Toward Millimagnitude Photometric Calibration

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Bois d'Arc Observatory
Kansas

Motivation for this work

Pursuits:

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)

Motivation

Simulations

Statistics

Conclusions *so far*

What's Next?

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.

Our plan:

Simulation:

1. Compute instrumental magnitudes
2. Compute "catalog" magnitudes in bandpass

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

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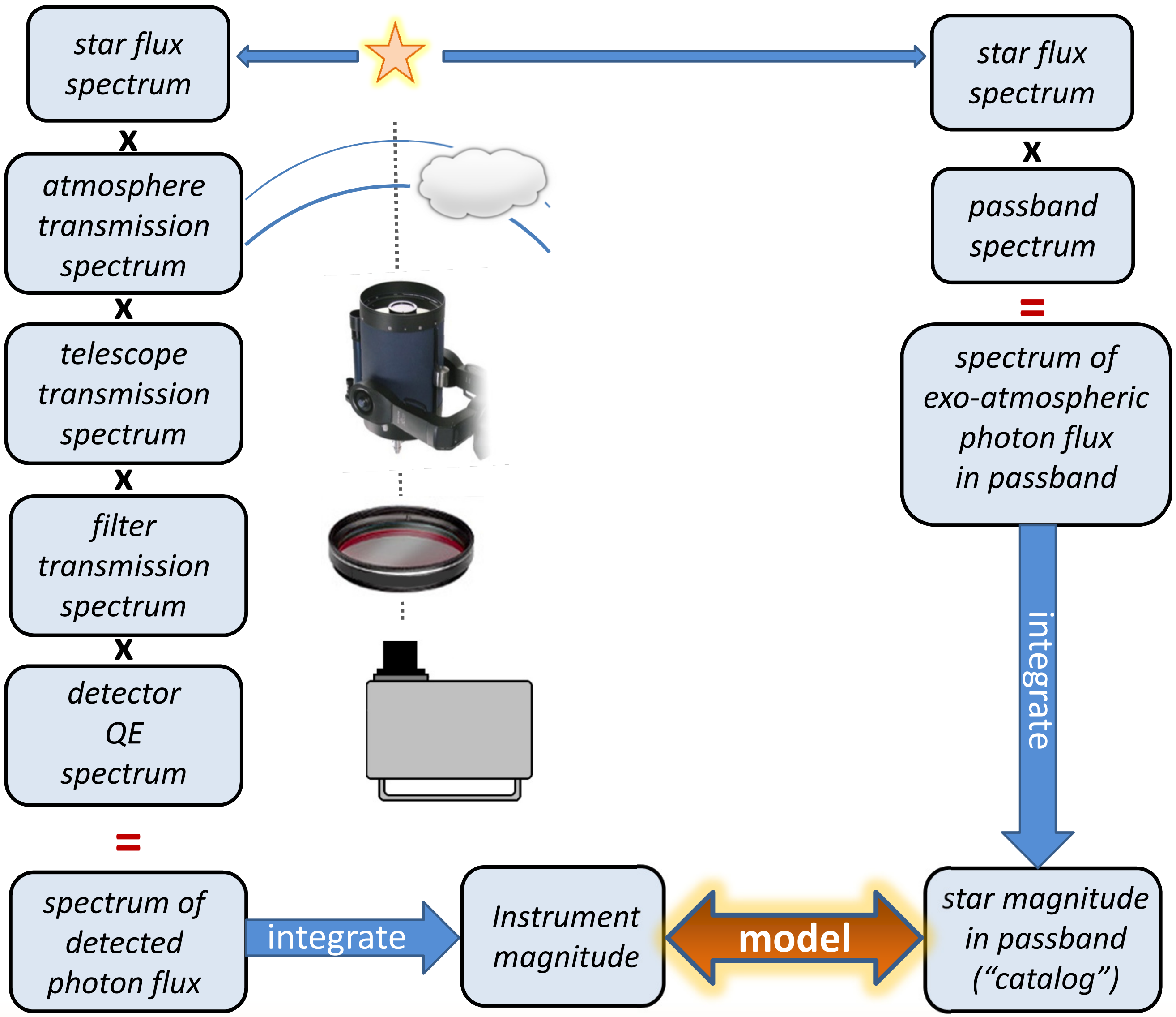
Simulation: the scheme

Simulation Scheme



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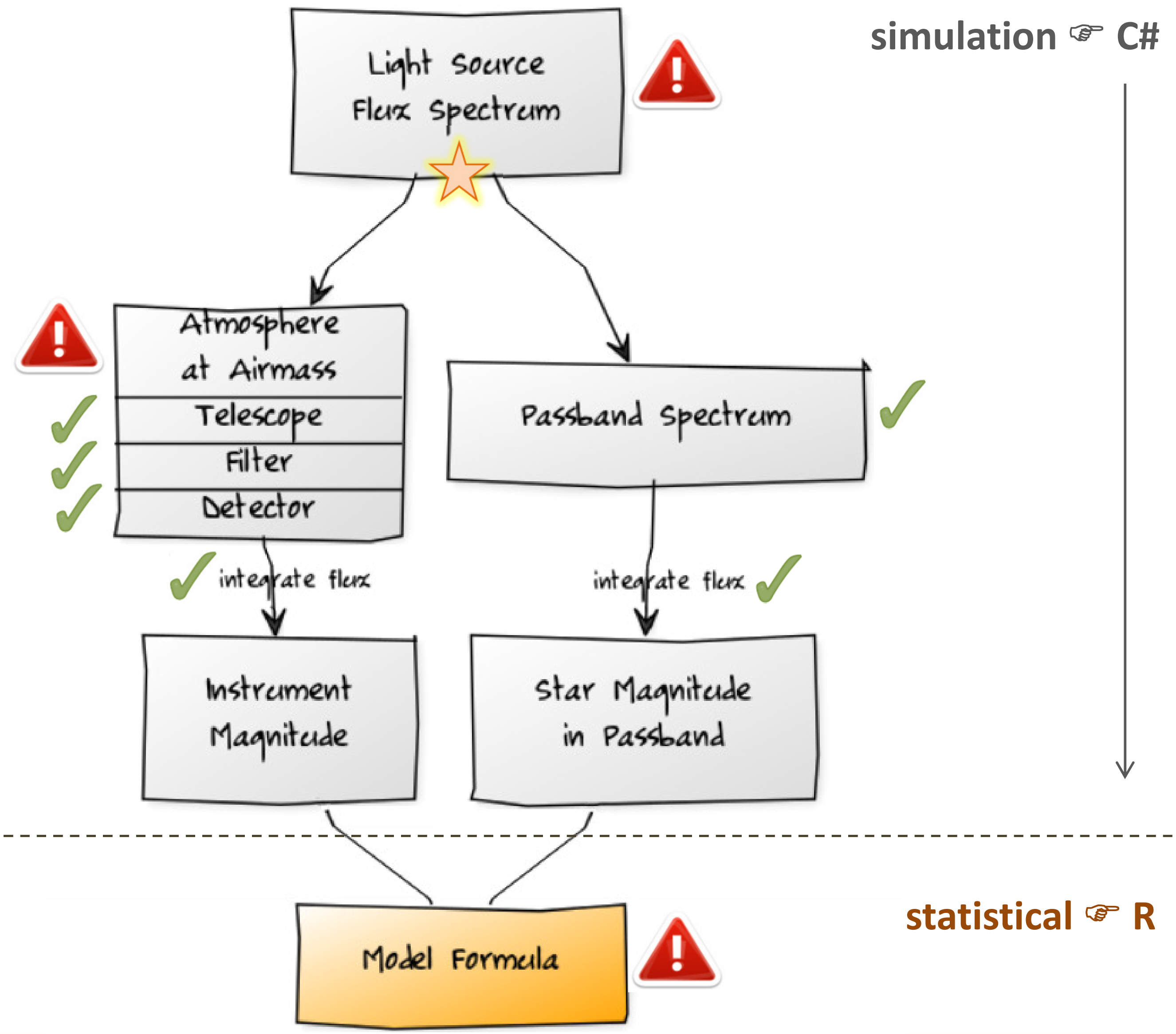
Simulation Scheme



☞ Find STAR SPECTRA

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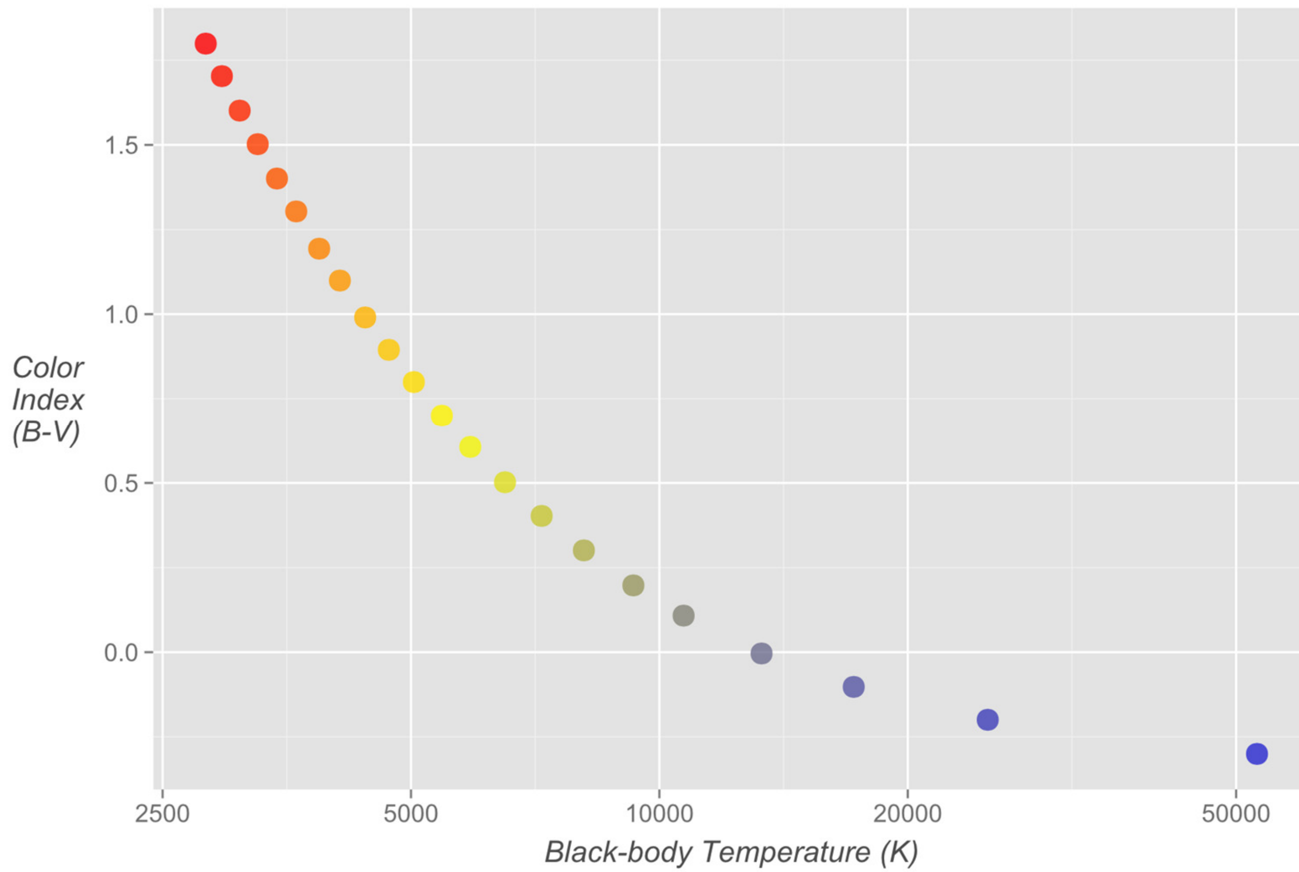
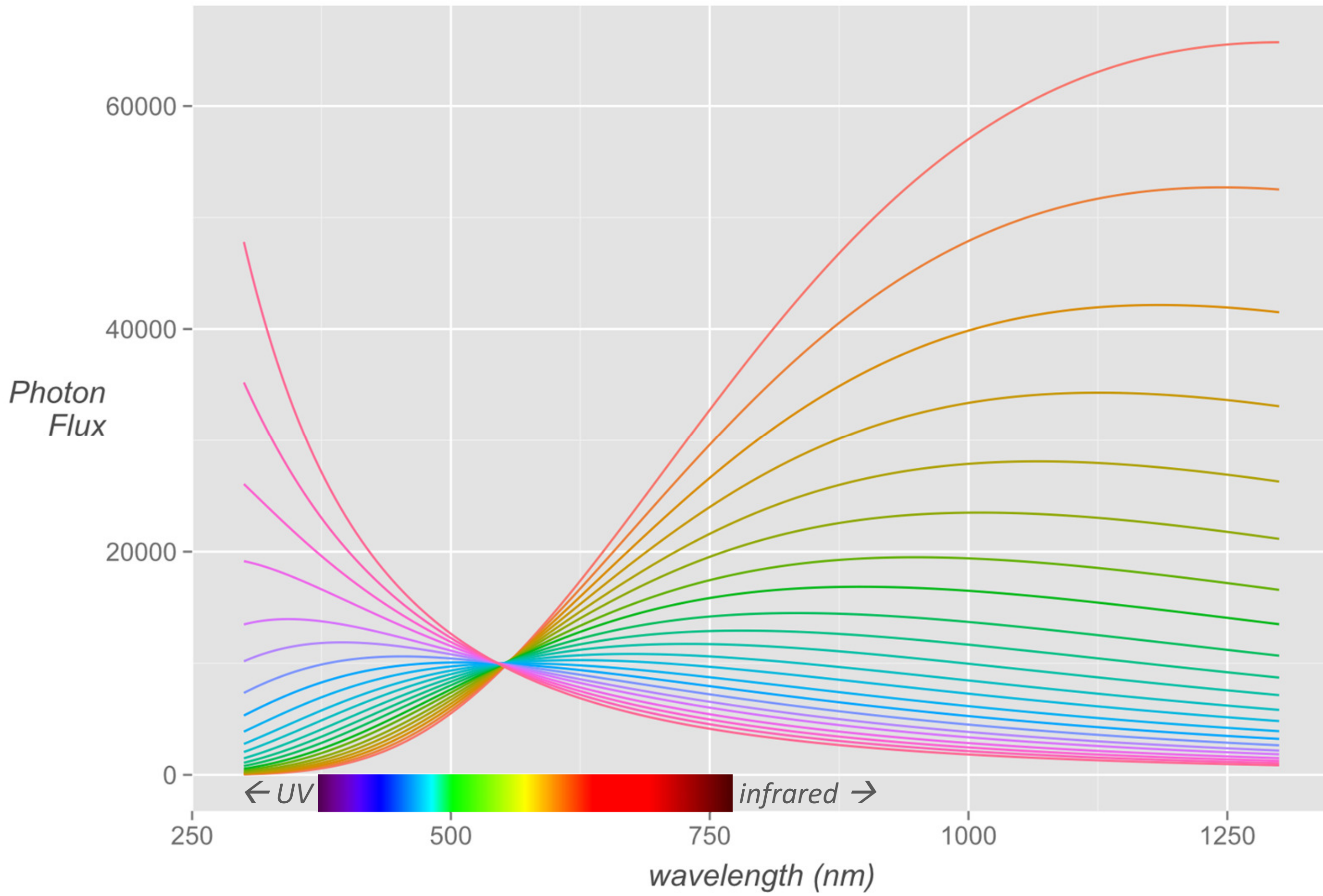
Black-body stars



Black-body stars



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

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Spectral Flux Library stars
(Pickles, 1998)

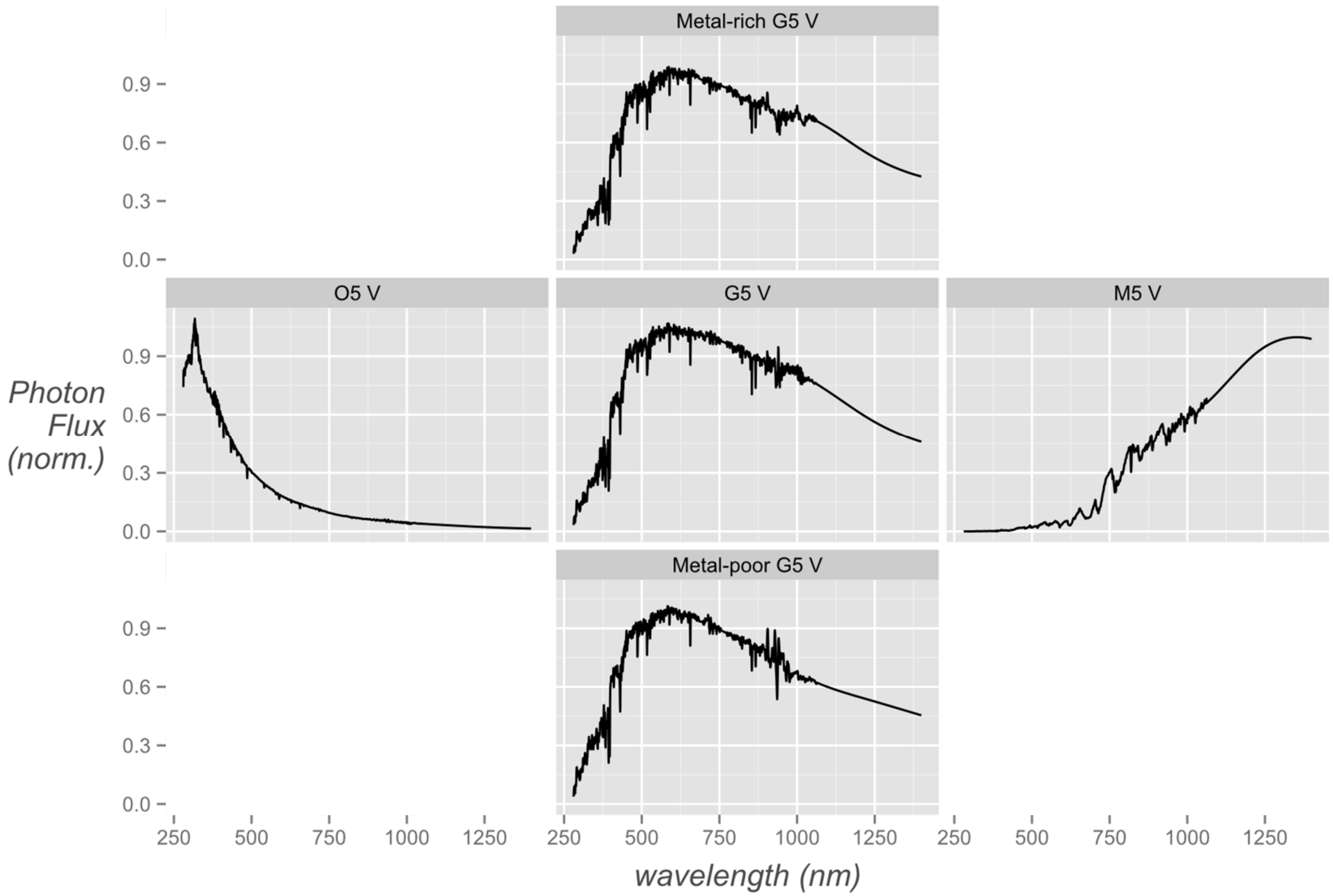
[Motivation](#)

[Simulations](#)
- Scheme
- **Star spectra**
- Atm. spectra
- Sanity checks
- First results

[Statistics](#)

[Conclusions](#) *so far*

[What's Next?](#)



- *spectra ~ normalized to peak photon flux*

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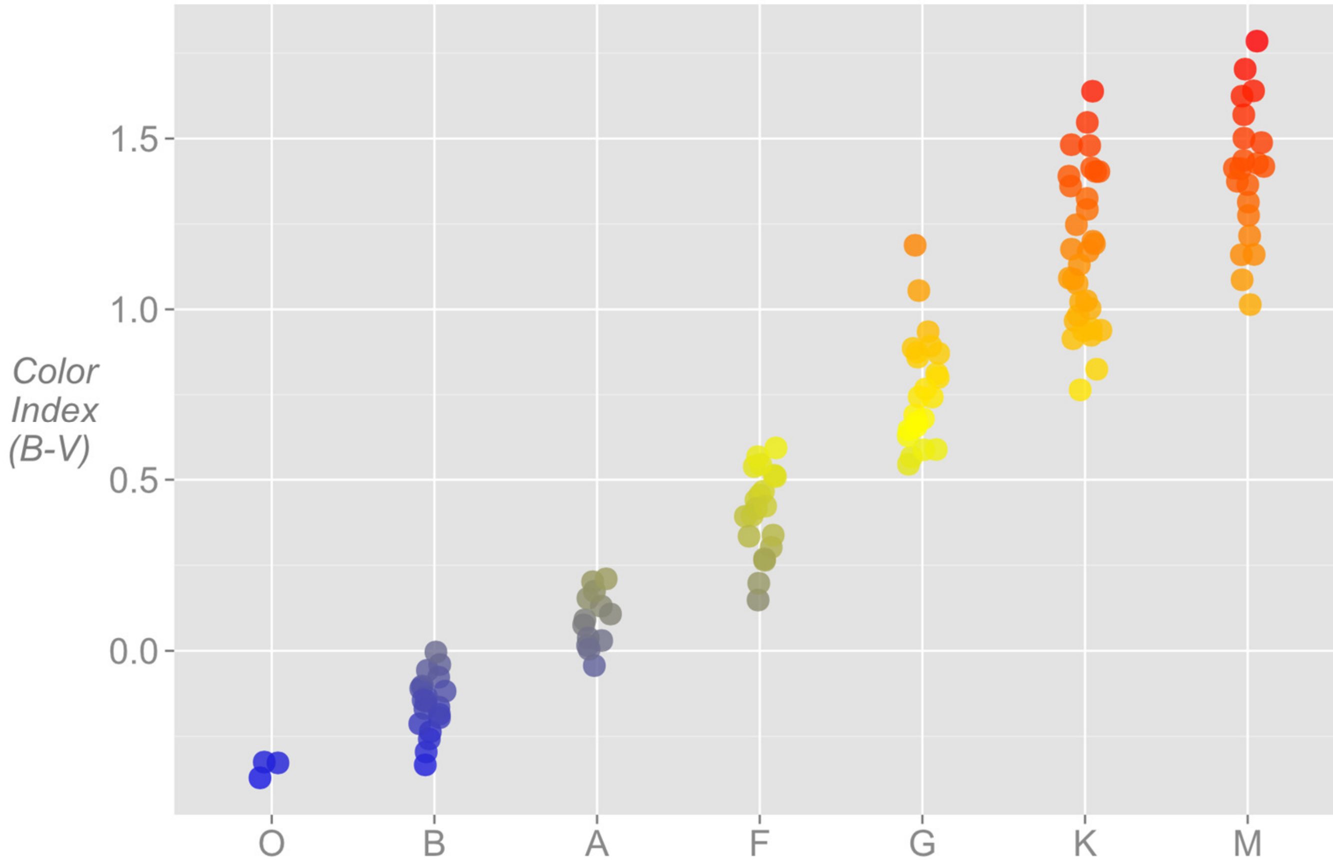
Spectral Flux Library stars

(Pickles, 1998)



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☞ Find an ATMOSPHERE MODEL

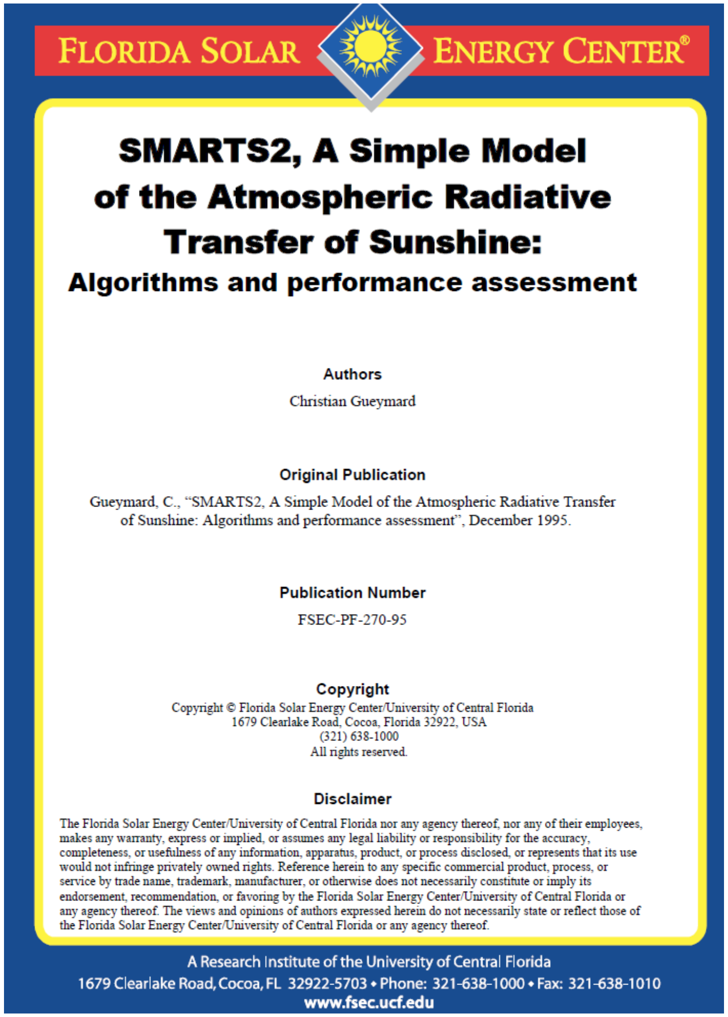
Atmospheric Spectral Transmission
(simulated)

*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 & CO_2*
  - *seasons, transient atmospherics*
- *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.*



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

Authors

Christian Gueymard

Original Publication

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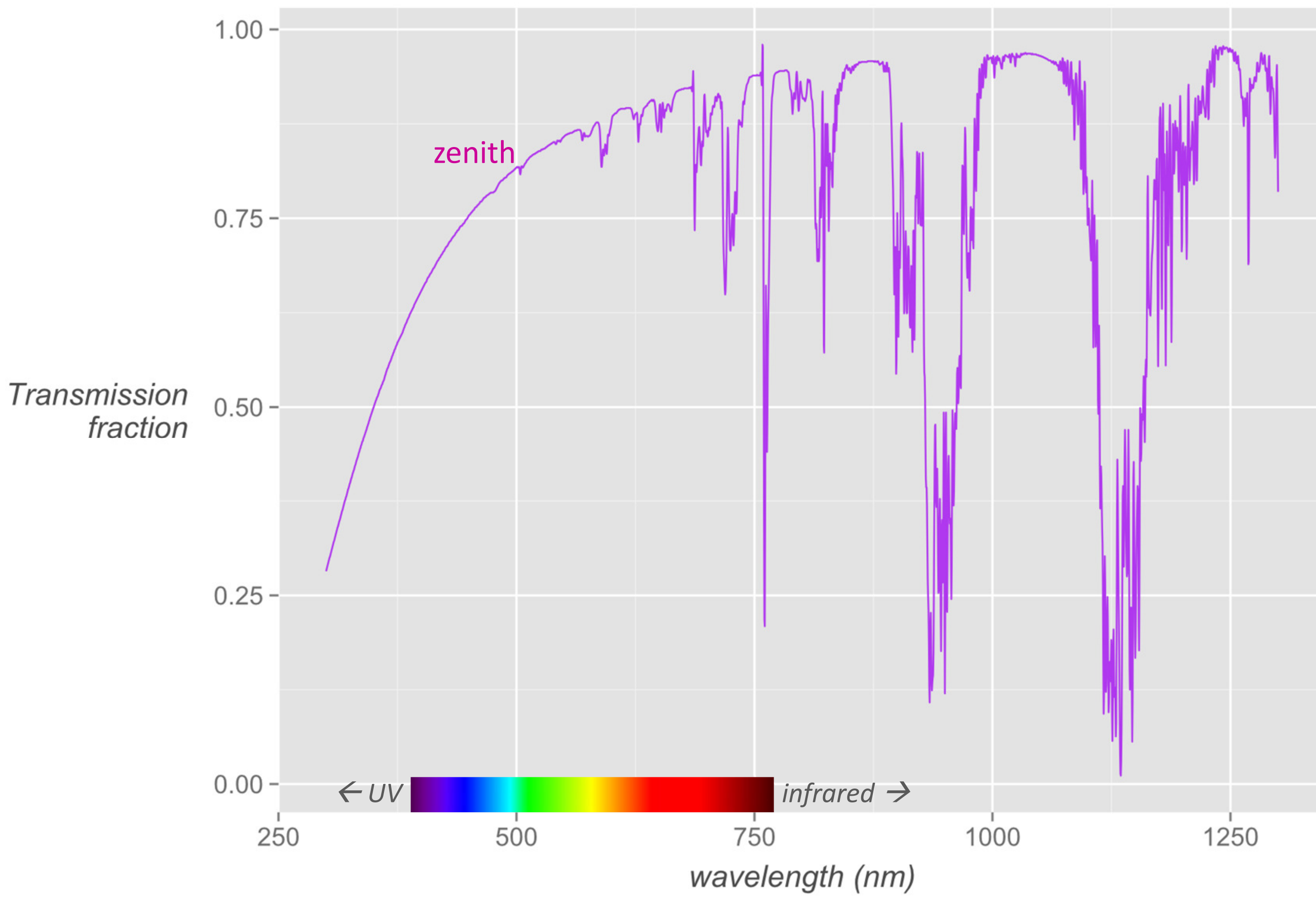
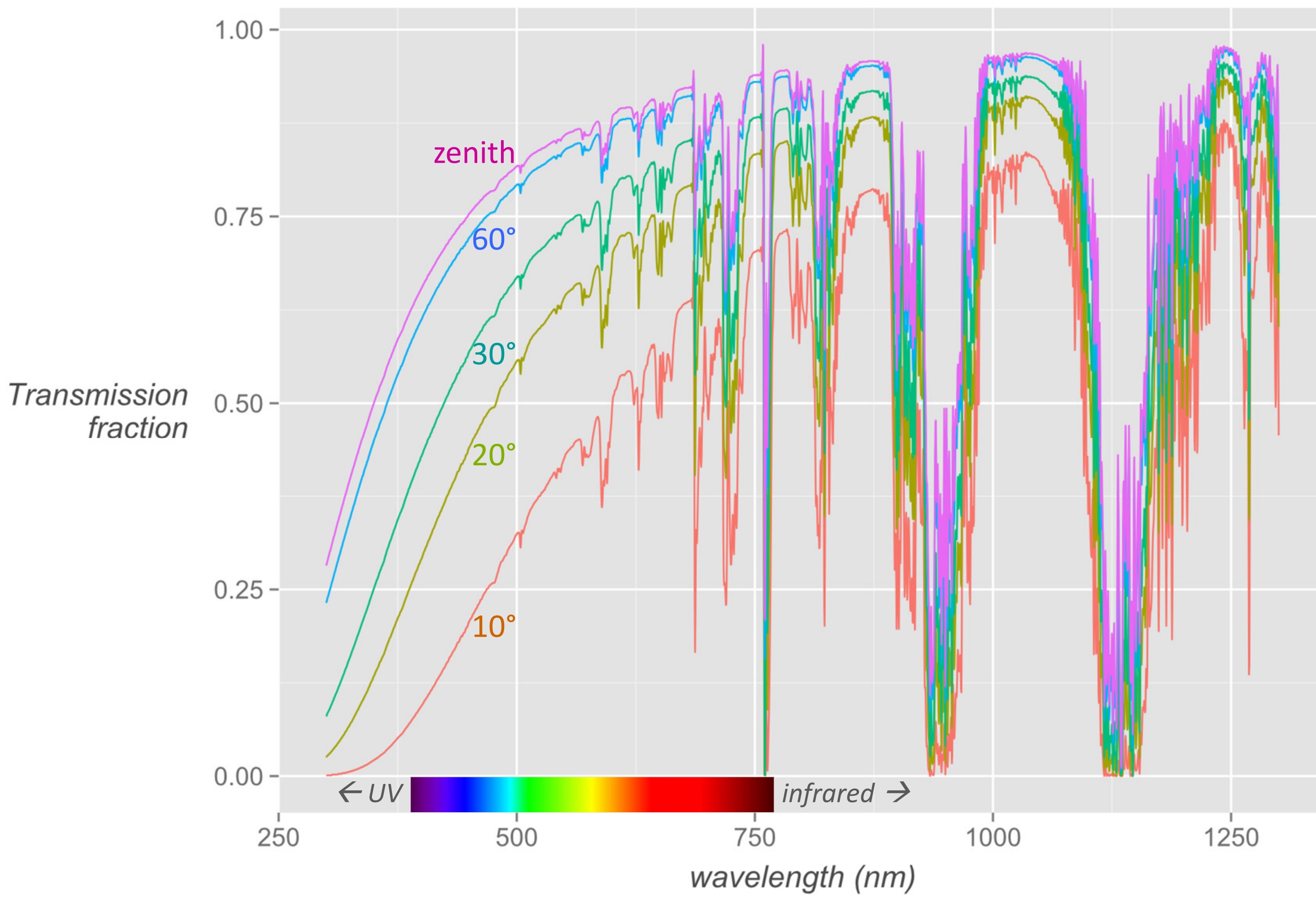
Atmospheric Spectral Transmission
(simulated)



- *computed with SMARTS software, Kansas skies, winter average*

Atmospheric Spectral Transmission
(simulated)



- *computed with SMARTS software, Kansas skies, winter average*

$2 + 2 = 4$ ✓

Simulation: Sanity Checks

Need for Color Correction

black-body stars

no atmosphere, perfect scope & detector

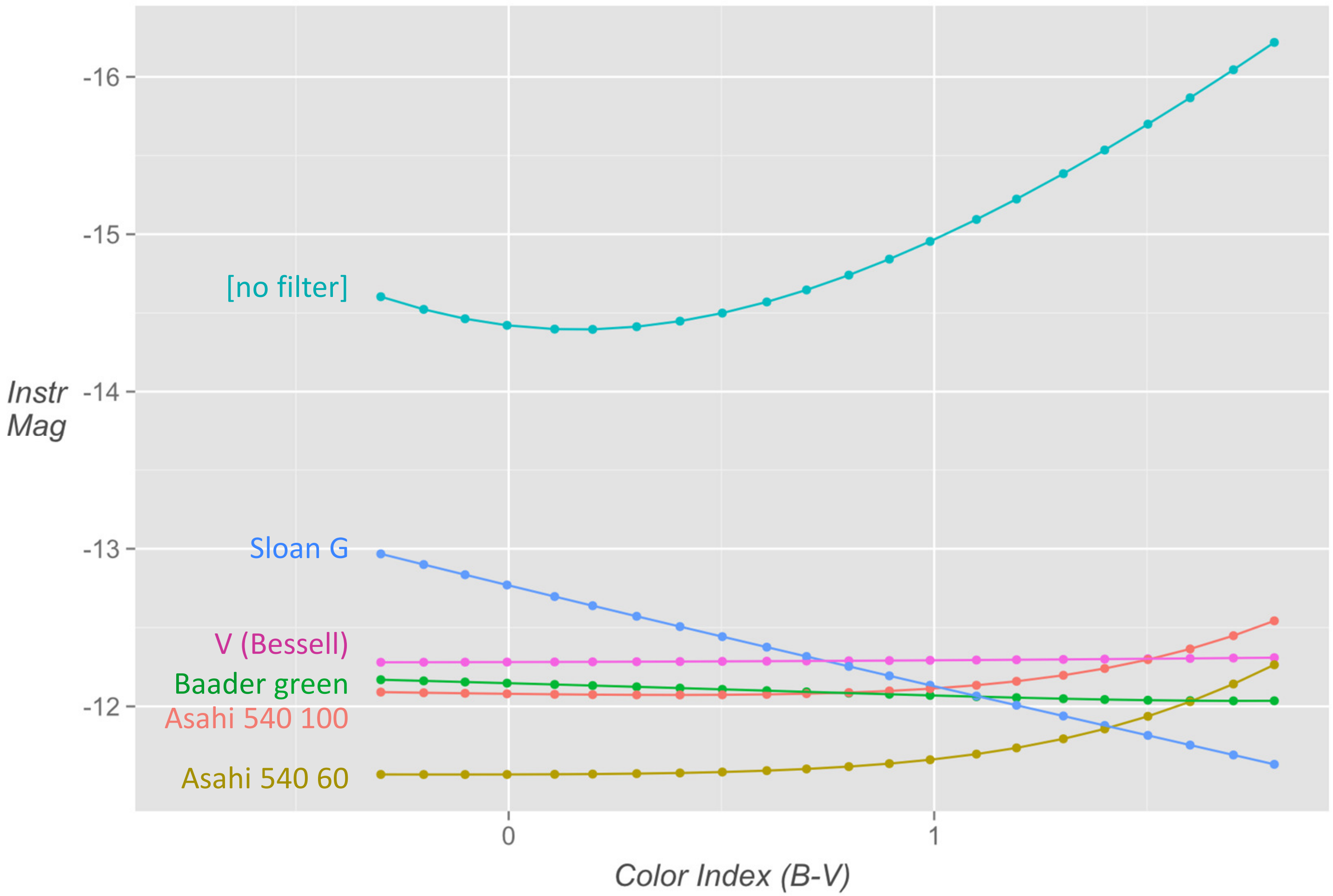
Motivation

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

Statistics

Conclusions *so far*

What's Next?

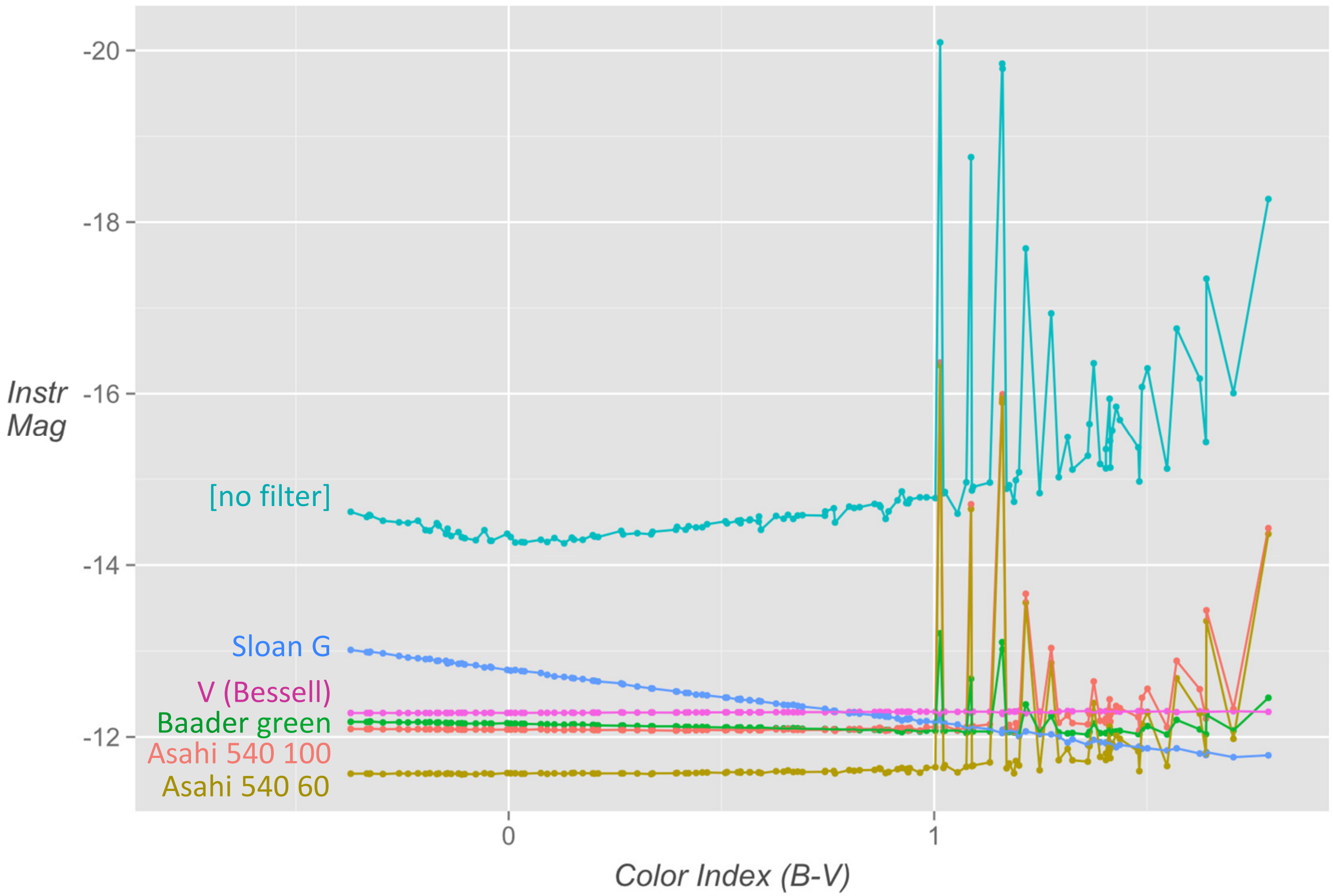


- *stars at V mag 10.*
- *mags & color index: Bessel 1990 passband.*

Need for Color Correction

131 simulated stars

no atmosphere, perfect scope & detector



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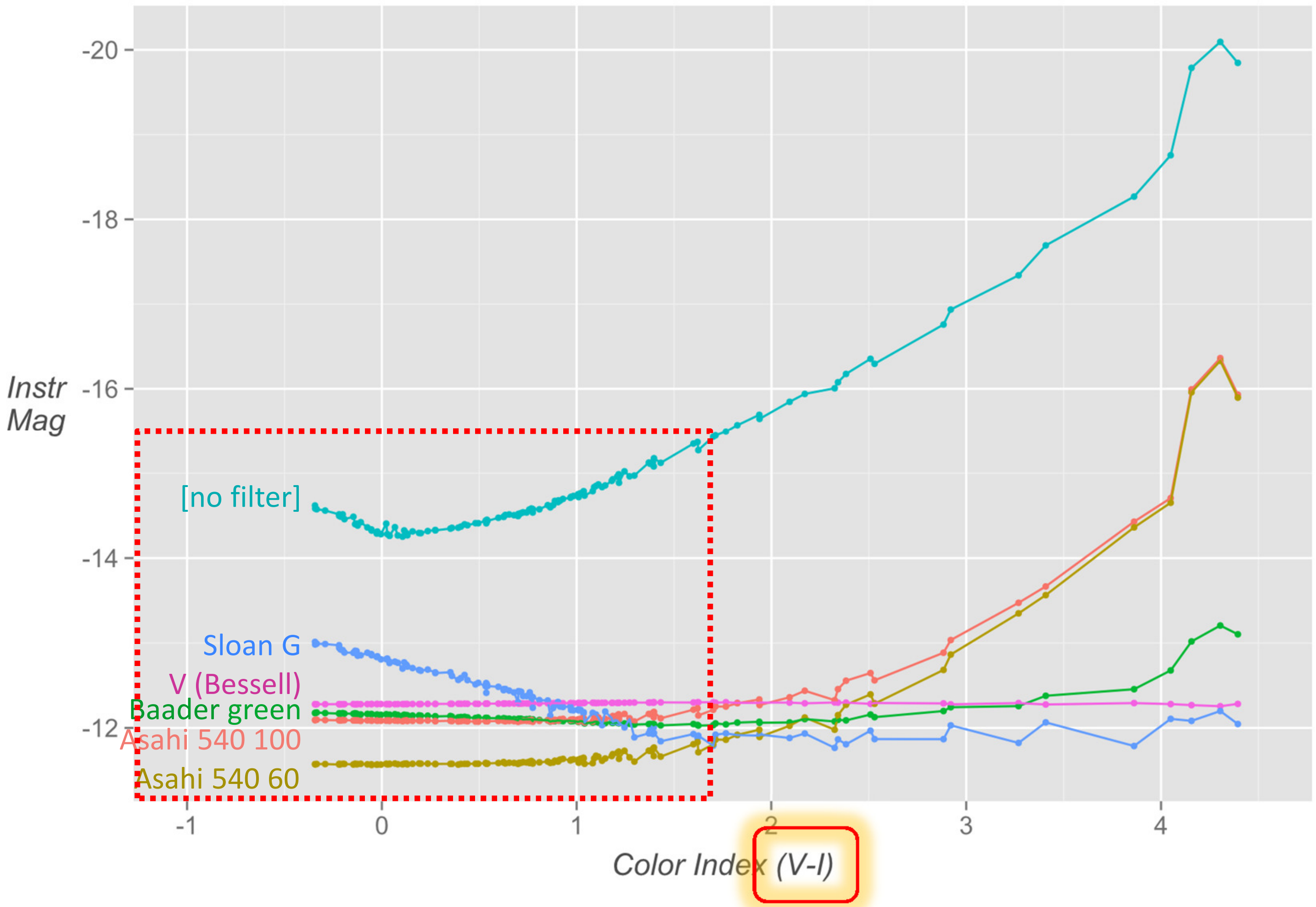
Need for Color Correction

131 simulated stars

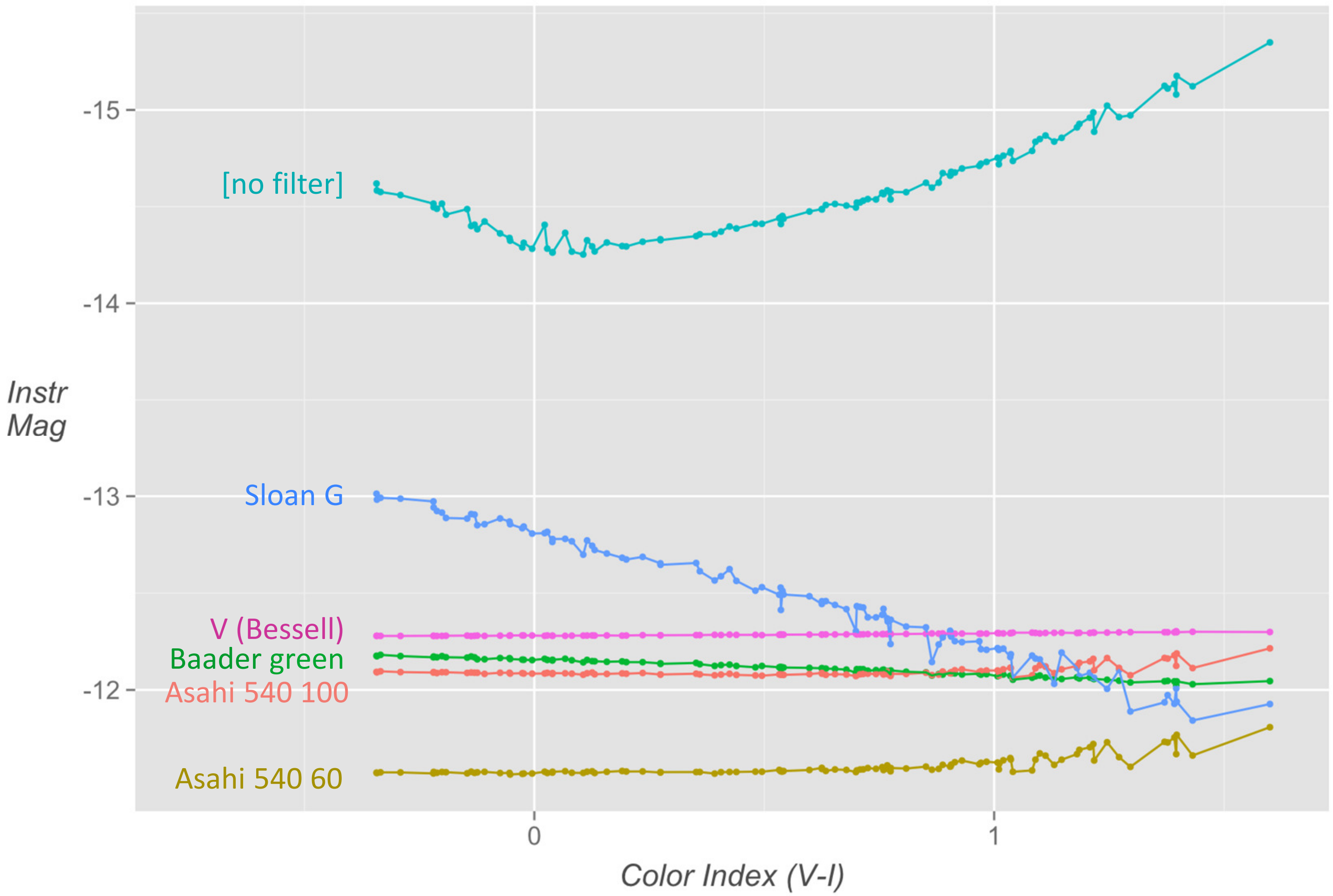
no atmosphere, perfect scope & detector



Need for Color Correction

107 simulated stars with V-I < 1.6

no atmosphere, perfect scope & detector



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Simulation: First results

Need for Color Correction

107 simulated stars, V-I < 1.6

No atmosphere, perfect optics & detector

Filter	Res. error *(mmag)*	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

Need for Color Correction

107 simulated stars, V-I < 1.6

Atmosphere (zenith), realistic optics & detector

☞ Millimagnitude calibration possible *in principle*.

Filter	**Res. error** *(mmag)*	**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?

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Statistics: the scheme

Motivation

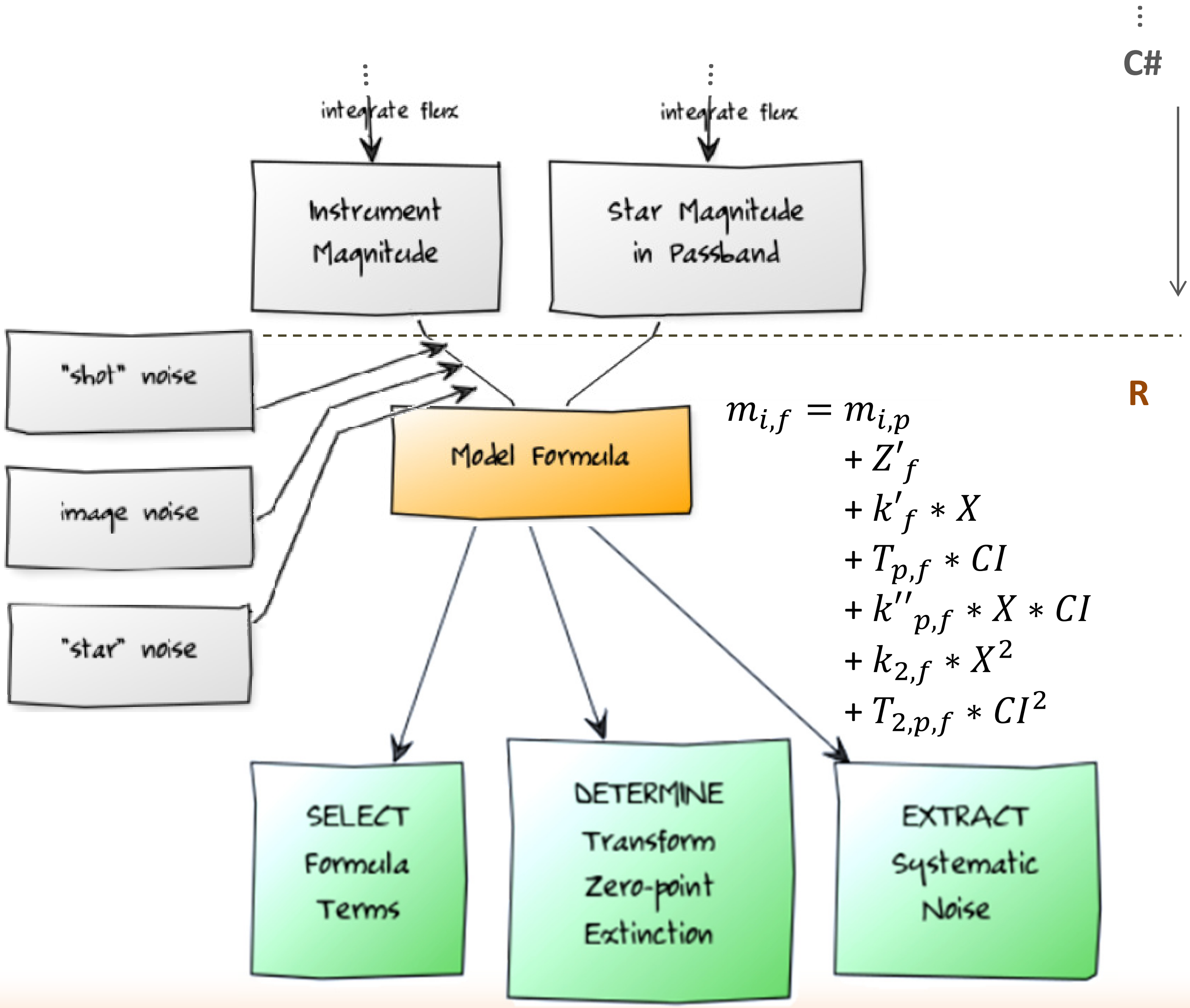
Simulations

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

Conclusions *so far*

What's Next?

Statistical Scheme



$$
\begin{aligned}
m_{i,f} = m_{i,p} & \\
&+ Z'_f \\
&+ k'_f * X \\
&+ T_{p,f} * CI \\
&+ k''_{p,f} * X * CI \\
&+ k_{2,f} * X^2 \\
&+ T_{2,p,f} * CI^2
\end{aligned}
$$

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Statistics: fixed-effects regression

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Fixed-effects regression

= standard multivariate regression

☞ *All coefficients have fixed values per fit.*

- 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

Fixed-effects regression

all 131 stars, no added noise (best case)

Filter	Res. error *(mmag)*	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

- ☞ Standard V filter is clearly best.
- ☞ Rectangular 540 nm center x 100 nm wide is next
- ☞ Sloan G surprisingly poor.

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Statistics: mixed-model regression

Mixed-model regression

= fixed-effects + "random effects"

☞ *Random effects decrease chosen systematic errors.*

- 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.

No noise added

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

Noise added:
3 mmag per-point
10 mmag per-image

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

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Conclusions & Wrap-up

Motivation

Simulations

Statistics

Conclusions *so far*

What's Next?

Conclusions *so far*

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 modern CCDs
- **V-I much better**, not necessarily best

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Conclusions *so far*

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*

Star catalogs to 0.01 mag are no good for millimagnitude work

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

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Conclusions *so far*

**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?

Motivation

Simulations

Statistics

Conclusions *so far*

What's Next?

Conclusions *so far*

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*

Motivation

Simulations

Statistics

Conclusions *so far*

What's Next?

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*
    - *similar to ensemble of comp stars*
    - *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