Extremely Large Clusters in the Era of Extremely Large Telescopes (Cosmology, not Galaxy Evolutionism*)

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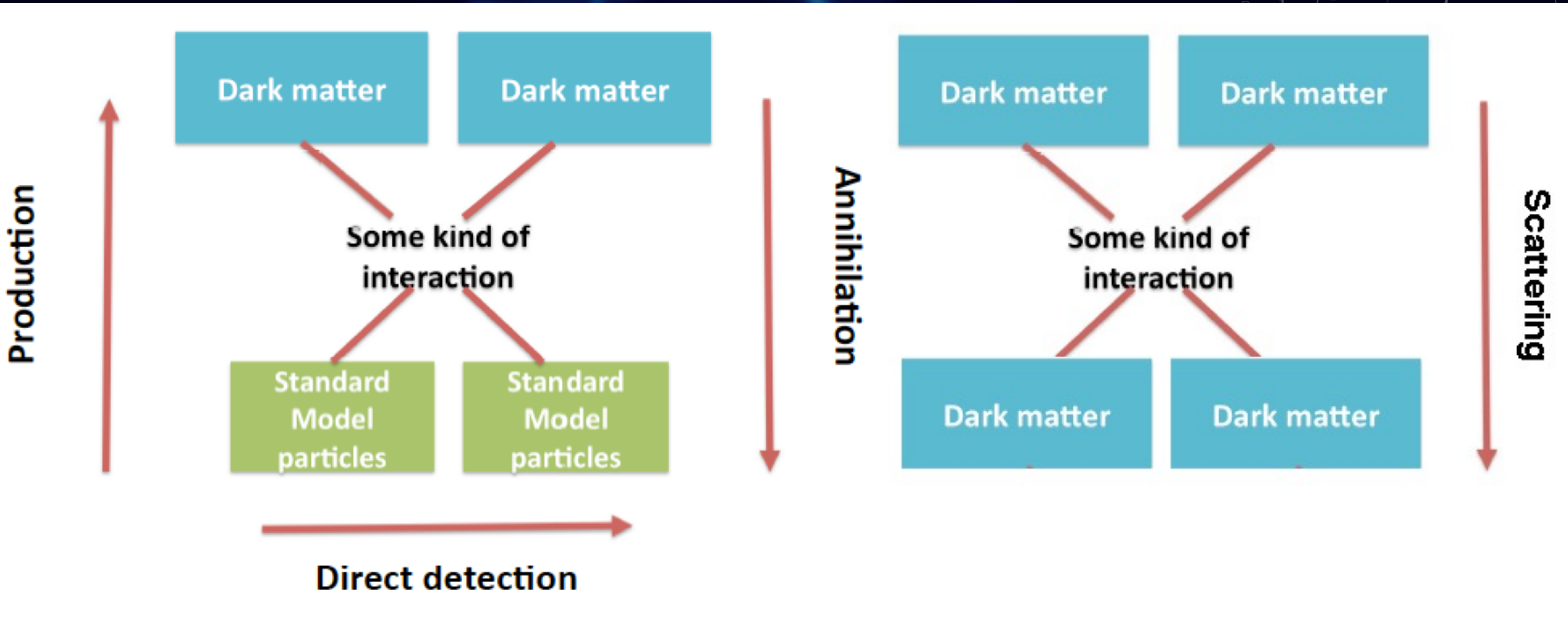
Looking at the DM from many directions

LHC

Fermi, Early Universe



Xenon, CDMS, Dama, etc.

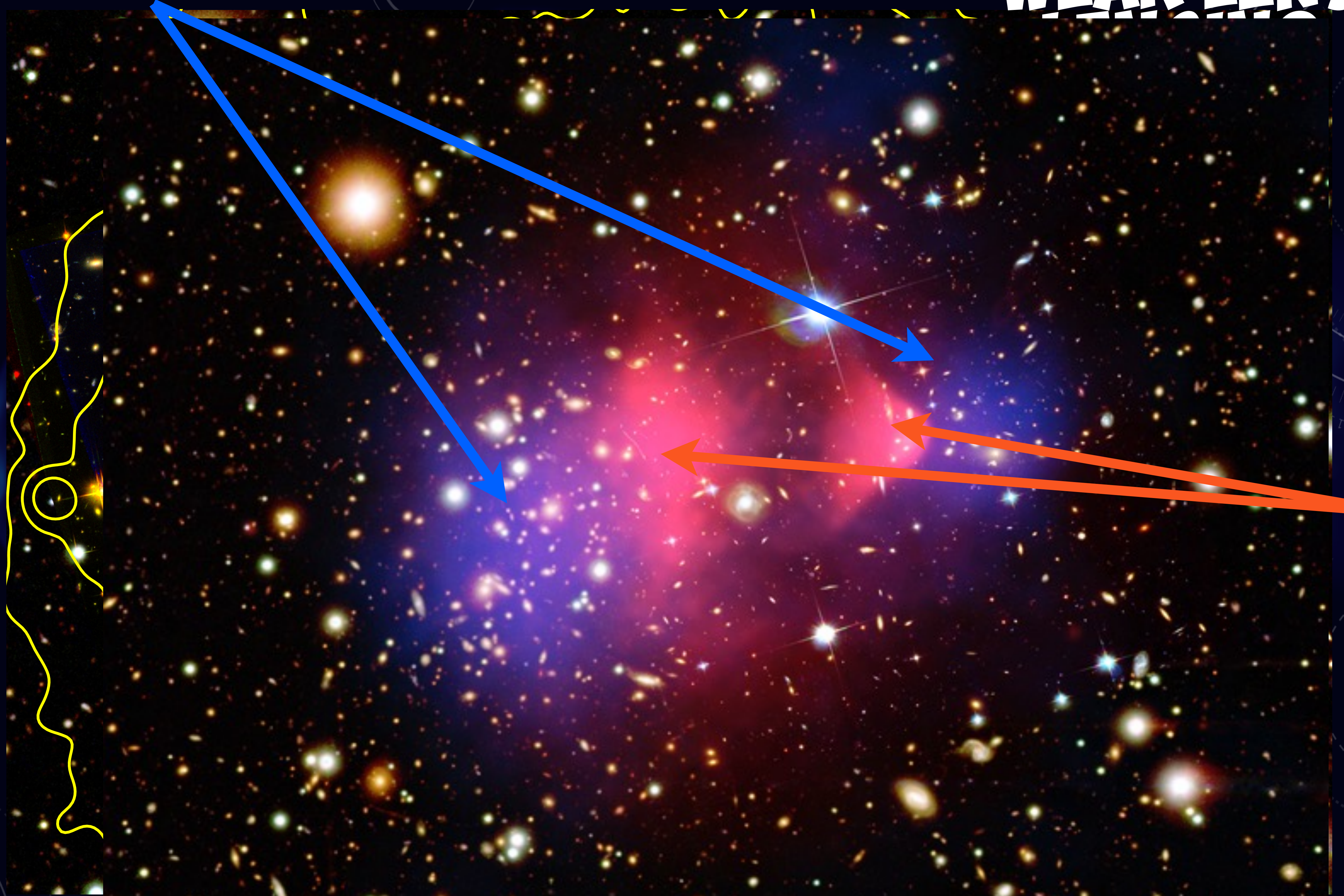
adapted from Peter et al. 2012

The Bullet Cluster 1E0657-56

WEAK & STRONG LENSING

WEAK LENSING

Total Matter



Gas

Clowe, M. et al 2006

Bradač, M. et al 2006

Dark Matter Self-(non)Interaction

$\sigma/m < 0.7\ \mathrm{cm^2 g^{-1}}$
Randall et al. 2008

$\sigma/m < 4\ \mathrm{cm^2 g^{-1}}$
Bradač et al. 2008

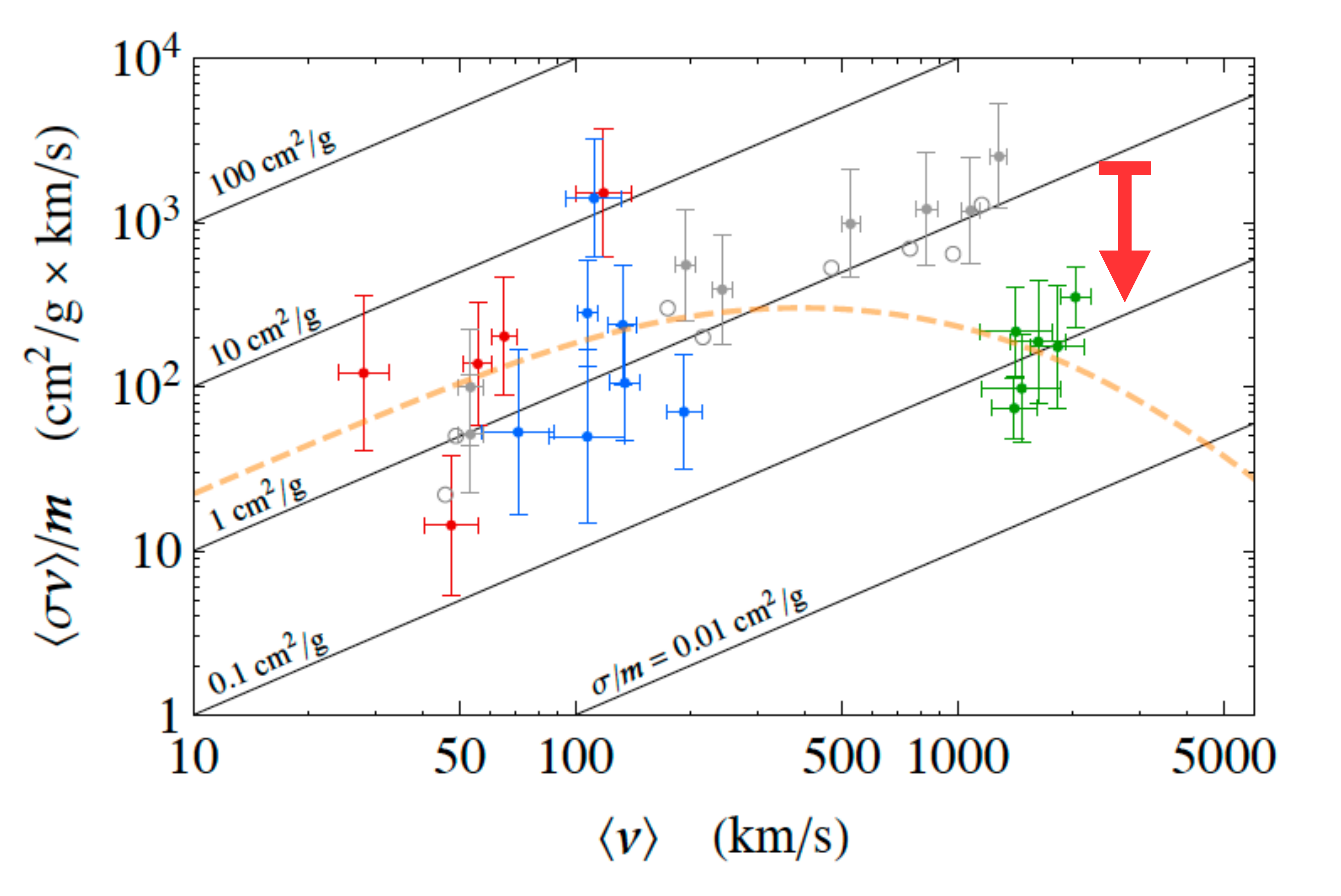
$\sigma/m < 3\ \mathrm{cm^2 g^{-1}}$
Merten et al. 2011

$\sigma/m < 3\ \mathrm{cm^2 g^{-1}}$
Clowe et al. 2012

$\sigma/m < 7\ \mathrm{cm^2 g^{-1}}$
Dawson et al. 2012

- $\sigma/m < 0.05\ \mathrm{cm^2 g^{-1}}$ will be effectively the same as CDM in terms of observables of structure (halo profiles, shapes, substructure fraction)

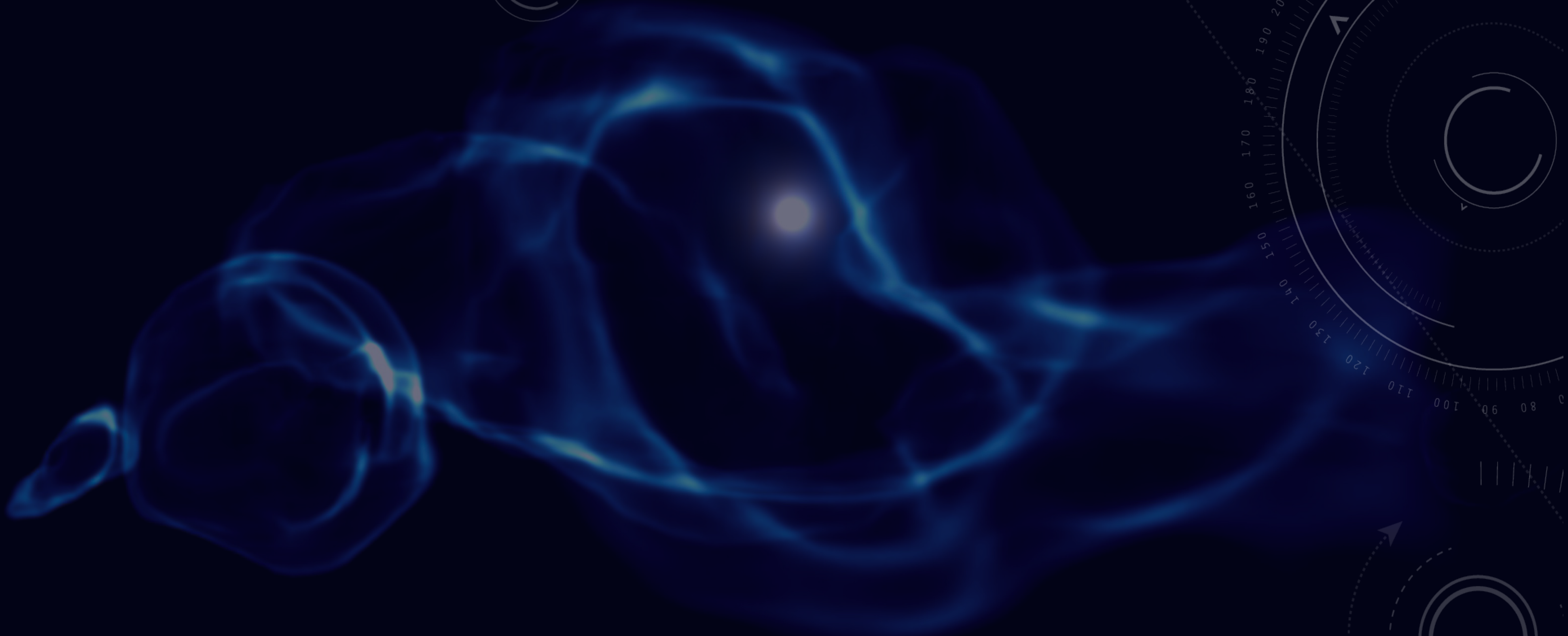
Self-interaction



Kaplinghat et al. 2015

MERGING CLUSTER COLLABORATION

Will we ever do better?



- Merging Cluster Collaboration–MC^2
- UC Davis – UC Irvine collaboration led by PI Dawson
- Radio Relics: 29 clusters; 8 in the GOLD sample (Golovich, incl. MB et al. 2018)

Merging Cluster Collaboration

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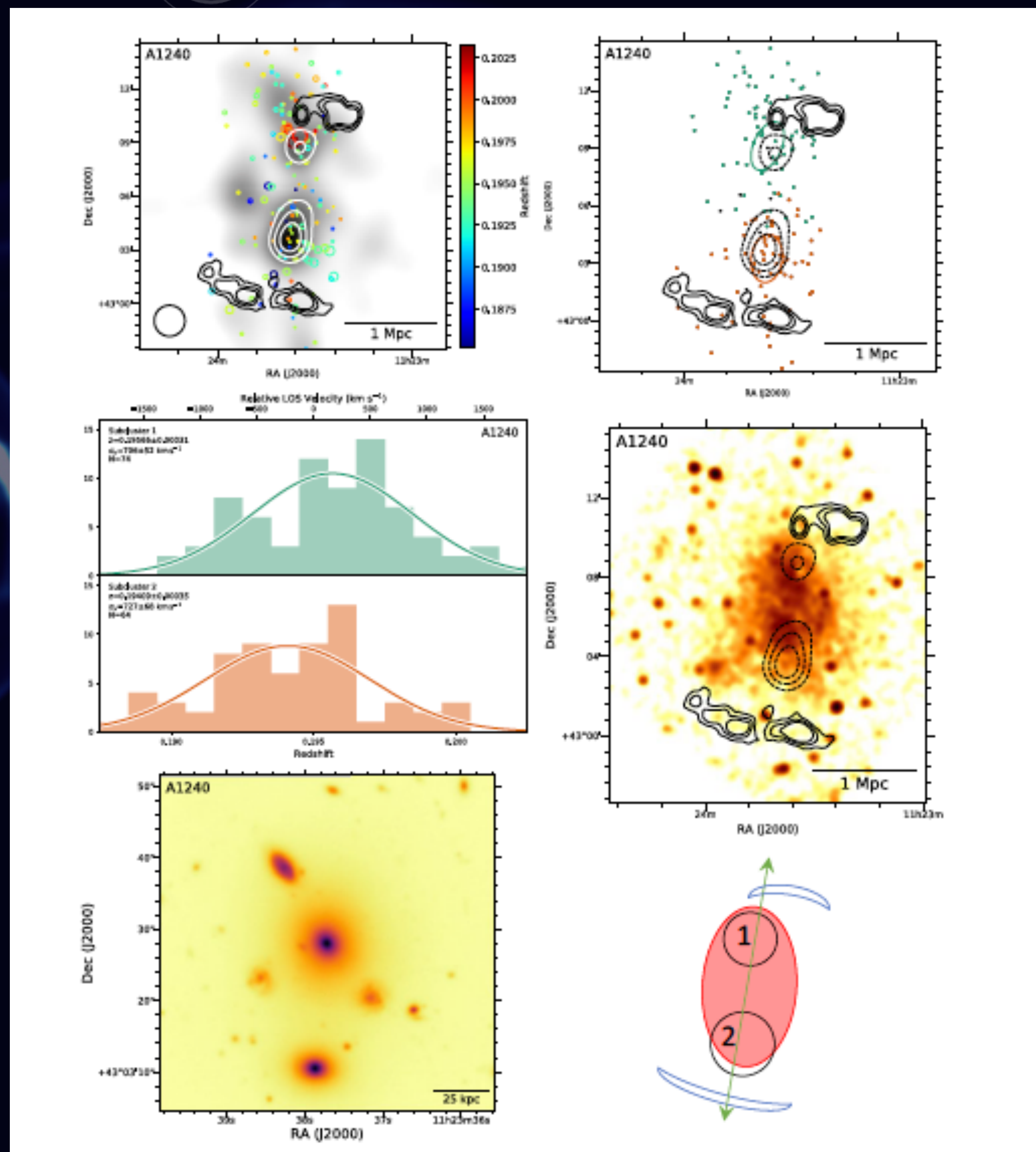
- Golovich, incl. MB et al. 2018

Will we ever do better?



Golovich et al. 2018a,b

MERGING CLUSTER COLLABORATION

- Golovich, incl. MB et al. 2018

What do we need?

- Gravitational lensing measurement (HST, WFIRST, ELTs)
- Radio, Xray observations
- Dynamical analysis (ELTs)
- Simulations!! (DM properties, but also systematics)

Systematics

- Brightest cluster galaxies (BCG) oscillate around the centre of the merger remnant on stable orbits of 100 kpc (SIDM simulations $1 cm^2/g$, Kim et al 2017)
- But also in LCDM things move (Ng et al. 2017; Ilustris):
  - BCG $\lesssim$ 4 kpc offsets and the luminosity peak $\lesssim$ 32 kpc
  - Shrinking aperture, number density and centroid give a large offset scatter of about 50–100 kpc
  - Sloshing, geometry, etc.
- Also need accurate lens models…

Spectroscopic redshifts are key!

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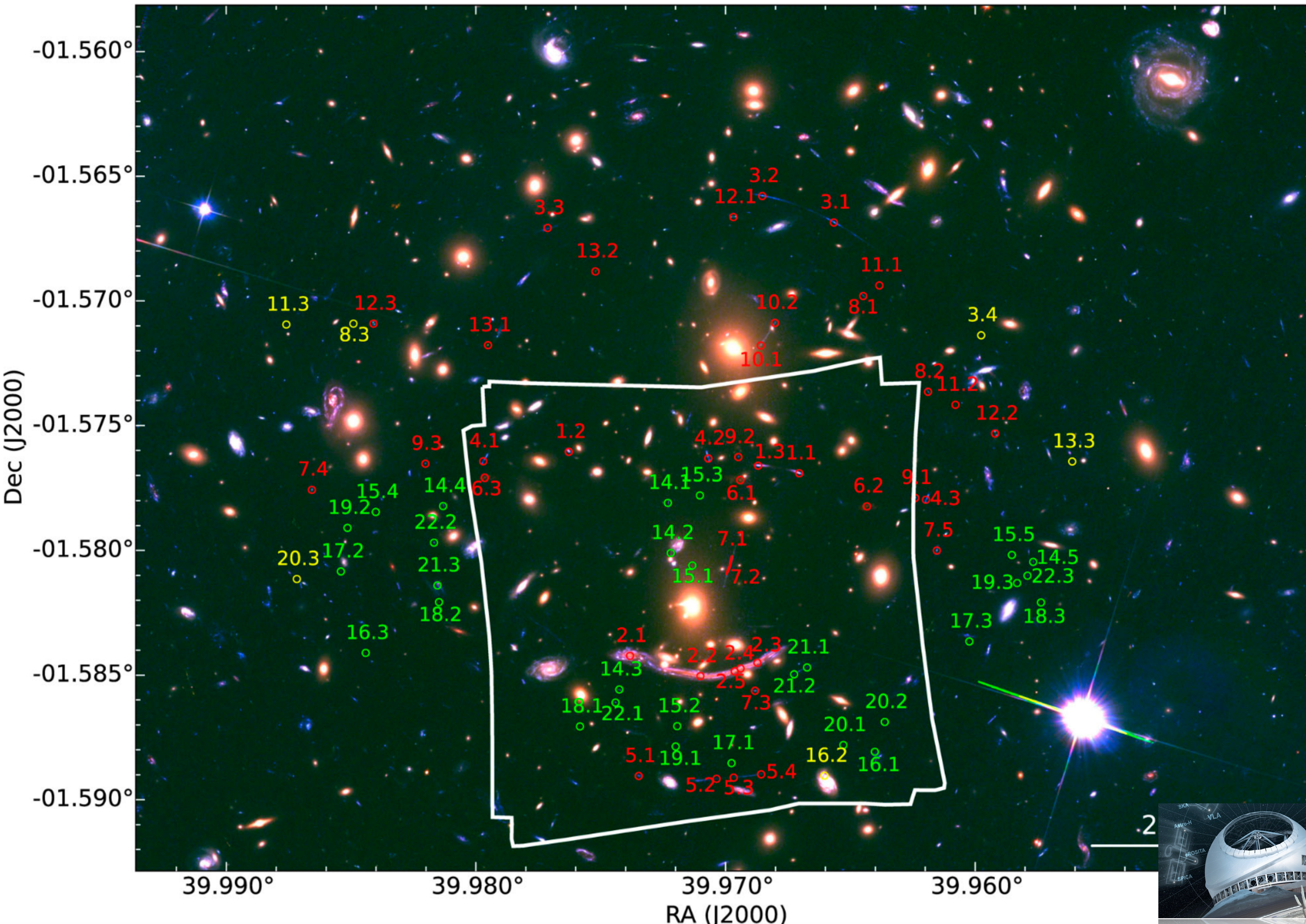
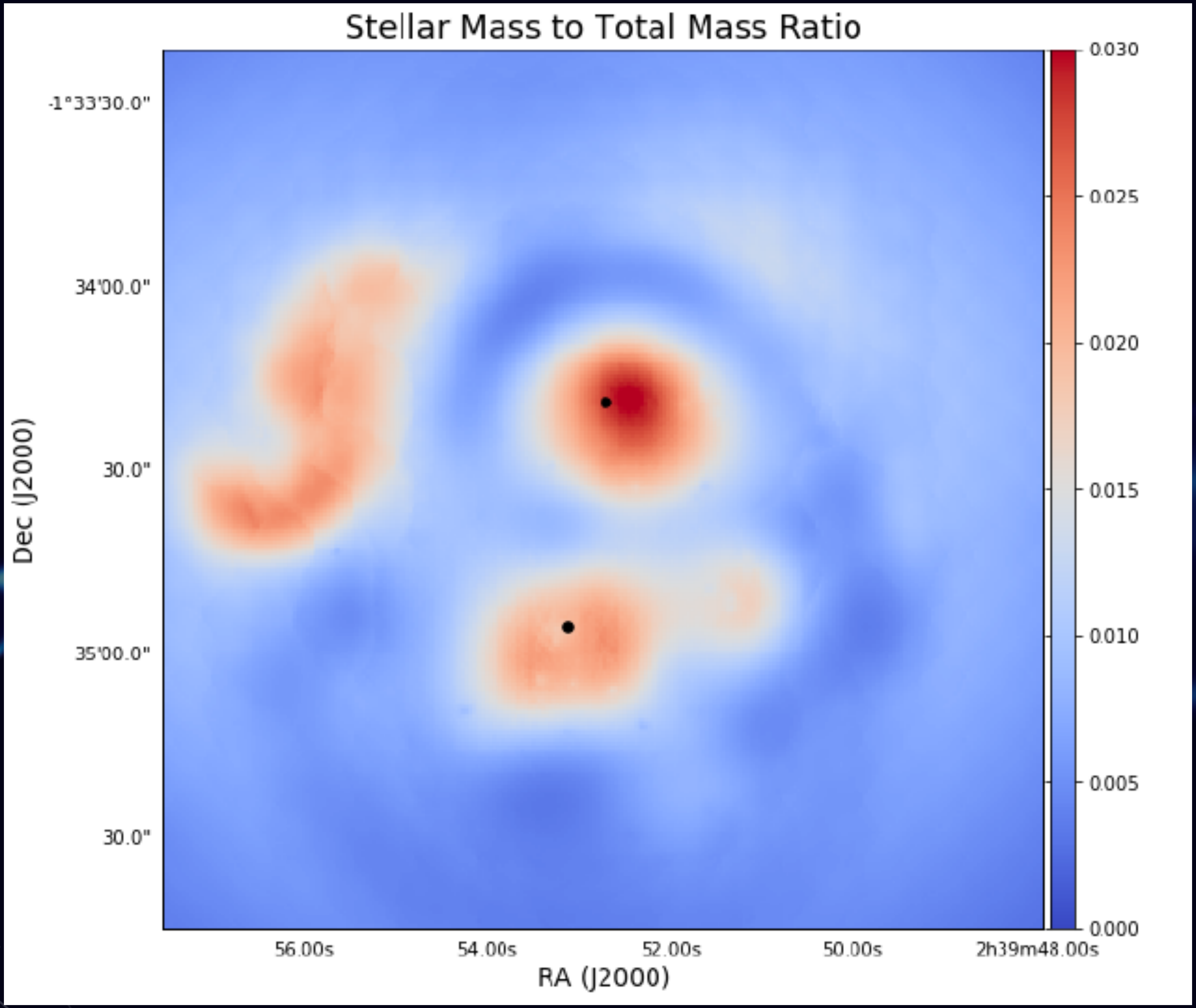


Lagattuta et al. 2017 MUSE; also see CLASH-VLT, GLASS

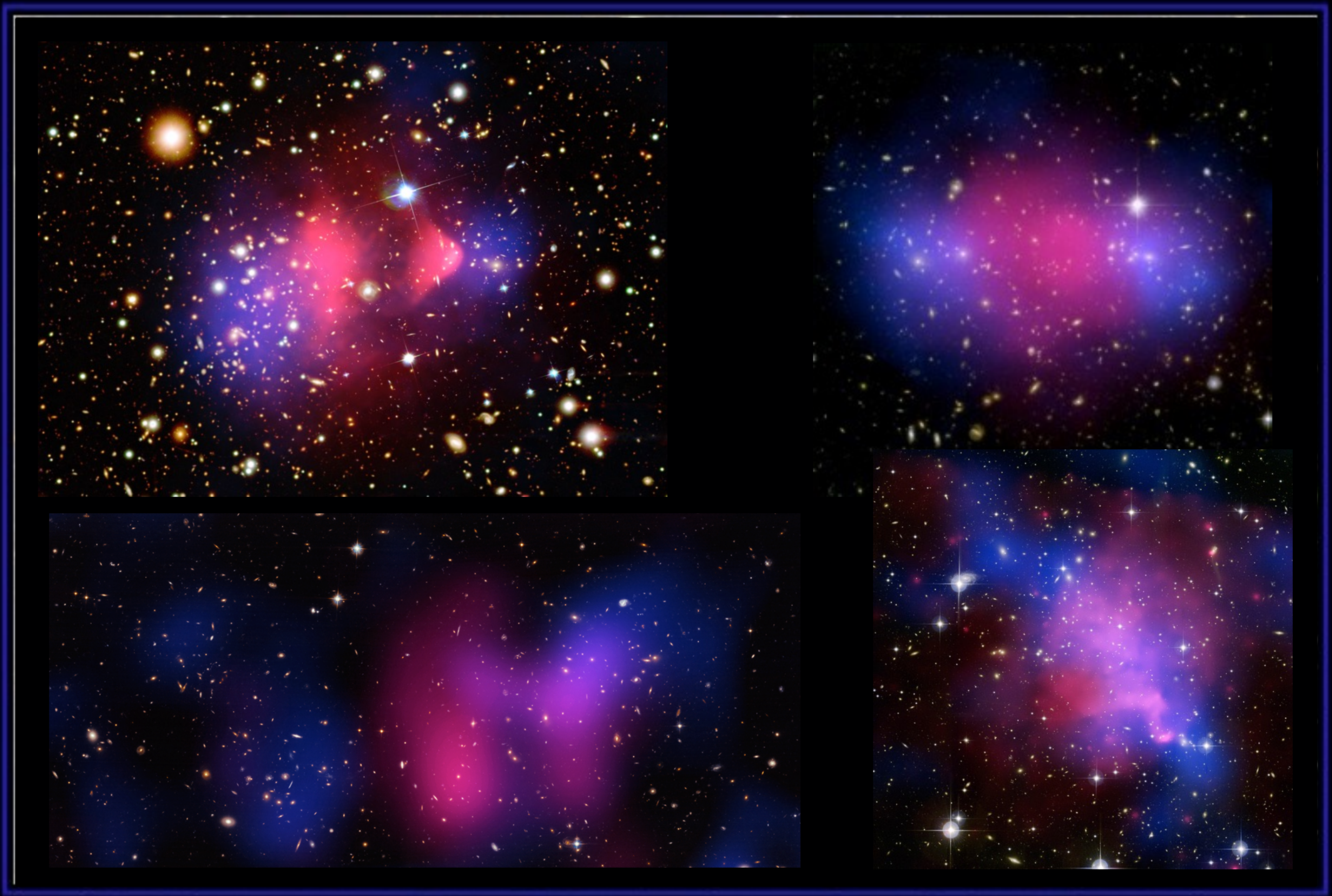
Systematics



$f^{*}=0.008\pm0.003$

A370

Strait et al. 2018

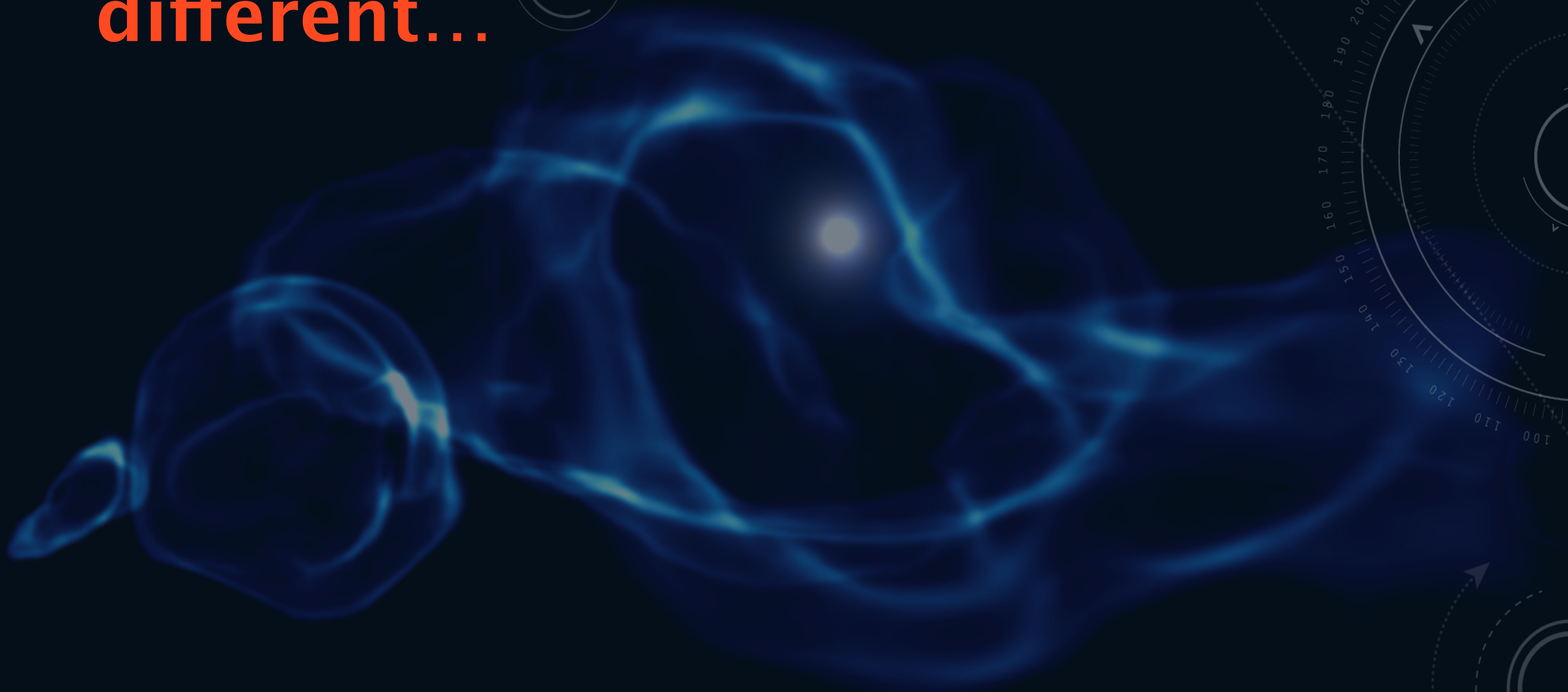


DARK MATTER

Most of the universe can't even be bothered to interact with you.

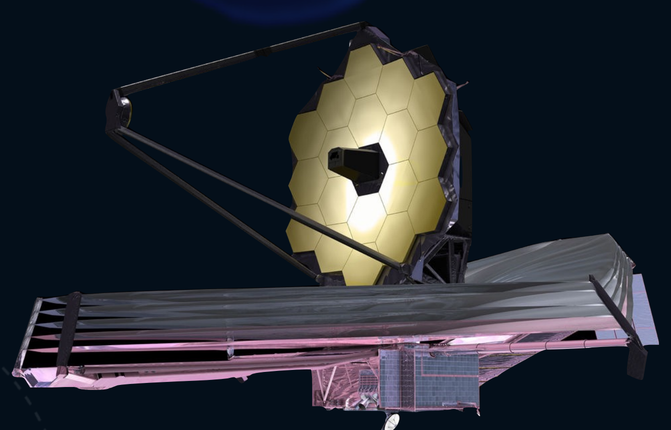
S.Caroll

And now for something completely different…



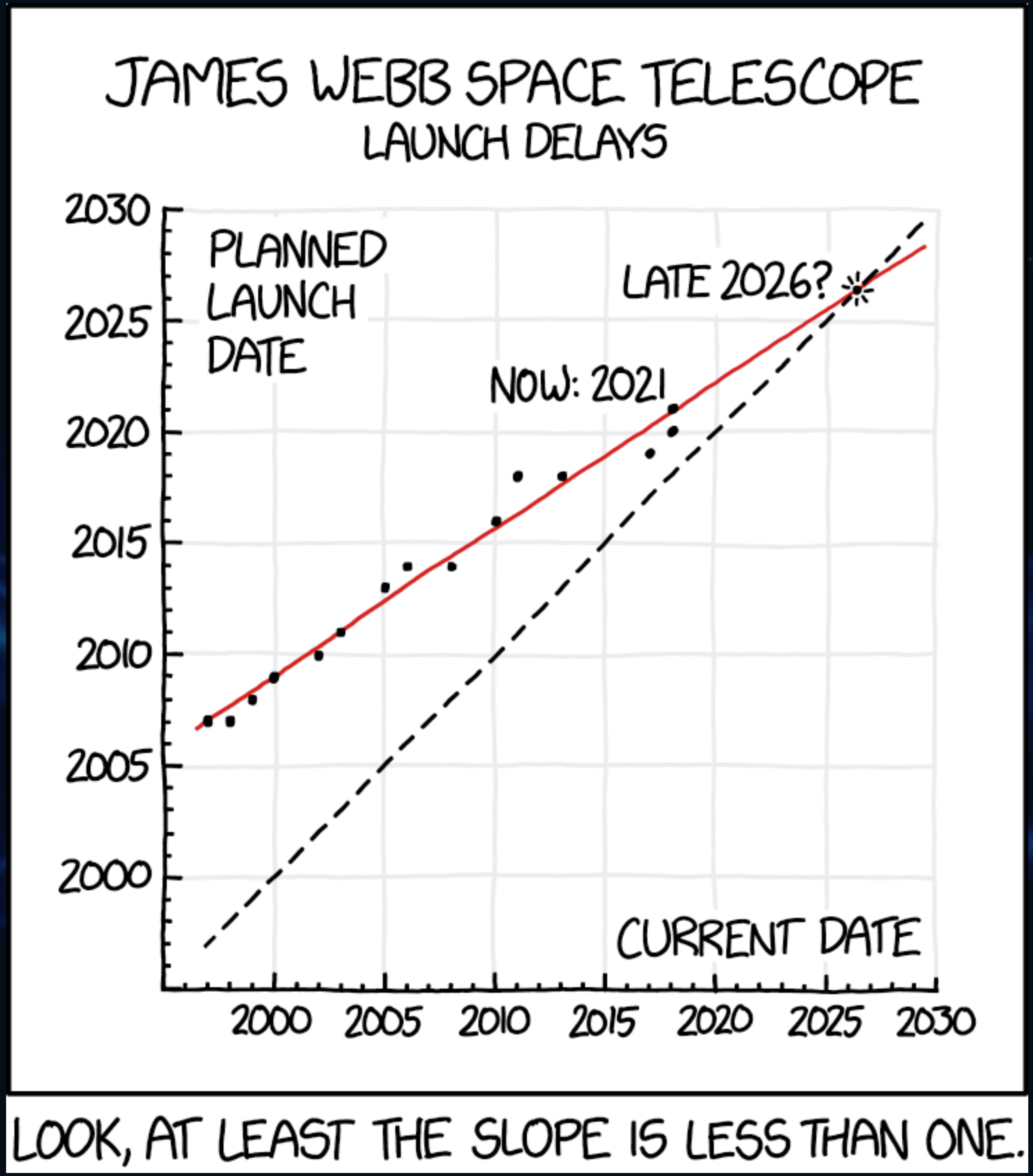
And now for something completely different….

- When did reionization occur and how?
- What are the sources of first light? Can they sustain reionization?
- What are the properties of first galaxies?



vs

…to see the first light in the Universe…

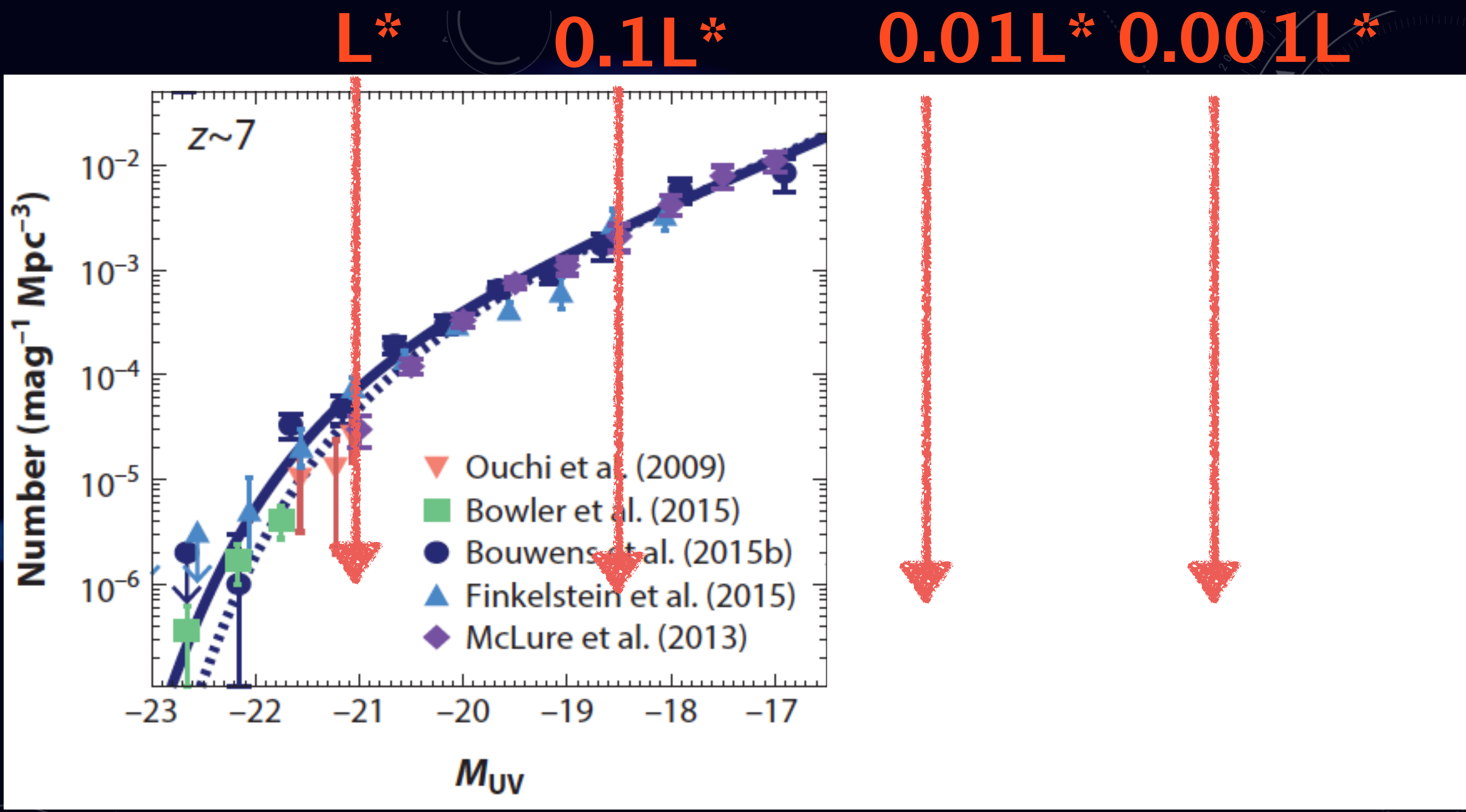


…to see the first light in the Universe…

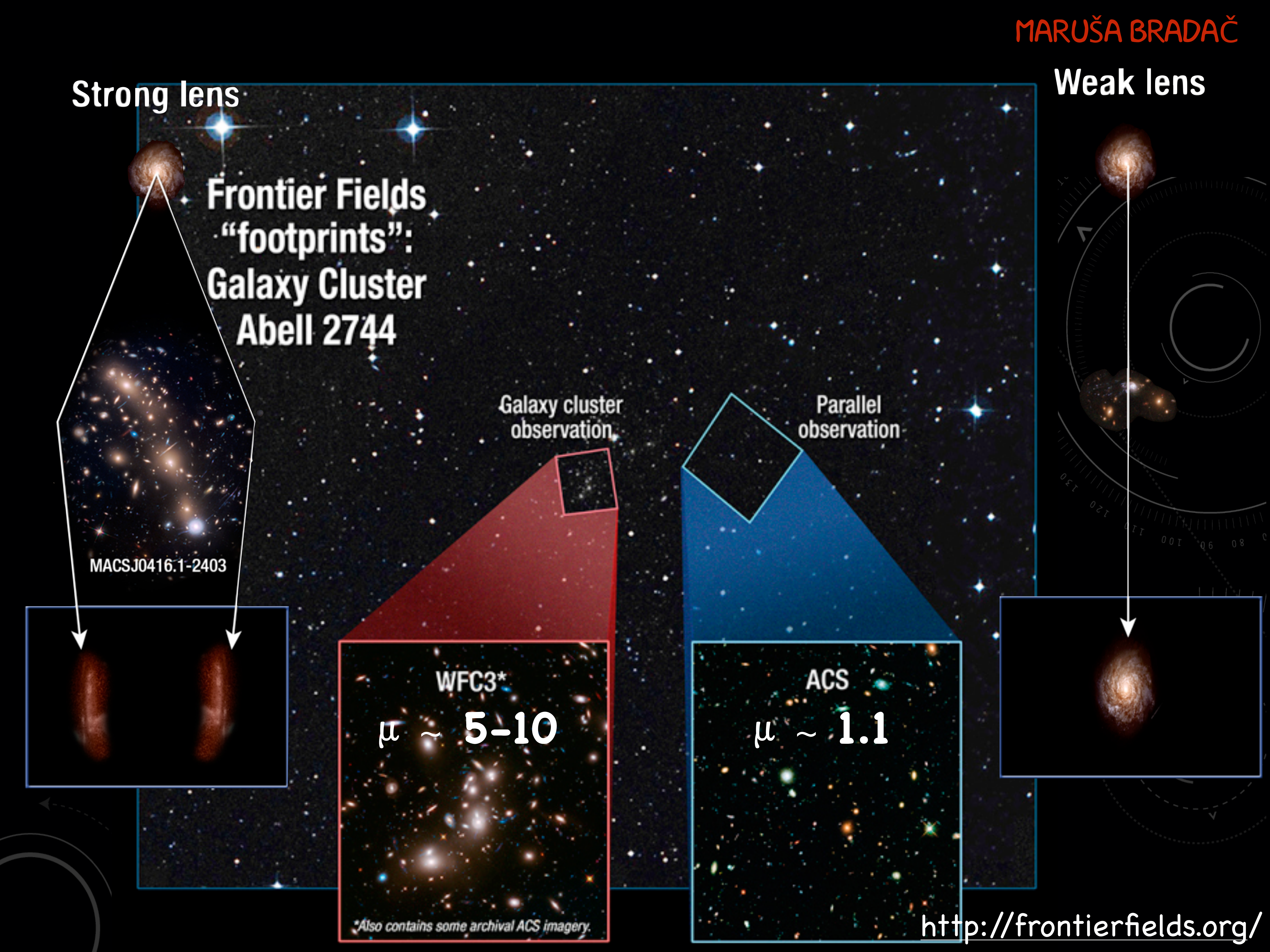
Some big open questions....

- When did reionization occur?
- What are the sources of first light? Can they sustain reionization?
  - Galaxies: steep LF ❓, older stellar population ❓, large ξ_{ion} ❓, f_{esc}=0.2 ❓
  - Quasars: f_{esc}=1.0 ❓, faint-end LF ❌
- What are the properties of first galaxies? 👀

A LF extending to 0.001L*?



Stark et al. 2015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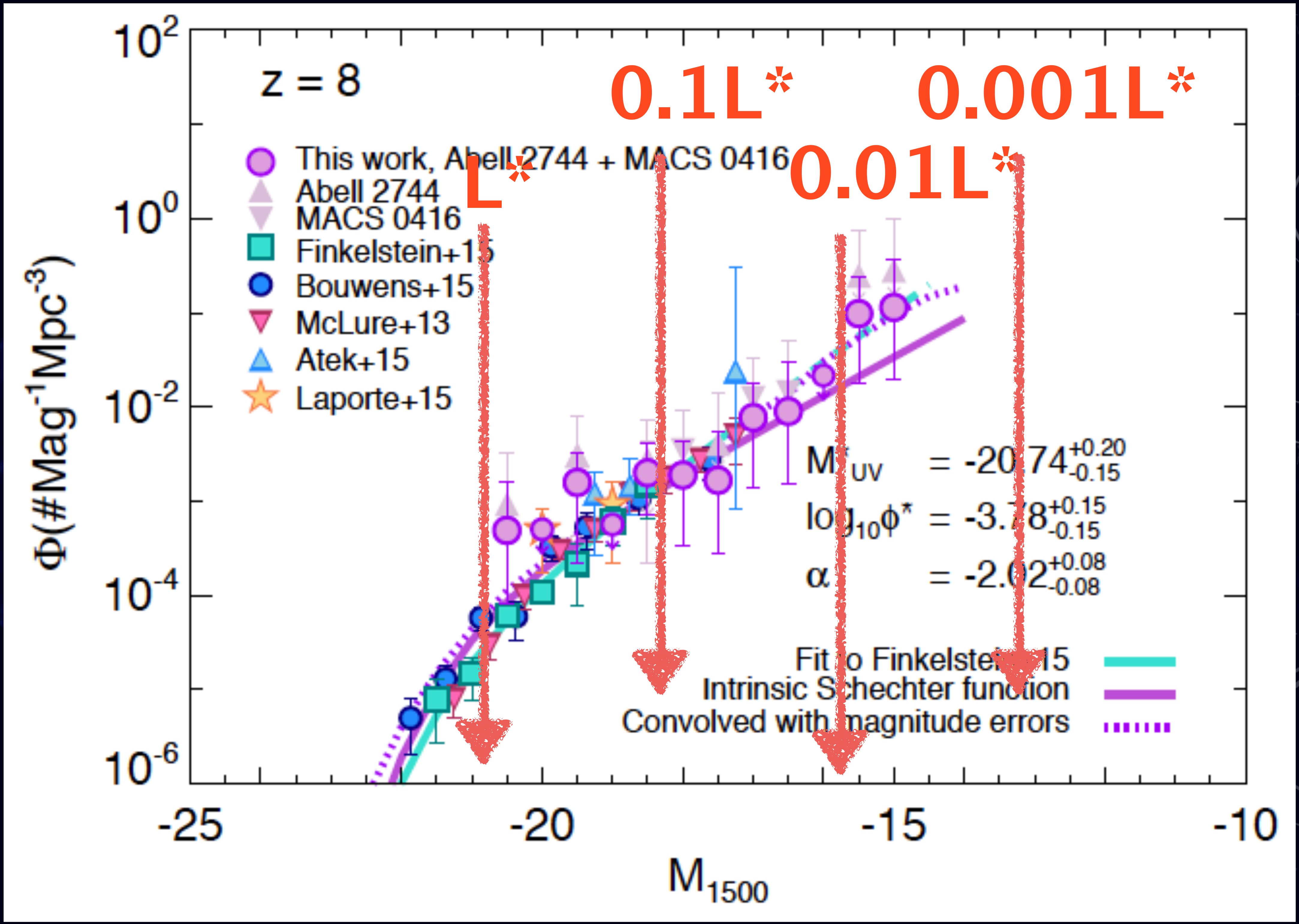
Strong lens
Weak lens
Frontier Fields
"footprints":
Galaxy Cluster
Abell 2744
MACSJ0416.1-2403
Galaxy cluster
observation
Parallel
observation
WFC3*
μ ~ 5-10
ACS
μ ~ 1.1
*Also contains some archival ACS imagery.
http://frontierfields.org/

Luminosity function → lensed version



Livermore et al. 2016

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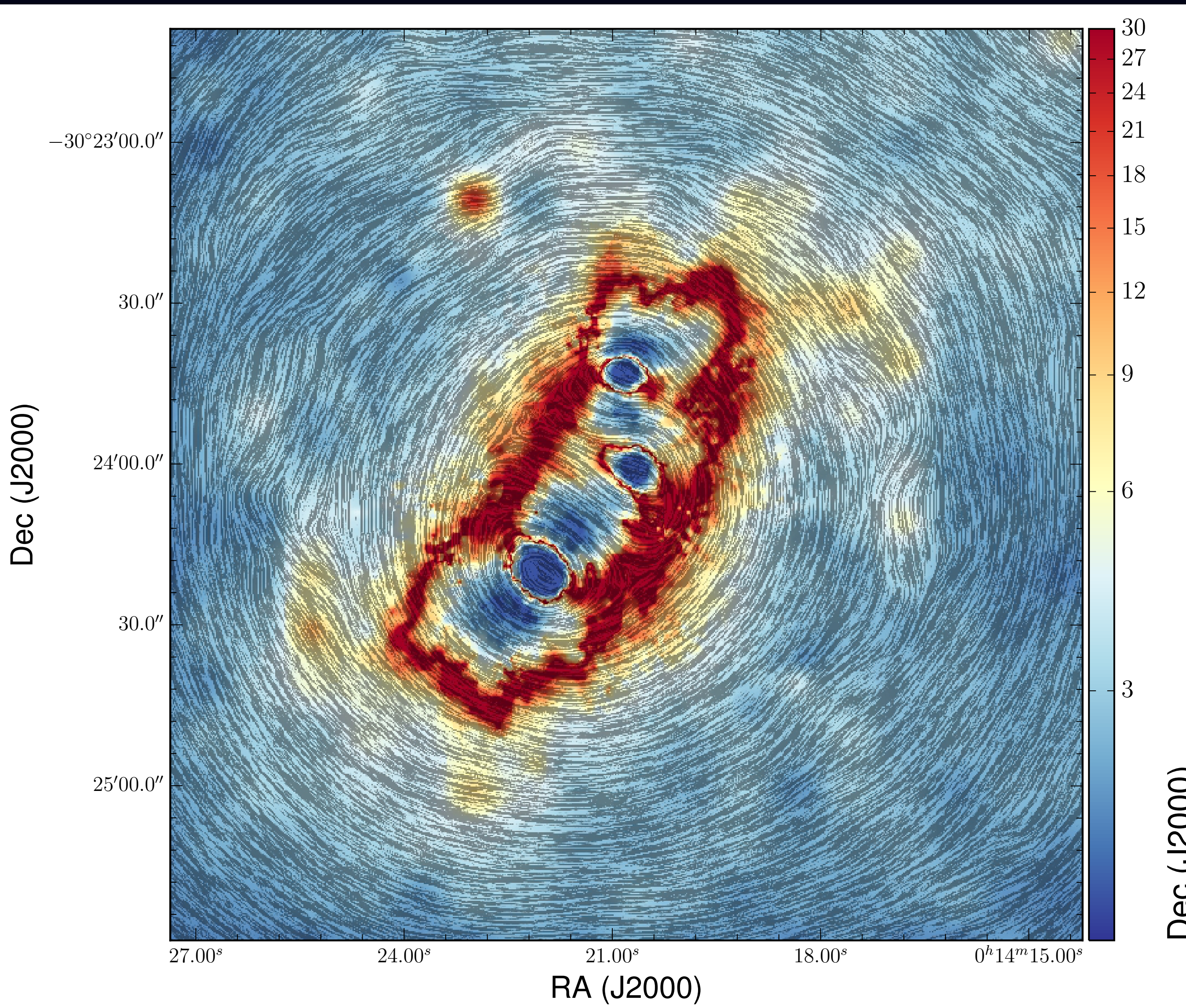
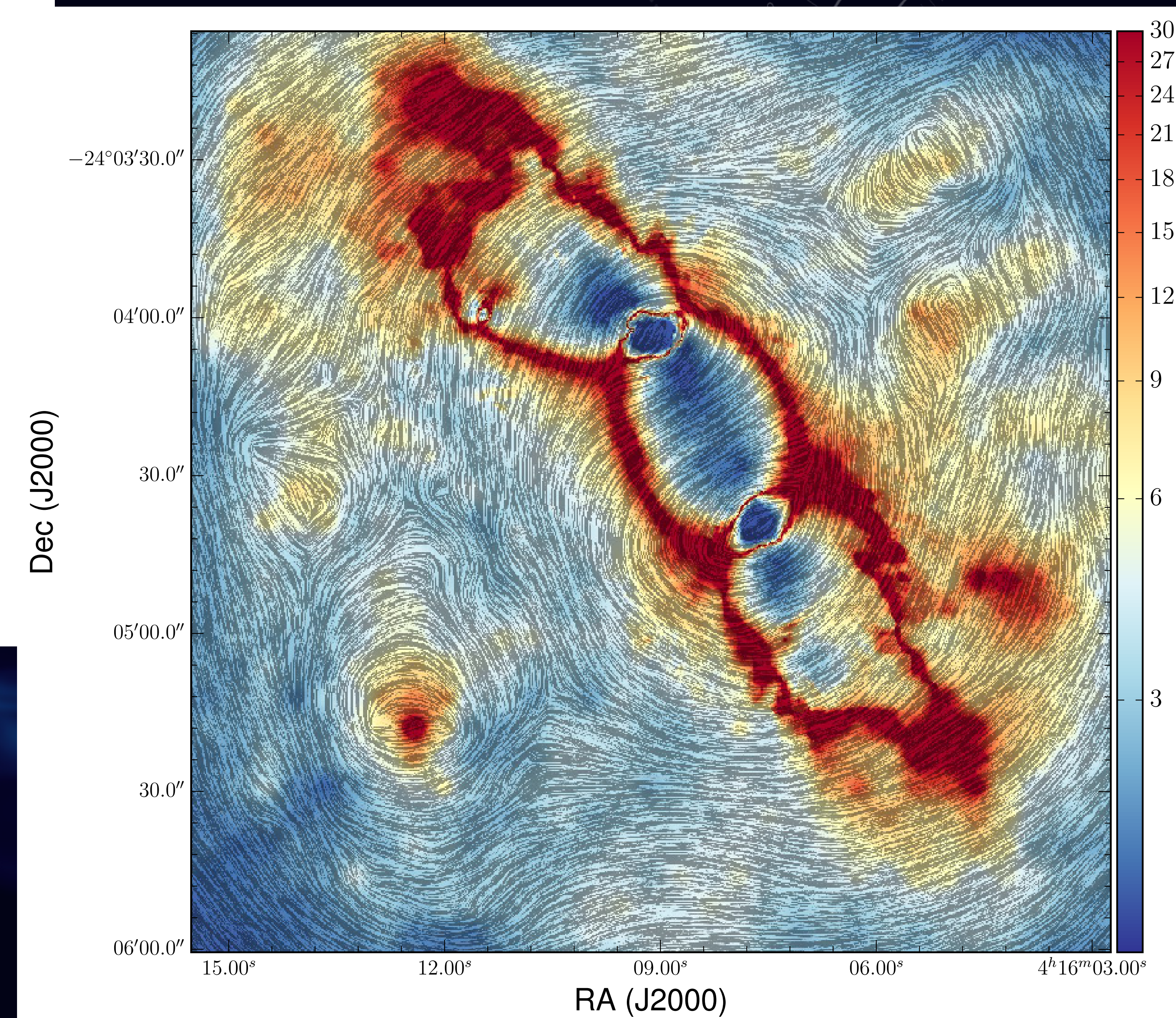
LENS MODELS ARE REQUIRED

Wang, Hoag et al (incl MB). 2015
A2744



Hoag et al (incl MB). 2016
MACS0416



https://archive.stsci.edu/prepds/frontier/lensmodels/

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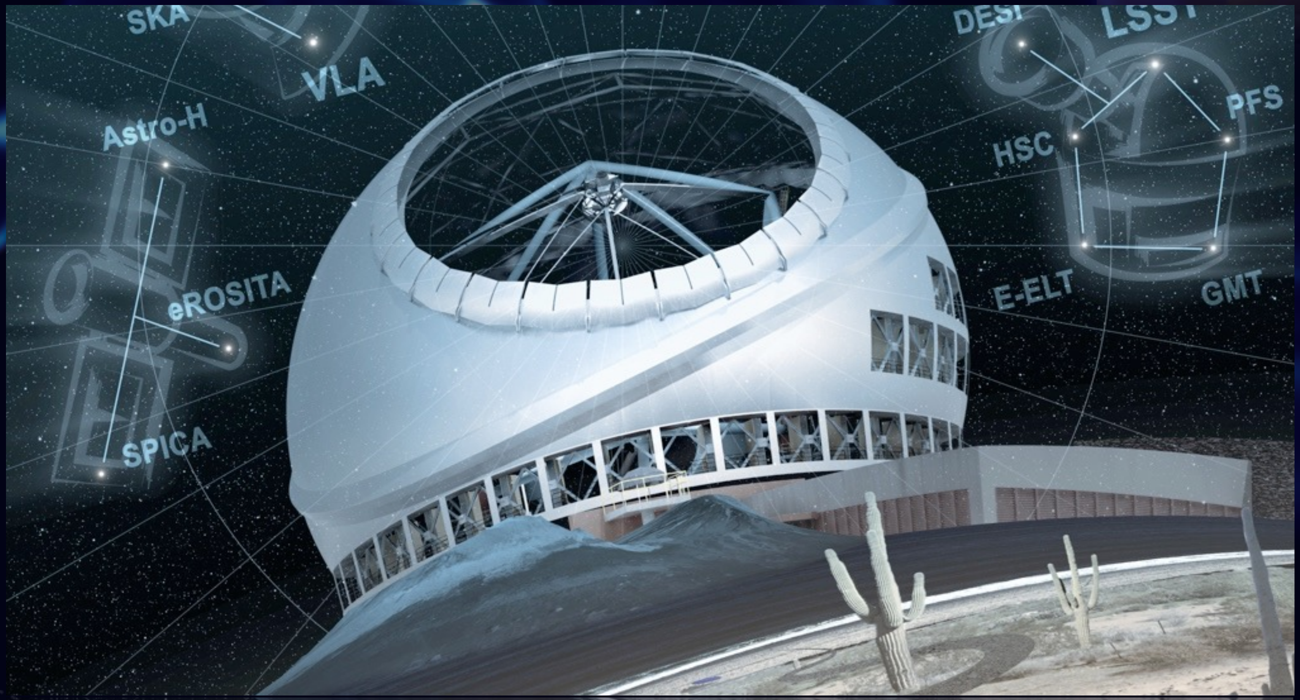
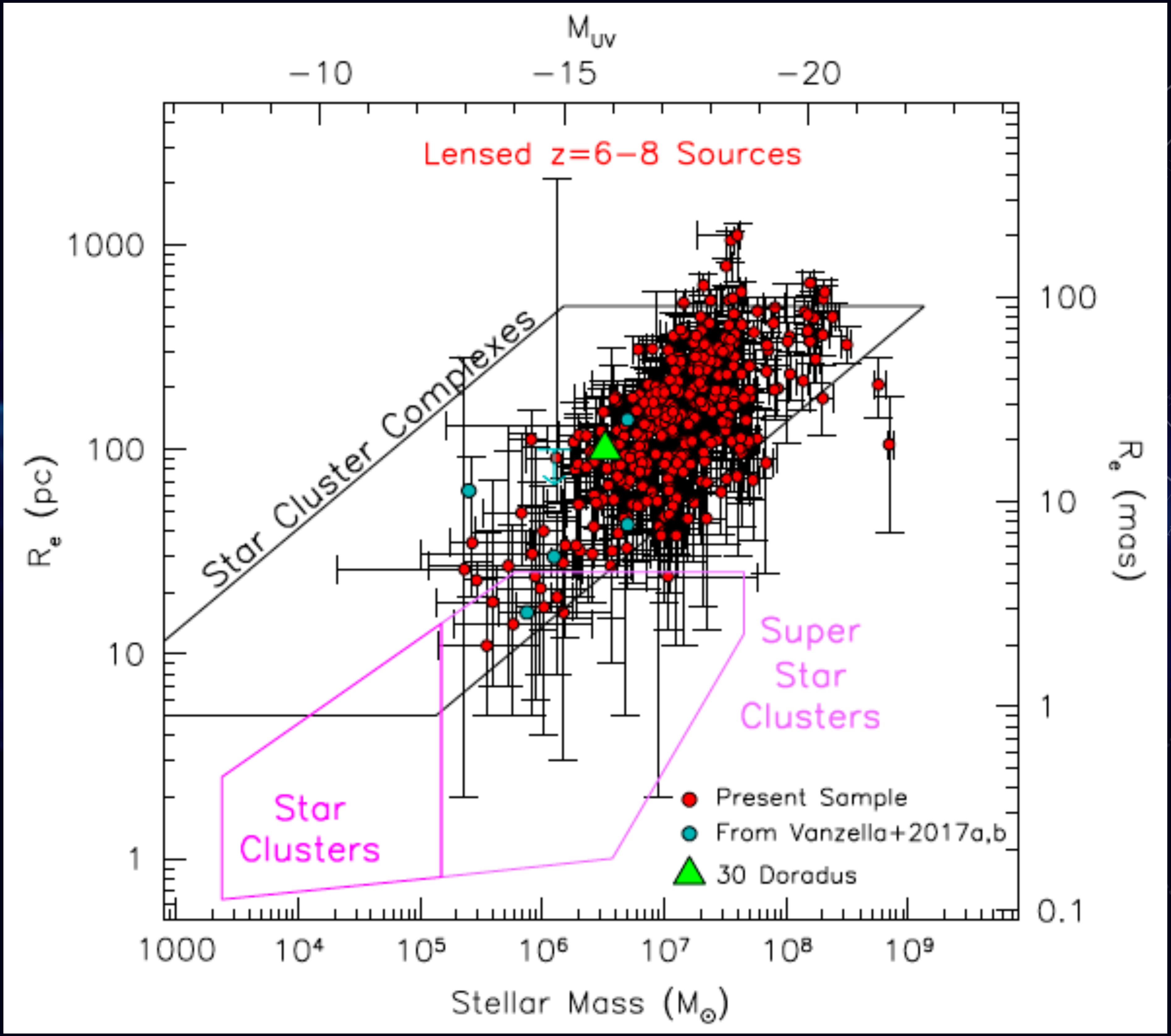
PROPERTIES OF FIRST GALAXIES



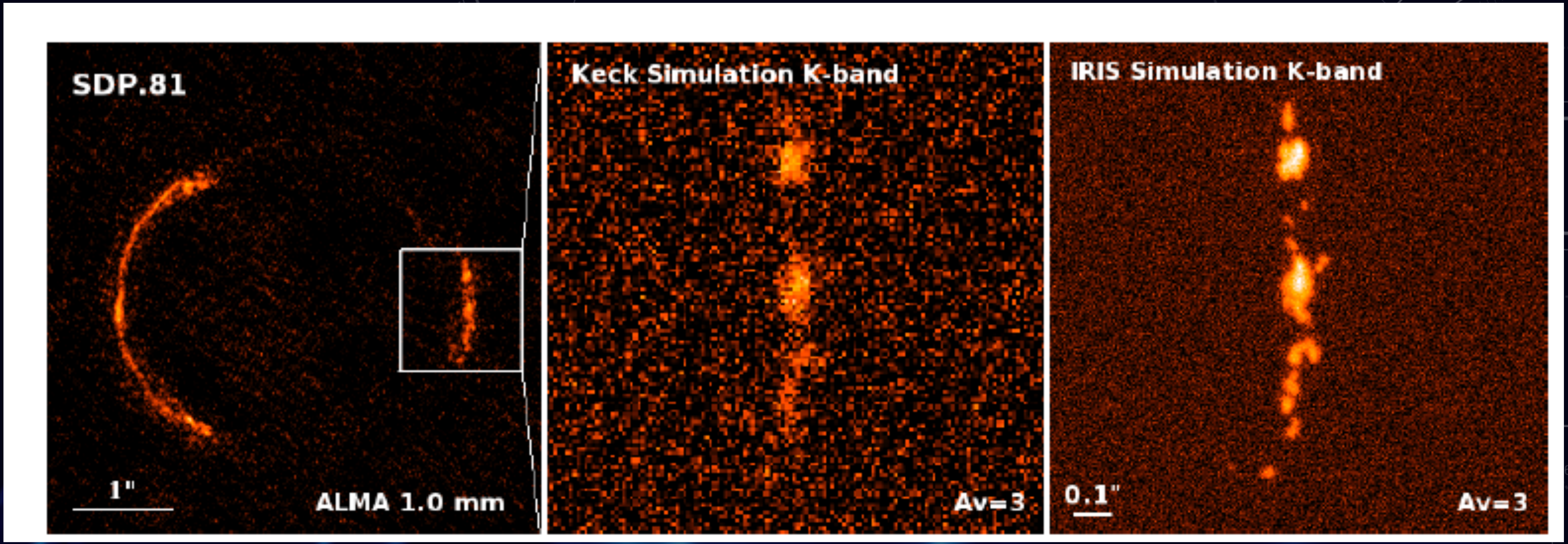
A spectrum is worth 10,000 pictures…

First galaxies are small



Bouwens et al. 2017

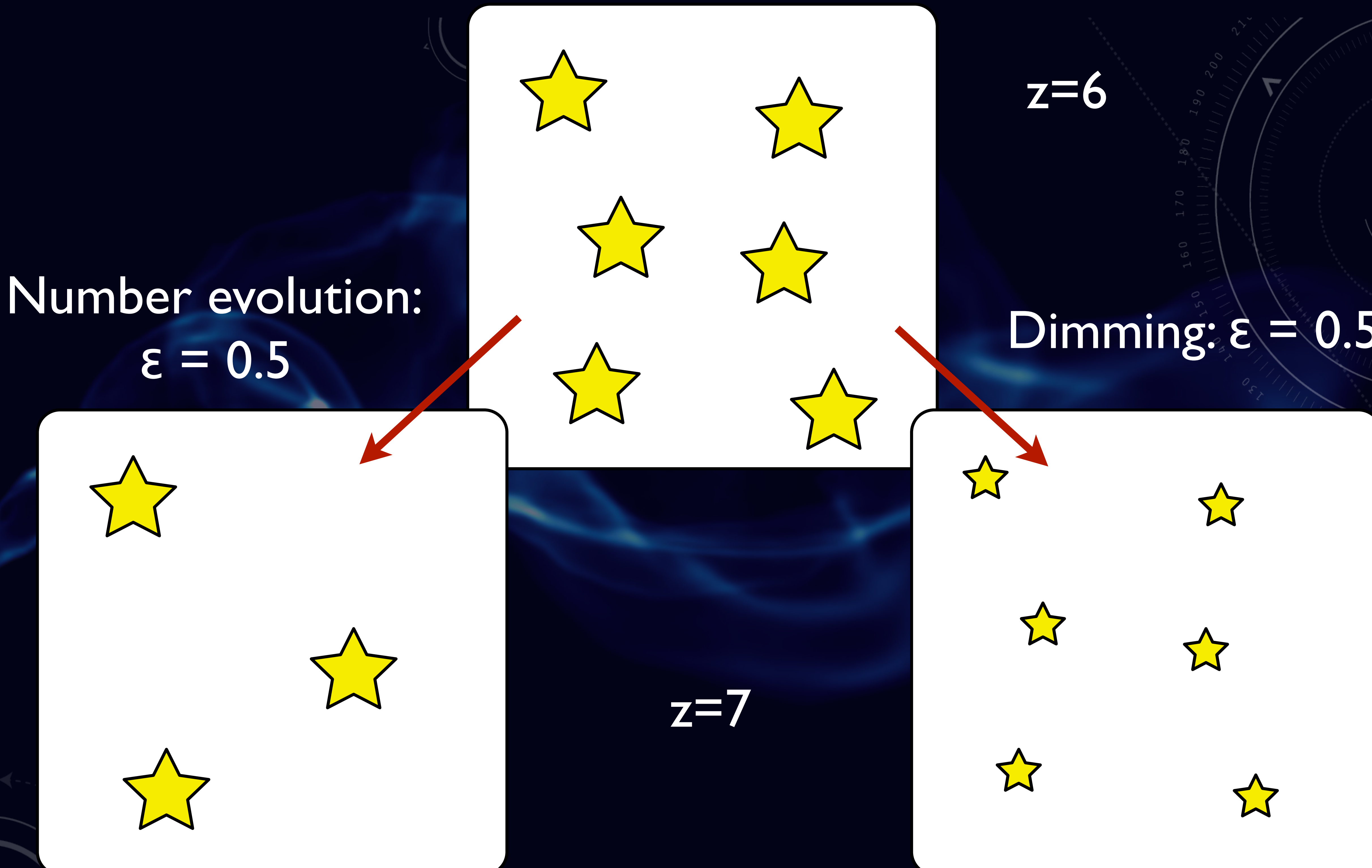
Resolution+lensing FTW!



Re~10mas

Wright et al. 2016

LAEs as a probe of reionization



Tilvi et al.

Keck Follow-Up

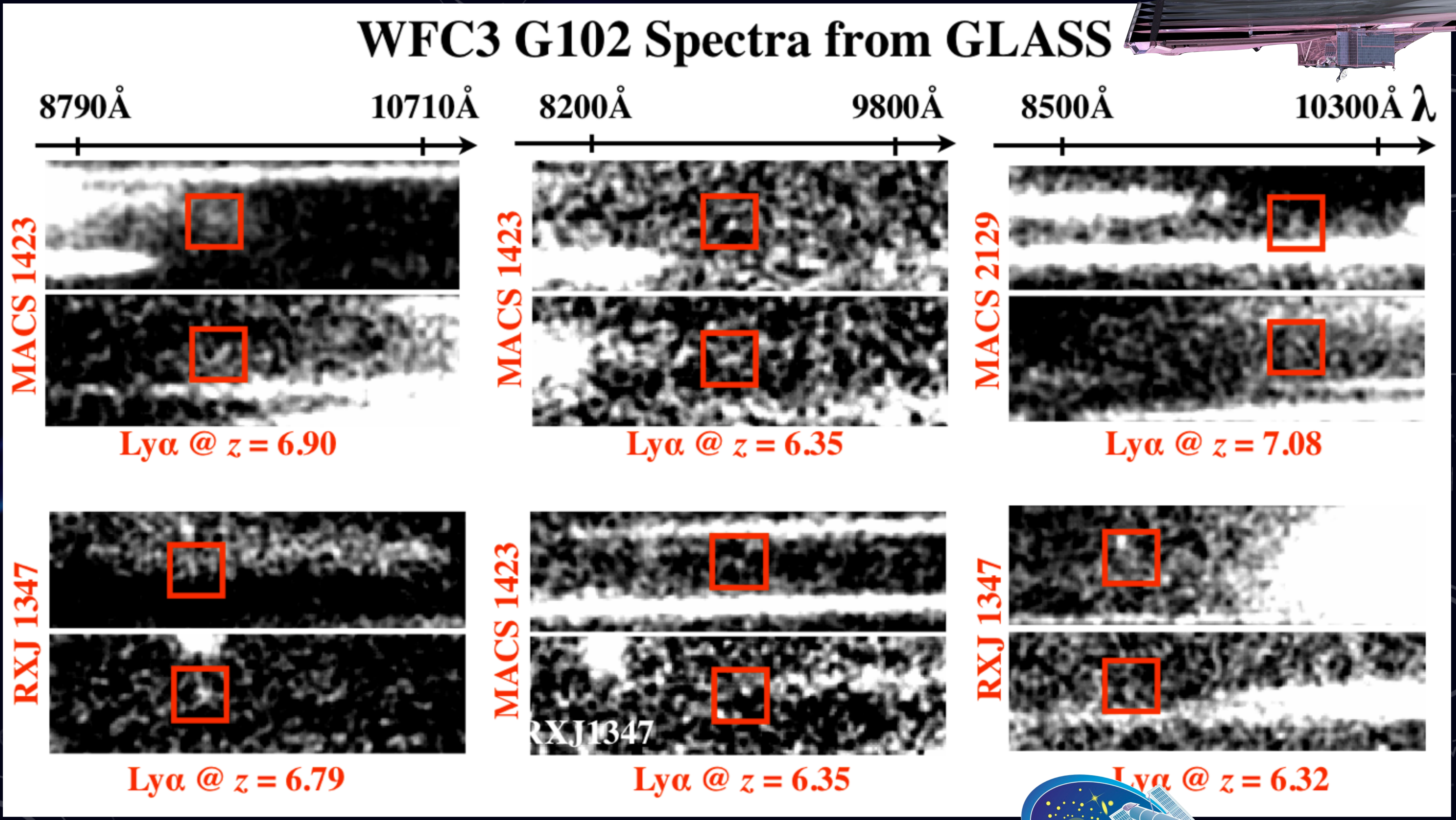
DEIMOS (1.5n/cluster) MOSFIRE (0.5n/cluster)

10 clusters
28 nights with MOSFIRE and DEIMOS
200LBGs at z~6
150LBGs at z~7
50LBGs at z~8
Hoag et al. in prep; Fuller et al. in prep.

W. M. KECK OBSERVATORY
On the summit of Mauna Kea, Island of Hawai'i

LAEs as a probe of reionization

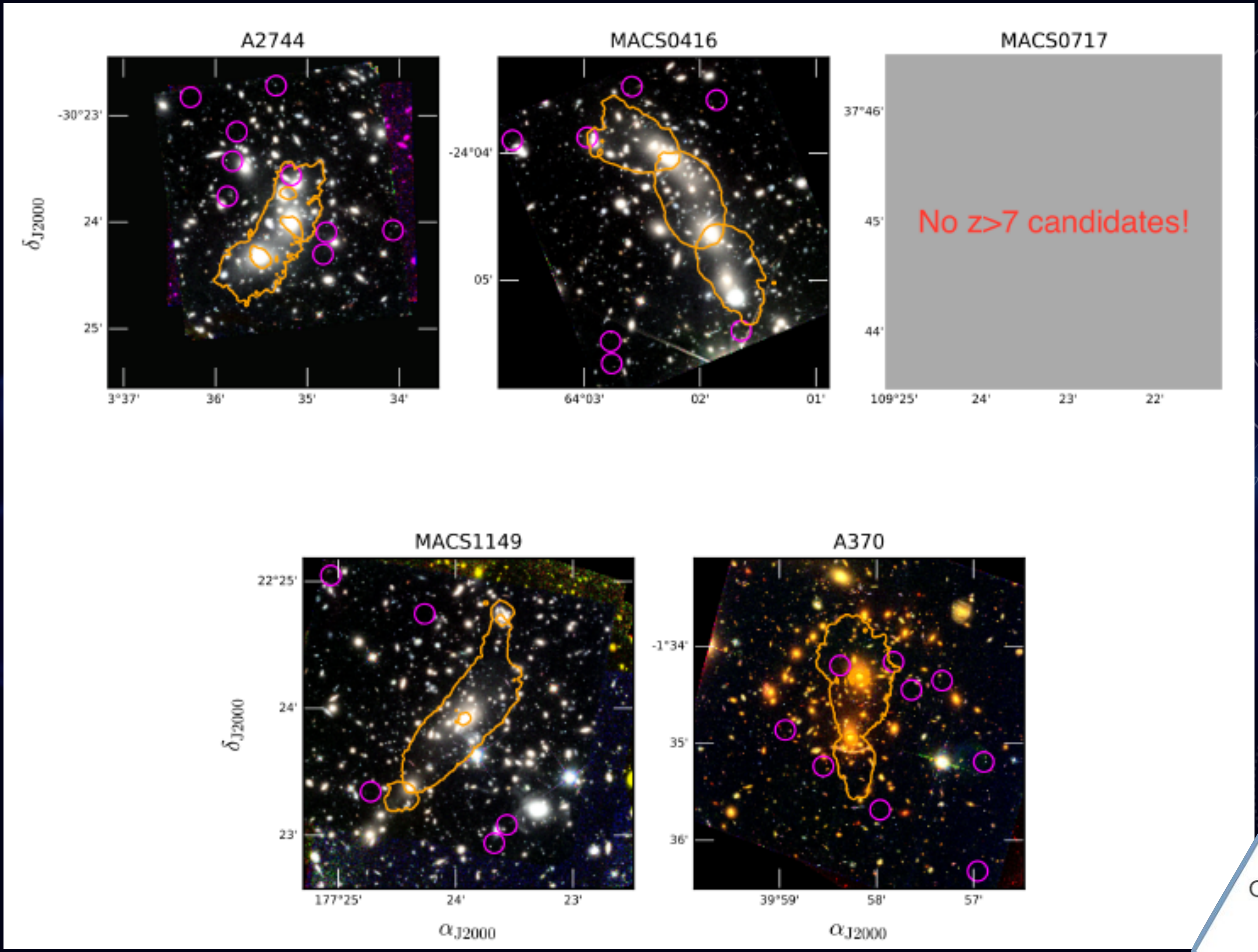
GLASS - PI Treu



GLASS

Schmidt et al. (incl MB) 2016

Keck Follow-Up z>7



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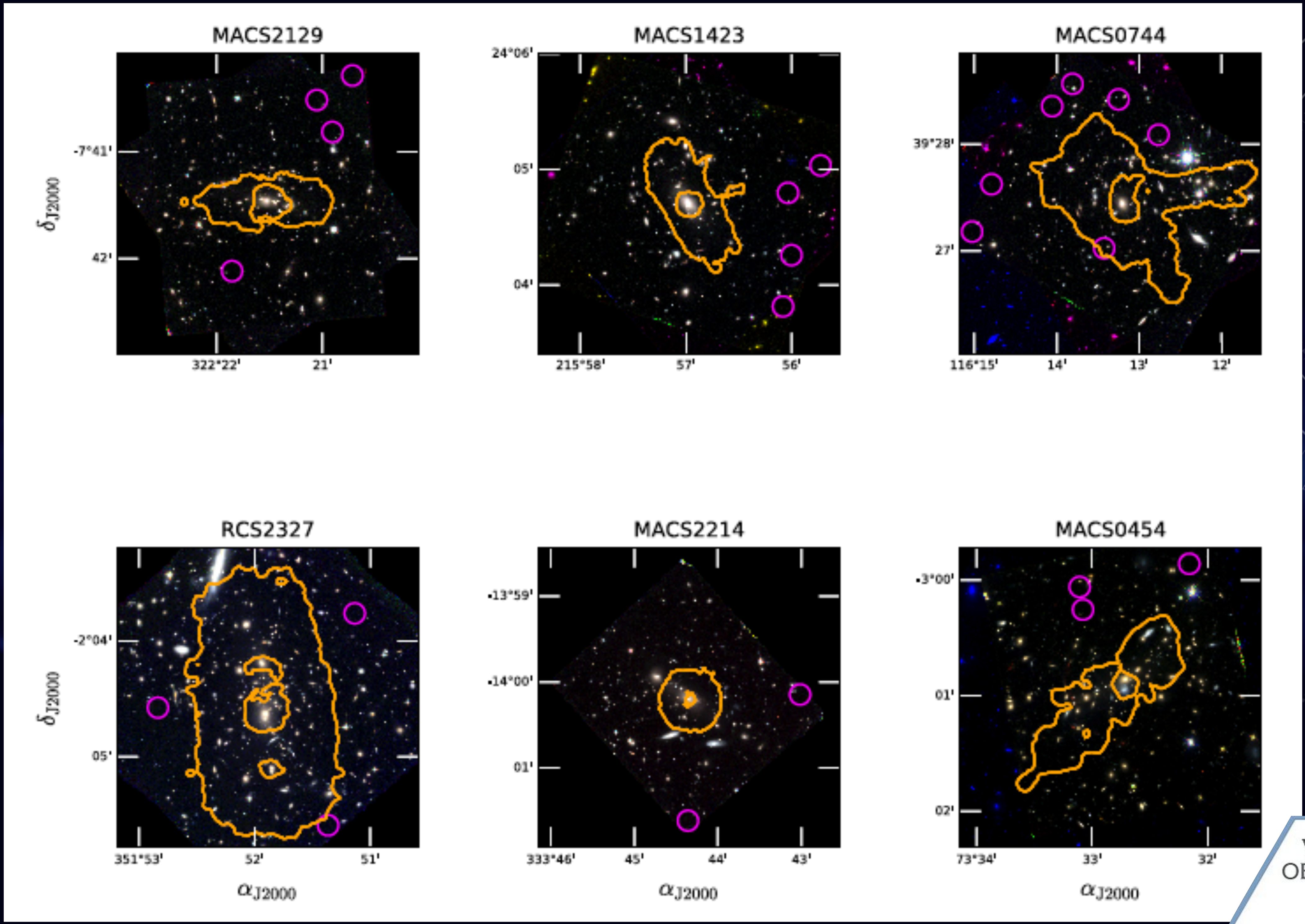
Keck Follow-Up z>7



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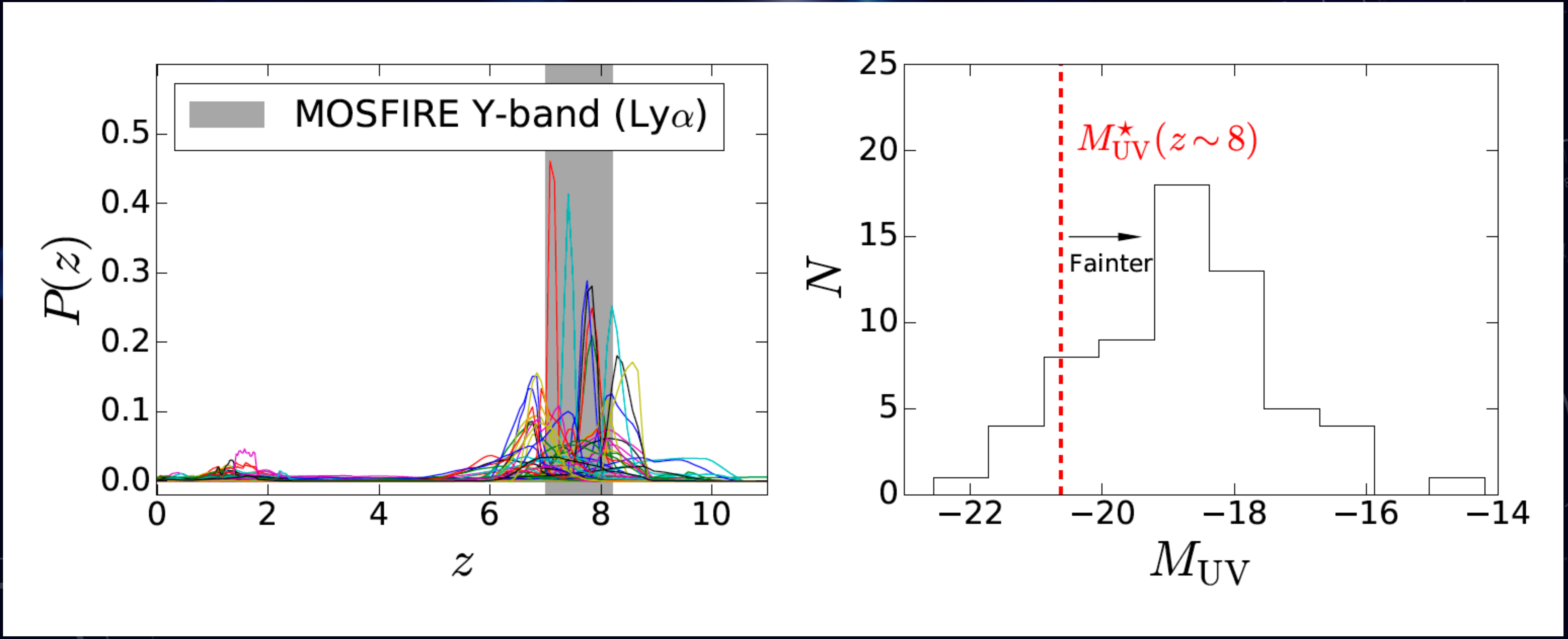
On the summit of Mauna Kea, Island of Hawai'i

Meanwhile in Hawaii

Keck Follow-up MOSFIRE

- Targeted 63 galaxies in Y-band ($7 < z_{Ly\alpha} < 8.2$)



LAEs From A Large Sample of Galaxies

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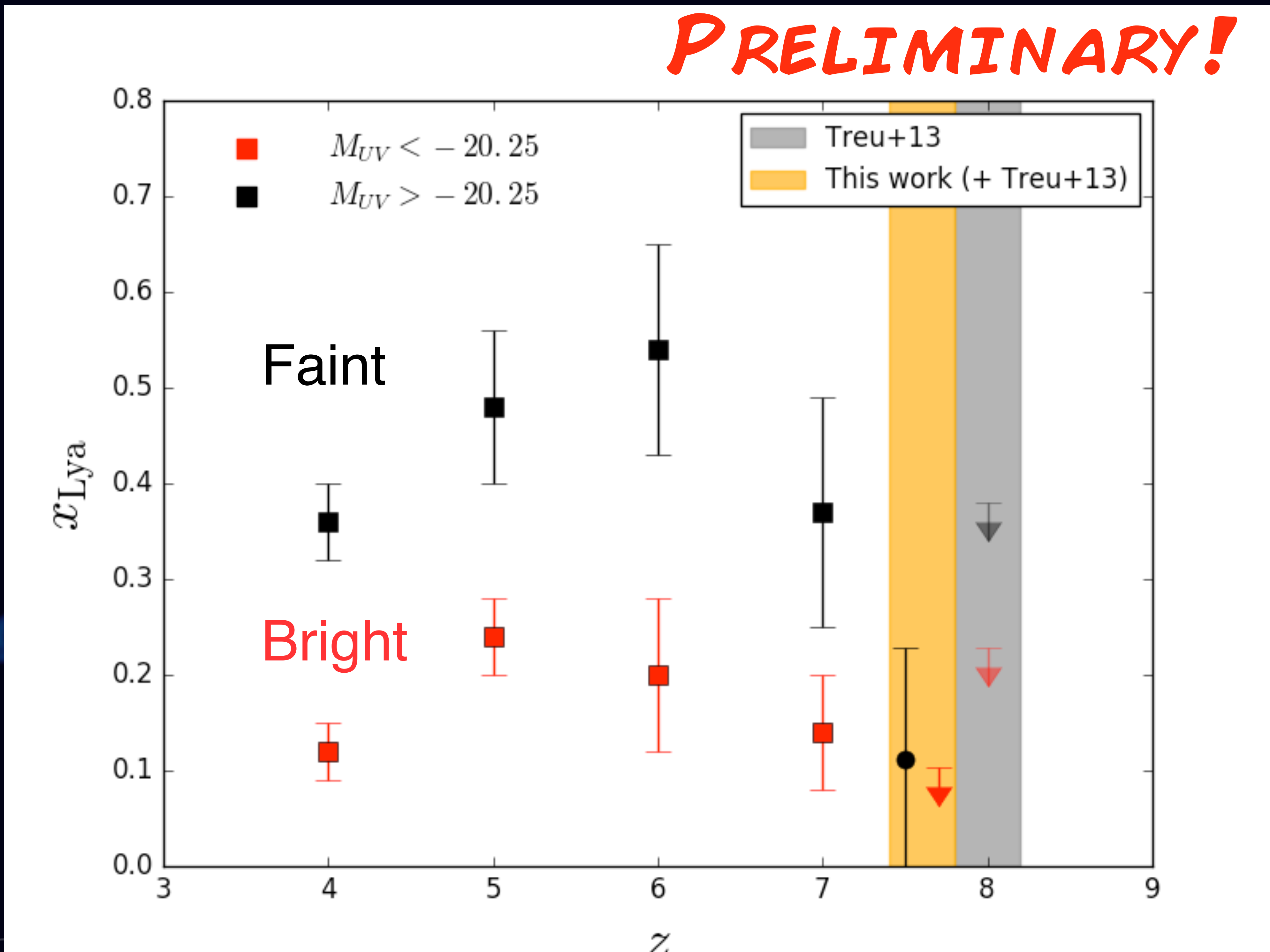


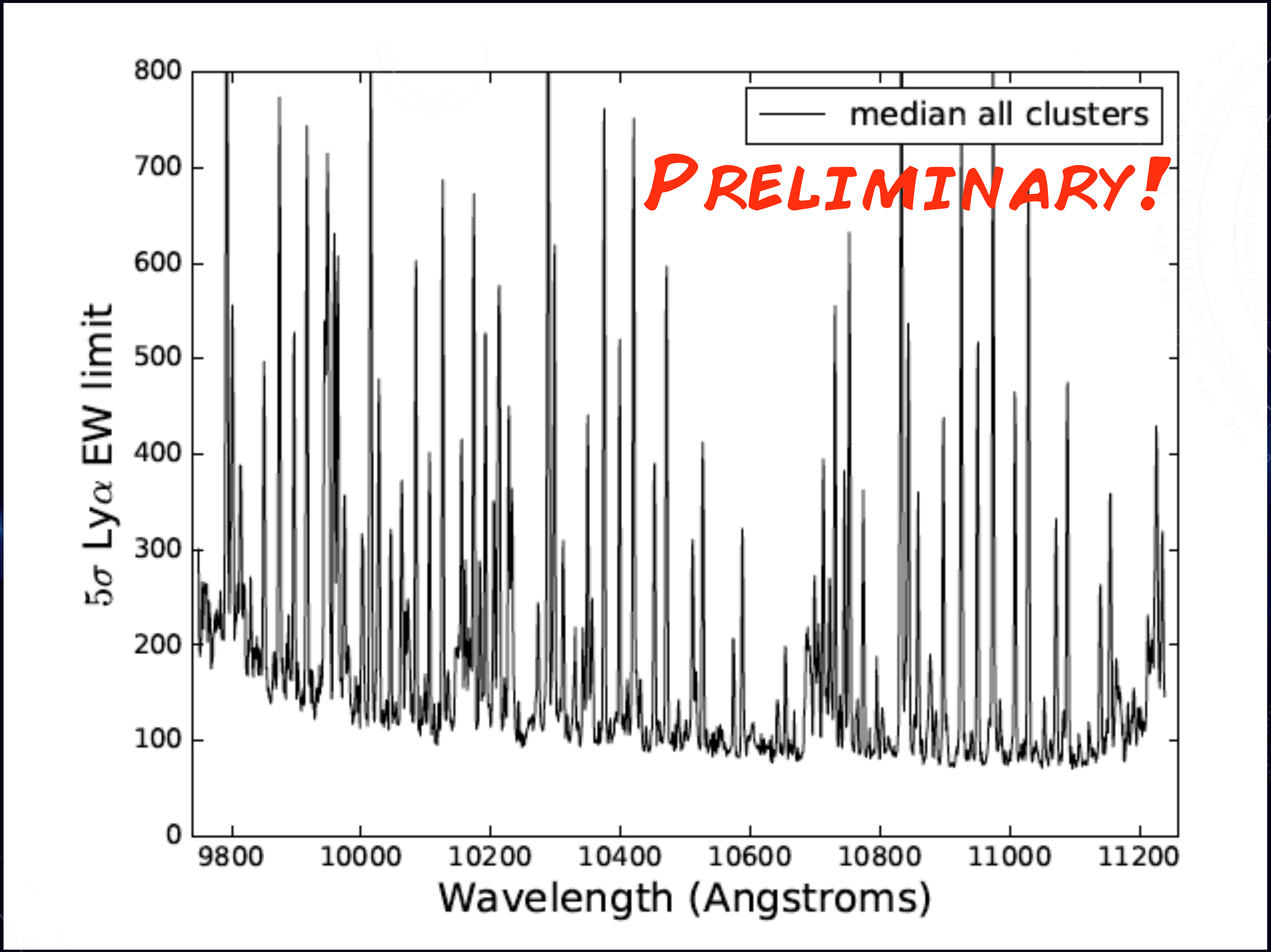
NOT completeness corrected!!!

NOT a good statistic to infer neutral fraction!!!!

et al 2017

Hoag et al. in prep.

The other 61 galaxies…

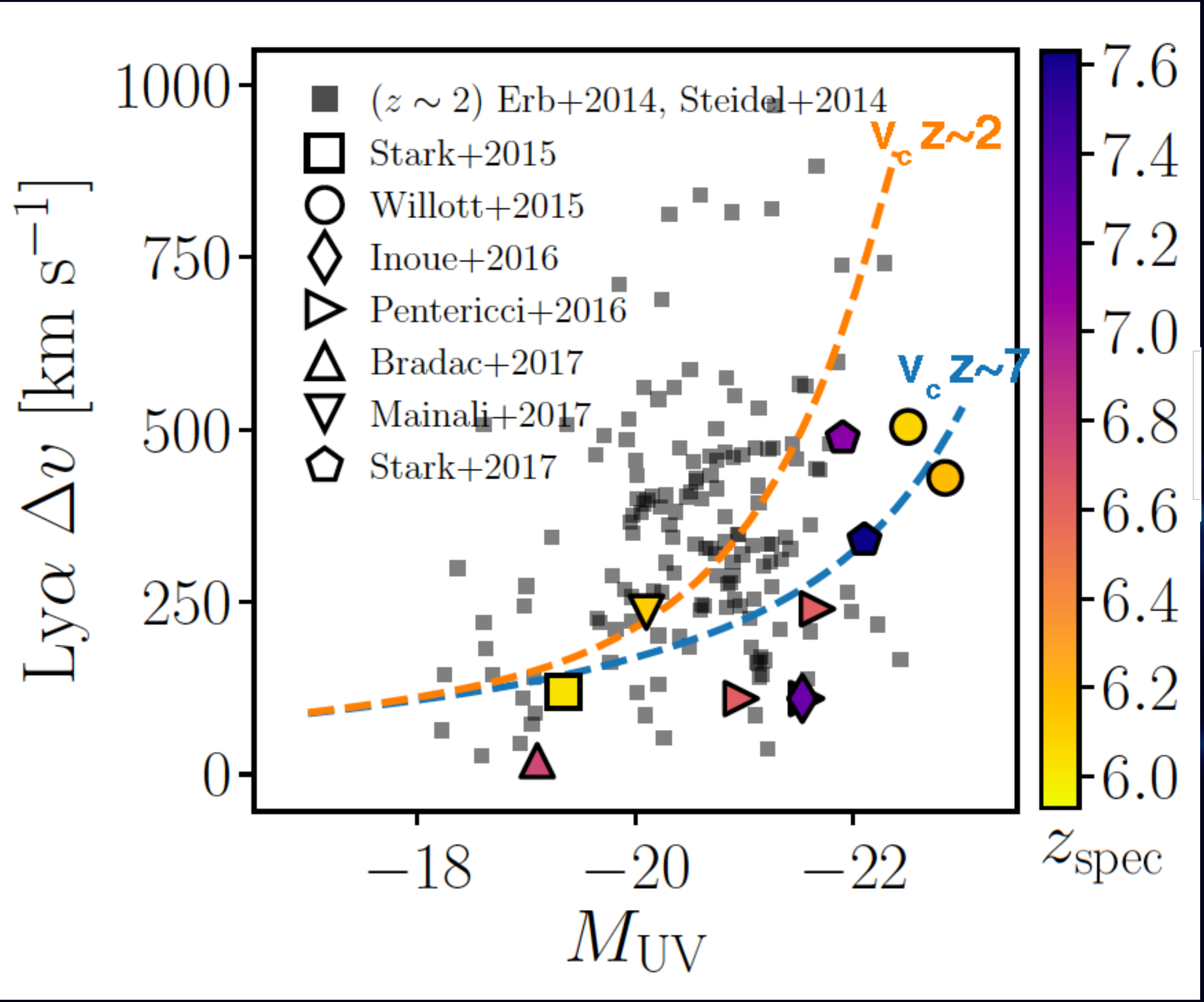


Hoag et al. in prep.

How do we connect Lyα observations to the neutral fraction, x_{HI}?

Mason et al.

Velocity offset as a probe of neutral gas



R~100 JWST/ NIRISS

R~2700 JWST/ NIRSPEC

R~5000 for IRMS

Mason et al. 2018

Conclusion

- Mergers are important probe of DM physics → need good data and simulations to interpret.
- JWST won't do everything at the Epoch of Reionization → need ground based follow up - for resolution; both spectral (velocity offsets, Lyα shape) as well as imaging (first galaxies are small)