# Two Classes of Exoplanets: Hot and Hotter

Joseph Harrington
and the UCF Exoplanets Group

Planetary Sciences Group
University of Central Florida
Orlando, Florida

# Atmospheres and Astrophysics

- Exoplanets combine planetary science and astrophysics observation
- For astrophysics, exoplanet data are awesome!
- For planetary science, quality is terrible!
- More data 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 < 1000K
- No comparable sensitivity at these wavelengths
  - Complements obs. at other wavelengths
- Eclipses can absolutely calibrate spectra
- Demonstrates need for FINESSE! (next talk, Swain)
  - Purpose-built for stability on exoplanet spectra

# UCF's Spitzer Exoplanet Program

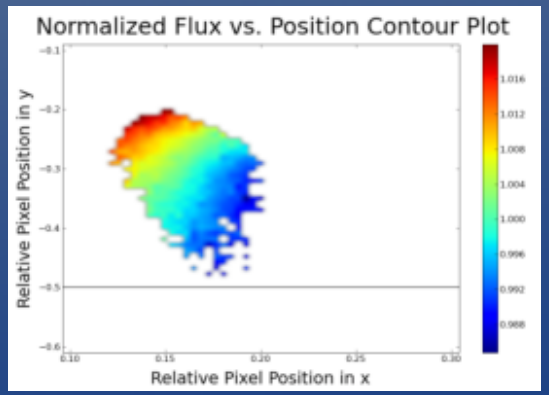
- Dozens of Spitzer secondary eclipses
- POET: Photometry of Orbits, Eclipses, Transits
  - Interpolated aperture photometry
  - Try dozens of systematics models
  - Statistical rigor: BIC selects/eliminates models
  - BLISS intrapixel mapper (Stevenson talk Wed.)
  - TIDe wavelet-based noise filtering (Blecic poster)
  - Tests: convergence, red noise, monomodality,...
  - Detailed methods descriptions in papers
- *Reliability slows things down and costs more*
- ~6 papers / yr, lead ~2+ / yr, ~1 *Nature* / yr

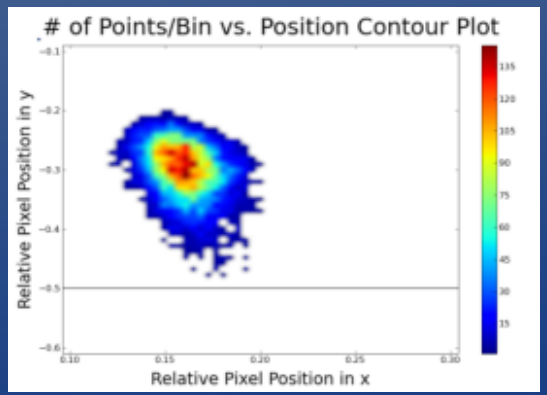
# Why So Careful?

- Reanalyses: problems with simple analyses
- Events often weak, <4σ, upper limits
- Most analyses have right eclipse depths
  - A few non-monomodal 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

# WASP-43b – Jasmina Blecic

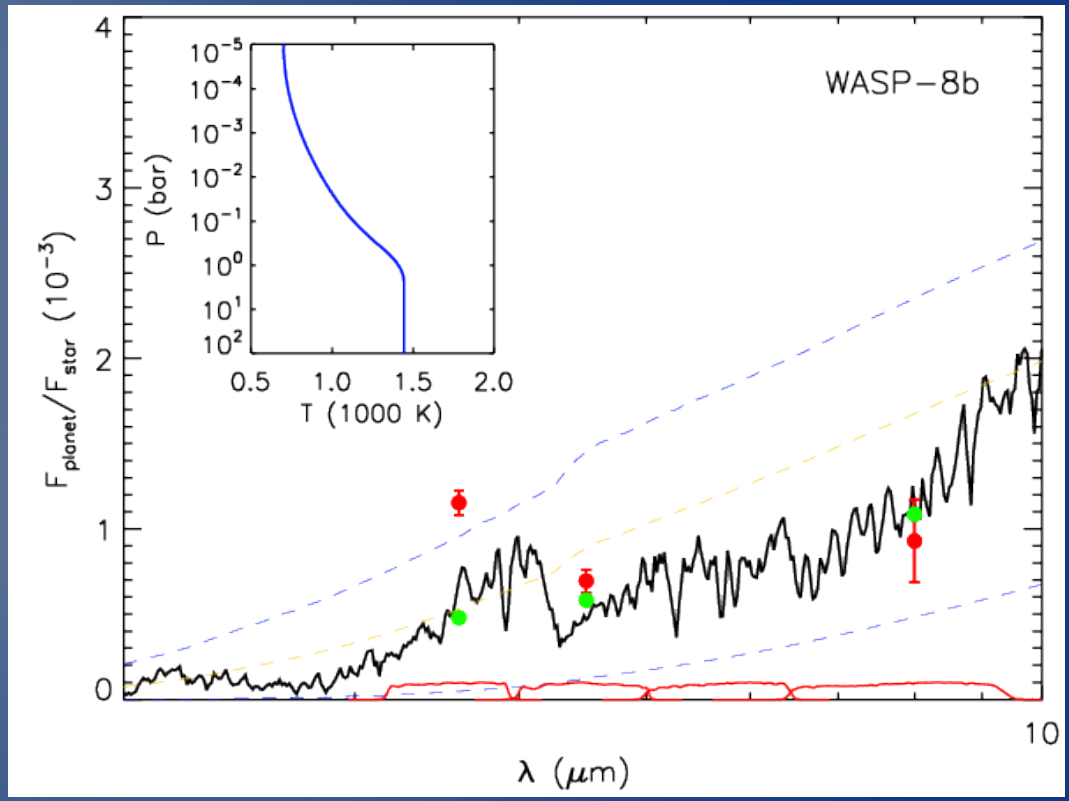
- Poster Pitch!
- IRAC 3.6, 4.5 μm
- High S/N
- No inversion
- Yet, similarly irradiated to HD 209458b...
- BLISS, TIDe, MCMC orthogonalization




BLISS pixel mapping method
Stevenson et al. (2010),
submitted to *ApJ*

# WASP-8b – Patricio Cubillos

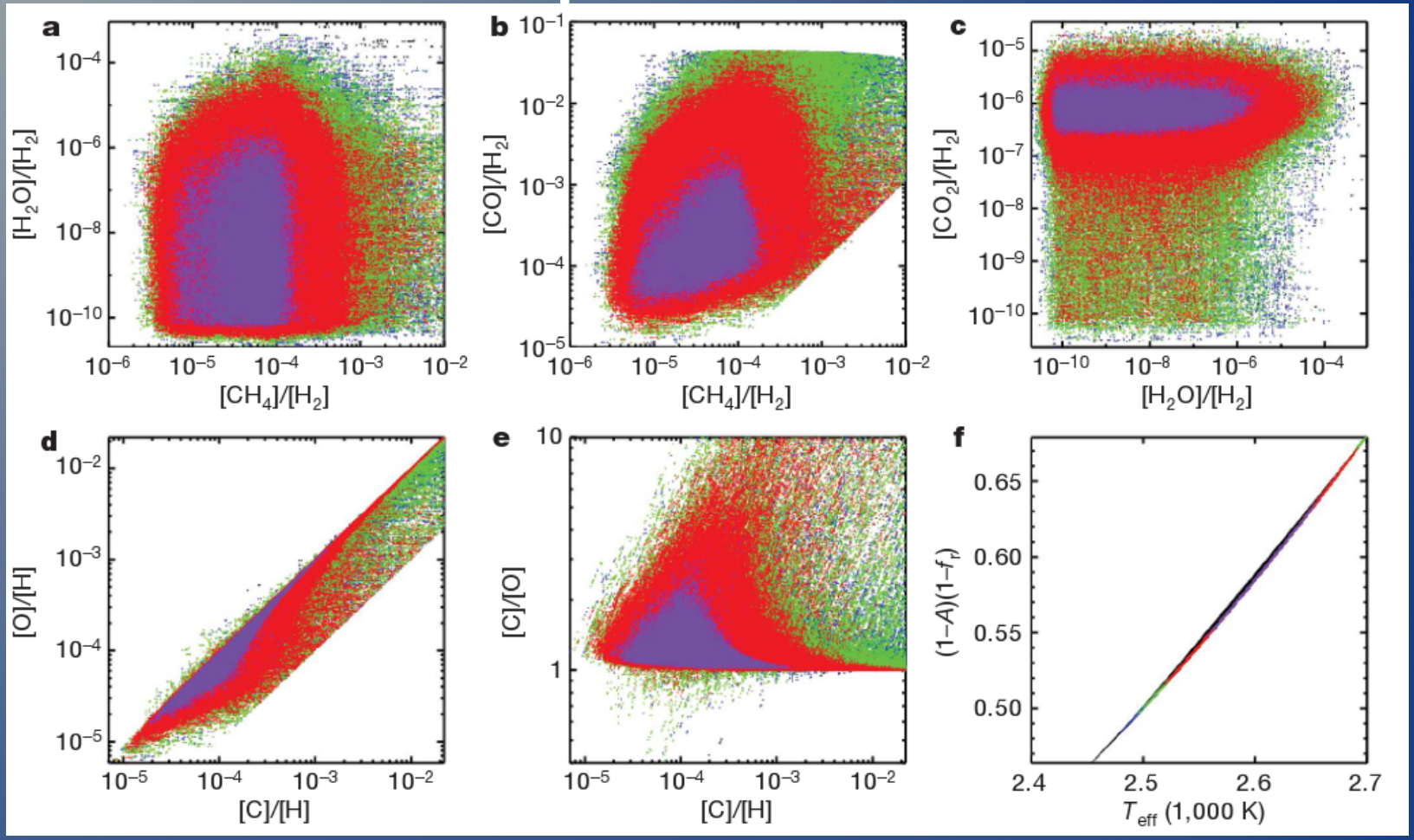



- Poster Pitch!
- $T_{eq}$ = 940K, $e$ = 0.31
- IRAC 3.6, 3×4.5, 8 μm
- Temp. near maximum $T_{eq}$ on orbit
- No inversion, high $T_b$ possible if $T_{rad}$ < 100 hrs

# Dataset Utility Per Planet

- Want to characterize planet
- But, low resolution, small number of points
- Cannot justify 2D or 3D models
- Cannot definitively identify unique composition
  - Good way to justify spectroscopy!
- CAN identify interesting effects
  - Disequilibrium chemistry (Stevenson et al 2010)
  - C/O > 1 (Madhusudhan et al 2011)
  - Inversions and rough thermal structure

# Atmospheric Constraints




Poster Pitch: Mike Line developing optimal inverse Bayesian approach, much less computation, better intuition. Talk this morning by Lee.

- MCMC tells what questions data can answer
- For WASP-12b, C/O > 1 jumps out
- J. Blecic to make an open-source version

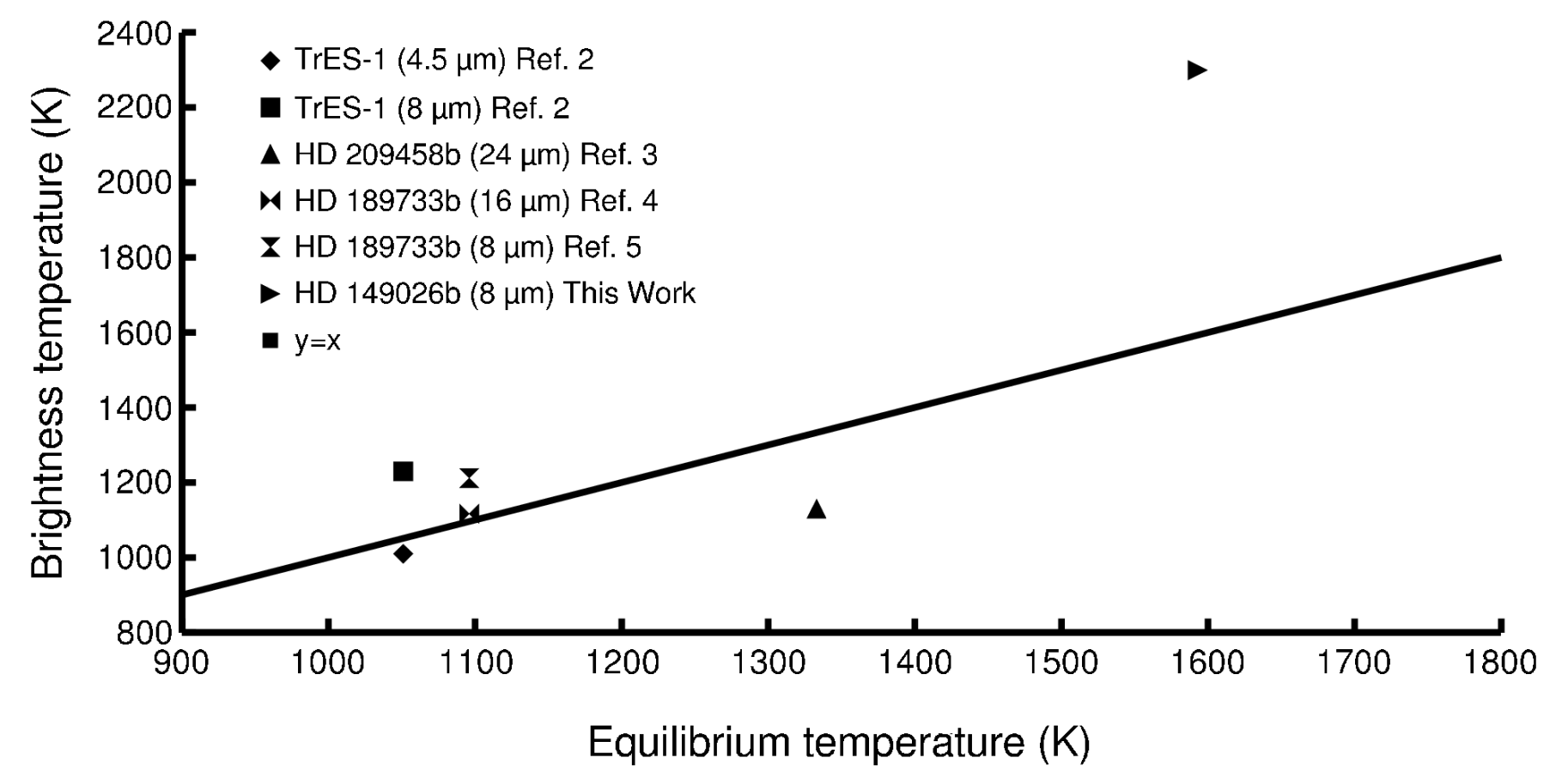
# Datasets' Utility In Ensemble

- “When the going gets tough, the tough... do statistics?”
- Plot aggregate information
  - 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 output fluxes to each other
  - Same or different planet
- Stellar fluxes differ for each planet, not intuitive
- Want intuitive units wrt chemistry, clouds
- Temperature is usual energy parameter in atm.
- Try brightness ($T_b$) *vs.* equilibrium ($T_{eq}$) temps

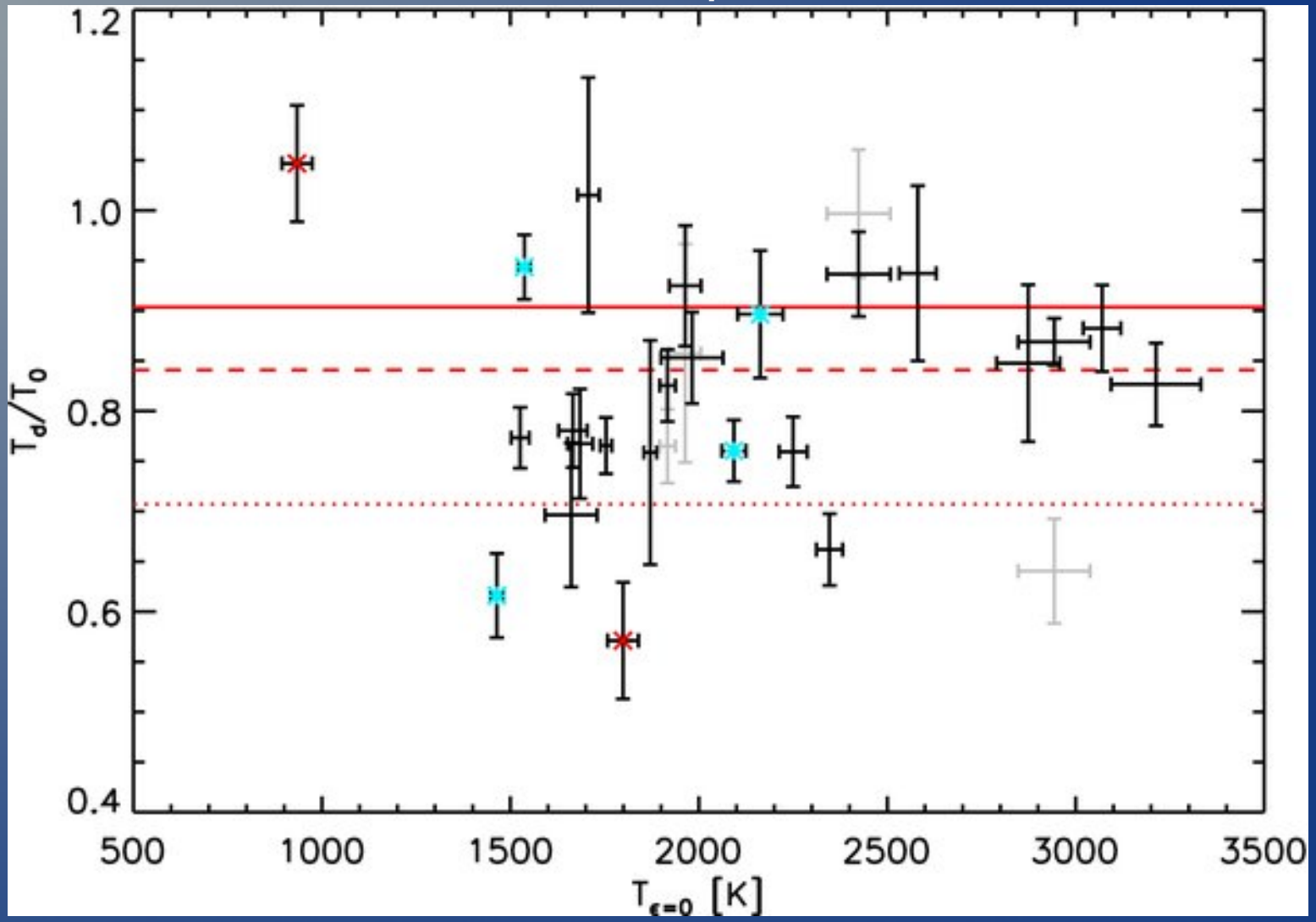
# $T_b$ *vs.* $T_{eq}$: 2007




Just 6 measurements on 4 planets!

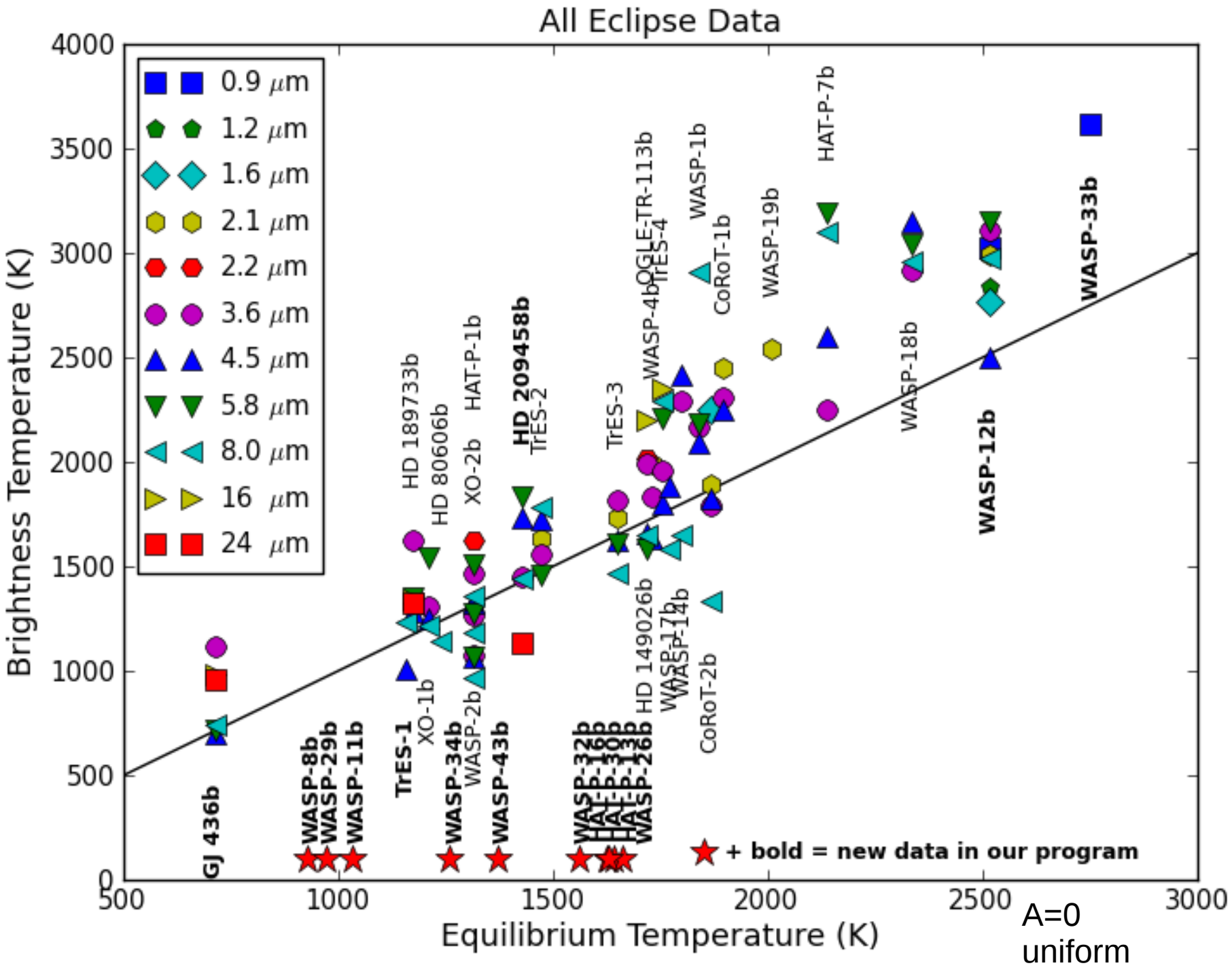
Harrington et al. (2007), *Nature*
Assumes A=0.3, uniform emission

# $T_b$ *vs.* $T_{eq}$ : 2011




High temp more consistent than low.

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


All Eclipse Data
Brightness Temperature (K)
Equilibrium Temperature (K)
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
+ bold = new data in our program
GJ 436b
WASP-8b
WASP-29b
WASP-11b
TrES-1
XO-1b
HD 189733b
HD 80606b
WASP-34b
WASP-2b
XO-2b
HAT-P-1b
WASP-43b
HD 209458b
TrES-2
WASP-32b
HAT-P-16b
HAT-P-30b
HAT-P-13b
WASP-26b
TrES-3
HD 149026b
WASP-4b
OGLE-TR-113b
TrES-4
WASP-14b
WASP-17b
CoRoT-2b
WASP-1b
CoRoT-1b
WASP-19b
HAT-P-7b
WASP-18b
WASP-12b
WASP-33b
A=0
uniform

# Mechanisms

- Transition cloudy -> cloudless (cf brown dwarfs)

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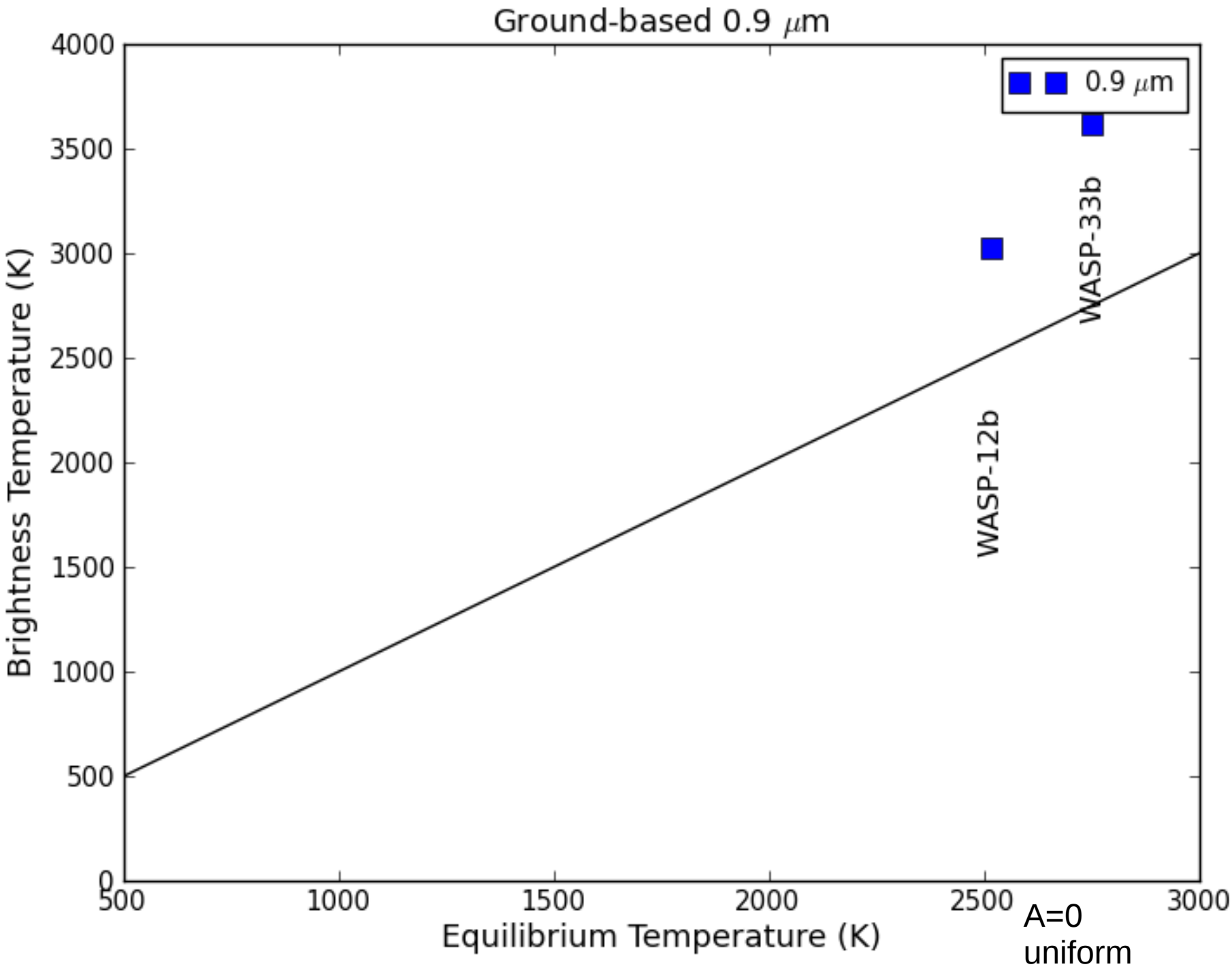
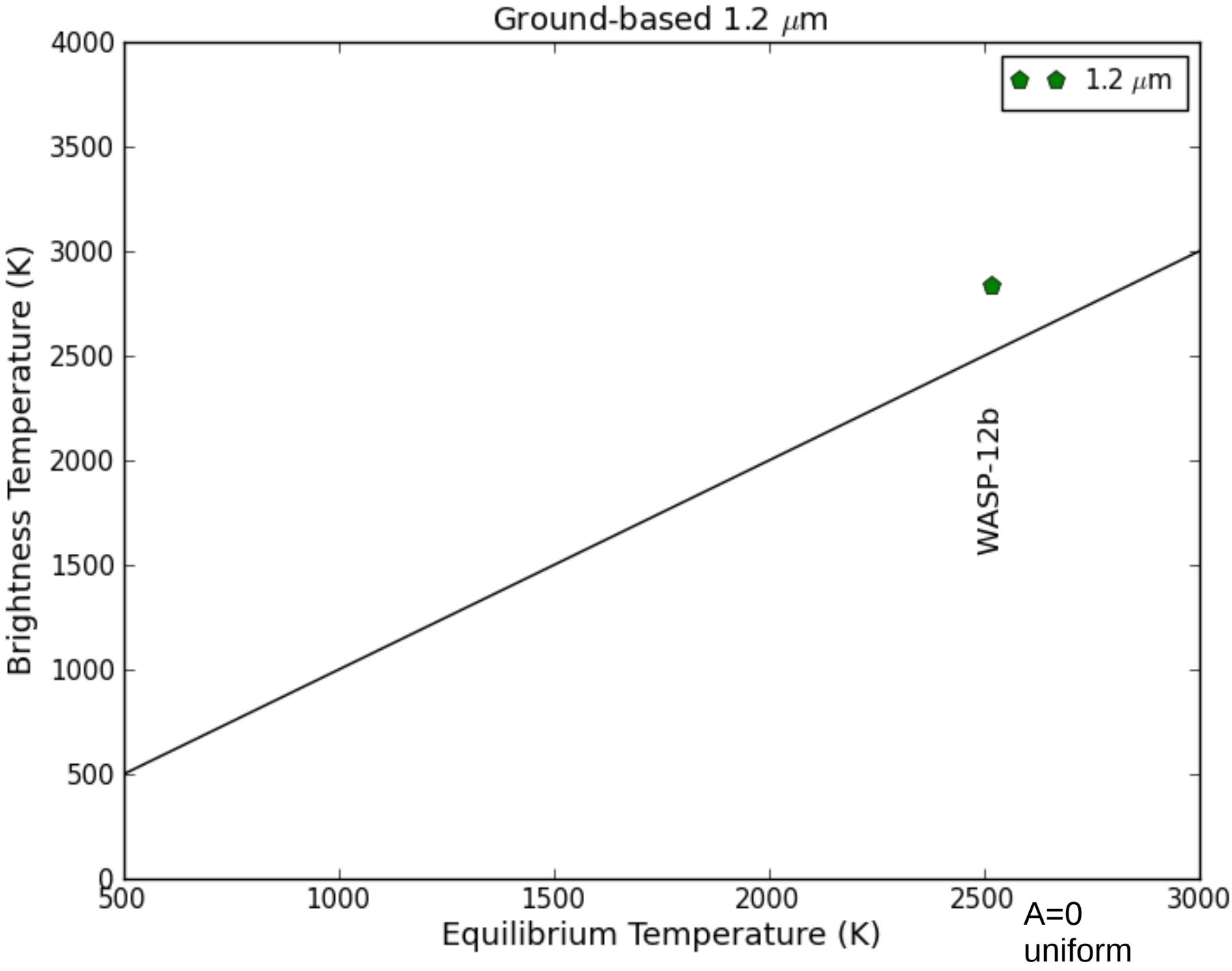
- Lack of TiO cold trap
- Mechanical (*K*zz) greenhouse
- Ohmic heating
- High opacity of ions from ohmic heating?
- Onset seems sharp
- Need to fill in gaps & get points ~1800-2000K

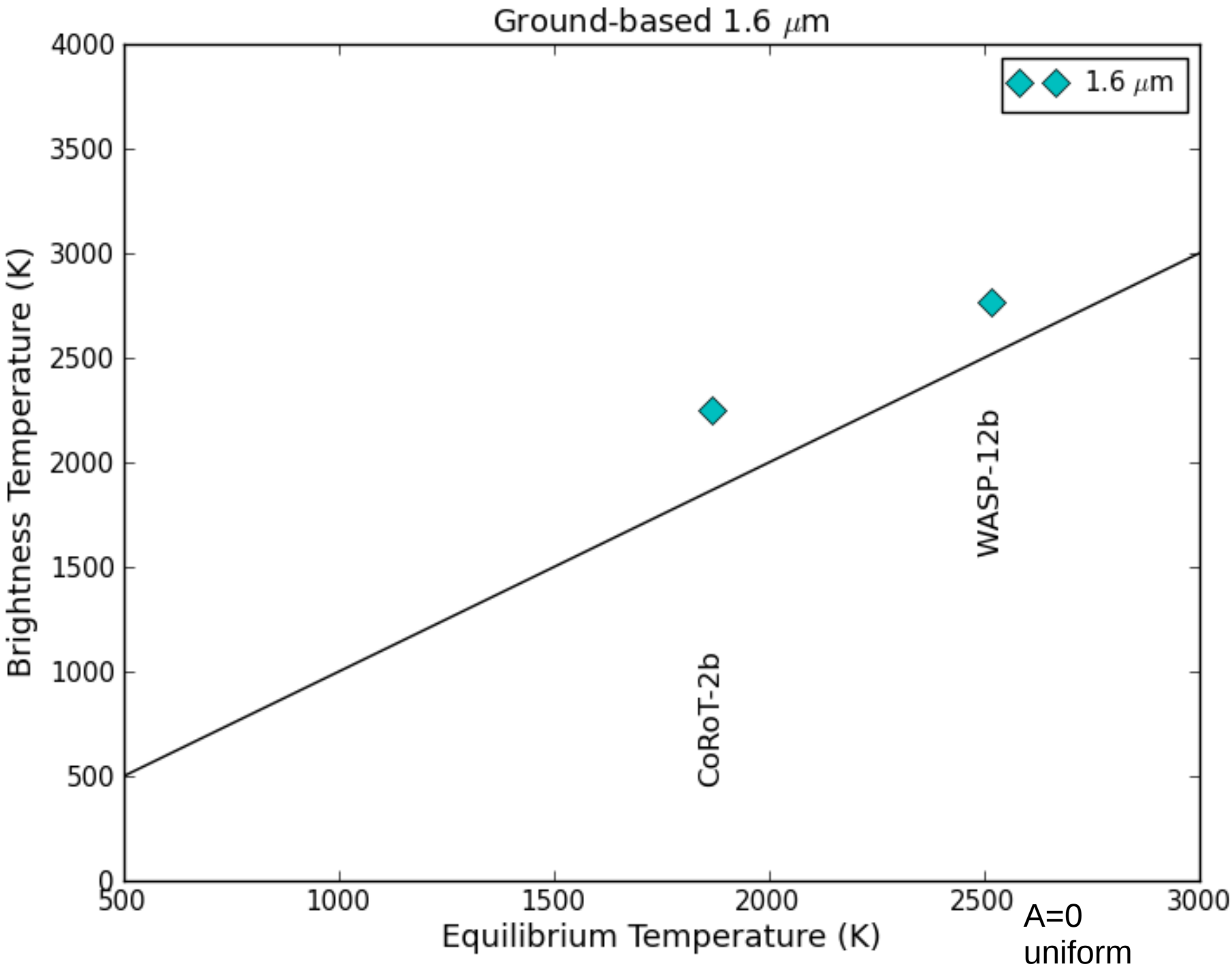
# Conclusions

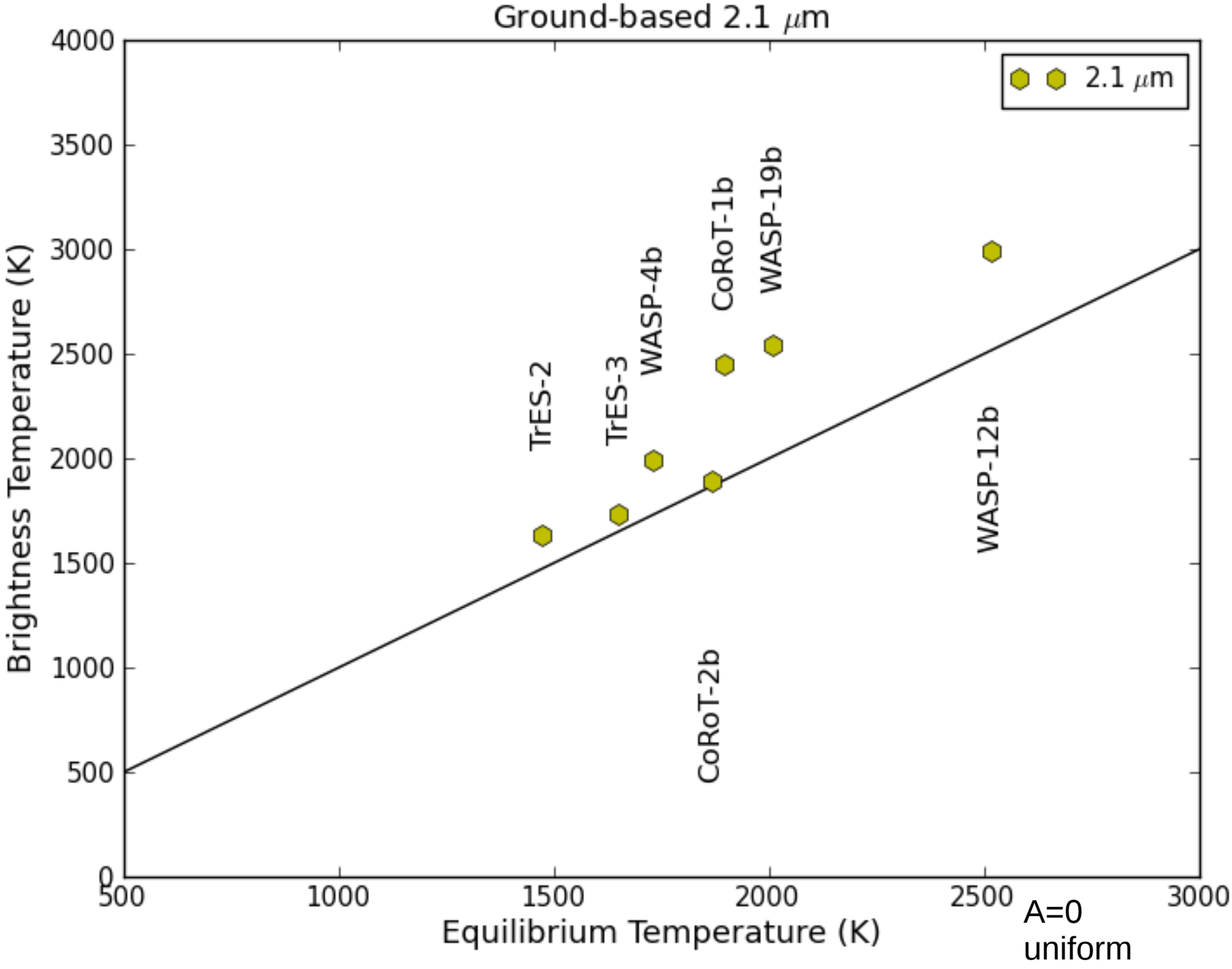
- Spitzer is an atmosphere measuring machine!
  - Even SOFIA can't reach longer Spitzer λs
- Model-independent $T_b$ *vs.* $T_{eq}$ plot shows
  - Clear difference between $T_{eq}$ <> ~2000 K
  - Numerous possible mechanisms (go theorists!)
  - Need more $T_{eq}$ < 1200 K obs (hard!)
  - $T_{eq}$ > 2000 K possible from ground!
- Rigor in analyses critical, often missing
  - Want to fit models to $T_b$ *vs.* $T_{eq}$ plot
  - But, errors problematic, $\chi^2$ unreliable


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

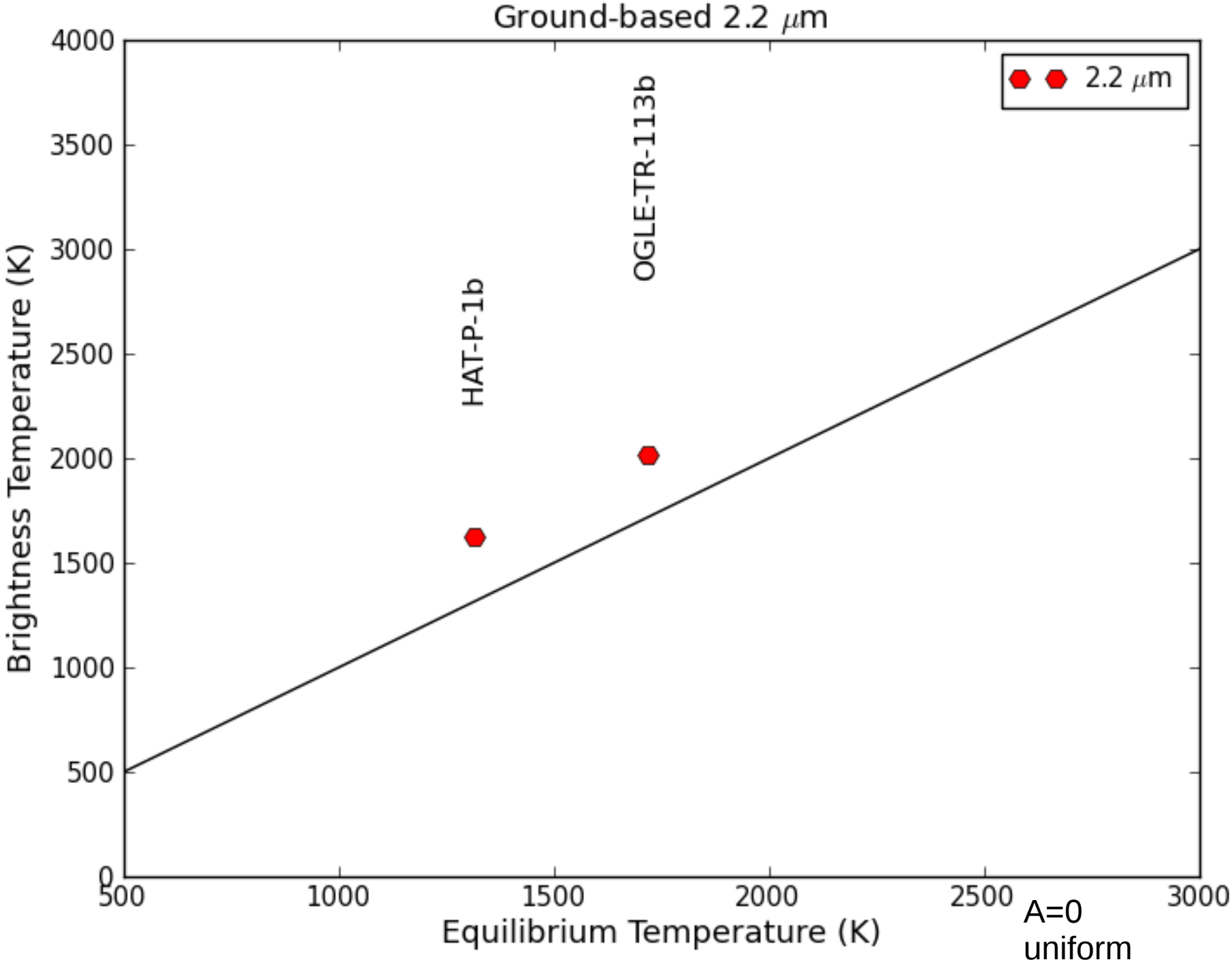

Ground-based 1.2 μm
1.2 μm
WASP-12b
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000

A=0
uniform

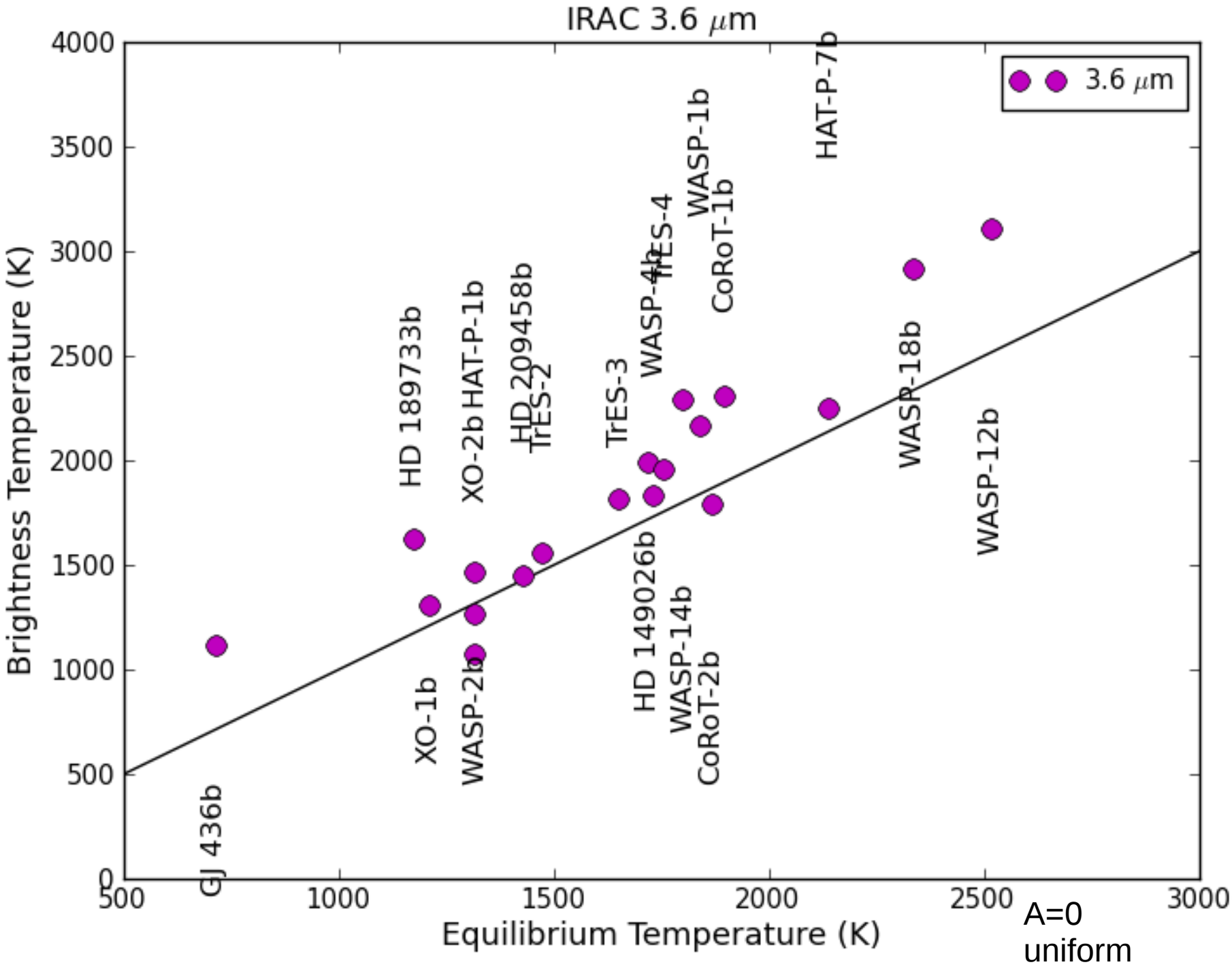

Ground-based 1.6 μm
1.6 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000
CoRoT-2b
WASP-12b
A=0
uniform


Ground-based 2.1 $\mu$m
2.1 $\mu$m
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000
TrES-2
TrES-3
WASP-4b
CoRoT-1b
WASP-19b
WASP-12b
CoRoT-2b

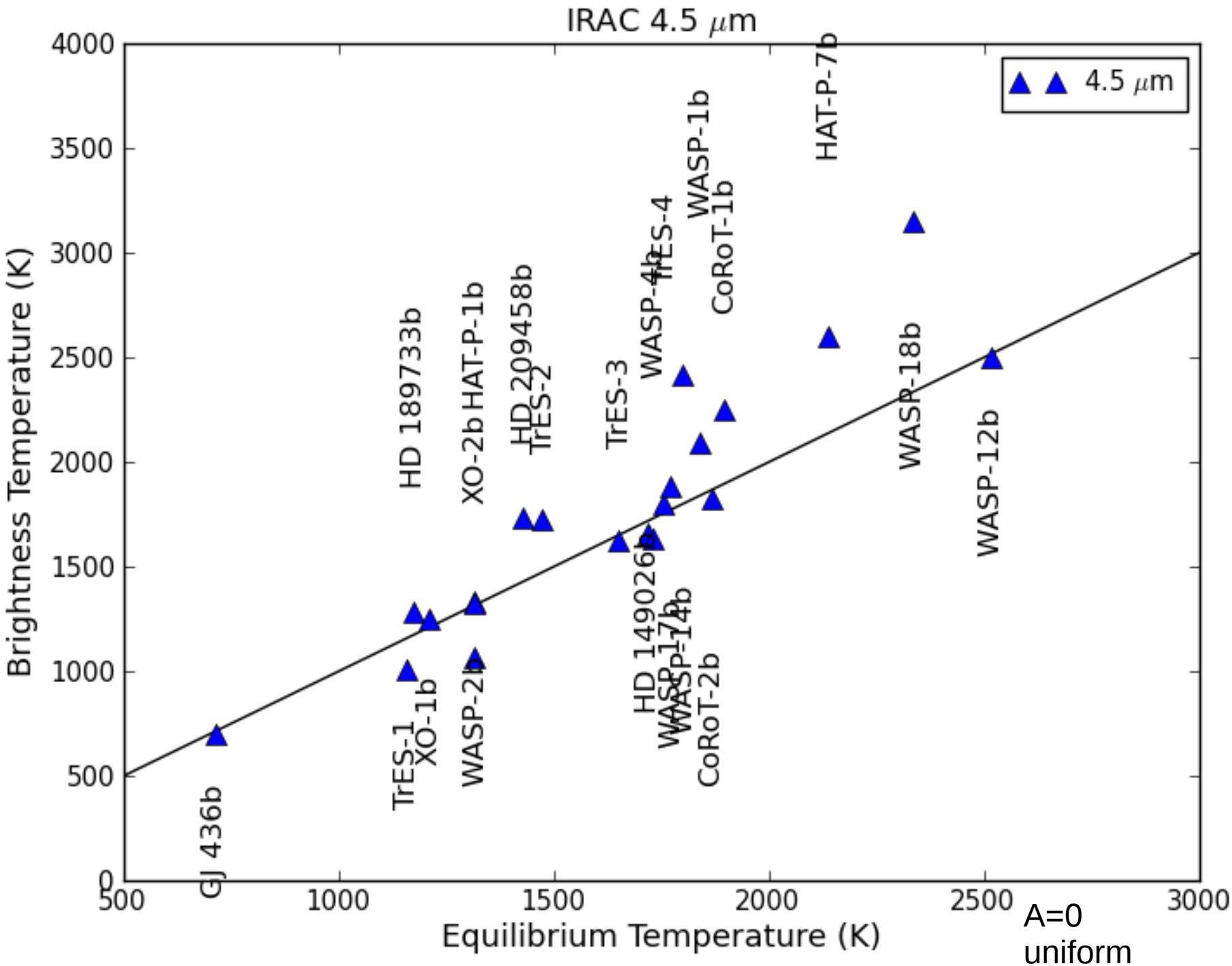
A=0
uniform


Ground-based 2.2 $\mu$m
2.2 $\mu$m
HAT-P-1b
OGLE-TR-113b
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000

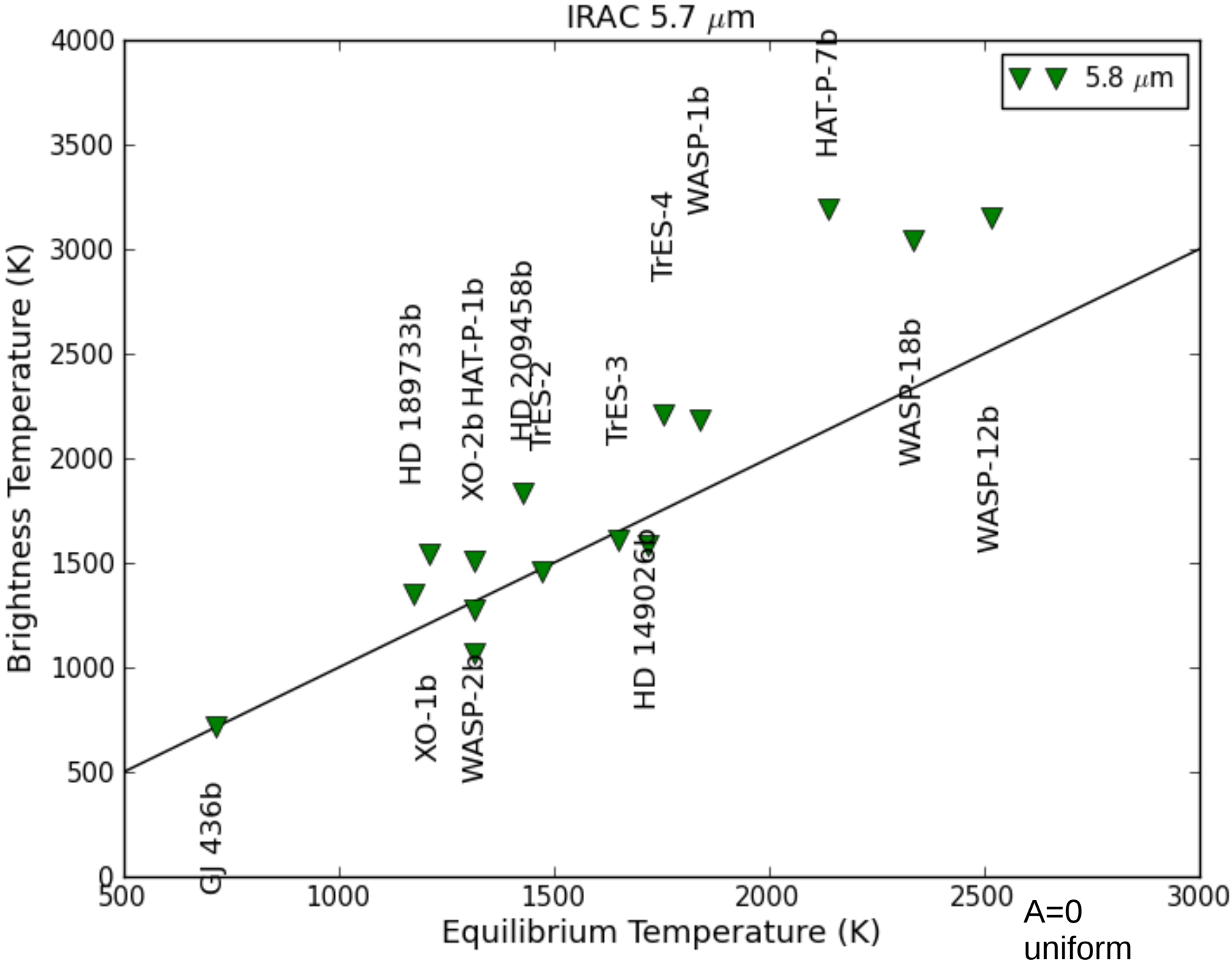
A=0
uniform


IRAC 3.6 μm
3.6 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000
GJ 436b
XO-1b
WASP-2b
HD 189733b
XO-2b
HAT-P-1b
HD 209458b
TrES-2
TrES-3
WASP-4b
TrES-4
HD 149026b
WASP-14b
CoRoT-2b
WASP-1b
CoRoT-1b
HAT-P-7b
WASP-18b
WASP-12b

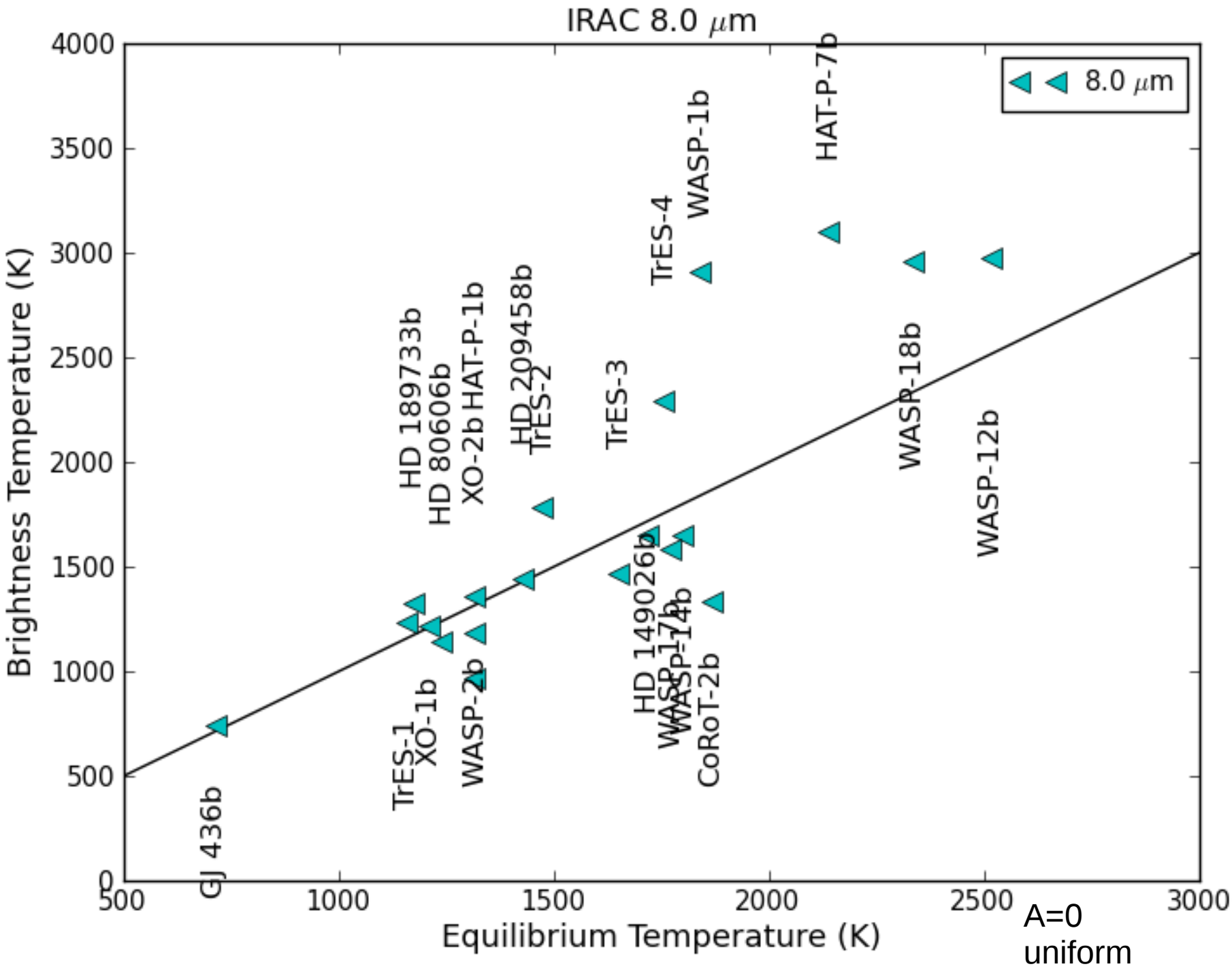
A=0
uniform


IRAC 4.5 μm
4.5 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000
GJ 436b
TrES-1
XO-1b
WASP-2b
HD 189733b
XO-2b
HAT-P-1b
HD 209458b
TrES-2
TrES-3
HD 149026b
WASP-17b
WASP-14b
WASP-4b
TrES-4
CoRoT-2b
WASP-1b
CoRoT-1b
HAT-P-7b
WASP-18b
WASP-12b

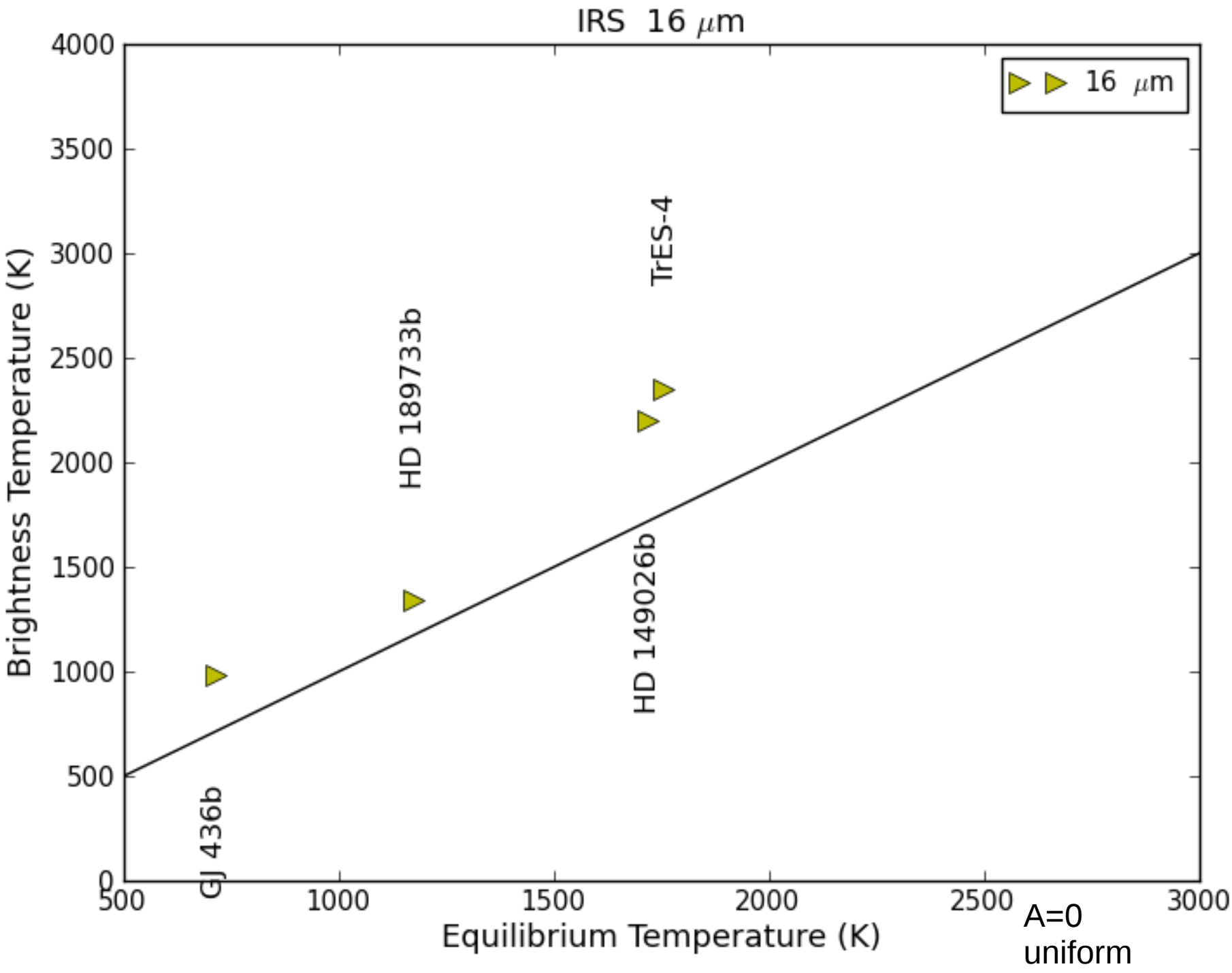
A=0
uniform

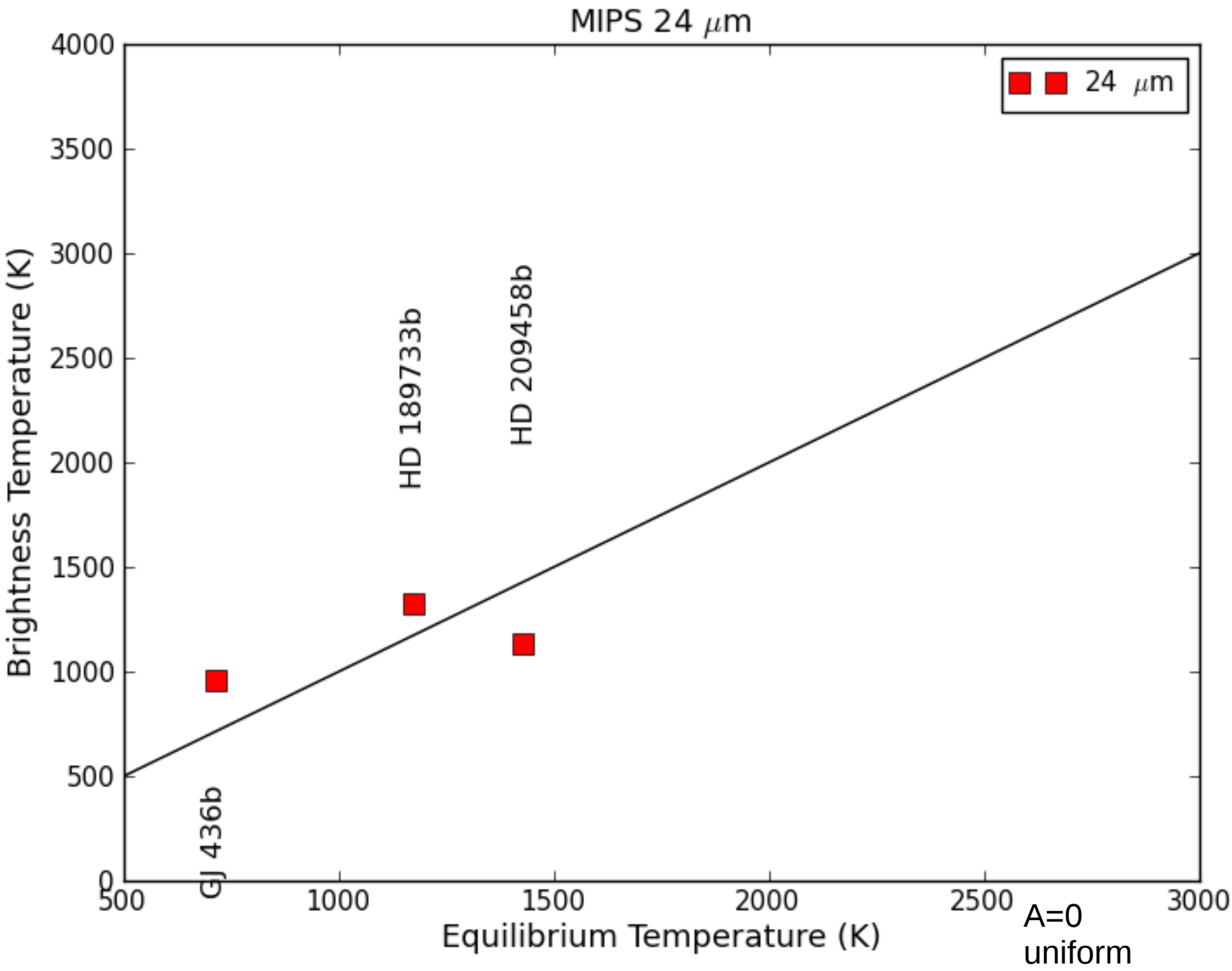

IRAC 5.7 μm
5.8 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000
GJ 436b
XO-1b
WASP-2b
HD 189733b
XO-2b
HAT-P-1b
HD 209458b
TrES-2
TrES-3
HD 149026b
TrES-4
WASP-1b
HAT-P-7b
WASP-18b
WASP-12b

A=0
uniform


IRAC 8.0 μm
8.0 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000
GJ 436b
TrES-1
XO-1b
WASP-2b
HD 189733b
HD 80606b
XO-2b
HAT-P-1b
HD 209458b
TrES-2
TrES-3
TrES-4
WASP-1b
HAT-P-7b
HD 149026b
WASP-17b
WASP-14b
CoRoT-2b
WASP-18b
WASP-12b

A=0
uniform


IRS 16 μm
16 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000
GJ 436b
HD 189733b
HD 149026b
TrES-4
A=0
uniform


MIPS 24 μm
24 μm
Brightness Temperature (K)
Equilibrium Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
500
1000
1500
2000
2500
3000
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 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 1$^{st}$ 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 $\chi^2$, reminimize from there and restart MCMC
- Assess errors & correlations with MCMC
- Gelman-Rubin test for MCMC convergence
- Inspect histograms and correlation plots
- Ensure monomodality or include all maxima

# 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