

The Formation and Evolution of Submillimeter Galaxies

The Team:

Chris Hayward



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Josh Younger



Shane Bussmann



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Mark Brodwin



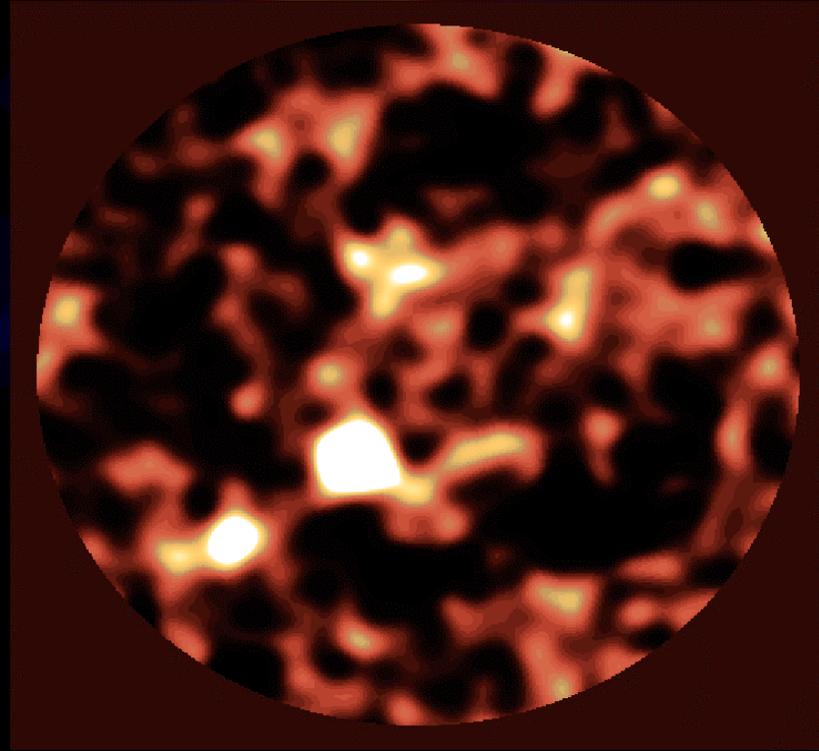
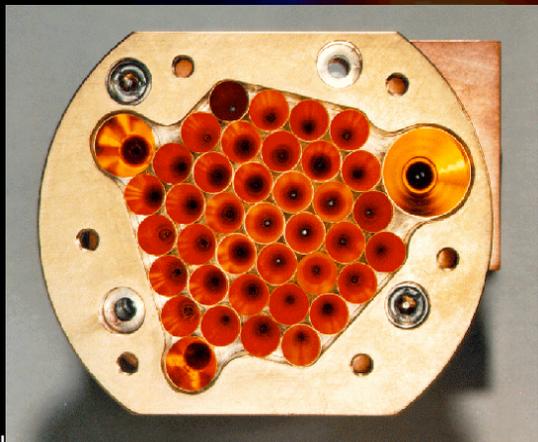
Arjun Dey



Lars Hernquist



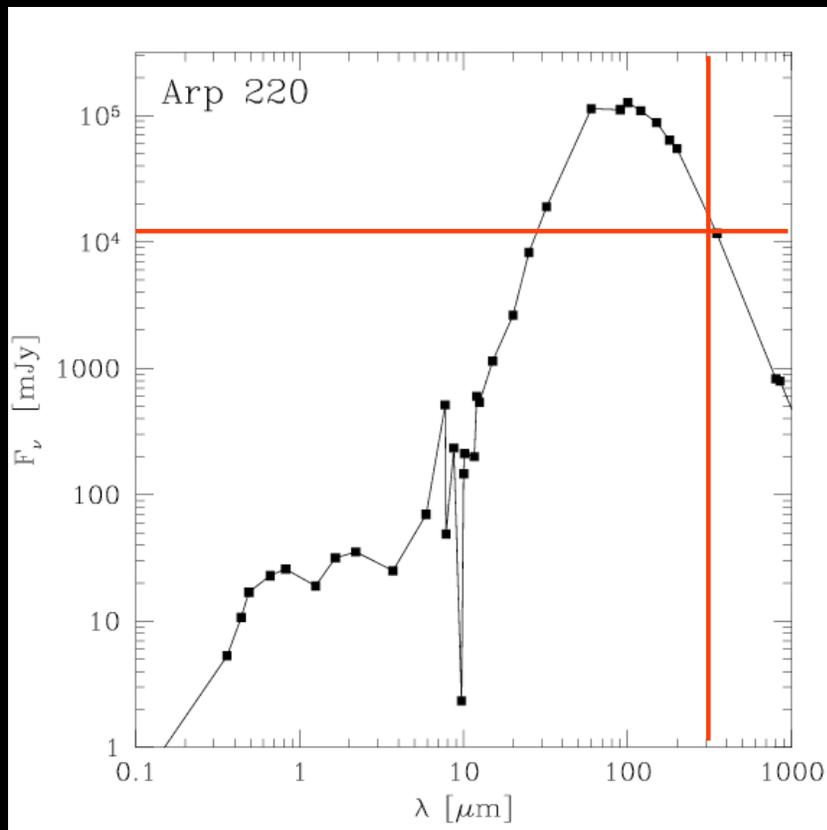
Discovery History



Barger et al., Hughes et al.
 $S_{850} = 5-20 \text{ mJy}$

The Incredible Fluxes from SMGs:

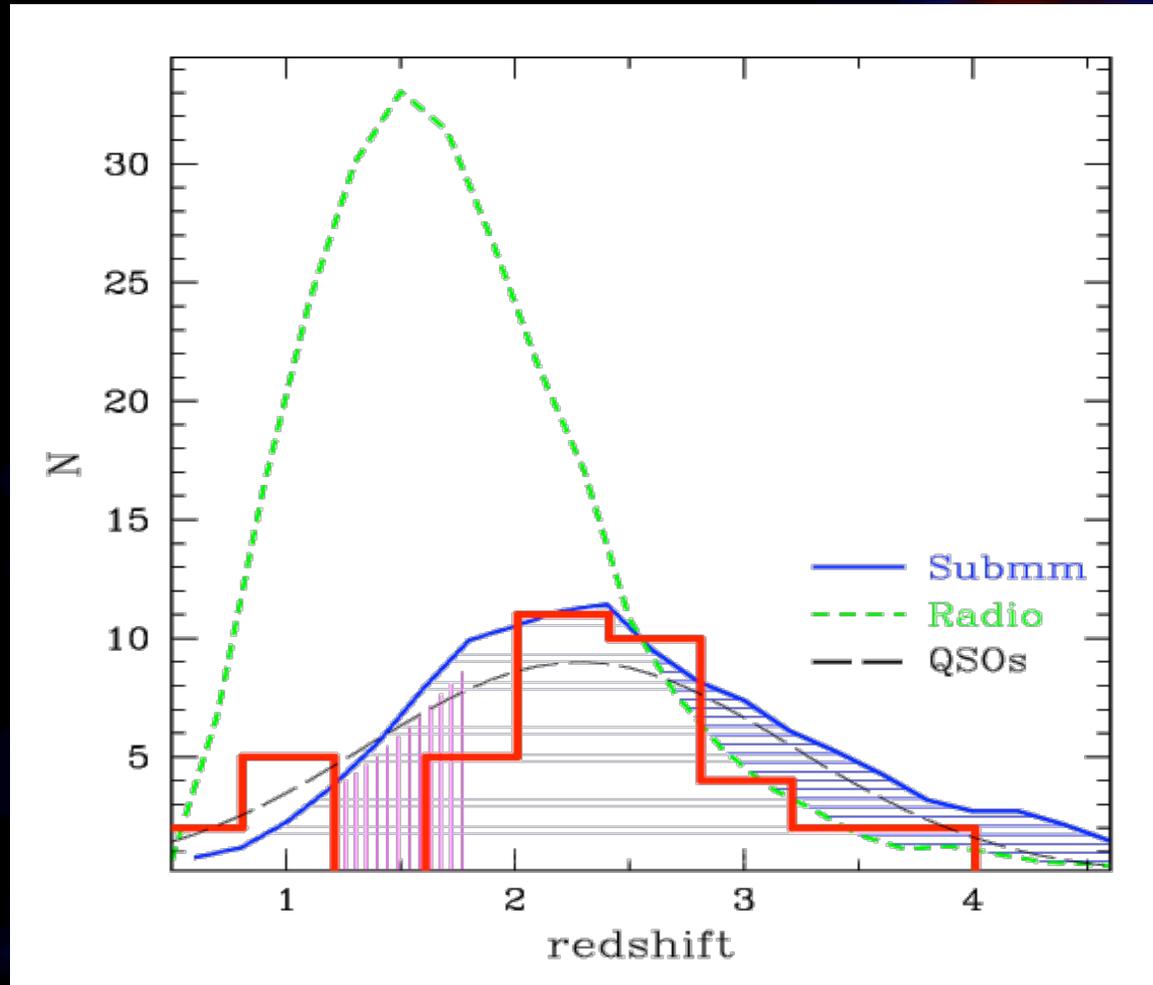
Selected at $S_{850} > 5$ mJy, though some seen up to $S_{850} \sim 20$ mJy (and brighter!) (e.g. Vieira et al. 2009)



~0.7 mJy source
 $z \sim 2.4$

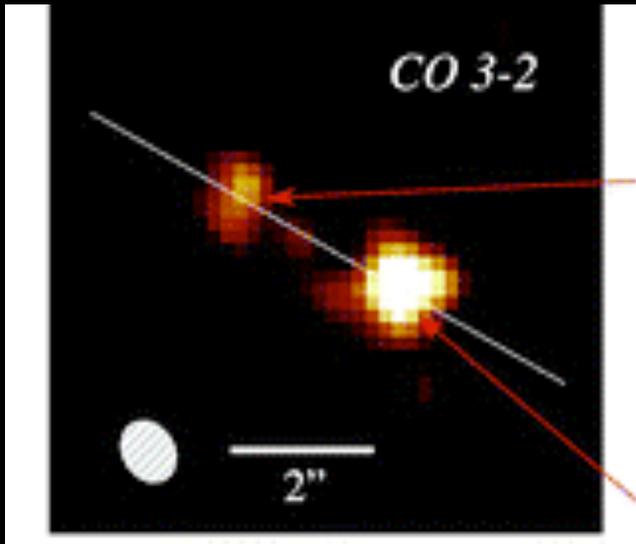


What do we Know about SMGs: Redshift Distribution: $z \sim 2$ Sources

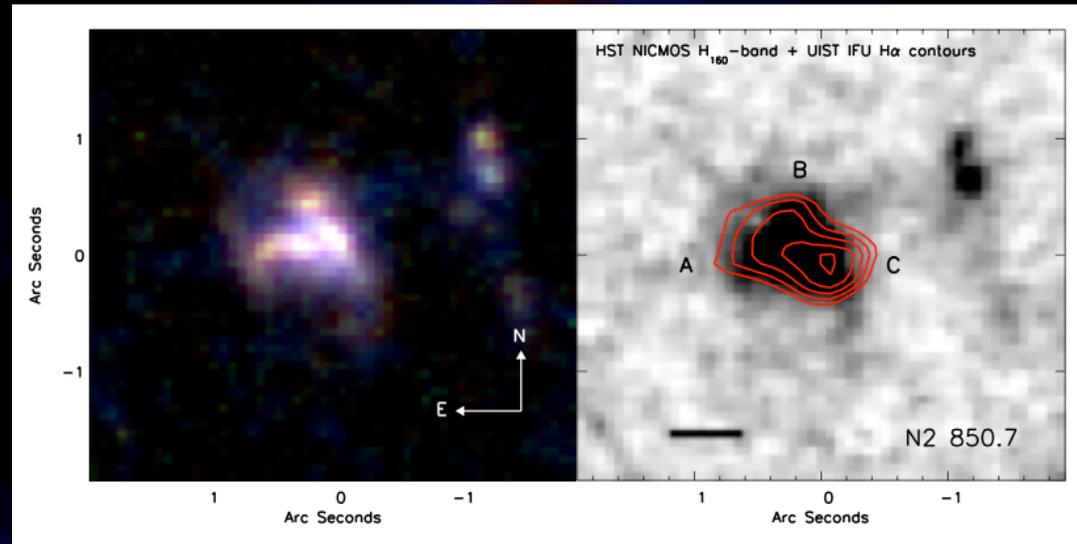


Chapman et al. (2004)
- with a high- z ($z > 4$) tail (Younger et al. 2008)

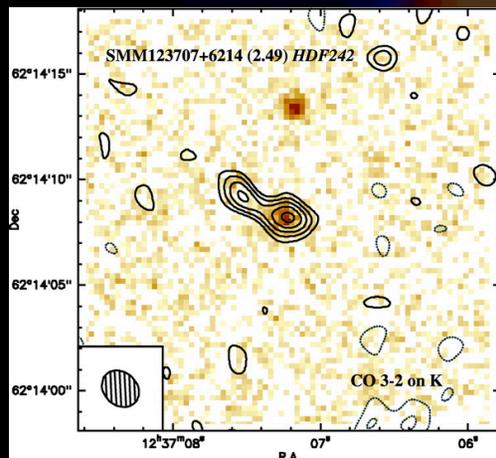
What do we Know about SMGs: Mergers?



CO 3-2: Tacconi et al. 2008



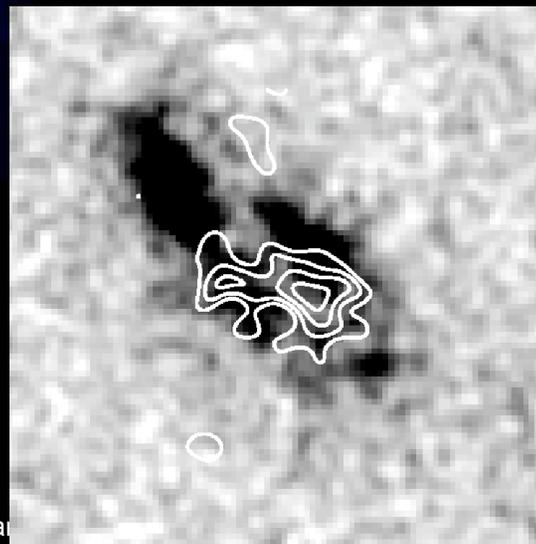
IFU UV (rest-frame): Swinbank et al. 2006



K-band + CO 3-2; Tacconi et al. 2006

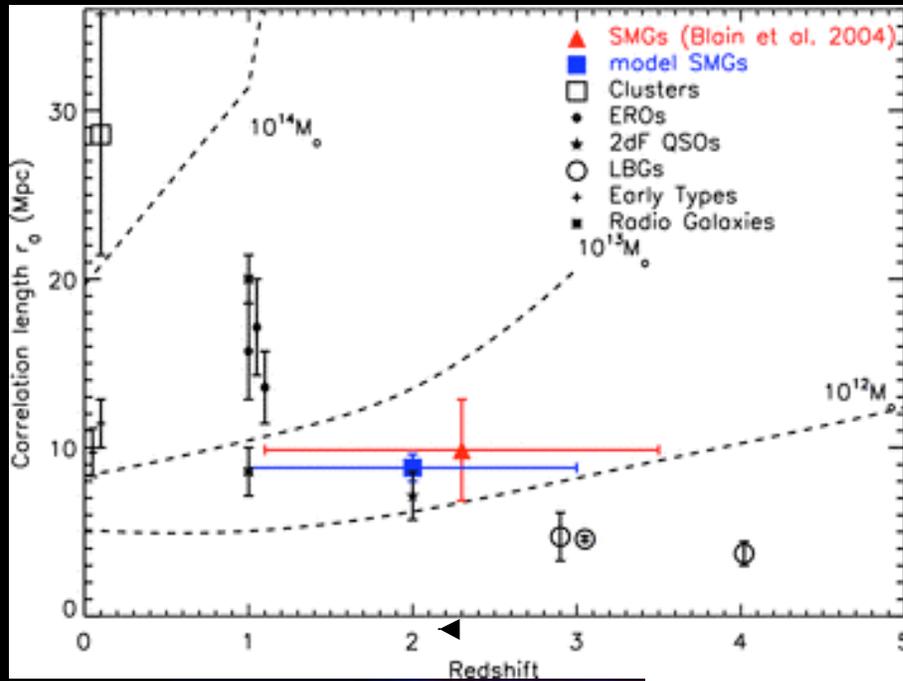
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HST+VLA:
Chapman + 2005

Halo, Stellar Masses - Tip of the Iceberg

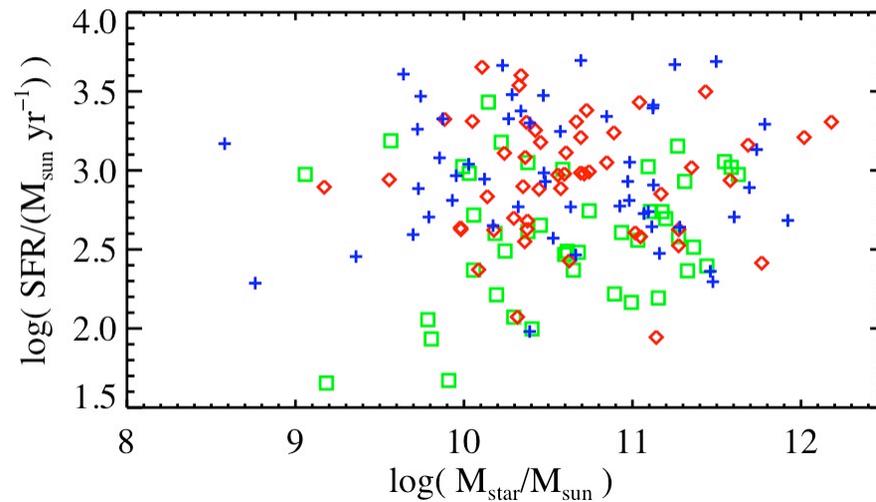


Halos few $\times 10^{12} M_{\odot}$

Swinbank+ 2008
Blain et al. 2004

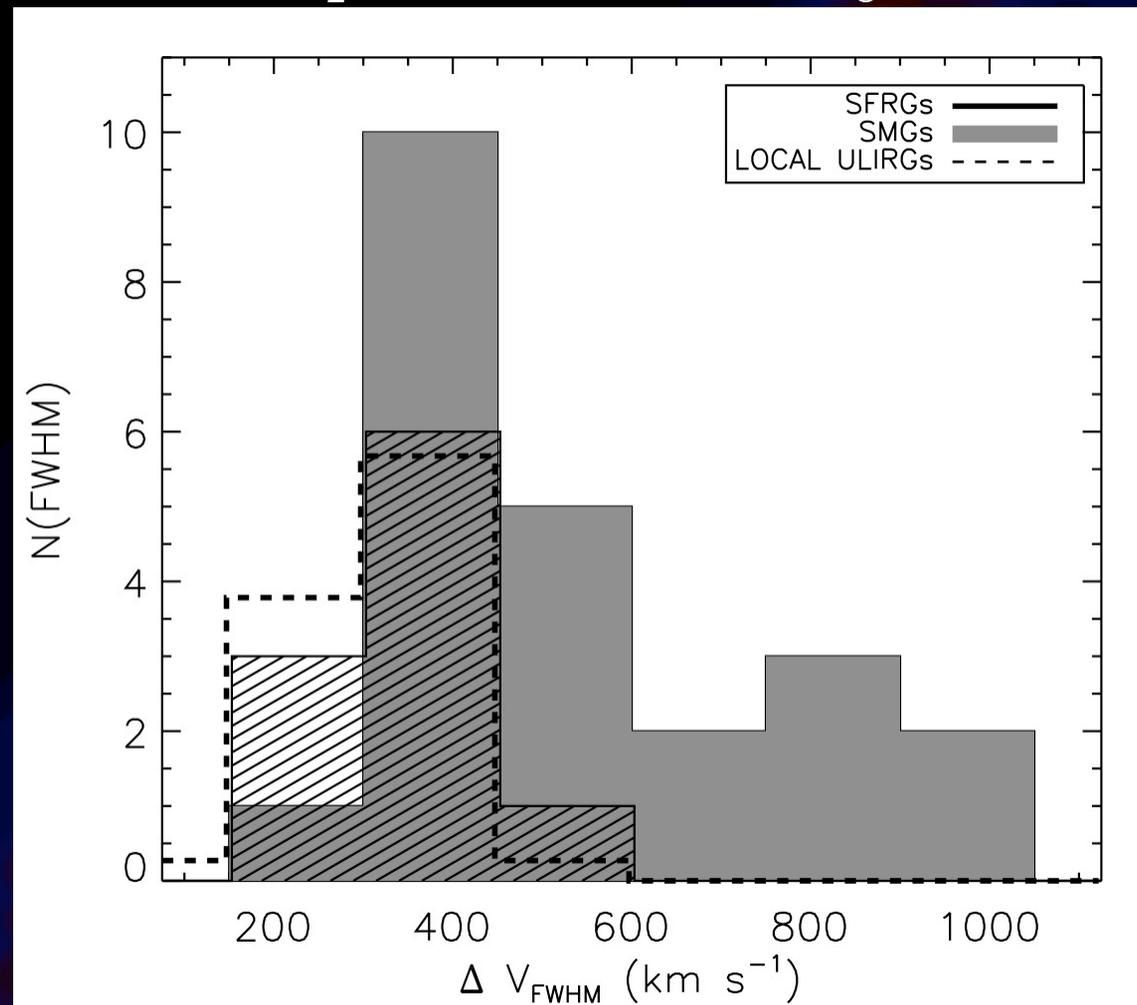
Stars few $\times 10^{11} M_{\odot}$

Shane Bussmann et al. in prep.
Pope et al., Borys et al,
Hainline et al., Michalowski et al....



Incredibly Gas Rich with very broad CO lines

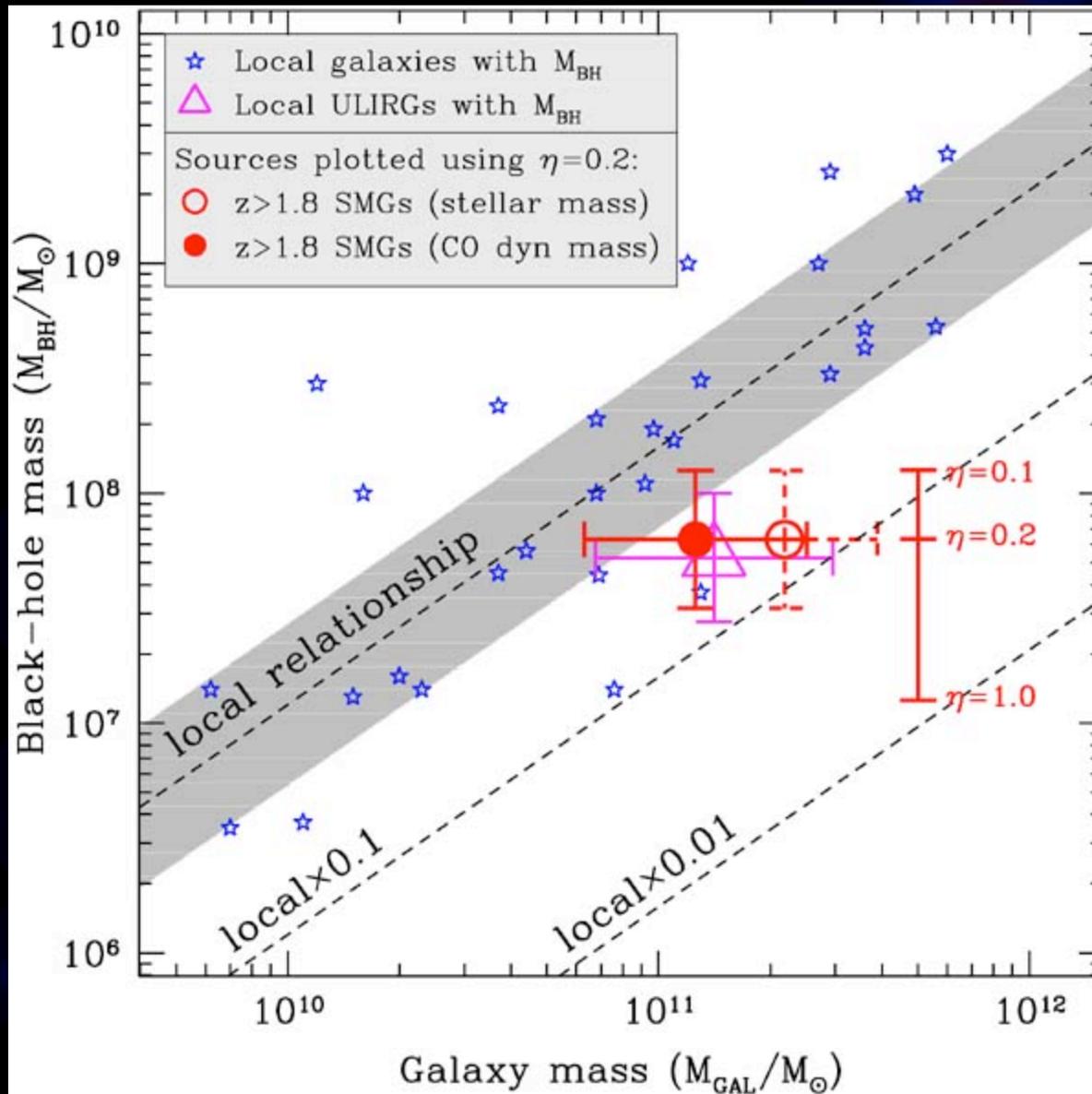
$-H_2$ masses $\sim 5 \times 10^{10} M_{\odot}$



Casey et al. 2009

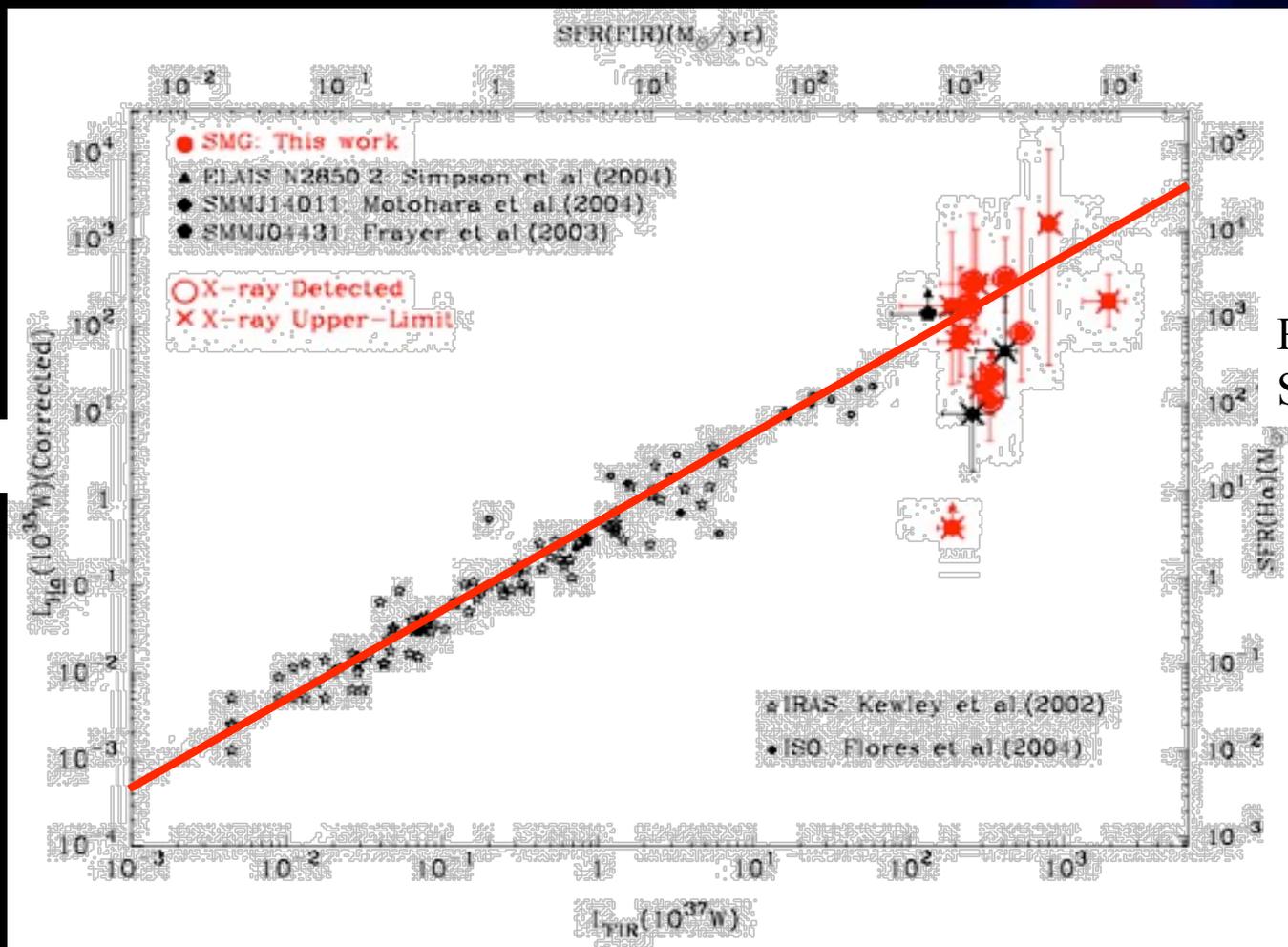
Greve et al, 2005; Coppin et al. 2008,
Tacconi et al. 2006, 2008

M^*-M_{BH} relation



Huge Star Formation Rates (and power source)

H α

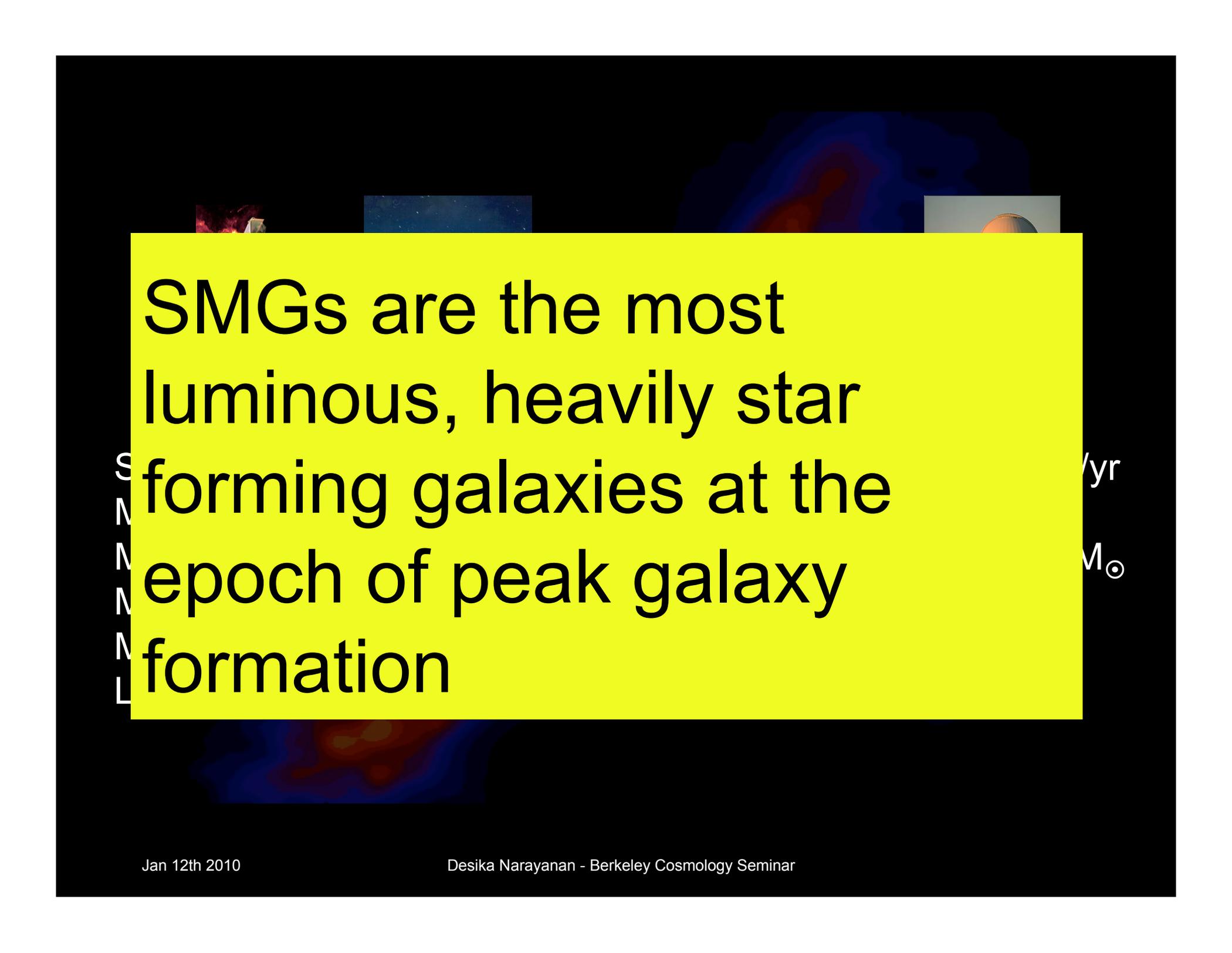


Reddening-corrected SFR

FIR

Tight correlation between H α and FIR suggests star formation origin for large IR luminosity

Swinbank et al. (2004); also Alexander+, Menéndez-Delmestre+ for similar conclusions



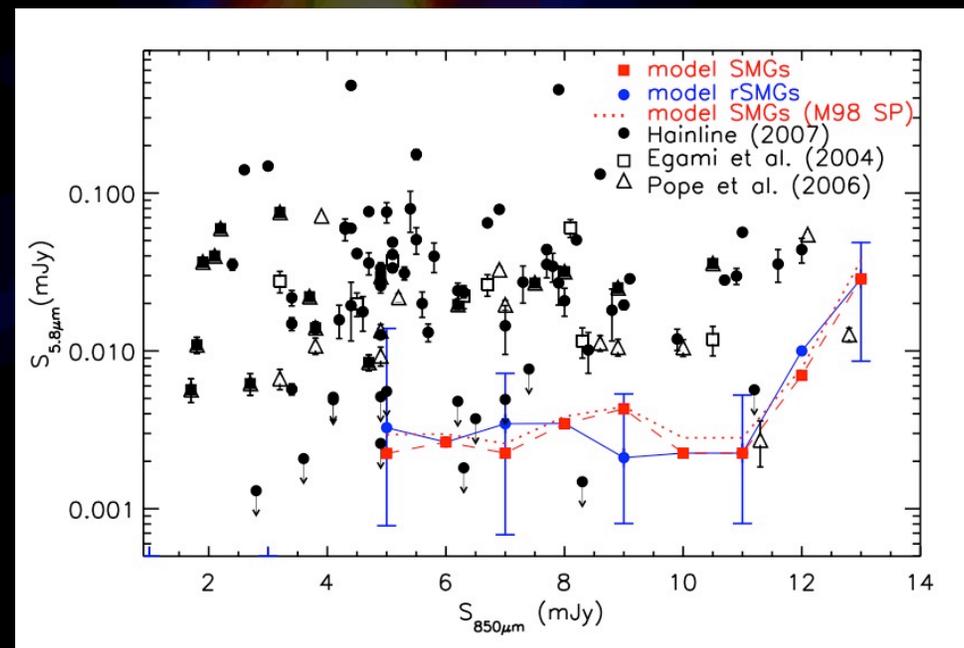
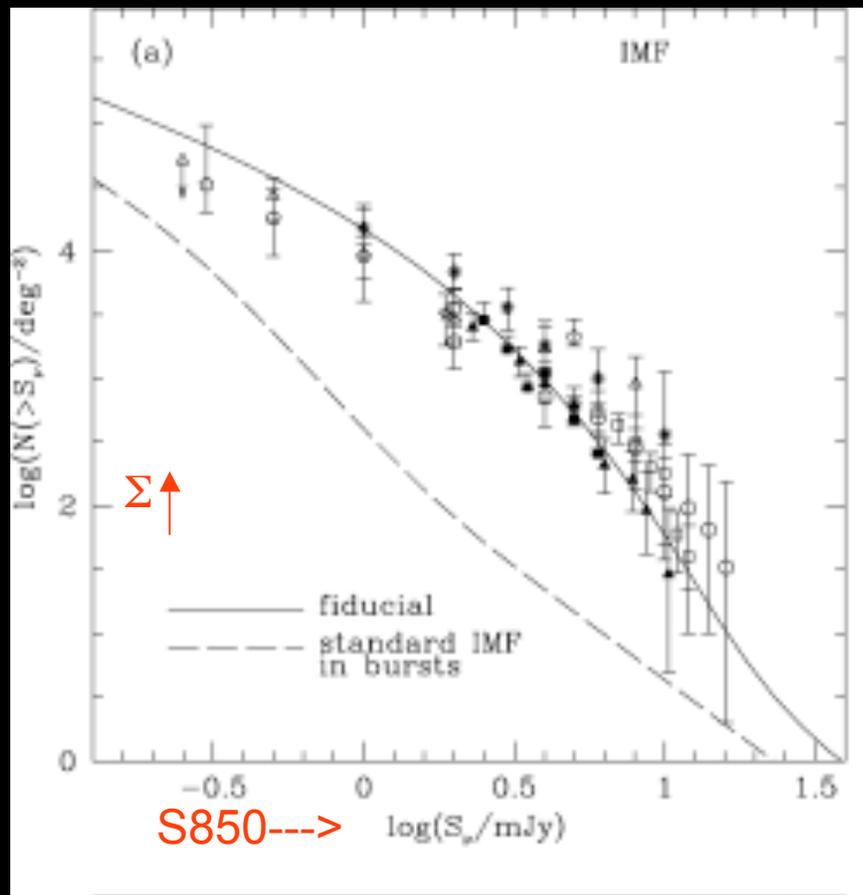
SMGs are the most
luminous, heavily star
forming galaxies at the
epoch of peak galaxy
formation

/yr
 M_{\odot}

Forming SMGs: Keeping Theorists up at Night

SAMs + RT:

Mergers + Flat IMF: $dn/d\ln(m) \sim m$



Swinbank et al. 2008

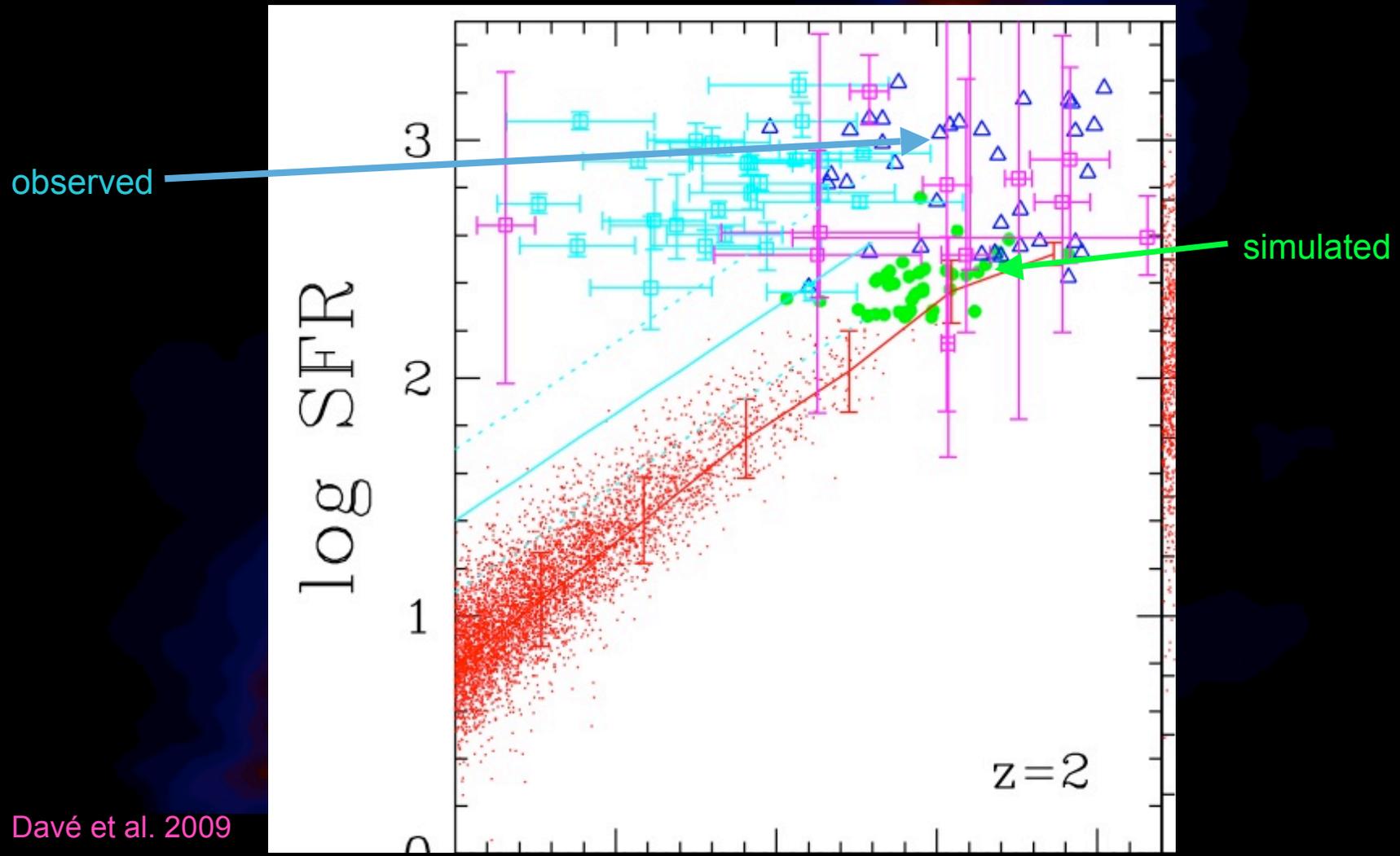
Baugh et al. 2004

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Forming SMGs: Keeping Theorists up at Night

Cosmological Hydrodynamic Simulations:
Non-mergers (Harassment); low SFRs



Davé et al. 2009

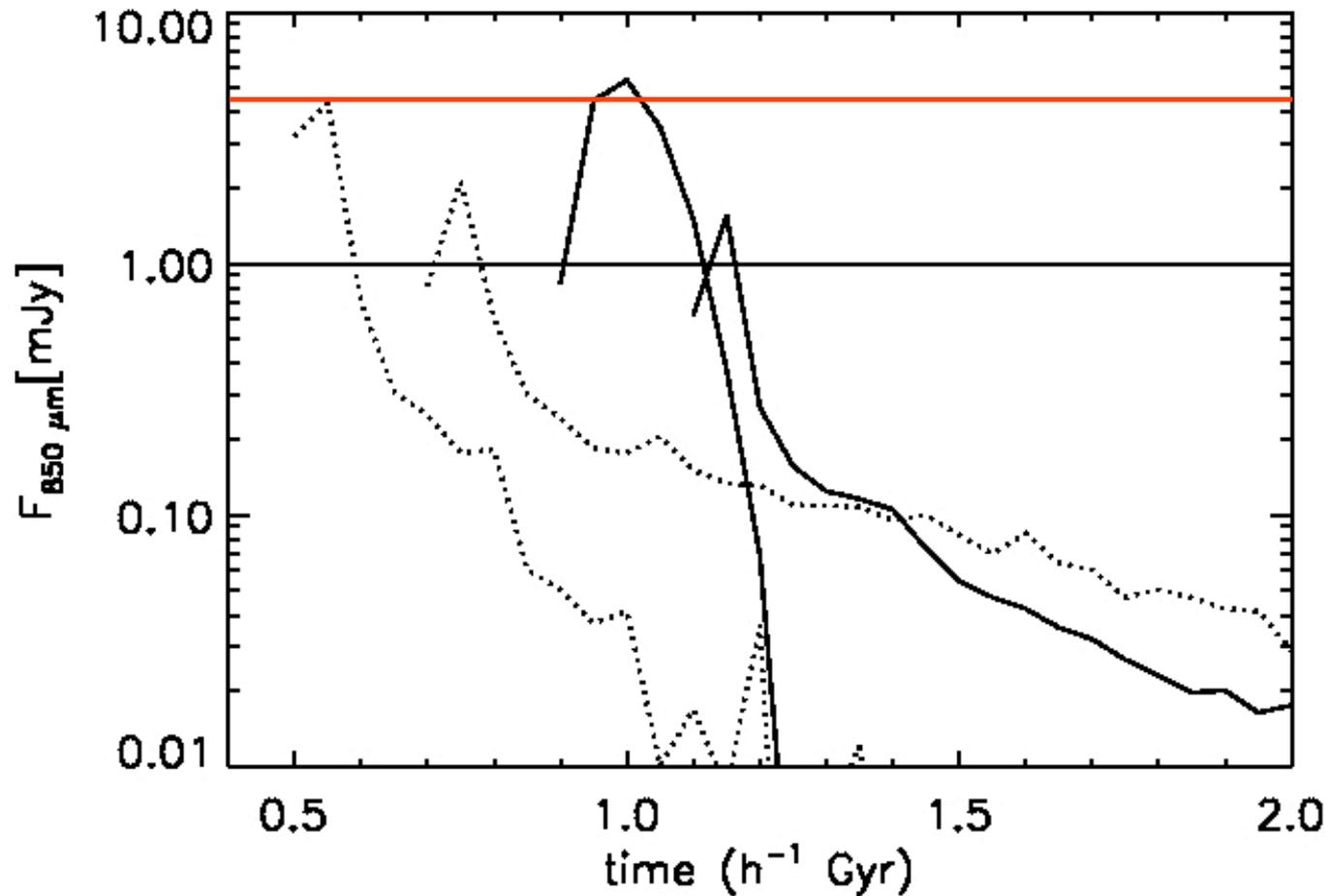
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Forming SMGs: Keeping Theorists up at Night

Cosmological Hydrodynamic Simulations:
Non

observe



simulated

Forming SMGs: Keeping Theorists up at Night

Cosmological Hydrodynamic Simulations

Bottom Up (instead of Top Down)

1. Hydrodynamically simulate galaxies in evolution - isolated galaxies and mergers at $z \sim 3$
 2. Apply dust radiative transfer modeling to analyze the synthetic SEDs
 3. Convolve with galaxy merger rates and mass functions to get cosmological statistics
- *has advantage of maintaining relatively high (~ 50 pc) spatial resolution, allowing us to dissect properties of galaxies

Dave et al. 2009

Stellar Mass ---->

Forming SMGs: Keeping Theorists up at Night

Cosmological Hydrodynamic Simulations

Bottom Up (instead of Top Down)

1. Develop physical model for SMGs
2. Compare with Observations
 - a. Assess validity of model
 - b. Understand relationship to other populations
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4. Develop observational tests of model

Dave et al. 2009

Stellar Mass ---->

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GADGET (SPH) + SUNRISE (IR)+ Turtlebeach (Molecular Line)

Physics Included in Hydrodynamics:

- numerically follows DM, Gas, Stars and BH dynamics
- Multi-phase McKee-Ostriker ISM
- Star formation follows KS relations
 - 1.5 power, though see Bouché et al. 2007 Bothwell et al. 2009
- BH growth and associated AGN feedback
- Supernovae pressurization of ISM
- Halo Masses: 10^{12} - $10^{13} M_{\odot}$
- MMW Disks
- 1:1 --> 1:10 mergers and isolated (1: ∞)

There used to be movies here...

GADGET (SPH) + SUNRISE (IR) + Turtlebeach (Molecular Line)



Physics Included in Monte Carlo IR RT:

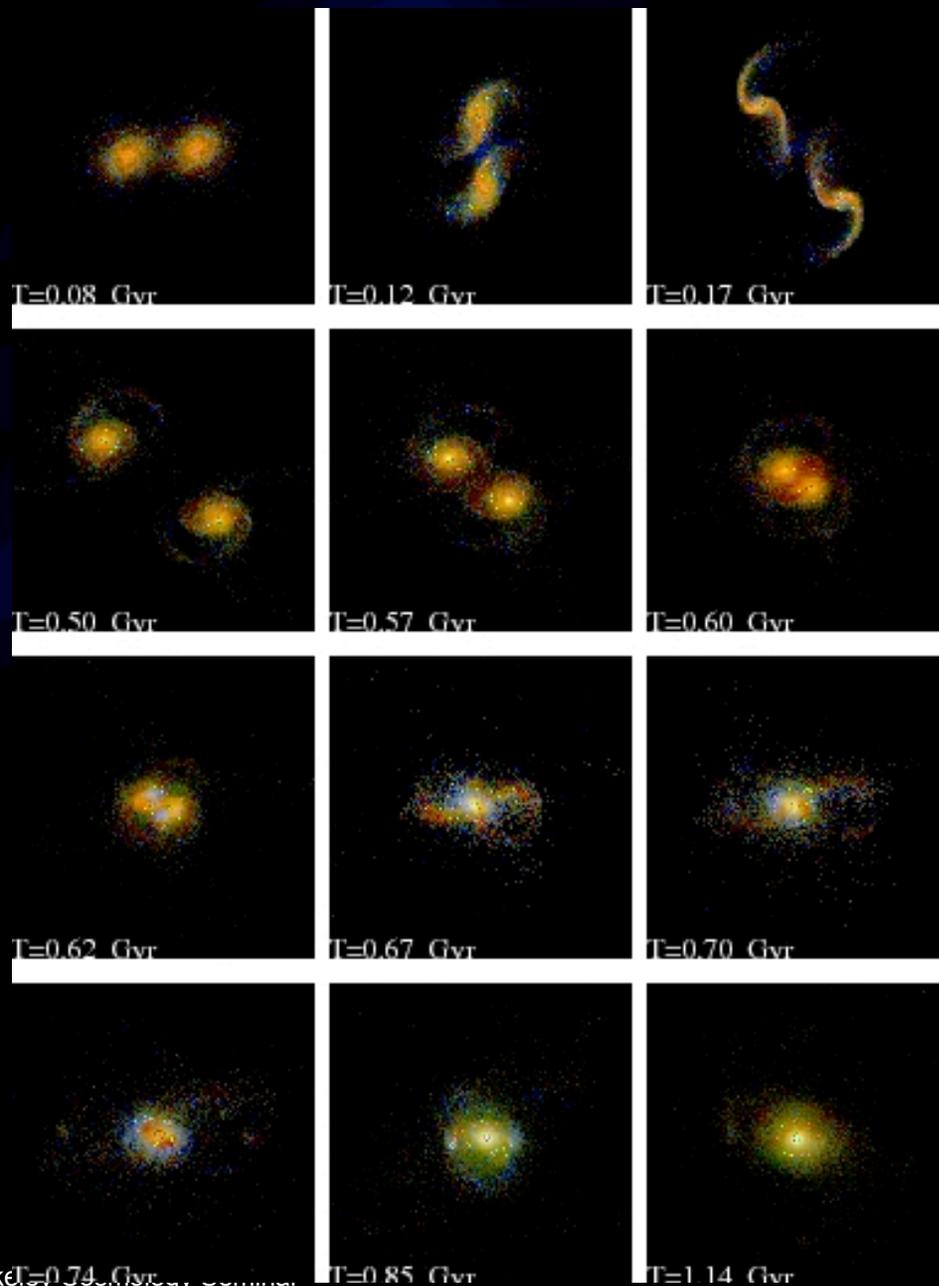
-IR transfer of stellar and AGN spectrum (starburst 99 for stars and Hopkins+ 07 for AGN)

-dust radiative equilibrium

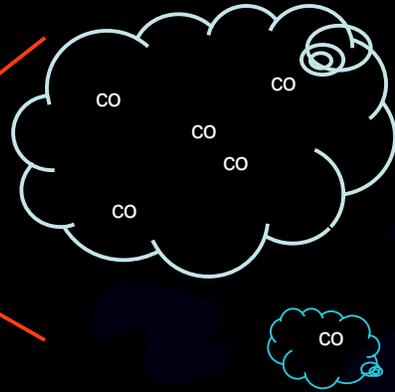
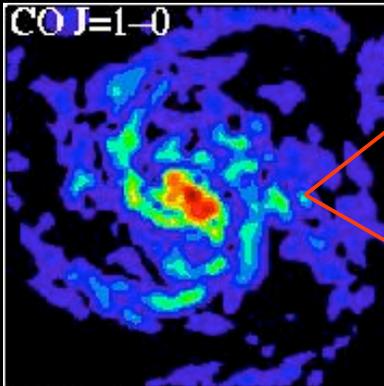
-Kroupa IMF, ULIRG/SMG DTG (same as MW DTM)

-Stellar Clusters surrounded by HII regions and PDRs (MAPPINGS; Groves et al. 2008)

Jonsson, Groves & Cox (2009)



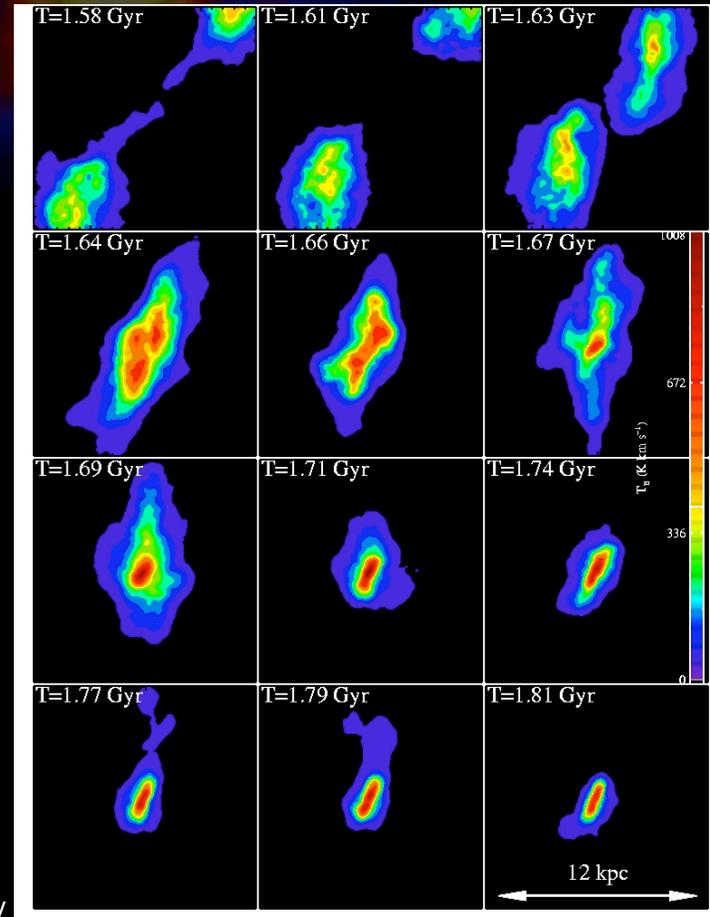
GADGET (SPH) + SUNRISE (IR) + Turtlebeach (Molecular Line)



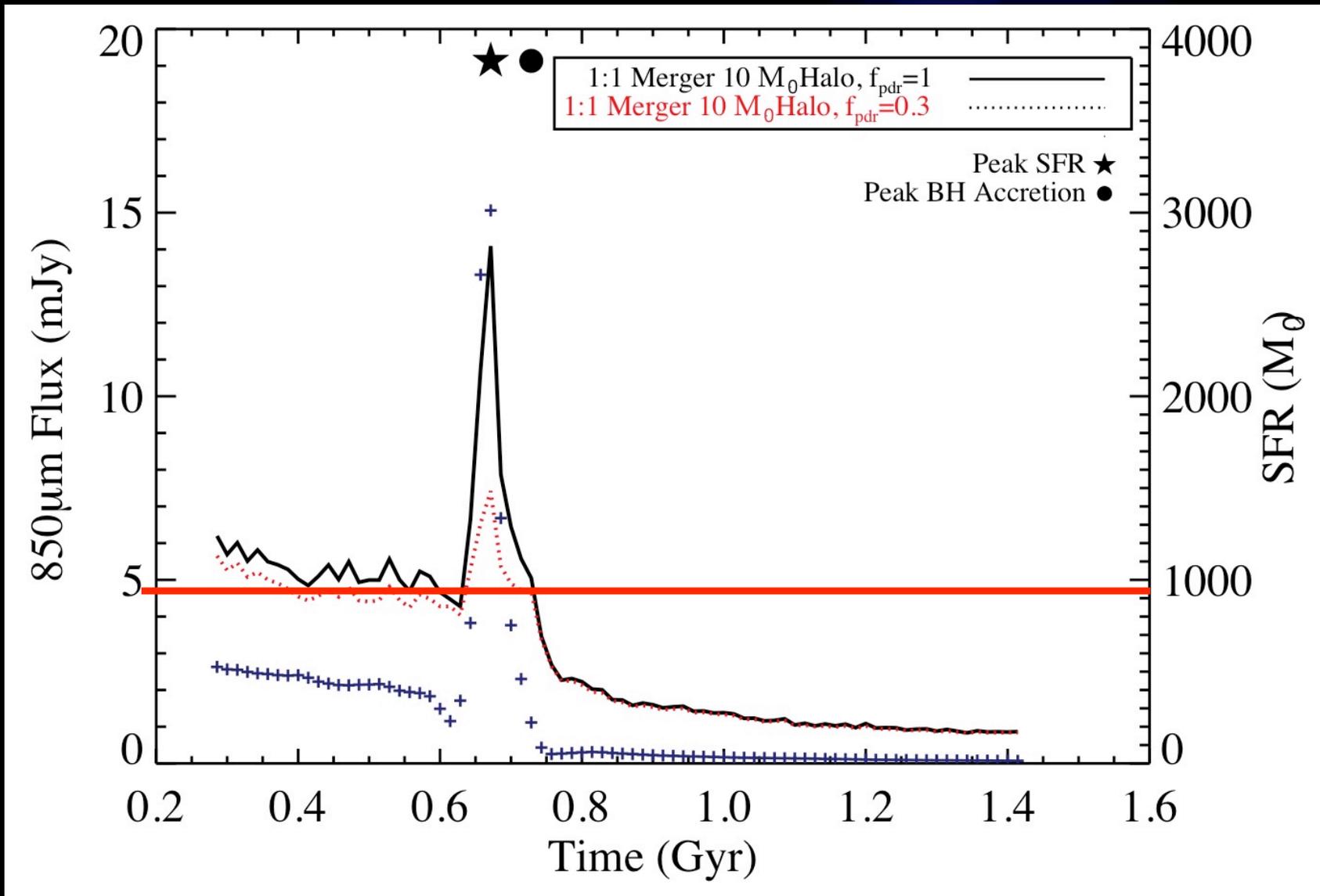
Narayanan, Cox et al. (2008)

Physics Included in Monte Carlo CO RT

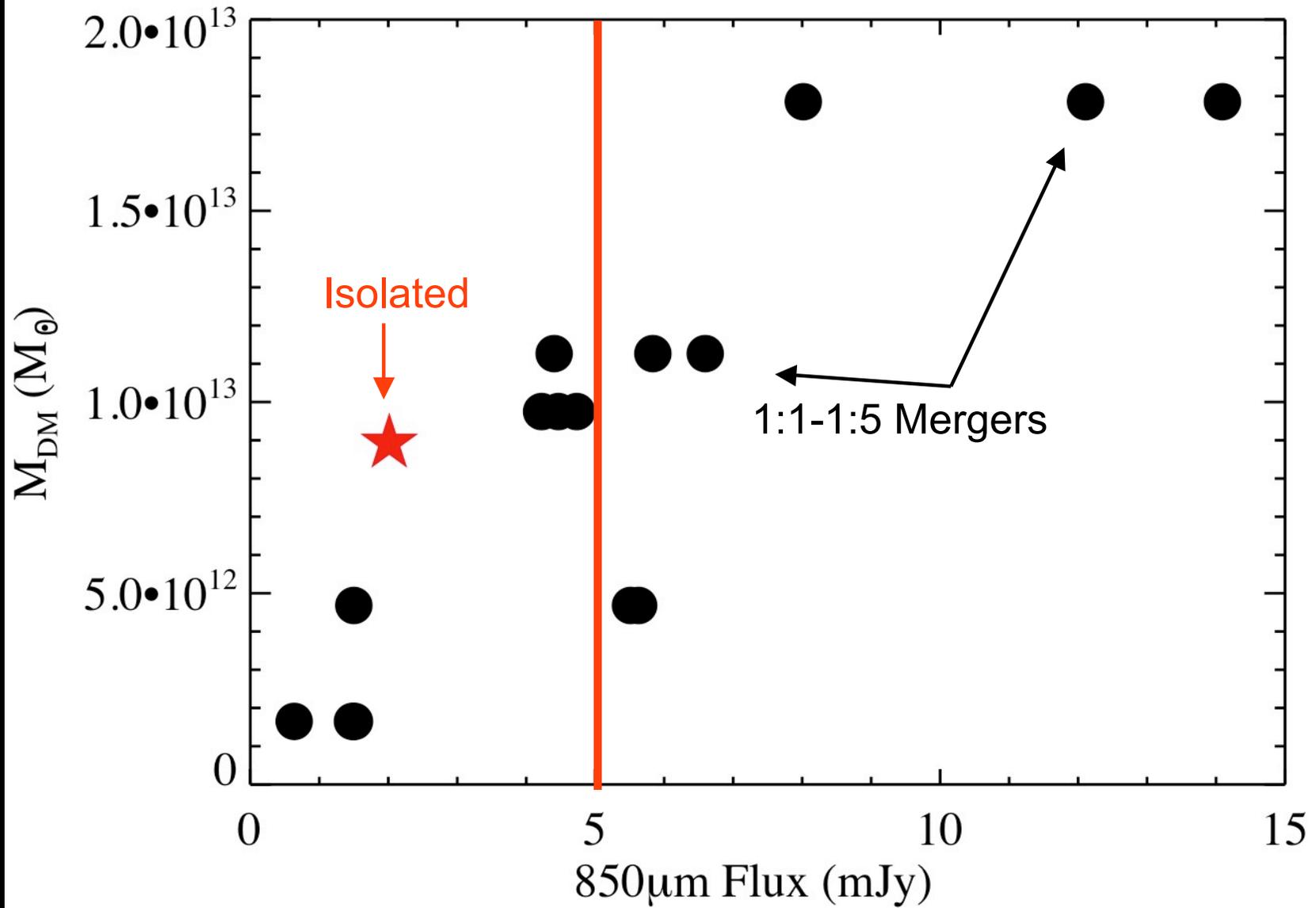
- Mass spectrum of GMCs included as SISs
- Molecular statistical equilibrium (collisions and radiation)
- Pressure-driven H₂ formation/destruction (based on observations of local galaxies) (Blitz & Rosolowsky 2006)
- Milky Way Abundances for CO



The Physical Model: SMGs form in Mergers



The Physical Model: SMG form in Mergers

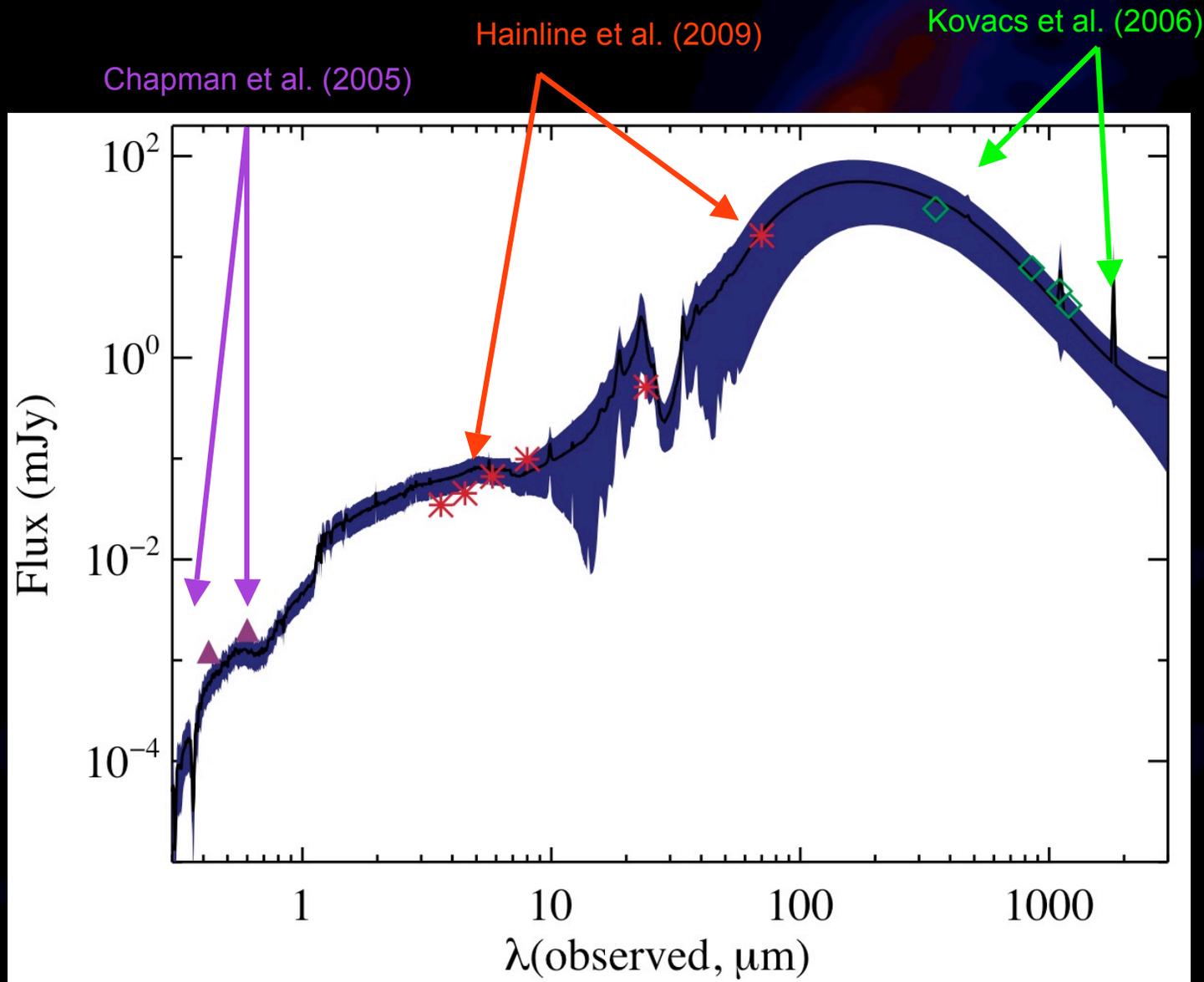




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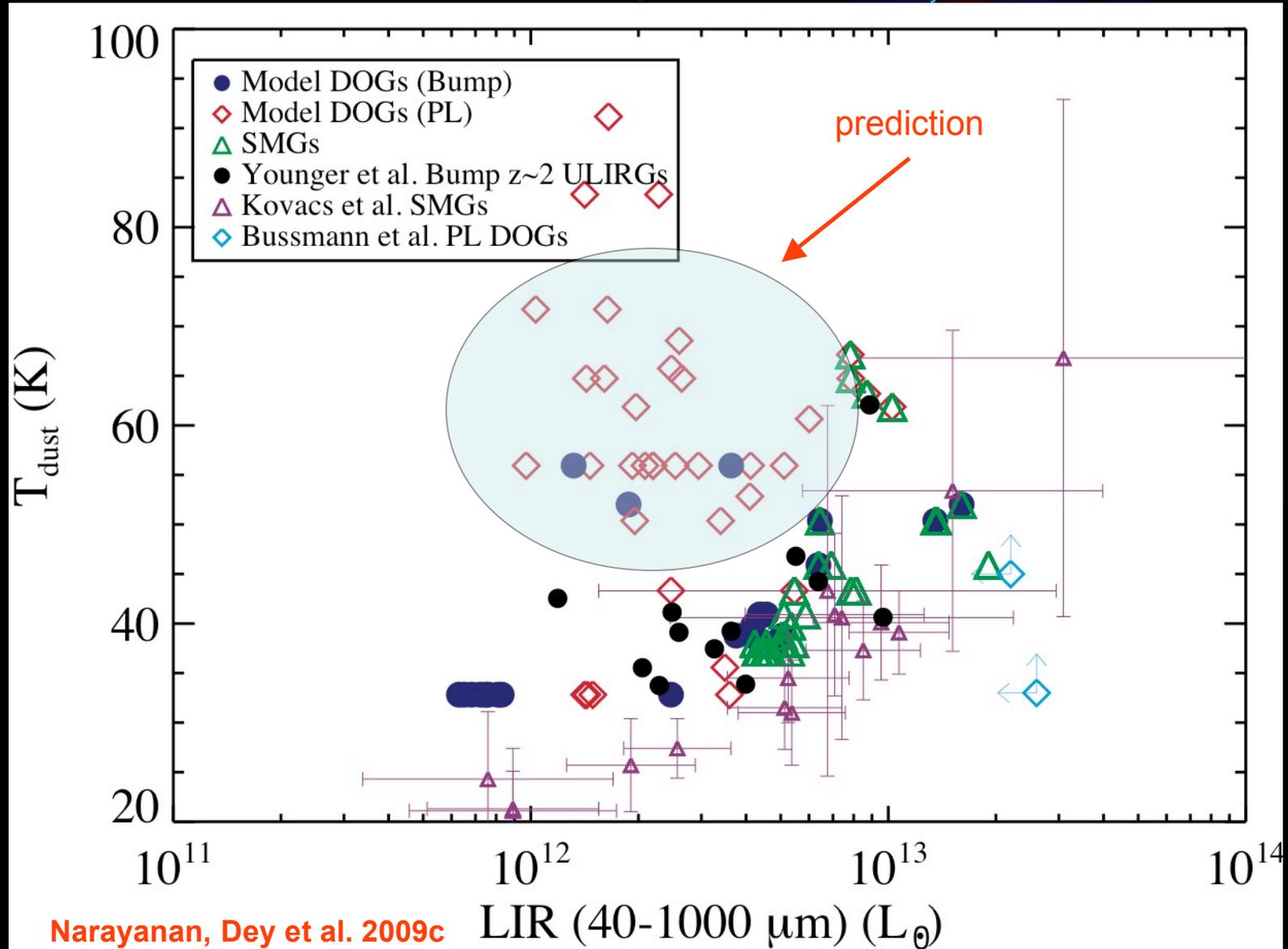
Model Validation: SEDs



Model Validation

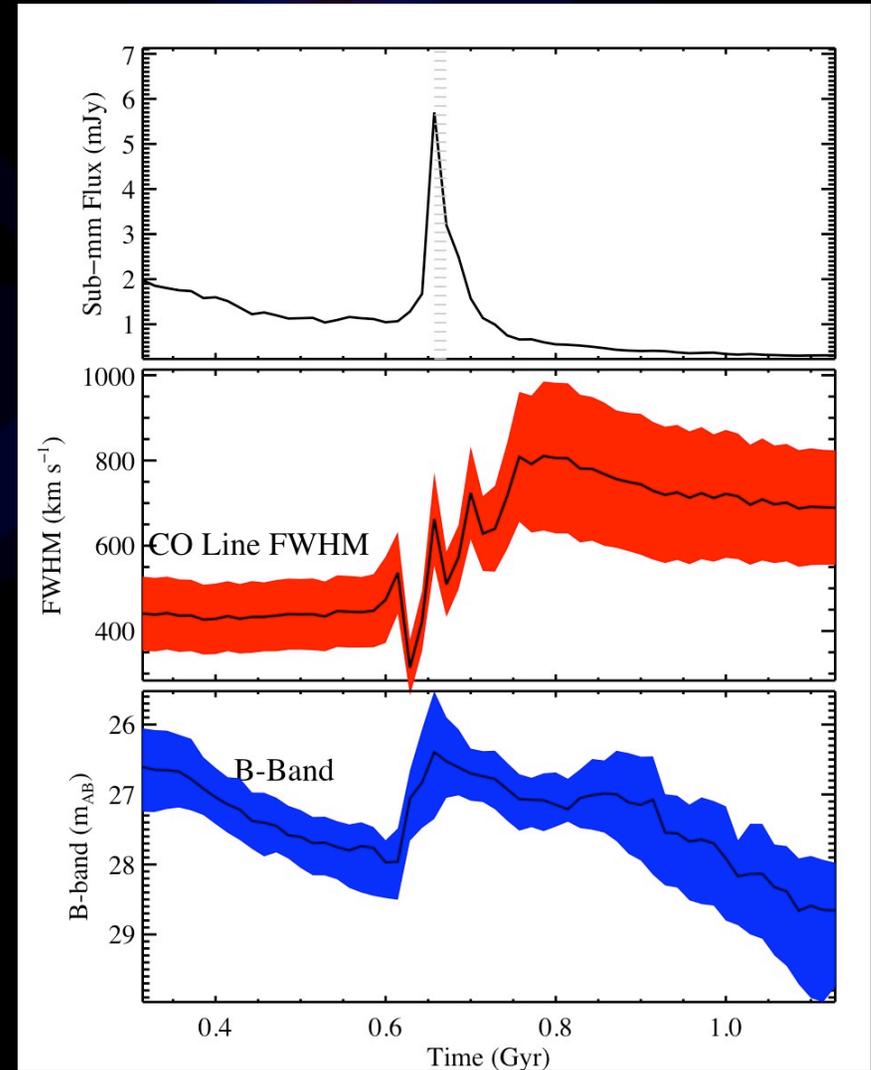
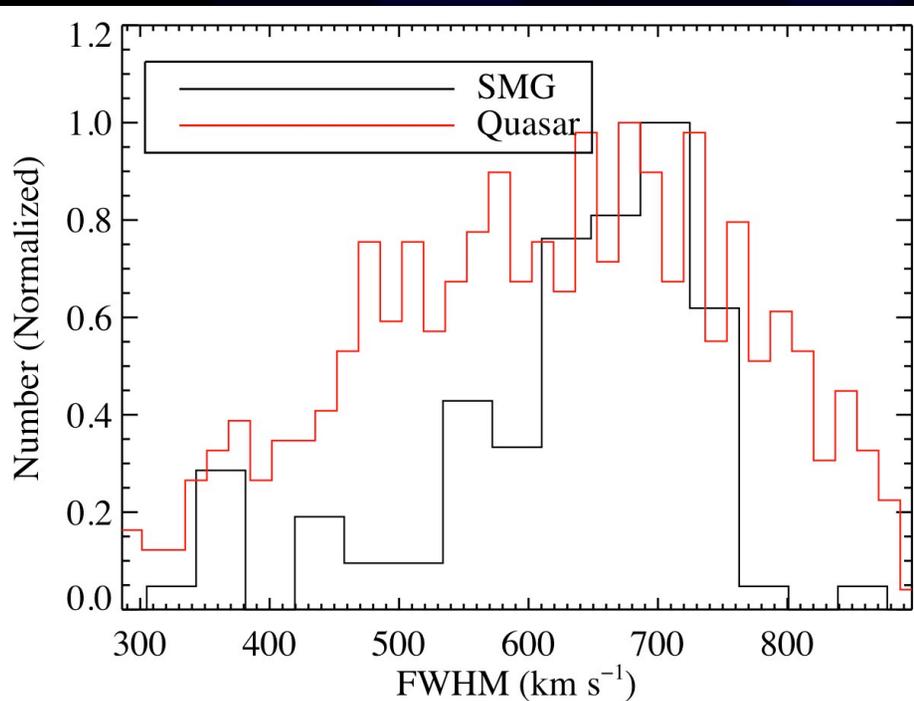
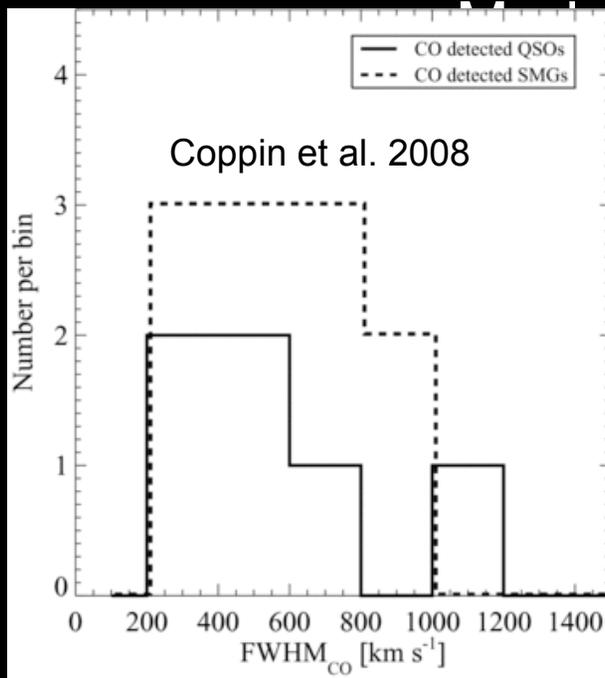
Dust Temperatures

Narayanan et al 2009c



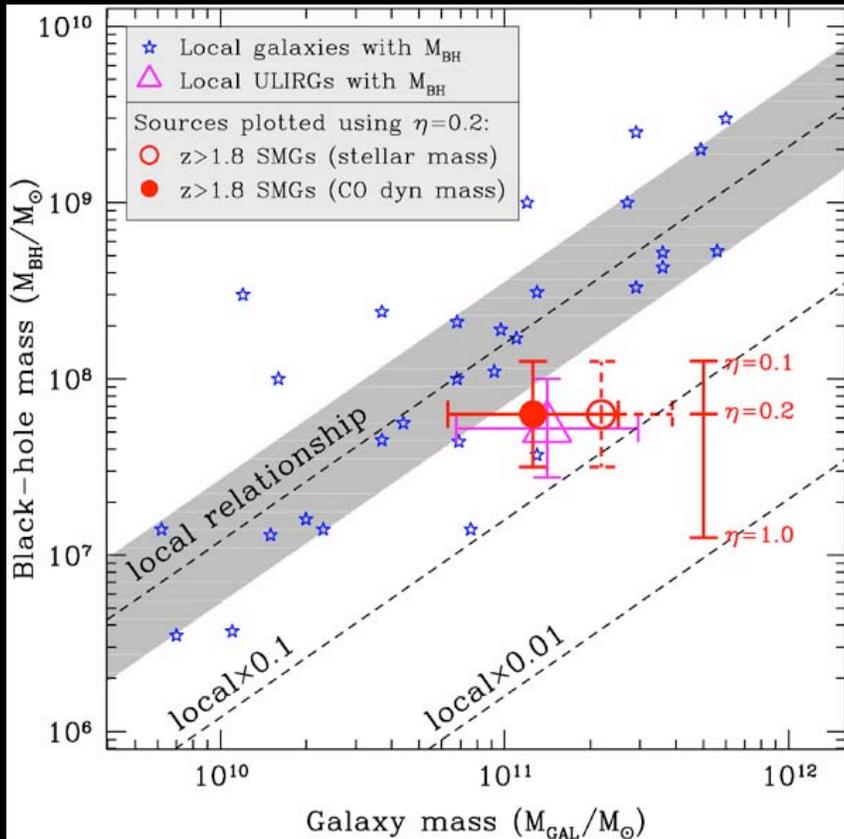
Validation (and analysis)

CO Properties of SMGs

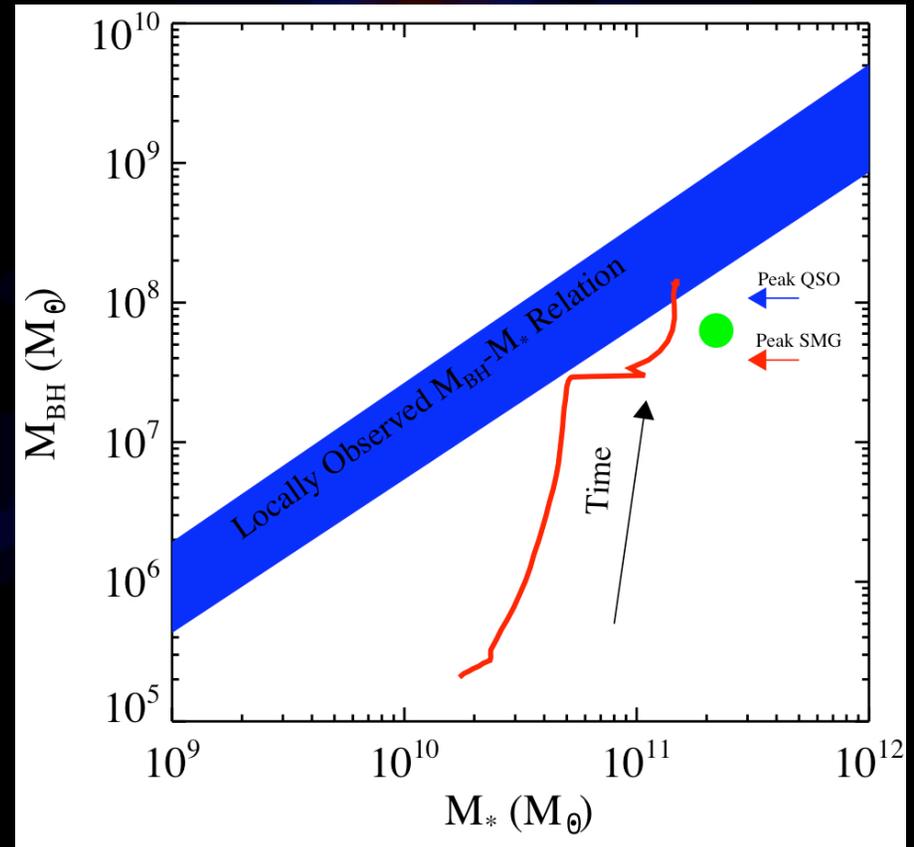


Narayanan, Cox, Hayward et al. 2009b

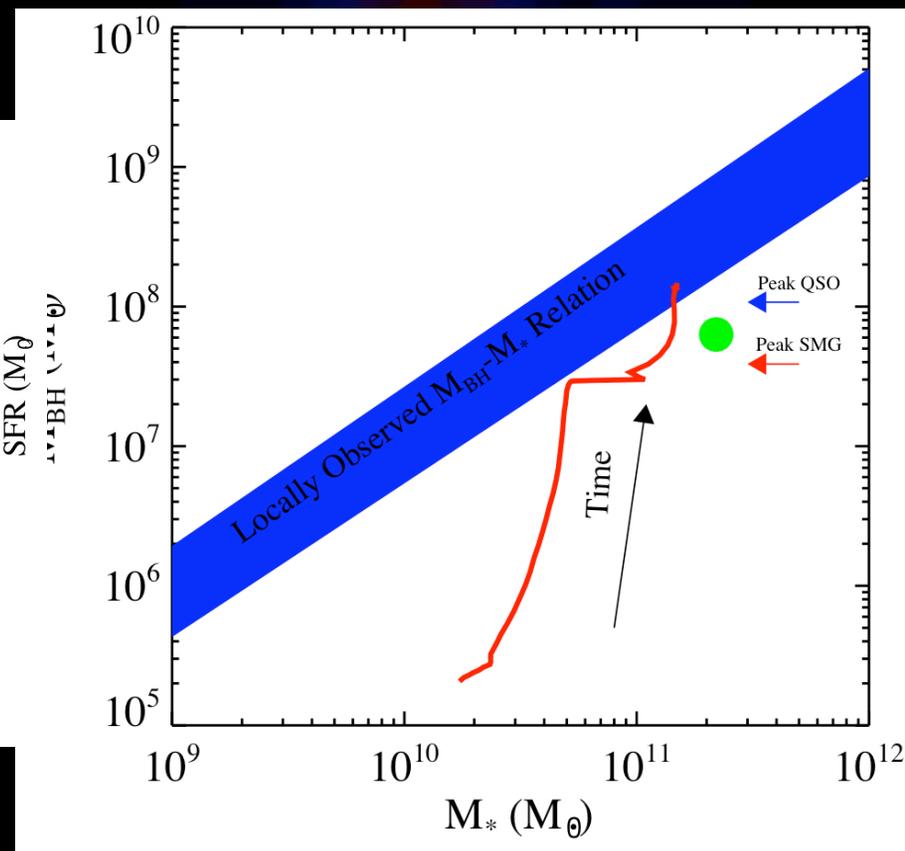
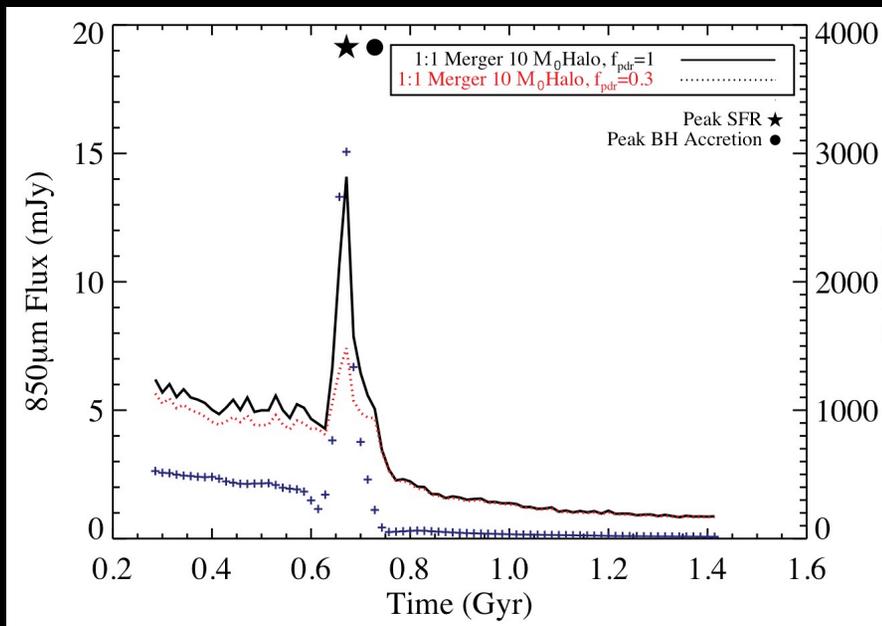
Model Validation (and analysis) : The Trip toward the Magorrian Relation



Alexander et al. 2008



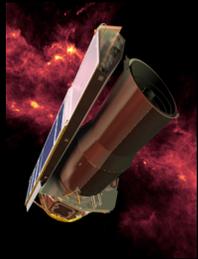
Model Validation (and analysis) : The Trip toward the Magorrian Relation





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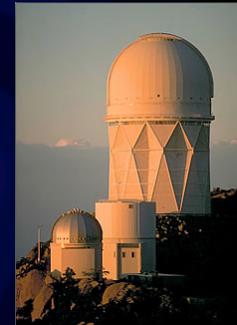
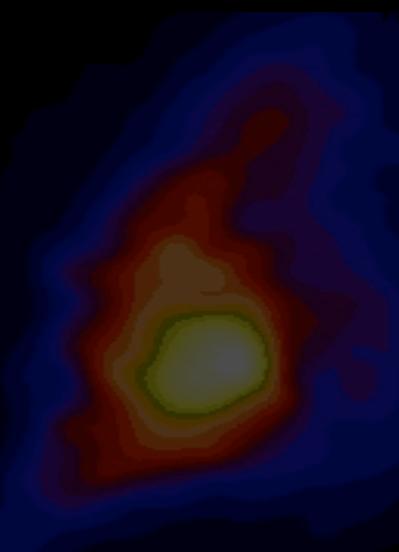
24 μm DOGs



OFRGs



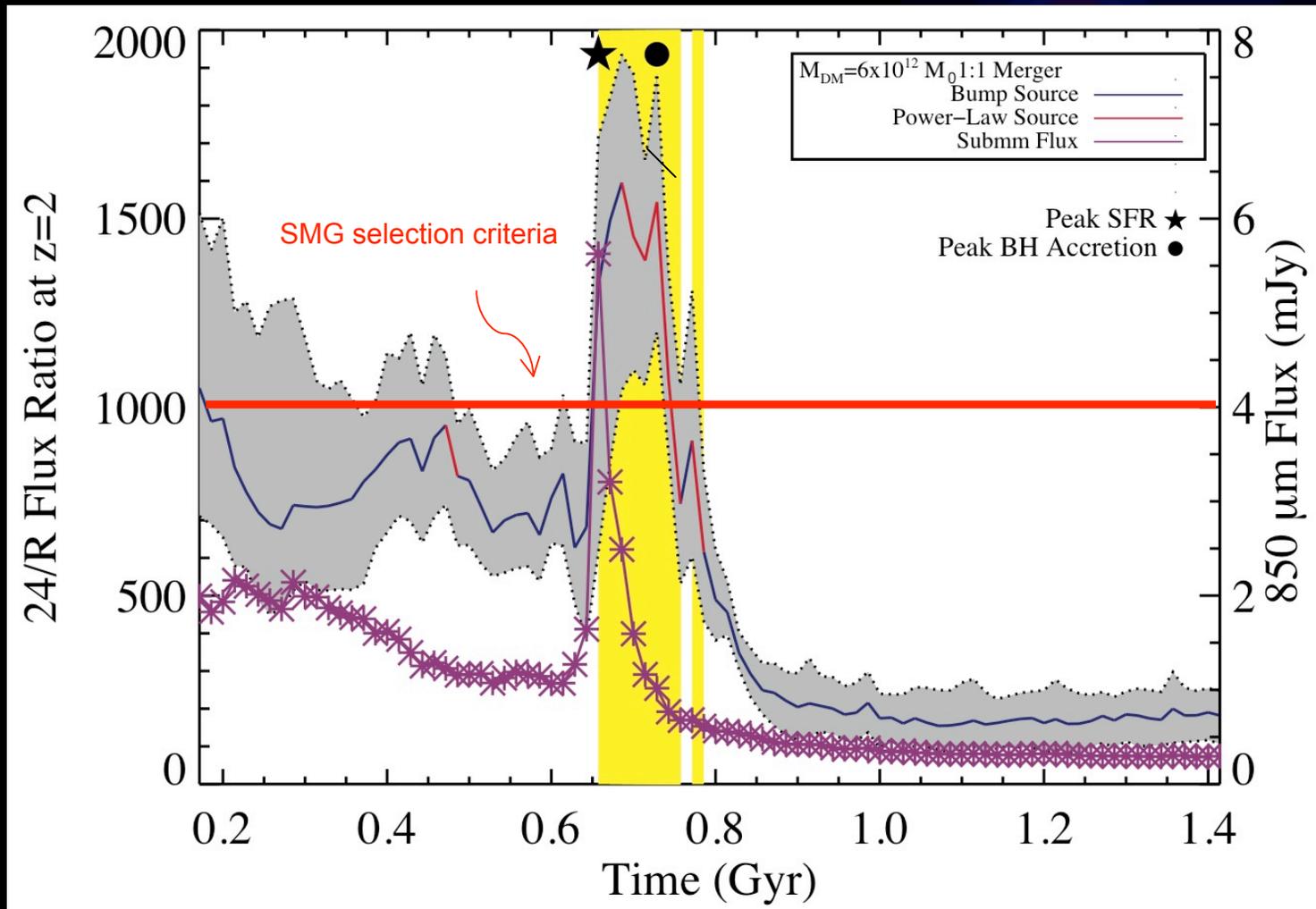
SMGs



BzKs

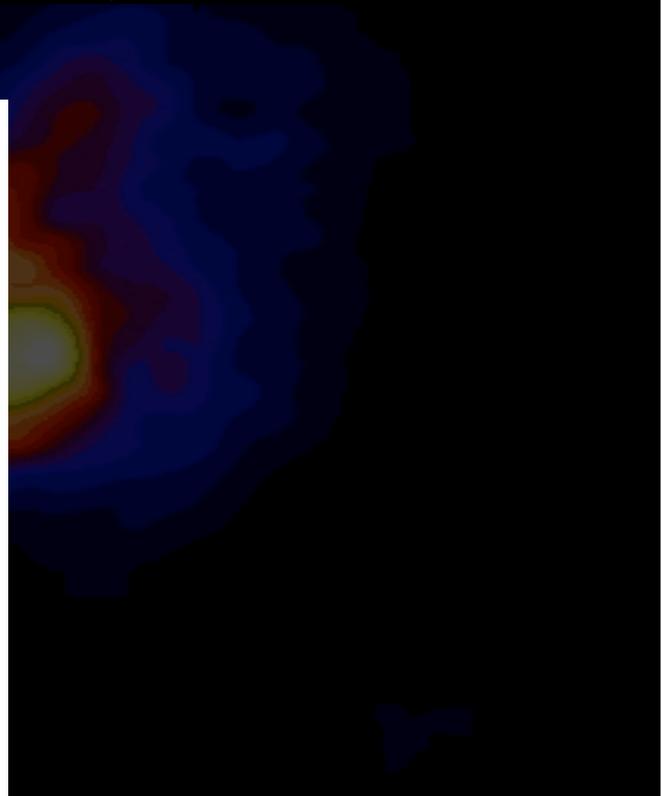
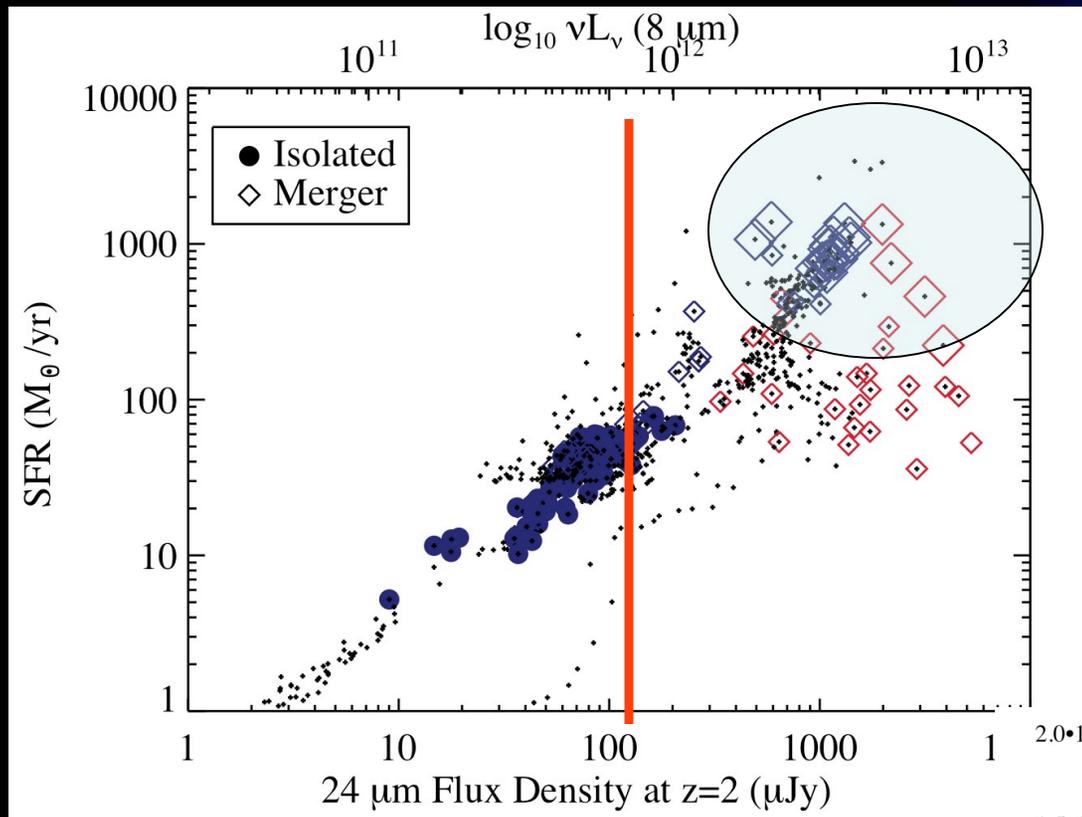
SFR:	100-500 M_{\odot}/yr	500-3000 M_{\odot}/yr	50-100 M_{\odot}/yr
M^*		$\sim 10^{11} M_{\odot}$	$\sim 10^{10} M_{\odot}$
M_{DM}		$\sim 5 \times 10^{12} M_{\odot}$	$\sim 3 \times 10^{11} M_{\odot}$
M_{H_2}		$\sim 5 \times 10^{10} M_{\odot}$	$\sim 10^{11} M_{\odot}$
M_{BH}		few $\times 10^8 M_{\odot}$	typically small
L_{bol}		$\sim 10^{13}-10^{14} L_{\odot}$	$< 10^{12} L_{\odot}$

Connecting High - z ULIRGs: How are SMGs and 24 μm sources connected? In Mergers, via Evolution

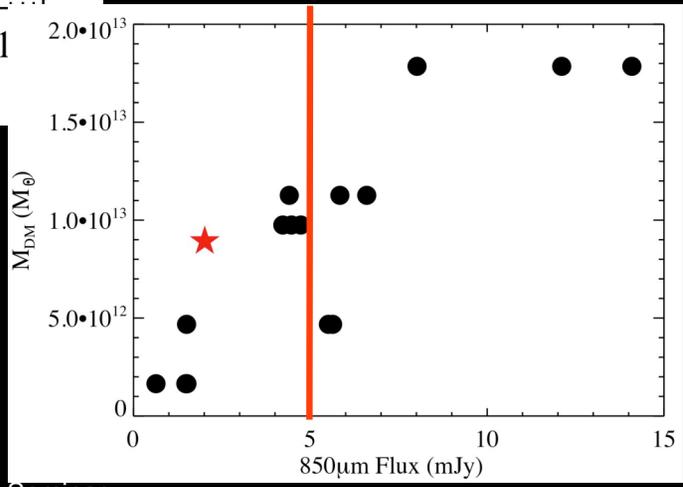


Narayanan, Dey et al. 2009c

SMGs are a narrow (more extreme) subset of 24 μm sources



Narayanan, Dey et al. 2009c

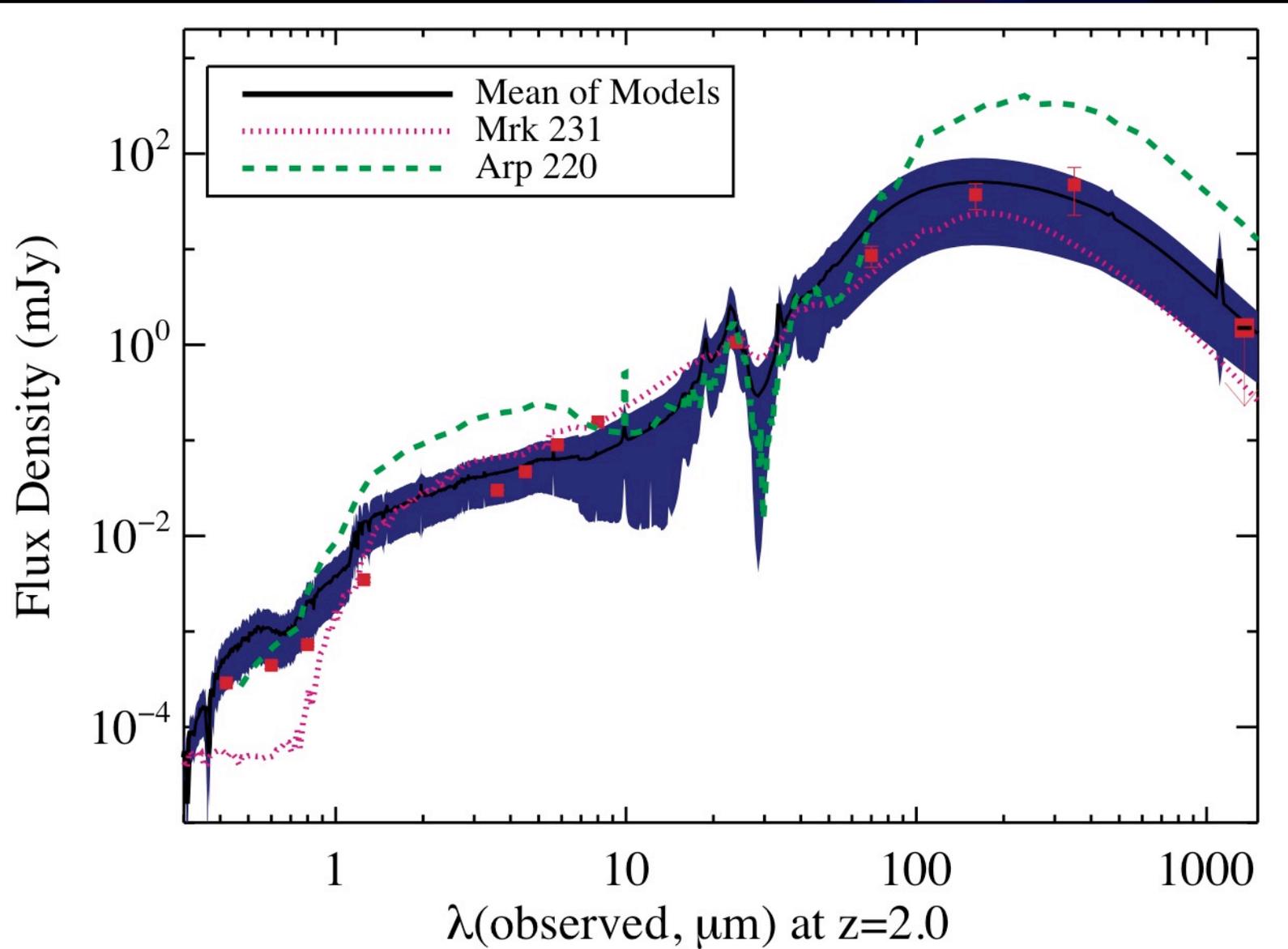




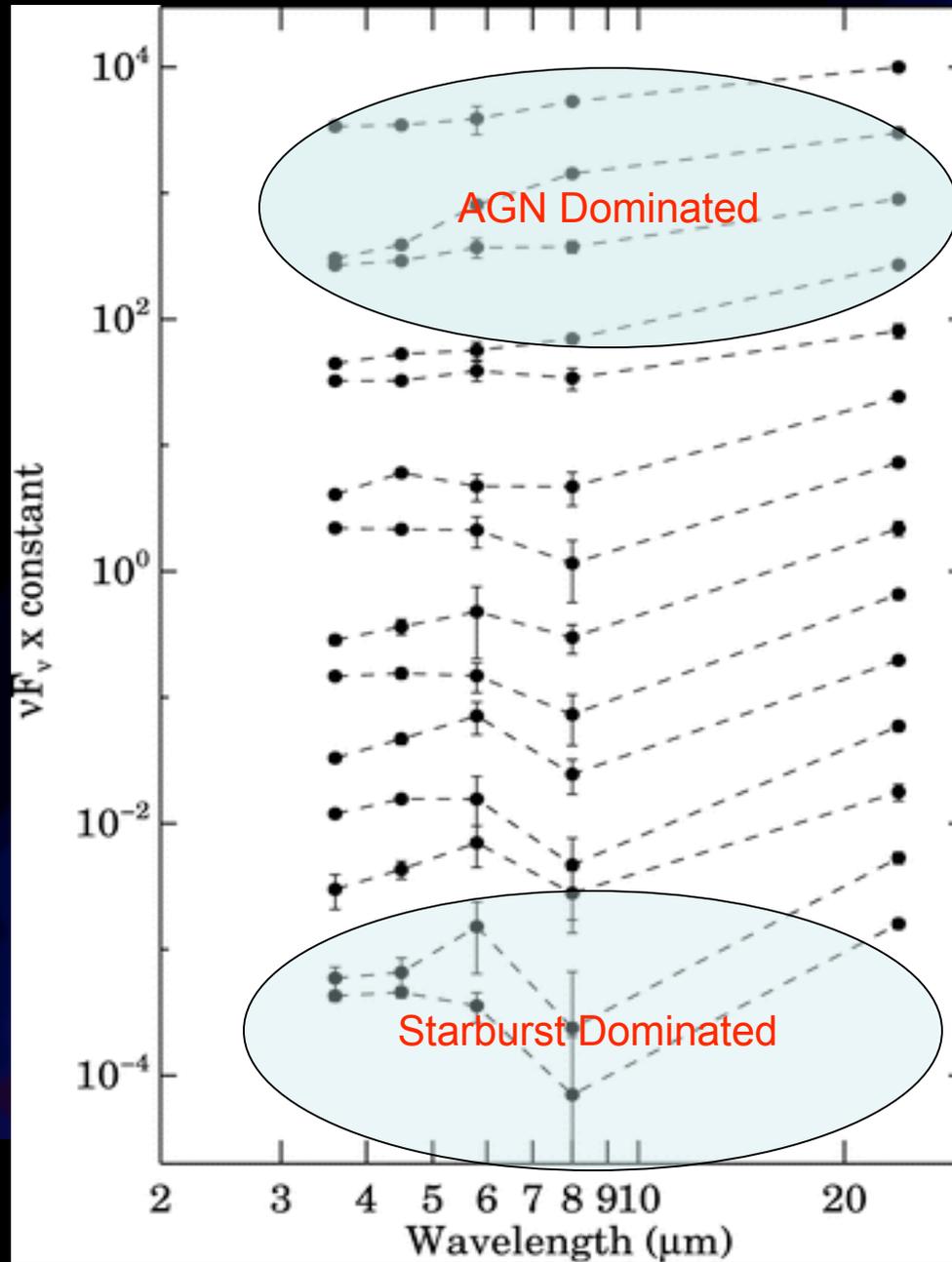
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How good are local SED templates?

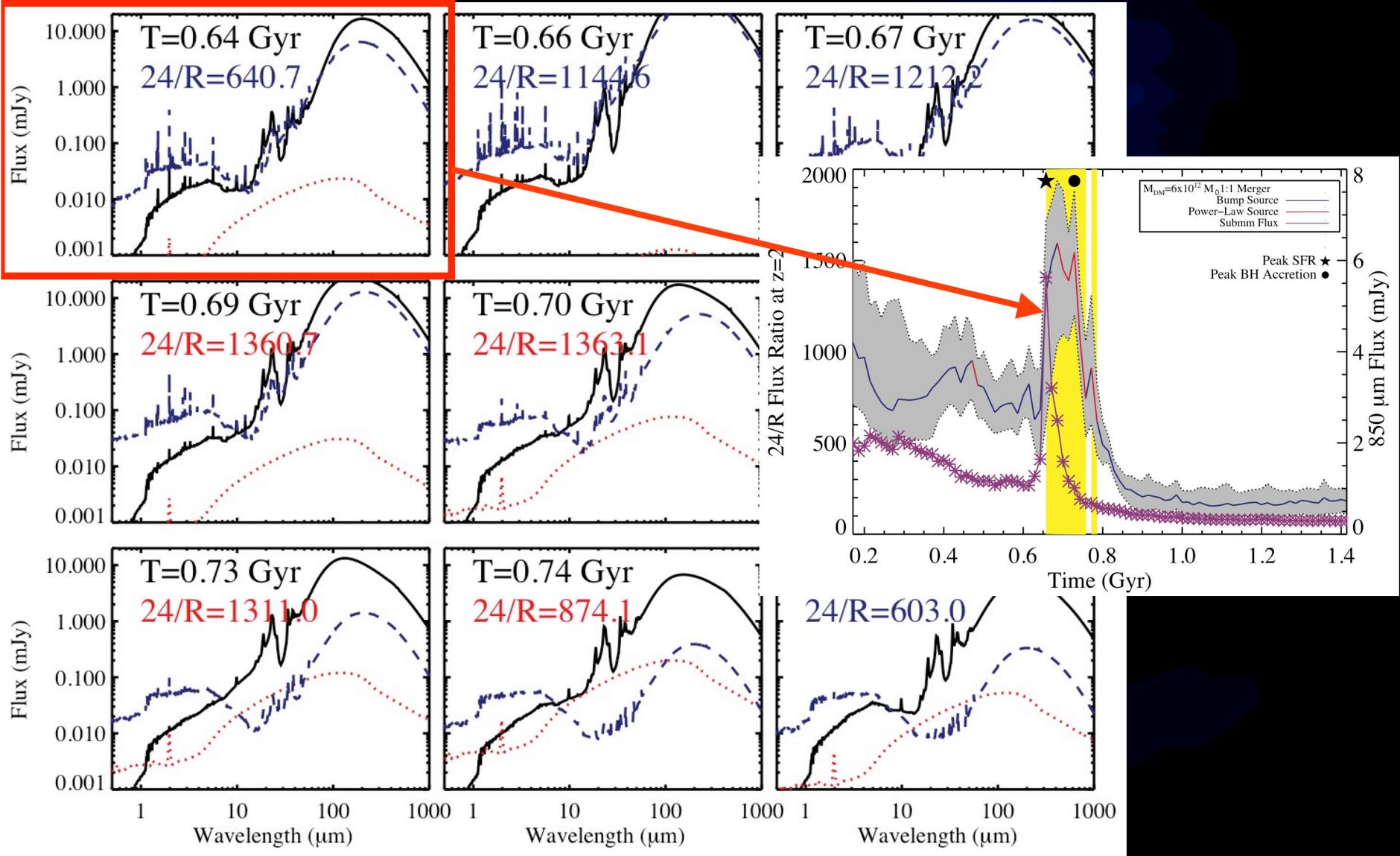


Mid-IR AGN Indicators



Dey et al. 2008

Does Bump/PL Designation Betray Underlying Power Source?



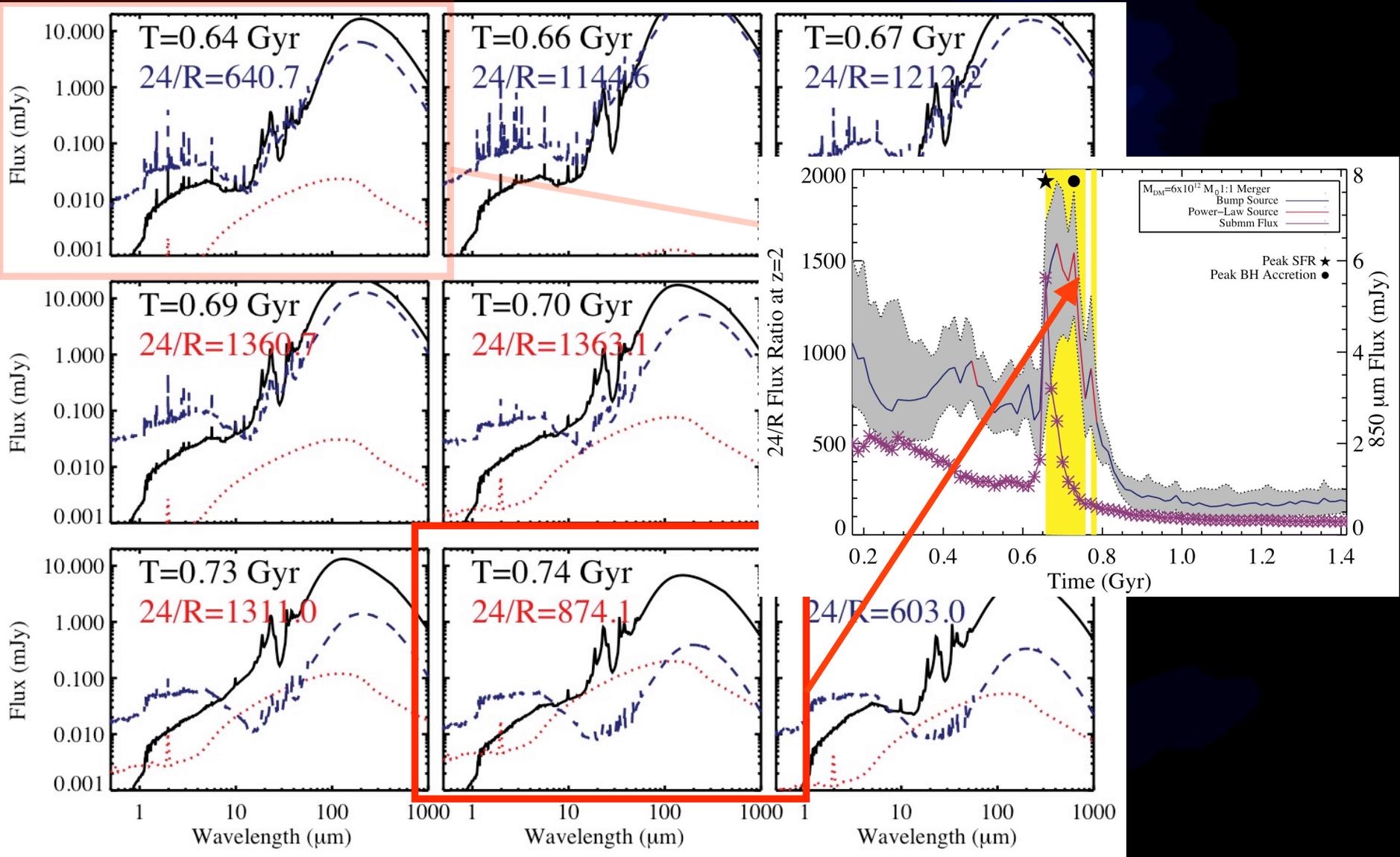
Starburst dominated "Bump" galaxy

Narayanan, Dey et al. 2009

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Does Bump/PL Designation Betray Underlying Power Source?



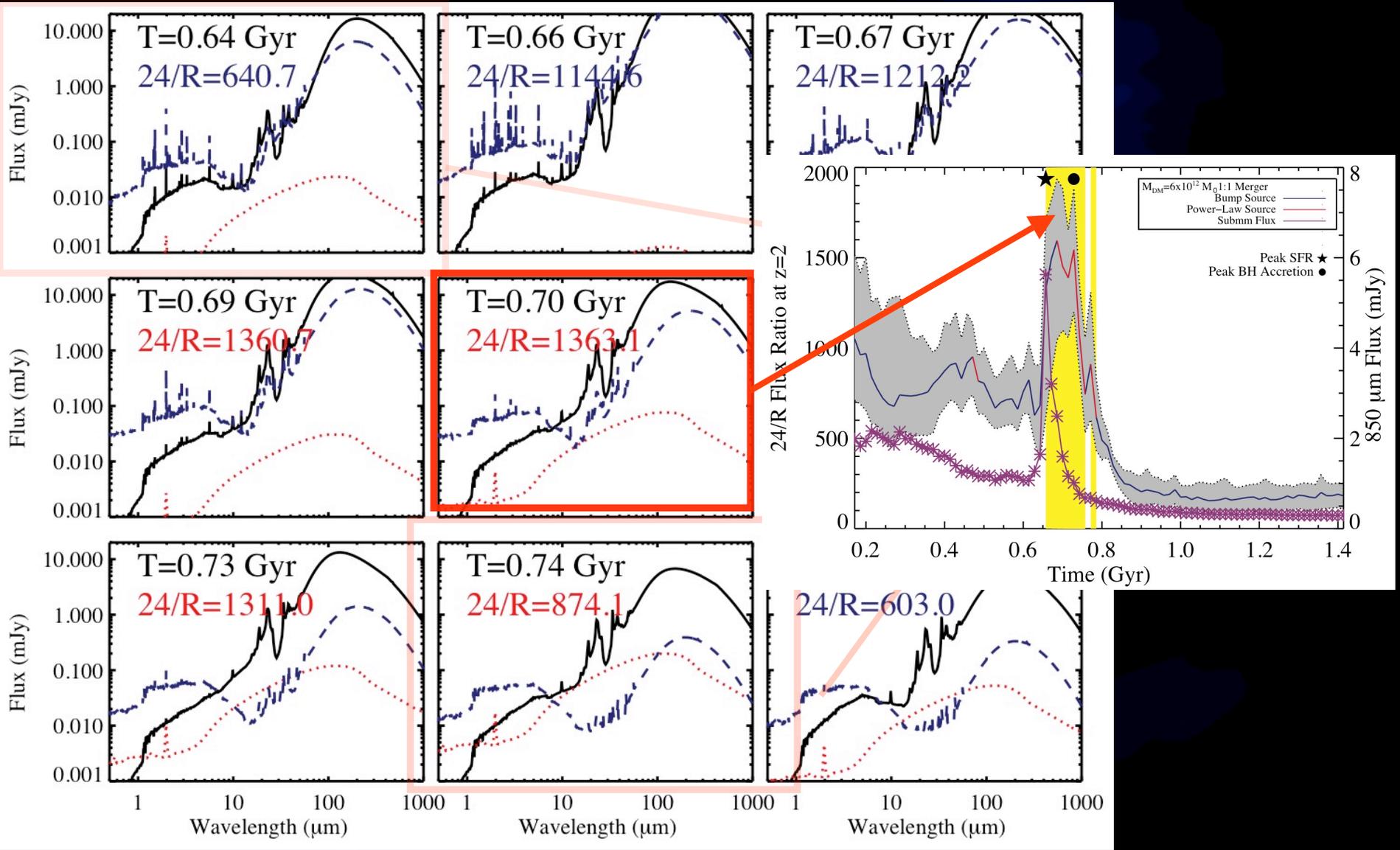
AGN dominated "Powerlaw" galaxy

Narayanan, Dey et al. 2009

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Does Bump/PL Designation Betray Underlying Power Source?



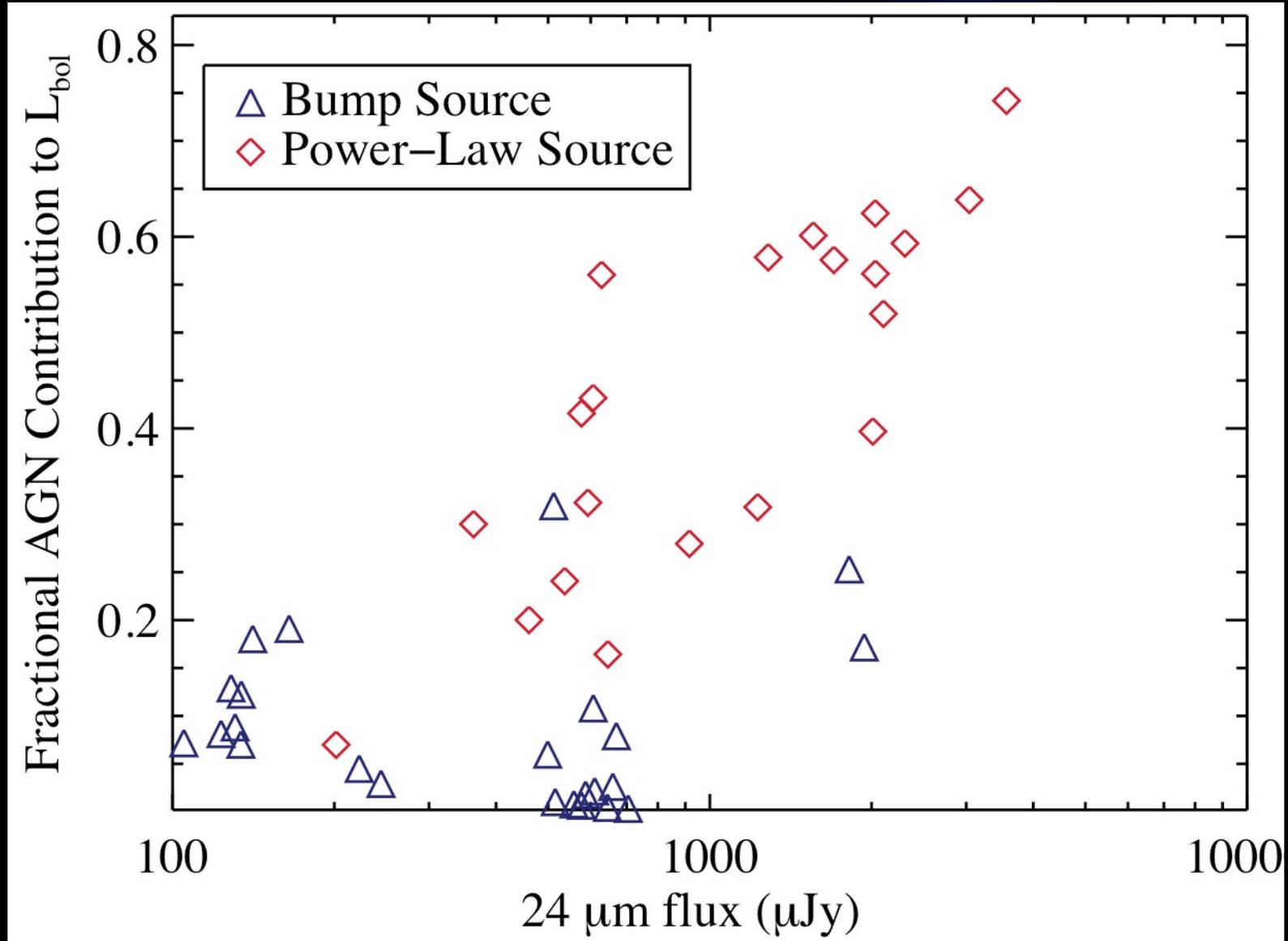
Starburst dominated "Powerlaw" galaxy

Narayanan, Dey et al. 2009

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Does Bump/PL Designation Betray Underlying Power Source?



PL galaxies not always AGN dominated!

Narayanan, Dey, Hayward, Cox, Bussmann, Brodwin + 2009

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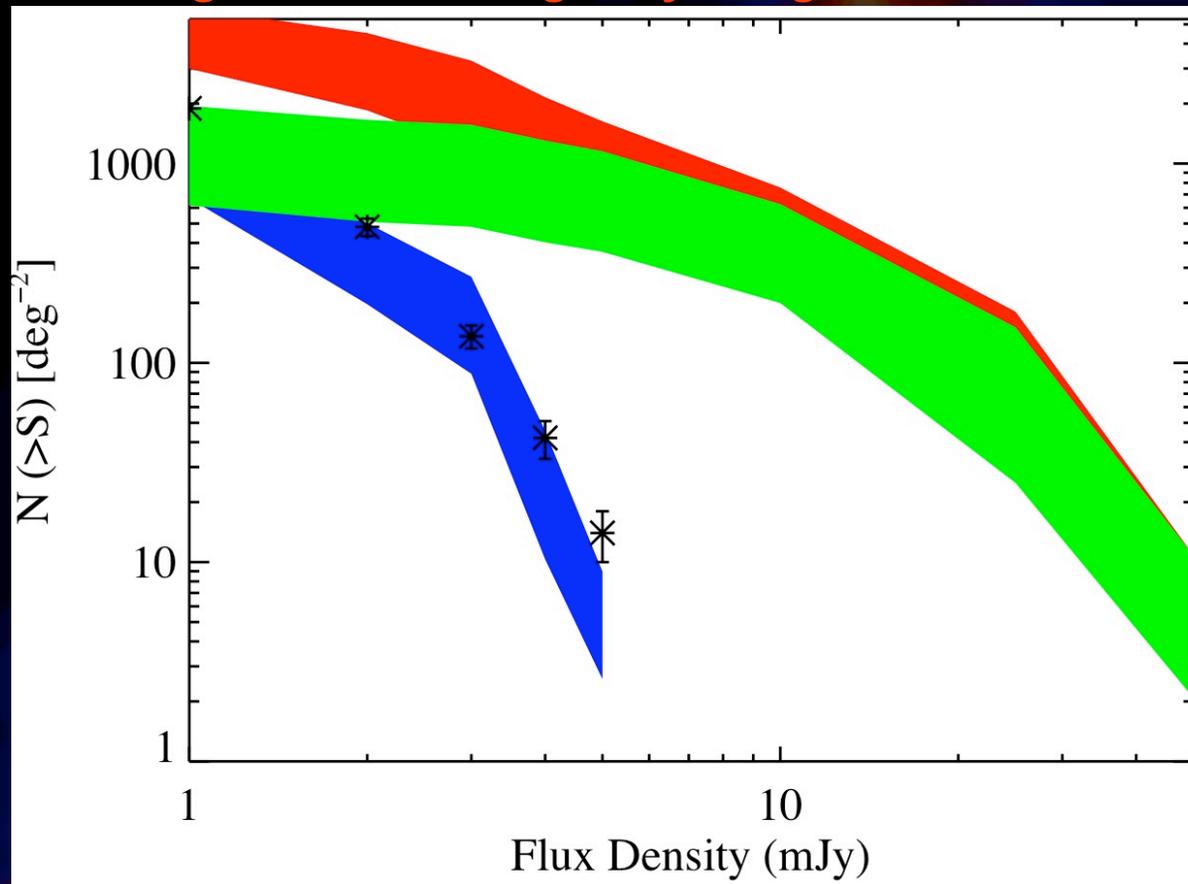


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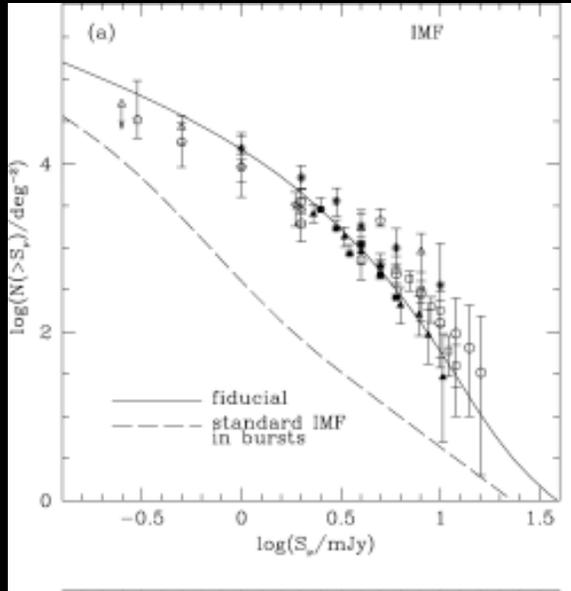
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SMG Number Counts

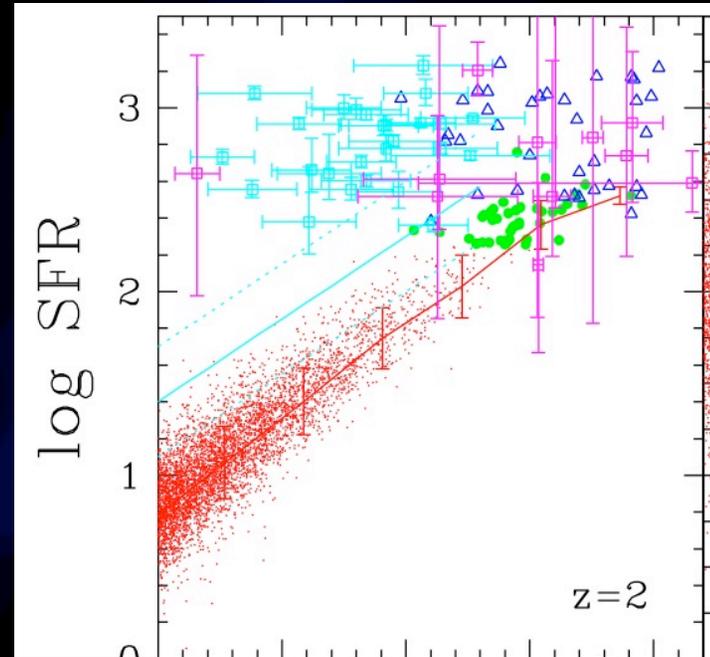
(take Fakhouri & Ma merger rates, populate halos with galaxies via some HOD, and convolve lightcurves with galaxy merger rates and mass functions)



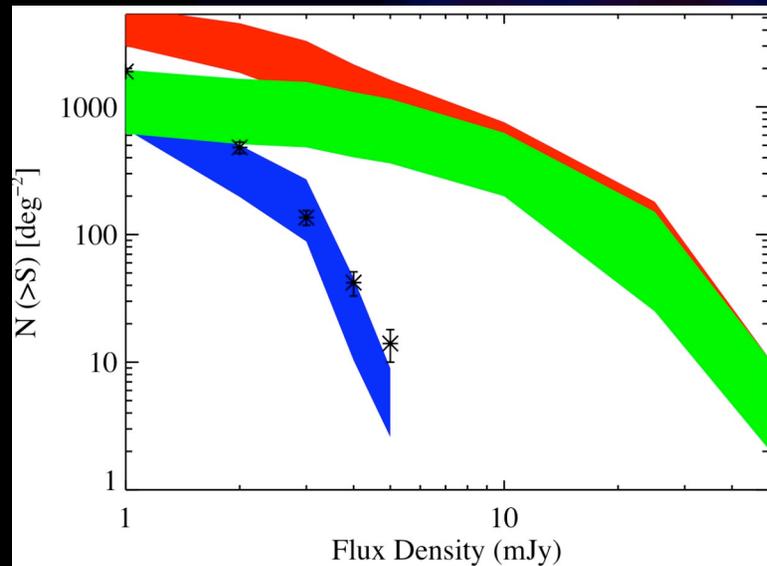
Distinguishing between Models



FLAT IMF (mergers): Baugh et al. 2005

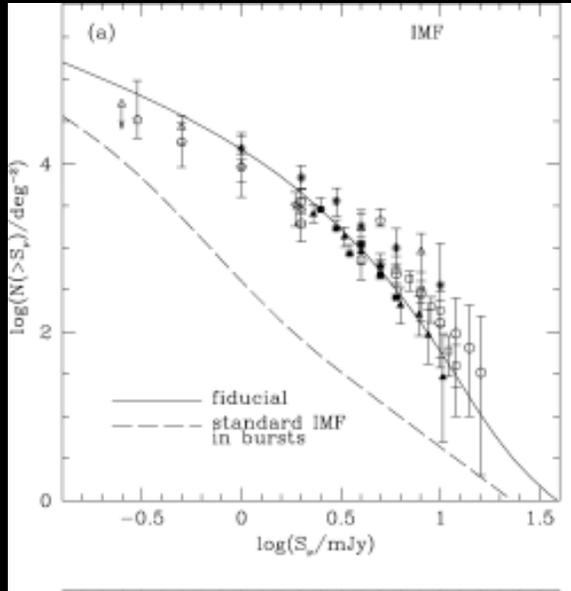


Overestimated SFRs; no mergers;
Davé et al 2009

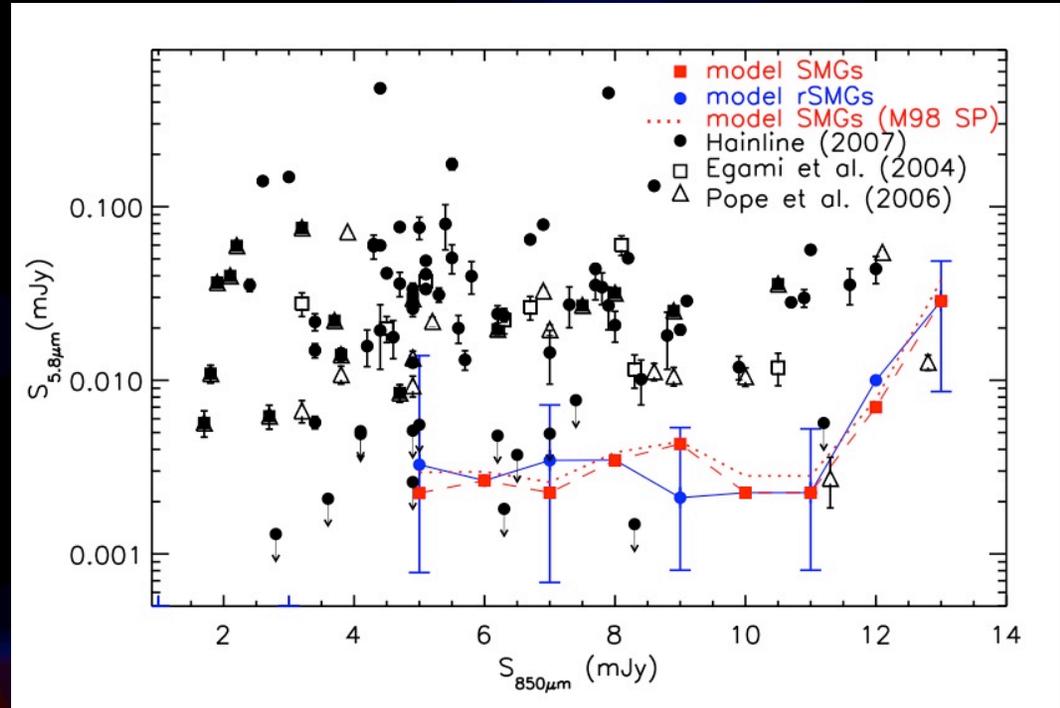


Kroupa IMF, mergers
Gas rich, total obscuration of O+B stars
Hayward, DN et al. 2009

Distinguishing between Models: SAMs



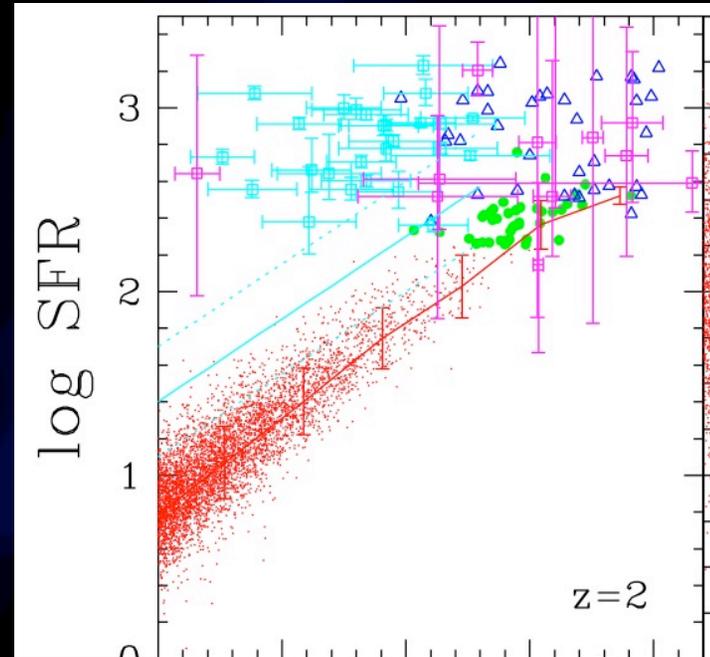
FLAT IMF (mergers): Baugh et al. 2005



Swinbank et al. 2008

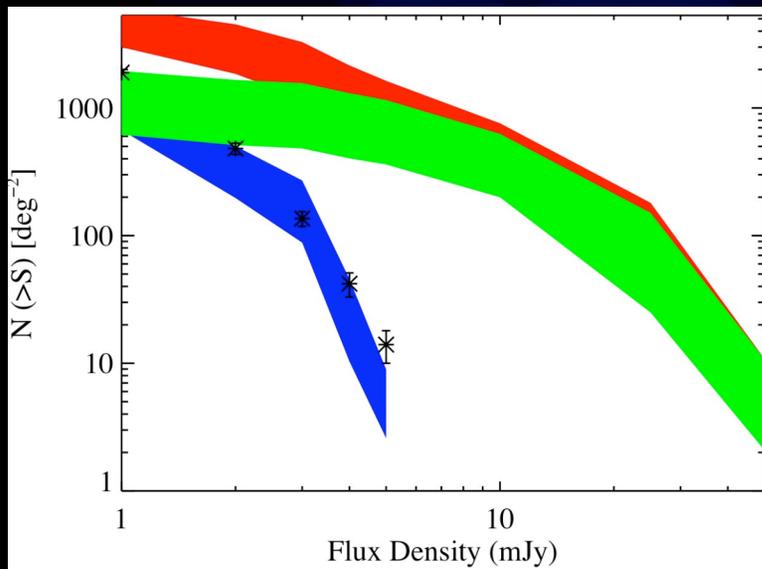
Though note SAM reproduction of present-epoch K-band luminosity function, FIR background, SMG redshift distribution...

Distinguishing between Models

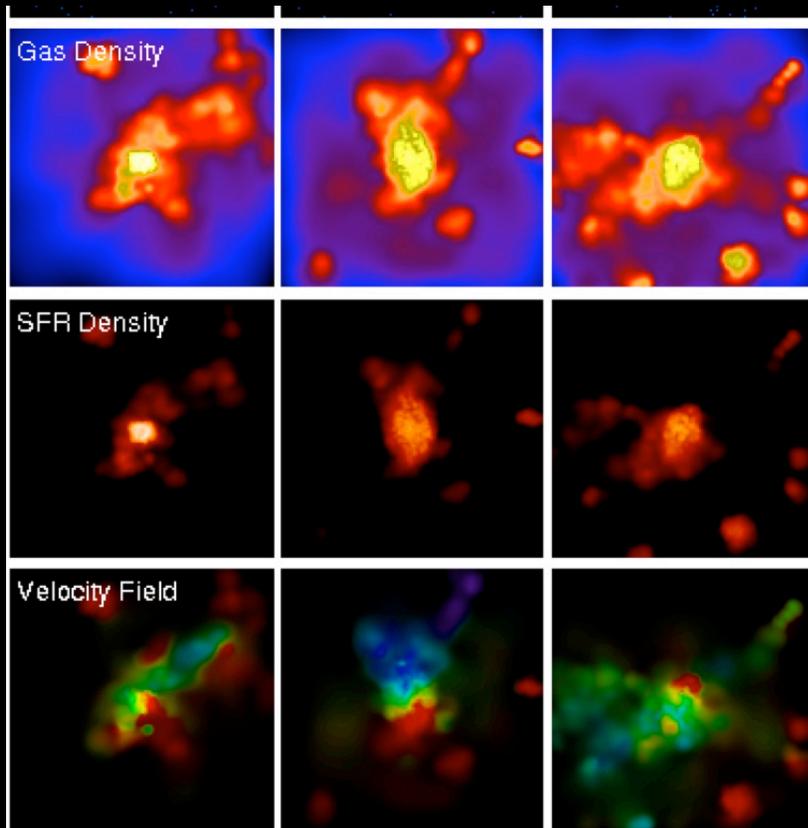


Requires Overestimated SFRs; few mergers;
Davé et al 2009

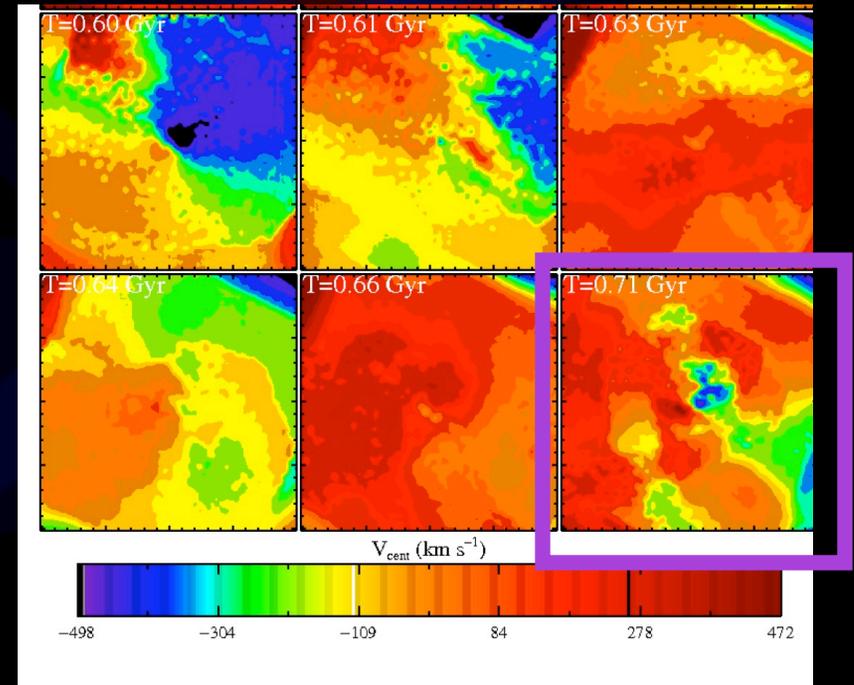
Kroupa IMF, major mergers
Requires gas rich mergers, total obscuration of O+B stars
Hayward, DN et al. 2009



Ways Forward: Velocity Fields with ALMA

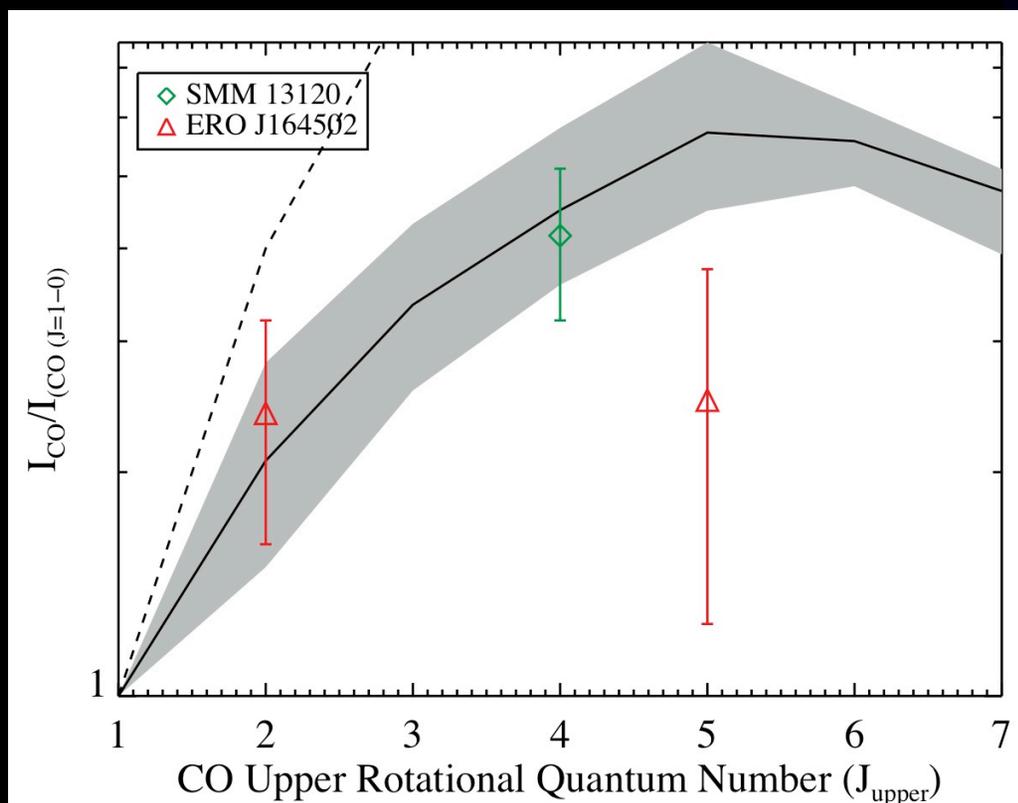


Davé et al 2009: Harassment

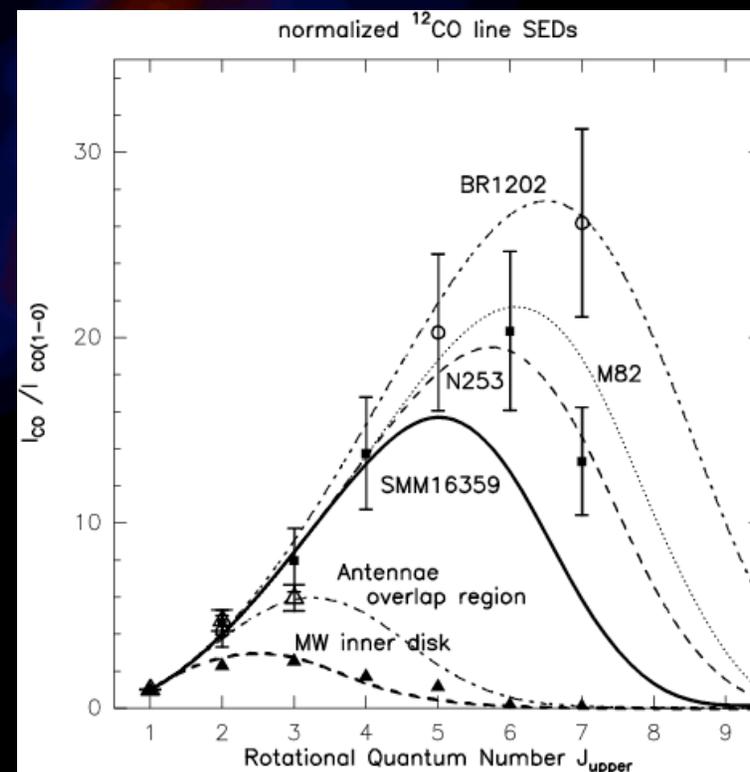


Narayanan et al 2009b: Major Mergers

Ways Forward: The CO Excitation of SMGs (with ALMA)



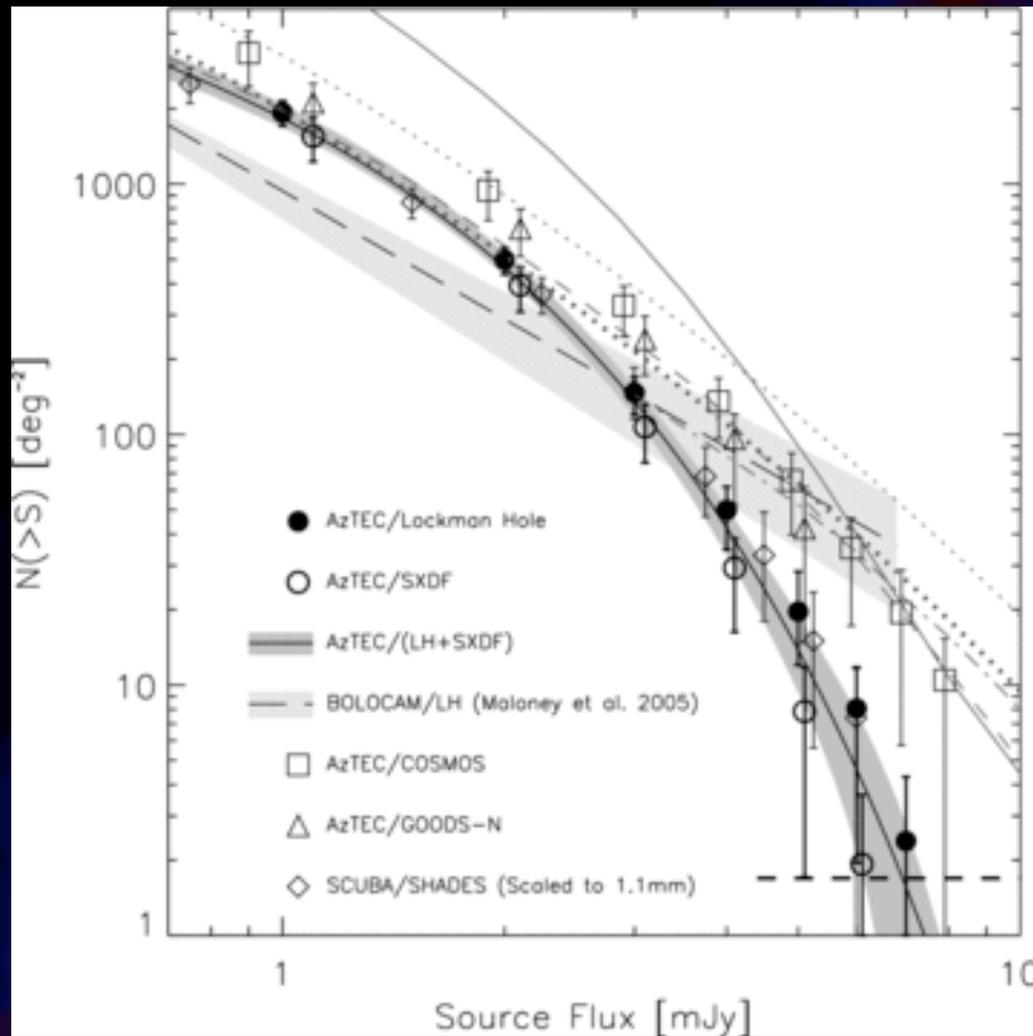
Narayanan , Cox et al. 2009b



Weiß et al. 2005

D. Riechers et al. in prep.

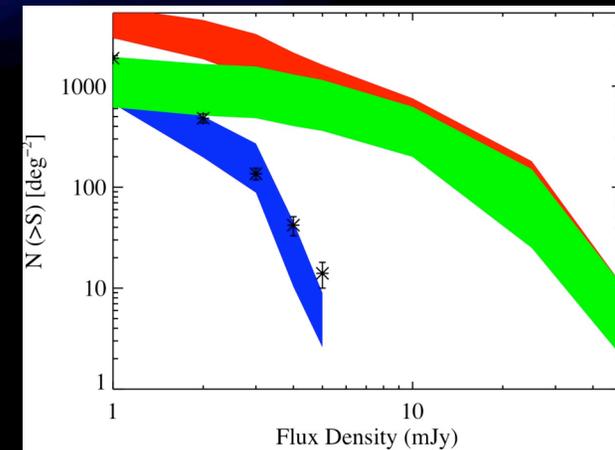
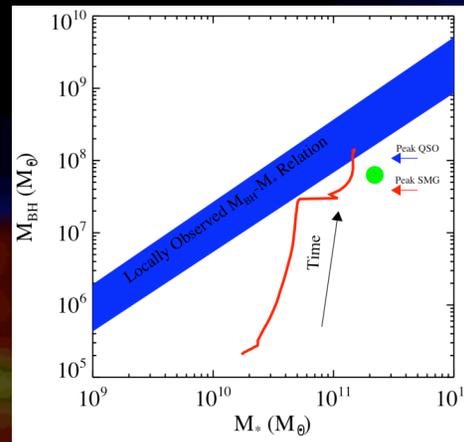
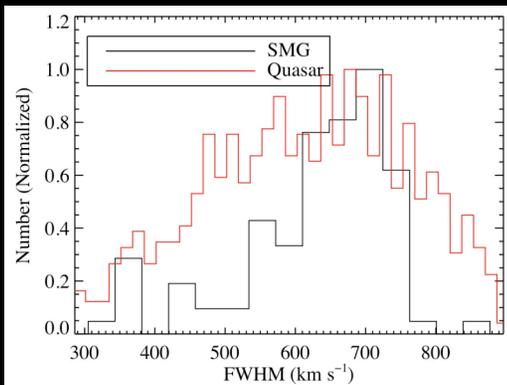
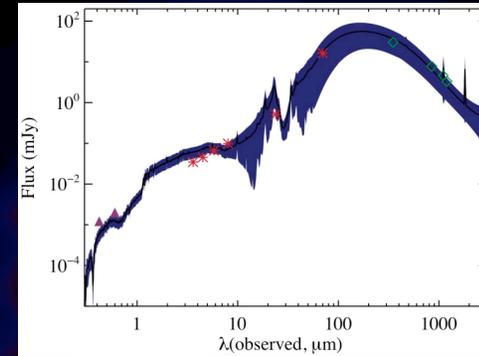
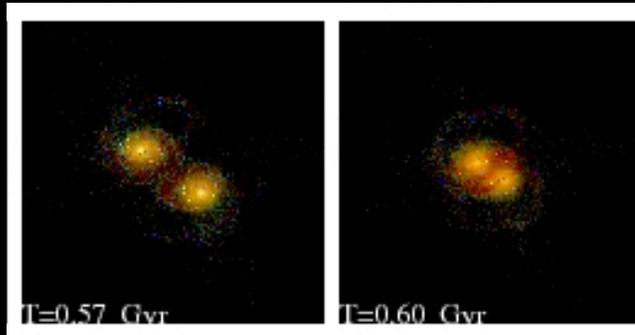
Ways Forward (with Herschel, AzTEC, MAMBO, SCUBA2): Precision Number Counts



Austermann et al. 2009

Conclusions

1.



Mergers make SMGs which naturally reproduce SED, CO properties, location on M^*-M_{BH} relation, number counts

Conclusions

1. Mergers may be a reasonable model for high-z SMGs
2. Merger-driven SMGs may naturally be related to 24 μm sources through evolution; BzK galaxies may be progenitors of SMGs
3. Mid-IR AGN indicators may pick out dusty starbursts as well as AGN
4. ALMA will be able to distinguish between varying models of SMG formation via resolved observations