Irradiated Atmospheres from the Spitzer Exoplanet ToO Program as of September 2010

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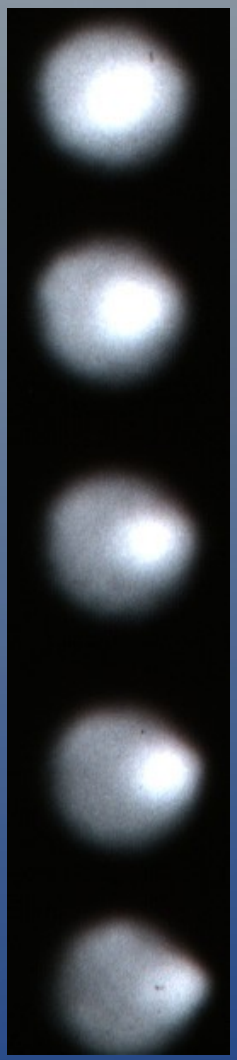
Atmospheres and Astrophysics

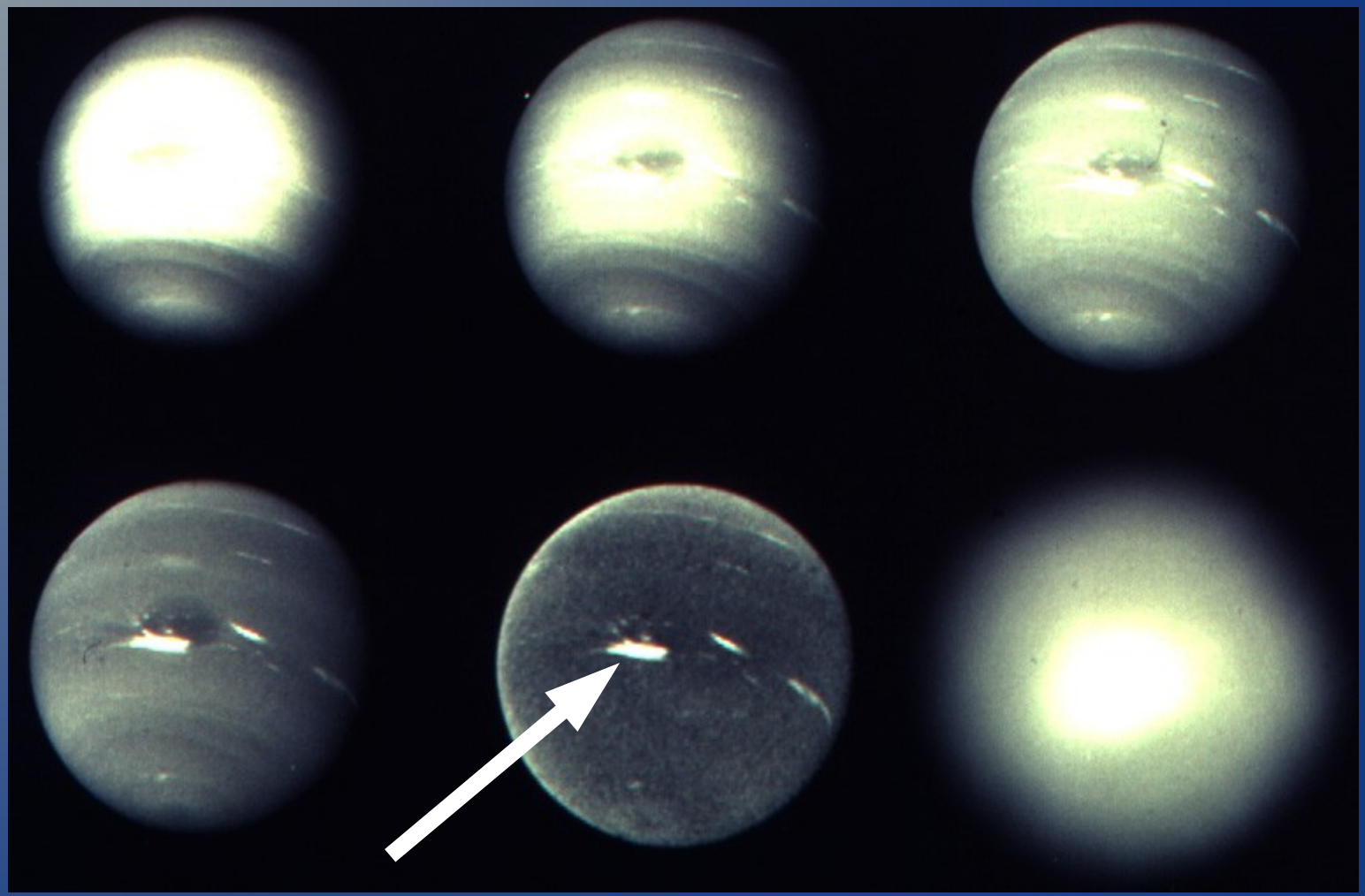
- Exoplanets is a field combining planetary science and astrophysics observation
- People want to affiliate with just one community
- Result: Everyone is “green” about something!
  - “Stars” people believe in planetary HR diagram
  - “Planets” people think stars are blackbodies
- Unification efforts started pre-2007 DPS
- Workshops like this are crucial – and too rare!
- Go to the *other* kind of conference – AAS, DPS
- Commit to formal learning – stars, planets, stats

Phase-Curve Note: Neptune 1989

UH 2.2m

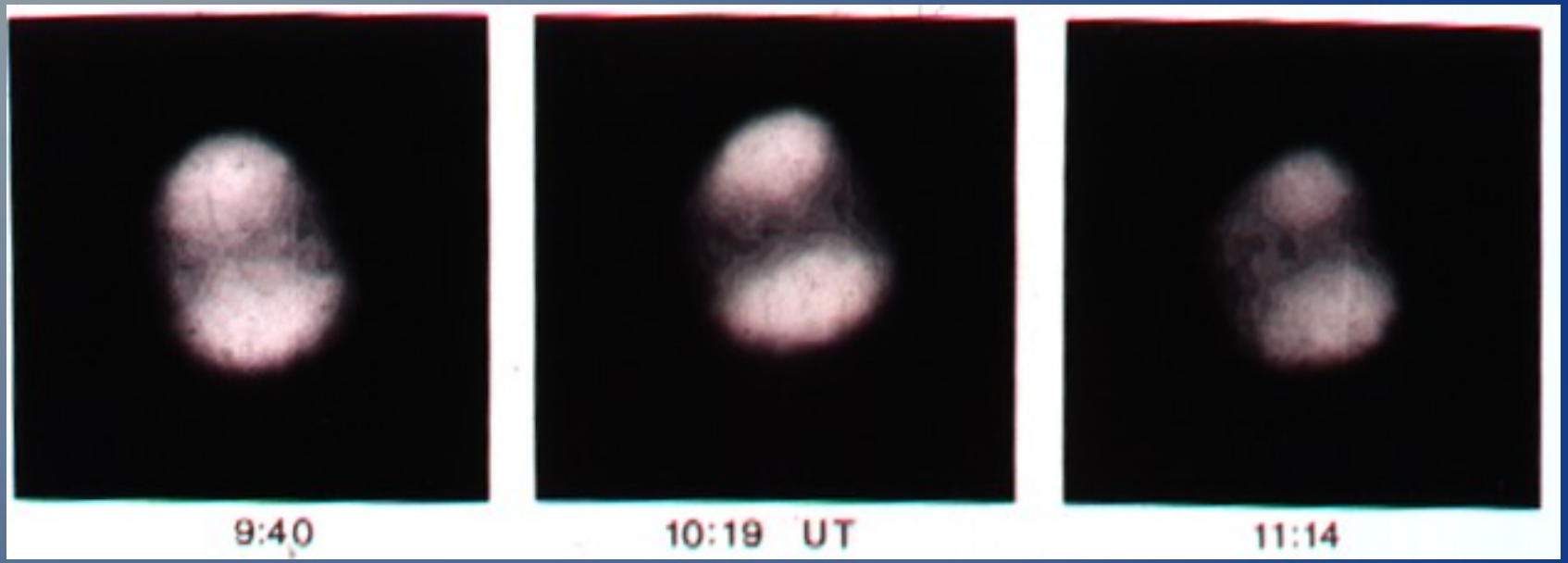


890 nm



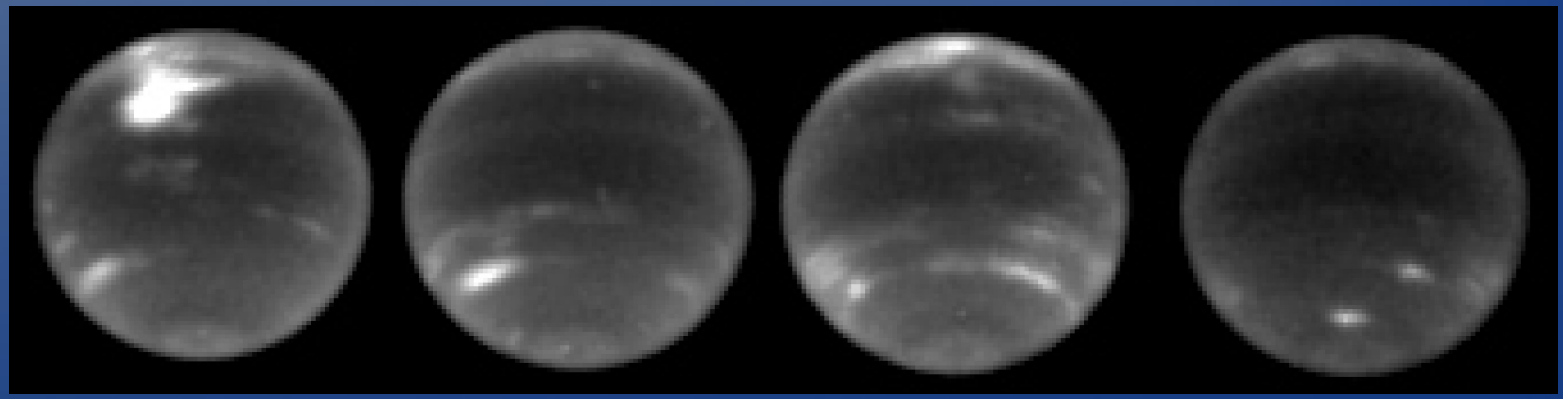
Large phase-curve amplitude due to tiny feature transiting disk.
Hammel et al. (1992), *Icarus*

Neptune Variability



1979

1989



1994 1997 2002 2004

Spitzer Exoplanet ToO Program

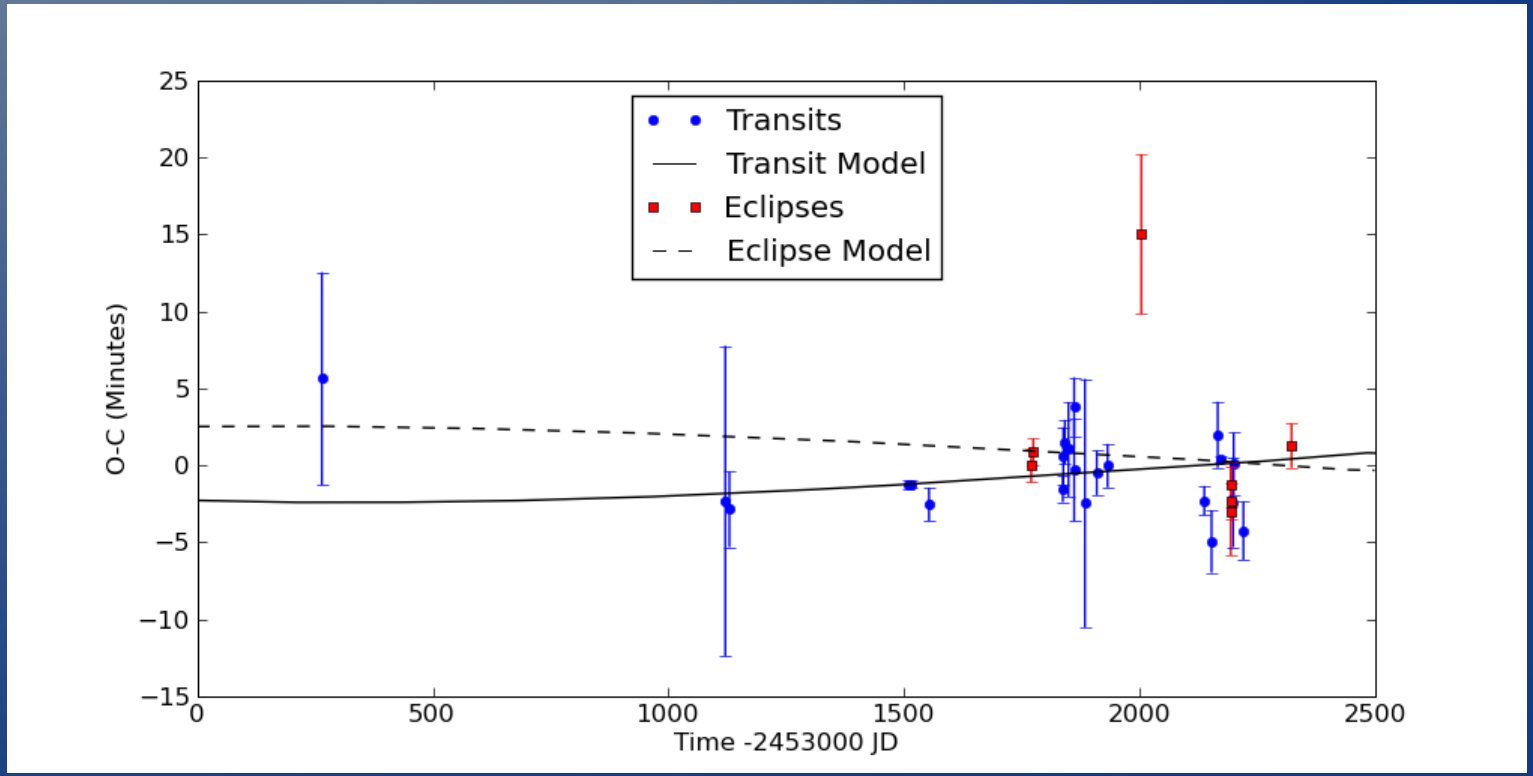
- Secondary eclipses of new exoplanets
- Target of Opportunity (ToO): obs in 2-8 months
- Data open to facilitate fast follow-up studies
- WE COLLABORATE WITH EVERYONE!
- Not ∞ time – S/N & “interestingness” criteria
- Optimize: observations, photometry, systematics modeling, light curve production
- Very careful about believing results
- ~8 papers in 2010

New in the Past Year

- TrES-2 – inverted or not?
- HAT-P-1b – modest inversion
- GJ 436b – all 6 Spitzer channels! Low CH_4??
- υ And b – new phase curve
- WASP-12b – orbit circular (stay tuned for atm.)
- WASP-18b – hot, nearest to a BB, phase curve
- WASP-14b – new result, new intrapixel method
- WASP-17b – (new result)
- HD 209458b – “new” eclipse in “ch5” (IRS blue)
- Orbits – eccentricity, periastron longitude, etc.

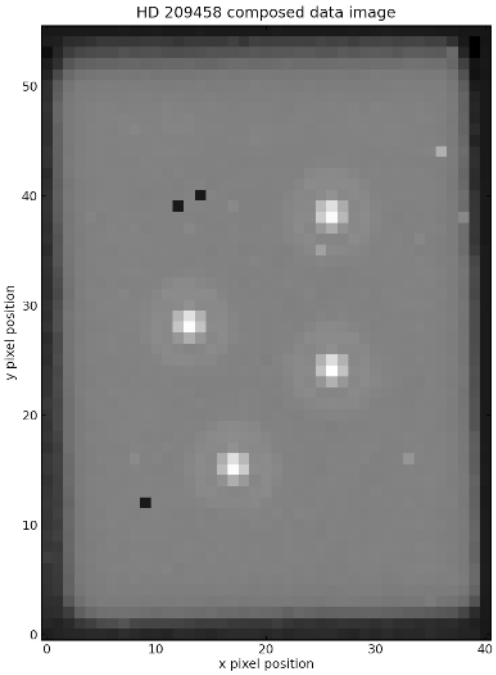
Orbit Dynamics – Ryan Hardy

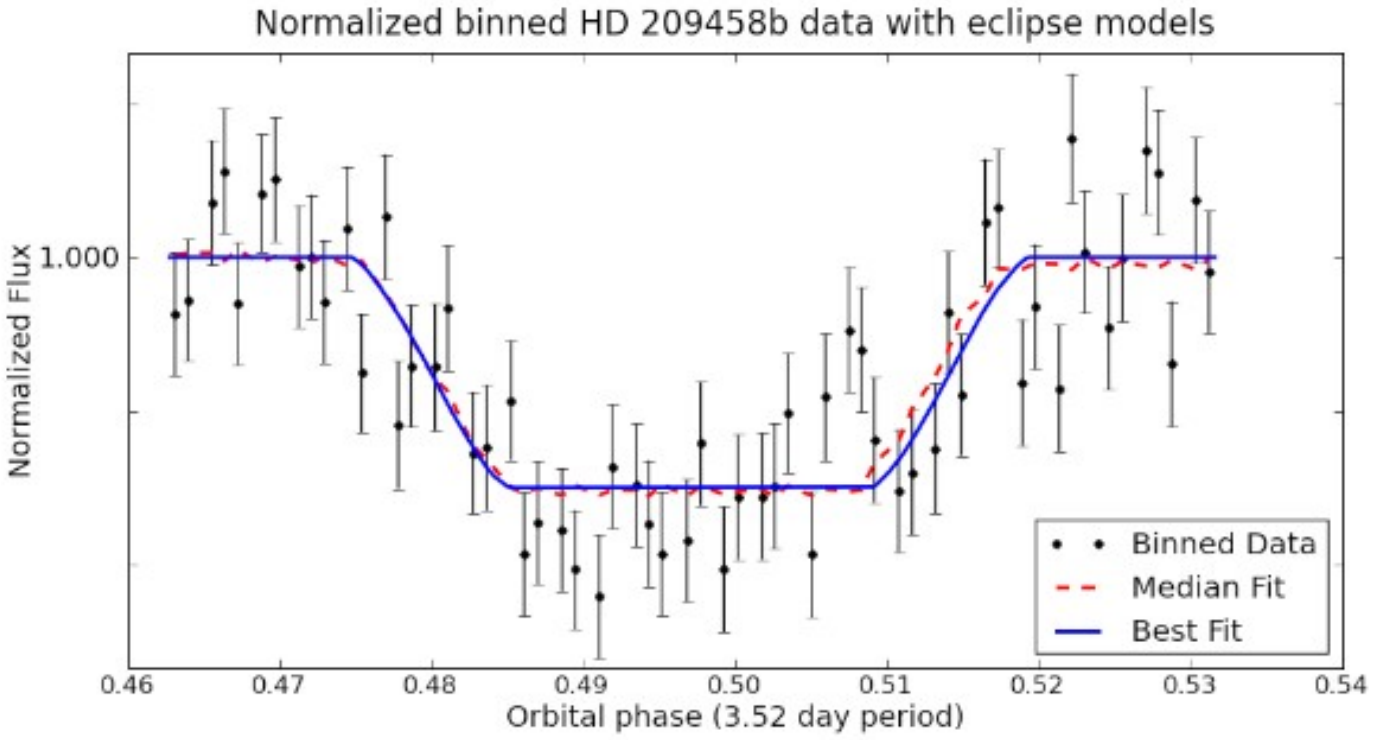
- Secondary eclipse timing constrains $e \cos \omega$
- Include also RV, transit times (pro + amateur)
- MCMC explores orbit model parameter space
- WASP-12b, 14b, 18b, GJ 436b, HAT-P-13b



HD 209458b – Patricio Cubillos

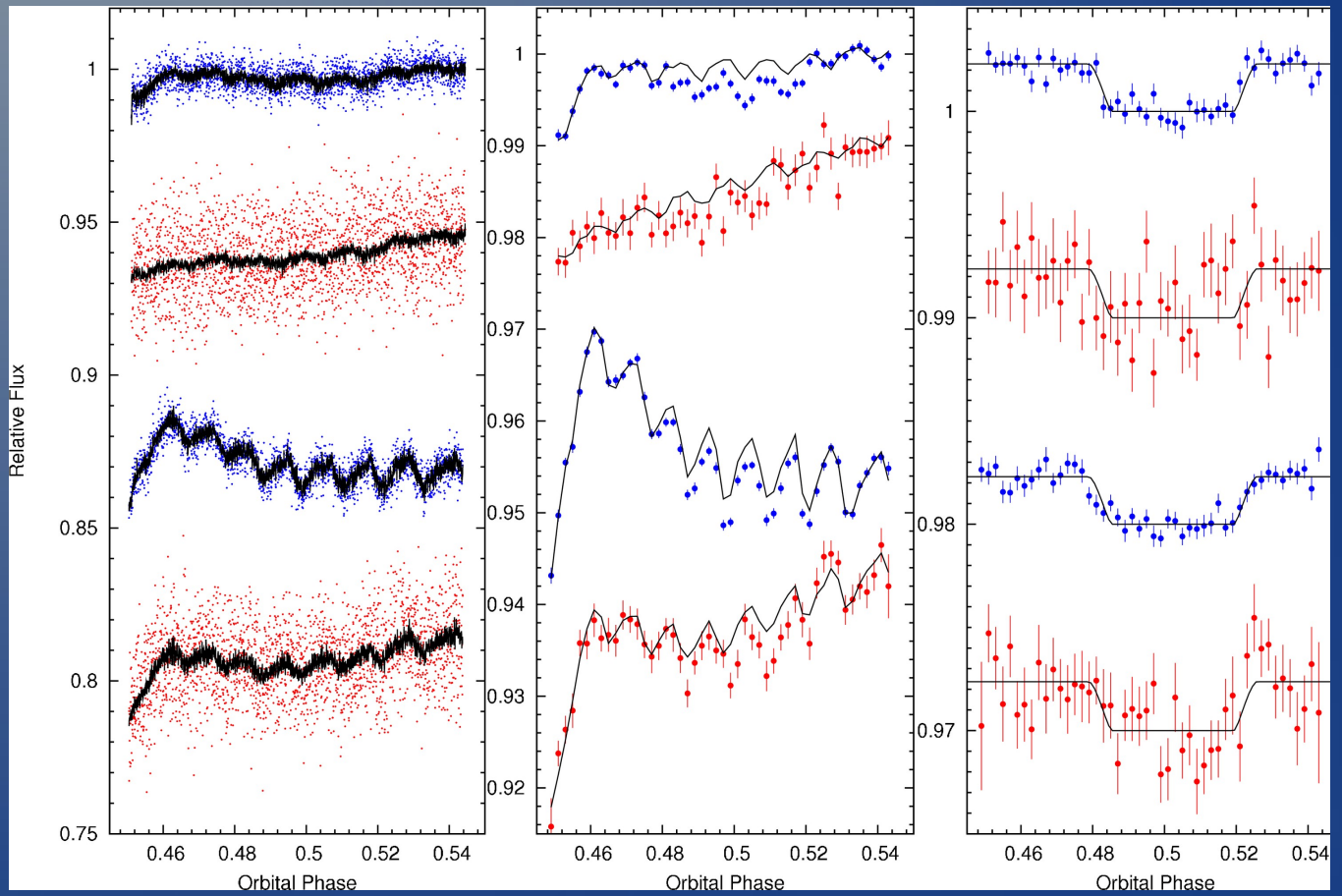
- IRS Blue Peak-up Array (“ch5”)
- 4 positions, 1 bad (hot pixel)
- Fills in between MIPS and IRAC
- Still refining photometric analysis





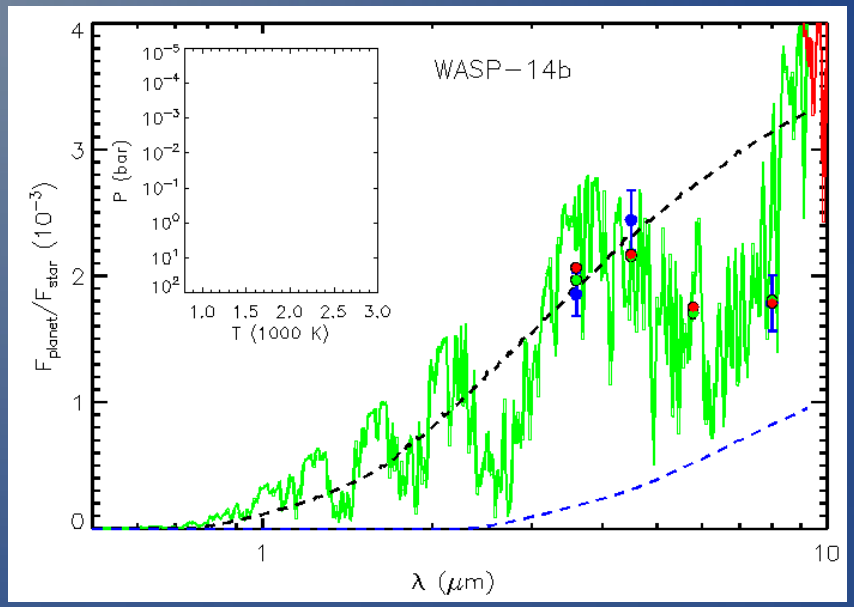
WASP-17b – D Anderson & A Smith

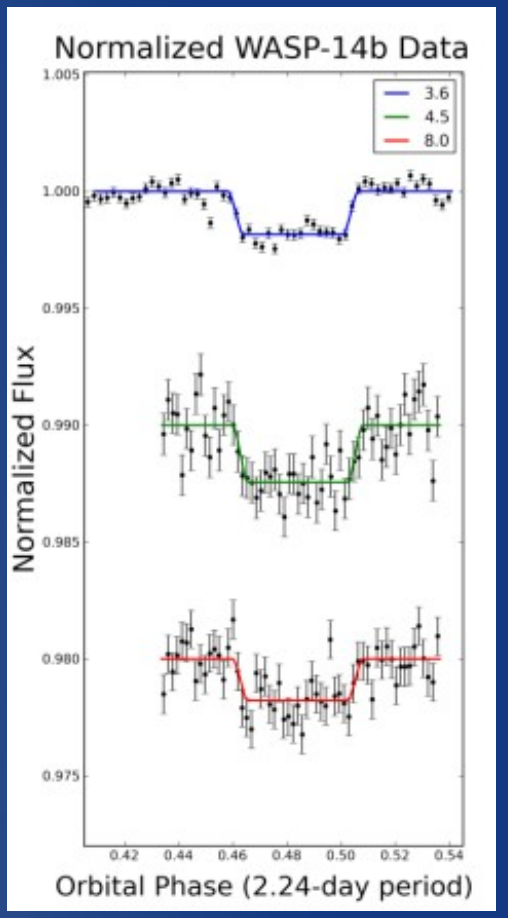
- Eclipses in 4 IRAC channels
- Atmospheric modeling in process

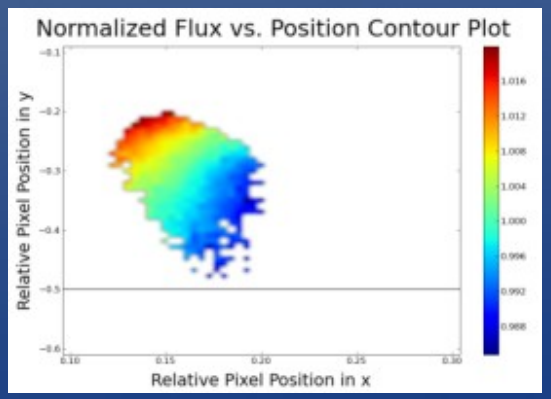


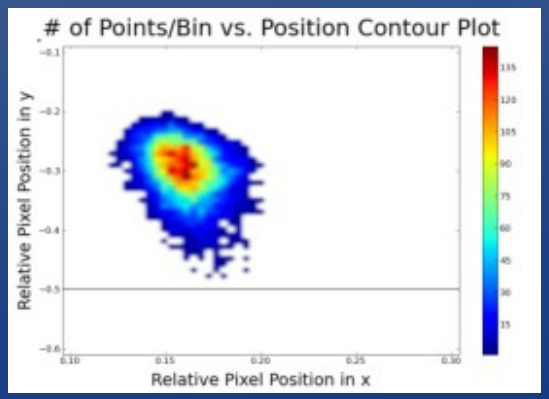
WASP-14b – Jasmina Blecic

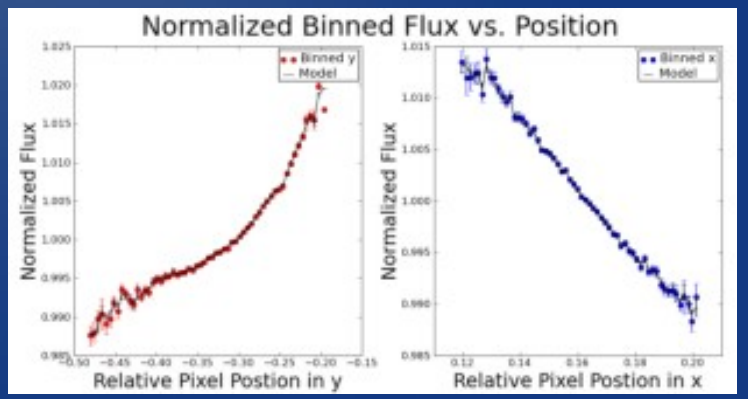
- IRAC 3.6, 4.5, 8 μm
- New pixel-map method
- Not BB!
- See poster





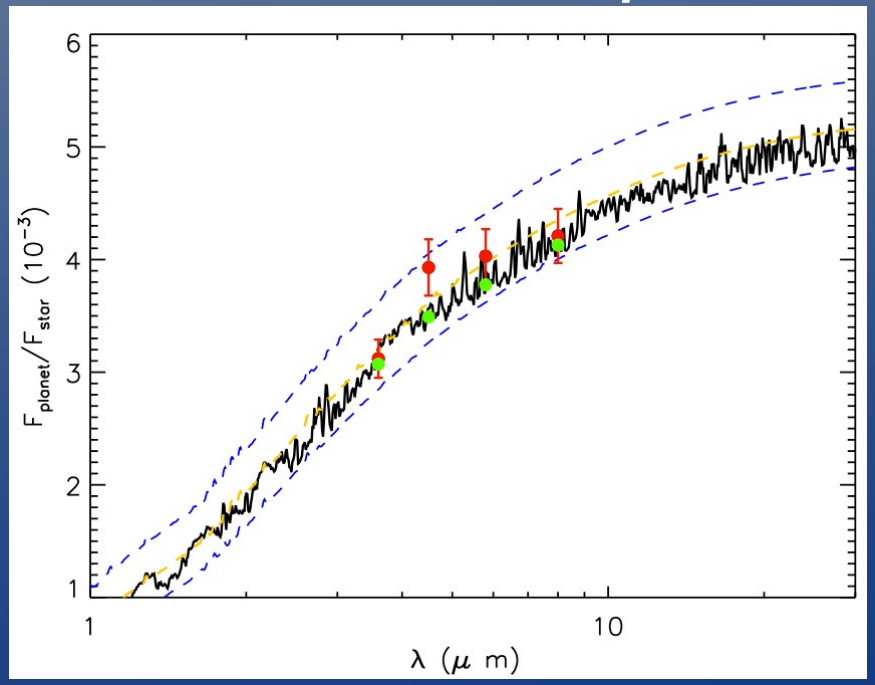


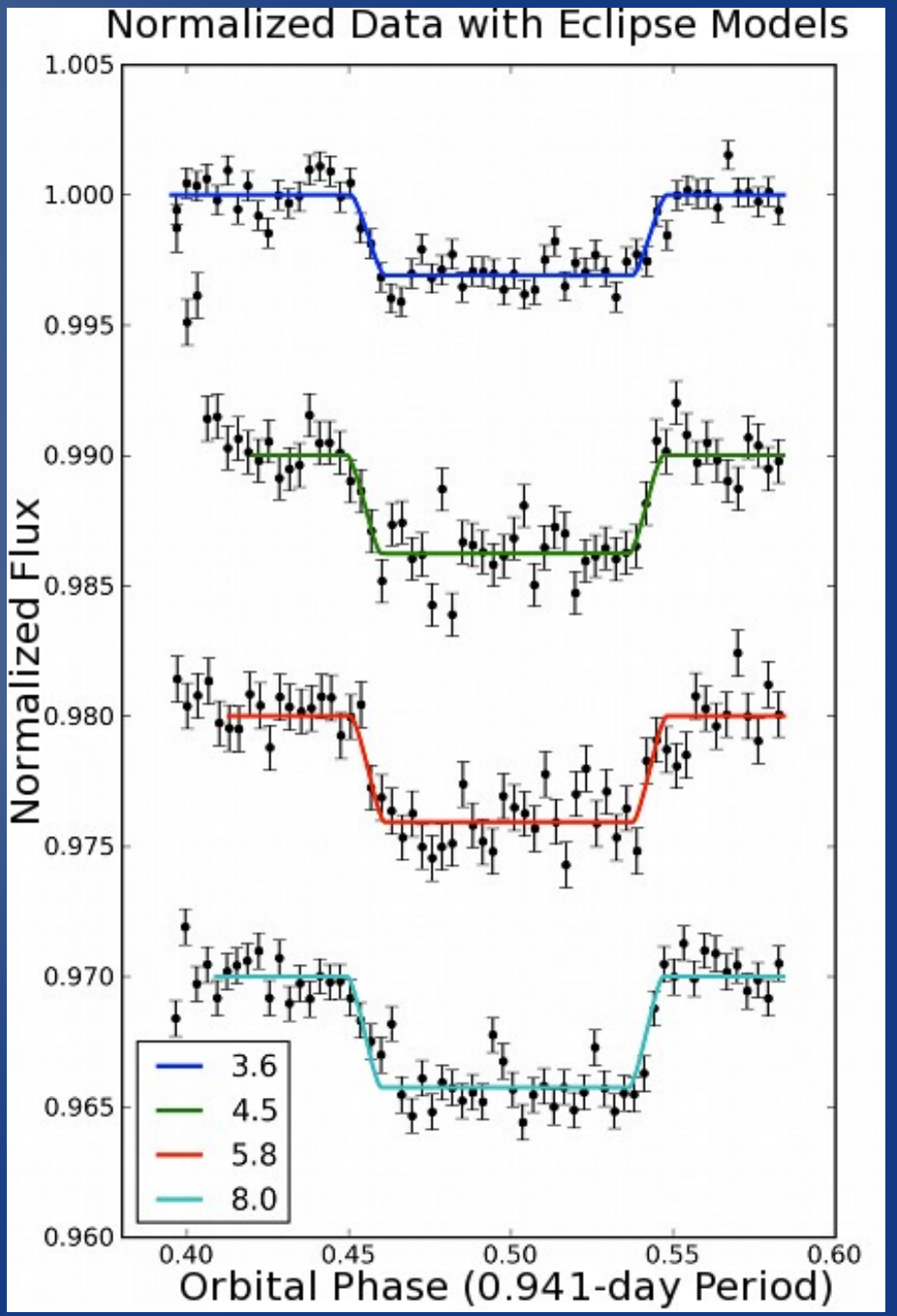




WASP-18b – Nymeyer, Maxted

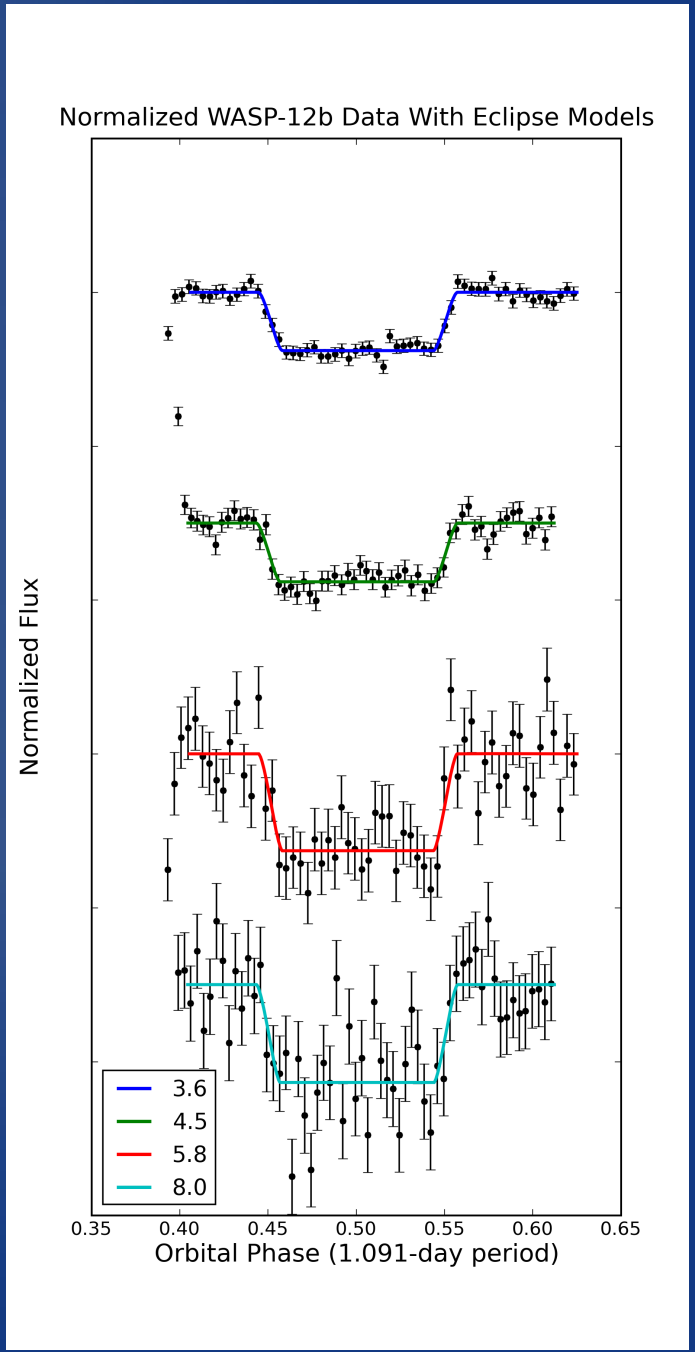
- 4 IRAC eclipses, 2 orbits
- ~3000 K, BB-like
- *A*~0, low day-night redist.
- Inversion suggested
- Submitted to *ApJ*





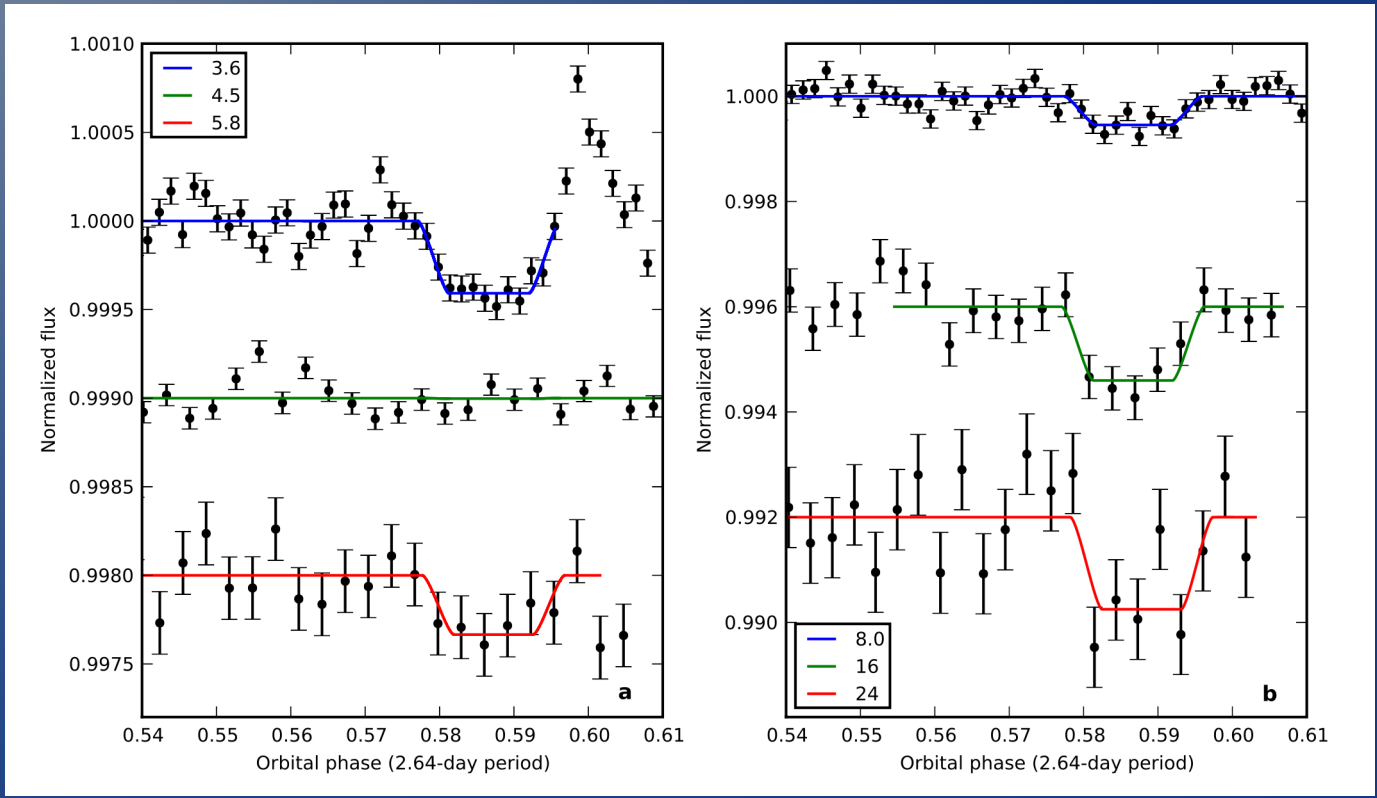
WASP-12b – Christopher Campo

- 4 IRAC eclipses + 2 reshoots
- Highest S/N of all our datasets!
- Campo et al. submitted to *ApJ*:
  - Orbit likely circular
- Madhusudhan et al. submitted
  - Atmospheric analysis
- Hardy et al. in prep. (re-shoot)
  - Circular orbit, no precession
  - Consistent depths



GJ 436b

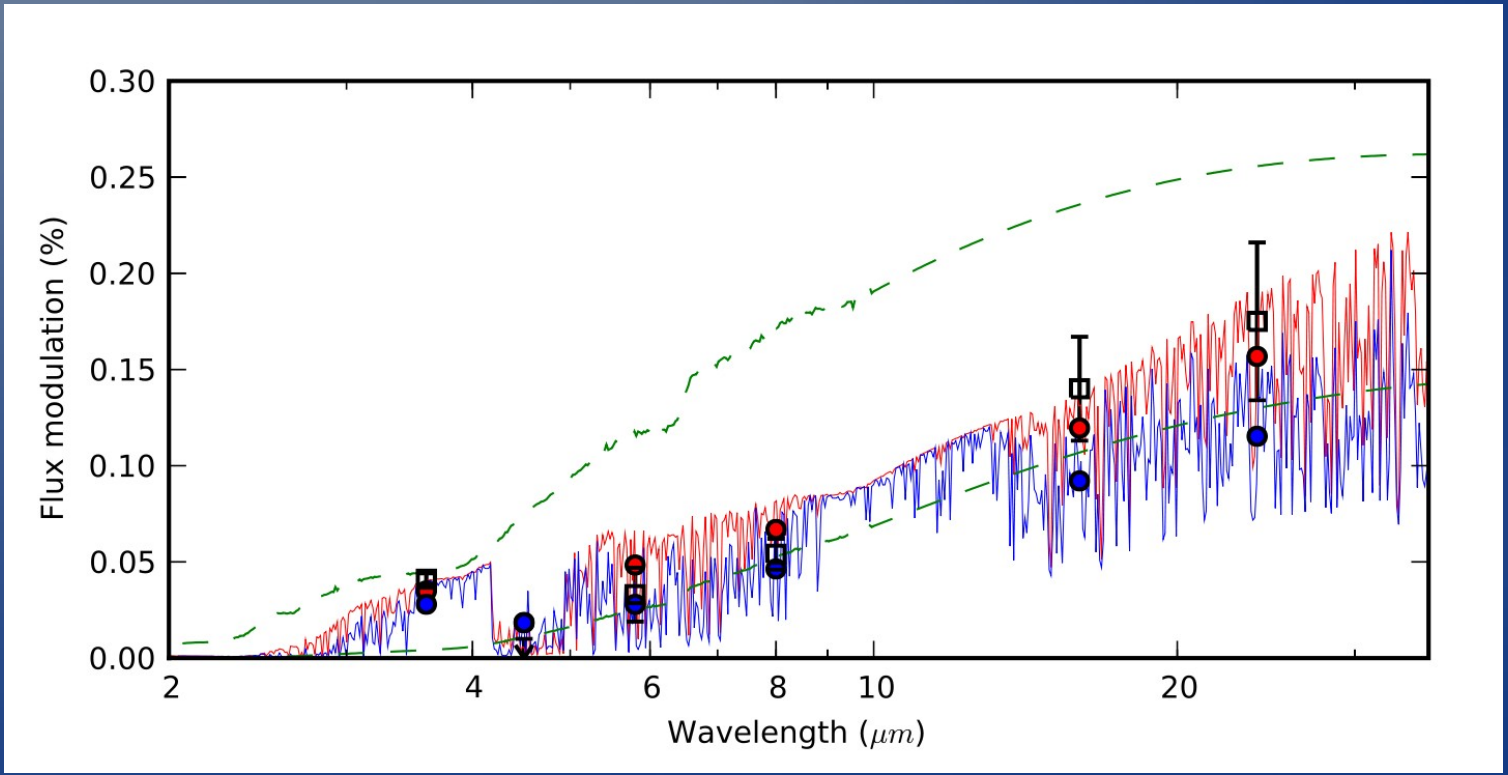
- Cool, Neptune-sized planet, M dwarf star
- 6 Spitzer channels!
- No detection at 4.5 μm



Stevenson et al. (2010), *Nature*

GJ 436b

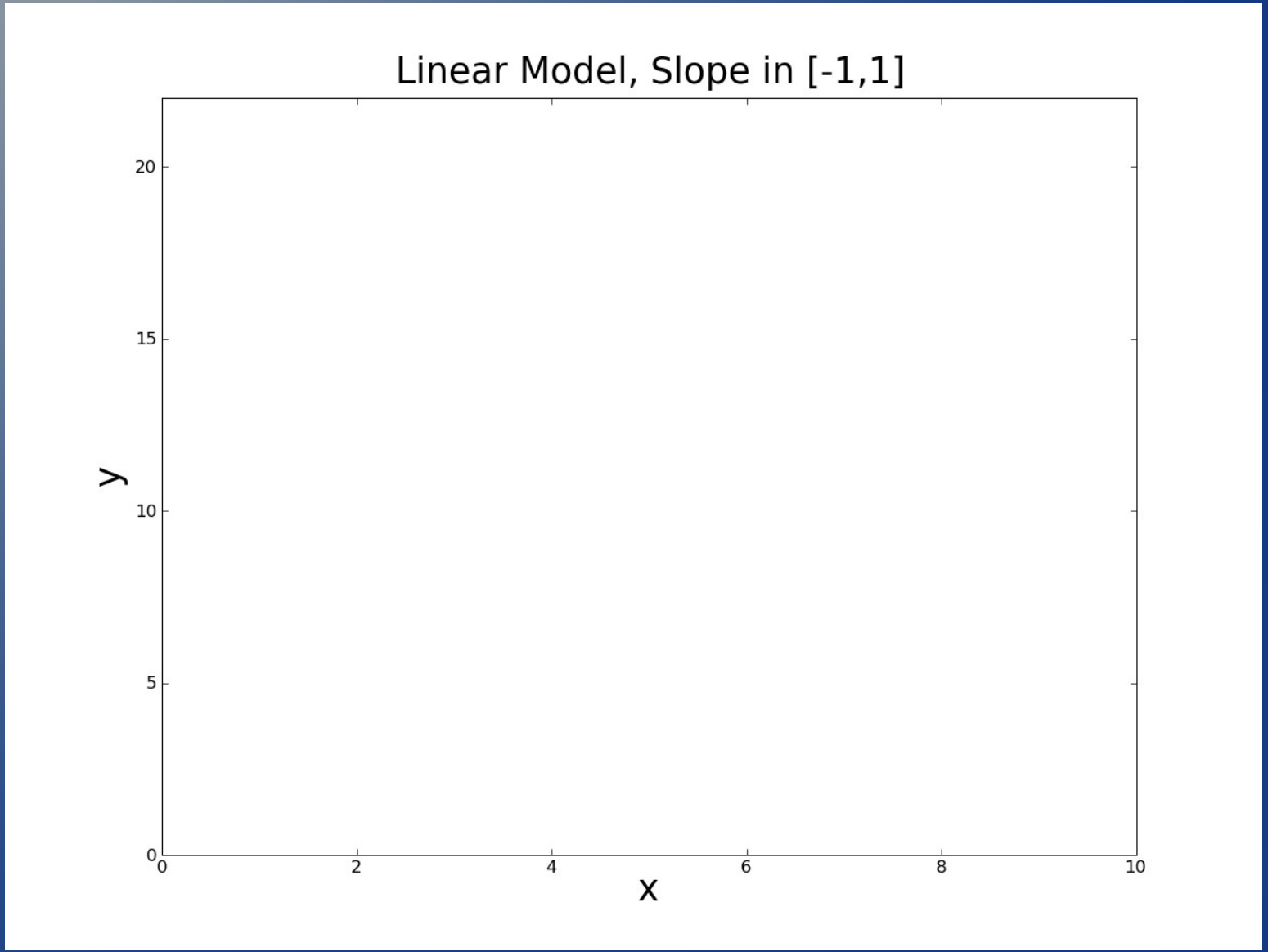
- Madhusudhan atmosphere model
- CO, CH_4, CO_2, H_2O + 6 *T(p)* parameters
- 1 million spectra computed, integrated, compared to data via MCMC sampler



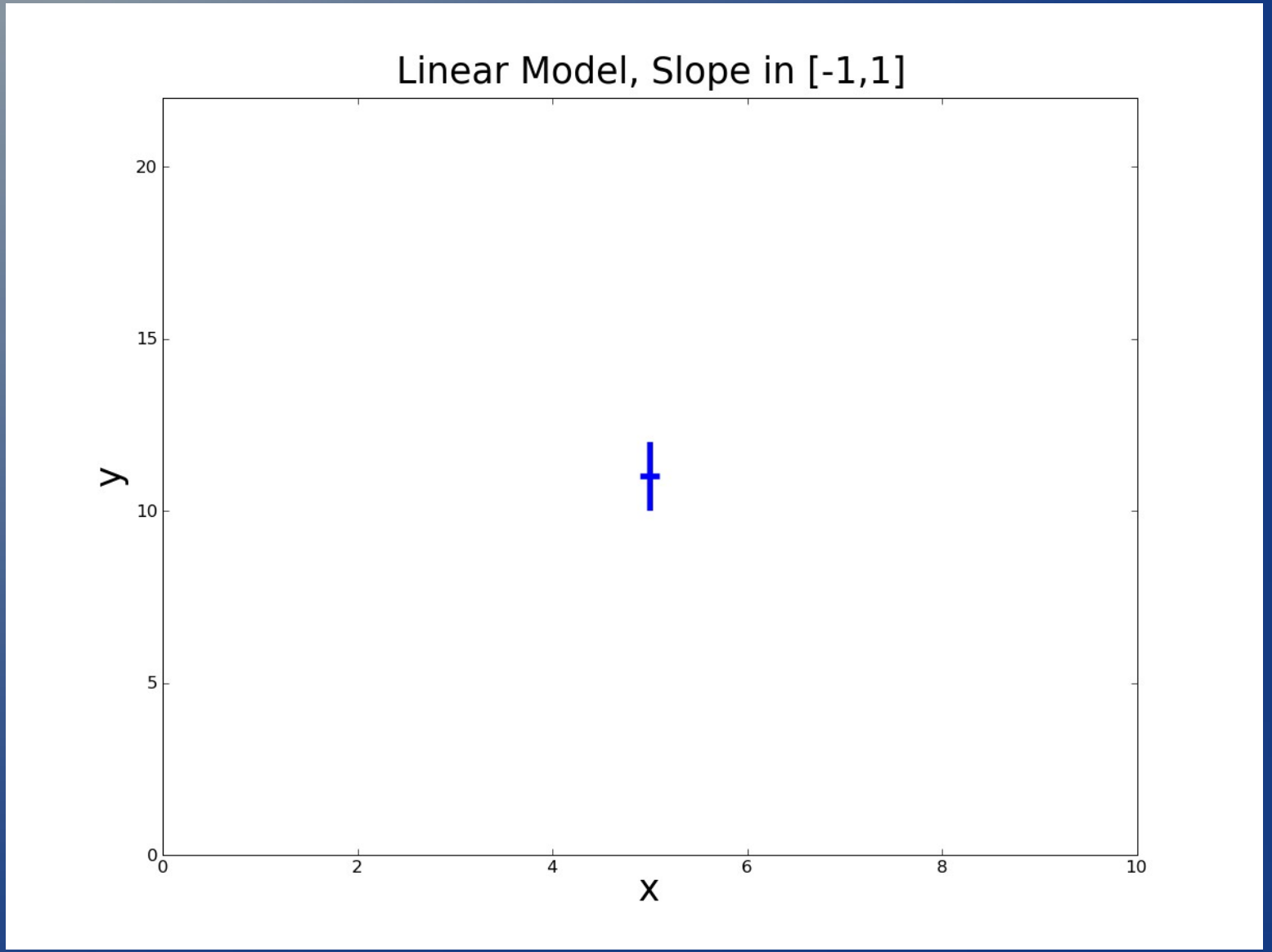
GJ 436b

- Thermochemical equilibrium: lots of CH_4
- Data: 7000× less CH_4 than prediction!
- Abundant CO
- Beaulieu et al.: CH_4 in transit spectrum
- Transit spectrum has 2 limbs, dawn and dusk
- Night-side CH_4 could be blown over dawn limb
- CH_4 then destroyed by daytime photochemistry
- CO brought up by vertical mixing?

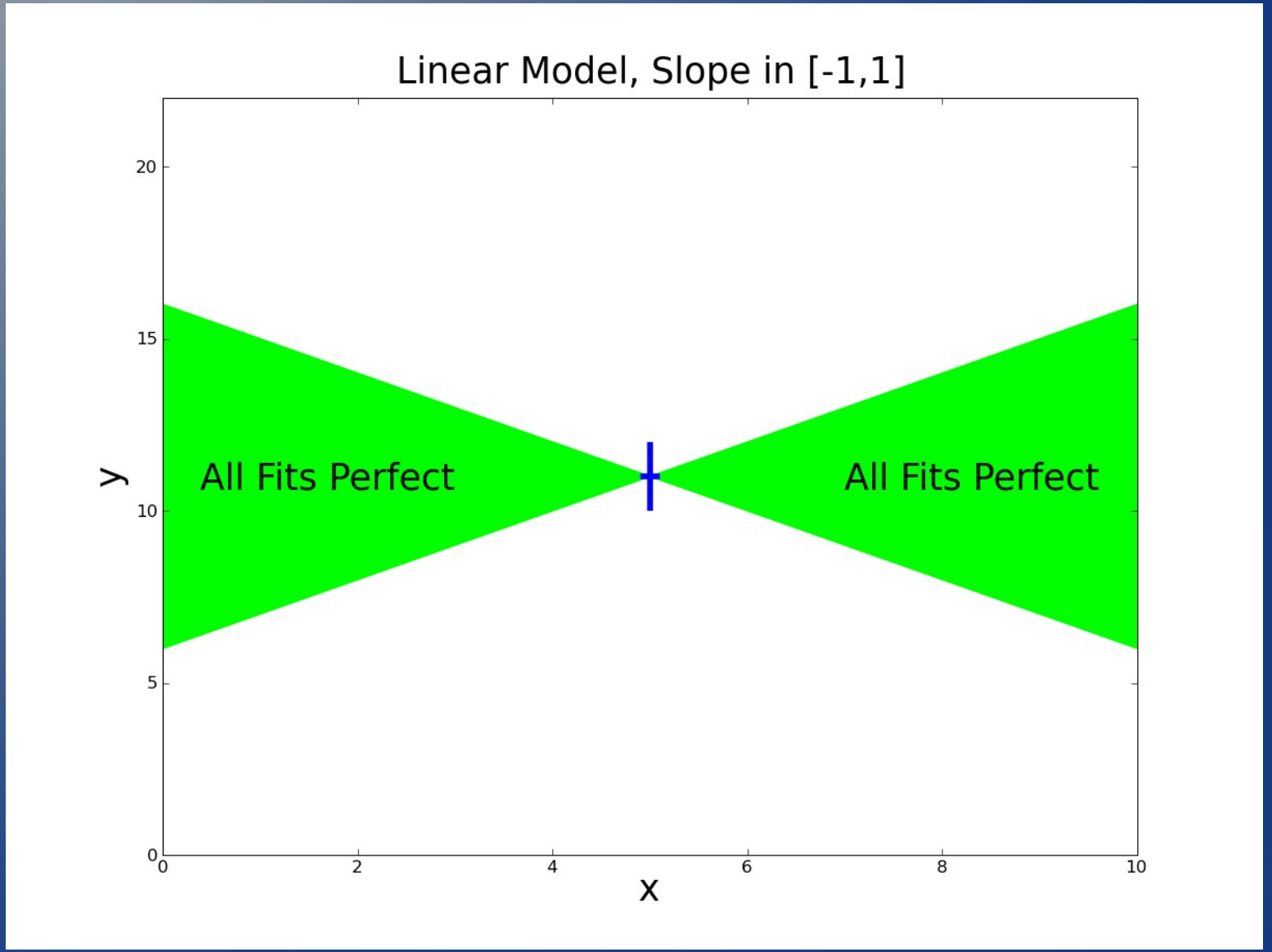
Eliminating Phase Space



Eliminating Phase Space



Eliminating Phase Space



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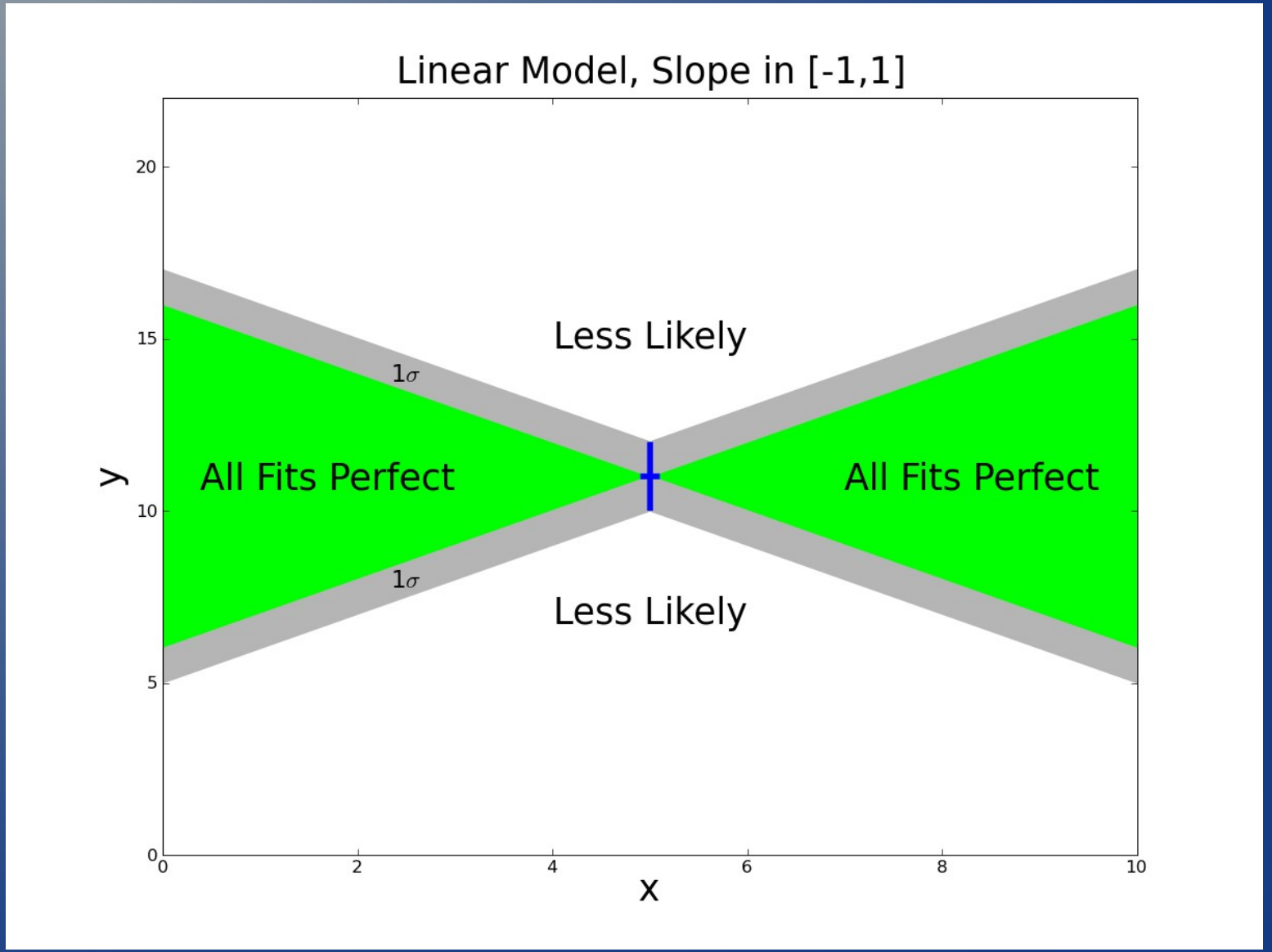

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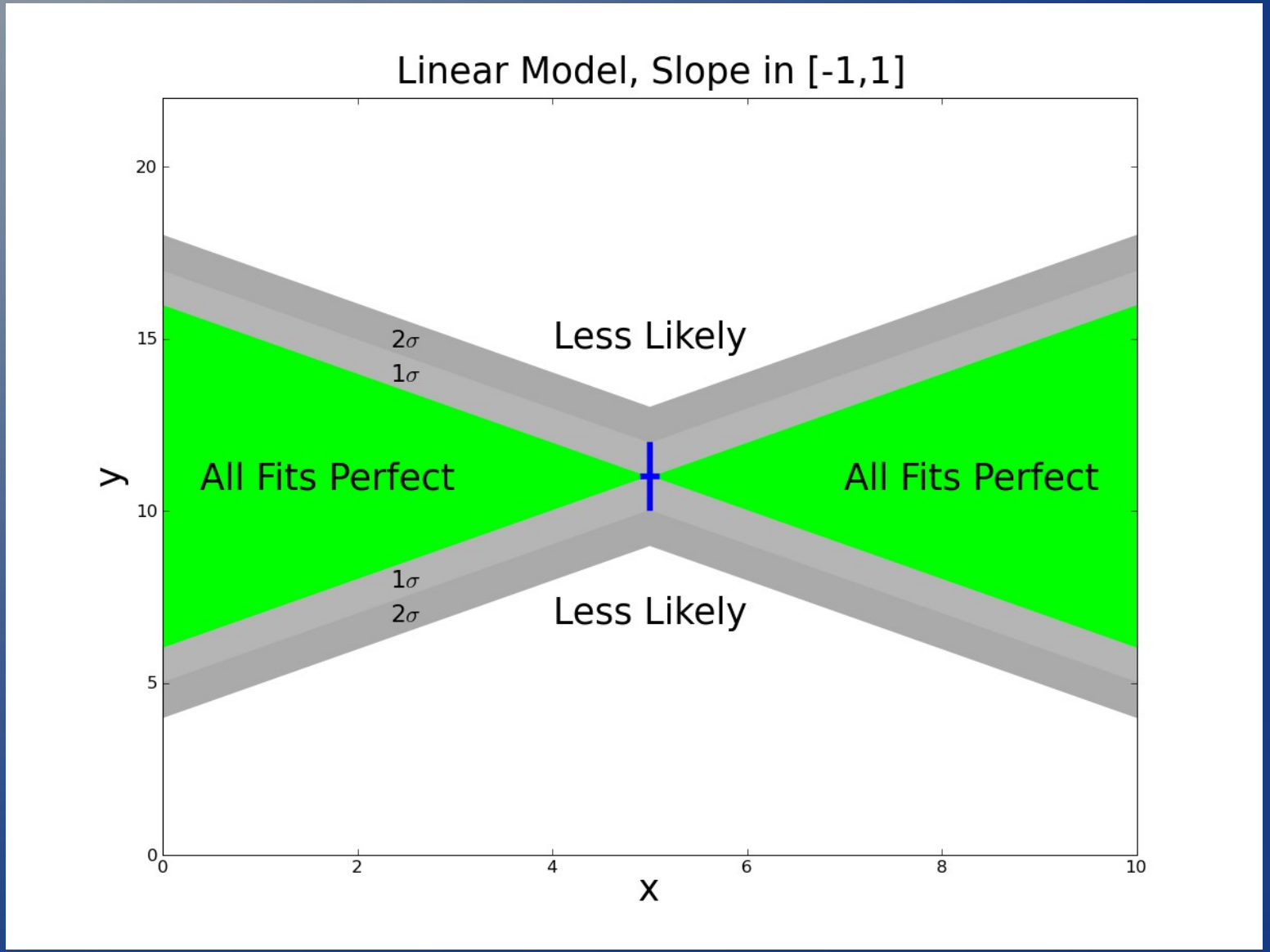

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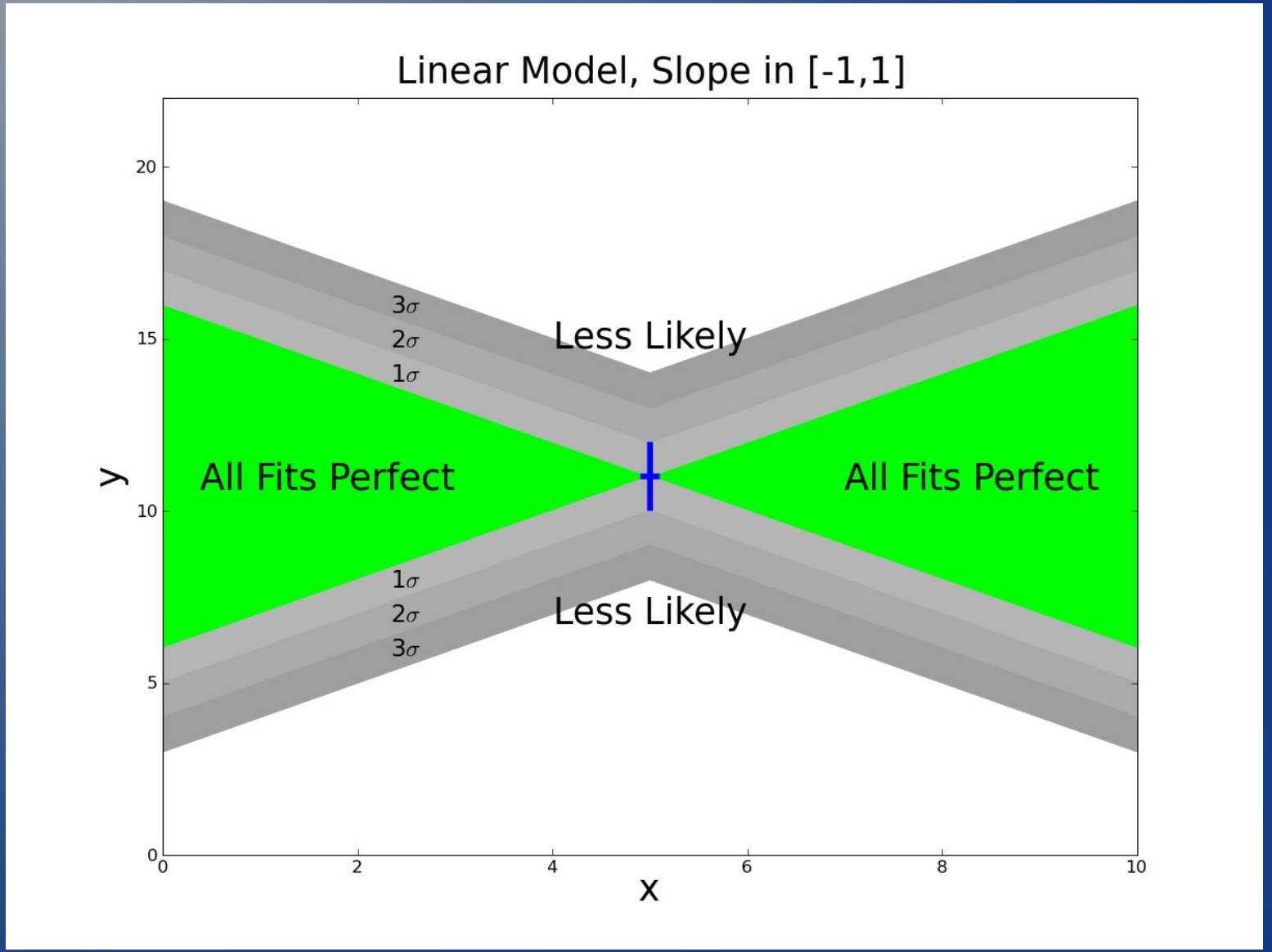

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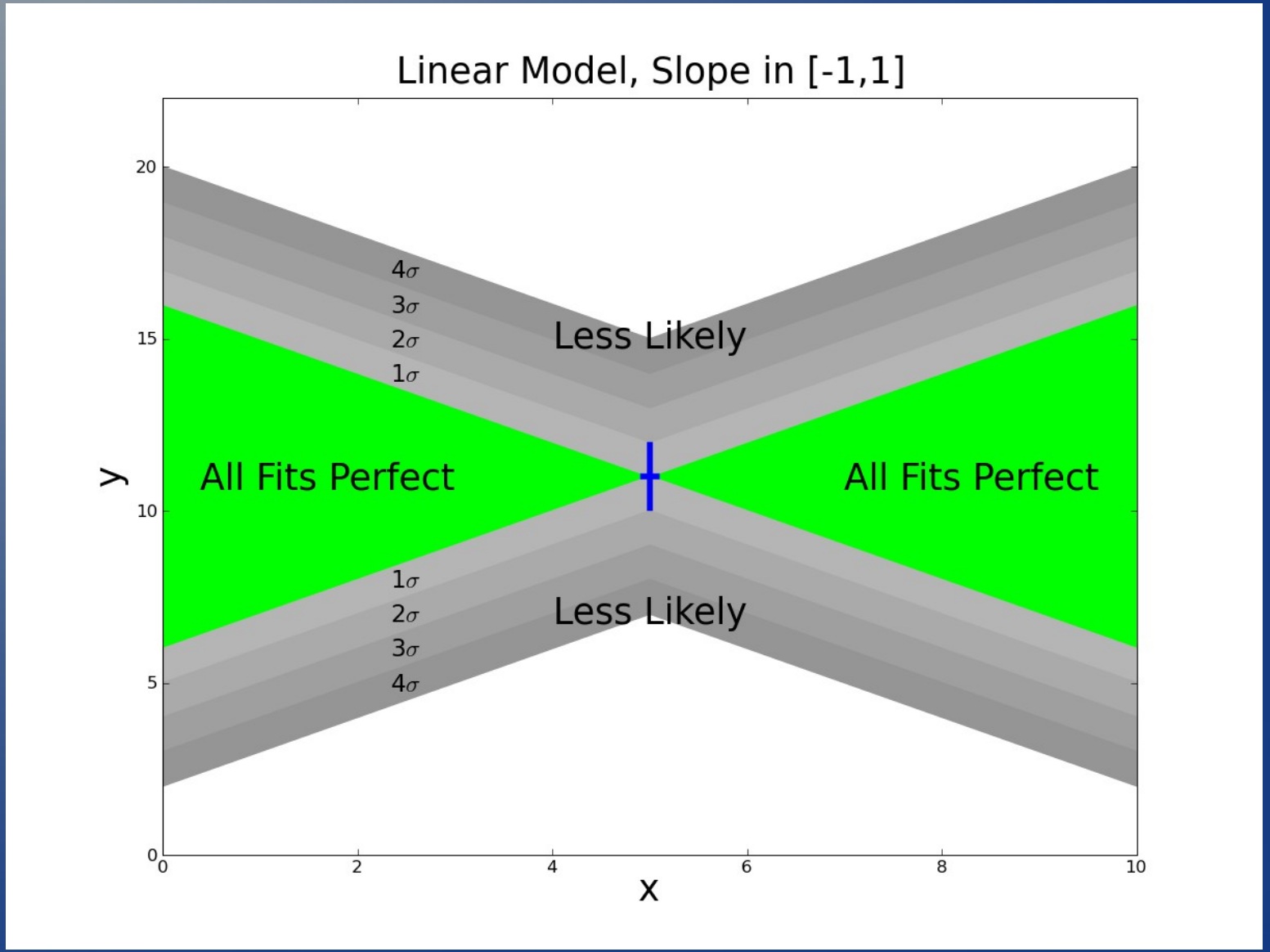

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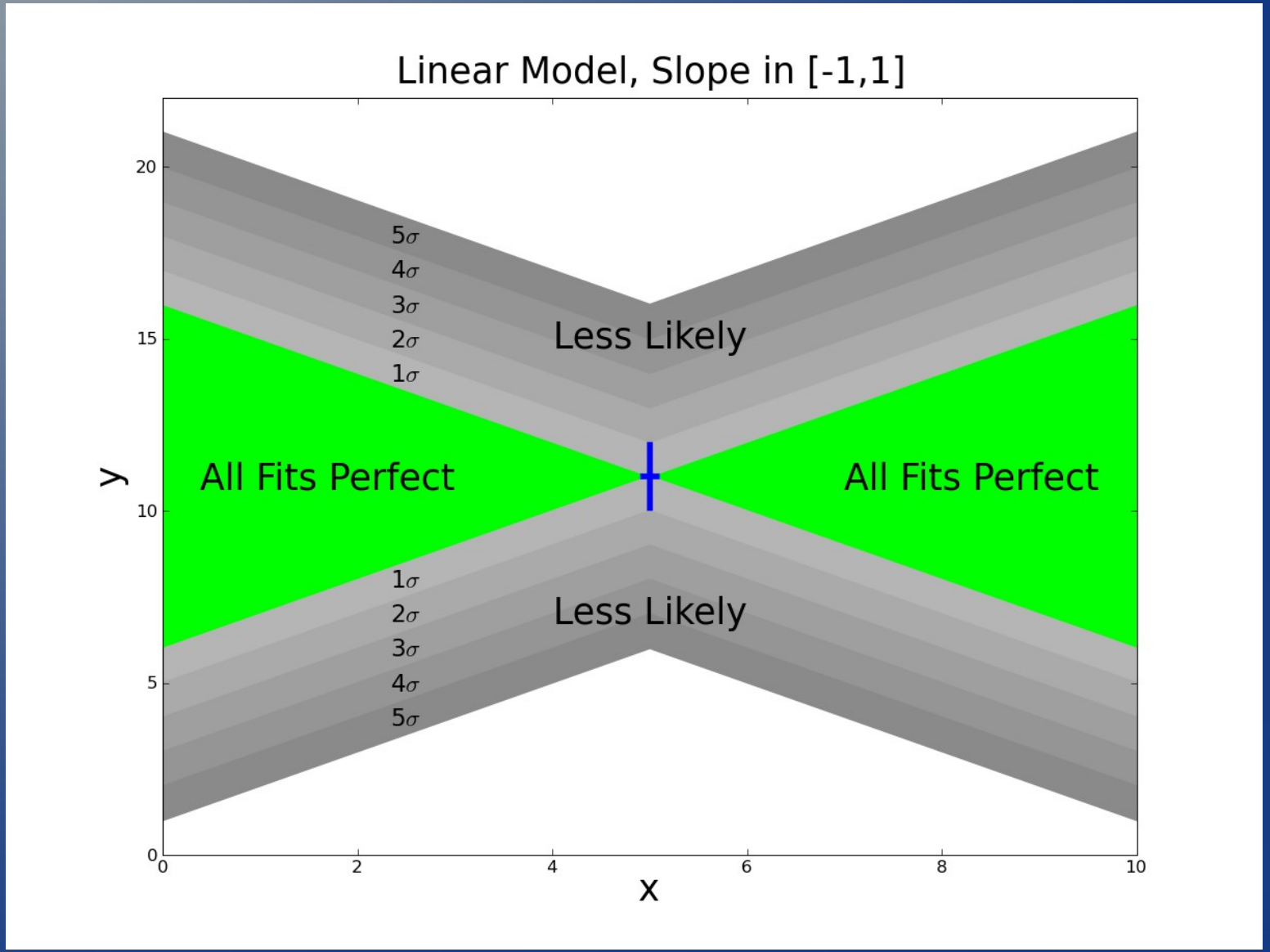

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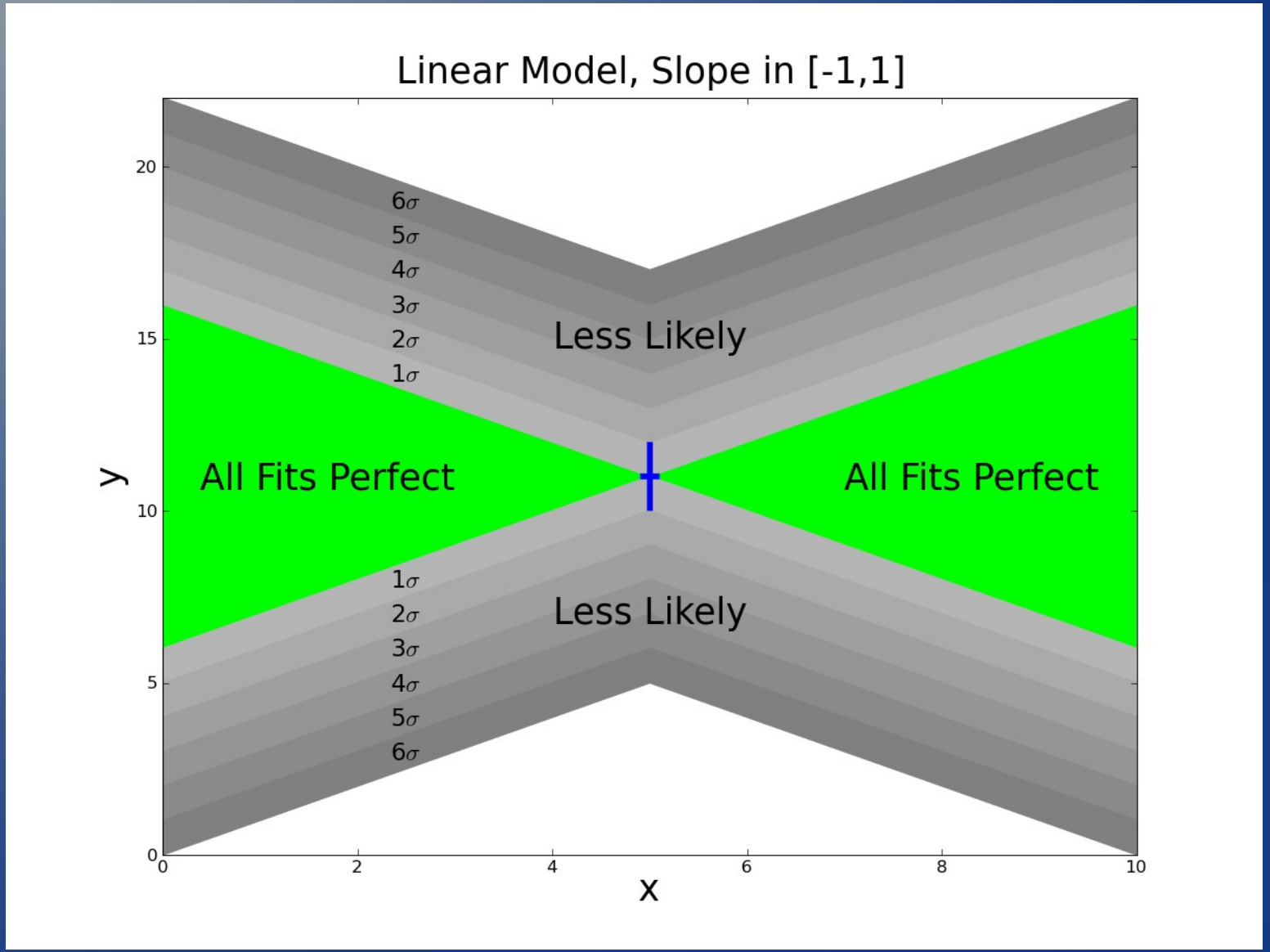

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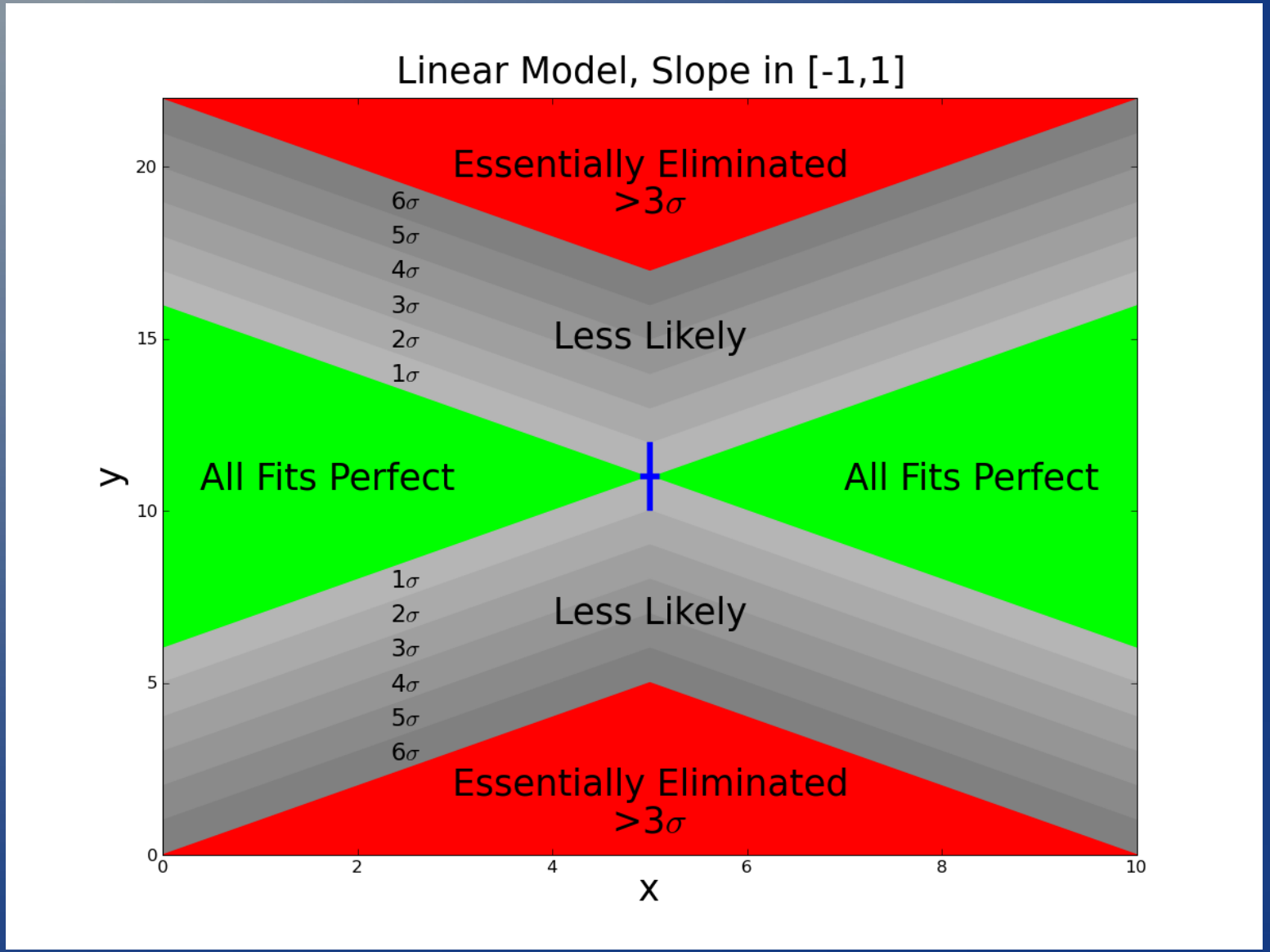


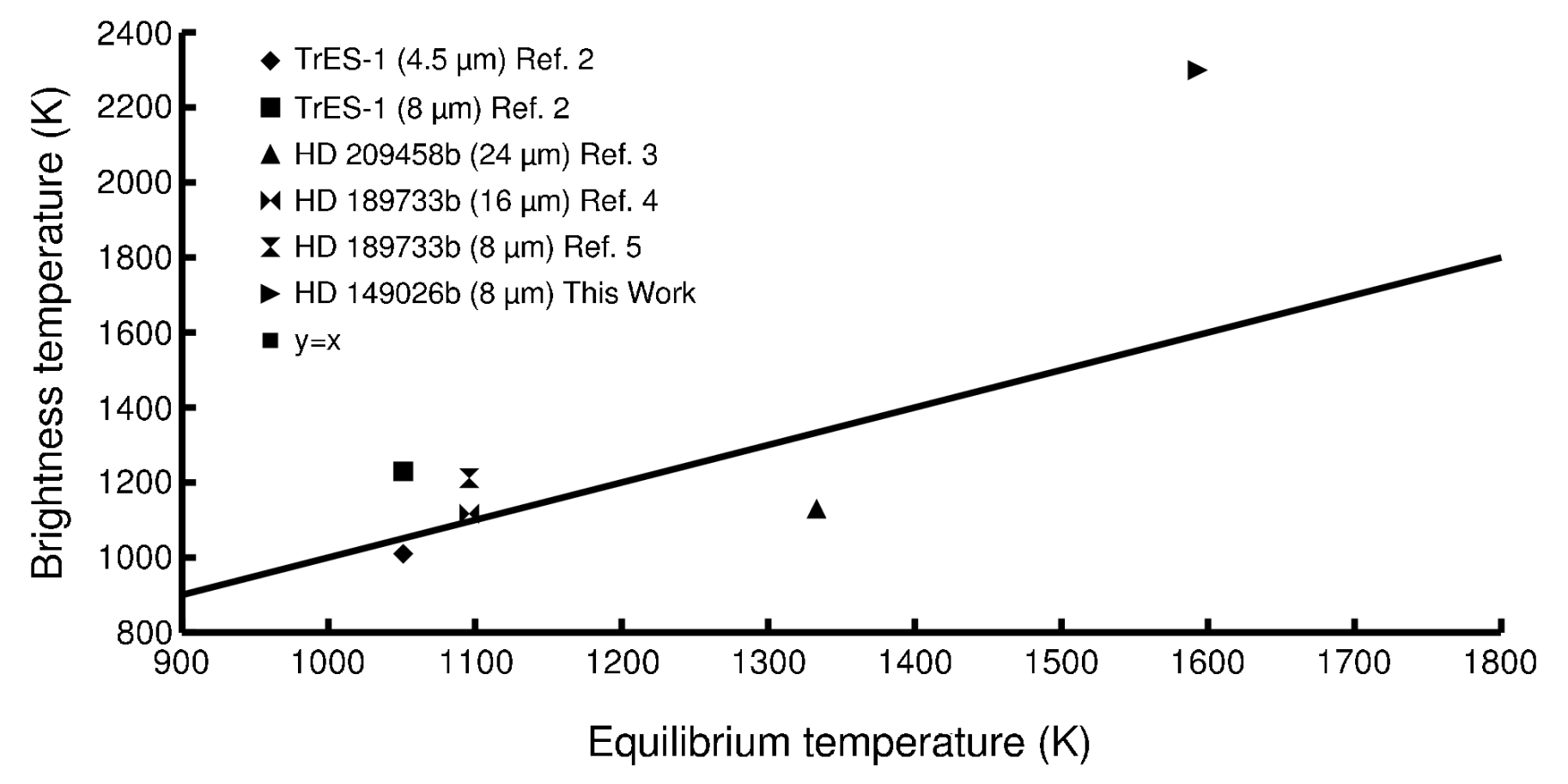
Model-Independent Comparison

- Want model-independent atmospheric statistic
- Compare planetary output to input fluxes
- Compare measured output fluxes to each other
  - Same or different planet
- Intuitive units wrt chemistry, clouds
- Stellar fluxes differ for each planet, not intuitive
- Temperature usual energy parameter in atmos.
- Try brightness (T_b) *vs.* equilibrium (T_{eq}) temps

Brightness Temperature

- Temperature of a similar blackbody that would give observed flux in that bandpass
- Measure of *flux*, not *T*, but related to object *T*
- If object is BB → $T_b = T$ in all filters
- T_{eff} is T_b of whole spectrum (infinite bandpass)
- T_{eq} is BB temp balancing received radiation
- $T_b \sim T$ at max. of filter contribution function
- Can relate T_b to chemical & cloud temps

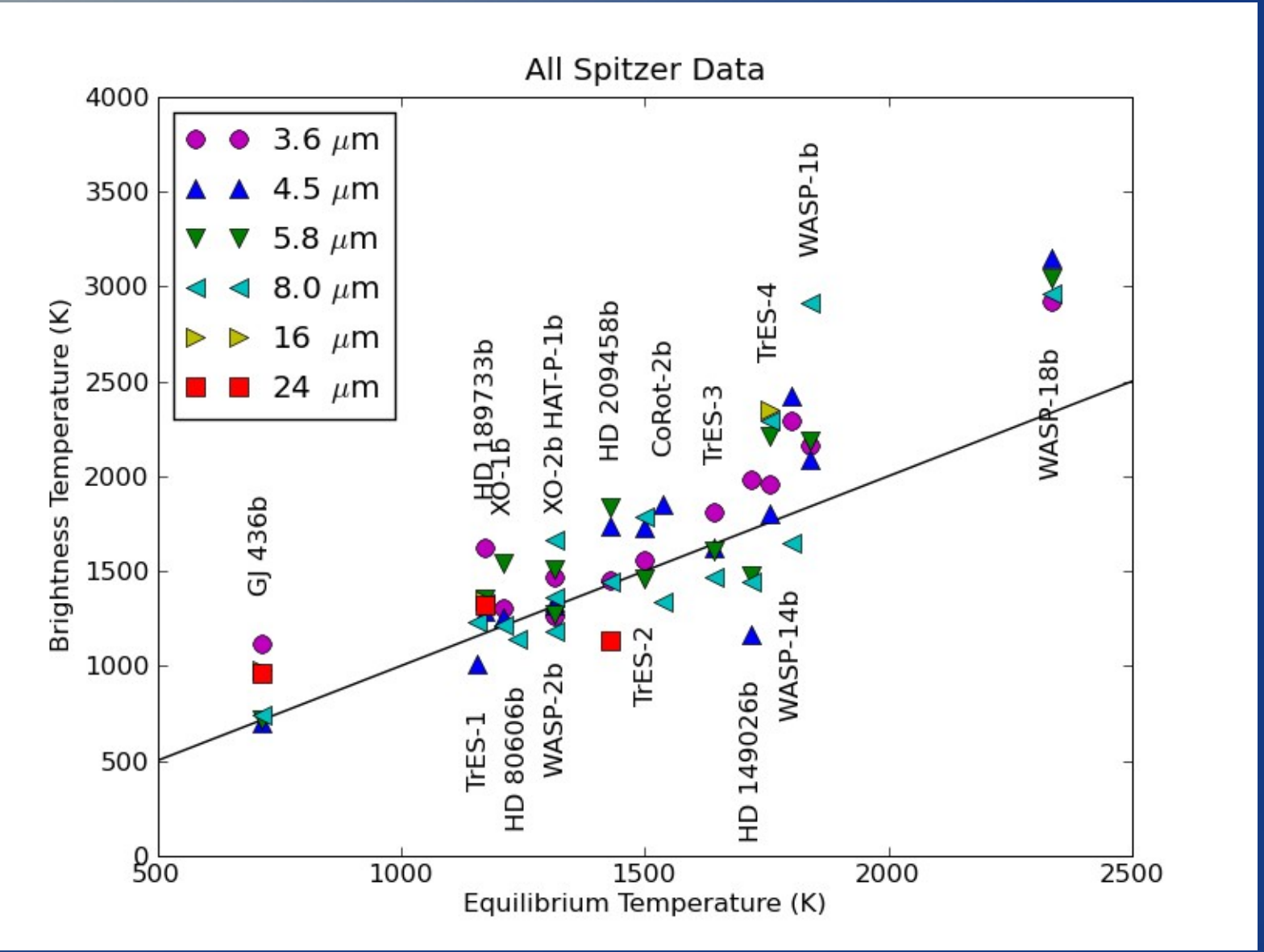
T_b *vs.* T_{eq}: 2007



Just 6 measurements on 4 planets!

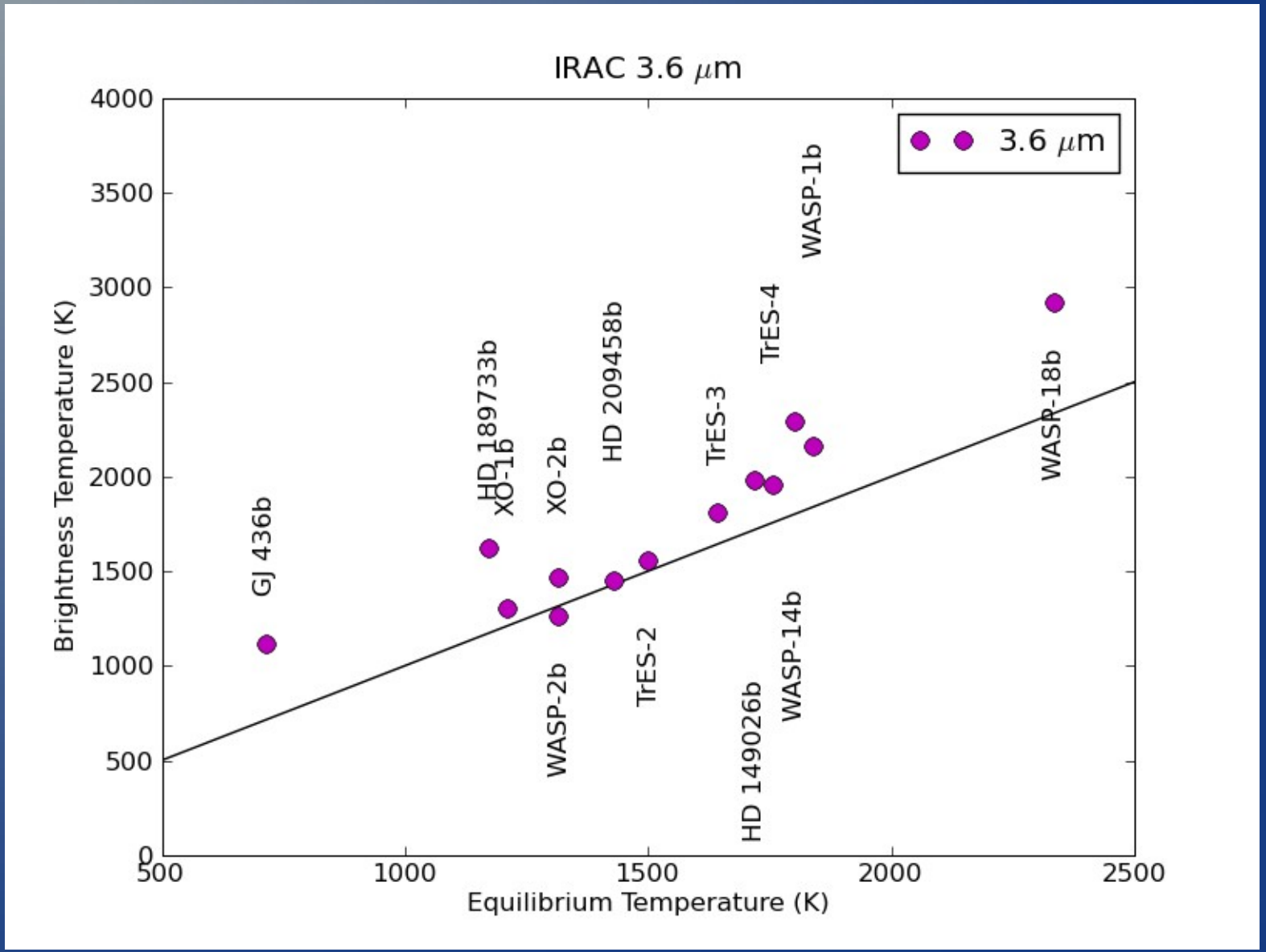
Harrington et al. (2007), *Nature*
Assumes A=0.3, uniform emission

T_b *vs.* T_{eq}: 2010 Sep 8



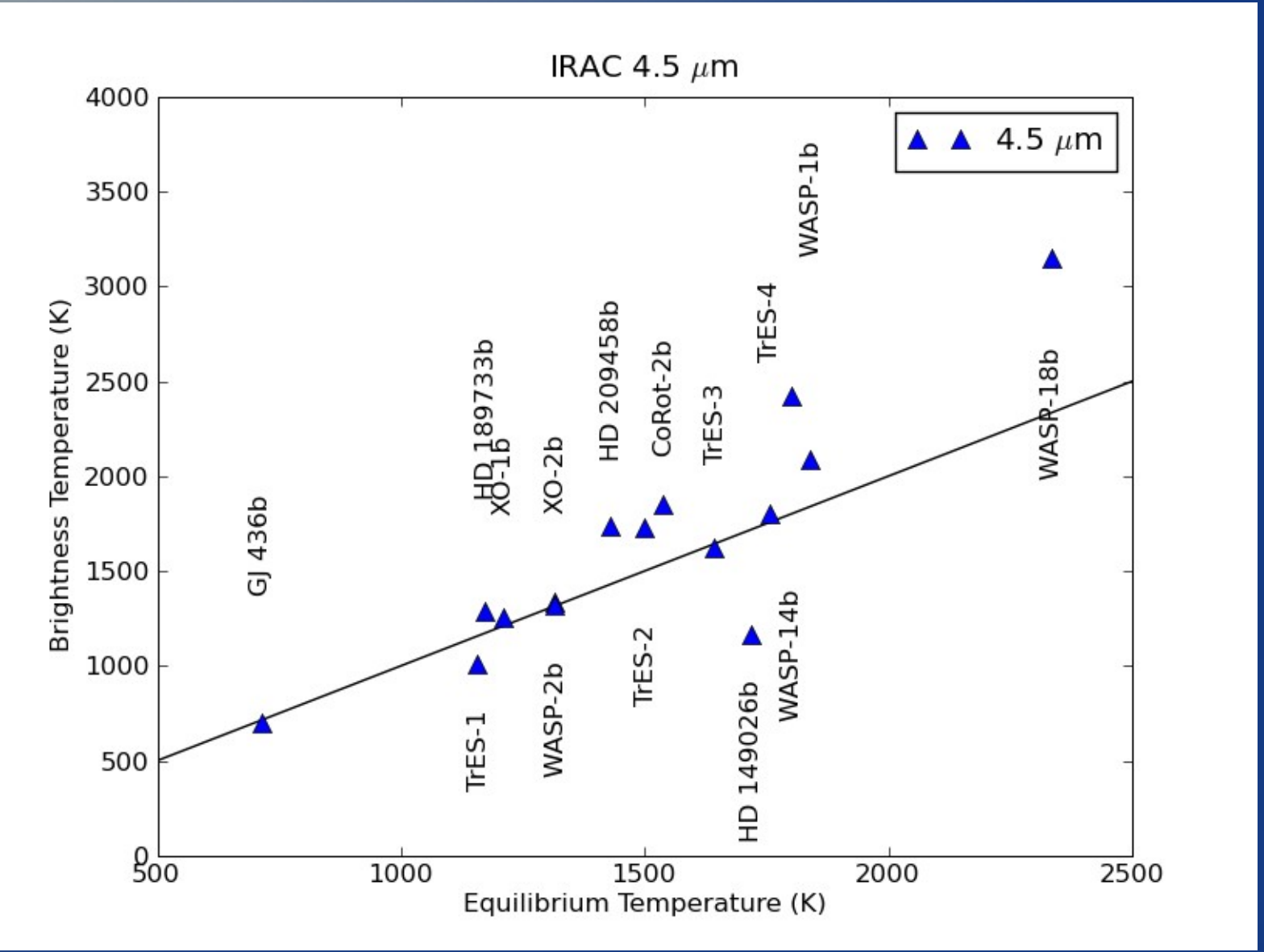
A=0
uniform

T_b *vs.* T_{eq}: 2010 Sep 8



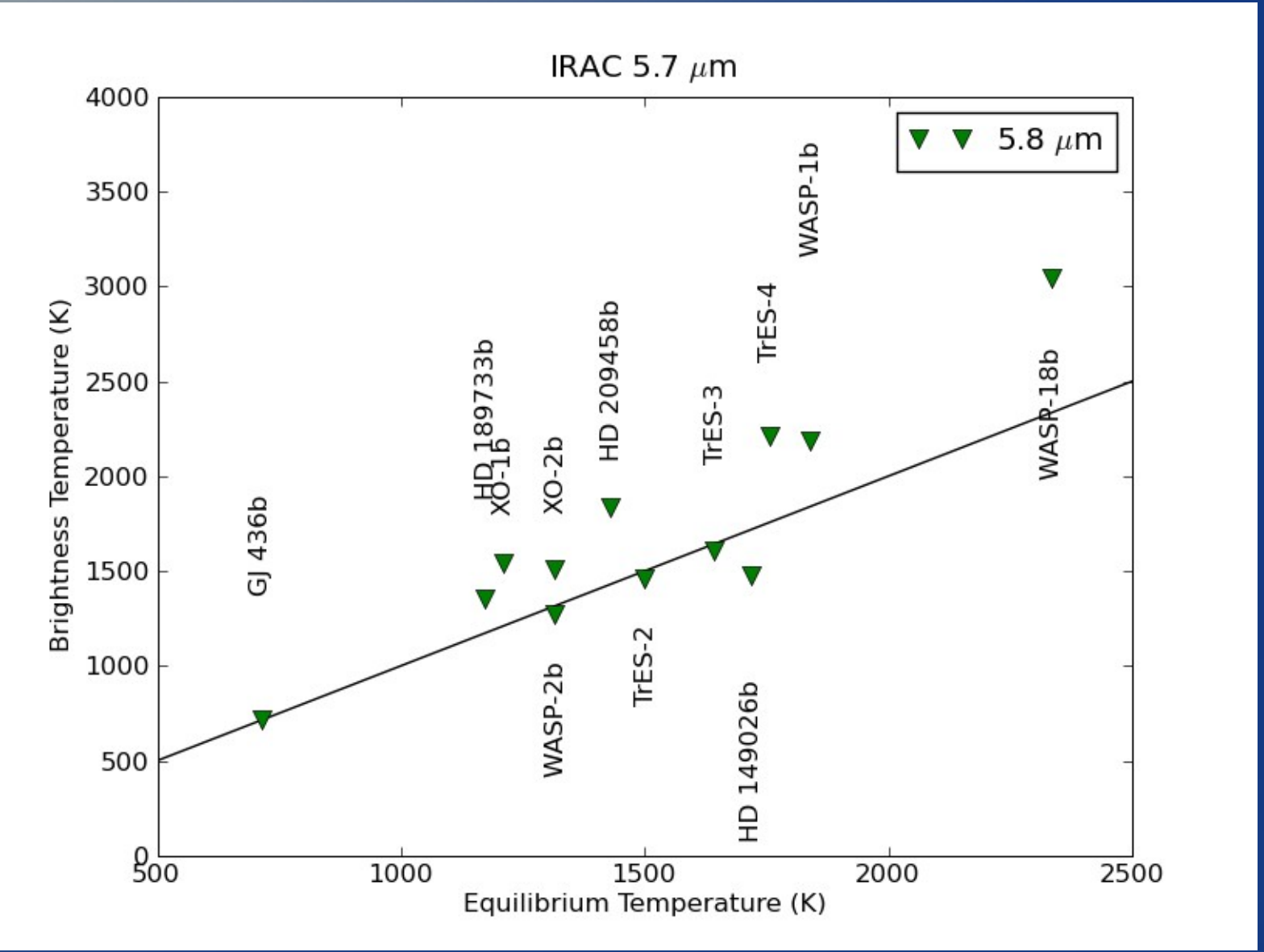
A=0
uniform

T_b *vs.* T_{eq}: 2010 Sep 8



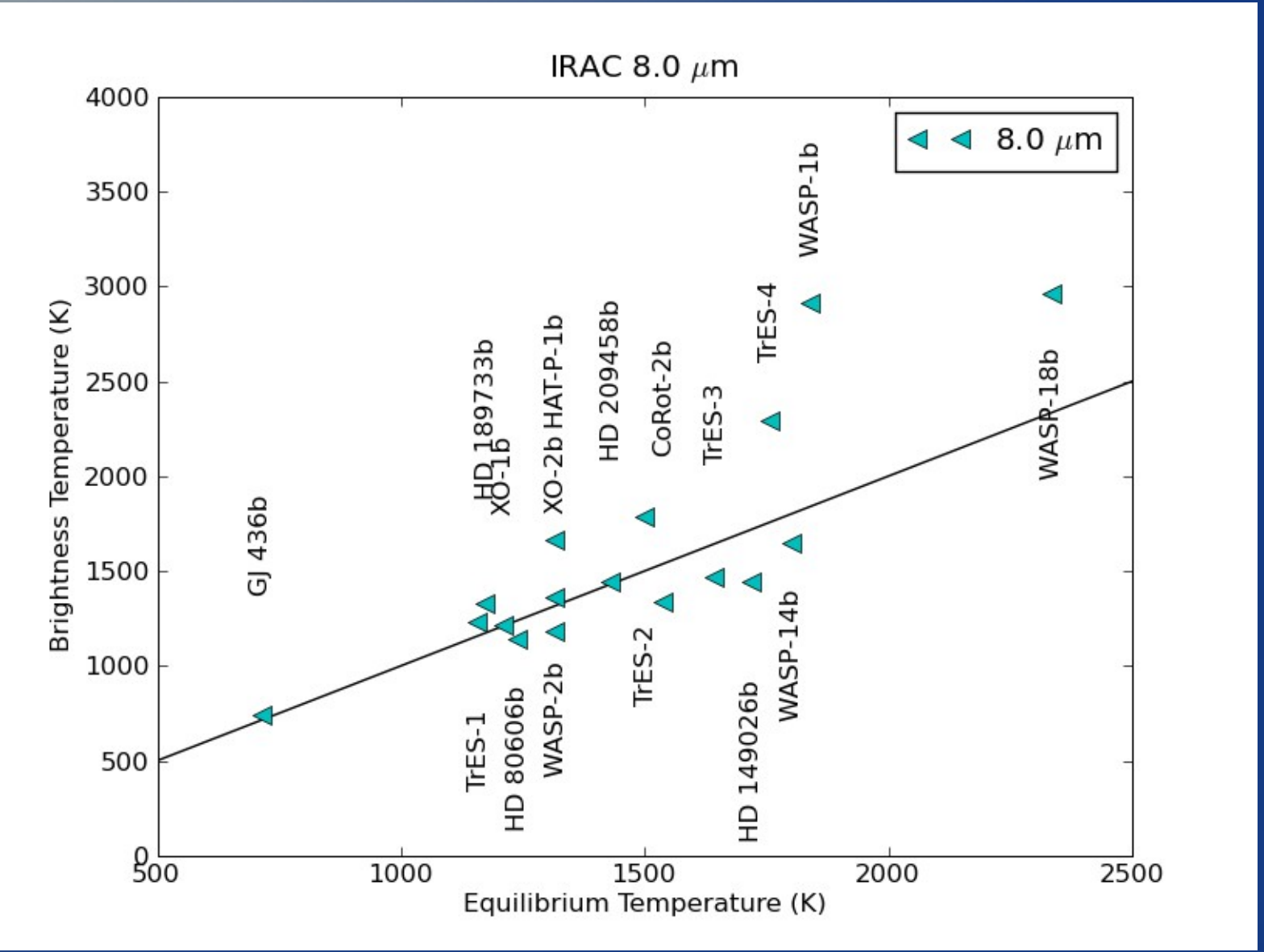
A=0
uniform

T_b *vs.* T_{eq}: 2010 Sep 8



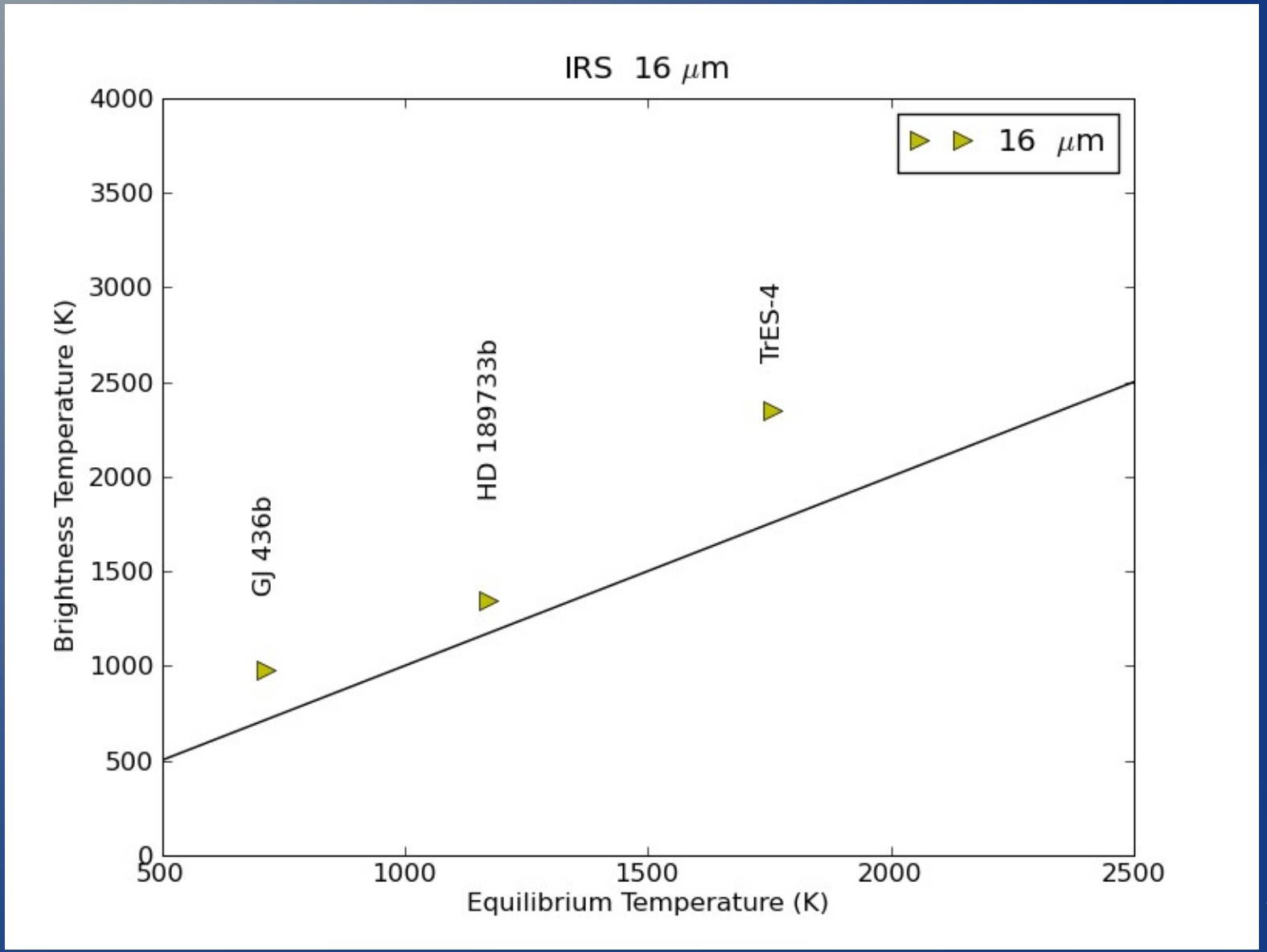
A=0
uniform

T_b *vs.* T_{eq}: 2010 Sep 8



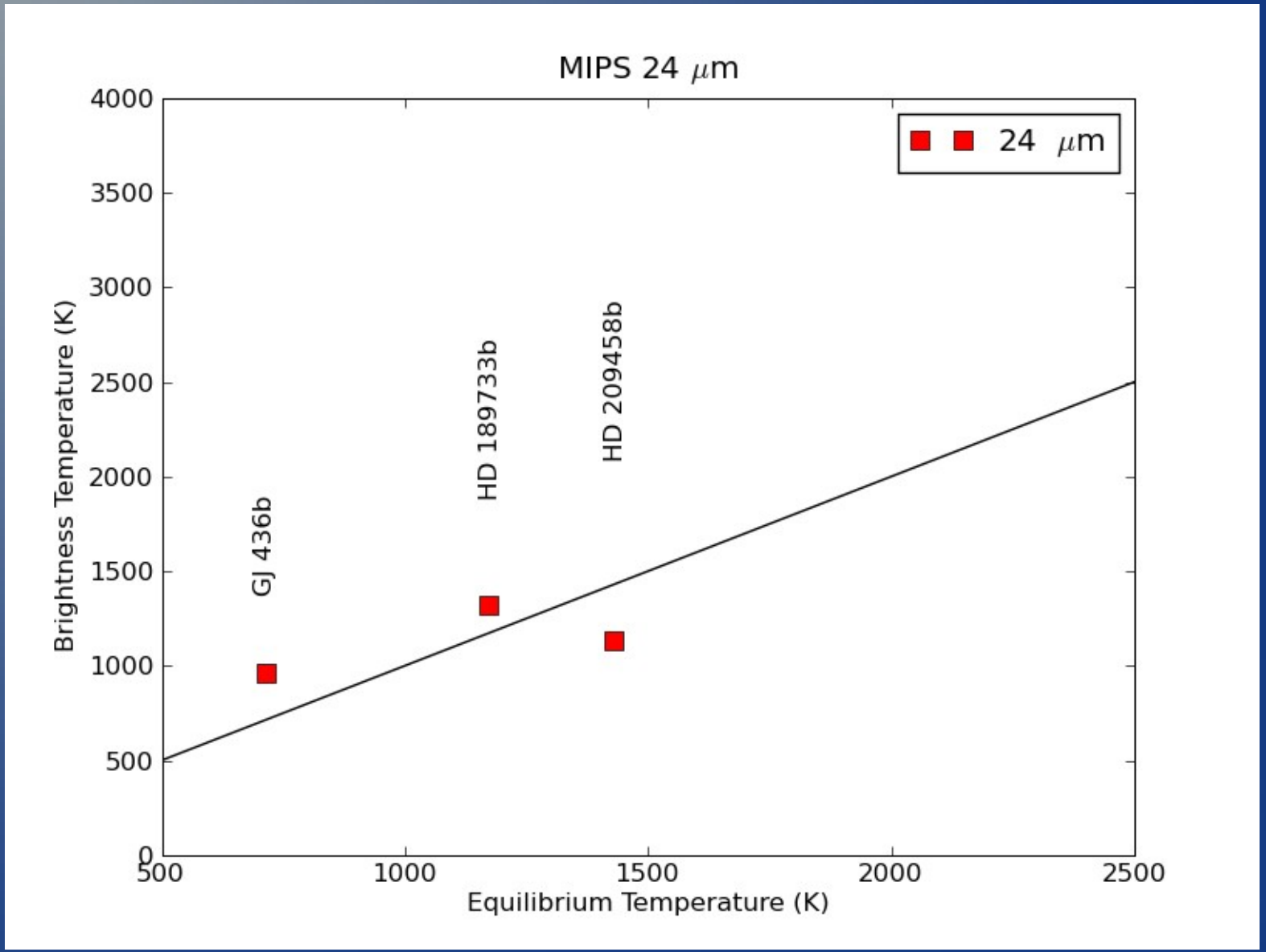
A=0
uniform

T_b *vs.* T_{eq}: 2010 Sep 8



A=0
uniform

T_b *vs.* T_{eq}: 2010 Sep 8



A=0
uniform

Spitzer Analysis Checklist

- Just because model fits does not mean it's right
- Eclipses require 10^{-4} accuracy!
- Worry about 2^{nd}- & 3^{rd}-order effects
- Observe in a flat pixel, 3 hours before, 2 after
- Try many apertures, centering methods
- Use subpixel photometry
- Try many intrapixel and ramp functions
- Run variations in all reasonable combinations
- Use SDNR, BIC, AIC to choose best, report ties
- Atmos: Report *T(p)* and contribution functions

MCMC Checklist

- Find the minimum with a minimizer
  - Rescale errors after 1st good fit, Spitzer's high
  - Test RMS error vs. bin size (red noise)
  - DO NOT report peak/median of each parameter distribution as best joint solution!
  - If MCMC *ever* finds better χ^2, reminimize from there and restart MCMC
- Assess errors & correlations with MCMC
- Gelman-Rubin test for MCMC convergence
- Inspect histograms and correlation plots

Boring but Important: BS vs. MCMC

- MCMC: How likely is theory given the data?
- BS: Compared to the best fit, where does the truth lie, given the model? truth:data as data:BS
- BS is subtle!
- There are several BSs (using the right one?)
- Short section in Press et al. inadequate
  - Does not discuss assumptions, limitations, interpretation (many adjustments needed)
- Read Efron & Tibshirani (1993 book) to do right
- Or just do MCMC, which is what you want

Conclusions

- Spitzer is an atmosphere measuring machine!
  - Even SOFIA can't reach longer Spitzer λs
- New results for WASP-12b, 14b, 17b, 18b, HD 209458b
- Exciting puzzle for GJ 436b!
- Model-independent statistic
- Lessons learned: observing and analyzing depends on the details