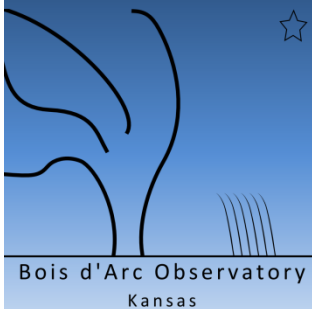


Toward Millimagnitude Photometric Calibration

*Eric Dose
SAS, Ontario, California
June 13, 2014*



Motivation for this work

Motivation

Simulations

Statistics

Conclusions *so far*

What's Next?

Demanding targets (millimagnitude):

- asteroid rotation
- variable stars
- exoplanet transits

More **collaboration**:

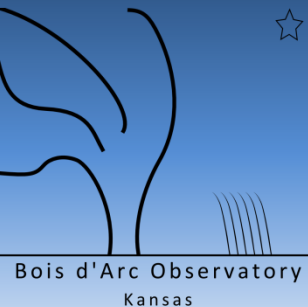
- more continuous coverage
- differing equipment

Tools:

Spectral **simulation**

Multivariate regression

- more robust to missing data, etc
- bigger model formulas possible
- mixed-model regression (systematic errors)



Before we start:

The end goal of **photometric calibration** is:

To characterize your apparatus and sky

So that you can estimate

TRUE MAGNITUDES in a PASSBAND

Image calibration (flats, darks, etc) is a separate subject.

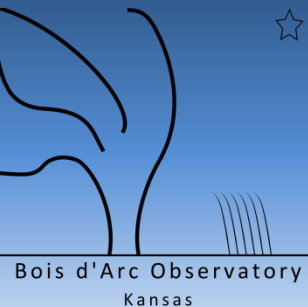
[Motivation](#)

[Simulations](#)

[Statistics](#)

[Conclusions](#) *so far*

[What's Next?](#)



Our plan:

[Motivation](#)

[Simulations](#)

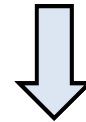
[Statistics](#)

[Conclusions](#) *so far*

[What's Next?](#)

Simulation:

1. Compute instrumental magnitudes
2. Compute “catalog” magnitudes in passband



Statistics:

1. Regress instrumental magnitudes *vs*:
 - catalog magnitudes, color index, airmass.
2. Extract coefficients
 - transforms, extinction, zero-point, etc.
3. Find smallest effective model formula
 - drop terms where possible

Motivation

Simulations

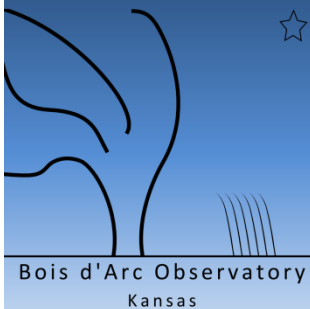
- Scheme
- Star spectra
- Atm. spectra
- Sanity checks
- First results

Statistics

Conclusions *so far*

What's Next?

Simulation: the scheme



Simulation Scheme

Motivation

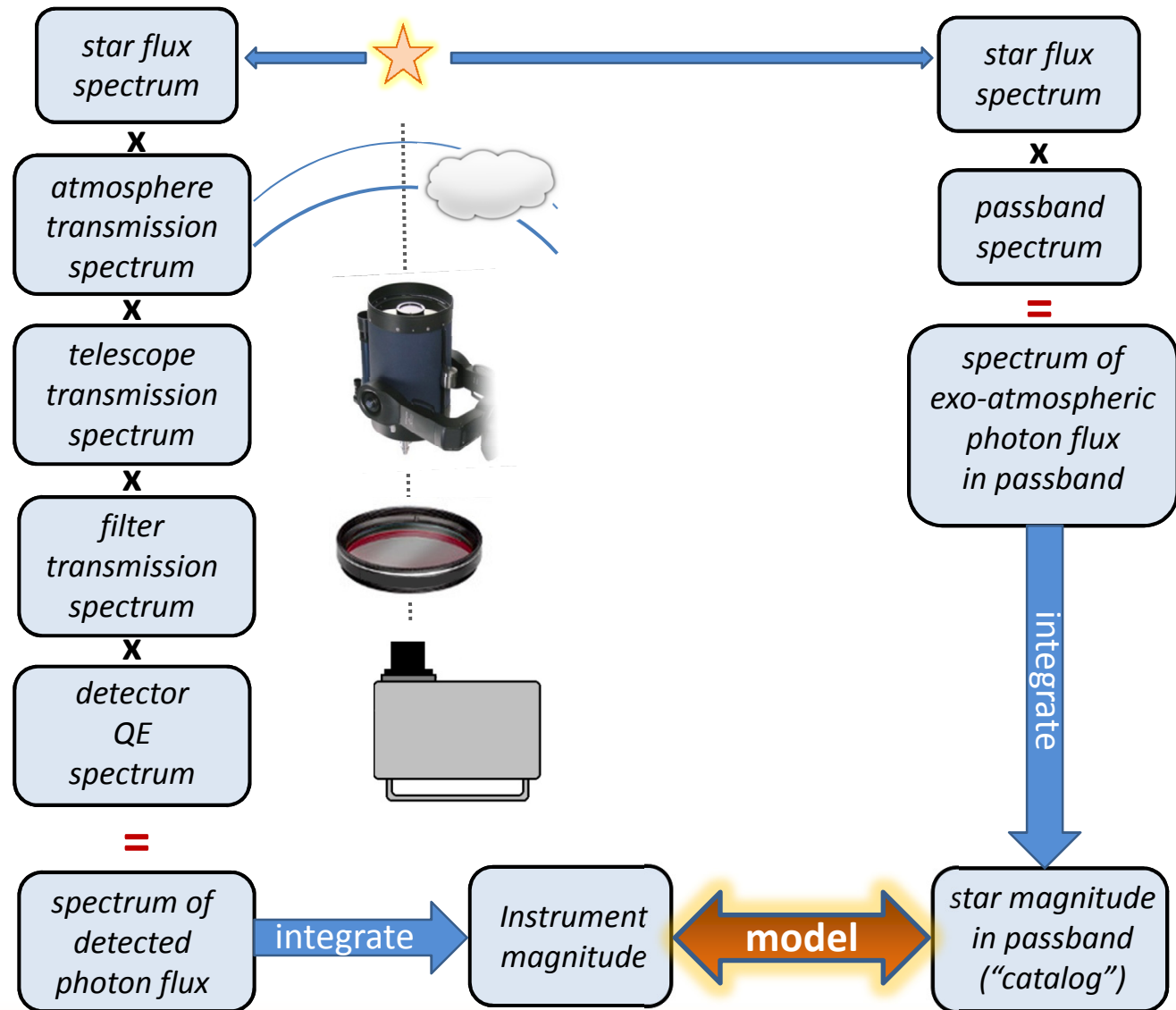
Simulations

- **Scheme**
- Star spectra
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- First results

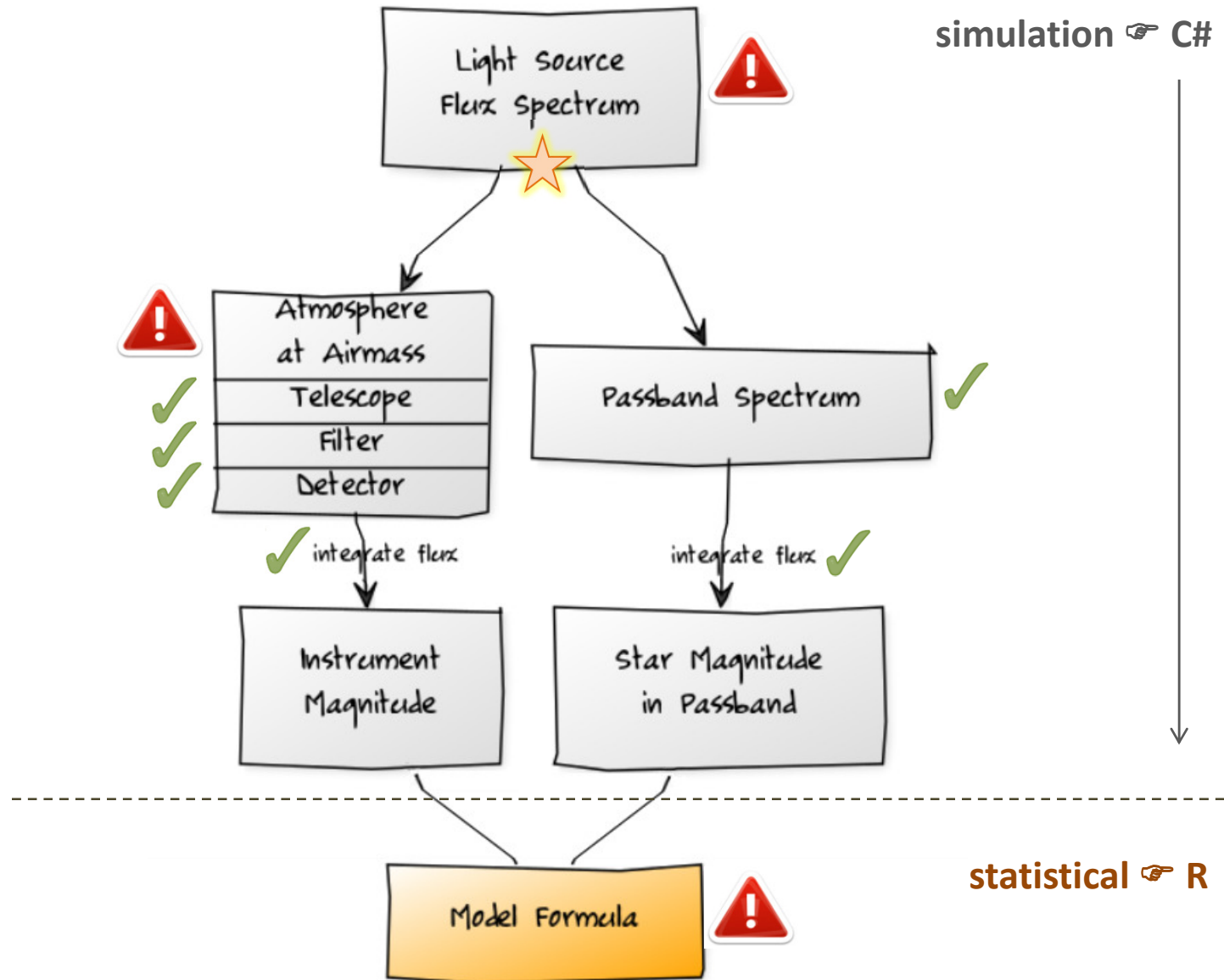
Statistics

Conclusions so far

What's Next?



Simulation Scheme



Motivation

Simulations

- **Scheme**
- Star spectra
- Atm. spectra
- Sanity checks
- First results

Statistics

Conclusions so far

What's Next?

Motivation

Simulations

- Scheme
- **Star spectra**
- Atm. spectra
- Sanity checks
- First results

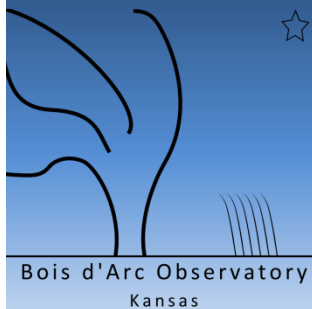
Statistics

Conclusions *so far*

What's Next?



Find STAR SPECTRA



Bois d'Arc Observatory
Kansas

Black-body stars

Motivation

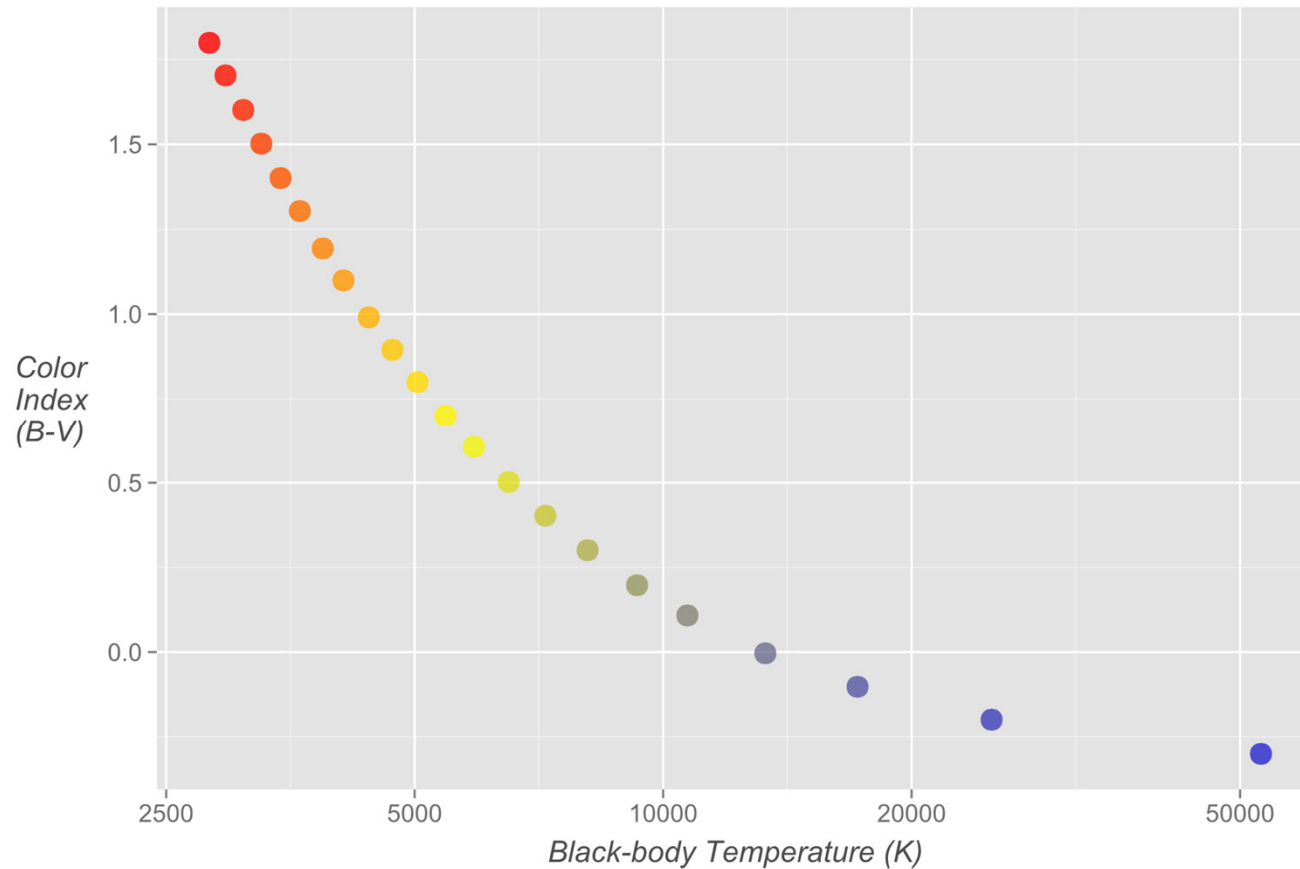
Simulations

- Scheme
- **Star spectra**
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- First results

Statistics

Conclusions so far

What's Next?



Black-body stars

Motivation

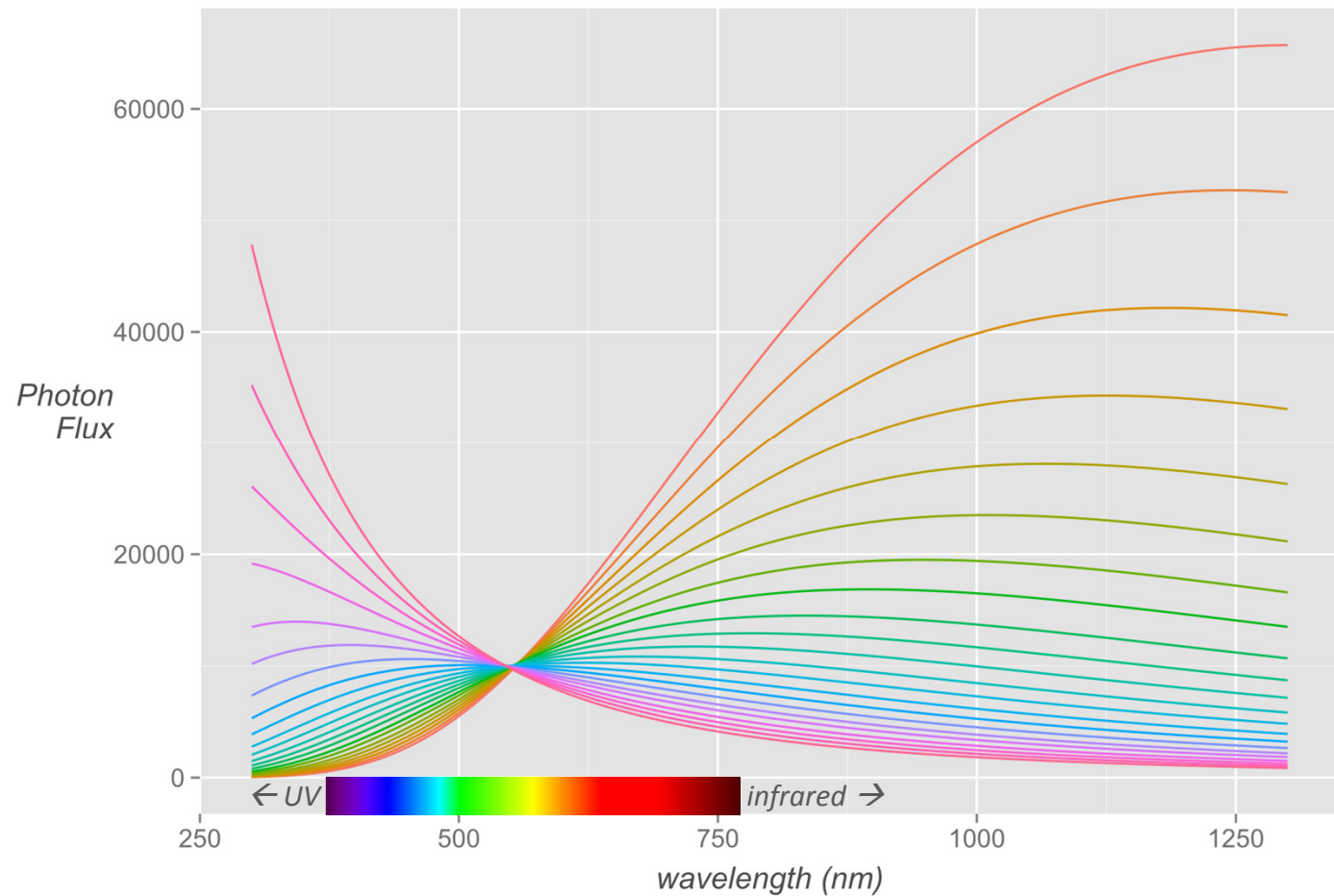
Simulations

- Scheme
- **Star spectra**
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Statistics

Conclusions so far

What's Next?



- spectra from Planck's law, then normalized to magnitude 10.0 in V passband.
- flux in photons/s/nm/m²

Spectral Flux Library stars

(Pickles, 1998)

Motivation

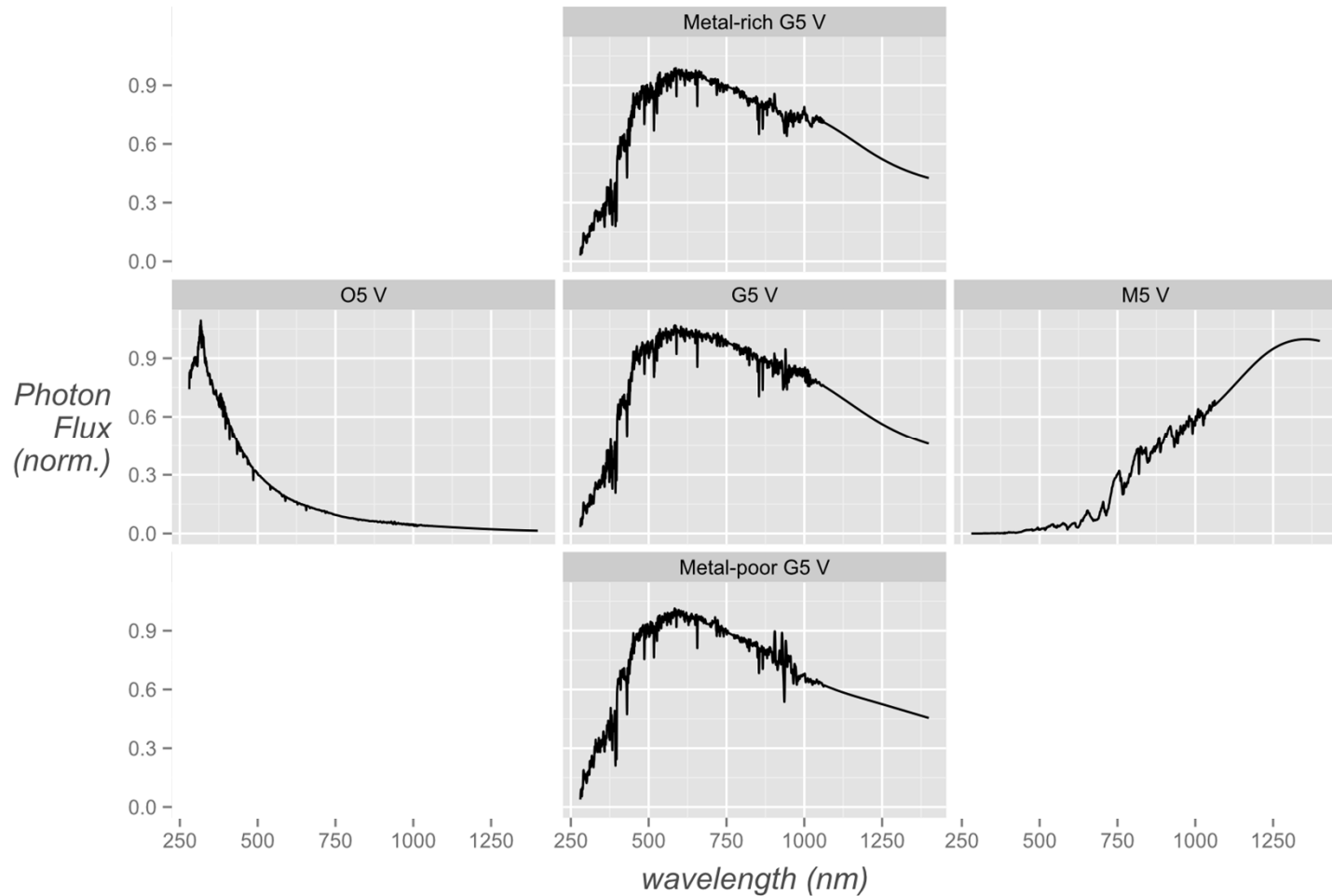
Simulations

- Scheme
- **Star spectra**
- Atm. spectra
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- First results

Statistics

Conclusions so far

What's Next?



- spectra ~ normalized to peak photon flux

Spectral Flux Library stars

(Pickles, 1998)

Motivation

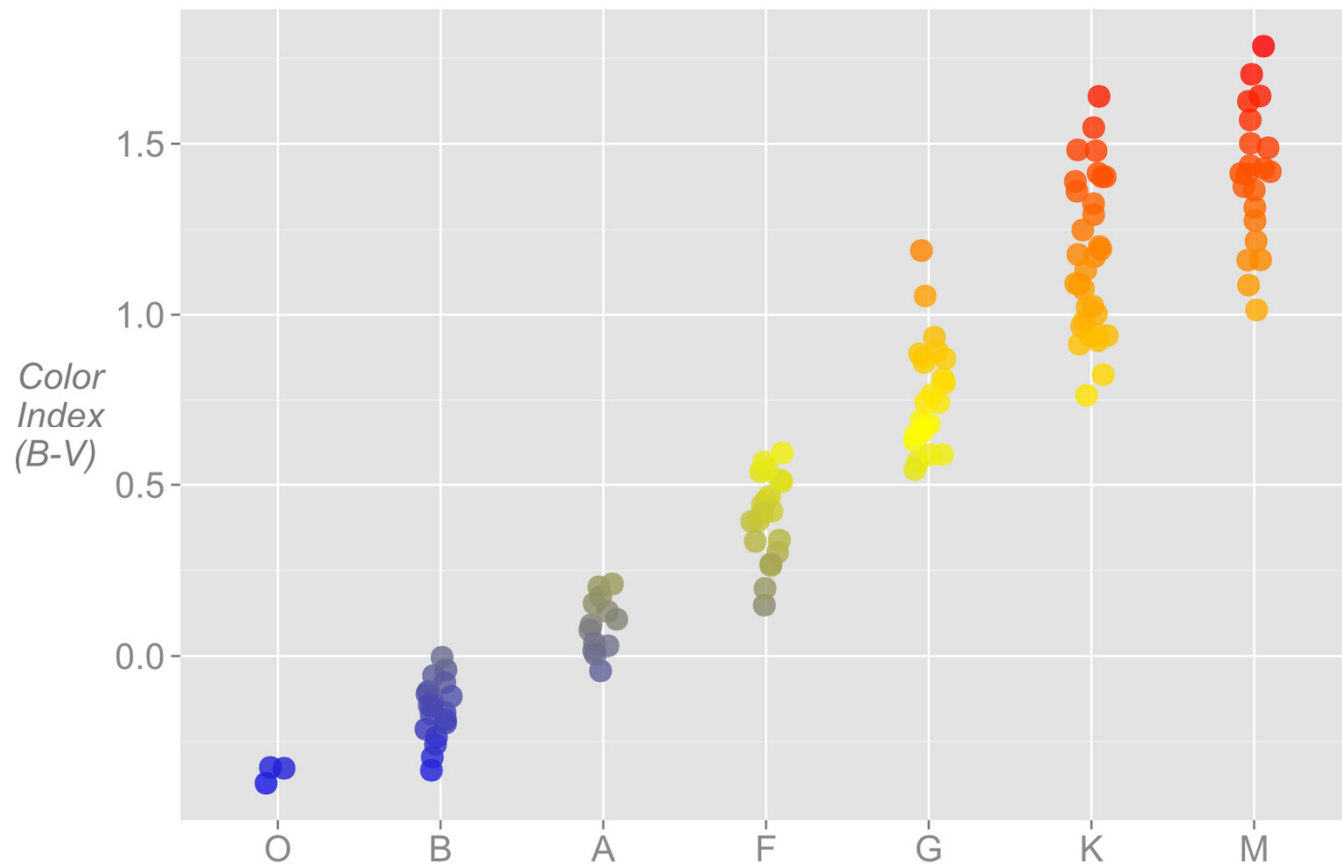
Simulations

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- **Star spectra**
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- Sanity checks
- First results

Statistics

Conclusions so far

What's Next?



Motivation

Simulations

- Scheme
- Star spectra
- **Atm. spectra**
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- First results

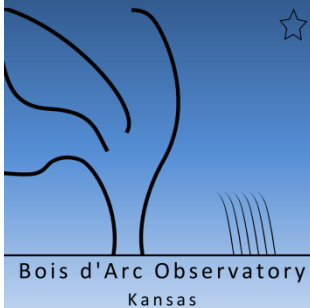
Statistics

Conclusions so far

What's Next?



Find an ATMOSPHERE MODEL



Atmospheric Spectral Transmission (simulated)

Motivation

Simulations

- Scheme
- Star spectra
- **Atm. spectra**
- Sanity checks
- First results

Statistics


Conclusions so far

What's Next?

Who **needs** to compute accurate transmission spectra of the atmosphere?

Solar energy!

- Approximation to MODTRAN standard.
- Accounts for:
 - altitude, temperature, humidity, aerosol
 - zenith angle
 - dozens of gases, incl ozone & CO₂
 - seasons, transient atmospheric
- Supplies wide range of reference inputs
- May disable diffuse radiation including ground reflectance (relevant to solar energy but not to photometry)
- Fast: ~ 1 second.
- Text inputs: can automate generation, then call SMARTS & return.

FLORIDA SOLAR  **ENERGY CENTER®**

**SMARTS2, A Simple Model
of the Atmospheric Radiative
Transfer of Sunshine:
Algorithms and performance assessment**

Authors
Christian Gueymard

Original Publication
Gueymard, C., "SMARTS2, A Simple Model of the Atmospheric Radiative Transfer of Sunshine: Algorithms and performance assessment", December 1995.

Publication Number
FSEC-PF-270-95

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www.fsec.ucf.edu



Atmospheric Spectral Transmission (simulated)

Motivation

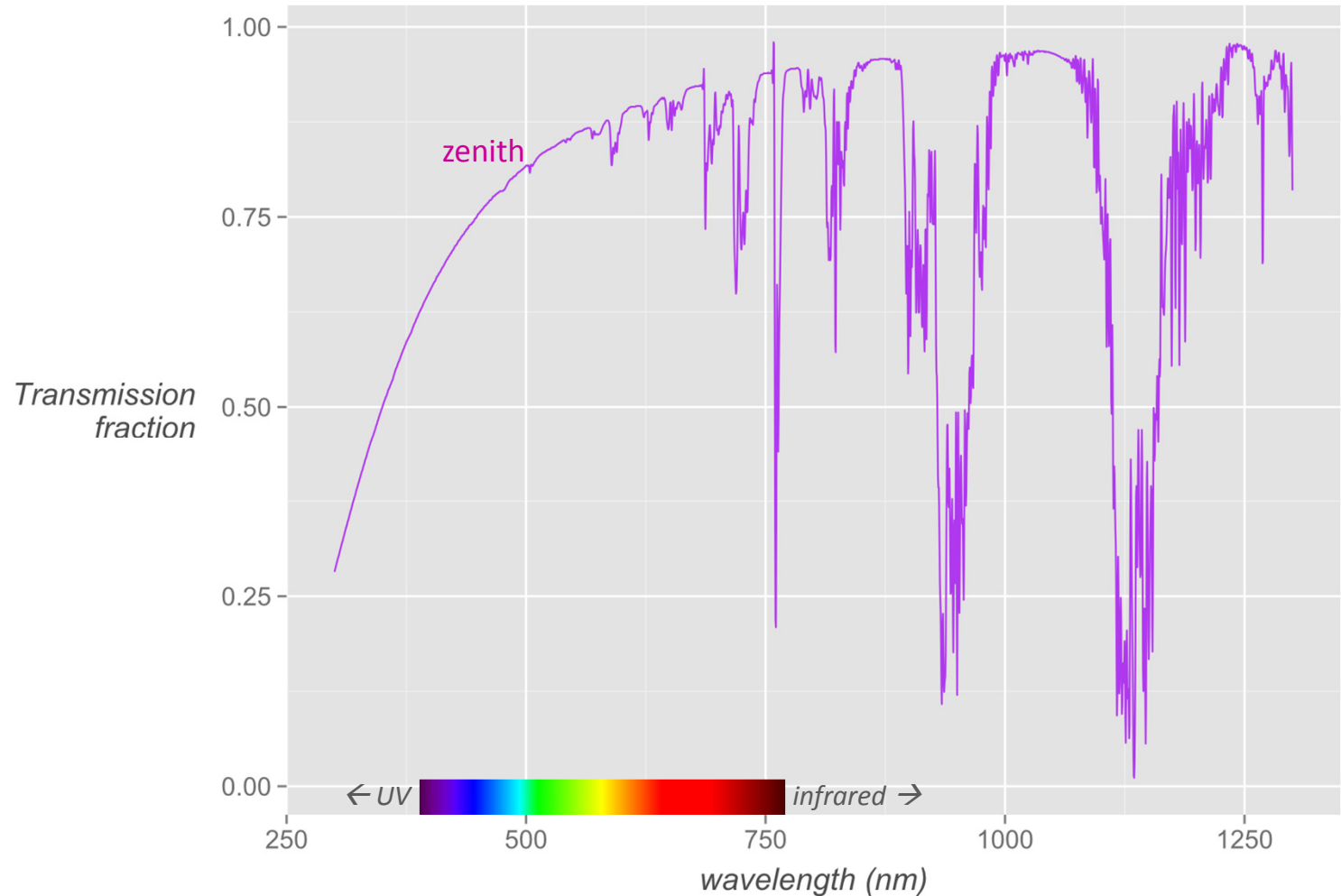
Simulations

- Scheme
- Star spectra
- **Atm. spectra**
- Sanity checks
- First results

Statistics

Conclusions so far

What's Next?



- computed with SMARTS software,
Kansas skies, winter average

Atmospheric Spectral Transmission (simulated)

Motivation

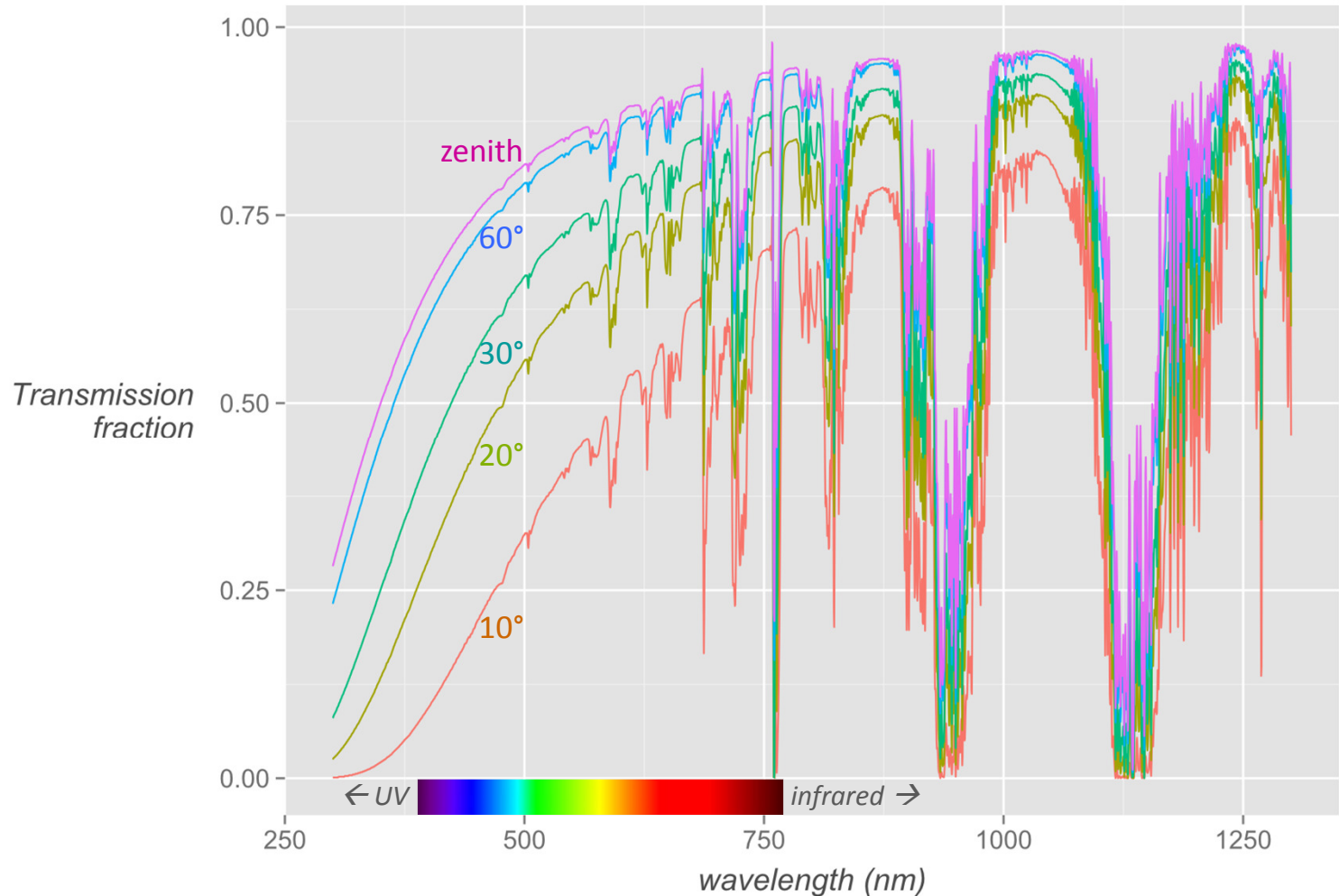
Simulations

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- First results

Statistics

Conclusions so far

What's Next?



- computed with SMARTS software,
Kansas skies, winter average



Motivation

Simulations

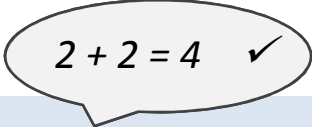
- Scheme
- Star spectra
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- **Sanity checks**
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Statistics

Conclusions *so far*

What's Next?




$$2 + 2 = 4 \quad \checkmark$$

Simulation: Sanity Checks

Need for Color Correction

black-body stars
no atmosphere, perfect scope & detector

Motivation

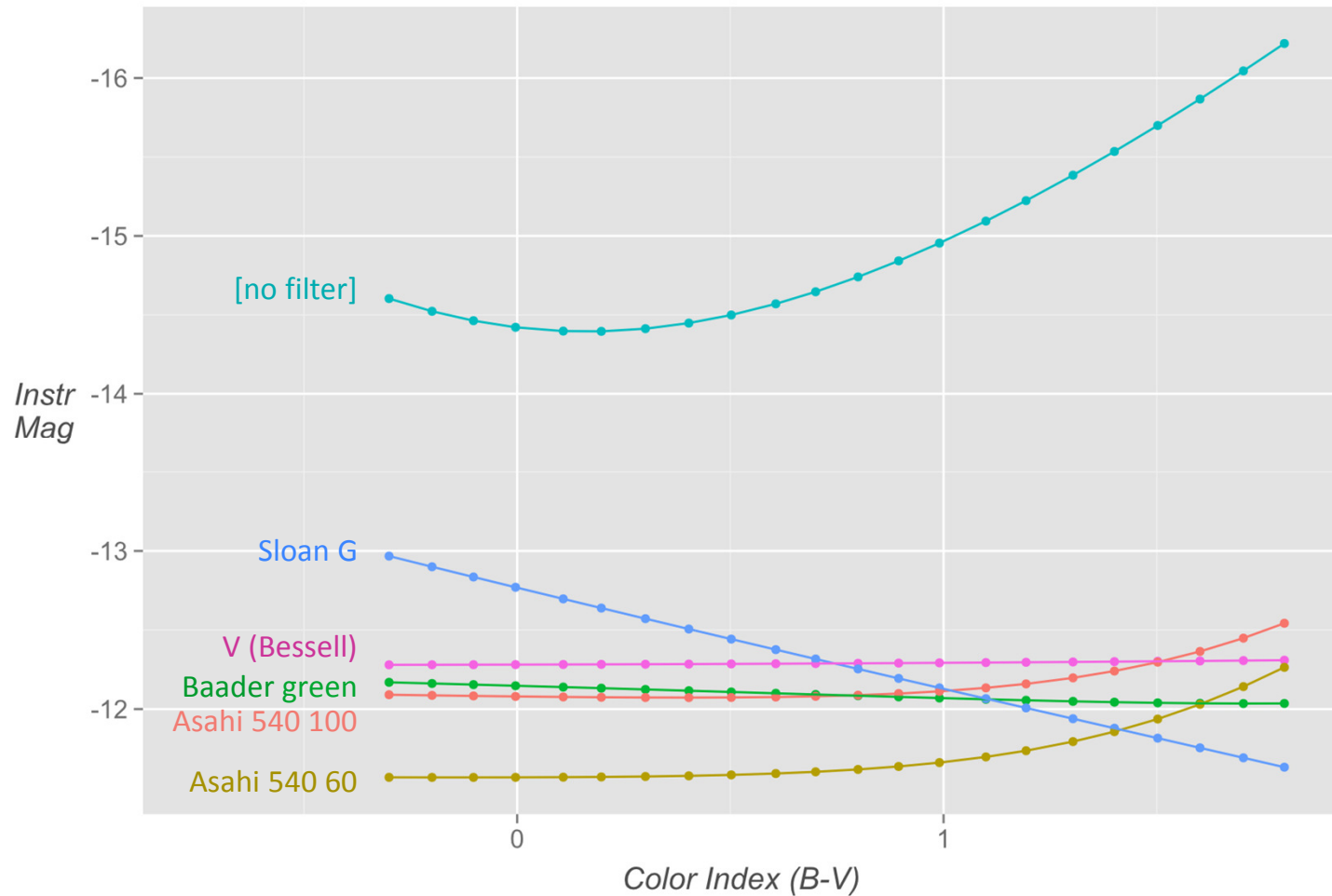
Simulations

- Scheme
- Star spectra
- Atm. spectra
- **Sanity checks**
- First results

Statistics

Conclusions so far

What's Next?



- stars at V mag 10.
- mags & color index: Bessel 1990 passband.

Need for Color Correction

131 simulated stars
no atmosphere, perfect scope & detector

Motivation

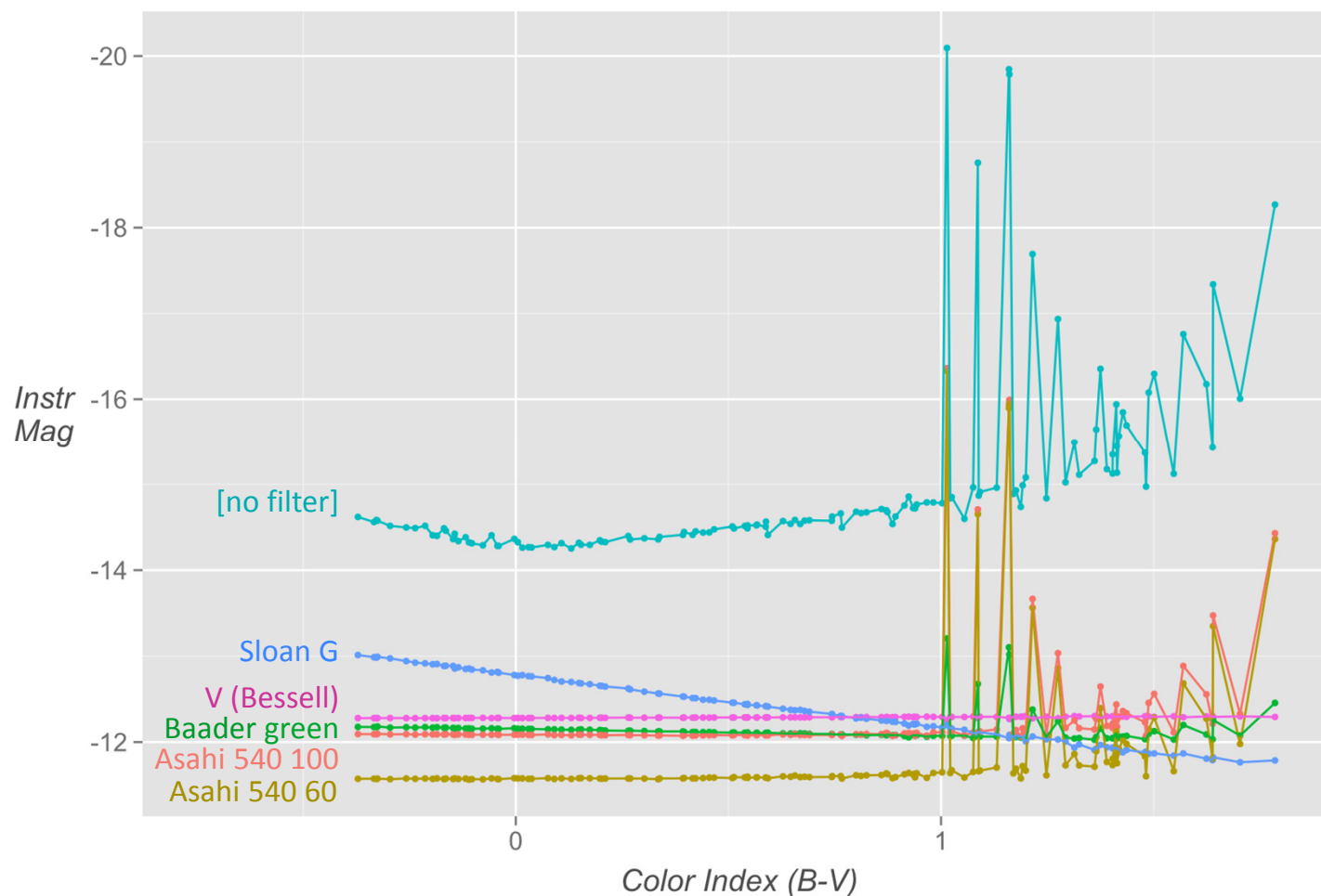
Simulations

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- Star spectra
- Atm. spectra
- **Sanity checks**
- First results

Statistics

Conclusions so far

What's Next?



Need for Color Correction

131 simulated stars
no atmosphere, perfect scope & detector

Motivation

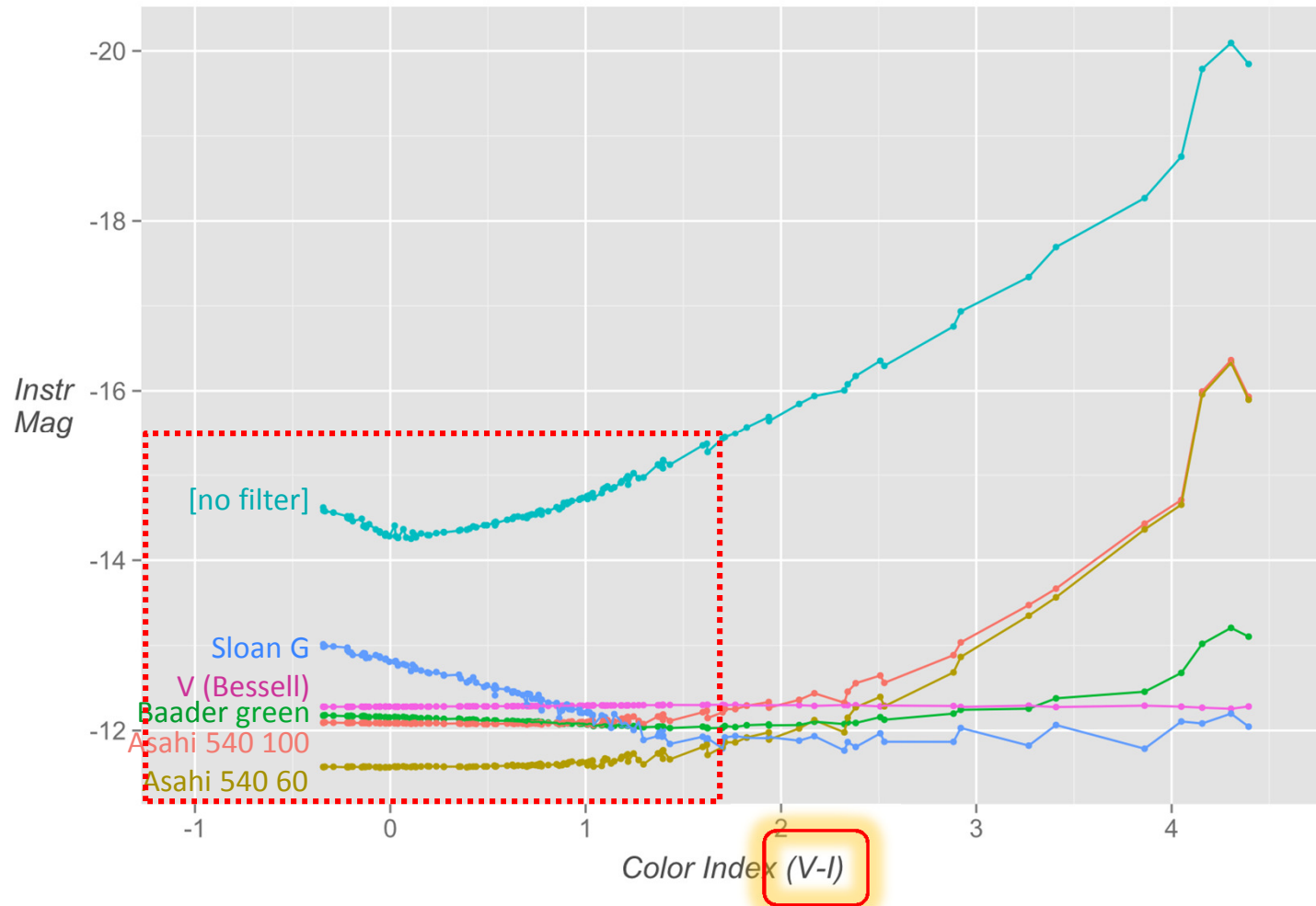
Simulations

- Scheme
- Star spectra
- Atm. spectra
- **Sanity checks**
- First results

Statistics

Conclusions so far

What's Next?



Need for Color Correction

107 simulated stars with $V-I < 1.6$
no atmosphere, perfect scope & detector

Motivation

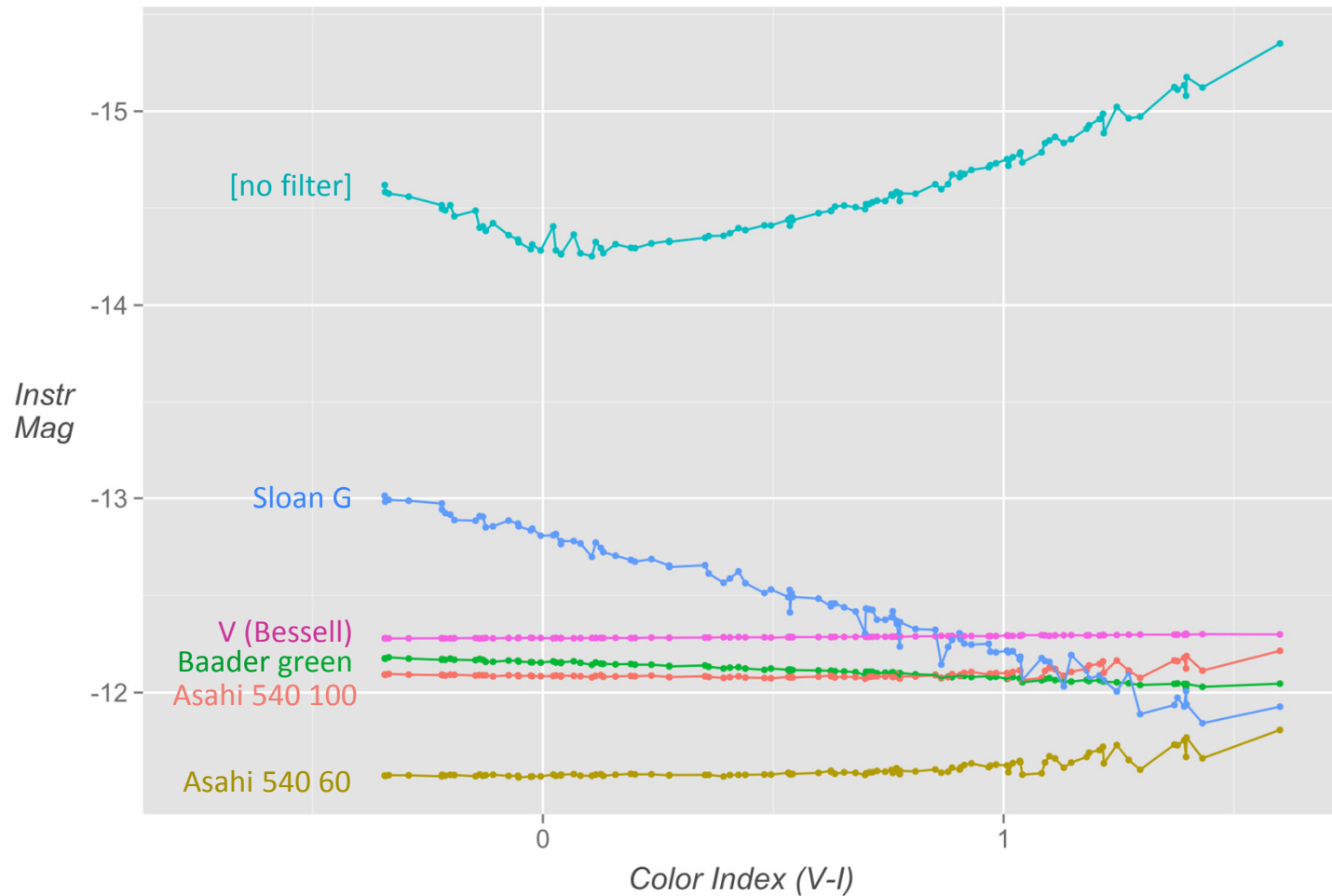
Simulations

- Scheme
- Star spectra
- Atm. spectra
- **Sanity checks**
- First results

Statistics

Conclusions so far

What's Next?



Motivation

Simulations

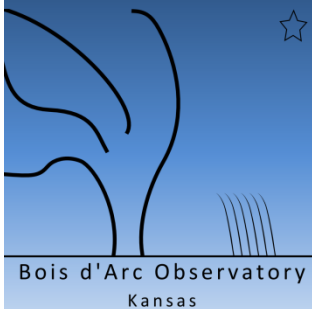
- Scheme
- Star spectra
- Atm. spectra
- Sanity checks
- **First results**

Statistics

Conclusions *so far*

What's Next?

Simulation: First results



Transform to V Passband

107 simulated stars, $V-I < 1.6$

No atmosphere, perfect optics & detector

Motivation

Simulations

- Scheme
- Star spectra
- Atm. spectra
- Sanity checks
- **First results**

Statistics

Conclusions so far

What's Next?

Filter	Res. error (<i>mmag</i>)	Transform	Transform std error
None	141.7	-0.410	0.027
V Bessell	2.1	-0.022	0.0004
Green Baader	5.6	+0.071	0.001
Sloan G	40.3	+0.601	0.008
Rect. 540 x 100	22.2	-0.037	0.004
Rect. 540 x 60	32.2	-0.082	0.006



Transform to V Passband

107 simulated stars, $V-I < 1.6$

Atmosphere (zenith), realistic optics & detector

☞ Millimagnitude calibration possible *in principle*.

Filter	Res. error (<i>mmag</i>)	Transform	Transform std error
None	54.0	-0.270	0.010
V Bessell	3.6	-0.046	0.0007
Green Baader	4.5	+0.057	0.001
Sloan G	32.9	+0.506	0.006
Rect. 540 x 100	2.6	+0.031	0.0005
Rect. 540 x 60	5.2	0.040	0.001

this minimum error of ~ 3 mmagnitudes is very persistent.

Motivation

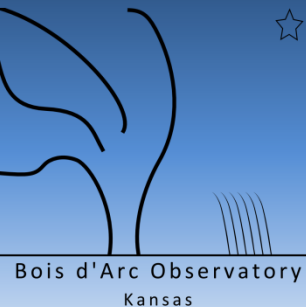
Simulations

- Scheme
- Star spectra
- Atm. spectra
- Sanity checks
- **First results**

Statistics

Conclusions so far

What's Next?



Motivation

Simulations

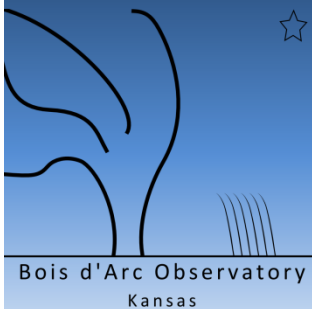
Statistics

- **Scheme**
- Fixed-effects reg.
- Mixed-model reg.

Conclusions *so far*

What's Next?

Statistics: the scheme



Statistical Scheme

Motivation

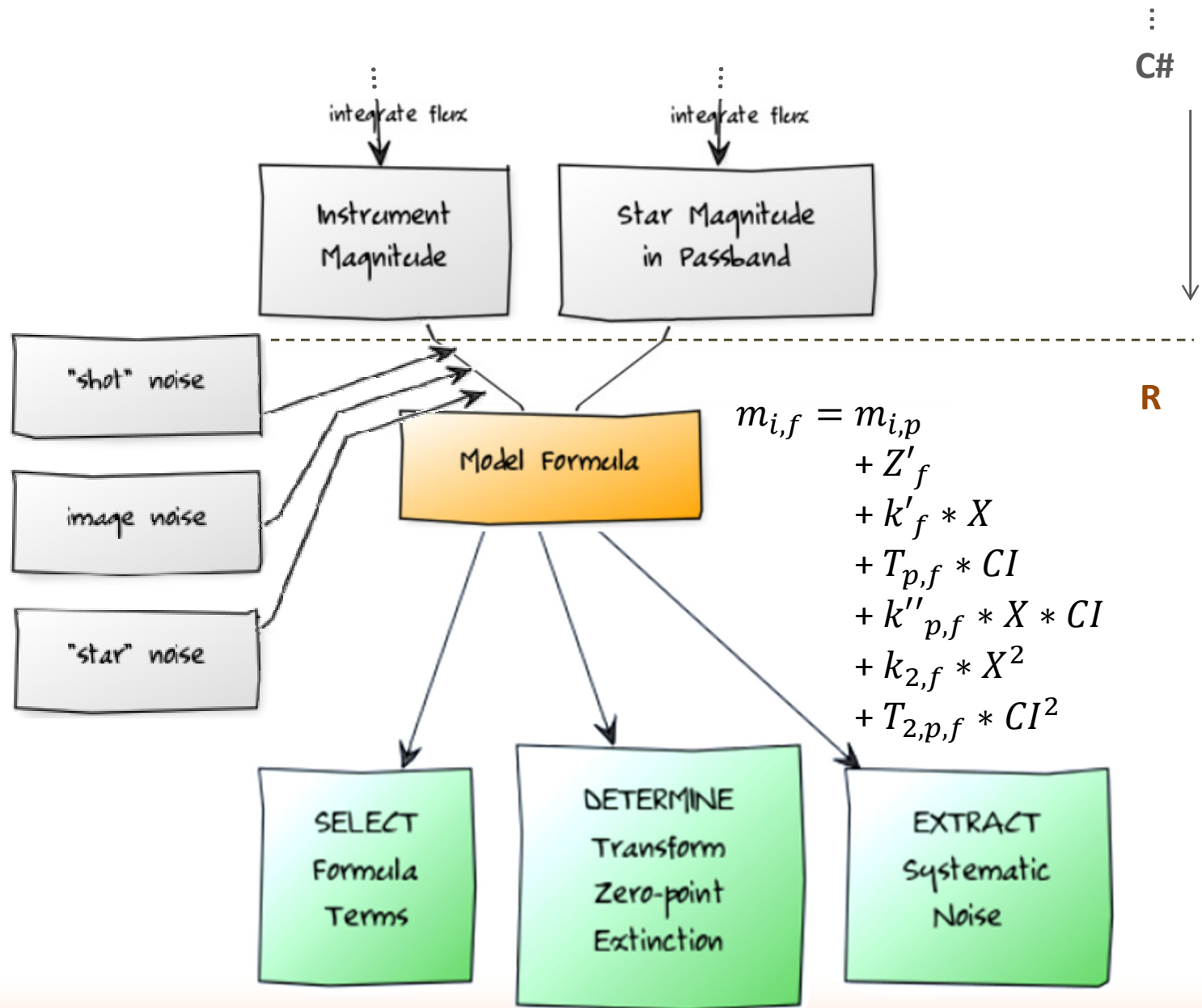
Simulations

Statistics

- Scheme
- Fixed-effects reg.
- Mixed-model reg.

Conclusions so far

What's Next?



Motivation

Simulations

Statistics

- Scheme
- **Fixed-effects reg.**
- Mixed-model reg.

Conclusions *so far*

What's Next?

Statistics: fixed-effects regression



Fixed-effects regression

= standard multivariate regression

☞ *All coefficients have fixed values per fit.*

Motivation

Simulations

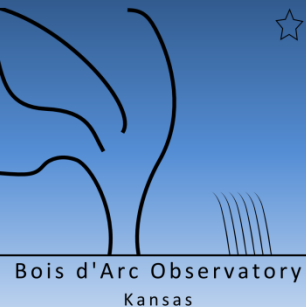
Statistics

- Scheme
- **Fixed-effects reg.**
- Mixed-model reg.

Conclusions so far

What's Next?

- Fit to all relevant data at once
- Extract all coefficients at once
 - transform, extinction, zero-point
 - + any higher terms
- **Lost:**
 - linear plots, some simplicity
 - step-wise fitting, some complexity
- **Gained:**
 - statistical power
 - robustness to missing data points
 - flexibility to change model



Motivation

Simulations

Statistics

- Scheme
- Fixed-effects reg.
- **Mixed-model reg.**

Conclusions *so far*

What's Next?

Statistics: mixed-model regression

Mixed-model regression

= fixed-effects + “random effects”

☞ *Random effects decrease chosen systematic errors.*

Motivation

Simulations

Statistics

- Scheme
- Fixed-effects reg.
- **Mixed-model reg.**

Conclusions so far

What's Next?

- Fixed-effect coefficients unchanged
 - minimize random error **per data point**
(e.g., “shot” error)
 - same transform, extinction, any higher terms
- “Random effects” are new
 - minimize error **per group** of data points
 - (e.g., per-image, per-star, per-night, etc)



Mixed-model regression

- ➡ Random errors are low.
- ➡ Most per-image error can be extracted.

Motivation

Simulations

Statistics

- Scheme
- Fixed-effects reg.
- **Mixed-model reg.**

Conclusions so far

What's Next?

No noise added

Coefficient	Mean	Std dev
<i>Transform</i>	-0.047	0.002
<i>Extinction</i>	+0.199	0.0002
<i>Zero-point</i>	-11.661	0.002
<i>Per-star error</i>	3 mmag	
<i>Per-image error</i>	<1 mmag	
<i>Residual</i>	1 mmag	

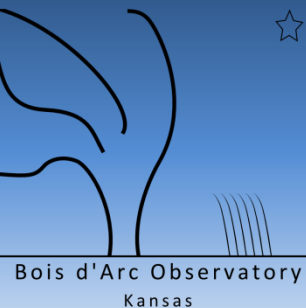
Noise added:

3 mmag per-point

10 mmag per-image

Coefficient	Mean	Std dev
<i>Transform</i>	-0.047	0.003
<i>Extinction</i>	+0.198	0.014
<i>Zero-point</i>	-11.661	0.023
<i>Per-star error</i>	3 mmag	
<i>Per-image error</i>	8 mmag	
<i>Residual</i>	3 mmag	

From bootstrap run of 1000 fits, each with 7 randomly chosen stars (subject to: 3 blue, 1 mid, 3 yellow)
& 5 randomly chosen airmasses (subject to: 2 low, 1 mid, 2 high). V Bessell filter, Meade 14", ST-1001E detector.



Motivation

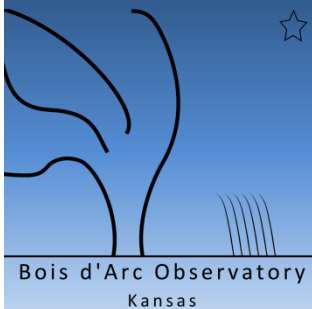
Simulations

Statistics

Conclusions *so far*

What's Next?

Conclusions & Wrap-up



Conclusions *so far*

[Motivation](#)

[Simulations](#)

[Statistics](#)

[Conclusions *so far*](#)

[What's Next?](#)

Simulating an optical stack is possible

- Star spectra can be had
- Atmospheric modeling is promising
- Star classifications in catalogs might help
- **Needs validation** via observations (2014-5)

Choose color index carefully

- B-V is especially suspect with most CCDs
- **V-I much better**, not necessarily best



Conclusions *so far*

[Motivation](#)

[Simulations](#)

[Statistics](#)

[Conclusions *so far*](#)

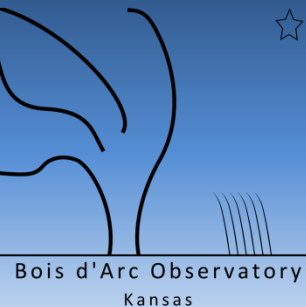
[What's Next?](#)

Simple models seem OK for intended use

- Airmasses below 2
- Colors close enough: calibration vs targets
- May not get us to millimagnitude calibration

Below 30° (*airmass 2*) → more model terms

- Airmasses below 2
- Multivariate regression very probably needed
- Choosing minimum set of terms may require considerable experimentation, but models help.



Conclusions *so far*

[Motivation](#)

[Simulations](#)

[Statistics](#)

[Conclusions *so far*](#)

[What's Next?](#)

Star catalogs to 0.01 mag are no good for millimagnitude work

- 0.01 magnitude format \rightarrow 2.9 millimagnitude min error
- this error *cannot be removed*



Conclusions *so far*

[Motivation](#)

[Simulations](#)

[Statistics](#)

[Conclusions *so far*](#)

[What's Next?](#)

**Spectral detail, if unaccounted for,
may limit photometric accuracy to ~ 3 mmag**

- star spectra have narrow spectral details
- atmospheric spectra have narrow spectral details
- this (real) **interaction** causes millimagnitude variations
- Project: should we calibrate only with stars similar in detail to photometric targets (e.g., same stellar class) ?
- Should we add spectral class to photometric catalogs?

Conclusions *so far*

[Motivation](#)

[Simulations](#)

[Statistics](#)

[Conclusions *so far*](#)

[What's Next?](#)

Mixed-model regression may help—a lot

- **per-image error:** seems possible to extract 60-80 %
 - *shutter inconsistency*
 - *passing cirrus*
 - *~ easy to test this*
- **per-star error:** may be feasible to extract some
 - *catalog error, especially if rare outlier*
 - *unusual star type*
 - *probably requires considerable data*
 - *problematic to test this*

What's Next?

[Motivation](#)

[Simulations](#)

[Statistics](#)

[Conclusions so far](#)

[What's Next?](#)

➤ **Validate with experiments**

- *multiple telescopes, detectors, nights*
- *full regression more robust to missing data?*

➤ **Push down to 20° altitude** (*airmass 3*)

- *which model terms do we need?*
- *how does random error increase (scintillation?)*
- *which systematic errors can we remove?*

➤ **Project Cirrus (2014-5)**

- *data reduction: use mixed-model regression*
 - *a generalization of comp-star ensembles*
 - *can we really remove per-image noise?*
- *at least: plot per-image noise as a data-quality metric*



Thanks!

code repository
+
this presentation:

<http://github.com/edose/spectral>

