Galaxy Formation in ΛCDM: A Theoretical Overview

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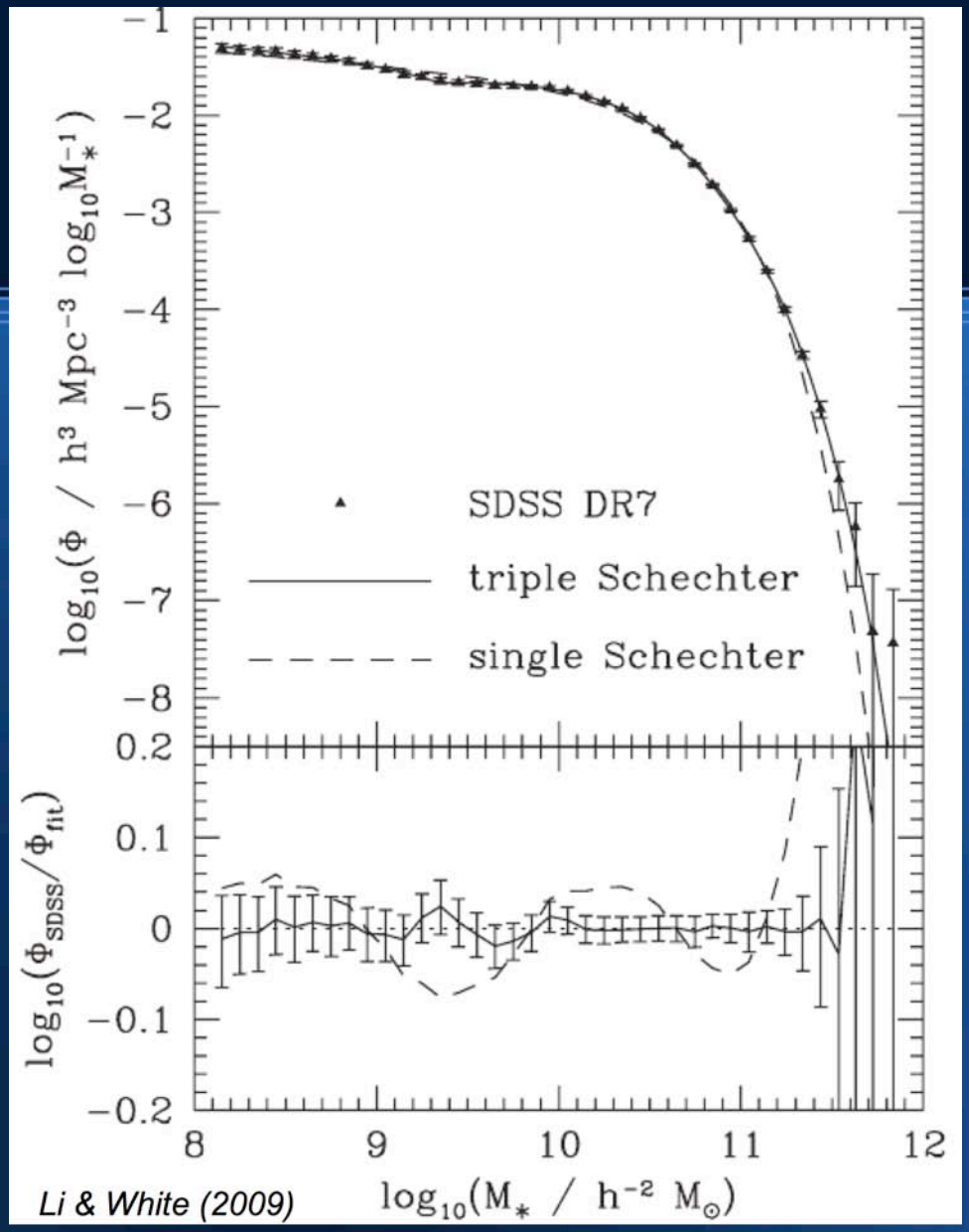
Galaxy Phenomenology

- Galaxies are a complex population of objects exhibiting a wide range of phenomena
- But, the population exhibits significant homogeneity (e.g. Fundamental Plane)
- Understanding galaxy formation requires explaining the homogeneity (and departures from it) in terms of the underlying physics
- Test by extrapolation to high-z and/or other wavelengths, then compare with observations

Local Universe



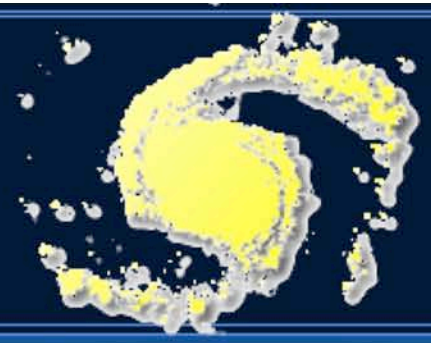
- Statistical properties of galaxy population at z=0 now extremely well characterized
- Theory can explain much of the data, even if not the fine details

Semi-Analytic Galaxy Formation

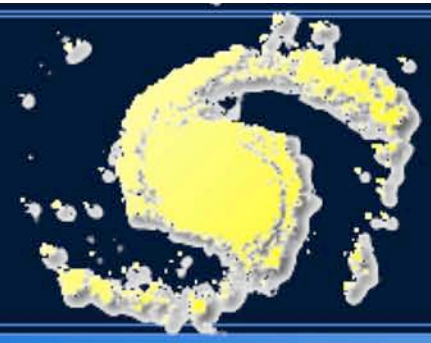
N-body/Hydro Galaxy Formation

Semi-Analytic vs. N-body Hydro

- Both solving same physics in same cosmological framework (hierarchical CDM)
- Different approaches to solving equations:
  - Analytic approximations
  - Direct solution on particles/grid
- N-body/Hydro include sub-grid semi-analytic recipes
- Each has strengths/weaknesses – choose which is best for specific problem



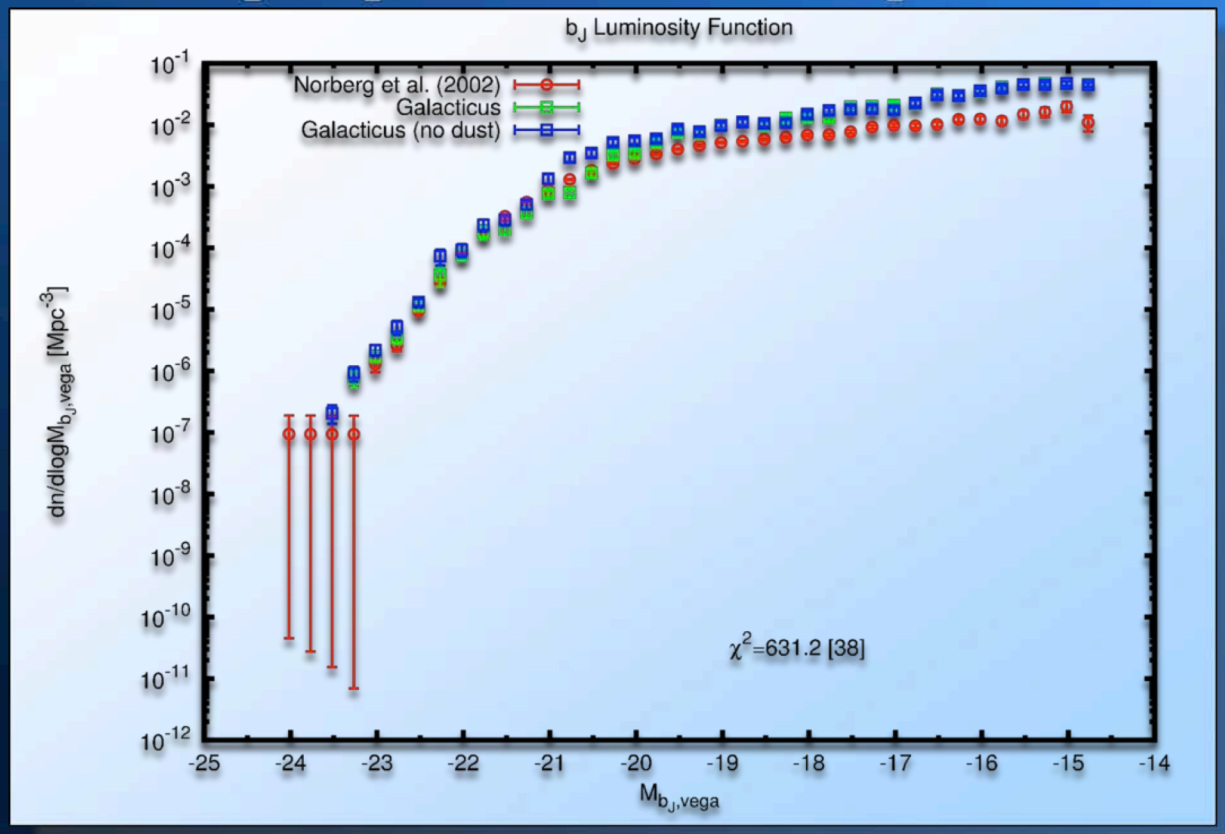
GALACTICUS



- Freely available for anyone to use
- Modular design
  - Each function can have multiple implementations, selected by input parameter.
  - “Node” can have arbitrary number of components (e.g. DM halo, disk, spheroid), all with multiple implementations
- Combination of smooth (ODE) evolution and instantaneous events (e.g. mergers)

GALACTICUS

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



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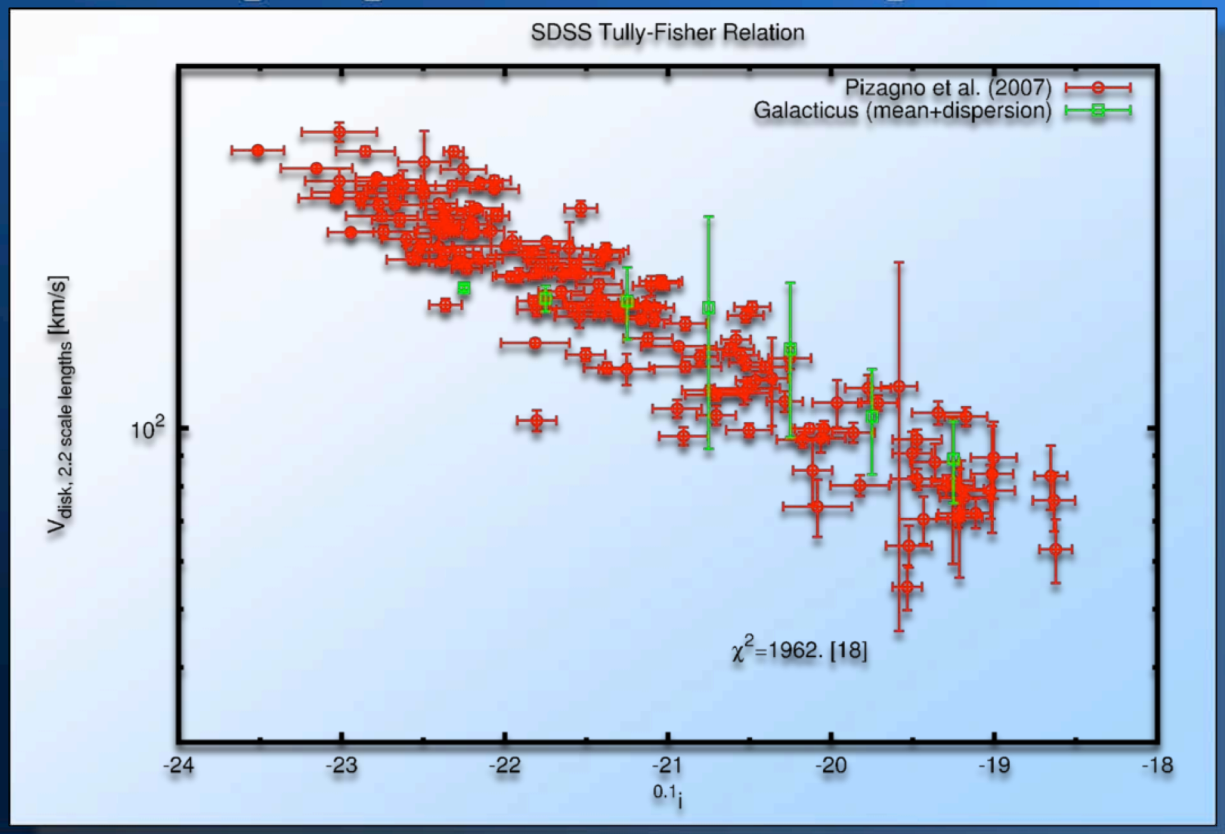

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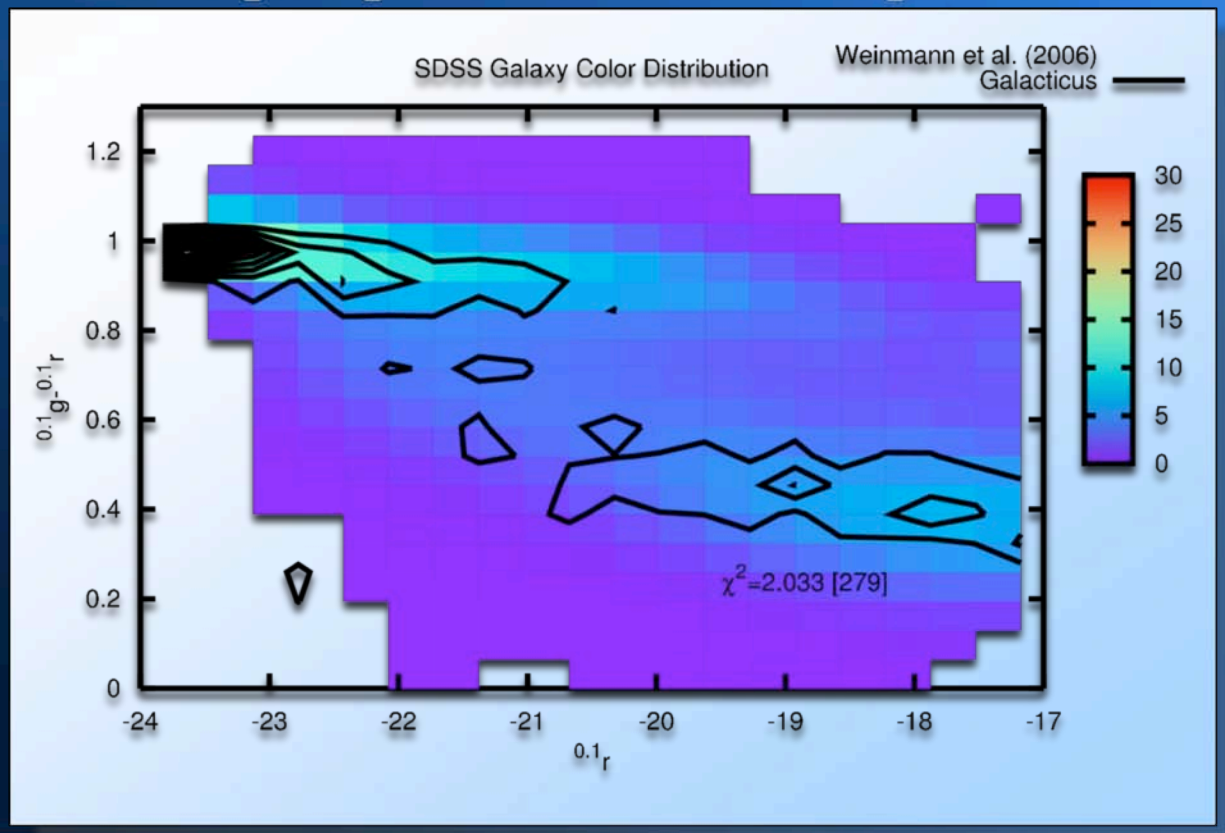
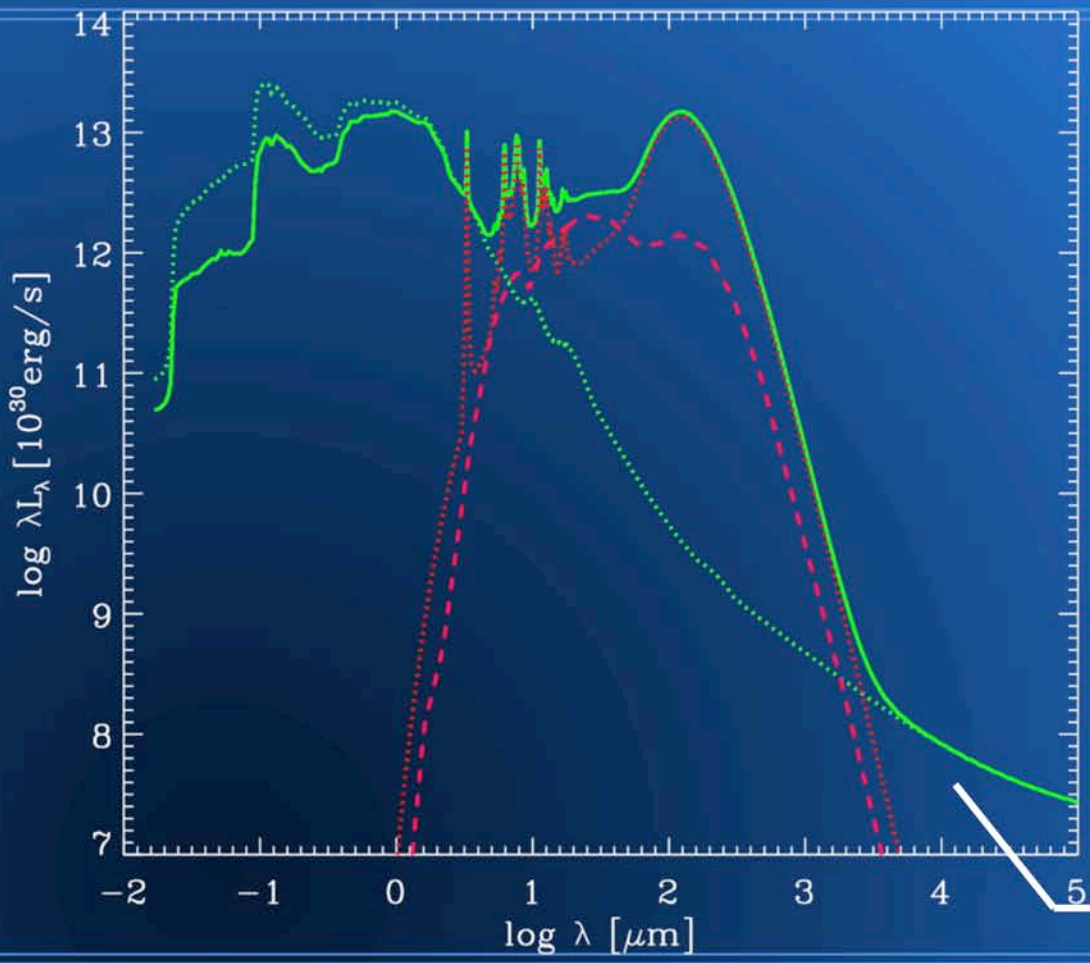


Computing Galaxy SEDs



SUNRISE
Jonsson

GALACTICUS + GRASIL
AJB + Granato, Silva

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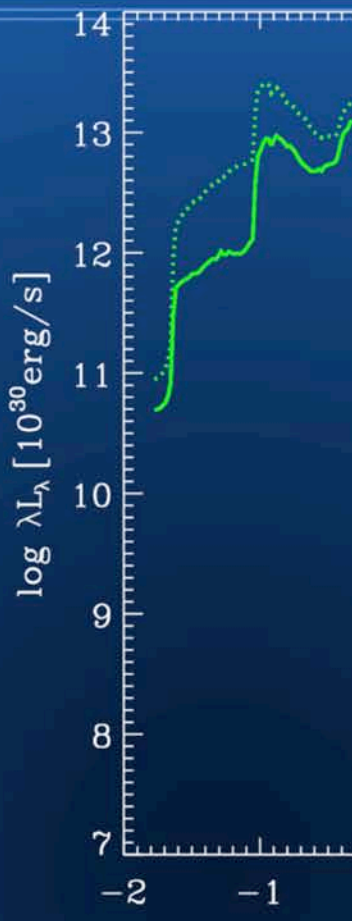
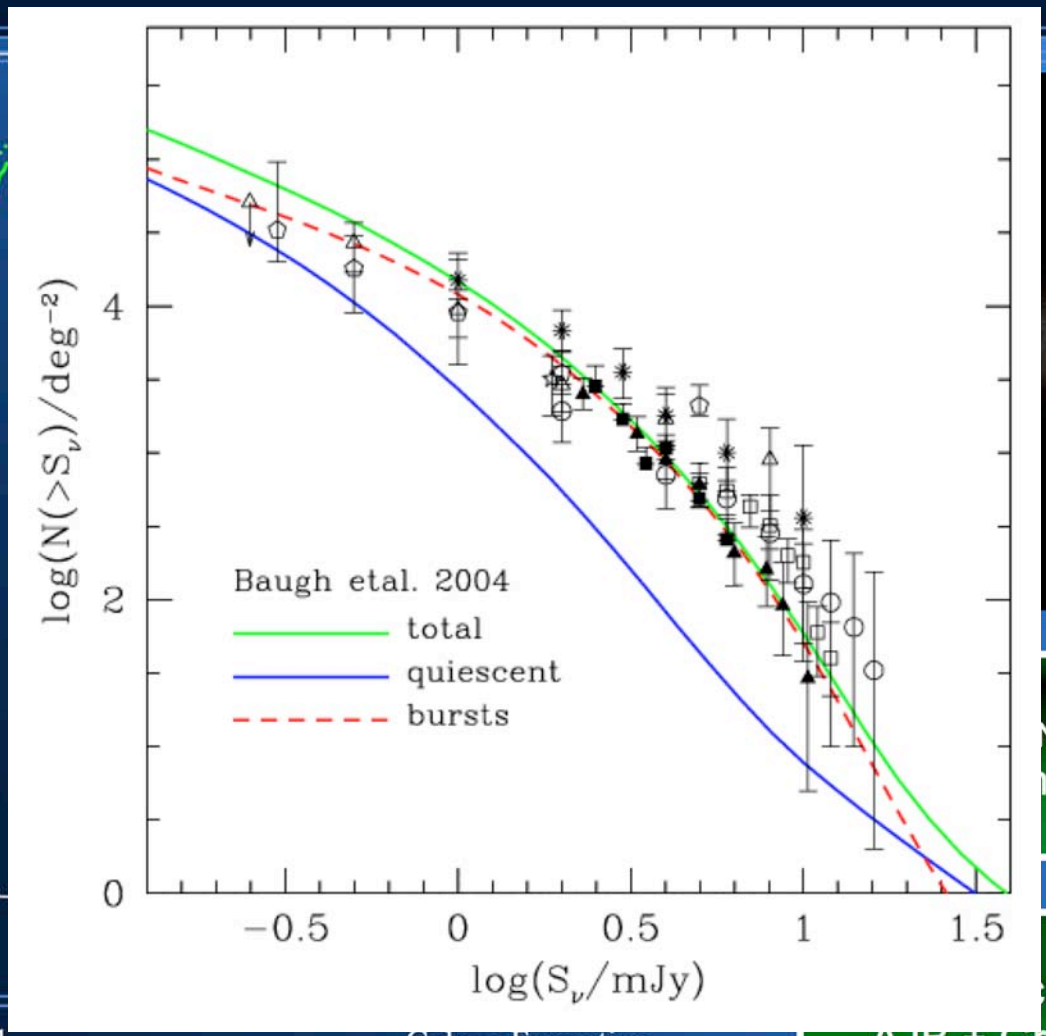
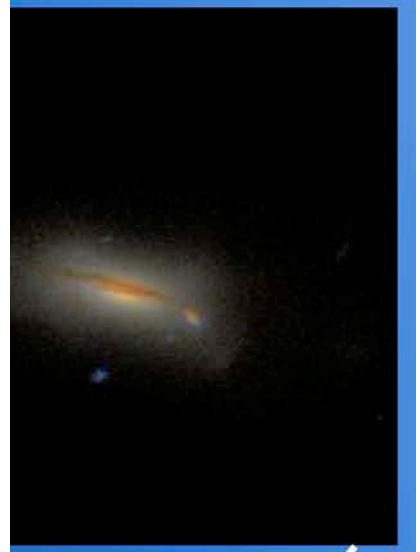






NRISE
sson

US + GRASIL
AJB + Granato, Silva

Computing Galaxy SEDs

- Solve galaxy formation; 
  - Generate star formation history for galaxy; Φ(t,Z)
  - Determine structure of galaxy
    - Disk? Bulge?
    - Sizes?
    - Gas content?
    - Metal/dust content?
- Get corresponding stellar SED;

$$\int_0^\infty \mathrm{d}Z \int_0^t \mathrm{d}t' \phi(t', Z) L_\nu(t - t', Z$$

Computing Galaxy SEDs

- Ray trace light through clumpy dust distribution
  - Compute absorption/scattering
  - Find equilibrium temperature for each grain type/size
  - Compute emission from dust
  - Ray trace dust emission through clumpy dust distribution
  - Iterate to find converged solution
- Compute emergent spectrum

Star Formation Laws

Lagos et al. (2010)

Parametric forms for the SF law

$$\psi = \frac{M_{\rm cold}}{\tau_\star}$$

What is ? ⟶ $\tau_\star = \frac{\tau_{\rm disk}}{\epsilon_\star} (V_{\rm disk}/V_0)^{\alpha_\star}$

Cole et al. (2000)

Free parameters

Star Formation Laws

Lagos et al. (2010)

Parametric forms for the SF law

$$\psi = \frac{M_{\rm cold}}{\tau_\star}$$

Robust predictions require modeling of the physics (as opposed to empirical rules)

What is ?

$$\tau_\star = \frac{\tau_{\rm disk}}{\epsilon_\star} \left(V_{\rm disk}/V_0\right)^{\alpha_\star}$$

Cole et al. (2000)

Free parameters

Obs./Theory Motivated Laws

(i) The Kennicutt-Schmidt law (KS) →

$$\Sigma_{\rm SFR} = A\Sigma_{\rm gas}^{1.4}$$

$$\Sigma_{\rm crit}$$

(ii) The Blitz & Rosolowski law (BR) →

$$\frac{\Sigma_{\rm H_2}}{\Sigma_{\rm HI}} = \left(\frac{P_{\rm ext}}{P_0}\right)^{\alpha}$$

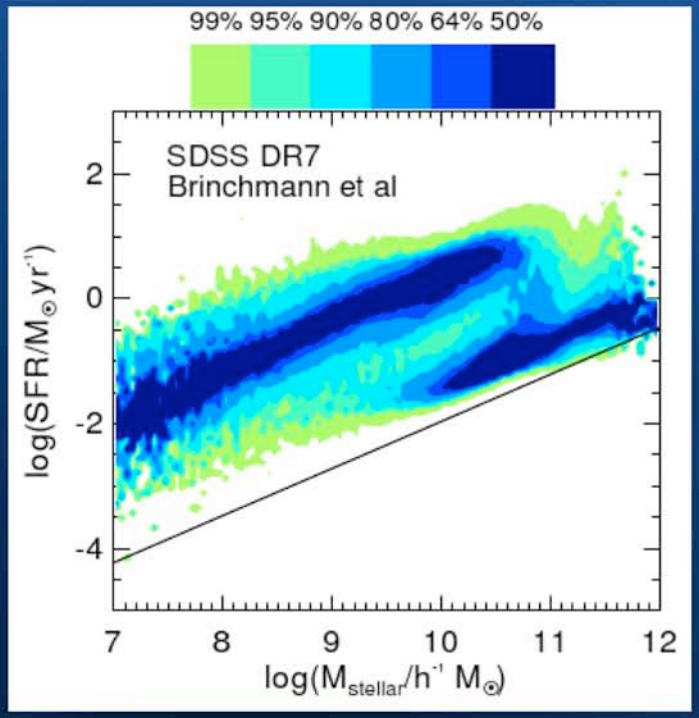
$$\Sigma_{\rm SFR} = \nu_{\rm SF}\Sigma_{\rm mol}$$

(iii) The Krumholz, McKee & Tumlinson theoretical law (KMT)

$$\Sigma_{\rm SFR} = \nu_{\rm SF}(\Sigma_{\rm gas}) f_{\rm mol}\Sigma_{\rm gas}$$

$$\nu_{\rm SF}(\Sigma_{\rm gas}) = \nu_{\rm SF}^{0} \begin{cases} (\Sigma_{\rm gas}/\Sigma_0)^{-1/3}, & \text{if } \Sigma_{\rm gas}/\Sigma_0 < 1 \\ (\Sigma_{\rm gas}/\Sigma_0)^{1/3}, & \text{if } \Sigma_{\rm gas}/\Sigma_0 > 1 \end{cases}$$

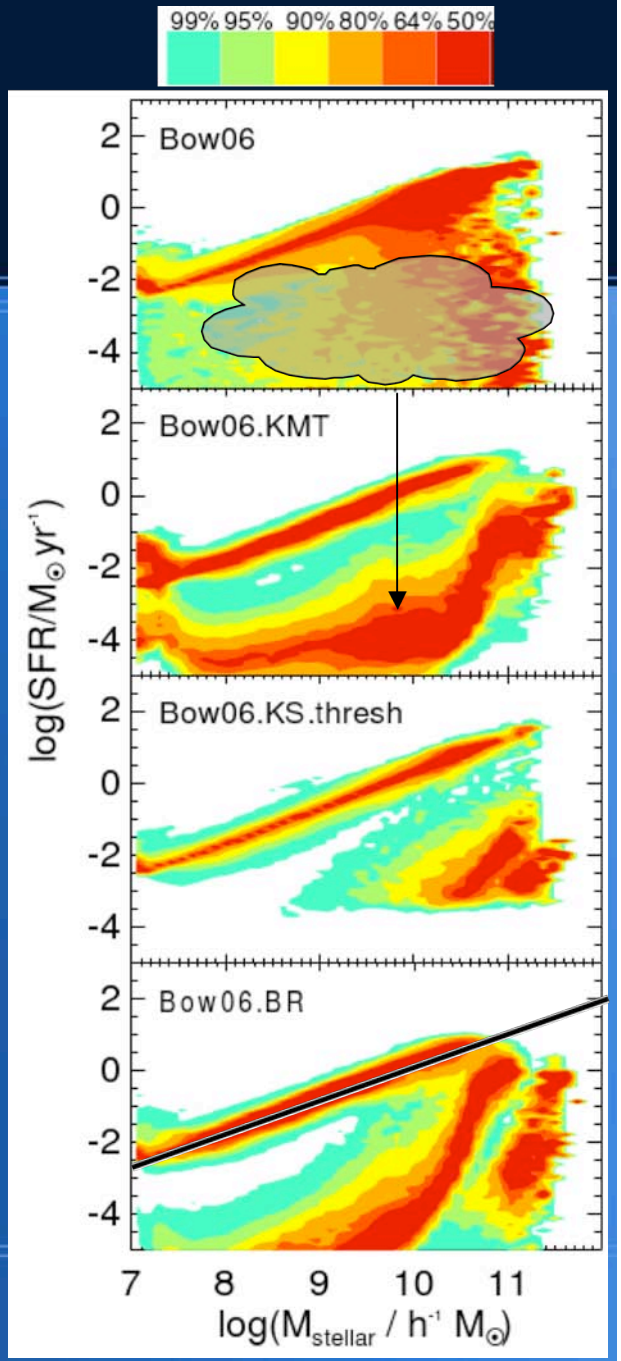
SF activity in galaxies: SFR-M_{star} plane



→ ***SFR sensitivity limit***
→ ***r-band magnitude cut***

Passive galaxies greatly affected **Shape of the passive sequence → form of the SF law**

Slope shaped by accretion/outflow balance



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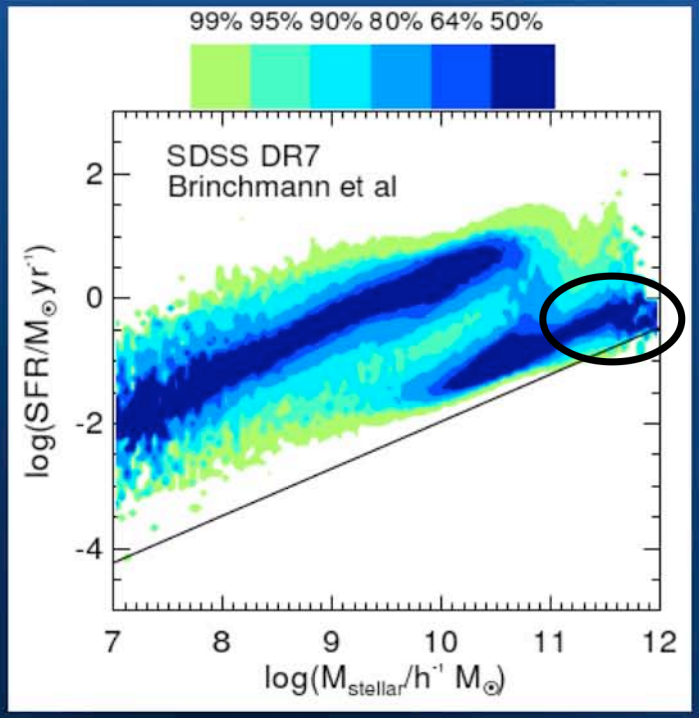

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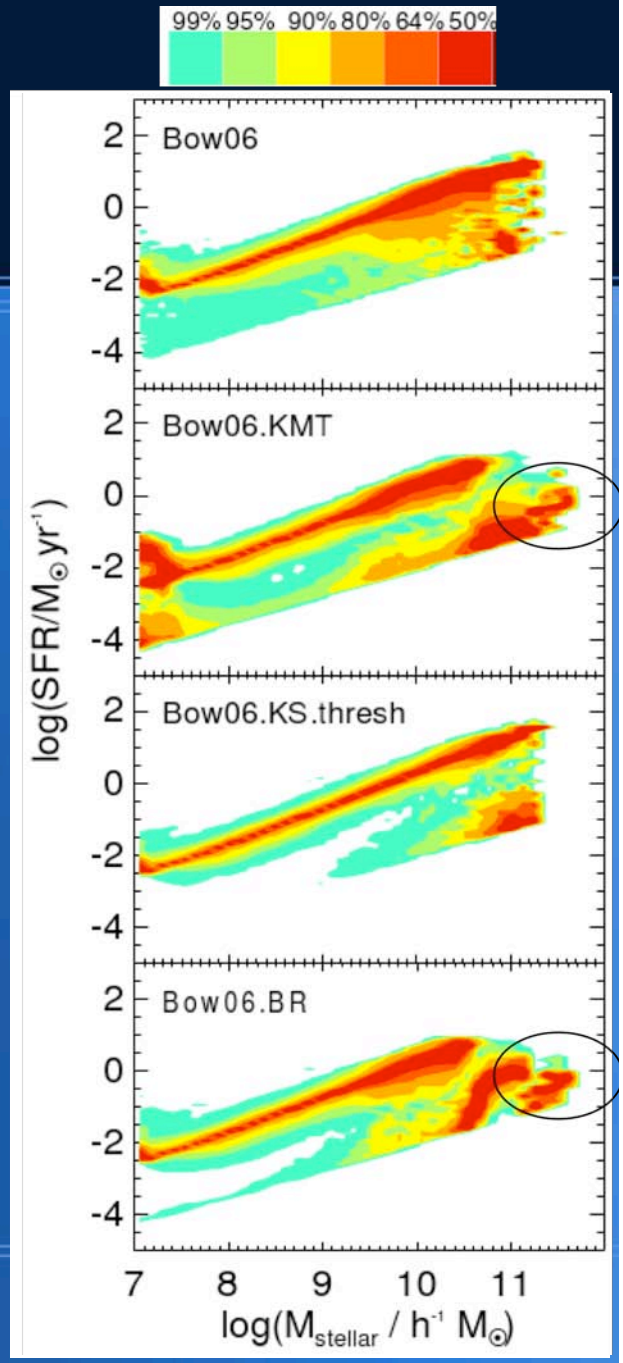
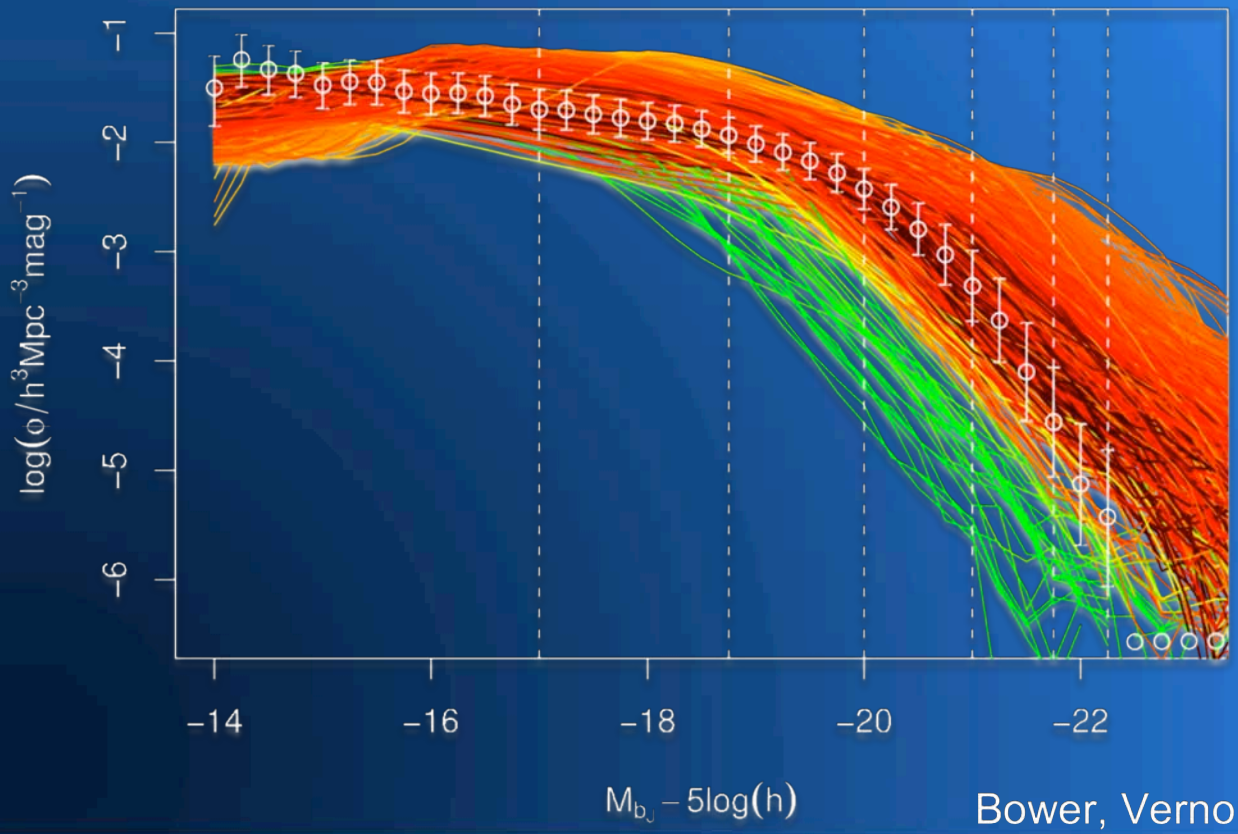


Constraining Model Parameters

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



Bower, Vernon, AJB et al. (2010

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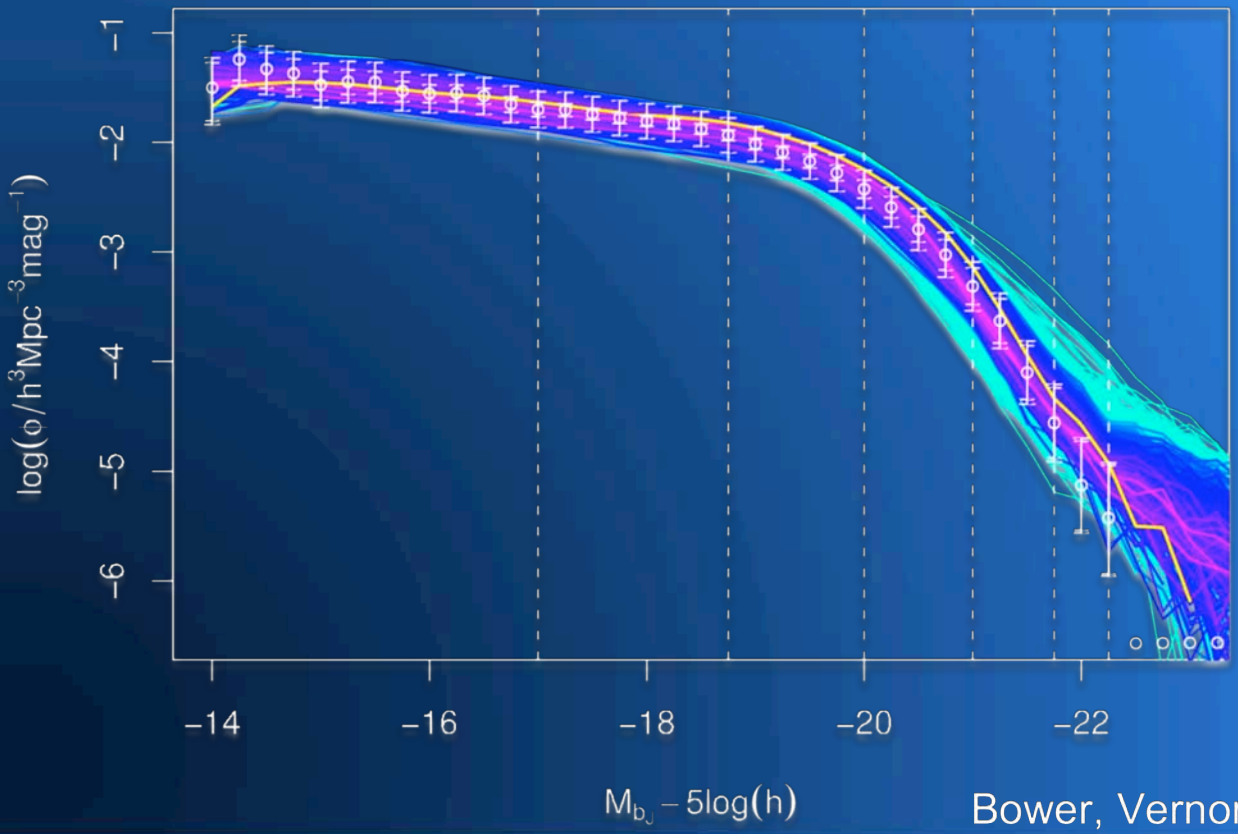
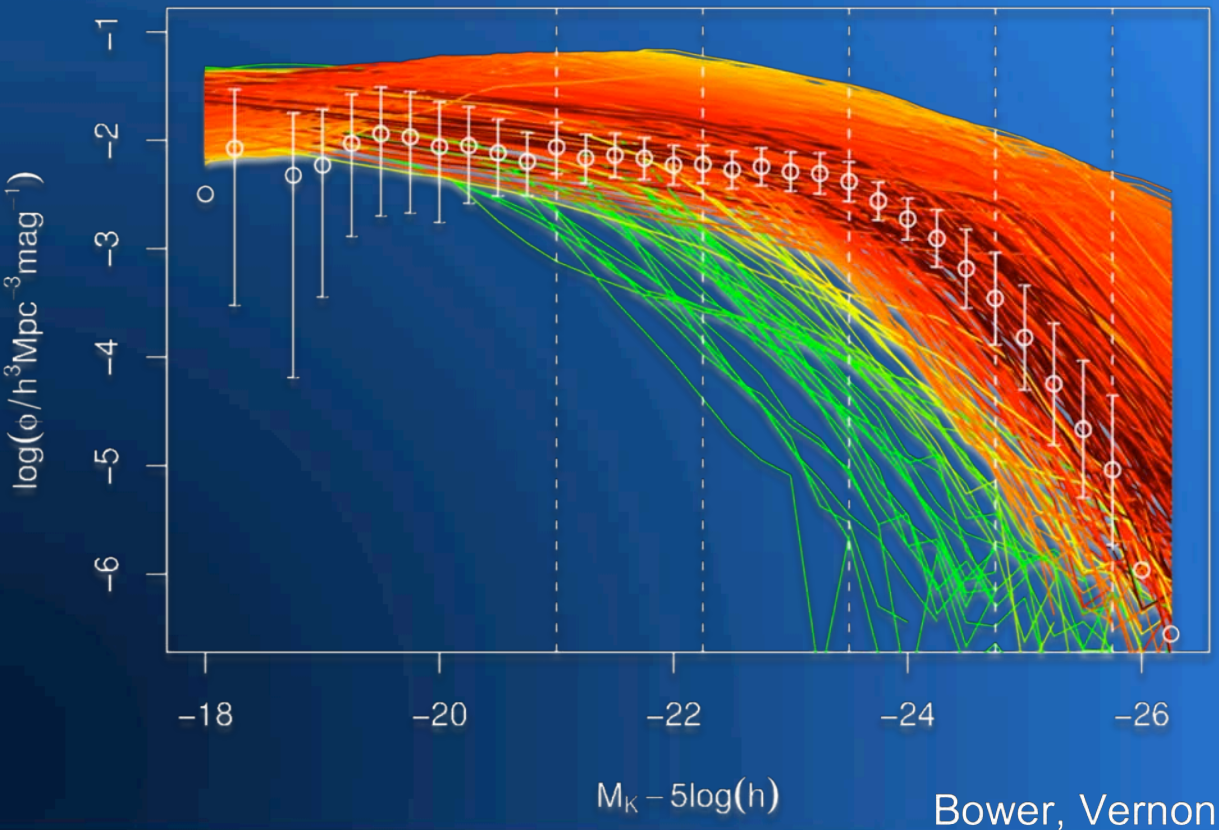


Bower, Vernon, AJB et al. (2010

Constraining Model Parameters

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



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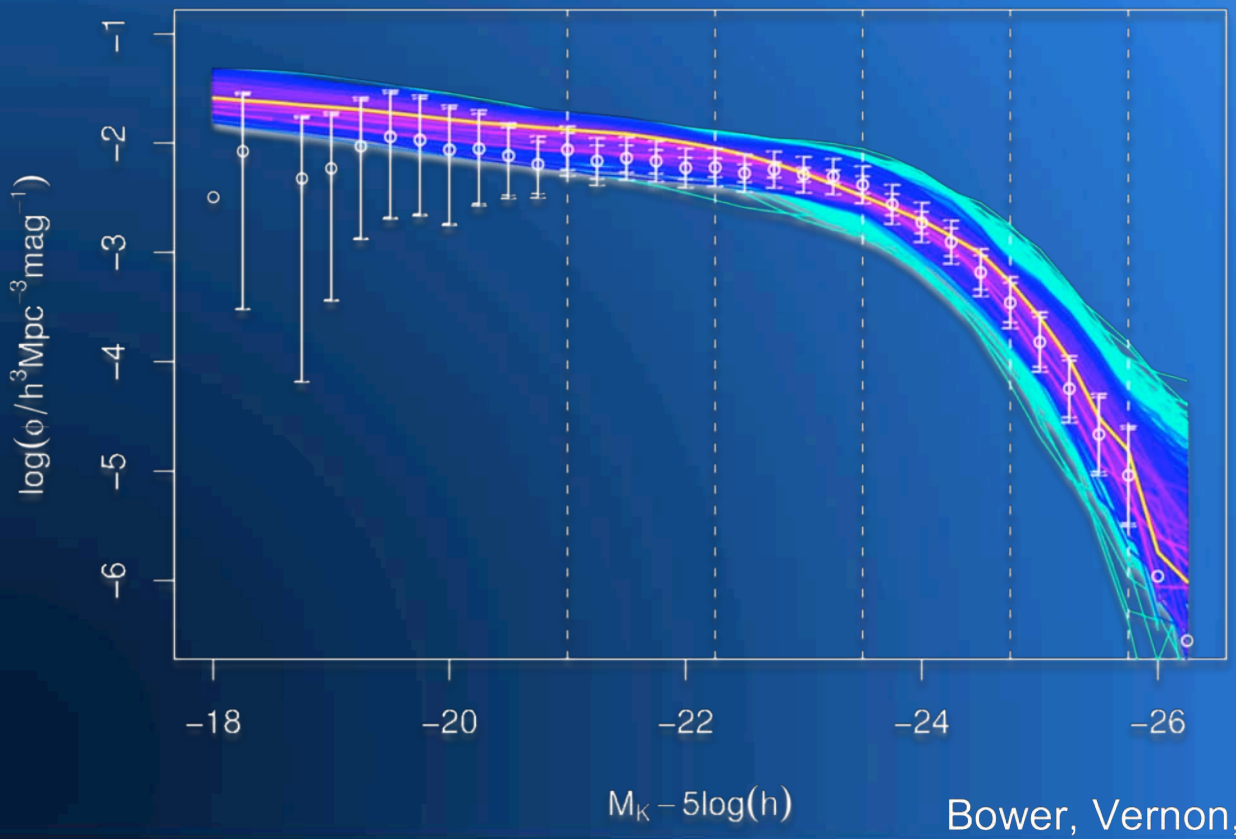

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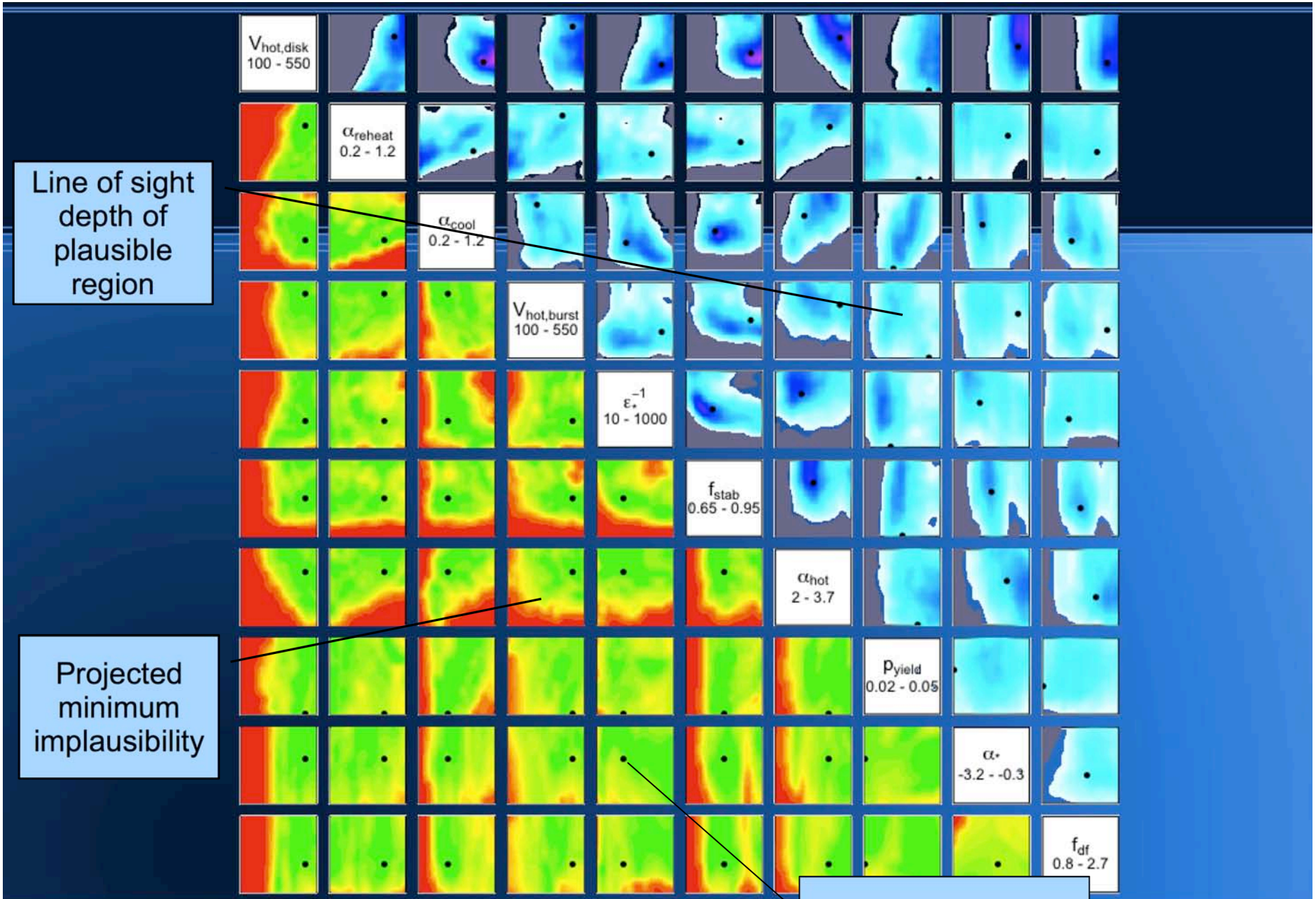
Line of sight depth of plausible region
Projected minimum implausibility
$V_{hot,disk}$ 100 - 550
α_{reheat} 0.2 - 1.2
α_{cool} 0.2 - 1.2
$V_{hot,burst}$ 100 - 550
ϵ_*^{-1} 10 - 1000
f_{stab} 0.65 - 0.95
α_{hot} 2 - 3.7
p_{yield} 0.02 - 0.05
α_* -3.2 - -0.3
f_{df} 0.8 - 2.7
Bower et al. (2006)

Summary

- Detailed calculations of galaxy SEDs exist, but many uncertainties remain.
- Physically motivated algorithms allow for robust predictions (or, at least, falsifiable theory).
- Yes, there are many parameters. But you can constrain them.
- GALACTICUS: complete semi-analytic model, easily modifiable.