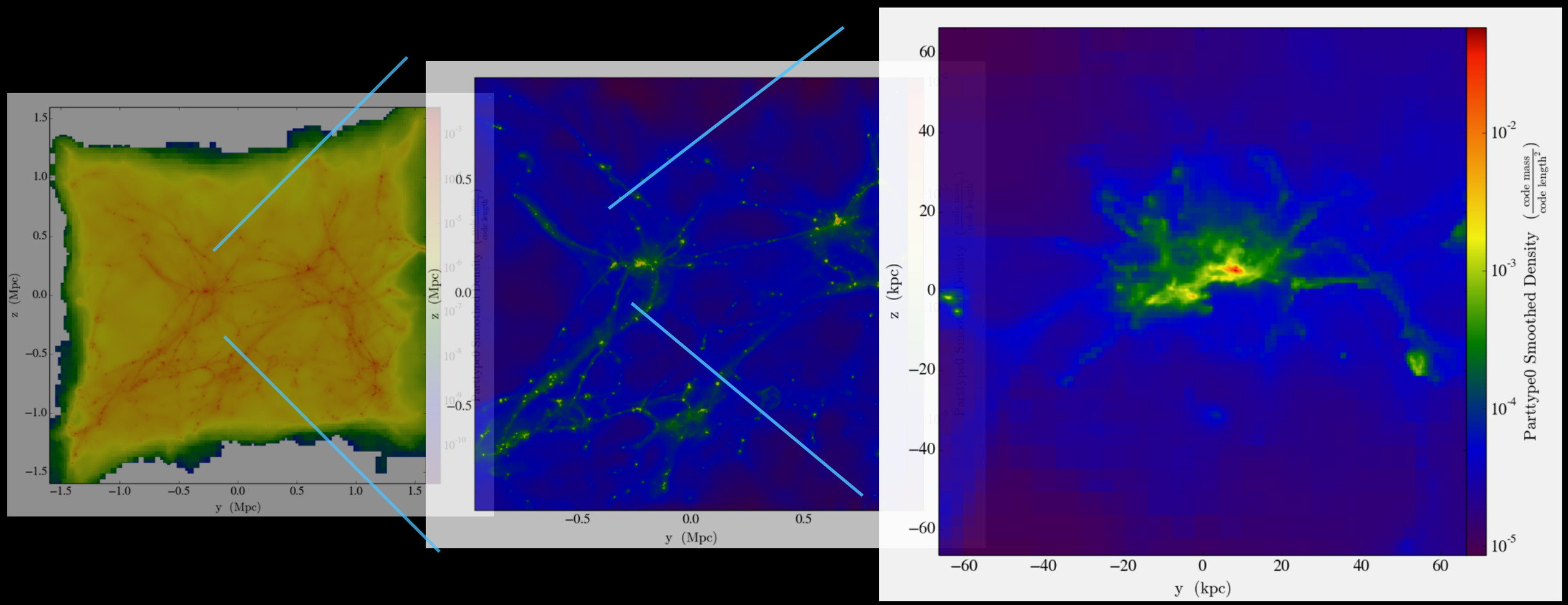
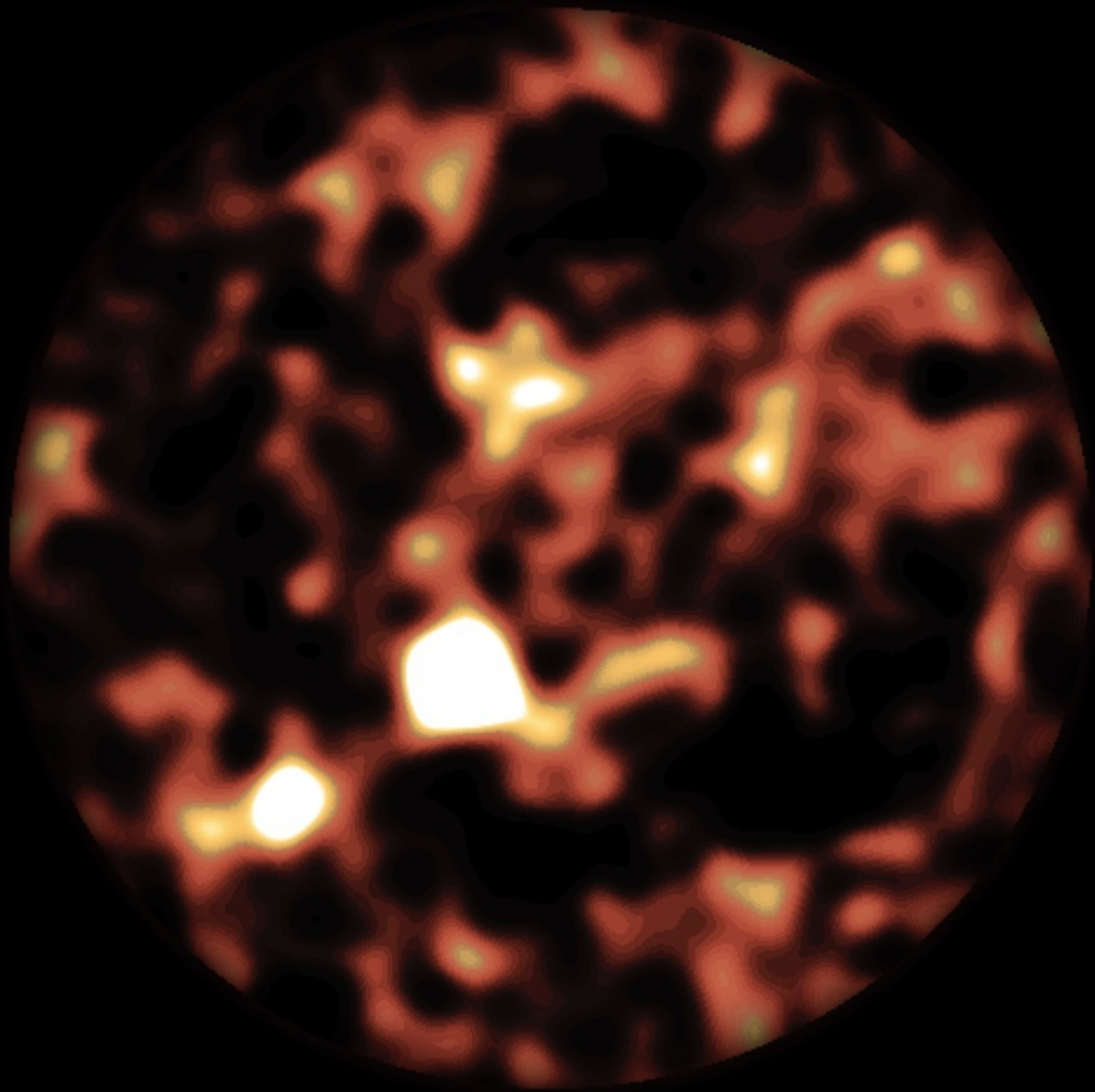
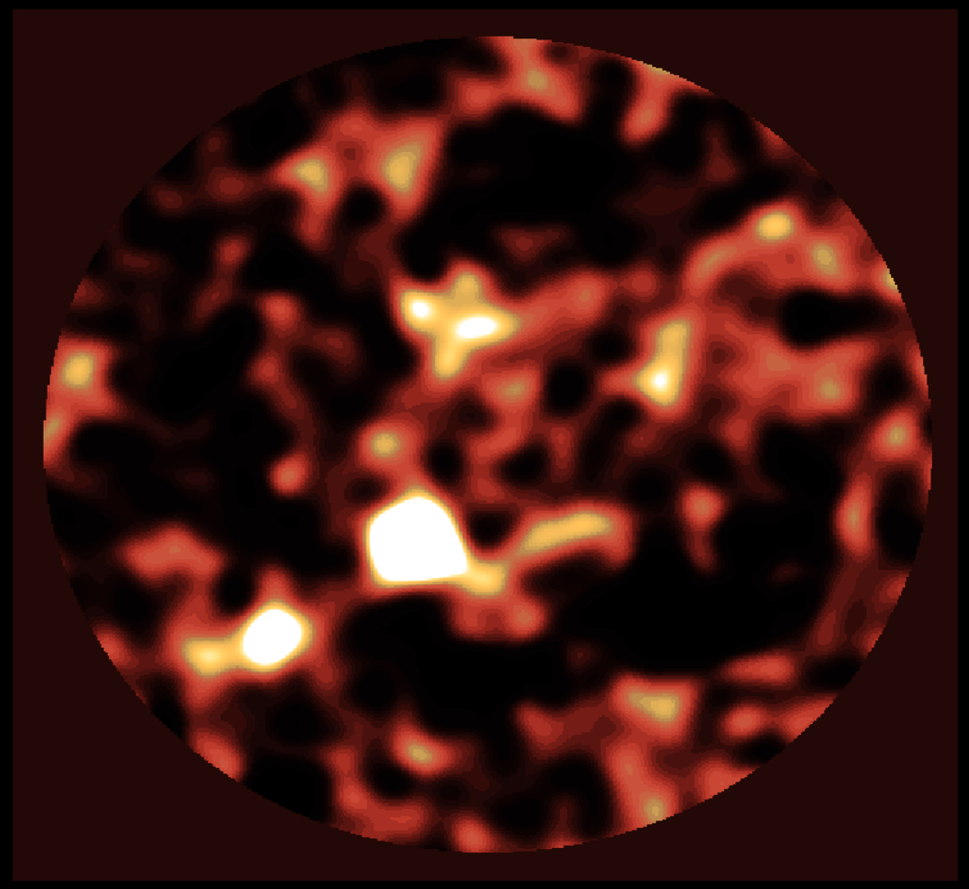
Submillimeter Galaxies in the Era of the SMA

Desika Narayanan
Haverford College

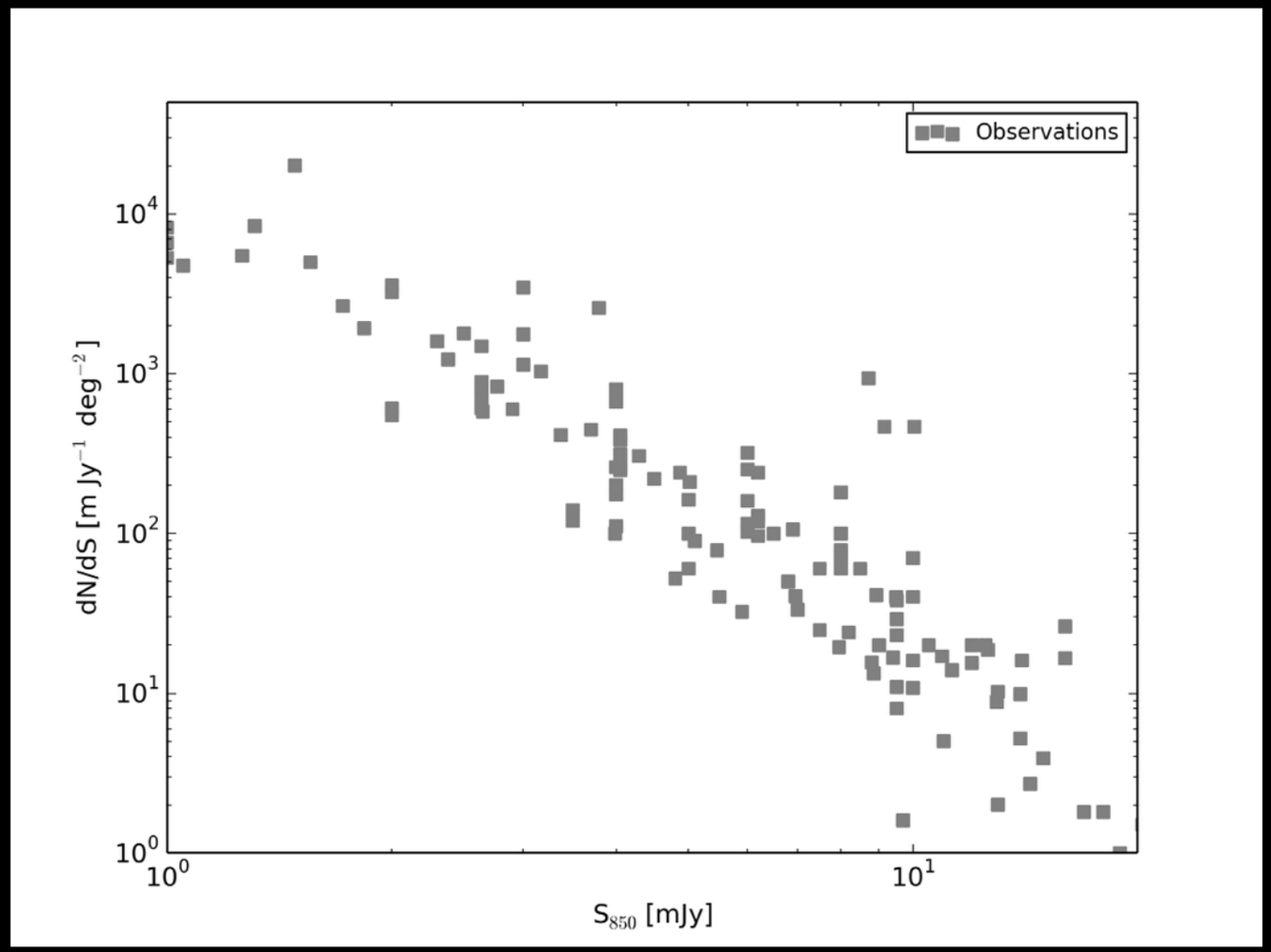




Barger et al. 1998
Hughes et al. 1998



submillimeter galaxy number counts



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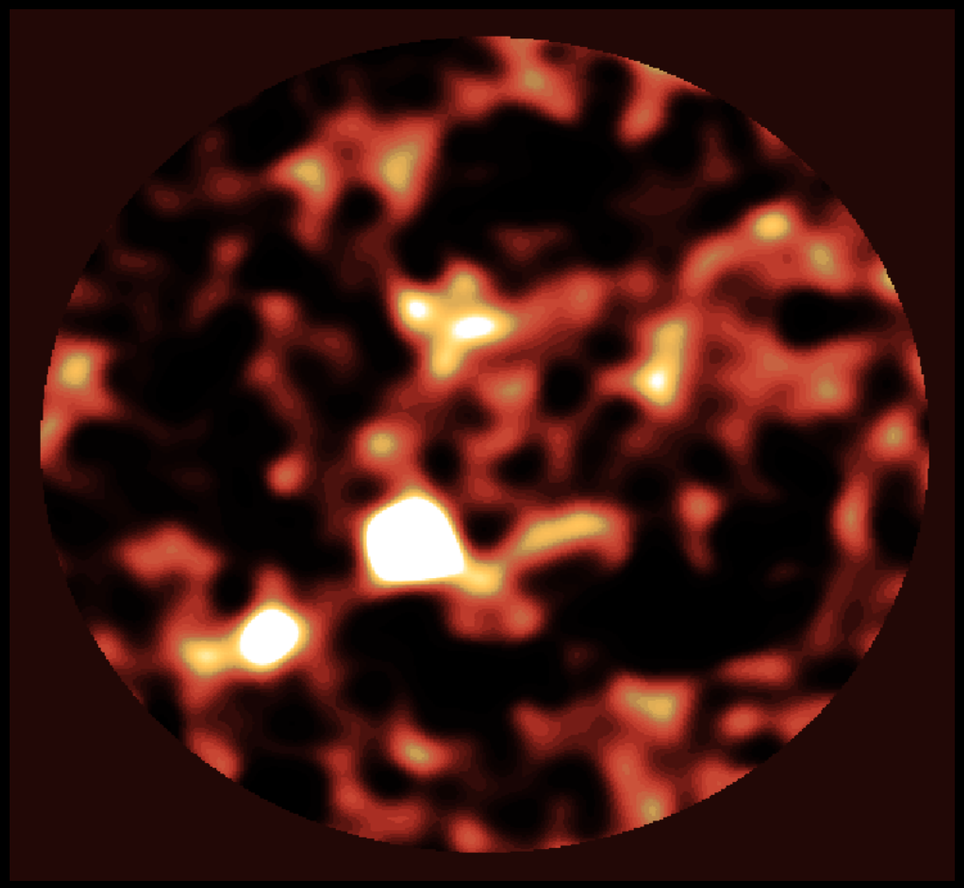
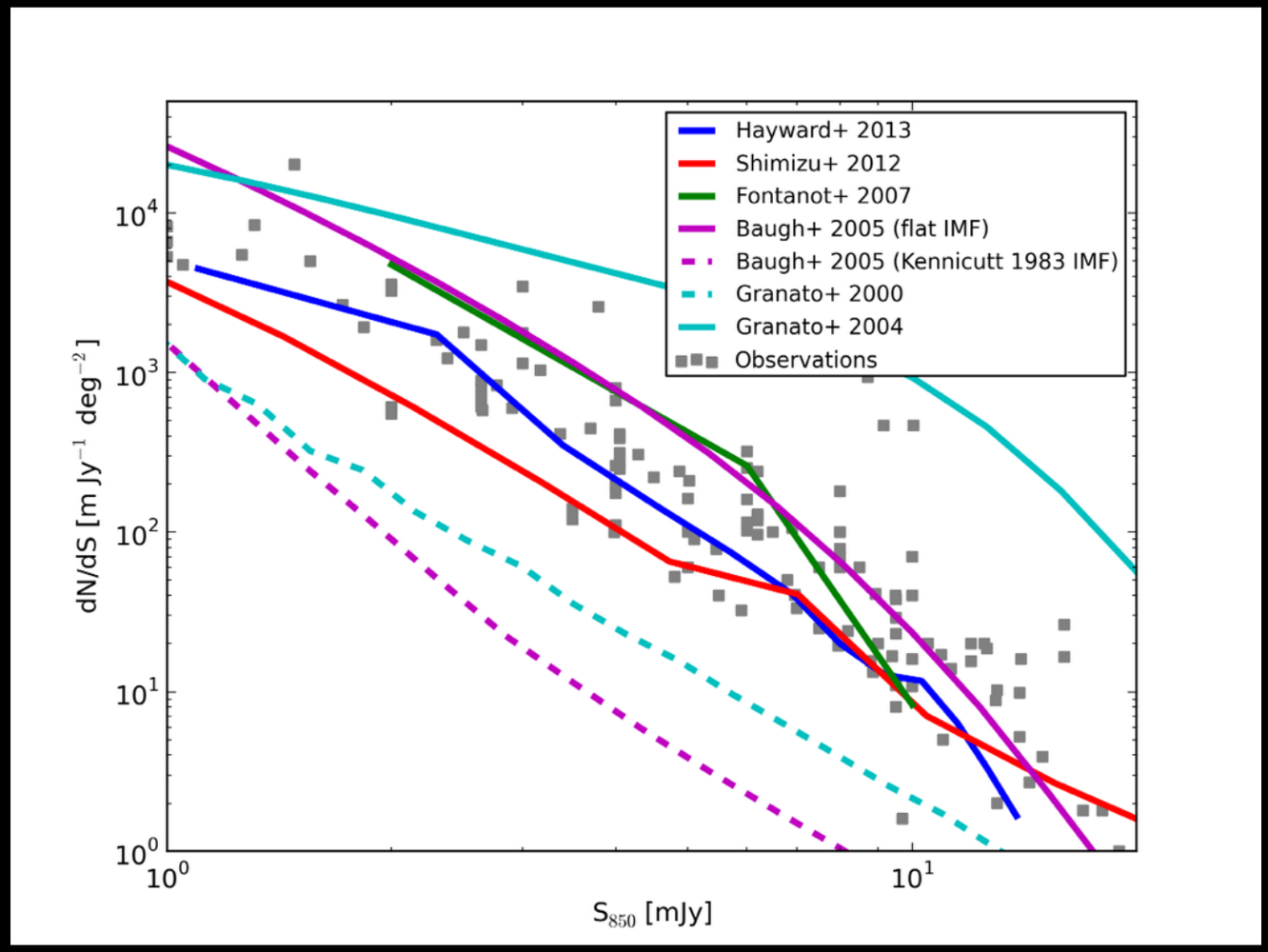


A comparison of cosmological models against submillimeter galaxy counts



Casey, Narayanan & Cooray 2014

Casey, Narayanan & Cooray 2014

Model Reference	Code	Methodology	Distinguishing Predictions for z=2 SMGs
Granato et al. (2004)	GALFORM	SAM	No Predictions Available
Baugh et al. (2005) González et al. (2011)	GALFORM GRASIL	SAM Dust Radiative Transfer	$M_* = 2.1 \times 10^{10\ddagger}$ M$_\odot$ $M_{\rm halo} = 2.2 \times 10^{12\ddagger}$ M$_\odot$ 22 % major ($M_1/M_2 > 1/3$) mergers 77 % minor ($M_1/M_2 < 1/3$) mergers $f_{\rm gas} > 0.75$ (for minor mergers) $S_{850} > 5$ mJy duty cycle‡: 0.1 Gyr Flat stellar IMF in starbursts
Chakrabarti et al. (2008)	GADGET RADISHE	Idealized Hydro Dust Radiative Transfer	$M_* > 9.4 \times 10^{11}$M$_\odot$ necessary for $S_{850} > 5$ mJy
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Dekel et al. (2009a)	RAMSES	Cosmological Hydro (AMR)	~1/2 of SMGs with $S_{850} > 5$ mJy will be mergers with $M_1/M_2 > 0.1$
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Somerville et al. (2012)	SANTA CRUZ	SAM	No Predictions Available*
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Hayward et al. (2013b) Narayanan et al. (2010c)	GADGET SUNRISE	Hybrid Dust Radiative Transfer	Physically Associated Galaxies: $M_* = 6 - 10 \times 10^{10}$ M$_\odot$ $M_{\rm halo} = 3 - 5 \times 10^{12}$ M$_\odot$ SFR > 160 M$_\odot$yr^{-1}
Hayward et al. (2013a)	ART	SAM	Physically Unassociated Galaxies (blends)*: Median $M_* = 9 \times 10^{10}$ M$_\odot$ Median $M_{\rm halo} = 5 \times 10^{12}$ M$_\odot$ Median SFR = 190 M$_\odot$yr^{-1}

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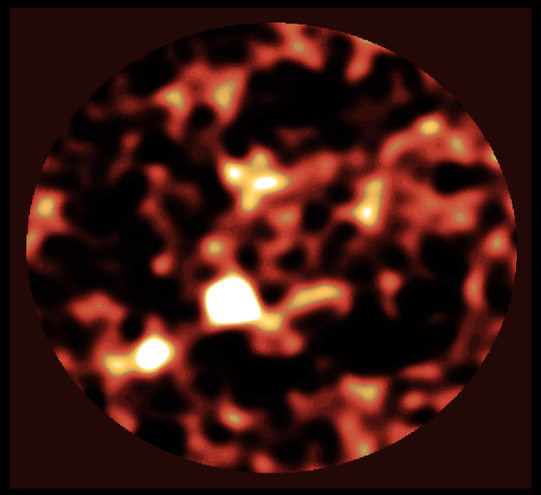
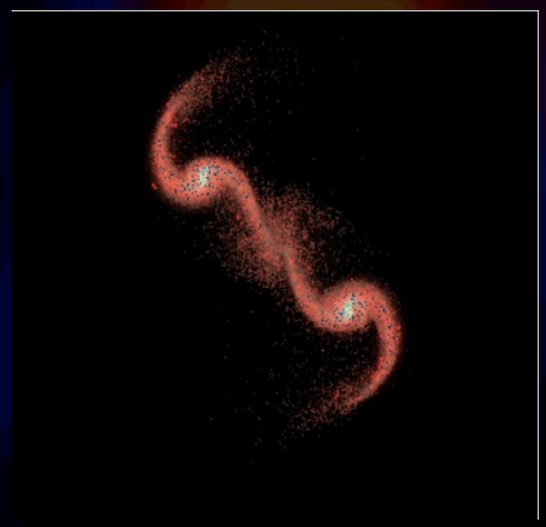


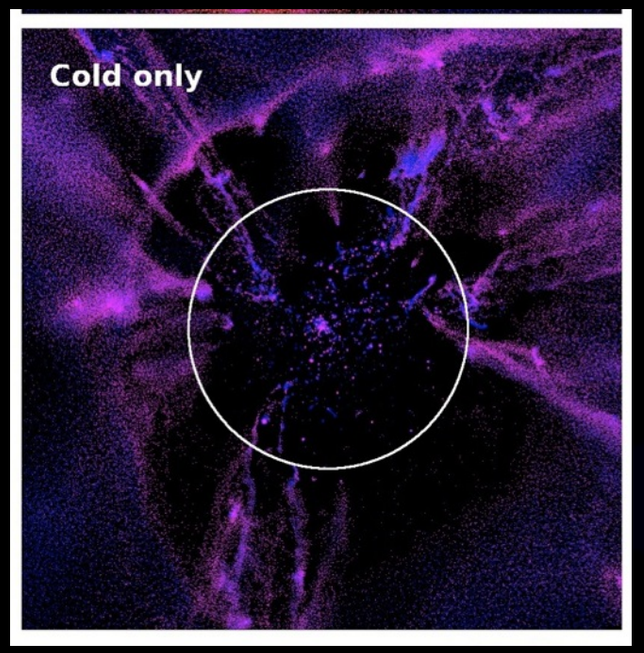
What are High-z Submillimeter Galaxies?

(The most Luminous, Heavily-Star Forming Galaxies in the Universe)

Baugh, Lacey, Frenk et al. 2005
Gonzalez et al. 2011
SMGs are mostly major and minor mergers with a flat IMF



Fardal et al. 2003
Dekel et al. 2009
Davé et al. 2010
SMGs are mostly discs fed by cold-flows (i.e very minor mergers)



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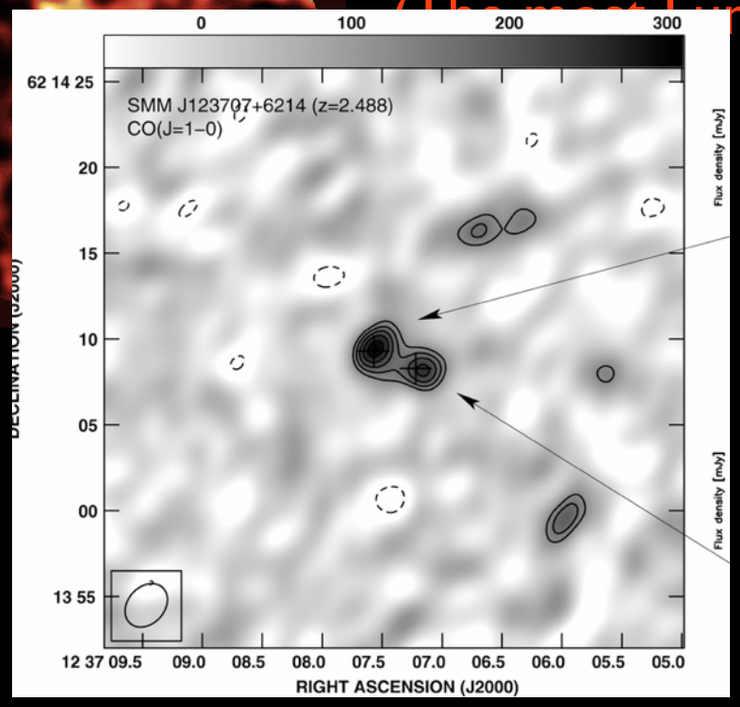

"Imaging...a Major Merger driving the Evolution of a z~2.5 Submillimeter Galaxy"

Riechers et al. 2011

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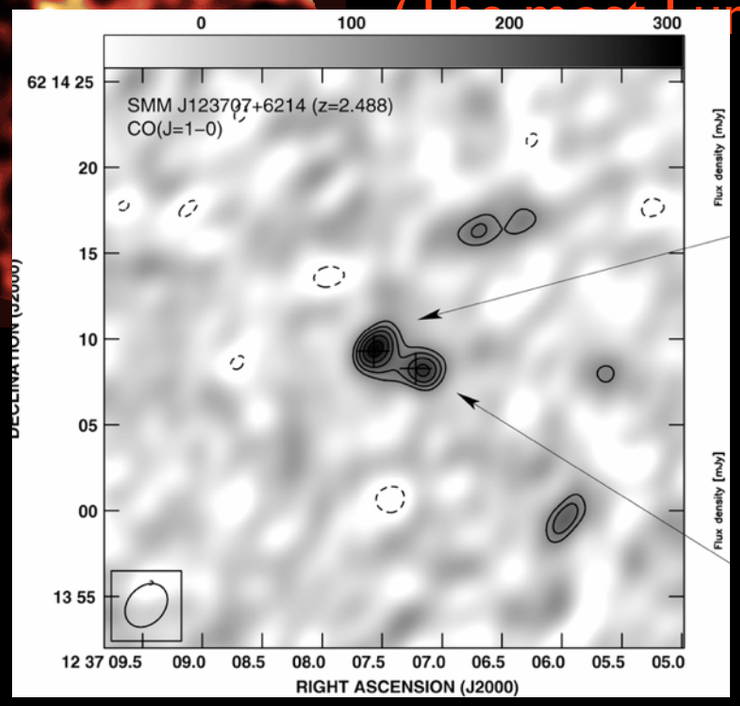

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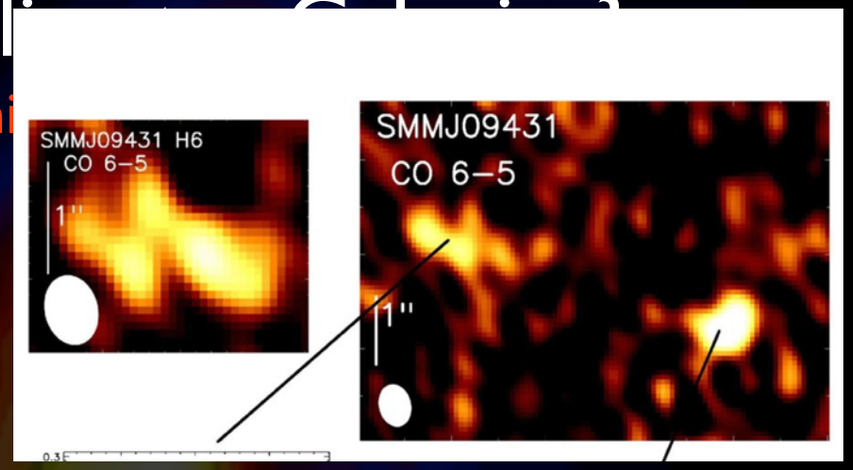

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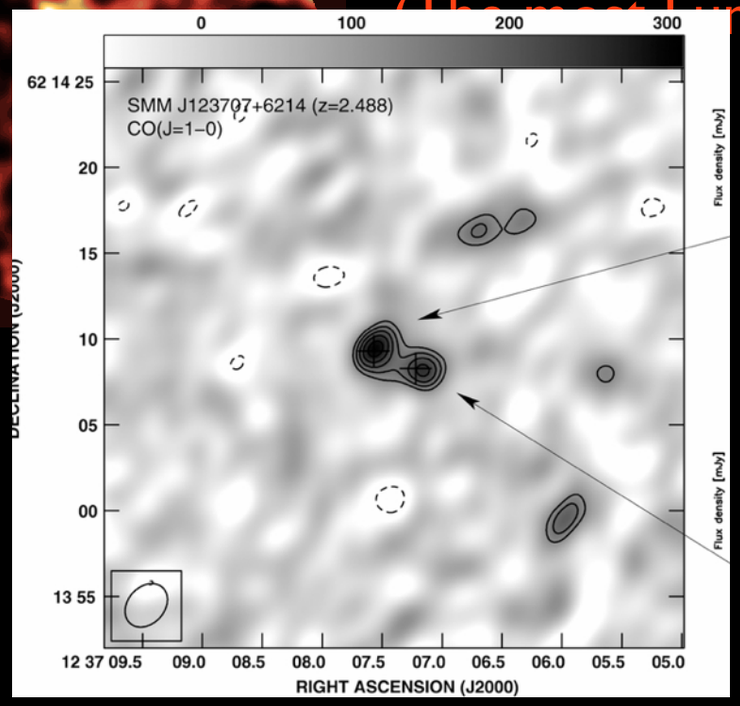

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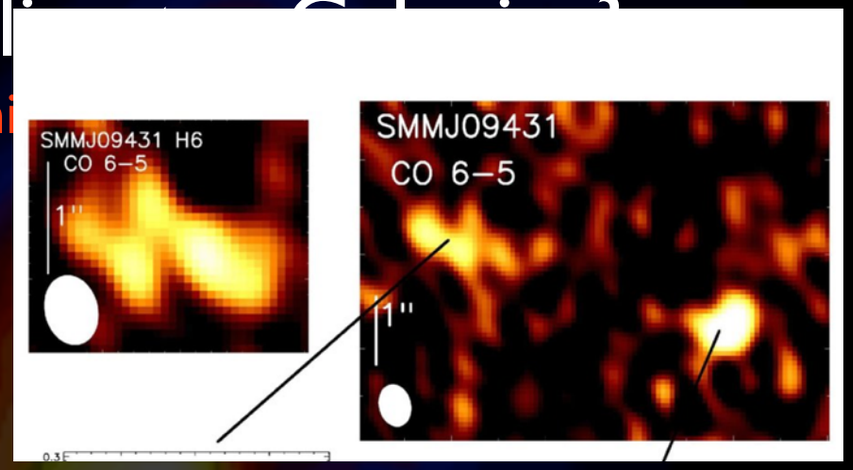

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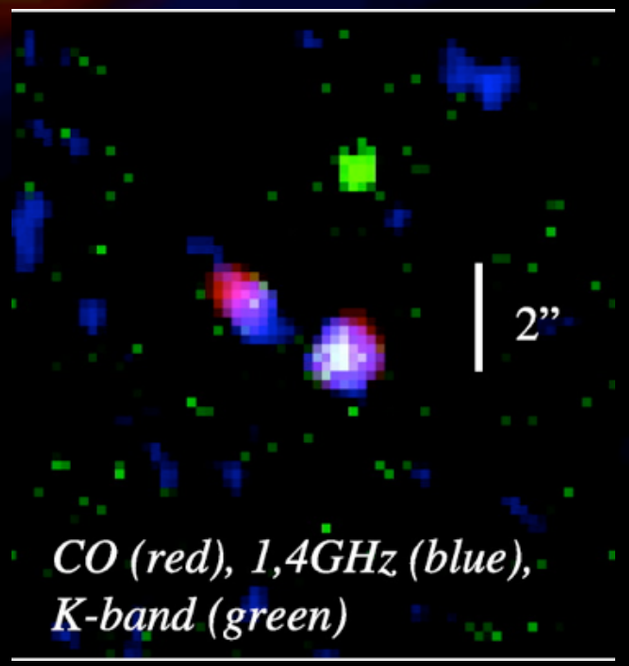

"Submillimeter Galaxies at z~2: Evidence for Major Mergers..."
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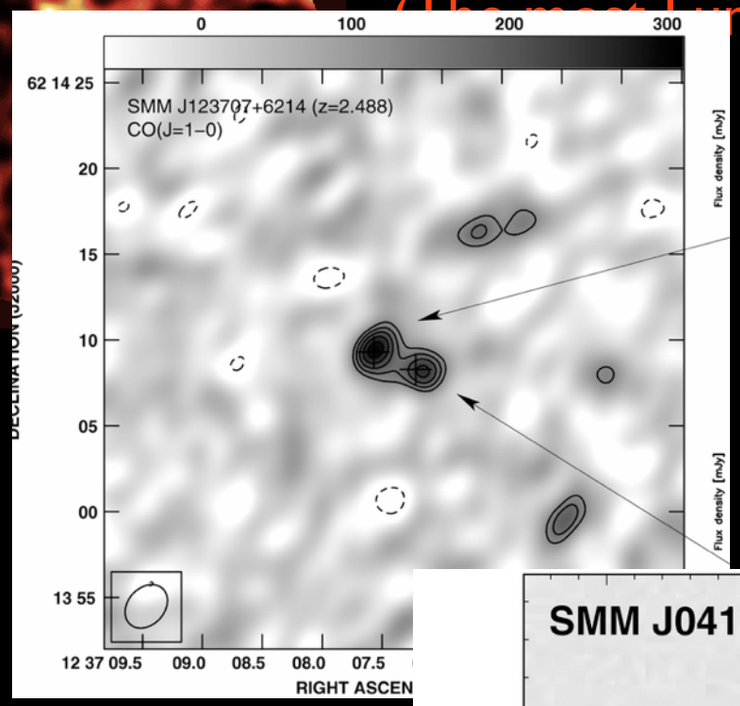

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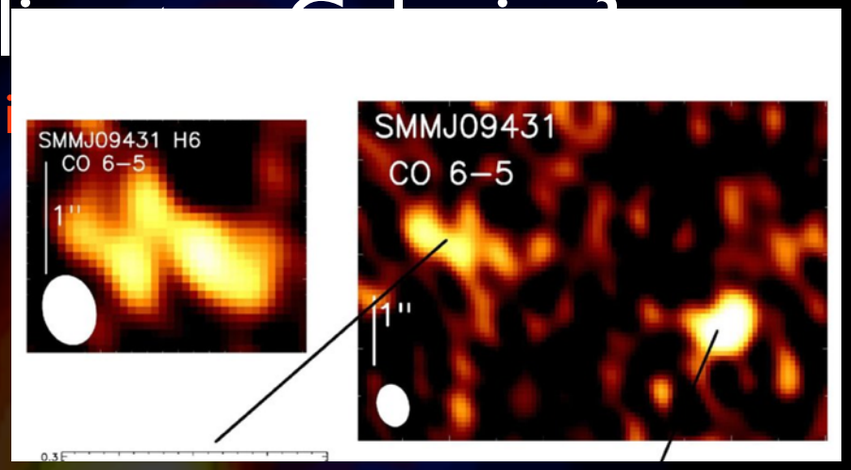

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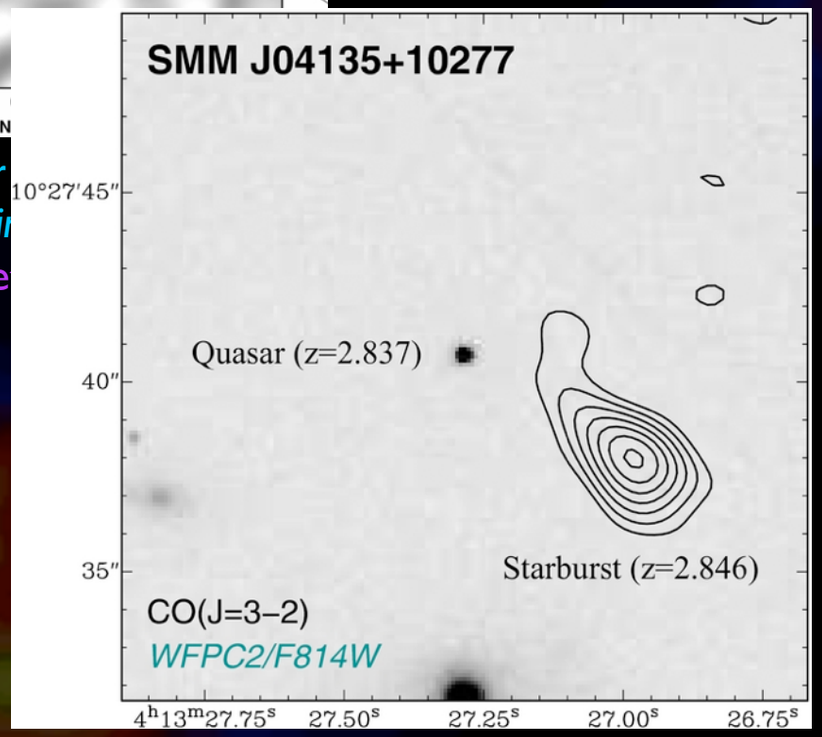

"SMM J04135:A Candidate Wet-Dry Merger.."
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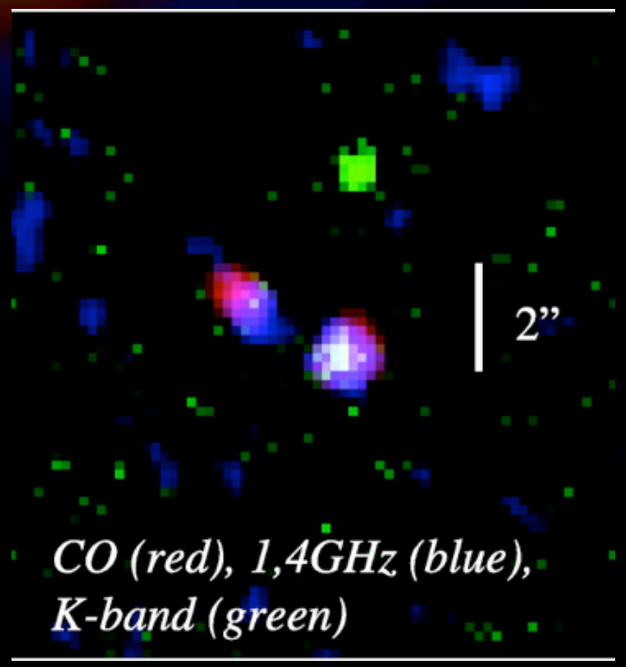

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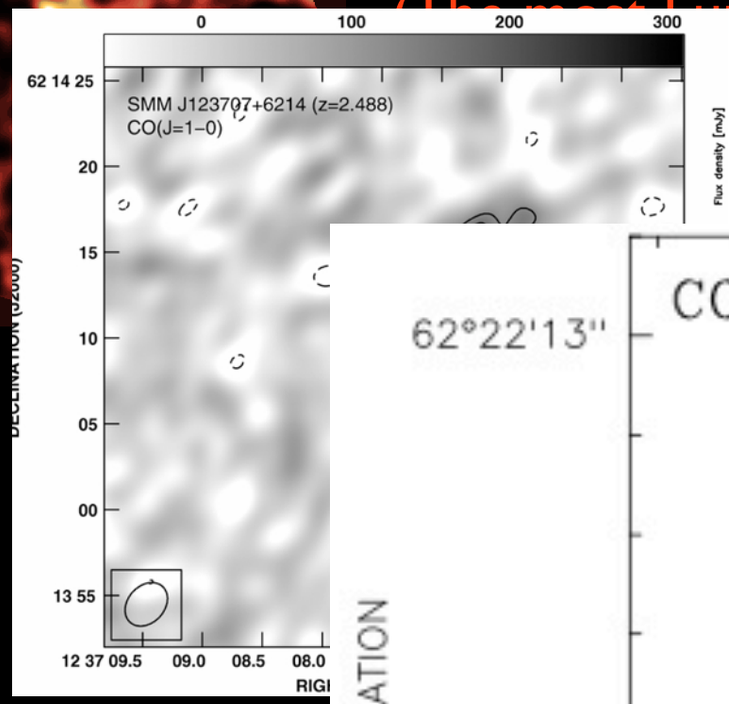

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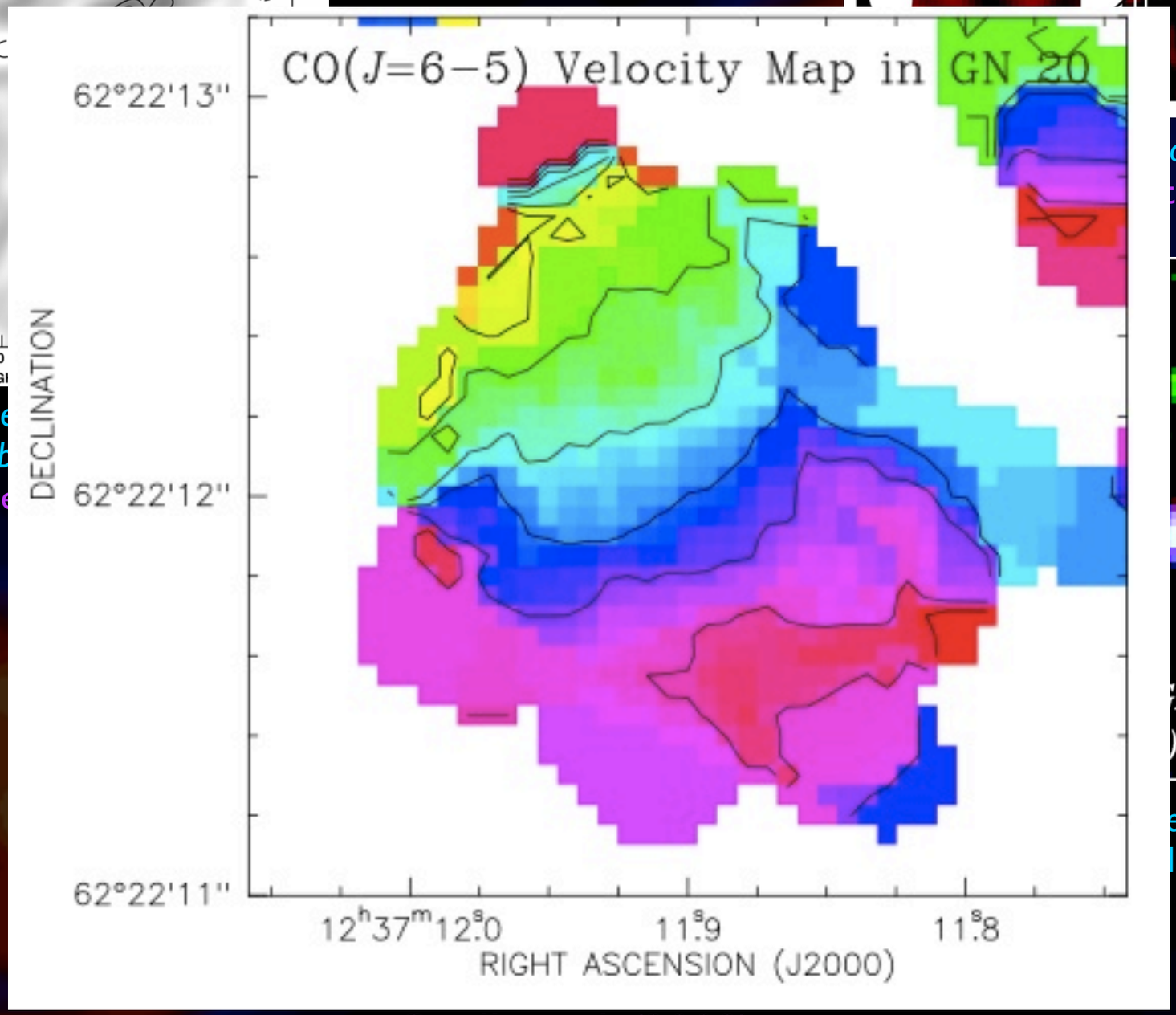
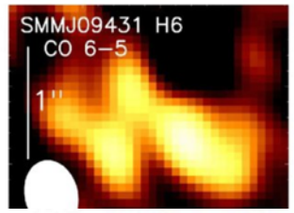
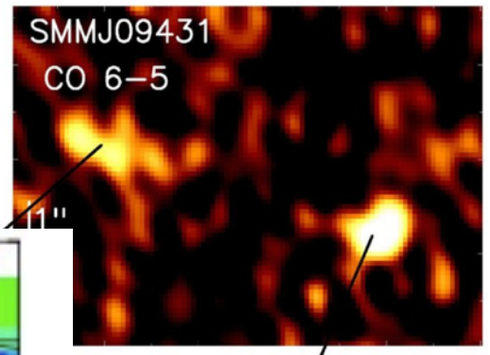
Rieche…







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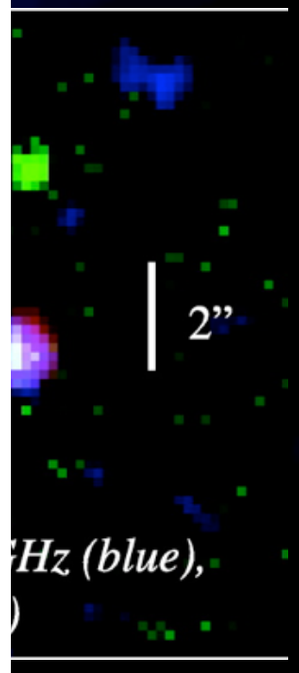

…Hz (blue),
…)

…es at z~2: Evidence
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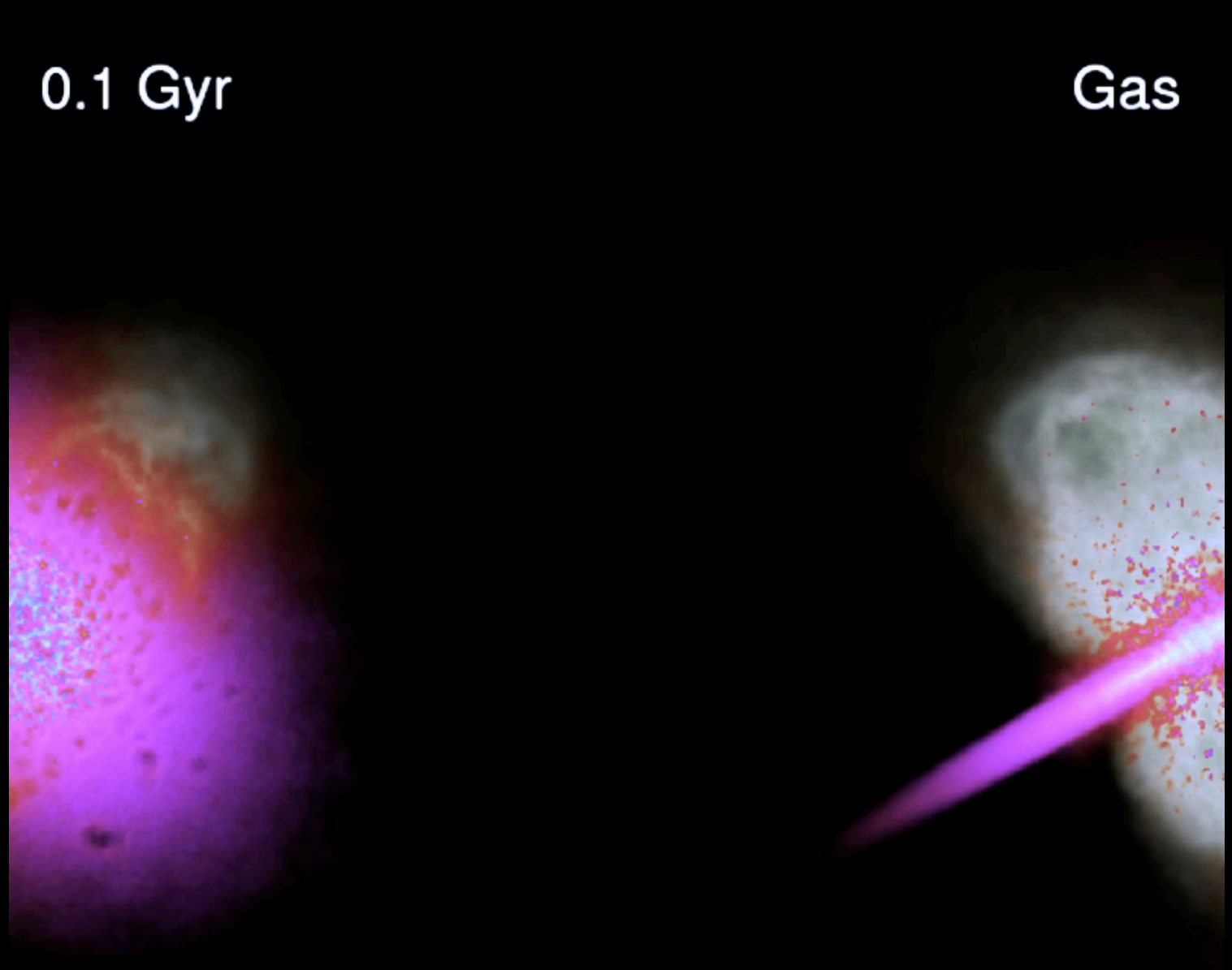
…al. 2008

Carilli et al. (2009)
Hodge et al. (2012)
GN20 has a huge gas disk



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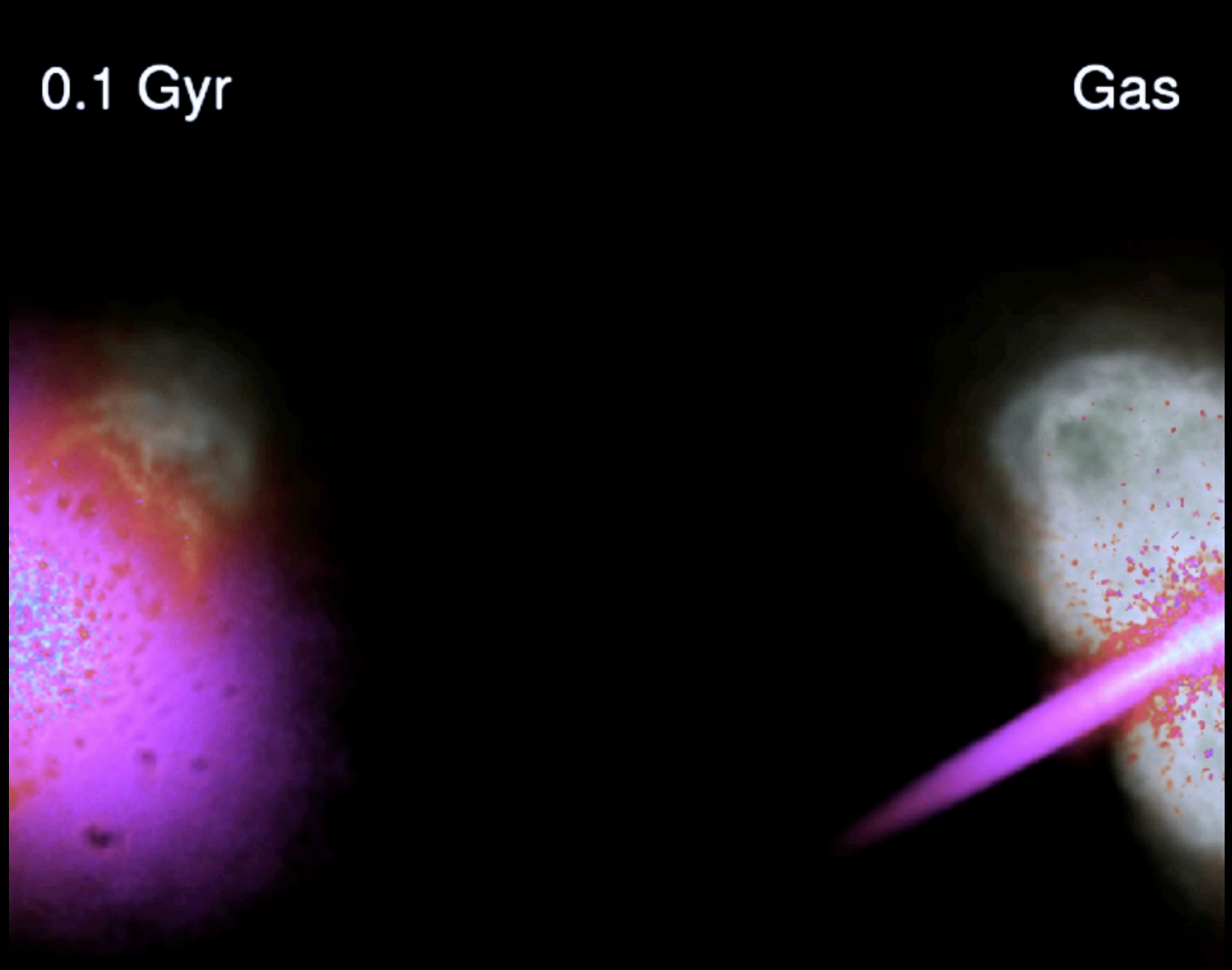
2. "Density-Independent" EOMs (improved SPH)

3. $P_{rad} \sim (1+\Sigma^{*}\kappa)L/c$

Simulations provide spatial distribution and temporal evolution of

1. SFR
2. M*
3. Stellar Ages
4. Metallicities
5. Gas density distribution



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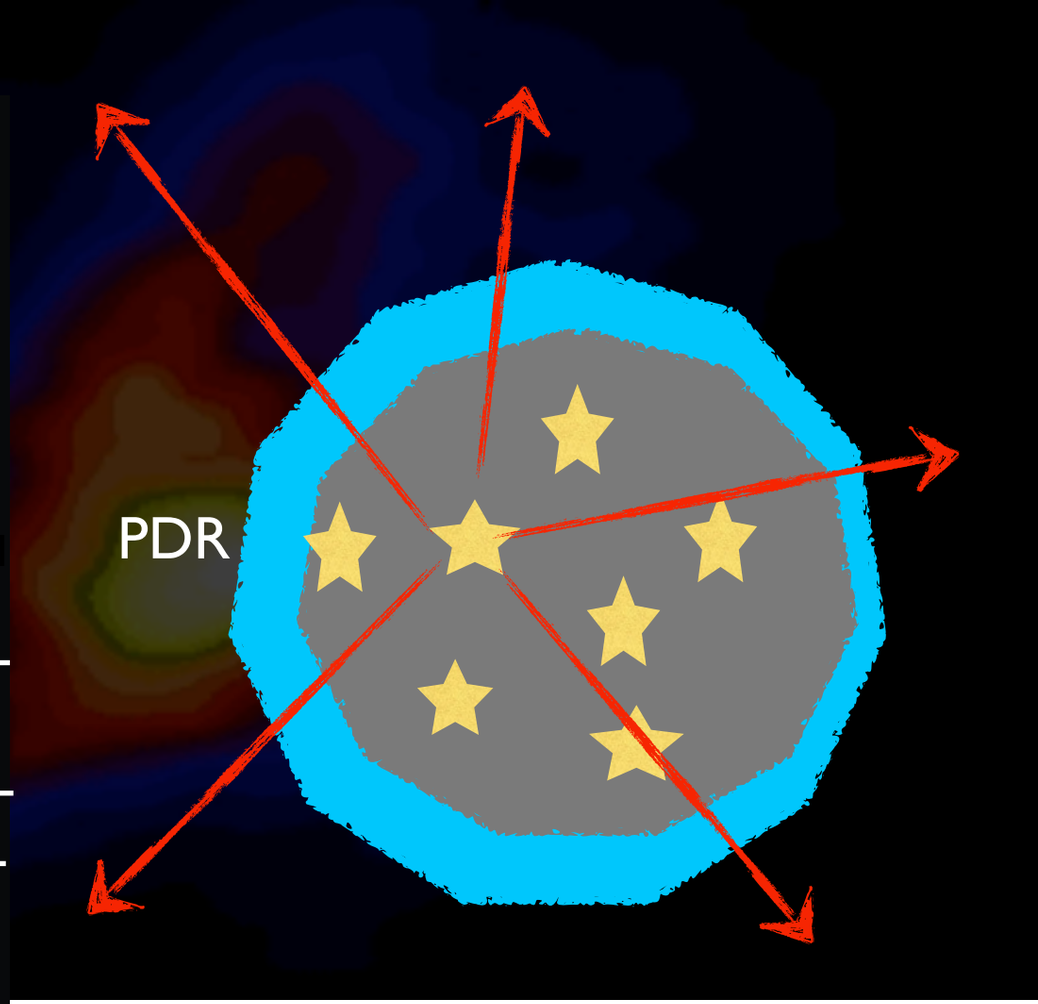
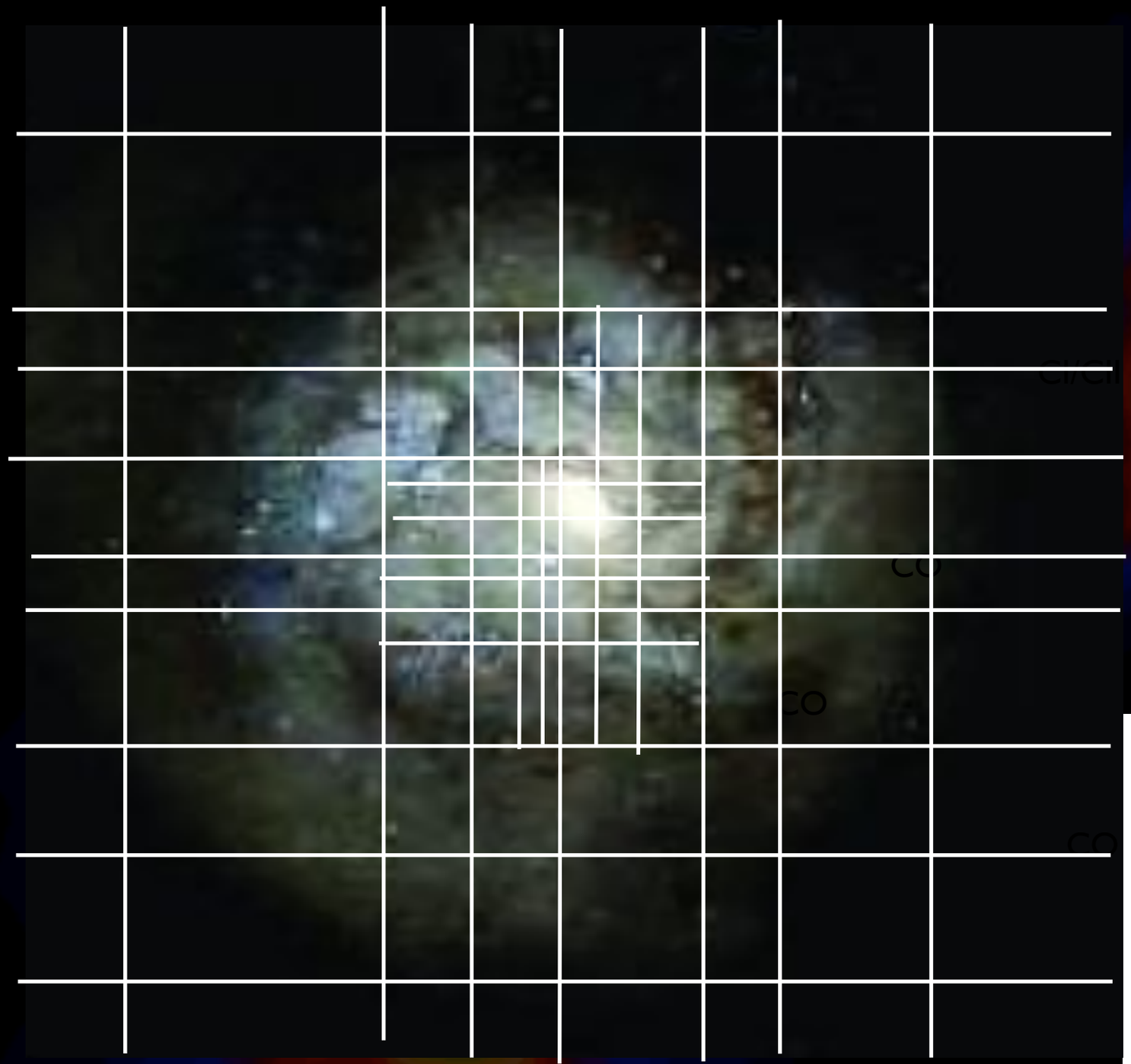
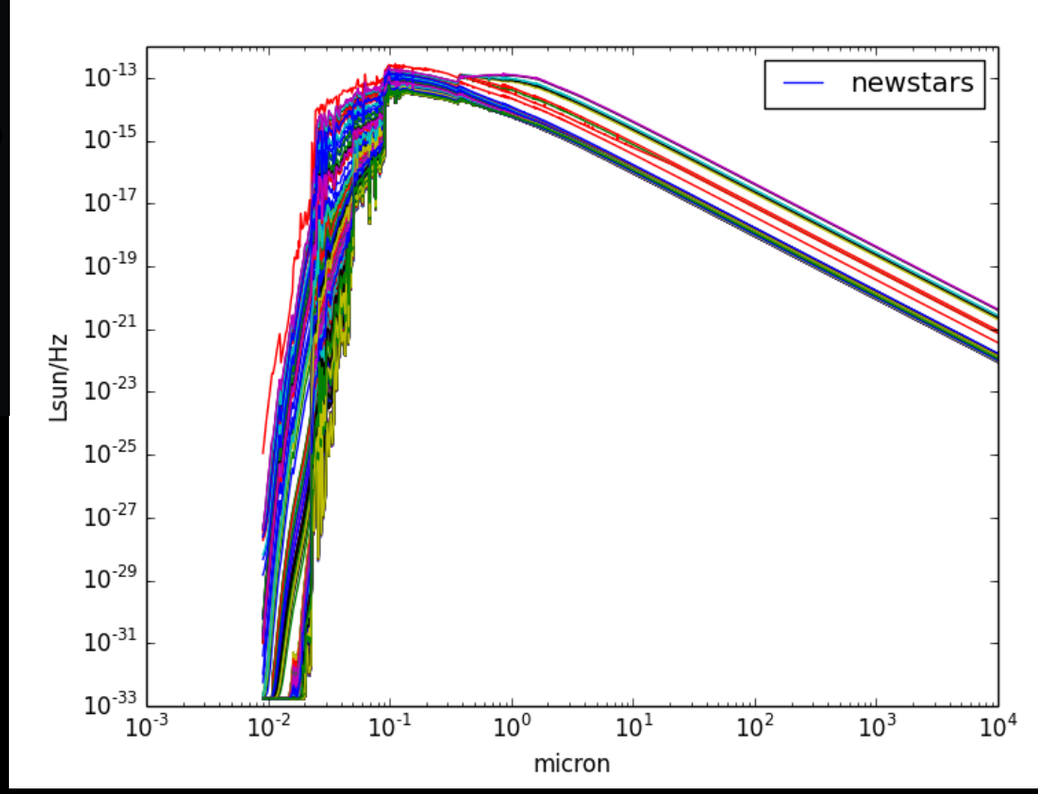


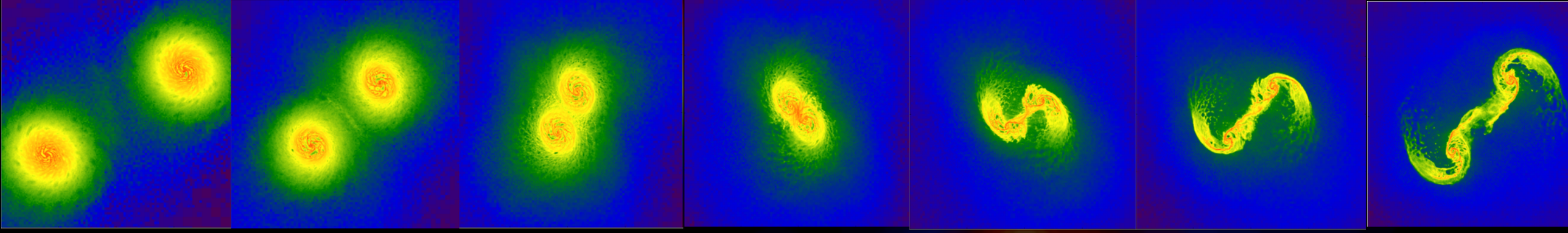


SUNRISE; Jonsson et al. 2006,2010

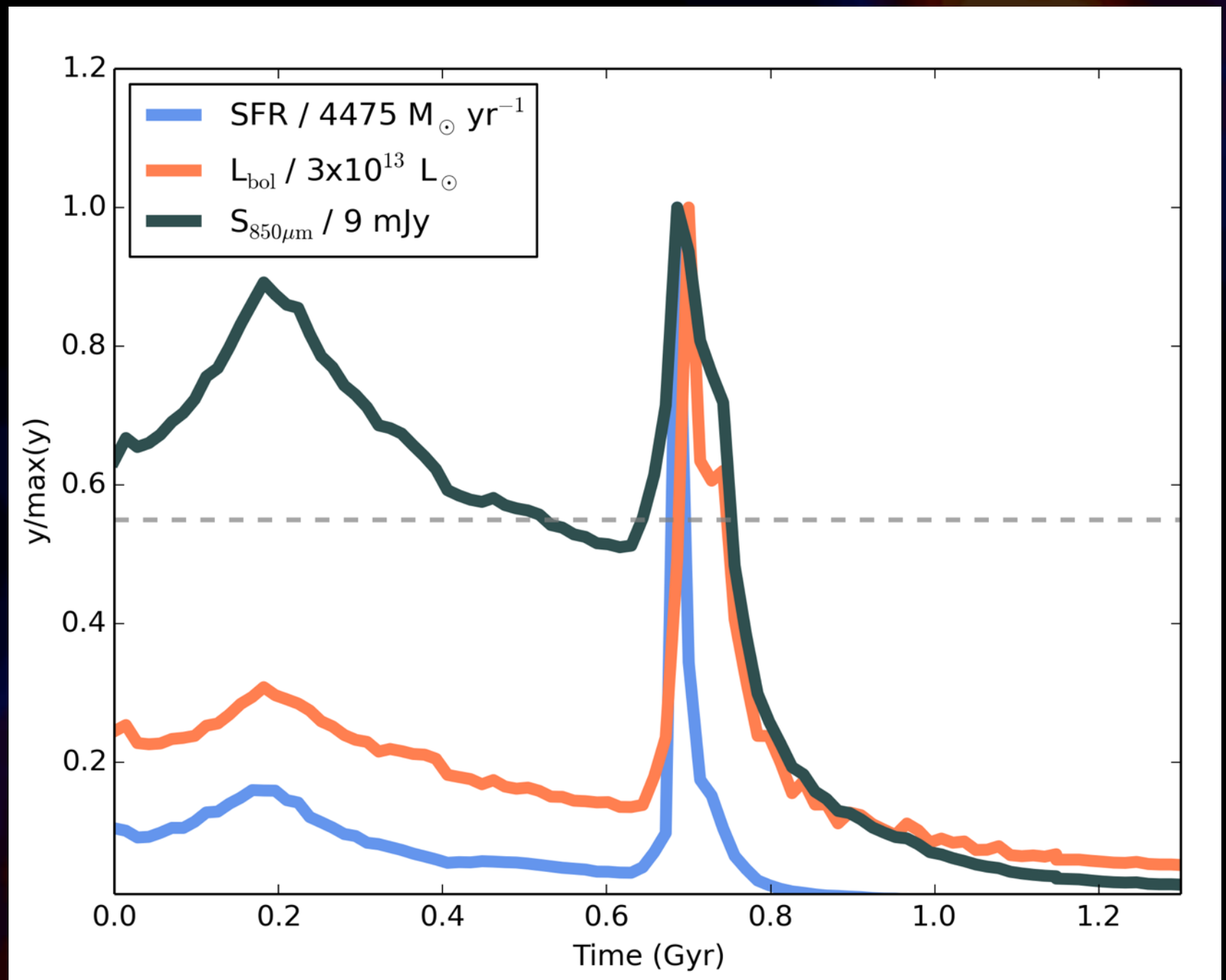


Narayanan et al. 2009

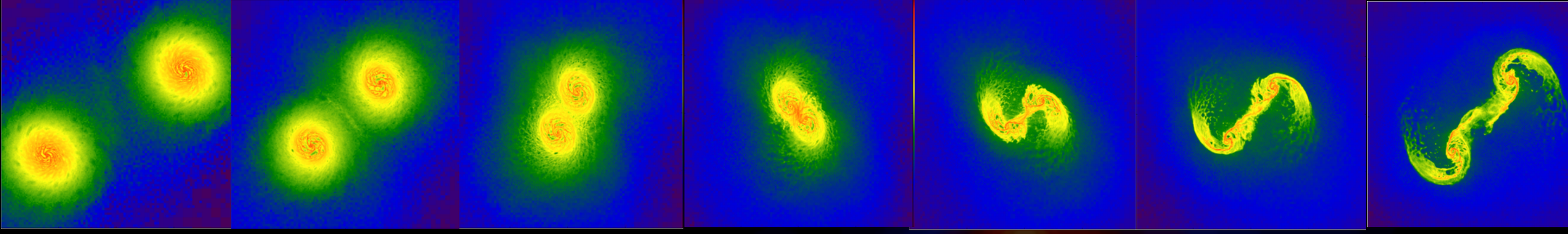
Desika Narayanan



The Evolution of a Galaxy Merger



Narayanan, Hayward et al. 2010
Narayanan, Dey et al. 2010
Hayward, Keres, Jonsson, DN, Hernquist 2011



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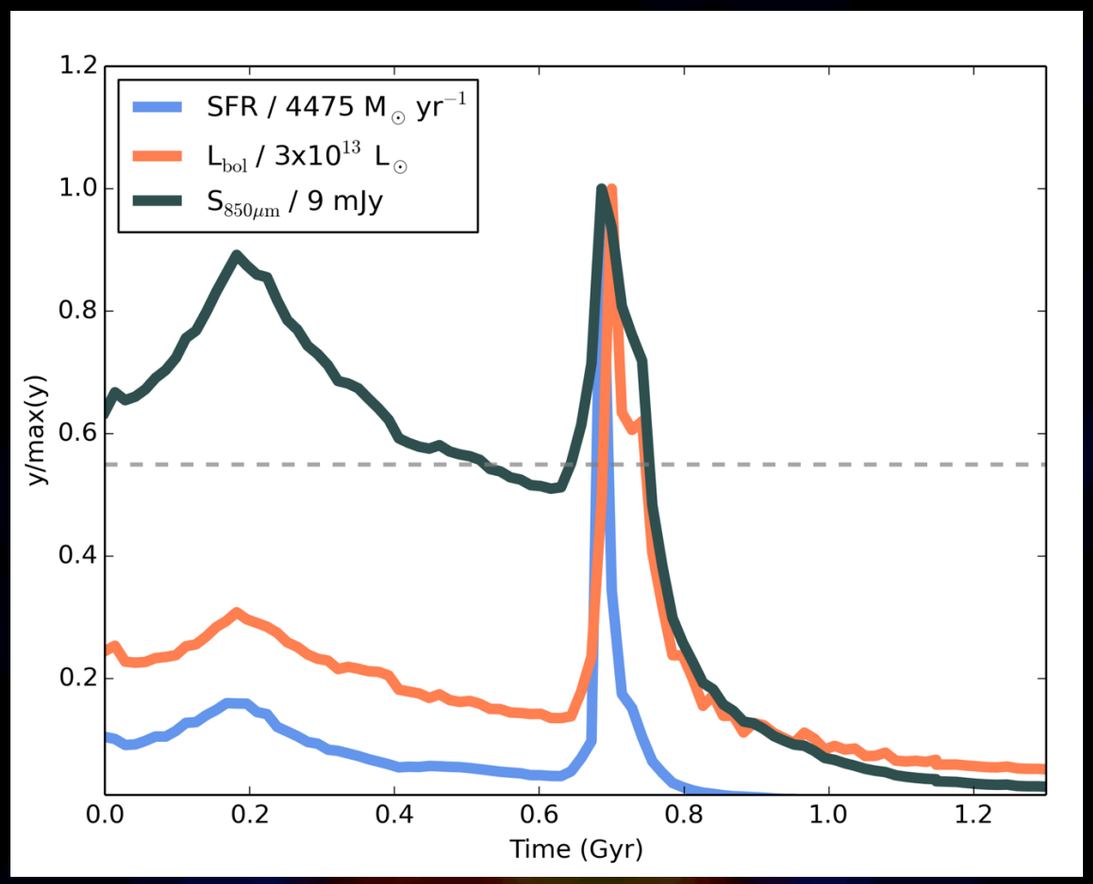

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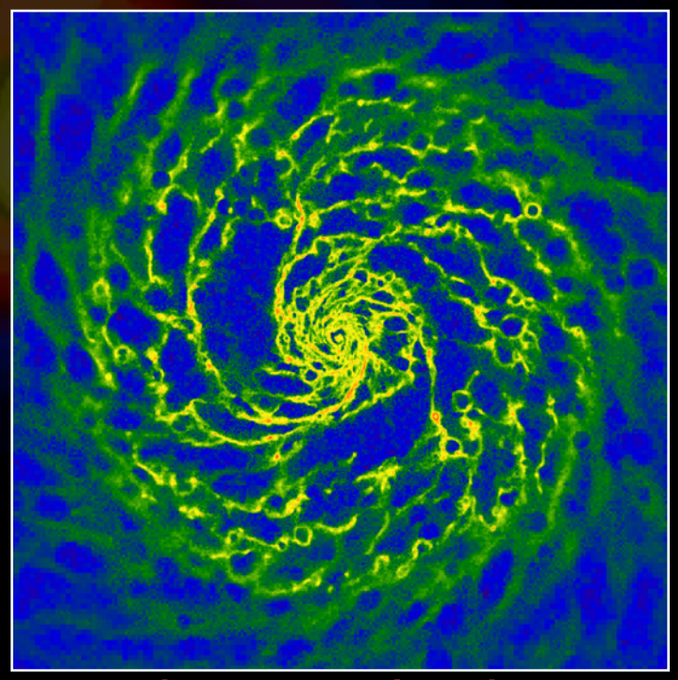
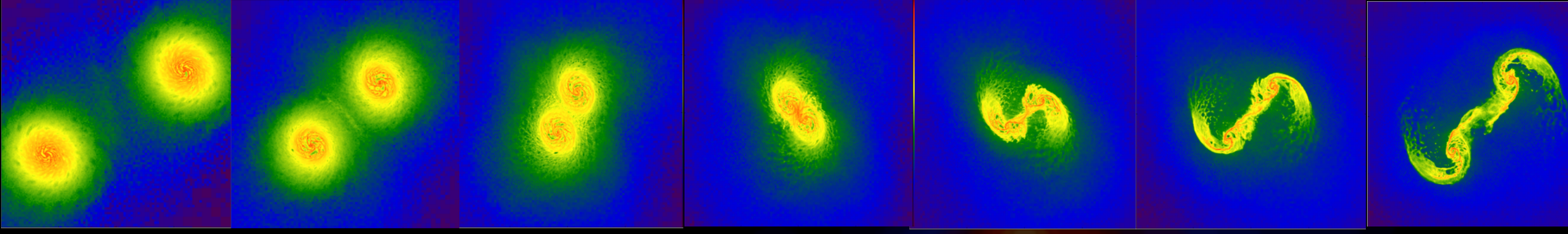


Galactic Pressure destroys cloud integrity, and results in ~uniform volume filling factor (huge columns of obscuration)



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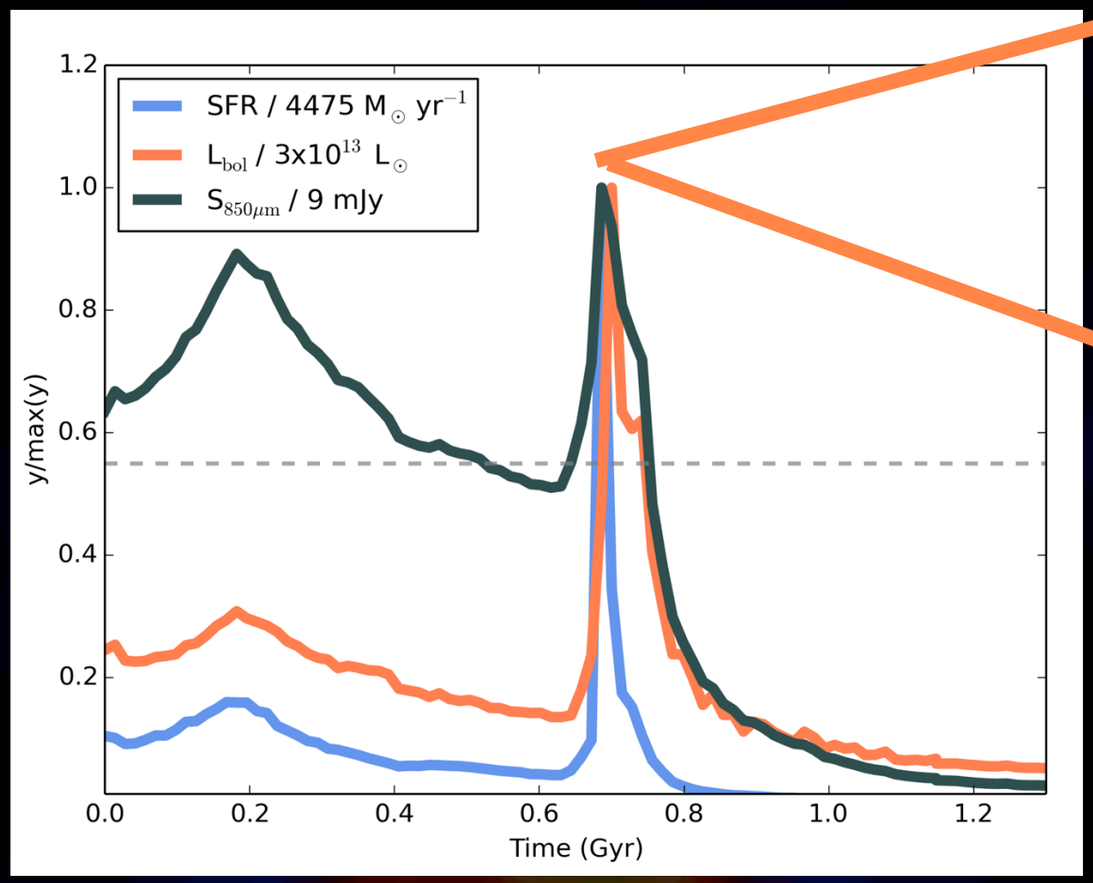

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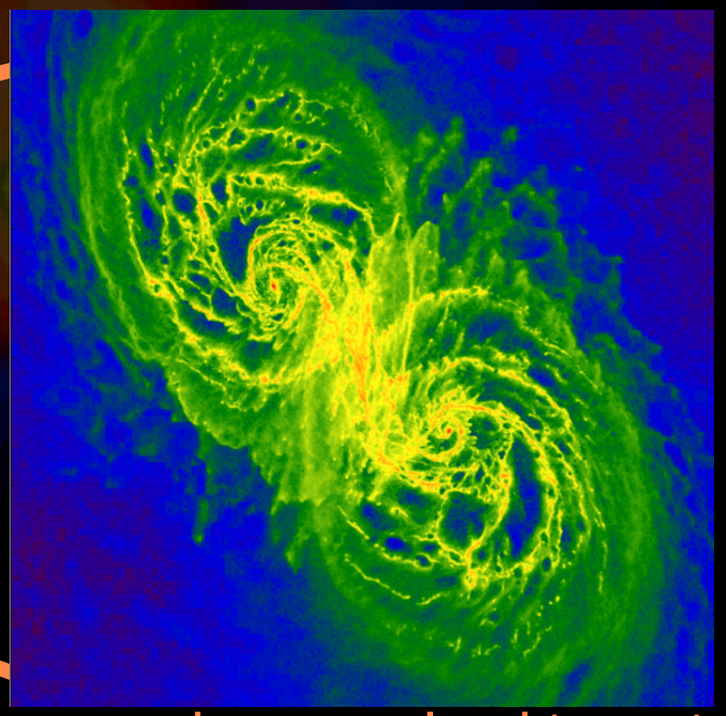

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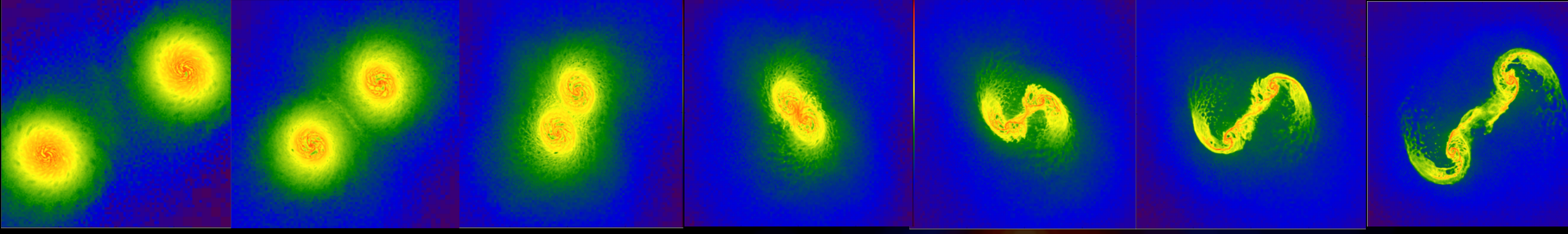

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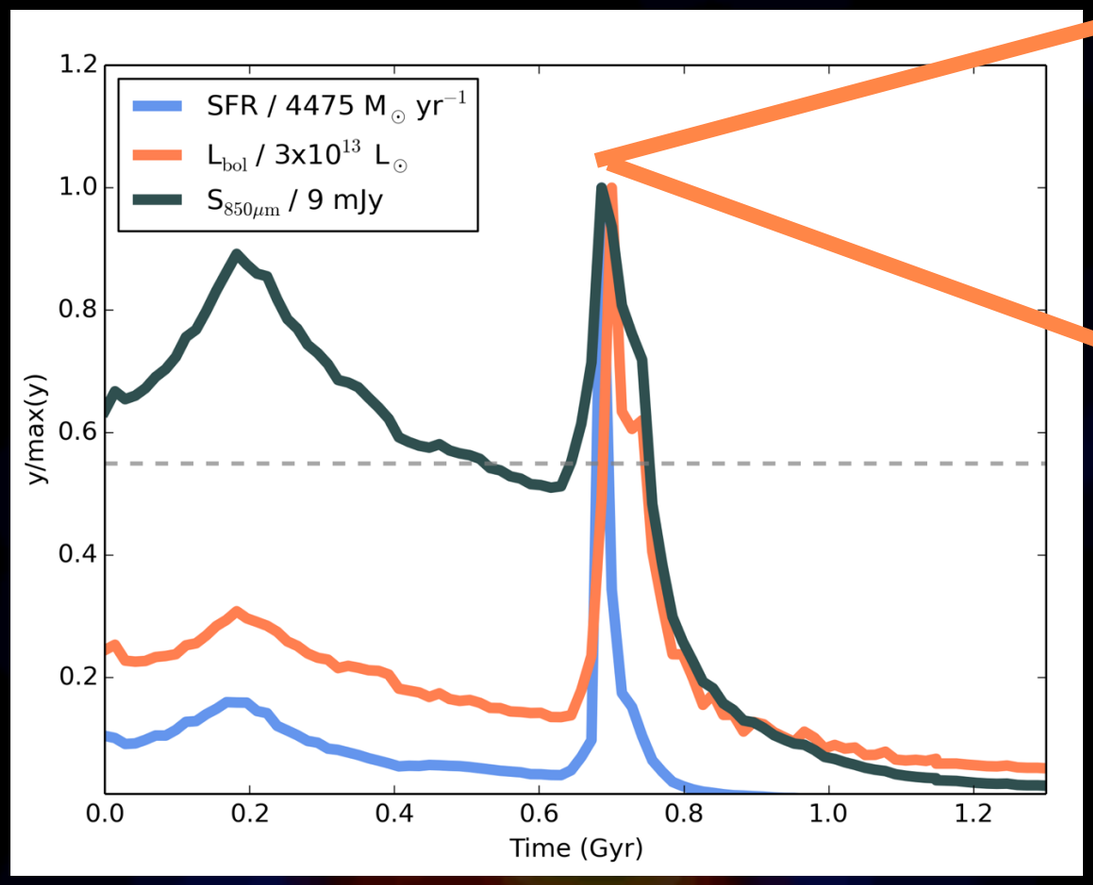

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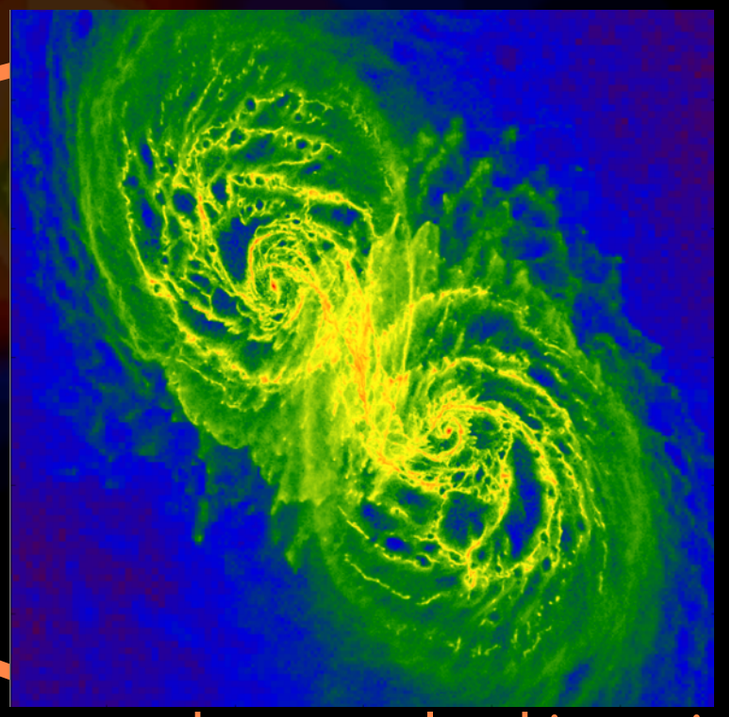
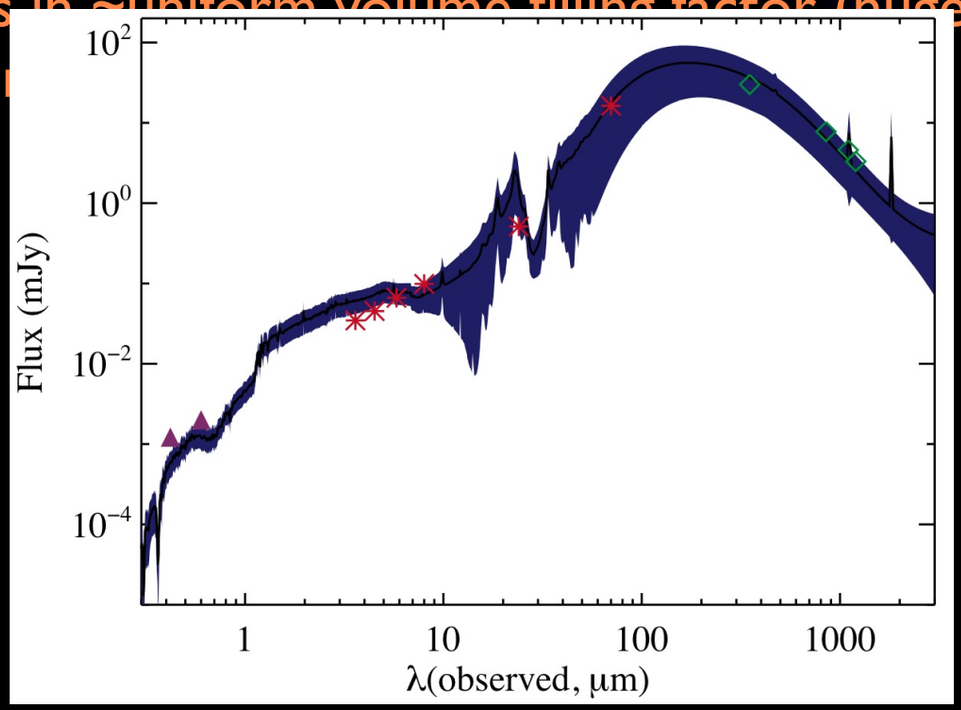
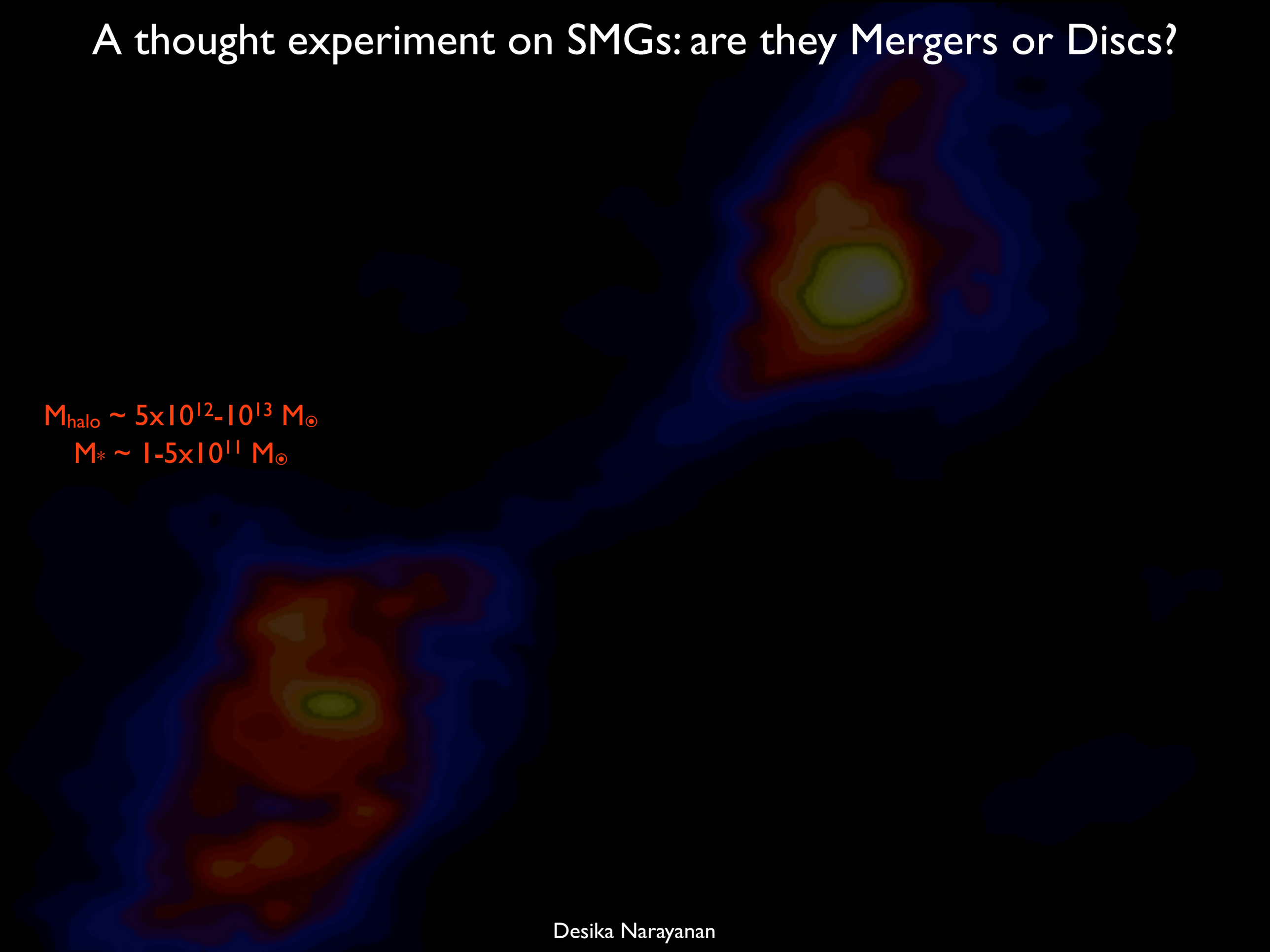


Galactic Pressure destroys cloud integrity, and results in ~uniform volume filling factor (huge column



A thought experiment on SMGs: are they Mergers or Discs?



M_{halo} ~ $5x10^{12}$-10^{13} $M_\odot$

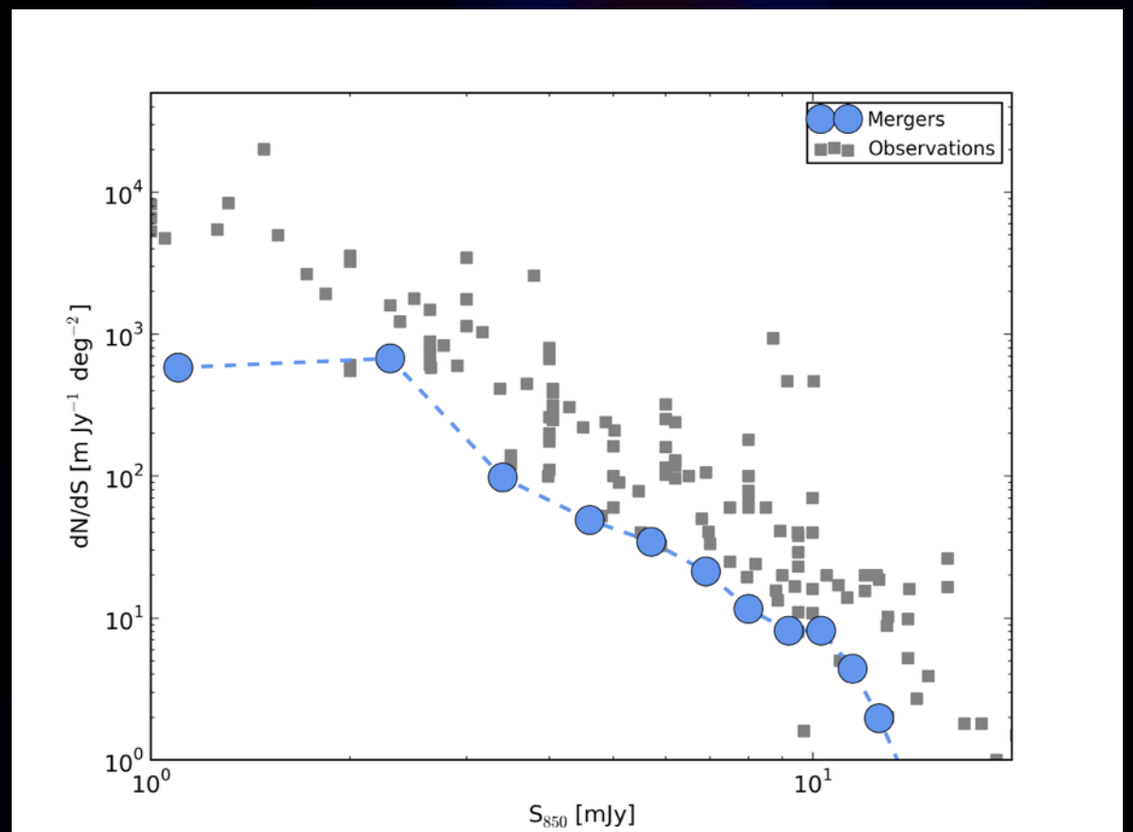
M_* ~ 1-$5x10^{11}$ $M_\odot$

Desika Narayanan

A thought experiment on SMGs: are they Mergers or Discs?

Merger rate ~1 per T_H at z~2
Space Density ~ 5×10^{-5} Mpc^{-3}
SFR_{burst}-M_{gal} relation
$S_{850} \sim SFR^{0.4}$

$M_{halo} \sim 5 \times 10^{12}$-$10^{13}$ $M_\odot$
$M_* \sim 1$-5×10^{11} $M_\odot$



Hayward, Narayanan et al. (2013)
Casey, Narayanan & Cooray (2014)

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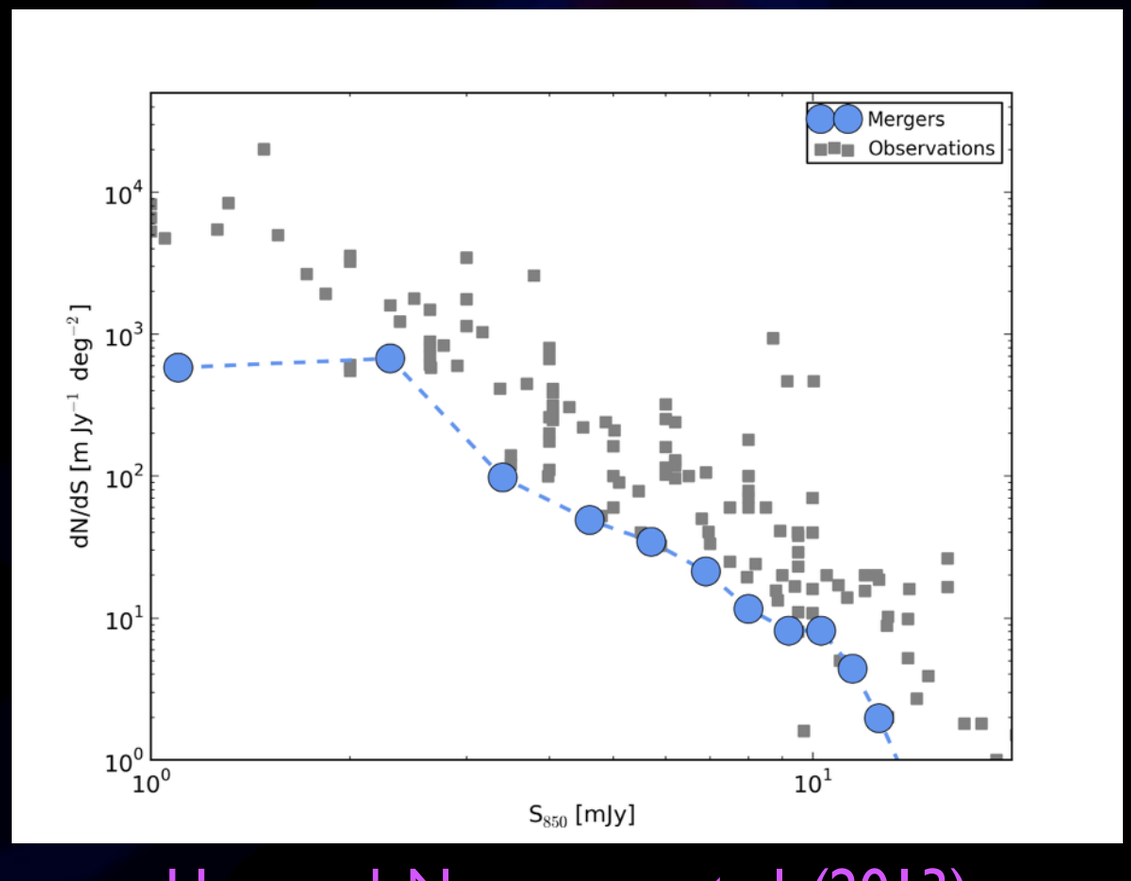
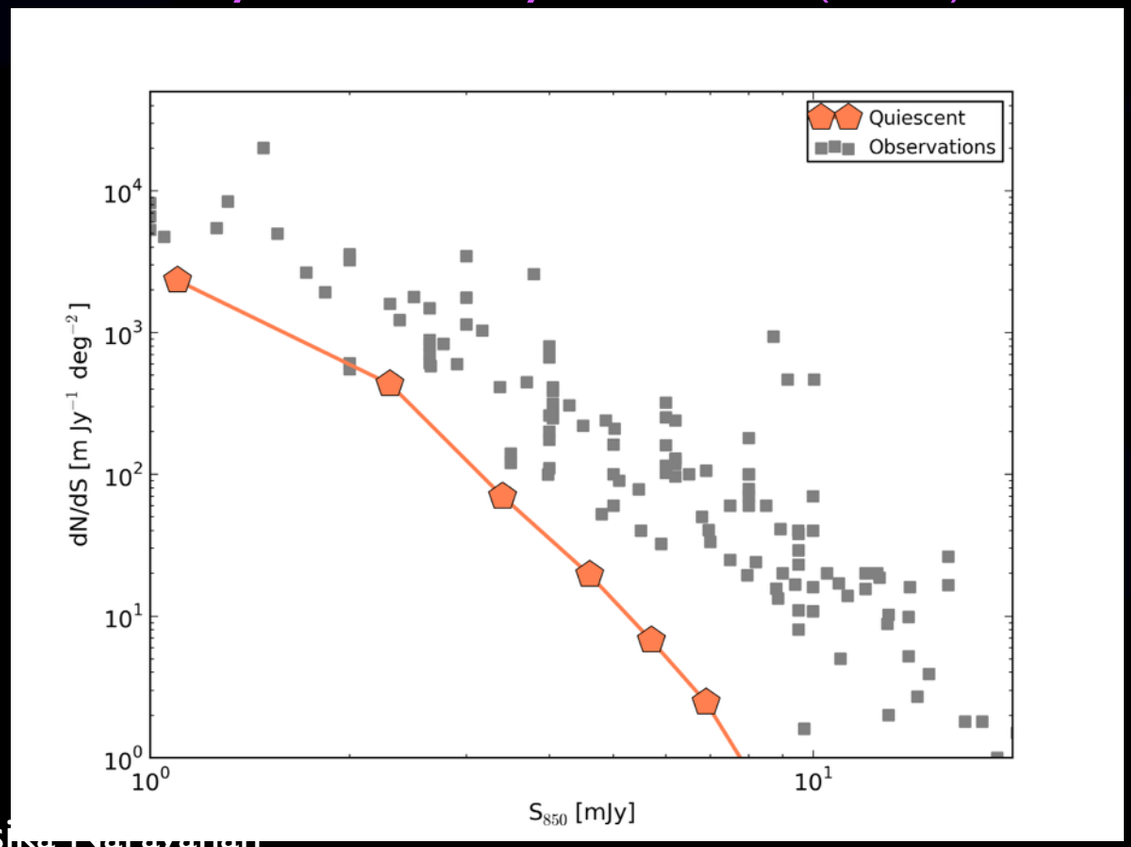


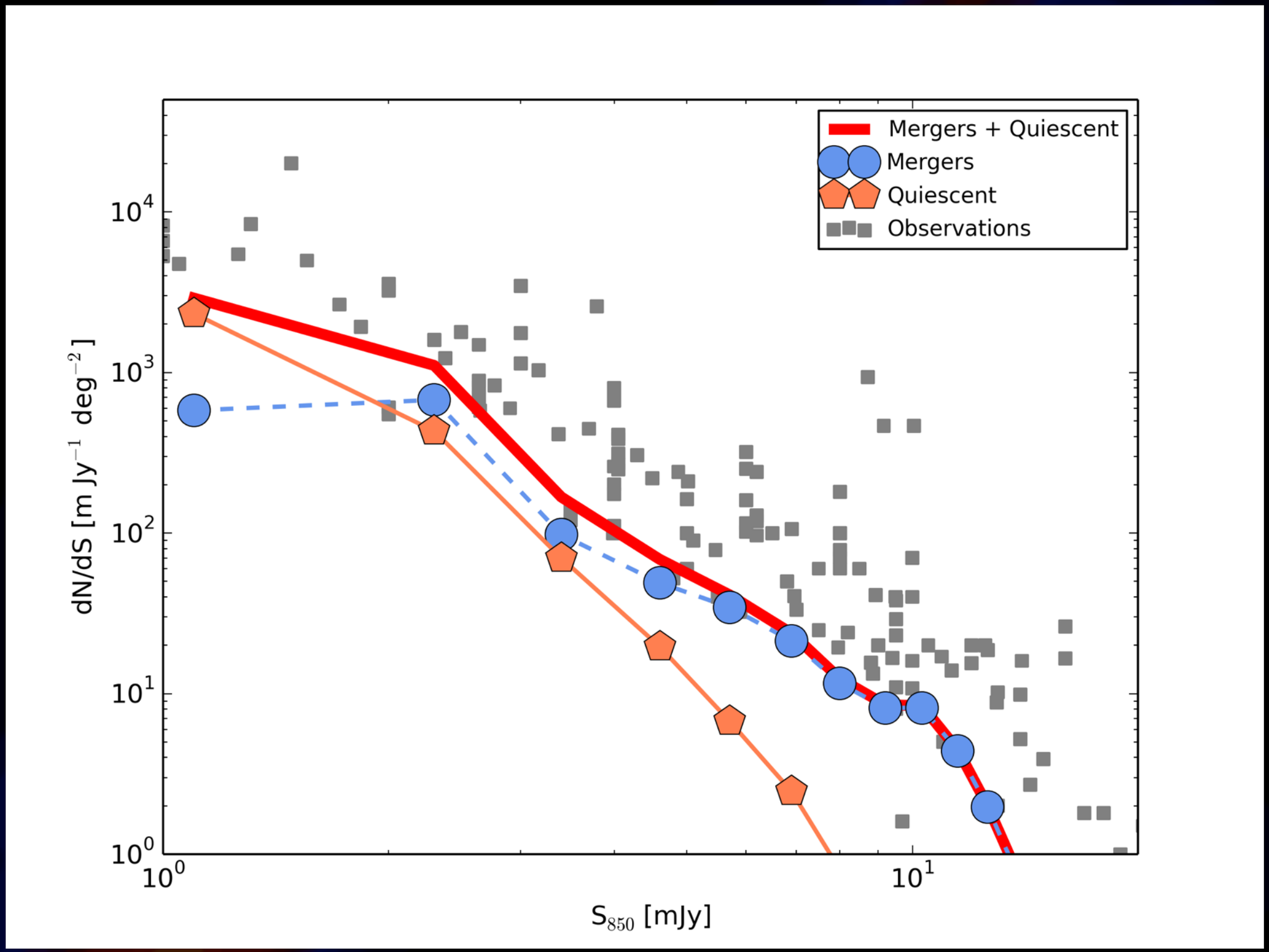
Hayward, Narayanan et al. (2013)

Stellar Mass functions at z~2-3
SFR-M_* relation (Main Sequence)
$S_{850} \sim SFR^{0.4}$



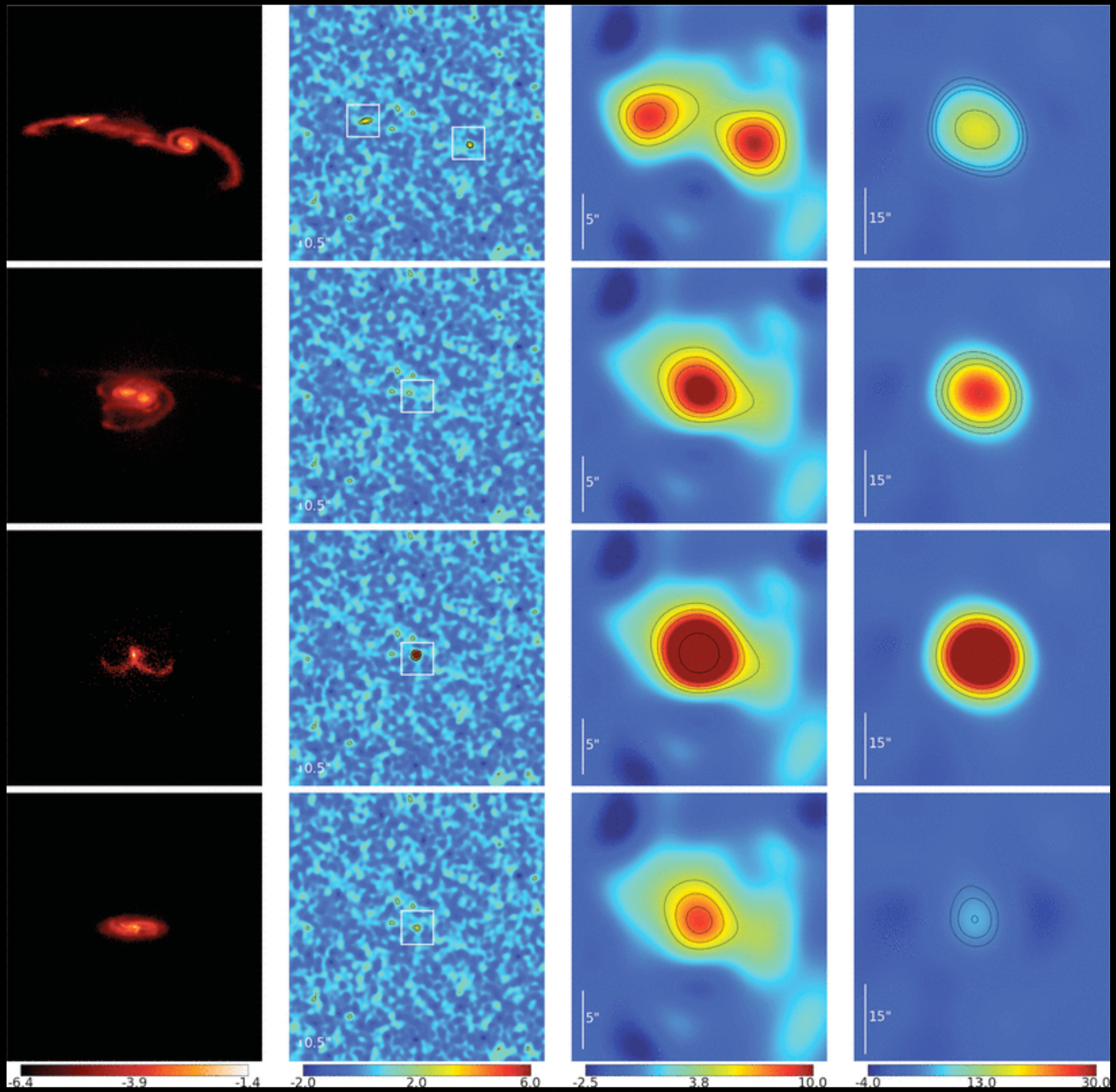
Desika Narayanan

SMG Number Counts: Isolated and Mergers only

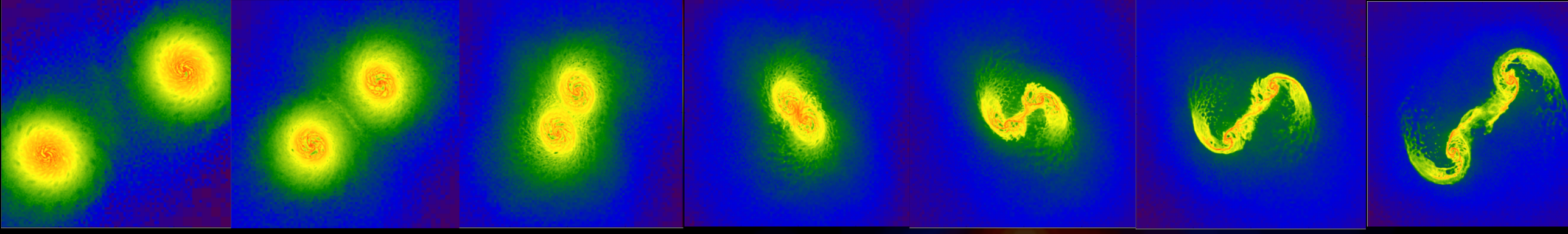


Hayward, Narayanan et al. 2013

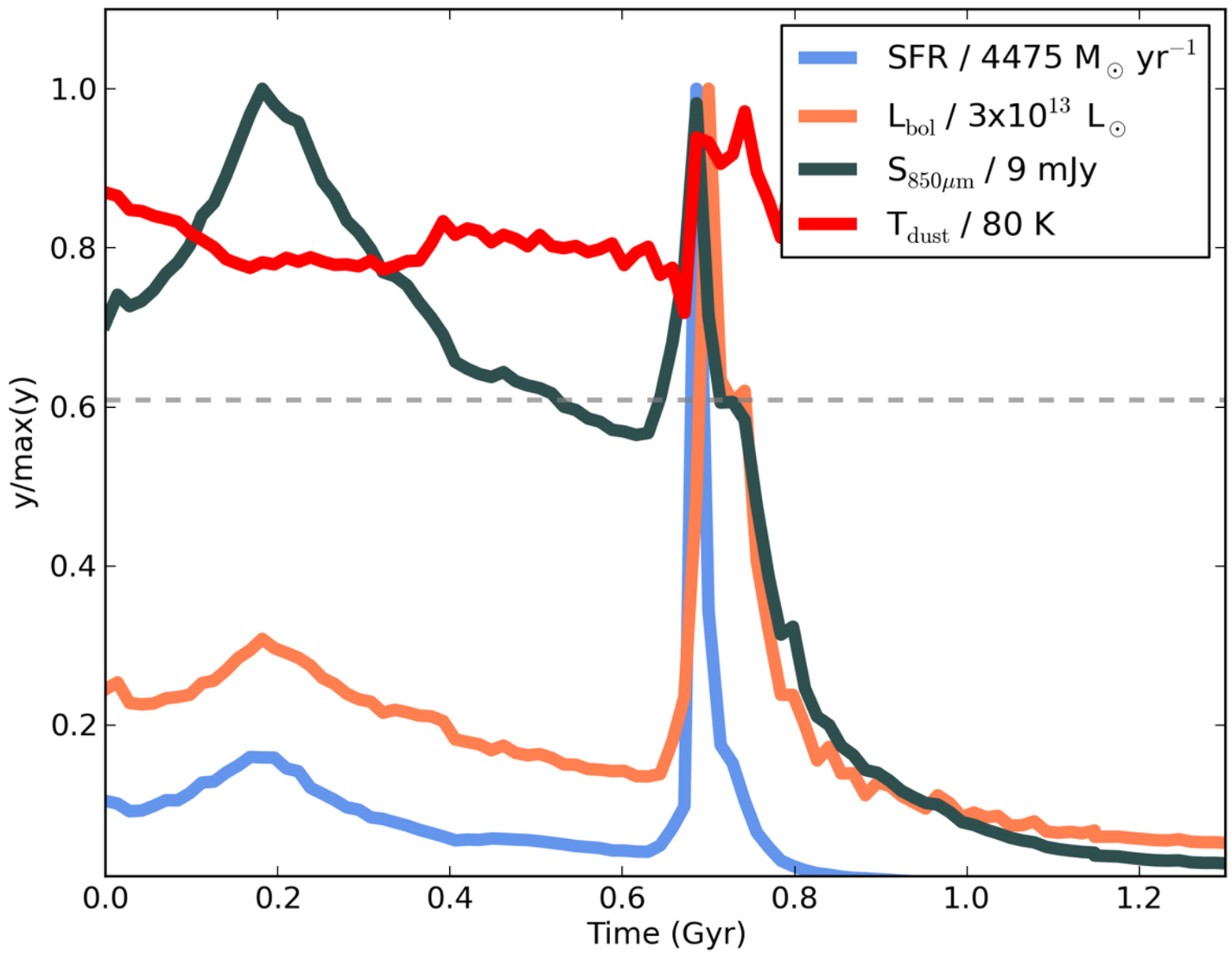
SMA JCMT



Hayward+2012

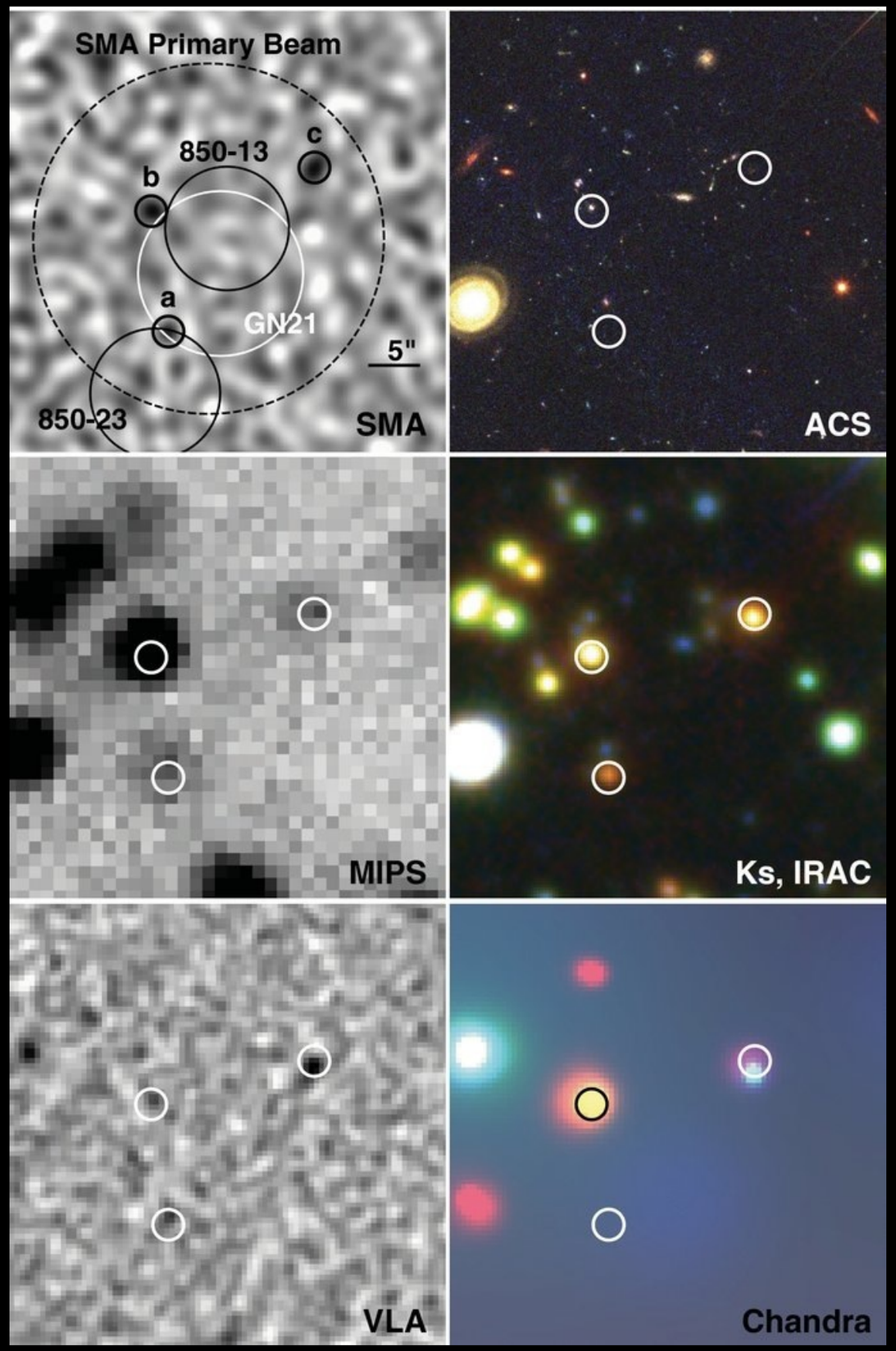


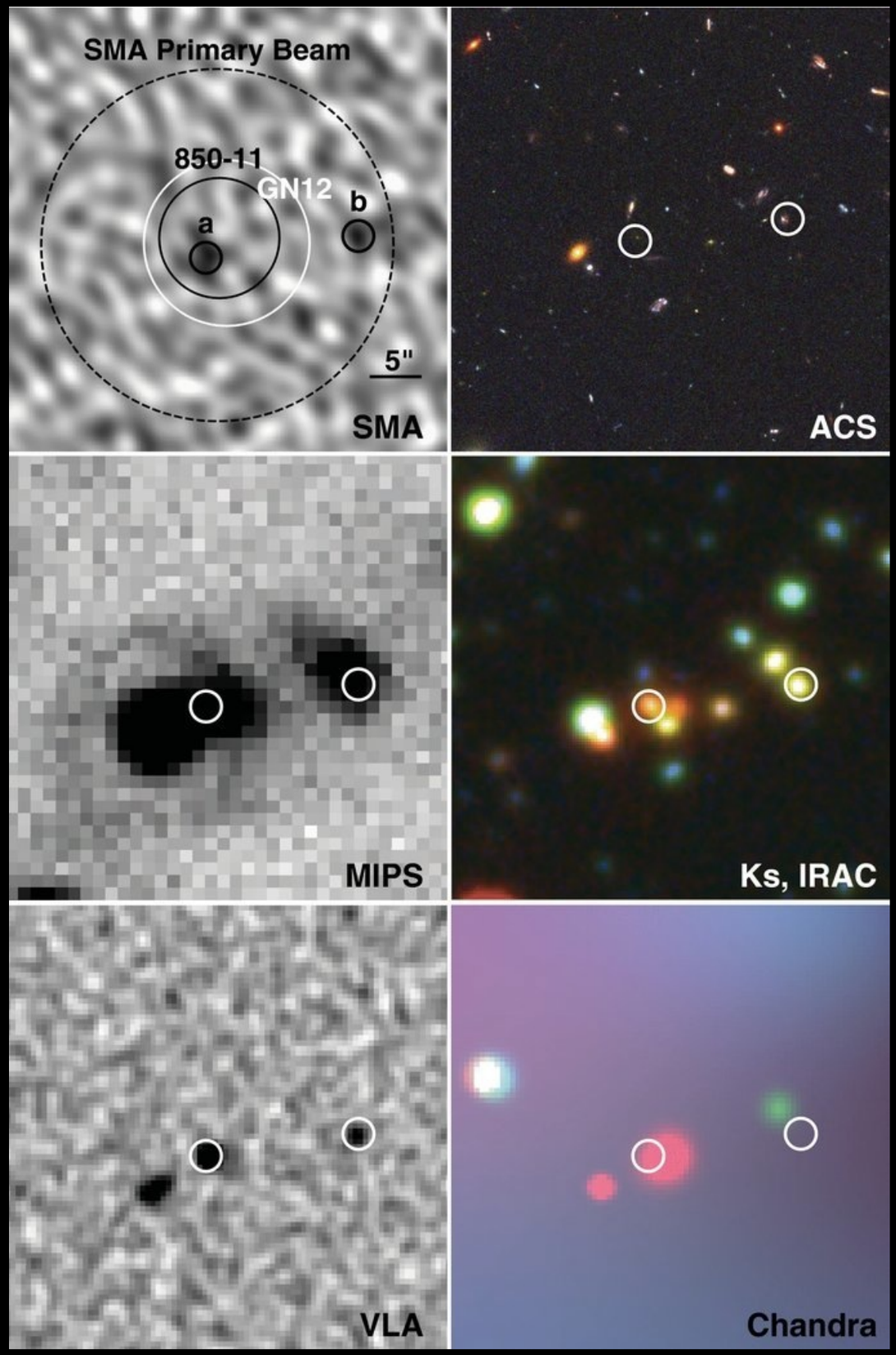
The Evolution of a Galaxy Merger



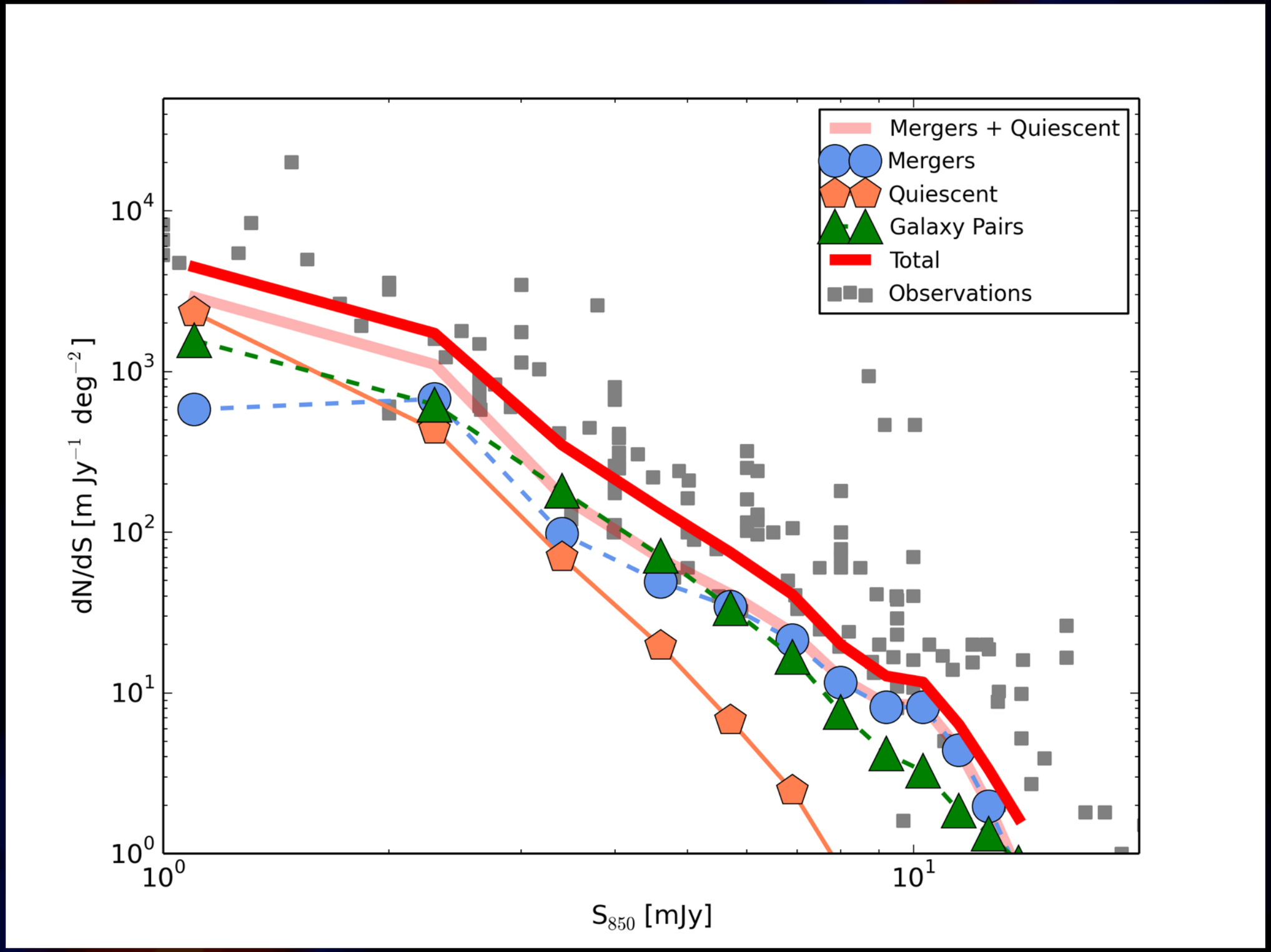
Narayanan, Hayward et al. 2010
Hayward, Narayanan et al. 2013
Hayward, Keres, Jonsson, DN + Hernquist 2011

Wang et al. 2009 (with SMA)



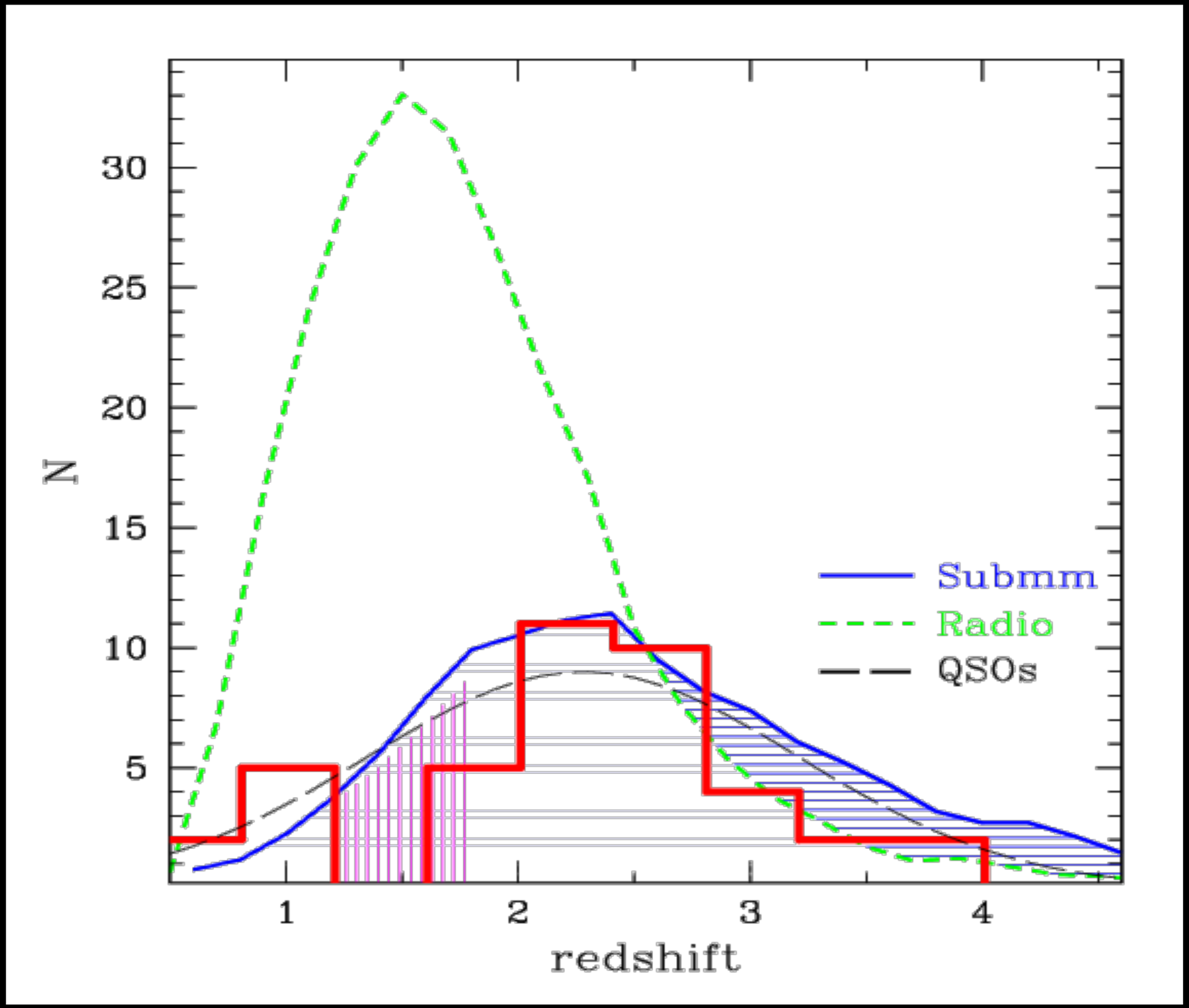


SMG Number Counts: Full Model (Isolated, Pairs and Mergers)



Hayward, Narayanan et al. 2013

Redshift Distribution



Chapman et al. (2003)

Redshift Distribution

The Astrophysical Journal, 671:1531–1537, 2007 December 20

EVIDENCE FOR A POPULATION OF HIGH-REDSHIFT SUBMILLIMETER GALAXIES FROM INTERFEROMETRIC IMAGING

Joshua D. Younger,[1] Giovanni G. Fazio,[1] Jia-Sheng Huang,[1] Min S. Yun,[2] Grant W. Wilson,[2] Matthew L. N. Ashby,[1] Mark A. Gurwell,[1] Kamson Lai,[1] Alison B. Peck,[1,3] Glen R. Petitpas,[1] David J. Wilner,[1] Daisuke Iono,[4] Kotaro Kohno,[5] Ryohei Kawabe,[6] David H. Hughes,[7] Itziar Aretxaga,[7] Tracy Webb,[8] Alejo Martínez-Sansigre,[9] Sungeun Kim,[10] Kimberly S. Scott,[2] Jason Austermann,[2] Thushara Perera,[2] James D. Lowenthal,[11] Eva Schinnerer,[9] and Vernesa Smolčić[9,12]
Received 2007 June 7; accepted 2007 August 6

ABSTRACT

We have used the Submillimeter Array to image a flux-limited sample of seven submillimeter galaxies, selected by the AzTEC camera on the JCMT at 1.1 mm, in the COSMOS field at 890 μm with $\sim 2''$ resolution. All of the sources—two radio-bright and five radio-dim—are detected as single point sources at high significance (>6 σ), with positions accurate to $\sim 0.2''$ that enable counterpart identification at other wavelengths observed with similarly high angular resolution. All seven have IRAC counterparts, but only two have secure counterparts in deep *HST* ACS imaging. As compared to the two radio-bright sources in the sample, and those in previous studies, the five radio-dim sources in the sample (1) have systematically higher submillimeter-to-radio flux ratios, (2) have lower IRAC 3.6–8.0 μm fluxes, and (3) are not detected at 24 μm. These properties, combined with size constraints at 890 μm ($\theta \lesssim 1.2''$), suggest that the radio-dim submillimeter galaxies represent a population of very dusty starbursts, with physical scales similar to local ultraluminous infrared galaxies, with an average redshift higher than radio-bright sources.

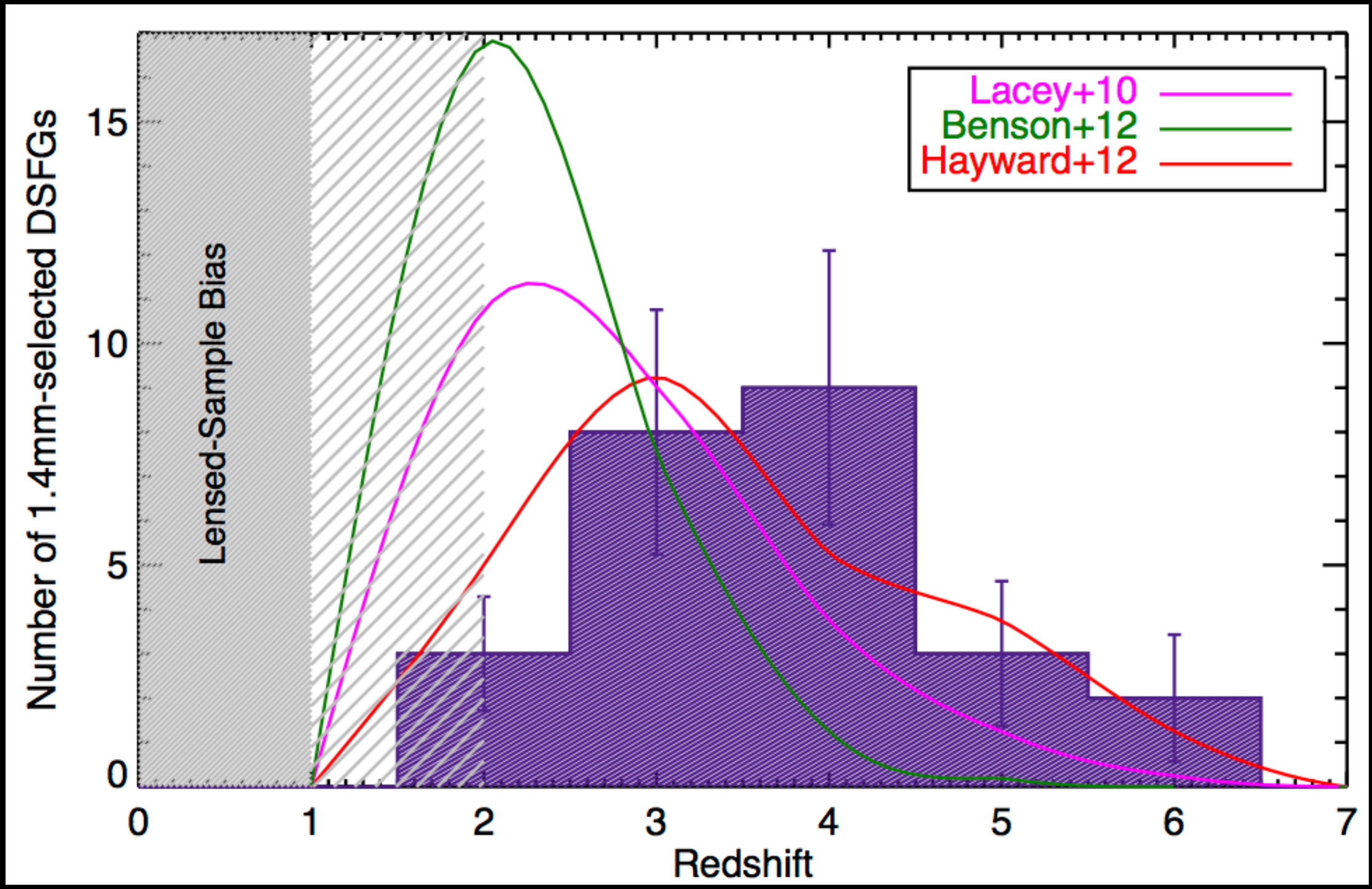
Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: starburst — submillimeter

1. INTRODUCTION

Early studies of the far-infrared (FIR) cosmic background in-

surveys at millimeter wavelengths (Greve et al. 2004; Dannerbauer et al. 2004; Carilli et al. 2005; Schlaerth et al. 2005; Laurent et al.

Redshift Distribution



Casey, Narayanan & Cooray 2014

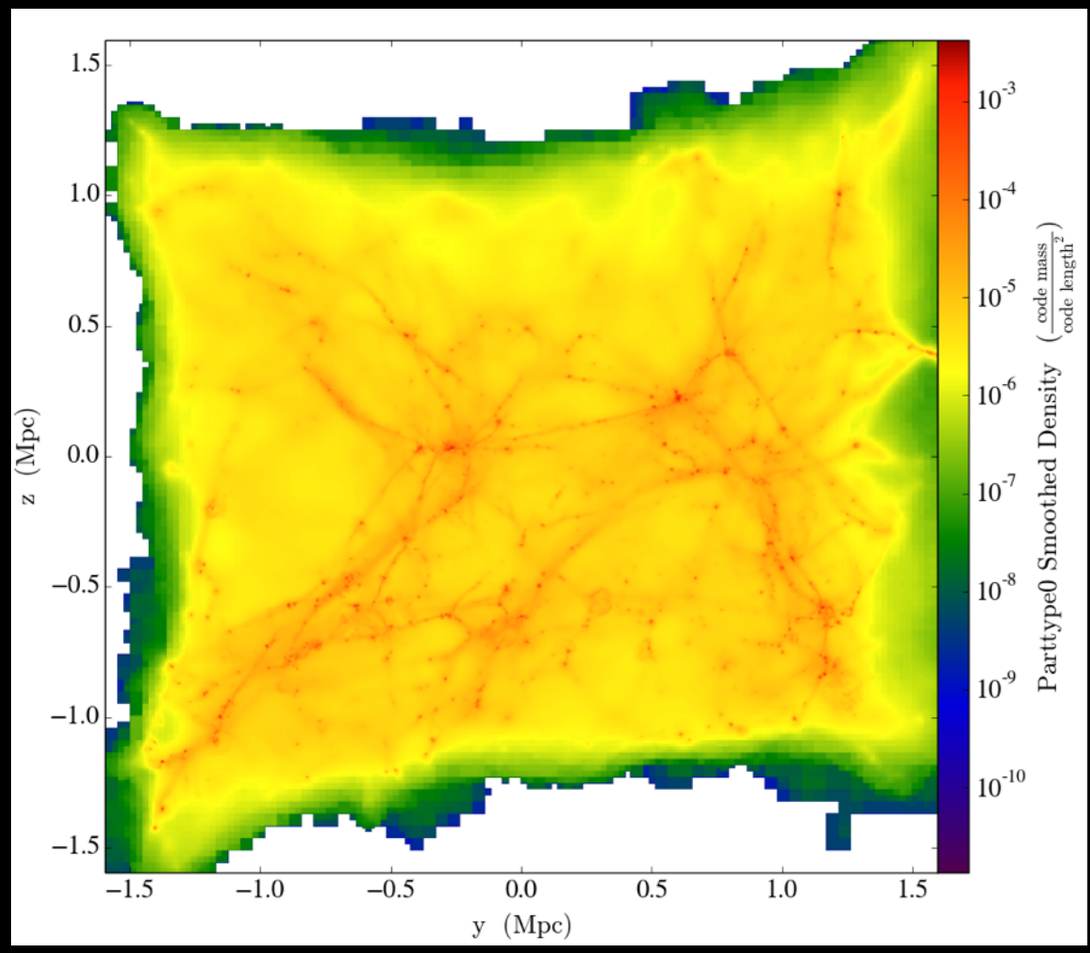
Yun et al. (2012)

Weiss, De Breuck, Marrone et al. 2013

The Way Forward: *Parsec Scale Cosmological Simulations*

FIRE = Feedback in Realistic Environments

+Powderday (Ultra-flexible/fast dust and nebular line RT)



(with Matt Turk, Tom Robitaille, Bobby Thompson, Romeel Davé, Phil Hopkins, Mark Krumholz, Greg Snyder, Chris Hayward, Dan Foreman-Mackey, Charlie Conroy)

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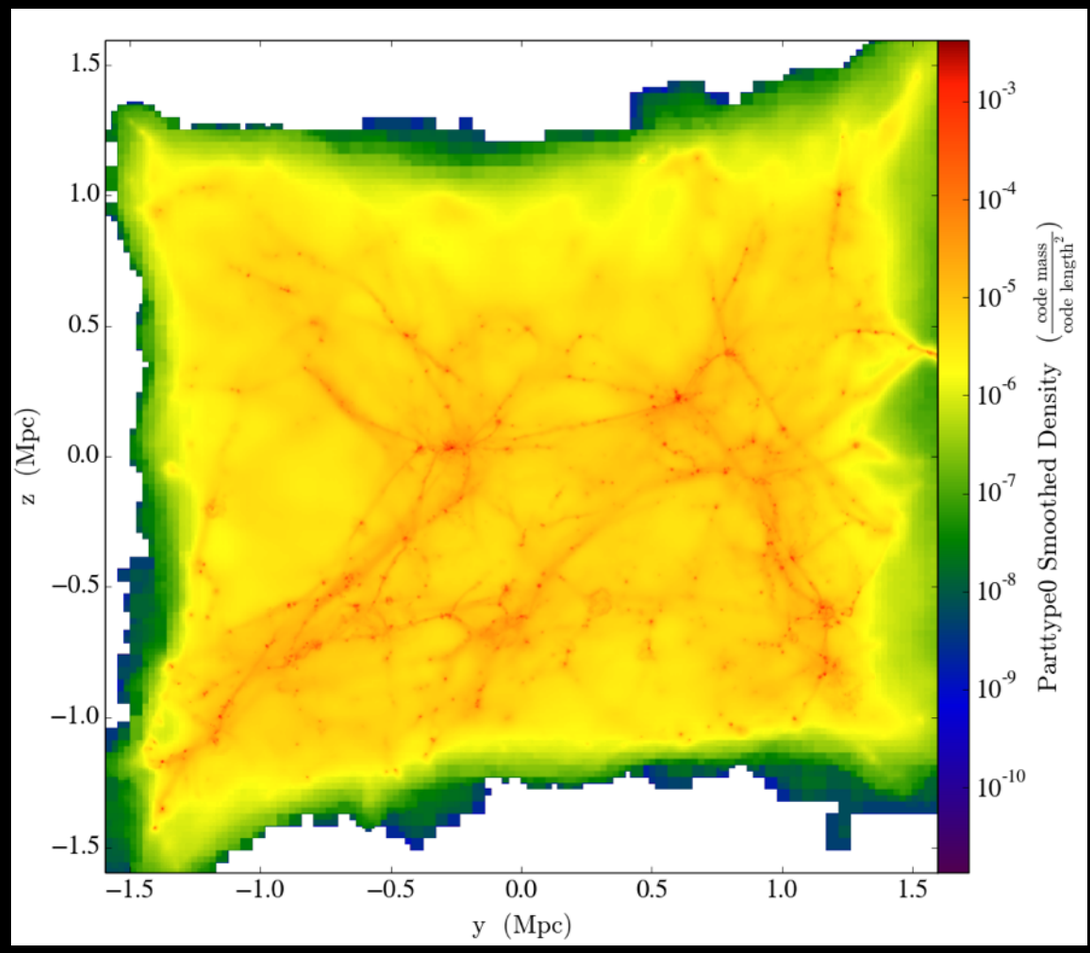

Powderday: GADGET; ART; ENZO; RAMSES; GASOLINE; FLASH; ATHENA + Stellar Pops + Monte Carlo Dust RT + Line RT + Visualization

(with Matt Turk, Tom Robitaille, Bobby Thompson, Romeel Davé, Phil Hopkins, Mark Krumholz, Greg Snyder, Chris Hayward, Dan Foreman-Mackey, Charlie Conroy)

Th… *…c Scale Cosmological Simulations*

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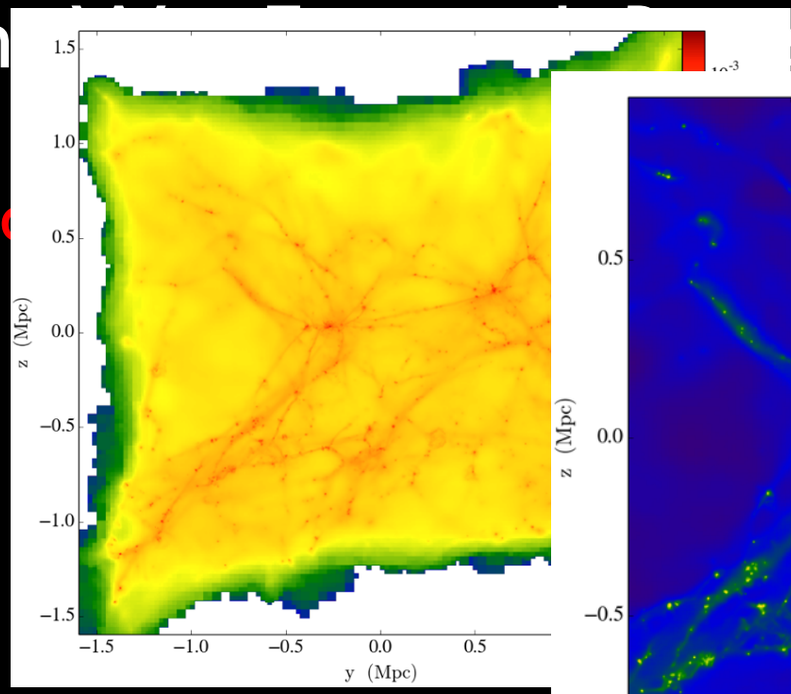
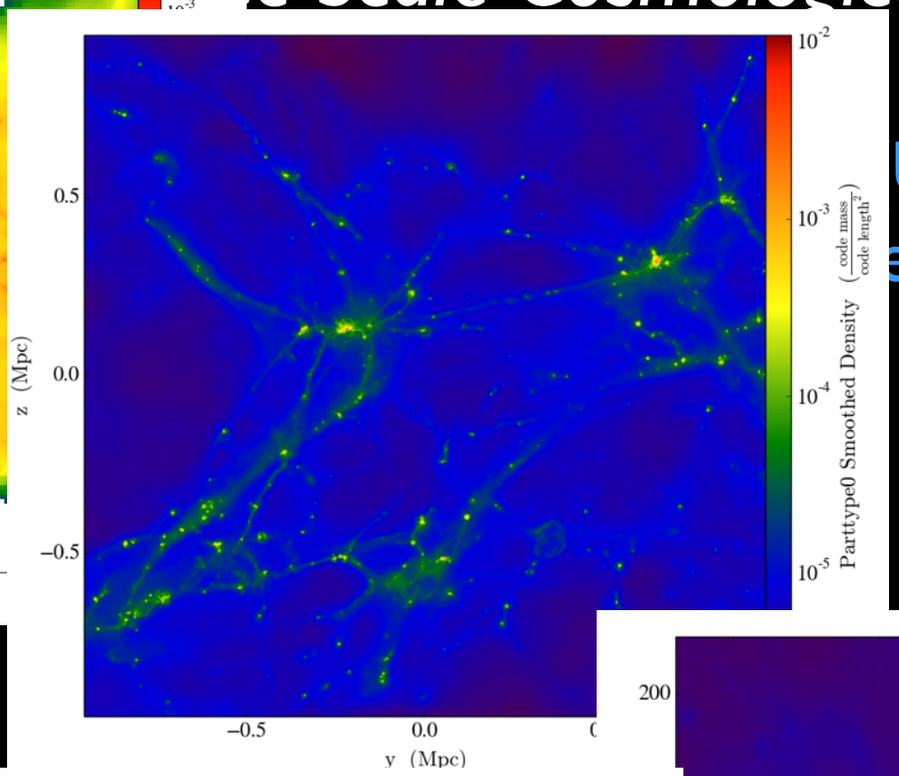
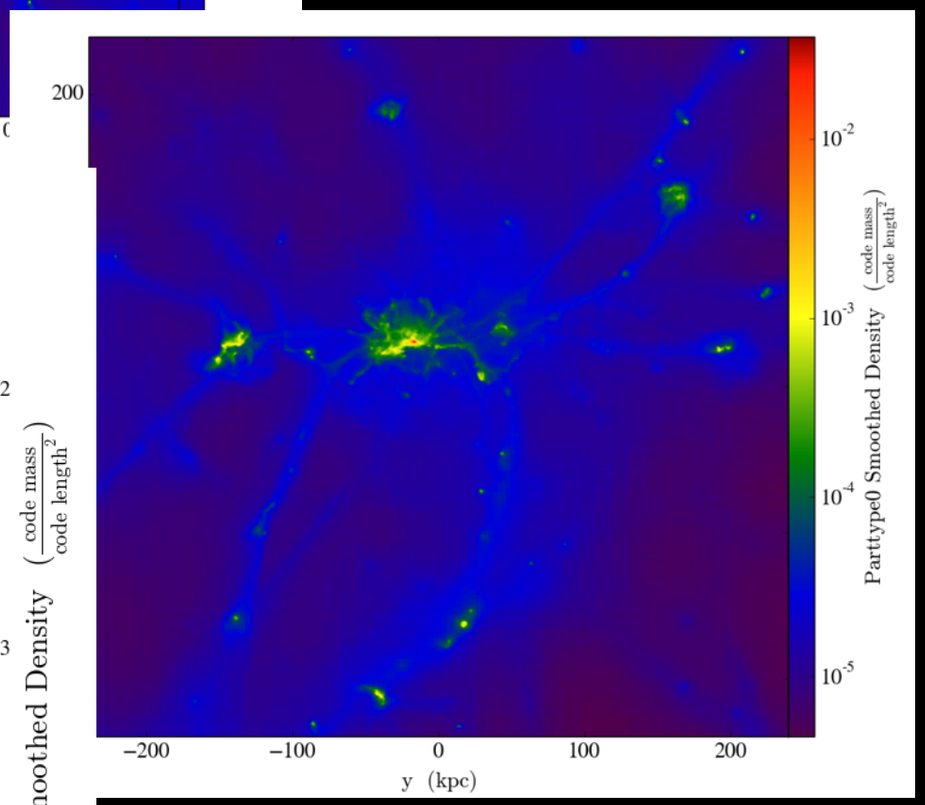
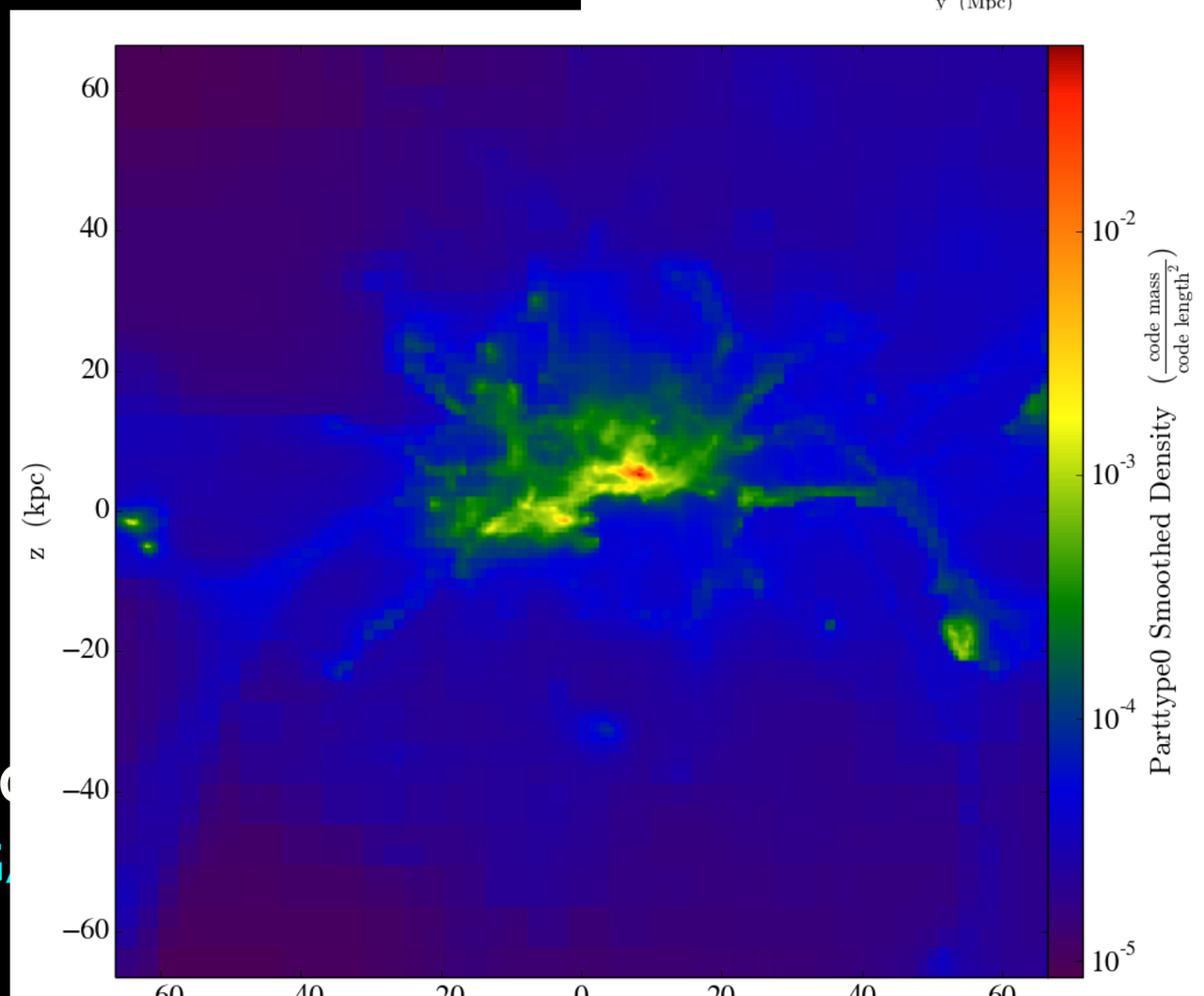




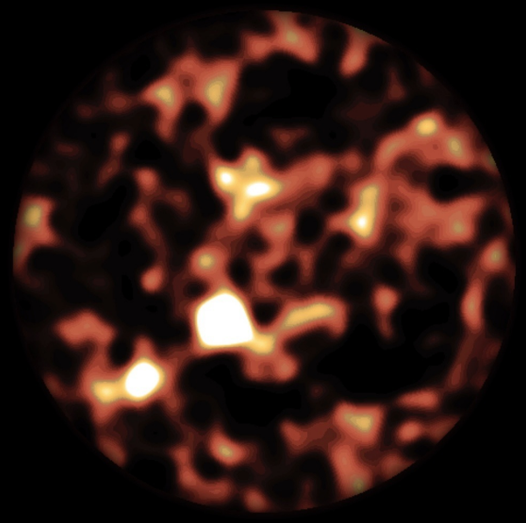




Powe… …o be integrated with yt):

G… …H;ATHENA + Stellar Pops +

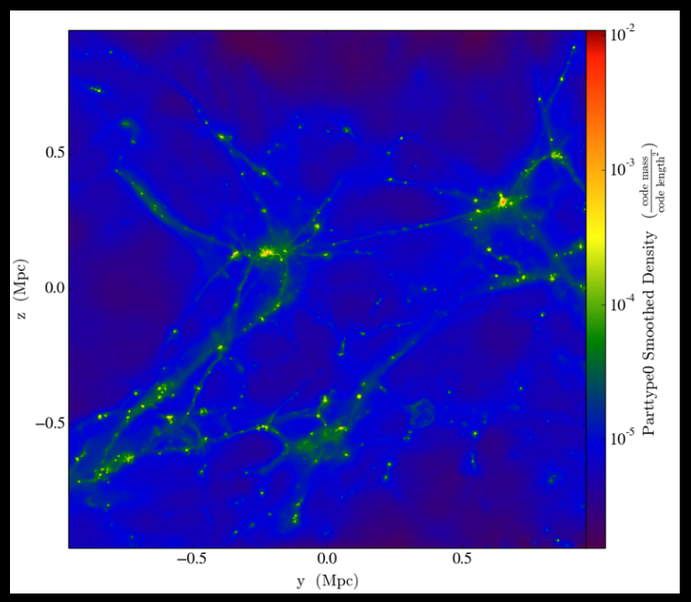
… Visualization



Summary: SMGs are complicated beasts

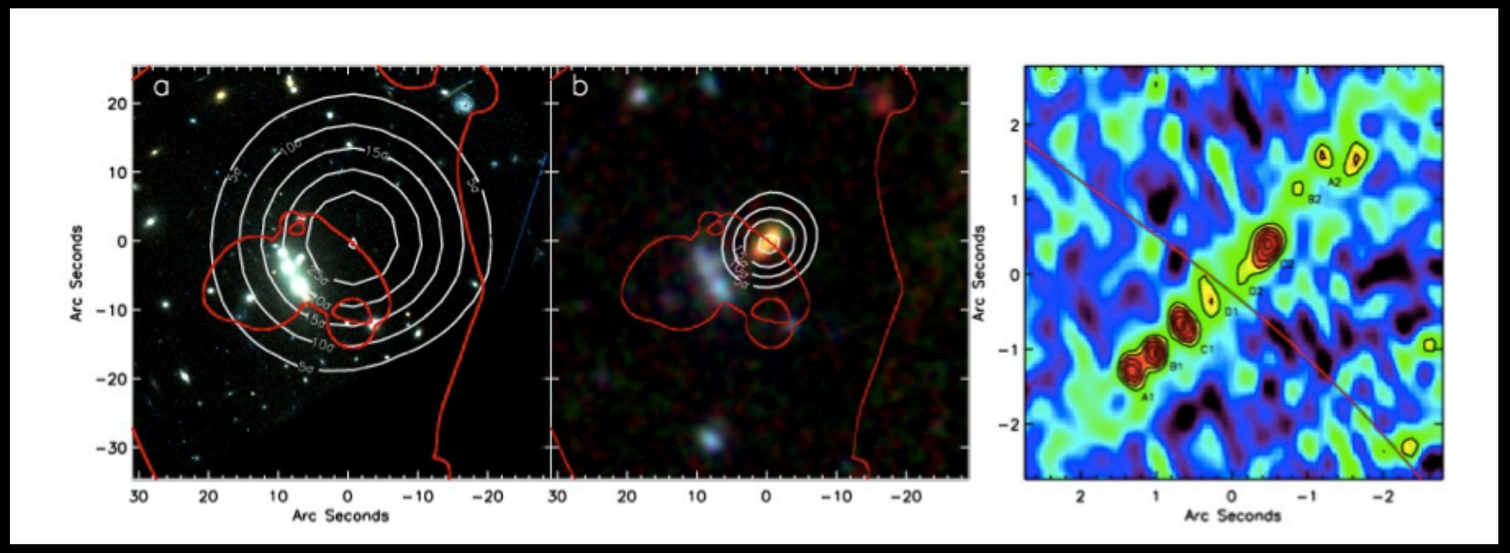
1. SMGs can be accounted for in cosmological simulations if they are heterogeneous:

a. The brightest ones are galaxy mergers
b. The least bright ones are typically gas-rich disks
c. Contaminating, throughout, are pairs of unassociated galaxies



2. The SMA has made critical discoveries to this end:

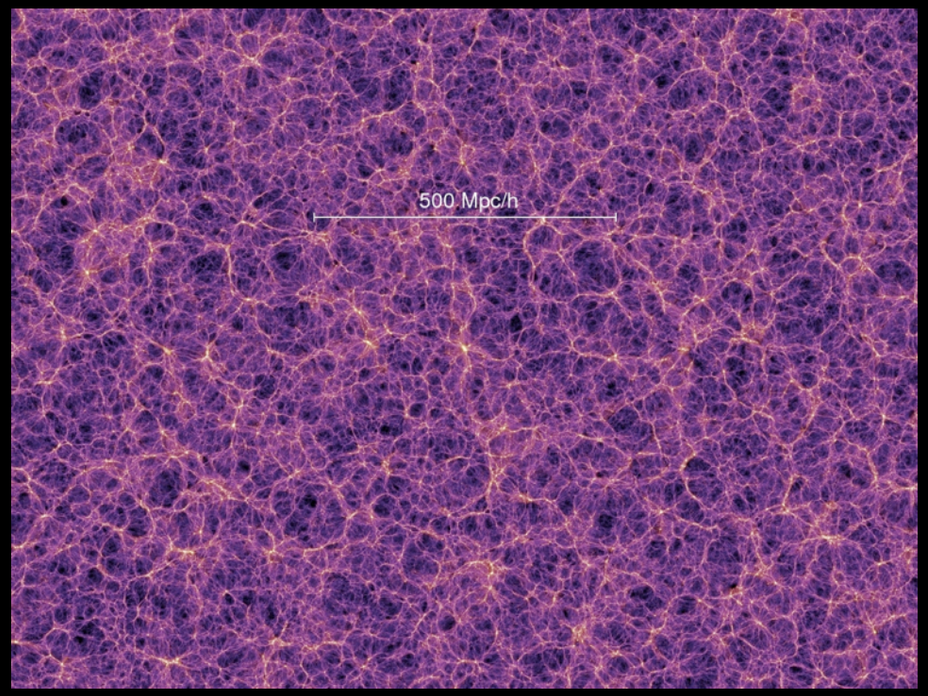
a. Provided the first clues of SMG multiplicity
b. Provided the first evidence of very high-z SMGs (z>4)



3. Exciting Possibilities:

a. Identification and analysis of Giant Molecular Associations in high-z lensed galaxies

Cosmological Statistics



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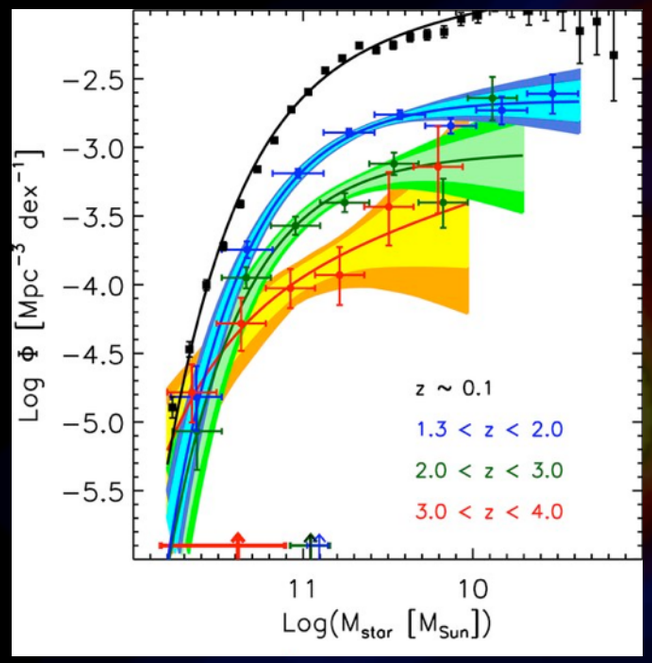
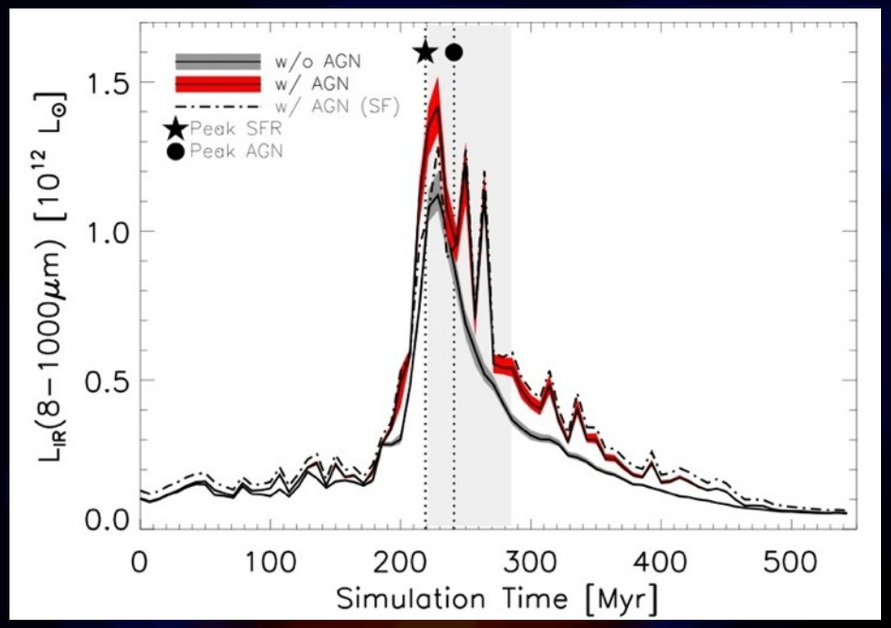


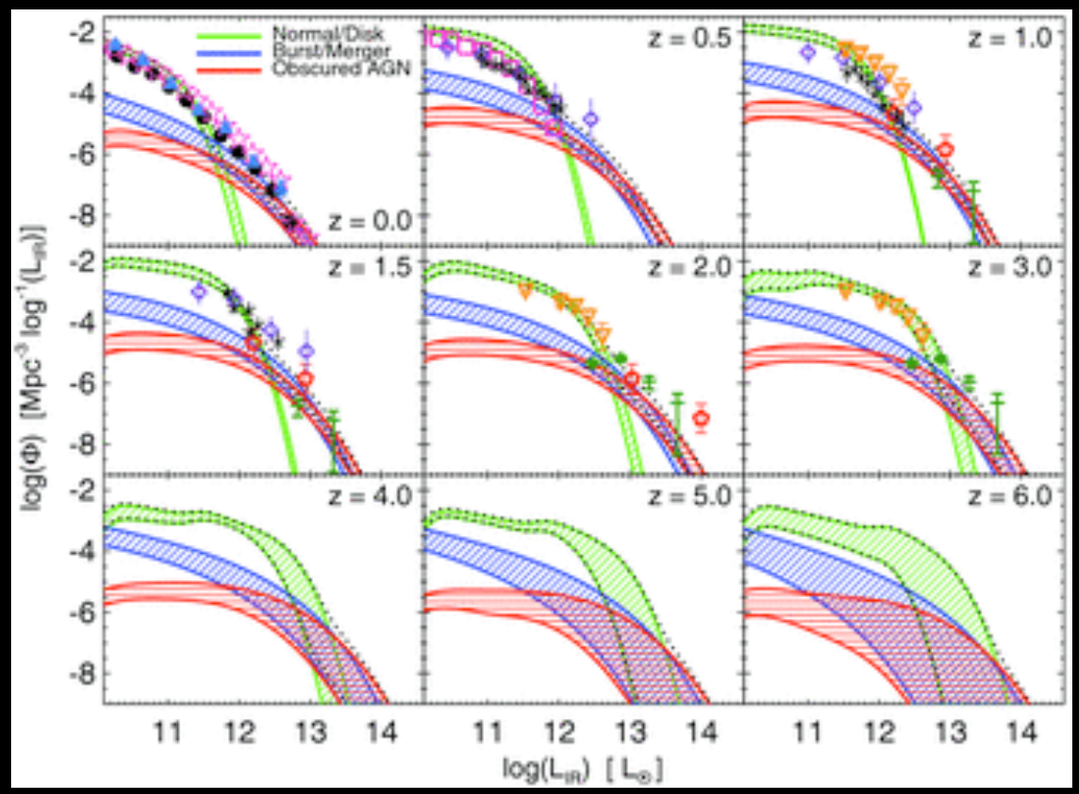
=

Halo Merger Rates (Millenium Simulation) + abundance matching (and observed SMF) = galaxy merger rates

+

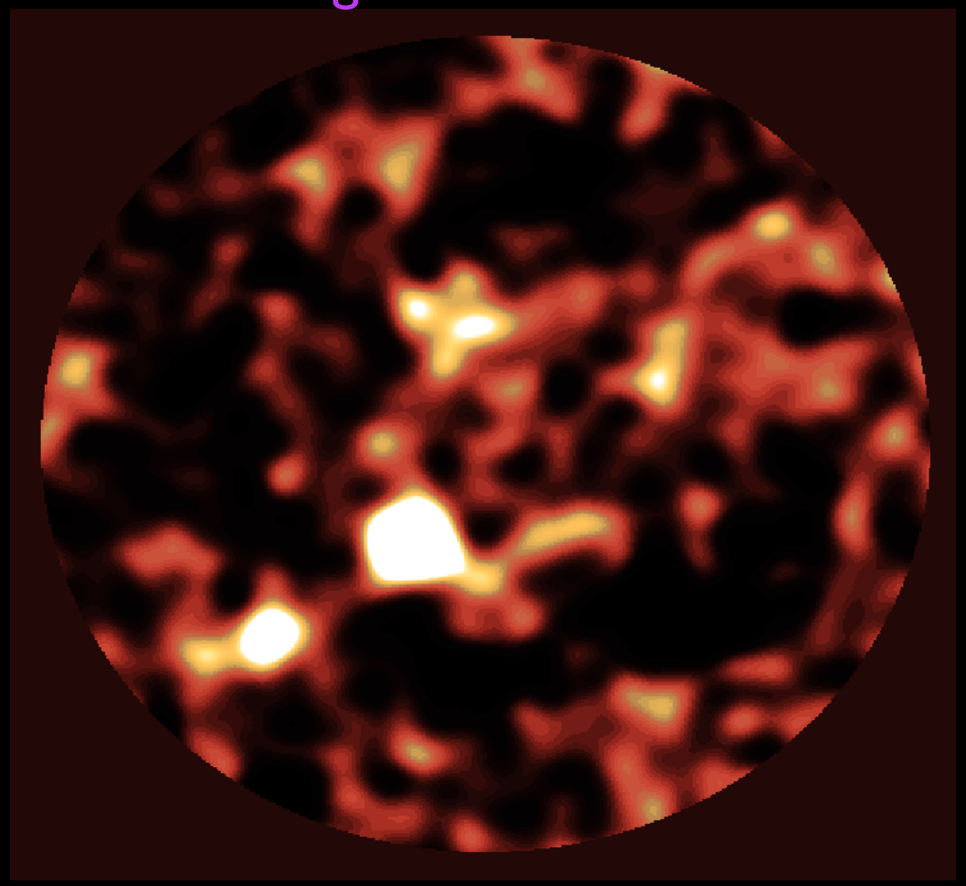


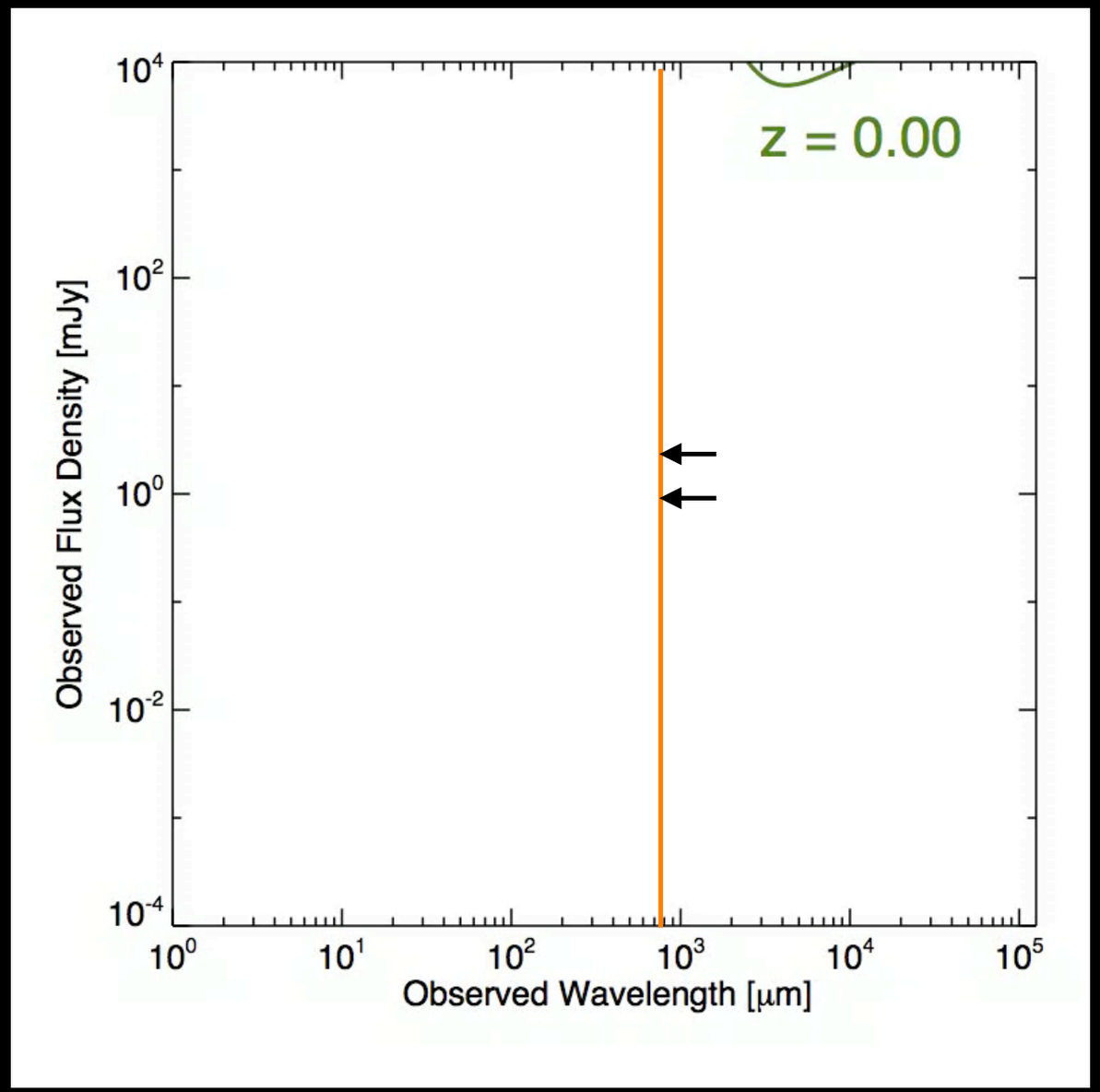
+ lightcurves (L_{IR}; S_{850} etc.)
(where we could resolve GMCs)



gives luminosity functions

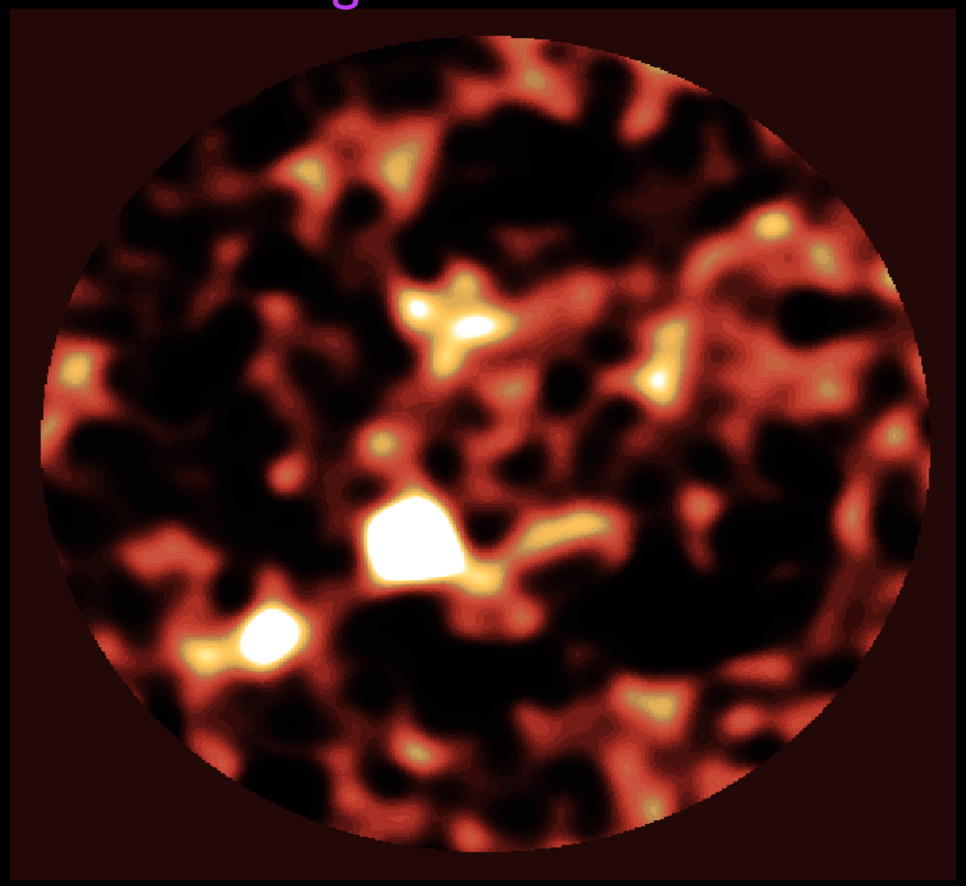
Barger et al. 1998
Hughes et al. 1998

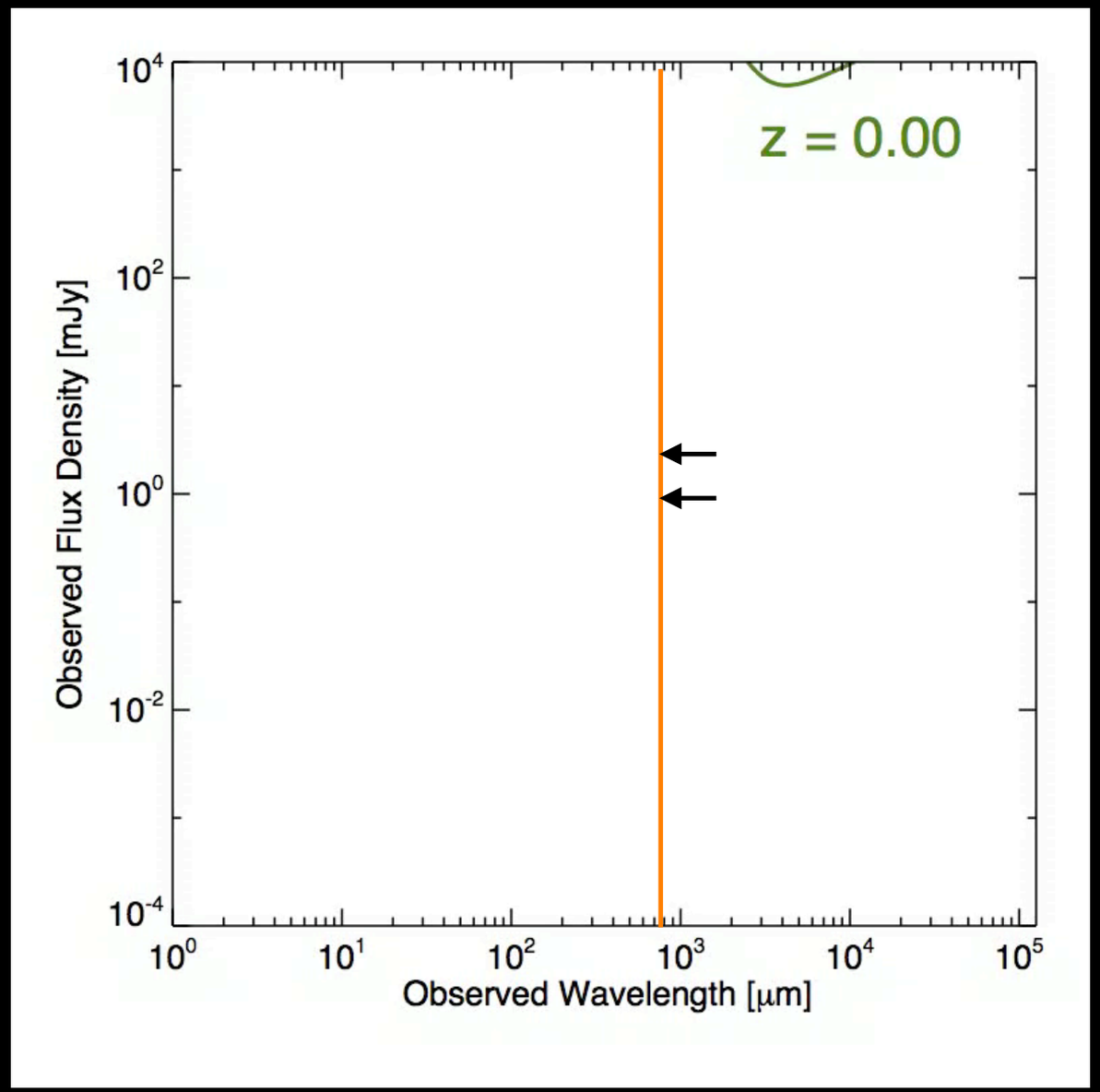




Casey, Narayanan & Cooray 2014

Barger et al. 1998
Hughes et al. 1998





Casey, Narayanan & Cooray 2014

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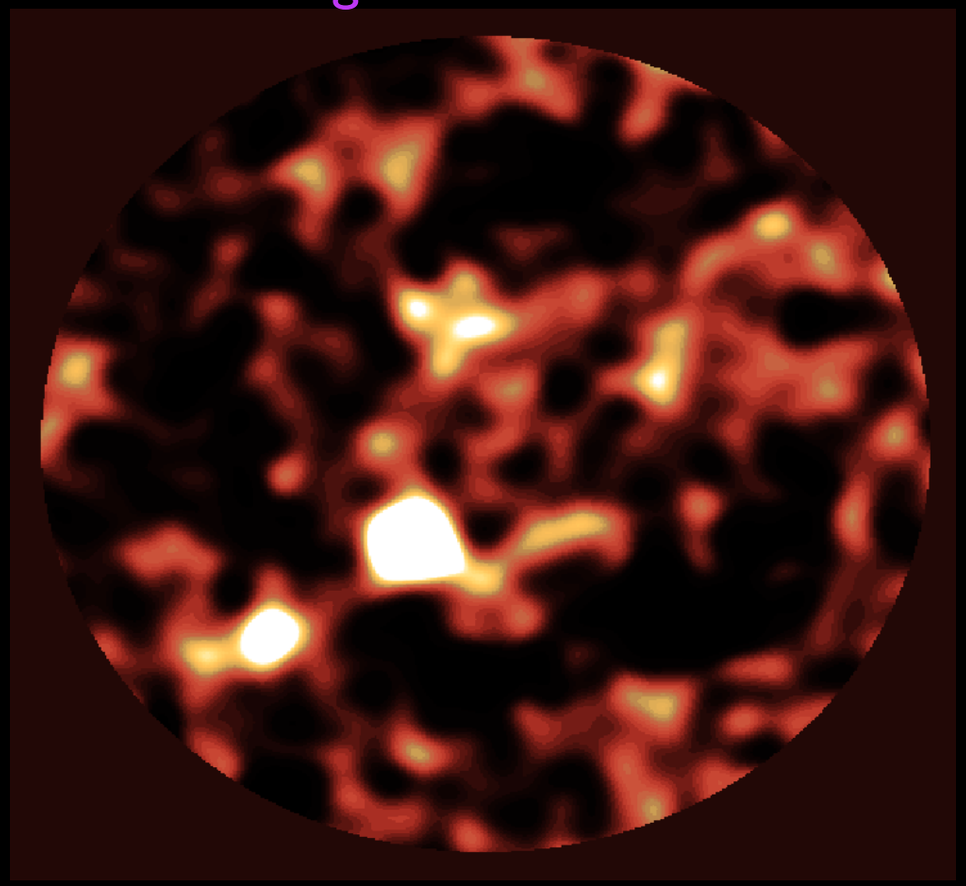
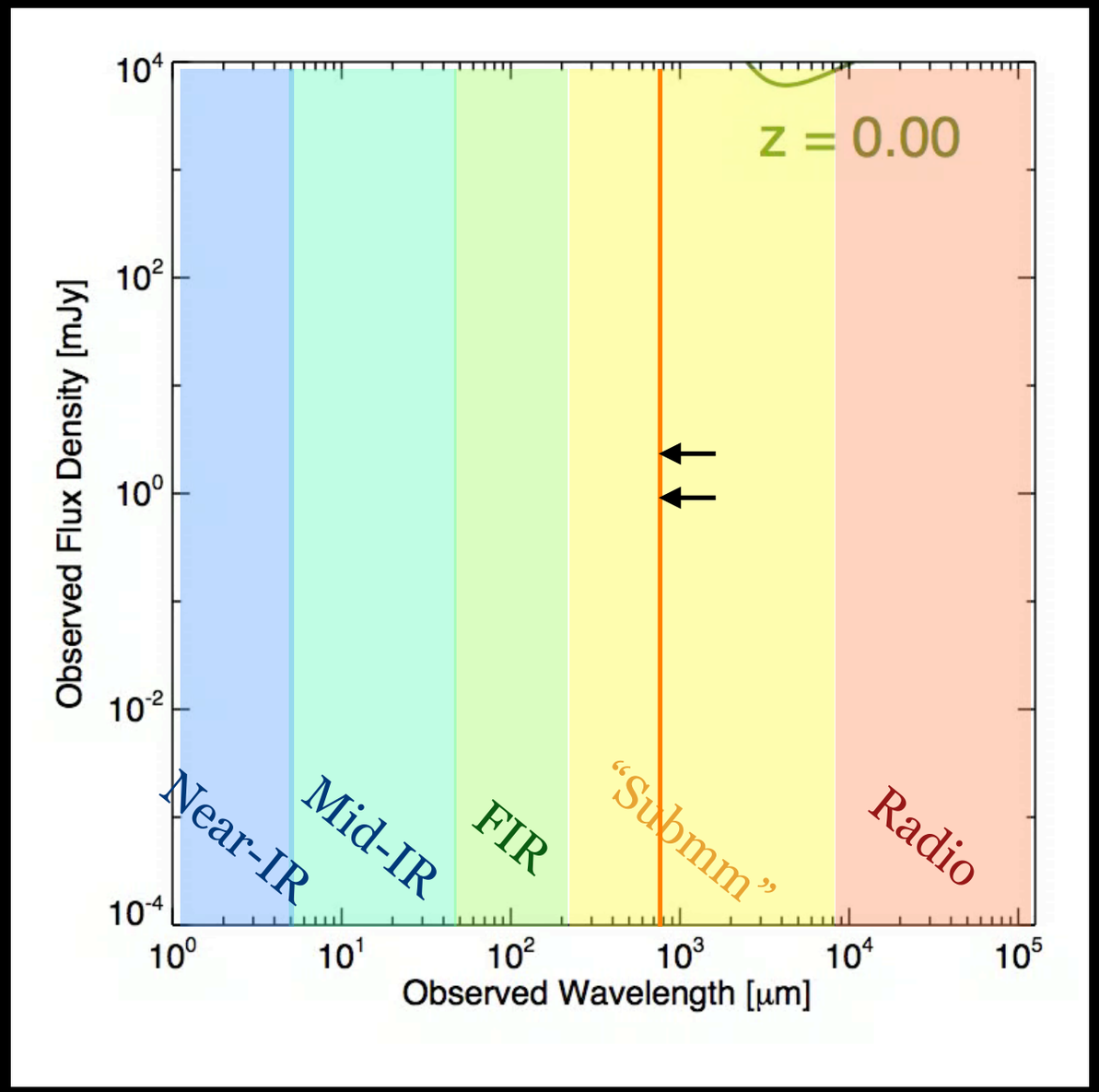
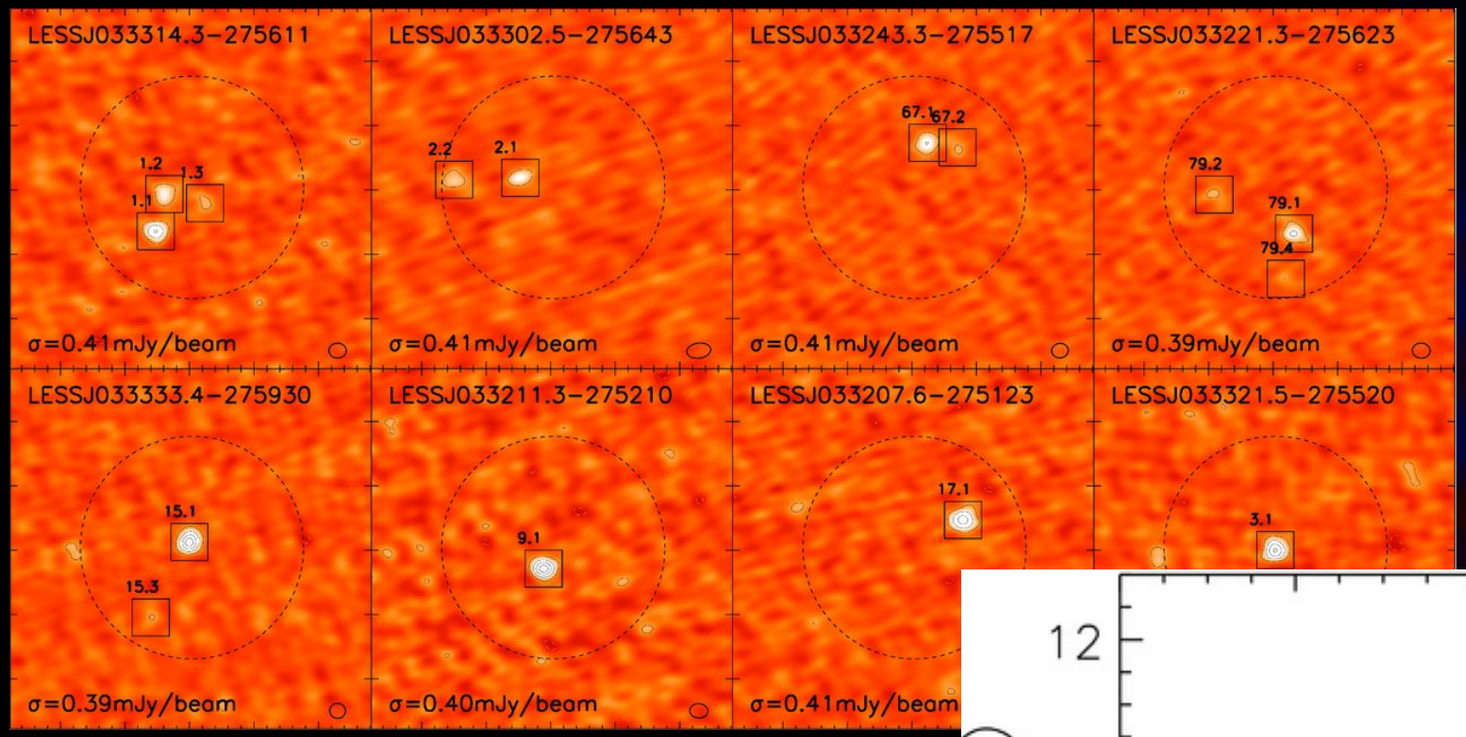


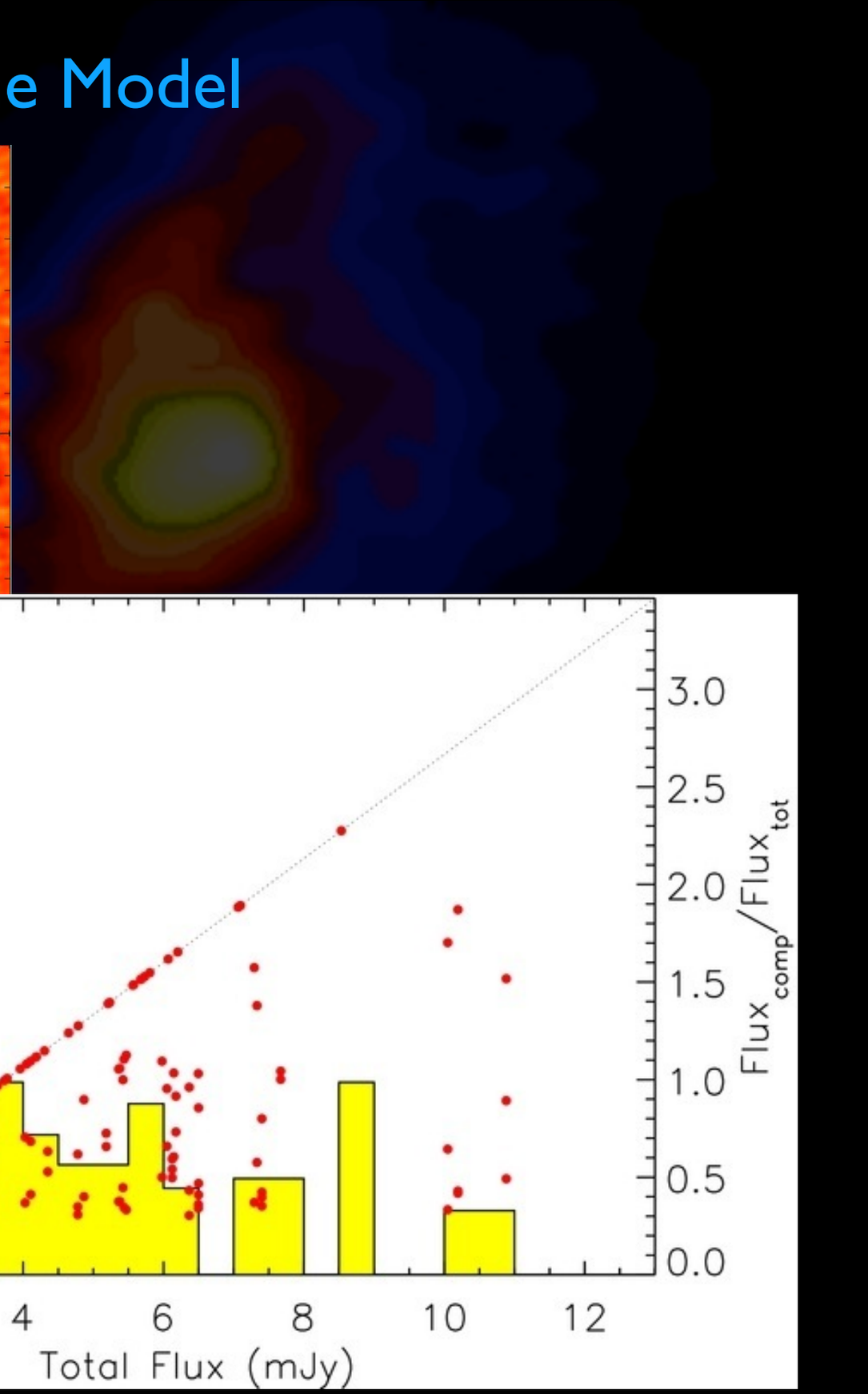


Casey, Narayanan & Cooray 2014

ALMA Tests of the Model



Karim et al. 2012



Hodge et al. 2012

the freakish nature of submillimeter galaxies

	submillimeter galaxies (SMGs)	the milky way
L	10	2x10
M	10	3x10
SFR	>1000 M	2-3 M
Age (z)	z~2-4	z=0