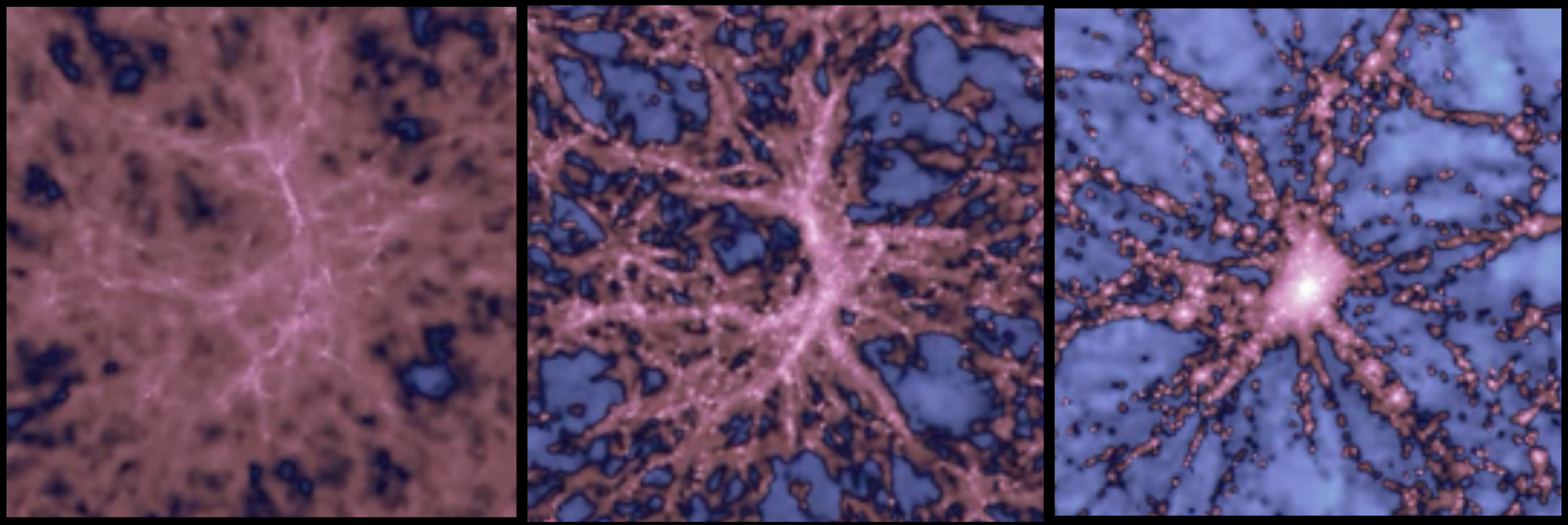
The Ubiquity of Coeval Starbursts in Massive Galaxy Cluster Progenitors

Caitlin M. Casey, the University of Texas at Austin

How do clusters — the most massive gravitationally bound structures in the Universe — assemble?



z~7 z~2.5 z~0

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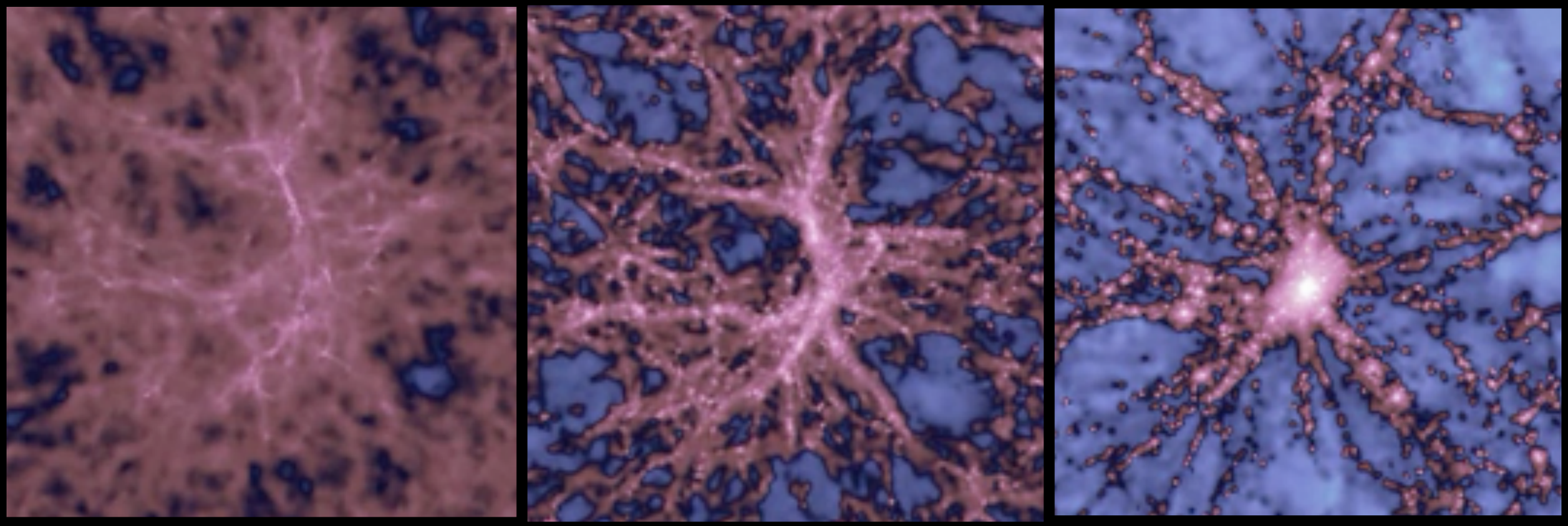

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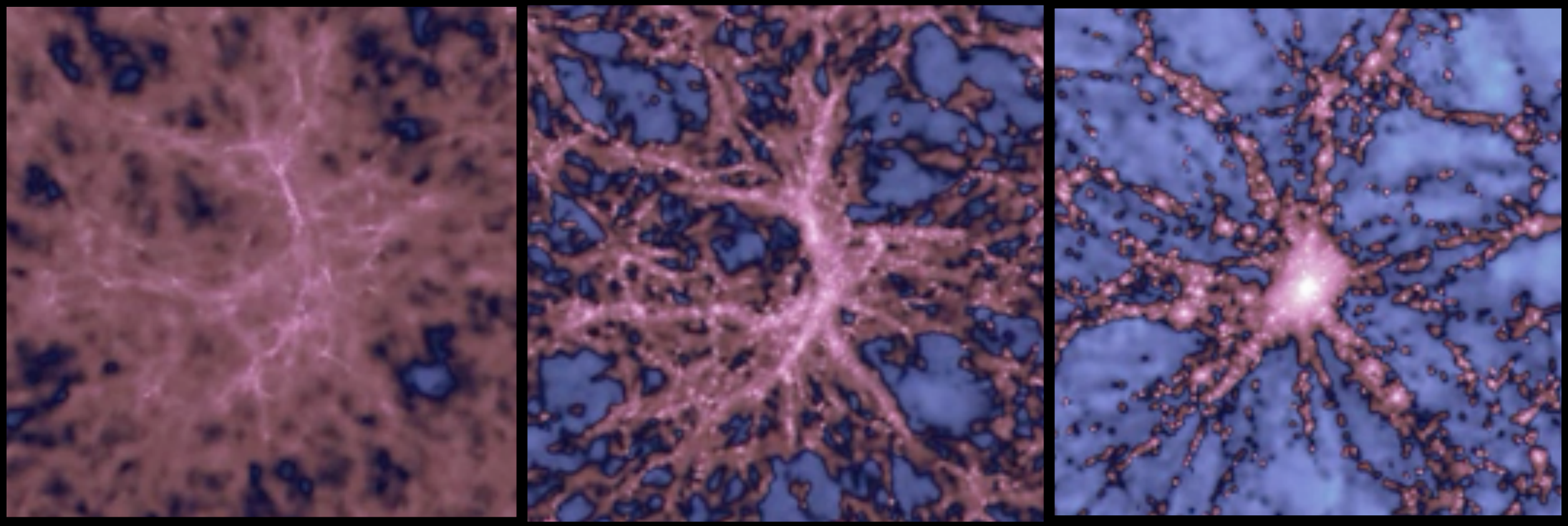
cosmological interest

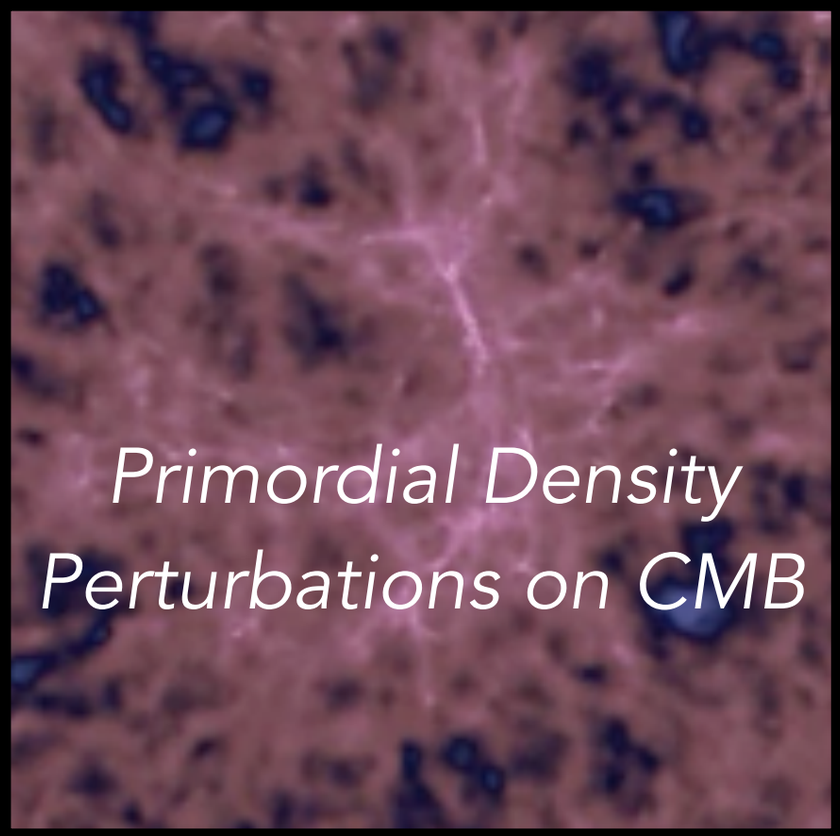
How do clusters — the most massive gravitationally bound structures in the Universe — assemble?

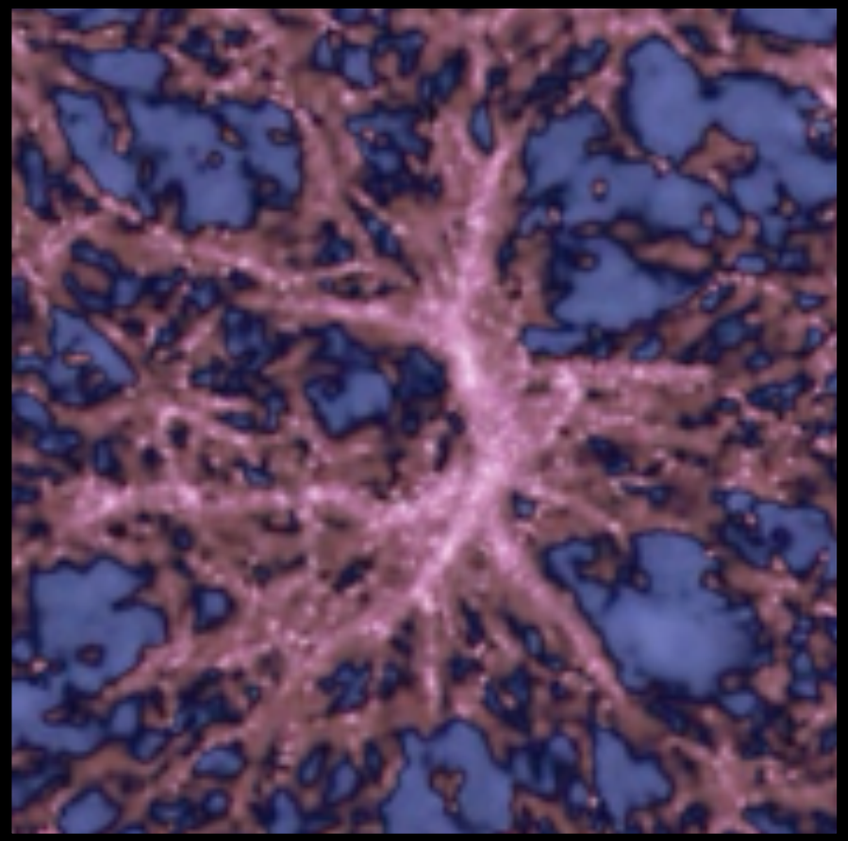


z~7 z~2.5 z~0

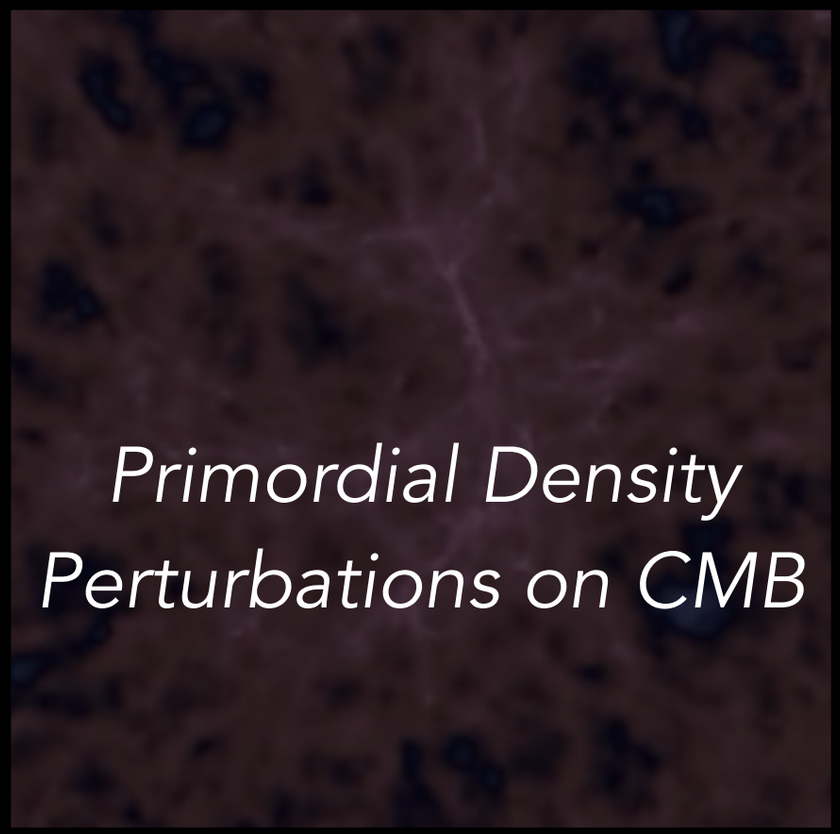
cosmological interest

environmental impact on galaxy evolution

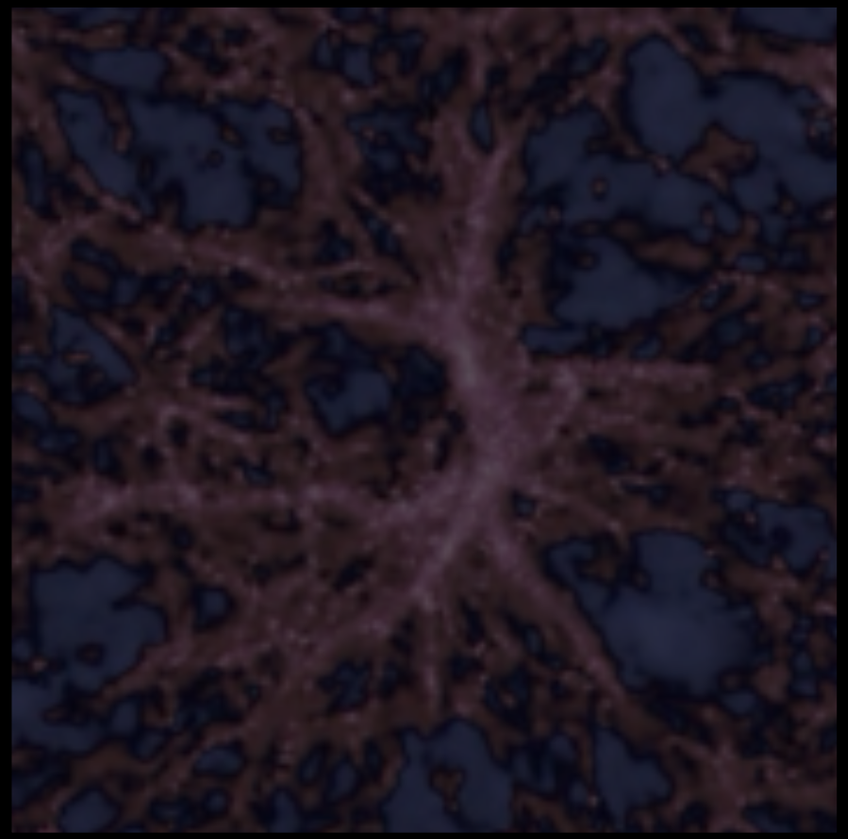

Primordial Density
Perturbations on CMB




Galaxy Clusters



Primordial Density Perturbations on CMB



Galaxy Clusters

Theoretical Framework linking the two

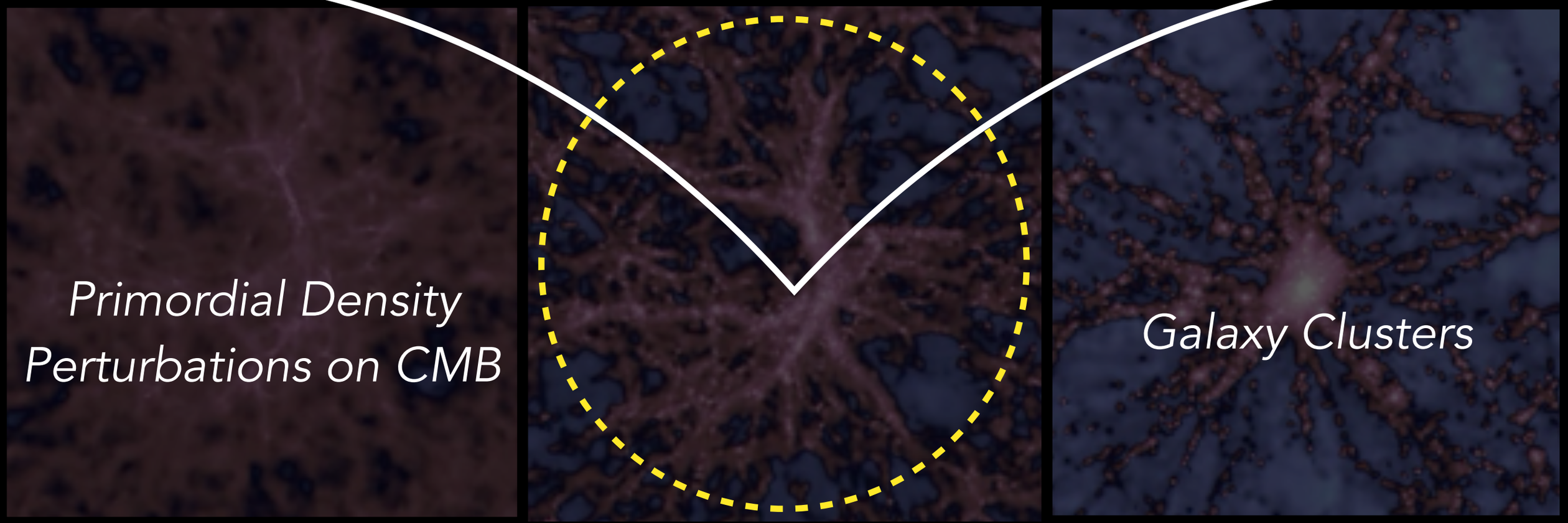
Primordial Density Perturbations on CMB

?

Galaxy Clusters

Theoretical Framework linking the two

Collections of Dusty Star-Forming Galaxies (DSFGs) can trace the extended halo structure of pre-virialized galaxy clusters. When present, they provide unique observational constraints on the assembly of those clusters because we know they are predominantly short-lived. They likely represent a triggered phase (100-200Myr) of enhanced star-formation across ~10Mpc scales coinciding with filamentary collapse.



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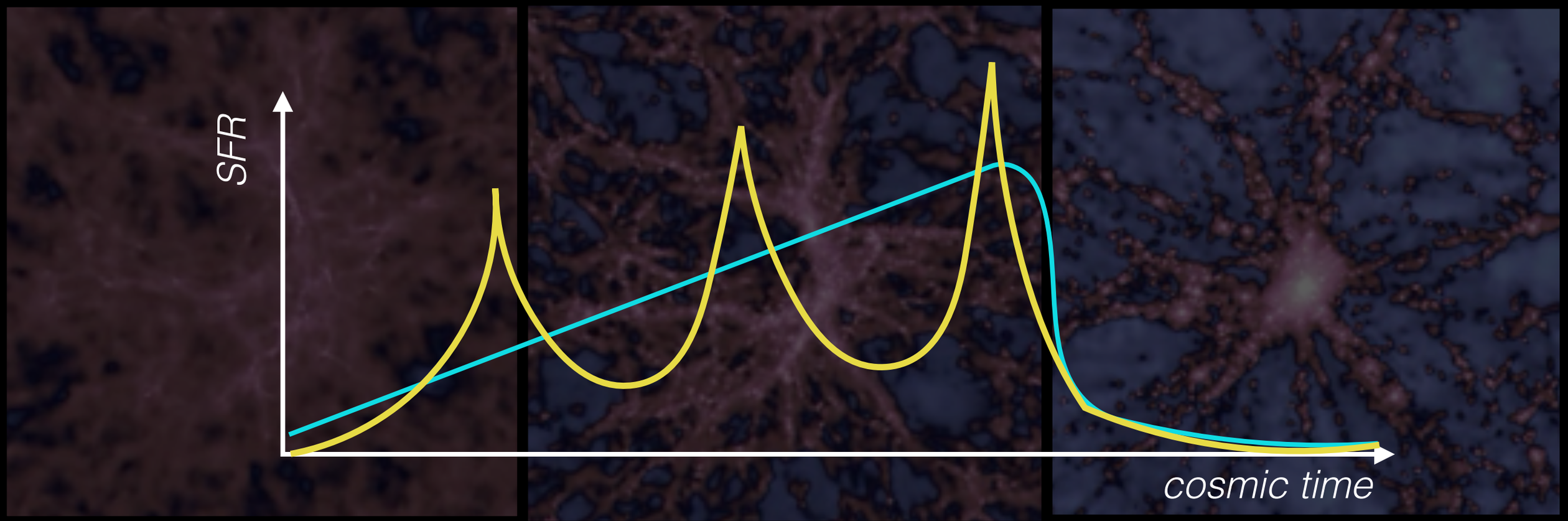


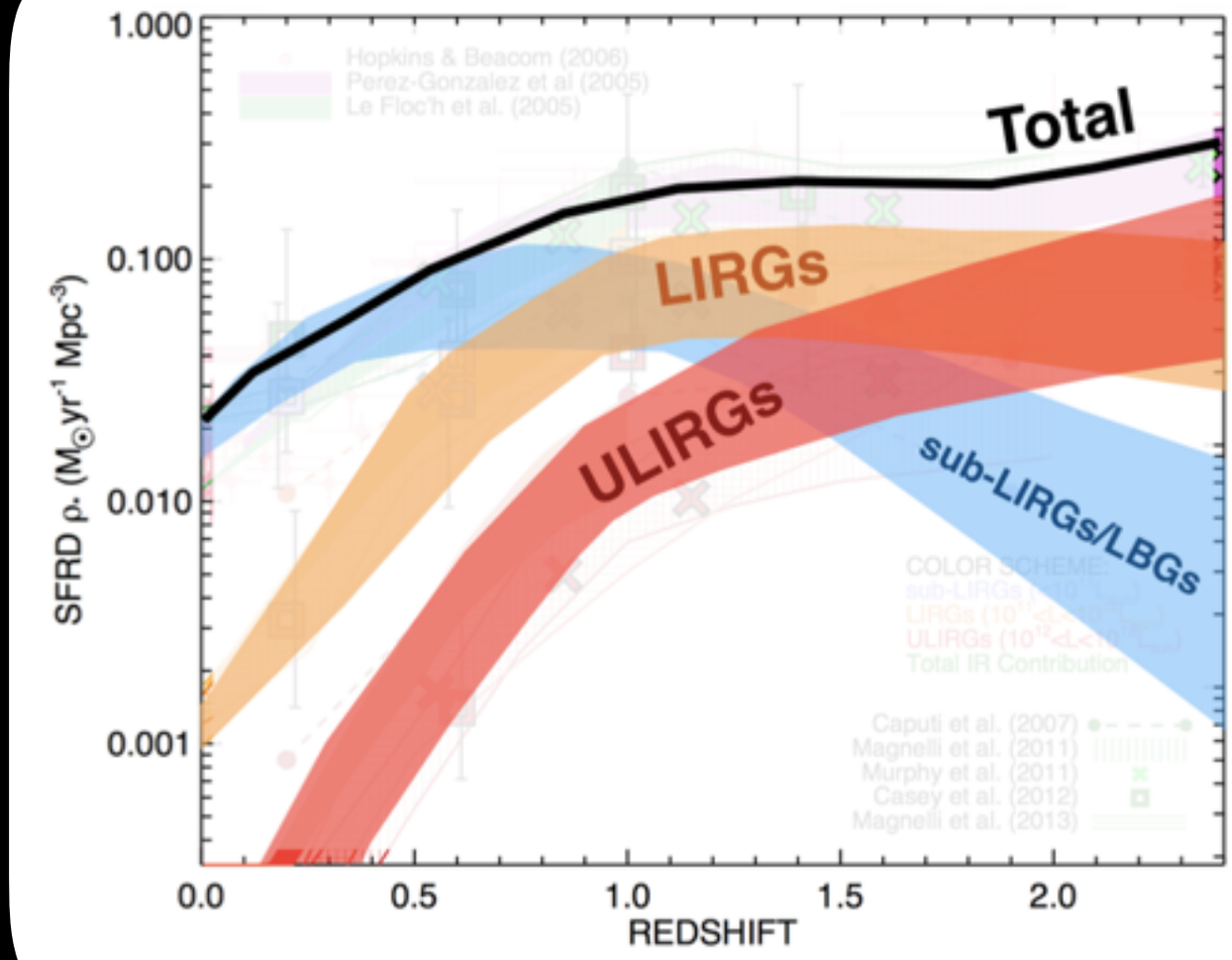
total cluster star-formation history
(Casey 2016 ApJ 824, 36)

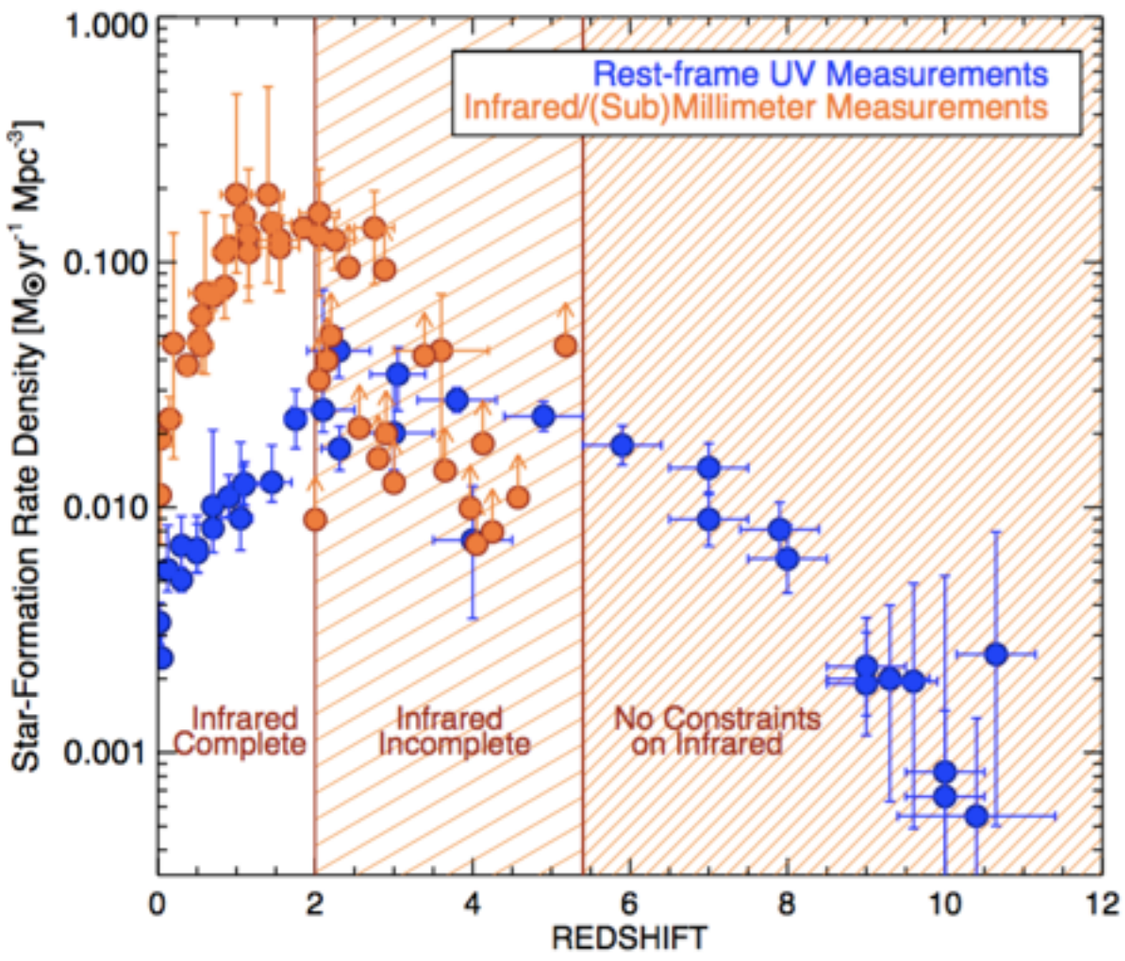
DSFGs in general

DSFG associations… protoclusters?

Dusty Star-Forming Galaxies (DSFGs)

See Casey, Narayanan & Cooray (2014) for review.





contribute substantially to cosmic star-formation.

Left: SFRD adaption from Casey, Narayanan & Cooray (2014). Right: CNC14 and Madau & Dickenson (2014)

Dusty Star-Forming Galaxies (DSFGs)

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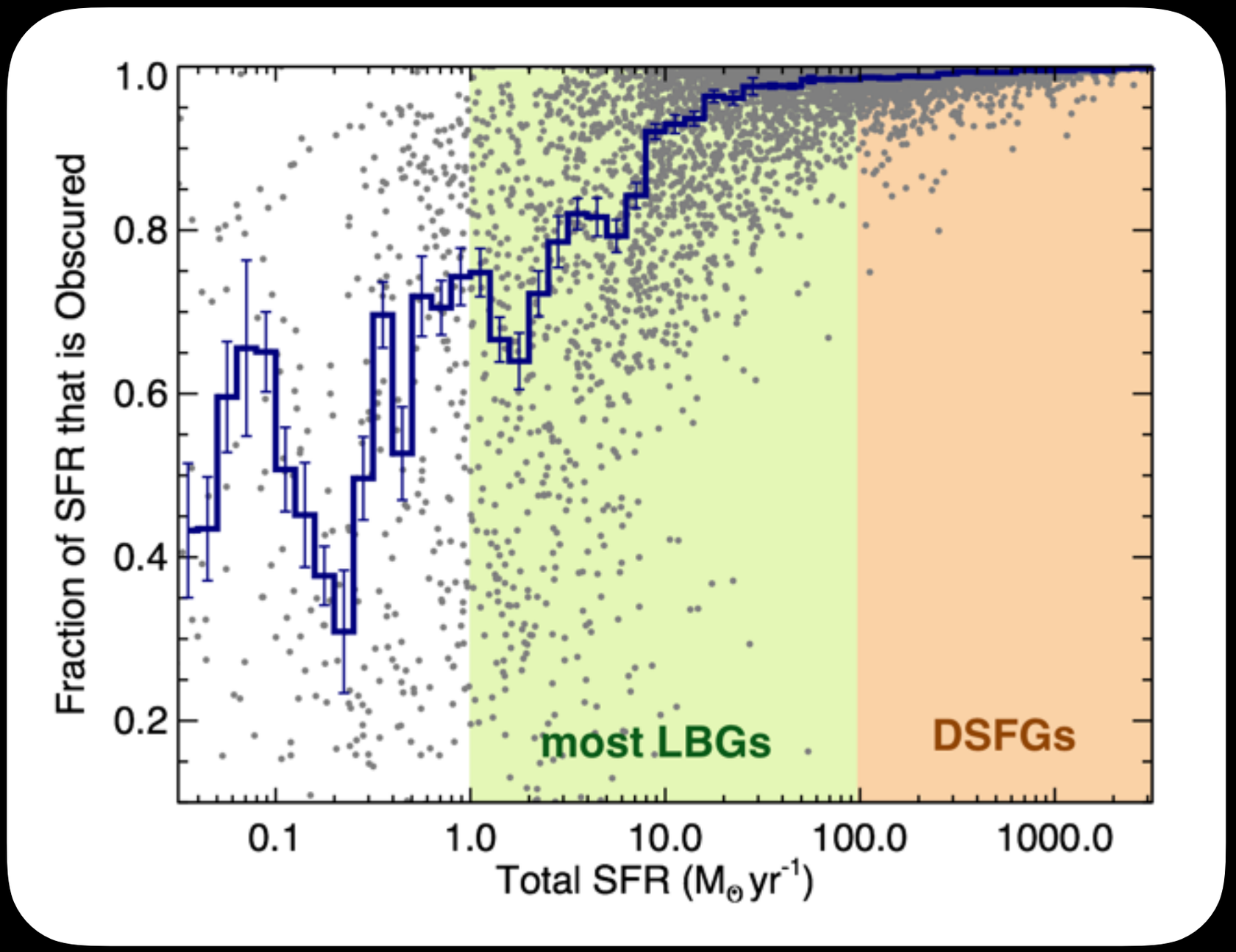
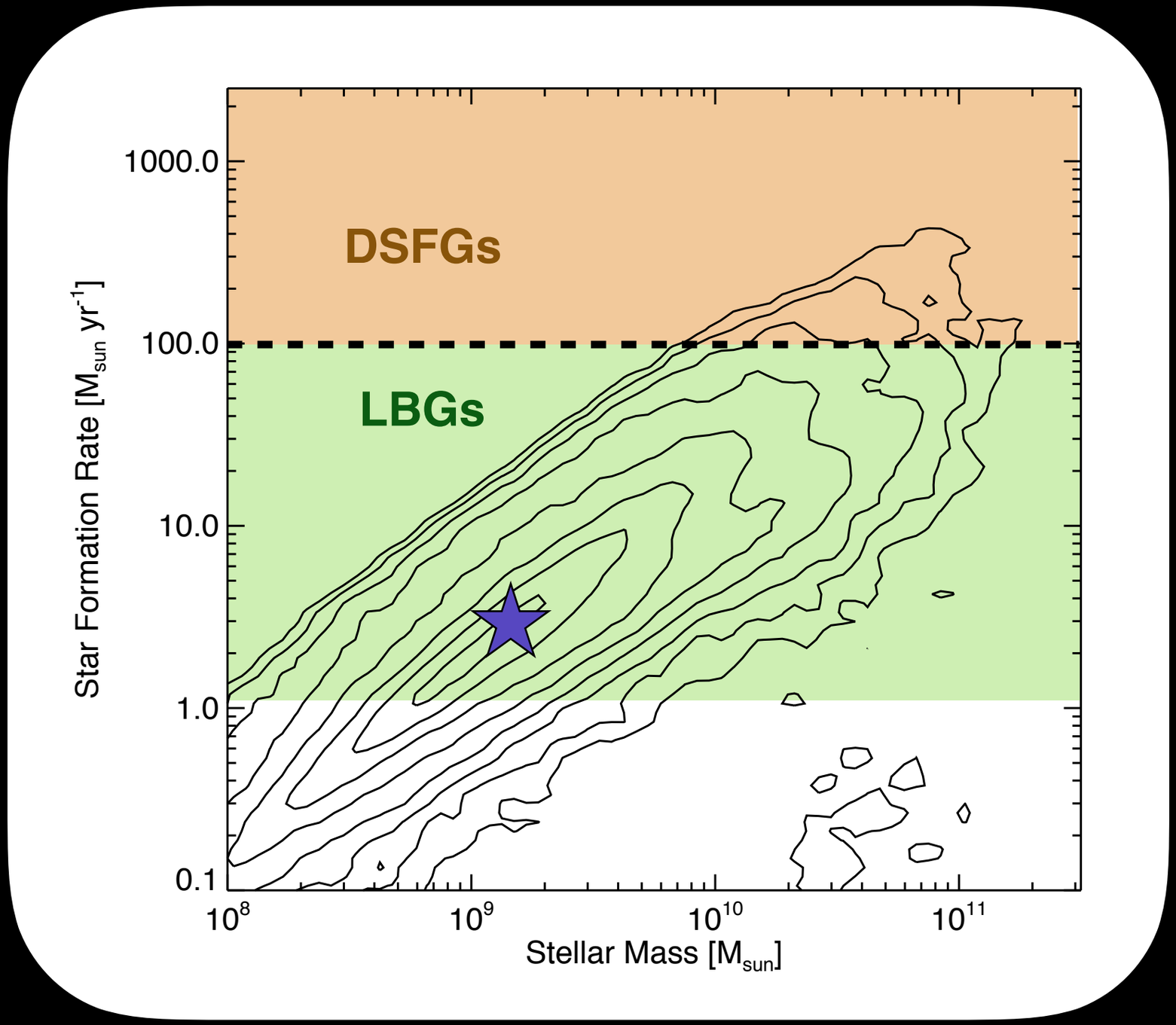


are >95% dust-obscured.

Compiled using data from Gil de Paz et al. (2007), Howell et al. (2010) and Casey et al. (2014b)

Dusty Star-Forming Galaxies (DSFGs)

See Casey, Narayanan & Cooray (2014) for review.

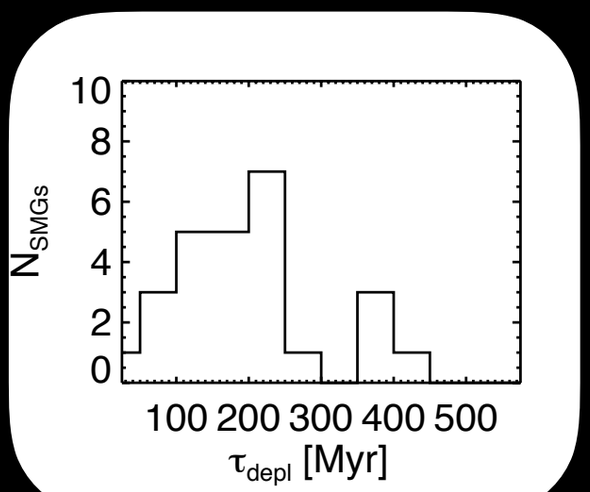


are rare ($\lesssim 10^{-4}\,\mathrm{Mpc}^{-3}$).

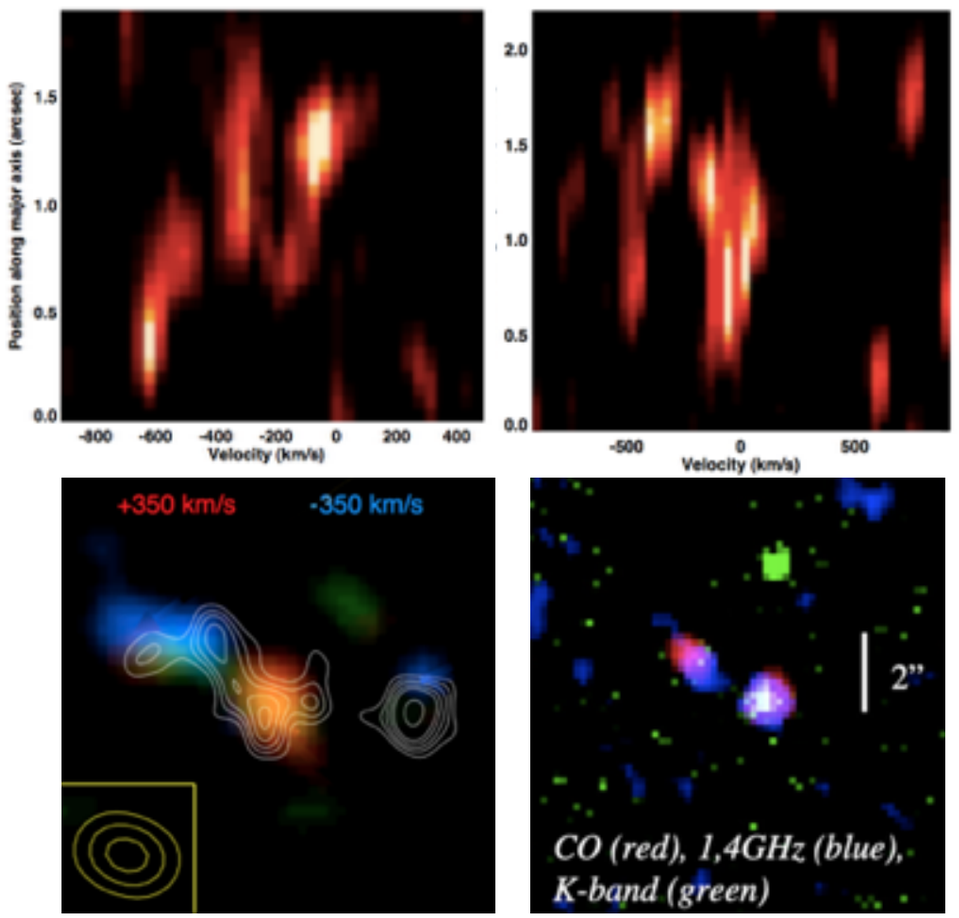
Compiled using data at z~2±0.5 from the COSMOS field; Ilbert et al. (2013)

Dusty Star-Forming Galaxies (DSFGs)

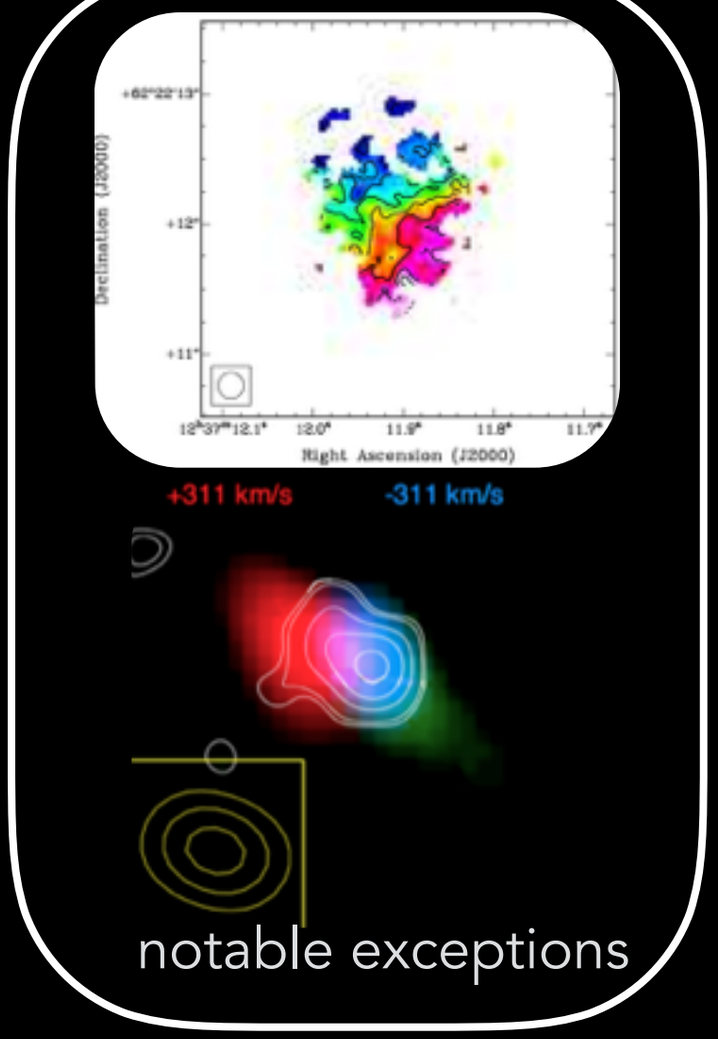
See Casey, Narayanan & Cooray (2014) for review.



Bothwell et al. (2013)



Tacconi et al. 2008, Bothwell et al. 2010, Engel et al. 2010, Casey et al. 2011, Ivison et al. 2012, Riechers et al. 2011, 2013



Daddi et al. 2009, 2010, Carilli et al. 2009, Hodge et al. 2012

are predominantly merger-driven and short-lived (<200Myr).

Dusty Star-Forming Galaxies (DSFGs)

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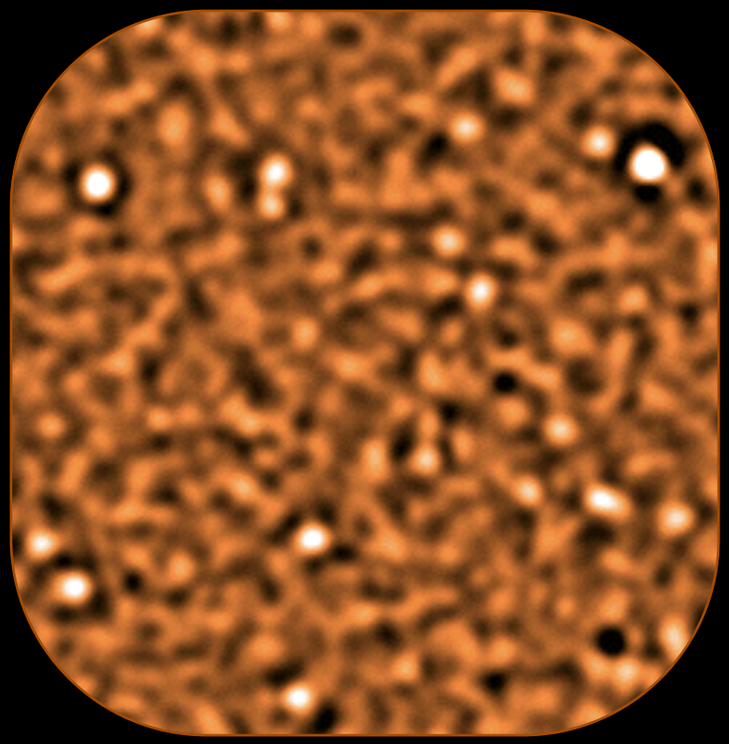

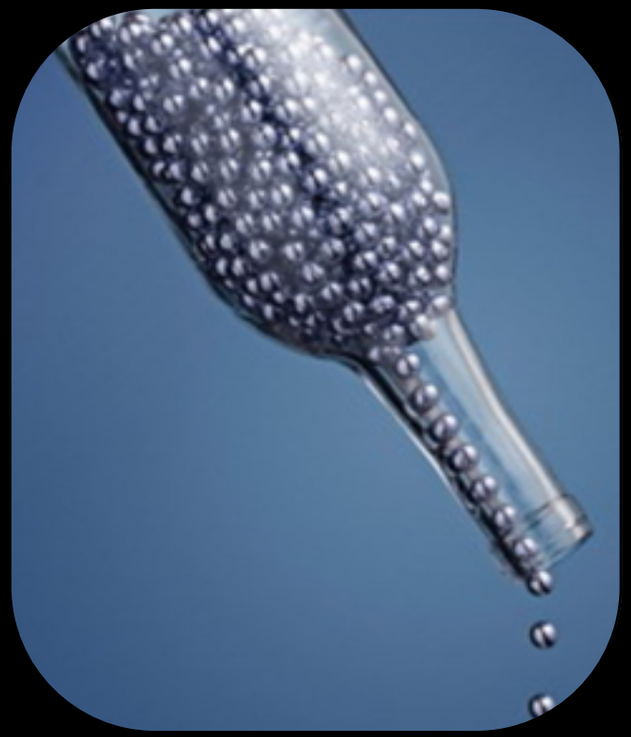

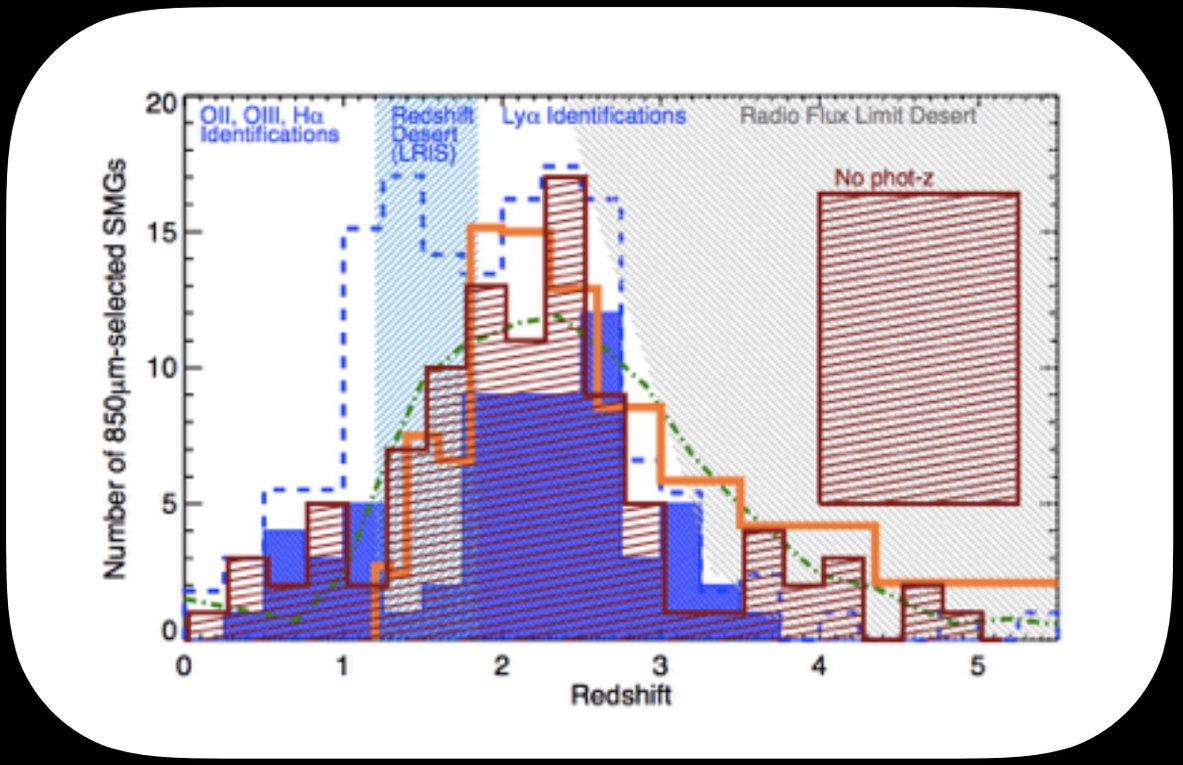

Chapman et al. (2005), Wardlow et al. (2011), Capak et al. (2011), Walter et al. (2012), Casey et al. (2012a,b), Vieira et al. (2013), Swinbank et al. (in prep), Casey et al. (in prep)

are incredibly difficult to spectroscopically confirm.

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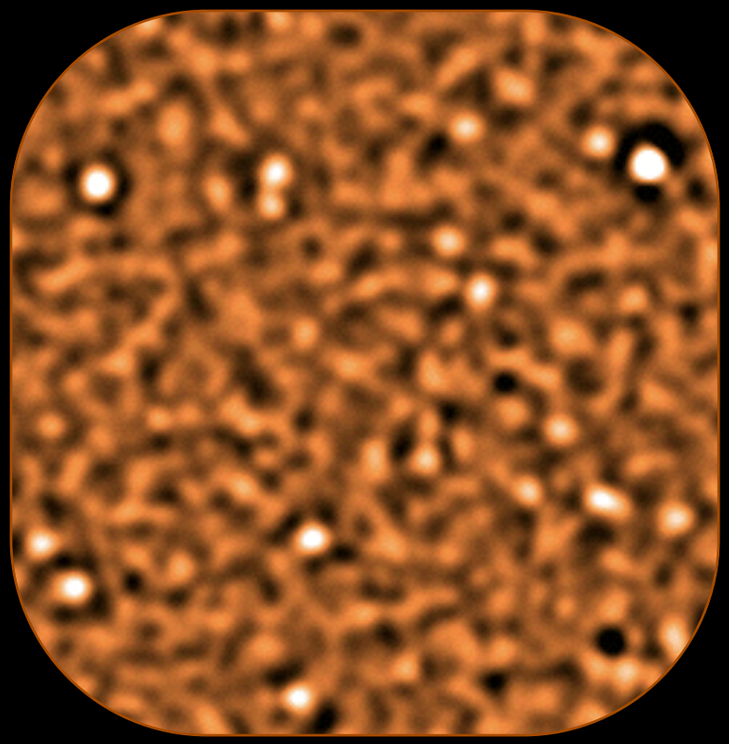
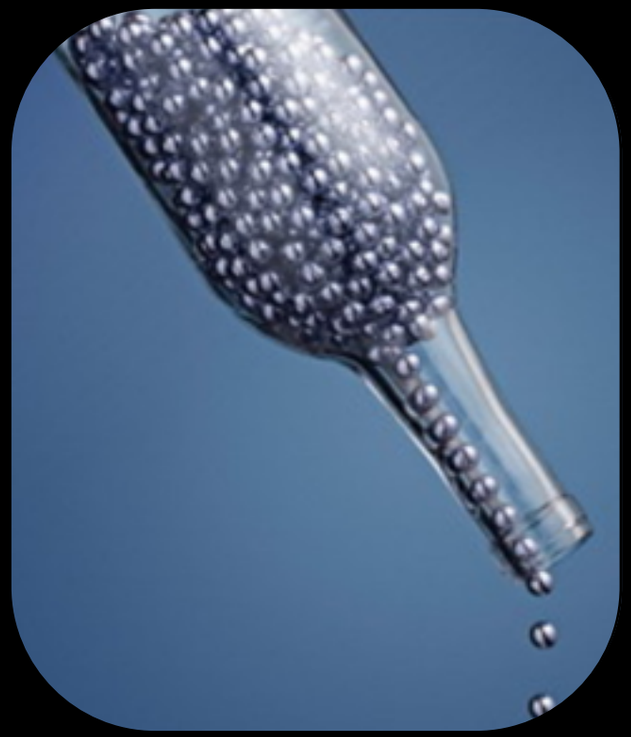
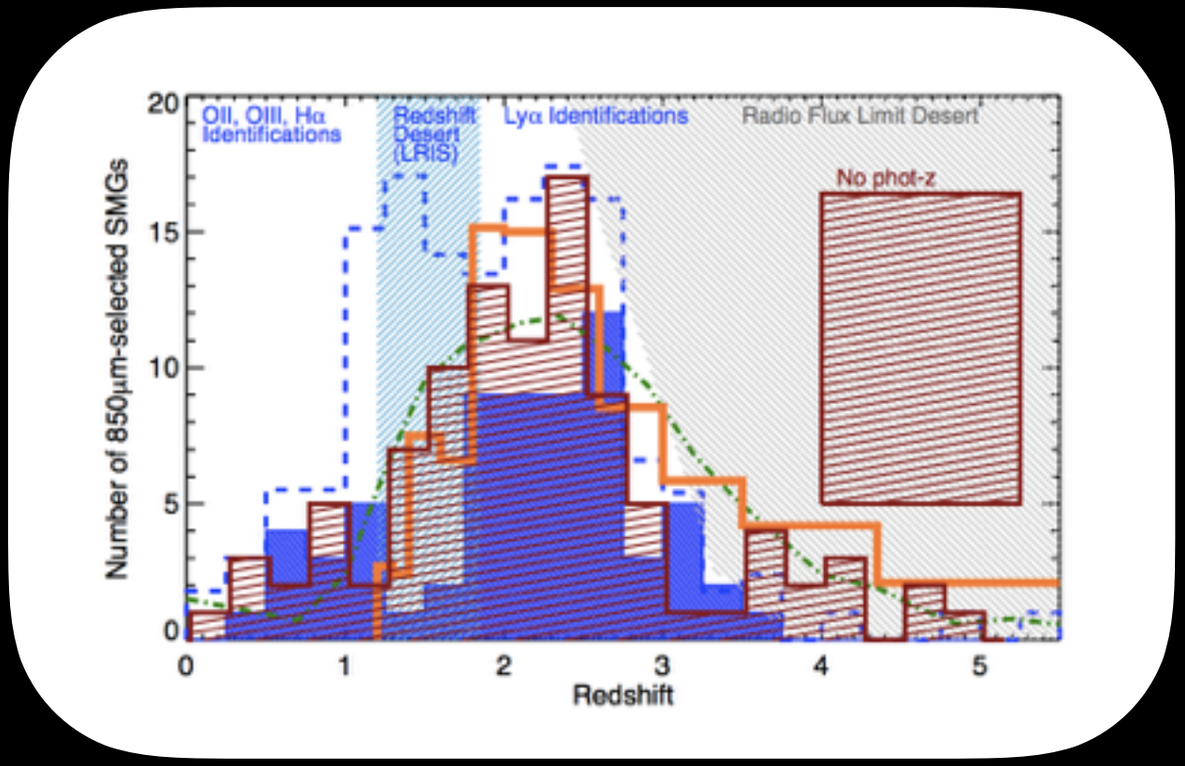
See Casey, Narayanan & Cooray (2014) for review.







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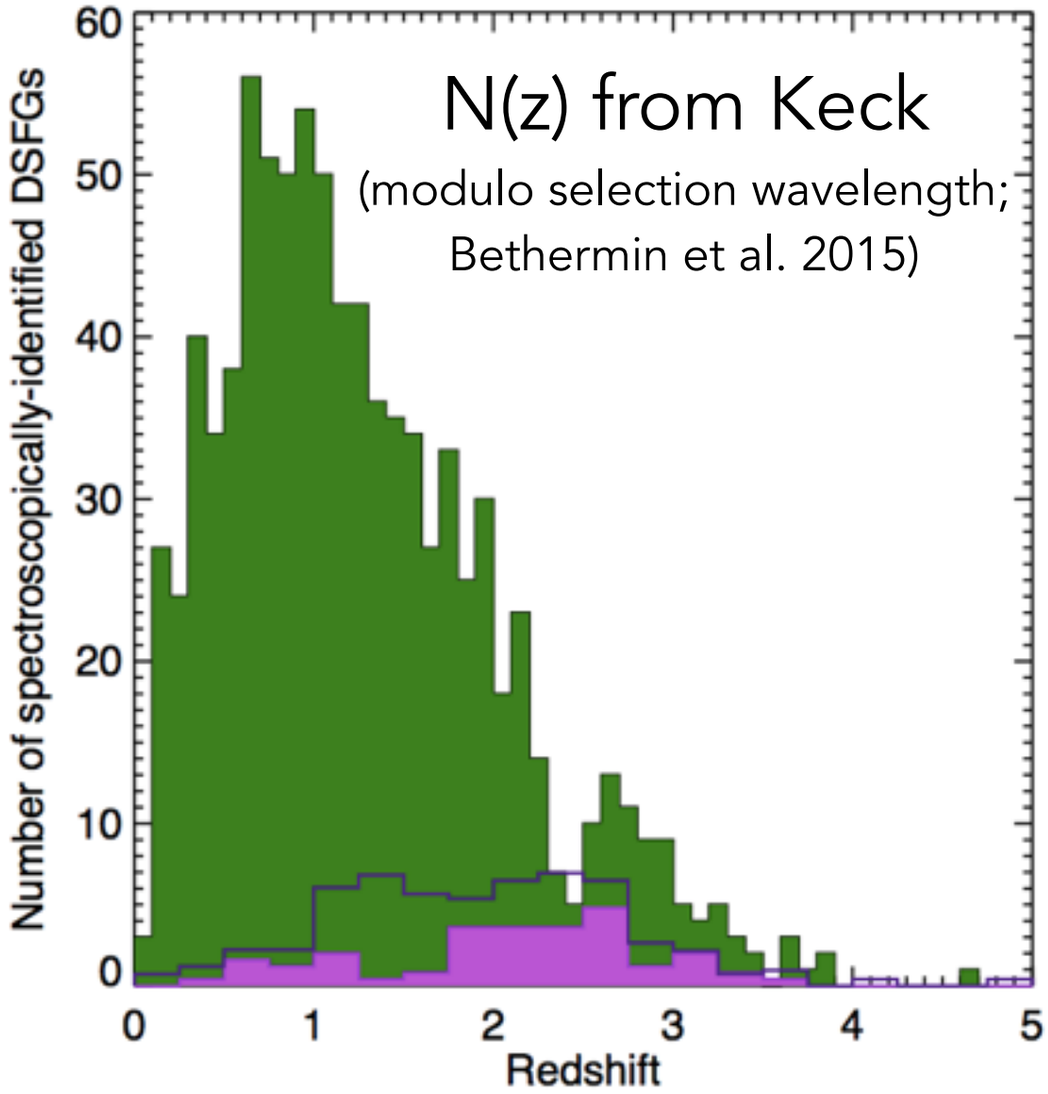
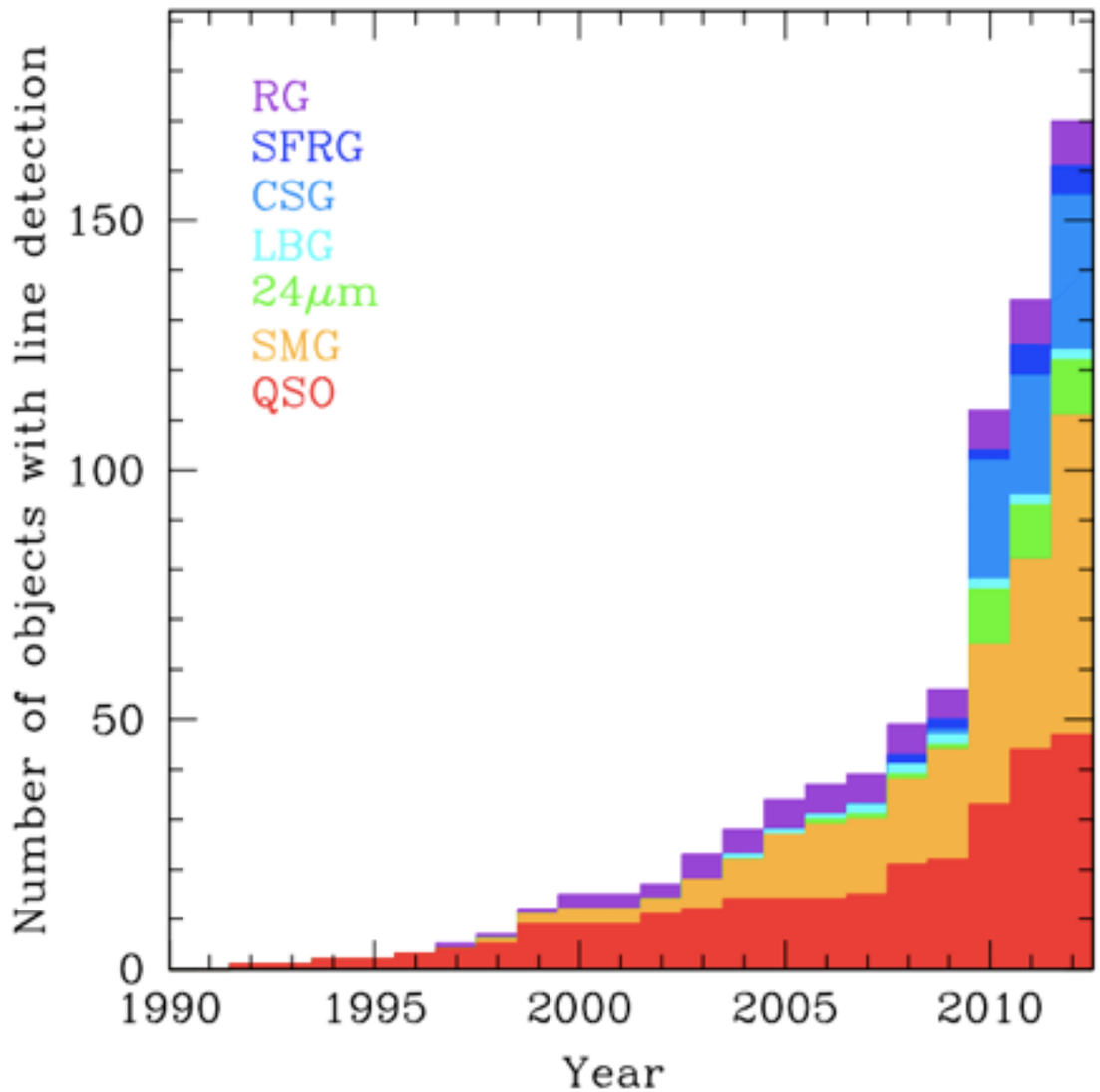
are incredibly difficult to spectroscopically confirm.

Optical/near-Infrared (cheaper) >> ALMA Spectral Scan (very time intensive)

Spectroscopically-confirmed DSFGs:



Chapman et al. (2005), Banerji et al. (2011), Casey et al. (2012b,c)



Carilli & Walter (2014)

Substantial improvement in the past ~5 years.

How do DSFGs relate to the assembly of galaxy clusters?

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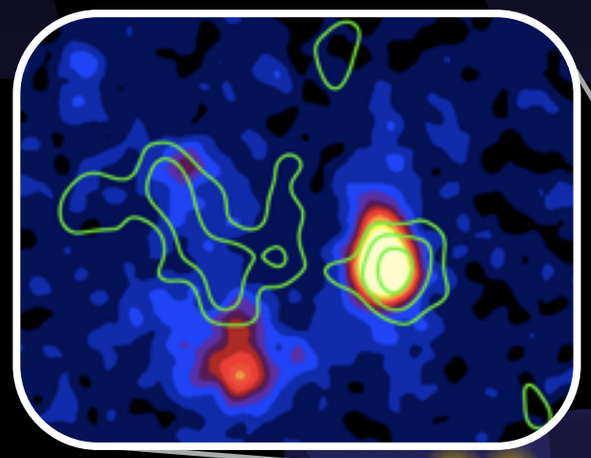

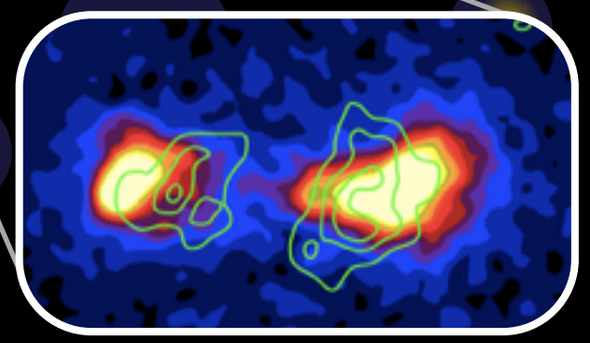

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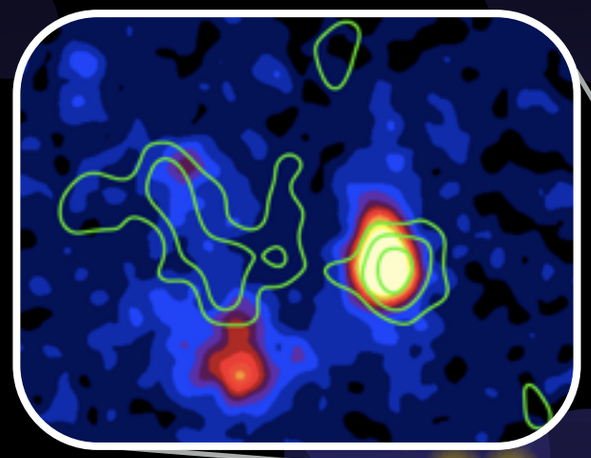

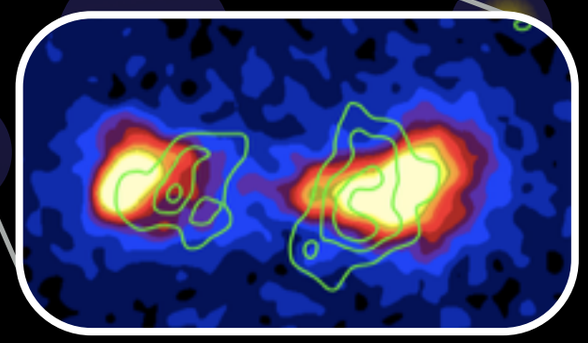

DSFG Surveys are far more spectroscopically complete than in the past, revealing a number of DSFG associations.

“Well-known” DSFG associations.

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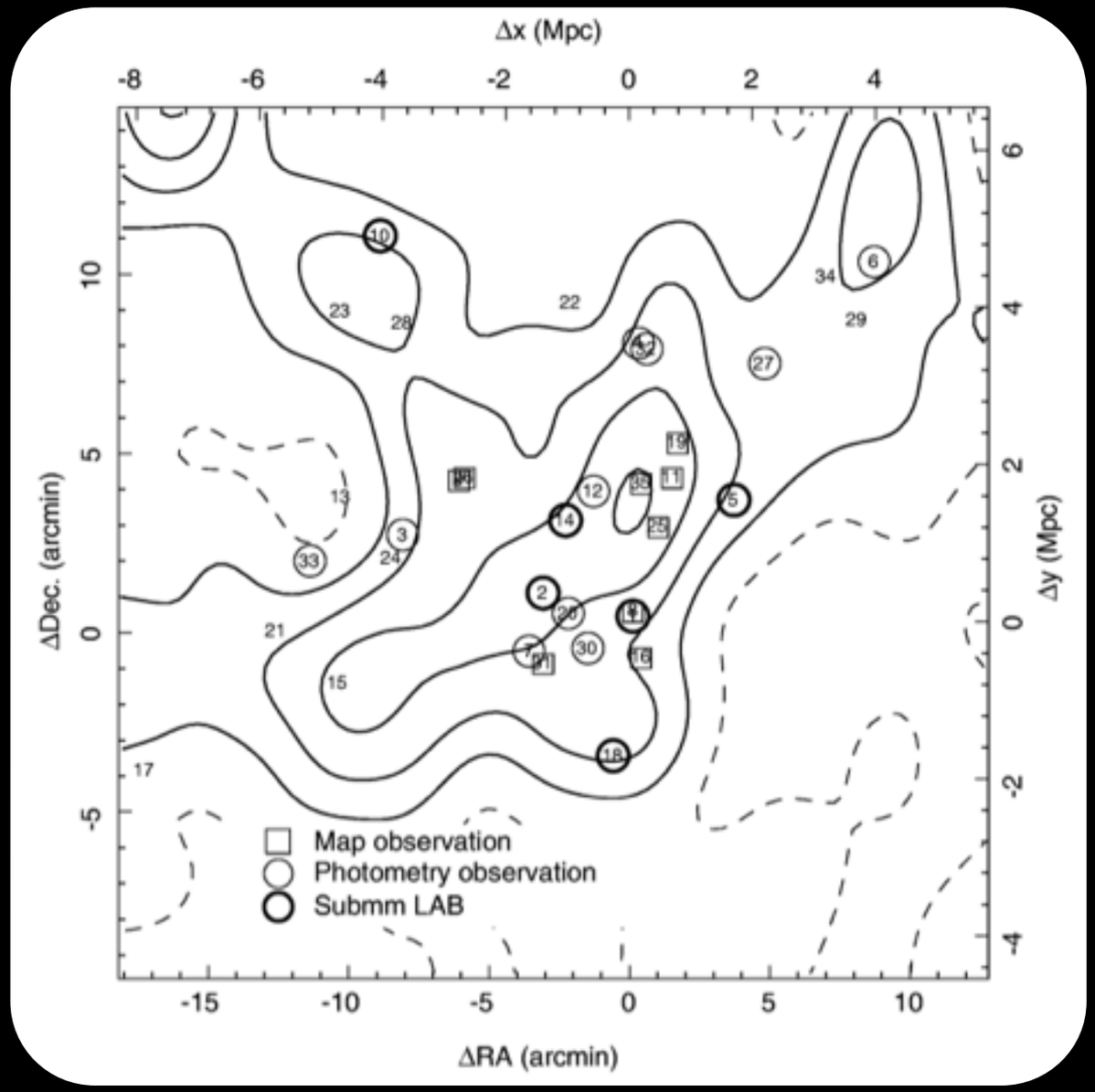
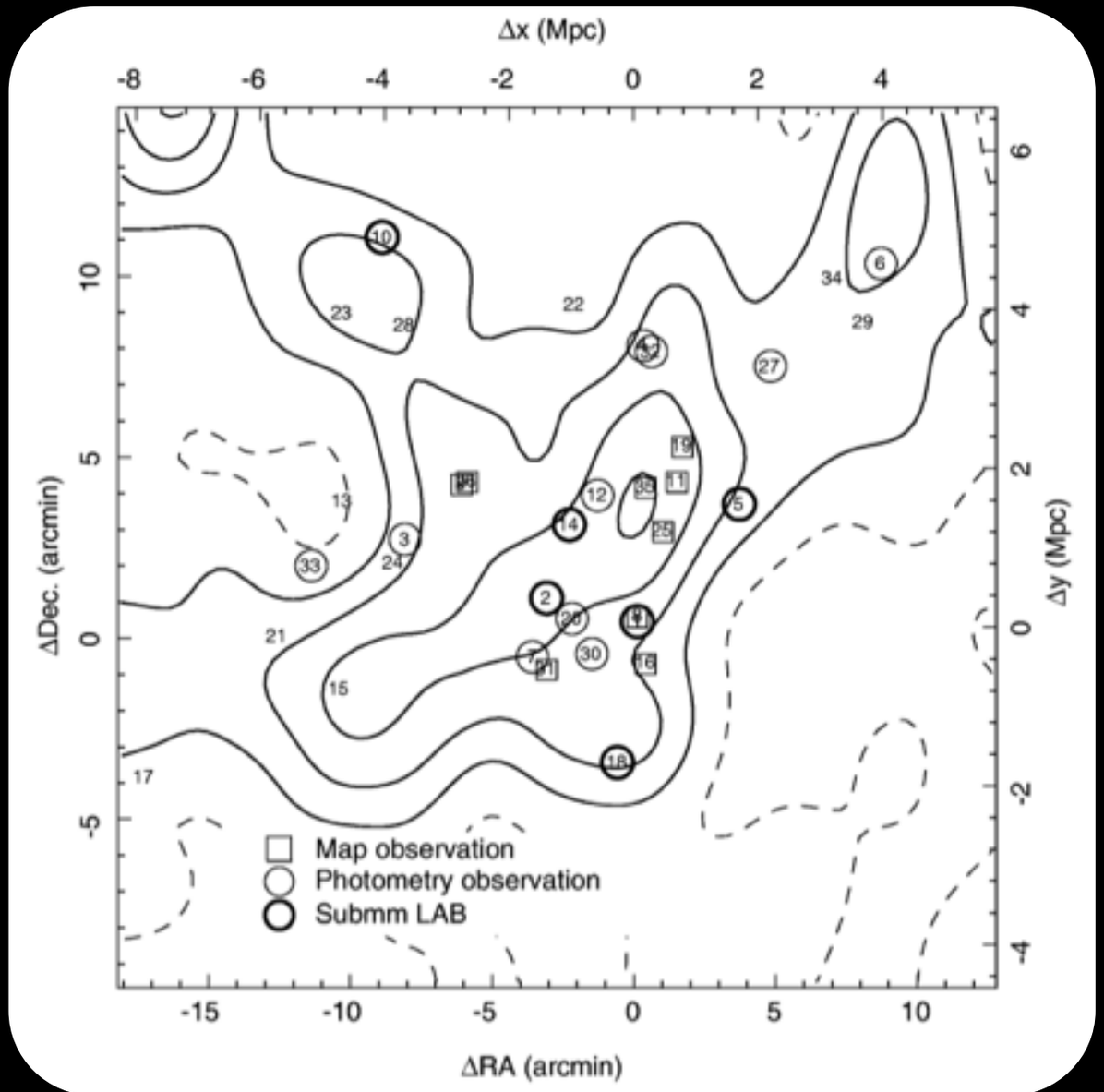


SSA22 Protocluster at z=3.09,
5-8 DSFGs associated with LABs

Steidel et al. (1998), Hayashino et al. (2004),
Matsuda et al. (2005), Yamada et al. (2012)

“Well-known” DSFG associations.



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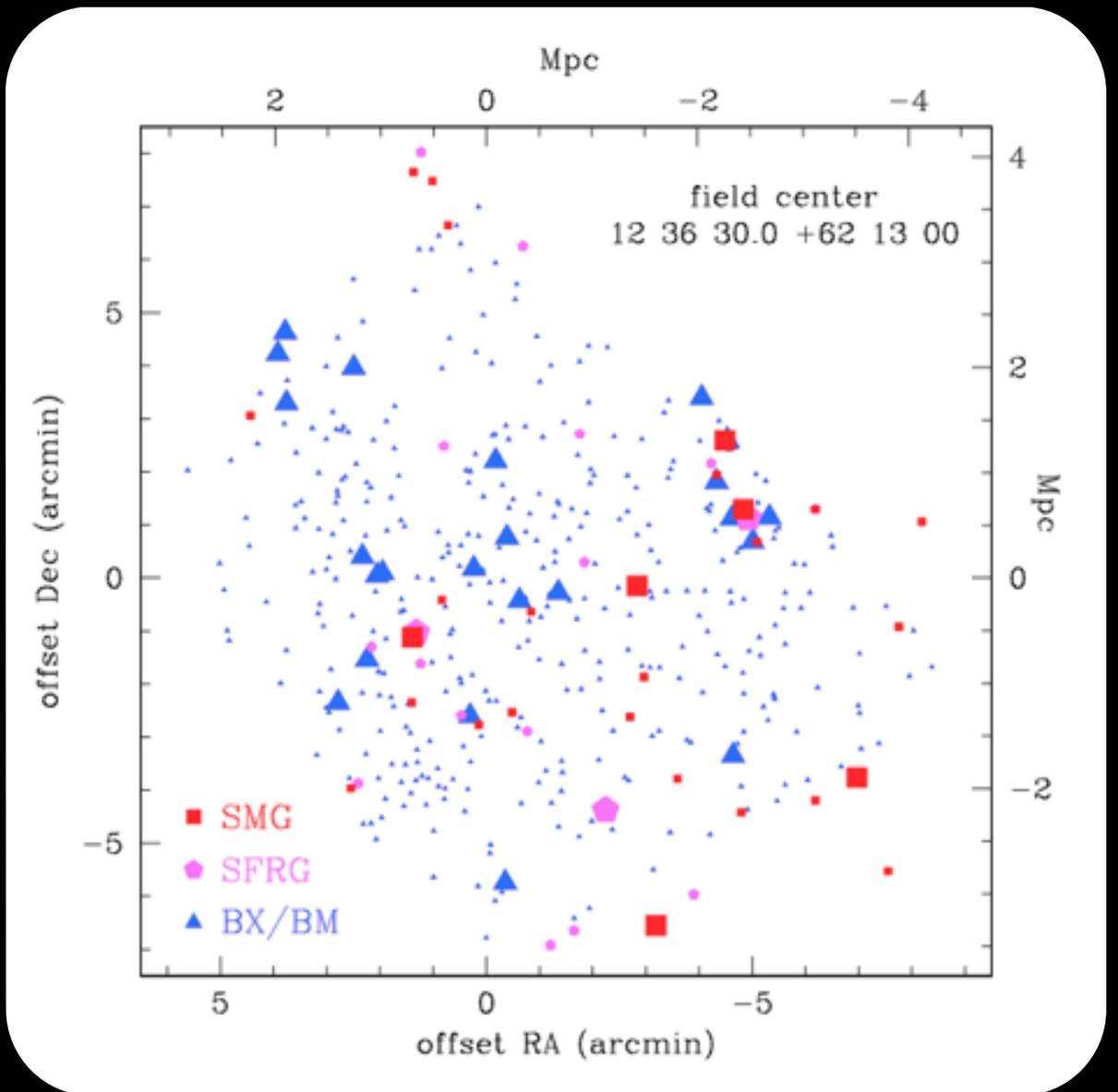


HDF Overdensity at z=1.99,
6-9 DSFGs with various spec-z’s

Blain et al. (2004), Chapman et al. (2009)

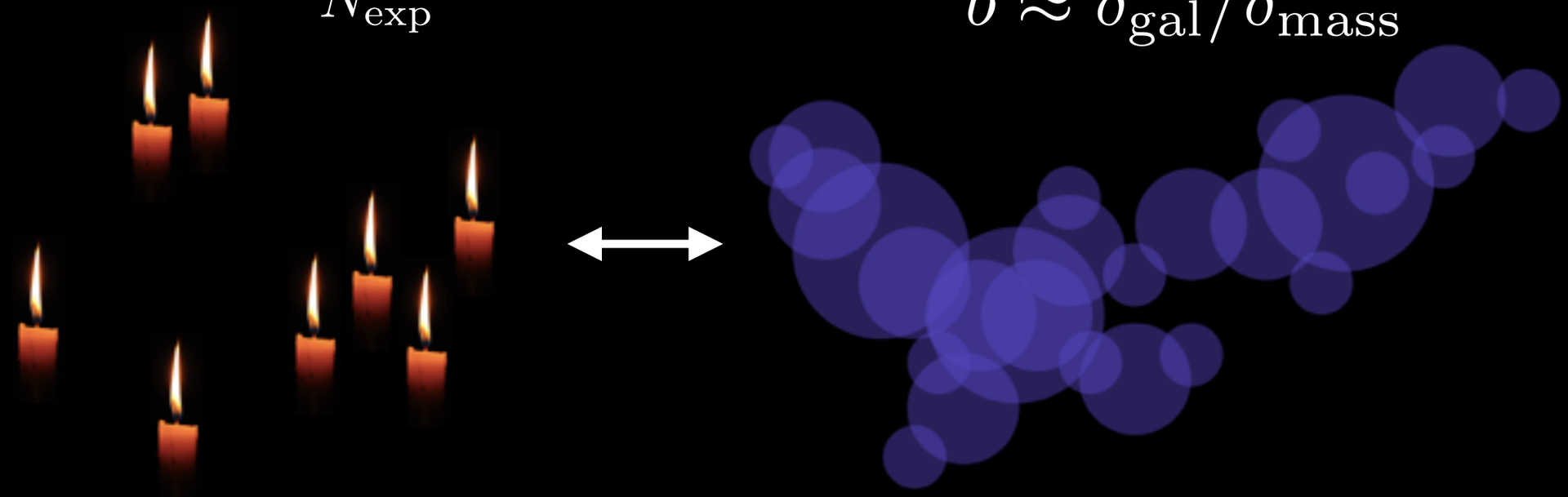
How do we interpret DSFG associations?

Are they good tracers of the underlying dark matter structure?

$$\delta_{\rm gal} = \frac{(N_{\rm obs} - N_{\rm exp})}{N_{\rm exp}}$$

$$1 + b\delta_{\rm mass} = C(1 + \delta_{\rm gal})$$

$$b \approx \delta_{\rm gal}/\delta_{\rm mass}$$



SSA22 z=3.09

$\delta_{\rm gal} = 3.6$

$\delta_{\rm DSFG} = 10$

HDF z=1.99

$\delta_{\rm gal} = 2.5$

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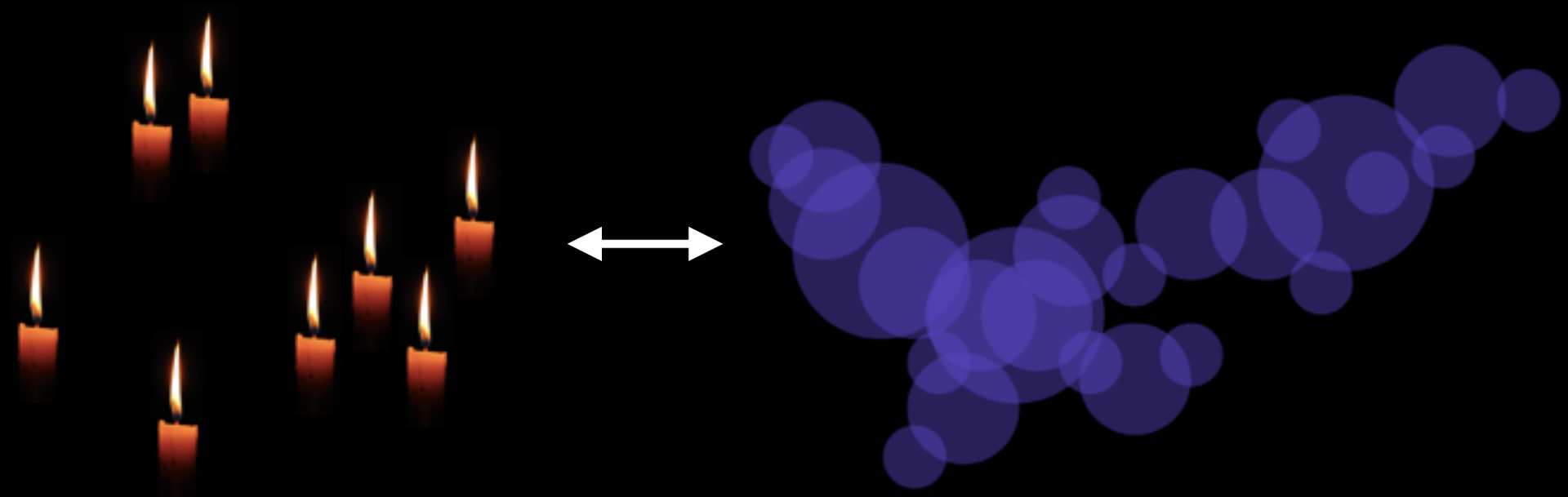

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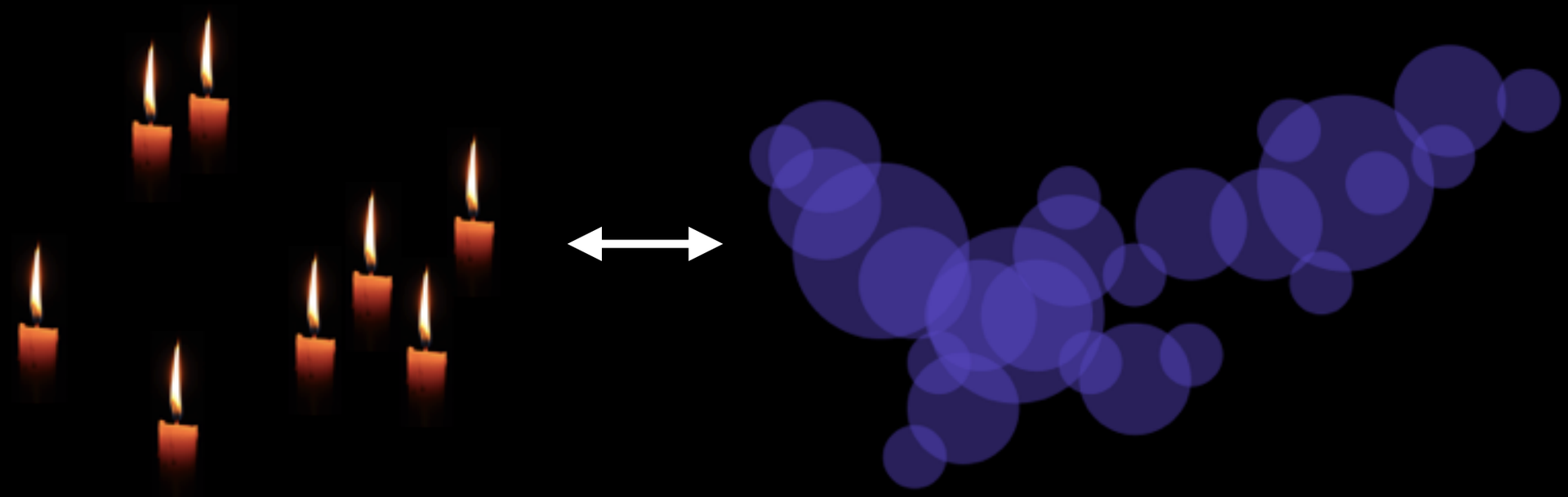

“[Probably not.]” — Chapman et al. (2009)

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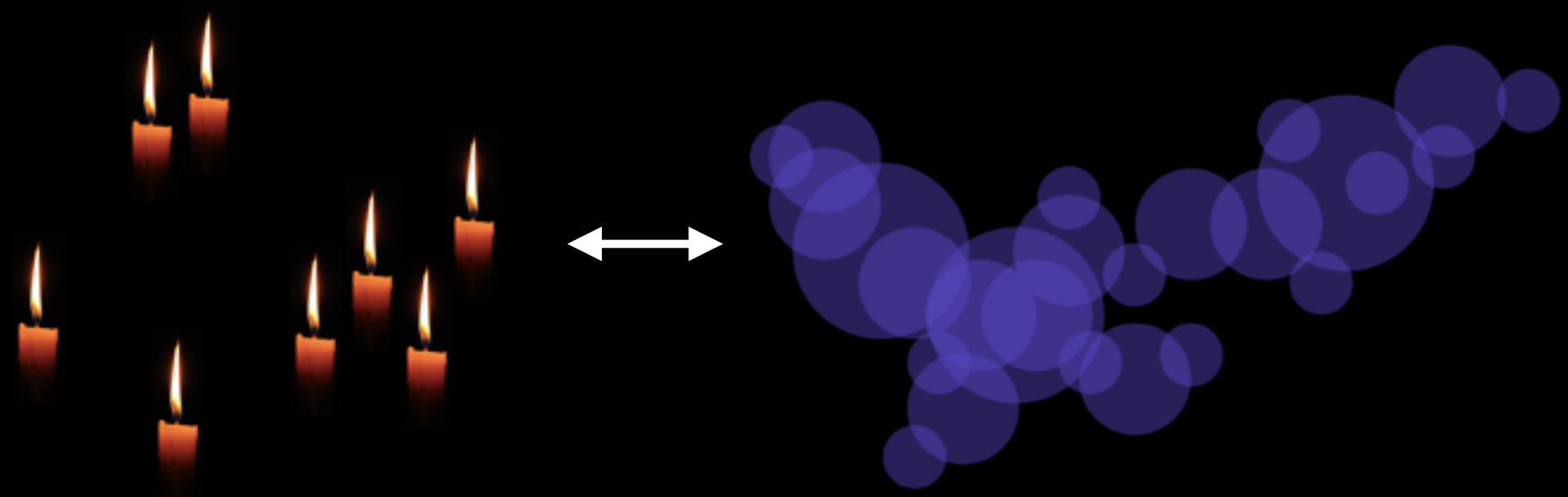
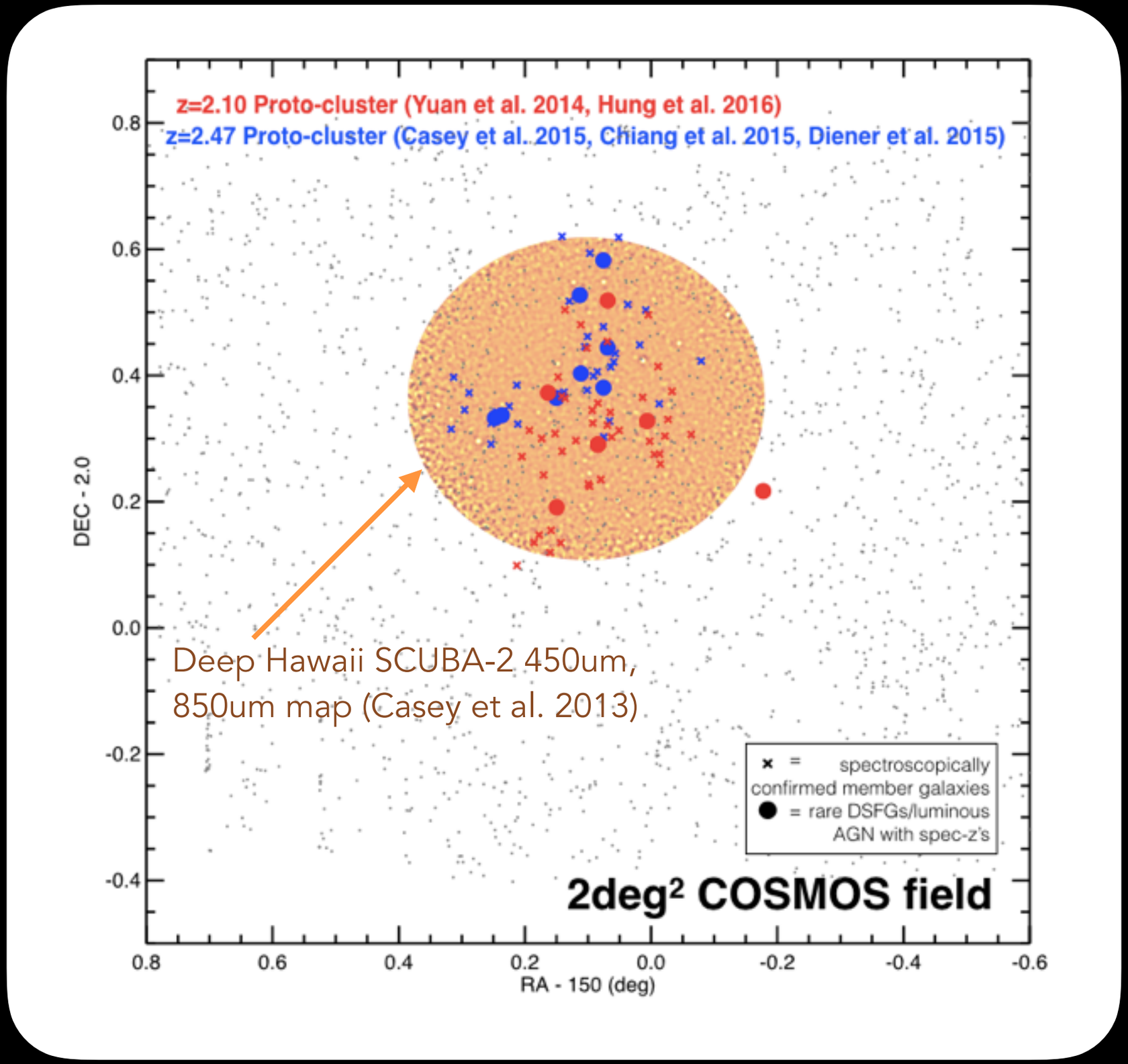


“[Probably not.]” — Chapman et al. (2009)

“Possion noise causes scatter in the [DSFG] overdensity at fixed dark matter overdensity.”— Miller et al. (2015)

More DSFG associations revealed…



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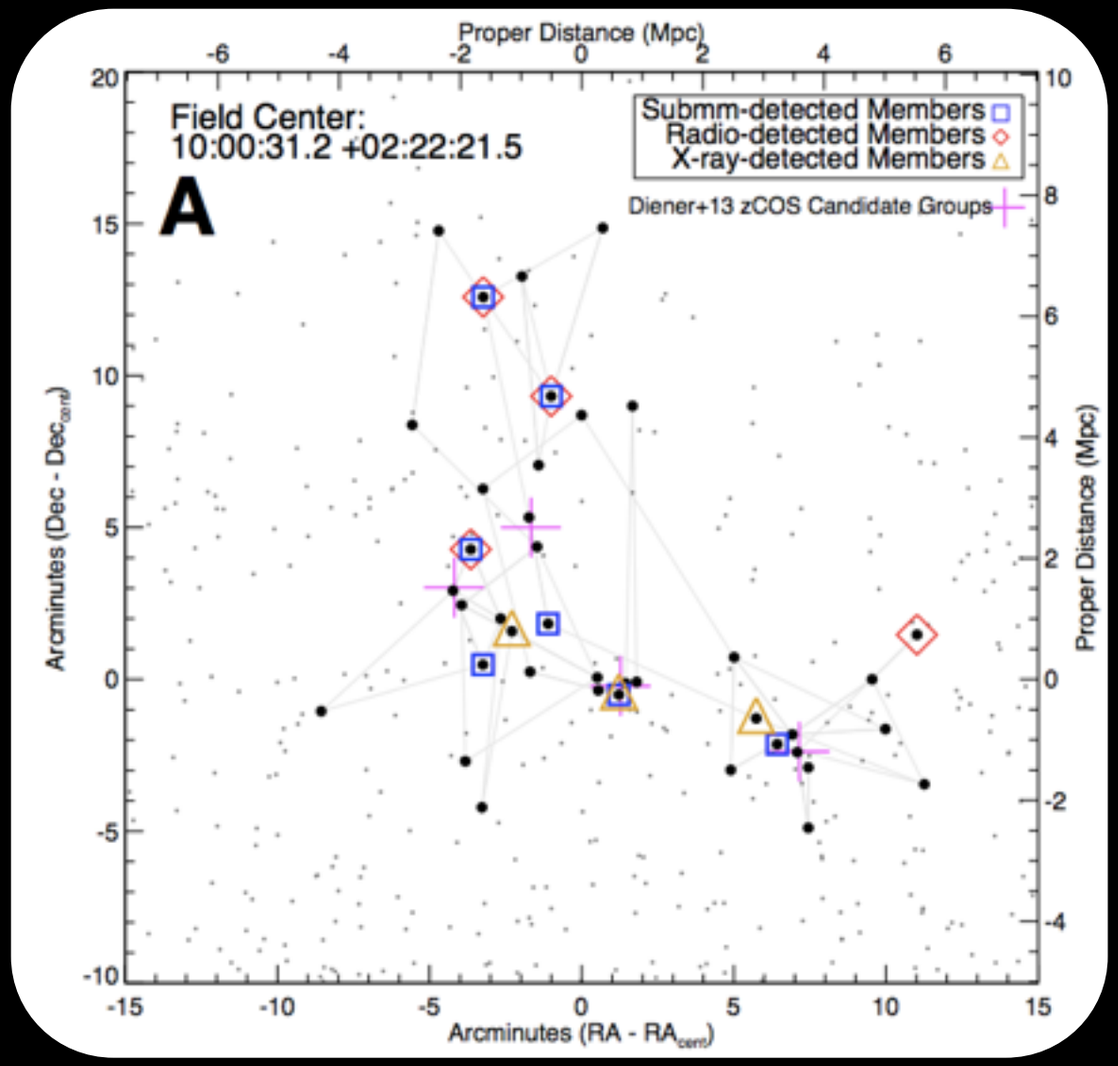
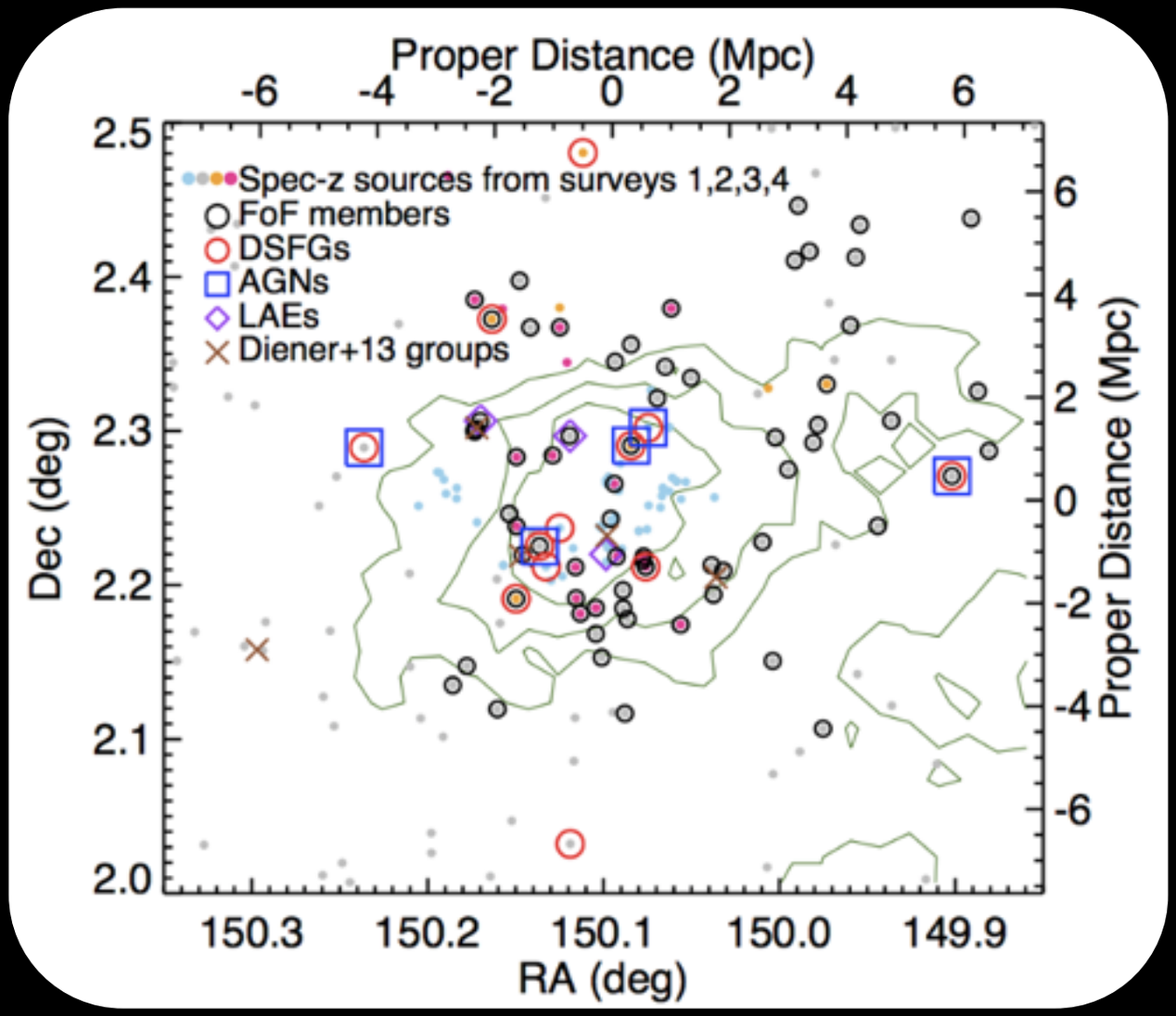


Casey et al. (2015), Chiang et al. (2015), Diener et al. (2015)



Yuan et al. (2014), Hung et al. (2016)

COSMOS z=2.47

$$\delta_{\rm gal} = 3.3$$

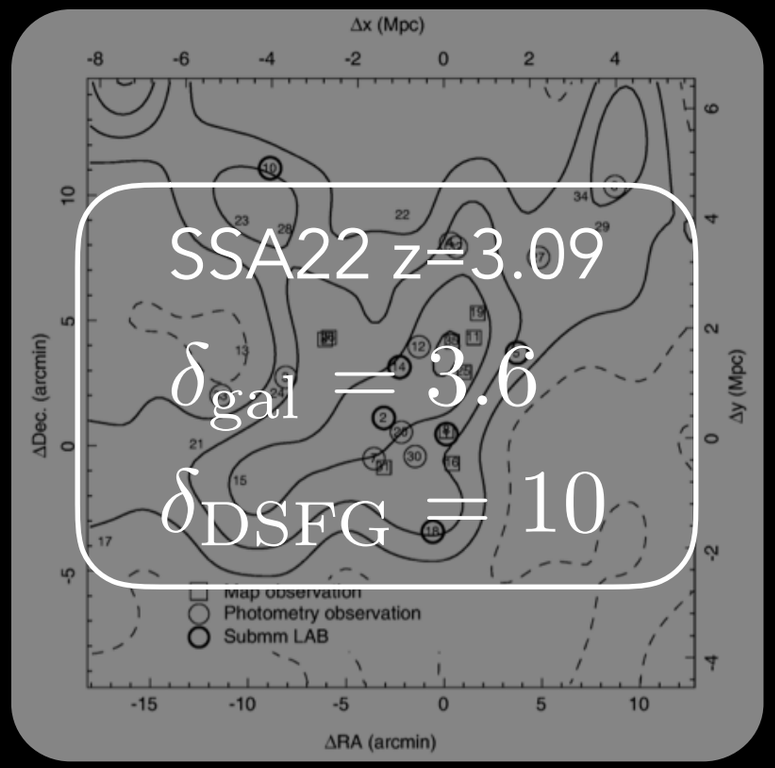
$$\delta_{\rm DSFG} = 10$$

COSMOS z=2.10

$$\delta_{\rm gal} = 8$$

$$\delta_{\rm DSFG} = 10$$

More DSFG associations revealed…



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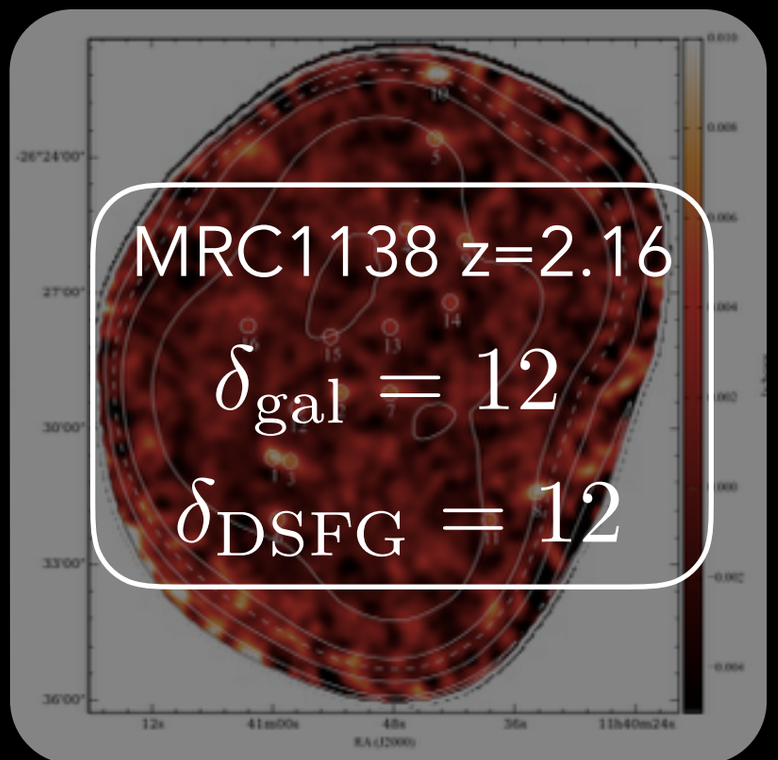
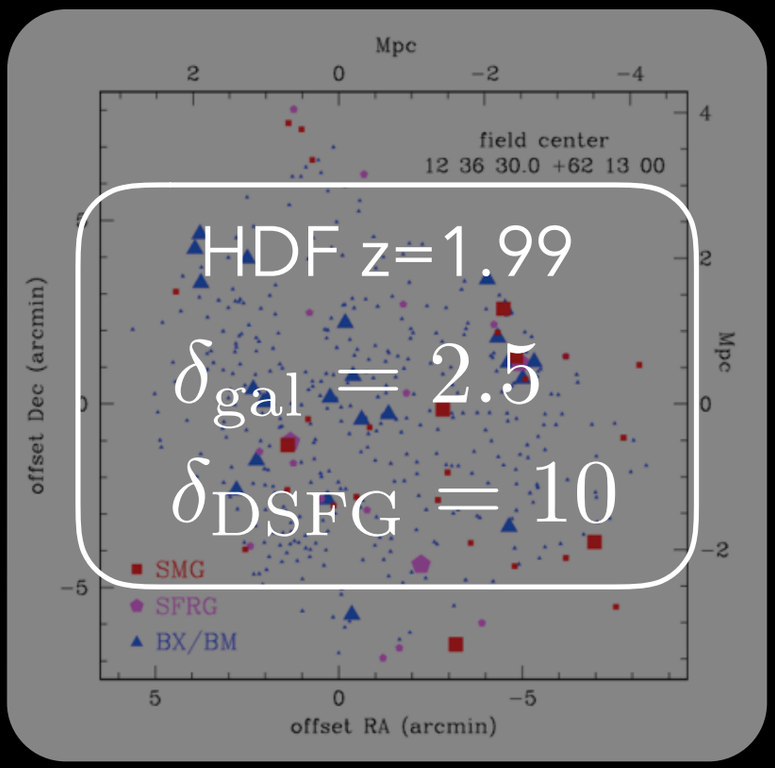


MRC1138 z=2.16

$\delta_{\rm gal} = 12$

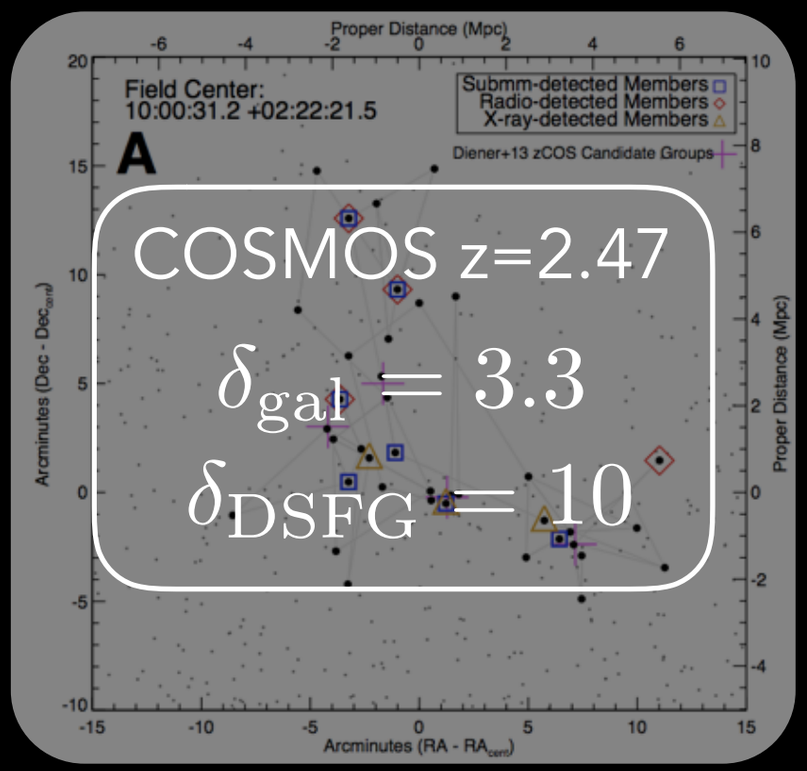
$\delta_{\rm DSFG} = 12$



HDF z=1.99

$\delta_{\rm gal} = 2.5$

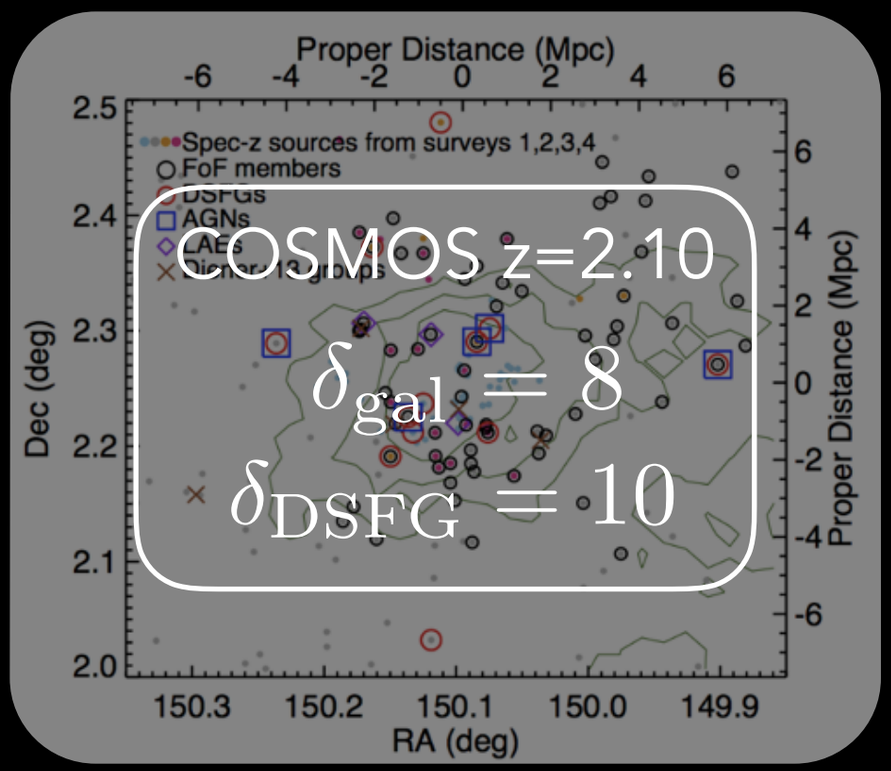
$\delta_{\rm DSFG} = 10$



COSMOS z=2.47

$\delta_{\rm gal} = 3.3$

$\delta_{\rm DSFG} = 10$

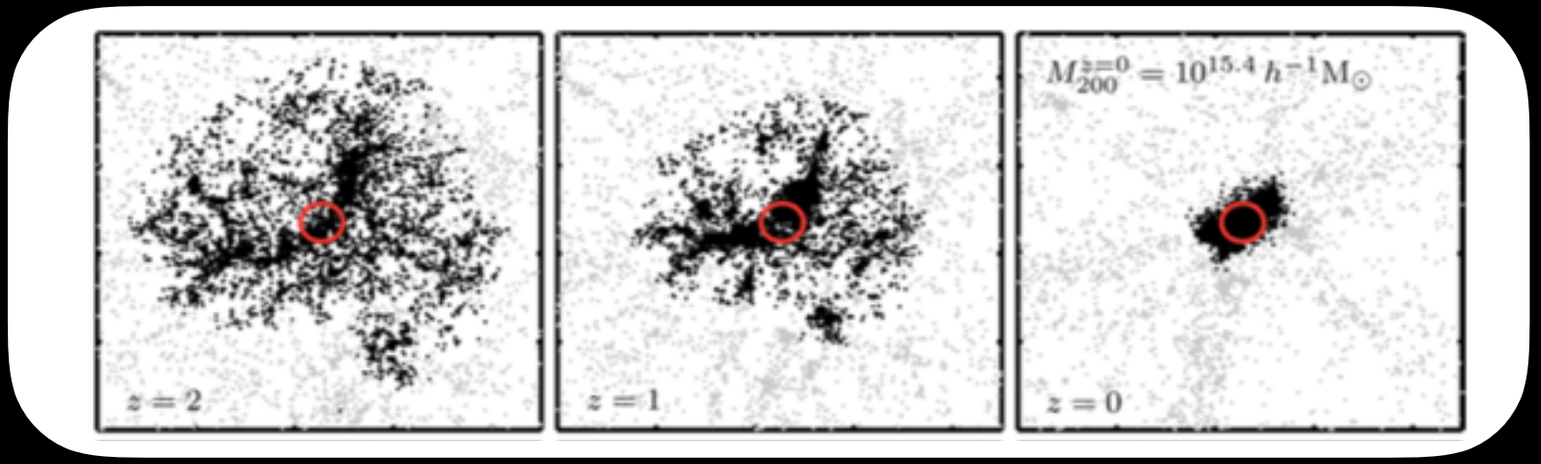


COSMOS z=2.10

$\delta_{\rm gal} = 8$

$\delta_{\rm DSFG} = 10$

Characteristics: massive protoclusters?

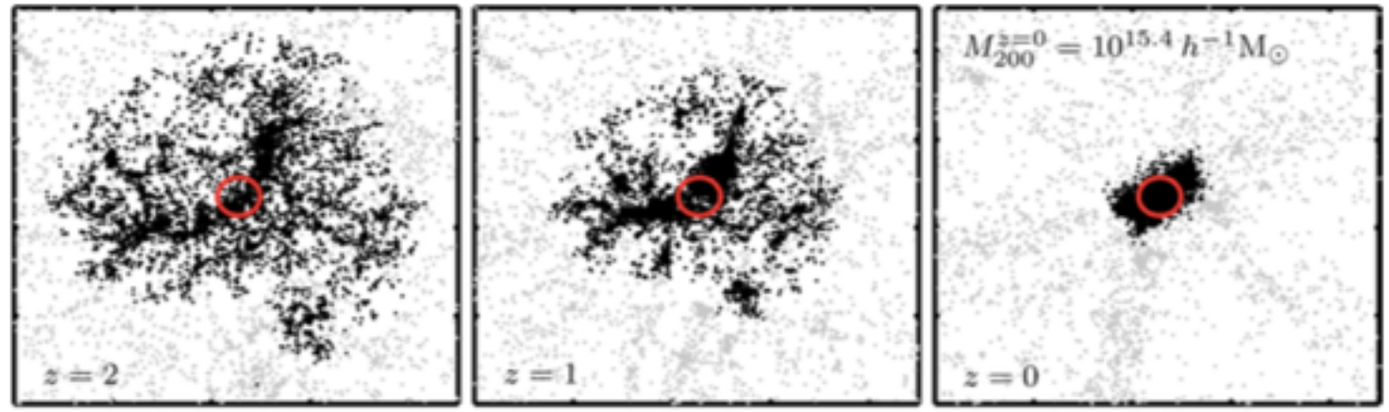


Chiang et al. (2013), Oñorbe et al. (2014), Muldrew et al. (2015)

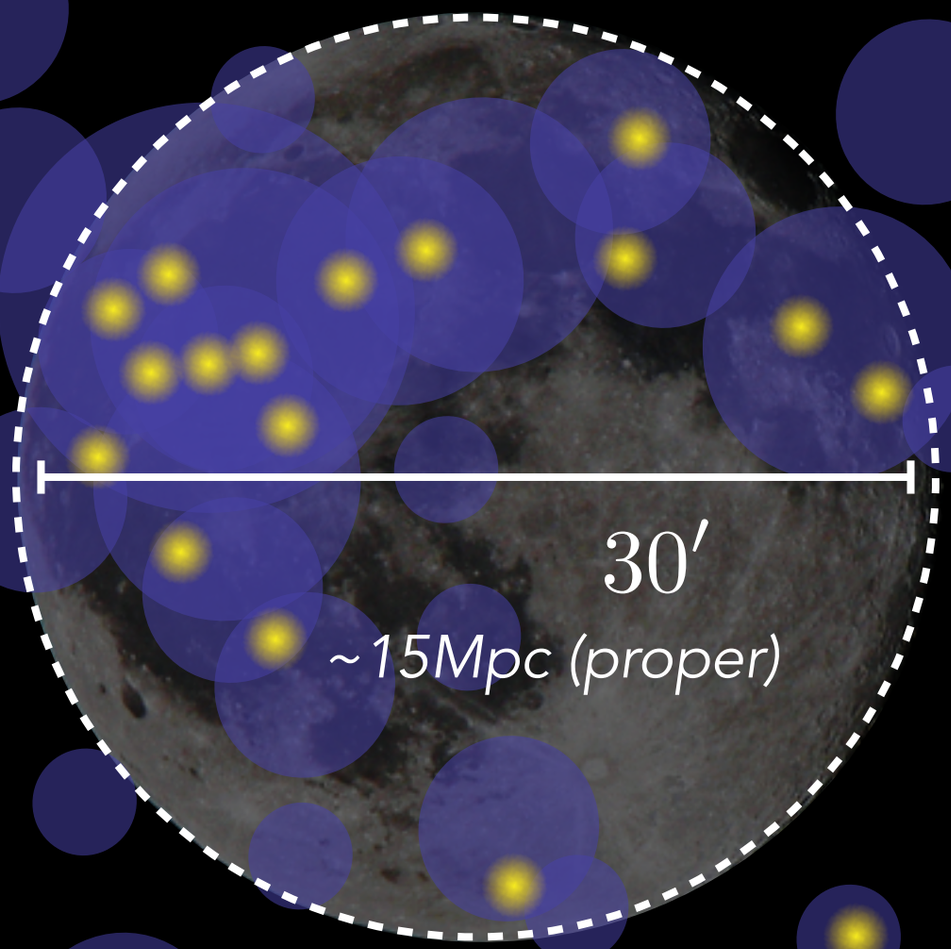
$30'$

~15Mpc (proper)

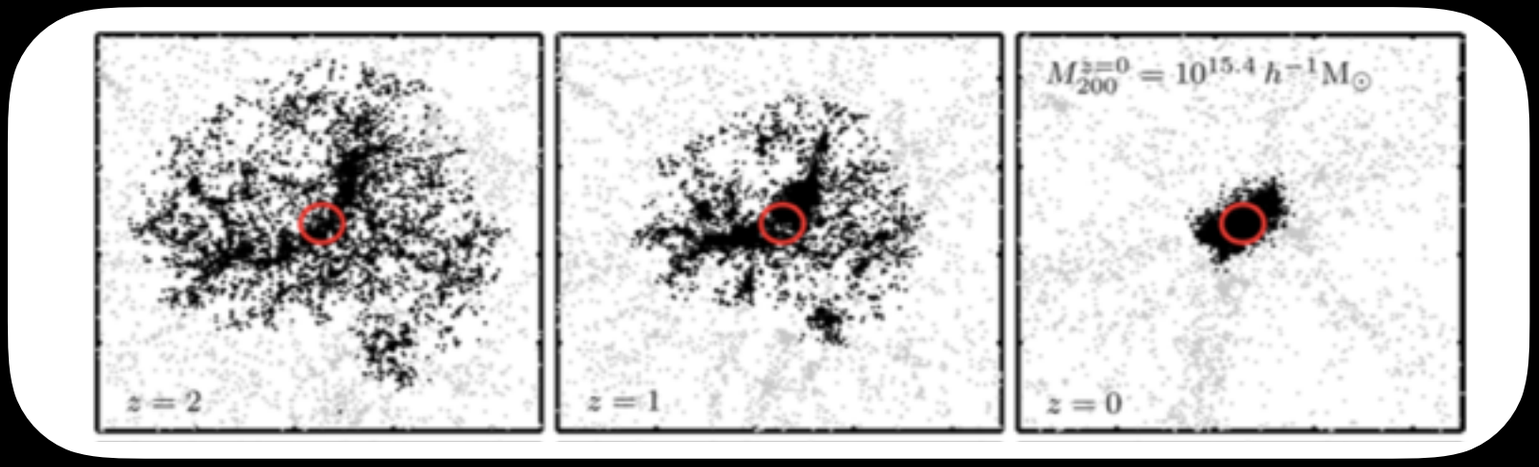
Characteristics: massive protoclusters?



Chiang et al. (2013), Oñorbe et al. (2014), Muldrew et al. (2015)



Characteristics: massive protoclusters?



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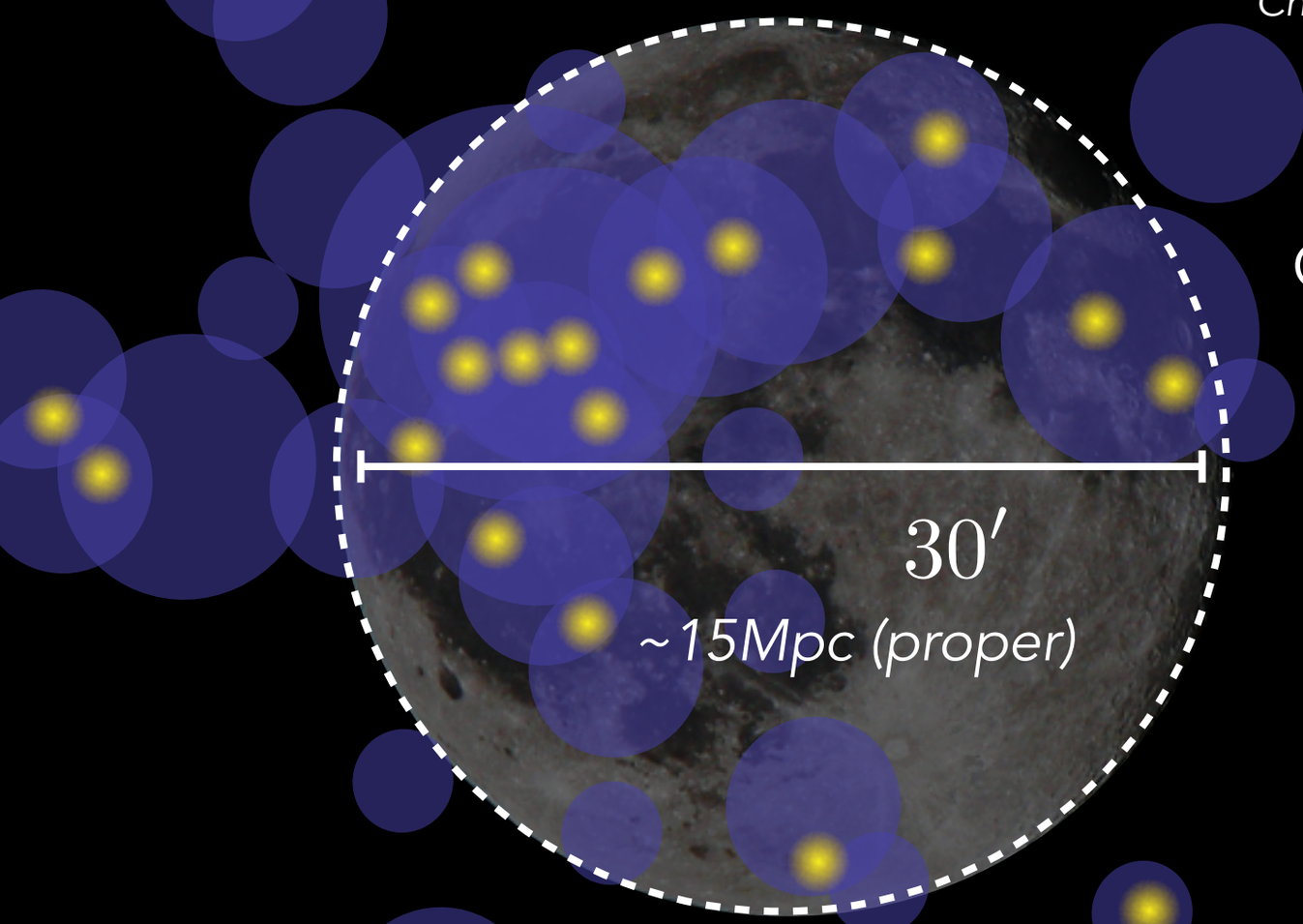
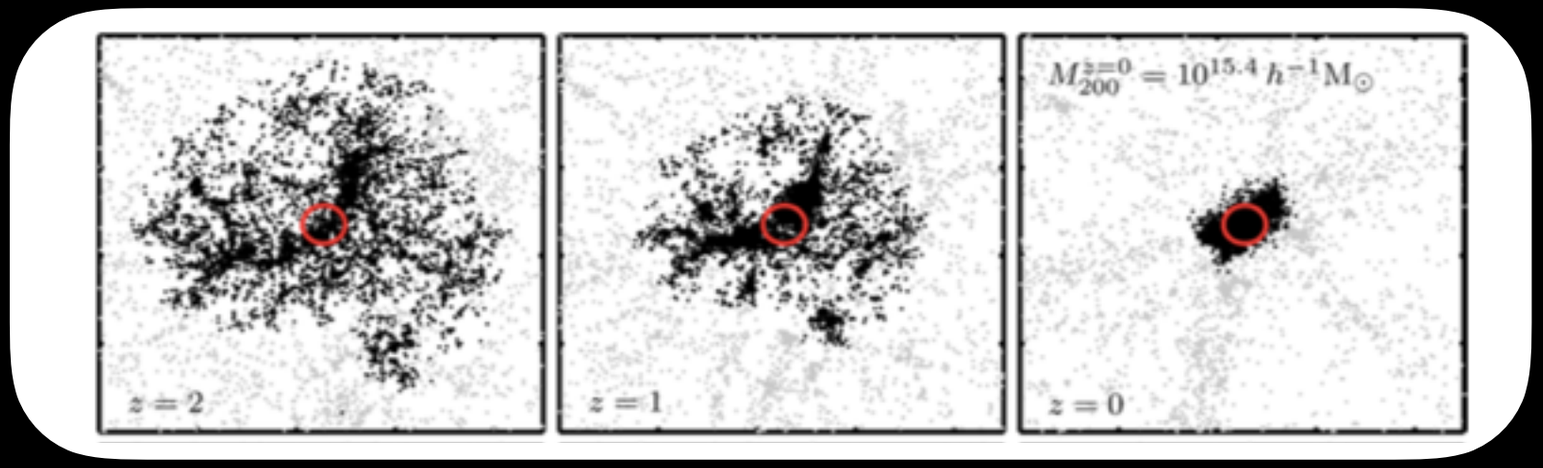


Observational limits on measuring δ_{gal}:

Characteristics: massive protoclusters?



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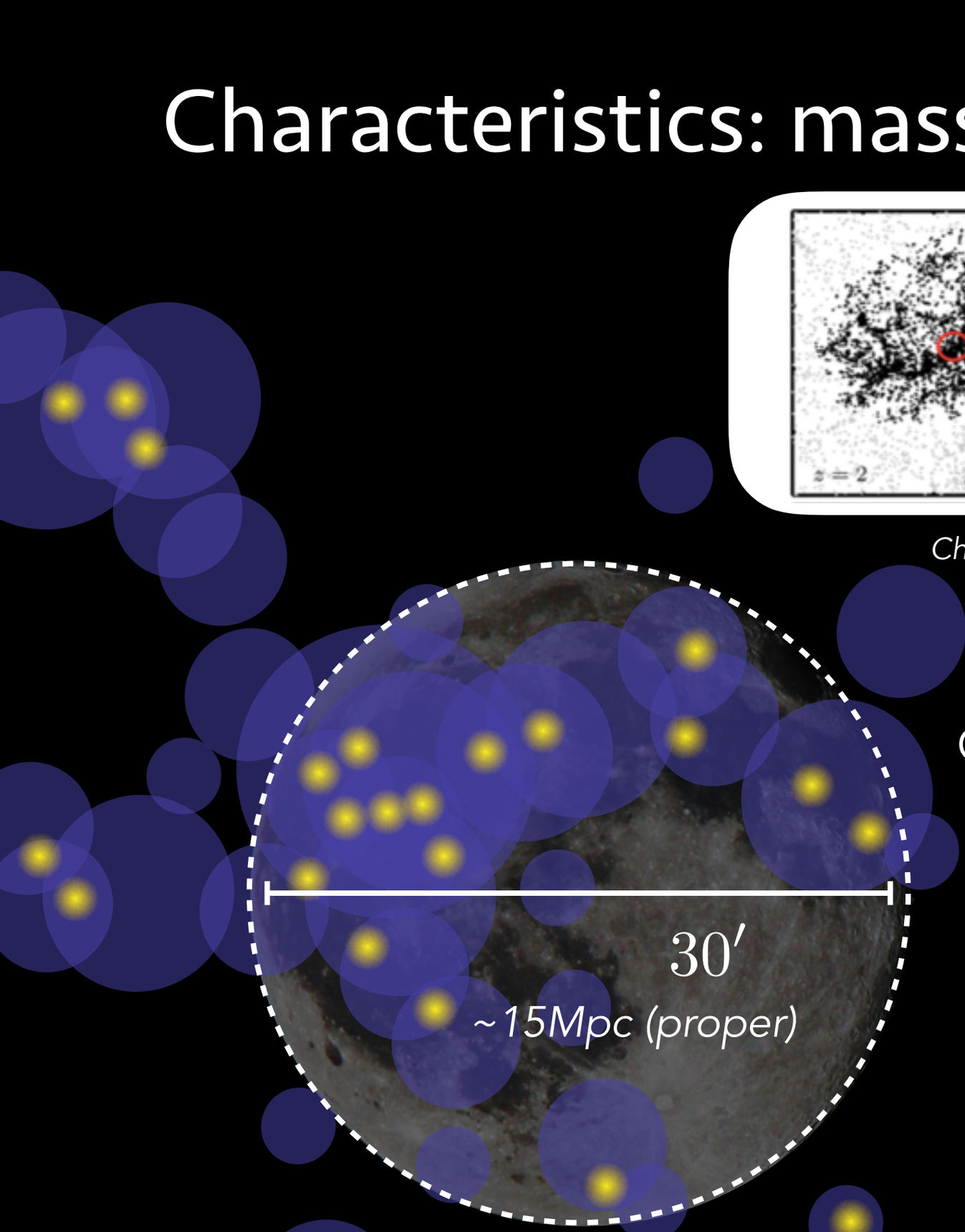

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—Field Luminosity Function—

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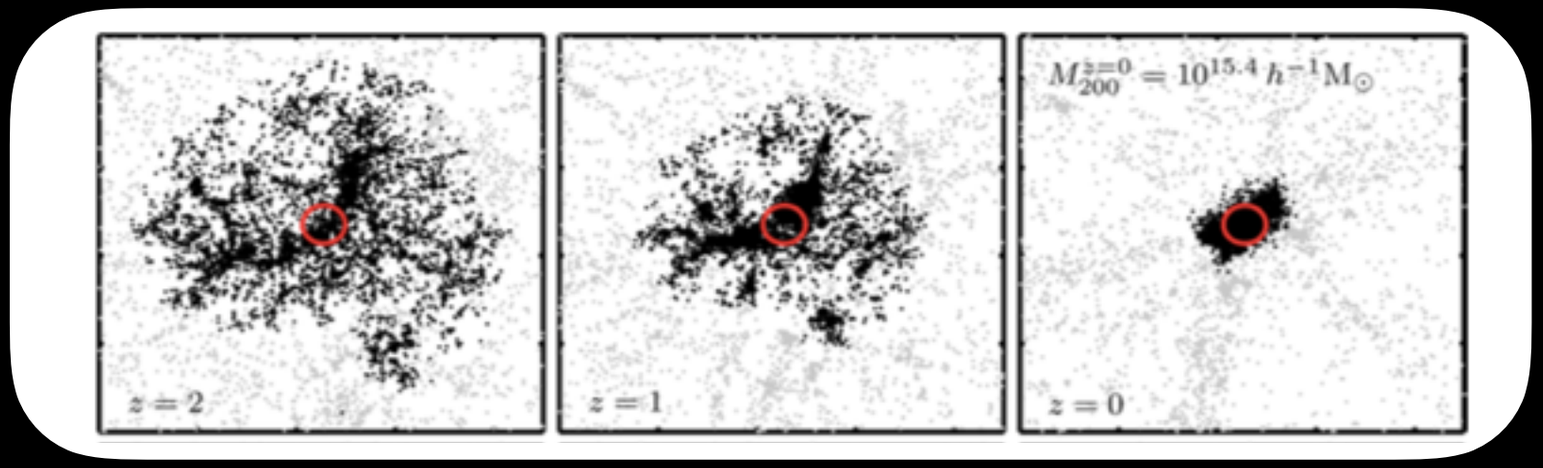

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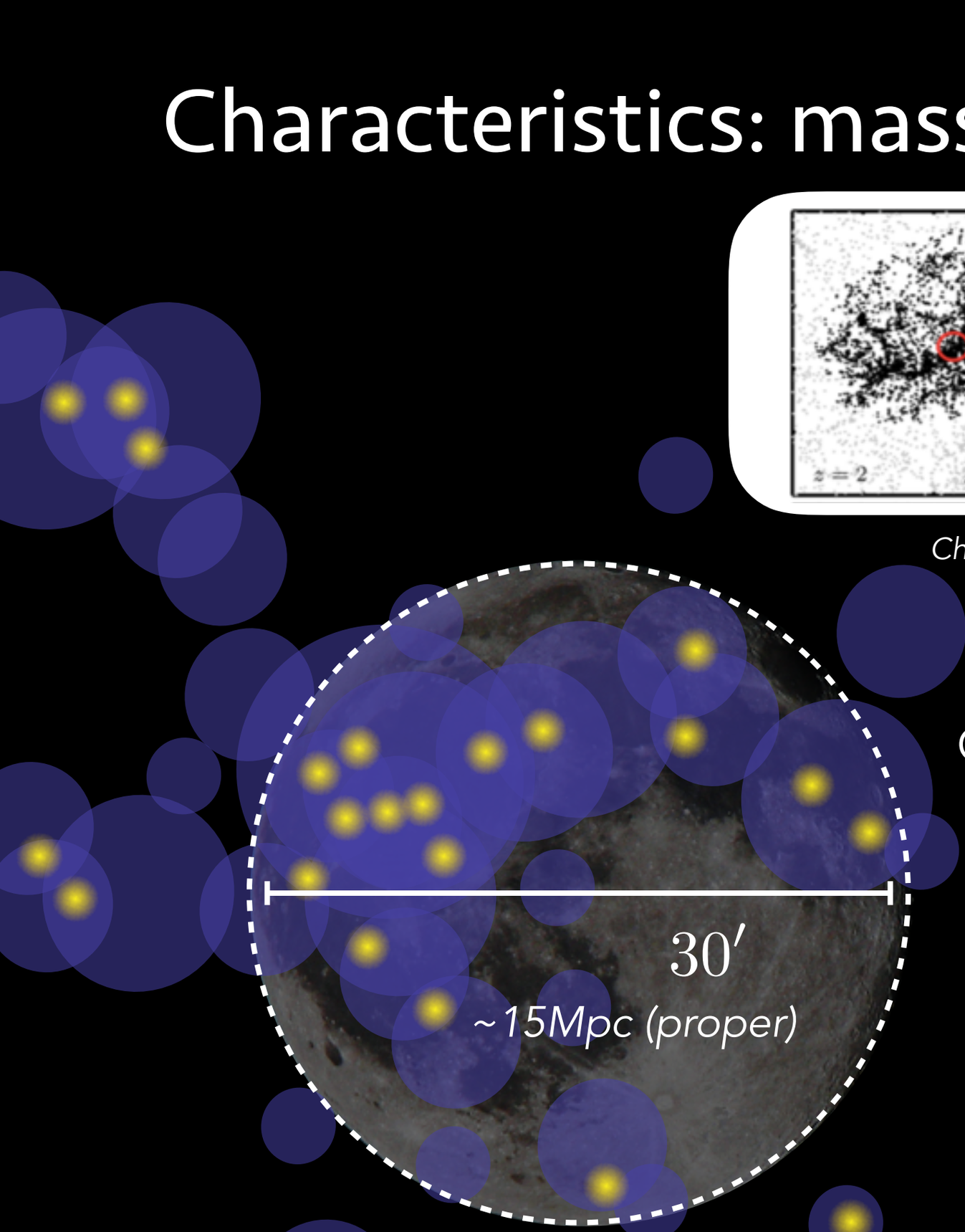
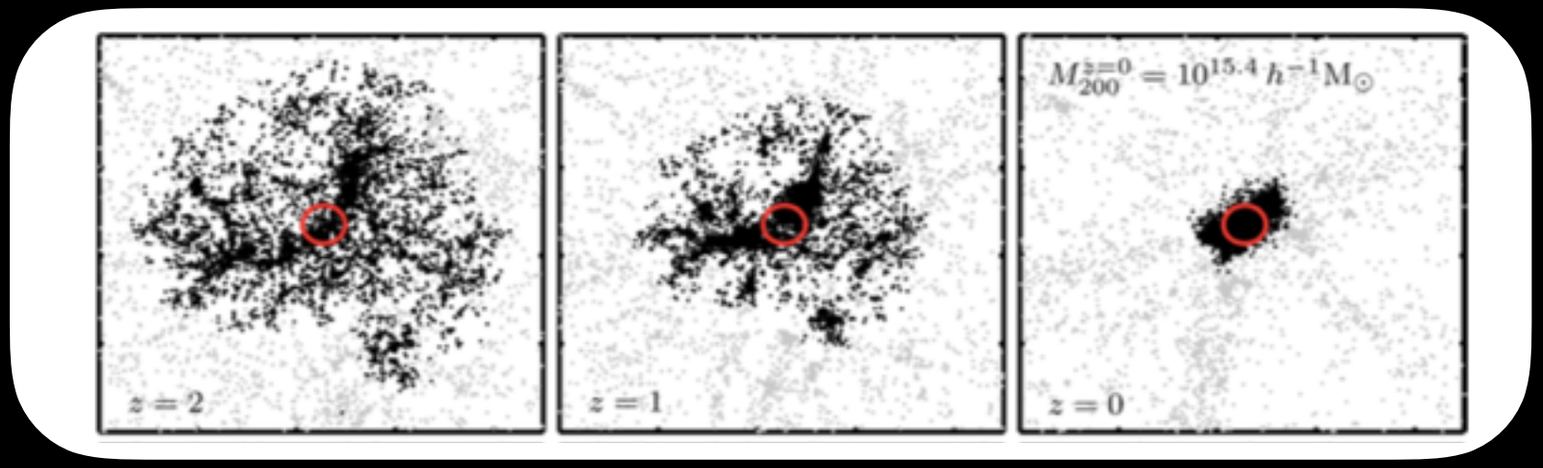


Observational limits on measuring δ_{gal}:

—Field Luminosity Function—

—Spectroscopic Completeness—

Characteristics: massive protoclusters?



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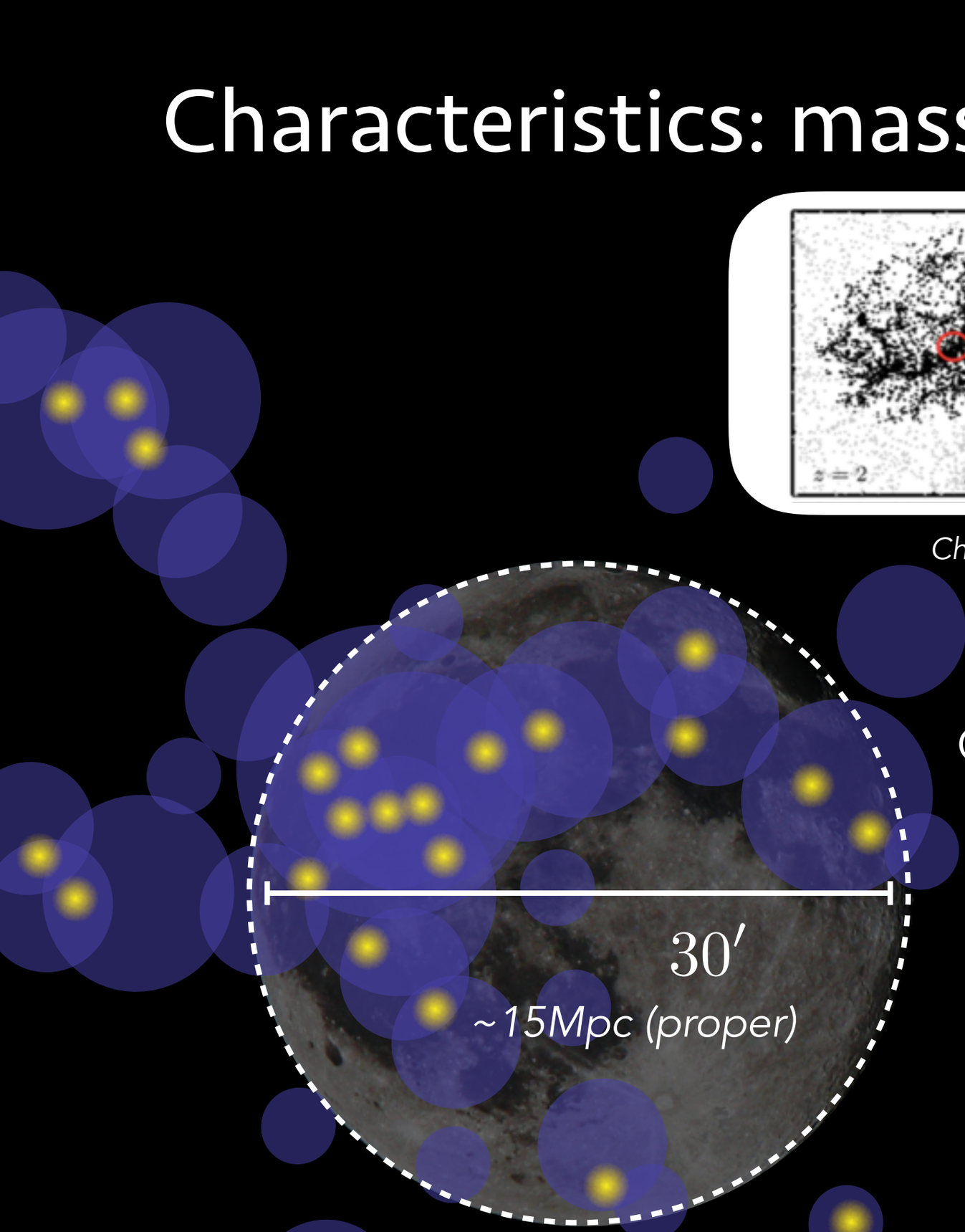


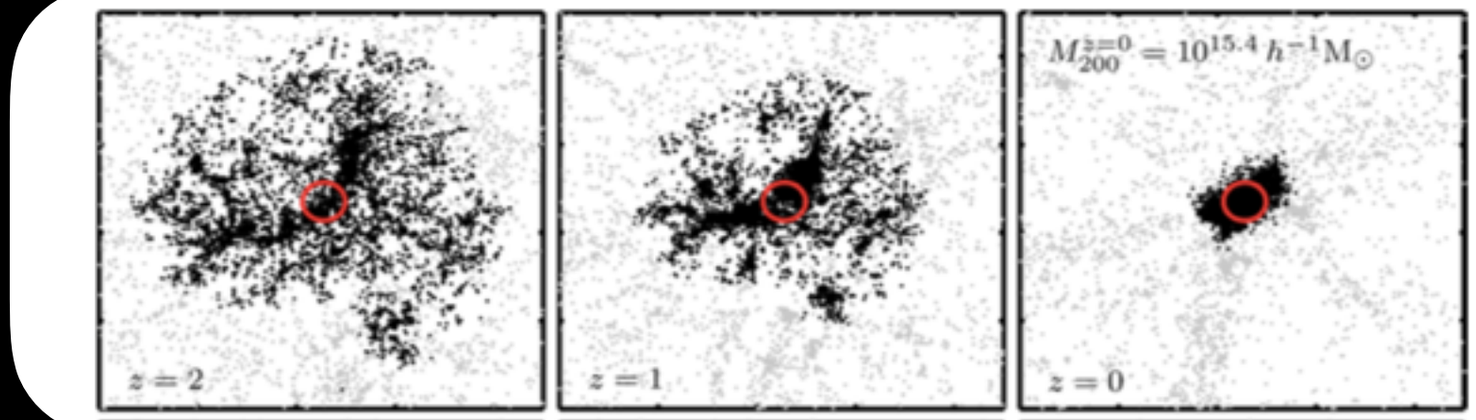
Observational limits on measuring $\delta_{\rm gal}$:

—Field Luminosity Function—

—Spectroscopic Completeness—

$$\delta_{\rm gal} \approx 3 - 8$$

Characteristics: massive protoclusters?



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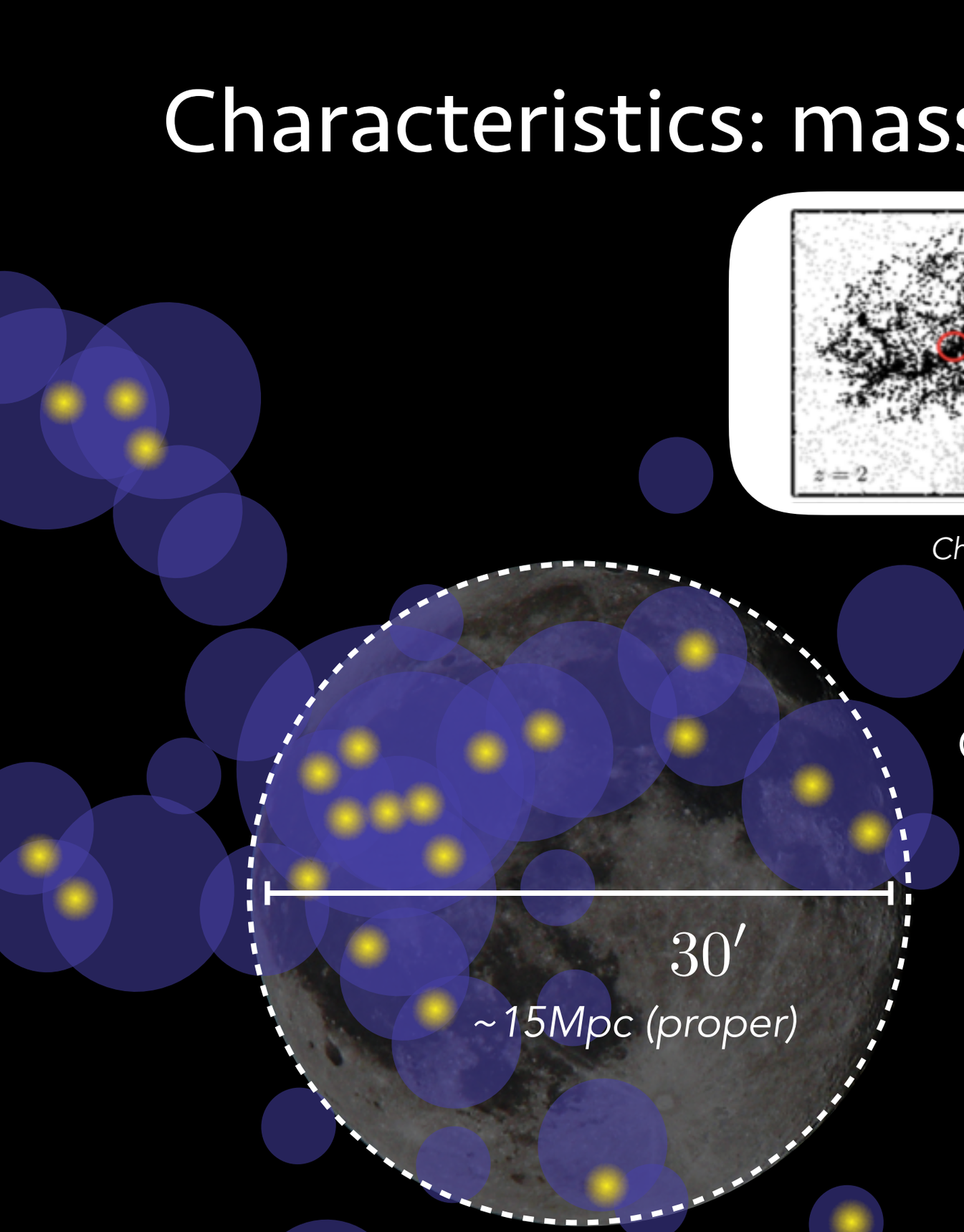


Observational limits on measuring $\delta_{\rm gal}$:

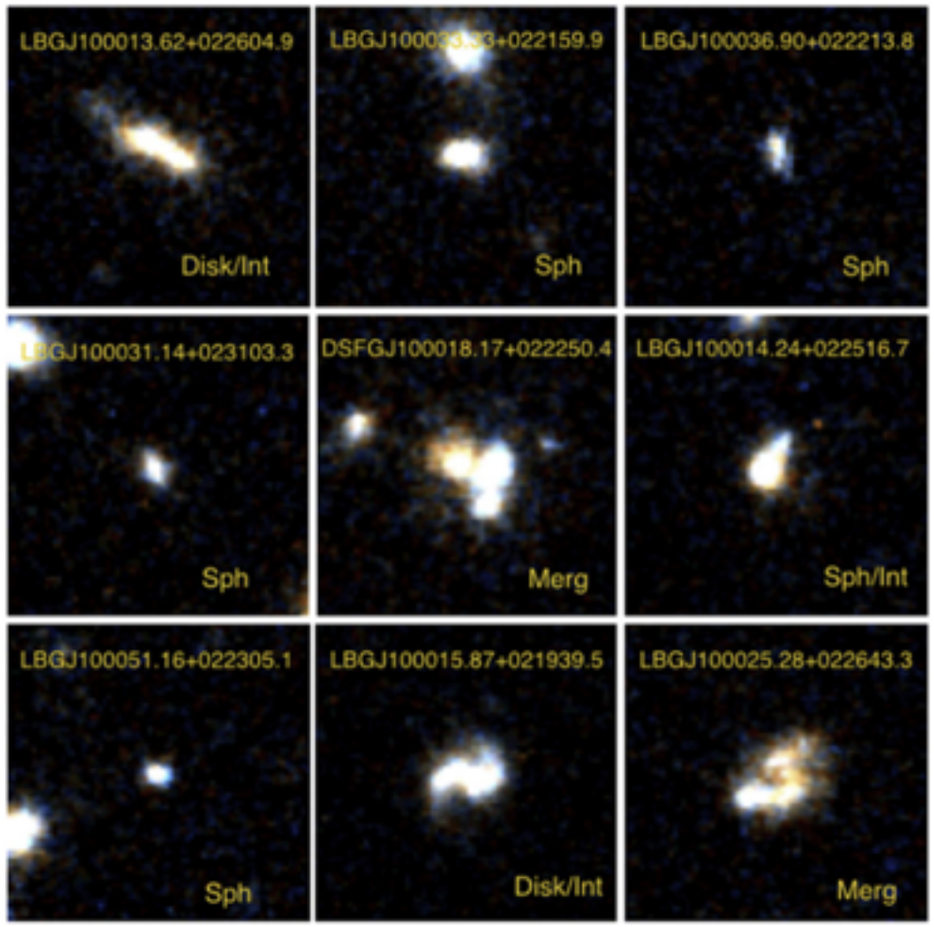
—Field Luminosity Function—

—Spectroscopic Completeness—

$$\delta_{\rm gal} \approx 3 - 8$$

Overdensity of rare galaxies easily distinguished from background.

Characteristics: massive protoclusters?

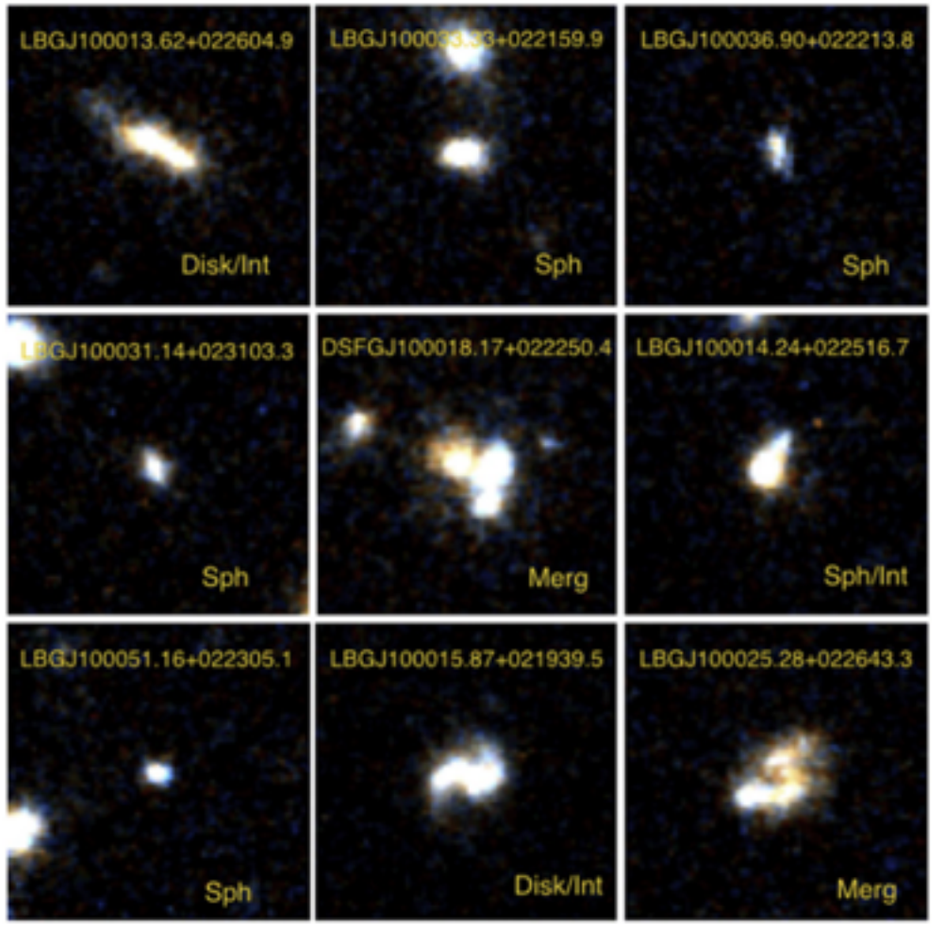


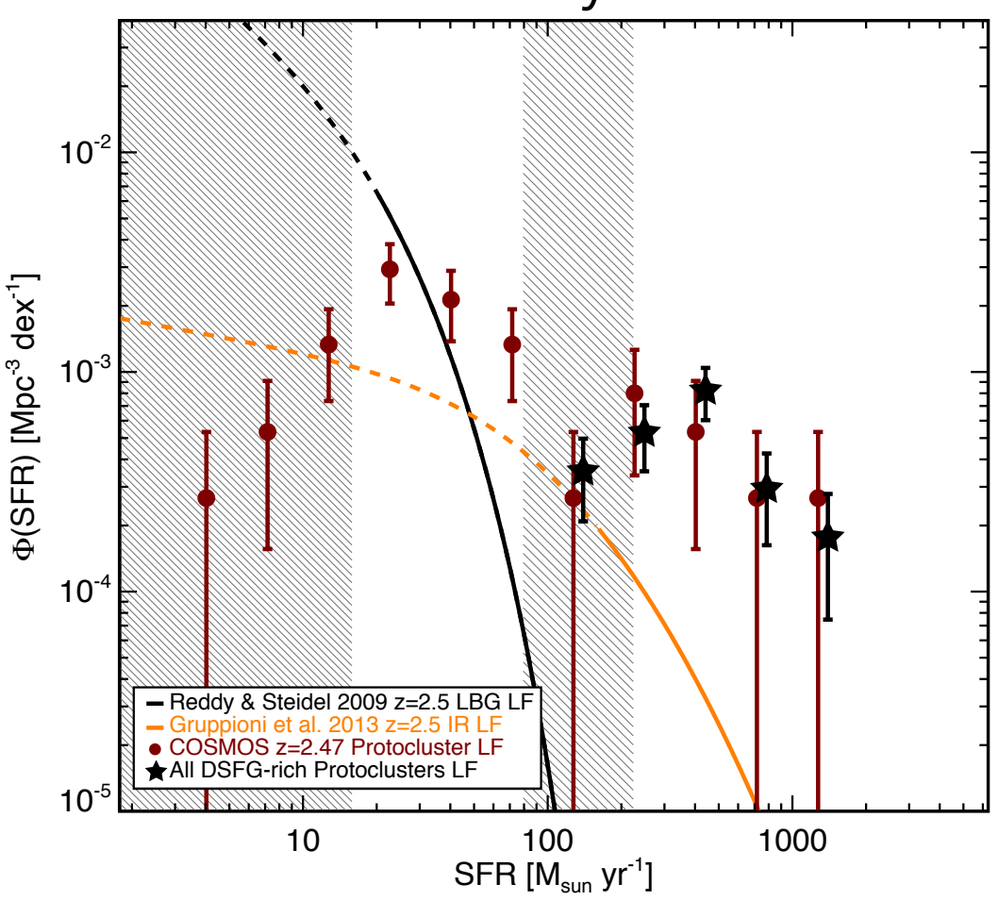
increased interaction fraction vs. control field sample (40% vs. ~20%)

Casey et al. (2015), Hung et al. (2016)

- each has 50-120 spectroscopic members
- aggregate SFR~1000-5000 $\mathrm{M_\odot\,yr^{-1}}$
- contain 5-12 DSFGs
- also enhanced AGN activity (5-10 luminous AGN/QSOs)
- span 5000—15000 $c\mathrm{Mpc}^3$
- submm stack suggests enhanced gas fractions (marginal)

Characteristics: massive protoclusters?





Casey (2016)

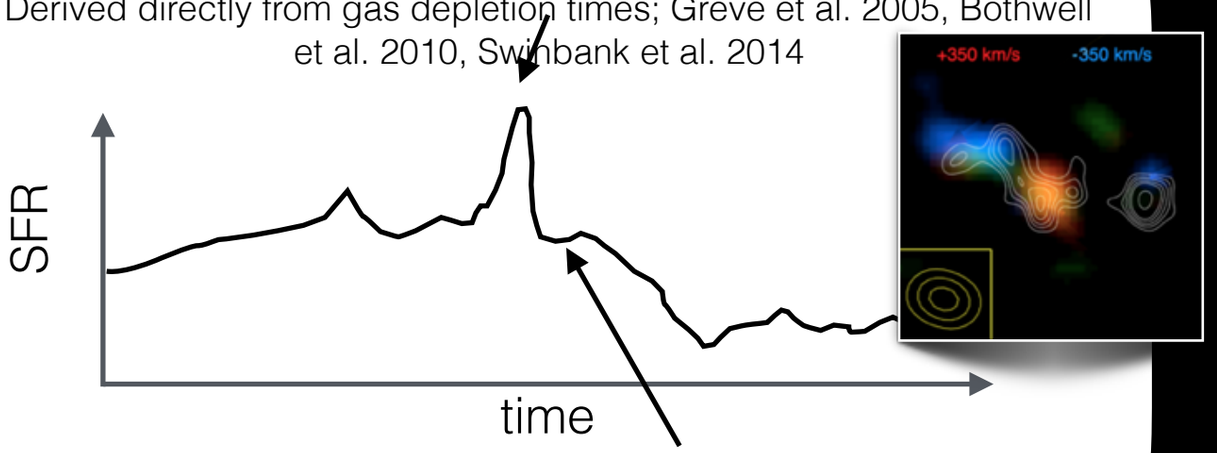
increased interaction fraction vs. control field sample (40% vs. ~20%)

Casey et al. (2015), Hung et al. (2016)

Triggered Filaments, or prolonged feeding?

DSFGs: short-lived, ~100Myr.

Derived directly from gas depletion times; Greve et al. 2005, Bothwell et al. 2010, Swinbank et al. 2014



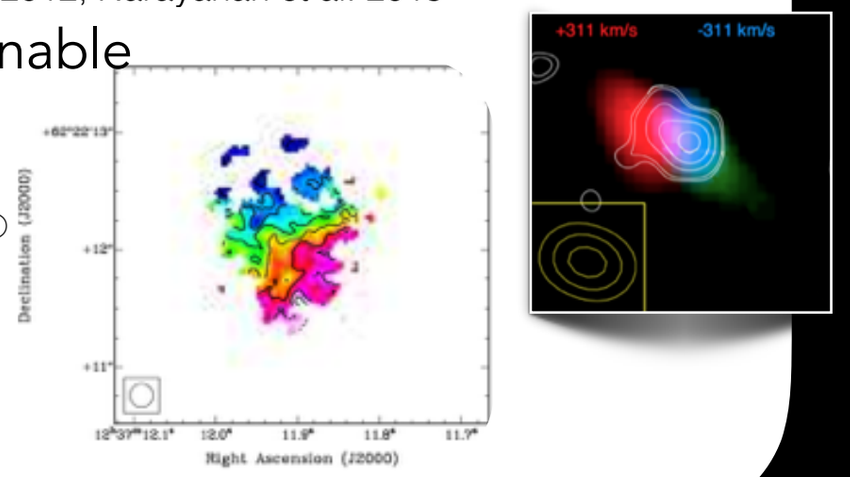
luminous AGN, QSO lifetimes? <100Myr.

DSFGs: long-lived, ~1Gyr.

Daddi et al. 2009, Carilli et al. 2009, Hodge et al. 2012, Narayanan et al. 2015

high SFR sustainable for up to 1Gyr?

building $10^{12}\ M_\odot$ galaxies

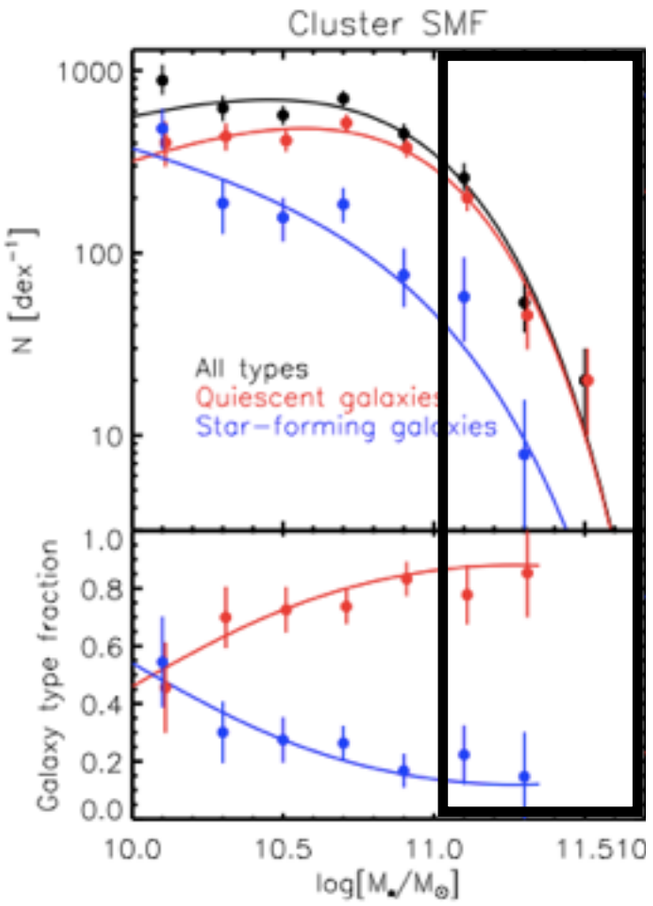


Duration of burst matters. Best probed through measures of gas reservoir, depletion time.

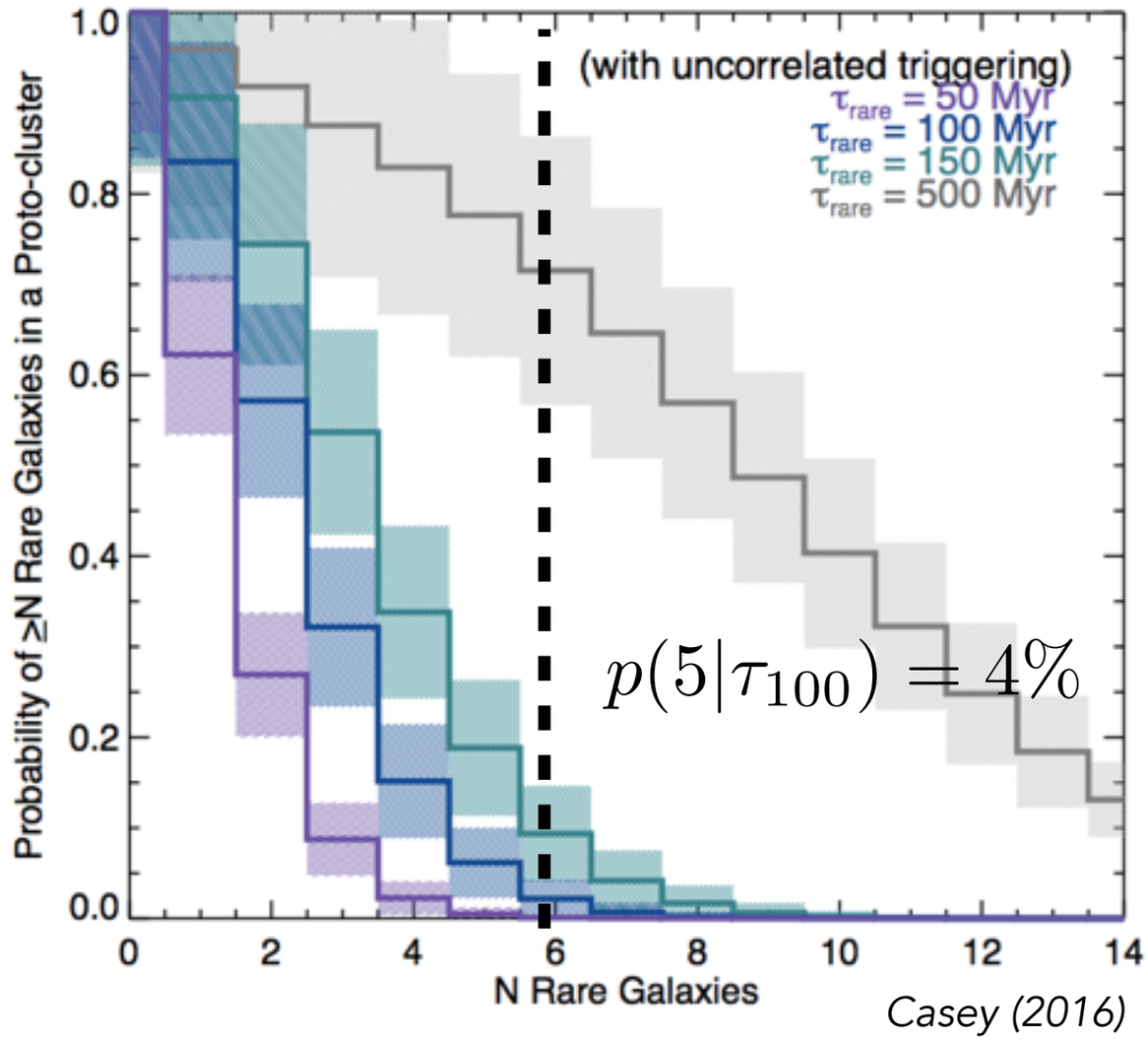
How likely is it to see 2, 3, 5, or 10 DSFGs (simultaneously) in a given protocluster?

Triggered Filaments, or prolonged feeding?

Count massive galaxies in low-z clusters



van der Burg et al. (2013)



Casey (2016)

How likely is it to see 2, 3, 5, or 10 DSFGs (simultaneously) in a given protocluster?

Triggered Filaments, or prolonged feeding?

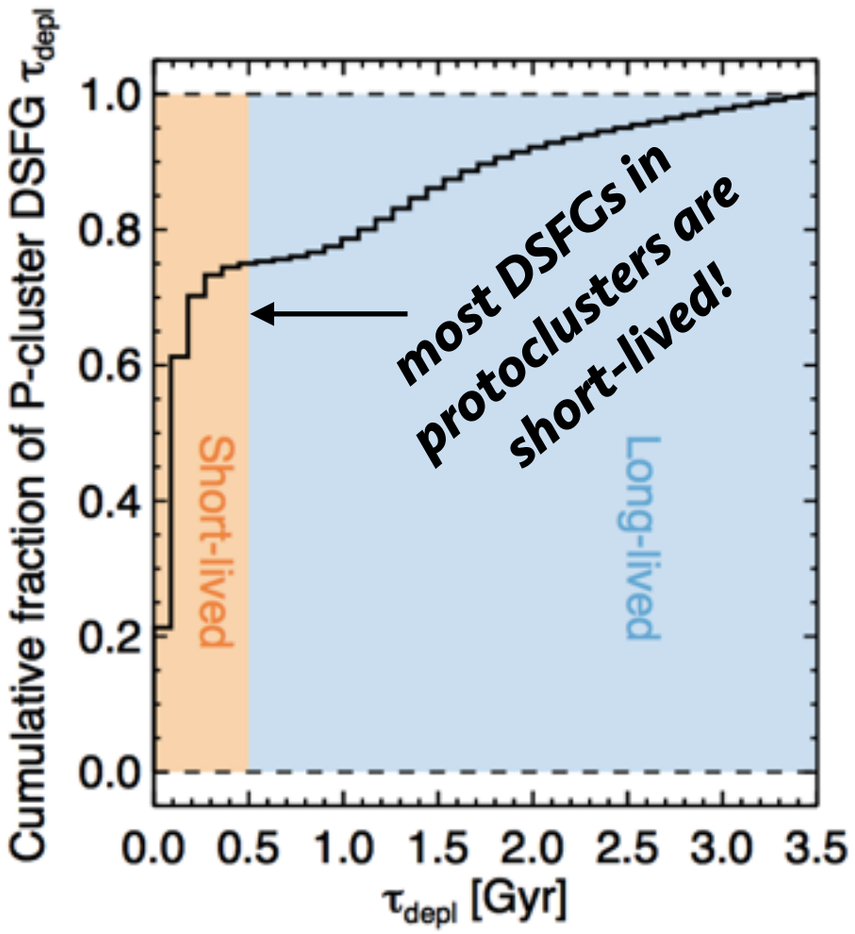
increased merger occurance in overdense environments?

increased gas fueling in overdense environments?

Casey (2016)

TABLE 4
DSFGs IN PROTOCLUSTERS WITH CO MEASUREMENTS

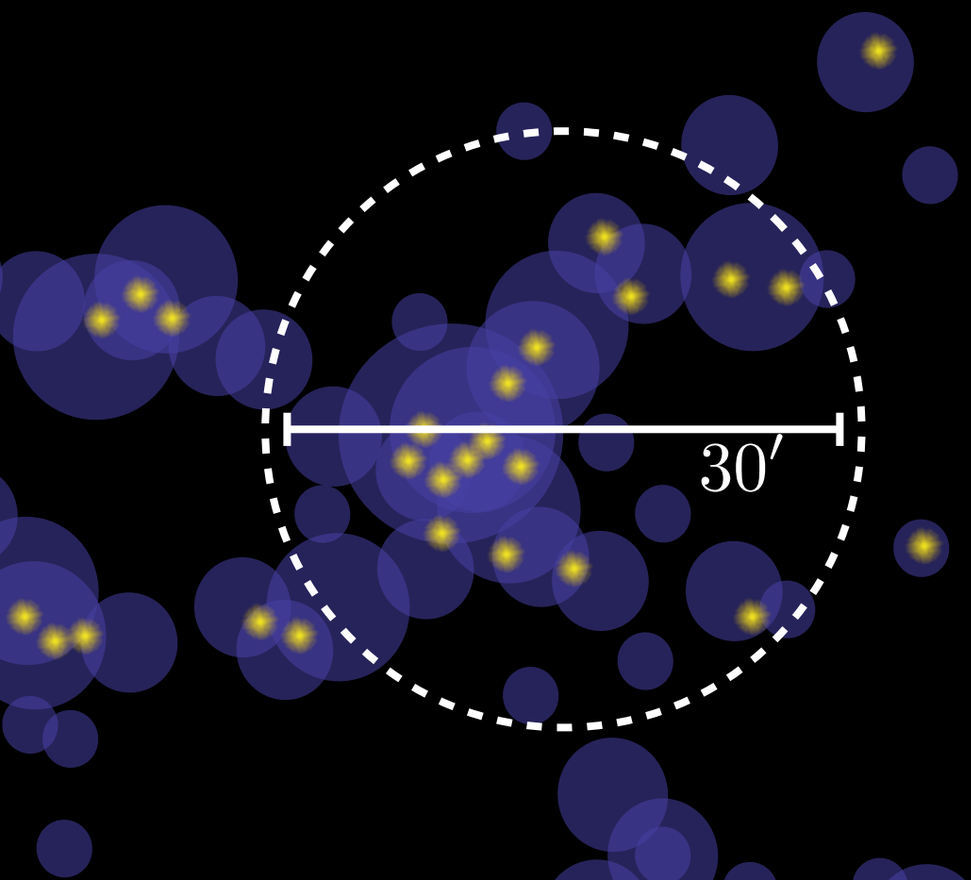
DSFG Name	z	Transition	L'_{CO} [K km s^{-1} pc^2]	M(H_2)‡ [$M_\odot$]	SFR [$M_\odot$ yr^{-1}]	τ_{depl} [Myr]	Reference
DETECTIONS:							
DSFG J123618+621550	1.996	CO(4-3)	$(9.4\pm1.4)\times10^{10}$	$(2.6\pm0.6)\times10^{11}$			Bothwell *et al.* (2010)
	2.001	CO(4-3)	$(6.5\pm0.9)\times10^{10}$	$(1.8\pm0.4)\times10^{11}$			Bothwell *et al.* (2010)
			total:	*$(4.4\pm0.7)\times10^{11}$*	330^{+110}_{-80}	**1300±400**	
DSFG J123711+621331	1.988	CO(4-3)	$(1.3\pm0.2)\times10^{10}$	$(3.6\pm0.8)\times10^{10}$			Casey *et al.* (2011)
	1.996	CO(4-3)	$(7.8\pm1.1)\times10^{9}$	$(2.2\pm0.5)\times10^{10}$			Casey *et al.* (2011)
	1.995	CO(3-2)	$(1.5\pm0.5)\times10^{10}$	$(3.4\pm1.2)\times10^{10}$			Casey *et al.* (2011)
			average:	*$(4.9\pm0.7)\times10^{10}$*	540^{+350}_{-210}	**110±60**	
DSFG J123712+621322	1.996	CO(4-3)	$(6.8\pm1.5)\times10^{9}$	$(1.9\pm0.5)\times10^{10}$			Casey *et al.* (2011)
	1.996	CO(3-2)	$(2.7\pm0.9)\times10^{10}$	$(6.0\pm2.2)\times10^{10}$			Bothwell *et al.* (2013)
			average:	*$(2.1\pm0.5)\times10^{10}$*	190^{+170}_{-90}	**110±80**	
DSFG J123632+620800	1.994	CO(3-2)	$^{t}(4.0\pm1.1)\times10^{10}$	$(8.9\pm2.8)\times10^{10}$	36^{+144}_{-30}	$\lesssim$ 9000	Bothwell *et al.* (2013)
DSFG J114048−262908	2.163	CO(1-0)	$(6.5\pm0.6)\times10^{10}$	$(6.5\pm0.6)\times10^{10}$			Emonts *et al.* (2013)
	2.150	CO(1-0)	$(6.9\pm2.3)\times10^{9}$	$(6.9\pm2.3)\times10^{9}$			Emonts *et al.* (2013)
					$^{s}740\pm80$	**97±13**	Seymour *et al.* (2012)
DSFG J114046−262913	2.147	CO(1-0)	$(3.3\pm0.2)\times10^{10}$	$(3.3\pm0.2)\times10^{10}$	$\dagger480^{+150}_{-110}$	**68±5**	Emonts *et al.* (2013)
DSFG J221735+001537	3.096	CO(3-2)	$(3.8\pm1.0)\times10^{10}$	$(8.5\pm2.5)\times10^{10}$	$^{ss}1100^{+300}_{-200}$	**80±30**	Greve *et al.* (2005)
DSFG J221726+001239	3.102	CO(4-3)	$(6.7\pm2.1)\times10^{10}$	$(1.9\pm0.7)\times10^{11}$	1400^{+1100}_{-600}	**140±90**	Chapman *et al.* (2004)
DSFG J221732+001744	3.092	CO(3-2)	...	...	$^{m}1180^{+890}_{-230}$	...	(Yun et al., in prep)
NON-DETECTIONS:							
DSFG J123621+621708	1.973–2.008	CO(4-3)	$<5.2\times10^{9}$	$<1.5\times10^{10}$	310^{+170}_{-110}	<50	Bothwell *et al.* (2013)
DSFG J123600+621047*	1.971–2.017	CO(3-2)	$<2.9\times10^{10}$	$<6.5\times10^{10}$			Greve *et al.* (2005)
		CO(3-2)	$<1.6\times10^{10}$	$<3.6\times10^{10}$			Bothwell *et al.* (2013)
					110^{+100}_{-50}	<300	



(awaiting more data [analysis] from the VLA in CO(1-0): crucial probe of total molecular gas potential and future potential for star-formation)

Conclusions

Collections of Dusty Star-Forming Galaxies (DSFGs) can trace the extended halo structure of pre-virialized galaxy clusters. When present, they provide unique observational constraints on the assembly of those clusters because we know they are predominantly short-lived. They likely represent a triggered phase (100-200Myr) of enhanced star-formation across ~10Mpc scales coinciding with filamentary collapse.



(Casey 2016 ApJ 824, 36)

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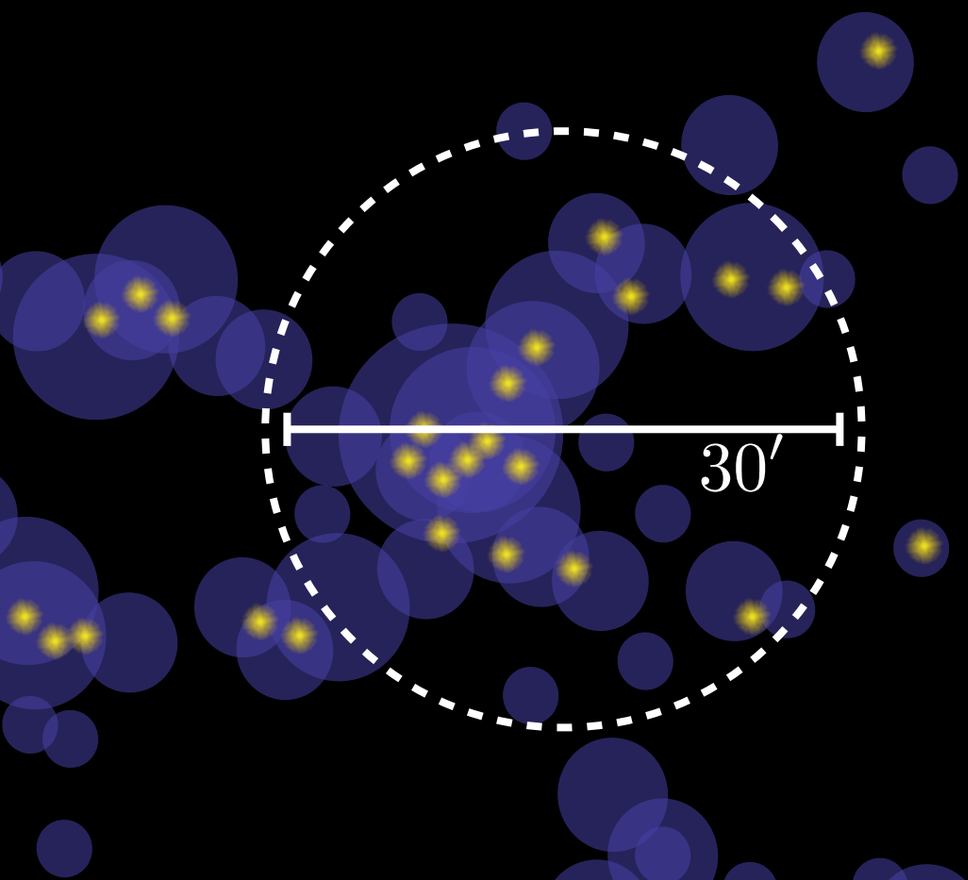
Protoclusters are huge and require observational campaigns on ~degree scales,



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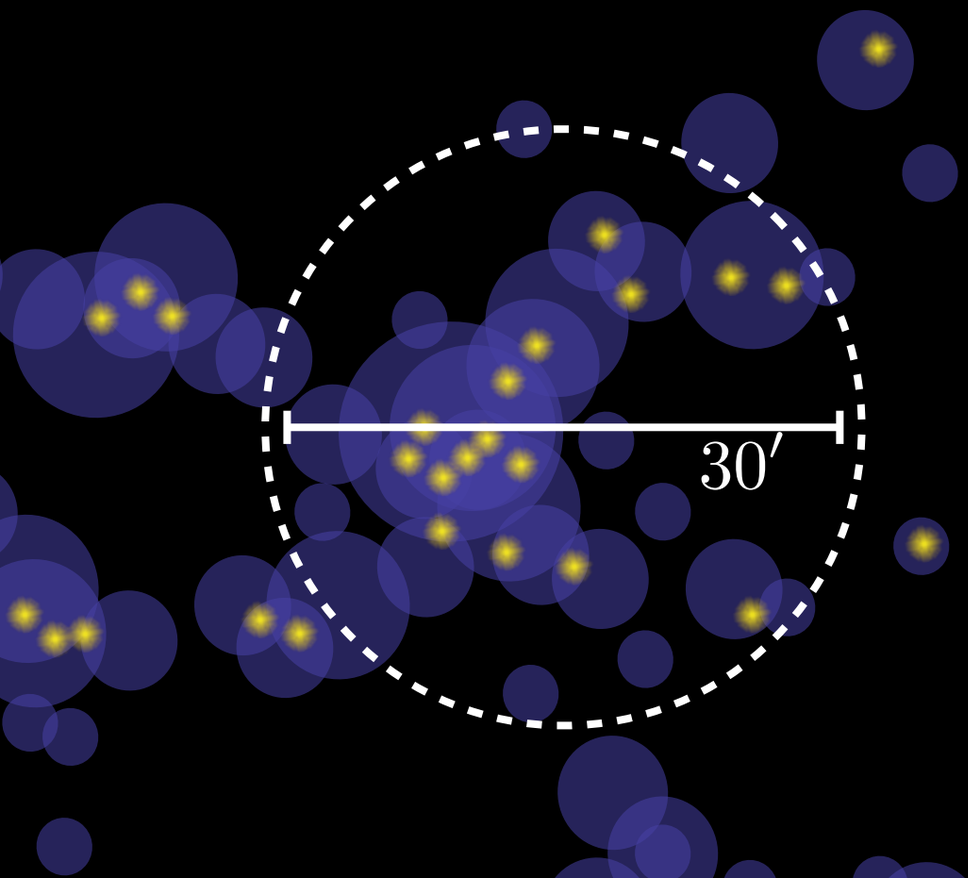

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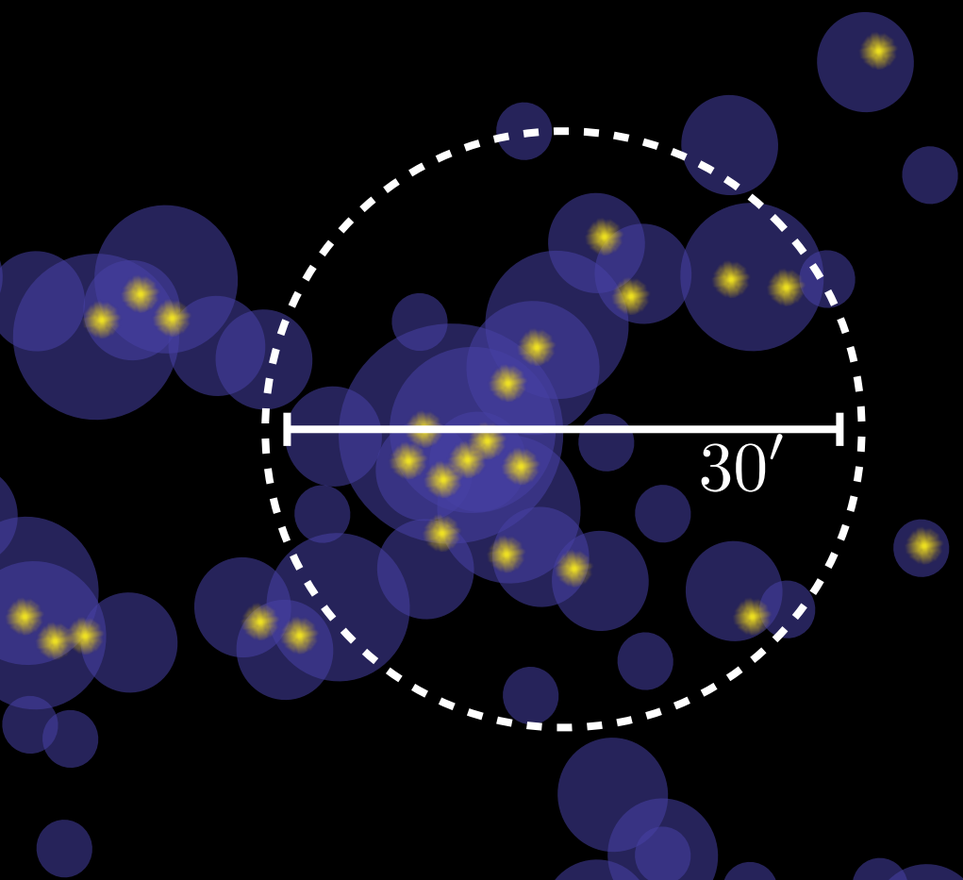

A remarkable excess of DSFGs can provide useful constraints on protocluster assembly history,

Meanwhile, improved techniques for following up DSFGs expands knowledge of most massive, luminous galaxies, place new constraints on theory.

(Casey 2016 ApJ 824, 36)