GALAXIES AND **DARK MATTER** SEEN THROUGH A GRAVITATIONAL LENS

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MIKE HUDSON

U.WATERLOO

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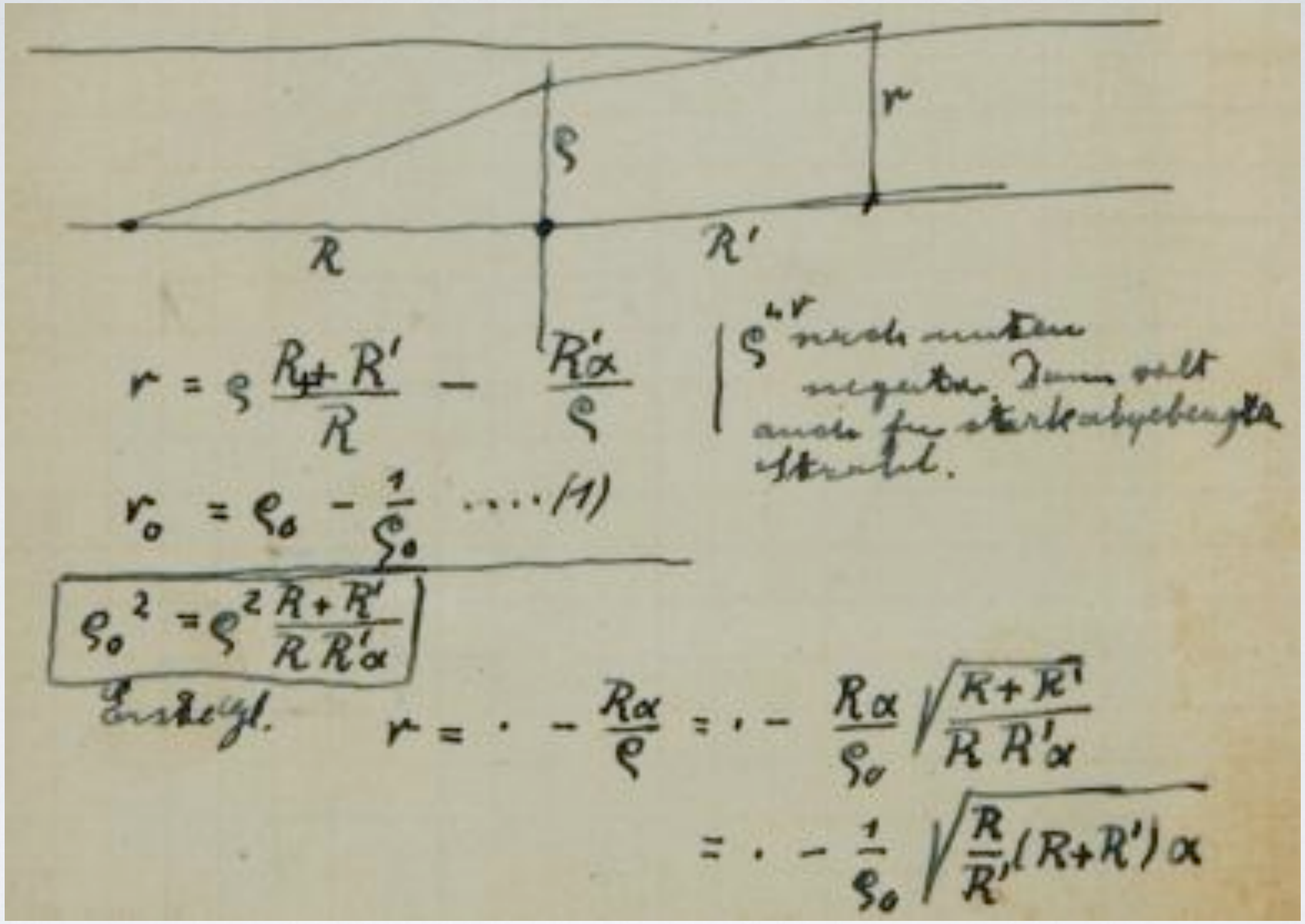
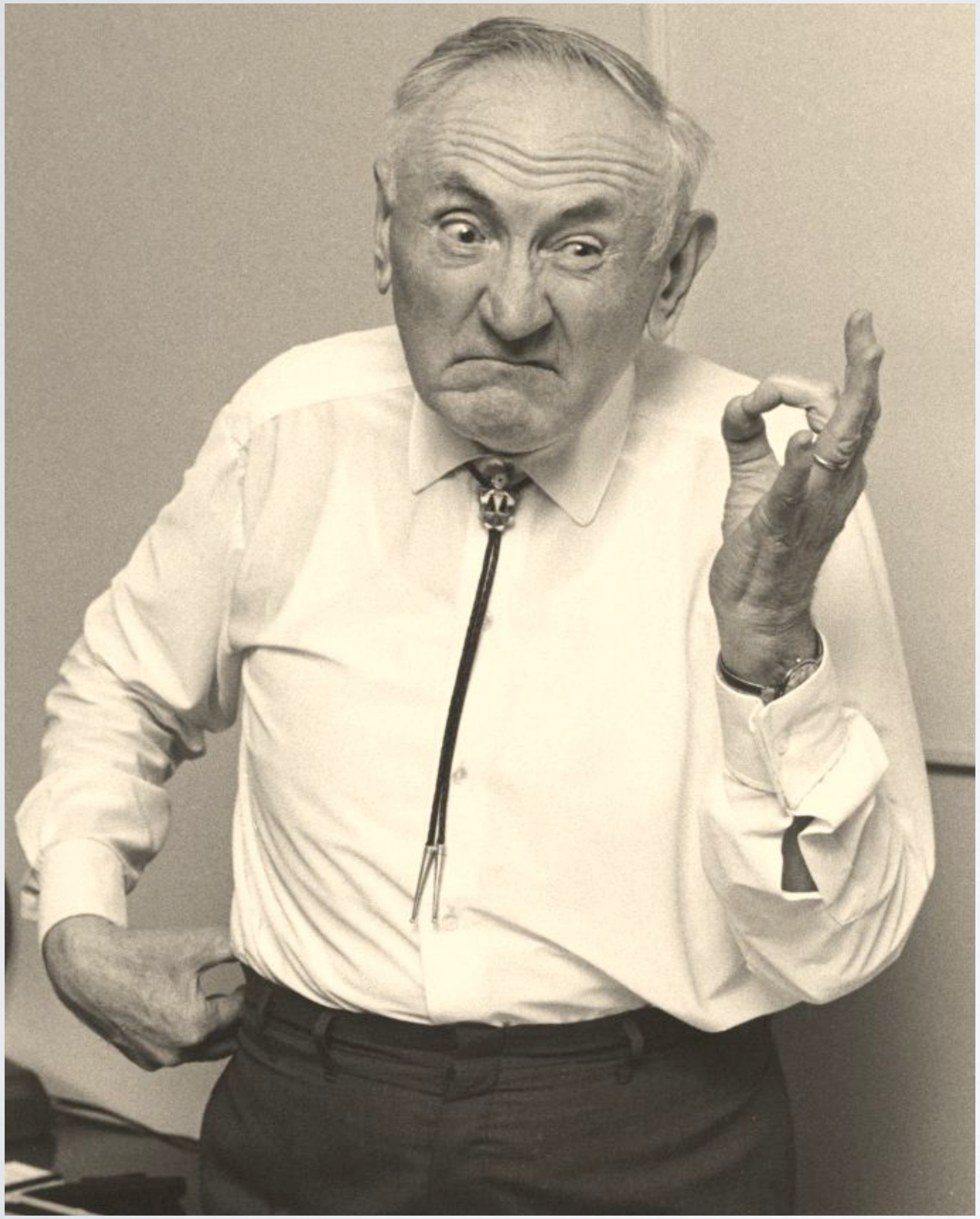


Einstein's notebook c. **1912**.
from Collected Papers of Albert Einstein, v 3.

FRITZ ZWICKY



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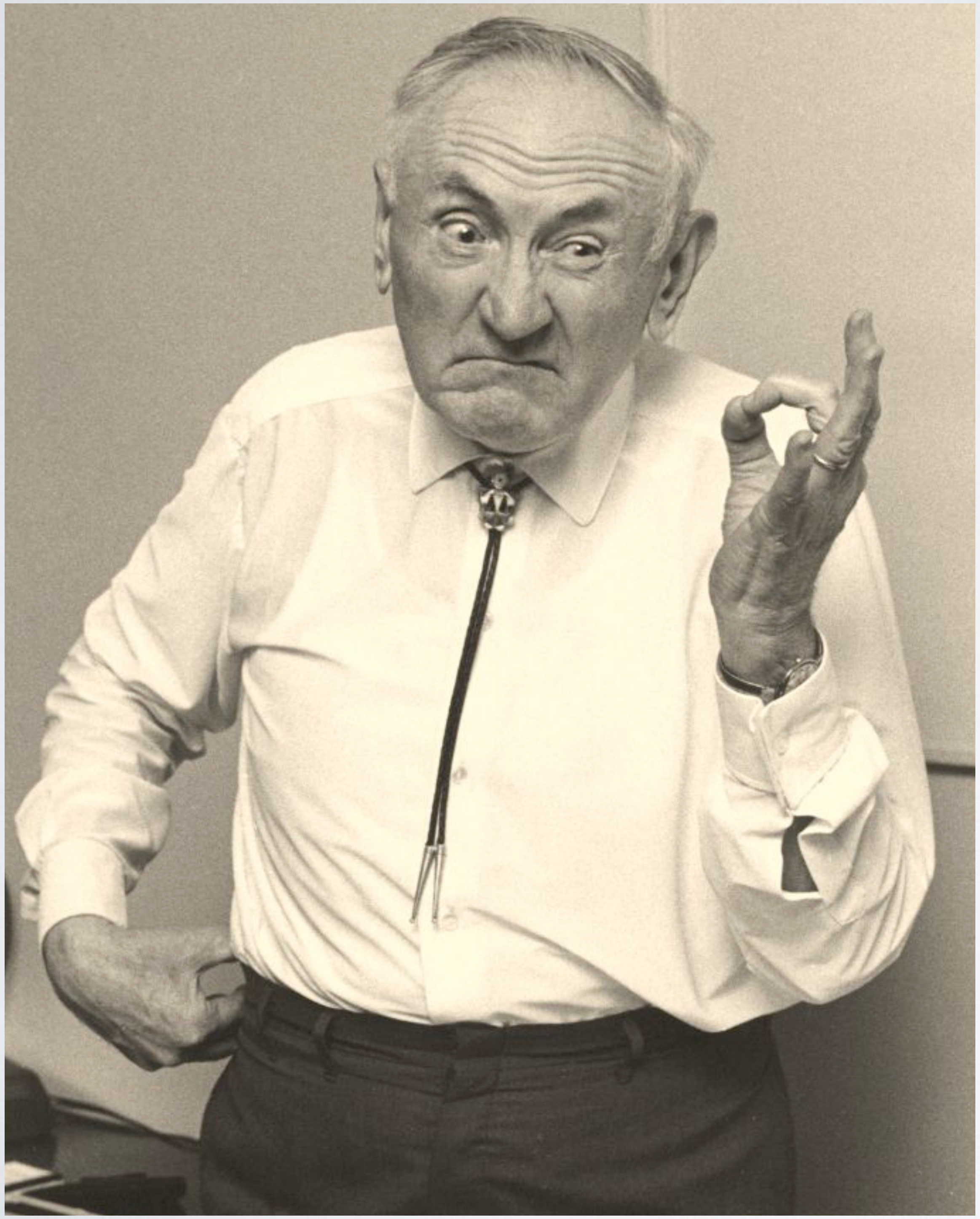

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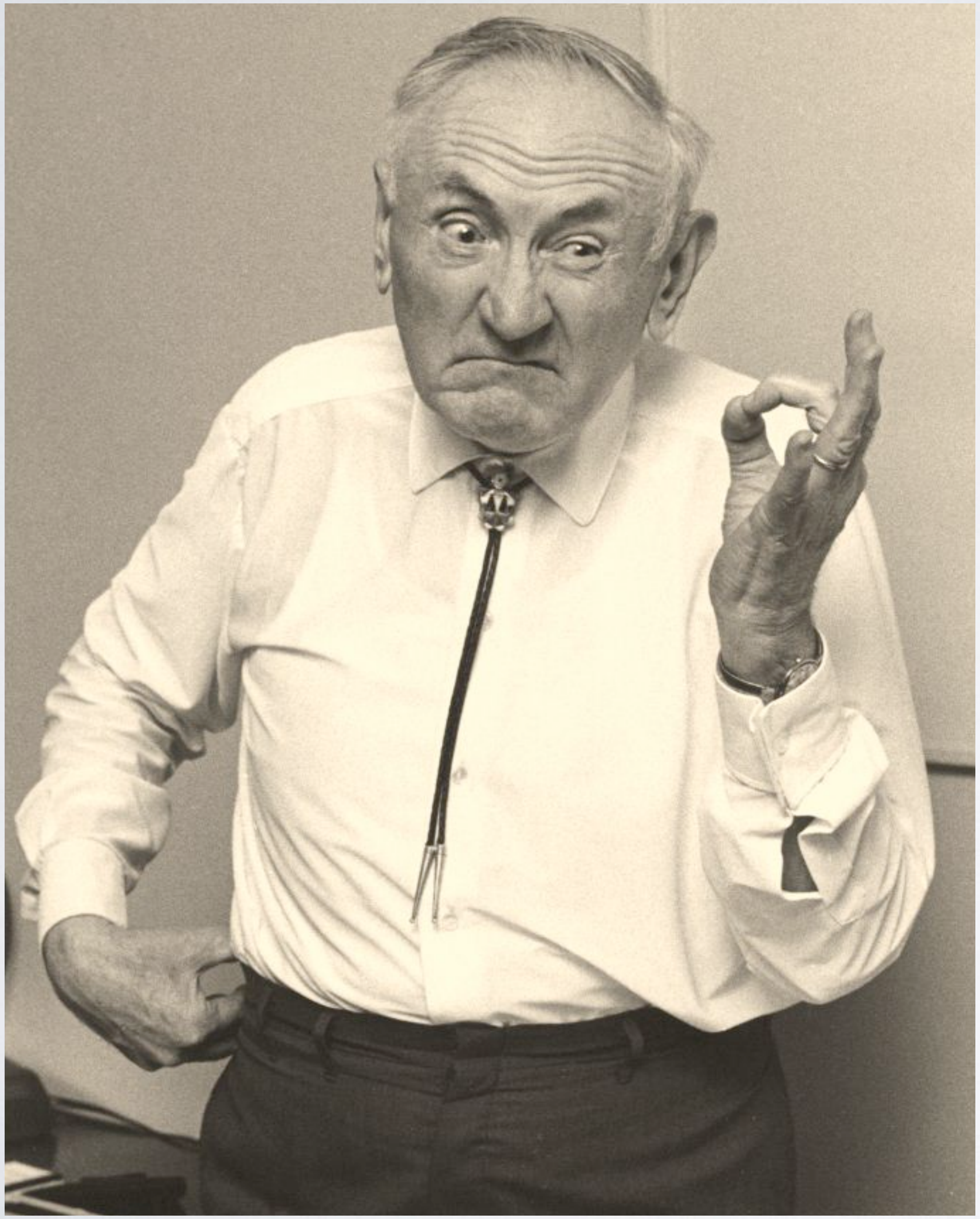

Zwicky had a difficult personality.

He referred to colleagues at CalTech as "**spherical bastards**" ….

ZWICKY AND DARK MATTER

In order to obtain the observed value of an average Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter.[8] If this would be confirmed we would get the surprising result that dark matter is present in much greater amount than luminous matter.

Zwicky **1933**, "The redshift of extragalactic nebulae", translated from German ("Dunkle Materie")

ZWICKY, PHYS REV, 1937

Nebulae as Gravitational Lenses

Einstein recently published[1] some calculations concerning a suggestion made by R. W. Mandl, namely, that a star *B* may act as a "gravitational lens" for light coming from another star *A* which lies closely enough on the line of sight behind *B*. As Einstein remarks the chance to observe this effect for stars is extremely small.

Last summer Dr. V. K. Zworykin (to whom the same idea had been suggested by Mr. Mandl) mentioned to me the possibility of an image formation through the action of gravitational fields. As a consequence I made some calculations which show that extragalactic *nebulae* offer a much better chance than *stars* for the observation of gravitational lens effects.

In the first place some of the massive and more concentrated nebulae may be expected to deflect light by as much as half a minute of arc. In the second place nebulae, in contradistinction to stars, possess apparent dimensions which are resolvable to very great distances.

Suppose that a distant globular nebula *A* whose diameter is 2ξ lies at a distance, a, which is great compared with the distance D of a nearby nebula *B* which lies exactly in front of *A*. The image of *A* under these circumstances is a luminous ring whose average apparent radius is $\beta=(\gamma_0 r_0/D)^{\frac{1}{2}}$, where γ_0 is the angle of deflection for light passing at a distance r_0 from *B*. The apparent width of the ring is $\Delta\beta=\xi/a$. The apparent total brightness of this luminous ring is q times greater than the brightness of the direct image of *A*. In our special case $q=2la/\xi D$, with $l=(\gamma_0 r_0 D)^{\frac{1}{2}}$. In actual cases the factor q may be as high as $q=100$, corresponding to an increase in brightness of five magnitudes. The surface brightness remains, of course, unchanged.

The discovery of images of nebulae which are formed through the gravitational fields of nearby nebulae would be of considerable interest for a number of reasons.

(1) It would furnish an additional test for the general theory of relativity.

(2) It would enable us to see nebulae at distances greater than those ordinarily reached by even the greatest telescopes. Any such *extension* of the known parts of the universe promises to throw very welcome new light on a number of cosmological problems.

(3) The problem of determining nebular masses at present has arrived at a stalemate. The mass of an average nebula until recently was thought to be of the order of $M_N=10^9 M_\odot$, where $M_\odot$ is the mass of the sun. This estimate is based on certain deductions drawn from data on the intrinsic brightness of nebulae as well as their spectrographic rotations. Some time ago, however, I showed[2] that a straightforward application of the virial theorem to the great cluster of nebulae in Coma leads to an average nebular mass four hundred times greater than the one mentioned, that is, $M_N'=4\times10^{11} M_\odot$. This result has recently been verified by an investigation of the Virgo cluster.[3] Observations on the deflection of light around nebulae may provide the most direct determination of nebular masses and clear up the above-mentioned discrepancy.

A detailed account of the problems sketched here will appear in *Helvetica Physica Acta*.

F. Zwicky

Norman Bridge Laboratory,
California Institute of Technology,
Pasadena, California,
January 14, 1937.

1 A. Einstein, Science **84**, 506 (1936).
2 F. Zwicky, Helv. Phys. Acta **6**, 124 (1933).
3 Sinclair Smith, Astrophys. J. **83**, 23 (1936).

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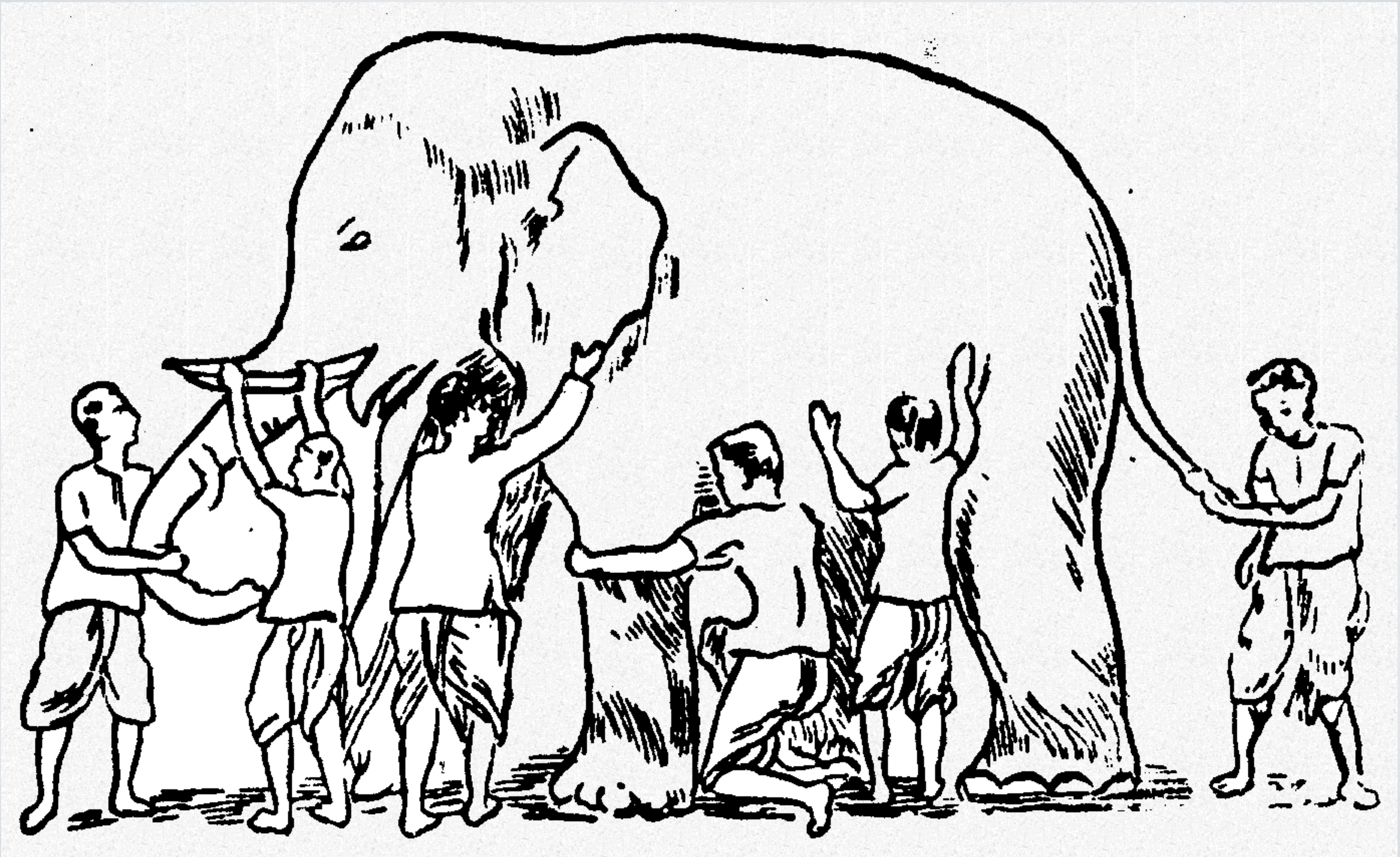
GALAXY FORMATION



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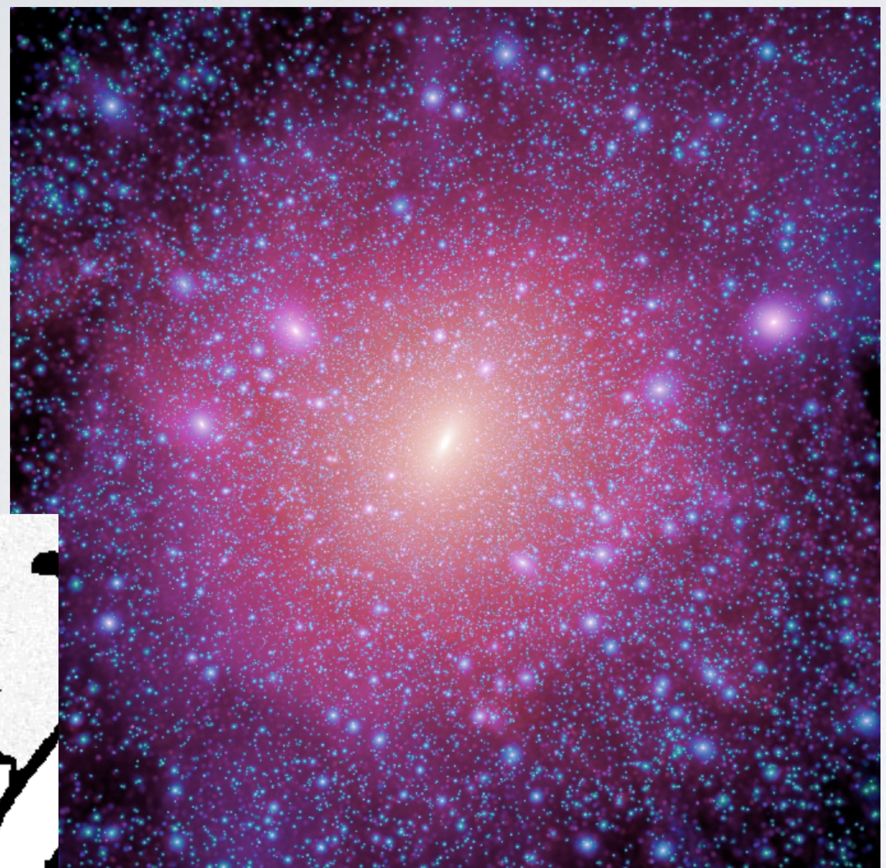
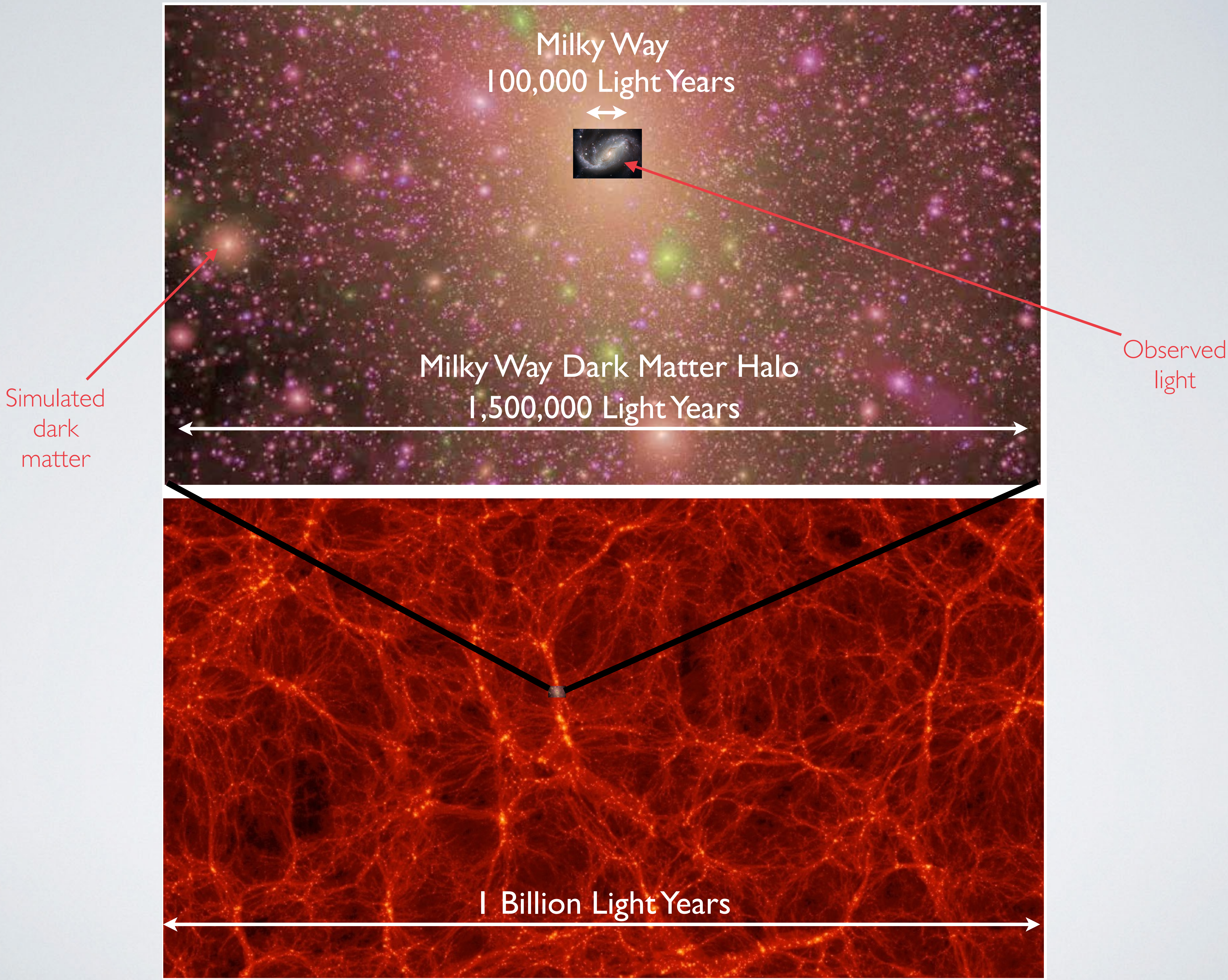


What the Theorist sees

What the Observer sees


Milky Way
100,000 Light Years
Milky Way Dark Matter Halo
1,500,000 Light Years
Simulated
dark
matter
Observed
light
1 Billion Light Years

GALAXIES AND DARK MATTER HALOS

What is the relationship between dark matter halos and their stellar content?

How do the dark and stellar components co-evolve?

Observations probe galaxy's stars at different epochs

Theory predicts how dark matter halos evolve

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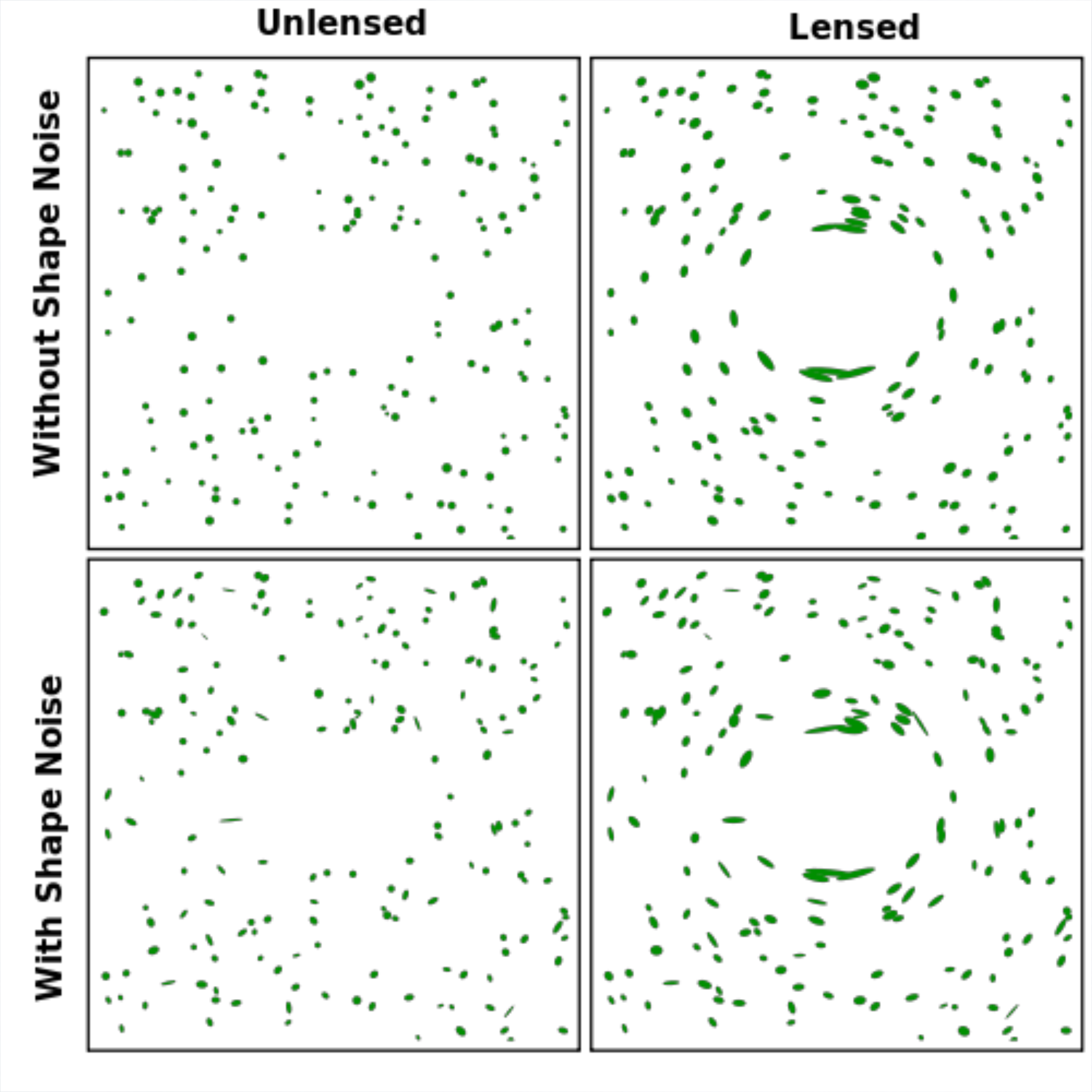
WEAK GRAVITATIONAL LENSING

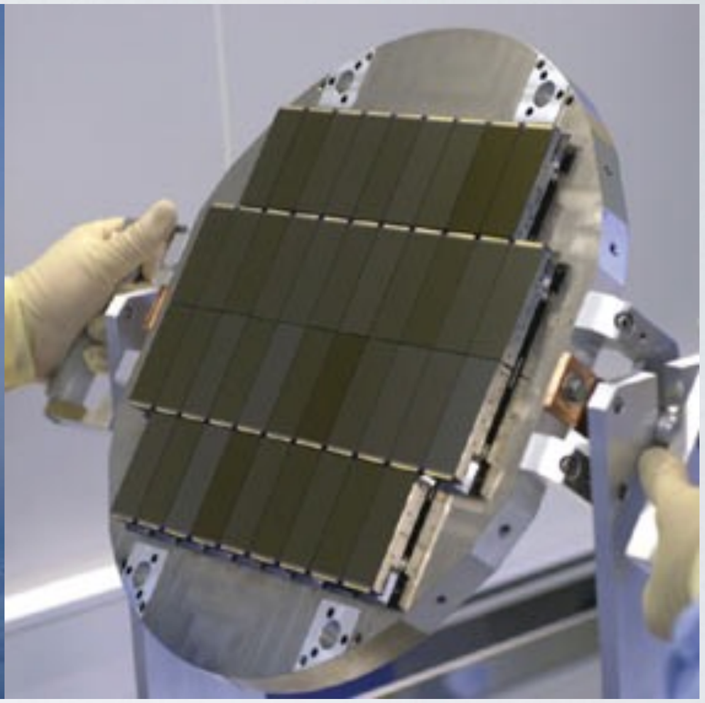


- Gravitational lensing from a circularly symmetric lens leads to tangential distortion

$$
\begin{aligned}
\gamma_t(r) &= \Delta\Sigma(r)/\Sigma_{cr} \\
&= [\overline{\Sigma}(< r) - \Sigma(r)]/\Sigma_{cr}
\end{aligned}
$$

- Background galaxies are randomly oriented but not circular
- S/N per foreground *lens galaxy* ≪ 1
- Need to *stack* many thousands of lens galaxies

CFHTLENS PROJECT

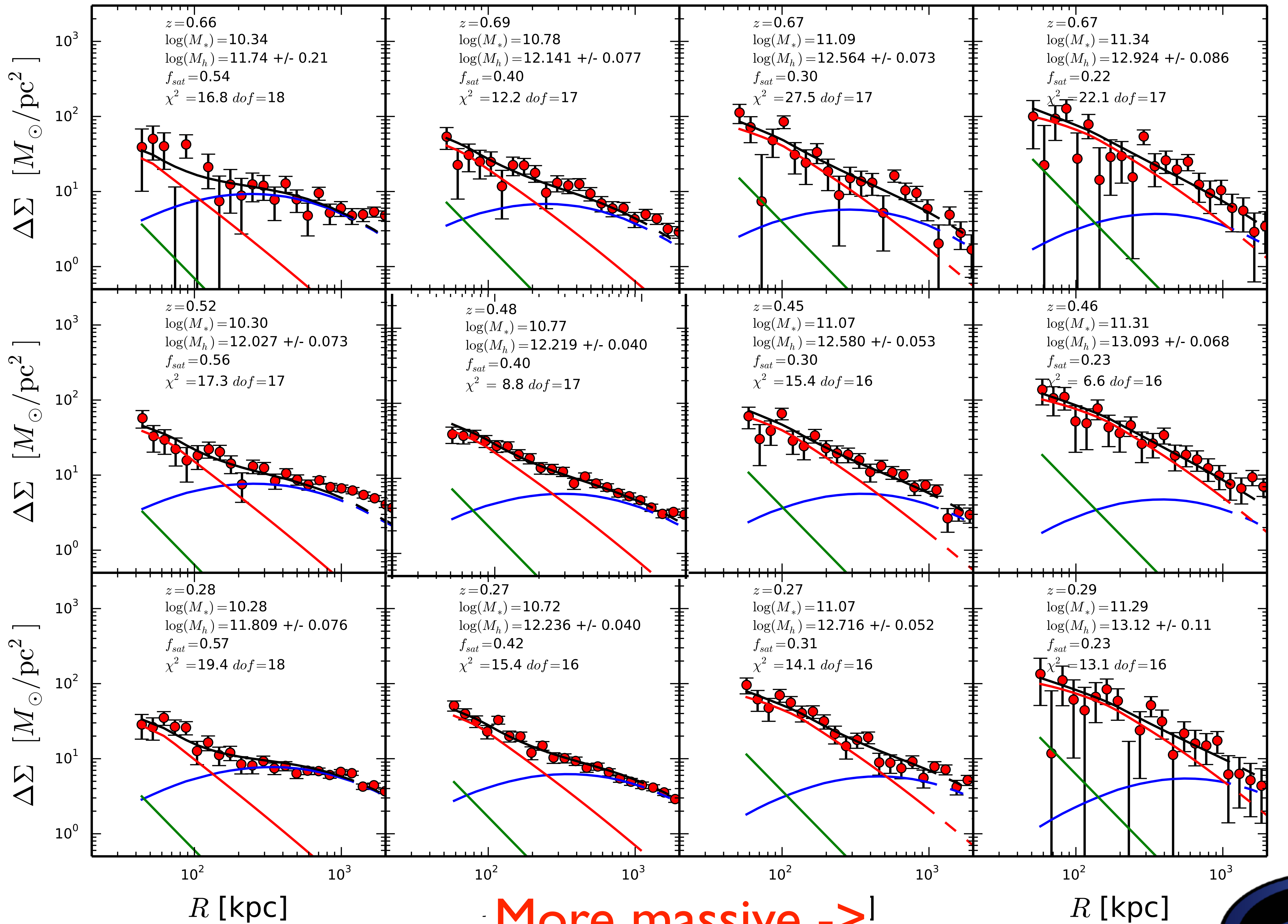


- 154 sq. deg. of deep multi-band imaging on CFHT, ~ 0.7'' PSF, i<24.7

- Stack thousands to hundreds of thousands of lens galaxies, split into bins of:
  - stellar mass (10^9-$10^{11.5}$ solar)
  - colour (red / blue)
  - (photo-) redshift (0.3 - 0.5 - 0.7)

- Fit tangential shear with model:
  - stellar mass
  - NFW halo density profile
  - nearby clustered haloes

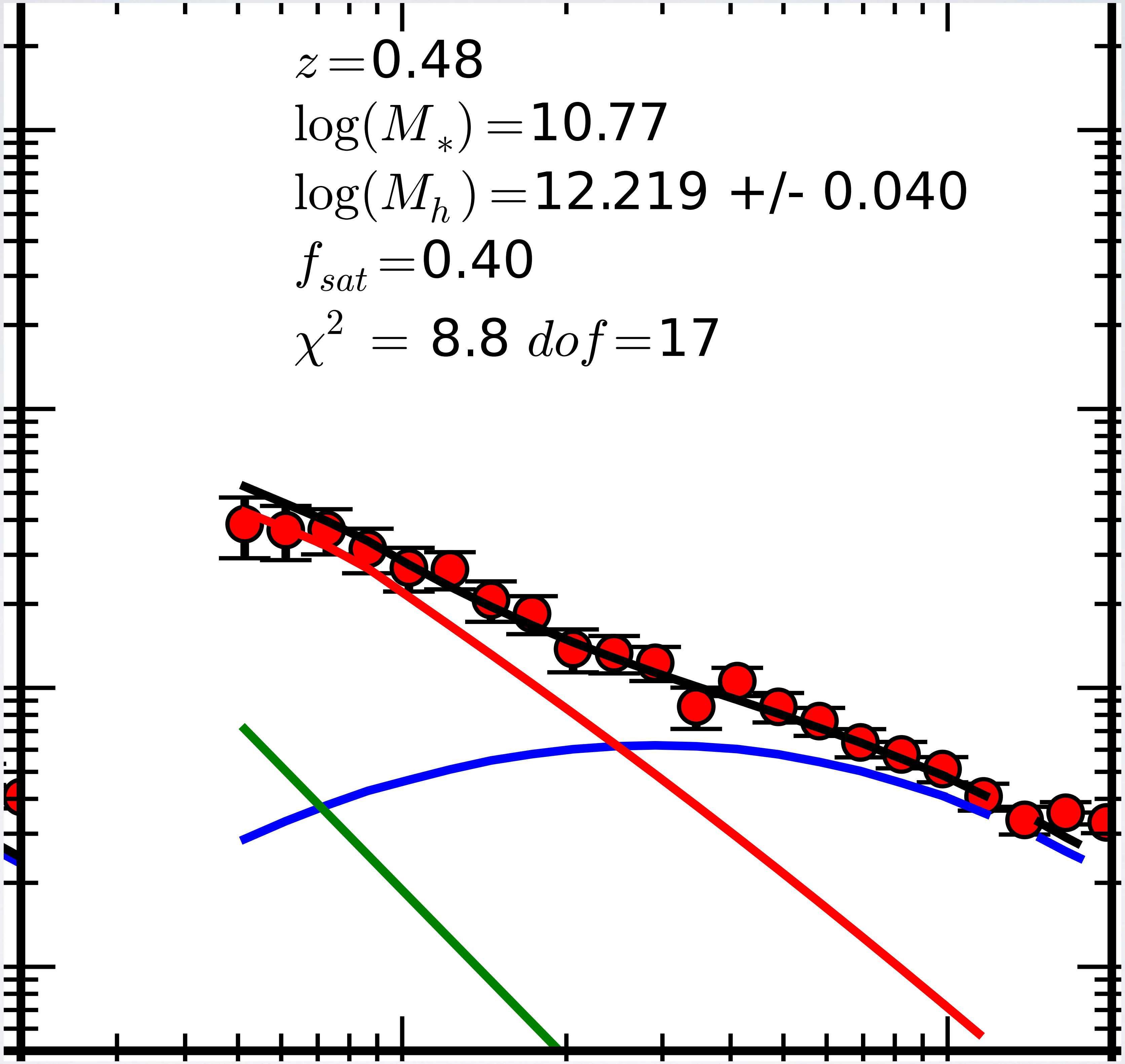
CFHTLENS GALAXY-GALAXY



More massive ->

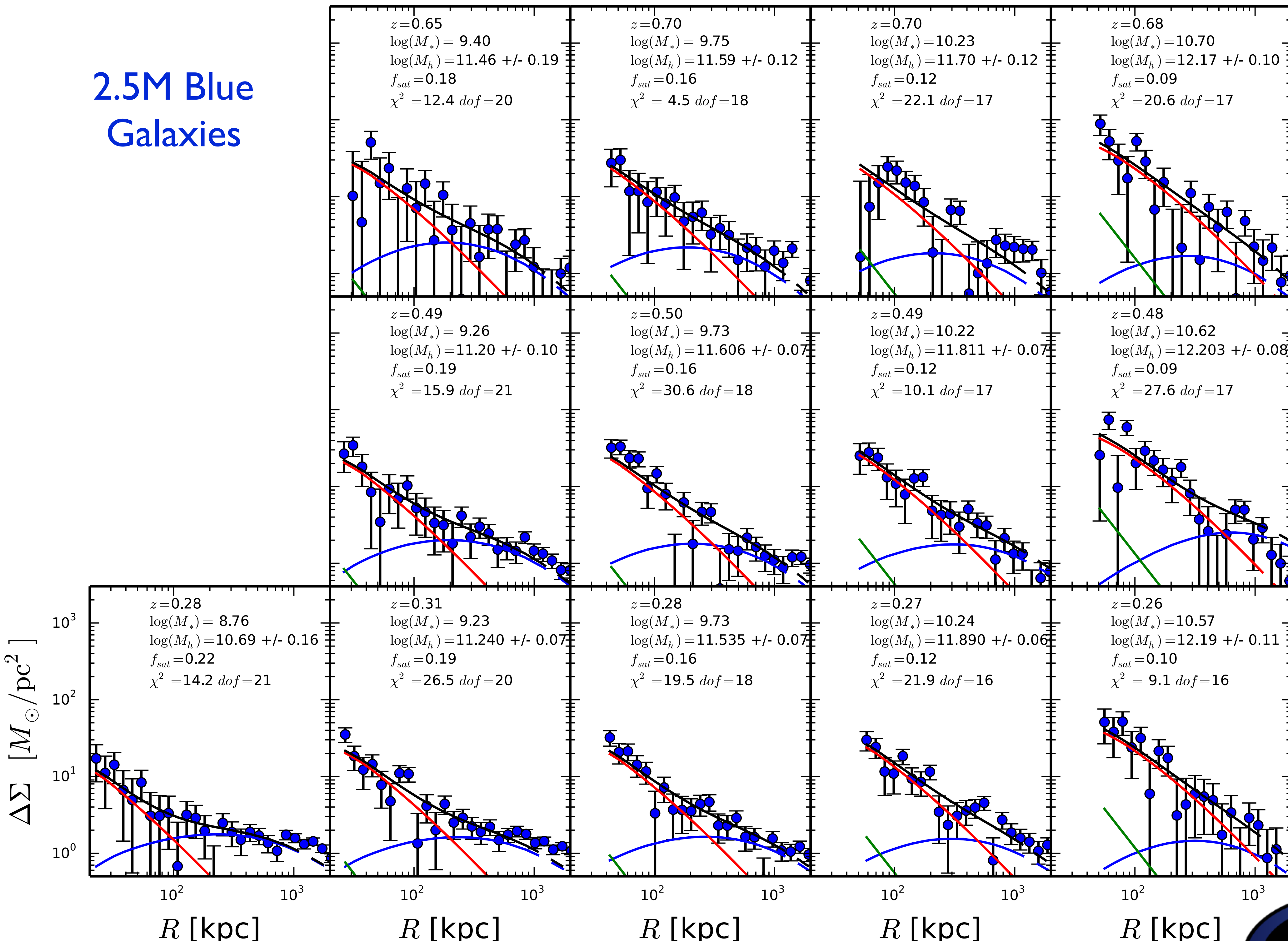
CFHTLenS

CFHTLENS GALAXY-GALAXY



CFHTLENS GALAXY-GALAXY

2.5M Blue Galaxies



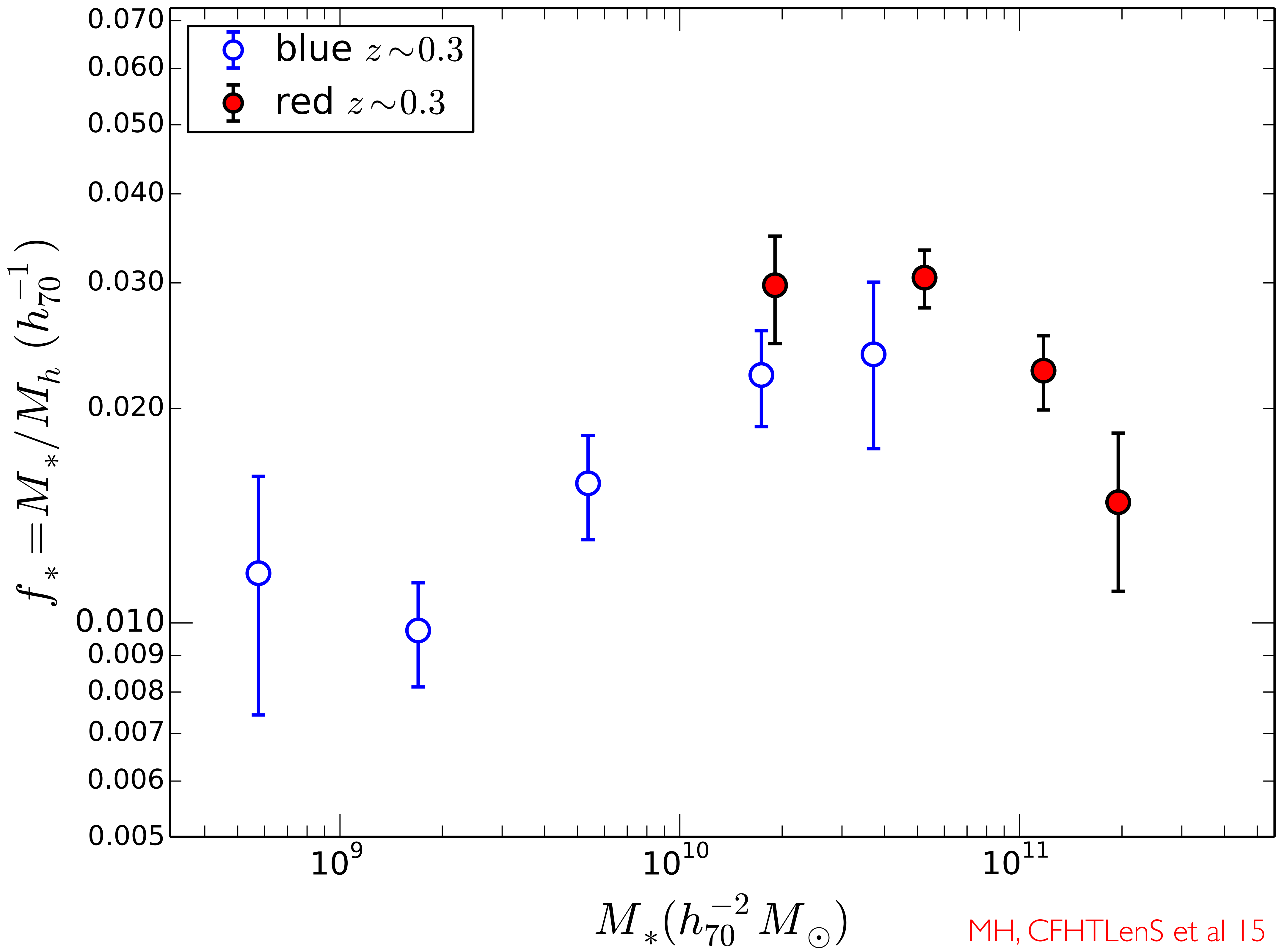
z=0.7

z=0.5

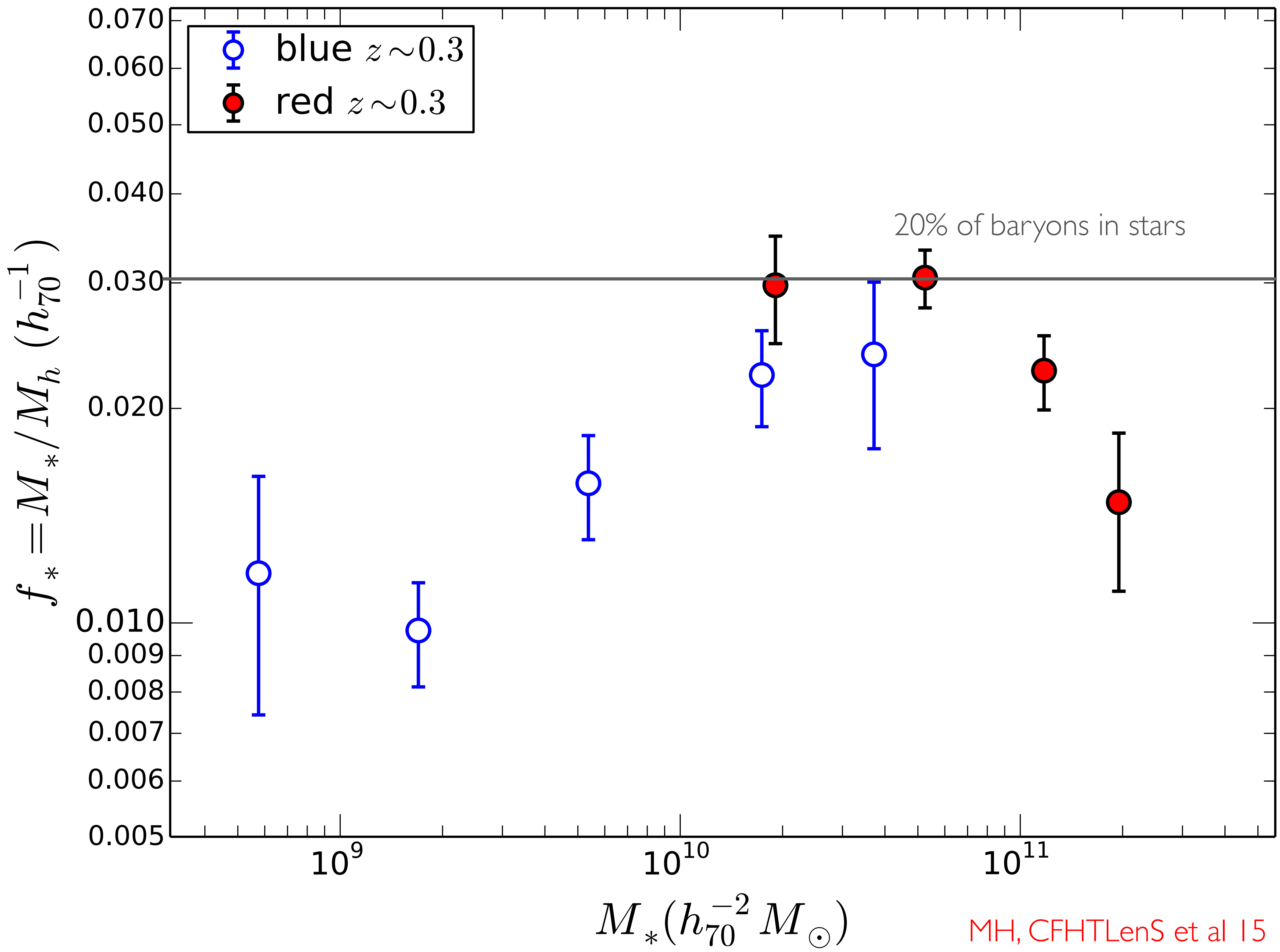
z=0.3

More massive ->

CFHTLenS



MH, CFHTLenS et al 15



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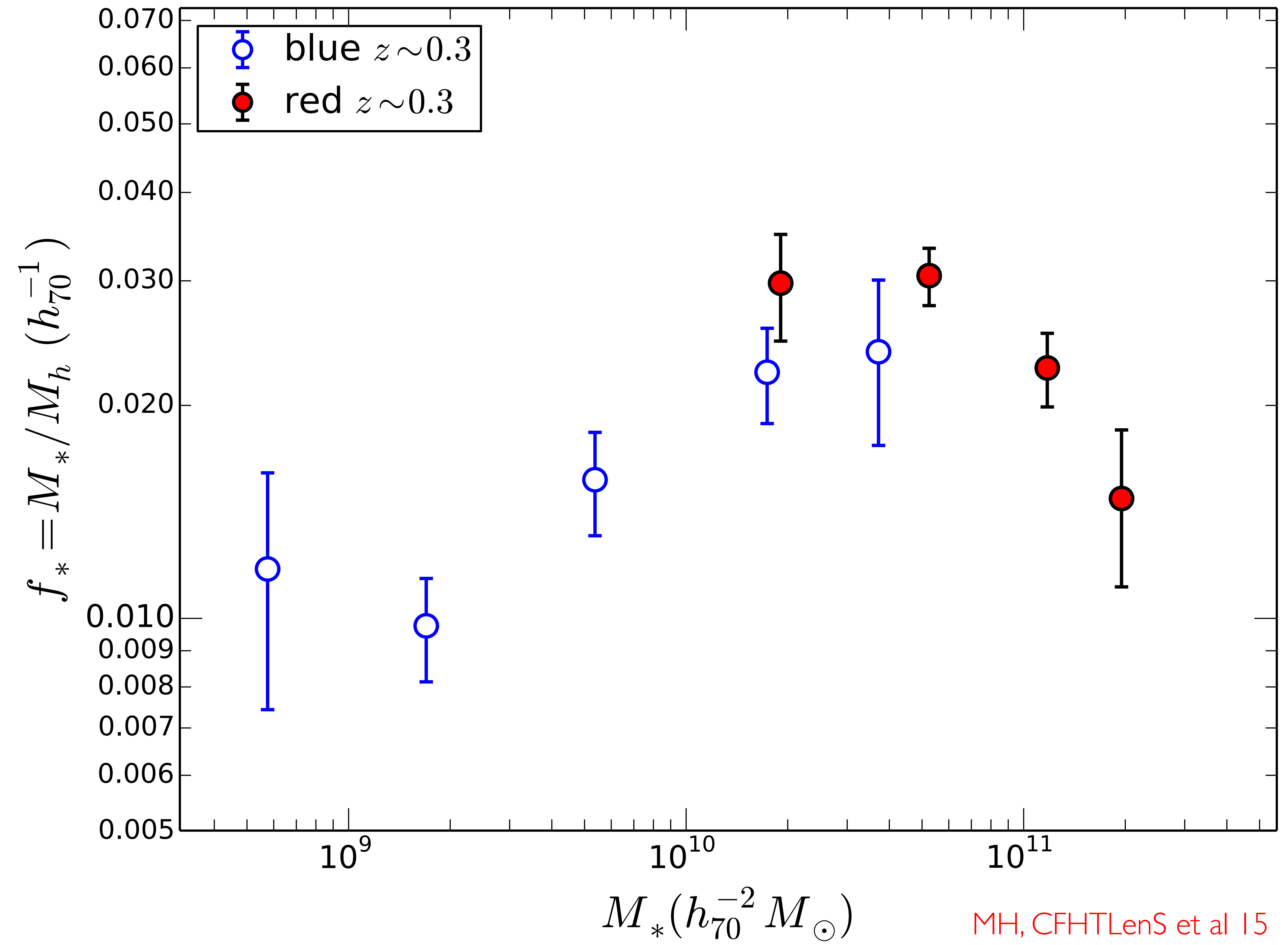

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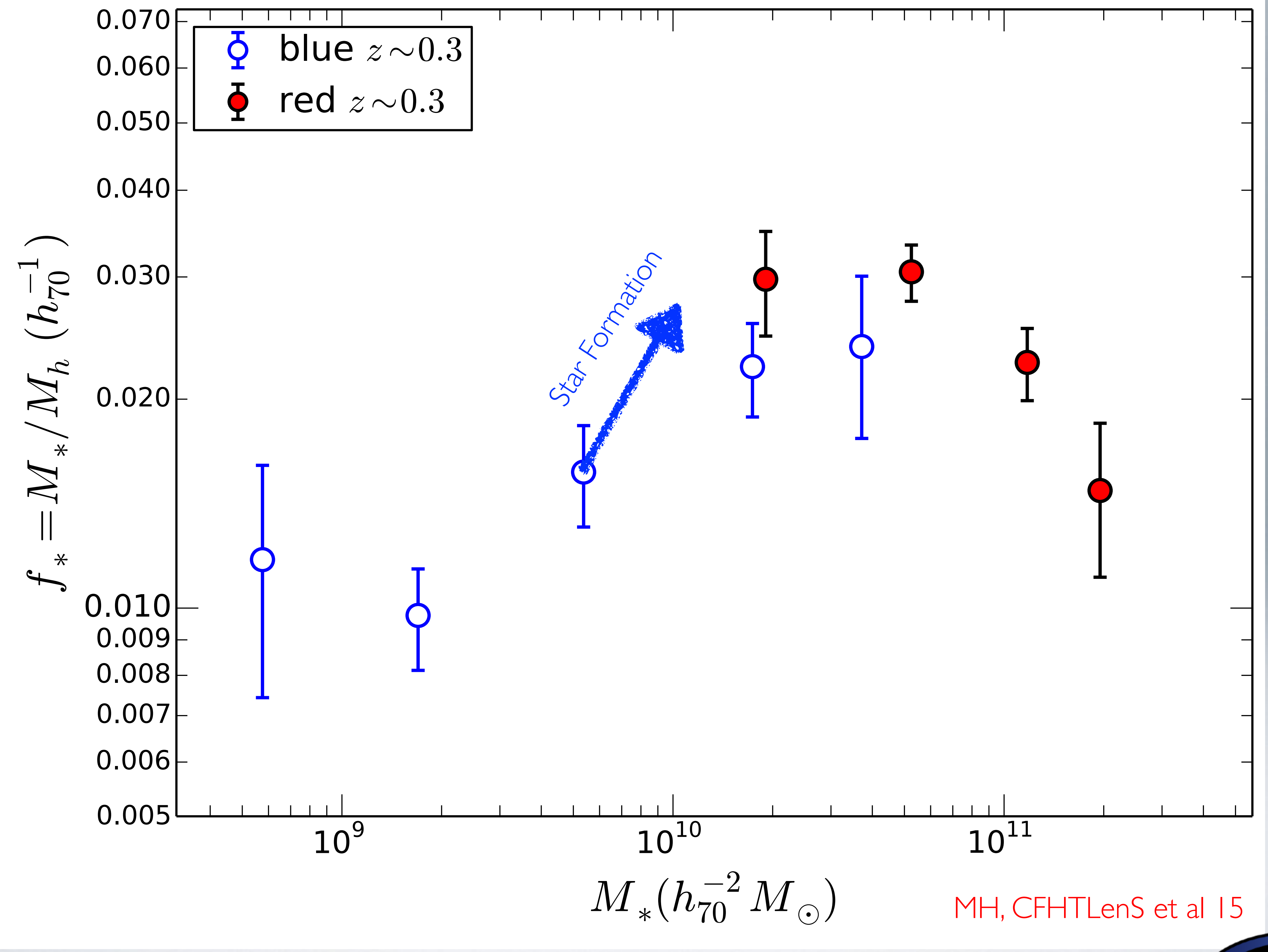
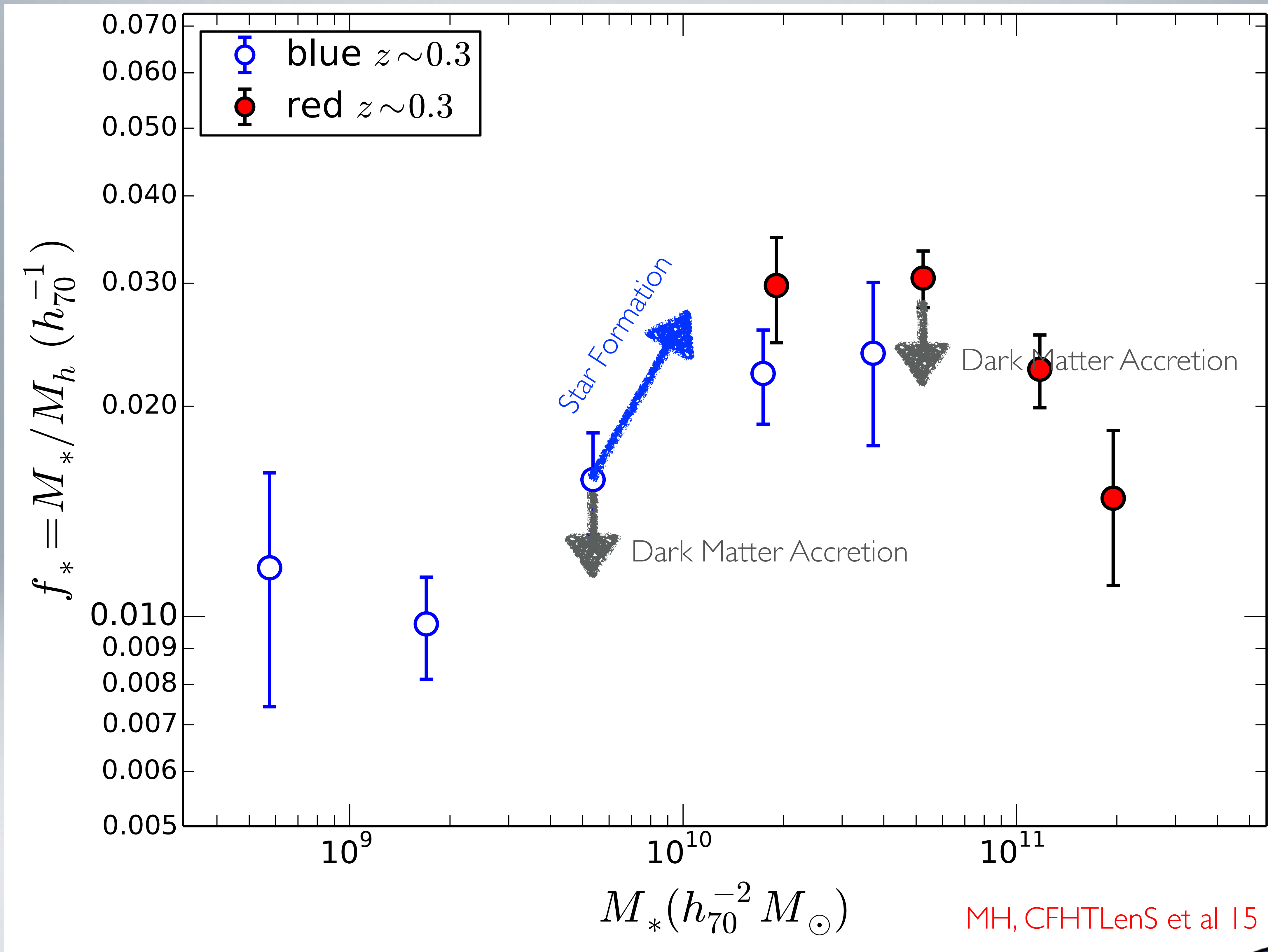


0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.009
0.008
0.007
0.006
0.005
blue $z \sim 0.3$
red $z \sim 0.3$
Star Formation
$f_* = M_*/M_h\ (h_{70}^{-1})$
10^9
10^{10}
10^{11}
$M_*(h_{70}^{-2}\,M_\odot)$
MH, CFHTLenS et al 15



blue $z\sim0.3$
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Star Formation
Dark Matter Accretion
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$f_* = M_*/M_h\ (h_{70}^{-1})$
$M_*(h_{70}^{-2}\,M_\odot)$
0.070
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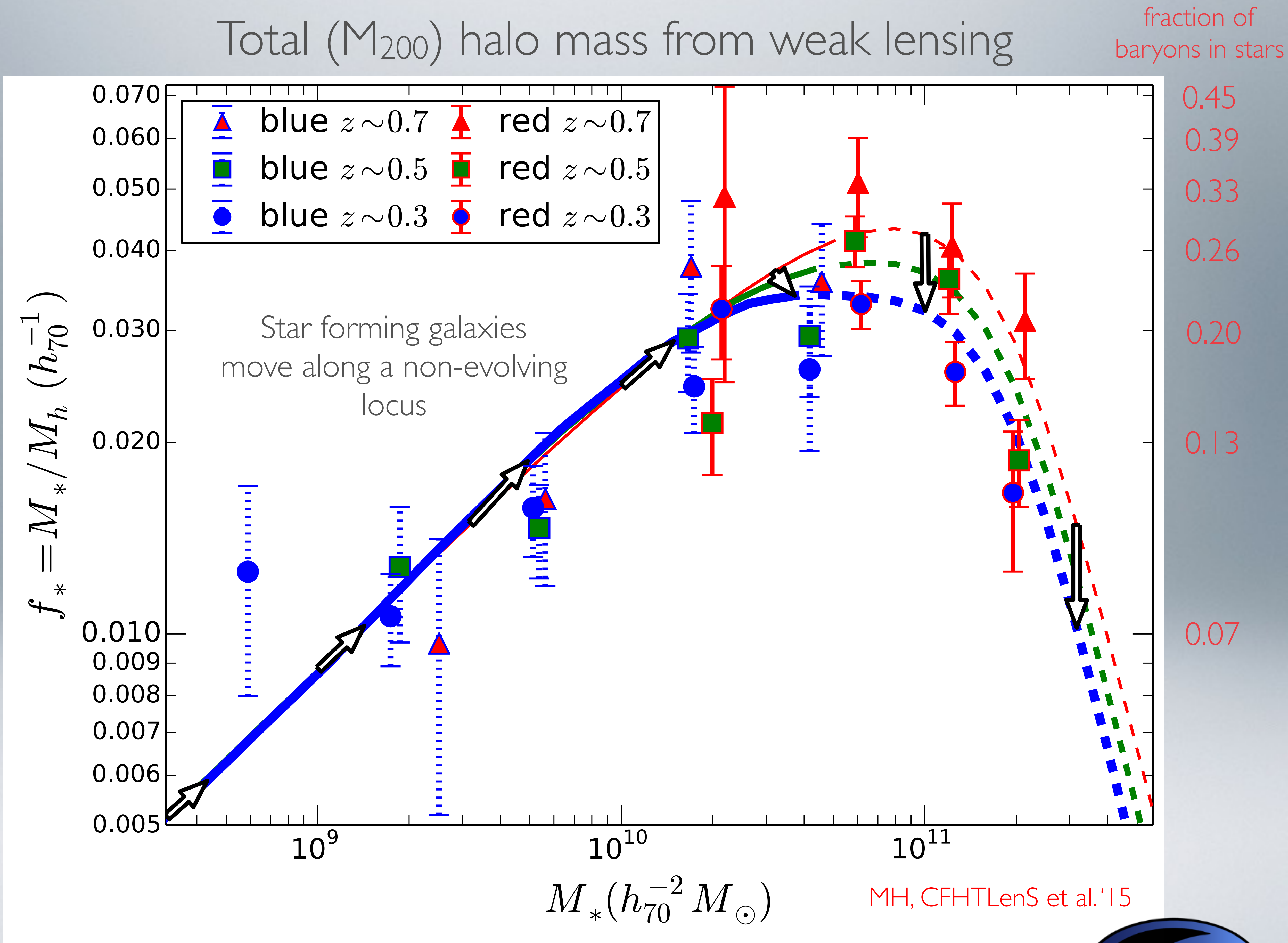
0.005
10^9
10^{10}
10^{11}
MH, CFHTLenS et al 15

TOWARDS A MORE PHYSICAL MODEL:

- Empirical star formation rates from the literature
- "Quenching" at a given halo mass
- N-body DM accretion rates
- (No mergers)

Total (M_{200}) halo mass from weak lensing



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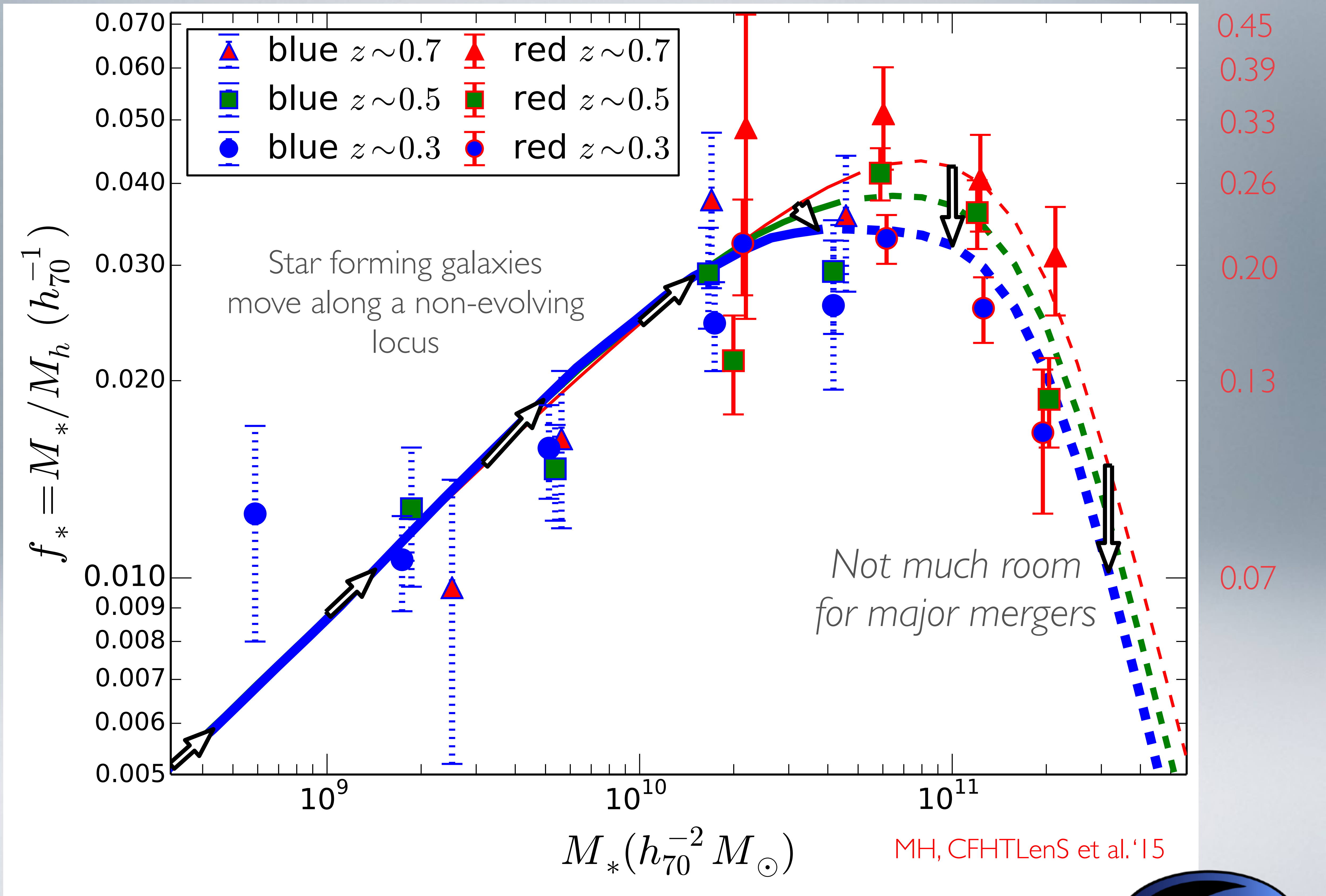

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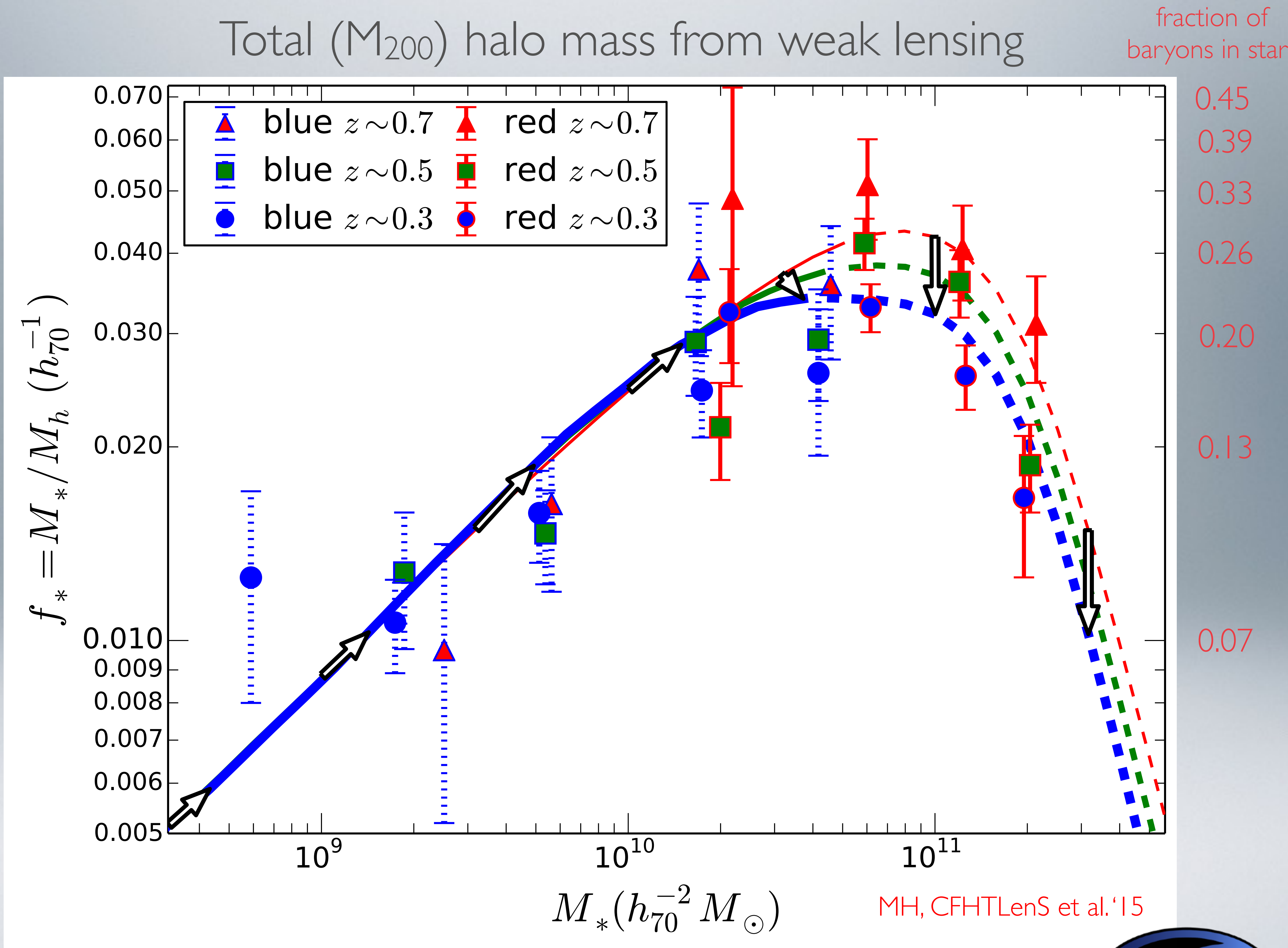

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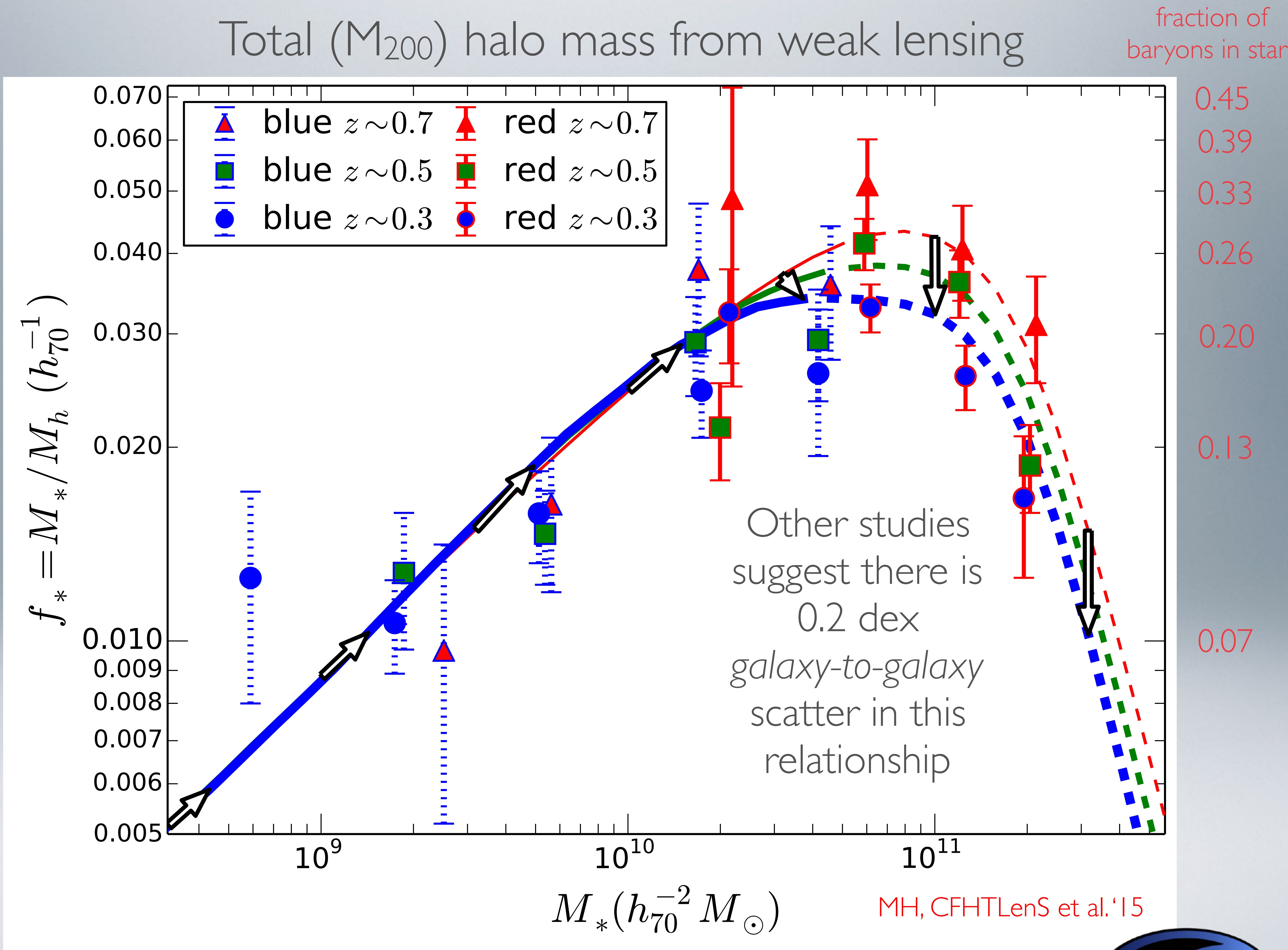

- Why does star formation balance halo accretion in such a way as to move galaxies ***along*** the SHMR?
  - Suggests a feedback process

- Quenching occurs at a *constant halo mass* of $\sim 2 \times 10^{12}$ solar
  - What process quenches galaxies?

- What is the source of the 0.2 dex scatter? Is stellar mass the only important parameter in galaxy formation?

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- $M_{halo}(M_*) \propto [R_e(M_*)]^{\eta}$

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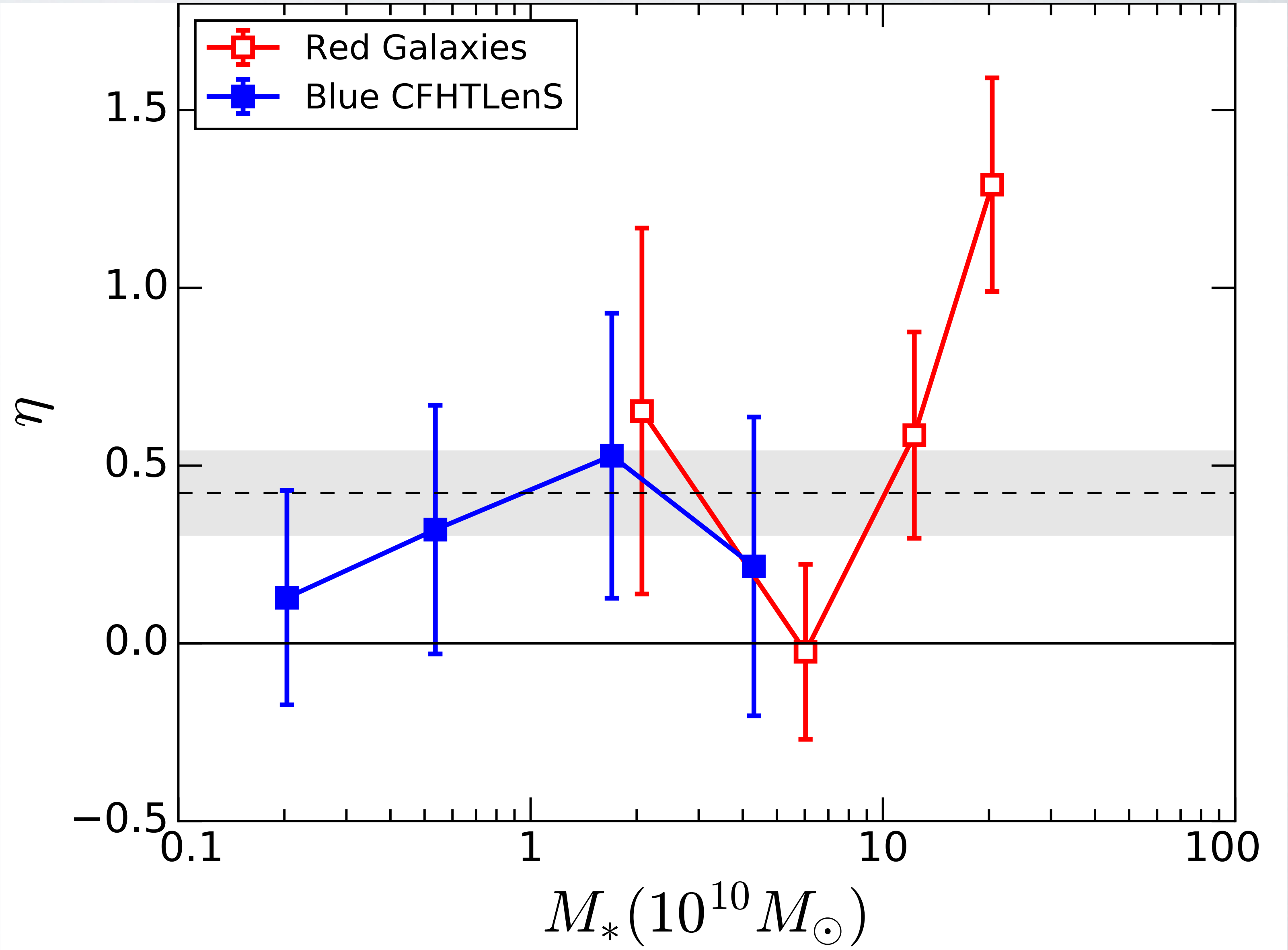

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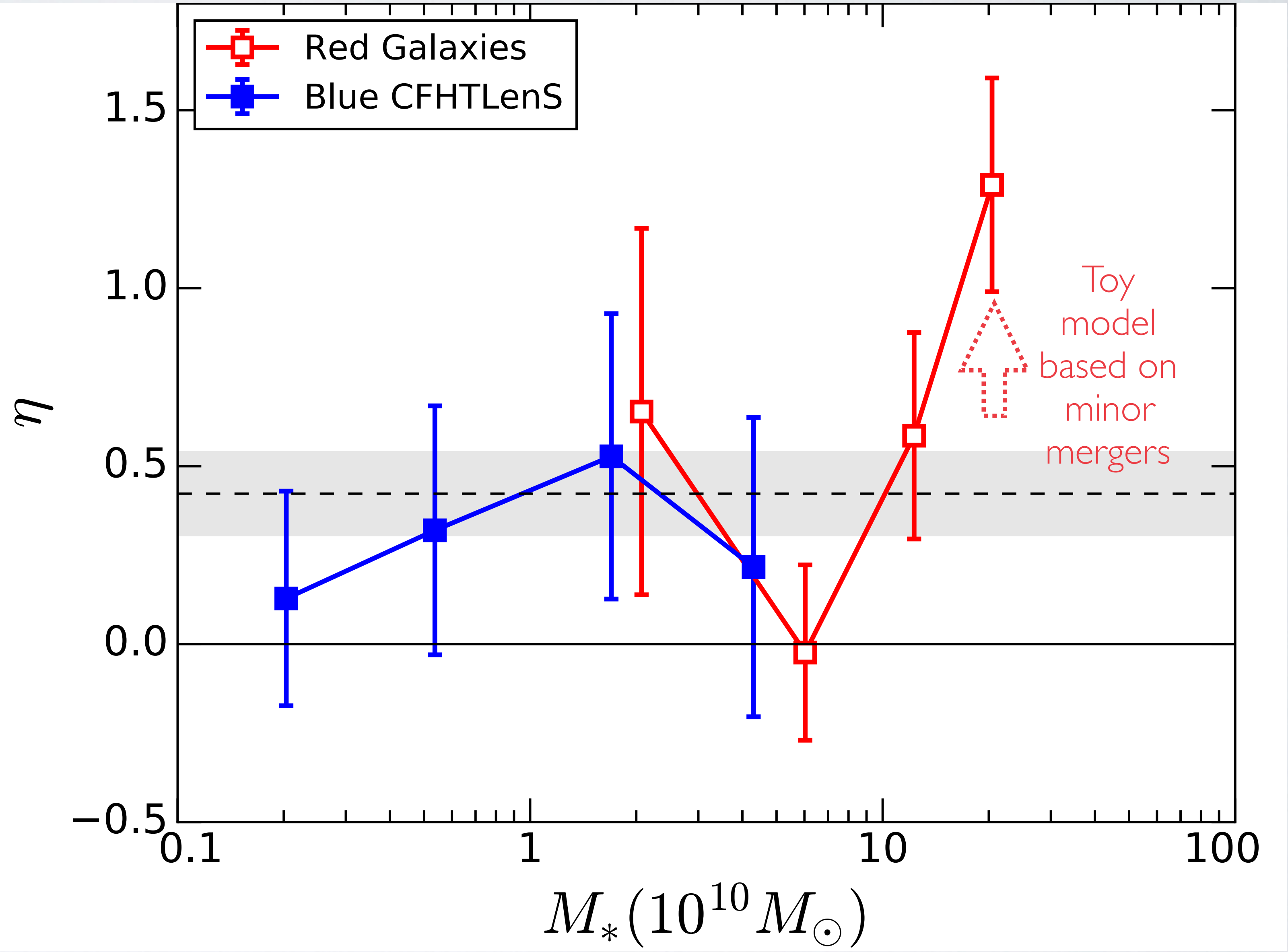
DOES SIZE MATTER?

- Split stellar mass bins by size, measure halo mass from WL at *fixed M_**
- $M_{halo}(M_*) \propto [R_e(M_*)]^\eta$
- From weak lensing on average, $\eta > 0$
- Especially high for red galaxies with $M_* \sim 2\times10^{11}$ (i.e. LRGs: dominant galaxies in rich groups)



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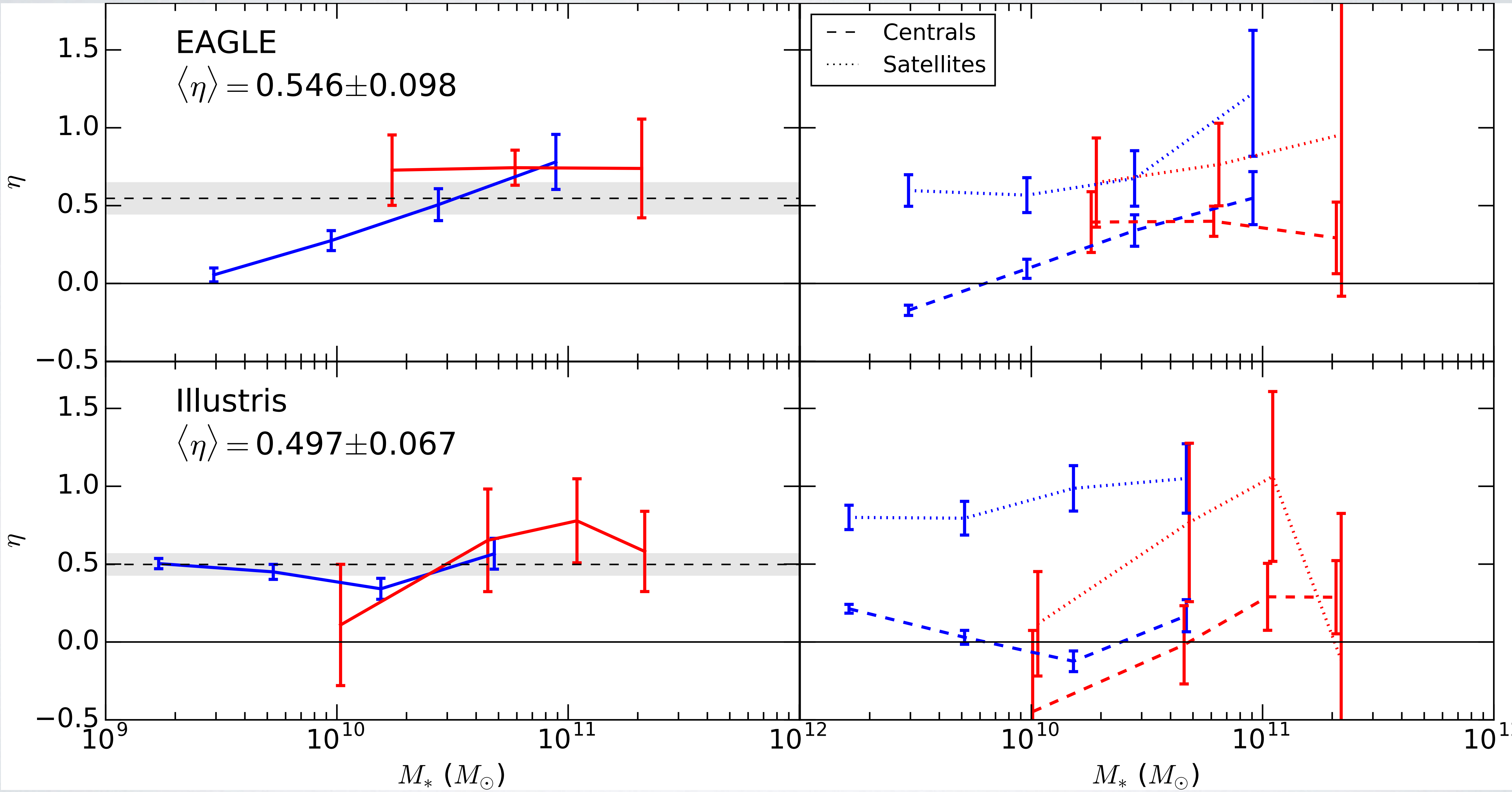
SIZE MATTERS: EVEN IN SIMULATIONS



Much of the effect from (stripped) satellites?

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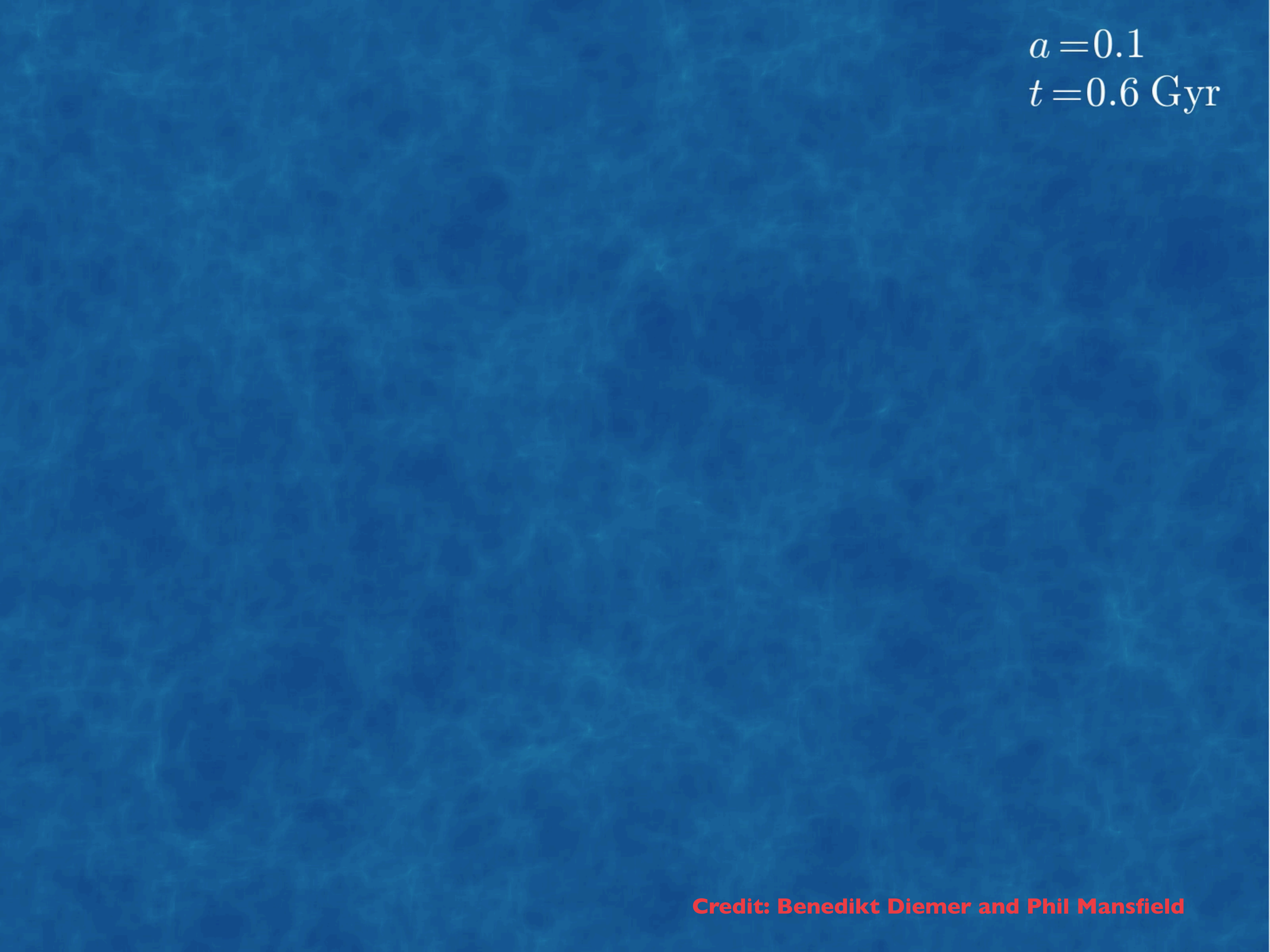
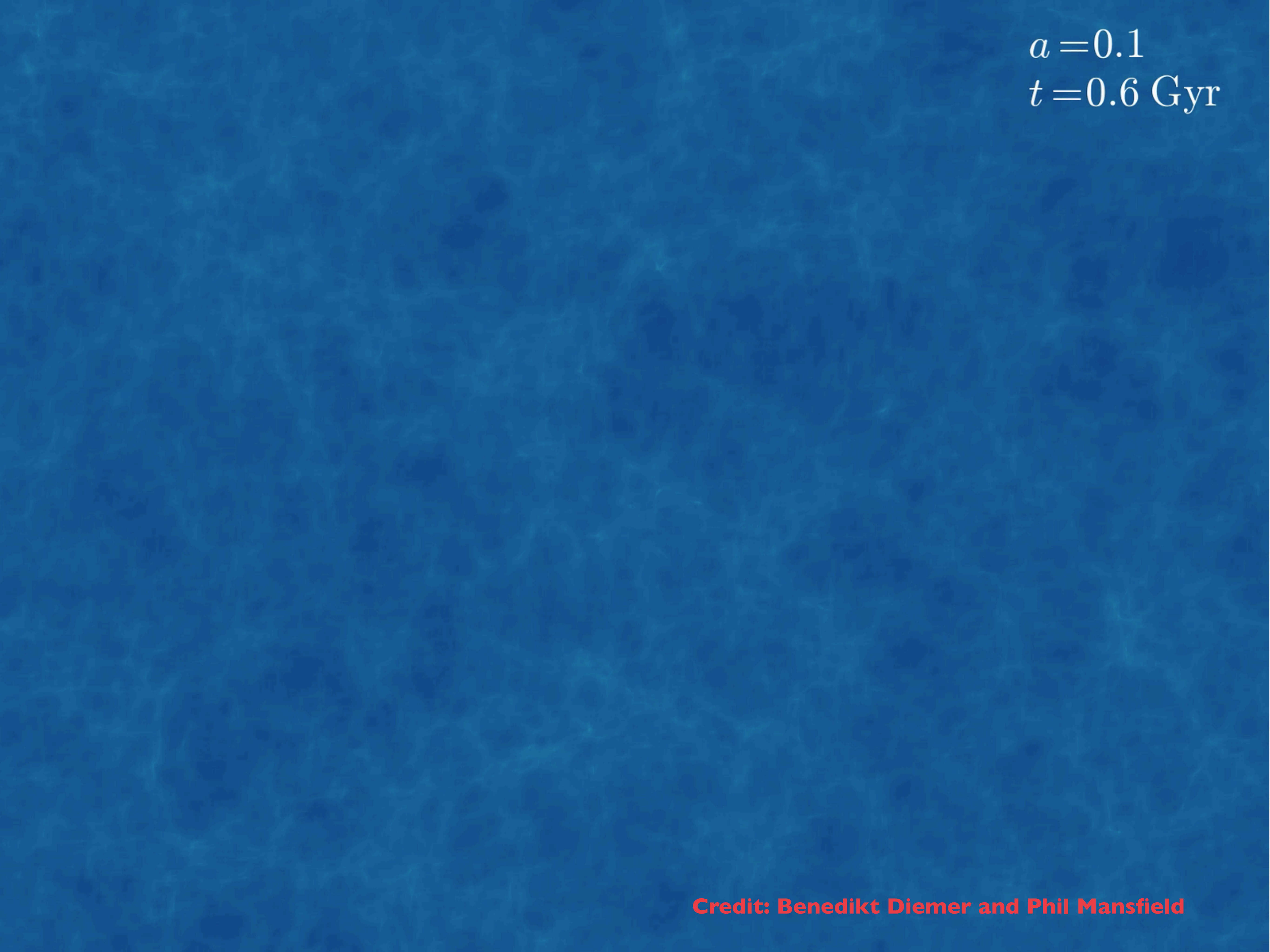


Credit: Benedikt Diemer and Phil Mansfield



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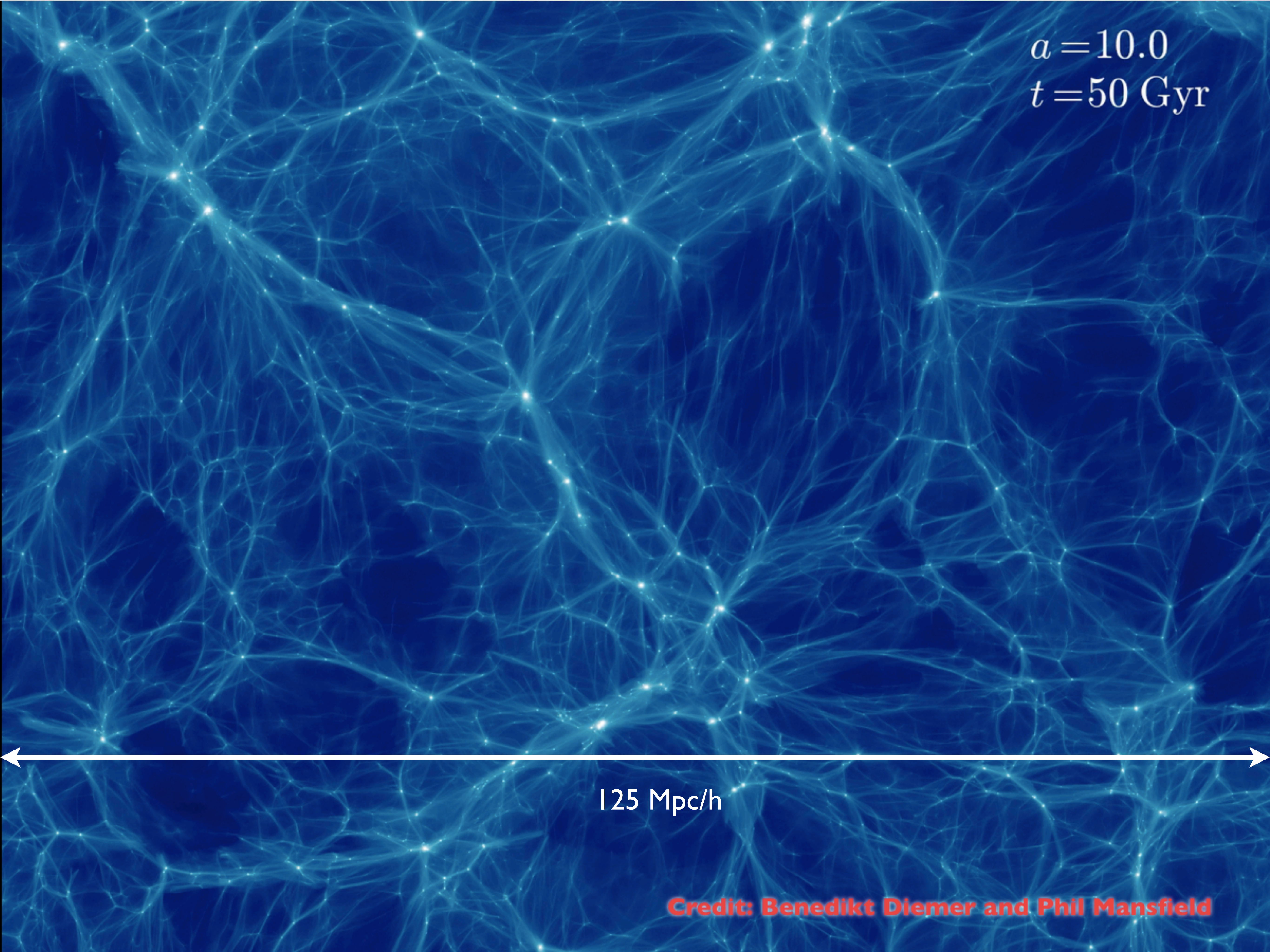
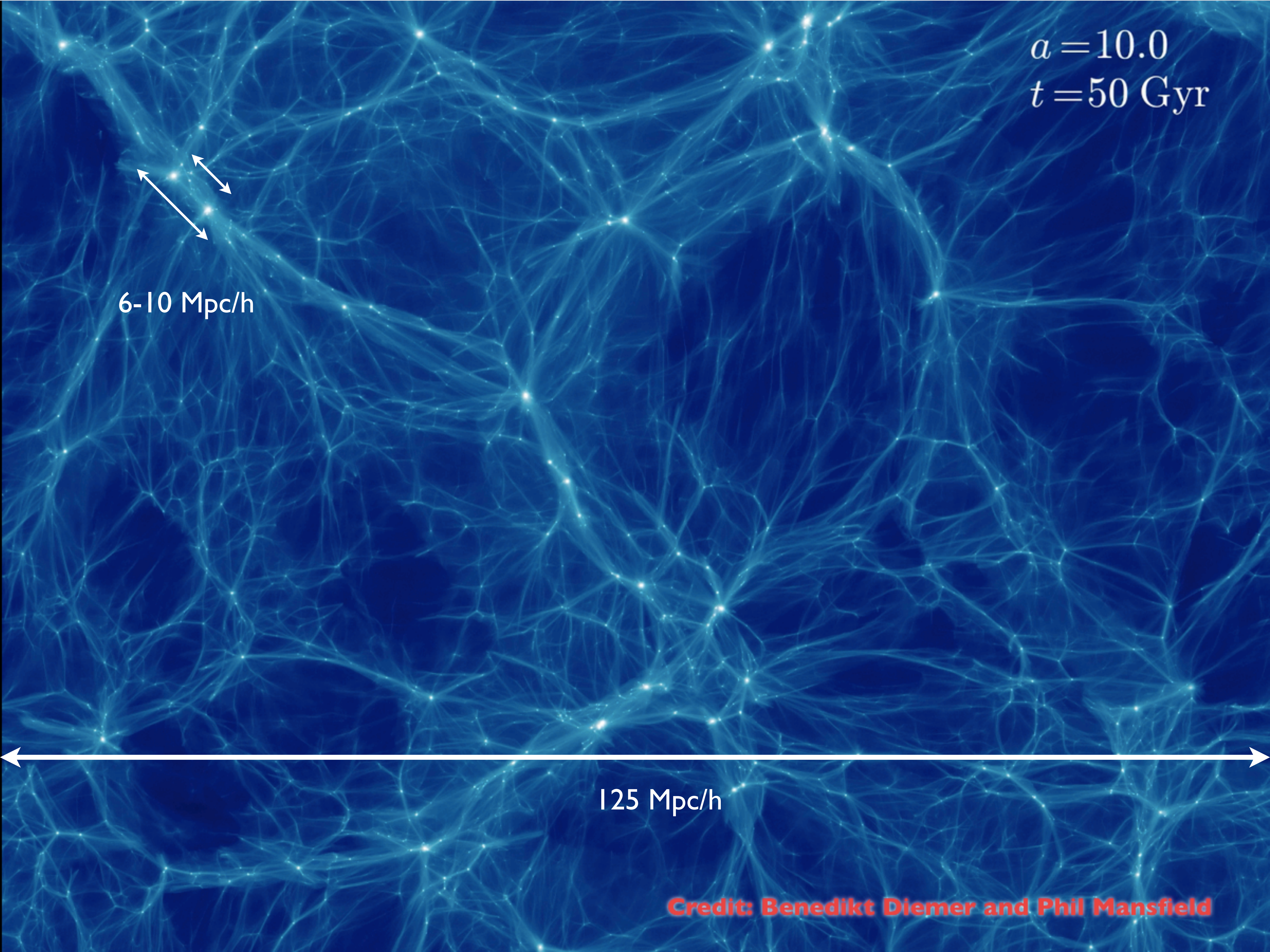

$a = 10.0$
$t = 50$ Gyr
125 Mpc/h
Credit: Benedikt Diemer and Phil Mansfield


$a = 10.0$
$t = 50$ Gyr
6-10 Mpc/h
125 Mpc/h
Credit: Benedikt Diemer and Phil Mansfield

DARK MATTER FILAMENTS

- Few Individual Detections For Massive Clusters
  - Dietrich ***et al***. 2012; Jauzac et al. 2012; Higuchi ***et al***. 2015
  - Massive Clusters $> 10^{14} M_{\odot}$
  - Detections at >~3σ
  - But filaments are close to the virial radii of their host clusters:
    - Elongation of clusters?

- Clampitt, Miyatake, Jain & Takada, 2016
  - Stacked LRG pairs in SDSS
  - Claimed 10σ Detection
  - Mass? Structure?

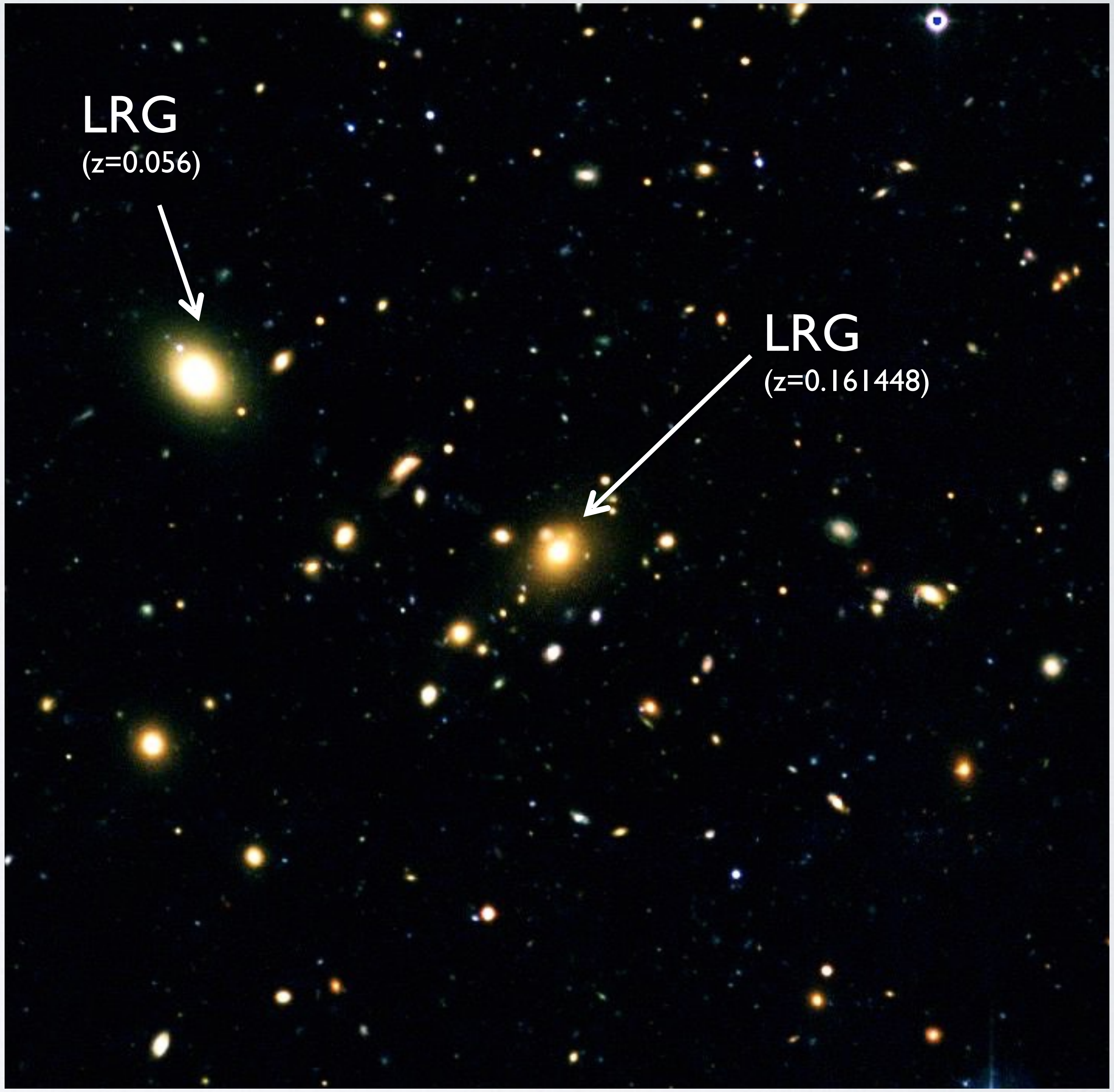
Weak Lensing

FINDING FILAMENTS

- Look between physically associated groups and clusters

- Luminous Red Galaxies(LRGs) live at the centre of rich groups

$$\sim 10^{13} M_{\odot}$$



OBSERVATIONAL DATA

CFHT: Erben *et al.*, 2013; Hildebrandt *et al.*, 2012; Miller *et al.*, 2013; Heymans *et al.*, 2012,2013

SDSS: Eisenstein *et al.*, 2011; Dawson *et al.*, 2012

23,000
Pairs of Luminous Red Galaxies (LRGs)

$$\langle z_\ell \rangle \sim 0.4 \quad \langle \log_{10} M_\star / M_\odot \rangle \sim 11.3$$

ROTATE, RESCALE, SHIFT AND STACK

- 23000 pairs of LRGs were selected between projected separation:

$$6h^{-1}\mathrm{Mpc} \leq R_{\mathrm{sep}} < 10h^{-1}\mathrm{Mpc}$$

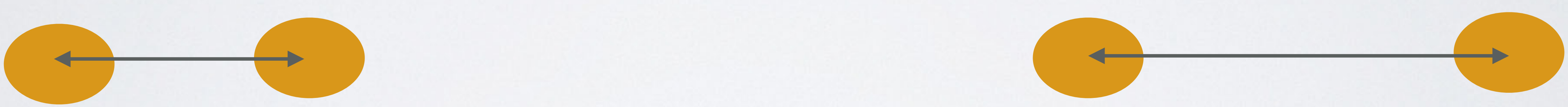
$$|\Delta z| < 0.002$$

ROTATE

- 23000 pairs of LRGs were selected between projected separation:

$$6h^{-1}\text{Mpc} \leq R_{\text{sep}} < 10h^{-1}\text{Mpc}$$

$$|\Delta z| < 0.002$$



RESCALE

- 23000 pairs of LRGs were selected between projected separation:

$$6h^{-1}\mathrm{Mpc} \leq R_{\mathrm{sep}} < 10h^{-1}\mathrm{Mpc}$$

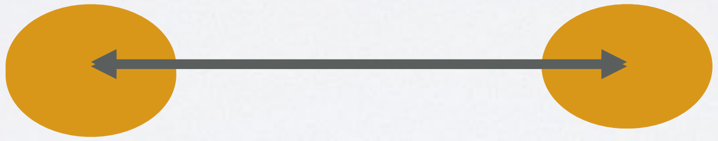
$$|\Delta z| < 0.002$$

SHIFT AND STACK

- 23000 pairs of LRGs were selected between projected separation:

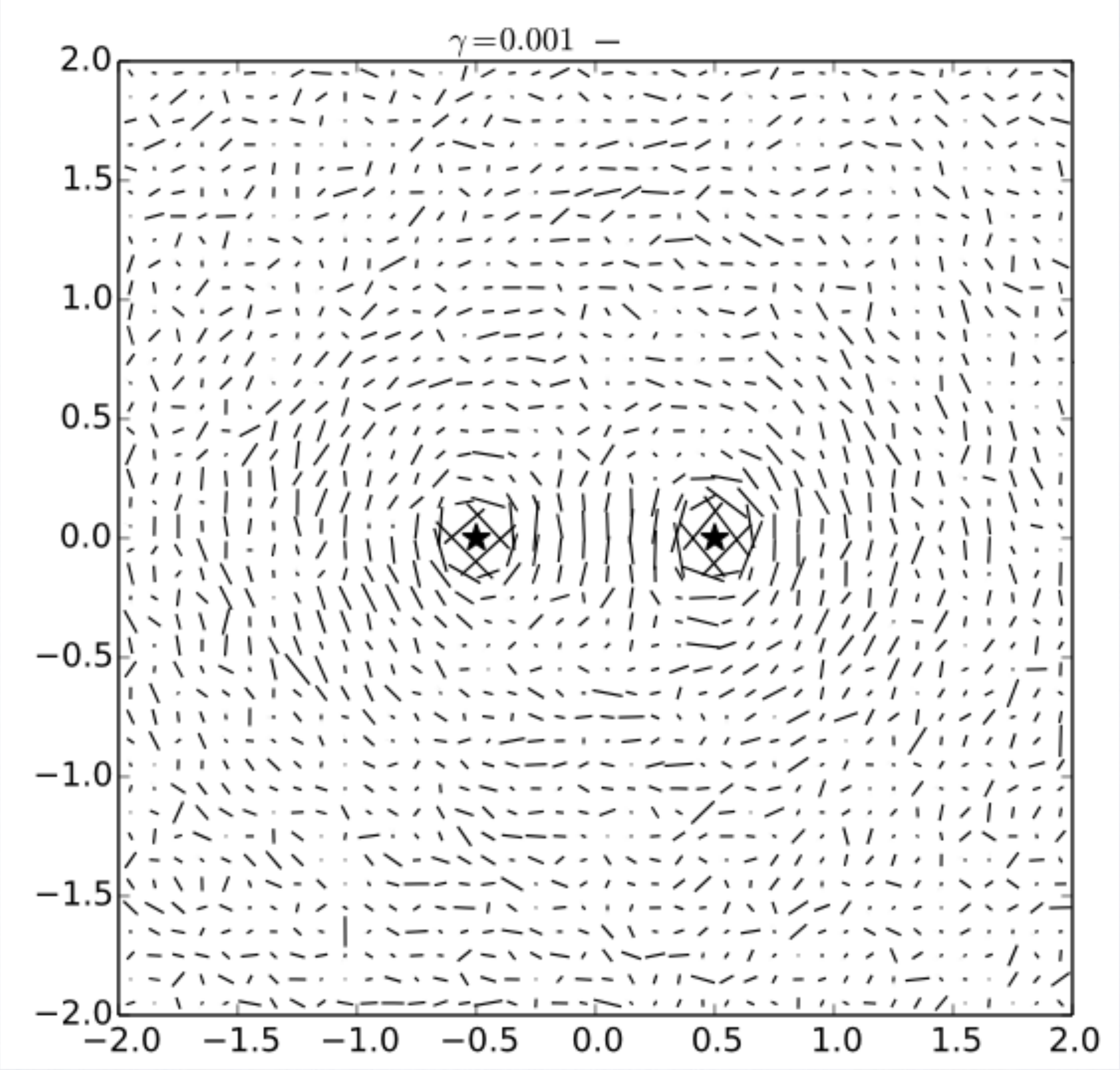
$$6h^{-1}\mathrm{Mpc} \leq R_{\mathrm{sep}} < 10h^{-1}\mathrm{Mpc}$$

$$|\Delta z| < 0.002$$

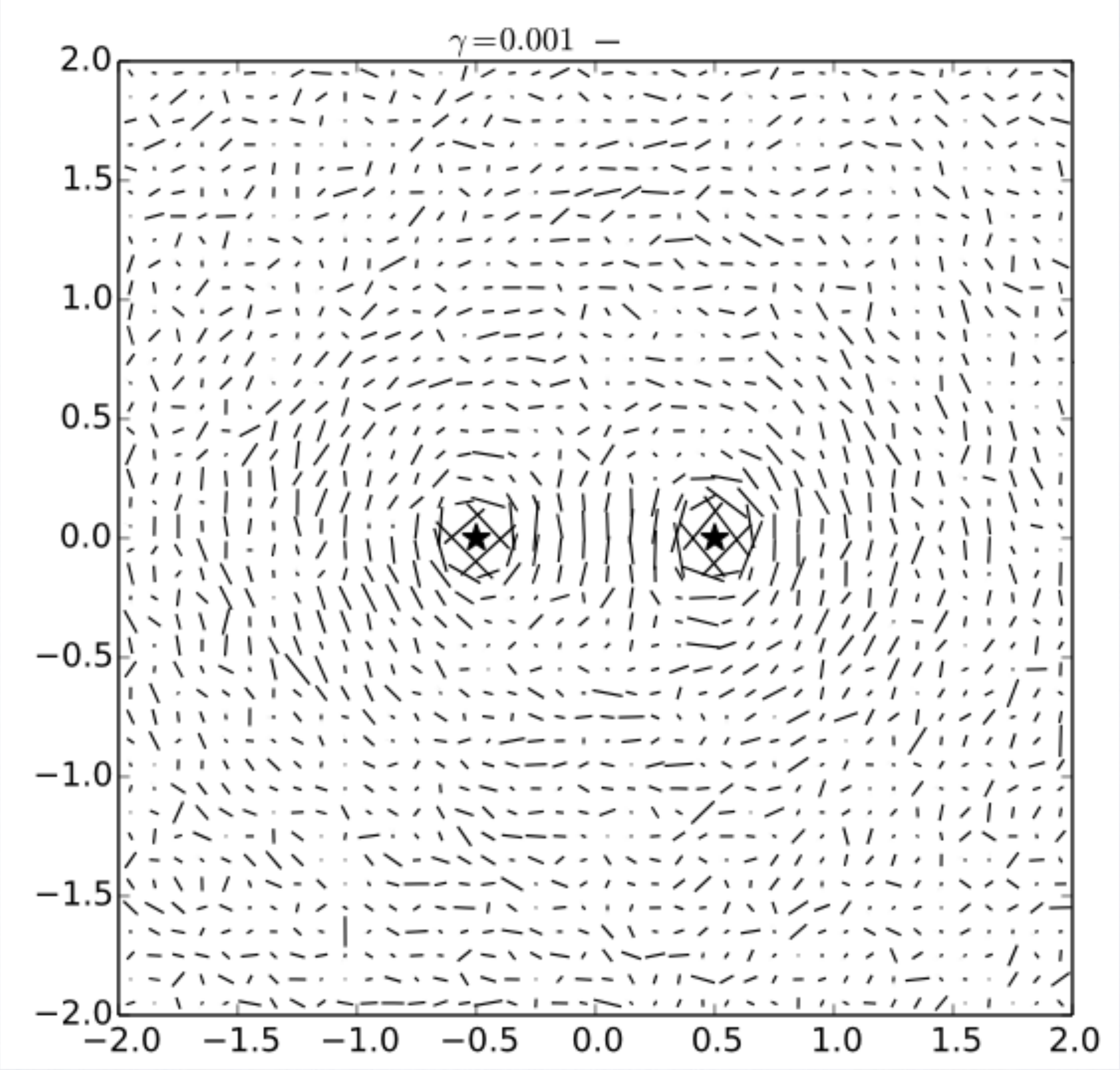


Rotate, rescale shift and stack background galaxies

RESULTING SHEAR MAP



RESULTING SHEAR MAP



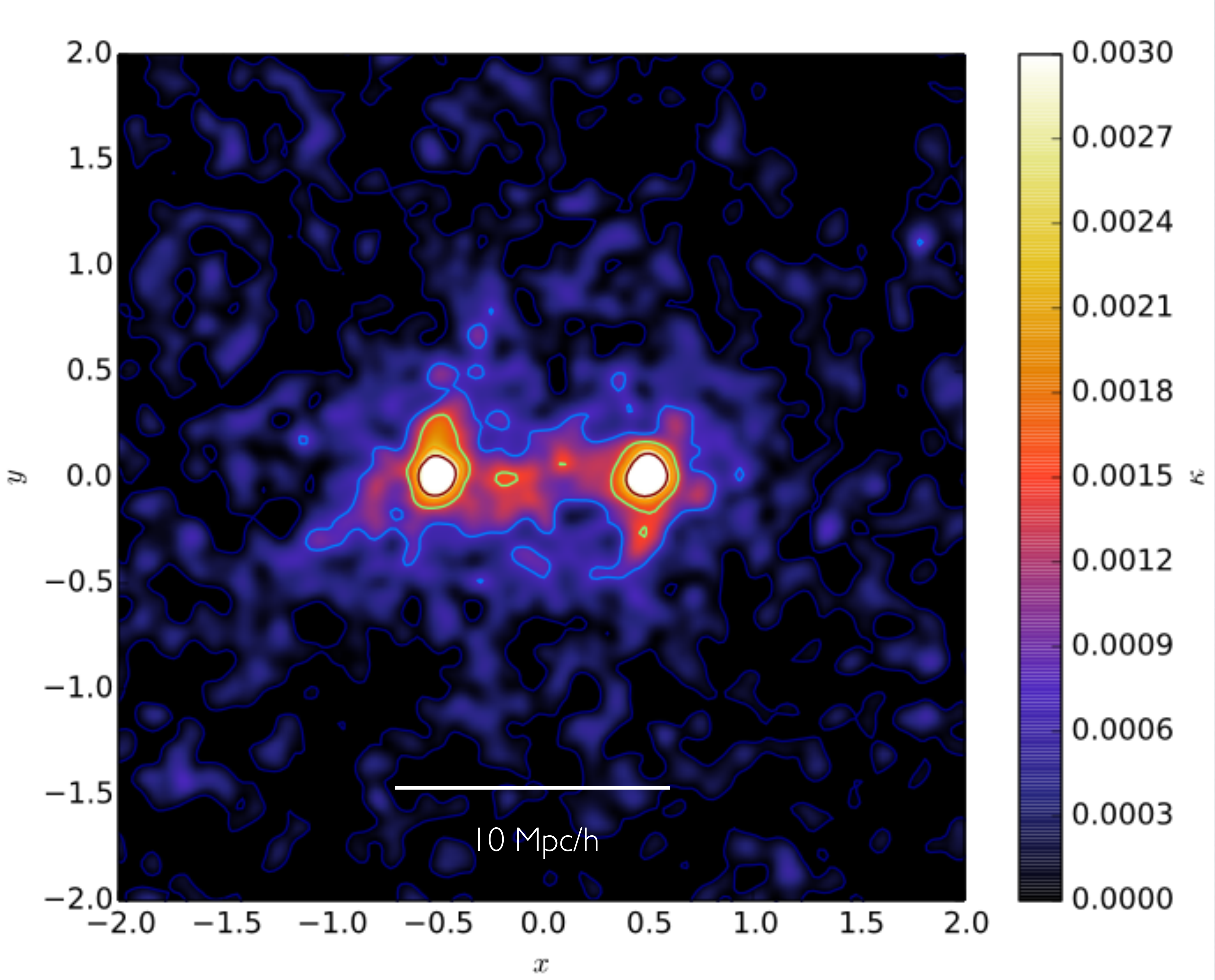
Kaiser & Squires `93 to get convergence (surface mass density) from shears

RESULTING DENSITY MAP

10 Mpc/h

Epps and Hudson 17

RESULTING DENSITY MAP



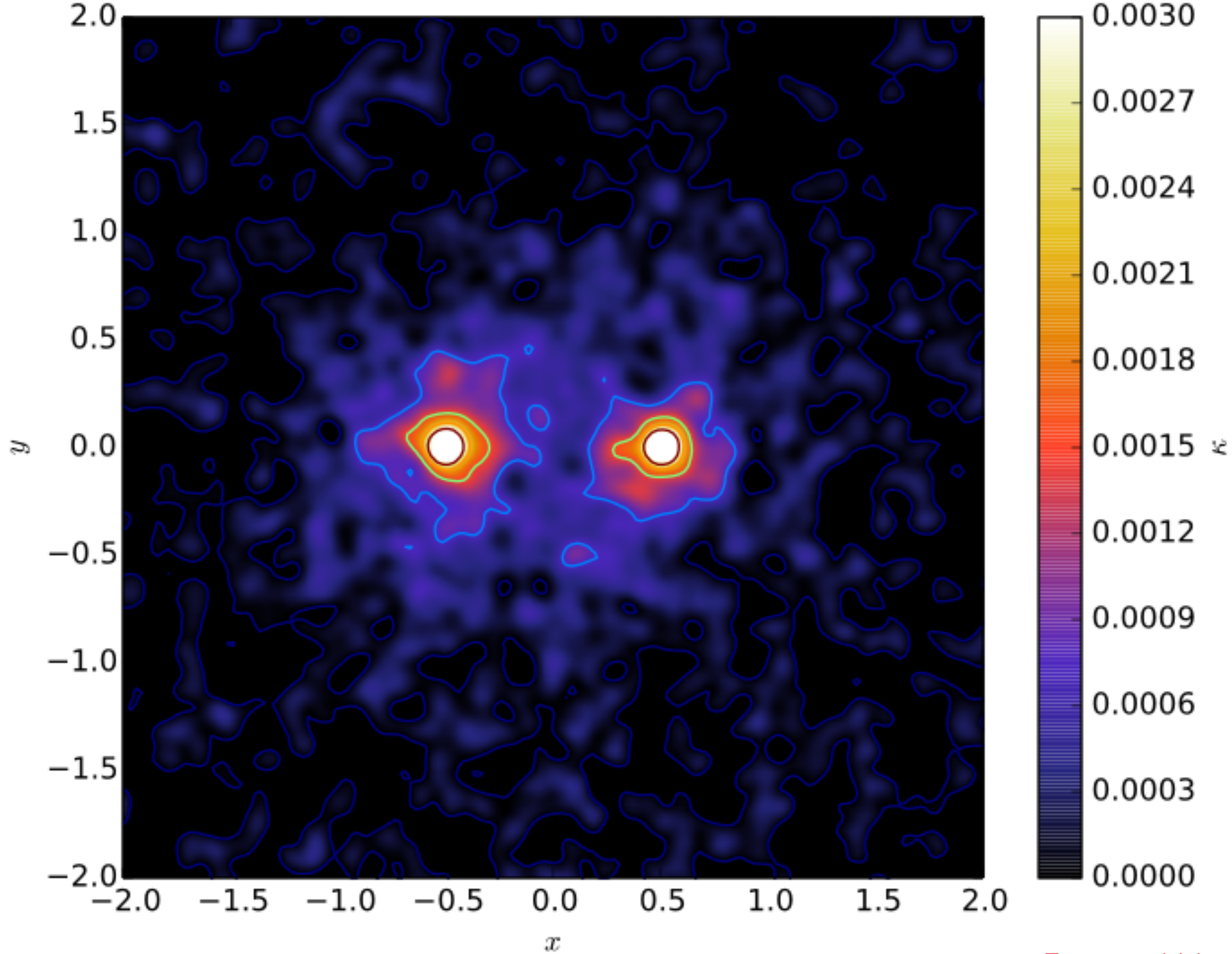
Epps and Hudson 17

ISOLATING THE FILAMENT

- Compare signal from projected (non-physical pairs) of LRGs

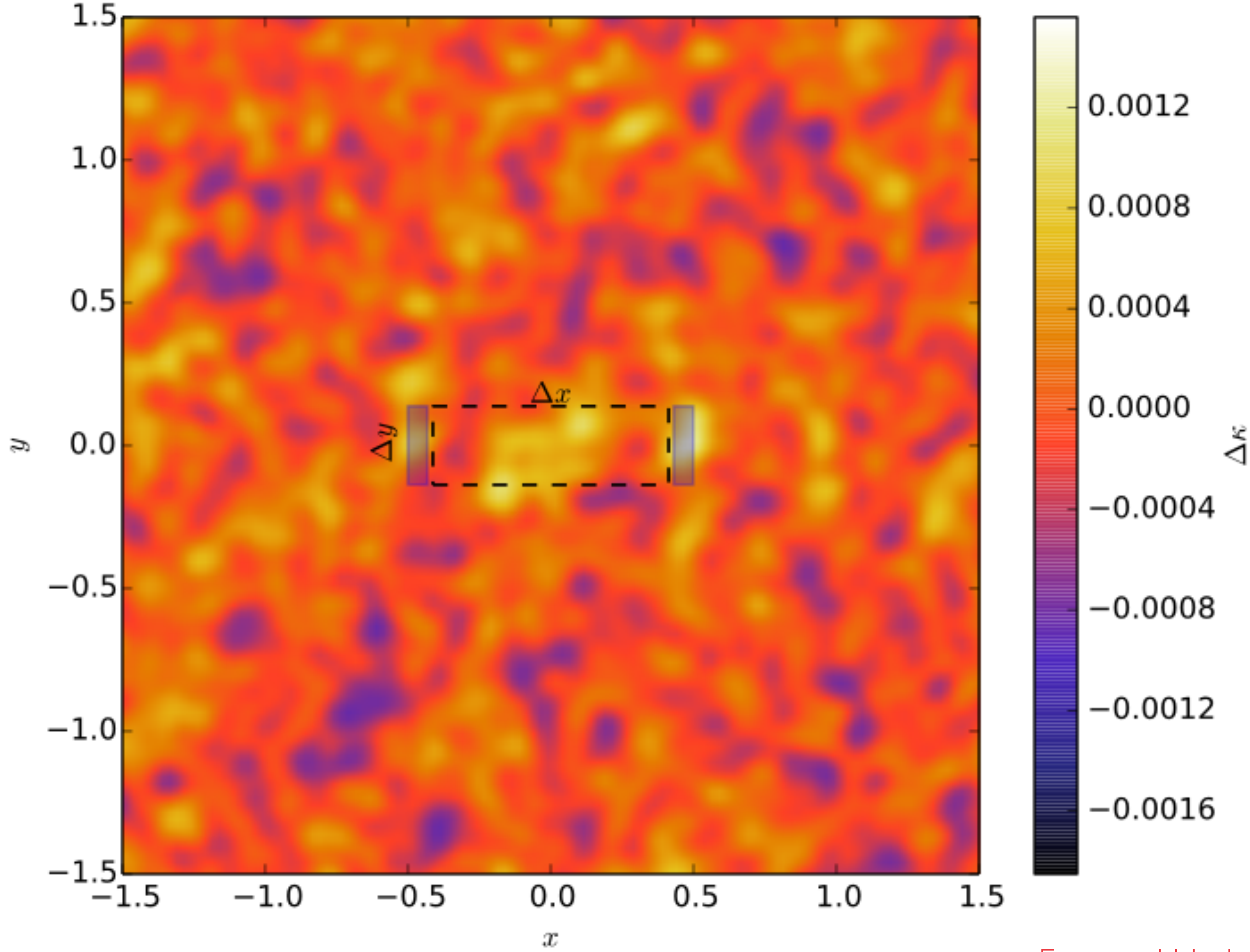
- Get Empirical Estimates of Filament Mass

NON-PHYSICAL PAIRS



Epps and Hudson 17

NON-PHYSICAL PAIRS



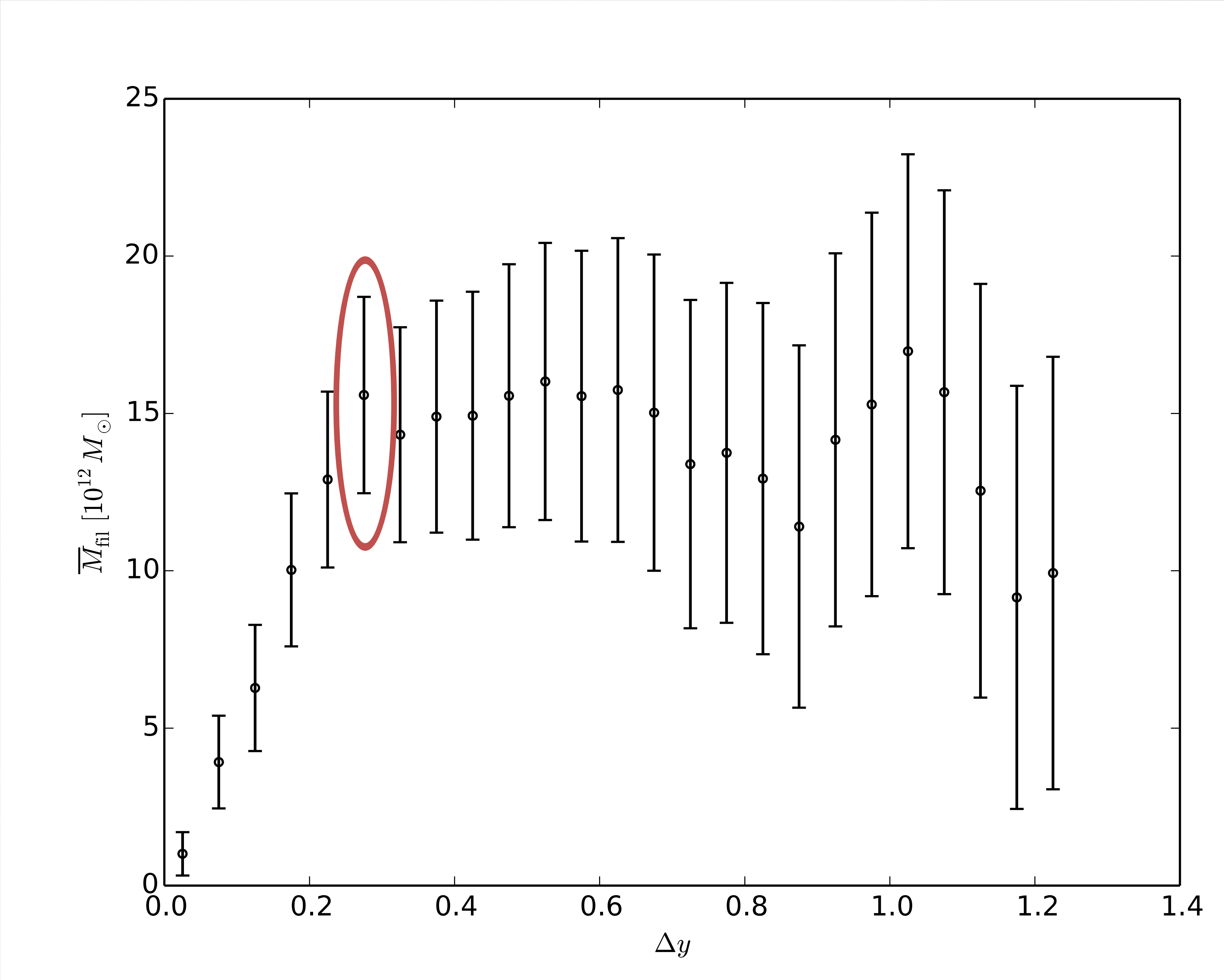
Epps and Hudson 17

CUMULATIVE MASS ENCLOSED

$\text{Width} \sim 2.37h^{-1}\text{Mpc}$

$\overline{M}_{\text{fil}} = (1.6 \pm 0.3) \times 10^{13} M_{\odot}$

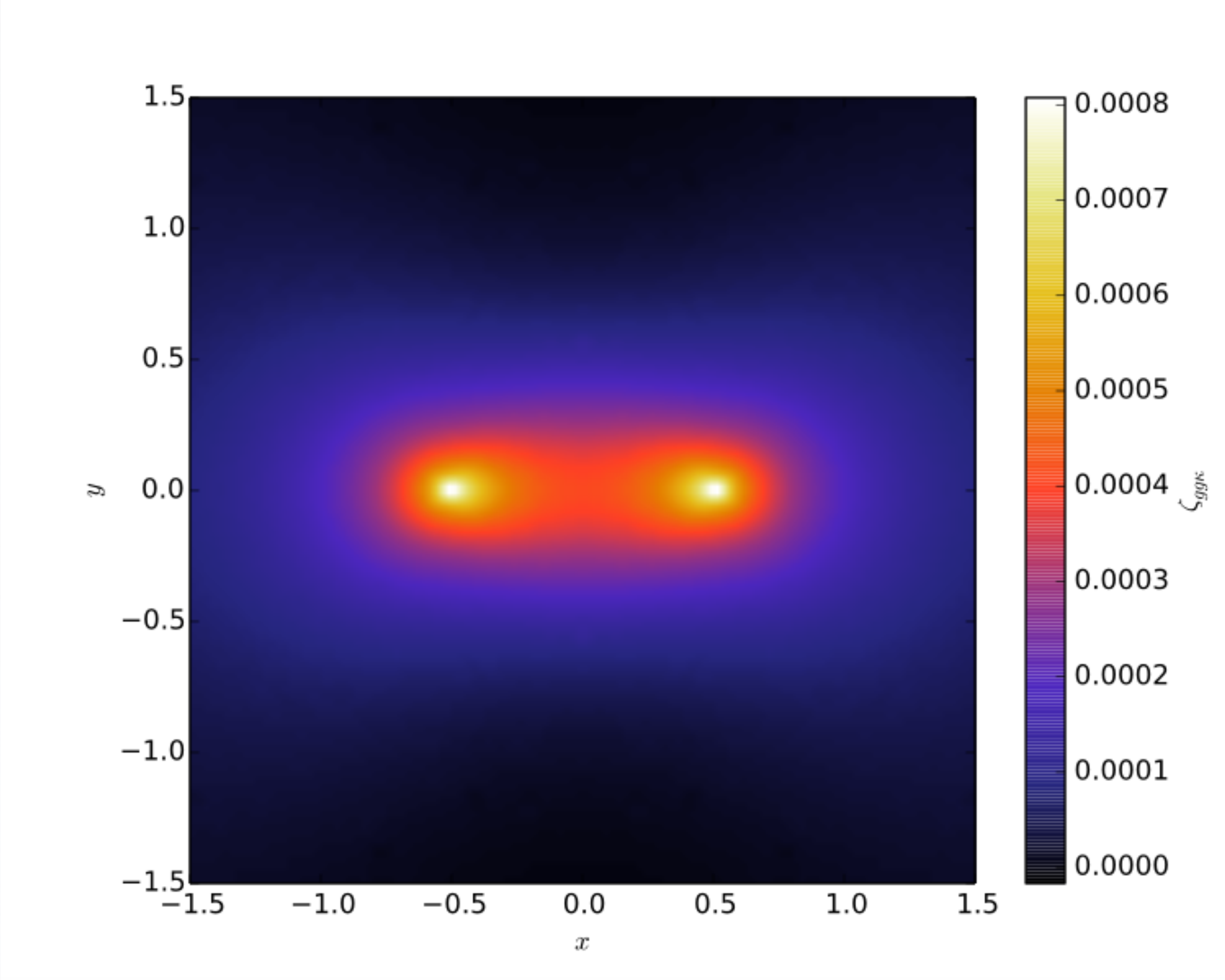
Typical overdensity ~ 5

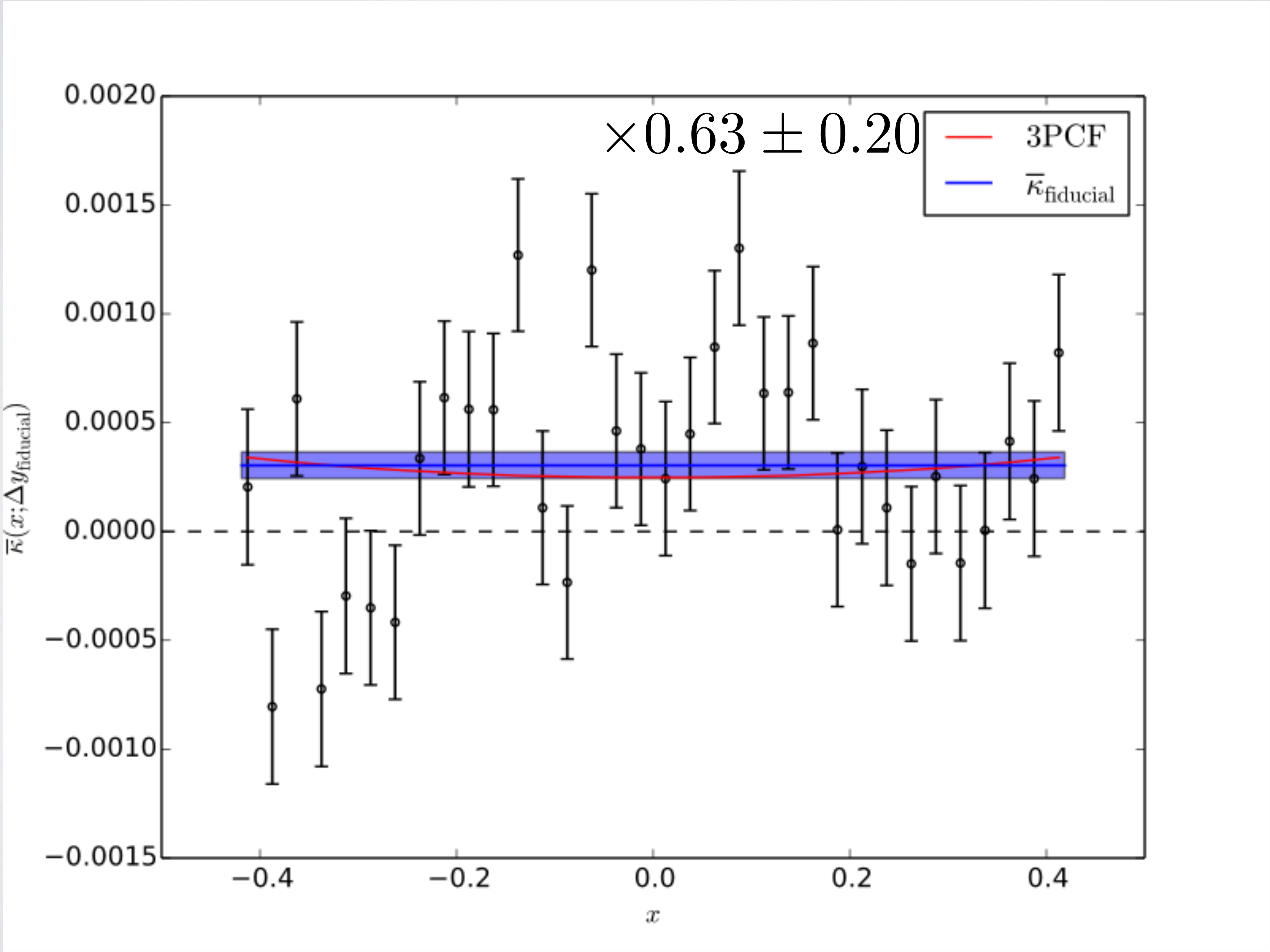


Epps and Hudson 17

COMPARISON TO MODEL

- Stacking Inherently Statistical
- Model Filament with 3-Point Correlation Function (3PCF) (following Clampitt ***et al.***, 2016)





×0.63 ± 0.20
3PCF
$\overline{\kappa}_{\rm fiducial}$
$\overline{\kappa}(x;\Delta y_{\rm fiducial})$
0.0020
0.0015
0.0010
0.0005
0.0000
−0.0005
−0.0010
−0.0015
−0.4
−0.2
0.0
0.2
0.4
x

LENSING SCIENCE

LENSING SCIENCE

- Mapping large-scale structure (in 3D) and cross-correlations

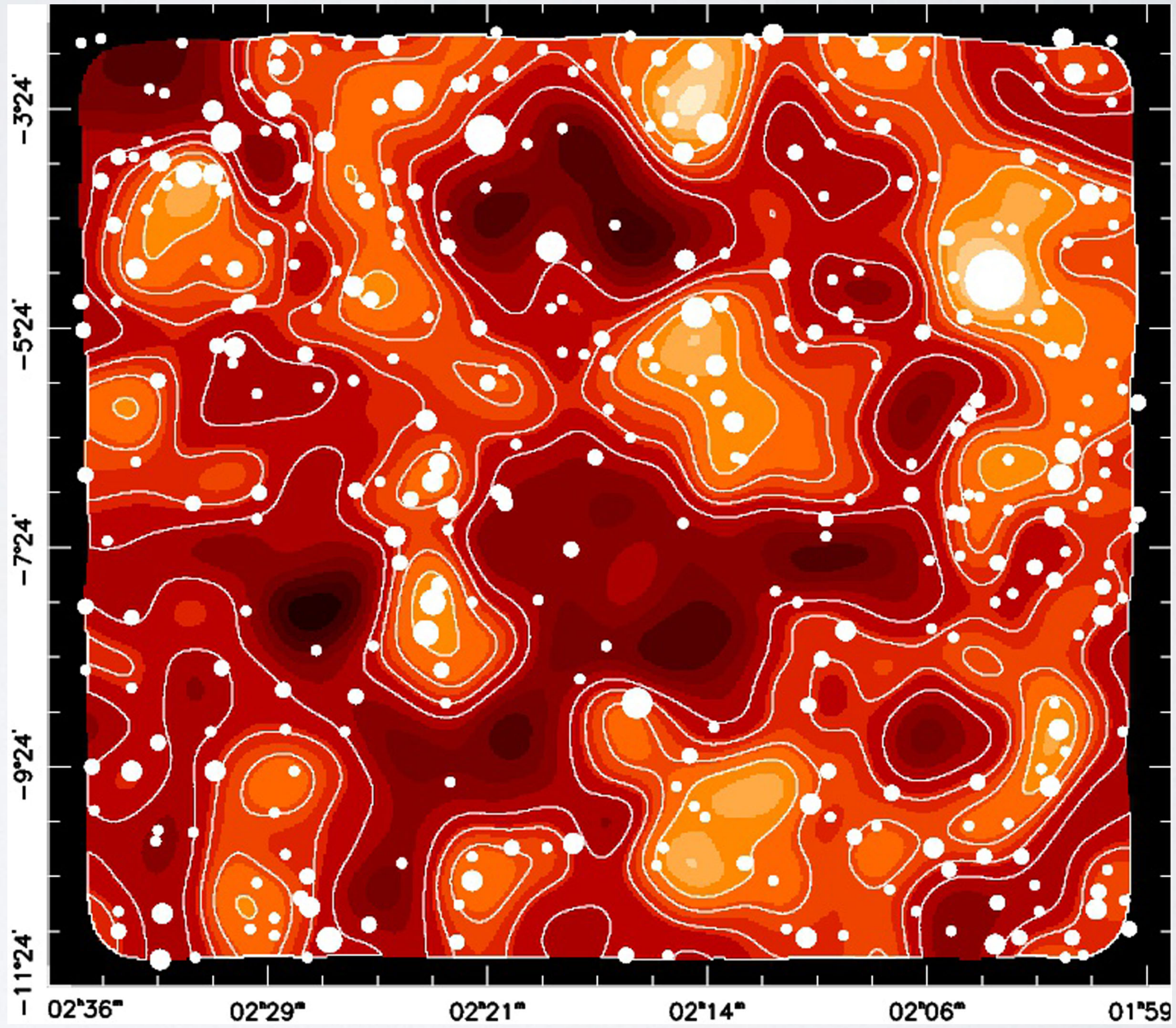
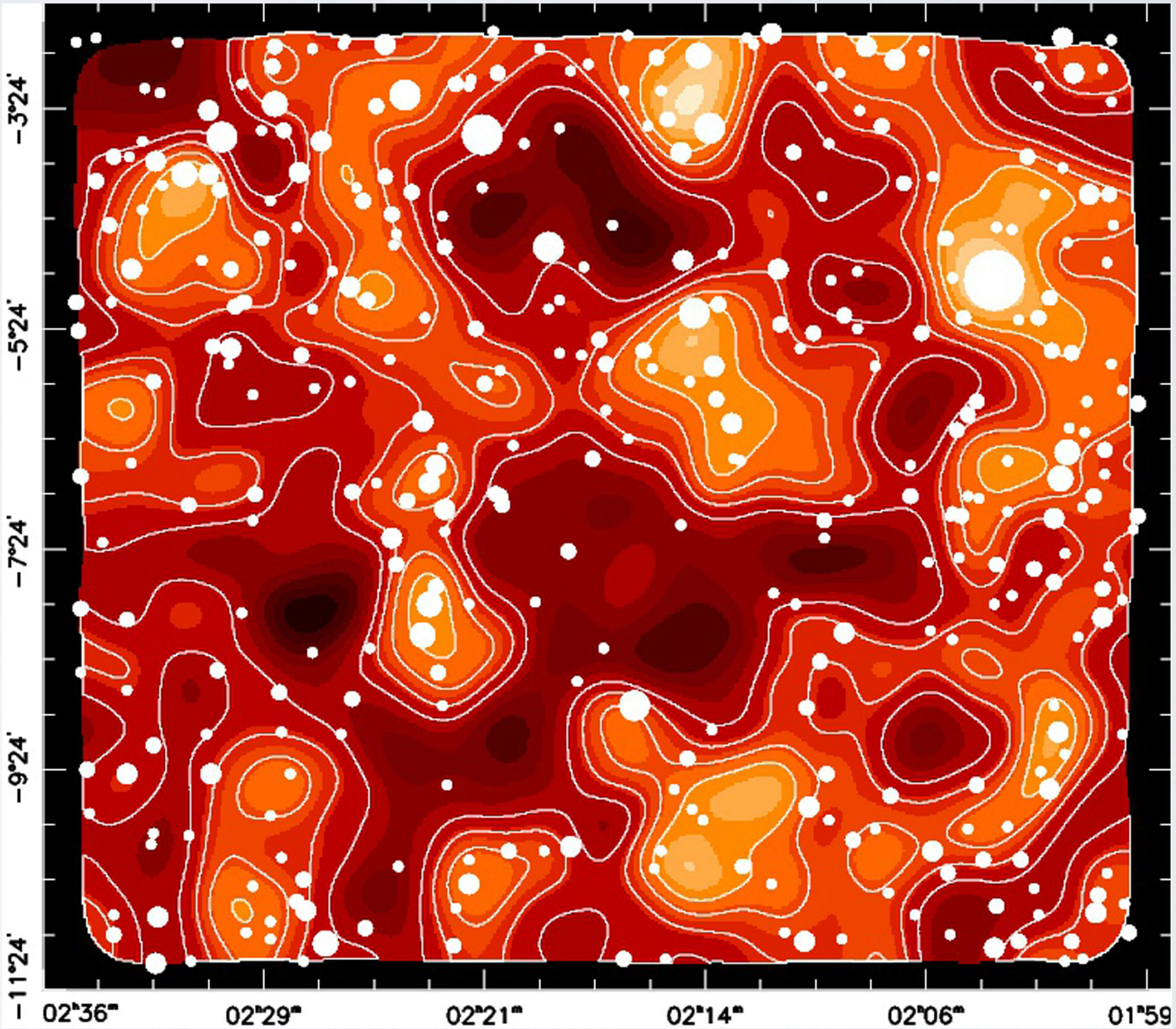


Figure 8. Mass maps for the W1 field. The continuous map with contours shows the mass reconstructed from gravitational lensing. The contours indicate the 1σ, 2σ, 3σ and 4σ on this map, where σ is the rms of the convergence. The open circles indicate the position of peaks in the predicted mass map, constructed from galaxies as described in Section 4.3. The circle size is proportional to the peak height. The field of view is approximately $9 \times 8\,\mathrm{deg}^2$.

LENSING SCIENCE

- Mapping large-scale structure (in 3D) and cross-correlations
- Cosmic shear



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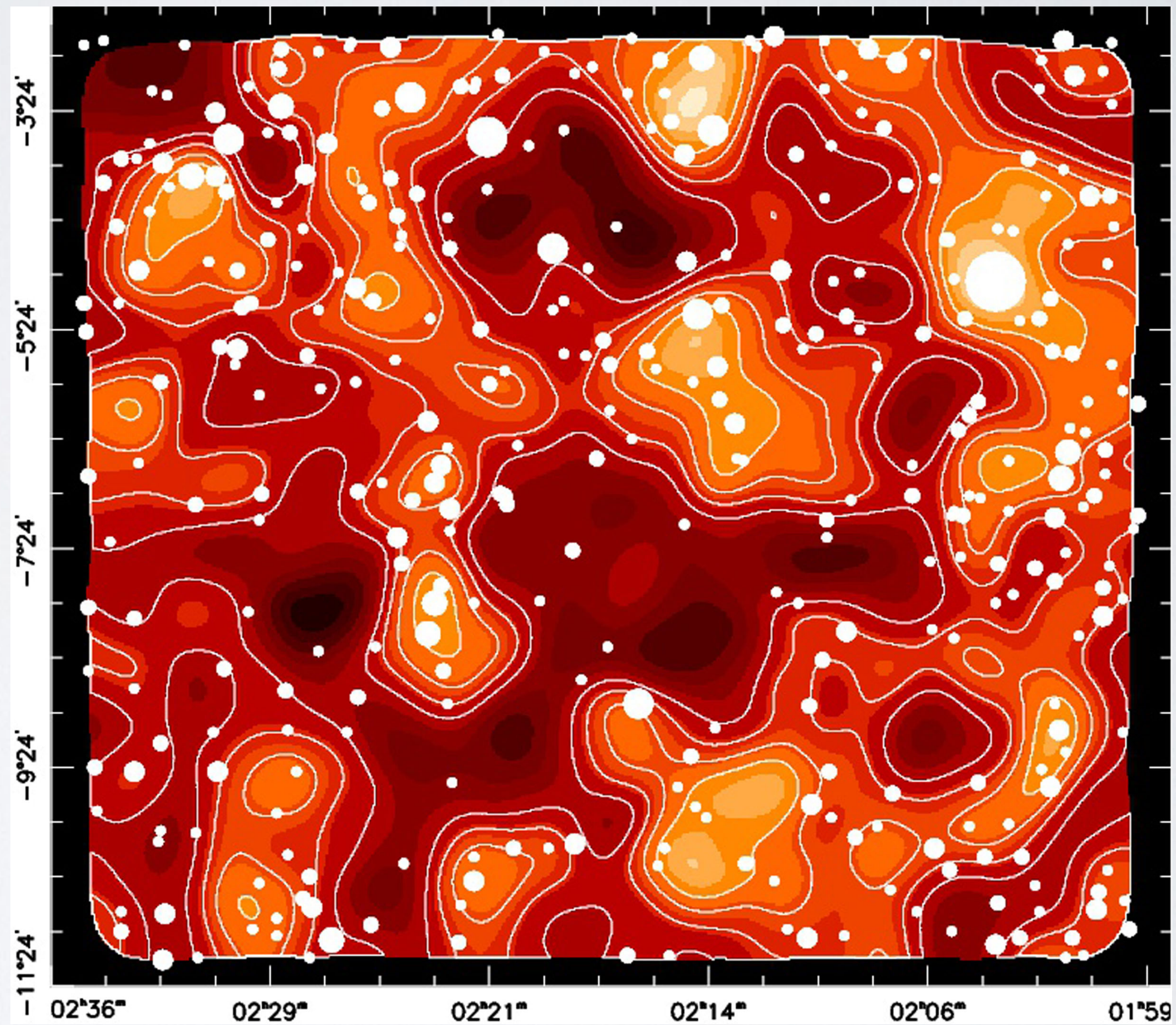
LENSING SCIENCE

- Mapping large-scale structure (in 3D) and cross-correlations
- Cosmic shear
- Testing General Relativity



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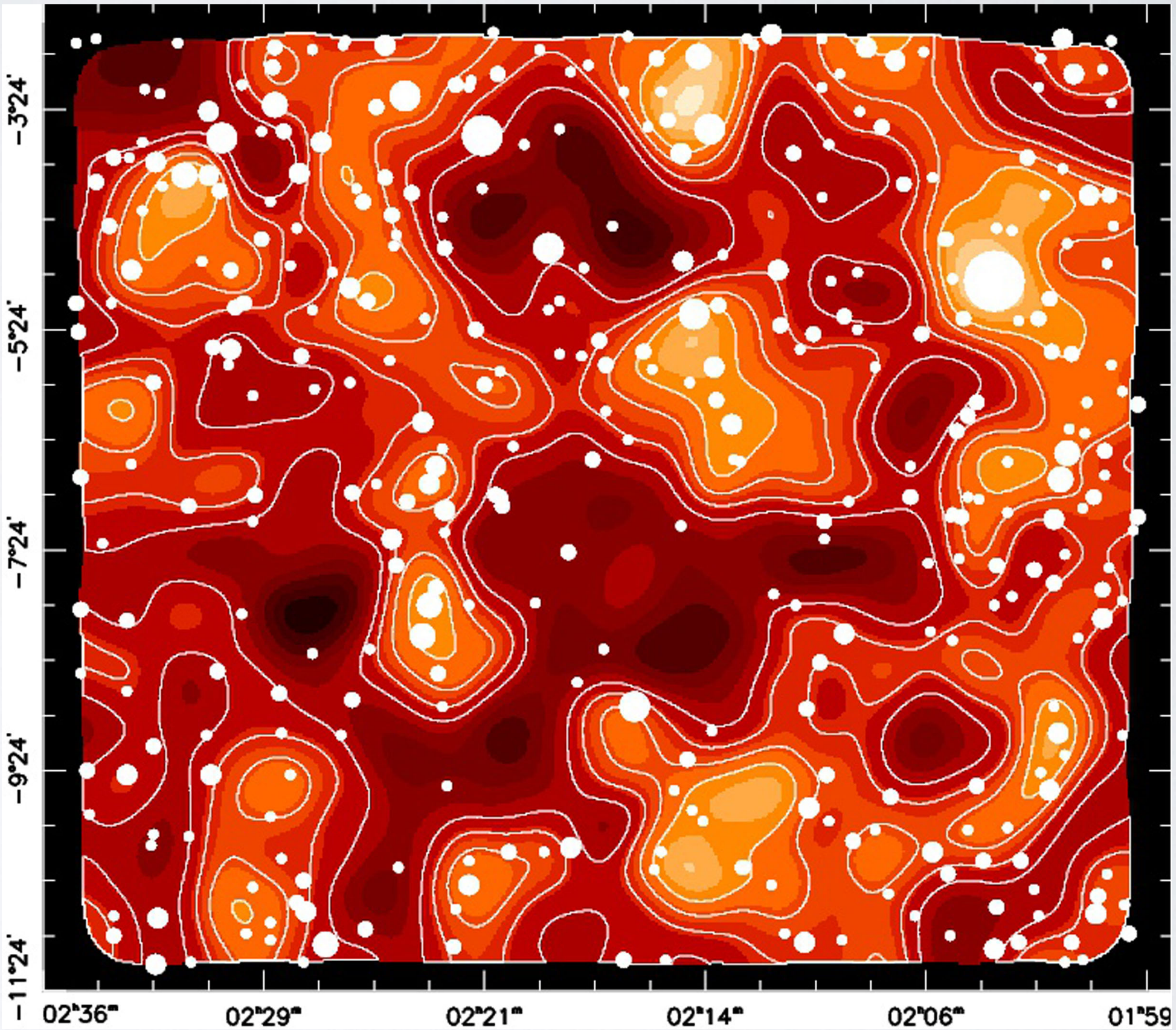
LENSING SCIENCE

- Mapping large-scale structure (in 3D) and cross-correlations
- Cosmic shear
- Testing General Relativity
- Masses and profiles of groups and clusters of galaxies



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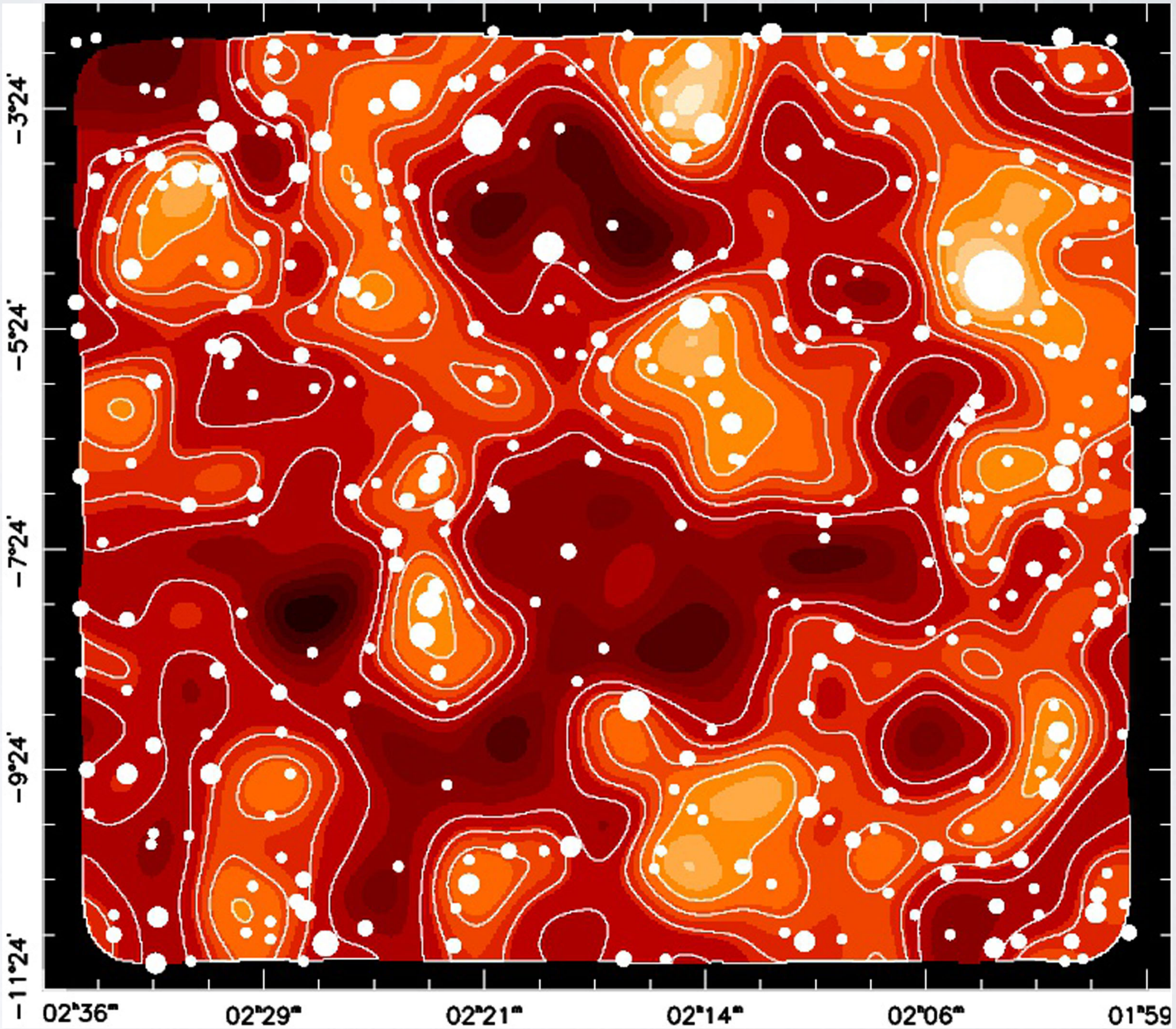
LENSING SCIENCE

- Mapping large-scale structure (in 3D) and cross-correlations
- Cosmic shear
- Testing General Relativity
- Masses and profiles of groups and clusters of galaxies
- Galaxy halos as a function of spectroscopic properties



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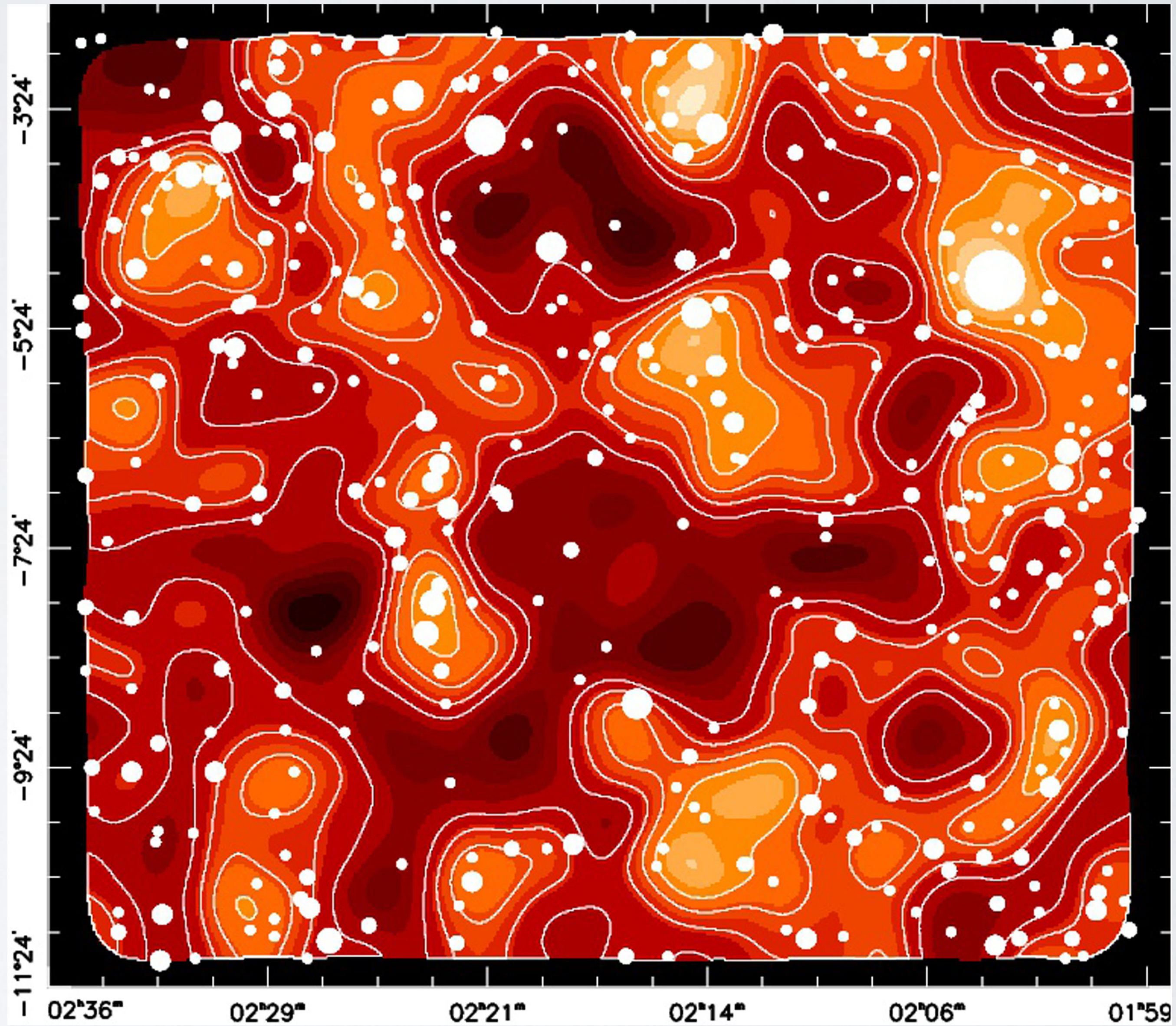
LENSING SCIENCE

- Mapping large-scale structure (in 3D) and cross-correlations
- Cosmic shear
- Testing General Relativity
- Masses and profiles of groups and clusters of galaxies
- Galaxy halos as a function of spectroscopic properties
- Tidal stripping of satellite galaxies



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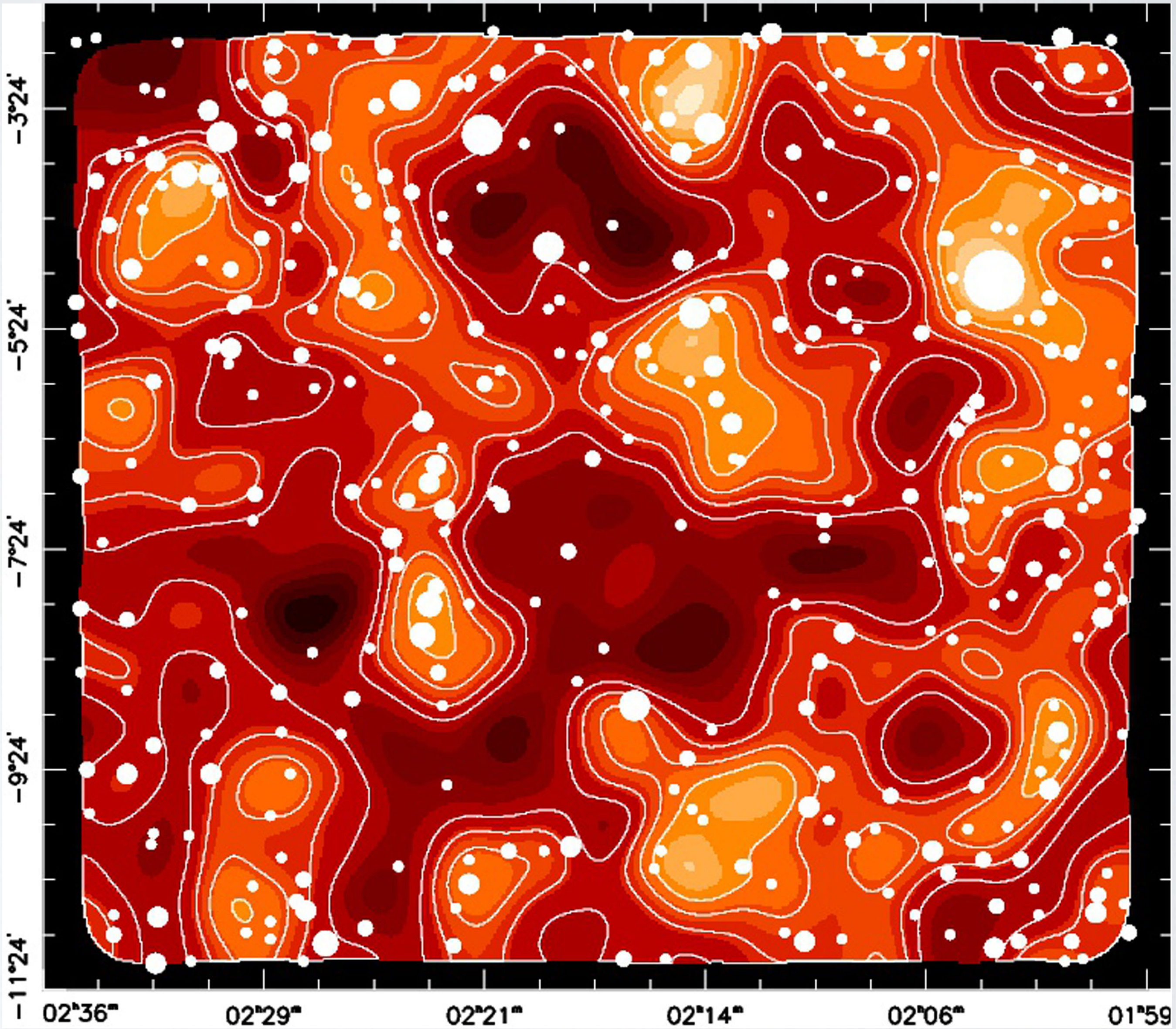
LENSING SCIENCE

- Mapping large-scale structure (in 3D) and cross-correlations
- Cosmic shear
- Testing General Relativity
- Masses and profiles of groups and clusters of galaxies
- Galaxy halos as a function of spectroscopic properties
- Tidal stripping of satellite galaxies
- Strong lensing "telescopes"



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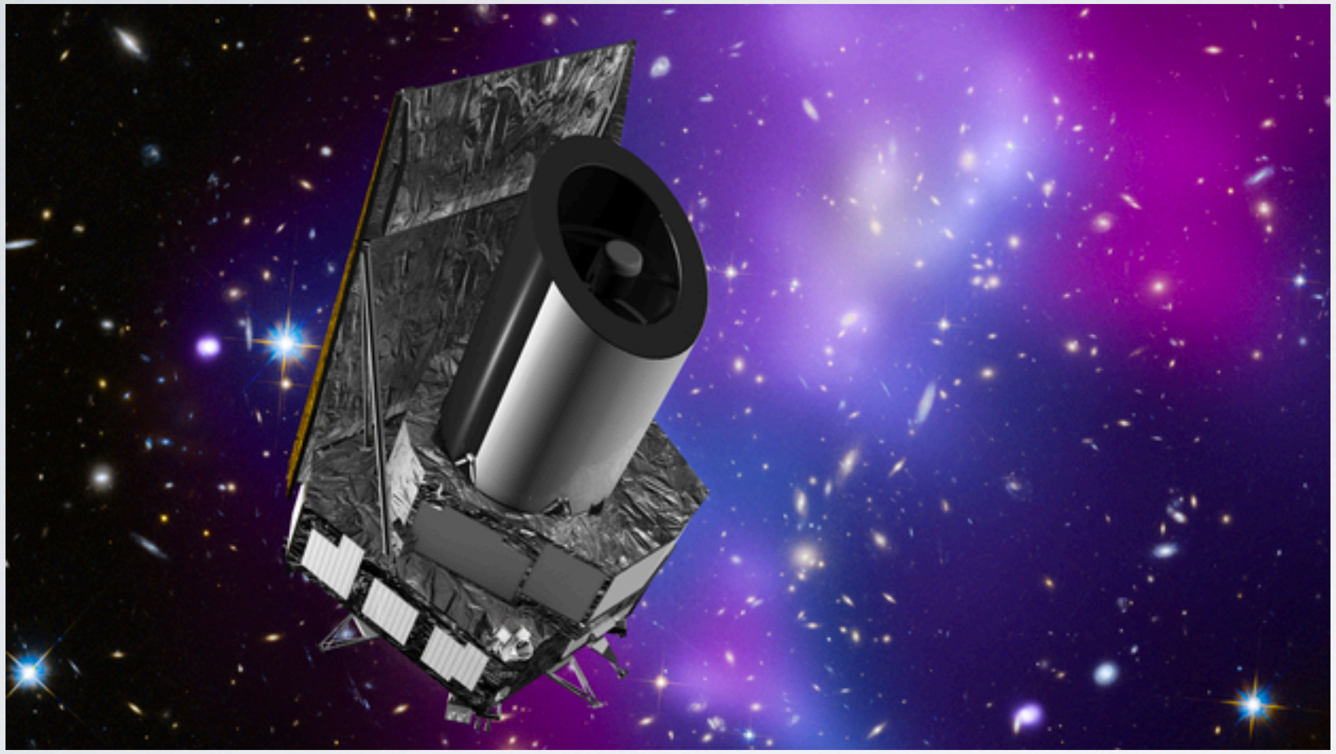
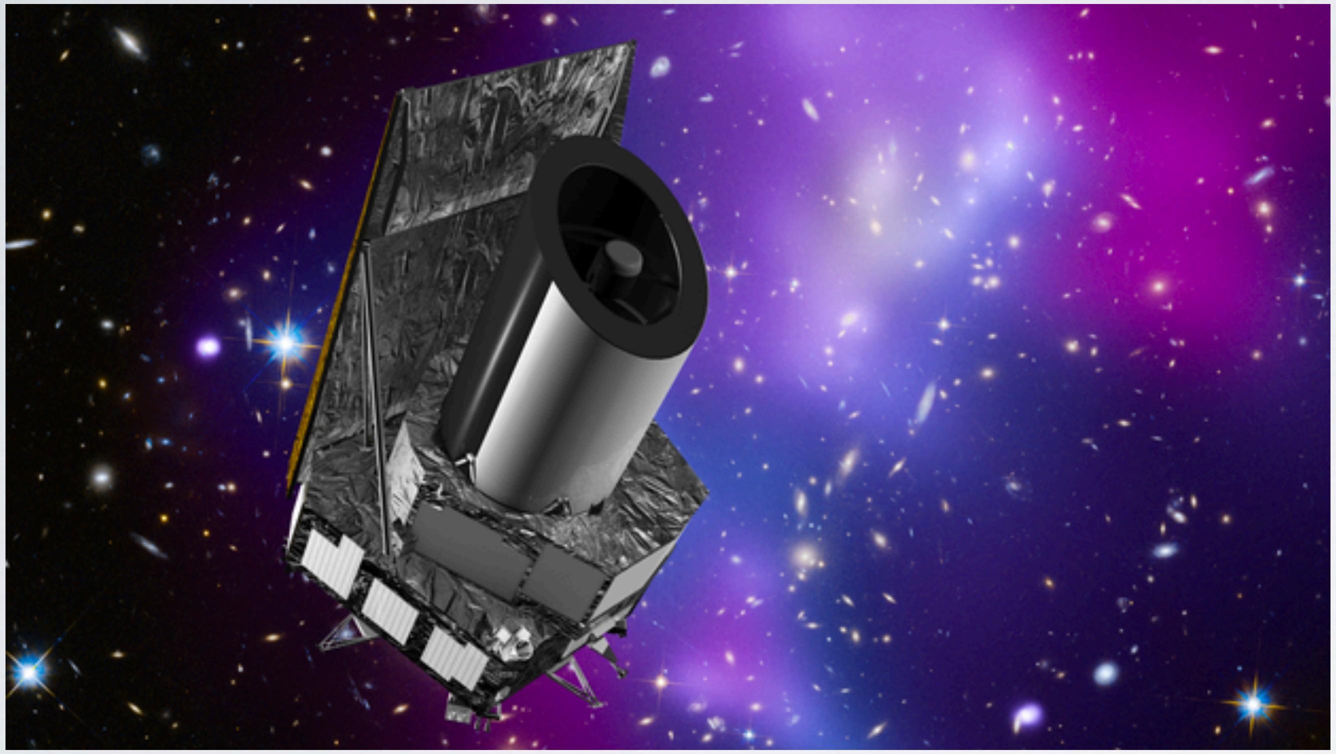
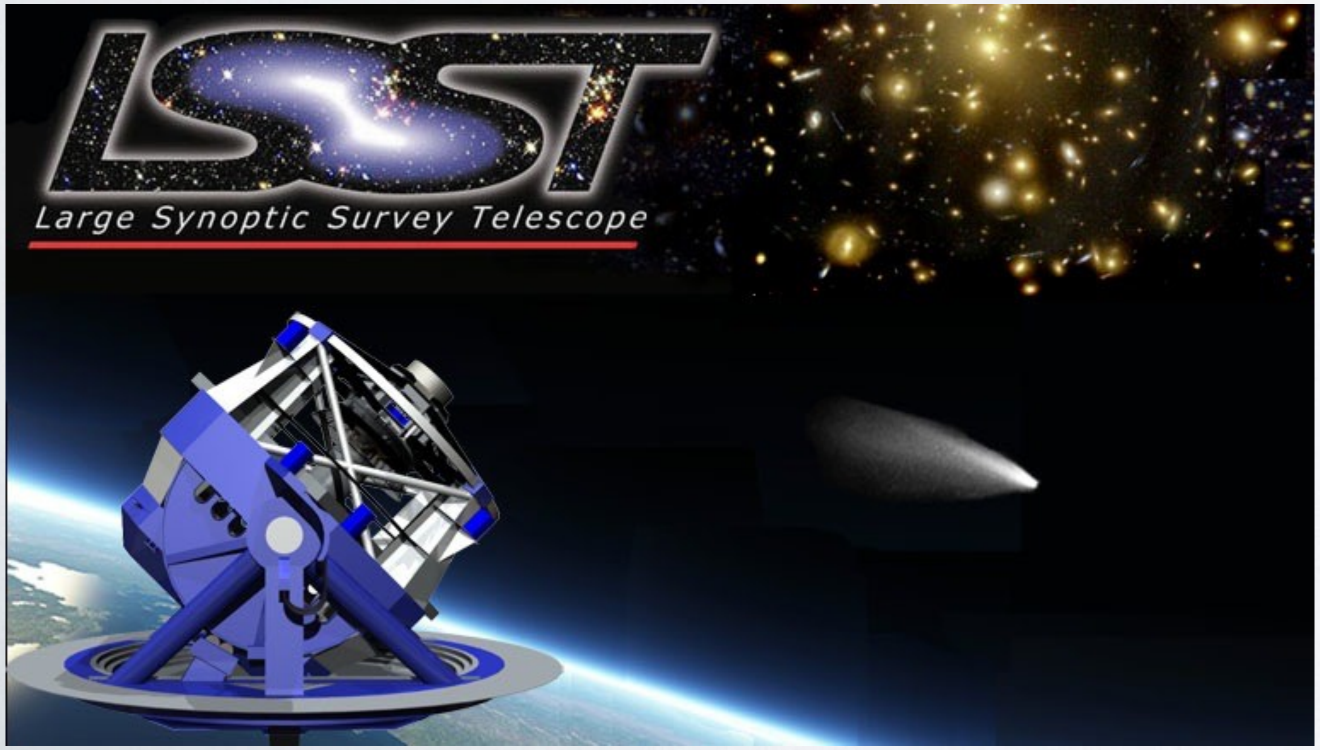
FUTURE LENSING MISSIONS



Euclid Telescope:
Gravitational Lensing,
Large-scale structure
1+ billion €
Lauch ~2021

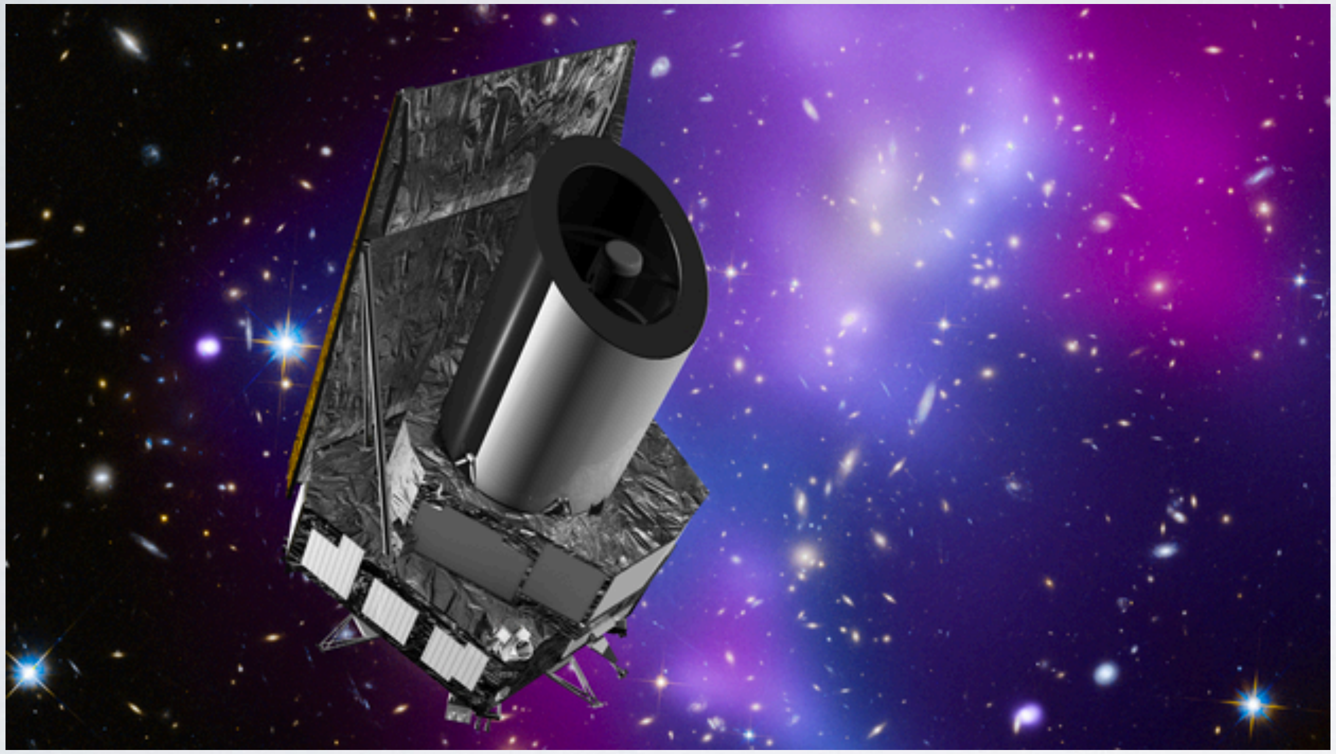
FUTURE LENSING MISSIONS





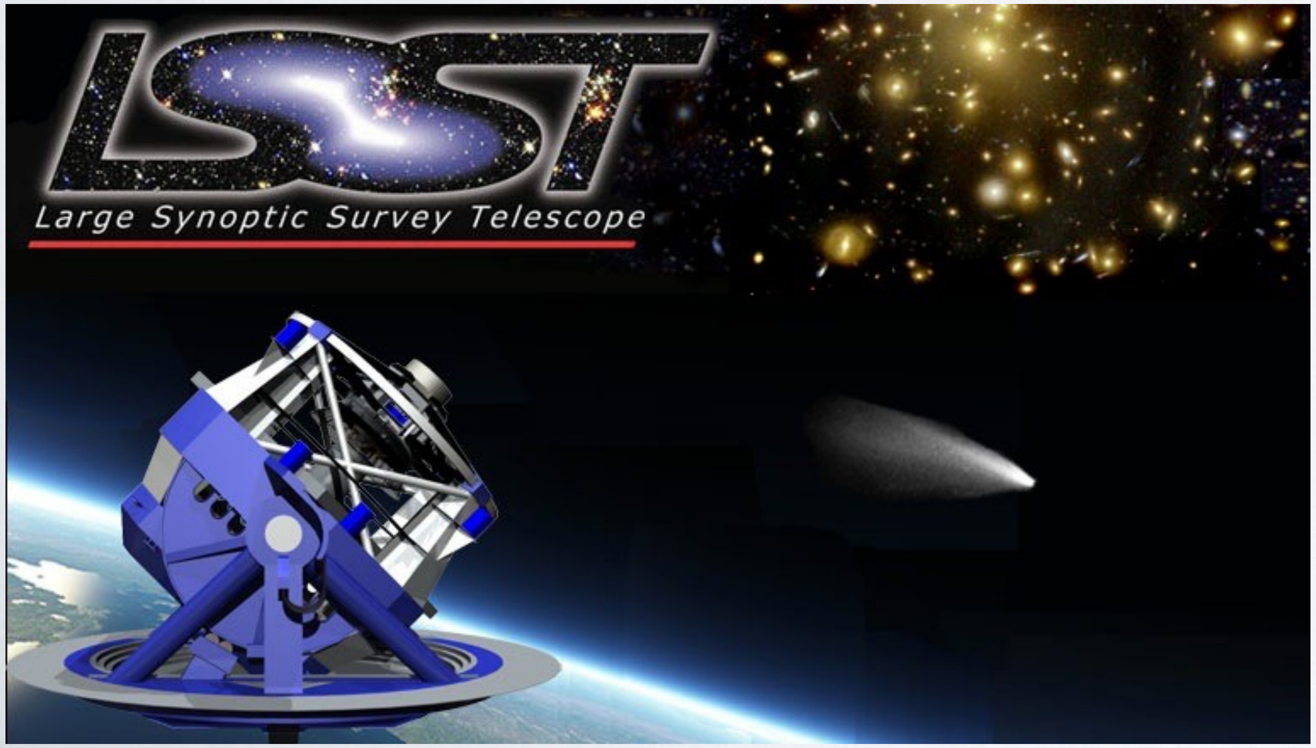
Gravitational Lensing, LSS
$700 M, 2021?

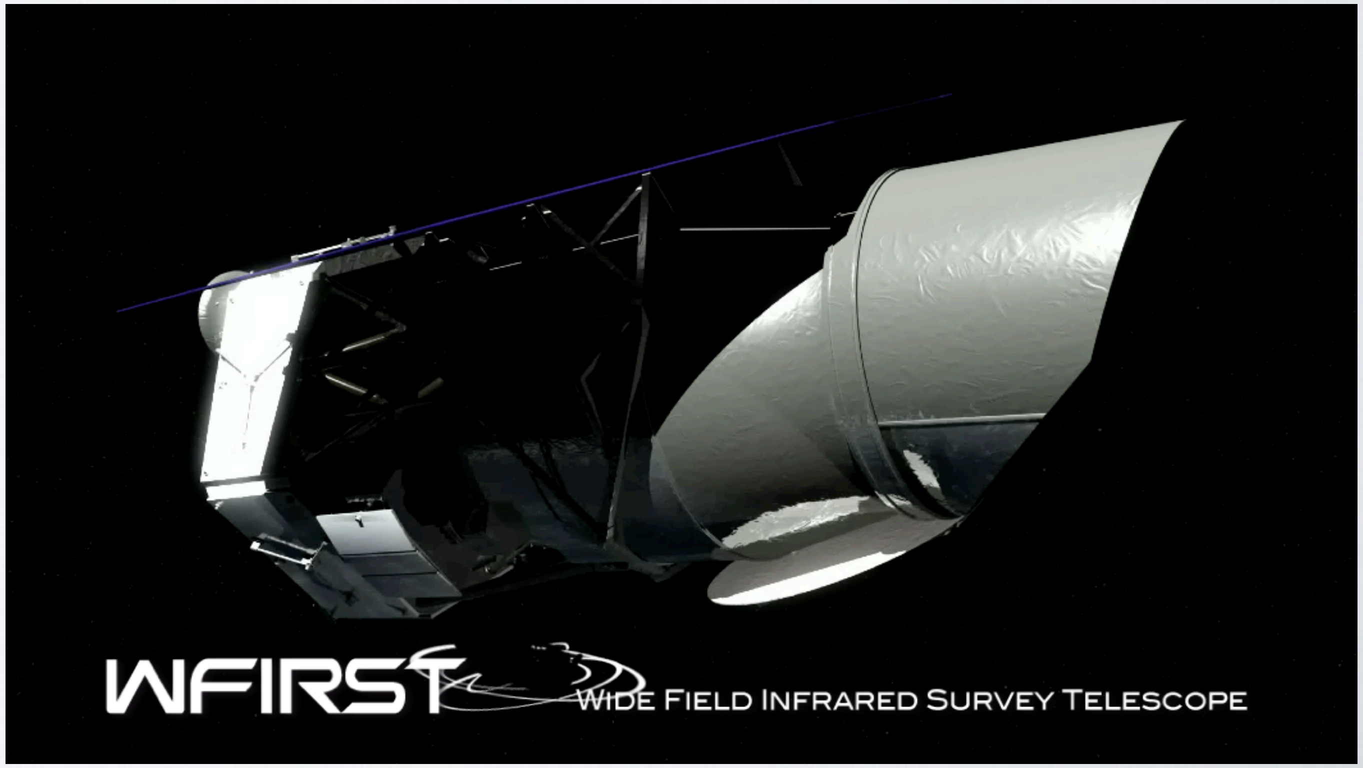
FUTURE LENSING MISSIONS



WFIRST

$3.2 billion USD
In Phase A
Launch 2025?





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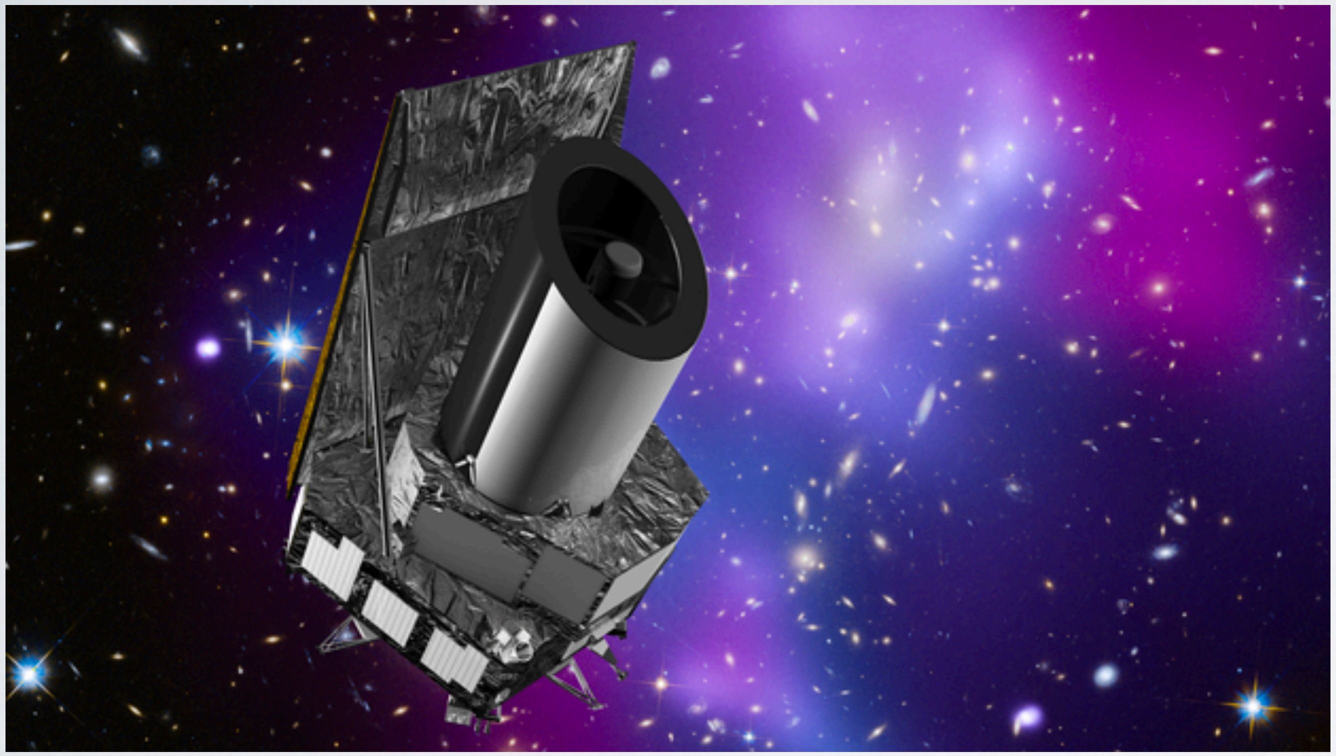

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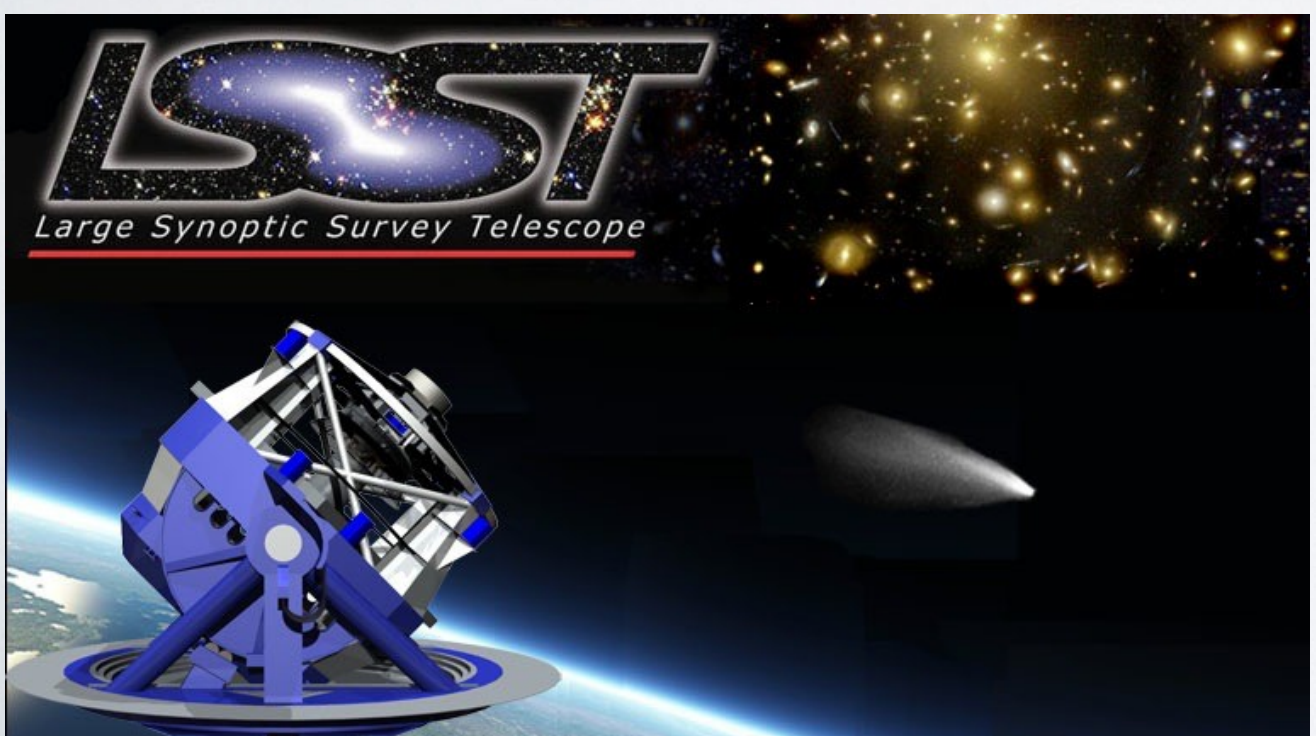

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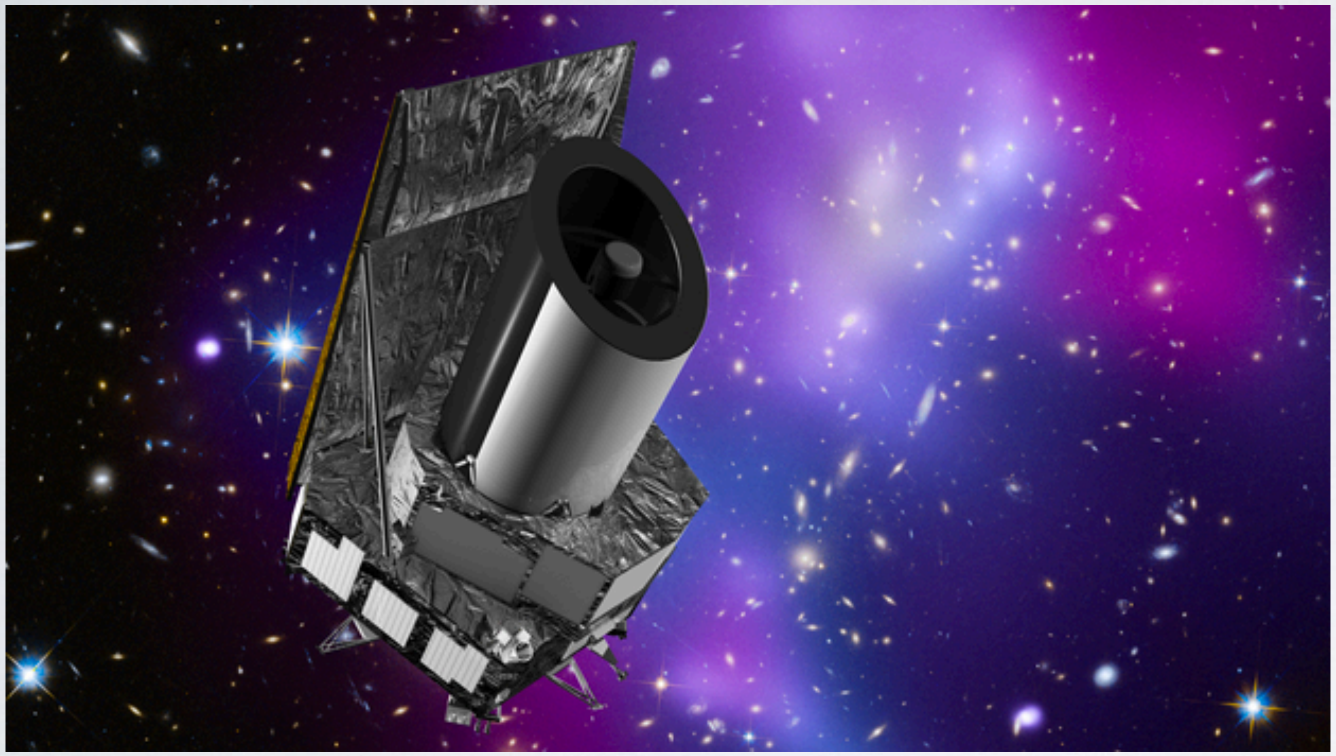

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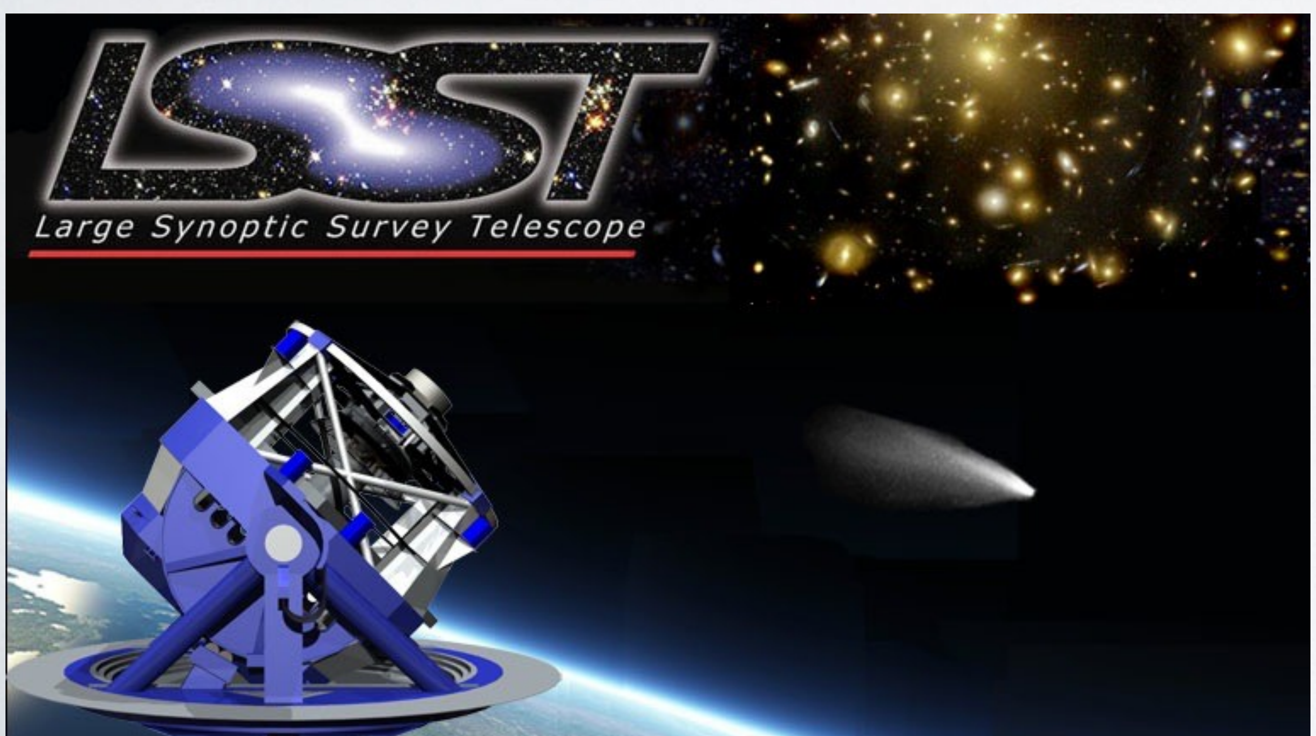
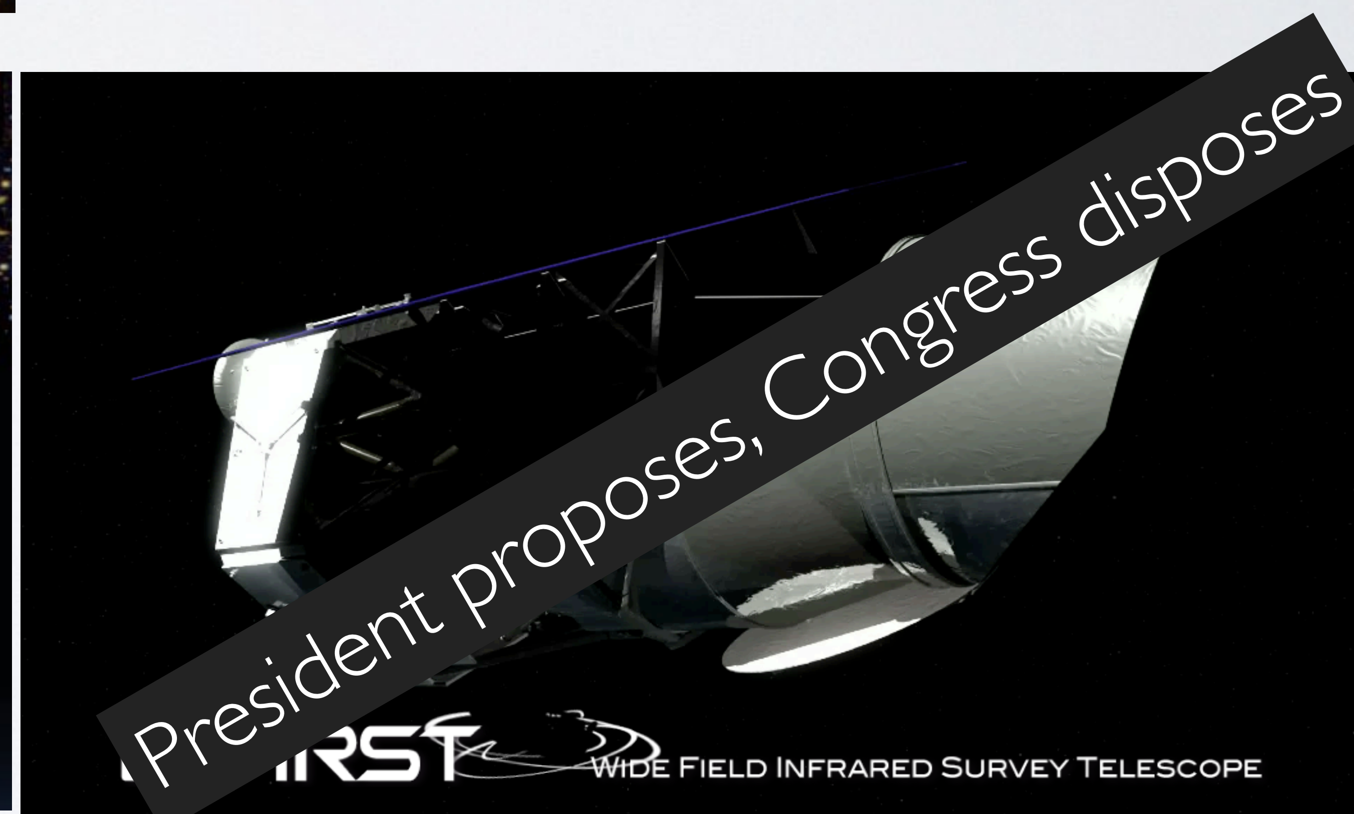
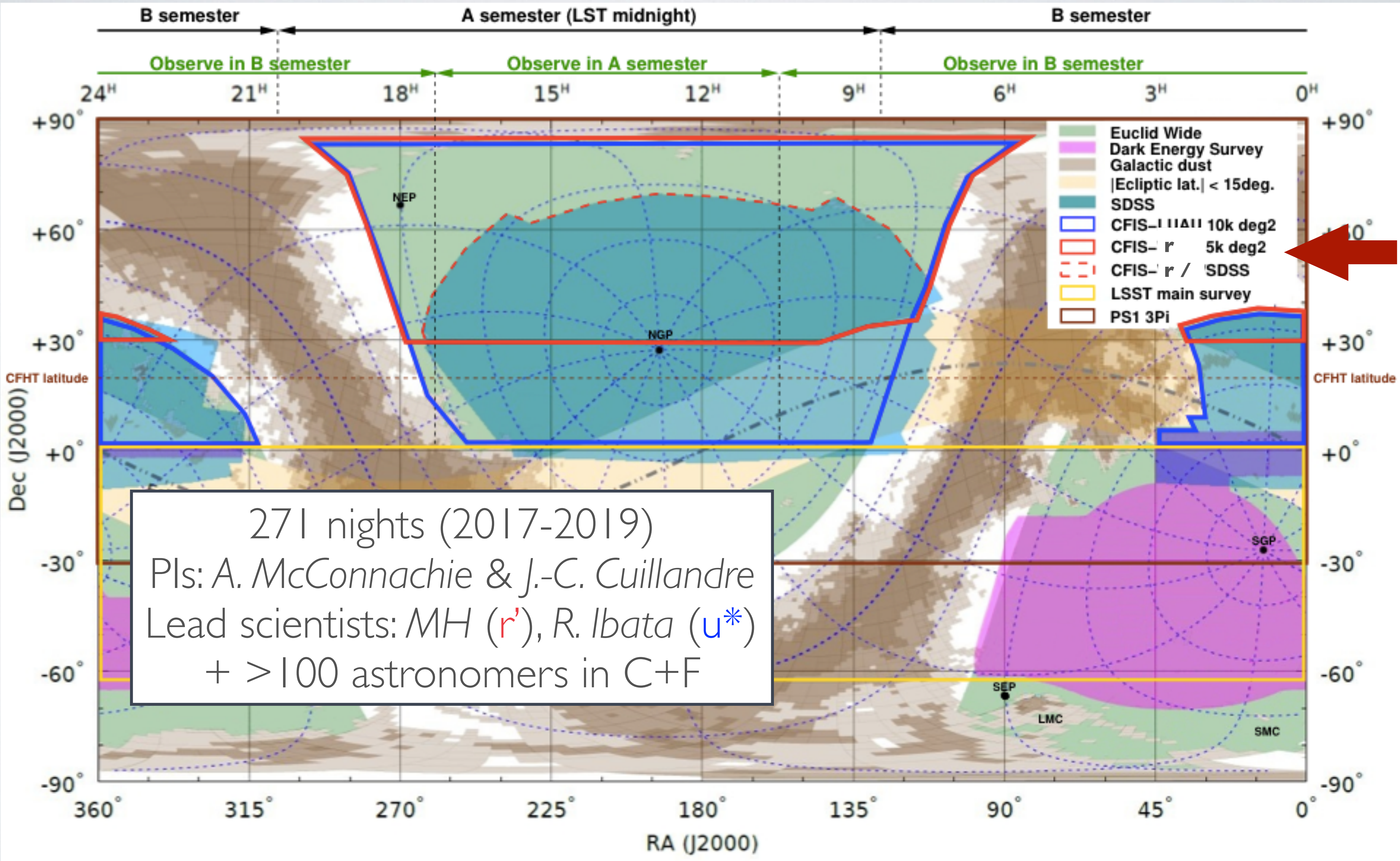




CANADA-FRANCE IMAGING SURVEY (CFIS)



271 nights (2017-2019)

PIs: *A. McConnachie & J.-C. Cuillandre*

Lead scientists: *MH* (r'), *R. Ibata* (u*)

\+ >100 astronomers in C+F

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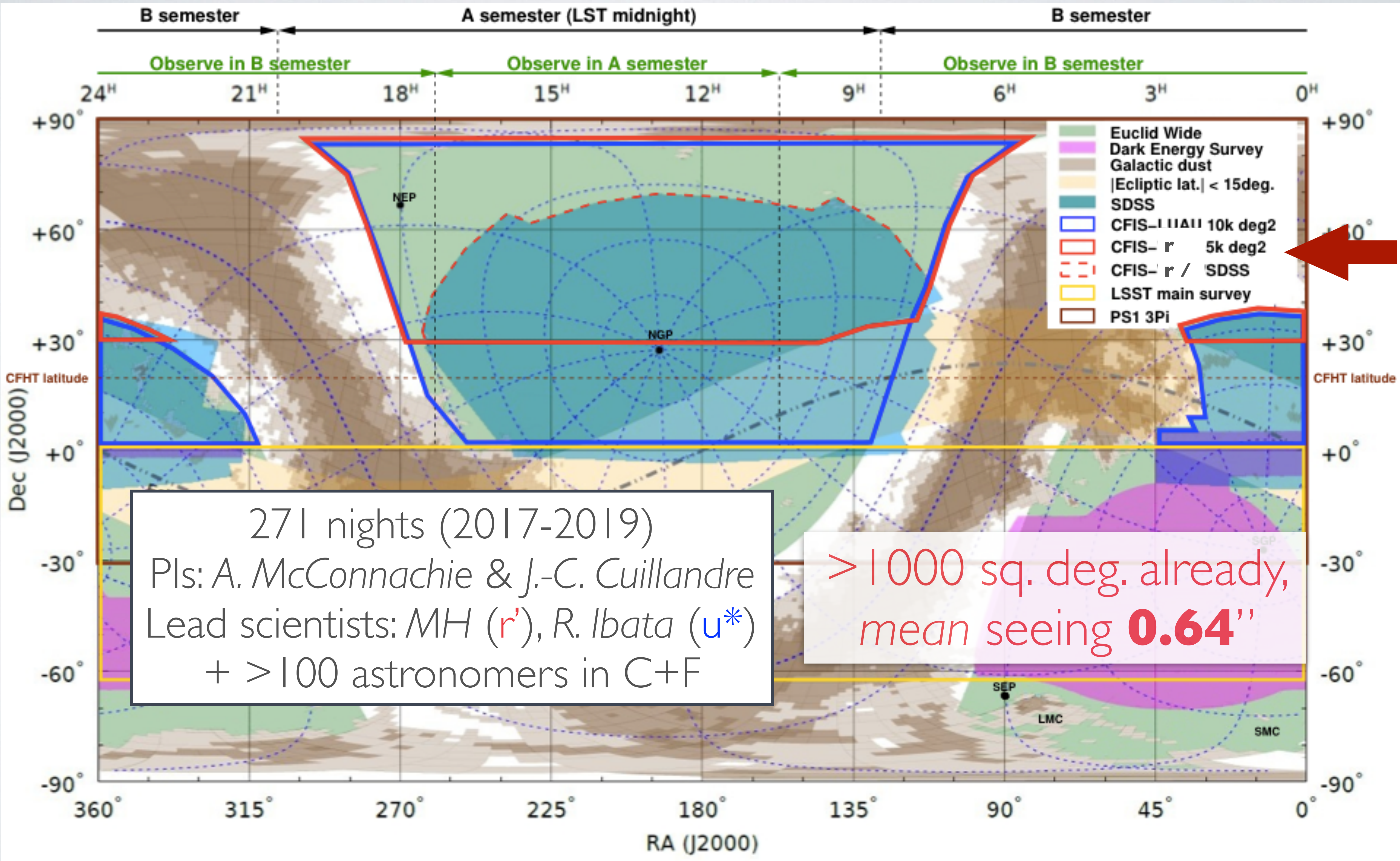

271 nights (2017-2019)
PIs: *A. McConnachie & J.-C. Cuillandre*
Lead scientists: *MH* (r'), *R. Ibata* (u*)
+ >100 astronomers in C+F

>1000 sq. deg. already,
mean seeing **0.64**''

~~CANADA FRANCE IMAGING SURVEY (CFIS)~~

SUMMARY

- There is a non-linear relation between stellar mass and DM-halo mass, that evolves with redshift:
    - New insights into feedback and quenching
- There is a (secondary) dependence of halo mass on galaxy size:
    - Mostly (but not only) due to tidal stripping of satellites, according to simulations
- Measurement of DM-dominated filaments between LRGs

Weak lensing provides a powerful way to map dark matter over a range of scales