A New Generation of Substellar Atmosphere & Evolution Models

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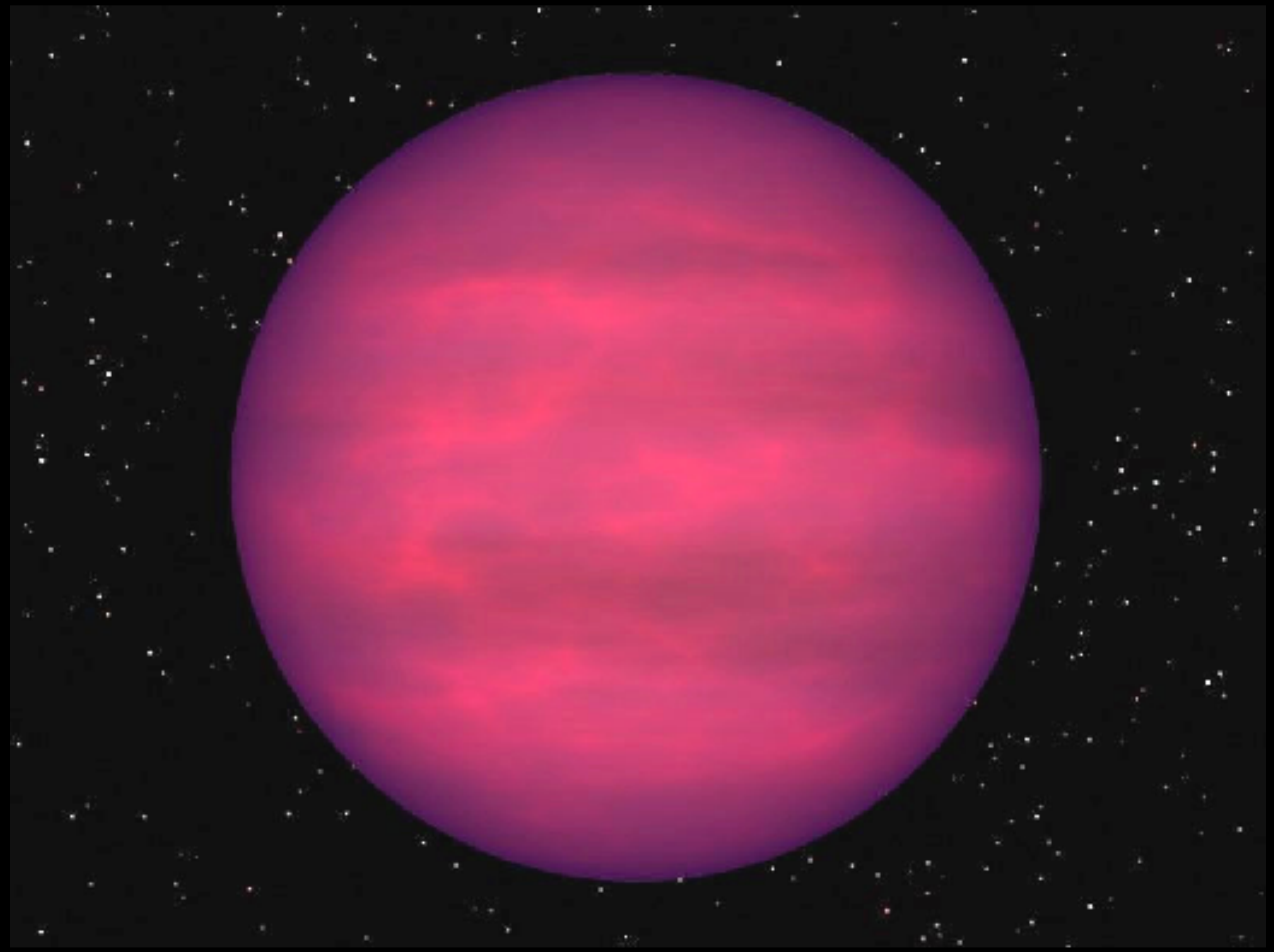
@astromarkmarley

10 years ago
Cool Stars 2008
changed my life in
an unexpected way.



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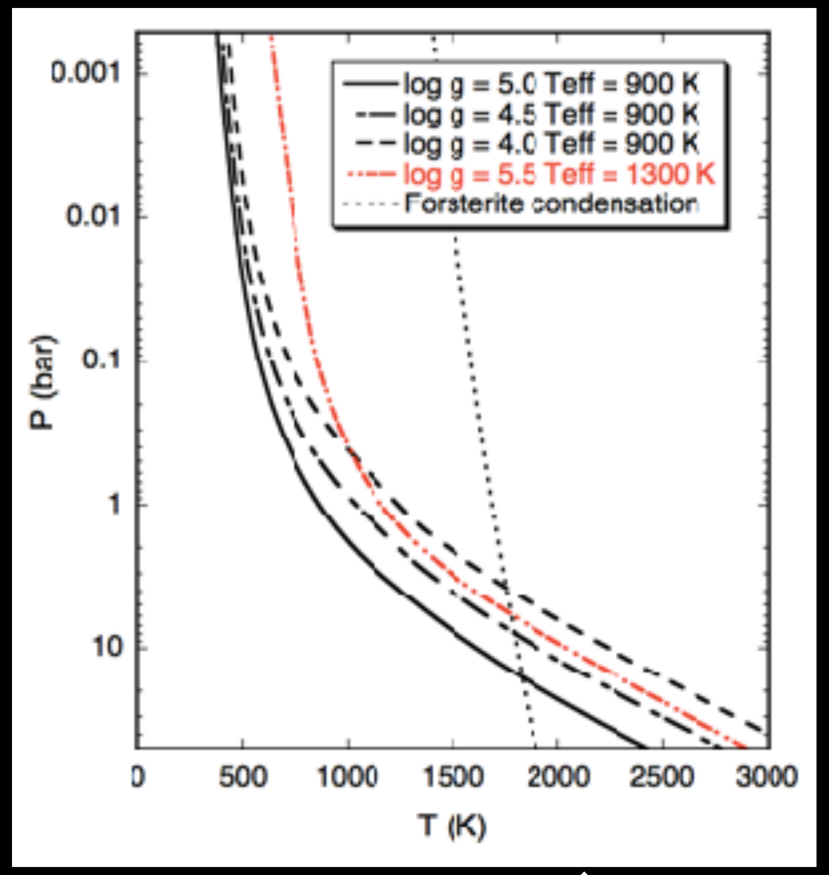
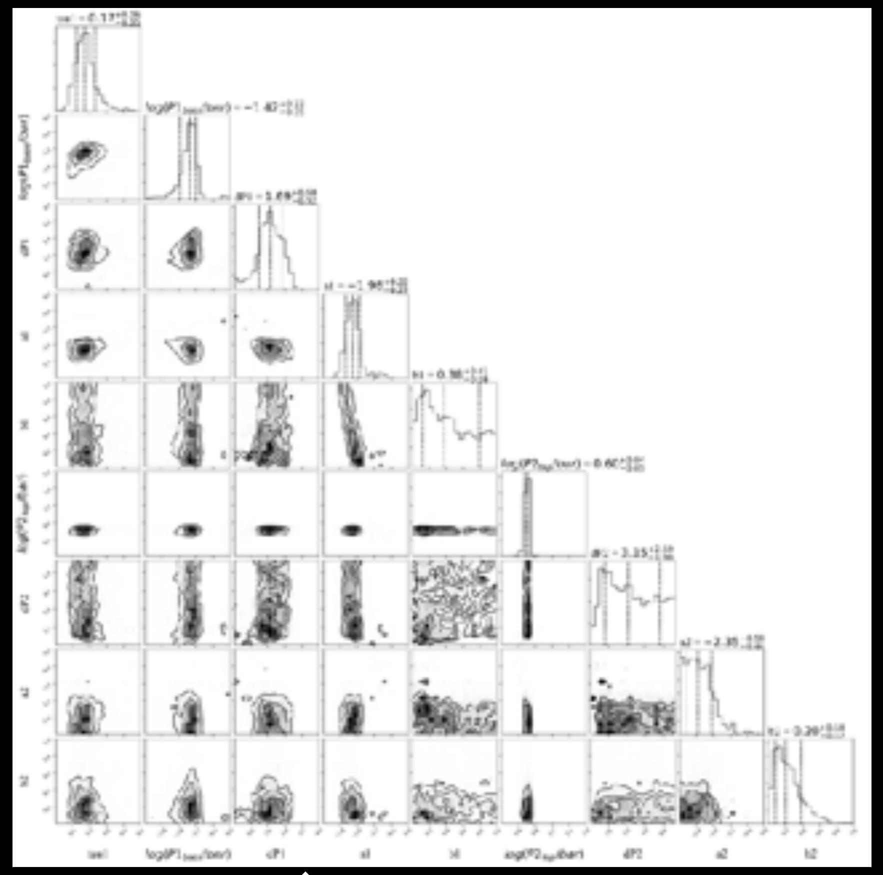
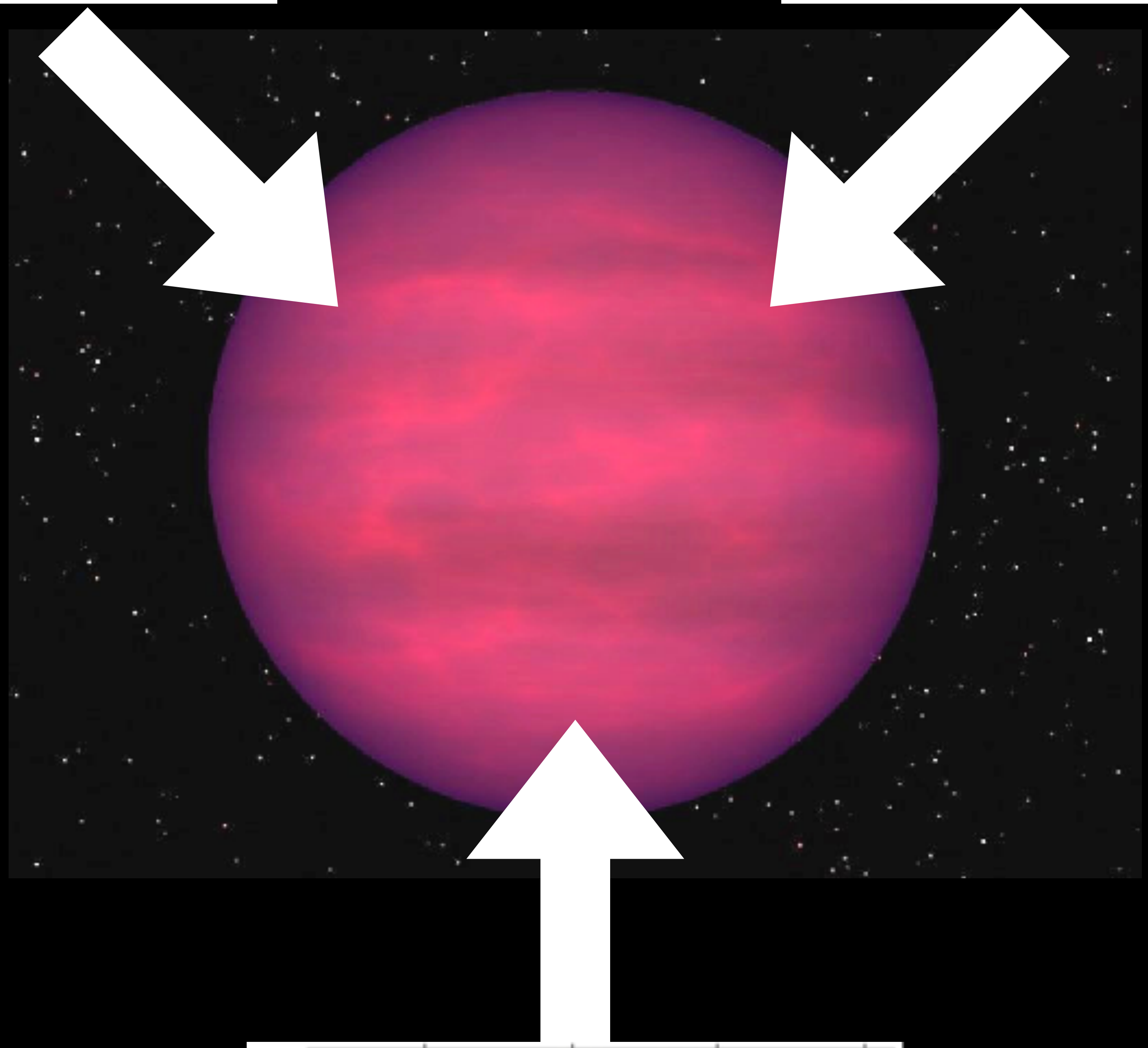
Today

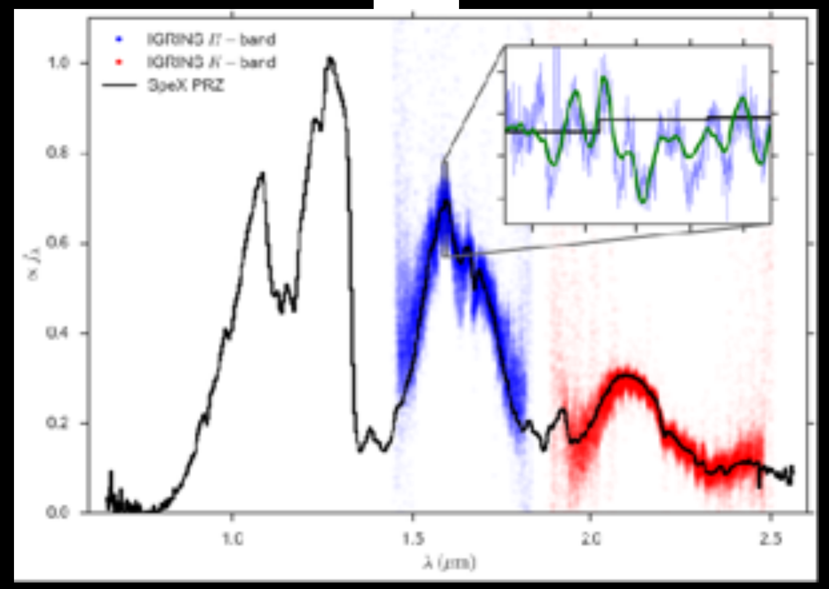
Understanding Brown Dwarfs

- Utility of forward models - aren’t these outdated?
- Forward models, grid searches, and retrievals - 3 keys to understanding
- Our new generation of models
- Illustrate synergy with examples
- Important unsolved problems



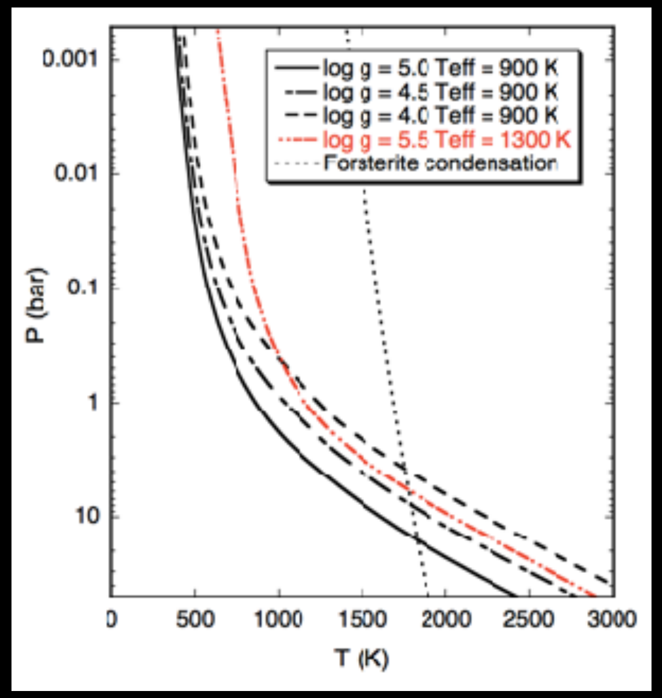




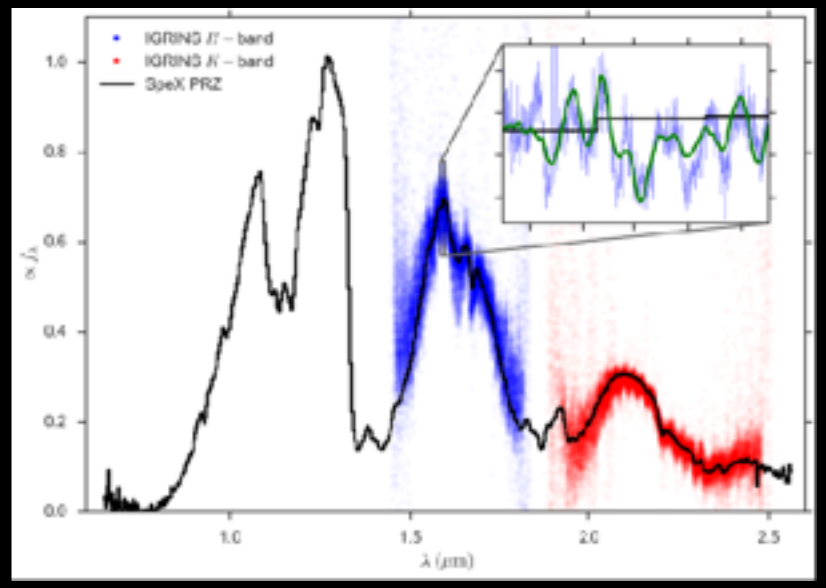


but

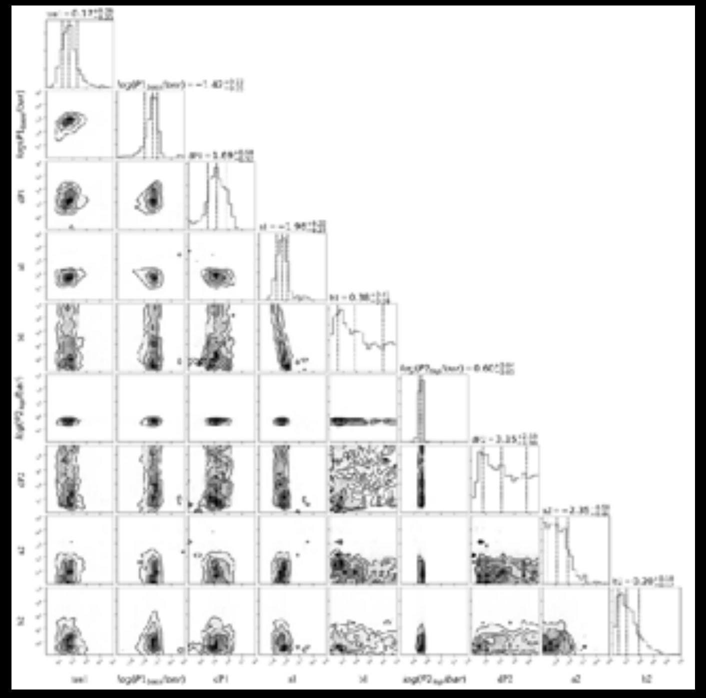
- Forward model: radiative-convective equilibrium atmospheric structure and consequent emergent spectrum with stated assumptions



- Fitting: Method of systematically comparing model spectra to data, e.g., chi-squared, Starfish, machine learning

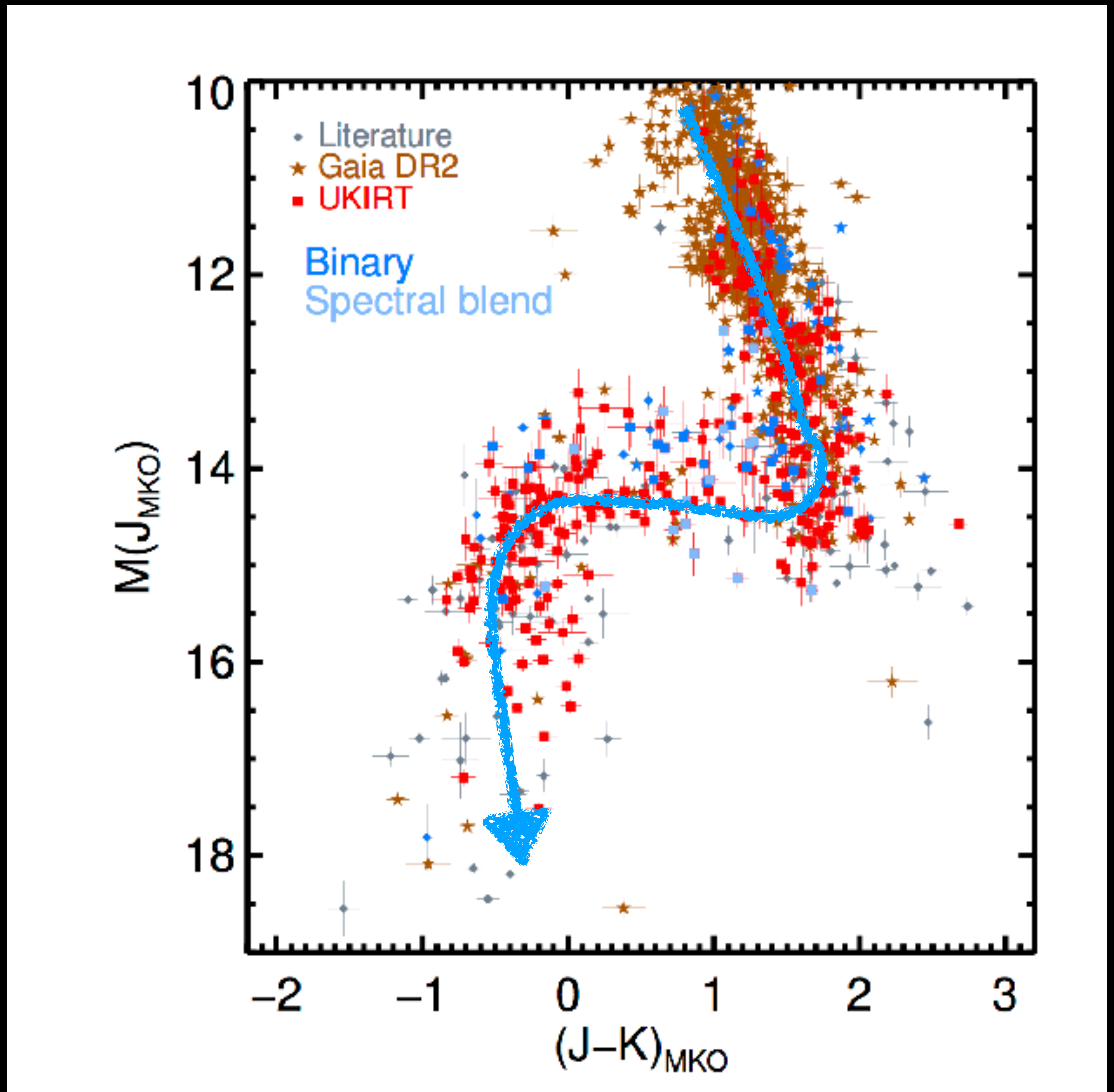


- Retrieval: Monte Carlo-based comparison of 100,000s parameterized atmosphere profiles with data to derive empirical model parameters (e.g., abundances, T(P), etc.)



Why Do We Need Forward Models?

- Boundary condition for evolution
- Grid models for characterization
- Develops our understanding
- Guide where to search for new discoveries
  - New molecules, clouds, processes
  - Motivate new laboratory work

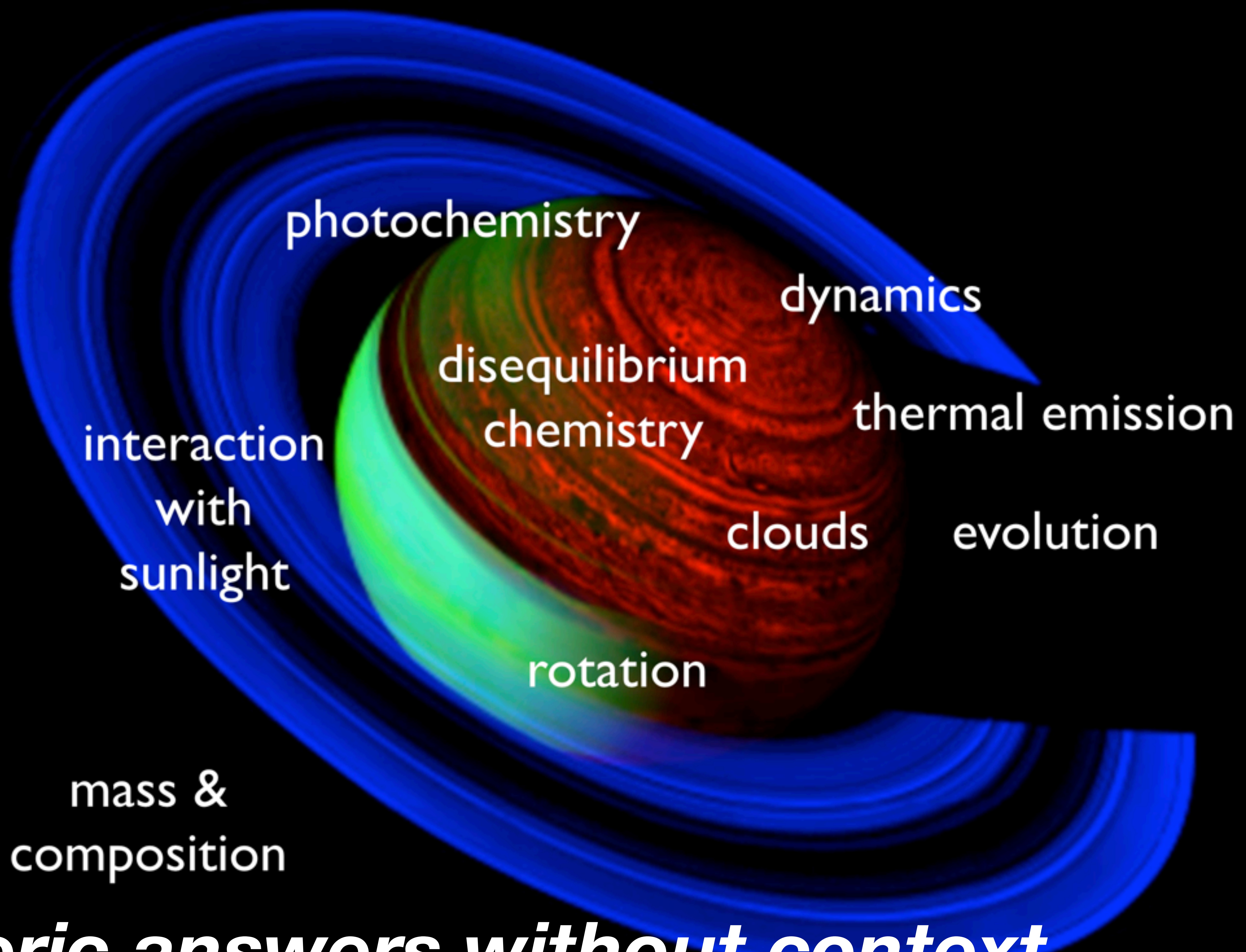


Best, Liu, Magnier & Dupuy, in prep.

Retrievals alone cannot do all of this!

Why Do We Need Forward Models?

- Test if we understand…
  - Abundances
  - Chemistry
  - Gravity
  - Mixing
  - Clouds
  - Opacities
  - Atmospheric structure



Retrievals alone give numeric answers without context.

EVOLUTION AND INFRARED SPECTRA OF BROWN DWARFS

JONATHAN I. LUNINE, WILLIAM B. HUBBARD, AND MARK S. MARLEY
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Received 1986 January 15; accepted 1986 April 8

TABLE 2

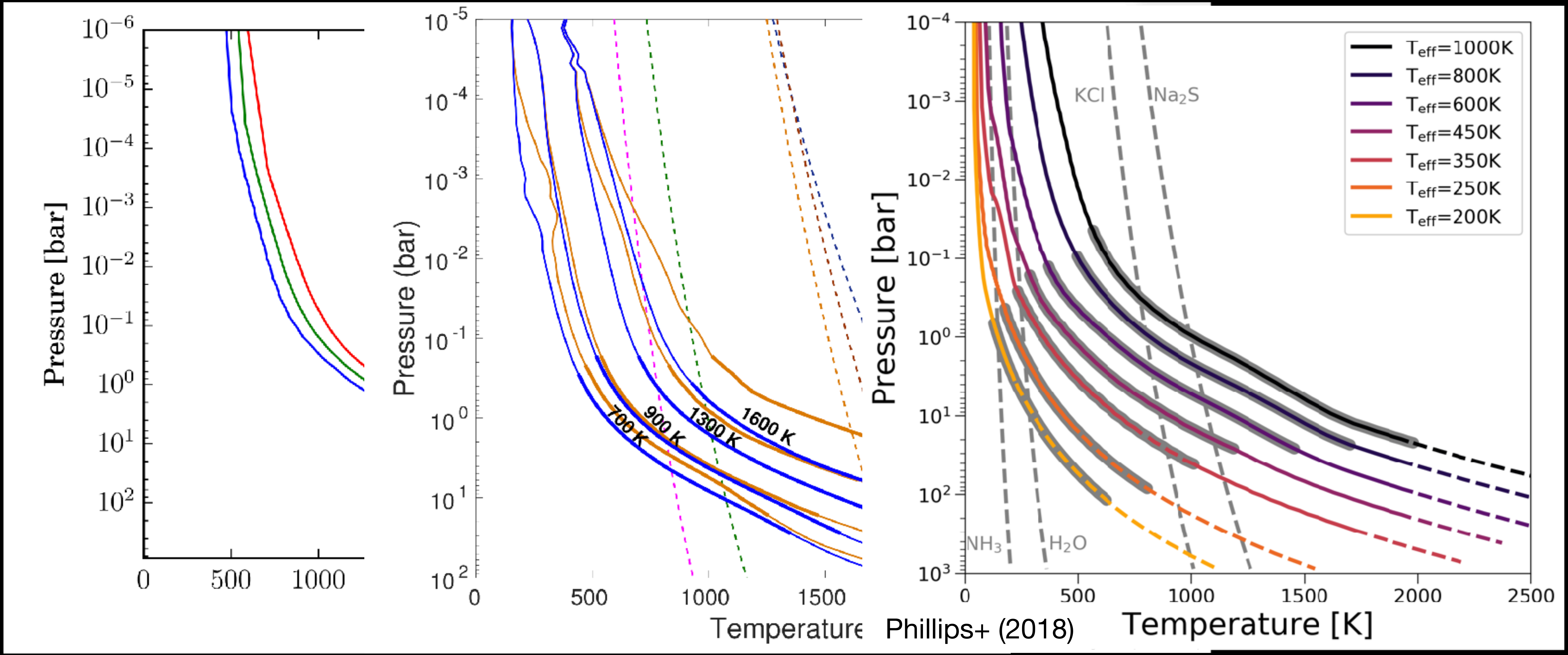
EVOLUTIONARY SEQUENCES

	P BOUNDARY CONDITION				R BOUNDARY CONDITION				C BOUNDARY CONDITION			
T_e (K)	R[a] (10^4 km)	T_c[b] (10^6 K)	ρ_c[c] (g cm^{-3})	t (10^9 yr)	R[a] (10^4 km)	T_c[b] (10^6 K)	ρ_c[c] (g cm^{-3})	t (10^9 yr)	R[a] (10^4 km)	T_c[b] (10^6 K)	ρ_c[c] (g cm^{-3})	t (10^9 yr)
$\dot{M} = 1000 \times 10^{30}$ g												
2200....	7.08	1.580	340	0.00	6.36	1.223	463	0.00	9.35	1.894	151	0.00
2090....	6.98	1.542	354	0.03	6.31	1.192	474	0.02	8.79	1.865	181	0.05
1985....	6.88	1.504	368	0.06	6.27	1.161	485	0.04	8.35	1.819	211	0.12
1886....	6.79	1.465	382	0.10	6.22	1.131	496	0.07	8.05	1.781	234	0.17
1791....	6.71	1.426	395	0.15	6.18	1.101	506	0.10	7.83	1.748	254	0.24
1702....	6.64	1.386	408	0.21	6.14	1.071	517	0.14	7.66	1.722	271	0.31
1617....	6.57	1.347	422	0.28	6.10	1.041	528	0.19	7.51	1.699	287	0.38
1536....	6.50	1.307	435	0.37	6.06	1.012	538	0.25	7.39	1.672	300	0.47
1459....	6.43	1.268	448	0.48	6.03	0.983	548	0.32	7.29	1.645	313	0.57
1386....	6.37	1.229	461	0.60	5.99	0.954	558	0.41	7.19	1.618	325	0.69
1317....	6.31	1.190	474	0.76	5.96	0.925	568	0.52	7.11	1.590	336	0.83
1251....	6.26	1.151	488	0.94	5.92	0.896	577	0.64	7.03	1.563	347	1.00
1188....	6.20	1.114	501	1.17	5.89	0.866	587	0.79	6.96	1.535	357	1.20
1129....	6.15	1.077	515	1.44	5.86	0.836	596	0.97	6.89	1.507	367	1.44
1072....	6.10	1.041	528	1.75	5.83	0.804	605	1.19	6.82	1.479	377	1.72
1019....	6.05	1.005	540	2.14	5.81	0.772	614	1.45	6.76	1.450	387	2.07
968....	6.01	0.970	553	2.59	5.78	0.737	622	1.76	6.71	1.421	397	2.50
919....	5.97	0.935	564	3.12	5.75	0.696	630	2.14	6.65	1.393	406	3.01
873....	5.93	0.899	576	3.77	5.73	0.663	638	2.59	...	...	...	...
830....	5.89	0.862	588	4.55	5.71	0.636	645	3.11	...	...	...	...
788....	5.85	0.822	600	5.51	...	...	...	...	...	...	...	...

Forward Models Have Played Major Role in the Field

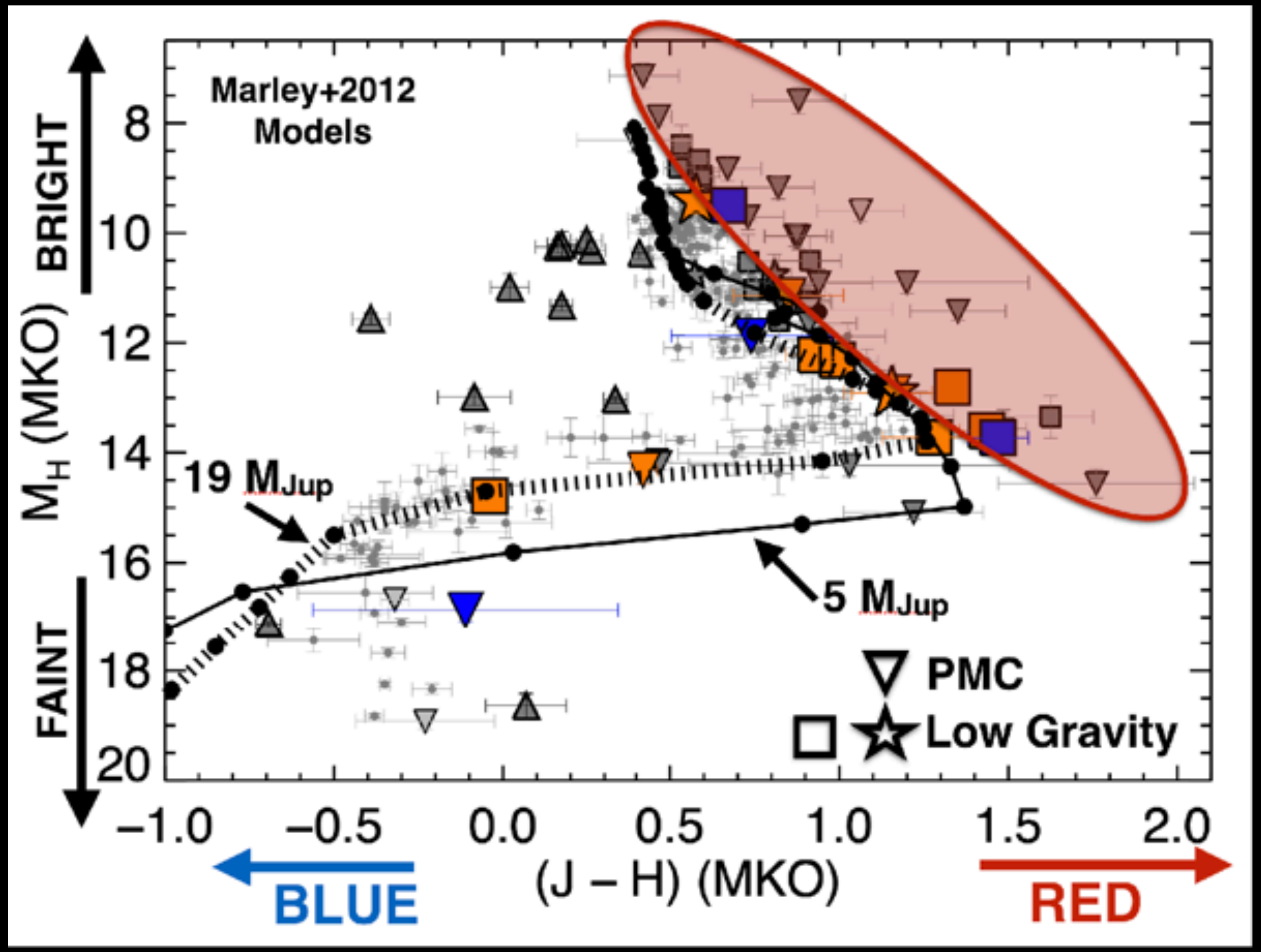
These four papers alone have over 2200 citations.

And Continue to Do So

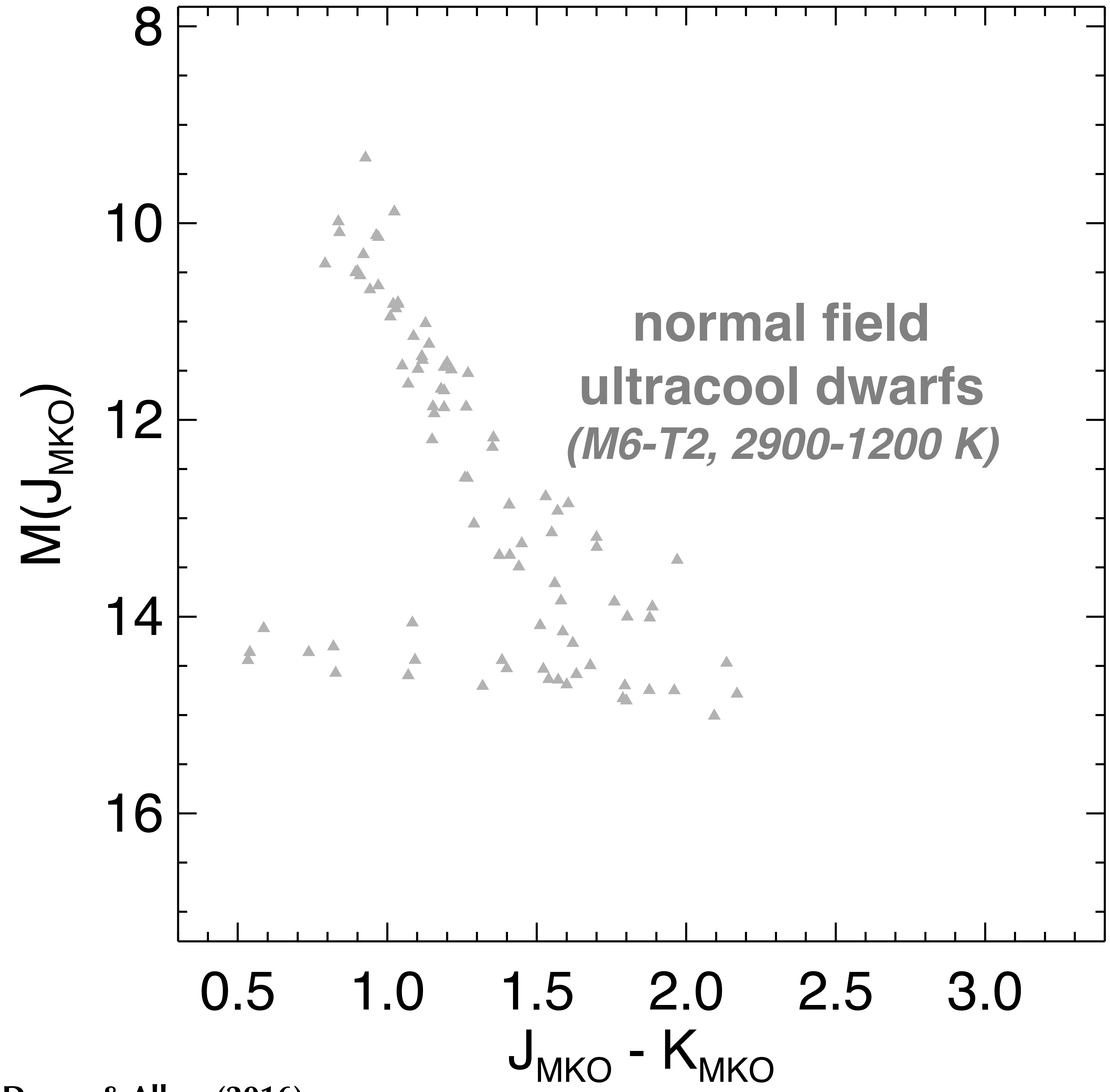


Why a New Generation Now?

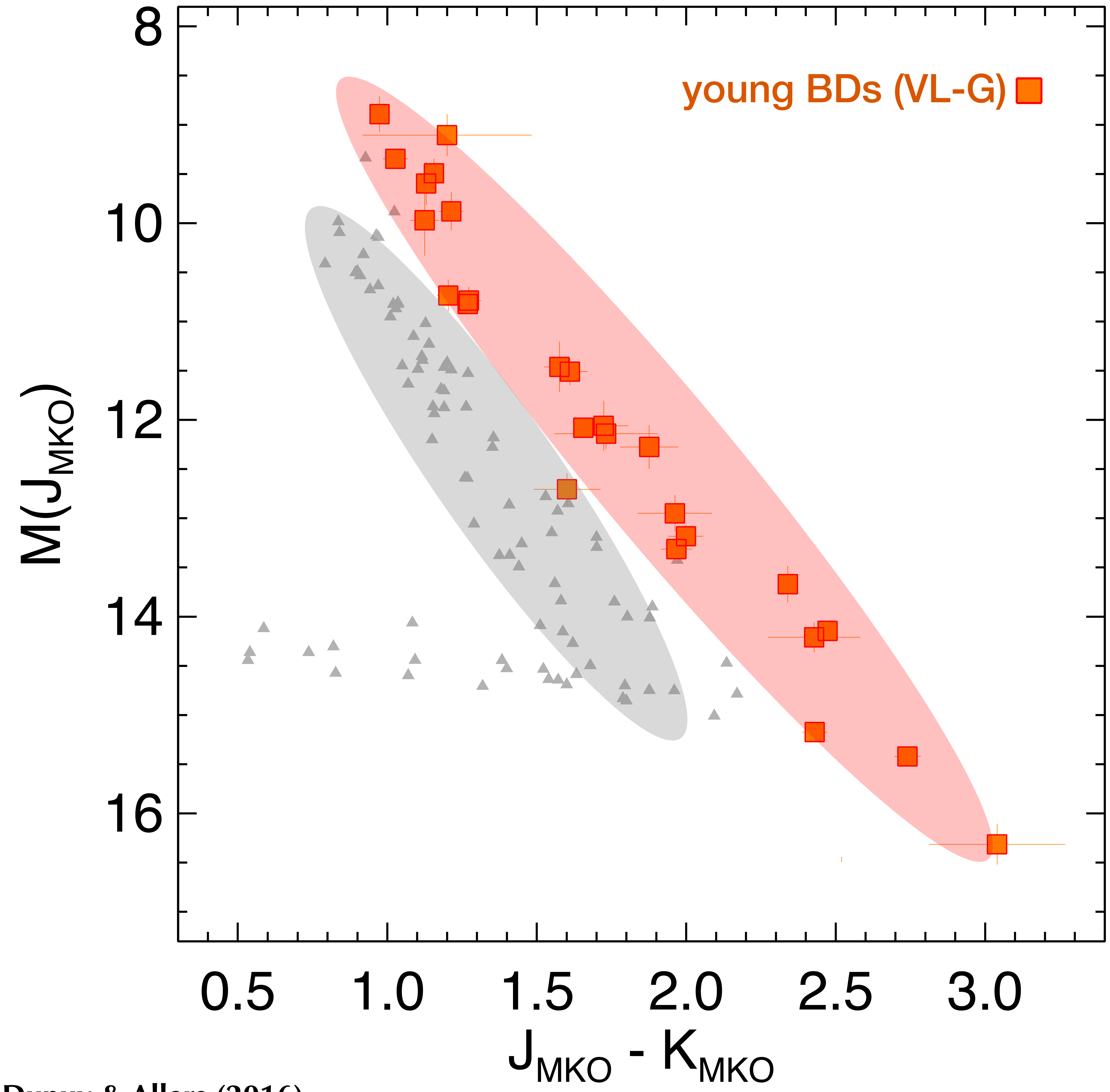
- Lots of new discoveries (Adam's talk)
    - Low gravity sequence
    - Sub-dwarfs
    - Directly imaged planets
- Huge advances in opacities (ExoMol, HiTemp, etc.)
- Innovative ideas presented, need to compare to 'legacy' theory
- New generation of instruments coming online, particularly high resolution
- Leverage value of retrievals, sophisticated fitting, and machine learning



Faherty+ in prep.



Data from Liu, Dupuy & Allers (2016)



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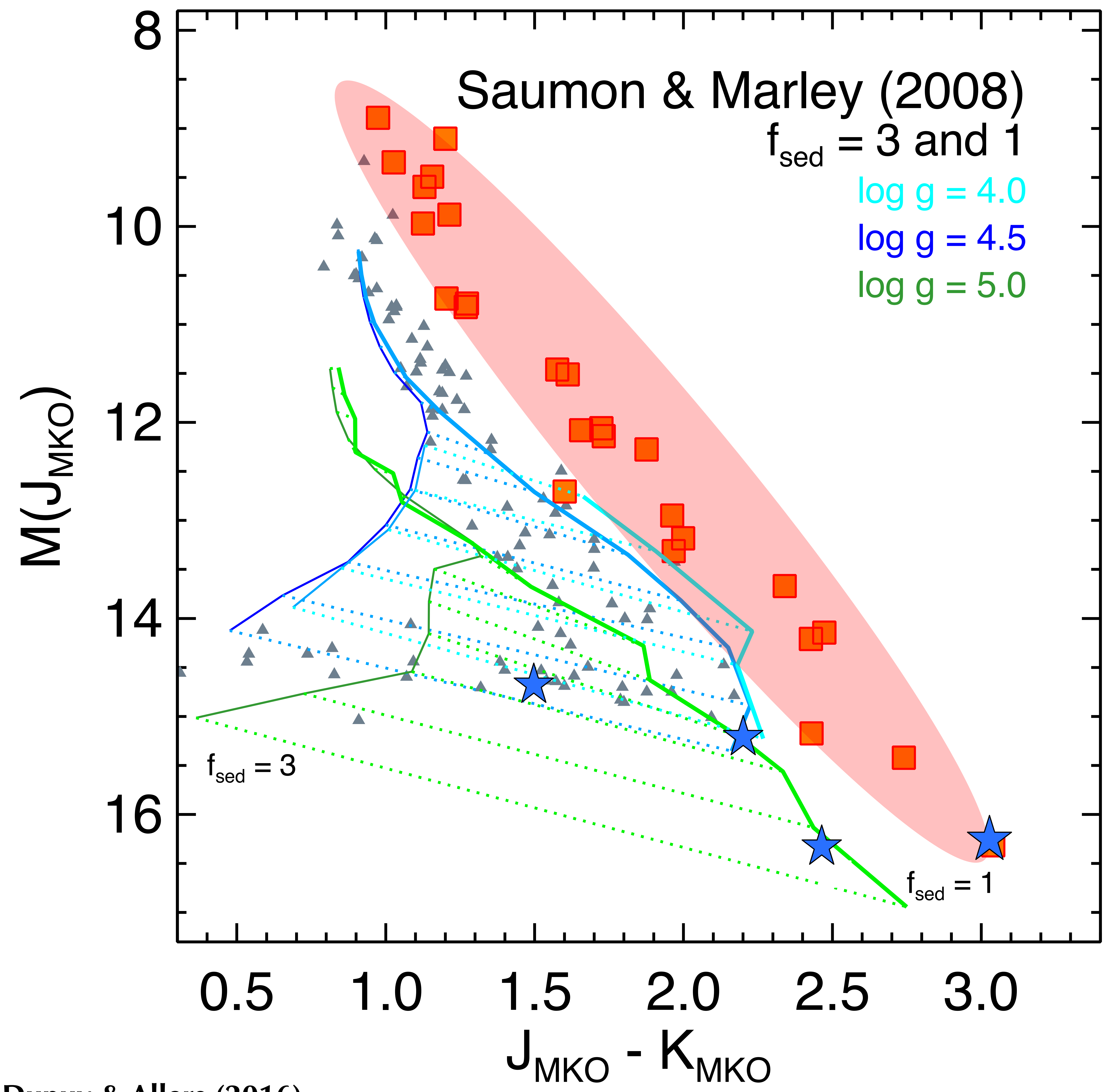

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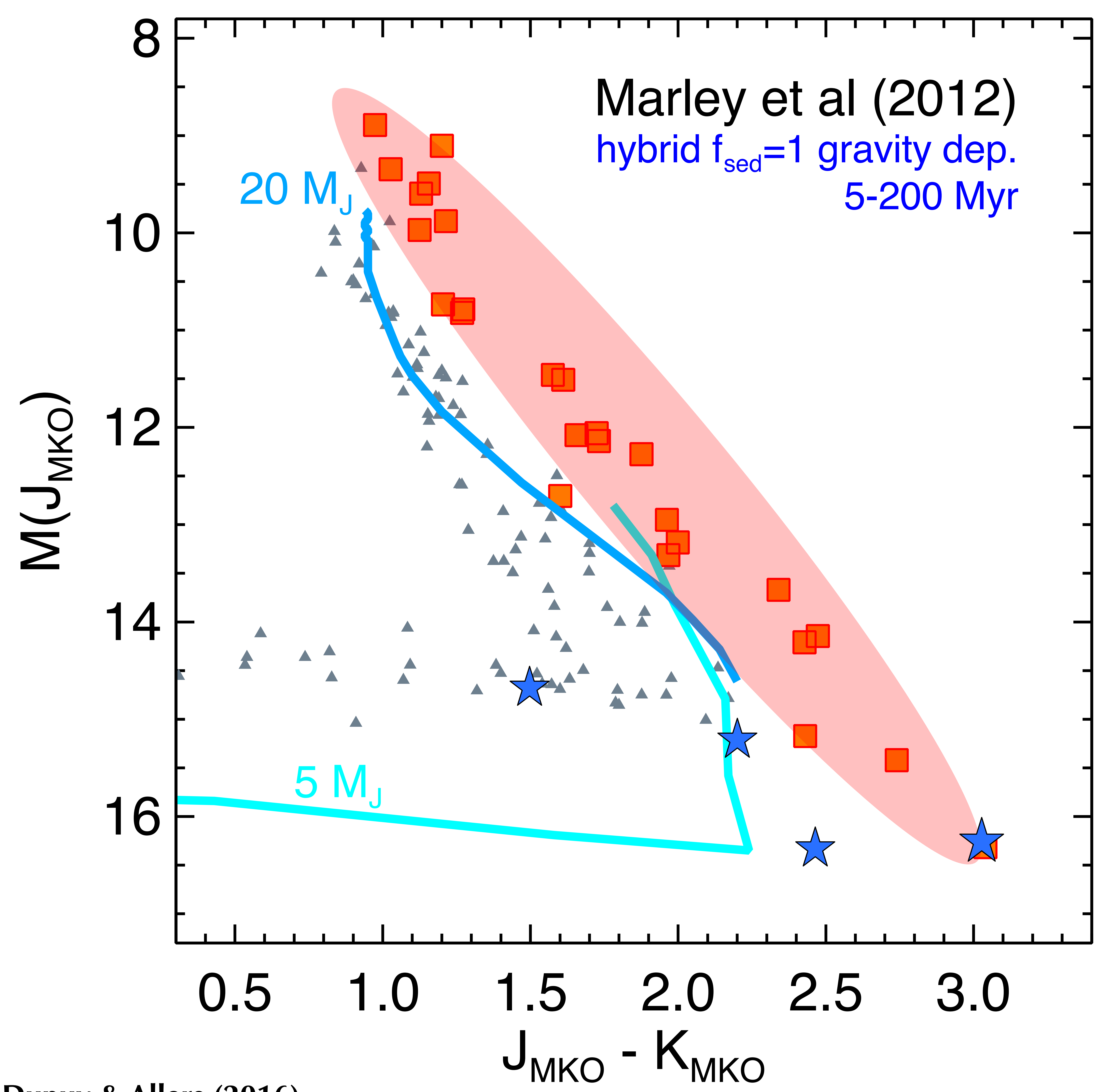

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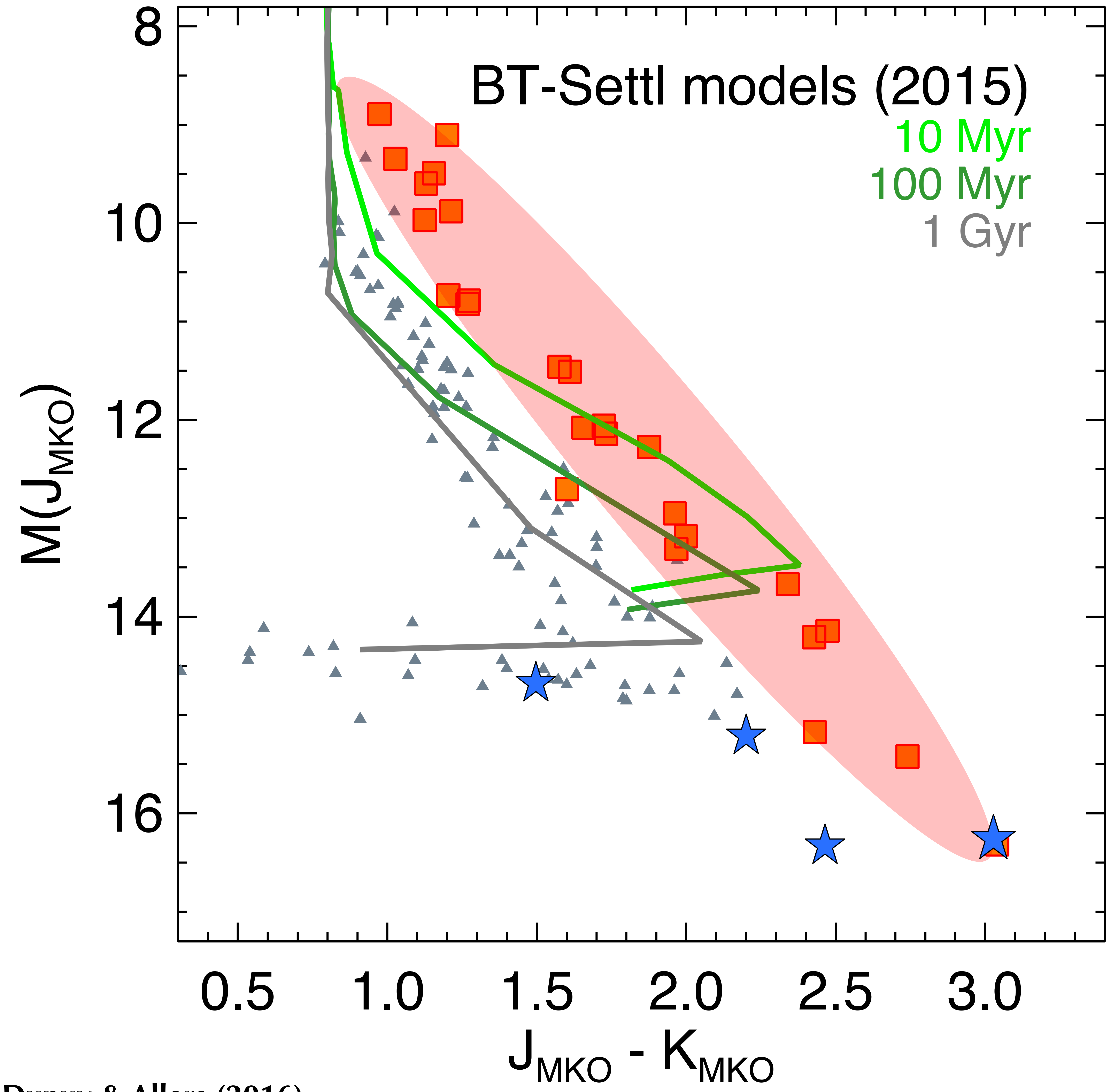
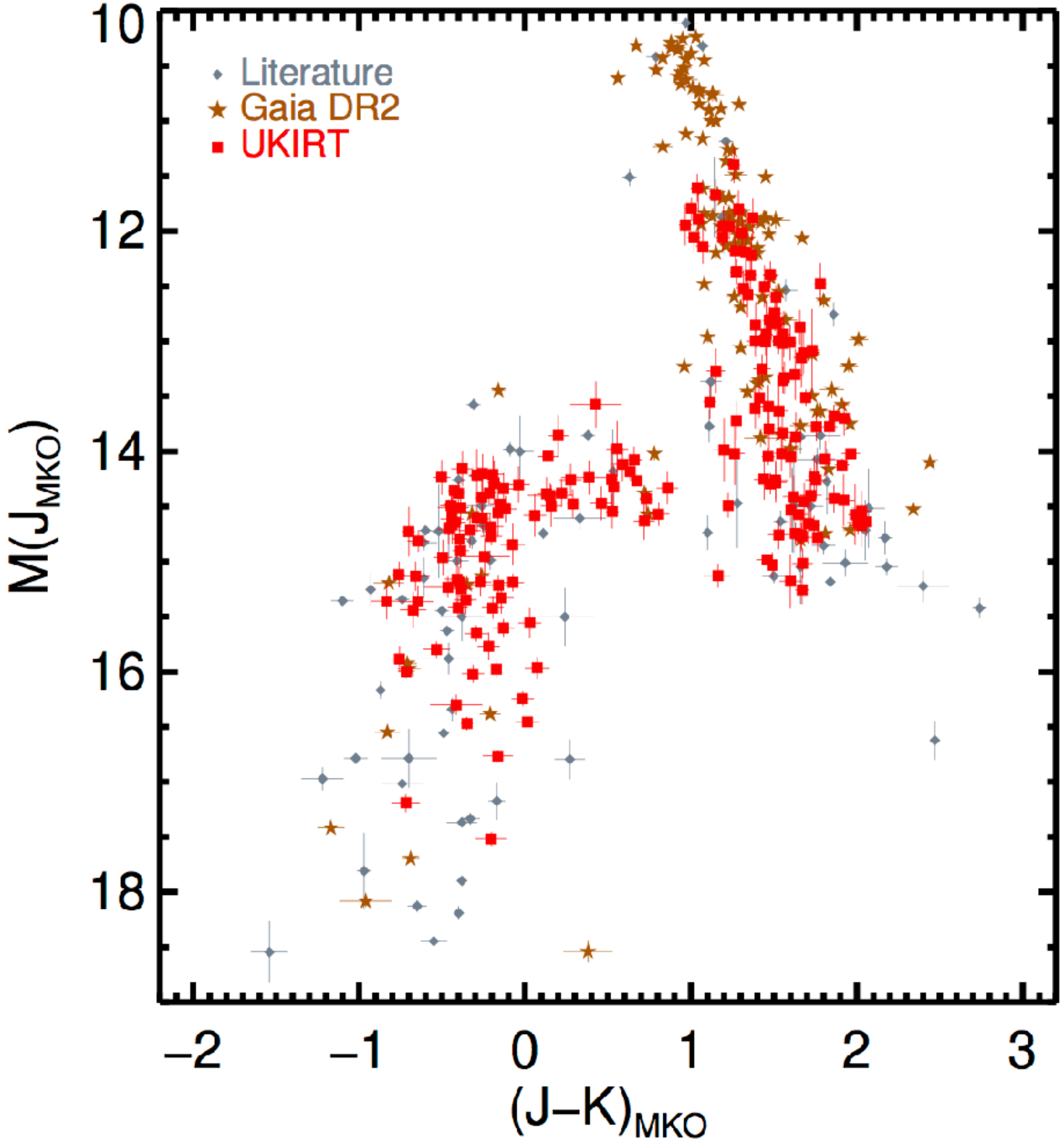


Data from Liu, Dupuy & Allers (2016)

Volume limited at 25 pc., 150 new UKIRT parallaxes, binaries removed

Best, Liu, Magnier & Dupuy, in prep.



Physics is Well Established

$$\frac{\mathrm{d}P}{P} = -\frac{gm}{k_\mathrm{B}T}\mathrm{d}z = -\frac{\mathrm{d}z}{H},$$

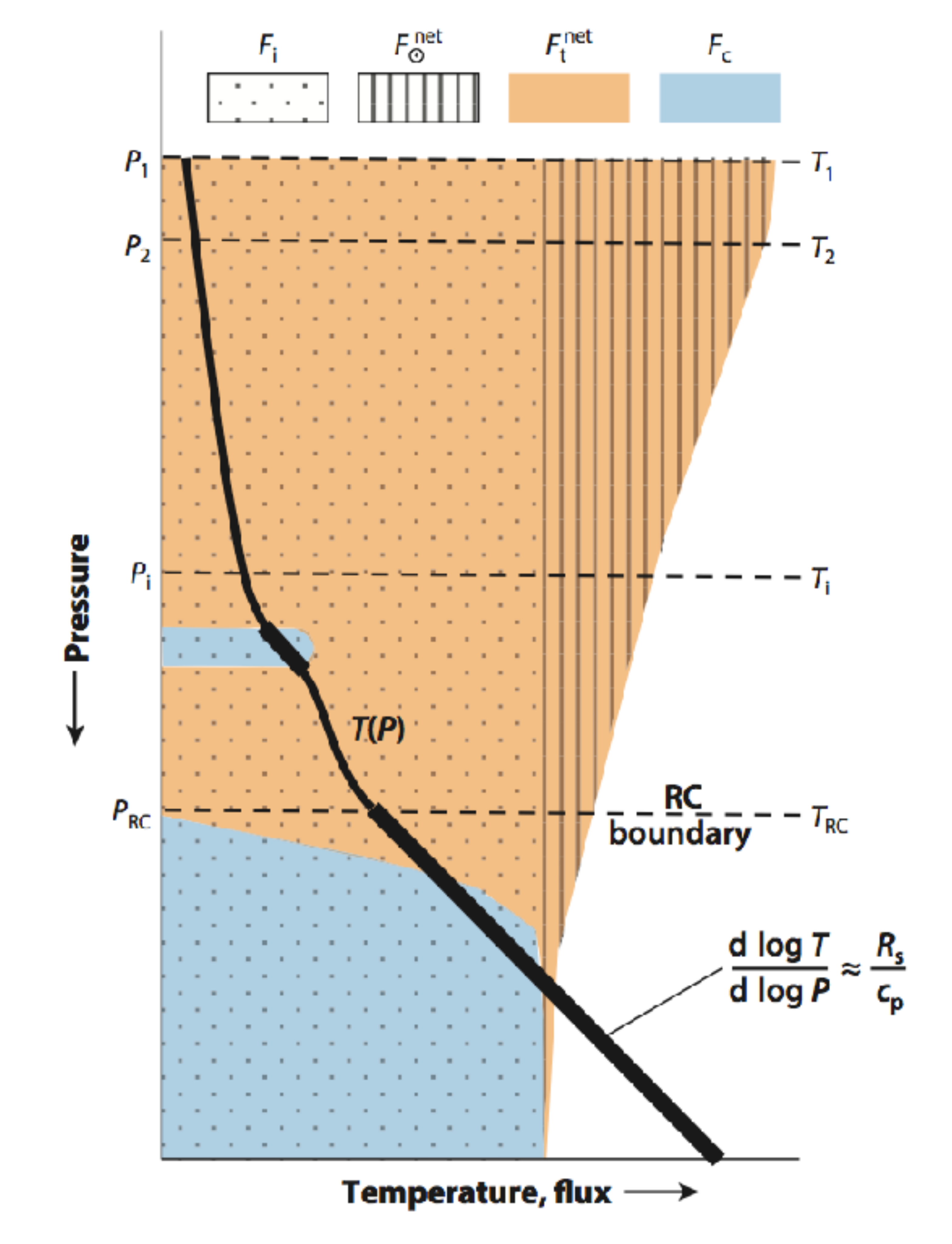
Hydrostatic equilibrium

$$F_\mathrm{t}^\mathrm{net}(P) + F_\mathrm{c}(P) + F_\odot^\mathrm{net}(P) - F_\mathrm{i} = 0,$$

Conserve energy

$$-\frac{\mathrm{d}T}{\mathrm{d}z} > \frac{g}{c_\mathrm{P}},$$

Convection



Marley & Robinson (2015)

Other Choices are not Clear Cut

Chemistry (Rainout?)

Table 1 Selected elemental abundances and species of interest

Element	Relative abundance[a] $\log[n(\mathrm{El})/n(\mathrm{H})] + 12$	Important species[b] (rainout chemistry)
H	12	H_2, H
He	10.9	He
O	8.7	CO, H_2O (v, s, l), silicates
C	8.4	CO, CH_4, CO_2
N	7.8	N_2, NH_3 (v, s), NH_4SH (s)
Mg	7.6	$MgSiO_3$ (s), Mg_2SiO_4 (s), MgH
Fe	7.5	FeH, Fe (l, s)
S	7.2	H_2S, NH_4SH (s), MnS (s), Na_2S (s), ZnS (s)
Al	6.5	Al_2O_3 (s),
Na	6.3	Na, Na_2S (s)
P	5.5	PH_3, P_4O_6
K	5.1	K, KCl (s)
Ti	4.9	TiO, $CaTiO_3$ (s)
V	4.0	VO, V-oxides

Clouds

Details

- Lodders solar abundances
- Chemistry framework - rainout
    - But which 'rainout' is right?
    - We use Visscher framework
- Opacities
    - Broadly updated
    - N. Allard alkali
    - ExoMol H_2O

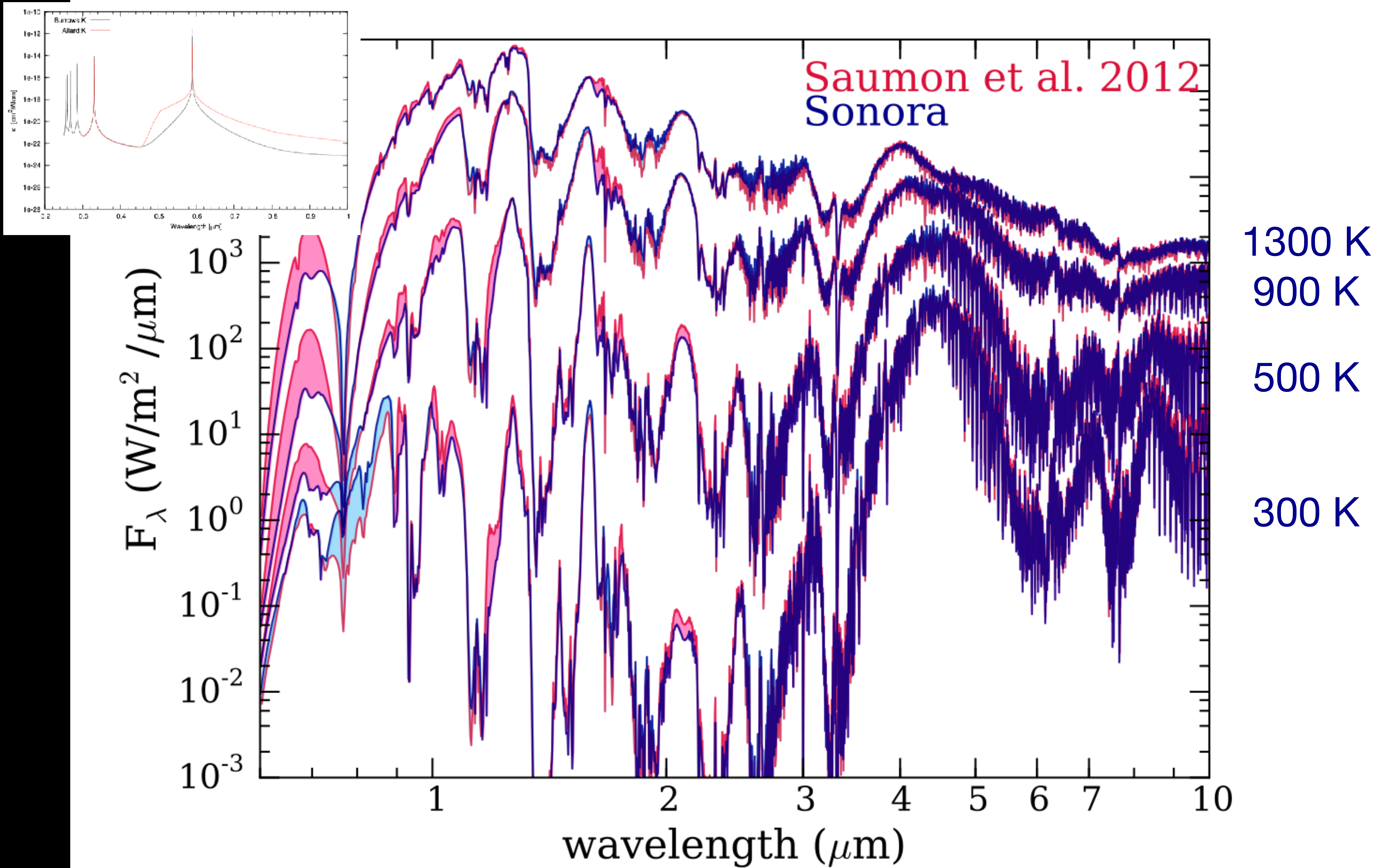
- 90 model layers
- Radiative-convective equilibrium
    - Convective adjustment
- Ackerman & Marley clouds - f_{sed}

[M/H] C/O:	-1.0	-0.75	-0.50	-0.25	0.0	0.50	1.0	1.5	1.7	2.0
0.25	X	X	X	X	X	X	X	X	X	X
0.50	X	X	X	X	X	X	X	X	X	X
1.0	X	X	X	X	X	X	X	X	X	X
1.5	X	X	X	X	X	X	X	X	X	X
2.0	X	X	X	X	X	X	X	X	X	X
2.5	X	X	X	X	X	X	X	X	X	X

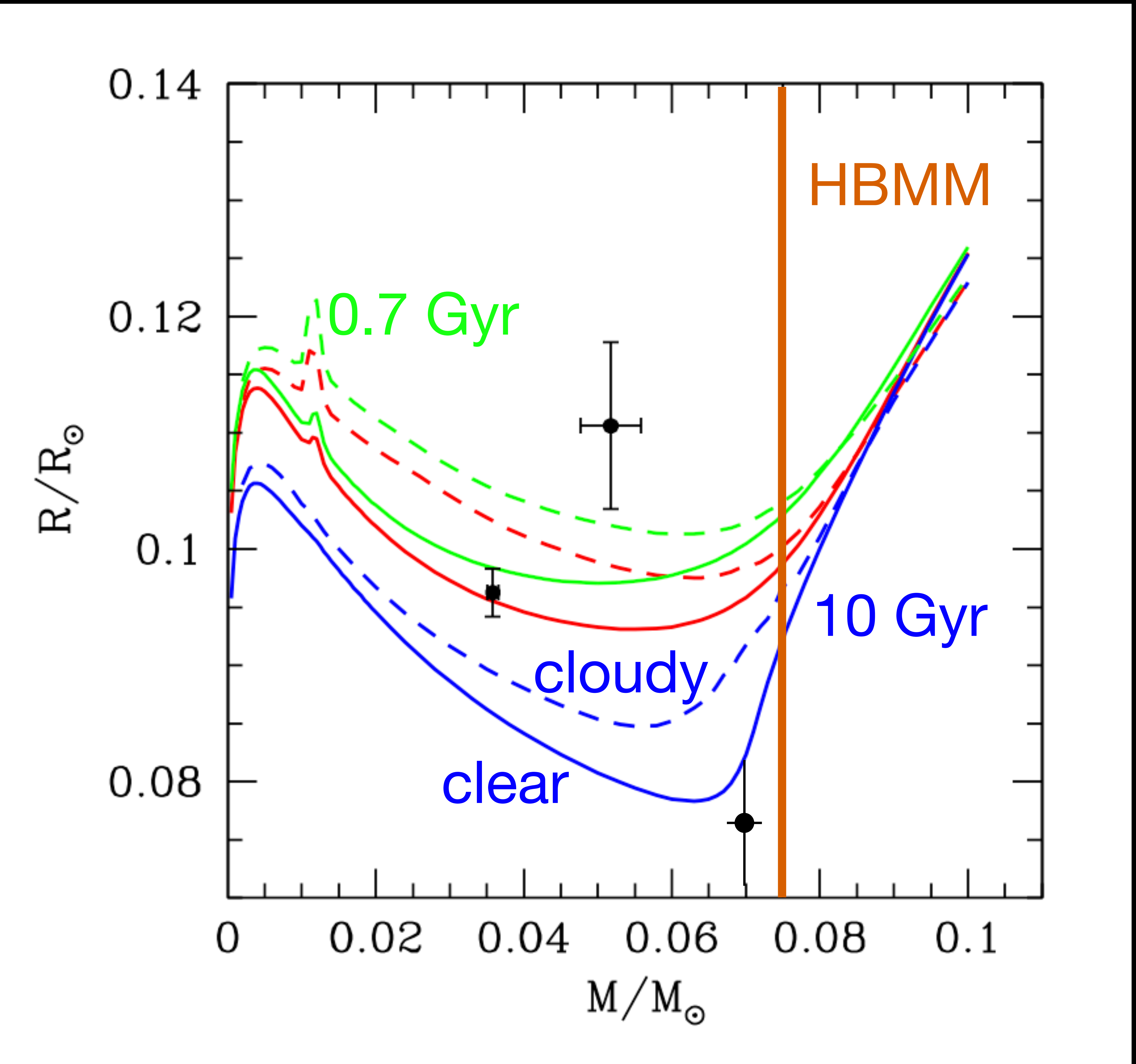
‘Sonora’ Grid

- Massive group effort (Marley, Saumon, Visscher, Morley, Lupu, Freedman, Fortney, students)
- Unified naming convention (Marley? Fortney? Morley? Saumon?; “Santa Cruz Group”)
- Equilibrium & disequilibrium chemistry
- $200 \leq T_{\mathrm{eff}} \leq 2400$ K; $-0.5 \leq [M/H] \leq 2$; cloudless & cloudy
- Thousands of models done, solar, cloudless online. More soon. Ask for beta versions.
- Spectra plus underlying T(P) and chemistry online
- Opacities also going online at MAST
- Code is not suitable for online distribution. Natasha Batalha is re-casting for eventual open source

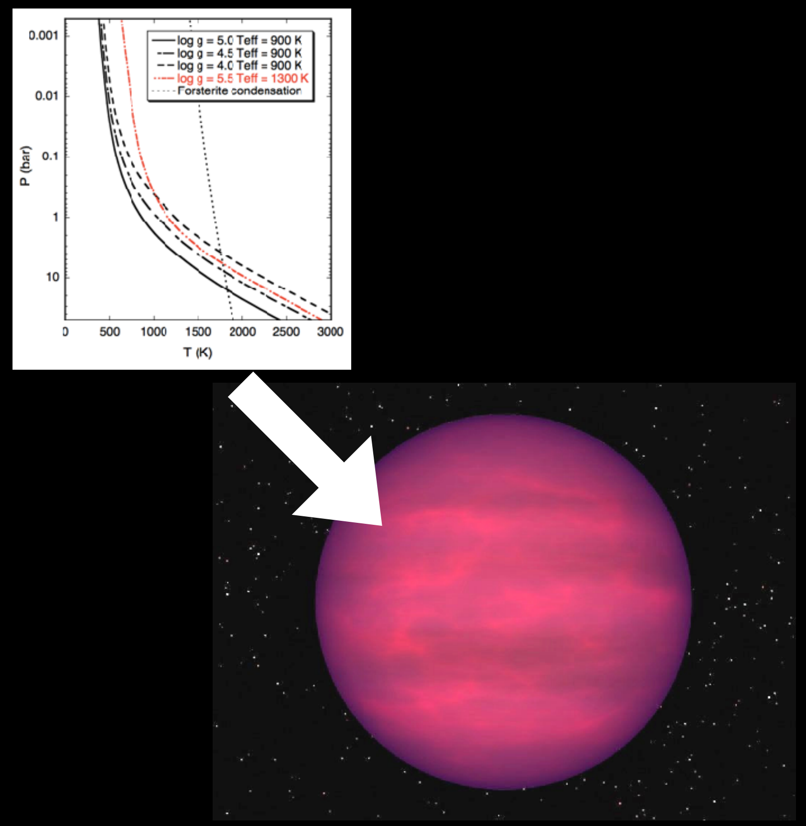
Cloudless


Burrows:K
Allard:K
Wavelength [μm]
Saumon et al. 2012
Sonora
F_λ (W/m² /μm)
wavelength (μm)
1300 K
900 K
500 K
300 K

HBMM

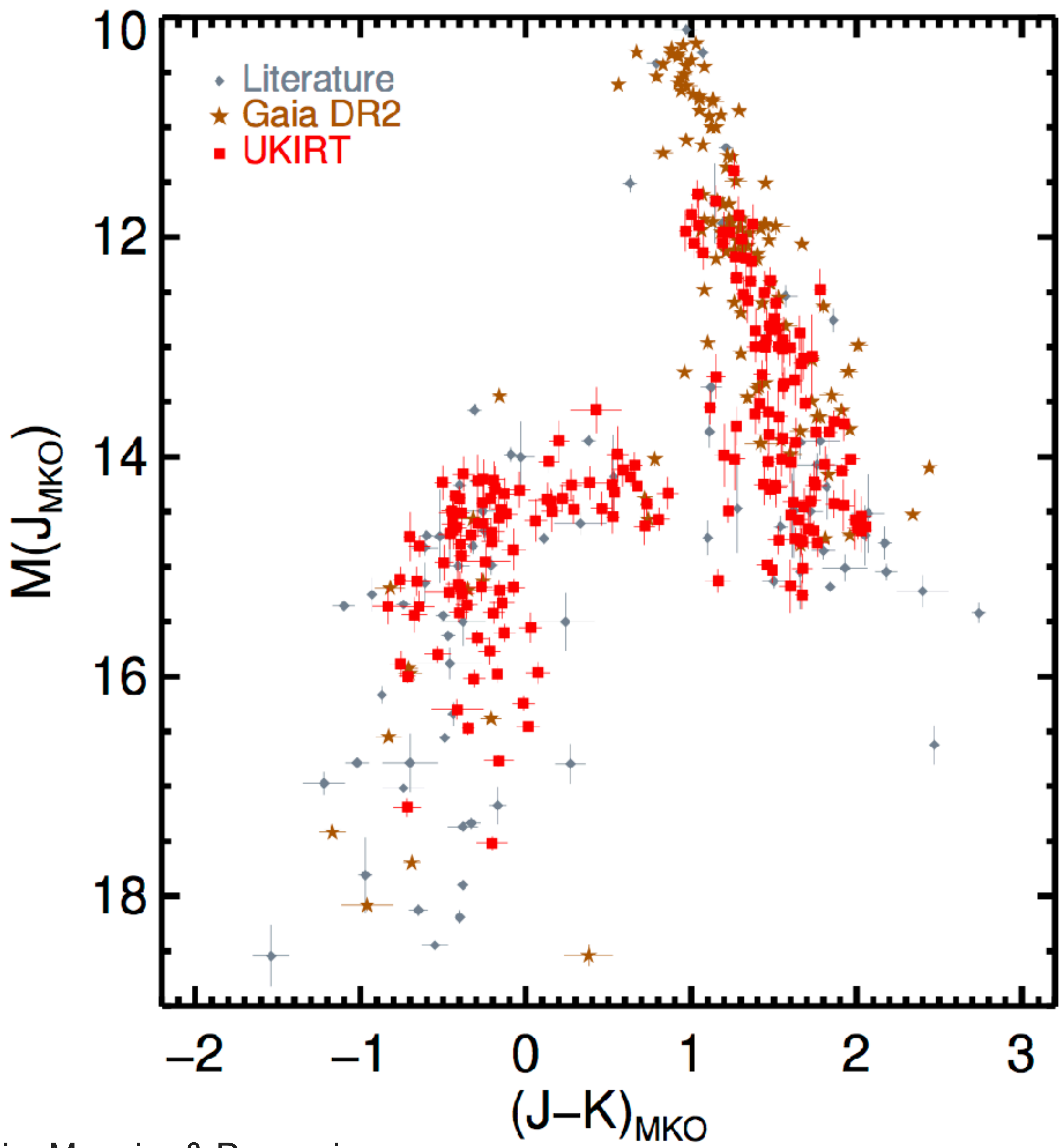


New models are a bit higher opacity near 1800 K, which lowers hydrogen burning minimum mass

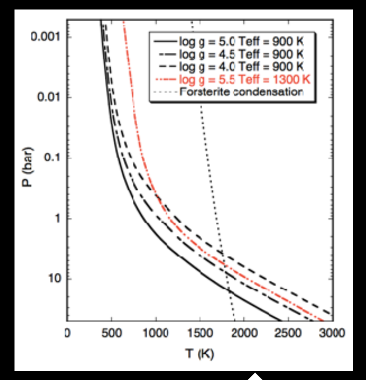


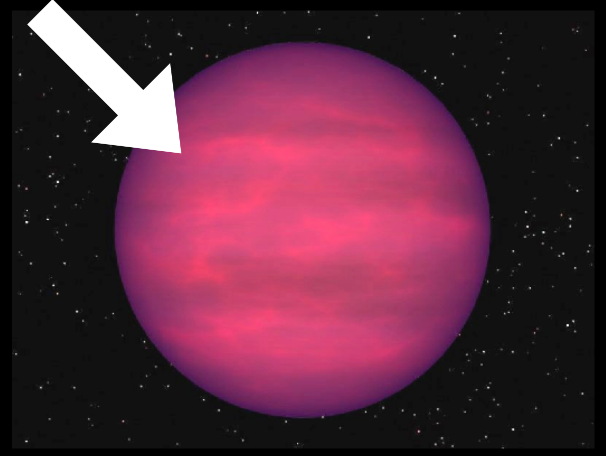
Model	HBMM (Mo)	Teff	DBMM (M_J)
SM08 nc	0.0750	1910	13.1
Sonora nc	0.0730	1800	12.95
SM08 f2	0.0700	1550	12.4

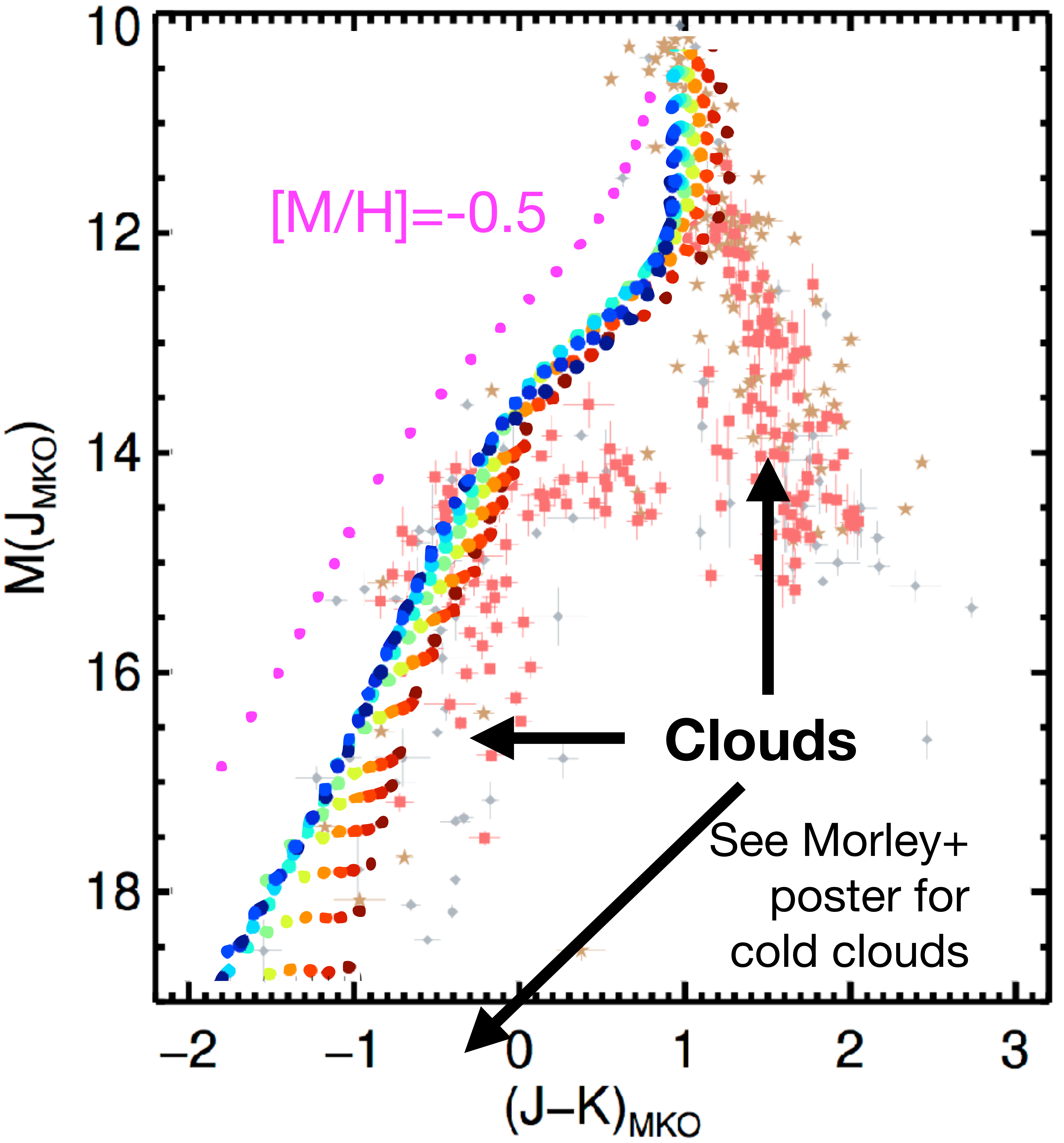
Marley, Saumon, in prep.



Best, Liu, Magnier & Dupuy, in prep





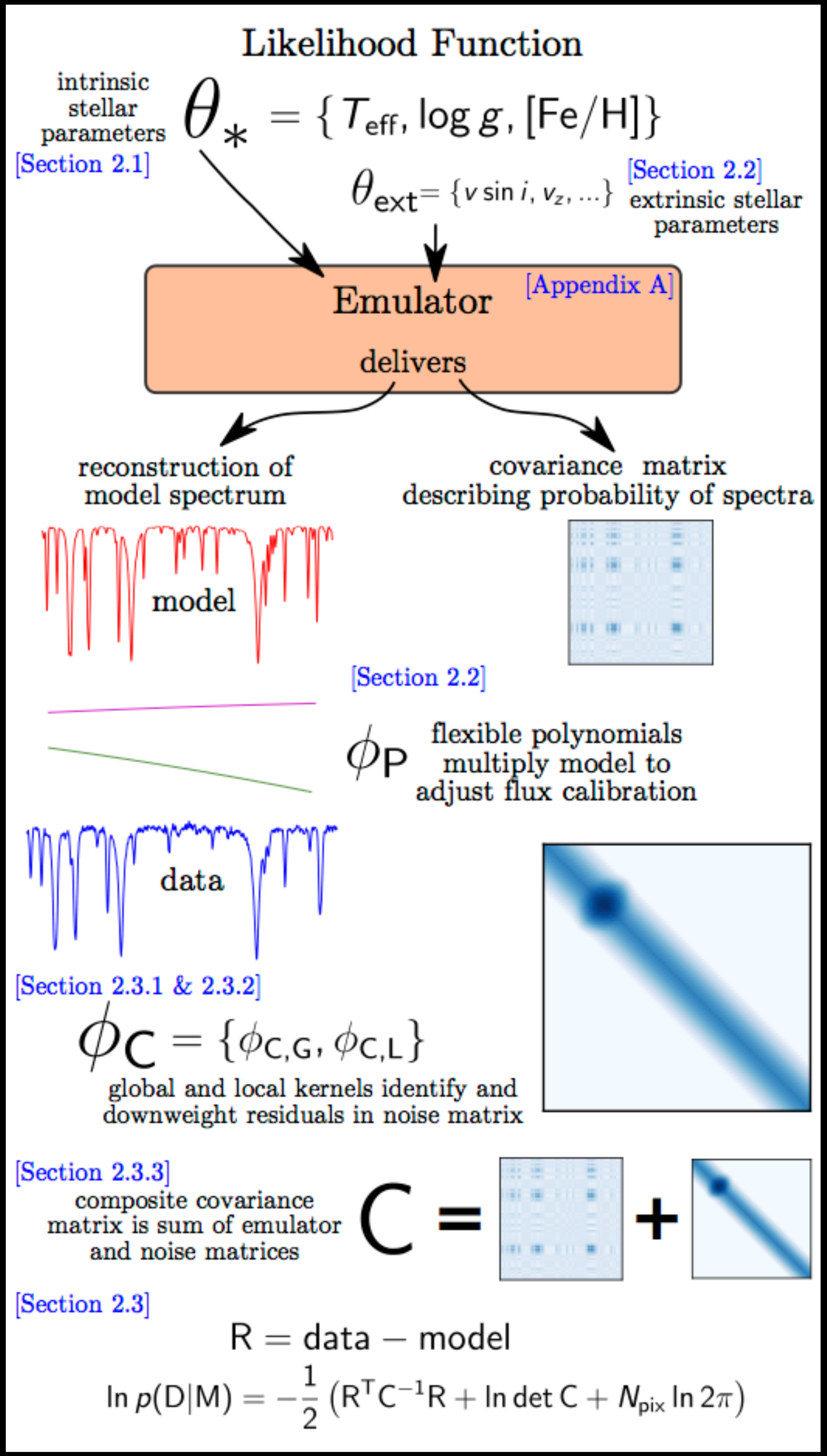


Solar [M/H]
10 log *g*
(3.0 to 5.5)
40 $T_{\rm eff}$
(200 - 2400 K)

400 models
(all online)

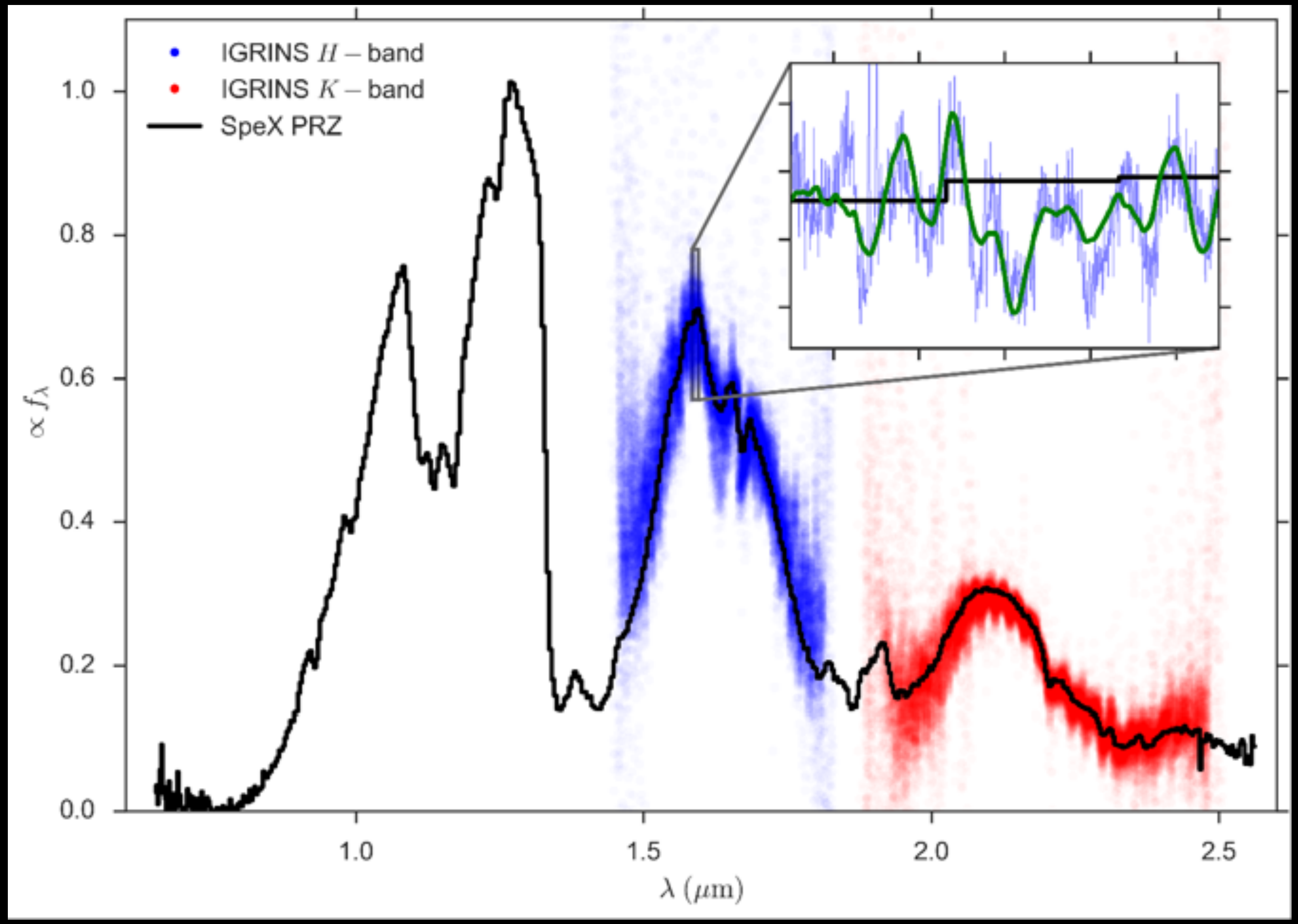
Best early L,
early T colors
from our group

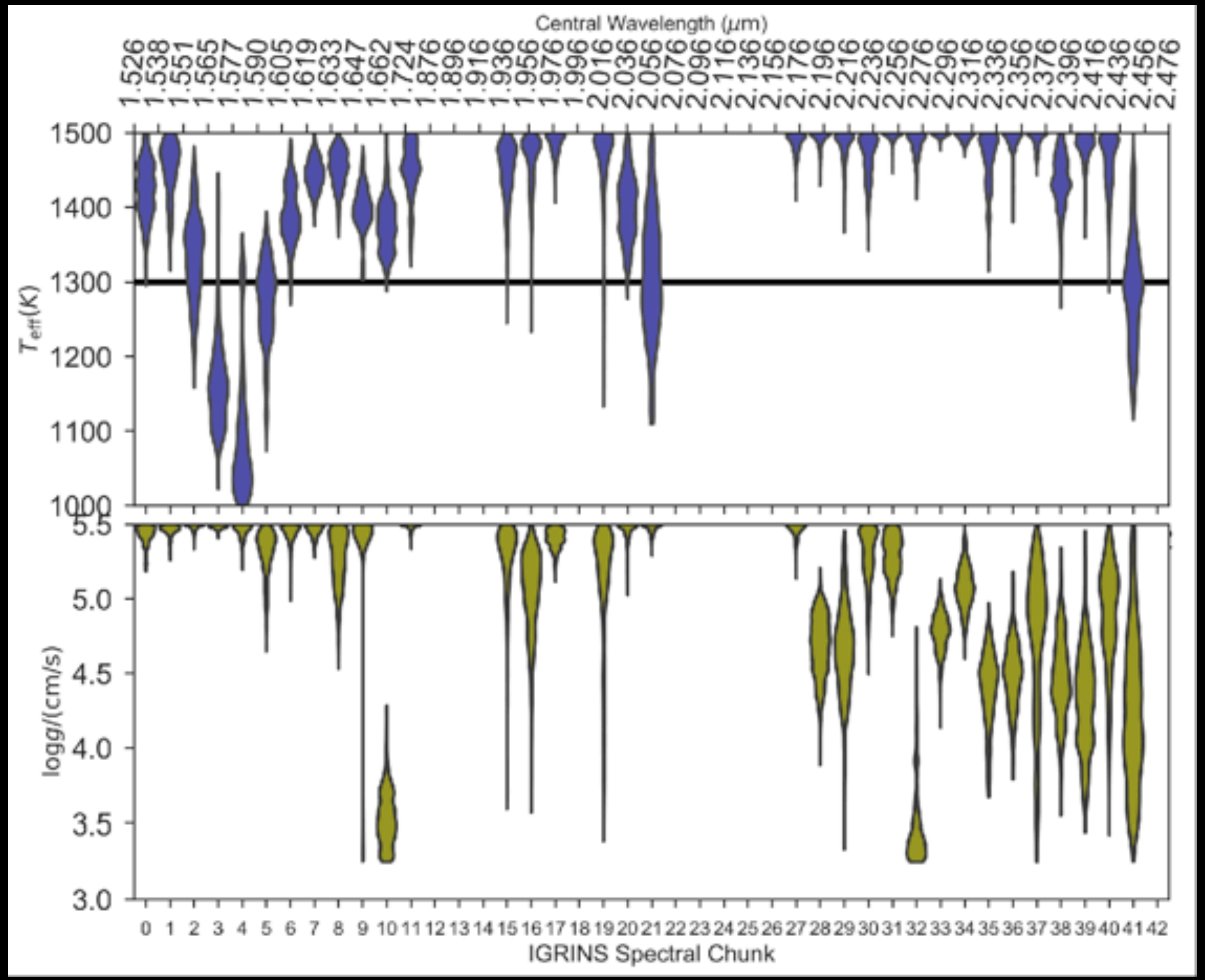
Spectra Fitting: Starfish



Czekala+ (2015)

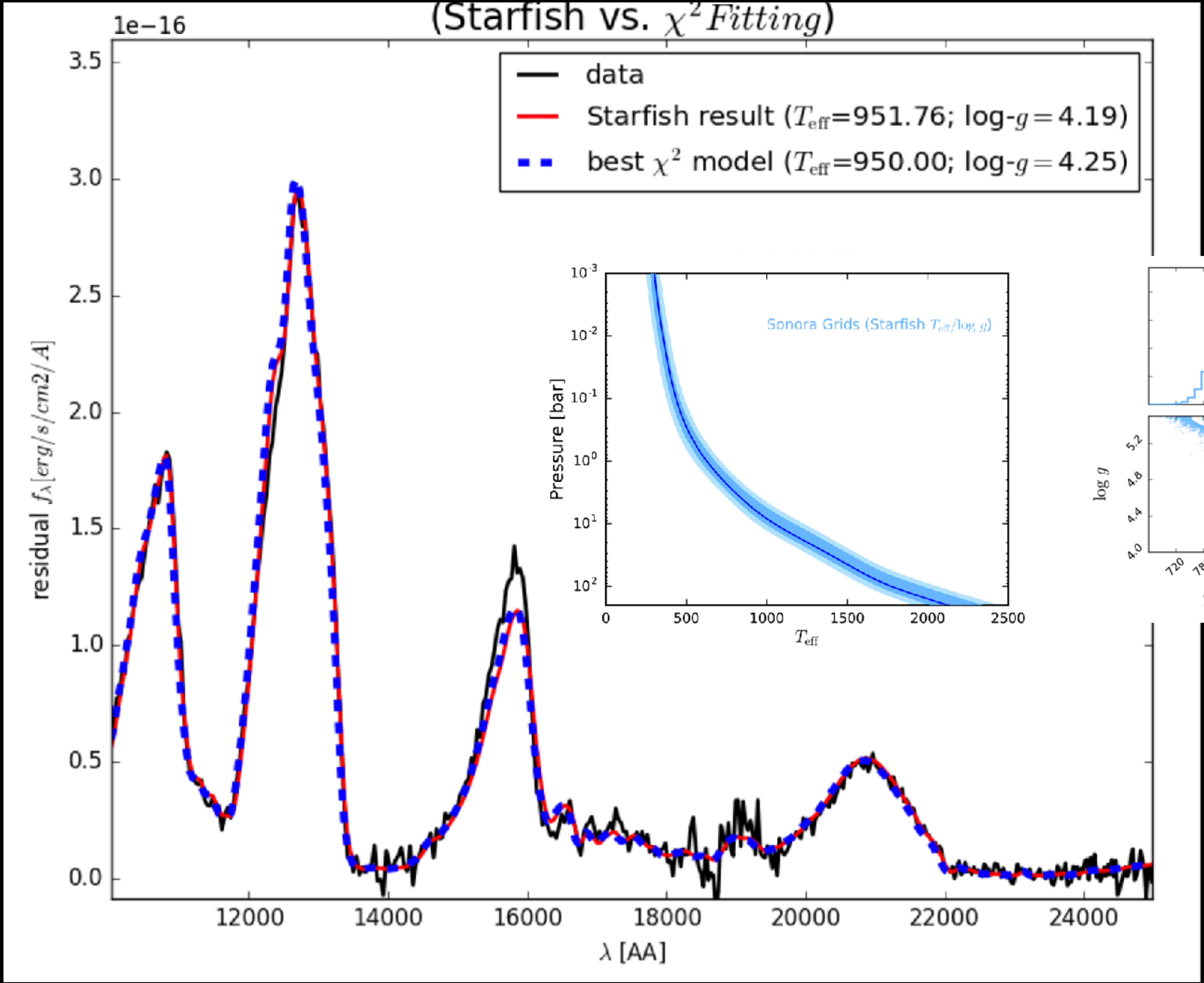
Gully-Santiago+ (2017)

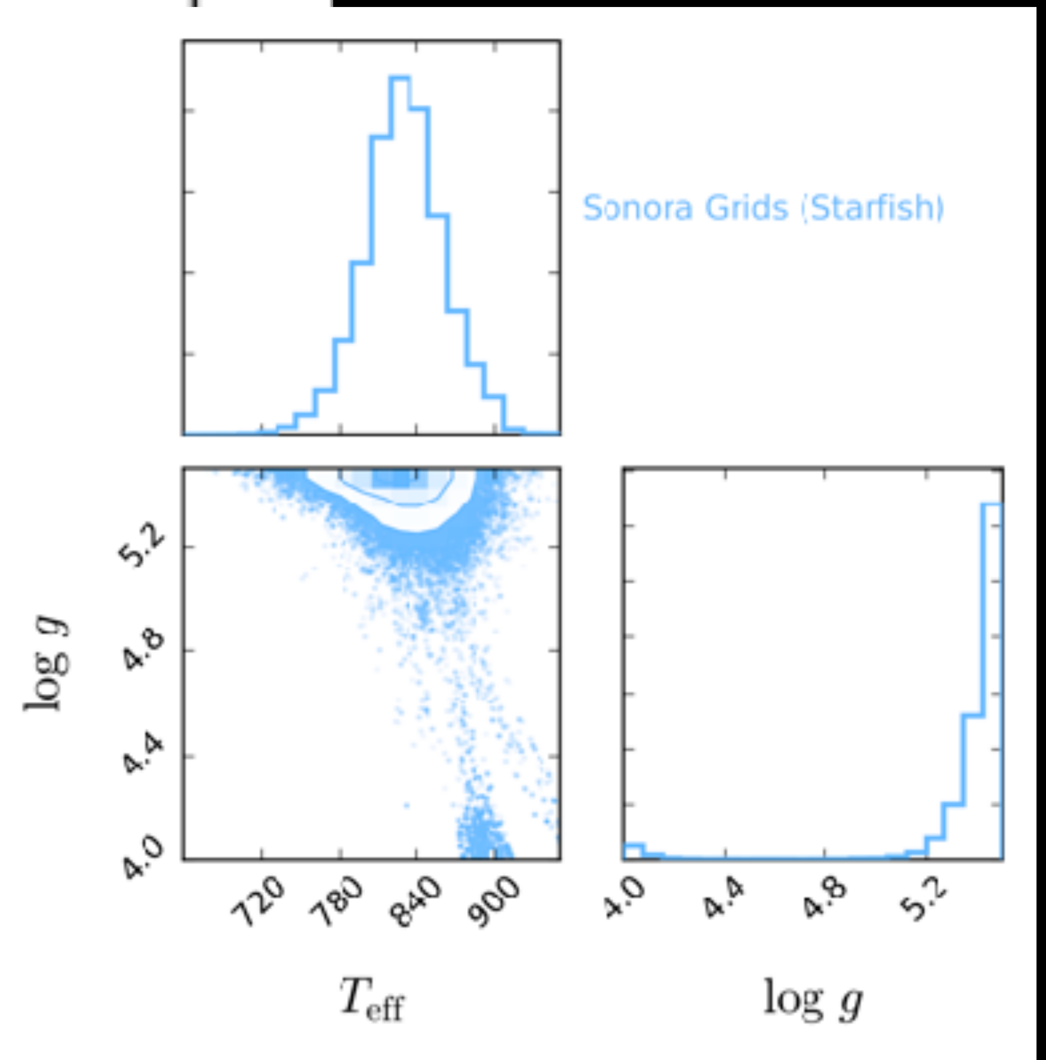


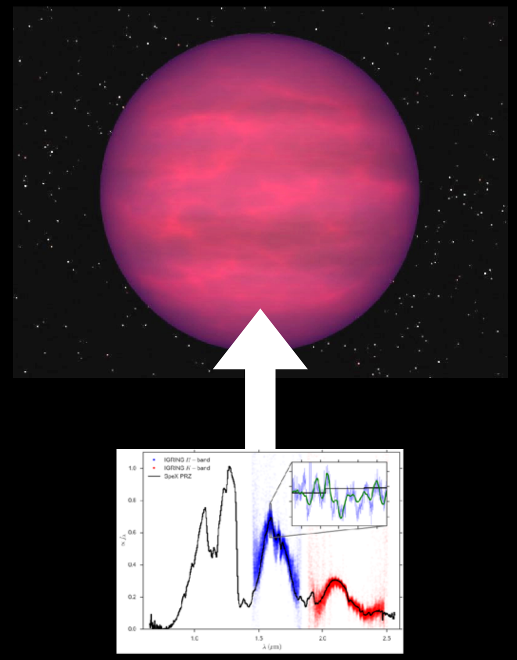


High R fits in progress.

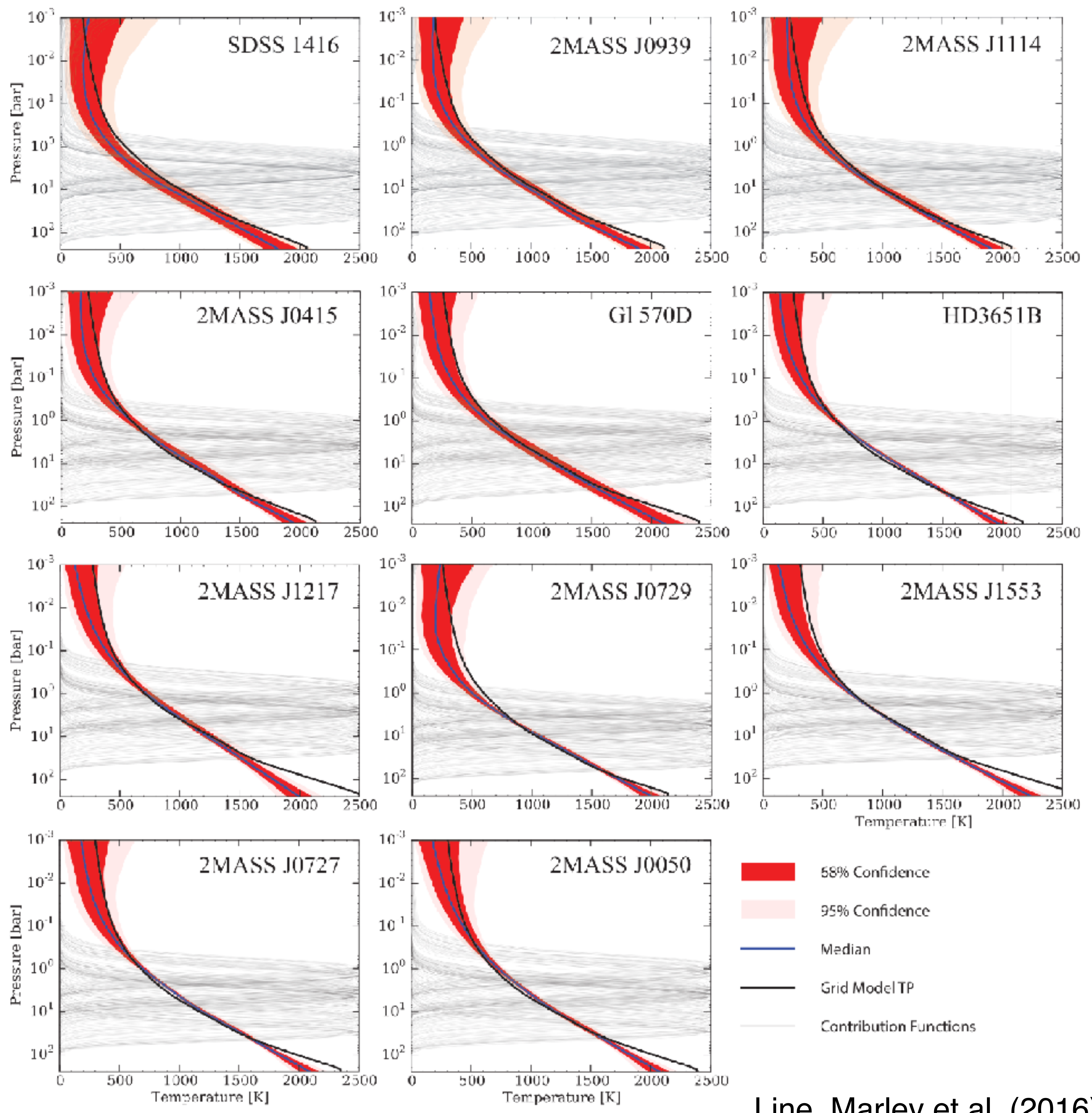
Low R studies by ZJ Zhang.







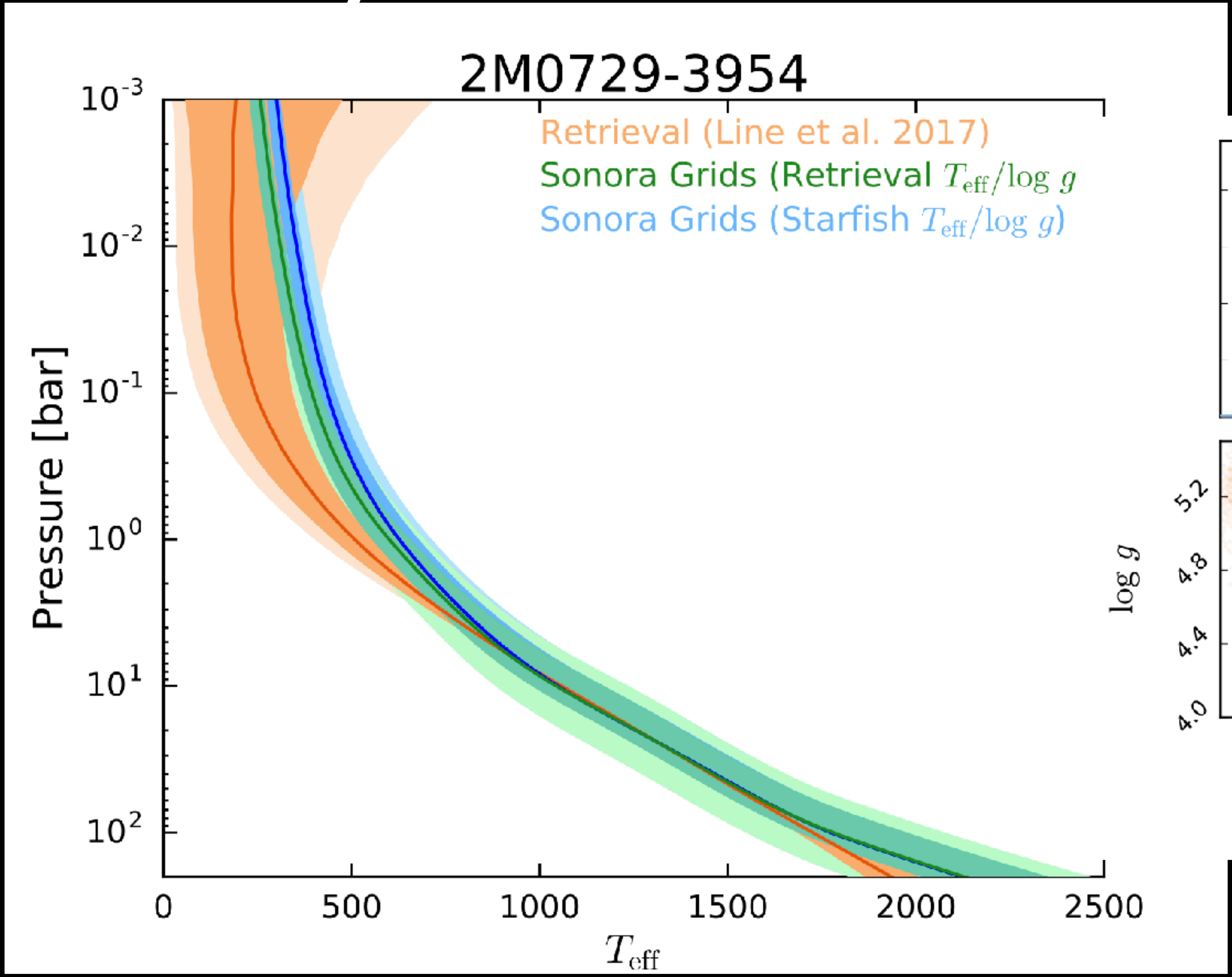
Zhang+ in prep.

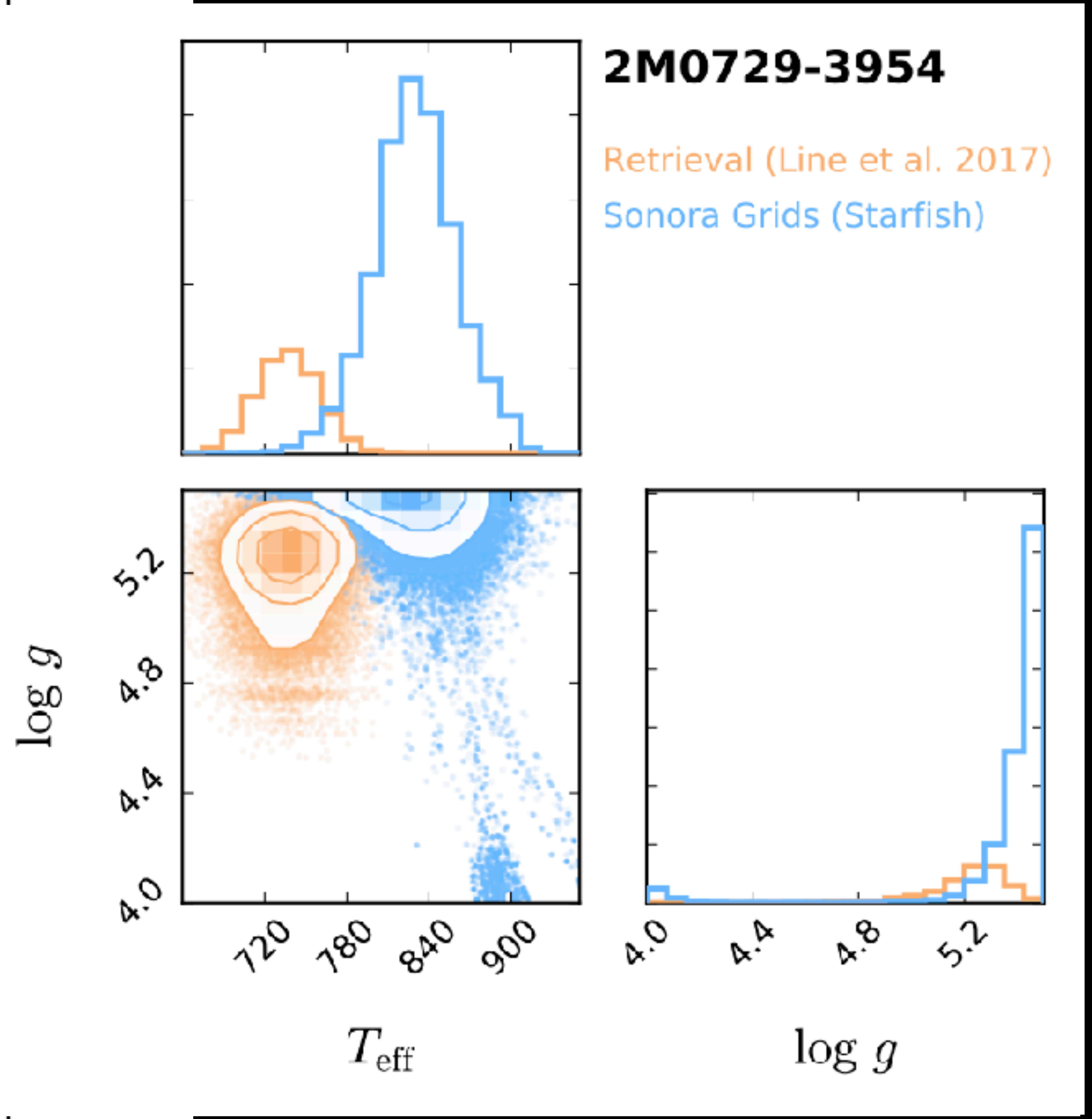


Line, Marley et al. (2016)

Analyzed same T dwarfs as Line+

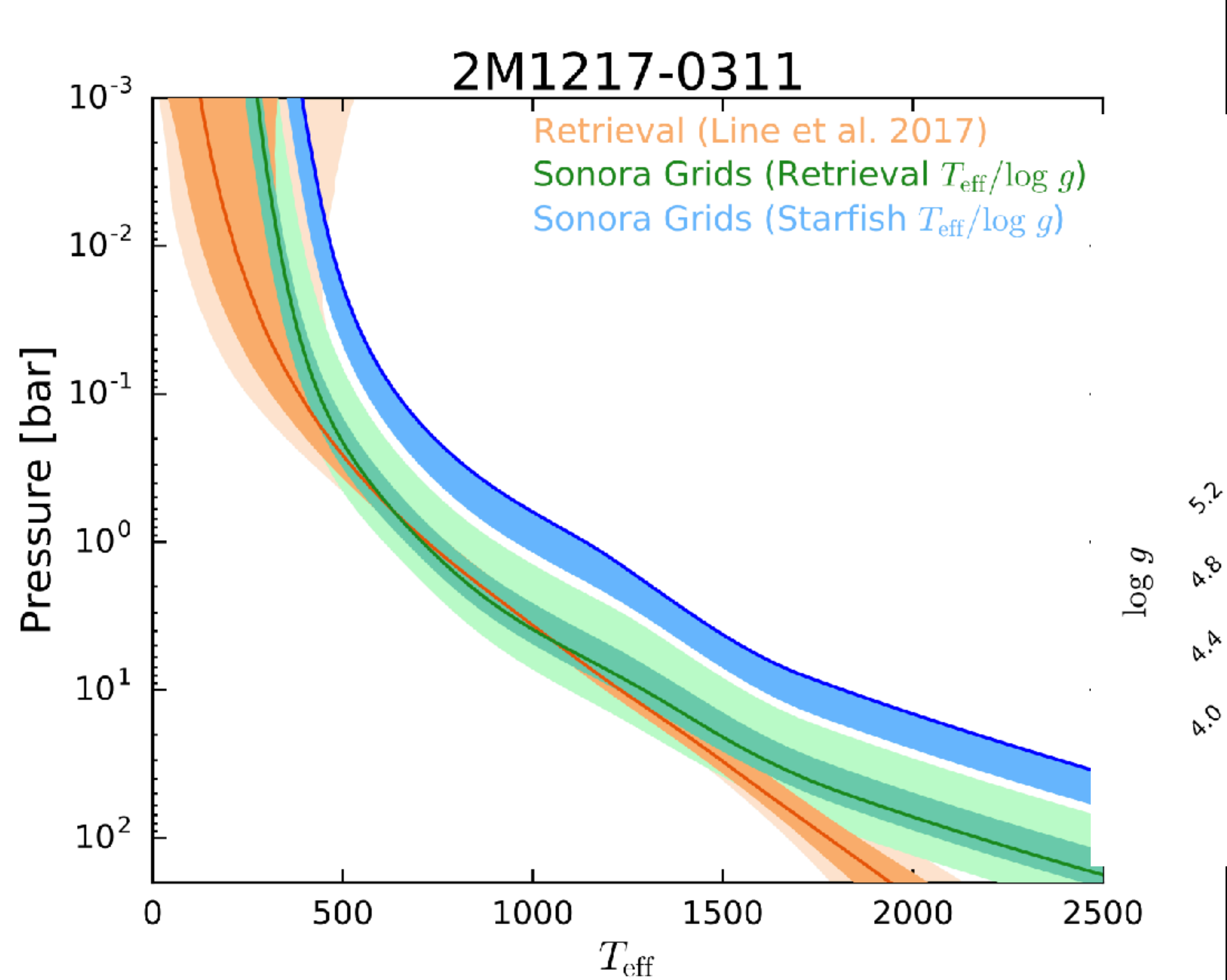
Many Show Excellent Consistency

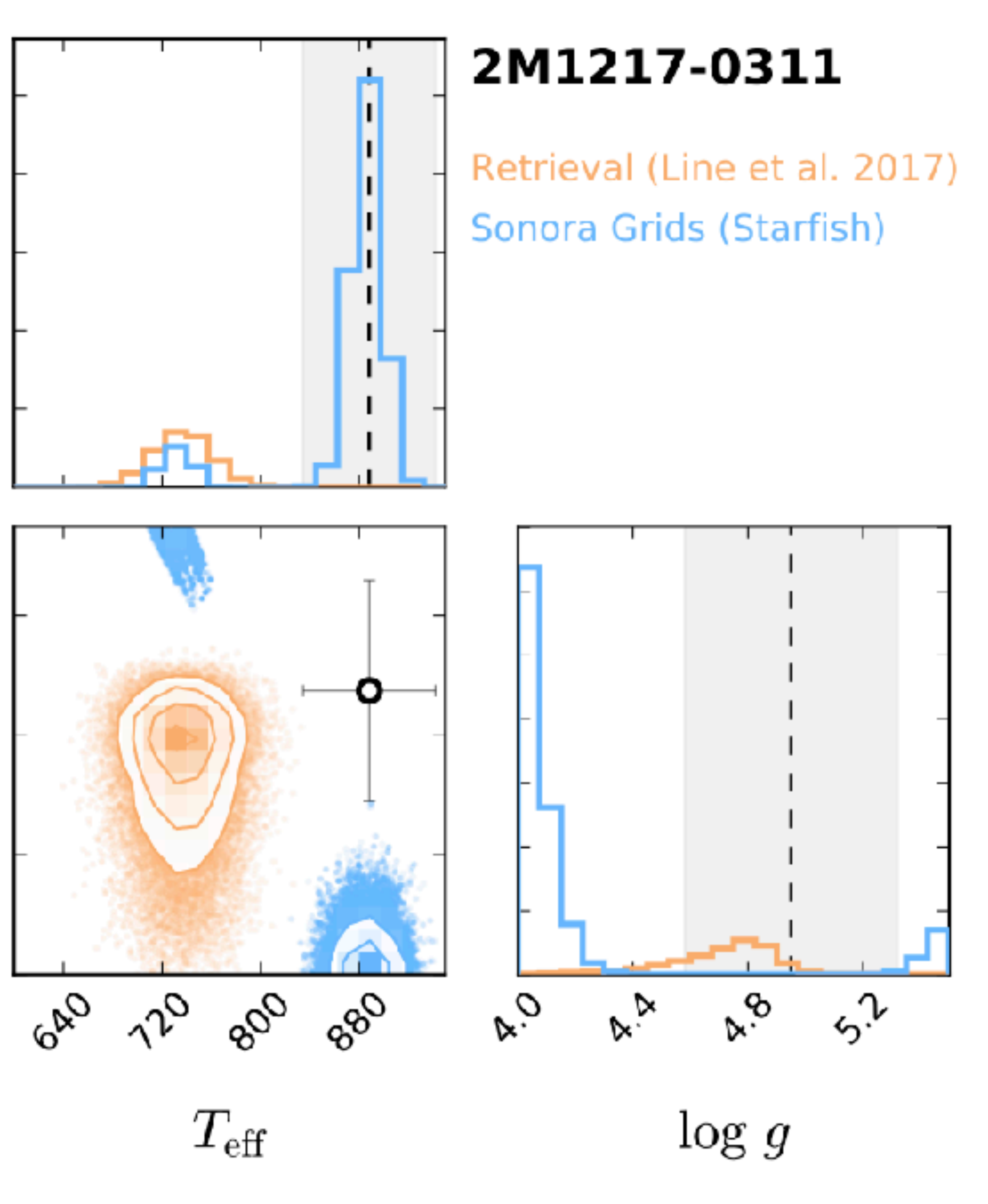




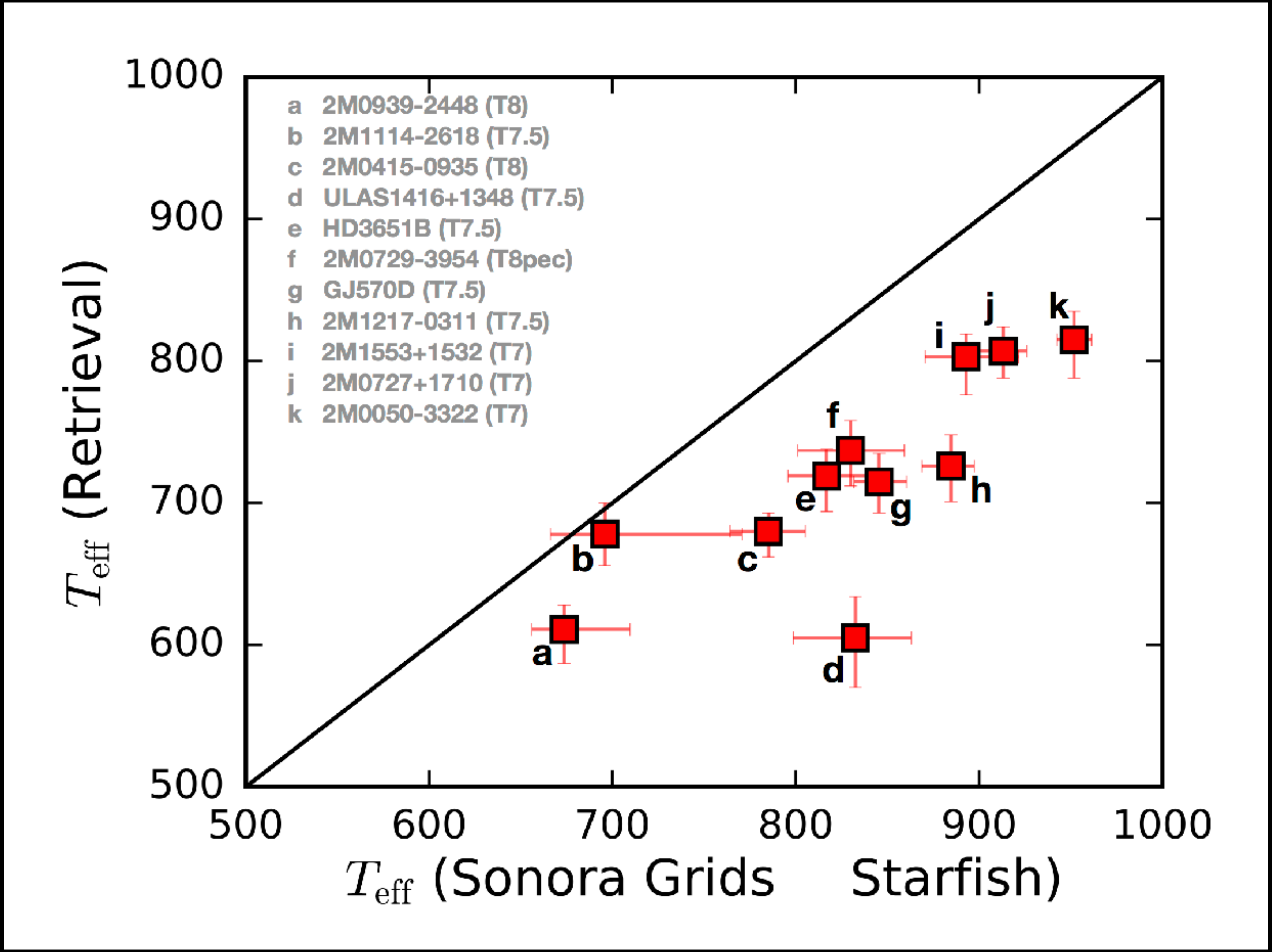
T8 (pec)

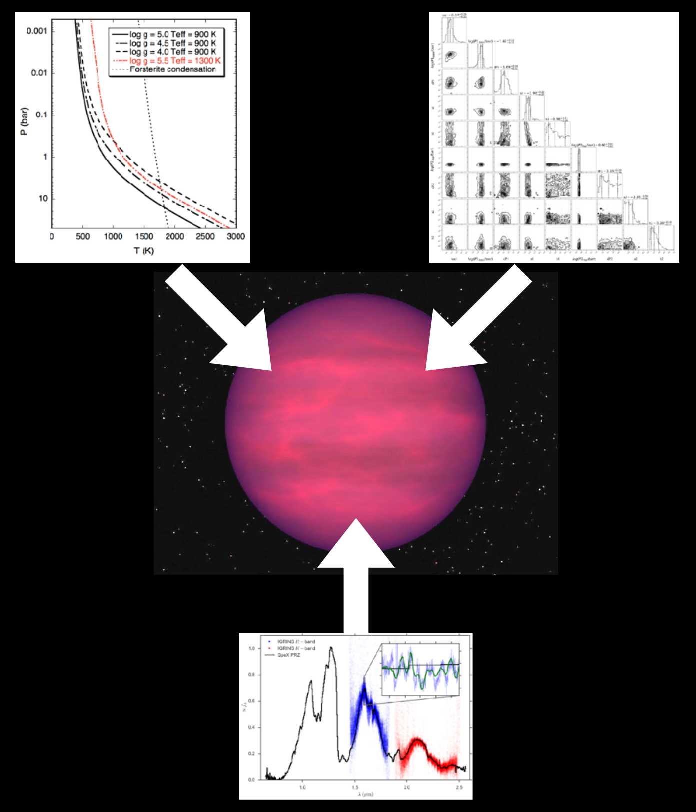
Others Do Not - Why?





T7.5



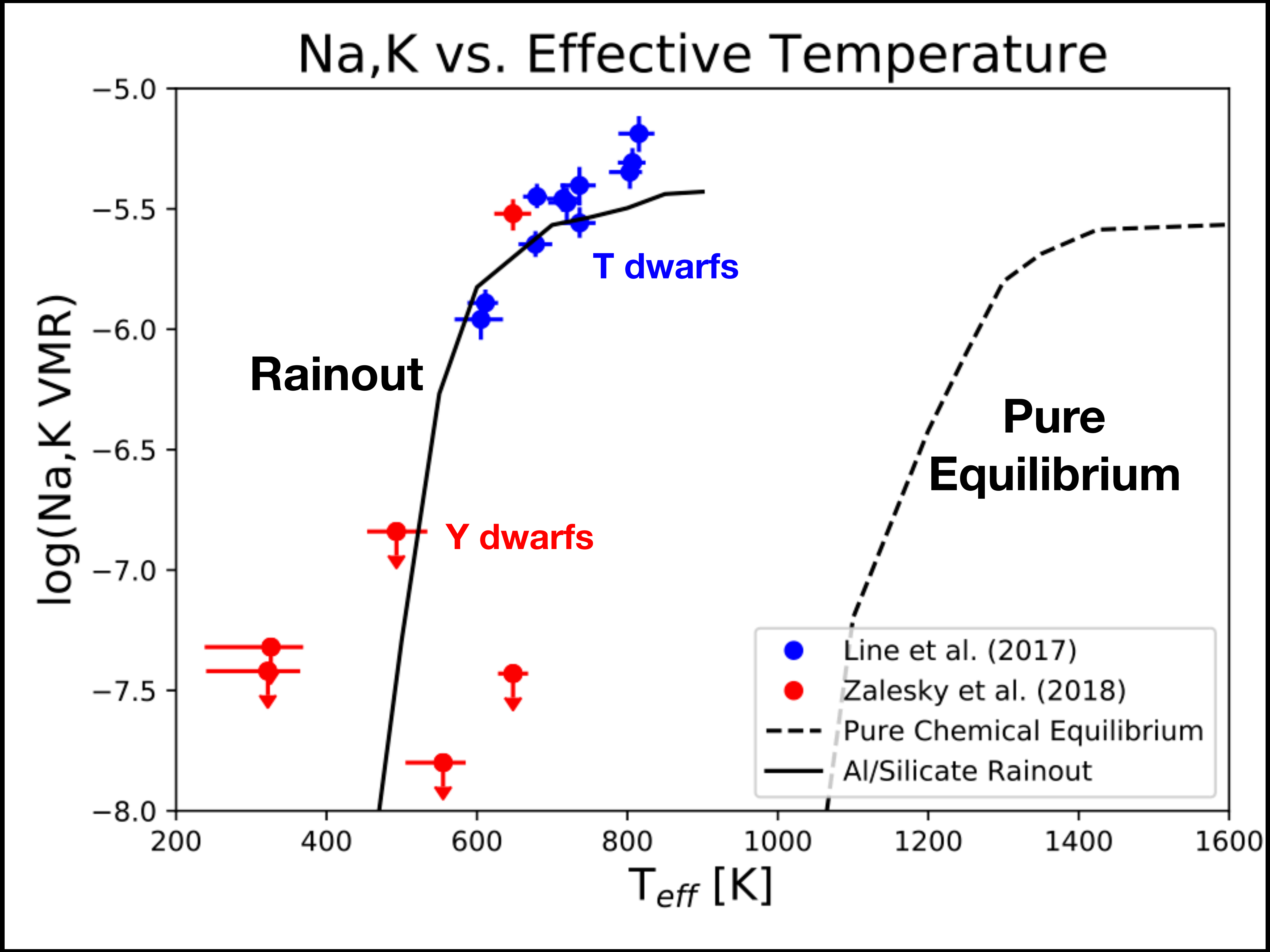


Why are grid models fitting higher T_{eff}?

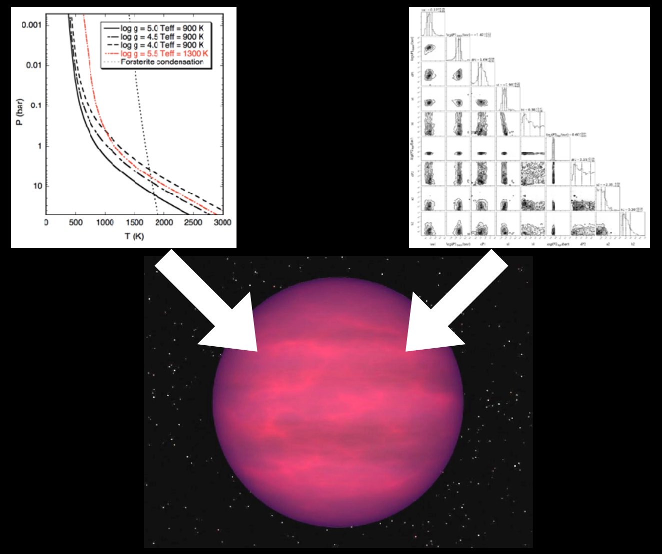
Unsolved

Theory Validation by Retrievals: Rainout
What Happens to Condensed Species?

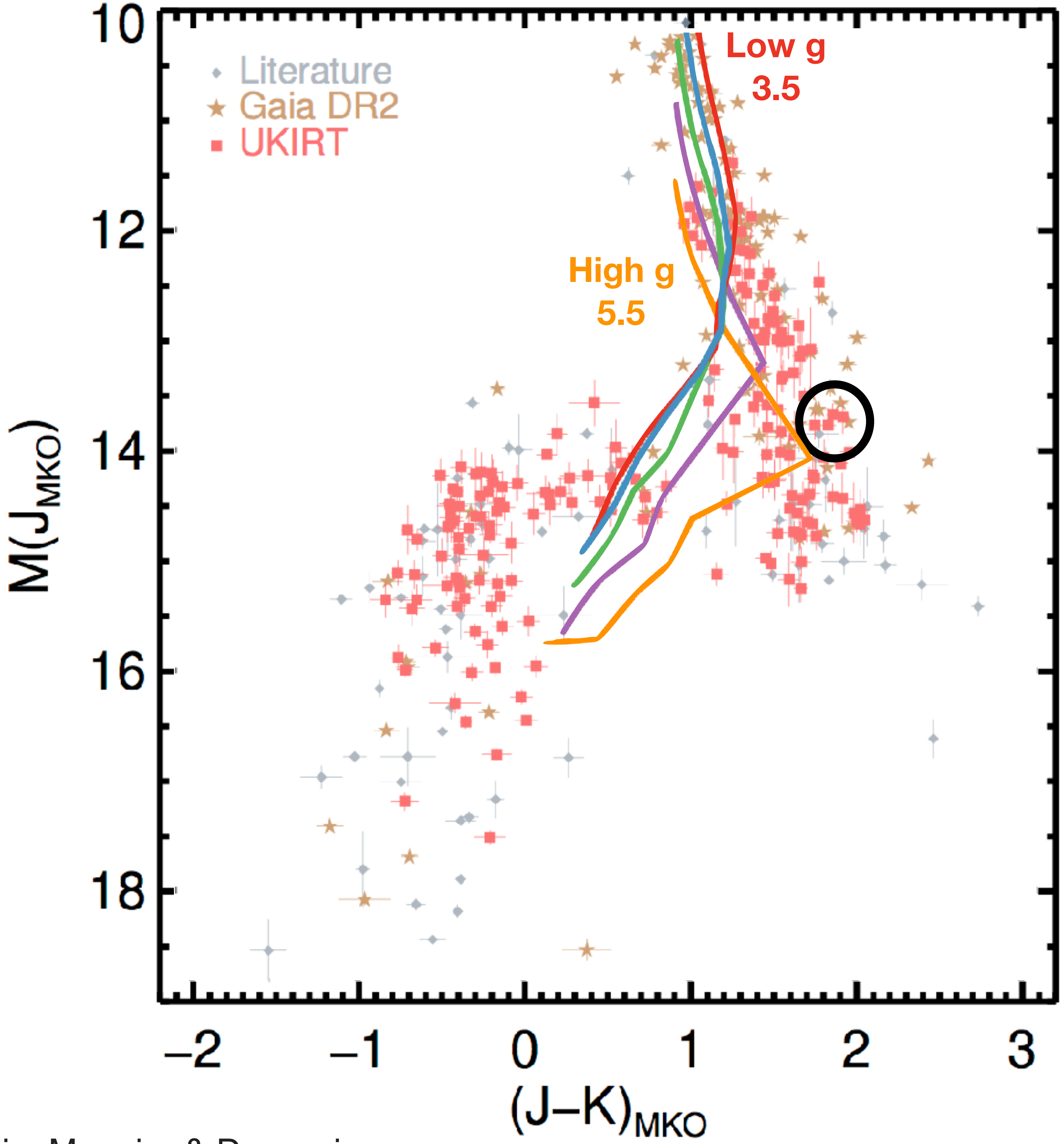
New work by
Joseph Zalesky



Don't use COND!



Clouds



Best, Liu, Magnier & Dupuy, in prep

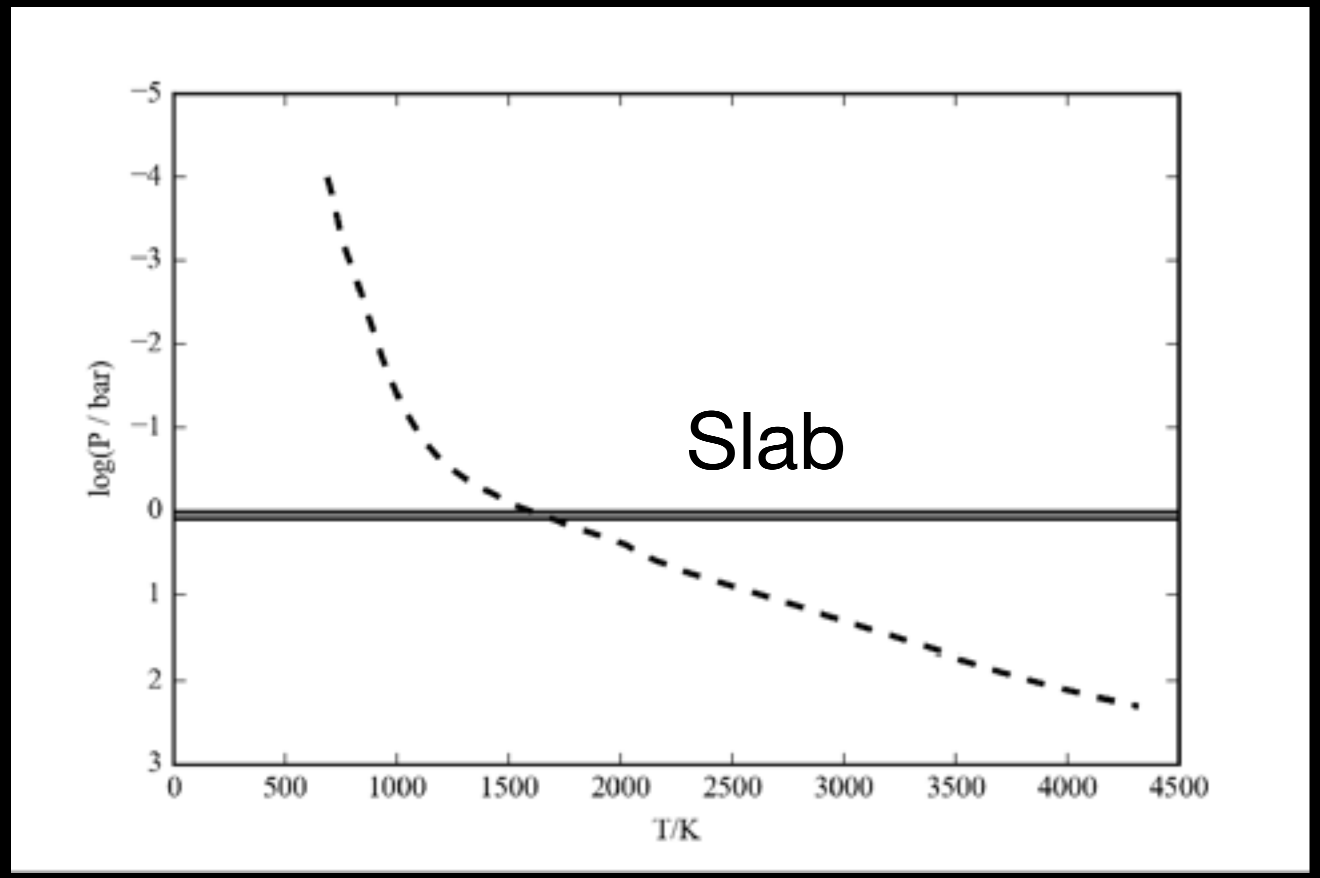
Solar [M/H]
f_{sed}=3

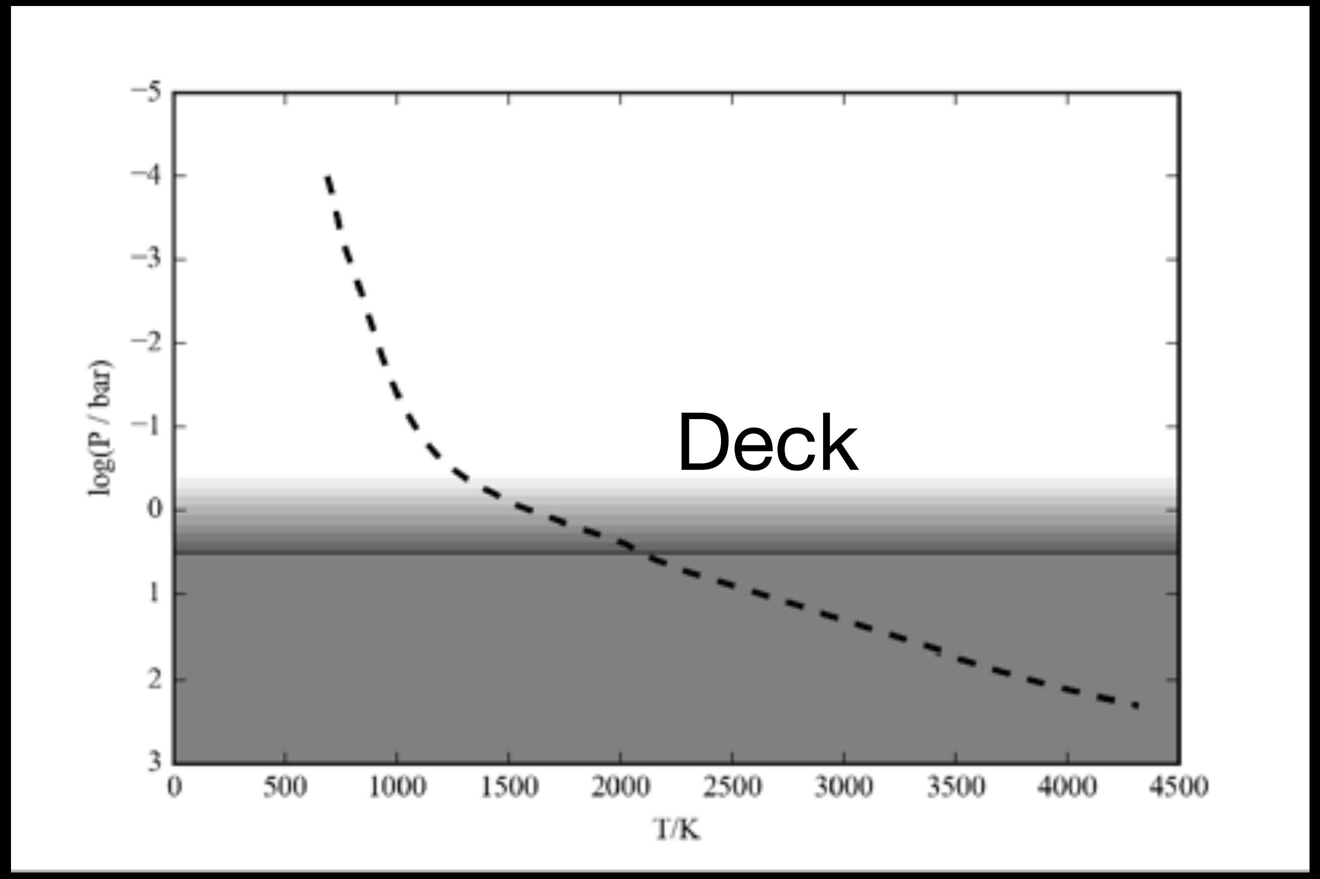
Clearly clouds still aren't right, but what specifically do models get wrong?

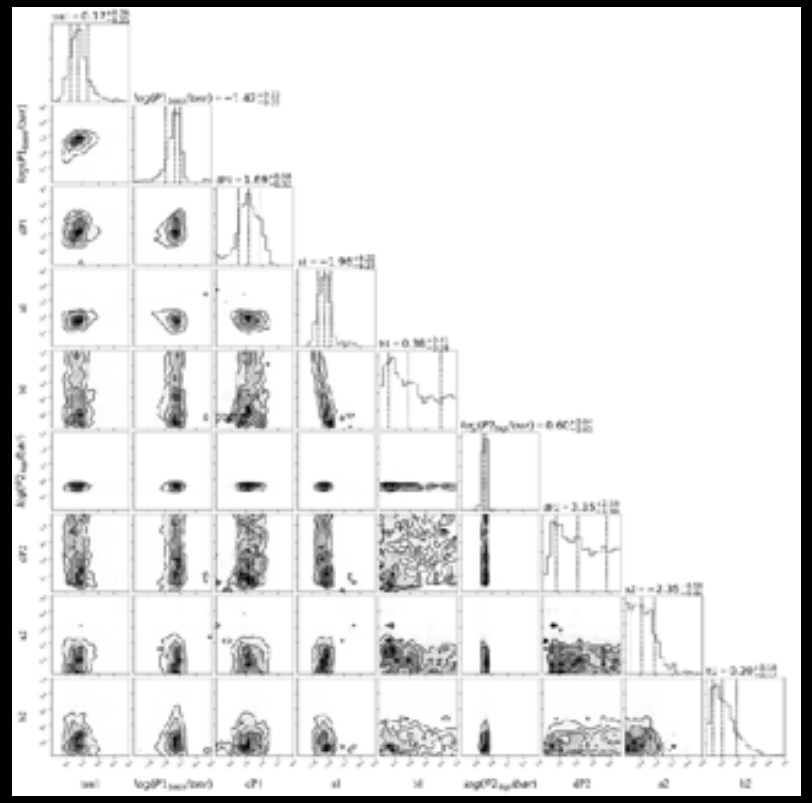
Complex set of interactions
T(P)
microphysics
dynamics
gravity
weather
…

Retrievals!

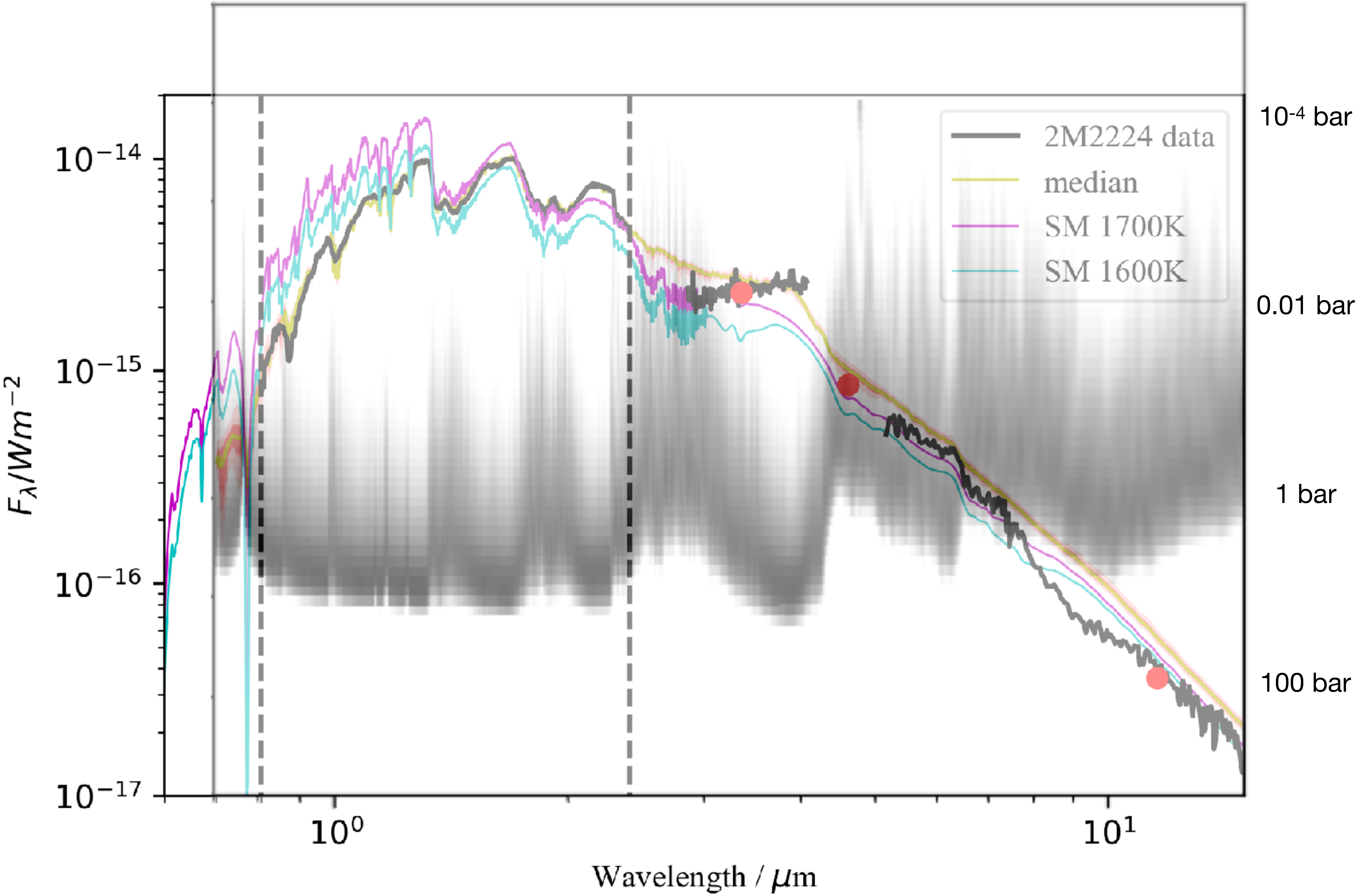
Brewster



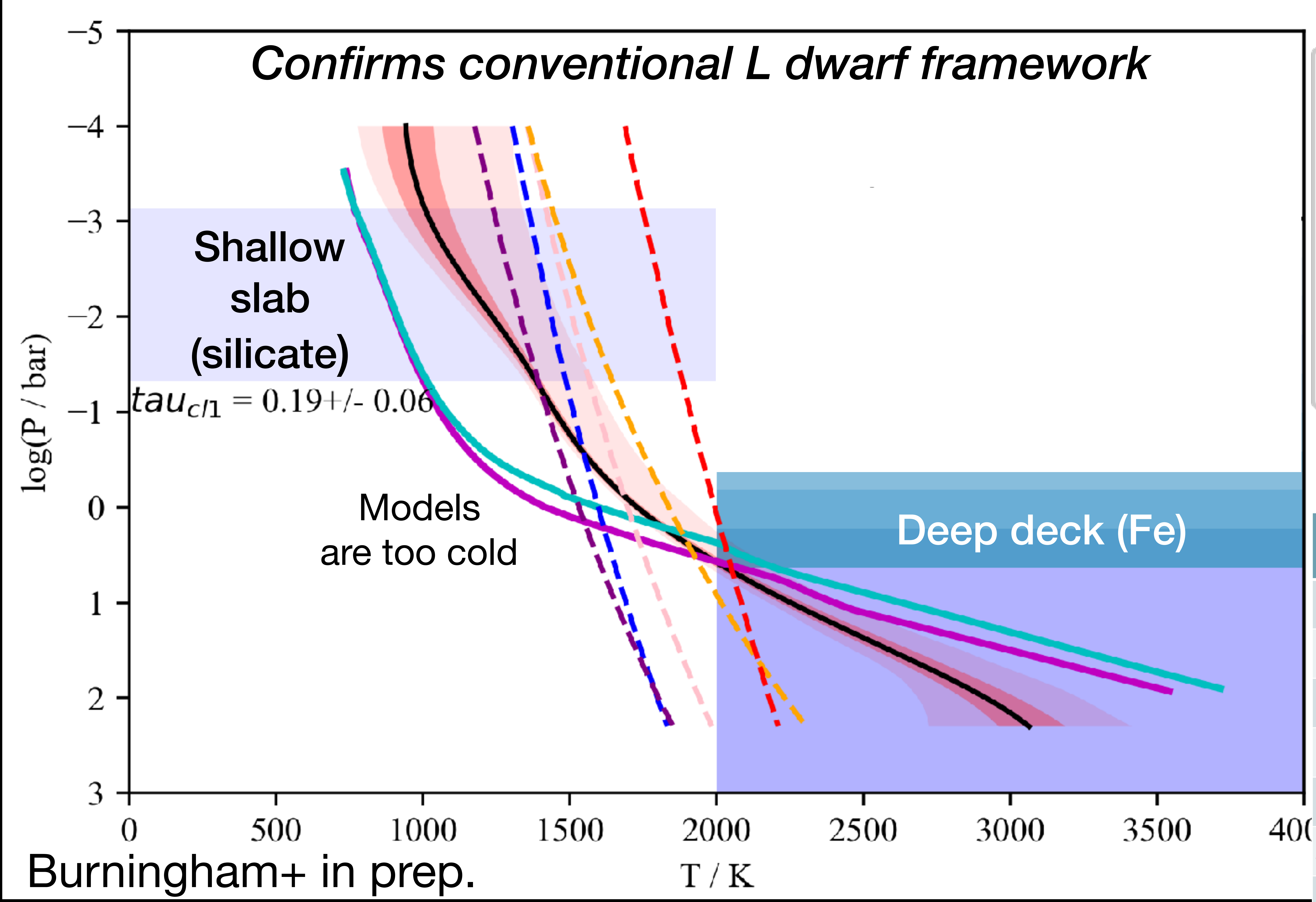


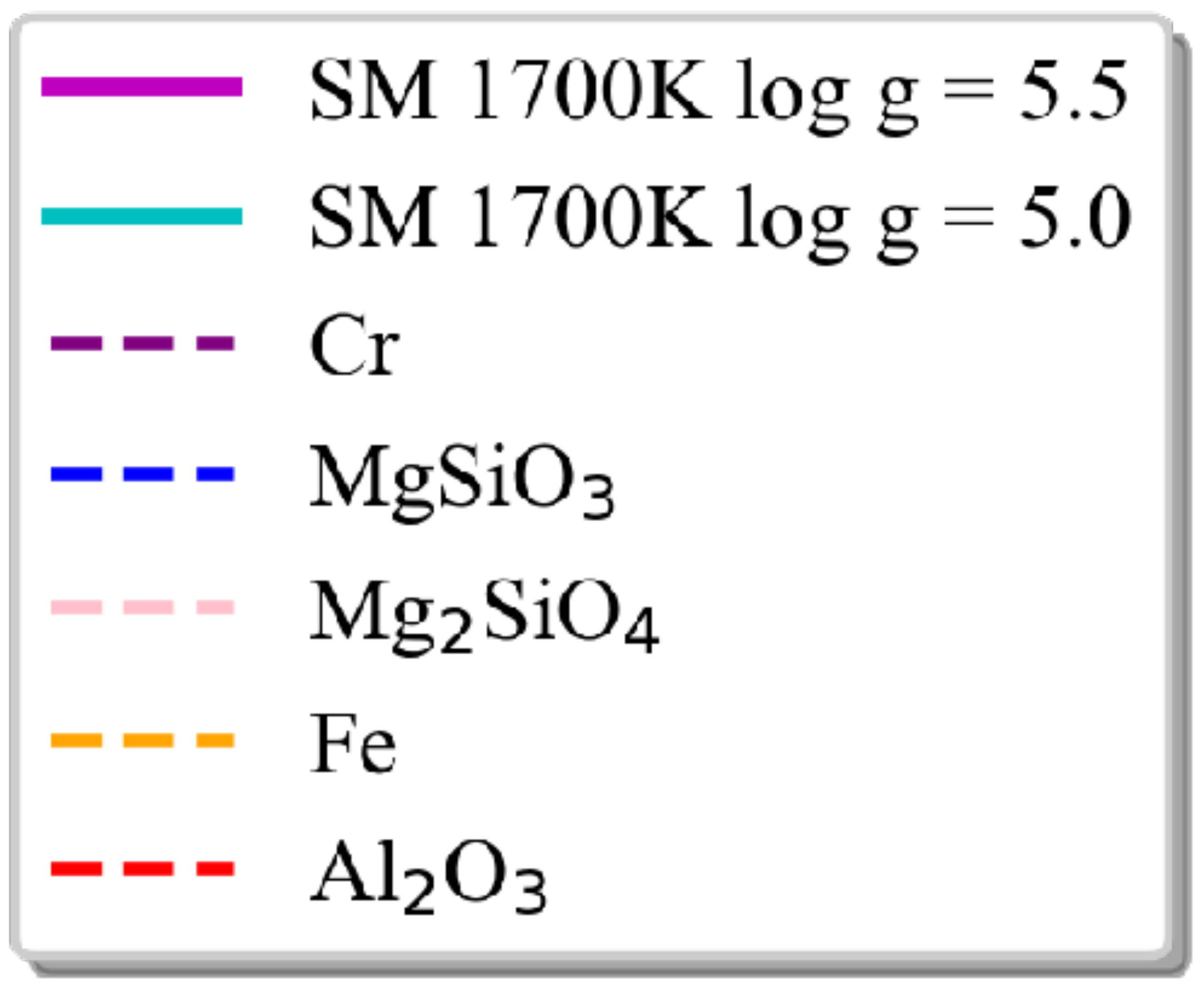


- See Burningham+ (2017) for details
- Uses EMCEE sampler (Foreman-Mackey 2013)
- It does clouds…various treatments available (grey, power law or Mie scattering)
  - various structures (e.g.deep deck, slab)
  - n clouds in n patches
- Flexible & simplified T-P profile options available

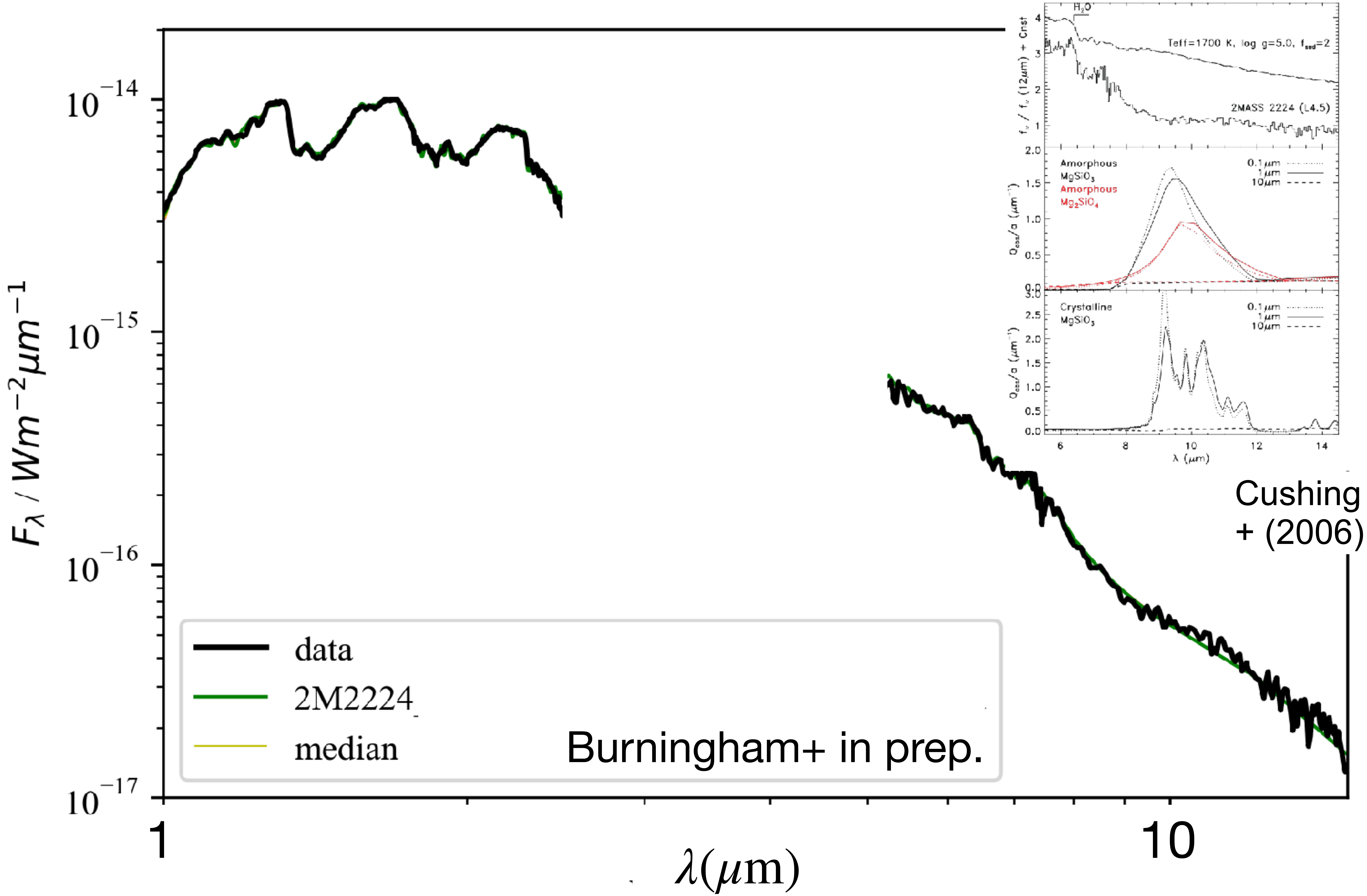


2M2224 data
median
SM 1700K
SM 1600K
10^{-14}
10^{-15}
10^{-16}
10^{-17}
F_λ/Wm^{-2}
10^0
10^1
Wavelength / μm
10^{-4} bar
0.01 bar
1 bar
100 bar

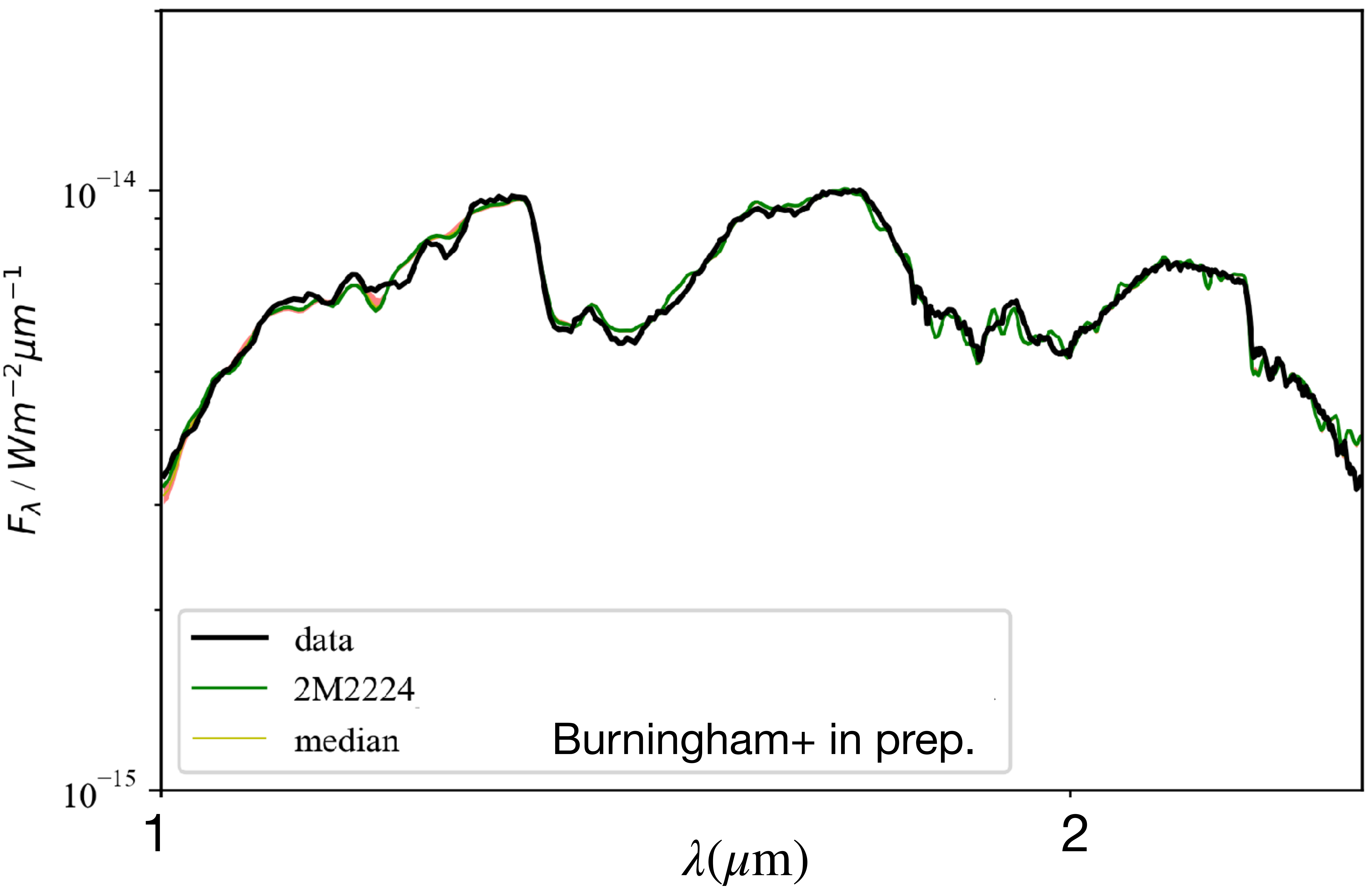




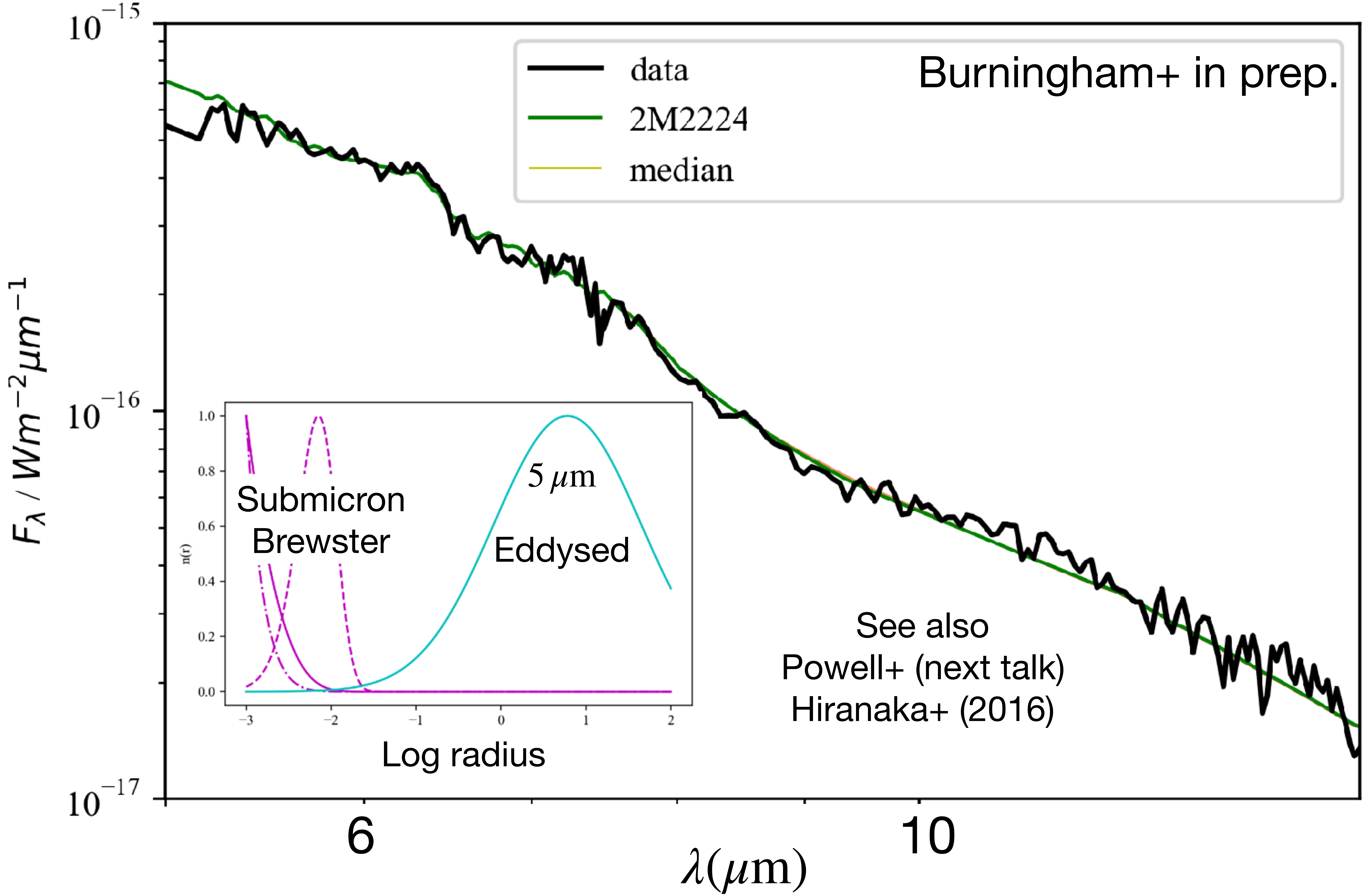
MODEL	ΔBIC
	2M2224
NC	559
NC_CE	661
DECK	134
DECK_CE	171
SLAB	314
SLAB_CE	180
SLAB+DECK	0



F_λ / $Wm^{-2}\mu m^{-1}$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
1
10
$\lambda(\mu m)$
data
2M2224
median
Burningham+ in prep.
H_2O
Teff=1700 K, log g=5.0, f_{sed}=2
2MASS 2224 (L4.5)
Amorphous
$MgSiO_3$
Amorphous
Mg_2SiO_4
Crystalline
$MgSiO_3$
0.1 μm
1 μm
10 μm
λ (μm)
Cushing + (2006)



10^{-14}
10^{-15}
F_λ / $Wm^{-2}\mu m^{-1}$
1
2
$\lambda(\mu m)$
data
2M2224
median
Burningham+ in prep.



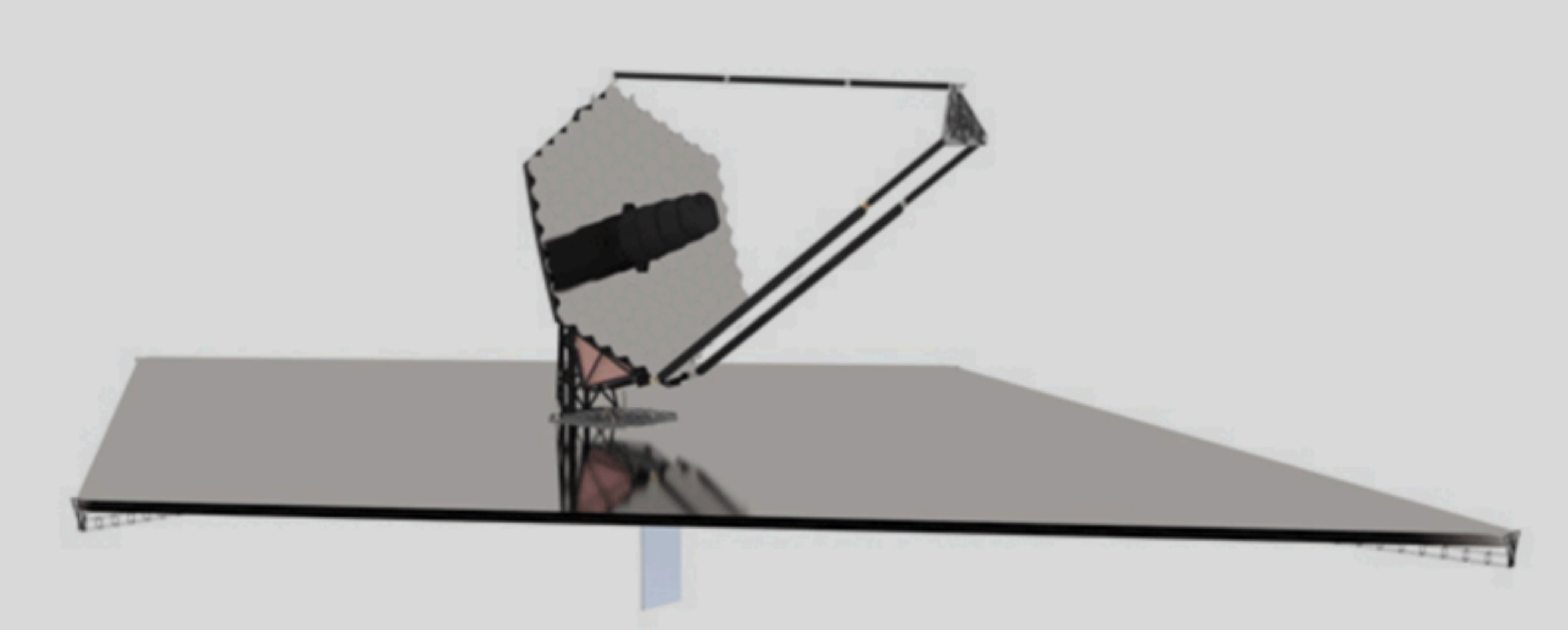
10^{-15}
10^{-16}
10^{-17}
F_λ / $Wm^{-2}\mu m^{-1}$
data
2M2224
median
Burningham+ in prep.
1.0
0.8
0.6
0.4
0.2
0.0
n(r)
Submicron
Brewster
$5\,\mu$m
Eddysed
−3
−2
−1
0
1
2
Log radius
See also
Powell+ (next talk)
Hiranaka+ (2016)
6
10
$\lambda(\mu m)$

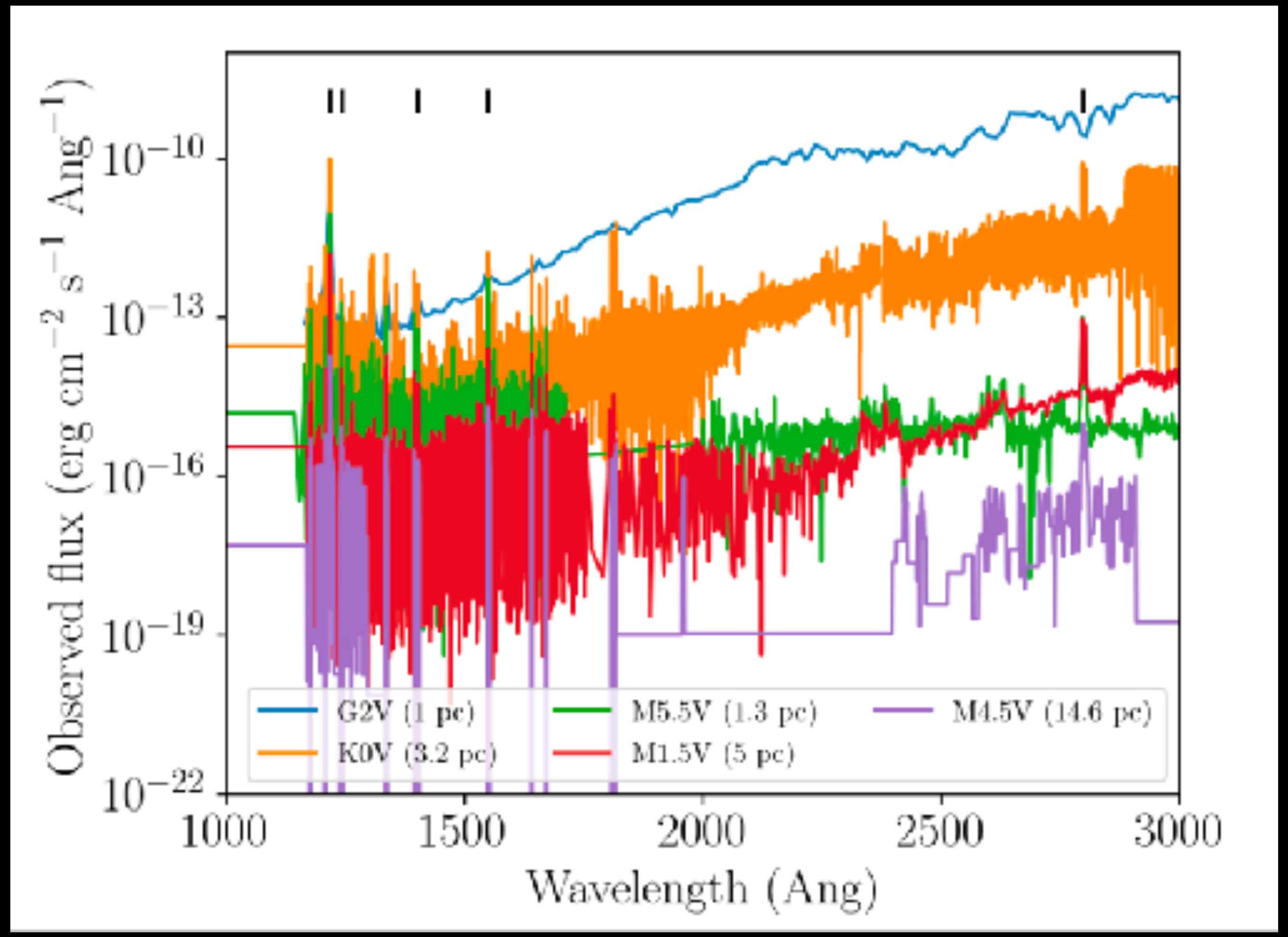
Some of the Remaining Issues

- Exactly how does rainout chemistry work?
- Clouds in 3D (vertical & horizontal structure)
  - Forward models
  - Retrievals
- Low *g* sequence
- L to T transition
- Na, K opacities
- Disequilibrium chemistry details
- How best to incorporate both low and high *R*?
- Variability
- Directly imaged planets (posters!)

LUVOIR

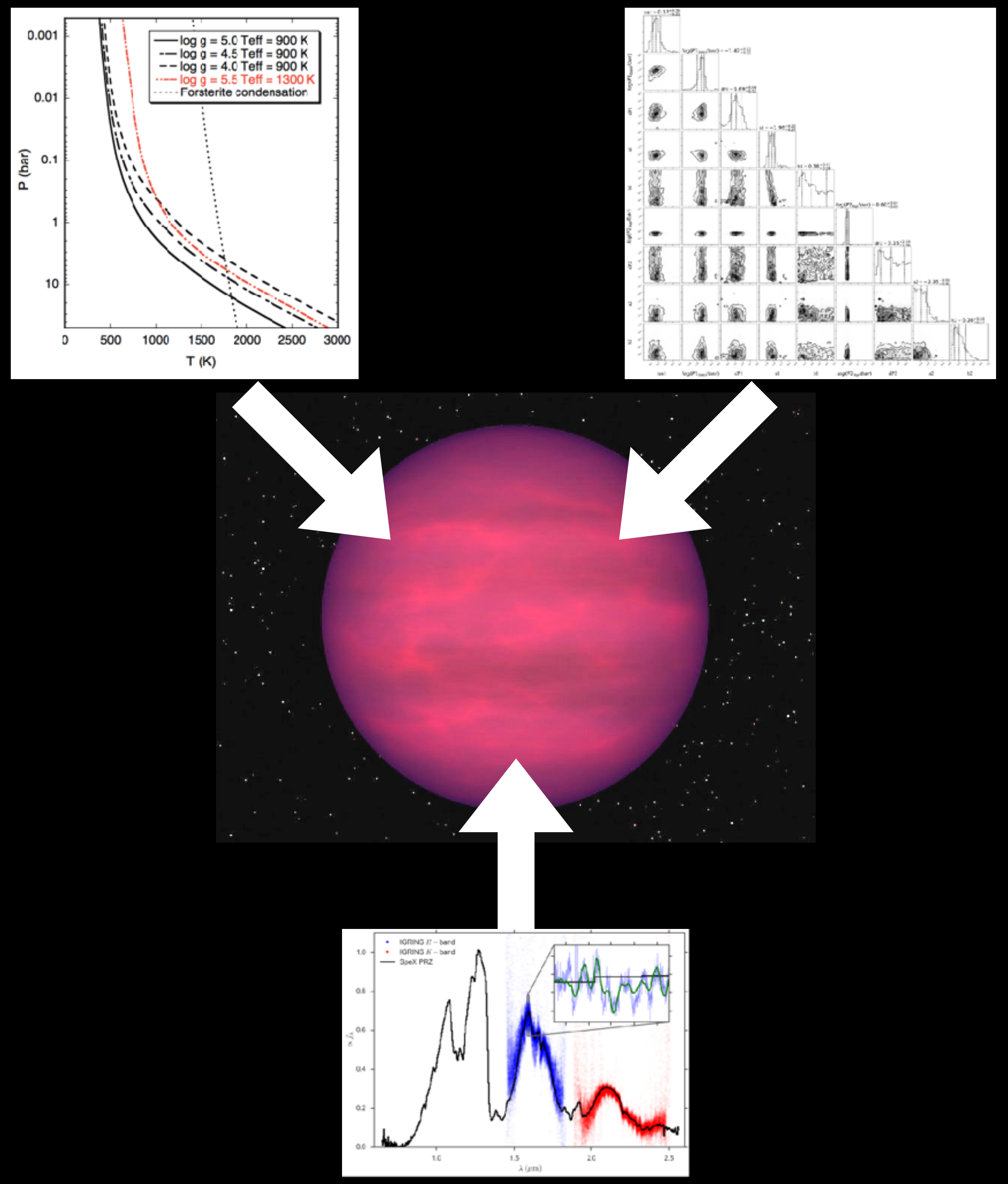
- R~30,000 1000 to 3000 A spectra, S/N > 10
- 5 hour integration time
  - FUV_{GALEX} = 23 mag (9-m)
  - FUV_{GALEX} = 25 mag (15-m
  - M2 V GJ 832 at d = 5 pc is FUV_{GALEX} = 21
- Time tagging photos so distinguish flares





Conclusions

- Brown dwarfs are uniquely challenging to model
    - Clouds, chemistry, atmospheric dynamics
    - Need new generation of microphysical models
- New models making progress
    - Early L, T’s colors and spectra
    - HBMM, but need to confront data still
- Multi-faceted approach still required to understand
- Download our grid & compare w/others



https://tinyurl.com/Sonora-nc