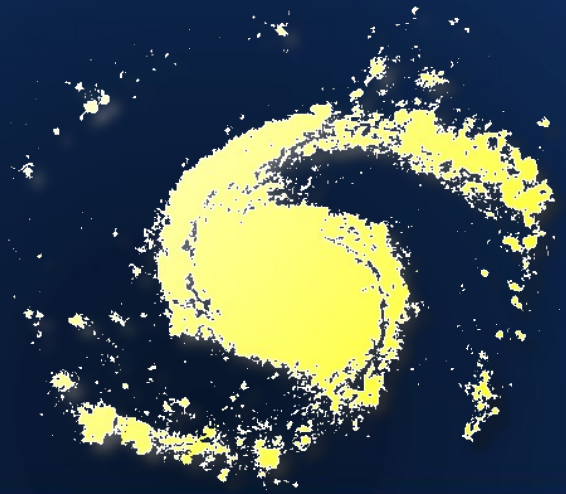
# Galaxy Formation Models: Past, Present & Future

**Andrew Benson**

*Carnegie Observatories*



CARNEGIE INSTITUTION FOR SCIENCE

THE OBSERVATORIES

# Overview



- Historical perspective
  - How did this all get started?
- Current modeling
  - What can state-of-the-art modeling do?
- Challenges
  - What can't it do?
- Wishlist
  - What do we need to meet those challenges?

# Historical Perspective



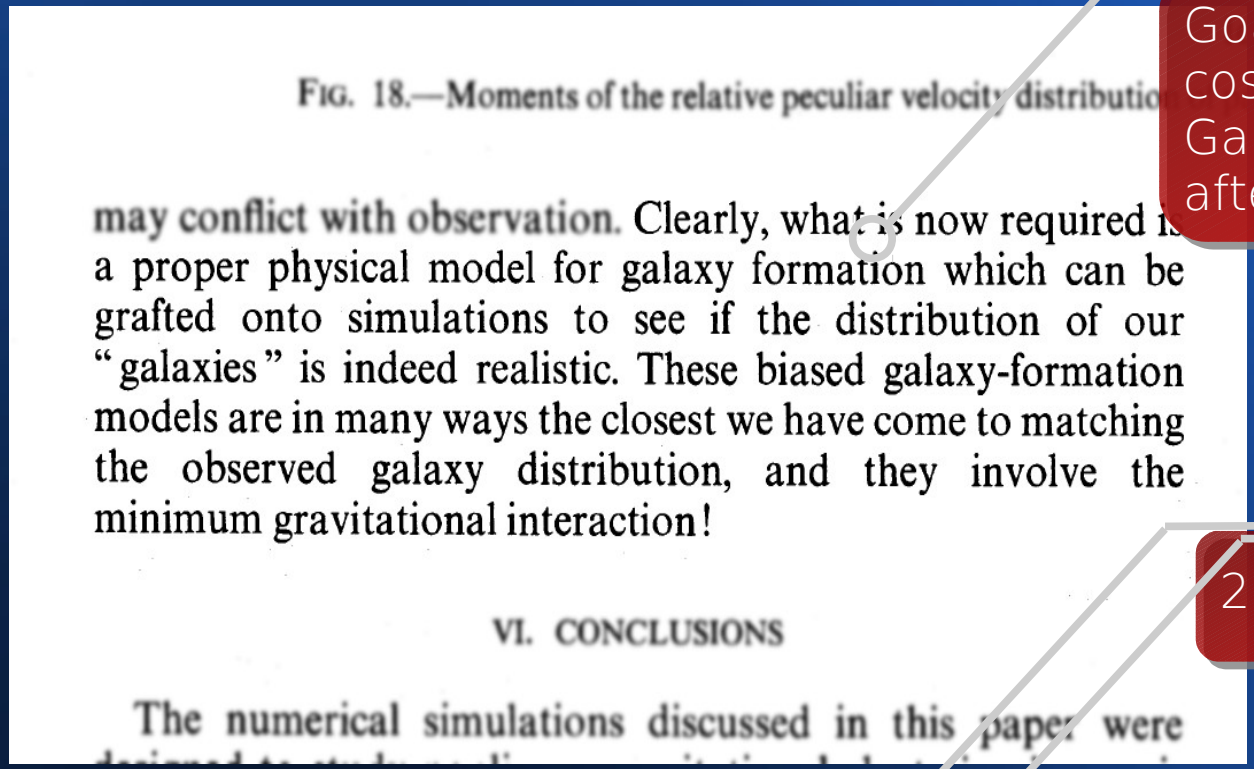


FIG. 18.—Moments of the relative peculiar velocity distributio

may conflict with observation. Clearly, what is now required is a proper physical model for galaxy formation which can be grafted onto simulations to see if the distribution of our "galaxies" is indeed realistic. These biased galaxy-formation models are in many ways the closest we have come to matching the observed galaxy distribution, and they involve the minimum gravitational interaction!

VI. CONCLUSIONS

The numerical simulations discussed in this paper were

Davis, Efstathiou, Frenk & White (1985)

Goal here was to understand cosmology/large scale structure. Galaxies were almost an afterthought.

28 orders of magnitude!

More importantly, factor of $2^{18}$ in particle number (they had 32768 particles)

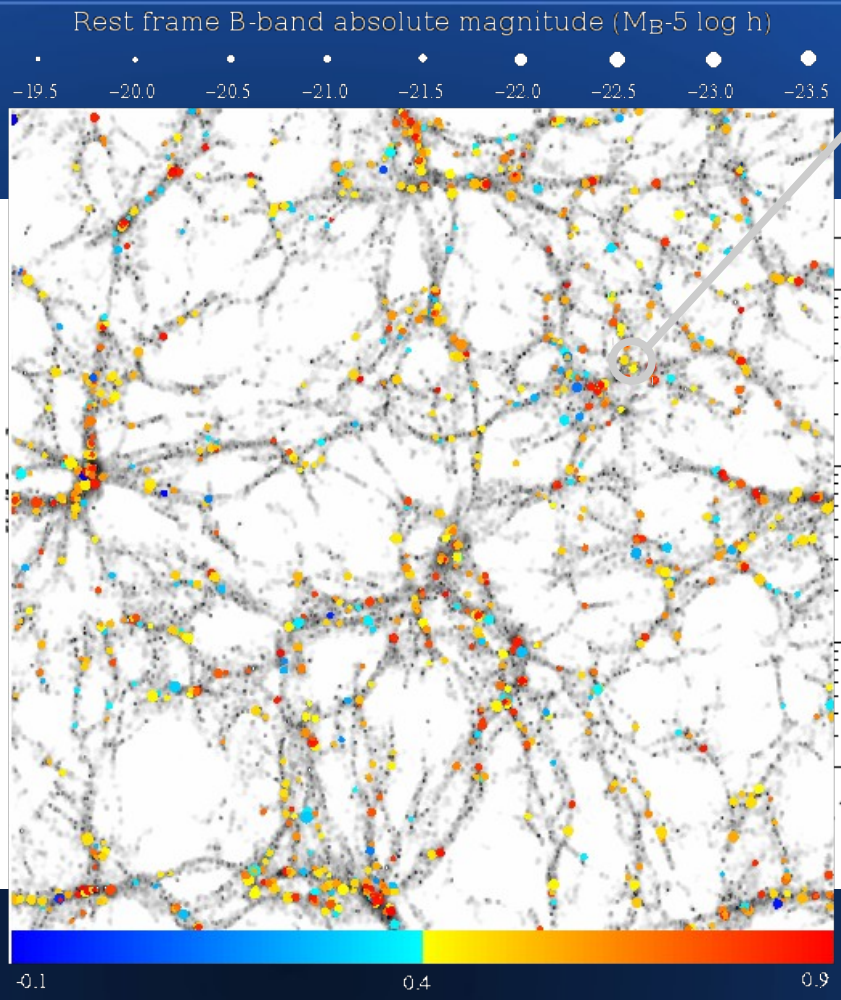
# Past Successes



- Definition of “success”
  - Able to match some pre-existing dataset
    - Obviously it would be better to predict....
  - Provide insight into the underlying physics
  - Become the *de facto* method for examining this problem in future

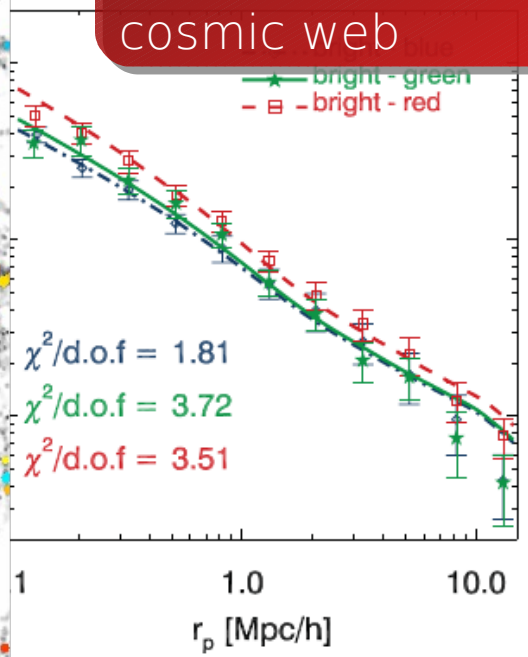
# Past Successes

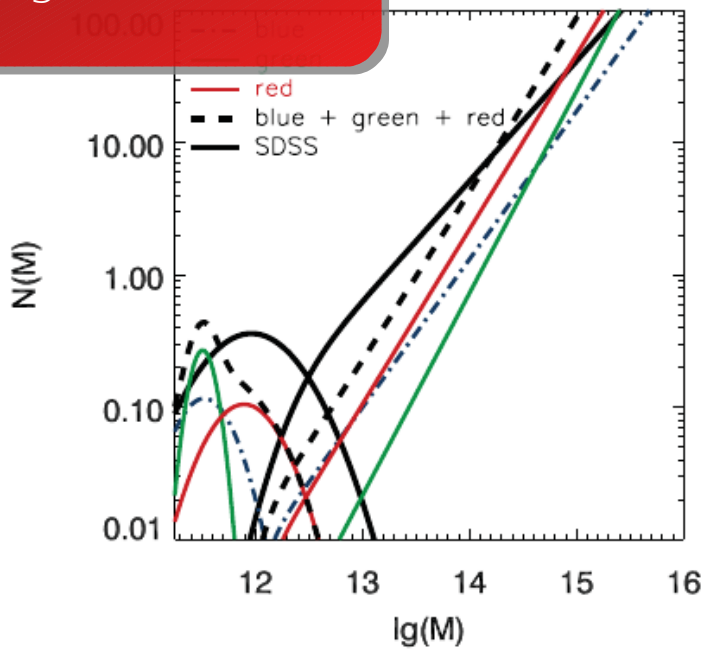





AJB (2000)

Physics-based model prediction for distribution of galaxies in the cosmic web




Krause et al. (2013)

# Past Successes



- “Missing Satellites” problem
  - Bullock, AJB, Somerville
- AGN feedback
  - AJB, Croton, Bower
- Millennium Database and similar

# Why Not More Successes?



- Modeling typical follows a paradigm of "narrative astronomy":
  - Telling a story rather than testing a theory and making predictions
- Has lead to limited to no real predictive power
- Need quantitative, statistical modeling
- How to do this really well?

# Current Modeling



- Models are now very capable:
  - Typically obtain reasonable matches to primary constraints
  - Include wide range of physical processes
  - Can directly connect to observable quantities

# GALACTICUS

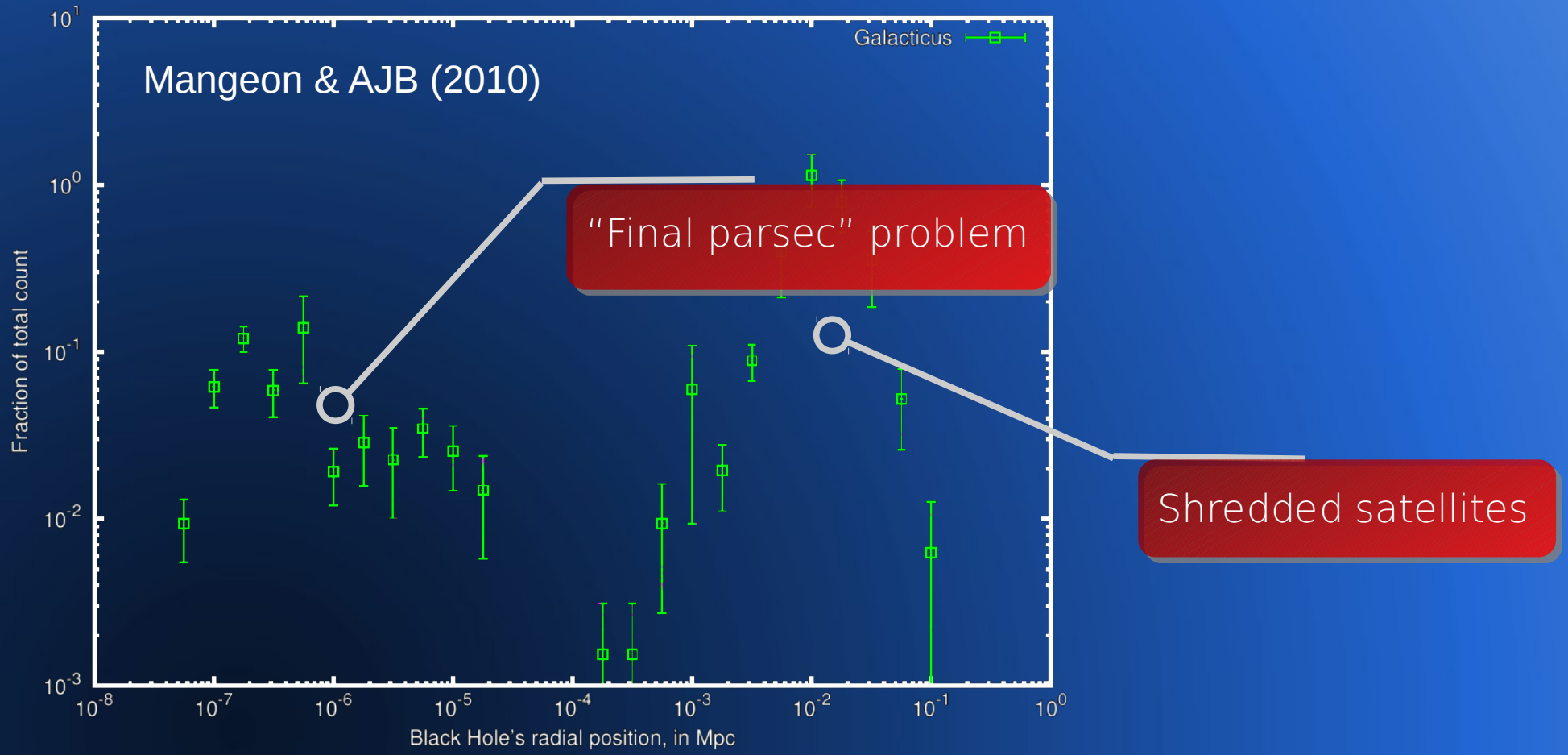


- A Galaxy Formation Toolkit
  - Modular
  - Comprehensive
  - Well documented
  - Open Source
  - Aims to include current best understandings and calibrations

https://sites.google.com/site/galacticusmodel/

# (Binary) Supermassive Black Holes





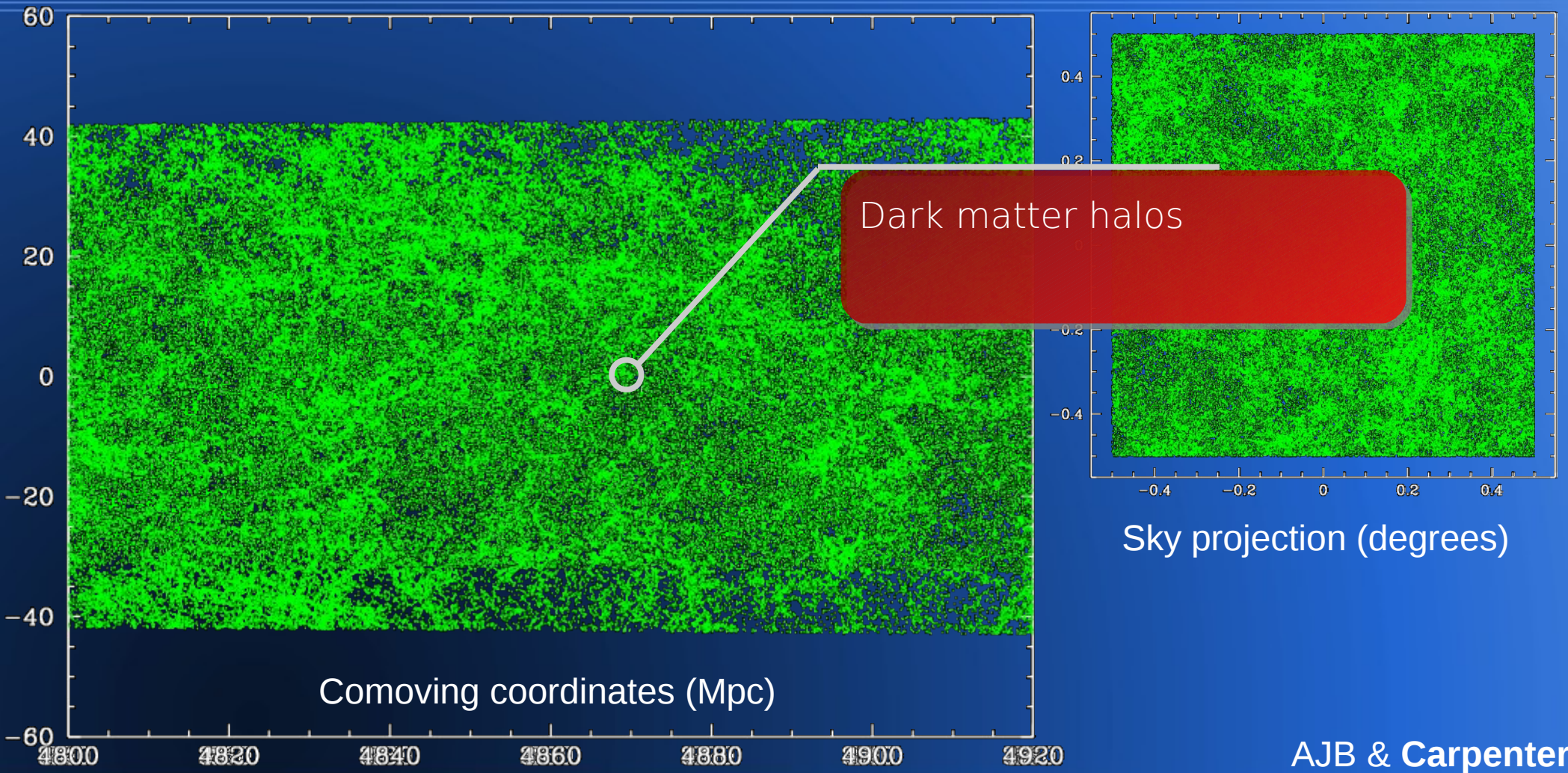
- 25 m sub-mm telescope
- Up to 1 square degree field of view
- 200μm to 3mm wavelength range

# Caltech-Cornell Atacama Telescope

http://www.submm.org

# CCAT Virtual Universes

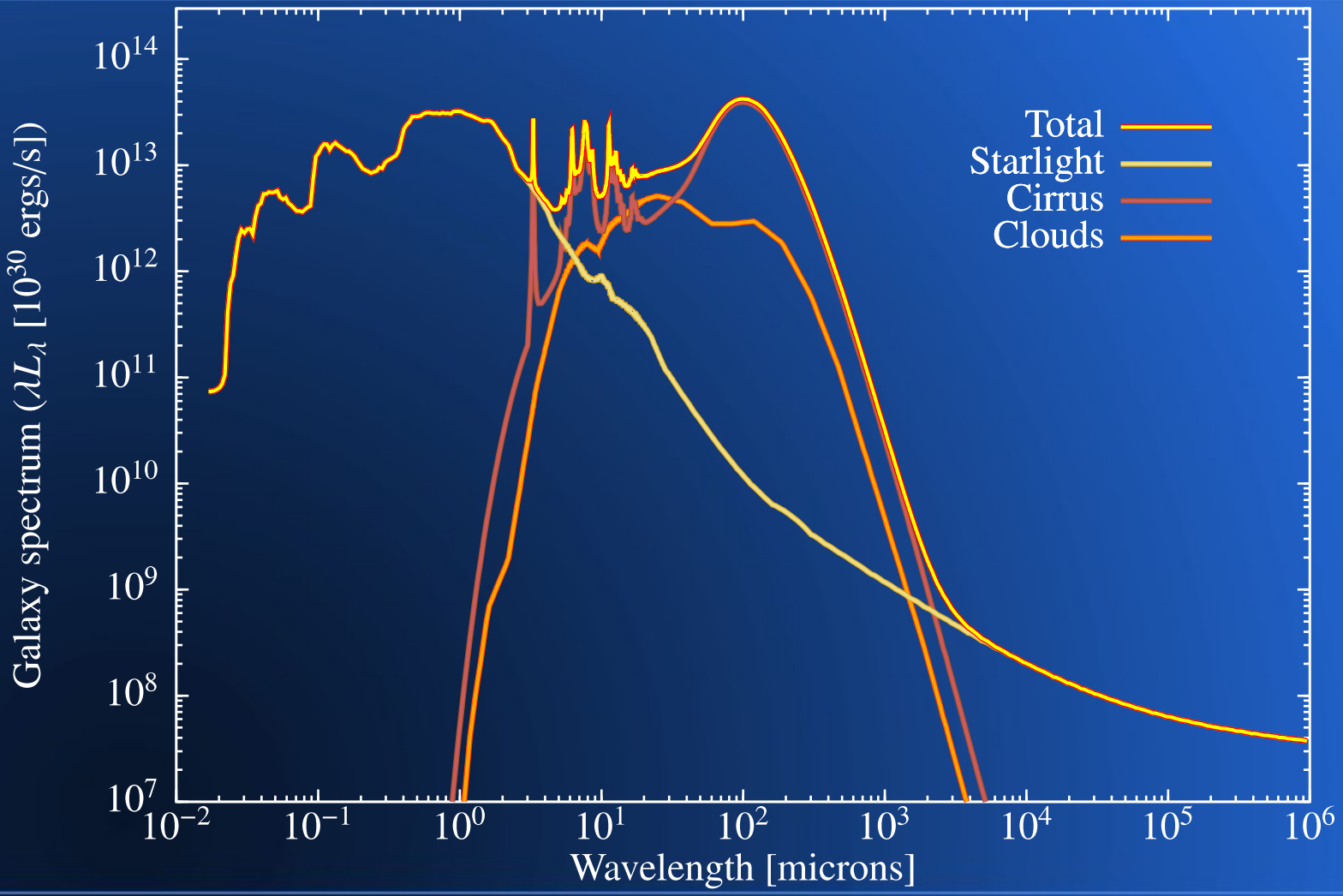


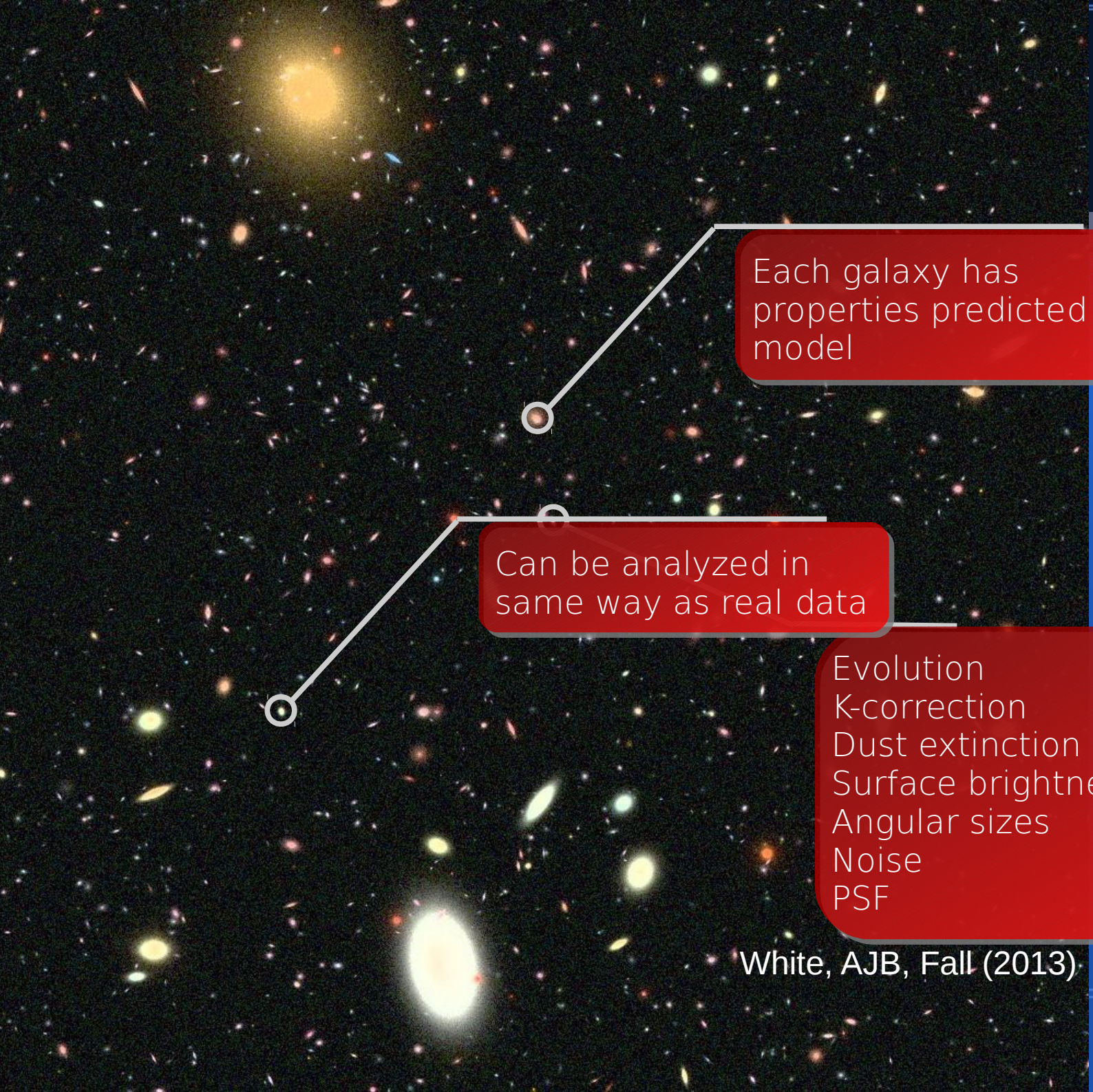



AJB & **Carpenter**

# Example Galaxy SED







Each galaxy has properties predicted by model

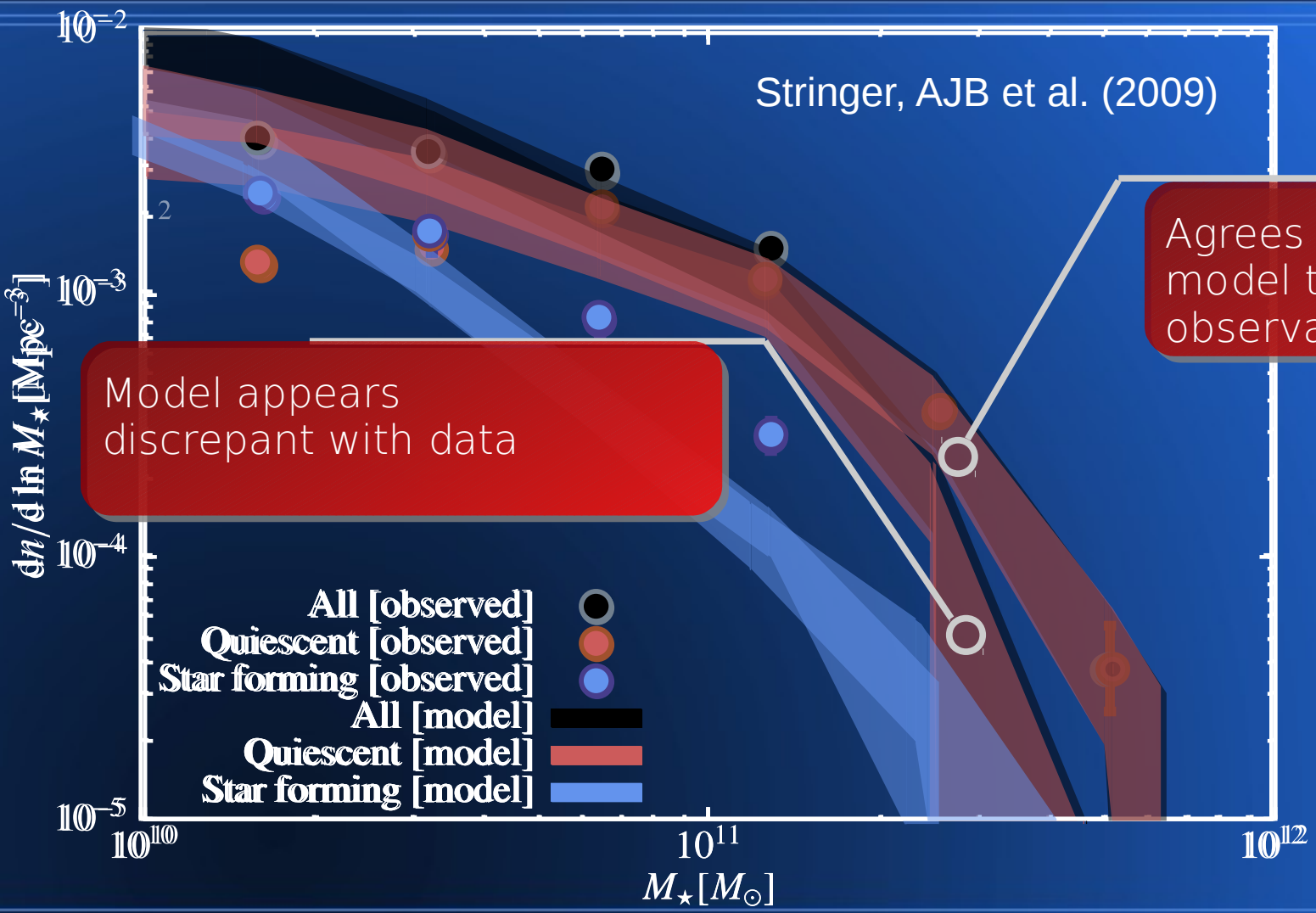
Can be analyzed in same way as real data

Evolution
K-correction
Dust extinction
Surface brightness dimming
Angular sizes
Noise
PSF

White, AJB, Fall (2013)

# Modeling Observations





# Challenges

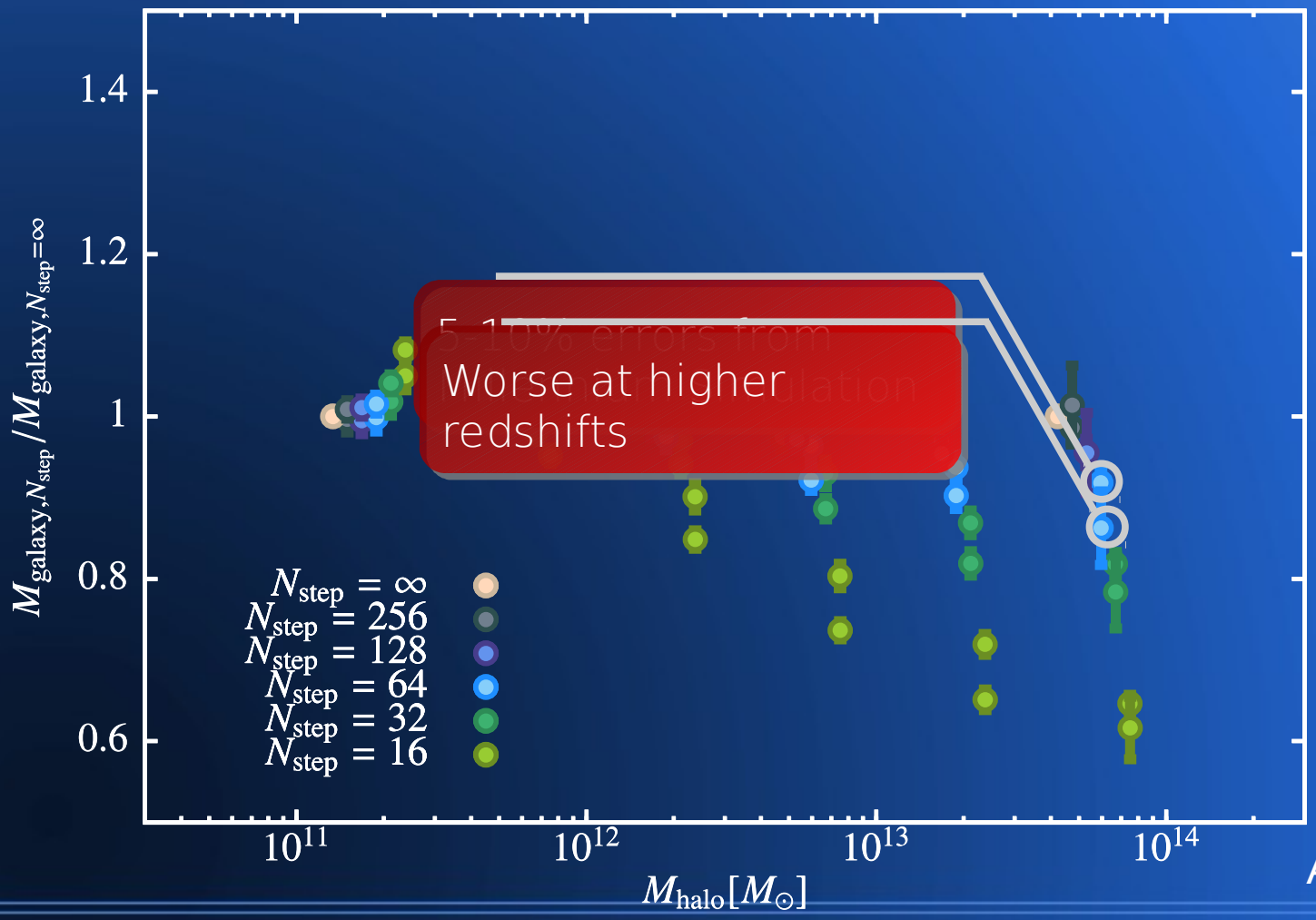


- Ensure that models are robust and accurate
  - Testing of each component required
- Carefully constrain models
  - Selected datasets with well-characterized errors and selections
  - Predictions from these (requires physics models)
- Connect to observables
  - Where along theory-observational spectrum should connection be made?

# Accuracy and Robustness



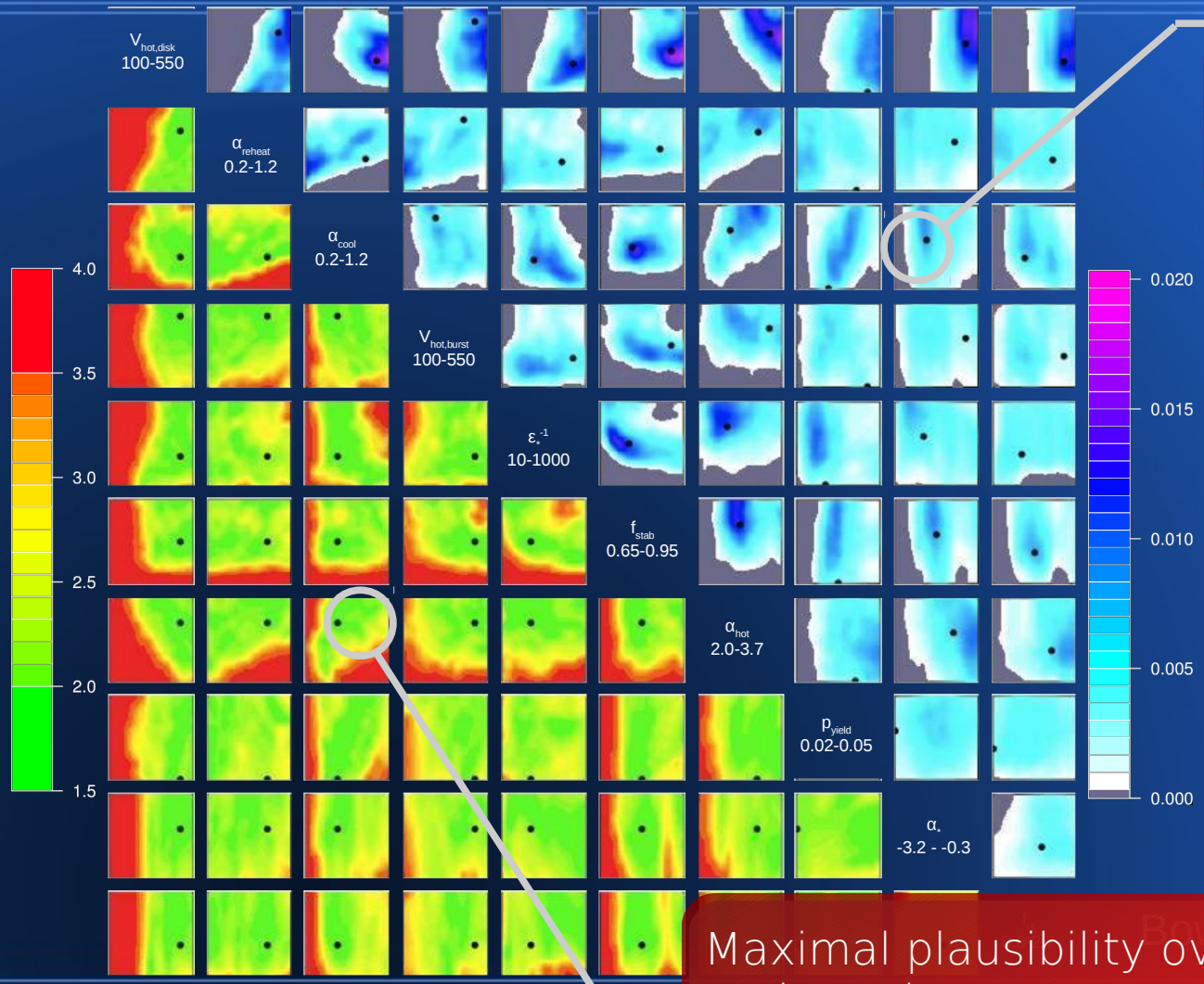
Simple model; Uniform in ln($a$) from $1 + z = 20$; Baryonic mass; Central galaxies; z=0




AJB et al. (2011)

# Bayesian Parameter Constraints






"Optical depth" through plausible regions

- Parameter space search
  - 10 parameters
  - 2 datasets
- Time consuming

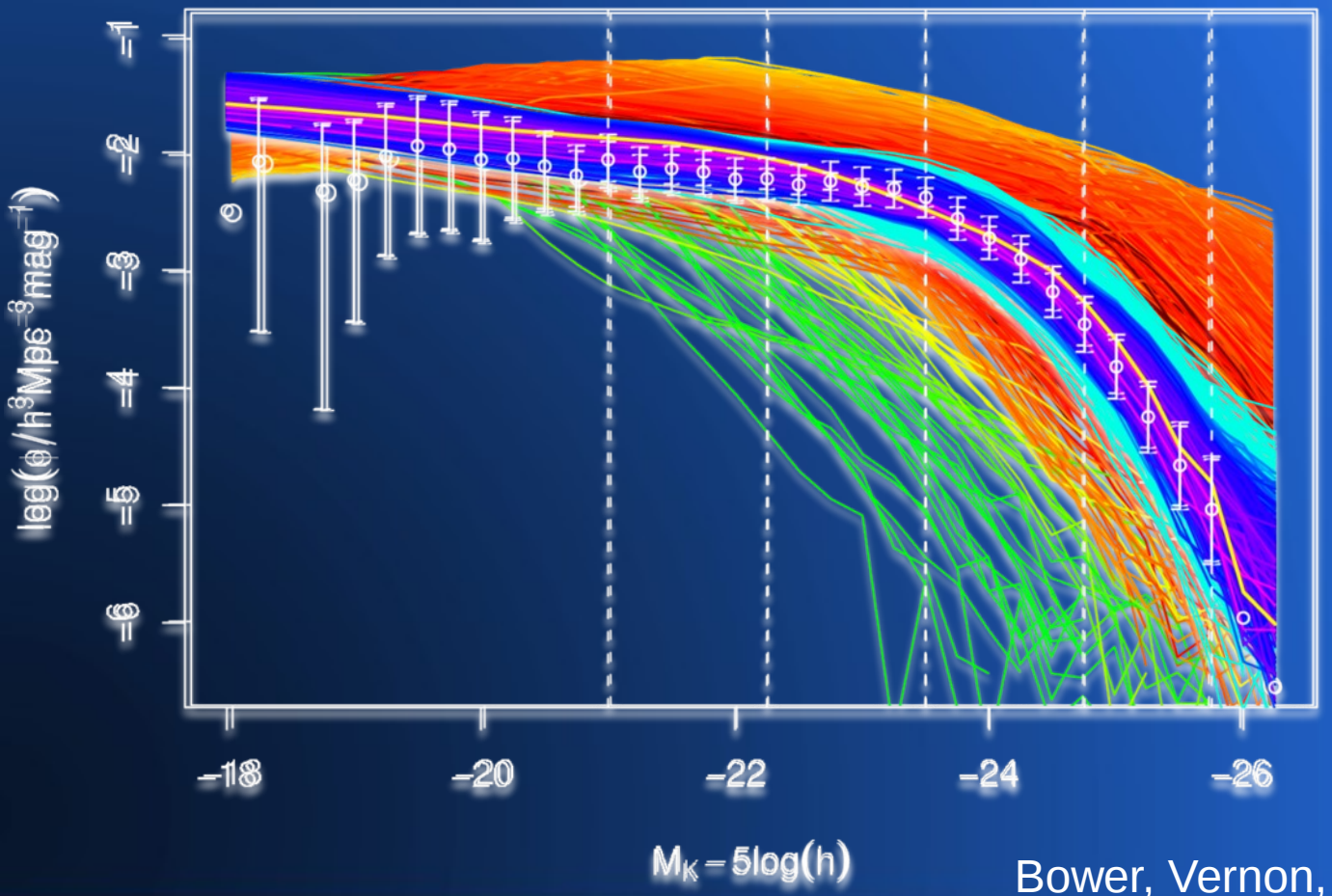
Maximal plausibility over projected parameters

Power Vernon, AJB + (2010)

# Constraining Model Parameters



K-band Luminosity Function; z=0; Wave 1




Bower, Vernon, AJB et al. (2010)

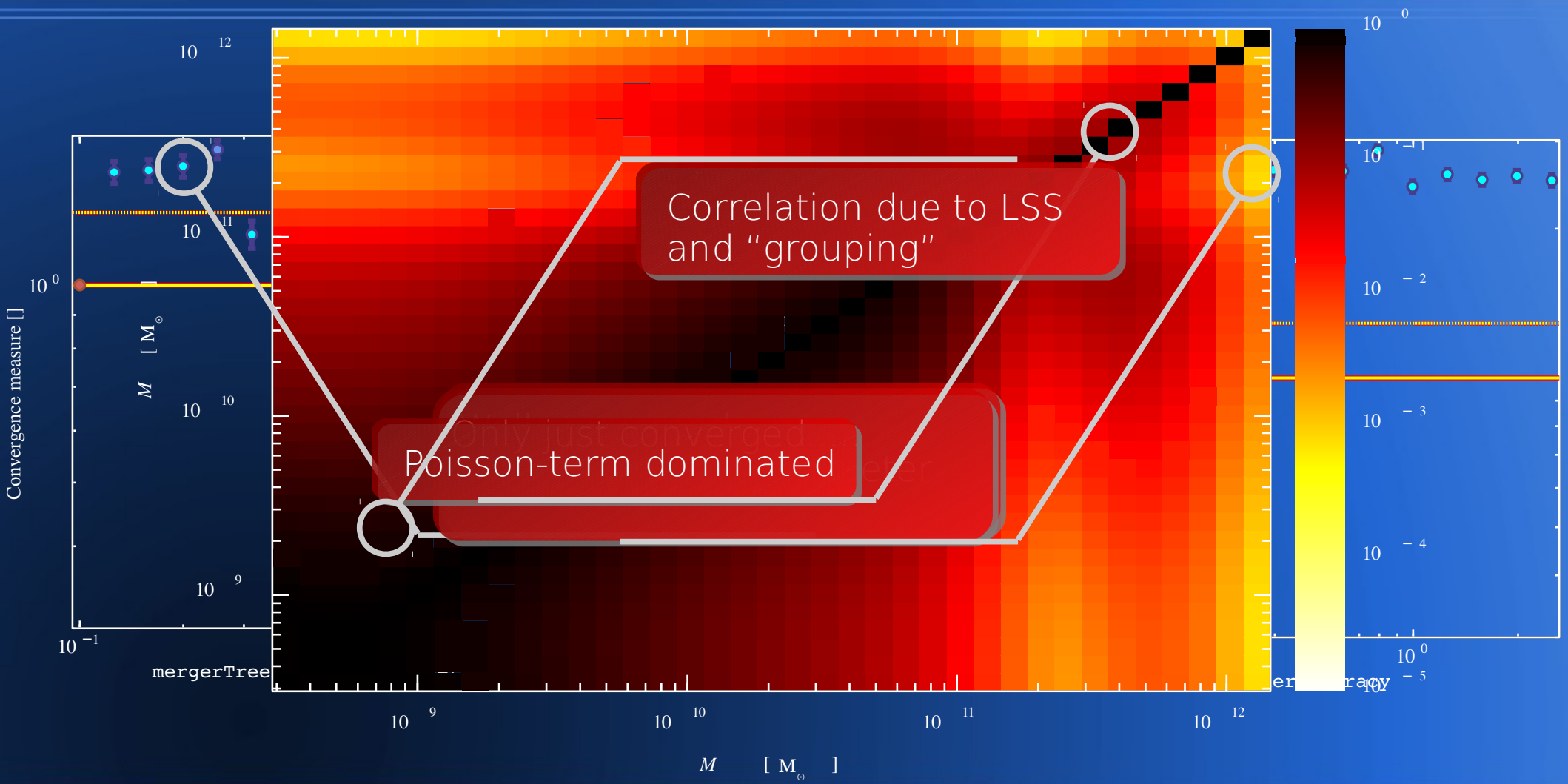
# My Wishlist
## (for this workshop and beyond.....)



- More careful checking of model results
  - Converged with numerical parameters?
  - Cross-checked against other codes/methodologies?
- Quantitative constraints on model parameters
  - MCMC/Emulator methods
  - Needs *very careful* attention to errors (random & systematic)
- *Testable* predictions

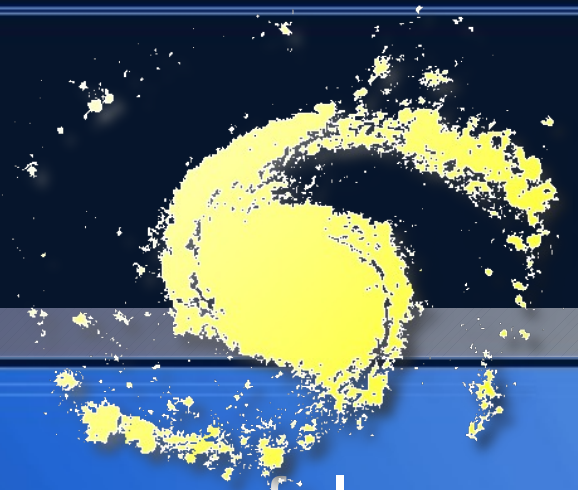
# Robustness & Accuracy





# Summary





- Galaxy formation models are now very powerful
- Current limitations arise from:
  - Lack of understanding of accuracy/robustness
  - Focus on “narrative astronomy”
- Tools and data to develop highly-constrained, highly accurate models exist
  - Necessary for reliable simulation of future surveys
  - Requires careful treatment

, and a lot of work!

https://sites.google.com/site/galacticusmodel/