X-raying the Interstellar Medium

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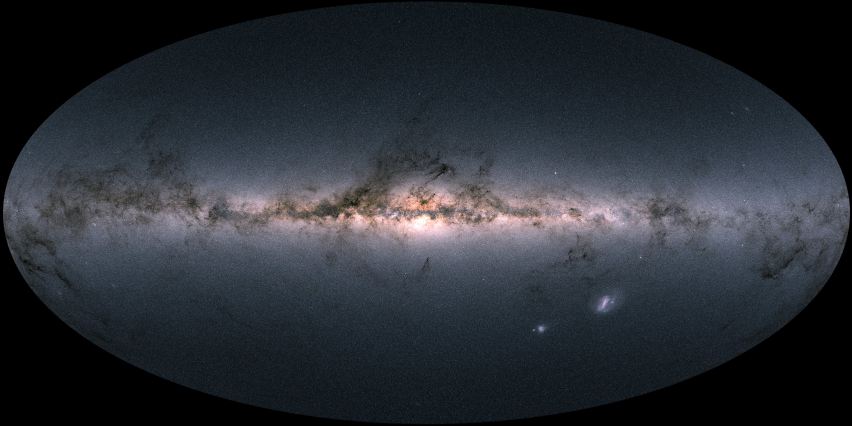
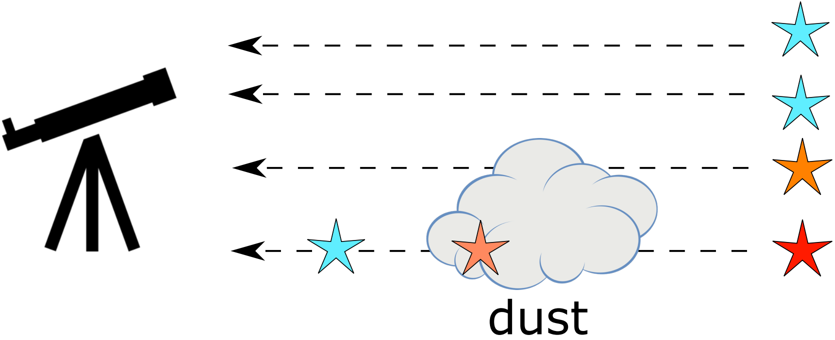
LIneA
August 8, 2019



Stars probe the ISM in 3D

My work uses stars to x-ray the dust and the ISM, giving a 3D view of the Galaxy's interstellar medium.



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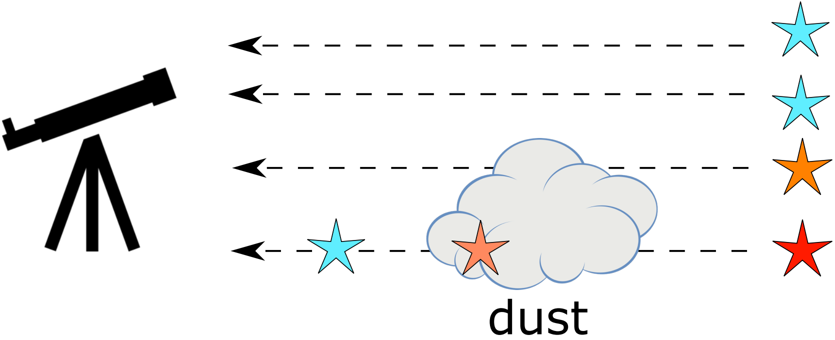

Observables: amount of material, its size distribution, its velocity, its chemical composition, the magnetic field . . .

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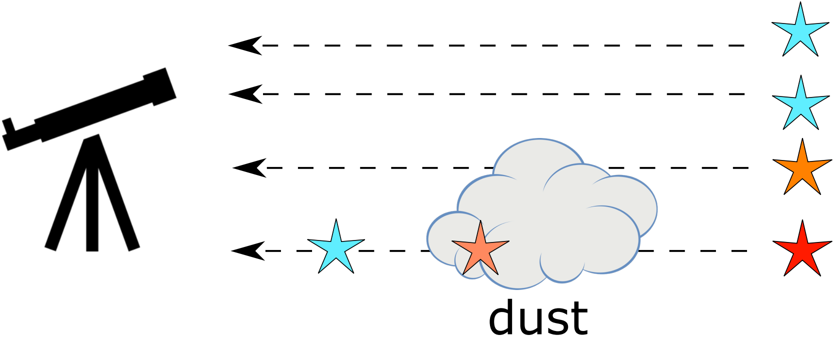

Observables: amount of material, its size distribution, its velocity, its chemical composition, the magnetic field ...

We can map all of these in three dimensions

Outline

Introduction

3D Maps of Dust Density

Dust Properties in 3D

New Surveys

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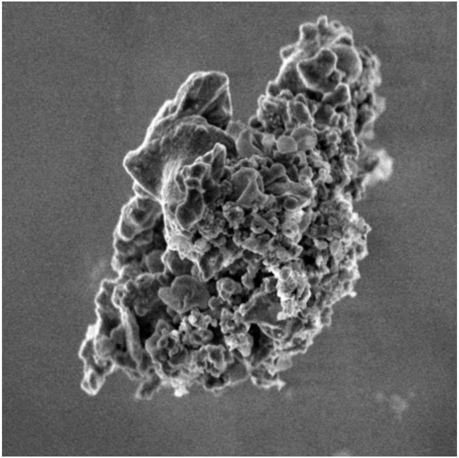
What is dust?



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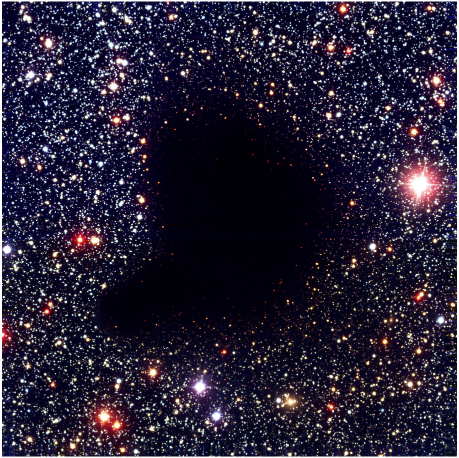

“holes in the heavens” (Herschel)

Dust is Important

- Astrophysically
- Observationally

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- enables star formation
  - cooling
  - shielding
  - catalyzing
- tiny mass (1% of gas)
- 30% of light from the Milky Way

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- planets

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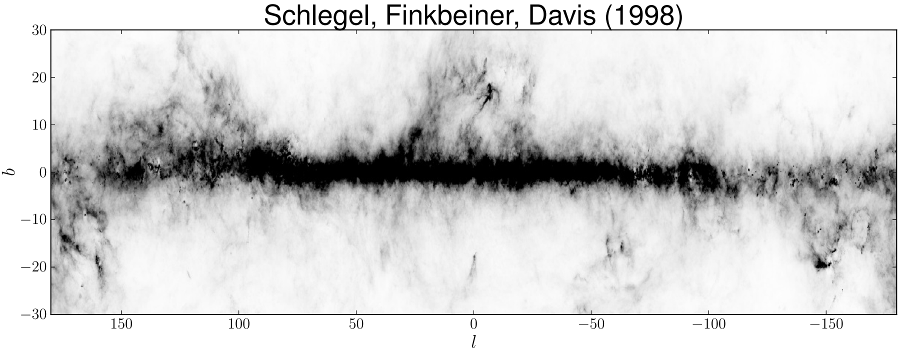

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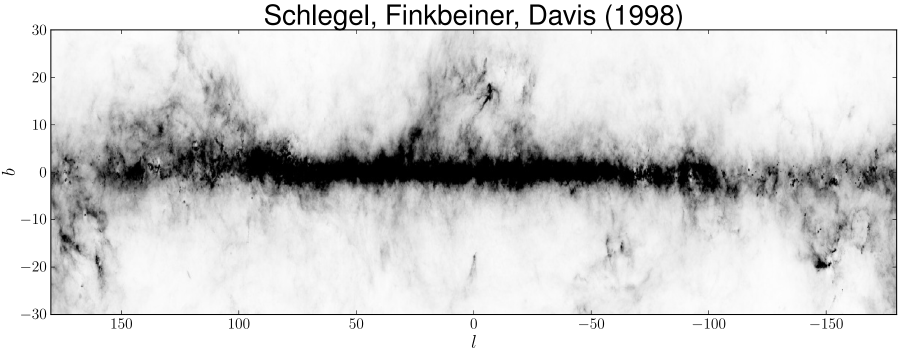

- dust *extinguishes* UV/optical/NIR light
- dust emits IR, millimeter, microwave light
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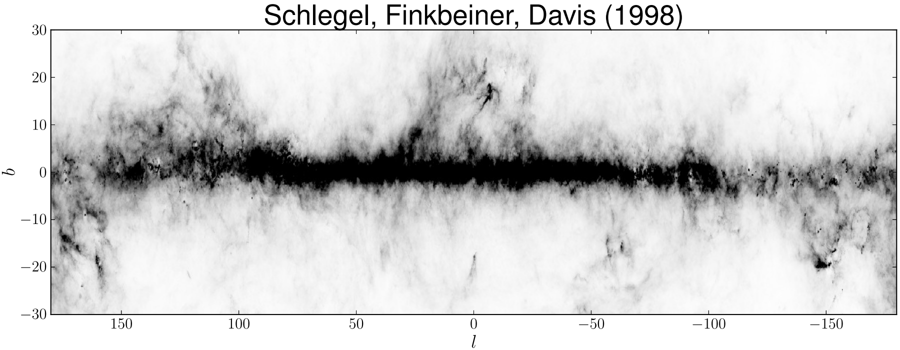

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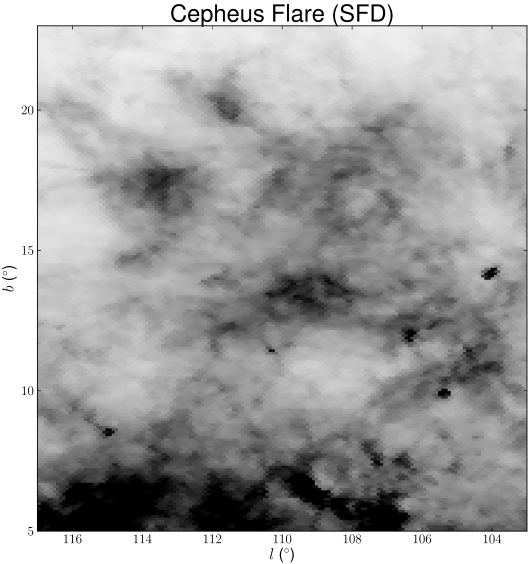
- dust emits IR, millimeter, microwave light
- observationally hard to avoid
- 10,000 citations

Current Dust Maps are only 2D

- Current maps give only the total dust column.
- Distance is also important!

Current Dust Maps are only 2D



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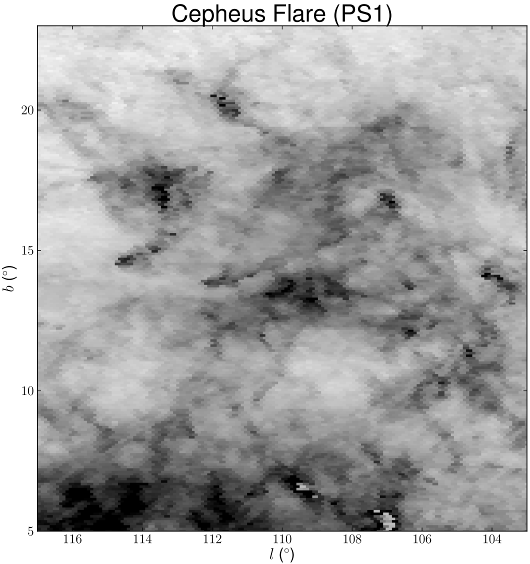

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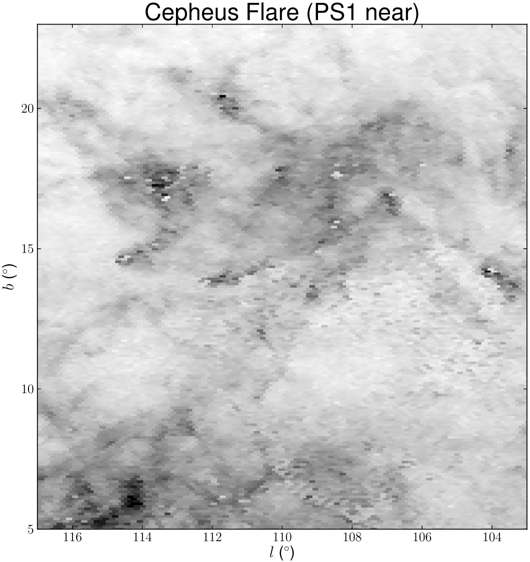

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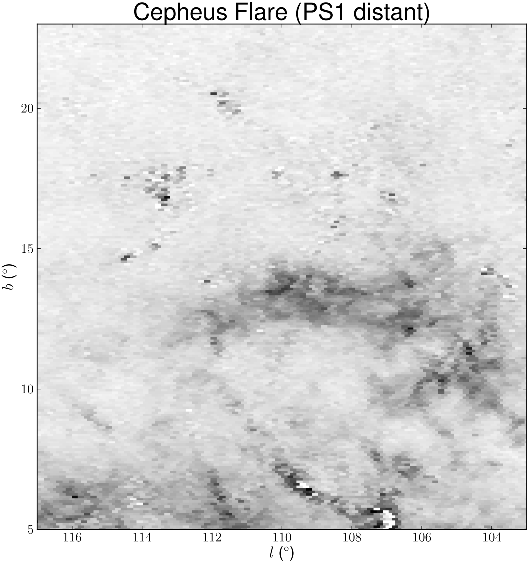

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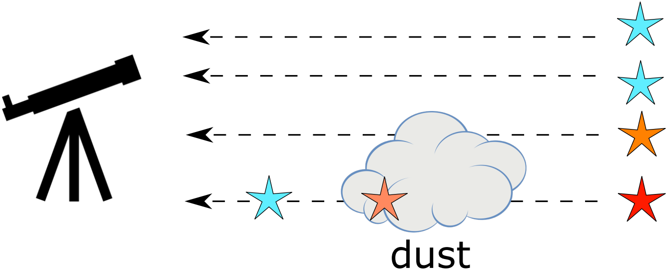
How to make a 3D map of dust

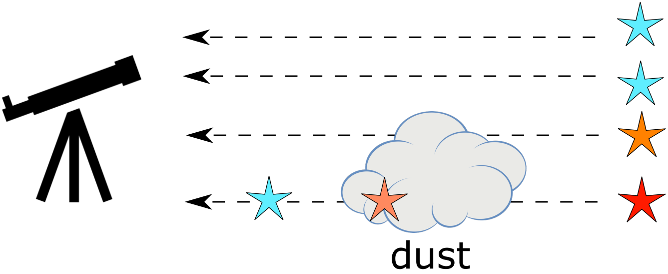
1. Large survey of stars
2. Precise photometry
3. Distance and reddening estimate for each star
4. Invert to get 3D map

Star-based 3D dust maps



- Generally, tomographic analysis
  - infer 3D structure from noisy measurements of integrated density
  - CT scan

Star-based 3D dust maps



- $\sim 10^9$ stars needed for good spatial resolution
- Distances and amounts of dust are very uncertain
- Fit parameters are all coupled
  - more distant stars must be behind more dust than nearby ones
  - dust clouds are spatially correlated
- naively several billion parameter model $\rightarrow$ impossible

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- cannot just average (e.g., with a Wiener filter): distances are uncertain
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- fit the amount of dust and the distance to each star, tracking full covariance
- pixelize sky and fit each line-of-sight independently
- iterate to introduce correlations

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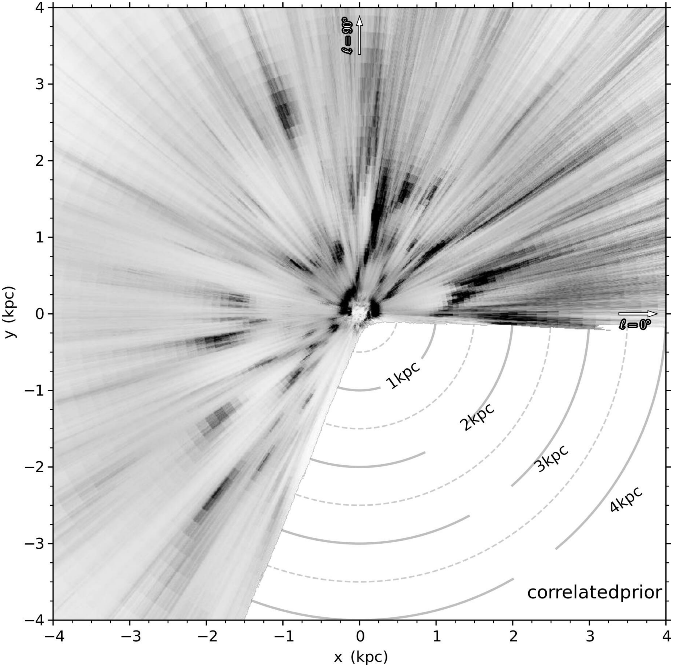
- fit the amount of dust and the distance to each star, tracking full covariance
- pixelize sky and fit each line-of-sight independently
- iterate to introduce correlations
- impossible problem $\rightarrow$ very expensive problem (2.5 million CPU hours) (Green, Schlafly+14, 15, 18)

Does it work?

(movies)


ℓ=90°
ℓ=0°
1kpc
2kpc
3kpc
4kpc
correlatedprior
y (kpc)
x (kpc)
4
3
2
1
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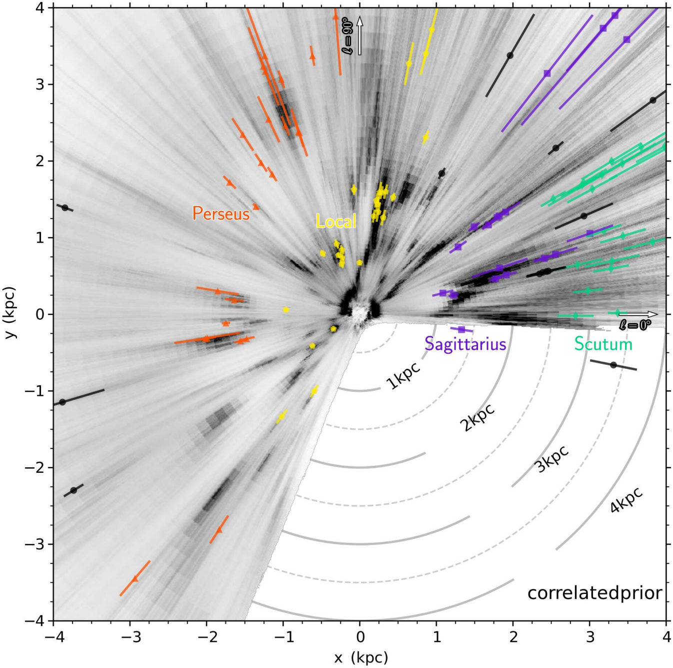
−4



y (kpc)
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ℓ=90°
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Perseus
Local
Sagittarius
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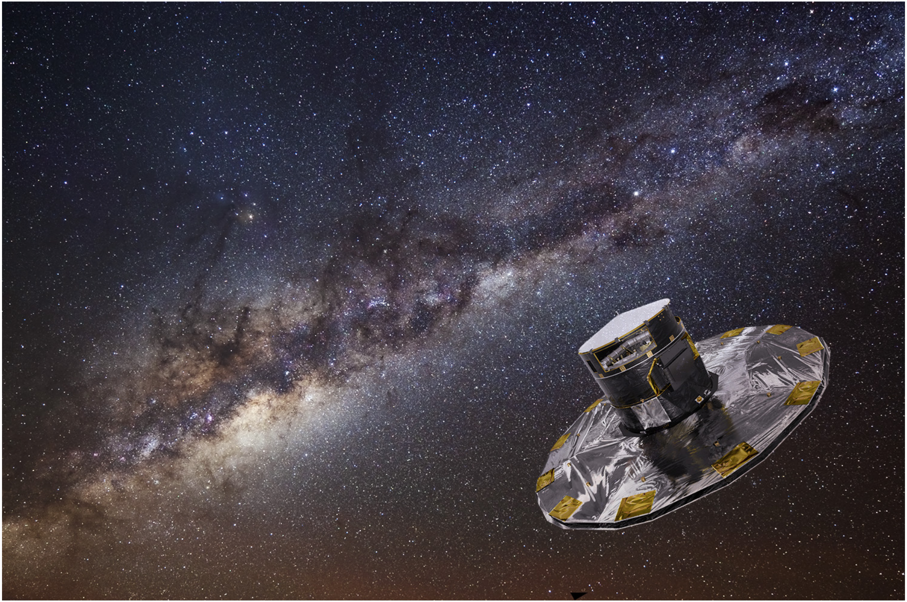
Results

- unprecedented map of Milky Way dust (Green, Schlafly+14, 15, 18)
- best distances to molecular clouds (Zucker, Schlafly+19)
- dust property variations in 3D (Schlafly+16, 17)



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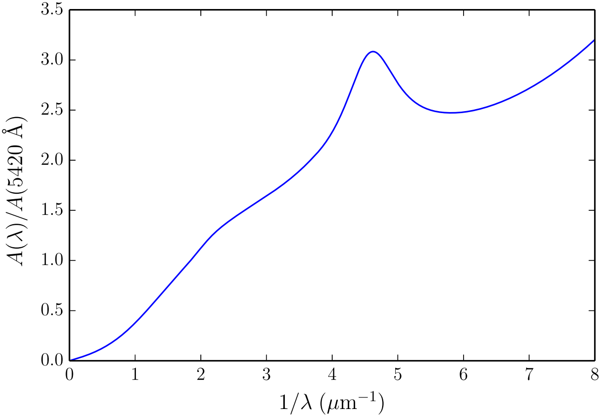
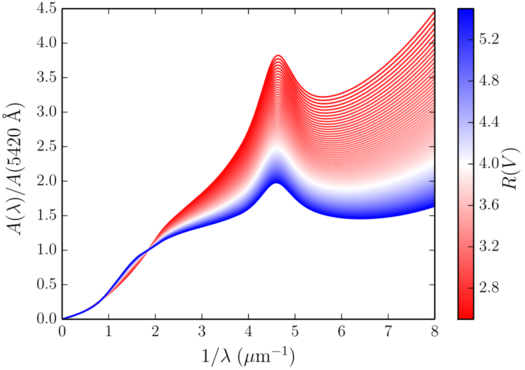
The Extinction Curve

Fitzpatrick (1999) extinction curve



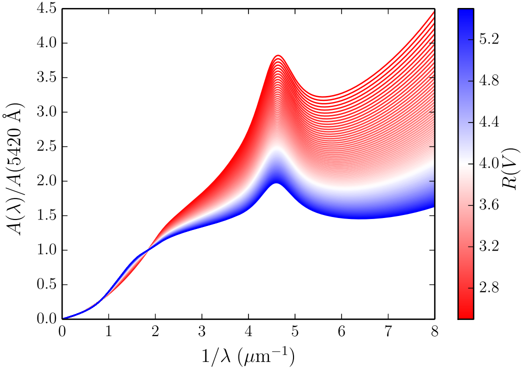
Diagnostic of dust grain size distribution

Variation in the extinction curve



Cardelli, Clayton, & Mathis (1989)

Variation in the extinction curve

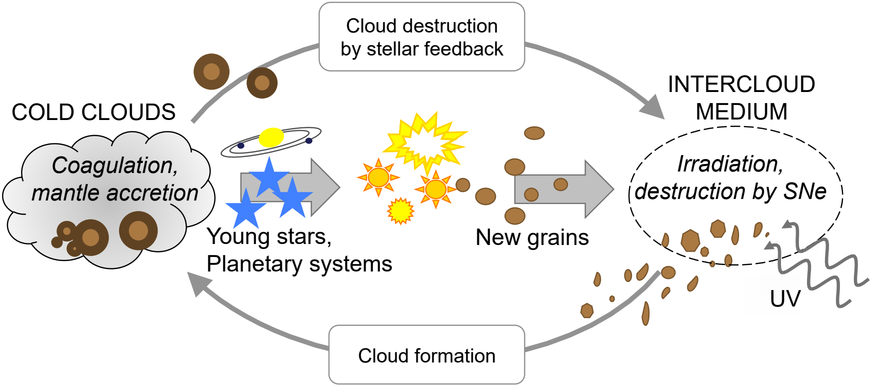


Cardelli, Clayton, & Mathis (1989)

Entirely empirical curve, presumably determined by:

- grain size distribution
- grain composition
- grain processing

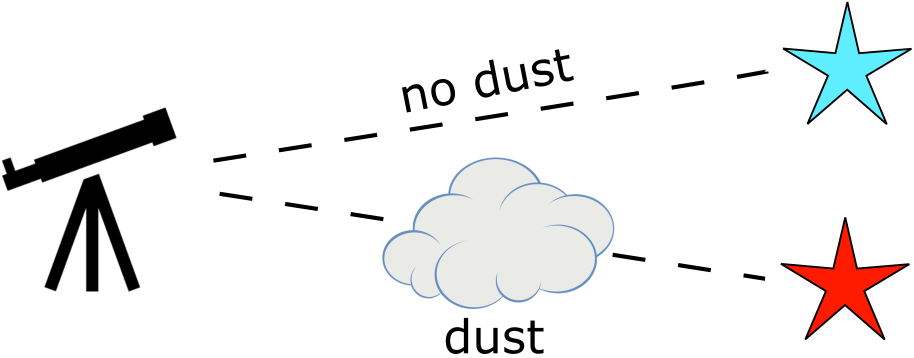
Dust evolution



Zhukovska & Henning (2014)

The Pair Method

- Simple method: compare spectra of reddened and unreddened stars
- Dates back to Trumpler, Johnson, ...
- Huge number of stars probing Milky Way available today



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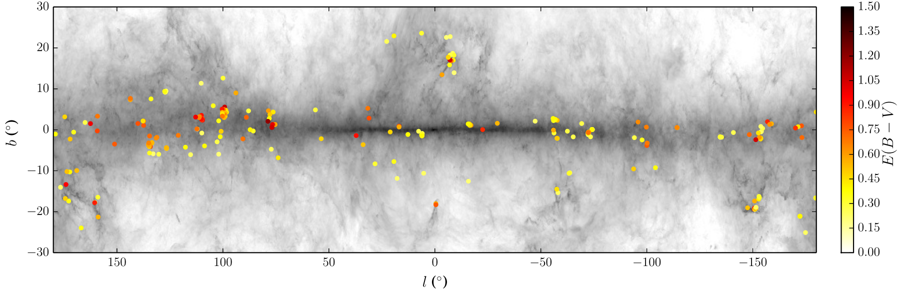

Fitzpatrick & Massa (2007), 328 stars

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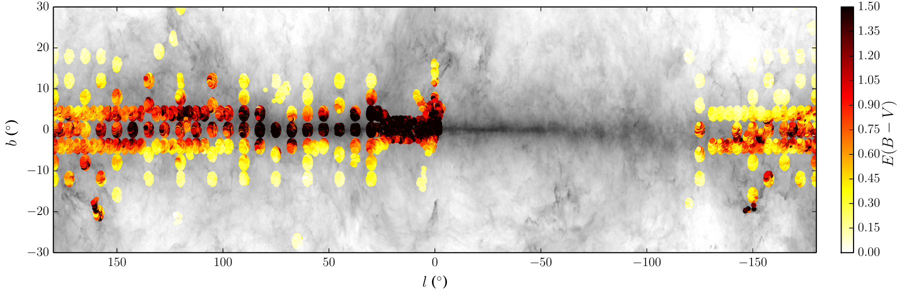
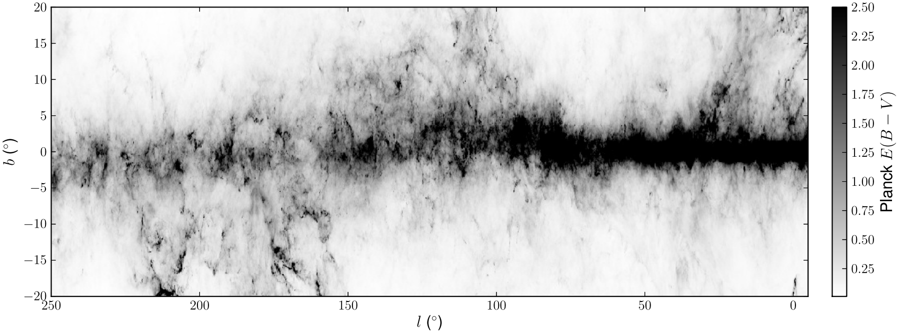
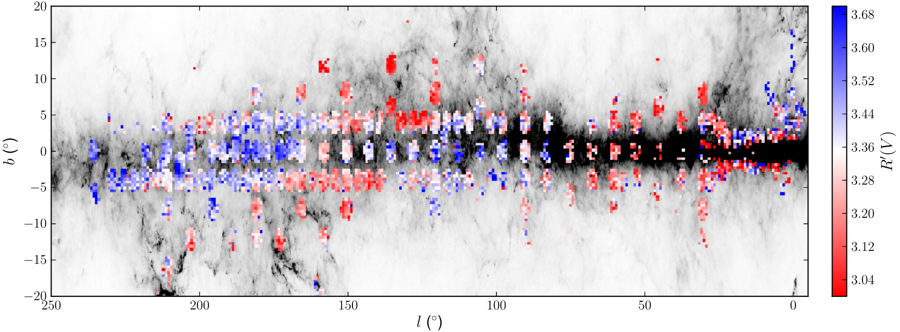


APOGEE & PS1 & 2MASS & WISE, 37000 stars (Schlafly+16)

How does the extinction curve vary spatially?



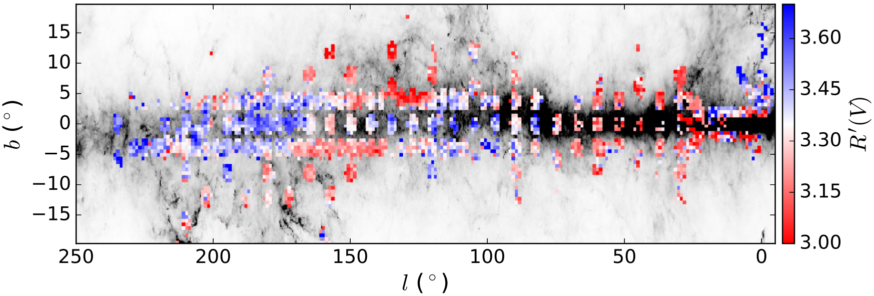
How does the extinction curve vary spatially?



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

But what about 3D?

2D → 3D



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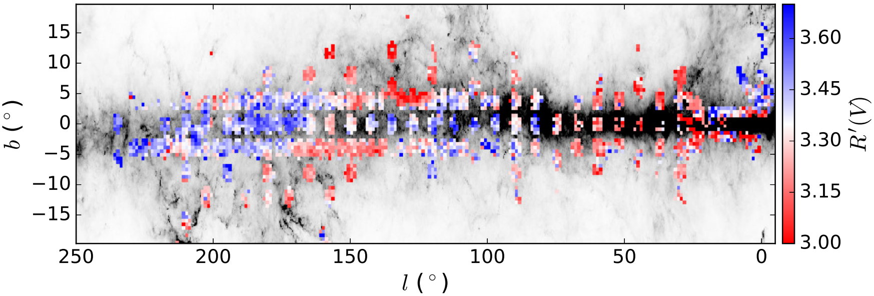

- 3D dust map made with 10^9 stars
- 20,000 stars with good $R(V)$ measurements
- How to infer 3D $R(V)$ map?

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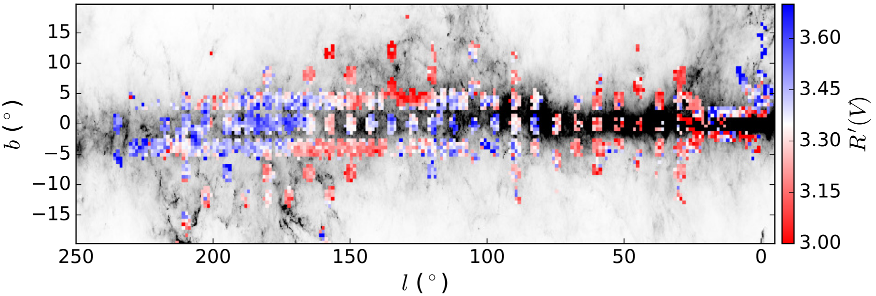

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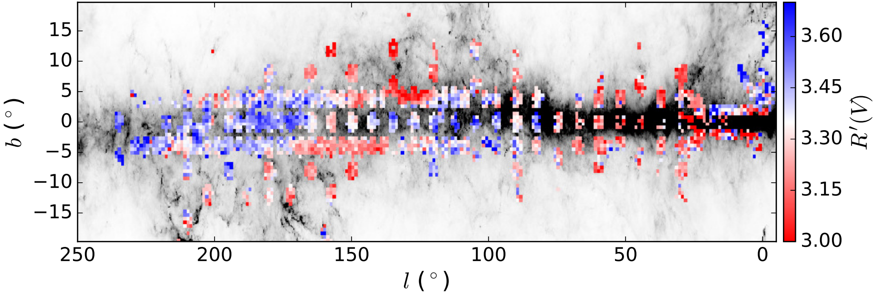
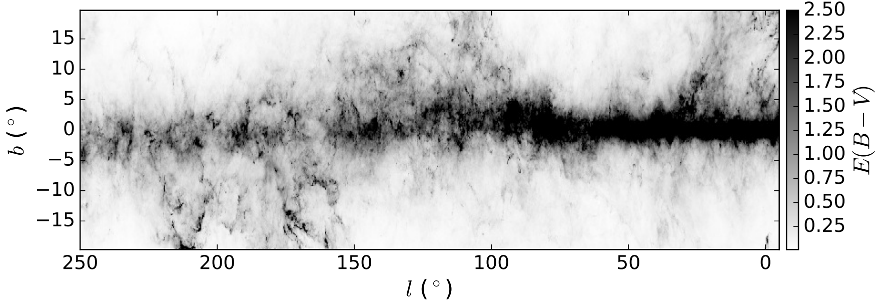
- $R(V) = \frac{\int_0^D ds\, \rho(l,b,s) R_{3D}(l,b,s)}{\int_0^D ds\, \rho(l,b,s)}$
- Linear problem, especially easy to solve if $R(V)$ is smooth in 3D.

2D → 3D



Clear imprint of 3D structure onto projected 2D $R(V)$ map

2D → 3D



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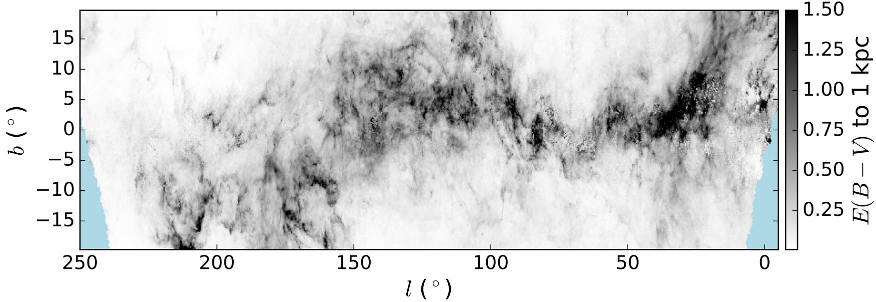

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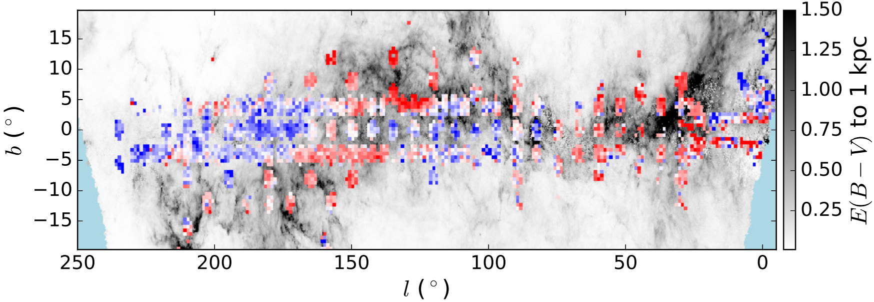

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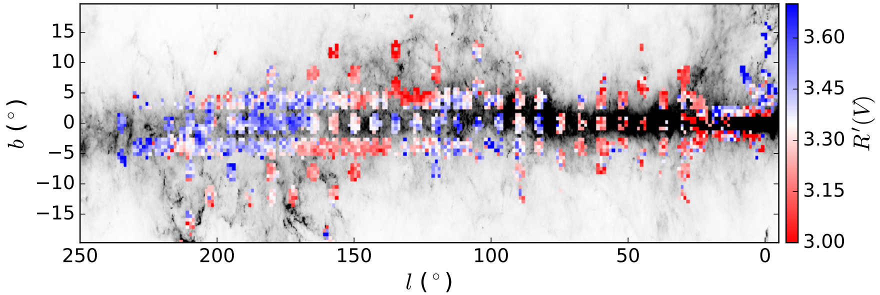

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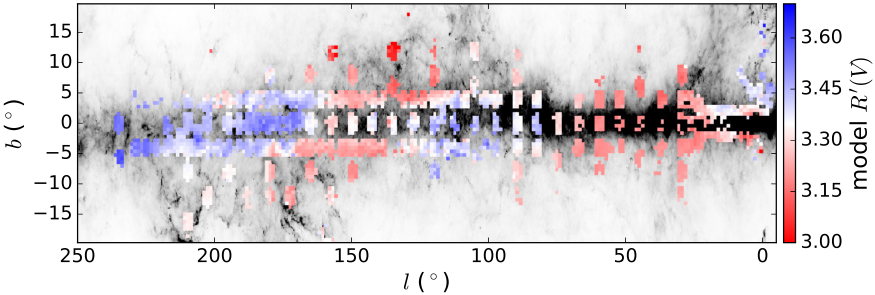
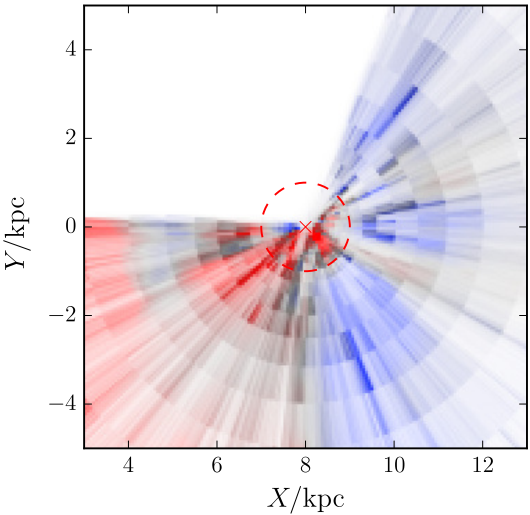
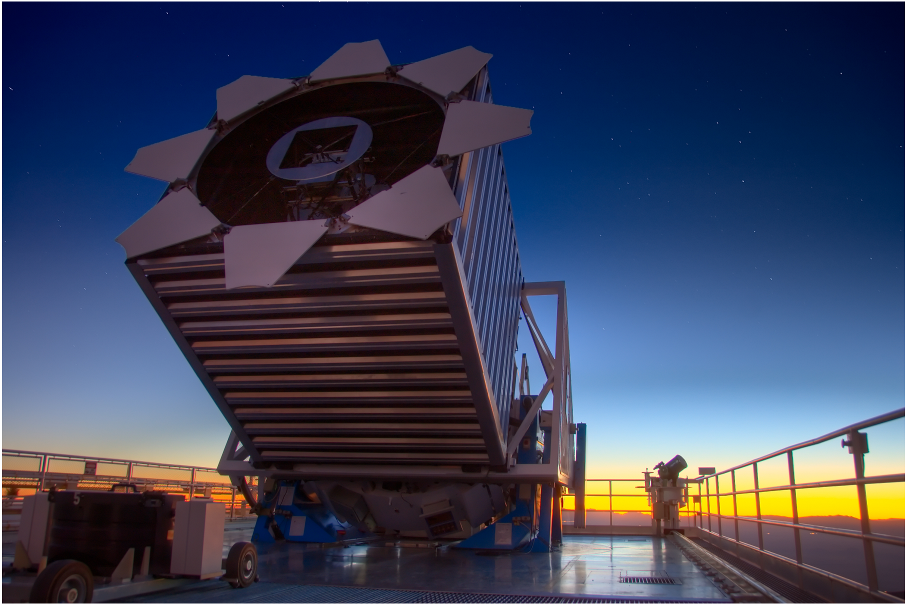


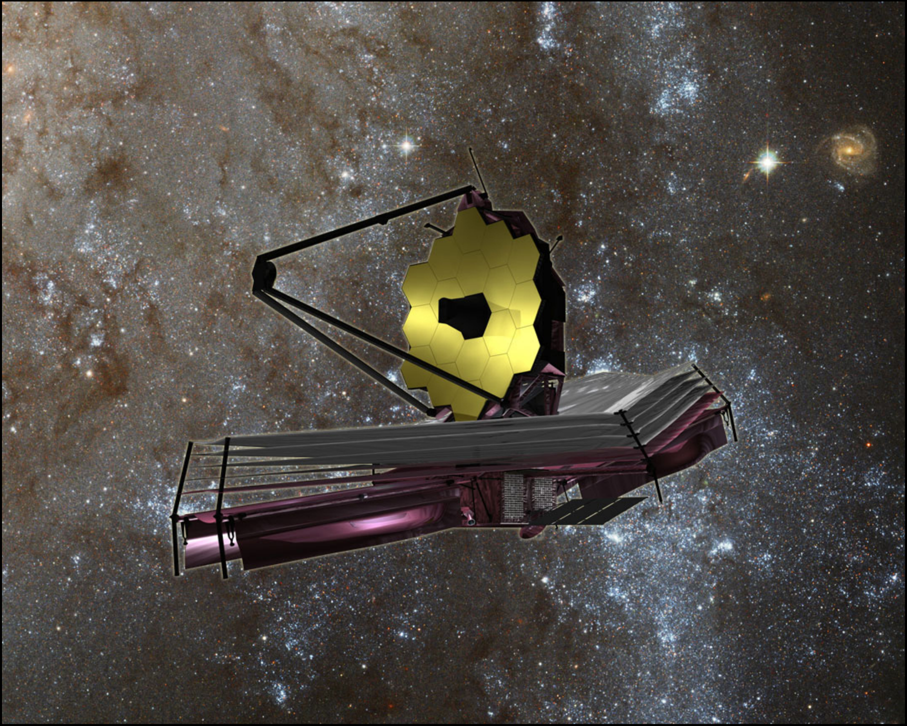
Clear imprint of 3D structure onto projected 2D $R(V)$ map

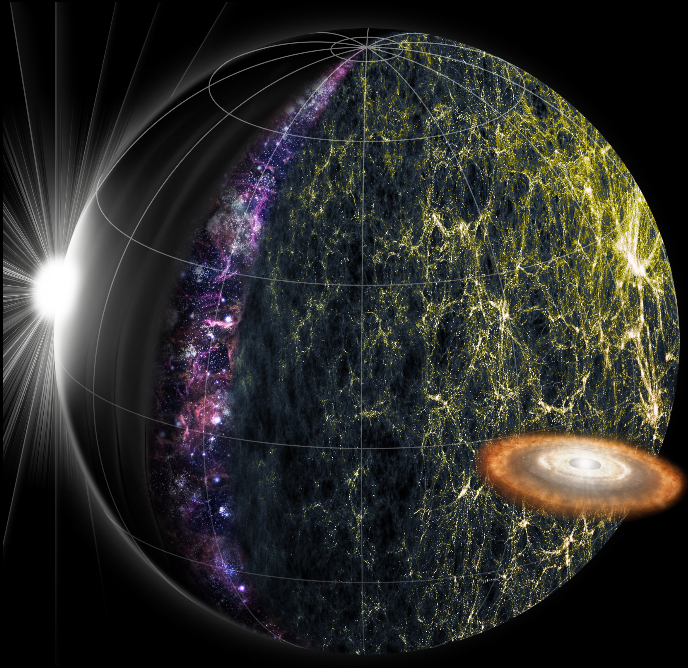
Galactic $R(V)$ Map



Kiloparsec scale structures, possible Galactic gradient?







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We can see a *lot* of stars in the Milky Way

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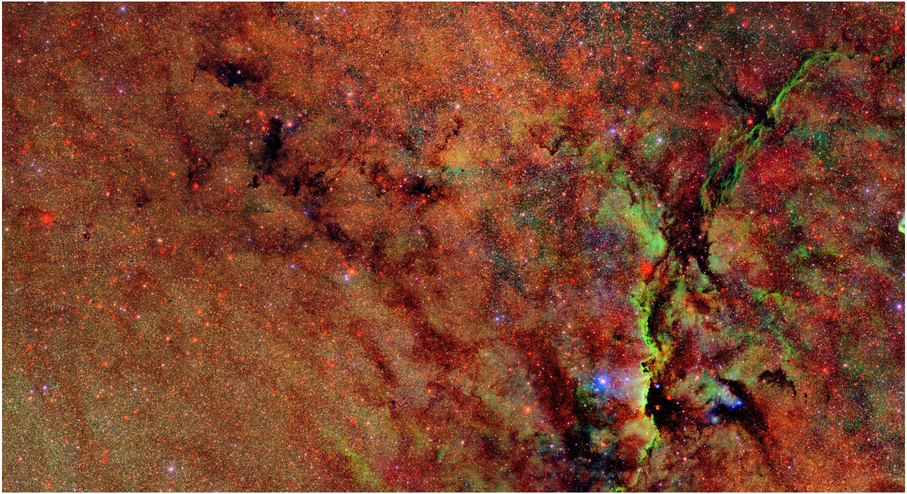
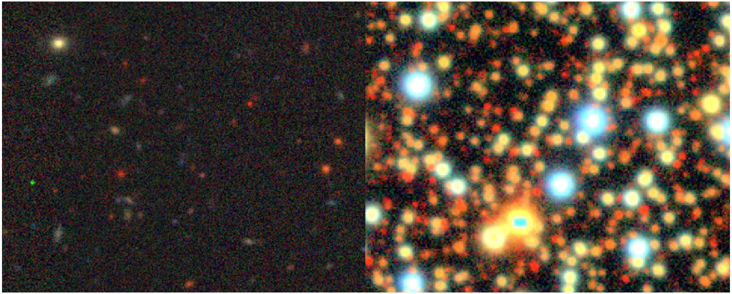


Precise photometry of billions of overlapping stars is challenging!

Modeling images: traditional approach



- Single object: easy
  - position, brightess, few shape parameters

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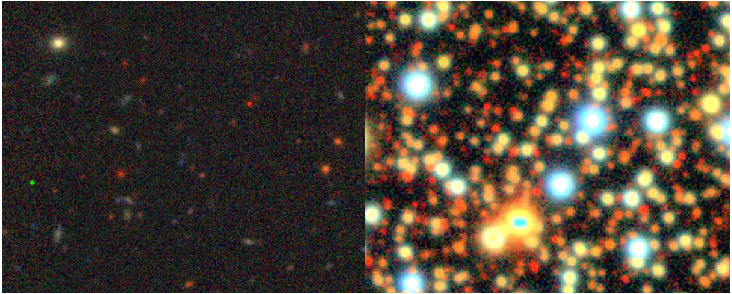

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- Must simultaneously solve for fluxes and positions of all the sources
- Can be 10^5 sources per image!

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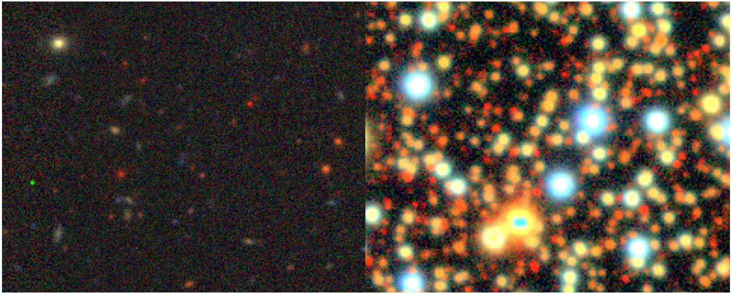

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- Many objects: hard, due to *blending*
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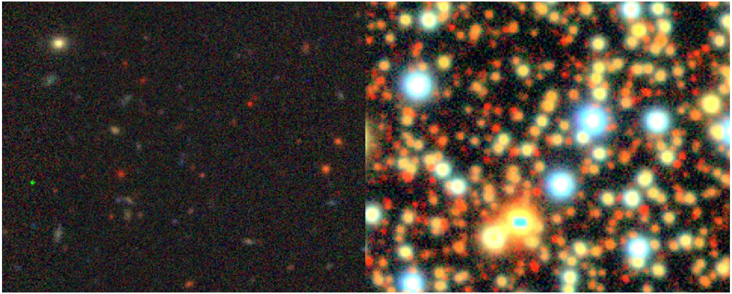
- Can be 10^5 sources per image!
- Typical approaches either ignore the problem, iterate, or try to cleverly segment the image.

Crowded Field Modeling: Our approach



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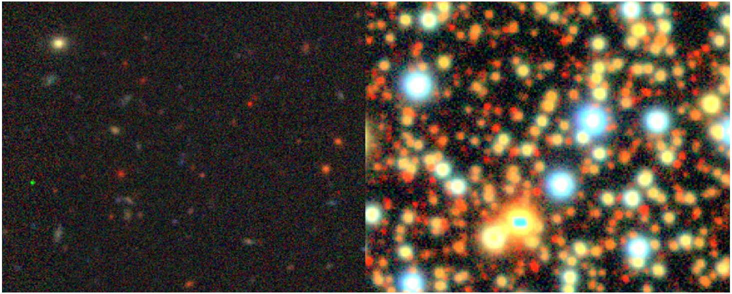

- This is very nearly a *linear* problem
  - $I(x, y) = \sum_i f_i P(x - x_i, y - y_i) + B(x, y)$
  - fluxes f are linear
  - sky background B can be parameterized with a linear model
  - positions x_i, y_i can have good initial estimates, can be linearized
- *sparse*: each source occupies only $\sim 10^{-4}$ of the image

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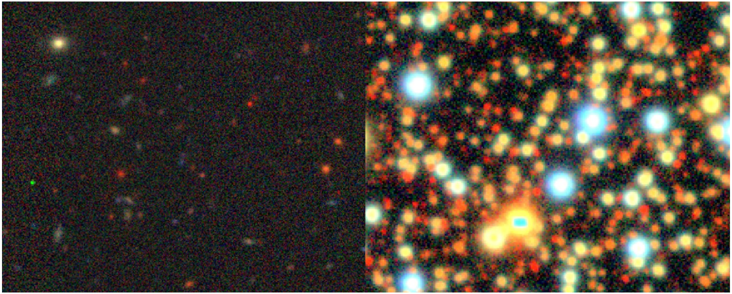

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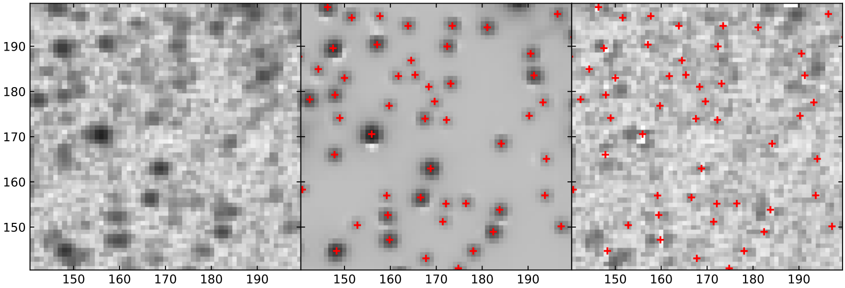
- Large scale linear algebra packages can solve problems with hundreds of thousands of parameters, e.g., via conjugate gradient method

A New Crowded Field Photometry Pipeline

This approach works!

- `crowdsource` (Schlafly+2018)
- Applied to DECam Plane Survey and WISE Survey (Schlafly+18, 19)
- $\sim$ 4 billion detected sources!



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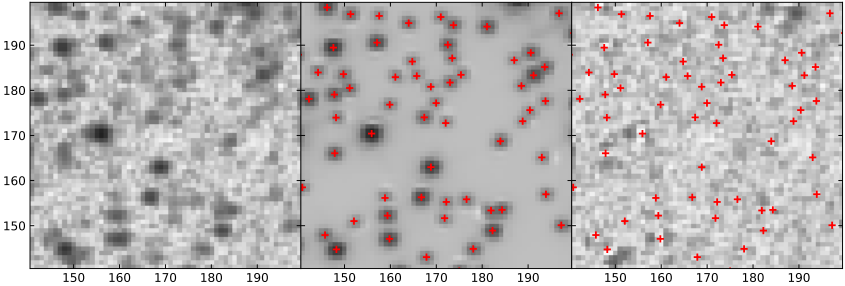

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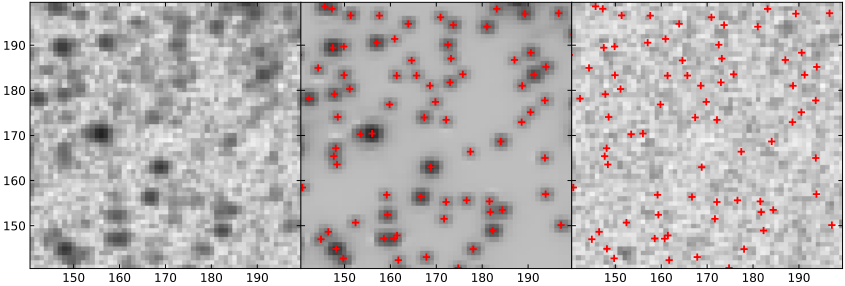

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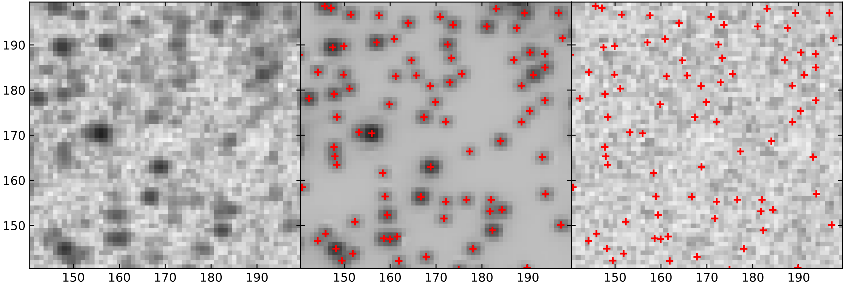

A New Crowded Field Photometry Pipeline

This approach works!

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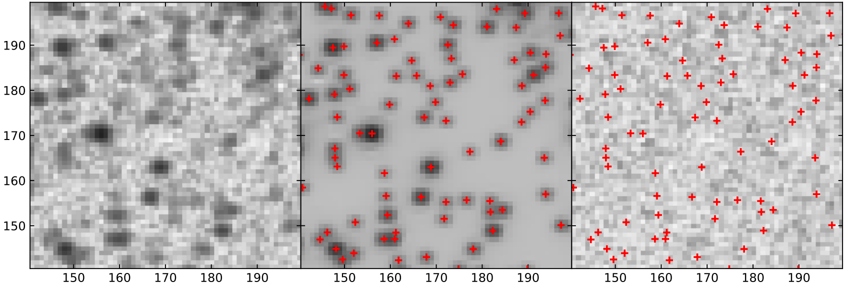

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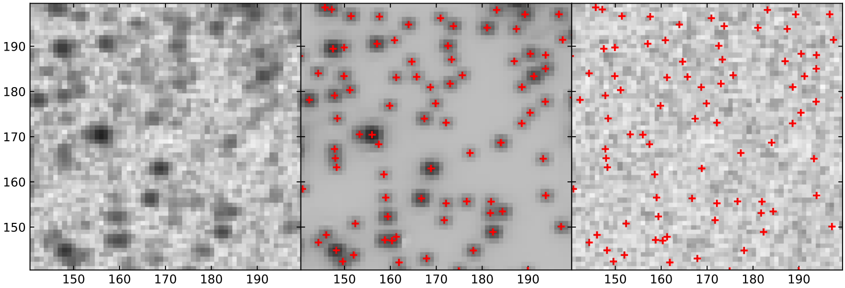
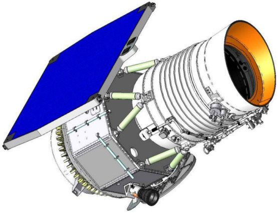


Applying `crowdsource` to real images



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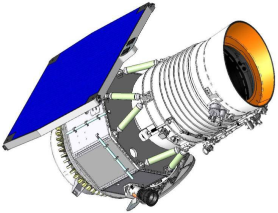
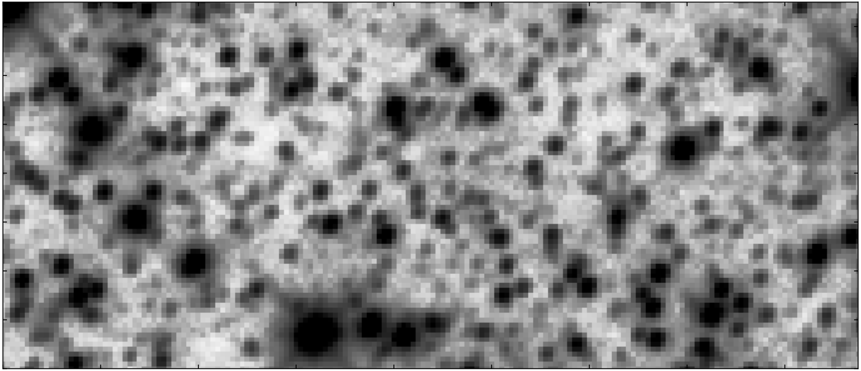


- Asteroid characterization
- Nearby, ultra-cool stars (Backyard Worlds)
- High-redshift quasars (e.g., $z = 7.5$, Bañados+2018)
- Galaxy surveys: $\sim$ 500 million galaxies over $0 < z < 2$ (Schlafly+19)
- Galactic structure: $\sim$ billion stars (Schlafly+19)

The unWISE Catalog (Schlafly+19)

Galactic Anticenter W1



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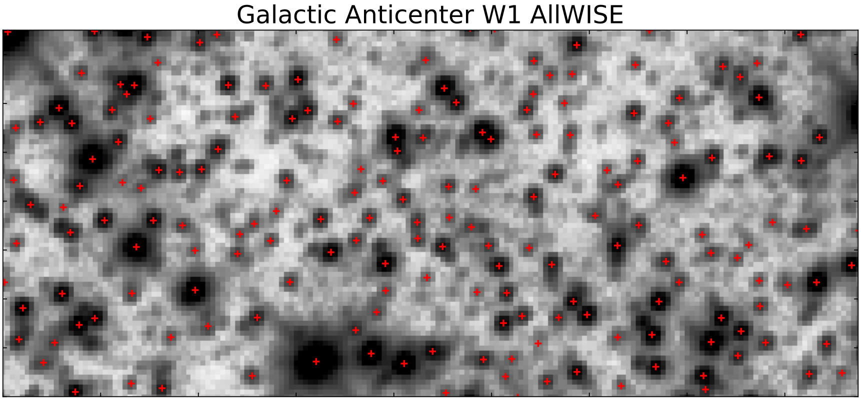

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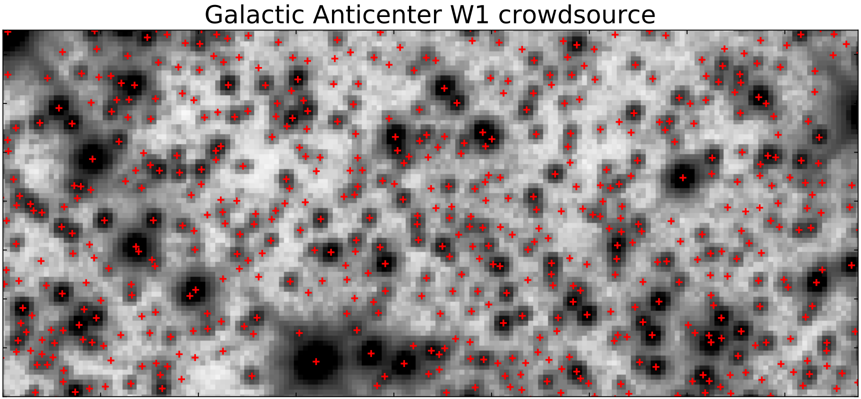

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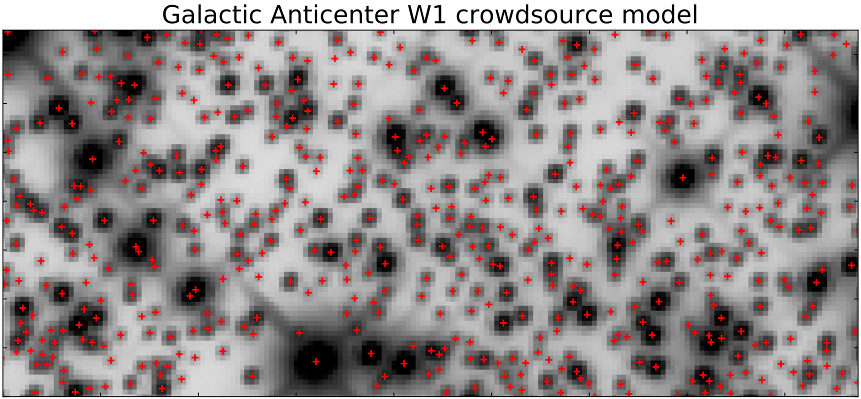


3× more stars and galaxies. . . what can we do with this?

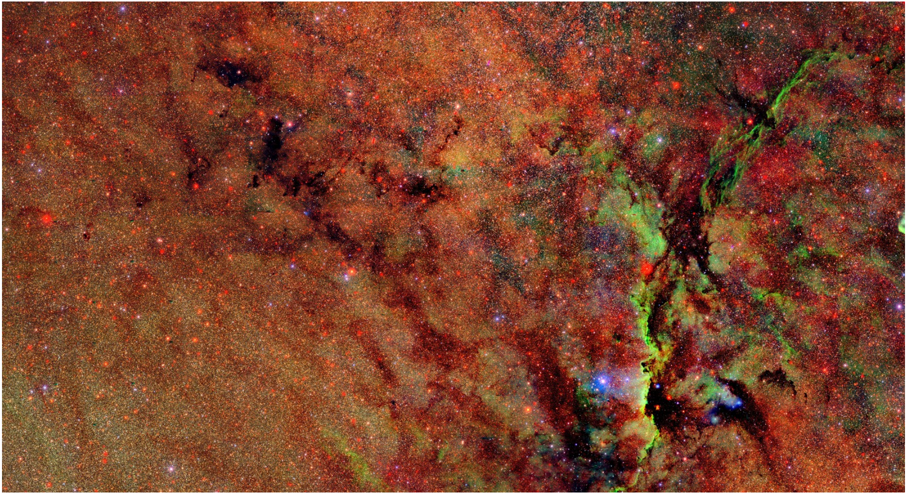
$3\times$ more stars and galaxies. . . what can we do with this?

- Correlation with Planck lensing, ISW maps (Ferraro, Krolewski, White, Schlafly)

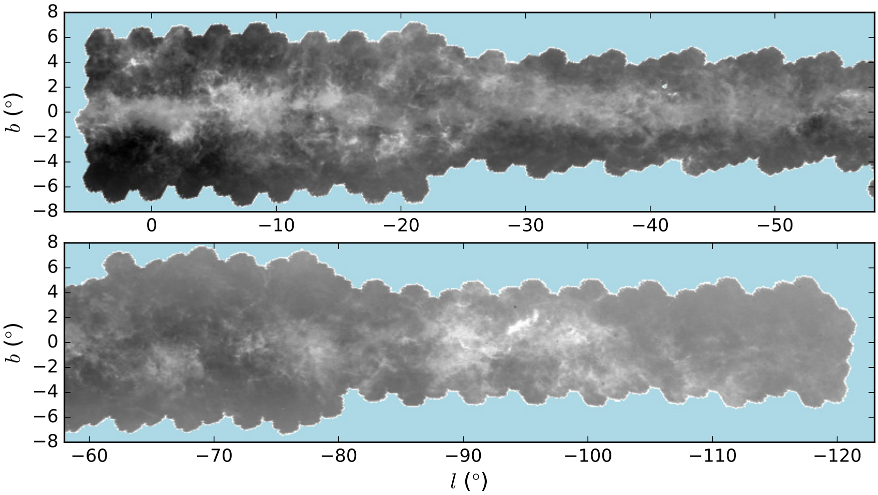
- MaDCoWS2 galaxy cluster search, sensitive to $1 < z < 2$ (Gonzalez)

- Nearby stars using six-month WISE coadds (Meisner, Schlafly)

The DECam Plane Survey



Source Density



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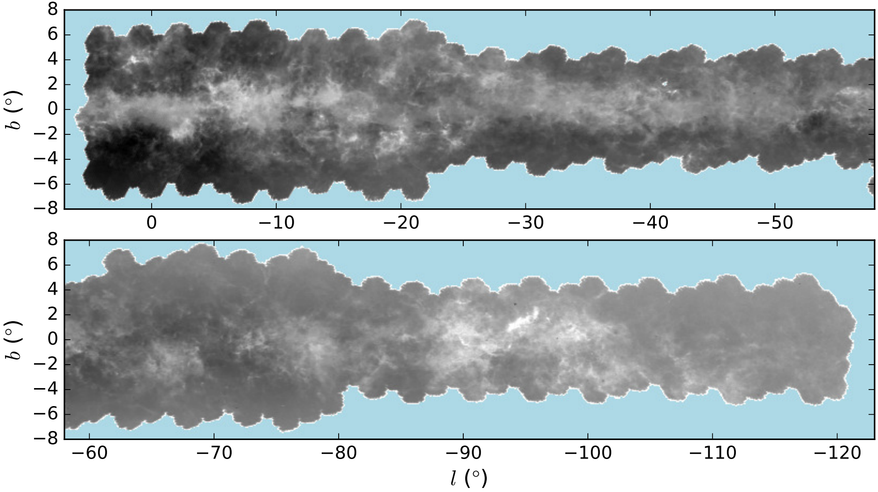


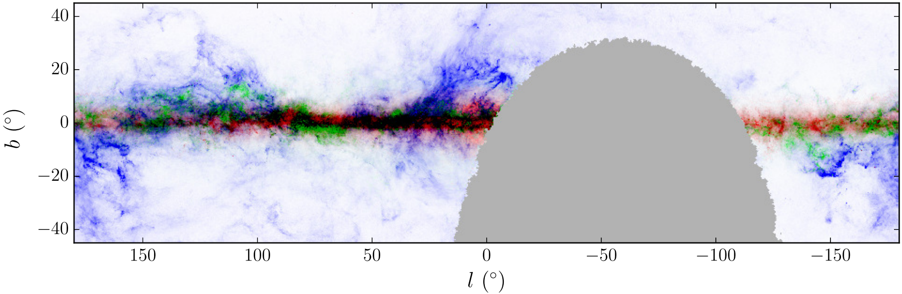
20 billion detections of 2 billion objects

Science

- New star clusters (Torrealba+2019)
- Predicted microlensing events (McGill+2018)
- High resolution 3D star & dust maps (Green, Zucker, Schlafly)


Conclusion

- Large, precise surveys x-ray the ISM, revealing
  - 3D density of dust at high resolution
  - Dust grain size distribution
  - Velocity field, magnetic field also accessible
- Bright future
  - DECam, WISE surveys of billions of stars
  - Transformative data from Gaia & SDSS-V
  - Numerous other forthcoming spectroscopic and photometric surveys



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- 10^9 PS1 stars

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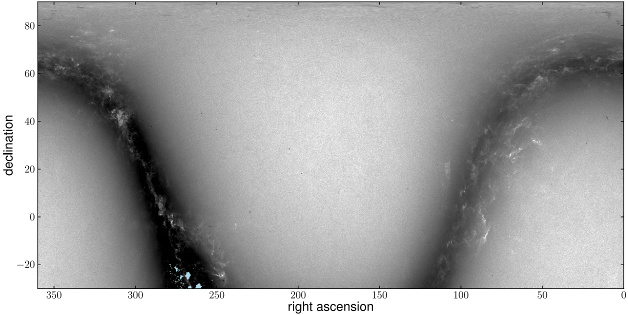

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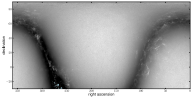

- Reddening and distance inference

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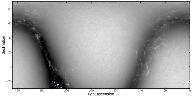

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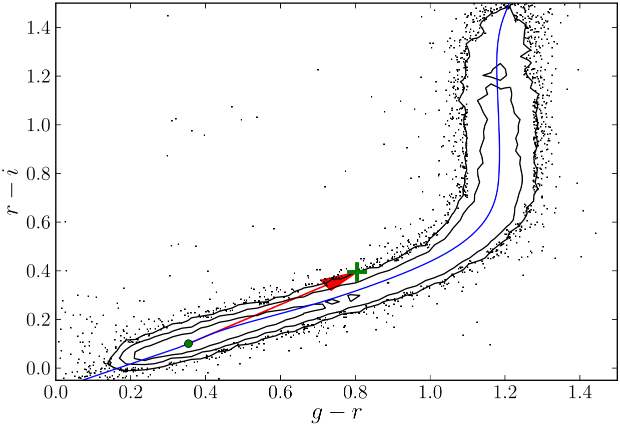

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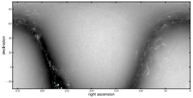

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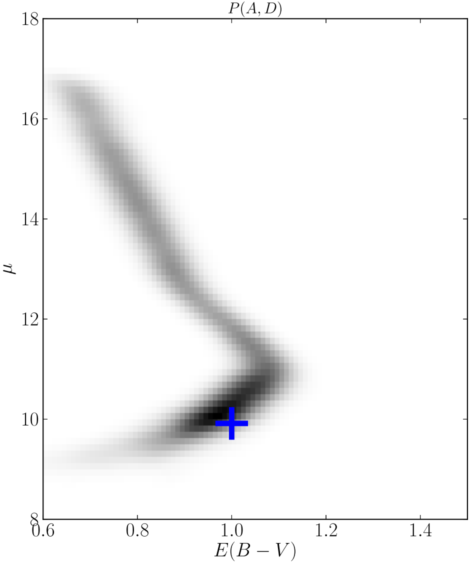

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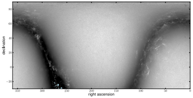

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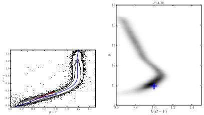

- Line of sight fit

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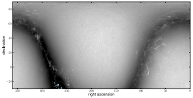

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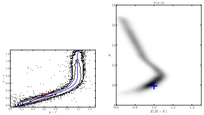

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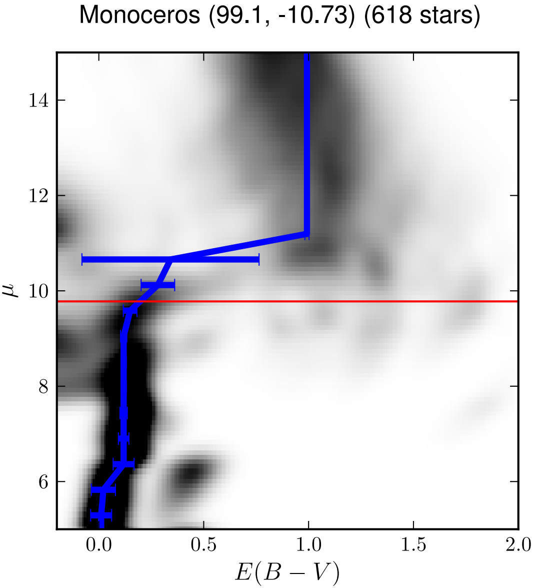

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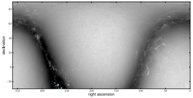

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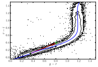

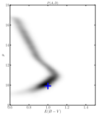

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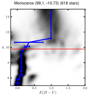

- 2.5M CPU hours
- Lots of related work!
  - Hanson, R. & Bailer-Jones (2014), (2015)
  - Sale+2014, Sale+2015, Sale+2017
  - Marshall+2006
  - Lallement+2014

For next-generation surveys, most fields are crowded

- Next generation surveys have more objects, meaning more overlapping objects
- Two-thirds of galaxies will be blended in LSST (Melchior+2018)
  - $\sim$15% of blends will be unrecognized (Dawson+2016)
- The easy case: assume all objects are point sources
  - surveys with low spatial resolution (WISE, Kepler, TESS)
  - microlensing surveys

Results (Schlafly+19)

- $3\times$ more stars and galaxies

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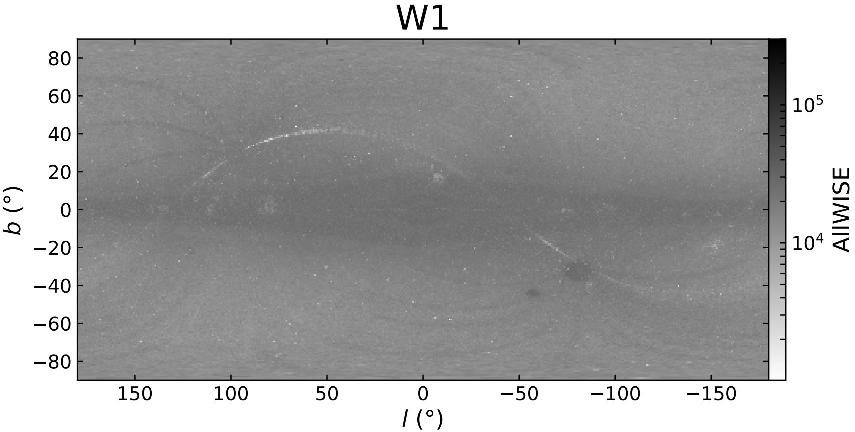

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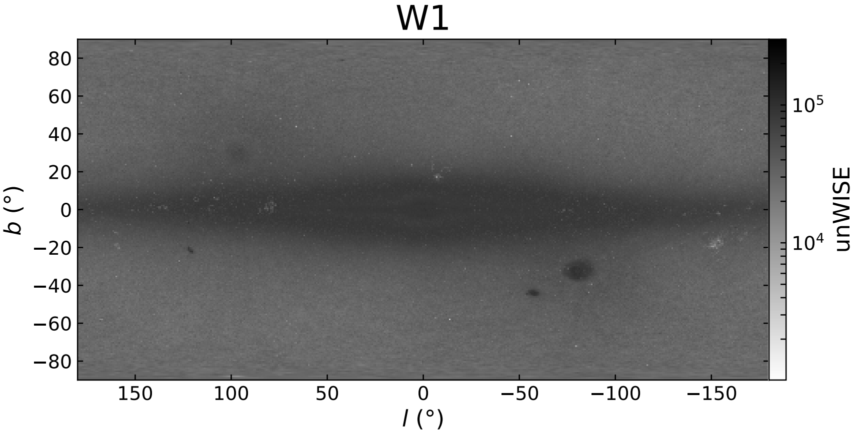

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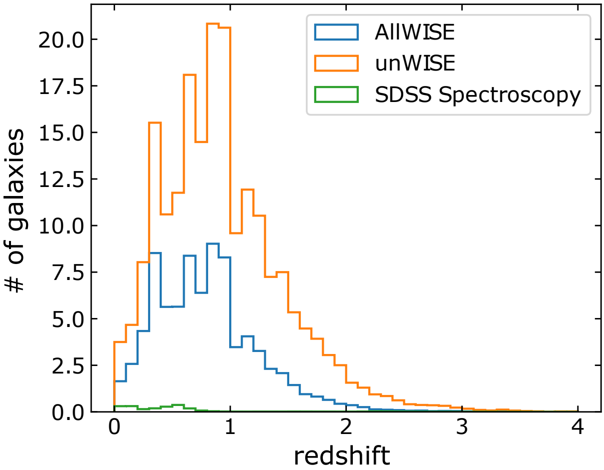

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- enhanced photometric uniformity

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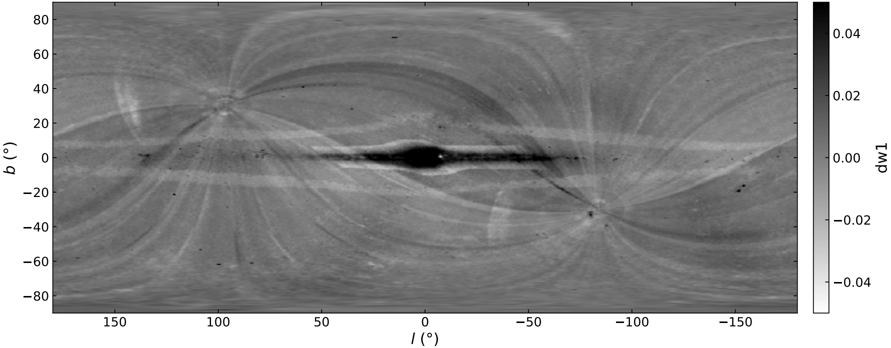

Future Directions

- Transdimensional searches (Daylan+2016)
- Beyond maximum likelihood point estimate
- Machine learning to tell stars from galaxies
- Multi-epoch, multi-band analysis

Extinction and Emission are Linked

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

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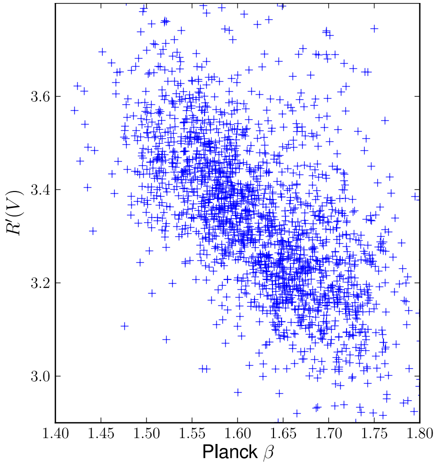
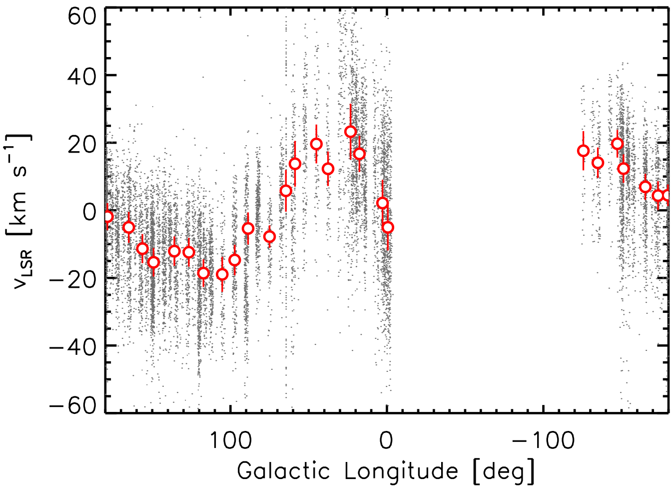
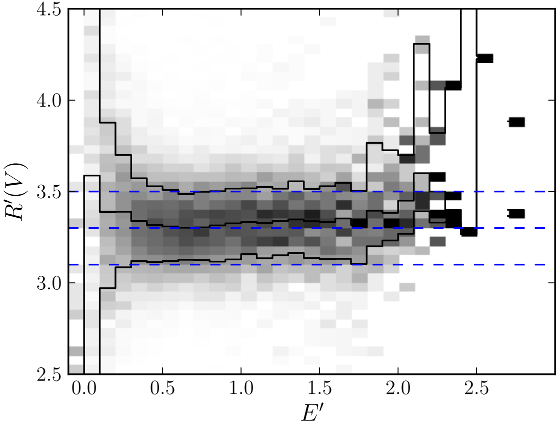


Strong correlation between dust SED and $R(V)$

Zasowski+2015



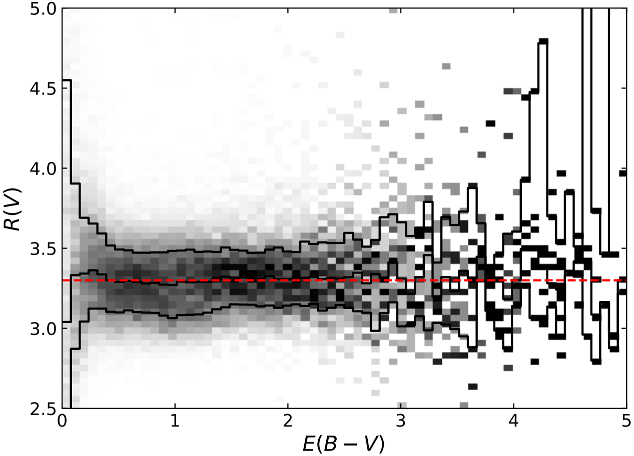
Does $R(V)$ vary systematically with $E(B-V)$?



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.

$R(V)$ with $E(B - V)$



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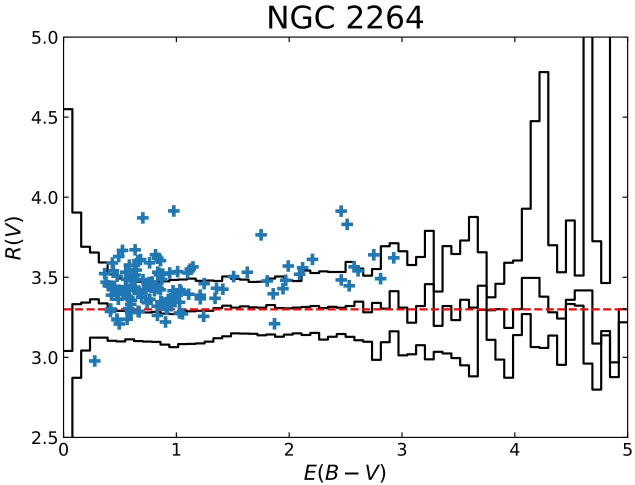

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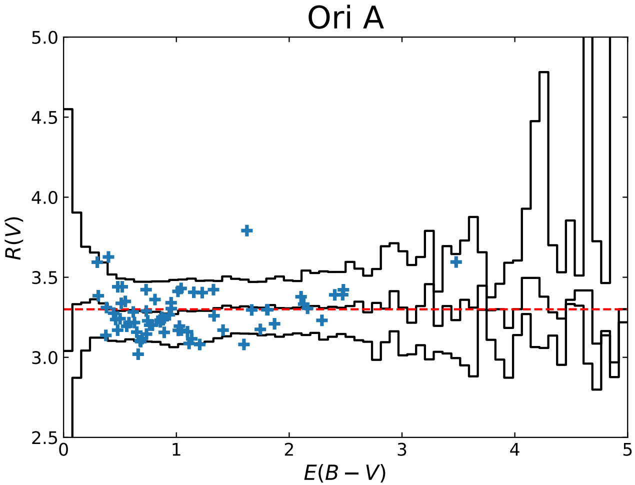

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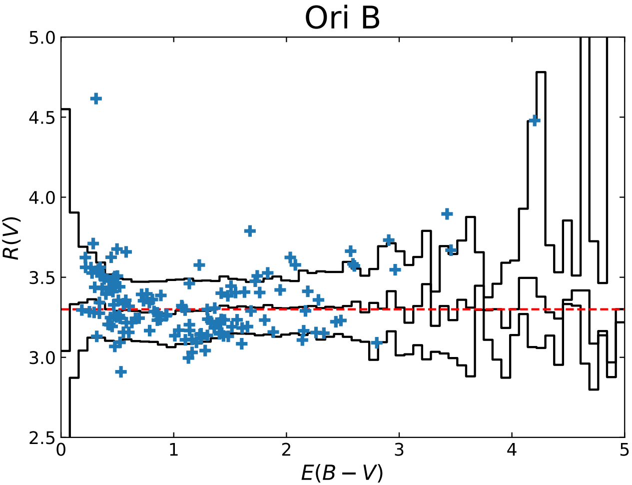

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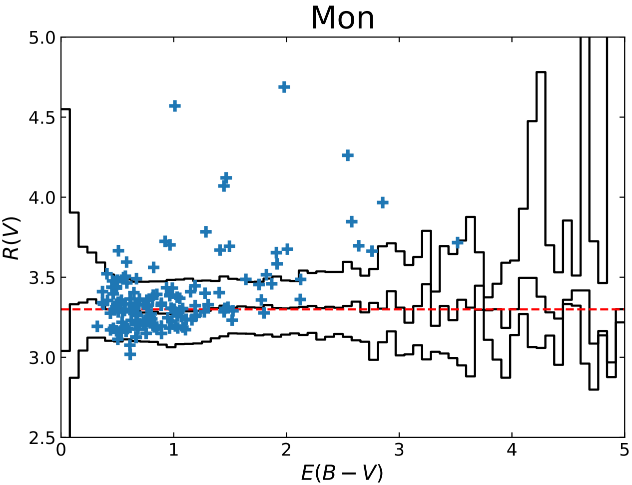

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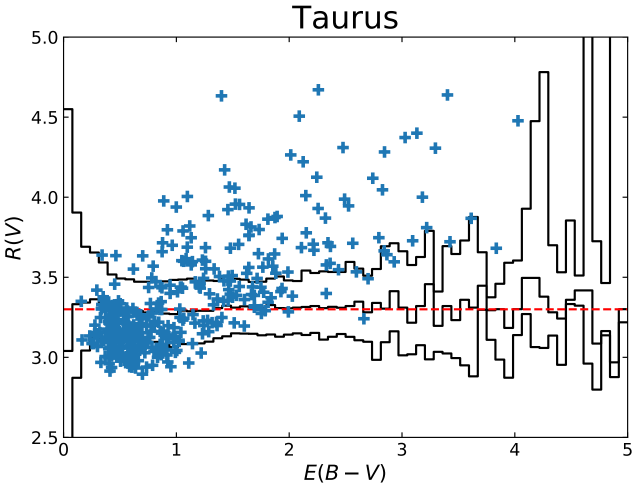
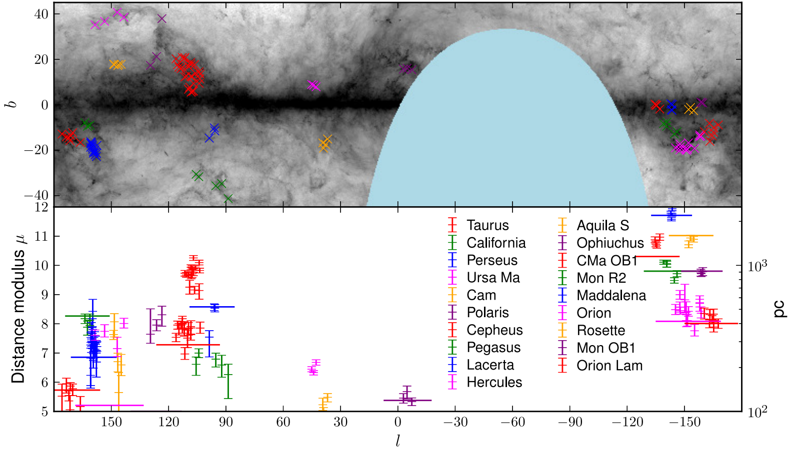


Distance Catalog



Schlafly+2014

The Orion Dust Ring

Slice dust into foreground, Orion, and background

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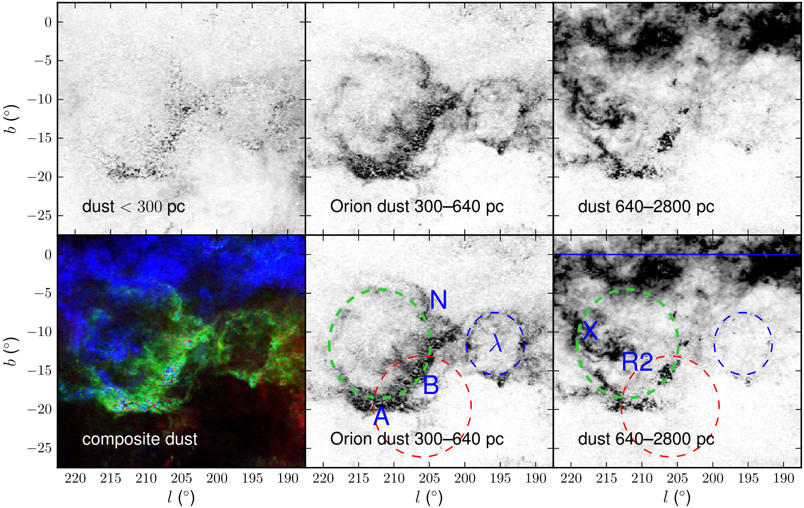
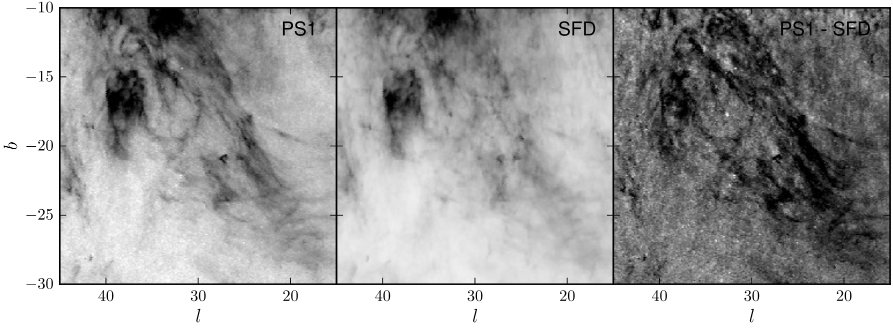


2D Comparison: Aquila South



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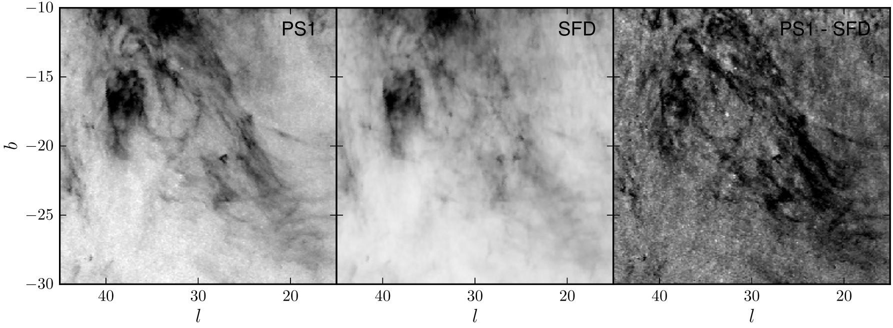
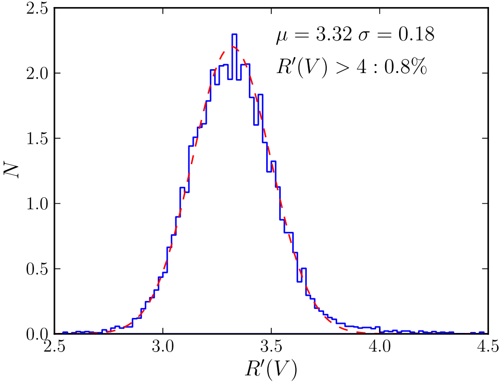


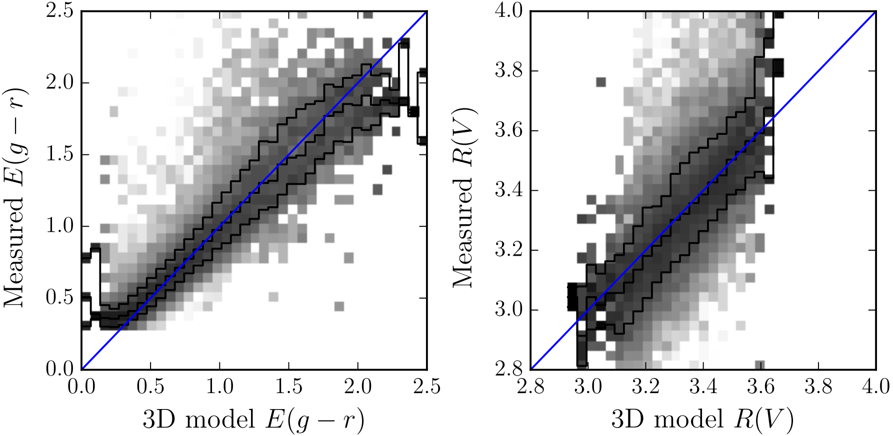
- Problems hard to avoid in “reddening” maps based on extinction.
- Future reddening maps will be star-based.

How variable is the extinction curve?

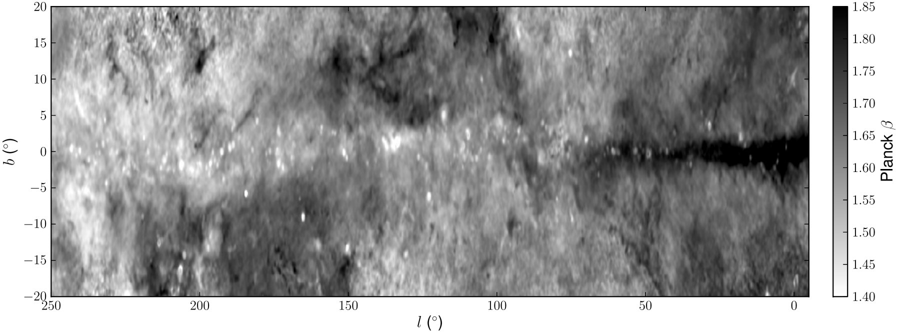


Somewhat smaller dispersion than literature (0.27), many fewer high $R(V)$ sight lines (9.5% in FM07)

3D $R(V)$ Map Accuracy



Extinction and Emission are Linked



Planck (2014) β map

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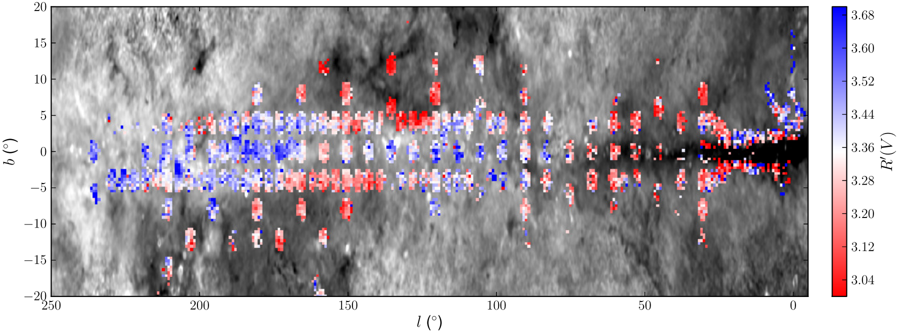

Large and small scale features in β closely linked to variations in $R(V)$.