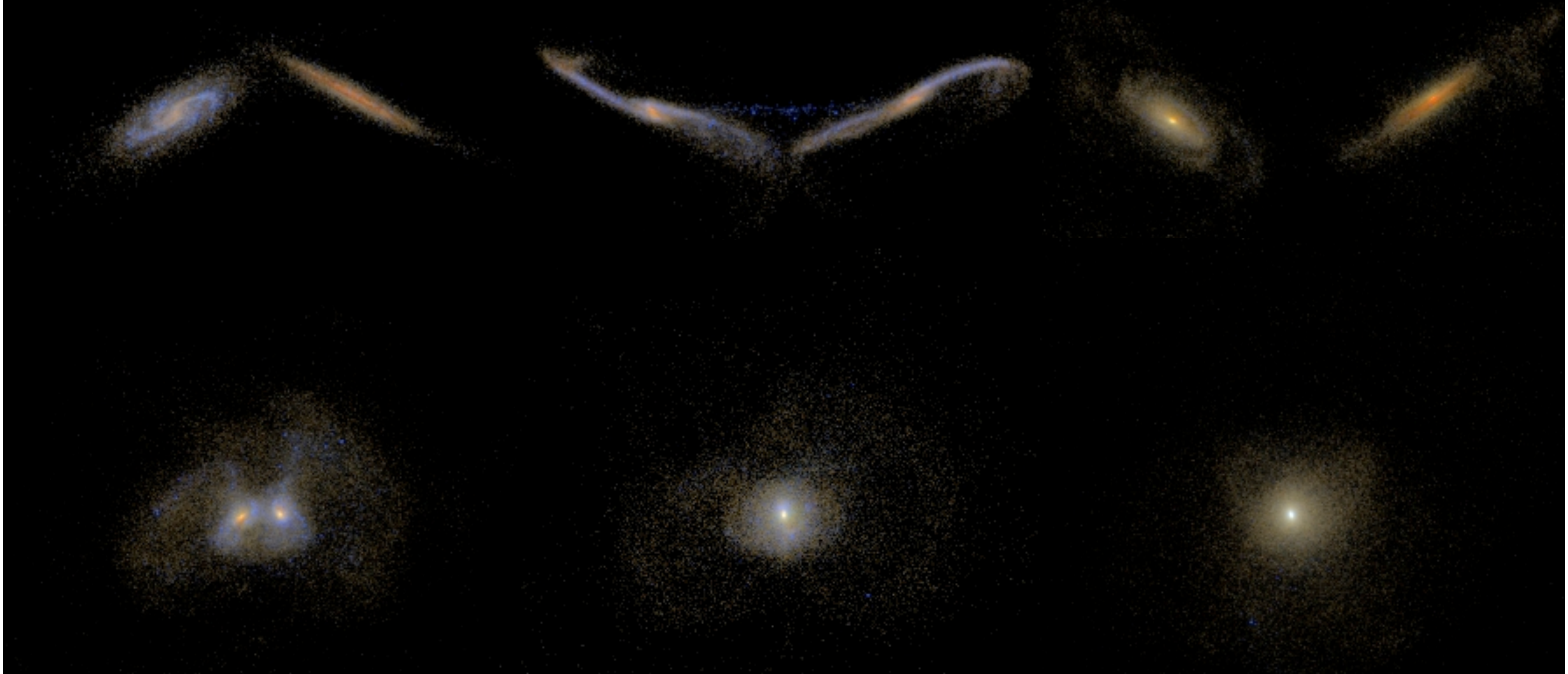
Directly comparing theoretical models with observations of high-z dusty galaxies via dust radiative transfer



Chris Hayward, CfA (chayward@cfa.harvard.edu)
P. Jonsson, D. Kereš, D. Narayanan, P. Hopkins, T. J. Cox, L. Hernquist
From Dust to Galaxies, IAP, 1 July 2011

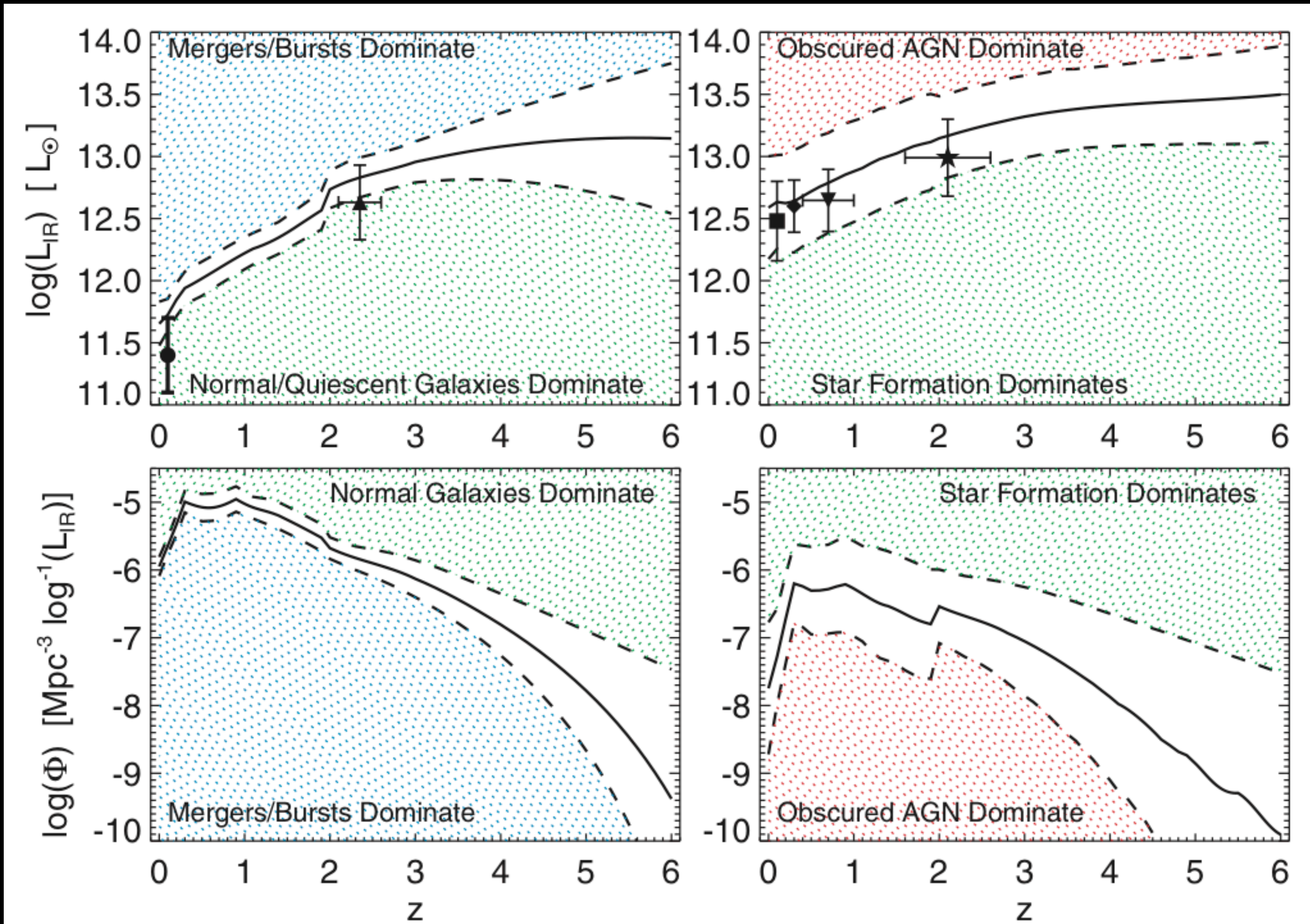
Outline

- Introduction
- Simulating dusty galaxies
- A heterogeneous population?
- How well do modified blackbody methods work?

Sub-millimeter galaxies (SMGs)

- Population of optically faint sources detected in sub-mm (fiducial cut $S_{850} > \sim 5$ mJy)
- 99% of L is emitted in IR
- Powered by SF rather than AGN
- $L_{IR} \sim 10^{12}$ - few x 10^{13} L_{sun} ⇒ SFR ~ few x10^{2}-10^{4} M_{sun}/yr
- Median z ~ 2.2, σ ~ 1.2 ⇒ sub-mm traces ~ 200-400 μm emission (longward of peak)

What powers high-z ULIRGs?



Hopkins, Younger, Hayward+10

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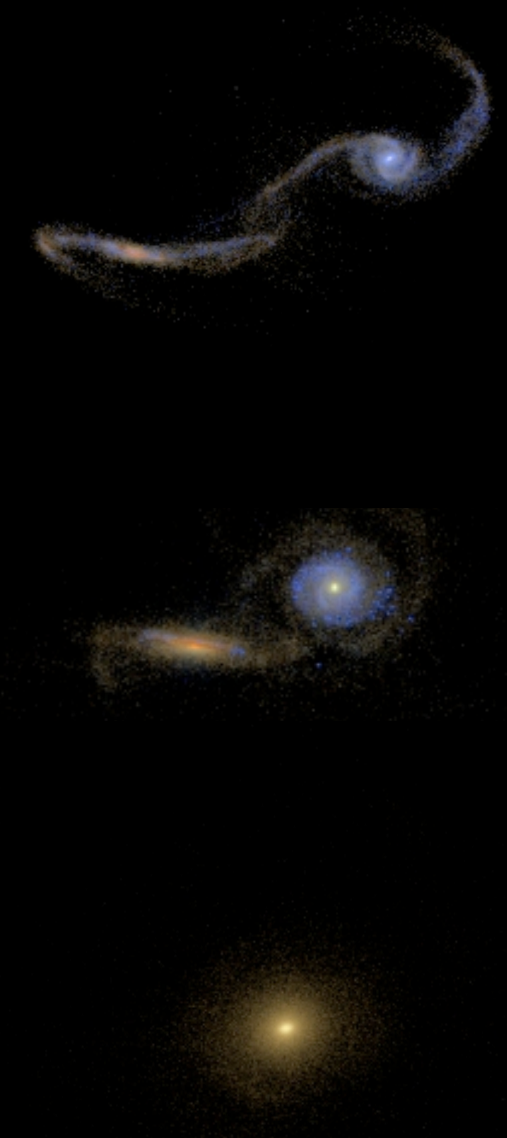
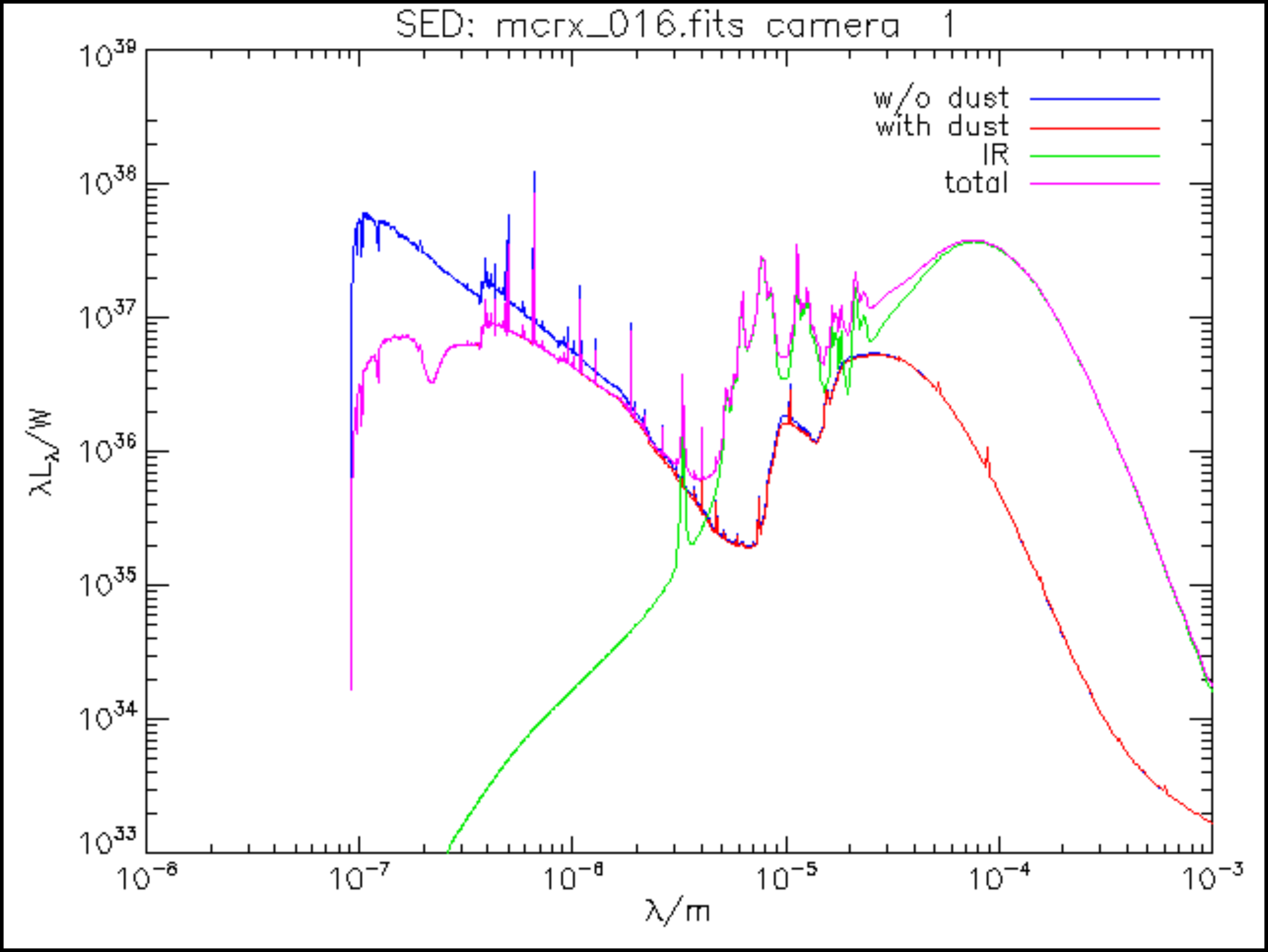
GADGET simulations

- Large suite of major & minor mergers, isolated disks; non-cosmological
- GADGET-2 N-body/SPH (Springel 05)
- Schmidt-Kennicutt SF recipe
- Two-phase ISM of Springel & Hernquist (03)
- Radiative heating & cooling (Katz+96)
- BH growth & feedback (Springel+05)



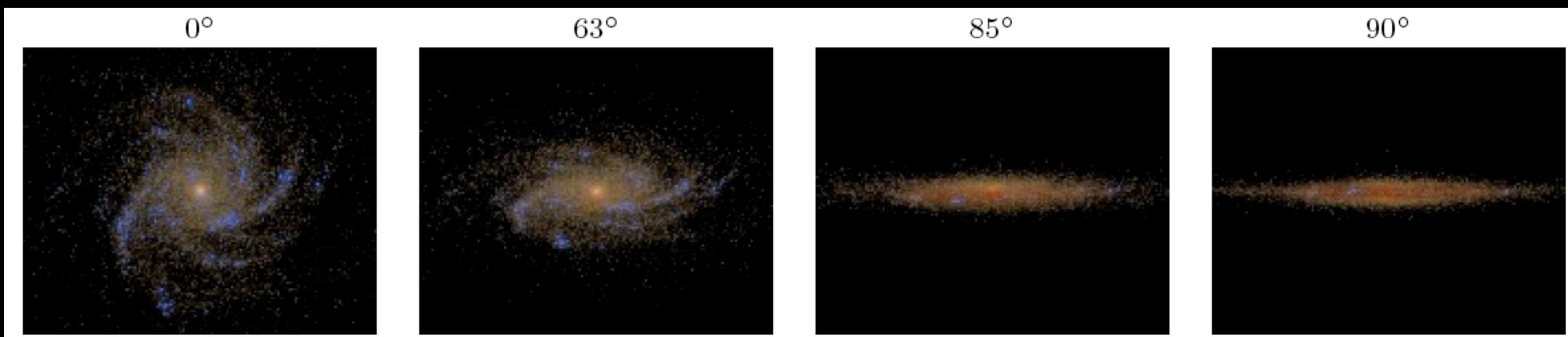
P.Jonsson, G. Novack, & J. Primack, UC Santa Cruz, 2008

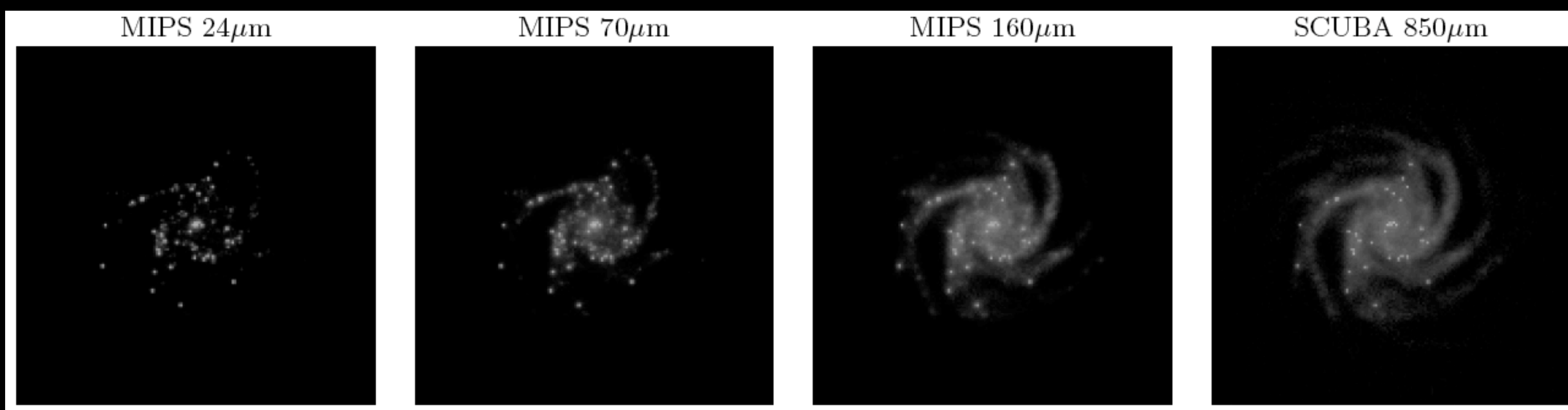
Sunrise outputs



Sunrise outputs

Broadband photometry & images



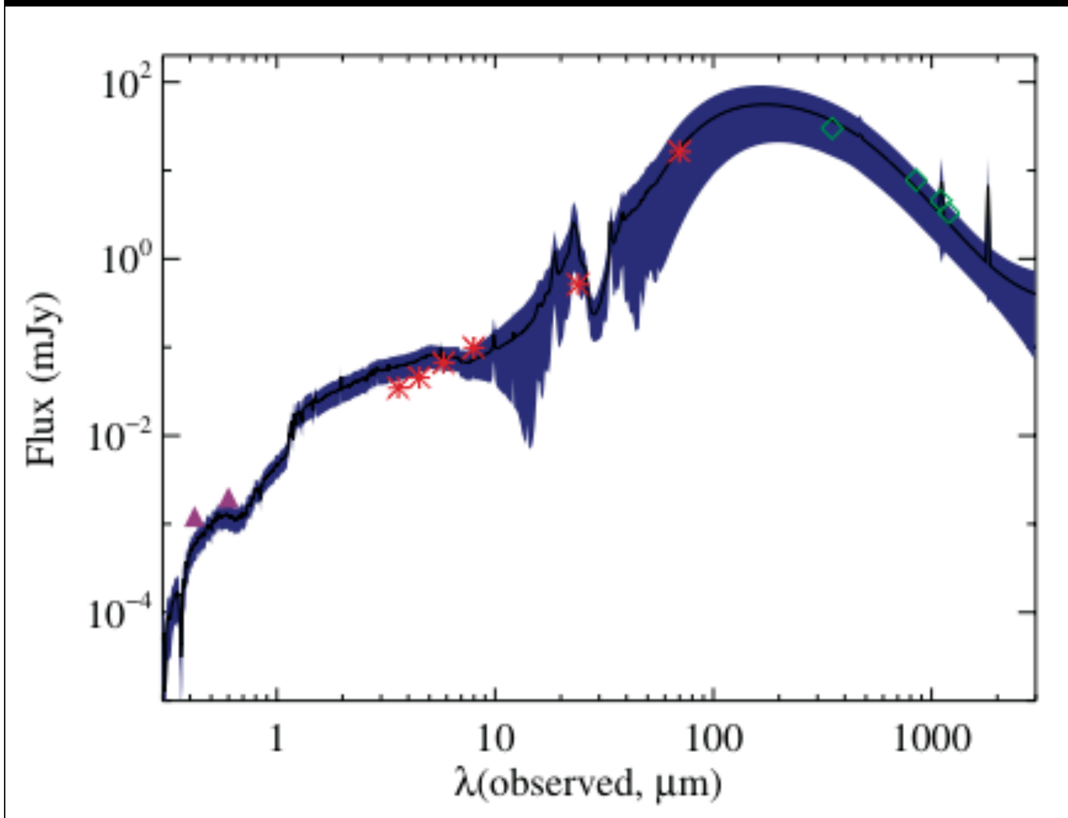


Jonsson, Groves, & Cox 10

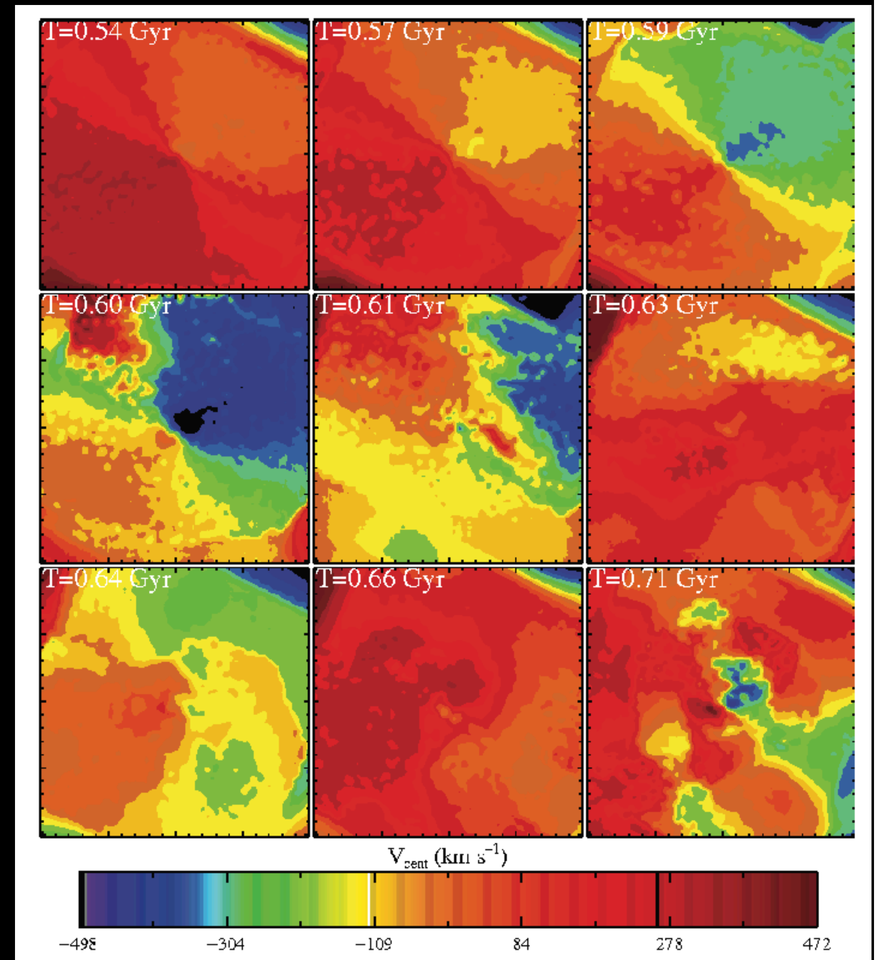
Sunrise details

- 3-D Monte Carlo dust RT code *Sunrise* (Jonsson 06; Jonsson, Groves, & Cox 2010)
- Stellar SEDs from *Starburst99* (Leitherer+99)
- Optionally HII region + PDR models from Groves+08
- AGN template of Hopkins+07
- Kroupa IMF
- WD01 + DL07 MW dust model, dust-to-metals = 0.4
- Solves for dust T iteratively (Juvela 05) to properly treat dust self-absorption -- key for high optical depths encountered in SMGs

How can we make an SMG?



Narayanan, Hayward+10



Narayanan, Cox, Hayward+10

Massive, gas-rich, major mergers can account for full range of sub-mm fluxes, typical SED, CO properties

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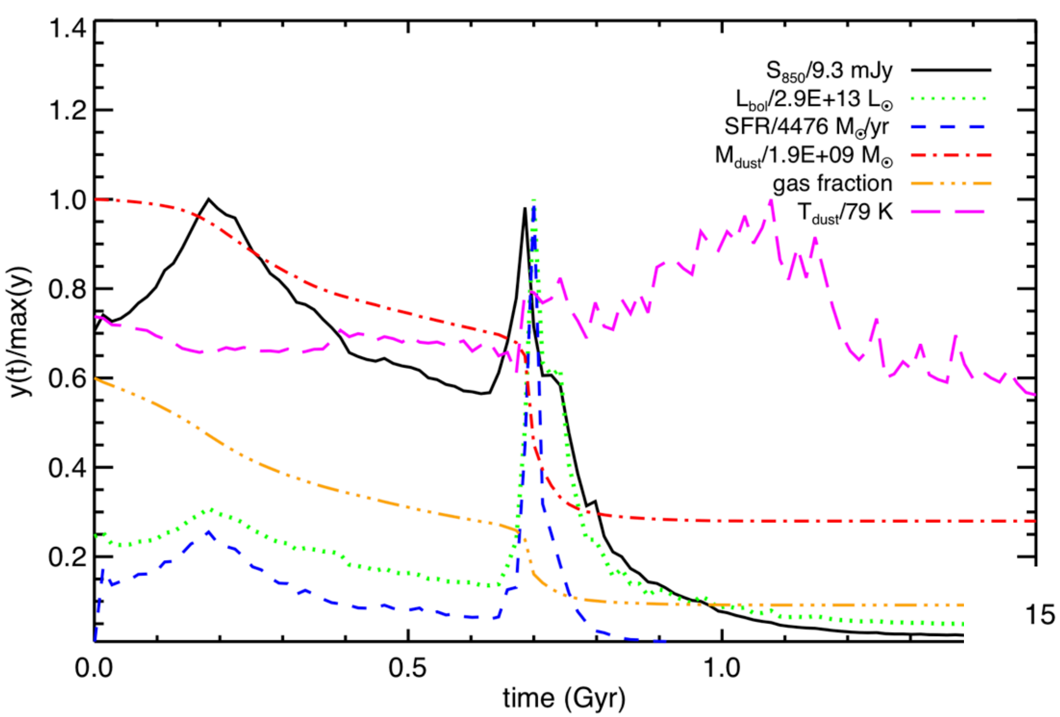
Merger evolution



Merger of two z ~ 2 disks, each w/ M_{halo} = 9e12, M_b = 4e11; initially 60% gas

Two SF regimes:

1. Quiescent disk (during infall)
2. Merger-driven burst

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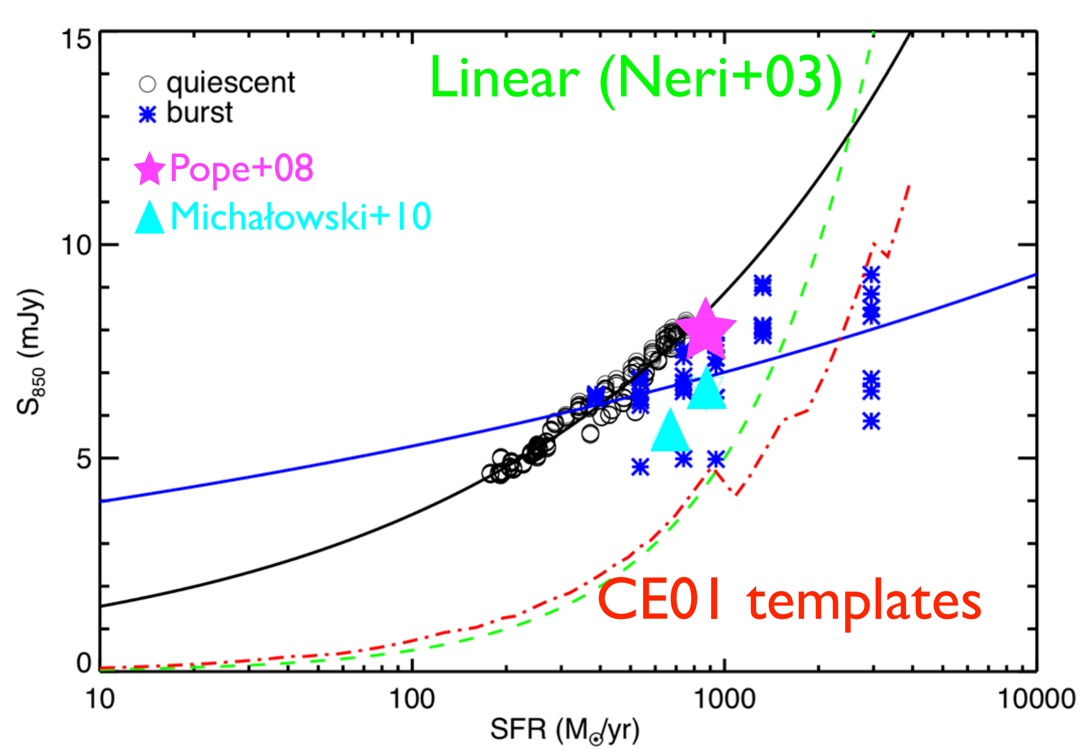
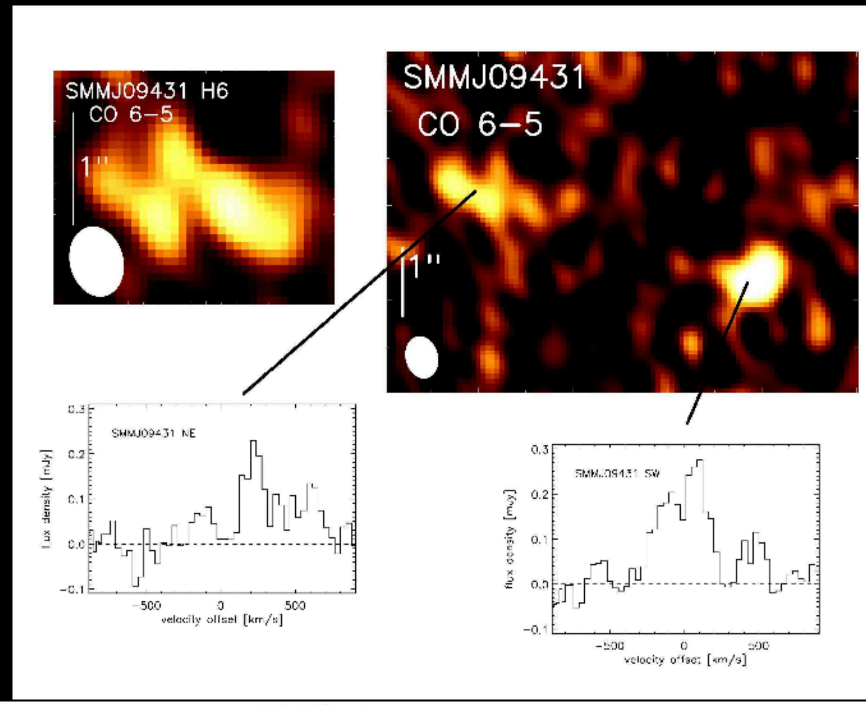
Bursts inefficient at boosting submm flux (~15x in SFR but <2x in S_{850})

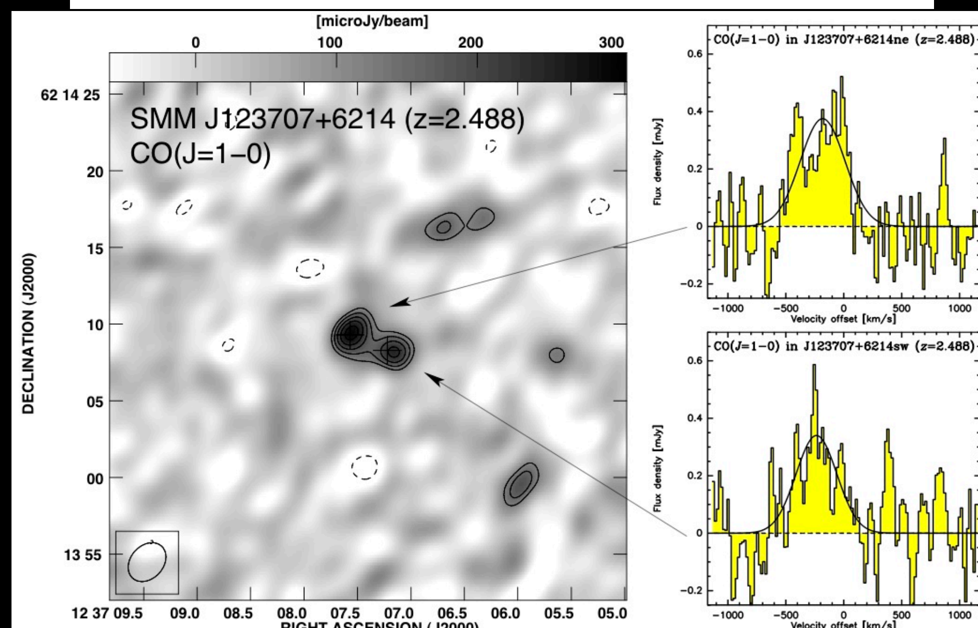


SMG bimodality

- SCUBA/AzTEC beams ~15" (~130 kpc at z = 2) ⇒ easy to fit two disks in beam
- Very efficient way to boost submm flux
- Early-stage merger; no strong interactions yet
- SMGs are a mix of merger-driven starbursts (near coalescence) and blended galaxy pairs (early-stage)

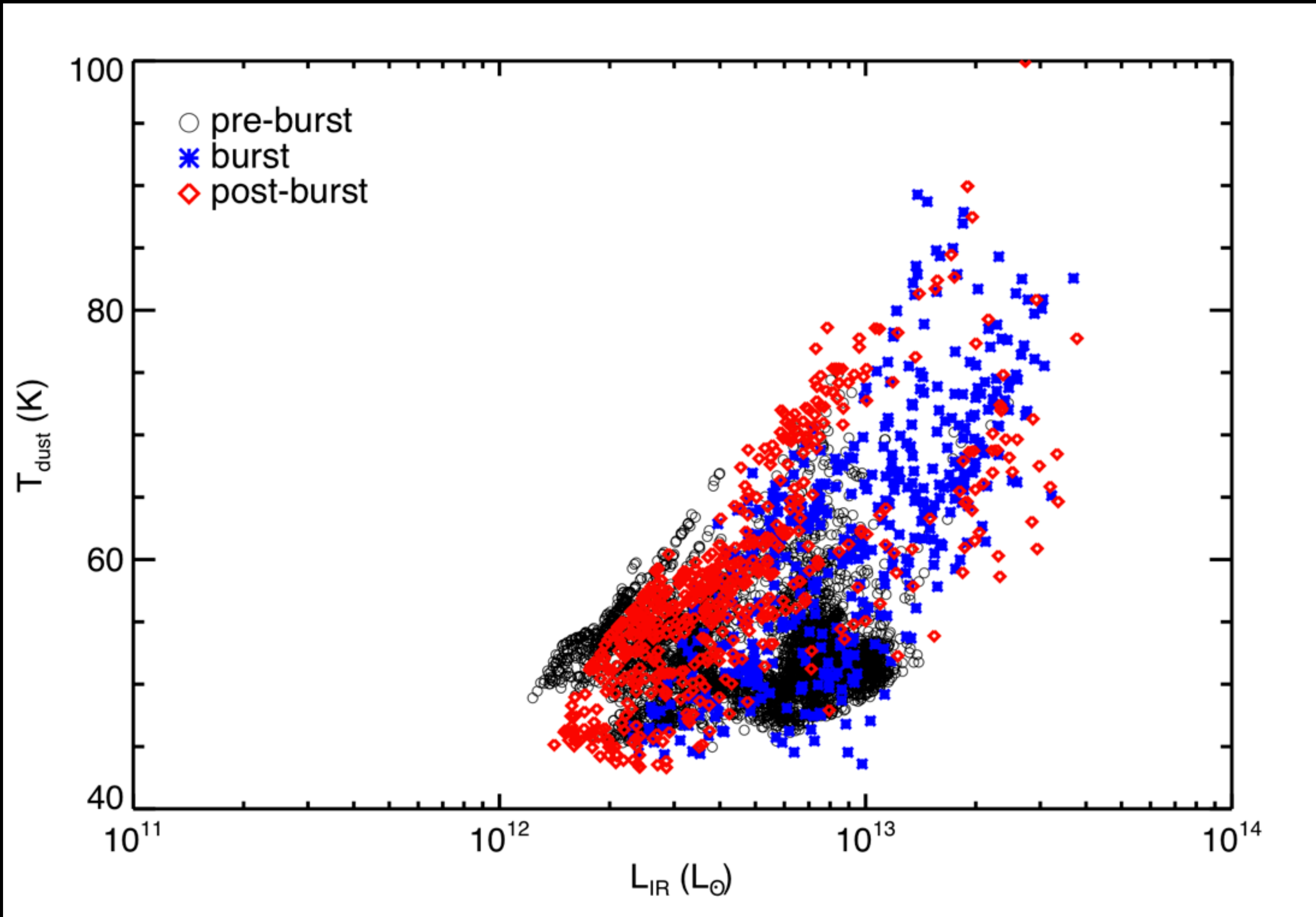


Engel+10



Riechers+11

Observational tests - one example



Hayward+, in prep

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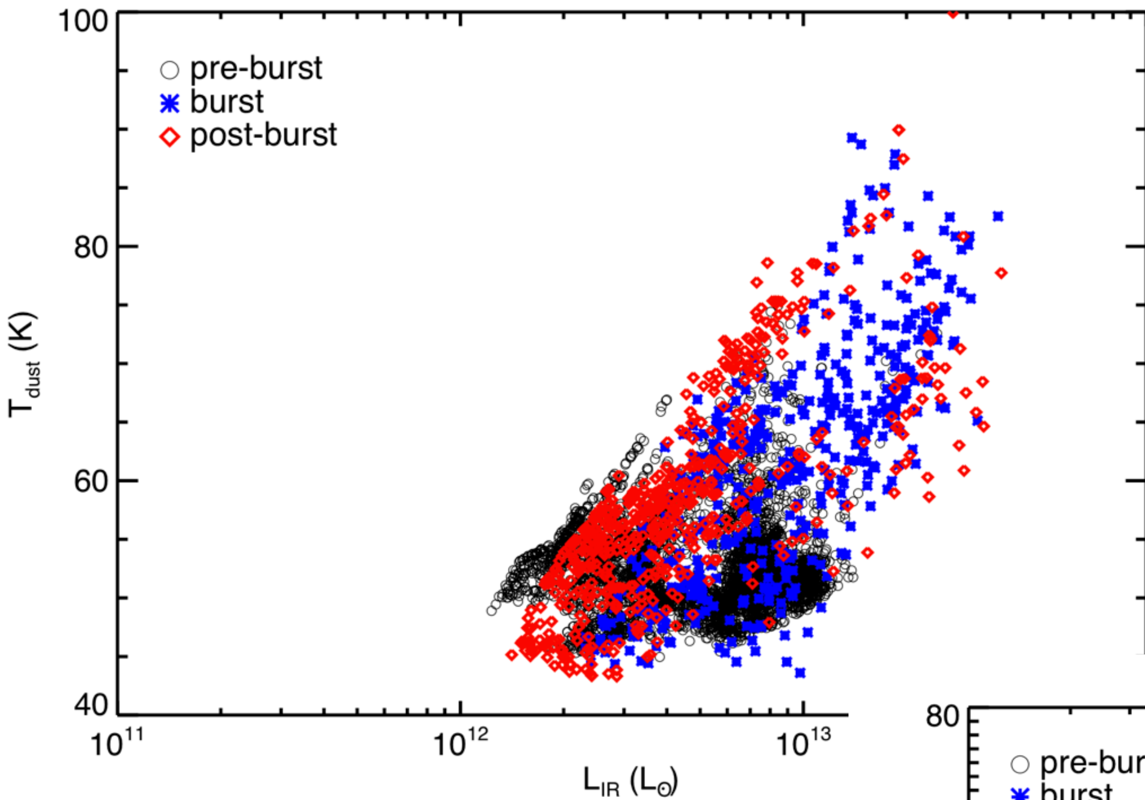
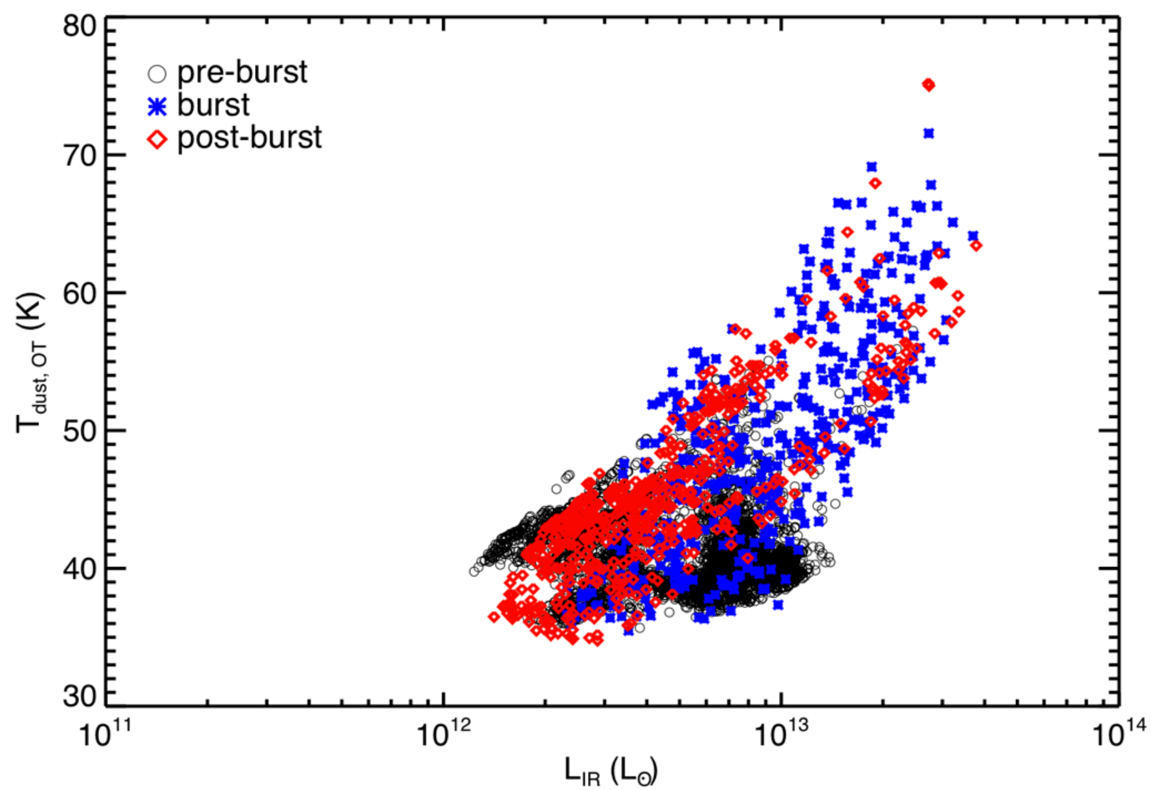
Fitting galaxy SEDs with modified BBs

- IR SEDs often fit with modified BBs (Gordon's talk for great detail)
- Usually assume optical thinness: $S_\nu \propto \nu^\beta B_\nu(T_d)$
- But can use full form instead: $S_\nu \propto (1 - e^{-(\nu/\nu_0)^\beta}) B_\nu(T_d)$
- Difficult to physically interpret T_d and β: even for MCs, physical T distribution & noise make T_d and β degenerate (e.g., Shetty+09ab, Helou talk -- but see also Bernard, Paradis talk); values depend on fitting method
- Our sims have intrinsic β = 2.0 but often better fit by β closer to 1
- Variations in τ for different LOS also problematic
- Should be worse for "blob astronomy"
- Fitting mod BB to galaxy SEDs should be considered a simple way to parameterize SEDs but not taken too literally!

"Dust temp"



Hayward+, in prep



Assuming optical thinness → systematically lower "dust T"

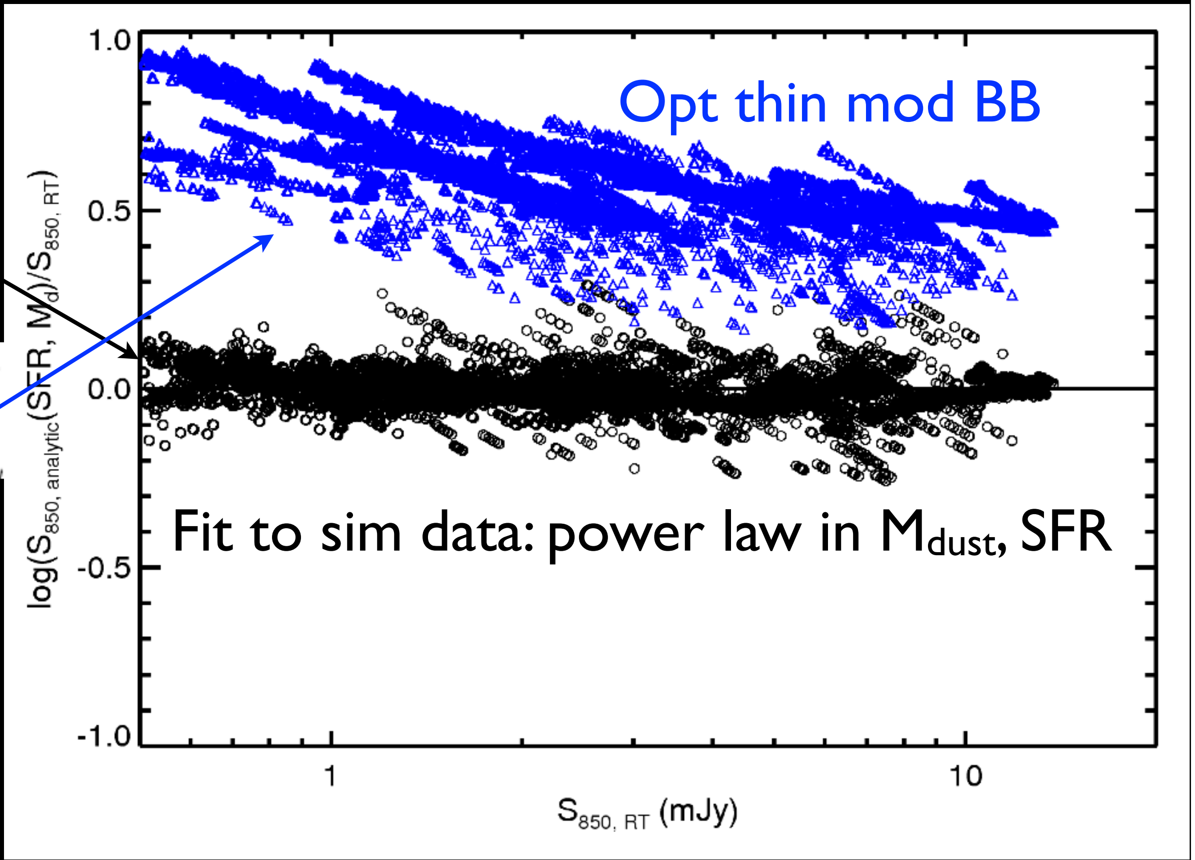
Don't assume optical thinness

Simulation:

$$S_{850} = 0.69\ \mathrm{mJy}\left(\frac{\mathrm{SFR}}{100\ M_\odot\ \mathrm{yr}^{-1}}\right)^{0.38}\left(\frac{M_d}{10^8 M_\odot}\right)^{0.63}$$

Opt-thin, single-T mod BB:

$$S_{850} = 1.1\ \mathrm{mJy}\left(\frac{\mathrm{SFR}}{100\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/6}\left(\frac{M_d}{10^8 M_\odot}\right)^{5/6}$$



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OT, single-T mod BB systematically overpredicts observed submm flux

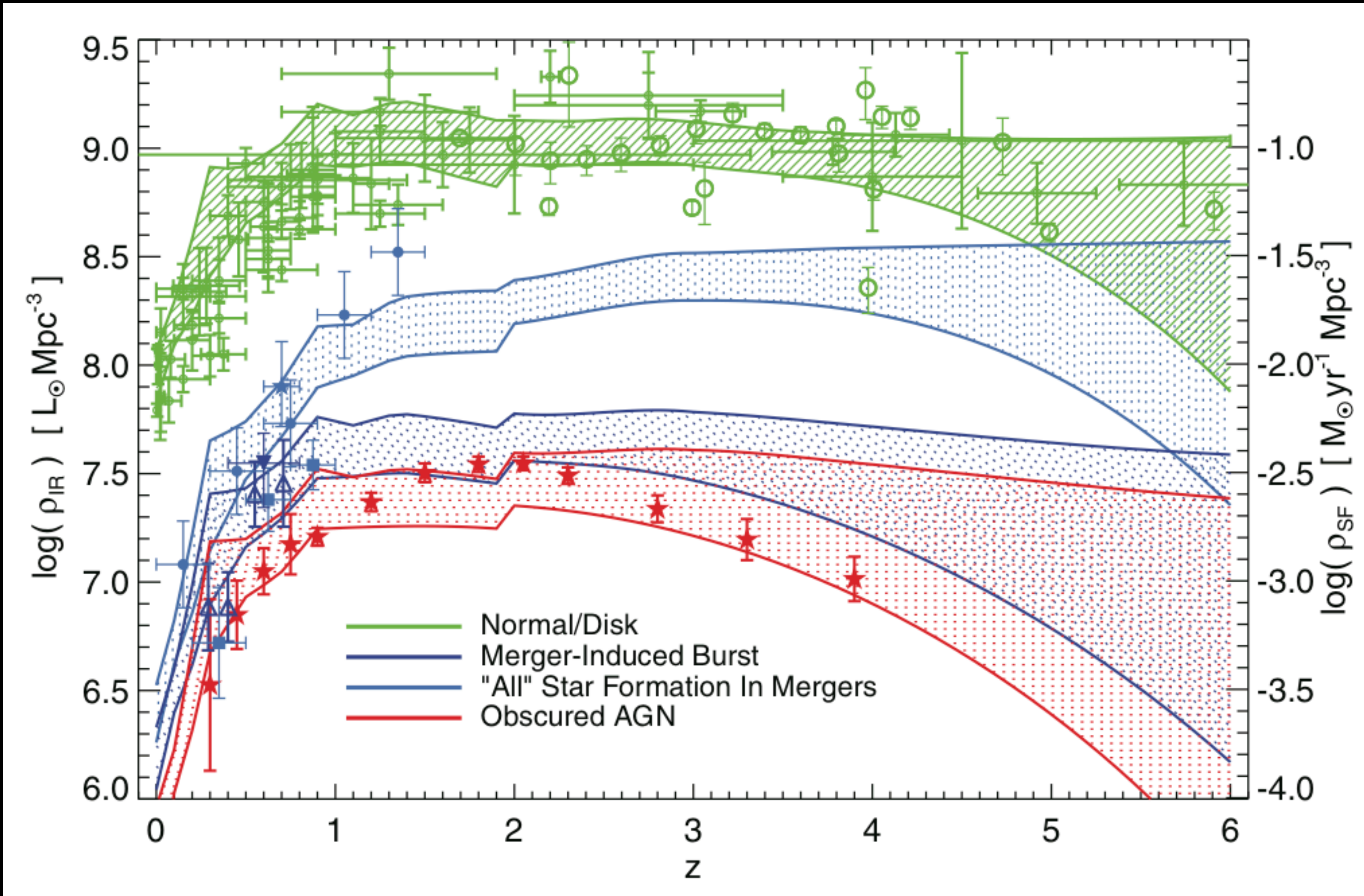
Galaxies are not single T & optically thin (obvious but surprisingly common implicit model!!!)

Summary

- Merger SMGs fall into two classes:
  1. Late-stage merger: starburst induced at coalescence
  2. Early-stage merger: two progenitor disks blended into one submm source ("galaxy pair SMGs")
- Unlike local ULIRGs, SMGs are a mix of quiescent and bursting sources -- clear observational tests of this
- For both observed and simulated high-z ULIRGs a single-T optically-thin modified blackbody provides a qualitatively inferior fit; don't ignore optical depths and use more sophisticated methods (DL07, Draine+07, Kovács+10...) if you have enough data to do so!

Why I'm wrong (future work)

- Don't actually resolve ISM; should/will move beyond simple effective EOS
- Move beyond crude model for SF; tie to molecular gas?
- Dust production: simplicity of current model good, but should/will implement model for dust production/destruction
- ...



Hopkins, Younger, CCH+10

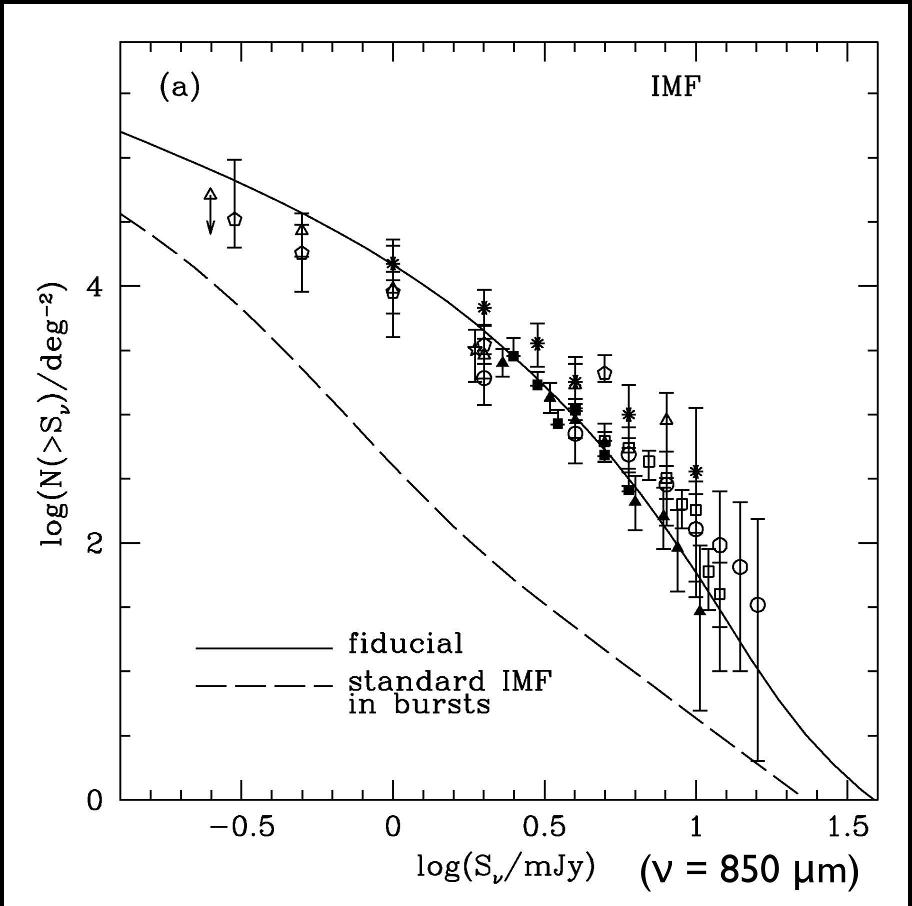
A flat initial mass function?

- Baugh+05 models: GALFORM (Cole +00) SAM + GRASIL (Silva+98)
- Under-predicts by 20-60x when using Kennicutt IMF
- Modified SAM matches; key change is use of flat IMF in bursts (more L & M_d/M_{sun} formed):

$$dN/d\ln m = \text{const},$$

$$0.15 < m < 125 M_\odot$$

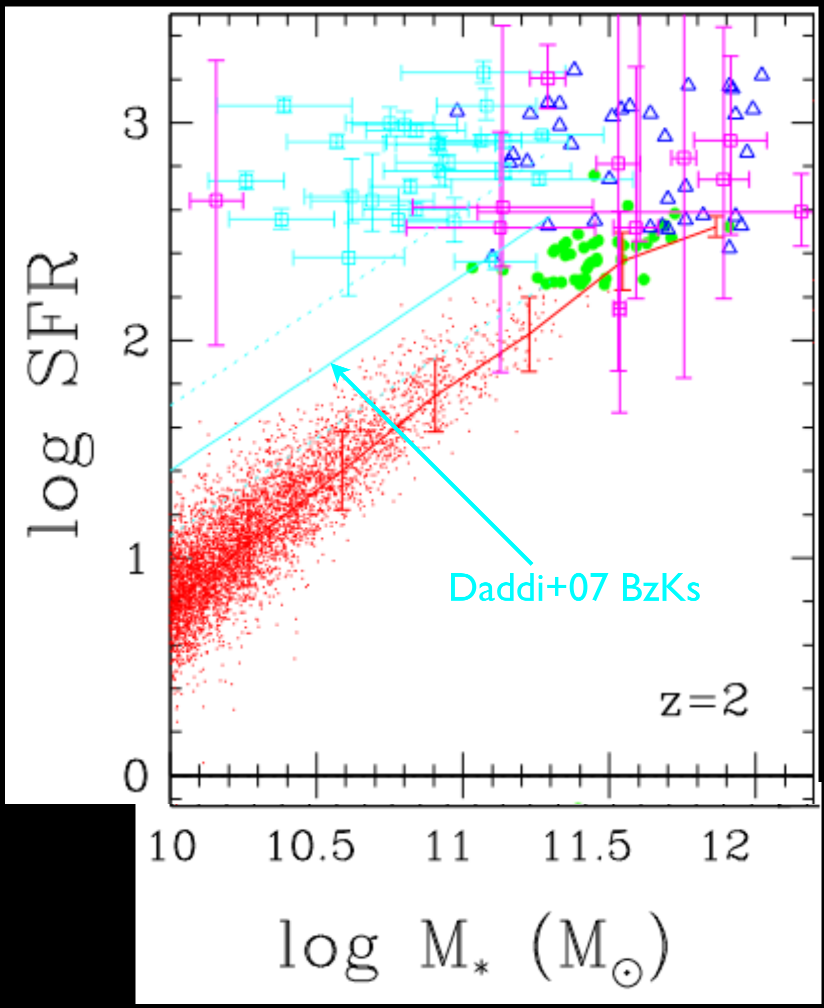
- See also Davé et al.'s cosmological sims



Baugh+05

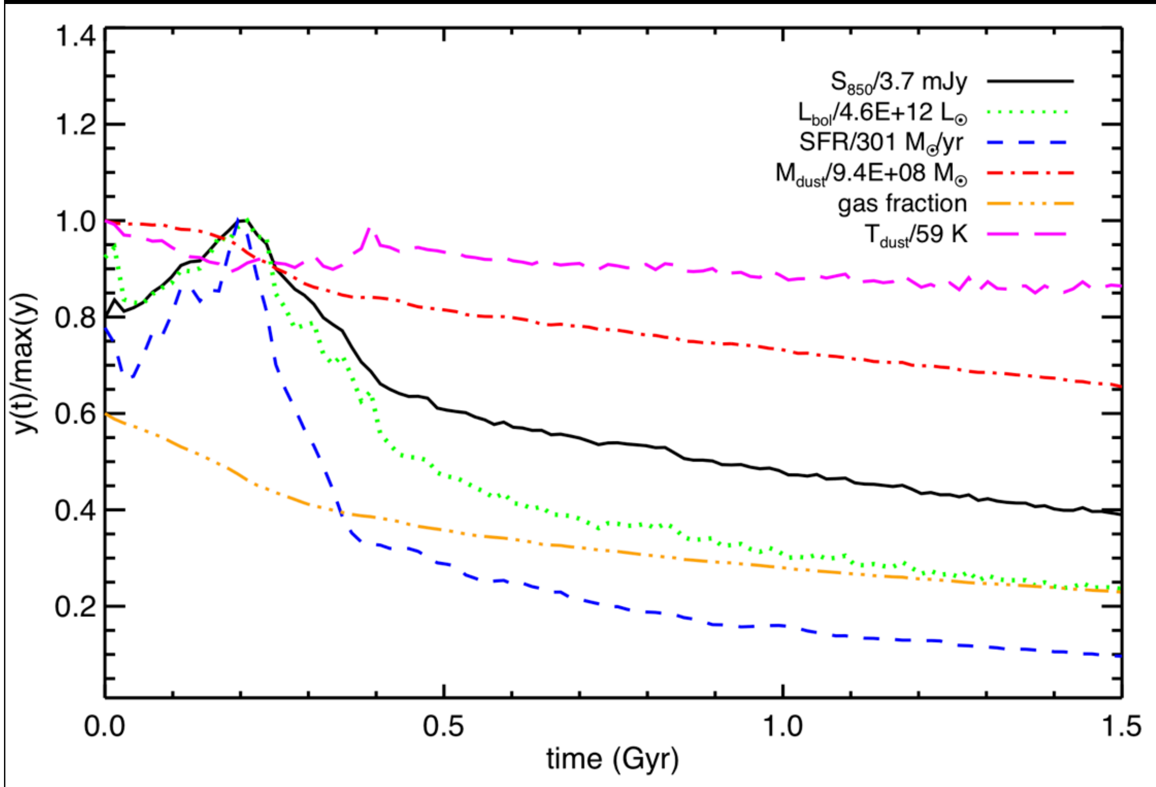
Or "bottom-light"?

- Davé+10 map SMGs to most star-forming galaxies in a cosmological simulation
- Simulated objects consistent w/ many observed properties, but SFR ~3x < inferred SFR
- SMGs' high L_{IR} confirmed by Herschel (Magnelli+10)
- AGN? Probably not (Alexander, Pope, others)
- Bottom-light IMF could explain (more L/M_{sun} formed → lower SFR)



Davé+10

Isolated disk evolution



CCH+11

Isolated disk w/ M_{halo} = 9e12, M_b = 4e11; initially 60% gas

Submm flux traces SFR well

Hard to produce classical SMG with even with such a massive, gas-rich disk