Calibrating galaxy clusters as natural telescopes

Masamune Oguri

RESCEU/Physics/Kavli IPMU
University of Tokyo

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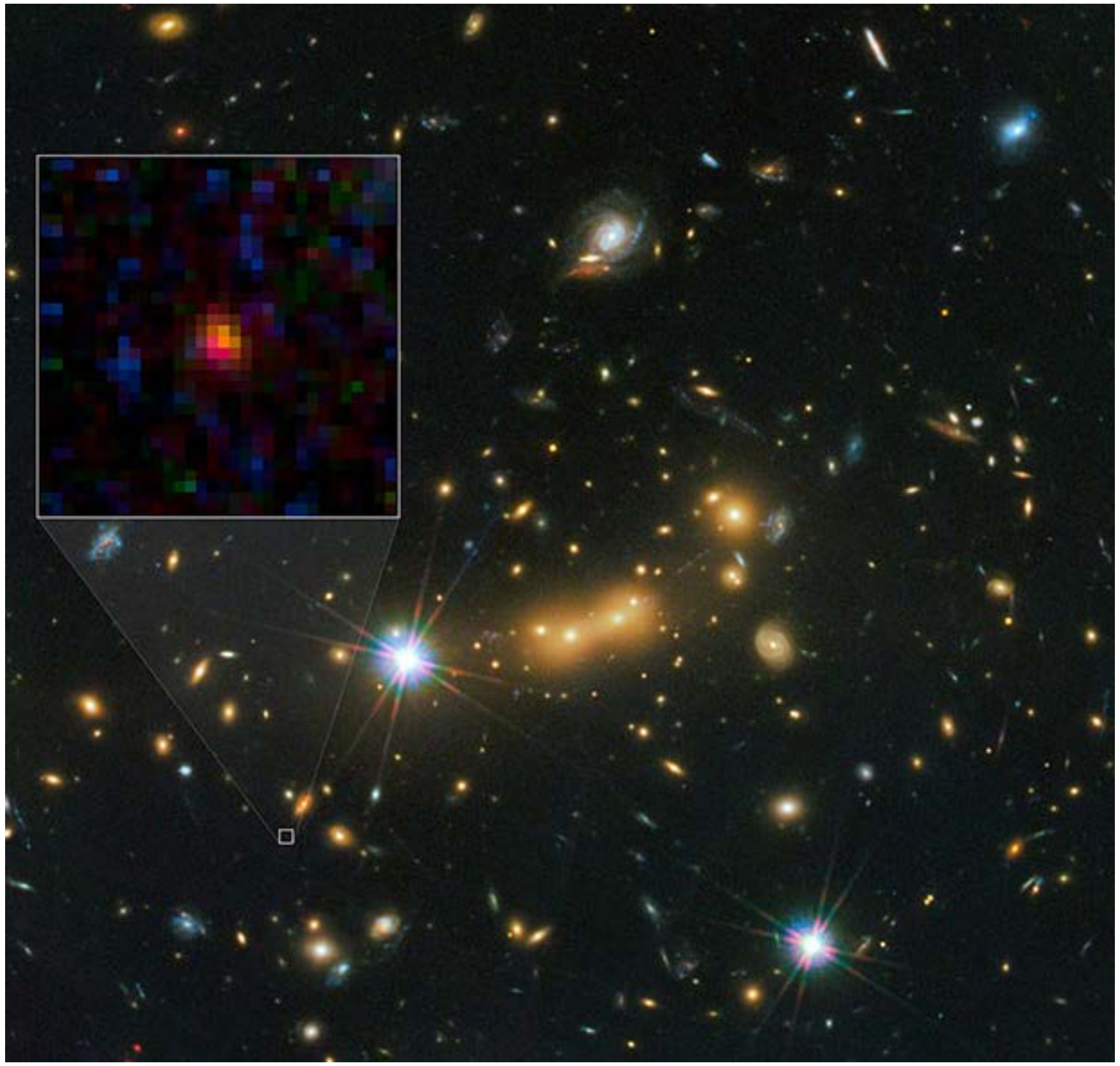
Clusters as natural telescopes

- massive clusters magnify large area of sky behind the clusters
- allow us to study faint and/or distant galaxies with help of lensing magnifications ("natural telescopes")
- need accurate cluster mass models to recover correct galaxy property

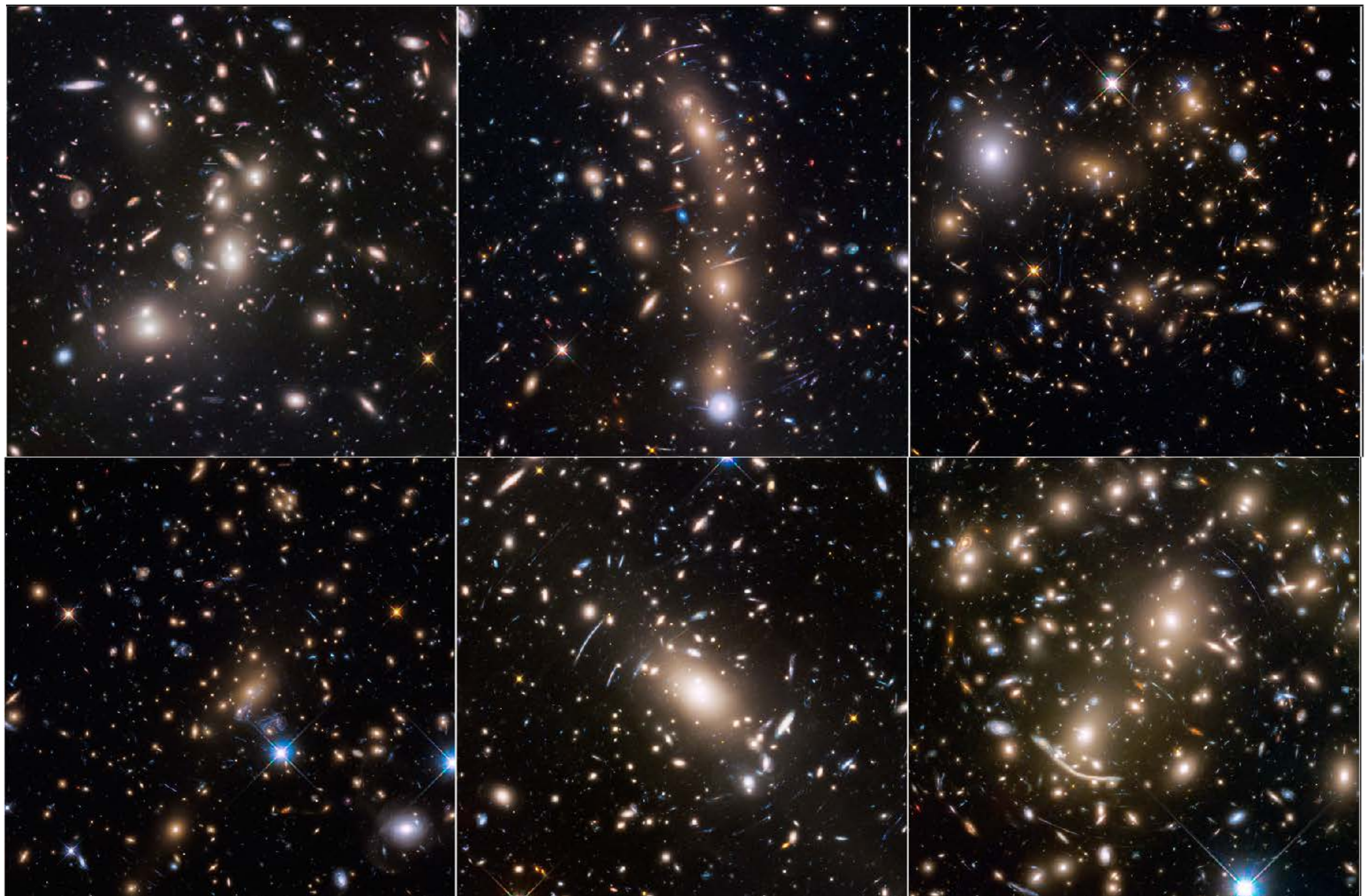


z=10.8 galaxy (Coe+2013)

Lotz, Koekemoer, Coe+ ApJ **837**(2017)97

HST Frontier Fields (HFF)

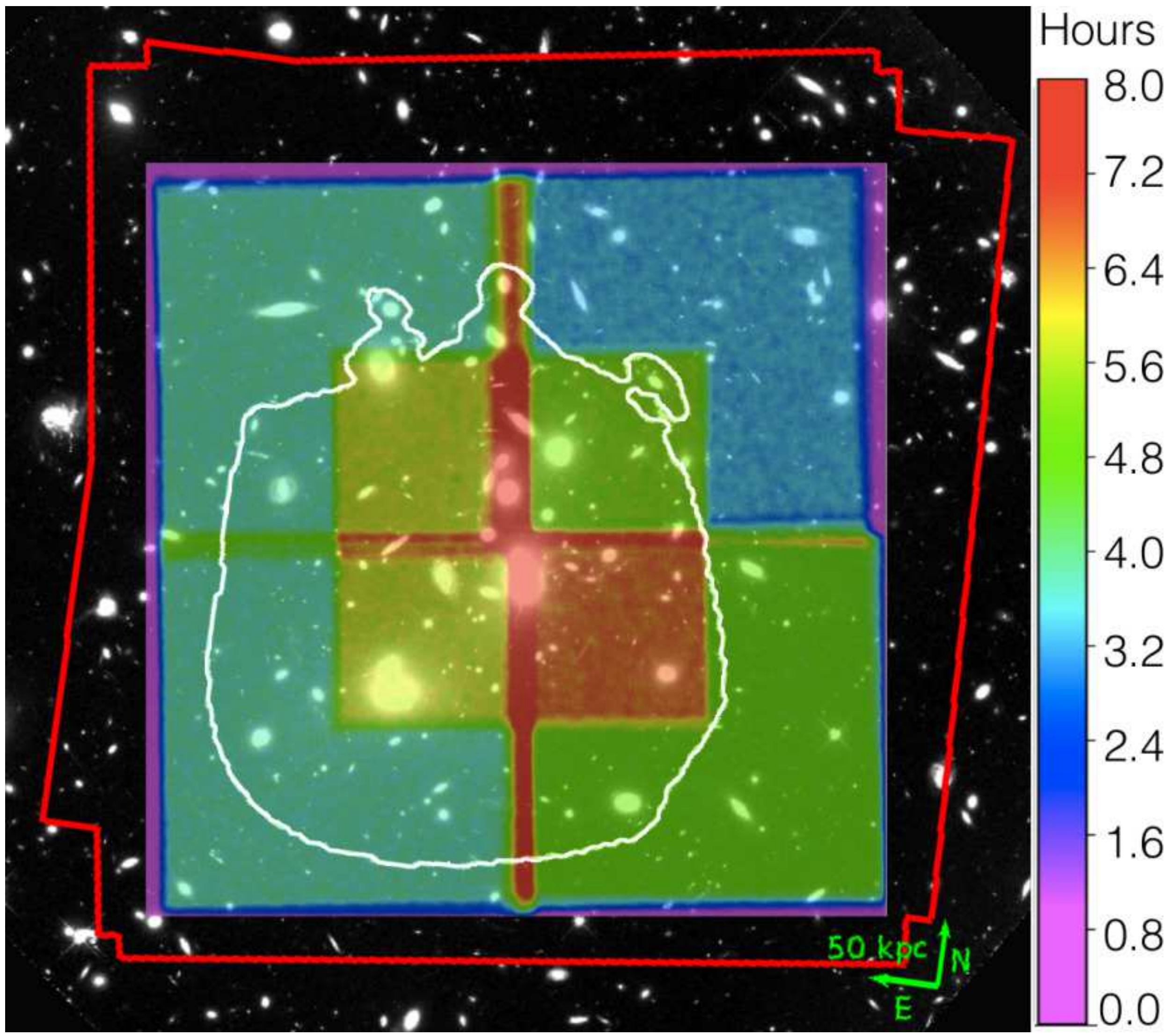
- >100 multiple images for each cluster led to significant progress in cluster strong lens study!



http://hubblesite.org

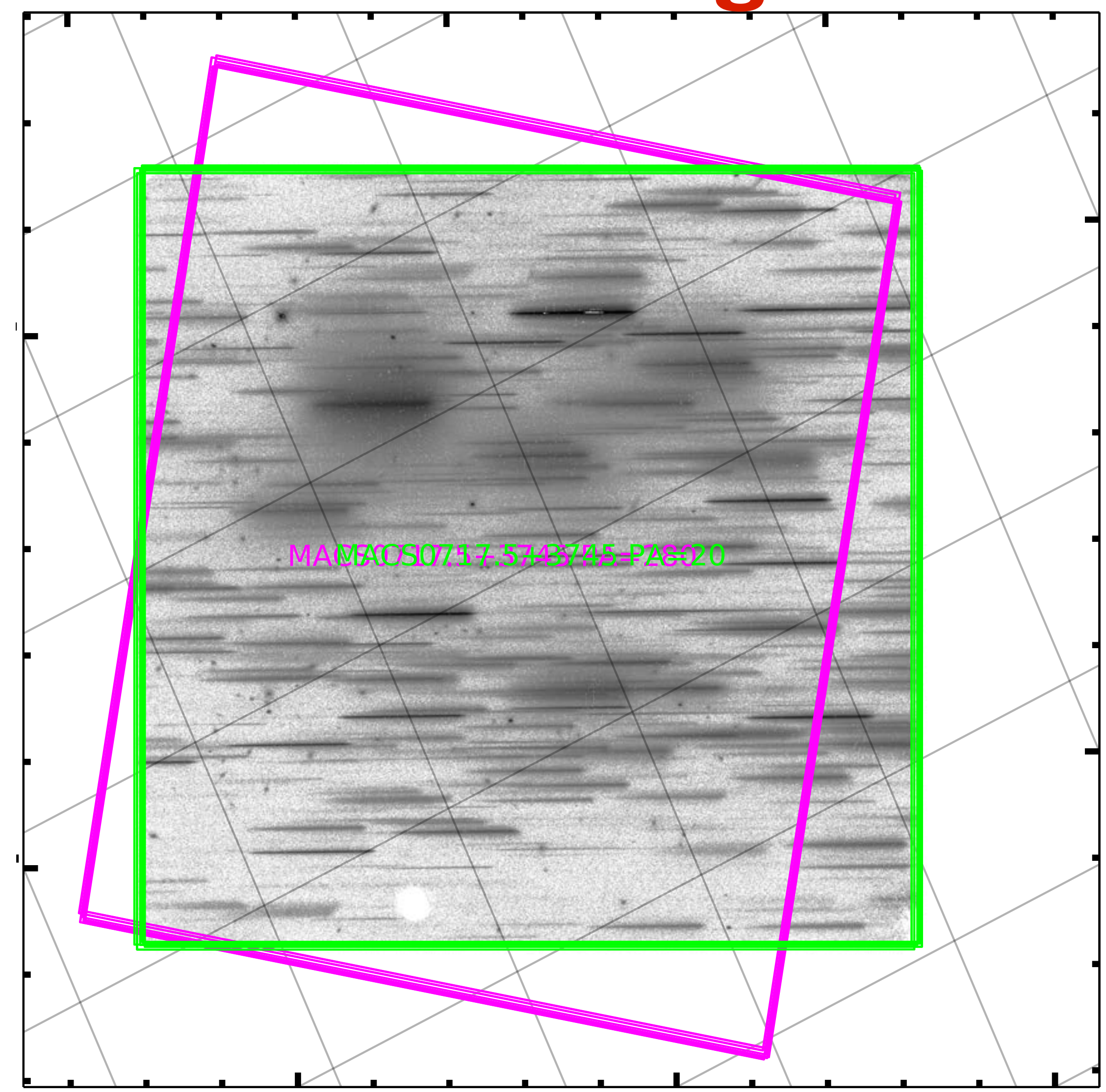
Spec-z revolutions

VLT MUSE



Mahler+2018

HST WFC3 grism



Treu+2015

- spec-z's for many multiple images
  → secure identifications & more constraints!

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

HFF mass models (v3, v4)

Parametric

LENSTOOL

CATS

Sharon

Caminha

GLAFIC

GLAFIC

LENSMODEL

Keeton

(also GLEE by Grillo, Suyu+)

Non-Parametric

LTM

Zitrin

WSLAP+

Diego Bernstein

Grale

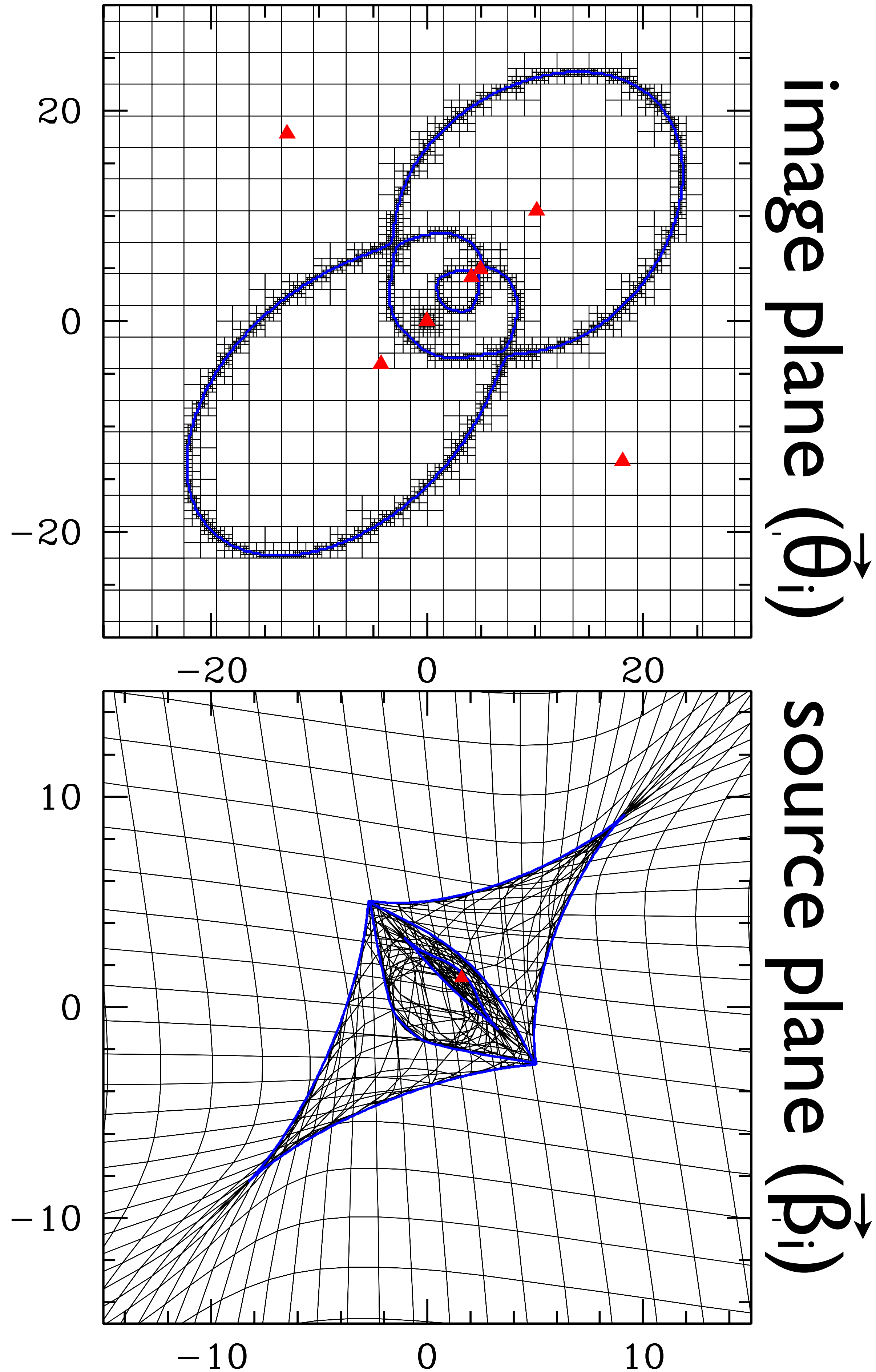
Williams

SWUnited

Bradac

http://www.slac.stanford.edu/~oguri/glafic/

GLAFIC



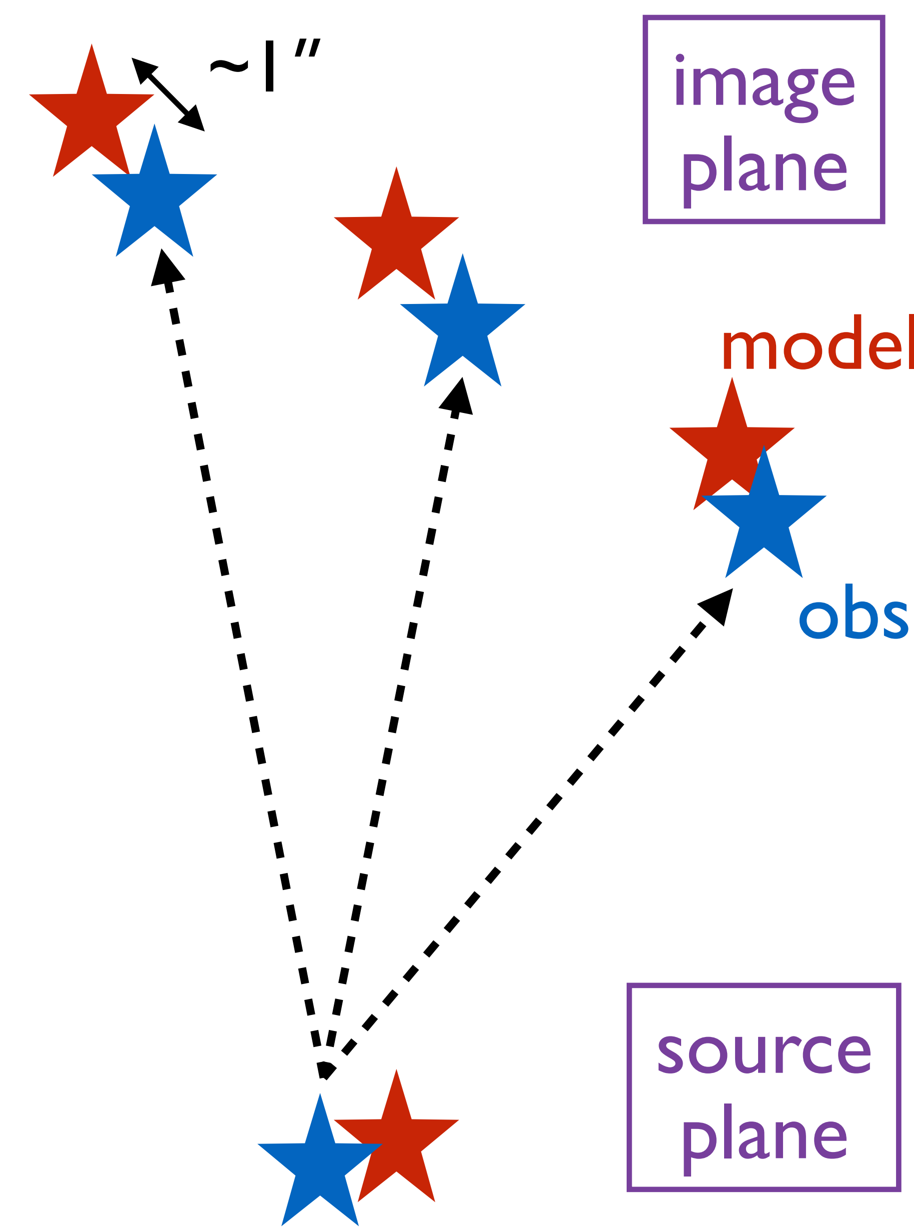
- public software for strong lensing analysis ("parametric" modeling)
- adaptive grid to solve lens equation efficiently
- support many kind of lens potentials
- see Kawamata, MO+ ApJ **819**(2016)114 for details of our HFF mass modeling

Quantify goodness of mass models

- **RMS of multiple image positions**
  root-mean-square of differences of multiple image positions btw obs and model
- **mock challenge**
  blind test from mass modeling of mock strong lensing clusters
- **lensed supernovae**
  blind test from magnifications and time delays of lensed supernovae

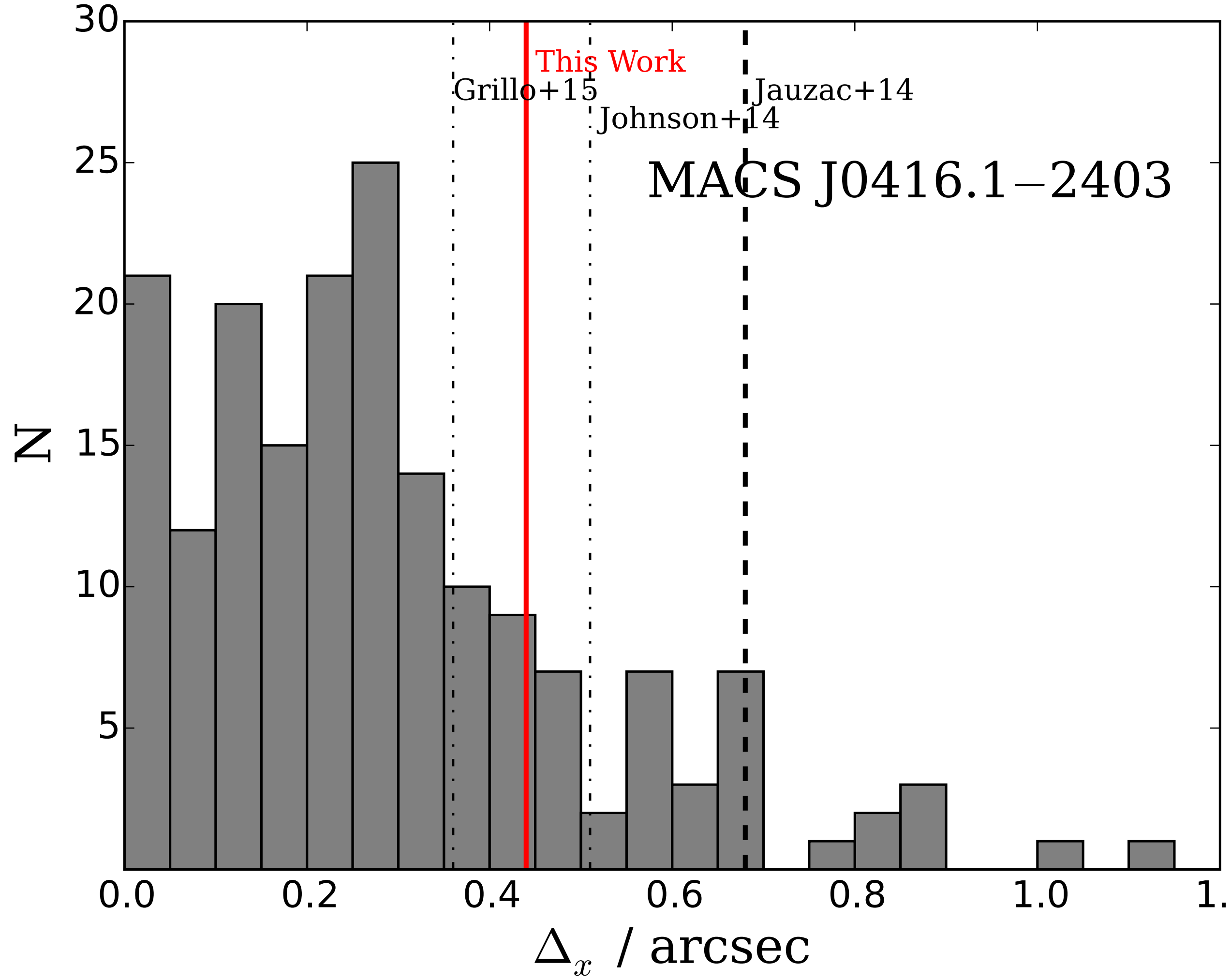
RMS of multiple image positions

- difference of image positions between best-fit model and observation
- in cluster strong lensing, typically RMS ~1″, much worse than meas. errors (≲0.1″ for HST)
- due to complex mass dist. of clusters (e.g., substructure)



RMS in HFF

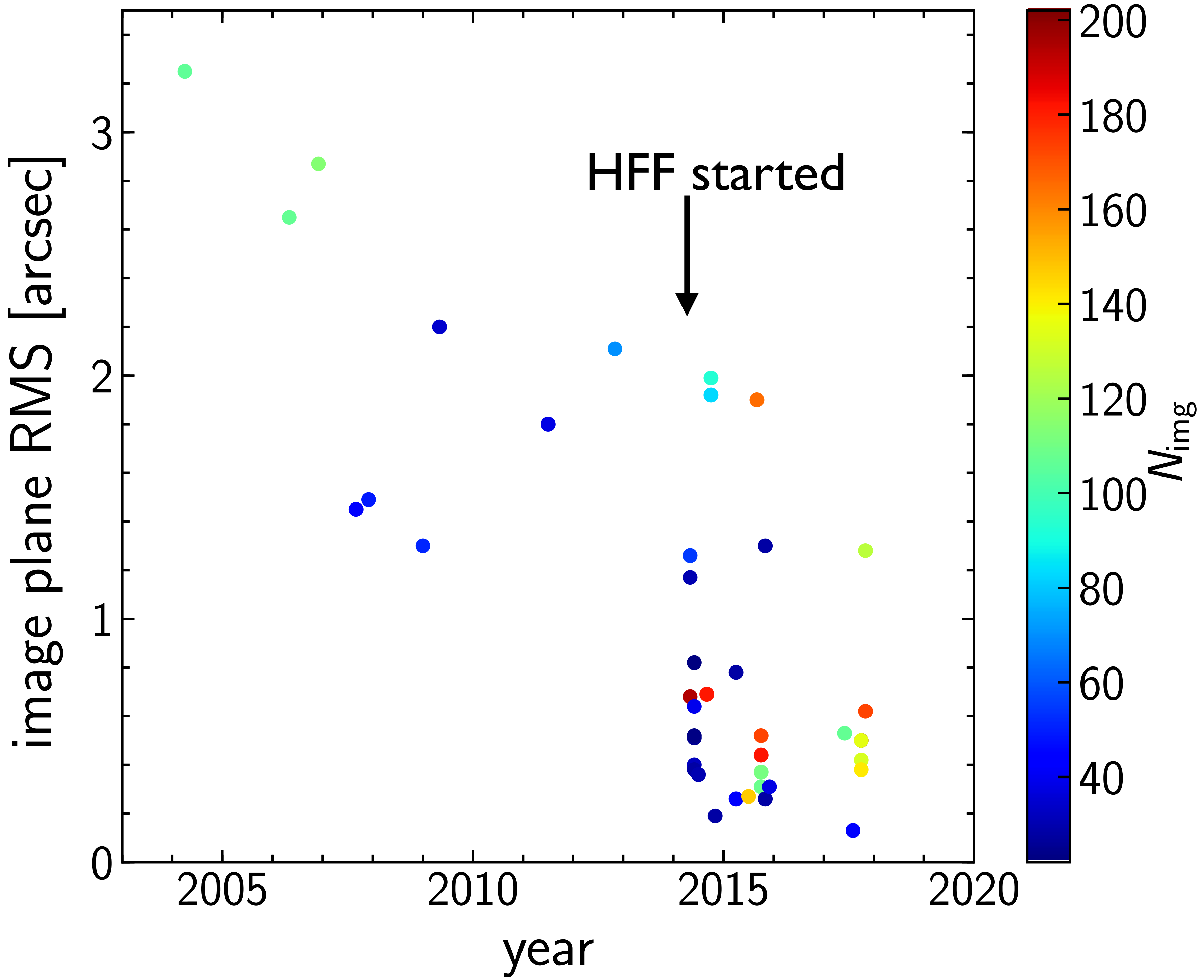
- despite large numbers of multiple images, RMS improved to ~0.4″ in HFF
- reasons?
  - less misidentification
  - improved modeling method
  - improved method to explore likelihood



Kawamata, MO+2016

Improvements of RMS

- mass modeling of clusters w/ ≳50 multiple images
- plotted data not complete
- RMS getting better….



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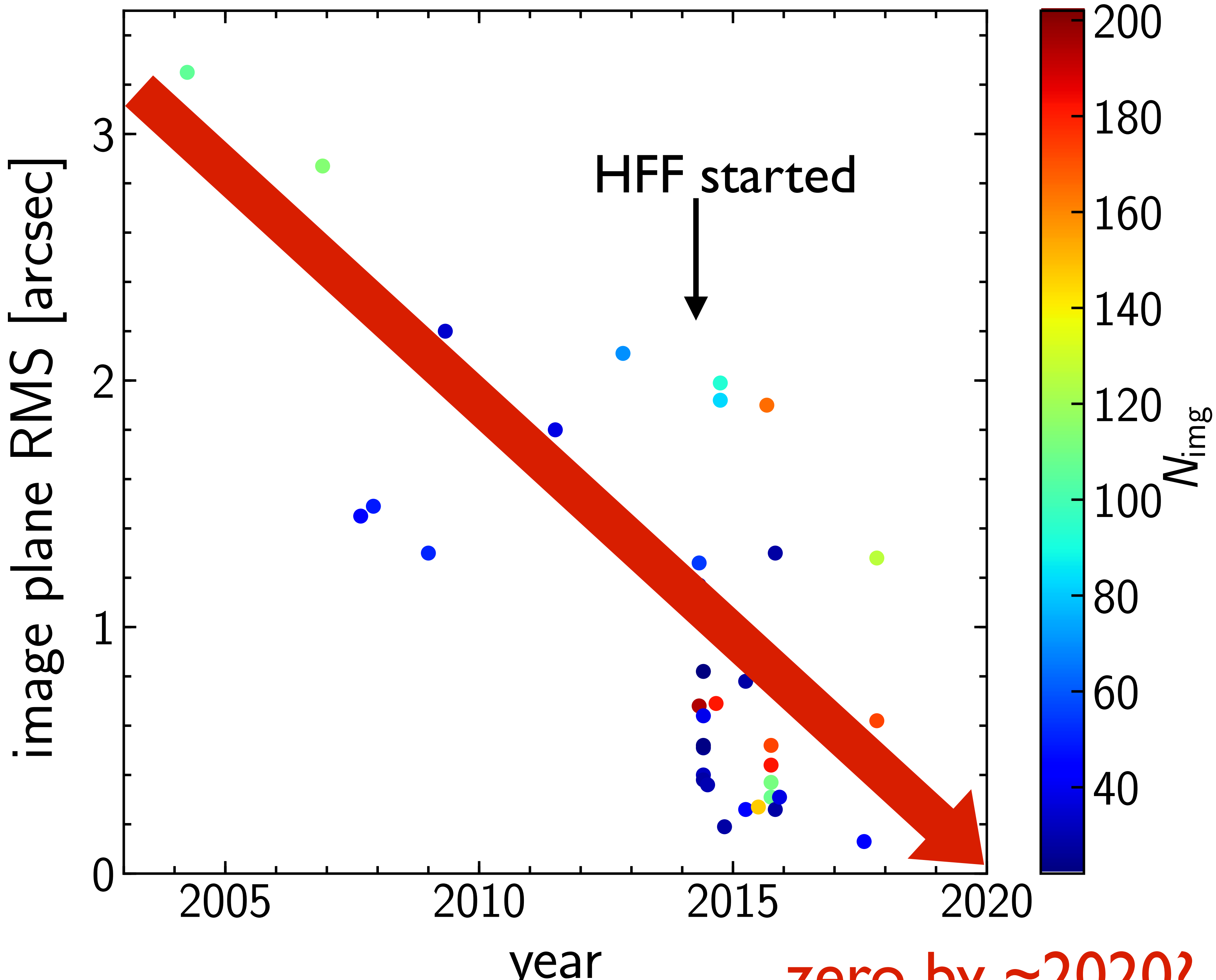

zero by ~2020?

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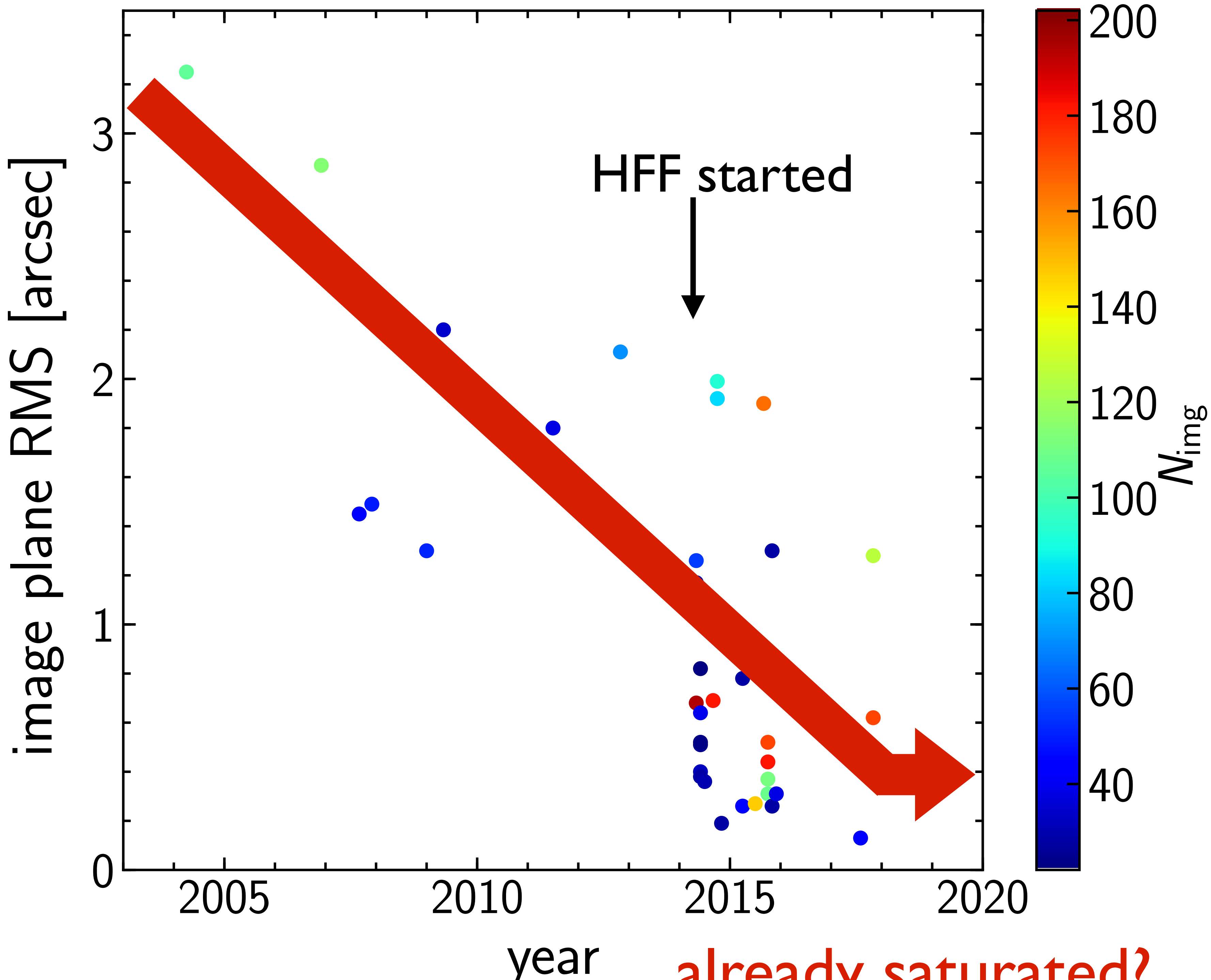


already saturated?

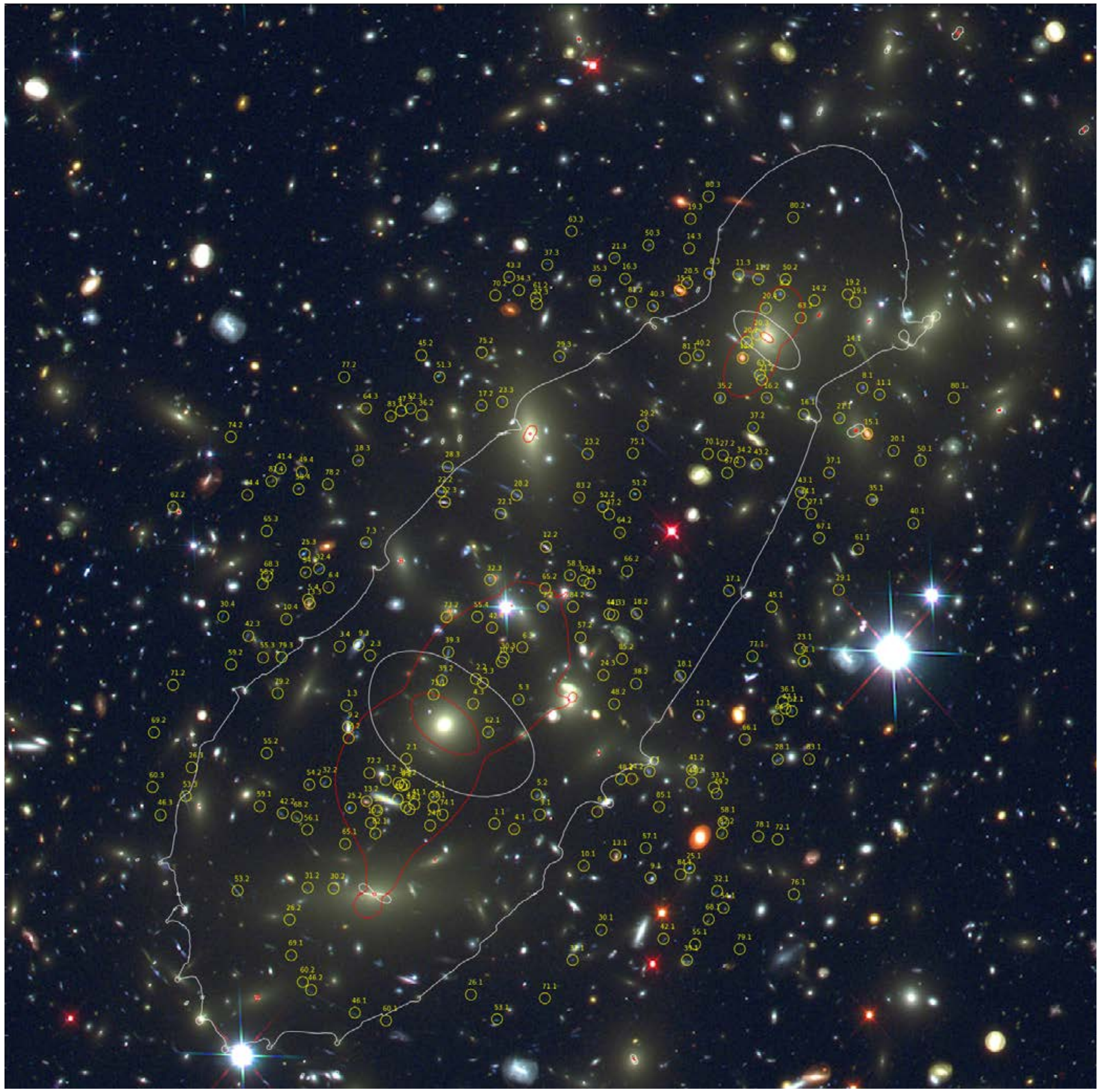
Meneghetti, Natarajan, Coe+ MNRAS **472**(2017)3177

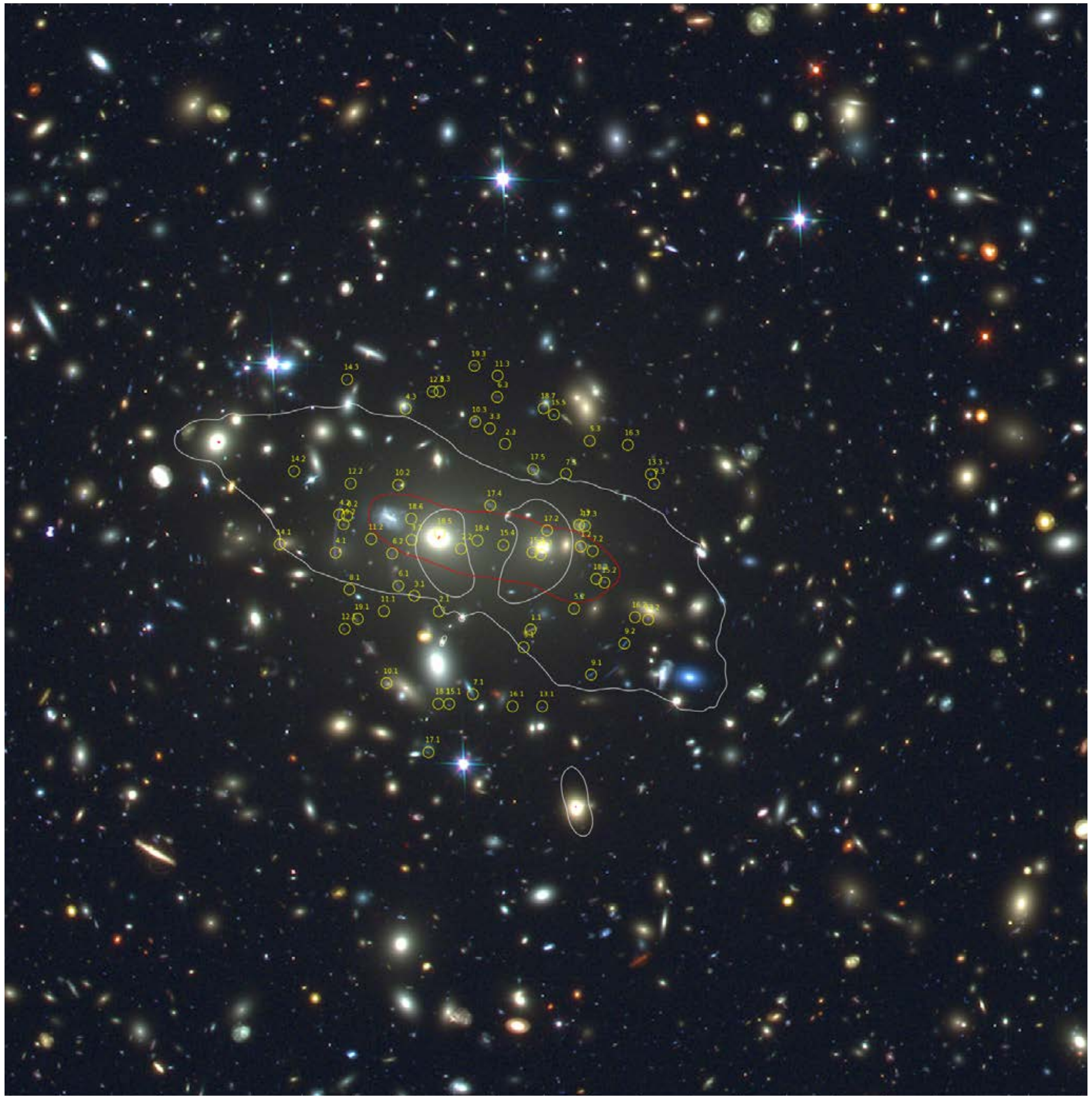
Mock challenge

- create HFF-like mock strong lensing cluster data, people analyze the mock data without knowing the answer
- this allows us to assess how accurate the reconstructed mass distributions are

Ares

Hera

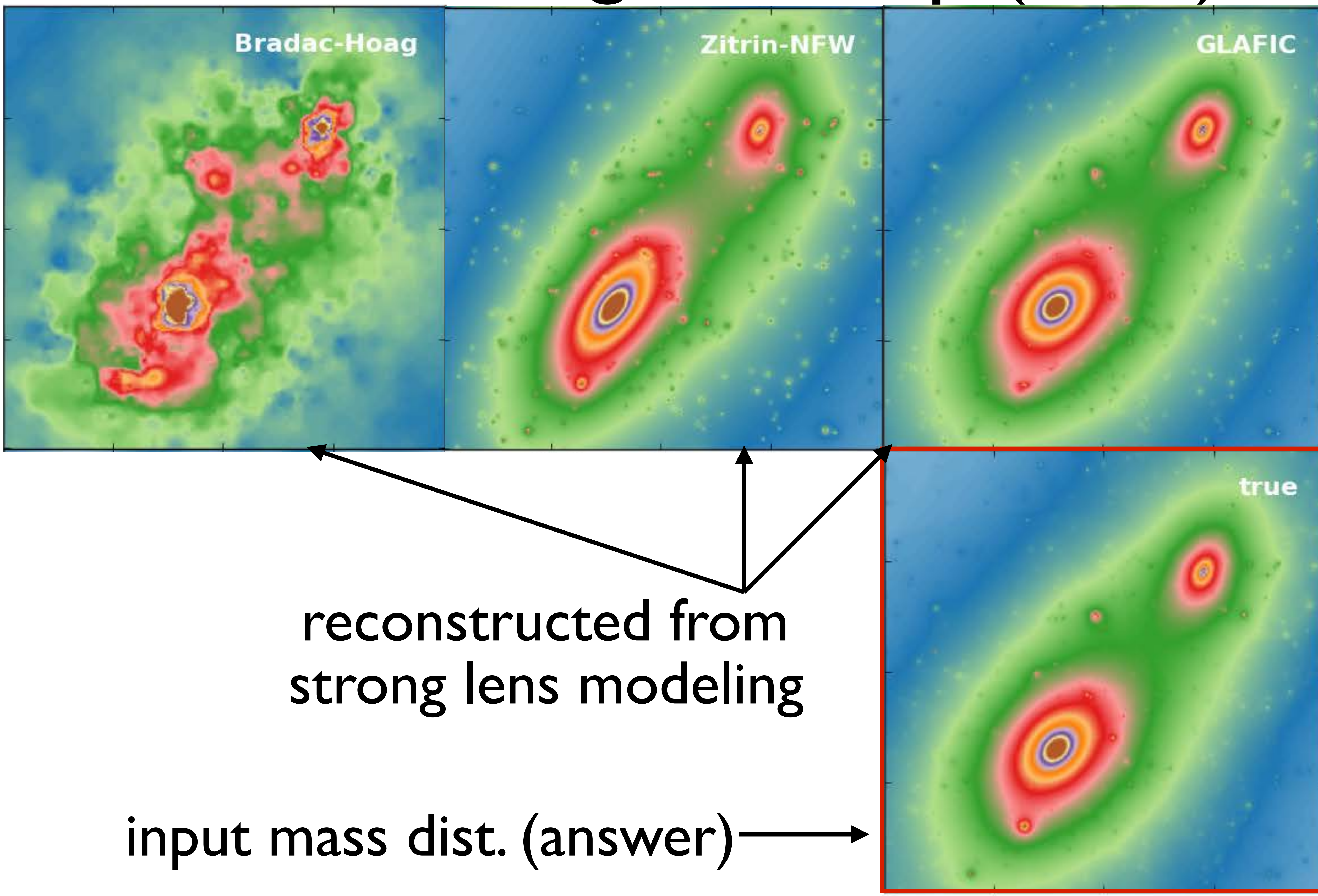




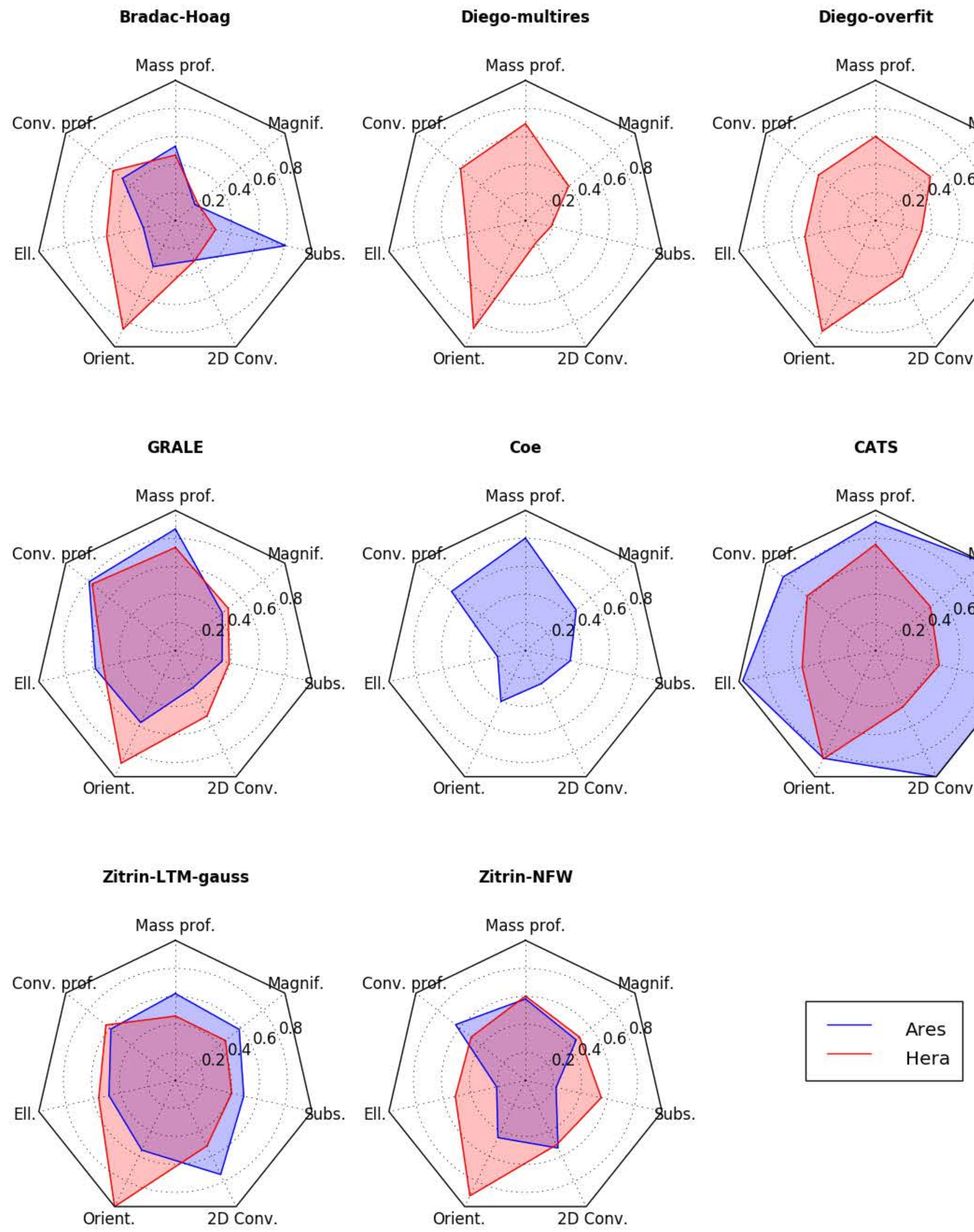
semi-analytic

N-body

Result: convergence map (Ares)



Meneghetti, Natarajan, Coe+ MNRAS **472**(2017)3177



larger area is better

different performance for different methods

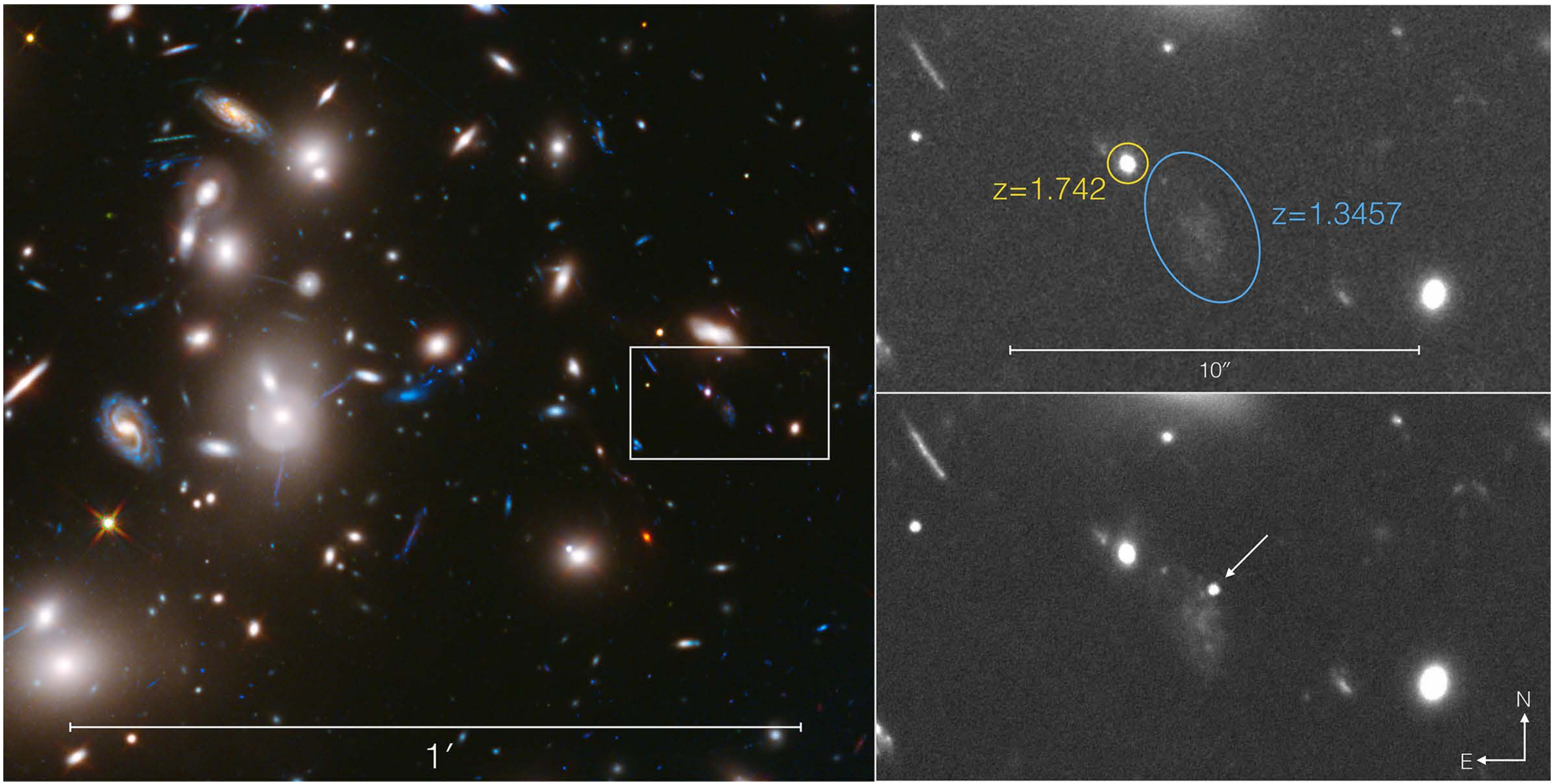
GLAFIC performs best!

Lensed supernovae

- provide totally new constraints beyond image positions
  - magnification factor
    Type Ia only, but even for single image
  - time delay
    when multiply imaged
- serve as a blind test of mass models made before the supernova explodes

Rodney, Patel, Scolnic+ ApJ **811** (2015)70

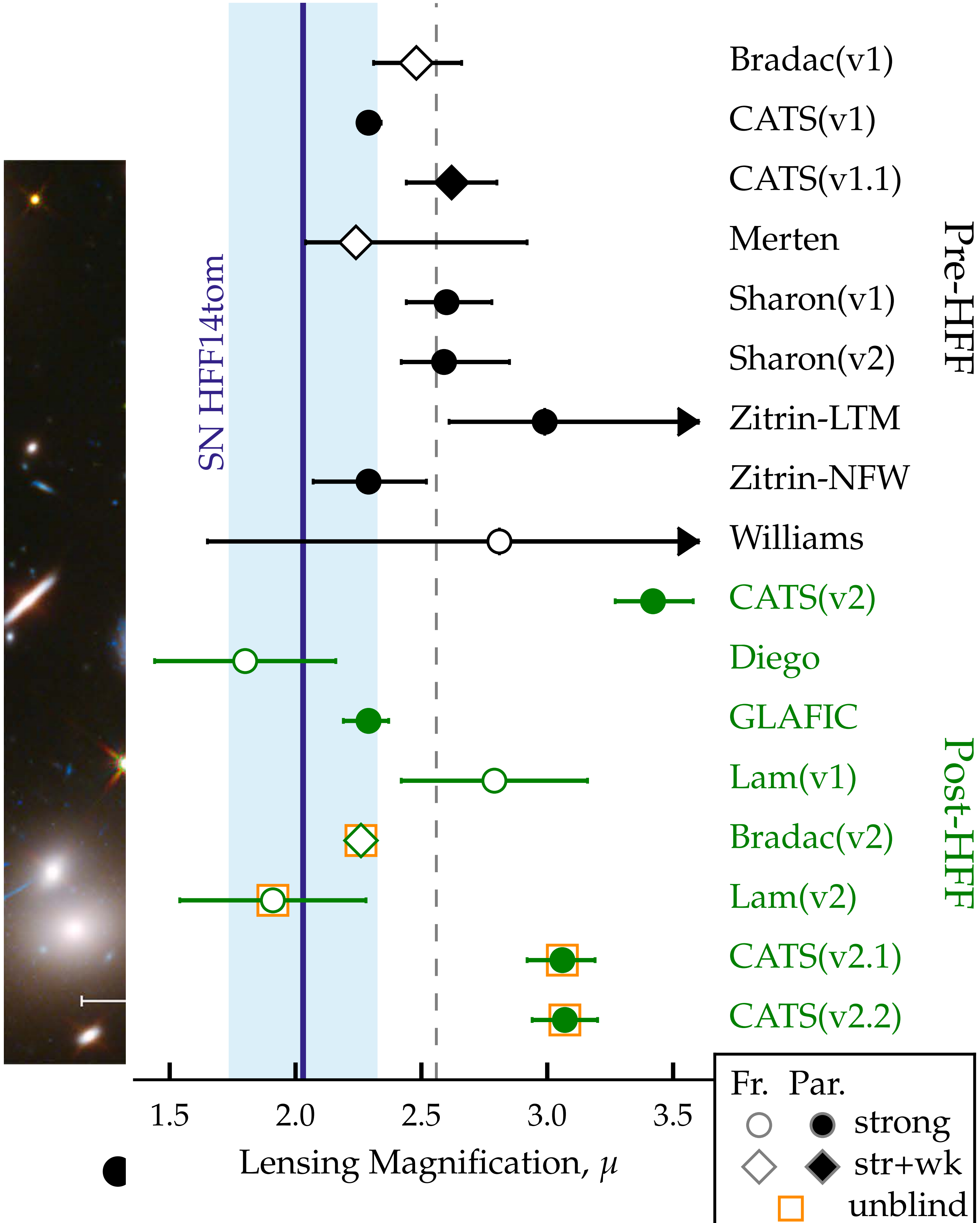
SN HFF14Tom

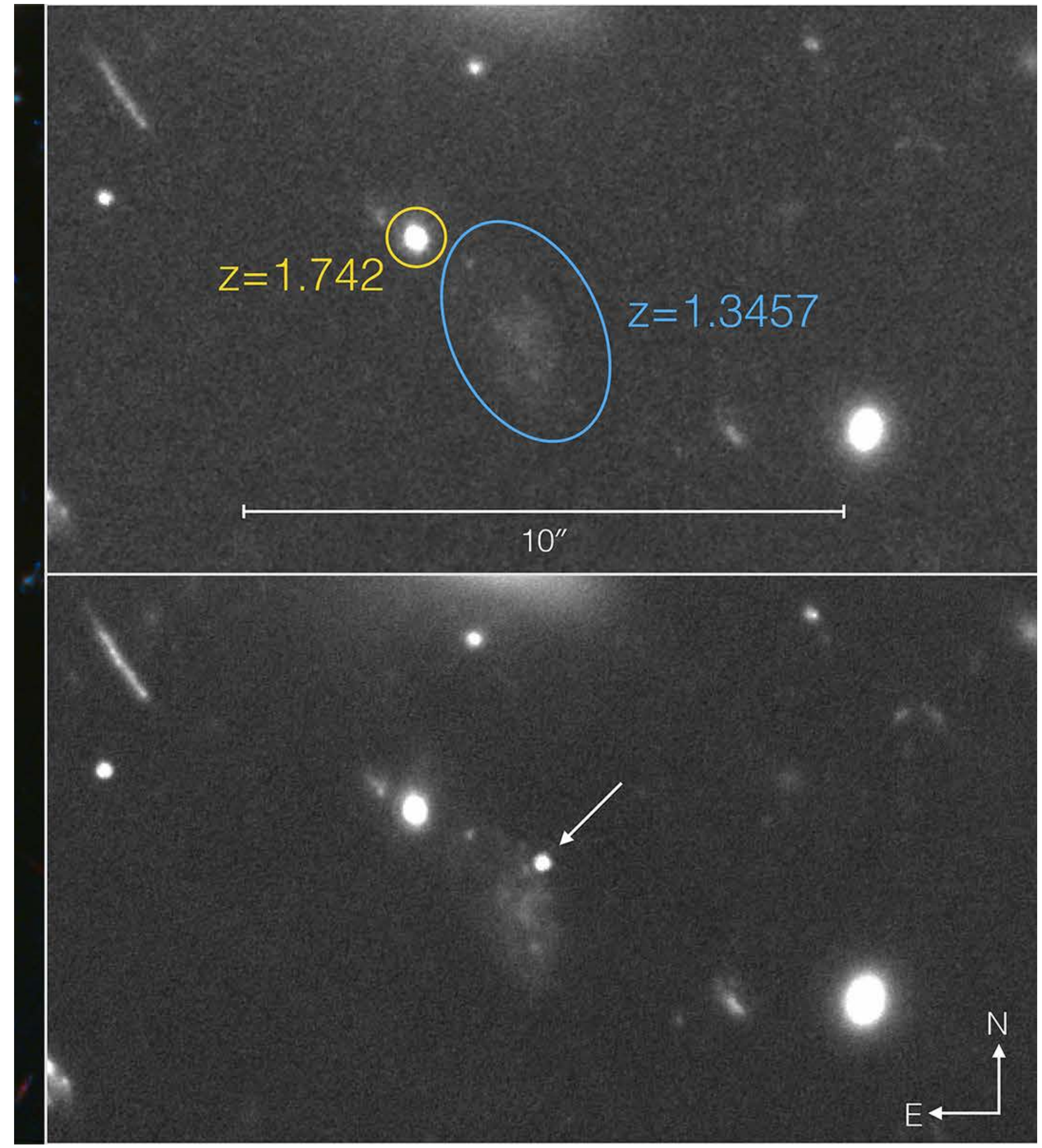


- lensed Type Ia at z=1.3457 (single image)

Rodney, Patel, Scolnic+ ApJ **811** (2015)70

4Tom

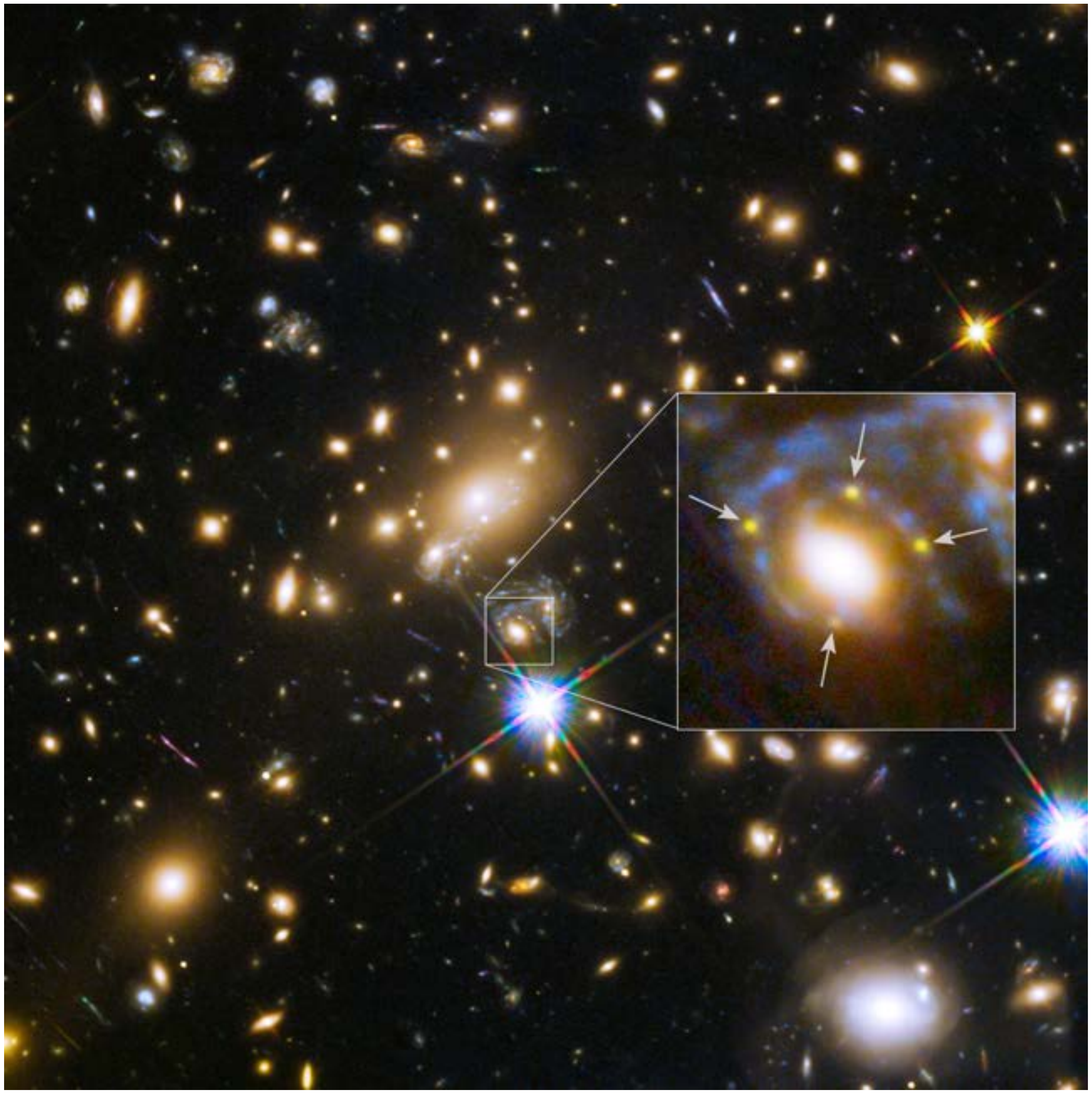




57 (single image)

Kelly, Rodney, Treu+ Science **347**(2015)1123

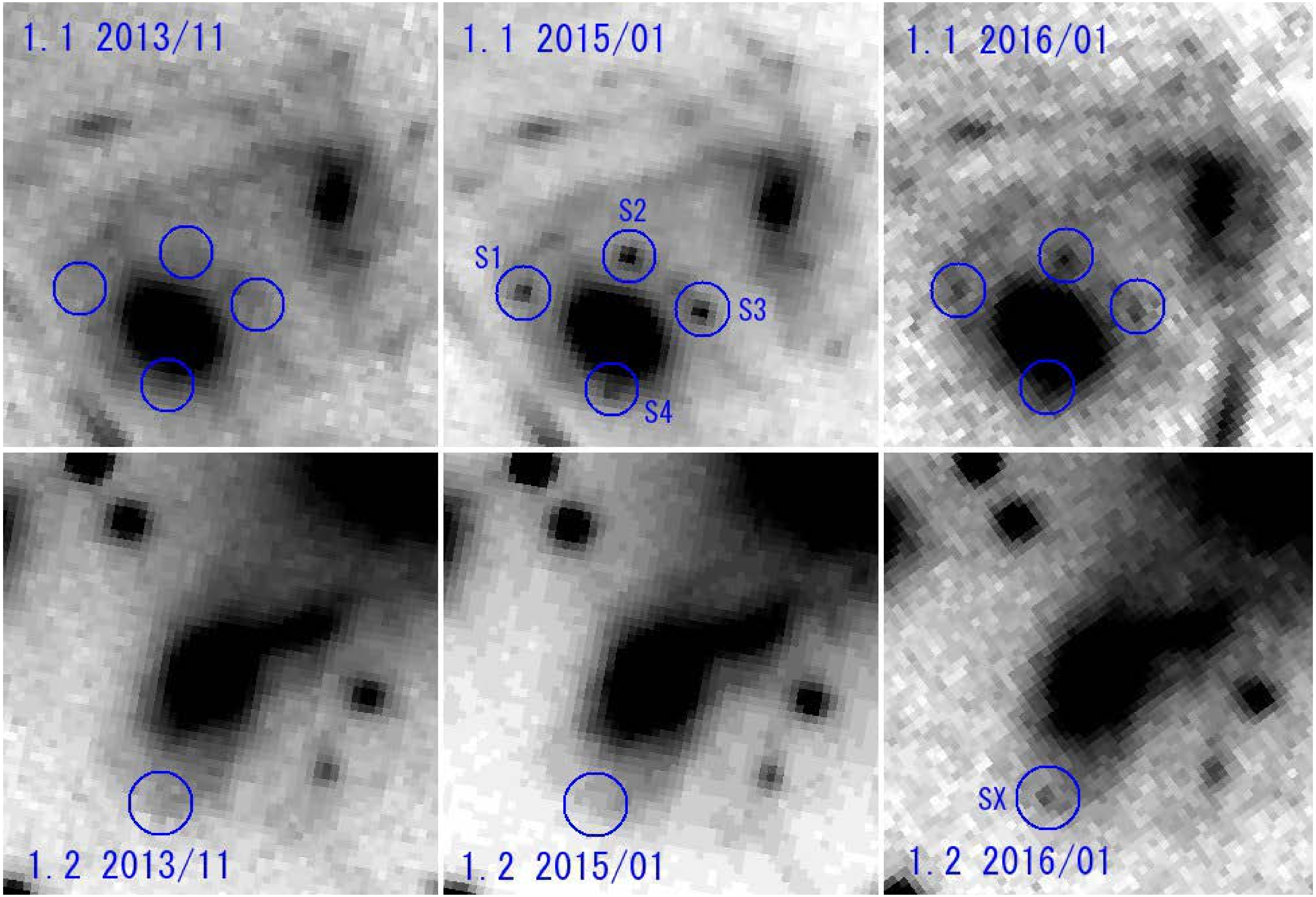
SN Refsdal



hubblesite.org

- lensed SNcc at z=1.49
- four Einstein cross SN images
- a new SN image predicted ~1 year after the 4 images!

(MO 2015; Sharon & Johnson 2015; Diego+2016; Jauzac+2016; Treu+2016; Grillo+2016)

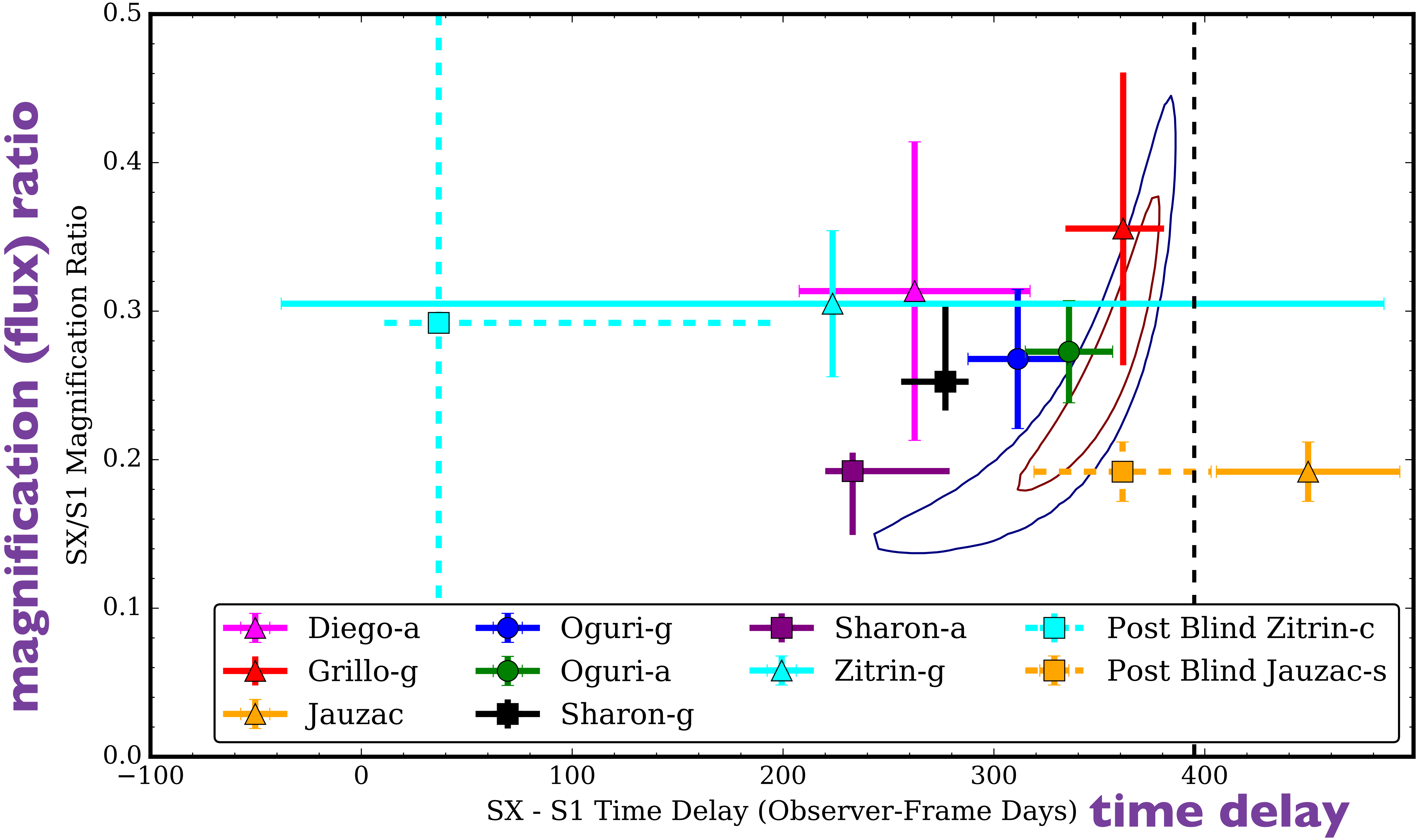


before SN

image S1-S4 appears (late 2014)

fifth image appears (late 2015)

Reappearance of SN Refsdal



- some models correctly predicted reappearance (includ. GLAFIC mass model!)

Summary

- rich dataset provided by HFF significantly advanced our understanding of cluster strong lens mass modeling
- various independent tests with mock challenge and lensed supernovae indicate that we are on the right track to improve mass modeling
- further improvements? line-of-sight effect, caustic crossing, …