Abundances of *r*-Process Elements in Stars

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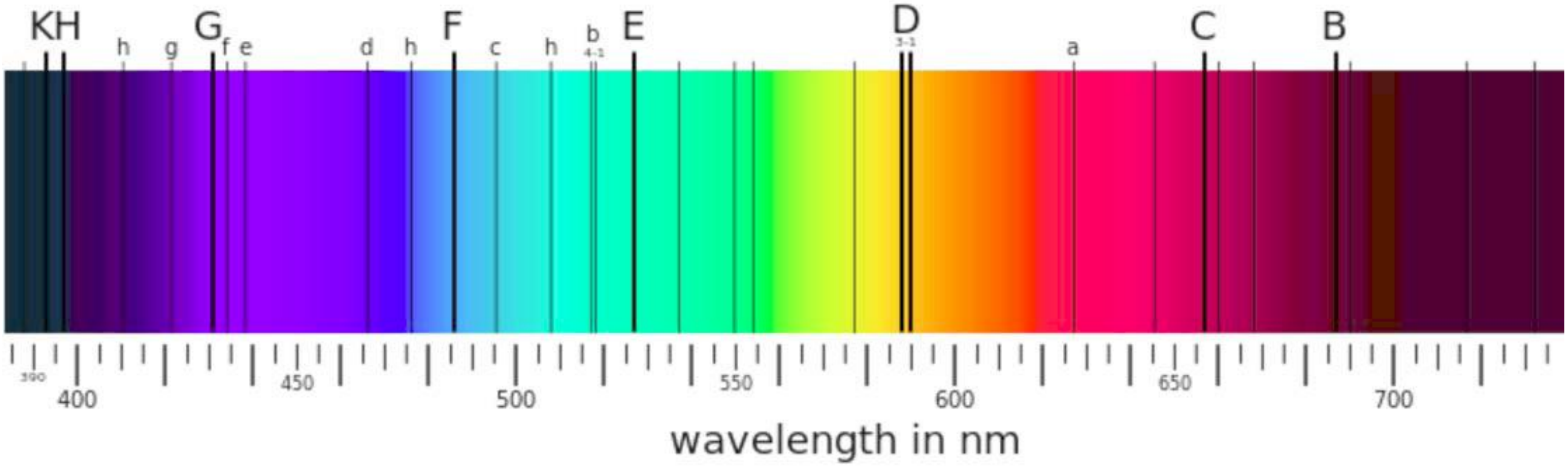
(A perspective from a laboratory spectroscopist. Sharp line spectroscopy & the possibility of line spectroscopy in kilonova)

Fraunhoffer Lines

In 1802 William Hyde Wollaston noted dark features in the Sun’s spectrum. In 1814 Joseph von Fraunhoffer also found these and launched a careful study of the features. Wavelengths were measured using prisms, most prominent features were “named” A through K, less prominent were given other names,….

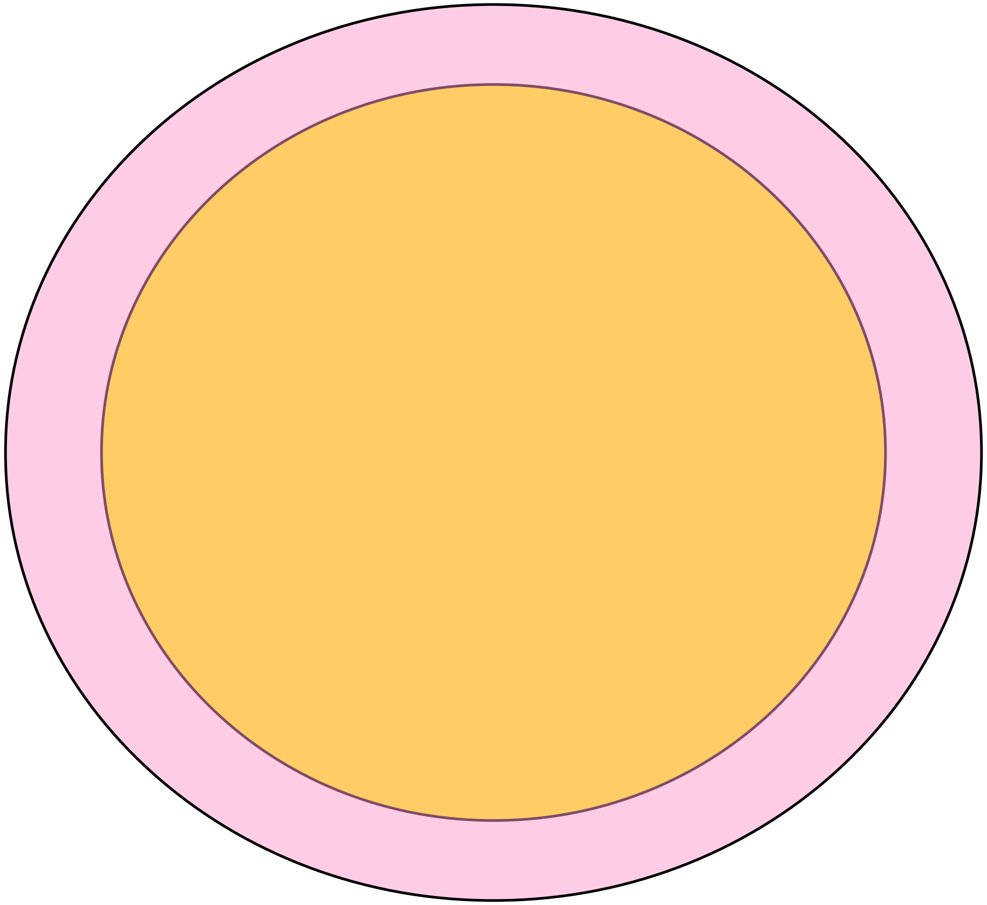


Wikipedia

Fraunhoffer Lines in the Sun & other Stars are from the temperature gradient.

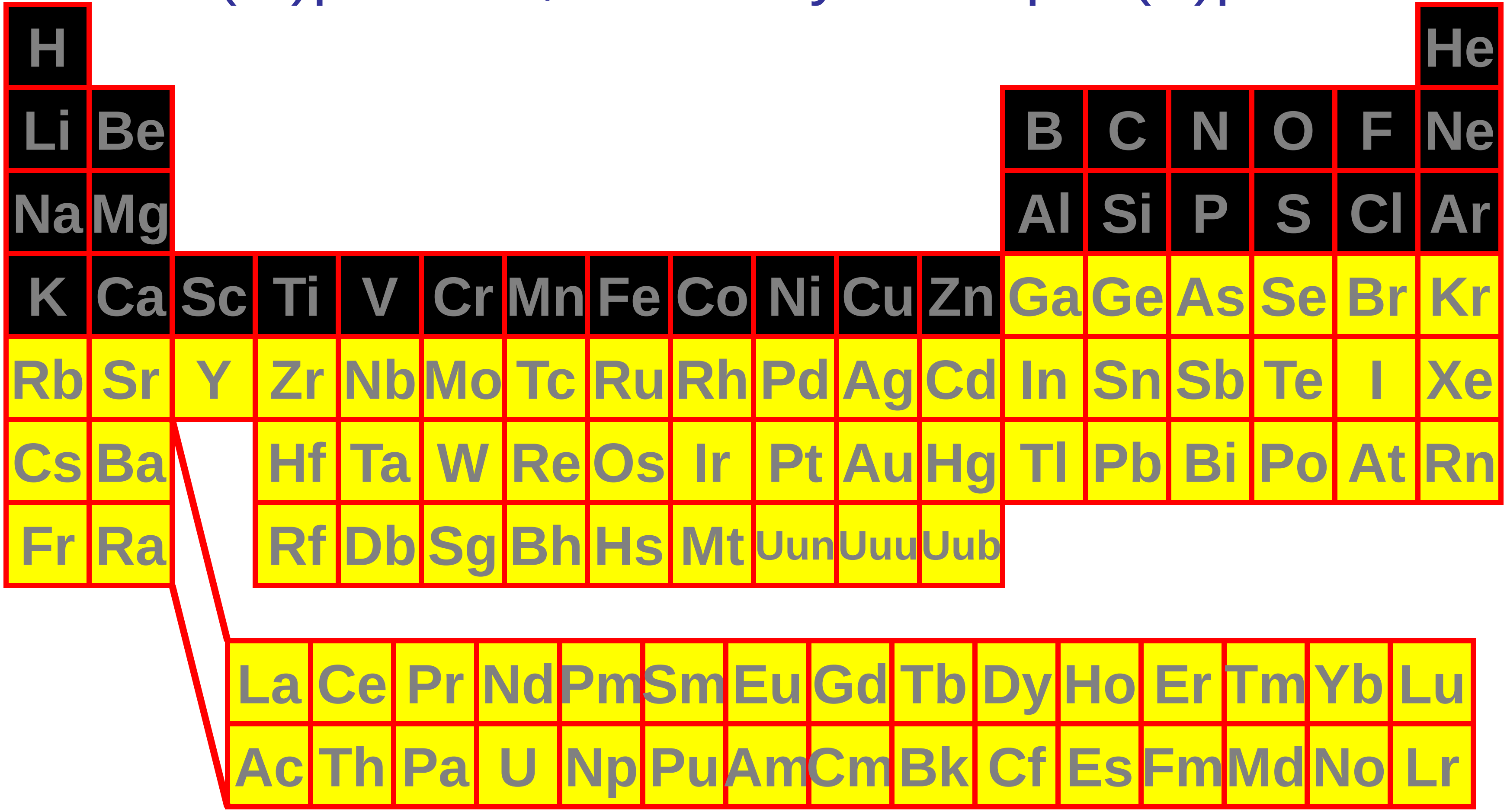
- For the Sun, T = 5778 K at surface
- Much like a black body but T increases with depth
- Deeper hotter layers provide a continuum for absorption features from outer cooler layers

Continuum from hotter interior yields absorption lines from cooler layer near surface



Real photospheric models do not have step boundaries. Temperature gradient is modeled using radiation transport equation typically with LTE/1D approximations.

Elements (Z > 30) are made by neutron (*n*-)capture. Some elements & isotopes are made primarily by the slow (*s*-)process, others by the rapid (*r*-)process.



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

n-Capture element definitions

- *s*-process: all β-decays can occur between successive *n*-captures - Site: AGB (Red Giant) Stars (proof: Tc short lived 200 kyear) in spectra
- *r*-process: rapid, short-lived neutron blast temporarily overwhelming β-decay rates …. *n*(eutron)-star (NS) mergers are a site of *r*-process based on electromagnetic follow up studies of GW-170917
- *r*- or *s*-process element: ones whose origin in solar-system material was dominated by one or the other process

Nucleosynthesis by *n*(eutron)–capture Some Milestones

- Paul & Merrill 1952, Tc (200 kyr lifetime) in Red Giant (AGB) Star…the *s(low)*-process *n*-capture site…stellar wind
- Hoyle’s 1954 paper
- B2FH Rev. Mod. Phys. 29, 547 (1957)
- SN 1987A …first nearby SN since Kepler…proton decay experiments detect neutrino burst…
- a-LIGO + VIRGO in 2017 find a *n*-star merger & teams study the electromagnetic flash

r-process is still tough to model

- Important nuclei are far from stability
- Facility for Rare Isotope Beams (FRIB) at MSU and facilities in Europe and Japan will produce the needed nuclear data
- Old metal poor (MP) stars enable us to trace nucleo-synthesis
- Big Telescopes, UV access with HST, & better Lab Astro

Key Question?

Is there any hope of seeing freshly made *r*-process elements via lines in absorption or emission?

How about emission after the cloud has expanded and cooled?

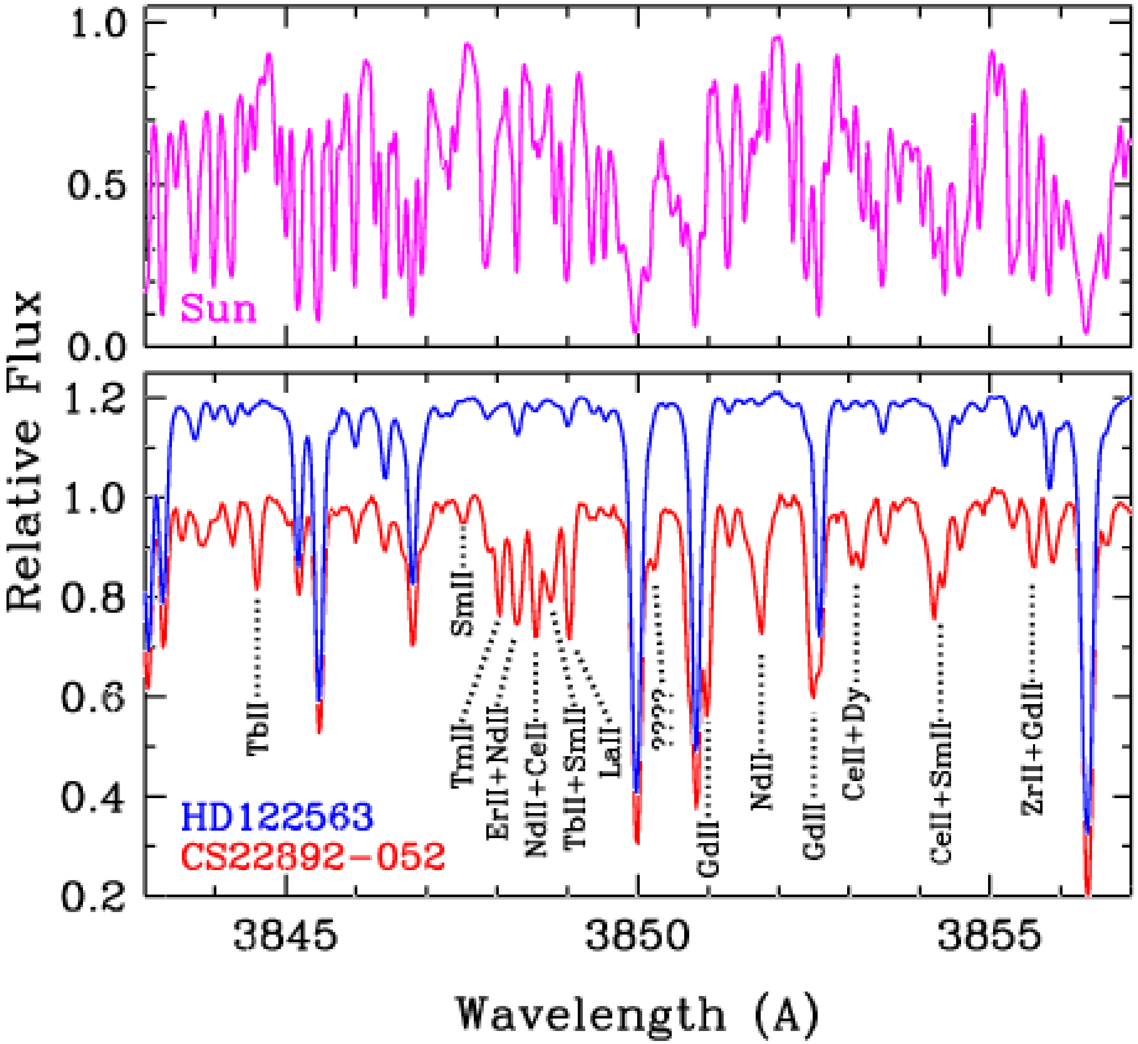
Harriet Dinerstein at UT – Austin has seen forbidden emission lines of *n*-capture elements in multiple nebulae.

The answer for the near term is NO Sharp Lines but …… ! The NS fireball is throwing out material at several tenths of c and a wide range of directions.

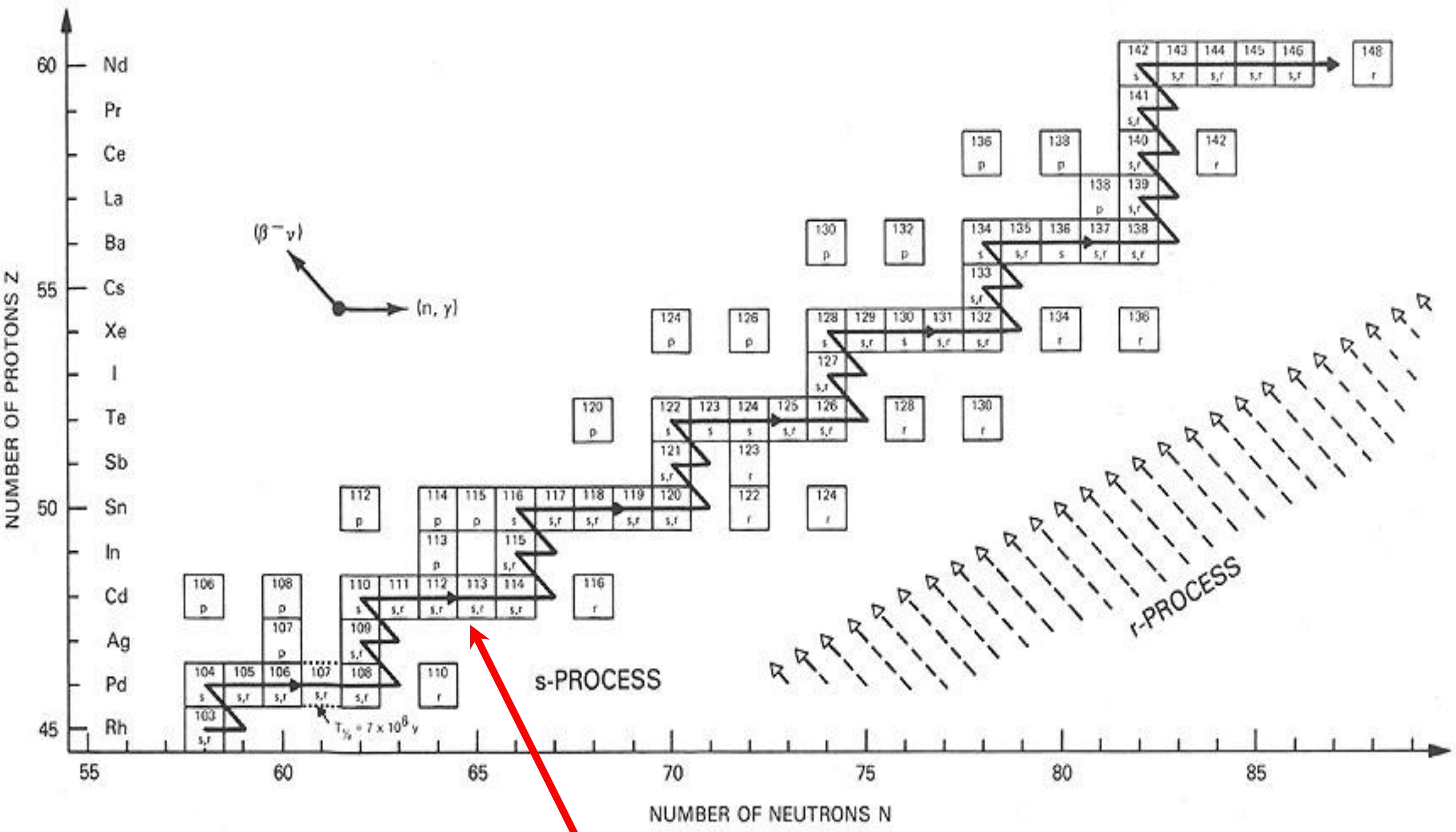
Sharp Line Spectroscopy

- Sharp line spectroscopy has greatly improved
- Review in the following slides is on Metal Poor (MP) stars & their relevance to the *r*-process
- After the review we will consider some possibilities for sharp line spectroscopy on kilonova.

MP stars have simpler spectra & are sometimes rich in *n*-capture elements



Isotopes built by *n*-capture syntheses



The valley of β-stability

Rolfs & Rodney (1988)

The s-process can now be modeled

- Nuclei of interest are either stable or slightly radioactive
- Many or most needed nuclear data have been measured
- Model *s*-process abundances can be subtracted from the total Solar System elemental abundance to determine the *r*-process Solar System abundance

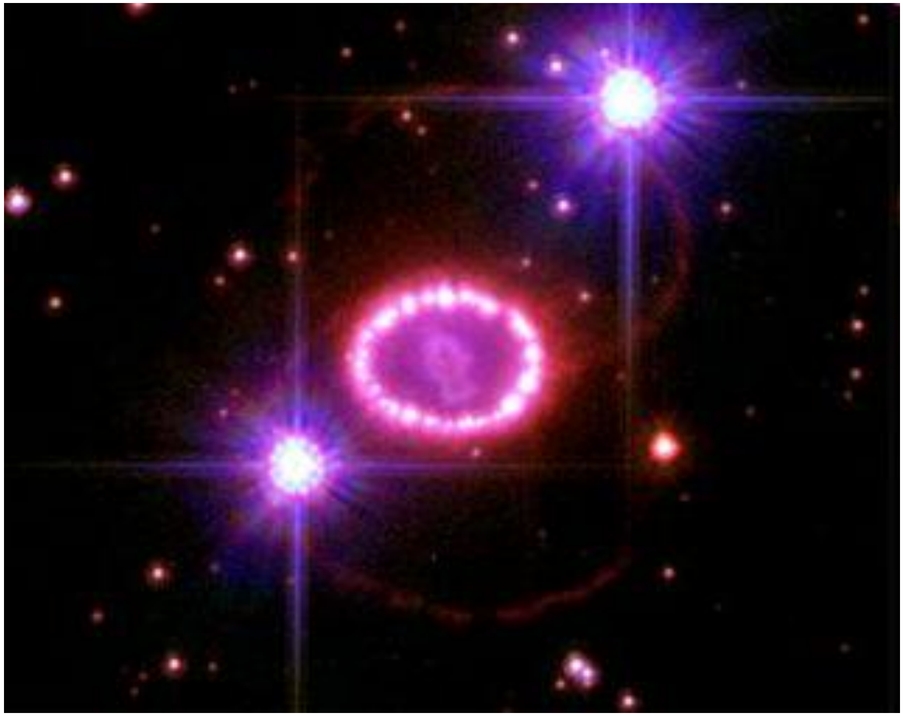
Site of *r*-process?

Type II (core collapse)

Supernovae are the leading candidate at this time.

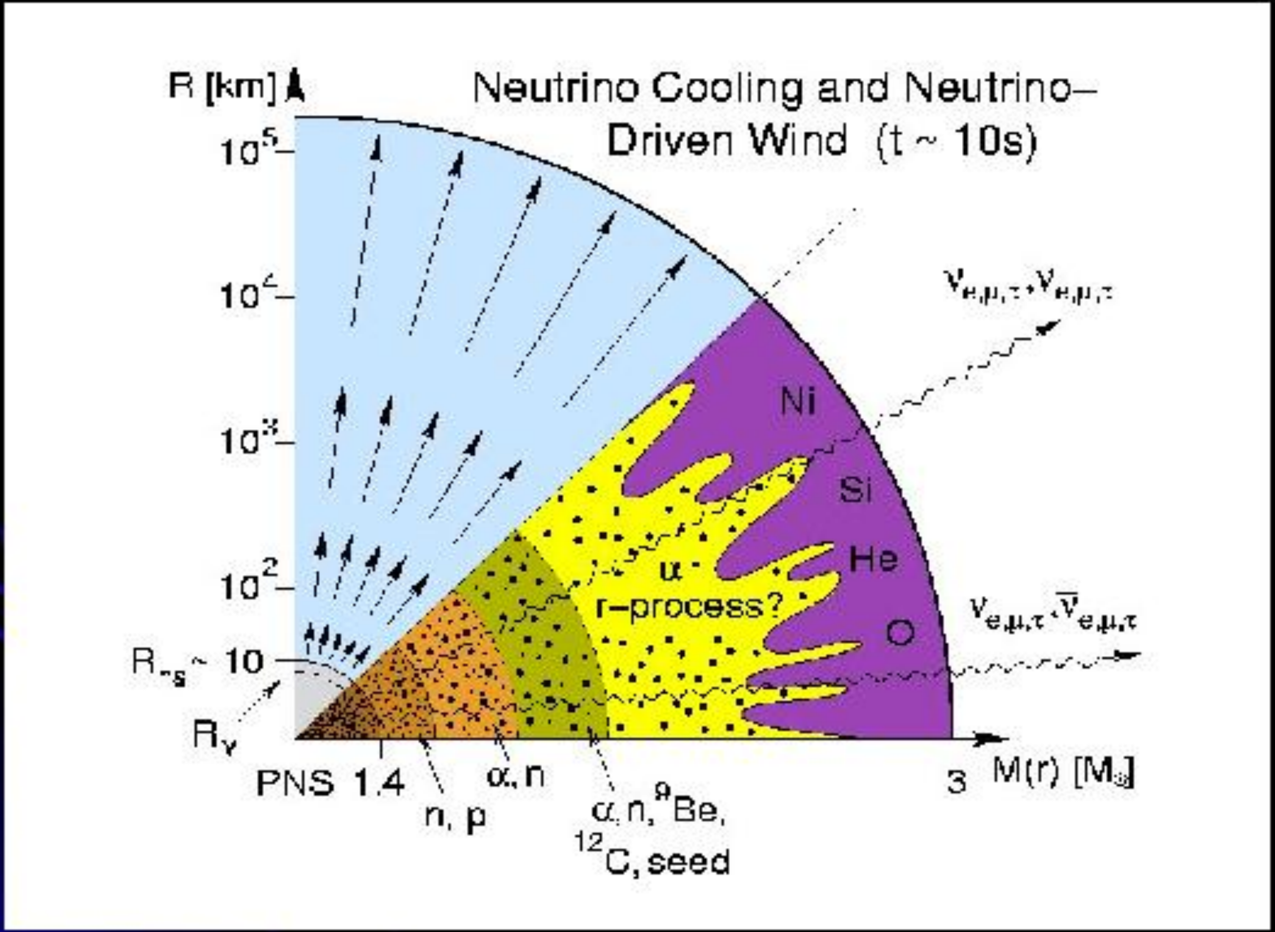
Stellar mass > 9 Solar Mass,

Fe core > 1.44 Solar mass.



The expanding remnant of SN 1987A, a Type II-P supernova in the Large Magellanic Cloud, *NASA image.*

Rapid Neutron Capture in Type II SNe ?



back

From Woosley & Janka 2005

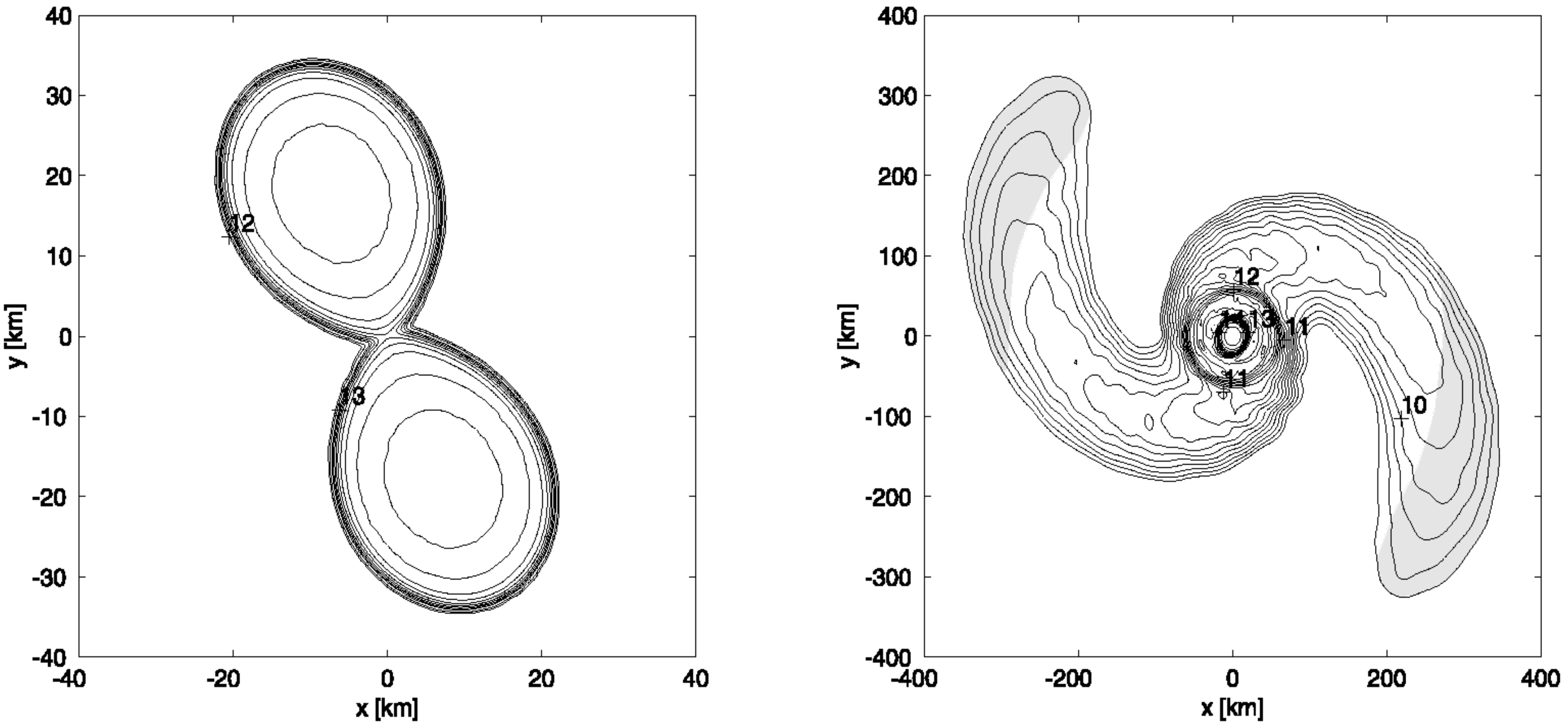
Site of *r*-process?

- *NS* mergers are surely a site of *r*-process nucleosynthesis.
- There is only a few 1000 Solar Masses or less of *n*-rich elements in the entire Galaxy.
- Short GRBs are likely from *NS* mergers
- There is still Lab Astro to be done.

r-PROCESS IN NEUTRON STAR MERGERS

C. Freiburghaus, S. Rosswog, and F.-K. Thielemann

ApJ 525:L121(1999)



Credit to Thielmann’s group for early work on *n*-star mergers does not detract from the many contributions of people here.

BH-NS merger ejecta 18

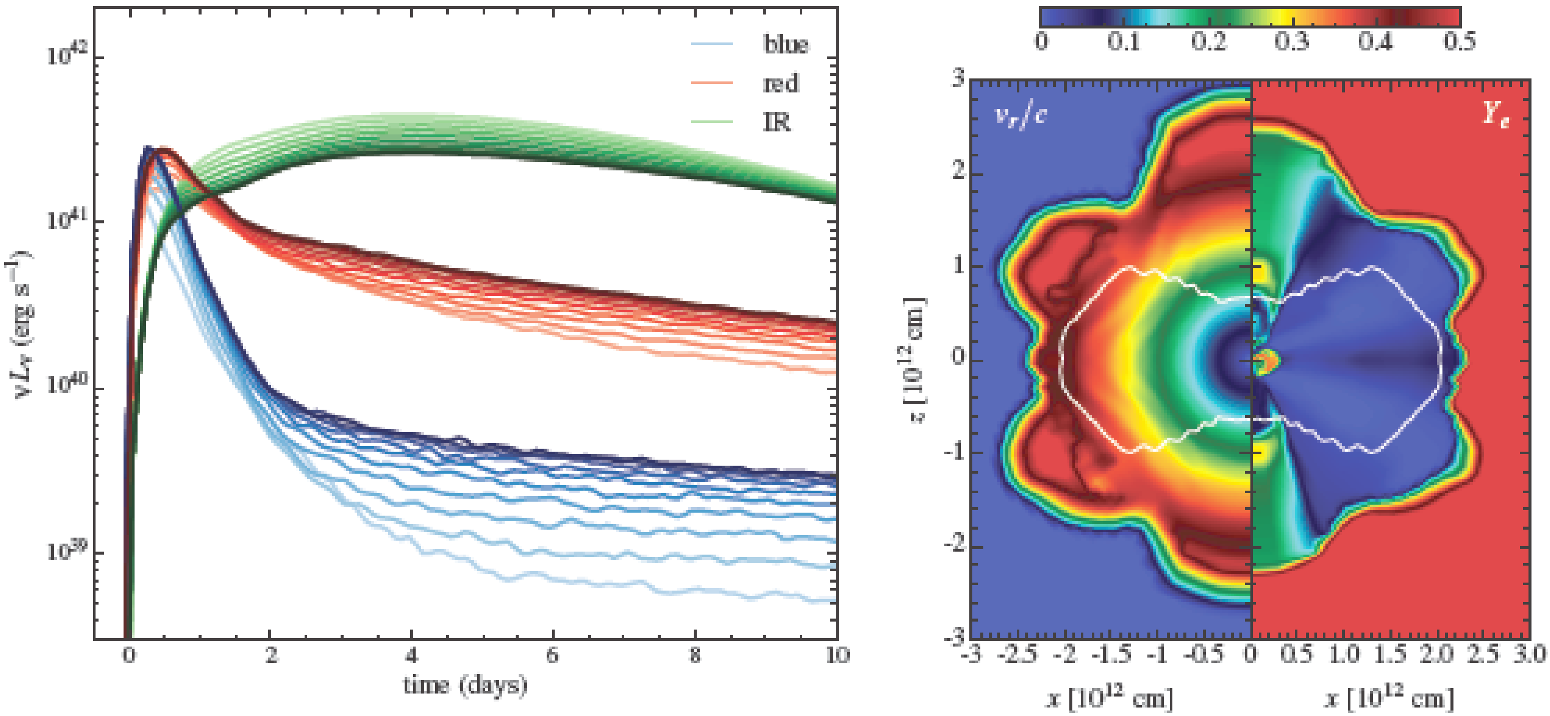


Figure 10: *Left:* Broadband light curves from model F0 in the wave bands $3500 - 5000\mathring{A}$ (blue), $5000 - 7000\mathring{A}$ (red), and $1 - 3\mu$m (green). For each color, 10 viewing angles equally spaced in their cosine are shown with different shades, spanning the range $\theta = 0$ (light, rotation axis) to $\theta = 90^\circ$ (dark, equatorial plane). *Right:* Snapshot of the radial velocity (left panel) and electron fraction (right panel) in model F0 at time $t = 150$ s, when most of the matter distribution has reached homology. This snapshot is used as input for radiative transfer calculations. The white contour corresponds to a density 10^{-6} g cm^{-3}.

Fernández et al. 2017 BH + NS merger

In the decades after Fraunhoffer absorption lines were matched to atoms and ions

- Wavelength measurements improved steadily
- Large grating spectrographs (Rowland Circle) were used to achieve ppm accuracy in the first half of the 20th Century
- Wavelength measurements could be improved to 10 ppb by late 1970s w FTS instruments.
- Optical frequency combs can now achieve better than 0.0000001 ppb (one line at a time)

What was left to work on circa 1980 in spectroscopy?

- Einstein A coefficients are essential to quantitative spectroscopy
- No really good (fast, accurate, v broadly applicable) measurement technique was available until tunable lasers
- Organic dye laser 1966 (P. Sorokin & F. Schafer et al.) provided broad tunability
- Dye lasers needed improvements but by mid 1970s they were ready

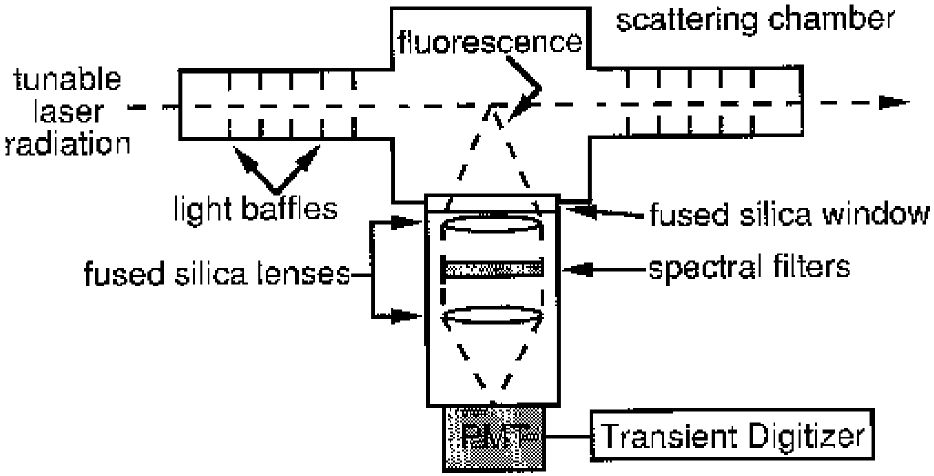
Pulsed Dye Lasers by mid 1970s

- Optical bandwidth of a few GHz ~ Doppler width of atom & ion lines
- Pulse duration of a few nsec, v low Q cavity yields v abrupt pulse termination
- Rep Rate 10 – 100 Hz well matched to fast data handling system
- Tunability 200 nm – 800 nm some non-linear crystals needed
- Dye lasers had been mastered by multiple groups

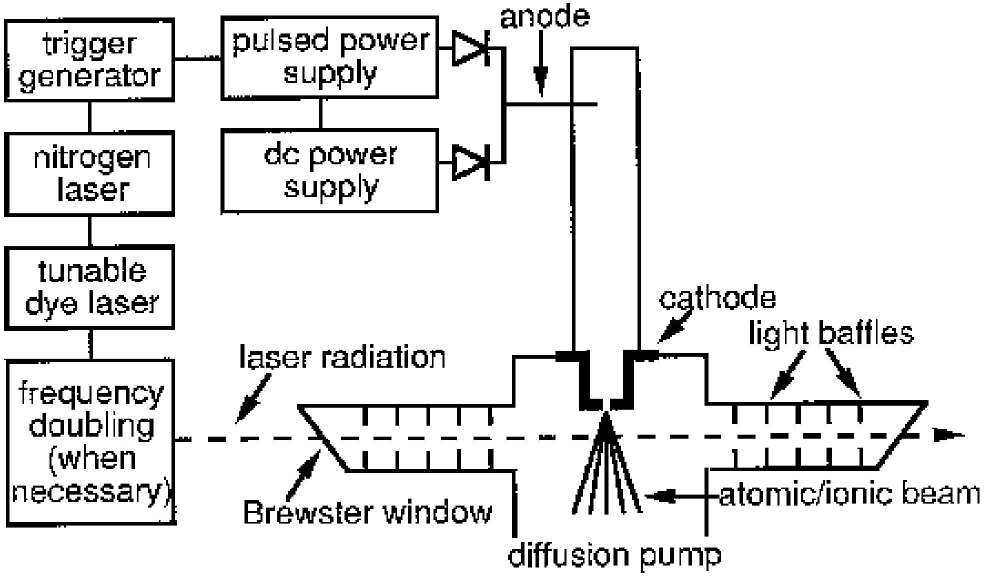
UW Lab Astro developed the atom/ion beam source 1980 - 81

- It works well with all metallic and most non-metallic elements
- It is highly reliable, down time < 1%
- It delivers 10^{14} atoms/(sec sr)
- The beam is rich in metastable atoms and ions, one can use levels 4 eV above the ground level as a lower level for LIF
- Time Resolved Laser Induced Fluorescence (TR LIF) yielded radiative lifetimes (**tau**’s) accurate and precise to ~ a few %
- Many **tau**’s can be measured per day

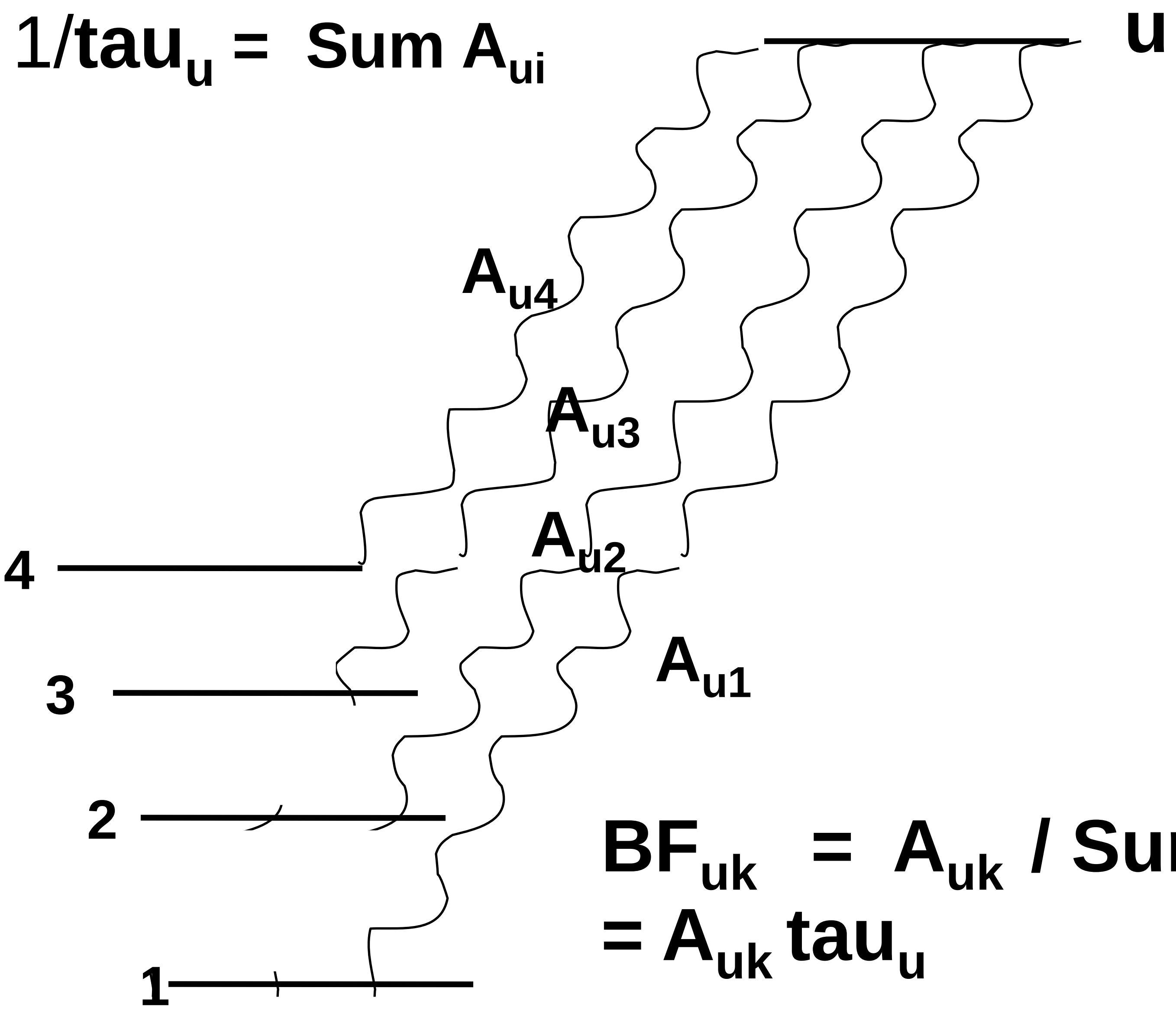
TOP VIEW



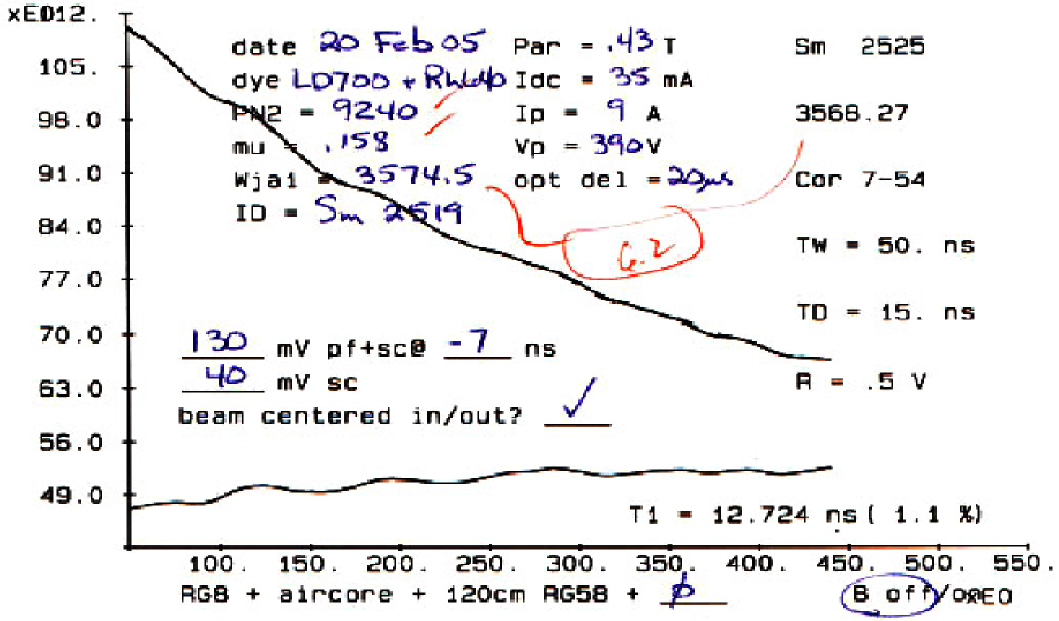
SIDE VIEW



$$1/\mathrm{tau}_u = \text{Sum } A_{ui}$$



$$BF_{uk} = A_{uk} / \text{Sum } A_{ui}$$
$$= A_{uk}\,\mathrm{tau}_u$$



date 20 Feb 05
dye LD700 + Rh6b
PN2 = 9240
mu = .158
Wjai = 3574.5
ID = Sm 2519

Par = .43 T
Idc = 35 mA
Ip = 9 A
Vp = 390V
opt del = 20μs

Sm 2525

3568.27

Cor 7-54

TW = 50. ns

TD = 15. ns

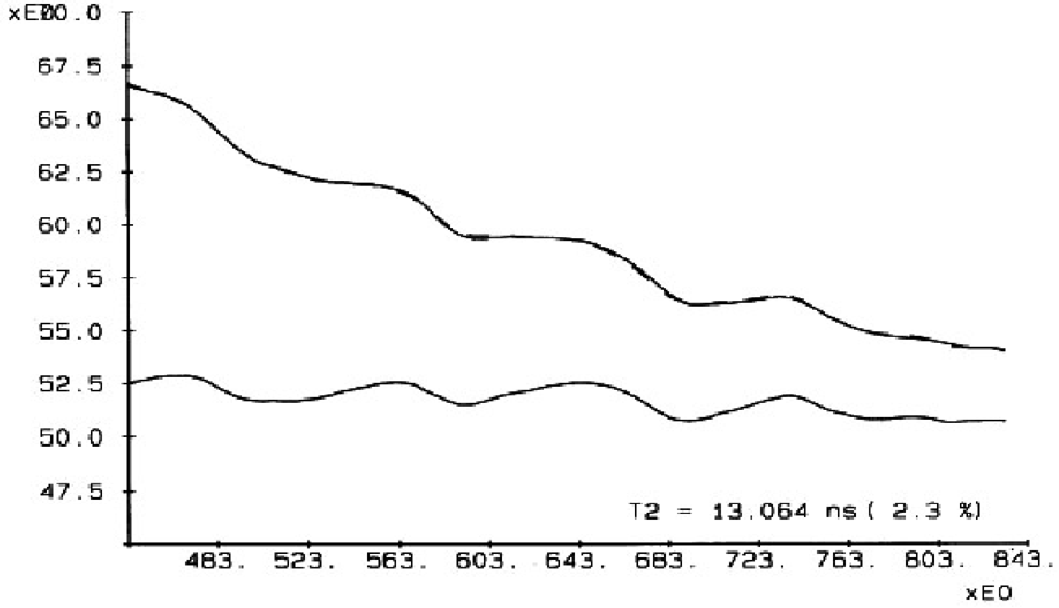
R = .5 V

130 mV pf+sc@ -7 ns
40 mV sc
beam centered in/out? ✓

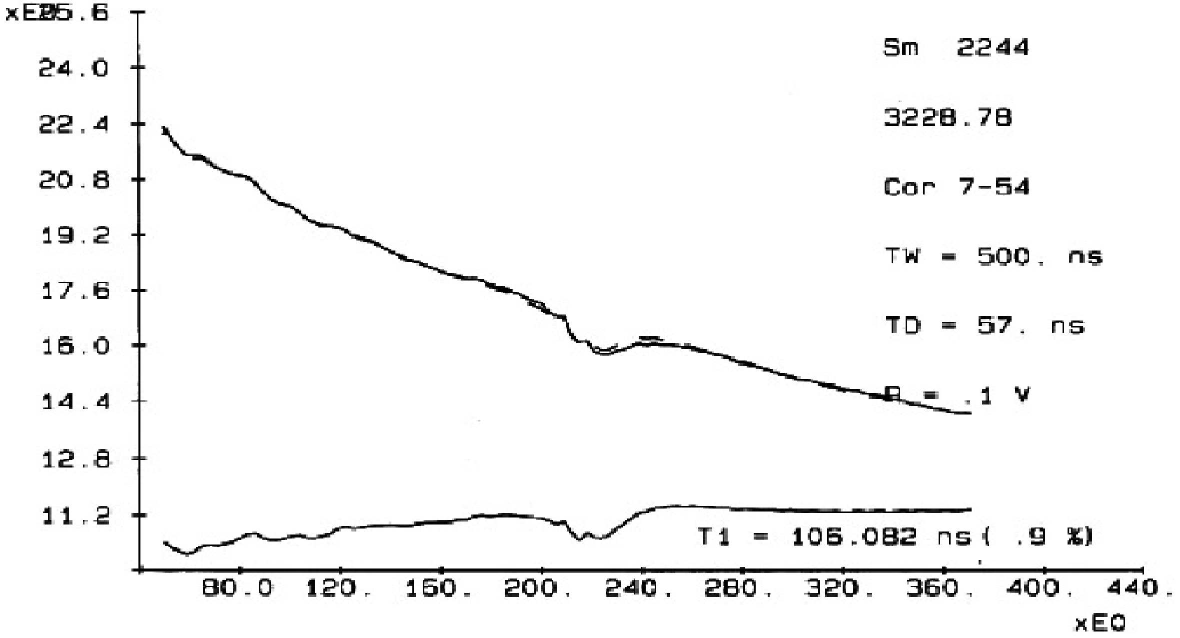
T1 = 12.724 ns (1.1 %)

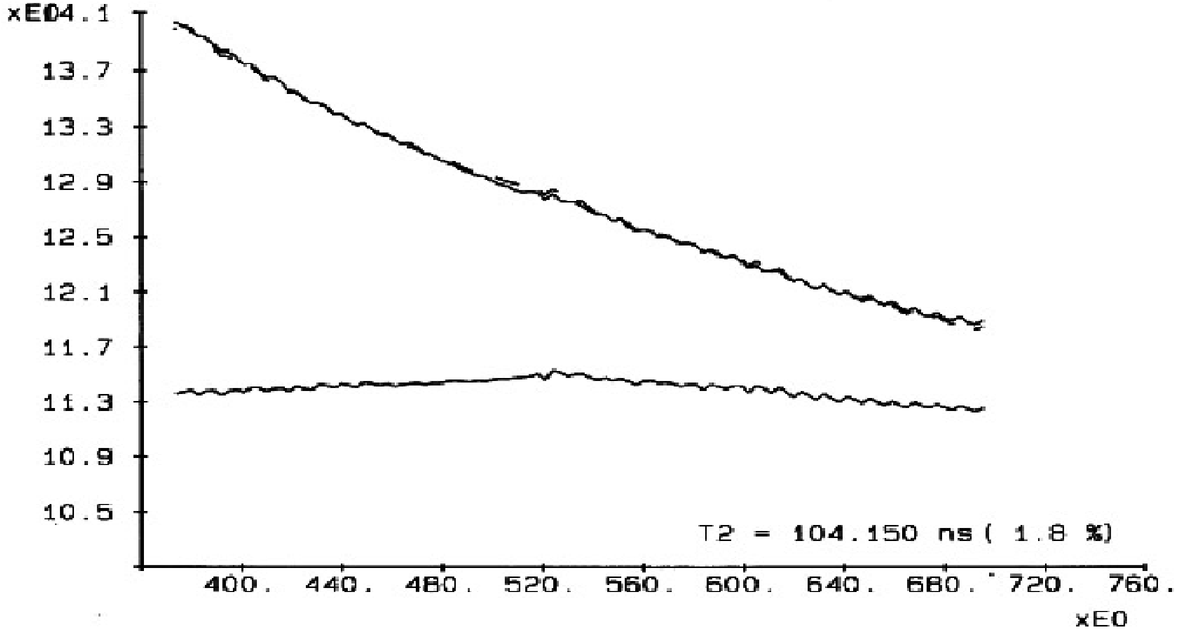
RG8 + aircore + 120cm RG58 + ϕ

[✓ B off]/on



T2 = 13.064 ns (2.3 %)

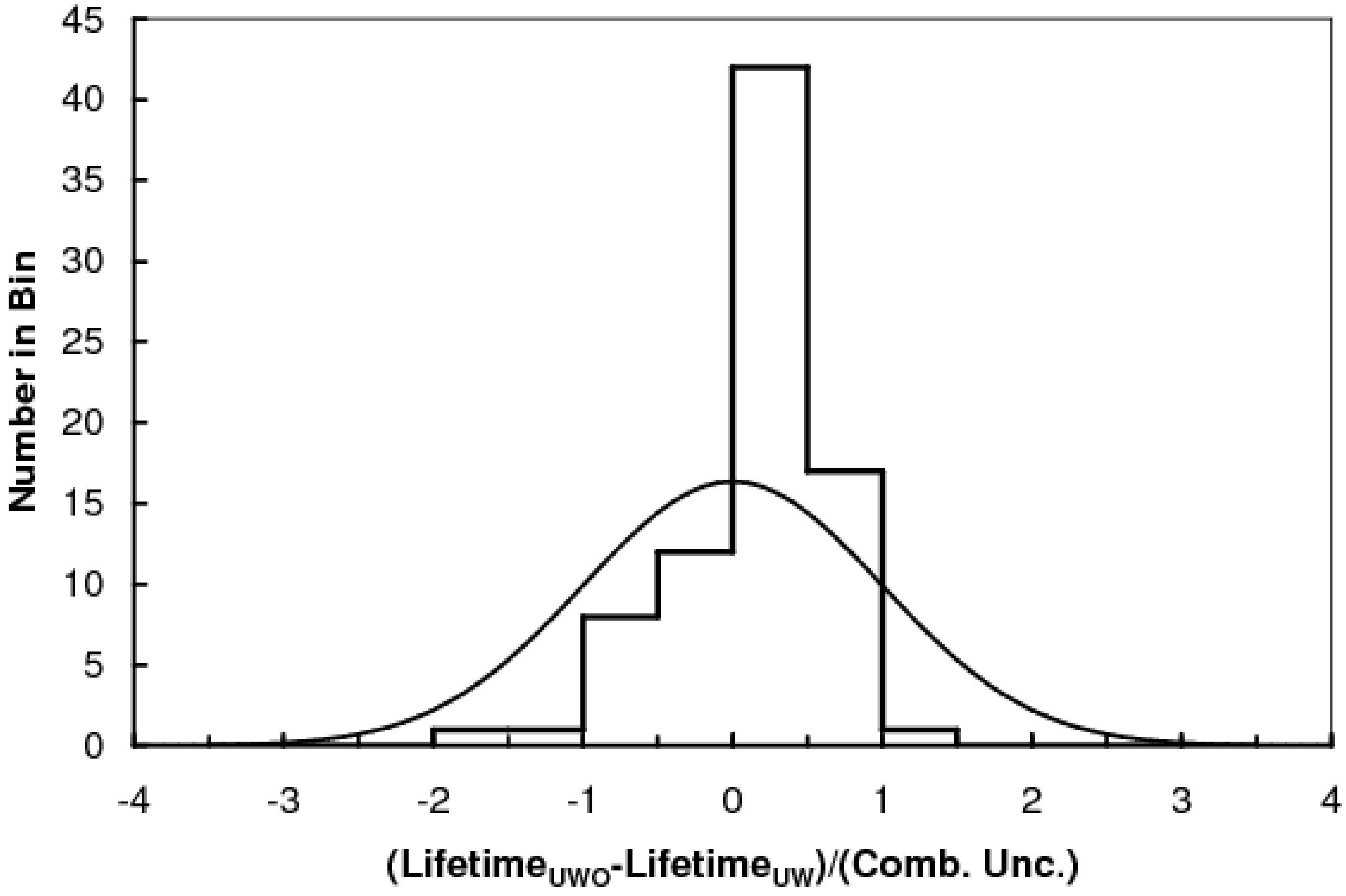

xE0 25.6
24.0
22.4
20.8
19.2
17.6
16.0
14.4
12.8
11.2
80.0
120.
160.
200.
240.
280.
320.
360.
400.
440.
xE0
Sm 2244
3228.78
Cor 7-54
TW = 500. ns
TD = 57. ns
B = .1 V
T1 = 106.082 ns (.9 %)


xE0 14.1
13.7
13.3
12.9
12.5
12.1
11.7
11.3
10.9
10.5
400.
440.
480.
520.
560.
600.
640.
680.
720.
760.
xE0
T2 = 104.150 ns (1.8 %)

Search for possible systematic errors

- Radiation trapping? Vary the beam density
- Collisional quenching? Throttle the pump
- Zeeman quantum beats? B = 0 (~ 10 milliGauss) for short lifetimes, B ~ 25 Gauss for long lifetimes
- Ultimate end-to-end test: Periodic re-measurement of benchmark lifetimes in He, Be,….

Comparison of Sm II lifetimes from UWO vs UW



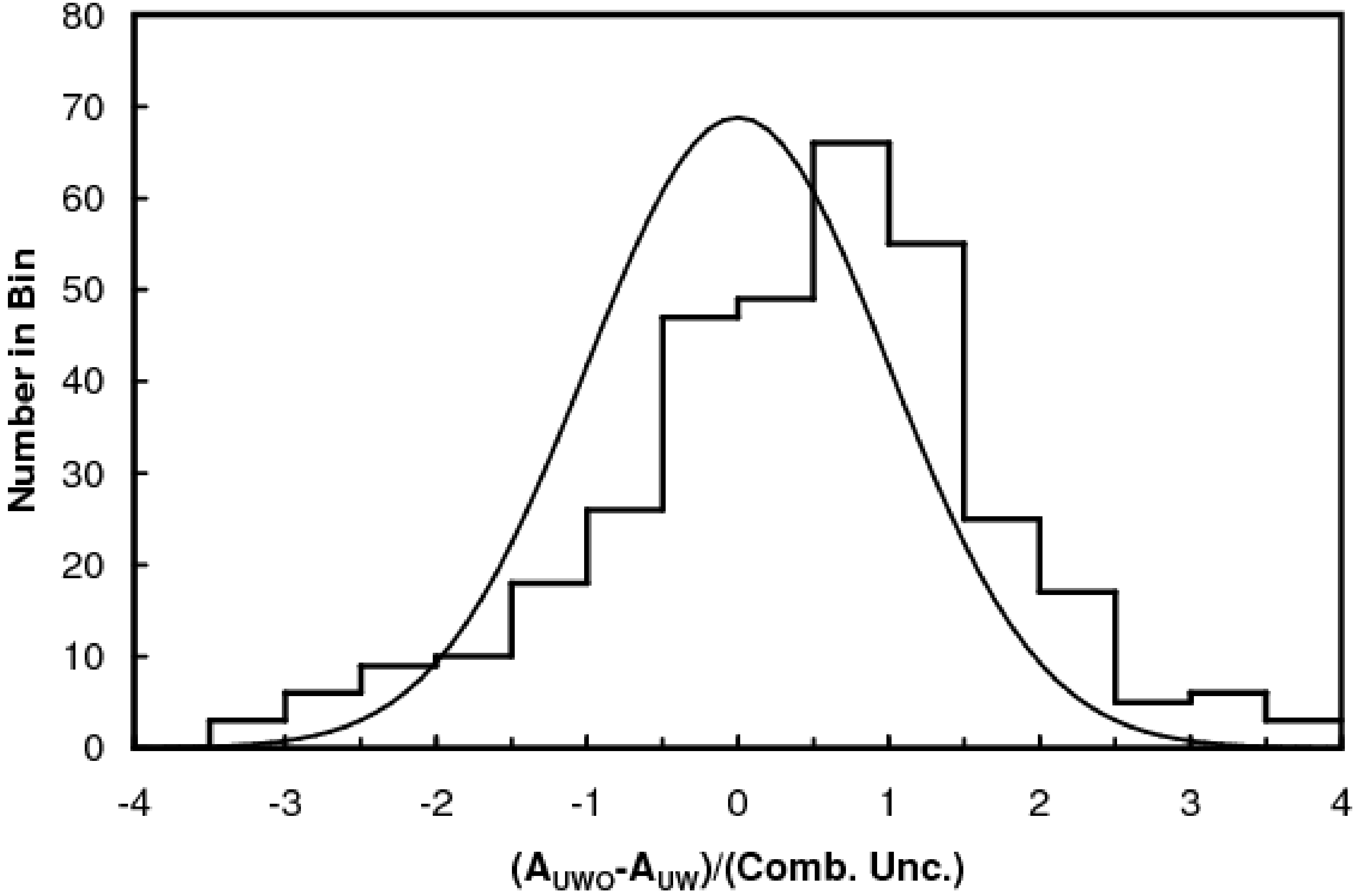
Clearly, LIF experiments can provide accurate, absolute radiative lifetimes.

Ab-initio theory provide good branching ratios in <u>simple</u> spectra, experiments provide good branching rations in <u>complex</u> spectra.

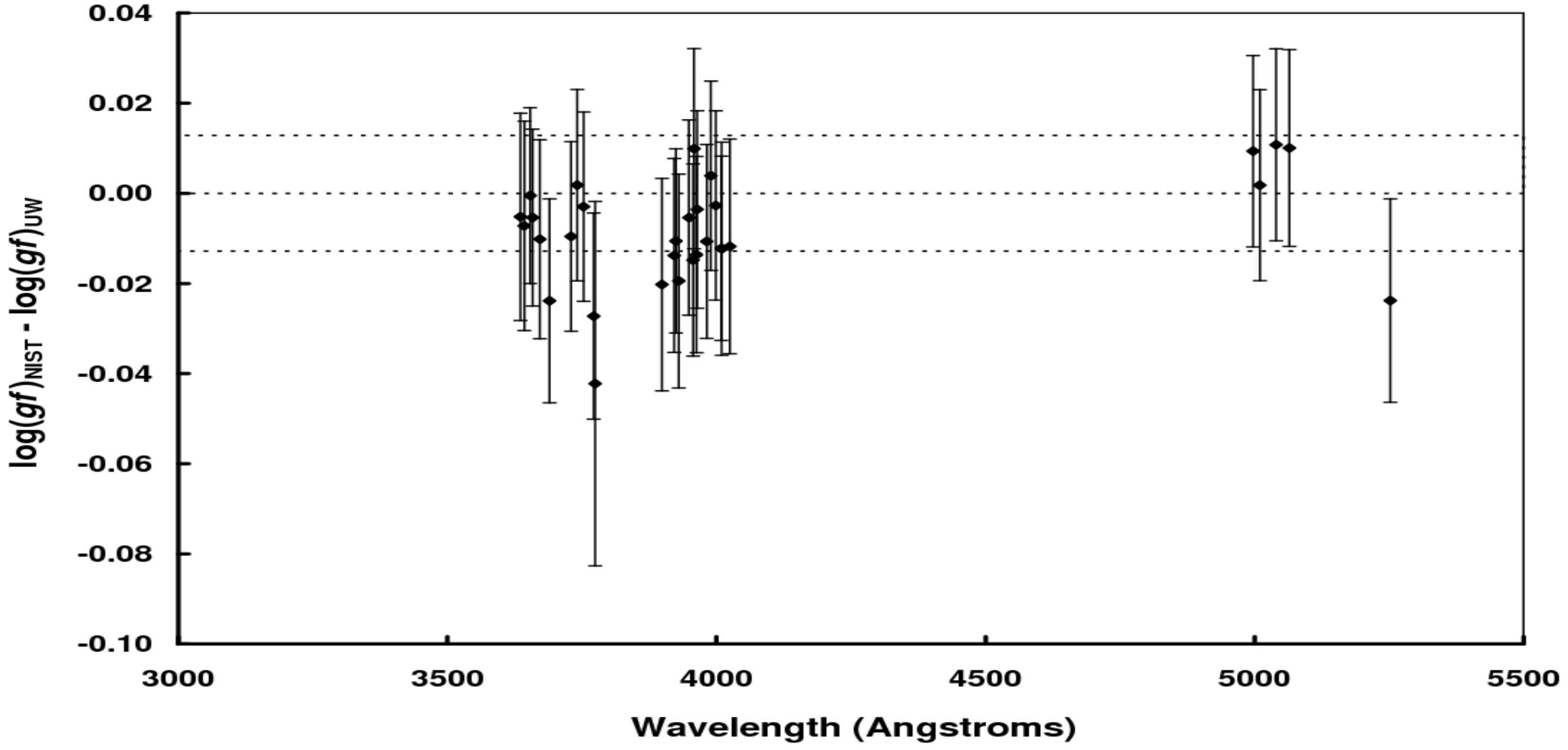
Advantages of an FTS: Kitt Peak (**James Brault**), NIST, Lund

- Very high spectral resolving power
- Excellent absolute wavenumber accuracy
- Extremely broad spectral coverage
- Very high data collection rates
- Insensitive to source intensity drifts
- Large etendue
- **Ward Whaling (Caltech) relative radiometric calibration of FTS**

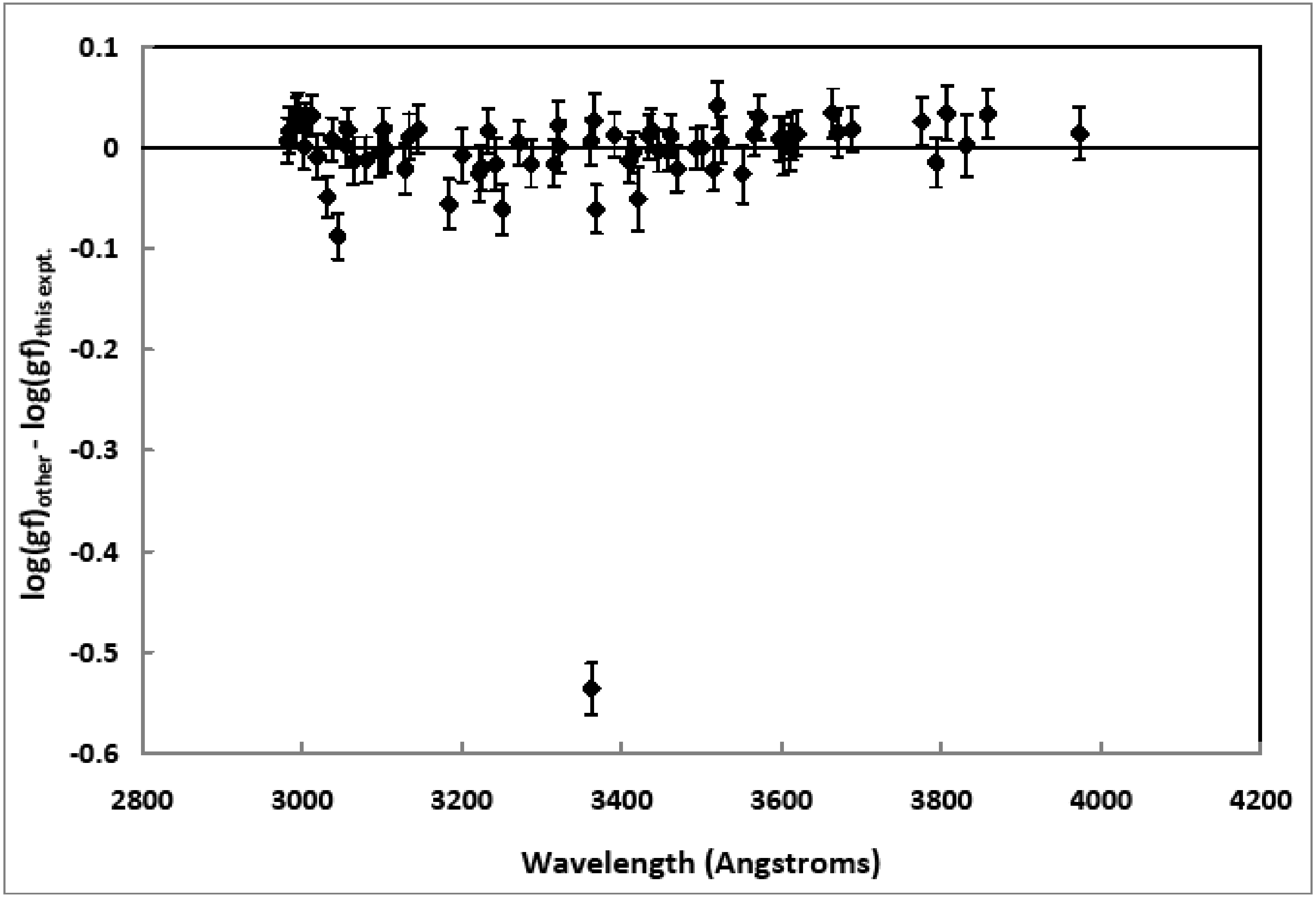
Comparison of Sm II A coefficients UWO vs UW

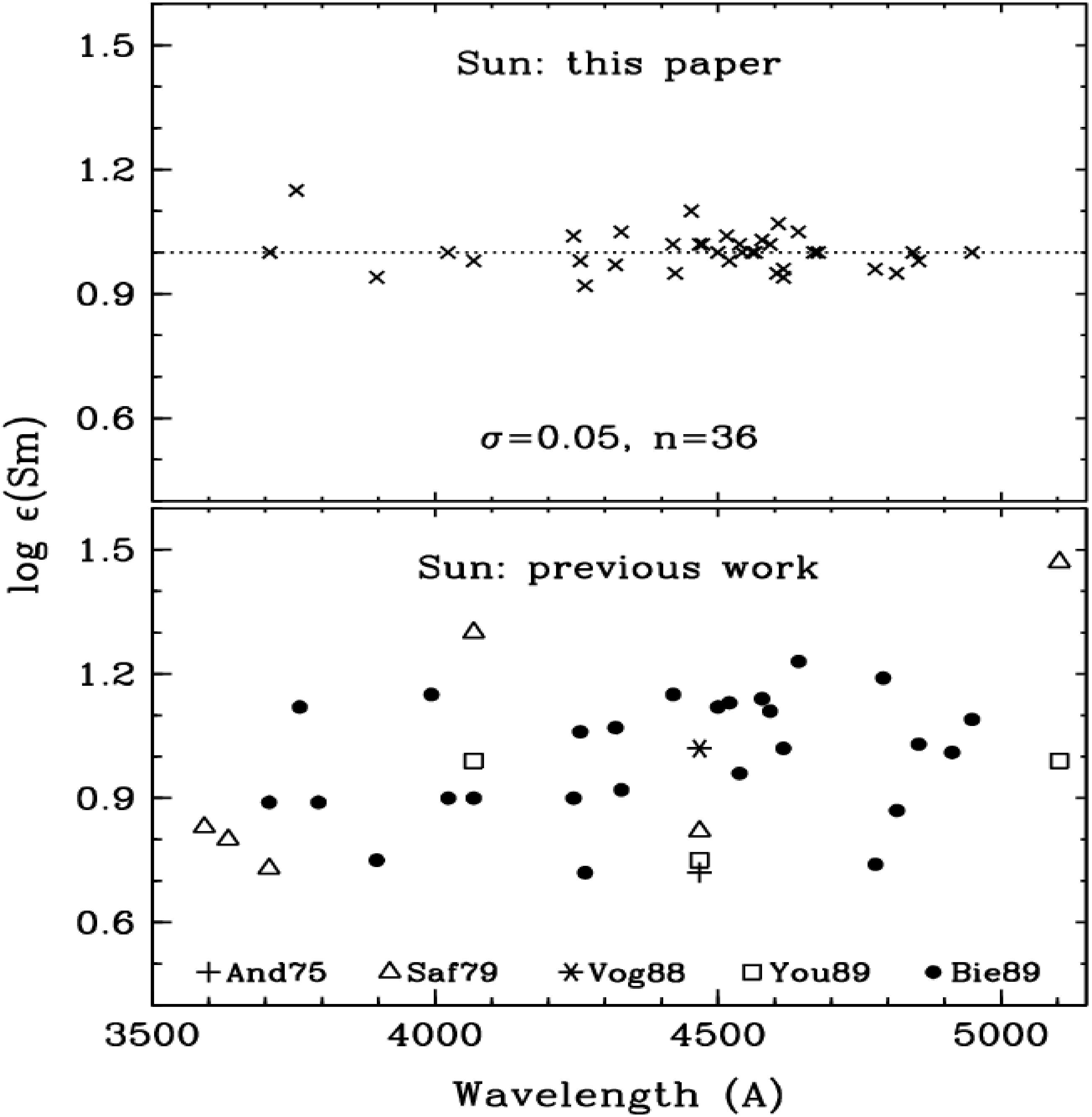


Comparison of Oxford to UW log(gf)s for Ti I



Comparison of Oxford to UW log(gf)s for Ni I




Sun: this paper
σ=0.05, n=36
Sun: previous work
+And75
△Saf79
✳Vog88
□You89
●Bie89
log ε(Sm)
1.5
1.2
0.9
0.6
3500
4000
4500
5000
Wavelength (A)

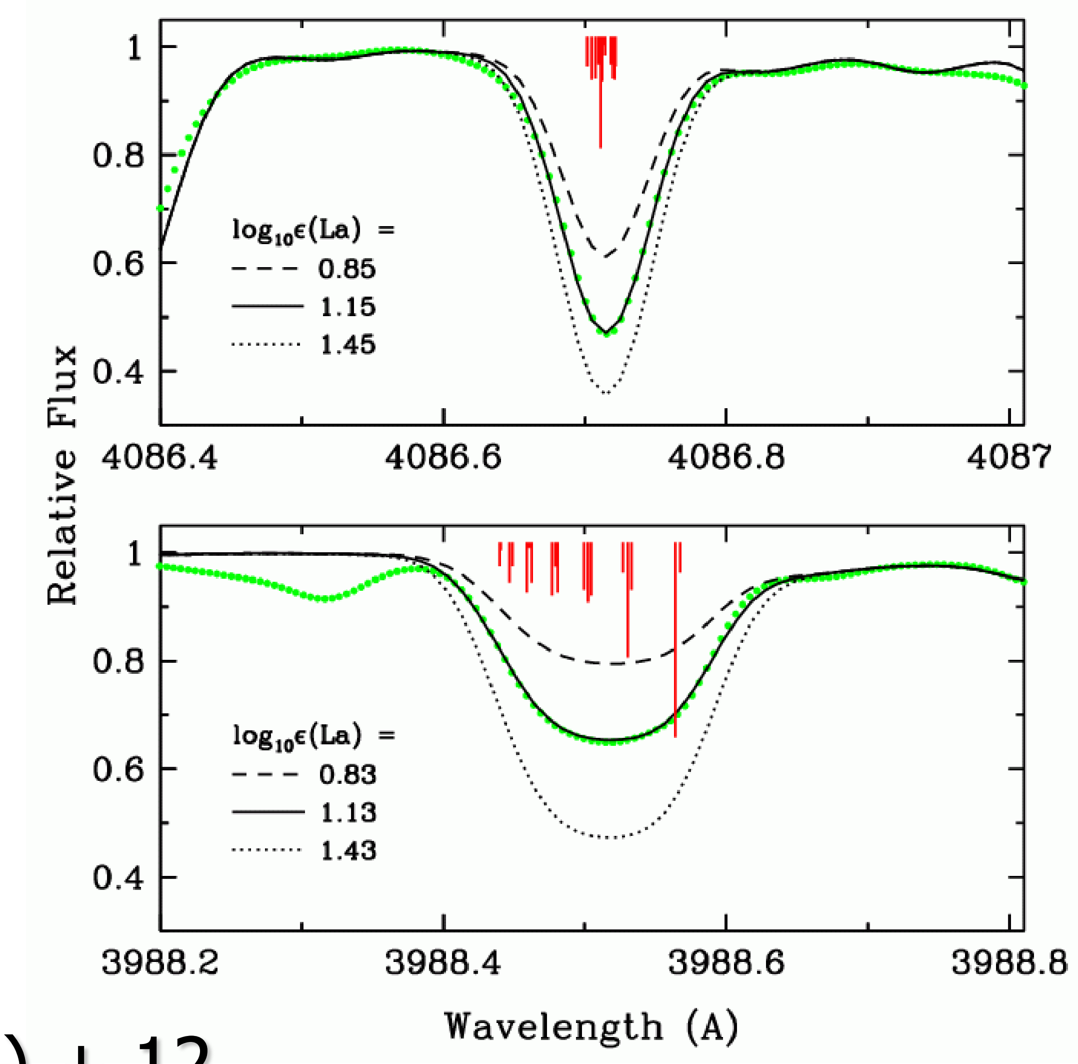
Attention must be paid to hyperfine, isotopic structures: typical La II lines

Solar photosphere: green lines

Hyperfine components: red sticks

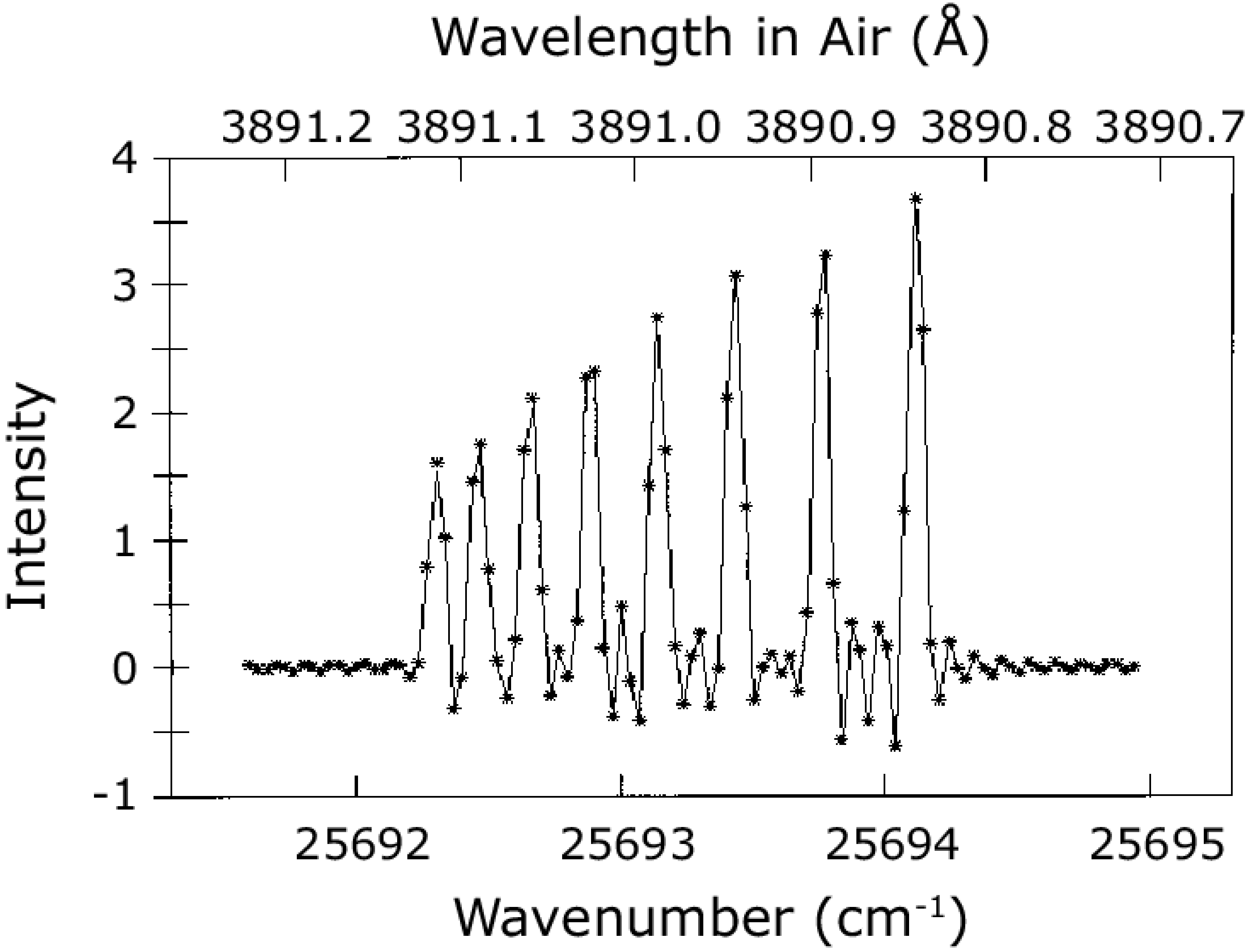
No isotopic worries; only ^{139}La

$\log \varepsilon(X) = \log(N_X/N_H) + 12$



Lawler et al. 2001

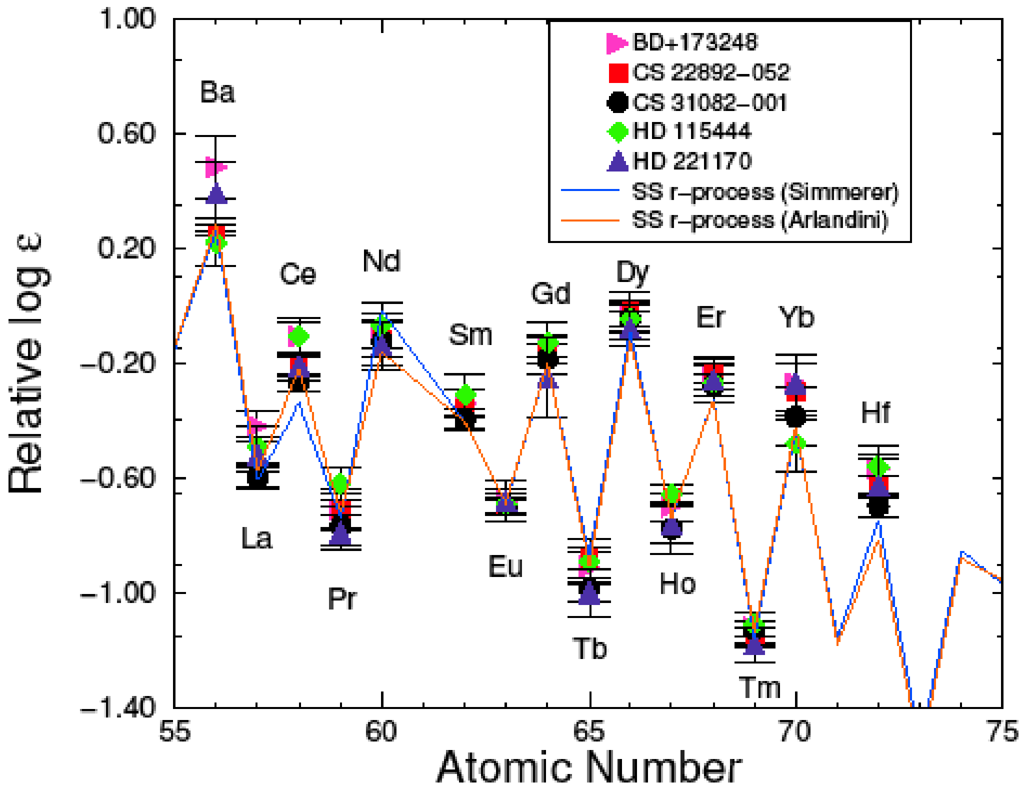
Classic hfs Flag Pattern of UV Ho II line



New Rare Earth Element Abundance Distribution for the Sun and Five *r*-Process-Rich Very Metal-Poor Stars

C. Sneden et al. ApJS 182:80 (2009)

Tightly define *r*-process abundance pattern will constrain future modeling efforts. **(Tens of person-years work underlie this plot.)**

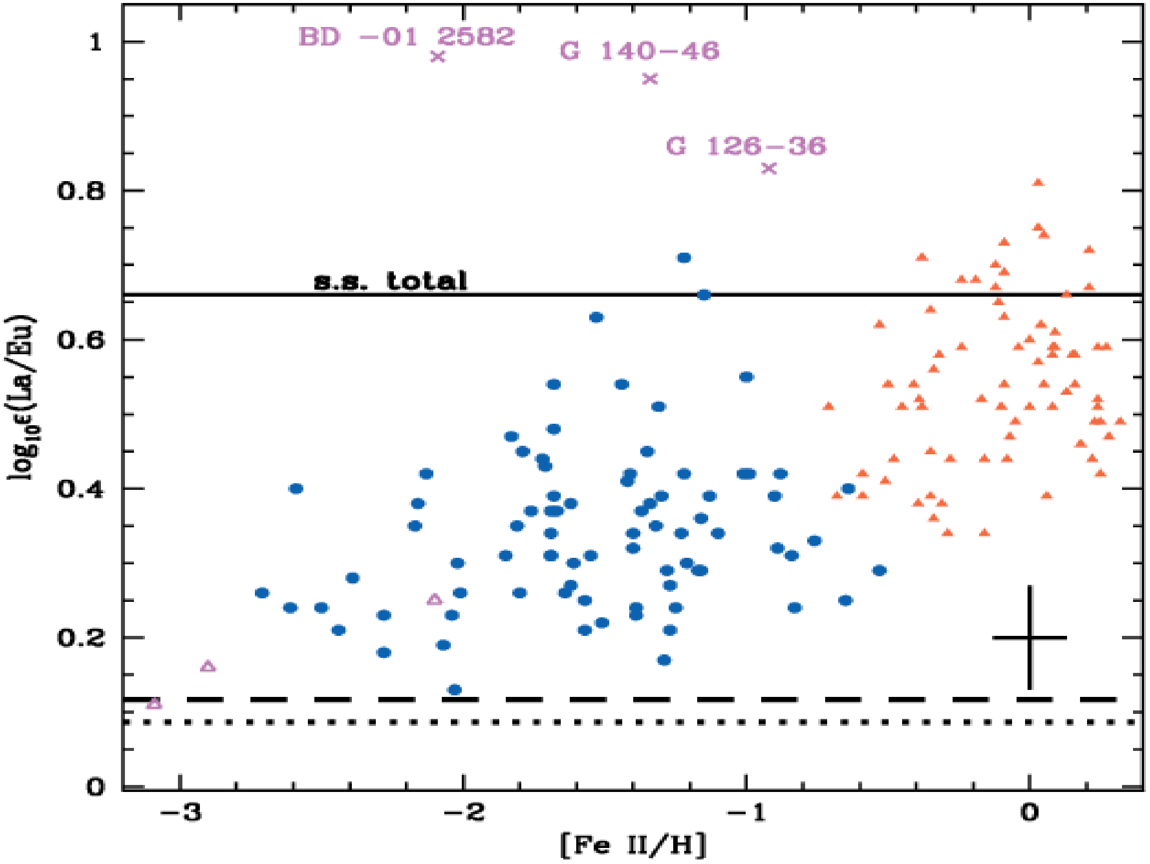


Key Questions?

Is the *r*-process abundance pattern the same for *NS* mergers and core-collapse SNe?

Is the *r*-process abundance pattern simply determined by fission recycling and/or related nuclear physics?

THE RISE OF THE *s*-PROCESS IN THE GALAXY
J. Simmerer et al. ApJ 617:1091 (2004)



Key Questions?

Clearly the *r*-process turned on abruptly when the Galaxy & Universe were young.

Is it possible to explain most or all *r*-process material using *NS* mergers? Possible but better statistics are needed.

How is it possible to make lots of *NS* binaries in tight orbits from the first generation of stars? Is Inhomogenity the explanation?

r-process peaks

- *r*-process peaks are due to neutron shell closures, N= 50, 82, 126, the foundation of the *r*-process distribution
- 1st peak As (Z=33), Se (Z=34),… just heavier than Fe-group, near Kr
- 2nd peak Te (Z=52), I (Z=53),…near Xe
- 3rd peak Os (Z=76), Ir (Z=77), Pt (Z=78) observed using HST by Cowan et al. 1996

UV spectroscopy enables the detection of elements that cannot be detected in optical or NIR stellar spectra.

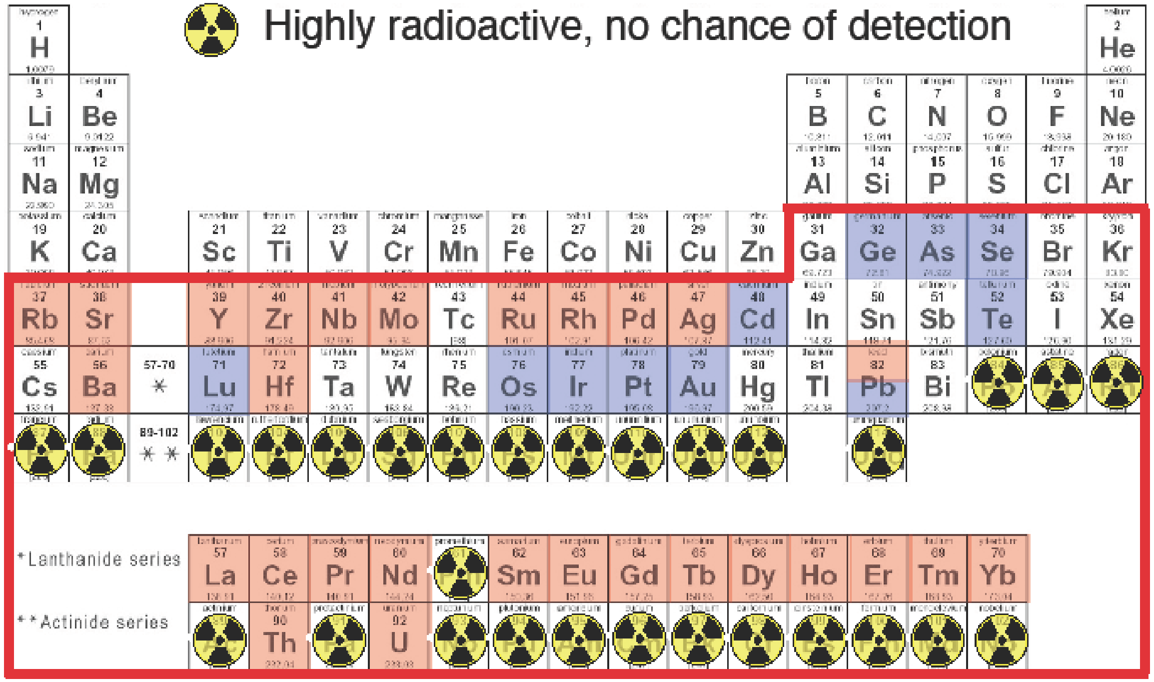
☐ Elements of interest to this kind of study

🟧 Ground-based detections OK

🟦 Only GHRS/STIS detections (1996-present)

☢ Highly radioactive, no chance of detection

40% increase over ground-based alone!

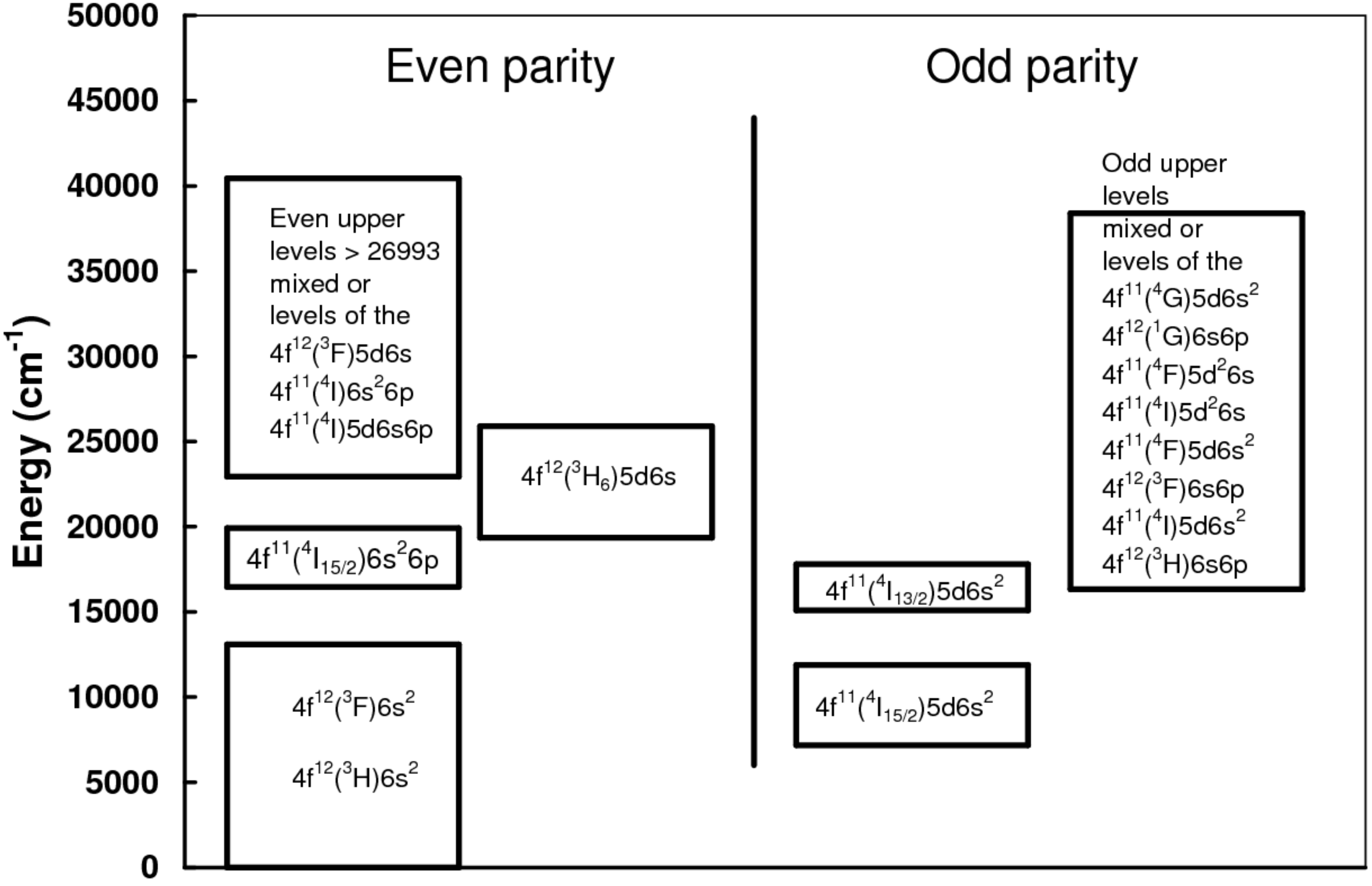


Ian Roederer

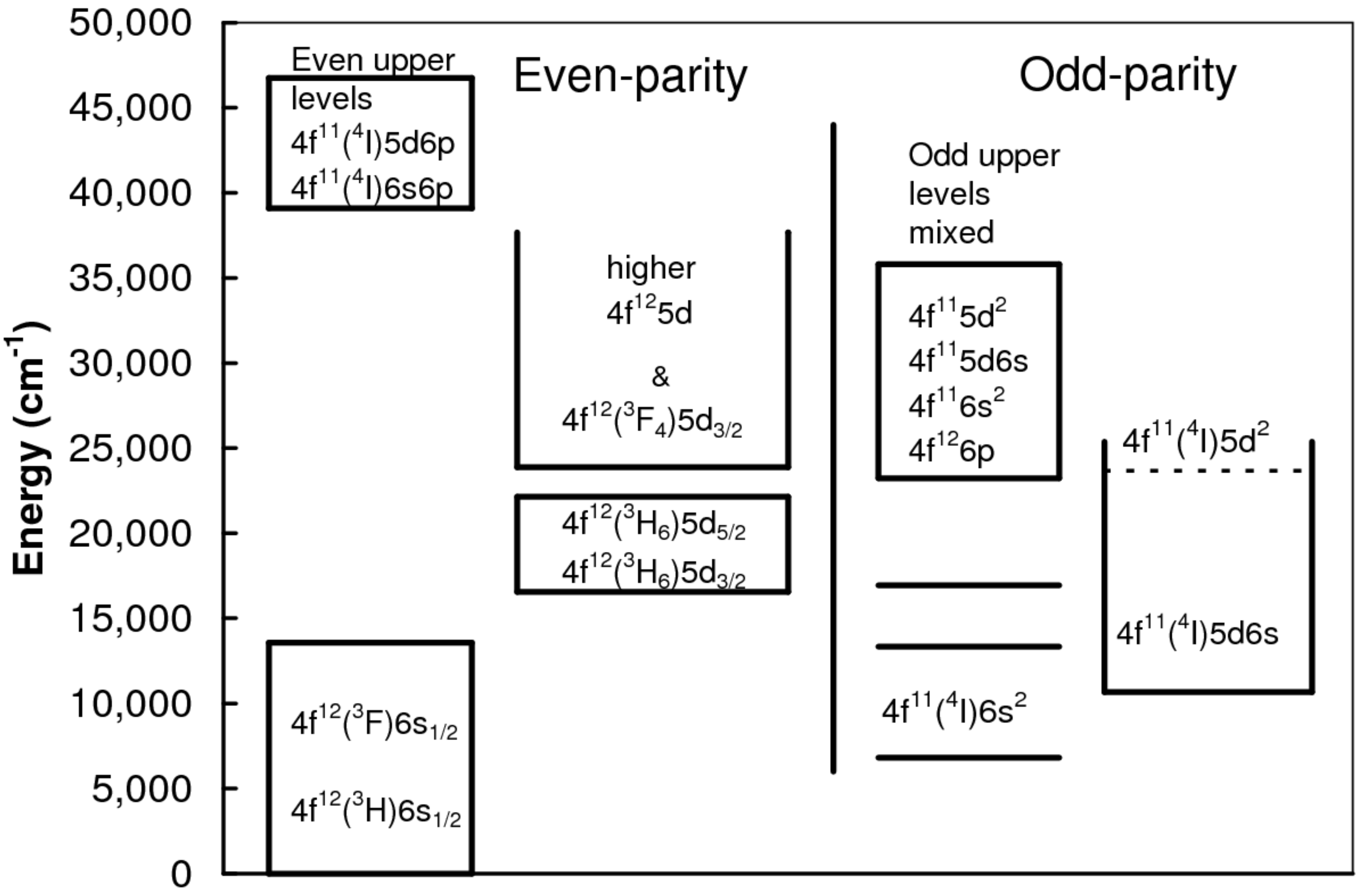
Why are the rare earths of so much interest?

- Some rare earths are primarily *r*-process elements, e.g. Eu, others are primarily *s*-process elements, e.g. La.
- **The ions are accessible to ground based observations!**

Er I is a nice example. The complexity of rare earth spectra is due to the near degeneracy of 4f, 5d, 6s, and 6p orbitals.



Er II is also nice example. The complexity of rare earth spectra is due to the near degeneracy of 4f, 5d, 6s, and 6p oribitals.



Key Question? Partial Answer

- Early UV portion of light curve may provide simpler spectra because 4f electrons are gone with some of the few times ionized Lanthanides.
- NASA Explorer Class Mission with rapid slewing toward the NS merger might be justified if the NS merger rate is high!

Key Question?

- What can be learned from the early, UV portion, of the kilonova decay curve?
- More kilonova will be seen. Every factor of 2 in a-LIGO sensitivity yields a factor of 8 in observed volume!
- A rate determination based on a single event has considerable uncertainty.

Might line spectroscopy of a kilonova be possible?

- Doppler shift is $\acute{\omega} = \omega\ (1 - v^2/c^2)^{1/2}\ /\ (1 + \cos(\theta)\ v/c)$ Geometry is critical, opening angles are critical, speed distribution is important
- Accretion disc or axial jet orientated (face on or edge on) such that $\theta = \pi / 2$ yield only 2nd order shifts
- $v/c = 0.1$ yields $(1 - v^2/c^2)^{1/2} \approx 0.995$
- $v/c = 0.3$ yields $(1 - v^2/c^2)^{1/2} \approx 0.95$

Spectra of multiply ionized n-capture elements need work

- Eu I (592 levels), Eu II (163 levels), Eu III (118 levels), Eu IV (13 levels) Eu V (2 levels, grnd level and I.P.)
- Gd I (634 levels), Gd II (321 levels), Gd III (28 levels), Gd IV (5 levels), Gd V (2 levels, grnd level and I.P.)
- Finding the energy levels is the first step toward more quantitative spectroscopy
- New technologies help this type of classical spectroscopy, laser driven plasmas, tokamaks, ebit machines,….

Europium may be special

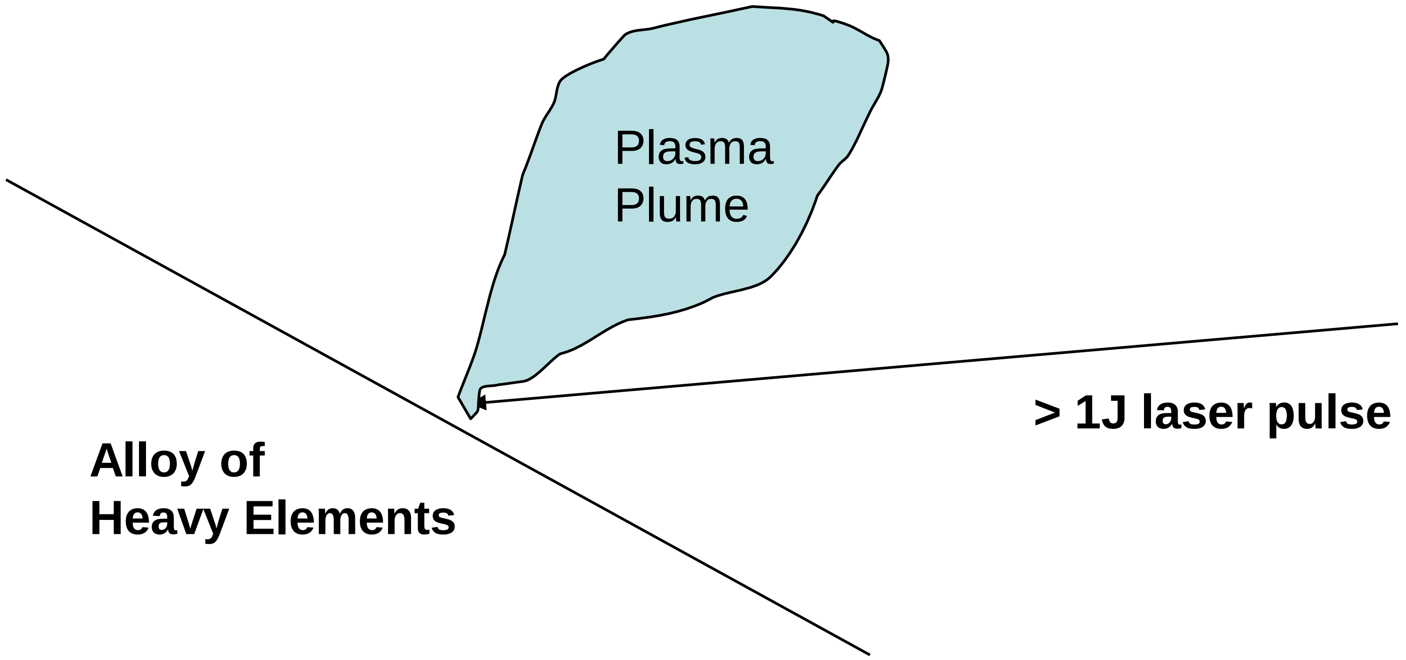
- Eu is a nearly pure (*r*-process) material in Solar System material
- The ground configuration of Eu^+ $4f^7(^8S)$ 6s, this single electron outside of a half closed 4f shell greatly simplifies the Eu II spectrum
- Other rare earths or Lanthanides have low lying interleaved even & odd parity levels
- SDSS APOGEE has Nd II, Ce II in the IR

How many experimental spectra are needed?

- Theory, e.g. Cowan Code, may provide most of the data needed for early UV opacities of ejecta. Opacities average over tens of thousands of lines.
- Some contact with experimental spectra will be needed.
- Will one or two experimental spectra suffice? More?

Needed Lab Astro?

- LIBS plasma jet from solid surface of heavy element alloy might be useful in testing kilonova models.



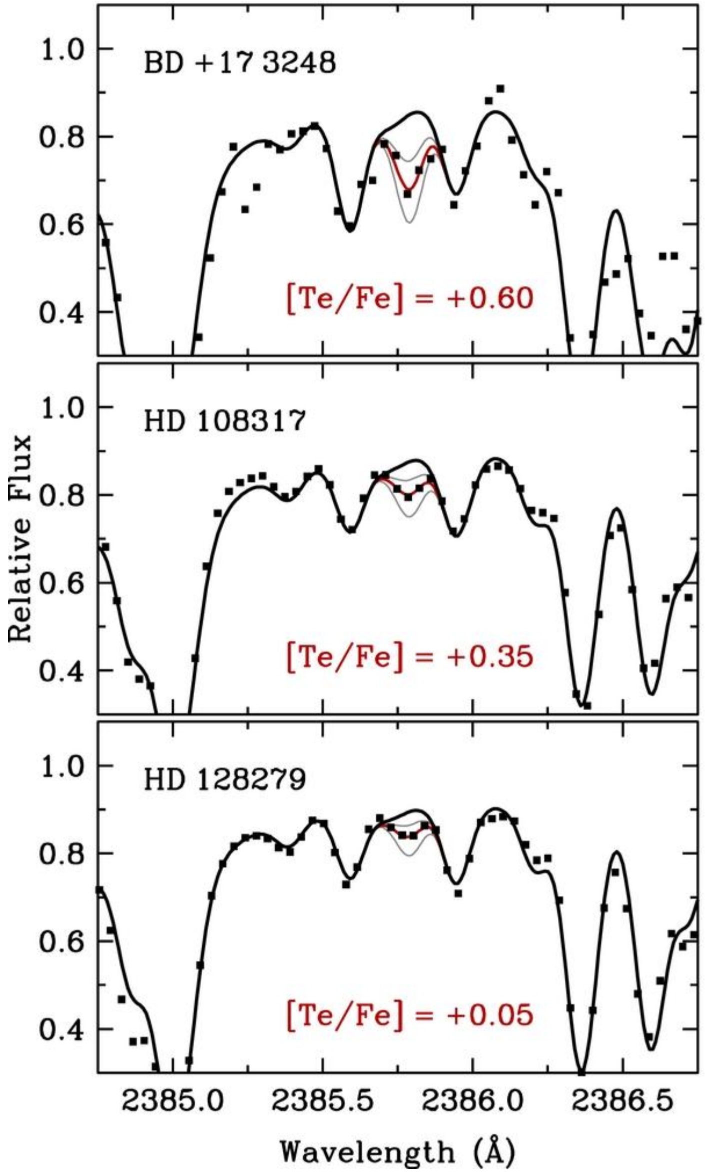
Project for the Future

- Sharp line spectroscopy is not likely.
- Early, e.g. UV portion, of kilonova light curve is interesting
- Energy level structures of multiply ionized heavy elements are needed
- A new type of discharge plasma which is applicable to all heavy elements and provides tight control over ionization stage is the key.

HST observing time is scarce

- Light *r*-process elements including 1st and 2nd peak (e.g. As, Se, Te,…) are not accessible to ground based telescopes,
- HST-GO-14232: *STIS Observations of Metal-Poor Stars: Direct Confrontation with Nucleosynthetic Predictions* has been approved (PI Ian Roederer Univ. of MI)
- UW lab astro is on team, but primary effort has moved to Fe-group elements

DETECTION OF THE SECOND *r*-PROCESS PEAK ELEMENT TELLURIUM IN METAL-POOR STARS

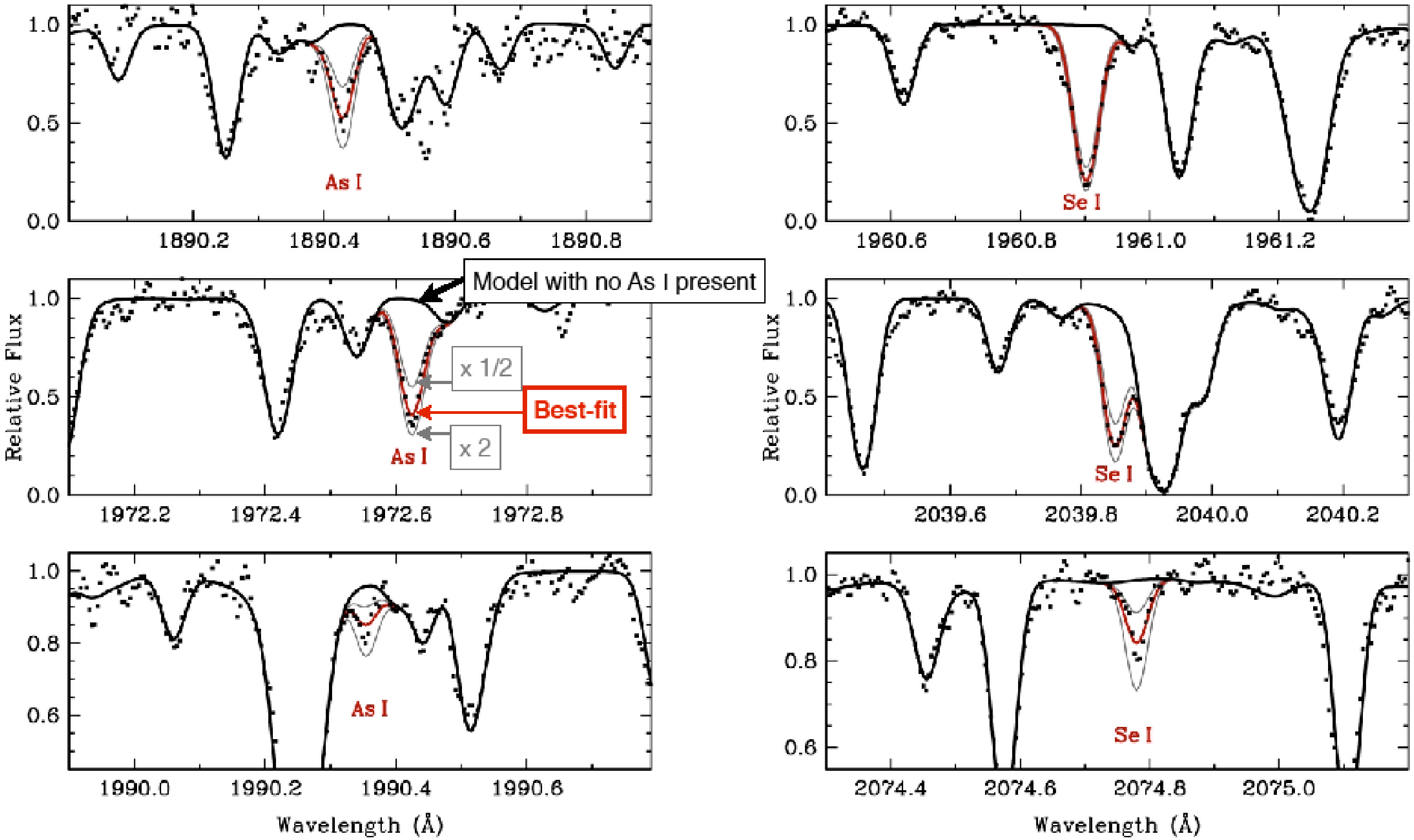


- Single line detection but in multiple stars
- Subsequently confirmed with other Te II lines to ground term

I. U. Roederer *et al.* 2012 *ApJ* **747** L8

DETECTION OF ELEMENTS AT ALL THREE *r*-PROCESS PEAKS IN THE METAL-POOR STAR HD 160617

The spectra show one metal-poor star, HD 160617, observed at R ~ 110,000 and S/N ~ 20-40 in 13 hours with HST+STIS.



Model with no As I present

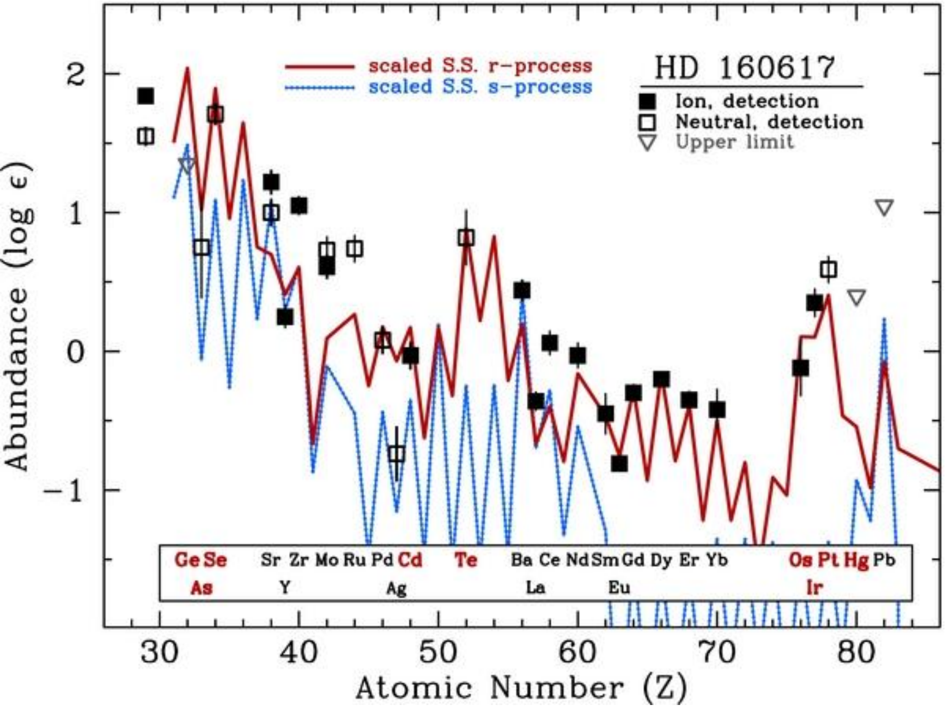
x 1/2

Best-fit

x 2

Roederer, I.U. & Lawler, J.E., Astrophys. J., **750**, 76, (2012)

DETECTION OF ELEMENTS AT ALL THREE *r*-PROCESS PEAKS IN THE METAL-POOR STAR HD 160617



Elements at all three r-process peaks are "right on" the S.S. r-process abundance curve scaled to this MP star!

I. U. Roederer and JEL 2012 ApJ 750 76