Discovery of a Thorne-Żytkow Object Candidate in the SMC

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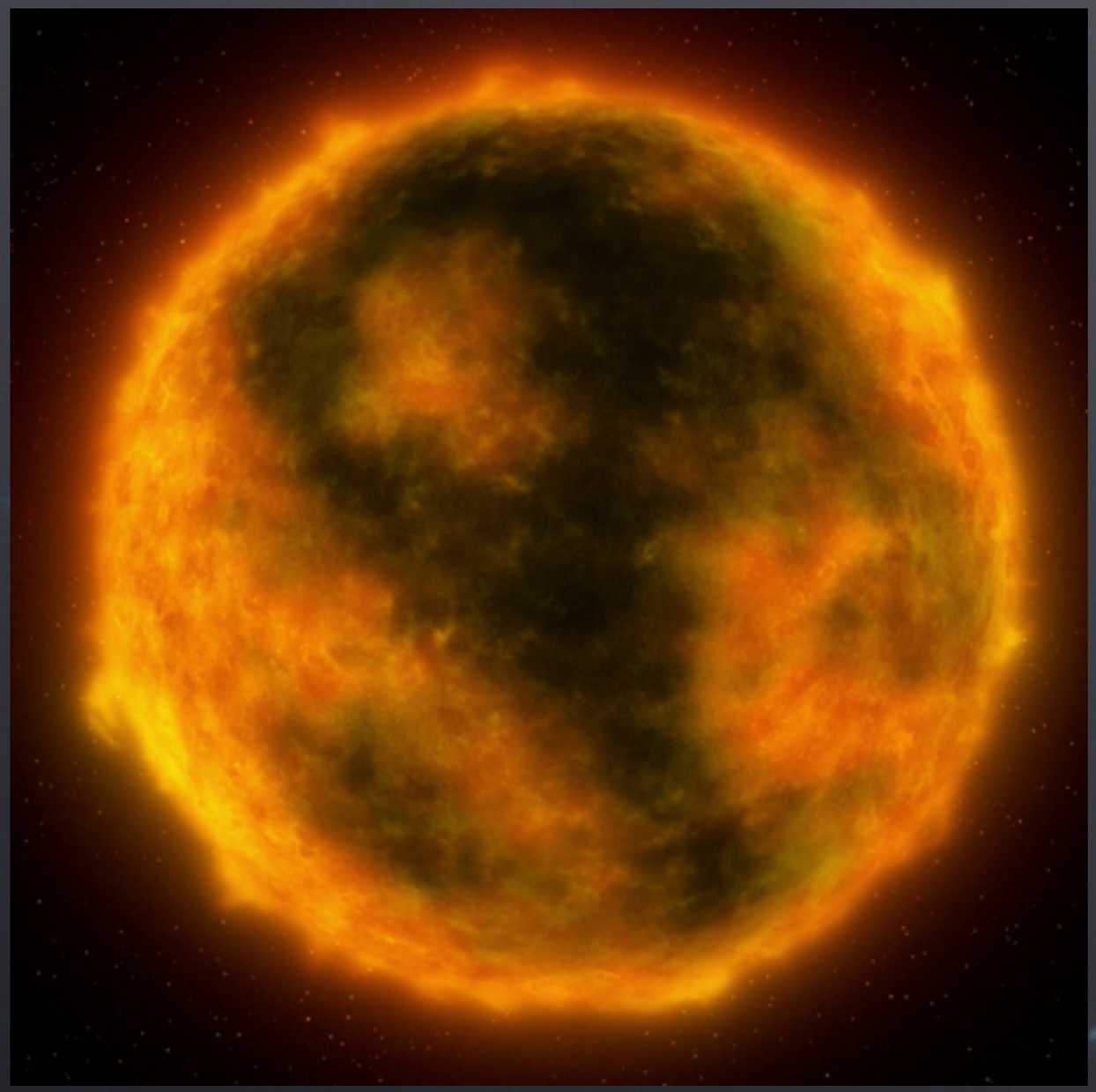
Virtual Institute of
Astroparticle physics

Aug 22, 2014

Thorne-Żytkow Objects (TŻOs) are a theoretical class of star: a neutron star "core" surrounded by a large diffuse envelope



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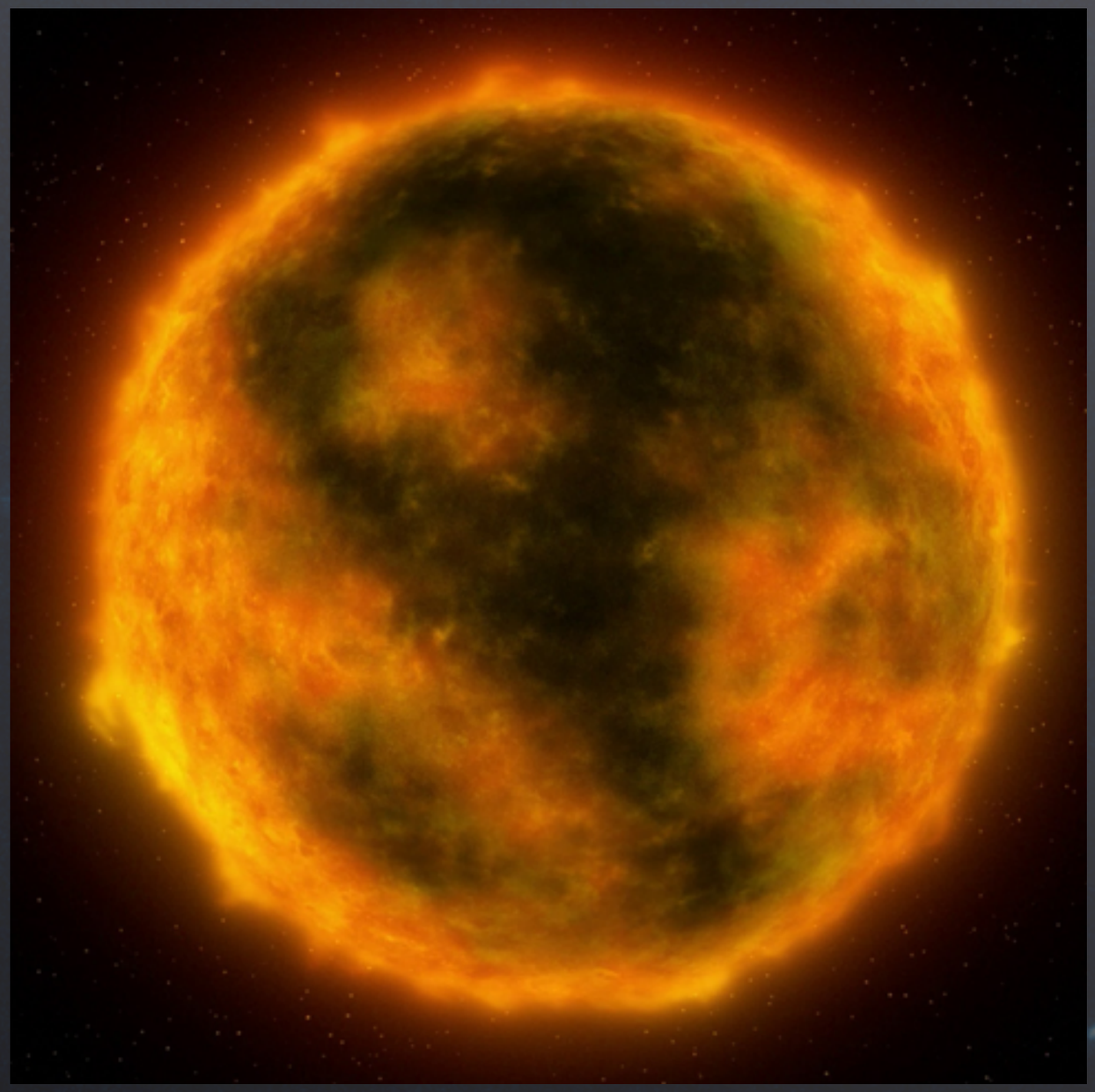
- Thorne & Żytkow (1977) predict supergiant TZOs ($M_c = 1.0M_\odot$, $M_t \geq 11.5M_\odot$)
- Powered by a combination of thermonuclear reactions and gravitational accretion
- Represent a completely new model for stable stellar interiors.



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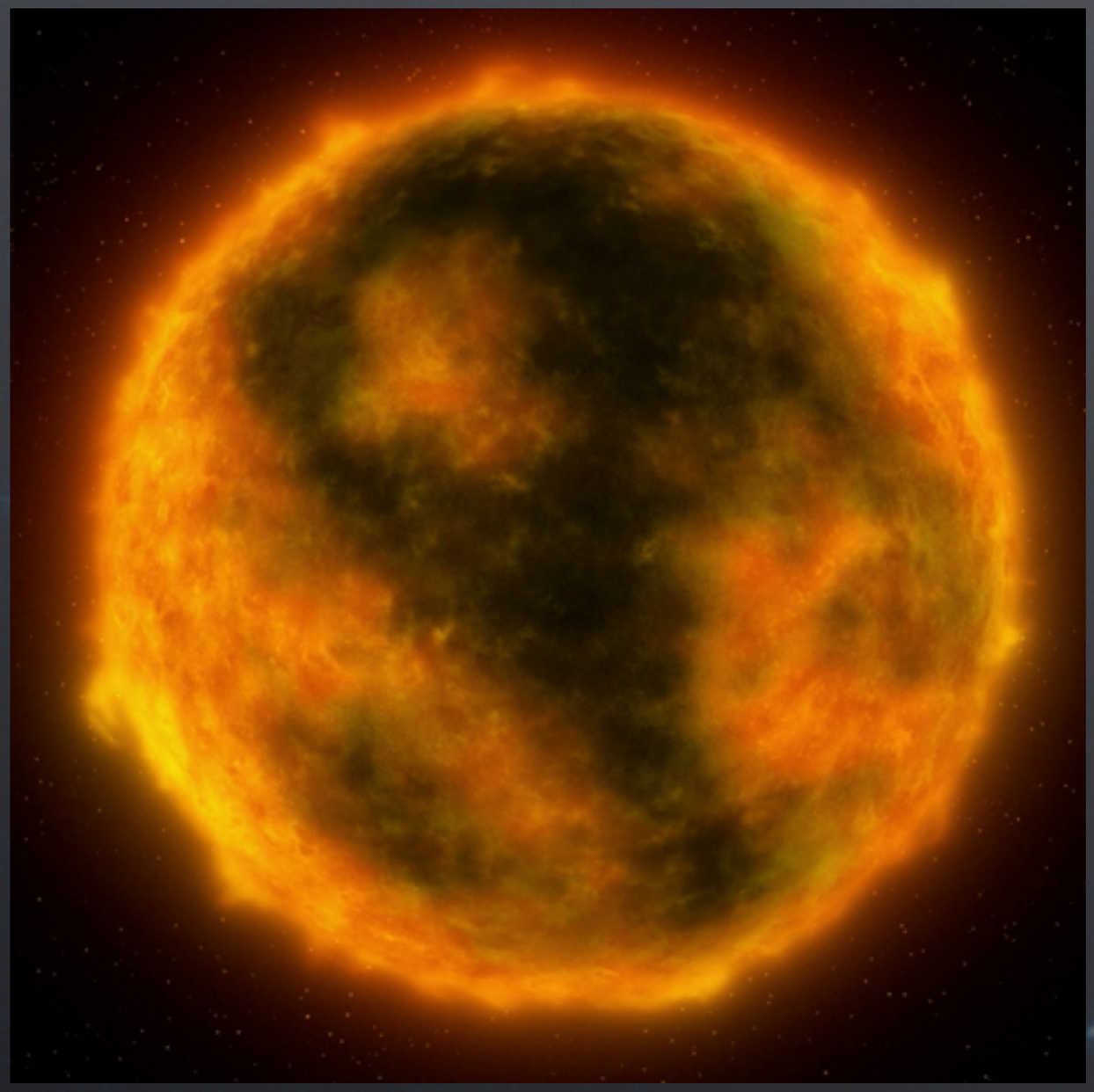
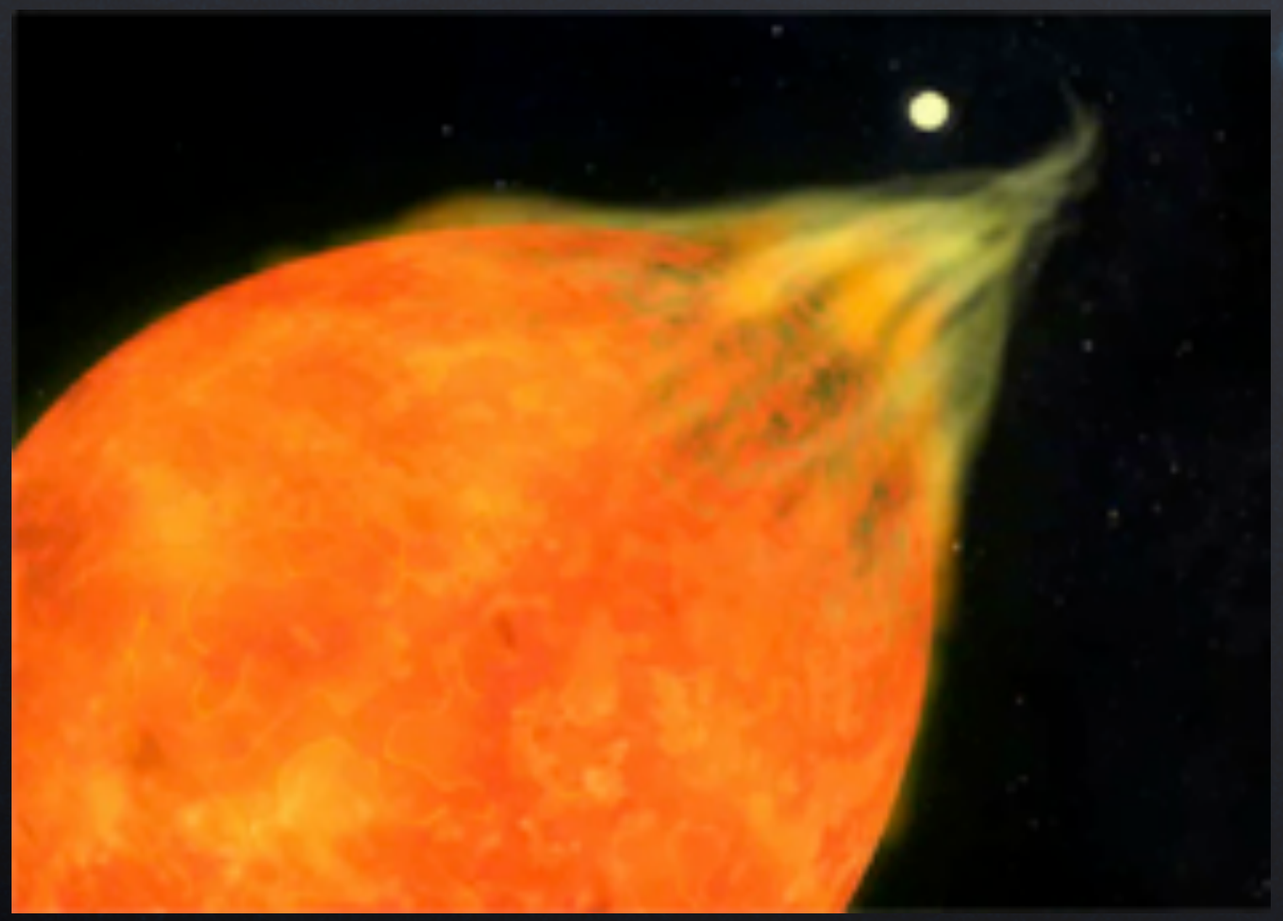


There has never been a confirmed observation of a TŻO.

Formation of TŻOs

1. Engulfing - an OB + NS HMXB; the OB companion leaves the main sequence, evolves into an RSG, expands, and engulfs the NS companion (Taam et al. 1978)



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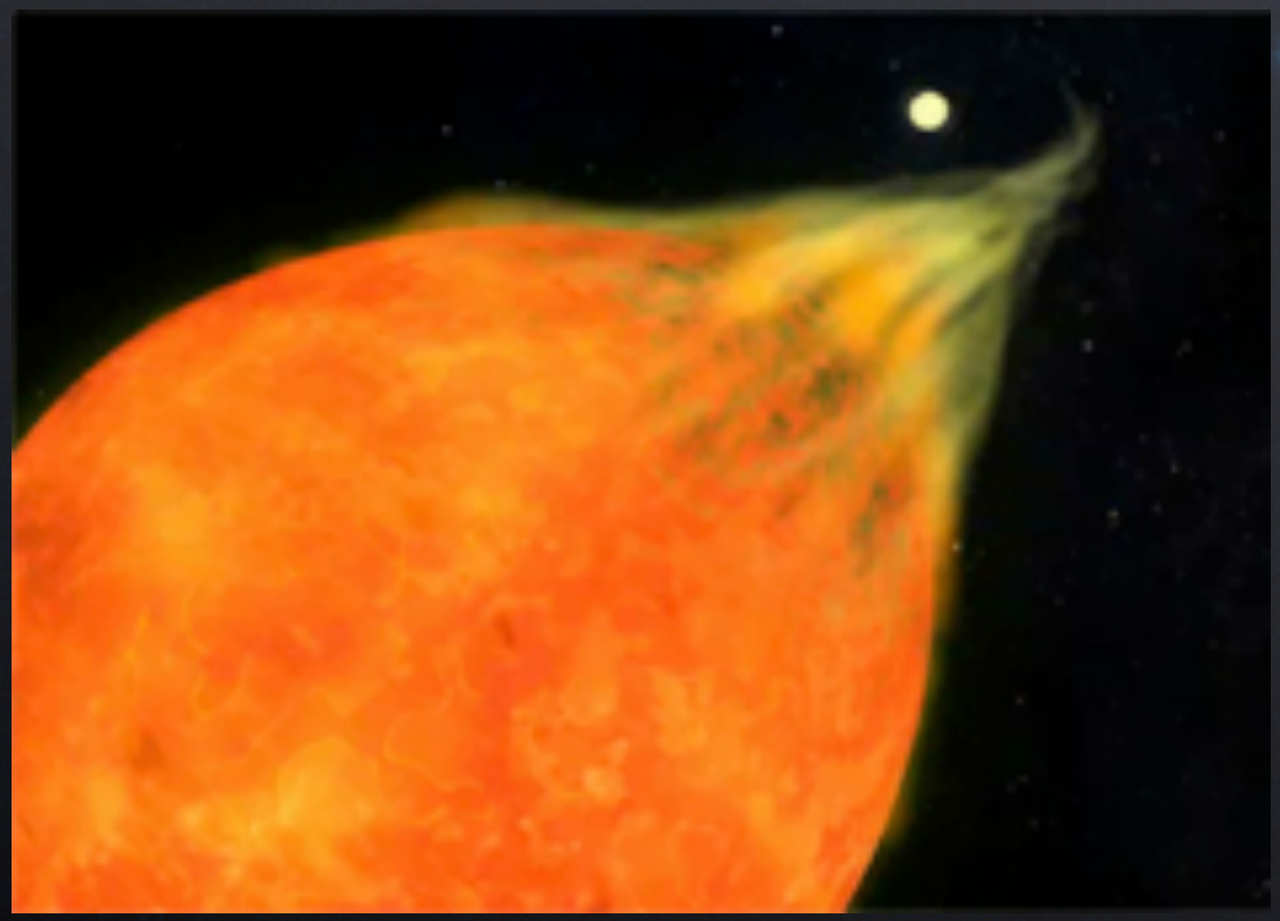
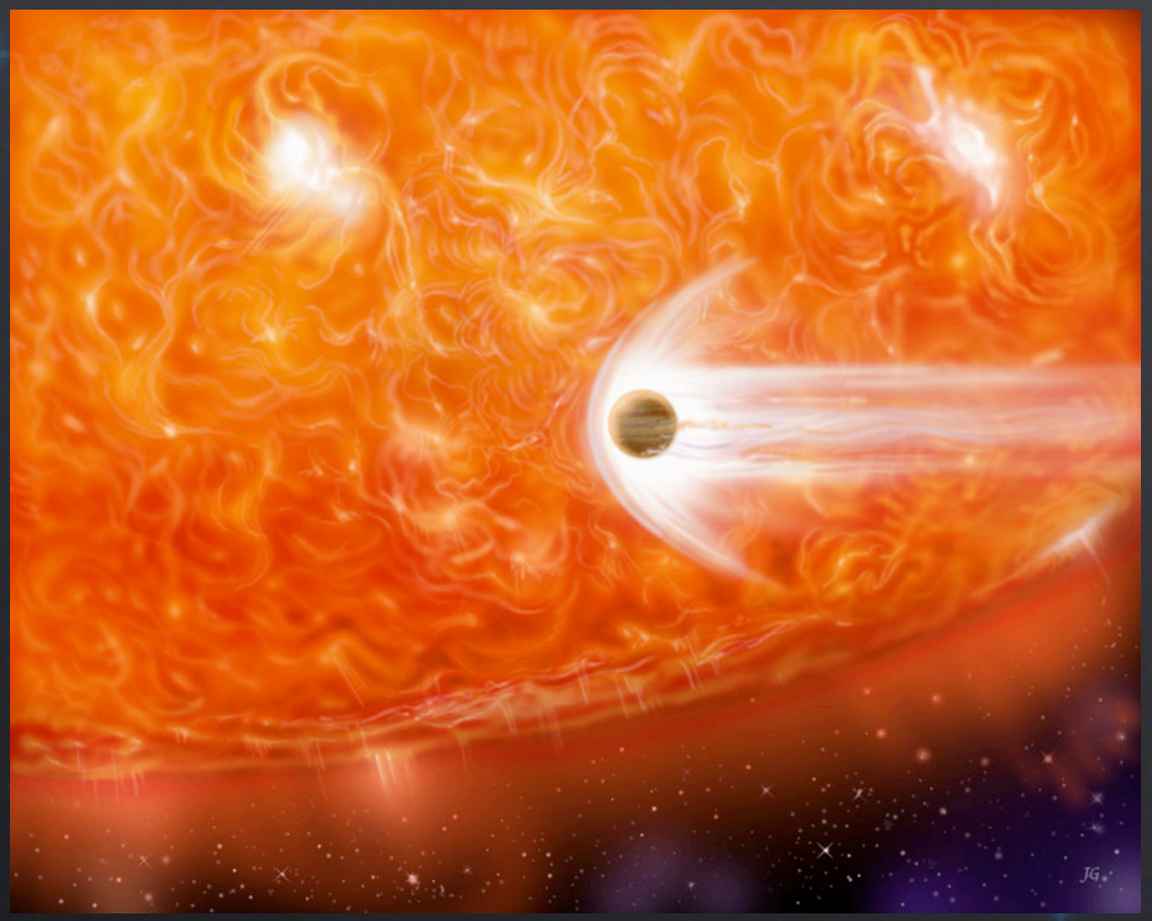
2. Collision - a massive binary system; one member collapses into a NS, and supernova kick velocity propels it into the massive companion (Leonard et al. 1994)





TŻOs are...

- cool and luminous, lying at or beyond the Hayashi limit for massive stars (Thorne & Żtykow 1977)
- strongly mass-losing as a result (van Paradijs et al. 1995)
- potentially more common at low Z (Linden et al. 2010)

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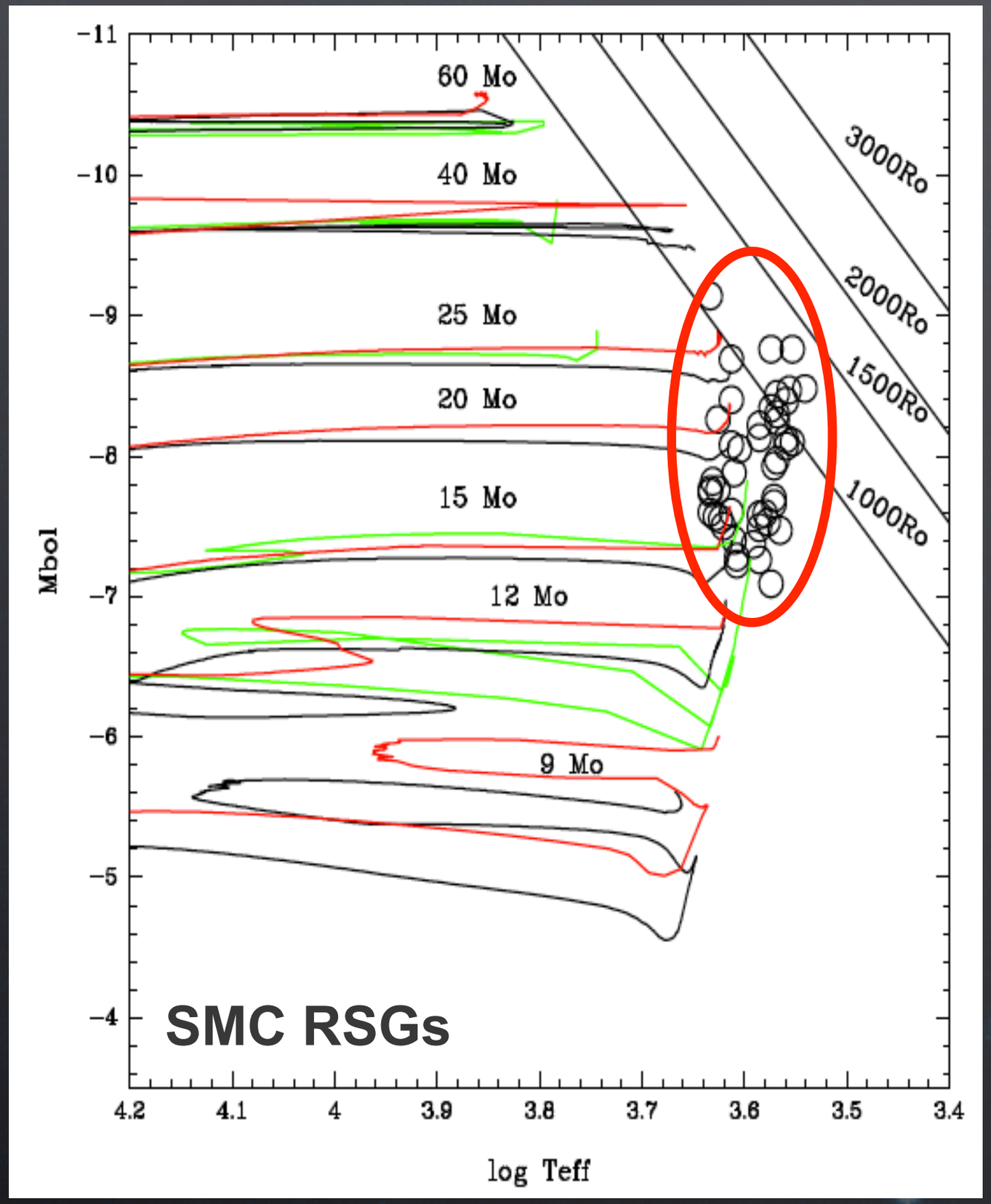

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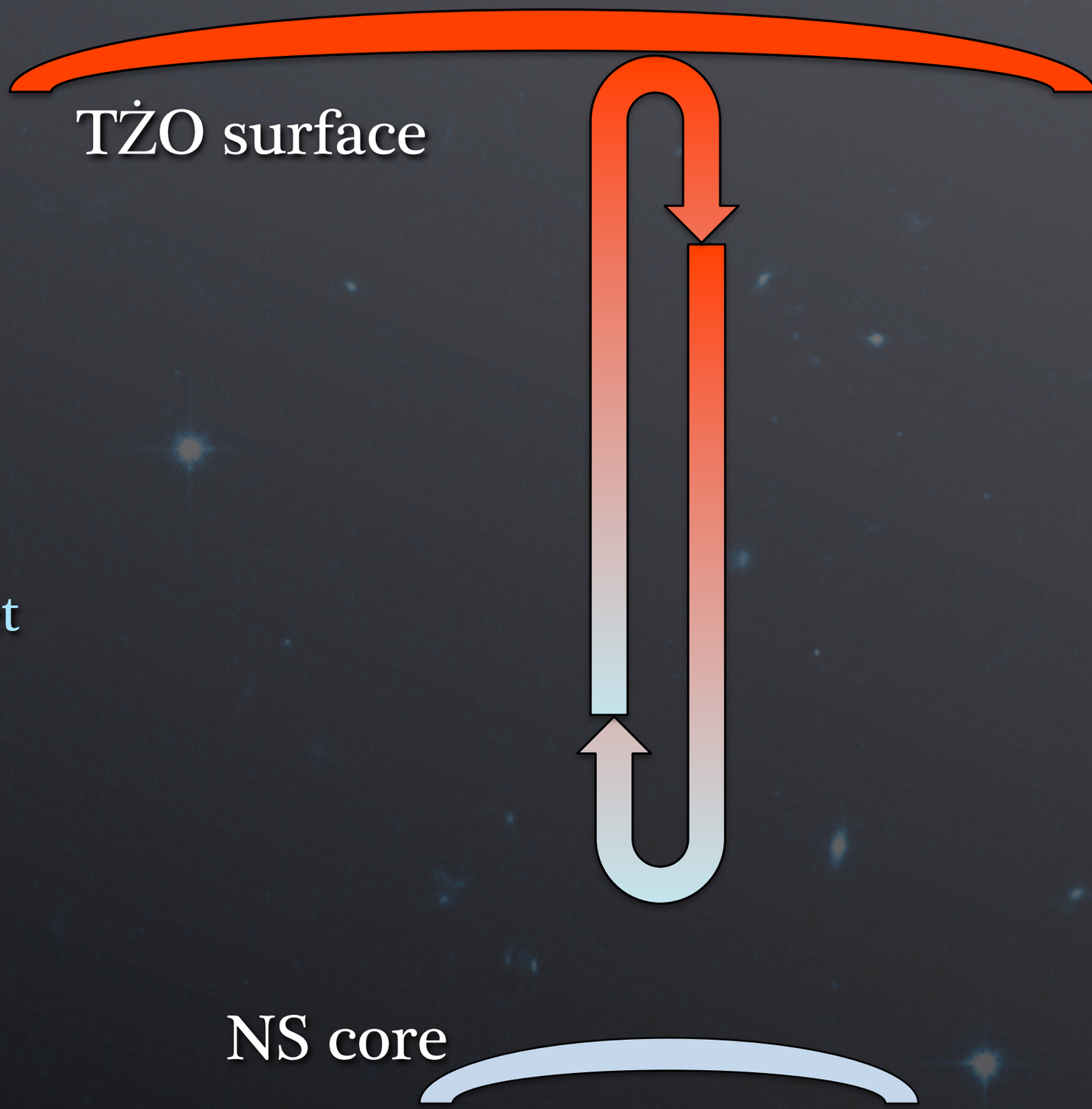

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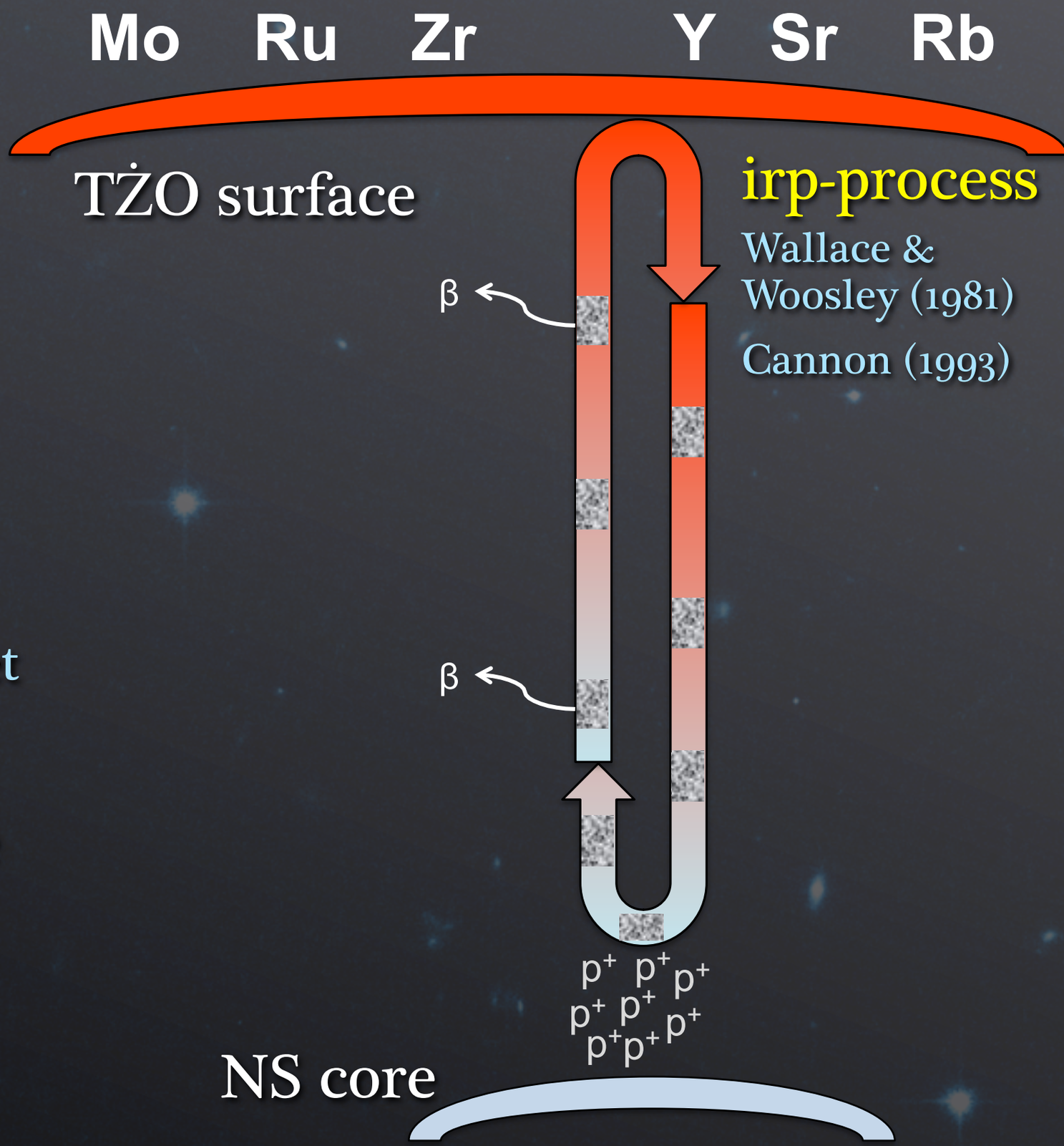

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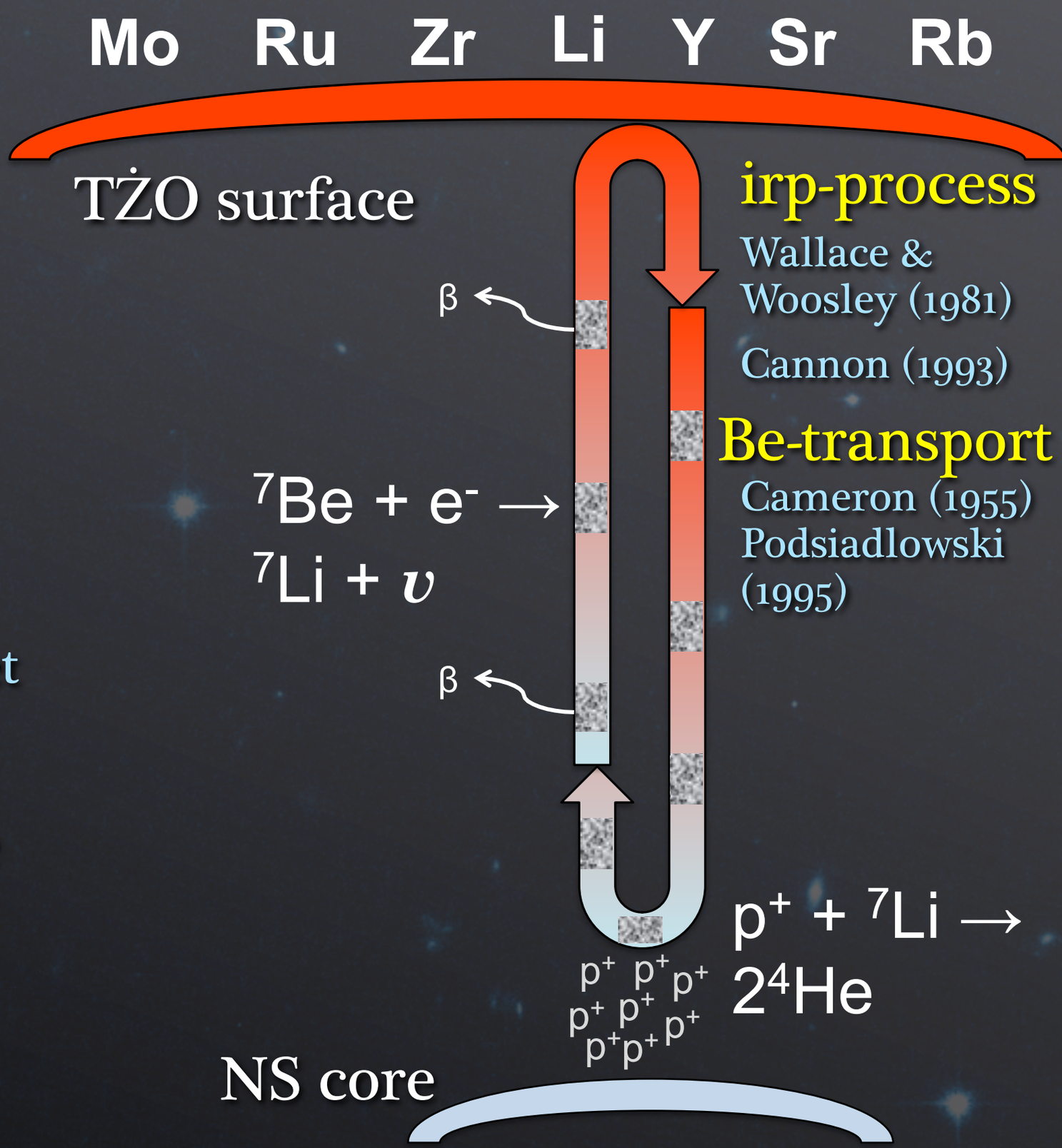

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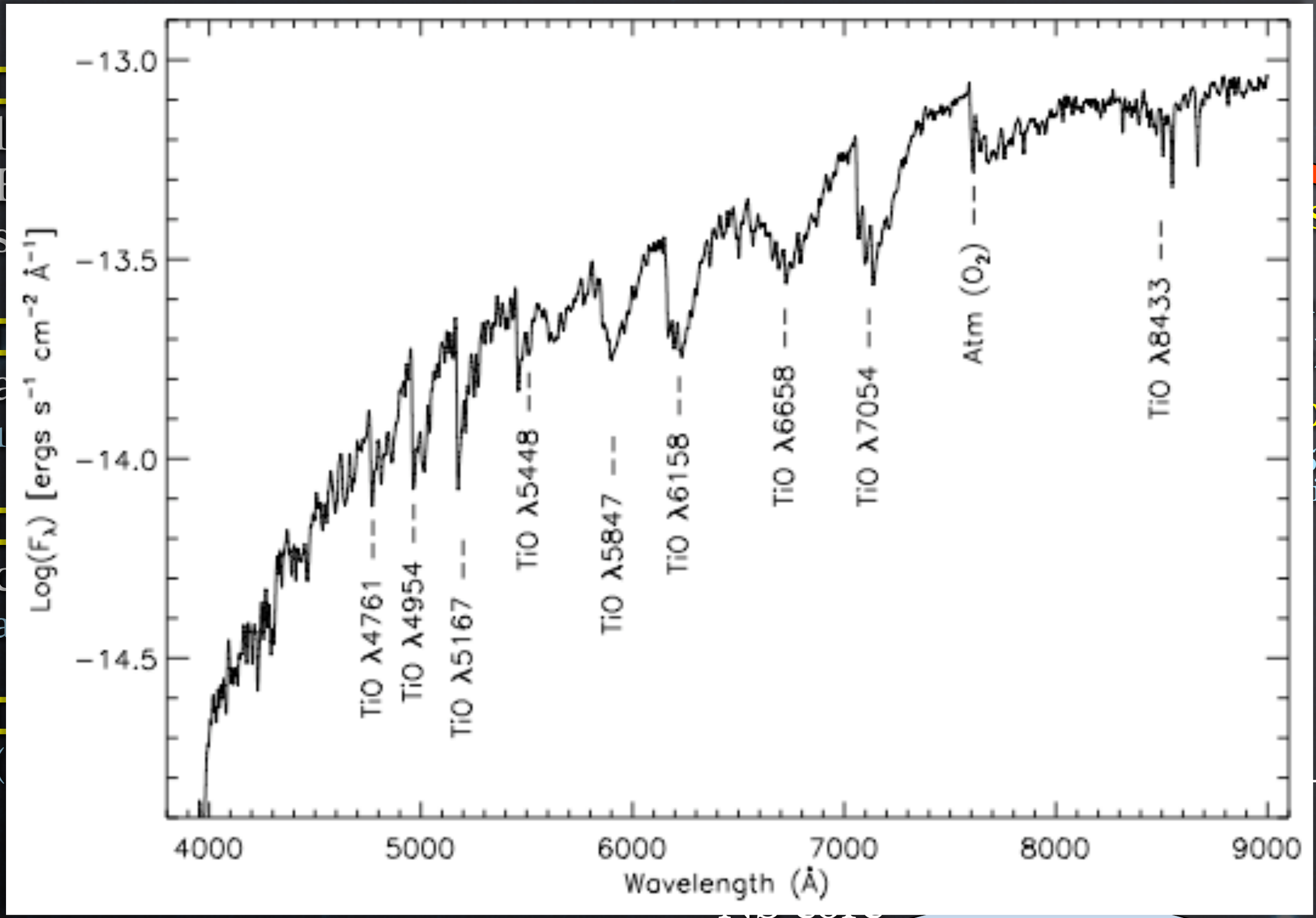

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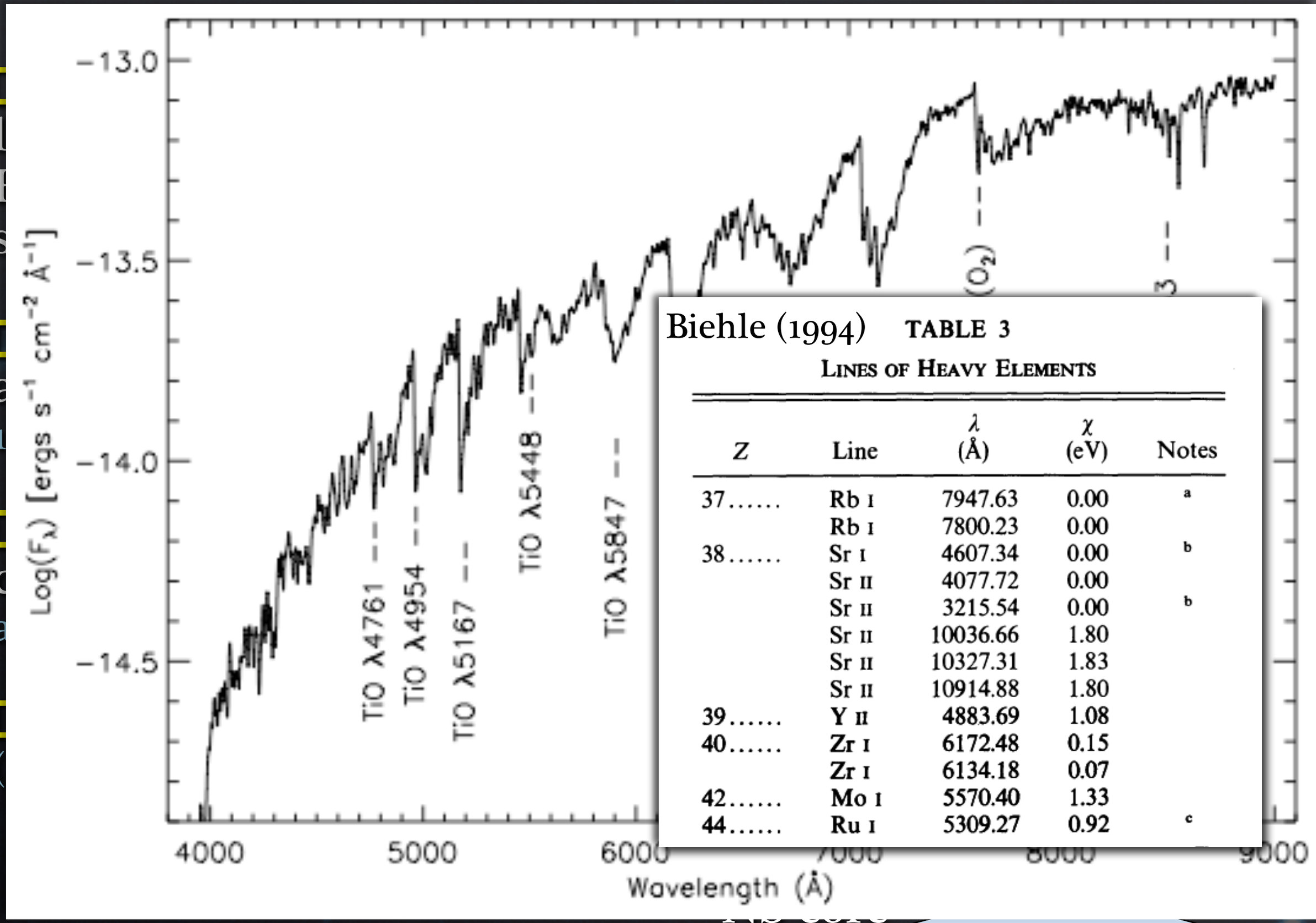
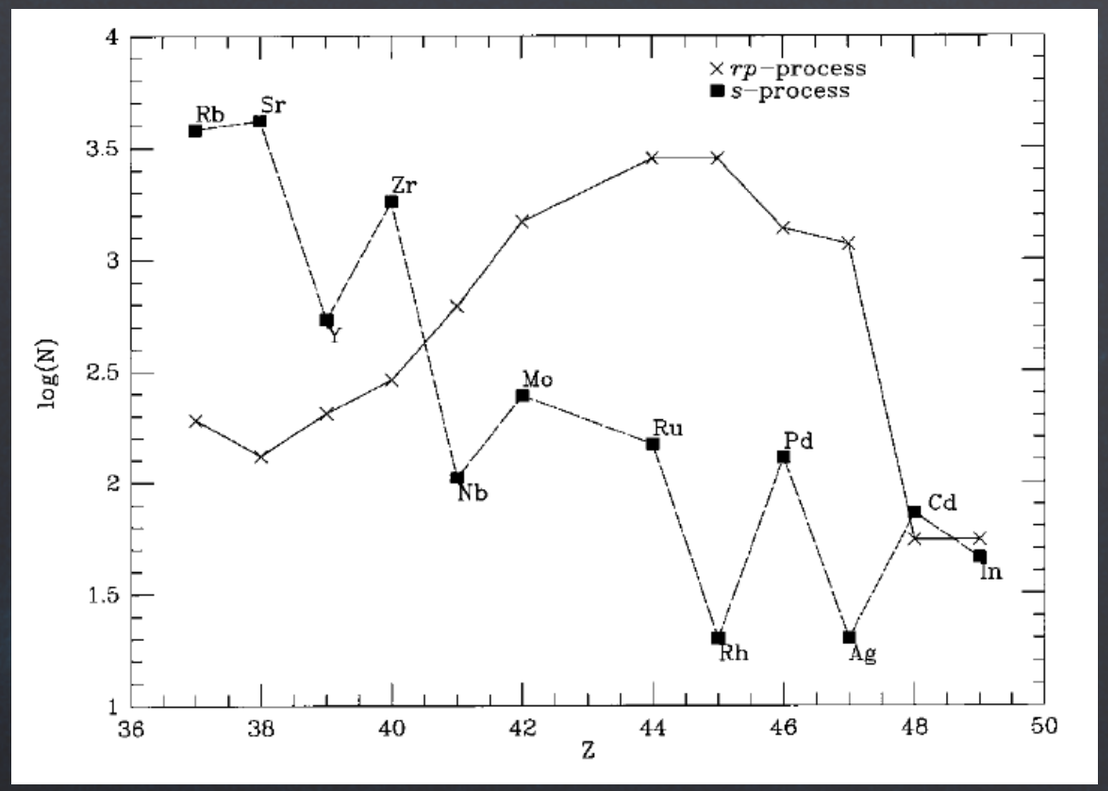


Biehle (1994) **TABLE 3**

LINES OF HEAVY ELEMENTS

Z	Line	λ (Å)	χ (eV)	Notes
37.....	Rb I	7947.63	0.00	a
	Rb I	7800.23	0.00	
38.....	Sr I	4607.34	0.00	b
	Sr II	4077.72	0.00	
	Sr II	3215.54	0.00	b
	Sr II	10036.66	1.80	
	Sr II	10327.31	1.83	
	Sr II	10914.88	1.80	
39.....	Y II	4883.69	1.08	
40.....	Zr I	6172.48	0.15	
	Zr I	6134.18	0.07	
42.....	Mo I	5570.40	1.33	
44.....	Ru I	5309.27	0.92	c

Past searches for TŻOs



Vanture et al. (1999)

- examined R Coronae Borealis star U Aqr with odd abundances
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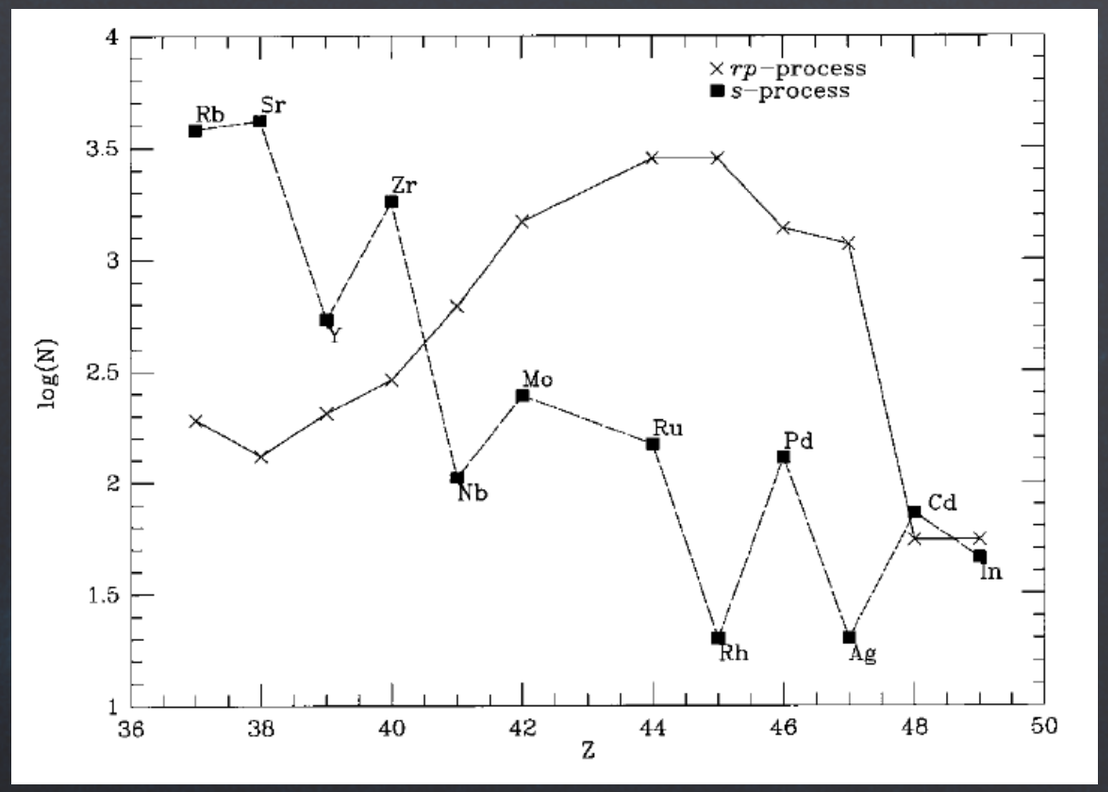

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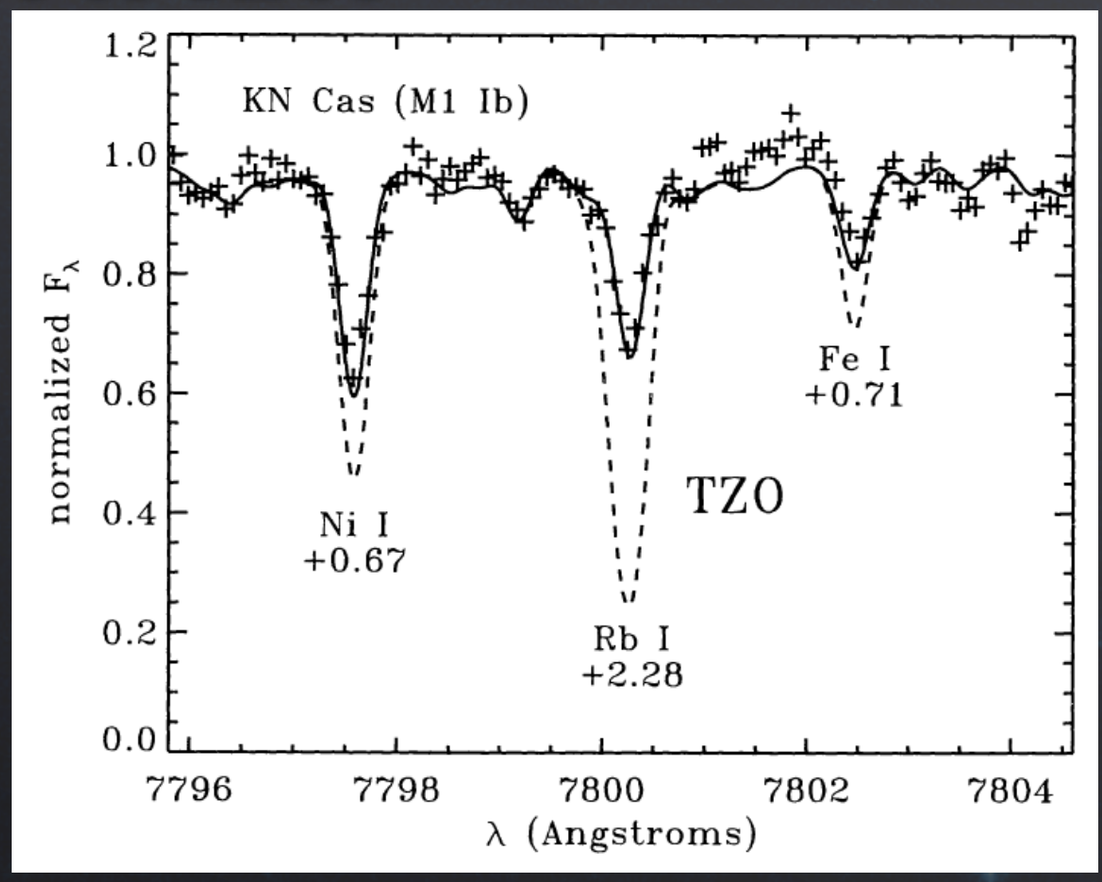
Kuchner et al. (2002)

- surveyed 59 Galactic RSGs
- compared observed Rb I abundances to models of synthetic spectra
- detect one RSG with enhanced Rb I, but can be explained by s-process



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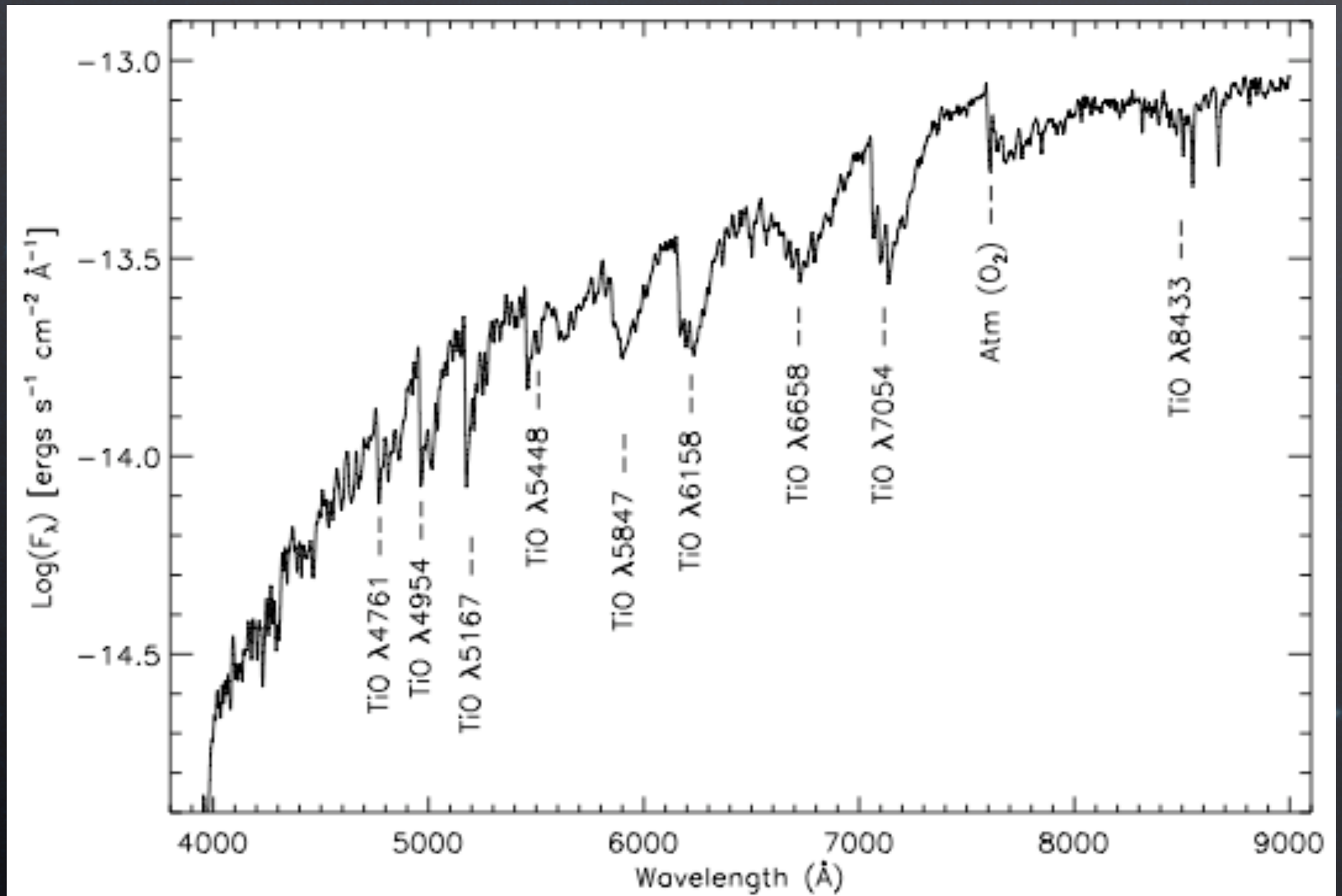

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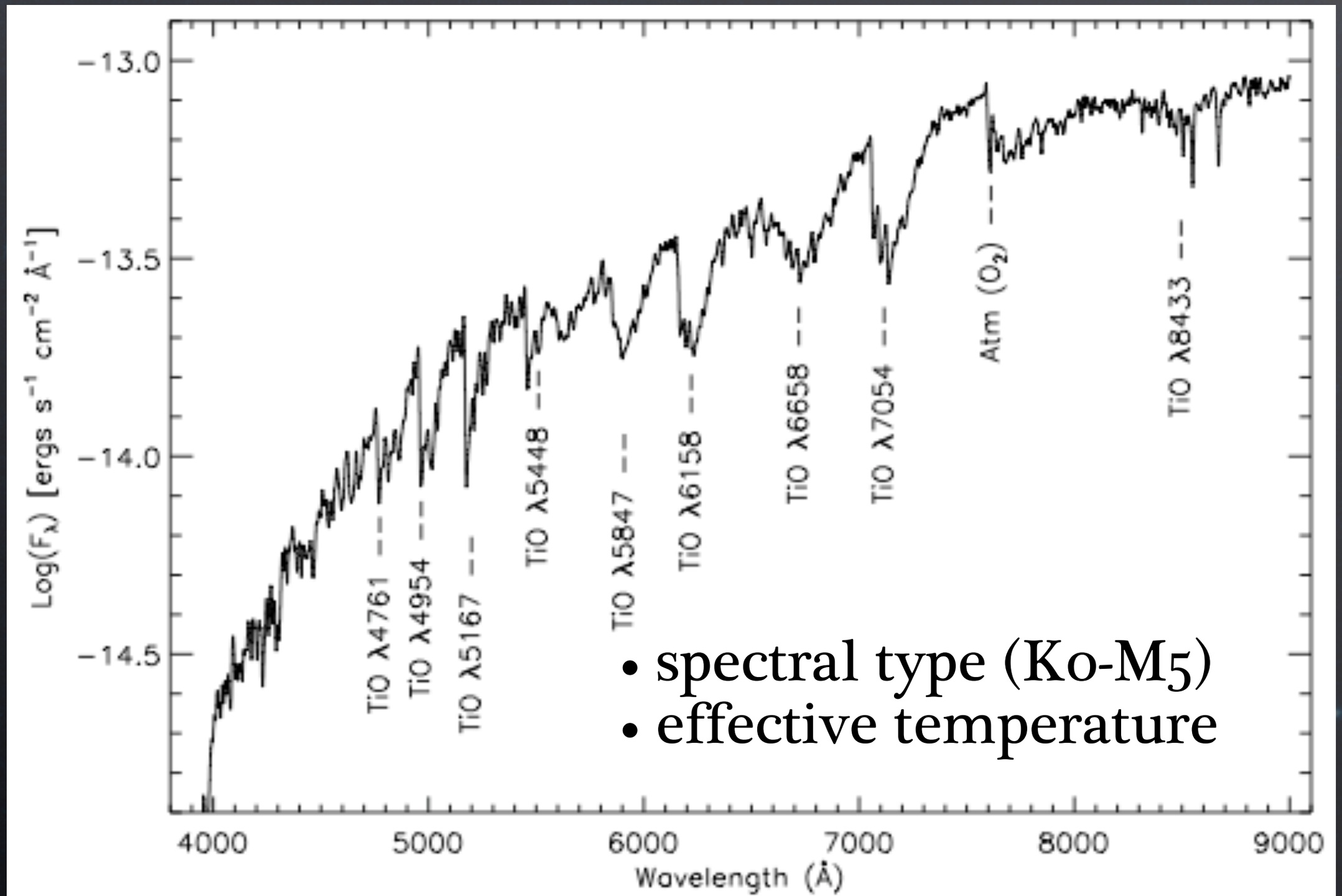
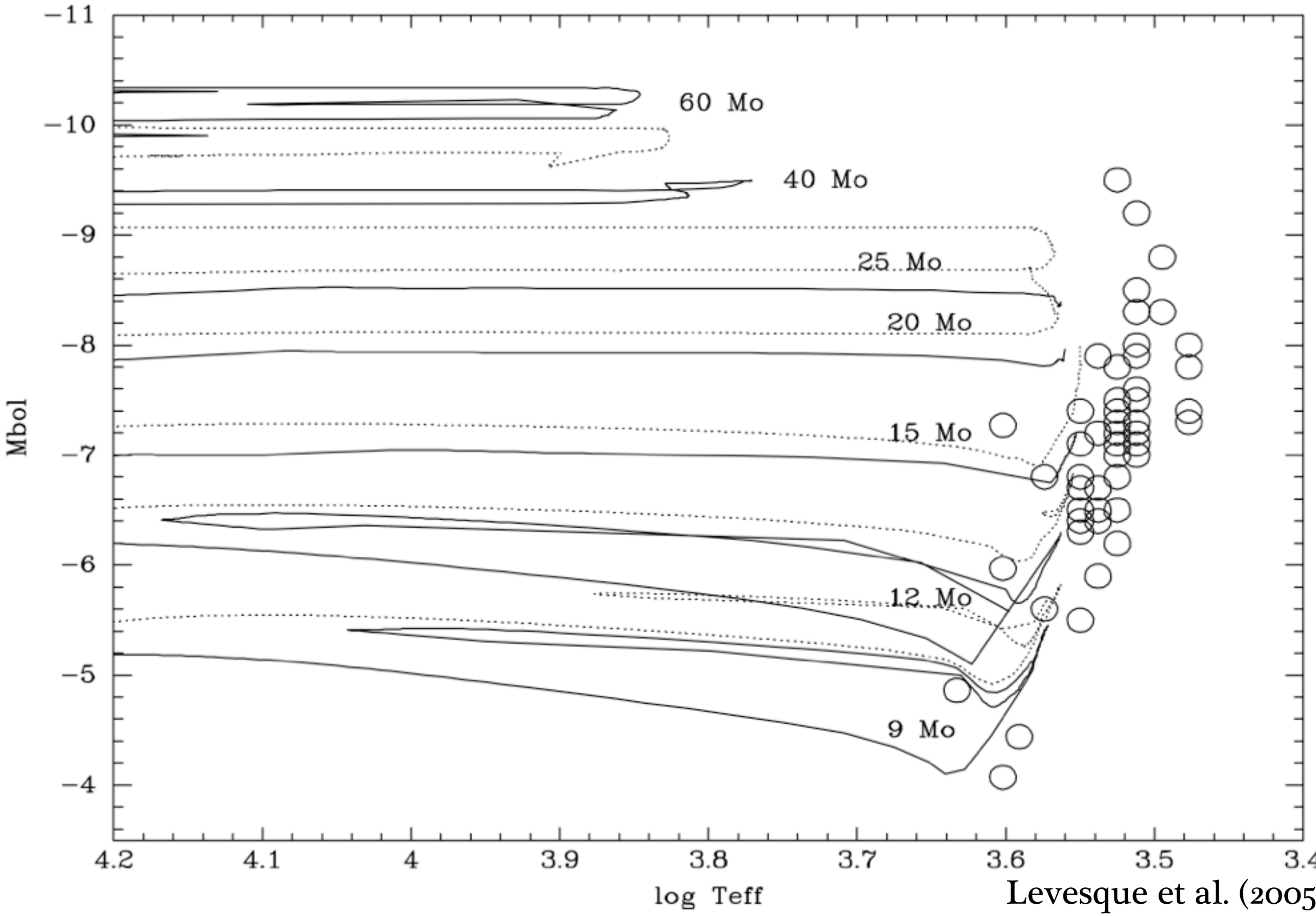


- spectral type (K0-M5)
- effective temperature

...and observations did not agree with theory...



Levesque et al. (2005)

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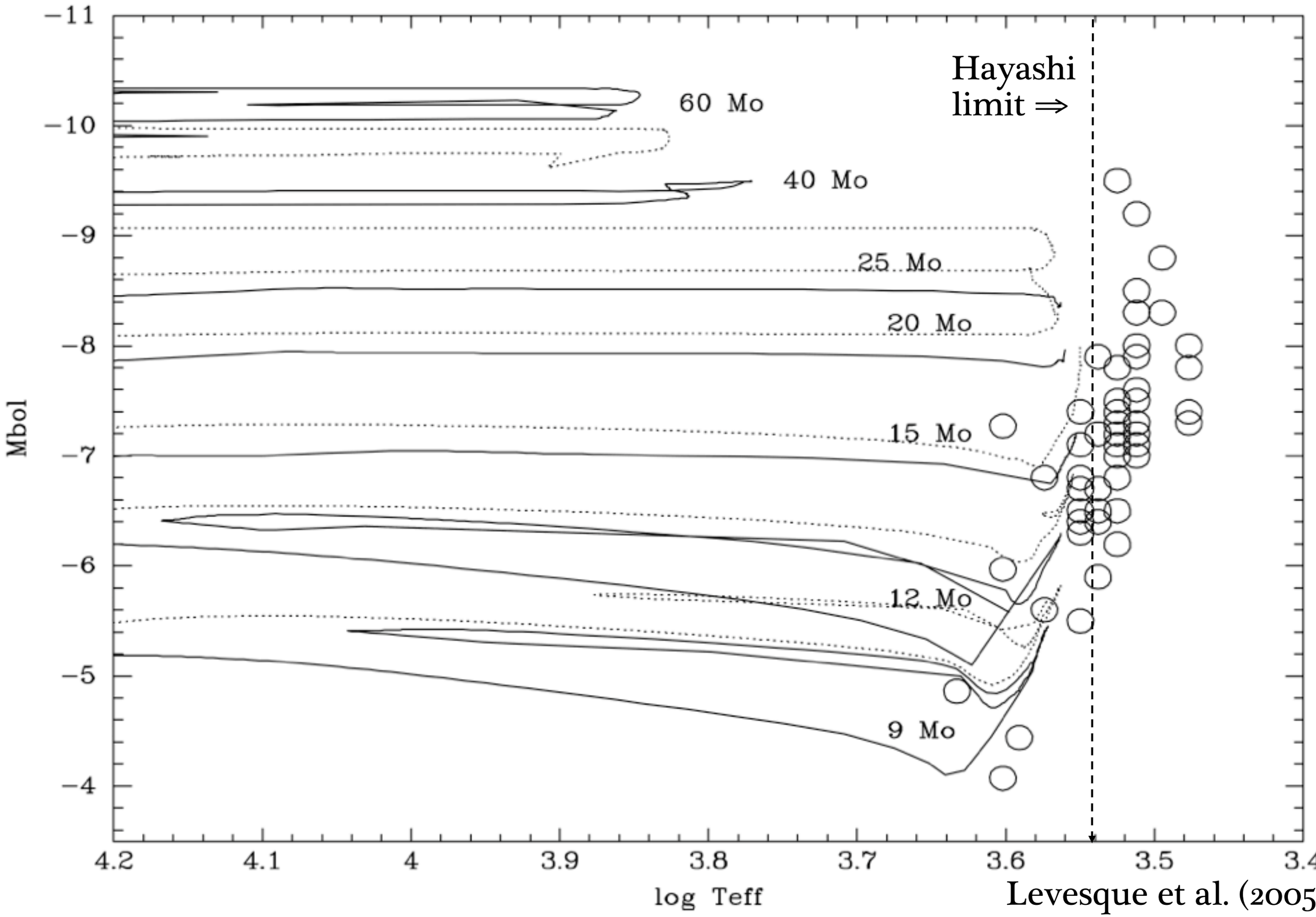

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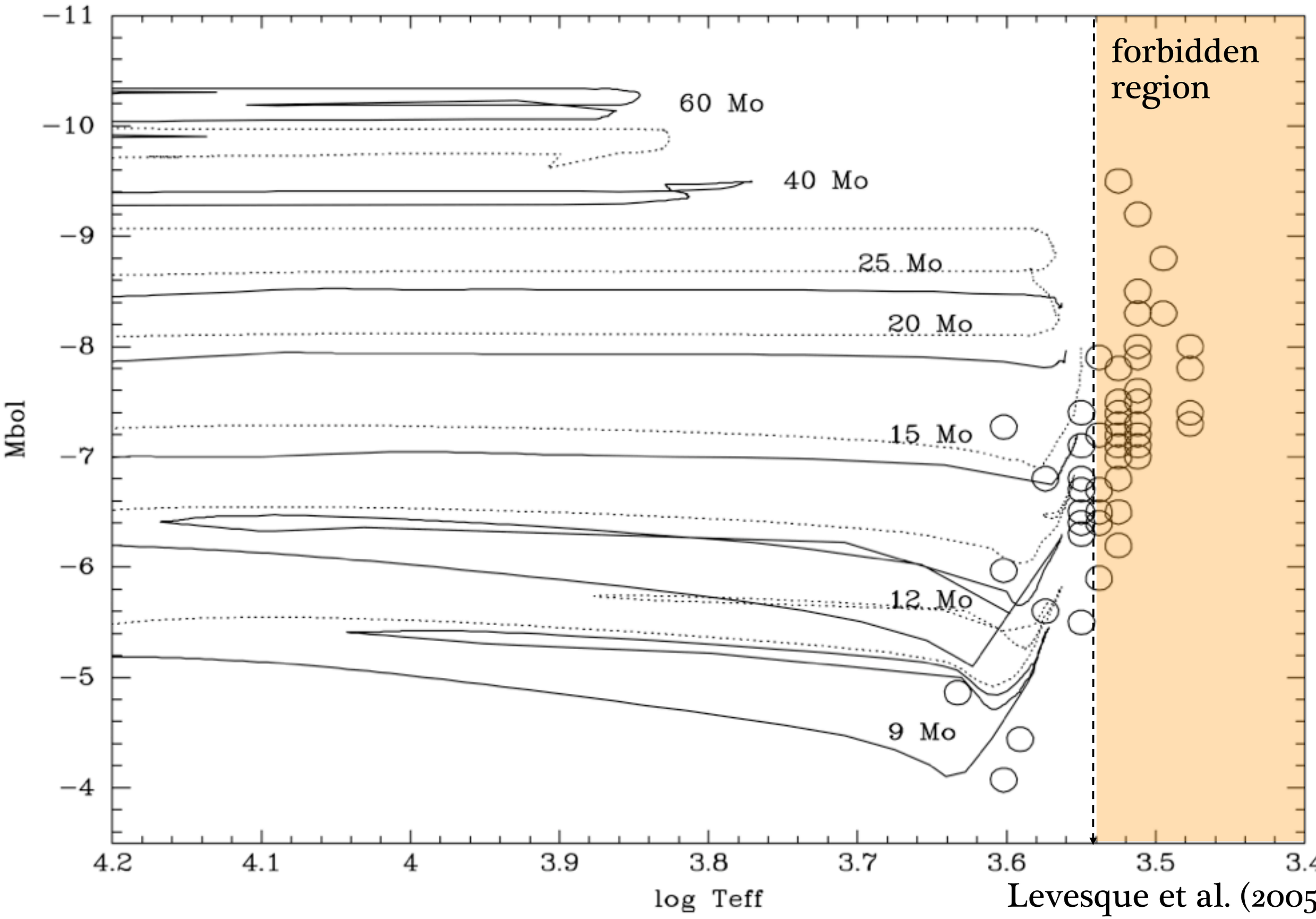

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- high-velocity convective layers
- highly extended atmosphere
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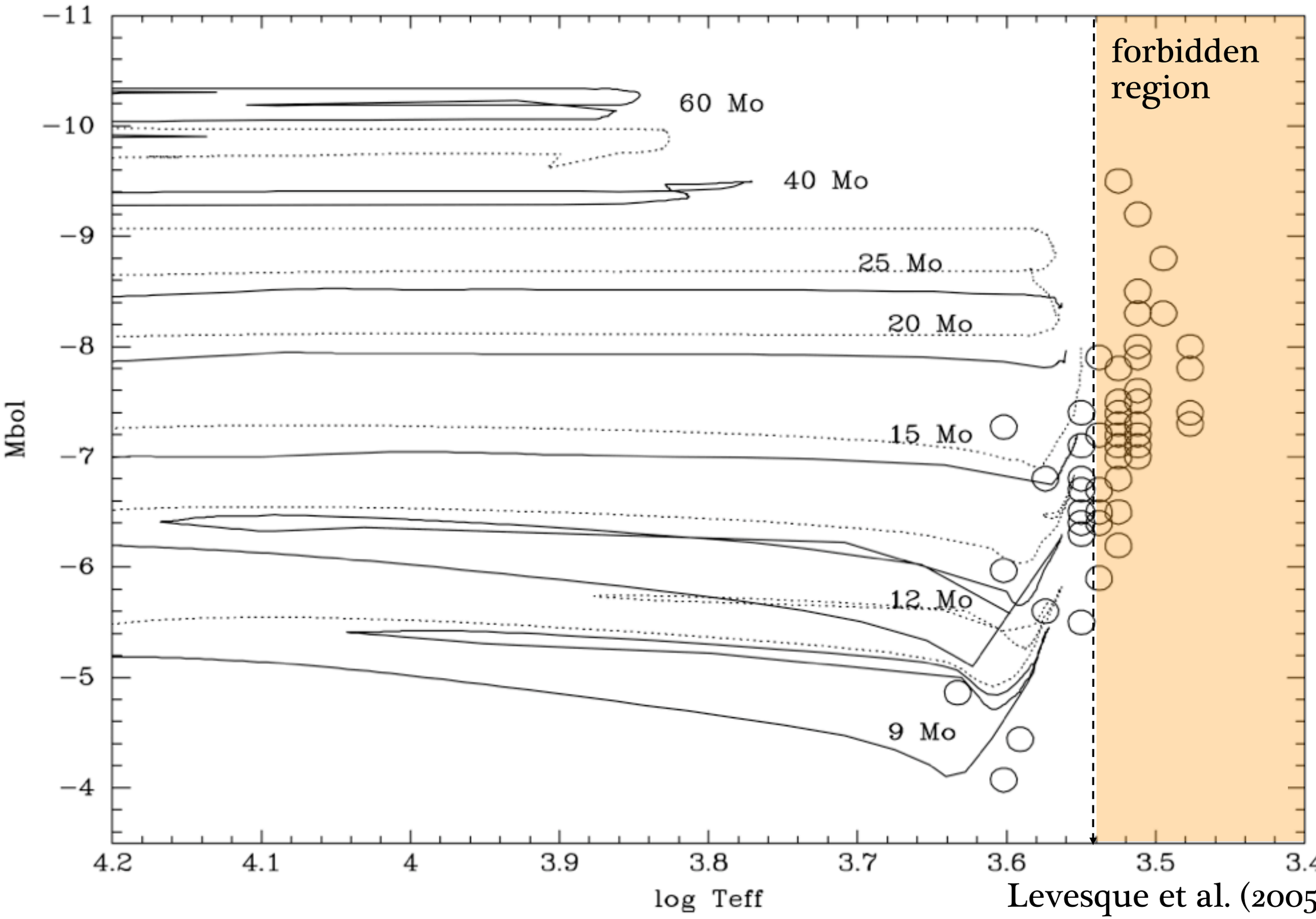

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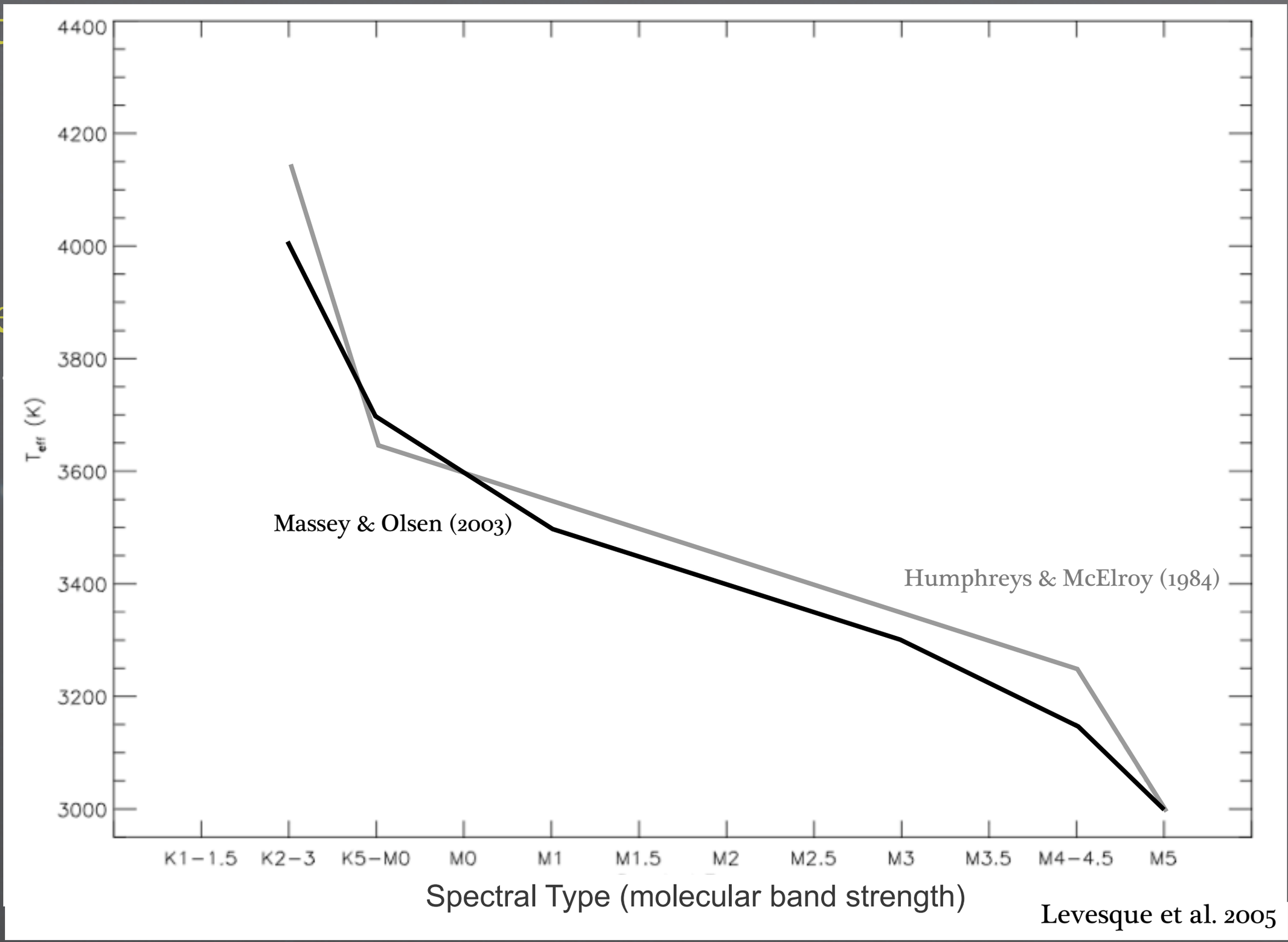

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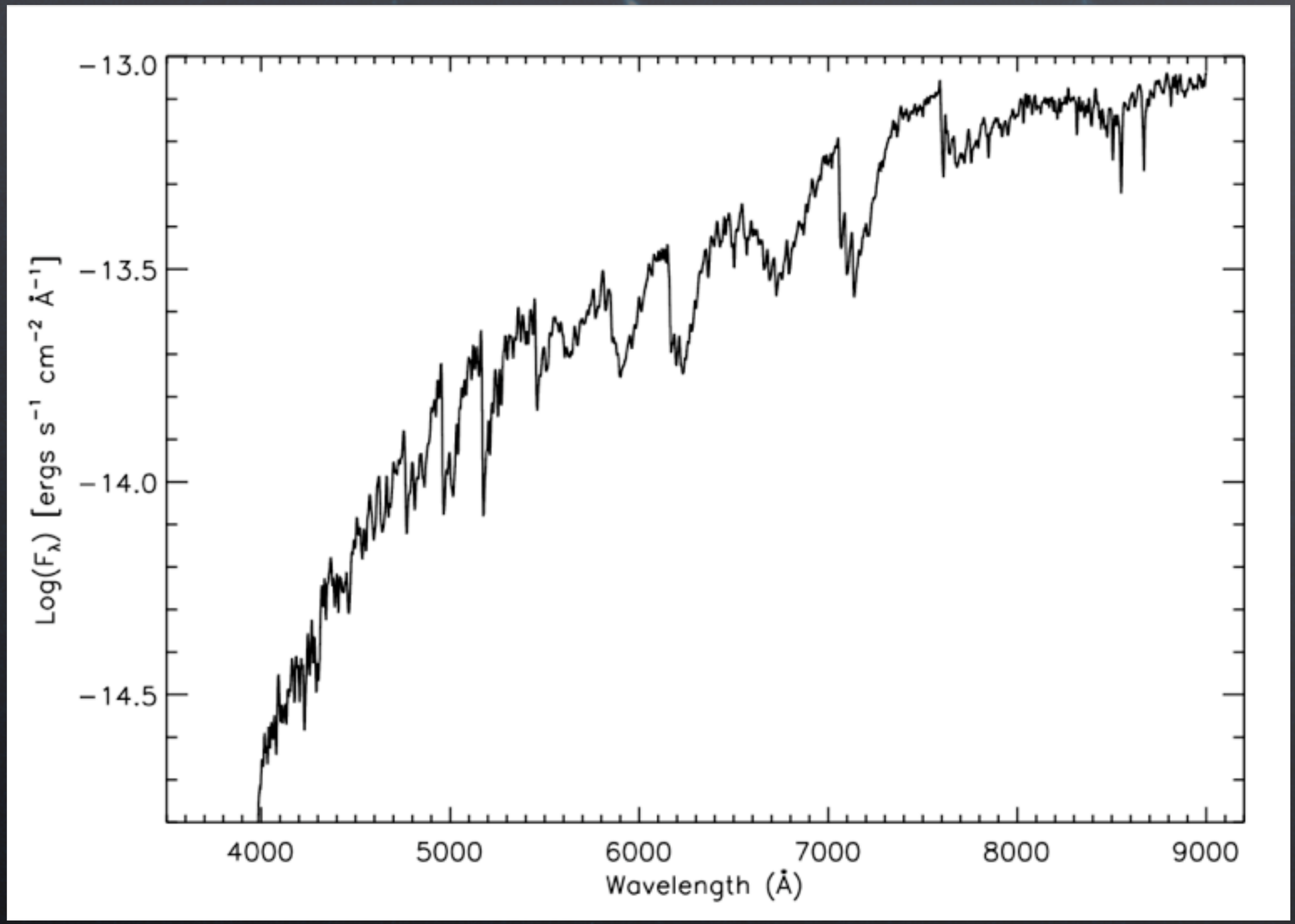
Step 3: A new approach?
- fit T_{eff}-sensitive TiO bands that dominate M-type spectra
- recent MARCS stellar atmosphere models have improved molecular opacities and make this possible

Defining RSG samples

Fitting Red Supergiant Spectra:



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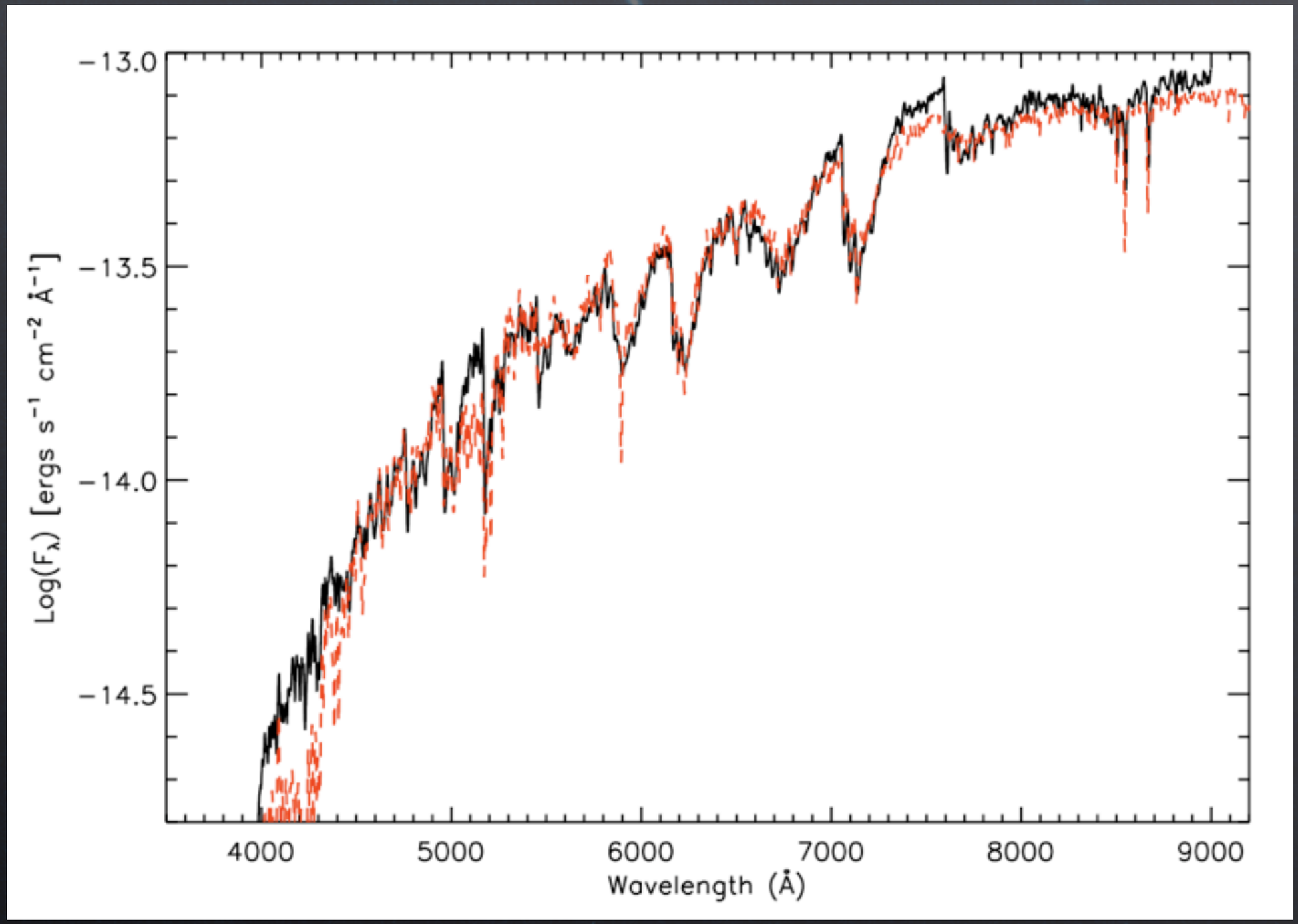

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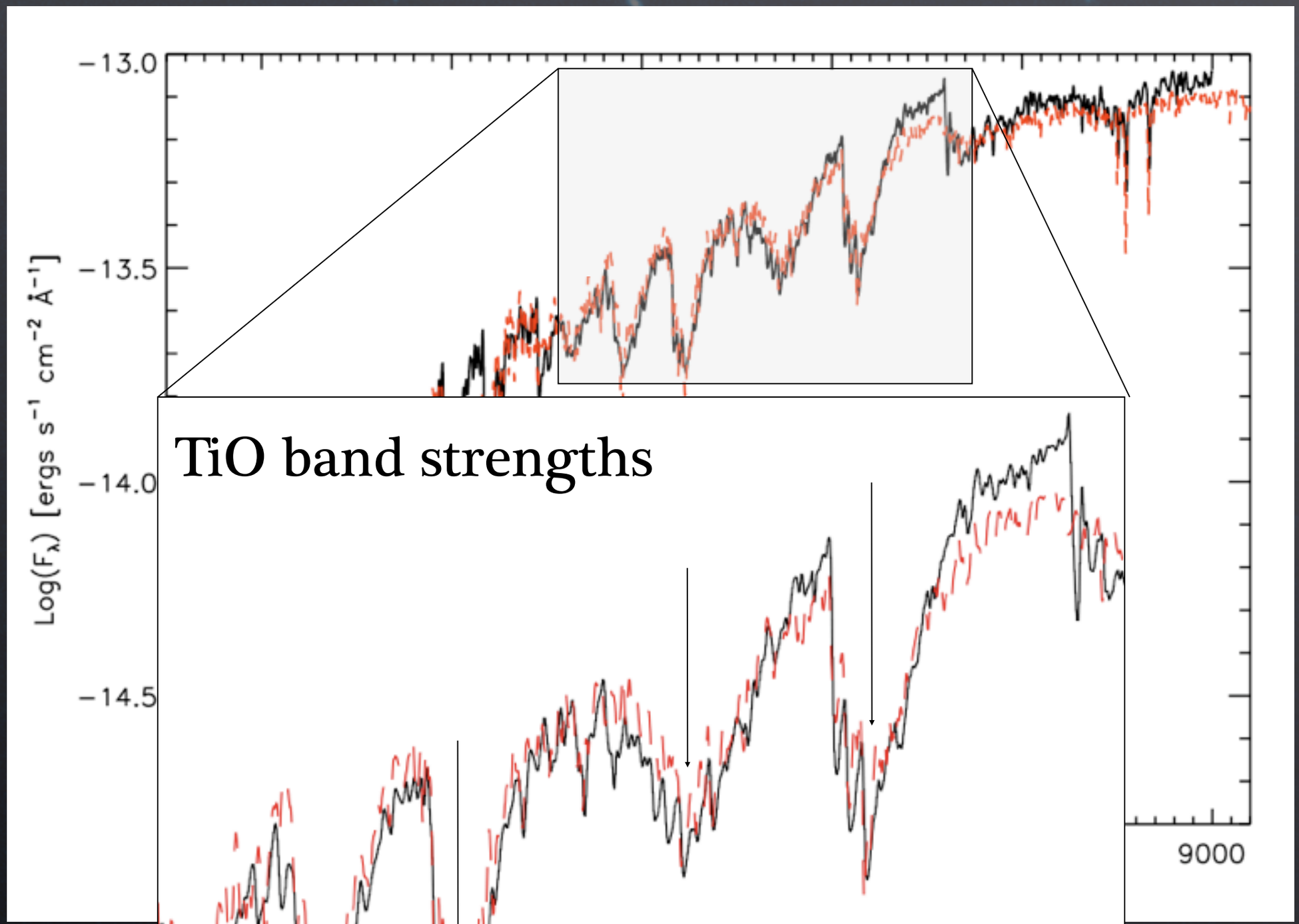

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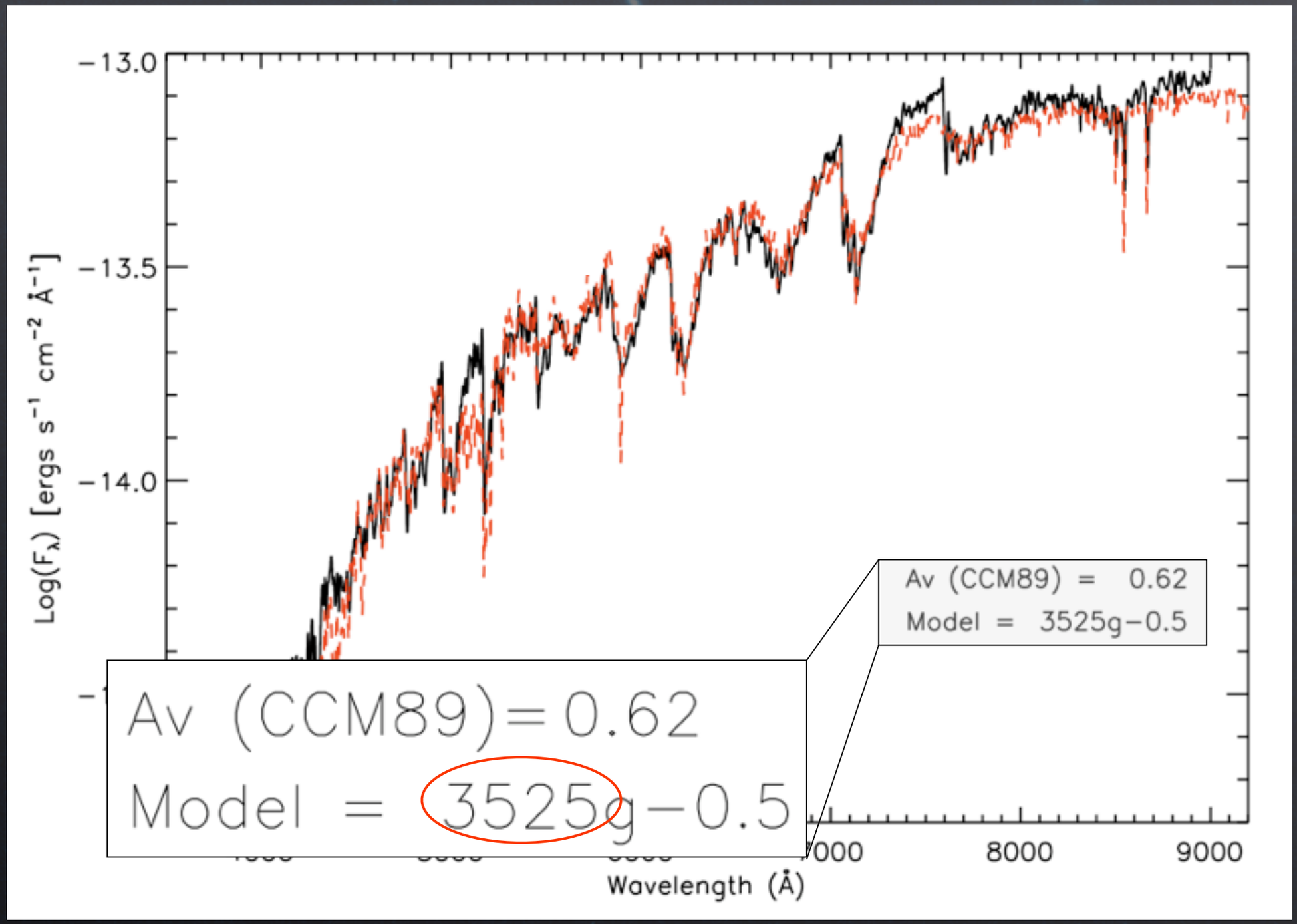

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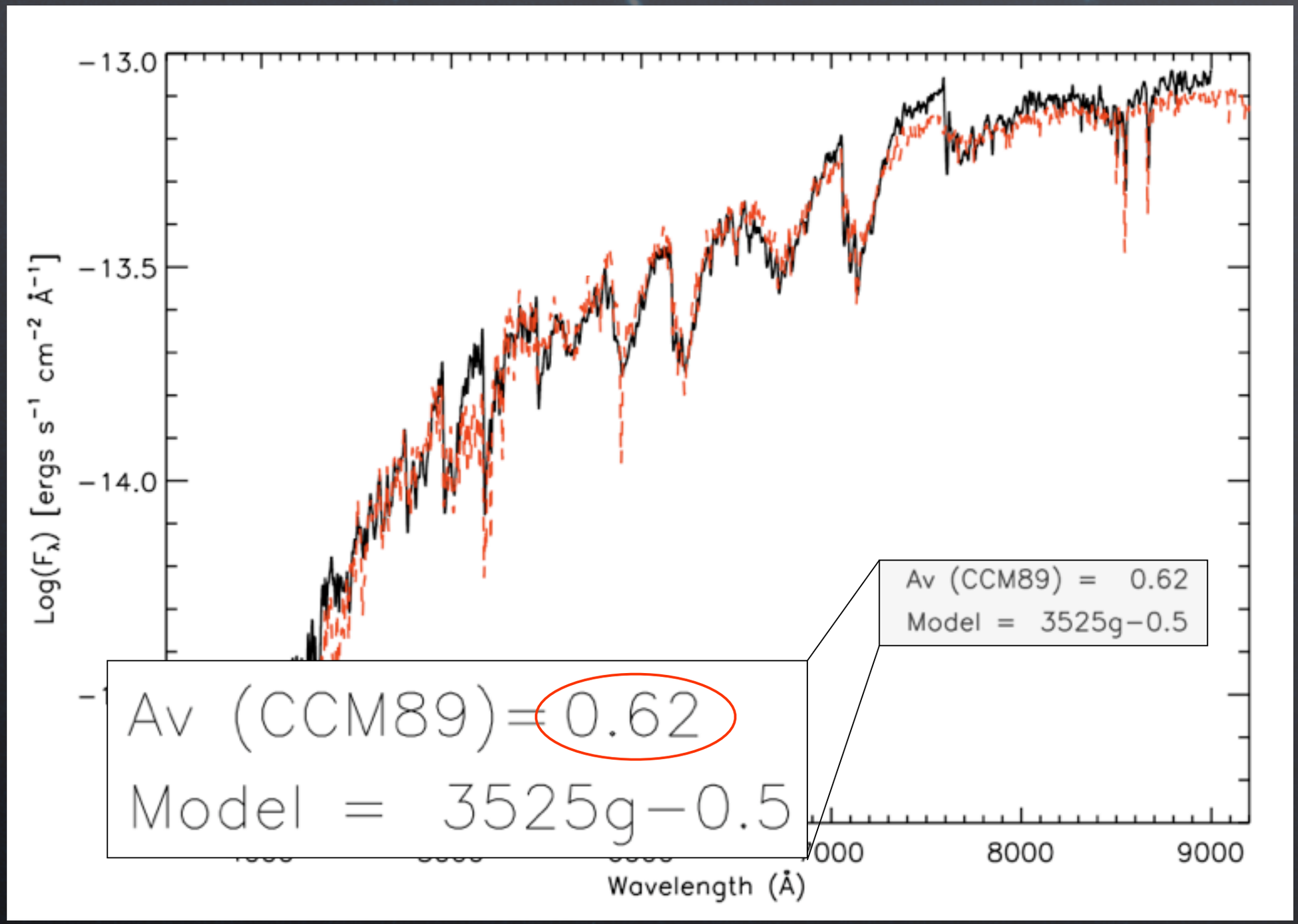

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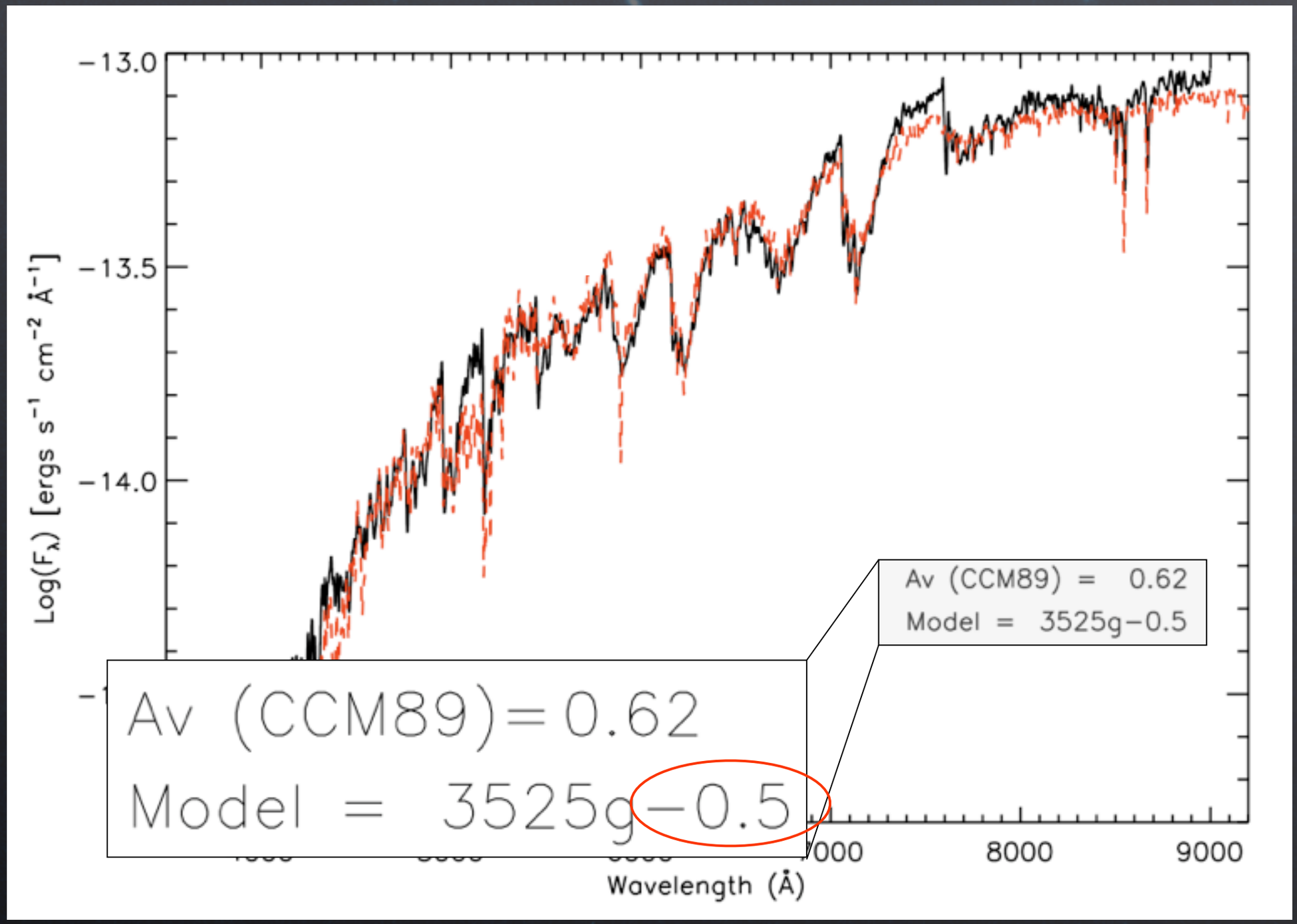

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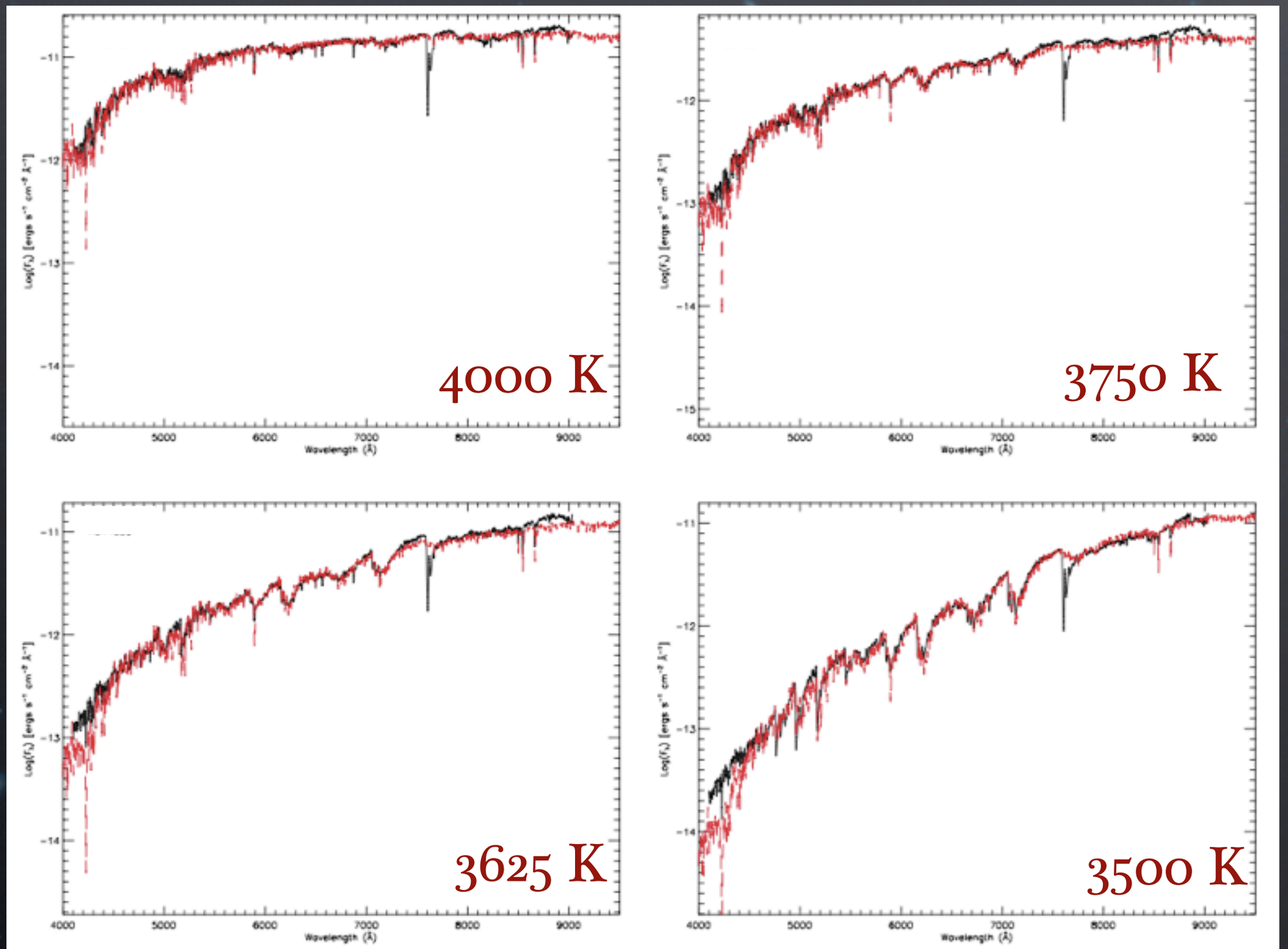

Levesque et al. 2005

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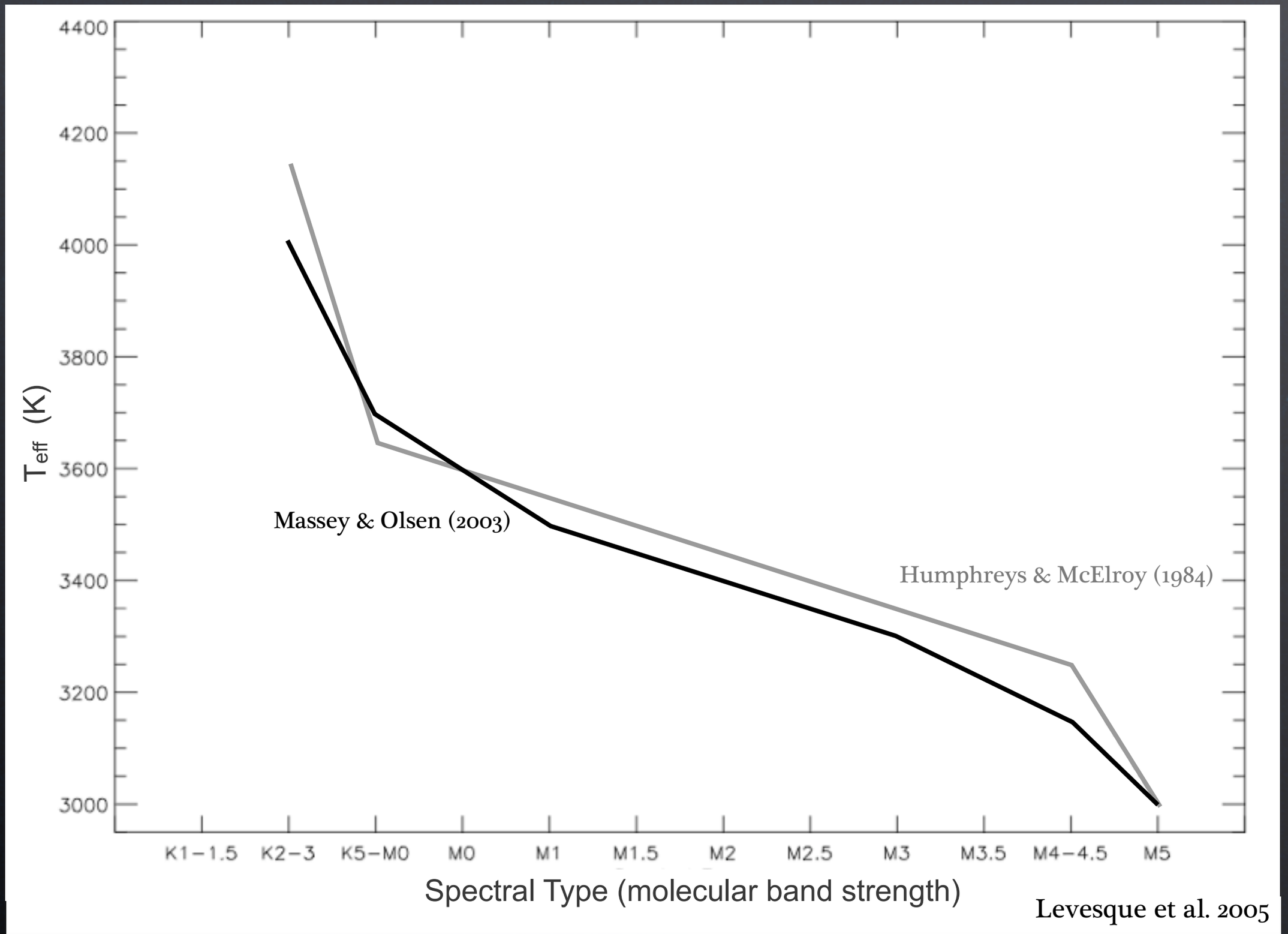

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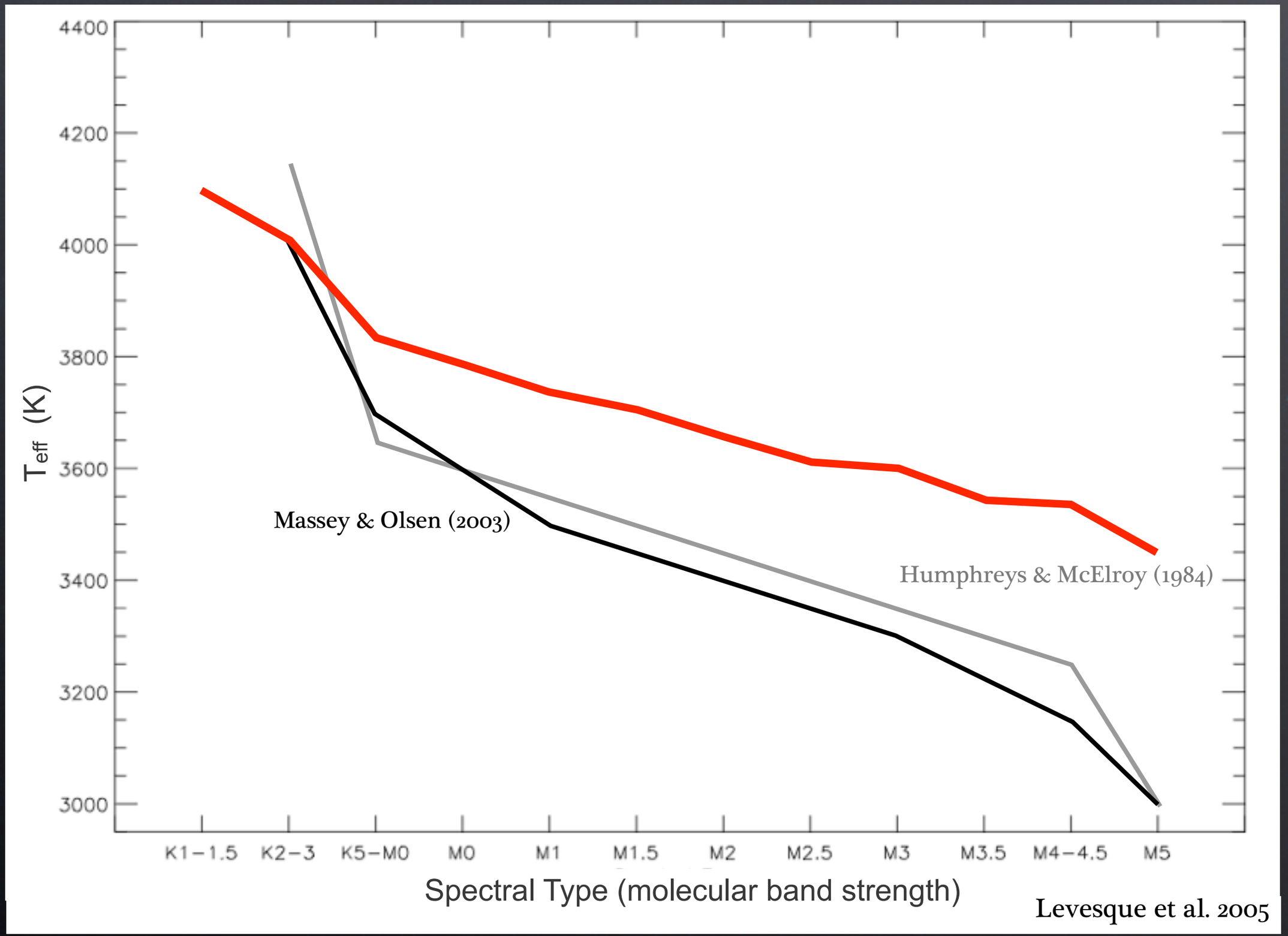

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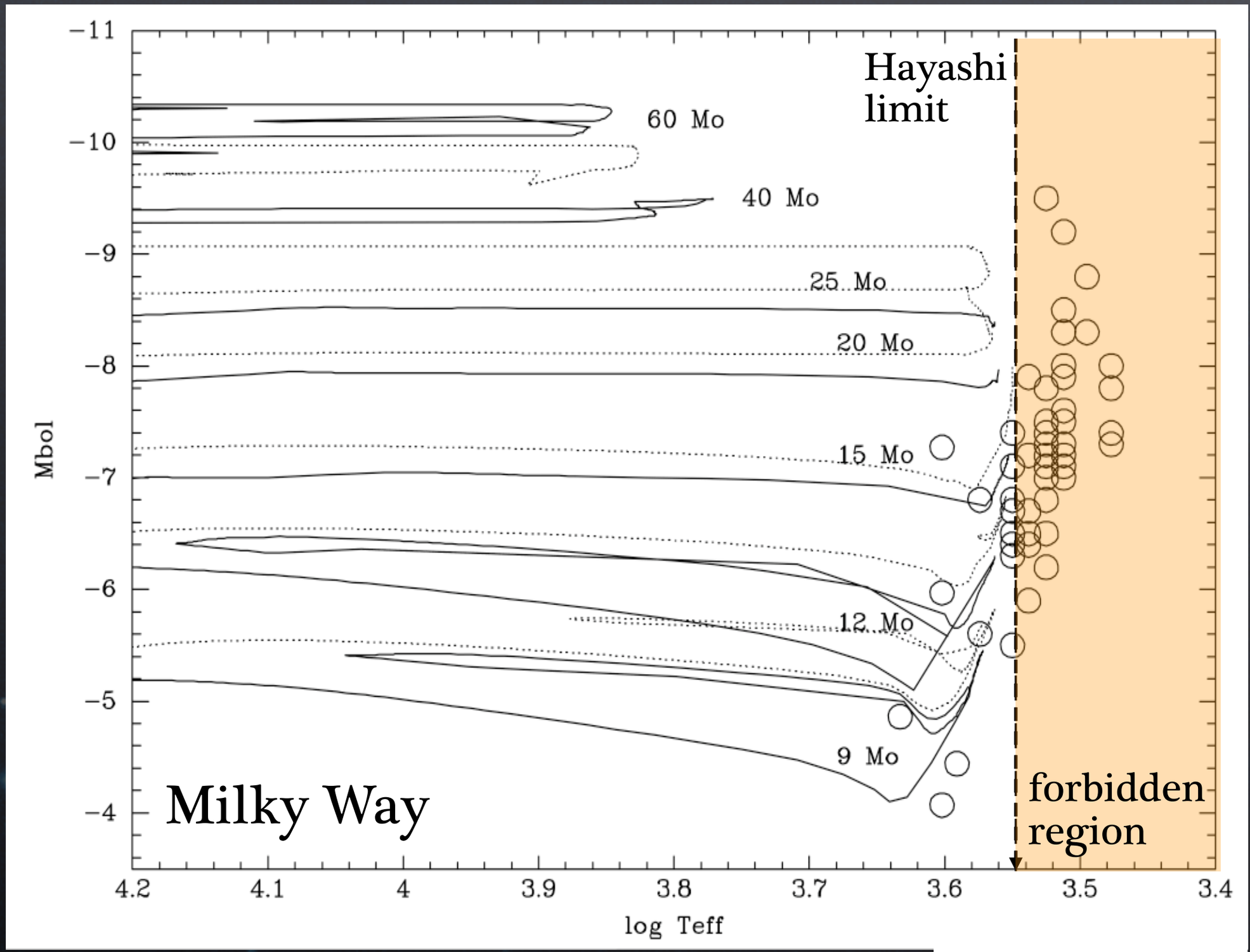

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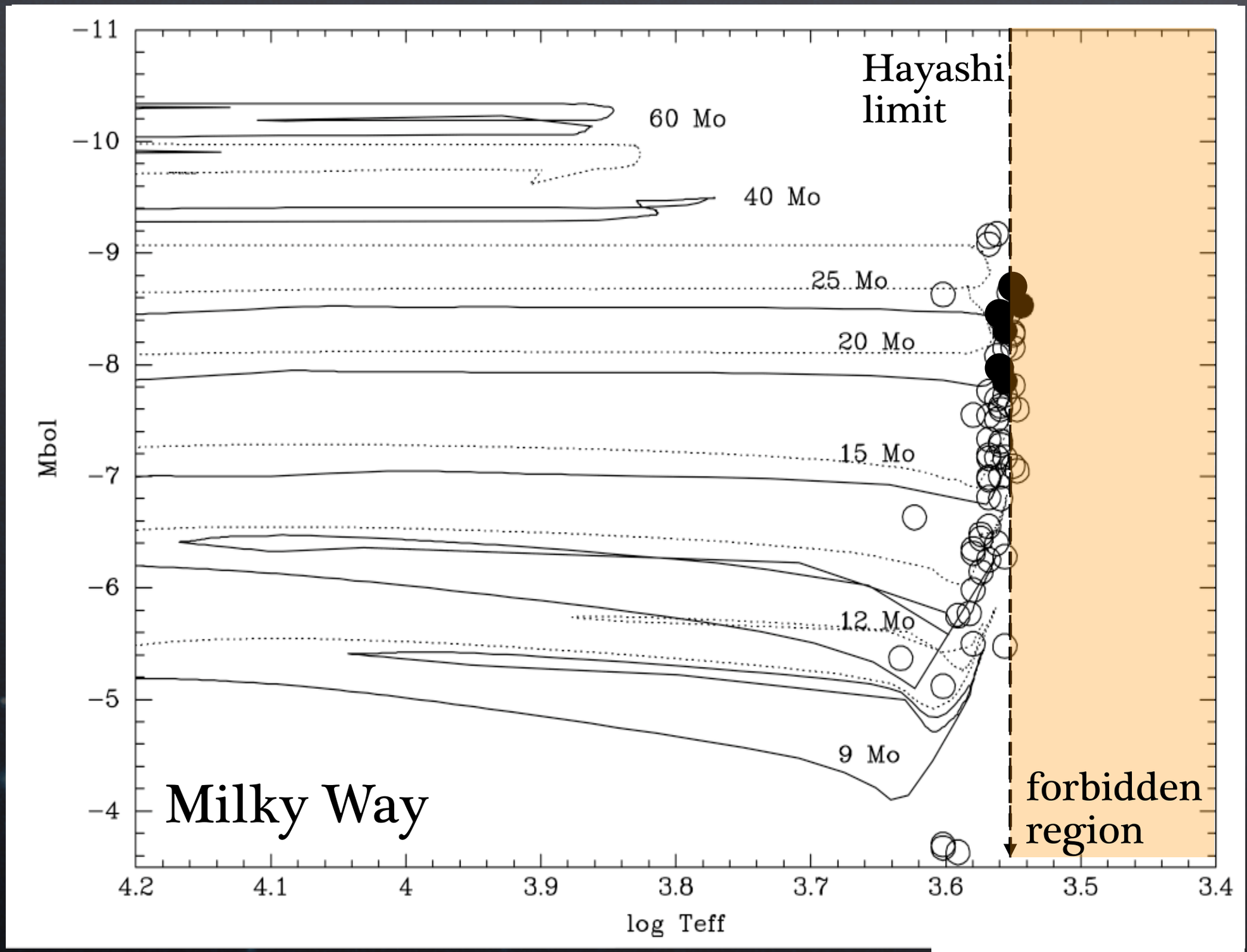
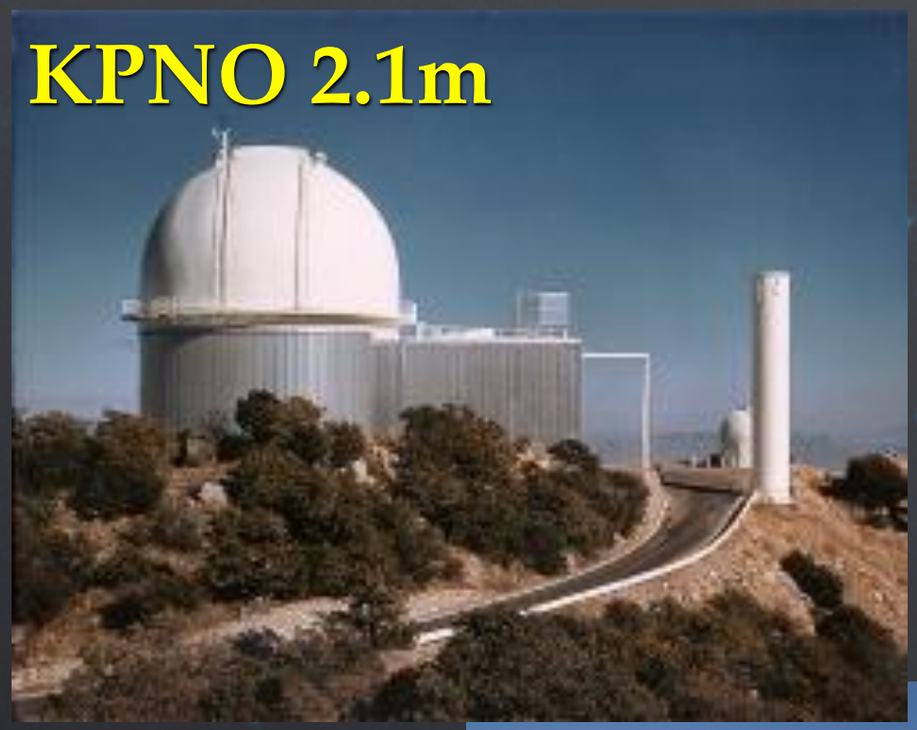
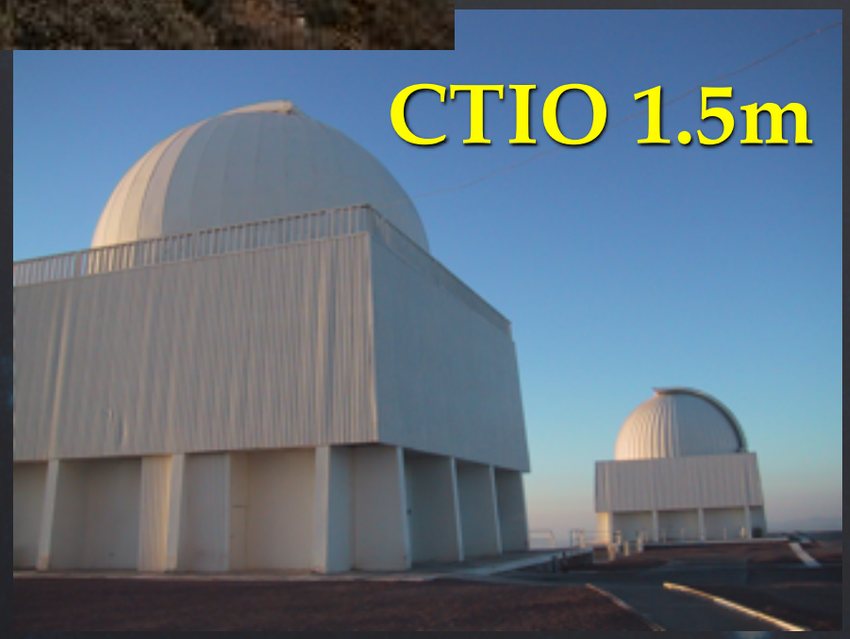


Levesque et al. 2005

Defining RSG samples

Local Group





Levesque et al. (2005)

Defining RSG samples

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Levesque et al. (2006)

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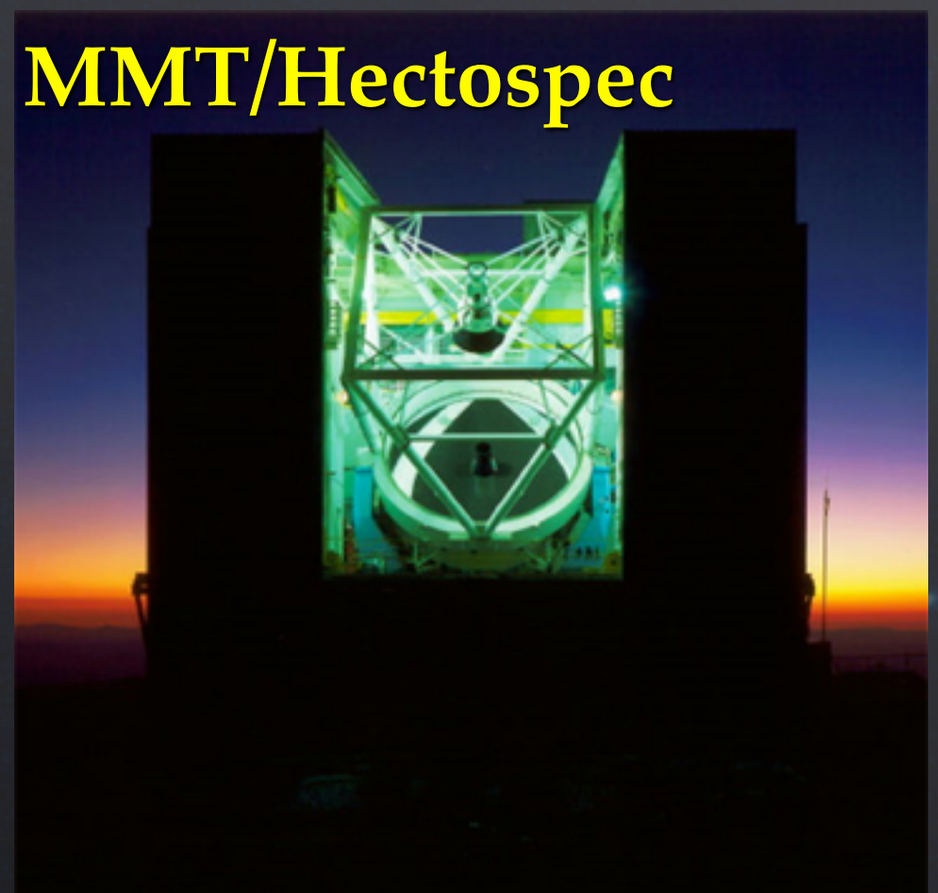
Massey et al. (2009)



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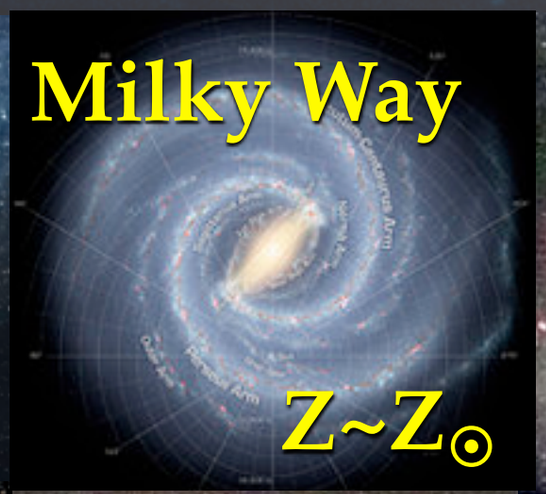


Levesque & Massey (2012)

Defining RSG samples

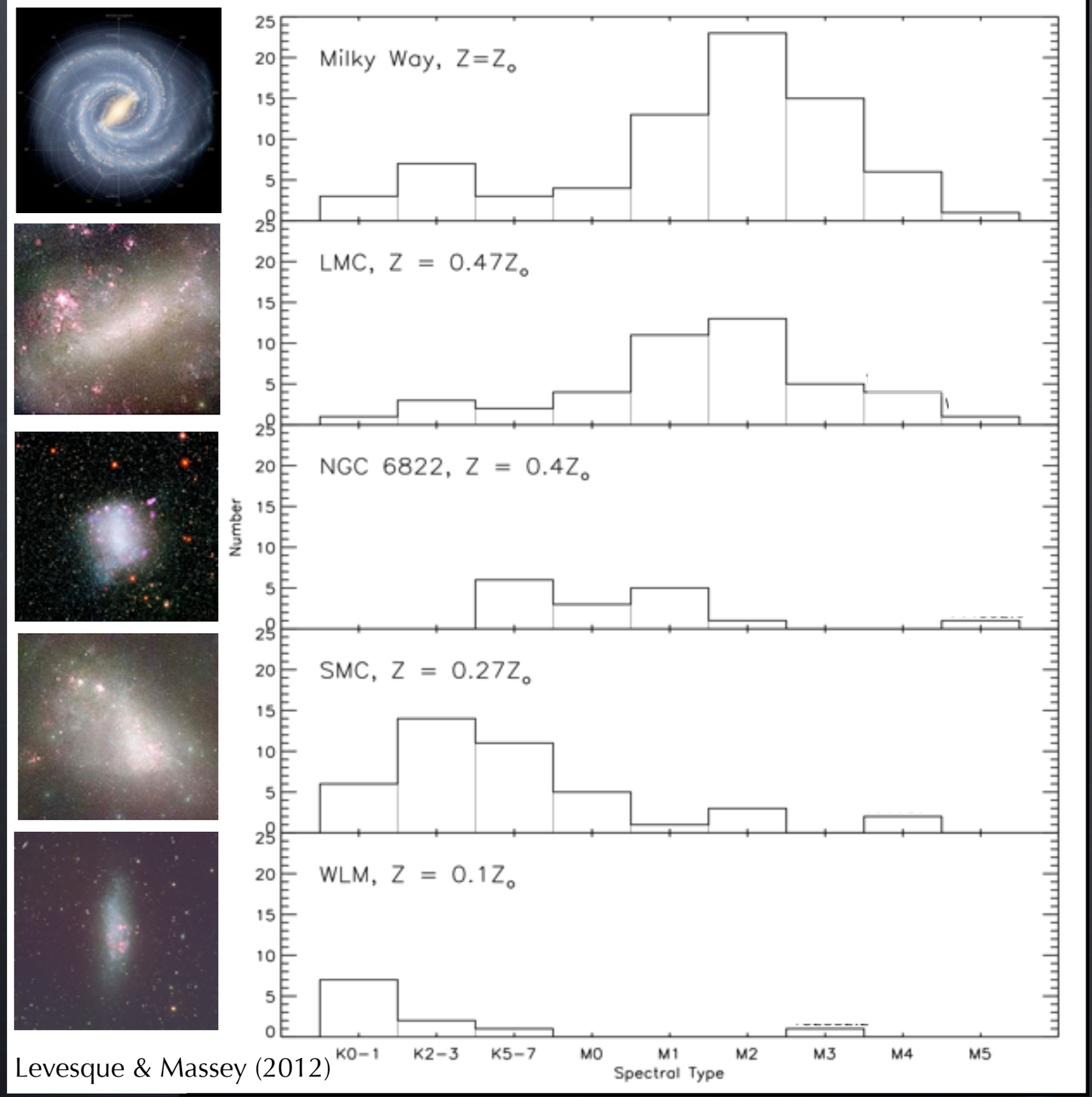
Local Group

...and beyond!

Next!

Defining RSG samples

Metallicity Effects



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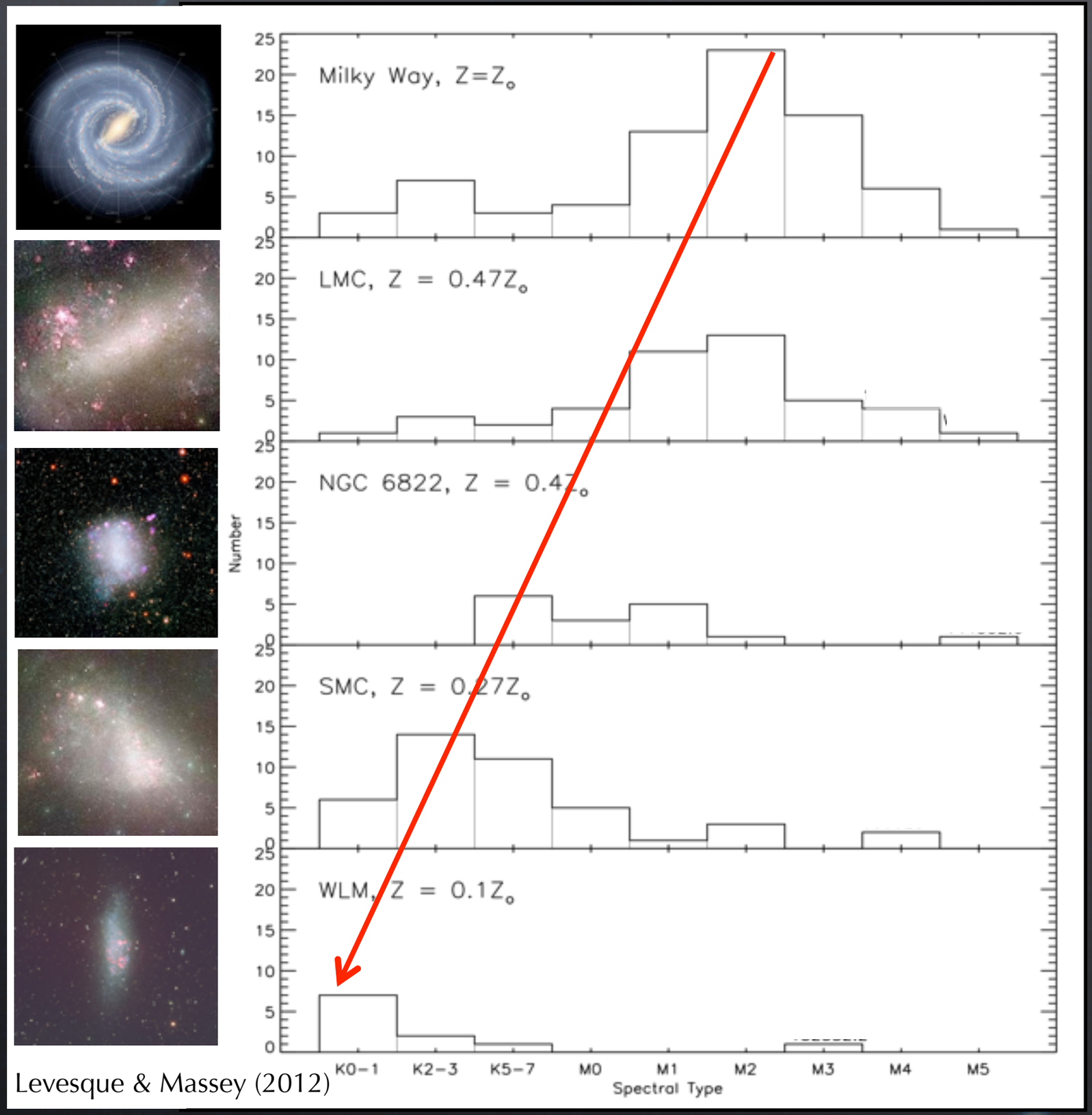

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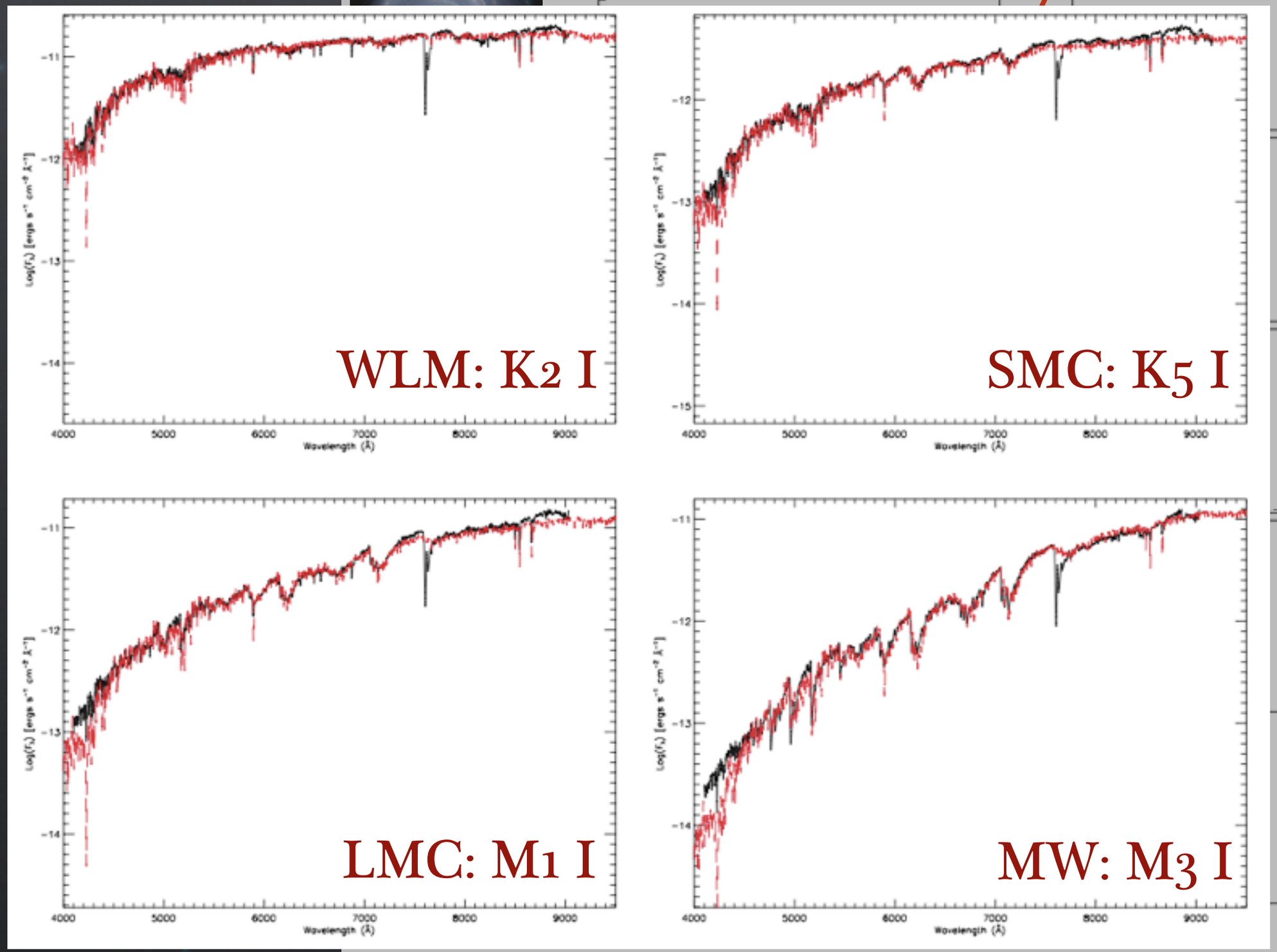

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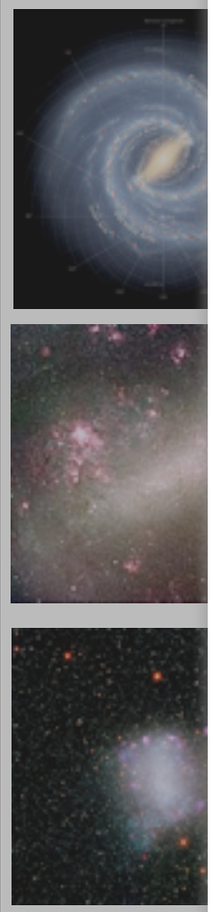
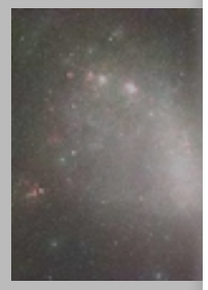
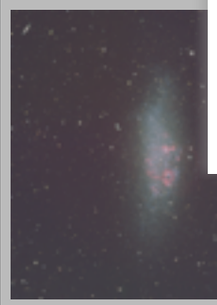
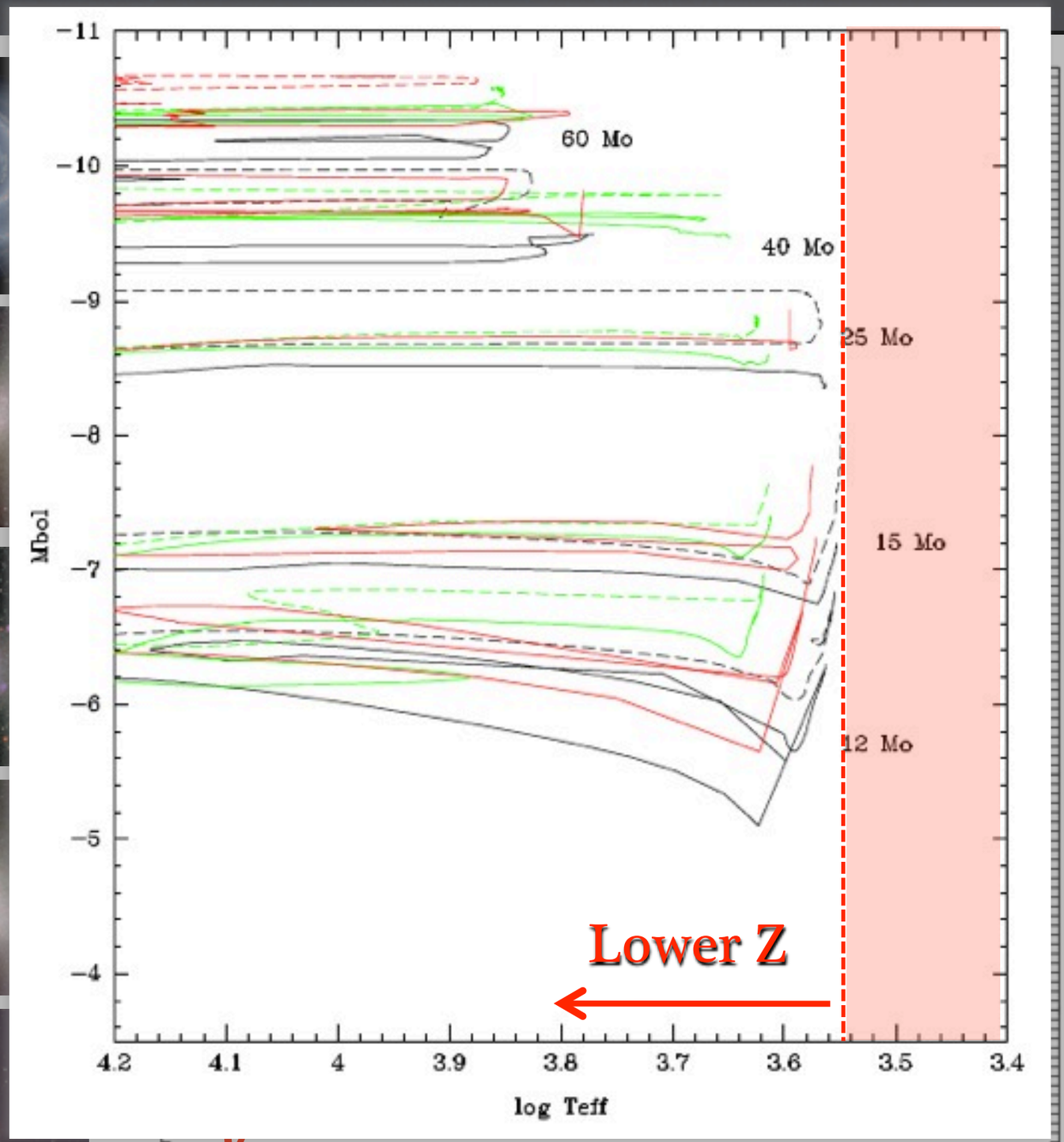
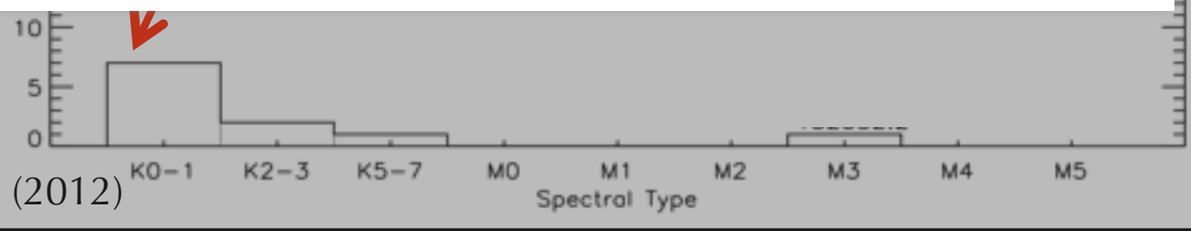






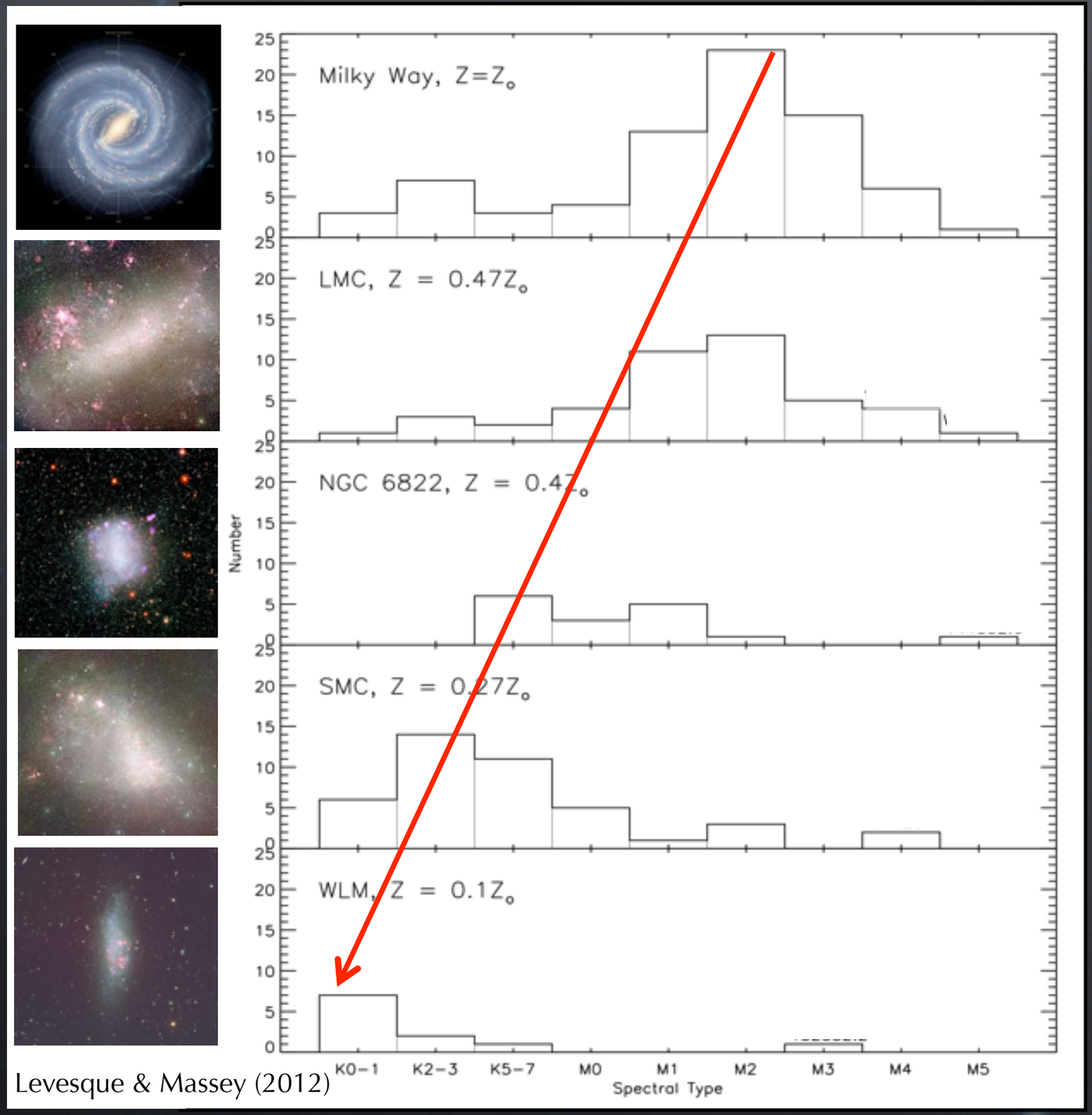




Levesque & Massey (2012)

Defining RSG samples

Metallicity Effects



Levesque & Massey (2012)

Defining RSG samples

Local Group

...and beyond!

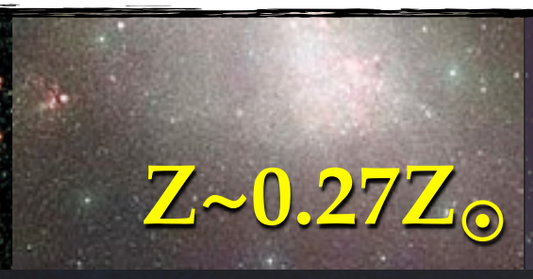
Next!

Defining RSG samples

Local Group **...and beyond!**

"...Years ago, Kip Thorne and myself 'invented' theoretical models of stars...

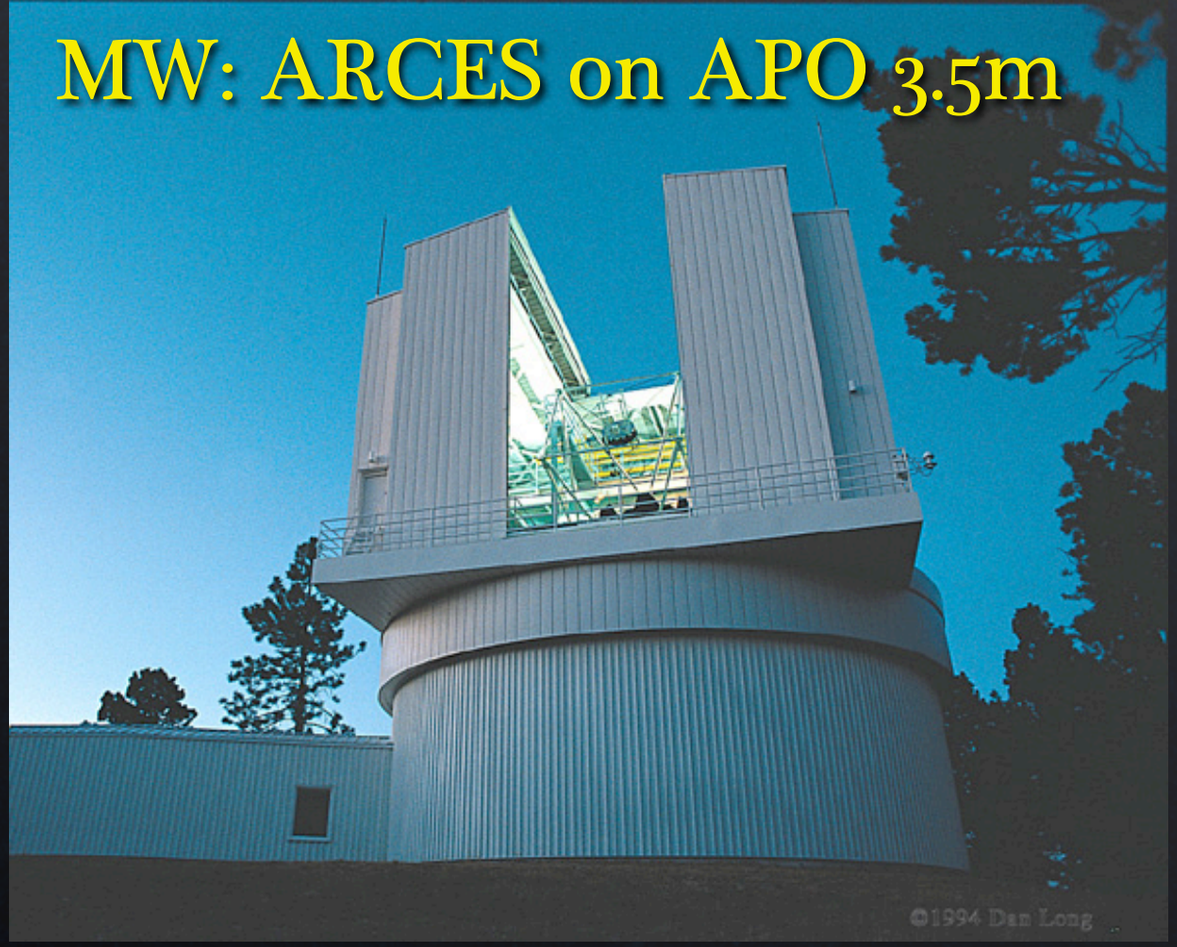
Please let me know if there may be some interest in pursuing these lines of enquiry." - Anna Żytkow



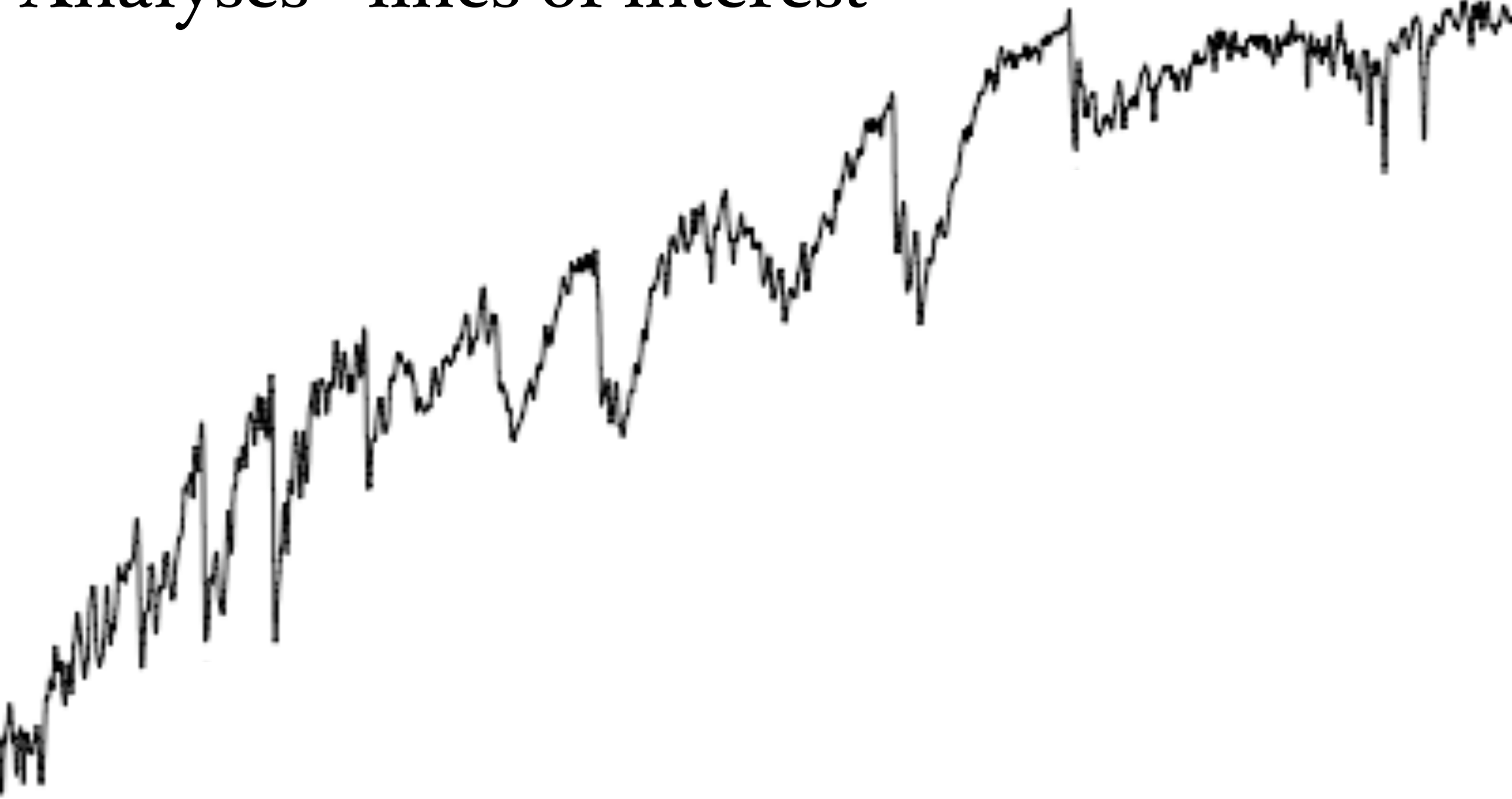
Next!

We surveyed our previously Galactic and MC RSG samples (Levesque et al. 2005, 2006):

- pre-selected M spectral types (24 MW, 16 LMC, 22 SMC)
- R~20,000-40,000; ARCES at APO and MIKE at Magellan
- used Ca II triplet to determine radial velocities



Analyses - lines of interest



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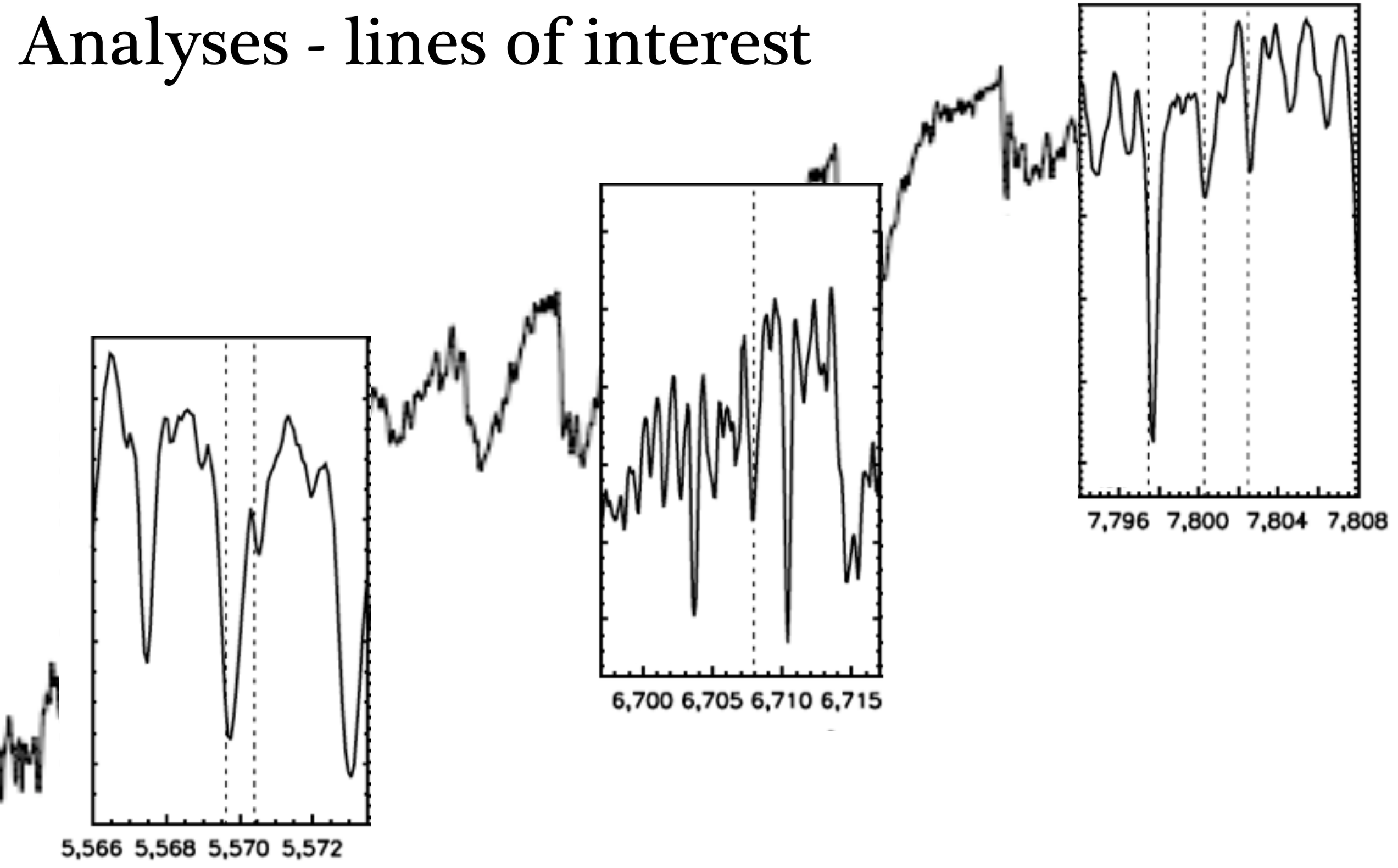

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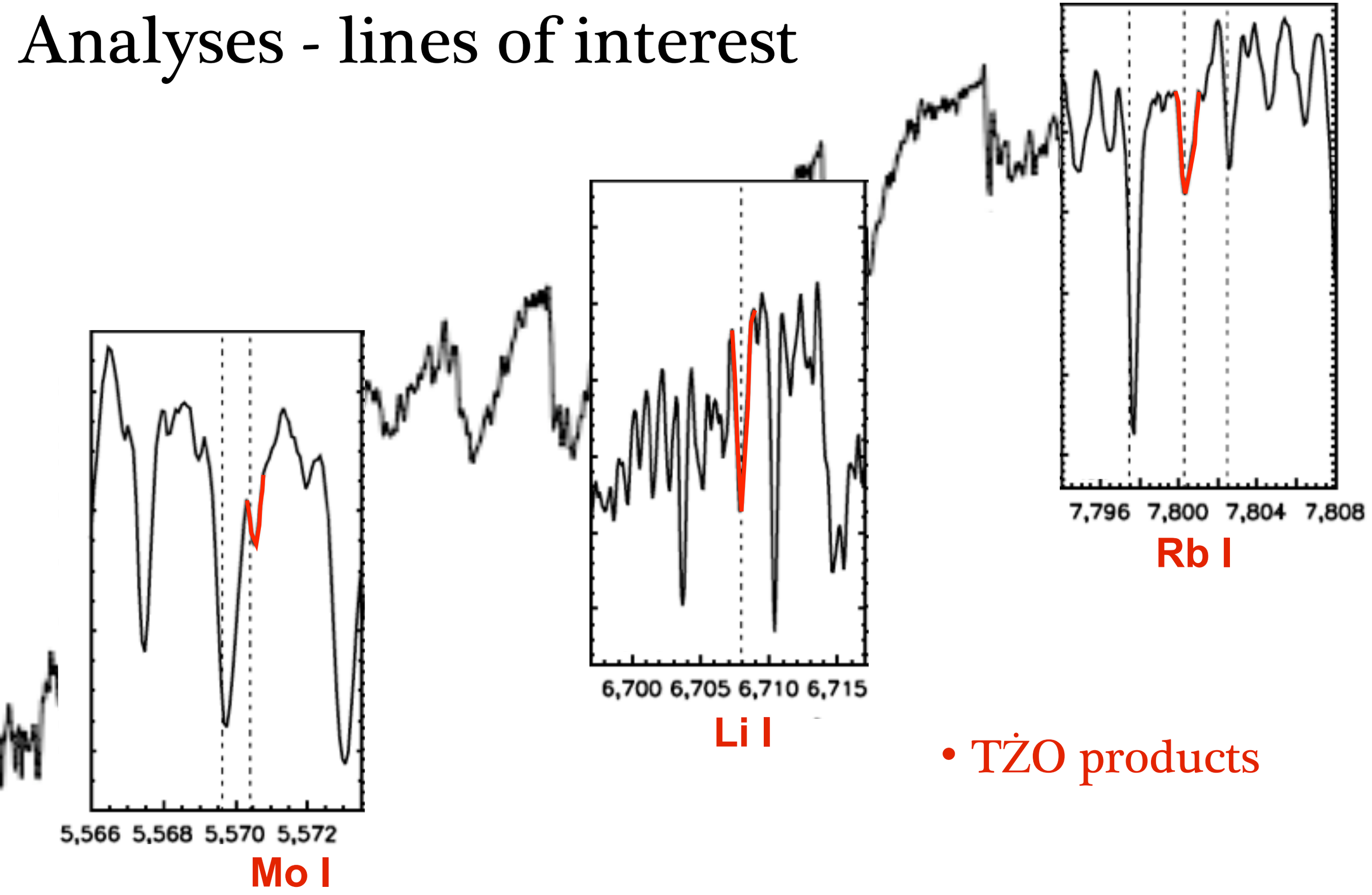
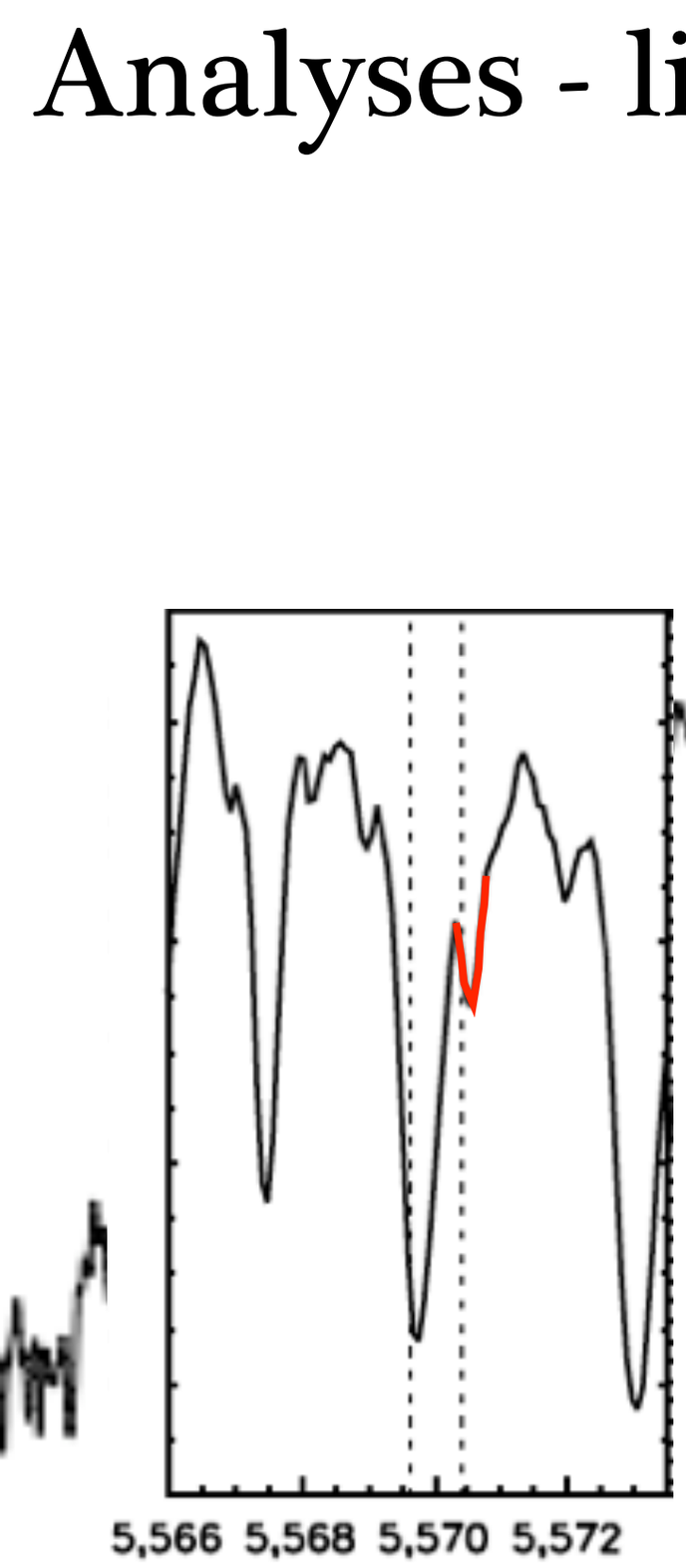
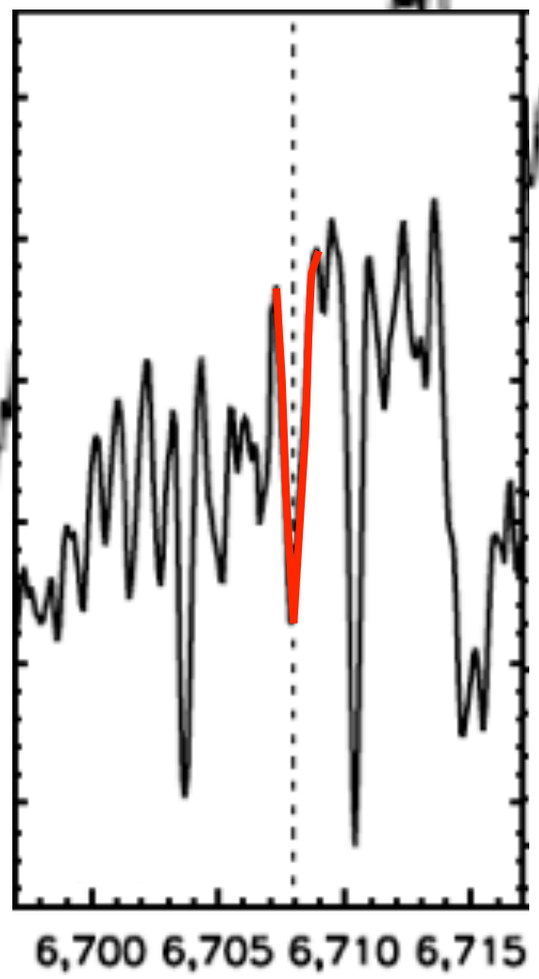


- TŻO products

Analyses - lines of interest

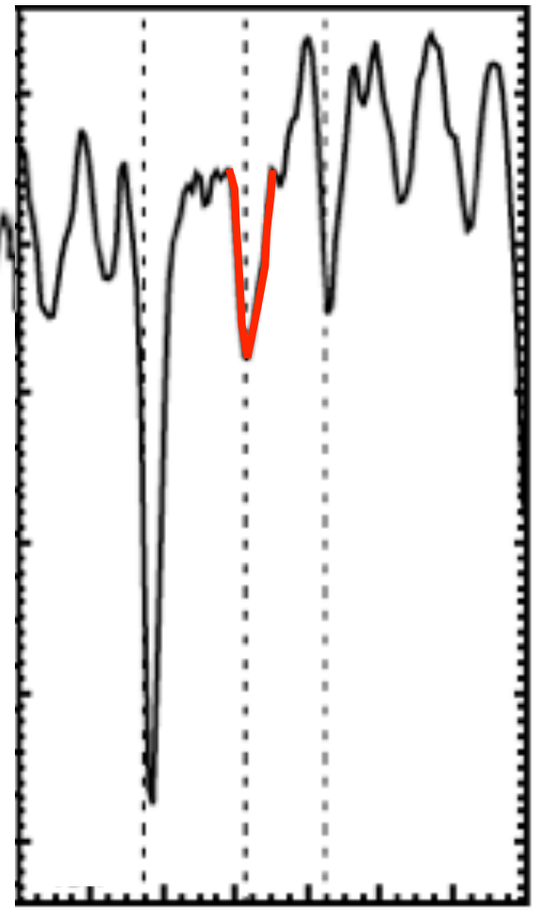


Fe I, **Mo I**



Li I

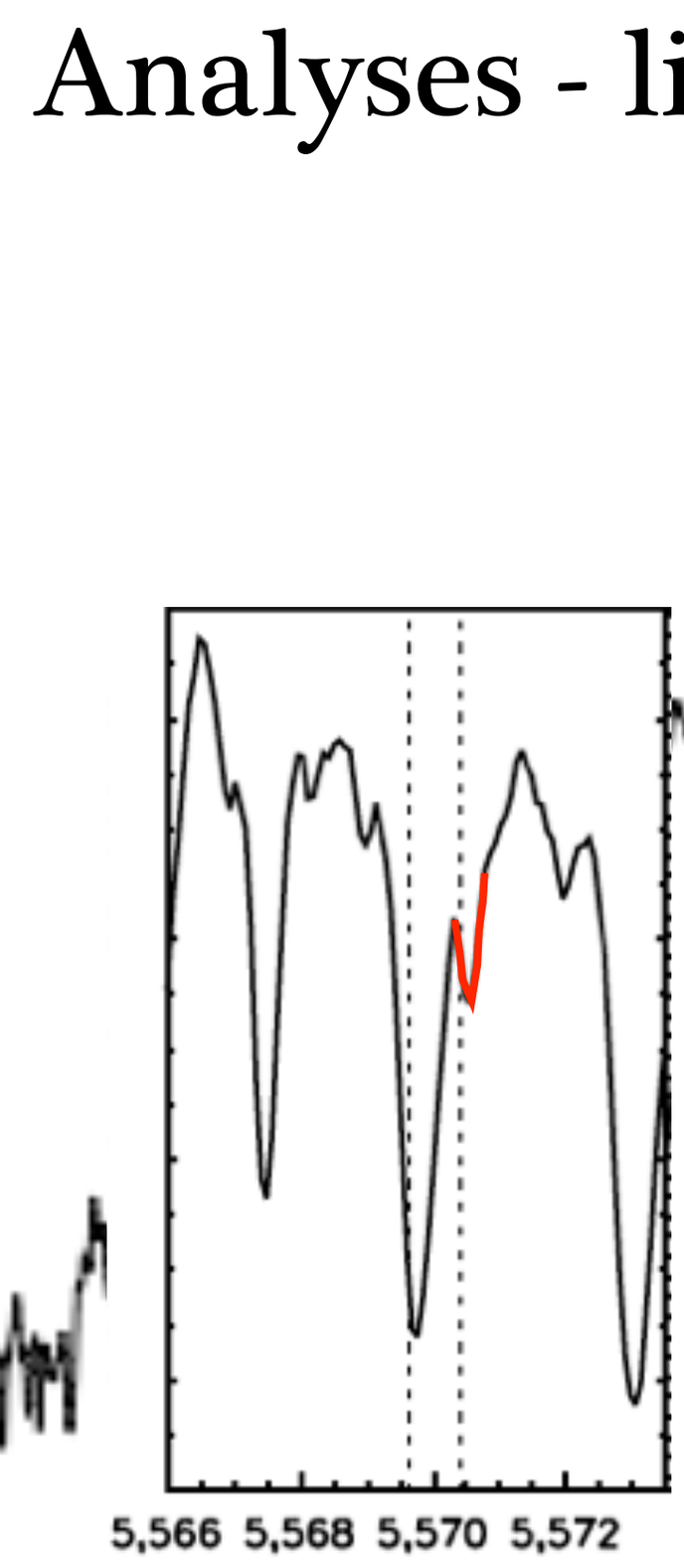
(Ca I, K I)



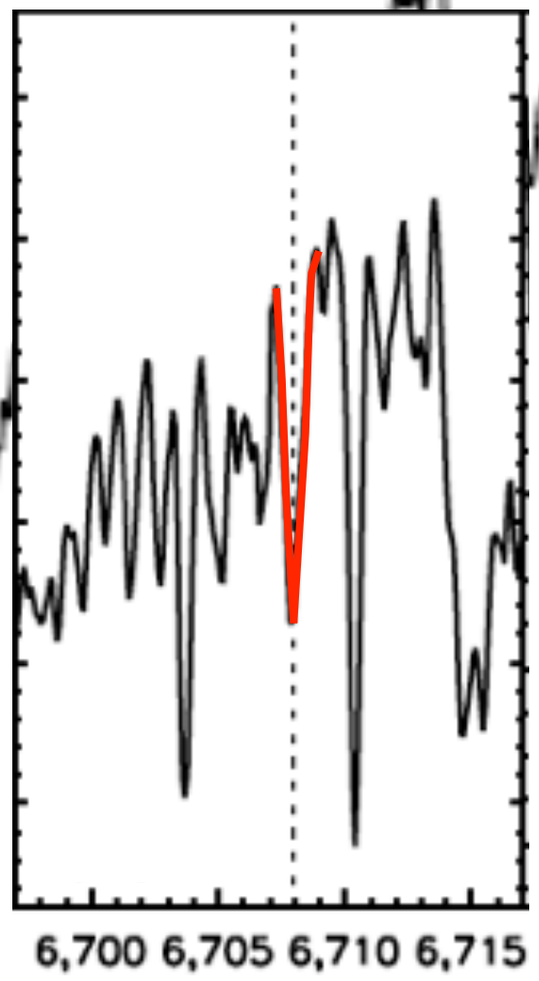
Ni I, **Rb I**, Fe I

- TŻO products
- “control” features

Analyses - lines of interest



Fe I, **Mo I**



Li I

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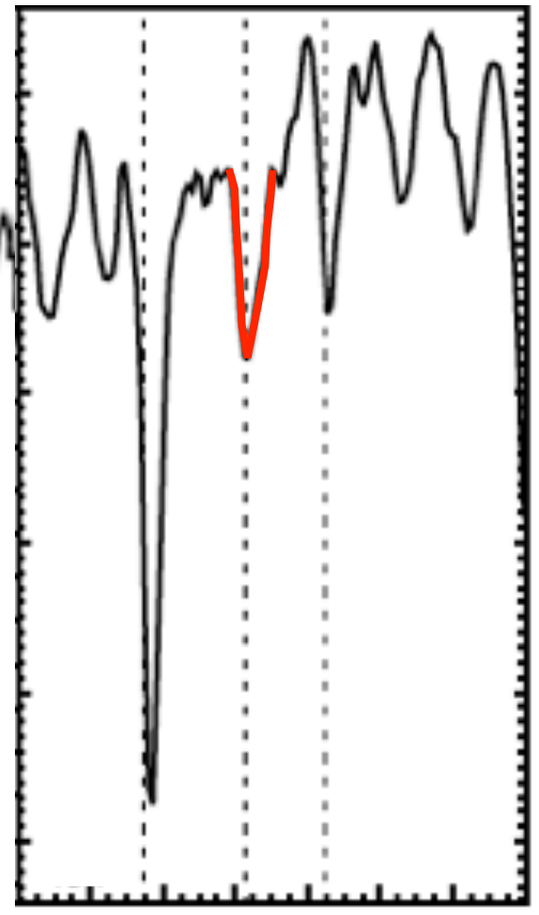
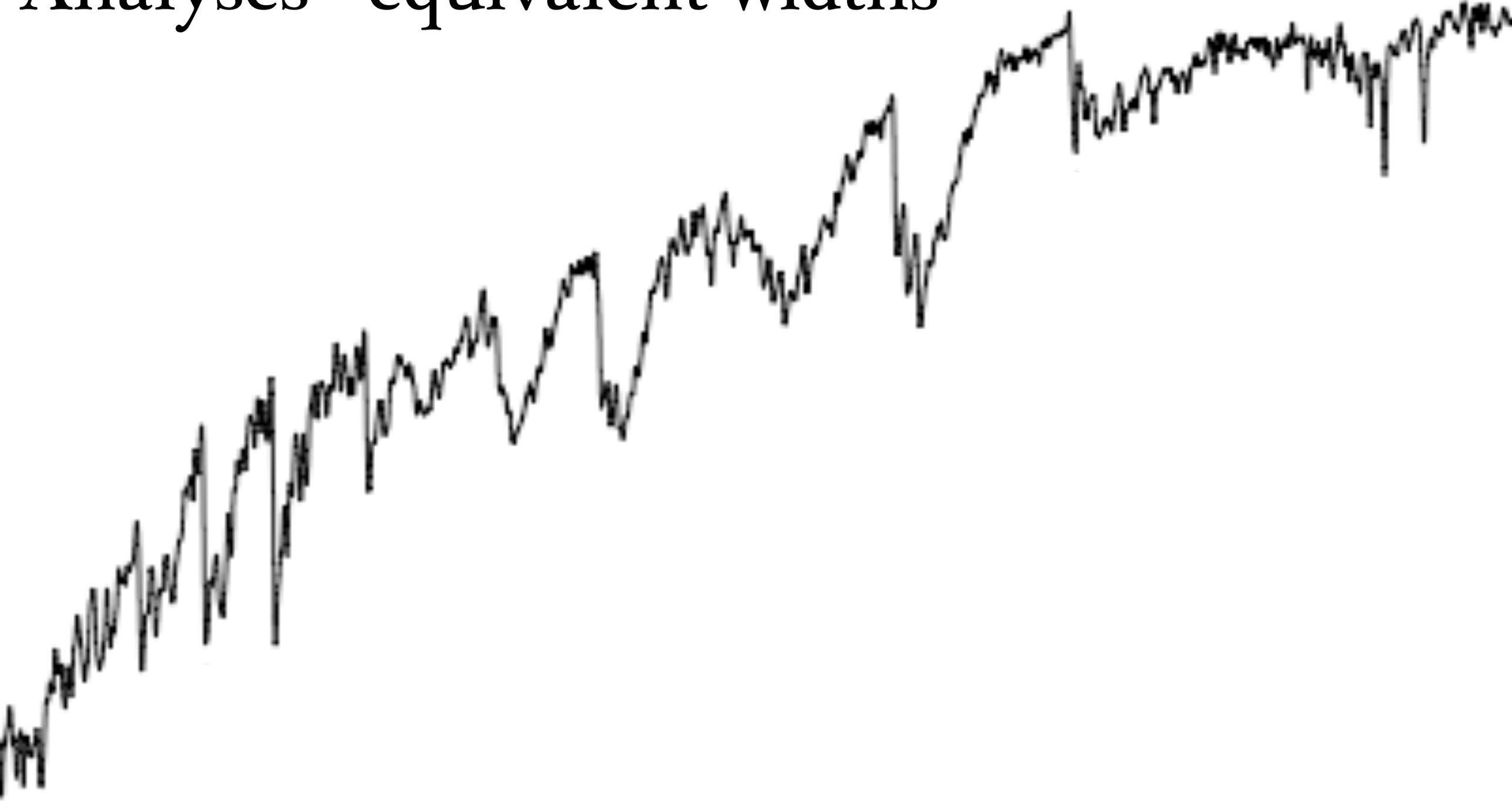


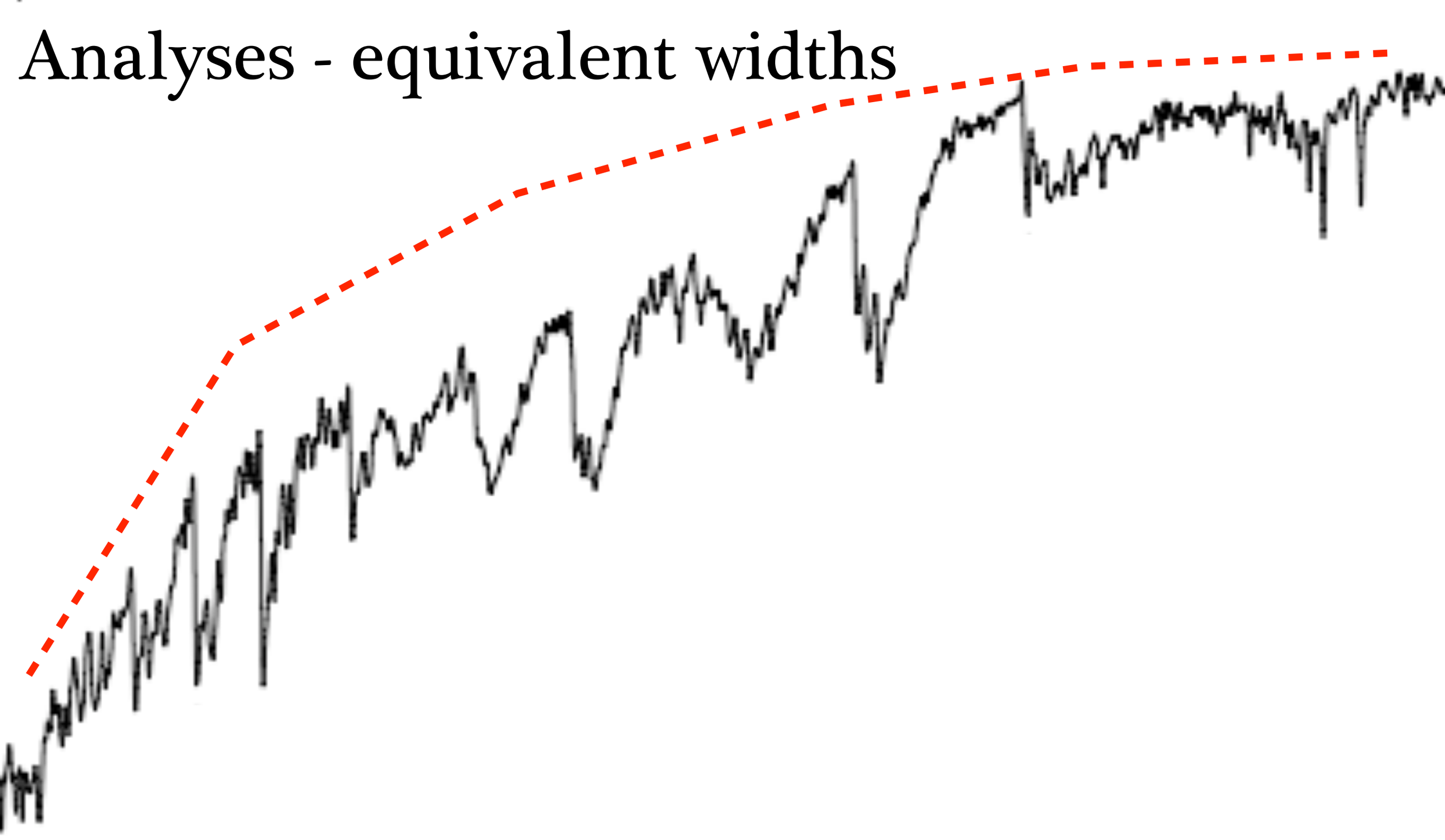
Ni I, **Rb I**, Fe I

- TŻO products
- "control" features
- measure equivalent width ratios of TŻO/control

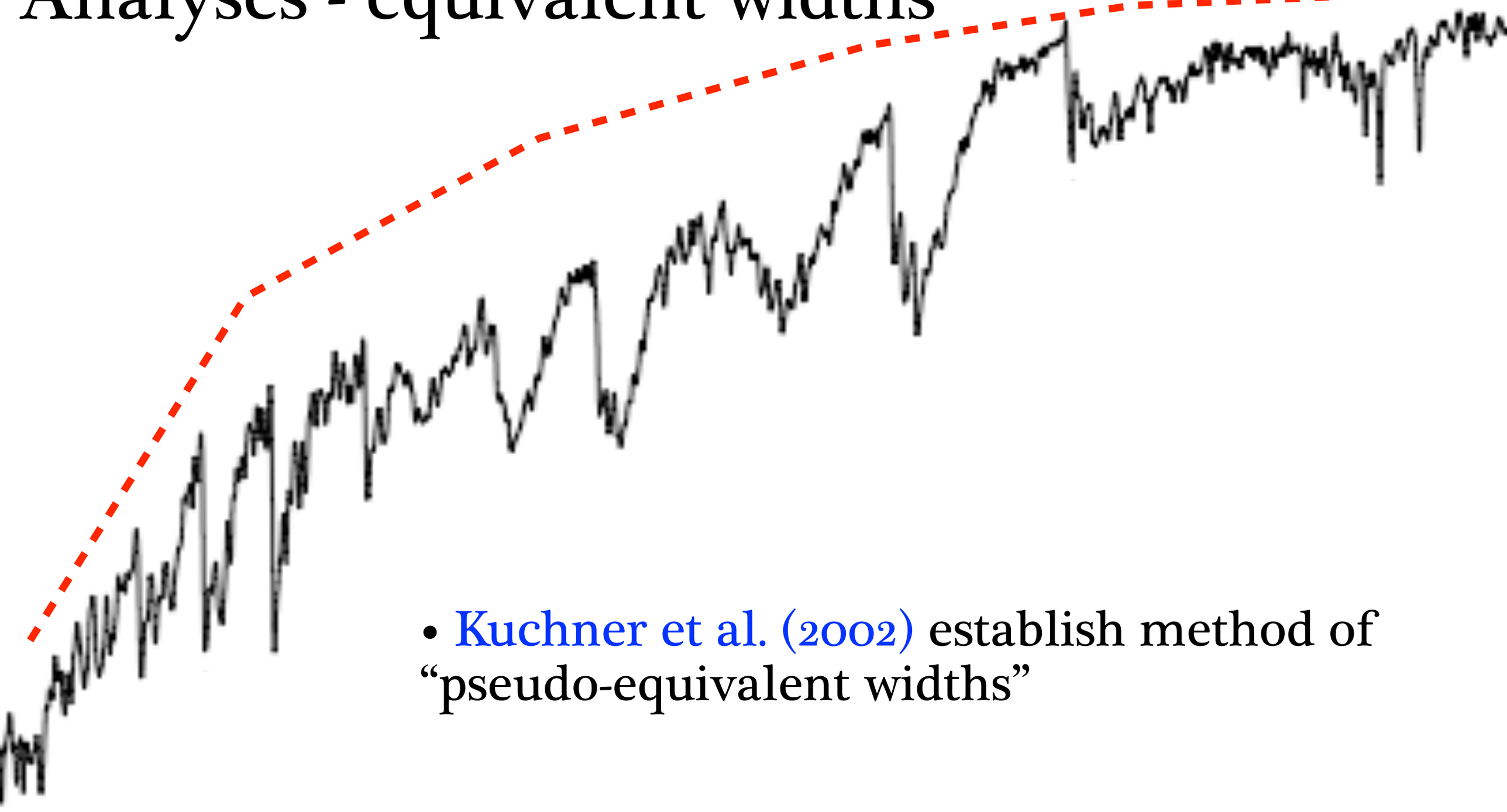
Analyses - equivalent widths



Analyses - equivalent widths

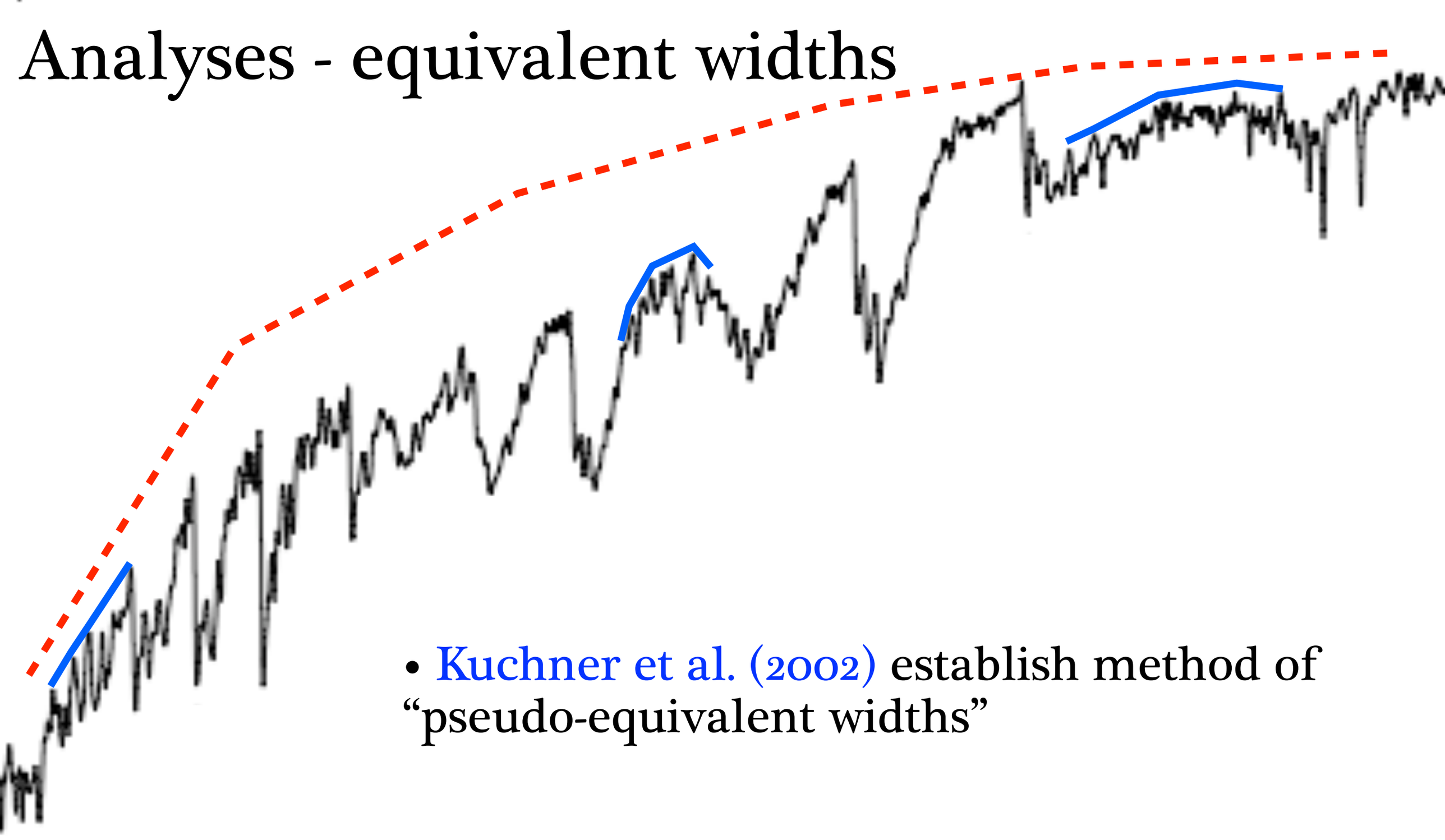


Analyses - equivalent widths



- Kuchner et al. (2002) establish method of “pseudo-equivalent widths”

Analyses - equivalent widths



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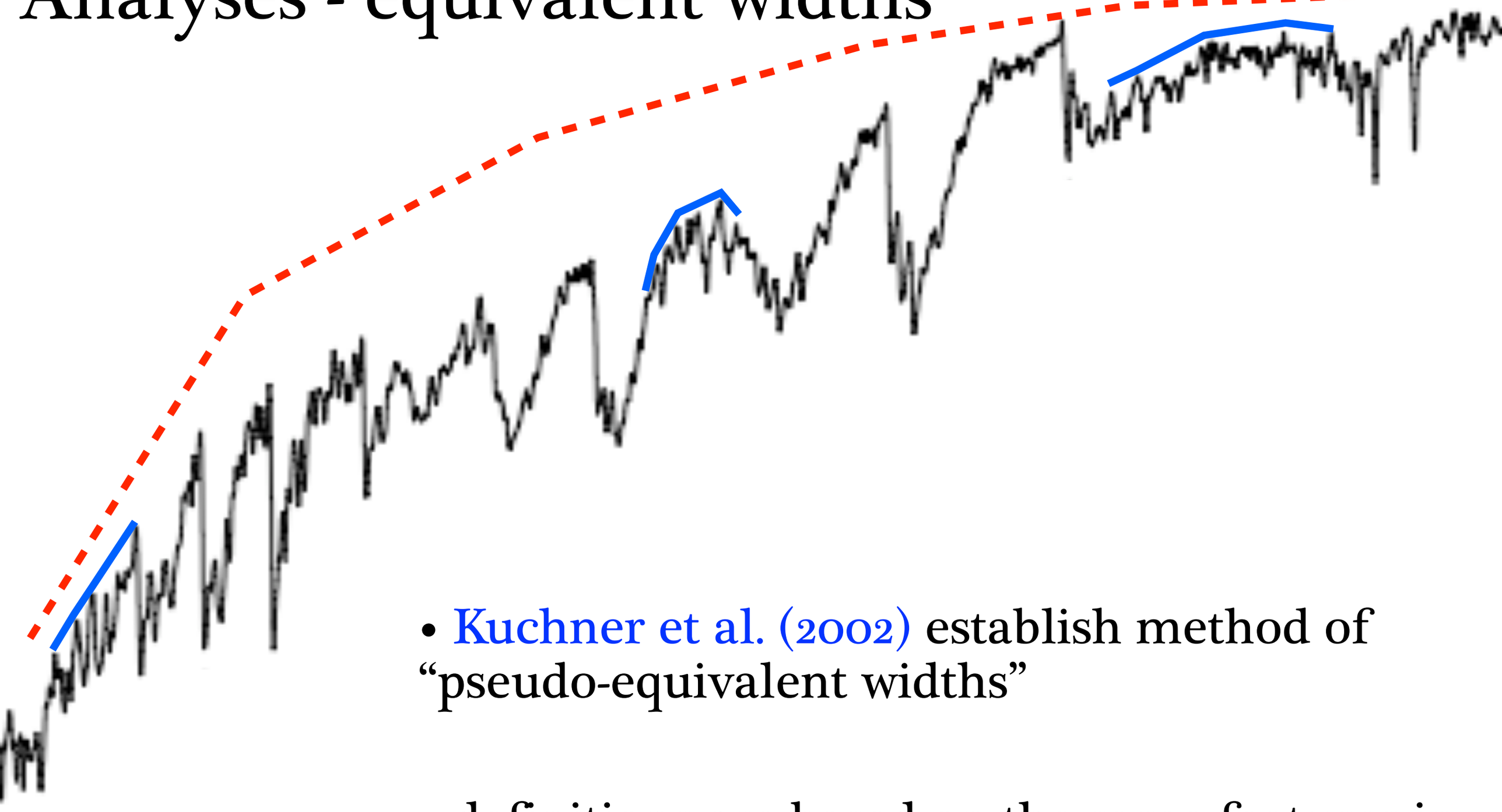
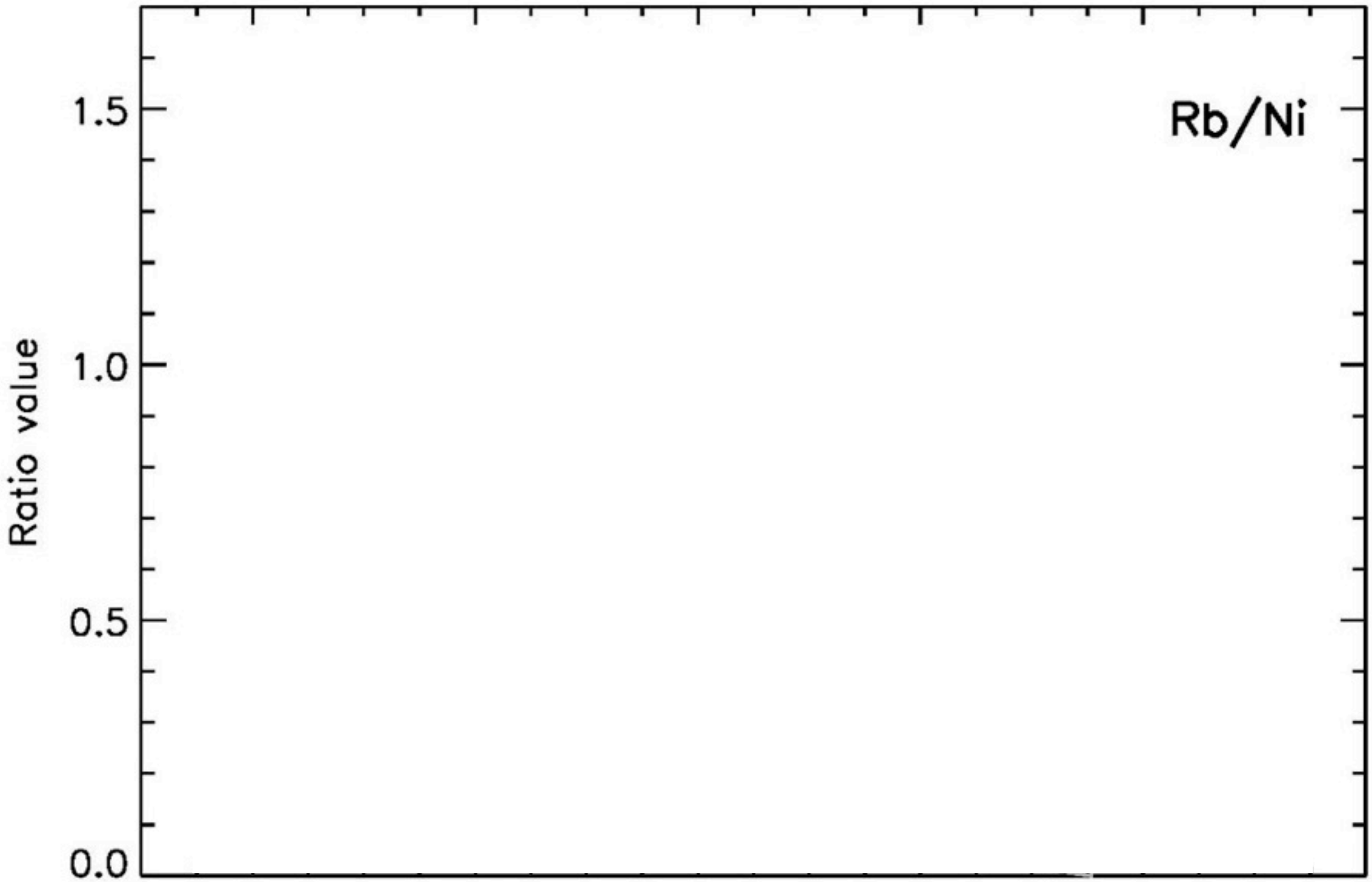
Analyses - equivalent widths

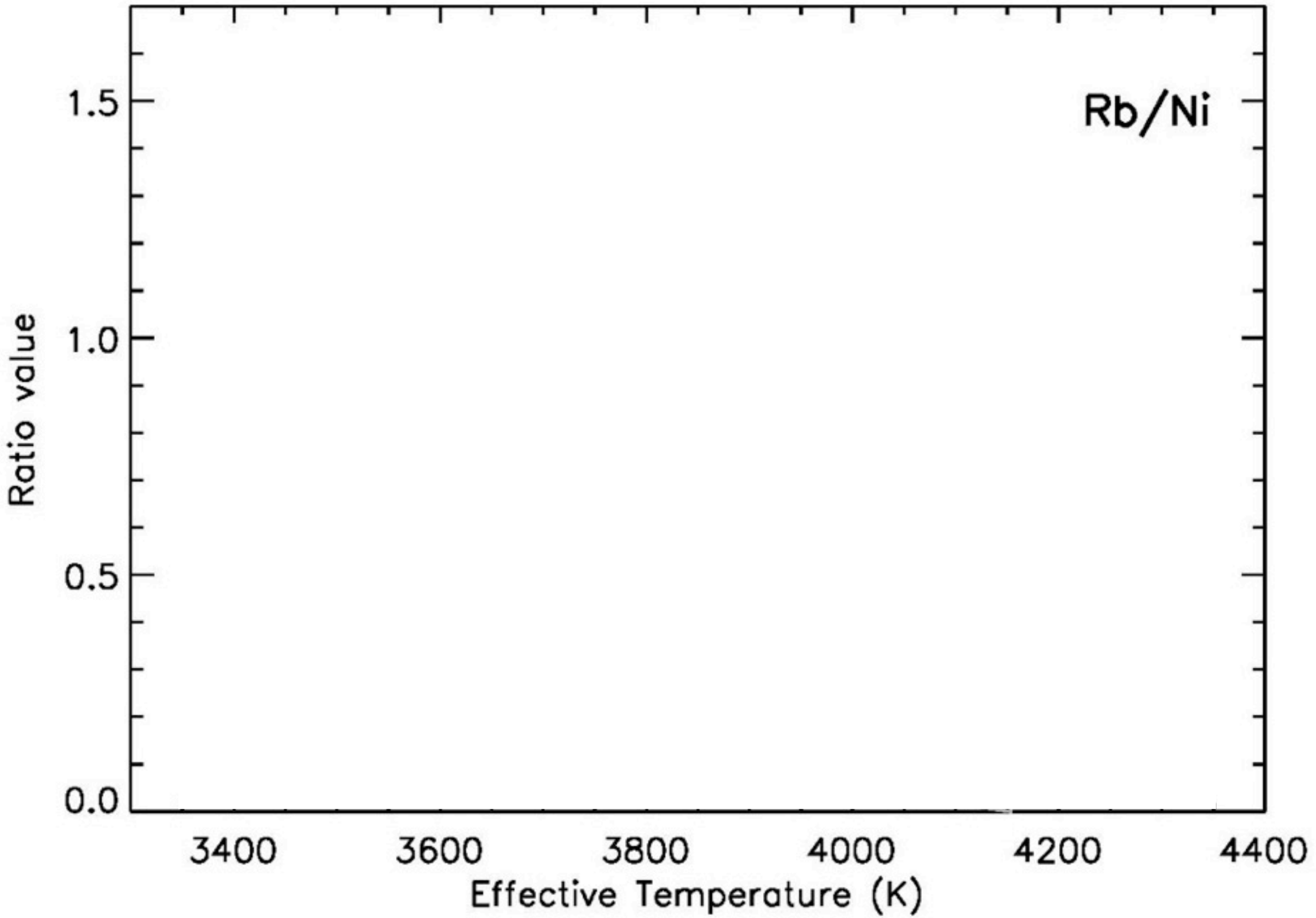


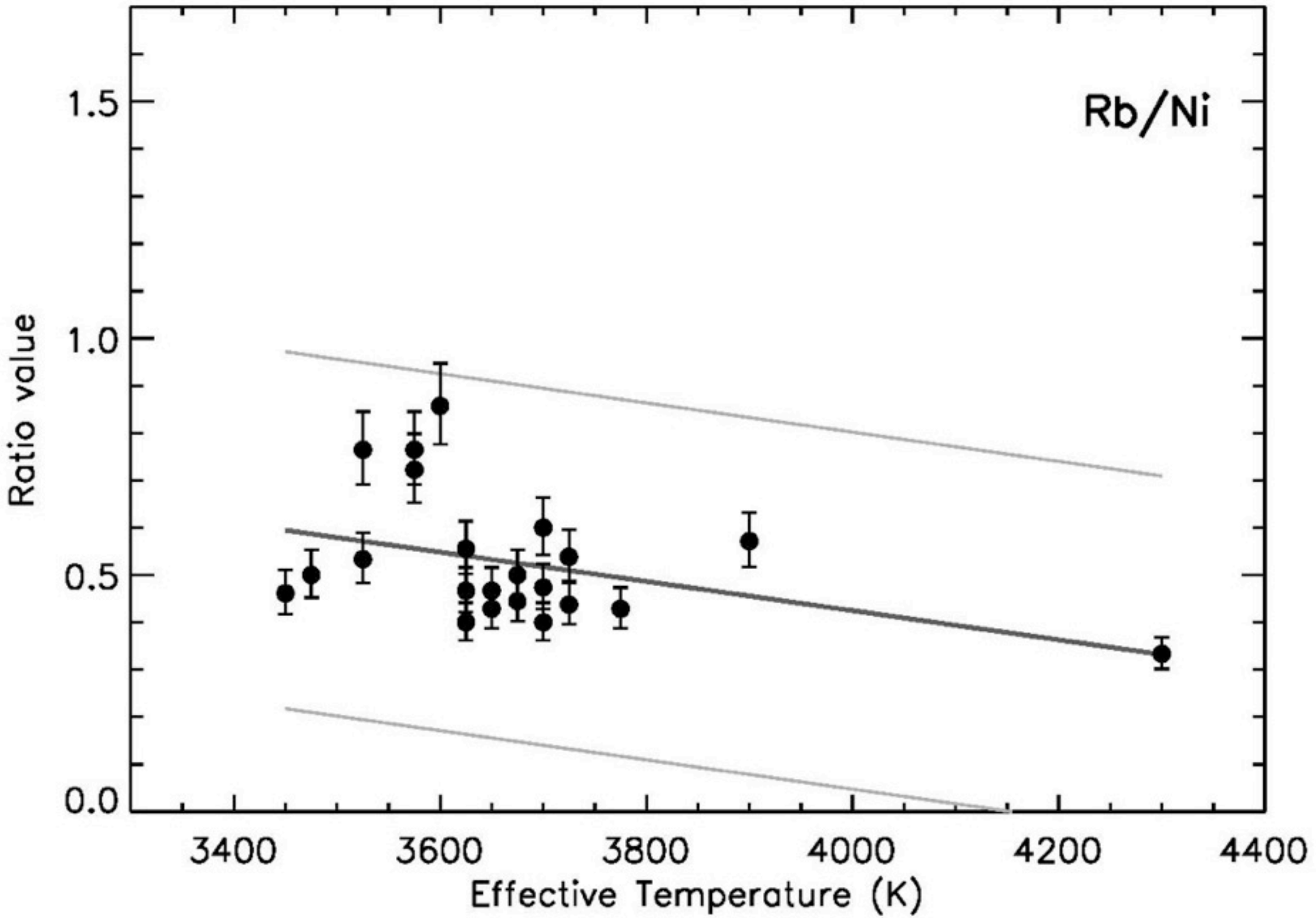
- Kuchner et al. (2002) establish method of "pseudo-equivalent widths"

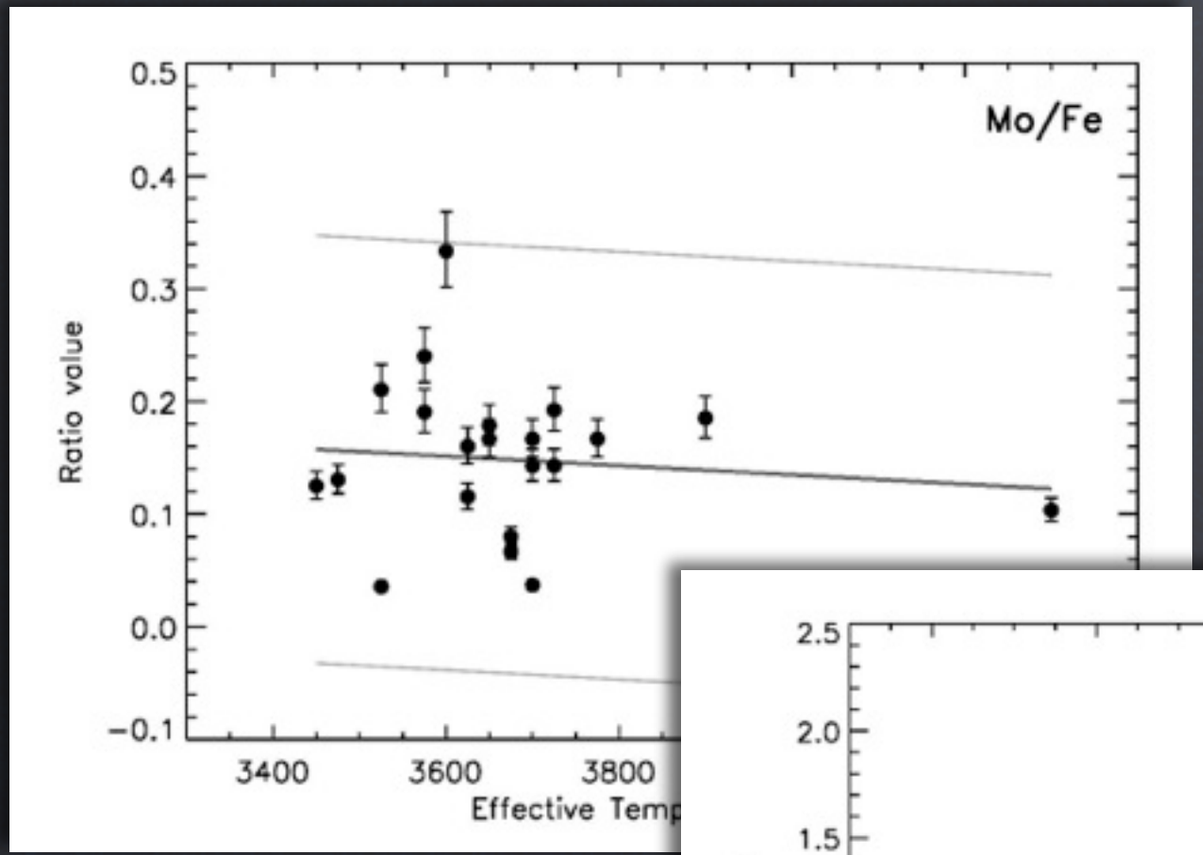
- definitions are based on the same features in each spectrum

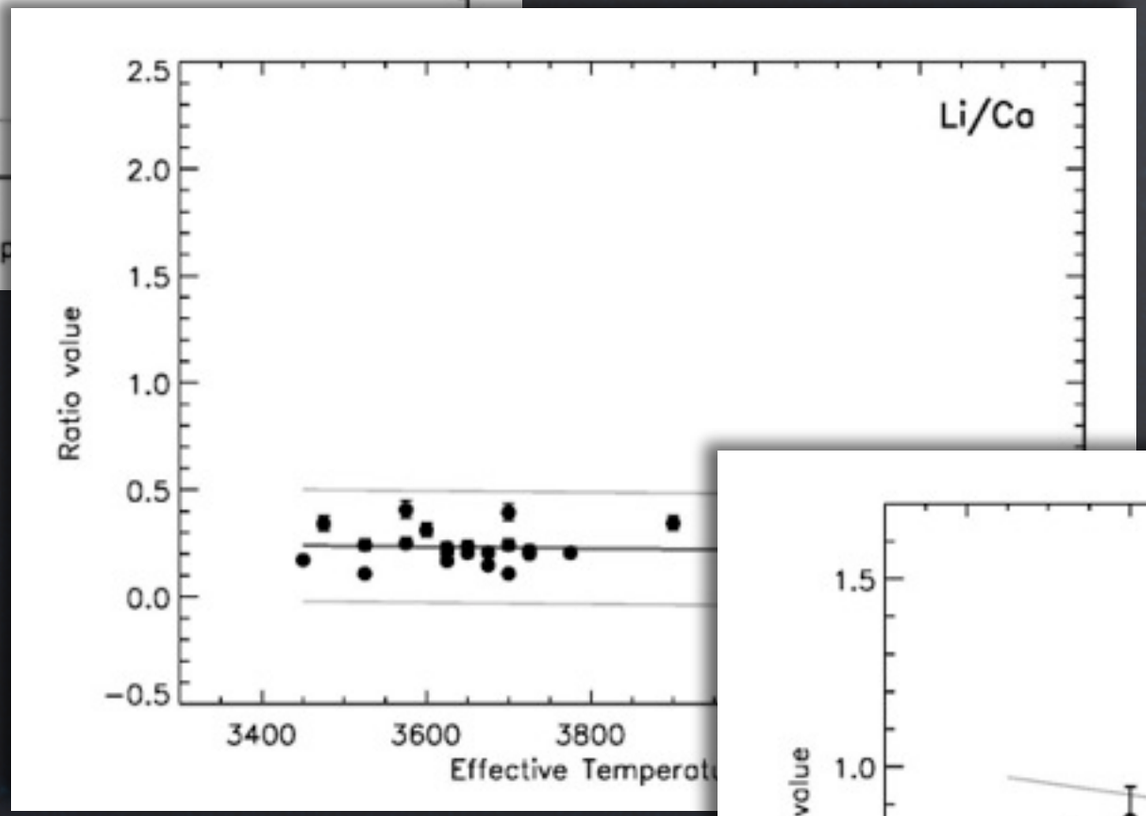
- all spectral features used depend on T_{eff}...

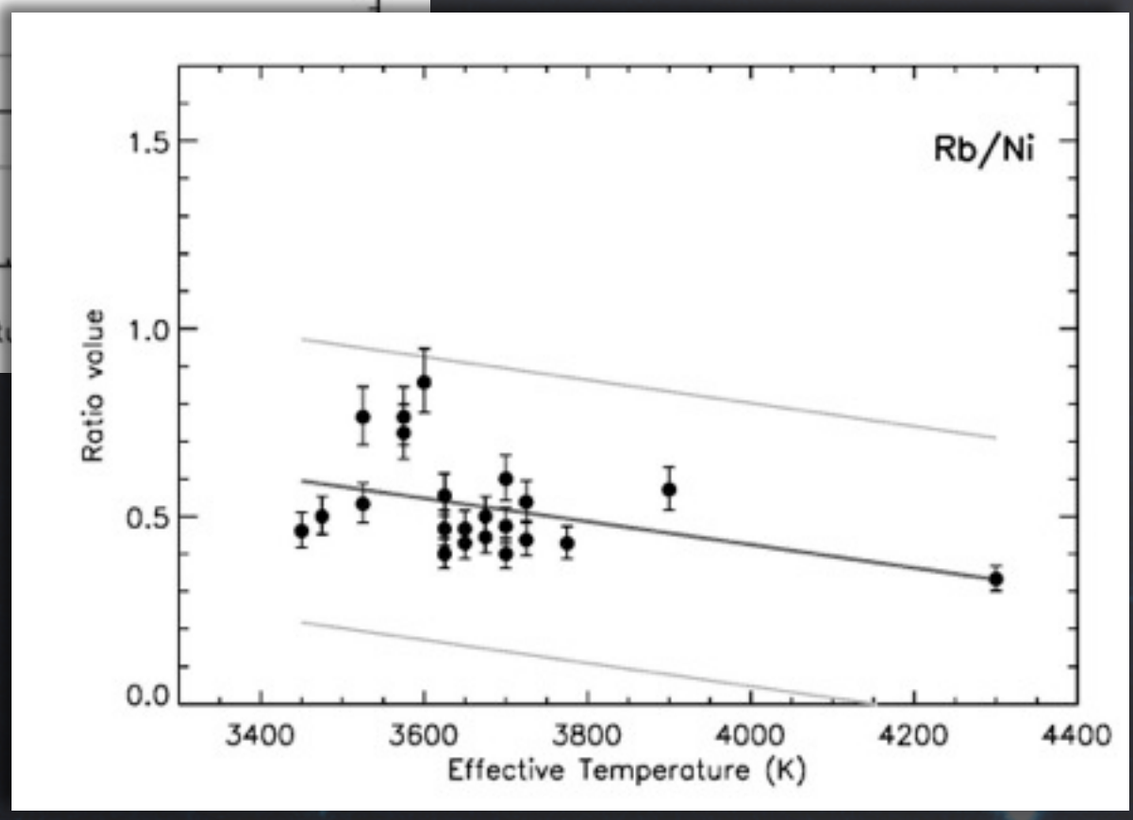

Rb/Ni
Ratio value
1.5
1.0
0.5
0.0

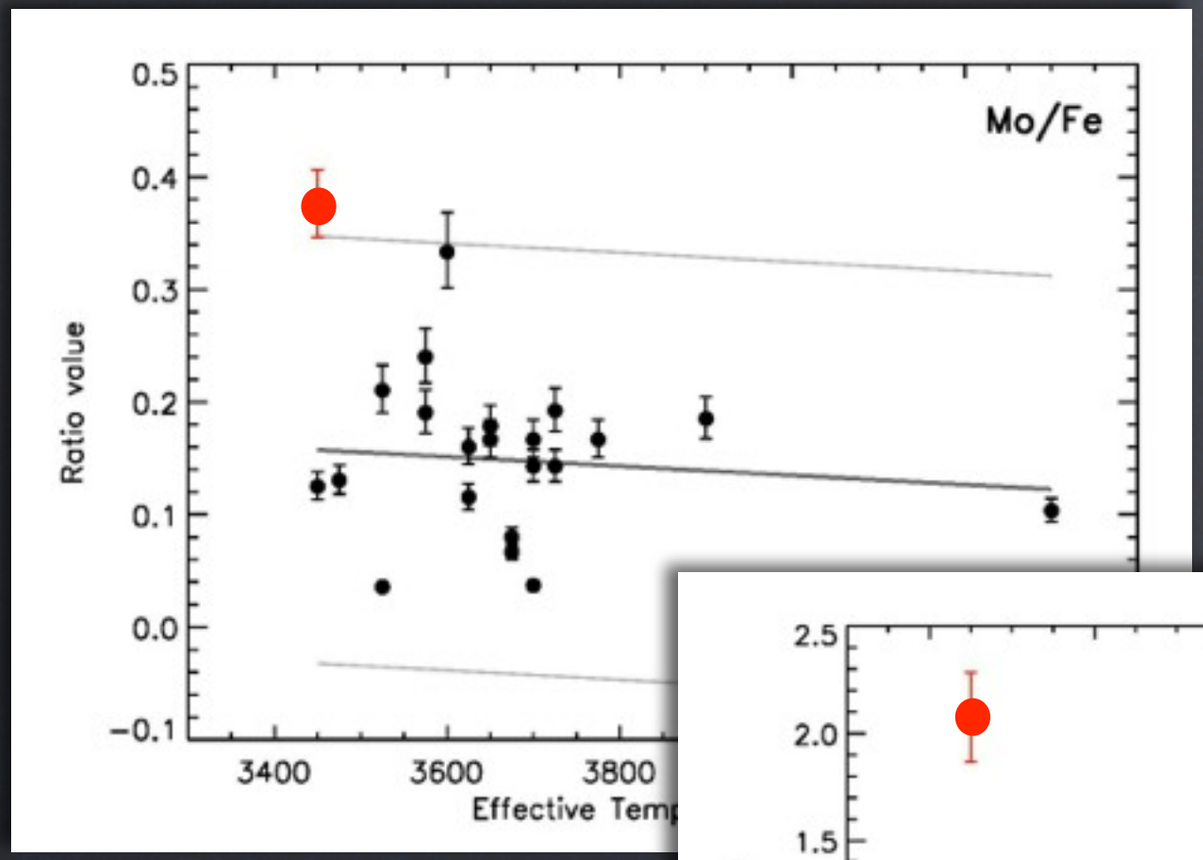

Rb/Ni
Ratio value
1.5
1.0
0.5
0.0
3400
3600
3800
4000
4200
4400
Effective Temperature (K)

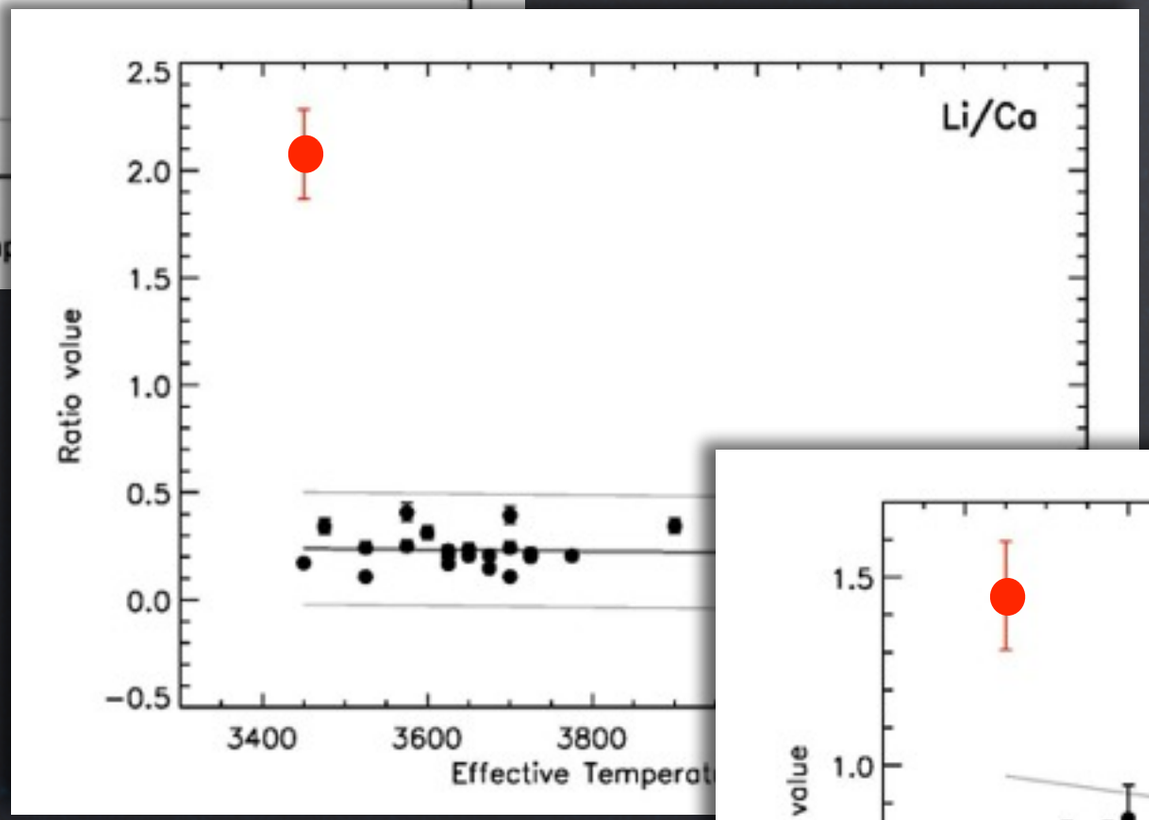

Rb/Ni
1.5
1.0
0.5
0.0
Ratio value
3400
3600
3800
4000
4200
4400
Effective Temperature (K)

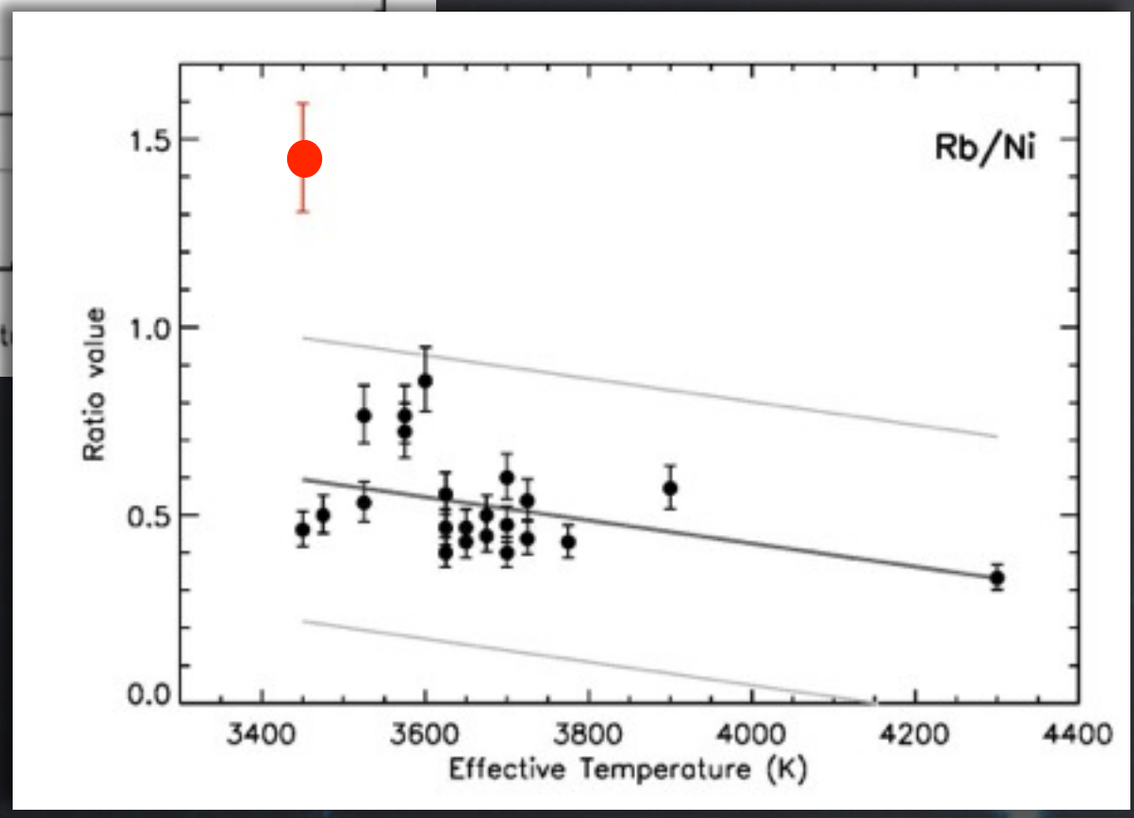

Mo/Fe
Ratio value
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
3400
3600
3800
Effective Temp


Li/Co
Ratio value
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
3400
3600
3800
Effective Temperatu

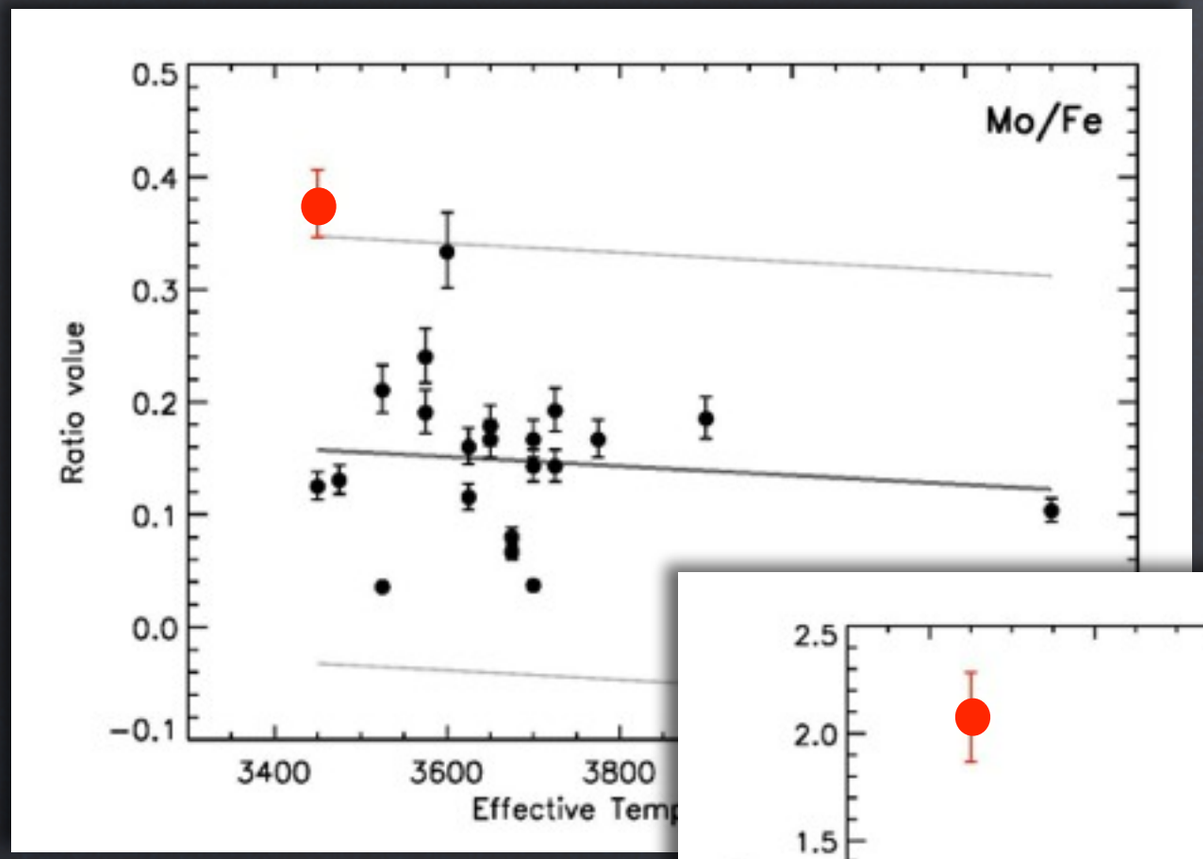

Rb/Ni
Ratio value
1.5
1.0
0.5
0.0
3400
3600
3800
4000
4200
4400
Effective Temperature (K)

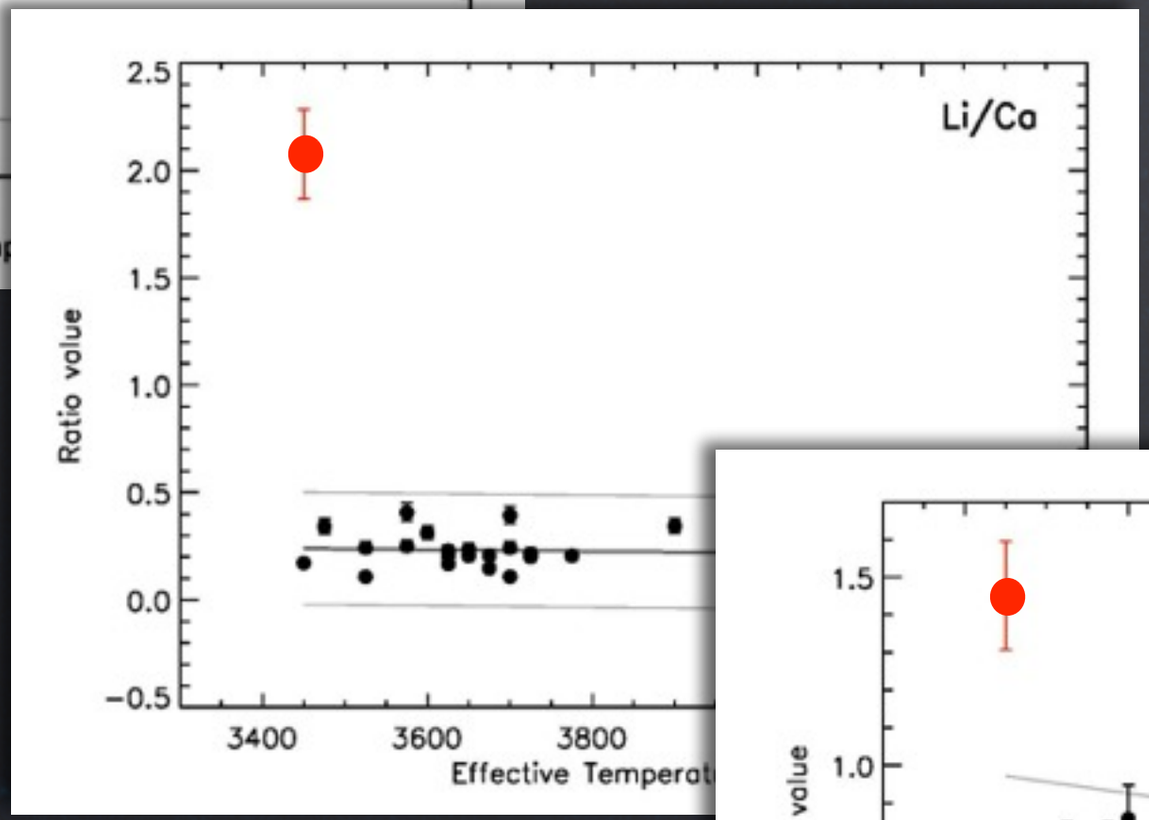

Mo/Fe
Ratio value
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
3400
3600
3800
Effective Temp

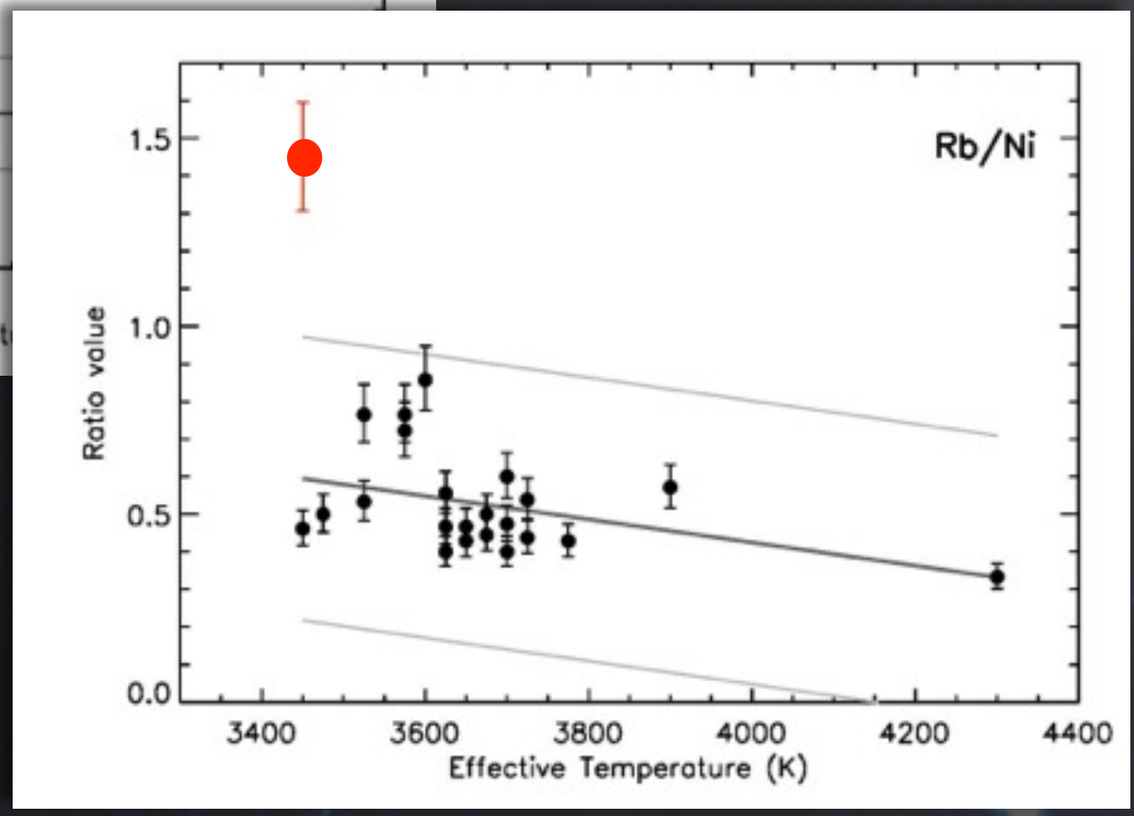

Li/Ca
Ratio value
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
3400
3600
3800
Effective Temperat


Rb/Ni
Ratio value
1.5
1.0
0.5
0.0
3400
3600
3800
4000
4200
4400
Effective Temperature (K)

HV 2112;
TŻO candidate!







Mo I

Li I

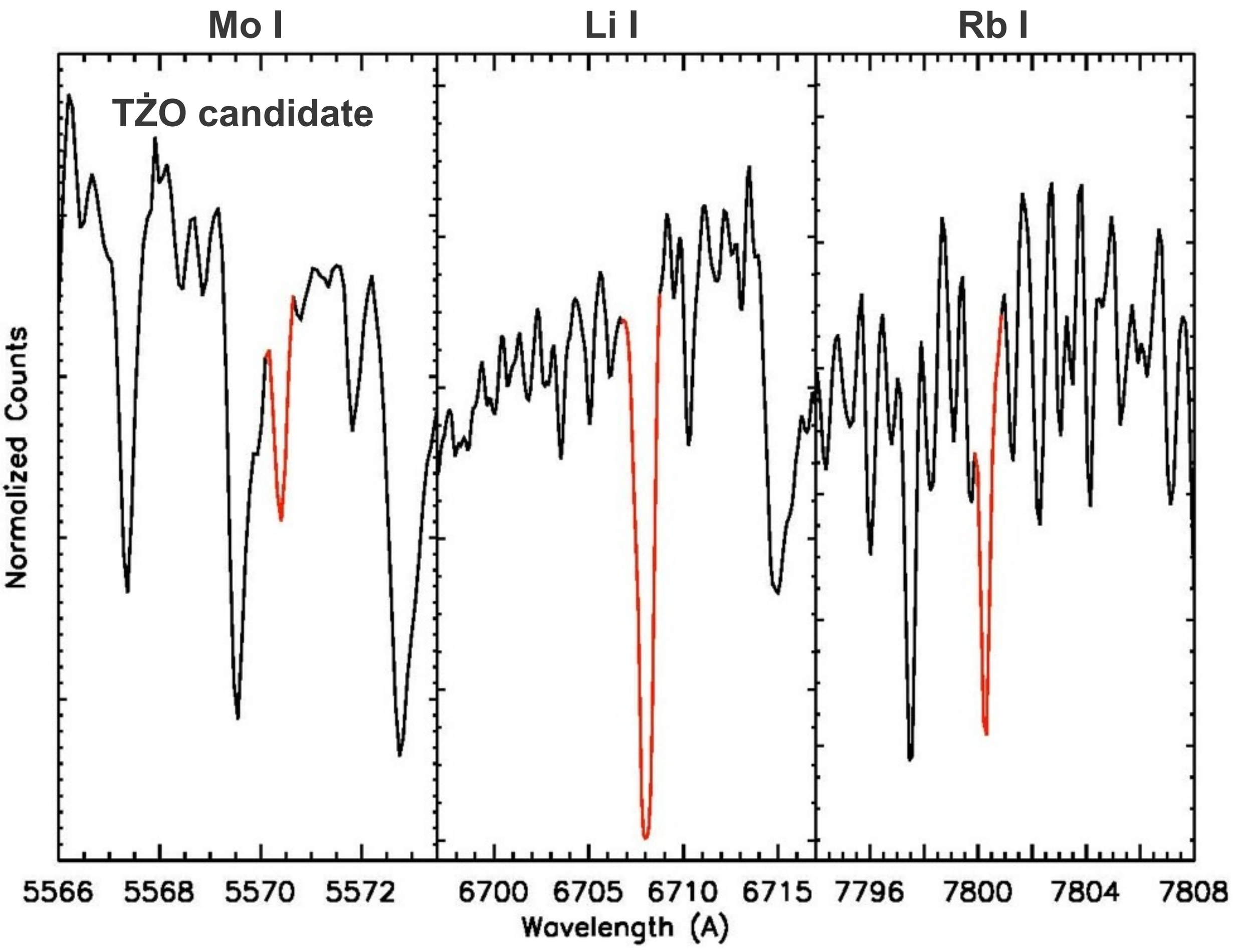
Rb I

Typical RSG

Normalized Counts

5566 5568 5570 5572 6700 6705 6710 6715 7796 7800 7804 7808

Wavelength (A)

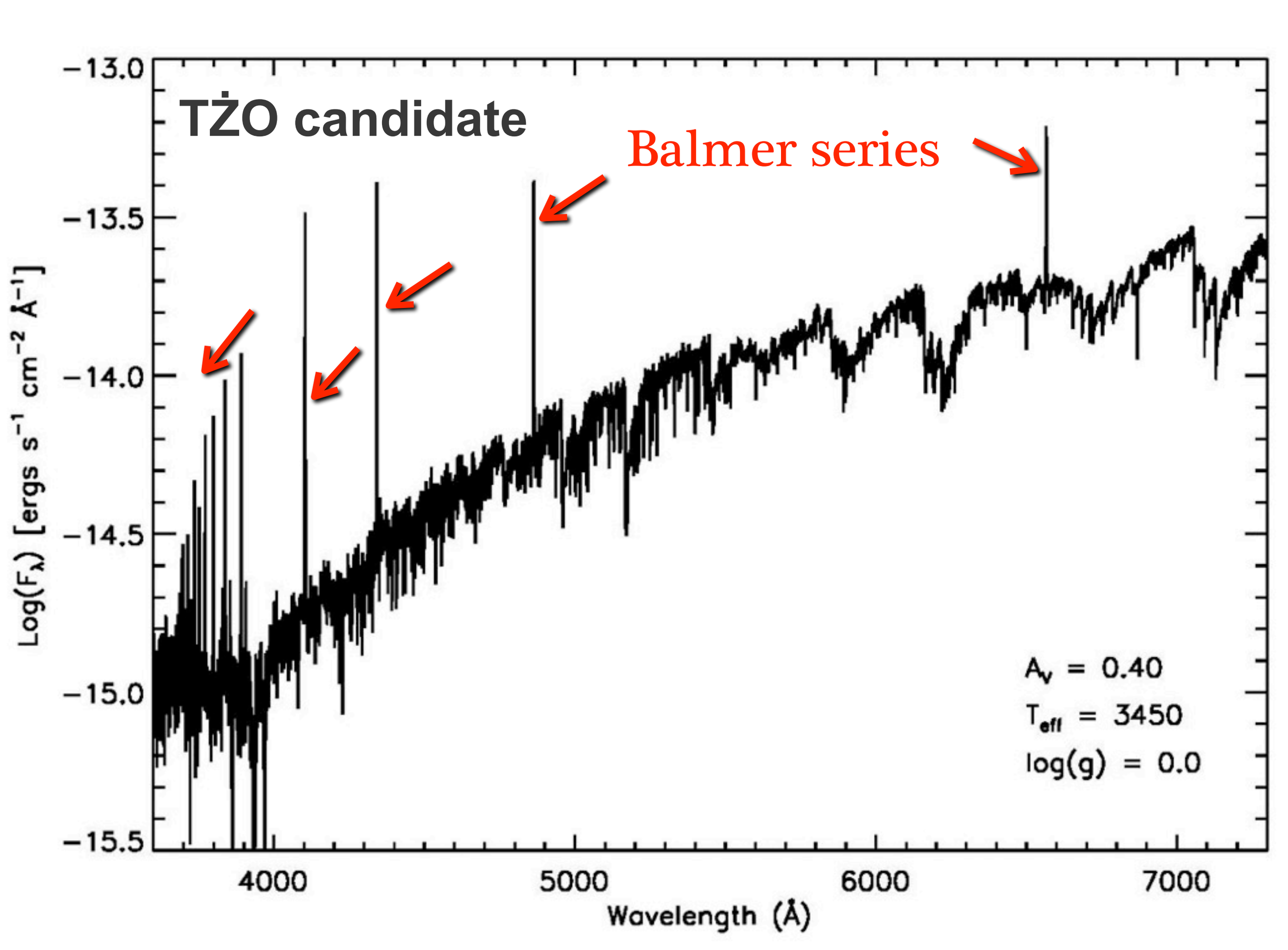

Mo I
Li I
Rb I
TŻO candidate
Normalized Counts
5566
5568
5570
5572
6700
6705
6710
6715
7796
7800
7804
7808
Wavelength (A)

TŻO candidate
(raw data)

TŻO candidate
(raw data)

TŻO candidate (raw data)

"I don't know what it is, but I know that I like it!" ~Nidia Morrell


TŻO candidate
Balmer series
−13.0
−13.5
−14.0
−14.5
−15.0
−15.5
Log(F$_\lambda$) [ergs s^{-1} cm^{-2} Å^{-1}]
4000
5000
6000
7000
Wavelength (Å)
A$_V$ = 0.40
T$_{eff}$ = 3450
log(g) = 0.0

But couldn't it be a...

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AGB/Mira in the SMC/Milky Way?

- M_{bol} is too high for SMC, falling above even the "super-AGB" cutoff; halo giant with a serendipitous RV quite unlikely

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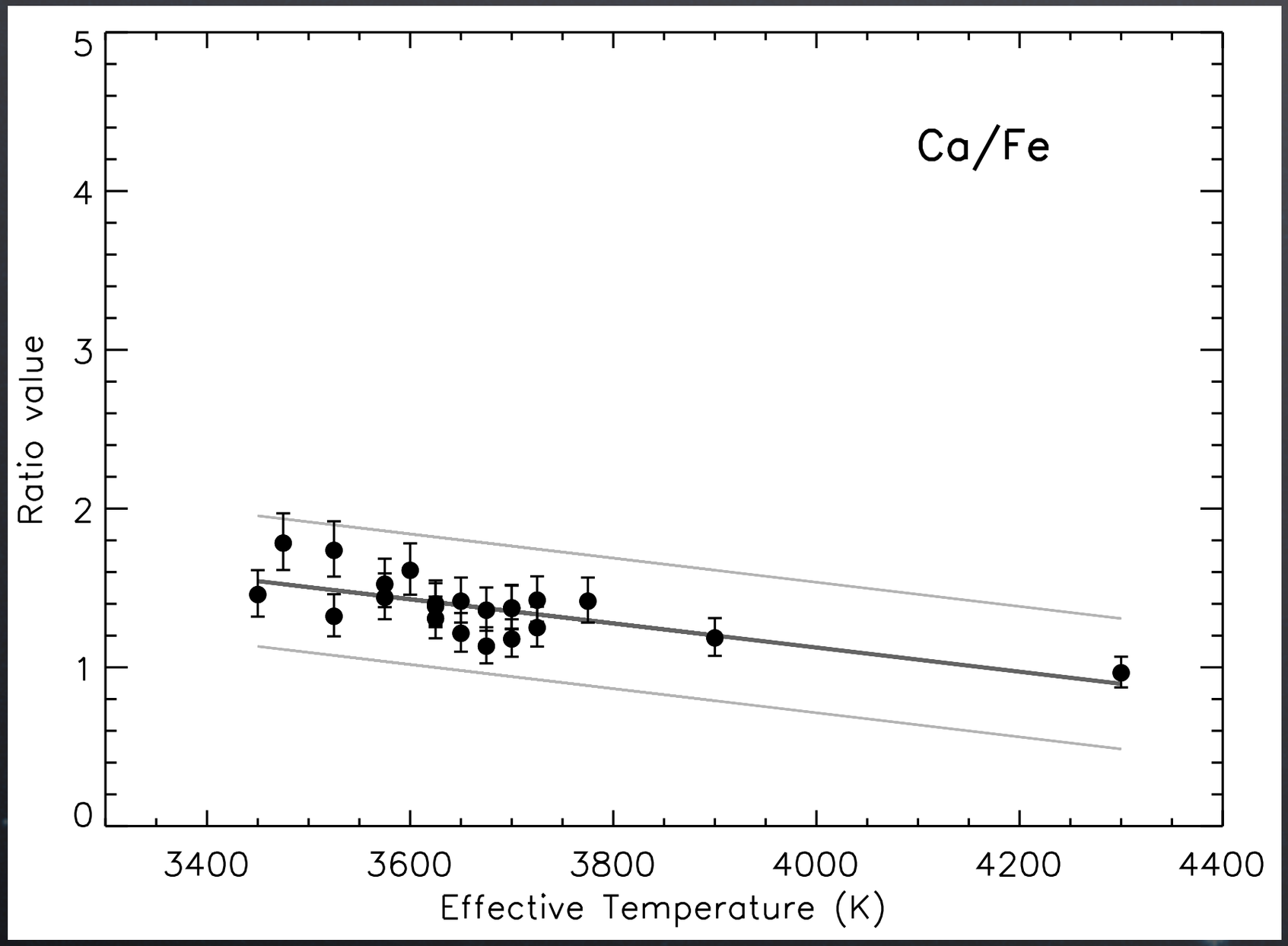

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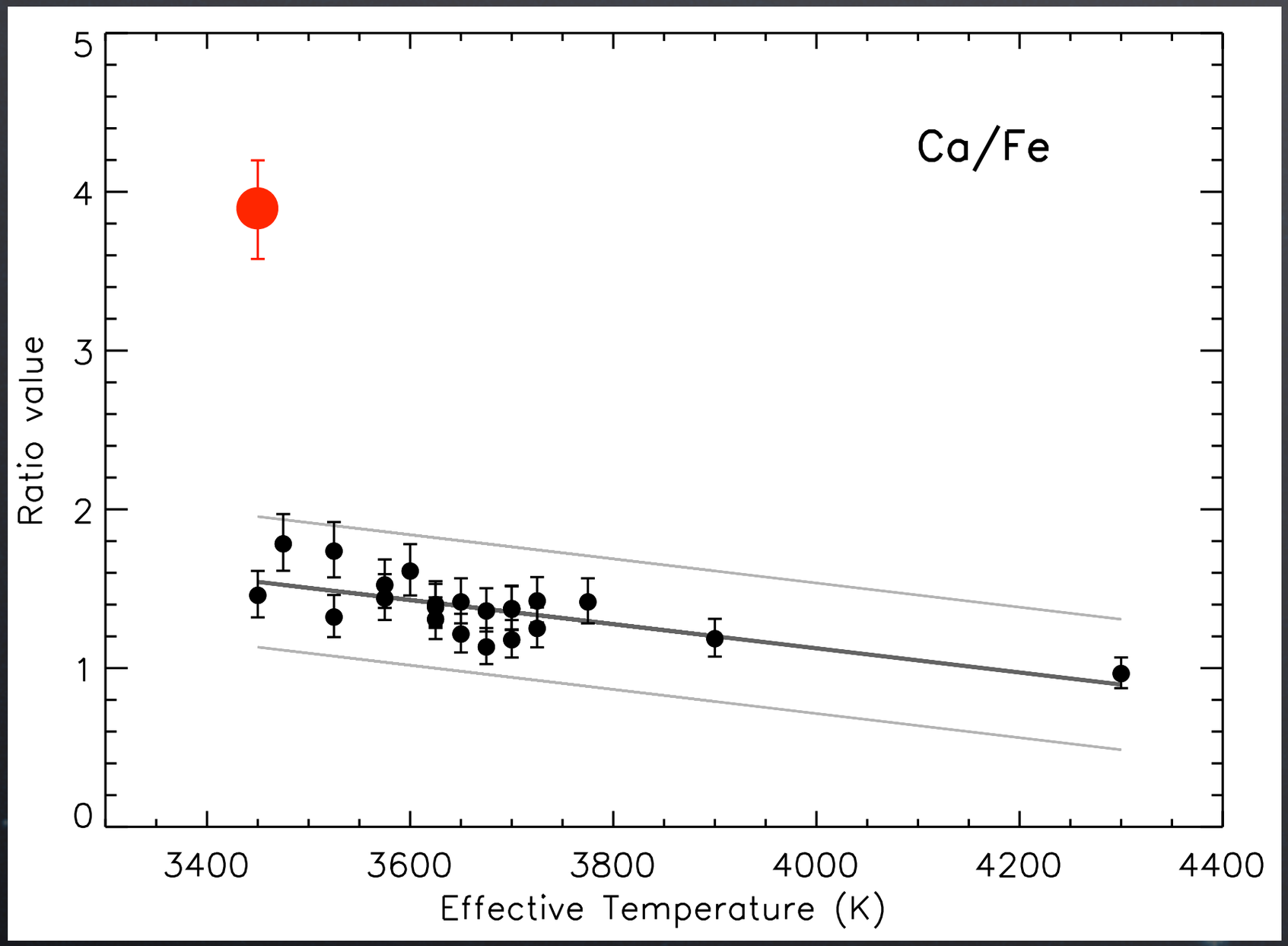

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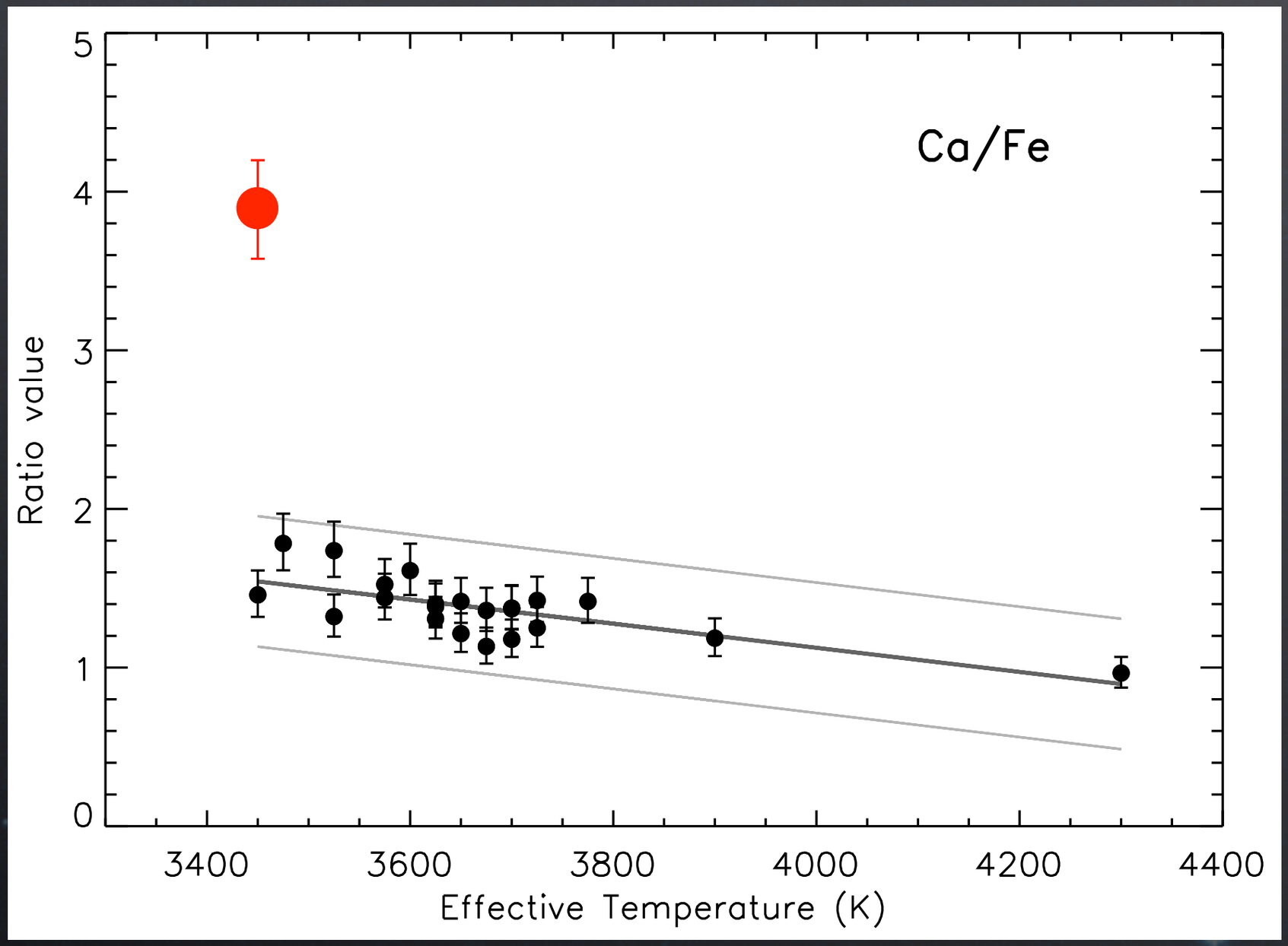
(SAGB stars cannot produce Ca...

...but TŻO formation can!)

Tout et al. (2014)



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foreground dwarf?

- radial velocity of 157 km s^{-1} agrees with SMC kinematics
- not a flaring M dwarf; H emission lasted over 2 nights

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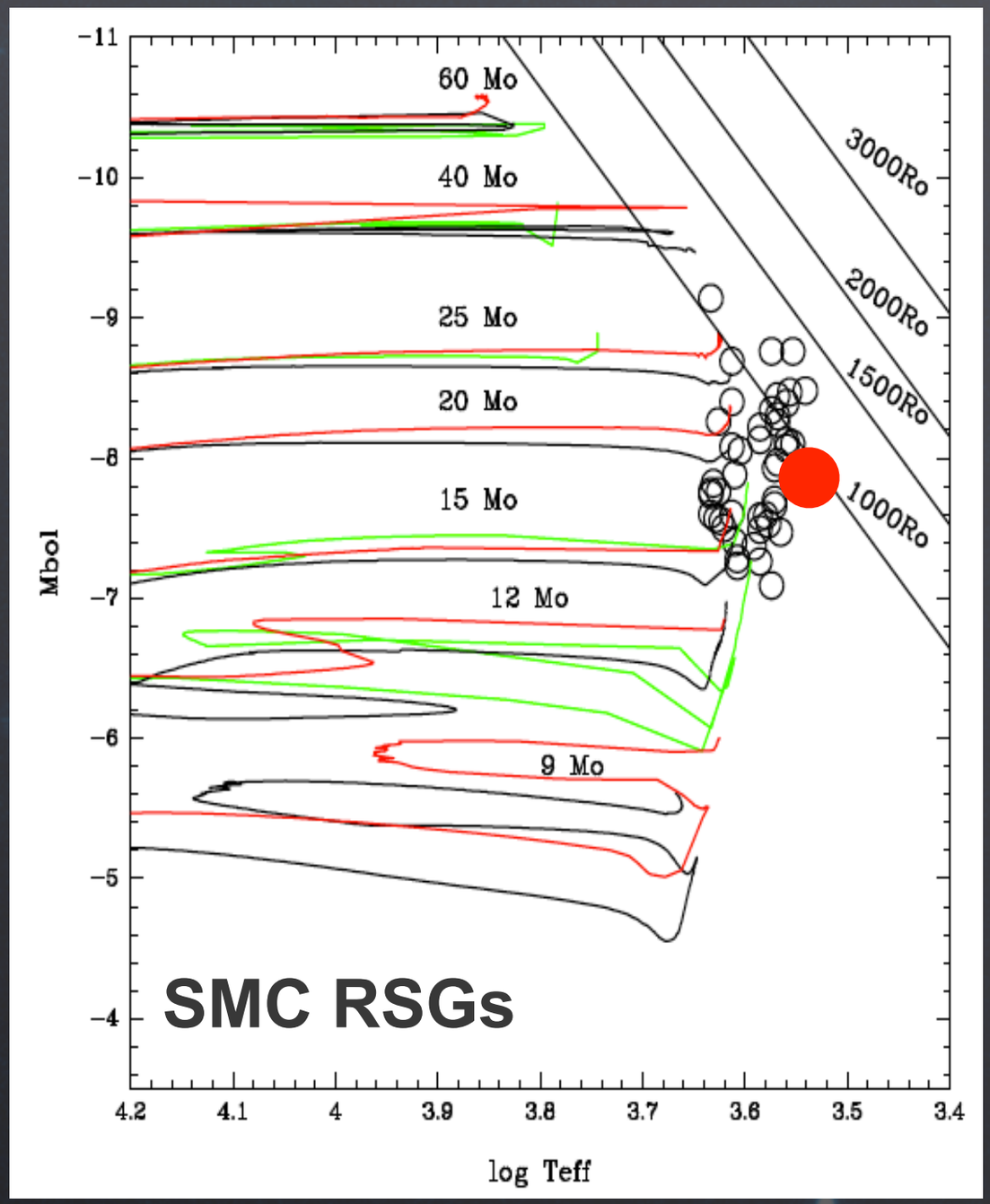
VV Cep/symbiotic-ish binary?

- not a binary within an ionized common envelope (lacks [NII], [OII], [OIII], etc.)
- OB companion strong enough to produce the Balmer spectrum would produce a strong blue continuum

Properties of our TŻO Candidate

- cool and luminous, lying at or beyond the Hayashi limit for massive stars (Thorne & Żtykow 1977)
- strongly mass-losing as a result (van Paradijs et al. 1995)
- potentially more common at low Z (Linden et al. 2010)
- unique chemical profile (Biehle 1994)



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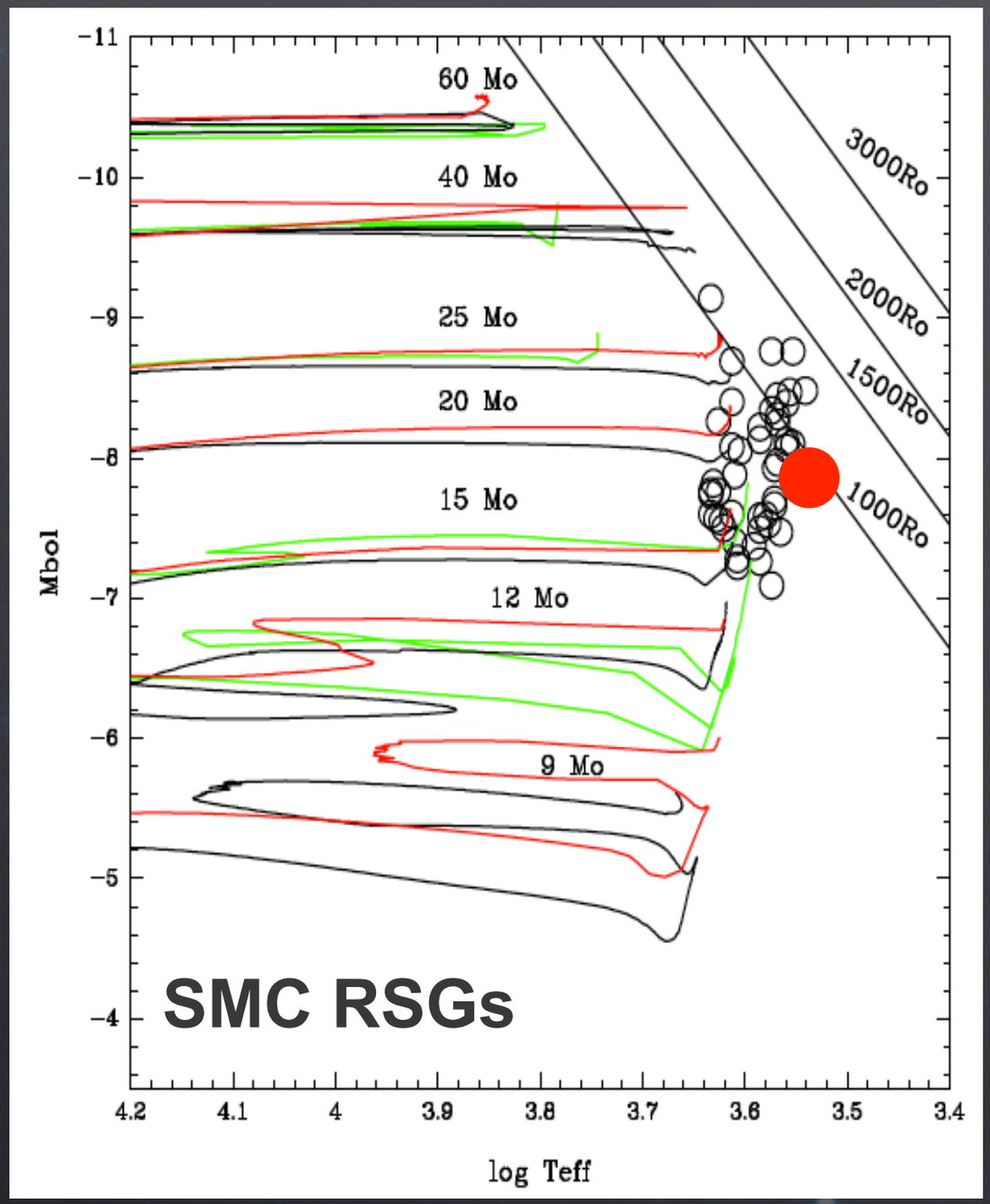

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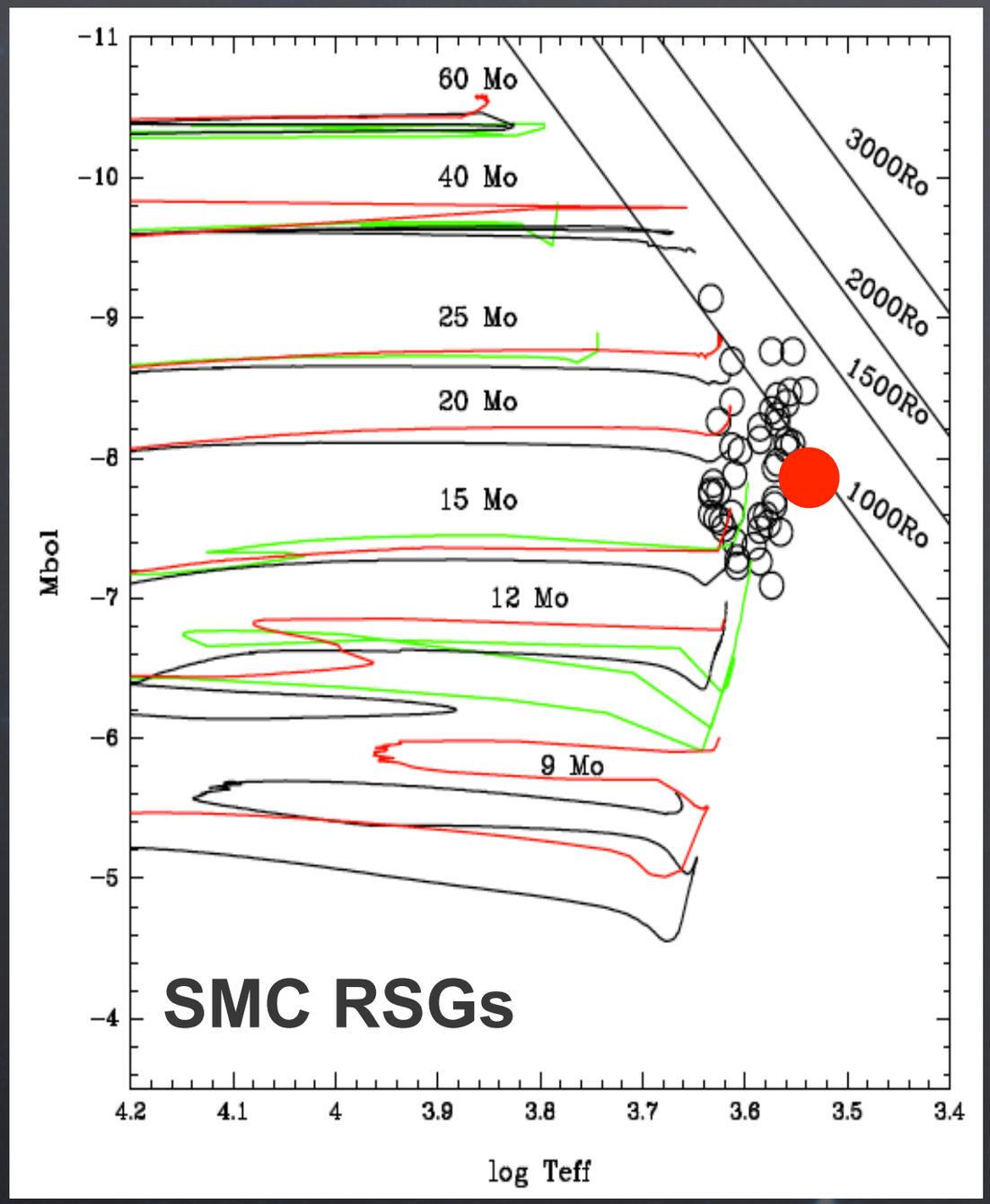

This star represents the most encouraging detection of a TZO to date.

The existence of TŻOs would have profound implications for stellar astronomy.

- completely new model of stable stellar interiors
- a new fate of massive binaries
- new nucleosynthesis channels for Li and heavy elements

Discovery of a Thorne-Żytkow Object Candidate in the SMC

Emily Levesque
University of Colorado at Boulder

Philip Massey (Lowell Observatory), Anna Żytkow (Cambridge), Nidia Morrell (LCO)

Virtual Institute of Astroparticle physics

Aug 22, 2014

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"Extraordinary claims require extraordinary evidence."
- the "Sagan Standard"

Virtual Institute of Astroparticle physics

Aug 22, 2014

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What's next?

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What's next?

- Compute modern models of TŻO interiors
- Determine other observable signatures of TŻOs
- Identify TŻO populations in (and beyond) the Local Group

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- Determine other observable signatures of TŻOs
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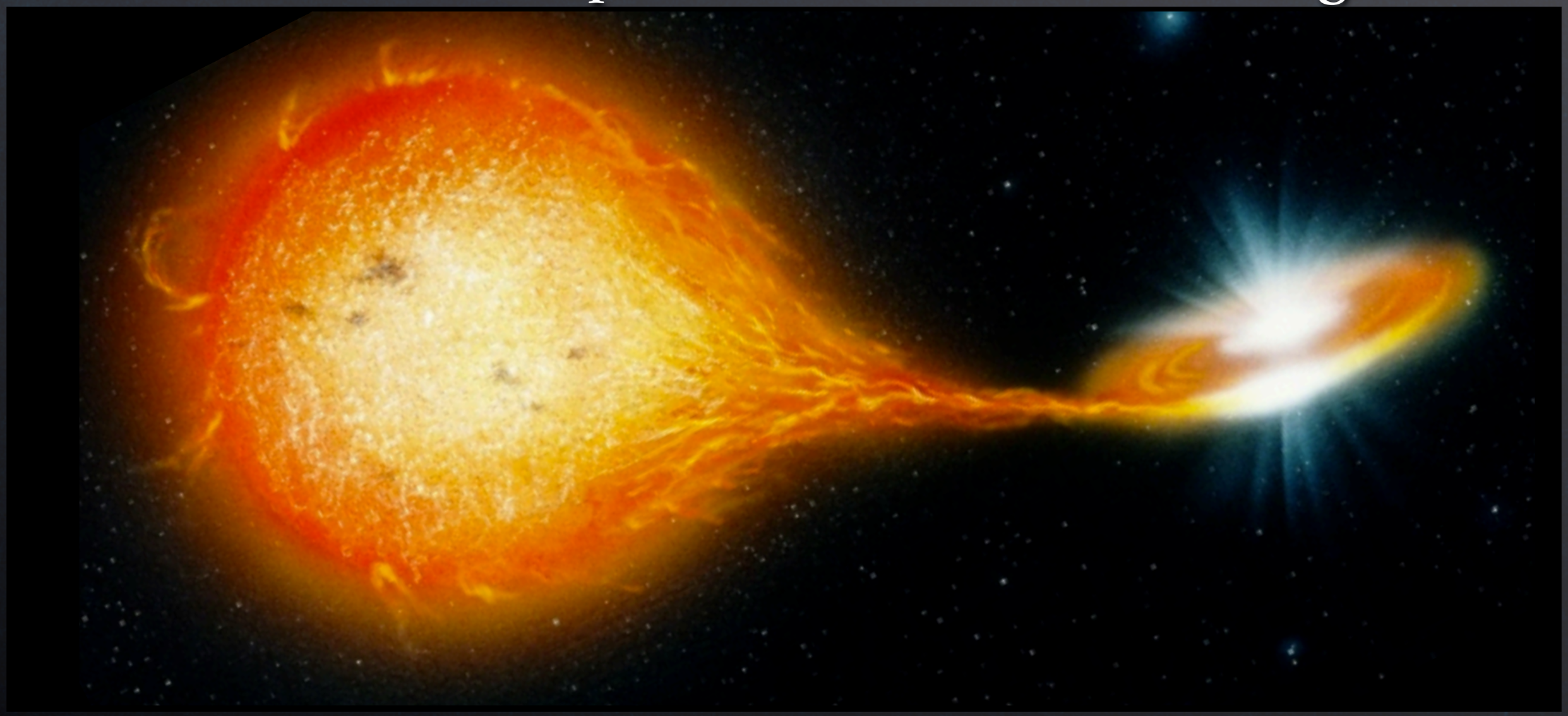
Other questions...

- what are the properties of proto-TŻOs?
- what are the lifetimes of TŻOs?
- what is the terminal product of a TŻO?

More exciting questions...

- What are TŻO evolutionary tracks like?
- How do they contribute to the chemistry of the universe?
- How many are there?
- How do TŻOs affect models of clusters? Stellar pops? Binaries?
- Are their numbers Z-dependent? Are there more at high z?...



Why don't the "abundances" match?

The models are dated!

-- Biehle (1994) does not use a full rp reaction network.

-- Cannon (1993) states that more work is required on envelope convecton and a more extensive reaction network is required to produce reliable abundances

-- there are unresolved issues with overshooting, mixing length theory, and convection models.

Where is the supernova kick velocity?

Kick would only appear in the Leonard et al. (1994) model and...

-- average runaway velocity of a Leonard TZO is 75 km/s

-- our candidate is at 157 km/s; even in "worst-case" scenario it's still either 82 km/s or 232 km/s, both still consistent with the range of radial velocities characteristic of SMC members (Neugent et al. 2010)

Past work on our TZO candidate

Known photometric and spectroscopic variable

-included in Harvard Variable catalog (Payne-Gaposchkin & Gaposchkin 1966)

-prior spectral types range from M3e to M7.5 (Wood et al. 1983, Reid & Mould 1990)

Originally incorrectly classified as an AGB star

-M_{bol} lie above "AGB limit" (Wood et al. 1983, Reid & Mould 1990, Smith et al. 1995, Paczynski et al. 1971)

-bolometric corrections for cool stars have since improved (Levesque et al. 2006)

-for variables, contemporaneous observations are also required

-new M_{bol} agrees with an RSG at SMC distance (Maeder & Meynet 2001)

Not previously ID'd as a TZO due to observational limitations

-variable spectrum led to disagreement over Li-rich status (Reid & Mould 1990, Smith et al. 1995)

-spectra lacked sufficient resolution or wavelength coverage for detecting TiO-free TZO features (Wood et al. 1983, Smith et al. 1995)