MODELING X-RAY SPECTRA OF ASTROPHYSICAL PLASMAS

IMPLICATIONS FOR STATISTICAL ANALYSIS

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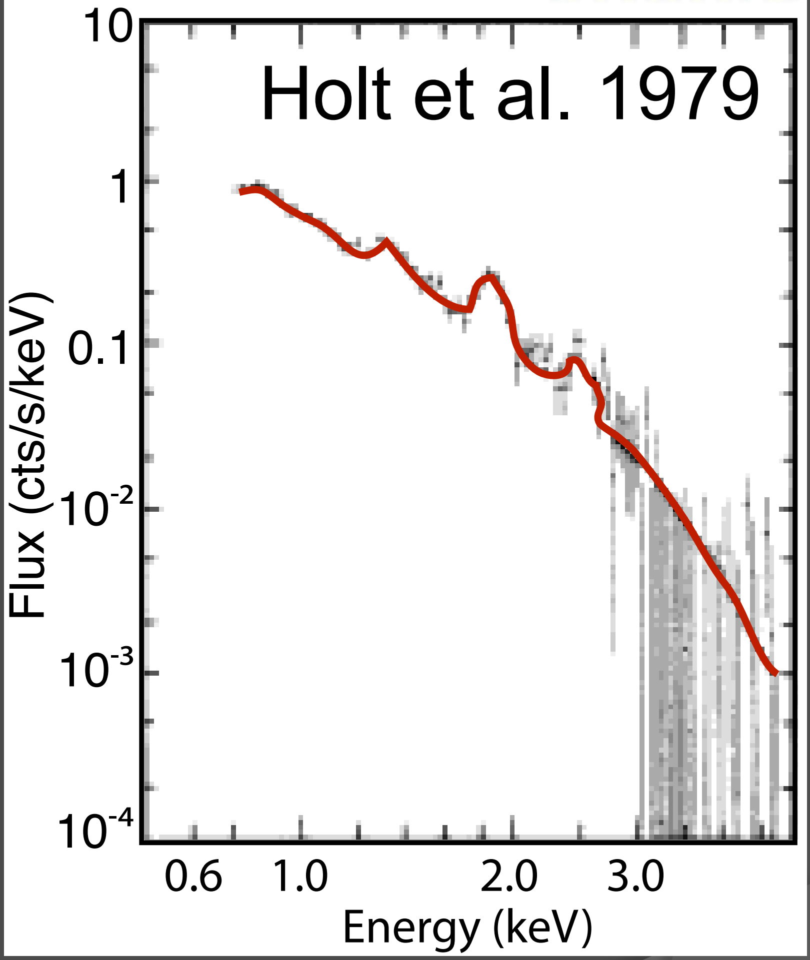
"X-ray Line Emission from Capella"

1980'S

- **Mg, Si, S, and Fe** are **unambiguously** detected
- **Inconsistent** with an isothermal corona, and **requires components between 6 – 24 x10^6 K** for an adequate fit.
- Suggests an **X-ray emitting plasma confined to magnetically contained loops** explains the data.



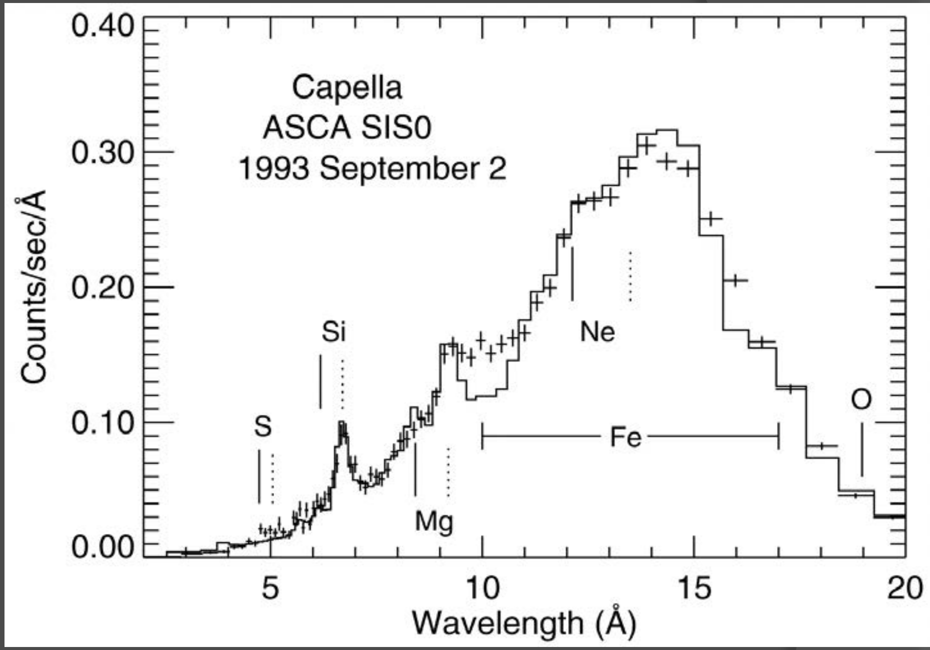
7 ksec exposure with the Einstein Solid State Spectrometer

"X-ray Line Emission from Capella"

1990'S

Coronal Structure and Abundances of Capella from EUVE and ASCA Spectroscopy

- Collisional plasma models **appear to have flux deficits**.
- **New atomic models** allow reliable determination of elemental abundances.
- **EUVE data are not well fitted with only two temperatures**.
- Mg, Si, S, and Fe consistent with solar photospheric values, while Ne appears to be underabundant by a factor of ~3 to 4.

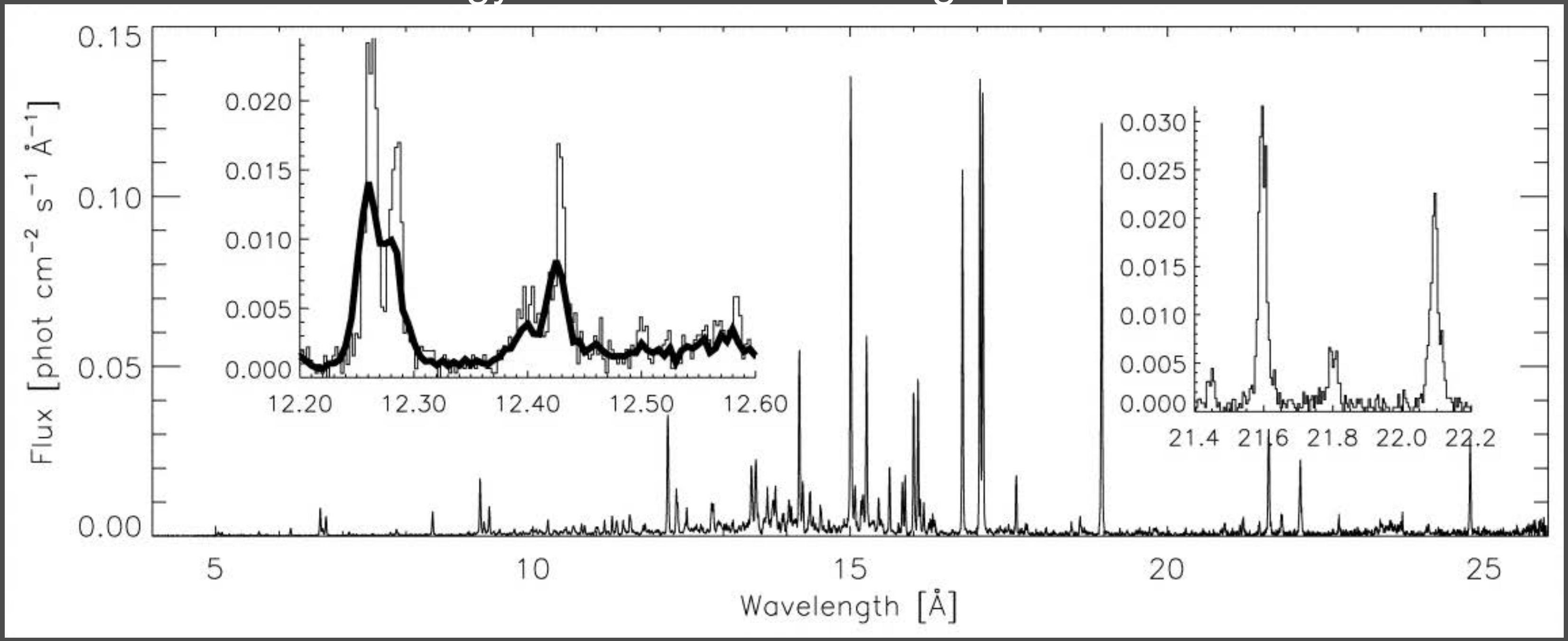


21 ksec obs. w/ASCA Silicon Imaging Spectrometer (Brickhouse et al. 2000)

"X-ray Line Emission from Capella"

2000'S

High-Resolution X-Ray Spectra of Capella: Initial Results from the Chandra High-Energy Transmission Grating Spectrometer



89 ksec w/Chandra HETG (Canizares et al. 2000)

- **Broad range of temperatures**, from log T = 6.3 to 7.2
- The **electron density** is ~ 10^{10} cm^{-3} at T_e~2 × 10^6 K.
- The density and emission measure show the **coronal loops are significantly smaller than the stellar radius**.

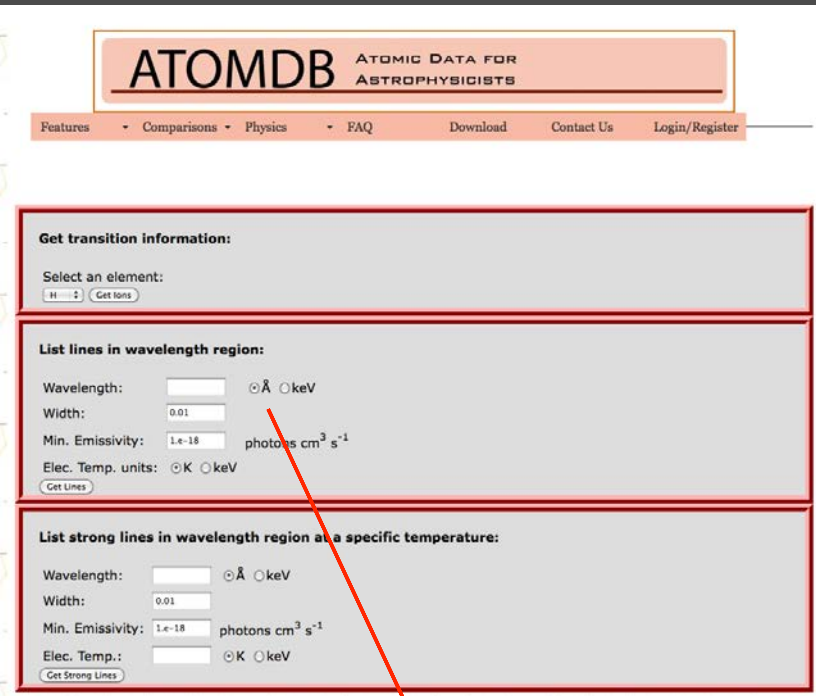
What is an AtomDB?

The AtomDB is database of atomic values – wavelengths & rates – useful for calculating emission & absorption in X-ray spectra, especially from astrophysical plasmas.

It's used by X-ray astrophysicists to identify the elements or ions that create features in an observed spectrum, and also to determine the parameters (temperature, density, etc) of the emitting plasma.

The first version of the AtomDB was released in 2001; it is now the standard source in the field.

http://www.atomdb.org



Energy level 1	
Electron configuration	2p6
Energy above ground (eV)	0
Quantum state	n=2, L=0, S=0.0, degeneracy=1, parity=even
Energy level data source	2006JPhB...39...85L
Photoionization data source	1995A&AS..109..125V

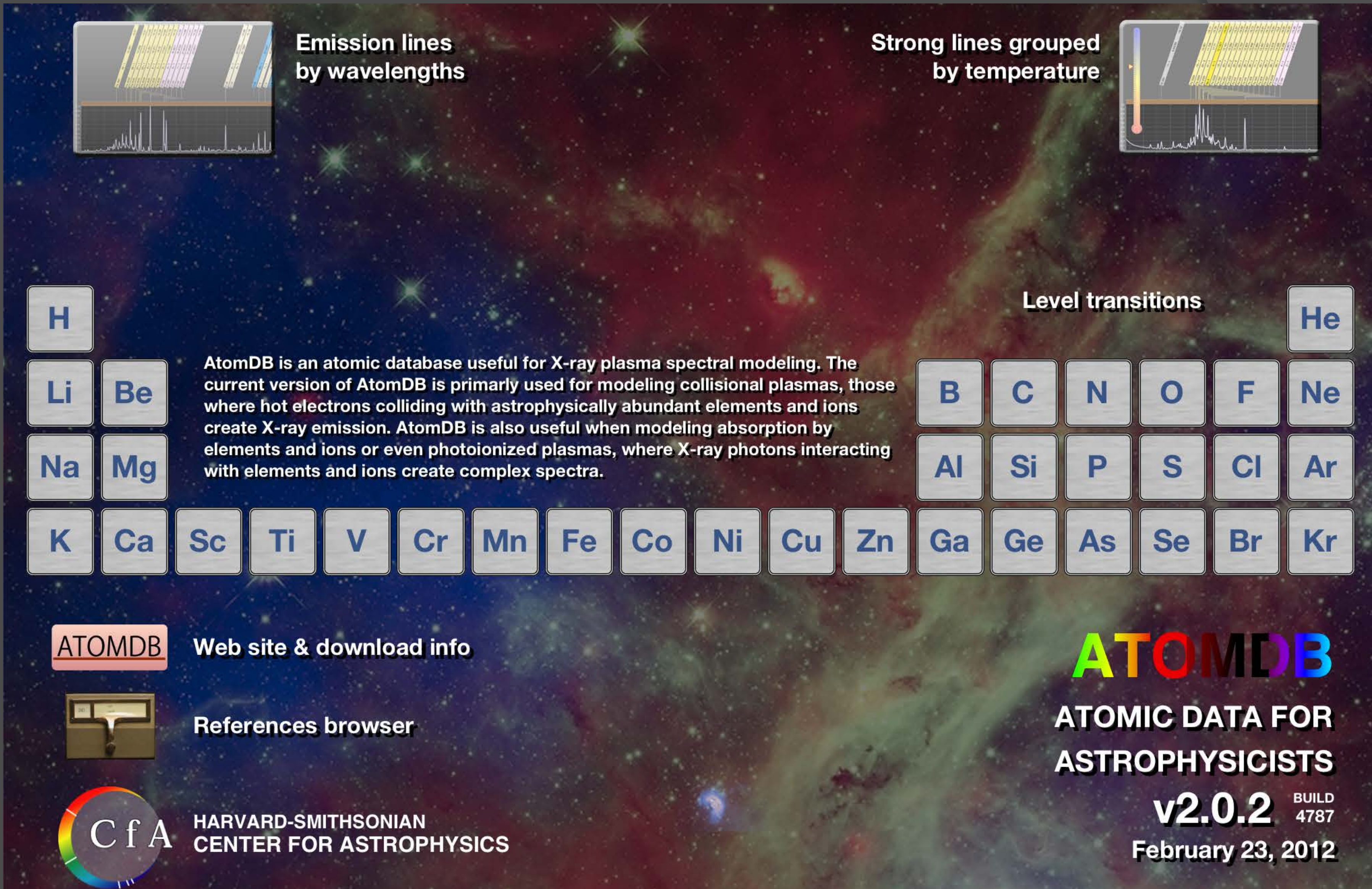
Energy level 27	
Electron configuration	2p5 3d1
Energy above ground (eV)	825.829
Quantum state	n=3, L=1, S=0.0, degeneracy=3, parity=odd
Energy level data source	2006JPhB...39...85L
Photoionization data source	

Level 27 → 1 Interactions	
Electron collision rate	Nonzero
Reference	2006JPhB...39...85L
Wavelength (lab/observed)	15.014±0.001Å
Wavelength (theory)	15.0133Å
Transition rate/Einstein A	$2.46e+13 s^{-1}$
Transition Type*	E1
Oscillator Strength $f_{1\rightarrow27}$*	2.4938e+0
Wavelength (lab/observed) reference	
Wavelength (theory) reference	2006JPhB...39...85L
Transition rate reference	2006JPhB...39...85L

Ion	Wavelength Å	Upper Level	Lower Level	Emissivity ph $cm^3 s^{-1}$	Te peak K	Relative Intensity
Fe XIX	14.961	12	1	6.819e-17	1.000e+7	0.03
Fe XIX	14.963	16	4	3.964e-17	1.000e+7	0.02
Fe XX	14.969	49	10	4.275e-18	1.000e+7	0.00
Fe XVIII	14.972	26	1	2.053e-17	7.943e+6	0.01
Fe XX	14.980	29	7	3.143e-18	1.000e+7	0.00
Fe XIX	15.000	26	5	3.323e-18	1.000e+7	0.00
Fe XIX	15.008	15	4	1.697e-17	1.000e+7	0.01
Fe XVII	15.014	27	1	2.228e-15	6.310e+6	1.00
Fe XX	15.047	22	6	1.663e-17	1.000e+7	0.01
Fe XX	15.047	27	7	9.682e-18	1.000e+7	0.00

Using AtomDB database 2.0.2 (Feb 2012)

We even have an iTunes App!



AtomDB: Atomic Data for X-ray Astrophysicists

1	$1s^2$	0.0000	1	0	0	1	2
2	$1s^1 2s^1$	561.24	2	0	1	3	1
3	$1s^1 2s^1$	569.68	2	0	0	1	1
4	$1s^1 2p^1$	568.81	2	1	1	1	1
5	$1s^1 2p^1$	568.86	2	1	1	3	1
6	$1s^1 2p^1$	568.95	2	1	1	5	1
7	$1s^1 2p^1$	574.79	2	1	0	3	1
8	$1s^1 3s^1$	662.45	3	0	1	3	1
9	$1s^1 3s^1$	664.63	3	0	0	1	1
10	$1s^1 3p^1$	664.48	3	1	1	1	1
11	$1s^1 3p^1$	664.49	3	1	1	3	1
12	$1s^1 3p^1$	664.52	3	1	1	5	1
13	$1s^1 3p^1$	666.11	3	1	0	3	1
14	$1s^1 3d^1$	665.63	3	2	1	3	1
15	$1s^1 3d^1$	665.63	3	2	1	5	1
16	$1s^1 3d^1$	665.64	3	2	1	7	1

8 15.9994

O VII

Oxygen

$1s^2 2s^2 2p^4$

Level	2 → 1
Electron configuration	$1s^1 2s^1 \rightarrow 1s^2$
Energy above ground	561.24 eV → 0.0000 eV
Energy level reference	Whiteford ICFT
Photoionization reference	1986ADNDT..34..415C

Quantum state:

n	*L*	*S*	*degeneracy*	*parity*
2 → 1	0	1 → 0	3 → 1	even → even

Electron collision rate	nonzero
Collision rate reference	TBD
Wavelength (theory)	22.0977 Å
Transition rate/Einstein A	912 s^{-1}
Transition type	M1
Oscillator strength $f_{2\rightarrow1}$	2.00296×10^{-10}
Wavelength (theory) reference	Whiteford ICFT
Transition rate reference	Whiteford ICFT

Radiative transition (1 found):

Wavelength (Å)	Wavelength Ref	Einstein A (s^{-1})	Einstein A Ref

Electron collision rate	nonzero
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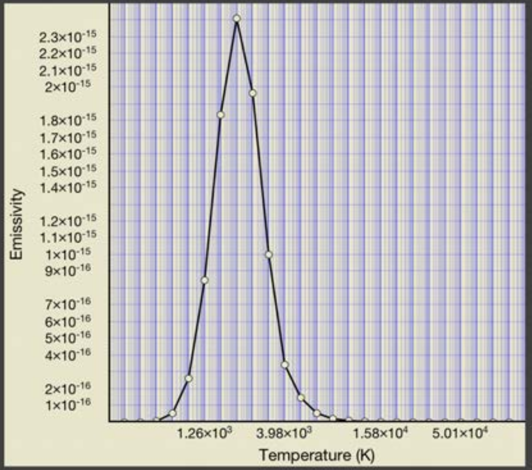
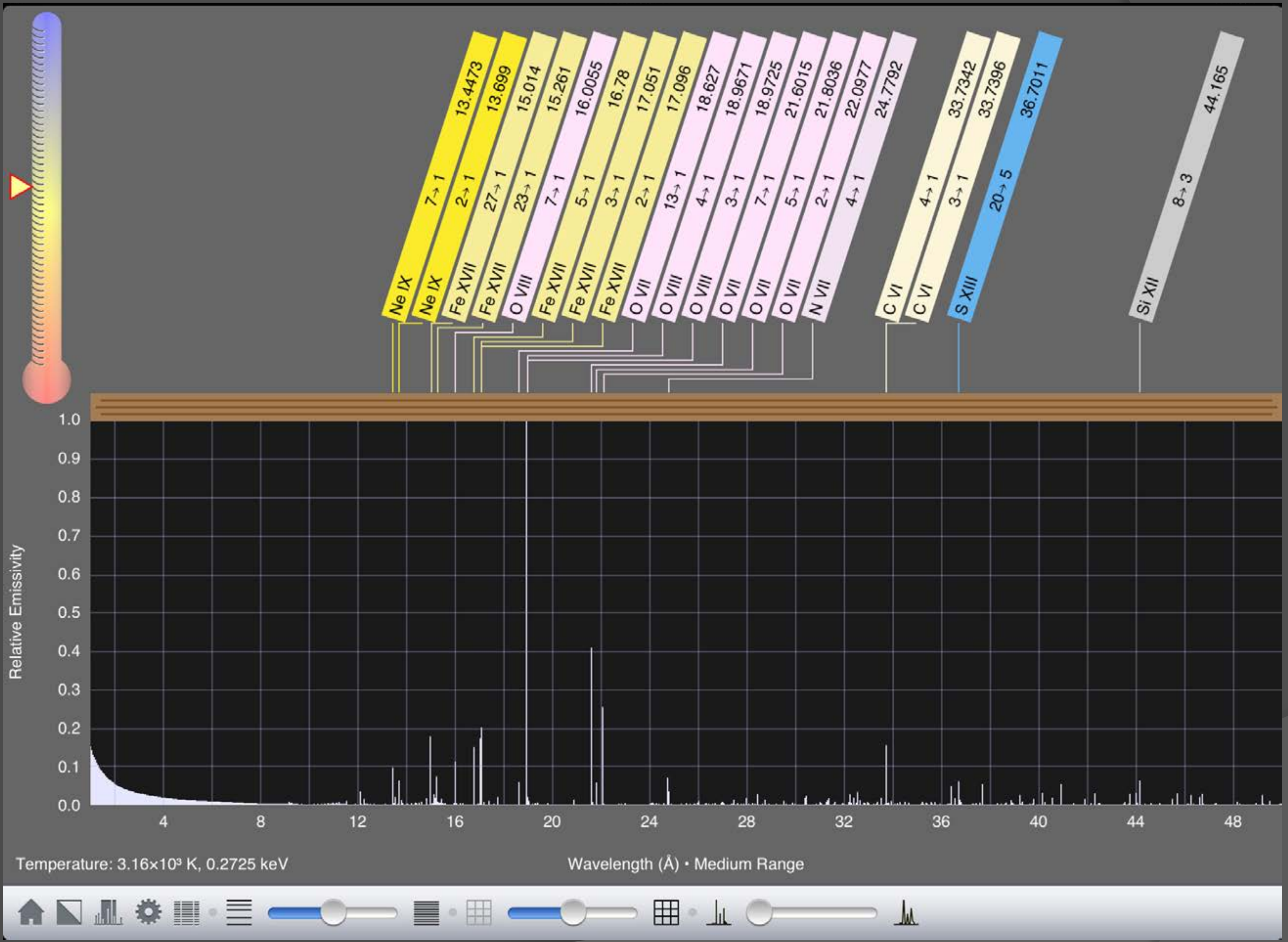
Radiative transition (1 found):

Wavelength (Å)	Wavelength Ref	Einstein A (s^{-1})	Einstein A Ref
22.1 ±0.007	Whiteford ICFT	912	Whiteford ICFT

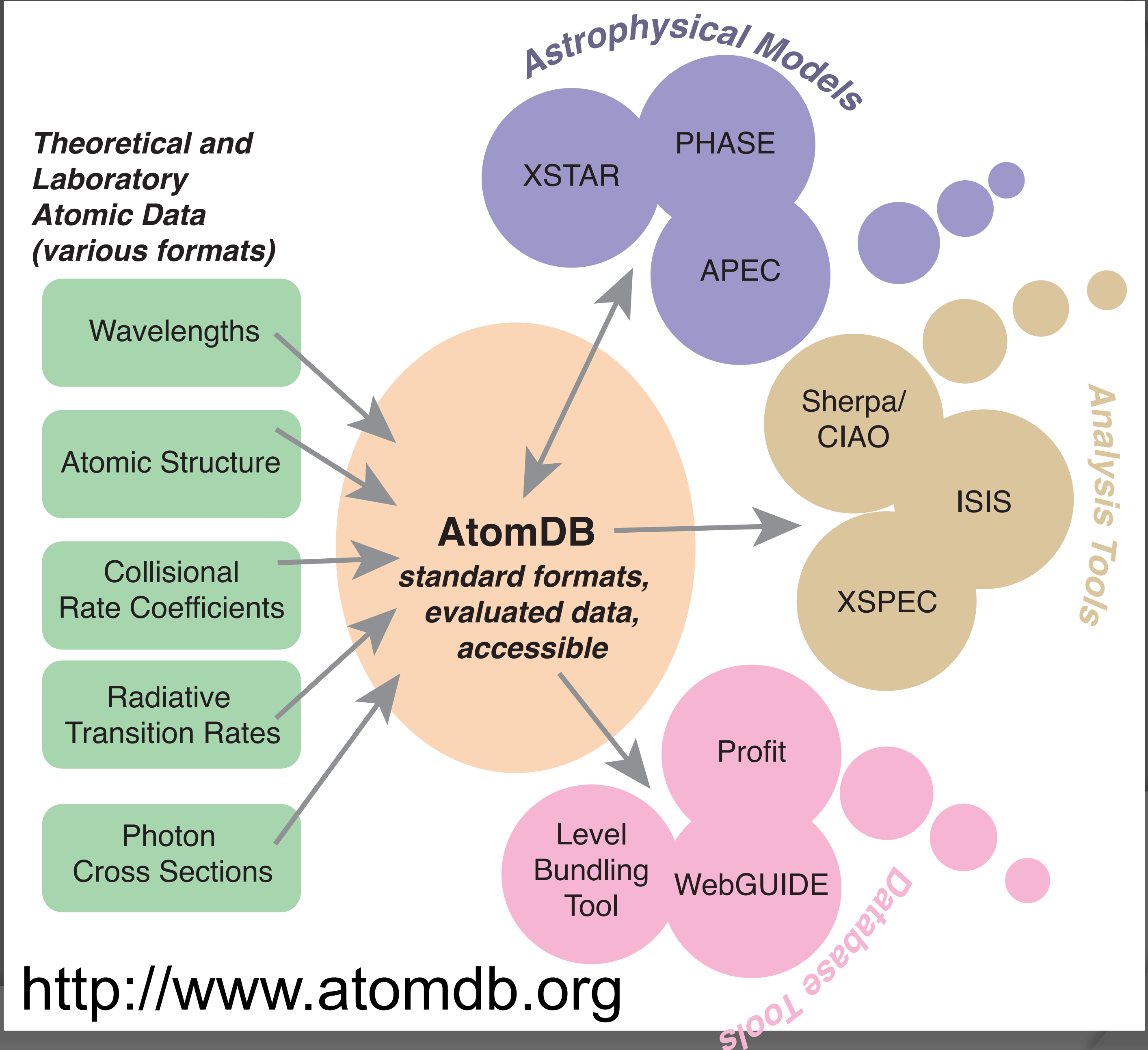
Temperature vs. emissivity for O VII 2 → 1:





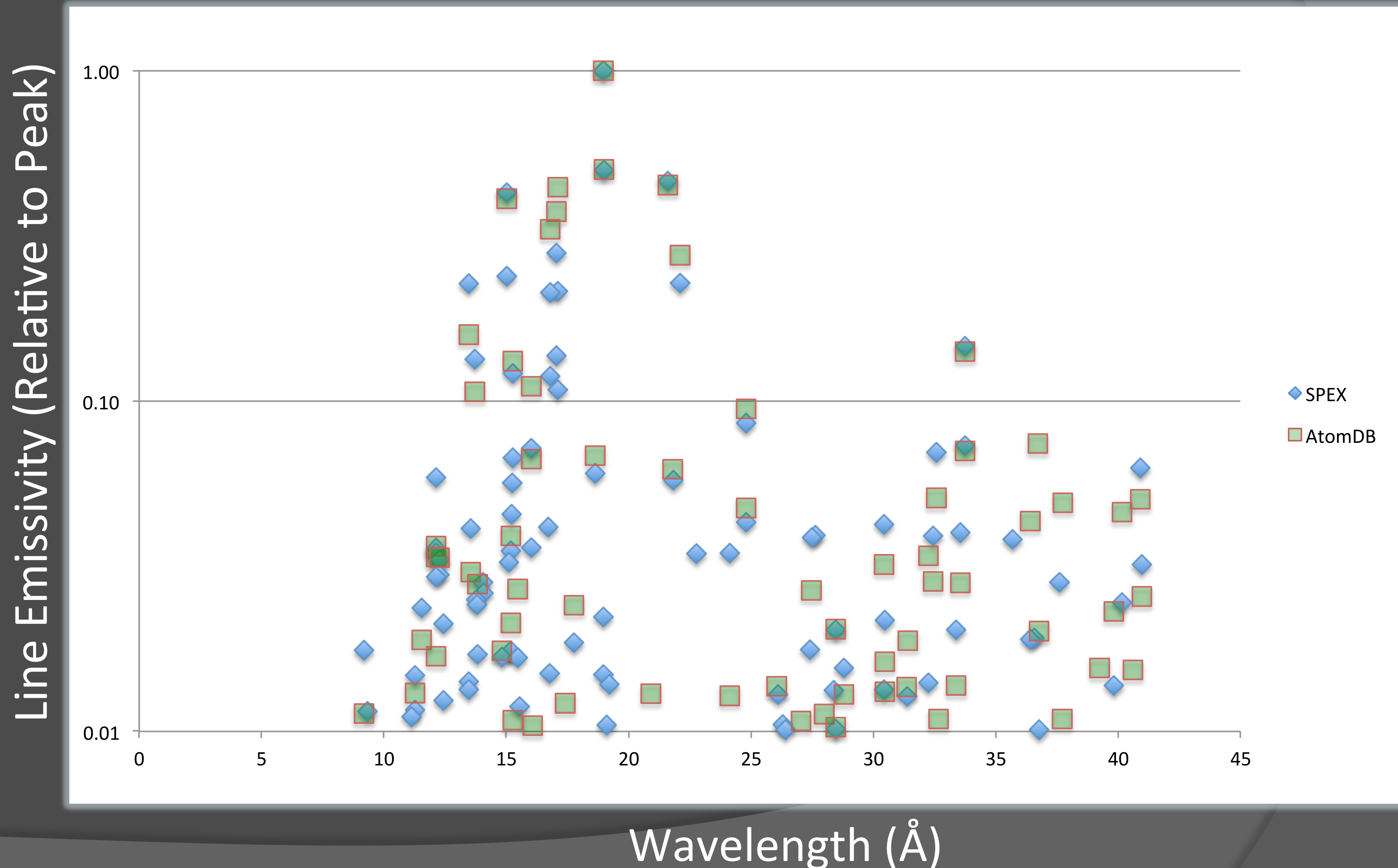
Ne IX 7→1 13.4473
Ne IX 2→1 13.699
Fe XVII 27→1 15.014
Fe XVII 23→1 15.261
O VIII 7→1 16.0055
Fe XVII 5→1 16.78
Fe XVII 3→1 17.051
Fe XVII 2→1 17.096
O VII 13→1 18.627
O VIII 4→1 18.9671
O VIII 3→1 18.9725
O VII 7→1 21.6015
O VII 5→1 21.8036
O VII 2→1 22.0977
N VII 4→1 24.7792
C VI 4→1 33.7342
C VI 3→1 33.7396
S XIII 20→5 36.7011
Si XII 8→3 44.165
Relative Emissivity
Temperature: 3.16×10⁶ K, 0.2725 keV
Wavelength (Å) • Medium Range

AtomDB: Rates, Emissivities, and more

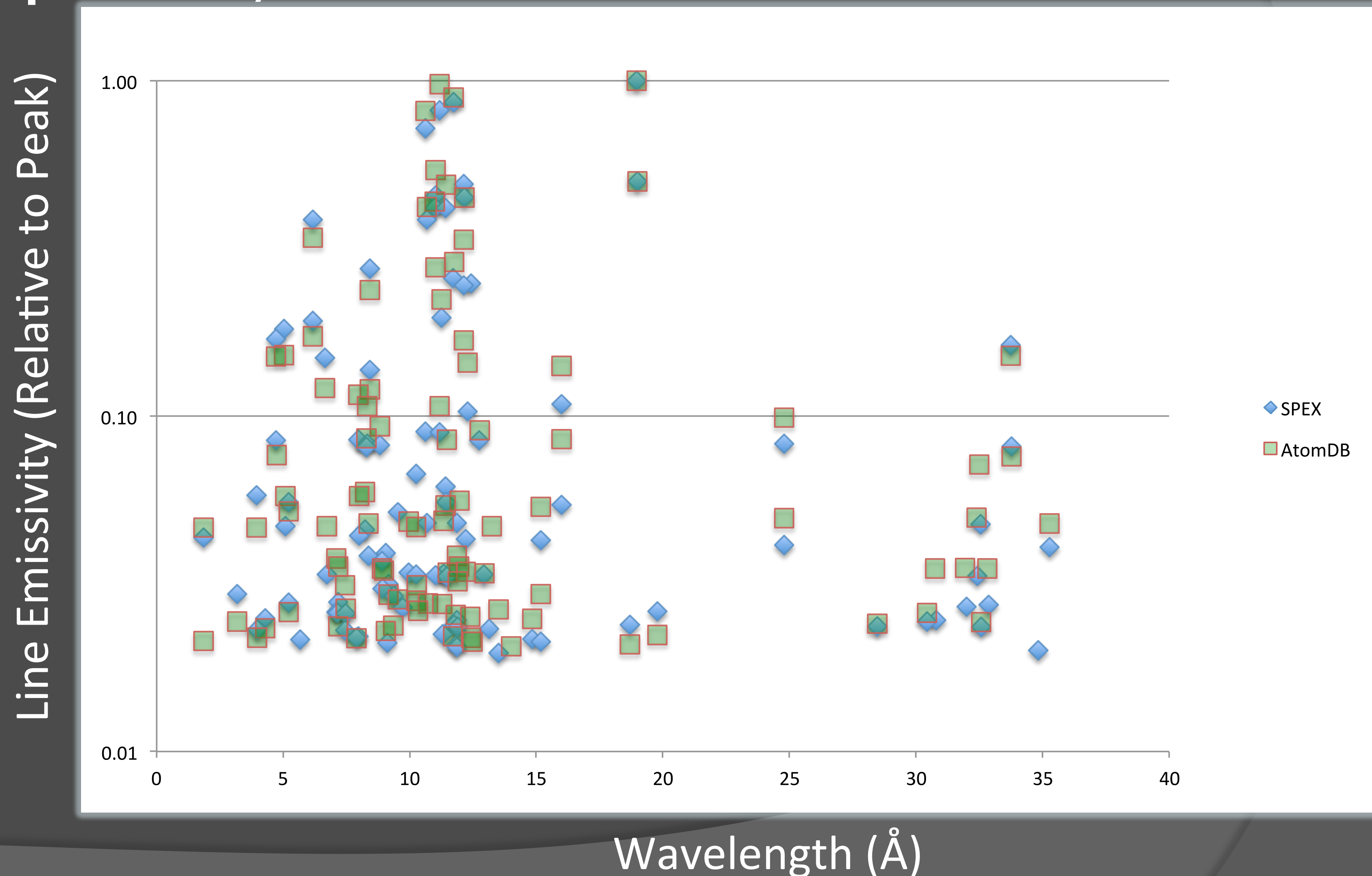


http://www.atomdb.org

100 strongest lines from a kT=0.3 keV plasma, SPEX vs AtomDB

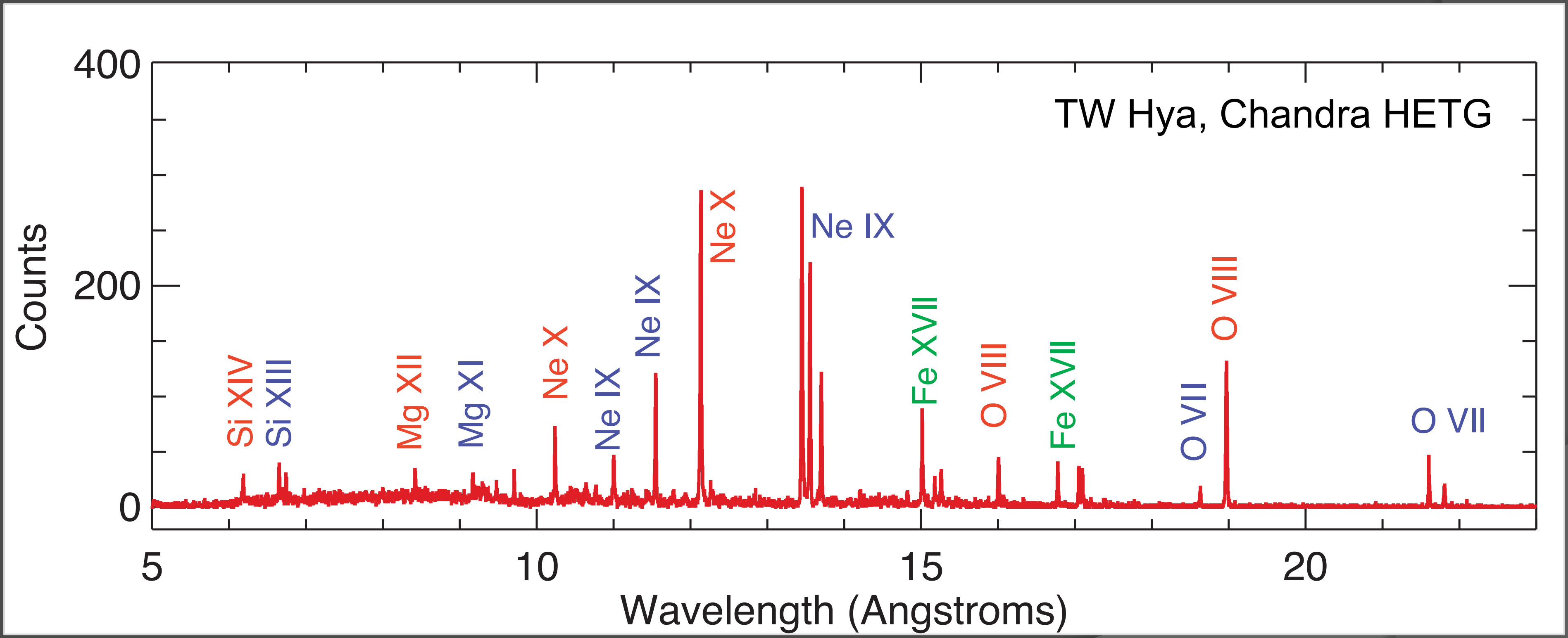


100 strongest lines from a kT=2 keV plasma, SPEX vs AtomDB



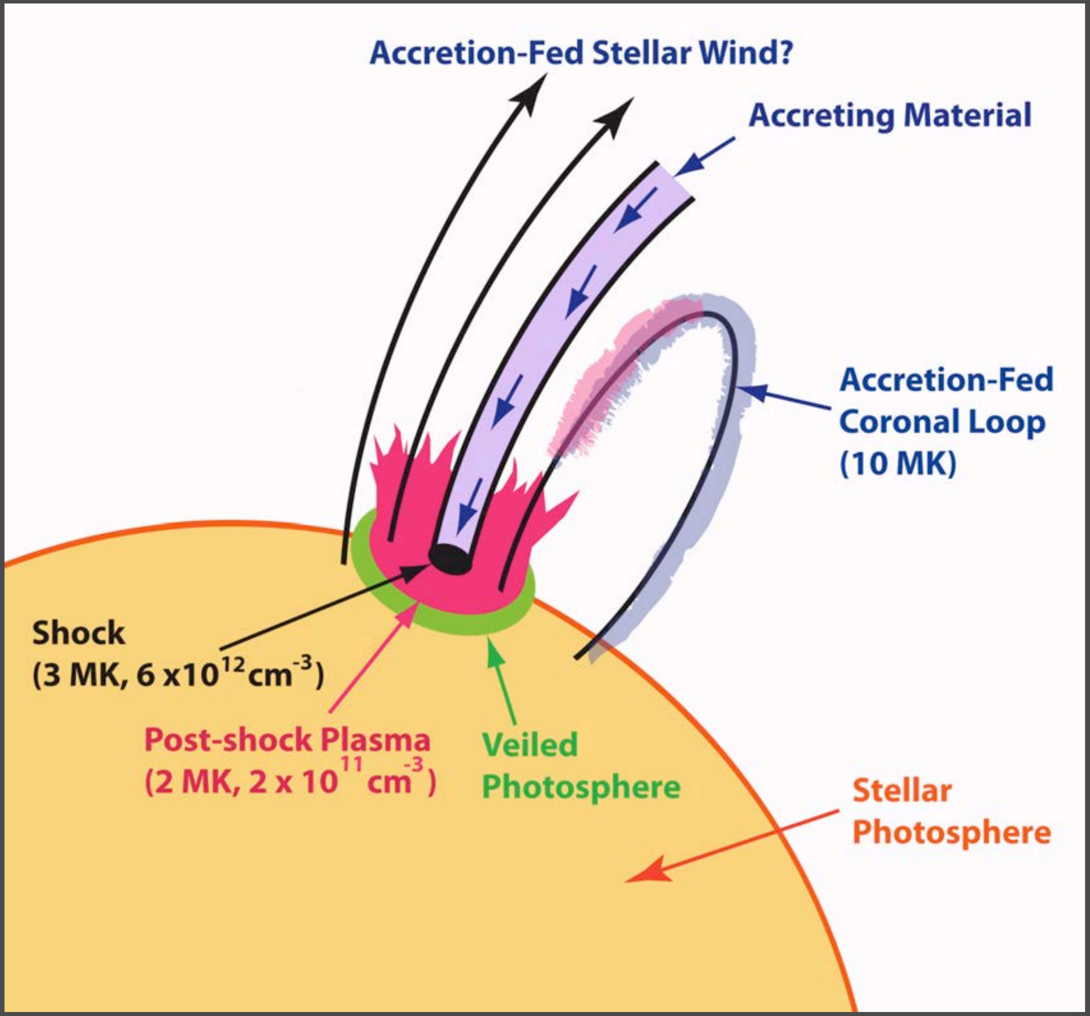
TW Hya: Accretion & X-rays

TW Hya: A 10 Myr old “Sun” that is still growing by accreting mass from a disk



Brickhouse et al. 2010

TW Hya: Accretion & X-rays



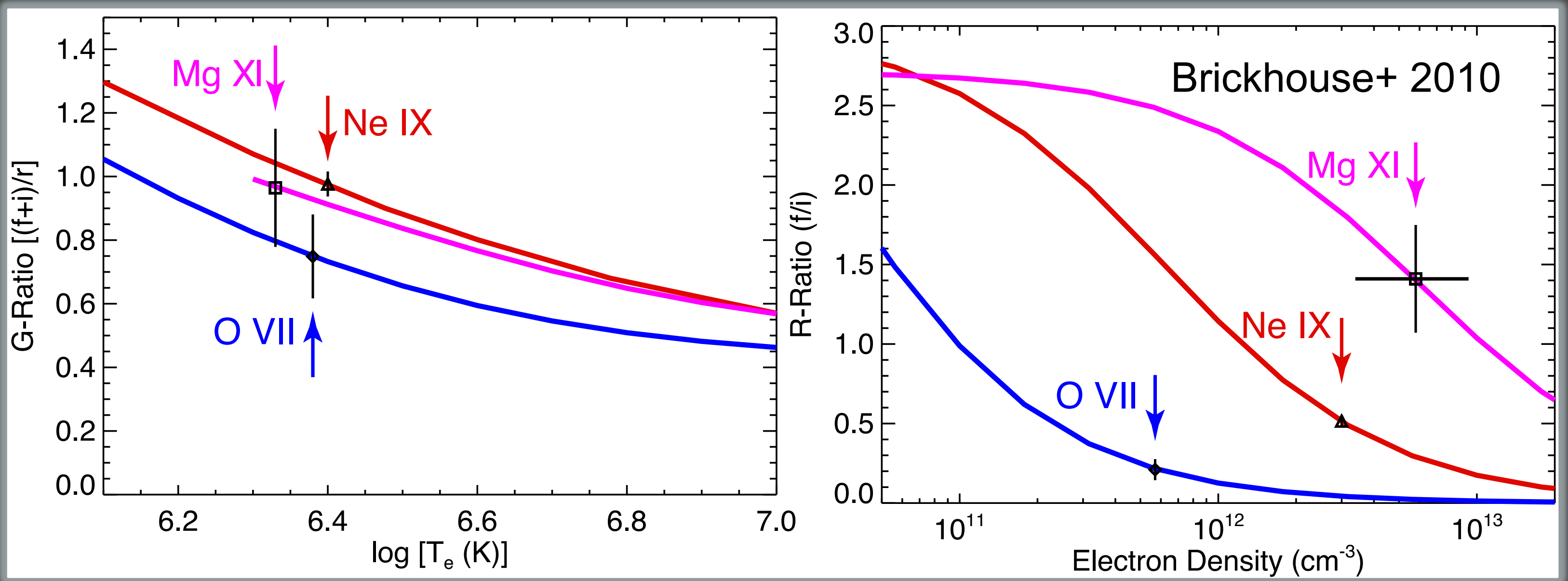
Brickhouse+ 2010

Our current best 'picture' of the situation

Accretion apparently heats a significant amount of coronal gas well beyond the shock itself.

How do stars form?

Helium-like Diagnostics



While the temperature diagnostics for Mg XI, Ne IX, and O VII all give roughly the same result, the density diagnostics are significantly different.

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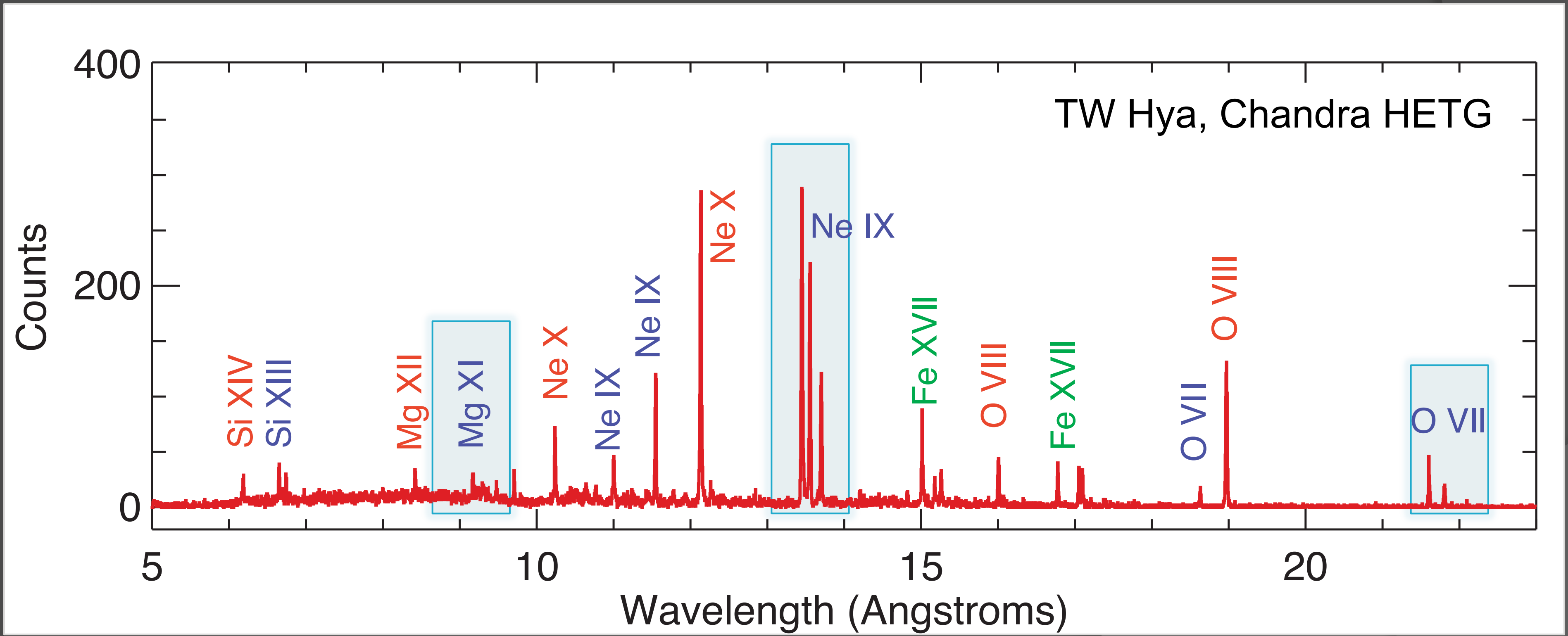
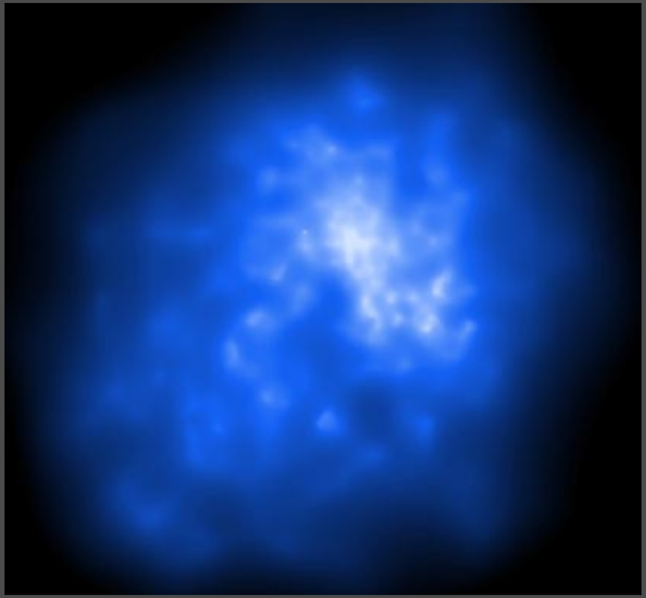


Brickhouse et al. 2010

How does matter and energy move in and around galaxies?

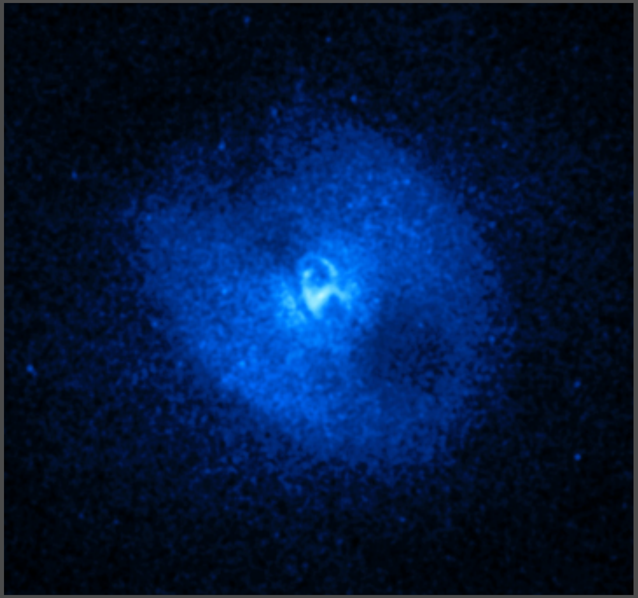
The Velocity of Intragalactic Gas in Elliptical Galaxies

NGC 5044



NASA/CXC/U. Ohio/T.Statler & S.Diehl

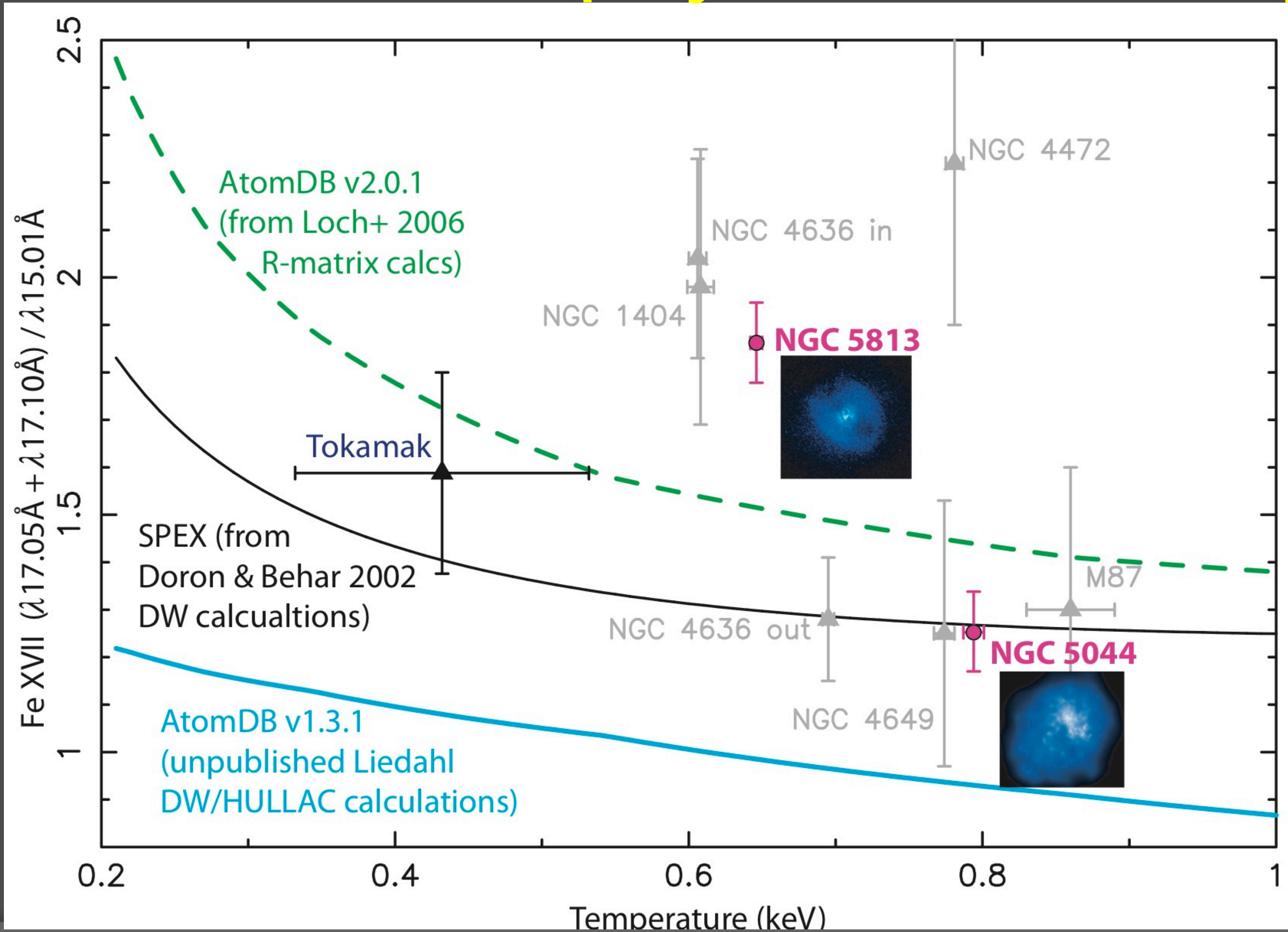
NGC 5813



NASA/CXC/SAO/S.Randall et al.

How does matter and energy move in and around galaxies?

Fe XVII: Astrophysics & Theory



dePlaa+ 2012

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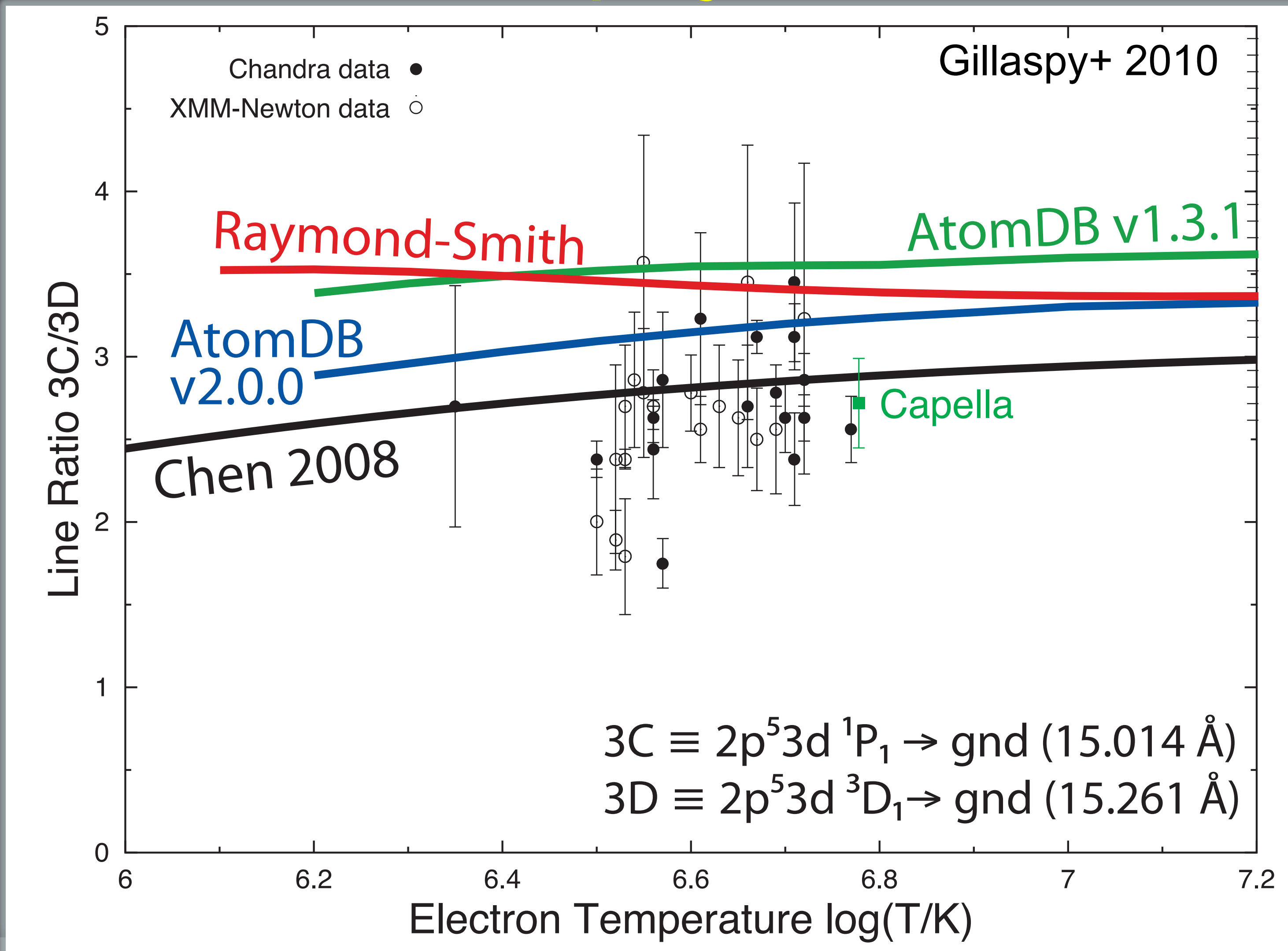
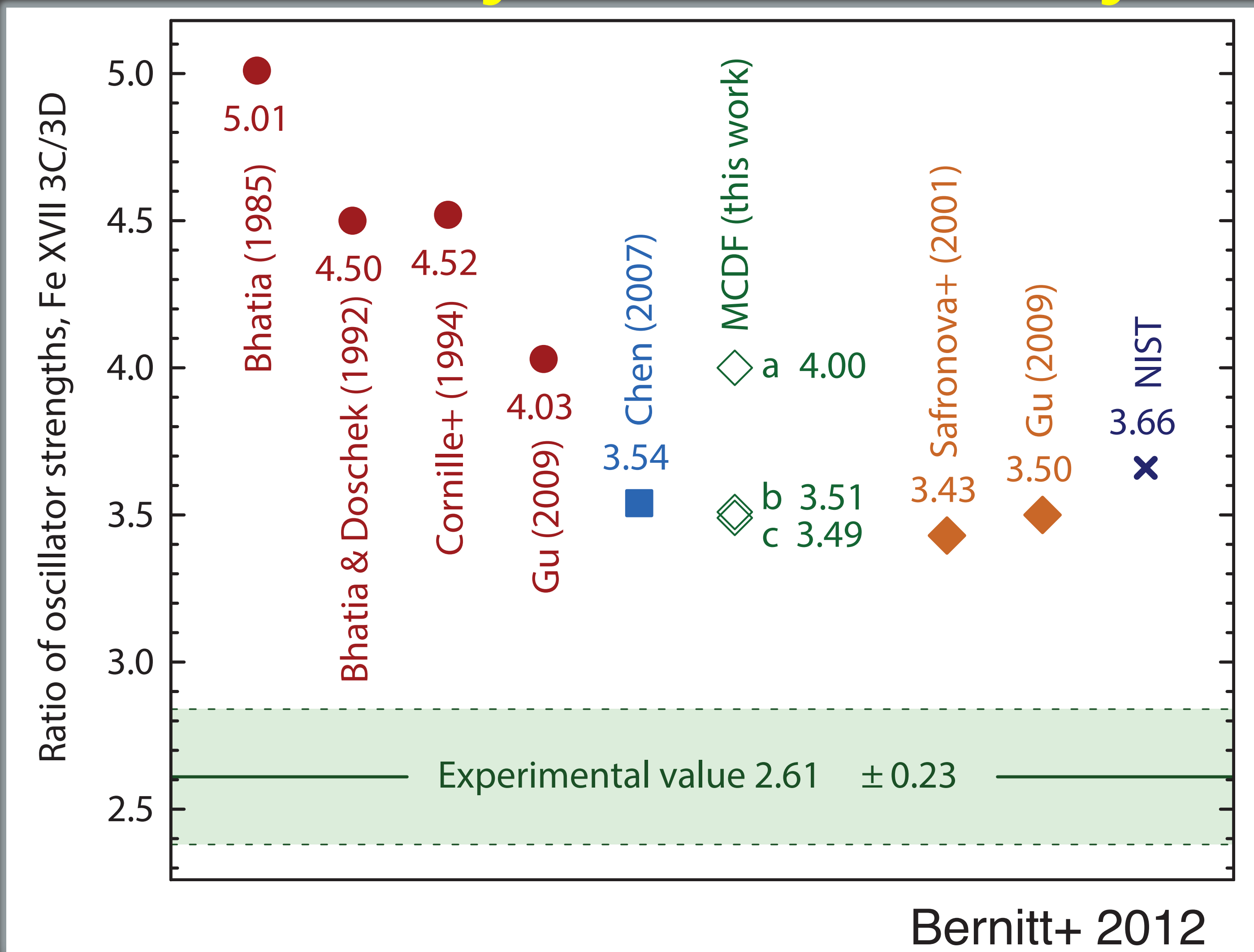
Fe XVII: Astrophysics & Theory



How does matter and energy move in and around galaxies?

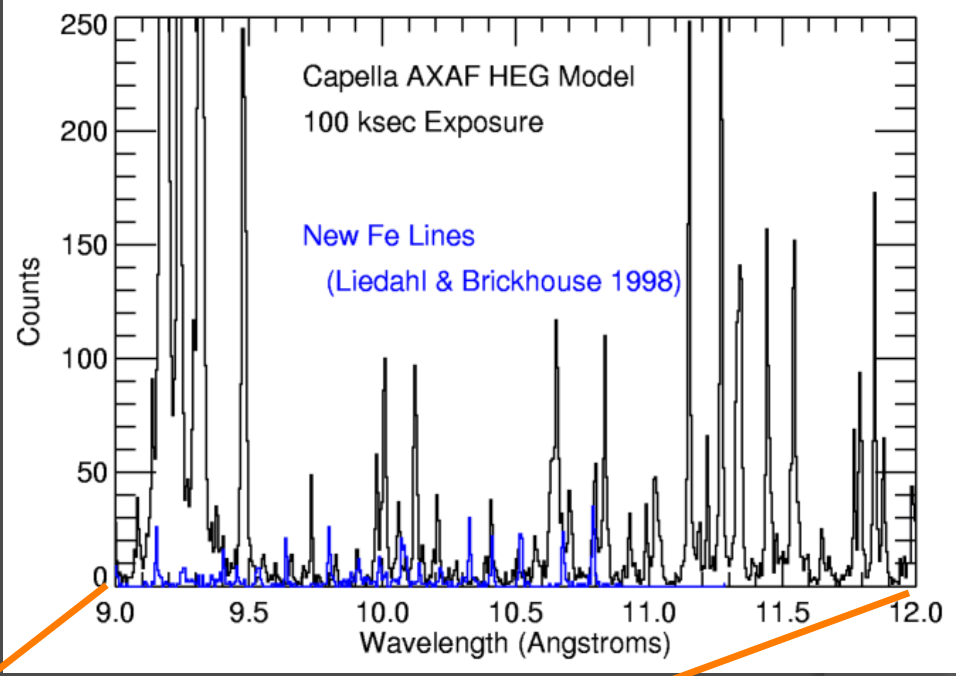
Fe XVII: Physics & Theory

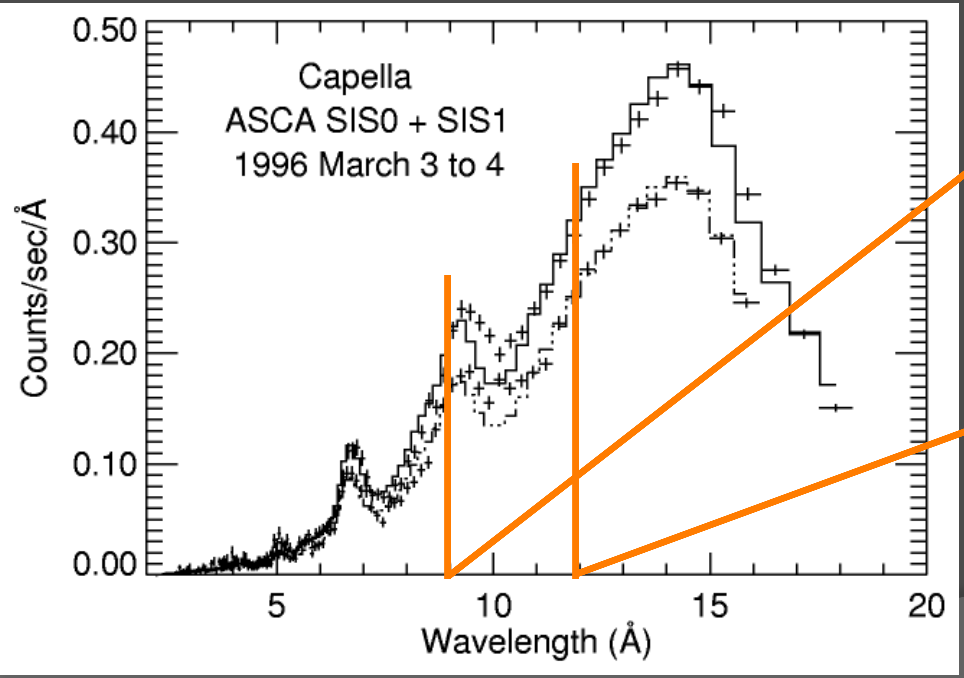


Data from LCLS

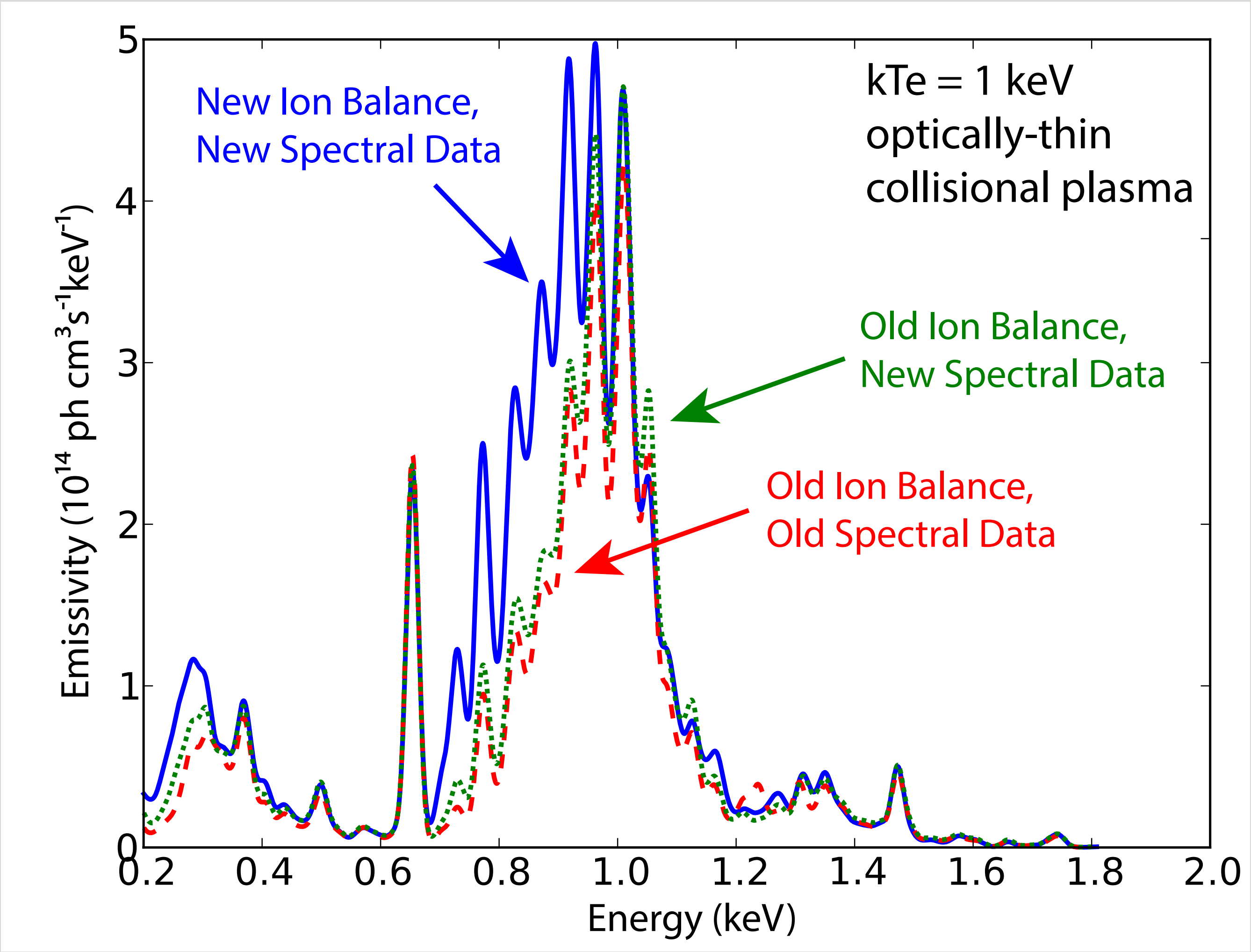
Early Improvements Pre-AtomDB

In this case, the poor fit between 9-12 Å is likely due to missing lines, not bad modeling.

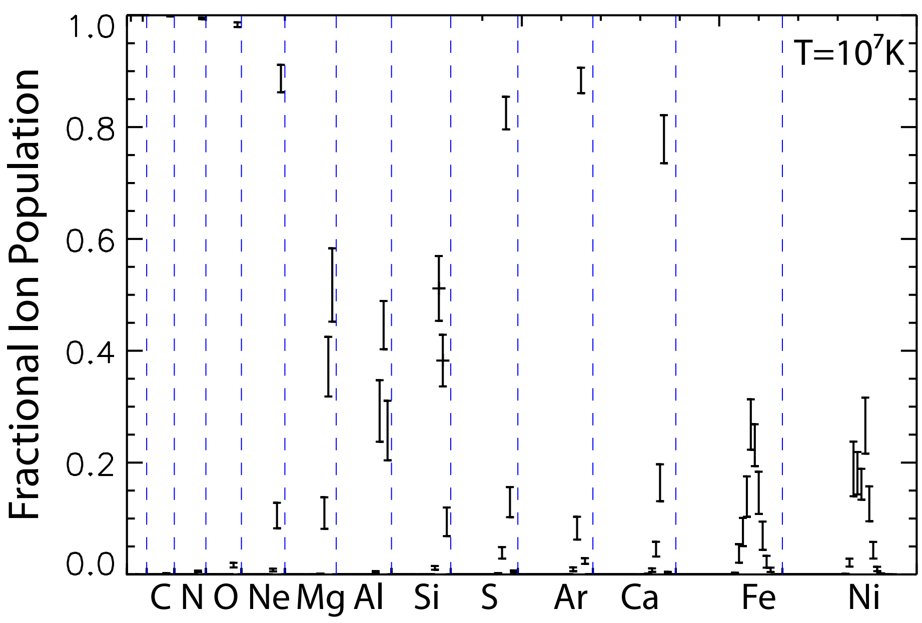


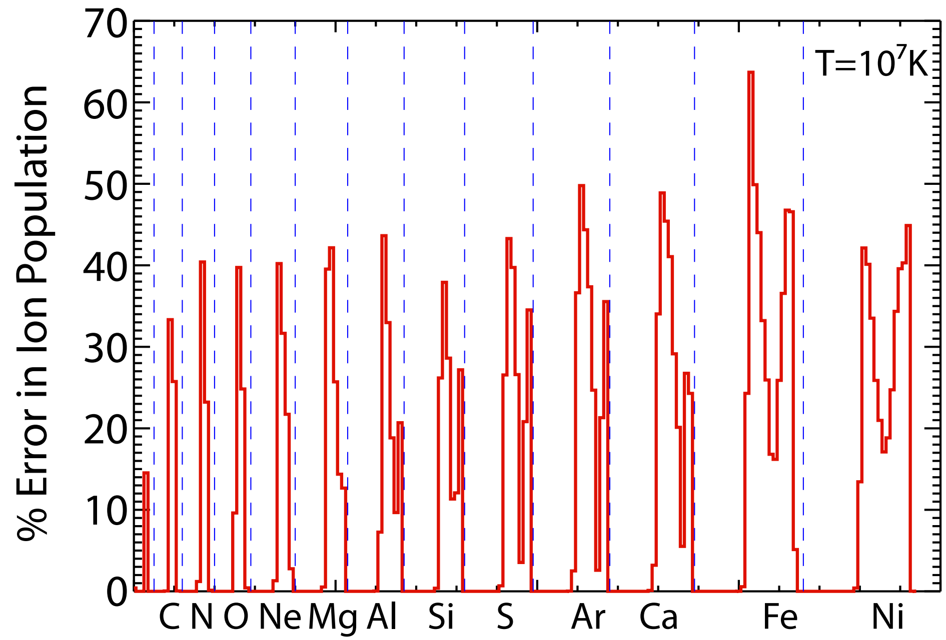


Impact of Data Updates



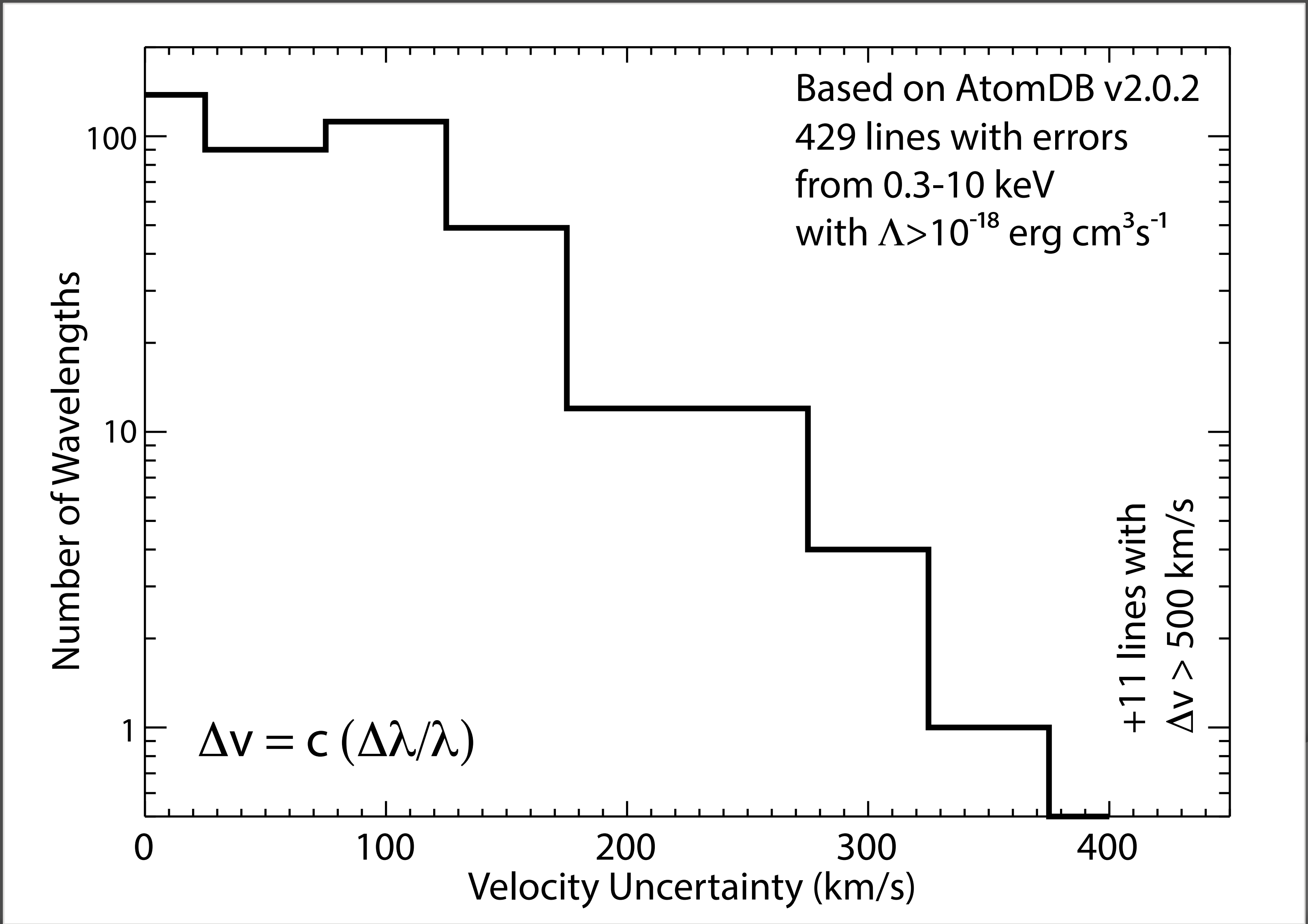
Current Problems: Ionization Balance



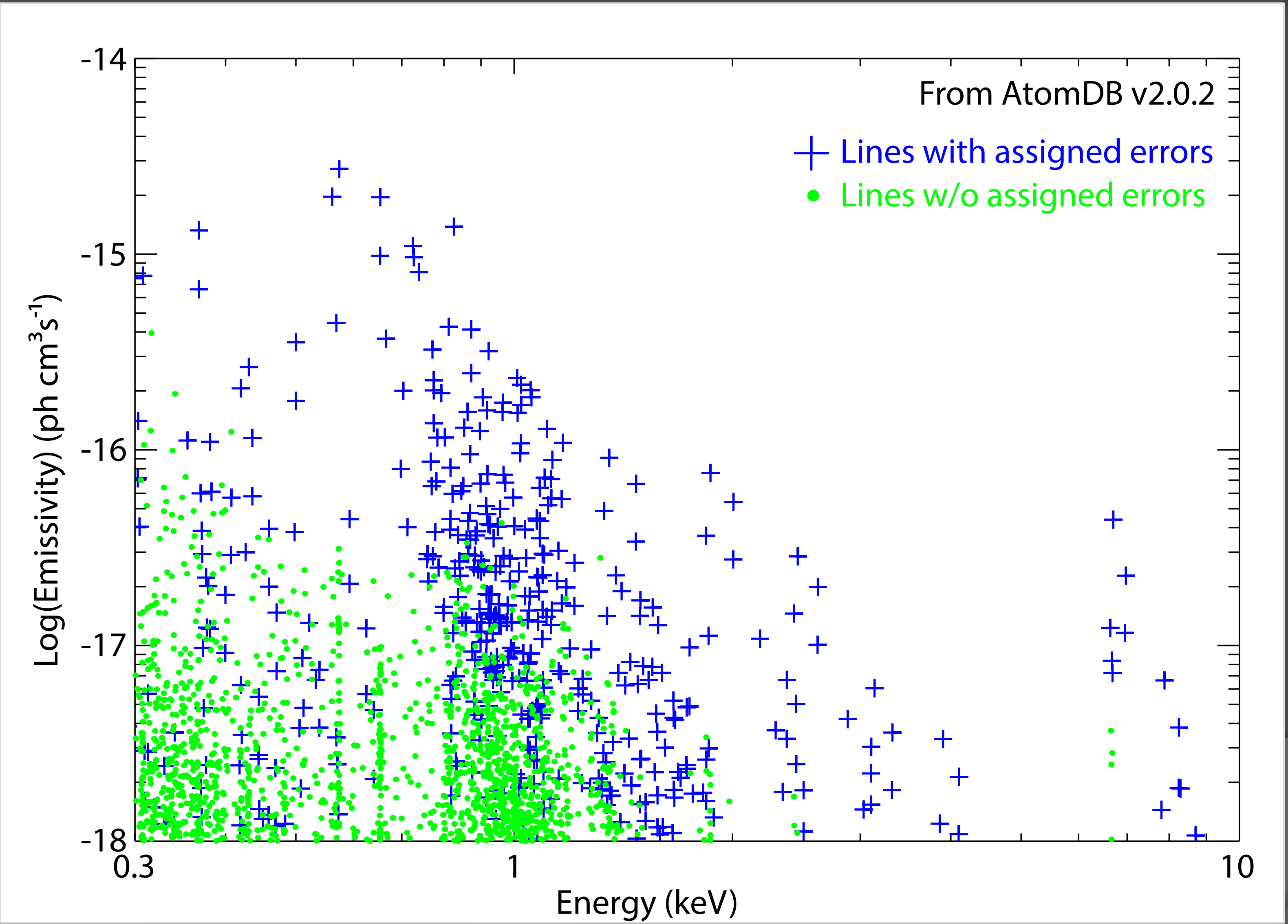


- 30% errors on the ionization & recombination rates leads to ~30% errors in the ion population.
- However, at the limits of an ion's population, these errors are increased up to 60%.

Wavelength Error Data

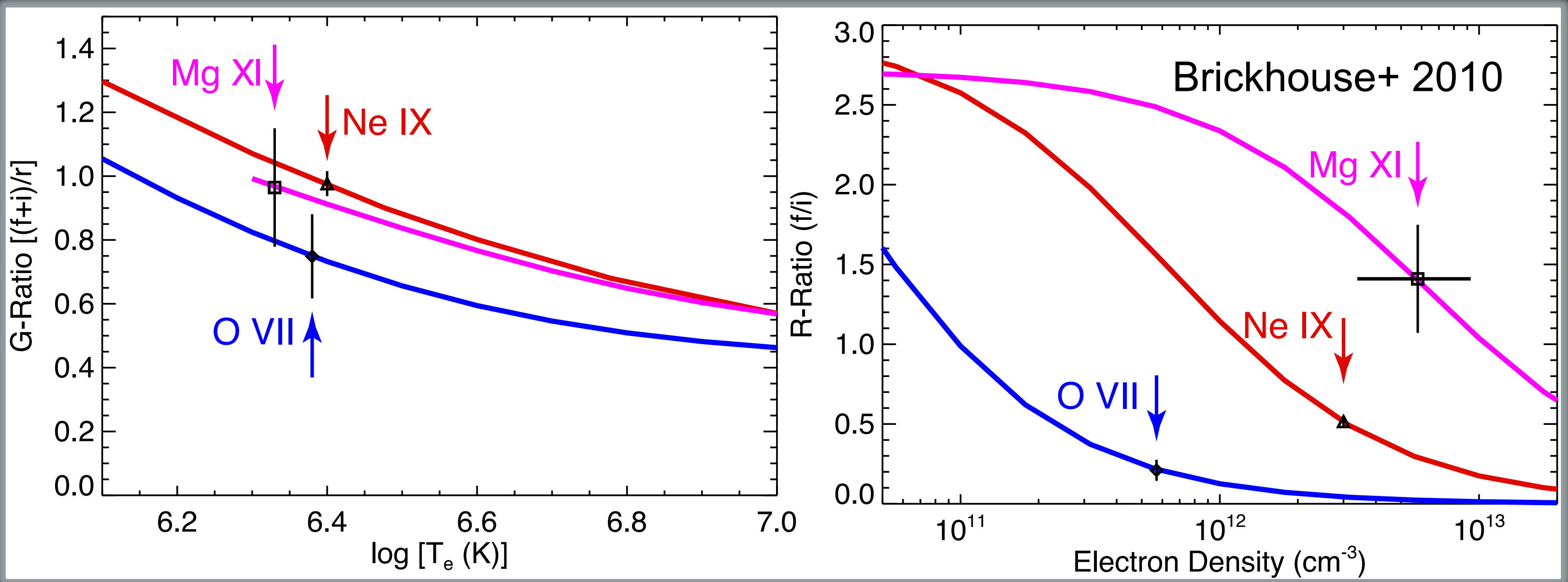


Wavelength errors incomplete



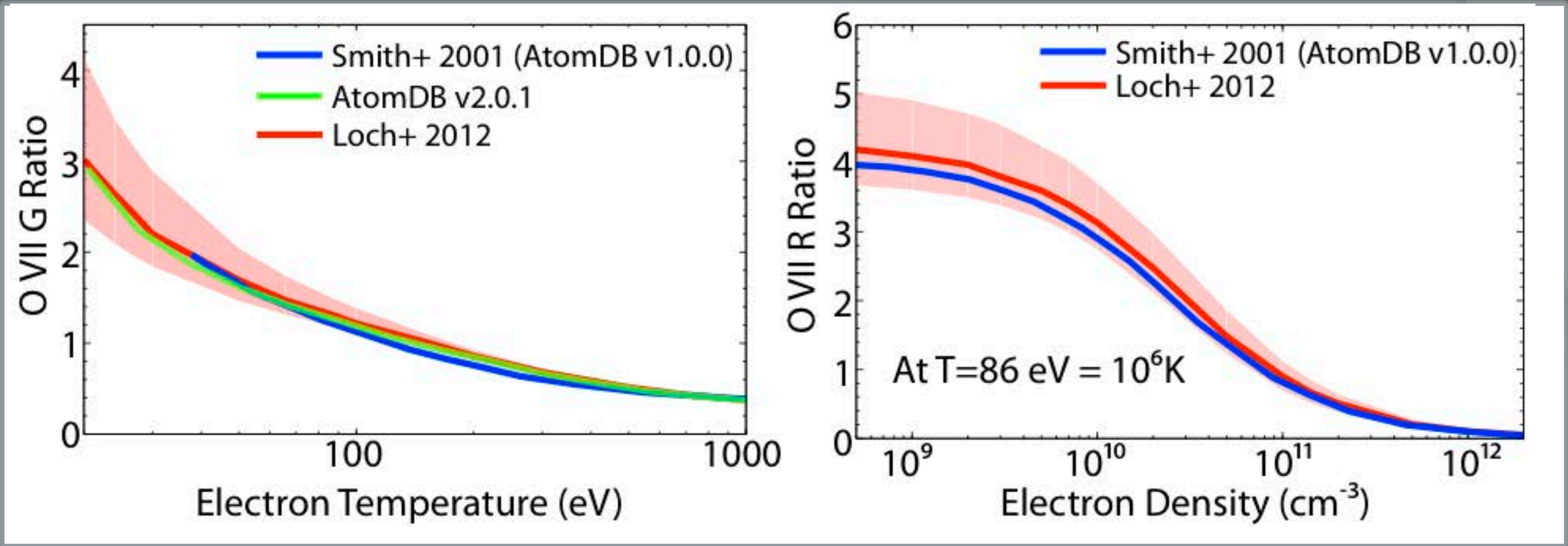
How do stars form?

Helium-like Diagnostics



While the temperature diagnostics for Mg XI, Ne IX, and O VII all give roughly the same result, the density diagnostics are significantly different.

Errors / Sensitivity Testing



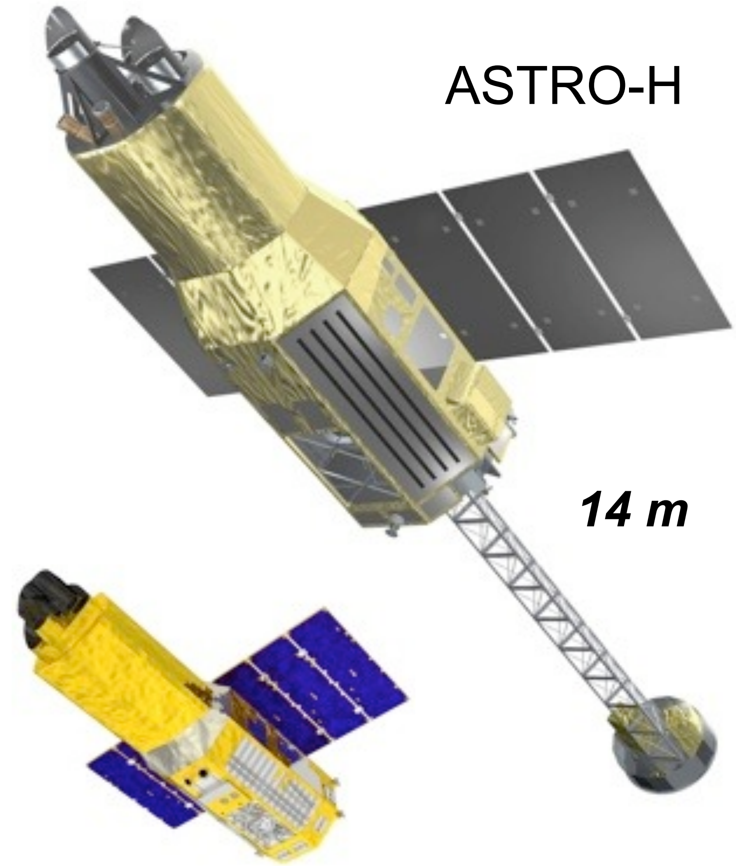
Theoretical calculations can use Monte-Carlo methods, varying the input atomic structure or calculation size to estimate sensitivities. Care is needed in using these, but they are **better than providing no estimate at all**.

See also Bravo & Martínez-Pinedo (2012)

Astro-H – Launching 2015 (!)

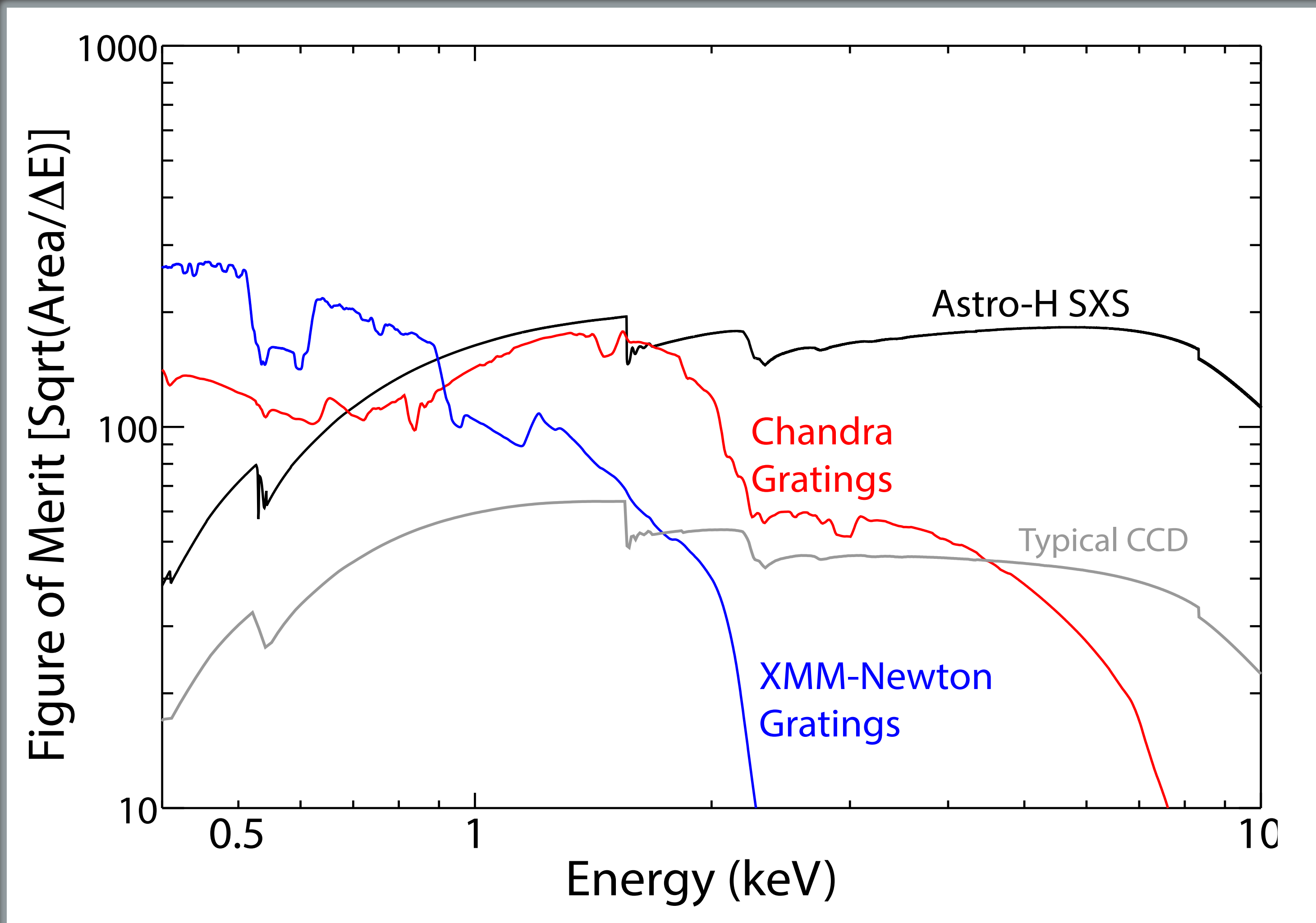
- **Launch site:**
  Tanegashima Space Center, Japan
- **Launch vehicle: JAXA H-IIA rocket**
- **Orbit Altitude: 550km**
- **Orbit Type: Approximate circular orbit**
- **Orbit Inclination: ~31 degrees**
- **Orbit Period: 96 minutes**

- **Total Length: 14m**
- **Mass: <2.6 metric ton**
- **Power: <3500 W**
- **Telemetry Rate: > 8 Mbps (X-band)**
- **Recording Capacity: > 12 Gbits**
- **Mission life : > 3 years**



Suzaku (6m, 1.7t)

Figure of Merit for Detecting Weak Lines

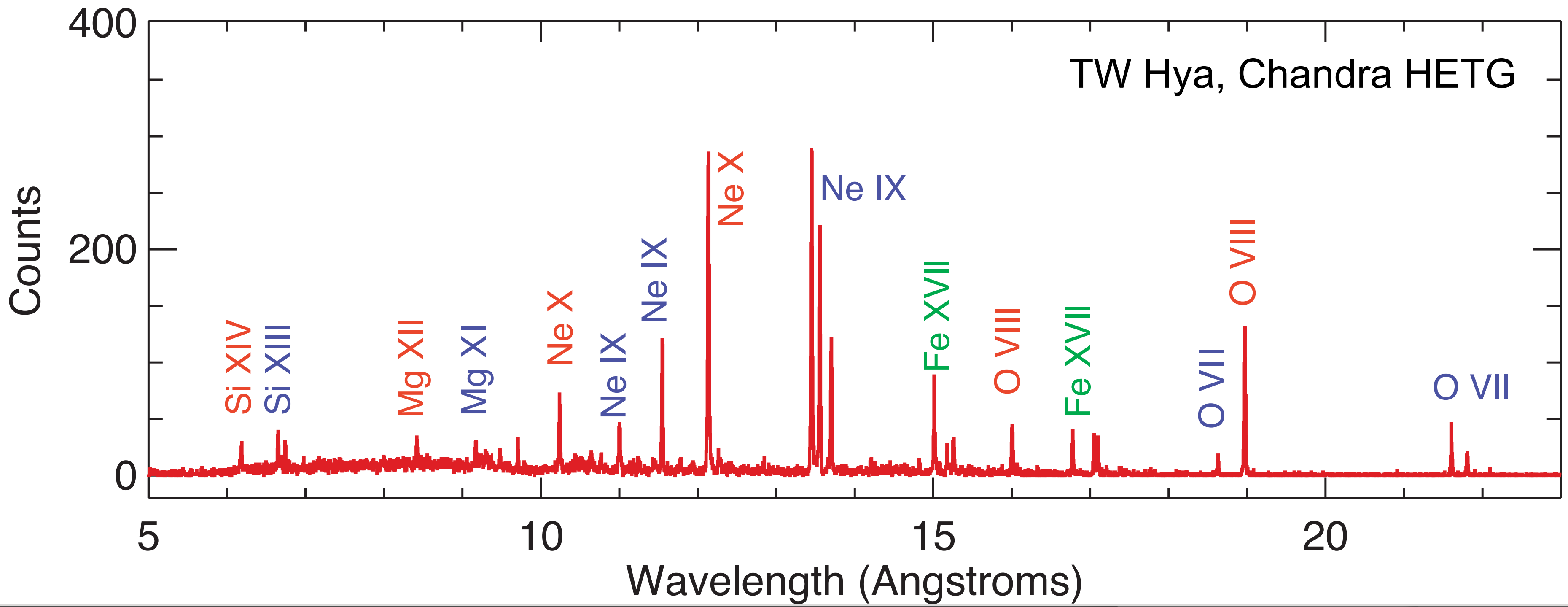


What Do X-ray Astronomers Need?

(To be ready for Astro-H)

- Precise and accurate data for calibration and interpretation. Ordered by importance:
  - Wavelengths
  - Line widths/shapes/blends
  - Fluxes
- Reliable and practical estimates of data accuracy (especially in X-ray astronomy!)

Major needs are the ***best possible*** **H-like**, **He-like**, and **Fe** (and to a lesser extent Ni) **L-shell** data (λ's, Einstein A's, collisional σ(E), etc).

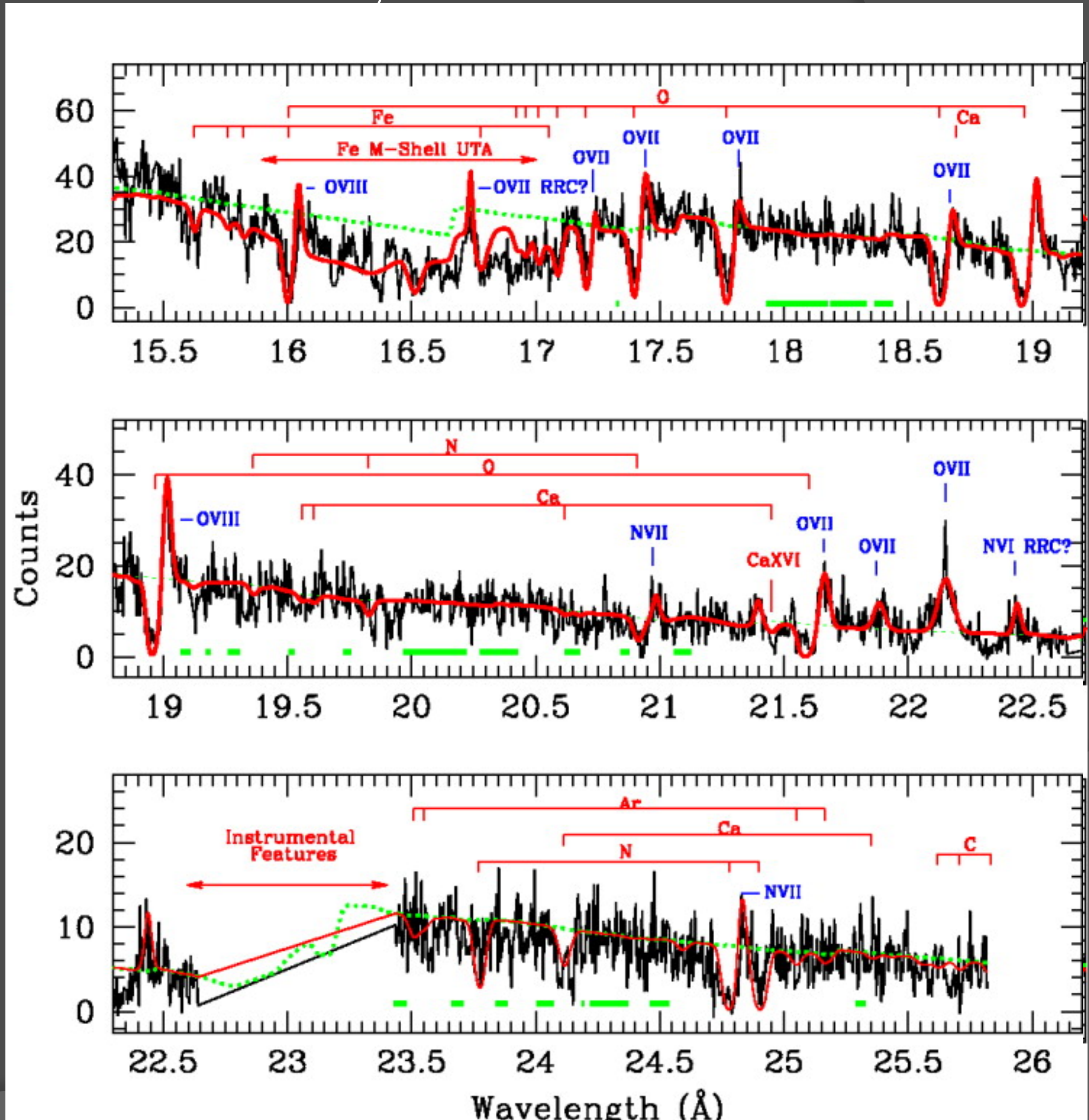


Brickhouse et al. 2010

A Few Words about X-ray Needs

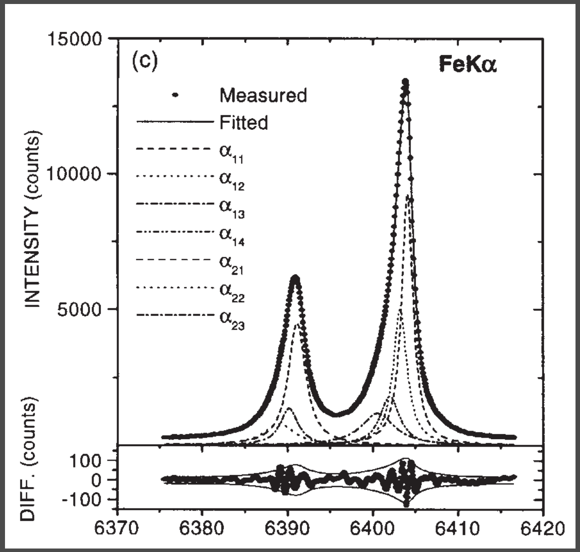
- Photoionized plasmas are more complex as both collisional and photon cross sections are relevant.
- However, H-like, He-like, and Fe ions are still key (although other ions play a larger role).

NGC 3783 – X-ray bright Seyfert galaxy; 900 ksec HETG, 280 ksec RGS observations

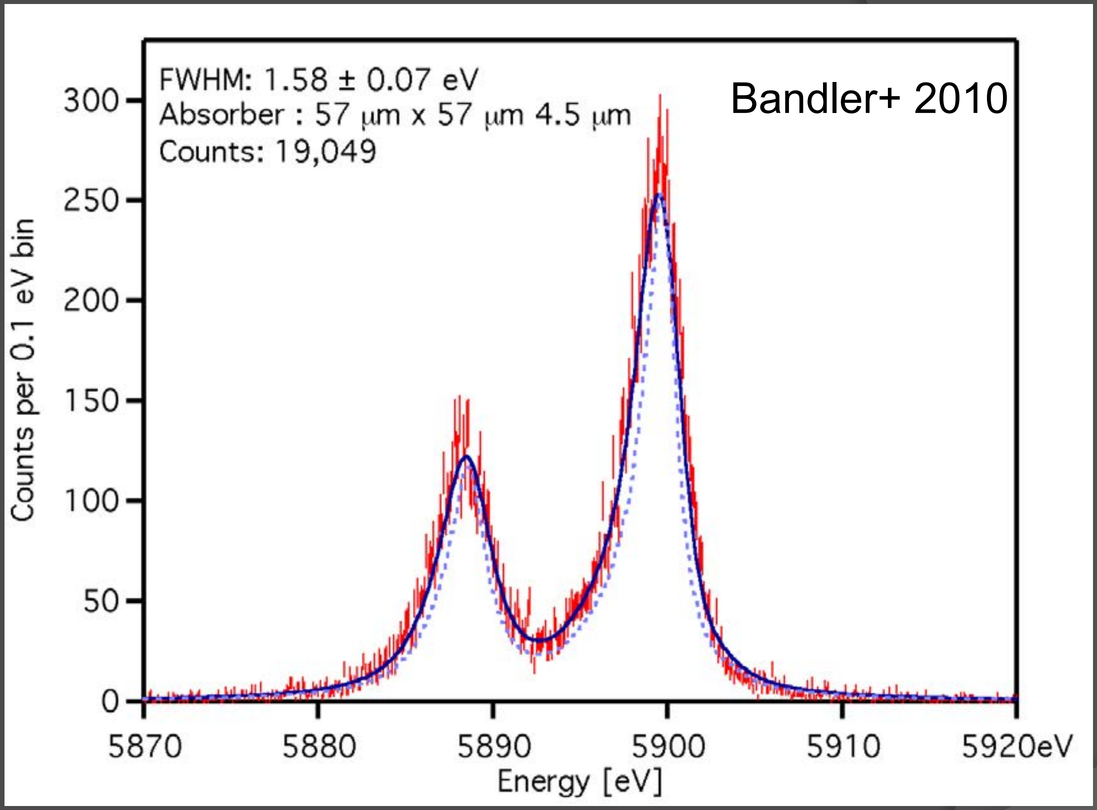


Krongold *et al.* 2003; also Netzer *et al.* 2003 and Behar *et al.* 2003

Calibration: Fluorescent Lines



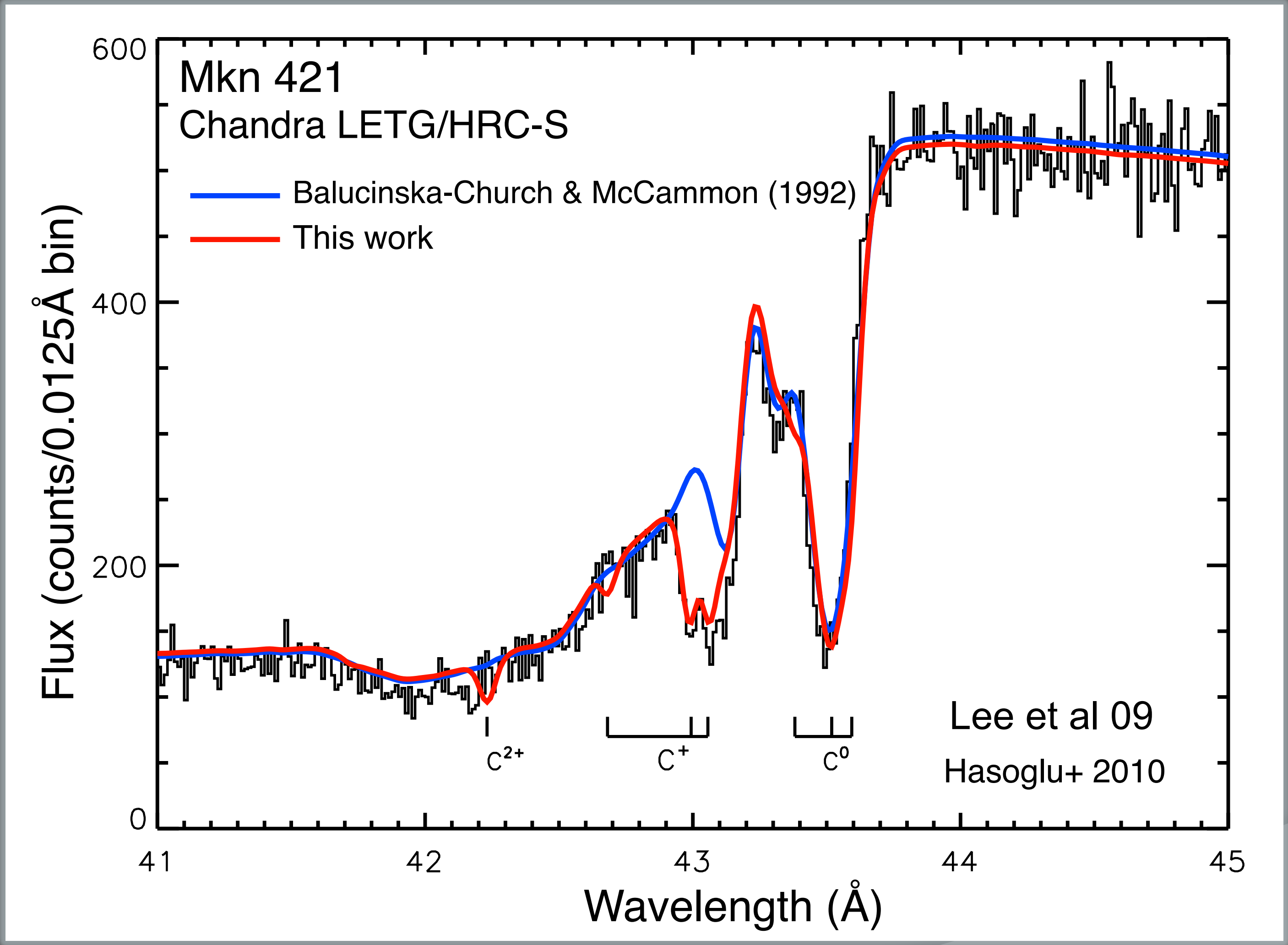
Hoelzer+ 1997



The fluorescent lines from radioactive sources are complex of many lines.

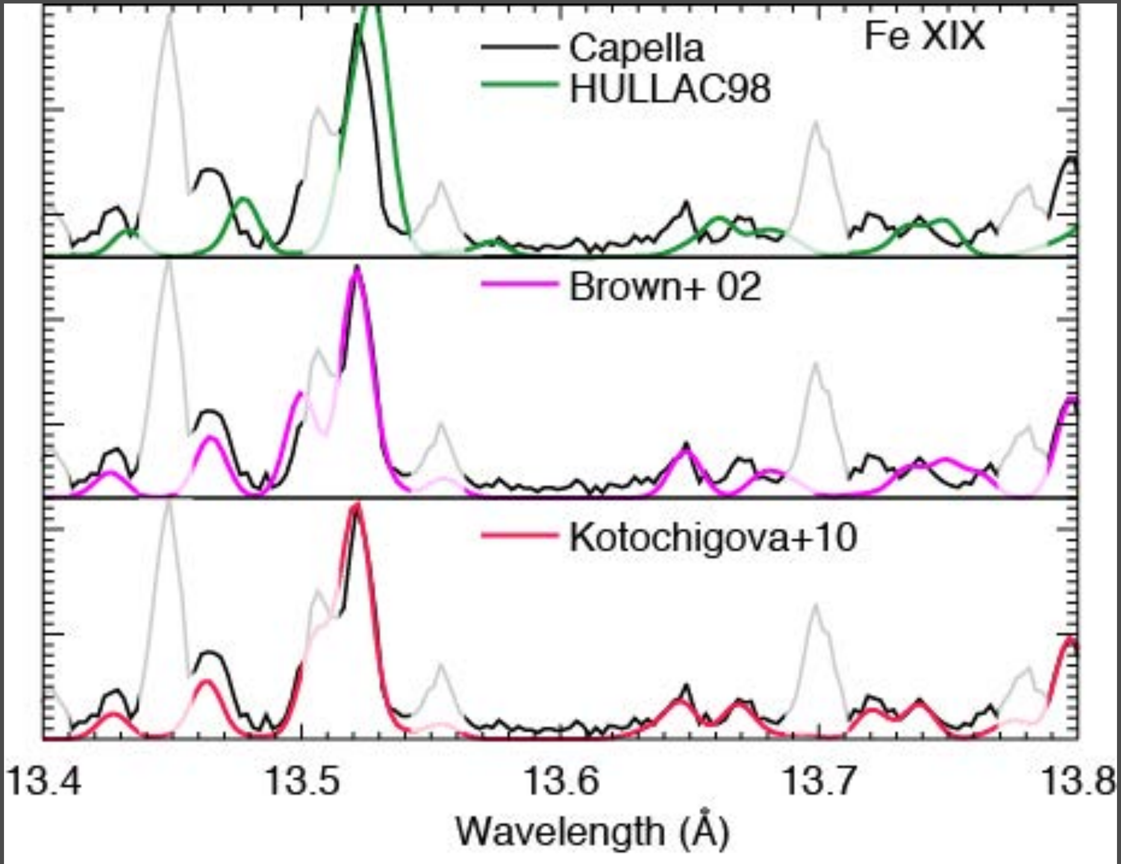
Line widths measured by current calorimeters are dominated by the natural line widths – which are not known for many useful elements!

Calibration: Absorption Cross Sections



Absorption edges and related features still need a lot of work…

Calibration: Wavelengths



Fit using 'raw' HULLAC wavelengths

Fit using lab (Brown et al. 1998) wavelengths

Fit using newly calculated wavelengths

Kotochigova+ 2010

- By combining laboratory measurements and theoretical structure calculations, can get highly accurate (few mÅ) wavelengths.
- Detectors with R>1000 require this kind of accuracy!

Conclusions

Point #1:

Maintaining a tight connection between identified astrophysical questions and lab astro measurements and calculations is key to motivating progress (and funding).

Conclusions

Point #2:

15 years ago, we knew existing X-ray spectral models would not survive the imminent arrival of new capabilities from Chandra and XMM-Newton

- Inadequate Fe L shell models with missing lines and inaccurate wavelengths
- Out of date models for H, He-like ions

Conclusions

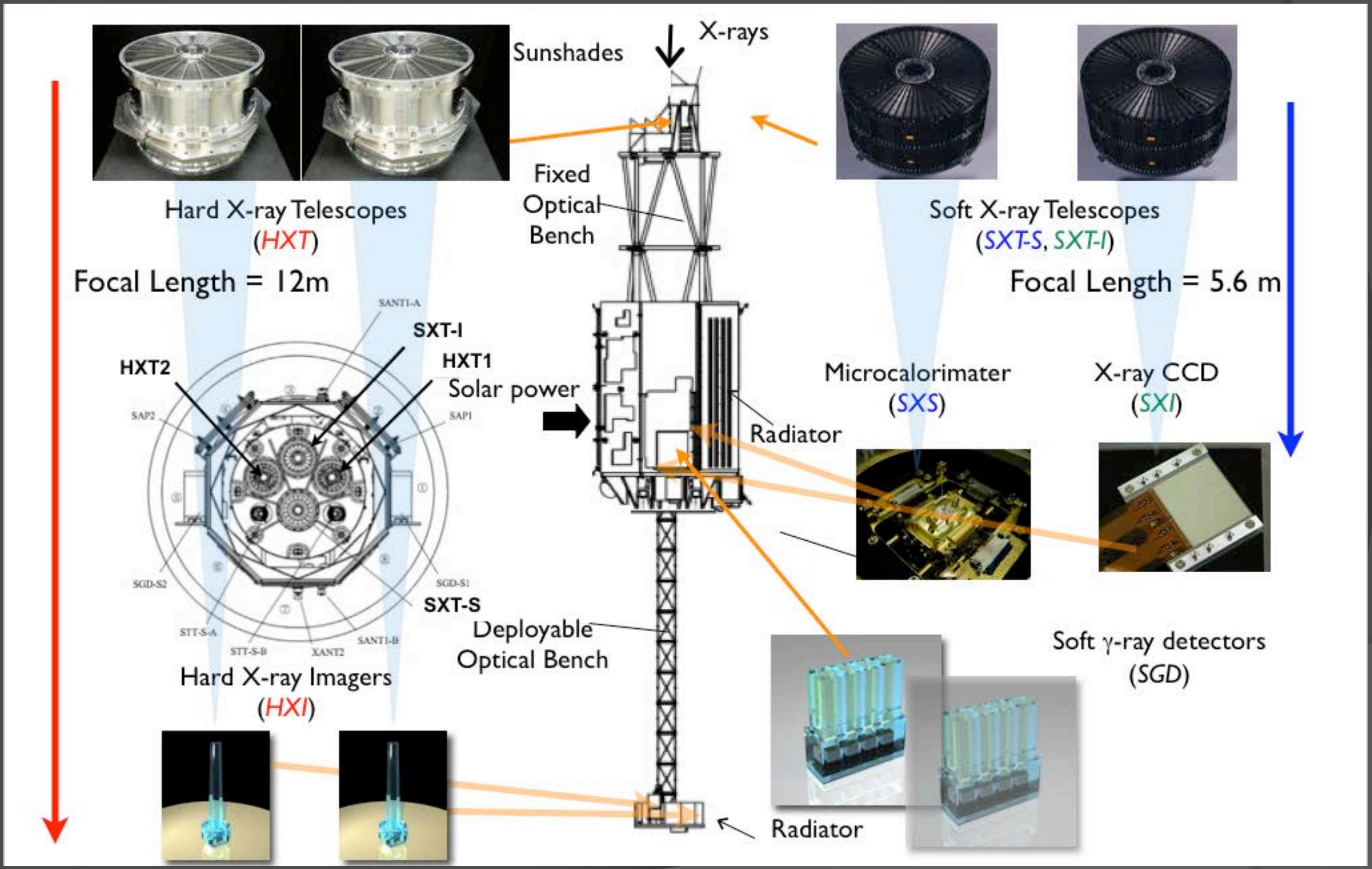
Point #3:

Astro-H will soon increase the effective area of X-ray spectroscopy 100-fold

- Some data are still missing: Ni L-shell, Fluorescent lines from select ions, Fe L-shell wavelengths, **AND**
- Current approach of assuming zero spectral model errors will lead to data that cannot be interpreted.

Backup

Astro-H Instrumentation



“X-ray Line Emission from the Sun”

Unexpectedly strong solar X-rays were first detected on August 5, 1948 from a repurposed V-2 rocket launch.

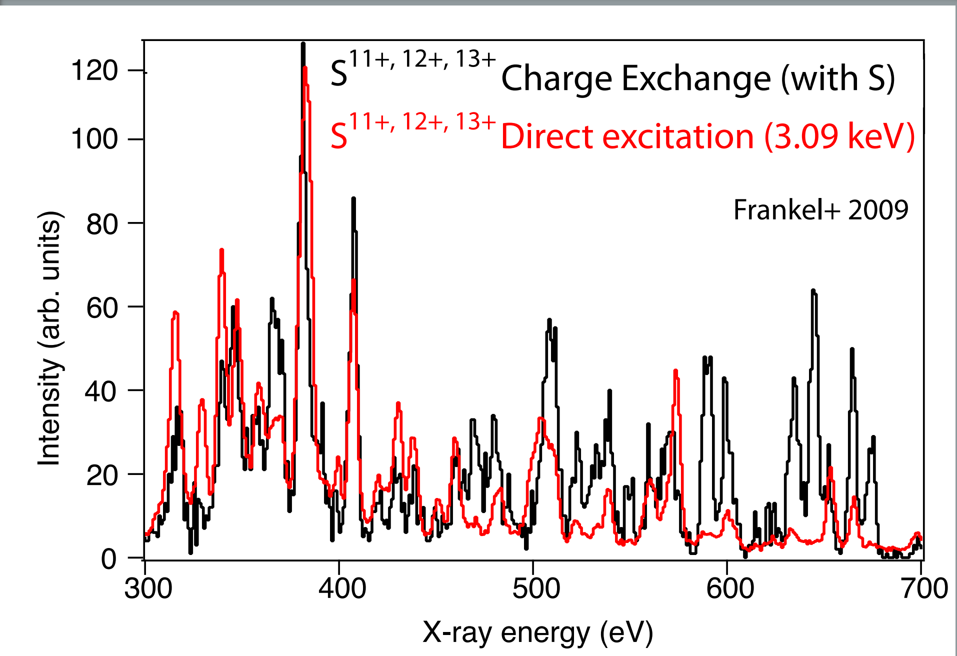
The X-rays and optical data on the Solar corona suggested a $\sim 10^6$K plasma was responsible

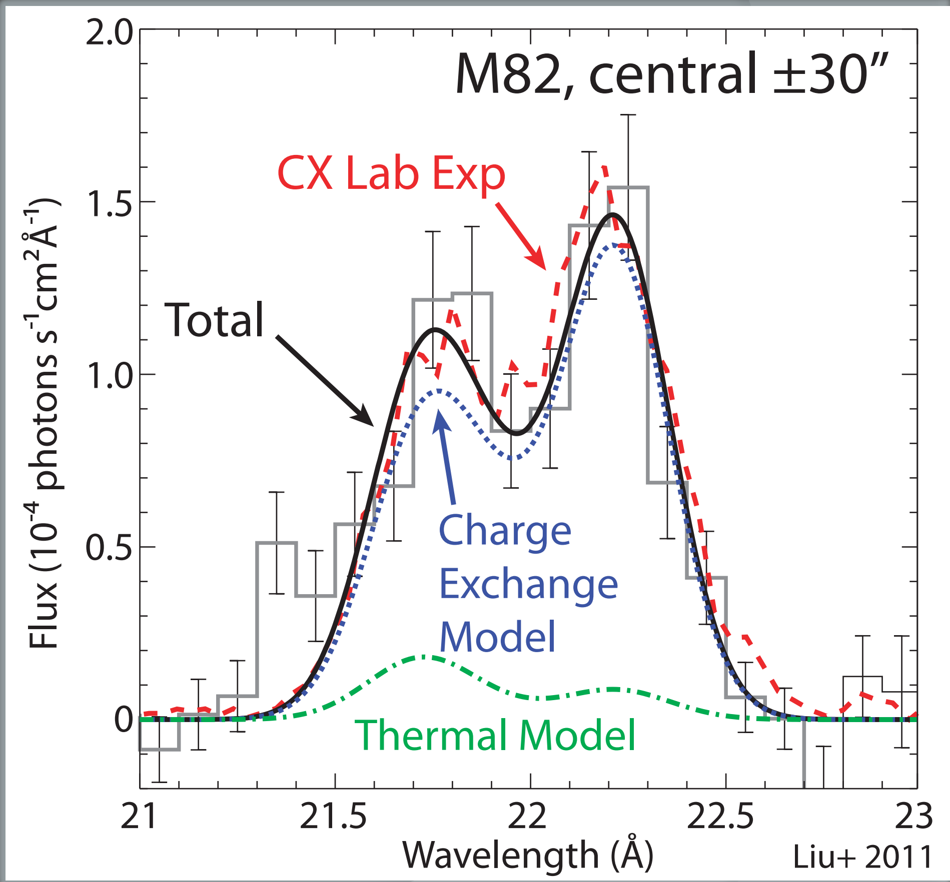
Burnight 1949, Phys Rev 76, 165

B12. Soft X-Radiation in the Upper Atmosphere. T. R. Burnight, *Naval Research Laboratory.*—A simple experiment consisting of small casettes containing photographic films and plates behind thin aluminum and beryllium windows of various thicknesses have been flown in a number of rockets at White Sands. On August 5, 1948 such an experiment obtained exposures through .076 cm beryllium windows indicating an unexpected intensity of radiation of wave-length shorter than 4 angstroms. On November 18, 1948 an experiment with .00076 and .00153 cm thickness aluminum and .0254 cm beryllium windows was flown with no indication of x-rays being obtained. On December 9, 1948 an identical experiment obtained appreciable blackening through .00076 cm aluminum windows but not through .0254 cm beryllium windows. The sun is assumed to be the source of this radiation although radiation of wave-length shorter than 4 angstroms would not be expected from theoretical estimates of black body radiation from the solar corona. A semiquantitative determination of the intensities indicated has been made, and the possible correlation with solar activity at the time of firing will be presented.

Identifying Recombining Plasmas – High-resolution spectra

In the lab…





In the sky…