Granulation-Driven Line Distortions in Disk-Integrated Solar Spectra

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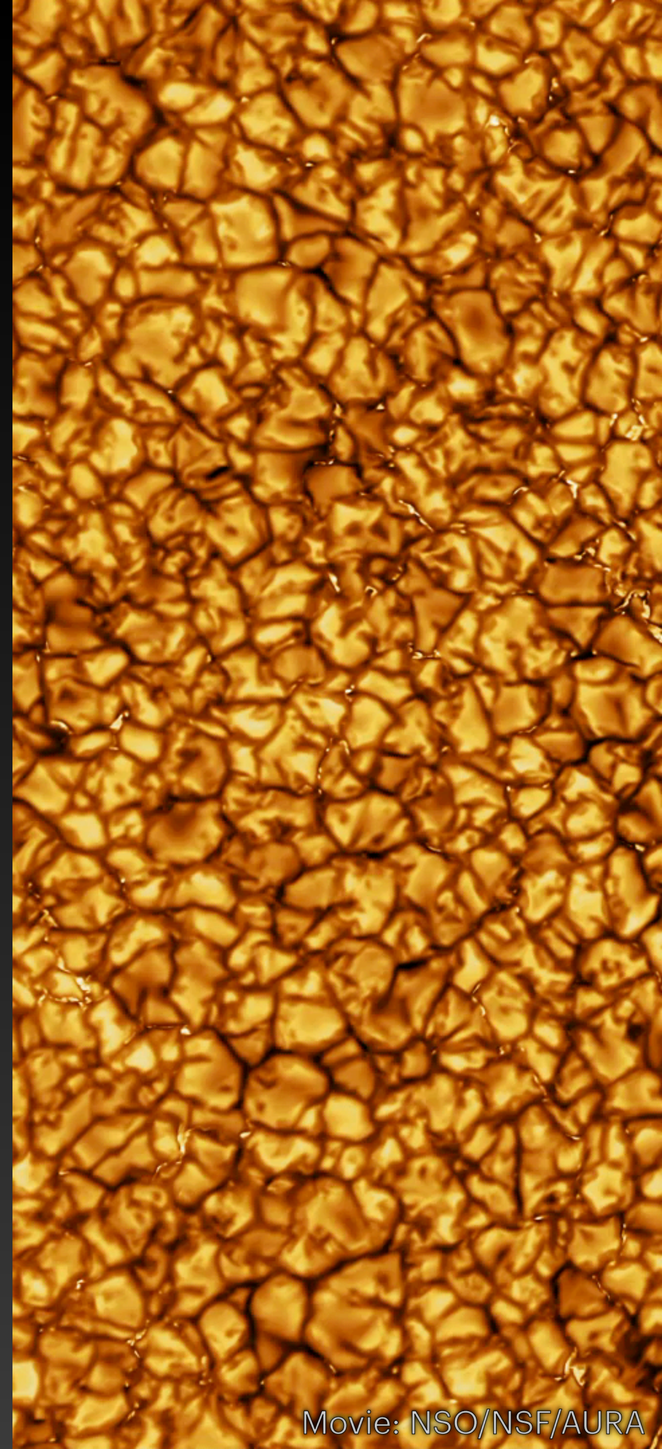
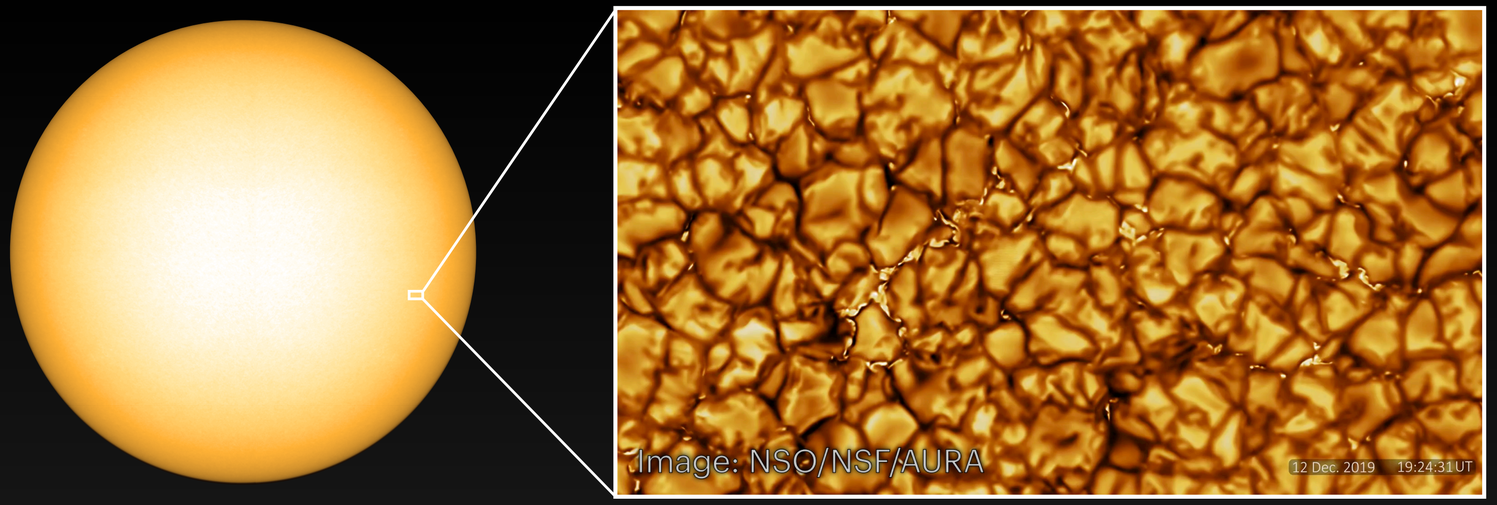
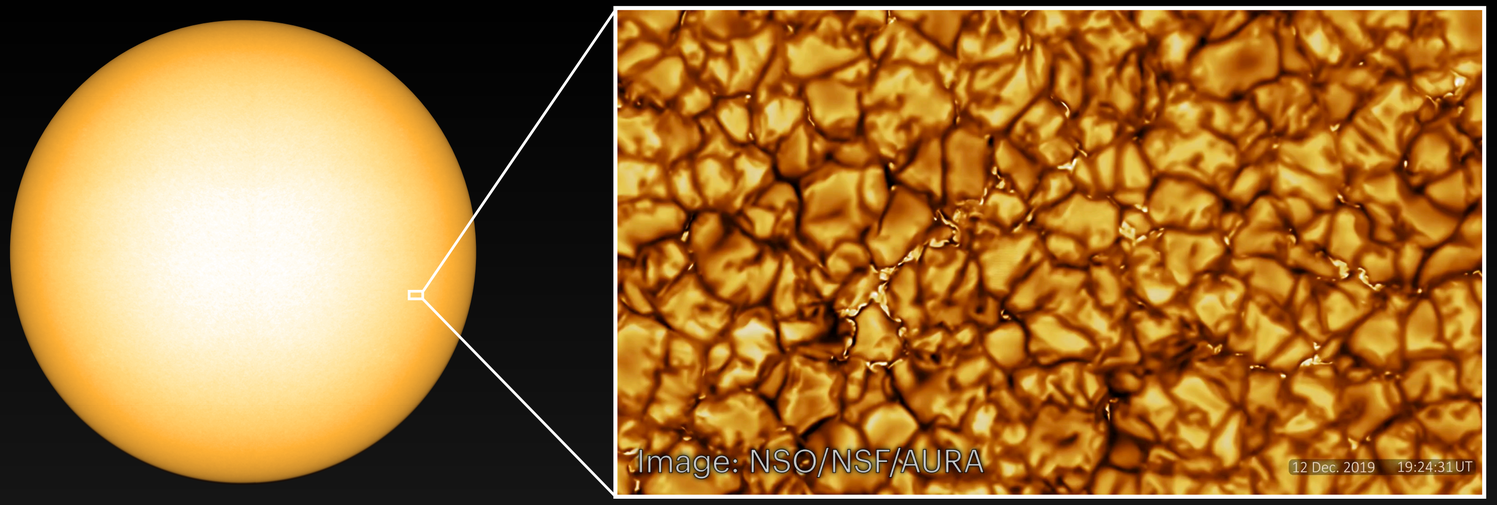


Movie: NSO/NSF/AURA

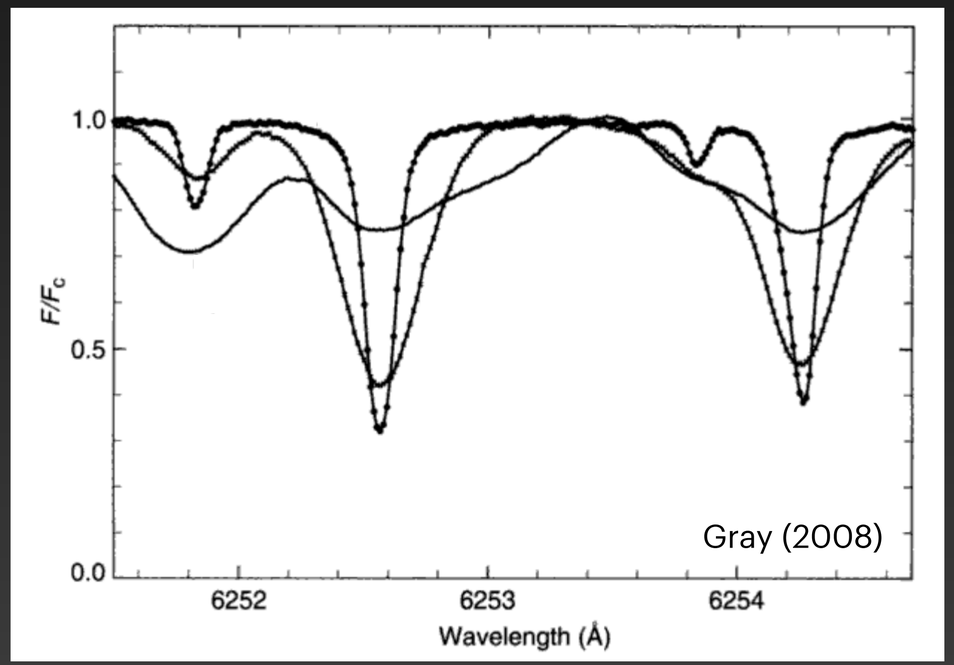


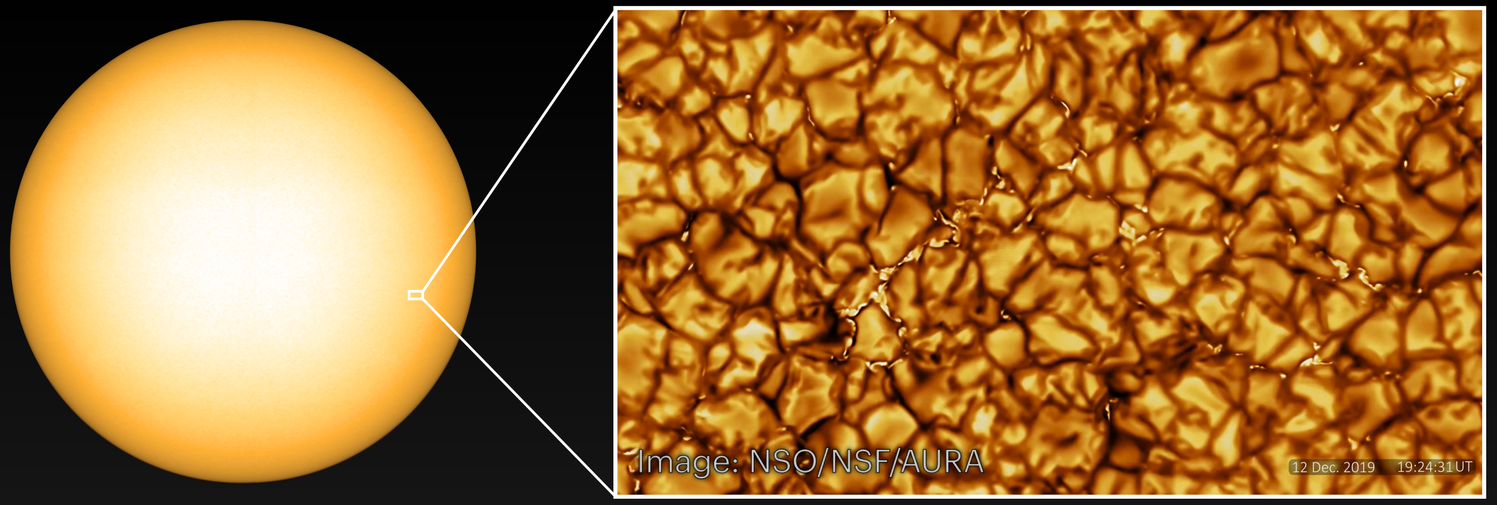
Granulation alters stellar spectra in three key ways



Granulation alters stellar spectra in three key ways

1. Broadening of lines





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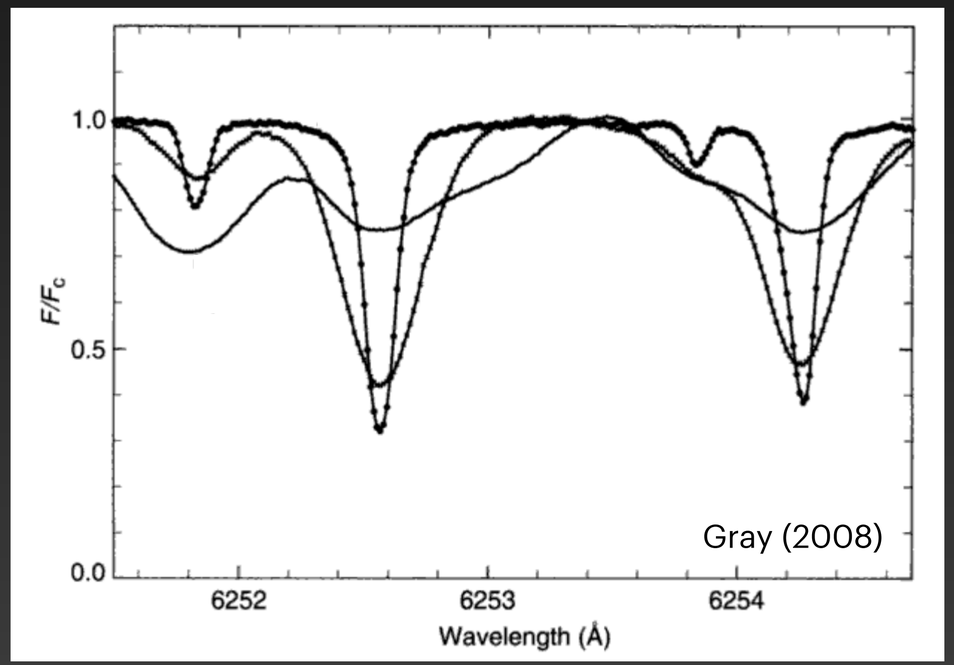
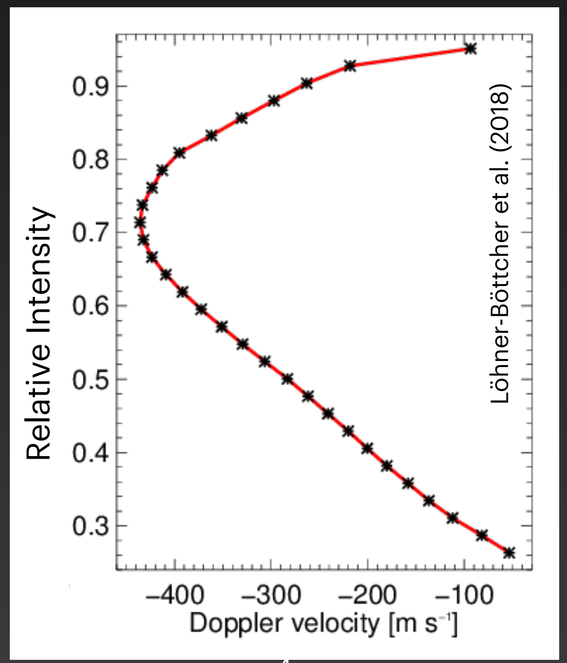
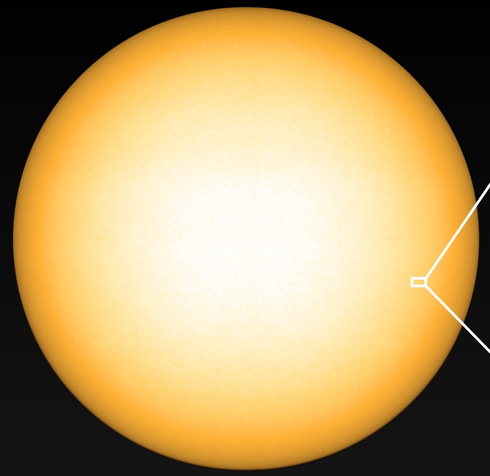
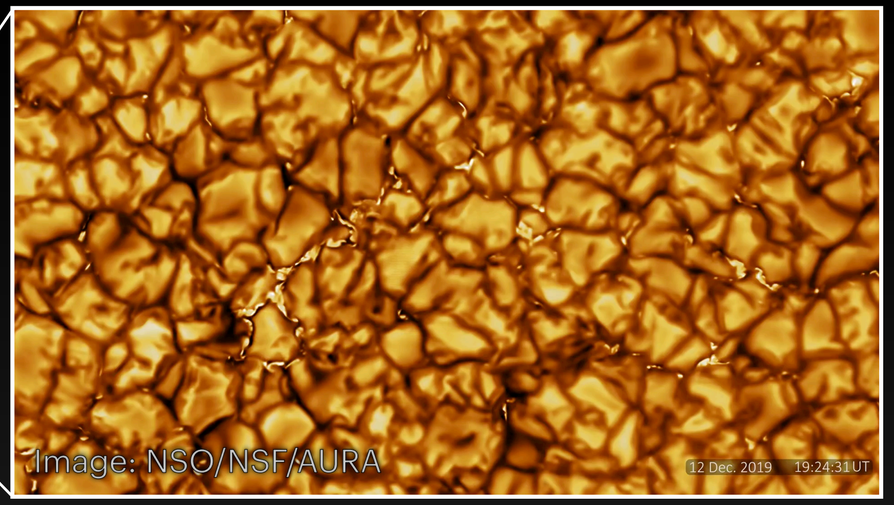


2. Asymmetry of lines







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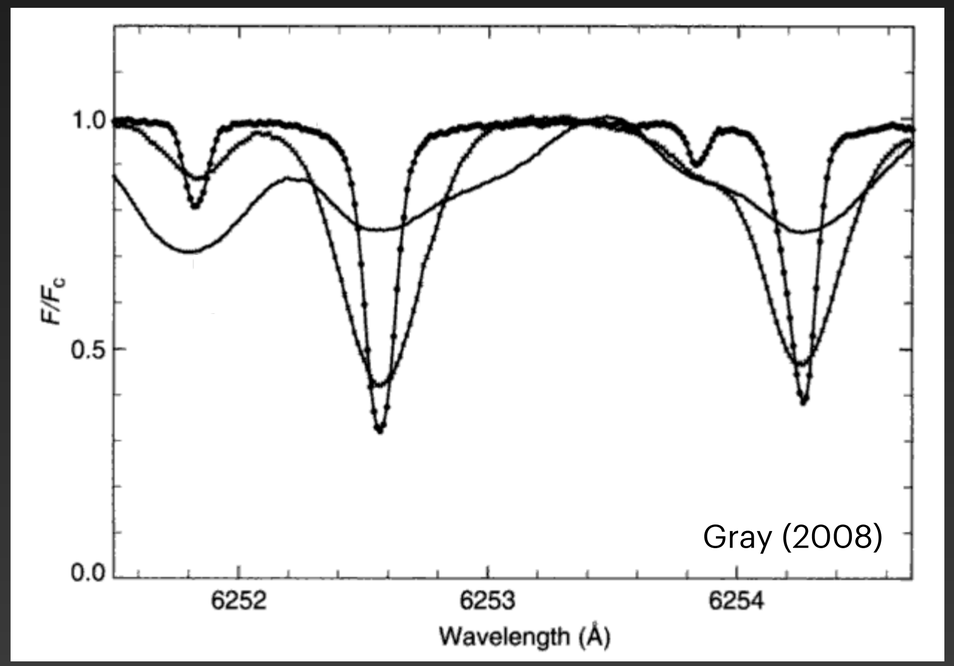

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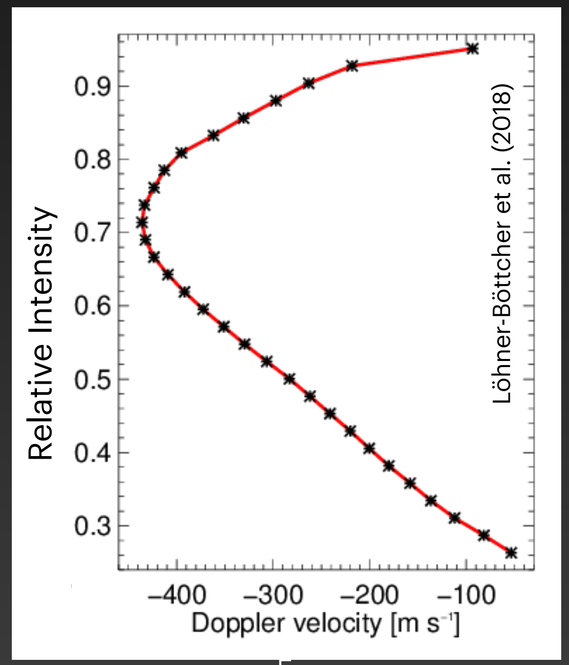
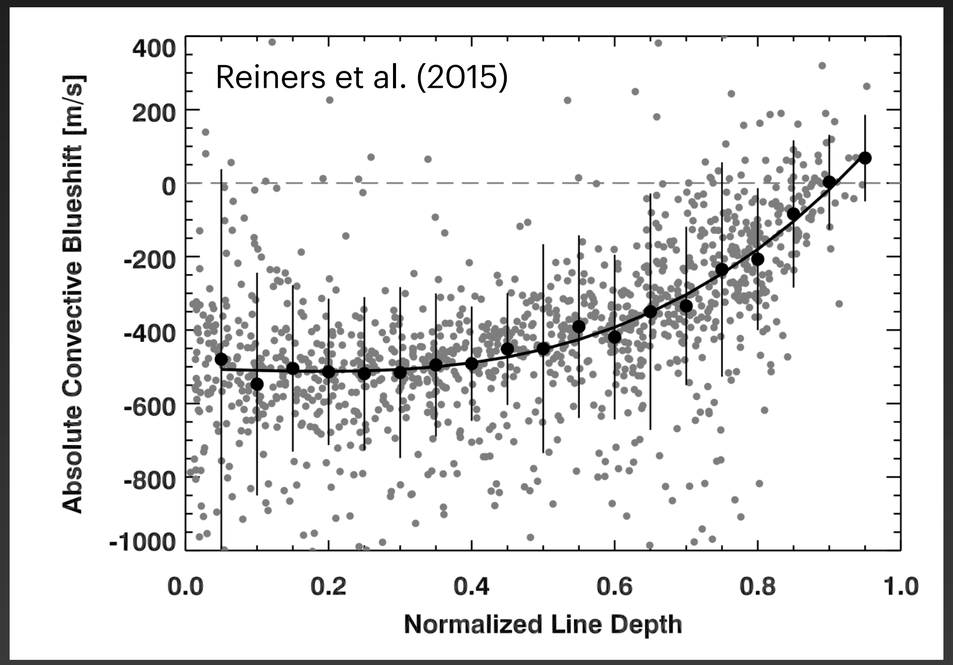
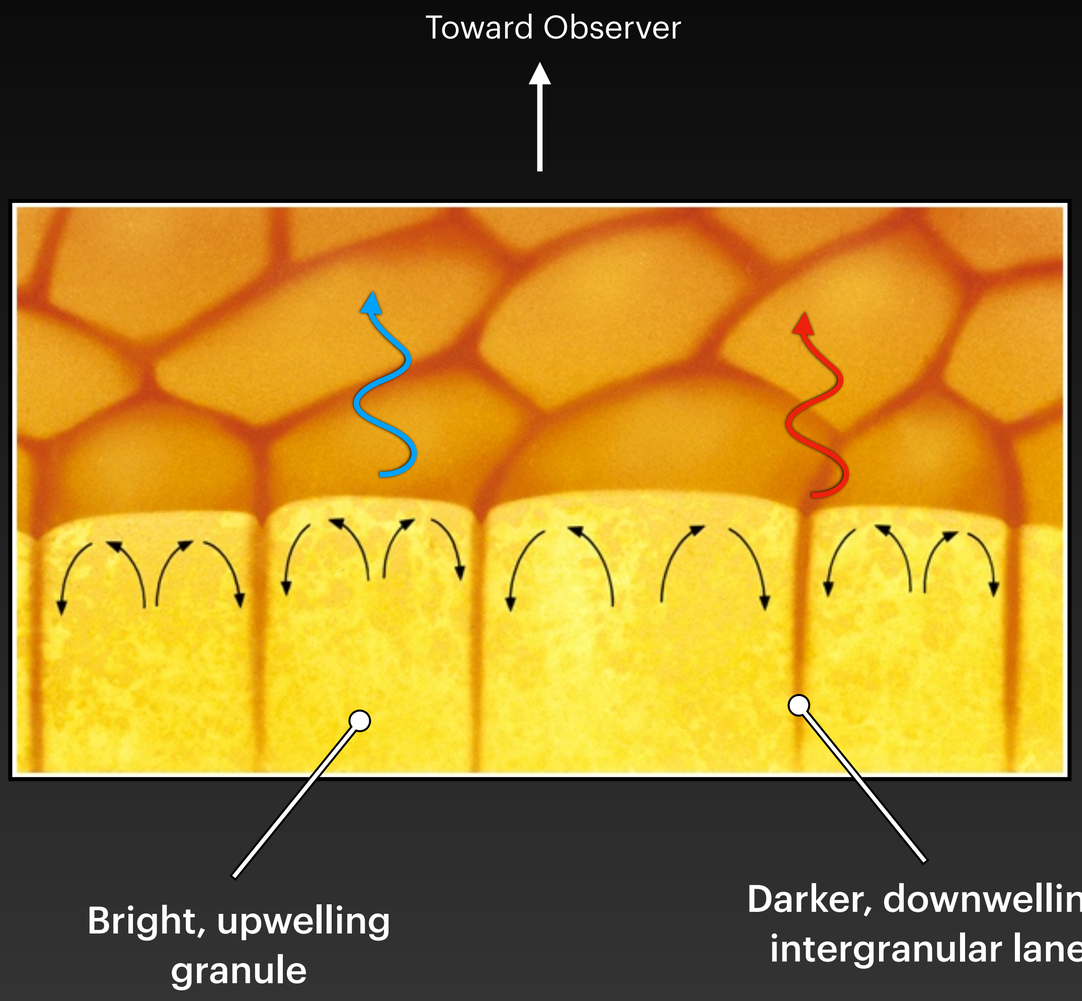
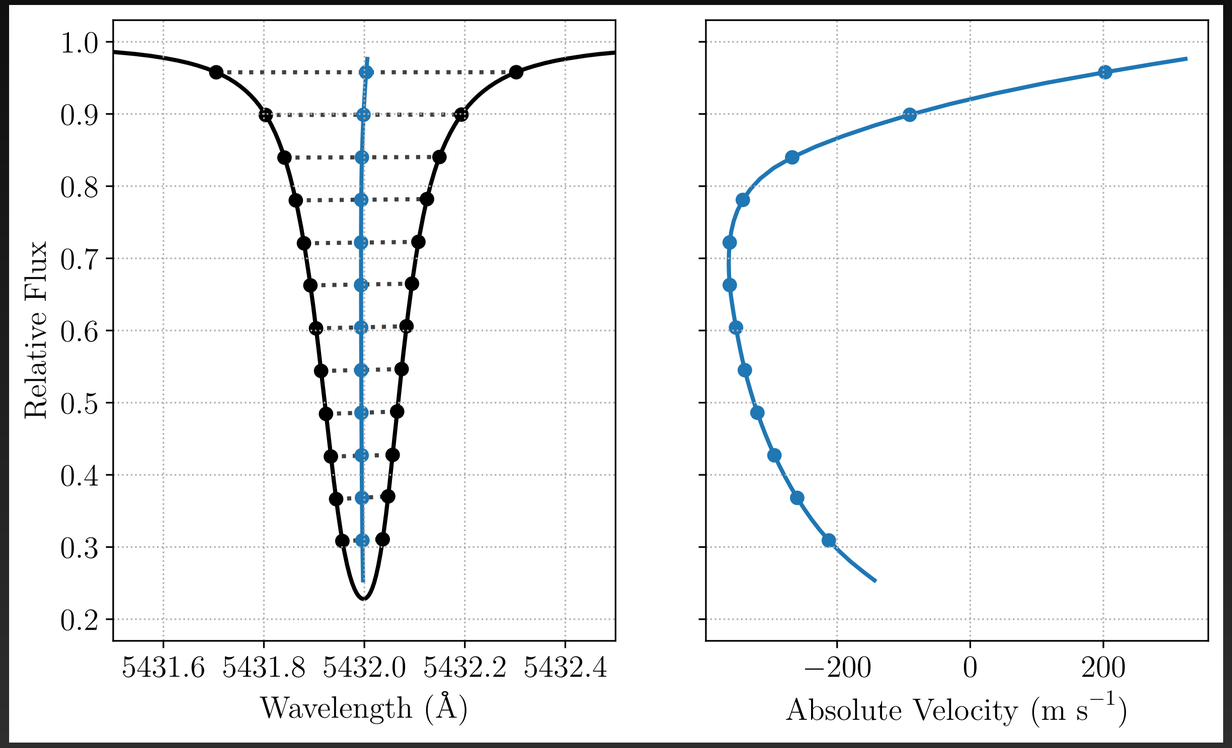


3. Absolute convective blueshift



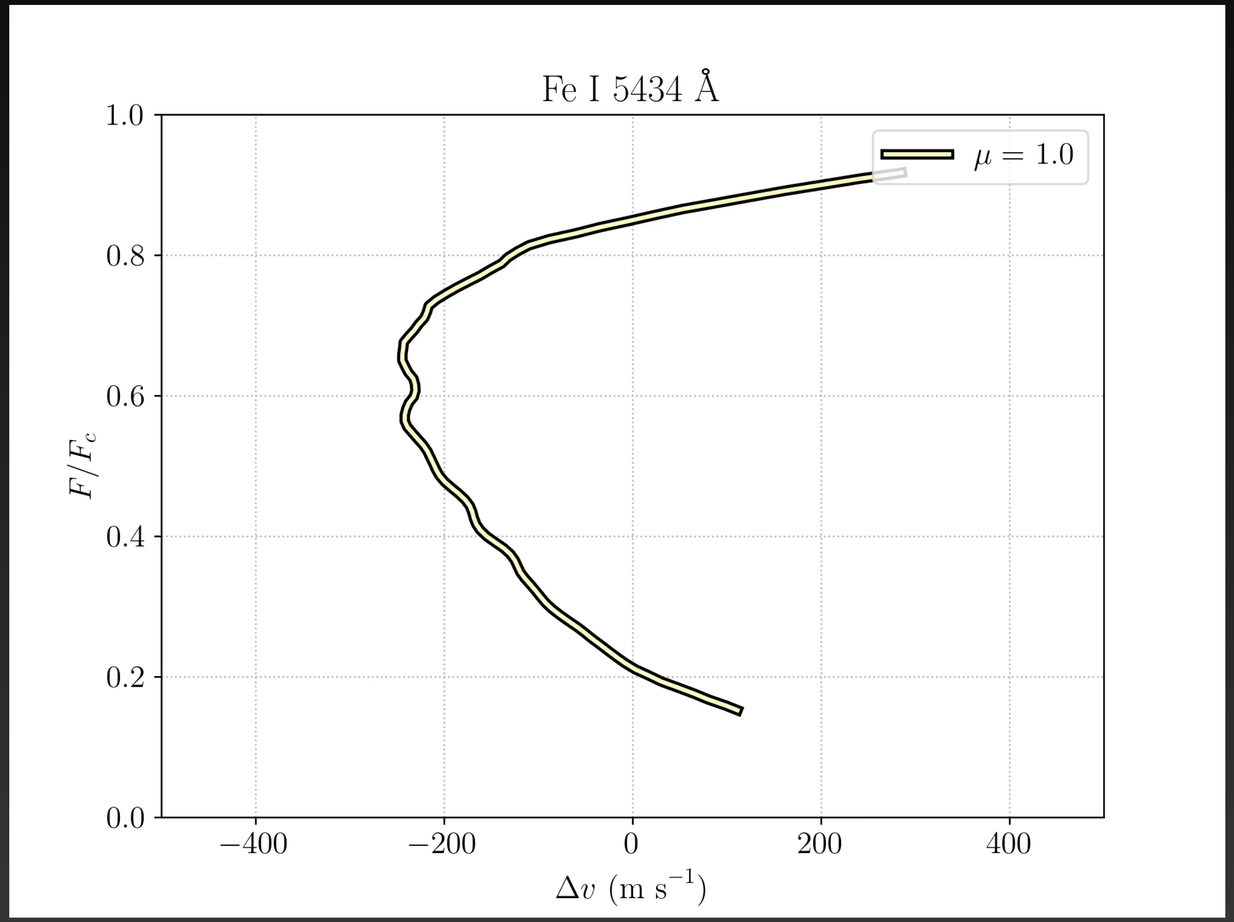
Intensity and velocity contrasts between granules and lanes create multiple 100 m/s asymmetries in lines

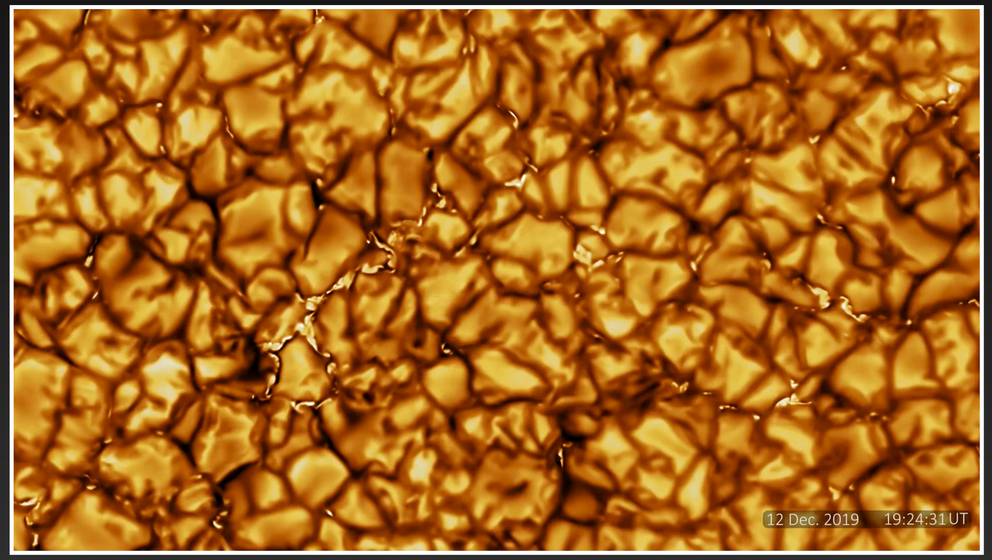




Palumbo et al. (2022)
Palumbo et al. (2024b)

And these asymmetries vary with time...





Palumbo et al. (2022)
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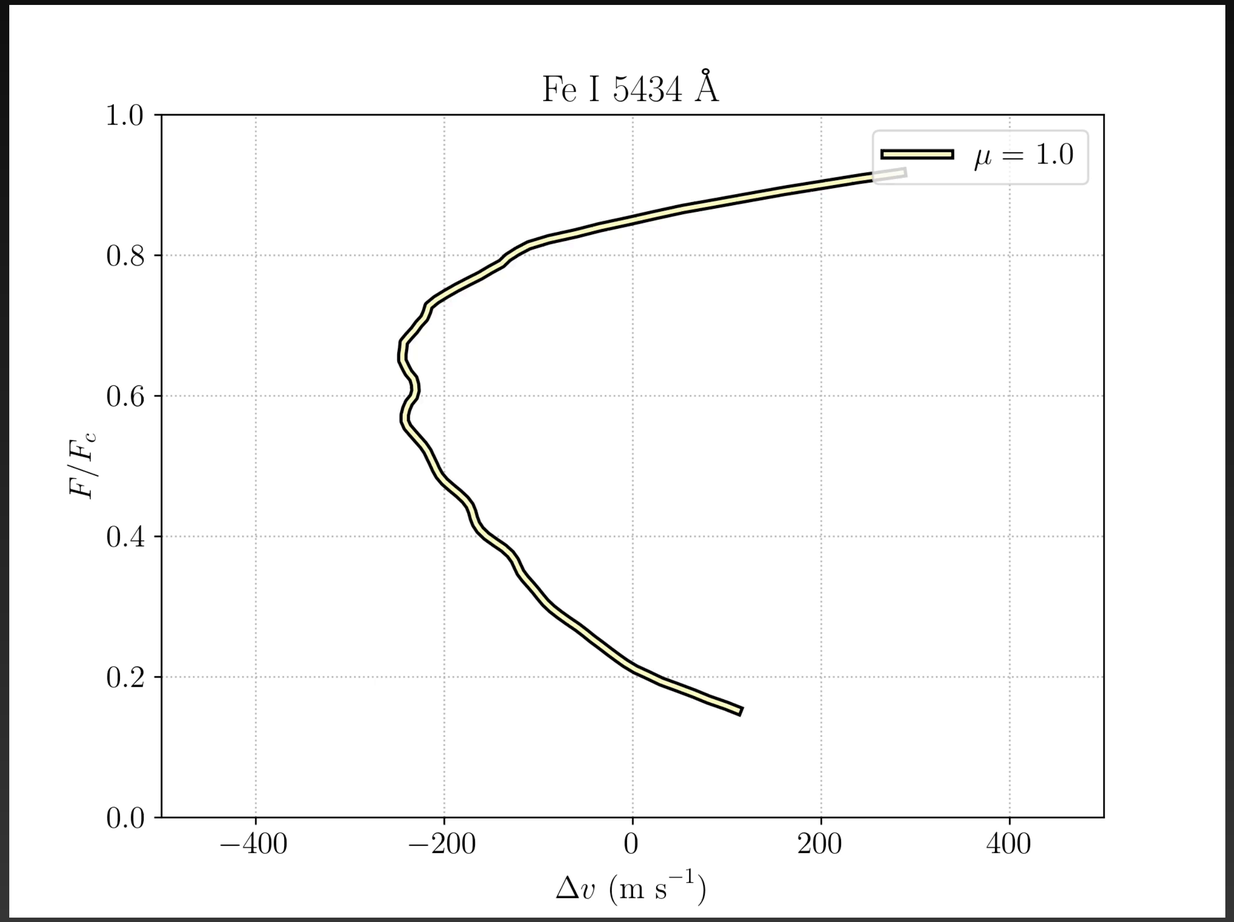
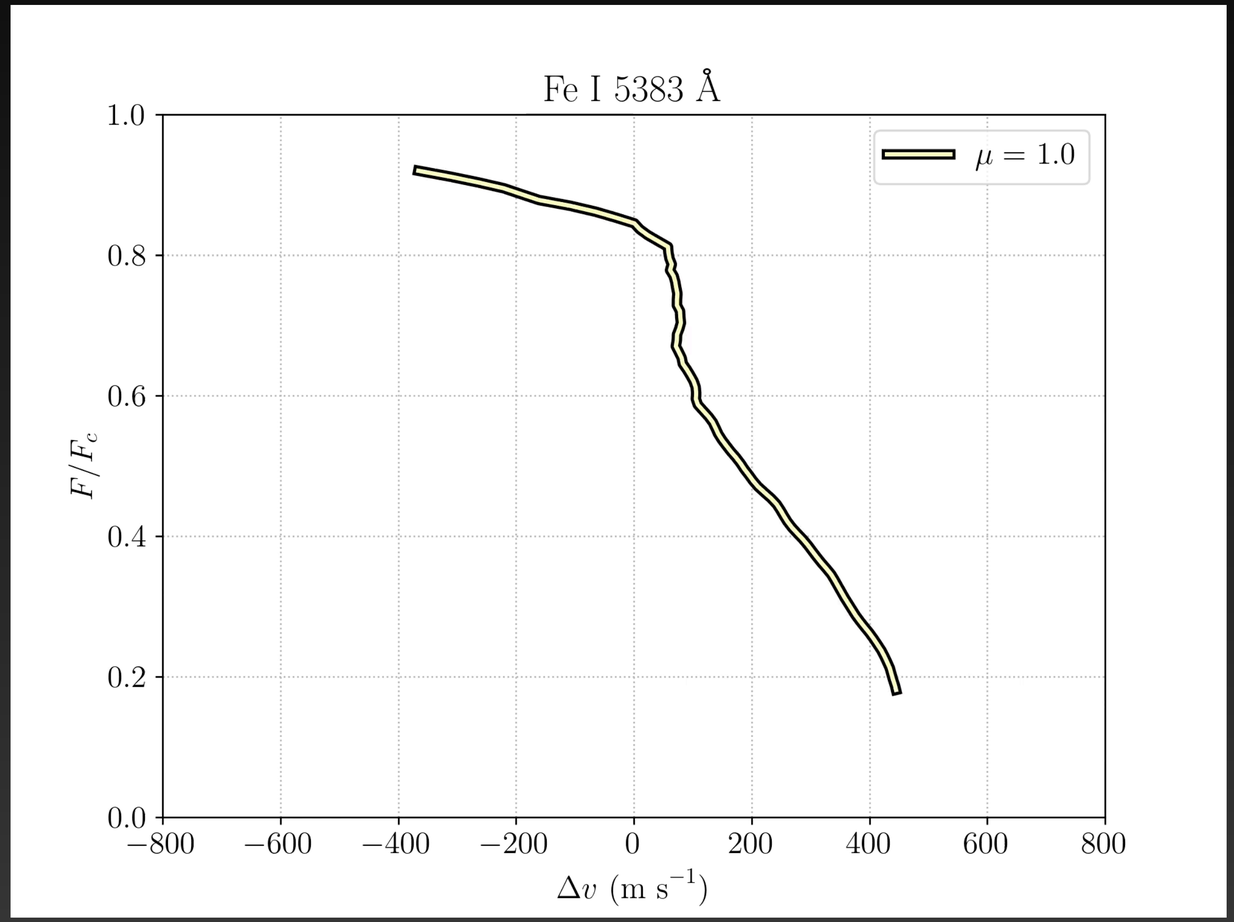
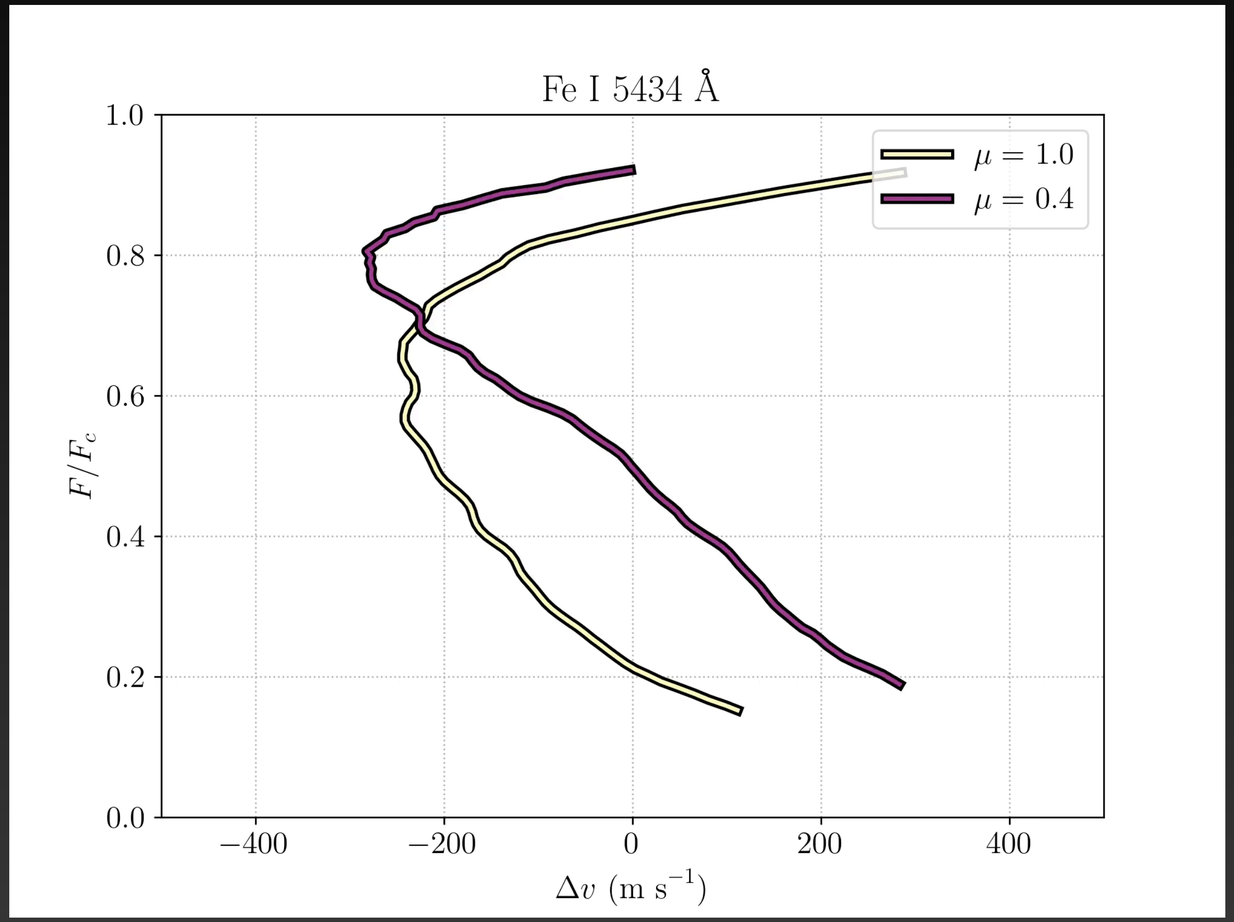
And these asymmetries vary with time...
... and absorption line ...

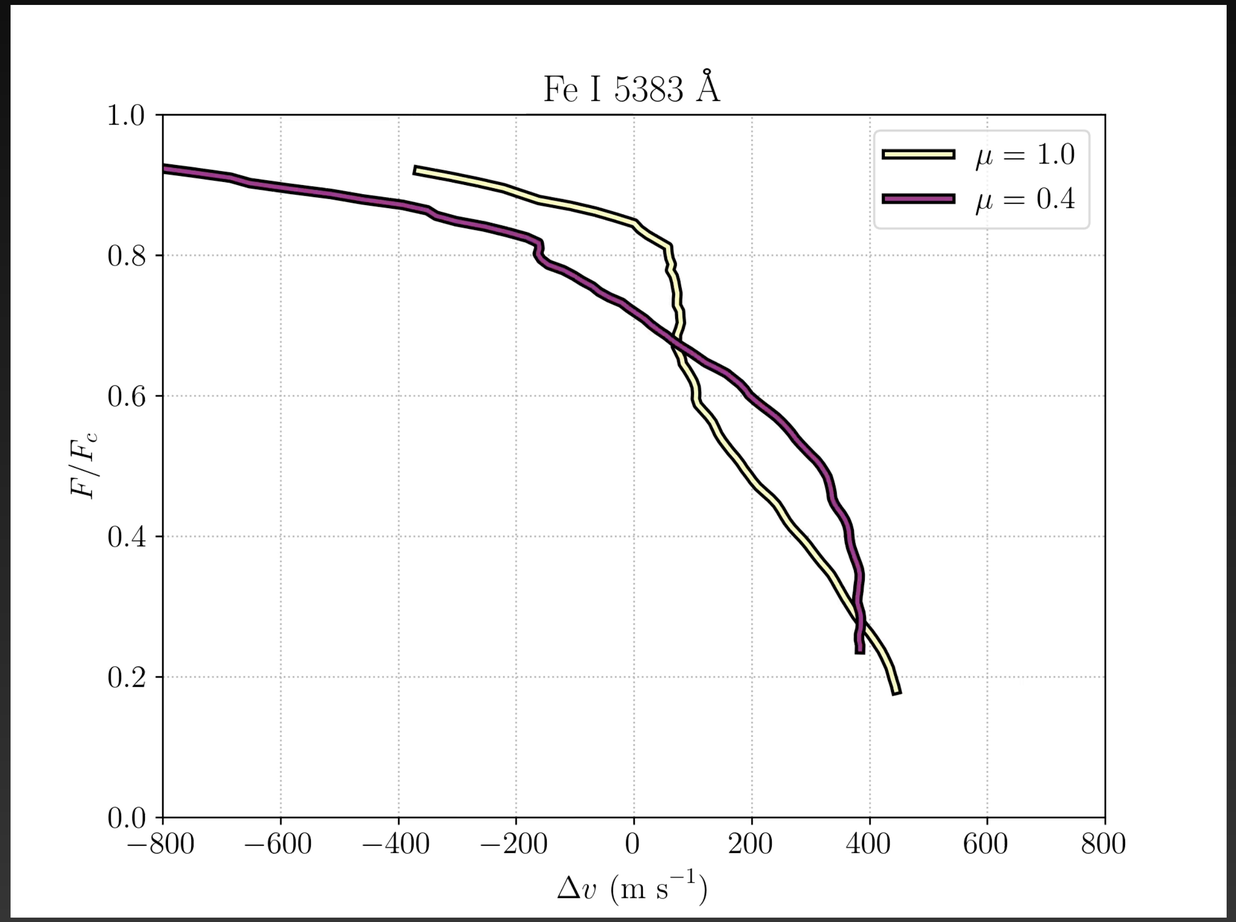




Palumbo et al. (2022)
Palumbo et al. (2024b)

And these asymmetries vary with time...
... and absorption line ...
... and viewing angle (in disk-resolved sunlight)

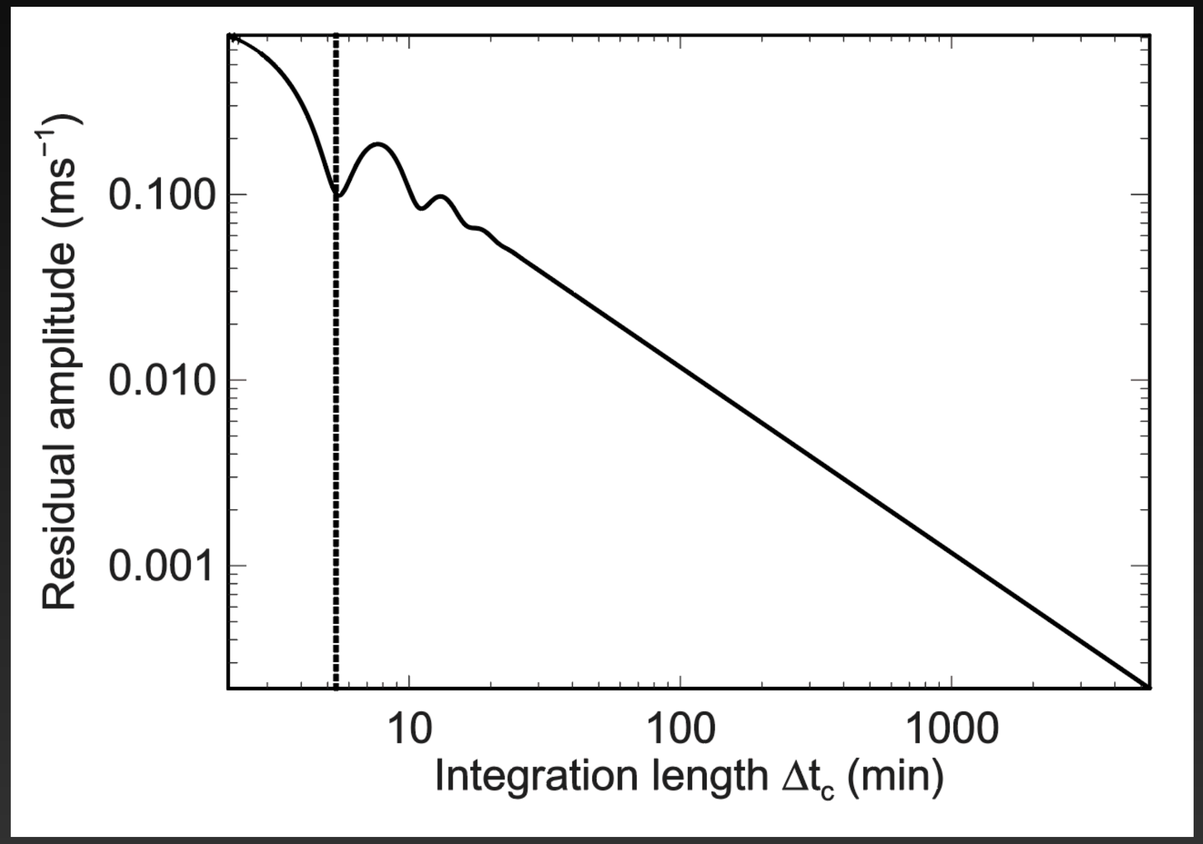




Palumbo et al. (2022)
Palumbo et al. (2024b)

Brute-force binning alone is not a viable strategy!

P-modes



Chaplin et al. (2019)

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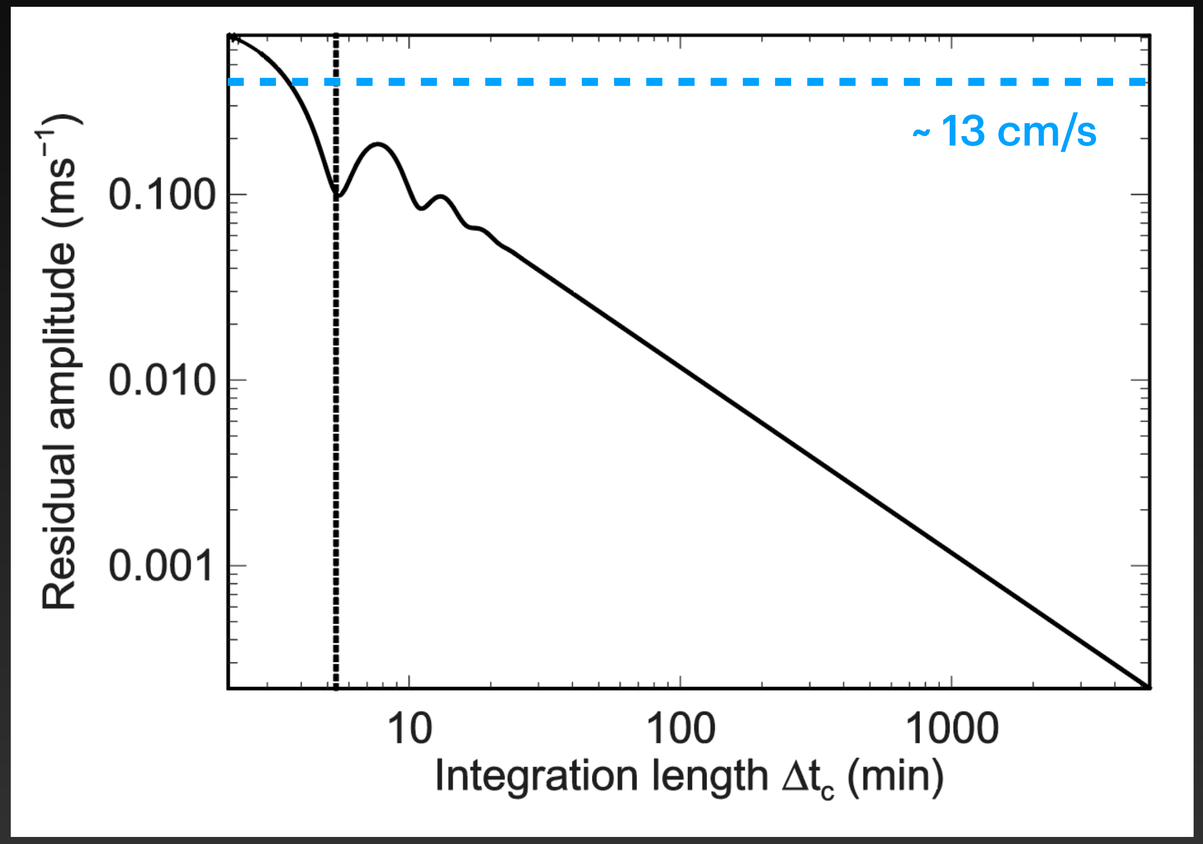
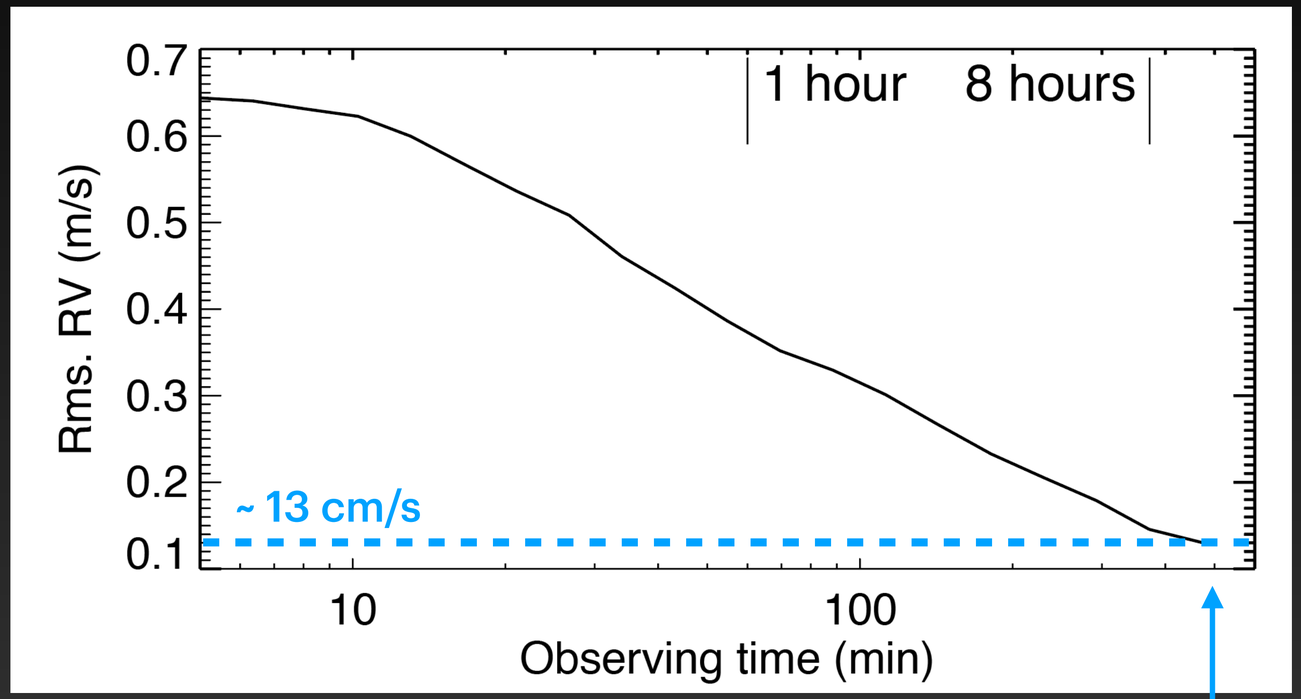


Chaplin et al. (2019)

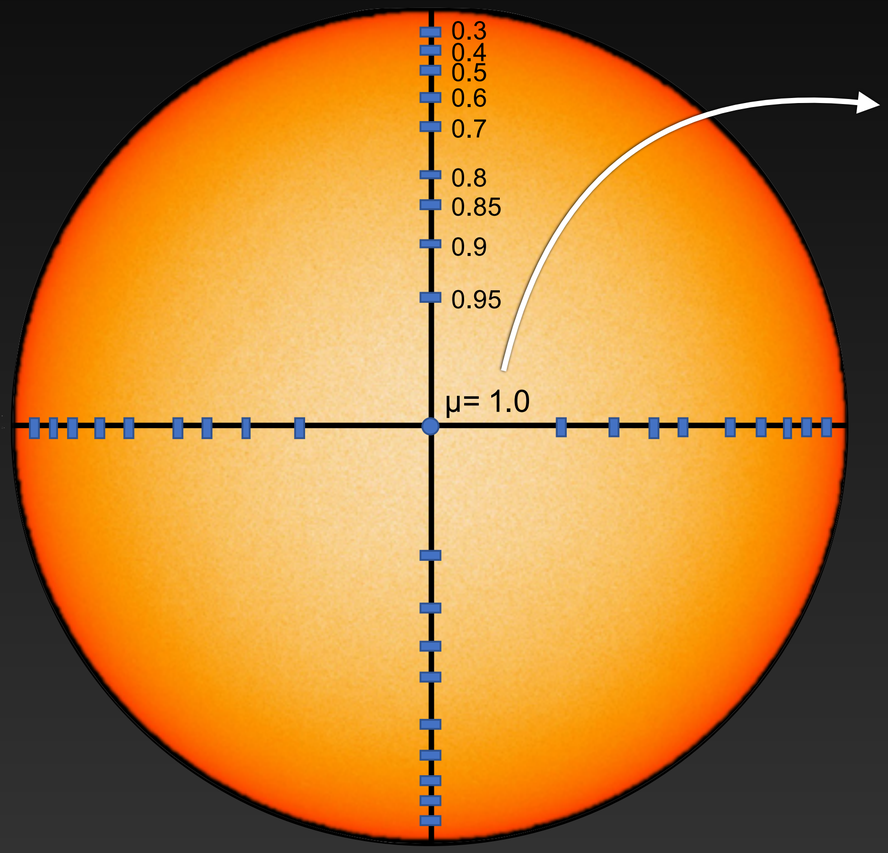
Granulation

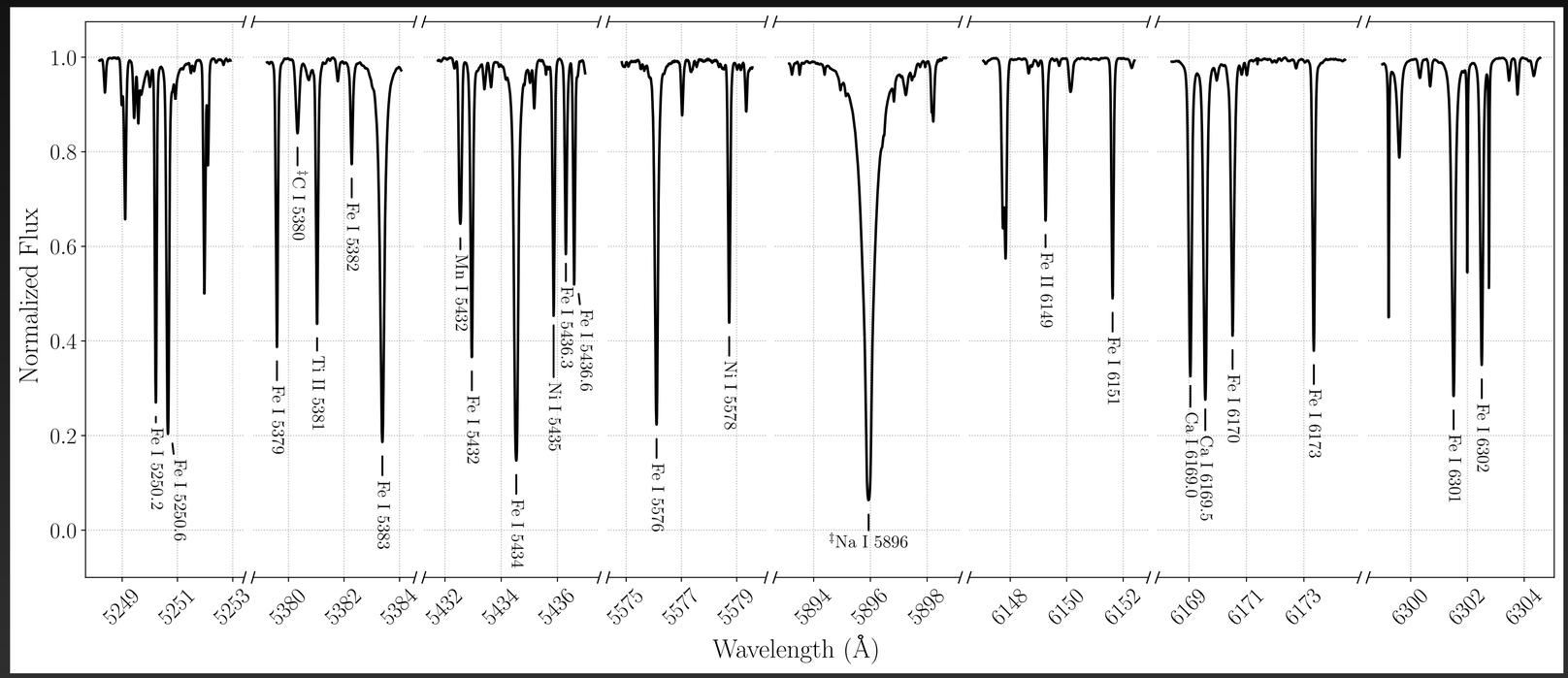


Meunier et al. (2015)

~13 cm/s precision is achieved only after observing a single target for an entire night!

GRASS - The GRanulation and Spectrum Synthesizer - uses spatially-resolved solar observations to empirically model granulation in disk-integrated spectra





Löhner-Bottcher et al. (2018, 2019)
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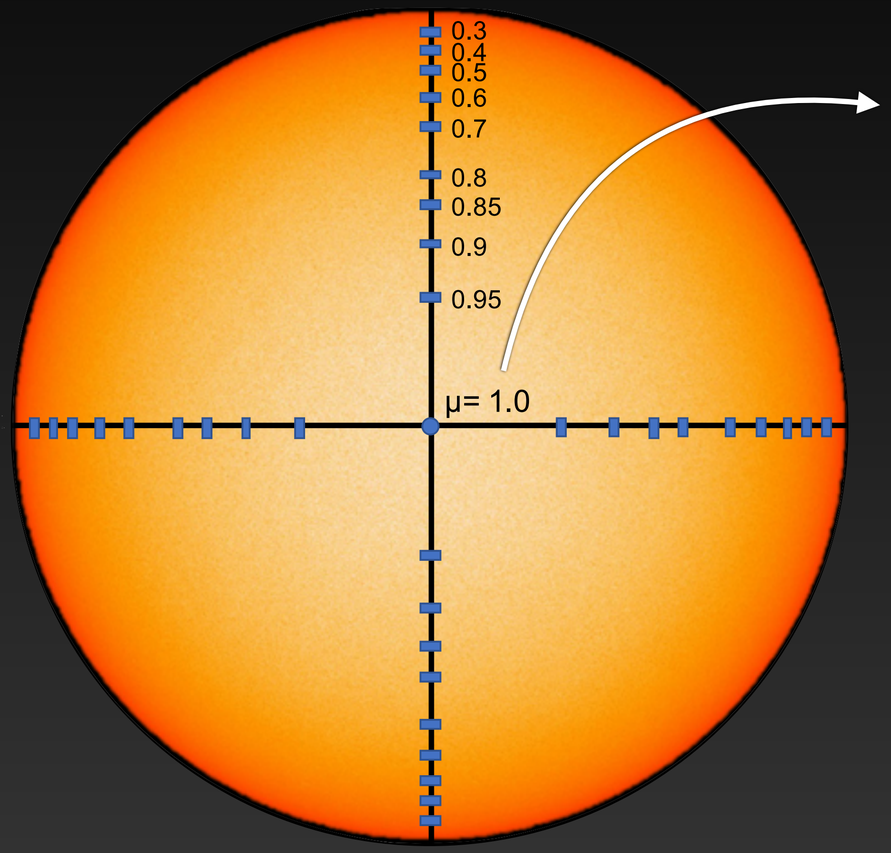

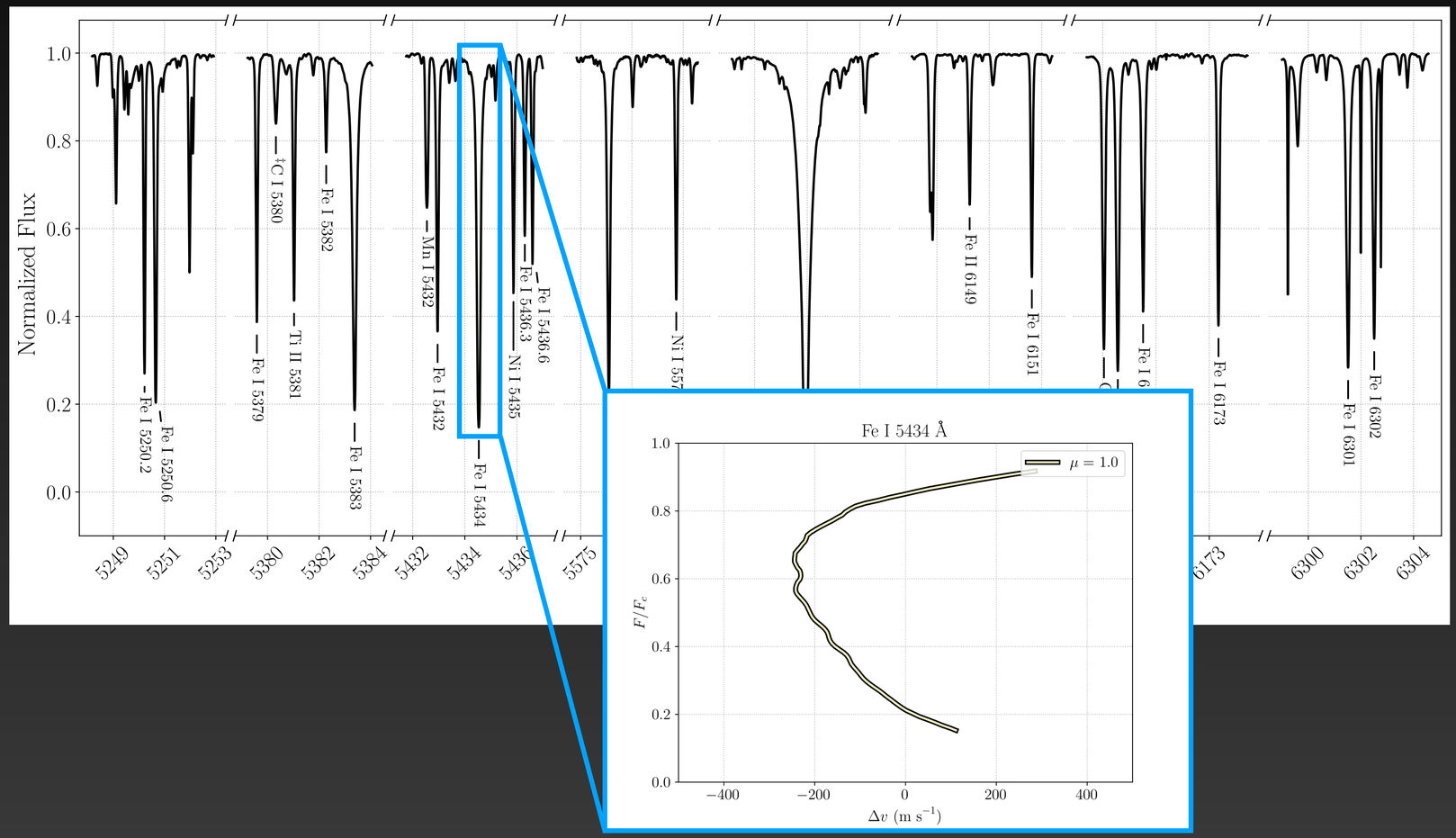

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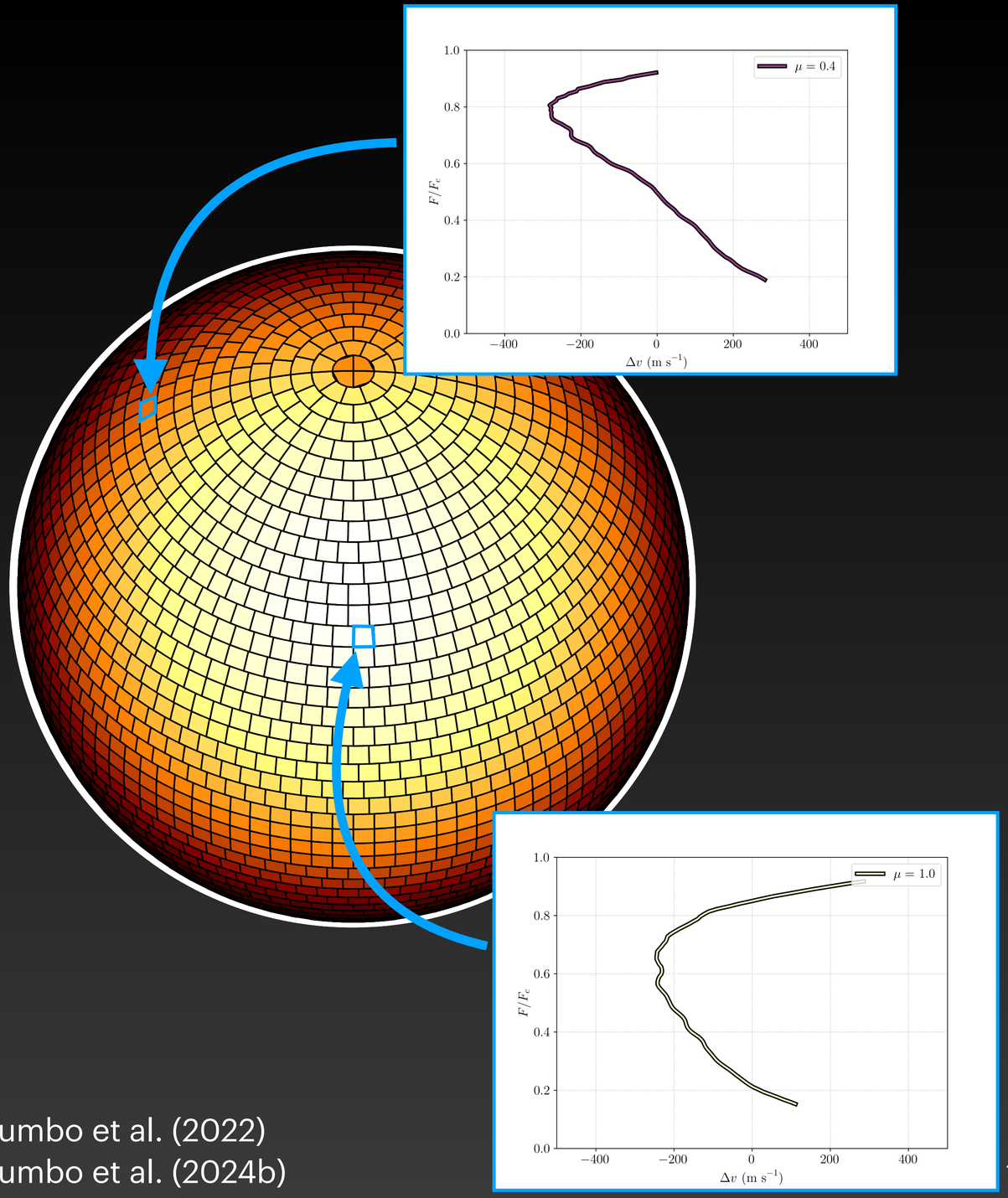

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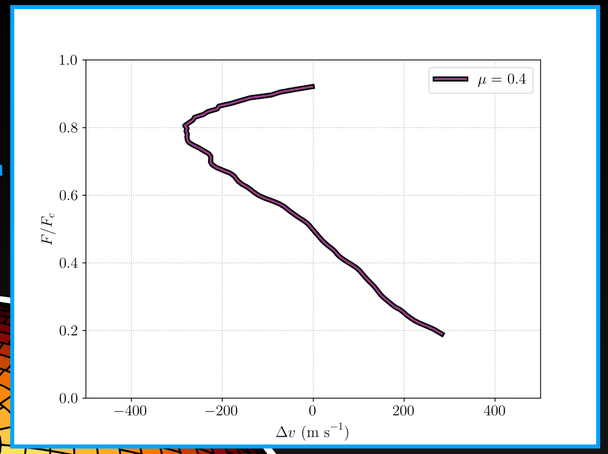
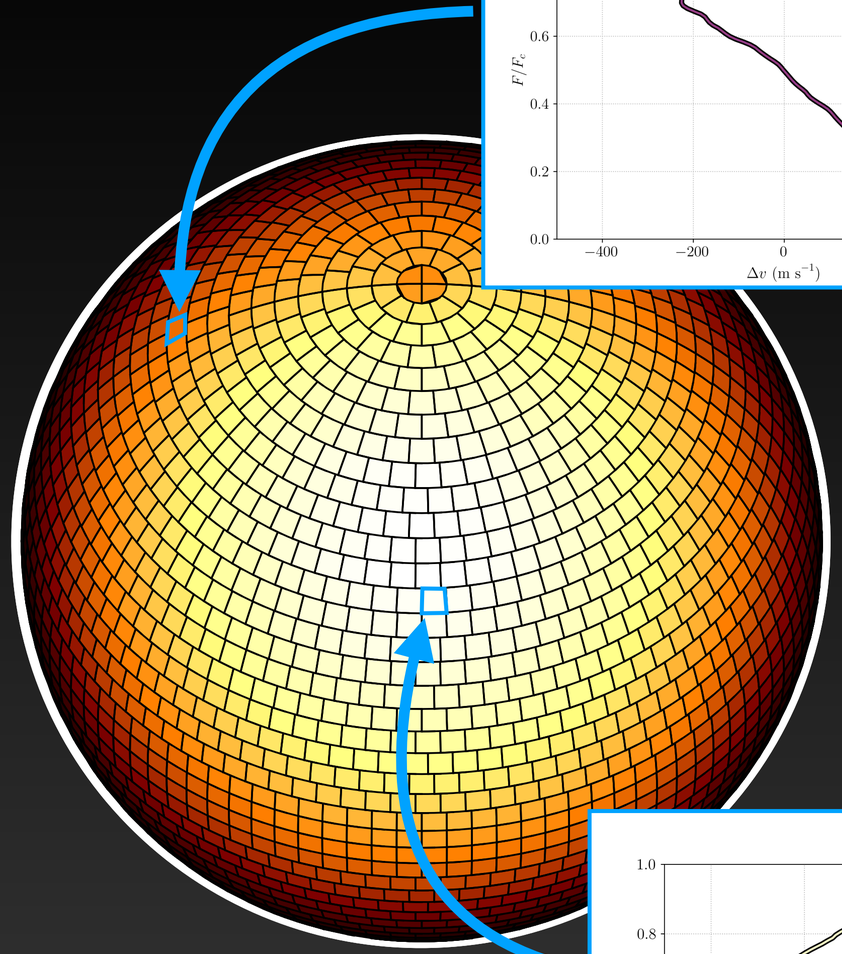
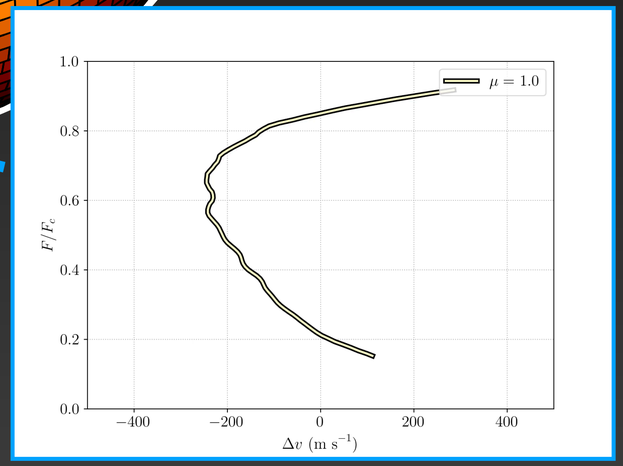


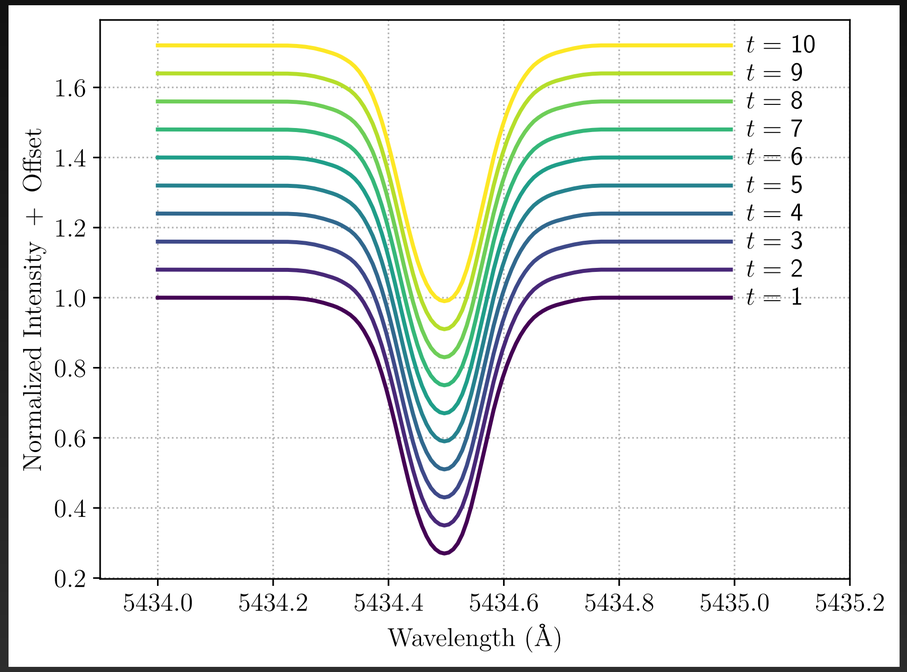




Sum over stellar grid

$$I(t,\lambda) = C \sum_{x=1}^{N} \sum_{y=1}^{N} I(t,\lambda,x,y)$$

Time series of disk-integrated line profiles



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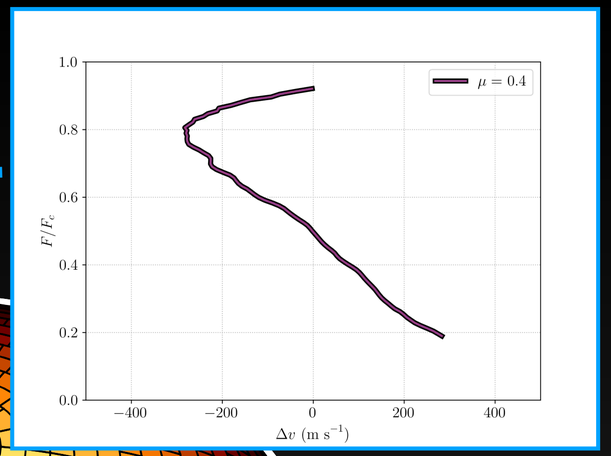

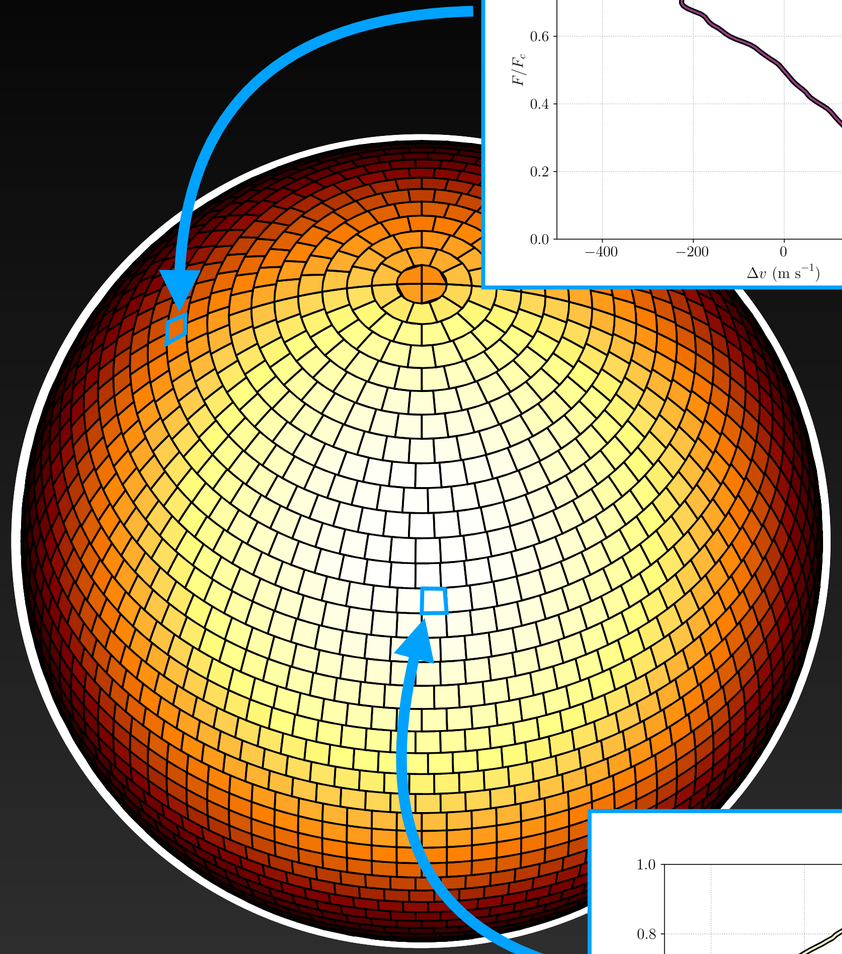

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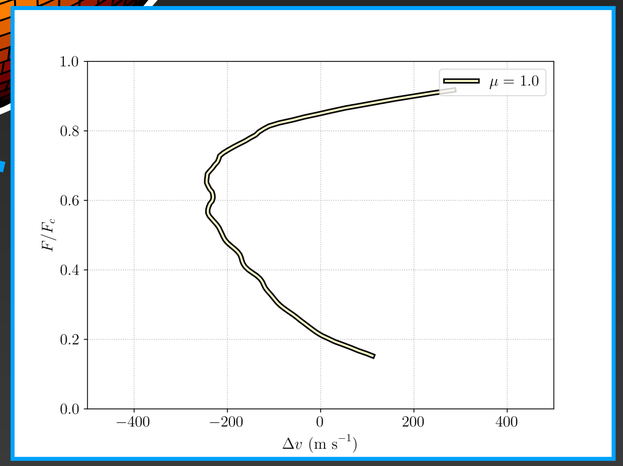

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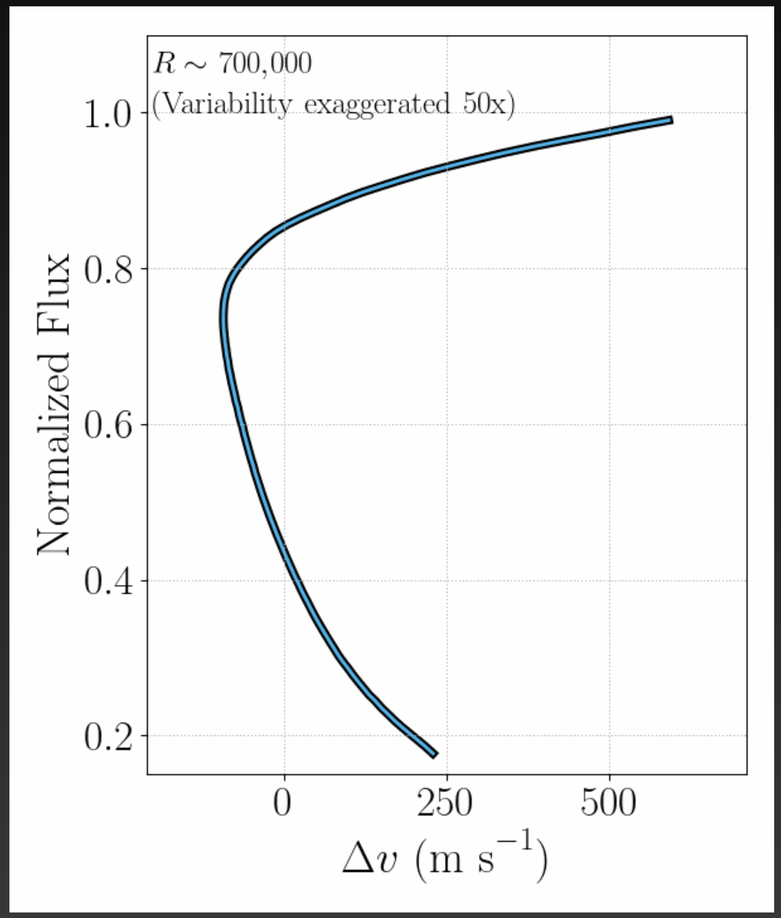
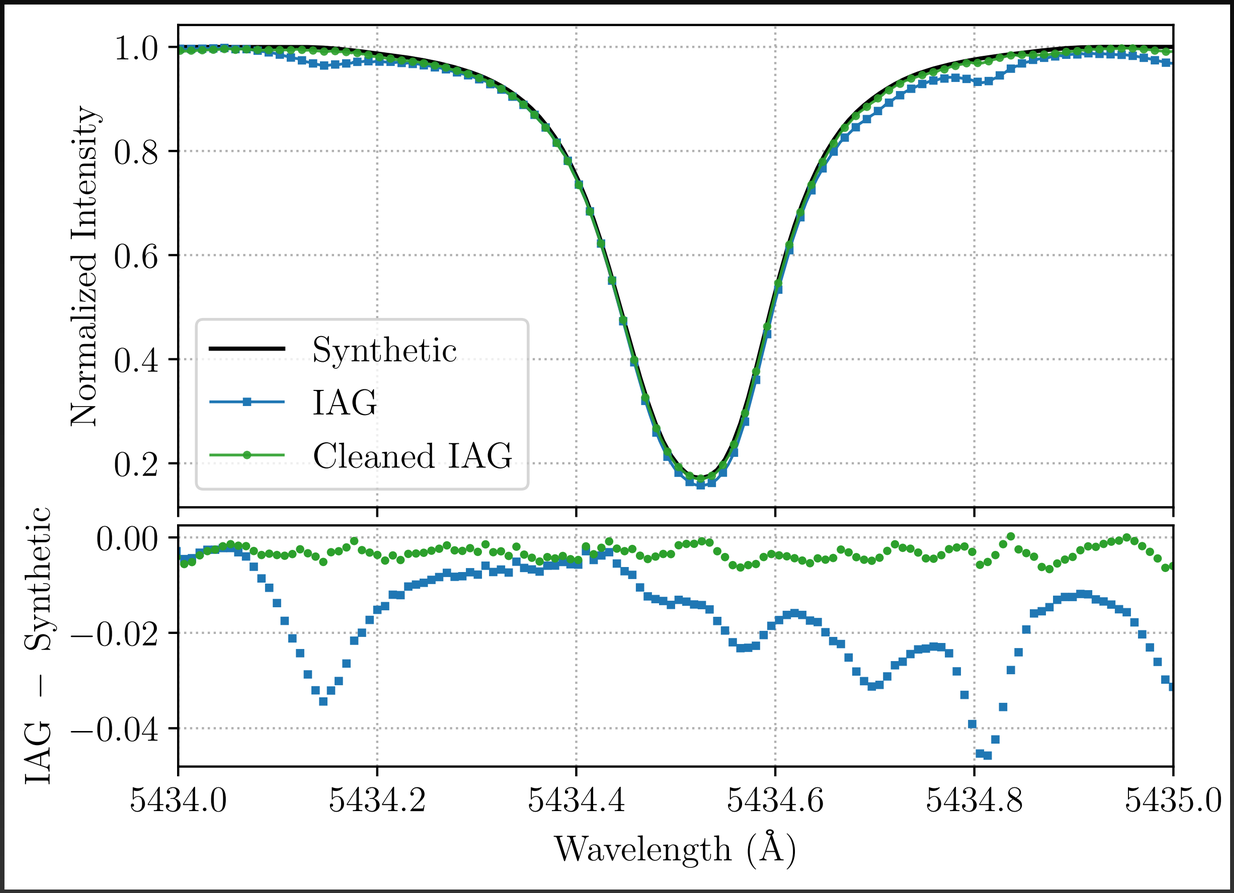


Palumbo et al. (2022)
Palumbo et al. (2024b)

GRASS accurately reproduces time-averaged solar line shapes



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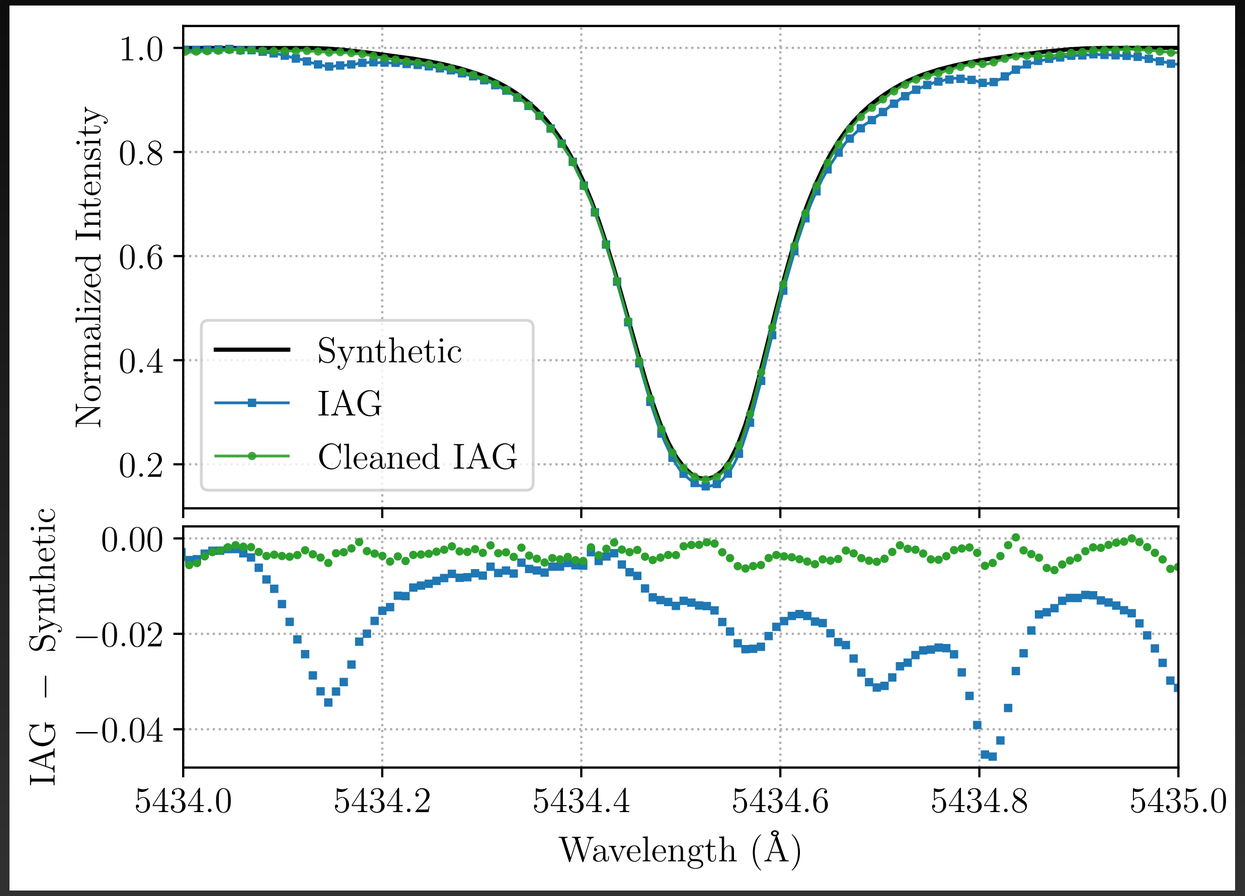

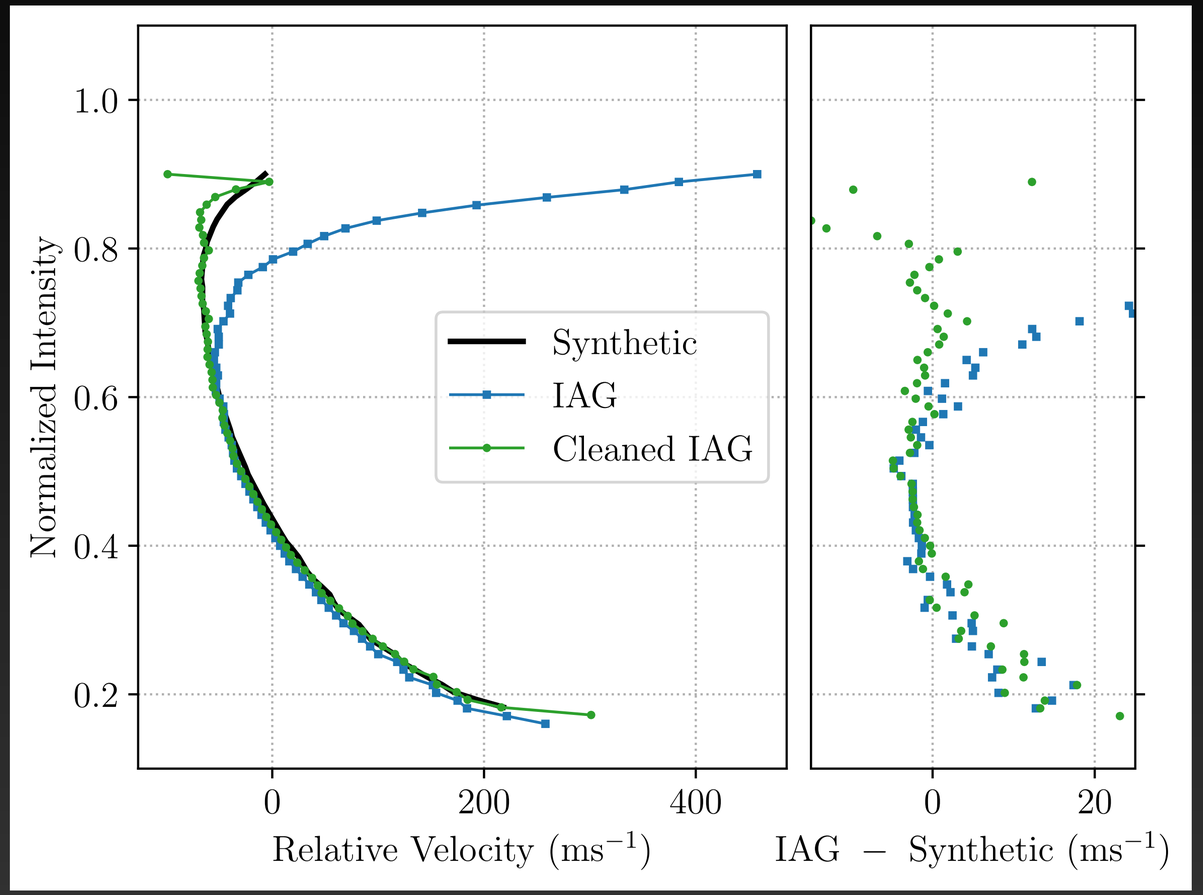

Palumbo et al. (2022)

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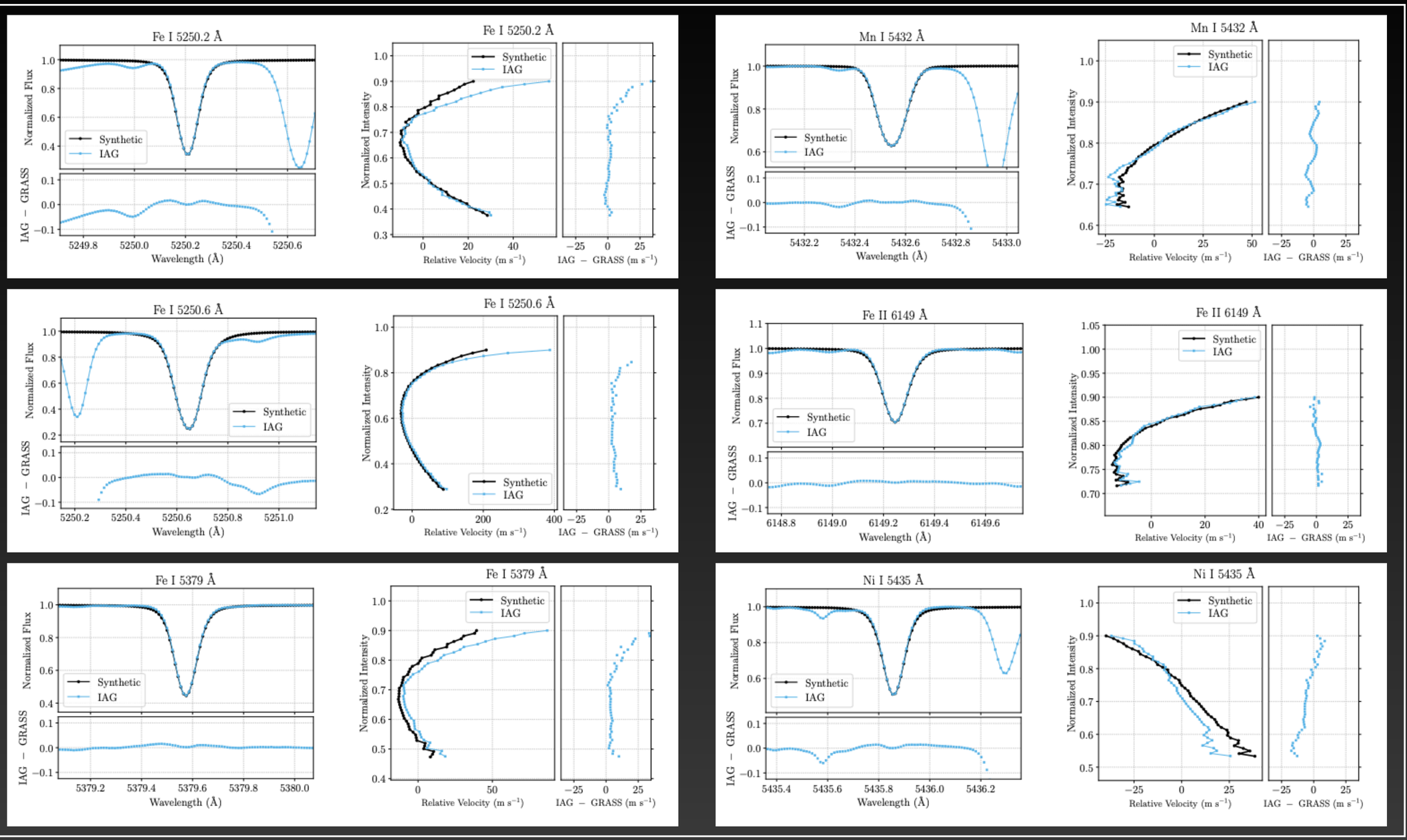
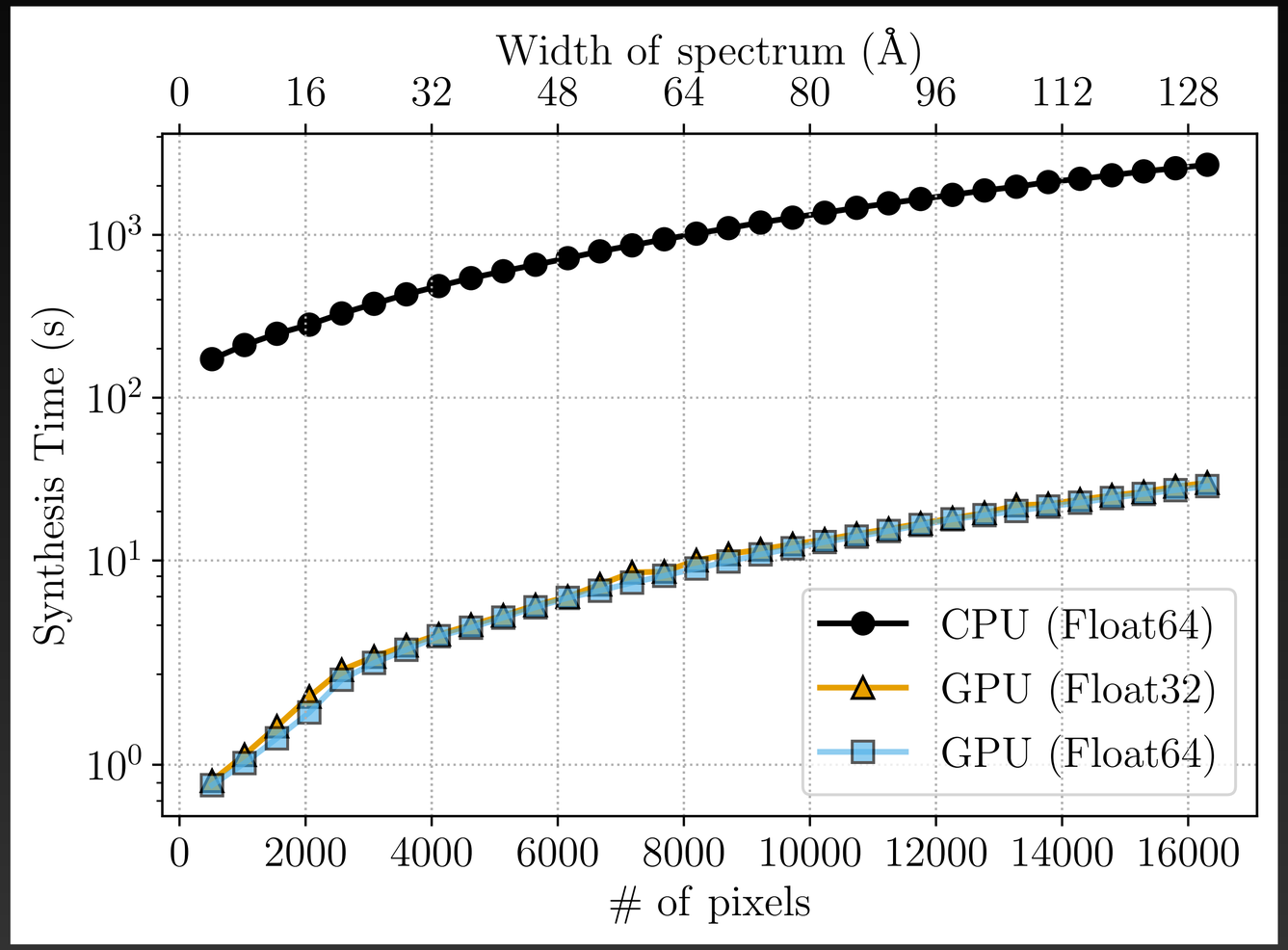
Palumbo et al. (2024b)



x4

GPU implementation synthesize full spectra *quickly*...



A dense time series of R~700,000 spectra in ~20 seconds!

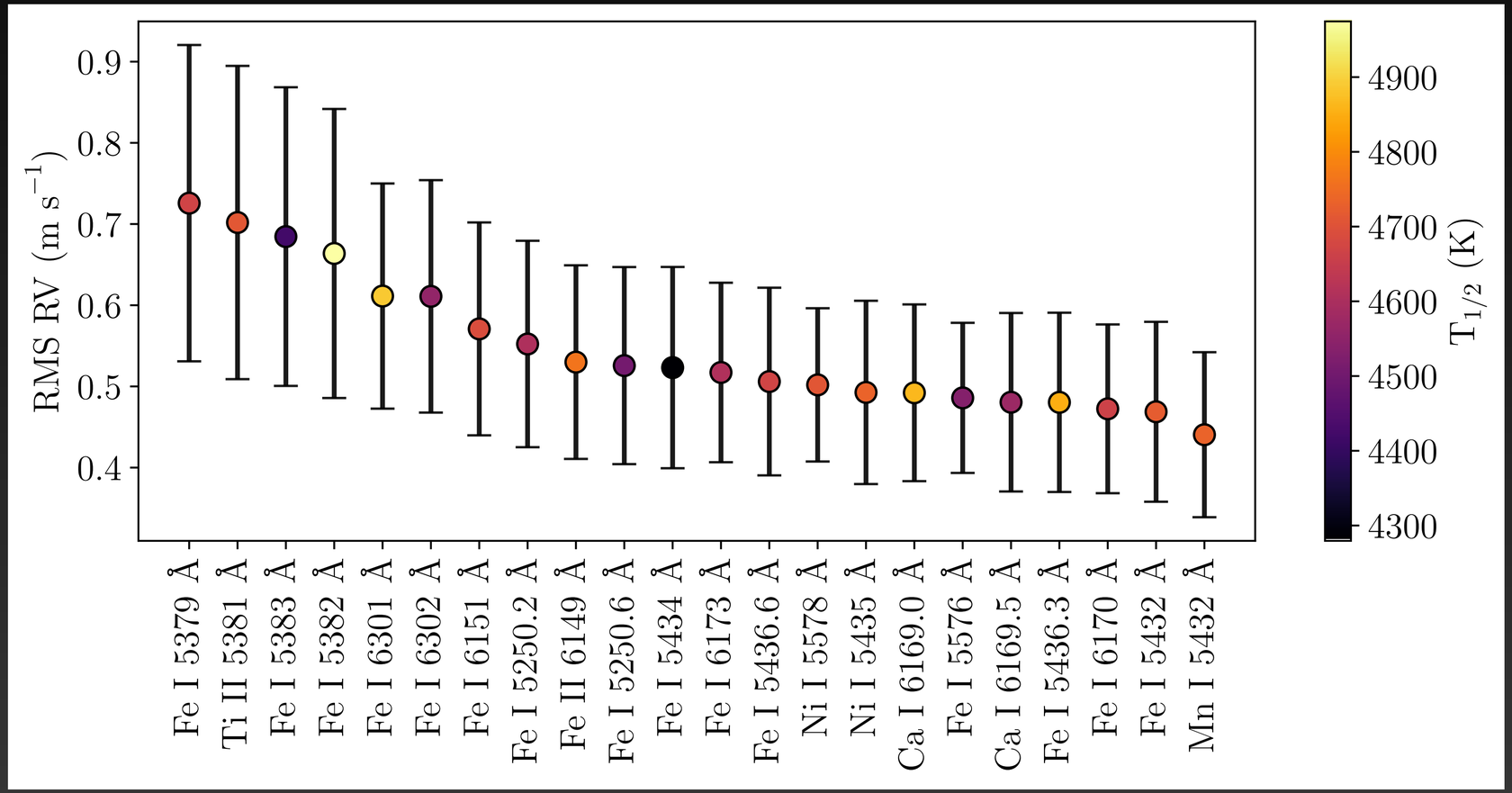
Palumbo et al. (2024b)

So how might we mitigate granulation noise?

Palumbo et al. (2024b)

So how might we mitigate granulation noise?

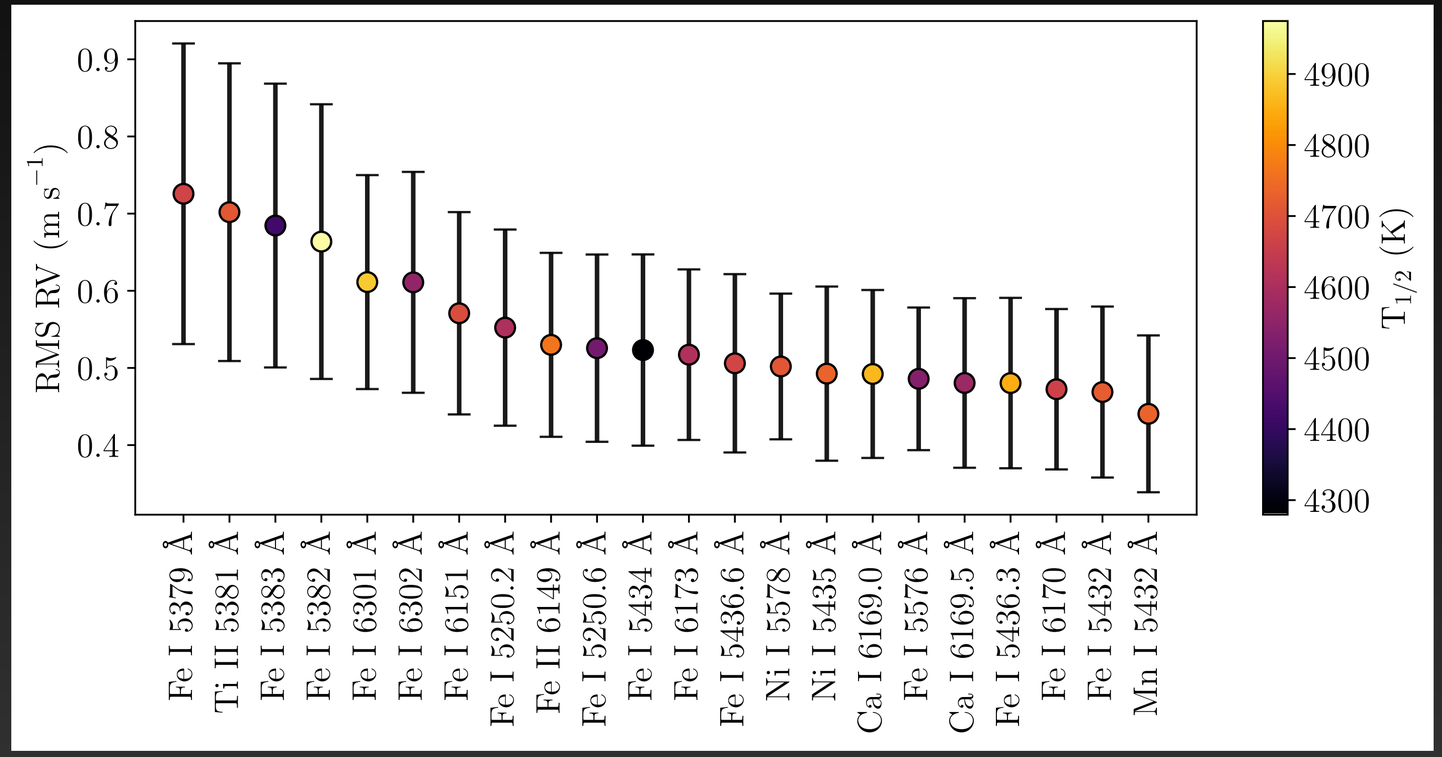
1. Measure Velocities from Less Variable Lines

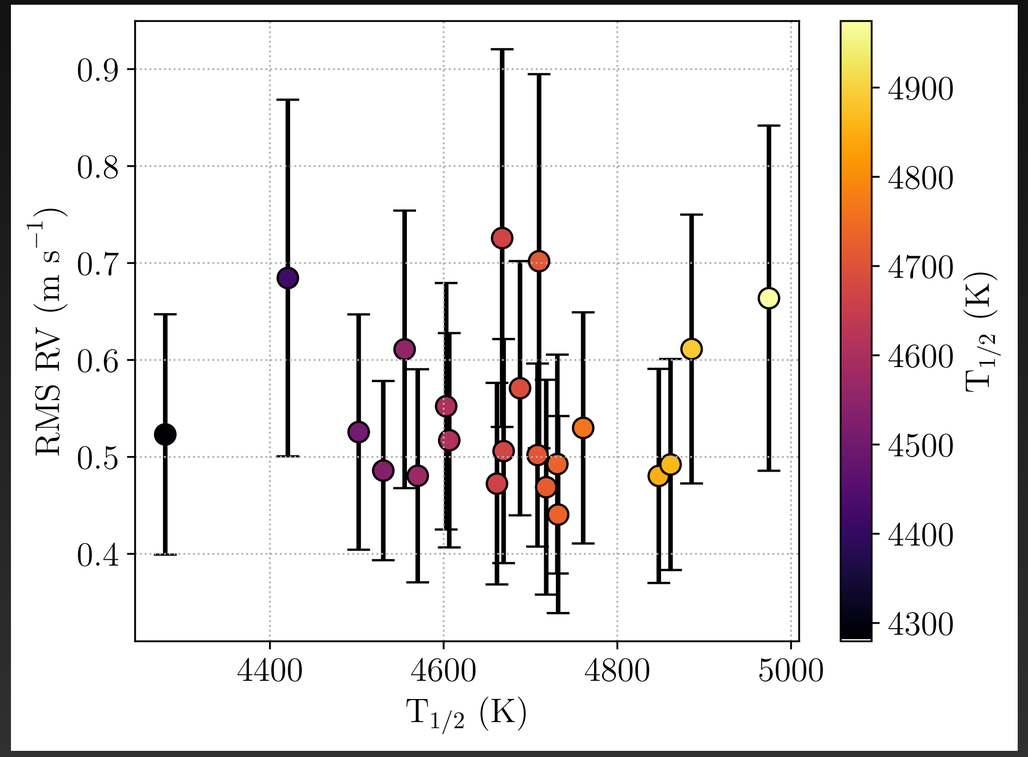


Palumbo et al. (2024b)

So how might we mitigate granulation noise?

1. Measure Velocities from “Quieter” Lines





... but it’s not clear how to predict which lines “should” be quiet!

Palumbo et al. (2024b)

So how might we mitigate granulation noise?

2. Use Line Asymmetry Information

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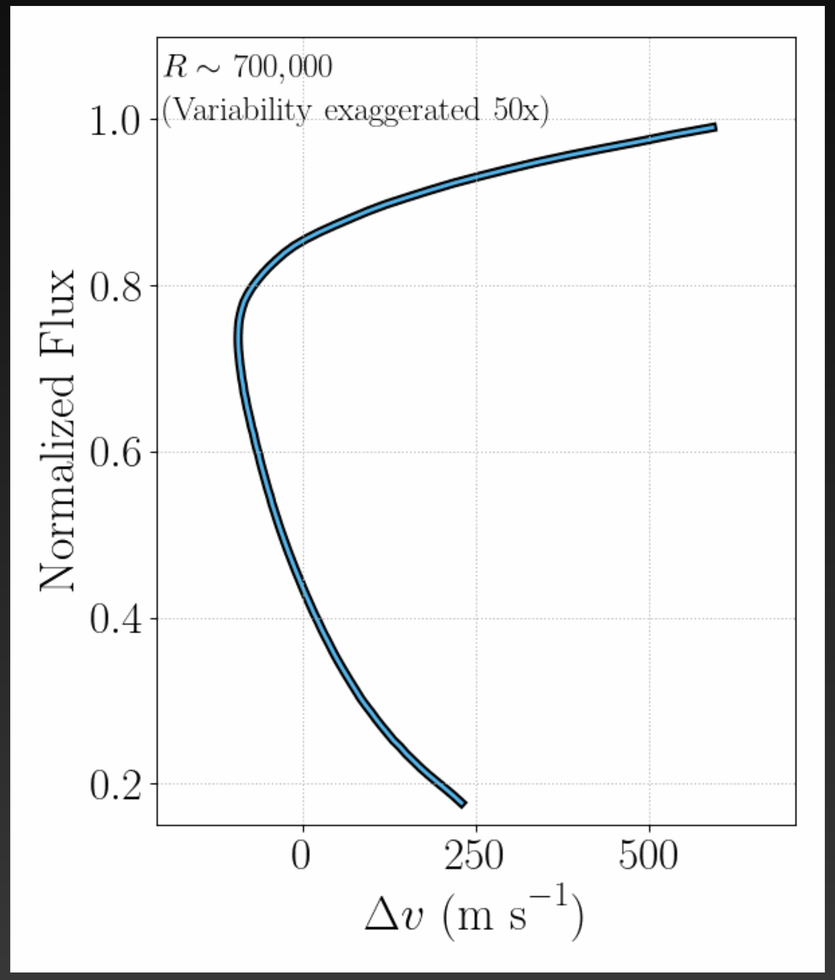
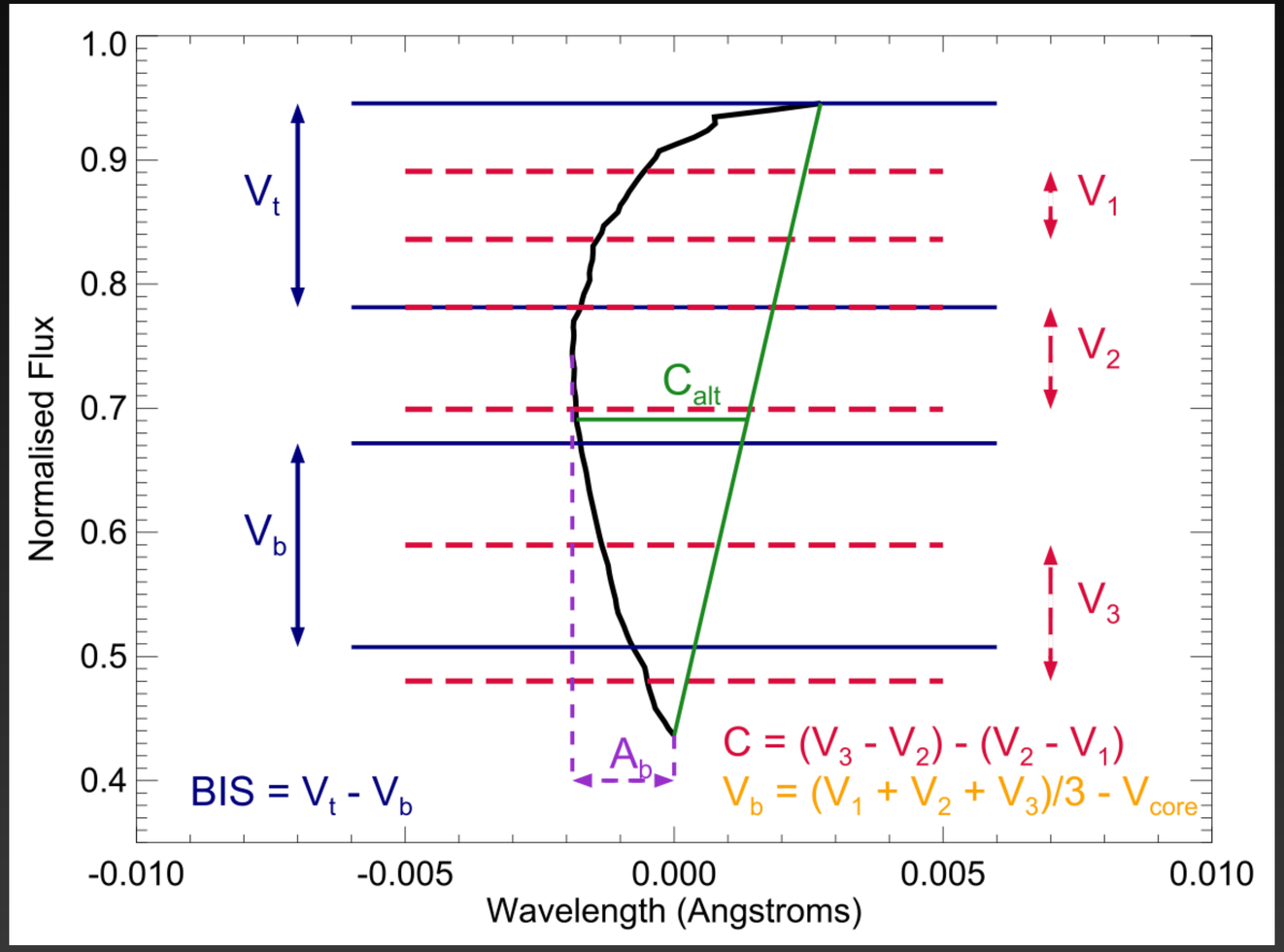


Palumbo et al. (2024b)



Cegla et al. (2019)

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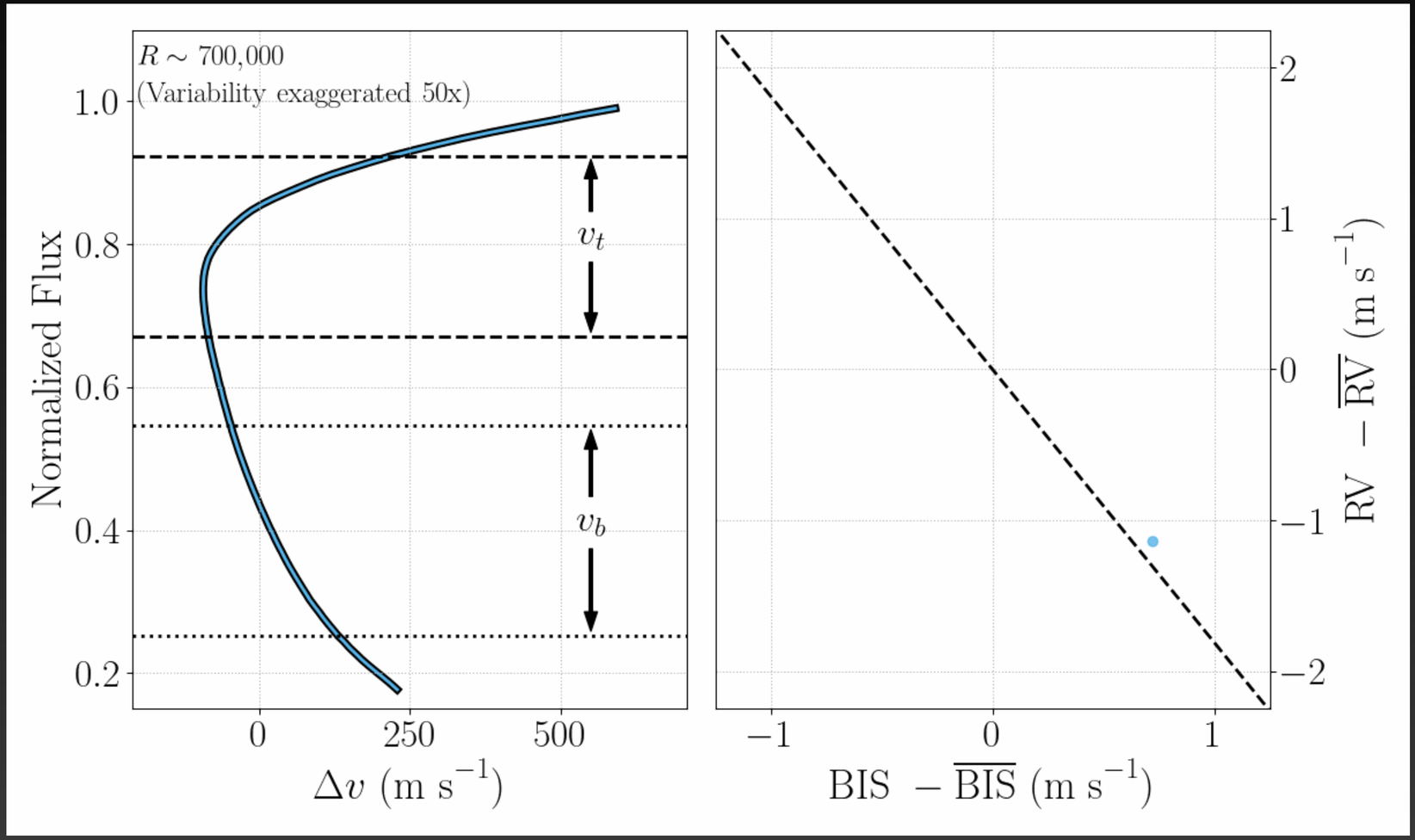
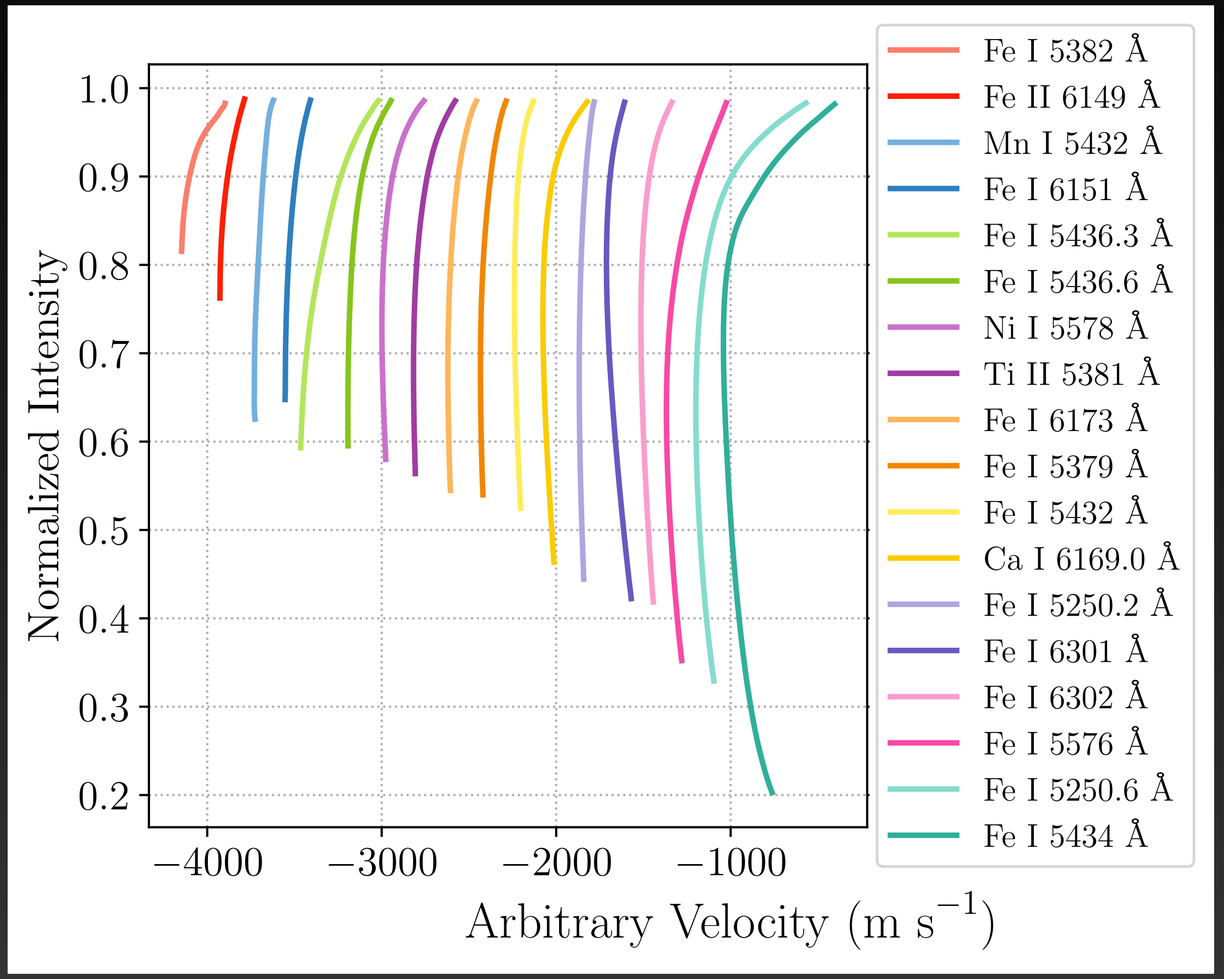
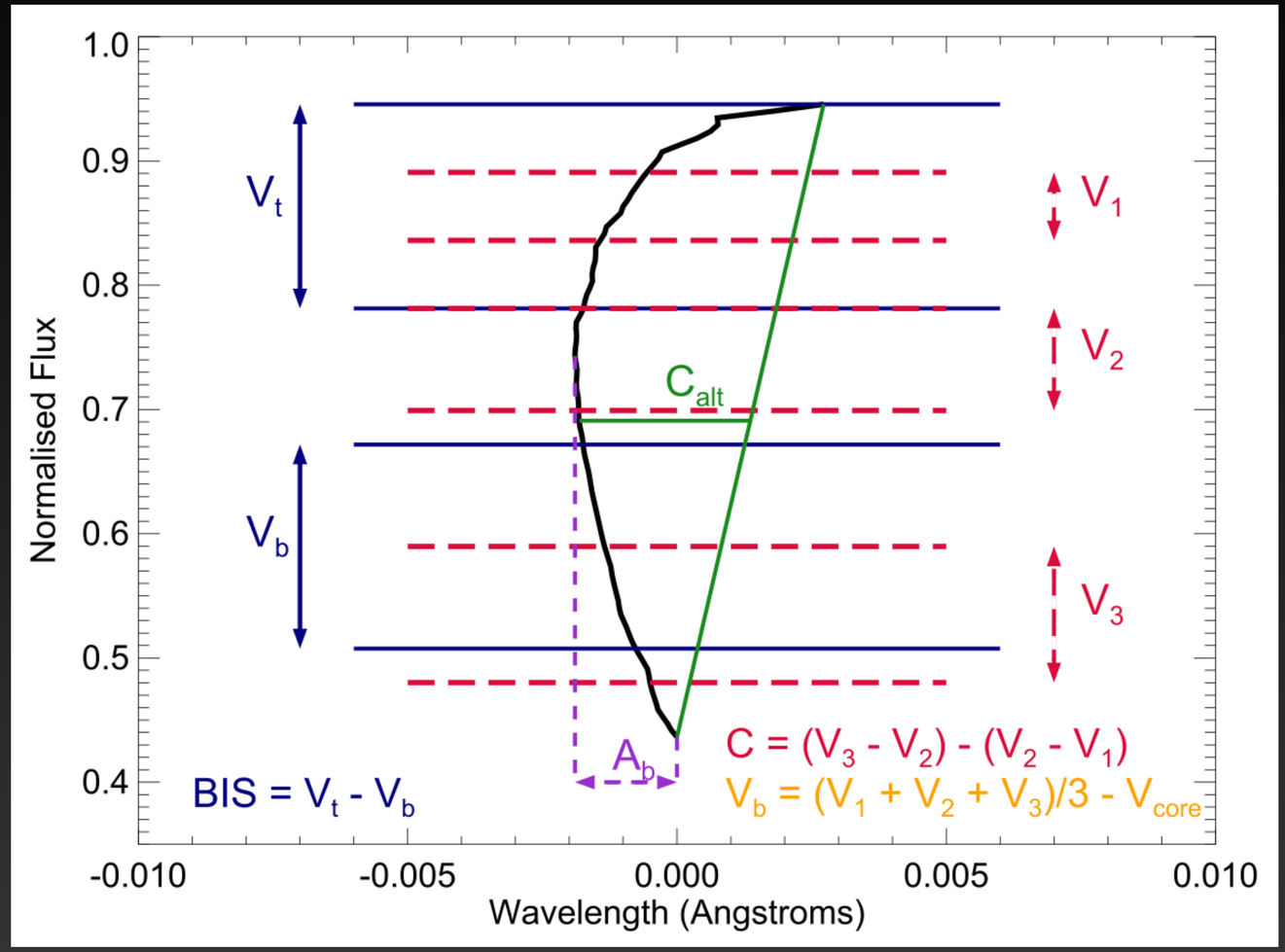


Palumbo et al. (2024b)

The optimal bisector diagnostic varies line by line



Palumbo et al. (2024b)



Cegla et al. (2019)

The optimal bisector diagnostic varies line by line

See Palumbo et al. (2024a) for the full nitty-gritty details...

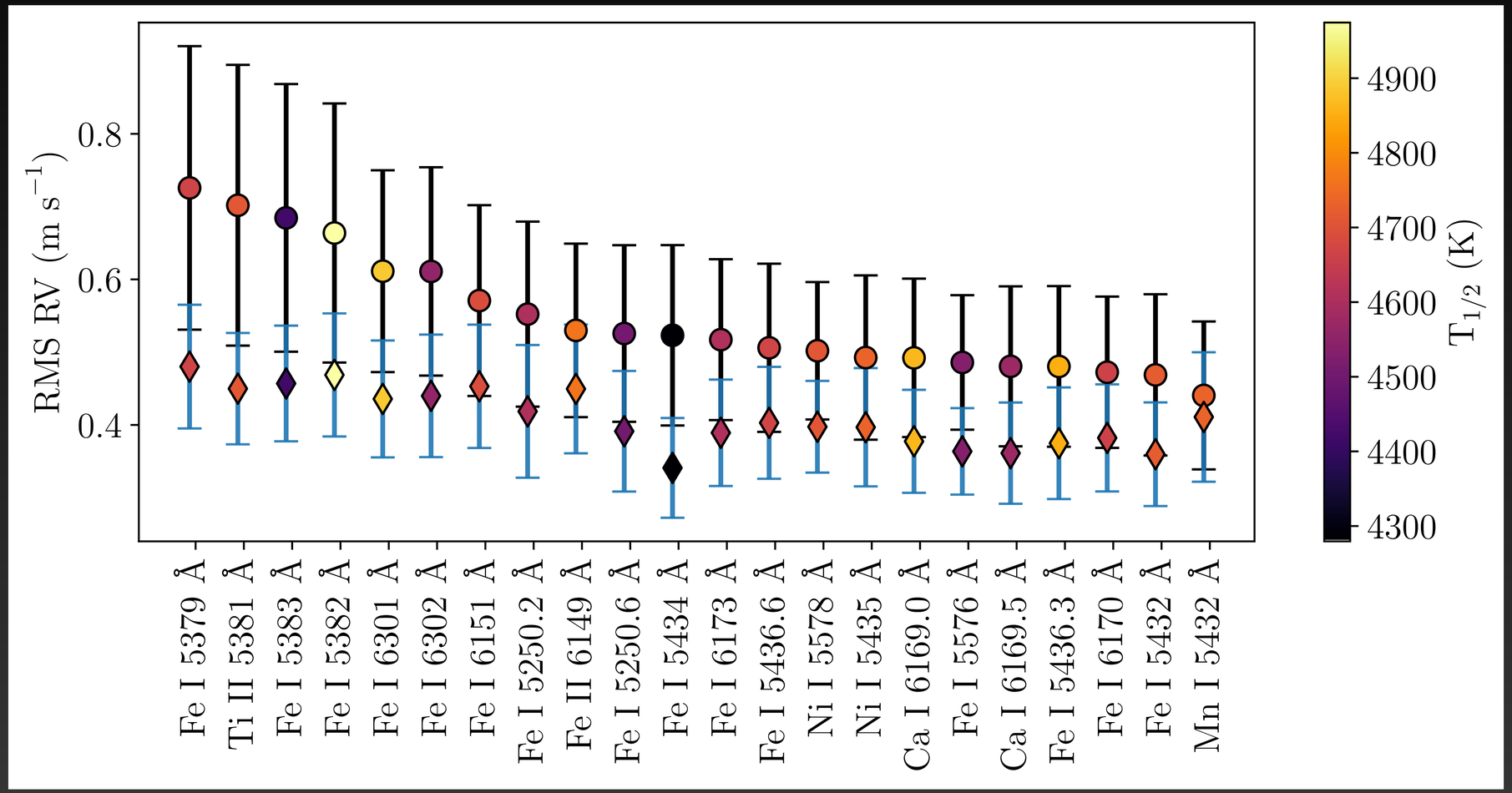
Table 4. Optimized regions for bisector diagnostics (BIS and C) and corresponding improvement in RMS RV. As in Table 3, the improvement is relative to the "intrinsic" RMS of each line and rounded to the nearest whole percent. The parameters b_1 and b_2 refer to the depths bounding the v_t region; b_3 and b_4 bound the v_b region (see Equation 3). Similarly for C: c_1 and c_2 bound v_1, and so on (see Equation 4).

Line	Tuned BIS								Tuned C									
	b_1	b_2	b_3	b_4	R	RMS RV	σ RMS RV	Imprv.	c_1	c_2	c_3	c_4	c_5	c_6	R	RMS RV	σ RMS RV	Imprv.
(Å)	(%)	(%)	(%)	(%)		(m s^{-1})	(m s^{-1})	(%)	(%)	(%)	(%)	(%)	(%)	(%)		(m s^{-1})	(m s^{-1})	(%)
Fe I 5250.2	17	35	79	93	-0.667	0.43	0.07	23	18	42	73	82	83	92	-0.598	0.45	0.07	20
Fe I 5250.6	15	66	70	93	-0.673	0.41	0.07	22	30	42	61	66	69	74	-0.584	0.44	0.08	15
Fe I 5379	43	60	73	79	-0.767	0.50	0.07	32	44	71	72	81	82	90	-0.714	0.52	0.07	29
Ti II 5381	19	60	75	95	-0.785	0.47	0.07	35	24	30	30	41	56	93	0.765	0.51	0.07	30
Fe I 5382	25	50	66	91	-0.730	0.48	0.07	29	19	35	79	88	89	95	-0.681	0.50	0.07	26
Fe I 5383	26	52	71	86	-0.760	0.50	0.07	31	26	67	77	84	87	94	-0.738	0.49	0.07	32
Mn I 5432	70	78	86	93	0.363	0.42	0.08	7	35	49	50	72	85	91	-0.387	0.42	0.08	7
Fe I 5432	21	67	84	92	-0.666	0.36	0.06	24	26	65	68	77	78	84	-0.627	0.39	0.06	20
Fe I 5434	20	41	45	93	-0.773	0.35	0.06	34	17	43	61	68	69	74	-0.725	0.37	0.06	30
Ni I 5435	22	79	82	94	-0.651	0.40	0.07	18	33	73	78	84	84	90	-0.647	0.39	0.07	20
Fe I 5436.3	23	41	57	91	-0.646	0.39	0.06	19	27	34	72	81	83	91	-0.626	0.40	0.06	17
Fe I 5436.6	32	50	72	81	-0.642	0.40	0.07	20	38	43	66	80	81	87	-0.595	0.42	0.07	17
Fe I 5576	20	61	75	88	-0.687	0.38	0.05	25	30	45	75	86	87	93	-0.651	0.38	0.05	25
Ni I 5578	33	56	62	77	-0.624	0.41	0.05	20	40	78	80	86	87	92	-0.595	0.40	0.04	21
Fe II 6149	18	56	77	94	-0.537	0.48	0.06	15	39	46	73	78	82	88	-0.503	0.48	0.07	14
Fe I 6151	36	49	64	90	-0.623	0.48	0.07	19	25	46	68	80	81	88	-0.595	0.49	0.07	16
Ca I 6169.0	22	63	74	95	-0.661	0.38	0.06	23	38	56	76	82	83	91	-0.588	0.40	0.06	18
Ca I 6169.5	22	42	74	87	-0.680	0.37	0.06	24	22	56	81	87	87	94	-0.624	0.38	0.06	23
Fe I 6170	17	77	82	89	-0.596	0.40	0.06	18	21	51	68	76	77	82	-0.530	0.42	0.06	14
Fe I 6173	20	51	61	83	-0.695	0.40	0.06	24	31	50	77	82	84	90	-0.648	0.41	0.06	23
Fe I 6301	21	64	74	91	-0.705	0.46	0.06	26	33	42	80	87	87	94	-0.675	0.47	0.07	25
Fe I 6302	18	56	79	92	-0.698	0.48	0.07	26	22	62	70	78	79	89	-0.651	0.50	0.08	22

Palumbo et al. (2024b)

The optimal bisector diagnostic varies line by line

See the paper for the full nitty-gritty details...

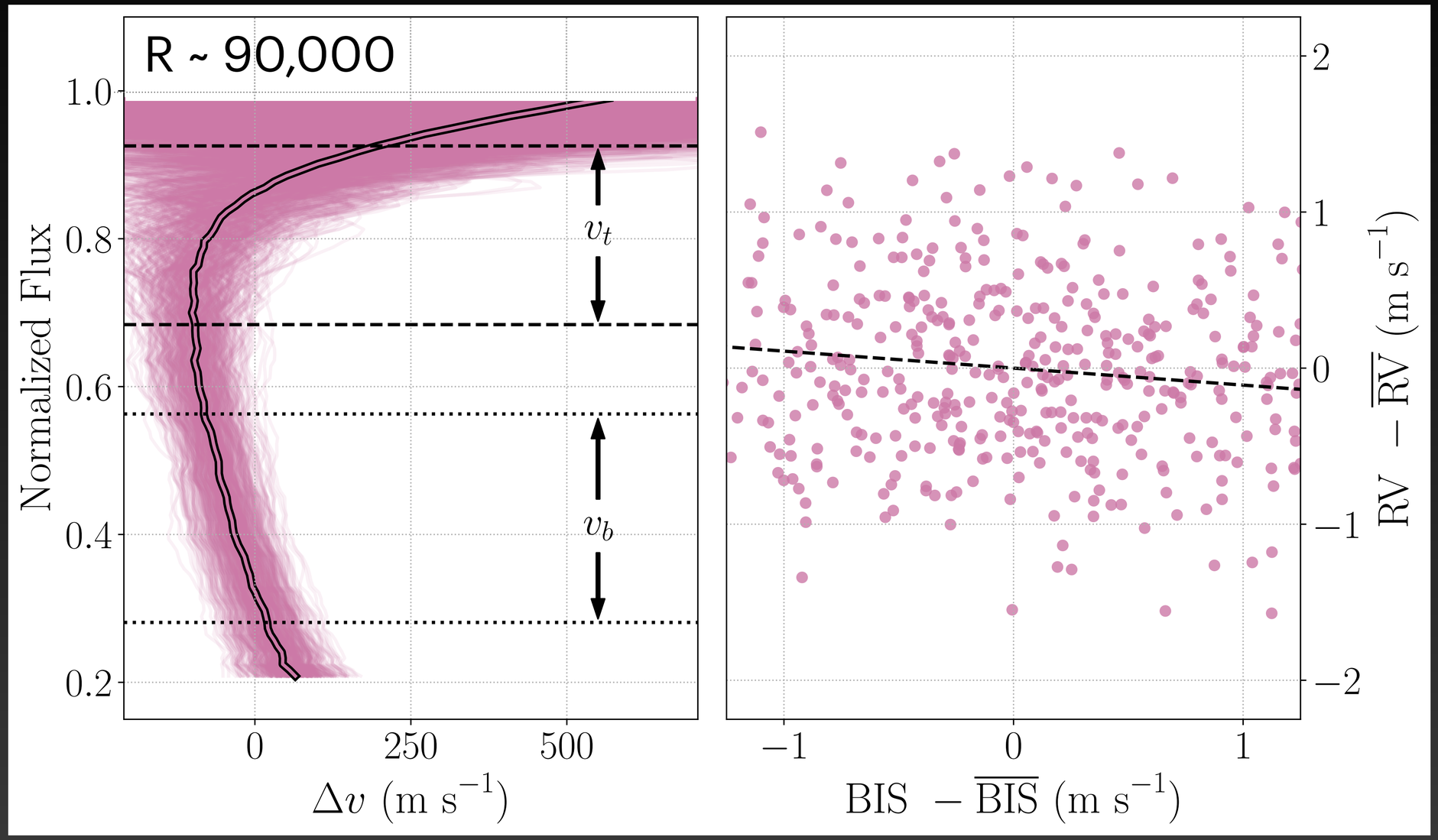


"Intrinsic" Variability

"Improved" Variability

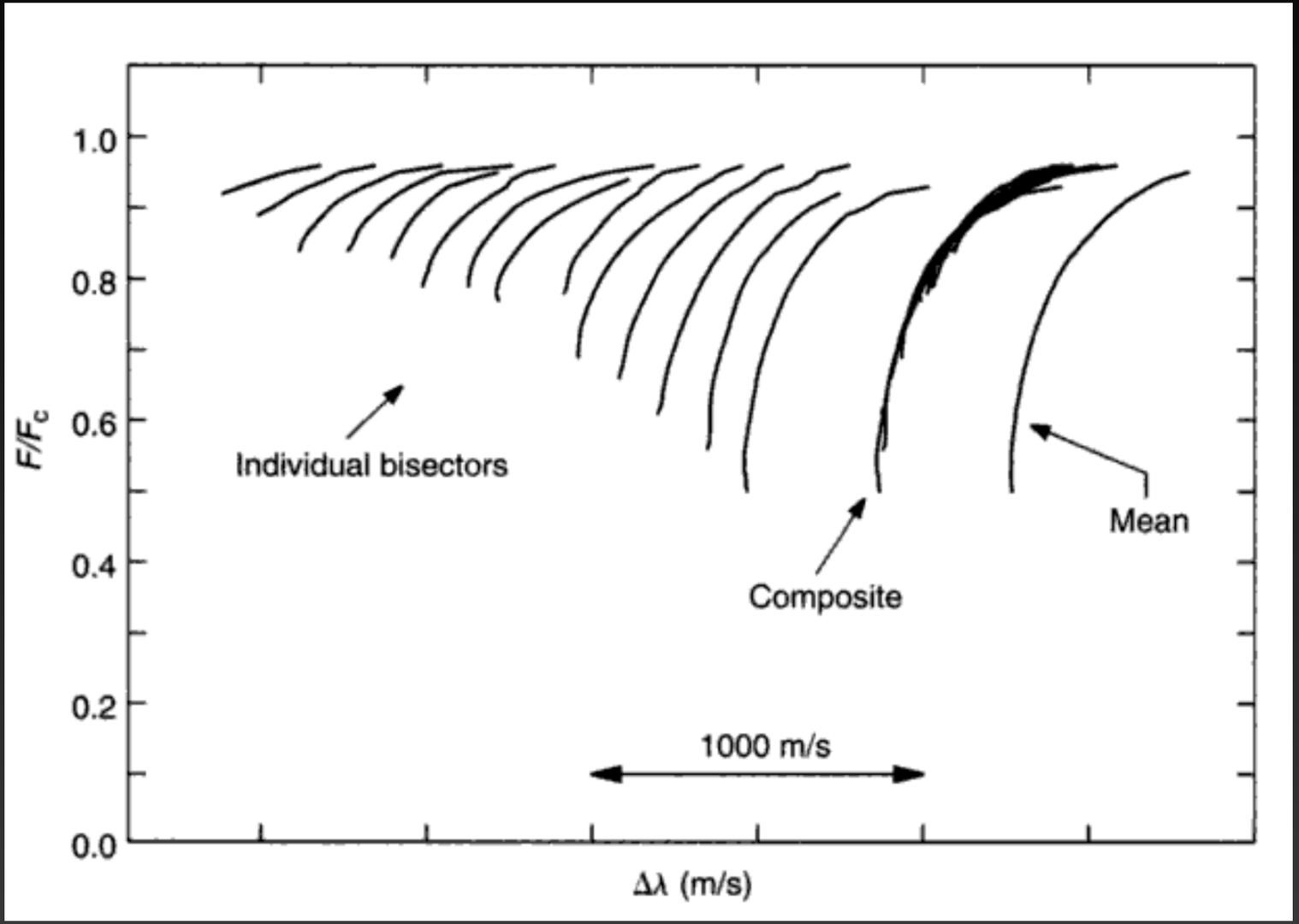
Palumbo et al. (2024b)

But at typical resolutions and SNRs achieved by current instruments, individual line-shape correlations can't be retrieved



Palumbo et al. (2024b)

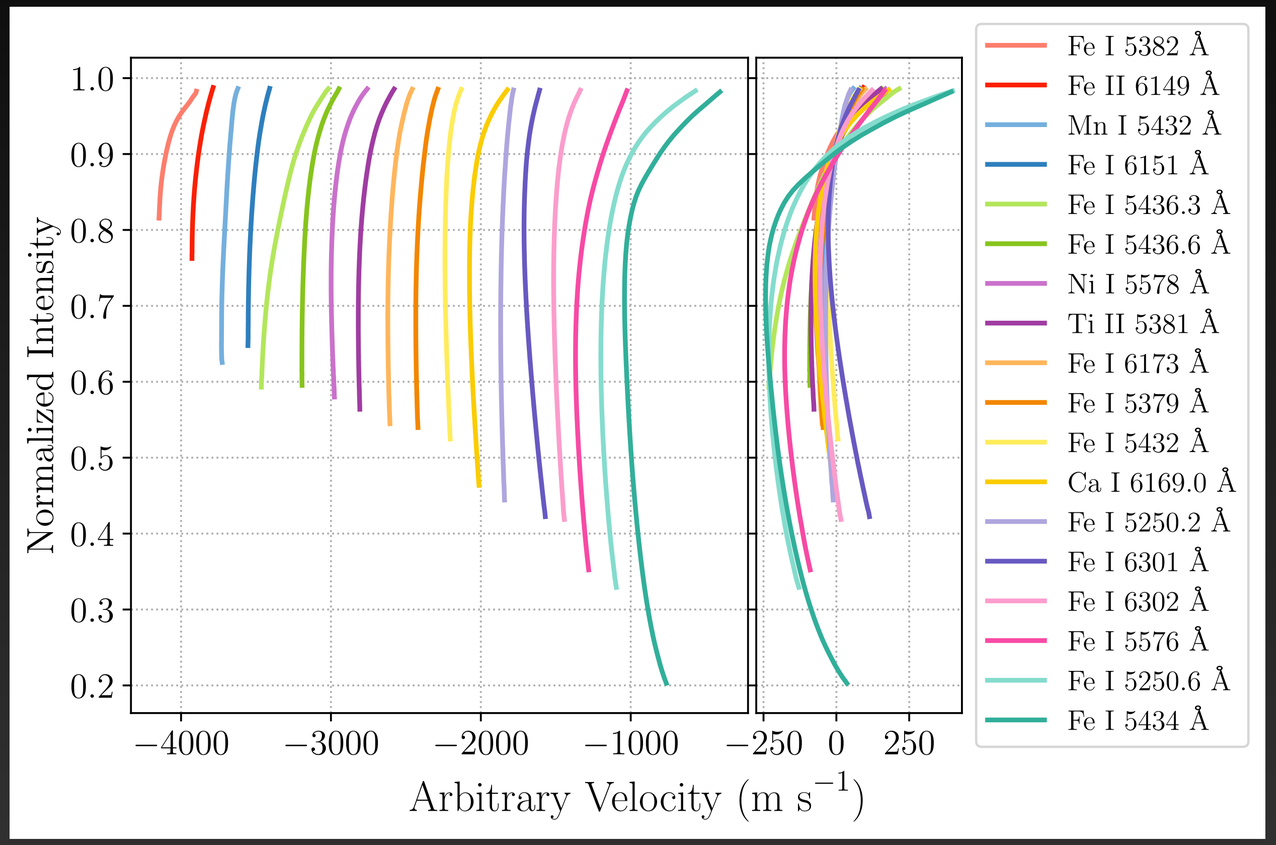
Although (cherry-picked) bisectors *can* resemble each other...



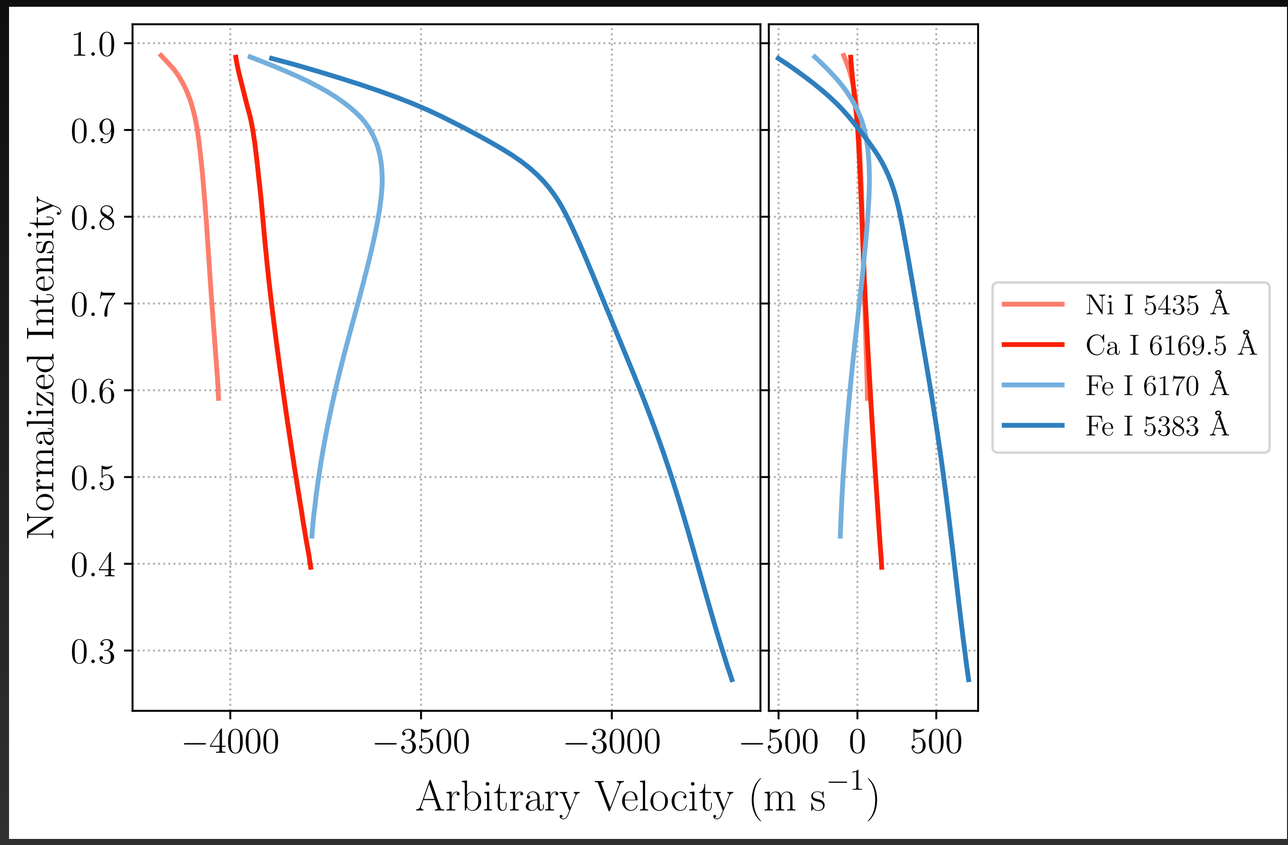
Gray (2008)

Although (cherry-picked) bisectors *can* resemble each other...

"Clean" Lines



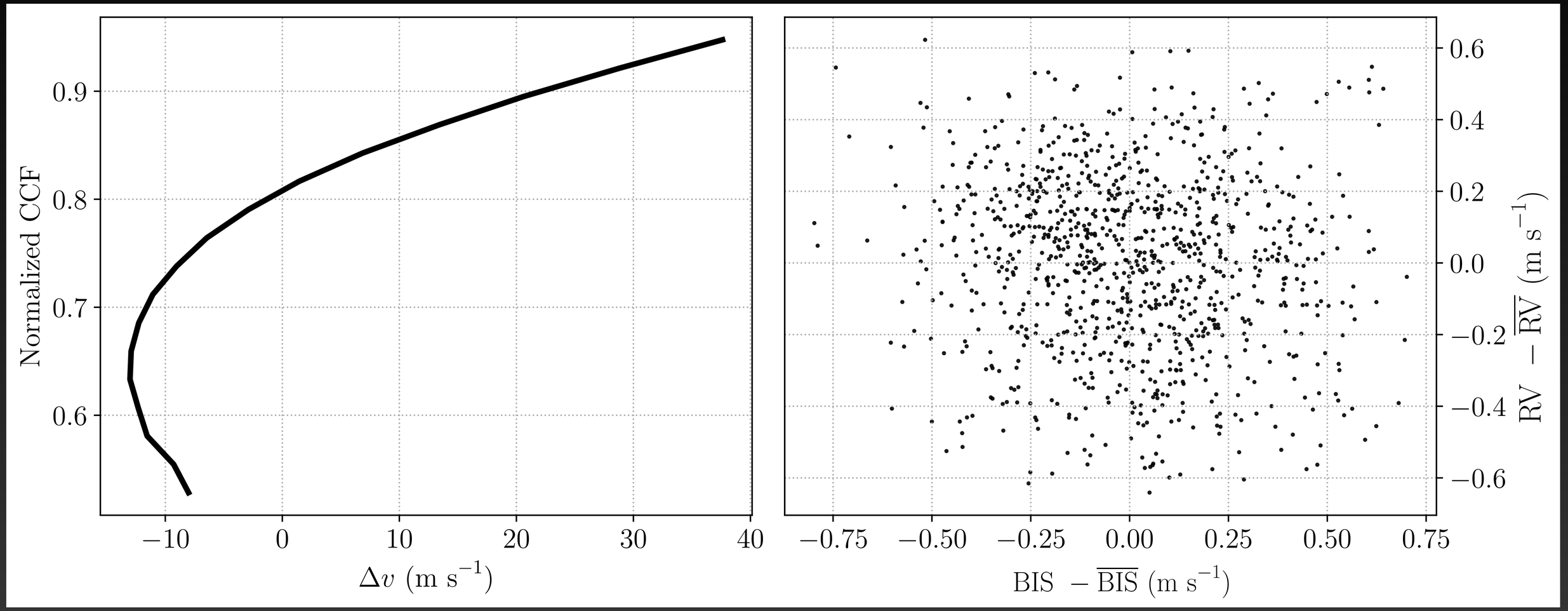
Unresolved Blends



...this is far from universally true

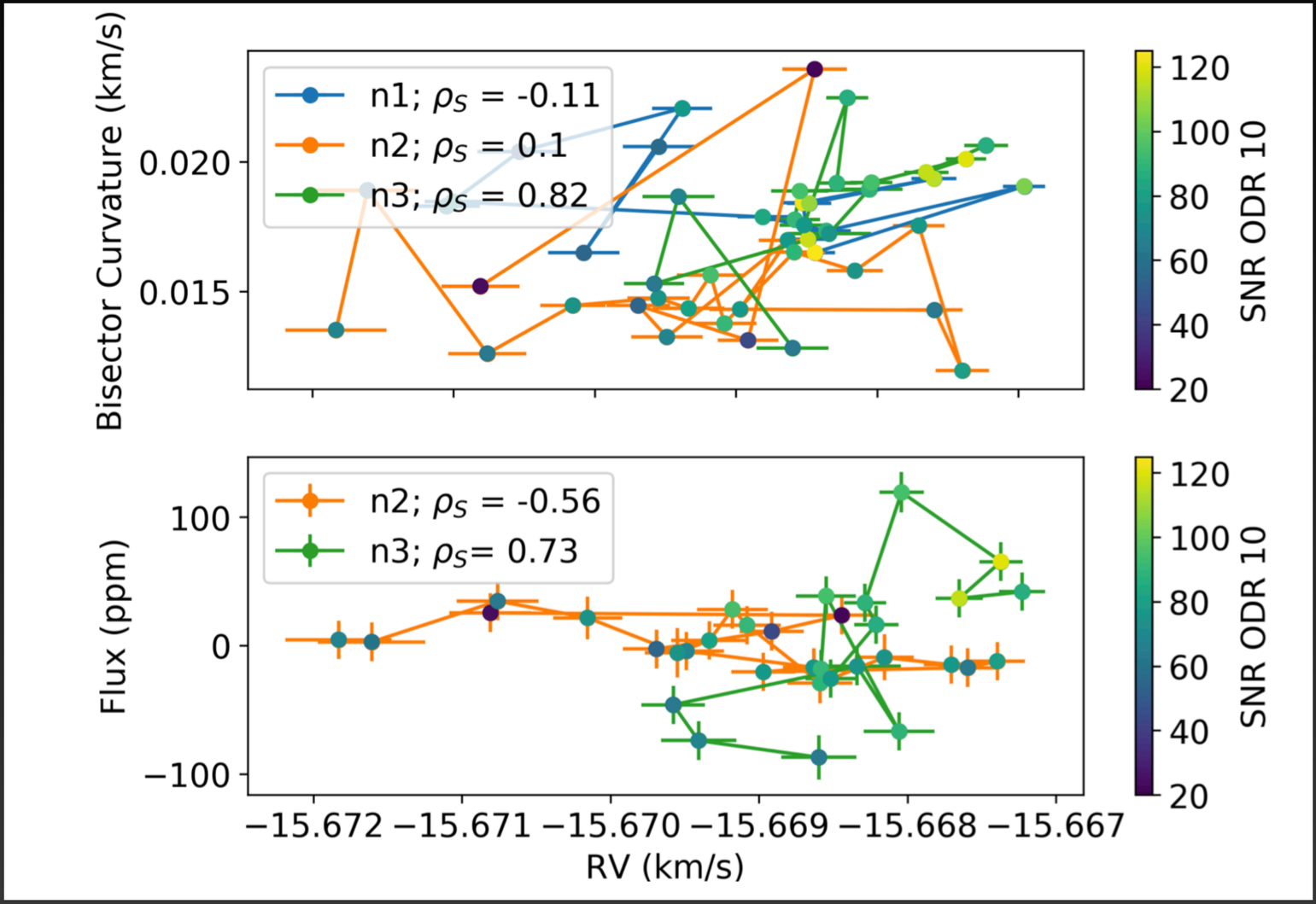
Palumbo et al. (2024b)

...these correlations also can't be retrieved from CCF bisectors because they bin *incoherent* granulation signals



Palumbo et al. (2024b)

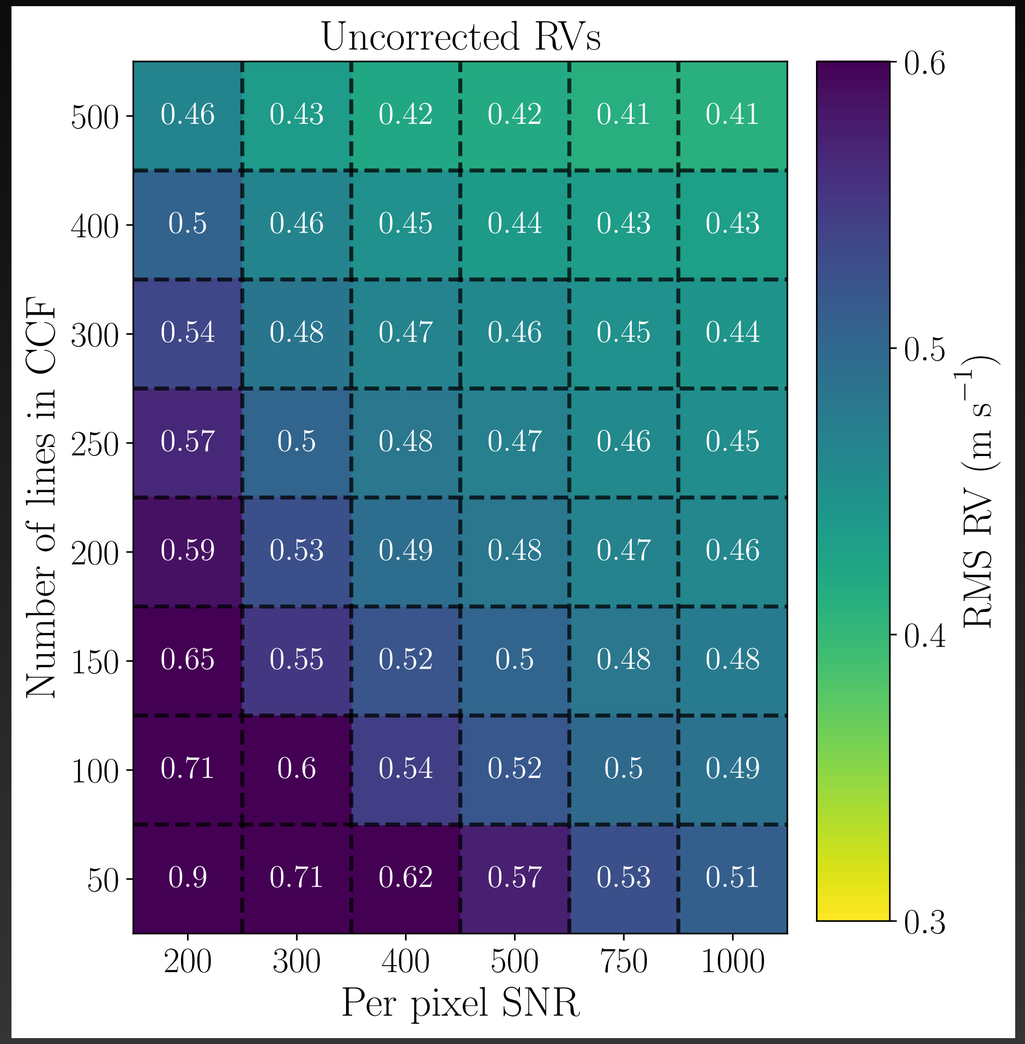
Indeed, a recent attempt to retrieve RV vs. shape correlations from CCFs failed



Sulis et al. (2023)

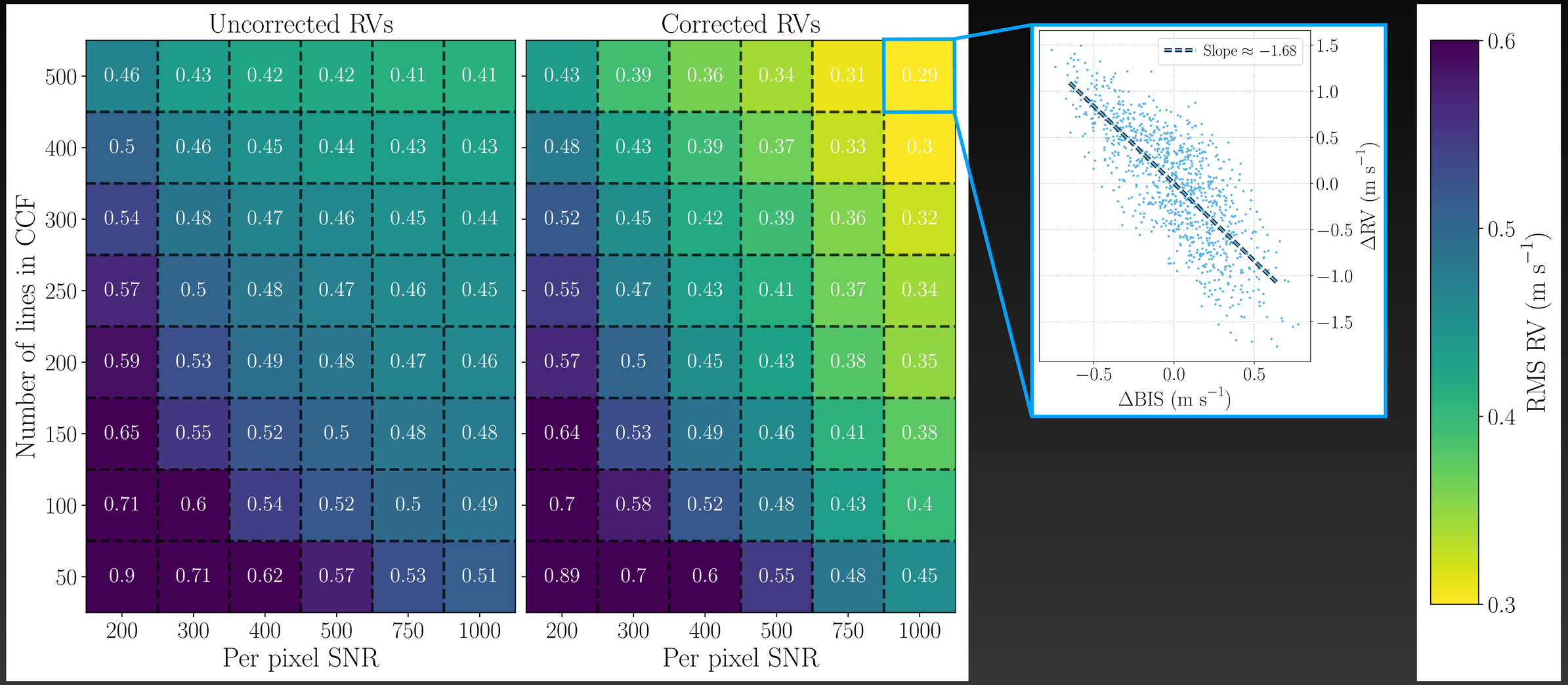
But what if we only *very selectively* binned lines?

But what if we only *very selectively* binned lines?



Palumbo et al. (2024b)

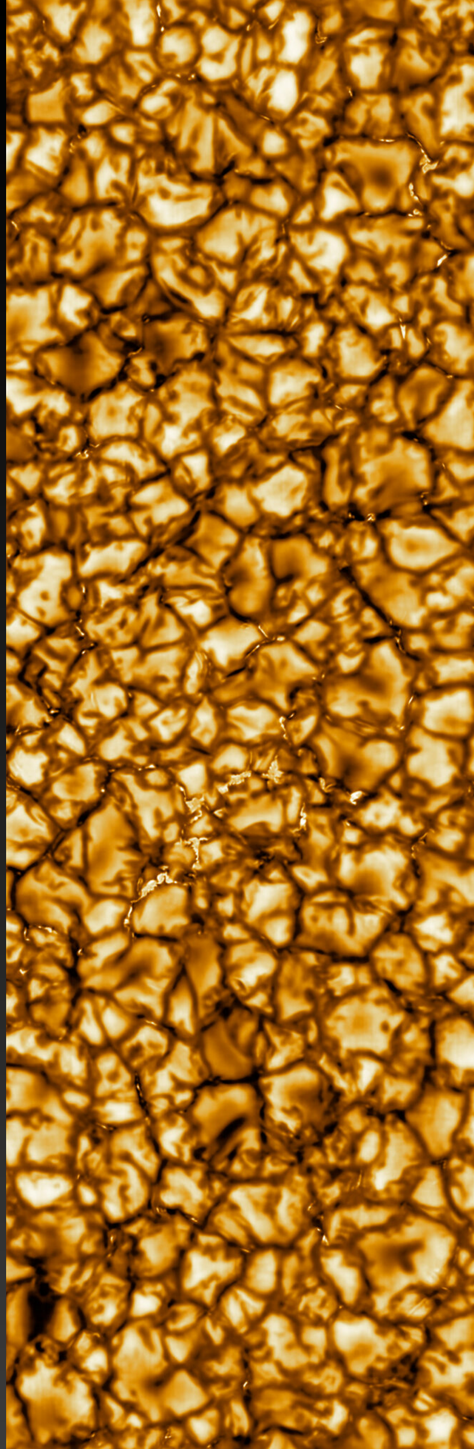
But what if we only *very selectively* binned lines?
Optimistically, the correlations *<u>can</u> be retrieved!*



Palumbo et al. (2024b)

Summary & Conclusions

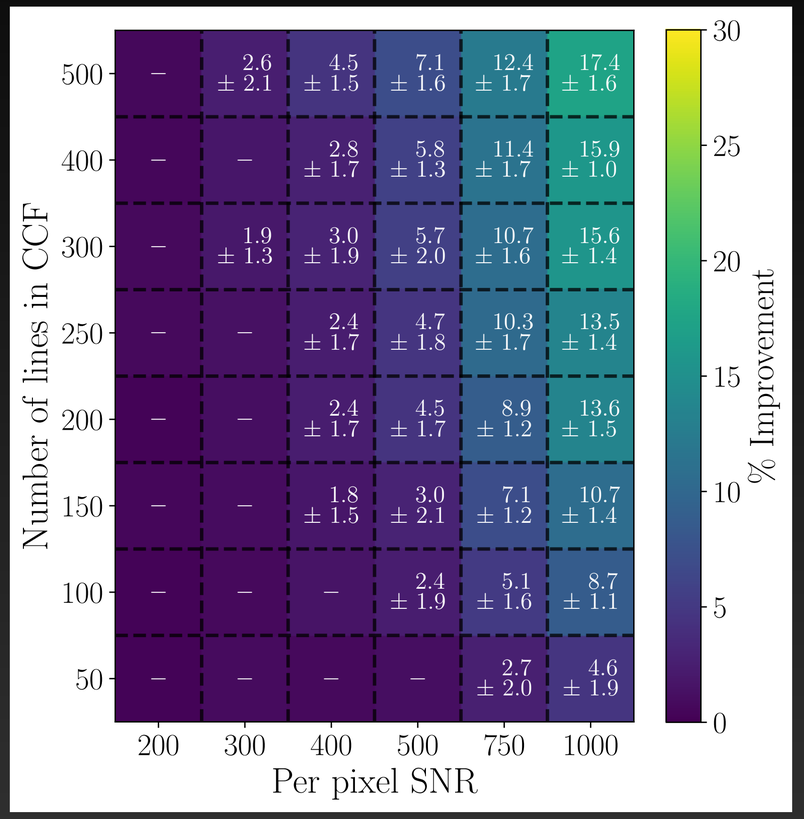
- Granulation encodes a time-variable *signal* in line shapes
- This *signal* will need to be resolved and studied in order to fully mitigate granulation in EPRV science
- `GRASS` uses existing solar data to empirically model granulation in spectra, but...
- ...only draws from a select handful of lines that have been observed.
- EPRV solar telescope data provide an excellent first avenue for identifying and coherently binning line-shape distortions imparted by granulation



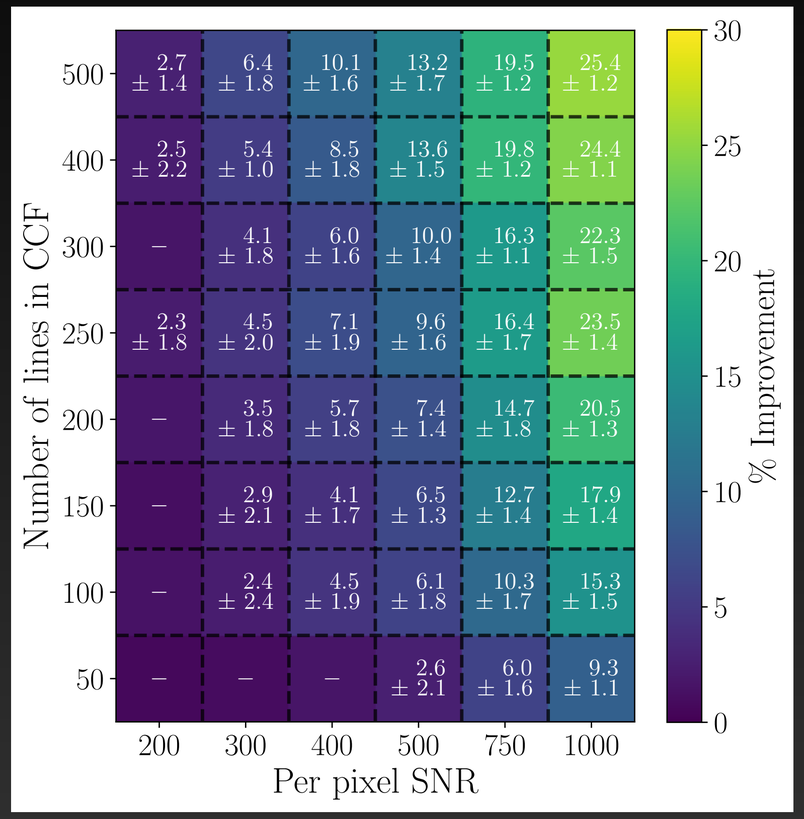
mpalumbo@flatironinstitute.org michaelpalumbo.me github.com/palumbom

Backup Slides

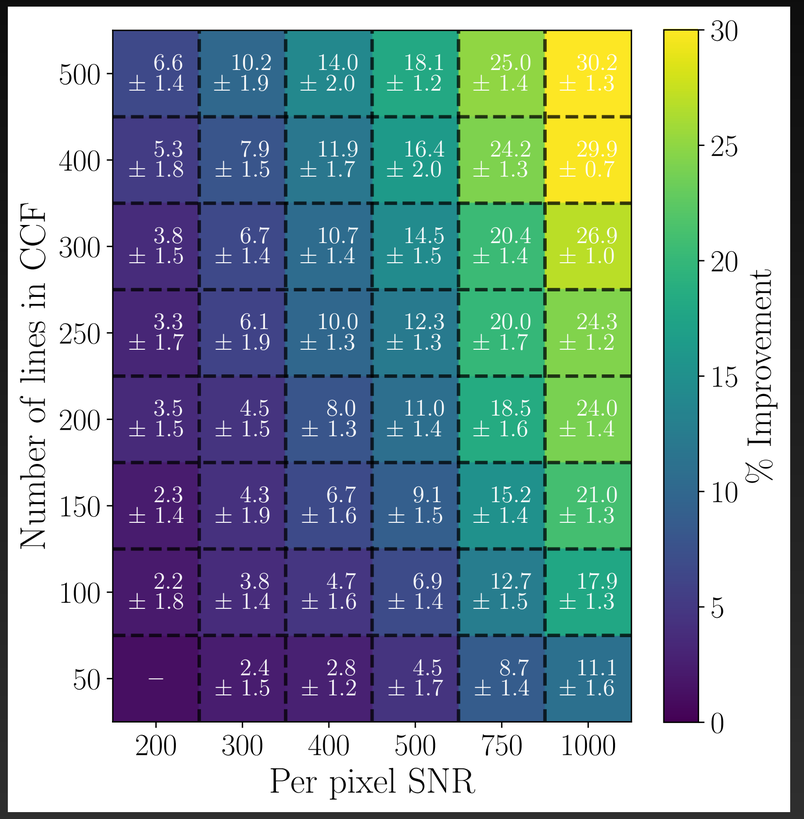
With informed line lists and higher SNR, shape information can meaningfully correct anomalous velocities



R ~ 190,000 (ESPRESSO UHR)

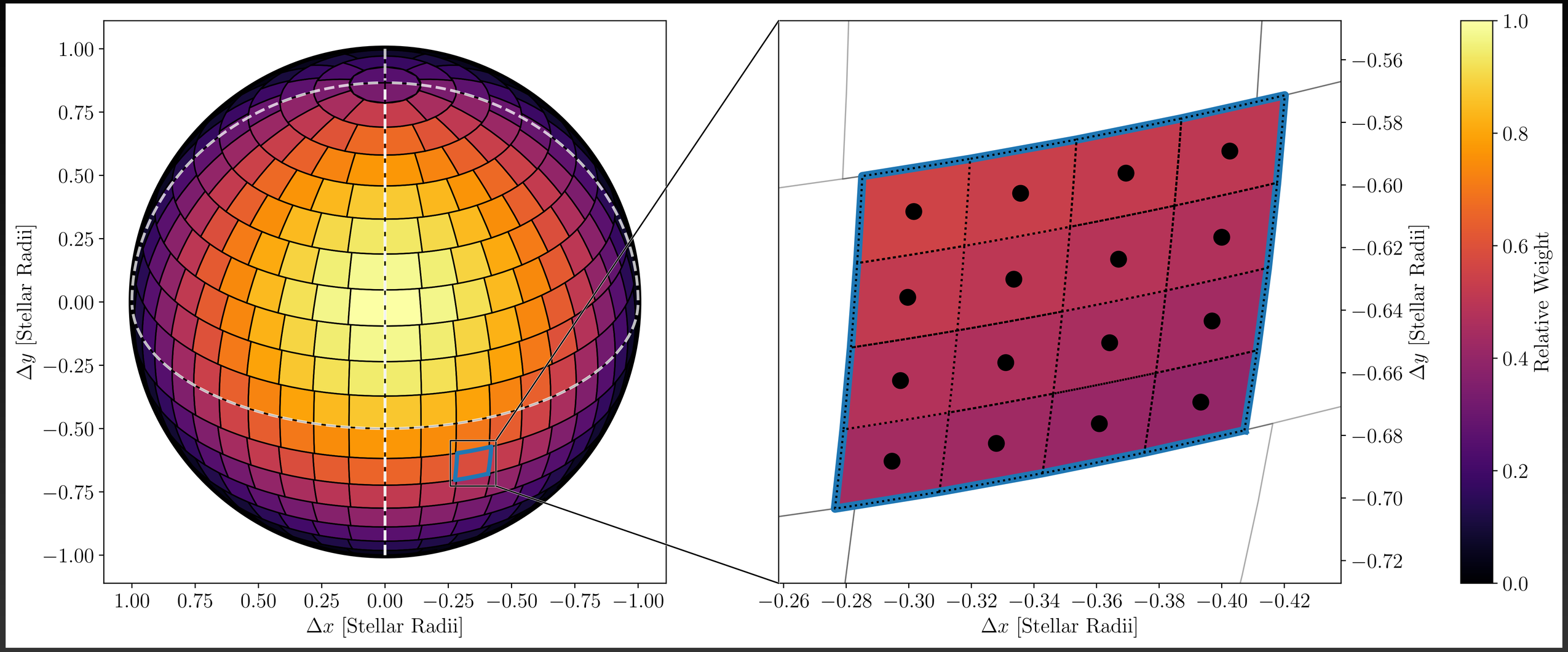


R ~ 270,000 (PEPSI)

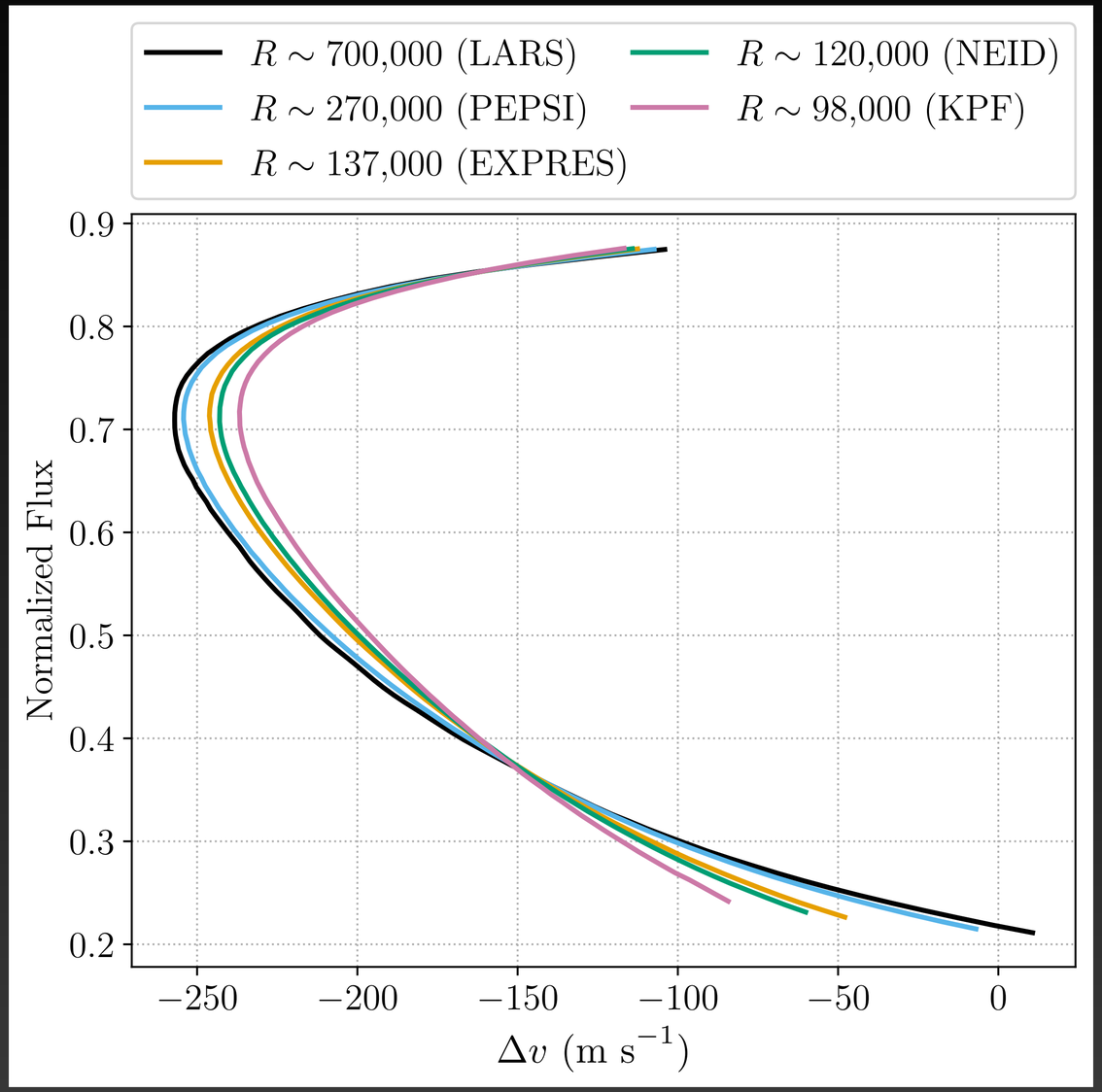


R ~ 350,000 (Fiducial)

Palumbo et al. (2024b)

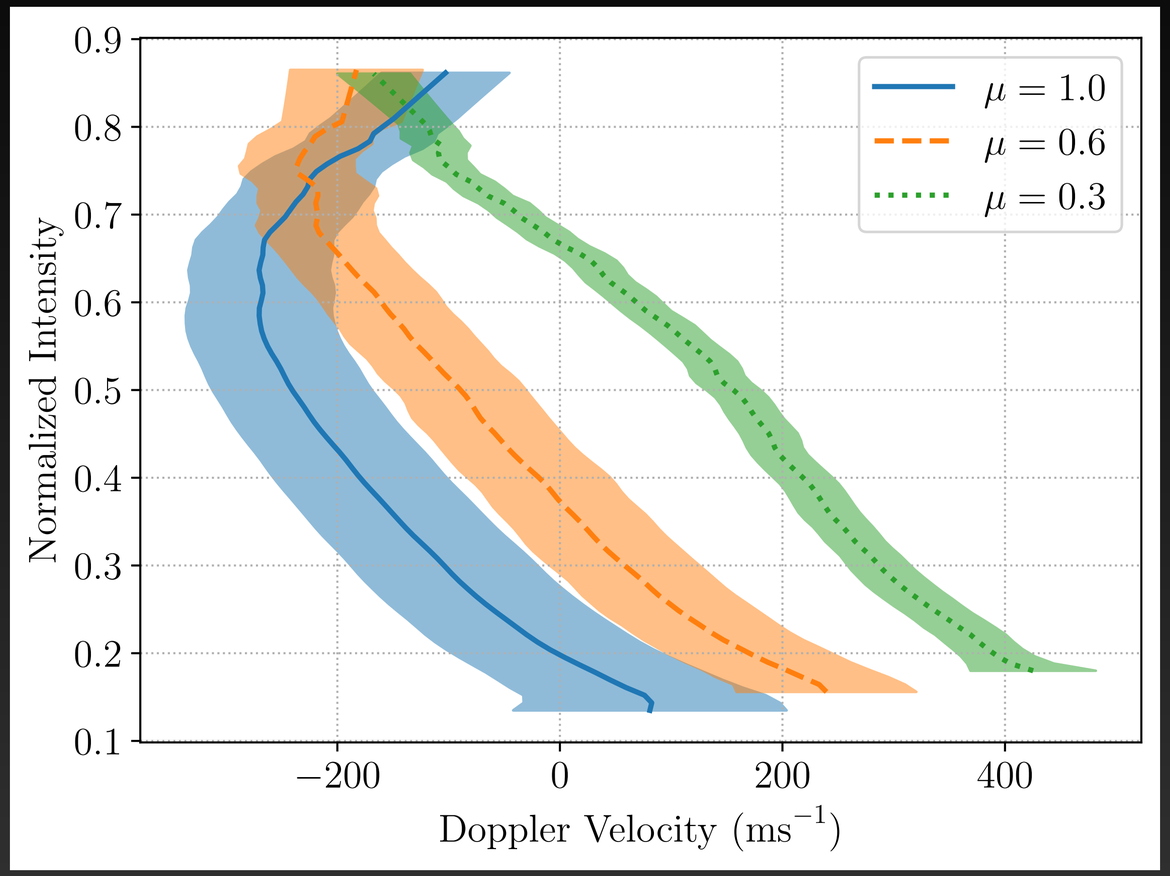

1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
Δy [Stellar Radii]
1.00 0.75 0.50 0.25 0.00 −0.25 −0.50 −0.75 −1.00
Δx [Stellar Radii]
−0.56
−0.58
−0.60
−0.62
−0.64
−0.66
−0.68
−0.70
−0.72
Δy [Stellar Radii]
−0.26 −0.28 −0.30 −0.32 −0.34 −0.36 −0.38 −0.40 −0.42
Δx [Stellar Radii]
1.0
0.8
0.6
0.4
0.2
0.0
Relative Weight

There is a large caveat: spectral resolution matters!



Palumbo et al. (2024b)

We use deep lines as models for shallower lines



Palumbo et al. (2022)

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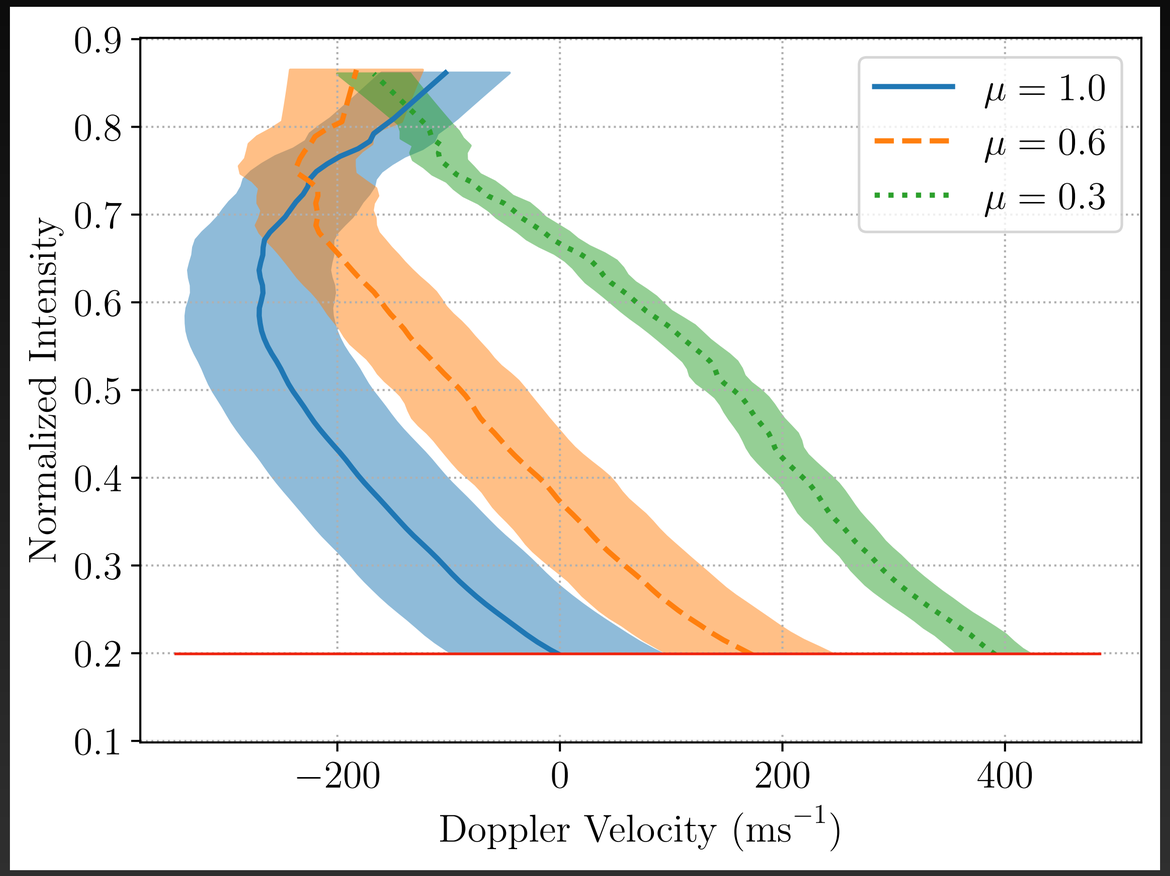

Palumbo et al. (2022)

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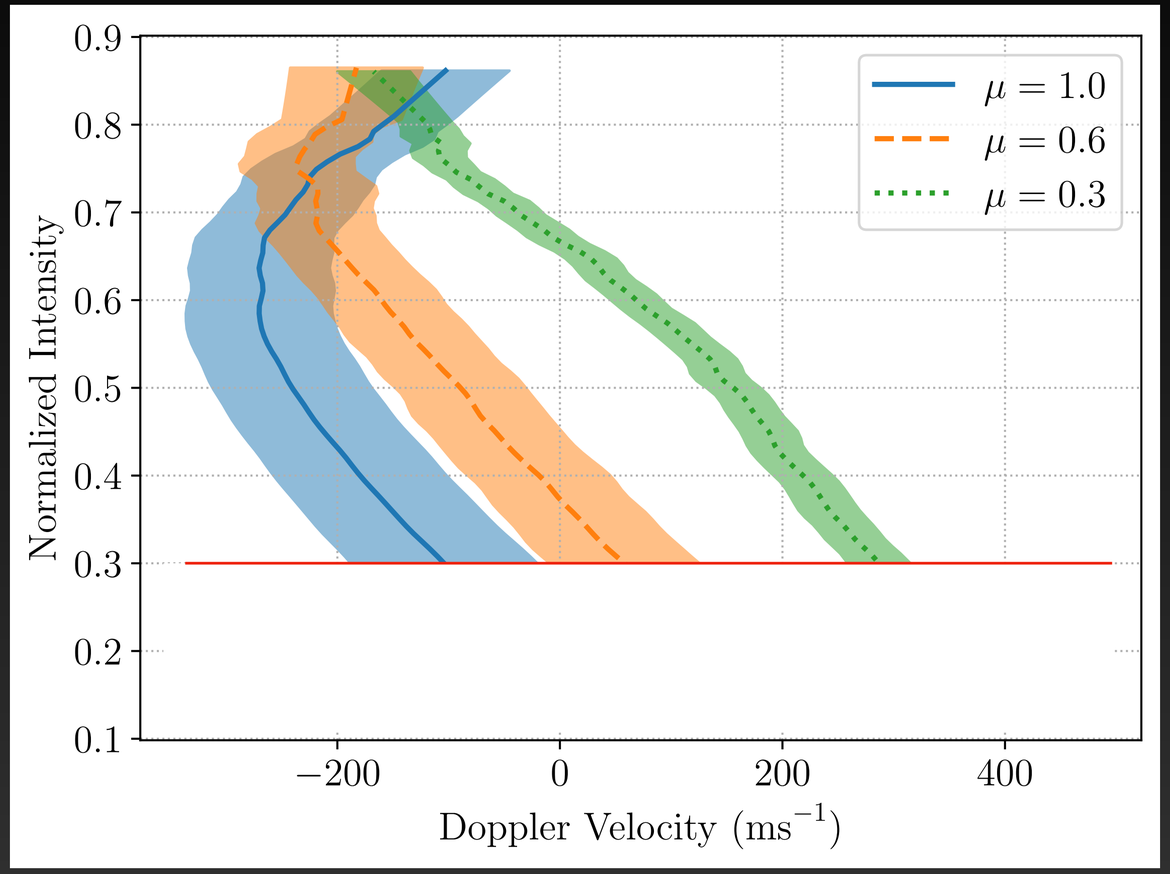
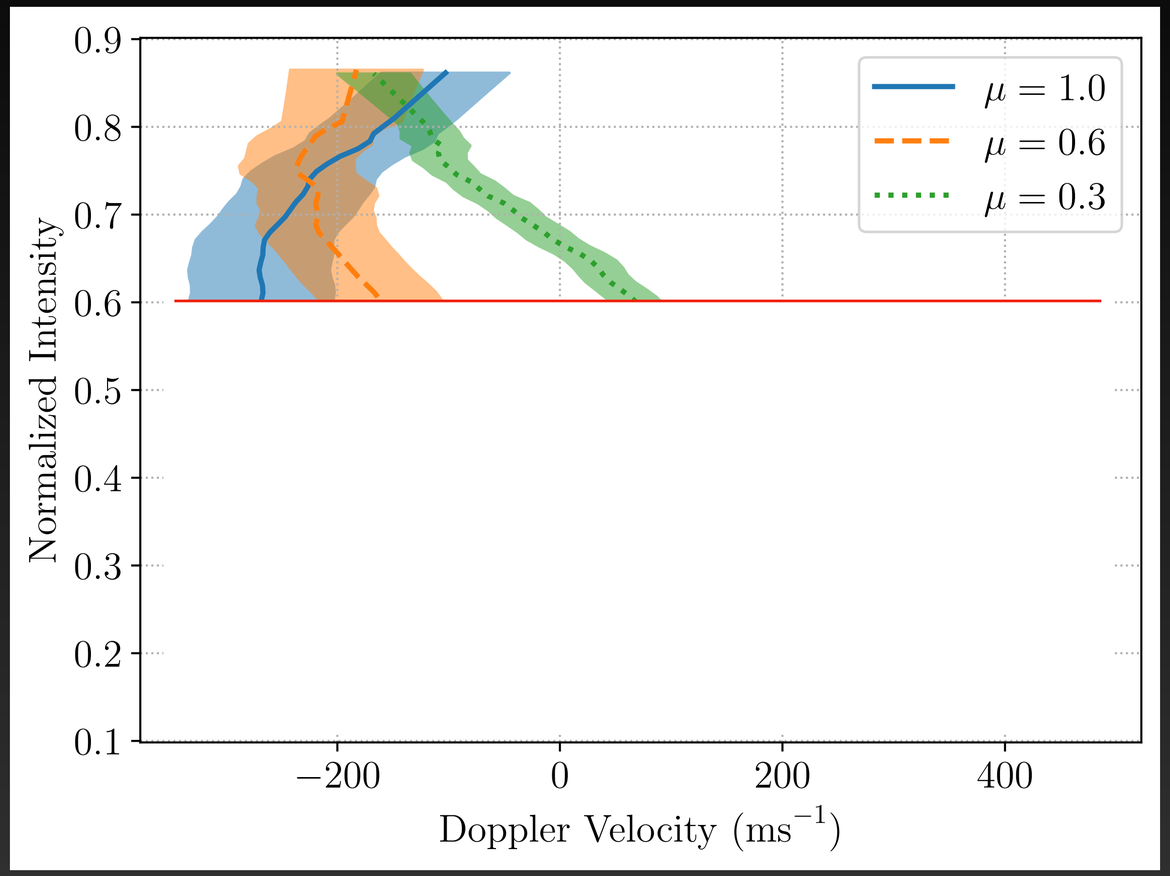


Palumbo et al. (2022)

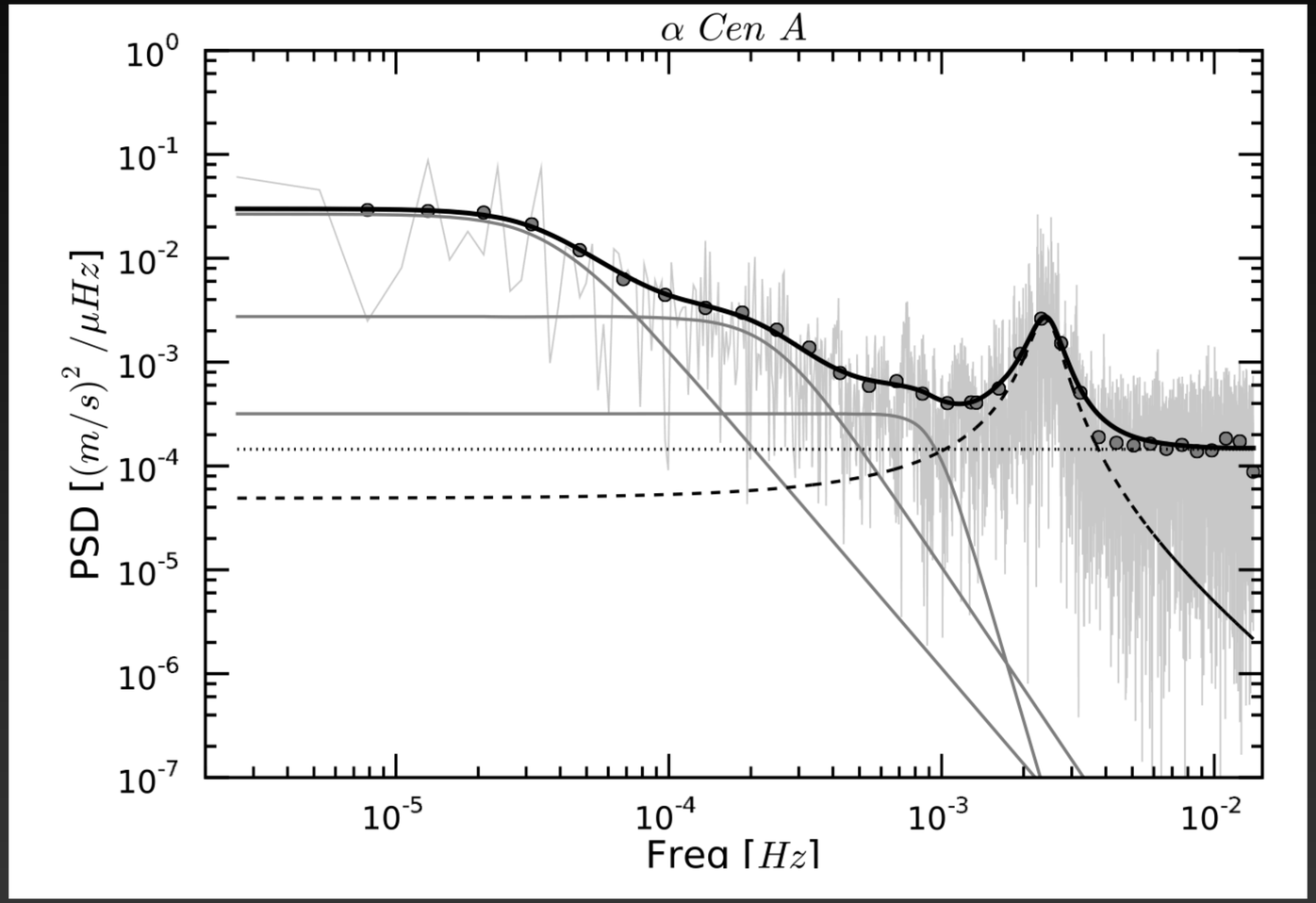
We use deep lines as models for shallower lines



Palumbo et al. (2022)

Brute-force binning is not a viable strategy!

Granulation is not white noise!



Dumusque et al. (2011)