A Spitzer Survey of Exoplanet Secondary Eclipses

I'll be looking for a grad school next year!

I'm looking for a new grad student!

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Atmospheres and Astrophysics

- Exoplanets combine planetary science and astrophysics observation
- For astrophysics, exoplanet data are awesome!
- For planetary science, quality is terrible!
- More info content in *one* Cassini image than all detected exoplanet photons combined
- Must interpret data or it's not science
- What can models do with so few points?
- When should we believe them?
- What can we do without them?

Spitzer Secondary Eclipses

- Emission by planets in bands 1-few μm wide
- 3.6, 4.5, 5.7, 8.0, 16, 24 μm
- Many dozen planets accessible
- Access some planets < 1000 K
- No comparable sensitivity at these wavelengths
  - Complements obs. at other wavelengths
- Eclipses can absolutely calibrate spectra
- Demonstrates need for EChO!
  - Purpose-built for stability on exoplanet spectra

UCF's Spitzer Exoplanet Program

- Dozens of Spitzer secondary eclipses
- POET: Photometry of Orbits, Eclipses, Transits
  - Precision centering (~0.01 pix)
  - Interpolated aperture photometry (cures pixelation)
  - Try dozens of systematics models per event
  - Statistical rigor: BIC selects/eliminates models
  - BLISS intrapixel mapper (Stevenson *et al.* 2012a)
  - Markov-chain Monte Carlo phase-space exploration
  - Tests: convergence, red noise, unimodality,...
  - Detailed methods descriptions in papers
- *Reliability slows things down and costs more*
- ~6 papers / yr, lead ~2+ / yr, ~1 high impact / yr

Why So Careful?

- Reanalyses show problems of simple analyses
- Events often weak, <4σ, upper limits
- Most analyses have right eclipse depths
  - A few multimodal ones might change
- BUT, many error bars are likely wrong
  - Too low: bad, eliminate valid theory
  - Too high: also bad, accept invalid theory
- Reviewers (*US!*) should be pickier!
  - Many models, show posterior dist., show tests
  - Our papers discuss what to look for & why

Eclipses In Ensemble

- Plot aggregate exoplanet eclipse data
  - ID trends, behavior types
  - Motivate theoretical work
- Model-based comparisons
  - Who has an inversion (at depths probed)?
  - When does disequilibrium chemistry happen?
- Good to do, but depends on 1D models based on too few points

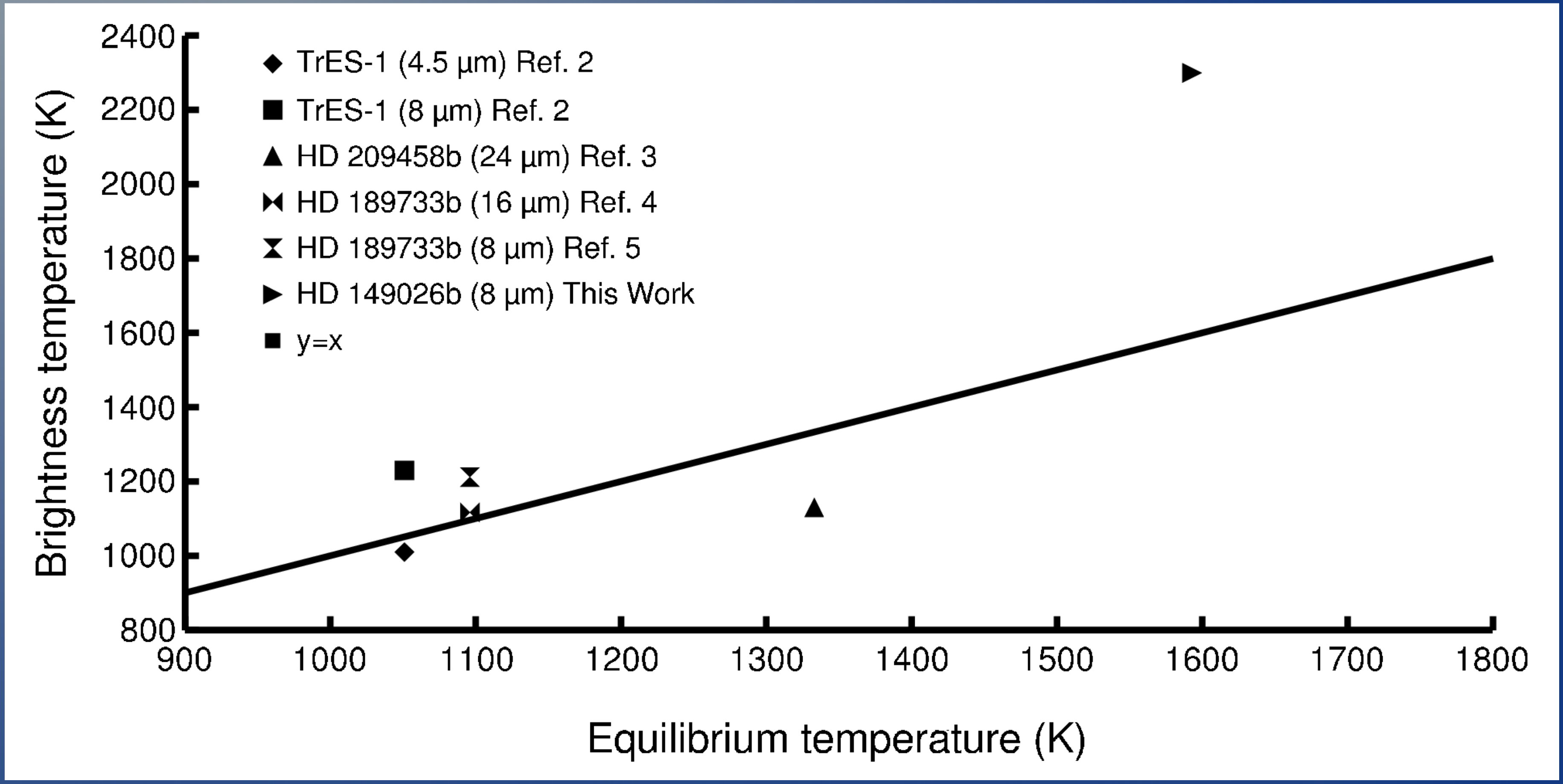
Model-Independent Comparison

- 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
- Neither are eclipse depths (depend on star)
- Temperature is usual atmos. energy parameter
- 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_{eq} is BB temp balancing received radiation
- Can relate T_b to chemical & cloud temps

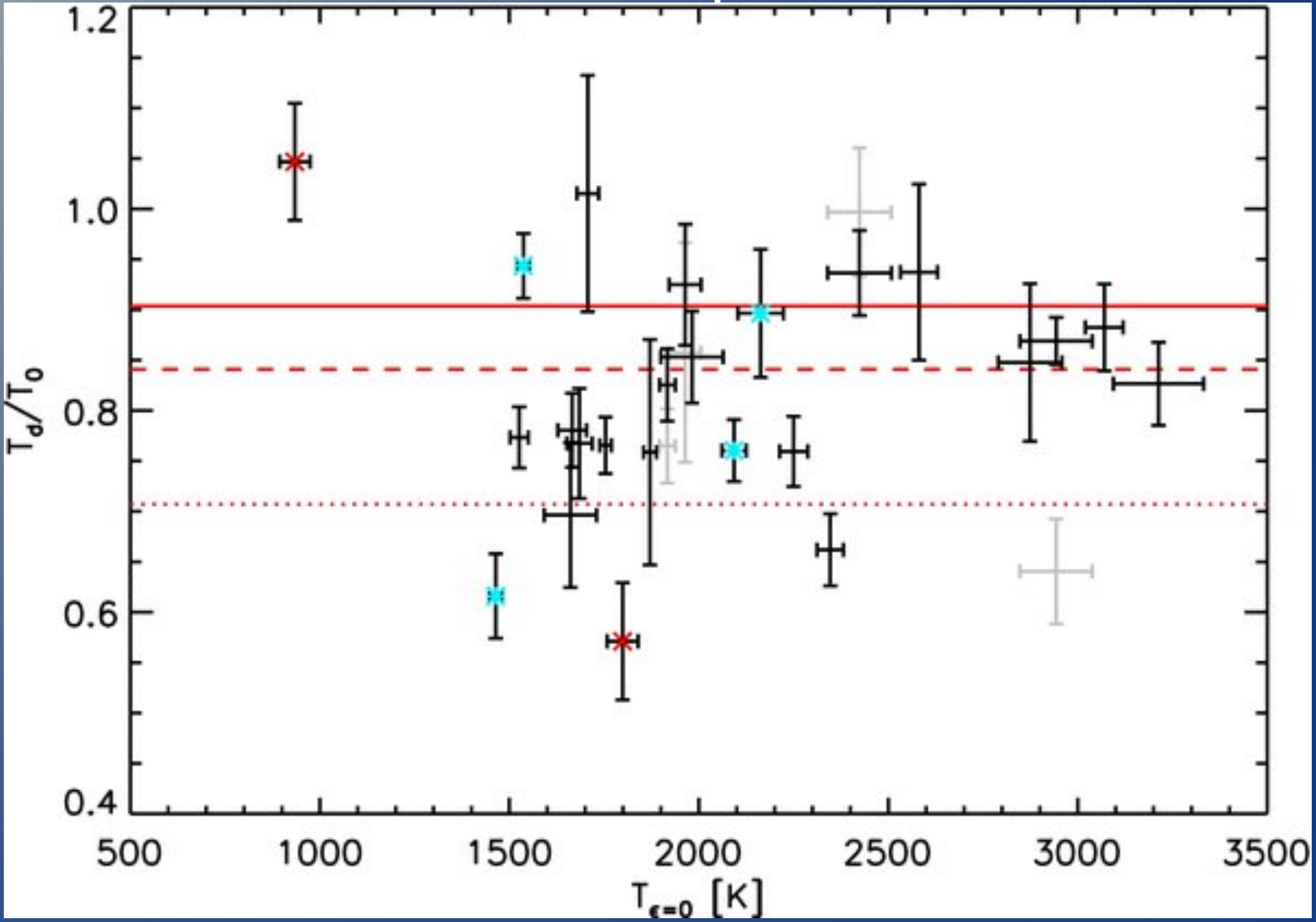
T_b *vs.* T_{eq}: 2007



Just 6 measurements on 4 planets!

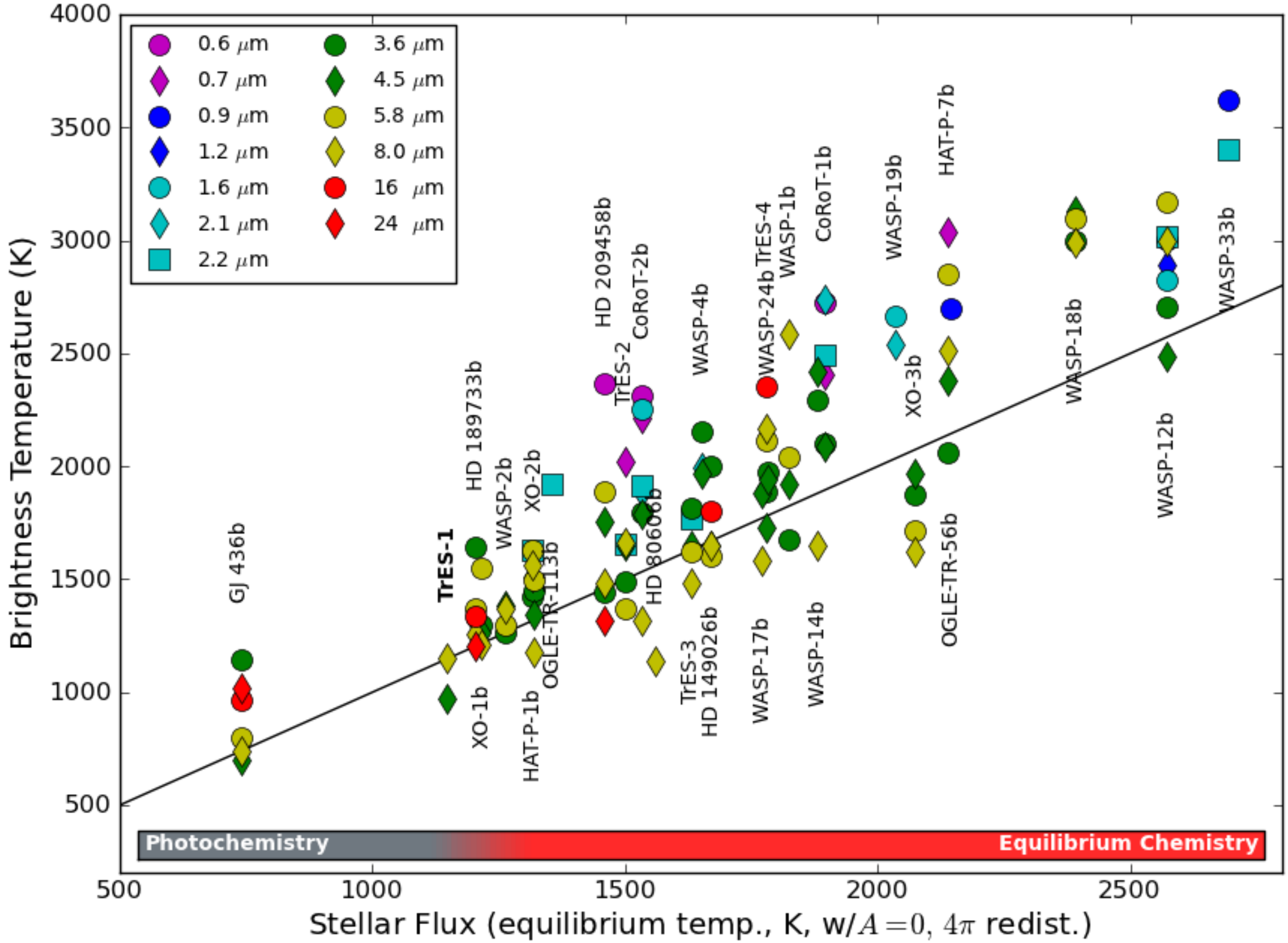
Harrington et al. (2007), *Nature*
Assumes A=0.3, uniform emission

T_b *vs.* T_{eq}: 2011

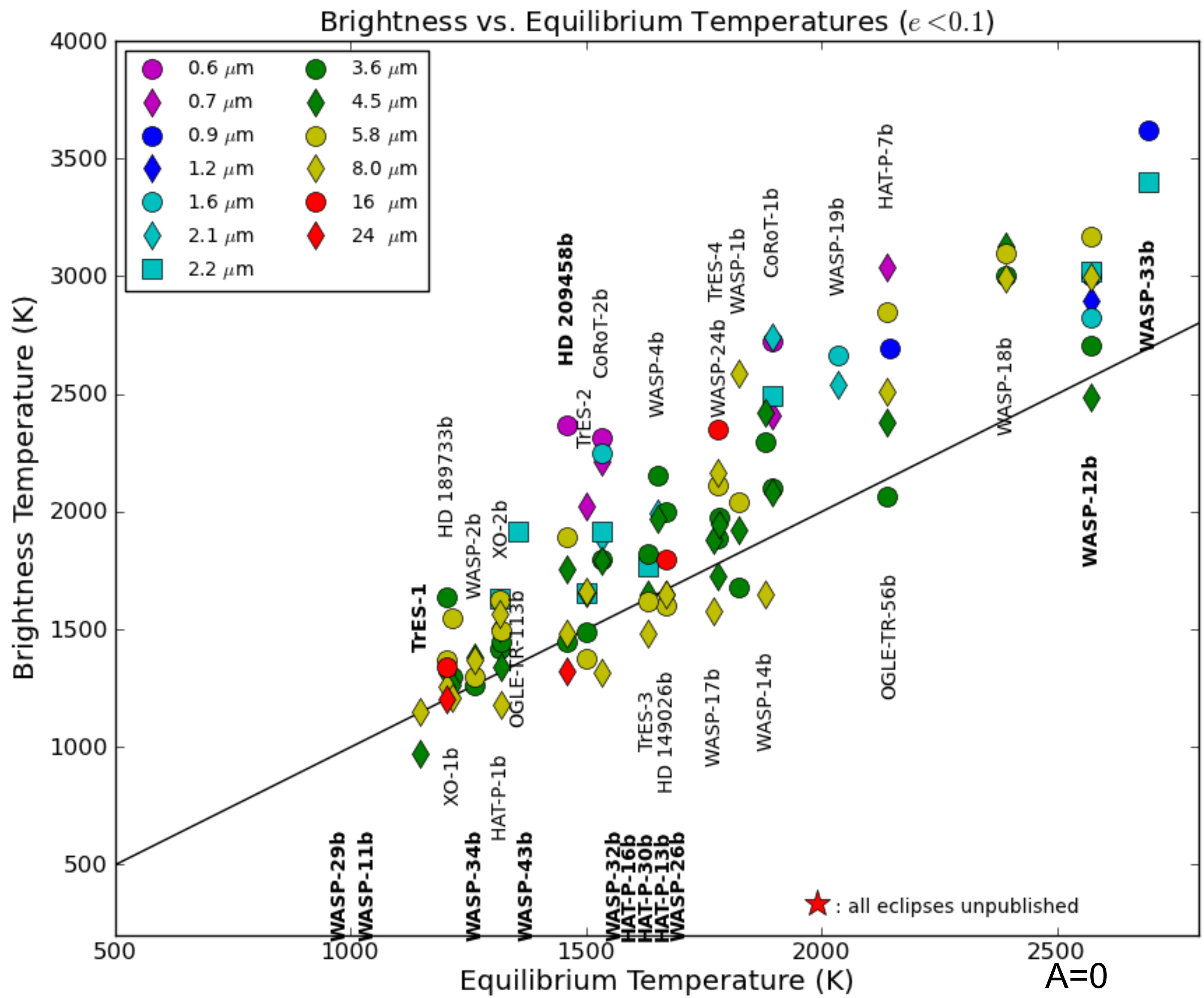


High temp more consistent than low.

Cowan and Agol (2011), *ApJ*
Assumes *A*=0, substellar



Brightness Temperature (K)
Stellar Flux (equilibrium temp., K, w/$A = 0$, 4π redist.)
0.6 μm
0.7 μm
0.9 μm
1.2 μm
1.6 μm
2.1 μm
2.2 μm
3.6 μm
4.5 μm
5.8 μm
8.0 μm
16 μm
24 μm
GJ 436b
TrES-1
XO-1b
HD 189733b
WASP-2b
HAT-P-1b
XO-2b
OGLE-TR-113b
HD 209458b
TrES-2
CoRoT-2b
HD 80606b
TrES-3
HD 149026b
WASP-4b
WASP-24b
TrES-4
WASP-1b
WASP-17b
WASP-14b
CoRoT-1b
WASP-19b
XO-3b
HAT-P-7b
OGLE-TR-56b
WASP-18b
WASP-12b
WASP-33b
Photochemistry
Equilibrium Chemistry


Brightness vs. Equilibrium Temperatures ($e < 0.1$)
Brightness Temperature (K)
Equilibrium Temperature (K)
0.6 μm
0.7 μm
0.9 μm
1.2 μm
1.6 μm
2.1 μm
2.2 μm
3.6 μm
4.5 μm
5.8 μm
8.0 μm
16 μm
24 μm
: all eclipses unpublished
TrES-1
HD 189733b
WASP-2b
XO-2b
OGLE-TR-113b
XO-1b
HAT-P-1b
HD 209458b
CoRoT-2b
TrES-2
WASP-4b
TrES-3
HD 149026b
WASP-24b
TrES-4
WASP-1b
WASP-17b
CoRoT-1b
WASP-14b
WASP-19b
HAT-P-7b
OGLE-TR-56b
WASP-18b
WASP-12b
WASP-33b
WASP-29b
WASP-11b
WASP-34b
WASP-43b
WASP-32b
HAT-P-16b
HAT-P-30b
HAT-P-13b
WASP-26b

A=0
uniform

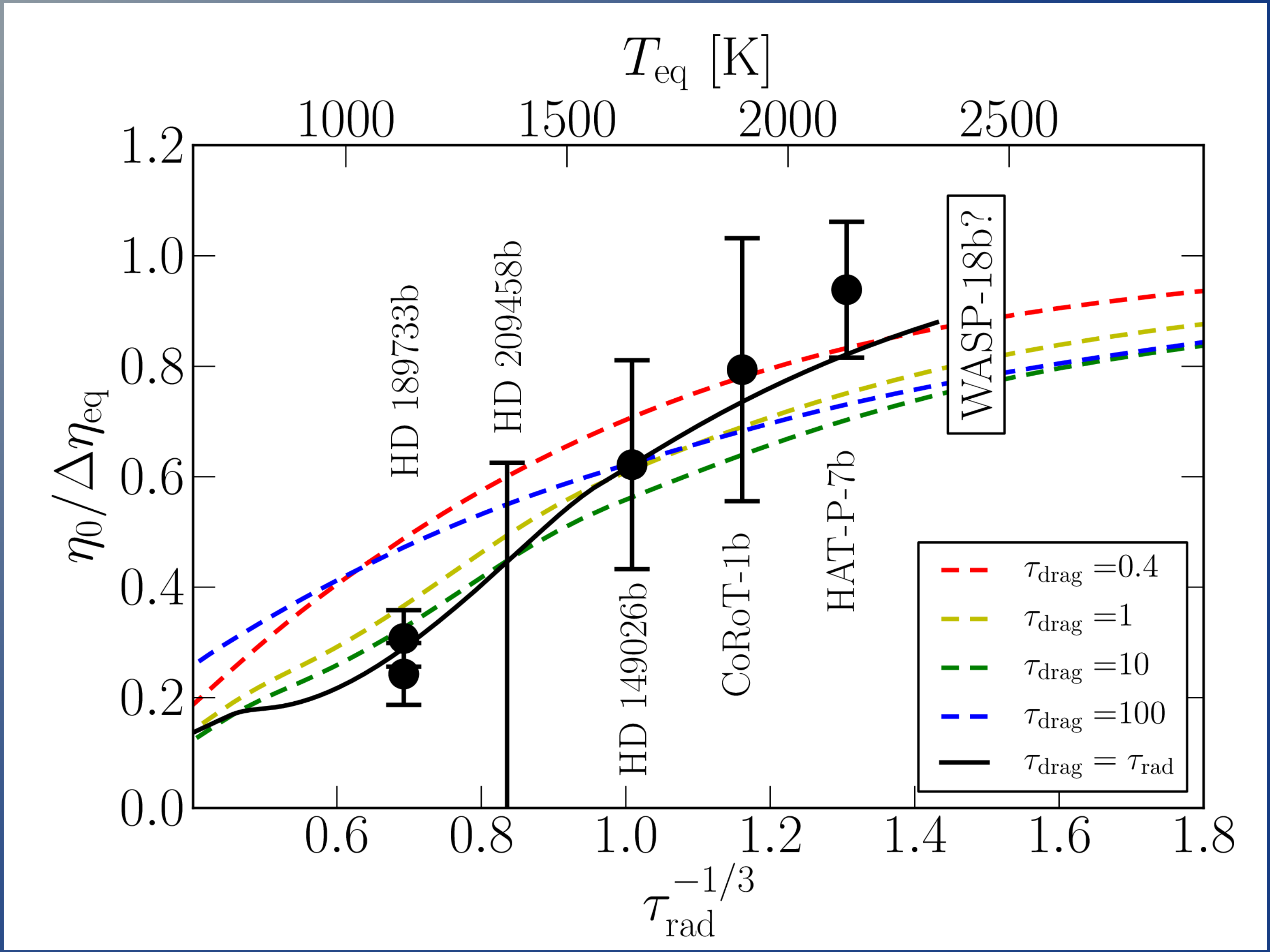
Mechanisms

- Transition cloudy -> cloudless (cf brown dwarfs)
  - But maybe *T(p)* profiles too steep to have clouds on many planets?
  - Data not yet clear
  - Just a few planets with higher albedo

Mechanisms

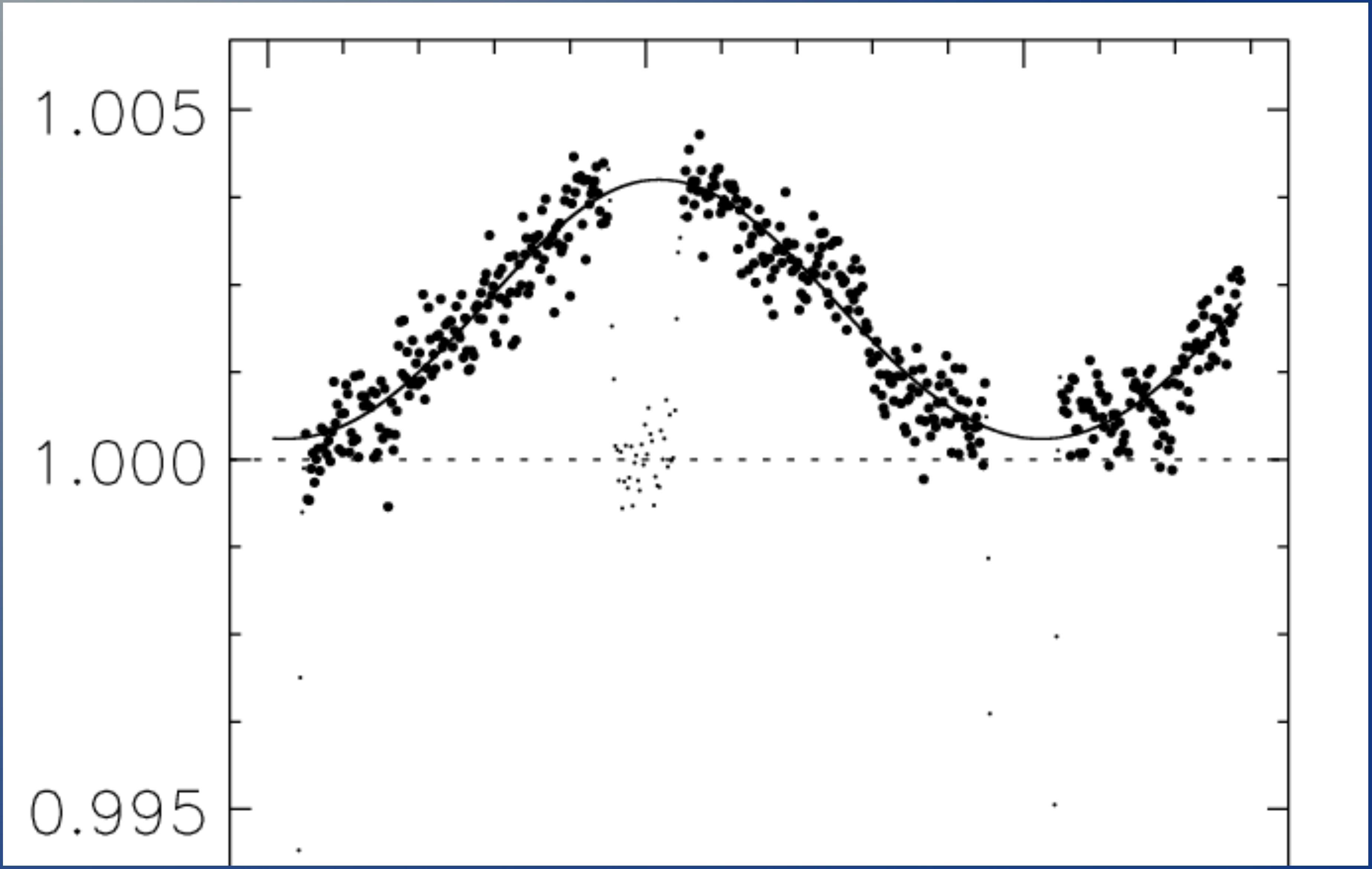
- Transition cloudy -> cloudless (cf brown dwarfs)
- Breakdown of circulation ($\tau_{rad} < \tau_{advect}$)
  - Discussed by Showman & Guillot (2002)
  - T_{rad} becomes so short that heat leaves fast
  - No time to advect to night side
  - Poor heat redistribution

Prediction for Phase Curves



Perez-Becker and Showman 2012

WASP-18b 4.5-μm Phase Curve



Maxted *et al*. 2012, *MNRAS*

Mechanisms

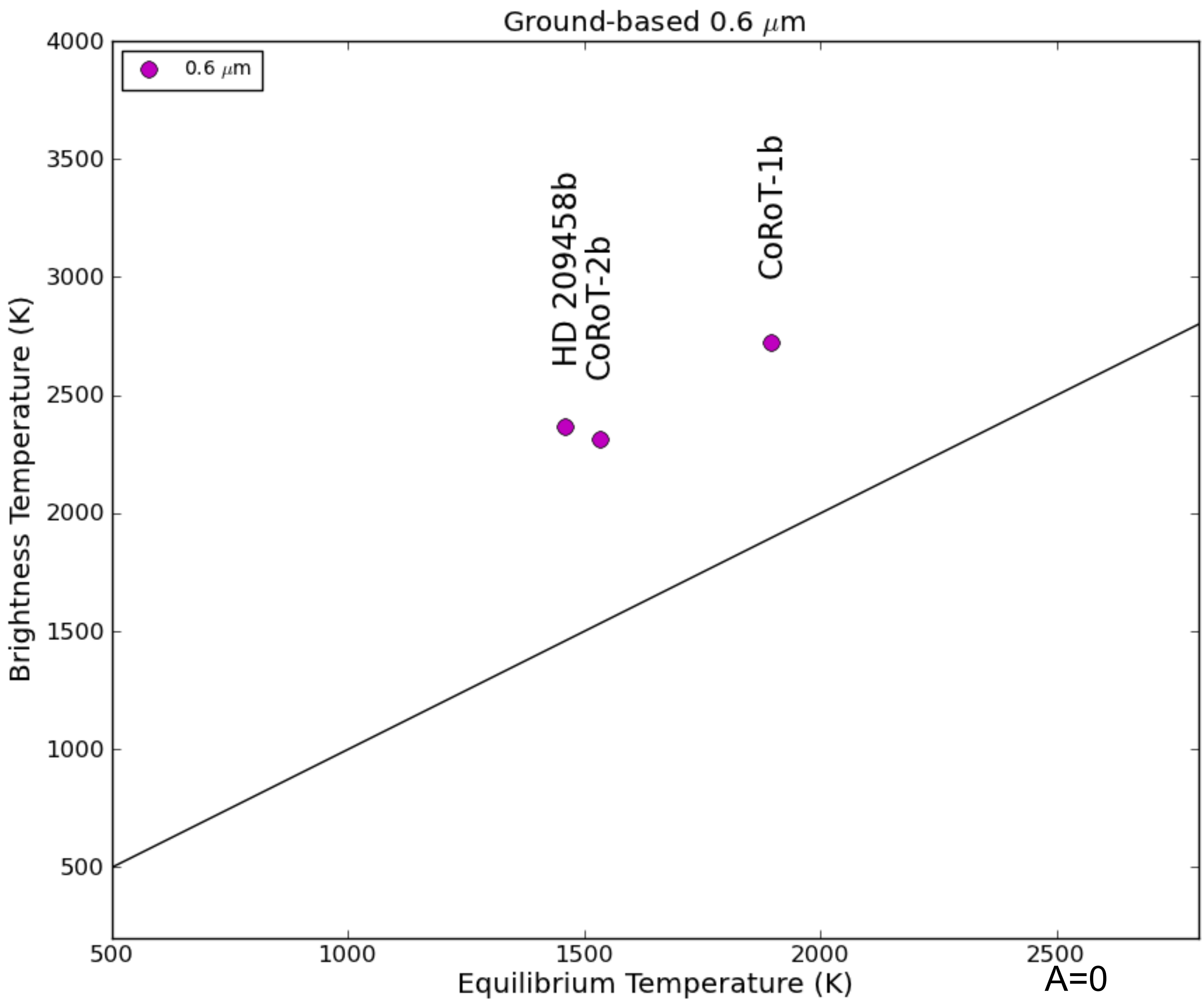
- Transition cloudy -> cloudless (cf brown dwarfs)
- Breakdown of circulation ($\tau_{rad} < \tau_{advect}$)
- Lack of TiO cold trap
  - Still not clear when it condenses
  - Should exist...
  - Should be abrupt

Mechanisms

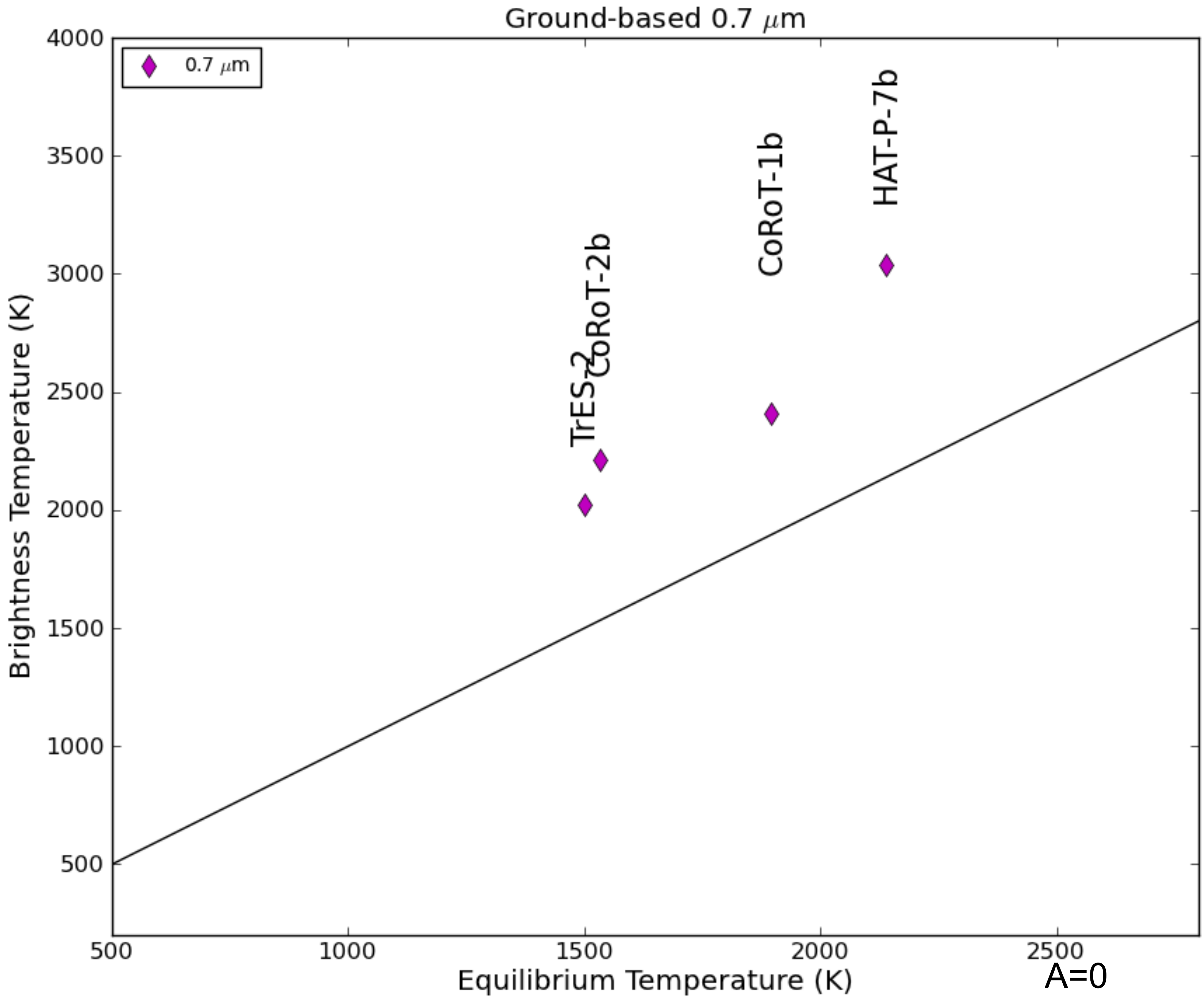
- Transition cloudy -> cloudless (cf brown dwarfs)
- Breakdown of circulation ($\tau_{rad} < \tau_{advect}$)
- Lack of TiO cold trap
- Other heating mechanisms
  - Mechanical (*Kzz*) greenhouse
  - Ohmic heating
  - High opacity of ions from ohmic heating?
- Onset seems sharp
- Need to fill in gaps & get points ~1800-2000 K

Conclusions

- Model-independent T_b *vs.* T_{eq} plot shows
  - Clear difference between $T_{eq} <> \sim 2000$ K
  - Promising: breakdown of circulation
  - Need more $T_{eq} < 1200$ K obs (hard!)
  - $T_{eq} > 2000$ K possible from ground!

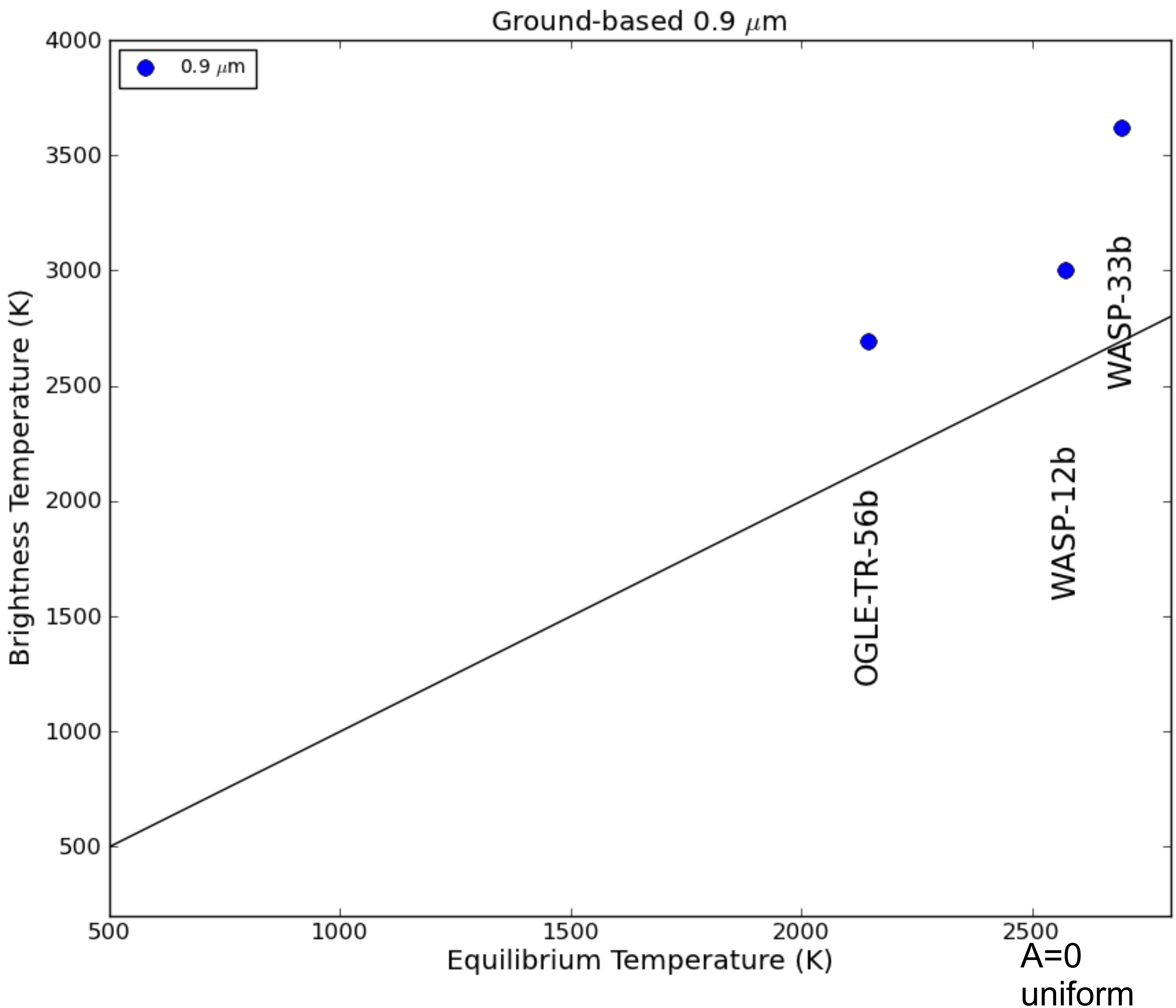

Ground-based 0.6 μm
0.6 μm
HD 209458b
CoRoT-2b
CoRoT-1b
Brightness Temperature (K)
Equilibrium Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500

A=0
uniform

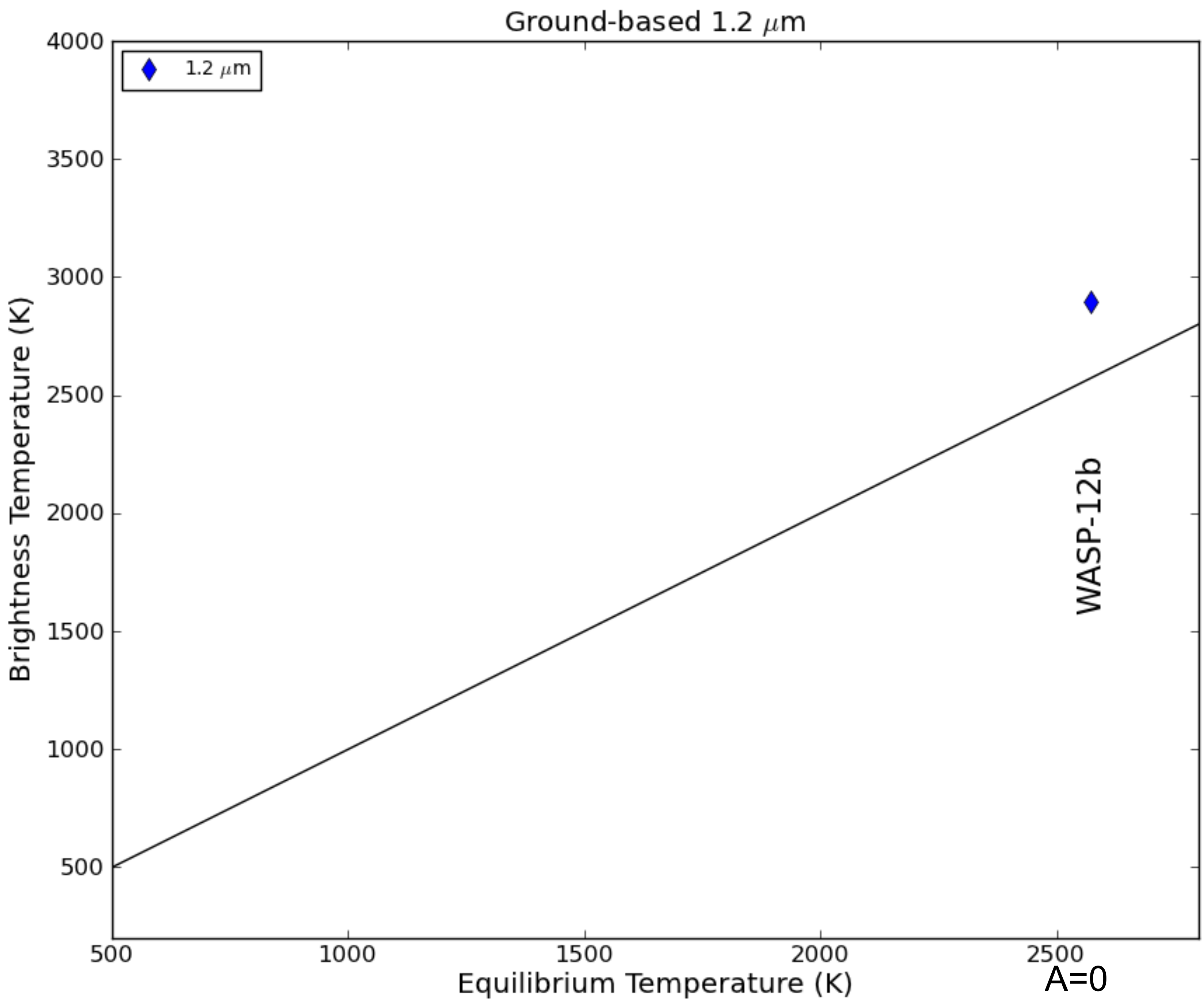


Ground-based 0.7 μm
0.7 μm
HAT-P-7b
CoRoT-1b
CoRoT-2b
TrES-2
Brightness Temperature (K)
Equilibrium Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500

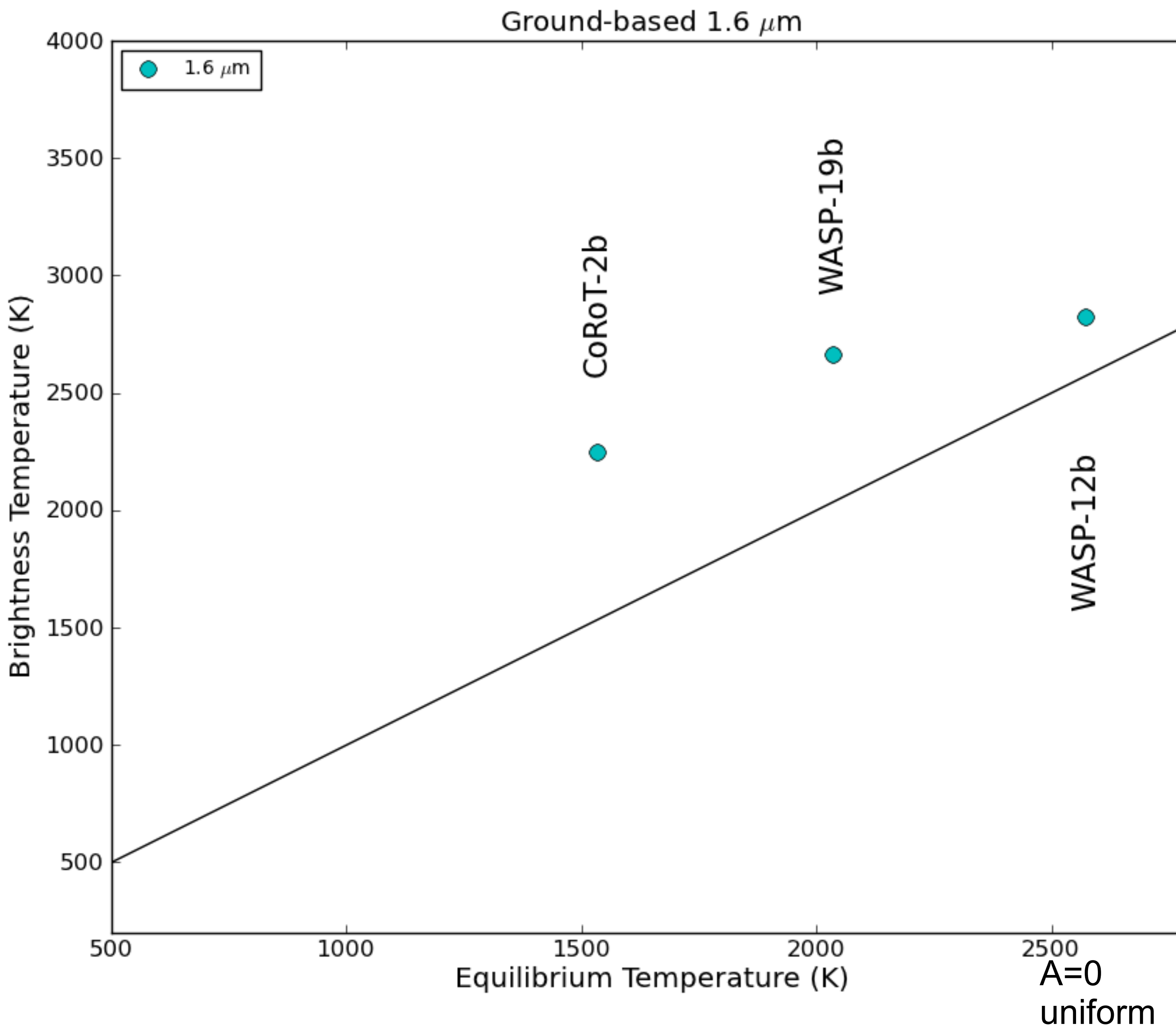
A=0
uniform

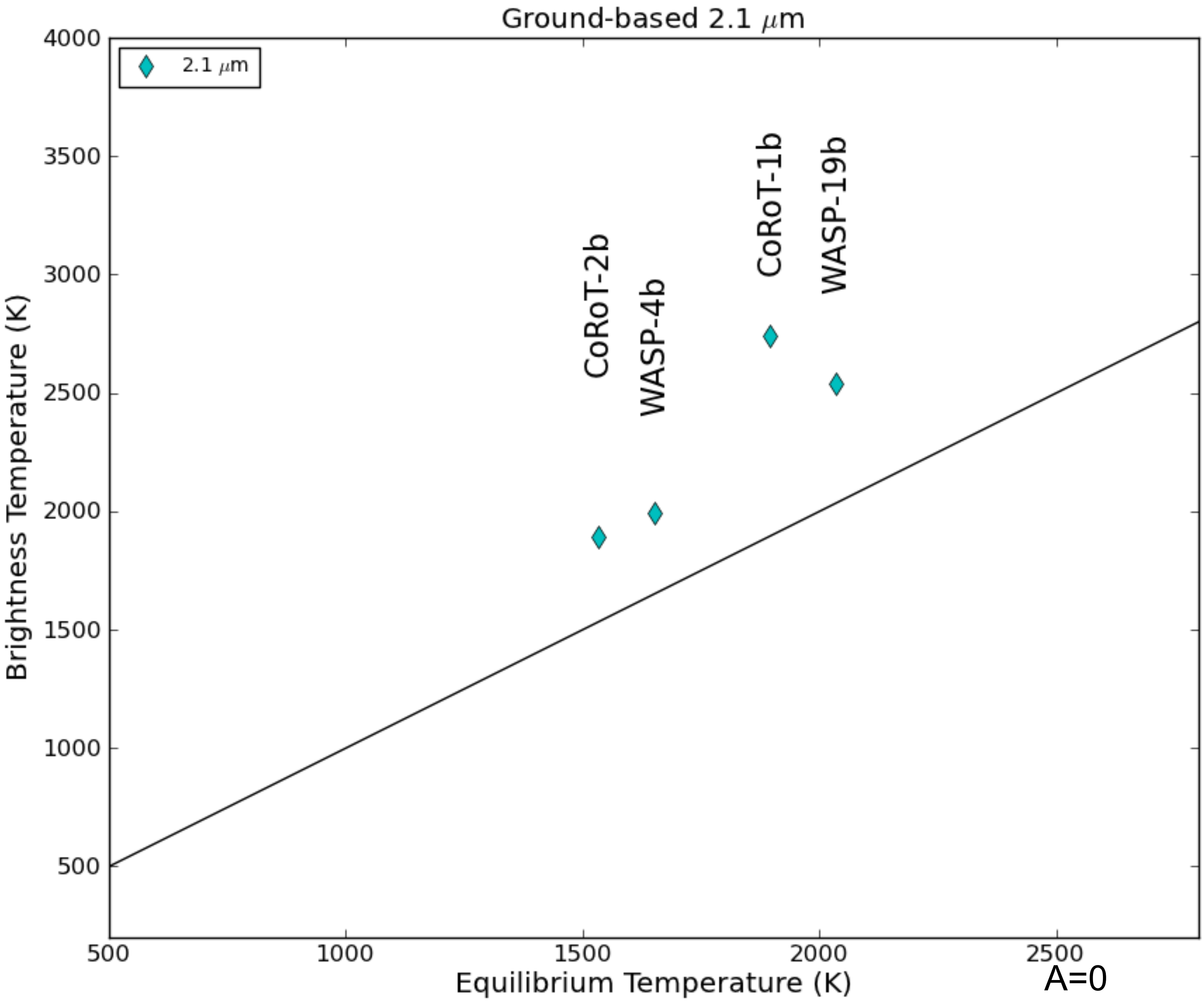


Ground-based 0.9 μm
0.9 μm
Brightness Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
Equilibrium Temperature (K)
OGLE-TR-56b
WASP-12b
WASP-33b
A=0
uniform

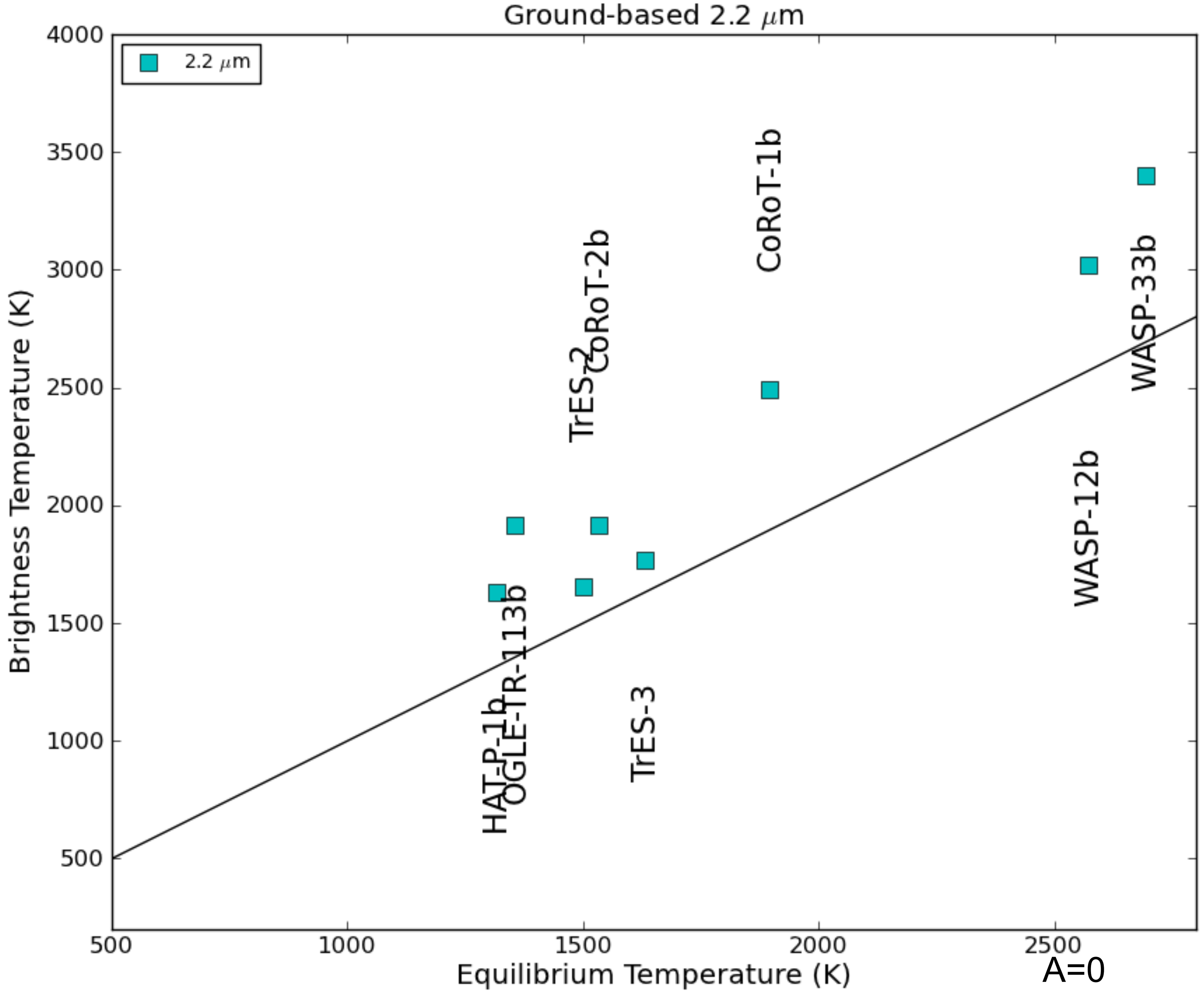

Ground-based 1.2 μm
1.2 μm
Brightness Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
Equilibrium Temperature (K)
WASP-12b

A=0
uniform

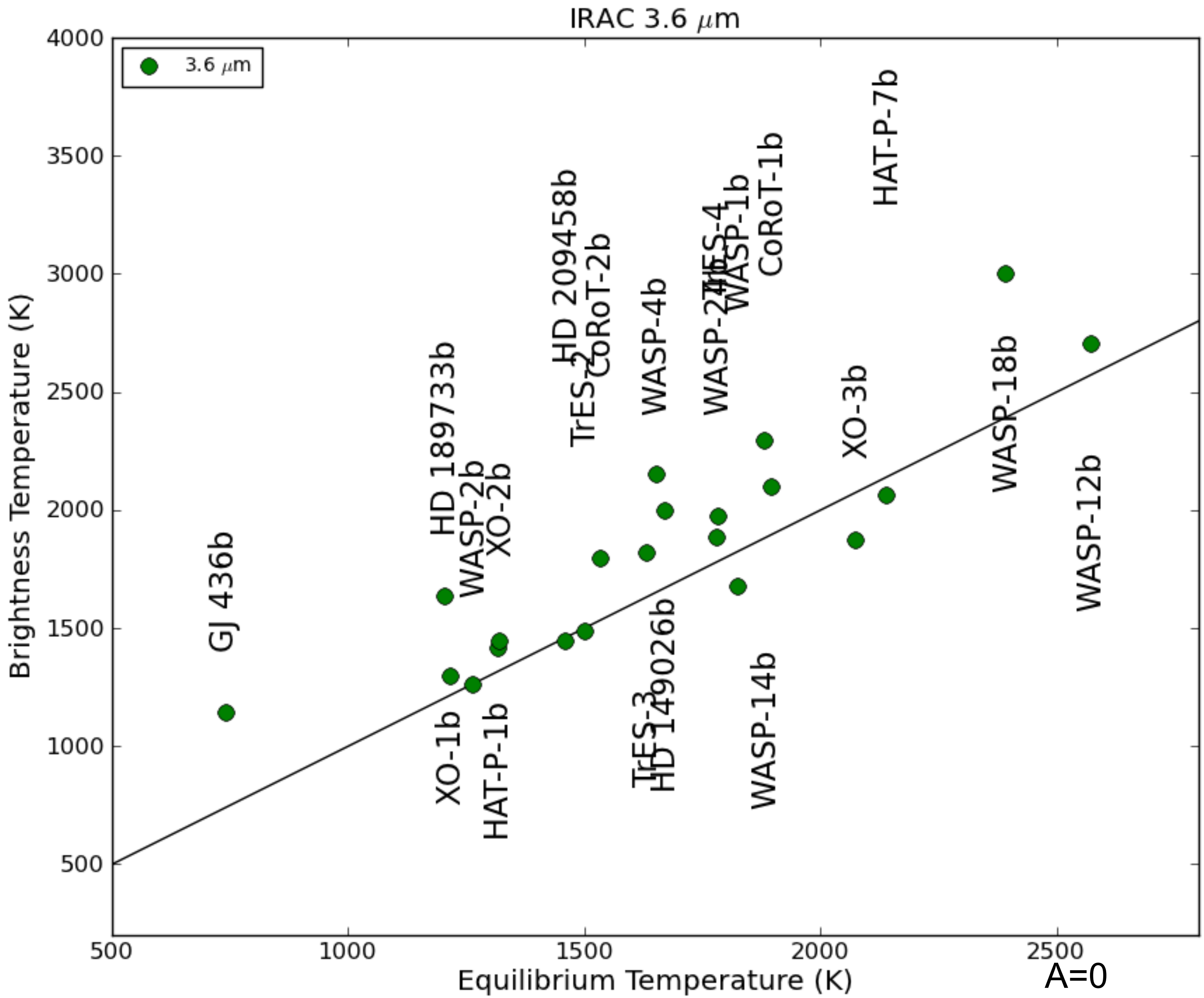

Ground-based 1.6 μm
1.6 μm
CoRoT-2b
WASP-19b
WASP-12b
Brightness Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
Equilibrium Temperature (K)
A=0
uniform


Ground-based 2.1 μm
2.1 μm
CoRoT-2b
WASP-4b
CoRoT-1b
WASP-19b
Brightness Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
Equilibrium Temperature (K)

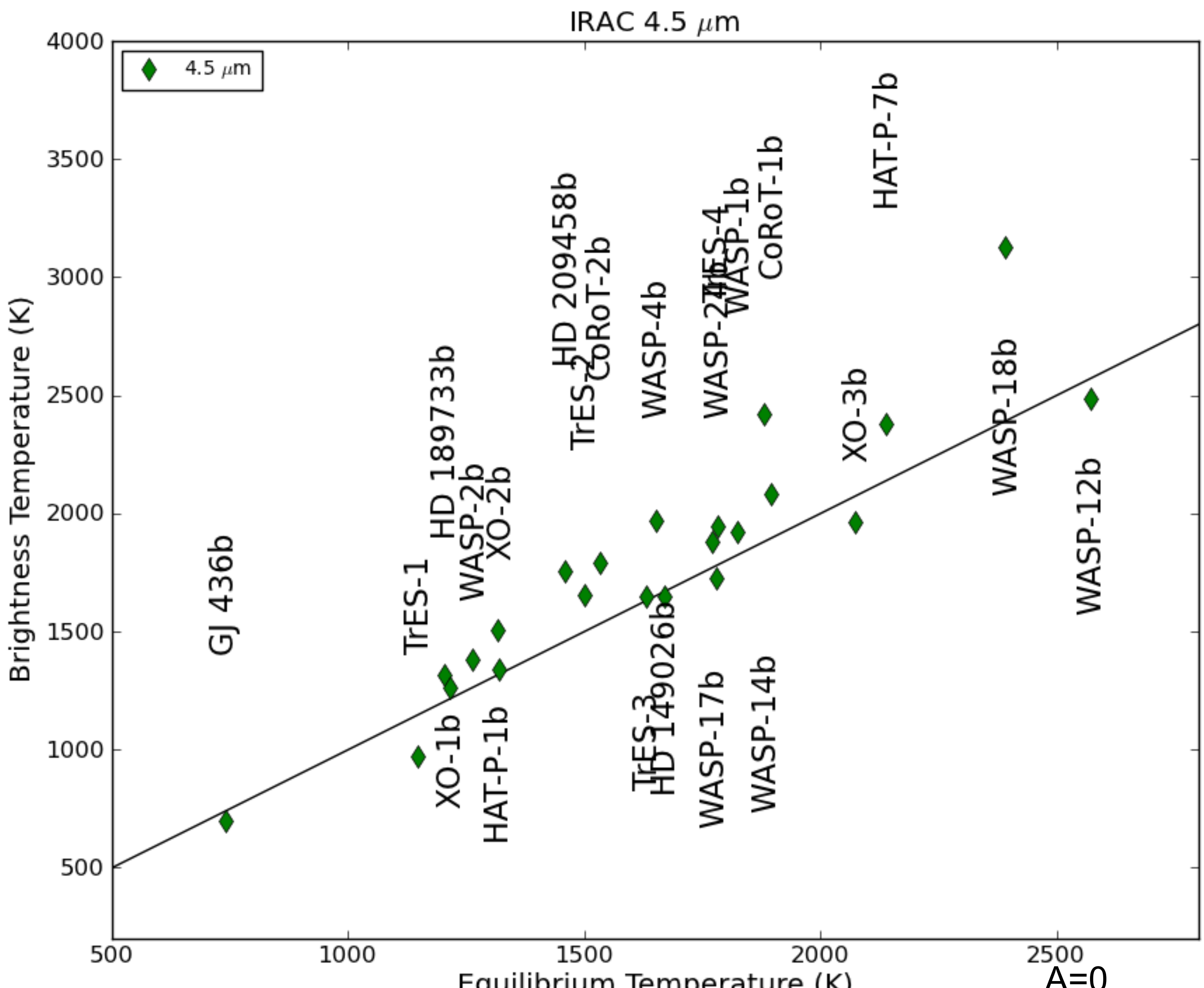
A=0
uniform


Ground-based 2.2 μm
2.2 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
CoRoT-1b
CoRoT-2b
TrES-2
WASP-33b
WASP-12b
OGLE-TR-113b
HAT-P-1b
TrES-3

A=0
uniform

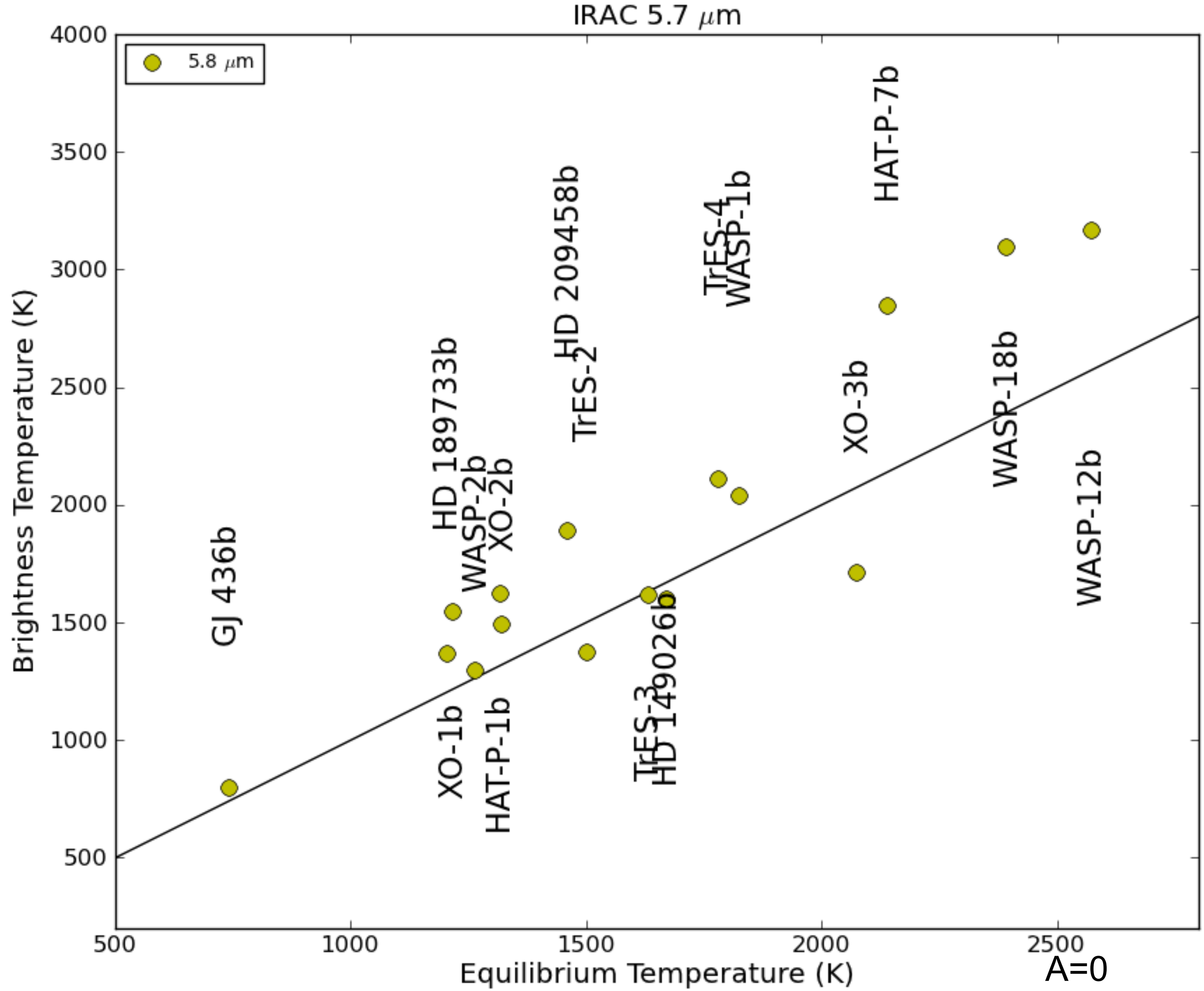

IRAC 3.6 μm
3.6 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
GJ 436b
HD 189733b
WASP-2b
XO-2b
XO-1b
HAT-P-1b
TrES-2
HD 209458b
CoRoT-2b
WASP-4b
TrES-3
HD 149026b
WASP-24b
TrES-4
WASP-1b
CoRoT-1b
WASP-14b
XO-3b
HAT-P-7b
WASP-18b
WASP-12b

A=0
uniform

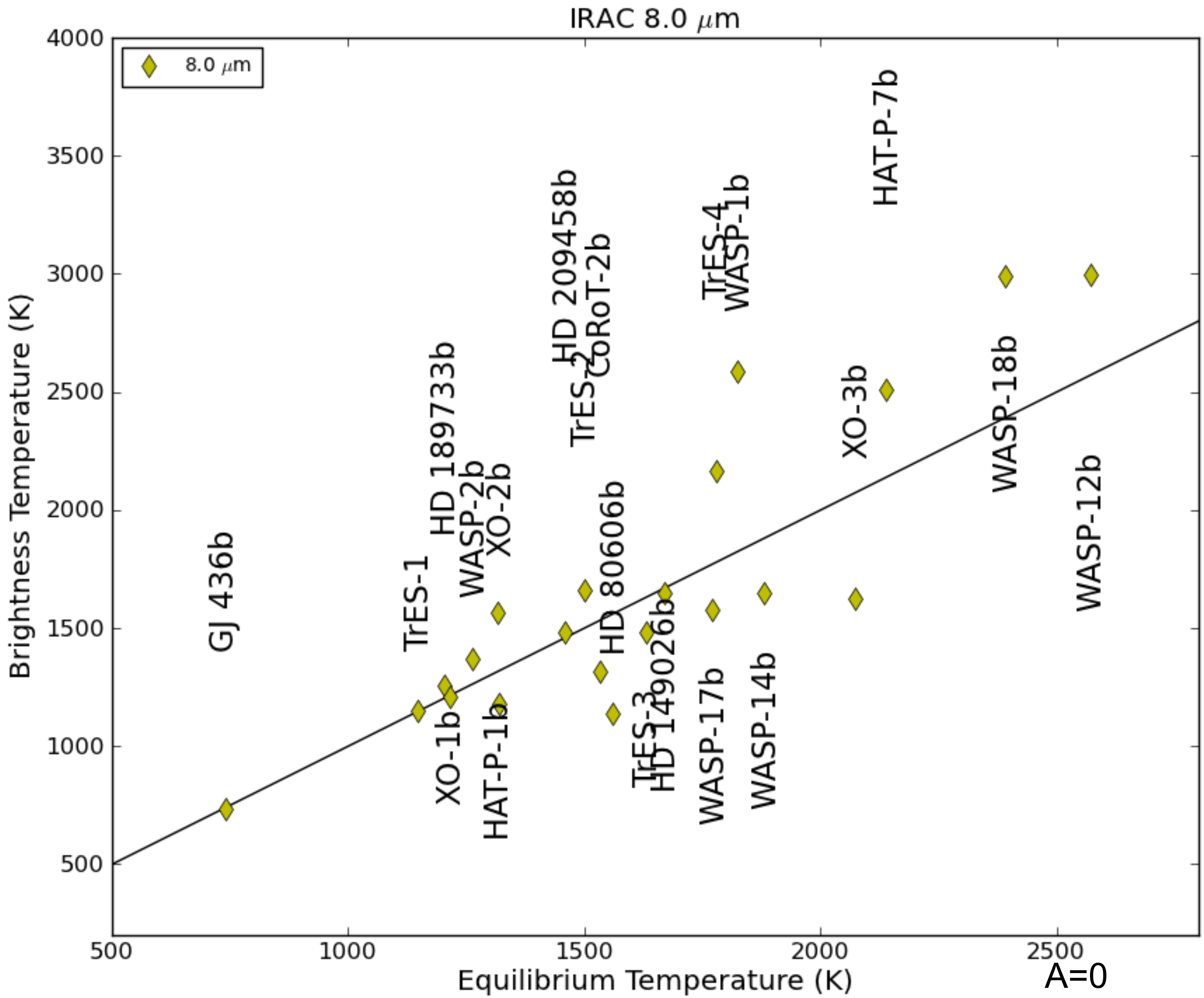


IRAC 4.5 μm
4.5 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
GJ 436b
TrES-1
HD 189733b
WASP-2b
XO-2b
XO-1b
HAT-P-1b
HD 209458b
TrES-2
CoRoT-2b
WASP-4b
TrES-3
HD 149026b
WASP-17b
WASP-14b
WASP-1b
CoRoT-1b
HAT-P-7b
XO-3b
WASP-18b
WASP-12b

A=0
uniform

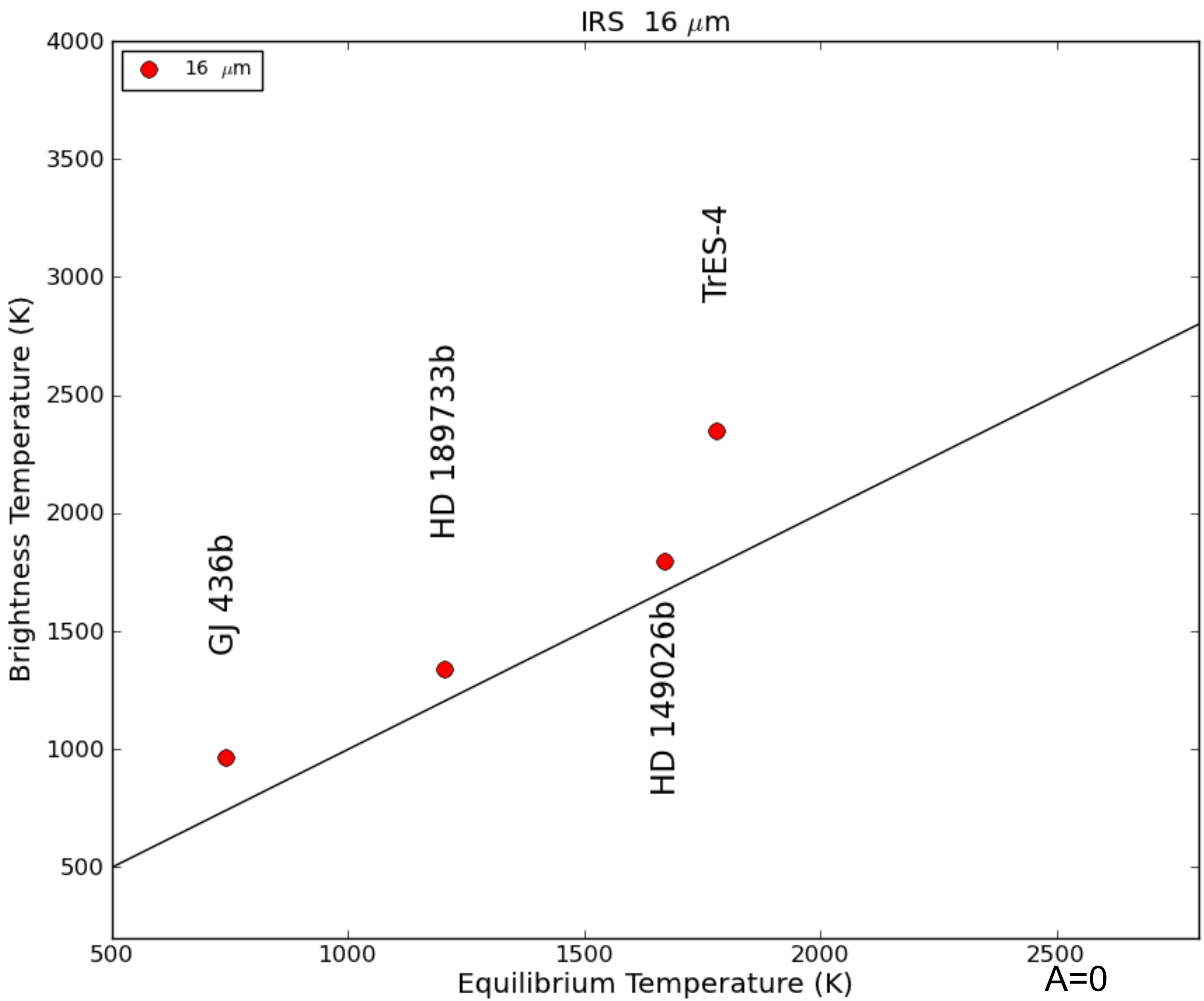

IRAC 5.7 μm
5.8 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
GJ 436b
XO-1b
HD 189733b
WASP-2b
XO-2b
HAT-P-1b
HD 209458b
TrES-2
TrES-3
HD 149026b
TrES-4
WASP-1b
XO-3b
HAT-P-7b
WASP-18b
WASP-12b

A=0
uniform



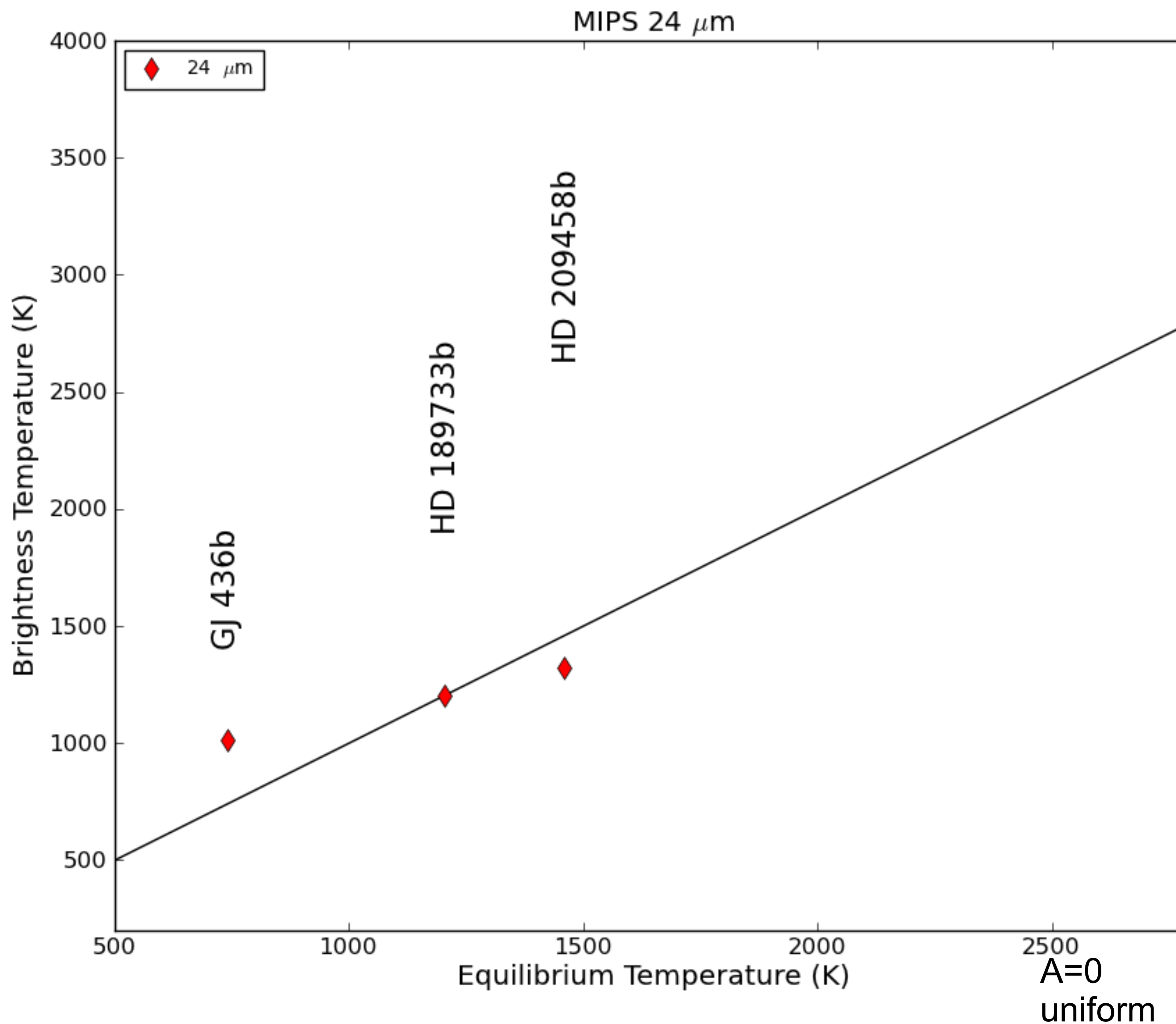
IRAC 8.0 μm
8.0 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
GJ 436b
TrES-1
XO-1b
HD 189733b
WASP-2b
XO-2b
HAT-P-1b
HD 209458b
TrES-2
CoRoT-2b
HD 80606b
TrES-3
HD 149026b
TrES-4
WASP-1b
WASP-17b
WASP-14b
XO-3b
HAT-P-7b
WASP-18b
WASP-12b

A=0
uniform



IRS 16 μm
16 μm
Brightness Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
Equilibrium Temperature (K)
GJ 436b
HD 189733b
HD 149026b
TrES-4

A=0
uniform


MIPS 24 μm
24 μm
Brightness Temperature (K)
4000
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
Equilibrium Temperature (K)
GJ 436b
HD 189733b
HD 209458b
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