# Theories of everything

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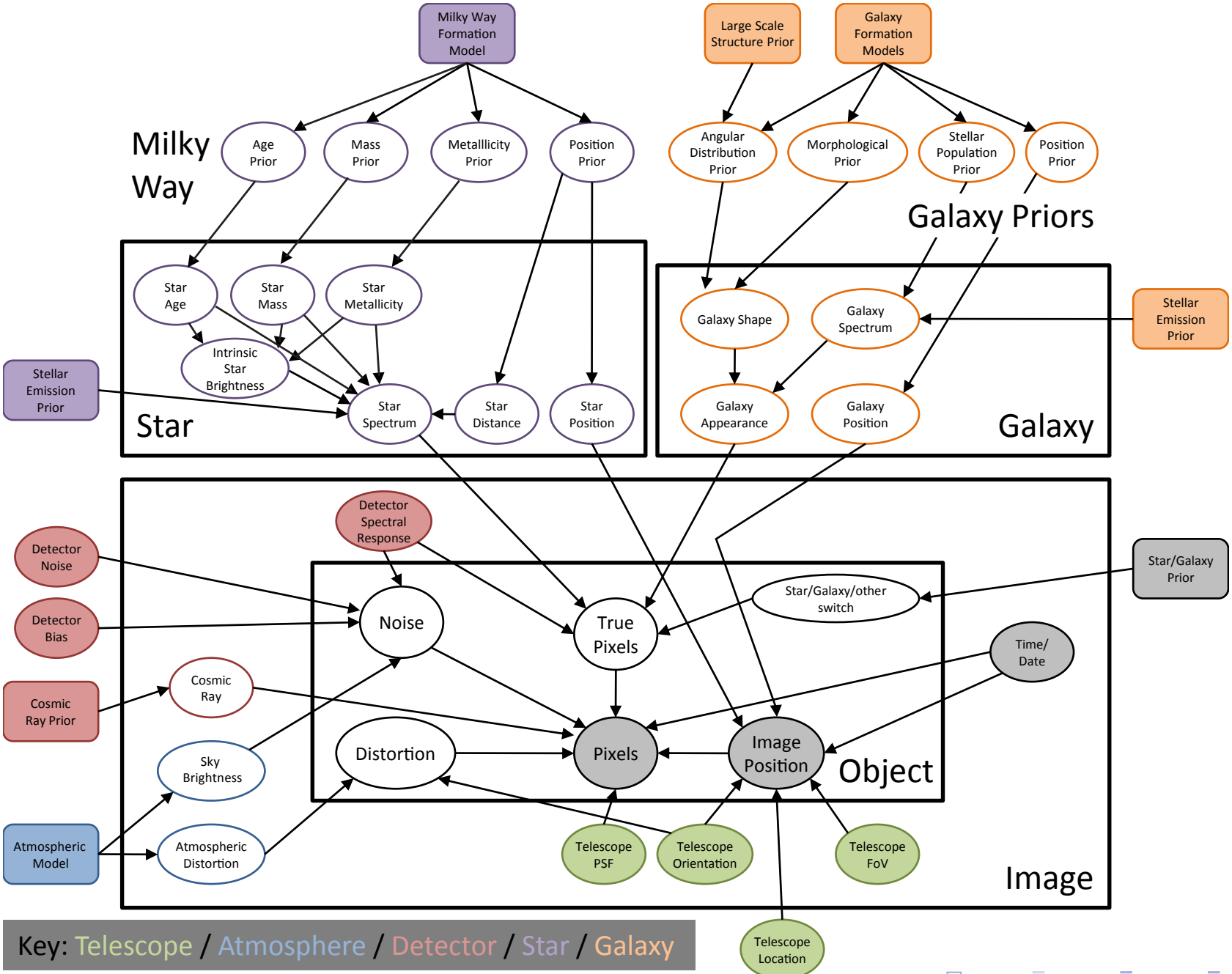
# what I am going to say

- Uniquely in astronomy, it is conceivable to have a justified probabilistic model of every observable source that explains every observed pixel of every image ever taken.
- We are working towards a few-$10^9$ parameter model of the $10^{13}$ pixels of large survey data we have in hand.
- **We would like to have a hierarchical model with a structure that mirrors the causal structure implicit in the cosmological model.**
- Collaborators:
  - Jo Bovy (IAS)
  - Rob Fergus (NYU)
  - Dan Foreman-Mackey (NYU)
  - Dustin Lang (Princeton)
  - Phil Marshall (Oxford)
  - Sam Roweis (deceased)
  - *NASA*, *NSF* (AST and IIS), *Humboldt Foundation*

# astronomy: scale

- in 2011: total imaging data $10^{13}$ to $10^{14}$ few-byte pixels
  - only hundreds of terabytes
  - I spin it in my own machine room
- $10^9$ to $10^{10}$ useful stars in the Milky Way
- $10^{10}$ useful galaxies in the observable Universe
- by 2020: $10^{16}$ pixels if we are lucky
  - note "optical" and "imaging" biases

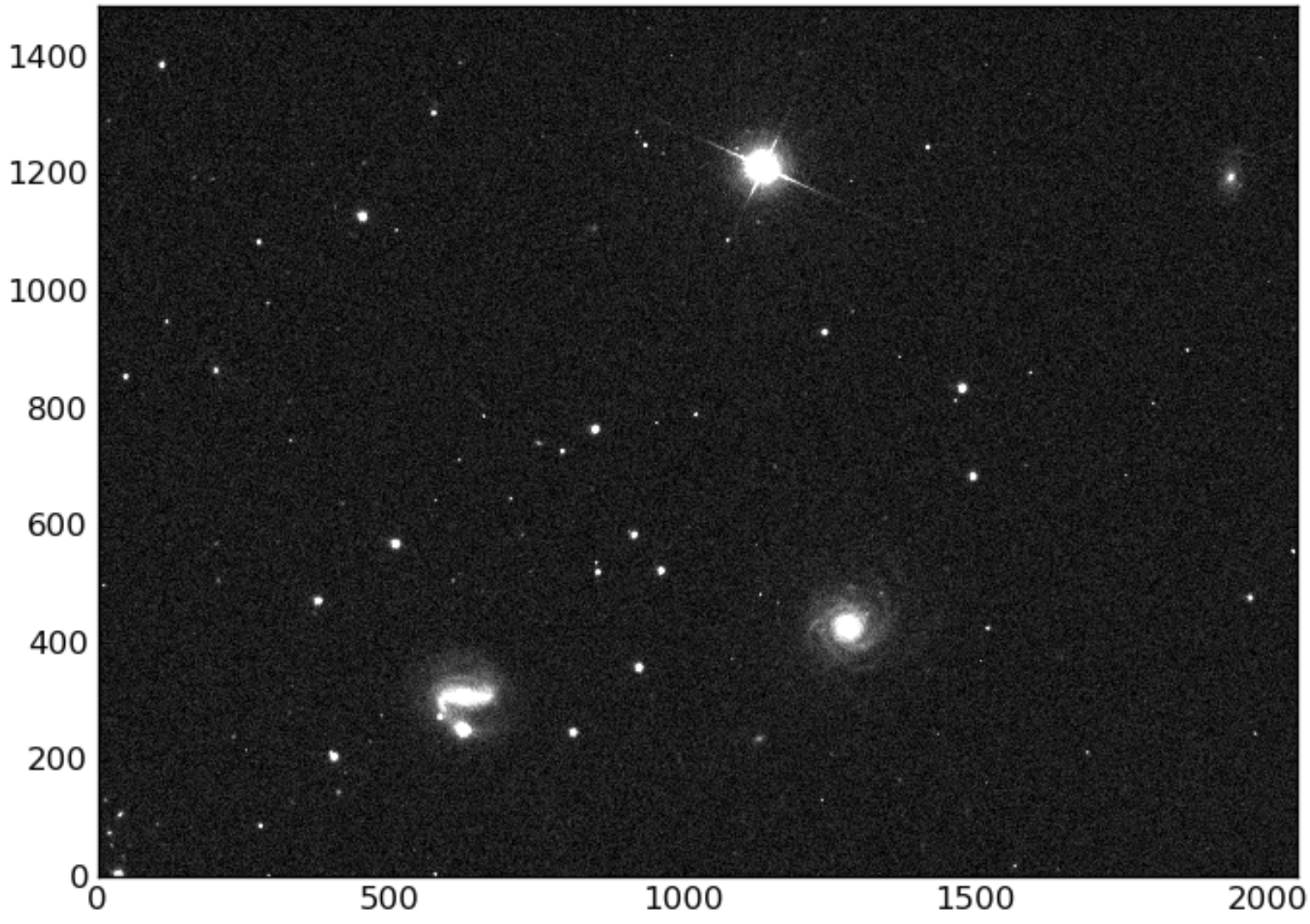
# astronomy is a sweet inference problem



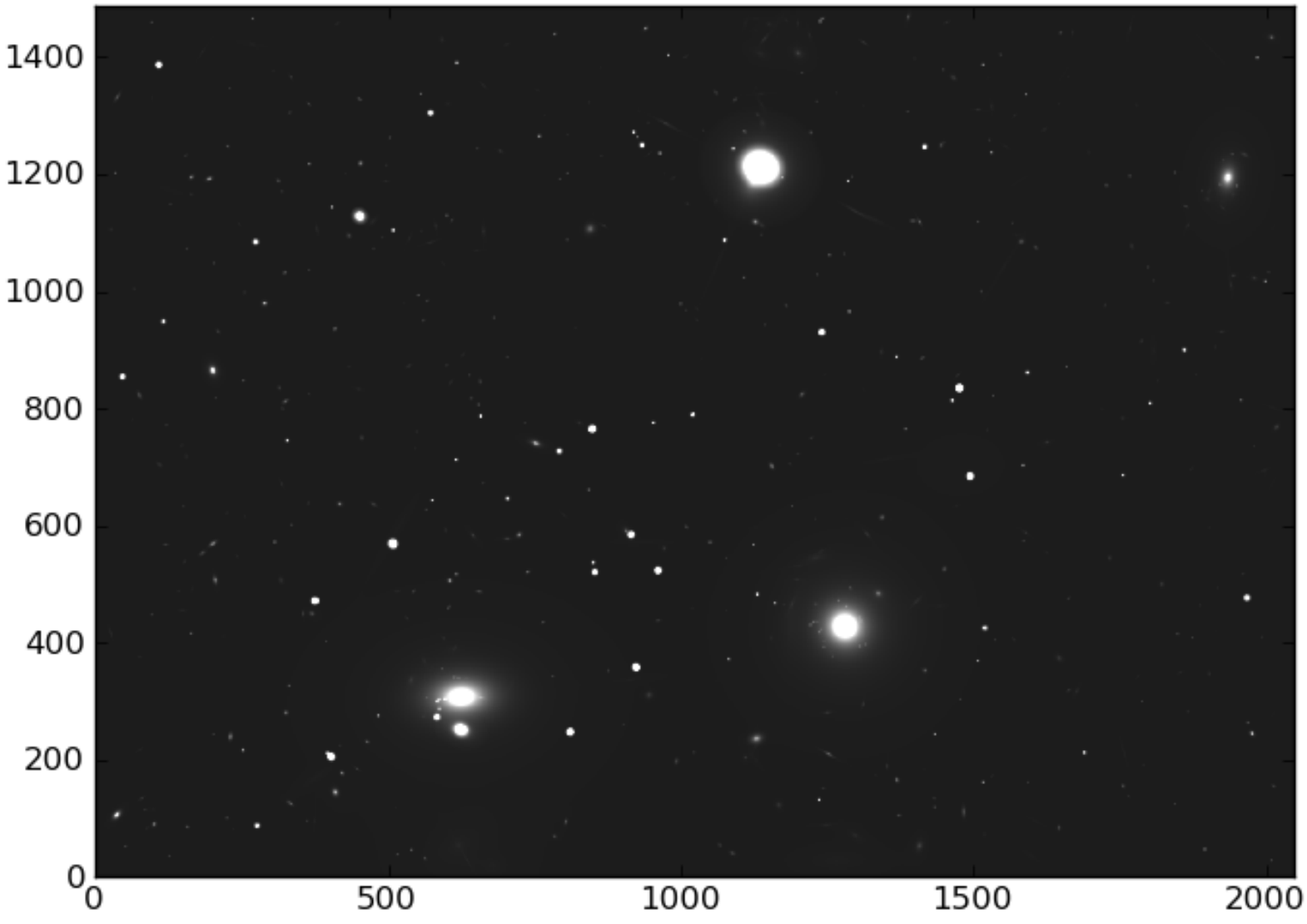
# astronomy: promise

- the Universe is driven by unseen constituents
  - dark matter
  - dark energy
- precise theory of gravity, the cosmological world model, and the growth of structure
- excellent physical models of stars
- working models for galaxies
- at the lowest level, the model is *exceedingly sparse*
  - each star touches only $10^{-11}$ of the full pixel database
  - each pixel touches only $\sim 1$ star or galaxy
- CCDs, IR arrays, receivers all well-understood in sensitivity and noise properties

# Image modeling (Lang): data



# Image modeling (Lang): model



# what is a model?

- probability of the data given assumptions and parameters (a likelihood)
- priors over parameters
- priors over qualitative choices
- produces only probabilistic information
- inherently hierarchical

# astronomers love catalogs

- list of stars and galaxies in the imaging you have
- *SDSS* Catalog has nearly $10^9$ sources
- objects detected using statistical significance tests
- object properties measured using "algorithms"
- no probabilistic interpretation
  - the likelihood function doesn't permit freedom in "algorithm choice"
  - no sampling over parameters
  - no sampling over *qualitatively different explanations*

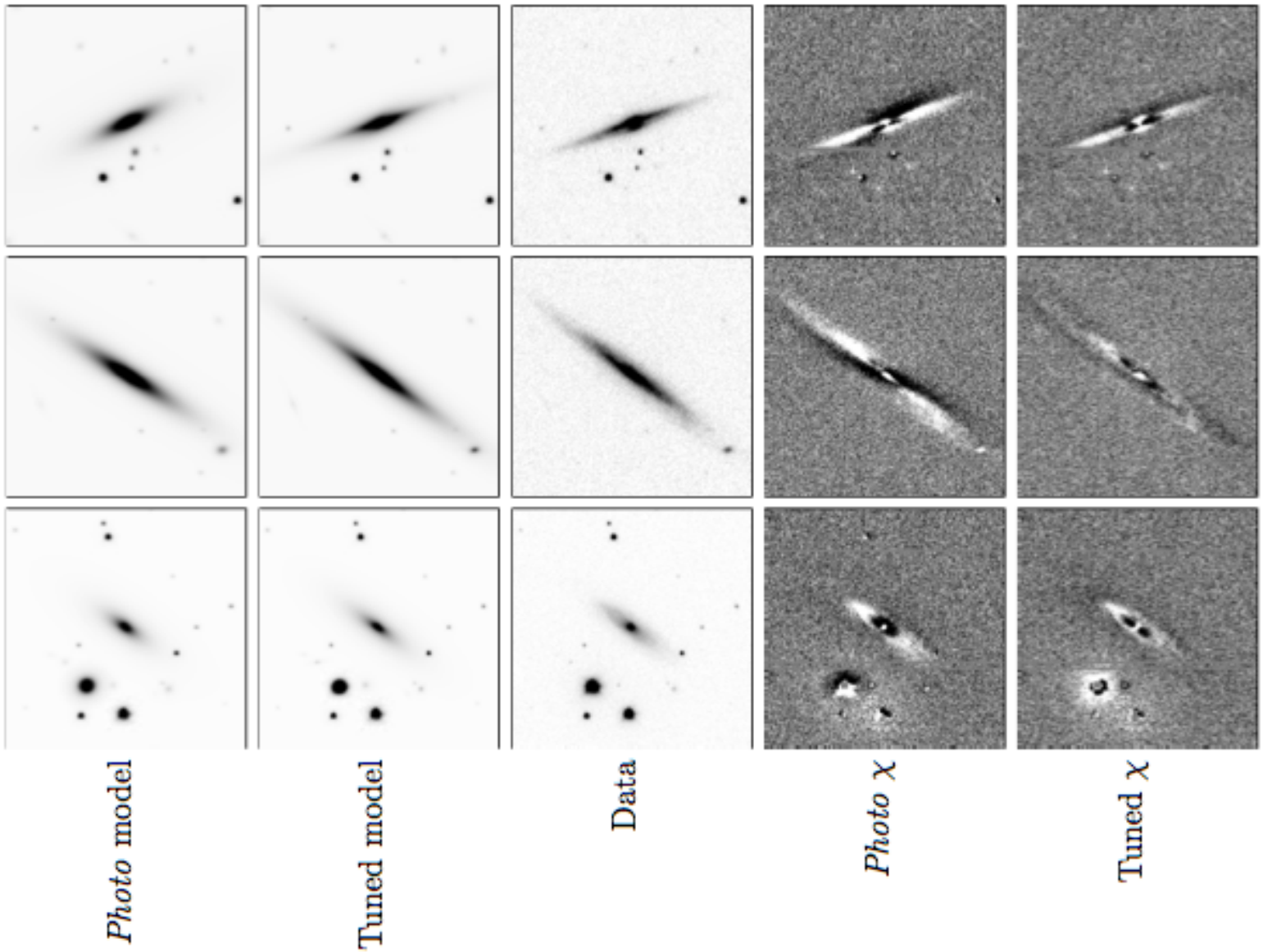
# blind deconvolution

- have an image $b$ (unwrapped into one huge vector)
- model is

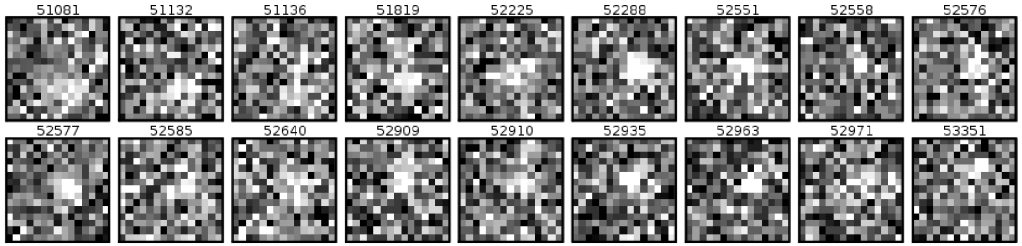
$$b = A \cdot x + e$$

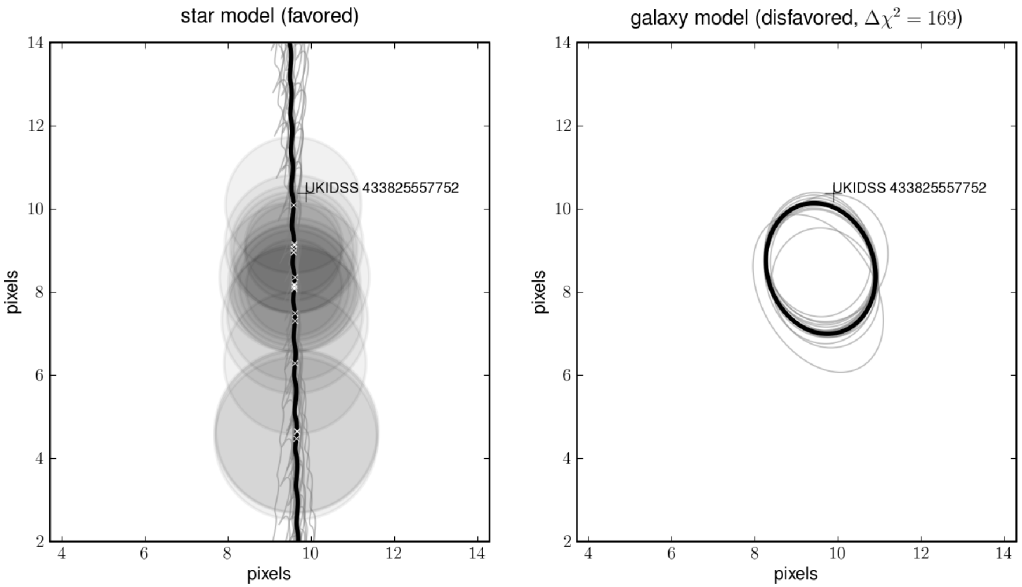
  where $A$ is a convolution matrix, $x$ is an unconvolved (true) scene, $e$ is noise
- $x$ has as many elements as $b$ and $A$ has far, far more (in general).
- regulation, restriction, or priors are required
- the likelihood function is just the noise model $p(e)$
- This is a standard idea underlying computer vision (see, *e.g.*, Hirsch, Schölkopf).

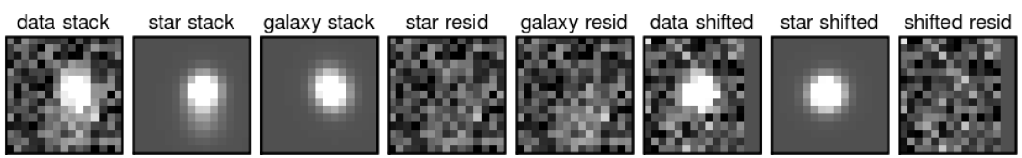
# Image modeling (Lang): tuning



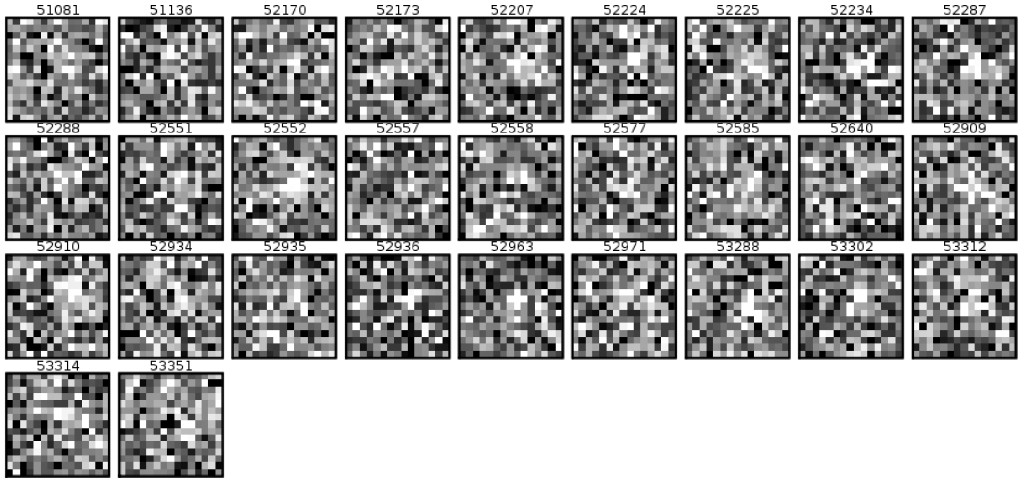
# Faint-source proper motions (0808.4004): brown dwarf

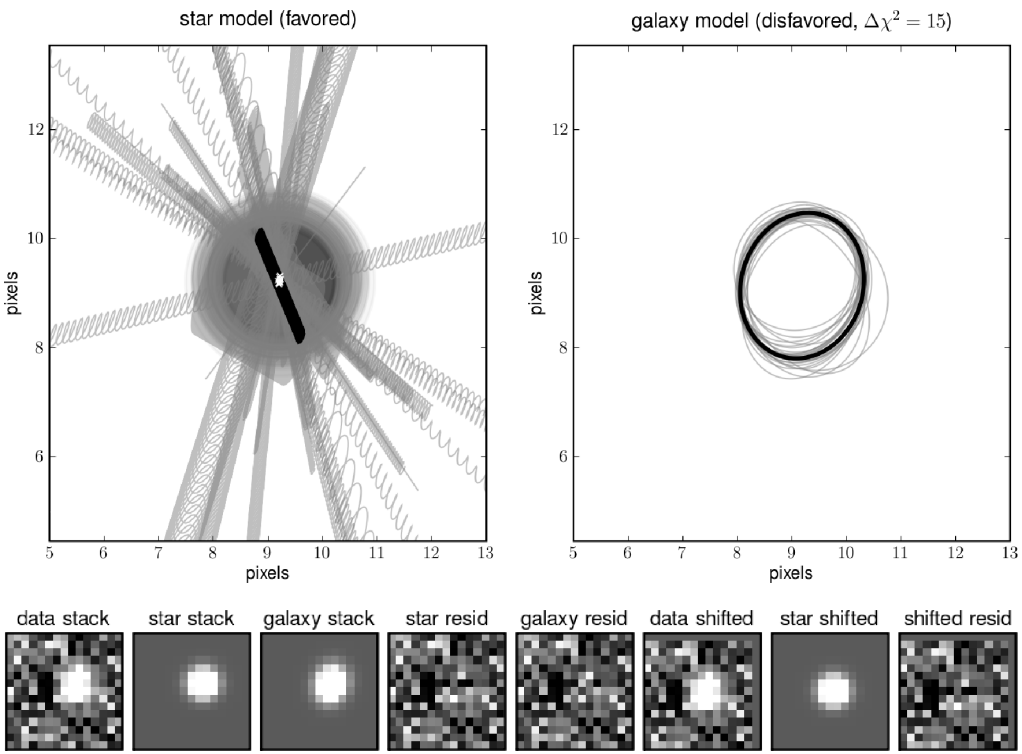


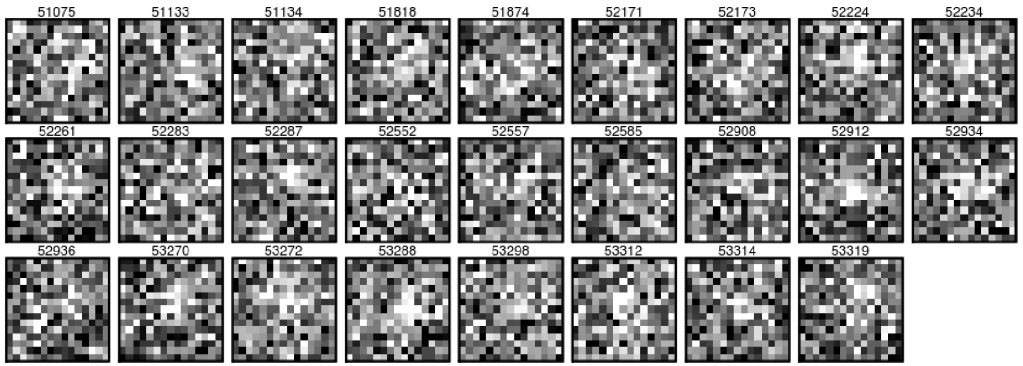



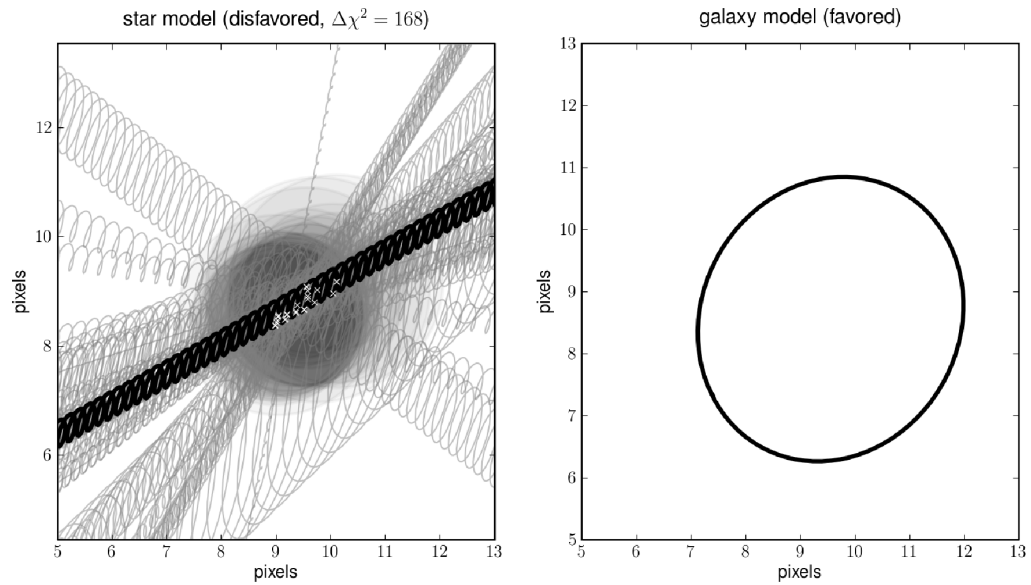
# Faint-source proper motions (0808.4004): $z \sim 6$ quasar

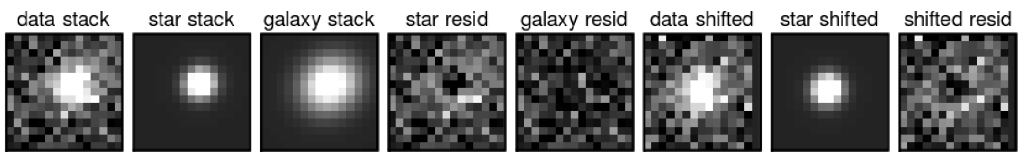


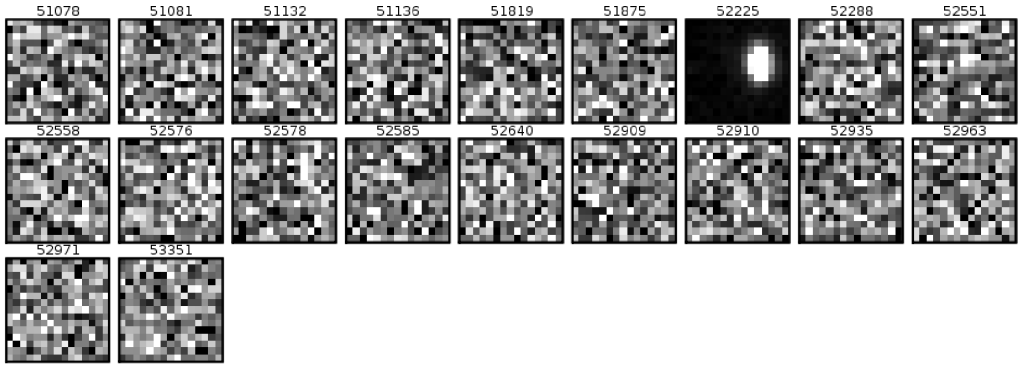
# Faint-source proper motions (0808.4004): faint galaxy

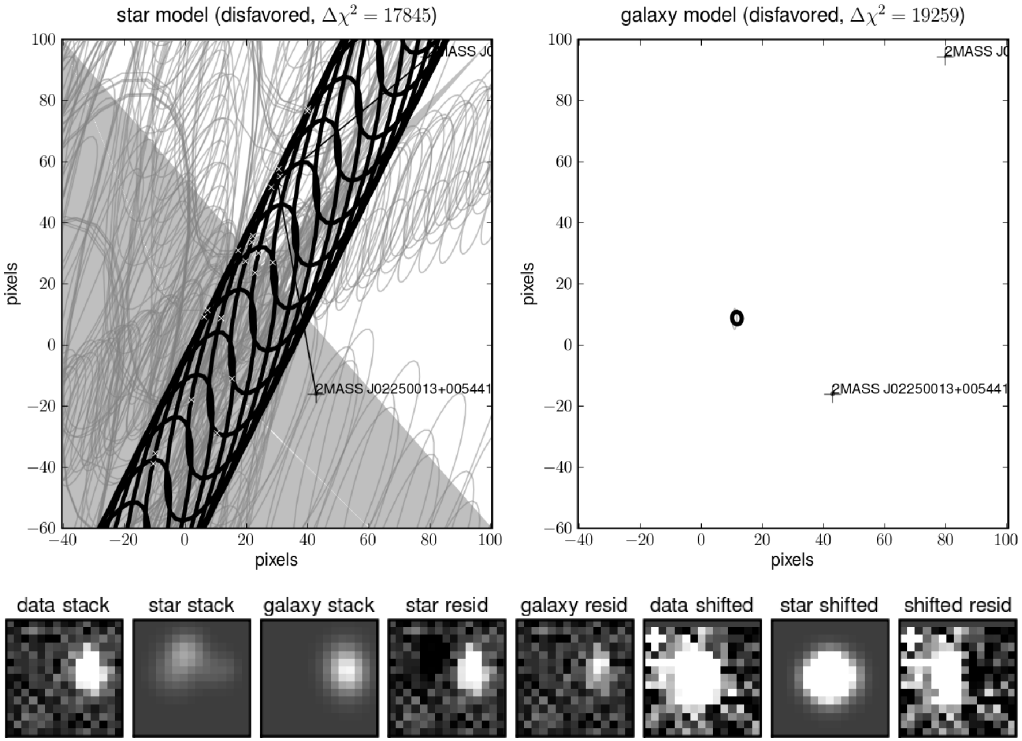


# Faint-source proper motions (0808.4004): defect



# hierarchical models

- "okay, you can model the stars, but that's the easy part!"
- stars are laid down by a process set by the Milky Way
- the Milky Way is created by a process set by the cosmological model

# Stream-finding

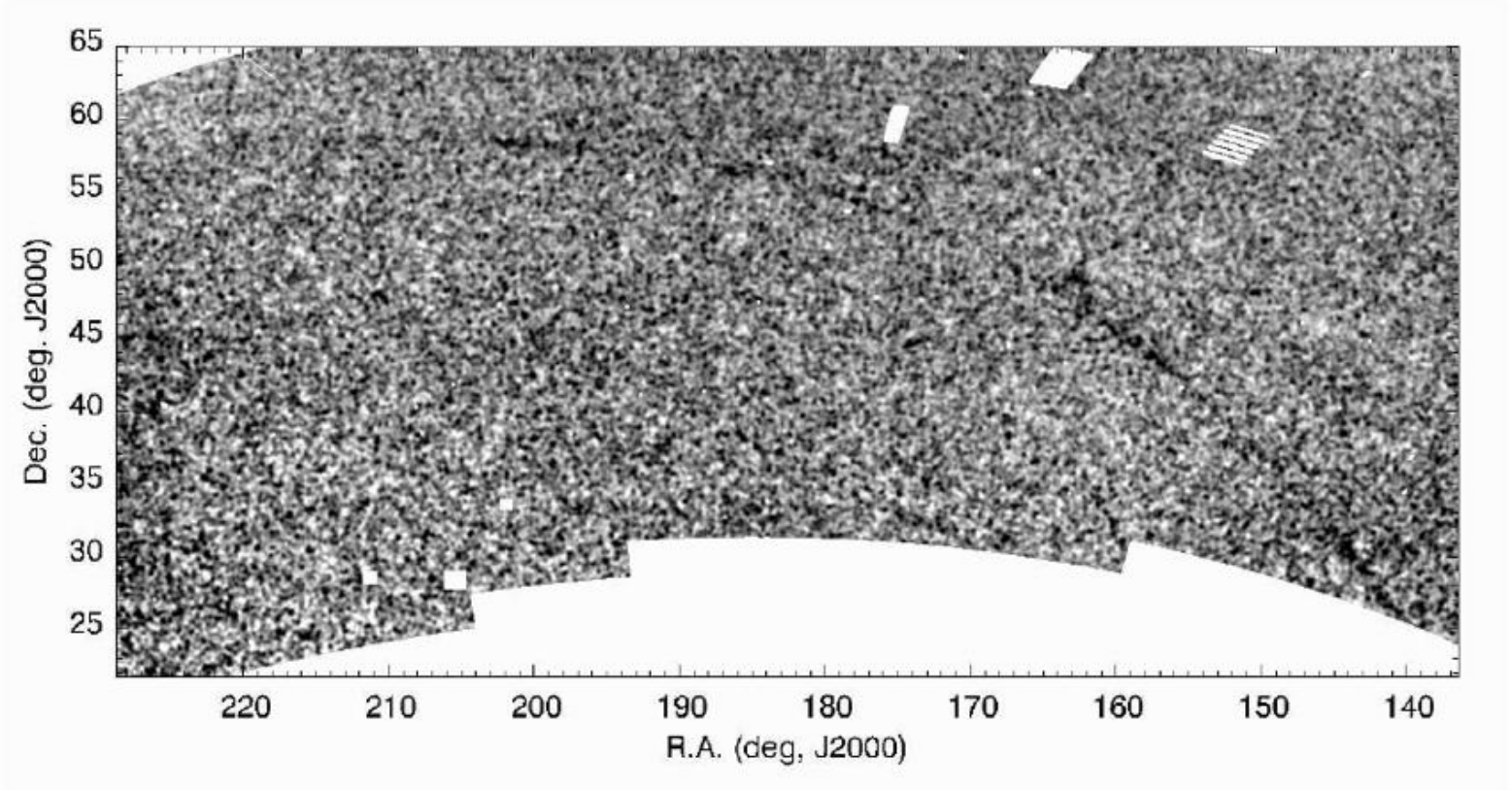
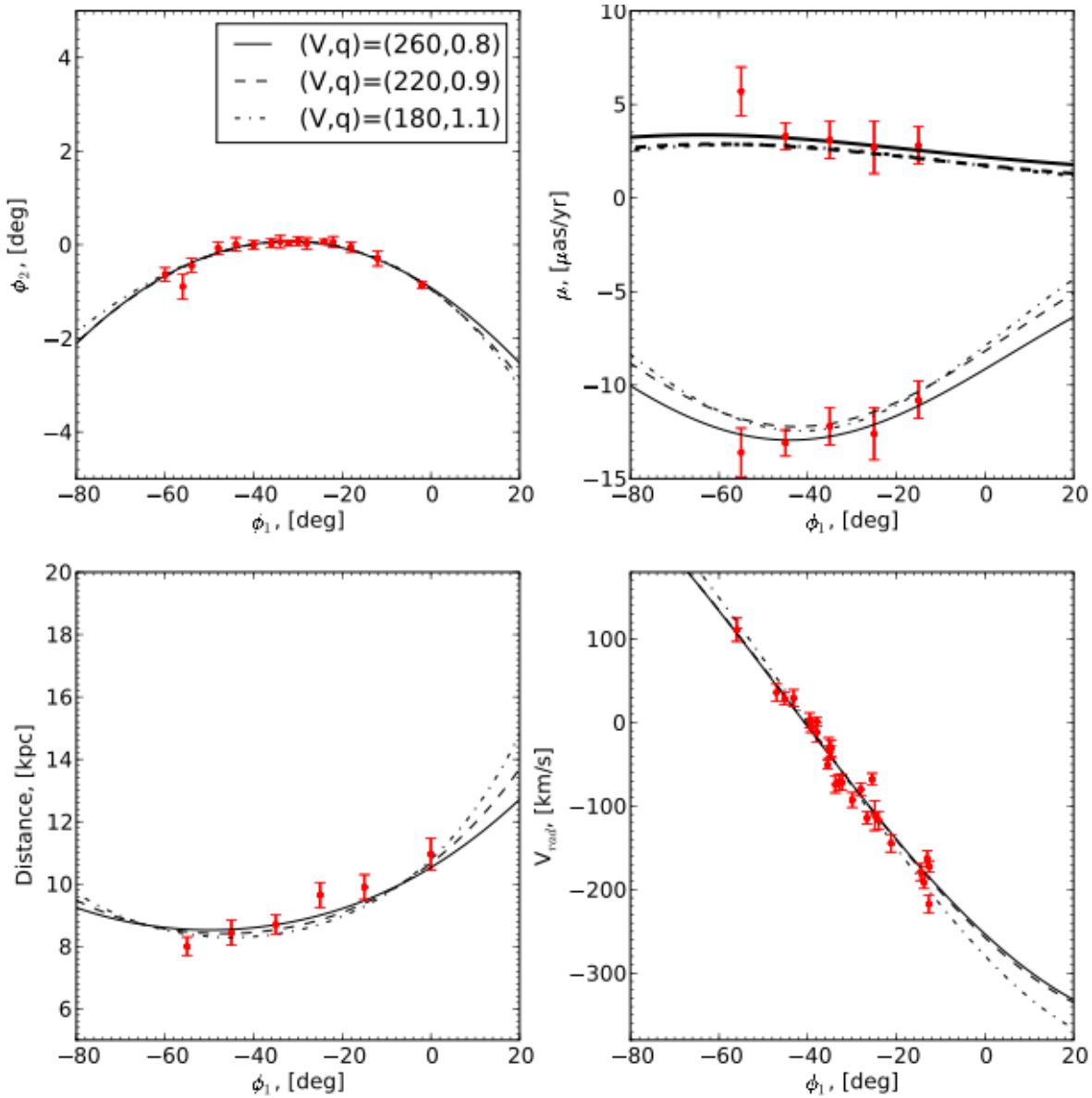



Fig. 1.— Smoothed, summed weight image of the SDSS field after subtraction of a low-order polynomial surface fit. Darker areas indicate higher surface densities. The weight image has been smoothed with a Gaussian kernel with $\sigma = 0.2°$. The white areas are either missing data, or clusters, or bright stars which have been masked out prior to analysis.

Grillmair & Dionatos 2006 *ApJL* **643** L17–L20.

# Stream-finding

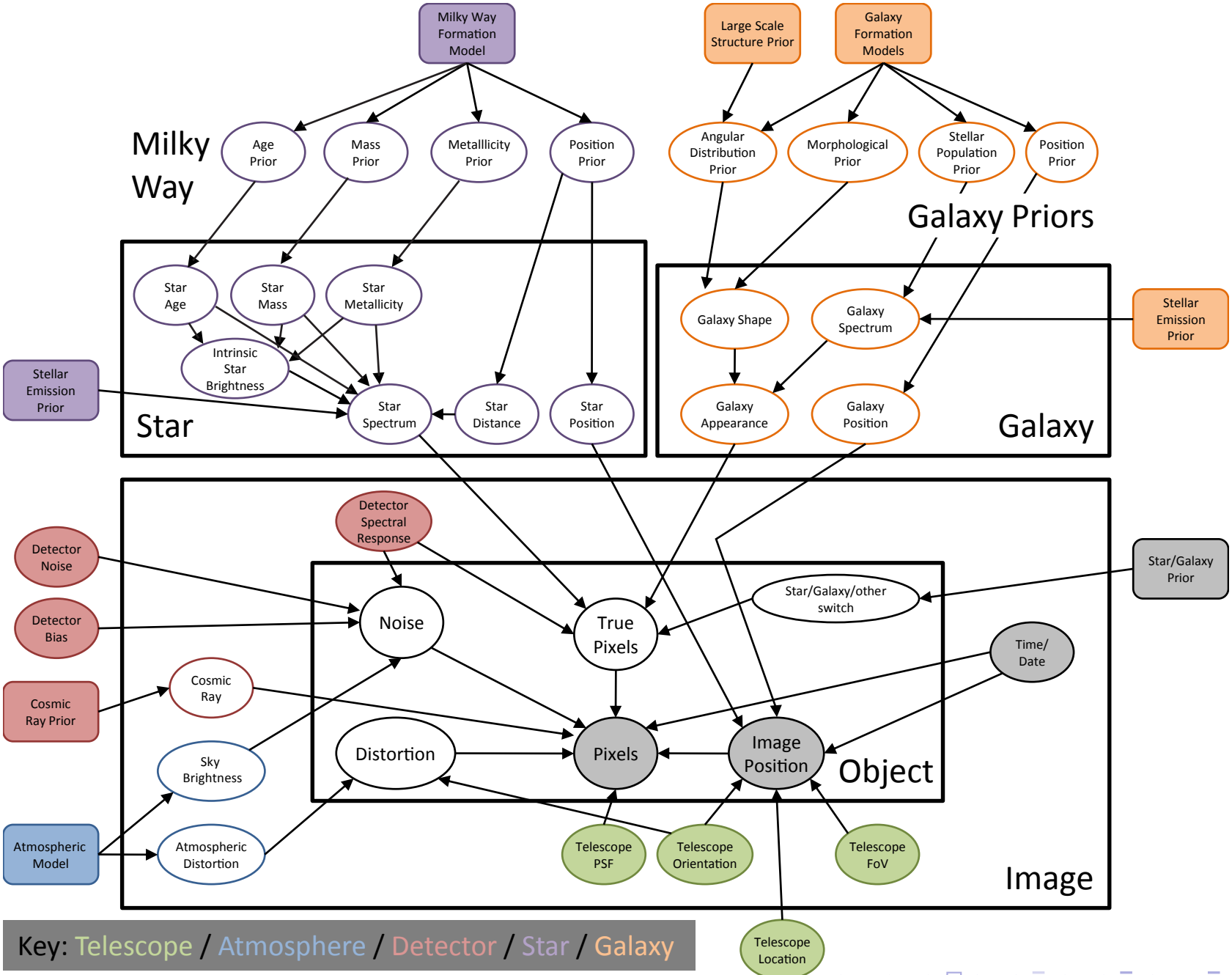



Koposov, Rix, & Hogg, 2010 *ApJ* **712** 260–273.

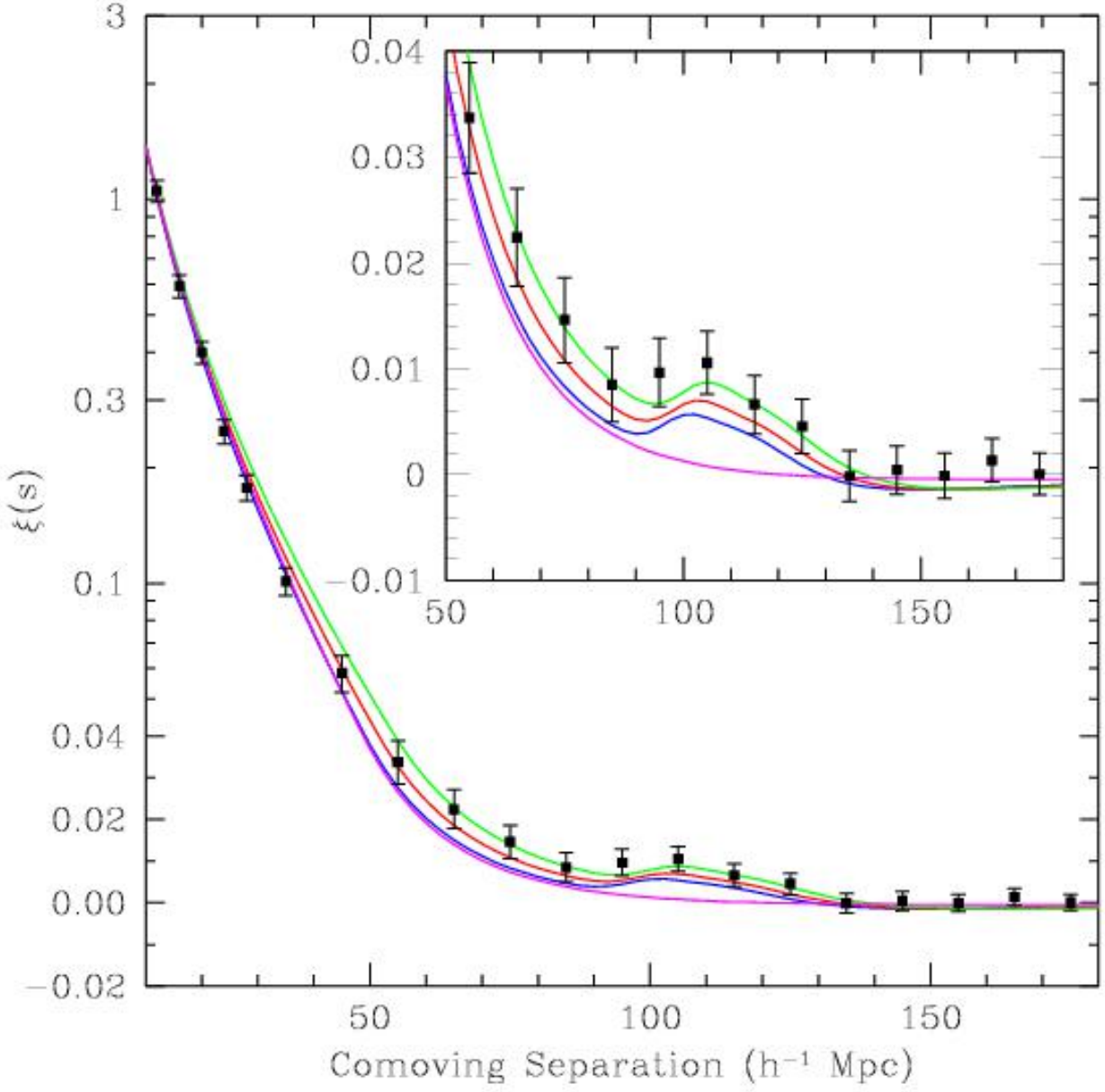
# going up the hierarchy

- stars are on orbits around the Milky Way
- the Milky Way is generated by gravitational collapse from initial conditions (and a whole lot of gastrophysics)
- the initial conditions and growth of structure are set by the cosmological parameters
- the cosmological parameters are set by...
- we don't know how to perform this inference, even approximately!
  - models of no fixed complexity
  - likelihood "calls" involve enormous dynamical computations
  - numbers of parameters in the billions
  - butterfly effects abound

# and we're back:



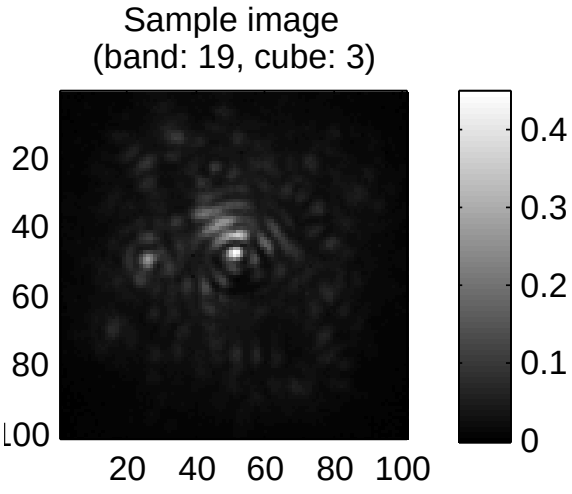
# baryon acoustic feature

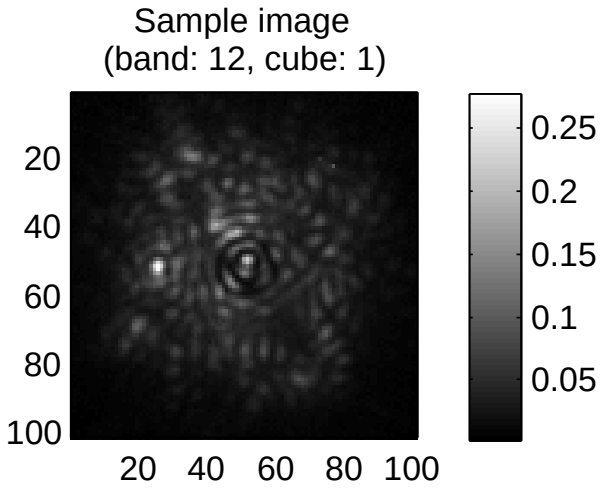


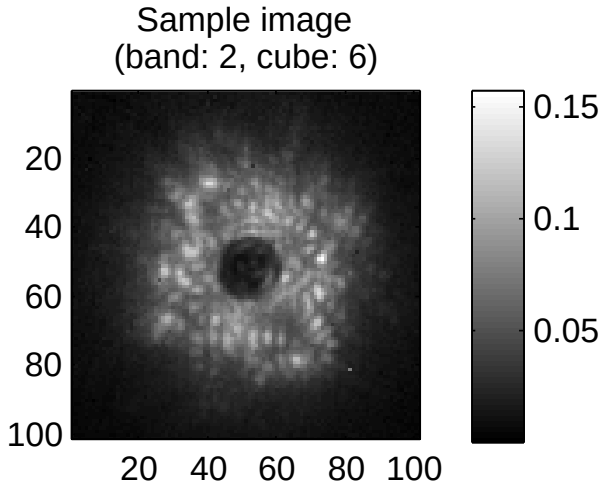
# two-point functions

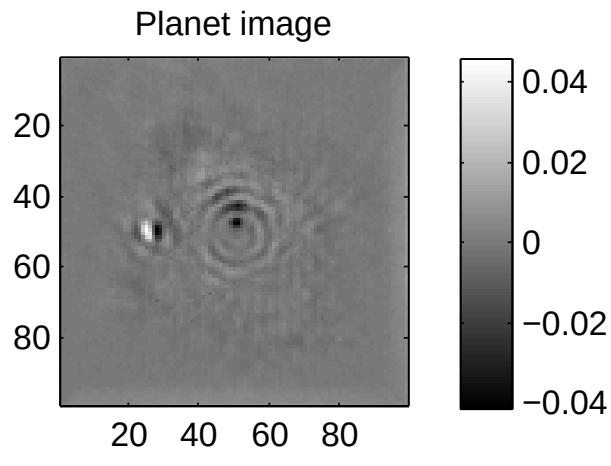
- much of cosmology depends on two-point functions
  - correlation functions
  - power spectra
  - variances as a function of scale
- two point functions are invariably point-estimated
  - count pairs as a function of separation
  - evaluate harmonic basis functions at galaxies
  - FFT a pixel map
  - insane "window functions"
- principled inference happens *after* that lossy point estimation
- can we do better?
  - Gaussian processes?
  - infer the density field?

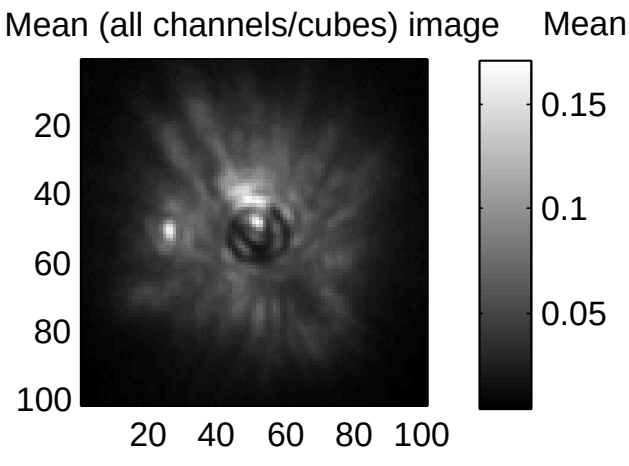
# exoplanet direct imaging (Fergus, in prep)

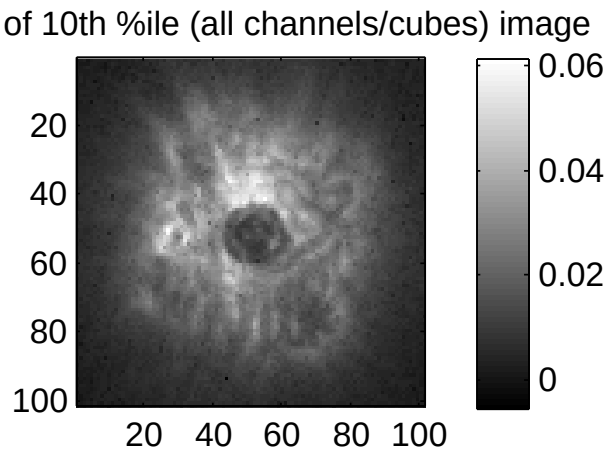


# what I said

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