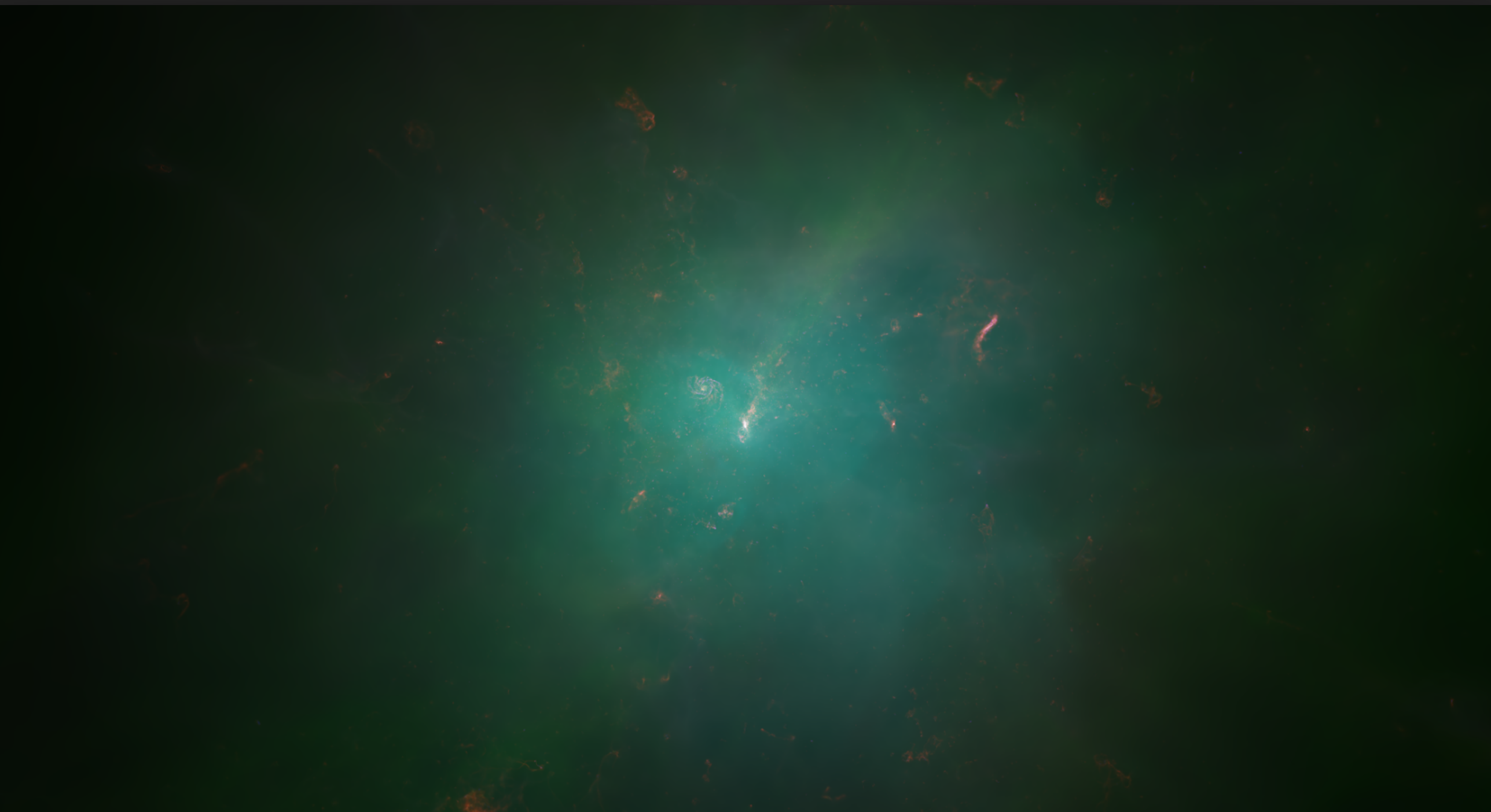
FORMING SUBMILLIMETER GALAXIES: THE BANE OF GALAXY FORMATION THEORY

Desika Narayanan
The University of Florida



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Dusty star-forming galaxies at high redshift

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ABSTRACT

Far-infrared and submillimeter wavelength surveys have now established the important role of dusty, star-forming galaxies (DSFGs) in the assembly of stellar mass and the evolution of massive galaxies in the Universe. The brightest of these galaxies have infrared luminosities in excess of 10^{13} $L_{\odot}$ with implied star-formation rates of thousands of solar masses per year. They represent the most intense starbursts in the Universe, yet many are completely optically obscured. Their easy detection at submm wavelengths is due to dust heated by ultraviolet radiation of newly forming stars. When summed up, all of the dusty, star-forming galaxies in the Universe produce an infrared radiation field that has an equal energy density as the direct starlight emission from all galaxies visible at ultraviolet and optical wavelengths. The bulk of this infrared extragalactic background light emanates from galaxies as diverse as gas-rich disks to mergers of intense starbursting galaxies. Major advances in far-infrared instrumentation in recent years, both space-based and ground-based, has led to the detection of nearly a million DSFGs, yet our understanding of the underlying astrophysics that govern the start and end of the dusty starburst phase is still in nascent stage. This review is aimed at summarizing the current status of DSFG studies, focusing especially on the detailed characterization of the best-understood subset (submillimeter galaxies, who were summarized in the last review of this field over a decade ago, Blain et al., 2002), but also the selection and characterization of more recently discovered DSFG populations. We review DSFG population statistics, their physical properties including dust, gas and stellar contents, their environments, and current theoretical models related to the formation and evolution of these galaxies.

Contents

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0370-1573/

PART 1: THEORETICAL METHODS

PART 2: AS APPLIED TO DUSTY GALAXIES

PART 3: OBSERVATIONAL OUTLOOK

PART 1: THEORETICAL METHODS

Example

Semi Analytic Models

Idealized Simulations

Cosmological Simulations

Zoom Simulations

Advantages

Drawbacks

Codes/Campaigns

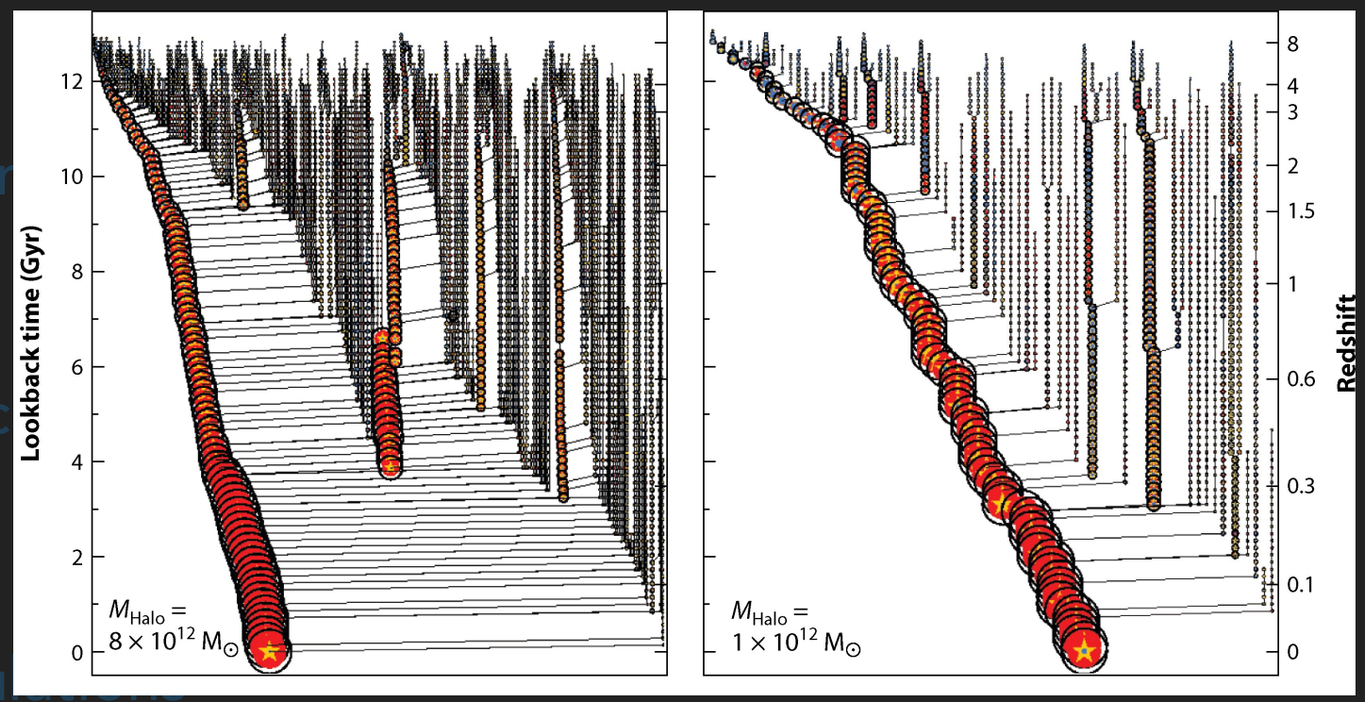
PART 1: THEORETICAL METHODS

Semi Analytic Models

Idealized Sim

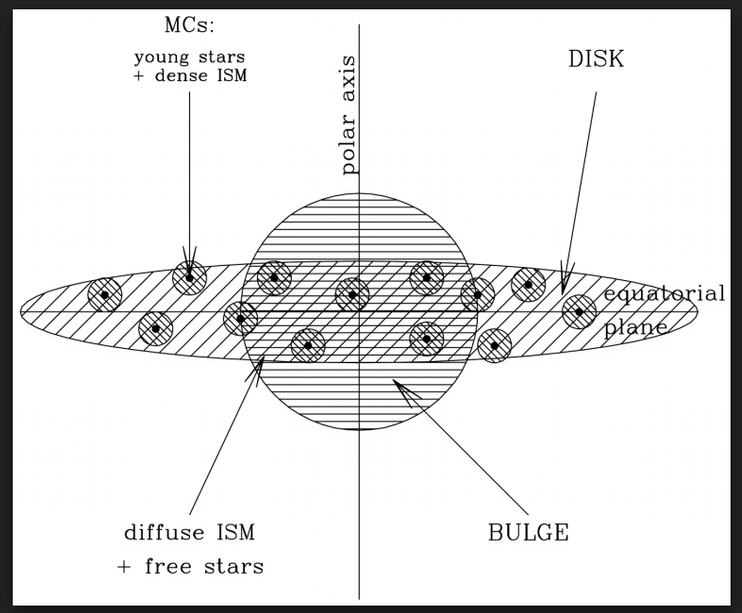
Cosmologic

Zoom Simulations



Somerville & Dave 2015

Example



Granato et al. 2000

Advantages

- Speed
- Can search parameter spaces efficiently
- Can isolate driving physical processes

Drawbacks

- Highly simplistic view of galaxies (Fluid processes not simulated)
- Structure of Galaxies not simulated
- Subresolution scale at the scale of dark matter halos

Codes/Campaigns

- Durham SAM (`GALFORM`)
- Munich SAM
- Santa Cruz SAM

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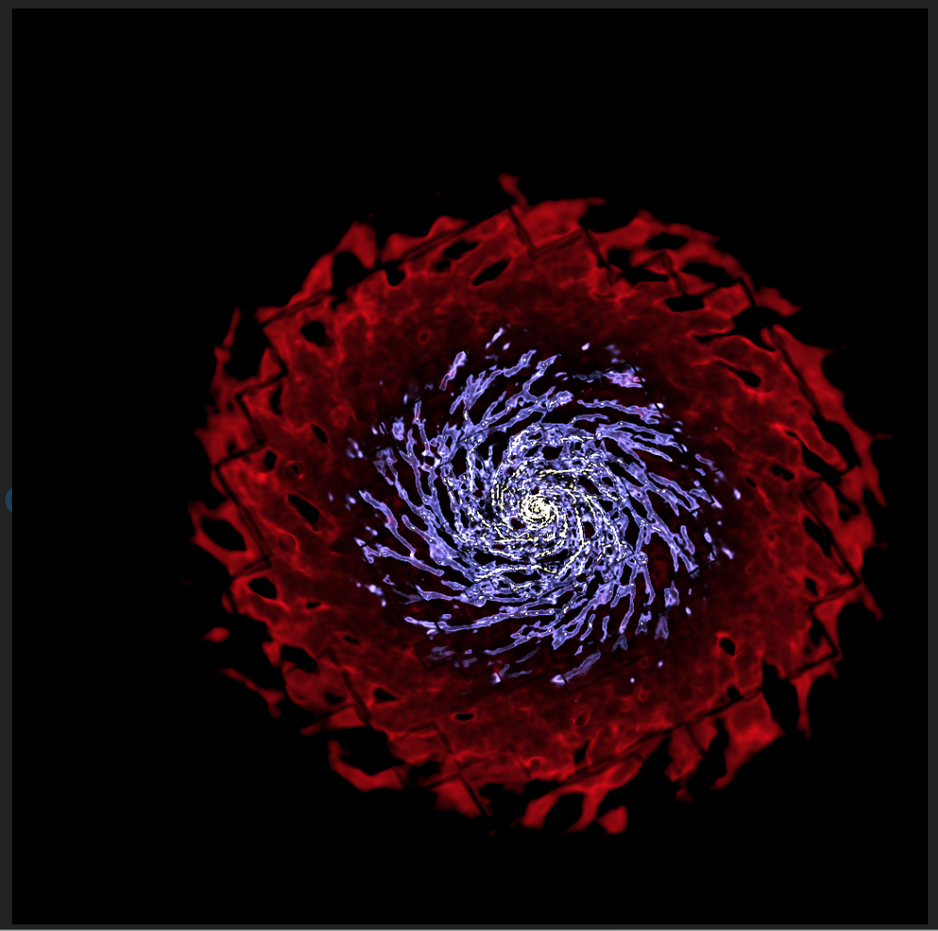
Semi Analytic Models

Idealized Simulations

Cosmological Simulati

Zoom Simulations



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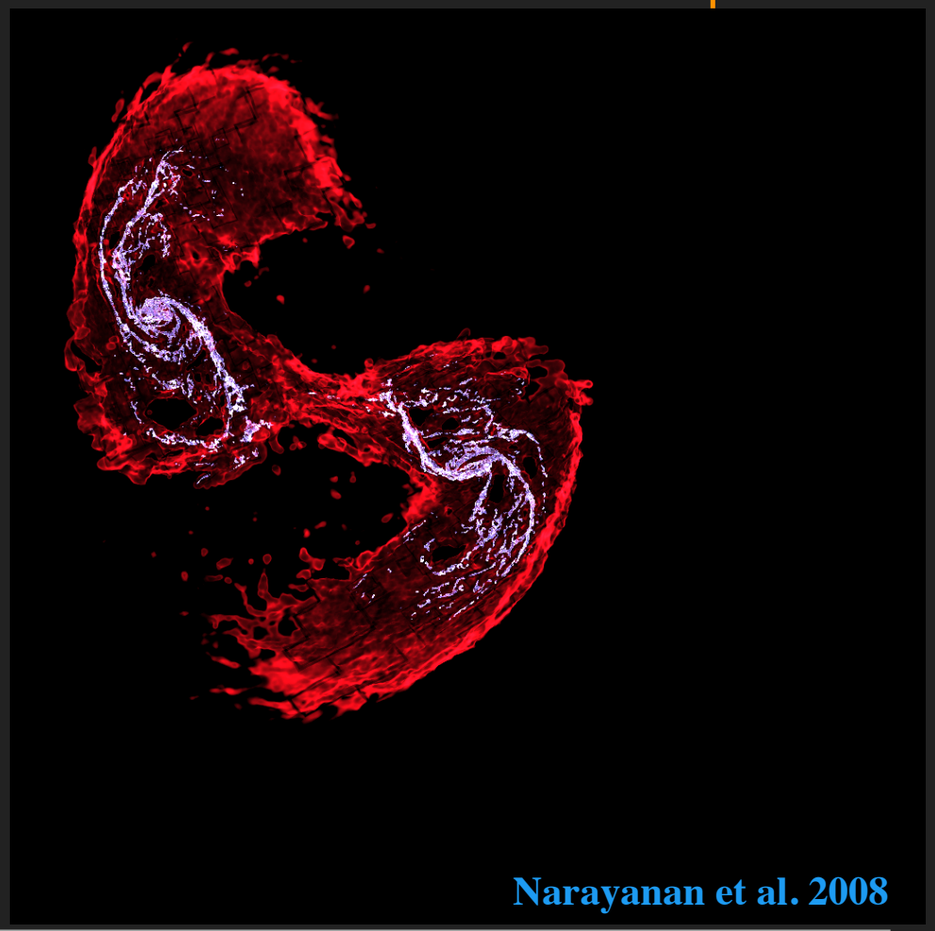

Advantages

- Highest possible resolutions of all the methods
- Relatively fast to run
- Can run radiative transfer
- Can isolate internal processes

Drawbacks

- Non cosmological (no environment)
- Early phases dominated by ICs and lack physical information
- Not obvious how to simulate statistics

Codes/Campaigns

- Gadget/GIZMO
  (2000s papers from Hernquist group, Naab, Ostriker)
- Ramses
  (Teyssier, Bournaud, Martig)
- Gasoline
  (Governato, Brooks, Brook, Stinson, Christensen)

PART 1: THEORETICAL METHODS

Semi Analytic Models

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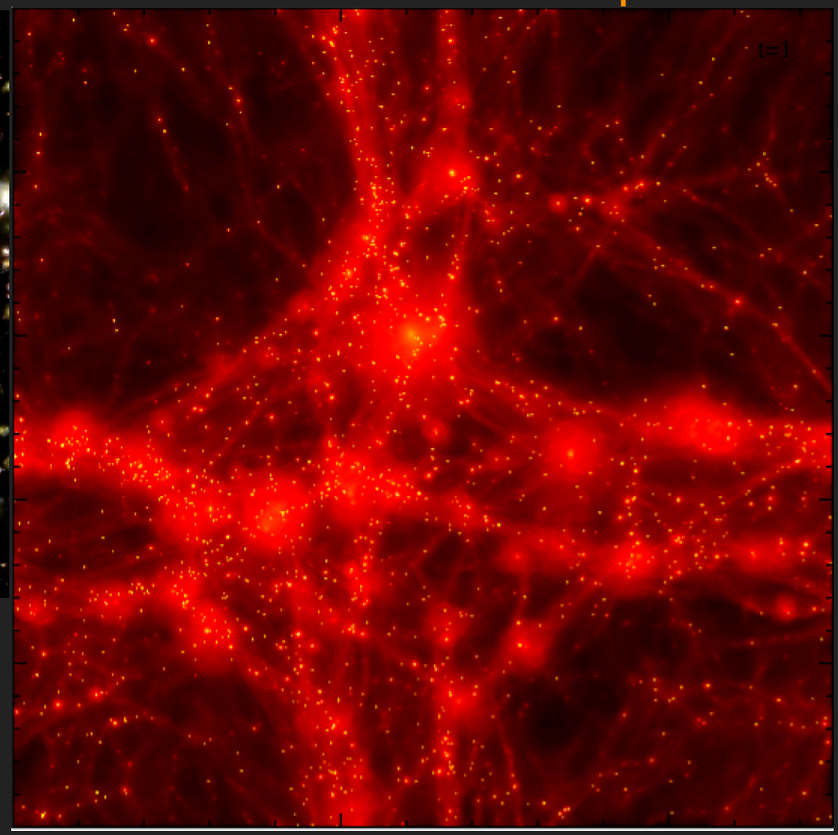
Cosmological Simulations

Zoom Simulations

HUDF Simulation
Snyder et al., Illustris

Example



HI Distribution at z~1
Davé et al., Mufasa

Advantages

- Numerous halos/galaxies
- Cosmic environment included
- Can simulate deep fields

Drawbacks

- Even state of the art resolution is relatively poor (~10^6 M⊙)
- Can be quite slow
- Not obvious you can resolve ISM enough to run RT

Codes/Campaigns

- EAGLE
- Mufasa
- Illustris
- BlueTides

PART 1: THEORETICAL METHODS

Semi Analytic Models

Idealized Simulations

Cosmological Simulations

Zoom Simulations

Example

Sick viz by J. Geach, R. Crain, D. Narayanan & R. Feldmann

Advantages

- Resolution can approach that of idealized
- Cosmic environment included
- Can run RT
- Best of both (hydro) worlds

Drawbacks

- Super slow. Like, terrible.
- The most technically challenging out of the four methods
- Not obvious how to simulate statistics
- They're destroying the planet with CO_2 emission

Codes/Campaigns

- FIRE
- Mufasa Zooms
- RAMSES Zooms

PART 1: THEORETICAL METHODS

PART 2: AS APPLIED TO DUSTY GALAXIES

PART 3: OBSERVATIONAL OUTLOOK

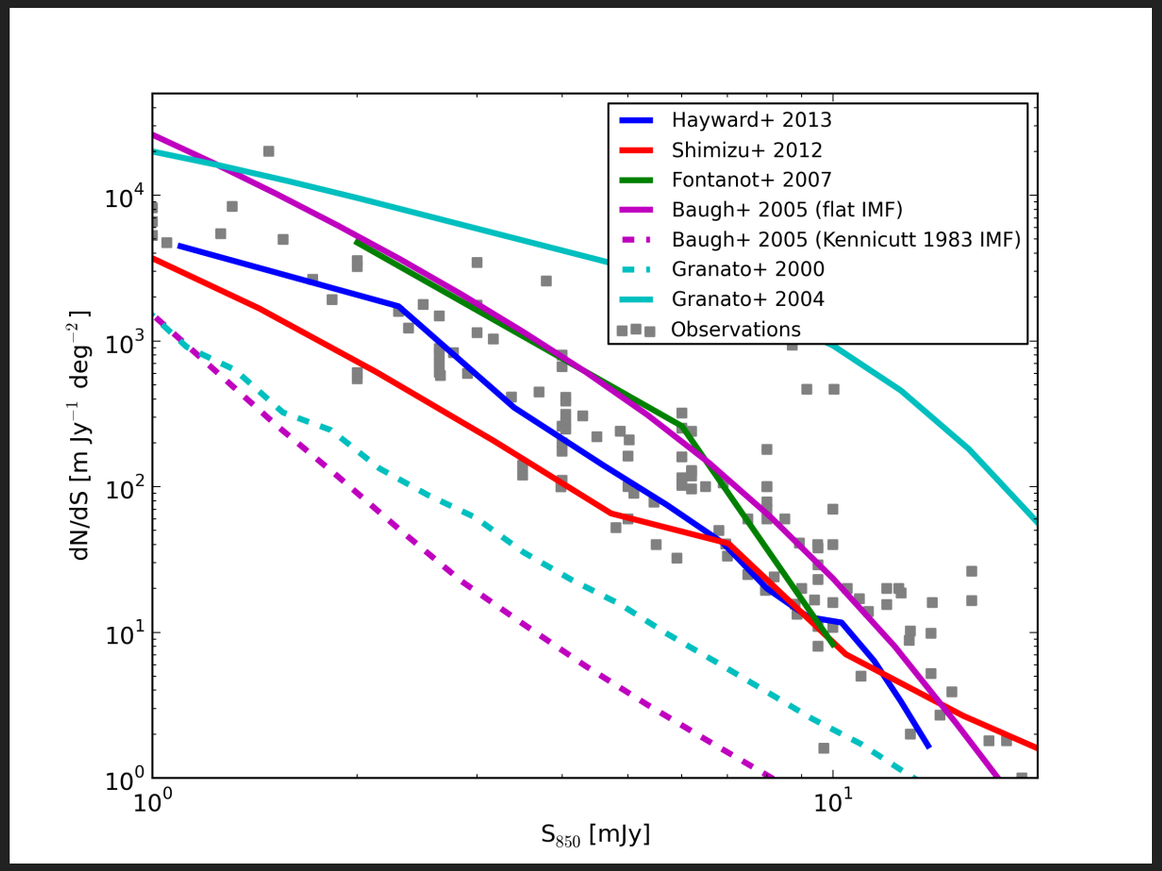
WHAT ARE THEORISTS TRYING TO DO?

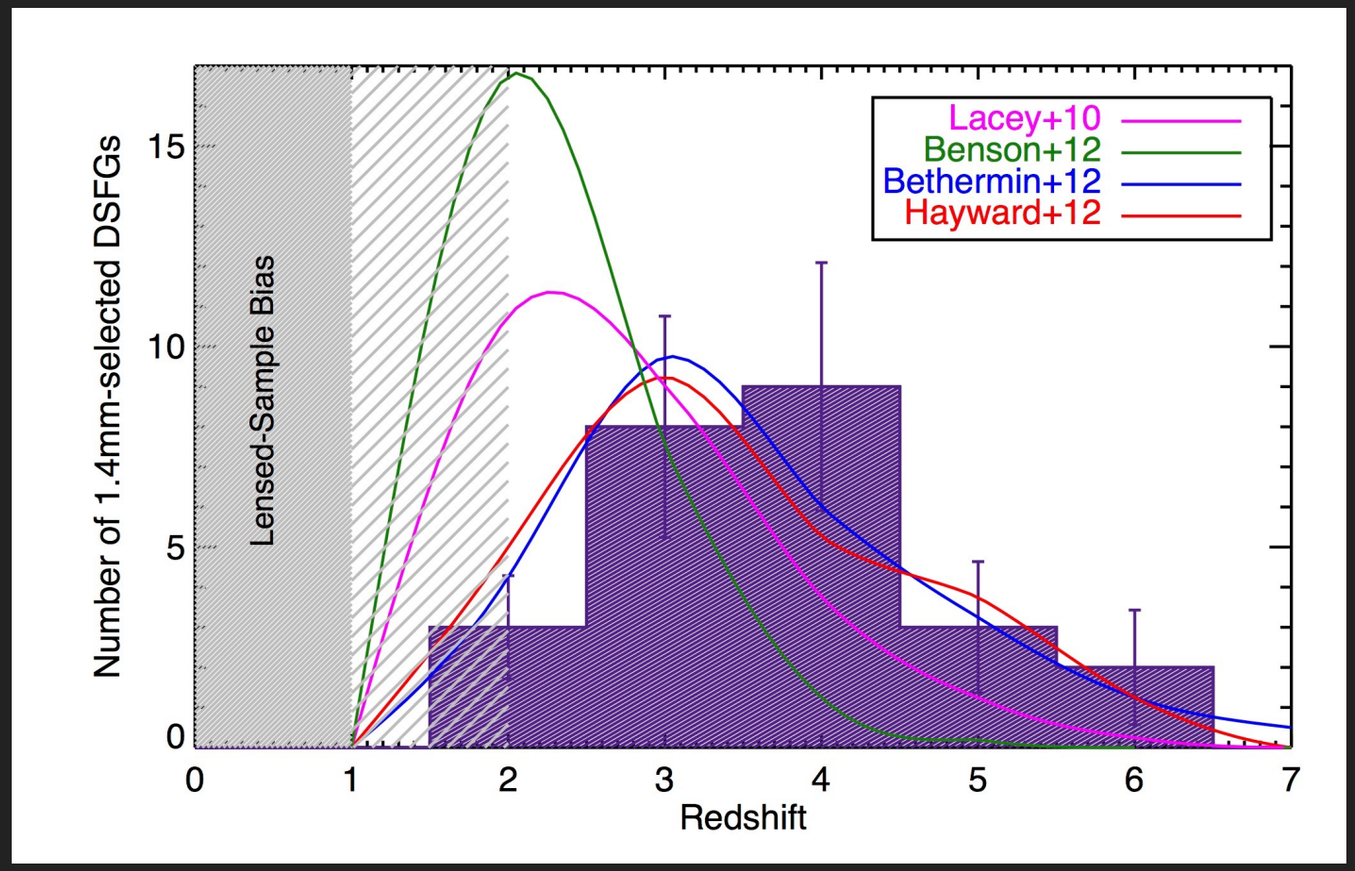
- Can we even make SMGs?
- What is the role of galaxy mergers/starbursts?
- What is the role of multiplicity?
- Do we require IMF variations?
- How do SMGs fit into a general model for galaxy formation?

PART 2: DUSTY GALAXIES

Casey, Narayanan & Cooray 2014

Missing: efforts since 2014 by
Lacey, Cowley, Narayanan, Hayward

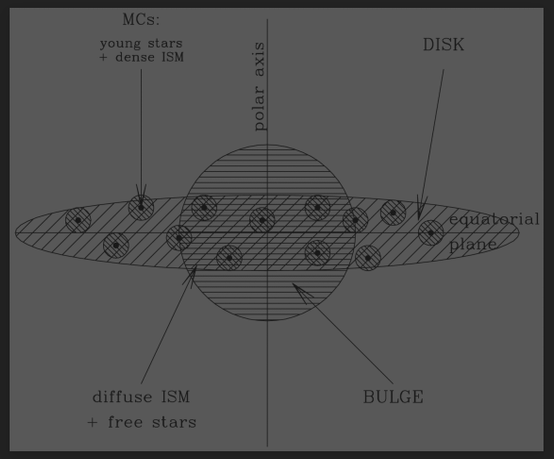




PART 2: DUSTY GALAXIES

Semi Analytic Models

Baugh et al. 2004
Lacey et al. 2014
Cowley et al. 2015,2016



Idealized

Chakrabarti et al. 2006
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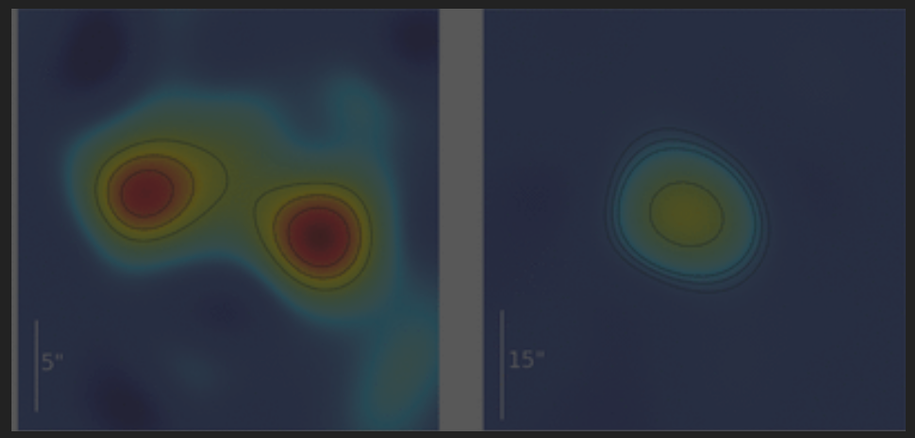
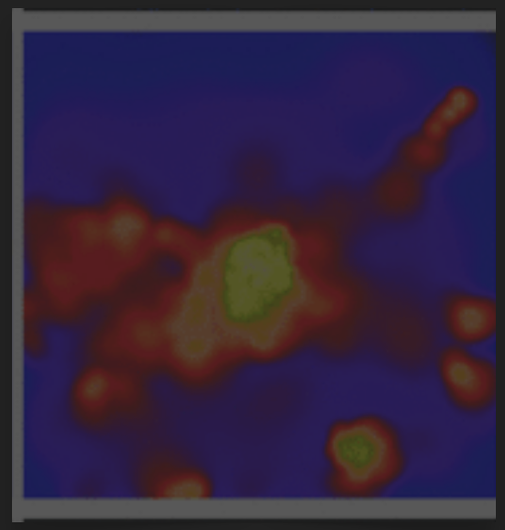
Hayward et al. 2010,2011,2014



Cosmological Simulations

Dave et al. 2010
Shimizu et al. 2012



Zooms

Key Predictions

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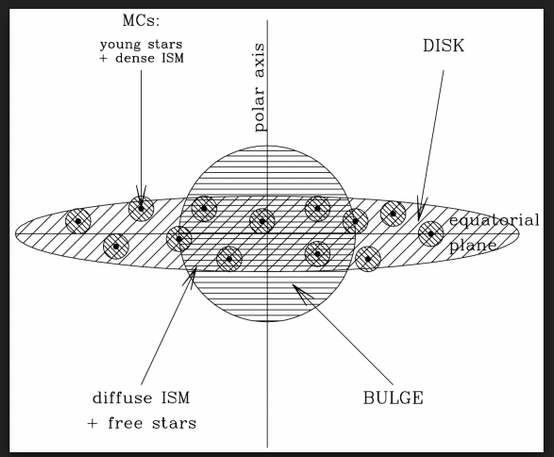

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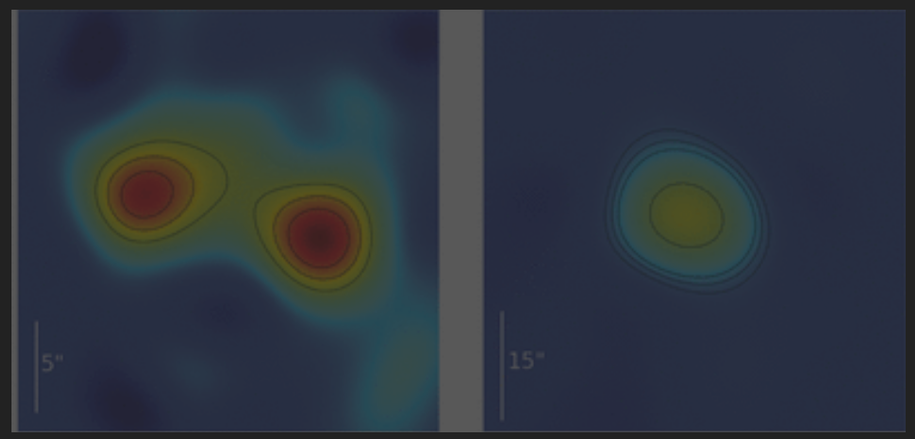

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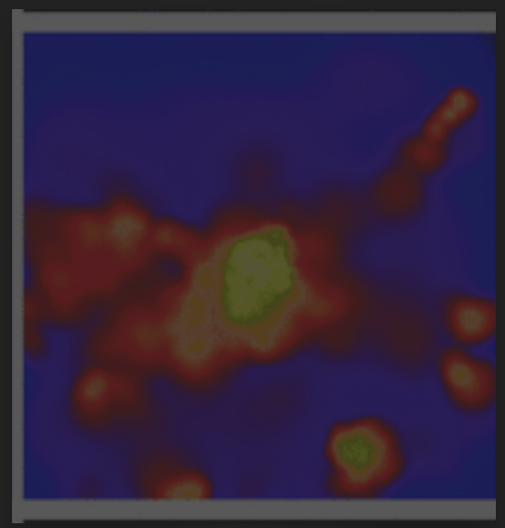

Zooms

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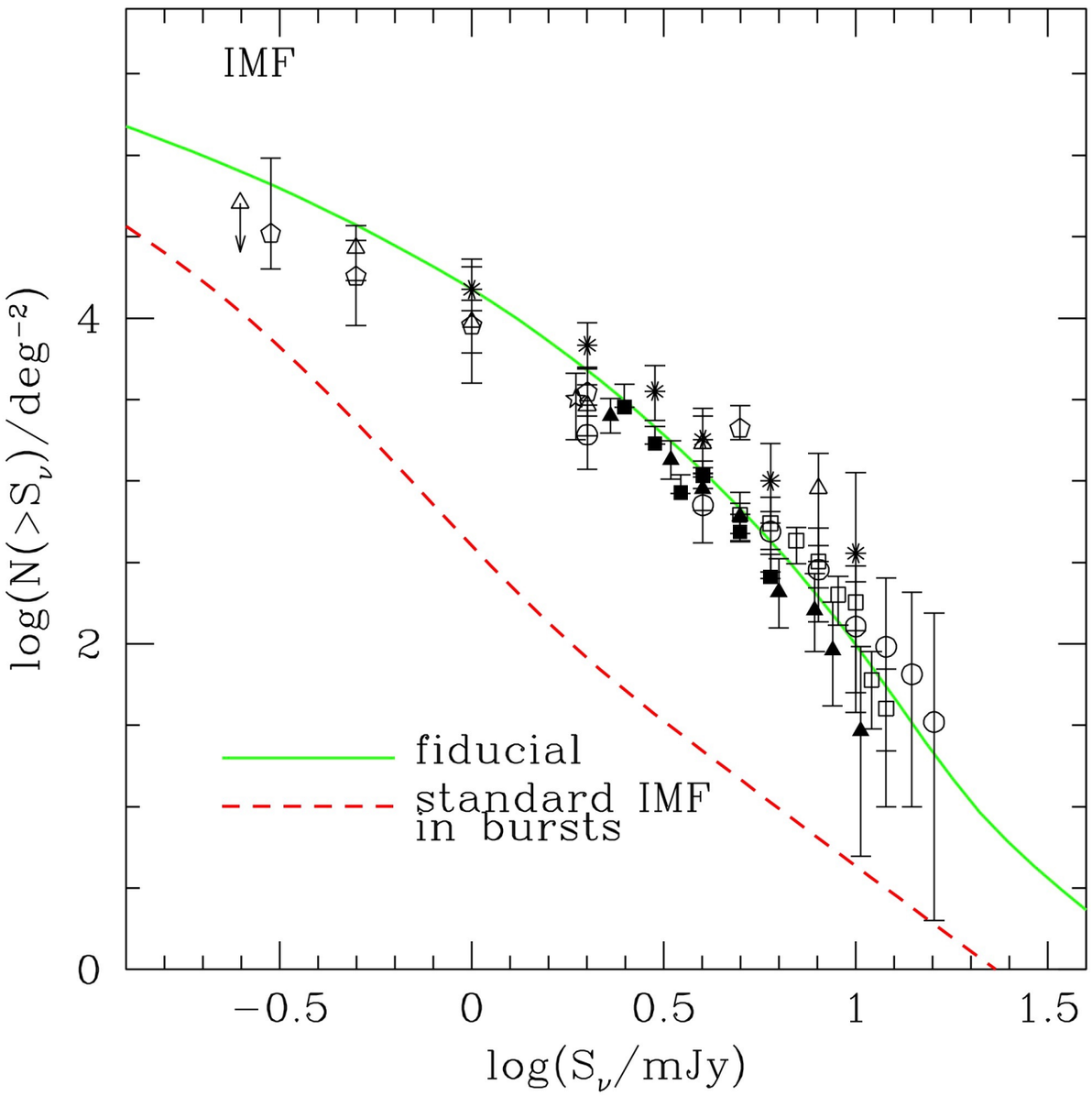
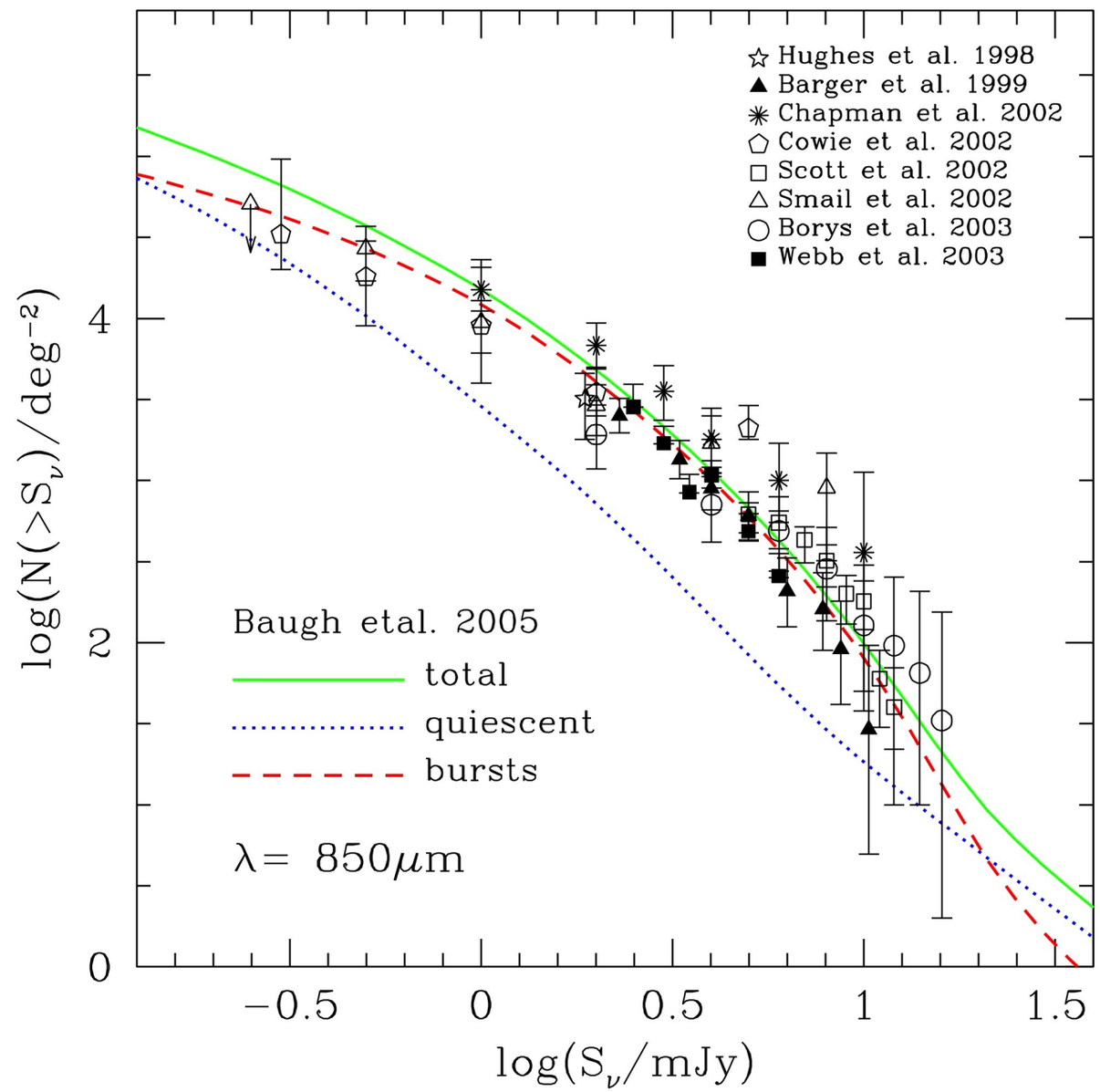
Baugh et al. 2005, 2006





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Lacey et al. 2016

PART 2: DUSTY GALAXIES

The first extension was introduced by Baugh et al. (2005). After an extensive exploration of the model parameter space, Baugh et al. concluded that the only way to reconcile the model predictions with observations of high-redshift galaxies was to adopt a top-heavy stellar IMF in bursts of SF triggered by galaxy mergers. This choice was not taken lightly. The framework of the GALFORM calculations imposes restrictions on the model parameter space that are widely underappreciated. By requiring that the model reproduce the local galaxy population, a large swathe of parameter space is immediately excluded (see Bower et al. 2010). Similarly, by adopting a self-consistent calculation of the extinction of starlight by dust and the radiation of this energy at longer wavelengths, much of the freedom present in more simplistic calculations (e.g. to set by hand the amount of dust extinction or the temperature of the dust) is removed. The Baugh et al. (2005) model gave an excellent match to

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Lacey et al. 2016

PART 2: DUSTY GA

tl;dr the problem is simultaneously making

- Massive Galaxies that are realistic in physical properties, and that are super bright
- loads of cold dust.
- radiative transfer

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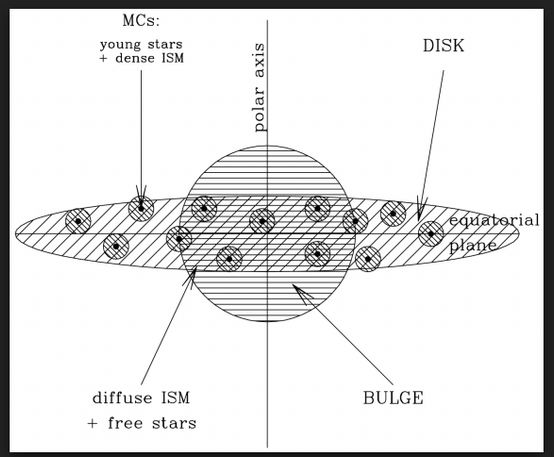

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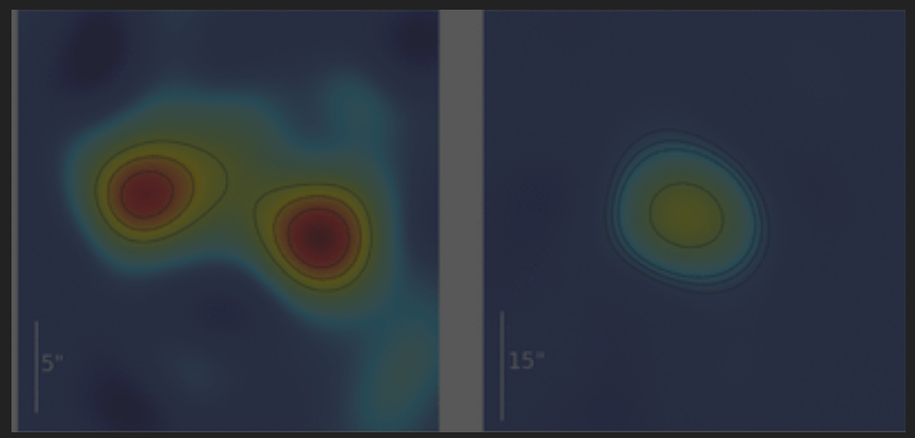

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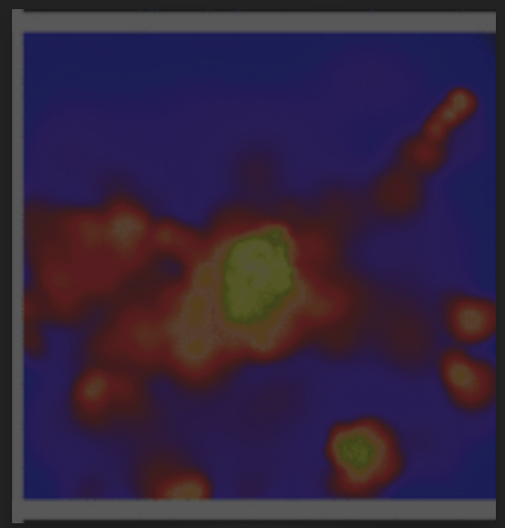

Zooms

Hayward, Behroozi et al. 2013

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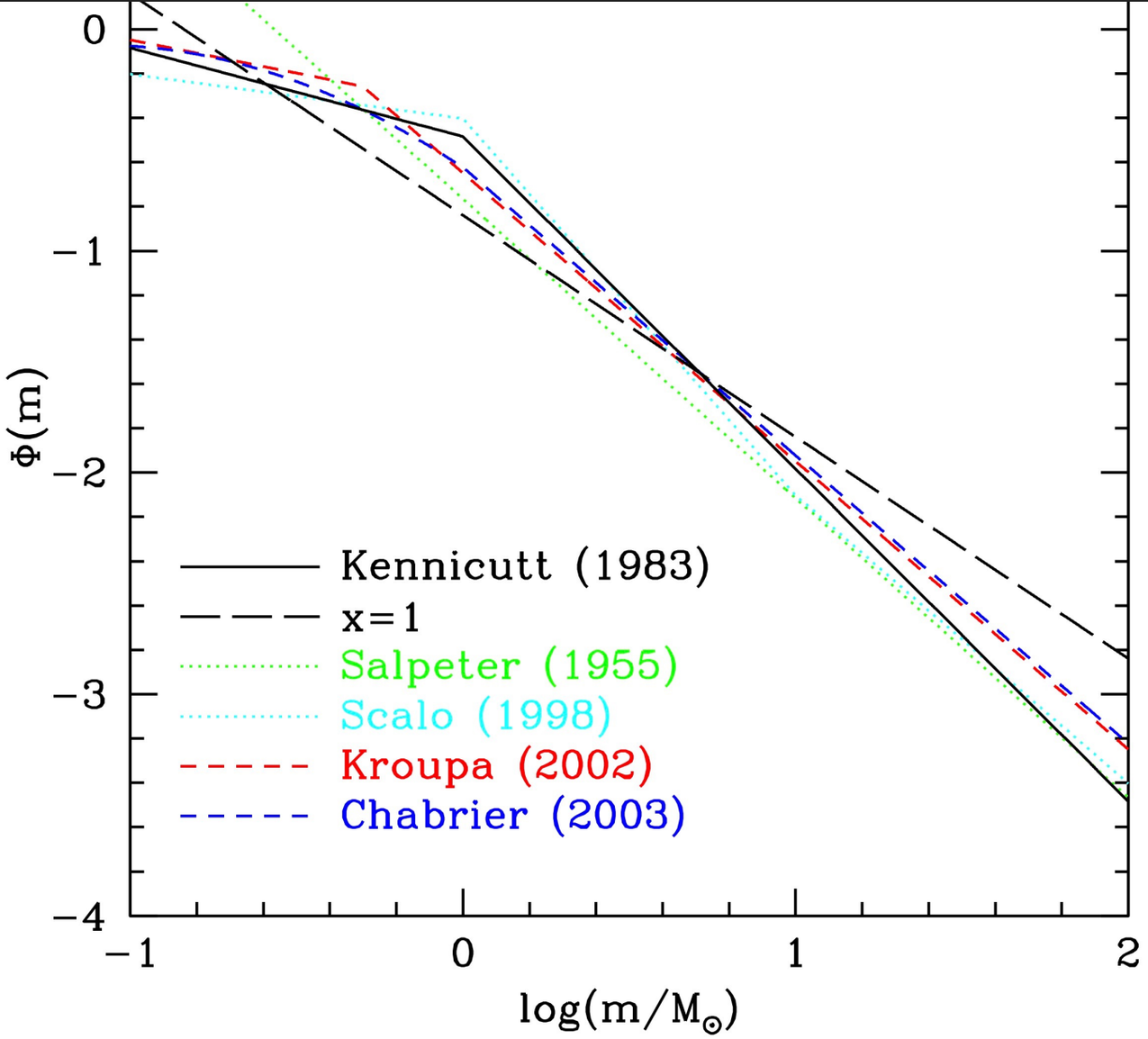
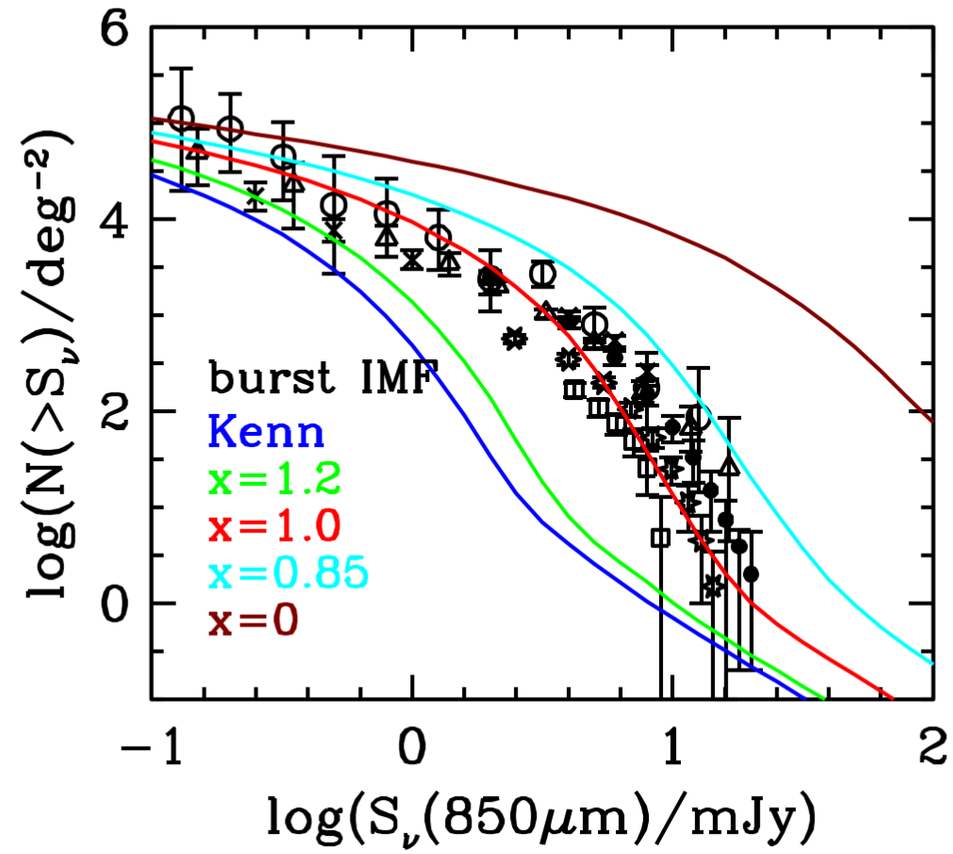
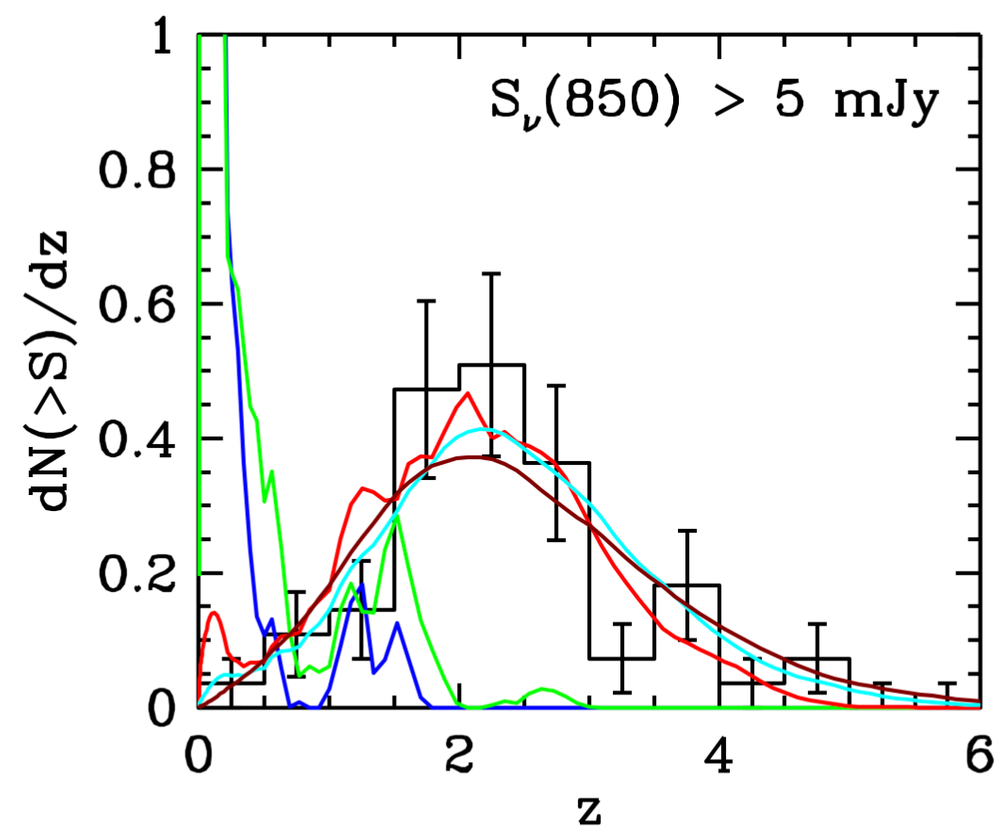
Lacey et al. 2016
Cowley et al. series







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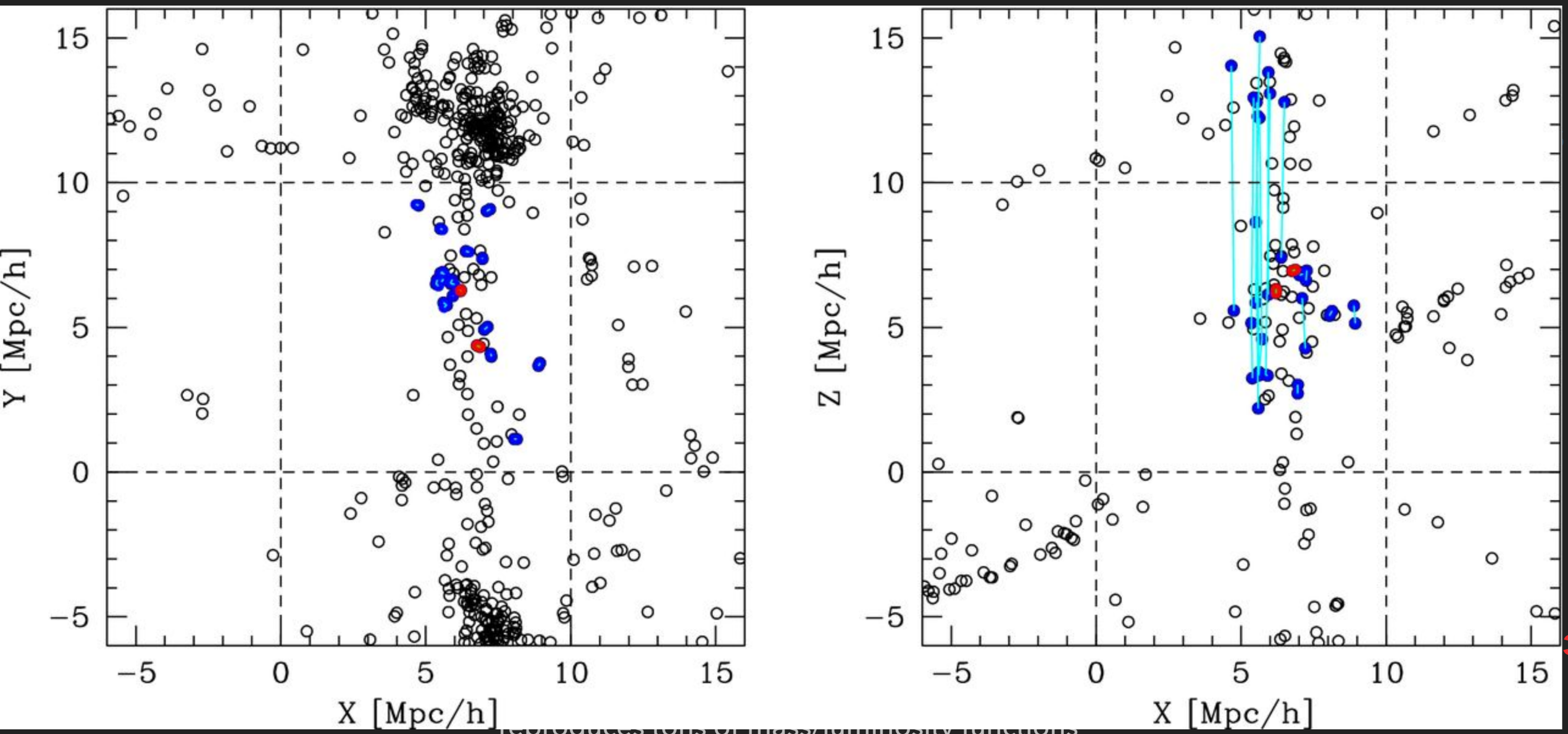

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Cowley et al. 2015

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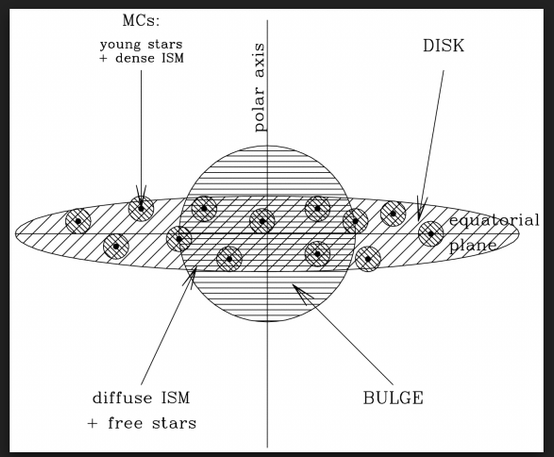

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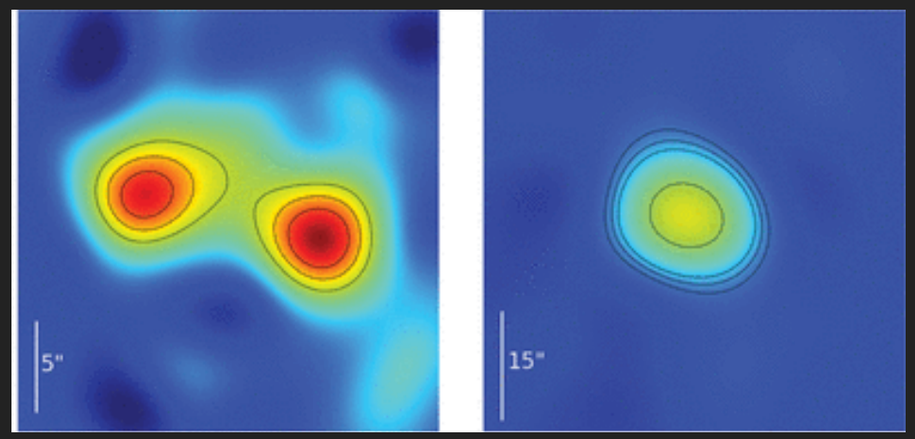

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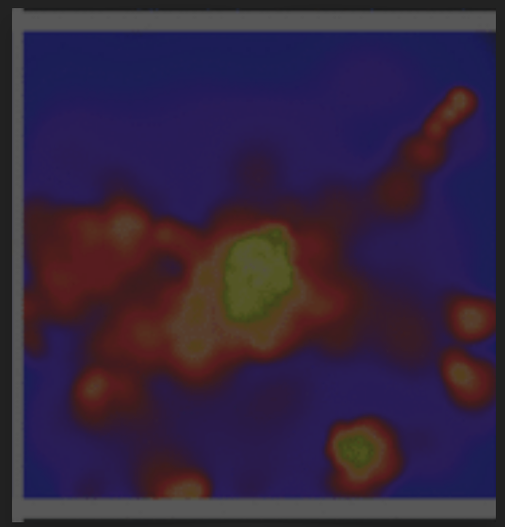

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PART 2: DUSTY GALAXIES

Semi A

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Lacey et al
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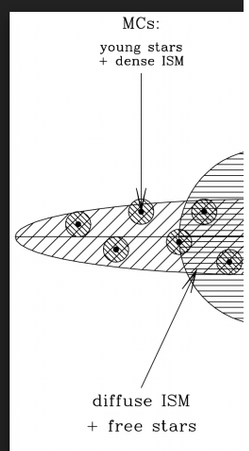

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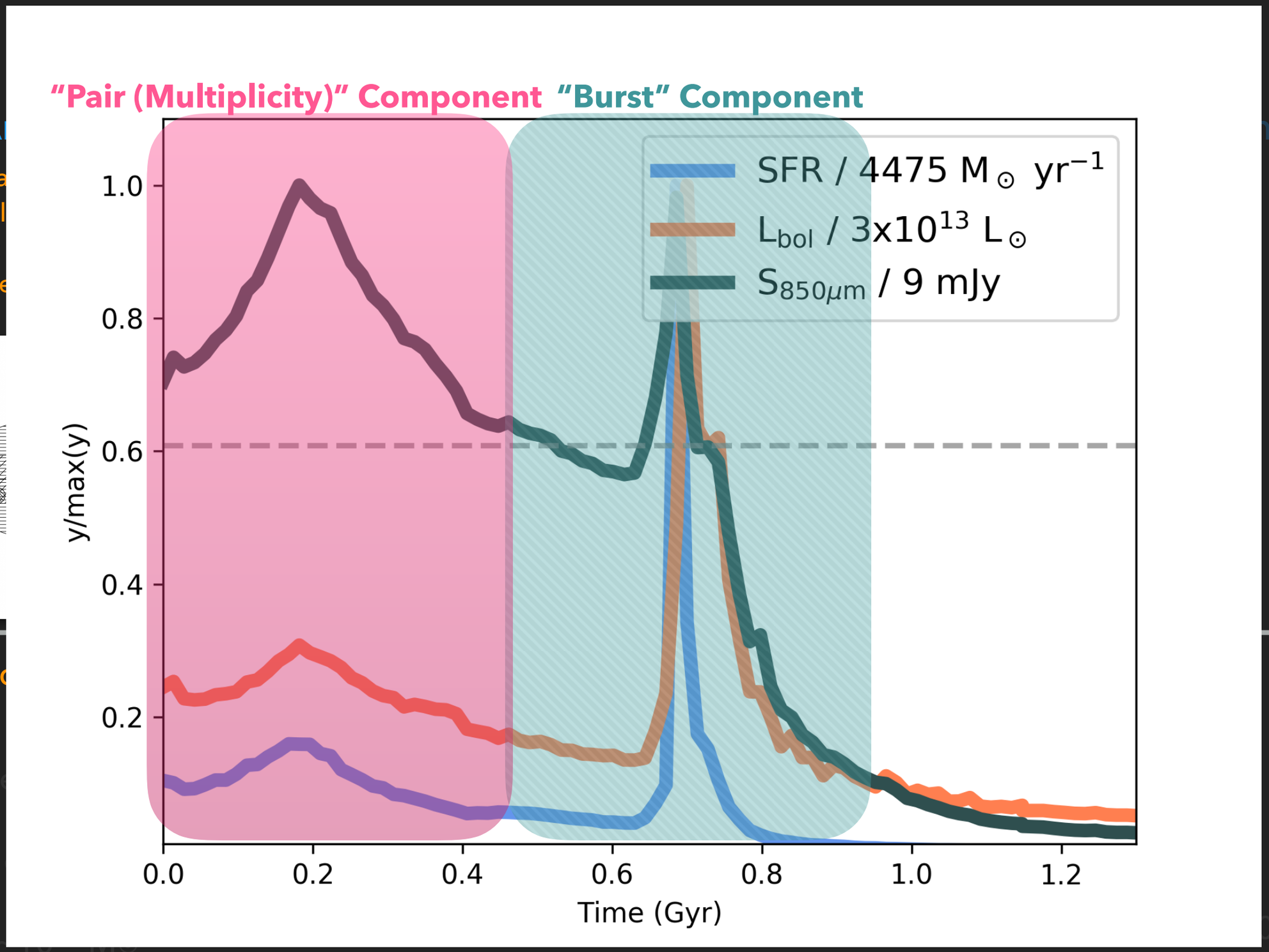

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Hayward, Jonsson et al. 2010
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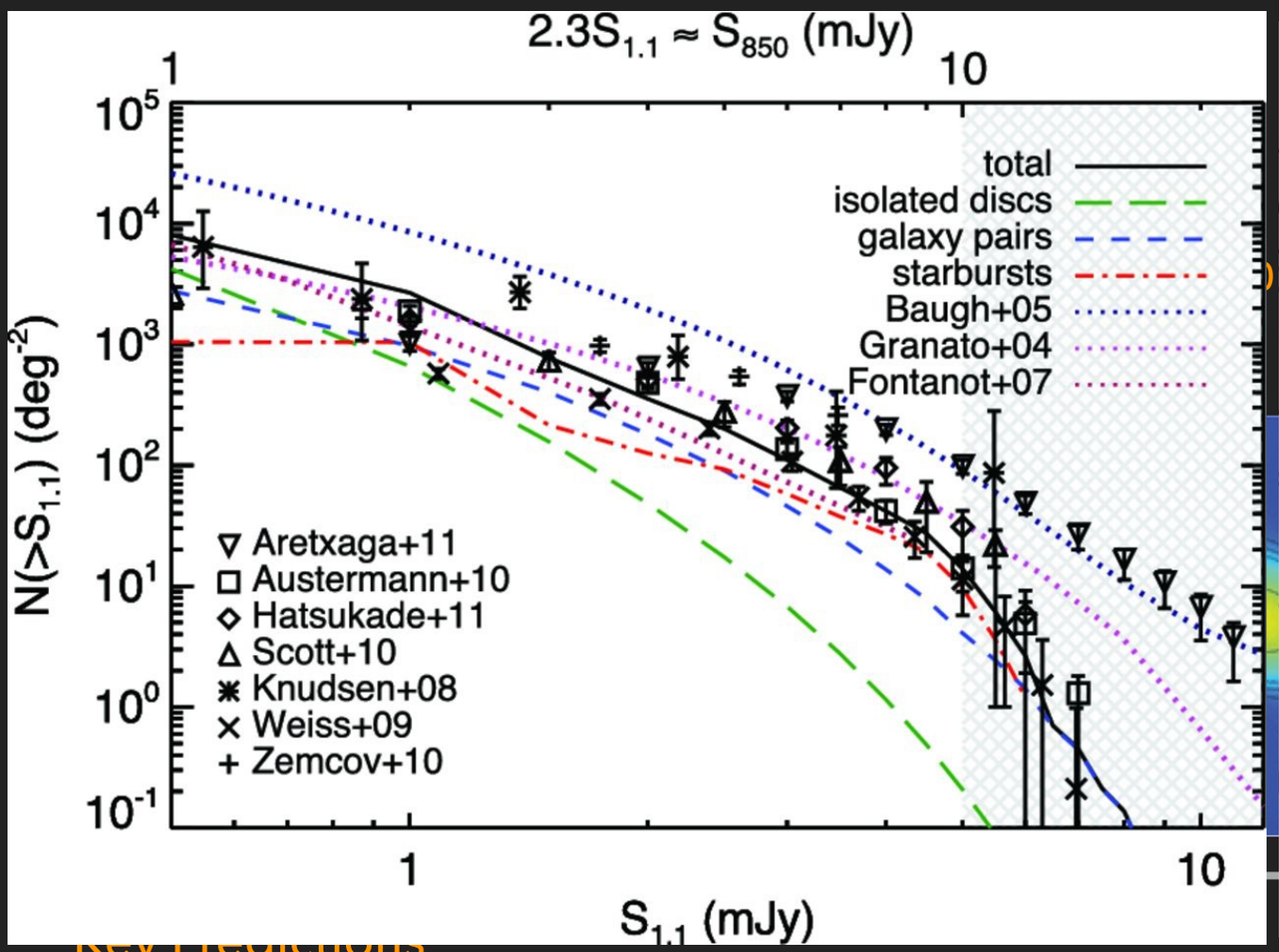

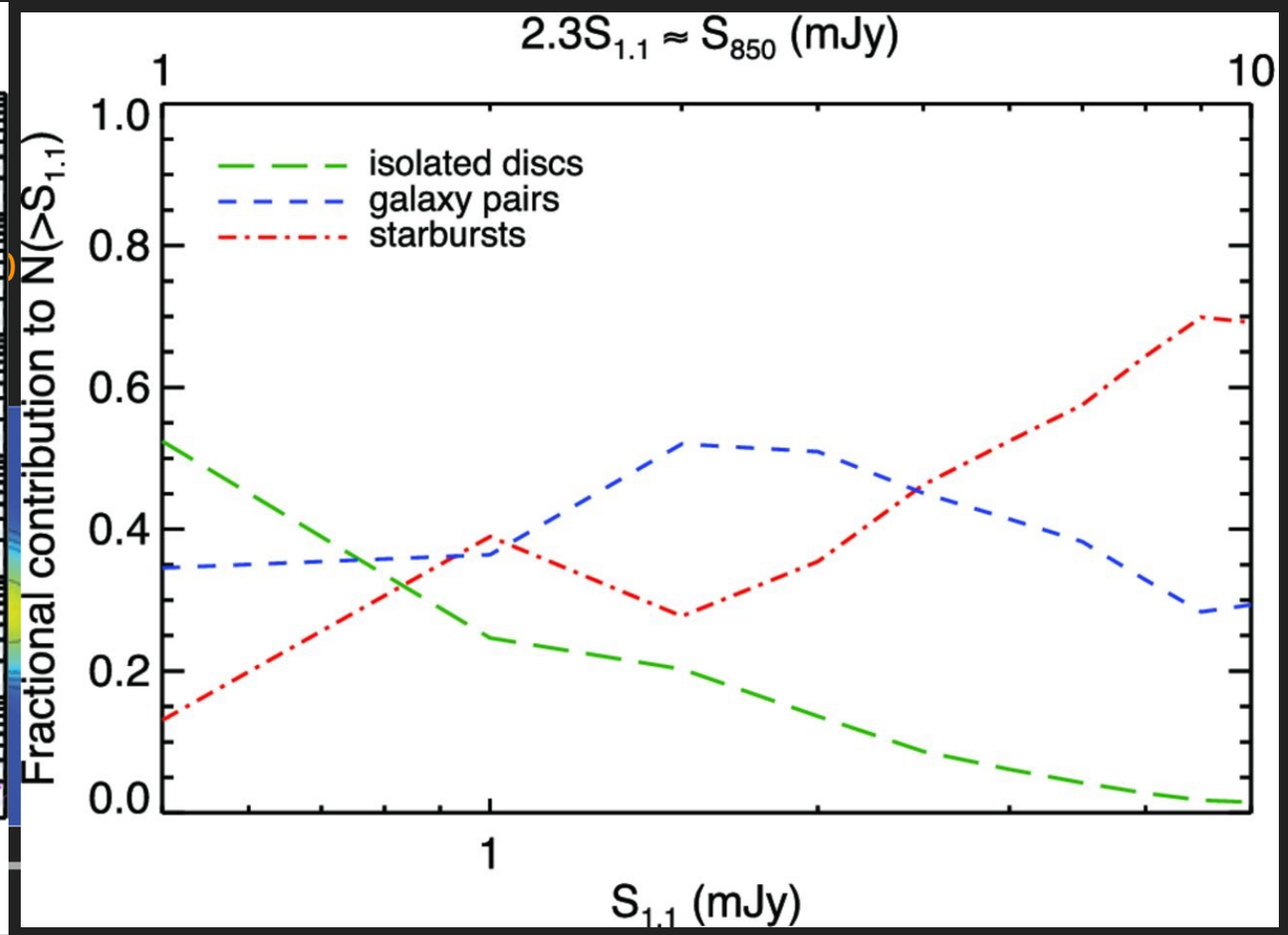

Hayward, DN+ 2014

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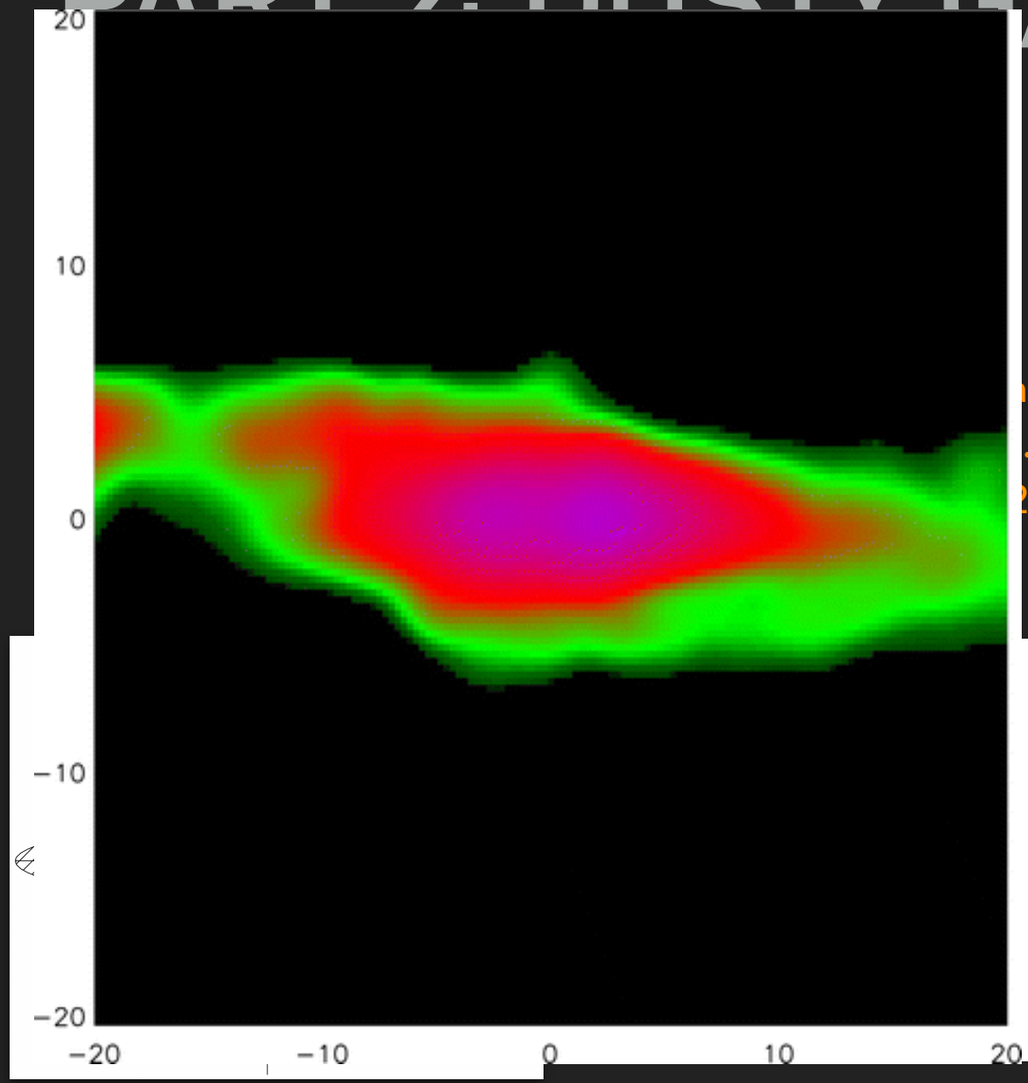

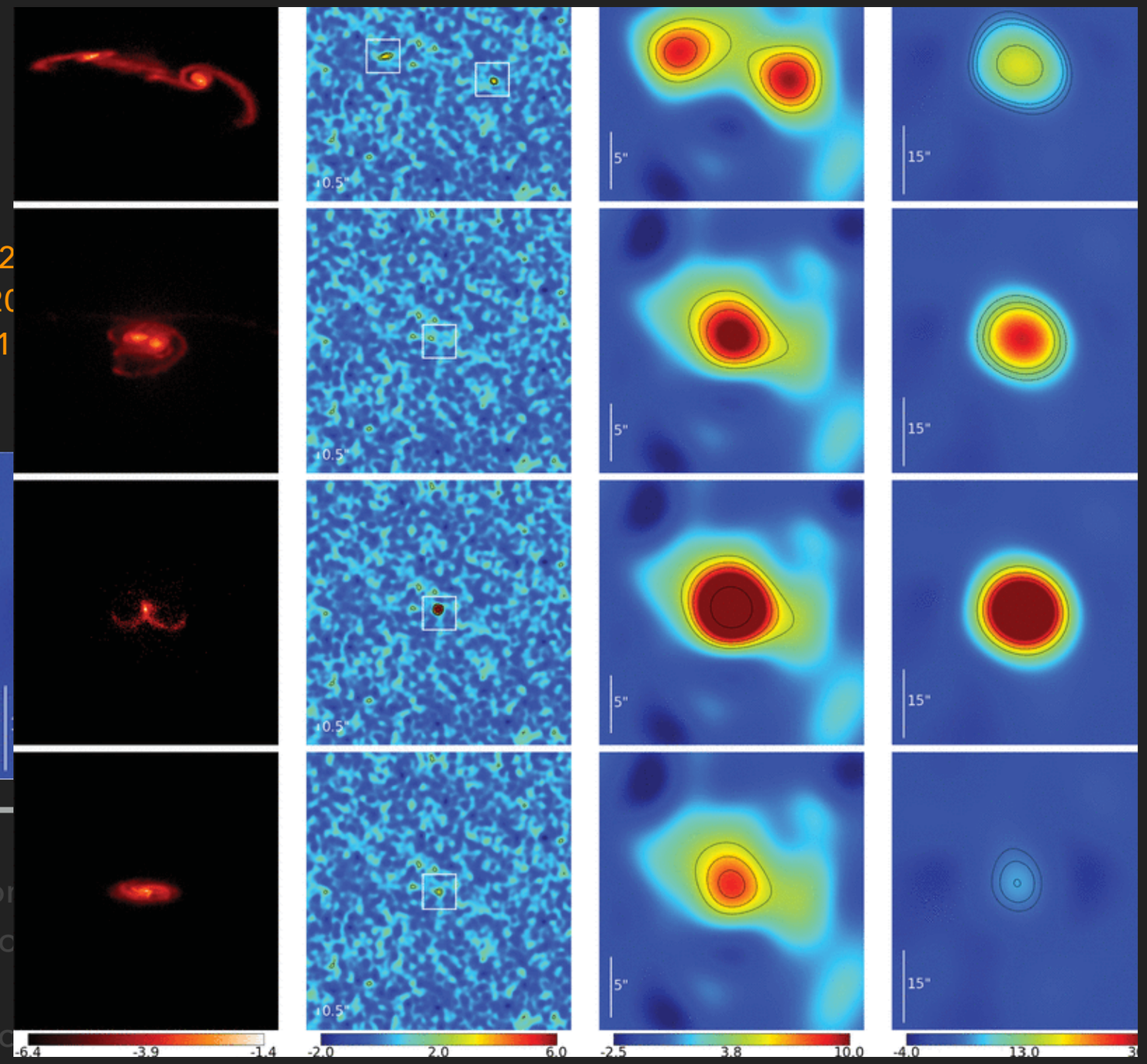

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Semi Analytic Models

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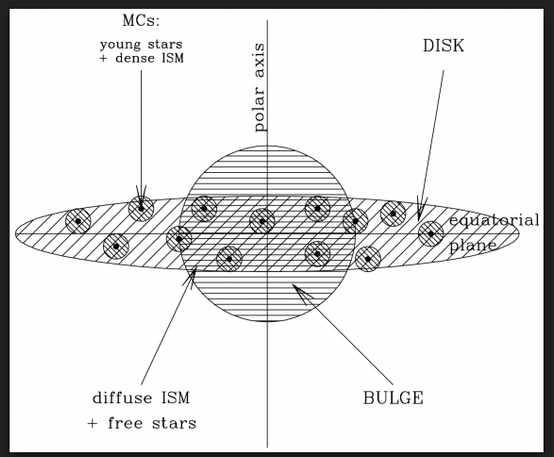
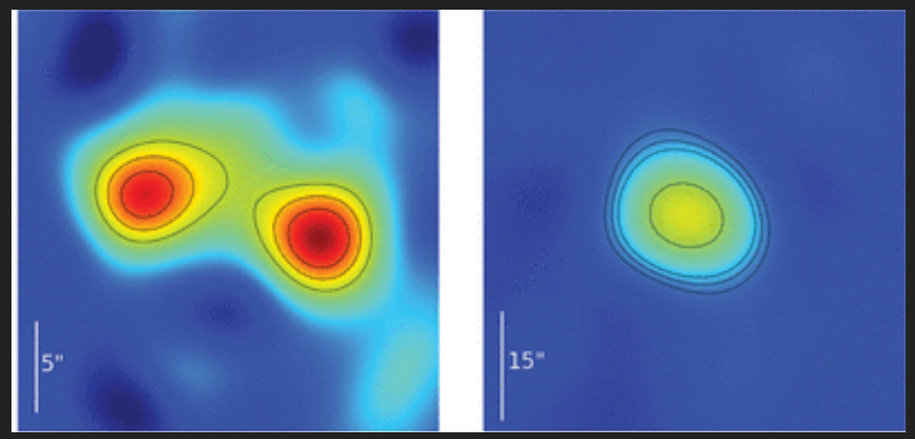
Lacey et al. 2014, 2016
Cowley et al. 2015,2016
Gonzalez et al. 2011



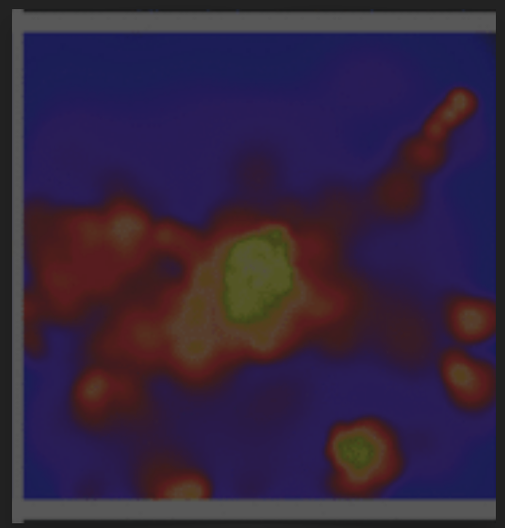
Idealized

Chakrabarti et al. 2006
Narayanan et al. 2008,2010
Hayward et al. 2010,2011,2014



Cosmological Simulations

Fardal et al. 2001
Dave et al. 2010
Shimizu et al. 2012



Zooms

Key Predictions

- Top heavy IMF
- Relatively low stellar/halo masses
- Multiplicity critical

- ~50% of SMGs are mergers
- ~50% of SMGs are blends
- Half of blends are unassociated
- Duty cycle (SB) ~ 0.1 Gyr
- $\langle M^* \rangle \sim 10^{11}\ M_\odot$

PART 2: DUSTY GALAXIES

Astrophysics

Sub-mm Galaxies in Cosmological Simulations

Mark A. Fardal, Neal Katz, David H. Weinberg, Romeel Davé, Lars Hernquist

(Submitted on 16 Jul 2001)

We study the predicted sub-mm emission from massive galaxies in a Lambda-CDM universe, using hydrodynamic cosmological simulations. Assuming that most of the emission from newly formed stars is absorbed and reradiated in the rest-frame far-IR, we calculate the number of galaxies that would be detected in sub-mm surveys conducted with SCUBA. The predicted number counts are strongly dependent on the assumed dust temperature and emissivity law. With plausible choices for SED parameters (e.g., T=35 K, beta=1.0), the simulation predictions reproduce the observed number counts above ~ 1 mJy. The sources have a broad redshift distribution with median z ~ 2, in reasonable agreement with observational constraints. However, the predicted count distribution may be too steep at the faint end, and the fraction of low redshift objects may be larger than observed.
In this physical model of the sub-mm galaxy population, the objects detected in existing surveys consist mainly of massive galaxies (several M_*) forming stars fairly steadily over timescales ~ 10^8-10^9 years, at moderate rates ~100 Msun/yr. The typical descendants of these sub-mm sources are even more massive galaxies, with old stellar populations, found primarily in dense environments. While the resolution of our simulations is not sufficient to determine galaxy morphologies, these properties support the proposed identification of sub-mm sources with massive ellipticals in the process of formation. The most robust and distinctive prediction of this model, stemming directly from the long timescale and correspondingly moderate rate of star formation, is that the far-IR SEDs of SCUBA sources have a relative high 850 micron luminosity for a given bolometric luminosity. [Abridged]

Comments: Submitted to ApJ. 34 pages including 8 PS figures
Subjects: **Astrophysics (astro-ph)**
Cite as: arXiv:astro-ph/0107290
(or arXiv:astro-ph/0107290v1 for this version)

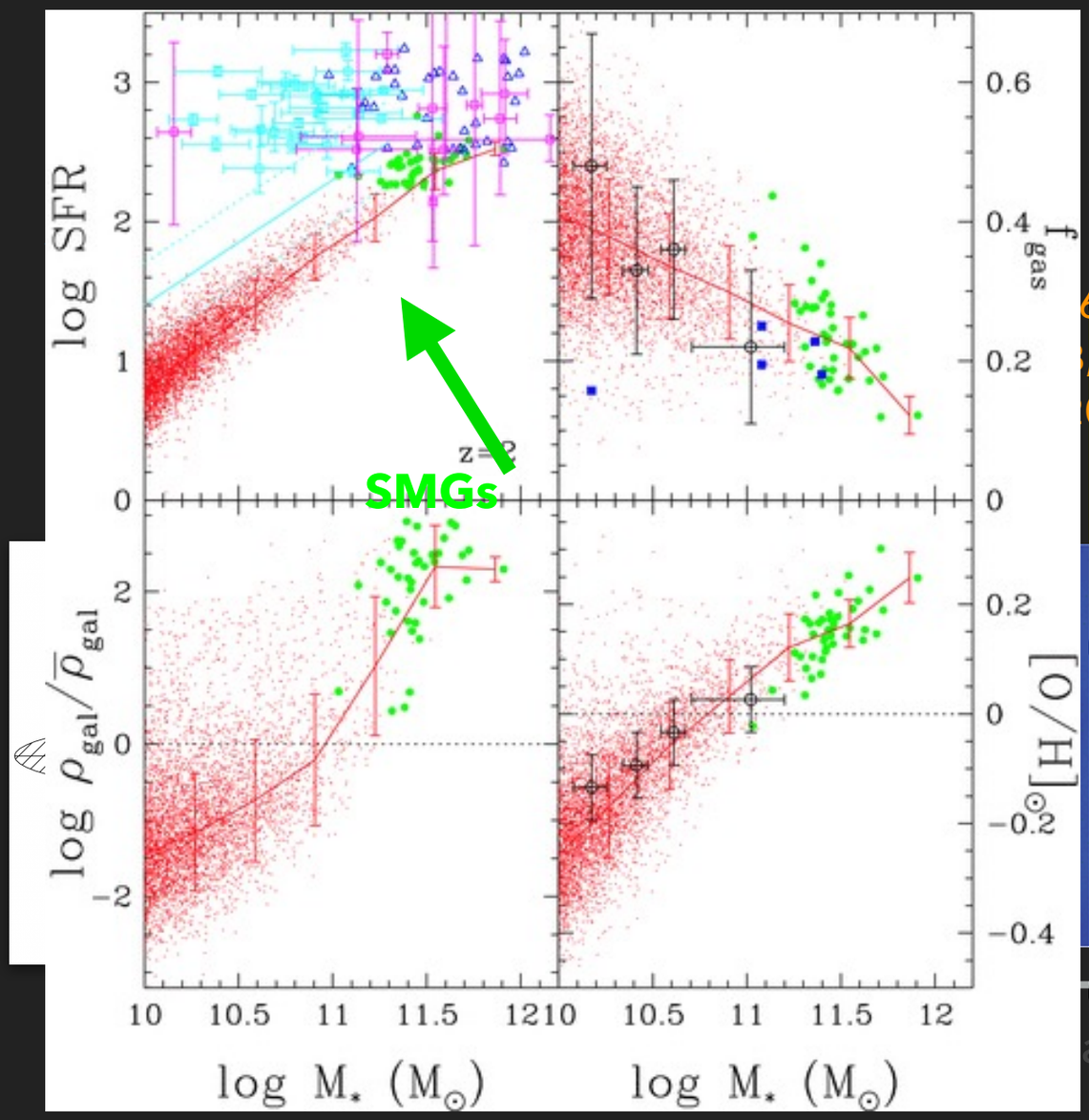
Submission history

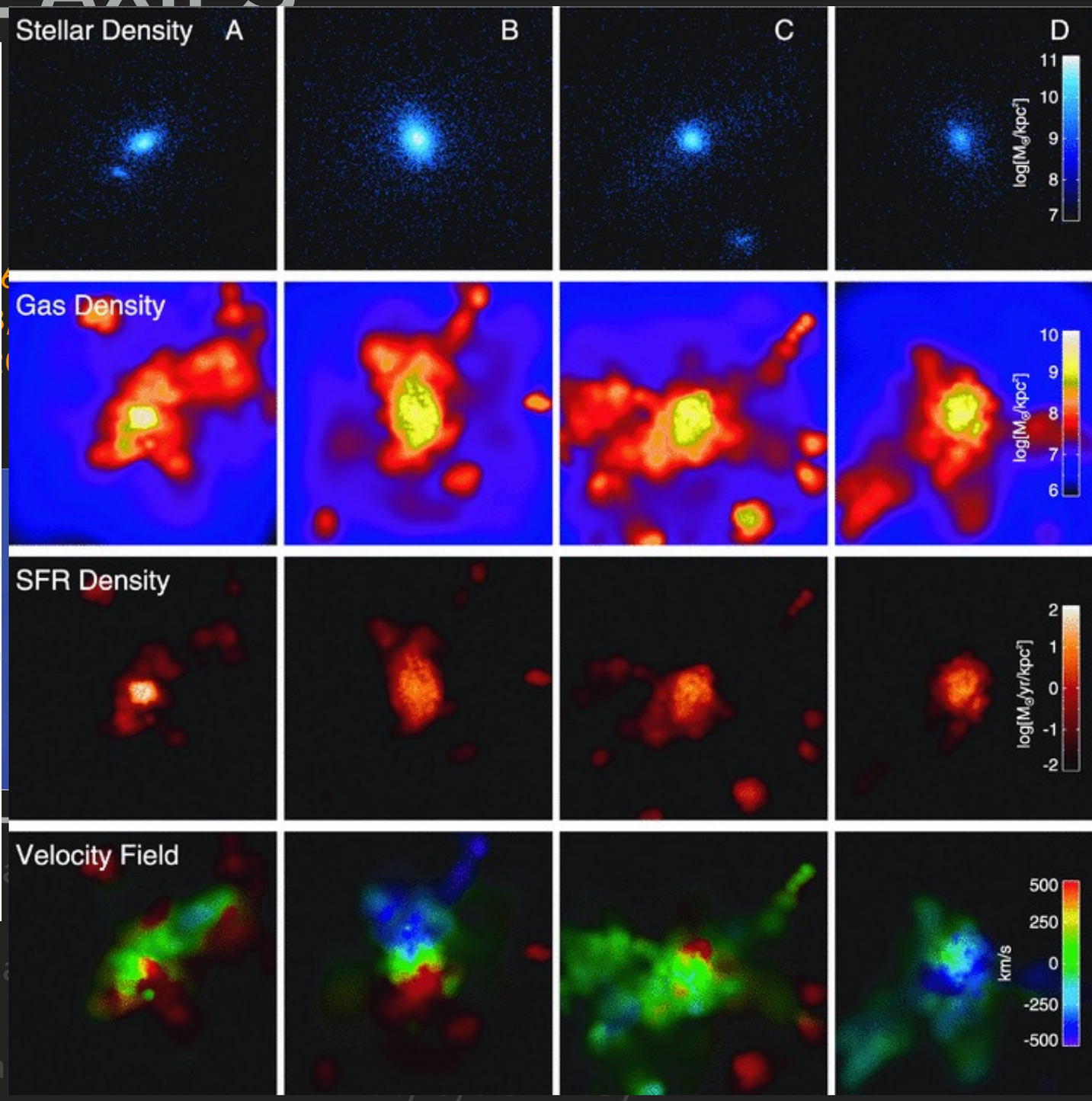
From: Mark Fardal [view email]
[v1] Mon, 16 Jul 2001 21:16:03 GMT (505kb)

<M*>~10^11 M⊙

PART 2: DUSTY GALAXIES

Davé et al. 2010





- Top Heavy IMF* in starbursts
- <duty cycle> = 0.1 Gyr
- <M*>~10^{10} M⊙
- 22% major mergers

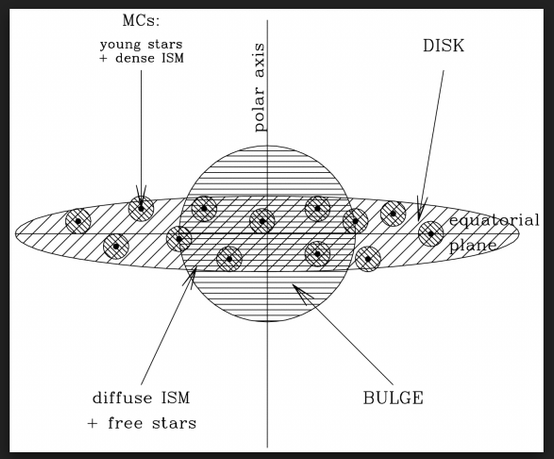
- ~50% of SMGs a
- Half of blends a unassociated
- Duty cycle (SB) ~ 0.1 Gyr
- <M*>~10^{11} M⊙

- <M*>~$5x10^{11}$ M⊙

PART 2: DUSTY GALAXIES

Semi Analytic Models

Baugh et al. 2004
Lacey et al. 2014
Cowley et al. 2015,2016



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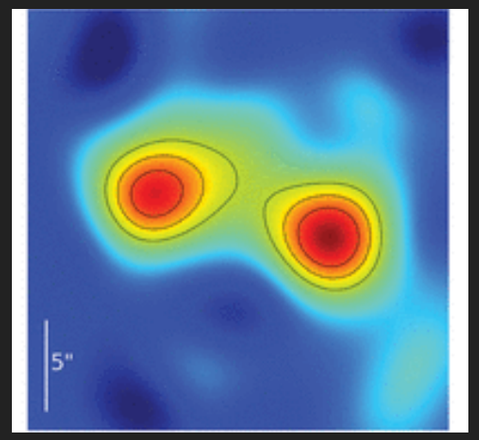

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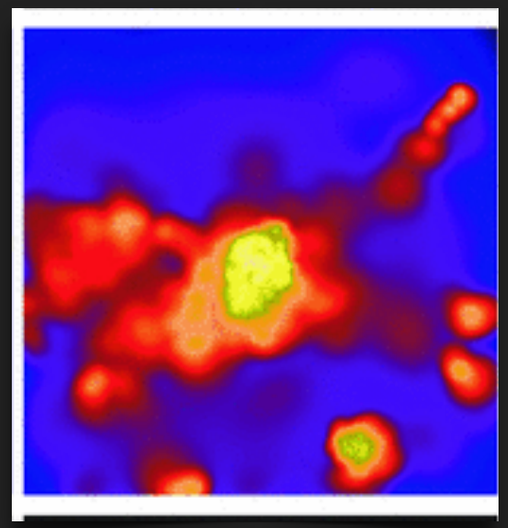

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- ~2% of SMGs are mergers
- SFR_{max} ~ 600 M⊙/yr
- Duty cycle ~1 Gyr
- $\langle M^* \rangle \sim 5 \times 10^{11}$ M⊙

PART 2: DUSTY GALAXIES

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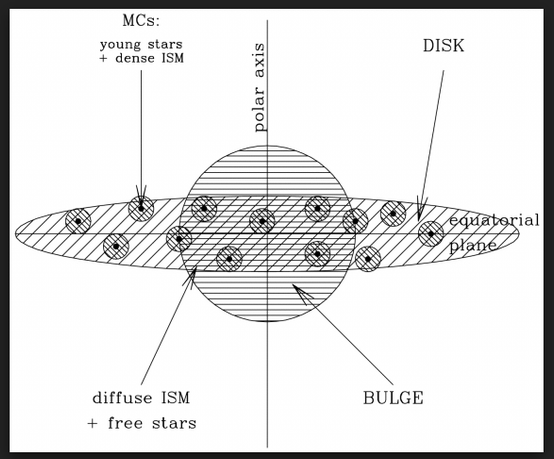
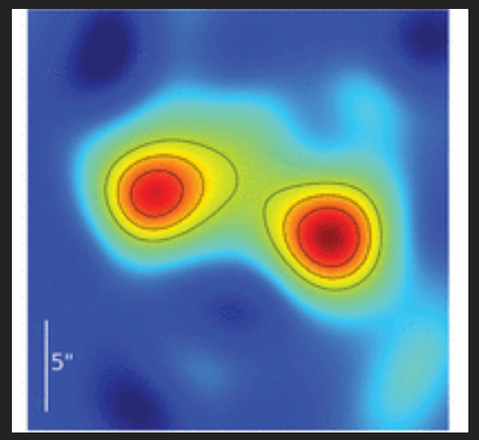
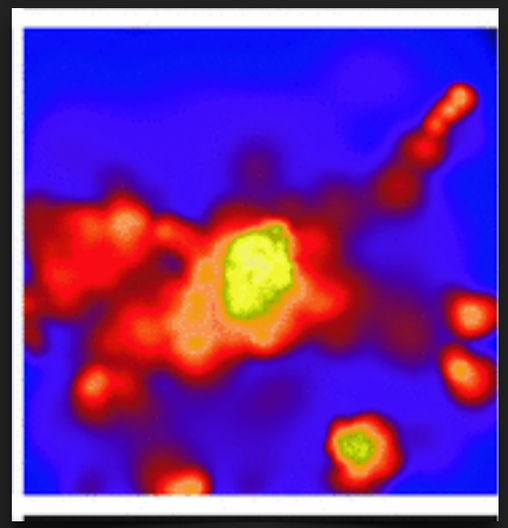
Zooms







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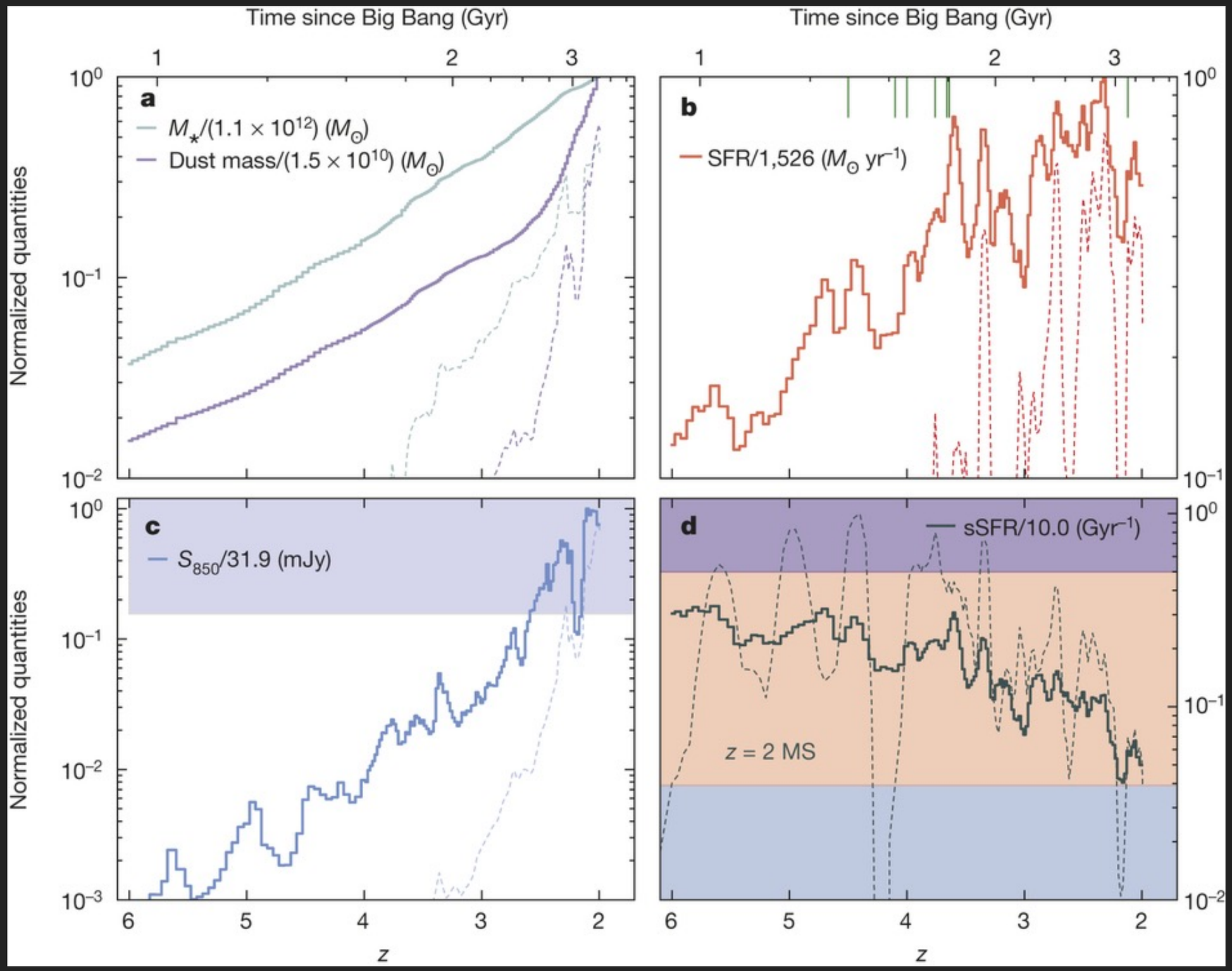
PART 2: DUSTY GALAXIES



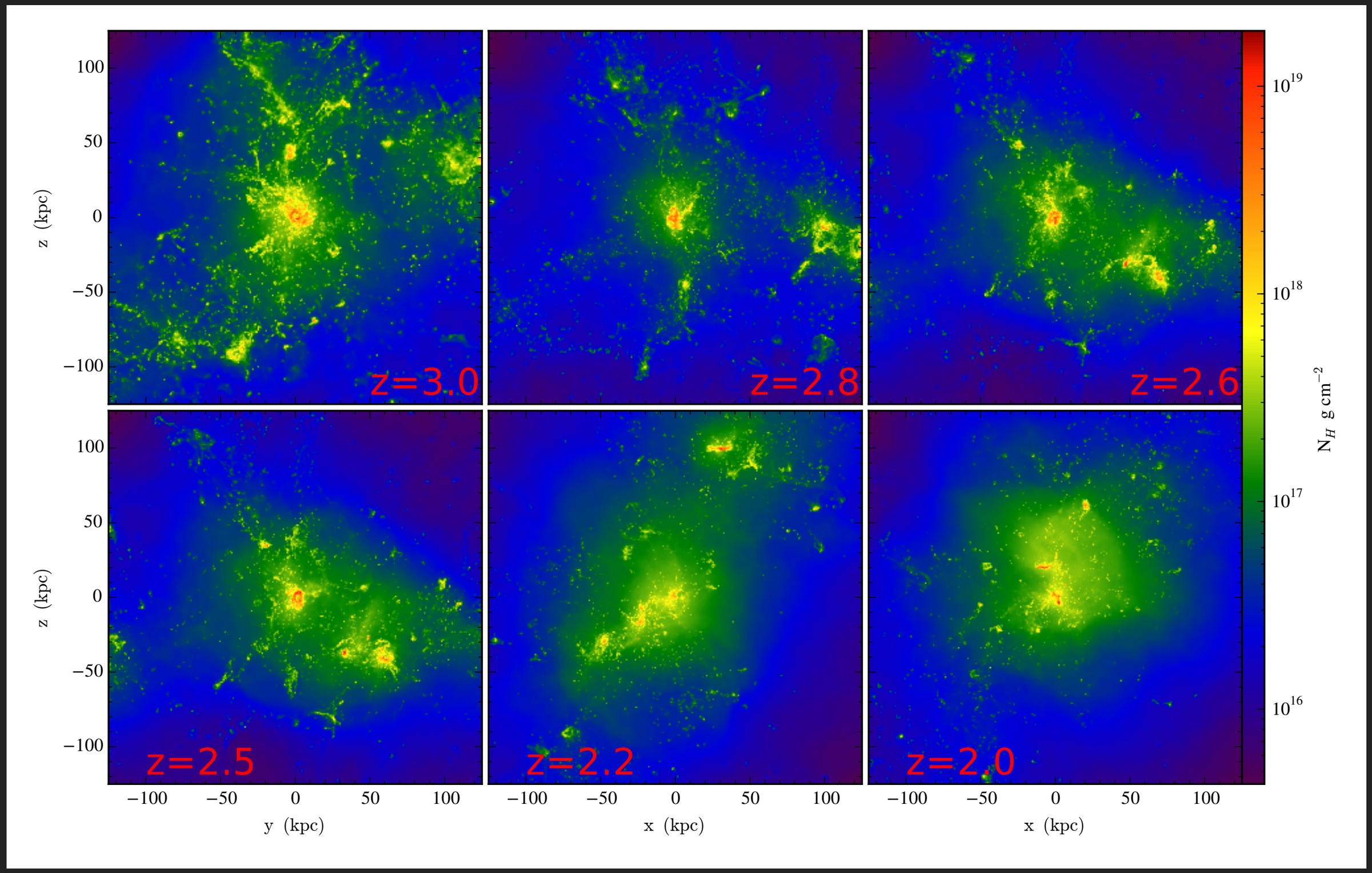
Narayanan, Turk, Feldmann et al. 2015, *Nature*

PART 2: DUSTY GALAXIES

-The central contributes ~70% of the total observed submm flux
-Typically 3-4 associated counterparts

Narayanan, Turk, Feldmann et al. 2015, *Nature*

PART 2: DUSTY GALAXIES



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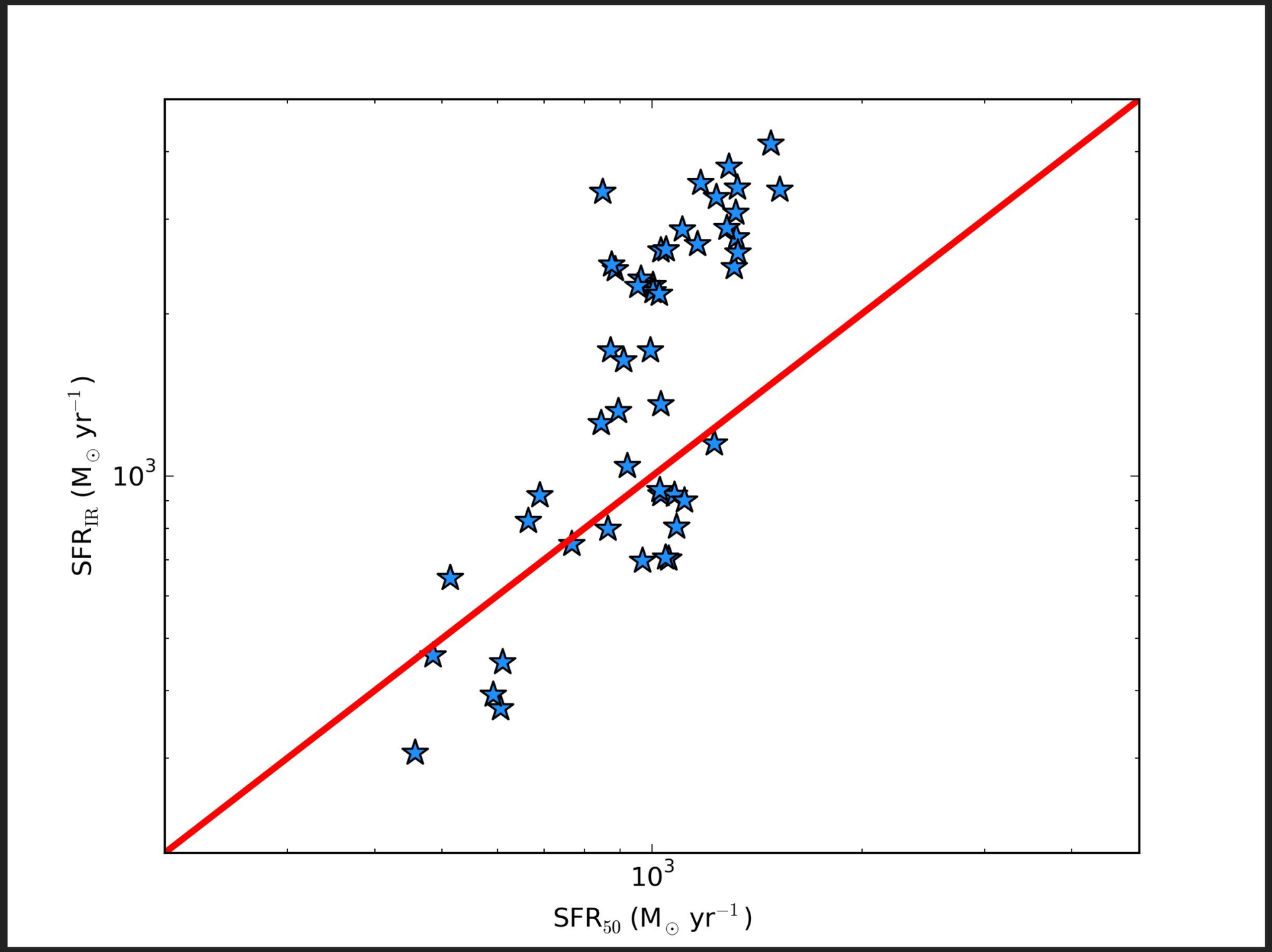
PART 2: DUSTY GALAXIES

(In Cosmological zoom simulations)

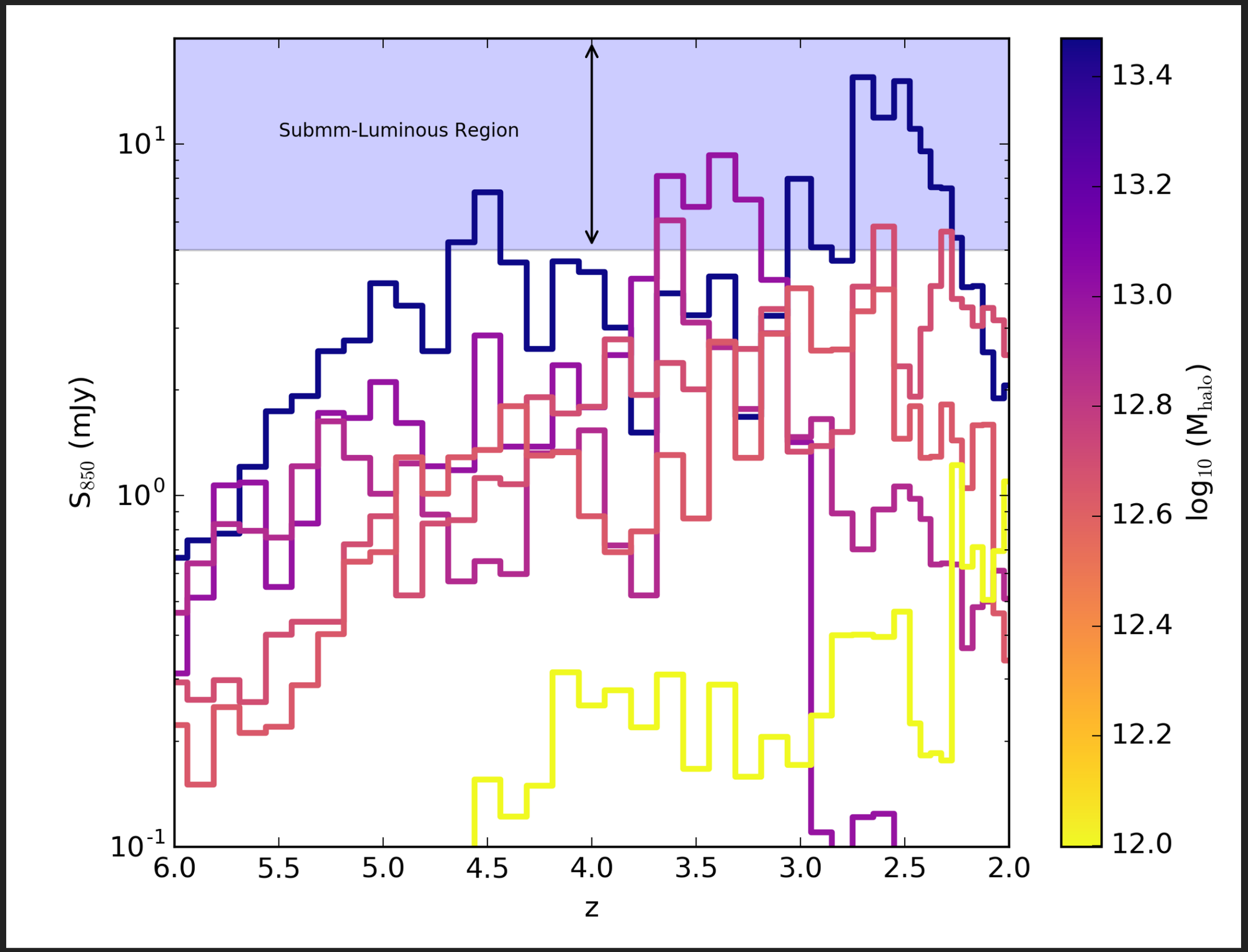


Evolved star contribution to IR luminosity significant, can cause over estimates of SFR by factor ~2-3

Narayanan, Turk, Feldmann et al. 2015, *Nature*

PART 2: DUSTY GALAXIES

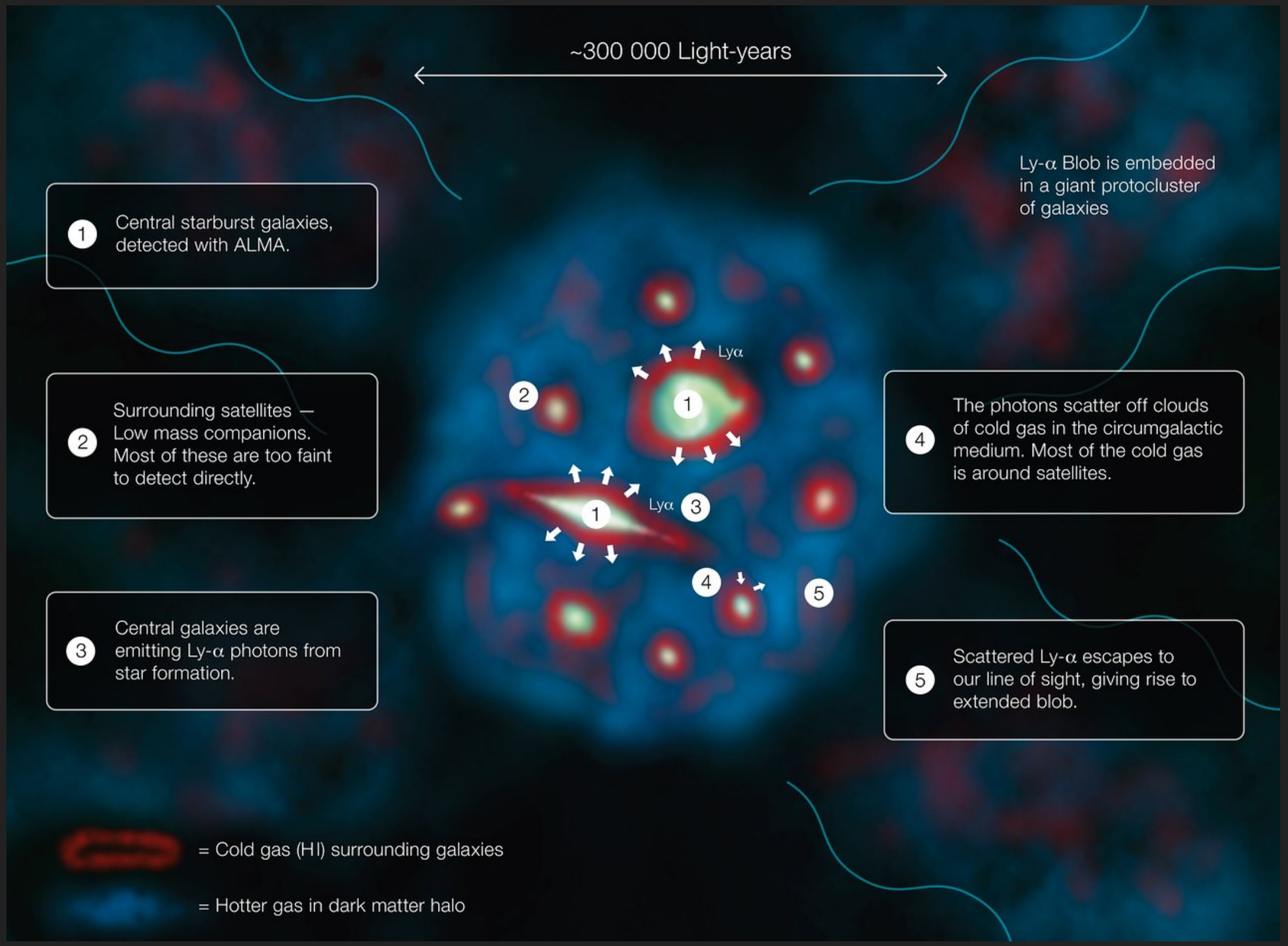
(In Cosmological zoom simulations)



Narayanan+ in prep.

PART 2: DUSTY GALAXIES

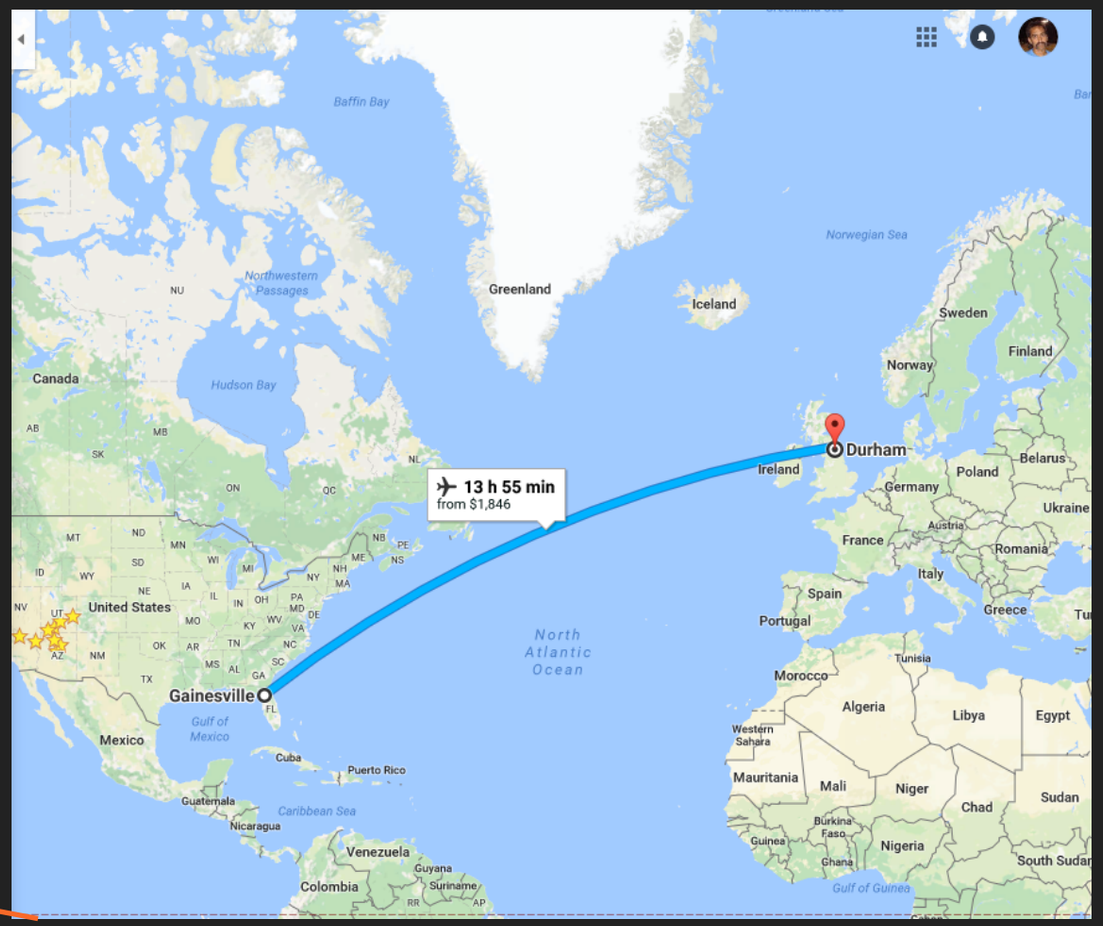
Connections to Lyman Alpha Blobs



Geach, Narayanan et al. 2016

ZOOMS: AWESOME FOR GALAXY FORMATION; HORRIBLE FOR THE ENVIRONMENT

- 2 lbs of CO_2 emitted per KW-h of electricity on average in the U.S.[1]
- Every zoom at $M_{bar} \sim 10^5\ M_\odot$ resolution takes 2 months on 768 cores
- This equates (to z~2) to ~9K lbs of CO_2 Assuming 135 W power supplies
- This equates to four (!!) round trips from Gainesville, FL to Durham, UK for 1 person
- (If you referee my papers, be cool)



1. drill baby drill

PART 2: DUSTY GALAXIES

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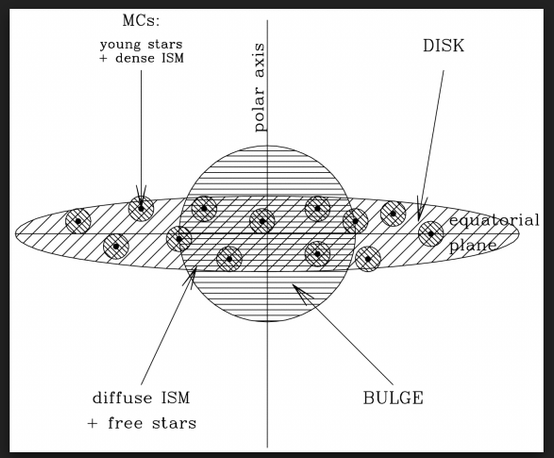
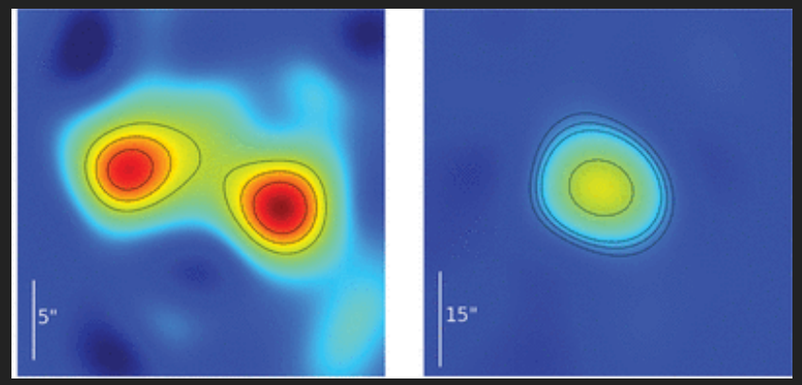
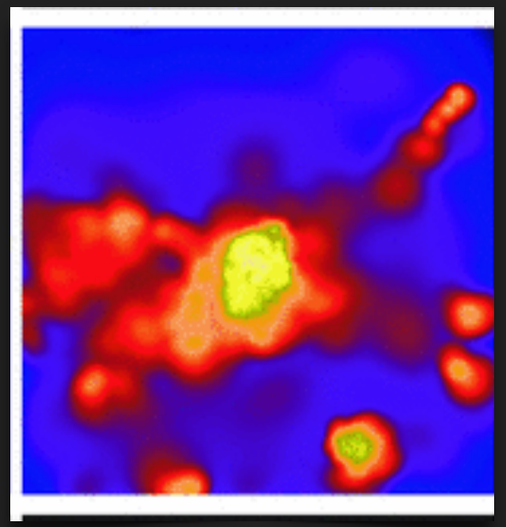






Key Predictions

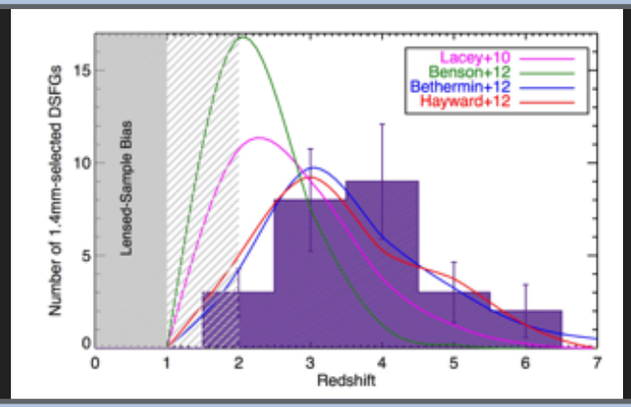
- Flat Stellar IMF*
- <duty cycle> = 0.1 Gyr
- 3-6 physically unassociated galaxies
- $\langle M^* \rangle \sim 10^{10}\ M_\odot$

- ~50% of SMGs are mergers
- ~50% of SMGs are blends
- Half of blends are unassociated
- Duty cycle (SB) ~ 0.1 Gyr
- $\langle M^* \rangle \sim 10^{11}\ M_\odot$

- ~2% of SMGs are mergers
- $SFR_{max} \sim 600\ M_\odot/yr$
- Duty cycle ~1 Gyr
- $\langle M^* \rangle \sim 5\times10^{11}\ M_\odot$

- Mergers happen, but mostly unimportant
- $SFR_{max} \sim 1500\ M_\odot/yr$
- Duty cycle ~1 Gyr
- $\langle M^* \rangle \sim 5\times10^{11}\ M_\odot$

PART 3: OBSERVATIONAL OUTLOOK

Physical Property	Why?	Obs Needed
M_{halo}	$10^{11.5}$-10^{13} $M_\odot$ (SAM–>Cosmological Hydro)	Clustering
M*	~10^{10} $M_\odot$ - 10^{12} $M_\odot$ (SAM–>Cosmological Hydro)	Strong NIR constraints for SED Modeling
Redshift Distribution		z>4 (c.f. HFLS3 and SPT 0311)
Multiplicity	Implicitly sets constraint on max (SFR,M_{dust}) of SMGs	2D & 3D Mapping
IMF in present-day ellipticals	If IMF is bottom heavy in progenitors, we're in trouble	Gravity-sensitive lines (e.g. FeH); dynamical modeling

CONCLUDING THOUGHTS: 20 YEARS LATER, WE'RE STILL IN BUSINESS

The game:

- The fundamental challenge is forming a luminous enough source with an extended, cold dust spectrum in massive numbers.

Where we're at:

- We have viable models that span 2 orders of magnitude in predicted galaxy and halo masses
- We're all quite happy with multiplicity
- We disagree on the value of mergers

Where we need to be:

- Converged theory for SFH, Σ_{SFR}, and Σ_{dust}
- Theoretical Comparison Project (i.e. make life easy for observers)

Homework for Theorists

- What fraction of SMGs owe to mergers?
- What are the number counts and redshift distribution?
- What are the cospatial and unassociated multiplicity distribution functions?
- What are the distribution of M*, Mhalo, M_{H2}?
- ? (For discussion)

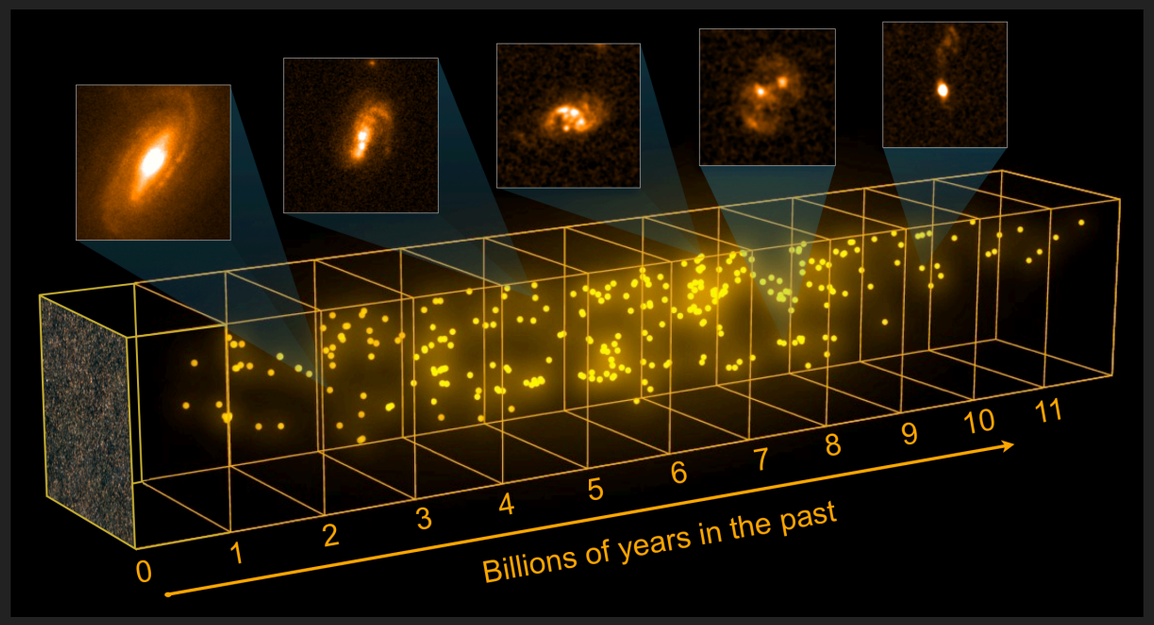


Image: Caitlin Casey