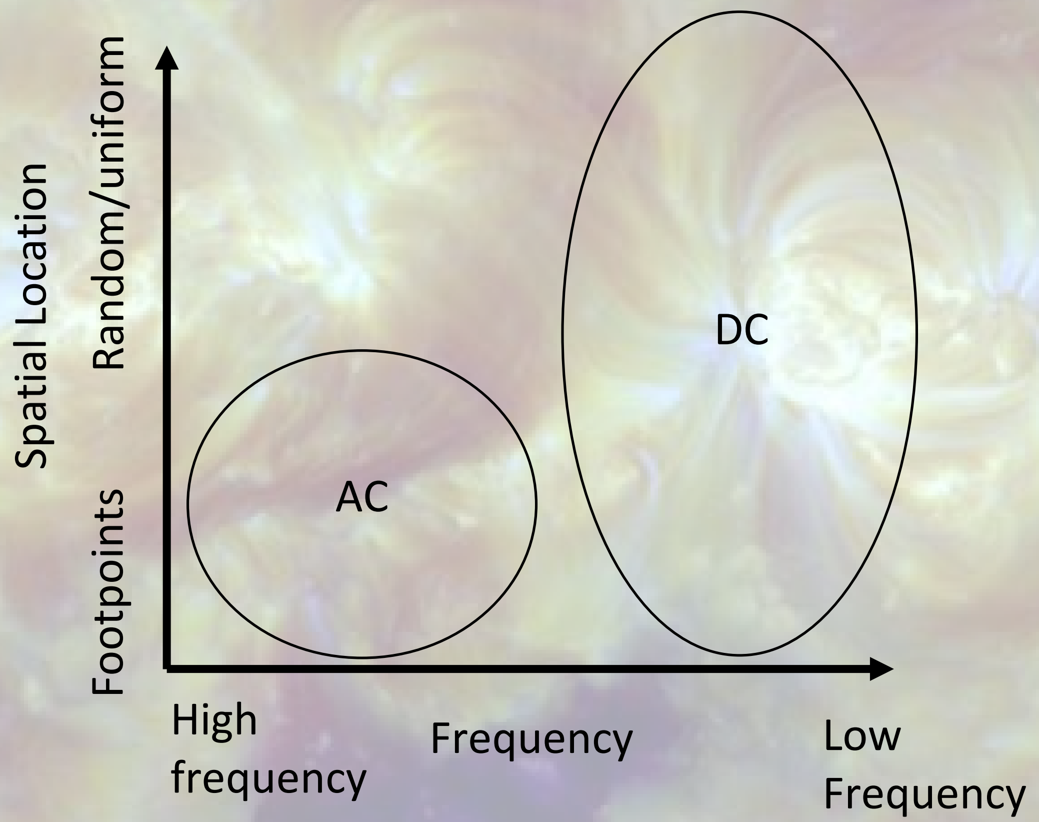
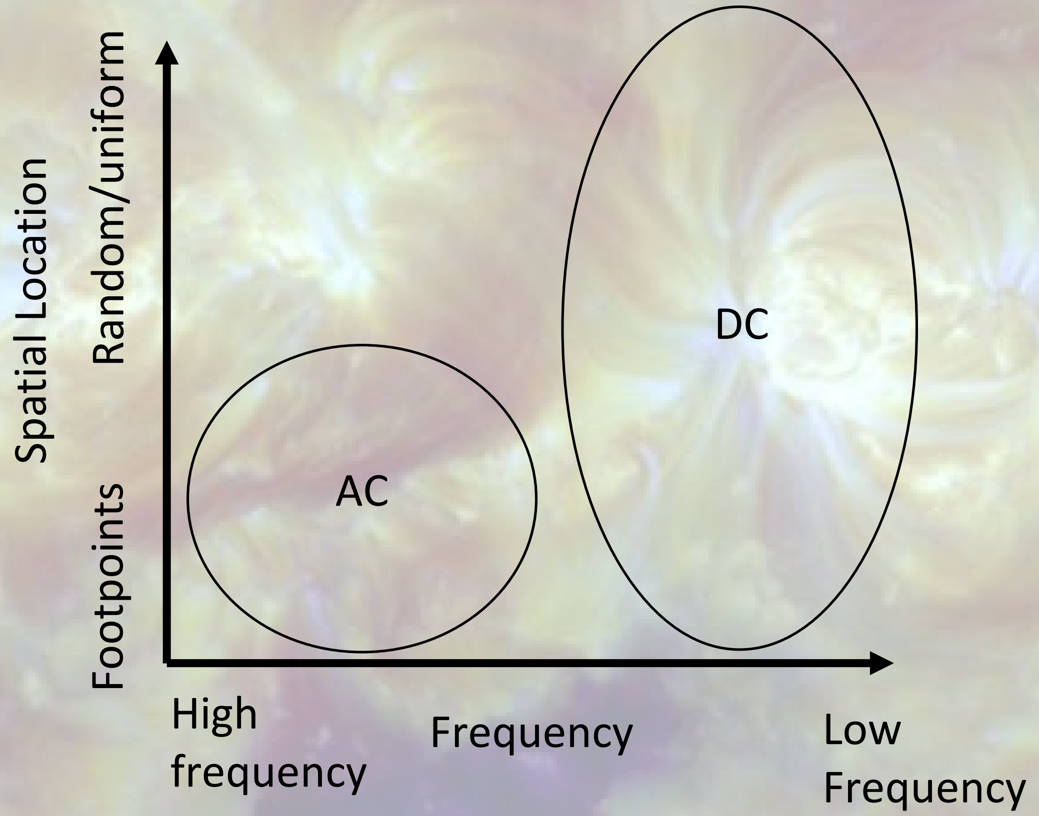


The rest of this talk

- Highlight recent work on plasma simulations and observations



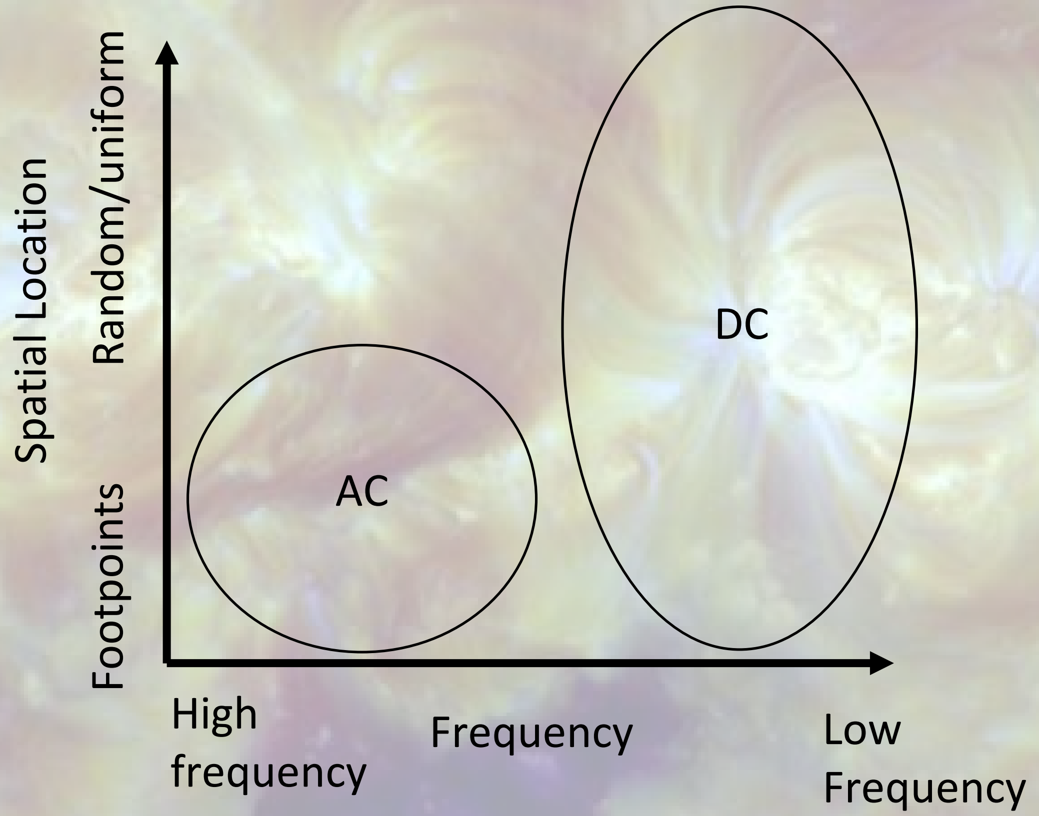
Is this true?

AC heating is based on MHD simulations

DC heating based on interpretations of stressing models.

The rest of this talk

- Highlight recent work on plasma simulations and observations

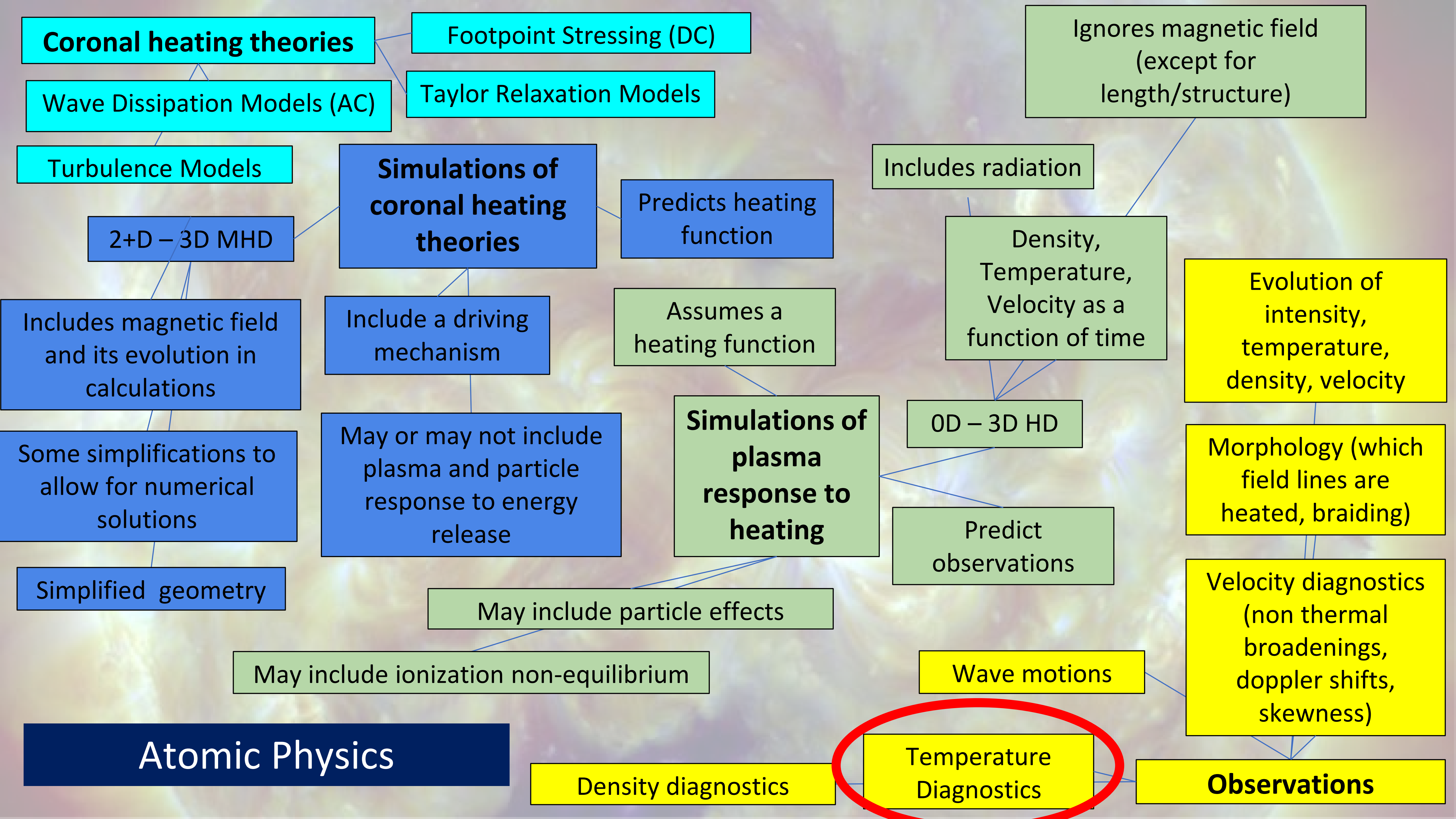


For plasma response, we define frequency relative to cooling time.

This is NOT a fundamental timescale for stressing.

High Temperature Plasma – the "smoking gun" for Nanoflare heating?

- At some point (maybe at an early Loops?) it was noted that high temperature plasma was an indicator of low frequency heating.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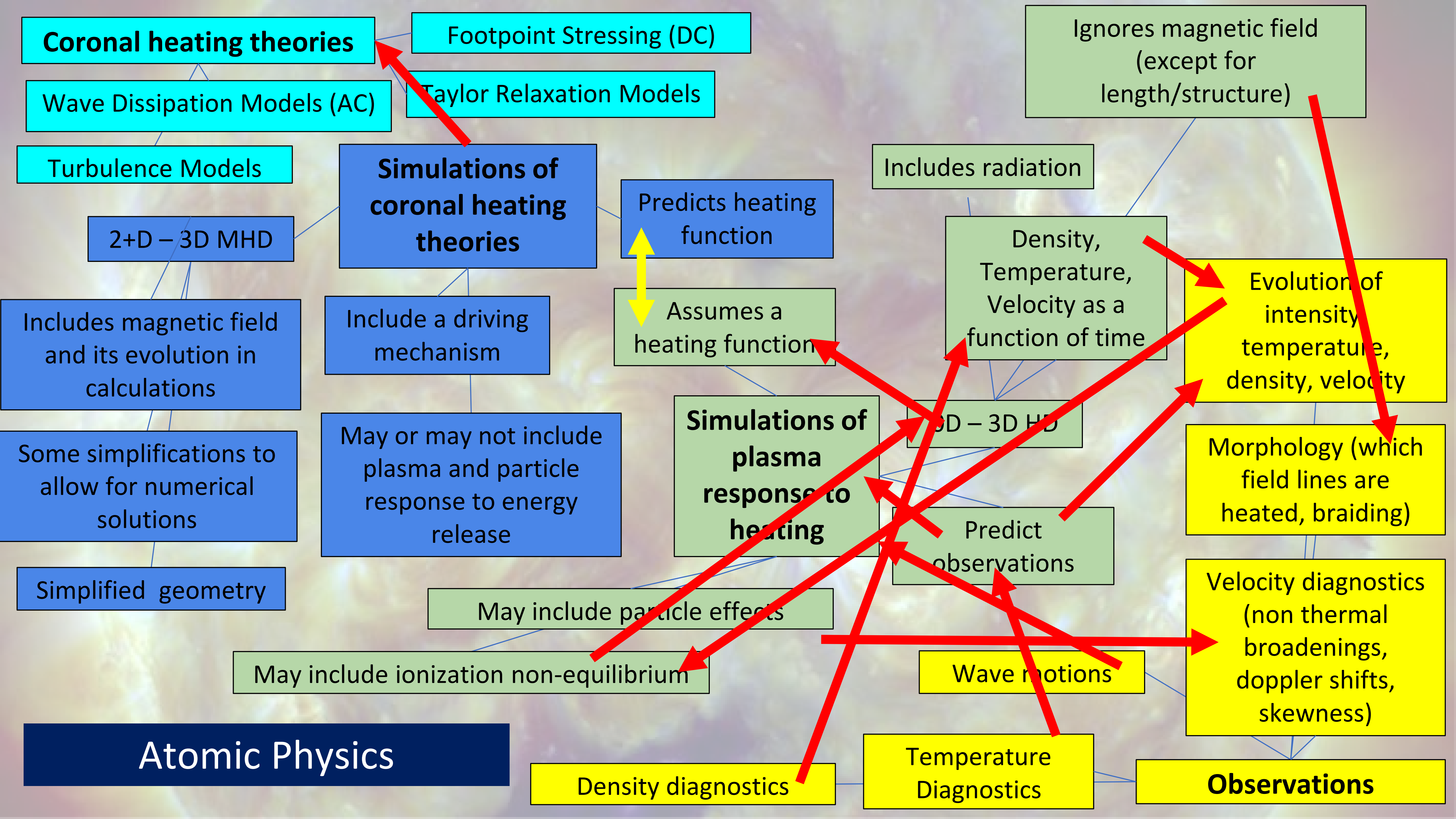
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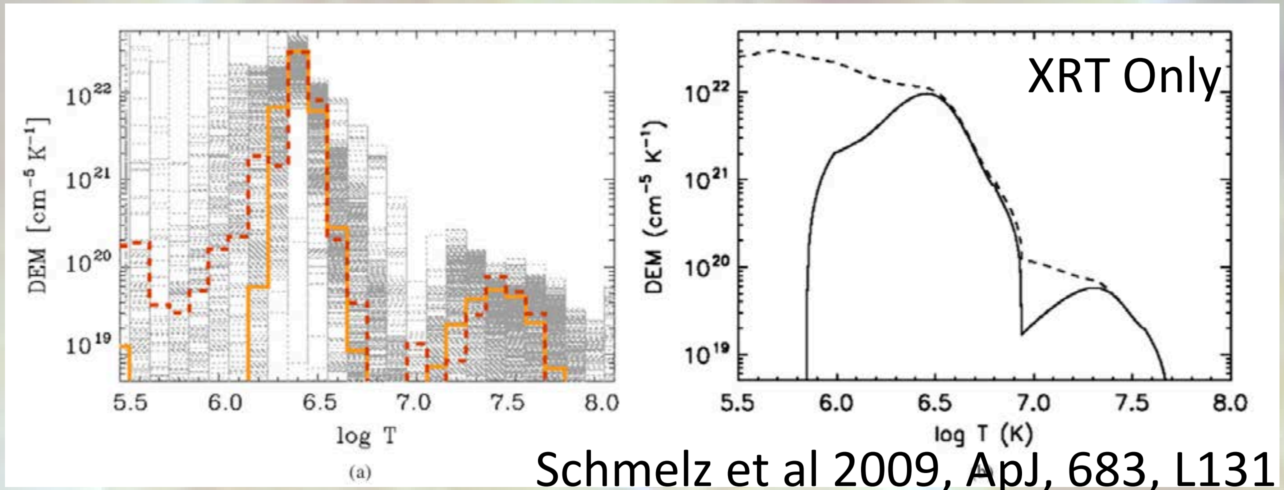
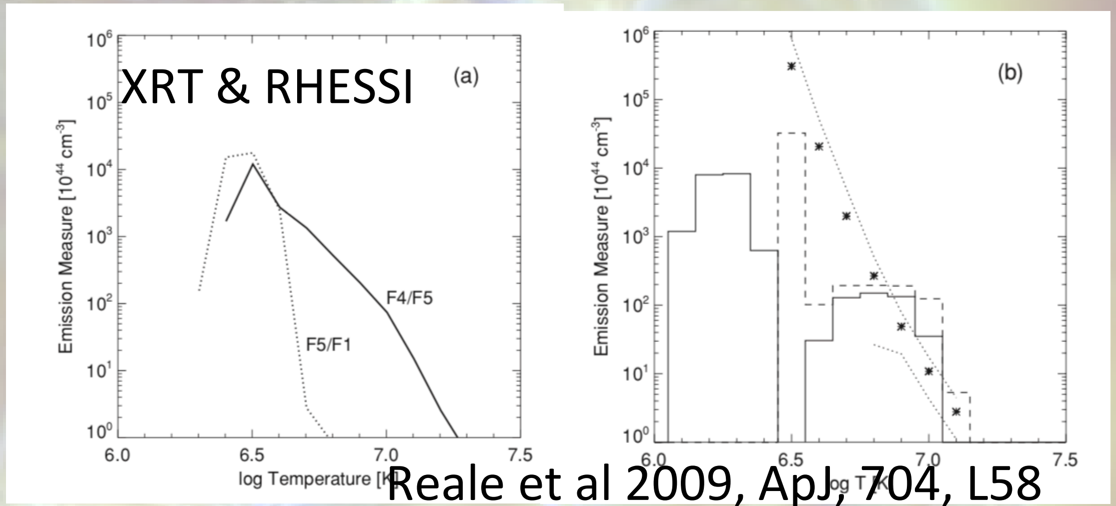
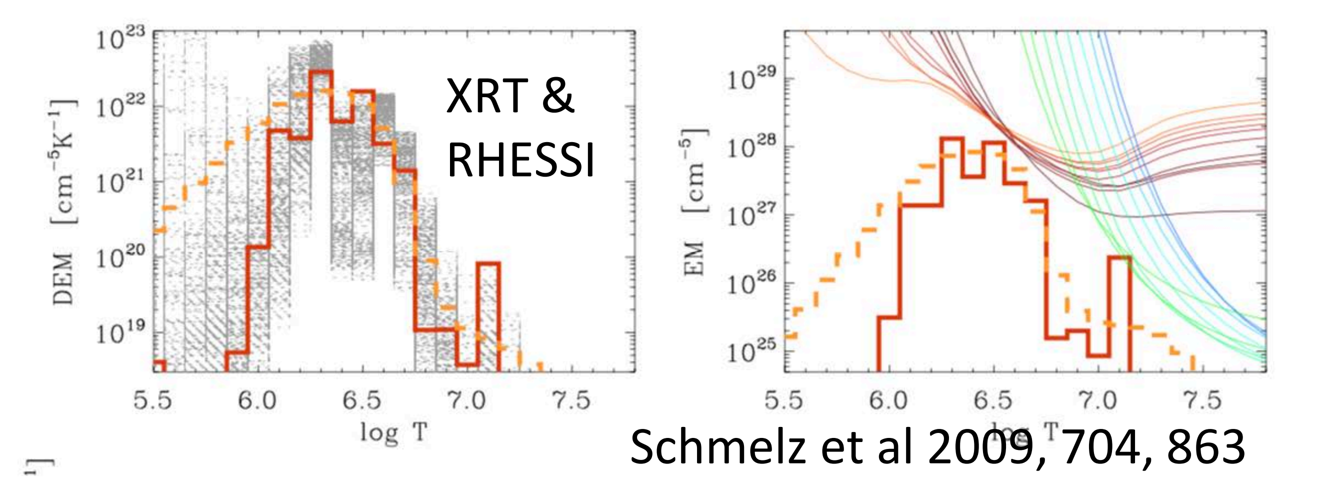
Hunt for high temperature plasma – Early results



Schmelz et al 2009, ApJ, 683, L131



Reale et al 2009, ApJ, 704, L58

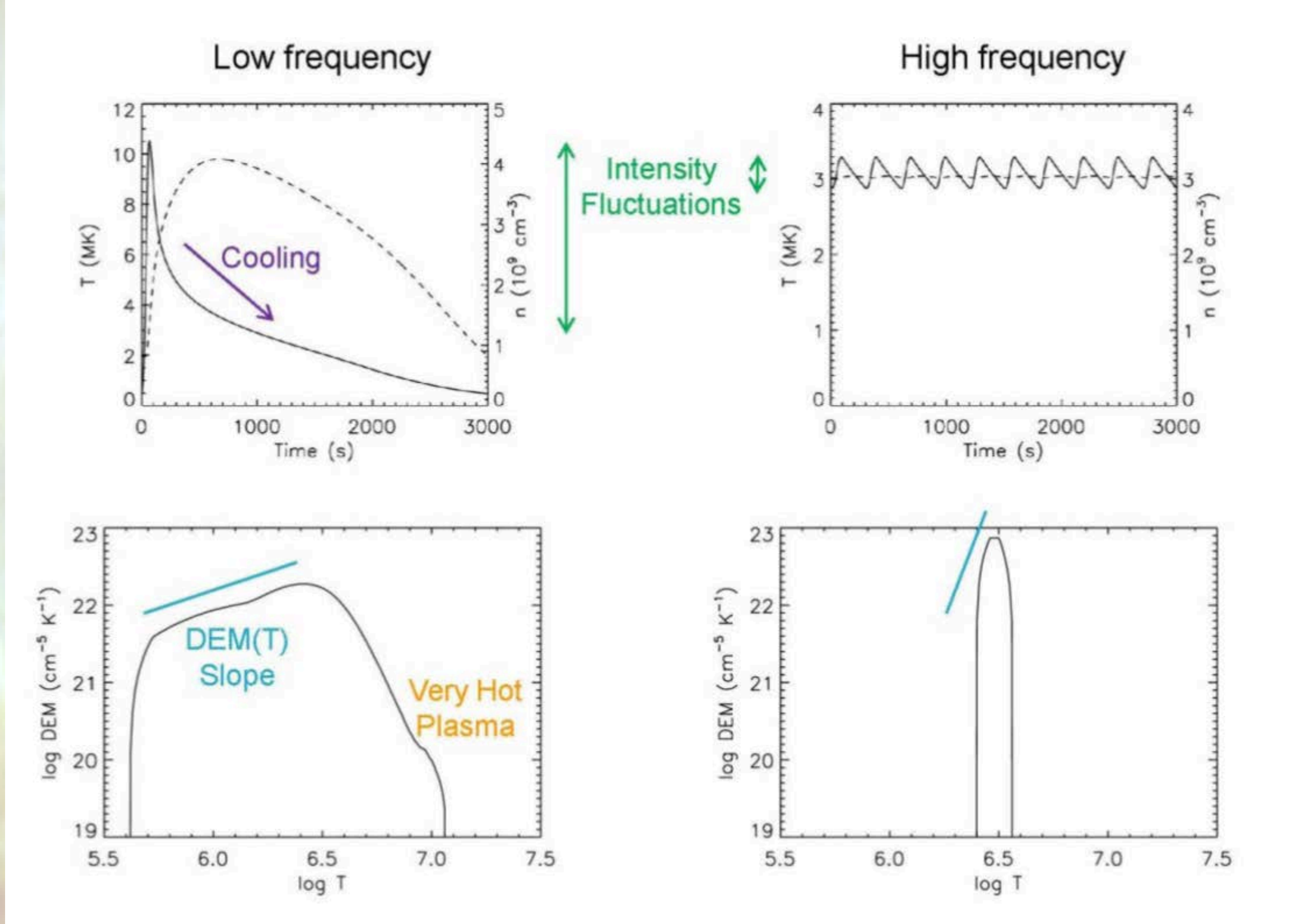


Schmelz et al 2009, 704, 863

Early results focusing on hard and soft X-ray observations.

Rely on the cross calibration of the two instruments.

High Temperature Plasma – the "smoking gun" for Nanoflare heating?

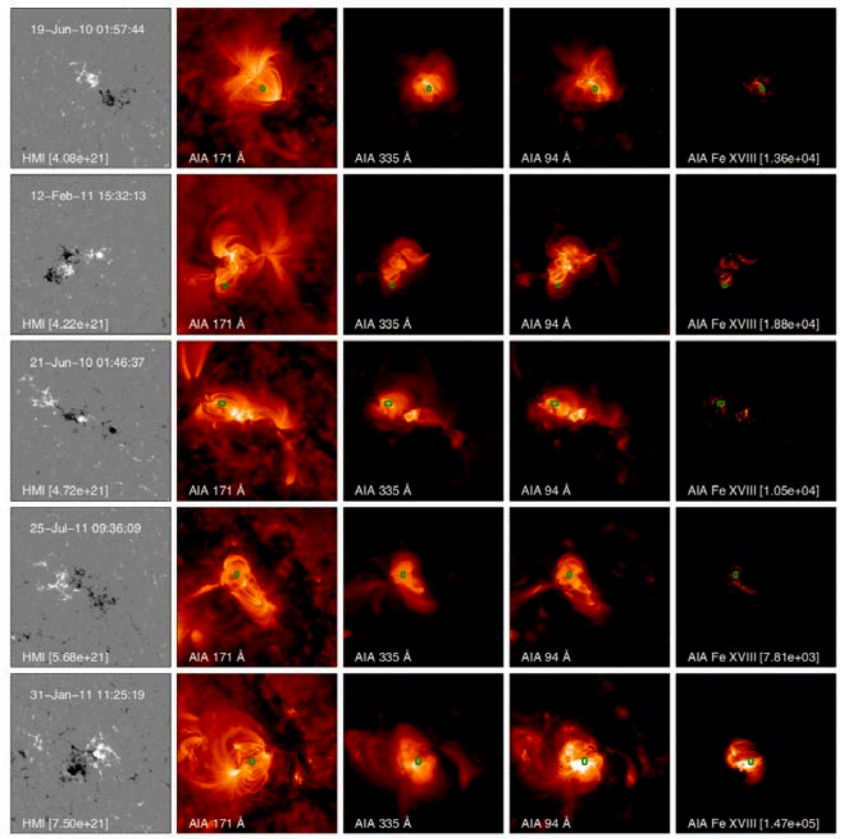


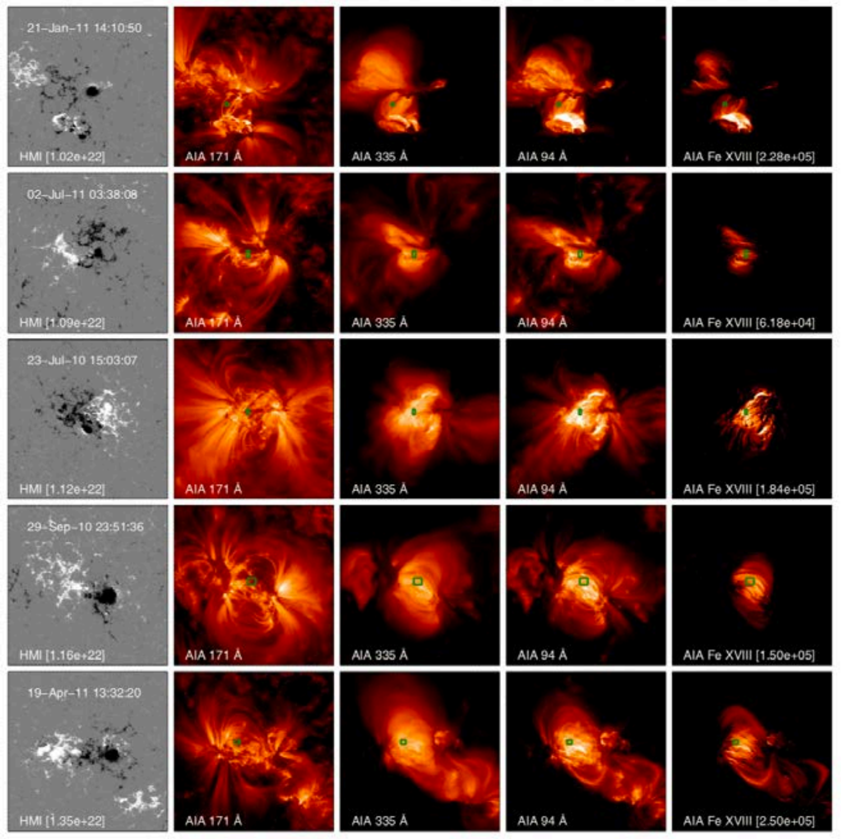
- Assume a coherent loop is a collection of strands
- Assume strands in loop are heated similarly

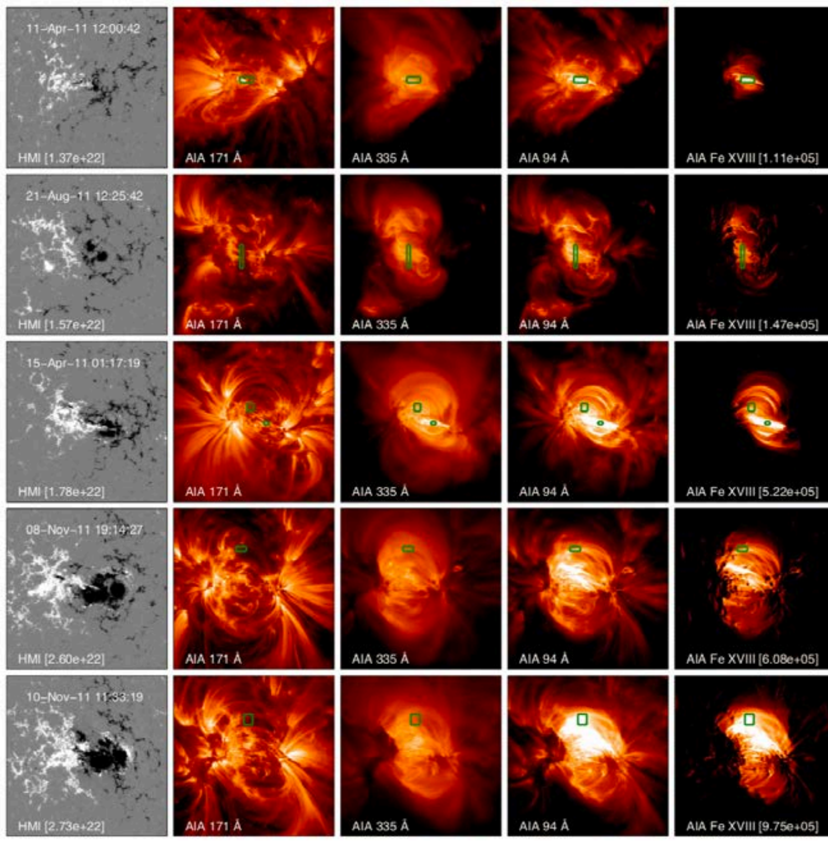
- Low-frequency heating – broad DEM with lots of low and cool plasma
- High frequency heating – narrow DEM.

Klimchuk 2017

Statistical Survey using EIS and AIA



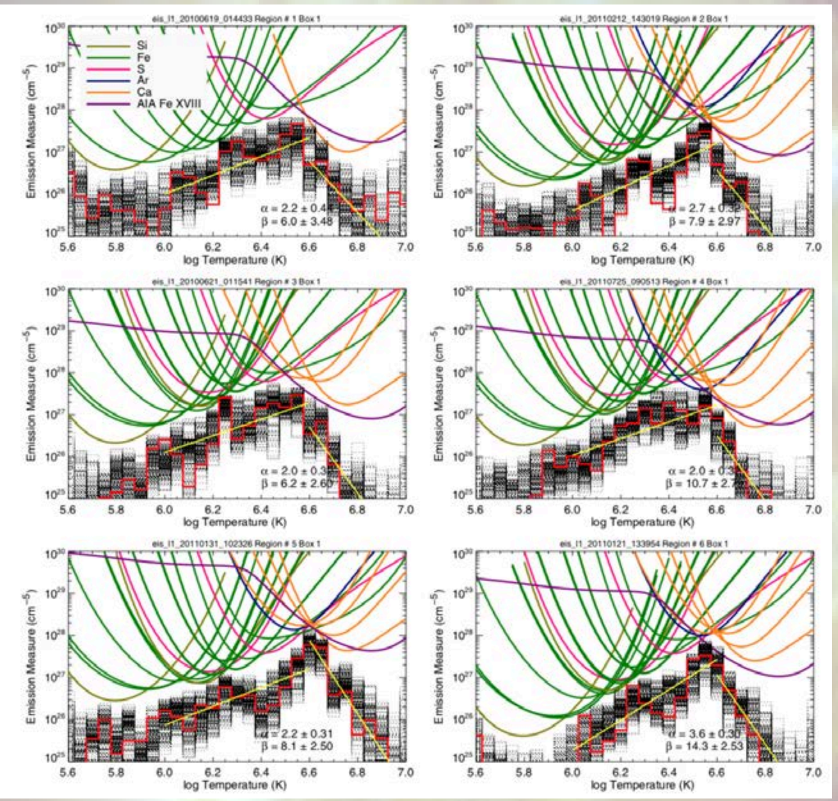


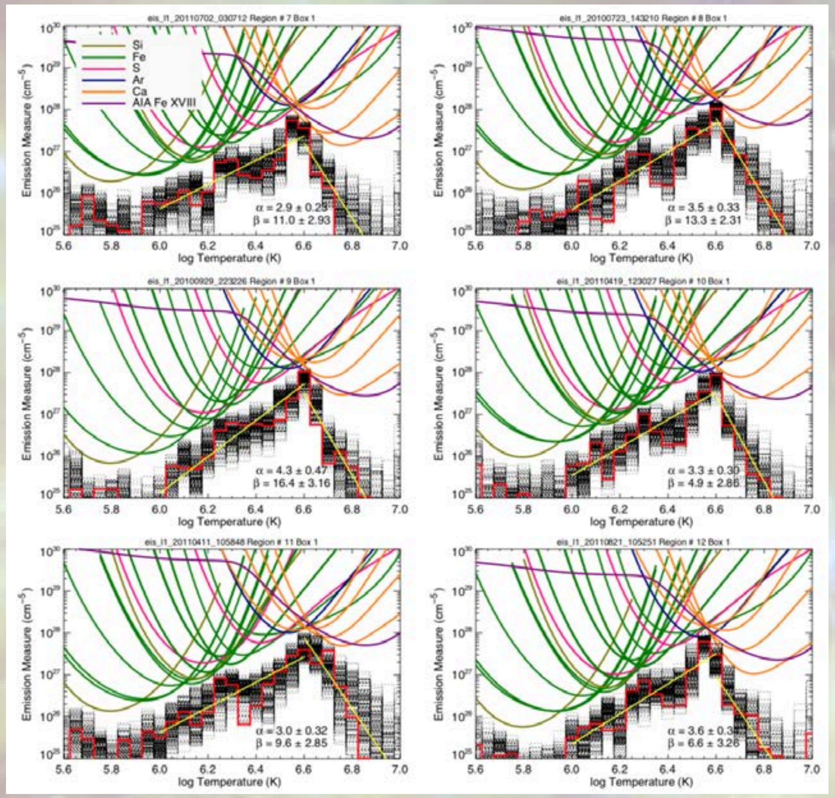


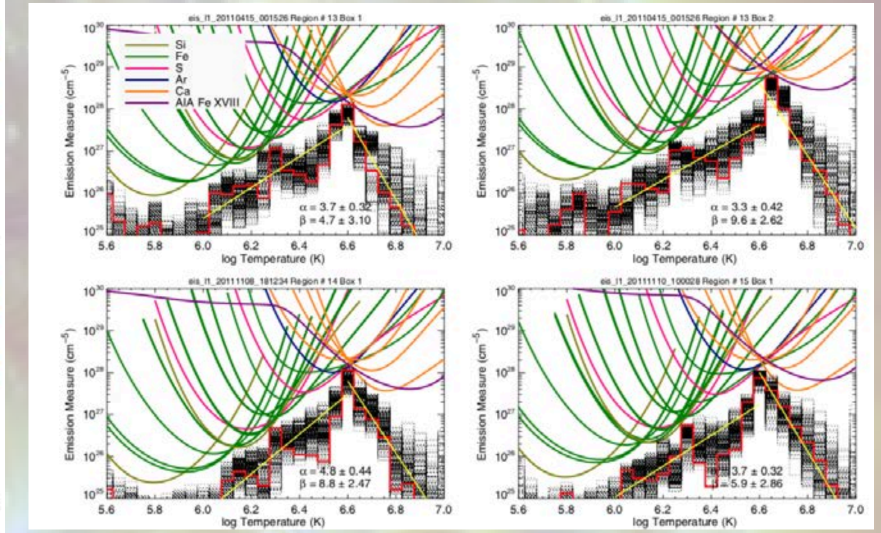
Warren et al used AIA Fe XVIII channel to expand the temperature sensitivity.

Warren et al 2012, ApJ, 759, 141

Statistical Survey using EIS and AIA







Parameterized the resulting EM as a broken power law with slopes alpha and beta.

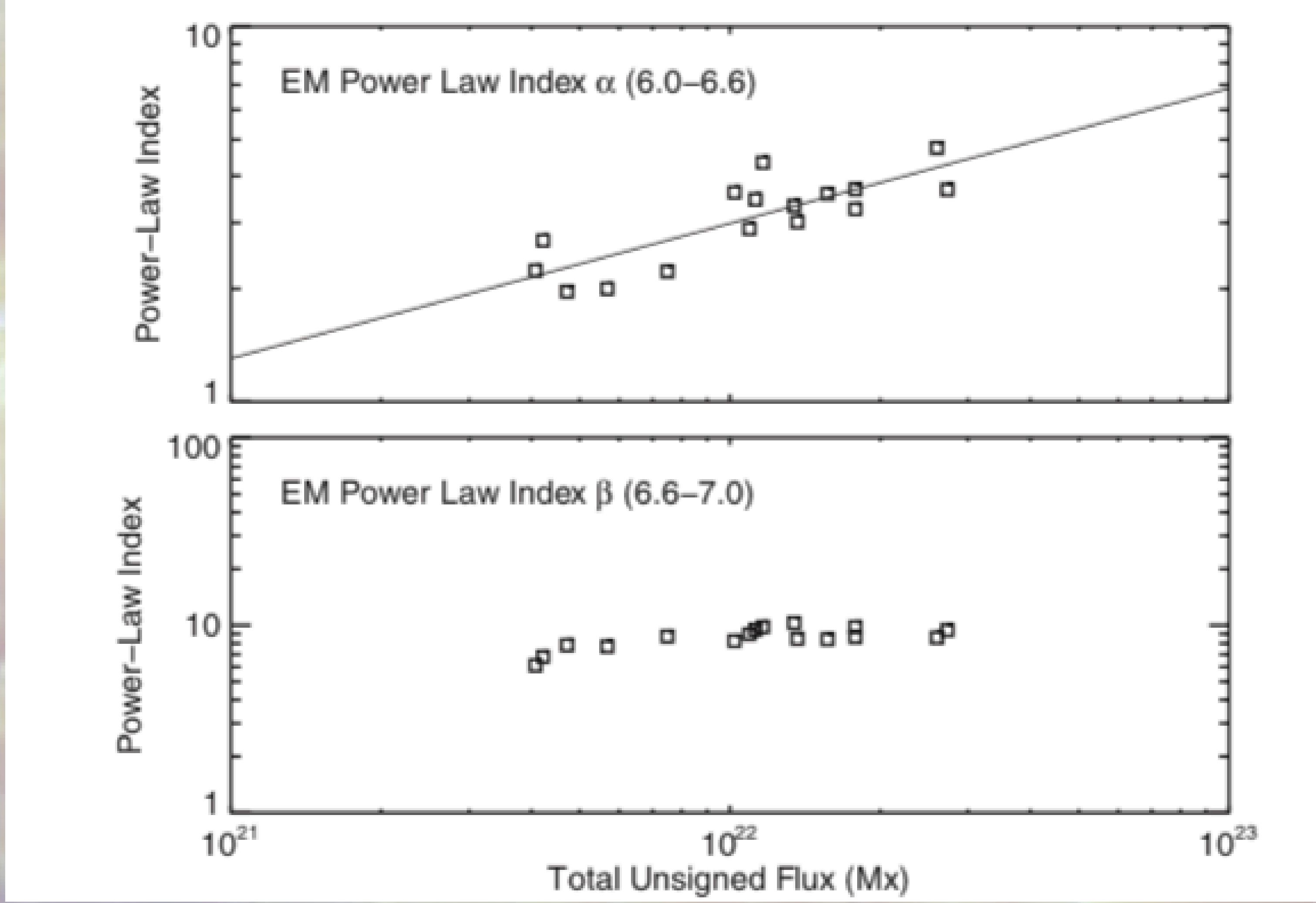
Warren et al 2012, ApJ, 759, 141

Statistical Survey using EIS and AIA

Found relationship between EM and magnetic flux.

Found beta was ~10 in all cases.

Large uncertainty due to limited high temperature sensitivity

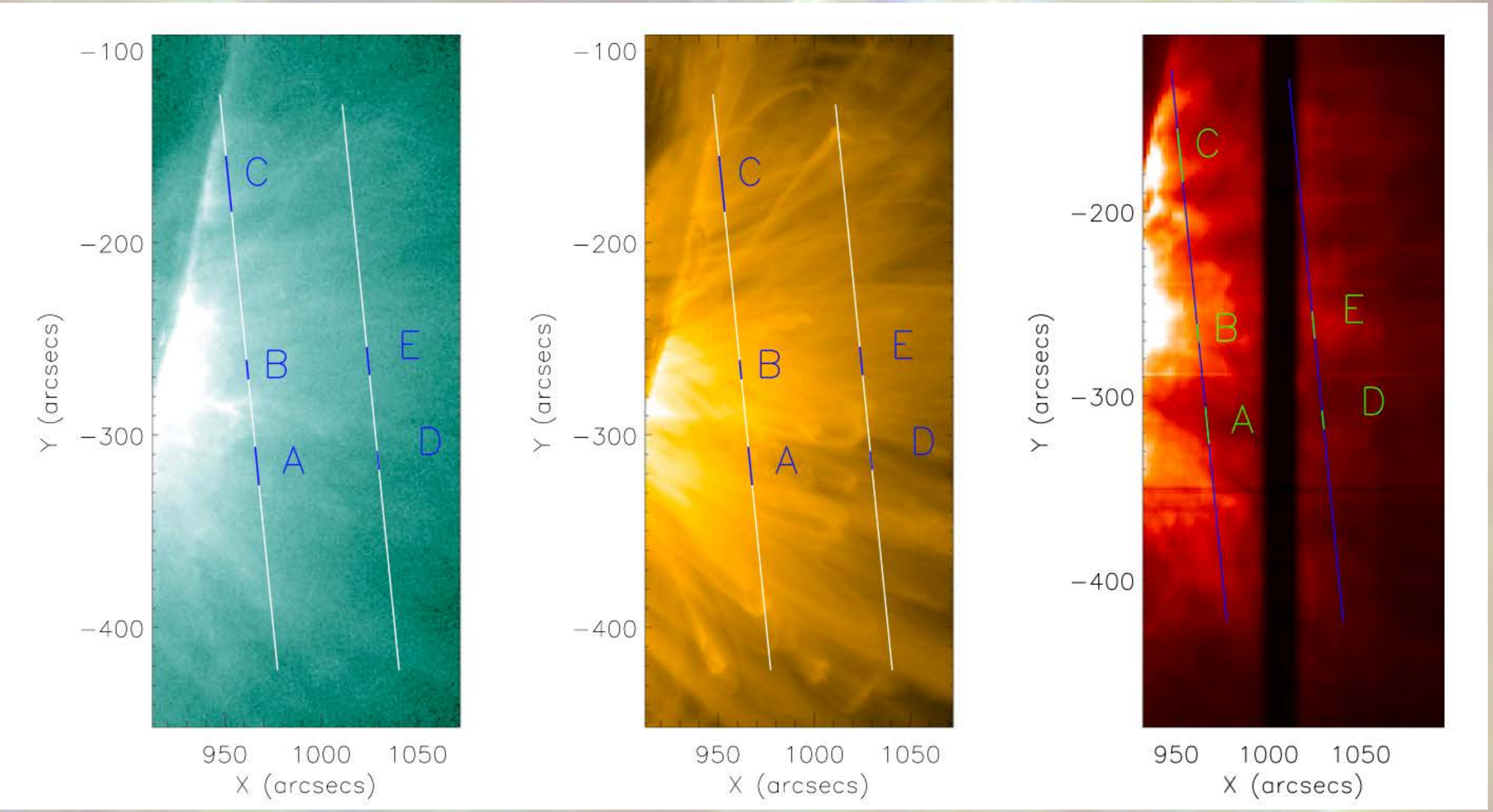


Warren et al 2012, ApJ, 759, 141

SUMER and EIS

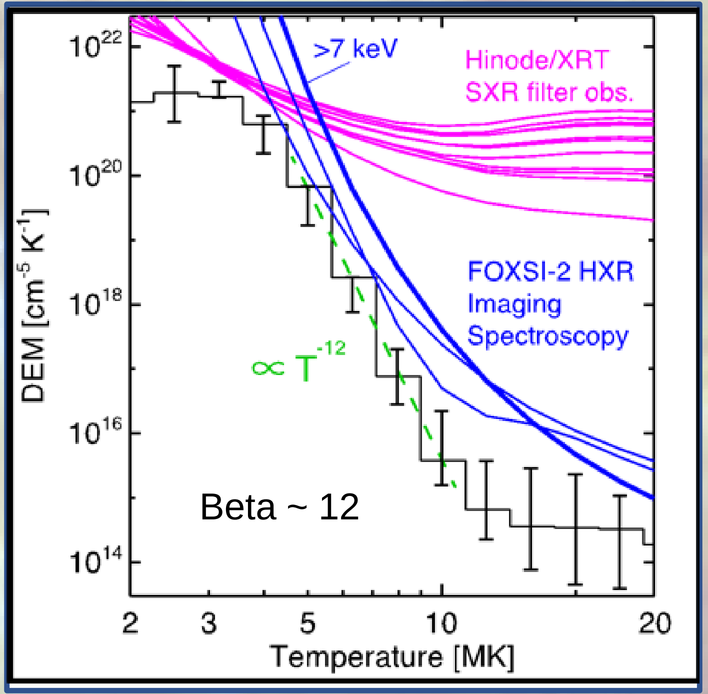
SUMER and EIS were combined to study thermal structure of an off limb active region

Beta between 8.5 – 4.5

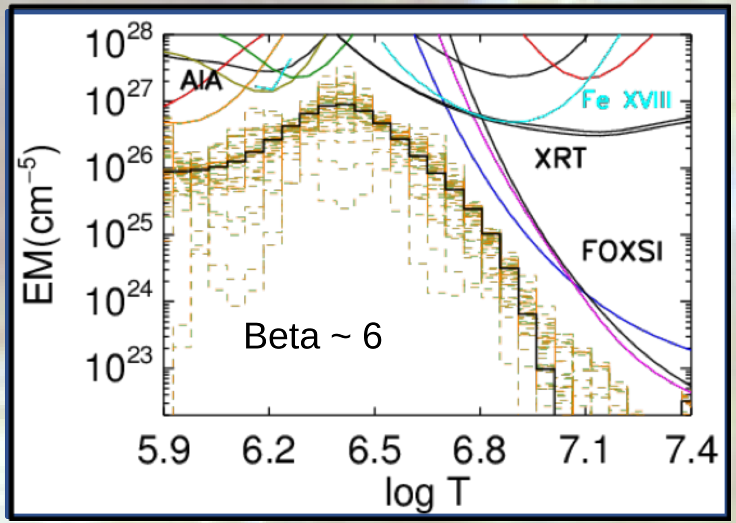


Parenti et al 2017, ApJ, 846, 25

Recent results – FOXSI sounding rockets



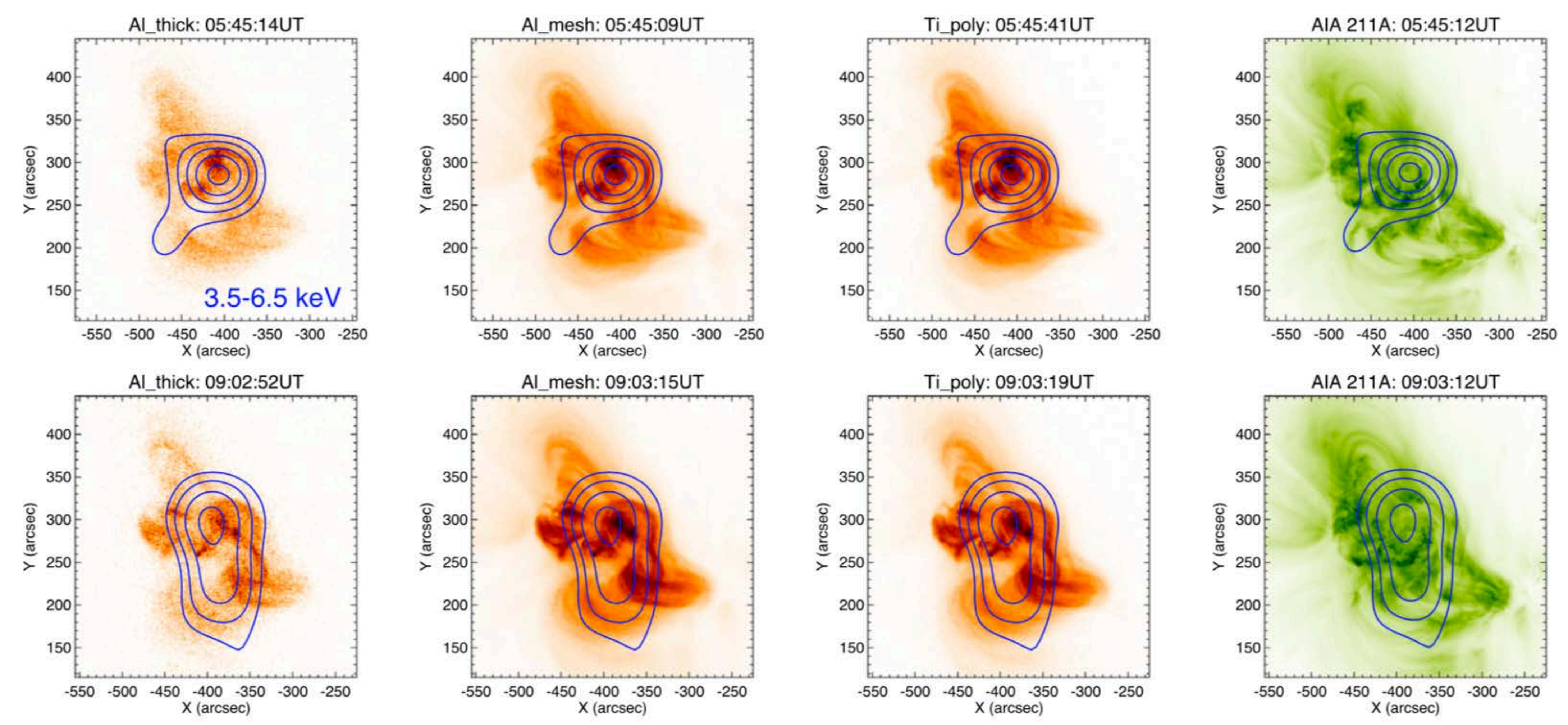
Ishikawa et al, 2017, Nature Astronomy, 1, 771



Athiray et al (2019, to be submitted)

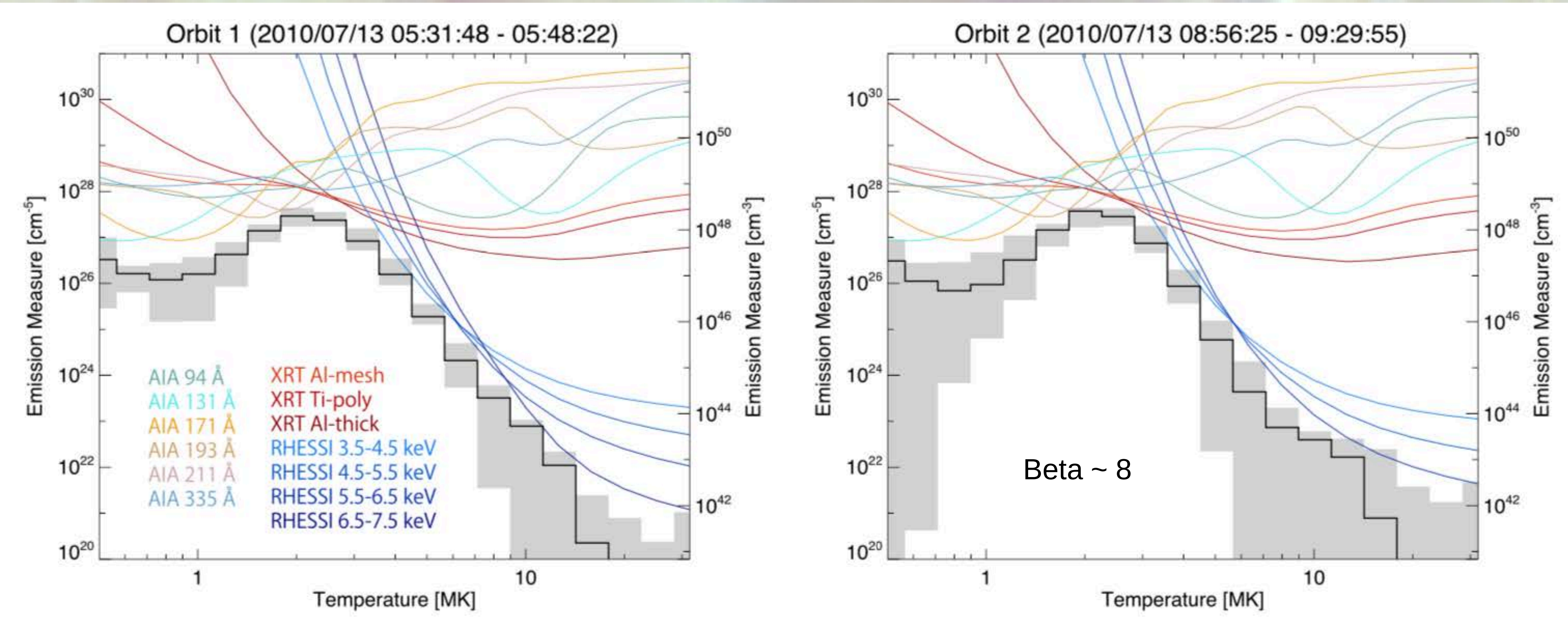
Recent FOXSI results measure slope with a combination of XRT, AIA and FOXSI.

Recent results



Ishikawa and Krucker 2019, 876, 111

Recent results



Ishikawa and Krucker did a detailed analysis of a non-flare AR with XRT, AIA, and RHESSI.

Ishikawa and Krucker 2019, 876, 111

Summary of Beta

Publication	Beta
Warren et al. 2012	10+- 3
Parenti et al 2017	4.5 – 8.5
Ishikawa et al 2017	12
Athiray et al (submitted)	6
Ishikawa & Krucker 2019	8

In a parallel effort…

Series of papers investigated the relationship between heating frequency and temperature diagnostics.

- Bradshaw et al, 2012, ApJ, 783, 53
- Reep et al., 2013, ApJ, 784, 193
- Cargill, 2014, ApJ, 784, 49
- Barnes et al, 2016, ApJ, 829, 31
- Barnes et al. 2016, ApJ, 833, 217

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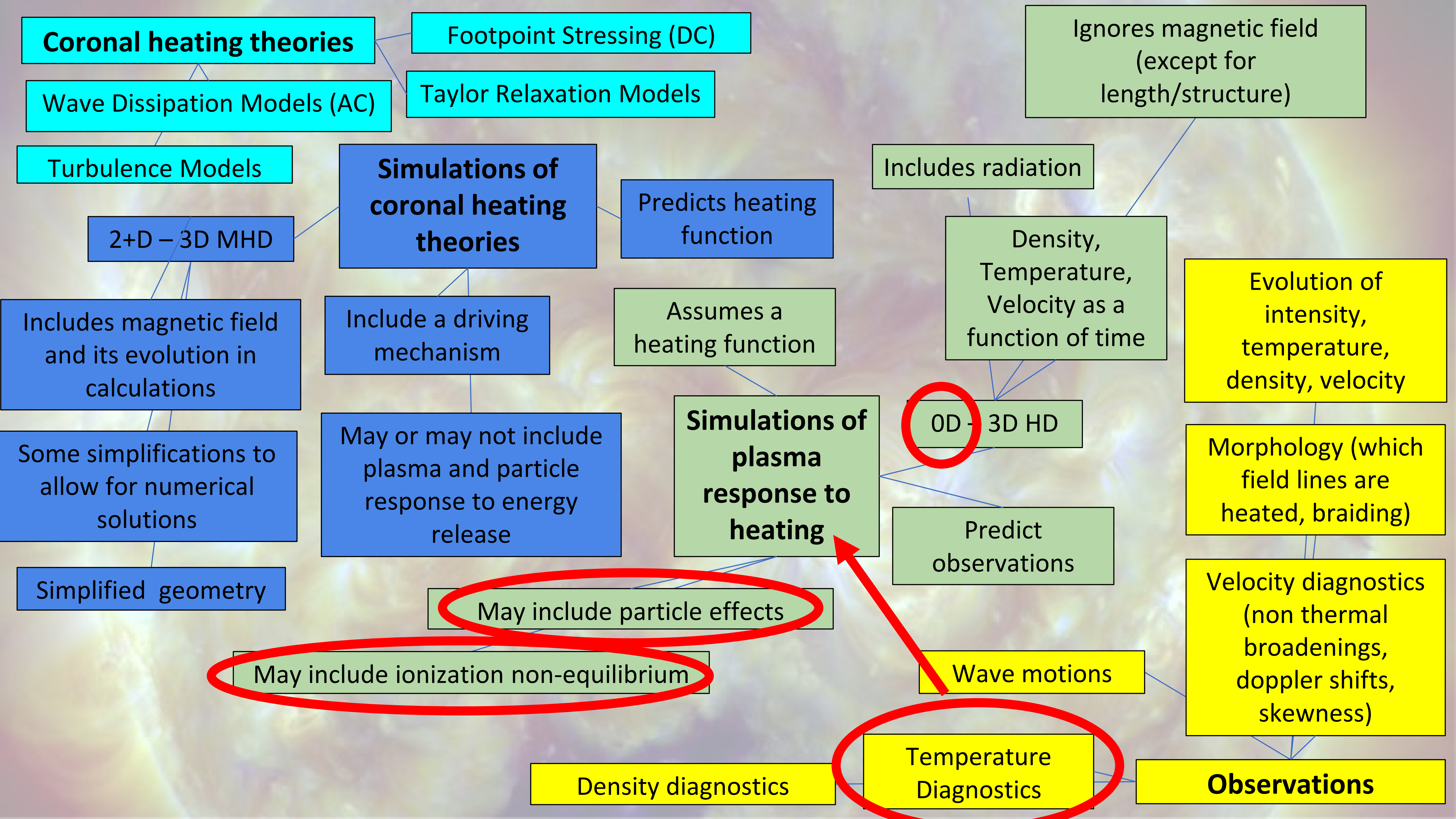
- Bradshaw et al, 2012, ApJ, 783, 53
- Reep et al., 2013, ApJ, 784, 193
- Cargill, 2014, ApJ, 784, 49
- Barnes et al, 2016, ApJ, 829, 31
- Barnes et al. 2016, ApJ, 833, 217



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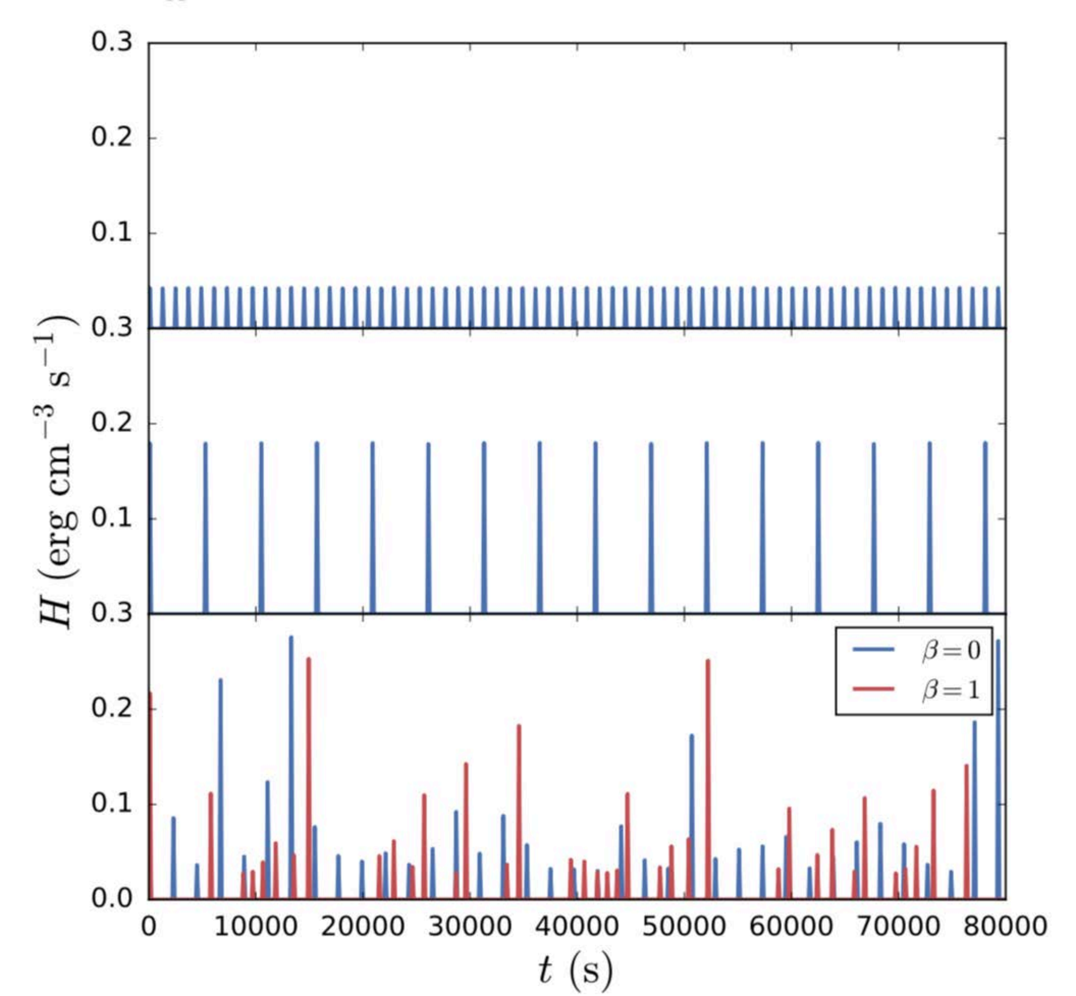
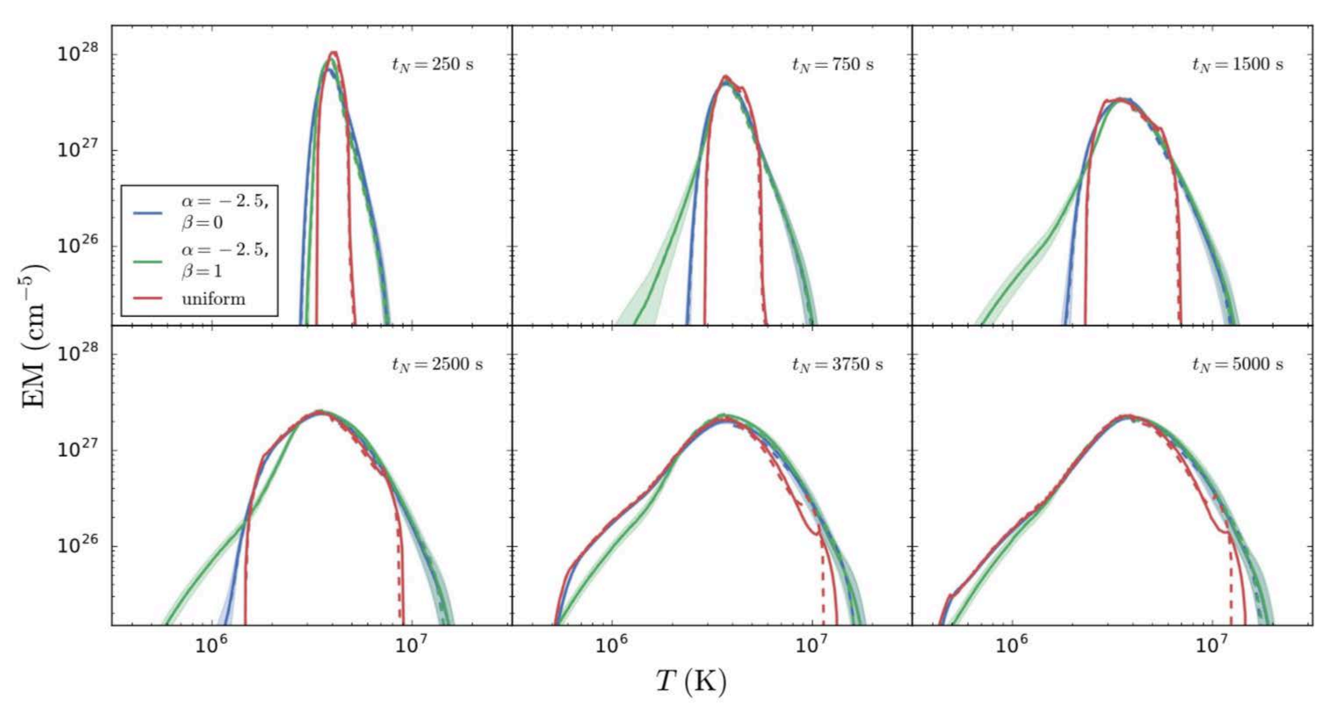
Description of Simulations



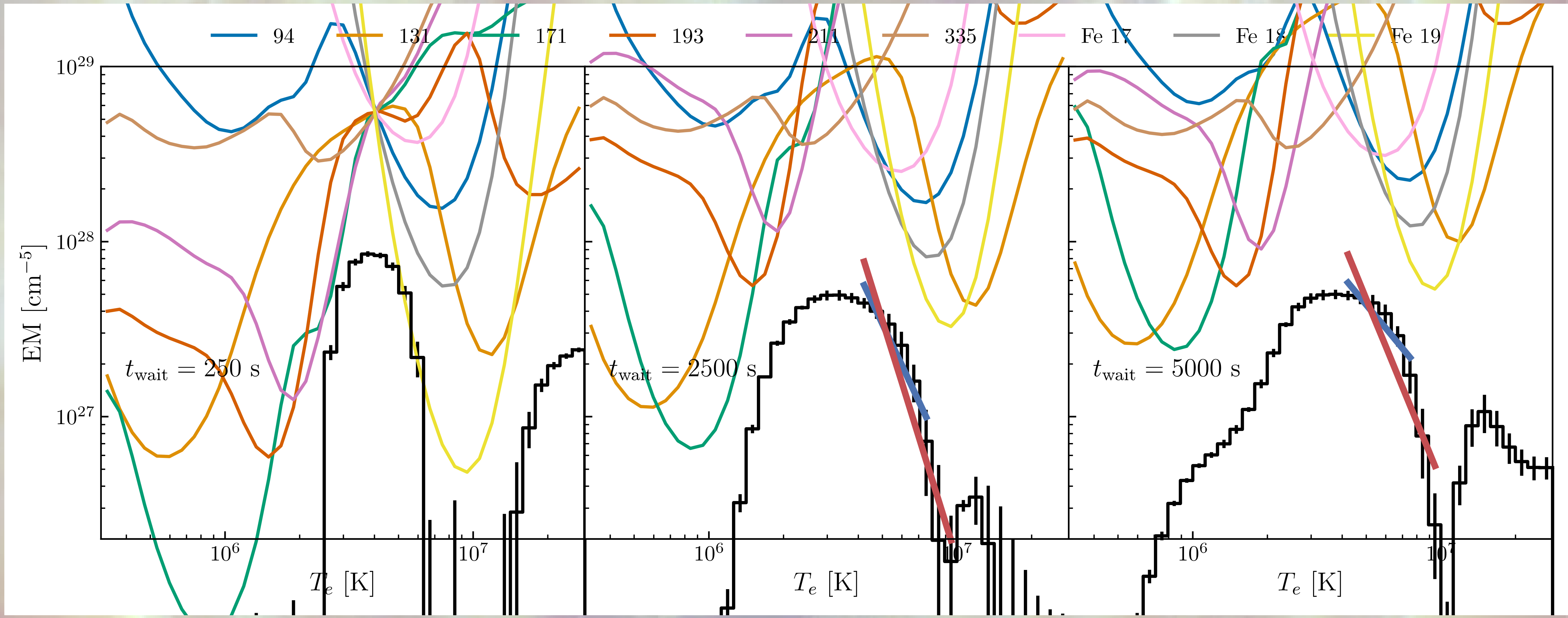


Barnes et al. considered different heating frequencies (regular and random) and different vehicles for heating (ions and electrons).

Included non-equilibrium ionization.

Barnes et al, 2016, ApJ, 833, 217

Maybe Beta isn't a great parameter?



Barnes (private communication)

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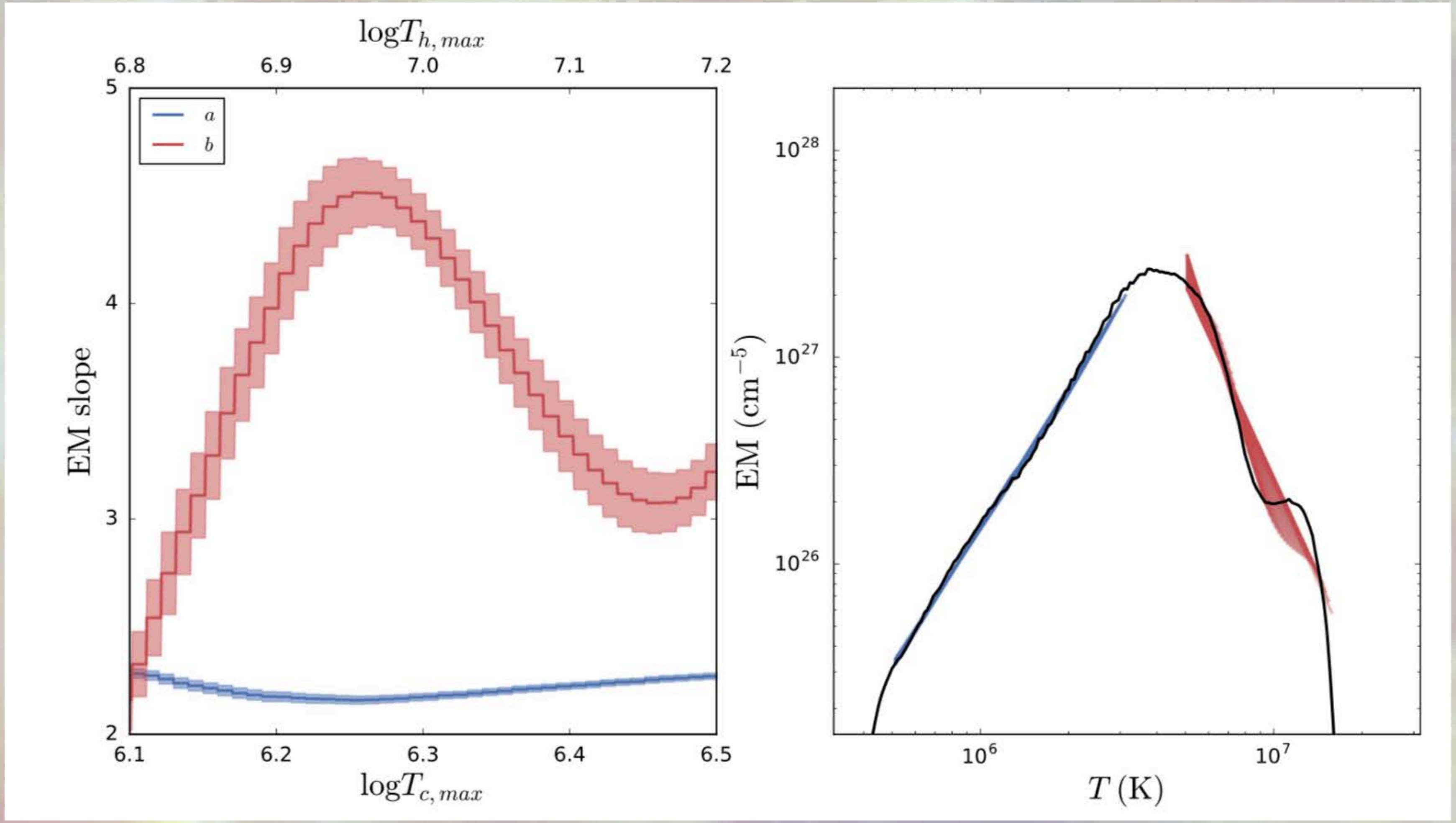
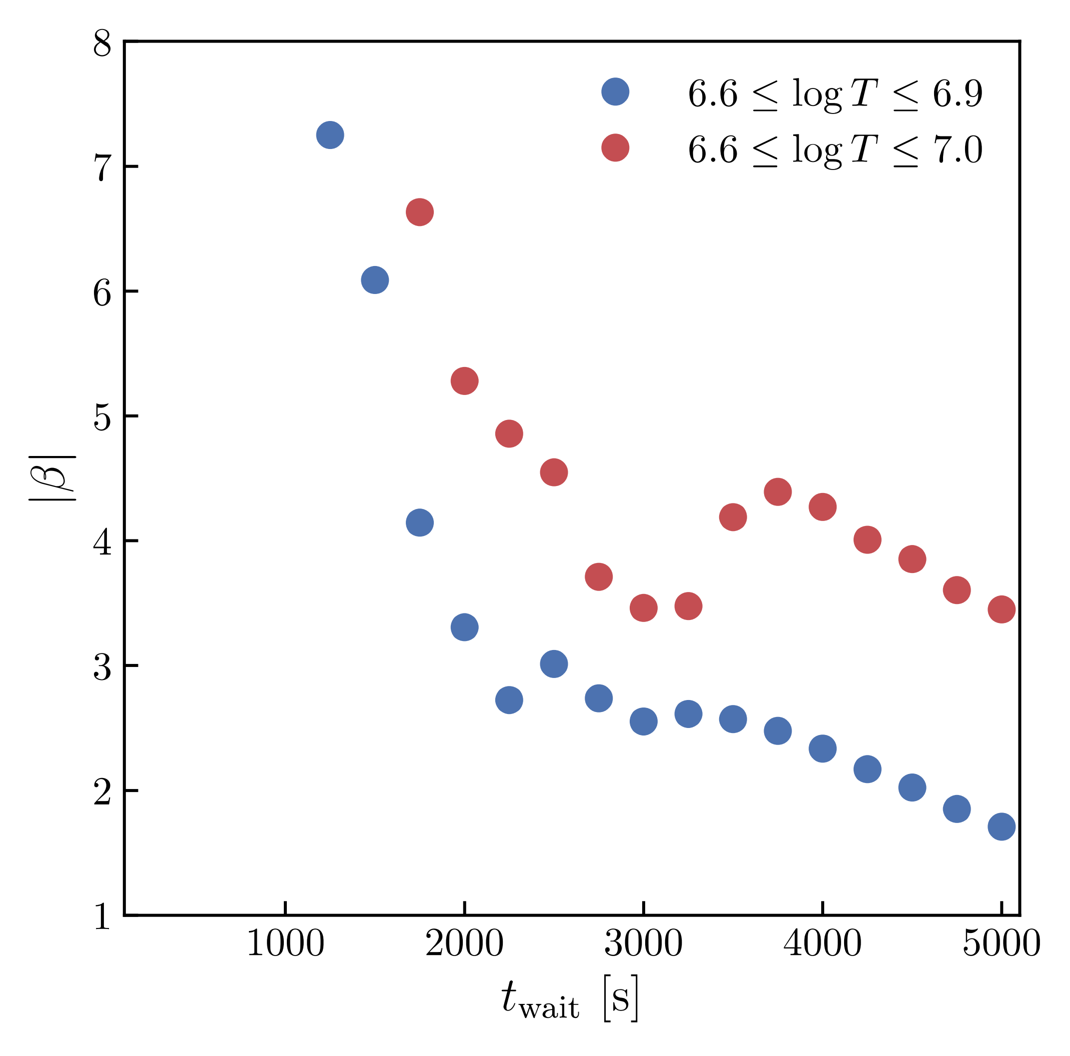


The measured beta depends strongly on the selected bounds.

Barnes et al, 2016, ApJ, 833, 217

Results from Simulations



Betas that have been recently measured (~10) indicate high frequency heating.

This is only for one loop length – 80 Mm.

Barnes (private communication)

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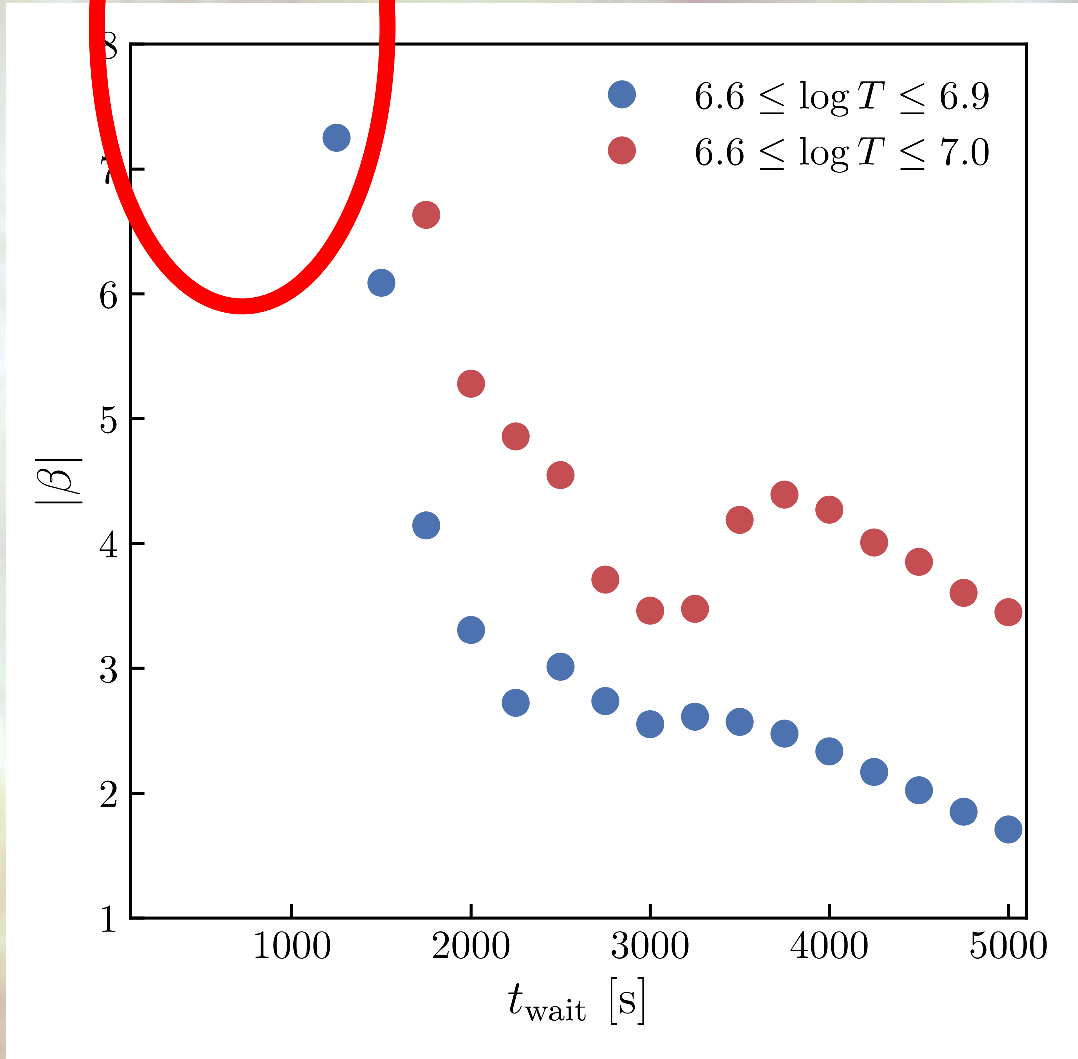

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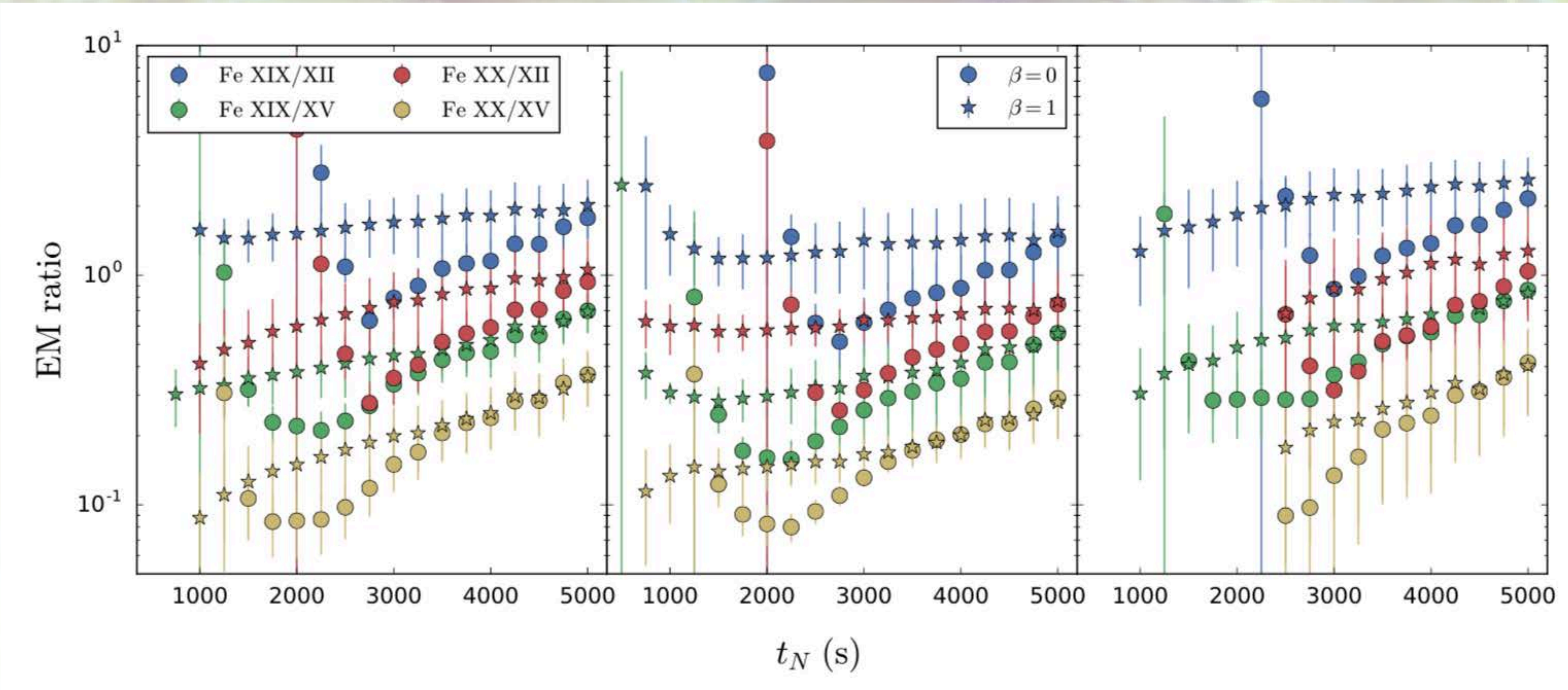
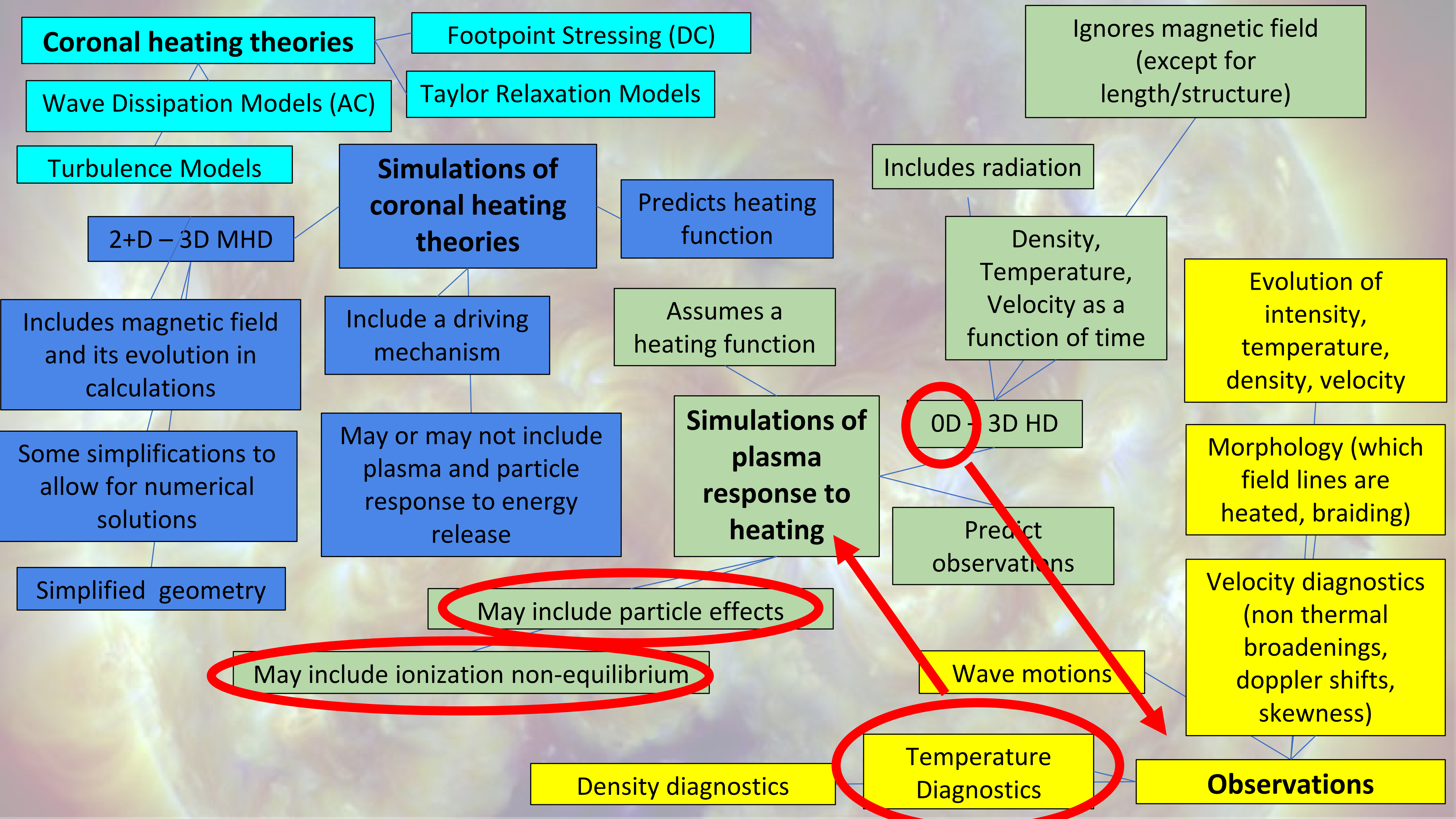


Barnes suggested that line ratios may be a better diagnostic tool than beta.

Barnes et al, 2016, ApJ, 833, 217



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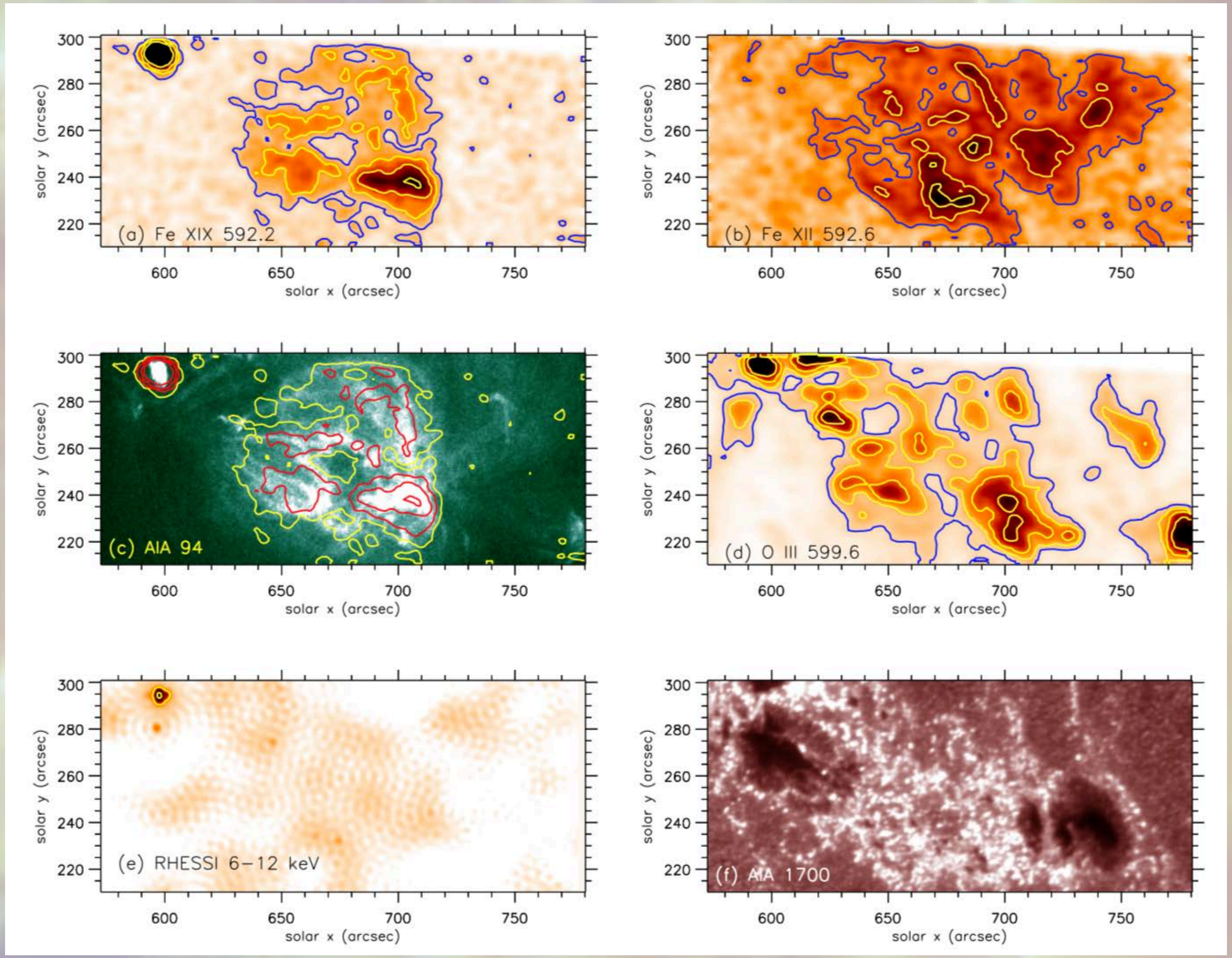
Fe XIX pervasive in Active Region

EUNIS sounding rocket experiment observed pervasive Fe XIX emission in a non-flaring Active Region.

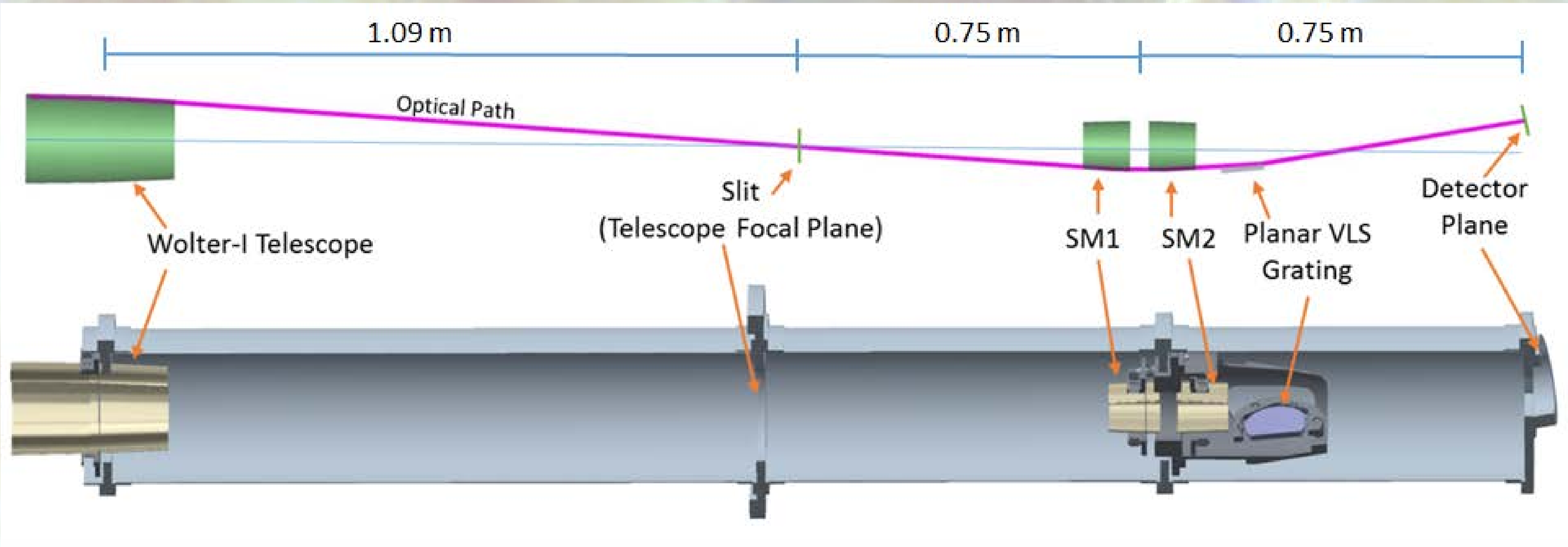
Determined this was consistent with nanoflare heating.

Determined ratio of Fe XIX to Fe XII inside and outside the Active Region Core.



Brosius et al 2014, ApJ, 790, 112

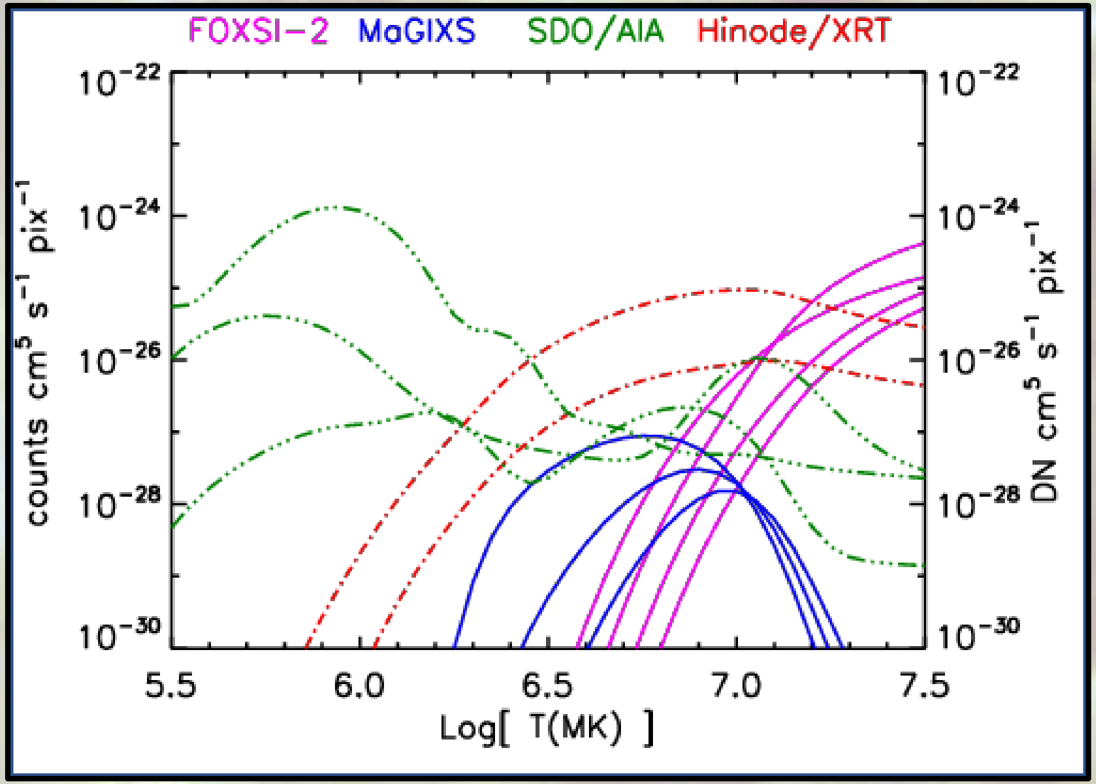
Upcoming Instrument - MaGIXS

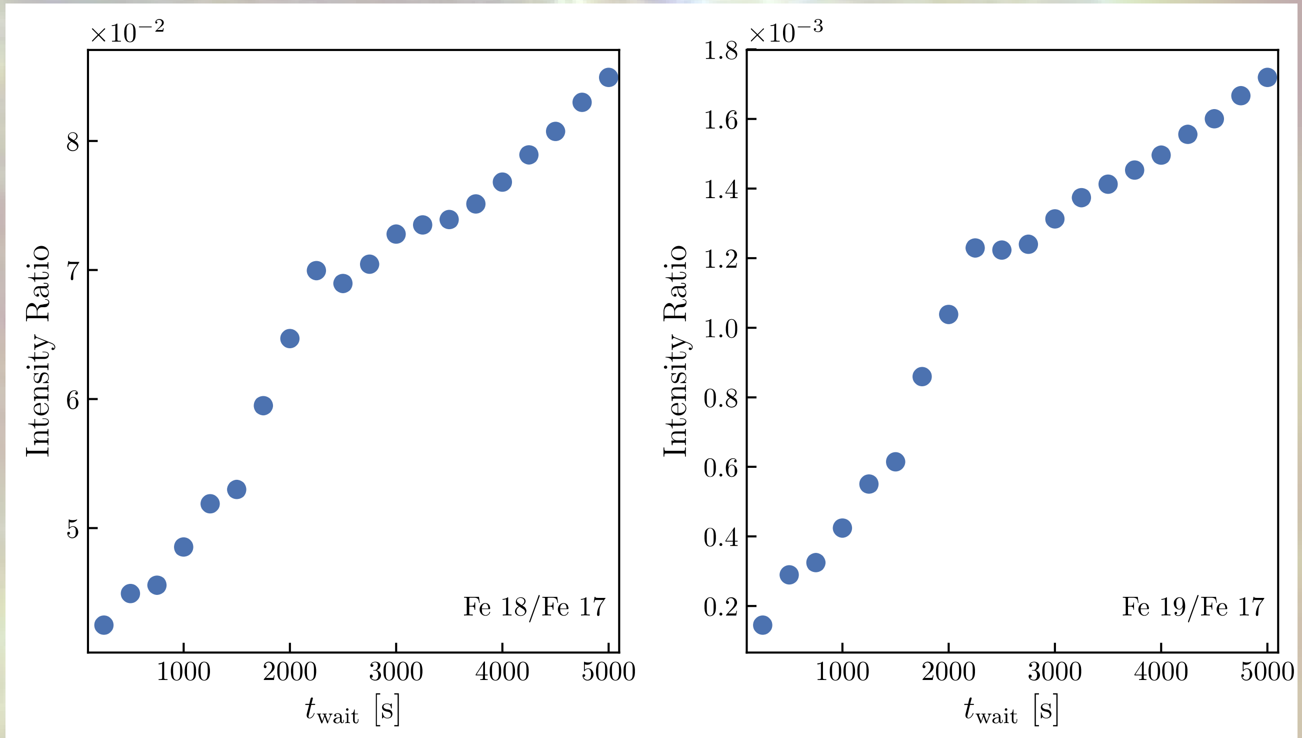


Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) sounding rocket instrument.

Spatially and spectrally resolve 6-25 Ang wavelength range (Fe XVII, Fe XVIII, Fe XIX)

Upcoming Instrument - MaGIXS



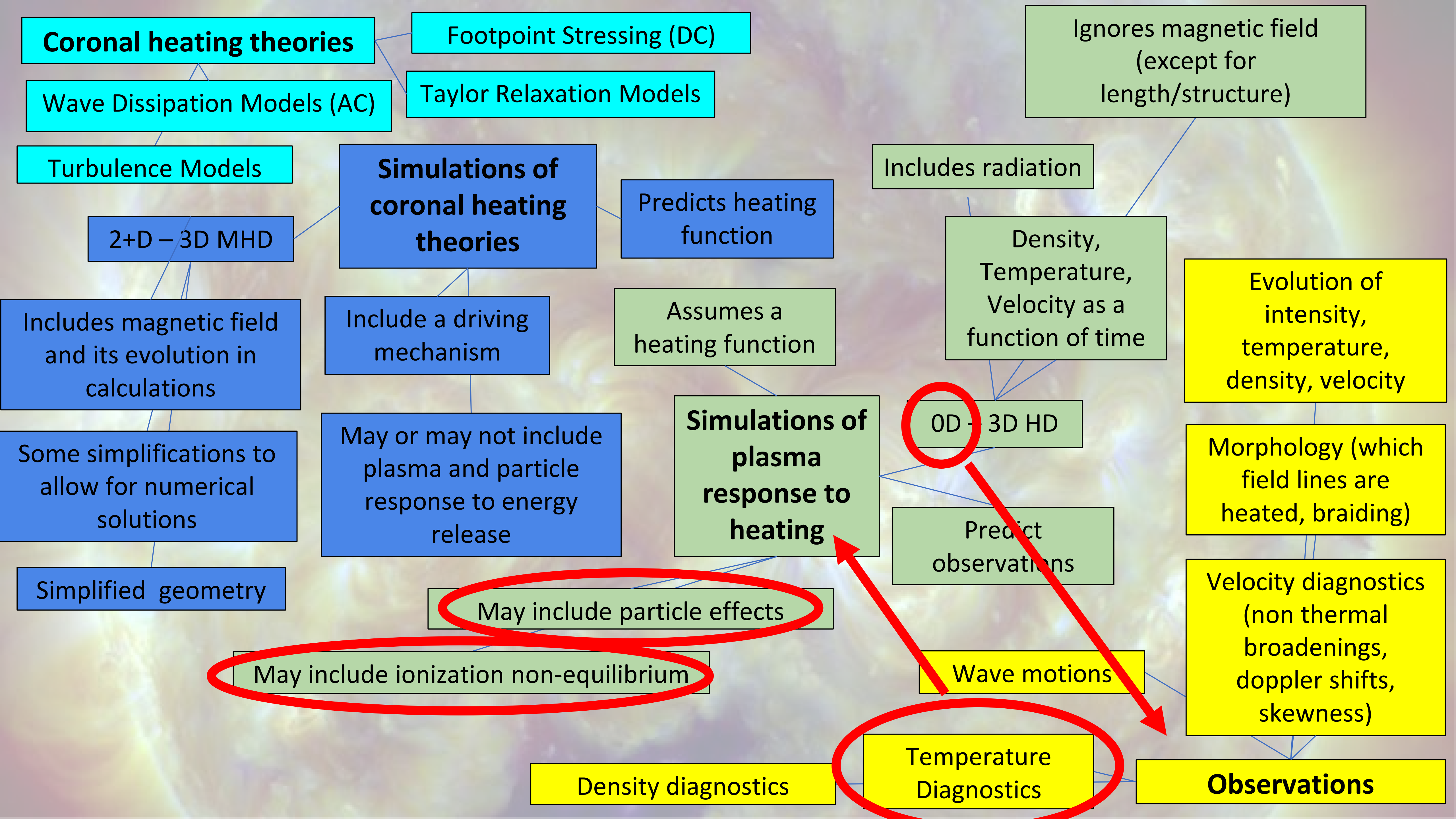


MaGIXS provides a bridge between XRT and FOXSI.

Athiray et al, 2019, to be submitted

Upcoming Instrument - MaGIXS

MaGIXS build it currently underway at MSFC!   To be flown in 2020.



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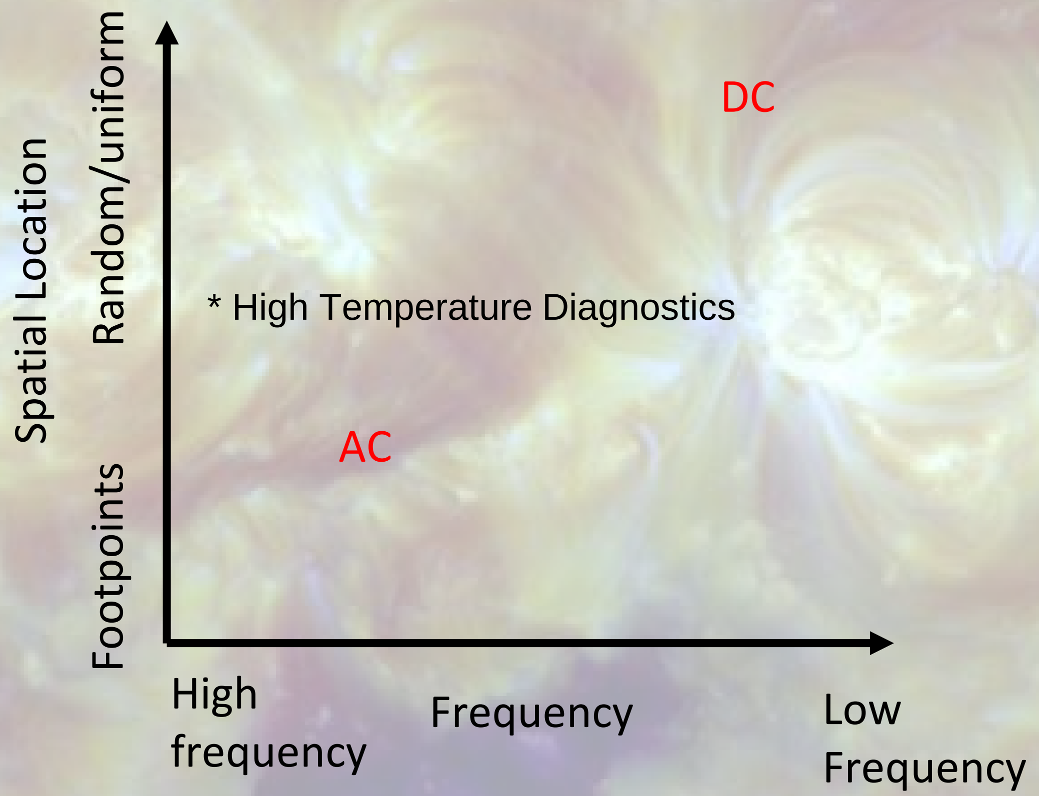
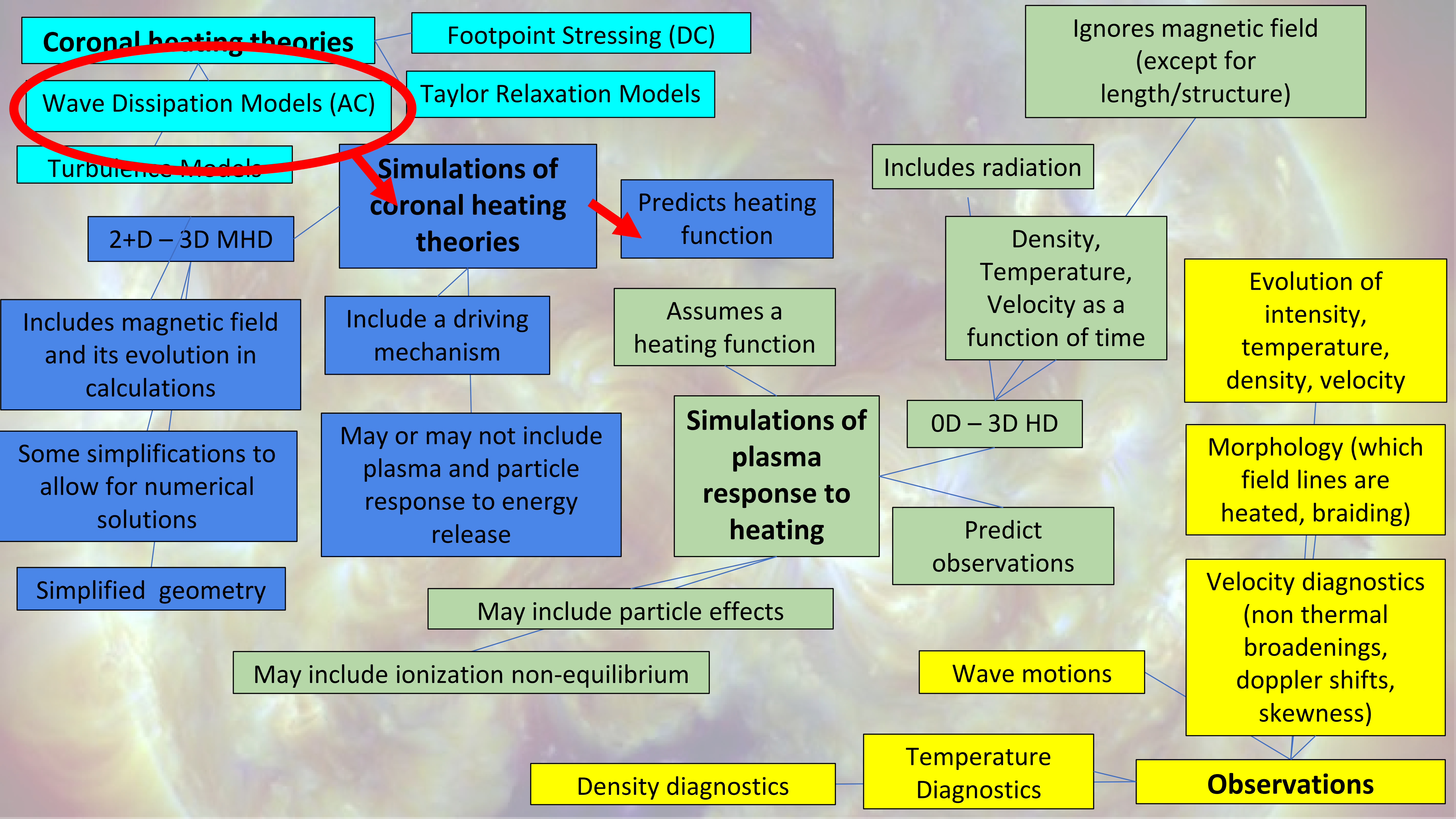
Tentative Link to Coronal Heating Theories

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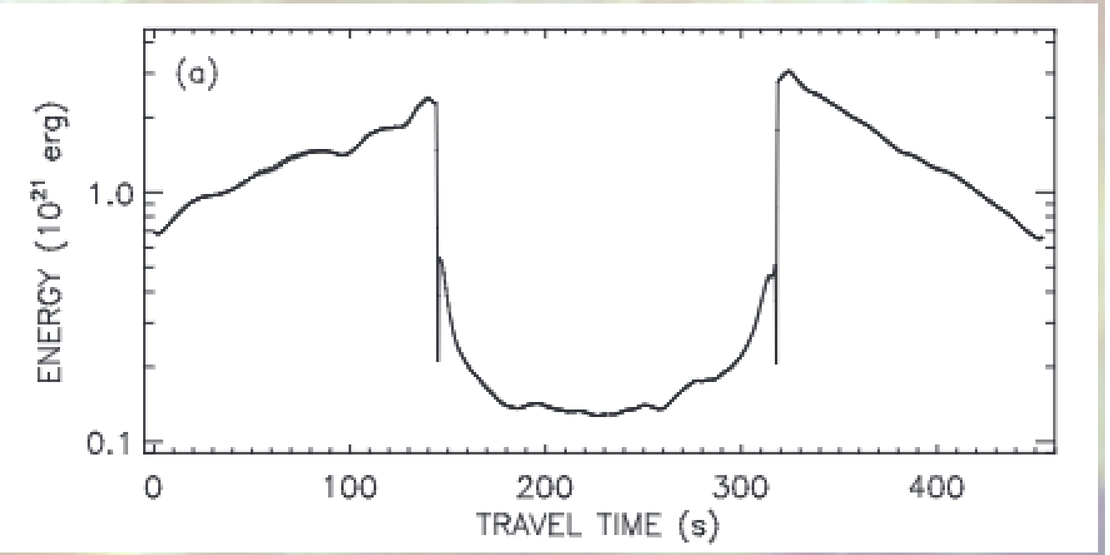
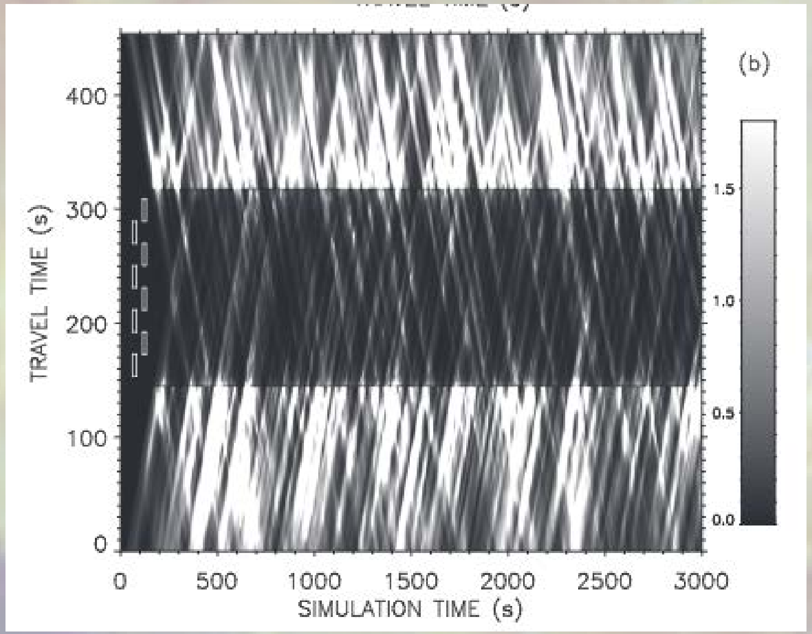
Dissipation of Alfven Waves

Series of papers that consider how Alfven waves might be dissipated to heat the corona.

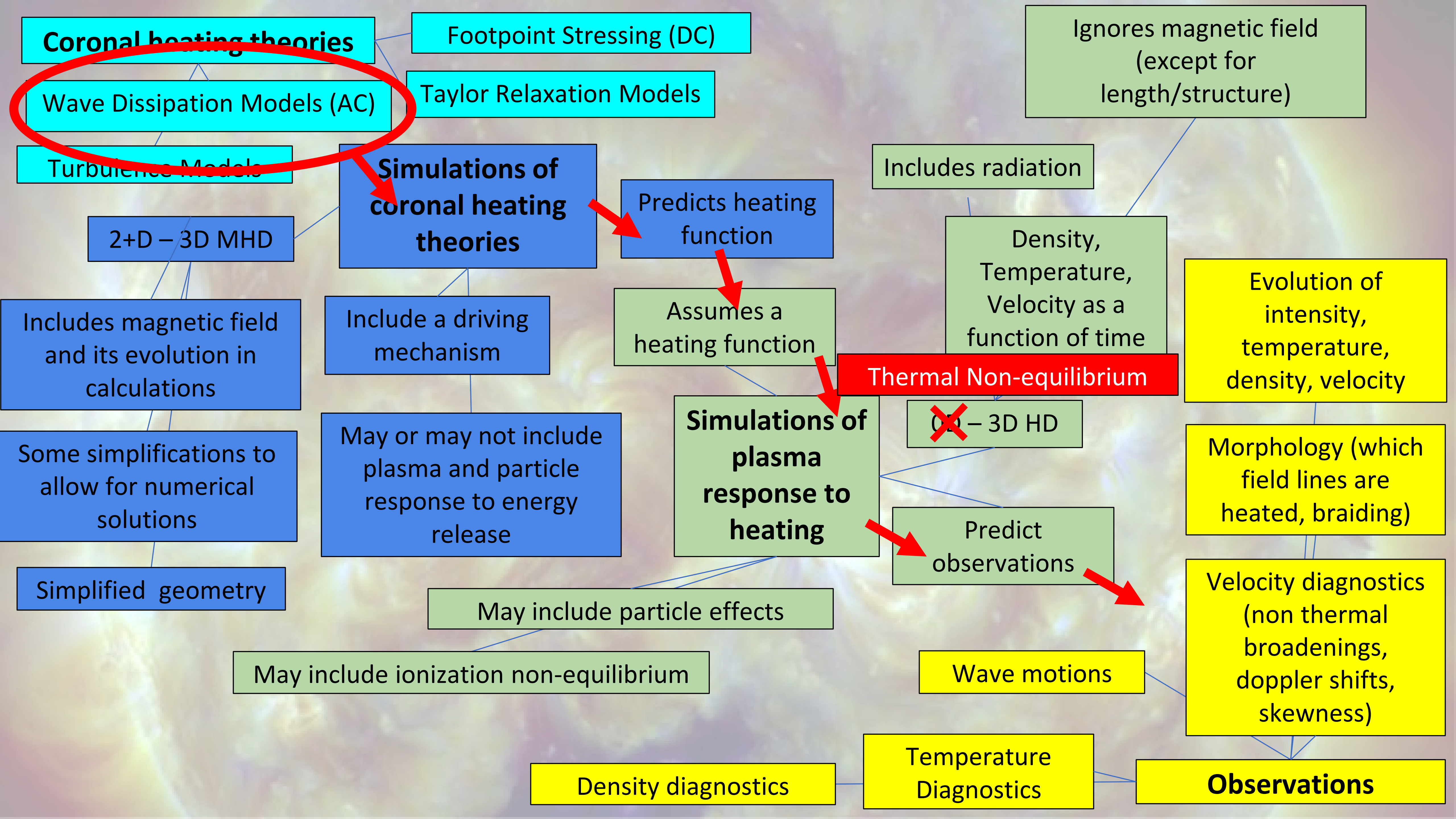
In these papers, they predict the energy release as a function of space and time.





Expectations from 3D RMHD model

Asgari-Targhi et al., ApJ, 2013, 773:111



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Observational Predictions

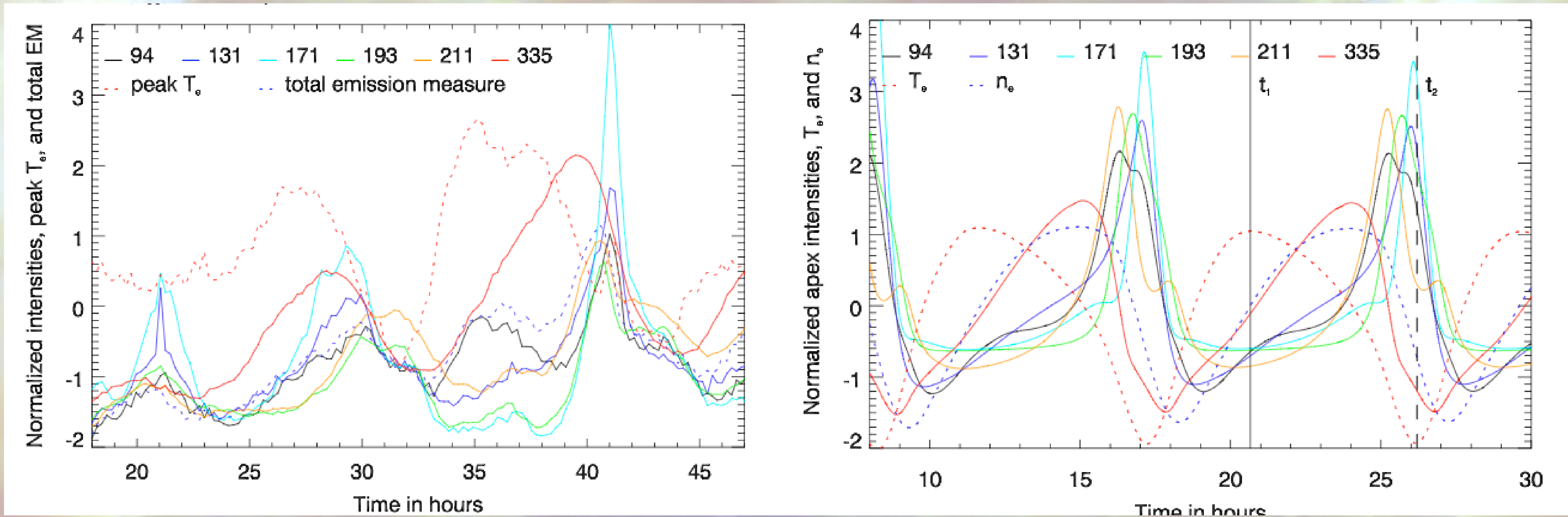
Long Term Pulsations

Coronal Rain

SlowlyEvolving Loops

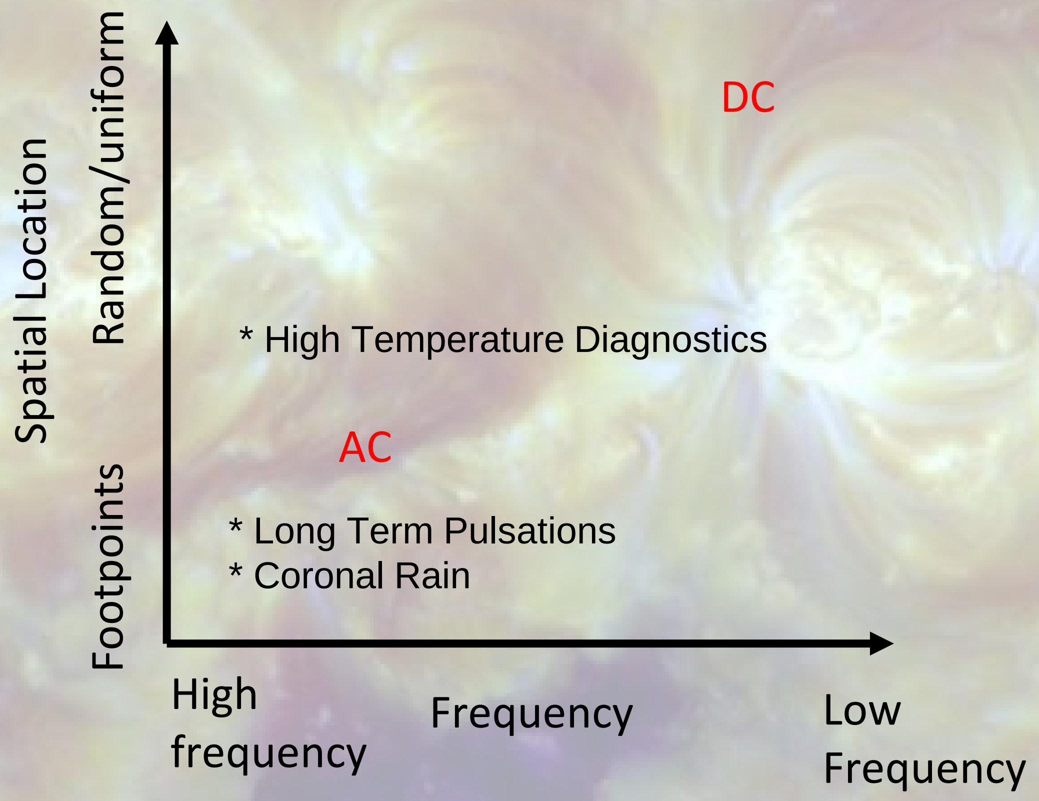
Observations

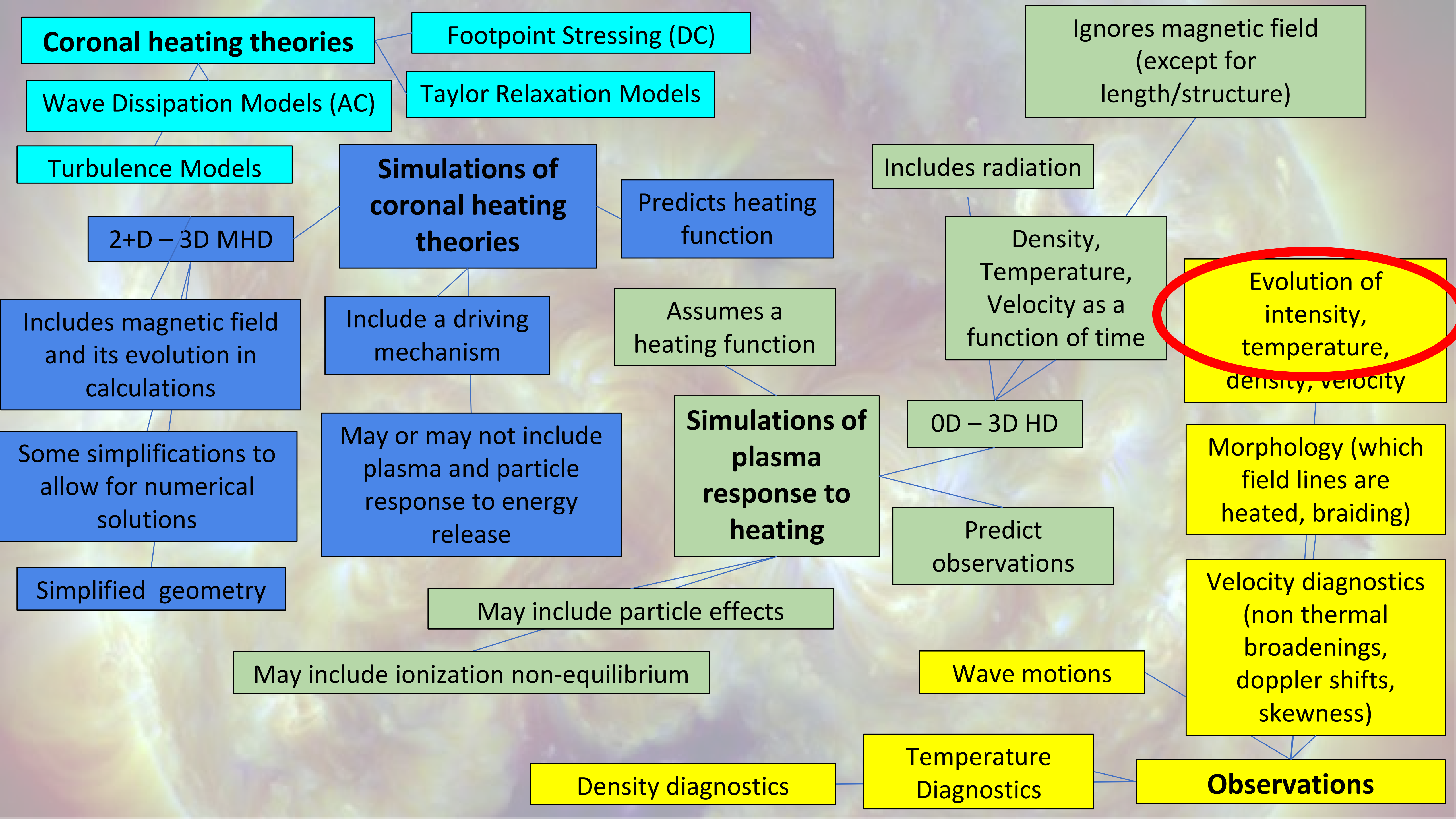
1D model



Froment, et al., ApJ, 2017, 835:272

Tentative Link to Coronal Heating Theories

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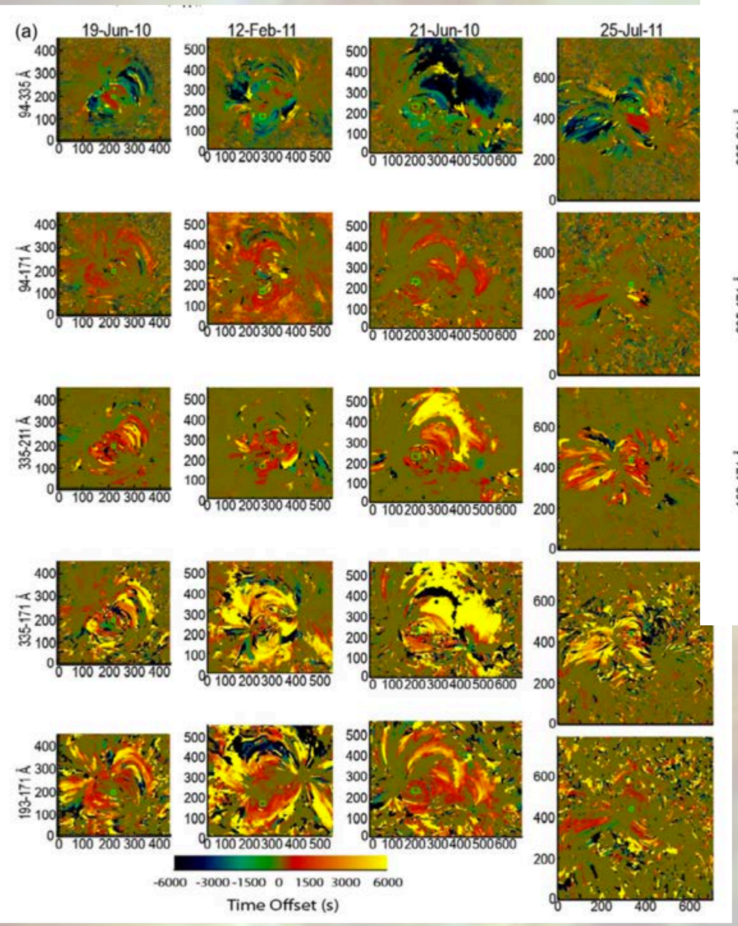
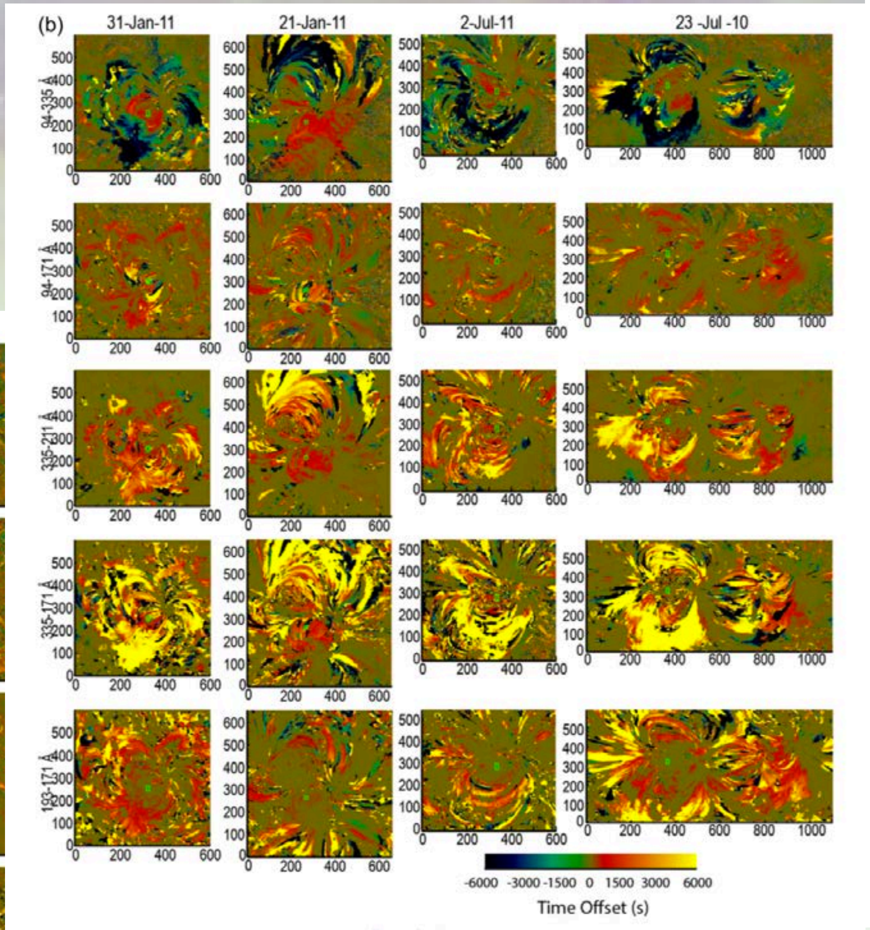
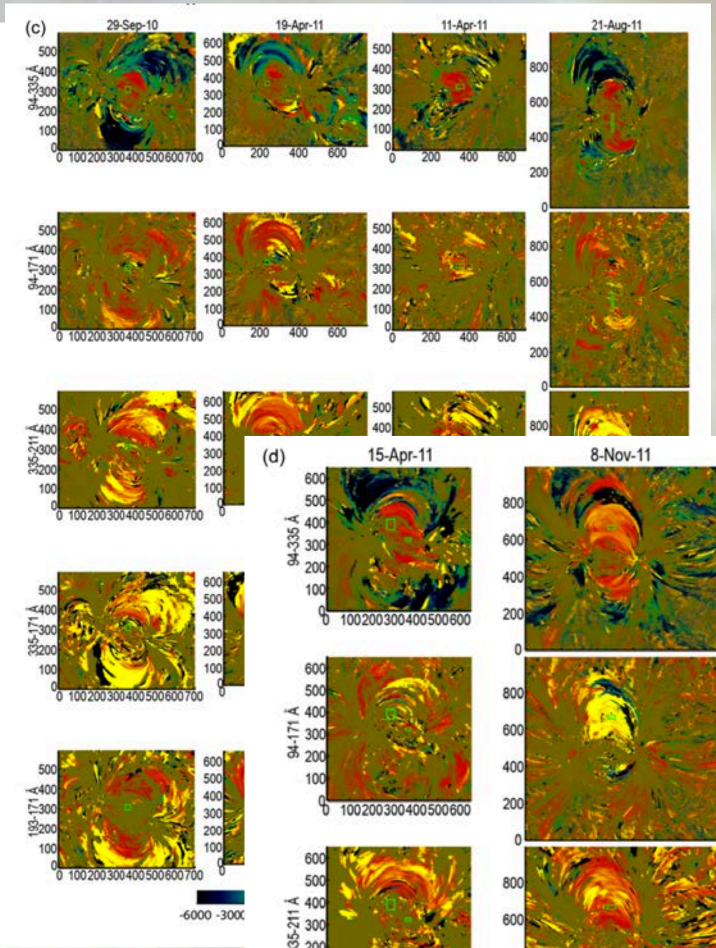
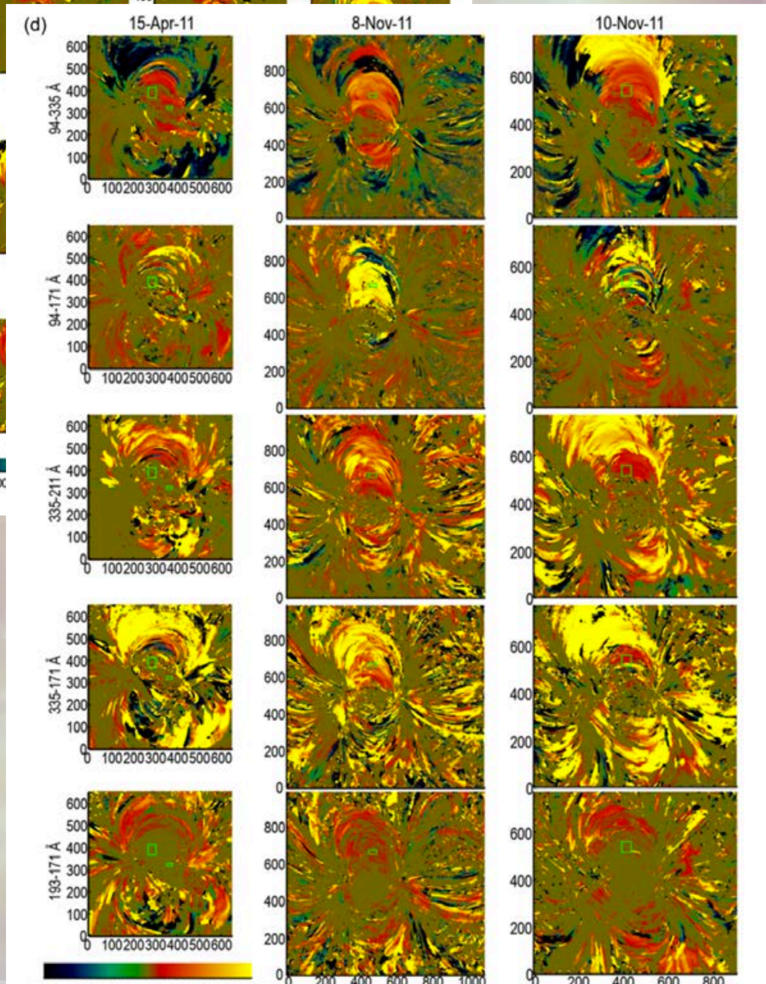
Time lags









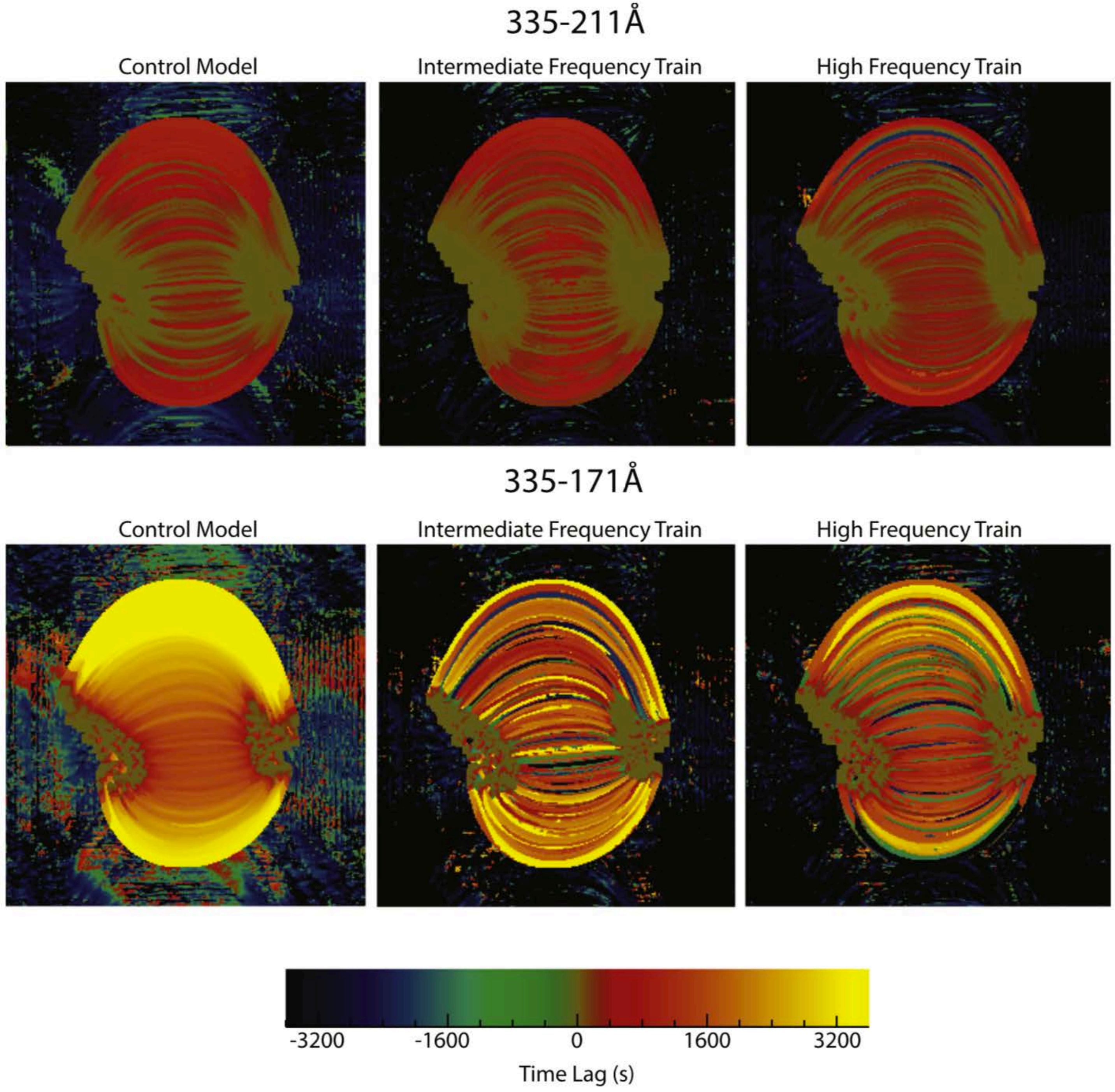
Viall & Klimchuk completed a study of the evolution of the same set of active regions studied by Warren et al. 2012.

Viall & Klimchuk, 2017, ApJ, 842, 108

Time lags

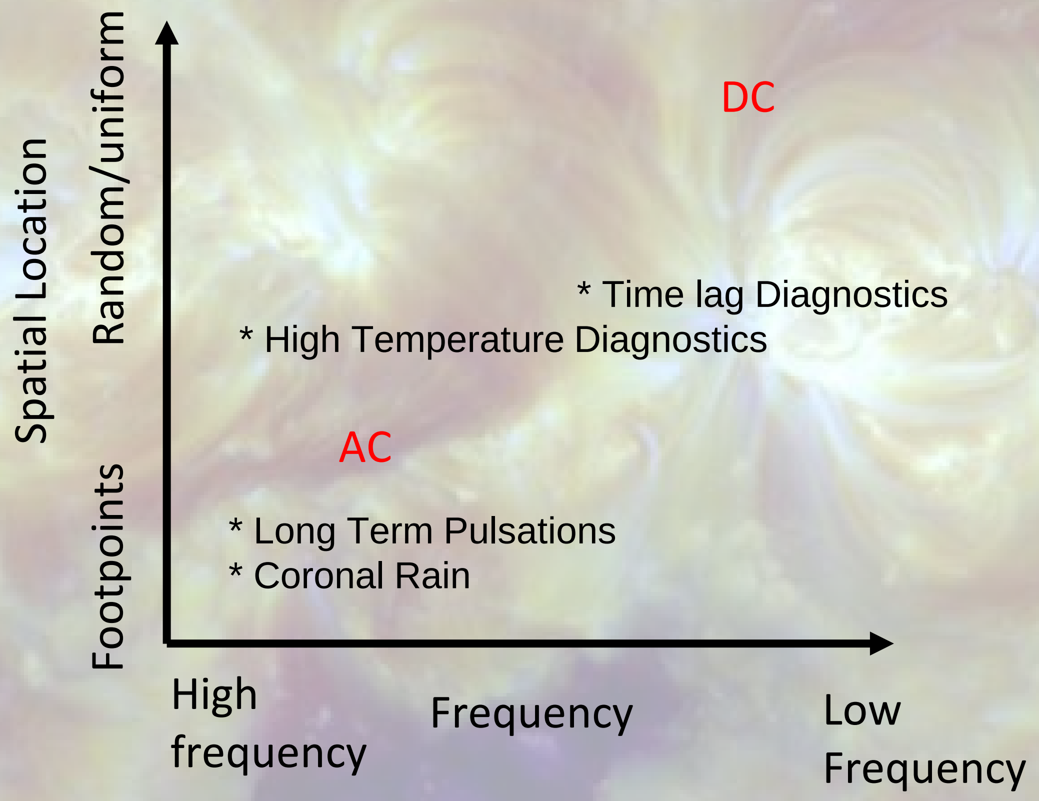
Bradshaw & Viall used ebtel to model time lag maps.

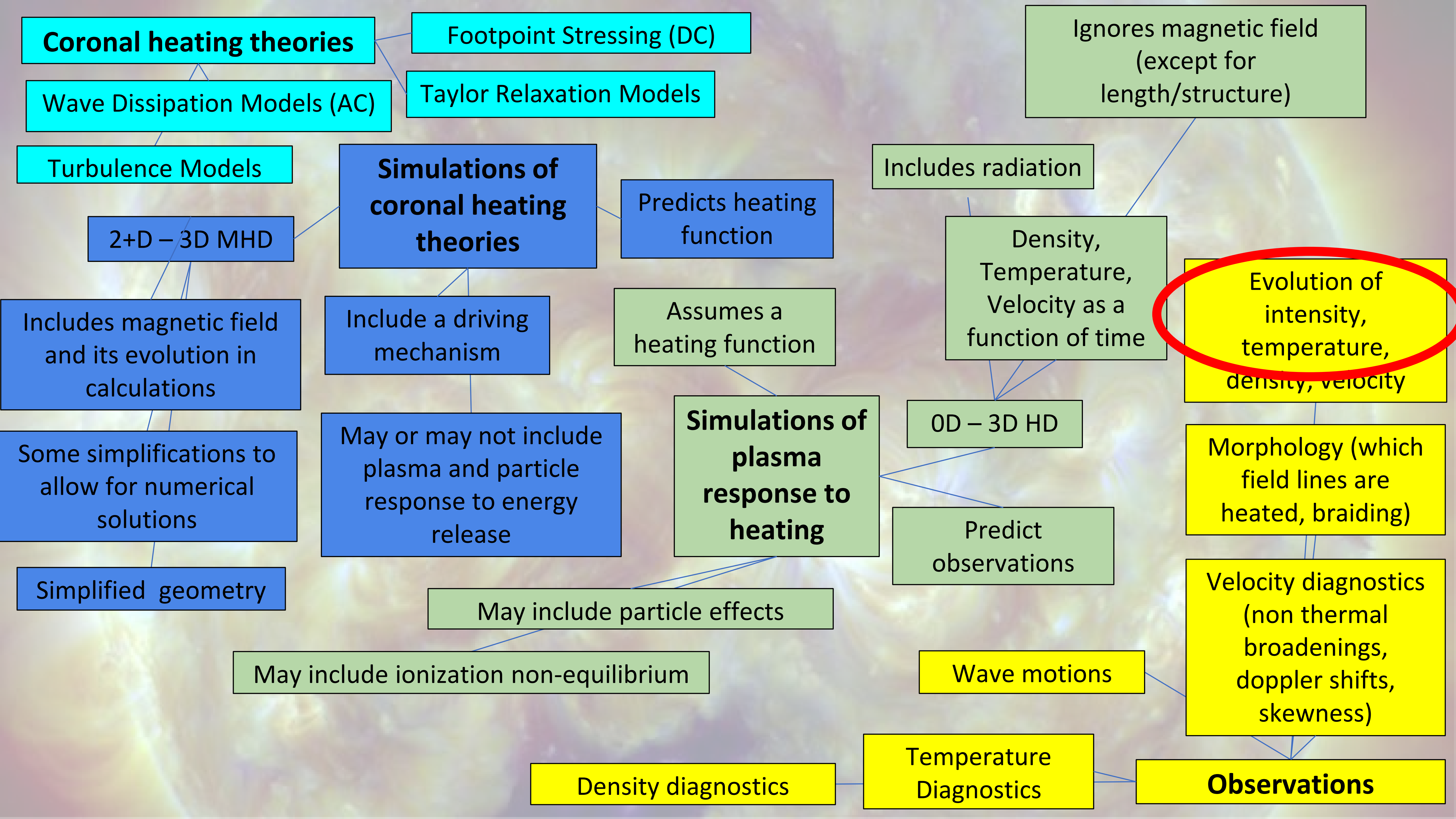
Determined intermediate or low frequency heating best matched observations.



Bradshaw & Viall, 2016, ApJ, 821, 63

Tentative Link to Coronal Heating Theories





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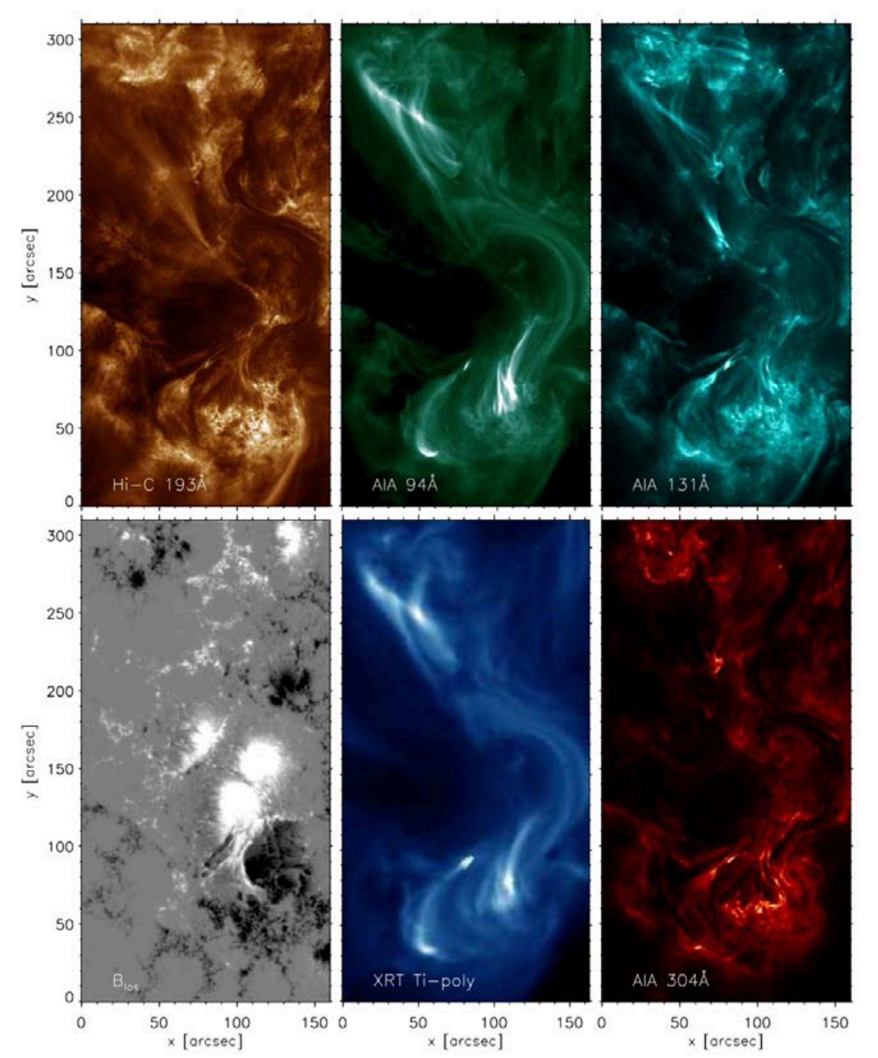
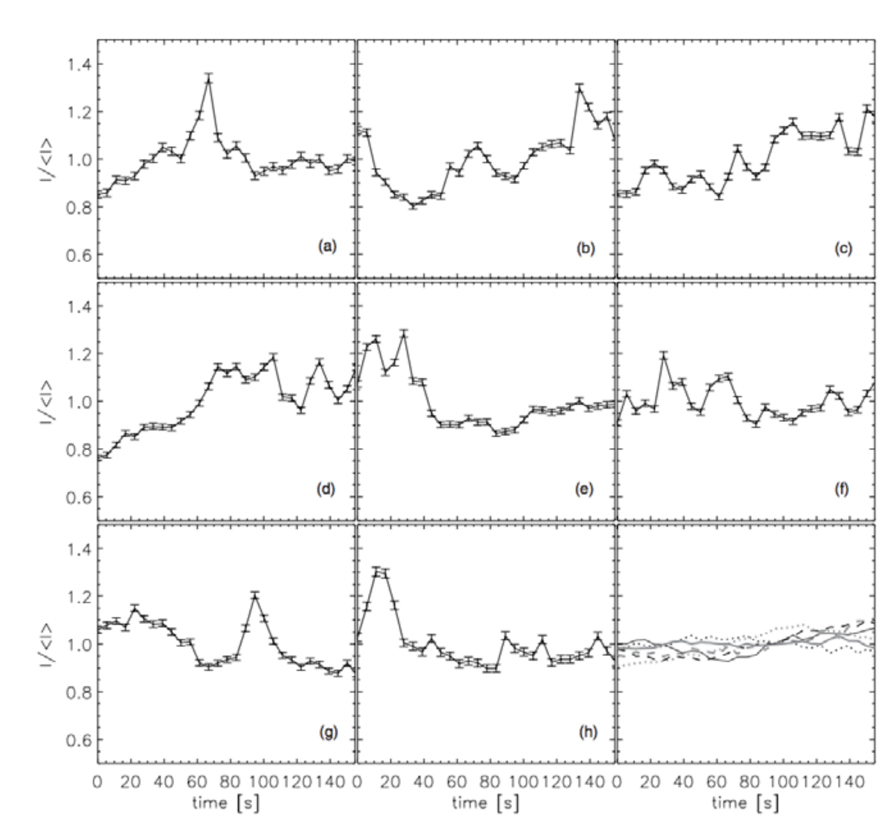
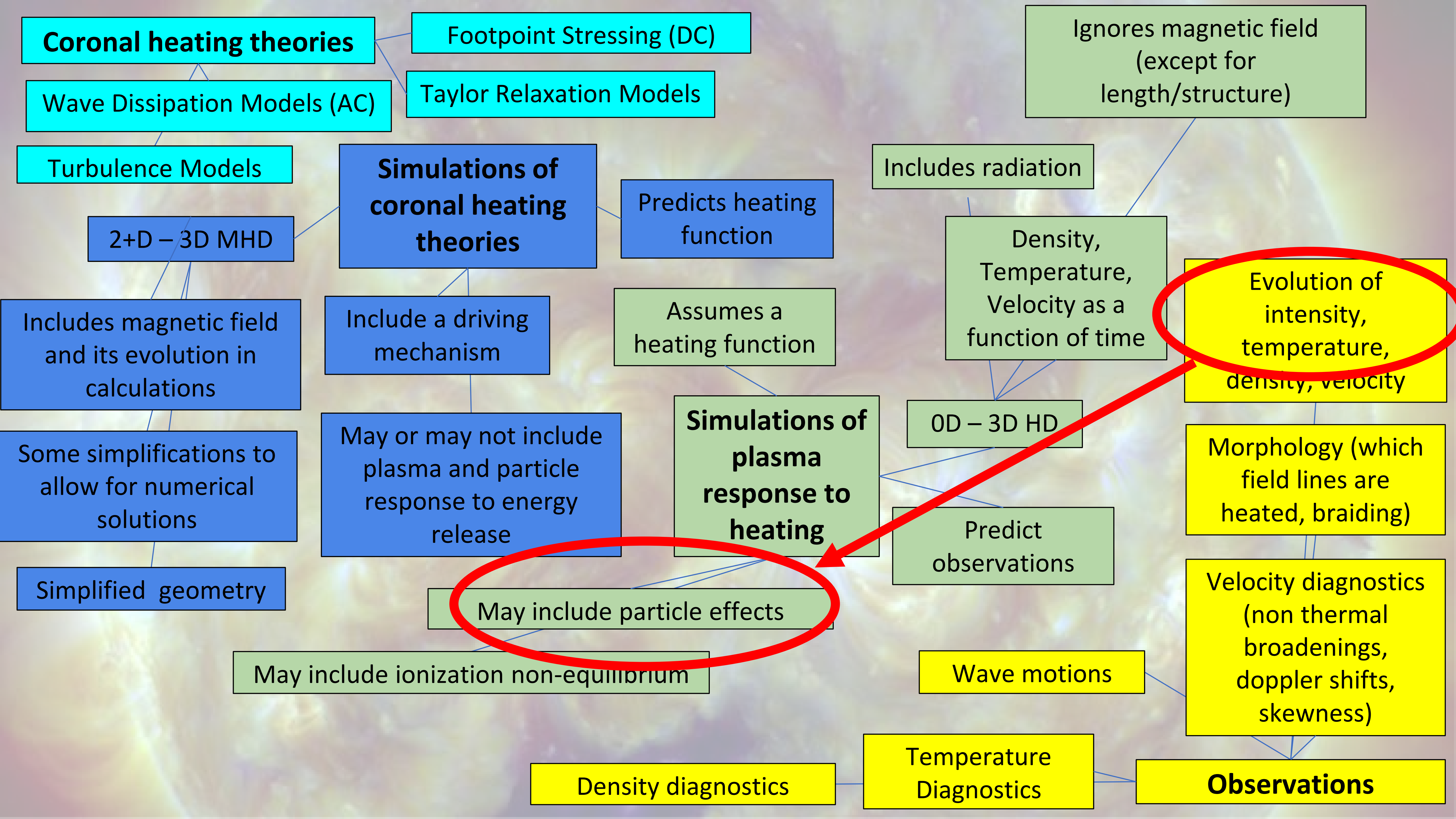
Short-lived, small-scale brightenings in the moss



Hi-C revealed short lived brightenings at the footpoints of high temperature loops.



Testa et al, 2013, ApJ, 770, L1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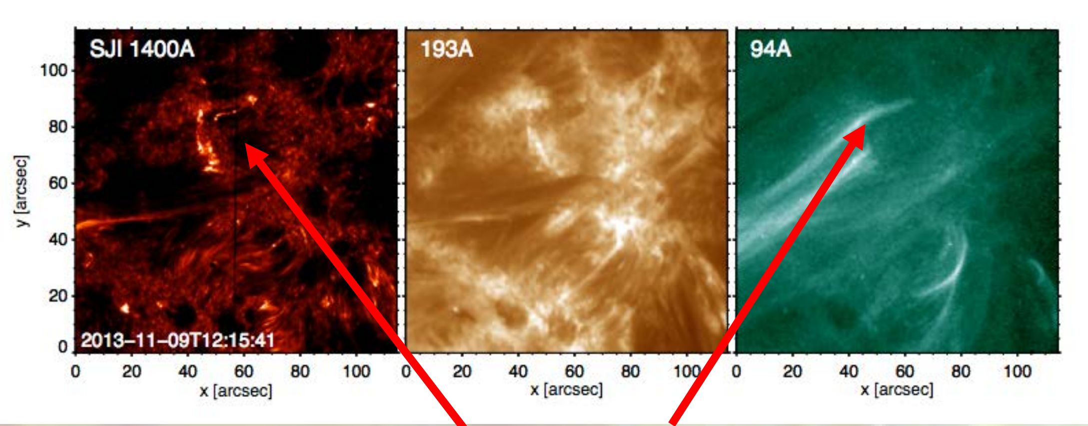
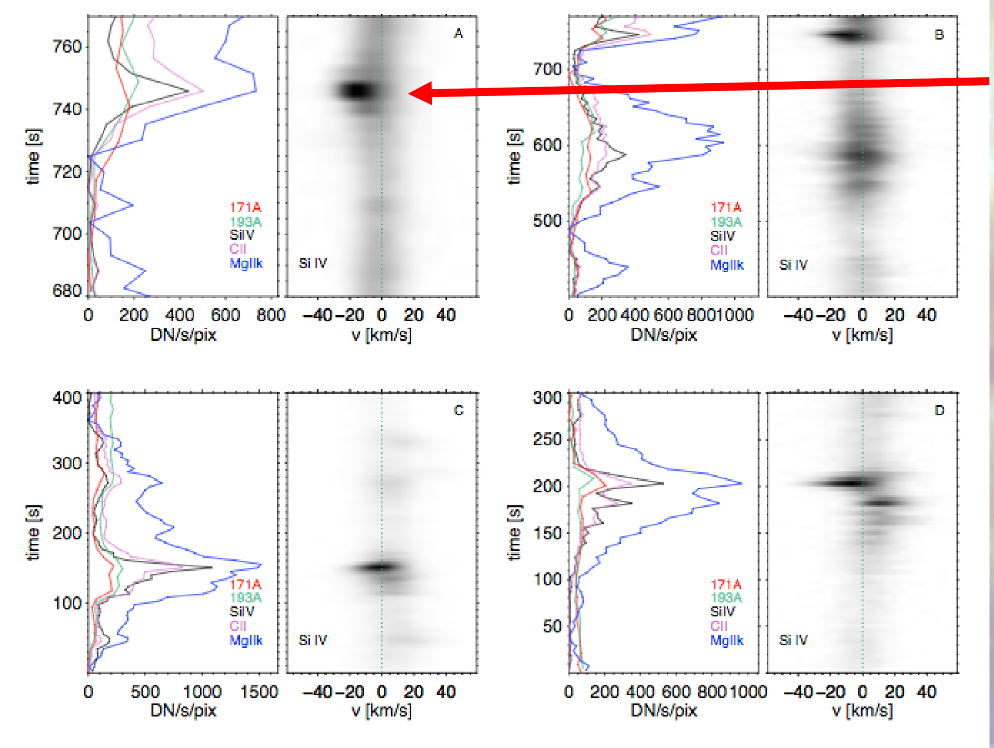
Observations supporting infrequent heating

Title: Evidence of Non-Thermal Particles in Coronal Loops Heated Impulsively by Nanoflares

Authors: P. Testa[1*], B. De Pontieu[2,3], J. Allred[4], M. Carlsson[3], F. Reale[5], A. Daw[4], V. Hansteen[3], J. Martinez-Sykora[6], W. Liu[2,7], E.E. DeLuca[1], L. Golub[1], S. McKillop[1], K. Reeves[1], S. Saar[1], H. Tian[1], J. Lemen[2], A. Title[2], P. Boerner[2], N. Hurlburt[2], T.D. Tarbell[2], J.P. Wuelser[2], L. Kleint[2,6], C. Kankelborg[8], S. Jaeggli[8]

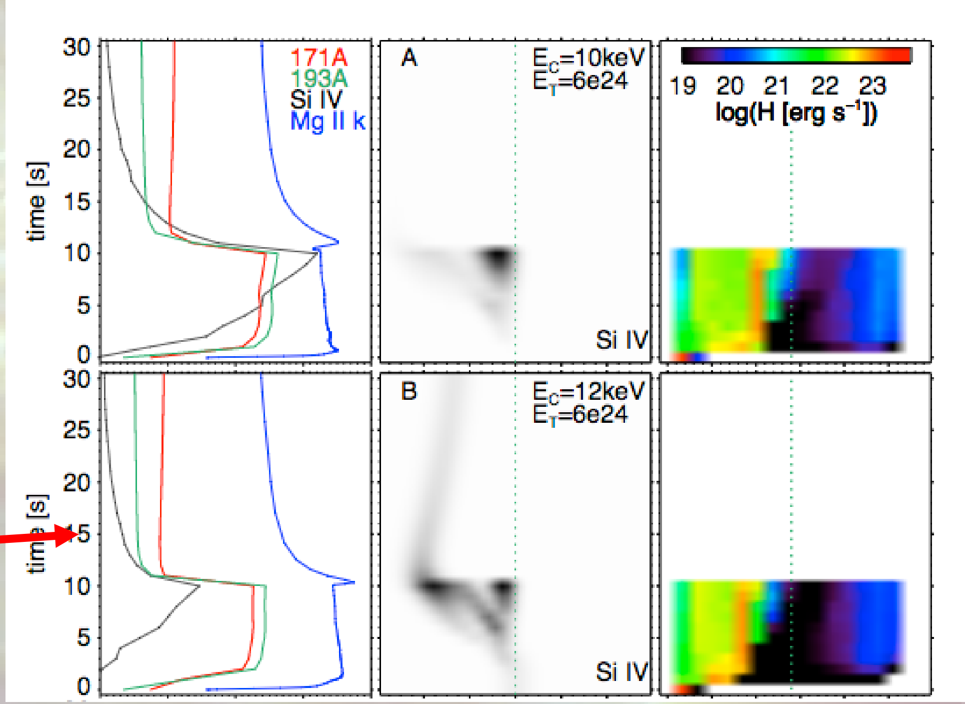




Brightenings are associated with blue shifts in Si IV.

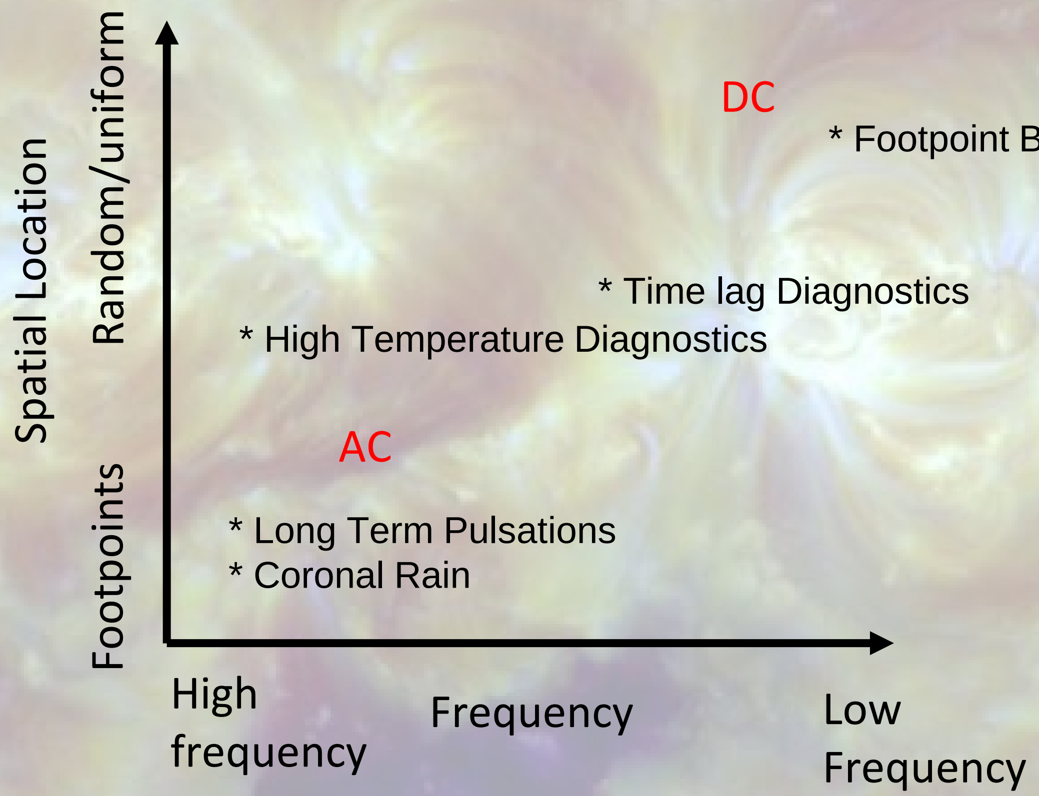
Consistent with nonthermal electron beams associated with magnetic reconnection.

Can be used to limit the models to determine heating rate and duration.



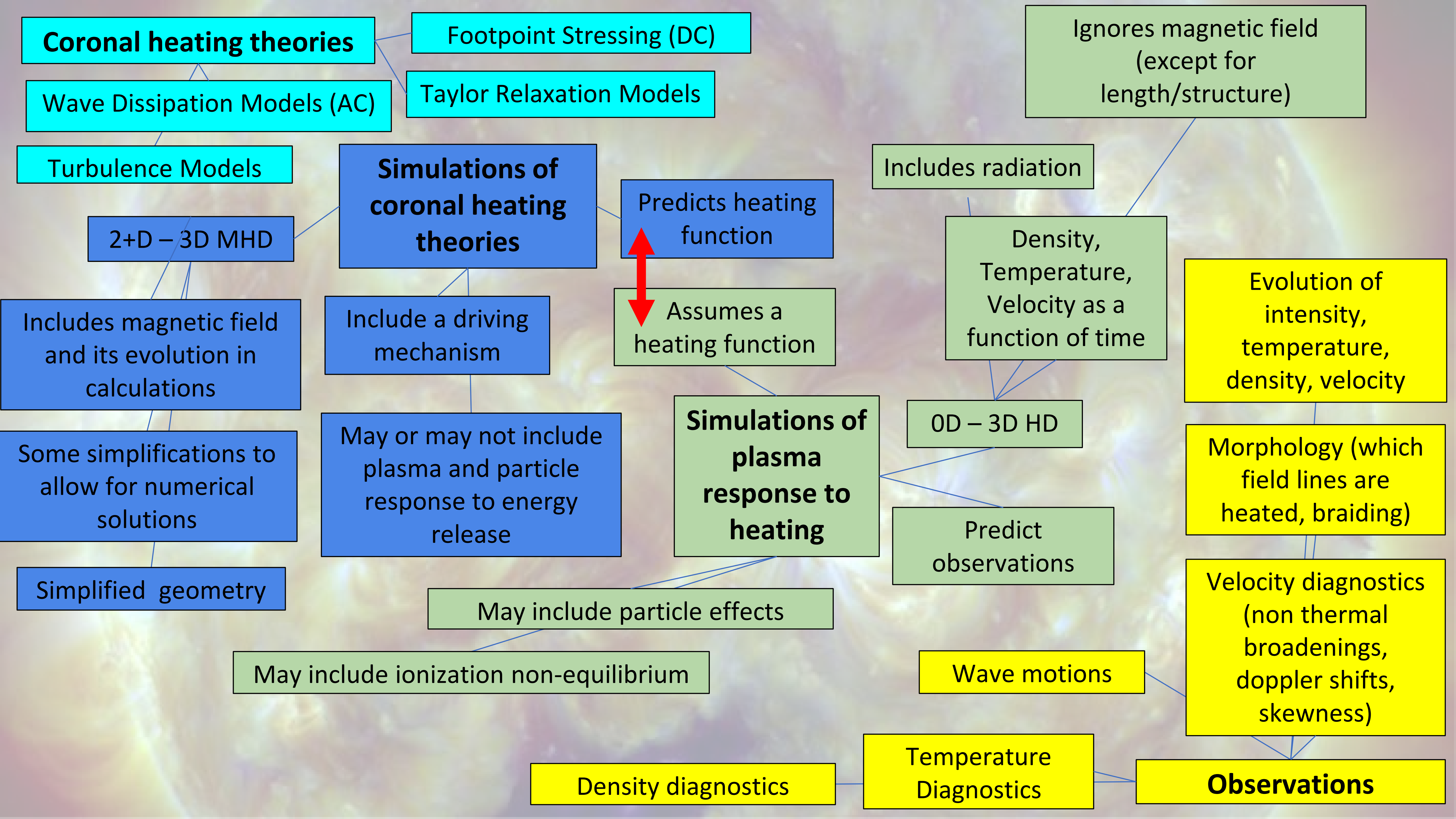
Tentative Link to Coronal Heating Theories

There is strong observational evidence for heating on multiple frequencies at multiple spatial locations.



Conclusions

- We are “hopscotching” our way toward constraining the coronal heating mechanism
- As instruments improve, so must the fidelity of the simulations
- We have made a lot of progress. There is still a long way to go!
- There needs to be better connection between the theoretical simulations and simulations of plasma response to heating.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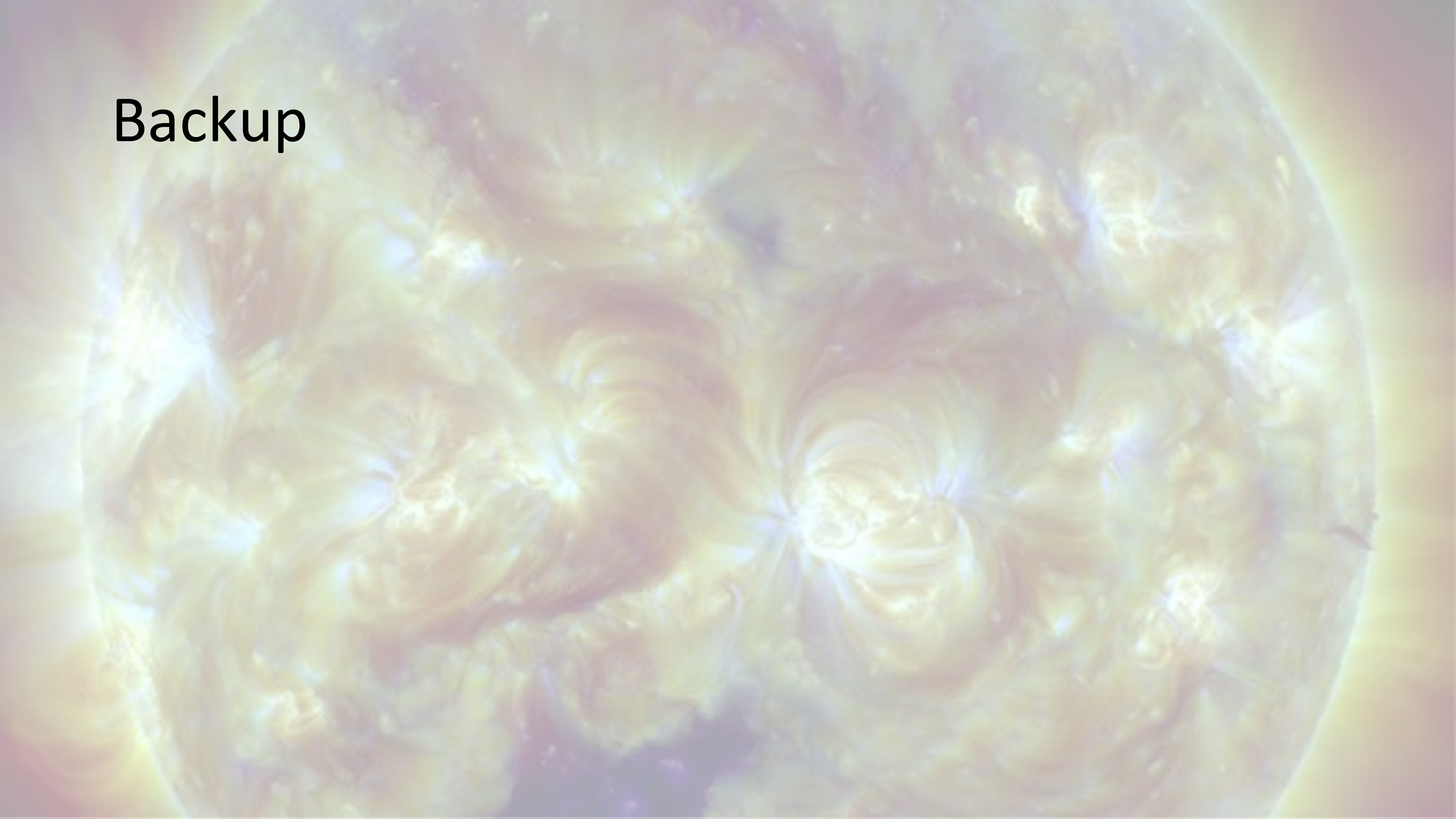
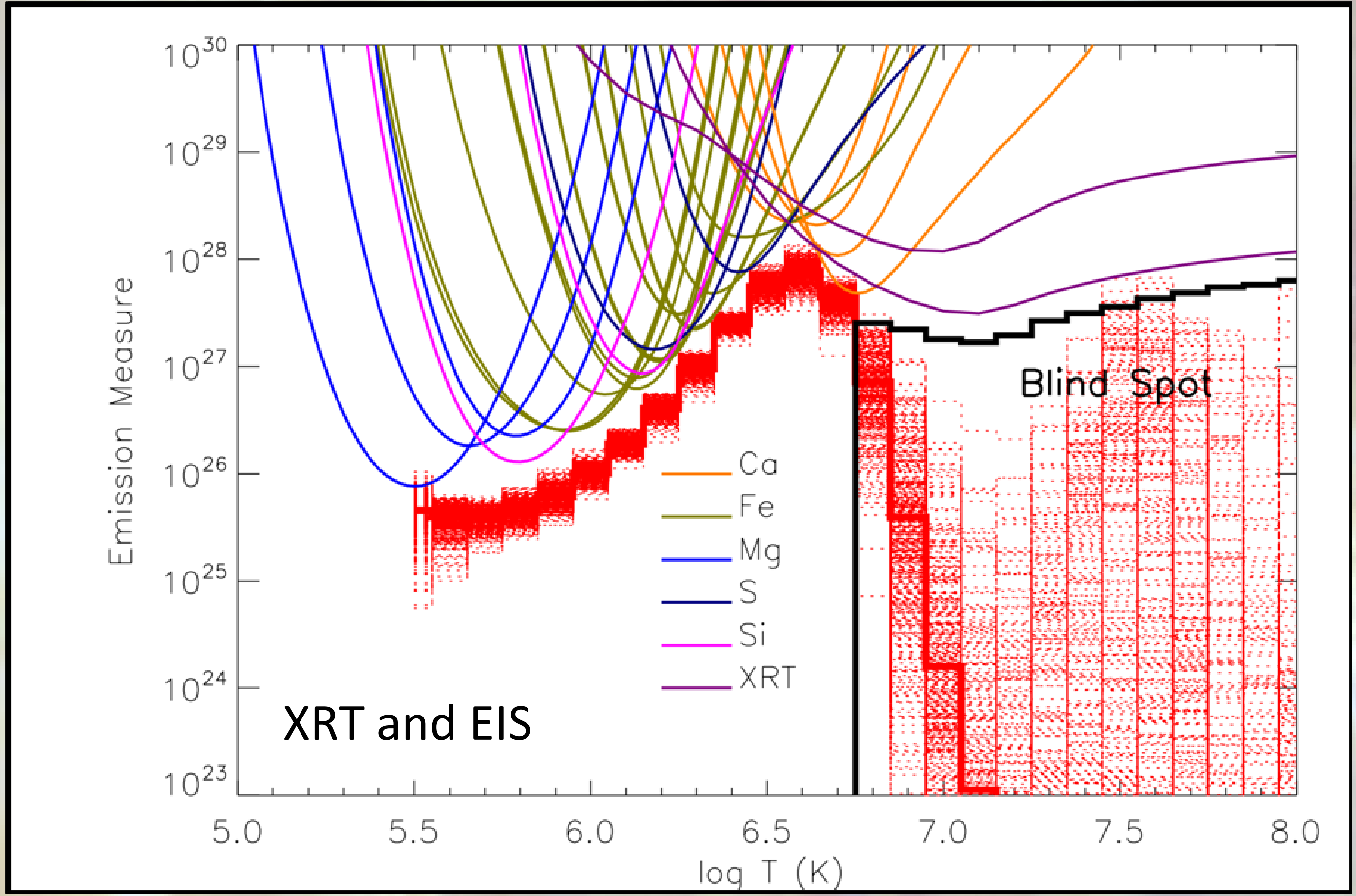
Backup



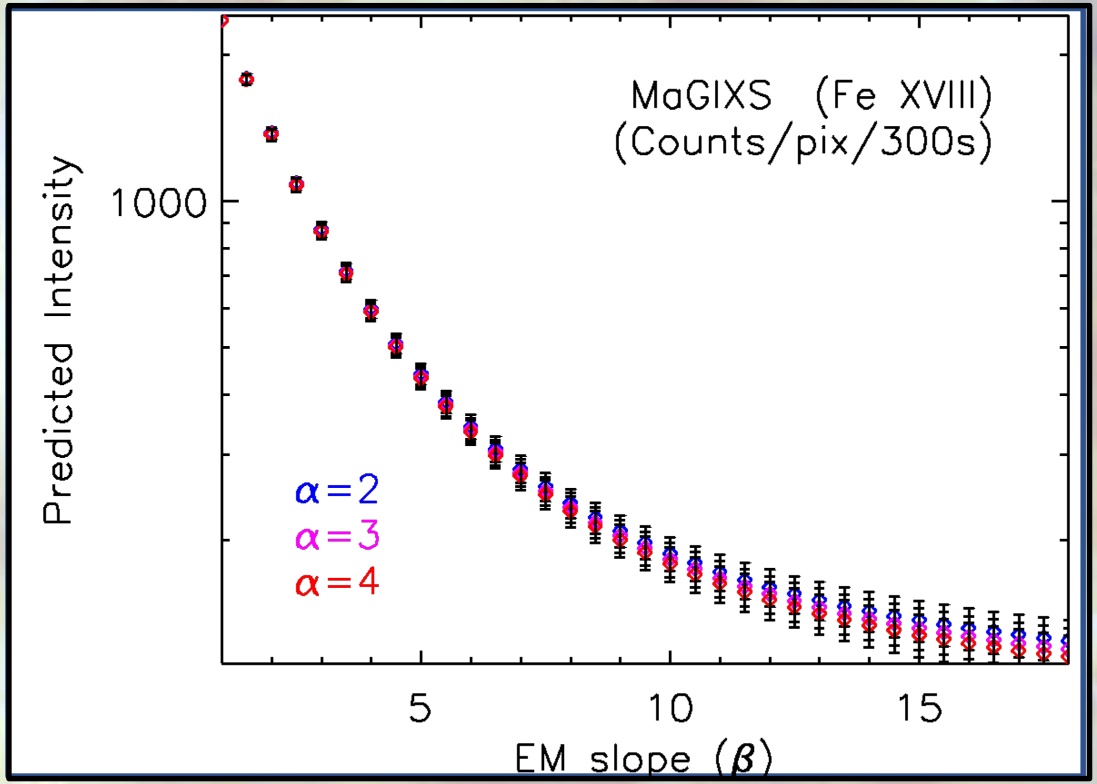
High temperature "blind spot" in Hinode

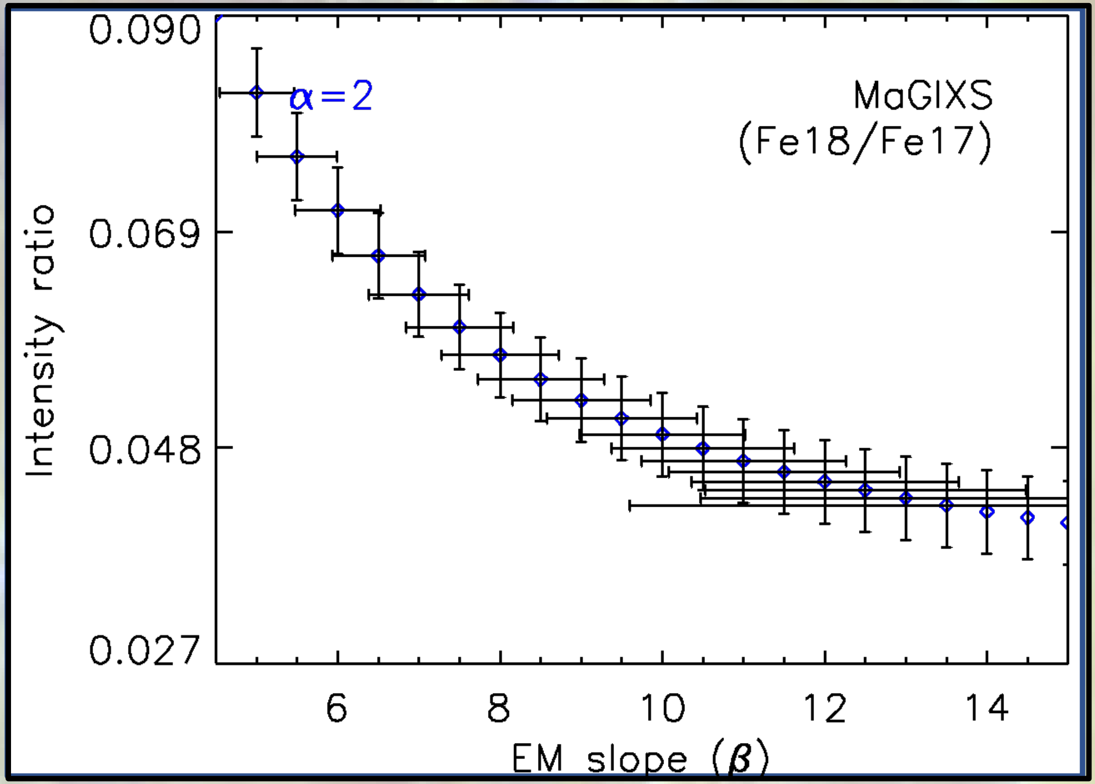


Winebarger et al 2012, ApJ, 746, L17

Two instruments are Hinode (XRT and EIS) have a blind spot at high temperatures.

Upcoming Instrument - MaGIXS





With MaGIXS measure Beta with better precision, a smaller spatial resolution and better "cross calibration."

Athiray et al, 2019, to be submitted