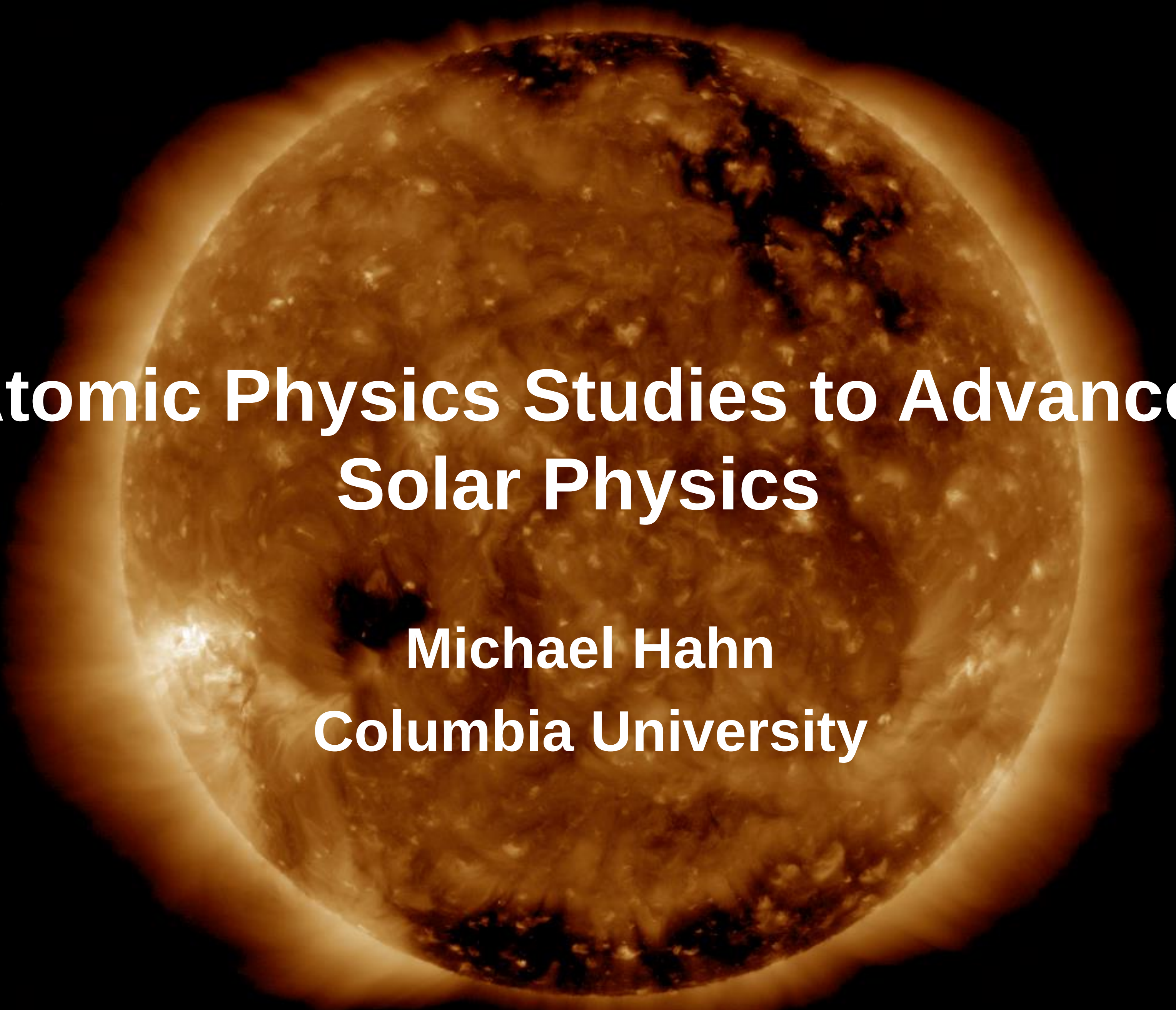


Atomic Physics Studies to Advance Solar Physics

Michael Hahn
Columbia University

Acknowledgements

Columbia
Thusitha Arthanayaka
Sayak Bose (PPPL)
Alex Fairchild
Chloe Guennou
Stefan Hofmeister
Garima Joshi
Alexandros Koukras
Daniel Wolf Savin

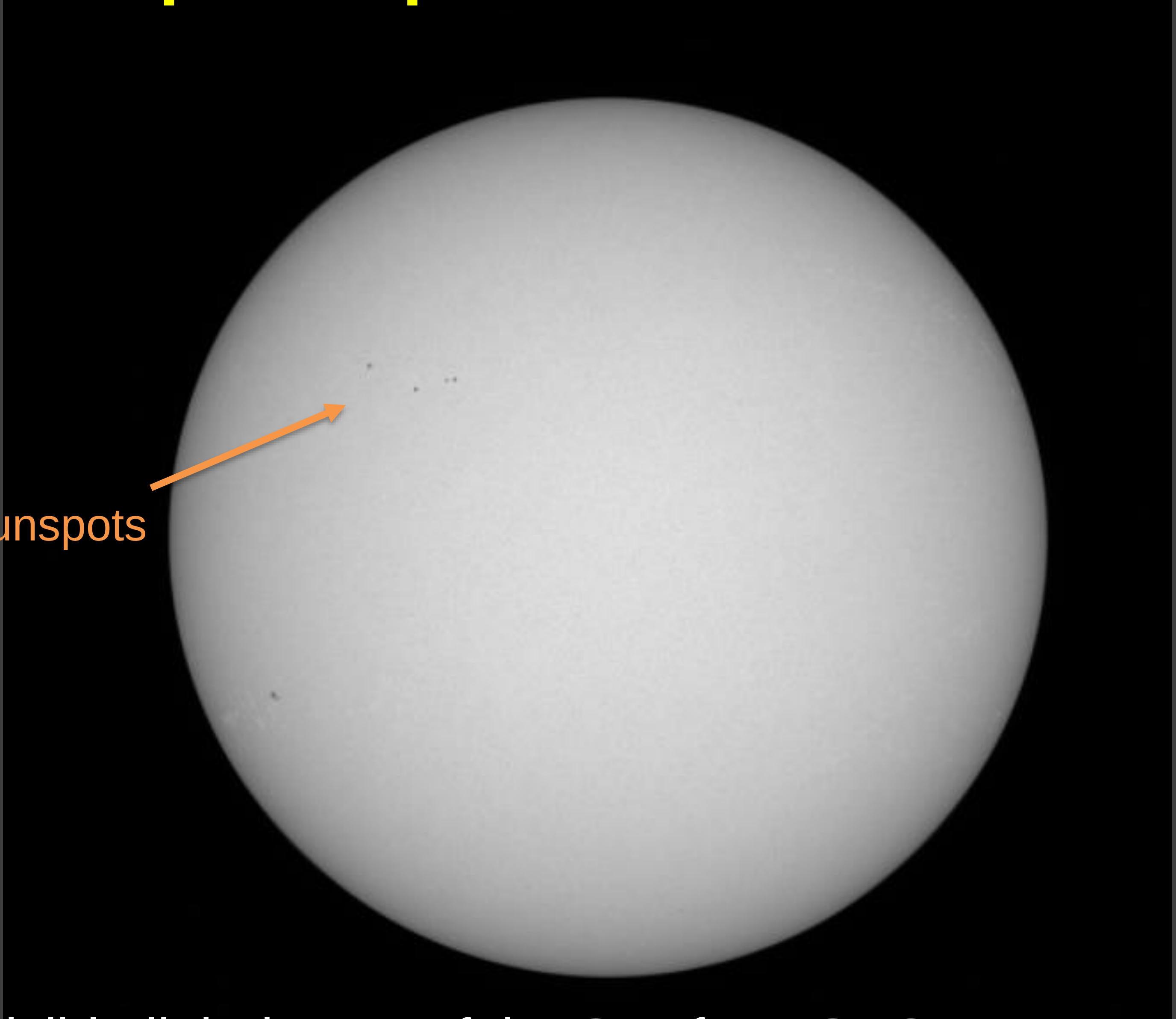
LLNL
Peter Beiersdorfer
Greg Brown
Ming Feng Gu
Natalie Hell
Tom Lockard

MPIK
Dietrich Bernhardt
Manfred Grieser
Claude Krantz
Michael Lestinsky
Alfred Müller
Oldrich Novotny
Roland Repnow
Stefan Schippers
Kaija Spruck
Andreas Wolf

Outline

- Basic structure of the Sun and the coronal heating problem.
- Temperature measurements
  - Rely on the balance between ionization and recombination.
- Density measurements
  - Rely on level populations and long-lived electronic states.
- Line identifications

The photosphere is about 6000K



Visible light image of the Sun from SDO

The corona is about 1 million K

Why?

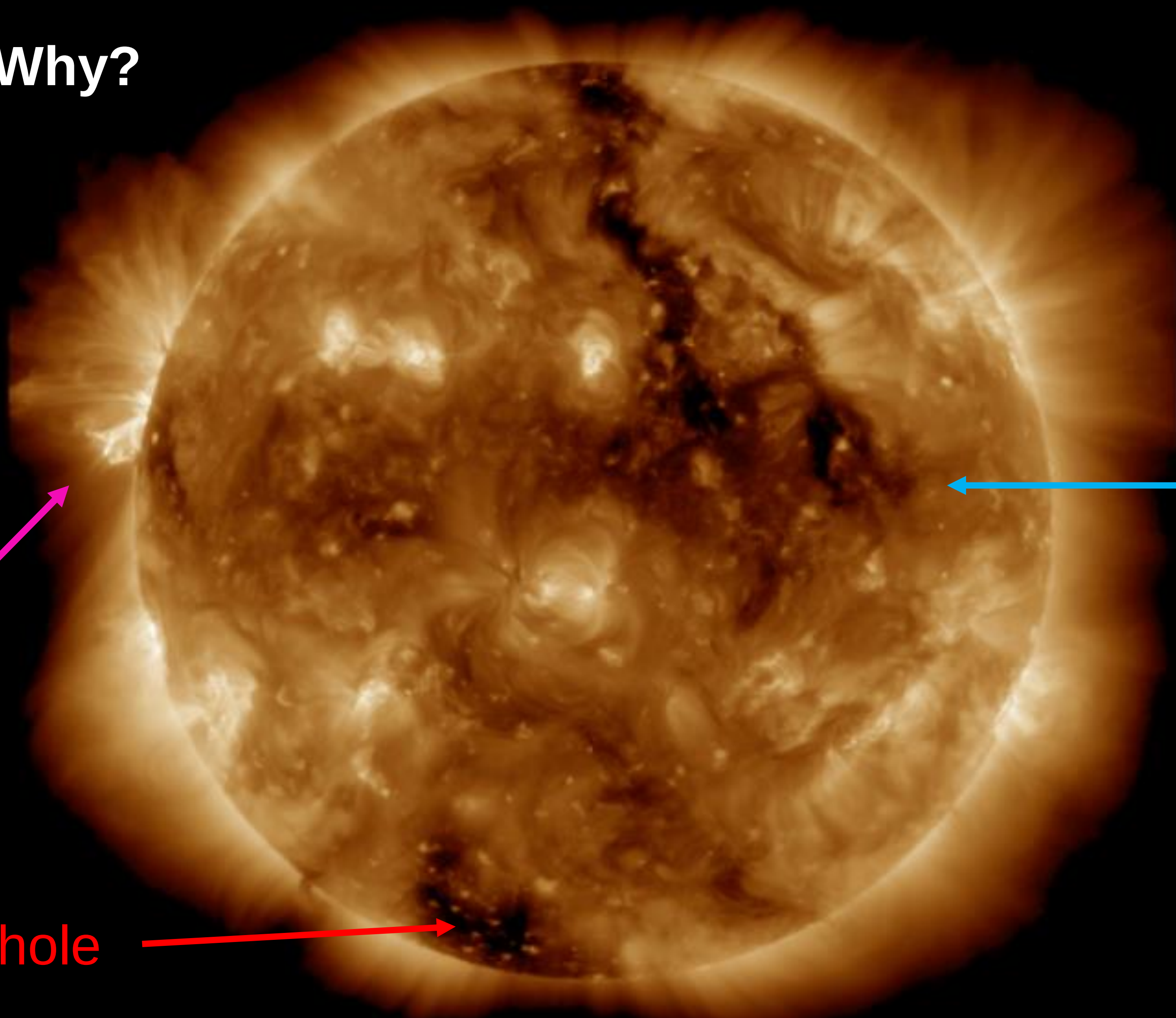


Image at 193 Å, showing emission from Fe^{11+}.

The coronal heating problem

An unresolved problem is to explain why the corona is so hot.

The main theories are

- waves transport energy from lower layers
- reconnection of magnetic fields release energy

To test theory, need to accurately measure the energy in the corona.

How hot is it?

T – average energy of particles in gas or plasma.

n – number density of particles

So, energy density $E \sim nT$

Spectroscopy

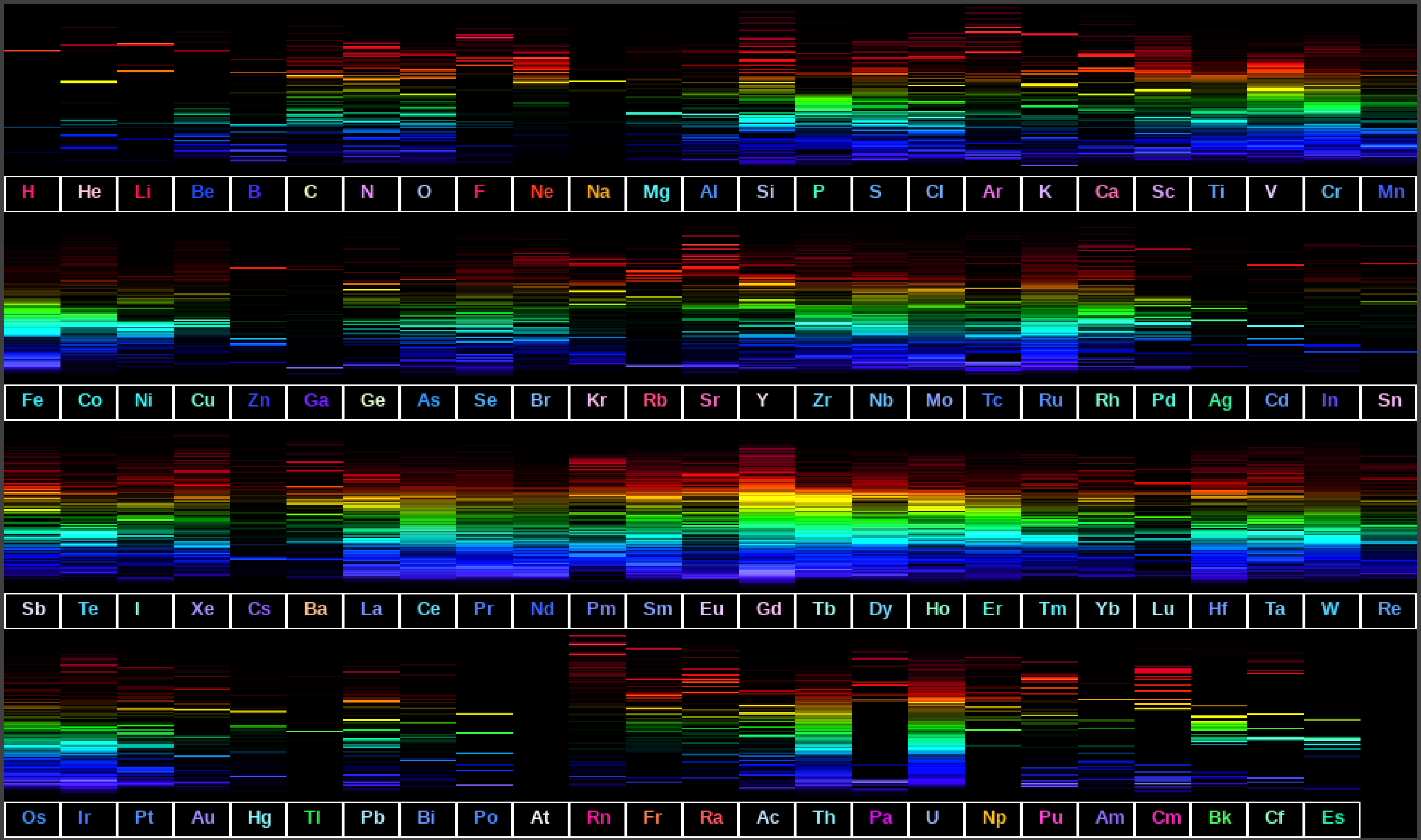


image: umop.net based on NIST data.

Green spectral line at 530 nm

First observed in 1869 during an eclipse.

An unknown element "coronium"?

1939 quantum theory showed it was from Fe^{13+} .

The corona must be very hot!

Total Solar Eclipse 1981 © 1981 Július Sýkora © 2007 Miloslav Druckmüller

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Interpreting spectra quantitatively

Intensity of spectral line depends on atomic properties

$$I_{ji} \propto G_{ji}(T,n)\mathrm{EM}$$

where

Average rate [s^{-1}] for electrons to fall from level j to i

$$G_{ji}(T,n) = \frac{n_j(X^{+q})}{n(X^{+q})}\frac{n(X^{+q})}{n(X)}\frac{n(X)}{n(H)}\frac{n(H)}{n}\frac{A_{ji}}{n}$$

Ions with electrons excited to level j (basis of n measurements)

fraction of element X ionized to +q (basis of T measurements)

amount of element X compared to H

amount of H compared to free electrons

Collisional Ionization Equilibrium (CIE)

Equilibrium ionization and recombination to *q* balances ionization from *q* to *q*+1 and recombination from *q* to *q*-1

$$\frac{dX^{+q}}{dt} = I_{q-1,q}X^{+q-1} - I_{q,q+1}X^{+q} - R_{q,q-1}X^{+q} + R_{q+1,q}X^{+q+1}$$

$I_{q,q+1}$ -- ionization rate from *q* to *q+1*
$R_{q,q-1}$ -- recombination rate from *q* to *q-1*

Derived from experimental or theoretical cross sections:

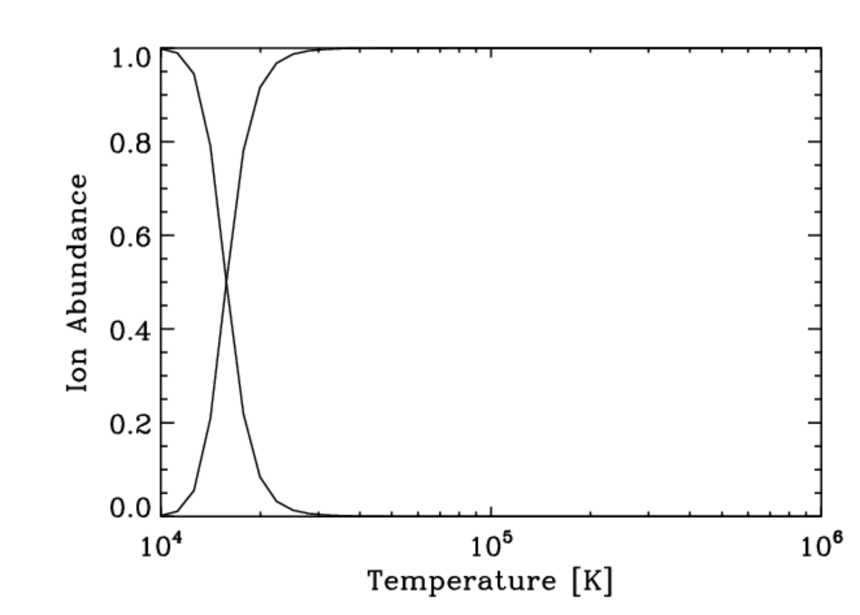
$$I_{q,q+1} = \sigma_{q,q+1} v n$$

σ = cross section units of area, v = speed, n =density

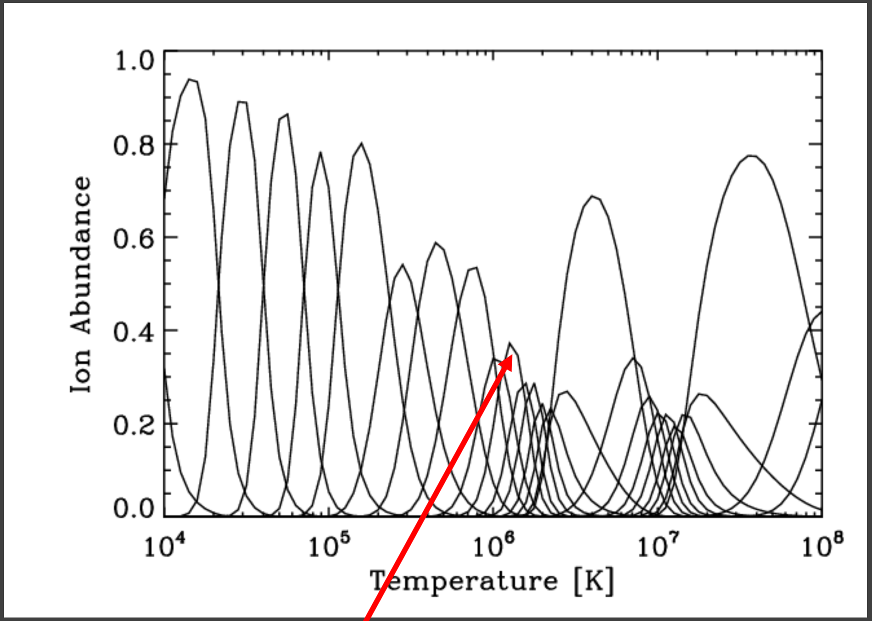
σ depend on collision energy, i.e., T

Ionization Equilibrium Examples

Hydrogen



Iron

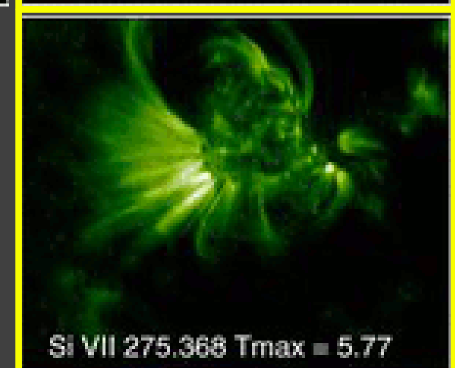


Peak is at the “formation temperature”

CIE problems in solar physics

hotter

$T = 6.5 \times 10^5$ K



$T = 5.9 \times 10^5$ K

T from calculations of Mazzotta et al. (1998)

$T = 6.5 \times 10^5$ K

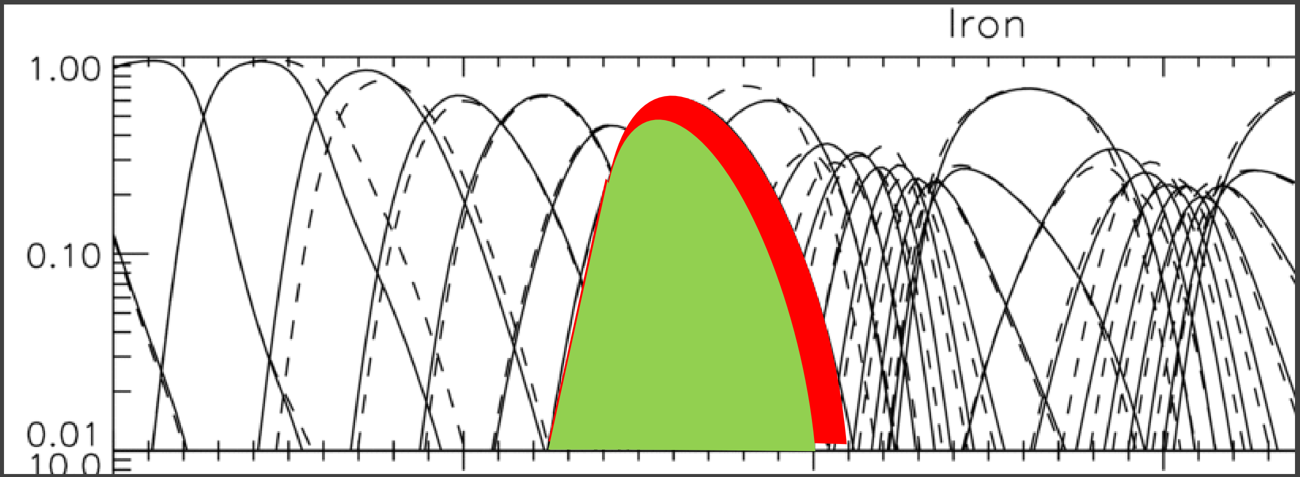
$T = 3.7 \times 10^5$ K

Brooks, Warren, & Young (2011)

CSD balances ionization and recombination

Fe VIII

Relative Abundance



4 5 6 7

Log temperature [K]

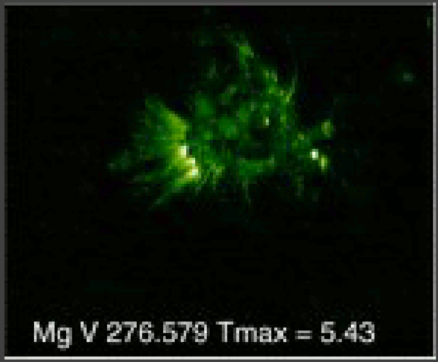
Green – Fe VIII from Mazzotta et al. (1998)

Red – Fe VIII from Bryans et al. (2009)

Improved data shows Fe VIII forms at higher *T*

New EII calculations move in right direction

hotter →



Tmax from CIE of ~~Mazzotta et al. (1998)~~

Bryans et al. (2009)

~~T = 5.9 x 10^5 K~~

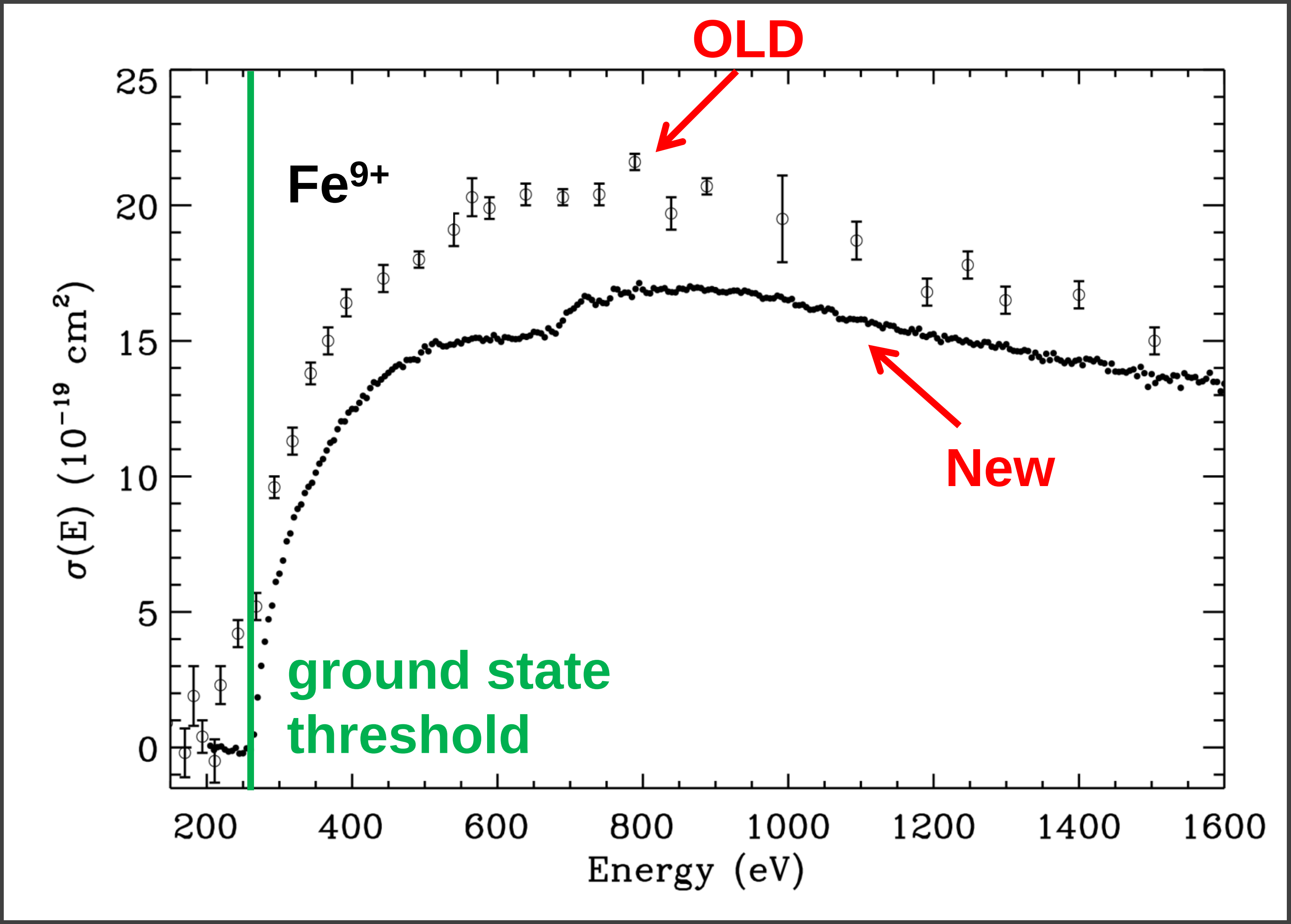
T = 6.0 x 10^5 K

~~T = 3.7 x 10^5 K~~

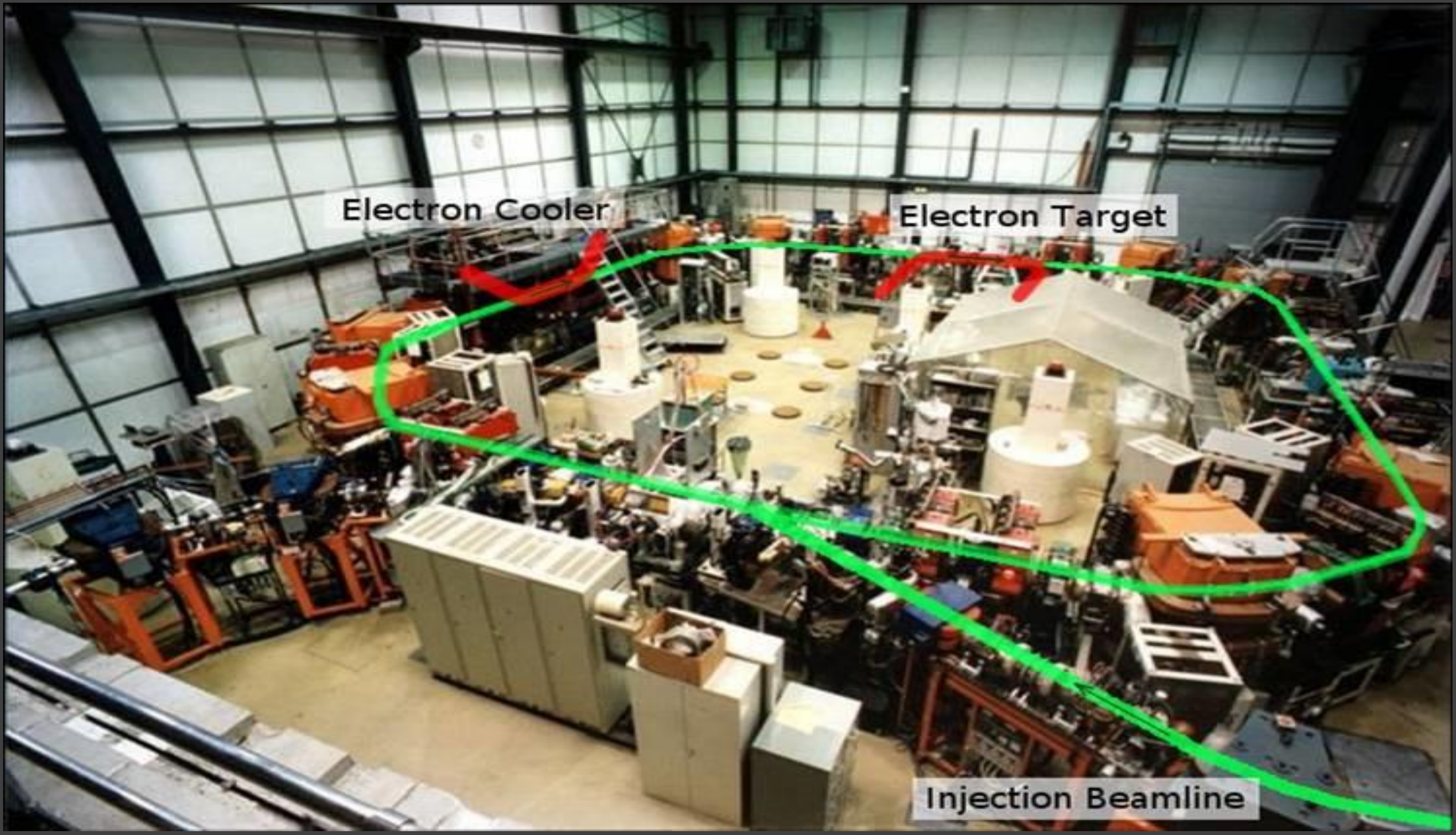
T = 4.2 x 10^5 K

Brooks, Warren, & Young (2011)

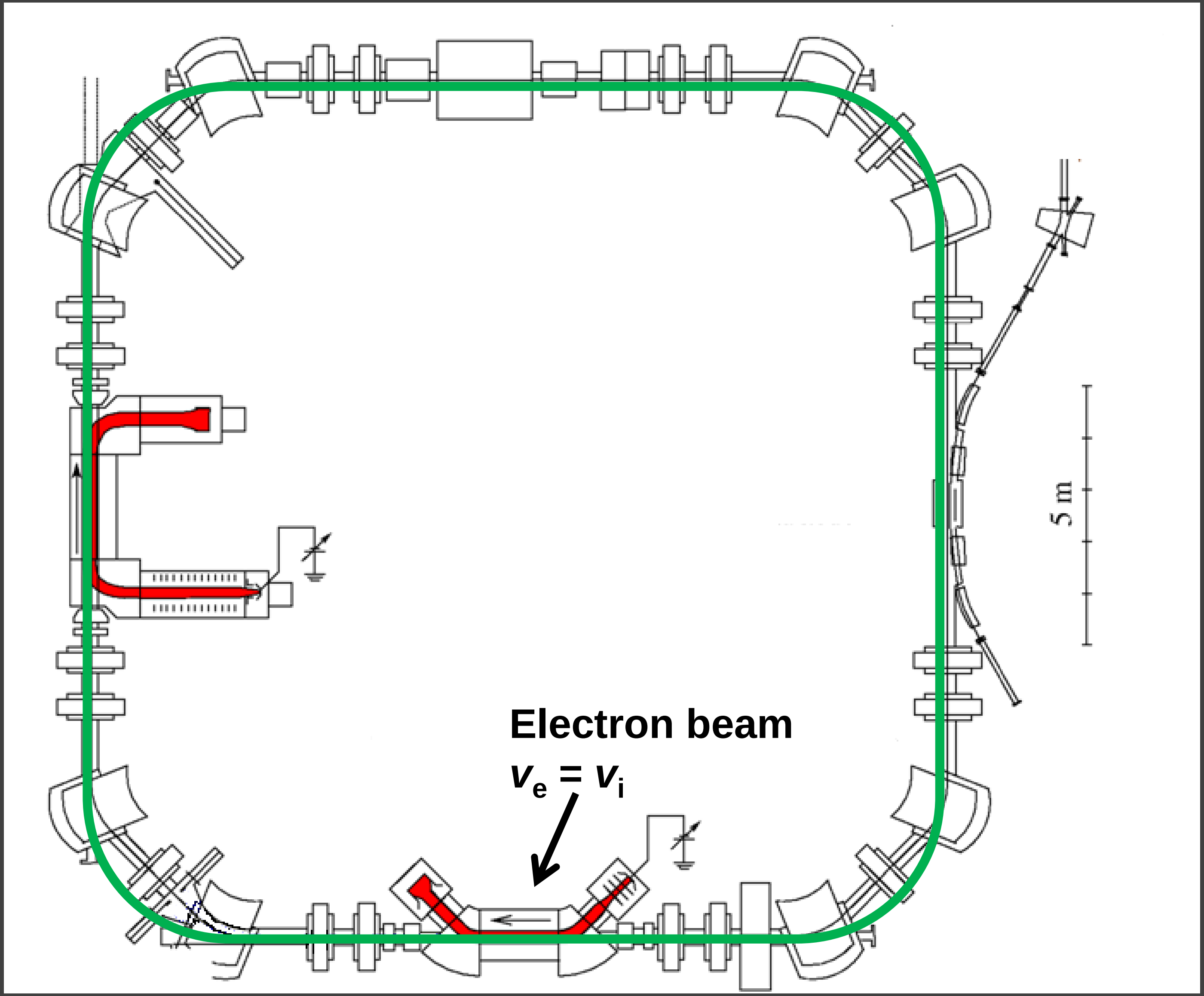
Challenge is to measure a known initial state



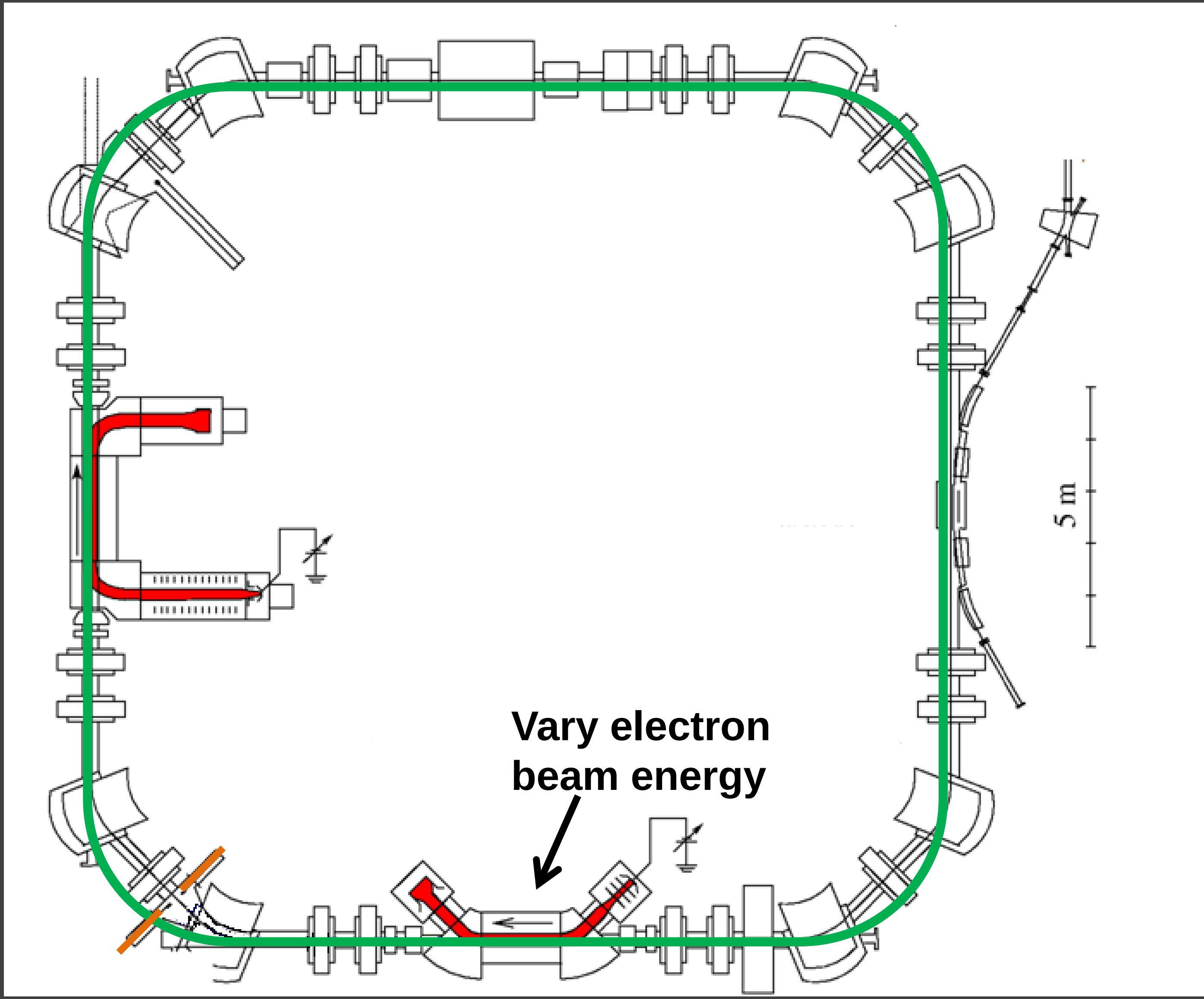
TSR heavy ion storage ring



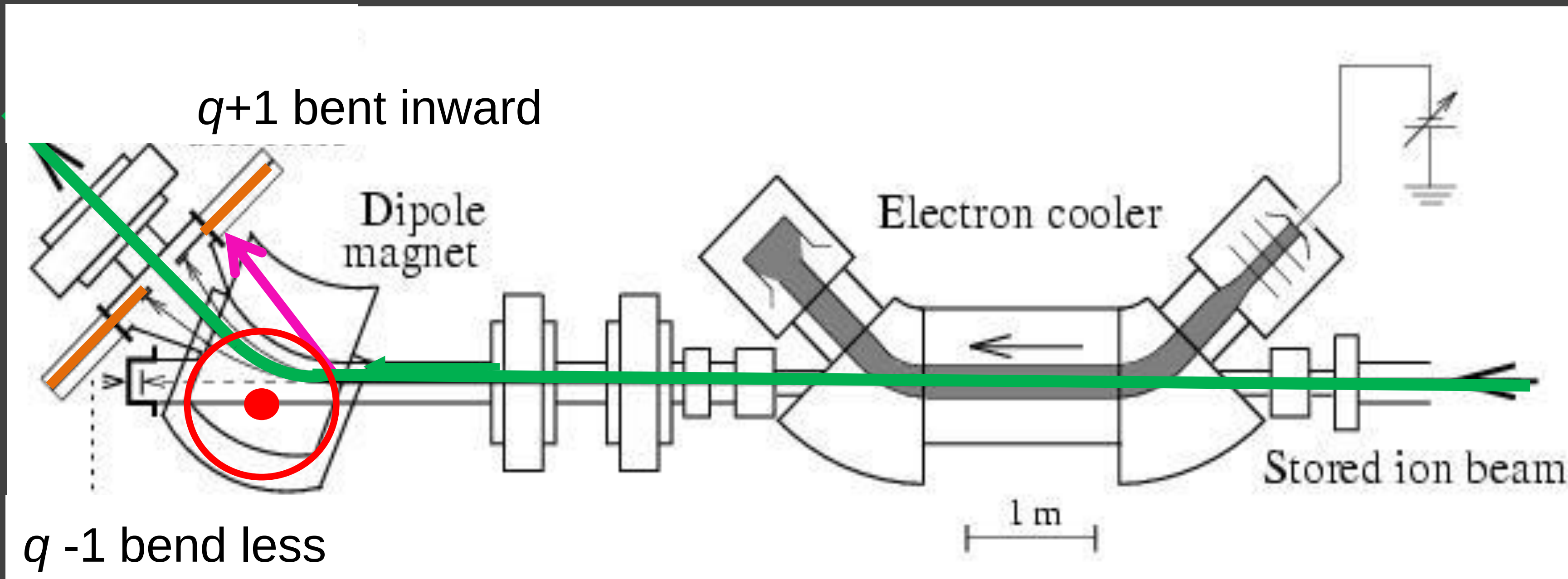
Step 1: store ions so metastables decay



Step 2: vary collision energy



Step 3: count collision products

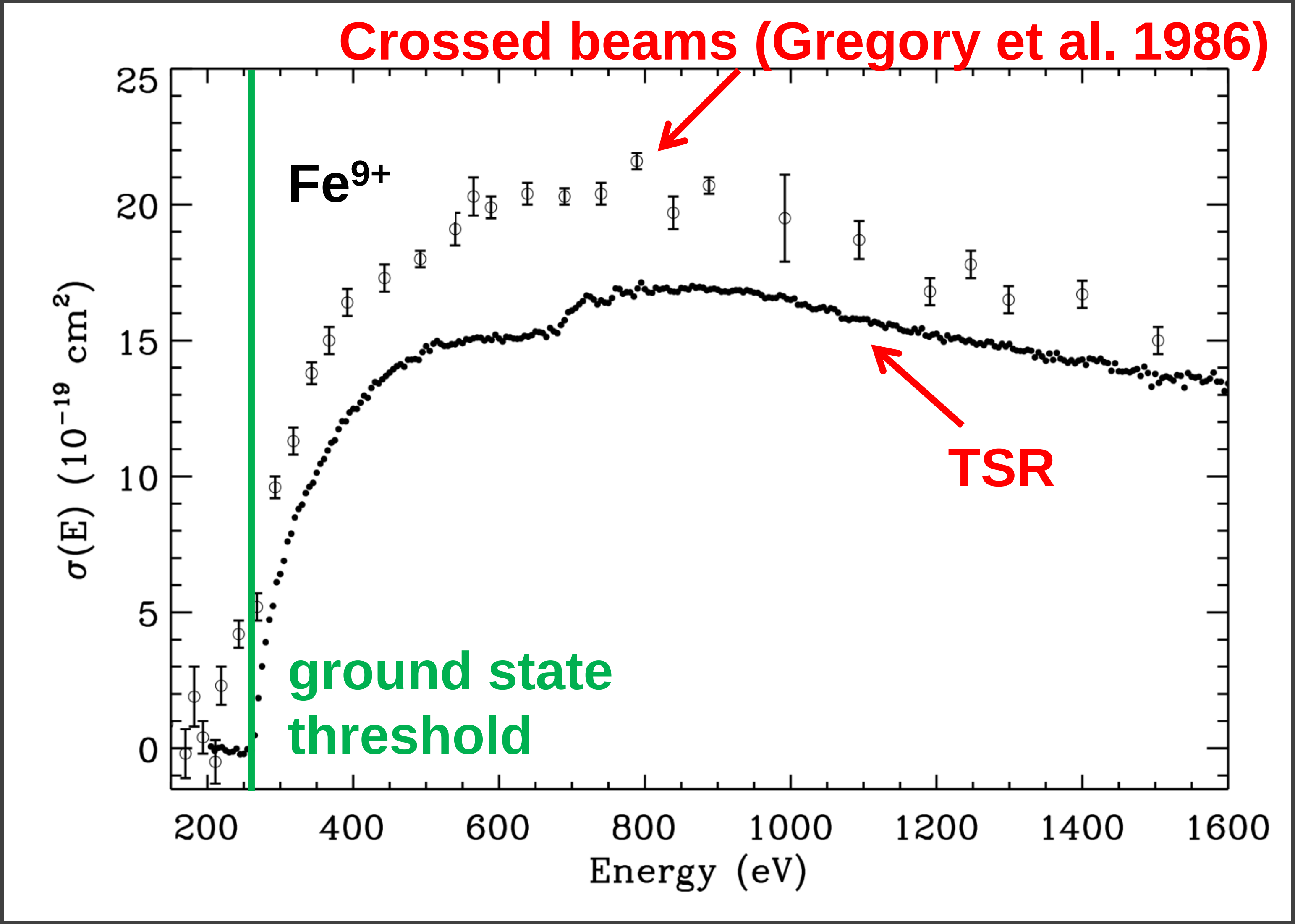


Ionized (*q*+1) and recombined ions (*q*-1) pushed toward detectors by magnets.

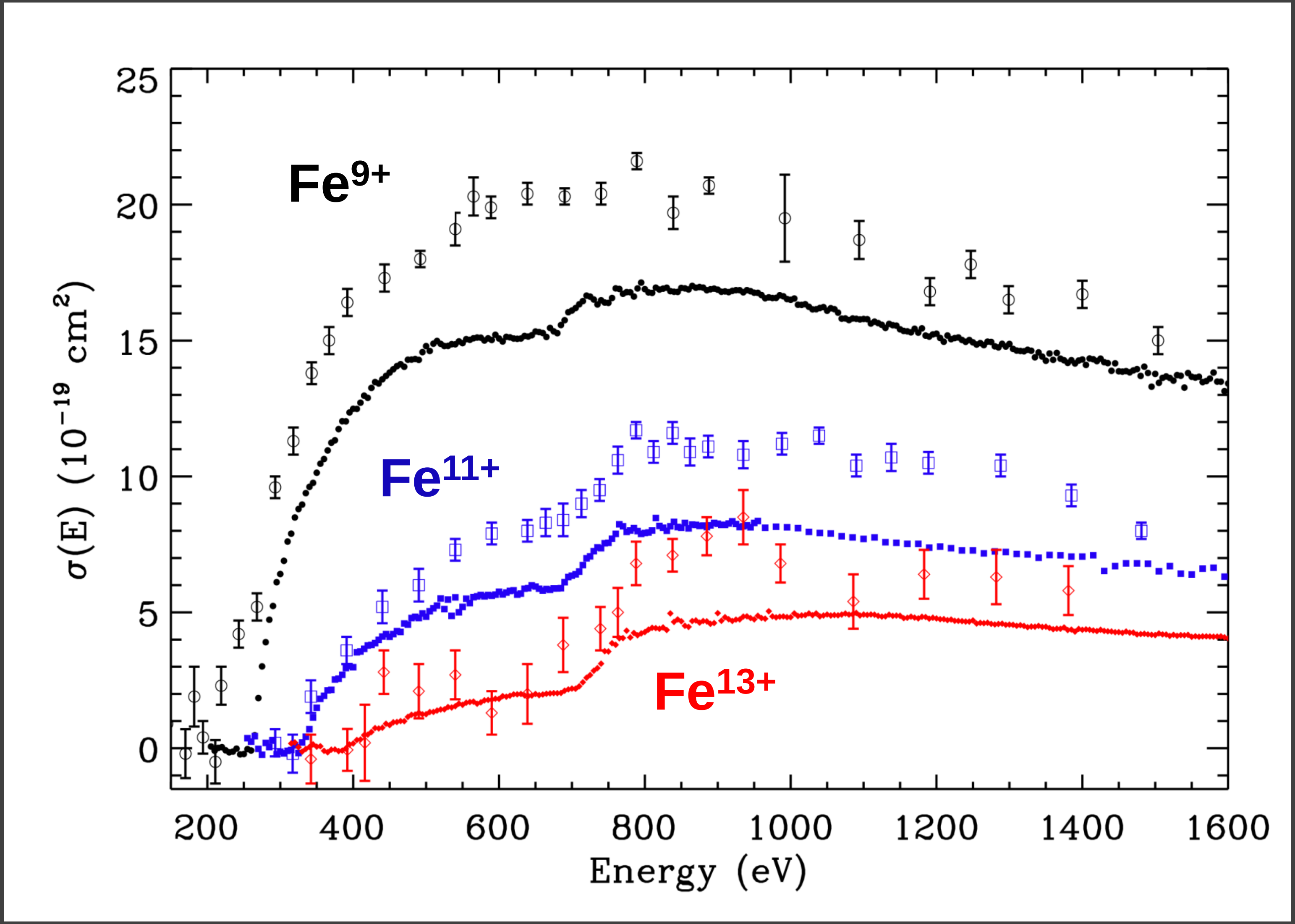
Particles whose *q* didn't change continue circulating

magnetic force: ***F*** = *q****v*** x ***B*** Larmor radius $\rho_L = \frac{mv}{qB}$

Storing removes metastables



Problem with metastables resolved



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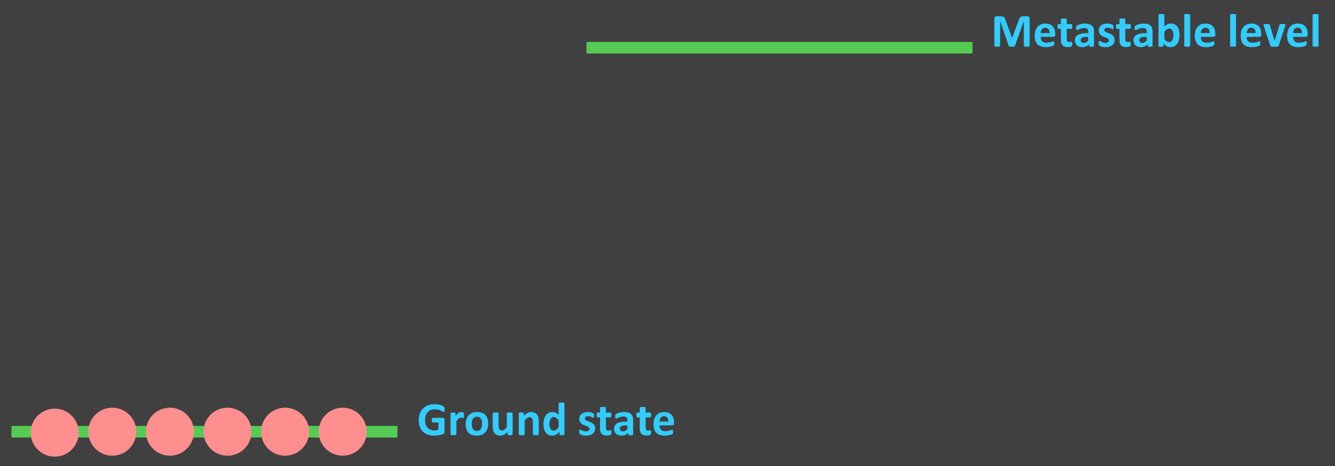
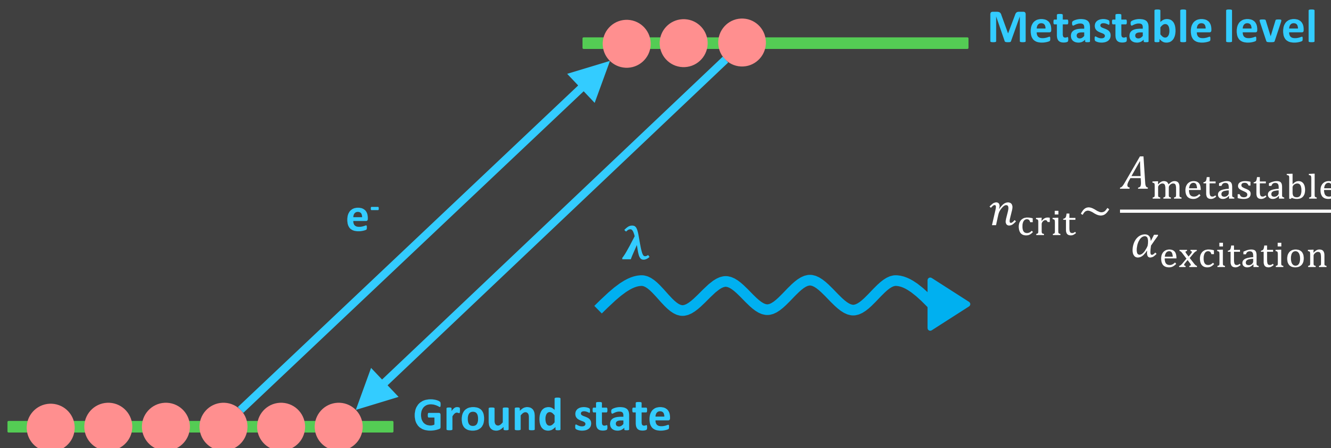
How electron density diagnostics work:

At low densities, most ions are in the ground state



How electron density diagnostics work:

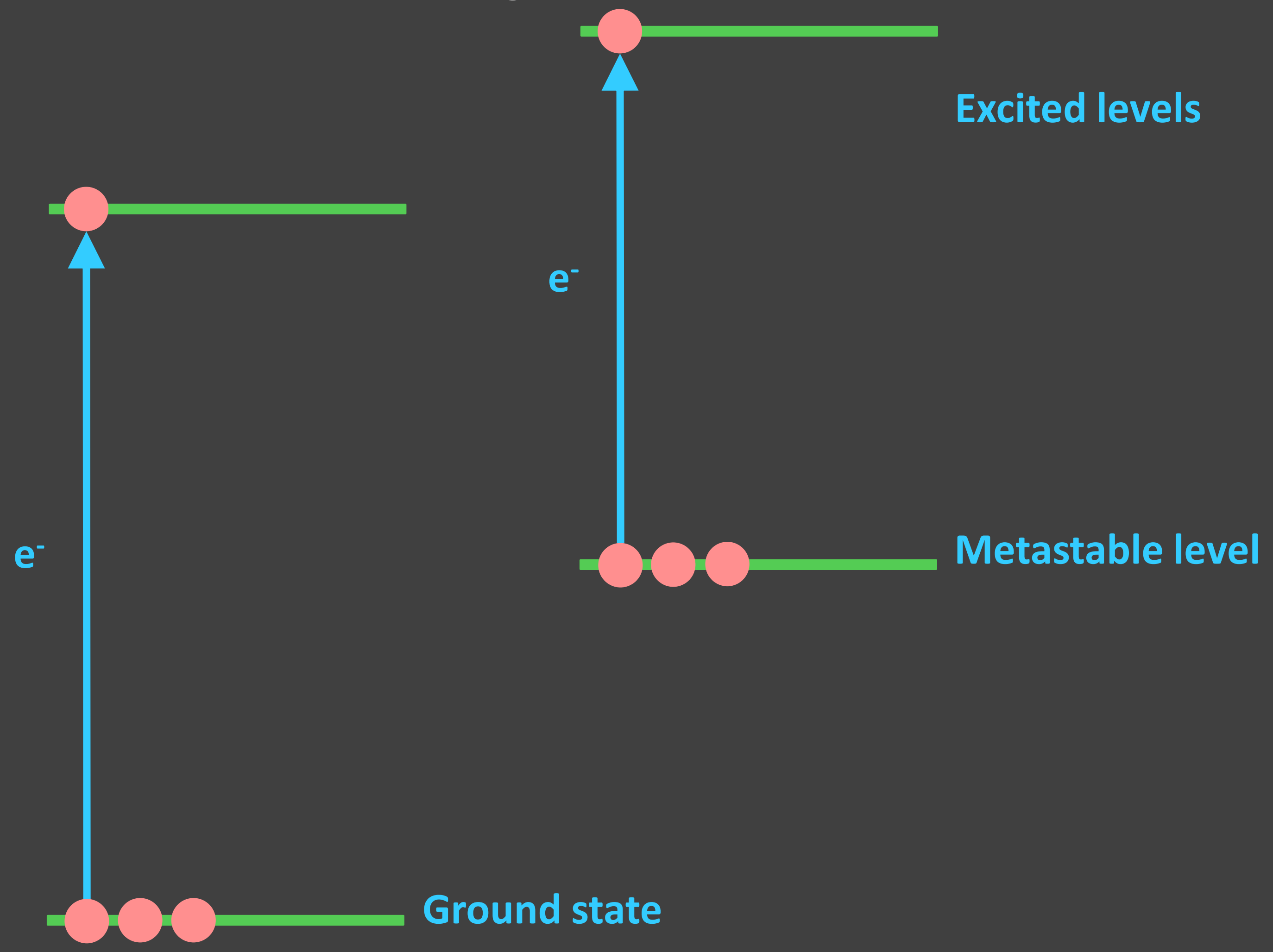
At higher densities, collisions populate metastable levels faster than they can decay.



$$n_{\text{crit}} \sim \frac{A_{\text{metastable}}}{\alpha_{\text{excitation}}}$$

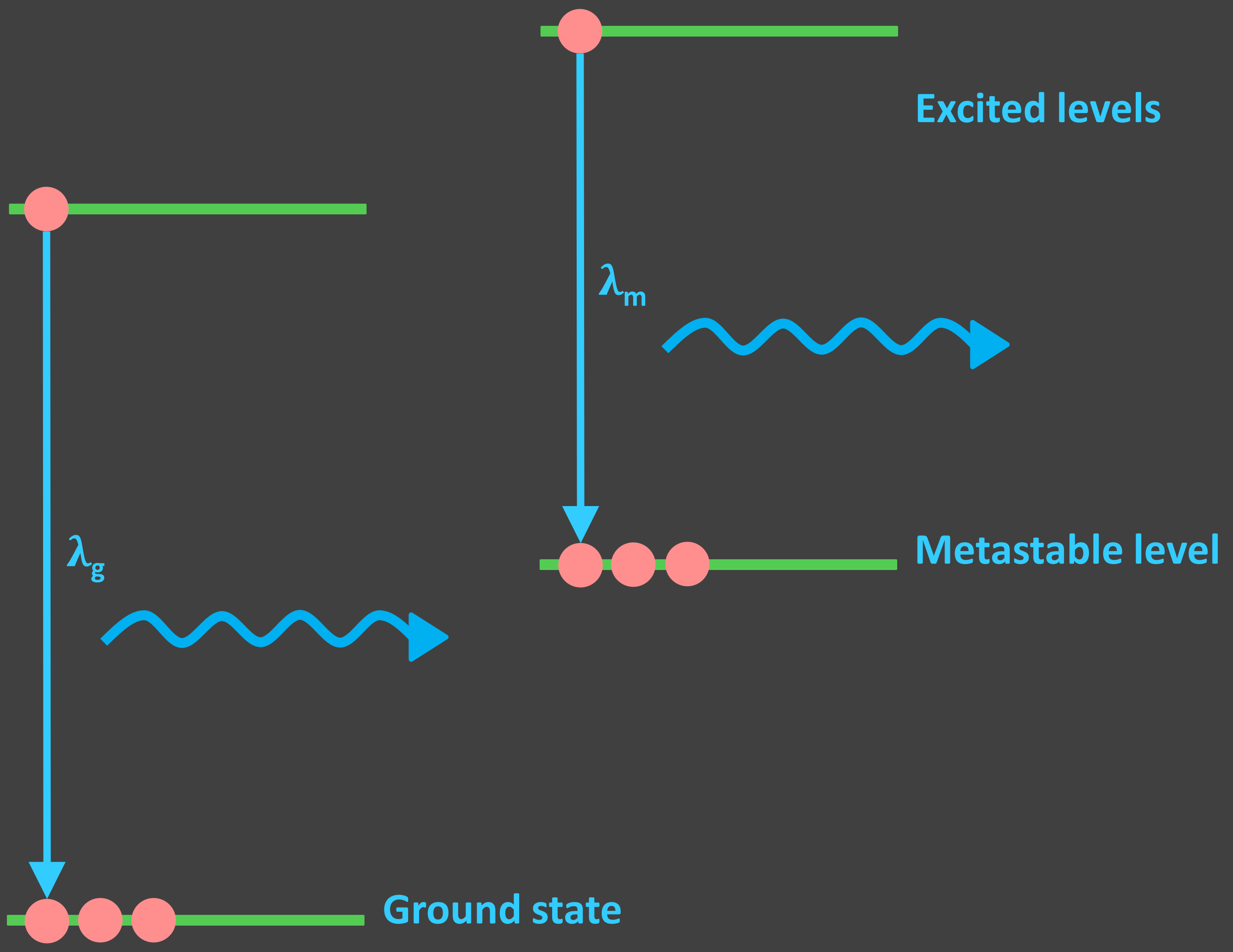
How electron density diagnostics work:

Higher levels are populated preferentially by collisions with ground or metastable ions.

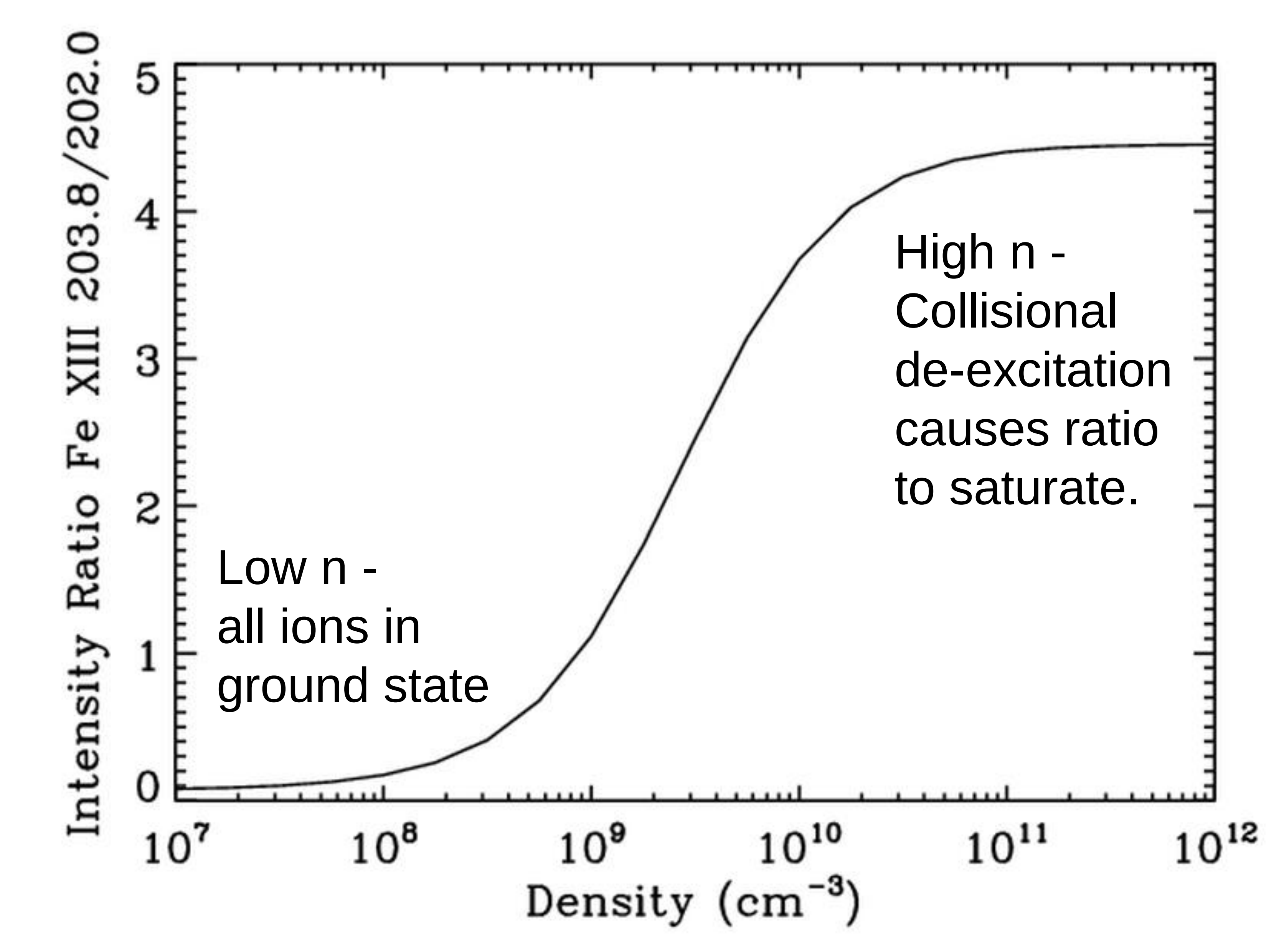


How electron density diagnostics work:

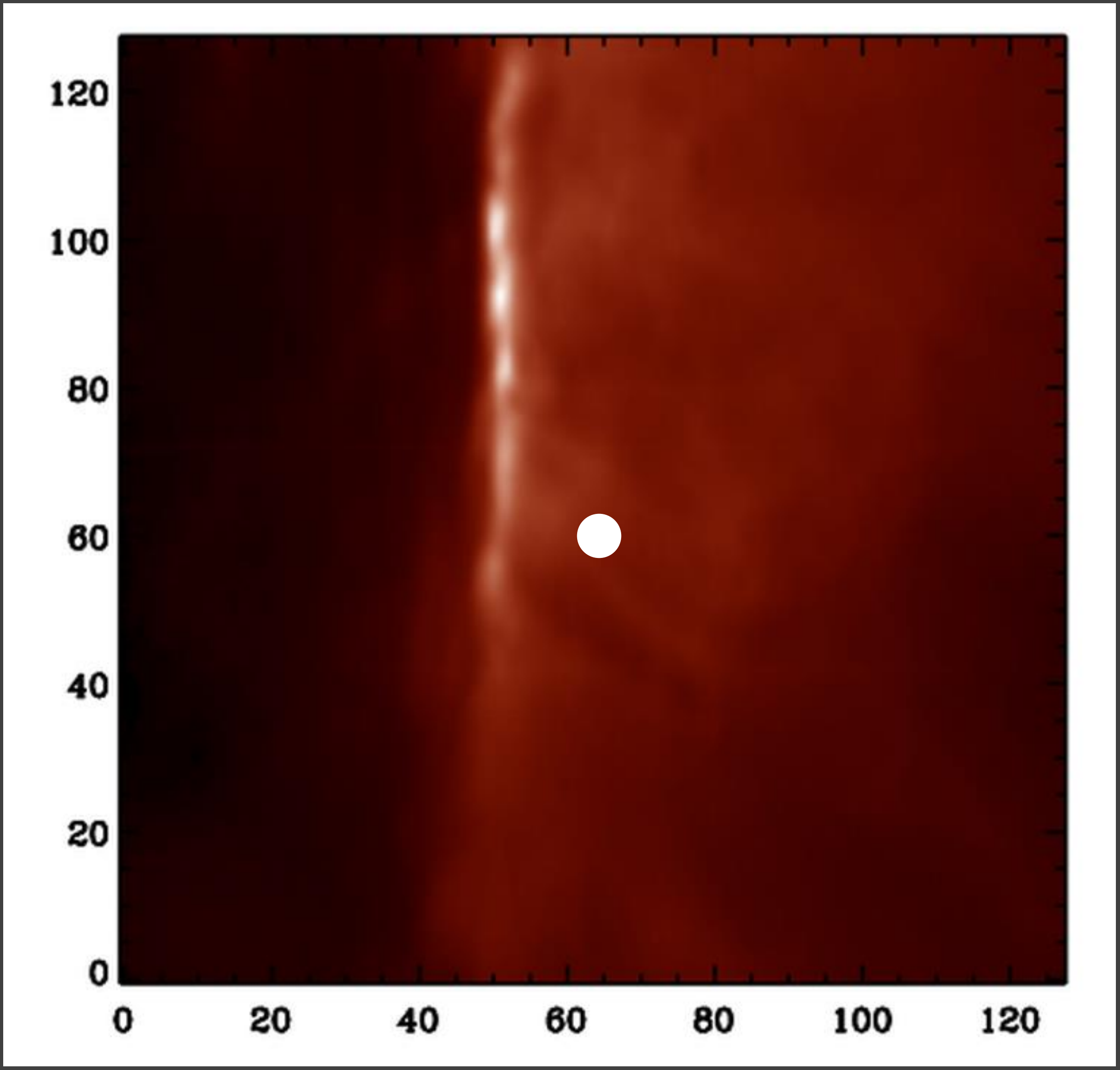
Allowed lines from the higher levels are observed.



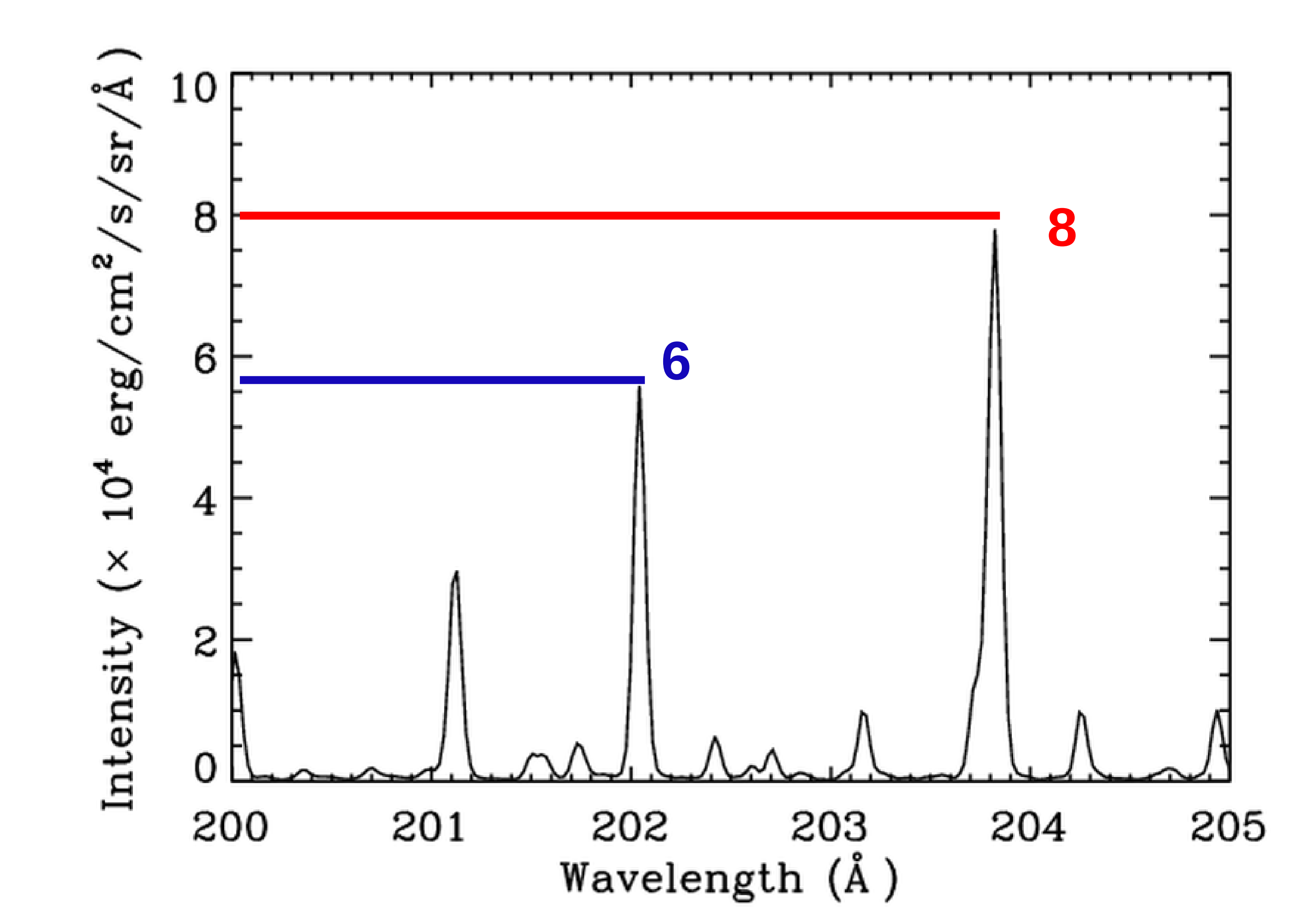
Example: Density using Fe XIII



Find the density in this solar active region

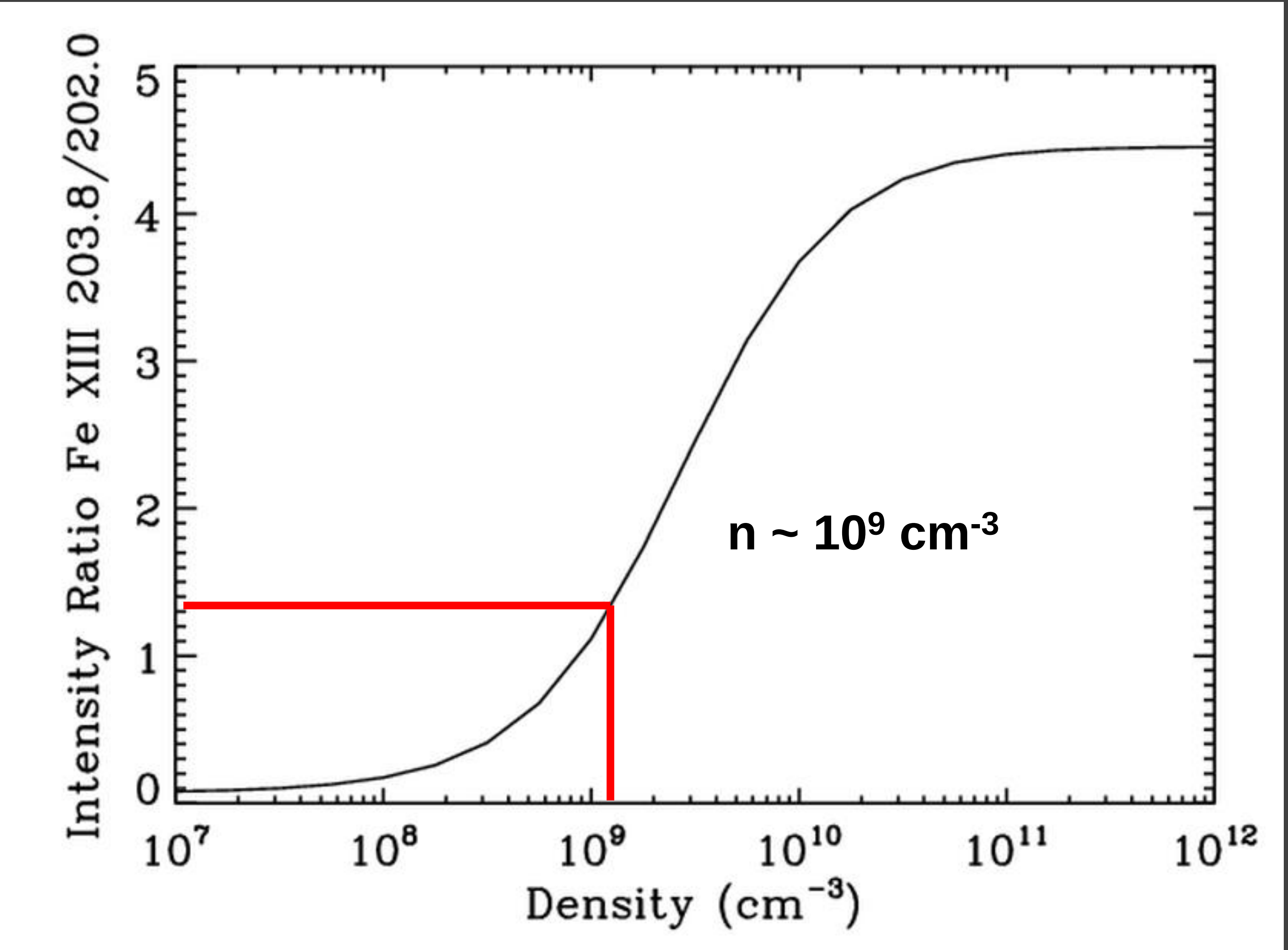


Spectrum from the active region

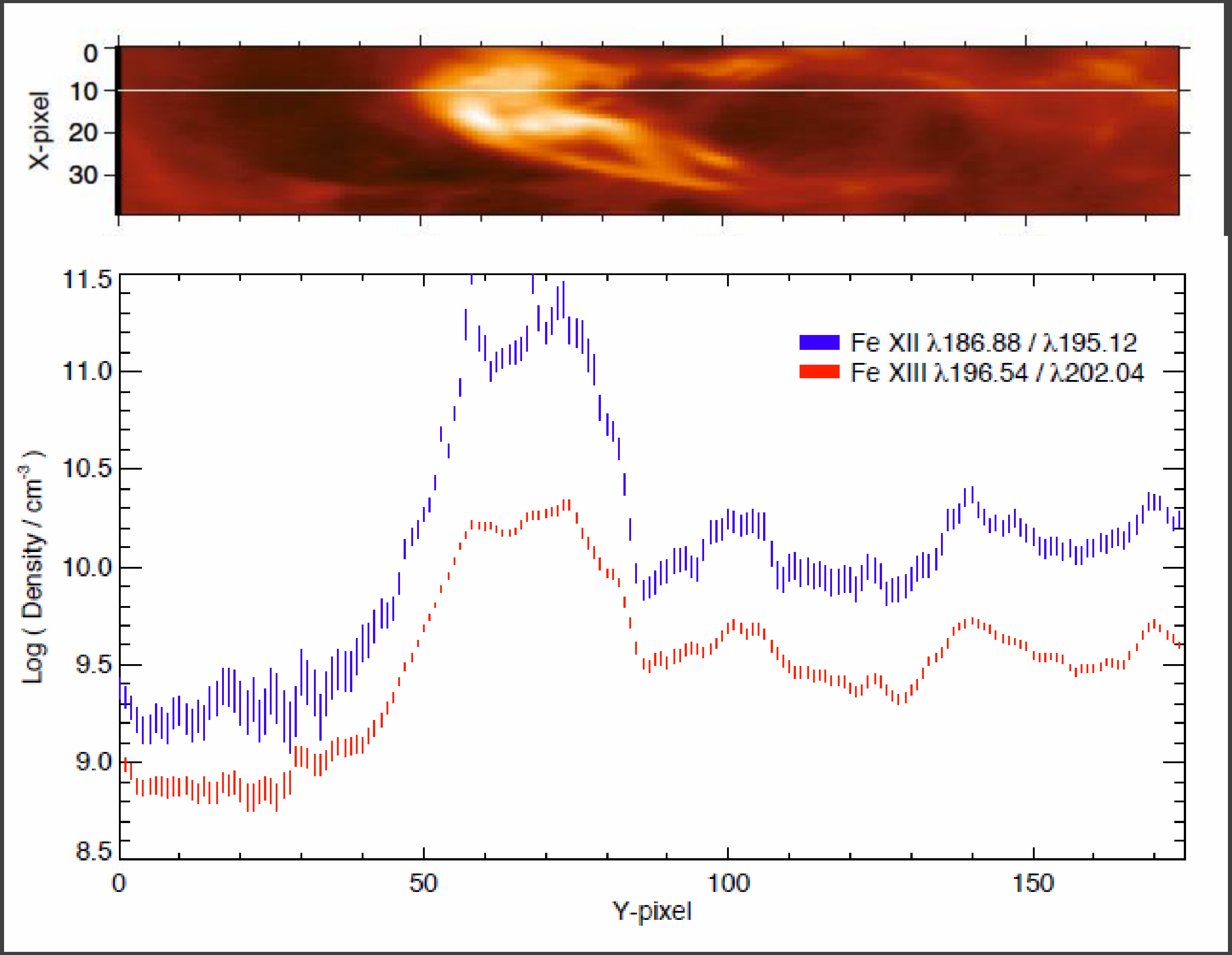


Ratio ~ 8/6 ~ 1.3

Example: Density using Fe XIII



Density diagnostics have large errors

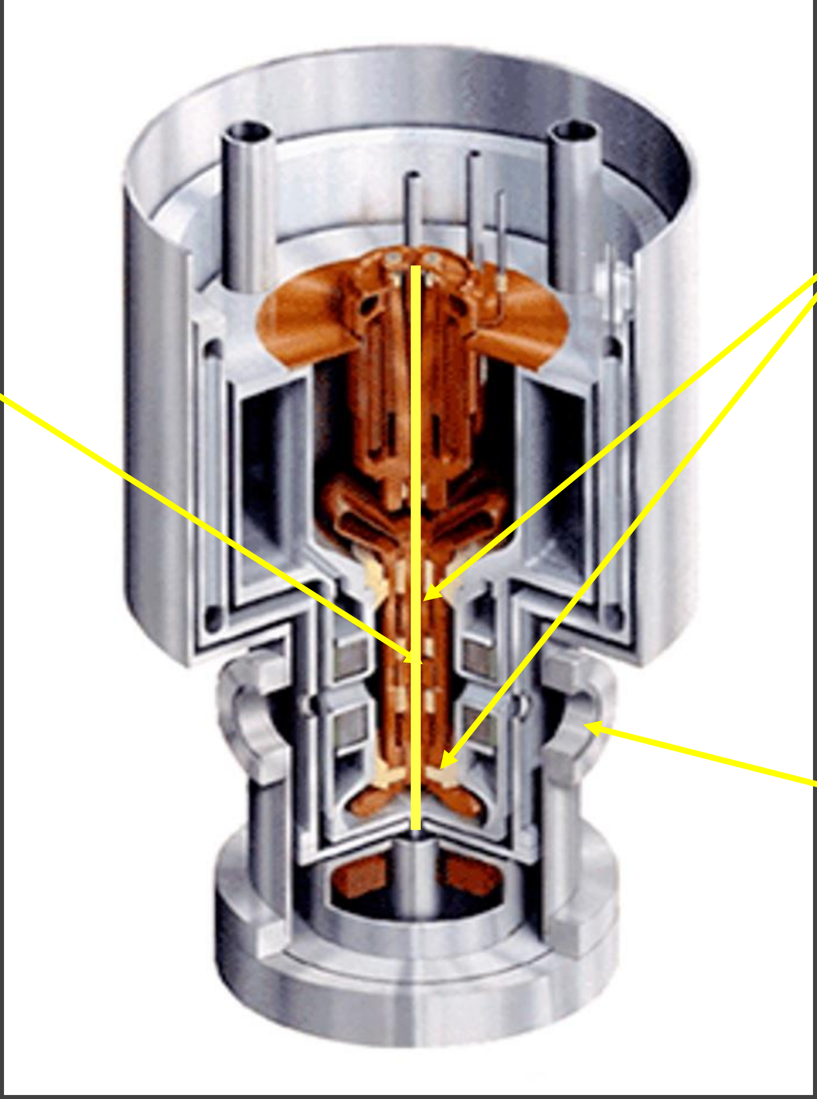


Young et al. (2009) rev. 2015

Electron Beam Ion Trap (EBIT) at LLNL

Electron beam and magnetic field confine ions radially

Electron-ion collisions occur in the beam.

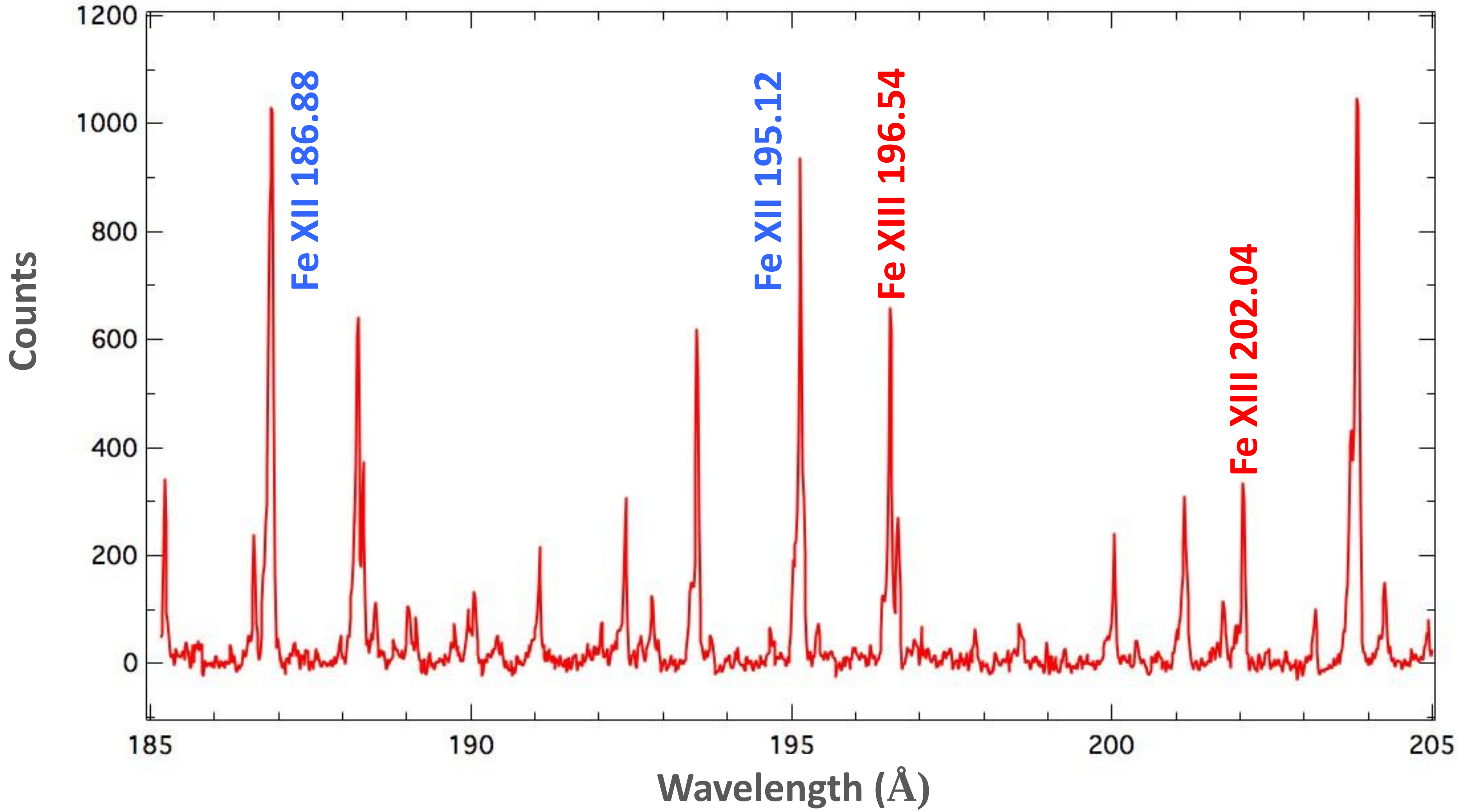


Biased electrodes confine ions axially

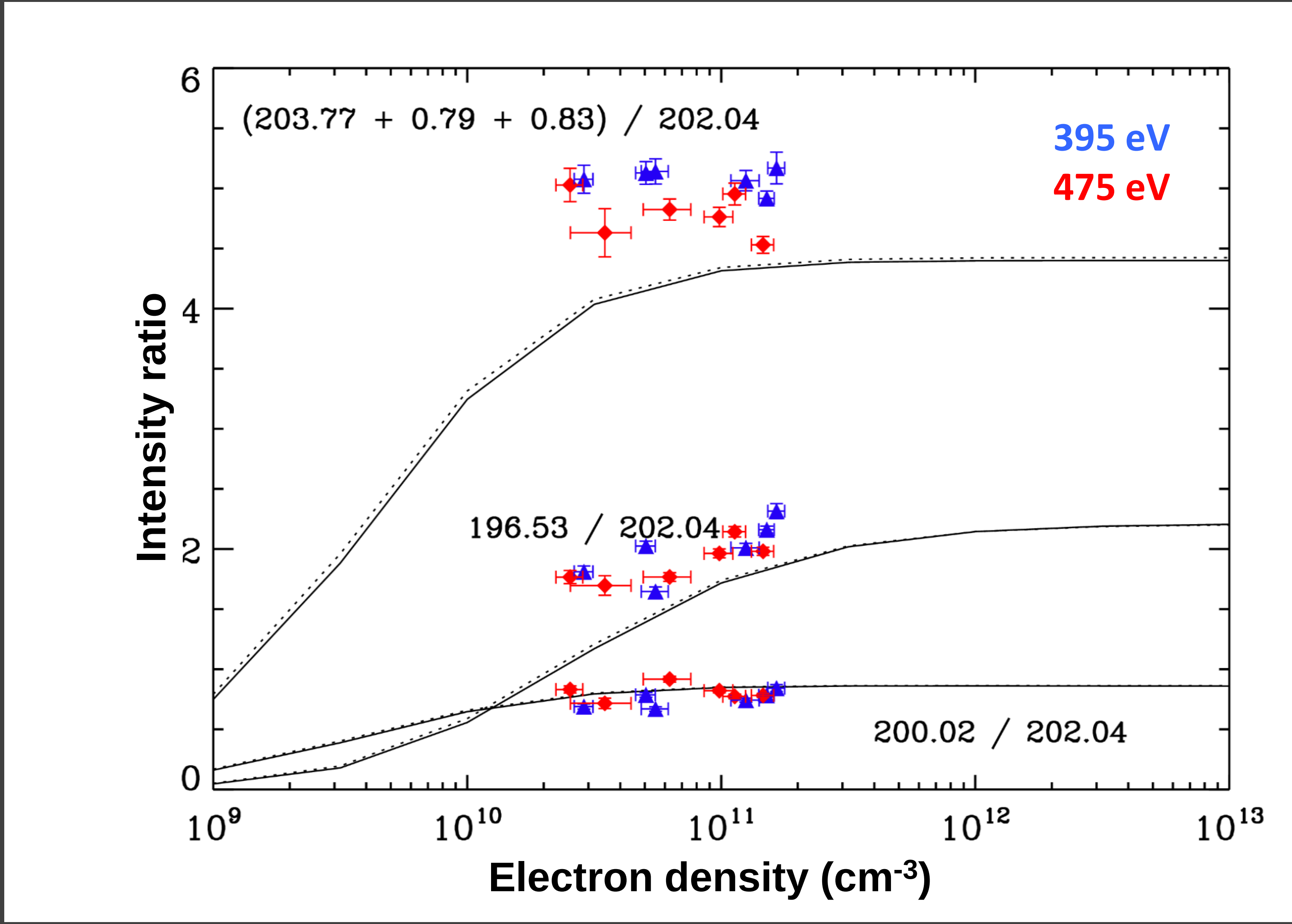
Spectrometers view emission through viewports

Can change density by varying the current: $I = nAv$

Representative EBIT Spectra



Representative EBIT Results



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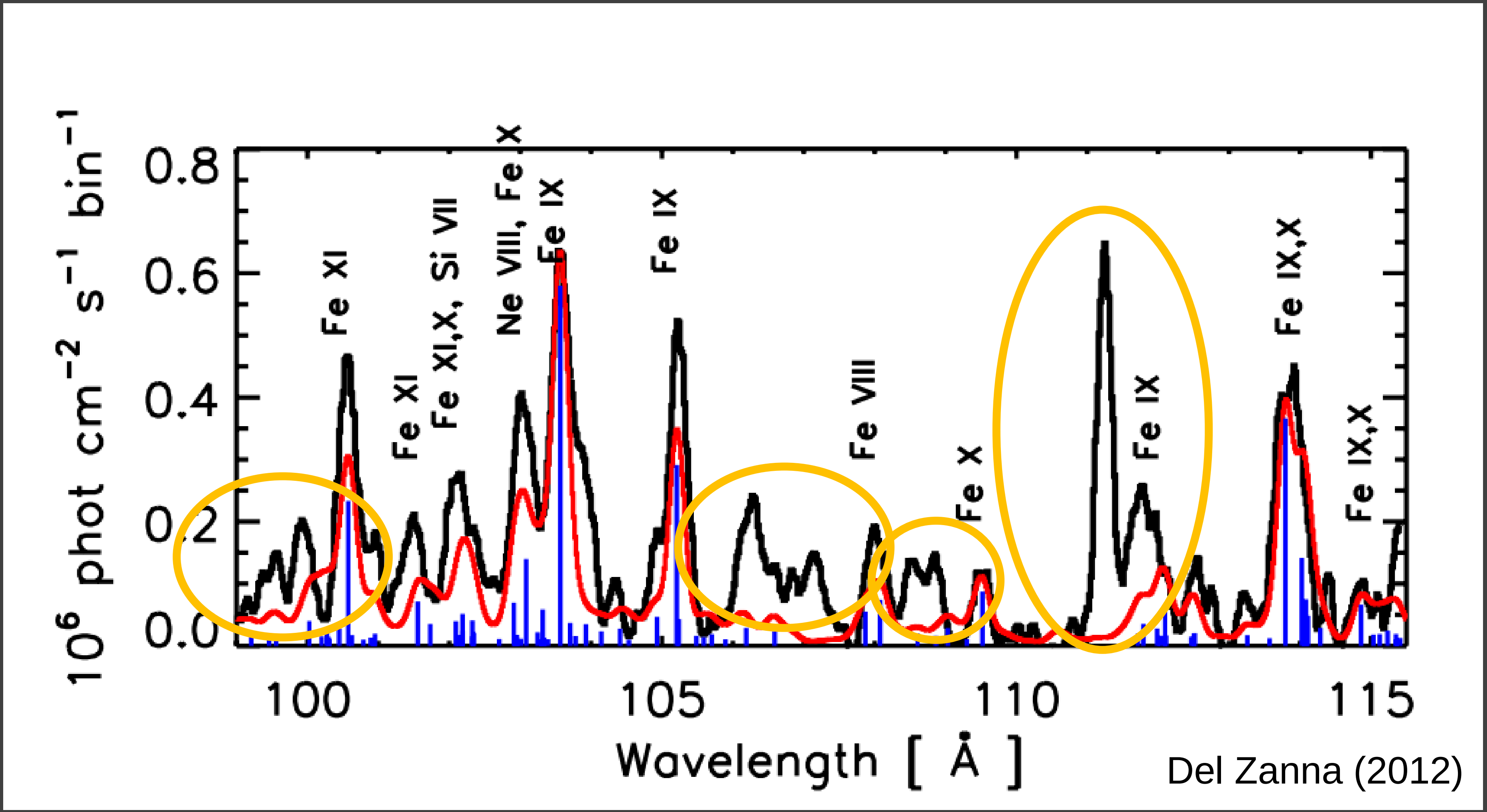
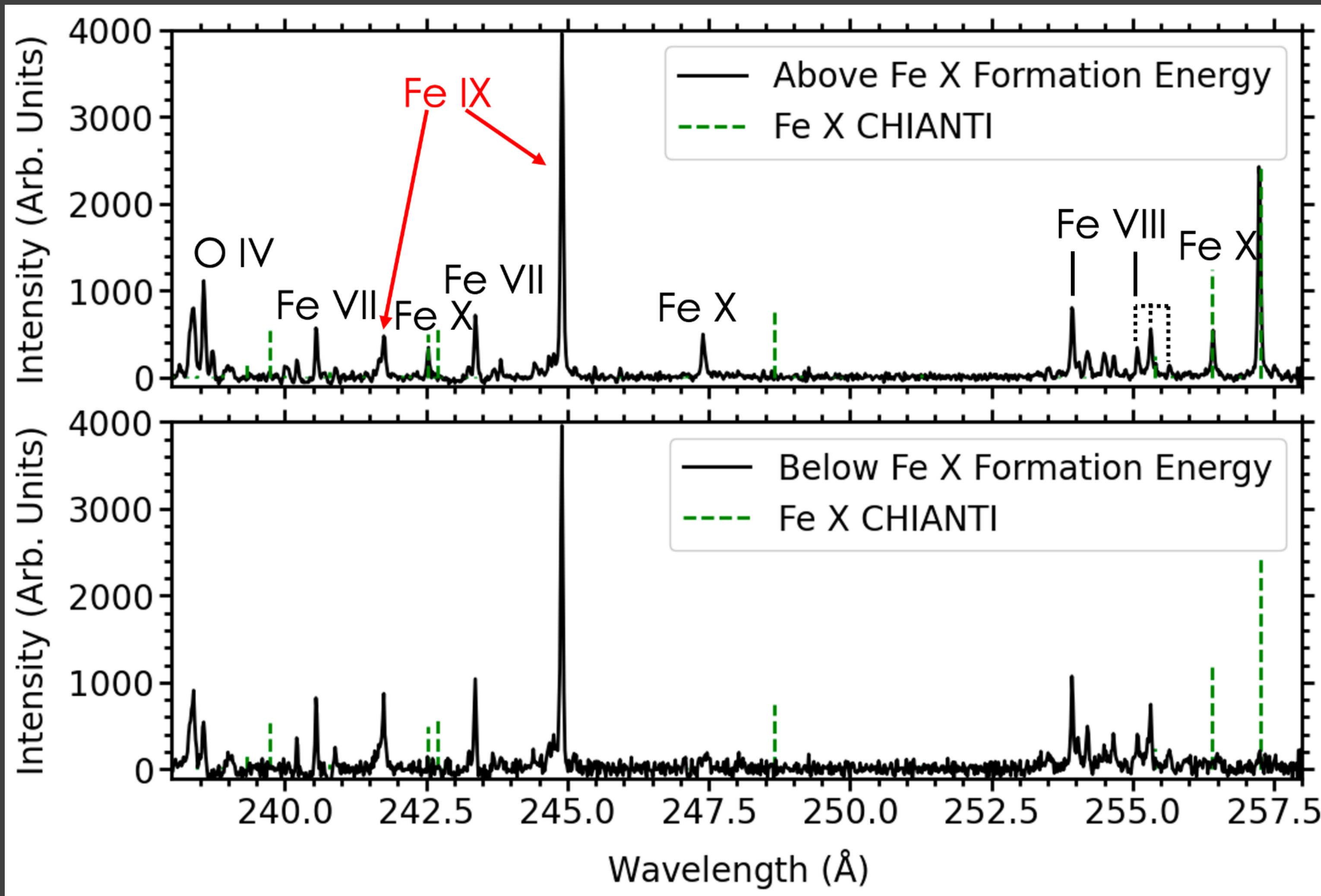
Many observed lines are unidentified



Quiet Sun spectrum (black) with CHIANTI atomic data (red)

Line identification with EBIT



Tuning the electron beam energy allows for associating lines with elements and charge states

Summary

- Accurate atomic data are needed to interpret observations of the Sun and for models.
- Ionization and recombination give temperature diagnostics.
- Excitation and de-excitation give density diagnostics – current diagnostics only accurate within a factor of a few.
- A large number of observed lines remain unidentified.

Future Work

- Fe IX important for cooler regions, but many transitions not identified and density diagnostics need calibration.

- Atomic data needed for new instruments e.g.
  - DKIST observes infrared
  - EUVST/Solar-C VUV: 460-1220 Å
  - Shorter wavelengths (e.g, MUSE near 108 Å)