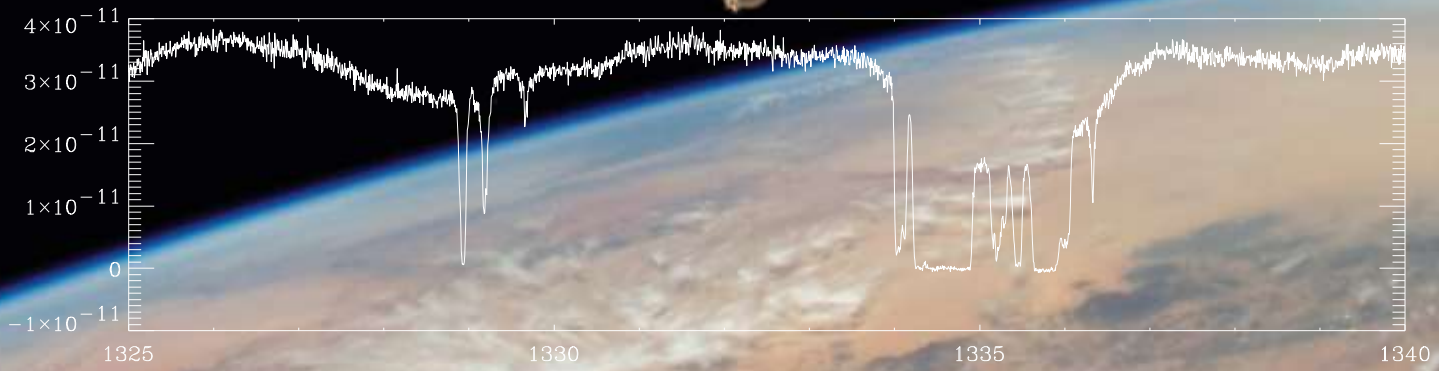
THE LEGACY OF HST SPECTROSCOPY



Edward B. Jenkins
Princeton University Observatory

HST Spectroscopic Capabilities in the Ultraviolet

- Current instruments:
  - **ACS prism:** $R \approx 100$ @ 1500 Å, λ coverage =1250 — 1800 Å, A_{eff} = 800 cm^{-2}
  - **COS:** 7 different 1st order grating modes: $3000 \leq R \leq 20{,}000$, λ coverage = 900 — 3000 Å, $200 \leq A_{eff} \leq 2000$ cm^{-2}
  - **STIS:** 11 spectral modes:
    - 1st order gratings: $500 \leq R \leq 10{,}000$, λ coverage = 1150 — 3200 Å , $300 \leq A_{eff} \leq 1200$ cm^{-2}
    - Echelle gratings: $30{,}000 \leq R \leq 114{,}000$, λ coverage = 1150 — 3100 Å , $130 \leq A_{eff} \leq 300$ cm^{-2}
    - Prism: R highly variable, λ coverage = 1150 — 3620 Å , $A_{eff} \approx 500$ cm^{-2}
    - Wide selection of entrance slits, including ones 52" long $\perp$ to disp.

HST Spectroscopic Capabilities in the Ultraviolet

- Previous instruments:
  - **FOS:** $250 \leq R \leq 1300$, λ coverages =1150 — 5400 Å & 1620 — 8500 Å , capable of doing spectropolarimetry (but only for $\lambda > 1650$ Å post costar)
  - **GHRS:** 1st order and echelle gratings: $2000 \leq R \leq 80{,}000$, λ coverages =1150 — 1800 Å & 1680 — 3400 Å
- *While these early-generation instruments were generally inferior to the current ones, an important capability that we no longer have is a tolerance for high detector count rates* (e.g. 50,000 counts $s^{-1}resel^{-1}$ allowed for the Digicons on FOS and GHRS, compared with 100 counts $s^{-1}resel^{-1}$ for the STIS MAMA detectors) ; this precludes obtaining high *S/N* in short observing times.

The Dark Ages 2004-2009

Date: Fri, 13 Aug 2004 16:22:40 -0400 (EDT)
From: STScI-Generic@stsci.edu
To: ebj@astro.princeton.edu
Subject: STIS Update

Dear HST User,

On Tuesday, August 3, STIS entered a "suspend" state in response to the loss of 5-volt power in the Side 2 electronics. The Side 1 electronics suffered a short circuit in May 2001 and are currently not working. Failures in the two redundant Sides make STIS unusable. While it is possible that further investigation will point out a way to restore STIS to a useful state, we believe it unlikely that STIS can be revived without physical servicing. Fortunately, all other science instruments and the observatory itself continue to function normally.

The observing programs that use the unique capabilities of STIS will be suspended. We expect to notify all STIS observers about the status of their programs within the next several weeks


The Dark Ages 2004-2009


The People who do Imaging

Figures of Merit

- Primary:
  - The effective area $A_{\mathbf{eff}}$ that is the product of the area of the unobscured primary mirror and the efficiencies of the optics and the detector
  - The multiplexing factor M that represents the number of independent resolution elements that can be recorded in a single exposure
  - The wavelength resolving power $R = \lambda/\delta\lambda$

Figures of Merit

- Secondary:
  - F_{min}: a minimum flux where noise sources other than the statistical uncertainty of photon counts start to dominate.
  - F_{max}: a maximum flux that can be tolerated by a detector without suffering long term damage.

Figures of Merit

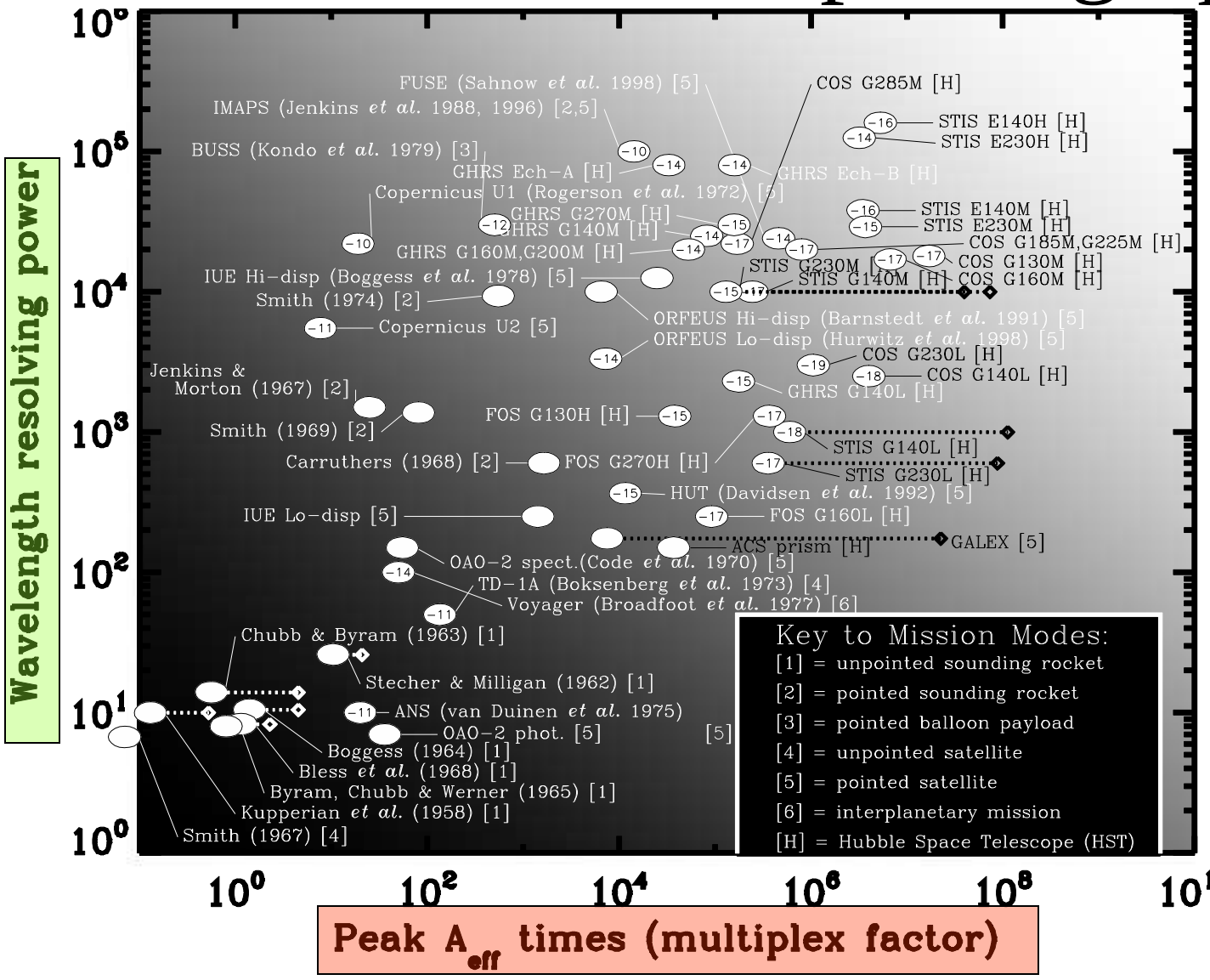
- Which figures of merit matter for a given observing program depends on the nature of a source and the science goals of the research.
- Let us consider two fundamental quantities:

$$R$$

and

$$A_{\text{eff}} \times M$$

Evolution of UV spectrographs



-15

Number inside ellipse indicates F_{bkg} (dex) in units of erg cm^{-2} s^{-1} Å^{-1}

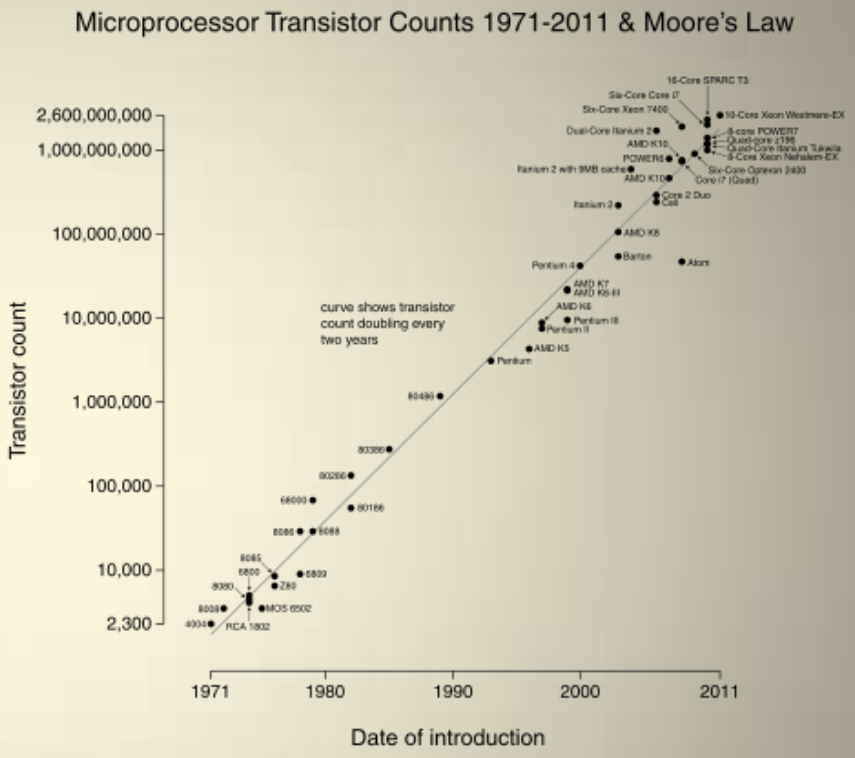
Spectral multiplex only

Spatial multiplex factor

White labels indicate past missions no longer operating; black labels indicate current missions.

Moore's Law

The number of transistors that can be placed inexpensively on an integrated circuit doubles approximately every two years

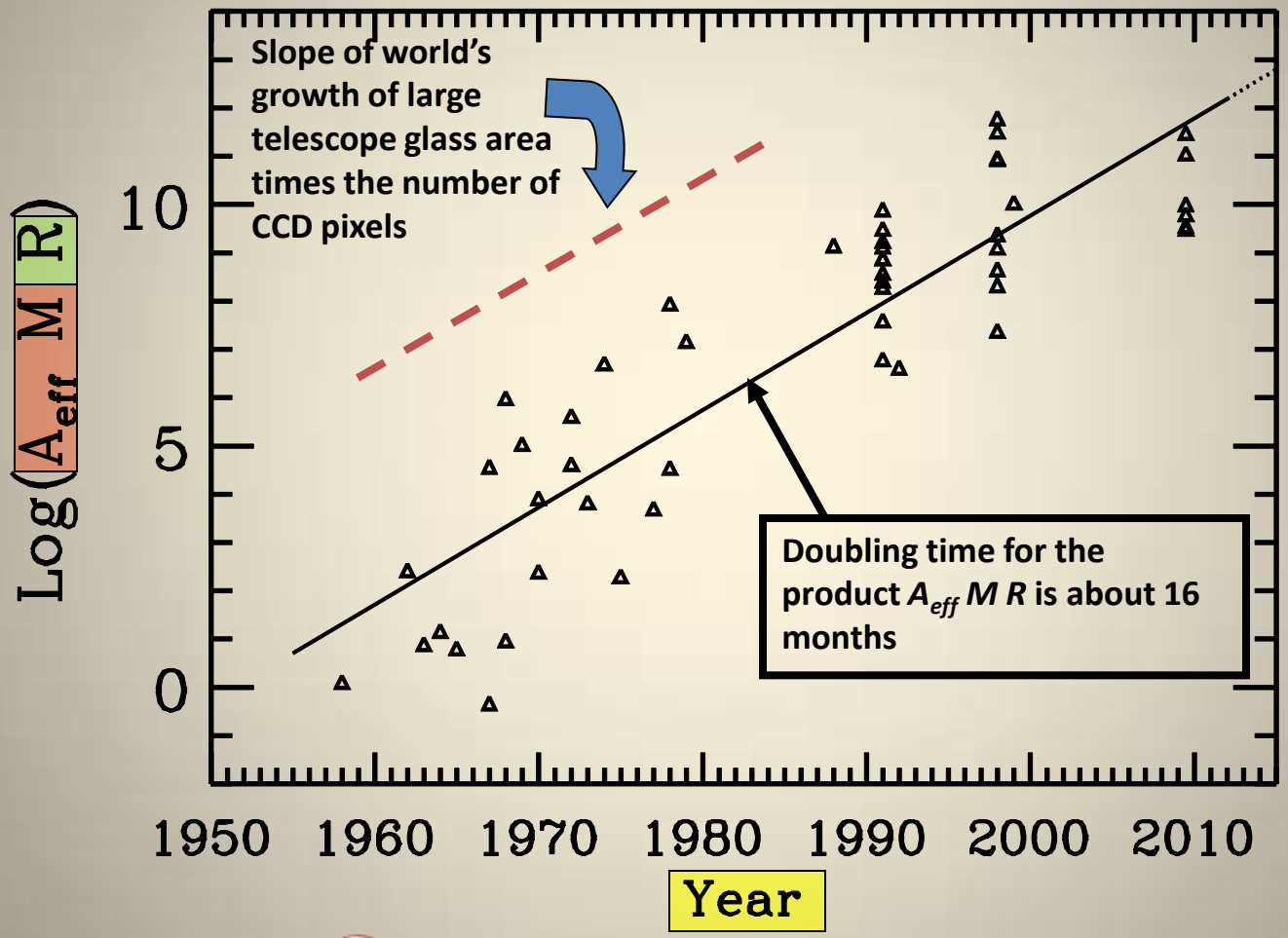


Wirth's Law:

Software is getting slower more rapidly than hardware becomes faster.

Niclaus Wirth (1995)

Jenkins's Law



The time needed to analyze and interpret the results increases faster than the increase in observing capability.

My Review of Achievements from HST Spectroscopy

- Downloaded articles listed in http://archive.stsci.edu/hst/bibliography/ and filtered according to usages of FOS, GHRS, STIS or COS
- How many of them are there?
  - 2763 (but a few of which used only imaging, not spectroscopy)
  - That means I can spend an average of (30 min)(60 sec/min)/2763 articles = 0.65 sec/article

The Legacy of HST UV Spectroscopy

Edward B. Jenkins

Princeton University Observatory

7:00

A Representative Sample* of Results from HST UV Spectroscopy

Edward B. Jenkins

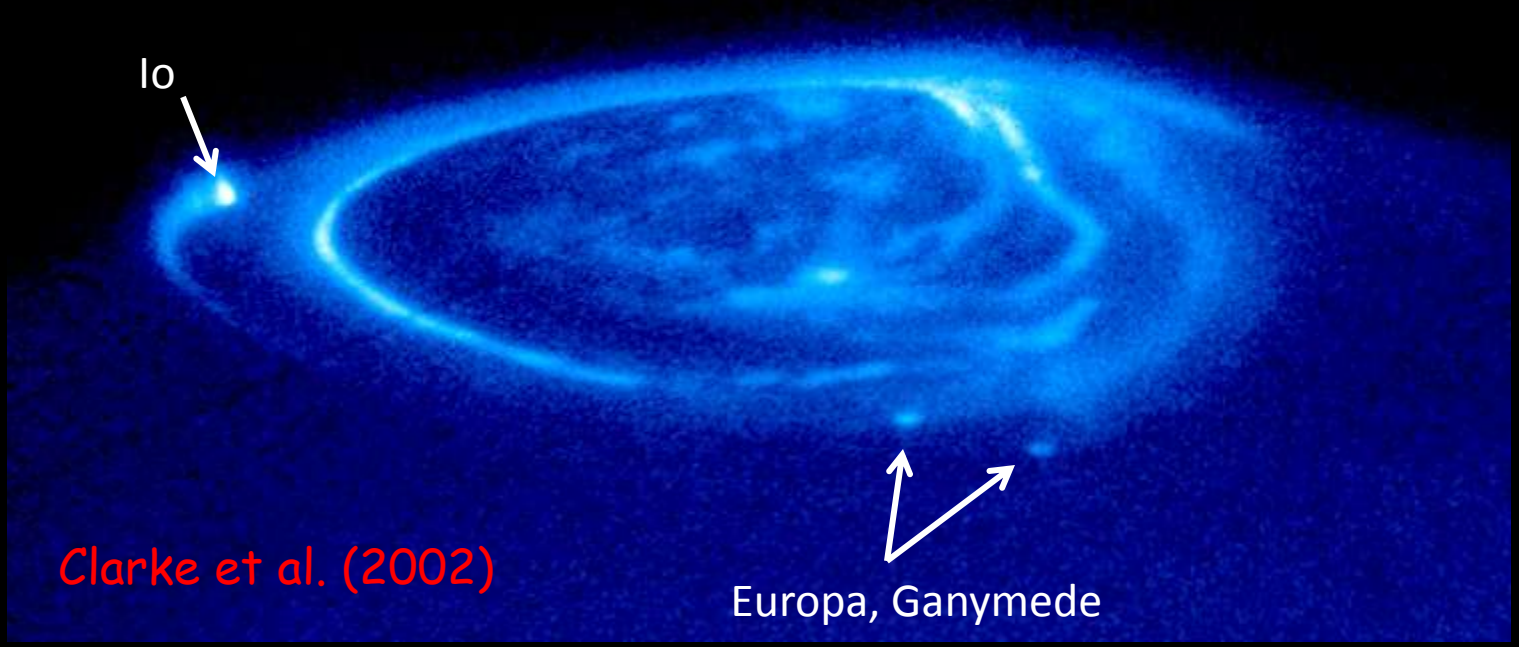
Princeton University Observatory

*** I tried my best to overcome a bias against subject areas that were unfamiliar to me. Obviously, there is insufficient time to cover many good, interesting papers .**

7:00

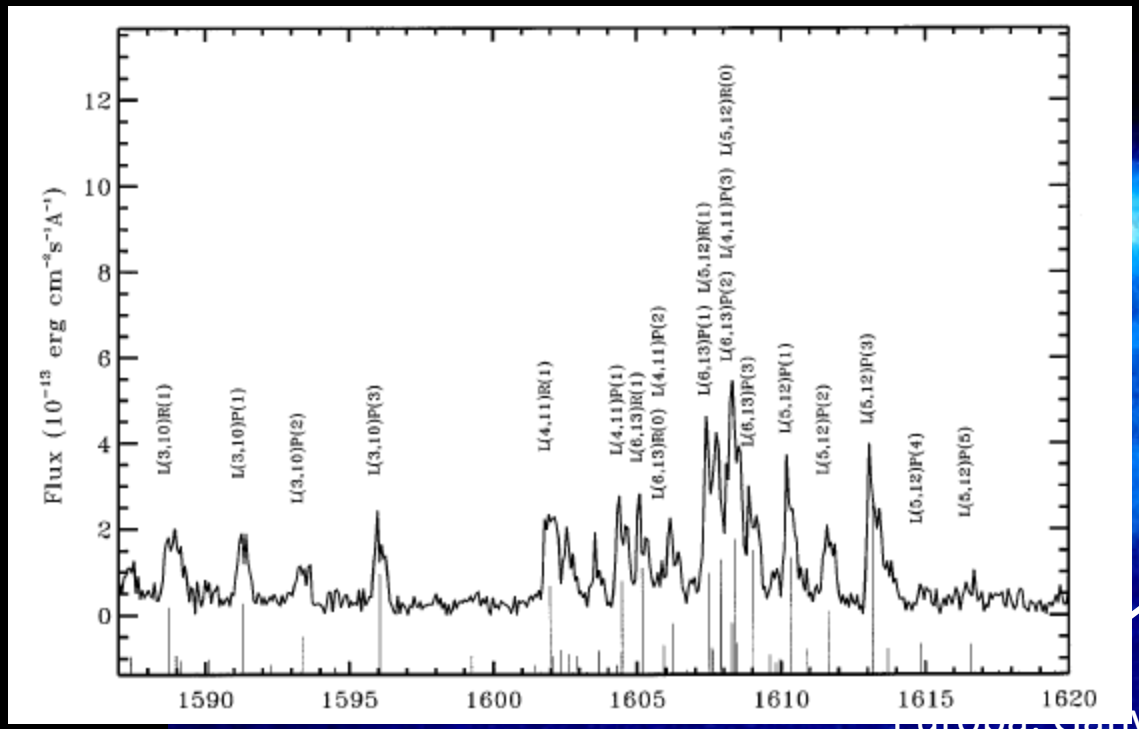
Objects in our Solar System

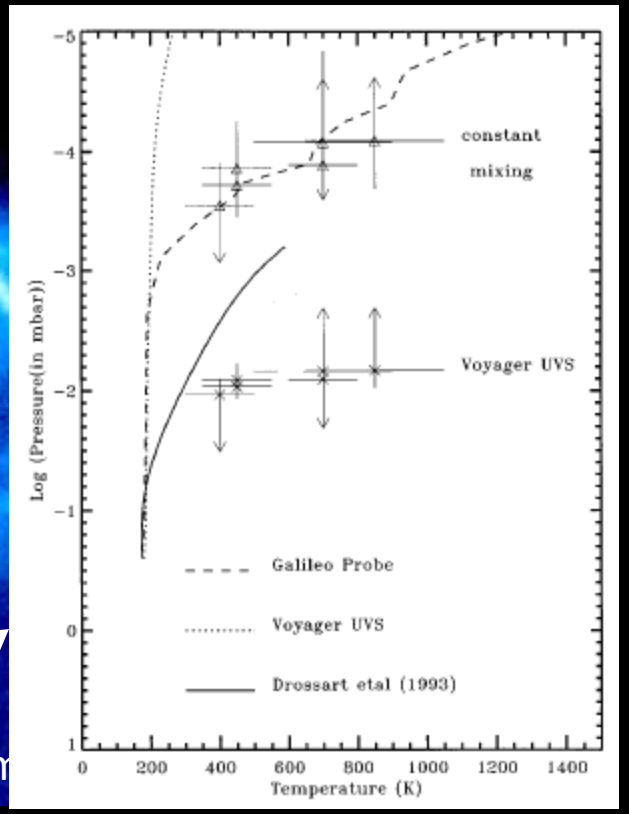
Footprints of the magnetic flux tubes from the Galilean satellites in the auroral regions of Jupiter



Brightness ≈ 10^3 × terrestrial aurora

Objects in our Solar System





Kim, Fox & Caldwell (1997)

Brightness ≈ 10^3 × terrestrial aurora

Objects in our Solar System

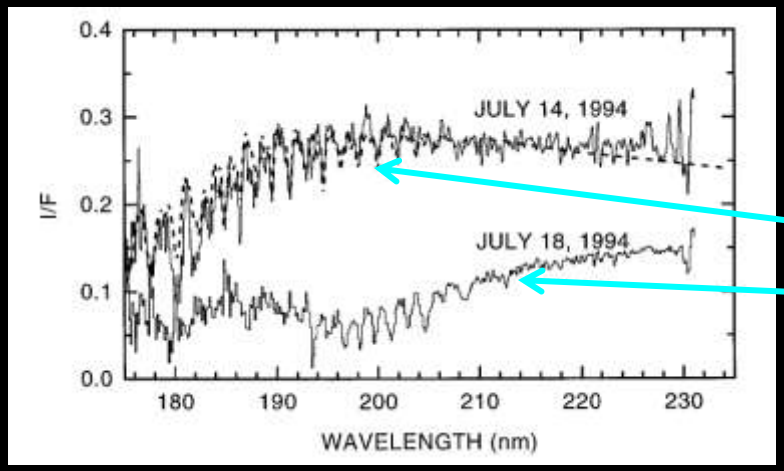
Impact of Comet Shoemaker-Levy on Jupiter
July 1994

Objects in our Solar System

Impact of Comet Shoemaker-Levy on Jupiter
July 1994

Objects in our Solar System

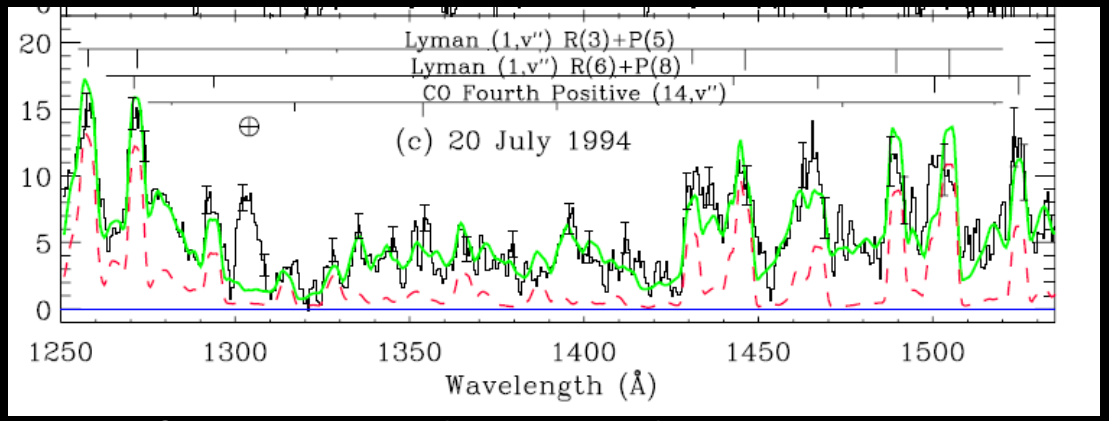
Detected CS_2, H_2S & NH_3, but no SO_2



Reflectivities:
Pre-impact
Post-impact

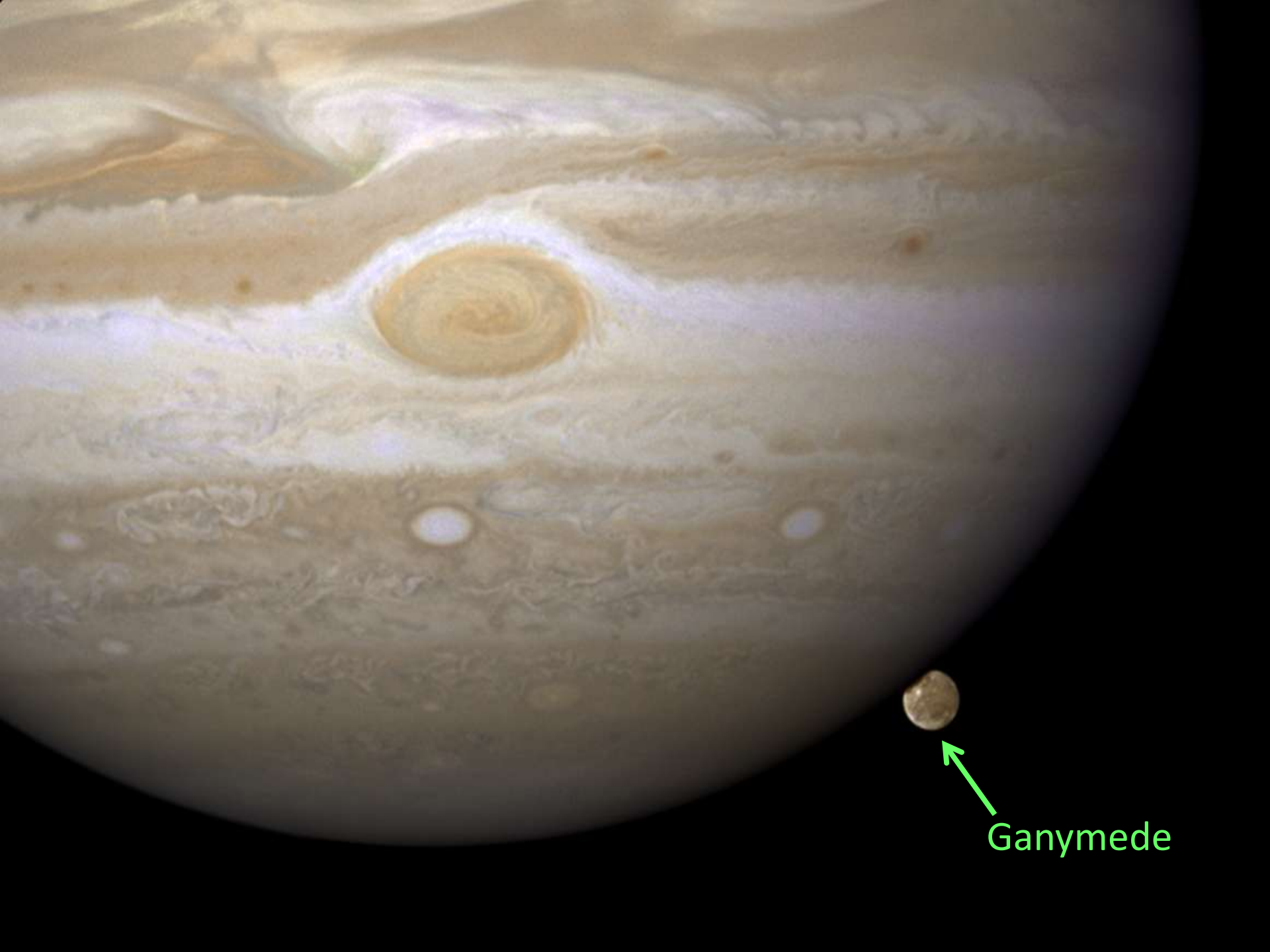
Yelle & McGrath (1996)

Fluorescence of H_2 caused by pumping from solar Lα emission

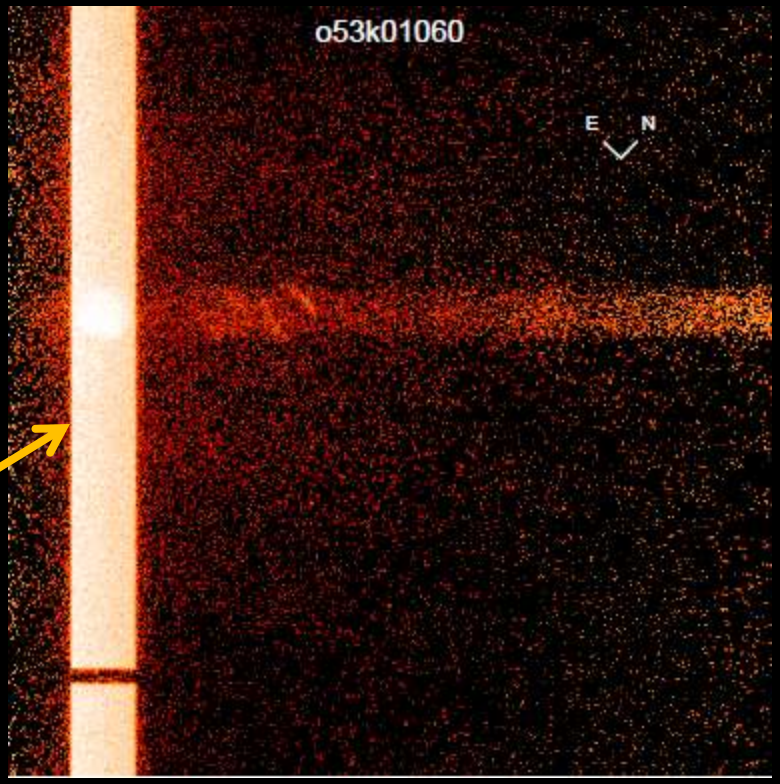


Wolven et al. (1997)

Impact of Comet Shoemaker-Levy on Jupiter
July 1994


Ganymede

Objects in our Solar System



Raw Image

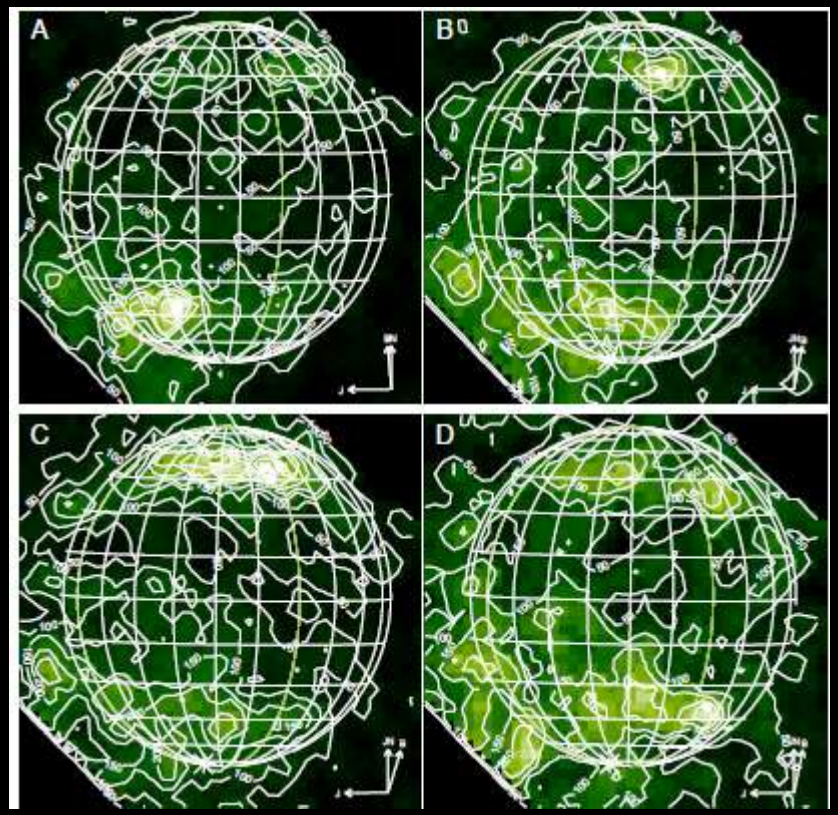
Geocoronal Lα filling the 52”×2” entrance slit of STIS

STIS Imaging spectrum of Ganymede in the far UV

Feldman et al. (2000)

Objects in our Solar System

Derivations of the 1356Å O I] emission at different times



STIS Imaging spectrum of Ganymede in the far UV

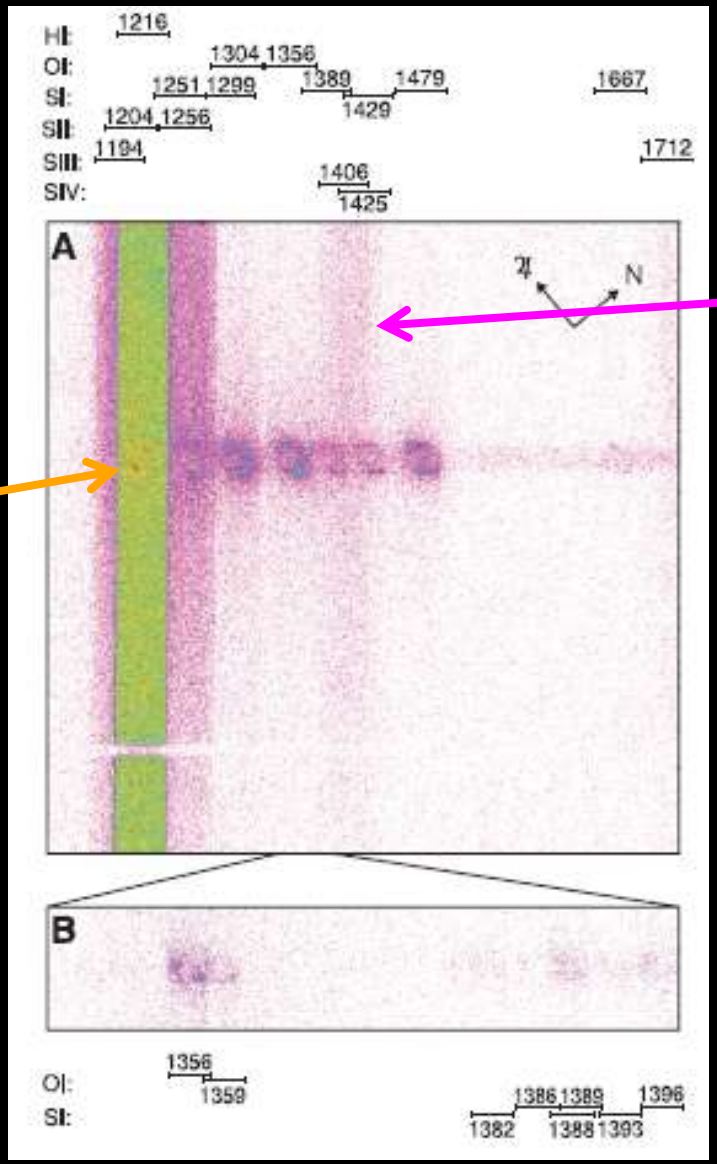
The ratio of 1356Å to 1302Å line strengths is consistent with electron impact excitation of O_2 with some contribution from O I

Feldman et al. (2000)

Objects in our Solar System

Io

Objects in our Solar System

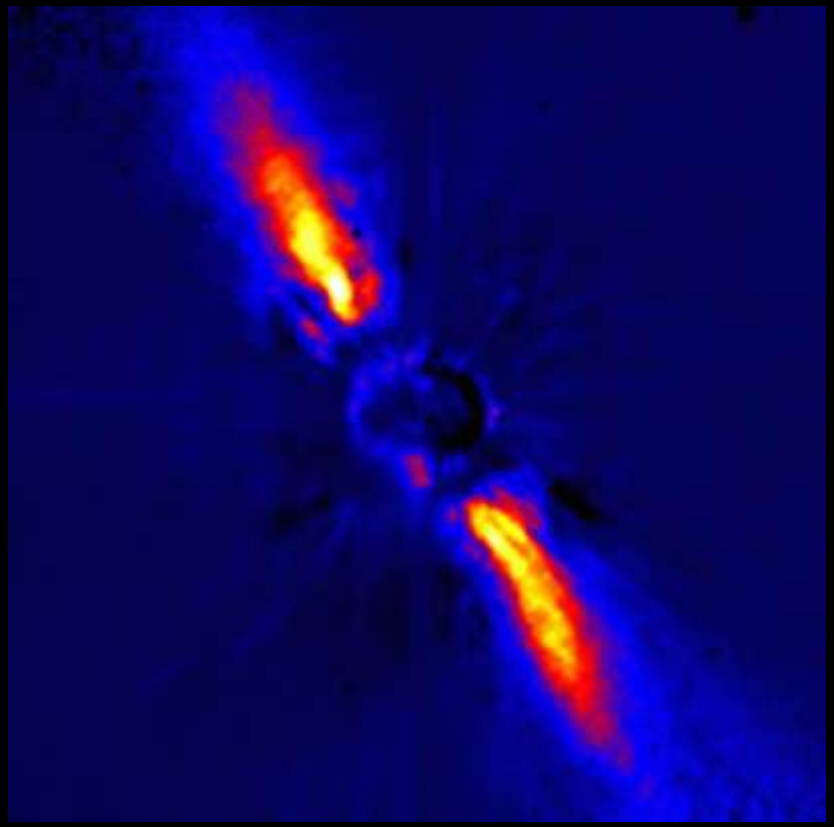


Lα emission

Extended emission from escaping neutral sulfur

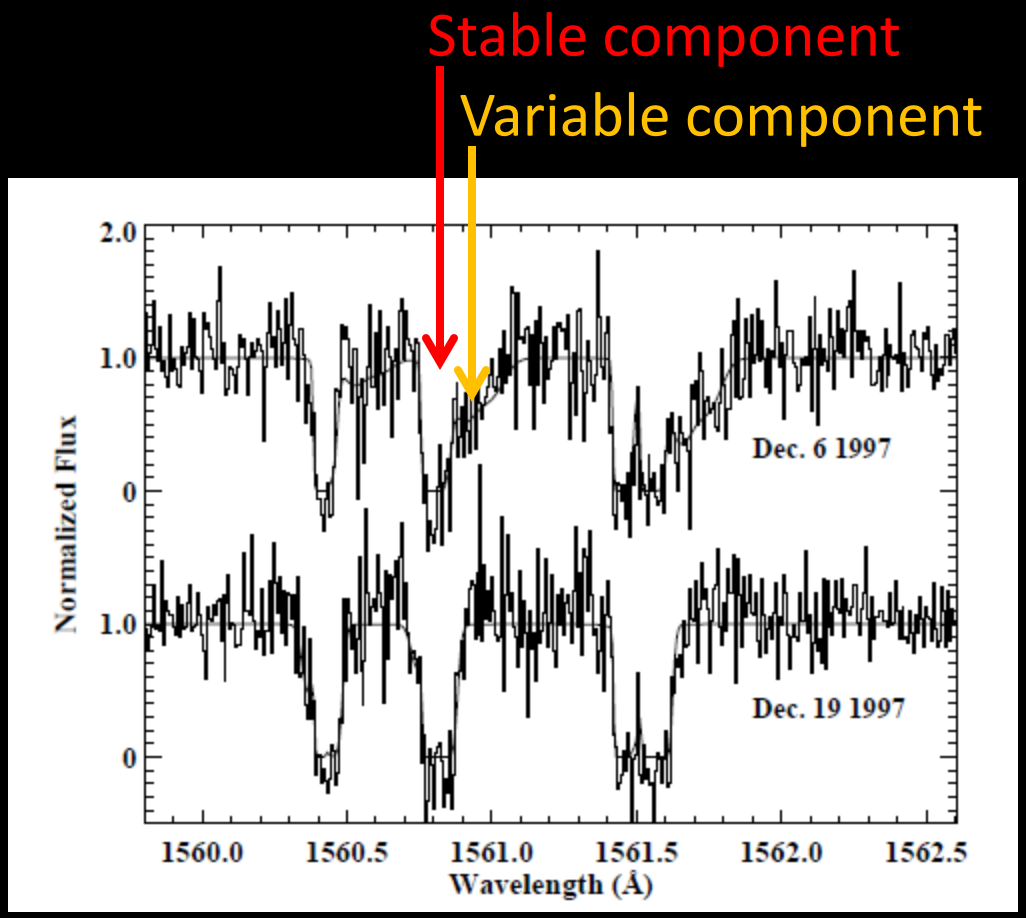
Roessler et al. (1999)

Things around other Stars: The Debris Disk Surrounding β Pic



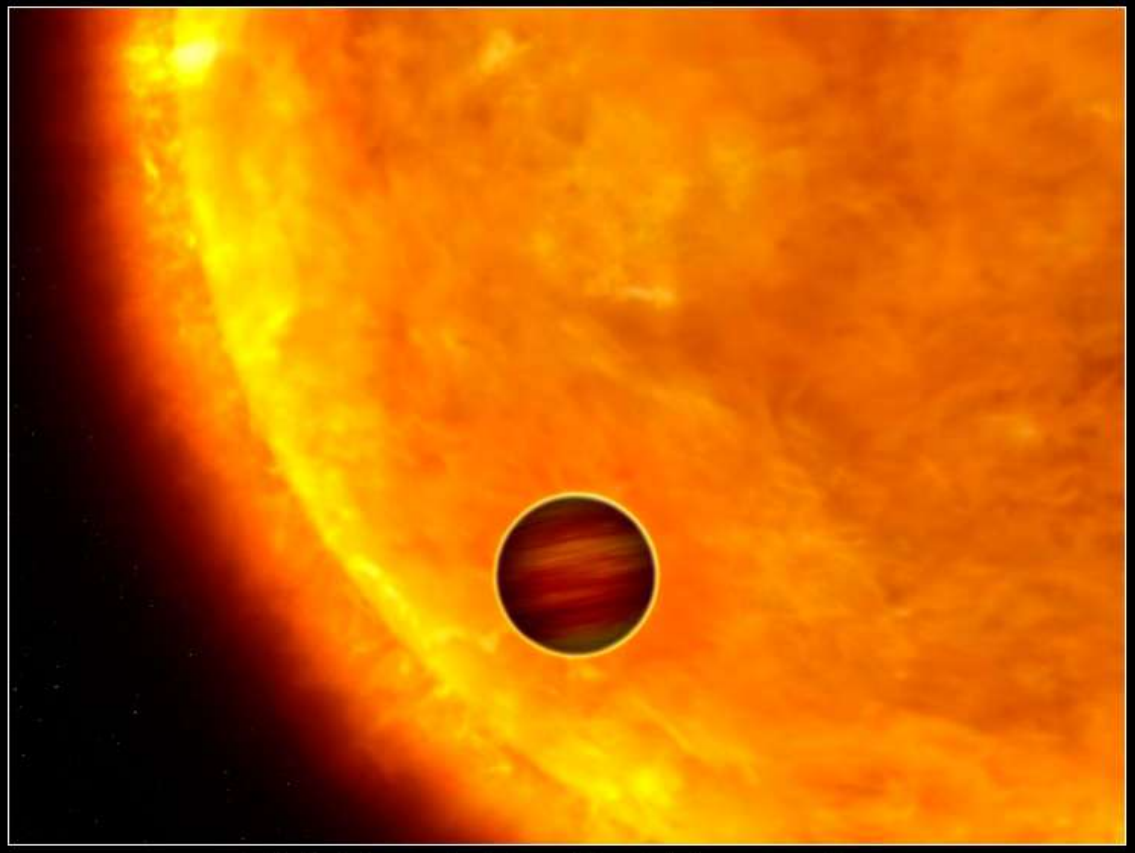
Things around other Stars: The Debris Disk Surrounding β Pic

Absorption by neutral carbon atoms



Roberge et al. (2000)

Things around other Stars: Transit of HD 209458b

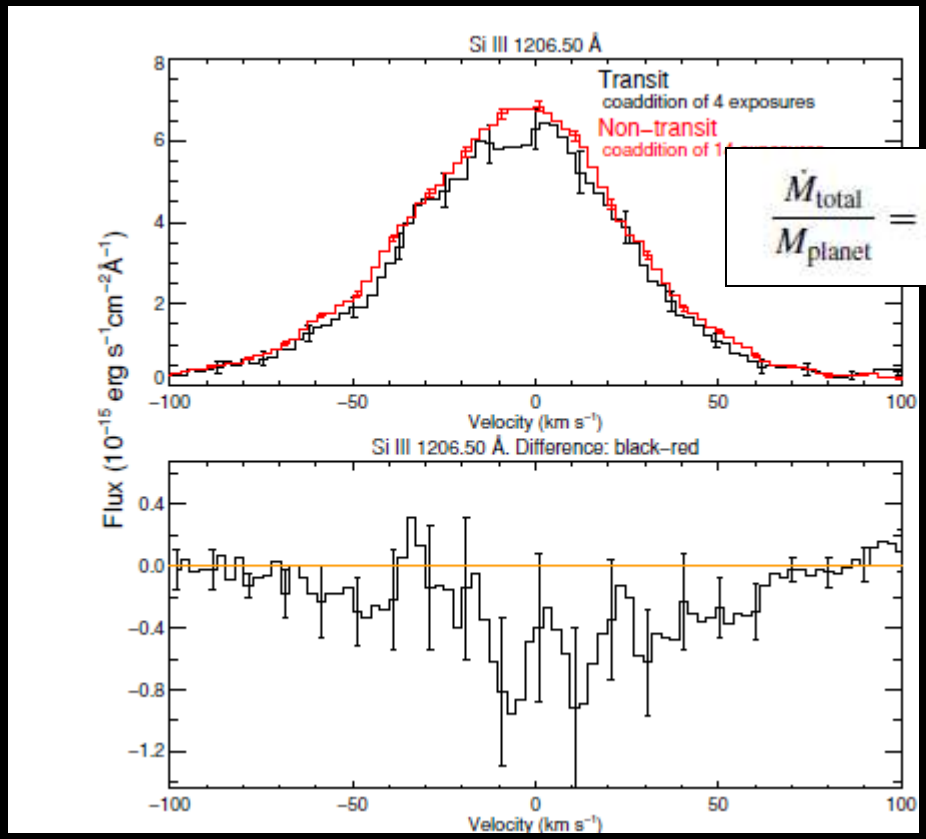


Artist's View of a Transiting Extrasolar Planet

NASA, ESA, and G. Bacon (STScI) ▪ STScI-PRC06-34b

Things around other Stars: Transit of HD 209458b

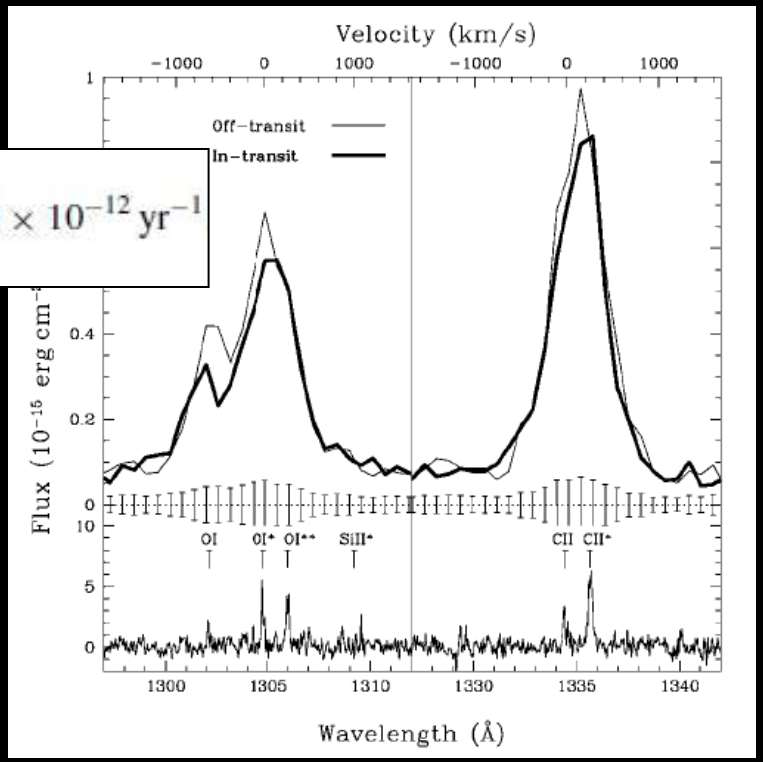
Si III



$$\frac{\dot{M}_{\rm total}}{M_{\rm planet}} = 2.0 \times 10^{-12}\,{\rm yr}^{-1}$$

Linsky et al. (2010)

O I C II



Vidal-Madjar et al. (2004)

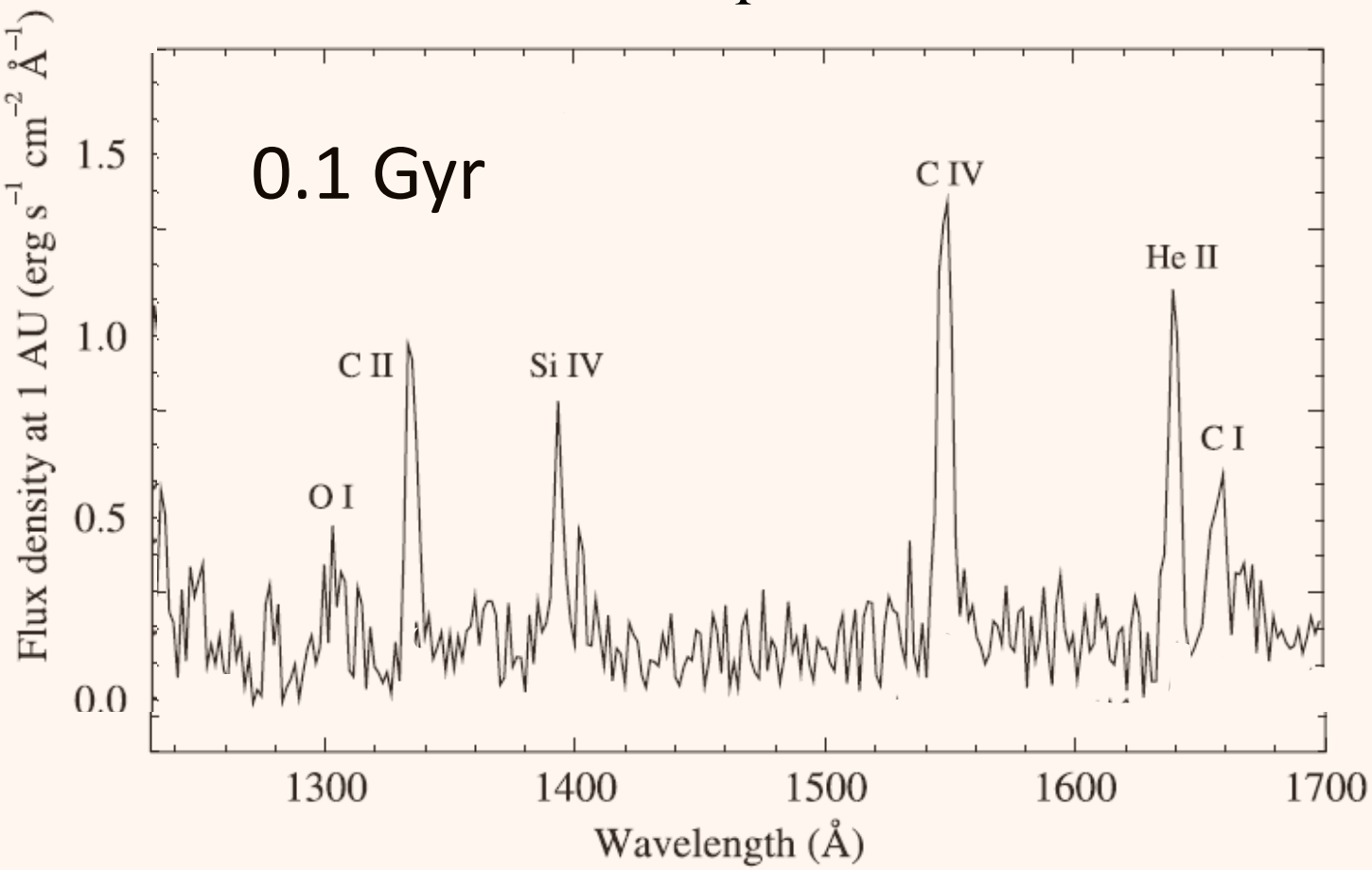
11:00

Behavior of Solar Analogs with Age

- From the work of Wilson (1963) and Wilson & Skumanich (1964), there has been evidence that the Ca II H & K reversals (and hence chromospheric activity) decrease with stellar age, probably as a result of the decrease in stellar rotation (Wilson 1966).

Behavior of Solar Analogs with Age

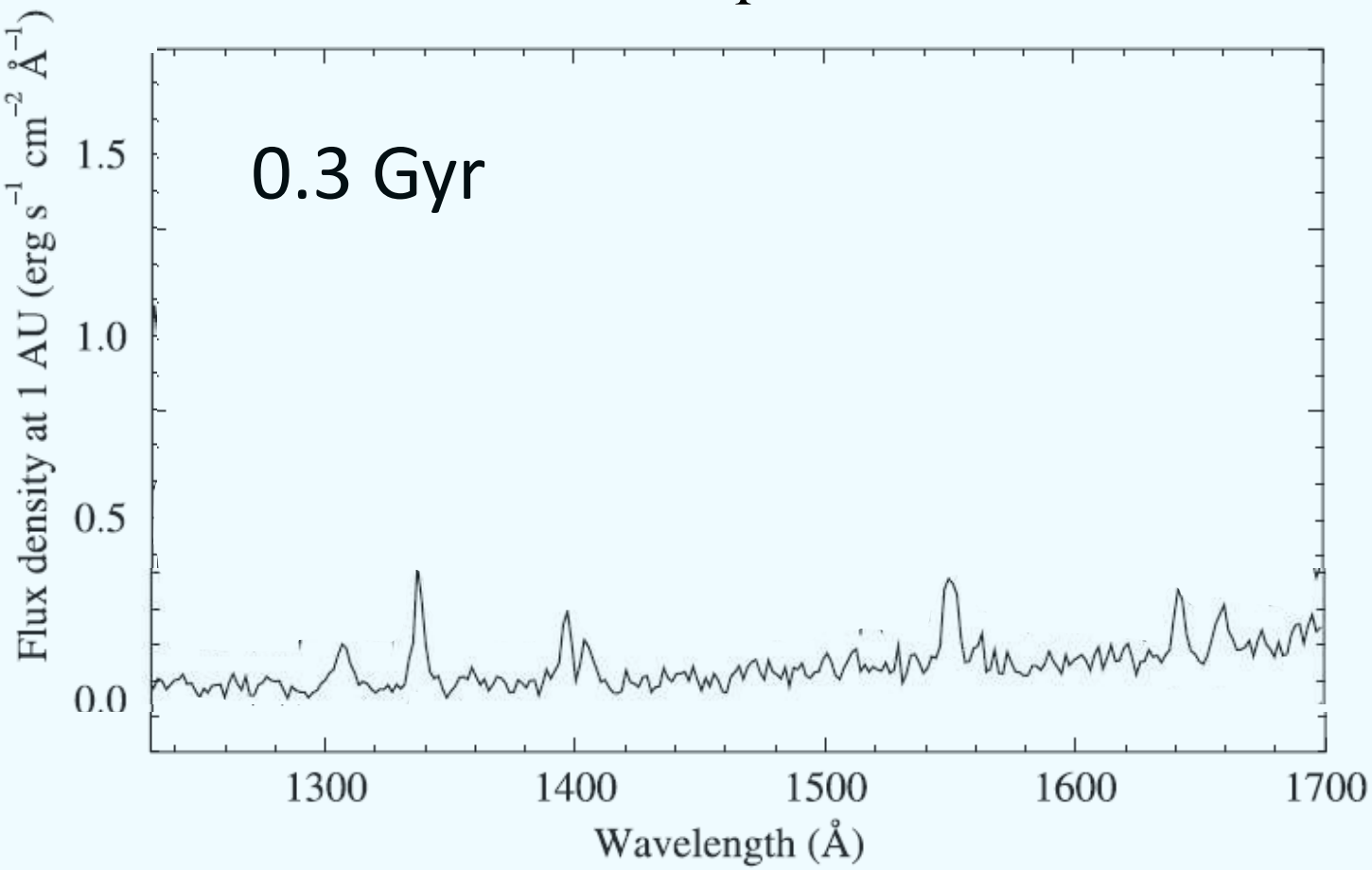
Ultraviolet Chromospheric Emission



Ribas et al (2005)

Behavior of Solar Analogs with Age

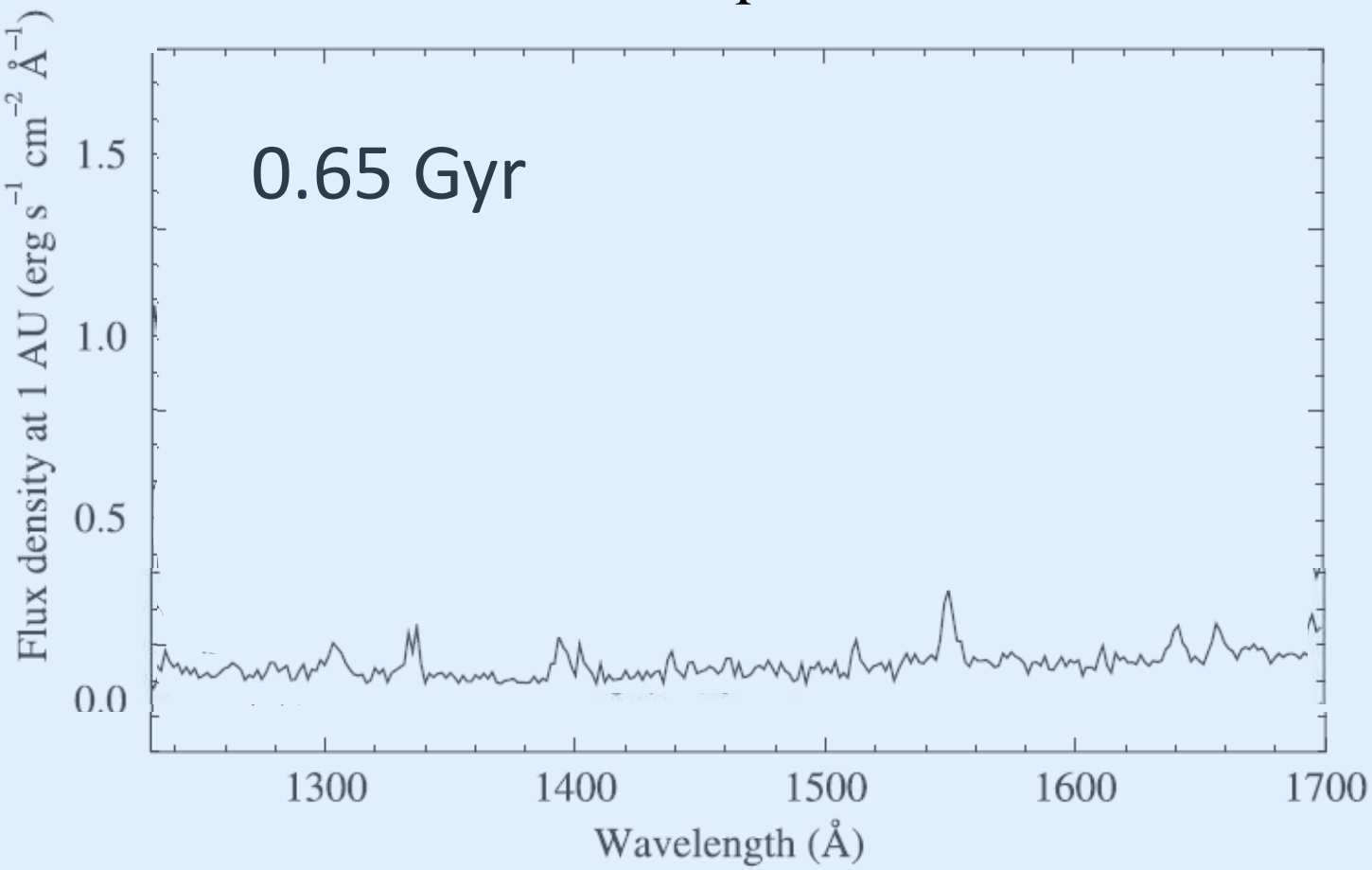
Ultraviolet Chromospheric Emission



Ribas et al (2005)

Behavior of Solar Analogs with Age

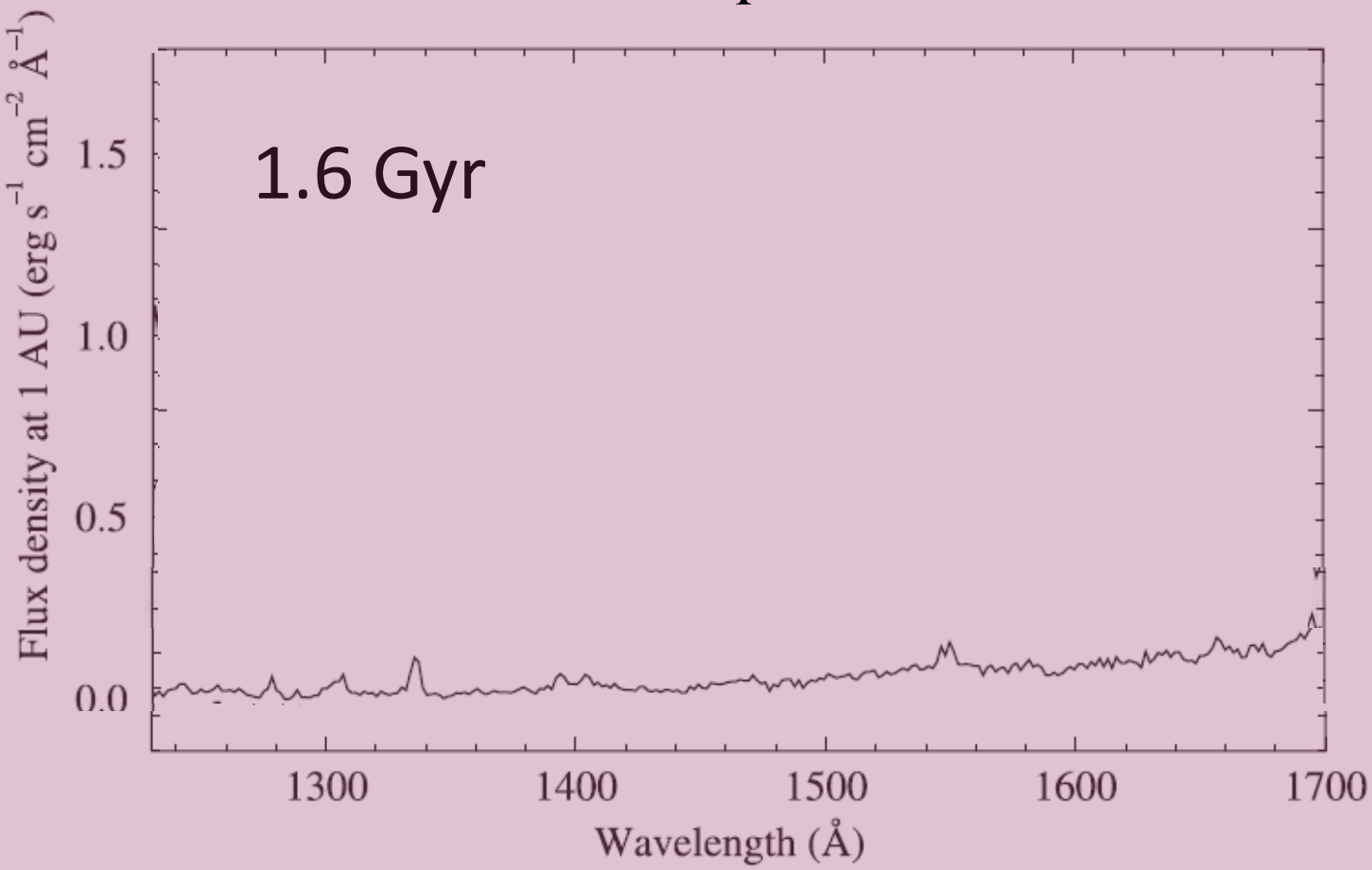
Ultraviolet Chromospheric Emission



Ribas et al (2005)

Behavior of Solar Analogs with Age

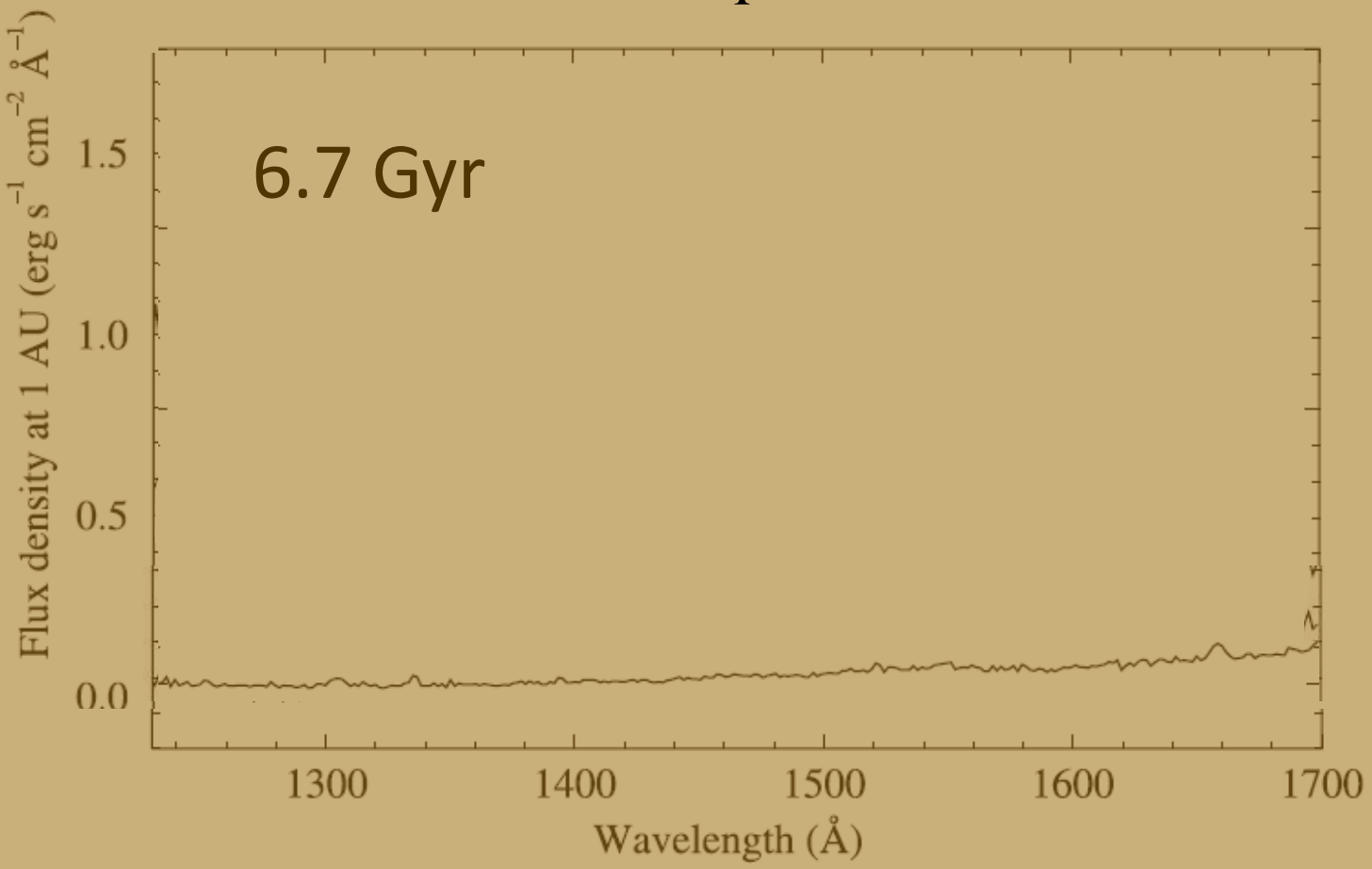
Ultraviolet Chromospheric Emission



Ribas et al (2005)

Behavior of Solar Analogs with Age

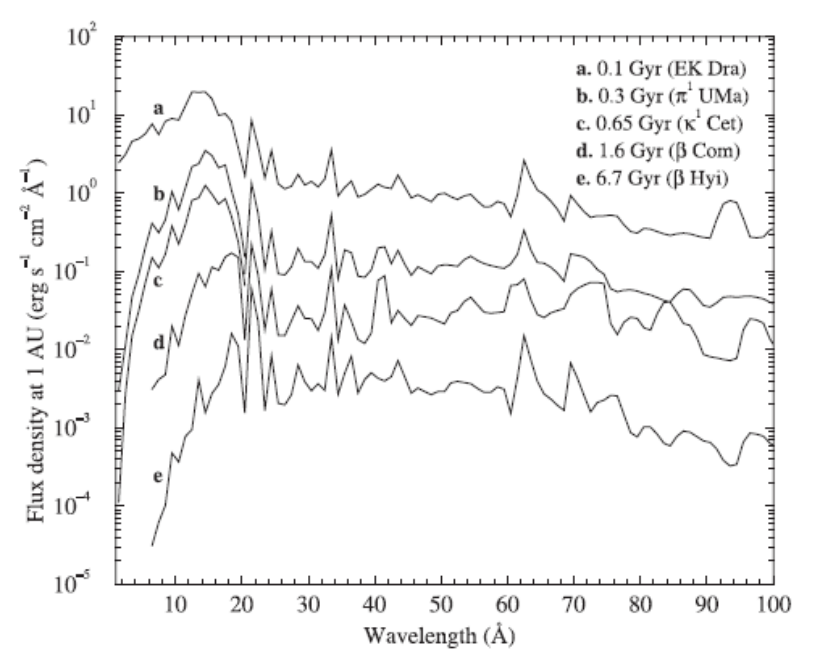
Ultraviolet Chromospheric Emission



Ribas et al (2005)

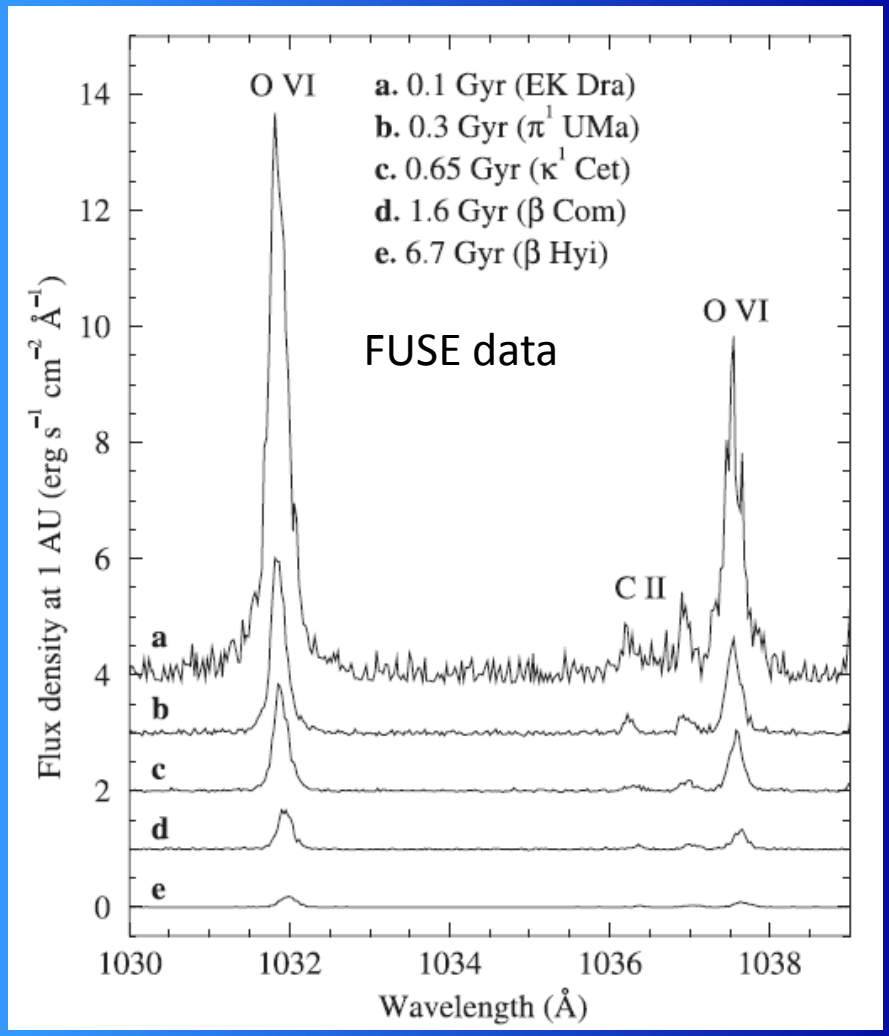
Behavior of Solar Analogs with Age

Shorter wavelengths



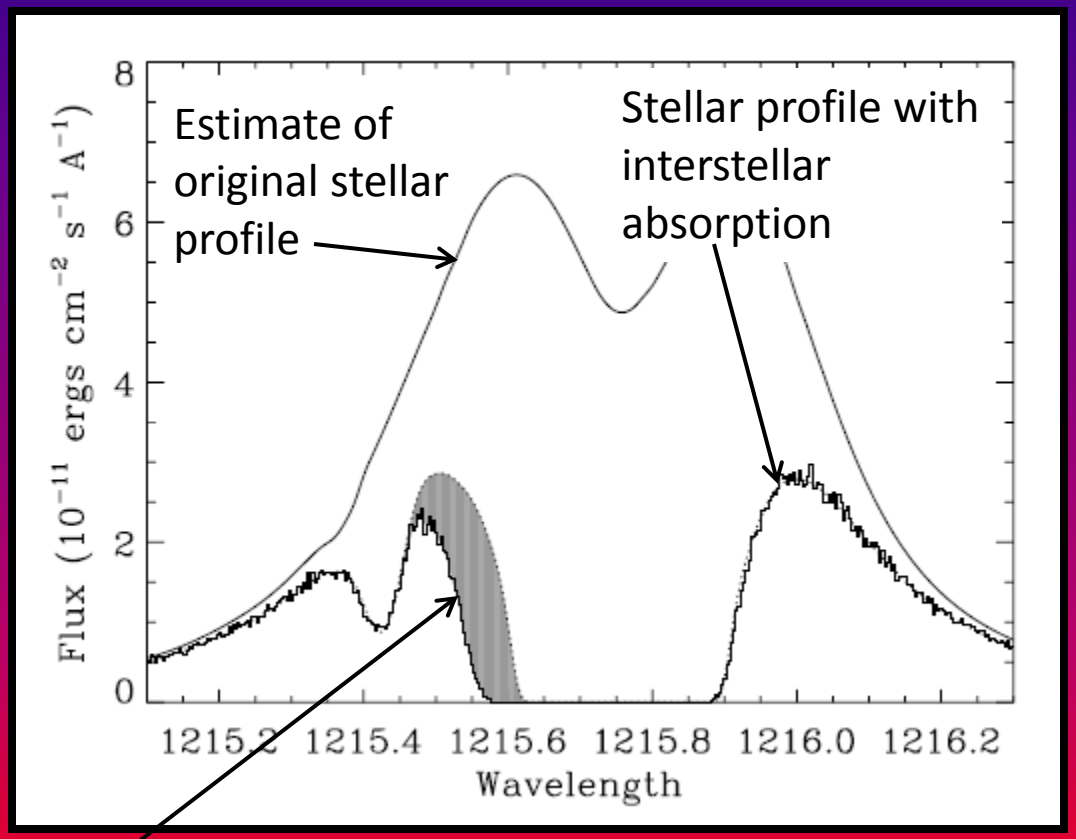
(Based on multi-T plasma fits to ASCA and ROSAT observations)

Ribas et al (2005)



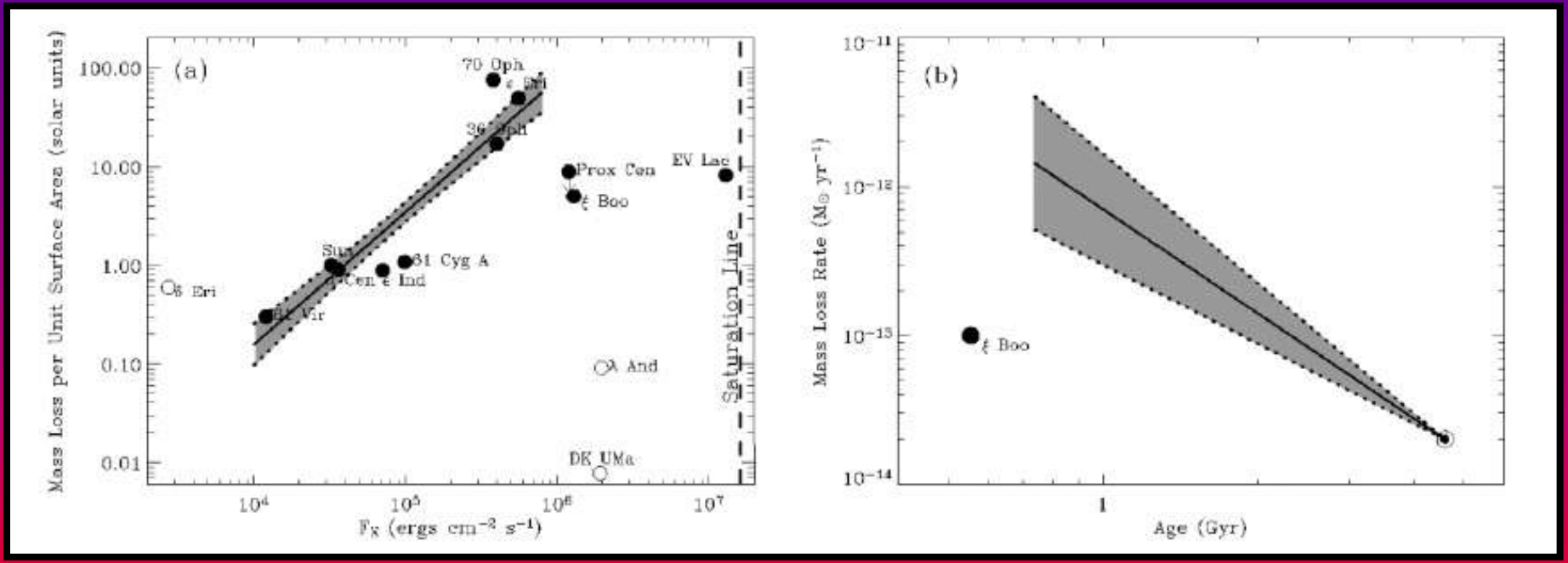
Guinan, Ribas & Harper (2003)

Mass Loss Rates from Astrospheres



Wood et al. (2002)

Mass Loss Rates from Astrospheres



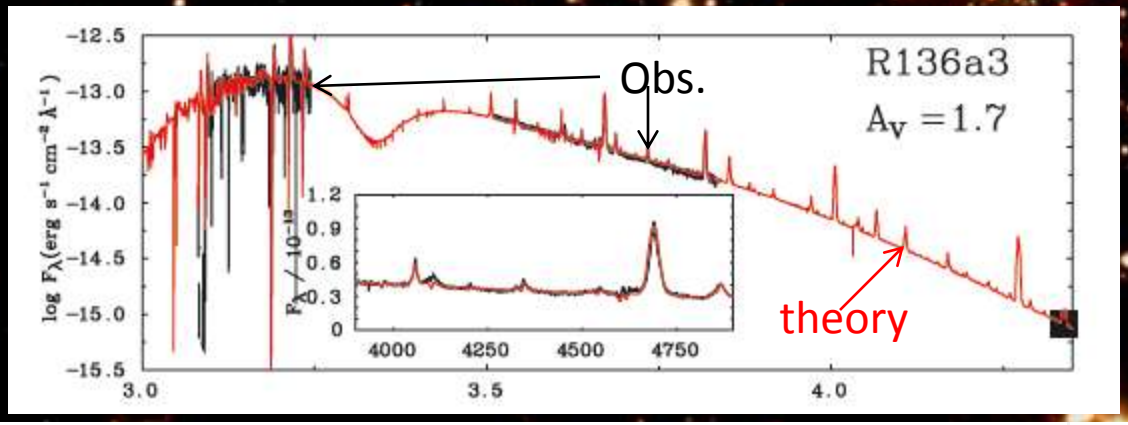
Wood et al. (2005)

Hot Stars

- Much has already been done in the past using IUE
- Much improvement came from better NLTE atmosphere models
- HST particularly good for crowded fields, like this one

Hot Stars

R136



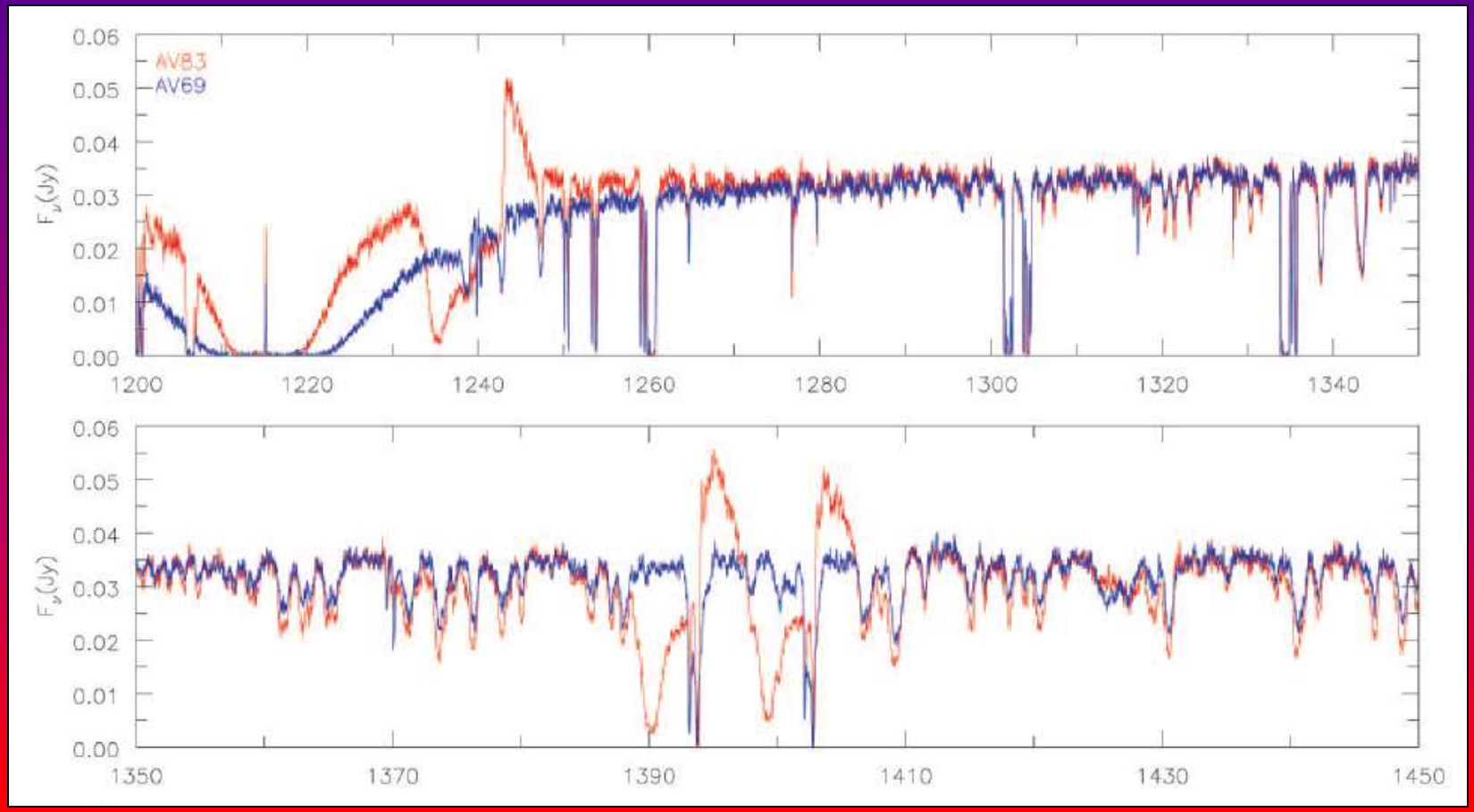
Crowther et al. (2010)

$M_{\rm init}$ $(M_\odot)^b$	320^{+100}_{-40}	240^{+45}_{-45}	165^{+30}_{-30}	220^{+55}_{-45}
$M_{\rm current}$ $(M_\odot)^b$	265^{+80}_{-35}	195^{+35}_{-35}	135^{+25}_{-20}	175^{+40}_{-35}

Stars: P-Cygni Profiles, Terminal Wind Velocities, Mass Loss Rates

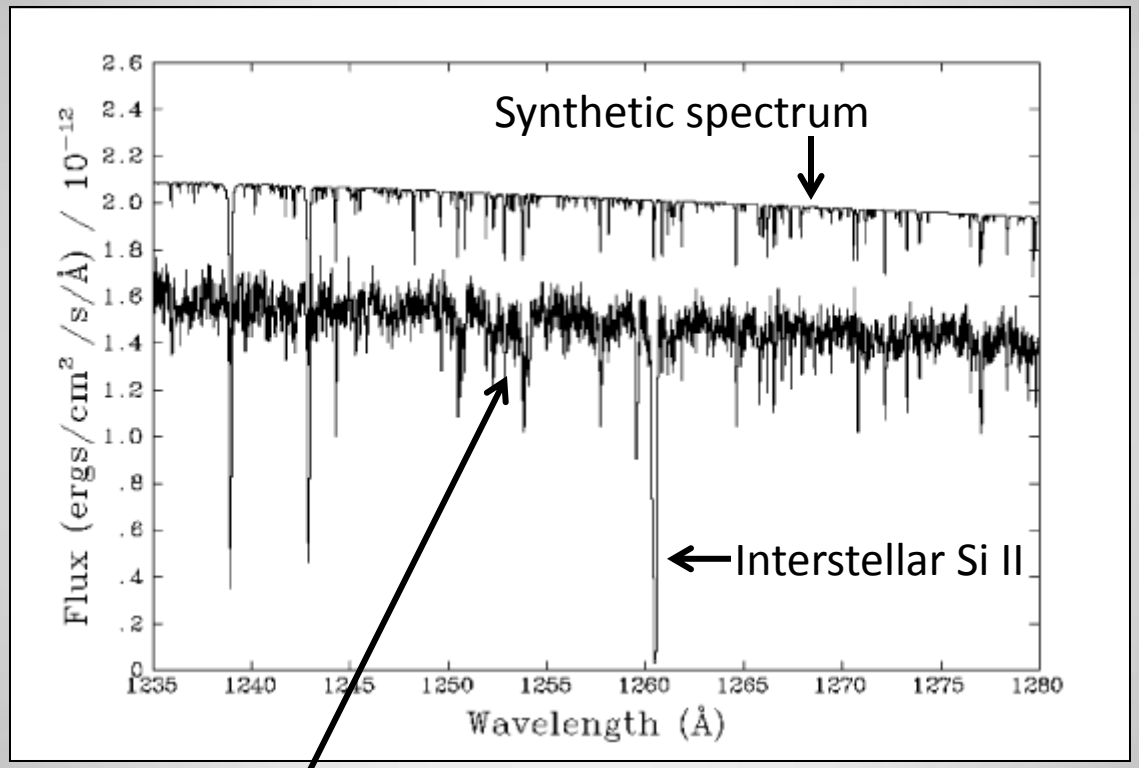
Hillier et al. (2003)

Stars: P-Cygni Profiles, Terminal Wind Velocities, Mass Loss Rates



Hillier et al. (2003)

Metal Abundances in the Atmospheres of DAZ White Dwarfs



Barstow et al. (2003)

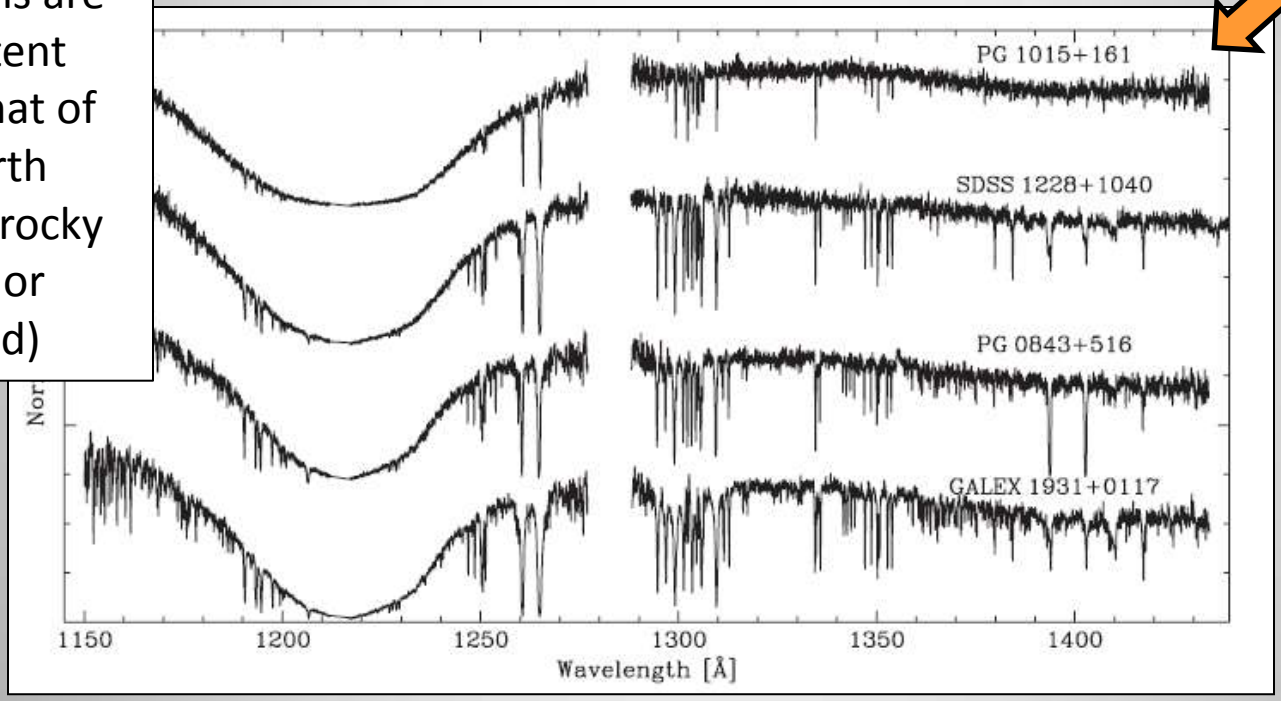
Obs. Spectrum of REJ0558-373
(T_{eff} = 59,508K, Log g = 7.70)

Radiative levitation overcomes diffusive settling for $T_{eff} \geq 50{,}000K$

Metal Abundances in the Atmospheres of DAZ White Dwarfs

Abundance patterns are consistent with that of the Earth (i.e., a rocky planet or asteroid)

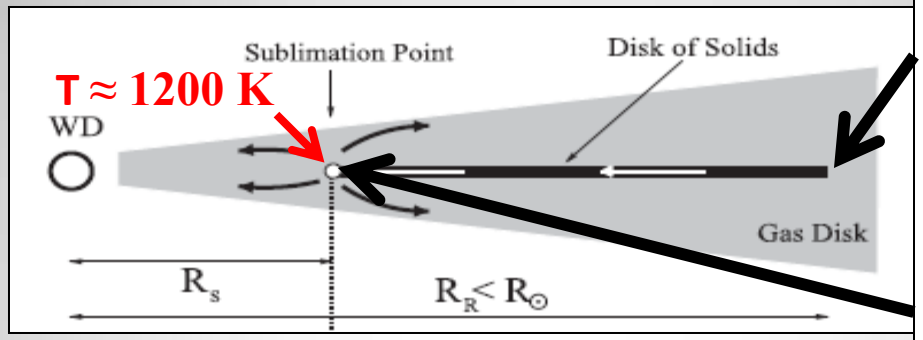
These WD stars have $T_{eff} \approx 20{,}000K$



Diffusive settling times for metals in these atmospheres are of order several days!

Gänsicke et al. (2012)

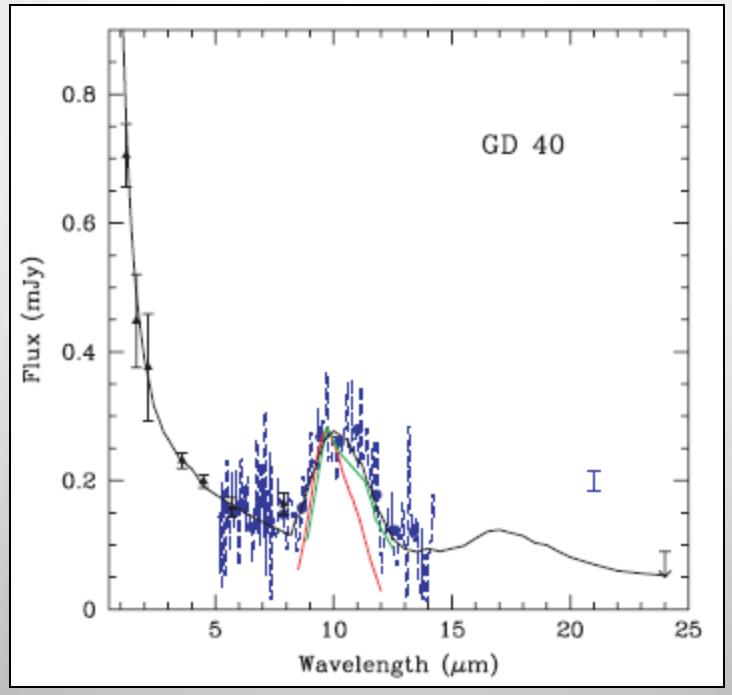
Metal Abundances in the Atmospheres of DAZ White Dwar



Initial transport: Tidal disruption of asteroids creates particles subject to Poynting-Robertson drag,

followed by sublimation that produces gas. This gas then creates a drag on the particles that assists the inward migration of solids onto the star.

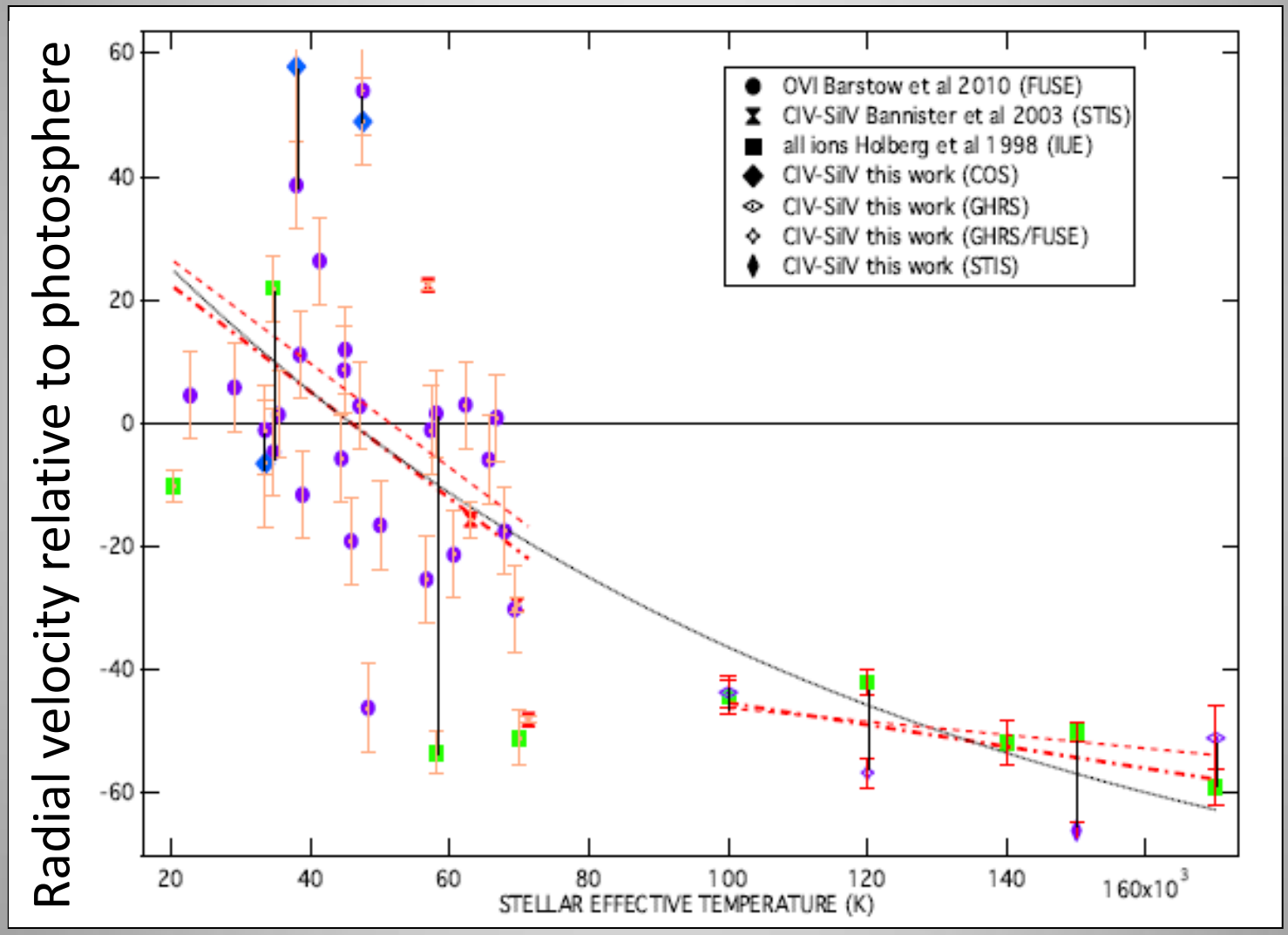
Metzger et al. (2012)



Some of these stars show 10μm silicate emission from their debris disks

Jura, Farihi & Zuckerman (2009)

Hot Winds from White Dwarfs

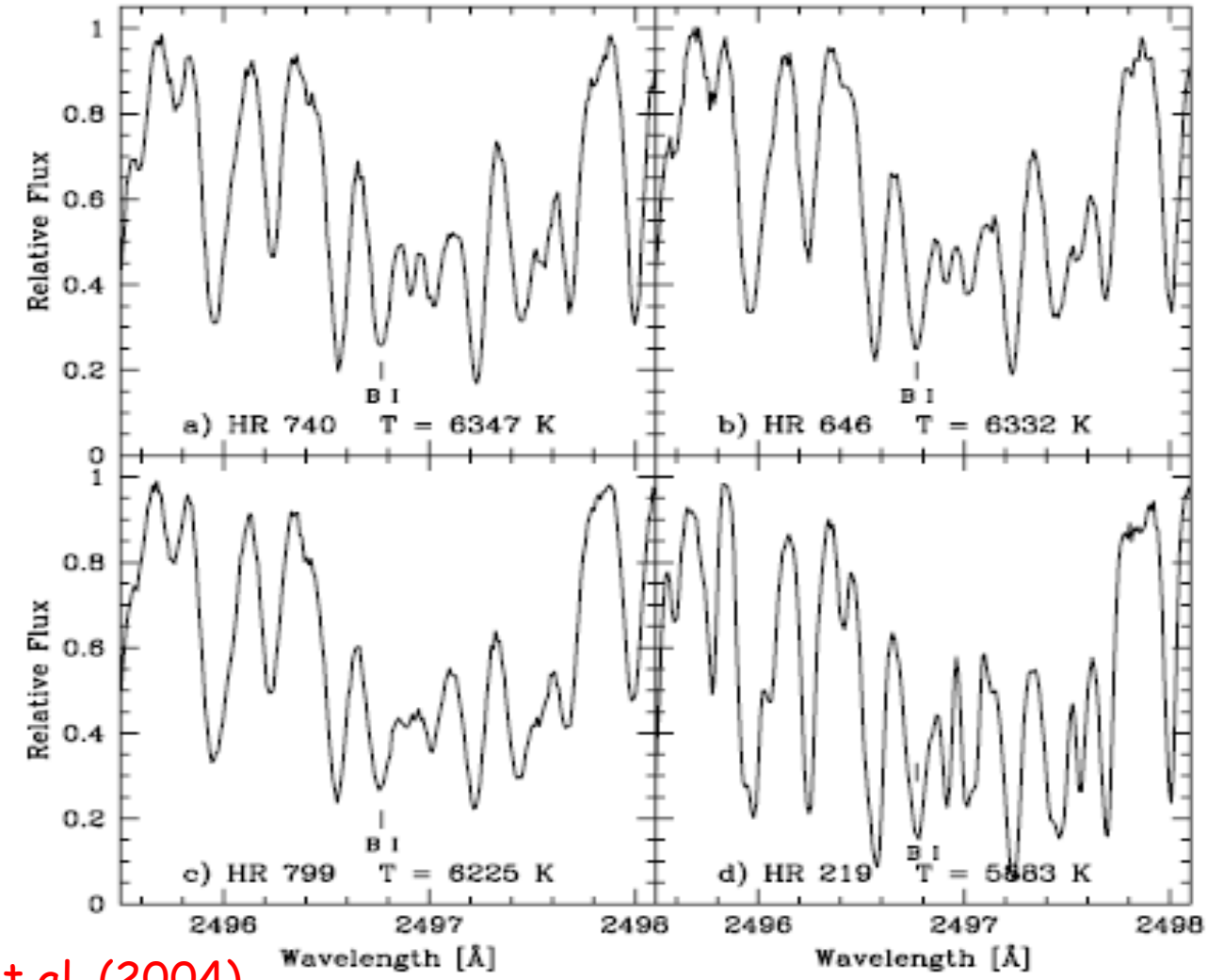


Lallement et al. (2011)

Some Element Abundances in Stars that Require UV Observations

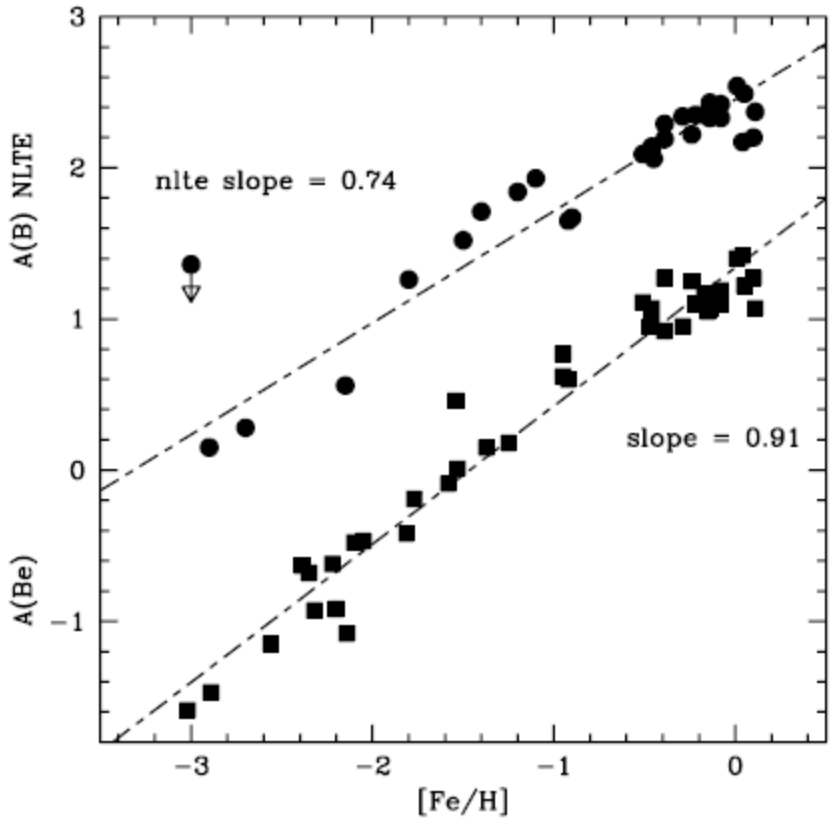
- Some peculiar elements in chemically peculiar stars
- Absorption lines of some neutron-capture elements can be seen in the visible, but many others (e.g., 3rd r-process peak) require UV spectra. Can study correlations, or lack thereof, of various abundances with each other and with [Fe/H]
- Boron abundances and how they scale with [Fe/H] — insights on light-element production by spallation

Boron Abundances vs. [Fe/H]



Boesgaard et al. (2004)

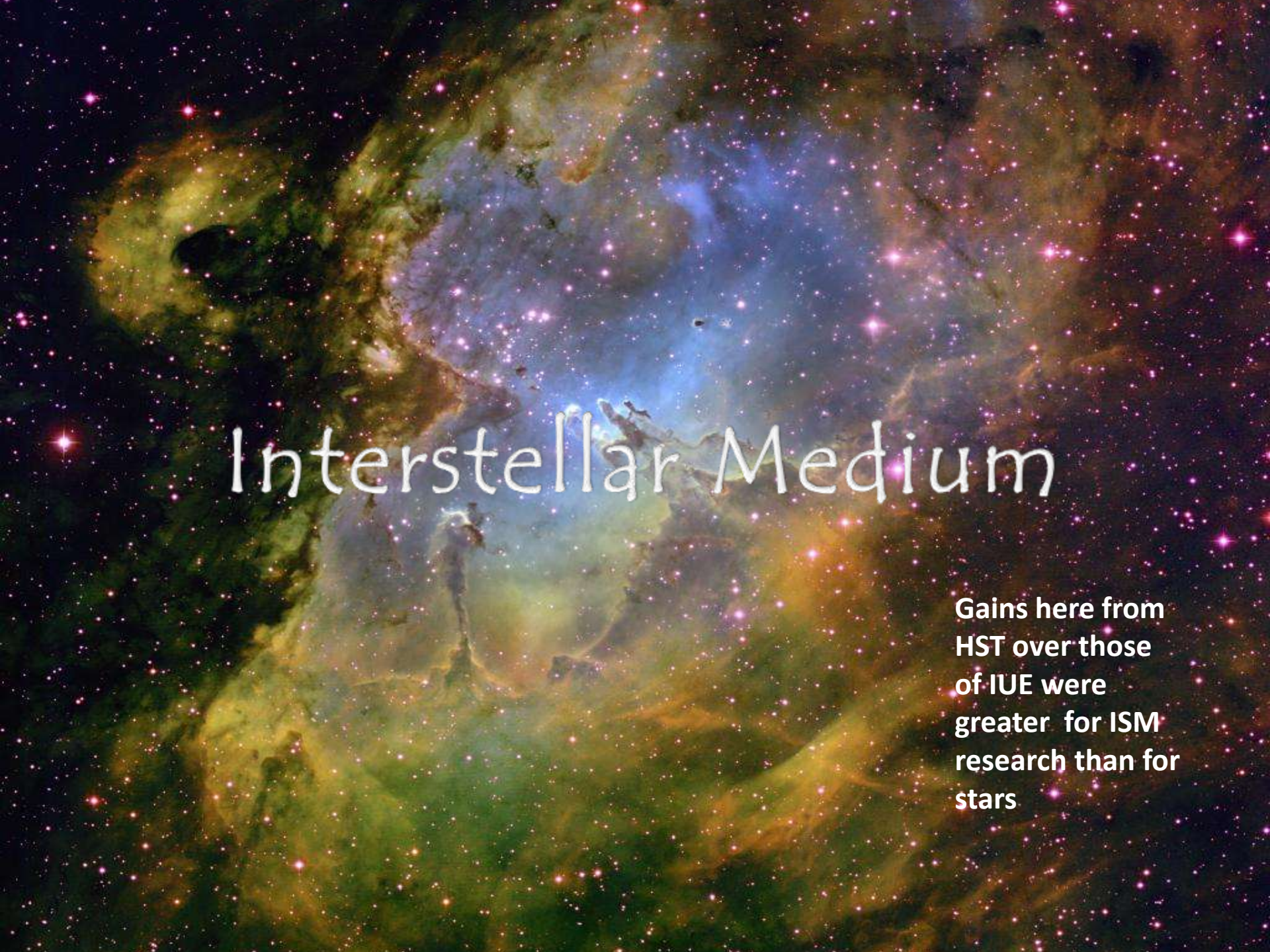
Boron Abundances vs. [Fe/H]



Boesgaard et al. (2004)

CR protons → C,N,O (ISM) should produce slope = 2, whereas
C,N,O (CR) → protons (ISM) would produce slope = 1
(Duncan et al. 1997)

We can guard against being misled by stellar burning of B by monitoring the abundances of Be and Li, which will be destroyed at lower temperatures.

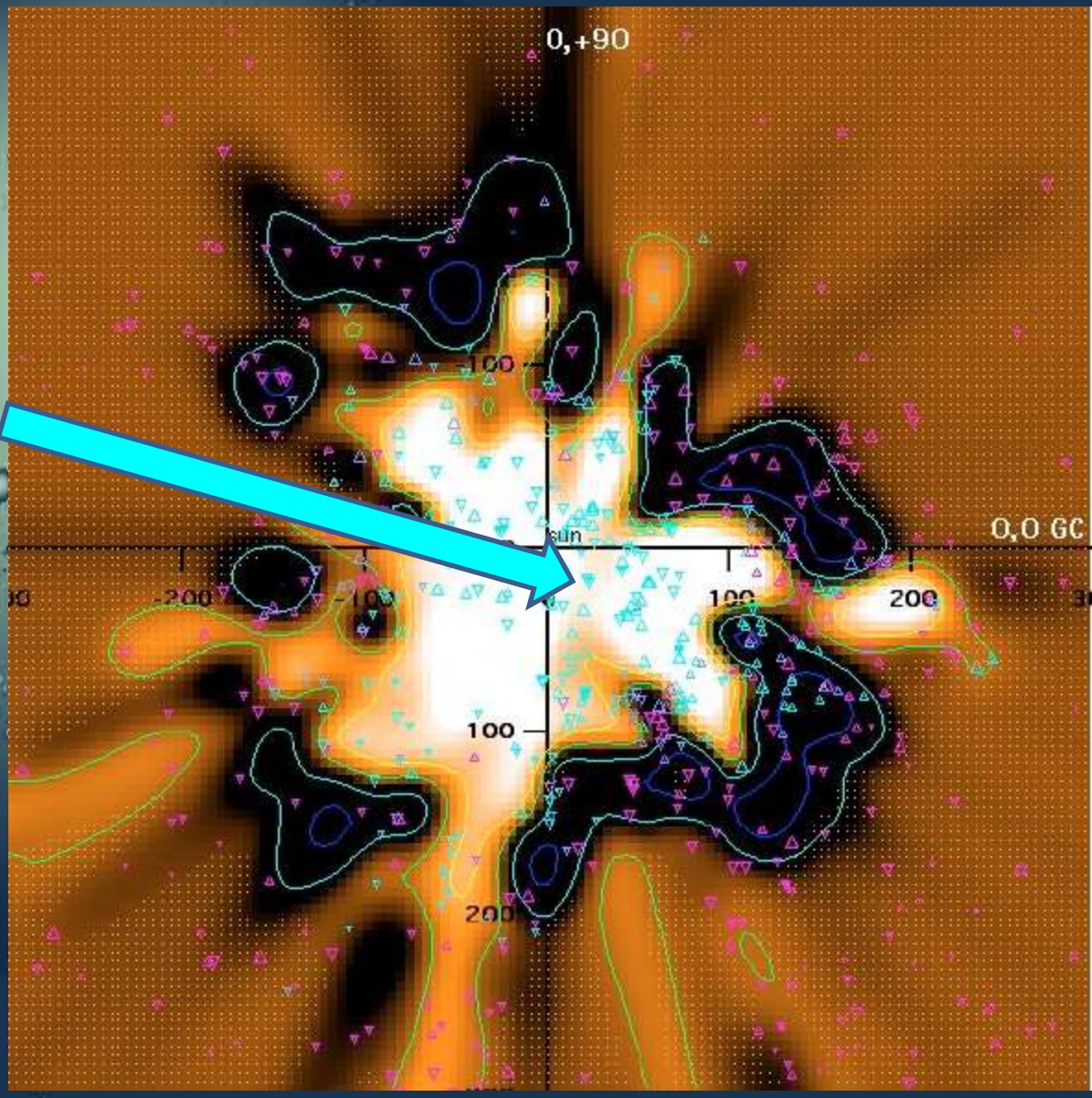


Gains here from HST over those of IUE were greater for ISM research than for stars


The Local Bubble

HST spectra of cool stars inside the Local Bubble indicate that there are warm, low density clouds embedded within the void shown in white.

Redfield & Linsky, (2008)



Temperatures and Turbulent Velocity Dispersions

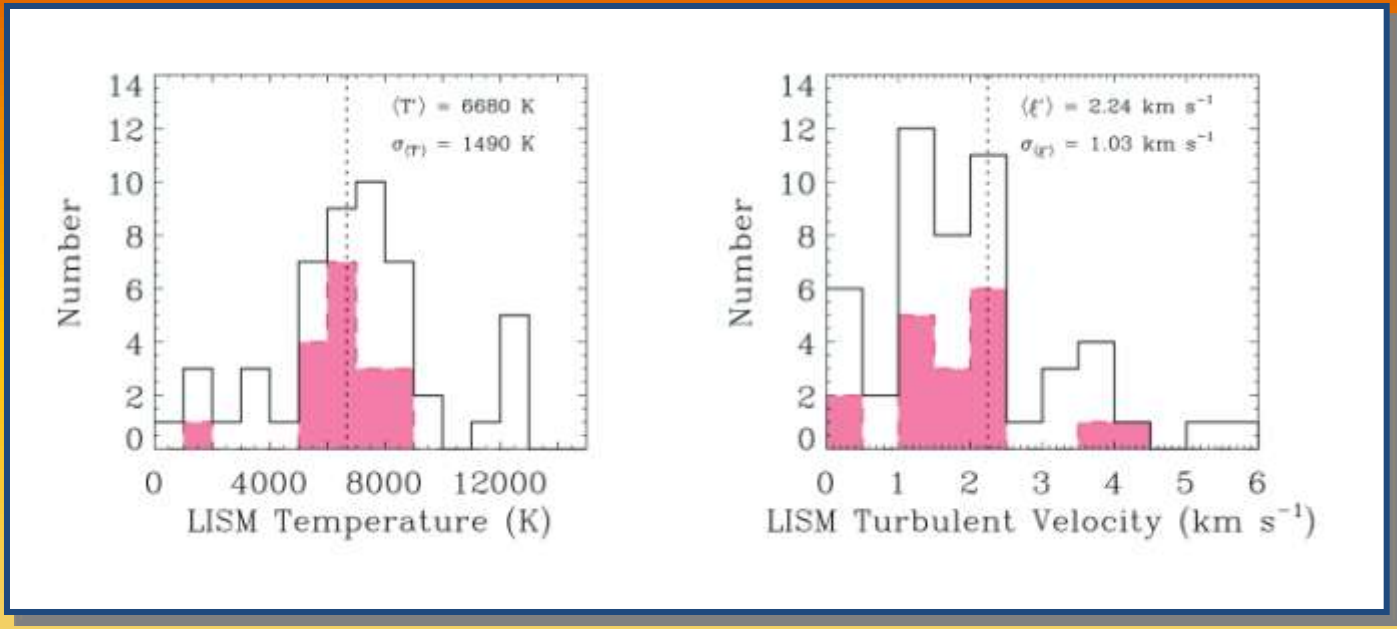
- Basic Formula – Doppler velocity dispersion adds in quadrature with turbulent velocities:

$$b^2 = \frac{2kT}{m} + \xi^2 = 0.016629\frac{T}{A} + \xi^2$$

This term varies with mass

This one doesn't

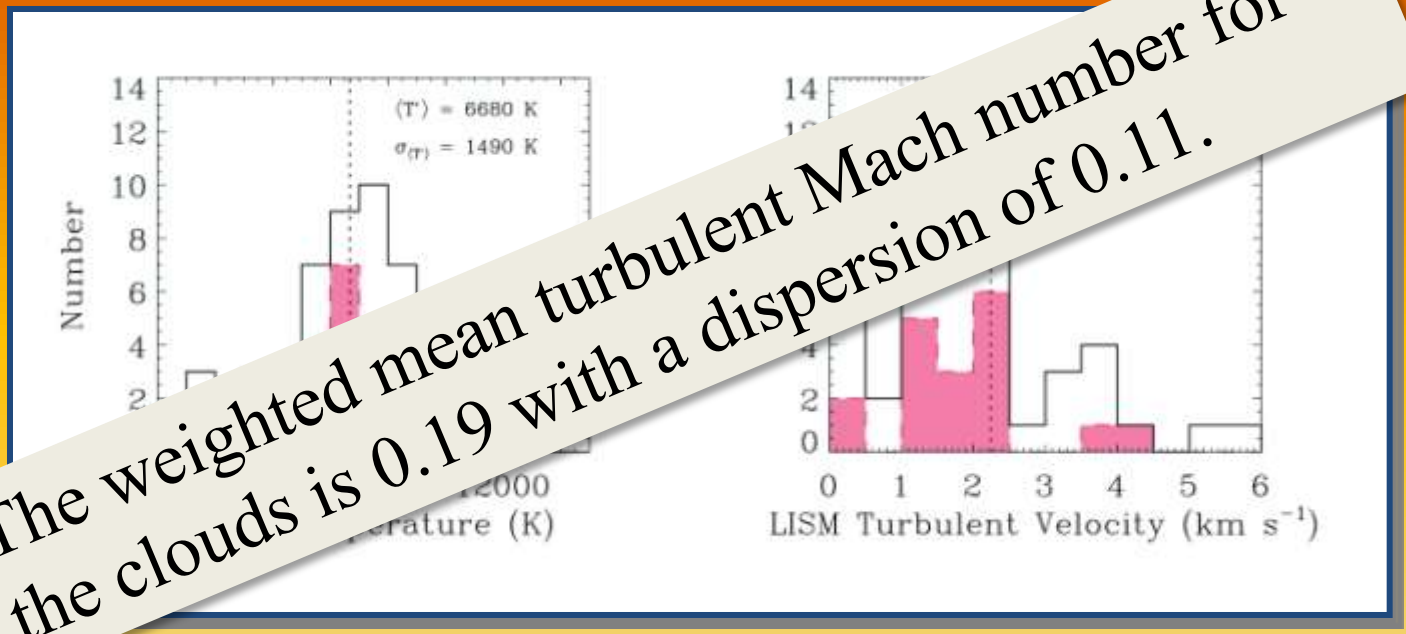
Temperatures and Turbulent Velocity Dispersions



Redfield & Linsky (2004)

Red portions indicate more precise measurements, i.e., those with errors less than the overall dispersion

Temperatures and Turbulent Velocity Dispersions



The weighted mean turbulent Mach number for the clouds is 0.19 with a dispersion of 0.11.

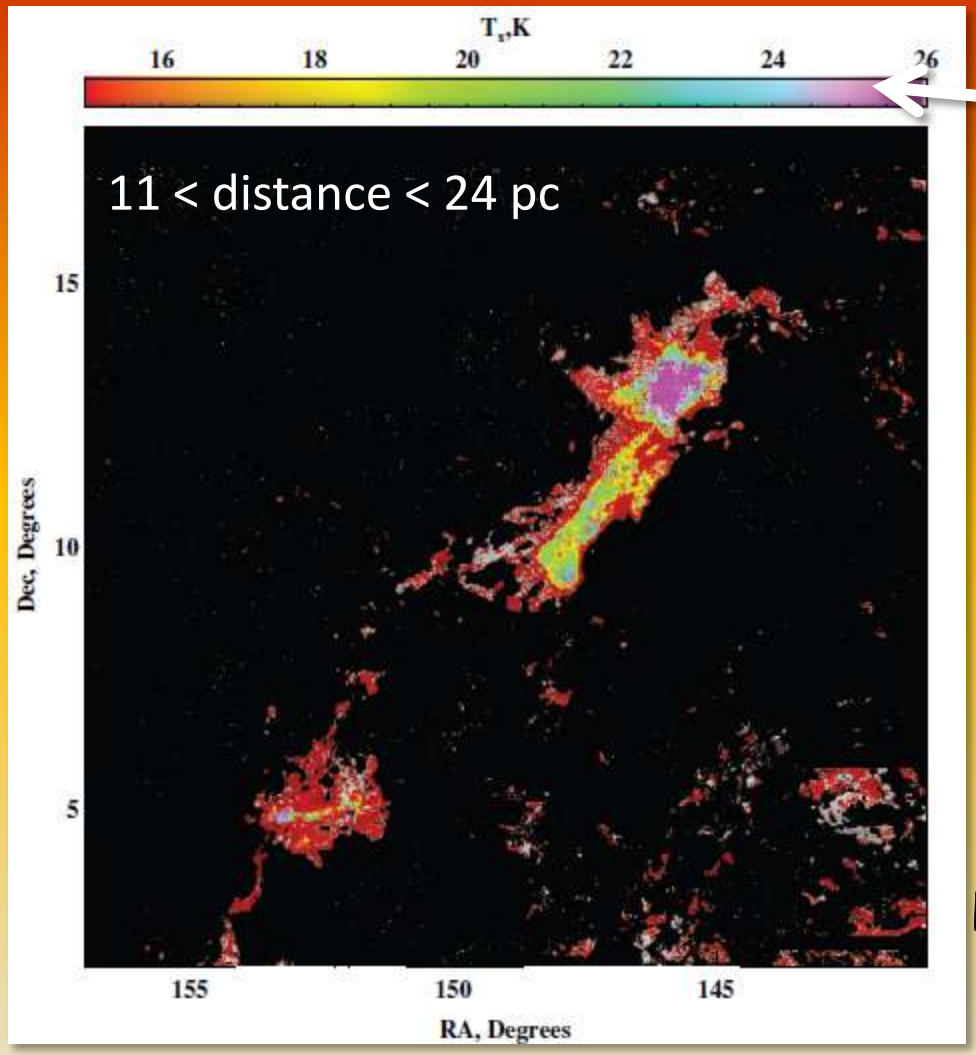
Redfield & Linsky (2004)

Red portions indicate more precise measurements, i.e., those with errors less than the overall dispersion

Temperatures and Turbulent Velocity Dispersions

However, there's an interesting exception to this picture ….

The Local Leo Cold Cloud



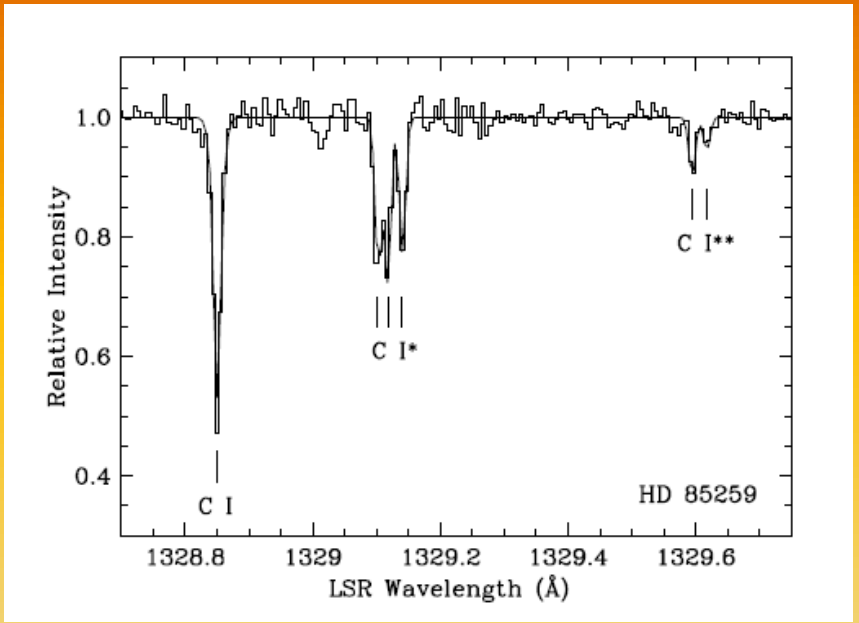
Very cold!

Peek et al. (2011)

The Local Leo Cold Cloud

Findings from high resolution STIS spectroscopy of stars behind the cloud

- C I fine-structure excitation and temperatures indicate that this cloud has a thermal pressure $p/k \approx 60{,}000\ cm^{-3}K$, which is far above normal.
- This condition could arise from the compression that occurs when two warm clouds collide.

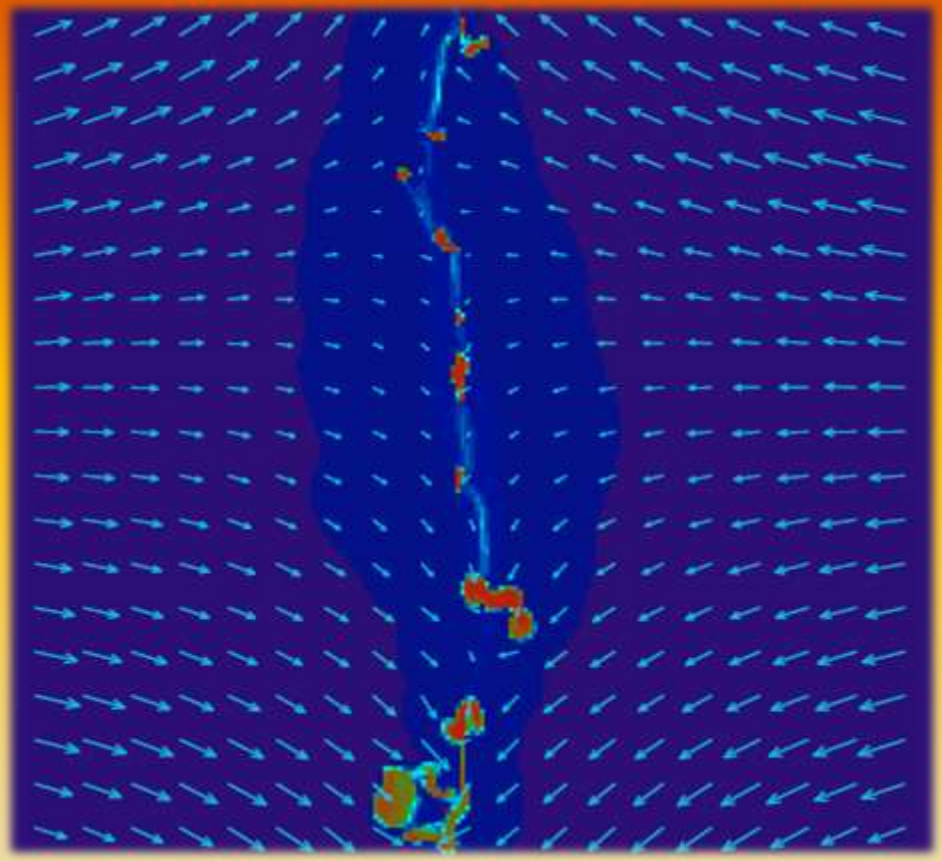


Meyer et al. (2012)

The Local Leo Cold Cloud

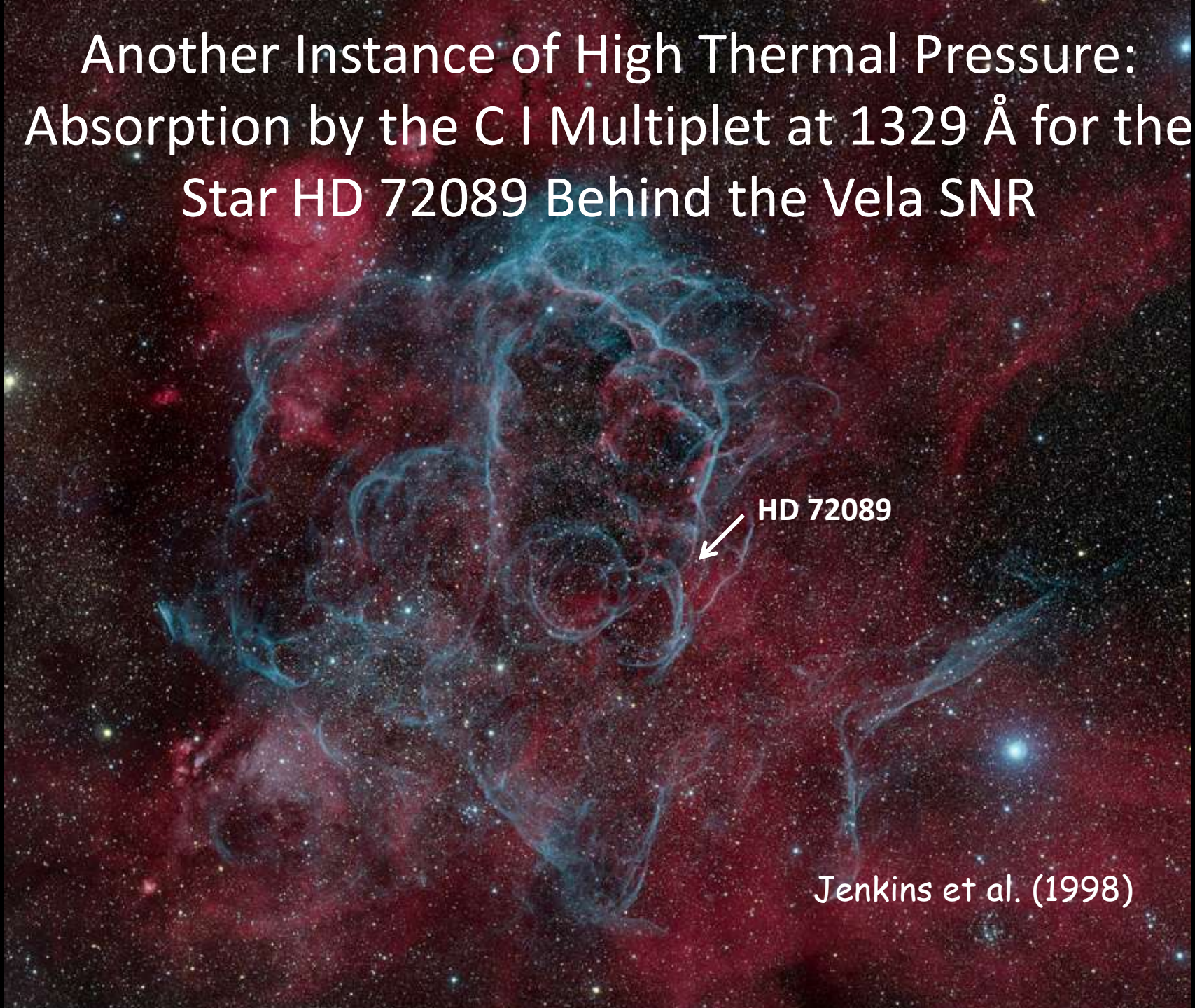
Findings from high resolution STIS spectroscopy of stars behind the cloud

- C I fine-structure excitation and temperatures indicate that this cloud has a thermal pressure $p/k \approx 60{,}000\ cm^{-3}K$, which is far above normal.
- This condition could arise from the compression that occurs when two warm clouds collide.

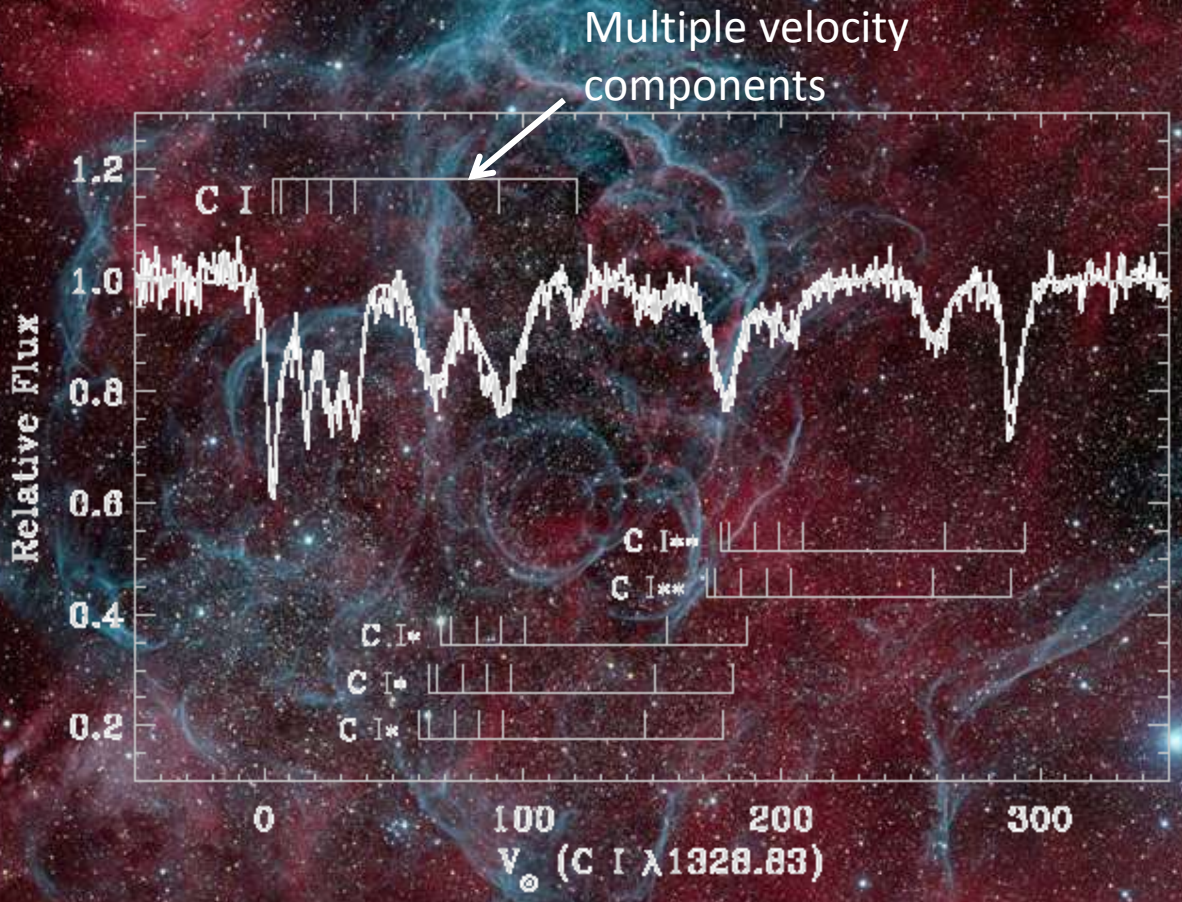


Audit & Hennebelle (2005)

Another Instance of High Thermal Pressure: Absorption by the C I Multiplet at 1329 Å for the Star HD 72089 Behind the Vela SNR

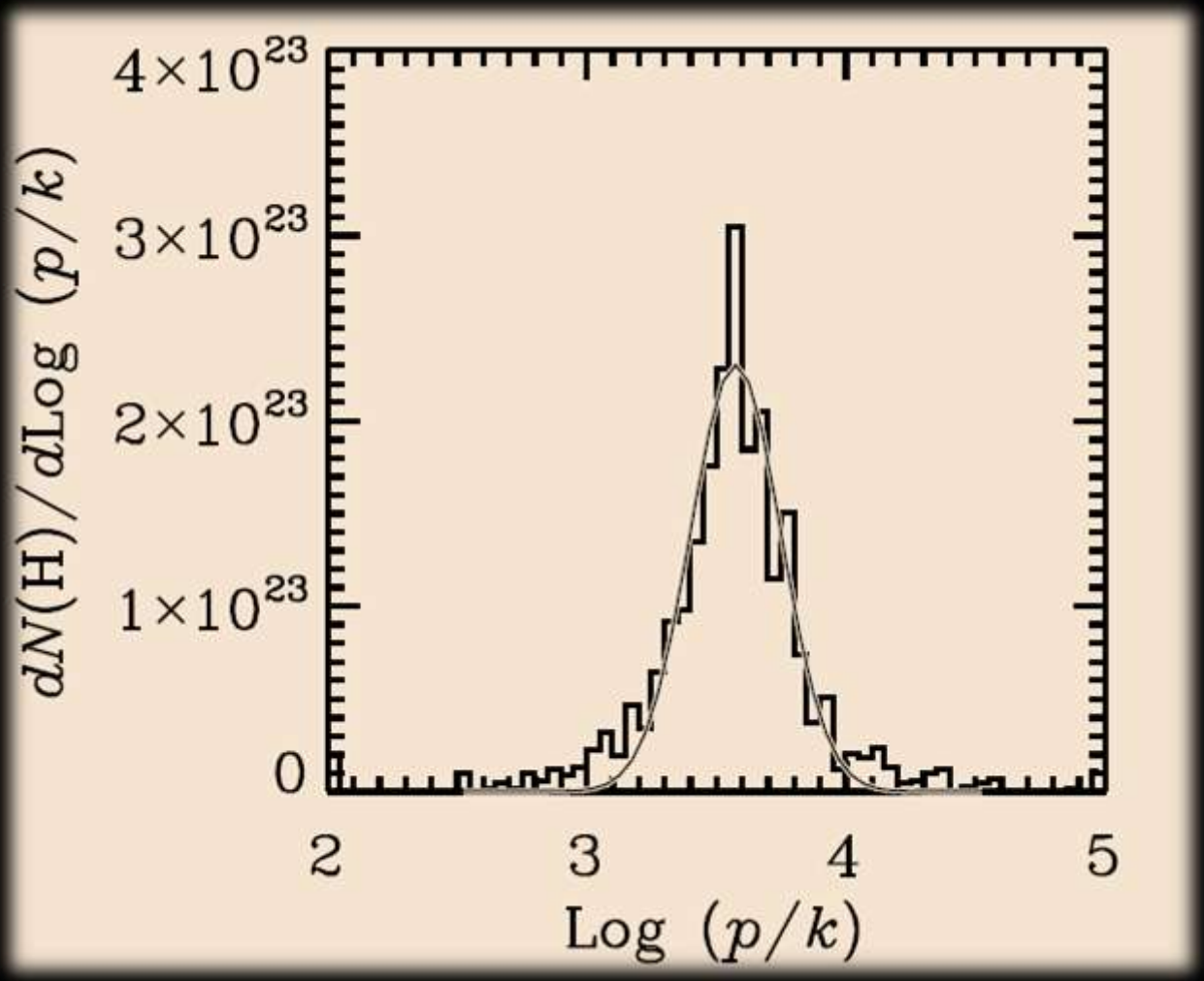


Another Instance of High Thermal Pressure: Absorption by the C I Multiplet at 1329 Å for the Star HD 72089 Behind the Vela SNR



Jenkins et al. (1998)

Thermal Pressure Distribution for Typical Translucent Interstellar Clouds



Jenkins & Tripp (2011)

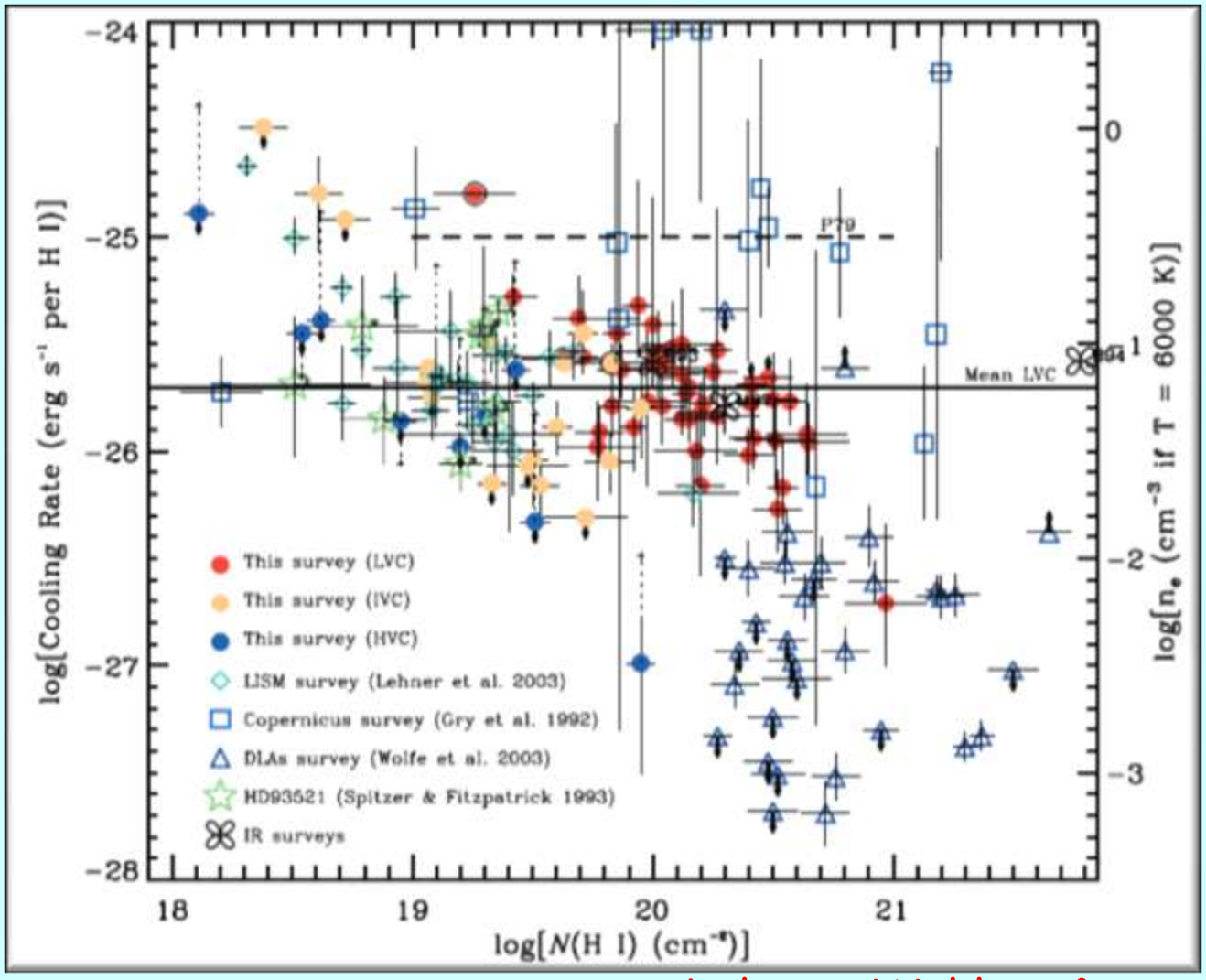
Cooling of the ISM

Principal coolant is C^+ in an excited fine-structure level which radiates at 158μm

$$\Lambda(C^+) = h\nu_{21}A_{21}n(C^{+*})$$
$$= 2.89 \times 10^{-20} n(C^{+*}) \text{ ergs s}^{-1} \text{ cm}^{-3}$$

$$l_c \equiv \frac{\int \Lambda(C^+)\,ds}{\int n(H^0)\,ds} = 2.89 \times 10^{-20} \frac{N(C^{+*})}{N(H^0)} \text{ ergs s}^{-1} \text{ (H atom)}^{-1}$$

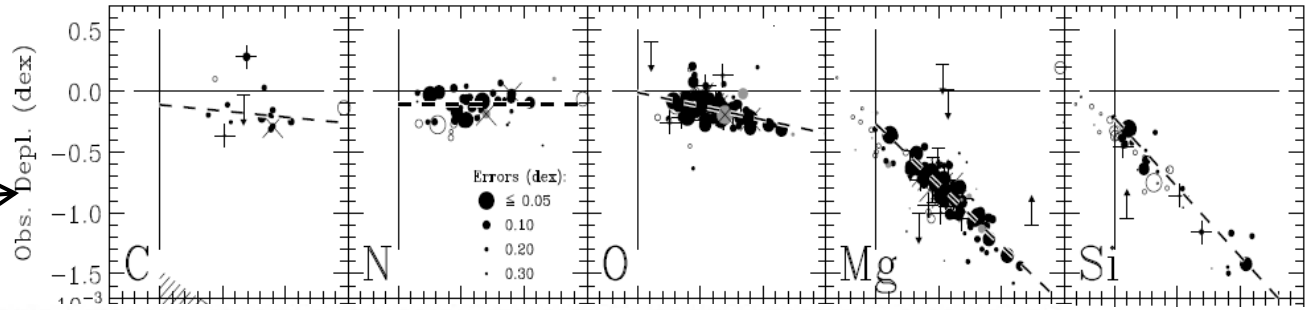
Cooling of the ISM

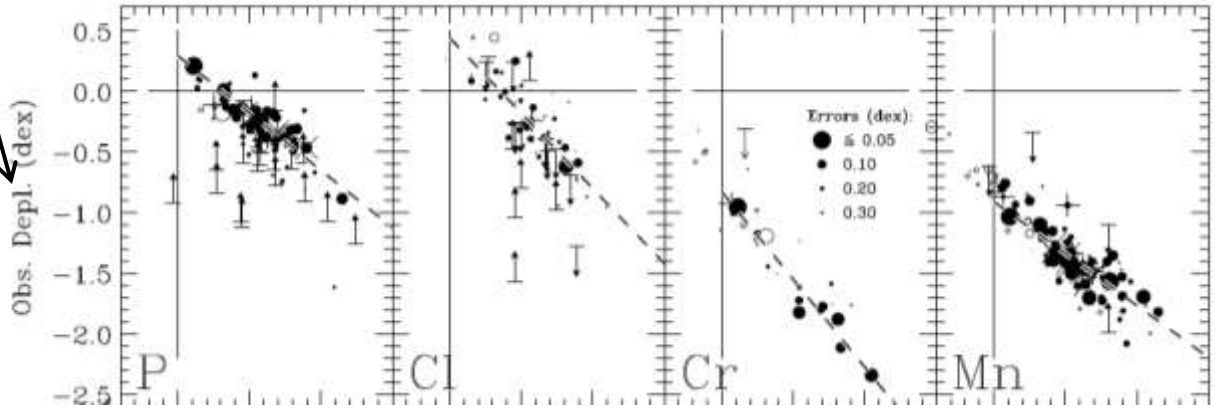


Lehner, Wakker & Savage (2004)

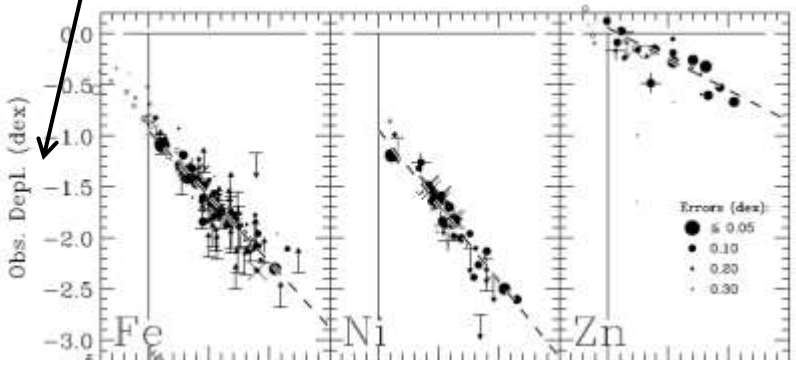
Depletions of Atoms in the Gas Phase

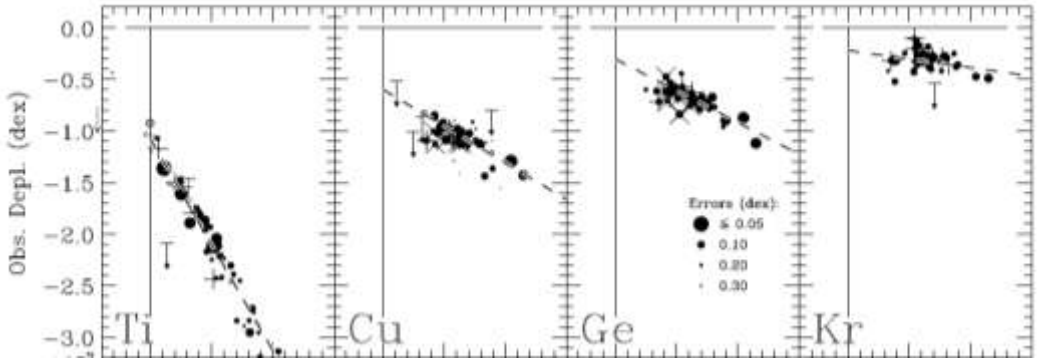
Depl. = Log[N(X)/N(H)] – Log[X/H]$_{Sun}$





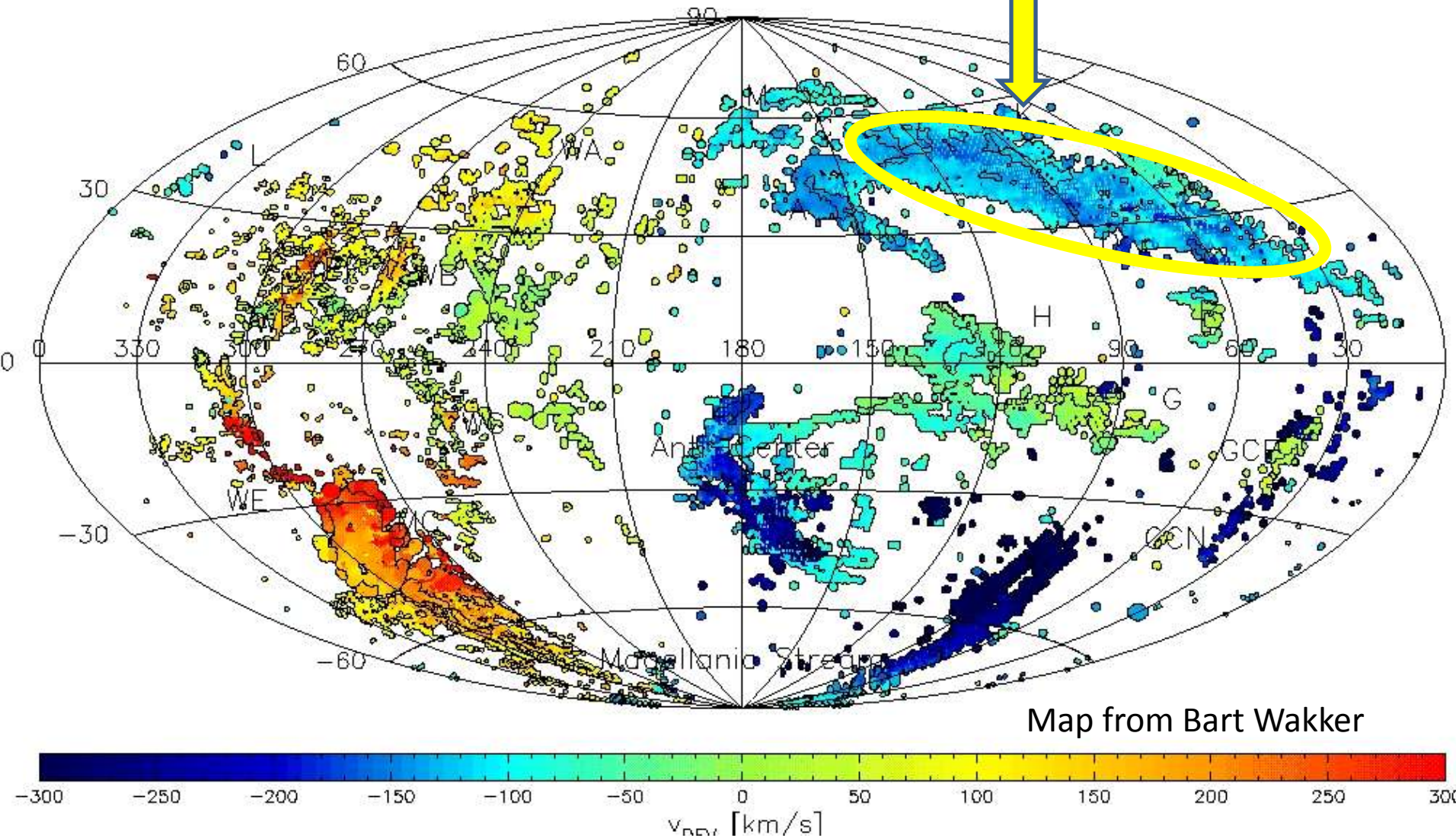
X axis in each plot represents a generalized depletion parameter for each line of sight





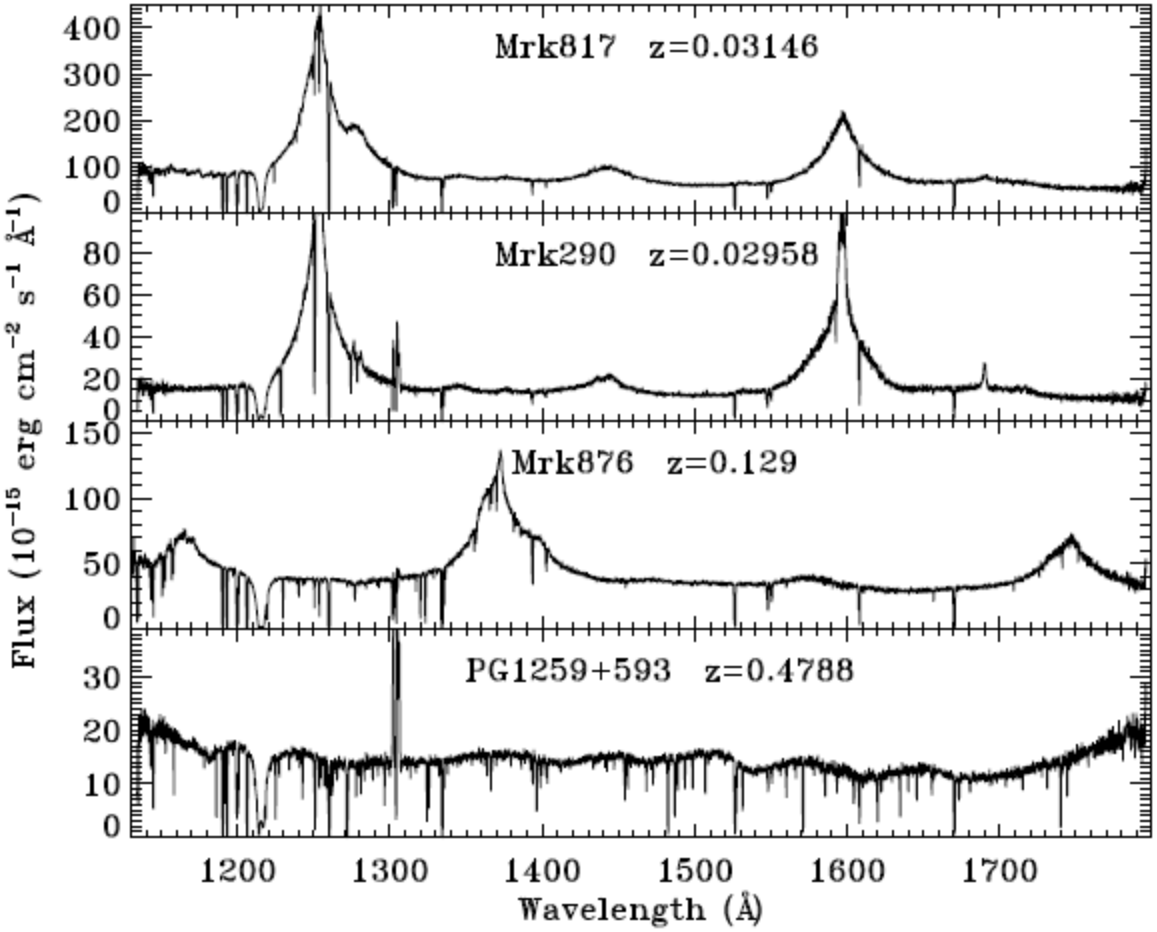
Jenkins (2009)

High Velocity Gas Clouds at High Galactic Latitudes: Complex C



Map from Bart Wakker

High Velocity Gas Clouds at High Galactic Latitudes: Complex C

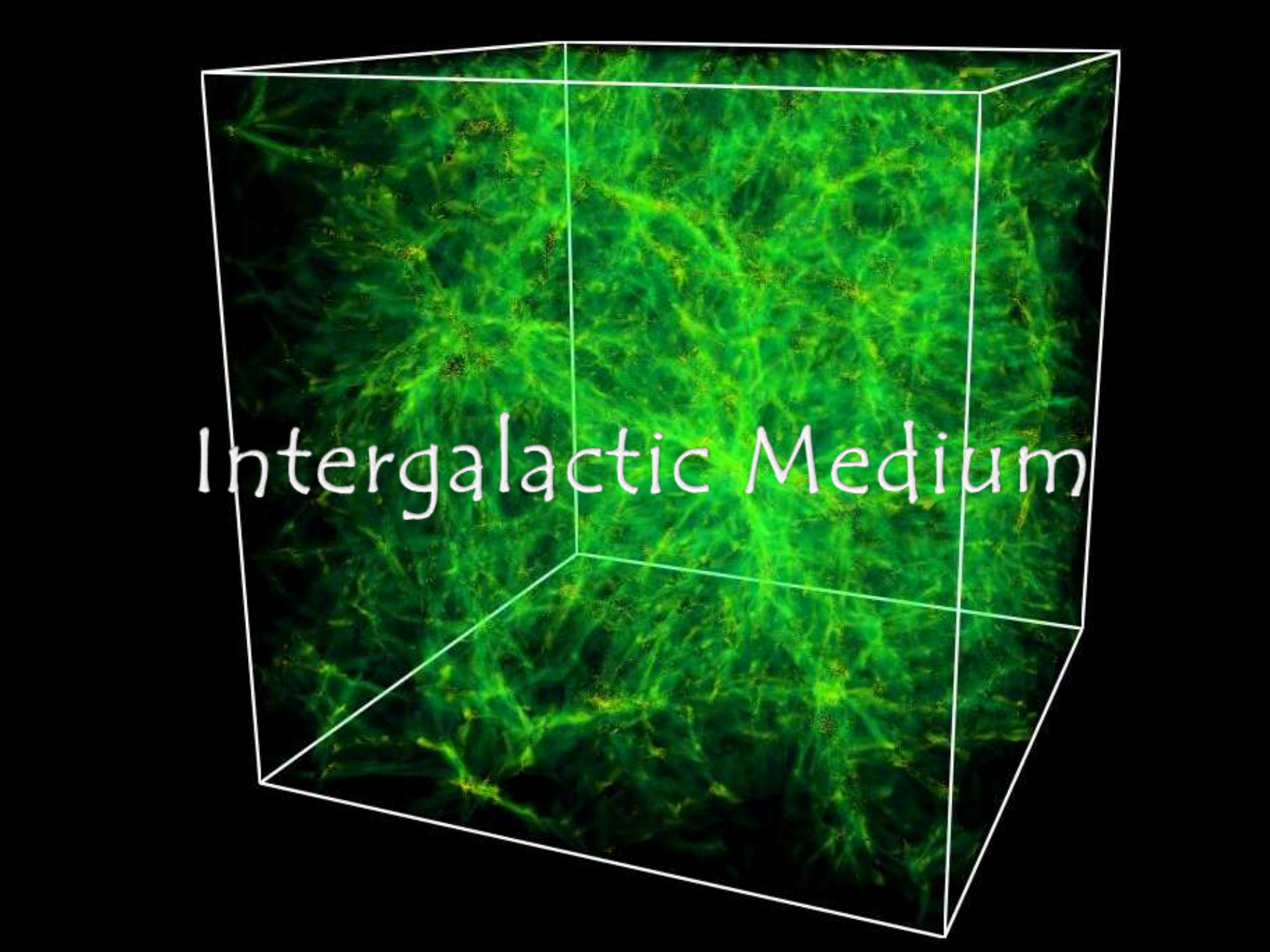


Conclusions from this and earlier investigations:

Metallicity of the gas is about 10-30% of the solar value.

Ratios of N V, C IV and O VI (measured by FUSE) are consistent with non-equilibrium ion ratios in cooling gas and with conductive heating.

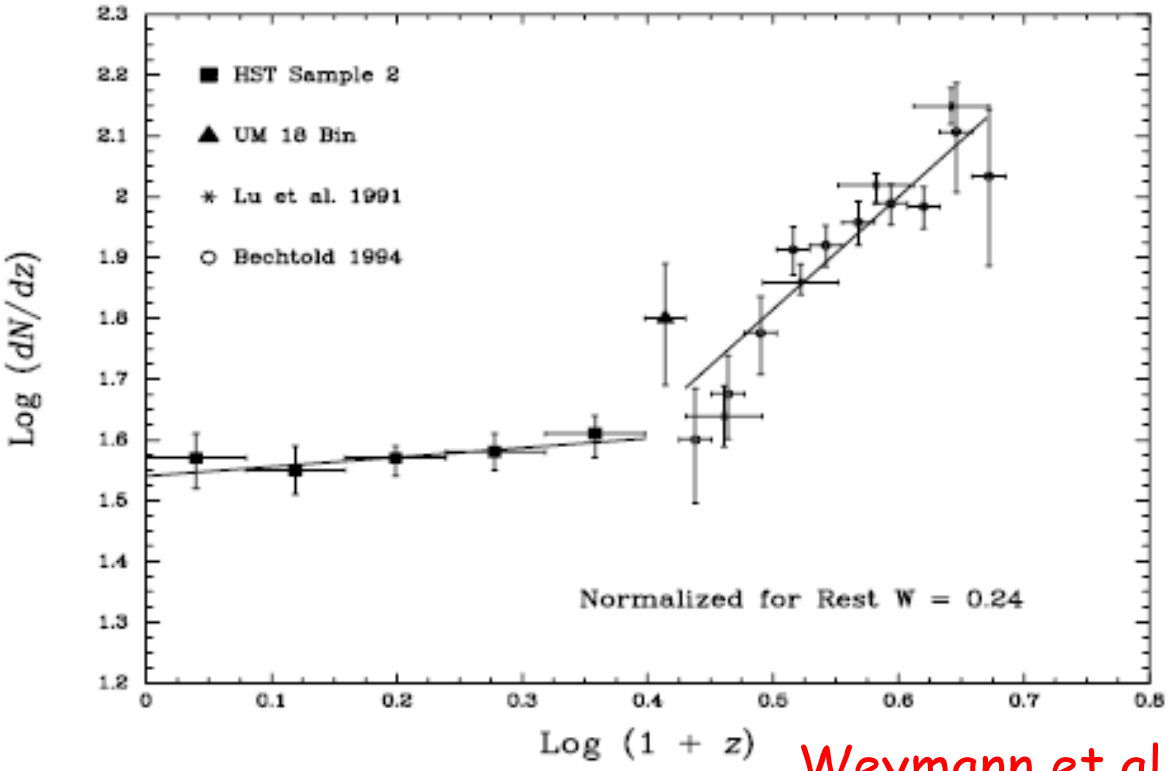
Shull et al. (2011)


Intergalactic Medium

Evolution of the Lyman-α Forest with Redshift

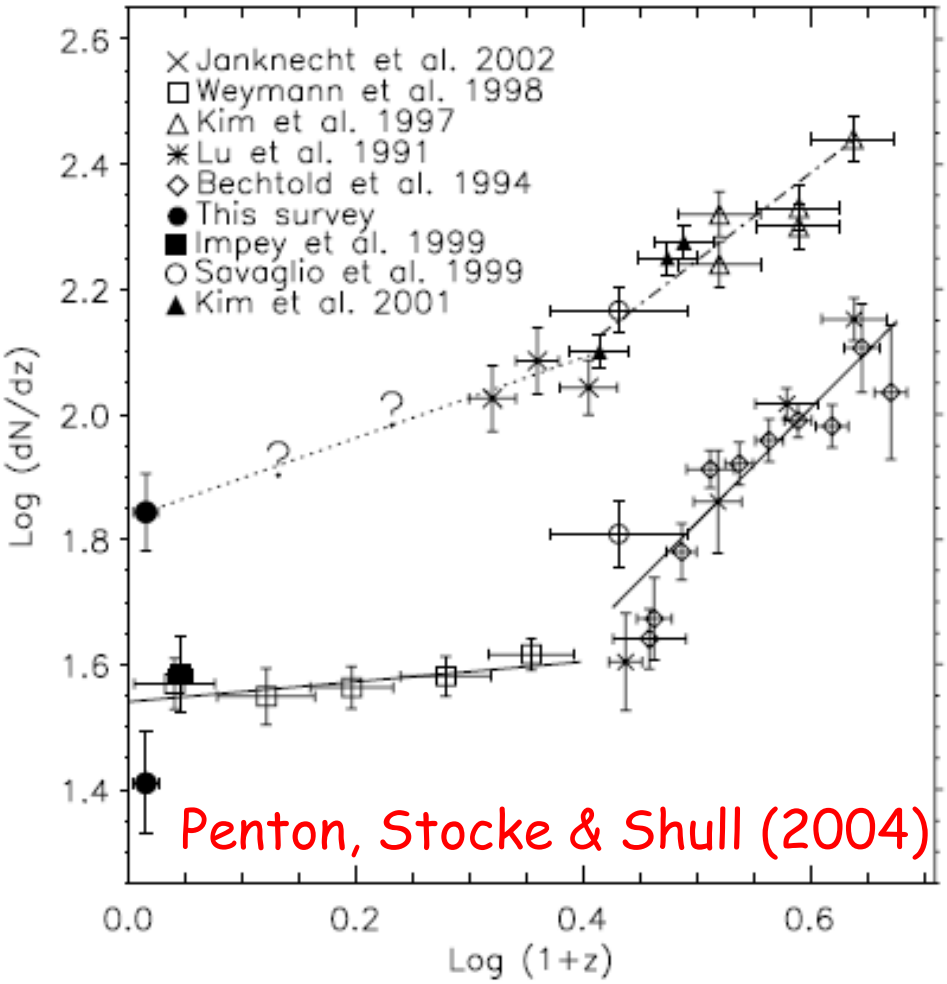
If we assume that the distribution of Lyα lines as a function of redshift and EW has the form and parameters derived at high redshift (as in Murdoch et al. 1986), then over the redshift range of 0.016–0.151 one predicts 0.8–2.1 lines with rest EW greater than 50 mÅ, whereas we observed 10. One predicts 0.9–2.3 lines with rest EW greater than 25 mÅ. whereas we have possibly observed 14. Morris et al. (1991)

Evolution of the Lyman-α Forest with Redshift

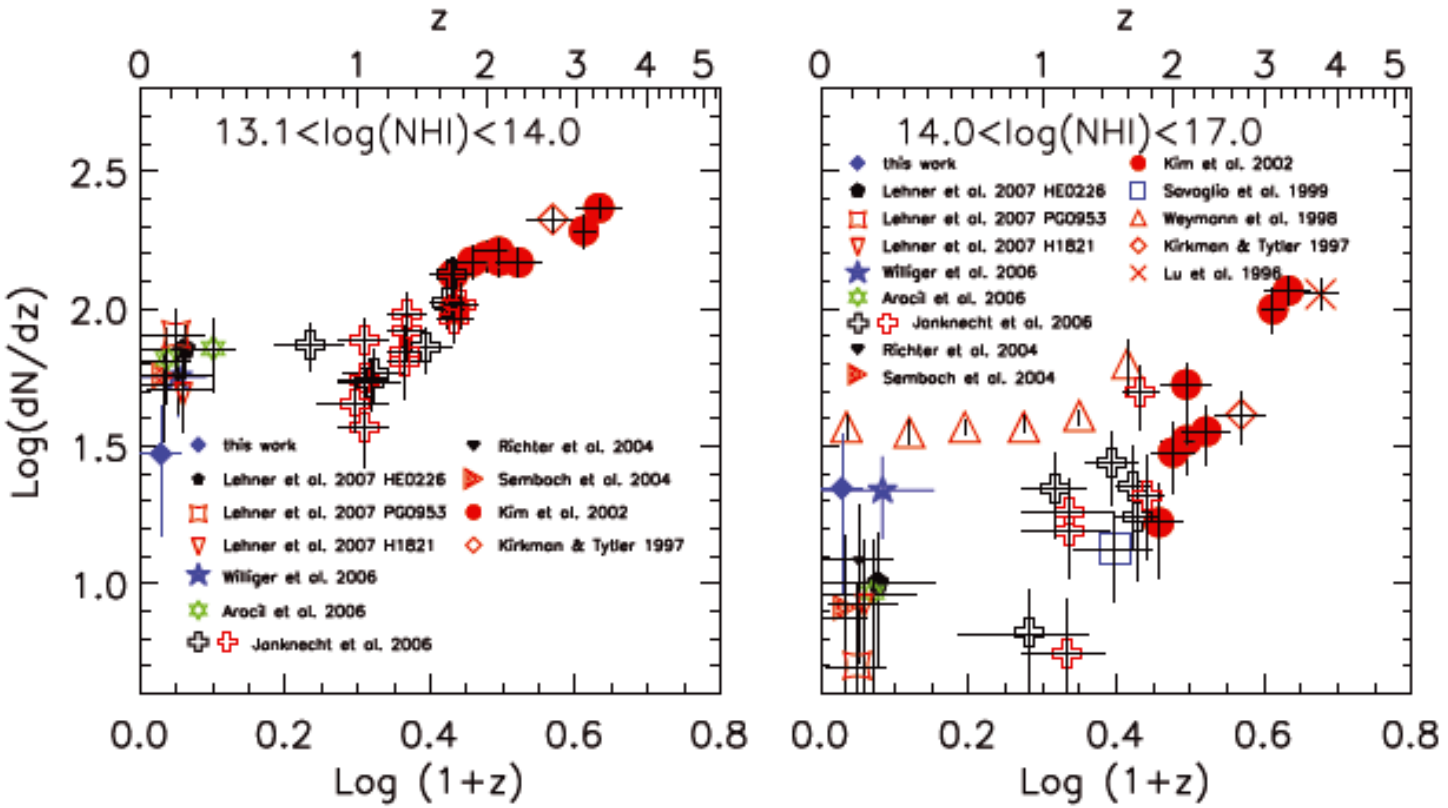


Weymann et al. (1998)

Evolution of the Lyman-α Forest with Redshift

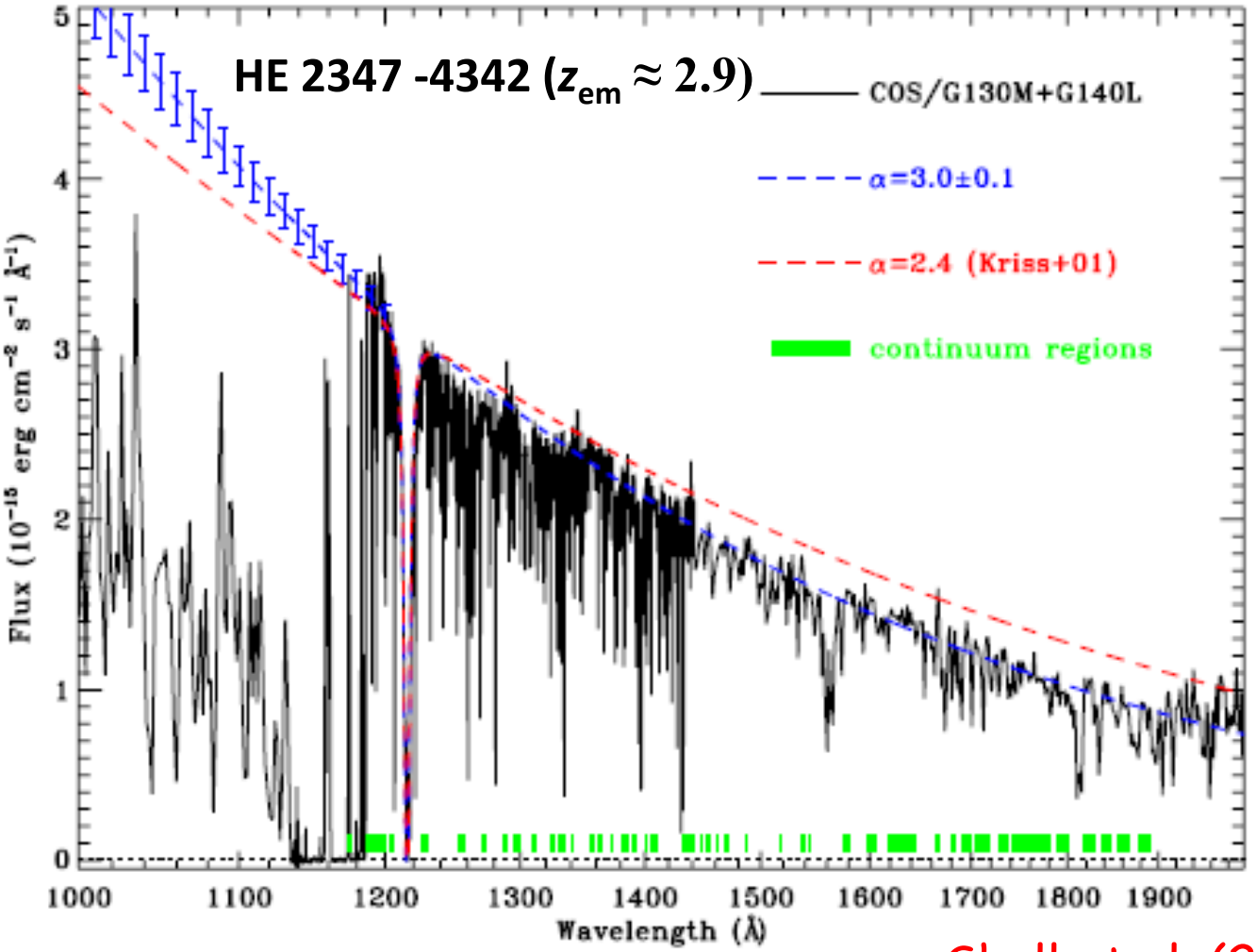


Evolution of the Lyman-α Forest with Redshift



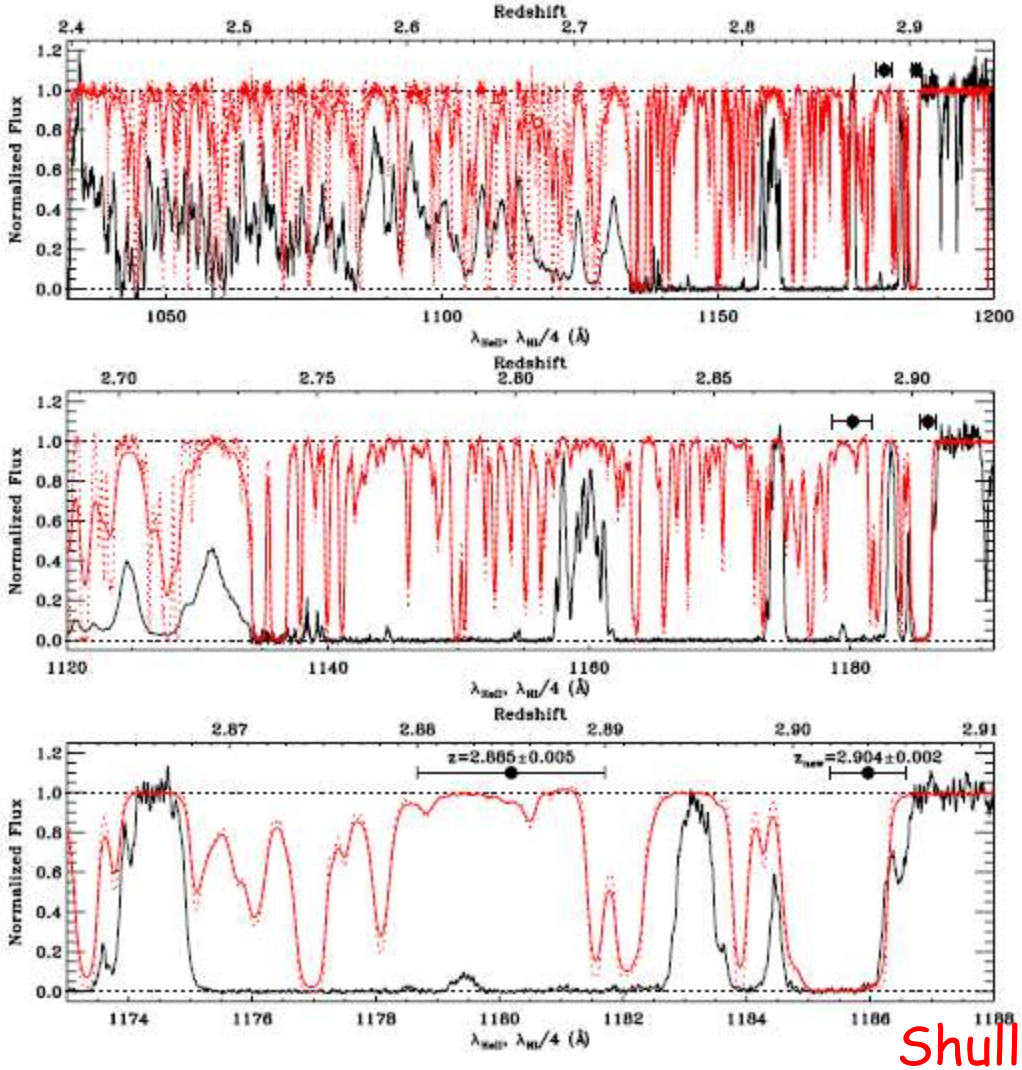
Williger et al. (2010)

He II Gunn-Peterson Absorption



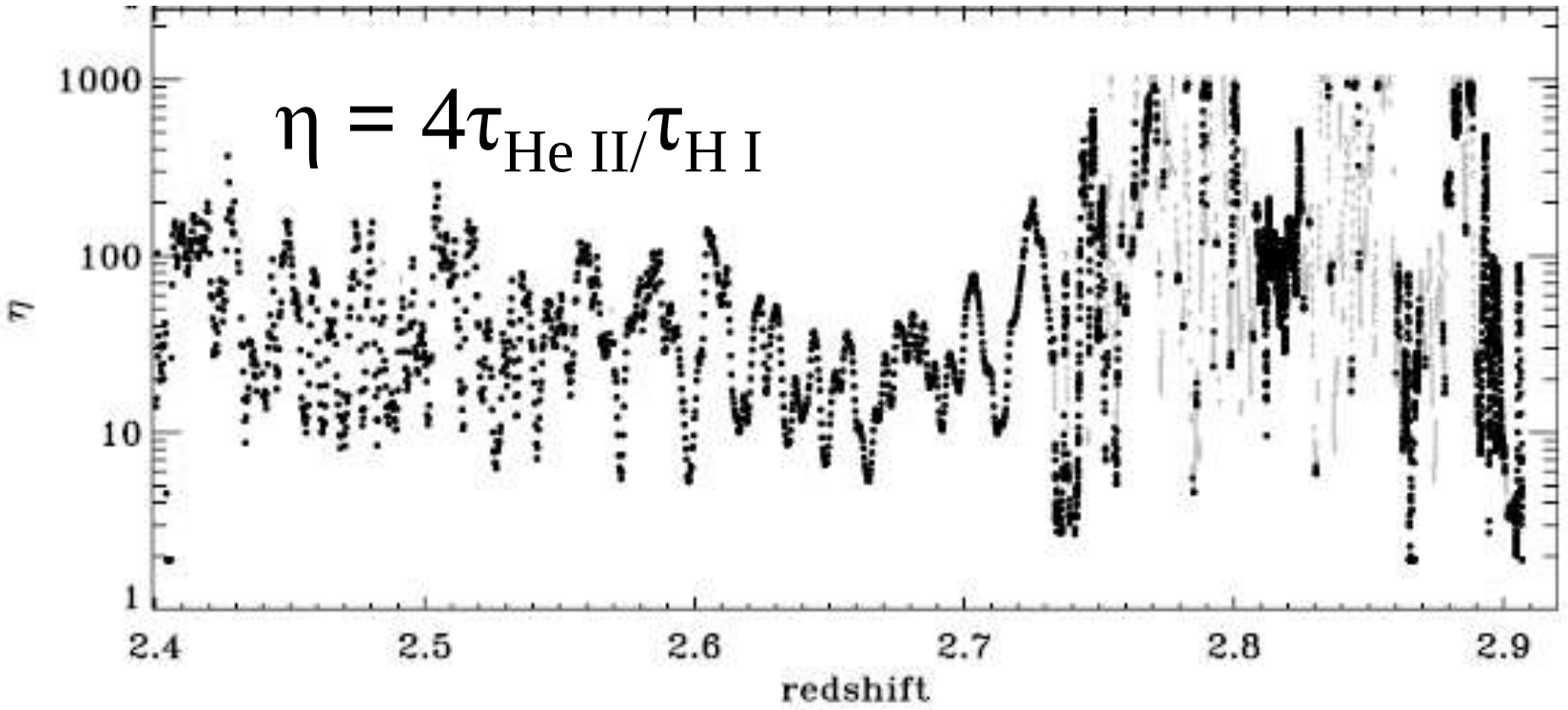
Shull et al. (2010)

He II Gunn-Peterson Absorption



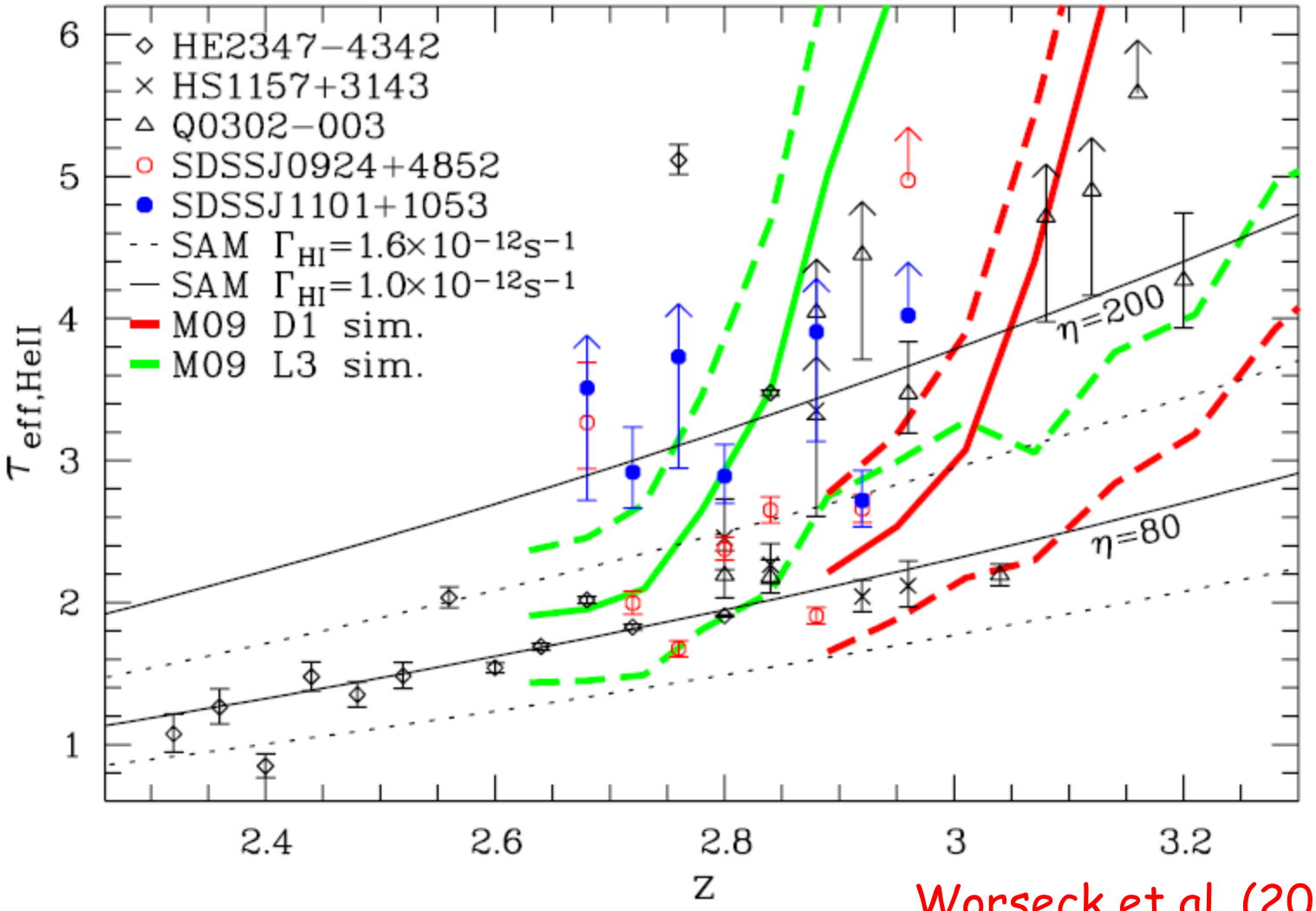
Shull et al. (2010)

He II Gunn-Peterson Absorption



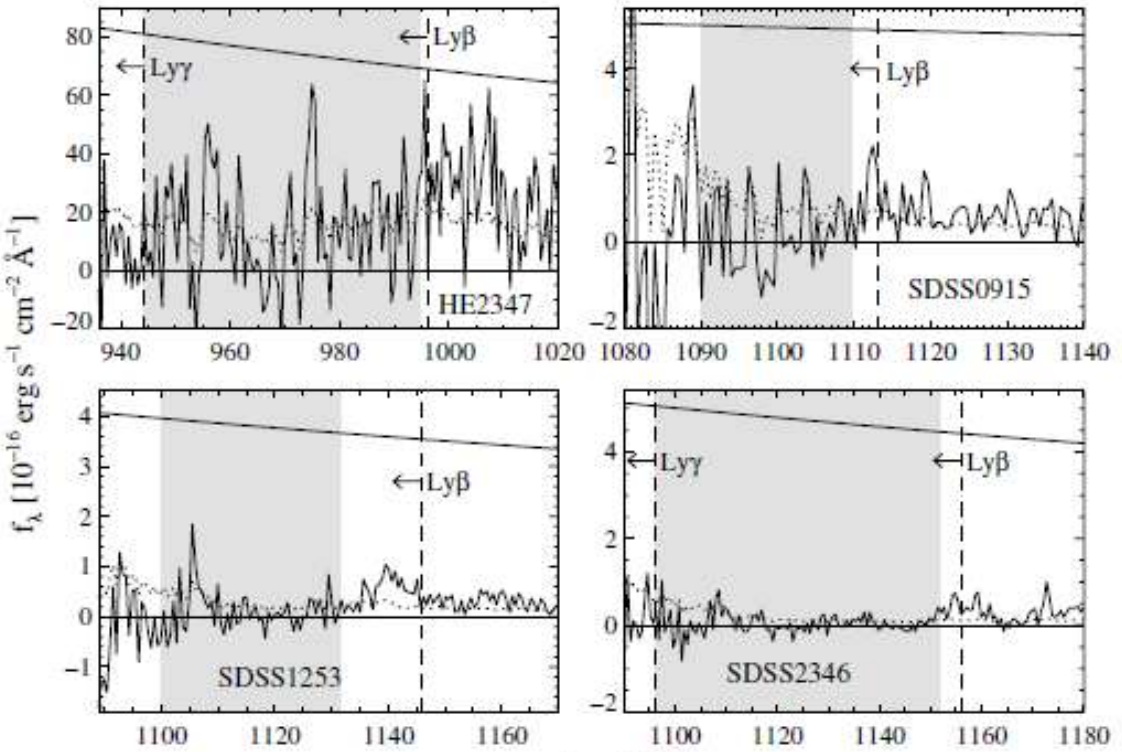
Shull et al. (2010)

He II Gunn-Peterson Absorption



Worseck et al. (2011)

He II Gunn-Peterson Absorption

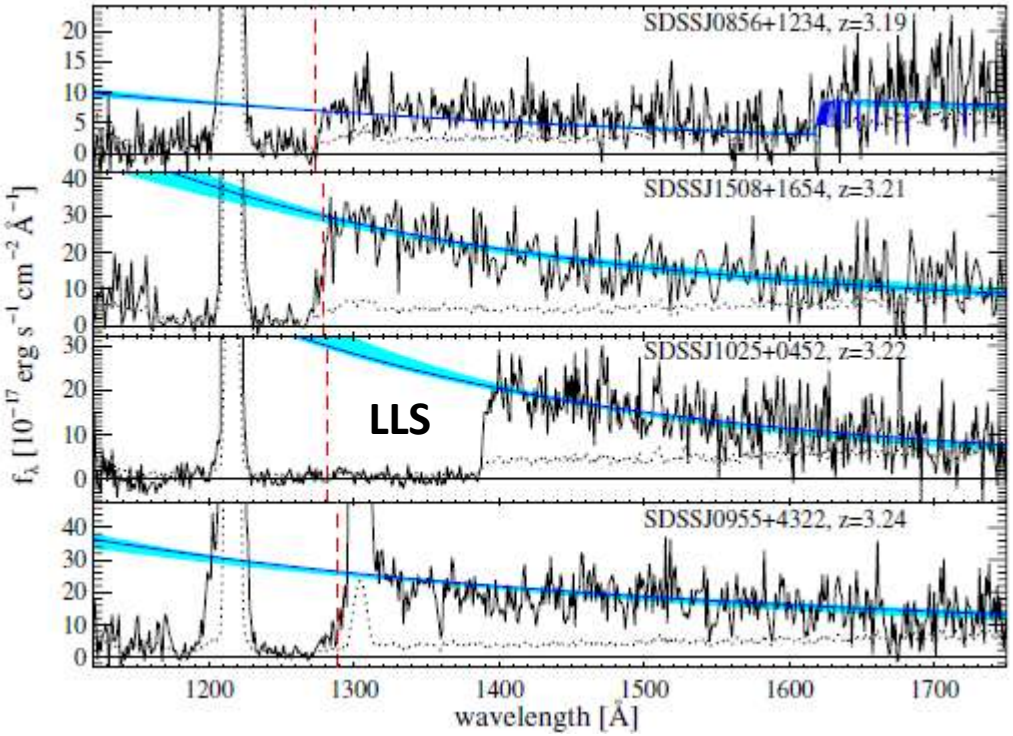


Syphers et al. (2011)

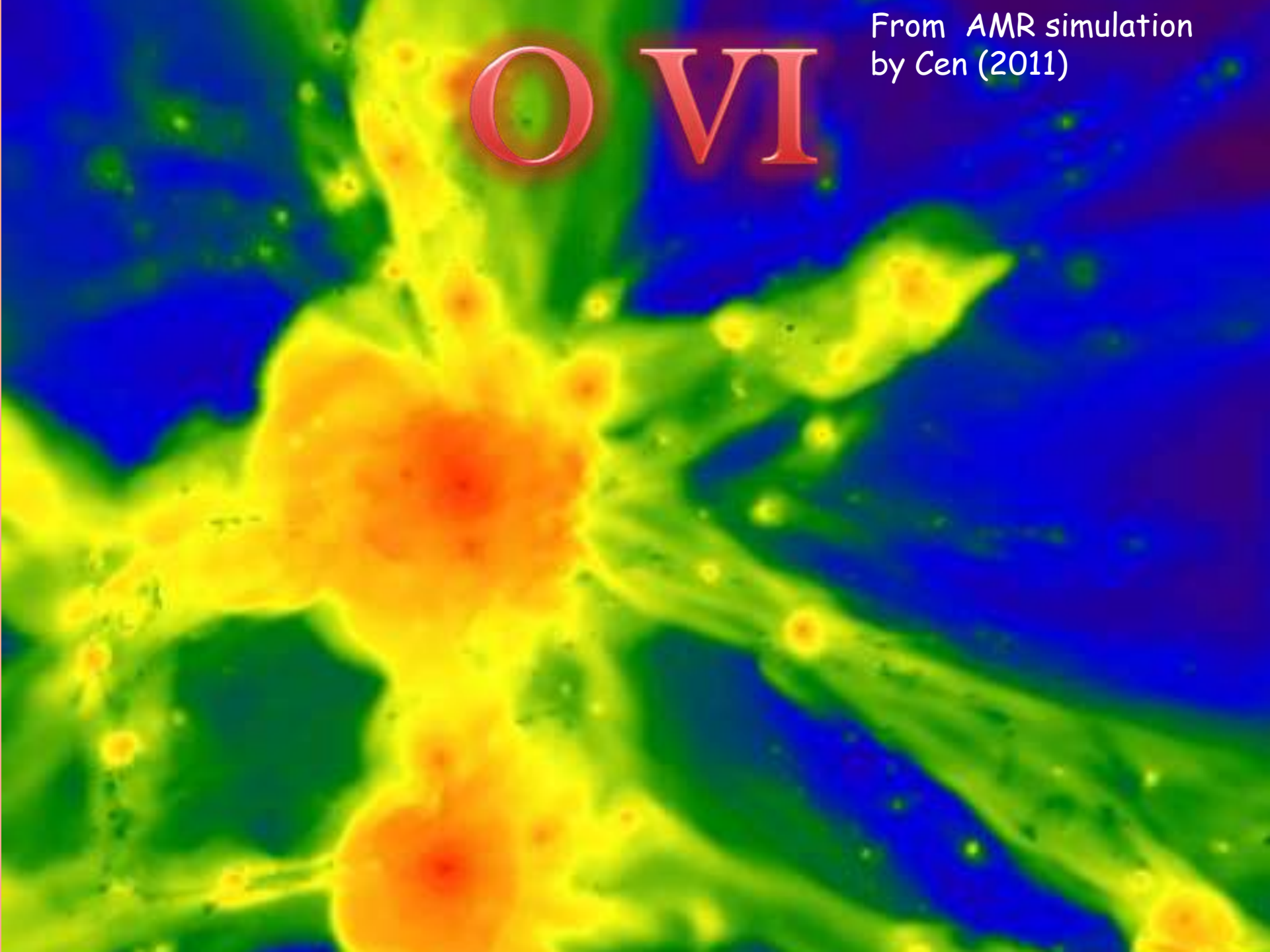
He II Gunn-Peterson Absorption

Use of GALEX and SDSS to find new target QSOs

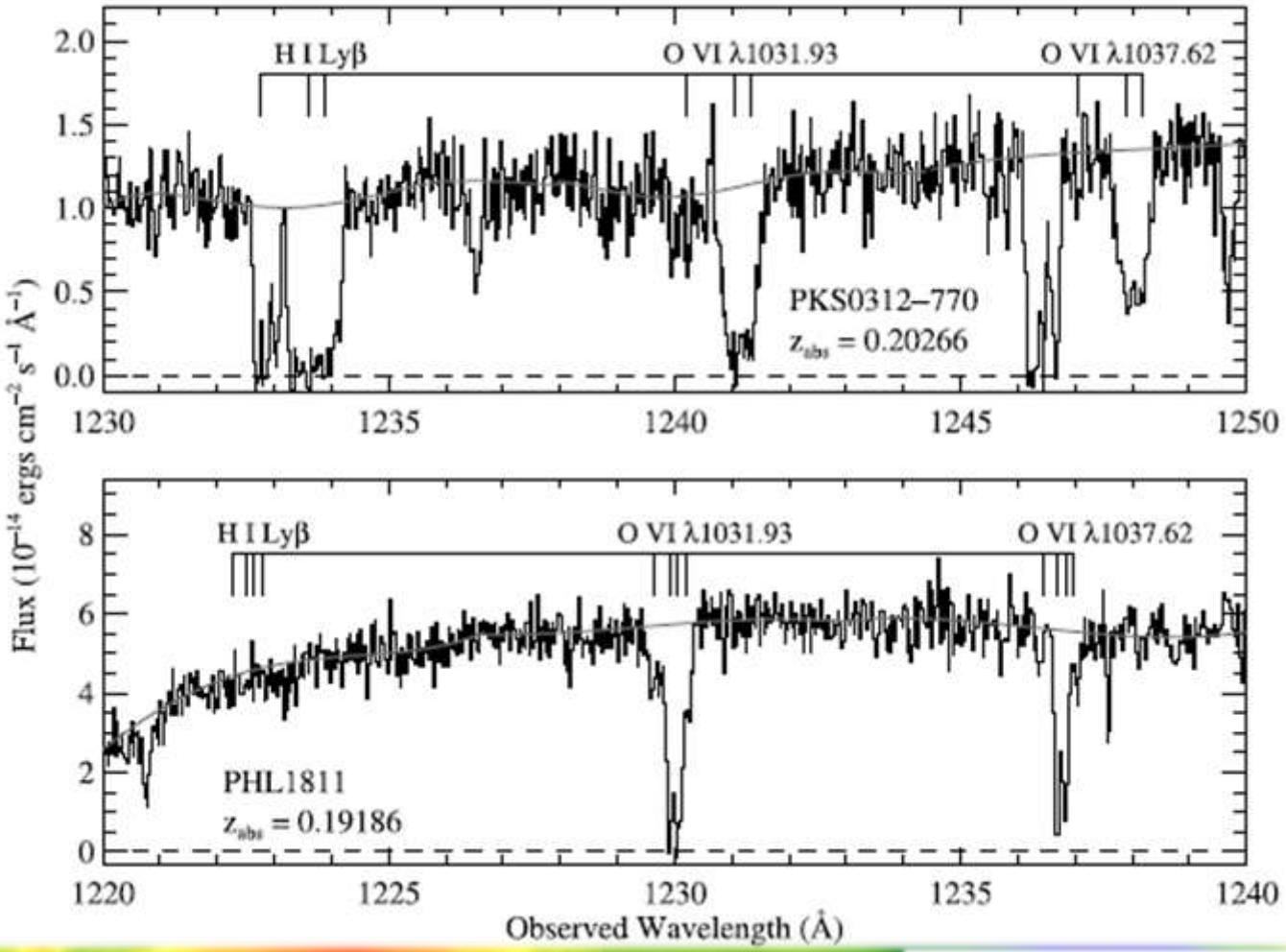
G140L mode of COS



Syphers et al. (2012)

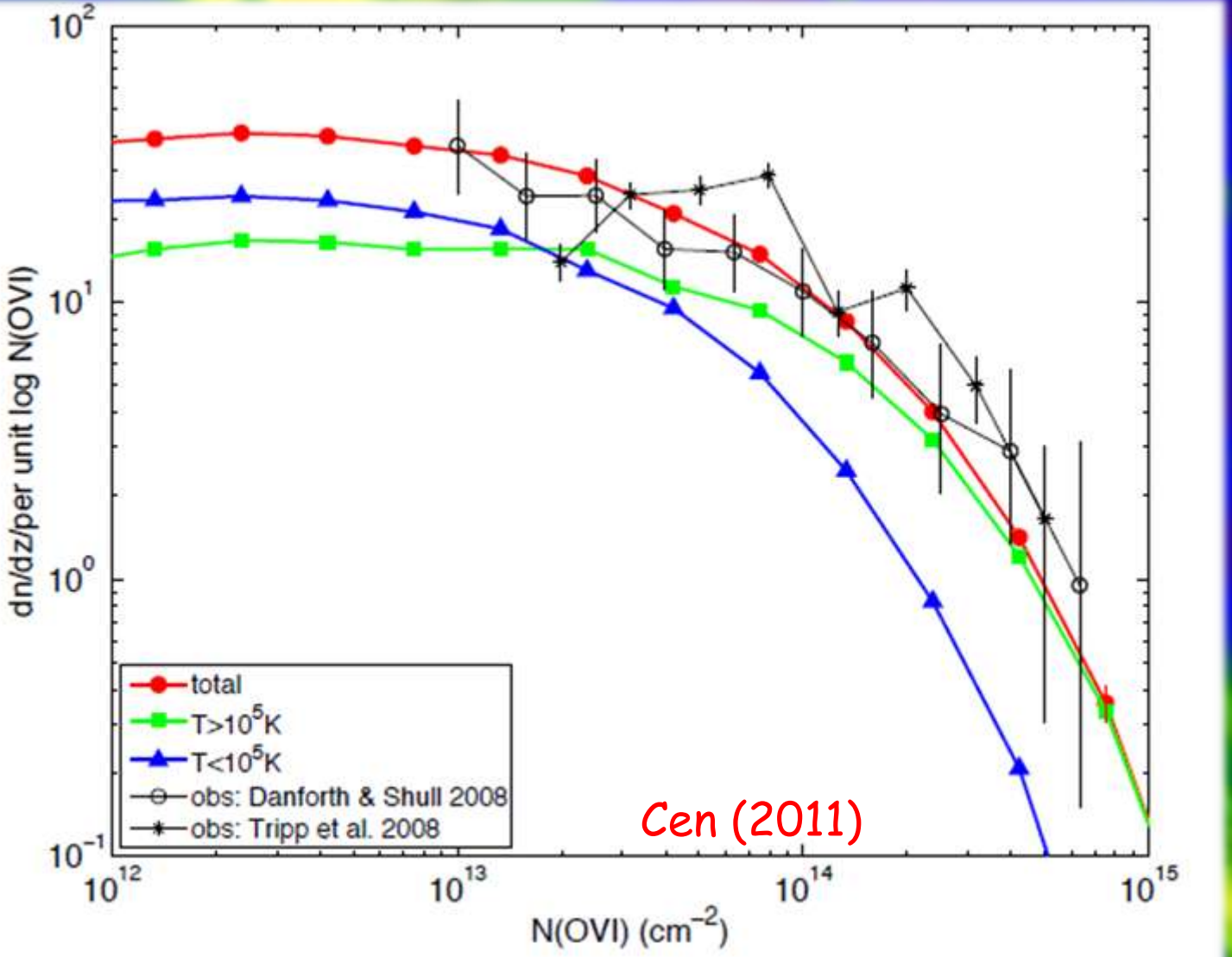

O VI
From AMR simulation
by Cen (2011)

O VI



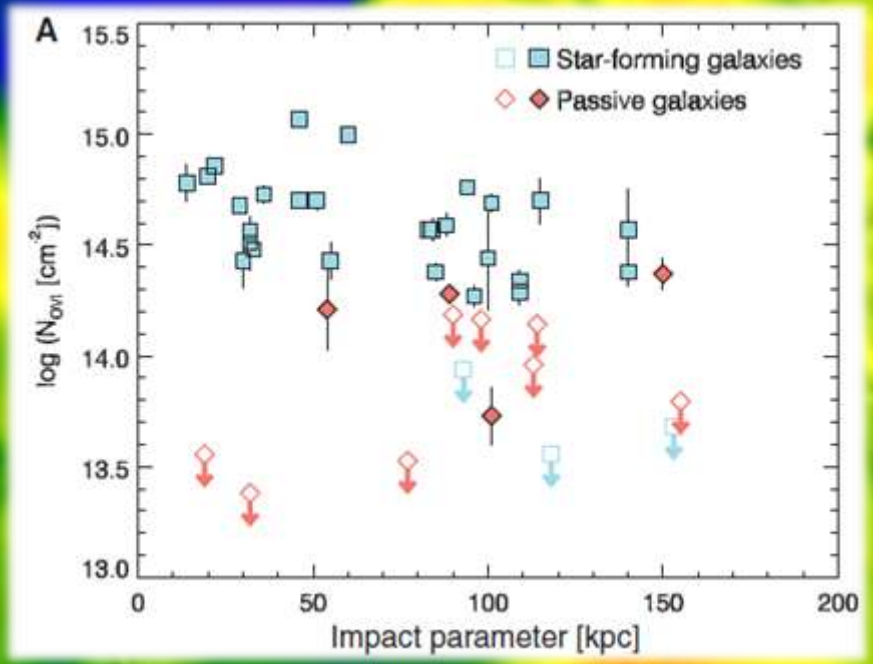
Tripp et al. (2008)

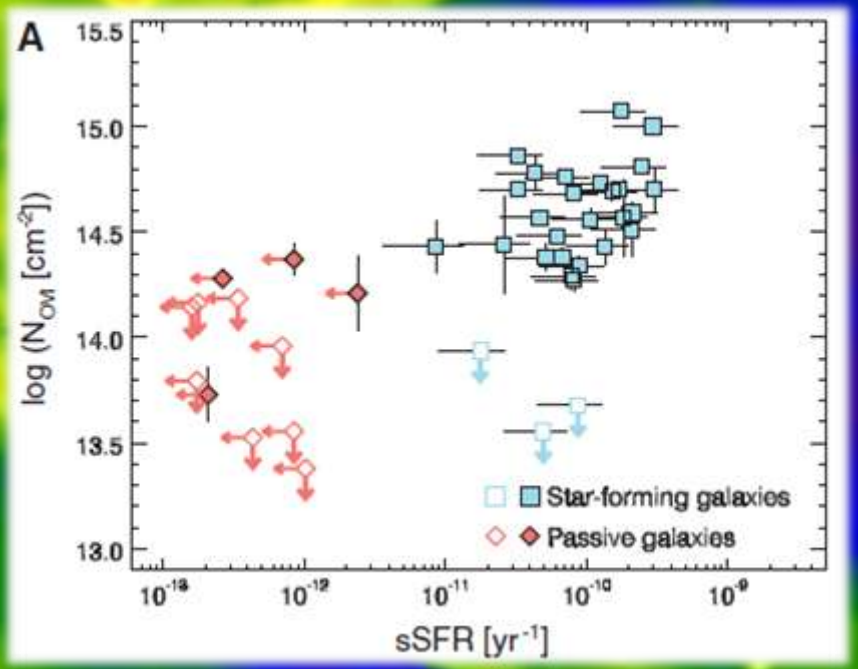
O VI


dn/dz/per unit log N(OVI)
N(OVI) (cm^{-2})
total
T>10^{5}K
T<10^{5}K
obs: Danforth & Shull 2008
obs: Tripp et al. 2008
Cen (2011)

O VI

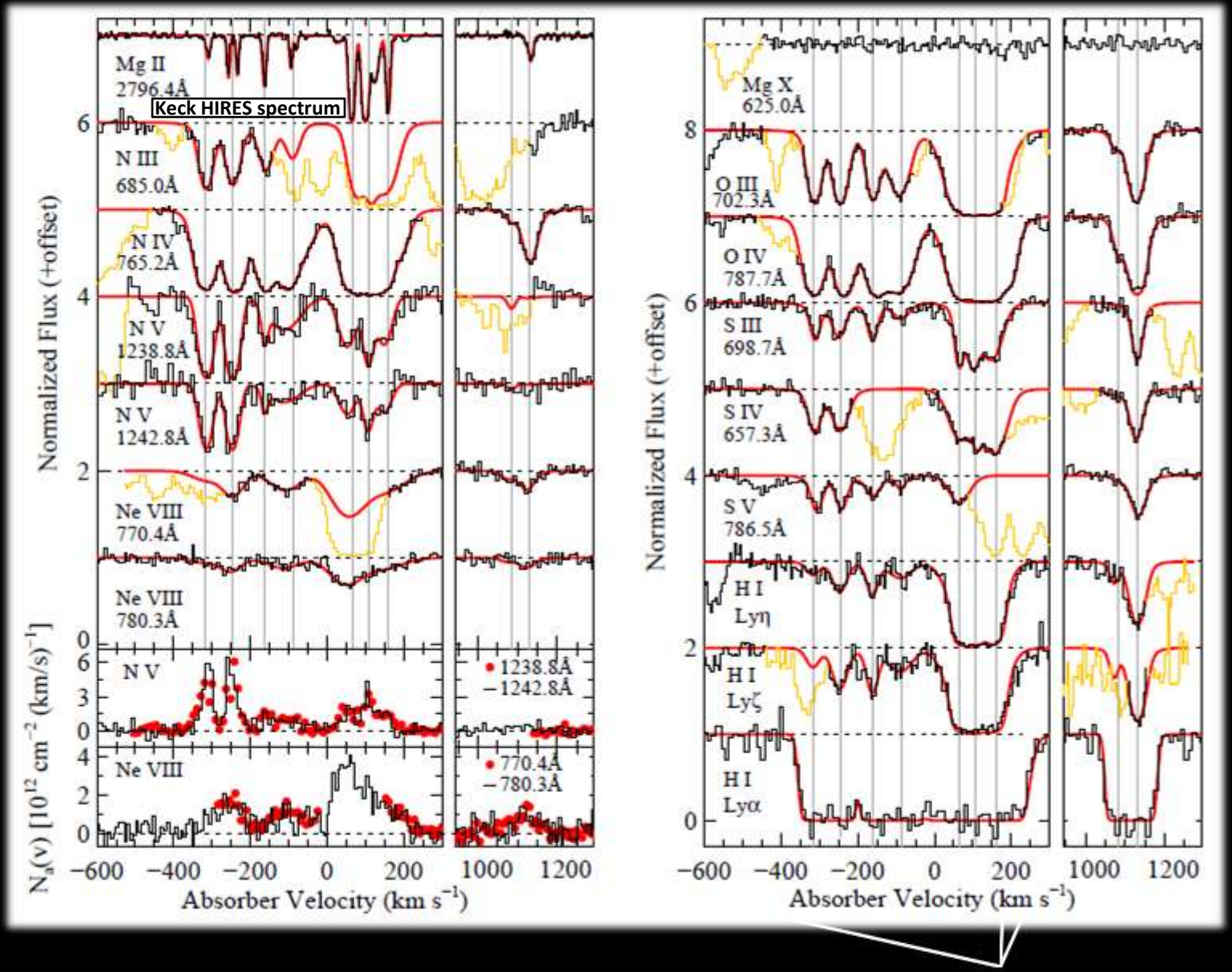
O VI in the vicinities of foreground galaxies





Tumlinson et al. (2011)

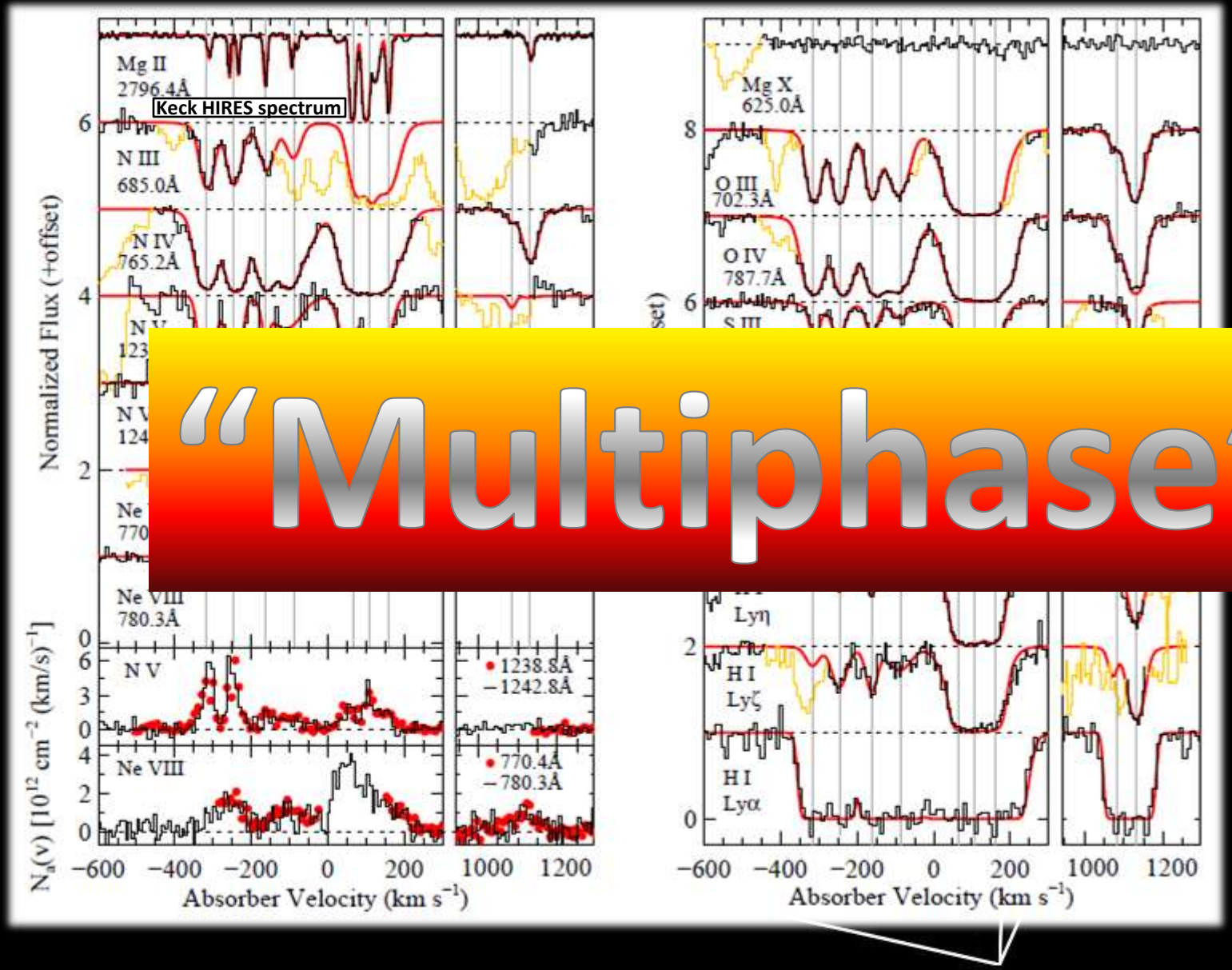
Absorption Systems at Moderately High *z*



$z_{abs} = 0.927$

Tripp et al (2011)

Absorption Systems at Moderately High *z*

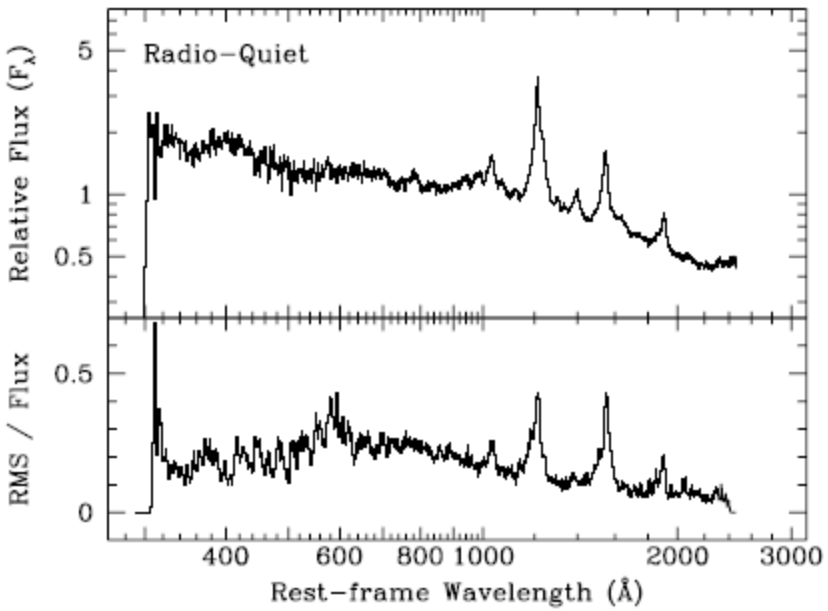


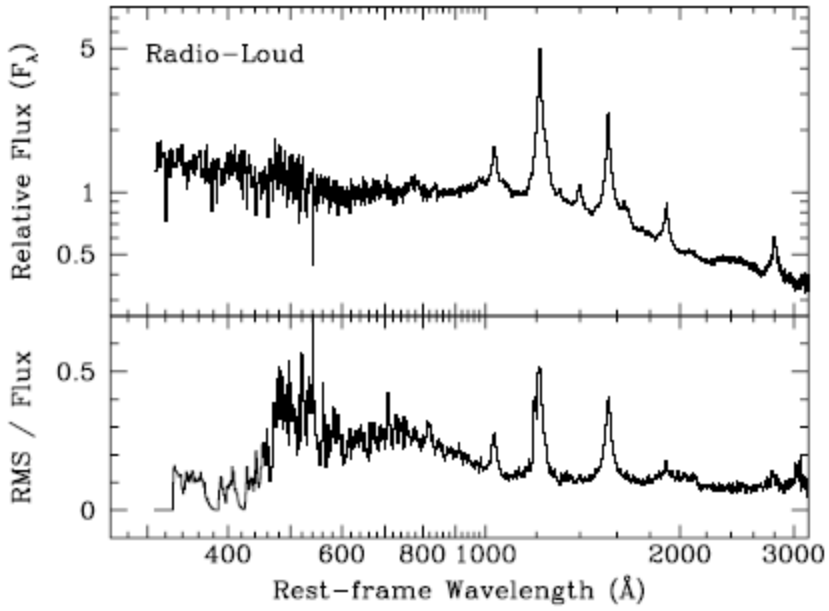
z_{abs} = 0.927

"Multiphase"

Tripp et al (2011)

Composite Spectra of Quasars

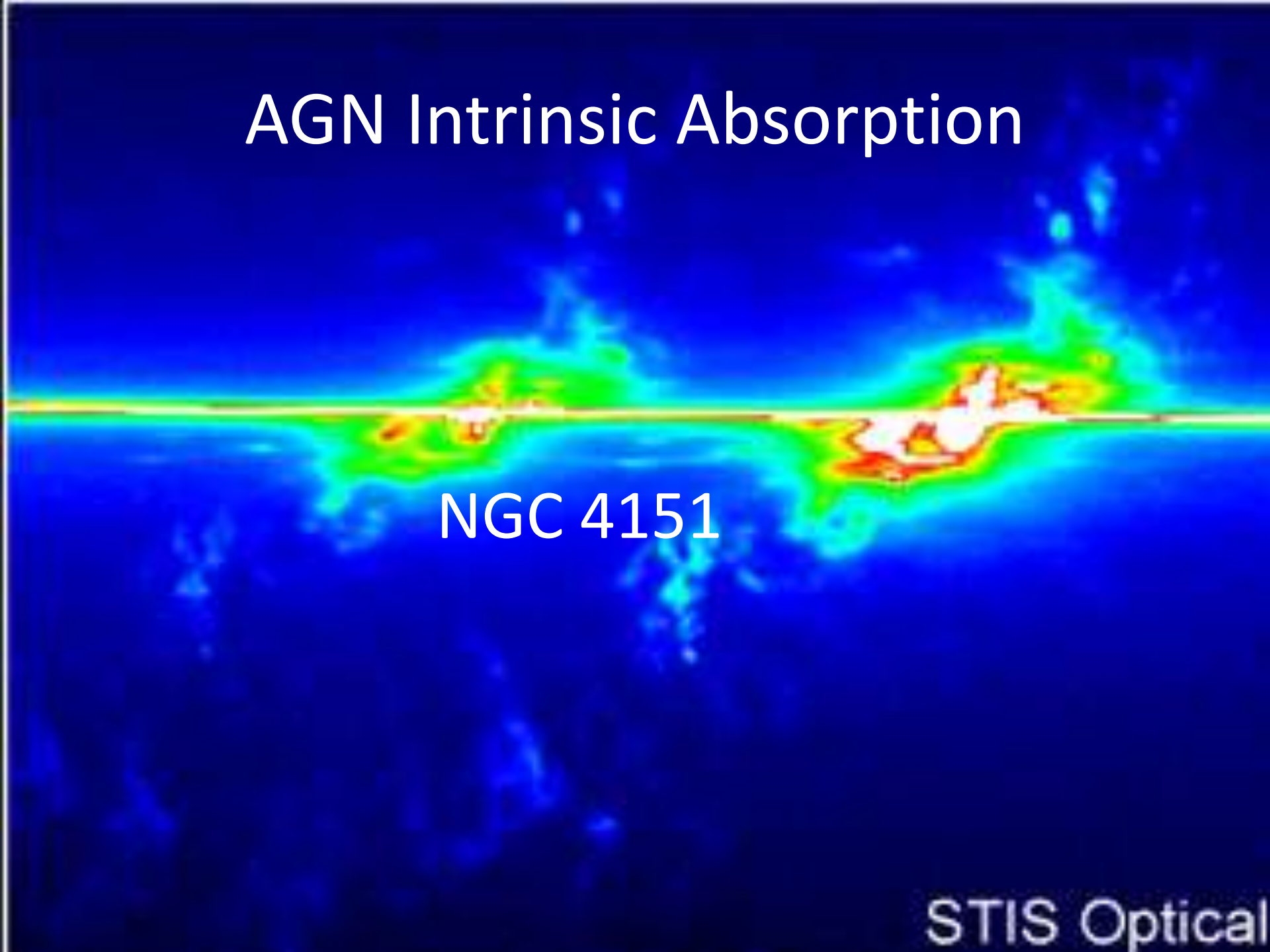




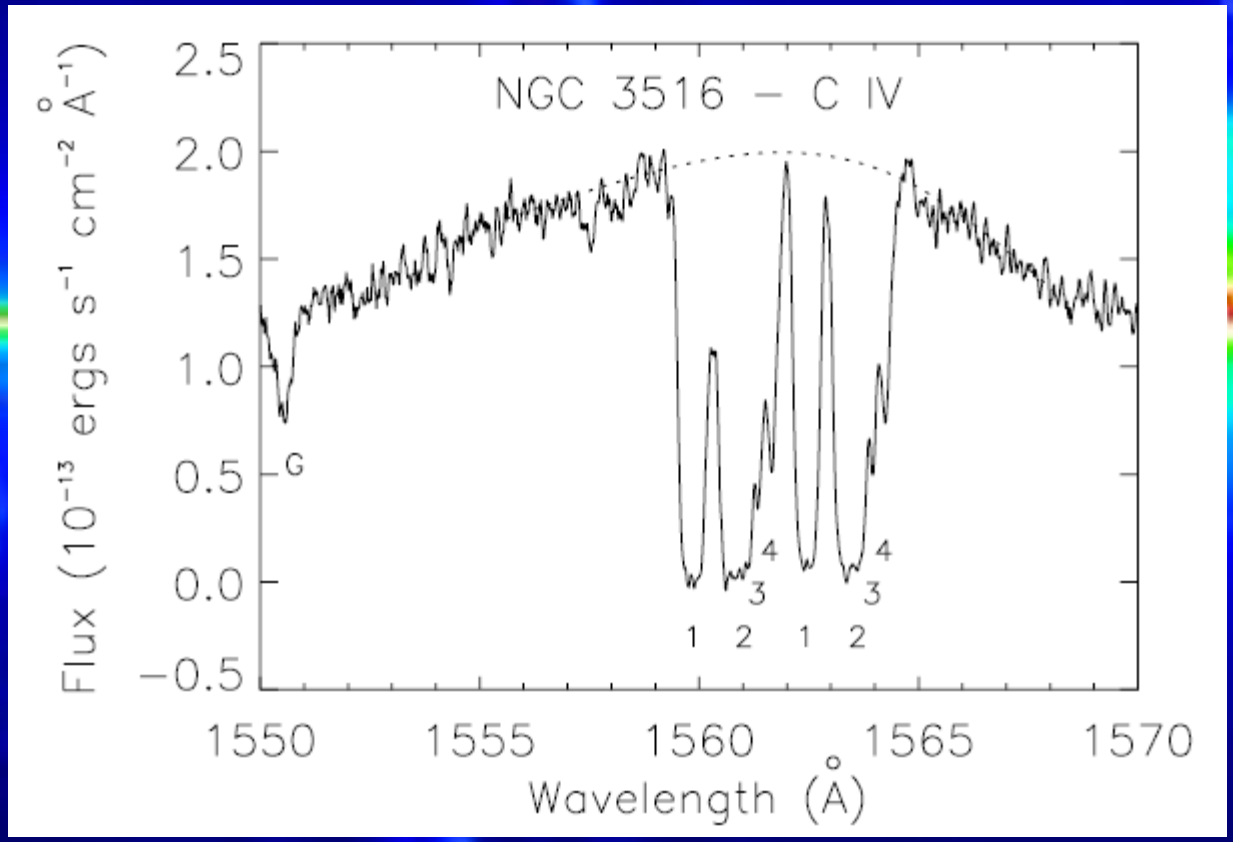
Telfer et al. (2002)

Spectral energy distributions are of relevance to our understanding of the ionization of the IGM

AGN Intrinsic Absorption



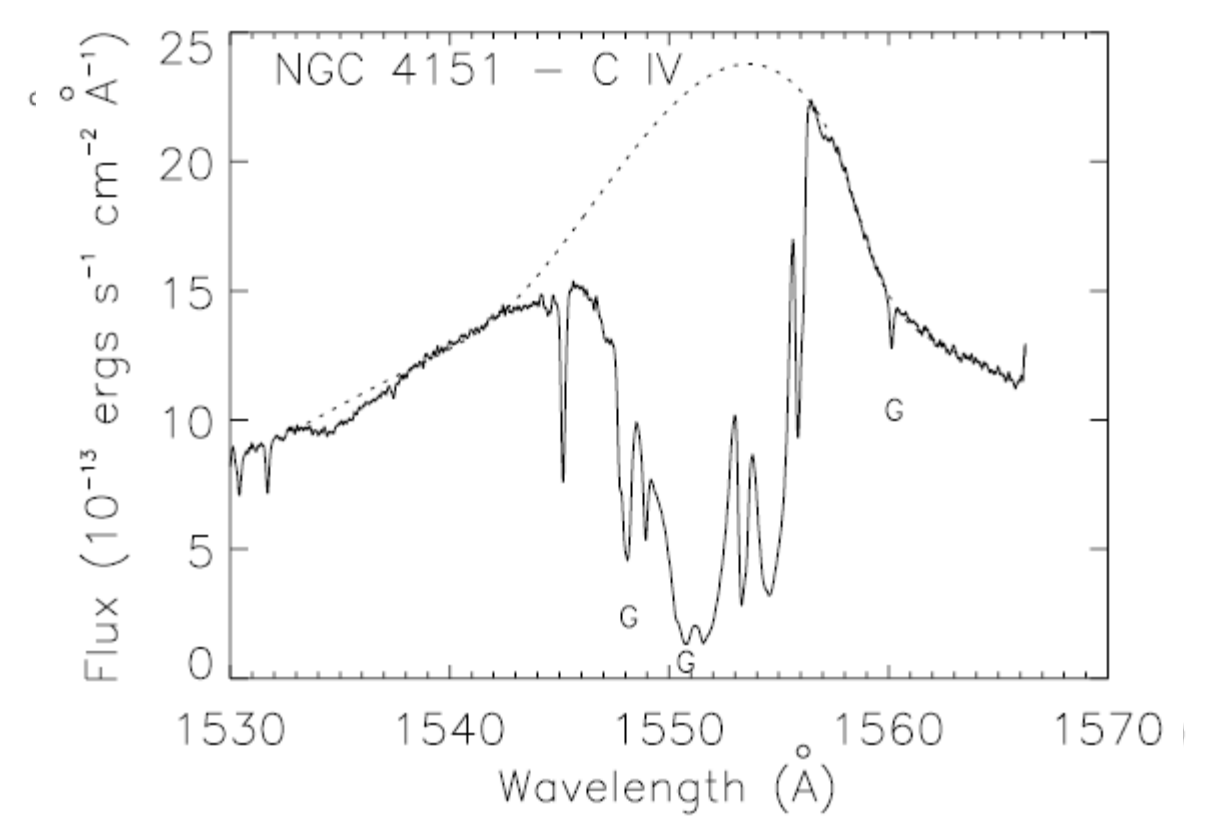
AGN Intrinsic Absorption



Crenshaw et al. (1999)

STIS Optical

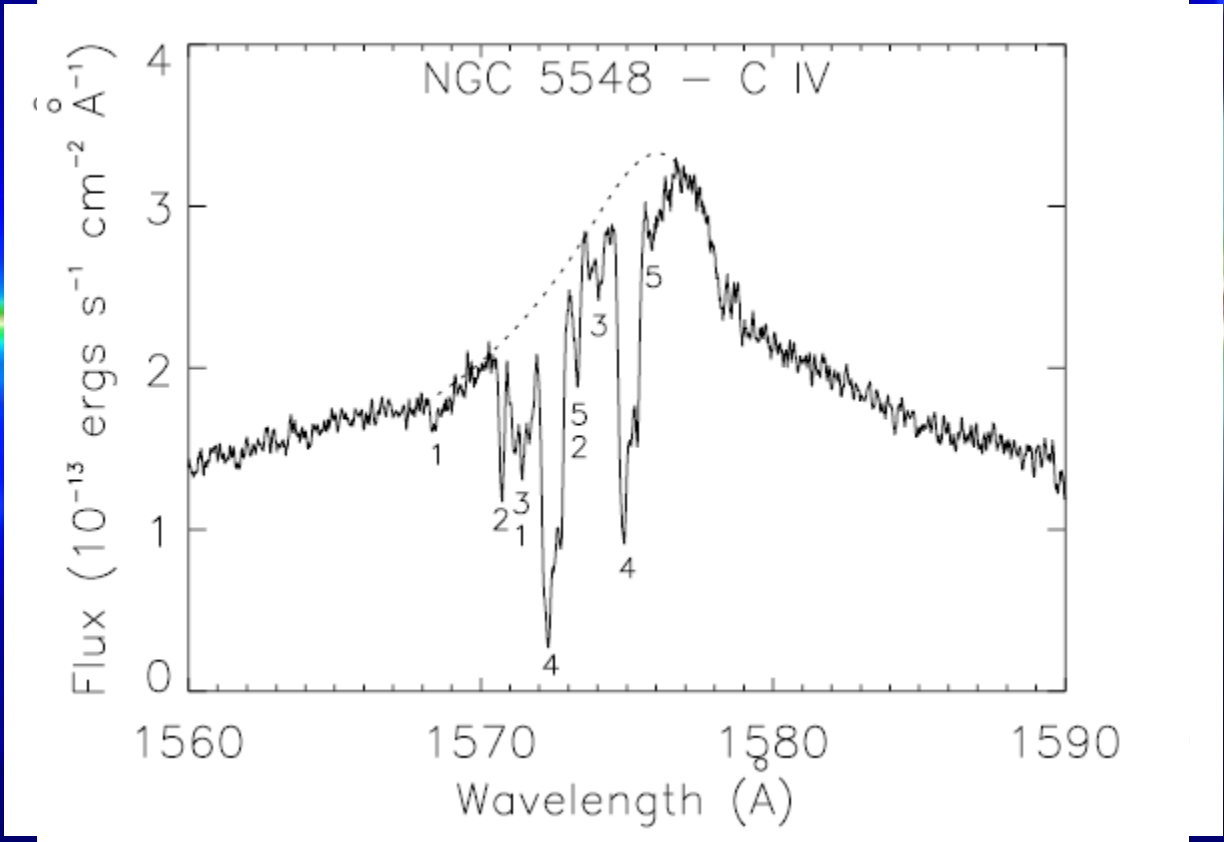
AGN Intrinsic Absorption



Crenshaw et al. (1999)

STIS Optical

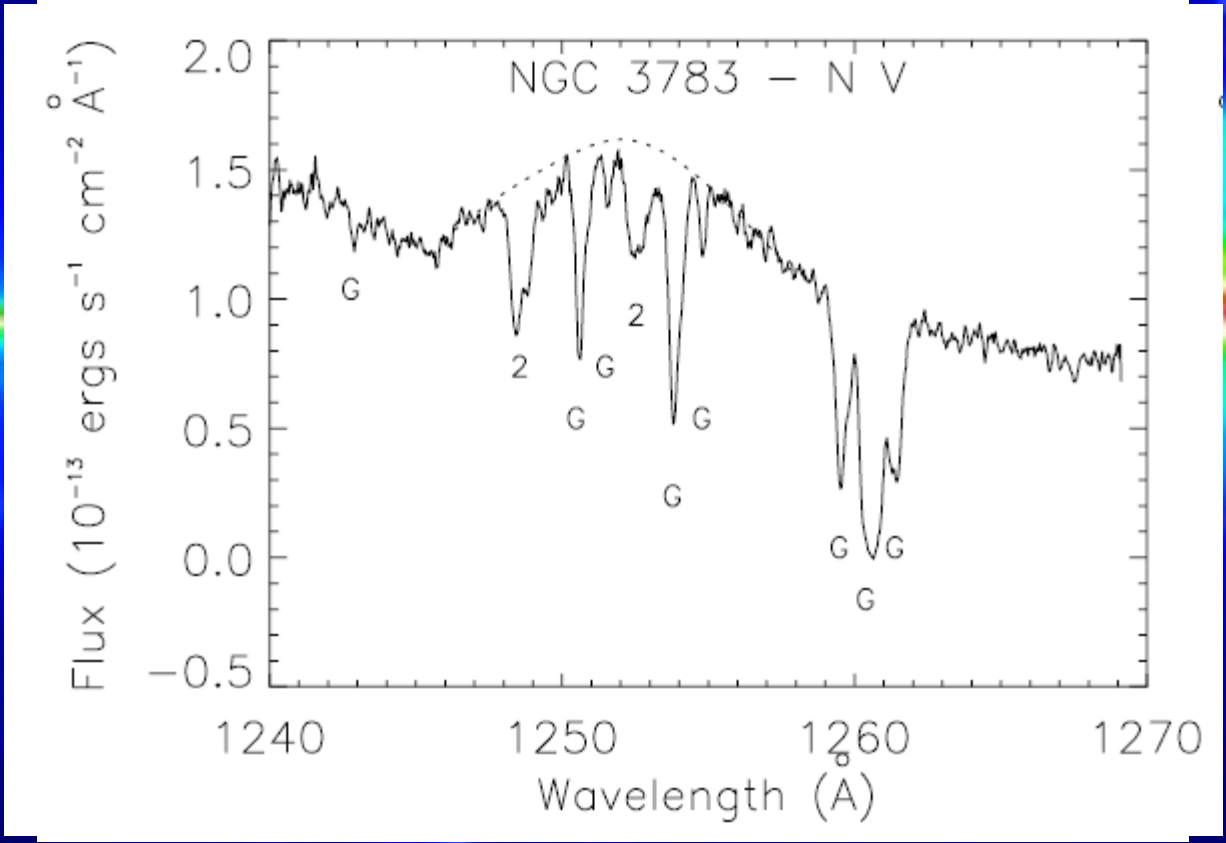
AGN Intrinsic Absorption



Crenshaw et al. (1999)

STIS Optical

AGN Intrinsic Absorption



Crenshaw et al. (1999)

STIS Optical

AGN Intrinsic Absorption

Conclusions:

1. Prominent features in high ionization stages of atoms

2. Frequency of appearance indicates that the covering factor ≈ 50% of the broad line region.

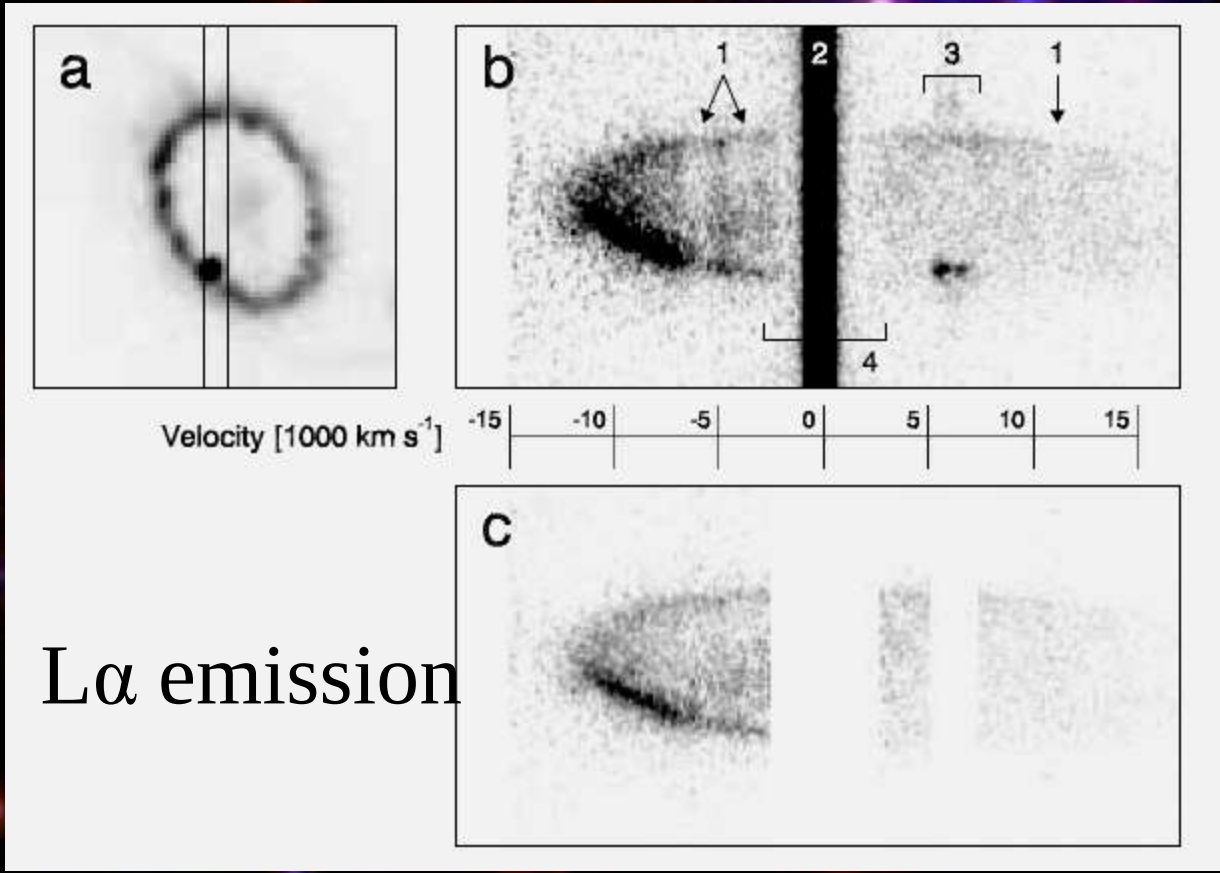
3. Features show time variability (indicates characteristic distances 100 – 10^4 lt-days) and have multiple narrow velocity components.

STIS Optical

Supernovae:
SN 1987A in the LMC

Lα emission

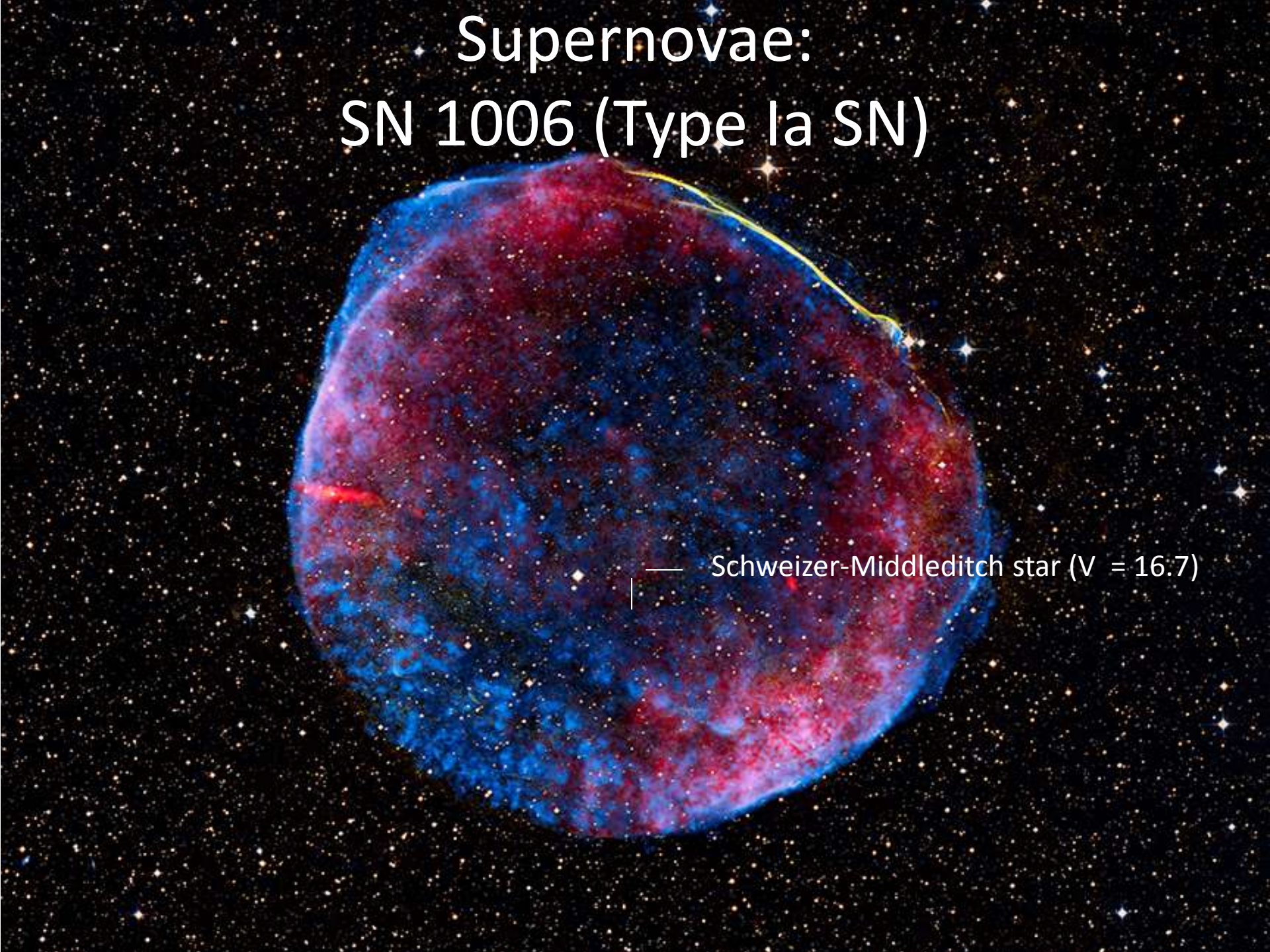
Supernovae:
SN 1987A in the LMC



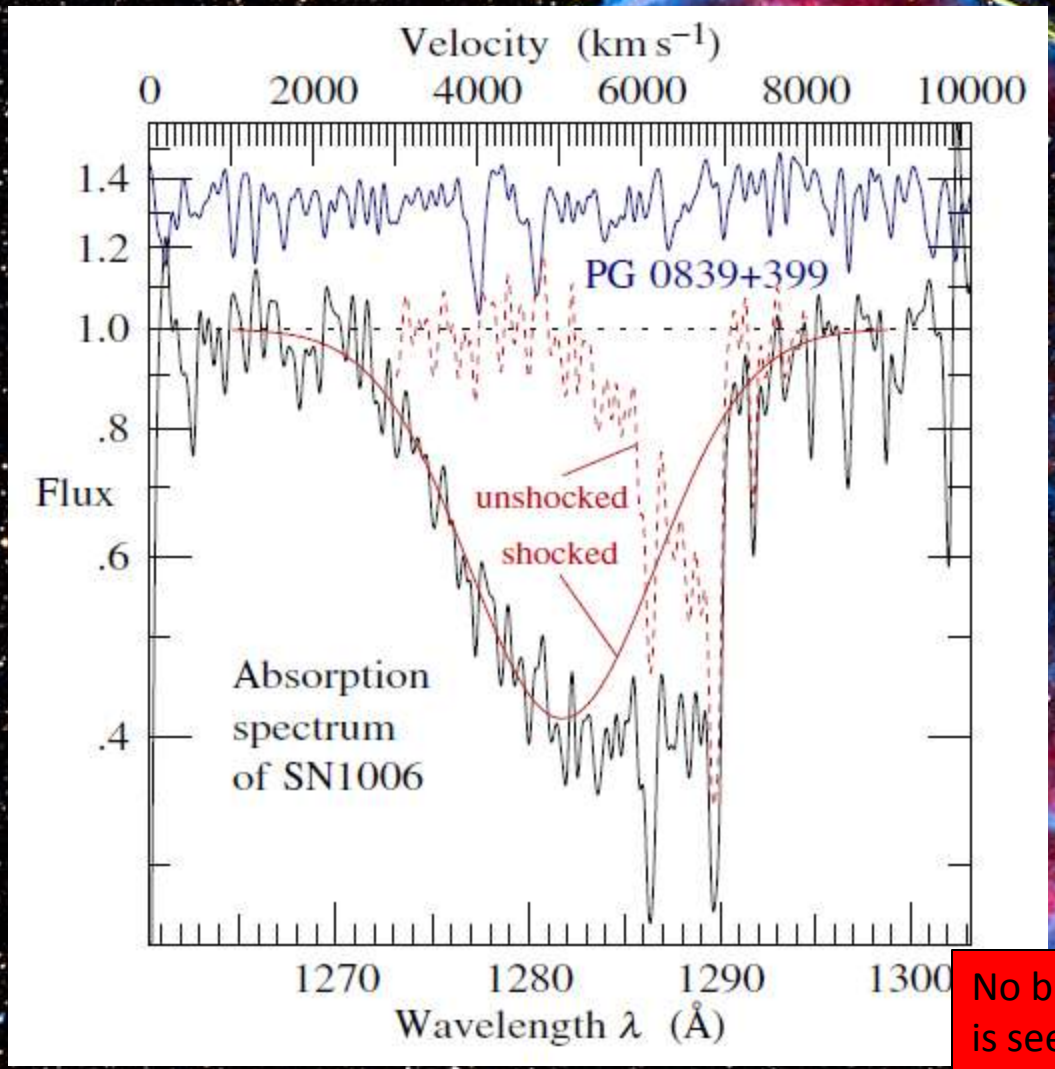
Lα emission

Michael et al. (2003)

Supernovae:
SN 1006 (Type Ia SN)



Supernovae:
SN 1006 (Type Ia SN)



The sharp edge on the right-hand side has moved to lower velocities by 44±11 km s^{-1} between a STIS exposure taken in 1999 and a COS exposure taken in 2010, indicating that the reverse shock is intercepting more slowly moving gas further inside the outflow.

Winkler et al. (2011)

No blueshifted counterpart to this absorption is seen. Possible reasons for this are discussed by Hamilton et al. (1997)

THE LEGACY OF HST SPECTROSCOPY

Barbara A. MIKULSKI ARCHIVE FOR SPACE TELESCOPES

High Level Science Products

High-Level Science Products (HLSP) are community contributed, fully processed (reduced, co-added, cosmic-ray cleaned etc.) images and spectra that are ready for scientific analysis. HLSP also include files such as object catalogs, spectral atlases, and README files describing a given set of data.

Spectral Atlases

- Search 10 Lac (O9V) Spectral Atlas (HST/GHRS) PI: Brandt, J.C.
- Search A FUV Atlas of Low-Resolution HST spectra of T Tauri Stars PI: Gregory Herczeg
- Search AGN and Quasar Spectral Atlas (HST/FOS) PI: Ian Evans
- alpha Ori Spectral Atlas (HST/GHRS) PI: GHRS Team
- chi Lupi (B9.5 pHgMn) Spectral Atlas (HST/GHRS) PI: GHRS GTO team
- Search CoolCAT - A cool-star UV spectral catalog PI: Thomas Ayres
- Copernicus Atlases of 6 Selected Stars PI: Copernicus Project
- Search Detailed Far-UV Spectral Atlas of B Main Sequence Stars PI: Myron Smith
- Search EUV Spectral Atlas of Stars (EUVE) PI: N. Craig
- Search FUSE Atlas of Starburst Galaxies PI: Anne Pellerin
- Search FUSE Magellanic Clouds Legacy Project PI: William Blair
- Search FUSE Spectral Atlas of Wolf-Rayet Stars PI: Allan J. Willis
- Search OB Stars (Galactic): FUSE Spectral Atlas PI: Anne Pellerin
- Search OB Stars (Magellanic): FUSE Spectral Atlas PI: Nolan Walborn
- Search Pre-Main Sequence Stars: IUE Spectral Atlas PI: Jeff Valenti
- Procyon (FV-IV) Spectral Atlas - Chromospheric Lines (HST/GHRS) PI: Brian Wood
- Standard Stars: IUE PI: Chi-Chao Wu
- Search StarCat: HST STIS Echelle Spectral Catalog of Stars PI: Thomas Ayres
- Search STIS Next Generation Spectral Library (AR10659) PI: Sally Heap
- White Dwarf Spectral Atlas: High dispersion IUE PI: Jay Holberg