

# The Frontier Fields

#### Jennifer Lotz, STScI

+ M. Mountain, K. Flanagan, K. Sembach

& FF implementation team

STUC May 2016



#### Answer:

Use Einstein's theory of general relativity - "gravitational lensing" - to go intrinsically deeper than the Ultra Deep Field.



Gravitational lensing magnifies and stretches light from distant galaxies behind massive clusters, making them appear brighter and larger.

Six very massive clusters of galaxies chosen as the best "zoom lenses", with input from community.

With six parallel fields, the Frontier Fields opens new parameter space by going both deeper and wider.

#### **Hubble Deep Fields Initiative Science Working Group:**

James Bullock (Chair, UCI), Mark Dickinson (NOAO), Steve Finkelstein (UT), Adriano Fontana (INAF, Rome), Ann Hornschemier Cardiff (GSFC), Jennifer Lotz (STScI), Priya Natarajan (Yale), Alexandra Pope (UMass), Brant Robertson (Arizona), Brian Siana (UC-Riverside), Jason Tumlinson (STScI), Michael Wood-Vasey (U Pitt)

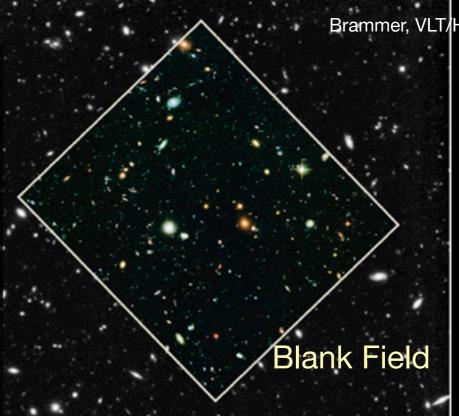
**6** strong-lensing clusters

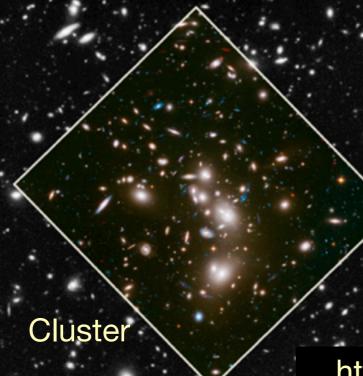
+ 6 adjacent parallel fields

140 HST DD orbits per pointing

ACS/ WFC3-IR in parallel

~29th ABmag in / bands





2 clusters per year x 3 years

 $\rightarrow 840$  total orbits

1000 hours Spitzer DD time for

~26.5 ABmag in IRAC 3.6, 4.5 μm

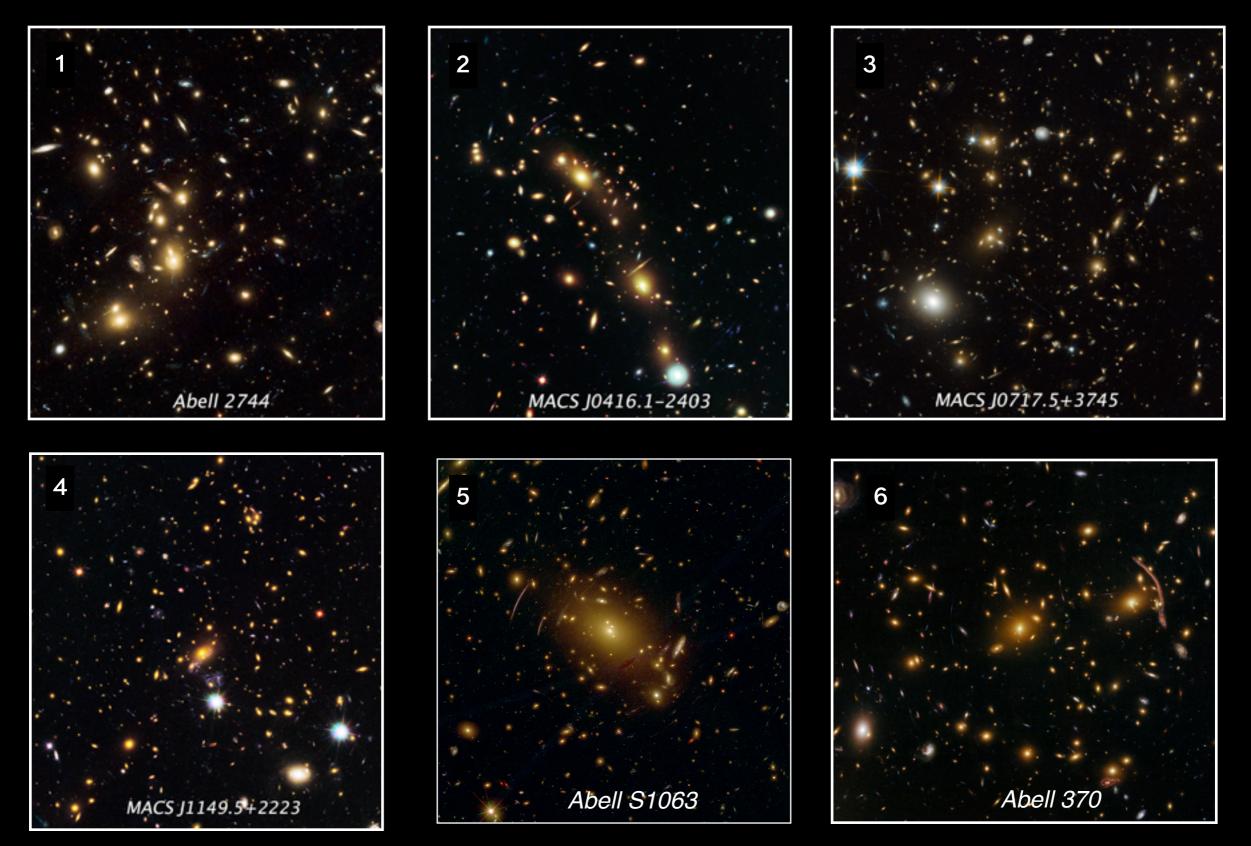
http://www.stsci.edu/hst/campaigns/frontier-fields/



- probe galaxies >10x intrinsically fainter than any seen before, particularly those during reionization
- study the early formation histories of galaxies intrinsically faint enough to be the early progenitors of the Milky Way
- study highly-magnified high-z galaxies in detail: structures, colors, sizes and provide targets for spectroscopic followup
- provide a statistical picture of galaxy formation at early times

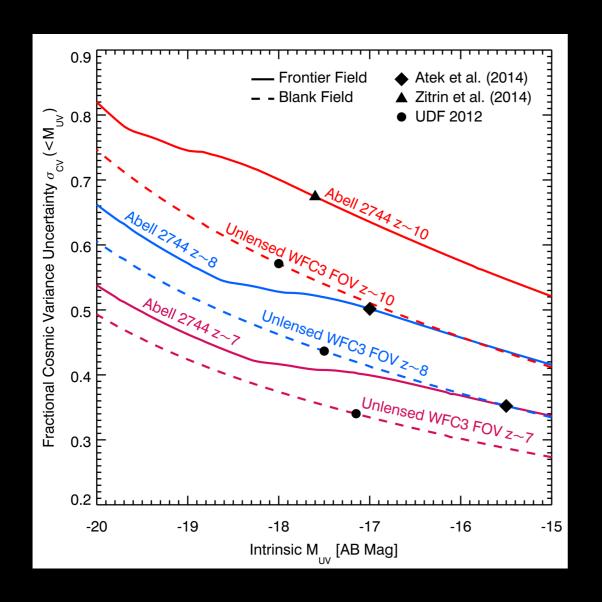
- + deep and high-spatial resolution studies of z~1-4 galaxies, (UV escape fraction, sub-kpc structures and star-formation)
- + map out dark matter and substructure in clusters
- + study cluster galaxies, dwarfs, intracluster light in clusters
- + search for (lensed) SN, transients in distant universe
- + use 100s of multiple images as probe of distance, DE
- + give proper motions of Milky Way stars
- + search for asteroids in solar system
- +???

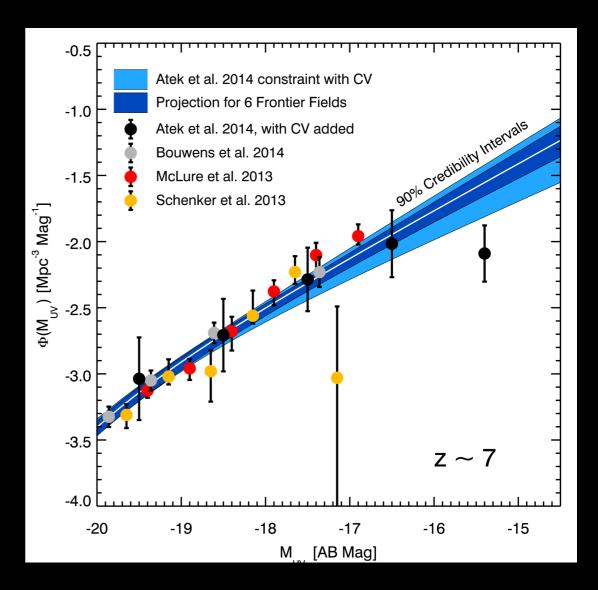
#### **HST Frontier Fields**



chosen based on known lensing strength, sky location, ancillary data

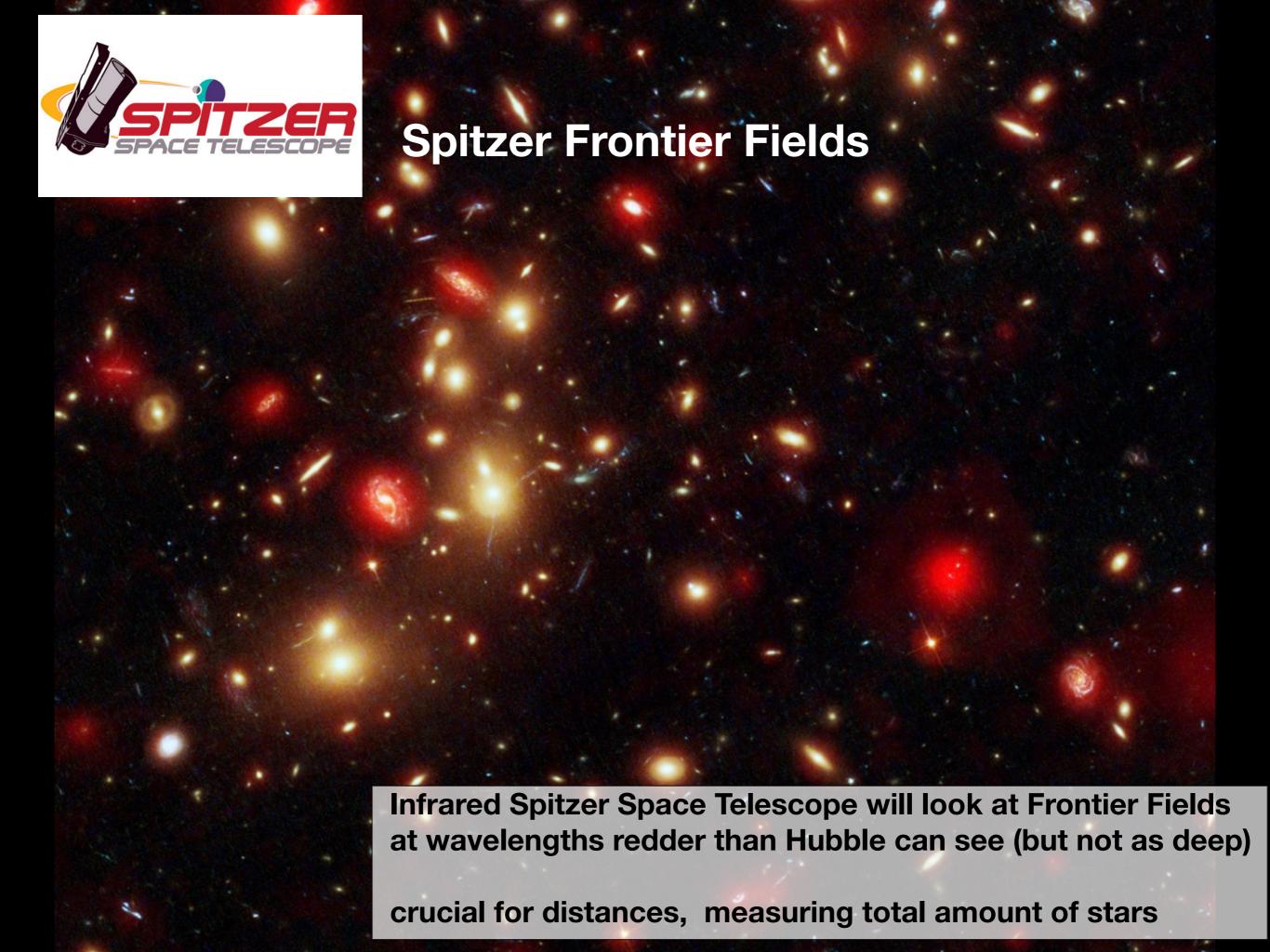
### why 6 clusters + parallel fields?





B. Robertson et al, 2014

cosmic variance 10-30% higher in 1 lensed field vs. HUDF; but 6 fields can provide critical constraints on faint galaxies required to reionize the universe

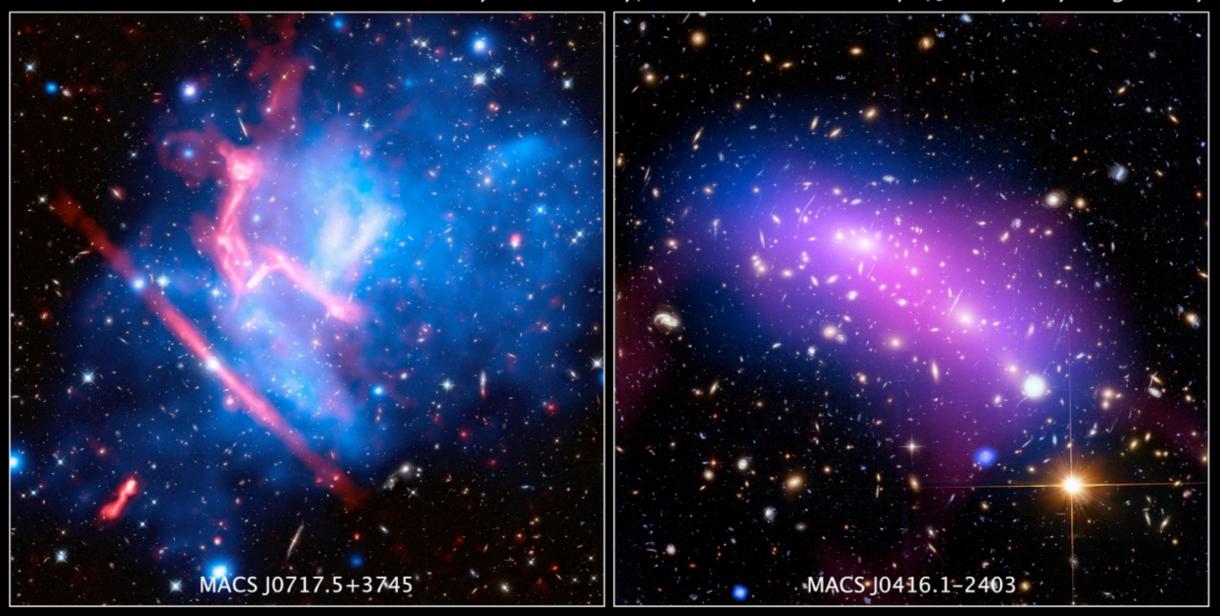




#### X-ray +Radio Frontier Fields

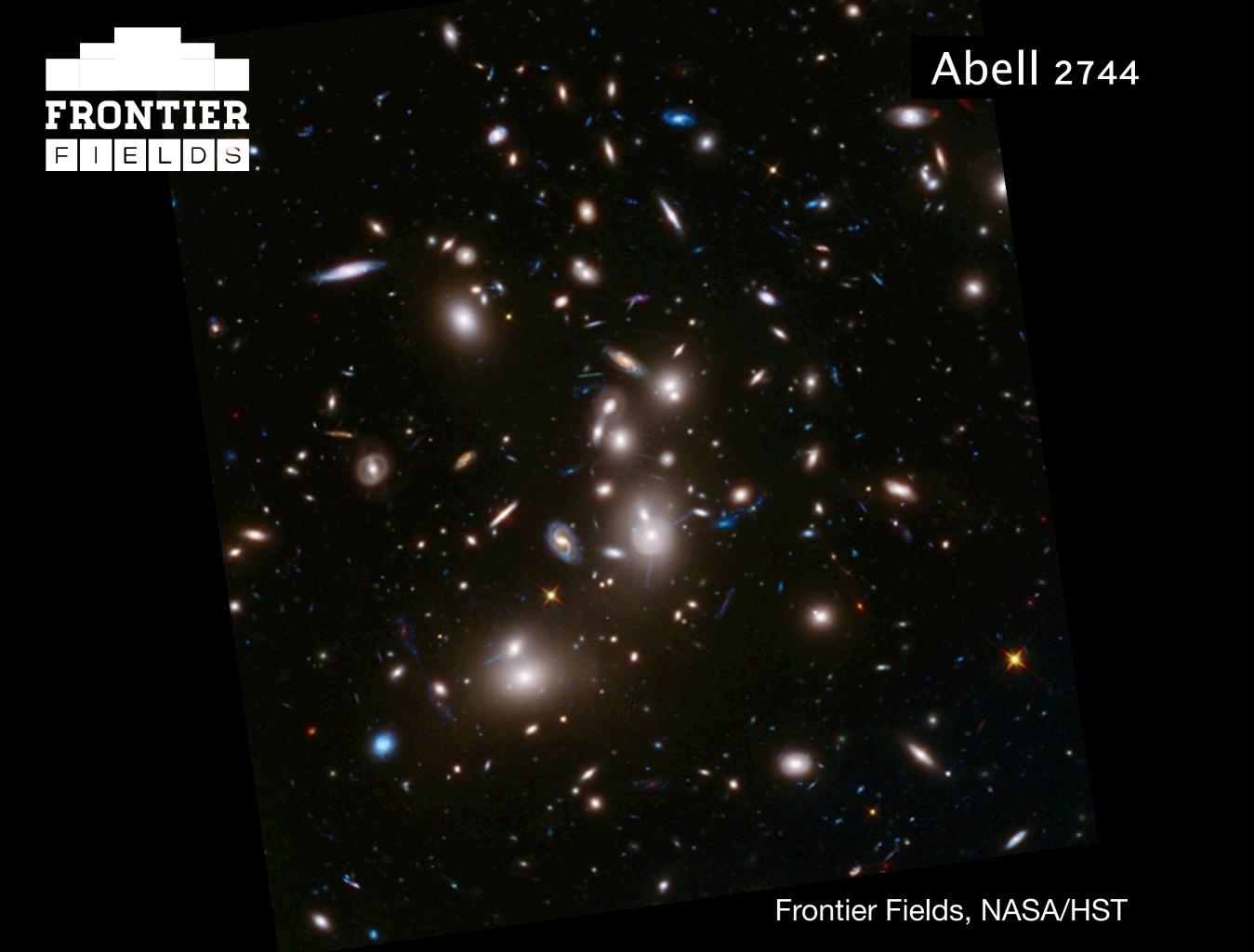


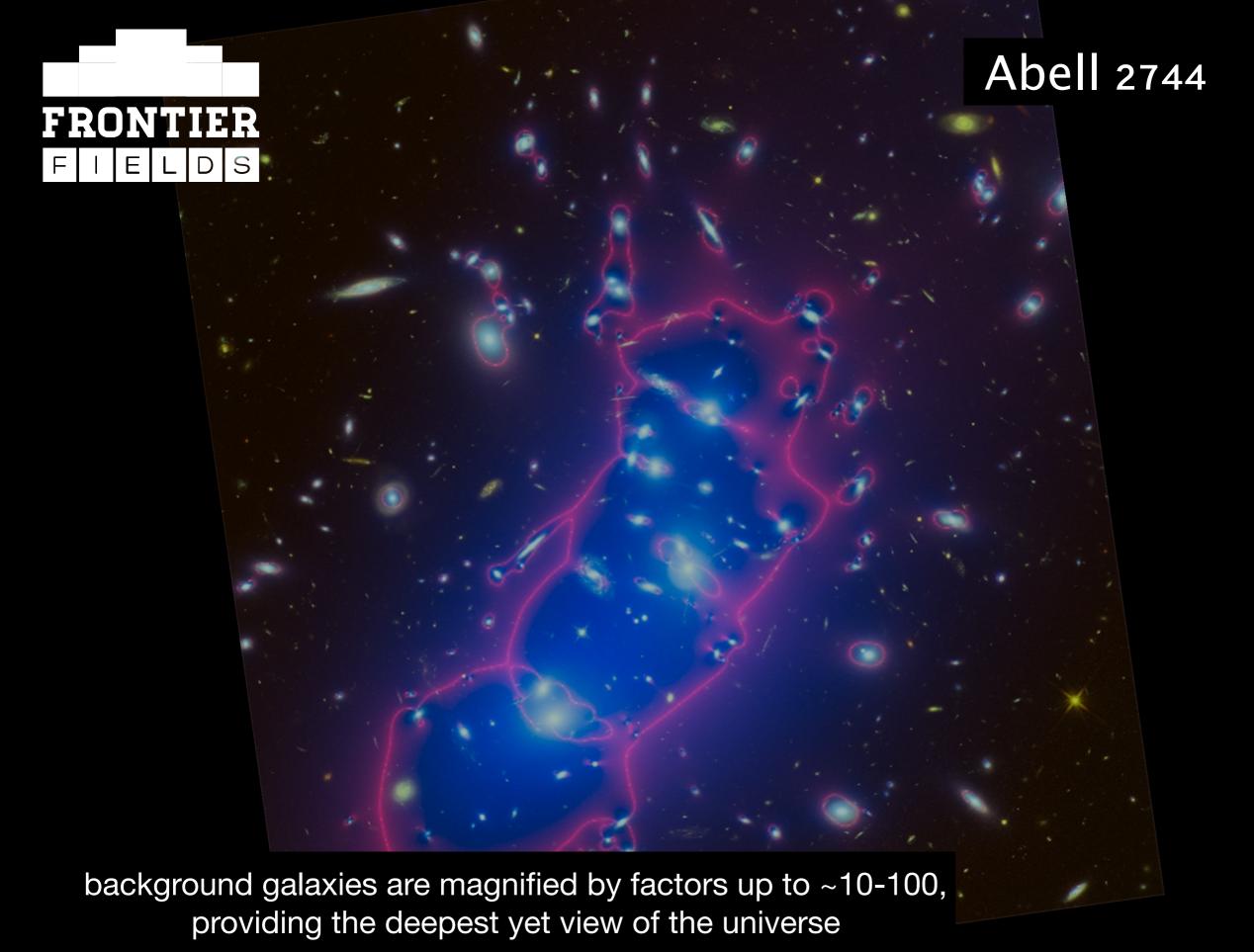
Hubble Frontier Fields ■ Chandra X-ray Observatory, Hubble Space Telescope, Jansky Very Large Array



NASA, ESA, CXC, NRAO/AUI/NSF, and STScI - STScI-PRC16-08

Chandra + XMM trace hot cluster gas, background AGN VLA - shocked cluster gas (red) + background lensed radio sources





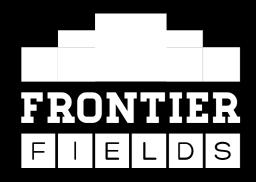
model credit: J. Richard, CATS team

**Table 4**. Frontier Field Lensing Models <sup>a</sup>

Team	Method	Parallel?	Version	Data <sup>b</sup>	Abell 2744	MACSJ0416.1	MACSJ0717	MACSJ1149.5	Abell S1063	Abell 370
CATS	LENSTOOL	no	1	pre-HFF	10/2013	12/2013	12/2013	12/2013	12/2013	12/2013
			2	HFF-	_	10/2014	_	_	_	_
			2.1	HFF-	9/2015	_	_	_	_	_
			2.2	HFF-	9/2015	_	_	_	_	_
			3	$\mathrm{HFF}+$	9/2015	9/2015	_	_	_	_
			3.1	HFF+	9/2015	9/2015	_	_	_	_
Sharon	LENSTOOL	no	1	pre-HFF	10/2013	12/2013	12/2013	12/2013	12/2013	12/2013
Sildion	ELITOTOOL	по	2	pre-HFF	5/2014	5/2014	_	-	_	_
			3	HFF+	9/2015	9/2015	_	_	_	_
7:+	NFW		1	nno IIIDE	0/2012	0/2012	9/2013	0/2012	0/2012	0/2012
Zitrin	LTM	no	1	pre-HFF	9/2013	9/2013	,	9/2013	9/2013	9/2013
&Merten		no	1	pre-HFF	9/2013	9/2013	9/2013	9/2013	9/2013 $9/2013$	9/2013
	LTM-G WL	no	1	pre-HFF pre-HFF	9/2013	9/2013	9/2013	9/2013 $9/2013$	9/2013 $9/2013$	9/2013 $9/2013$
	NFW	yes no	1 3	HFF+	9/2013 $9/2015$	9/2013 $9/2015$	9/2013 —	9/2013	9/2013	9/2013
	LTM-G	no	3	HFF+	9/2015	9/2015	_	_	_	_
	BIM G					0/2010				
GLAFIC		no	1	HFF-	11/2014	_	_	_	_	_
			3	HFF+	2/2016	2/2016	_	_	_	_
Williams	GRALE	no	1	pre-HFF	9/2013	9/2013	9/2013	9/2013	9/2013	9/2013
			2	HFF-	_	10/2014	_	_	_	_
			3	HFF+	_	11/2015	_	_	_	_
			3.1	HFF+	11/2015	11/2015	_	_	_	_
Bradăc		Troc	1	pre-HFF	9/2013	9/2013	9/2013	9/2013	9/2013	9/2013
Diadat		yes	2	HFF-	9/2015 $9/2015$	9/ 2013 —	9/2013 —	9/ 2013 —	9/ 2013 —	<i>9/2</i> 013 —
Diego		?	3	HFF+	_	2/2016	_	_	_	_

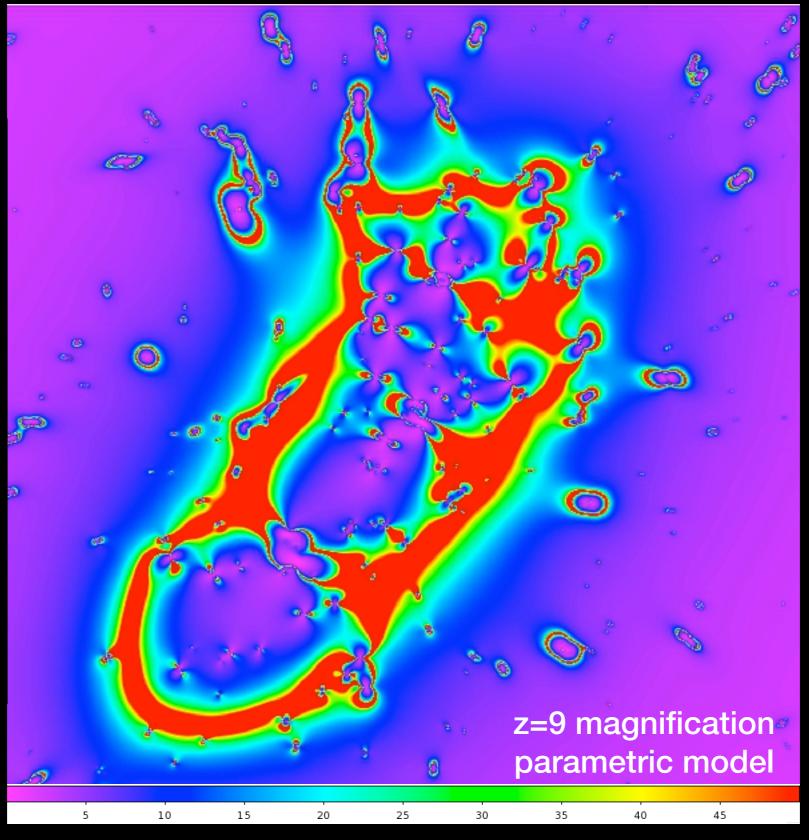
new lensing model contracts awarded to 5/8 proposals, including 2 new groups. work starts summer 2016; deliveries due 2/2017, 2/2018



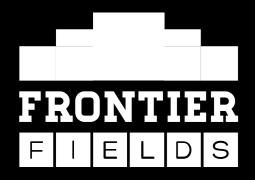


2 spec z + ground-based photz

post-HFF: 60 multiple image systems

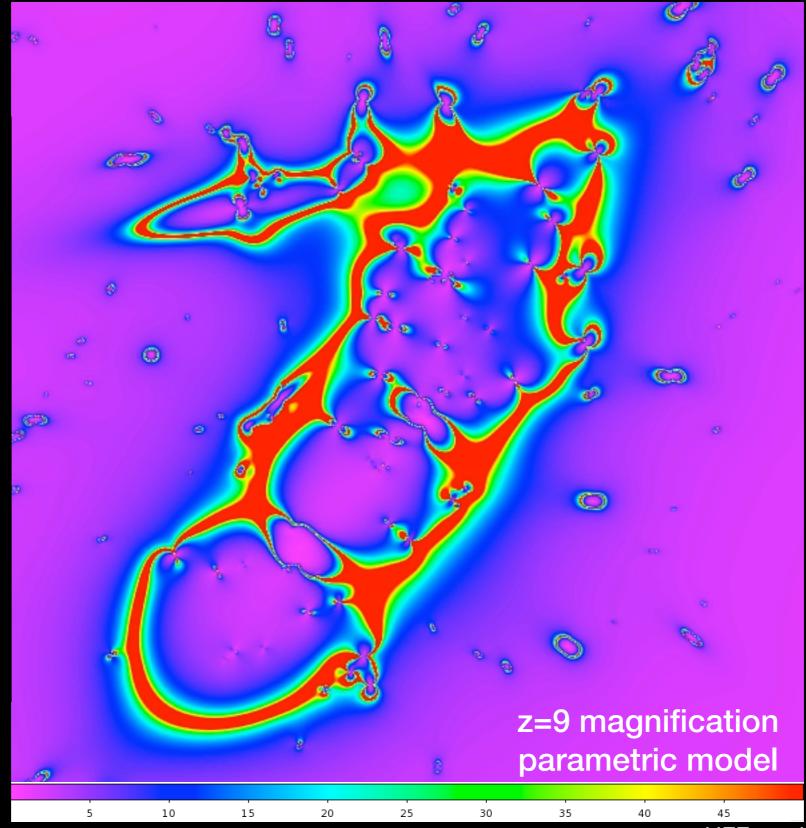




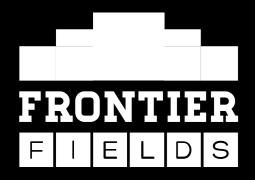


2 spec z + ground-based photz

post-HFF: 60 multiple image systems

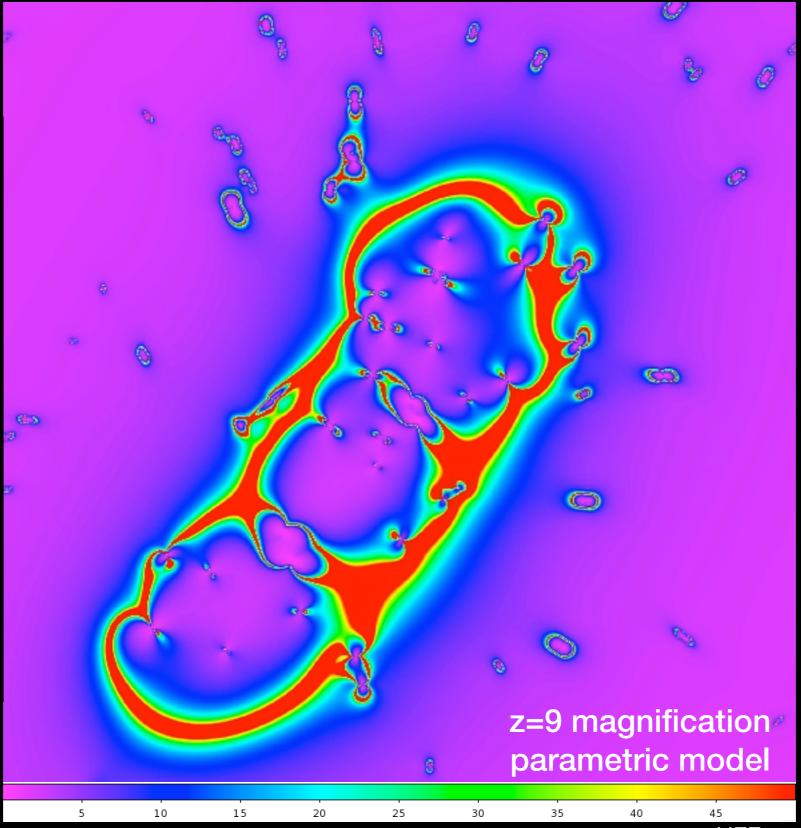




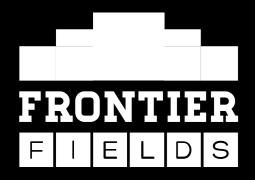


2 spec z + ground-based photz

post-HFF: 60 multiple image systems

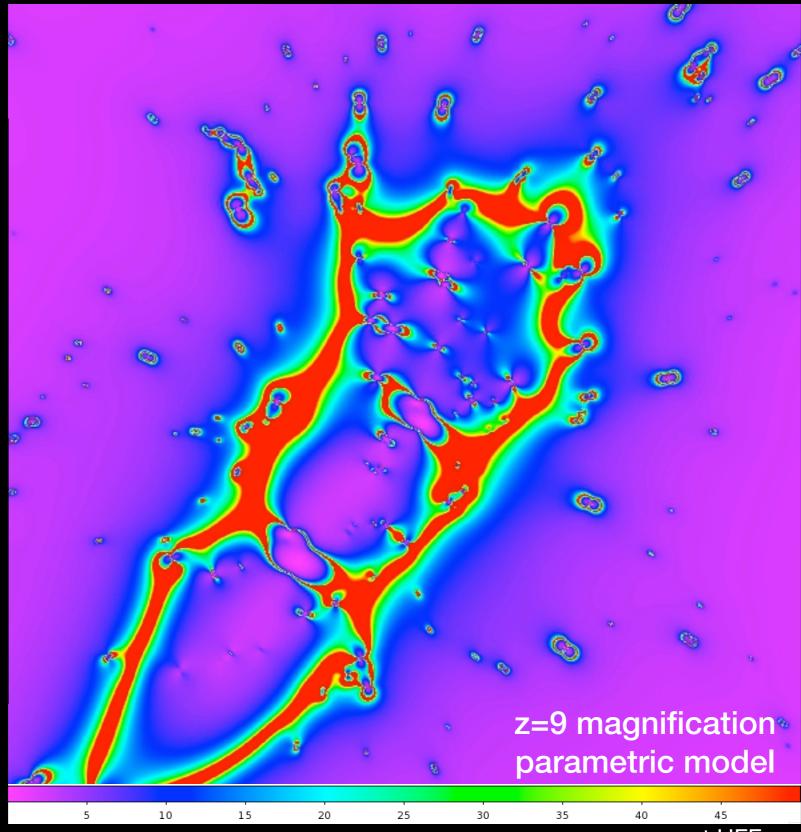






2 spec z + ground-based photz

post-HFF: 60 multiple image systems



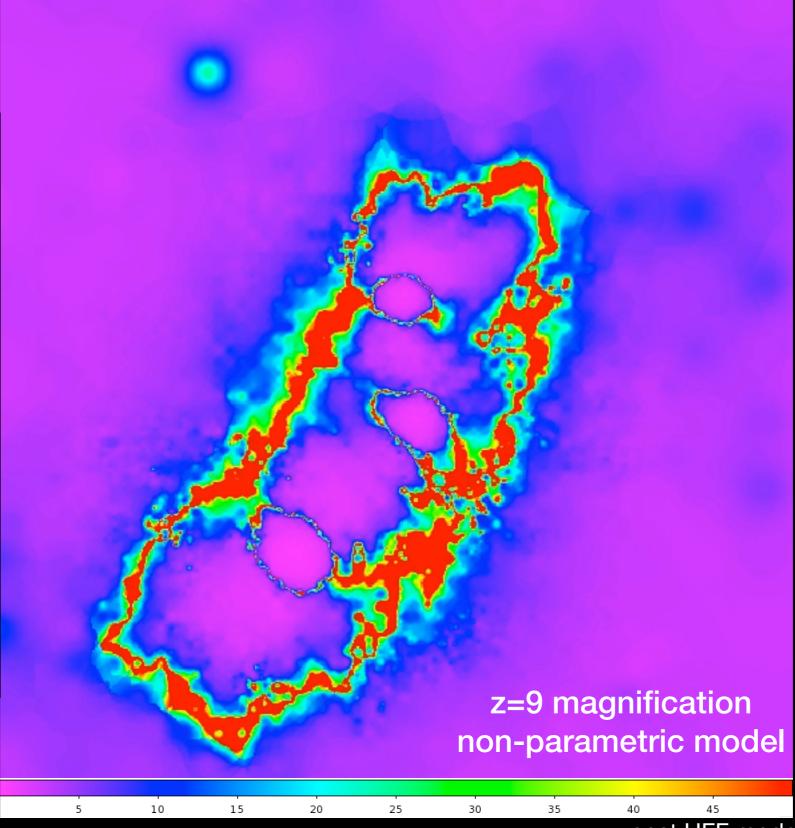


#### Abell 2744

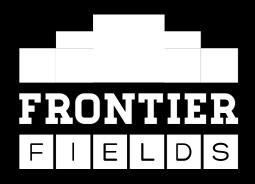
pre-HFF: 18 multiple image systems

2 spec z + ground-based photz

post-HFF: 60 multiple image systems

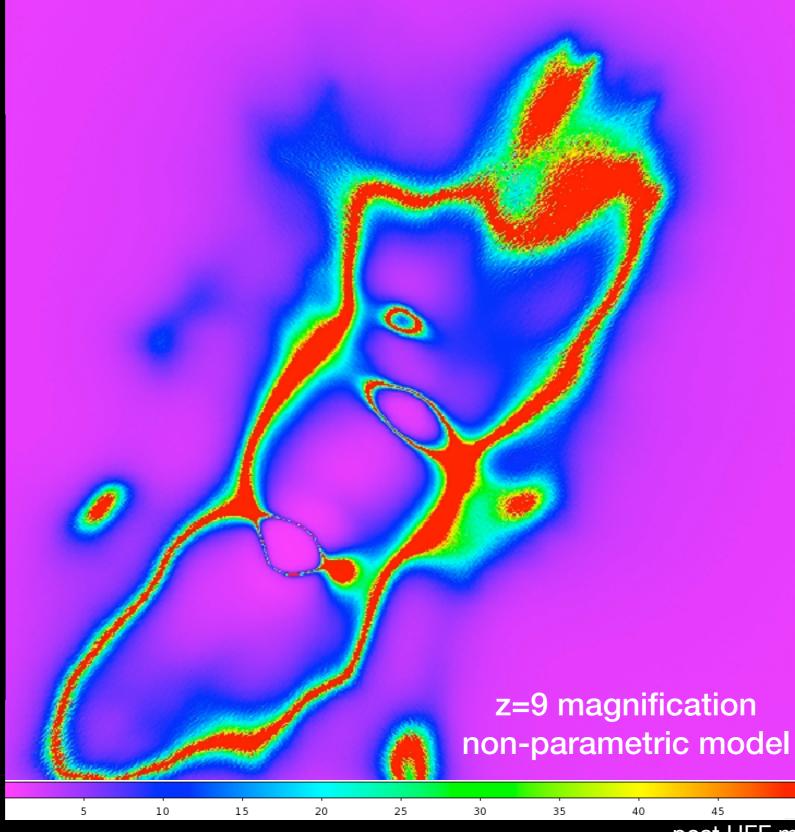




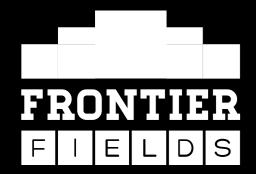


2 spec z + ground-based photz

post-HFF: 60 multiple image systems

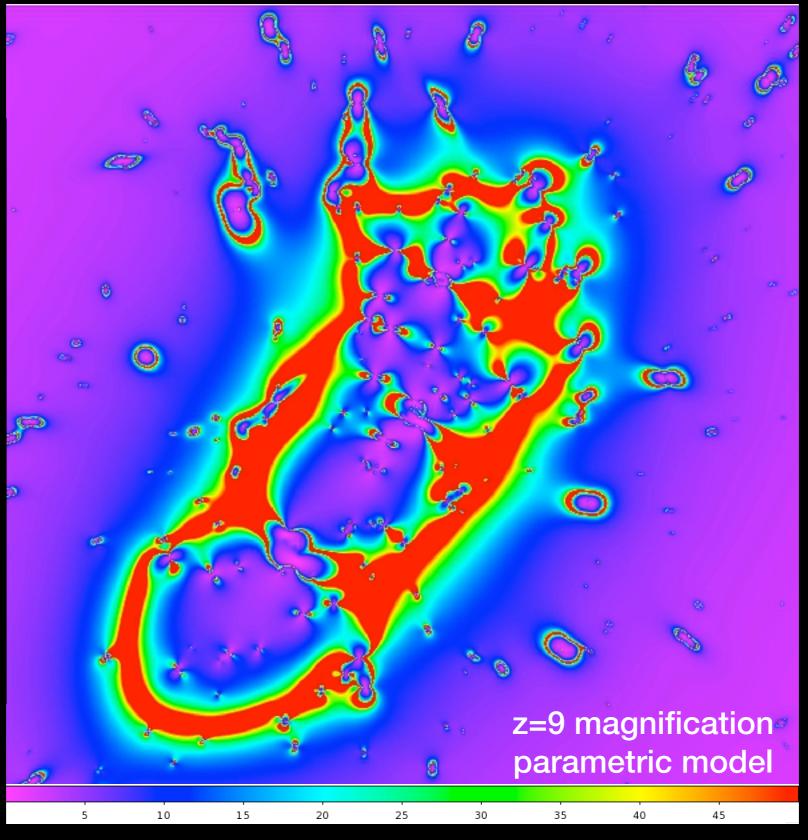






lensing models are converging

more specz will help

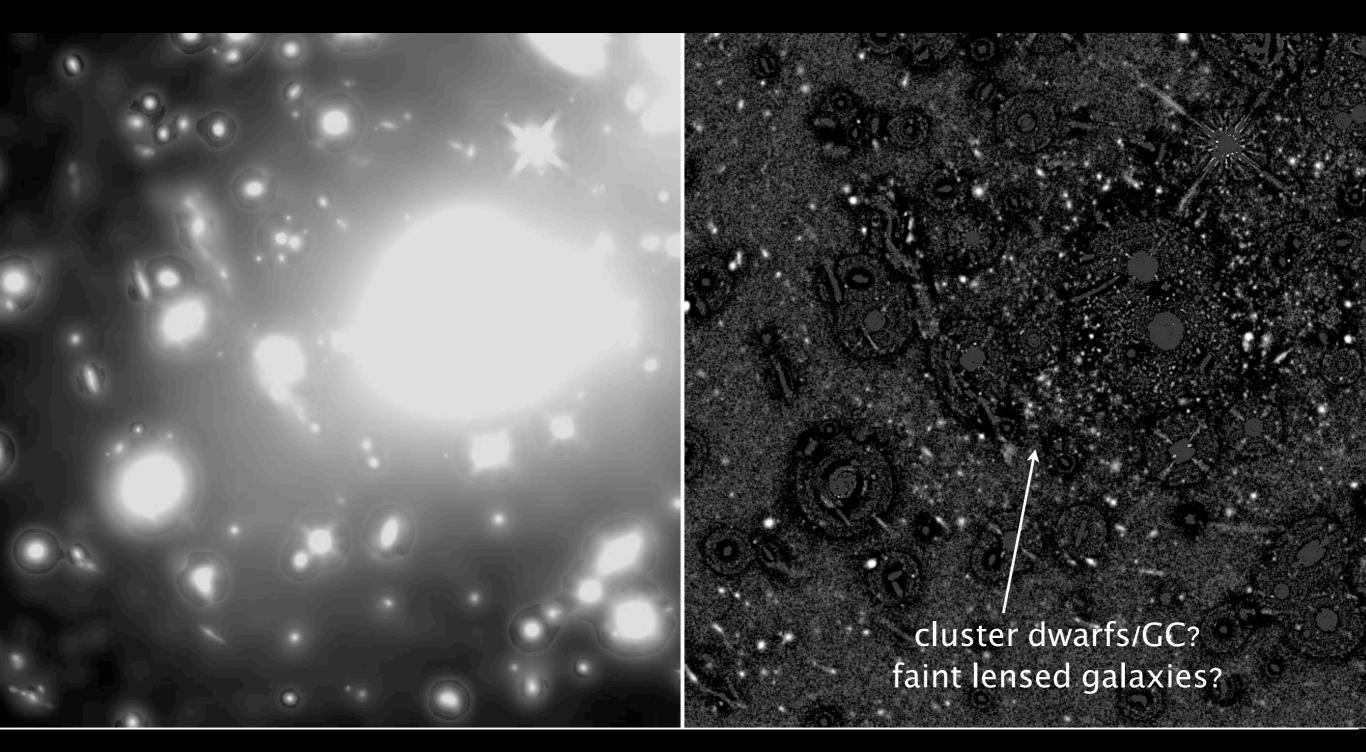




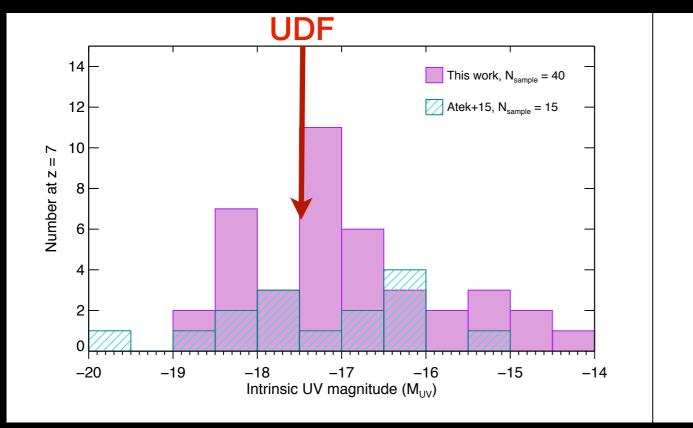


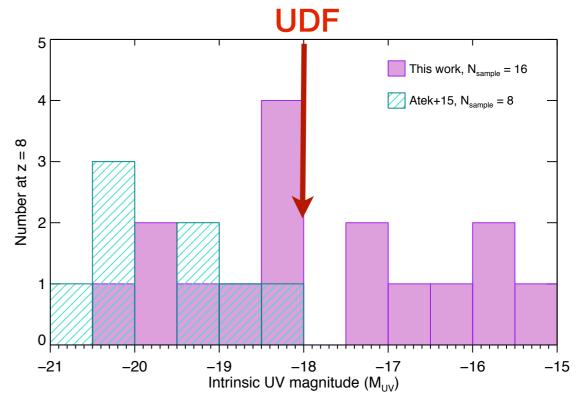
regions of highest magnification are in very crowded regions hard to detect faintest objects above background

wavelet decomposition -subtract large-scale "foreground" (cluster + ICL)
+ identify small-scale structures



## faintest high-z galaxies in Abell 2744 + MACSJ0416

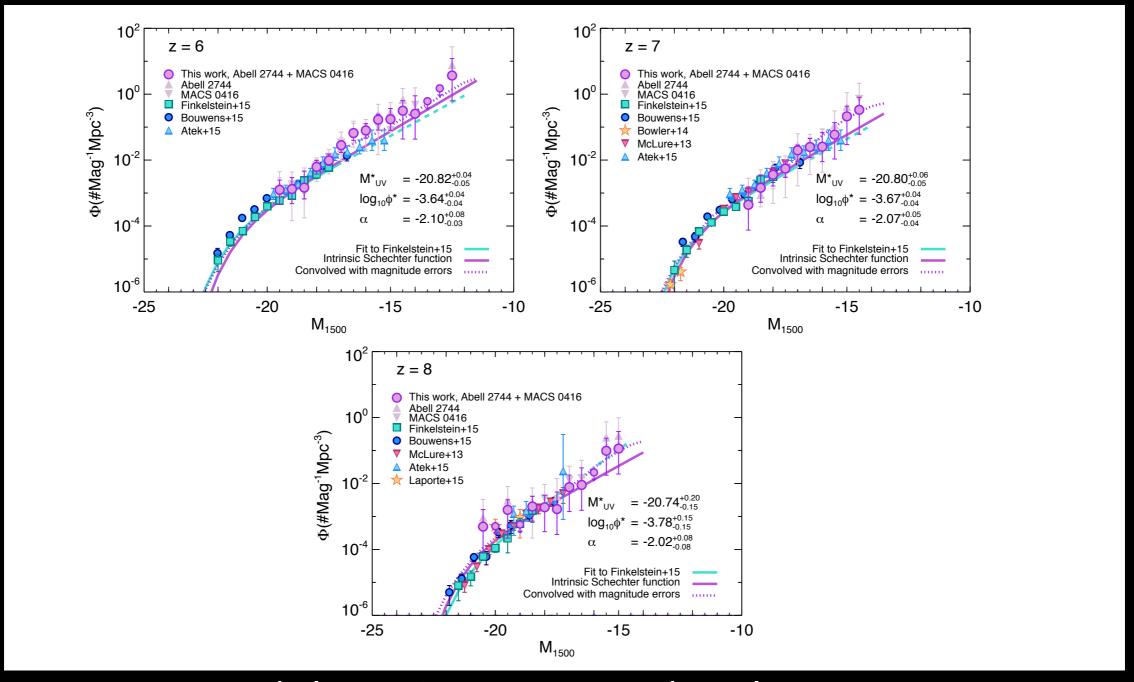




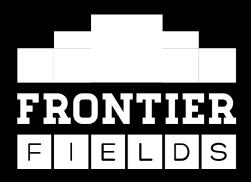
Livermore, Finkelstein, & Lotz 2016; Atek et al. 2015 high magnifications ⇒ intrinsic luminosities fainter than UDF

(also - Iskigaki et al. 2014; Atek et al. 2014; Laporte et al. 2014; Zitrin et al. 2014, Oesch et al. 2015; Merlin et al. 2016; McLeod et al. 2016; ... )

## faintest high-z galaxies in Abell 2744 + MACSJ0416



Livermore, Finkelstein, & Lotz 2016; Atek et al. 2015 high magnifications ⇒ intrinsic luminosities fainter than UDF



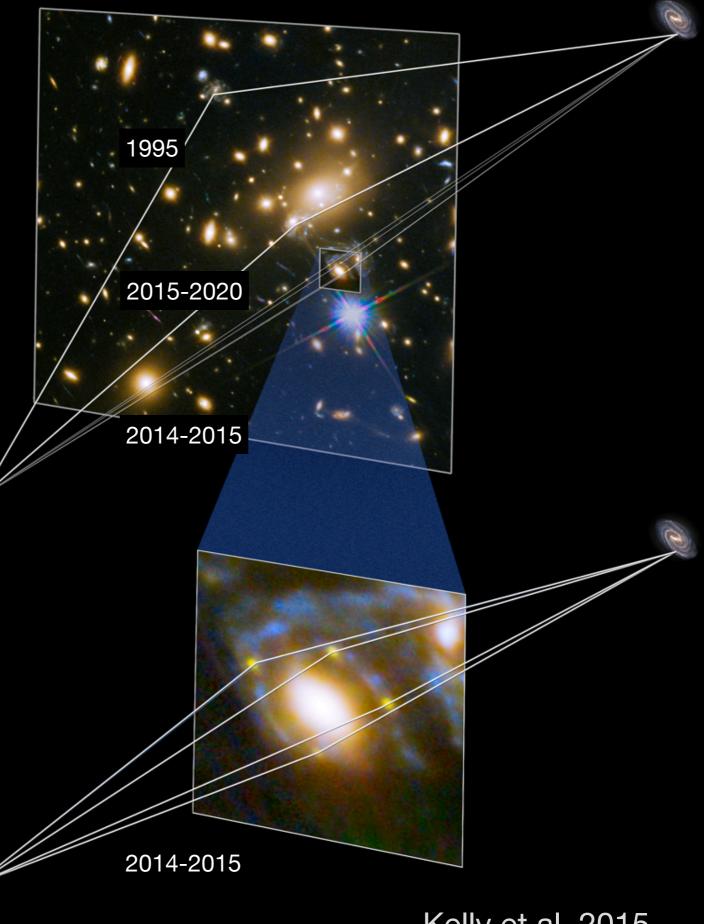
the unexpected ...

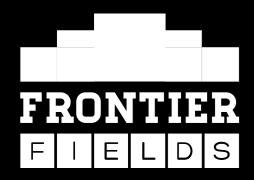
1 supernova far away exploded 9 billion years ago...

4 images appearing now

1 image appeared in past

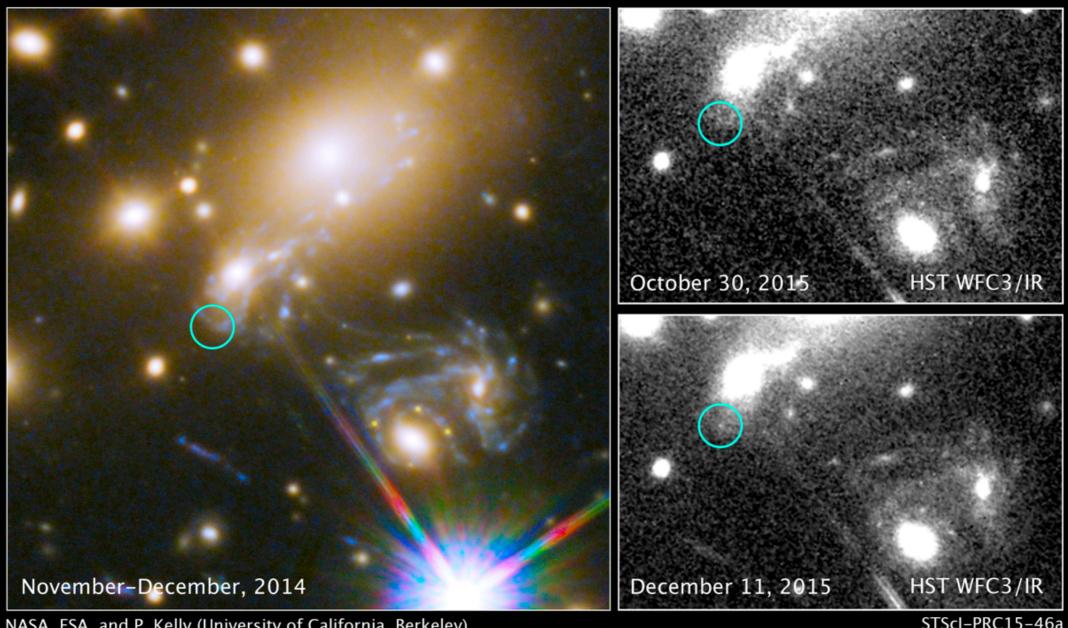
1 image will appear in future





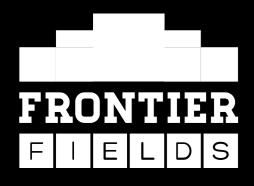
## successful prediction for SN Refsdal time-delay

#### Supernova Refsdal • Galaxy Cluster MACS J1149.5+2223 • HST WFC3 ACS

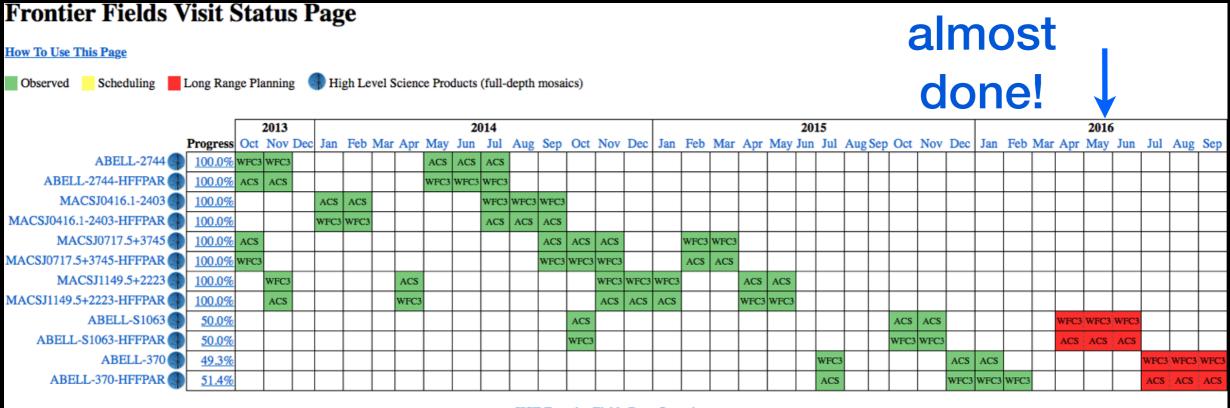


NASA, ESA, and P. Kelly (University of California, Berkeley)

STScI-PRC15-46a



# HST Observing Schedule Cycle 22, 23, 24



HST Frontier Fields Data Overview
HST Frontier Fields Archive Data Products Page

#### MAST High Level Data Pages:

- ABELL-2744 + Parallel Field
- MACSJ0416.1-2403 + Parallel Field
- MACSJ0717.5+3745 + Parallel Field
- MACSJ1149.5+2223 + Parallel Field
- ABELL-S1063 + Parallel Field
- MACSJ1149.5+2223 + Parallel Field
- ABELL-370 + Parallel Field



## Spitzer observations completed 12/2015

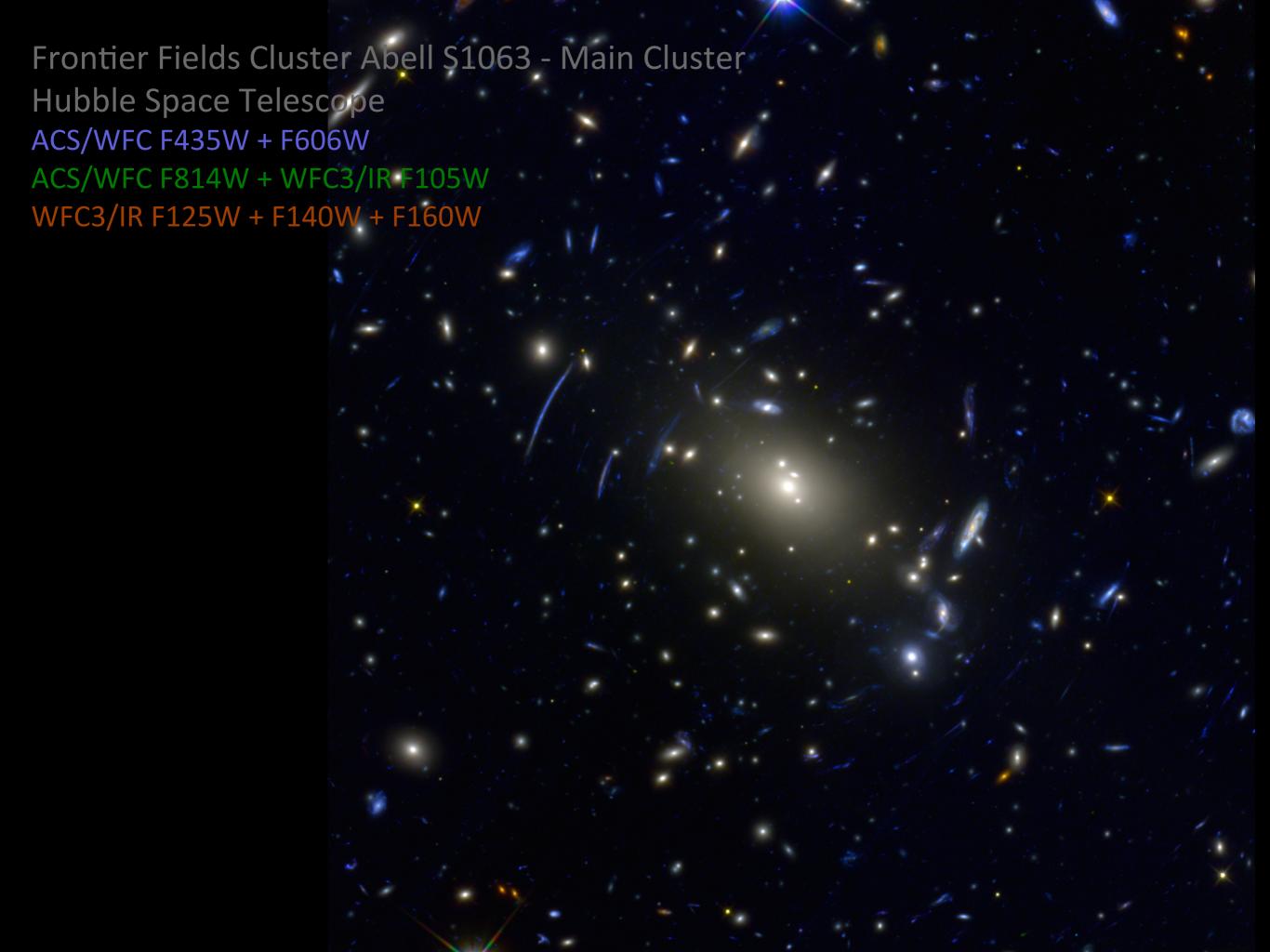
http://irsa.ipac.caltech.edu/data/ SPITZER/Frontier/

Last updated: 2016-03-08T23:01:03.318143

#### broader impacts for HST community

- astrodrizzle/drizpac testing by HFF data pipeline team
- improved ACS bias striping algorithms
  - developed ACS "self-calibration" of CTE effects in dark
  - testing of WFC3/IR "blob" mask, sky flats
  - •WFC3/IR variable sky ramp fitting algorithm
  - testing WFC3/IR bright sky avoidance observing strategy
  - better scheduling buffers for severe WFC3/IR persistence events
  - •first set of theoretical models in MAST directly linked to HST data

coming soon: v2.0 data reductions for first 4 clusters + parallels





4 clusters and parallels are done; last 2 complete in Sept 2016

Spitzer, Chandra, XMM, ALMA, LMT, VLA, VLT Hawk-I, MUSE, Gemini GEMS AO, Keck, GTC ancillary observing campaigns

public Abell 2744 + MACSJ0416 lensing models updated; future updated models planned for Spring 2017, Fall 2017

first 2 clusters have probed faintest galaxies ever seen during EoR

full HFF data + best models

⇒ strong constraints on faint UVLF during the EoR