Dust in 3D from Stellar Photometry

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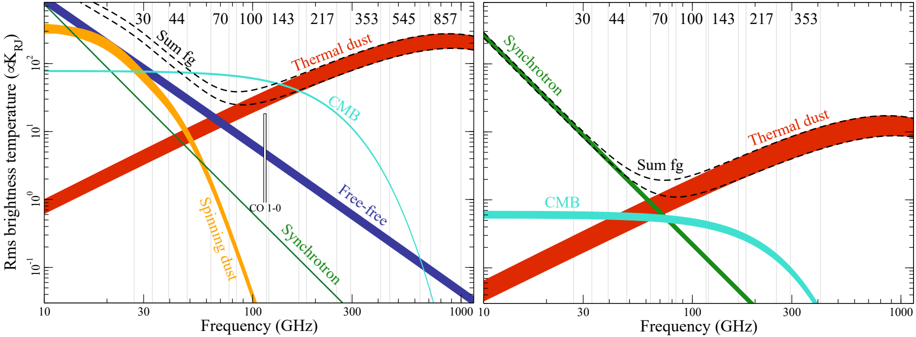
B-Modes from Space
December 4, 2017

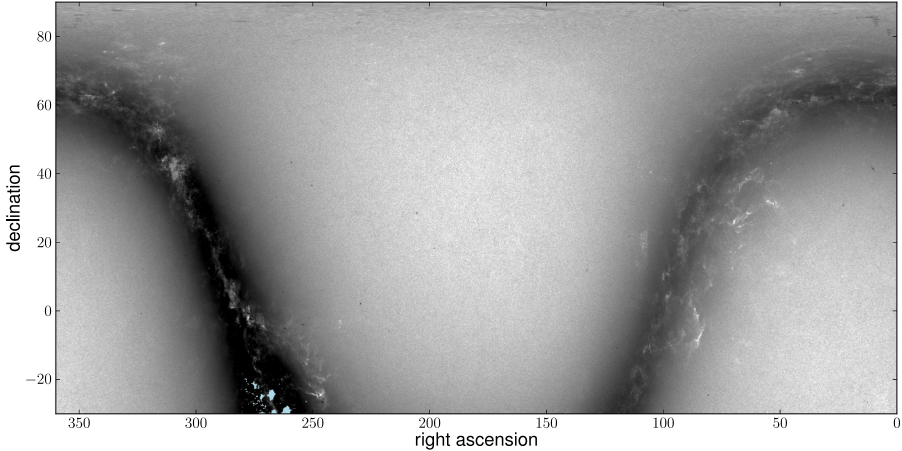
Introduction



- Dust is a major CMB contaminant
- Complicated morphology, polarized
- Many observational tracers (thermal emission, gas line emission, extinction, . . .)
- this talk: stellar photometry to trace dust column and properties

3D Dust Mapping

- Idea: use stars as lighthouses to map ISM
- Millions of stars from large surveys → high resolution map
- Challenge: only a few photometric bands available to determine distance and reddening to each star



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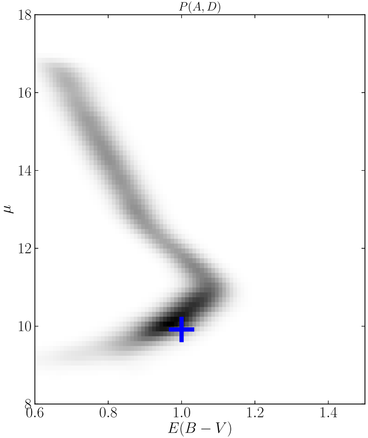

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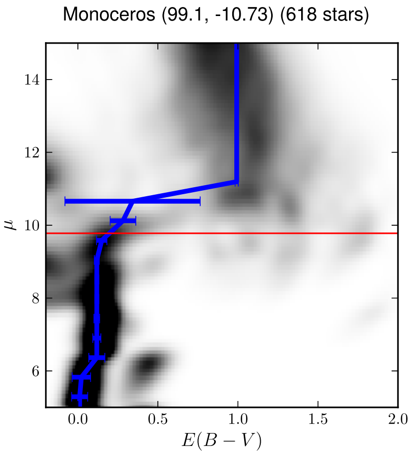

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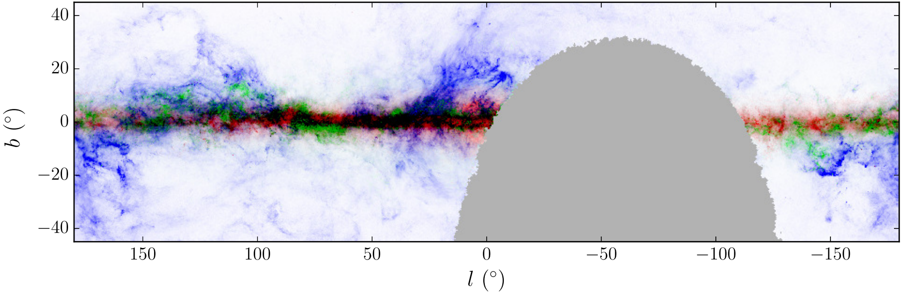
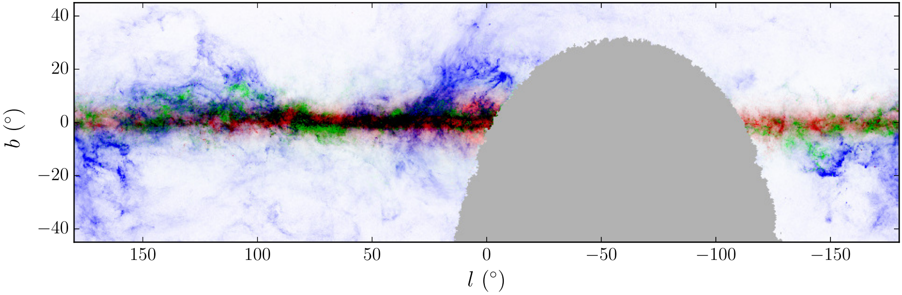


3D Dust Map (Green+2017)

Does it work?

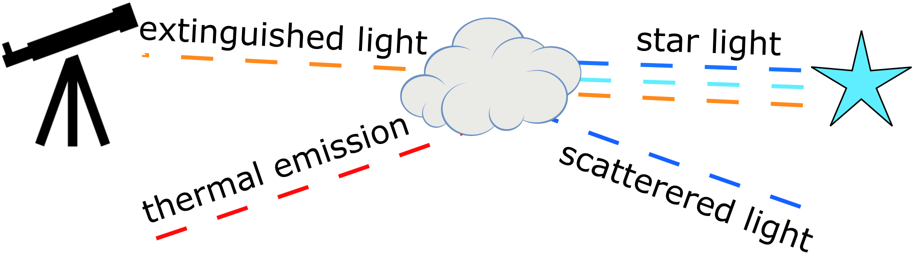
(movies)

Use for CMB studies?



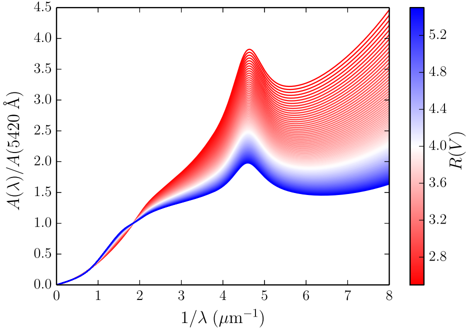
- 0.01 mag $E(B - V)$ statistical uncertainty
  - 20× larger than the uncertainty in 100 μm emission
  - hard to imagine reaching CMB-like precisions
- known distances to clouds with $E(B - V) > 0.15$
  - Considerable uncertainty in more diffuse clouds
- Not clear how to best use 3D map in CMB context

Dust and Light



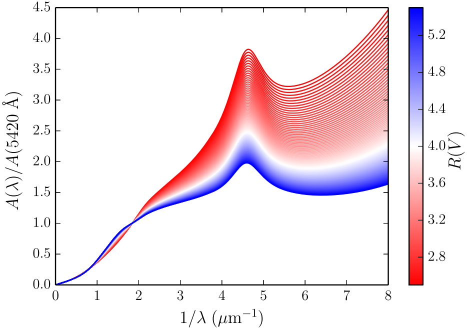
- light from star is "extinguished" passing through a cloud
  - absorbed and reradiated at long wavelengths
  - scattered
- CMB work focuses on thermal emission, but extinction is also relevant

The Extinction curve



Fitzpatrick (1999), Cardelli, Clayton, & Mathis (1989)

The Extinction curve



Fitzpatrick (1999), Cardelli, Clayton, & Mathis (1989)

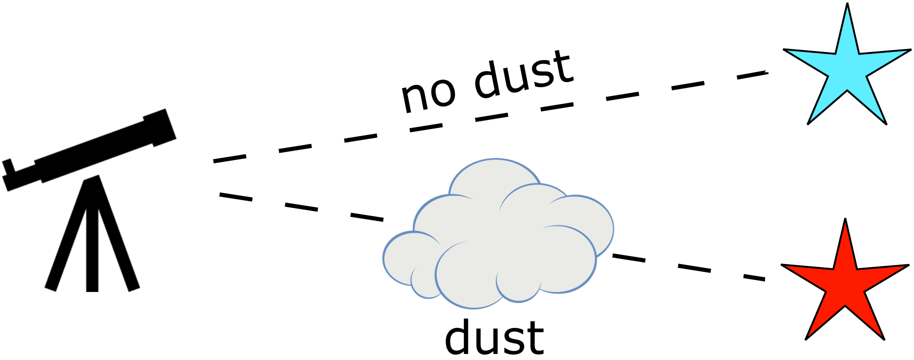
Entirely empirical curve, presumably determined by:

- grain size distribution
- grain composition
- grain processing

These properties also determines the dust emission at CMB frequencies.

Measuring the Extinction Curve

- Simple method: compare spectra of reddened and unreddened stars
- Dates back to Trumpler, Johnson, ...
- Many more stars accessible today



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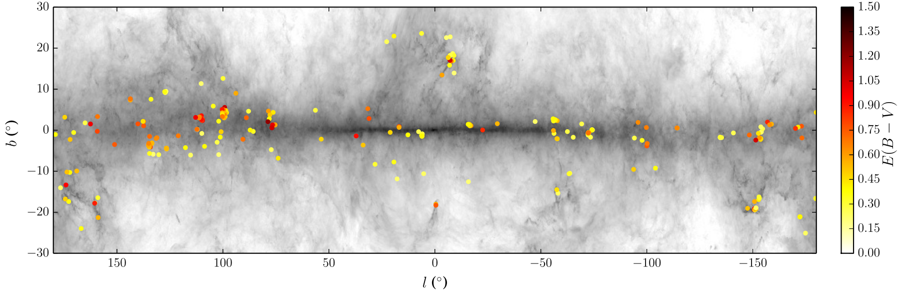

Fitzpatrick & Massa (2007), 328 stars

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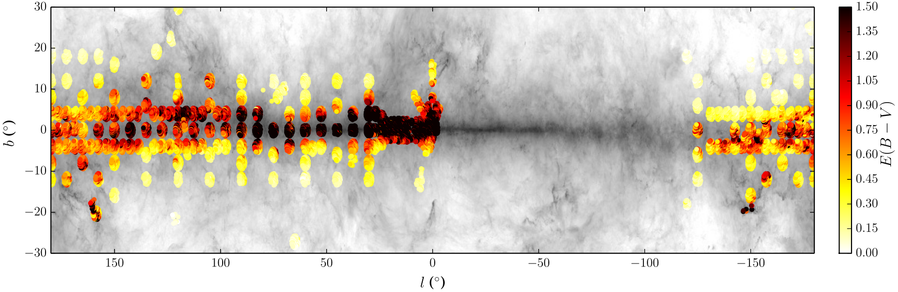

APOGEE & PS1 & 2MASS & WISE, 37000 stars

Extinction and Emission are Linked

Can model dust emission with a modified blackbody:
$I(\nu) = \tau_\nu B_\nu(T)(\nu/\nu_0)^\beta$

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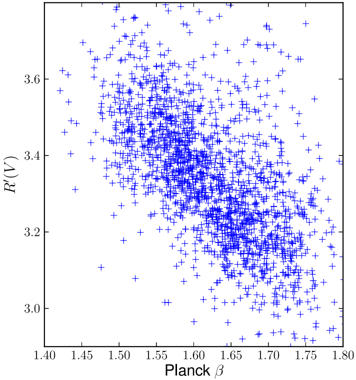
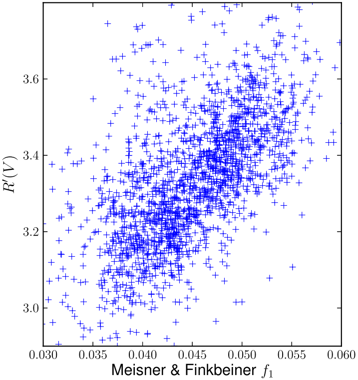
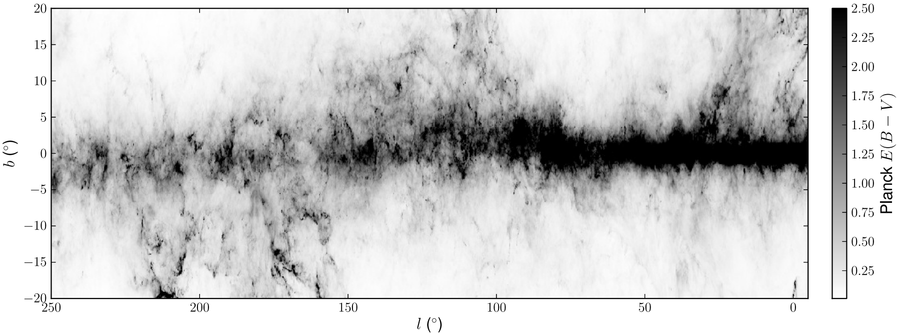




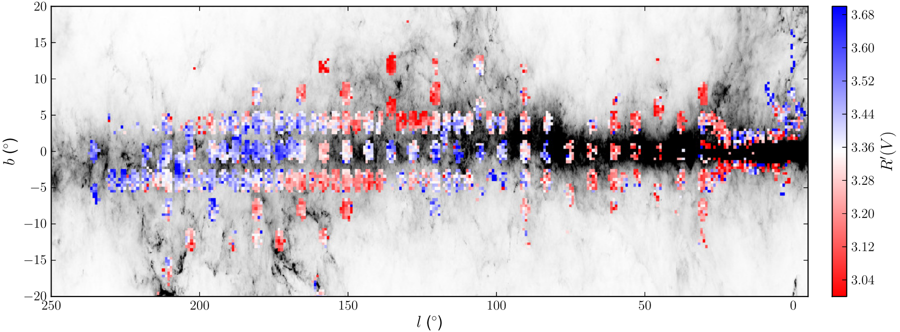
Strong correlation between dust SED and $R(V)$!

Mapping $R(V)$



20
15
10
5
0
−5
−10
−15
−20
b (°)
250
200
150
100
50
0
l (°)
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
Planck $E(B-V)$

Mapping $R(V)$



Dominant variations on large scales, as also seen in Planck β measurements.

3D $R(V)$ Map

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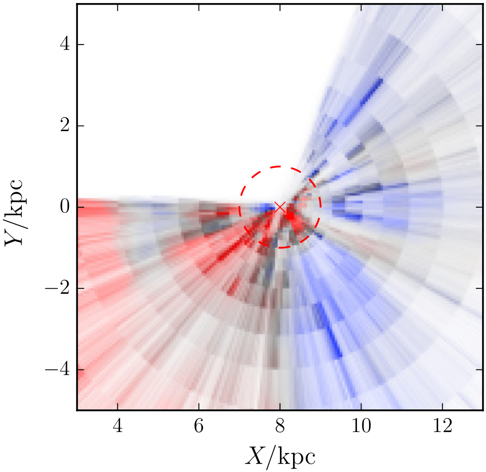
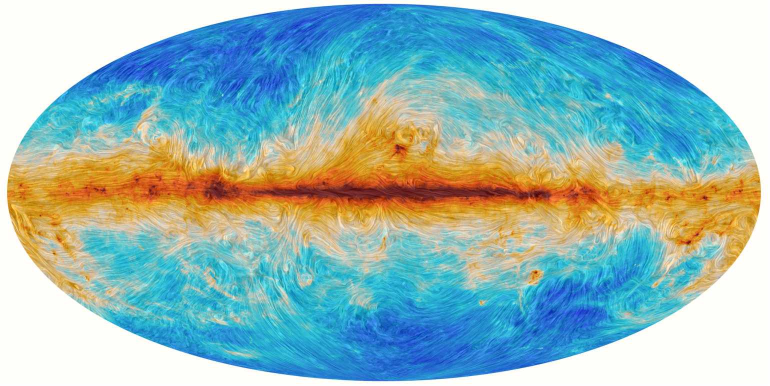


Kiloparsec scale sturctures, possible Galactic gradient?
Useful for predicting thermal dust SED for CMB dust decontamination?

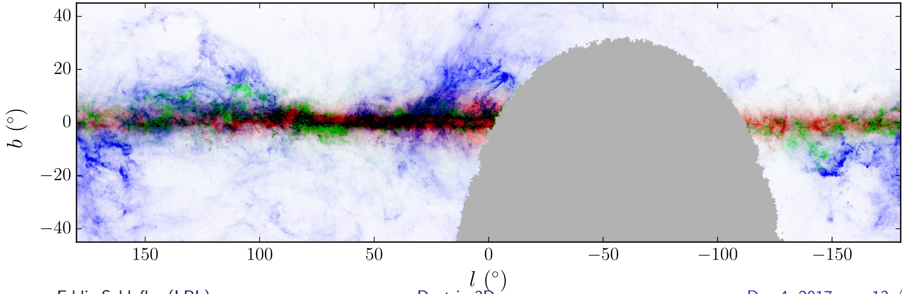
Starlight polarization and dust-polarized emission



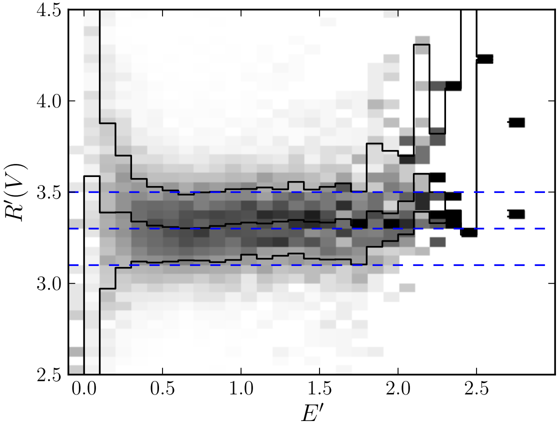
Starlight polarization and dust-polarized emission both come from aligned grains.

Conclusion

- Accurate 3D dust maps
- Extinction curves measured for tens of thousands of stars
  - Clear correlation between extinction curve and Planck β
- 3D dust map can serve as a foundation for unraveling the properties of the ISM in 3D
  - Dust properties
  - Velocity field
  - Magnetic field
- How to use this information to improve CMB studies?

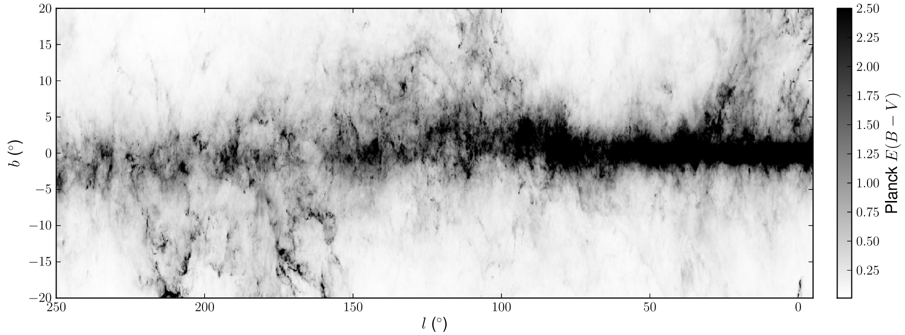


Does $R(V)$ vary systematically with $E(B-V)$?



No correlation between $R(V)$ and $E(B-V)$, but $E(B-V)$ is dust column density rather than volume density tracer.
APOGEE Reddening Survey in APOGEE-2 to resolve this issue.

How does the extinction curve vary spatially?



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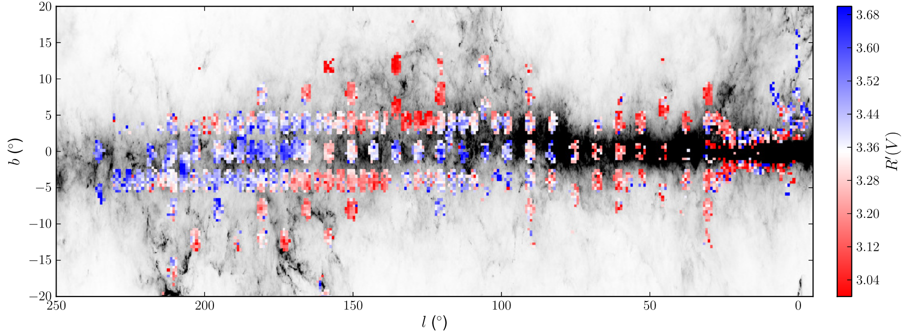
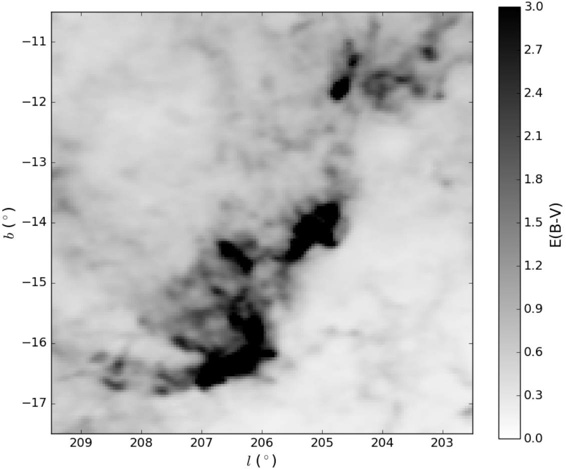


Dominant variations on large scales, *not* small scale variations in dense molecular clouds.

Map of $R(V)$ in Orion B



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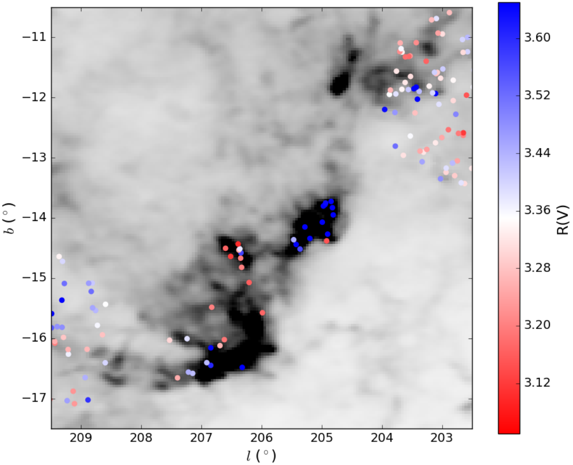
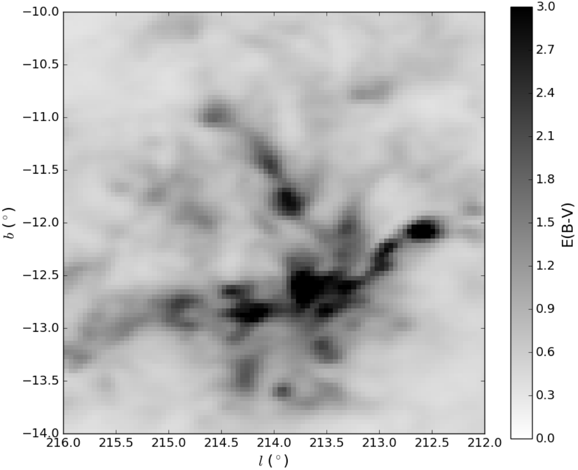


Map of $R(V)$ in Mon R2



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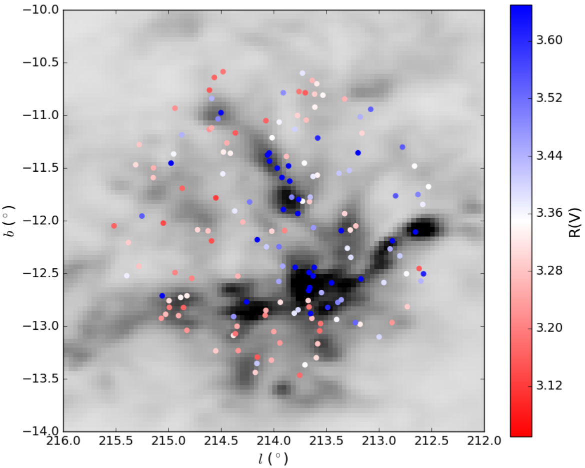
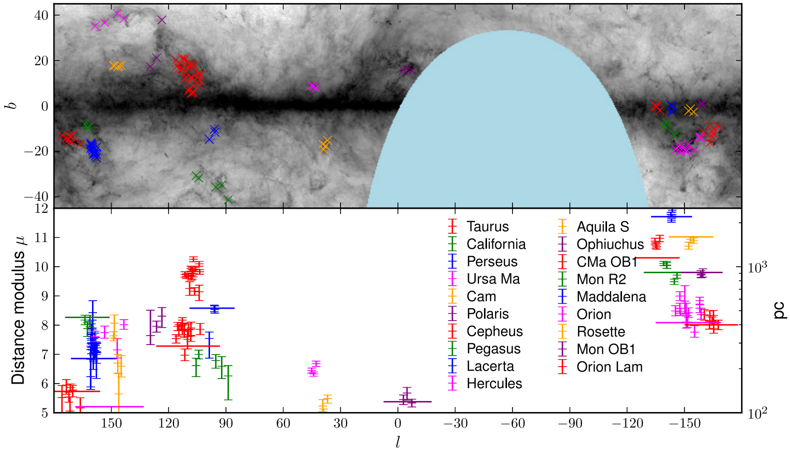


Distance Catalog



Schlafly+2014

The Orion Dust Ring

Slice dust into foreground, Orion, and background

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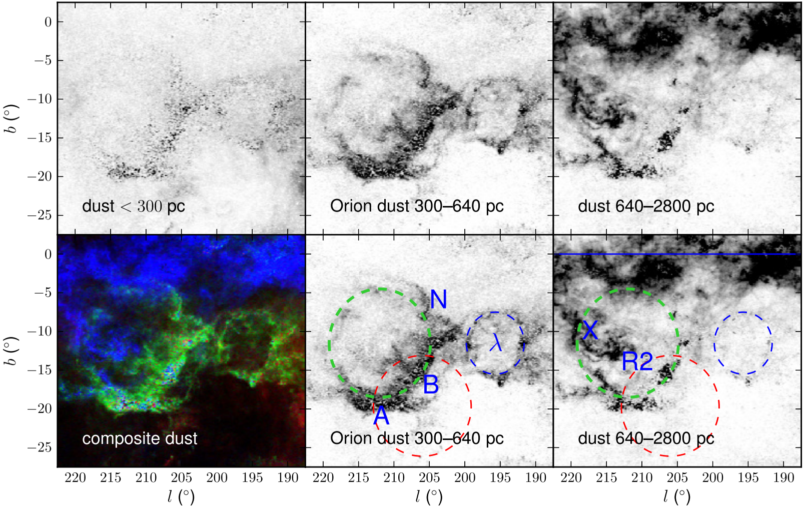
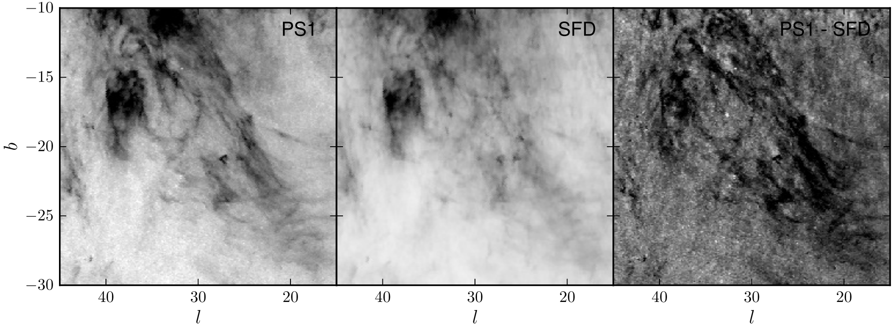


2D Comparison: Aquila South



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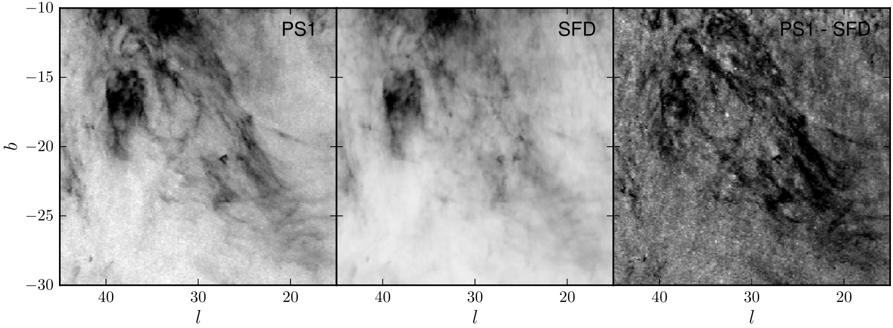


- Problems hard to avoid in “reddening” maps based on extinction.
- Future reddening maps will be star-based.

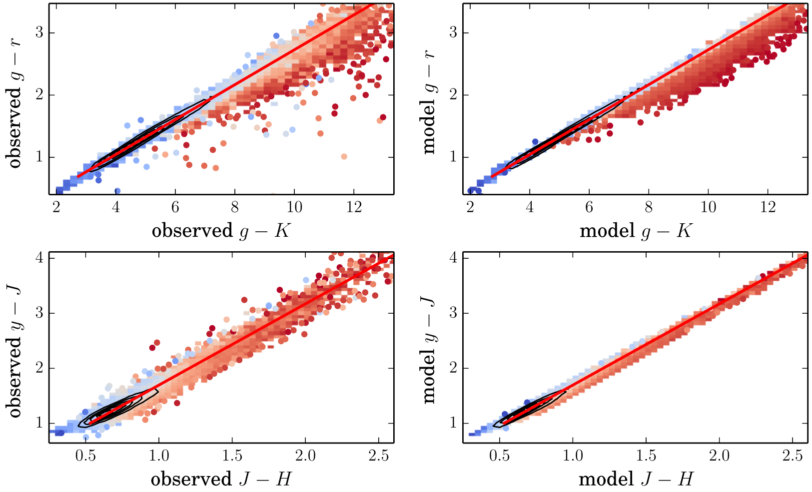
Model

$$\vec{m}^m = \vec{f}(T, [\mathrm{Fe/H}]) + \mu + \vec{R} \times E$$

$\vec{m}^m$	model magnitudes
$\vec{f}$	intrinsic colors ($n_{\mathrm{band}} \times 17$ free parameters)
T	temperature
$[\mathrm{Fe/H}]$	metallicity
μ	distance modulus (n_{star} free parameters)
$\vec{R}$	reddening vector (n_{band} free parameters)
E	extinction (n_{star} free parameters)

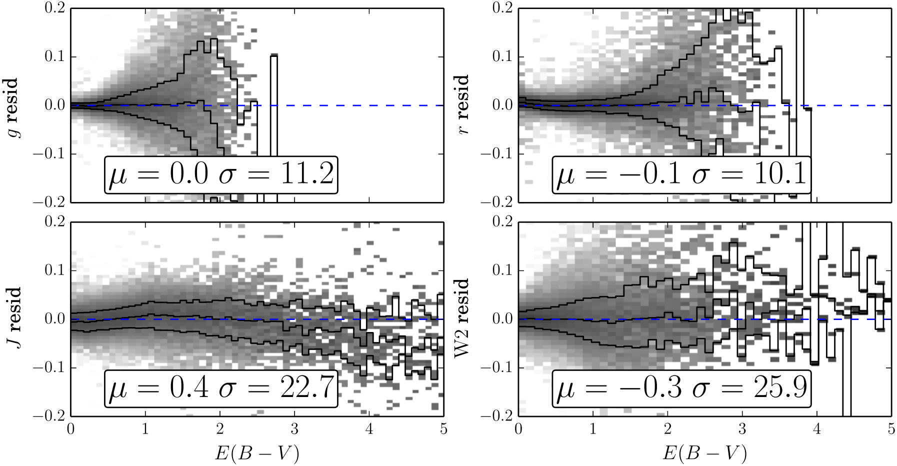
$n_{\mathrm{star}} = 37000$, $n_{\mathrm{band}} = 10$, so ~ 75000 free parameters, constrained with ~ 330k measurements, solve by expectation-maximization

Model versus Observations



Excellent match!

Residuals

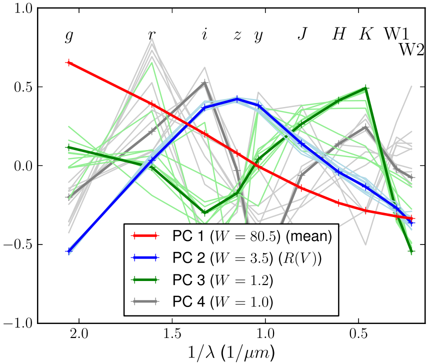


Residuals near photometric limit!

What about variation?

We have intrinsic colors for the objects, so reddenings are easy

Assess variation by PCA



- Almost all variation limited to two components
  - Extinction curve really is a one-parameter family!
- Higher order components consistent with noise

New Measurements of the Extinction Curve

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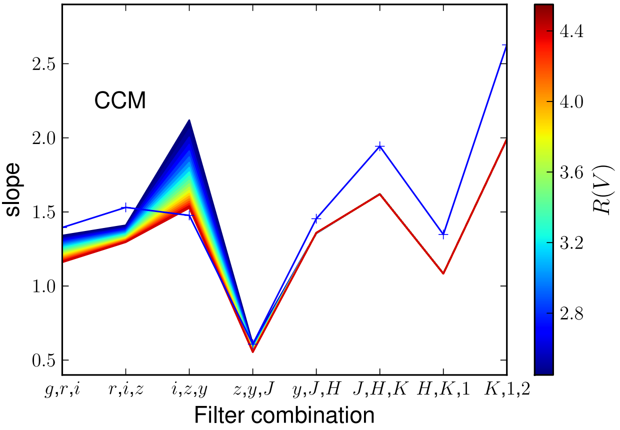

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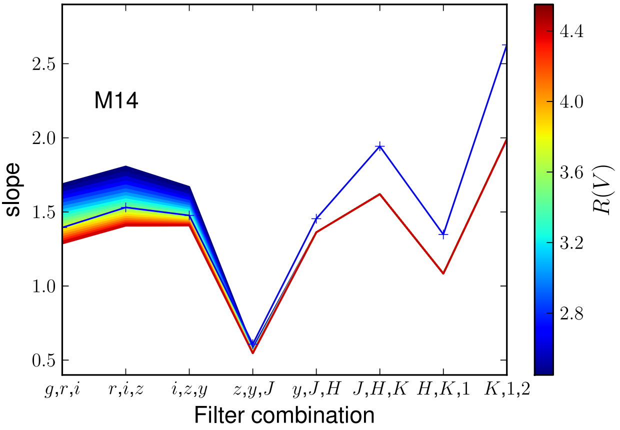

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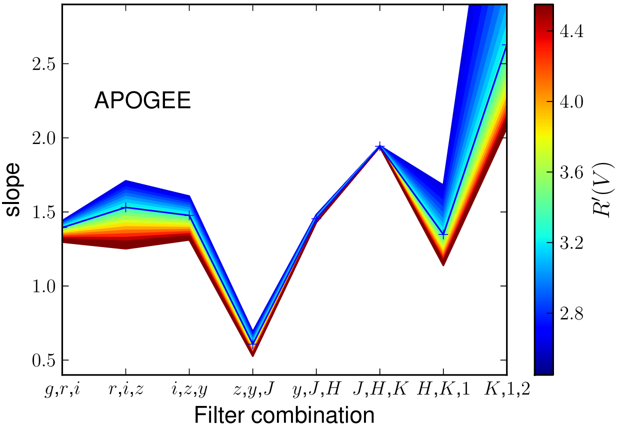

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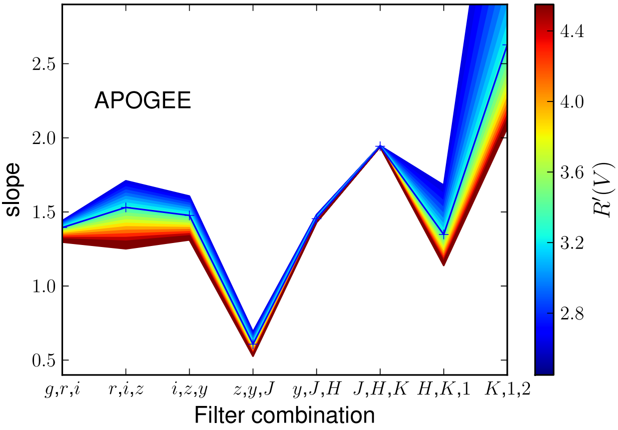
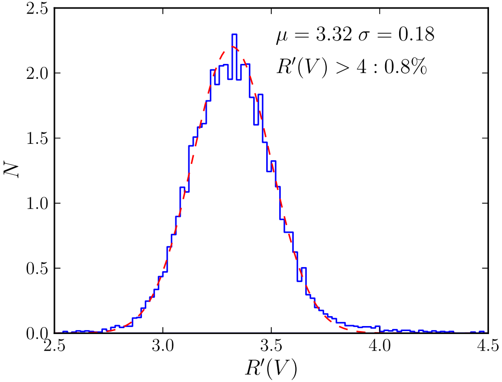


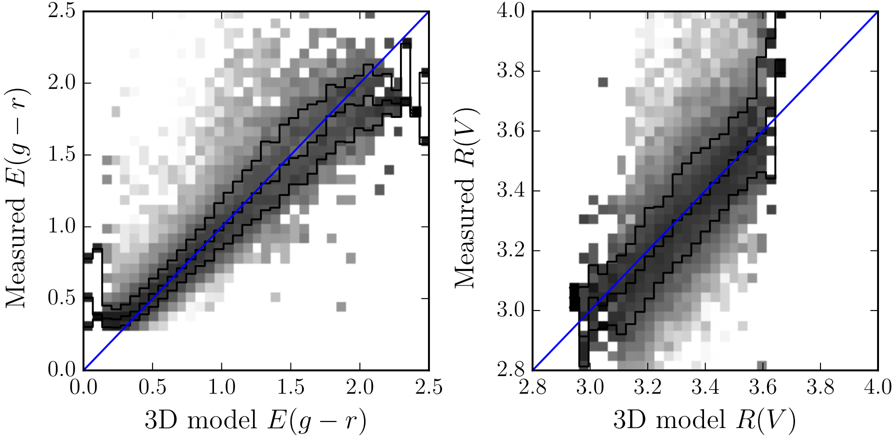
- extinction curve is a one-parameter family in the optical to infrared
- decreasing $R(V) \rightarrow$ increasing curvature (more small grains?)

How variable is the extinction curve?

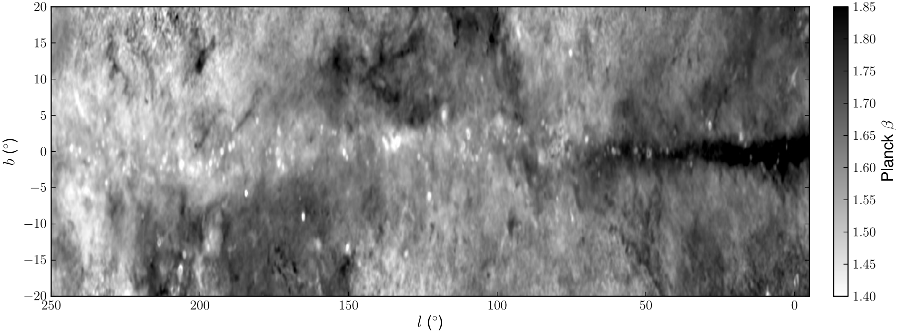


Somewhat smaller dispersion than literature (0.27), many fewer high $R(V)$ sight lines (9.5% in FM07)

3D $R(V)$ Map Accuracy



Extinction and Emission are Linked



Planck (2014) β map

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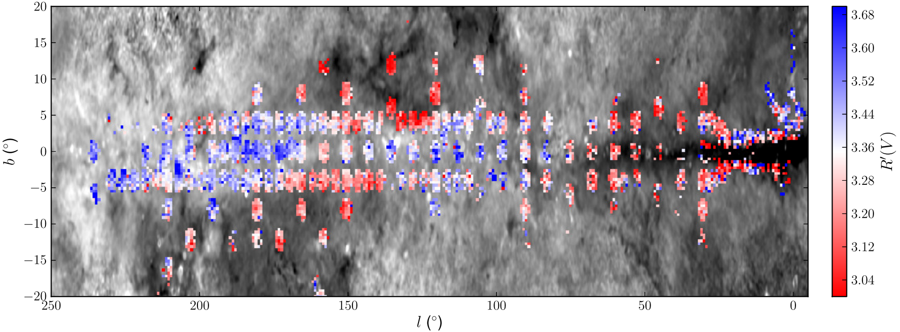

Large and small scale features in β closely linked to variations in $R(V)$.

Tracing dust with stars in 3D (Green, Schlafly+2014)

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- $>$5e8 PS1 stars

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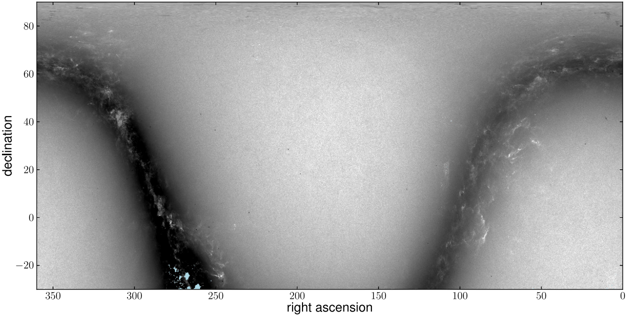

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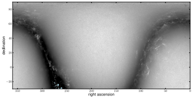

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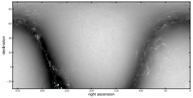
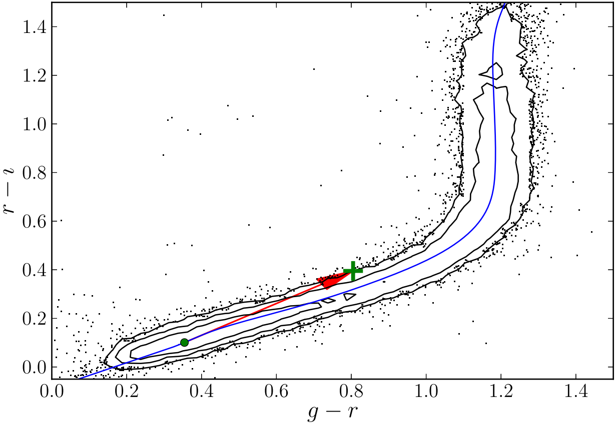


- Reddening and distance inference



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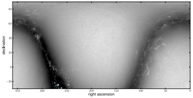

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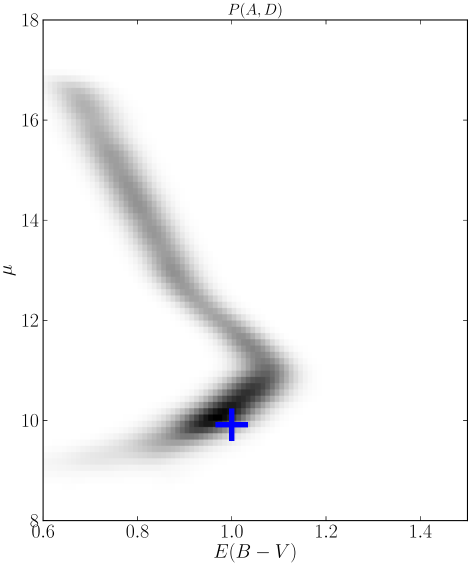

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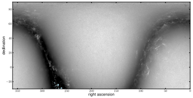

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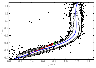

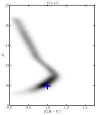

- Line of sight fit

Tracing dust with stars in 3D (Green, Schlafly+2014)

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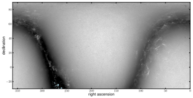

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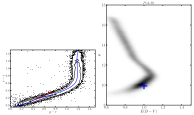

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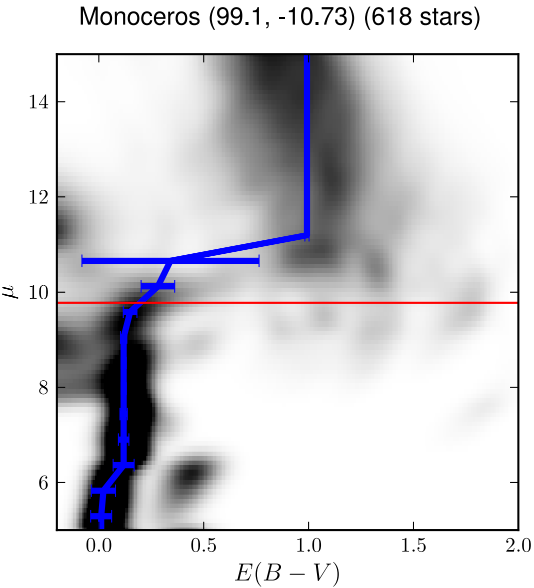

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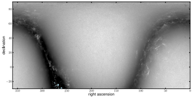

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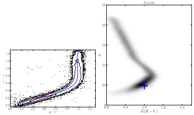

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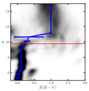

- Lots of related work!
  - Hanson, R. & Bailer-Jones (2014), (2015)
  - Sale+2014, Sale+2015, Sale+2017
  - Marshall+2006
  - Lallement+2014
- New data
  - DECaPS
  - Gaia
  - APOGEE-2, SDSS-V
- New techniques
  - Spatial correlations (Gaussian processes?)
  - Global fit with Galactic structural parameters