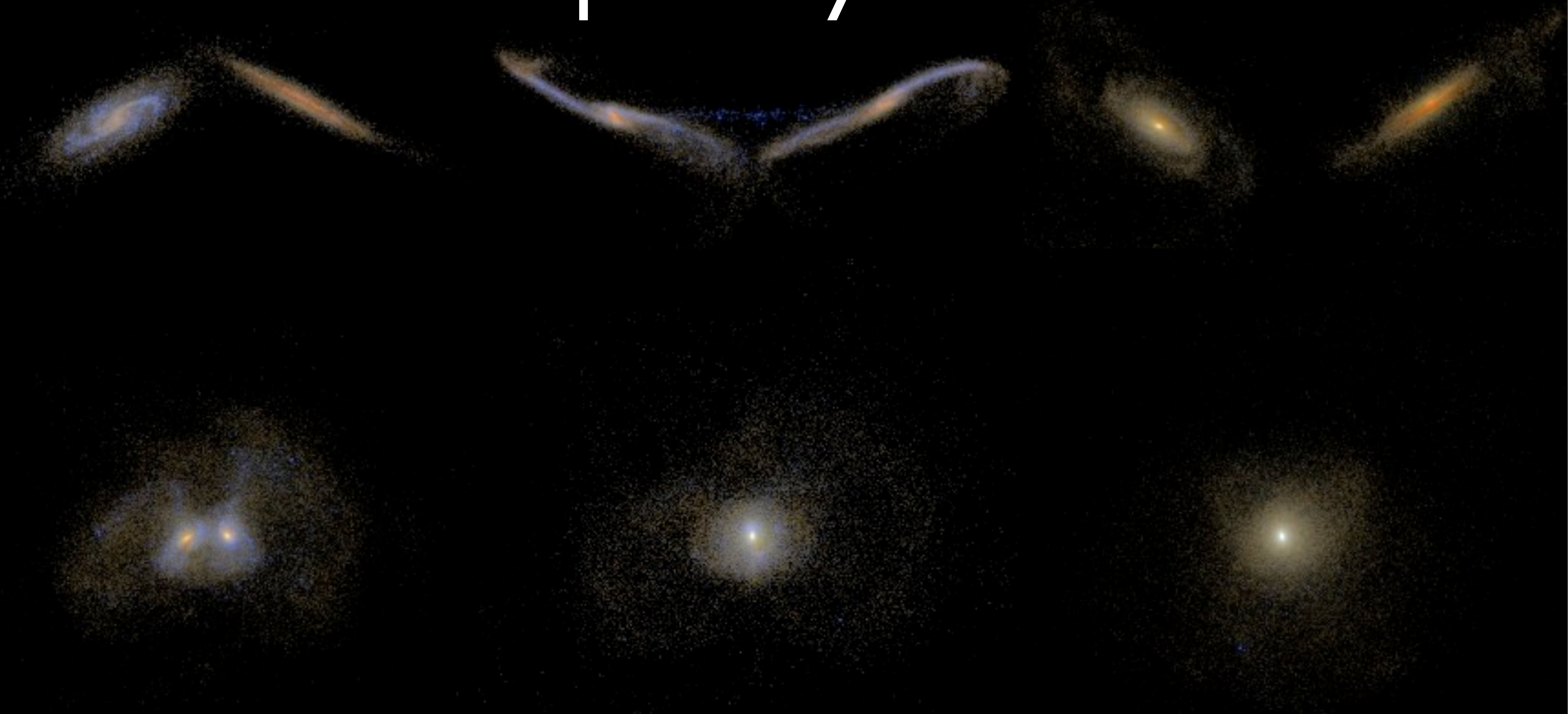
Do submillimeter-selected galaxy number densities provide evidence for a top-heavy IMF?



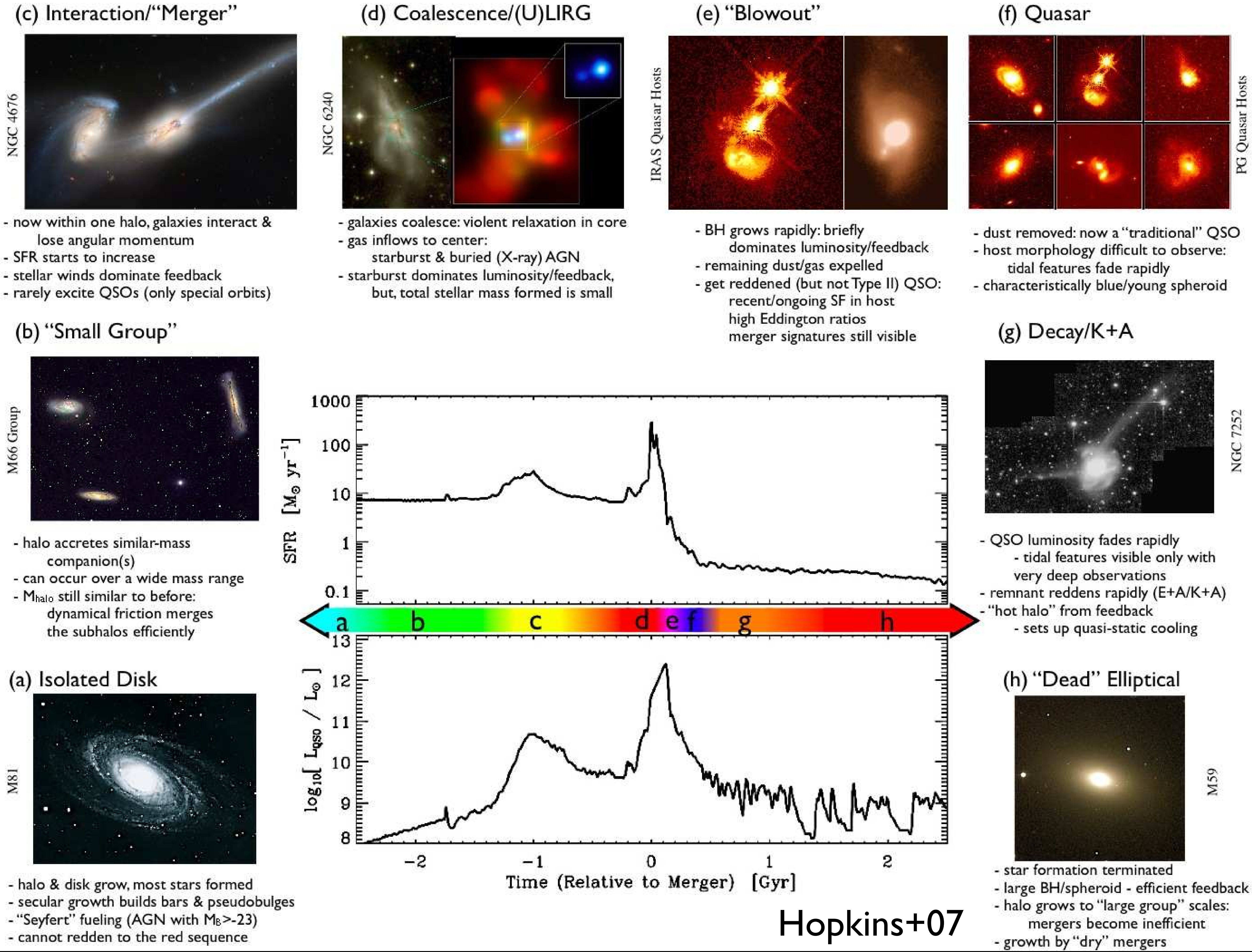
Chris Hayward, CfA
chayward@cfa.harvard.edu
Berkeley TAC lunch, 6 October 2010

Collaborators

- Patrik Jonsson, Desika Narayanan, Lars Hernquist (CfA)
- Dušan Kereš, Phil Hopkins (Berkeley)
- T.J. Cox (Carnegie Observatories)

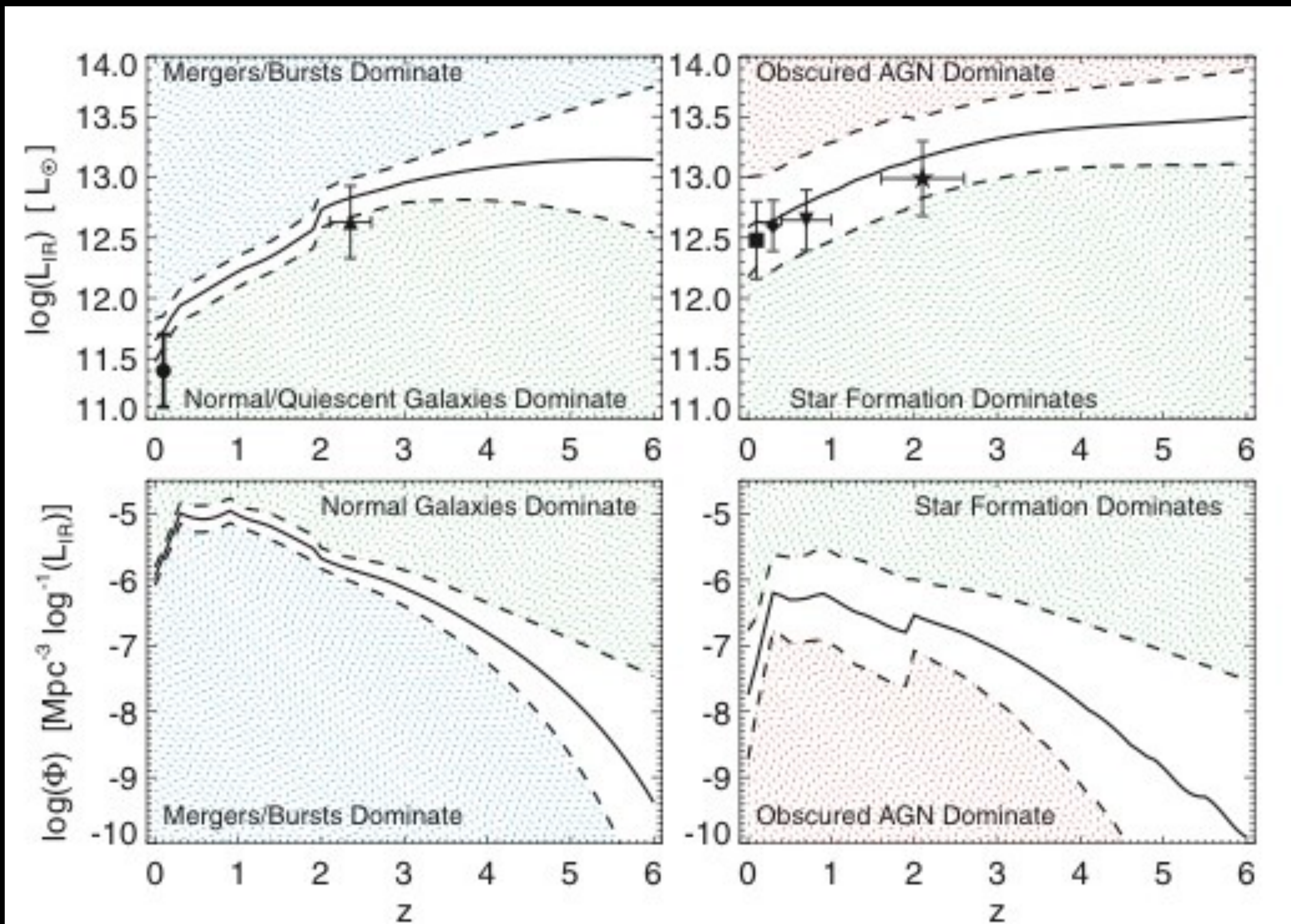
Outline

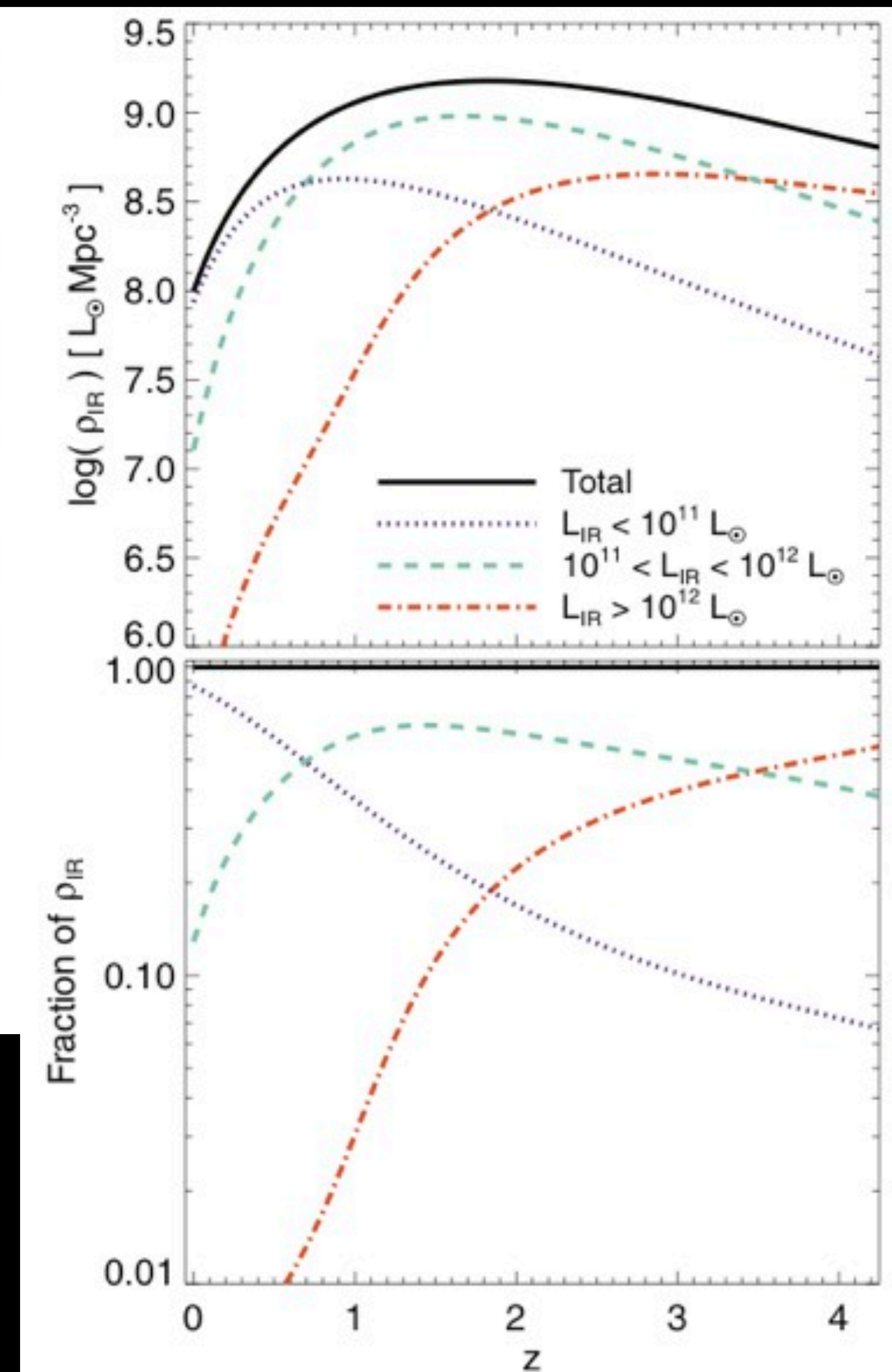
- Introduction
- Modeling dusty galaxies
- Making SMGs
- Predicted number counts
- Relation to DOGs


(c) Interaction/"Merger"
NGC 4676
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)
(d) Coalescence/(U)LIRG
NGC 6240
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small
(e) "Blowout"
IRAS Quasar Hosts
- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible
(f) Quasar
PG Quasar Hosts
- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid
(b) "Small Group"
M66 Group
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently
(g) Decay/K+A
NGC 7252
- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- "hot halo" from feedback
- sets up quasi-static cooling
SFR $[M_\odot\ yr^{-1}]$
1000
100
10
1
0.1
a b c d e f g h
$\log_{10}[L_{QSO} / L_\odot]$
13
12
11
10
9
8
−2 −1 0 1 2
Time (Relative to Merger) [Gyr]
(a) Isolated Disk
M81
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with M_B>-23)
- cannot redden to the red sequence
(h) "Dead" Elliptical
M59
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers

Hopkins+07

Why mergers matter





- Mergers dominate highest-L objects
- As z ↑, (U)LIRGs dominate SFR density

Hopkins+10

Submillimeter galaxies (SMGs)

- Population of optically faint sources detected in submm (fiducial cut $S_{850\ \mu m}$ > 3-5 mJy)
- 99% of L is emitted in IR
- Believed to be powered by SF rather than AGN
- $L_{IR} \sim 10^{12}$ - few x 10^{13} L_{sun} $\Rightarrow$ SFR ~ 10^2-10^4 M_{sun}/yr
- z ~ 1 - 5, mean z ~ 2.3 $\Rightarrow$ submm traces ~ 150 - 400 μm emission (longward of dust peak)
- Negative k-correction means given S_{850} corresponds to fixed L_{850} for any z in this range

Why care about SMGs?

- Extreme objects: is SF different in such high density environments? Are SMGs "Eddington-limited starbursts" (Murray, Quataert, Thompson 05, TQM05)?
- ULIRGs become dominant contributor to SFR density at high z; submm is one way to select ULIRGs
- How does galaxy formation at high z differ from local?
- Massive amounts of dust in SMGs challenges understanding of dust production
- Claimed that SMGs provide evidence for IMF variation

Wait, what do SMG number counts have to do with the IMF?

Models predict less bright submm sources than observed; top-heavy IMF can boost counts:

1. ↑ massive stars ⇒ ↑ L/SFR ⇒ ↑ submm flux

2. ↑ massive stars ⇒ ↑ M_{metals}/SFR ⇒ ↑ M_{dust}/SFR ⇒ ↓ dust T ⇒ ↑ submm flux

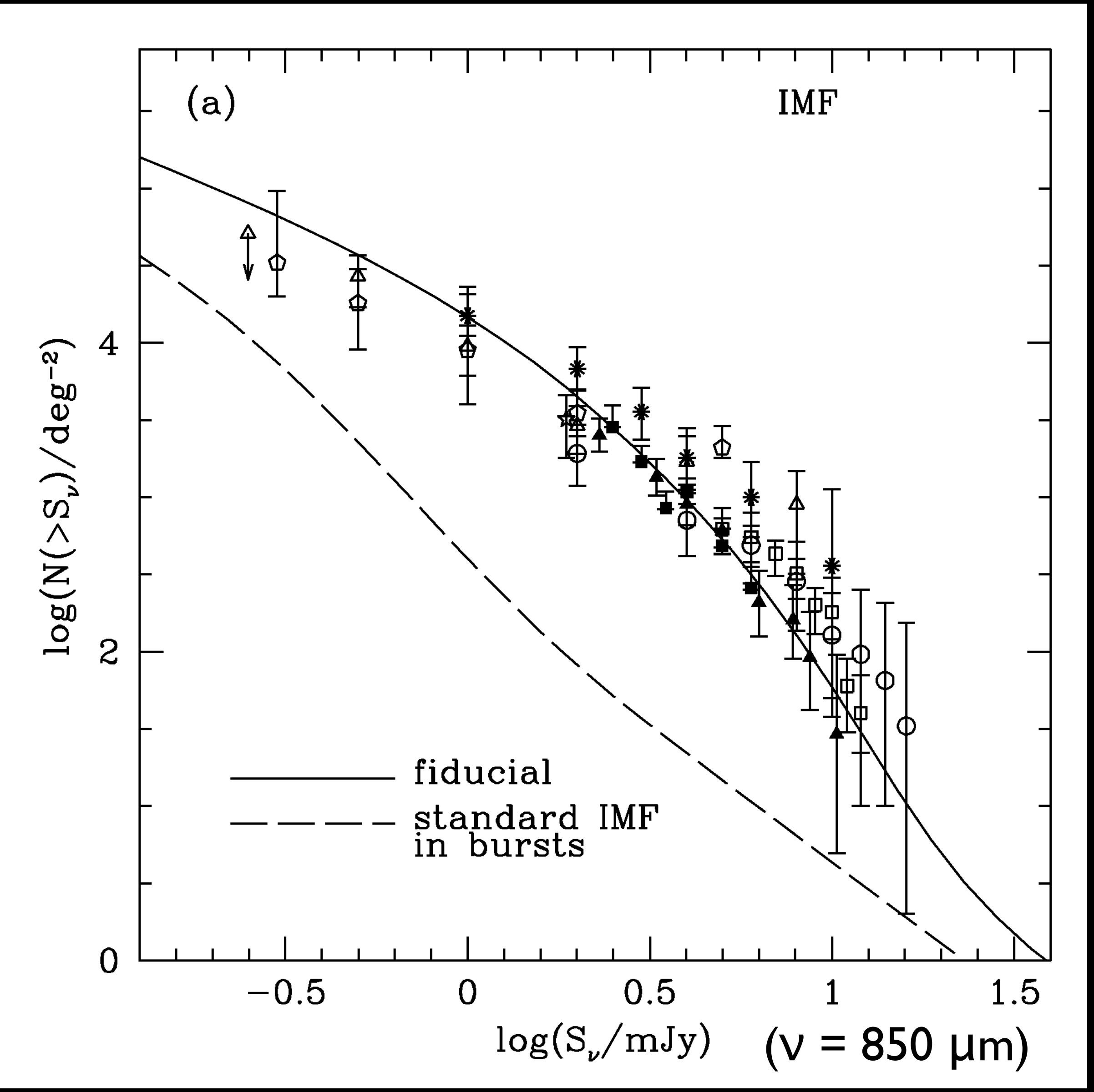
A flat IMF?

- 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):

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

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

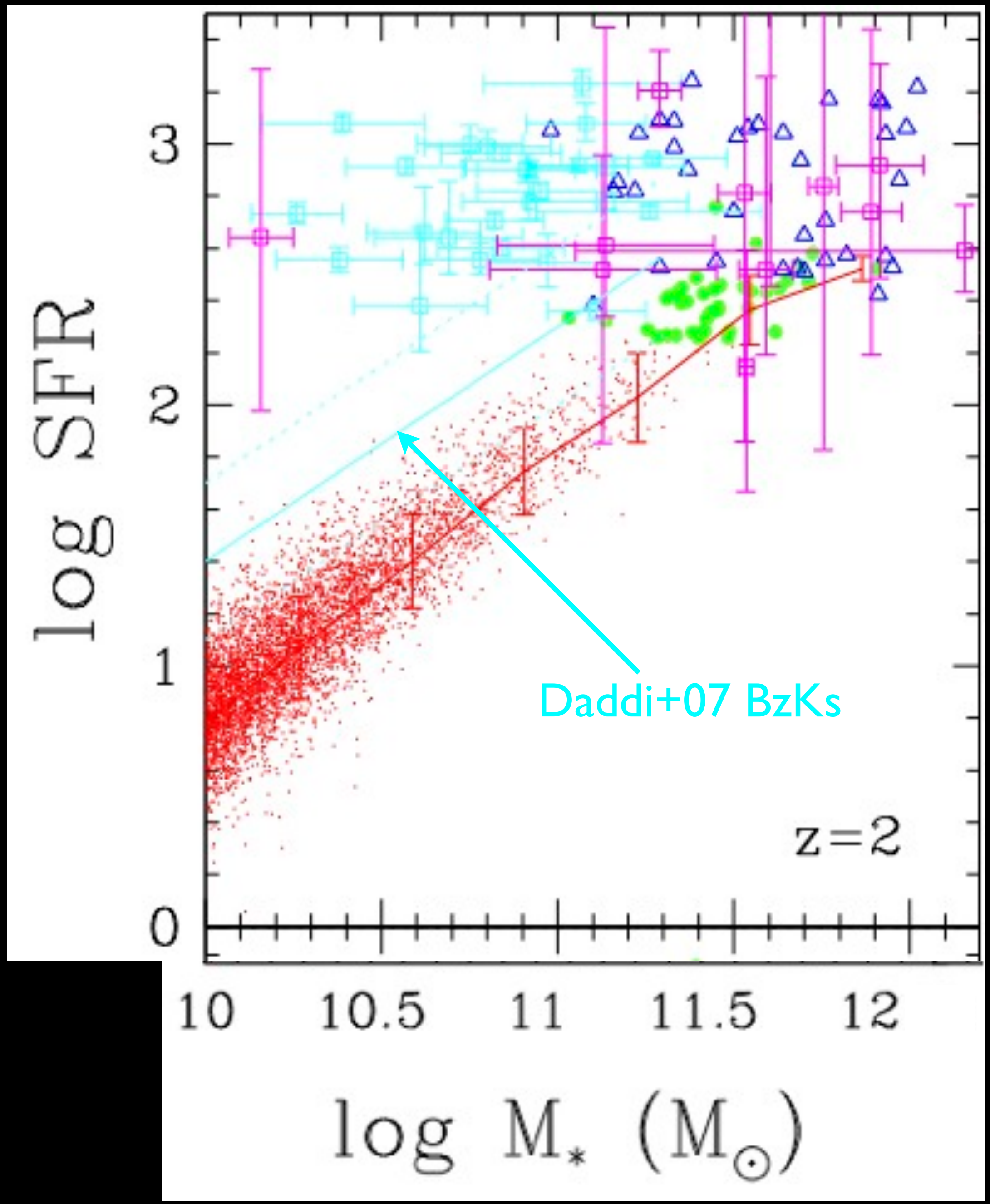
- 10^3 boost in burst contribution; becomes dominant over quiescent



Baugh+05

Or "bottom-light"?

- Davé+10 map SMGs to most star-forming galaxies in a cosmological simulation
- Sim objects consistent w/ many observed properties, but SFR ~3x < inferred SFR
- SMGs' high L_{IR} confirmed by Herschel (Magnelli+10, Chapman+10)
- Bottom-light IMF could explain (more L/M_{sun} formed → lower SFR)



Davé+10

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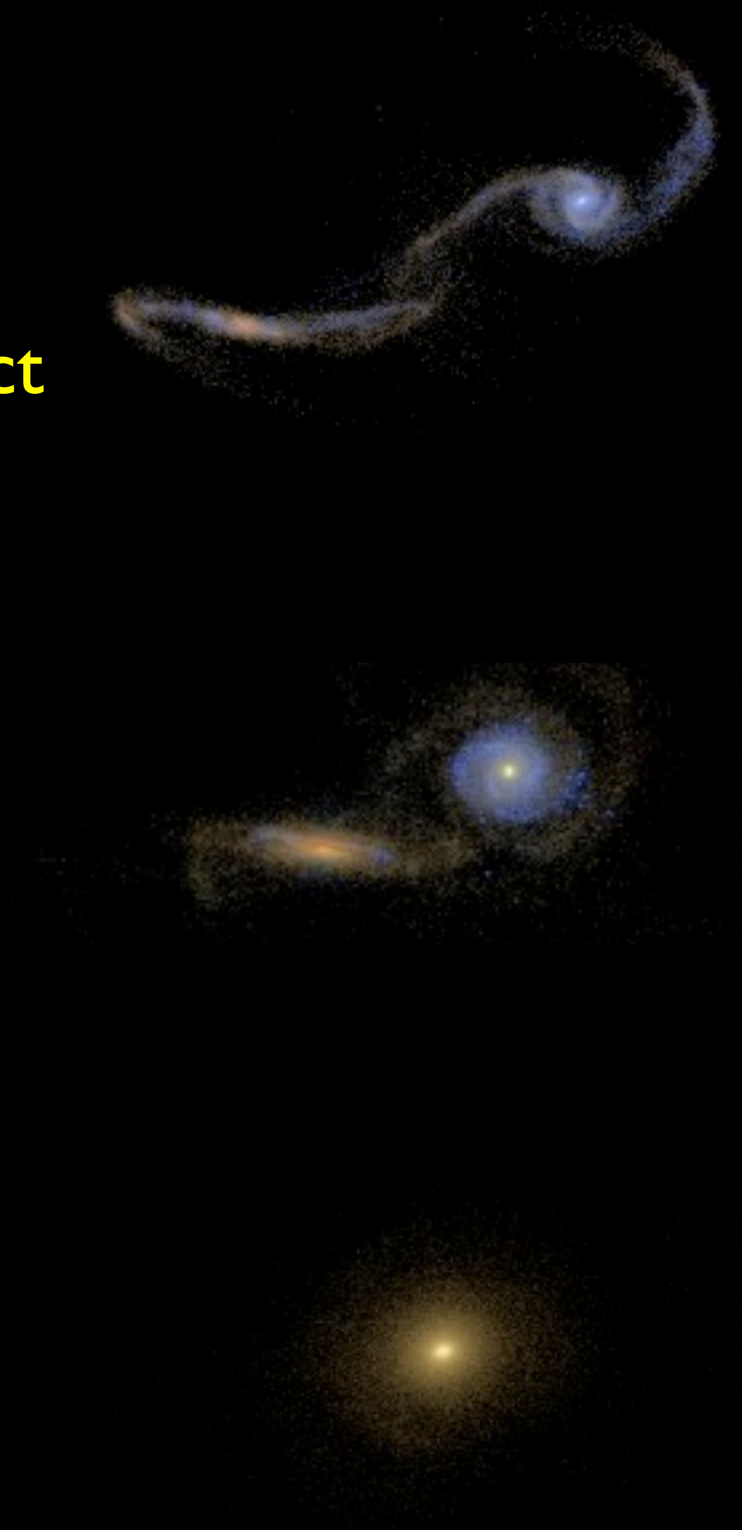
GADGET simulations

- 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)

V. Springel

Need for radiative transfer

- We observe light, so ideally theory should predict light
- Making inferences from observed SEDs relies on various crude assumptions & suffers from degeneracies
- We perform 3-D RT on galaxy simulations → more realistic SFH, dust & source geometry, etc.
- Less free parameters/assumptions
- Tradeoff is computational expense & increased complexity of simulations



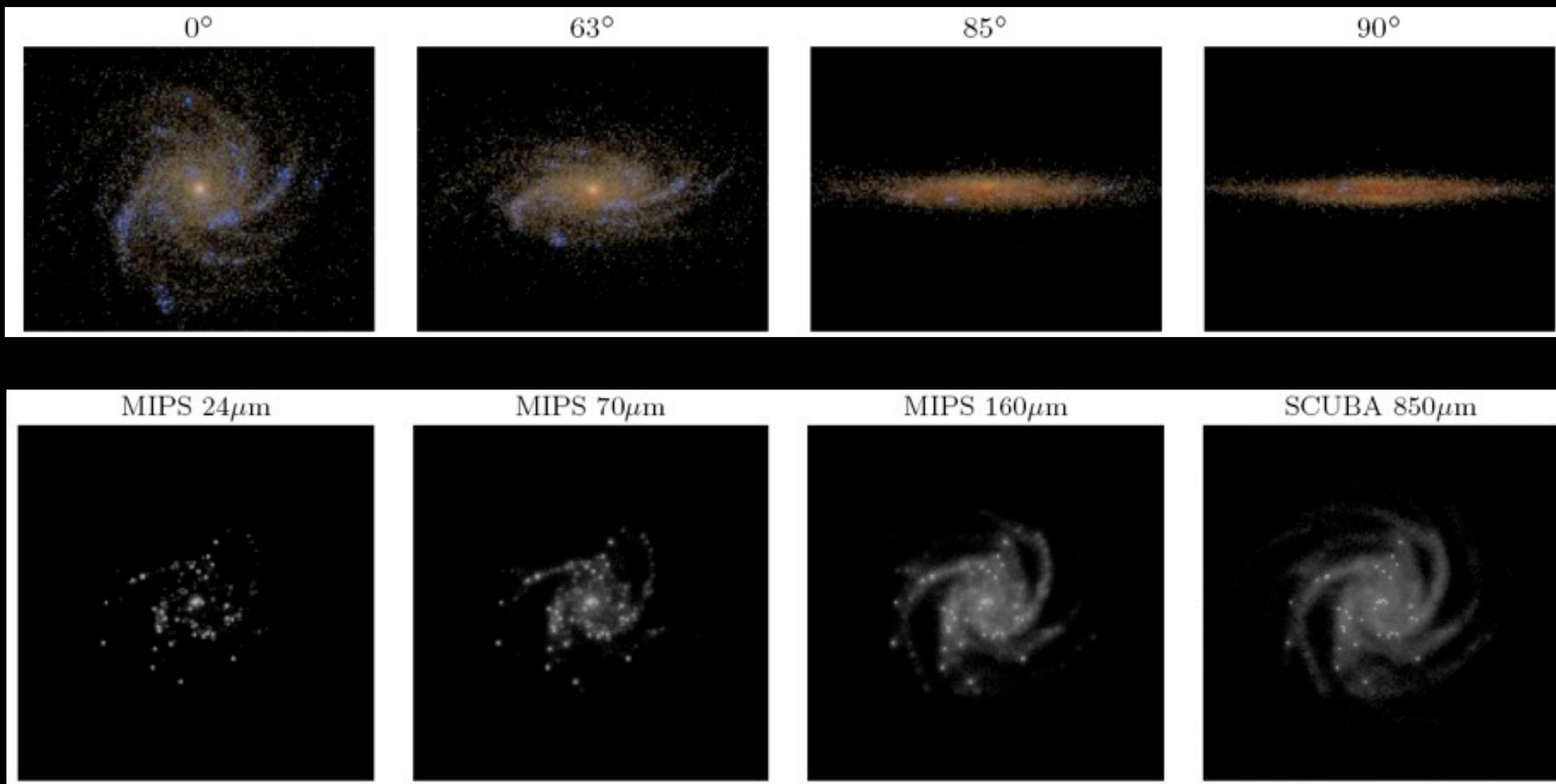
P.Jonsson, G. Novack

Sunrise details

- 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

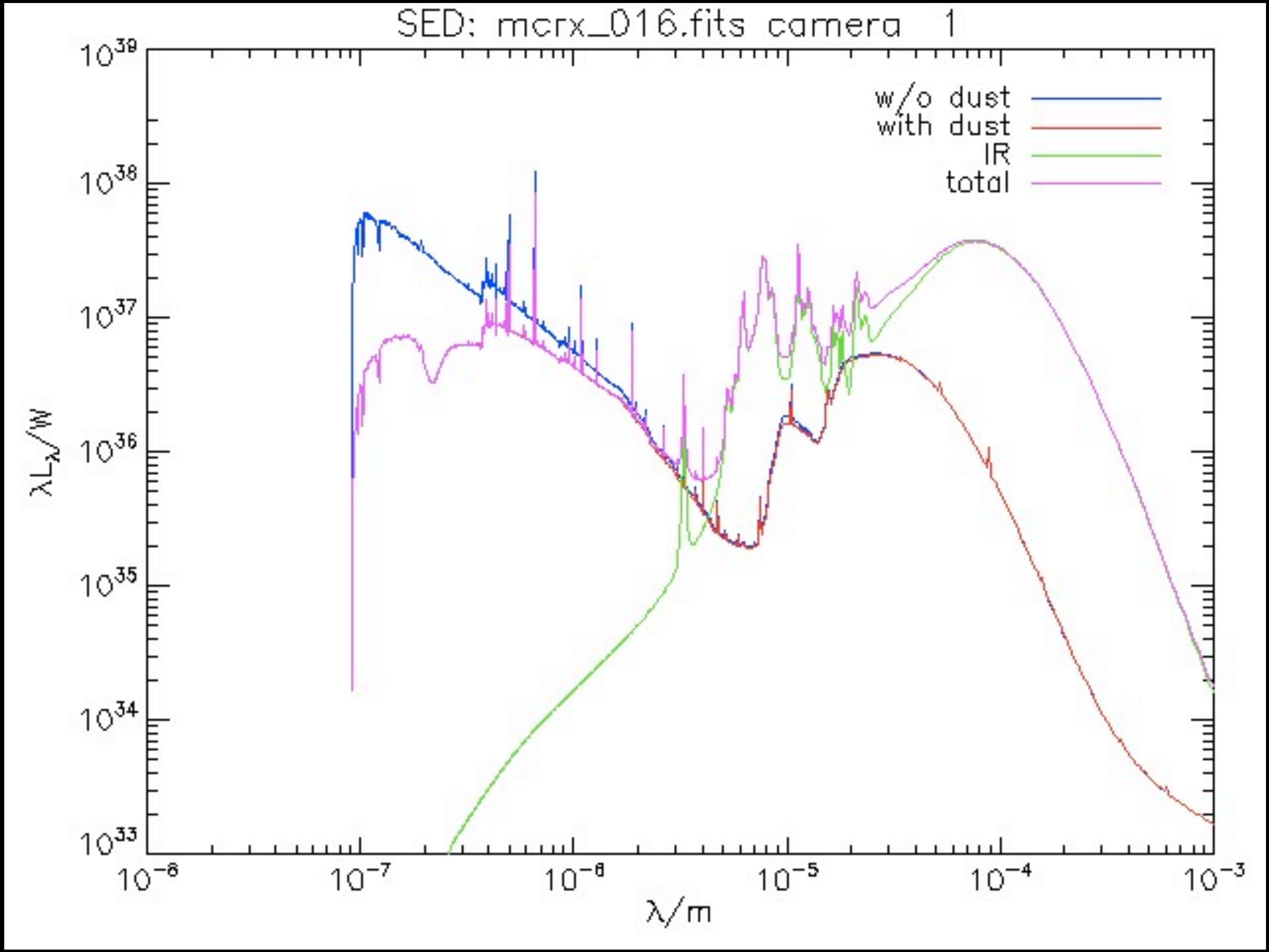
Sunrise outputs

Broadband photometry & images



Jonsson, Groves, & Cox 10

Sunrise outputs



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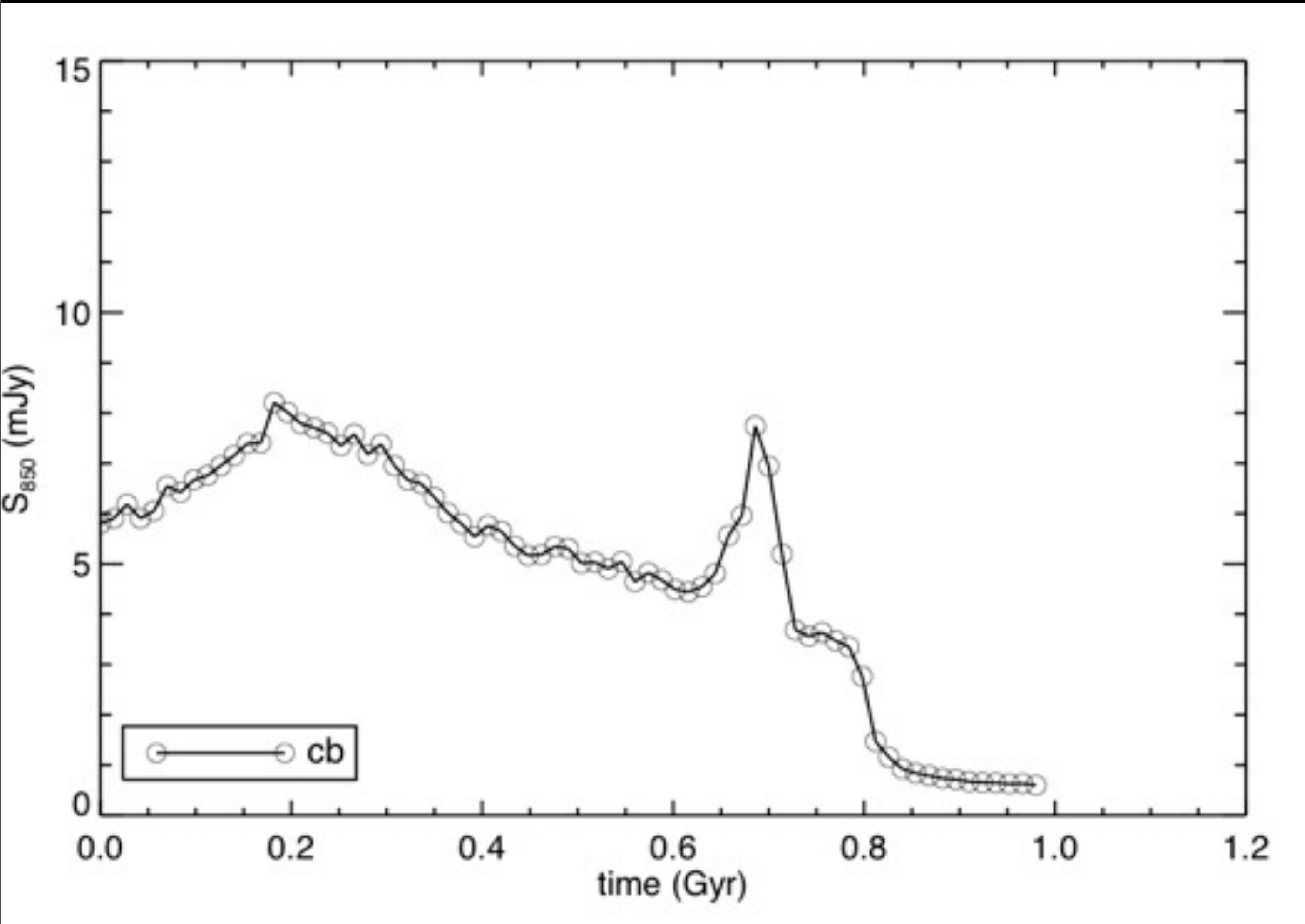
How can we make an SMG?



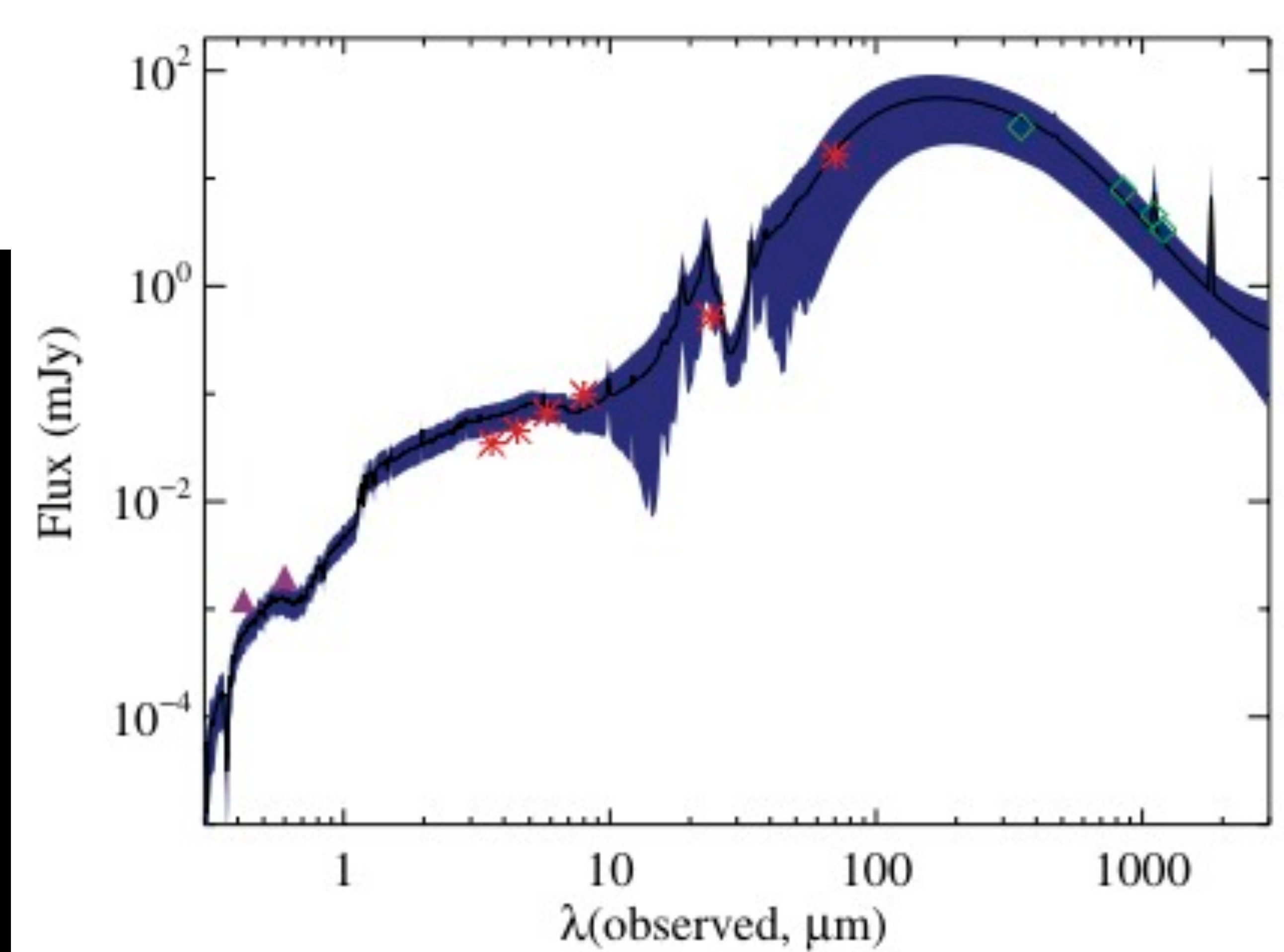
Answer: Merge two massive gas-rich, high-z disks

Need M_b > ~10^{11} M_{sun}, high gas fractions (>20% at coalescence), mass ratio >~ 1/3

Hard to get 5 mJy w/ all but most extreme isolated disks

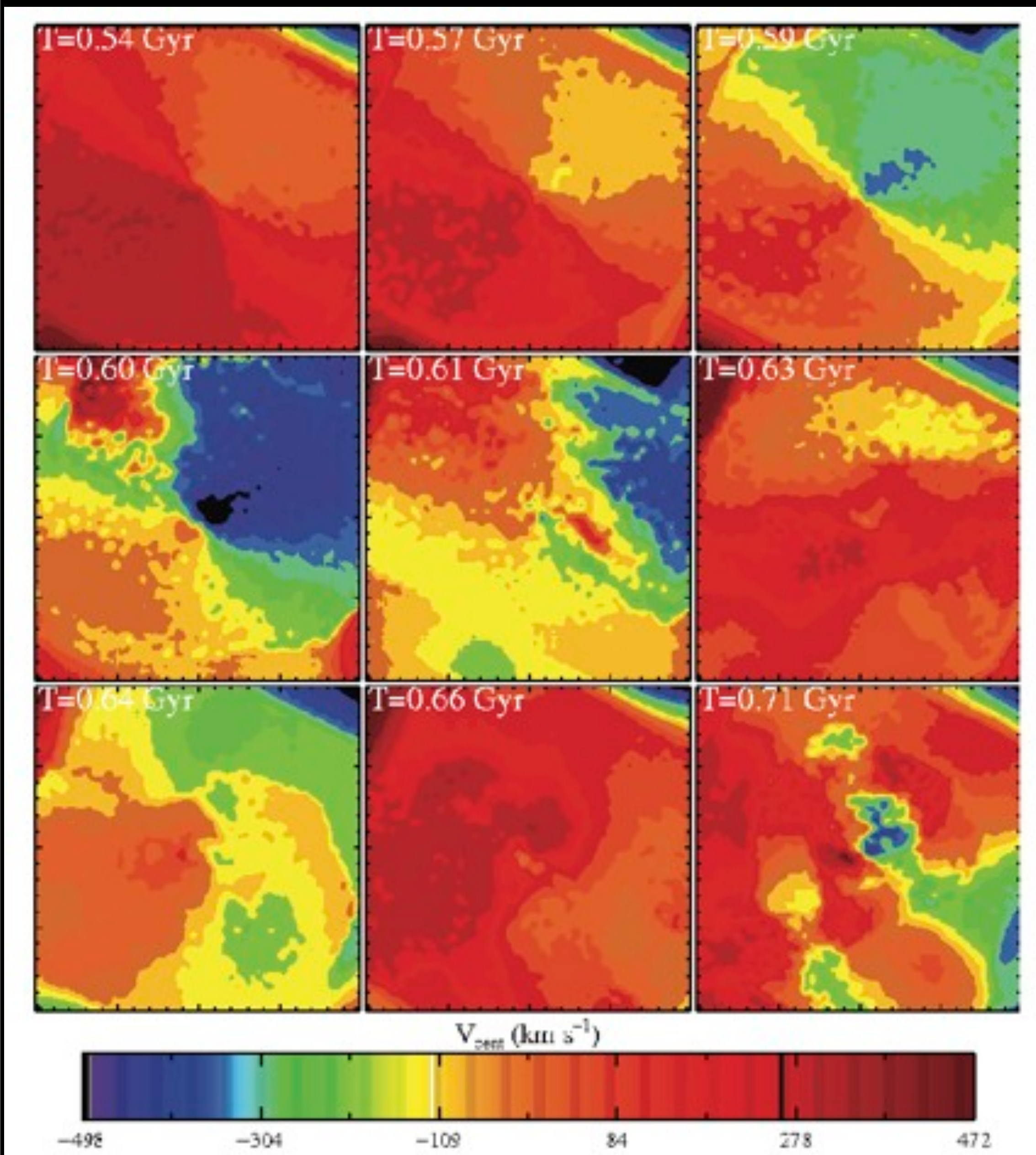
Narayanan, CCH+10

Can match full range of sub-mm fluxes and typical SED



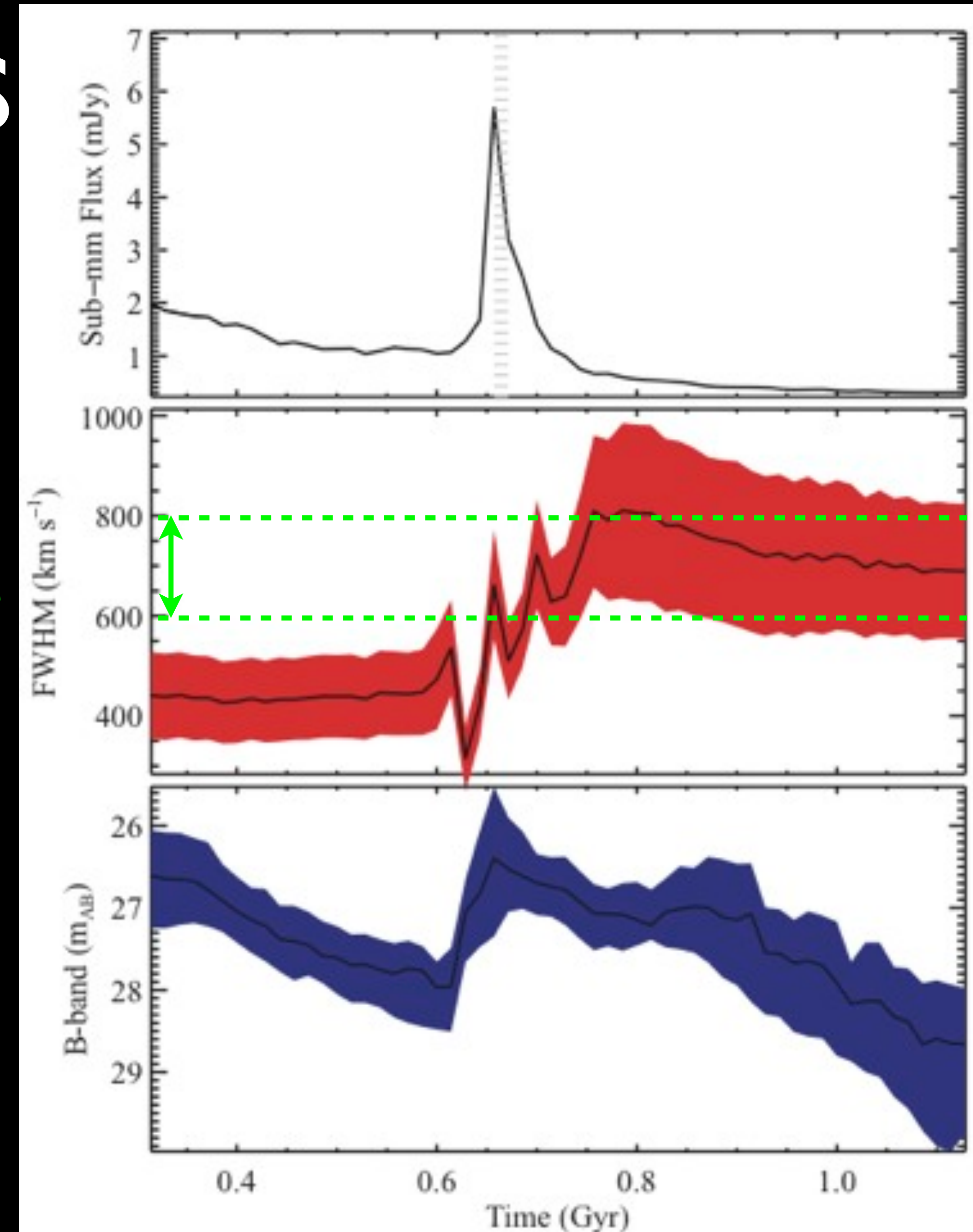
Molecular gas properties

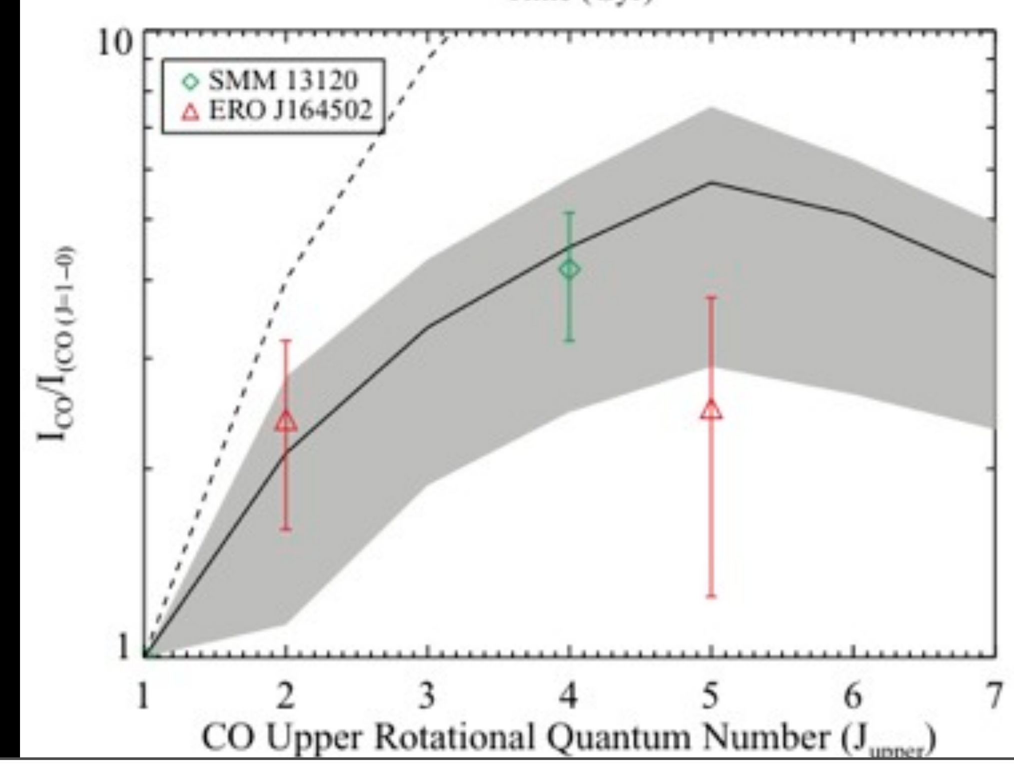
- 3-D non-LTE molecular line RT code (Narayanan+06,08)
- Good match to observed linewidths, CO SED



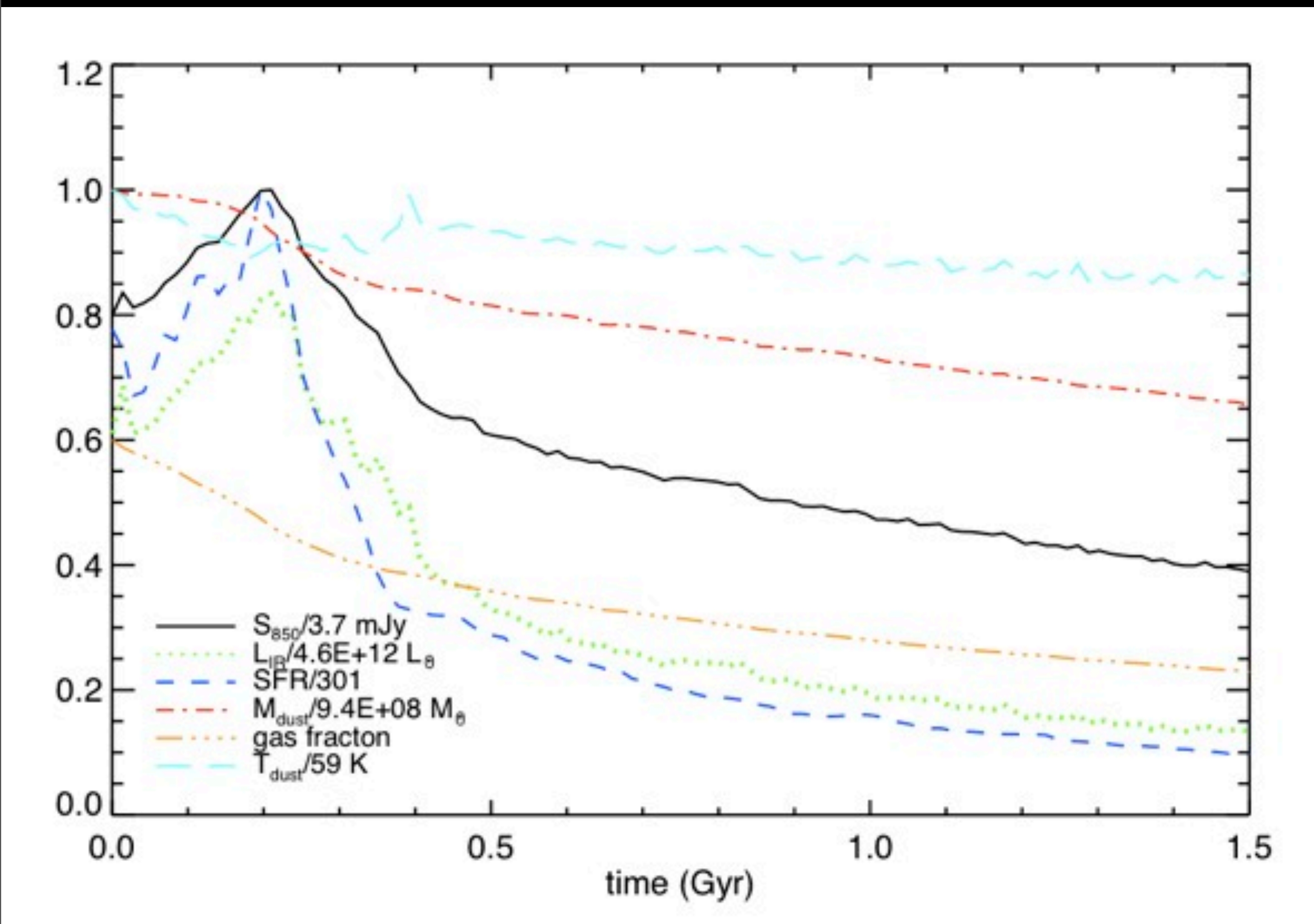
Narayanan, Cox, CCH+10

Coppin+08 observed range





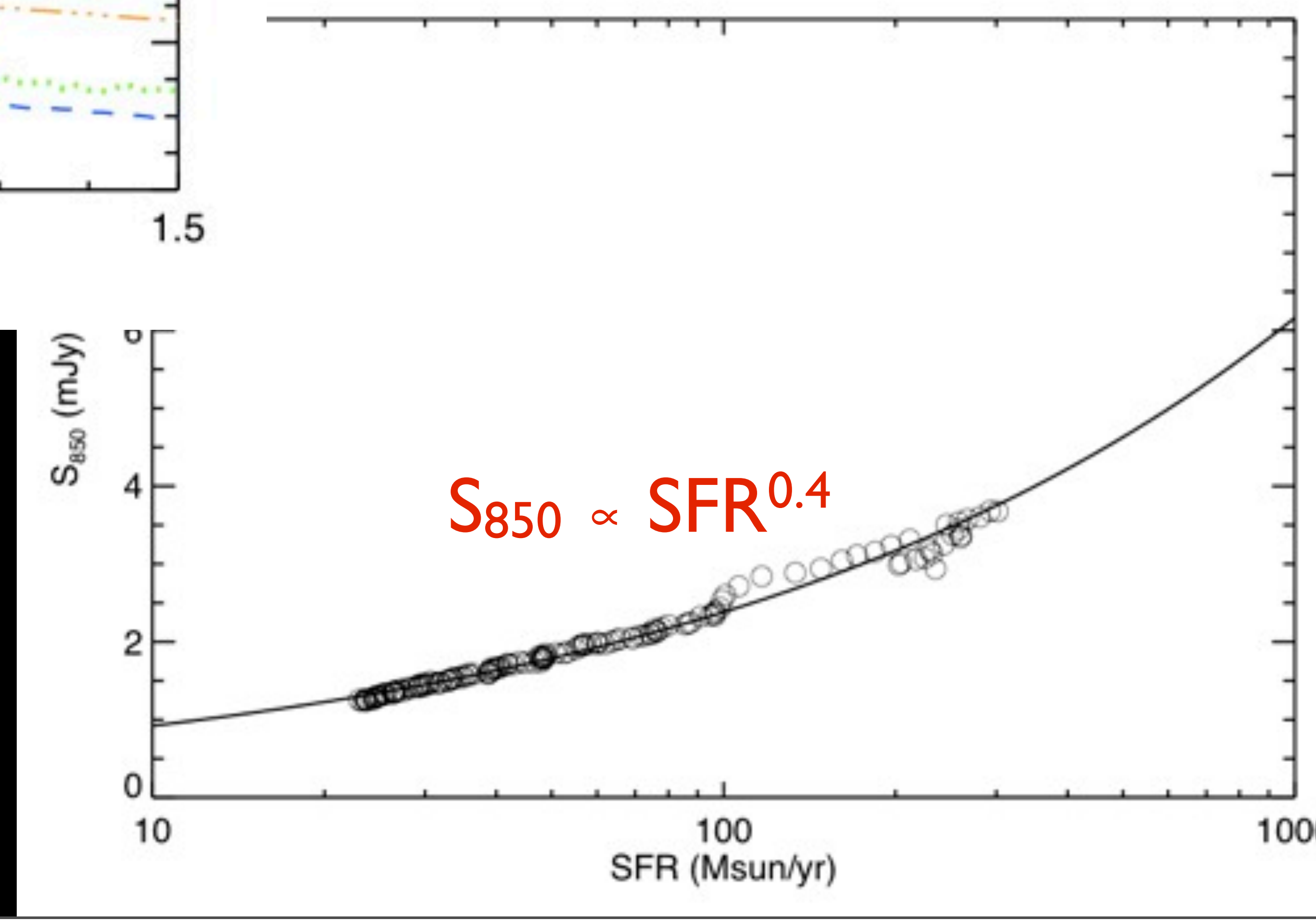
Isolated disk evolution



Sub-mm flux traces instantaneous SFR well

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

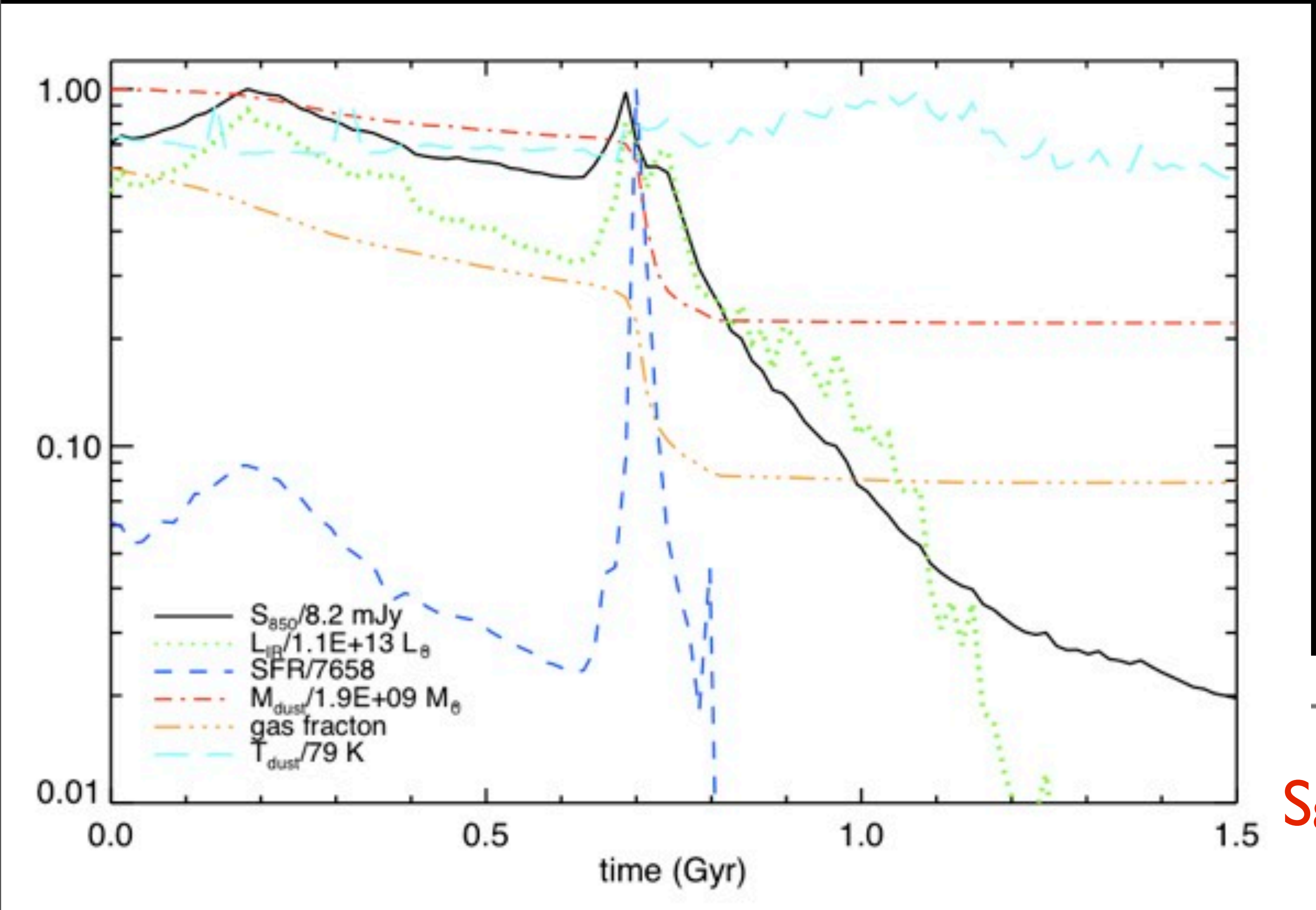
At most ~4 mJy

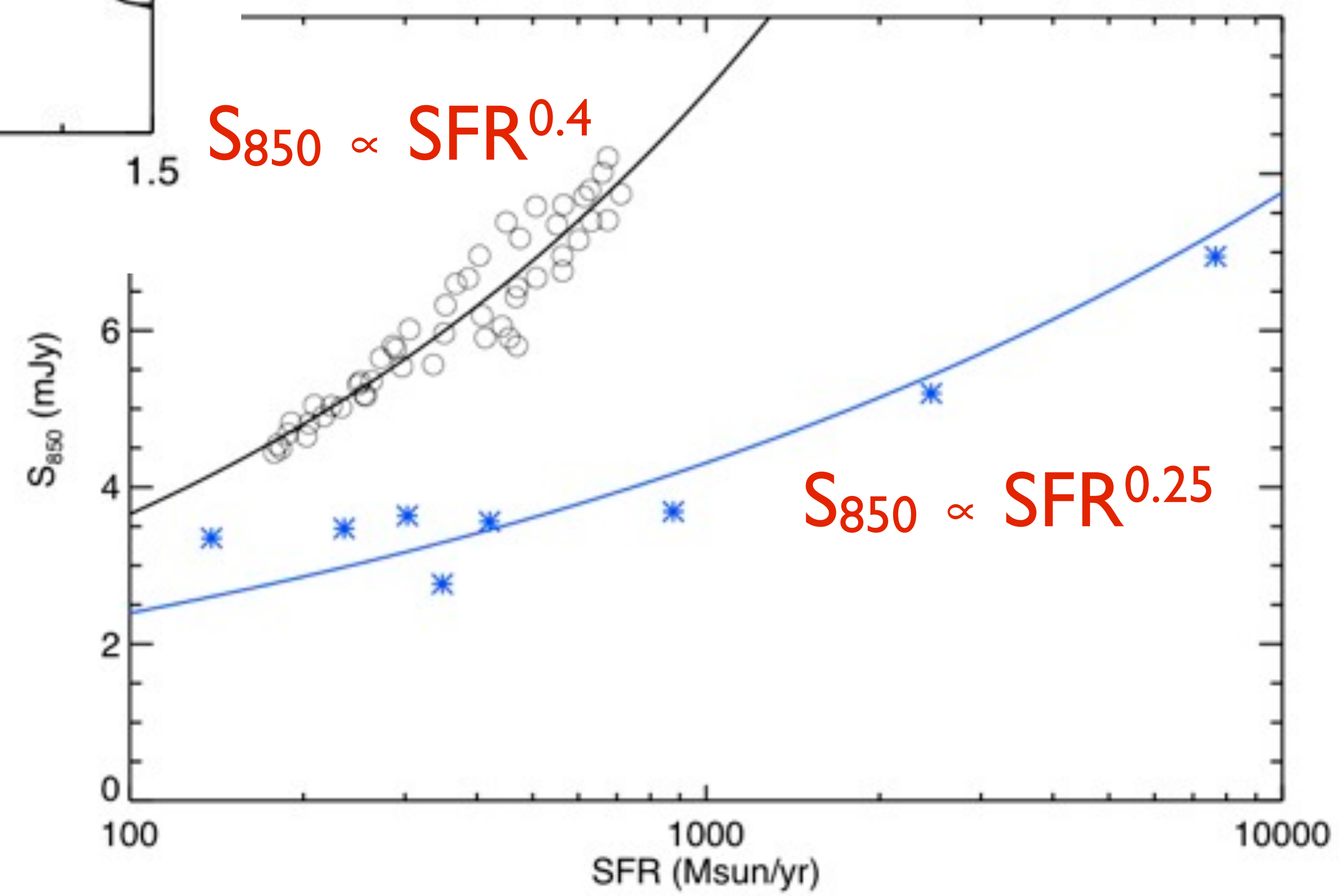


$S_{850} \propto SFR^{0.4}$

Merger evolution

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





Two regimes: 1. Quiescent disk/infall 2. Merger-driven burst (shallower relation than quiescent)

⇒ no simple rank-ordering between sub-mm flux & SFR

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Our model for number counts

1. High-resolution N-body/SPH simulations of mergers/disks + 3-D polychromatic RT → submm duty cycles
2. Merger rates from "semi-empirical" model of Phil Hopkins
3. Combine to get number counts:

$$\frac{dN(>S_\lambda)}{d\Omega} = \int \frac{dN}{dV\,dt\,d\log M_b d\mu df_g}(M_b,\mu,f_g,z)\tau(>S_\lambda,M_b,\mu,f_g,z)\frac{dV}{d\Omega dz}(z)d\log M_b d\mu df_g dz$$

Our philosophy: Use as many observational constraints as possible and systematically test importance of poorly constrained aspects of model - test IMF null hypothesis

Advantages & disadvantages

Advantages over previous work:

1. Full 3-D RT including dust self-absorption
2. SFH, sources, and dust directly from sims
3. Merger rates from semi-empirical model isolate SMG aspect from any general errors in merger rates not unique to SMGs

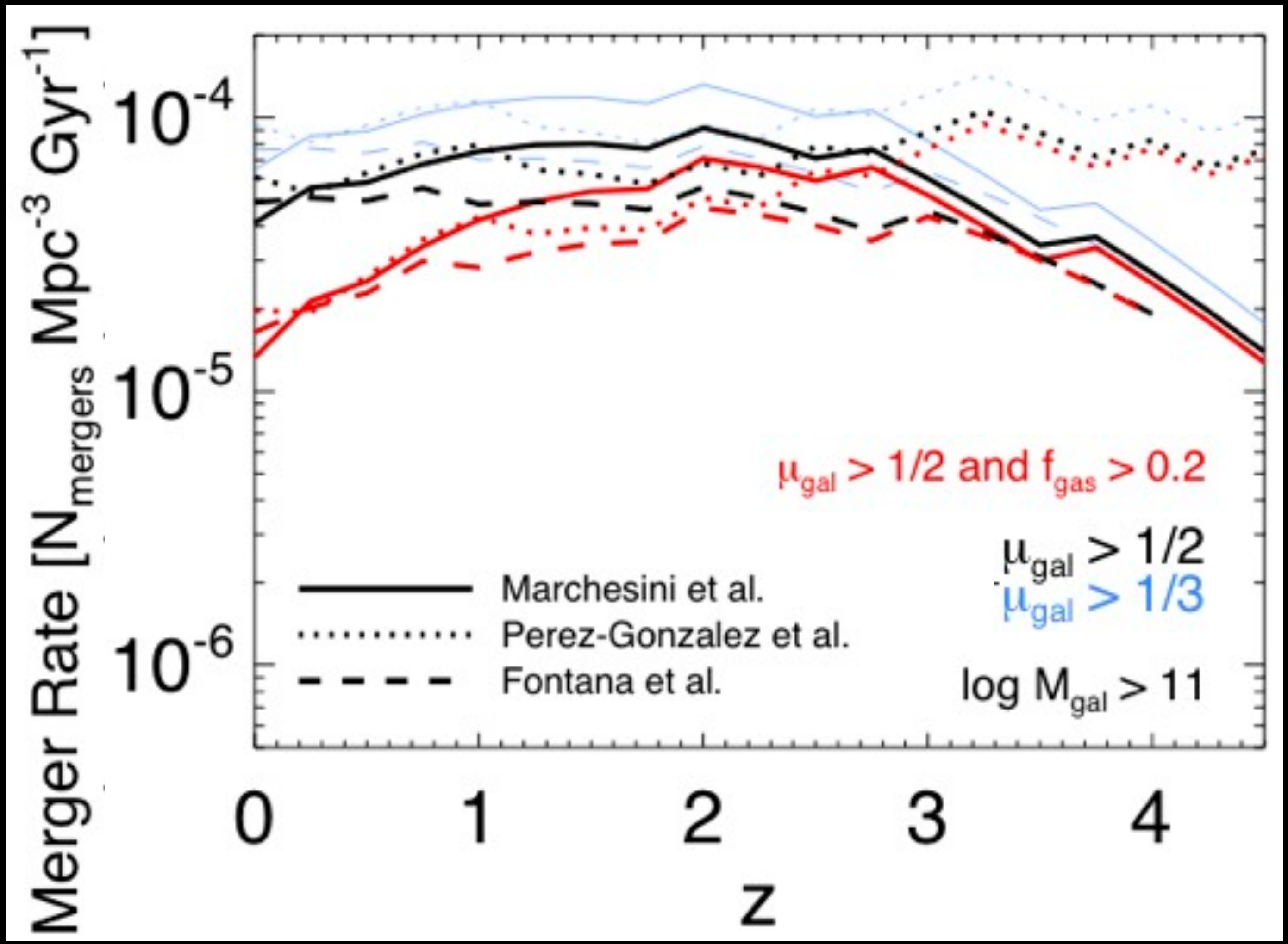
Disadvantages:

1. Non-cosmological (so no cosmological gas accretion)
2. Very expensive to explore large parameter space

Calculating merger rates

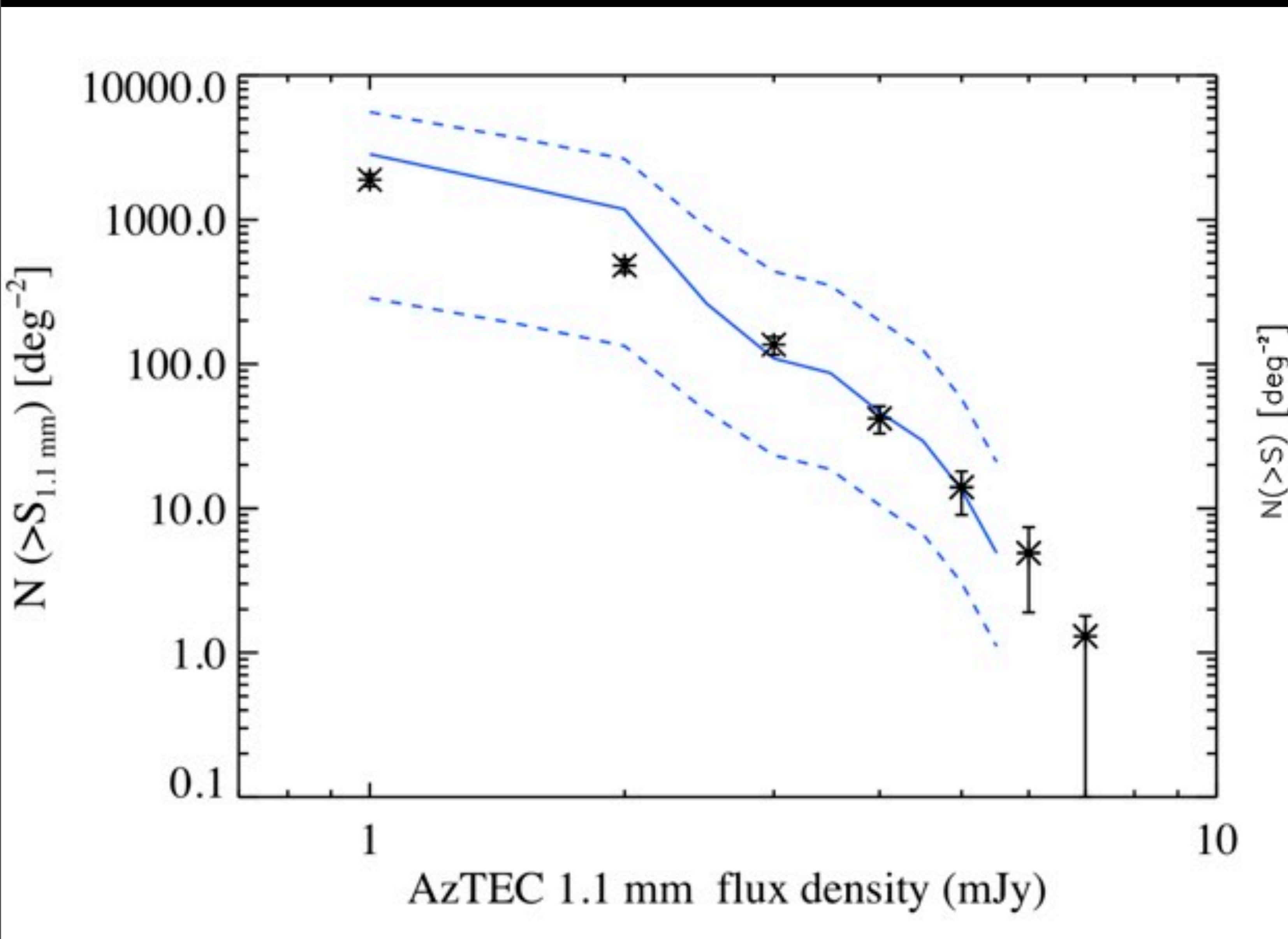
1. Start w/ stellar MF (Marchesini+09)
2. Assign f_g from observations
3. Assign galaxies to halos using HOD (Conroy & Wechsler 09)
4. Halo merger rates from N-body (Fakhouri & Ma 08)
5. Assume galaxies merge on dynamical friction timescale to link halo-halo to galaxy-galaxy mergers

Yields merger rate as a function of mass, mass ratio, gas fraction, and z

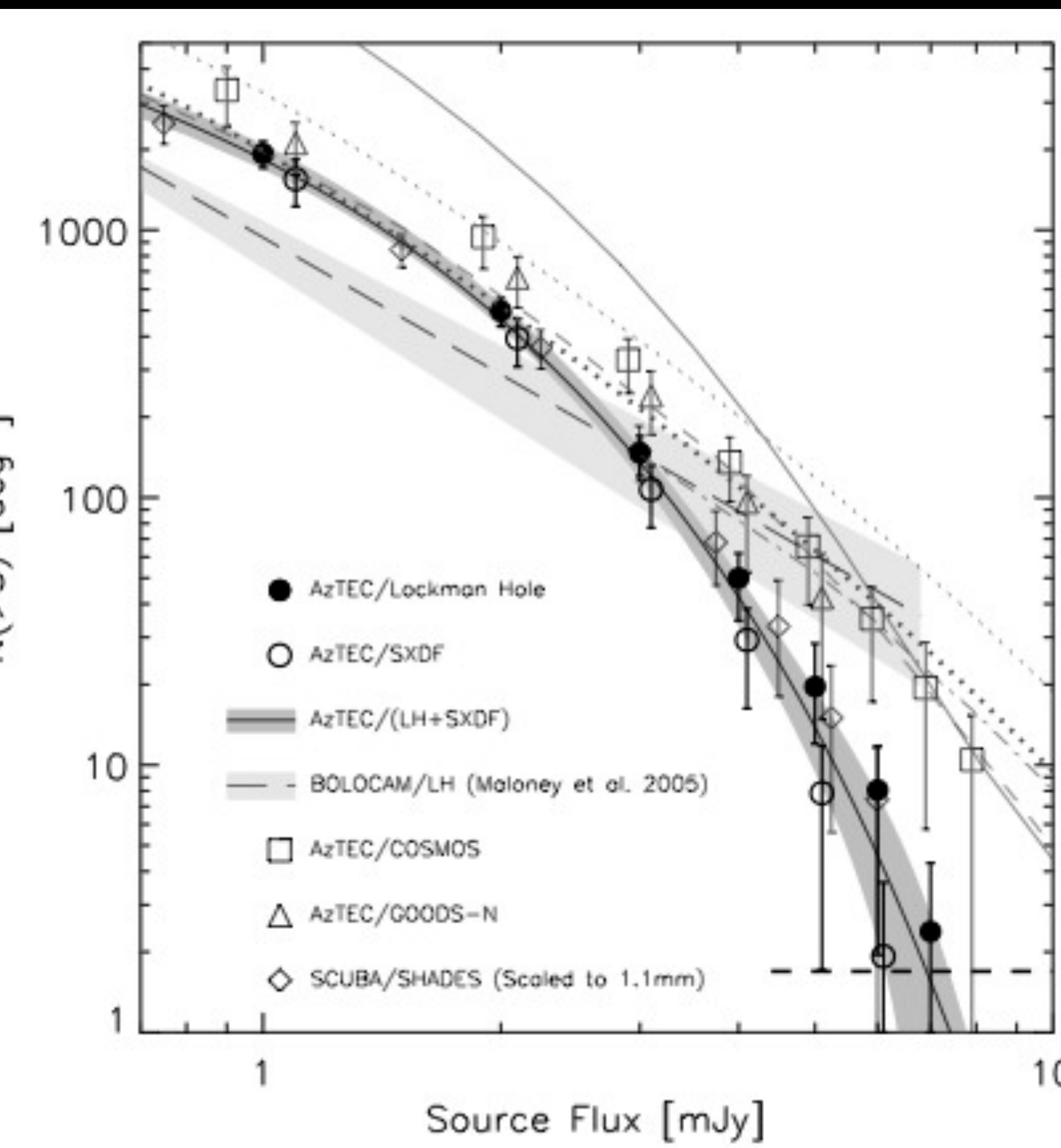


Hopkins+10

Predicted number counts



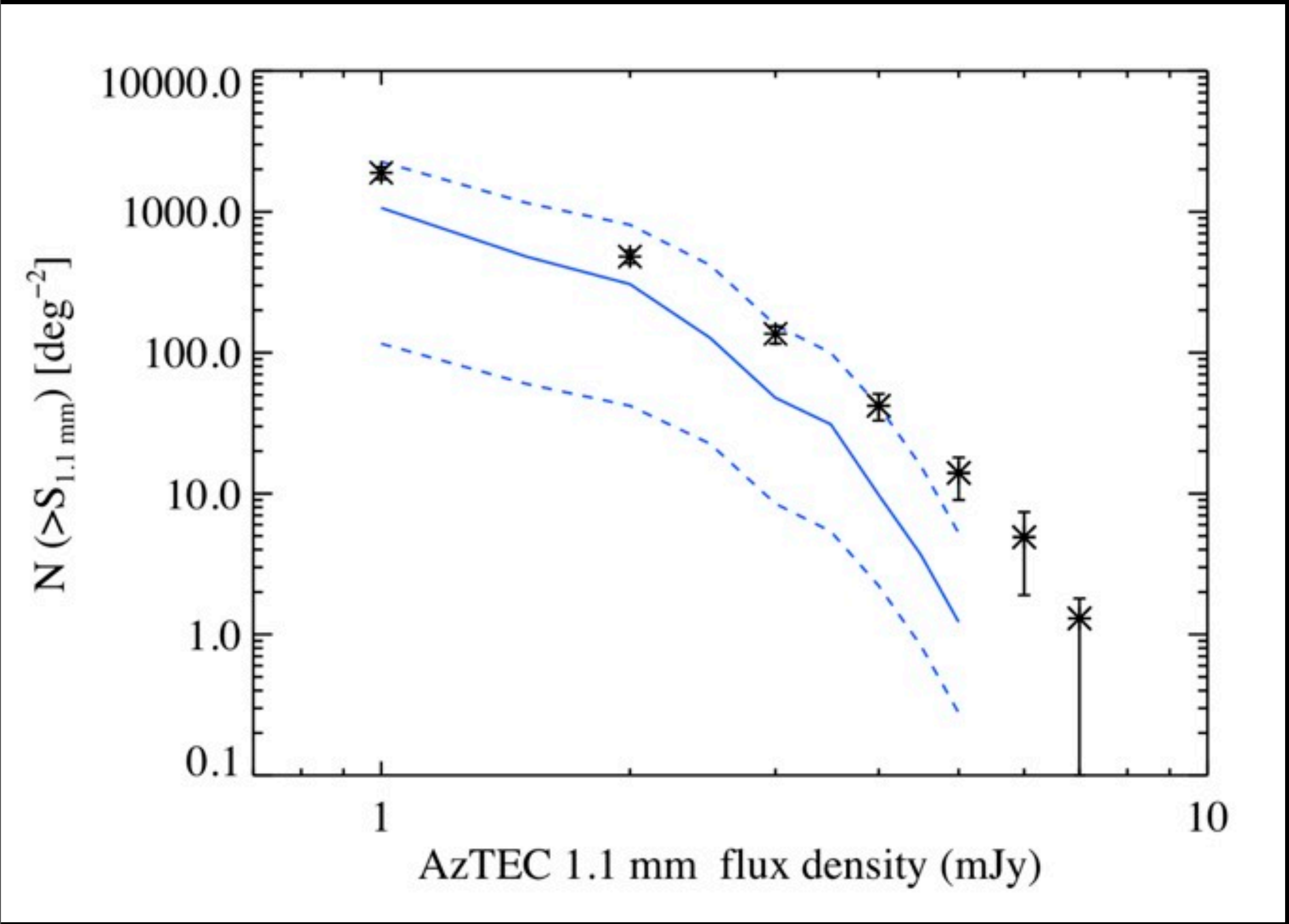
CCH+10



Austermann+10

Mergers can match counts with standard IMF

Merger-induced burst counts



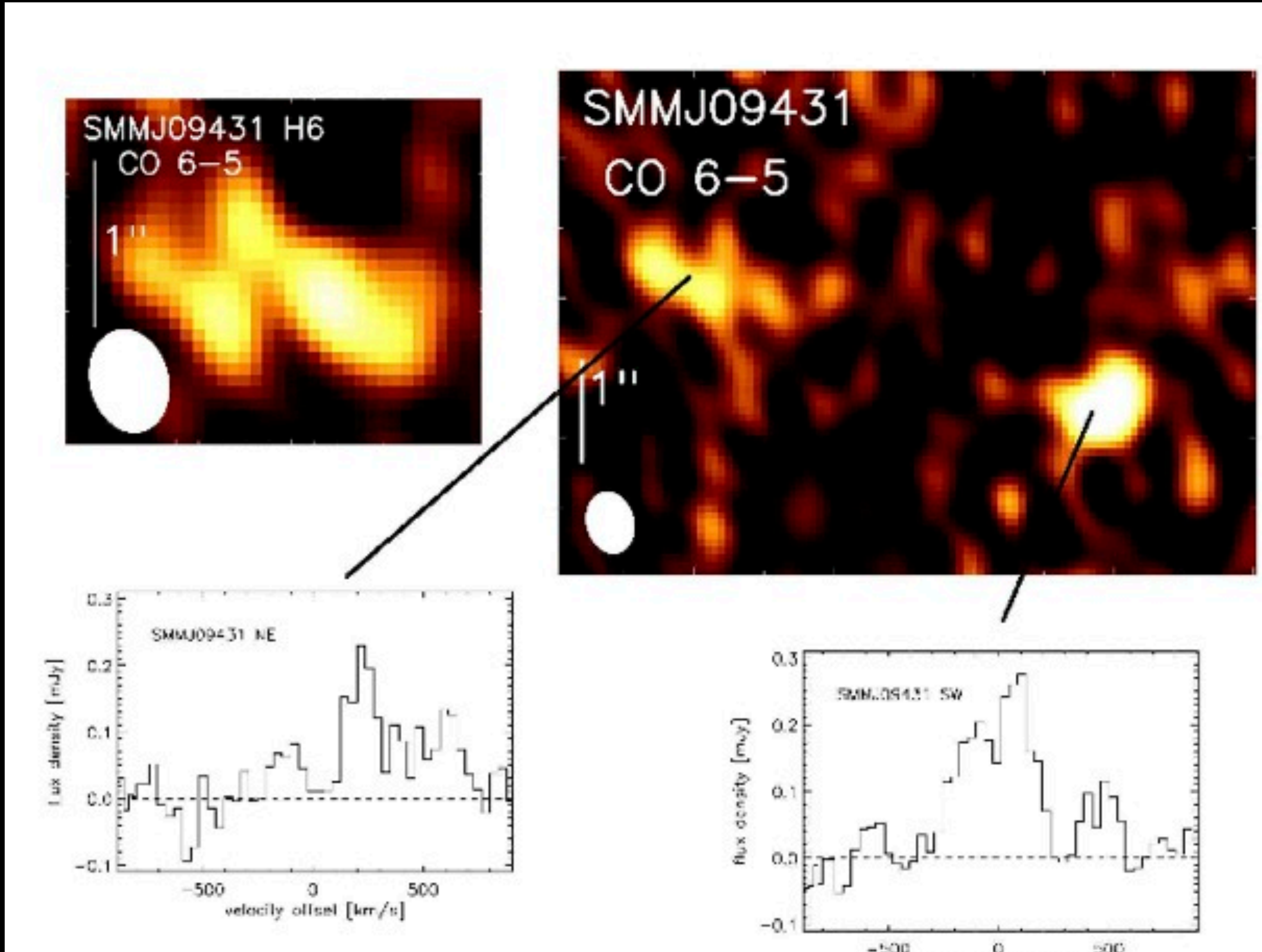
Bursts don't account for all SMGs - need contribution from multiple disks in ~15" (130 kpc at z = 2) beam during infall

i.e. 2 disks w/ S_{850} = 3 mJy in same beam give 6 mJy

CCH+10

SMG bimodality

- Two SMG types: merger-induced starbursts and 2+ disks in beam
- Infall stage should look like "normal" disks in terms of SSFR, SFE, etc.
- Supported by radio doubles (Ivison+02,07, A. Pope) & CO interferometry showing large fraction of SMGs are well-separated binaries (Engel+10)



Engel+10

Why our counts differ

Baugh+05:

1. Don’t account for contribution of multiple objects in beam
2. Many SAMs underpredict merger rates b/c satellite over-quenching (Hopkins+10)
3. GRASIL results disagree with full RT?

Dave+10:

1. Submm flux does not map easily onto SFR
2. Sims have z ~ 2 SFR-M* relation w/ normalization ~2-3x observed for *all* objects, not just SMGs
3. Insufficient resolution to fully capture bursts

Recent counts lower than Chapman+05

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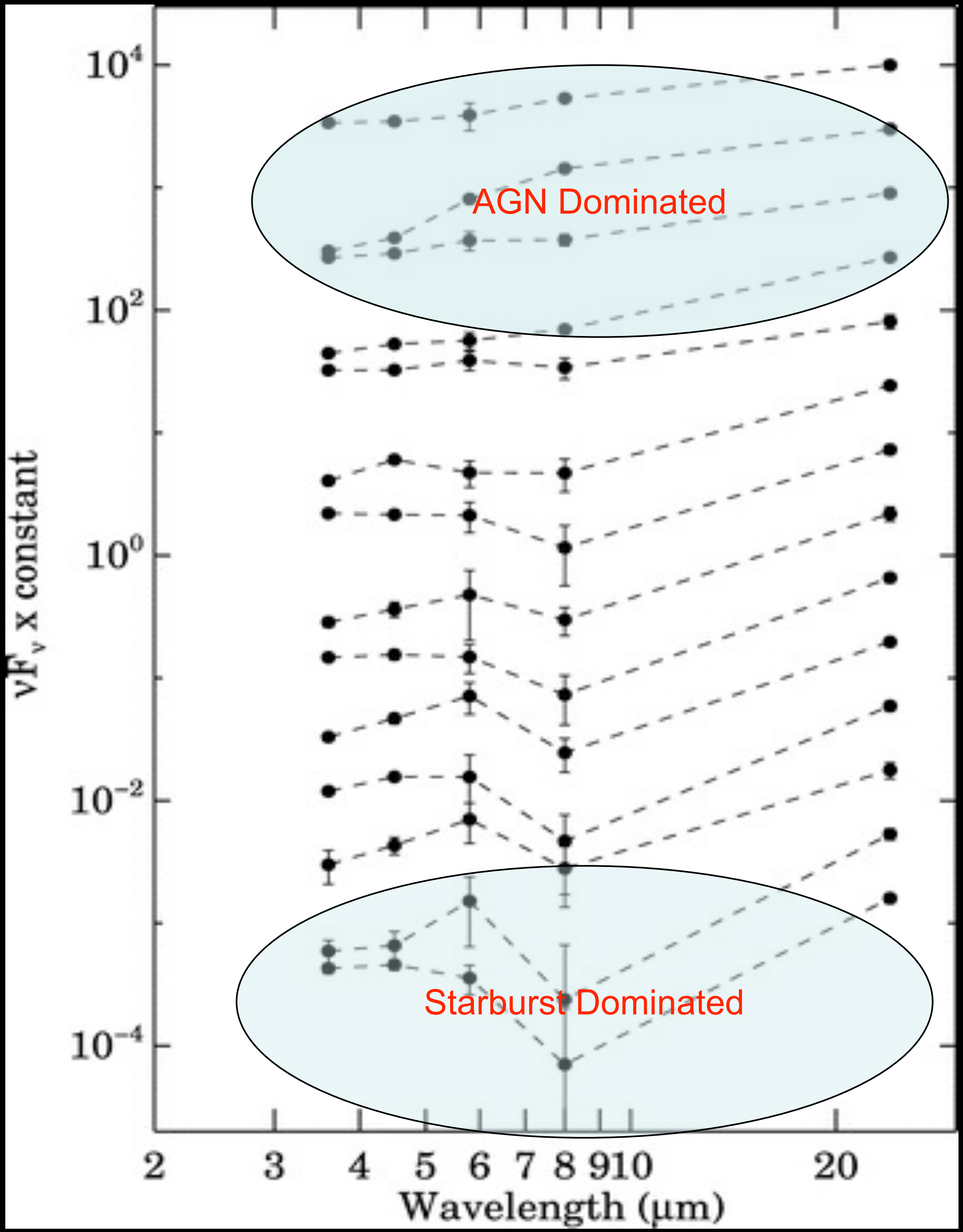
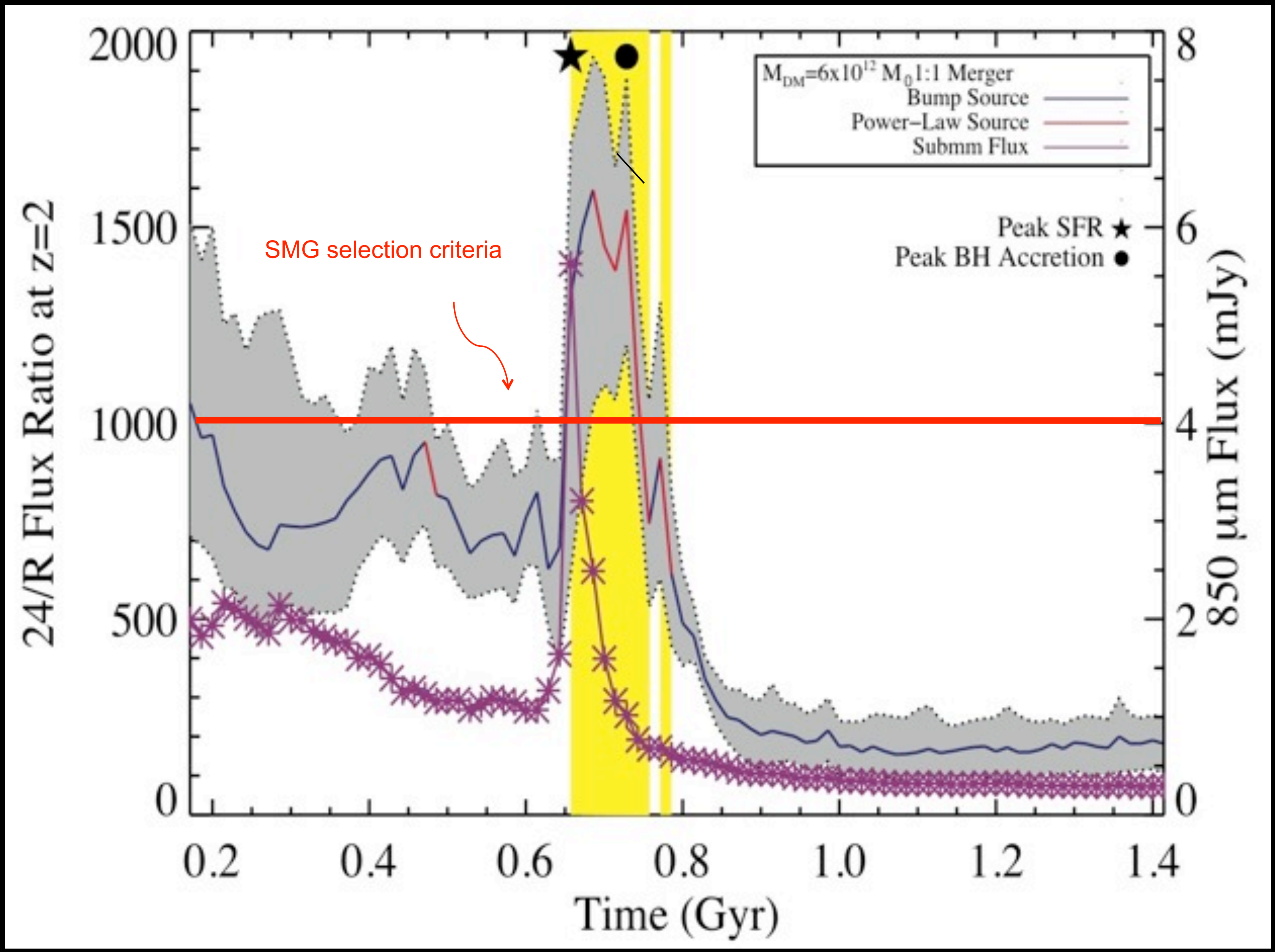
What is a DOG?

- Other ways to select high-z, dusty galaxies include 24 micron selection
- Dust-obscured galaxies (DOG): 24-micron selected; require to be optically faint ($F_{24}/F_R > 1000$) (Dey+08)
- Classified via MIR spectra as "bump" or "power-law"; idea is that rest-frame 1.6 μm bump can be used to distinguish starbursts from AGN
- What type(s) of galaxies does a 24-micron selection select?
- How are DOGs related to SMGs?



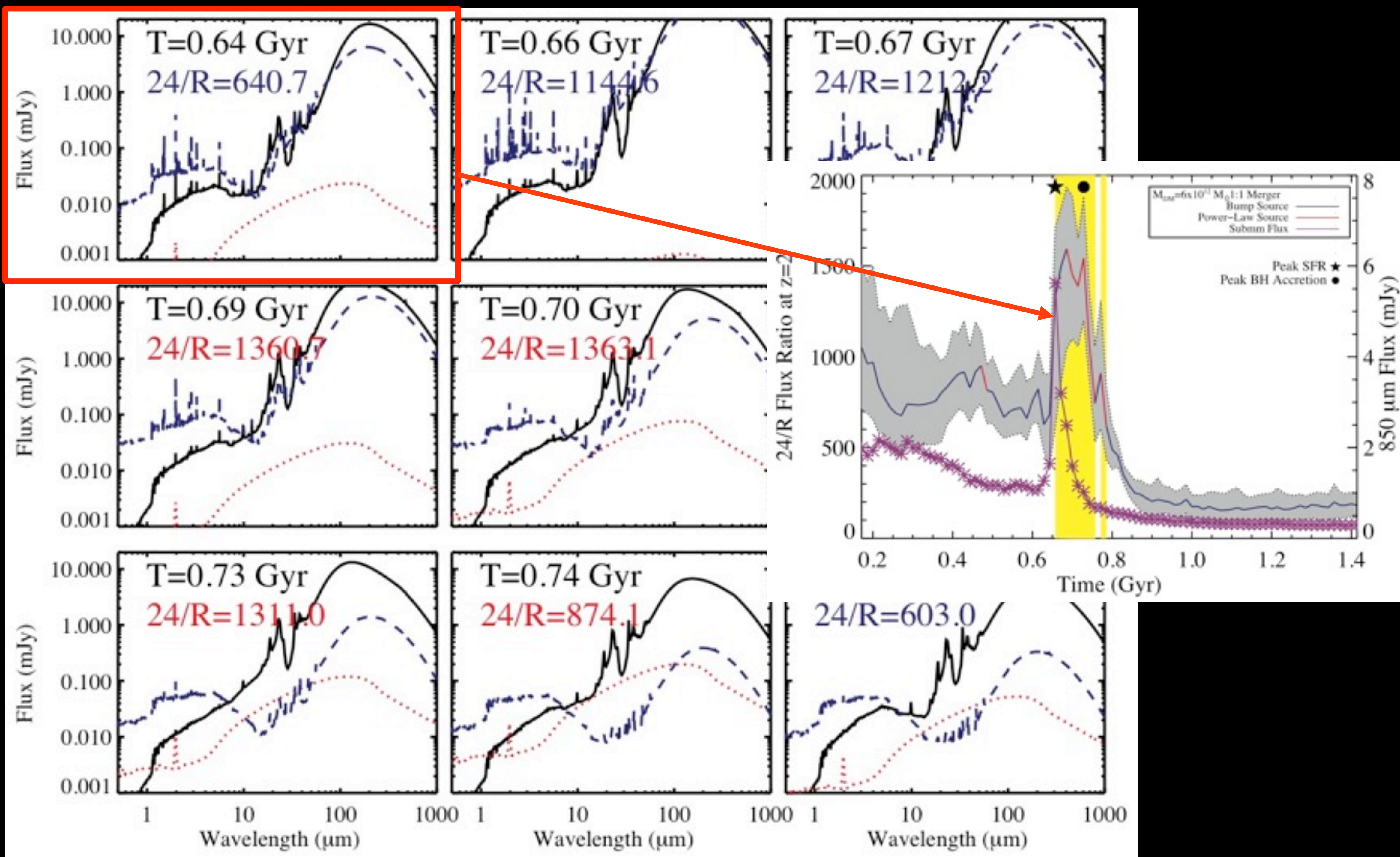
Dey+08

SMGs vs. DOGs



Narayanan, Dey, CCH+10

“Bump” DOG



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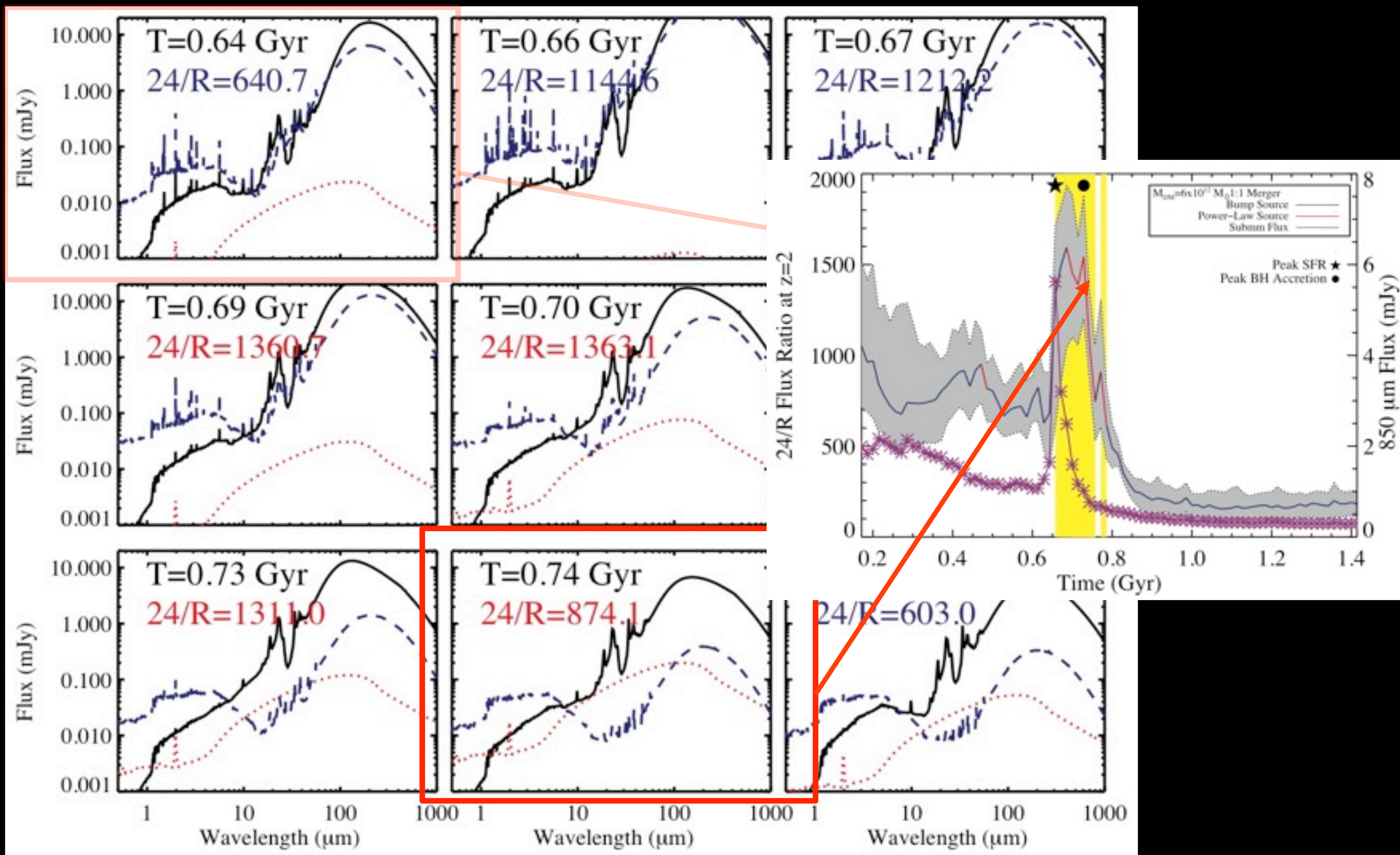
"Power-law" DOG - AGN



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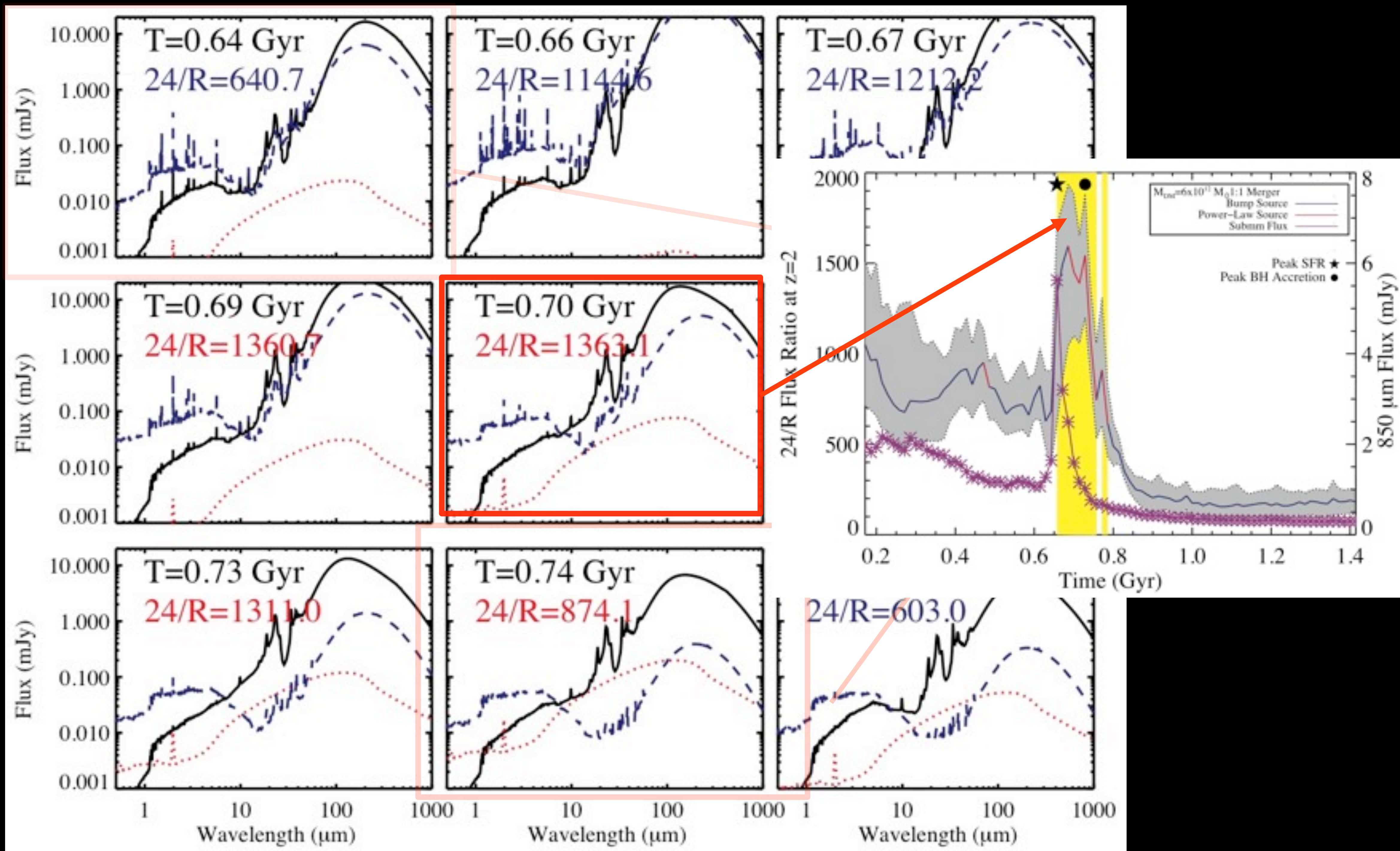
“Power-law” DOG - Starburst



Narayanan, Dey, CCH+10

Summary

- For the first time we have combined semi-empirical merger rates + high-res SPH sims + 3-D RT w/ full dust T calculation to predict SMG number counts
- Mergers create SMGs via 2 effects (SMGs are bimodal population):
  1. Pre-coalescence: sum of two massive gas-rich progenitors in beam
  2. Increase in luminosity owing to merger-induced burst (but mitigated by increase in dust T owing to rapid gas consumption)
- It is possible to match SMG number counts w/ Kroupa IMF
- SMGs tend to be DOGs, but most DOGs are not SMGs
- Power-law SED in MIR does not imply AGN dominance