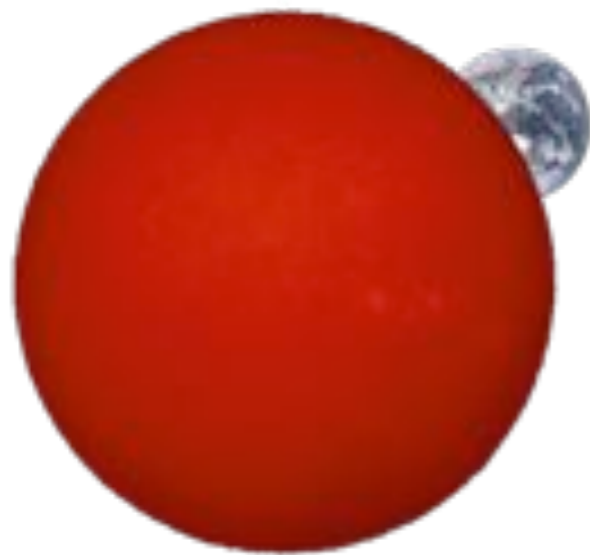


Precision Radial Velocities in the Near Infrared with TEDI

James Lloyd (Cornell University)



“Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature.”

-Albertus Magnus

1193-1280

Outline

- ~~M dwarfs & Infrared RV~~

Declare victory: 60/40 by talk emphasis

- Transits
- Accuracy, precision and efficiency
- TripleSpec Exoplanet Discovery Instrument

A brief history of Exoplanets



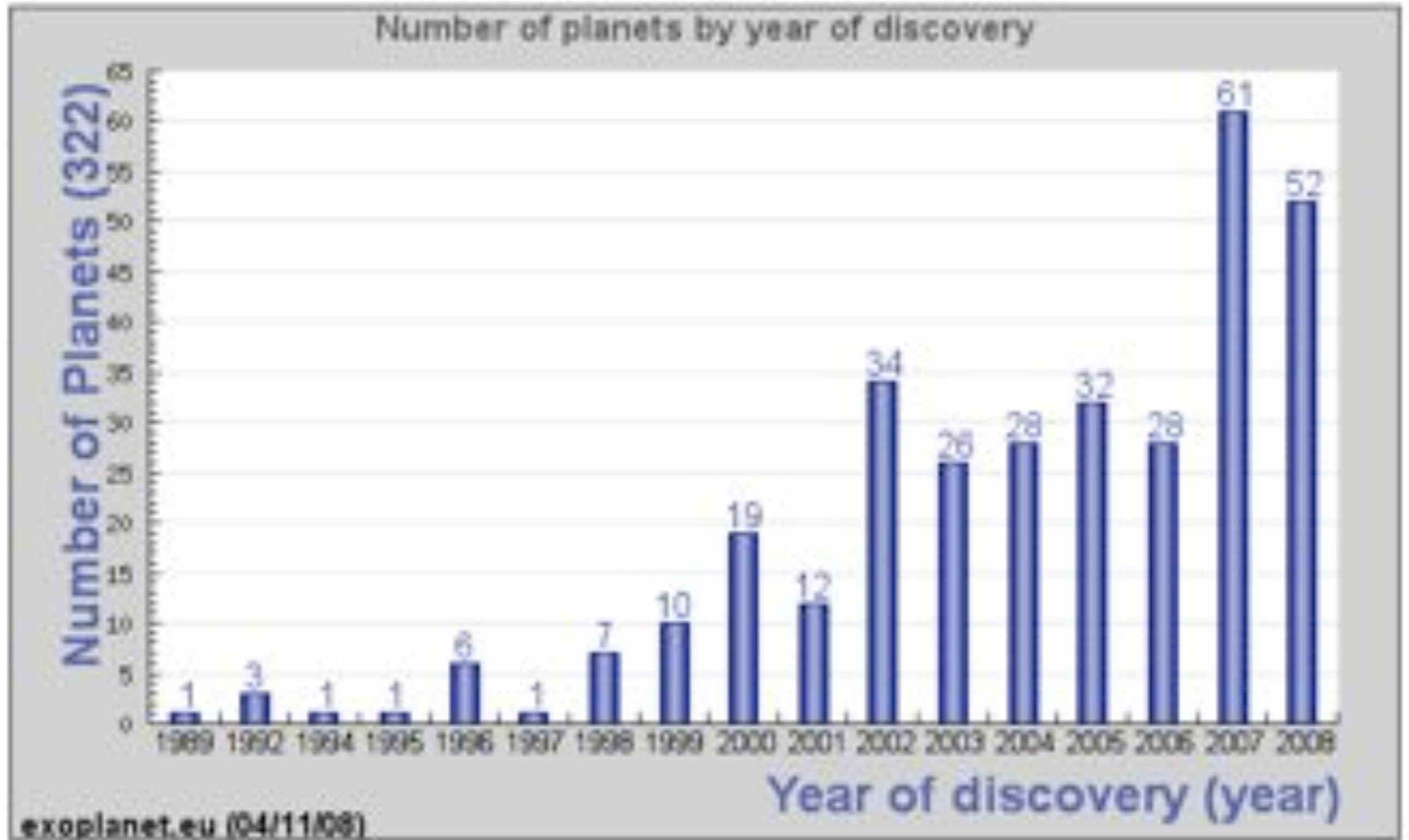
Giordano Bruno

De l'Infinito, Universo e Mondi (1584),

“Thus is the excellence of God magnified and the greatness of his kingdom made manifest; He is glorified not in one, but in countless suns; not in a single earth, a single world, but in a thousand thousand, I say in an infinity of worlds!”

Executed in 1600

Rate of Discovery

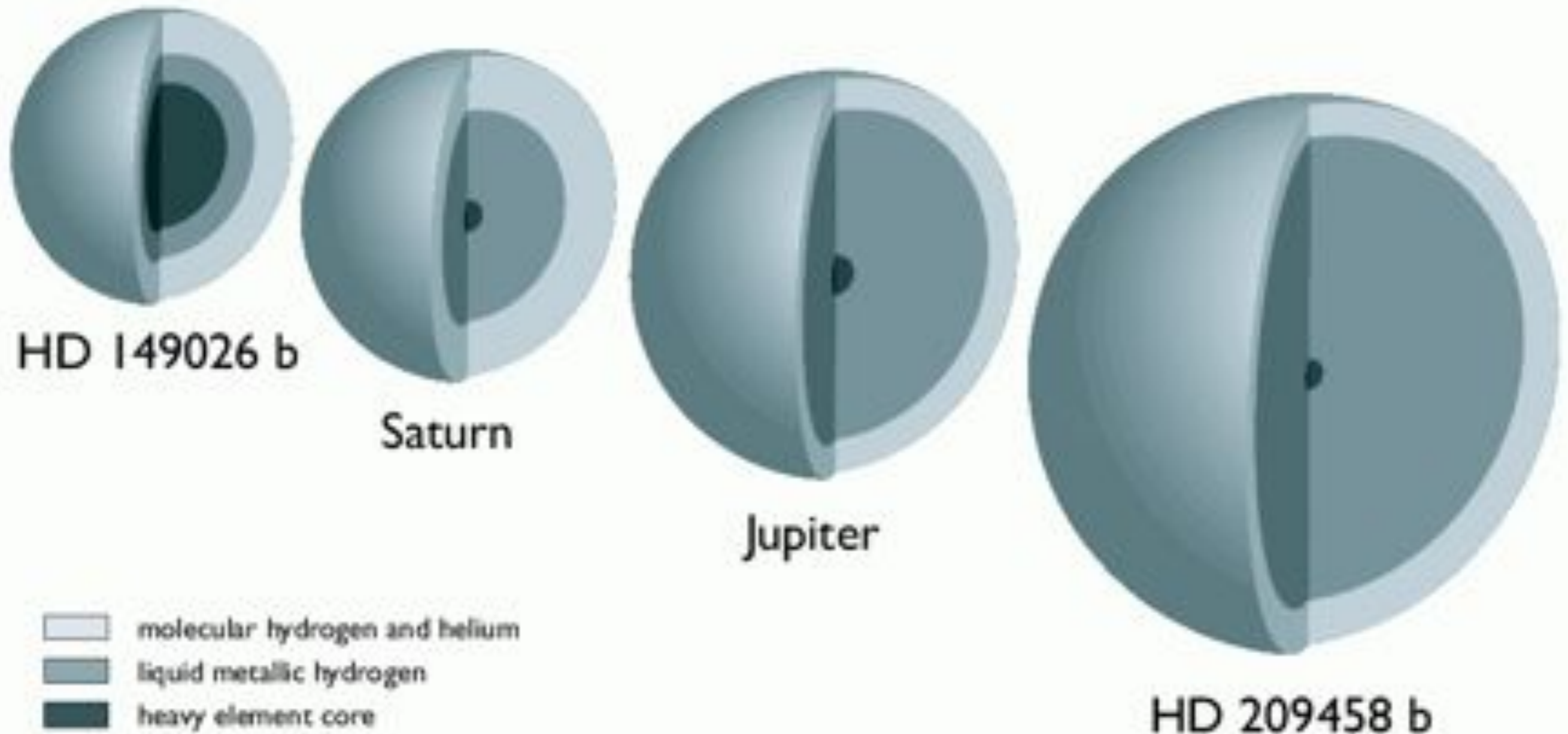


The Pothole of Comte's Positivism

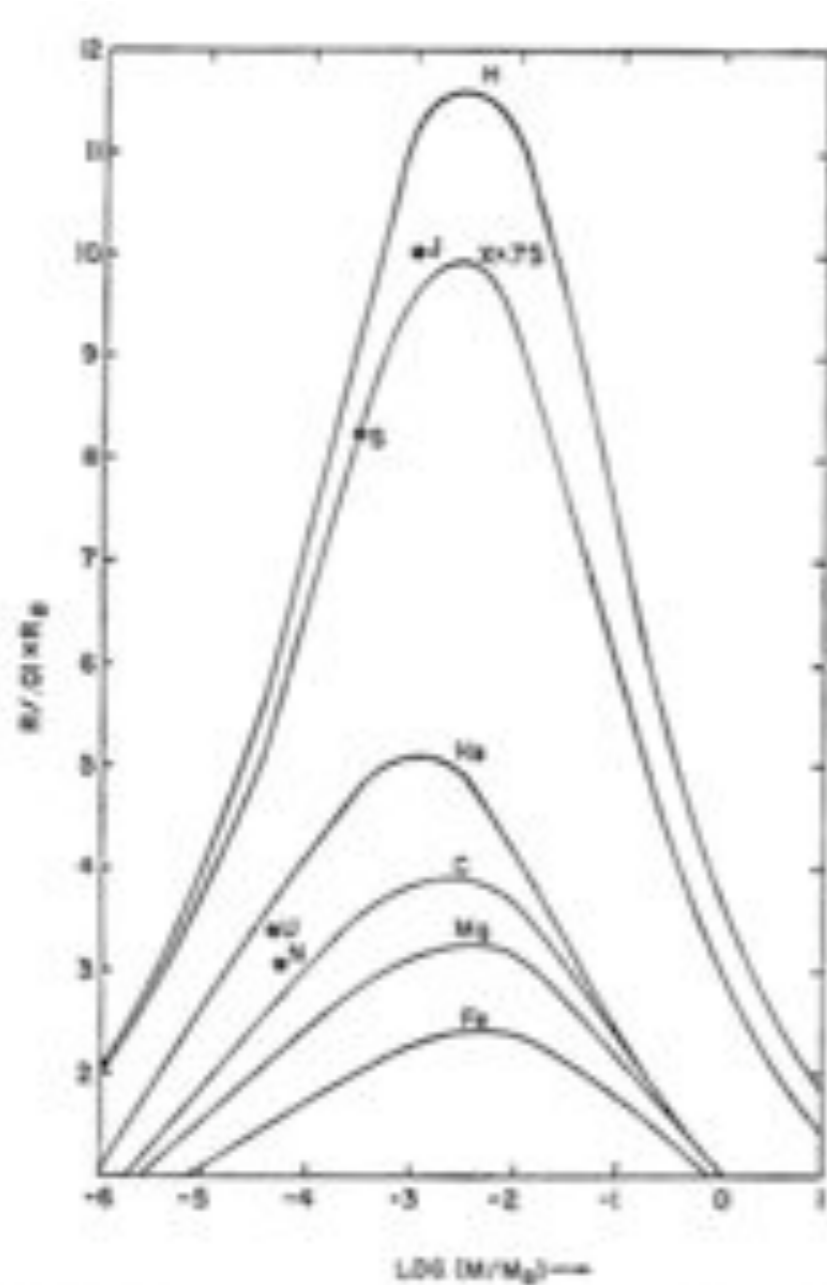
“we can determine the shapes, distances, sizes, and motions of celestial bodies, but never, by any means, will we be able to study their chemical compositions.”

Auguste Comte, 1835

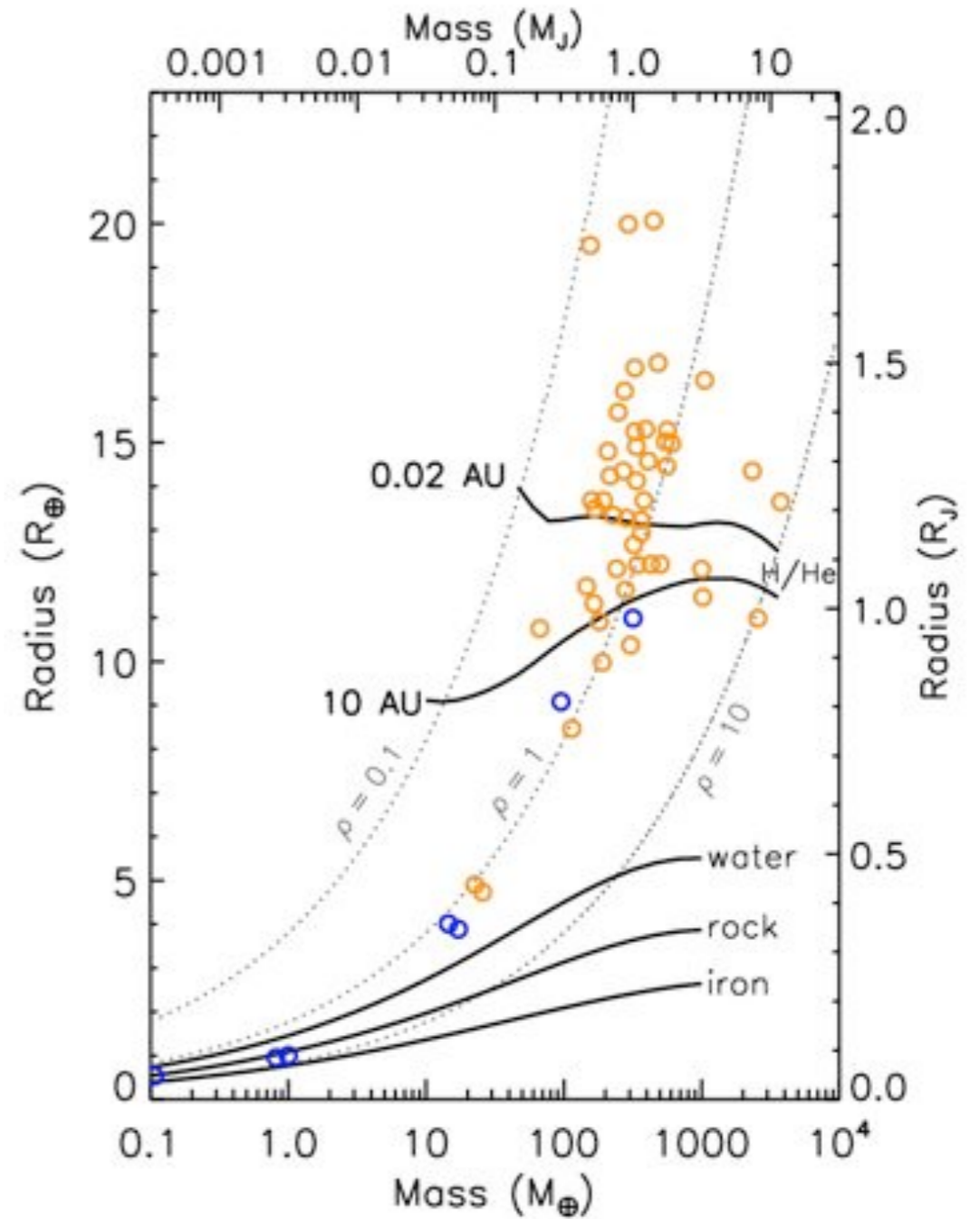
Mass + Size = Density



Transits \Rightarrow Astrophysics



Zapolsky & Salpeter 1969



credit: J. Fortney

Star

M5V
0.1 M_☉
2200K
0.1 R_☉

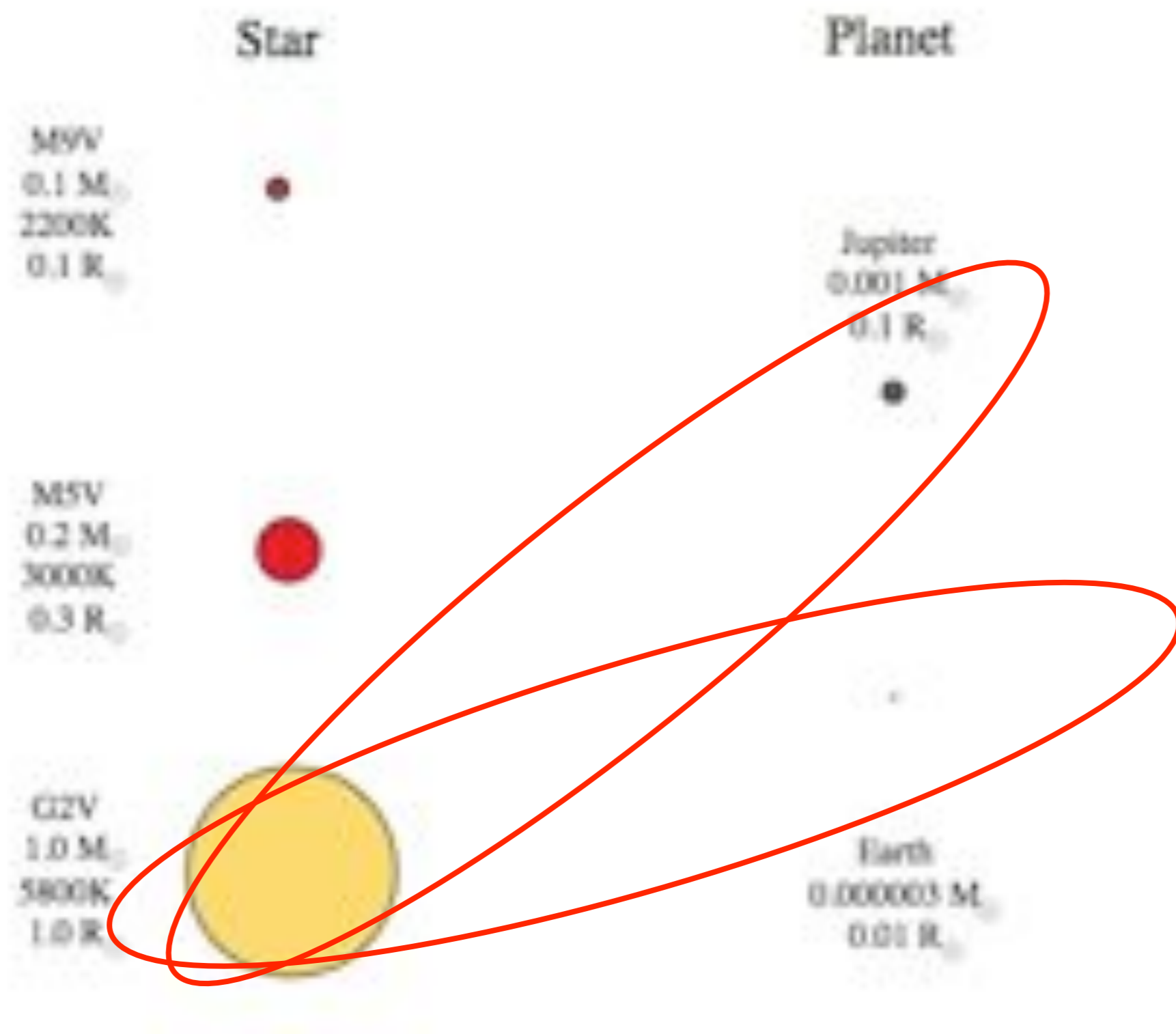


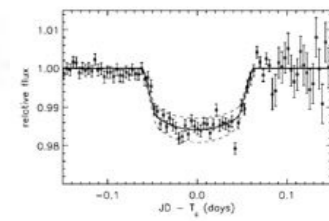
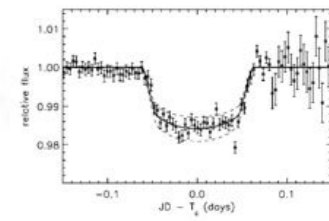
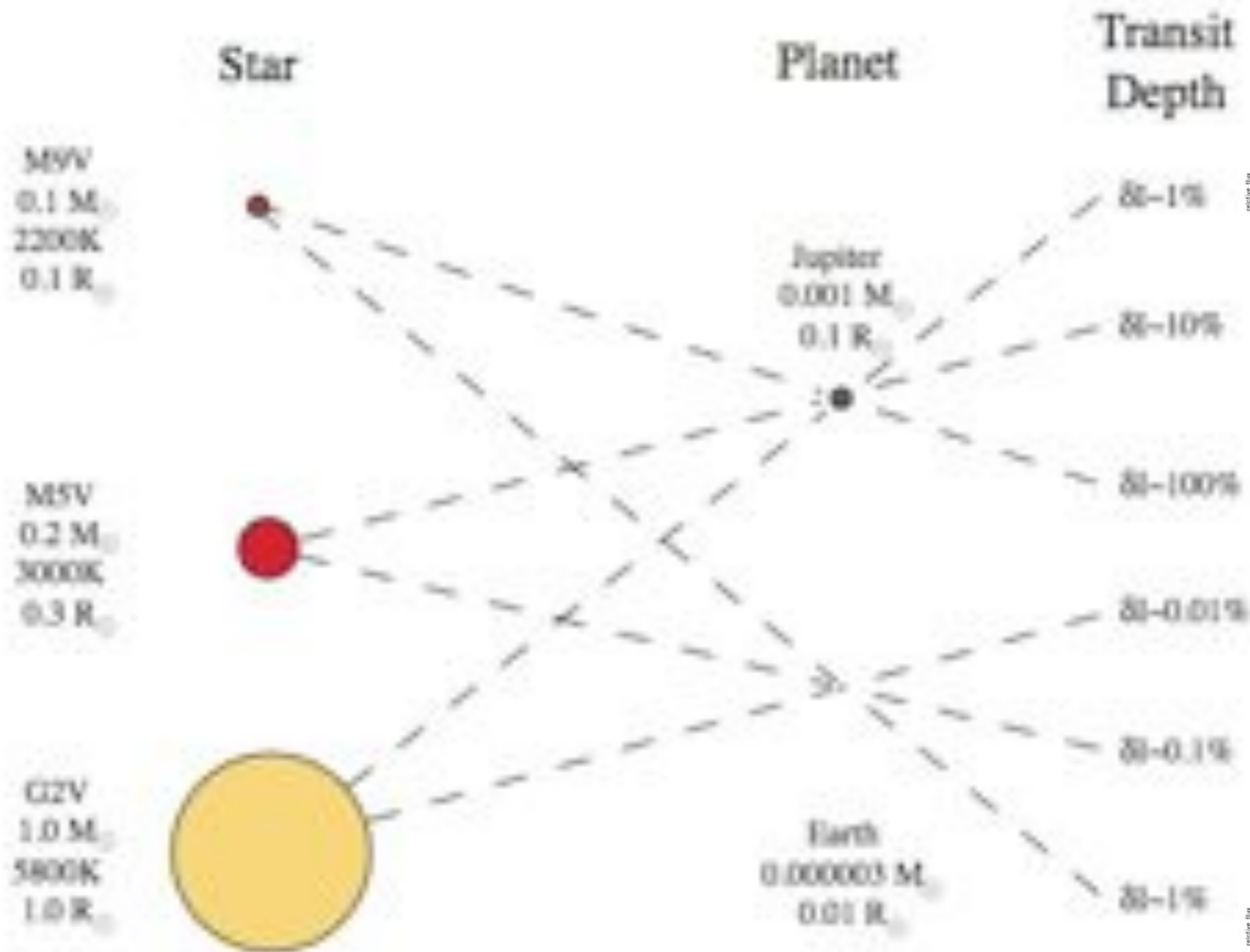
M5V
0.2 M_☉
3000K
0.3 R_☉



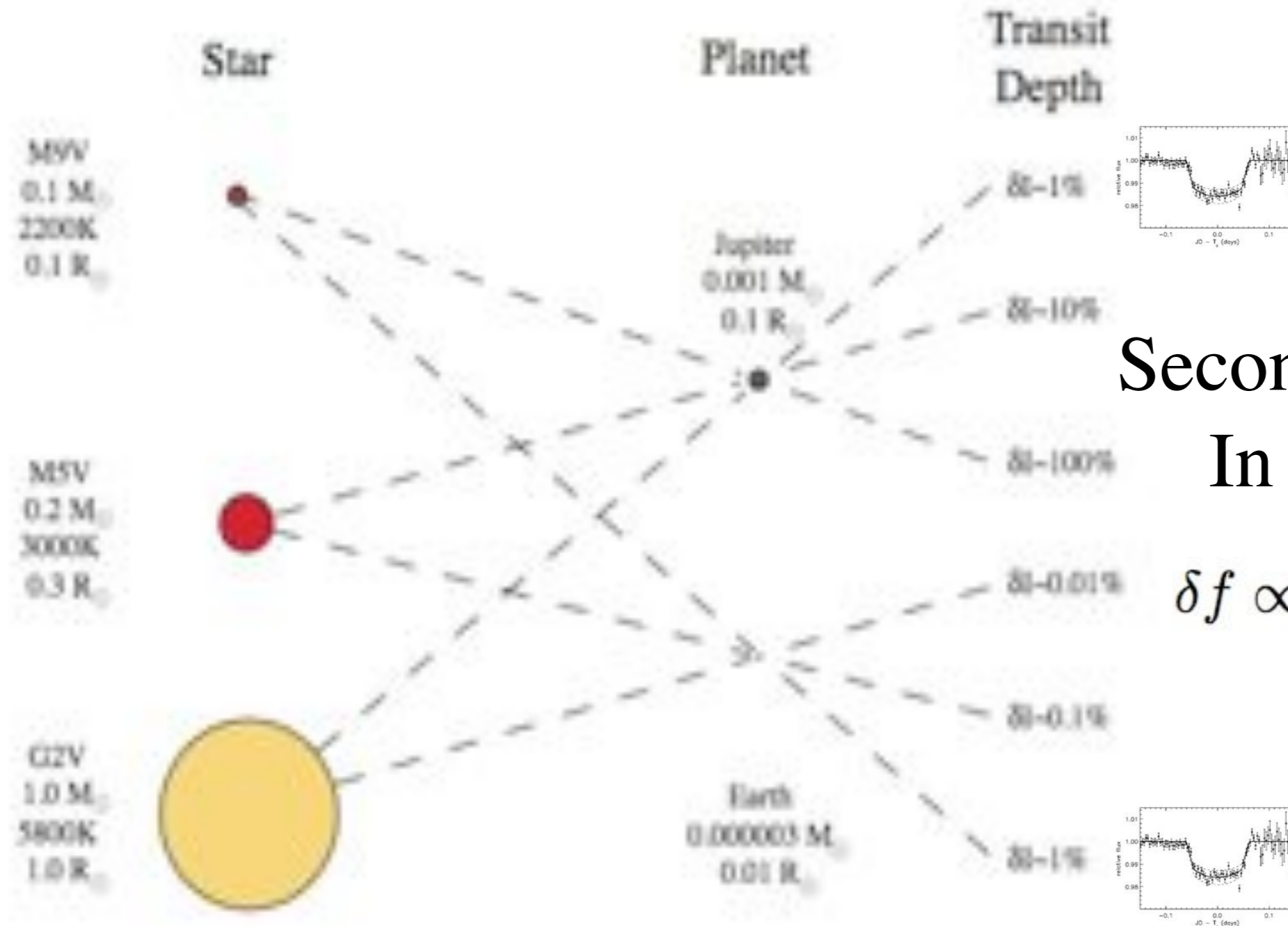
G2V
1.0 M_☉
5800K
1.0 R_☉







Transiting planets around M-dwarfs enables detection of Earth-radius planets from the ground

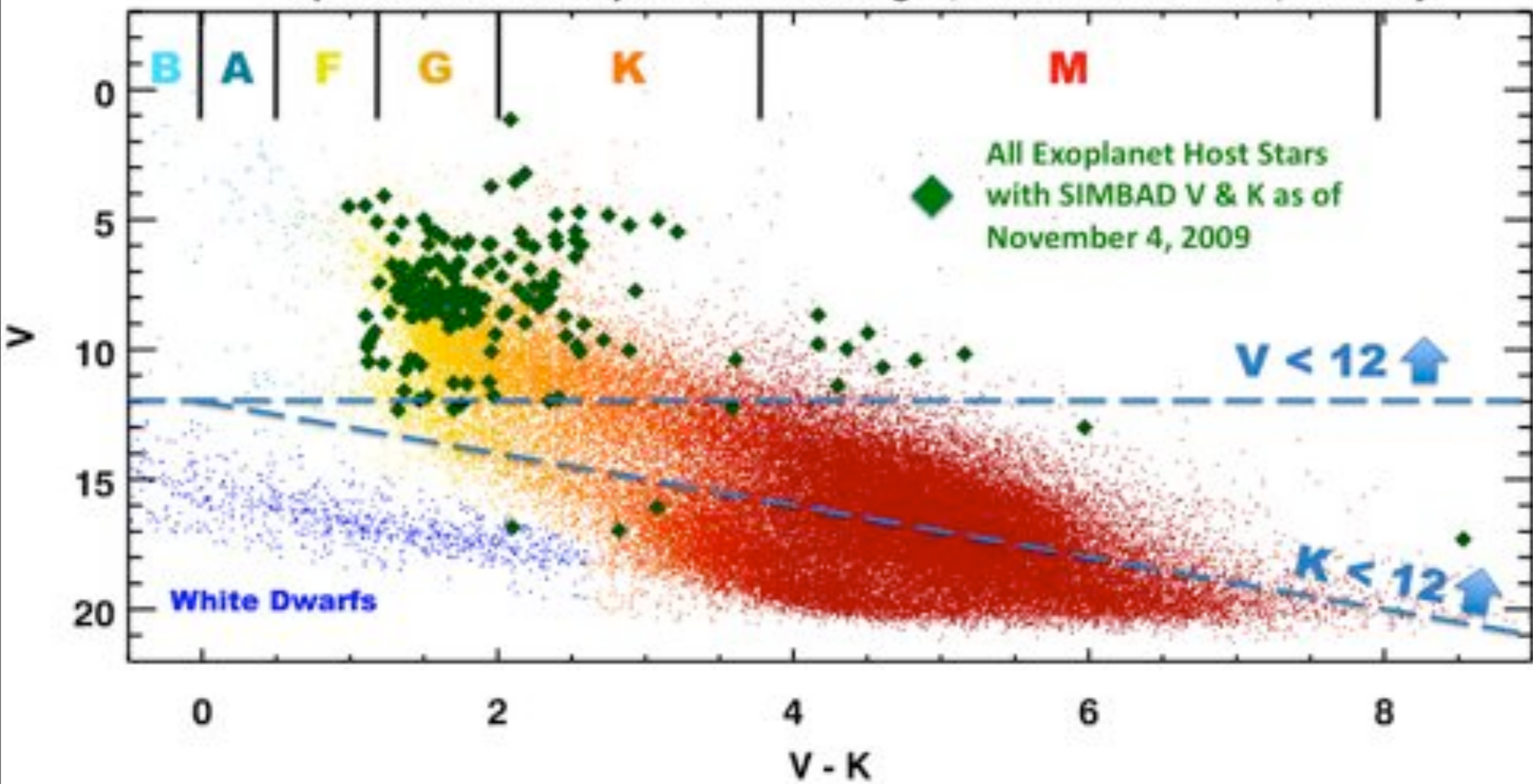


Secondary Transit

In R-J limit:

$$\delta f \propto \left(\frac{R_p}{R_\star} \right)^2 \frac{T_p}{T_\star}$$

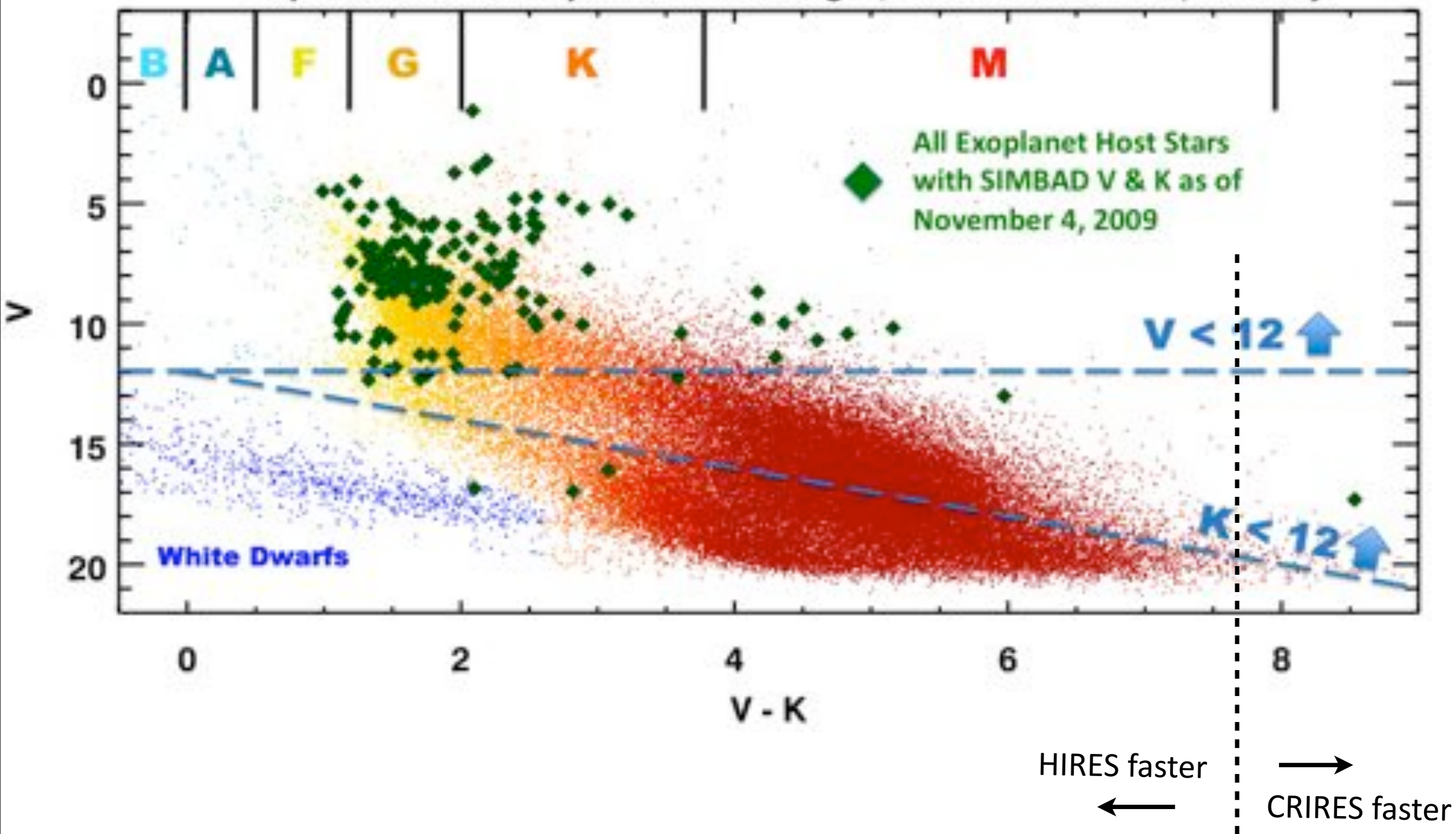
Lepine and Shara Proper Motion Catalogue, Northern Stars with $\mu > 0.15''/\text{yr}$



Accuracy & Precision

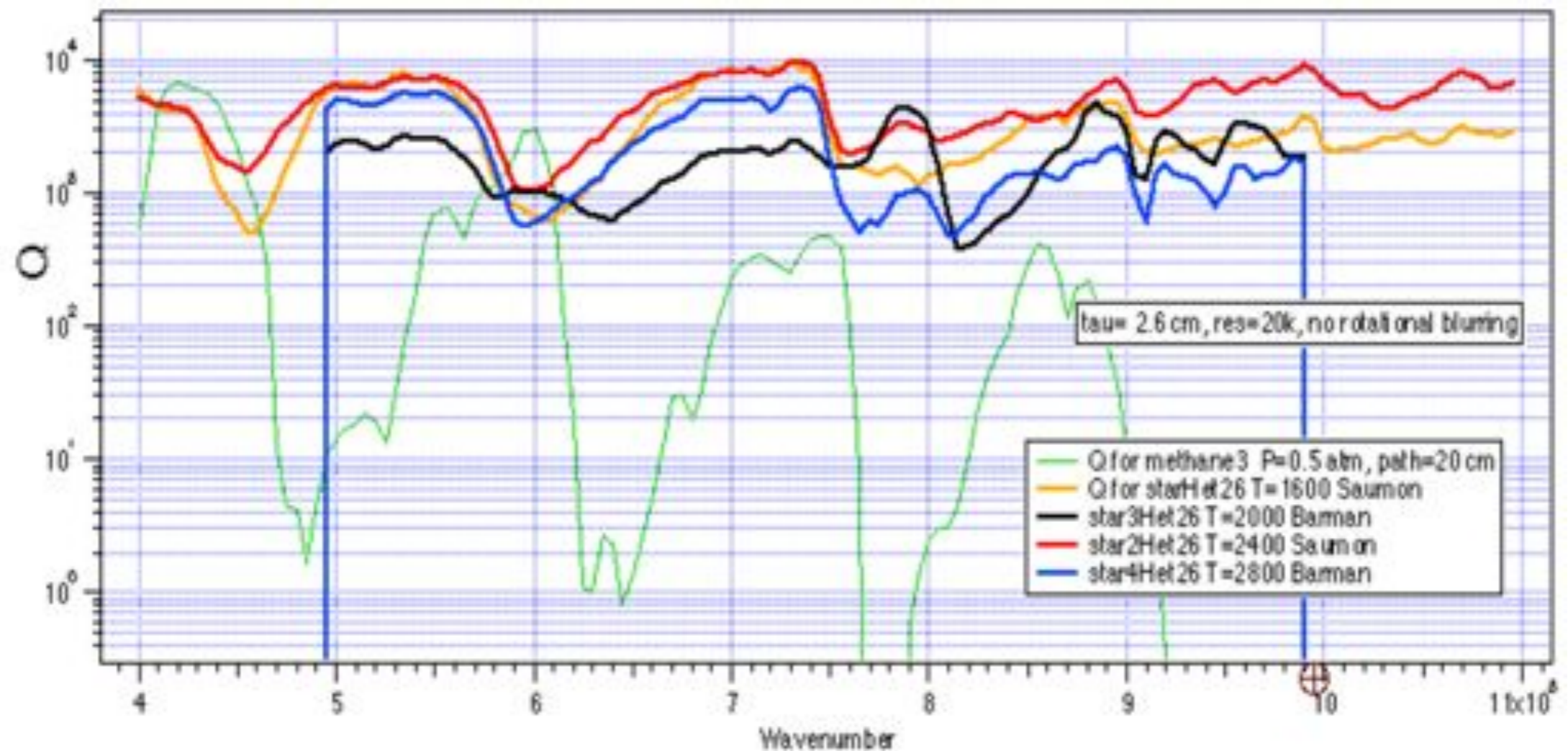
- Kepler-4b: Keck/HIRES (Borucki et al 2010; Howard pers. comm.)
- $V=12.8$
- 3.6 m/s in 20 min
- equal speed on same star ($\text{m/s hr}^{-1/2}$) at $V-K = 7.7$
- VB10: VLT/CRIRES (Bean et al 2010)
- $K=8.7$
- 10 m/s in 2.5hr

Lepine and Shara Proper Motion Catalogue, Northern Stars with $\mu > 0.15''/\text{yr}$

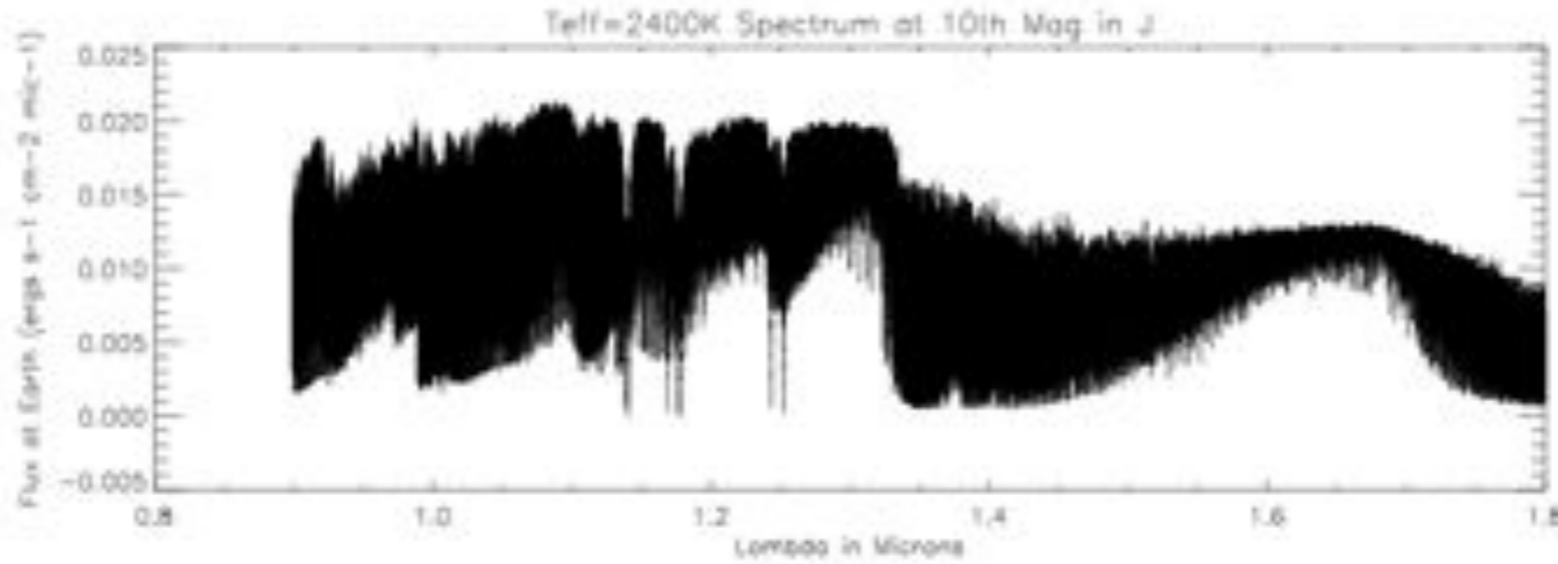


There is no gas cell analog of Iodine cell technique for M dwarfs

For calibration derived from an absorption cell, precision is set by the smaller of Q_{star} and Q_{abs}



Line vs Continuum Opacity

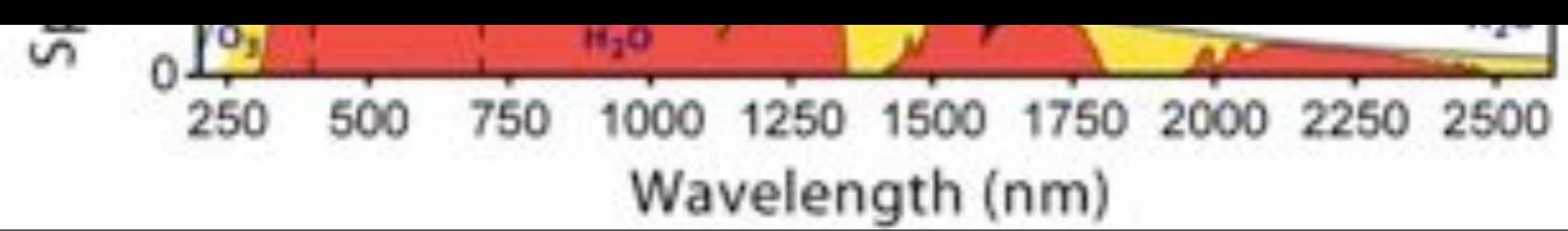


Al ₂	Al ₂ O	Al ₂ O ₂	Al ₂ O ₃	Al ₂ O ₄	Al ₂ O ₅	Al ₂ C	AlCl	AlCl ₂	AlCl ₃	AlF
AlF ₂	AlF	AlNO ₂	AlN	AlO	AlO ₂	AlOCl	AlOP	AlOP ₂	AlOH	AlOH
As	D ₂	DC	DCI	DF	DII	DII ₂	DII ₃	DN	DO	DO
BeO ₂	BeO ₂ H ₂	BS	BeCl	BeCl ₂	BeCl ₃	BeCl ₄	BeF	BeF ₂	BeF ₃	BeH
BeS	Be ₂ O	Be ₂ O ₂	Be ₂ O ₃	Be ₂ O ₄	Be ₂ O ₅	Be ₂ C	BeCl	BeCl ₂	BeF	BeF ₂
BeH	BeN	BeO	BeO ₂ H ₂	BeOH	BeS	C ₂	CaI	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆
C ₂ H ₈	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	C ₂ N	C ₂ N ₂	C ₂ O	C ₂	C ₂ H	CH	CH ₂
CH ₂	CH ₂ Cl	CH ₂	CHCl	CHF	CHP	CN	CNCl	CNOH	CO	CO
CO ₂	COF ₂	COH ₂	CP	CS	CS ₂	CaO	CaCl	CaCl ₂	CaCl ₃	CaCl ₄
CaF	CaF ₂	CaH	CaO	CaOH	CaS	Ca ₂	CaO	CaOH	CaCl	CaCl ₂
CaH	CaN	CaO	CaO ₂	CaO ₃	CaO ₄	CaO ₅	CaCl	CaOH	CaO	CaO
CaCl	CaF	CaH	CaO	CaS	F ₂	FeCl	FeCl ₂	FeF	FeF ₂	FeH
FeH	FeO	FeO ₂ H ₂	FeS	H ₂	H ₂ O	H ₂ S	H ₂ BO ₃	HBO	HBO ₂	HBO ₃
HOH	HCN	HCO	HCl	HF	HO ₂	K ₂ Cl ₂	K ₂ O ₂ H ₂	K ₂ SO ₄	K ₂ SO ₃	K ₂ SO ₂
KCN	KCl	KF	K ₂	K ₂ O	K ₂ CO ₃	LiCl	LiF	LiH	LiH	LiH
LiNO ₂	LiOCl	LiOH	Li ₂	Li ₂ O	Li ₂ CO ₃	MgF	MgF ₂	MgH	MgH	MgH
MgN	MgO	MgO ₂ H ₂	MgO	MgS	MgS ₂	MgS	N ₂	N ₂ O	N ₂ O	N ₂ O
N ₂	NH	NH ₂	NH ₃	NHO ₂	NO	NO ₂	NO ₂ H	NO ₂	NOH	NOH
NS	Na ₂	Na ₂ C ₂ N ₂	Na ₂ Cl ₂	Na ₂ O ₂ H ₂	NaBO ₂	NaCN	NaCl	NaF	NaH	NaH
NaO	NaOH	NaO	NCl	NCl ₂	NH	NO	NS	O ₂	O ₂ H ₂	O ₂ H ₂
O ₂	OHF	OCS	OCl	OF	OH	OHF	F ₂	F ₂	PCl	PCl
PCl ₂	PF	PF ₂	PH	PH ₂	PH ₃	PN	PO	PO ₂	PS	PS
PSF	HSCl	S ₂	S ₂ O	SC	SP	SS	SO	SO ₂	SO ₂	SO ₂
SO ₂	SeO	SeS	Si ₂	Si ₂ C	Si ₂ N	Si ₂	SiC	SiC ₂	SiCl	SiCl
SiF	SiH	SiH ₂	SiH ₂ F ₂	SiH ₂	SiH ₂ F	SiH ₄	SiN	SiO	SiO	SiO
SiO ₂	SiS	SiCl	SiCl ₂	SiF	SiF ₂	SiH	SiO	SiO ₂ H ₂	SiOH	SiOH
SiS	ThCl	ThCl ₂	ThCl ₃	ThCl ₄	ThF	ThF ₂	ThF ₃	ThI	ThN	ThN
TiO	TiO ₂	TiOCl	TiOCl ₂	TiOH	TiS	VN	VO	ZnCl	ZnCl	ZnCl
ZnCl ₂	ZnCl ₃	ZnCl ₄	ZnF	ZnF ₂	ZnF ₃	ZnH	ZnO	ZnO	ZnO	ZnO
ZnS										

Molecules

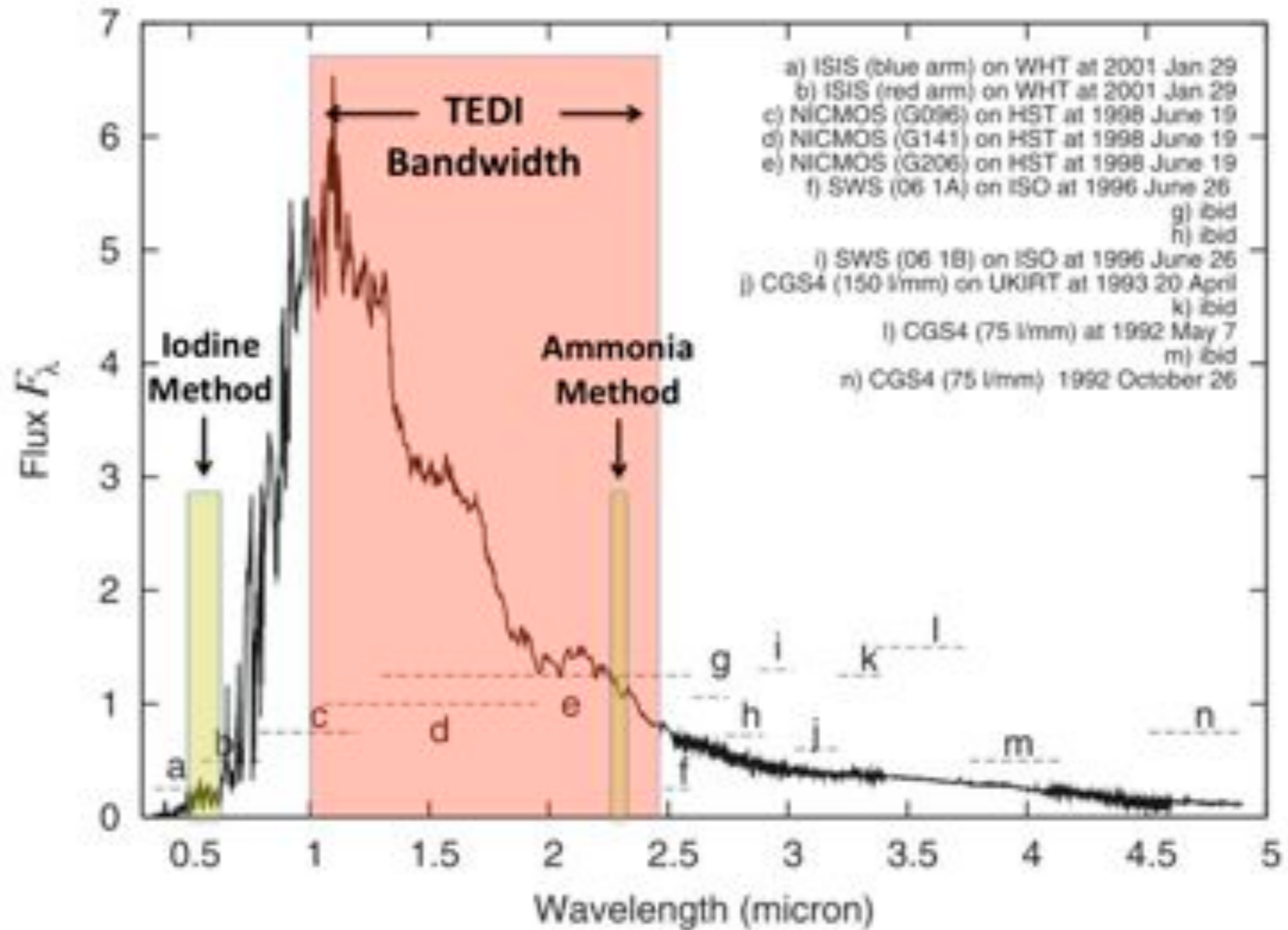
Al ₂	Al ₂ O	Al ₂ O ₂	Al ₂ O ₃	Al ₂ O ₄	Al ₂ O ₅	Al ₂ C	AlCl	AlCl ₂	AlCl ₃	AlF
AlF ₂	AlF	AlNO ₂	AlN	AlO	AlO ₂	AlOCl	AlOP	AlOP ₂	AlOH	AlOH
As	D ₂	DC	DCI	DF	DII	DII ₂	DII ₃	DN	DO	DO
BeO ₂	BeO ₂ H ₂	BS	BeCl	BeCl ₂	BeCl ₃	BeCl ₄	BeF	BeF ₂	BeF ₃	BeH
BeS	Be ₂ O	Be ₂ O ₂	Be ₂ O ₃	Be ₂ O ₄	Be ₂ O ₅	Be ₂ C	BeCl	BeCl ₂	BeF	BeF ₂
BeH	BeN	BeO	BeO ₂ H ₂	BeOH	BeS	C ₂	CaI	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆
C ₂ H ₈	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	C ₂ N	C ₂ N ₂	C ₂ O	C ₂	C ₂ H	CH	CH ₂
CH ₂	CH ₂ Cl	CH ₂	CHCl	CHF	CHP	CN	CNCl	CNOH	CO	CO
CO ₂	COF ₂	COH ₂	CP	CS	CS ₂	CaO	CaCl	CaCl ₂	CaCl ₃	CaCl ₄
CaF	CaF ₂	CaH	CaO	CaOH	CaS	Ca ₂	CaO	CaOH	CaCl	CaCl ₂
CaH	CaN	CaO	CaO ₂	CaO ₃	CaO ₄	CaO ₅	CaCl	CaOH	CaO	CaO
CaCl	CaF	CaH	CaO	CaS	F ₂	FeCl	FeCl ₂	FeF	FeF ₂	FeH
FeH	FeO	FeO ₂ H ₂	FeS	H ₂	H ₂ O	H ₂ S	H ₂ BO ₃	HBO	HBO ₂	HBO ₃
HOH	HCN	HCO	HCl	HF	HO ₂	K ₂ Cl ₂	K ₂ O ₂ H ₂	K ₂ SO ₄	K ₂ SO ₃	K ₂ SO ₂
KCN	KCl	KF	K ₂	K ₂ O	K ₂ CO ₃	LiCl	LiF	LiH	LiH	LiH
LiNO ₂	LiOCl	LiOH	Li ₂	Li ₂ O	Li ₂ CO ₃	MgF	MgF ₂	MgH	MgH	MgH
MgN	MgO	MgO ₂ H ₂	MgO	MgS	MgS ₂	MgS	N ₂	N ₂ O	N ₂ O	N ₂ O
N ₂	NH	NH ₂	NH ₃	NHO ₂	NO	NO ₂	NO ₂ H	NO ₂	NOH	NOH
NS	Na ₂	Na ₂ C ₂ N ₂	Na ₂ Cl ₂	Na ₂ O ₂ H ₂	NaBO ₂	NaCN	NaCl	NaF	NaH	NaH
NaO	NaOH	NaO	NCl	NCl ₂	NH	NO	NS	O ₂	O ₂ H ₂	O ₂ H ₂
O ₂	OHF	OCS	OCl	OF	OH	OHF	F ₂	F ₂	PCl	PCl
PCl ₂	PF	PF ₂	PH	PH ₂	PH ₃	PN	PO	PO ₂	PS	PS
PSF	HSCl	S ₂	S ₂ O	SC	SP	SS	SO	SO ₂	SO ₂	SO ₂
SO ₂	SeO	SeS	Si ₂	Si ₂ C	Si ₂ N	Si ₂	SiC	SiC ₂	SiCl	SiCl
SiF	SiH	SiH ₂	SiH ₂ F ₂	SiH ₂	SiH ₂ F	SiH ₄	SiN	SiO	SiO	SiO
SiO ₂	SiS	SiCl	SiCl ₂	SiF	SiF ₂	SiH	SiO	SiO ₂ H ₂	SiOH	SiOH
SiS	ThCl	ThCl ₂	ThCl ₃	ThCl ₄	ThF	ThF ₂	ThF ₃	ThI	ThN	ThN
TiO	TiO ₂	TiOCl	TiOCl ₂	TiOH	TiS	VN	VO	ZnCl	ZnCl	ZnCl
ZnCl ₂	ZnCl ₃	ZnCl ₄	ZnF	ZnF ₂	ZnF ₃	ZnH	ZnO	ZnO	ZnO	ZnO
ZnS										

Condensates



TEDI

- Interferometer and a moderate-resolution spectrograph
- Large simultaneous bandwidth at high spectral resolution



Pavlenko et al. 2006

The TripleSpec Exoplanet Discovery Instrument: Precise Radial Velocities

Cornell Team:

**Phil Muirhead, Kevin Covey, Katherine Hamren,
James Lloyd**

Berkeley Team:

**Jerry Edelstein, David Erskine, Phil Andelson, David
Kimber, Danny Mondo**

+ others



Think Picket Fence

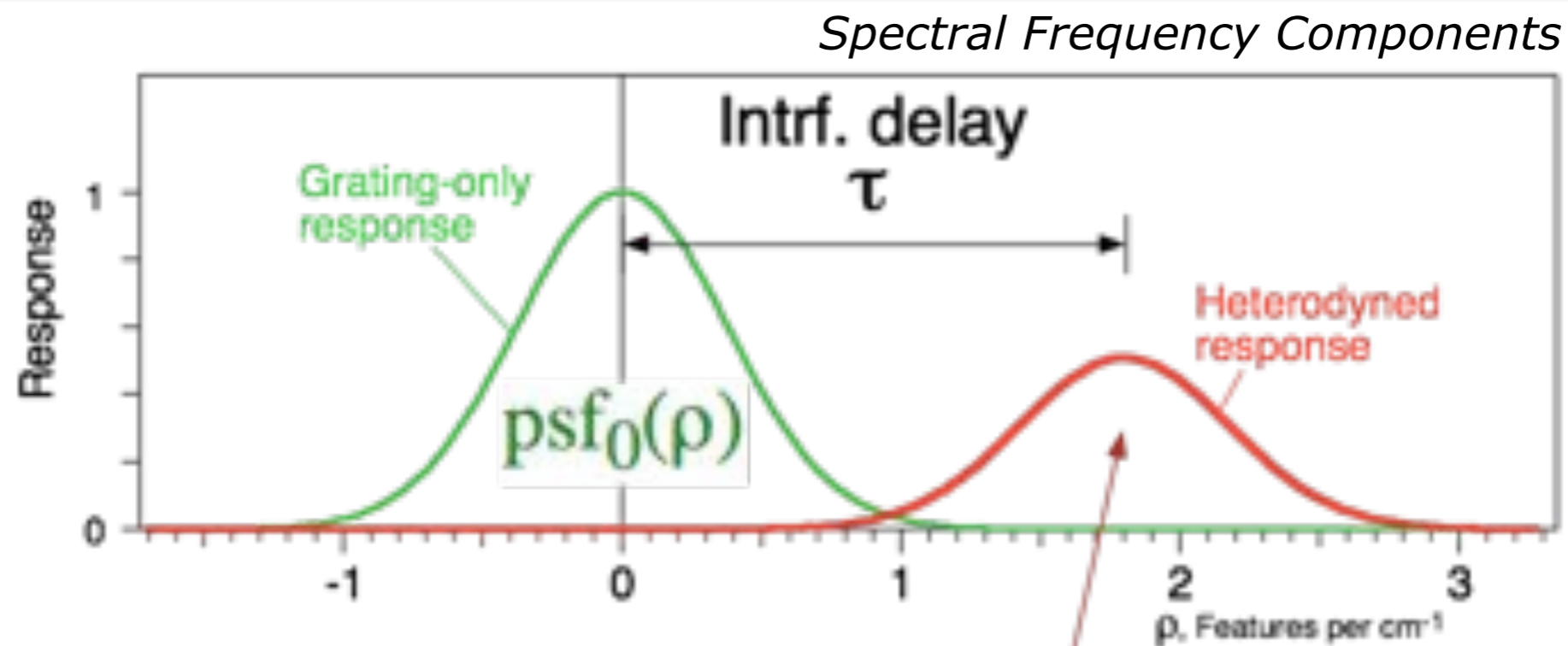


Picket Fence

- = Moiré
- = Vernier Caliper
- = Beat Frequency
- = Spatial Frequency Heterodyning

Moiré is a heterodyning effect

Heterodyning shifts grating response to higher details

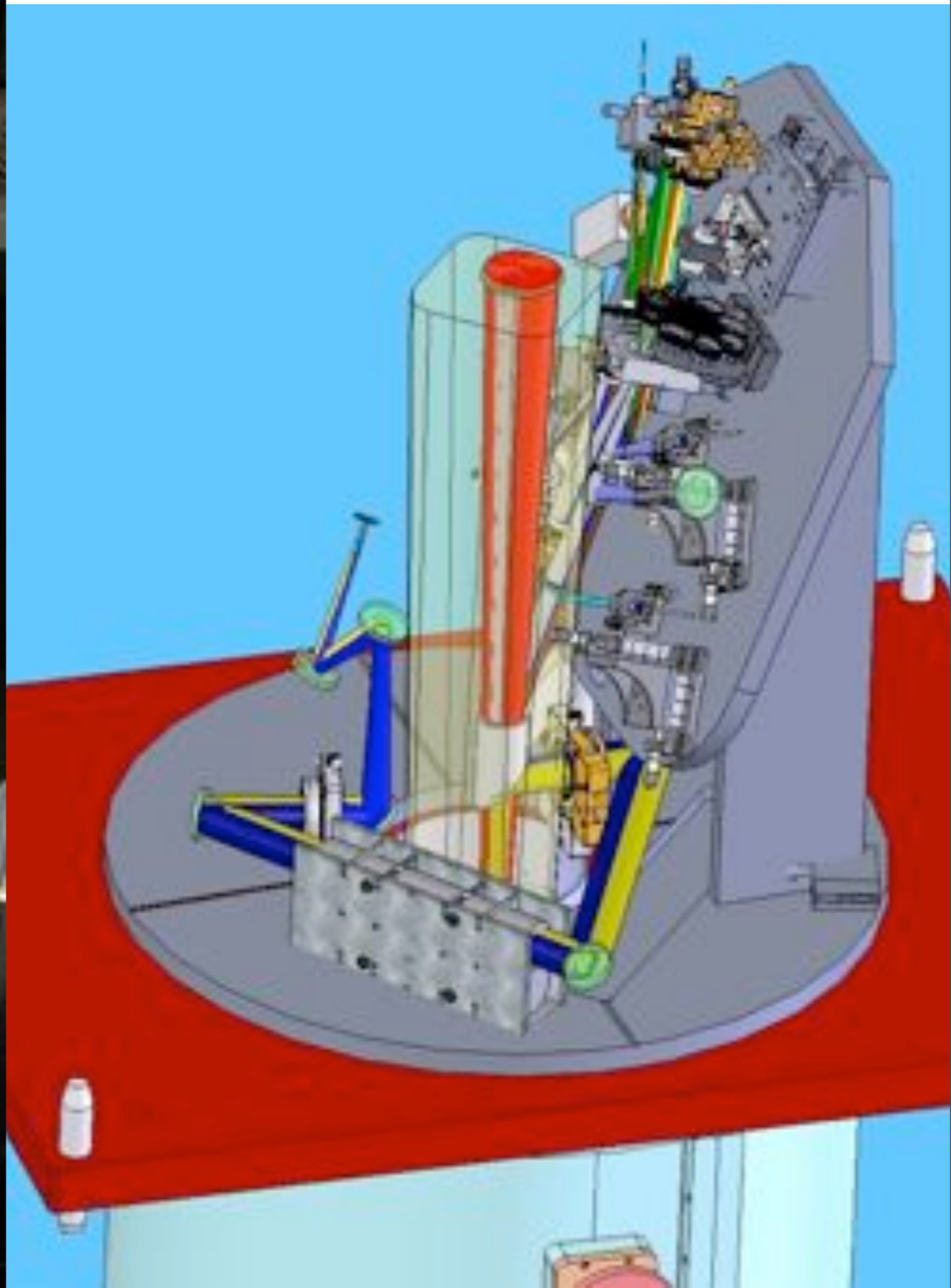
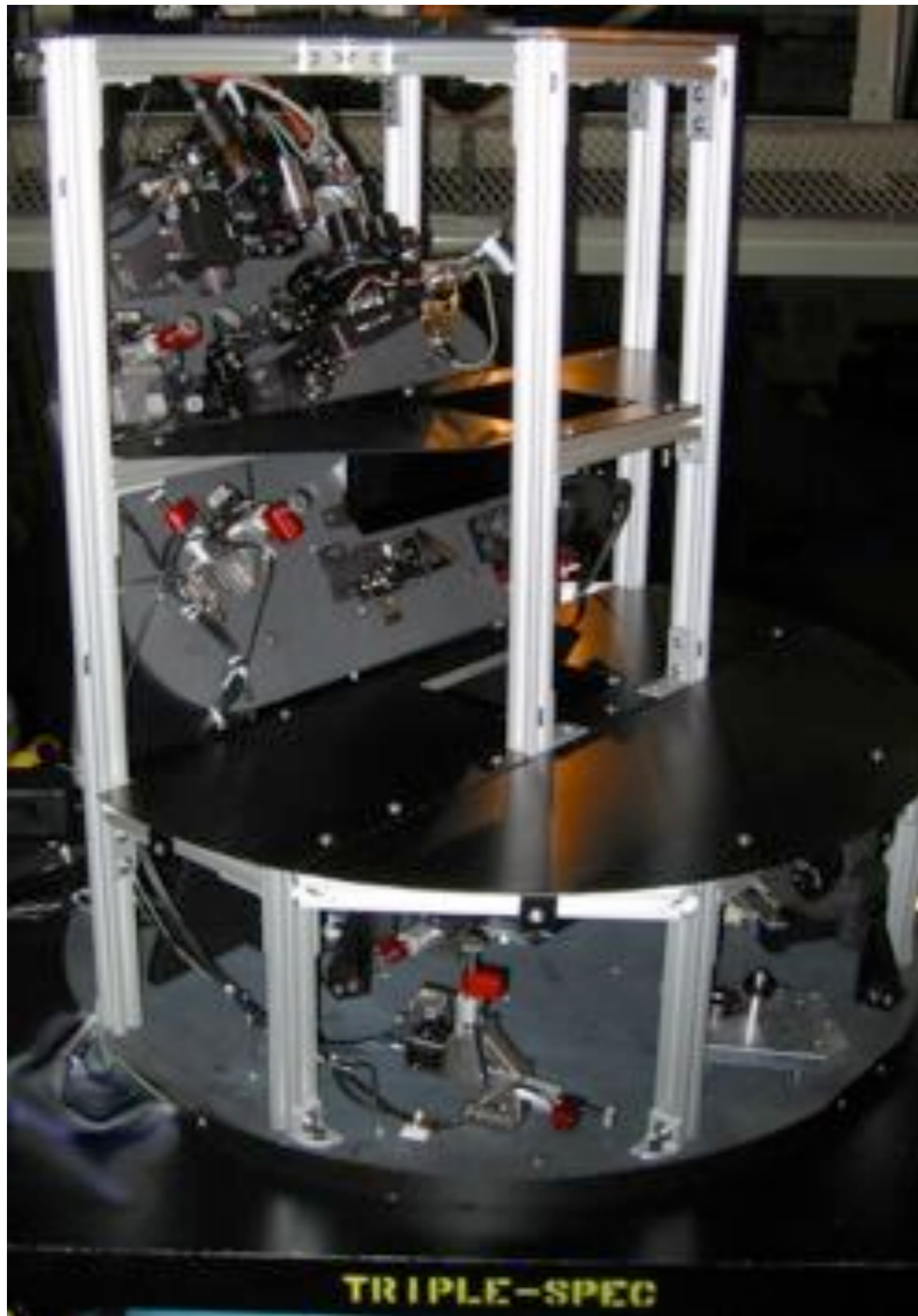


Ordinary response

$$G(\rho) = \text{psf}_0(\rho)$$

Fringing response

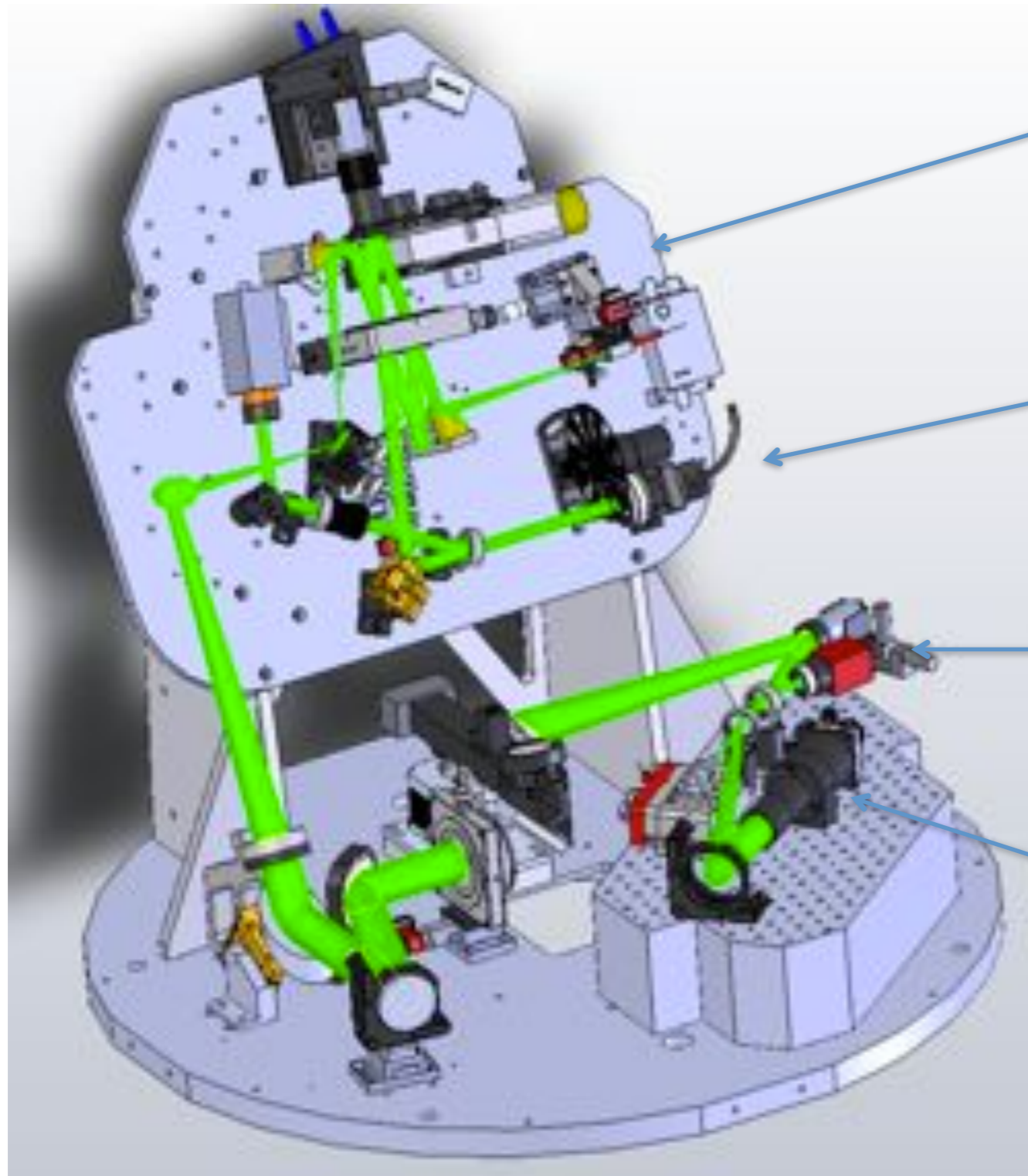
$$G(\rho) = (1/2) \text{psf}_0(\rho - \tau)$$





First Fringes Dec 30 2007

TEDI: Post 2010 Upgrade



Variable delay interferometer, up to 4cm optical path diff (Res boost up to 30k)

IR throughput monitor actively tracks system throughput

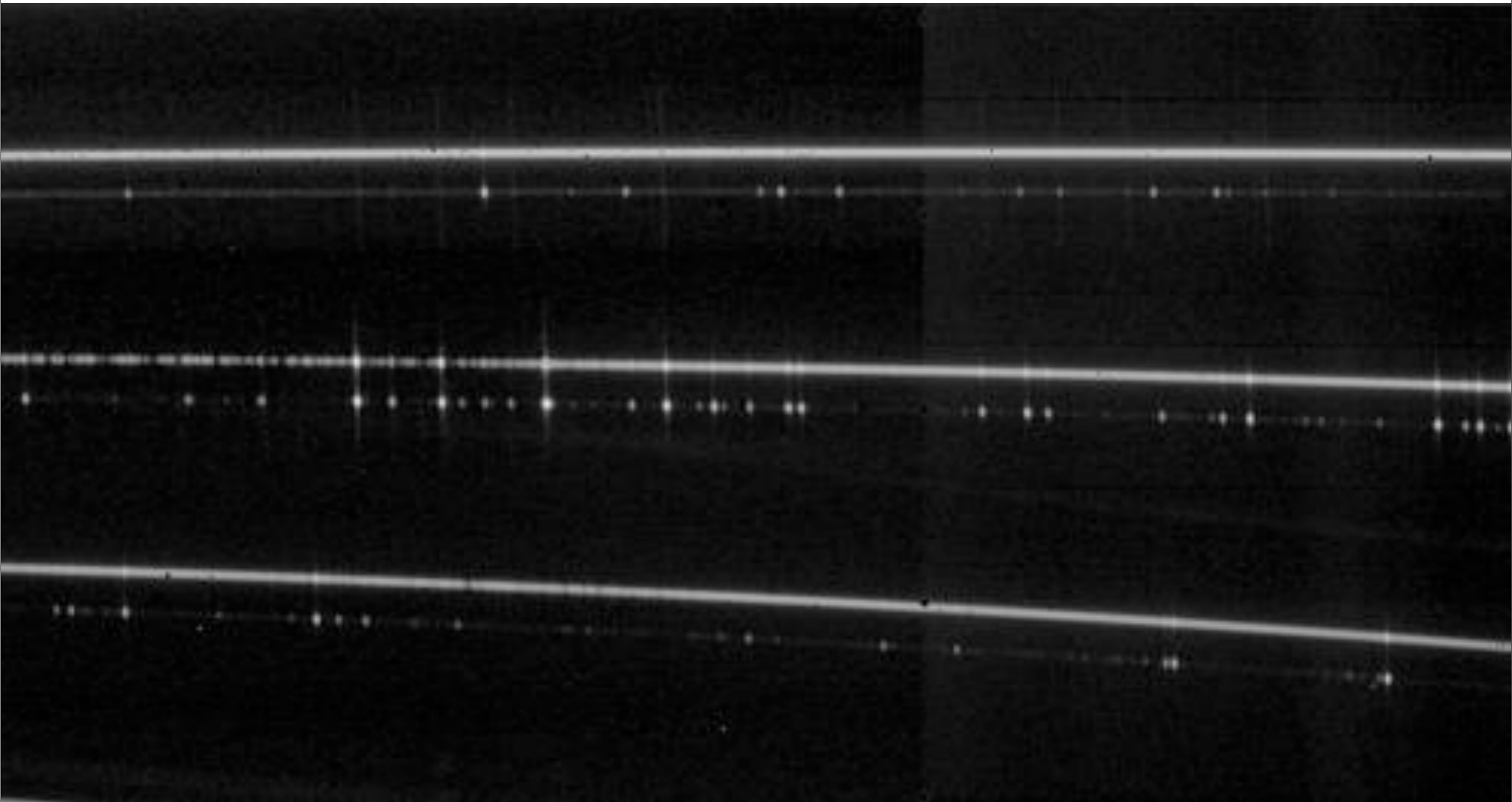
Visible light picked off by dichroic, guiding w/ high speed piezo

ThAr emission lamp injected into 2 fibers, calibrates interferometer delay/wavelength solution

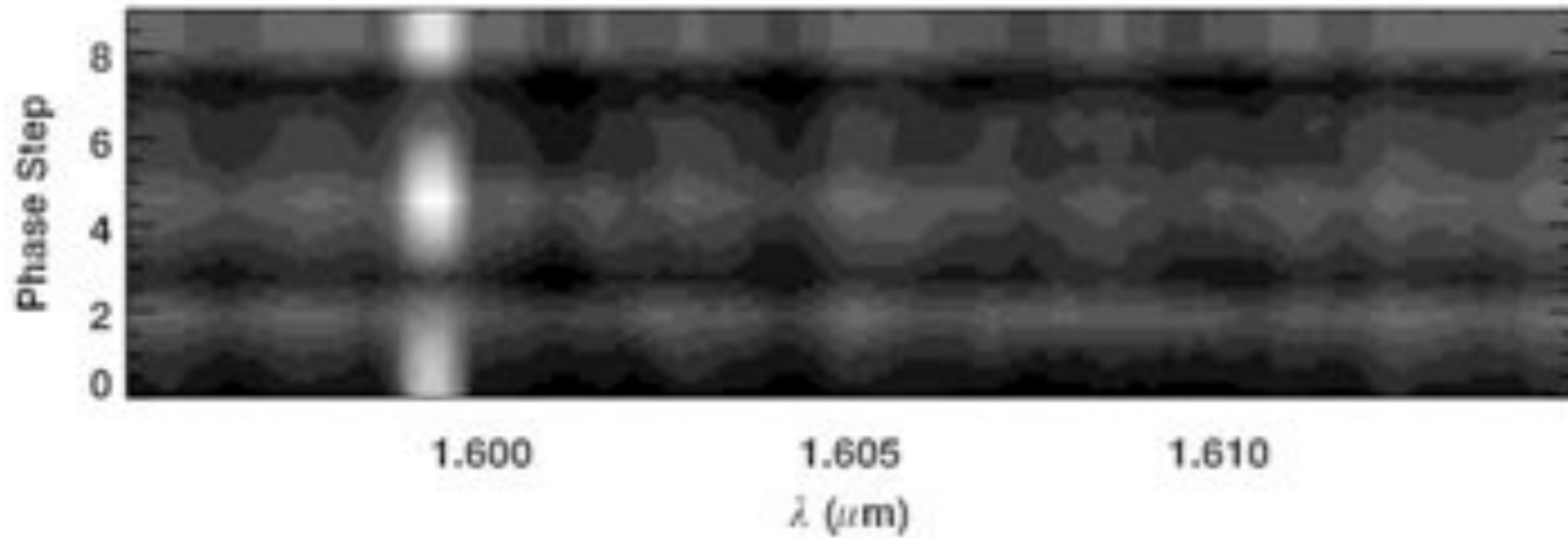


to spectrograph

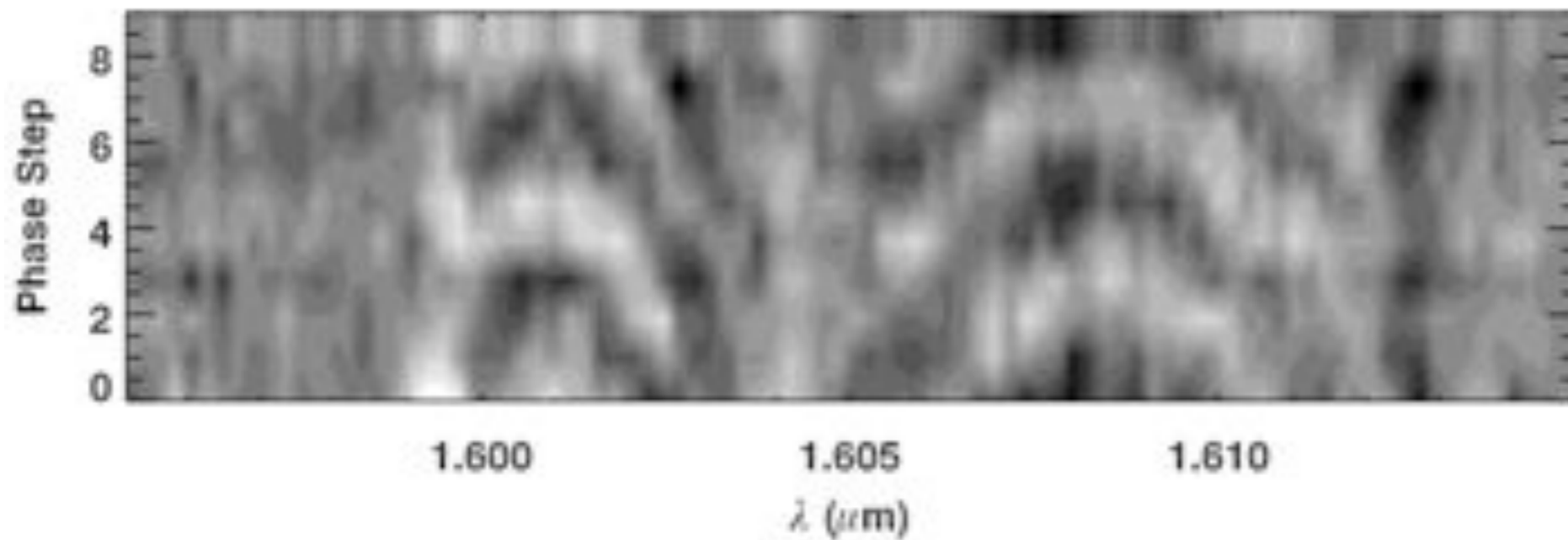
TEDI Data



TEDI Data

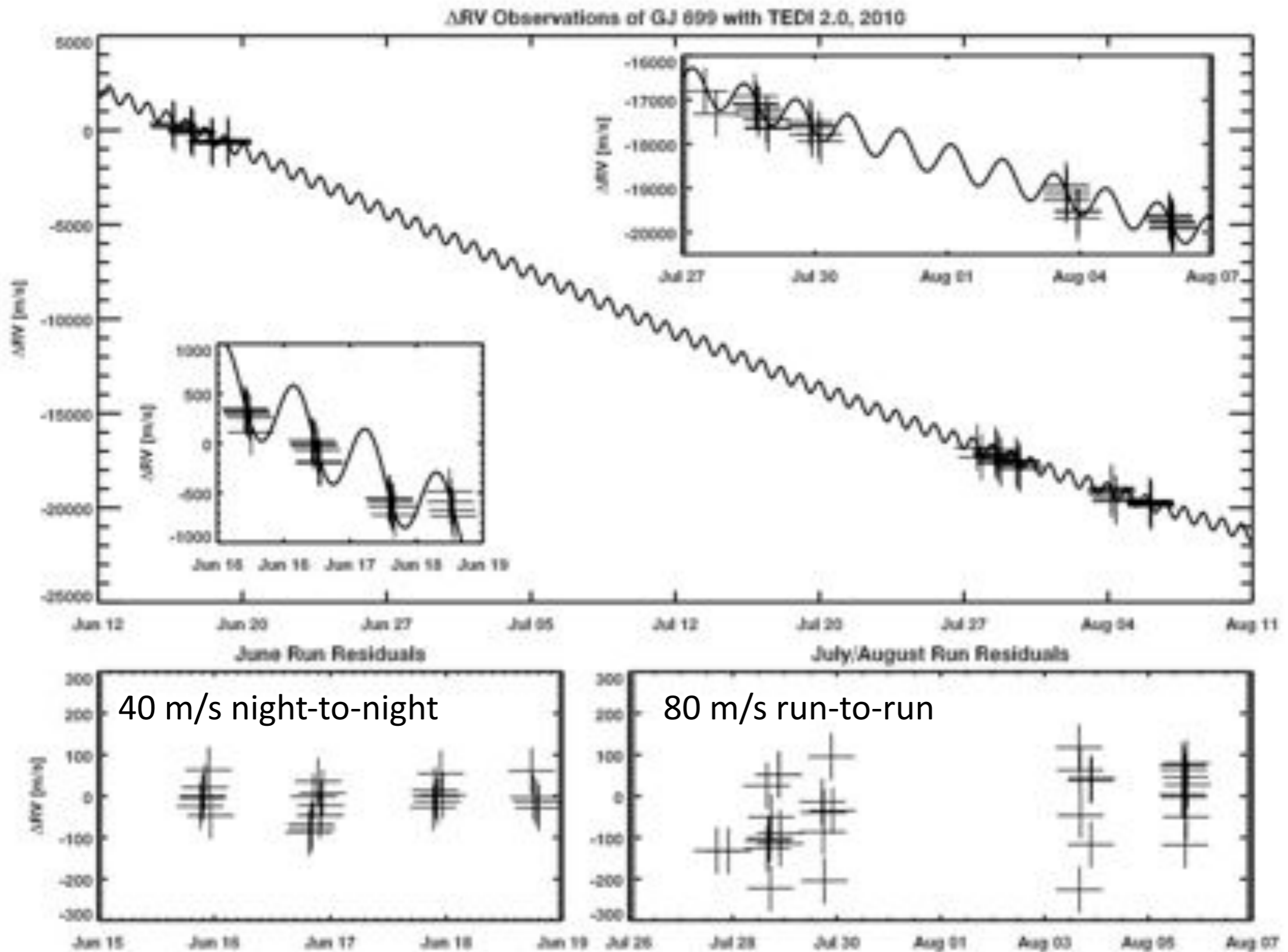


Use ThAr lines to get interferometer delays, then model and remove



Radial Velocity is proportional to shift vs phase

2 Runs with TEDI 2.0



Summary

- Accuracy, not just precision is critical for the M dwarf opportunity
- T-EDI is achieving $\sim 20 \text{ ms}^{-1}$ intranight, 40 ms^{-1} night-to-night, 80 ms^{-1} month-to-month precision
- Accuracy is 12 m/s BarnardStar-Hale-decihr $^{-1/2}$
- = $1 \text{ philmuirhead}^{-1}$

