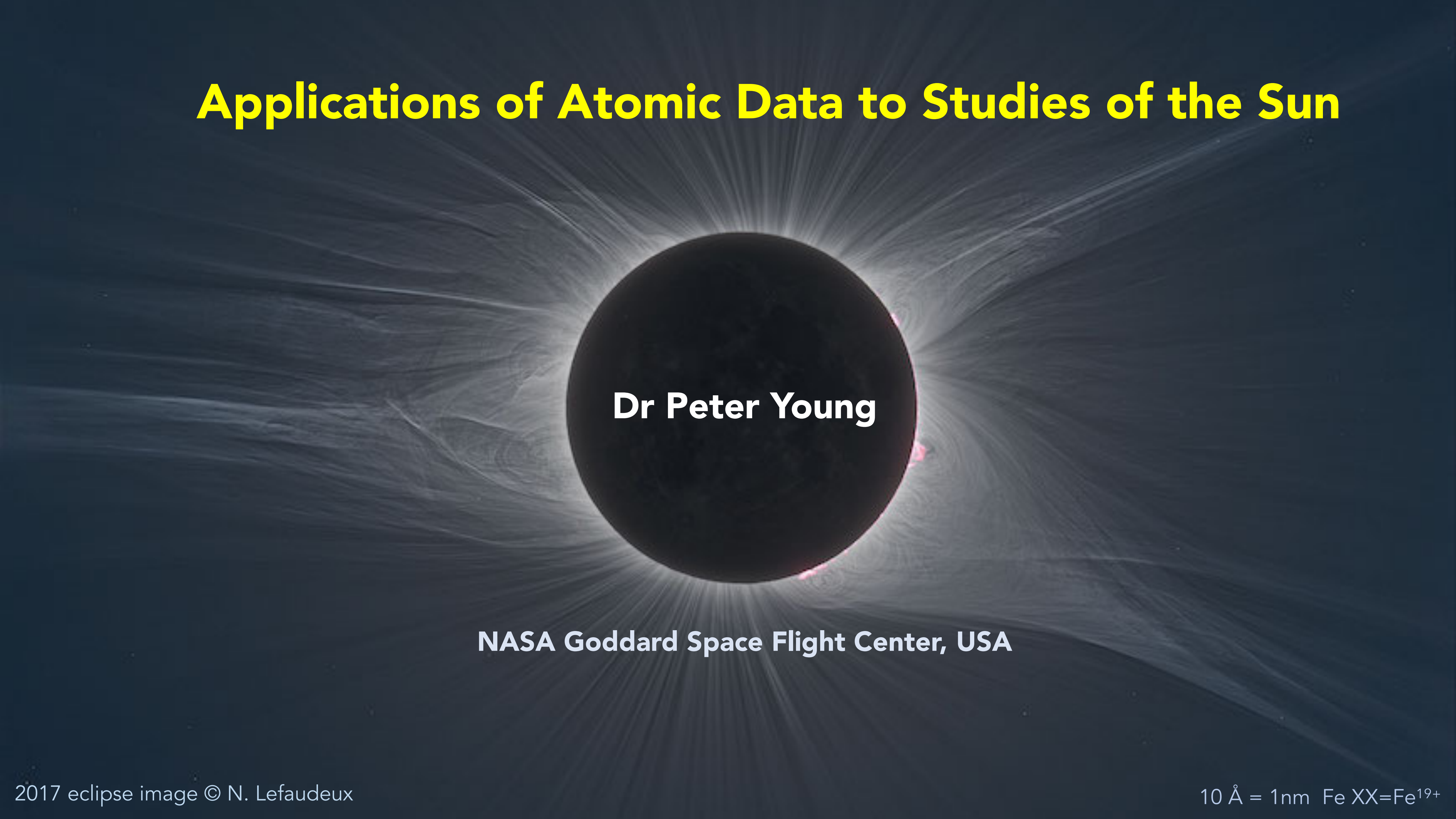


Applications of Atomic Data to Studies of the Sun

Dr Peter Young

NASA Goddard Space Flight Center, USA

2017 eclipse image © N. Lefaudeux

10 Å = 1nm Fe XX=Fe^{19+}

About Me

Career

1998: PhD, Cambridge University (UK)

1999: Harvard-Smithsonian CfA (US)

2002: Rutherford Appleton Laboratory (UK)

2008: Naval Research Laboratory (US)

2015: NASA Goddard (US)

Interests:

- UV/EUV spectroscopy
- CHIANTI atomic database
- Solar atmosphere
- Missions: SOHO, *Hinode*, SDO, IRIS, Solar Orbiter

Solar Physics Demographics

No. of researchers: 1560
No. of countries: 49

Country	Researchers
USA	30%
China	14%
UK	8%
Italy	6%
Germany	5%
ESA member states	40%

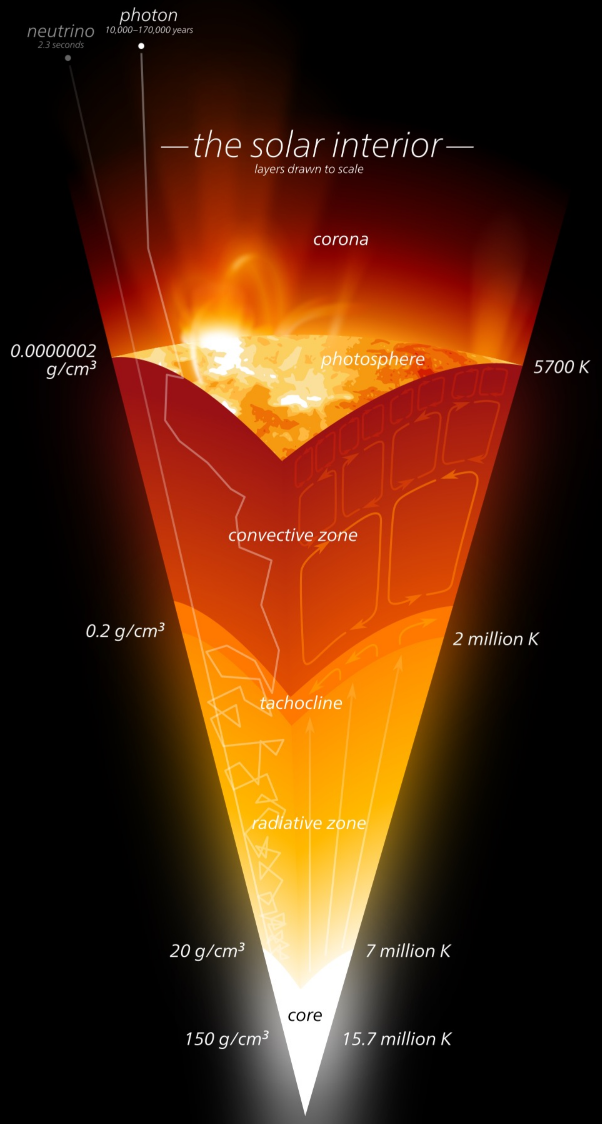
Motivations for atomic data in Solar Physics

1. Solar interior

- Sun is a reference object for Astrophysics
- For example, stellar structure, stellar dynamos, element abundances

2. Dynamic solar atmosphere

- Features dynamic events such as flares and CMEs that can impact Earth
- Main driver for new spacecraft and observatories



10 Å = 1nm Fe XX=Fe^{19+}

NASA space missions are a major driver for Solar Physics

Space-based observatories:

- NASA (US): SDO, STEREO, IRIS, Parker Solar Probe, EUVST, MUSE, PUNCH
- NOAA (US): GOES
- ESA: SOHO, Solar Orbiter, Vigil
- Japan: Hinode, Solar-C
- China: ASO-S
- India: Aditya-L1

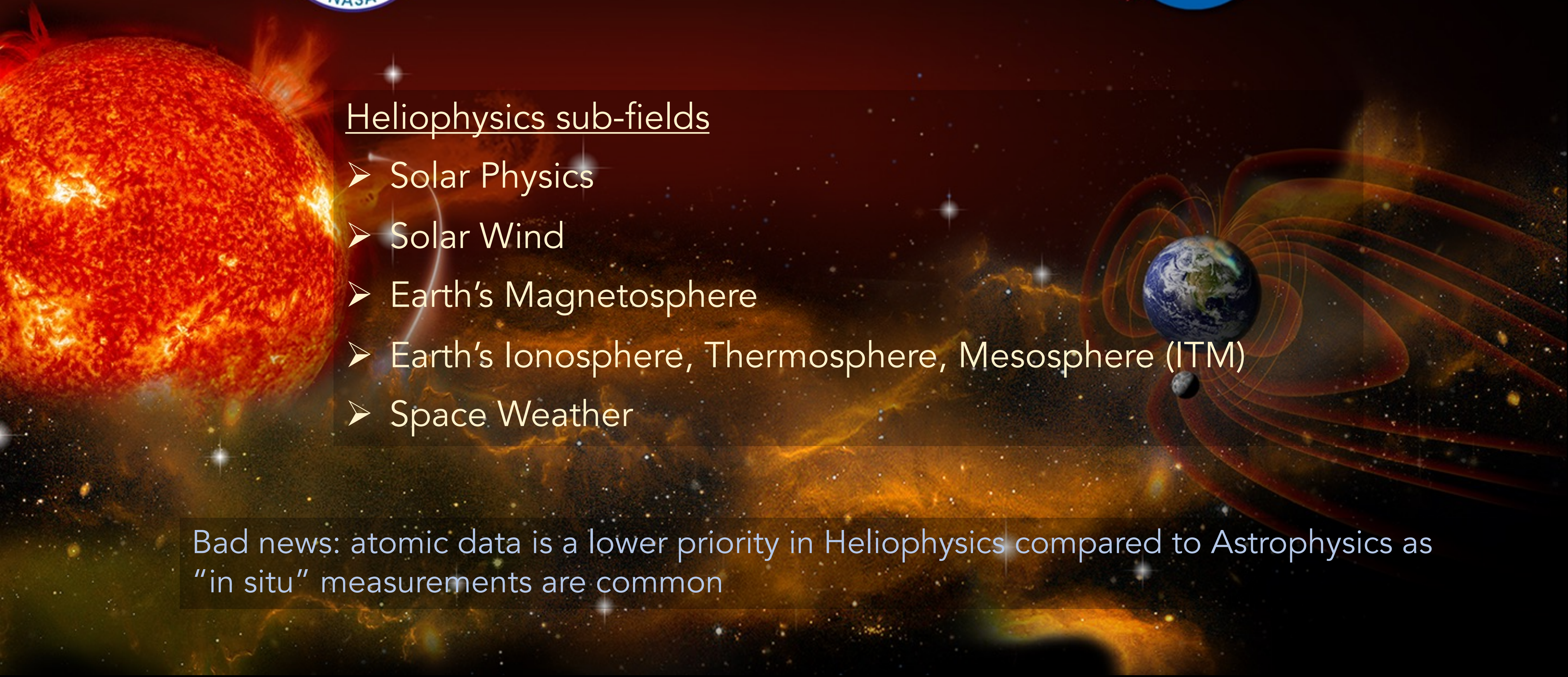
Underlined – NASA major contributor

Blue – missions in development

Structure of science at NASA

- Science Mission Directorate (SMD) [$7.8B]
  - Earth Science [$2.2B]
  - Planetary [$3.2B]
  - Astrophysics [$1.5B]
  - **Heliophysics [$0.8B]**

Good news: Solar Physics is "protected" within the SMD Heliophysics Division



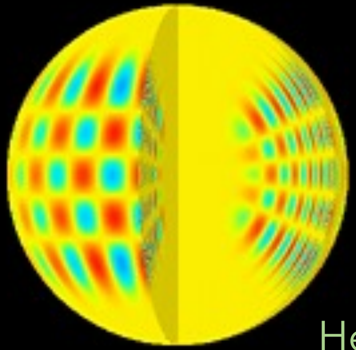
Heliophysics sub-fields

- Solar Physics
- Solar Wind
- Earth’s Magnetosphere
- Earth’s Ionosphere, Thermosphere, Mesosphere (ITM)
- Space Weather

Bad news: atomic data is a lower priority in Heliophysics compared to Astrophysics as “in situ” measurements are common

Observing the solar interior

- Mostly done through ground-based observatories
- Helioseismology: oscillations of photospheric absorption lines (visible)
- Photospheric element abundances (visible absorption lines)
- Neutrino flux measurements



Helioseismology – studies of solar oscillations

DKIST observatory Hawaii

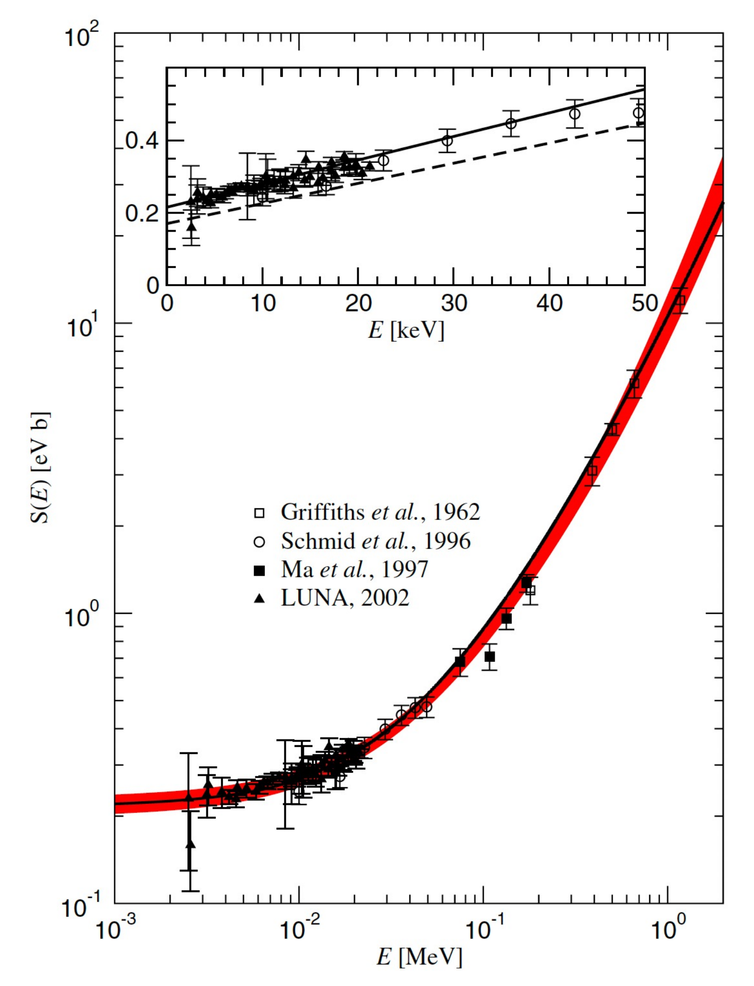
Solar interior: the “solar problem” remains

- The Standard Solar Model (SSM) disagrees with helioseismology measurements
- Improved photospheric abundance measurements (C, N, O) in the 2000’s wrecked the previous good agreement

Solar interior 1: nuclear reactions

Nuclear cross-sections

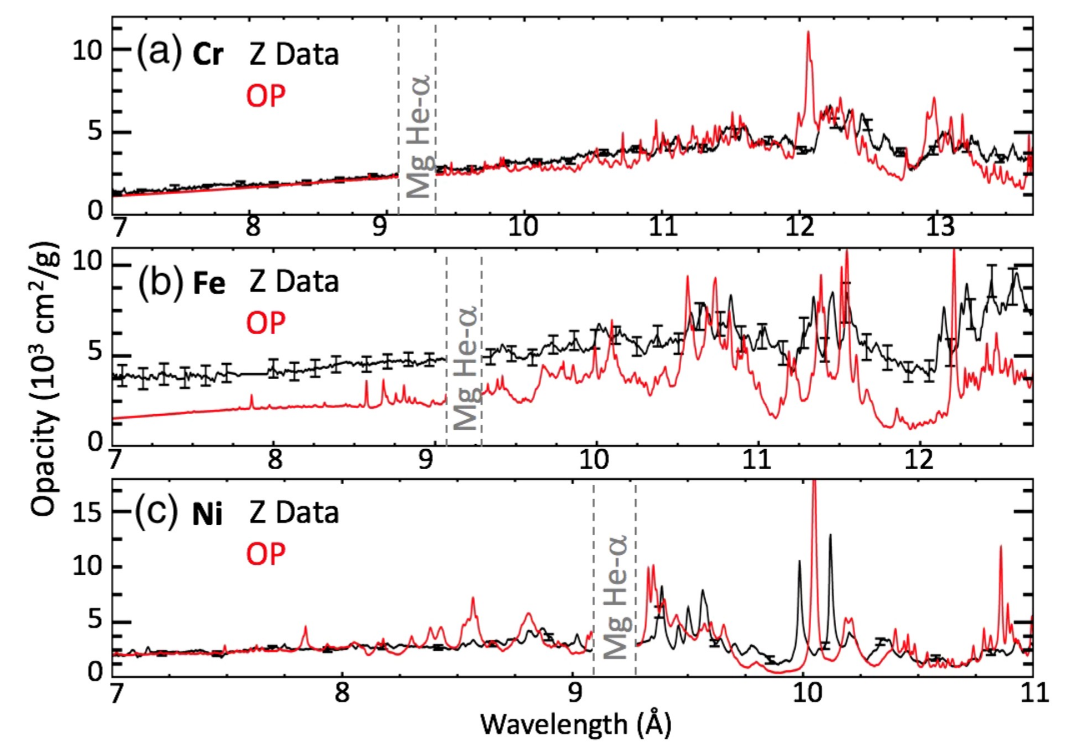
- p-p chain and CNO bicycle
- Lab measurements generally at higher energies than required
- Theory used to obtain cross-section variation with energy



Adelberger et al.
(2011, Rev. Mod. Phys.)

Solar interior 2: opacity

- Increased opacities can resolve the solar problem
- Opacity Project and OPAL theoretical opacities are in good agreement [Badnell et al. 2005]
- Lab measurements of identified problem with Fe at 2 MK [Bailey et al., 2015, *Nature*]
- Theoretical investigations underway [see Delahaye talk]

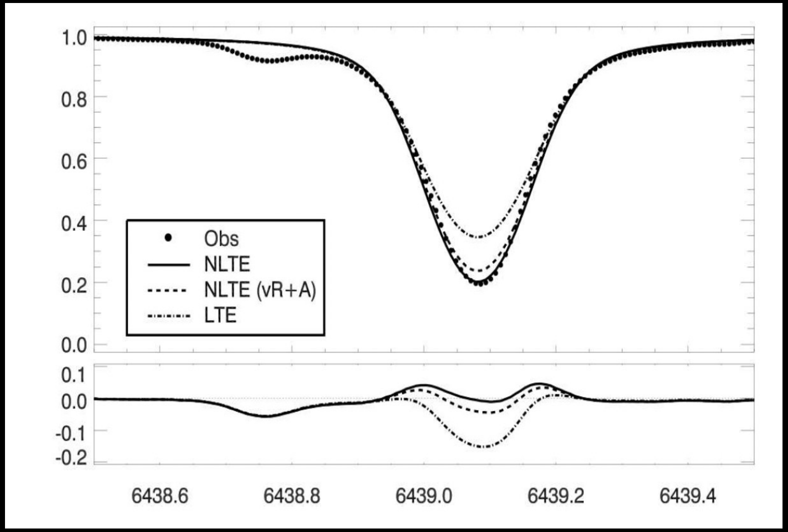


Nagayama et al. (2019, PRL)

10 Å = 1nm Fe XX=Fe^{19+}

Solar interior 3: element abundances

- Abundances obtained by fitting absorption profiles in photospheric spectrum
- Non-LTE modeling requires
  - Landé factors
  - Broadening parameters (radiative, Stark, Van der Waals)
  - Continuum data
  - Collision data (hydrogen, electron)
- Multi-ion models: neutral+singly-ionized[+doubly-ionized]
- Multi-element models may be needed [Osorio et al. 2020, A&A]
- See Amarsi talk



Allende Prieto (2020, JApA)

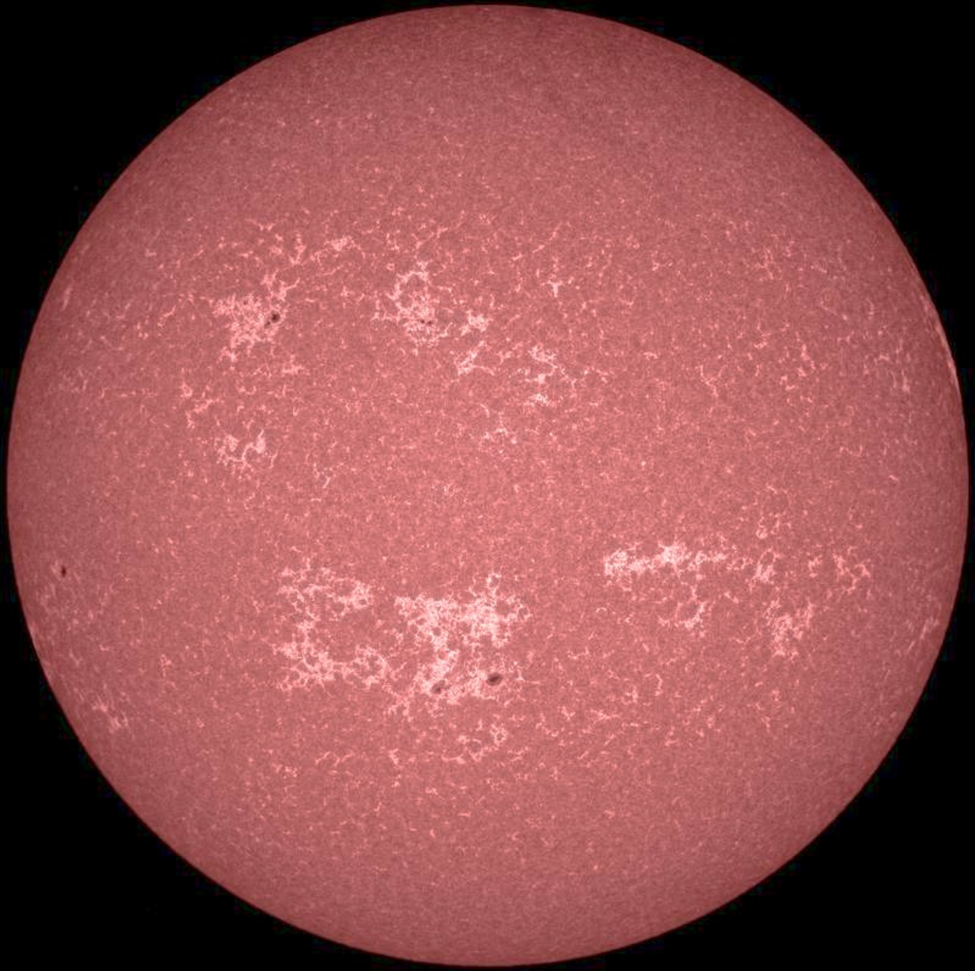
Solar atmosphere structure

Region	Temperature	Ion species	Wavelengths
Photosphere	5700 K	Neutral, +1	Visible
Chromosphere	10,000 K	Neutral, +1, +2	Visible, near-UV
Transition region	20 - 800 kK	+2 to +7	Far-UV, EUV
Corona	1 – 20 MK	+8 to bare	EUV, X-ray

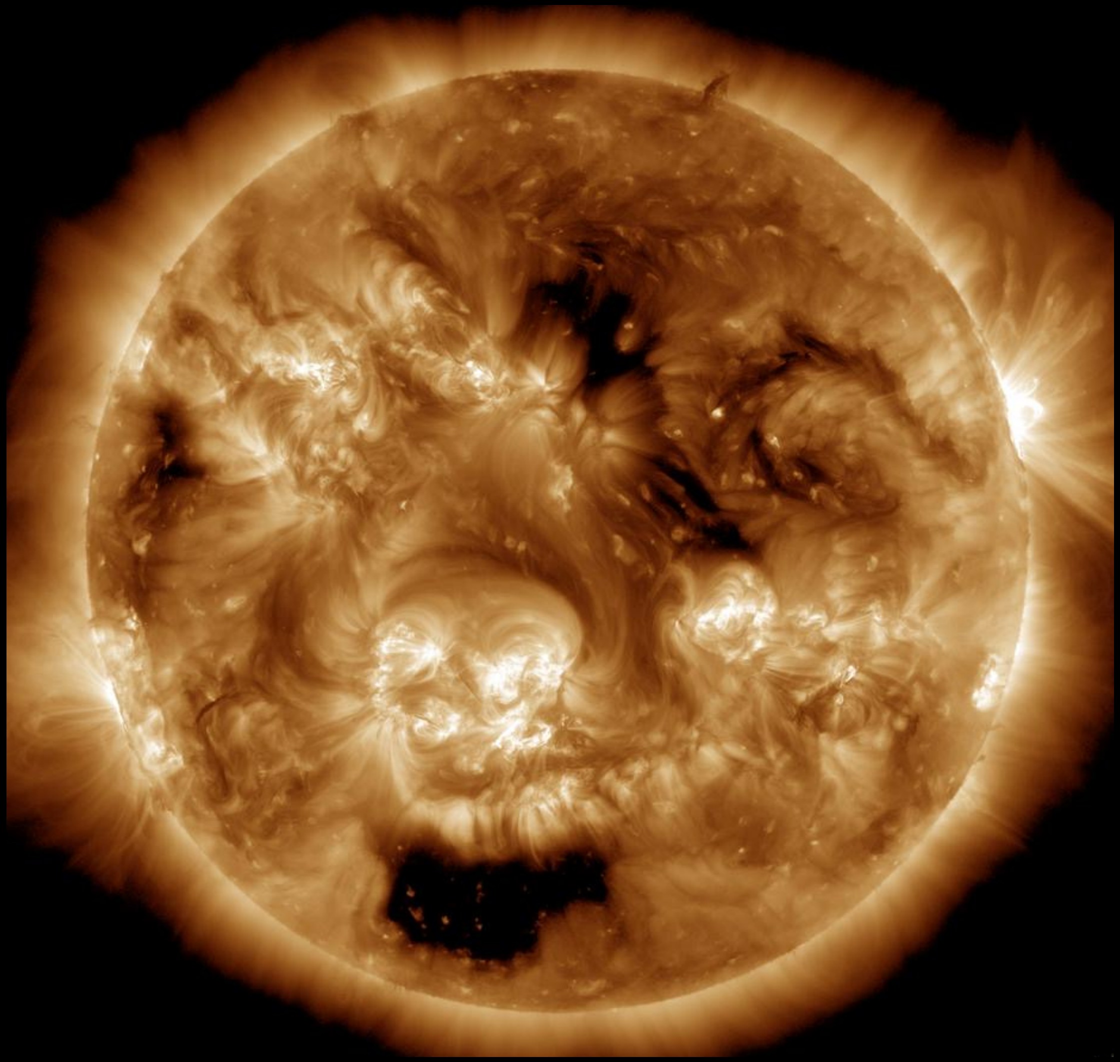
- The EUV (150-912 Å) is extremely important to Solar Physics
- This contrasts with Astrophysics where the EUV is mostly absorbed by the interstellar medium

10 Å = 1nm Fe XX=Fe^{19+}

Images of the Sun on 5 July 2023, obtained by SDO/AIA



Chromosphere, 1700 Å



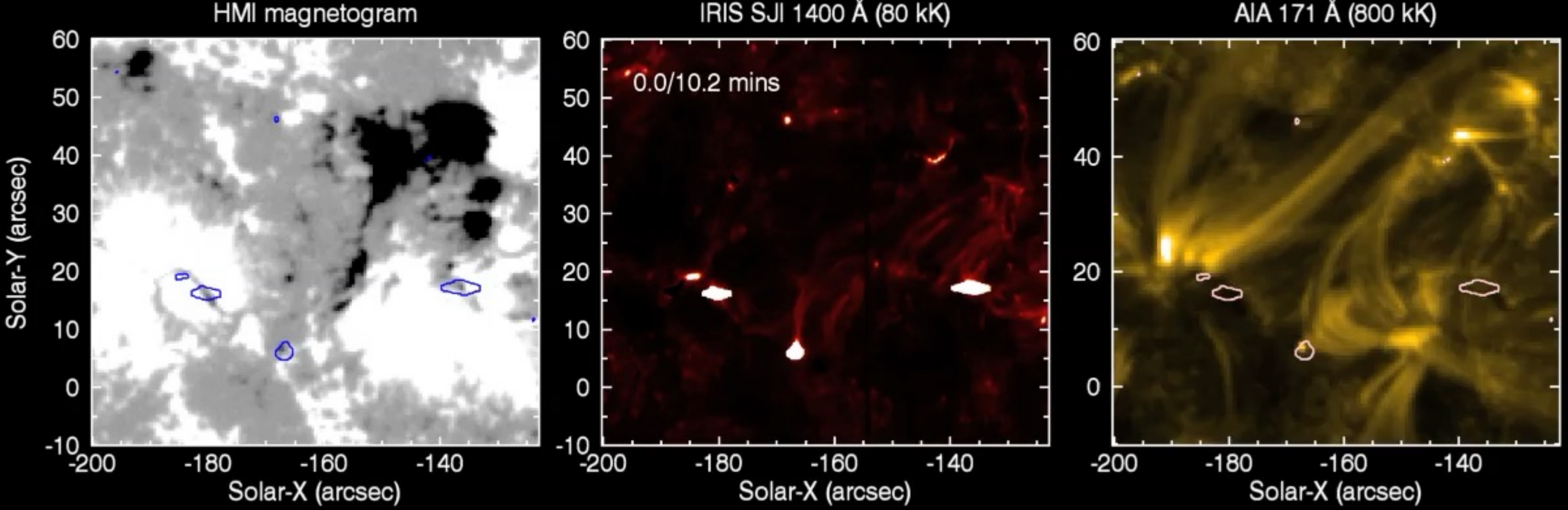
Corona, 193 Å

Dr Peter Young (NASA)

10 Å = 1nm Fe XX=Fe^{19+}

Transition region

Corona



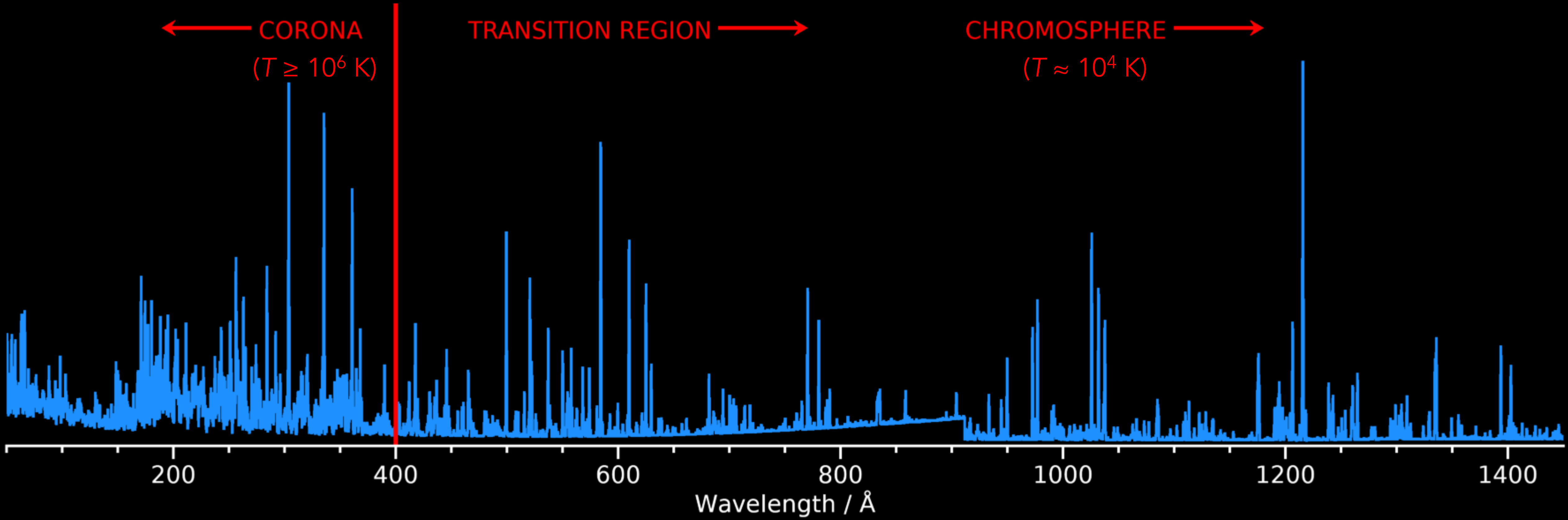
- The solar atmosphere is very dynamic – driven by magnetic field (left)
- This example shows UV bursts (Young et al. 2018), which evolve on timescales of 10’s of seconds

10 Å = 1nm Fe XX=Fe^{19+}

The Sun's far-UV and EUV spectrum mostly consists of emission lines from three layers of the atmosphere

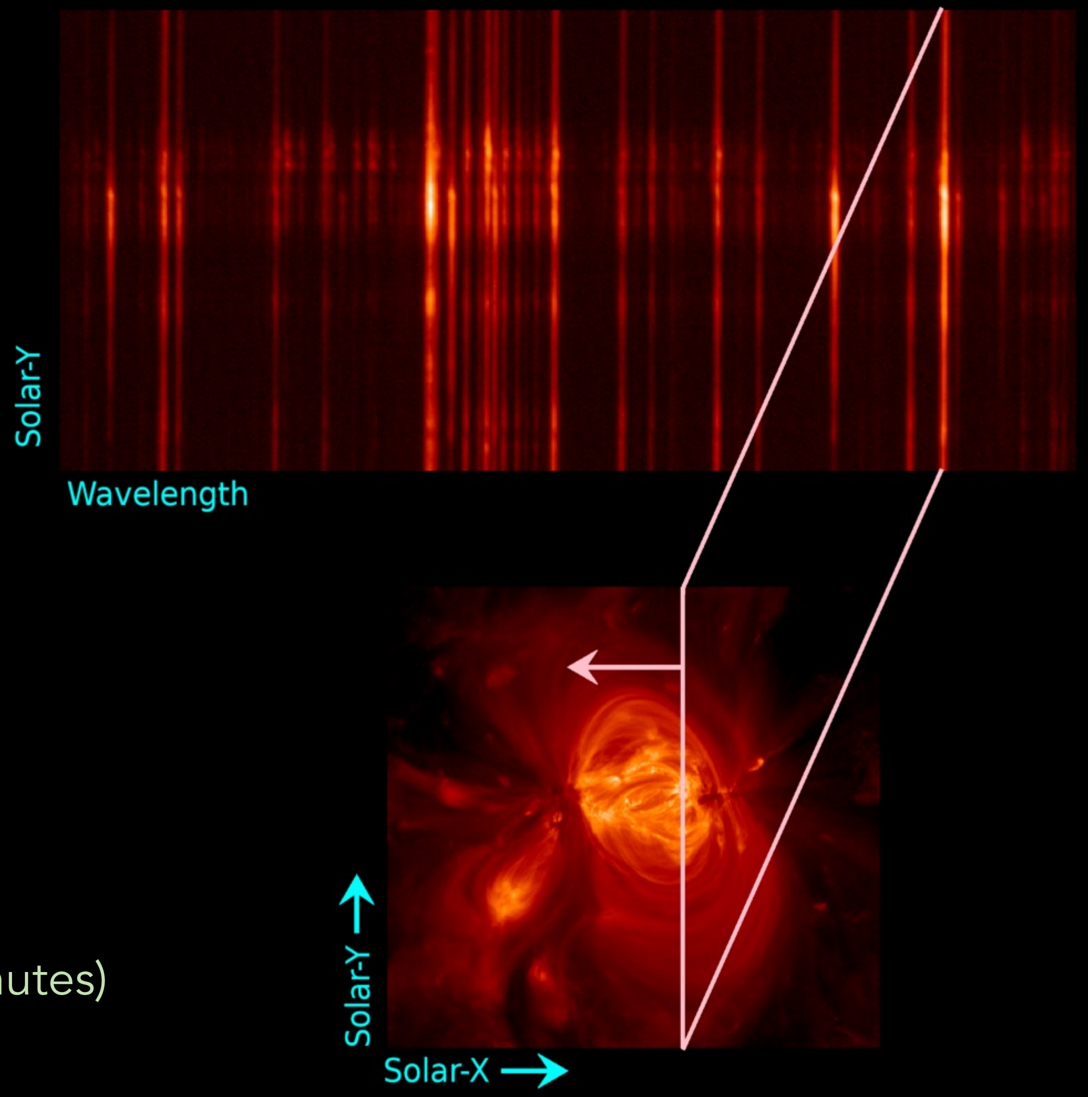
Key measurement techniques

1. imaging spectroscopy
2. spectroscopic imaging



Imaging Spectroscopy

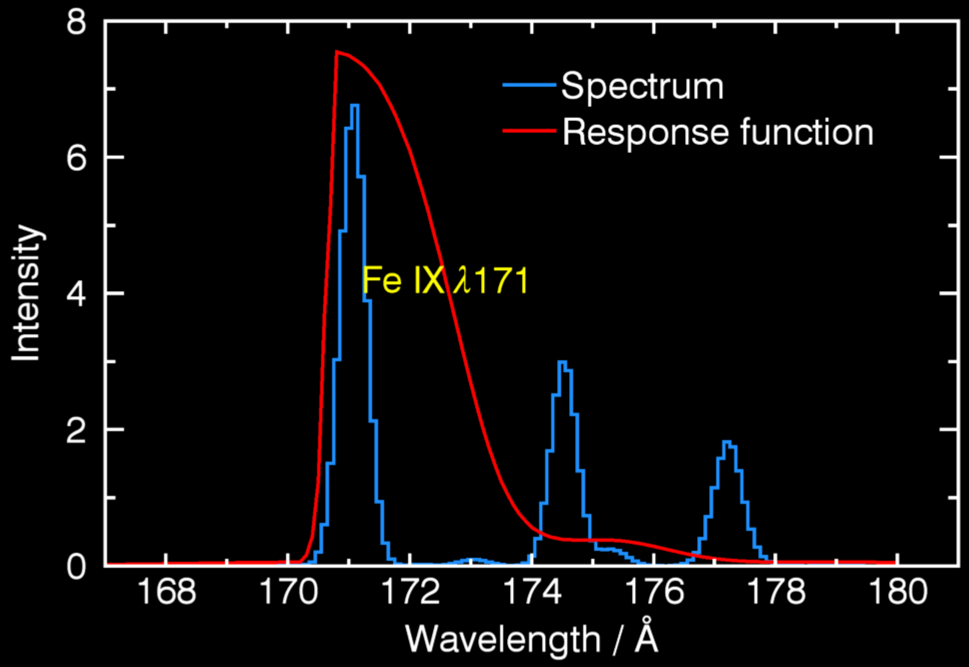
- Sun is imaged through a narrow slit
- A single exposure gives a spectrogram
- Scanning the slit across the Sun builds up an image



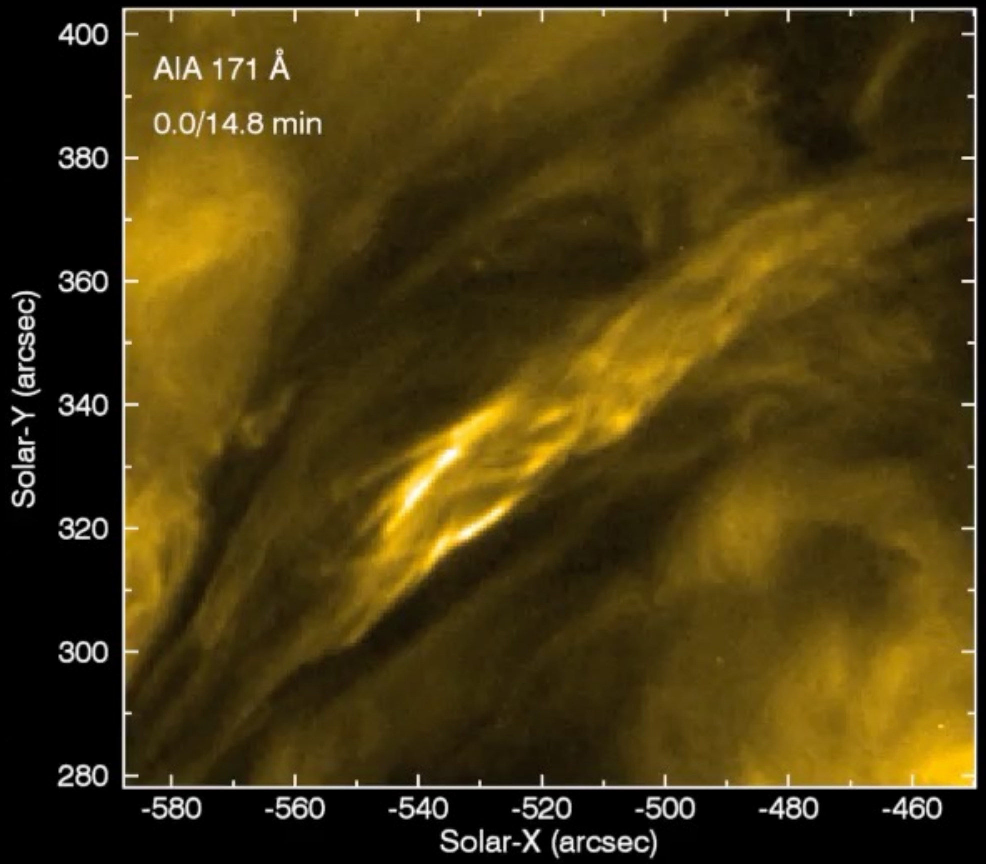
Detailed spectra, but slow to scan (10’s minutes)

10 Å = 1nm Fe XX=Fe^{19+}

Spectroscopic imaging



Filters extract a narrow portion of the EUV spectrum



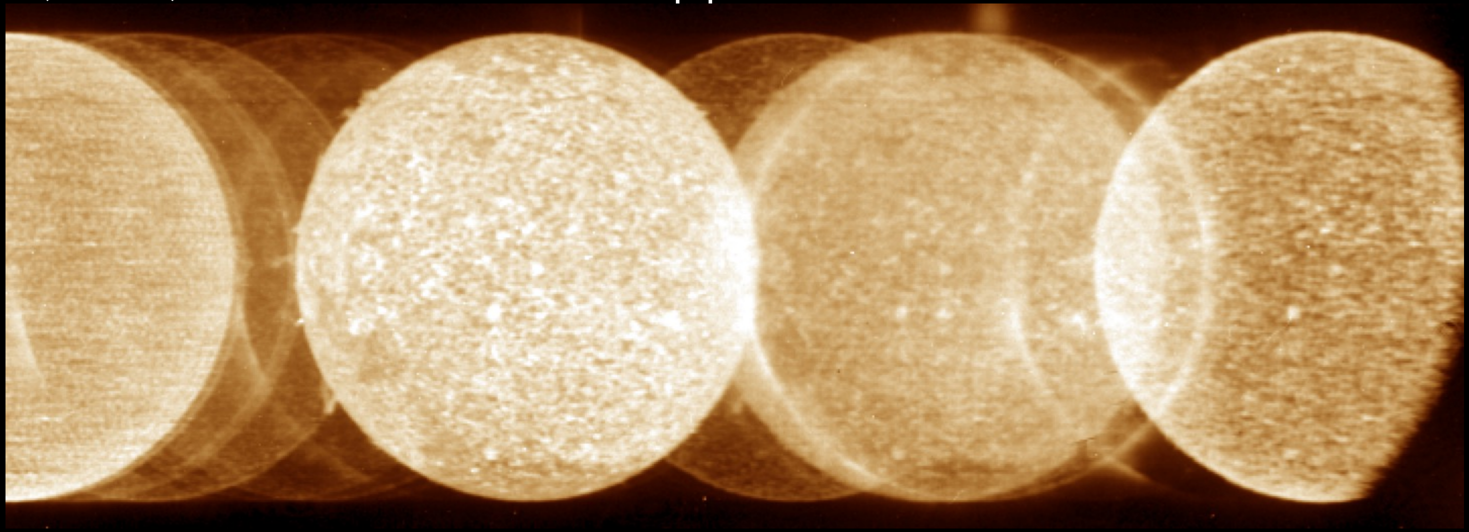
Enables high cadence, spectrally-pure imaging of the Sun [SDO/AIA instrument]

Dr Peter Young (NASA)

10 Å = 1nm Fe XX=Fe^{19+}

Hybrid approach

- Mix spectral and one spatial dimension
  - Slitless or multiple-slit designs
- Enables 2D imaging and spectroscopy
- Deconvolution techniques required; machine learning and AI may be useful
- NASA's MUSE mission (2027) will use a multi-slit approach



Skylab "overlappogram"

10 Å = 1nm Fe XX=Fe^{19+}

Atomic data requirements

- Fine structure states
- Non-LTE
  - Electron collision rates
  - Spontaneous radiative decay rates
- UV, EUV
  - Emission lines are resolved, so high accuracy data needed
  - Lines come from n=2,3 states
- X-rays
  - Emission lines come n=4,5,6,… states
  - Spectral resolution lower, line density higher

10 Å = 1nm Fe XX=Fe^{19+}

CHIANTI

First released in 1996

Open source: http://chiantidatabase.org

1. An <u>assessed</u> database of atomic parameters for ions
2. An IDL & Python software package for computing radiative emissions

Ken Dere (George Mason Univ., USA)
Enrico Landi (Michigan Univ., USA)
Peter Young (NASA Goddard, USA)
Giulio Del Zanna (Cambridge Univ., UK)
Helen Mason (Cambridge Univ., UK)

Dere et al. (1997, A&AS), Young et al. (2016, J. Phys. B)

CHIANTI atomic data

State-to-state
- state energies
- electron collision strengths
- radiative decay rates
- proton rate coefficients*
- radiative recombination rates*
- direct ionization rates*
- autoionization rates*

* select ions only

Ion-to-ion
- dielectronic recombination rates
- radiative recombination rates
- direct ionization rates
- excitation-autoionization rates

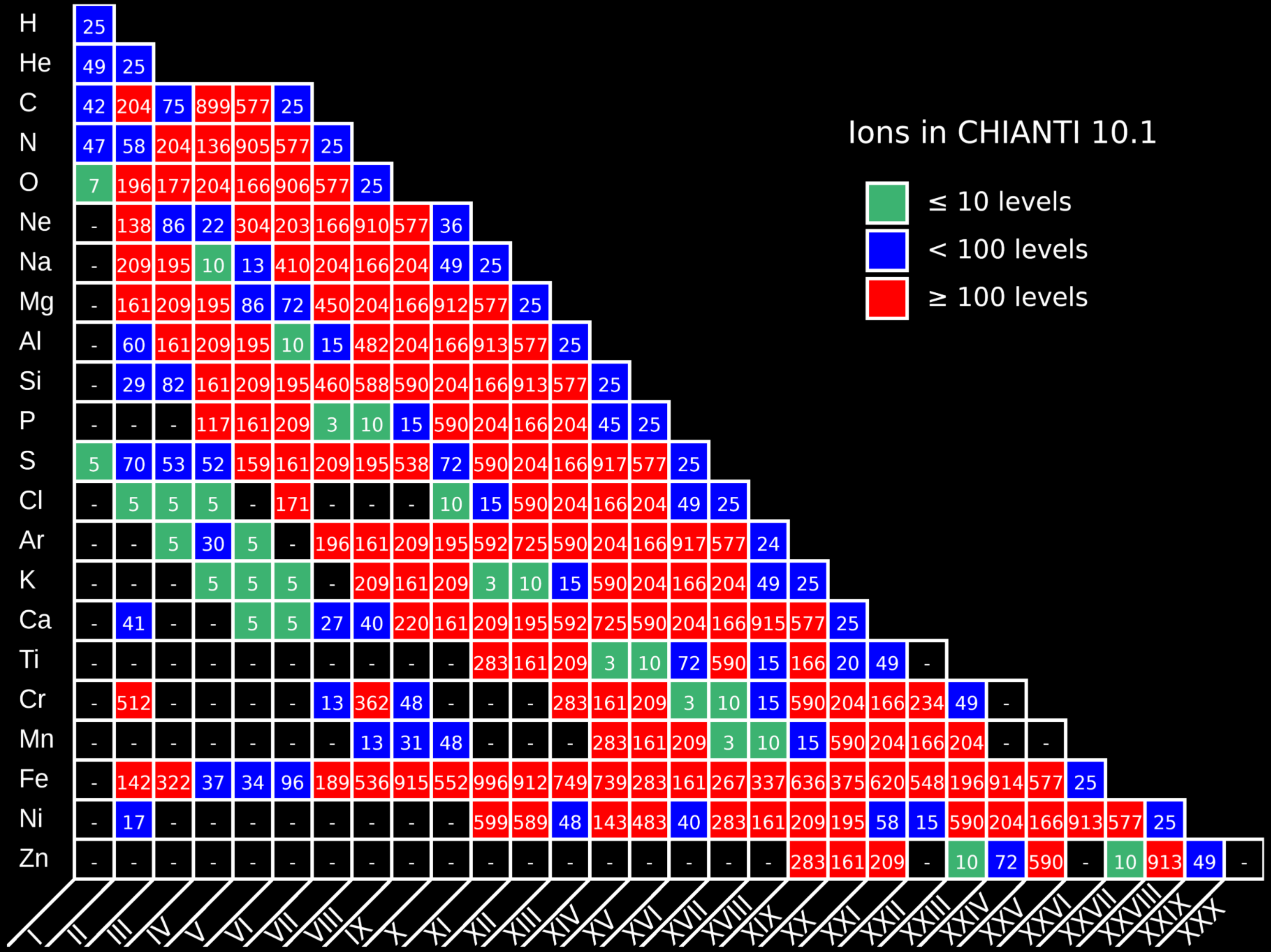
CHIANTI separates state balance equations from ion balance equations.

Ions in CHIANTI 10.1

🟩 ≤ 10 levels

🟦 < 100 levels

🟥 ≥ 100 levels



	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII	XXVIII	XXIX	XXX
H	25																													
He	49	25																												
C	42	204	75	899	577	25																								
N	47	58	204	136	905	577	25																							
O	7	196	177	204	166	906	577	25																						
Ne	-	138	86	22	304	203	166	910	577	36																				
Na	-	209	195	10	13	410	204	166	204	49	25																			
Mg	-	161	209	195	86	72	450	204	166	912	577	25																		
Al	-	60	161	209	195	10	15	482	204	166	913	577	25																	
Si	-	29	82	161	209	195	460	588	590	204	166	913	577	25																
P	-	-	-	117	161	209	3	10	15	590	204	166	204	45	25															
S	5	70	53	52	159	161	209	195	538	72	590	204	166	917	577	25														
Cl	-	5	5	5	-	171	-	-	-	10	15	590	204	166	204	49	25													
Ar	-	-	5	30	5	-	196	161	209	195	592	725	590	204	166	917	577	24												
K	-	-	-	5	5	5	-	209	161	209	3	10	15	590	204	166	204	49	25											
Ca	-	41	-	-	5	5	27	40	220	161	209	195	592	725	590	204	166	915	577	25										
Ti	-	-	-	-	-	-	-	-	-	-	283	161	209	3	10	72	590	15	166	20	49	-								
Cr	-	512	-	-	-	-	13	362	48	-	-	-	283	161	209	3	10	15	590	204	166	234	49	-						
Mn	-	-	-	-	-	-	-	13	31	48	-	-	-	283	161	209	3	10	15	590	204	166	204	-	-					
Fe	-	142	322	37	34	96	189	536	915	552	996	912	749	739	283	161	267	337	636	375	620	548	196	914	577	25				
Ni	-	17	-	-	-	-	-	-	-	-	599	589	48	143	483	40	283	161	209	195	58	15	590	204	166	913	577	25		
Zn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	283	161	209	-	10	72	590	-	10	913	49	-

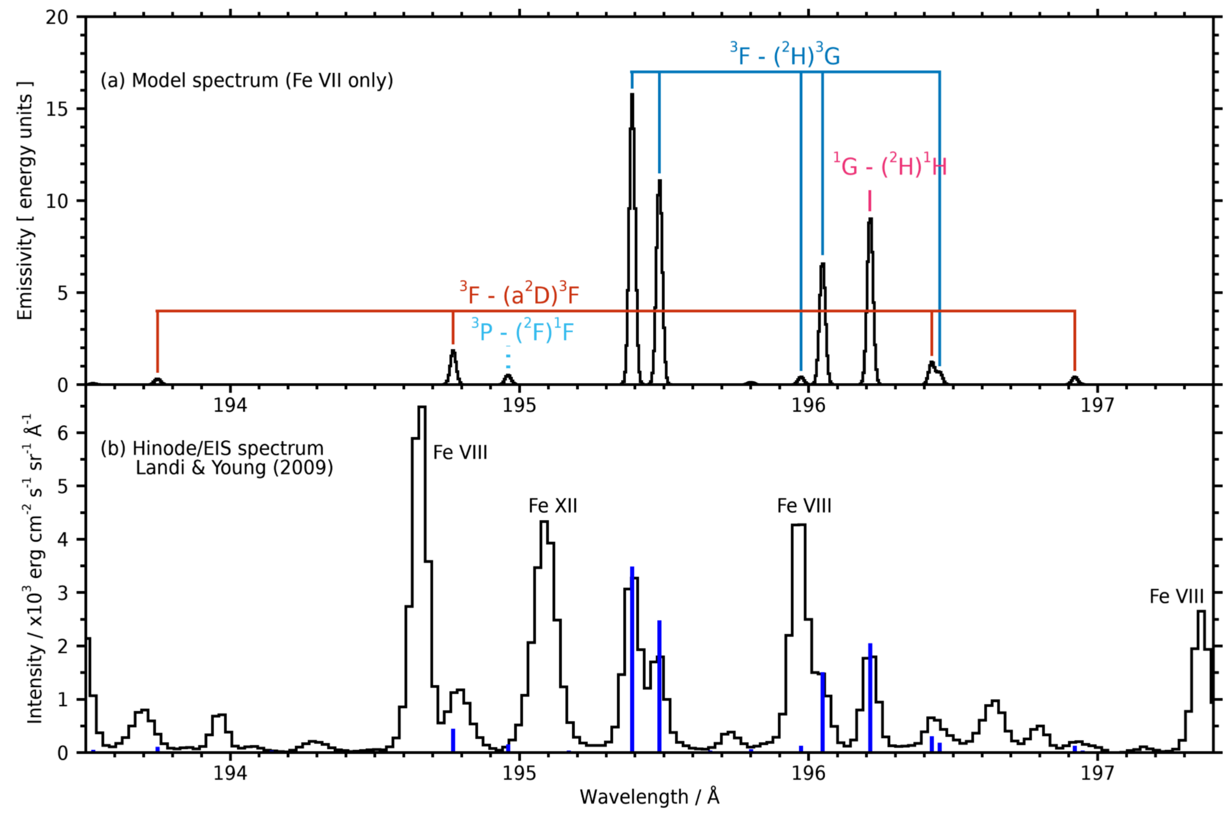
Fe XX=Fe^{19+}

Data needs: large atomic models

- The UK APAP Network (apap-network.org) has been critical to recent CHIANTI updates
- Electron collision strengths and radiative decay rates
- Large models (100's of states) for multiple isoelectronic sequences
    - Li, Be, B, C, N, O, F, Ne, Na, Mg
- STFC (UK) support for multiple postdocs (Witthoeft, Liang, Fernández Menchero, Mao, Zhang)
- See talk by Mao

Line identifications: Fe VII and Fe IX

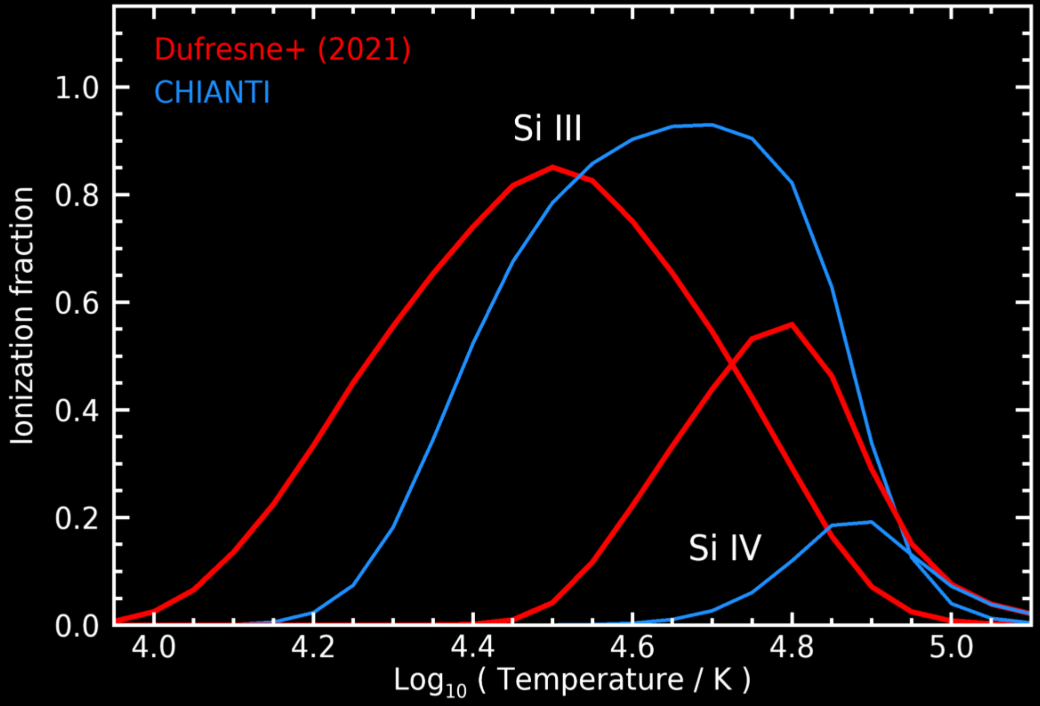
- 3p^{5}3d^3 (Fe VII) and 3p^{4}3d^2 (Fe IX) configurations give rise to a large number of mostly weak lines in the EUV (150-400 Å)
- Hinode/EIS spectra of Sun contain many lines from these ions
- Young et al. (2021), Kramida et al. (2021), Ryabtsev et al. (2022) made many new line identifications using EIS spectra and laboratory spectra



Fe VII lines in Hinode/EIS spectra (Young et al. 2021, ApJ)

Data needs: improved modeling

- The solar transition region is very dynamic, and the "coronal approximation" is not good enough
- Multi-species modeling is required, with level-resolved ionization and recombination rates, charge transfer and DR suppression
- R. Dufresne (Cambridge) has developed such models for application to the Sun



Impact of improved modeling on ion fractions of Si III and Si IV compared to CHIANTI

Final summary of data needs

- Solar Physics is a mature discipline
- Atomic data needs are not “new”
- We want radiative decay rates, electron collision strengths, photoionization cross-sections, etc.
- We want
  - more data (more atomic states)
  - improved accuracy
  - line identifications
  - improved modeling

10 Å = 1nm Fe XX=Fe^{19+}

Contact: peter.r.young@nasa.gov

This talk: https://pyoung.org/talks/

END OF TALK