GRAVITATIONAL LENSING AND HIGH REDSHIFT GALAXIES

LECTURE I - GRAVITATIONAL LENSING

Adi Zitrin

FIRST LIGHT: STARS, GALAXIES AND BLACK HOLES IN THE EPOCH OF REIONIZATION
Advanced School, São Paulo

Jul 30

Rule number 8:
PLEASE DON'T BE POLITE –
ASK QUESTIONS THROUGHOUT
(It will be alright)

About me…

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About me…

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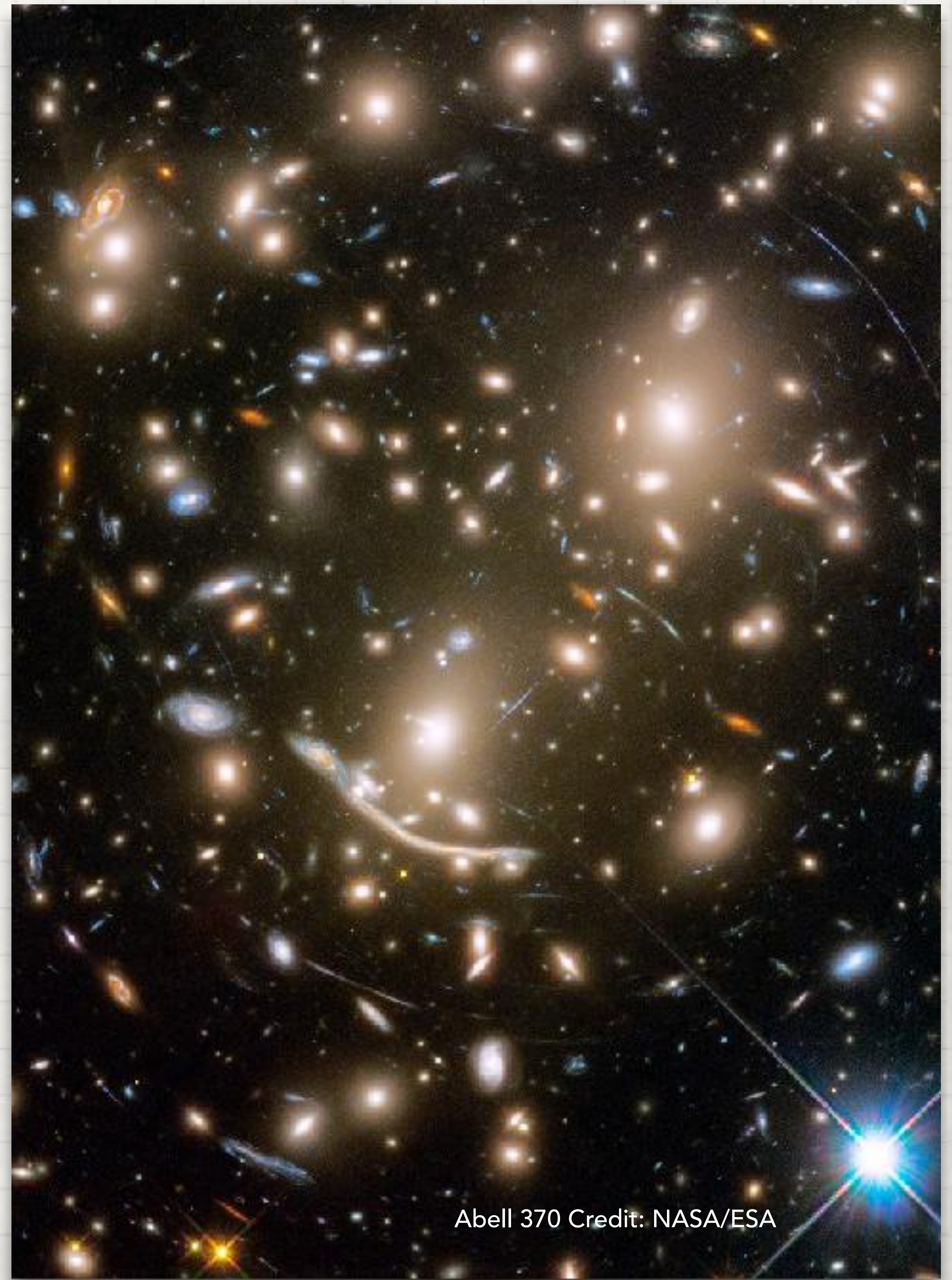
SERIES OF THREE TALKS:

I. **Gravitational lensing basics**

II. **Gravitational lensing of high-redshift galaxies**

III*. **"~Hands on" - let's build a lens model, luminosity function, and other fun stuff.**

***if we get to it!**


Abell 370 Credit: NASA/ESA

LECTURE I. GRAVITATIONAL LENSING

(such a lovely topic!)

Goal: An overview of gravitational lensing.

To make sure we all know what lensing is, what science we can do with it, to make the relation to first light sources (for Lecture II).

NOTE: Throughout will also mention: island universe, dark matter, rotation curves, caustics, critical curves, distances, ray tracing, different GL regimes (strong, weak, micro)

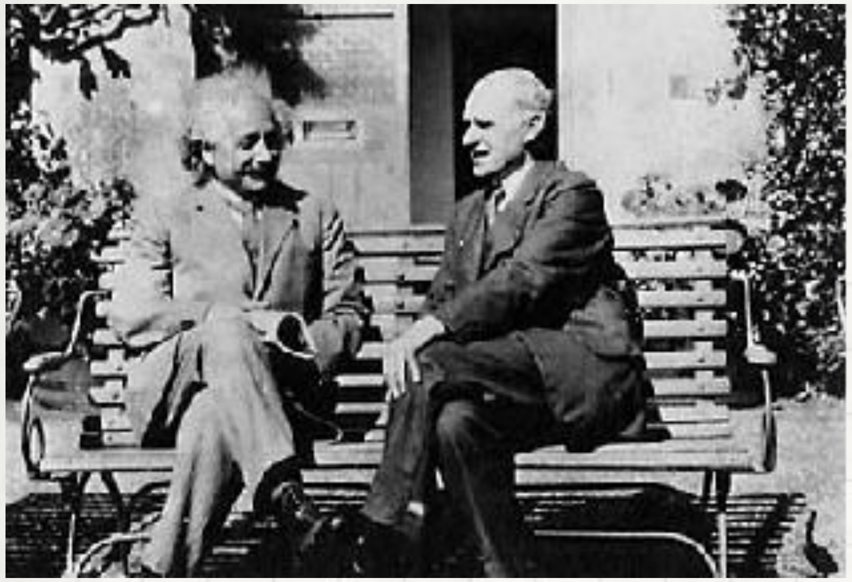
Also: many images throughout are taken from web, in case credit is missing, it is probably not mine but available freely online.
A partial list of recommended reviews and literature was given on website, and constitutes also much of the references for the talk.

LECTURE I. GRAVITATIONAL LENSING

(such a lovely topic!)

Outline:

- **1. Gravitational lensing (GL): history and introduction**
- **2. GL: Theory**
- **3. Science with GL, how**
- **4. Summary**



SCIENCE PHOTO LIBRARY

A VERY BRIEF HISTORY OF LENSING

Good read: Simon Singh, the Big Bang

https://www.nature.com/articles/d41586-019-01172-z

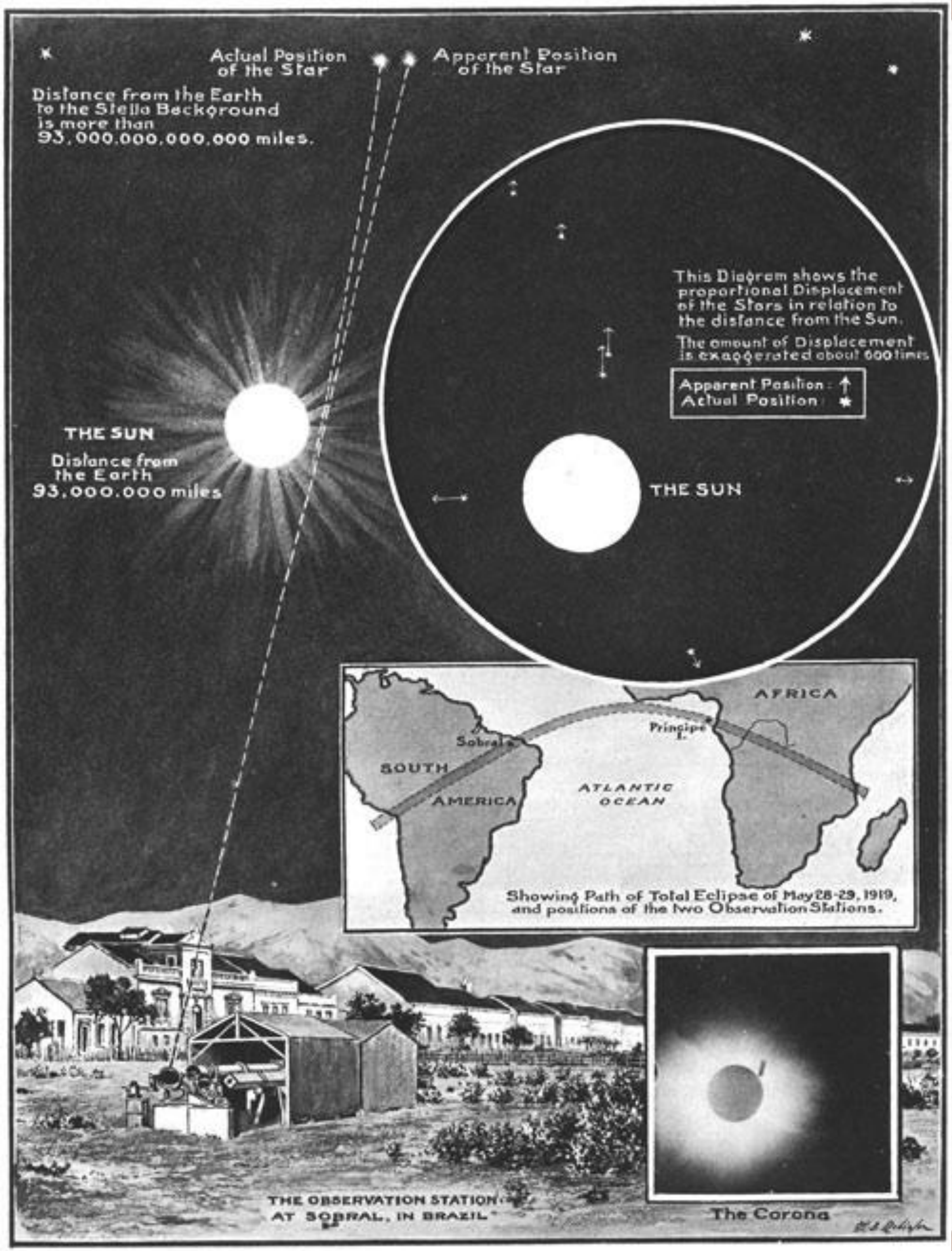
- 1911-1915: Einstein's GR, establishment of the correct deflection angle by an intervening mass: 4GM /rc^2

- Understanding (with Erwin Freundlich) that a solar eclipse would be needed to measure the deflection and compare to Newtonian prediction

- 1919: Eddington+ (and thanks to Dyson). measurement and later reconfirmation of the amplification of light of an object passing near/behind the sun (microlensing) during a solar eclipse

Solar Eclipse of May 29, 1919

London News Nov 22, 1919



IX. *A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May 29, 1919.*

By Sir F. W. Dyson, *F.R.S., Astronomer Royal, Prof.* A. S. Eddington, *F.R.S., and Mr.* C. Davidson.

(*Communicated by the Joint Permanent Eclipse Committee.*)

Received October 30,—Read November 6, 1919.

[Plate 1.]

1. The purpose of the
by a gravitational field
surprises, there appeare
discriminate between—

(1) The path is uninfl
(2) The energy or ma
matter. If the l
an apparent disp
outwards.
(3) The course of a ra
theory. This lea
to 1″·75 outwards.

In either of the last two cases the displacement is inversely proportional to the distance of the star from the sun's centre, the displacement under (3) being just double the displacement under (2).

the radius of the sun.

Table I.

No.	Names.	Photog. Mag.	Co-ordinates. Unit = 50′.		Gravitational displacement.			
					Sobral.		Principe.	
			x.	y.	x.	y.	x.	y.
		m.			″	″	″	″
1	B.D., 21°, 641	7·0	+0·026	−0·200	−1·31	+0·20	−1·04	+0·09
2	Piazzi, IV, 82	5·8	+1·079	−0·328	+0·85	−0·09	+1·02	−0·16
3	κ^2 Tauri	5·5	+0·348	+0·360	−0·12	+0·87	−0·28	+0·81
4	κ^1 Tauri	4·5	+0·334	+0·472	−0·10	+0·73	−0·21	+0·70
5	Piazzi, IV, 61	6·0	−0·160	−1·107	−0·31	−0·43	−0·31	−0·38
6	υ Tauri	4·5	+0·587	+1·099	+0·04	+0·40	+0·01	+0·41
7	B.D., 20°, 741	7·0	−0·707	−0·864	−0·38	−0·20	−0·35	−0·17
8	B.D., 20°, 740	7·0	−0·727	−1·040	−0·33	−0·22	−0·29	−0·20
9	Piazzi, IV, 53	7·0	−0·483	−1·303	−0·26	−0·30	−0·26	−0·27
10	72 Tauri	5·5	+0·860	+1·321	+0·09	+0·32	+0·07	+0·34
11	66 Tauri	5·5	−1·261	−0·160	−0·32	+0·02	−0·30	+0·01
12	53 Tauri	5·5	−1·311	−0·918	−0·28	−0·10	−0·26	−0·09
13	B.D., 22°, 688	8·0	+0·089	+1·007	−0·17	+0·40	−0·14	+0·39

* 'Monthly Notices, R.A.S.,' LXXVII, p. 445.

New York Times
Nov 10, 1919

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Before continuing with lensing: Three other historical milestones

- **1**. Hubble 1923,1929, more galaxies than Milky Way (Island universes), receding from us (Hubble's law). Universe expanding.

Slope is the
Hubble Constant H_0
$V=H_0*D$

Hubble's original result

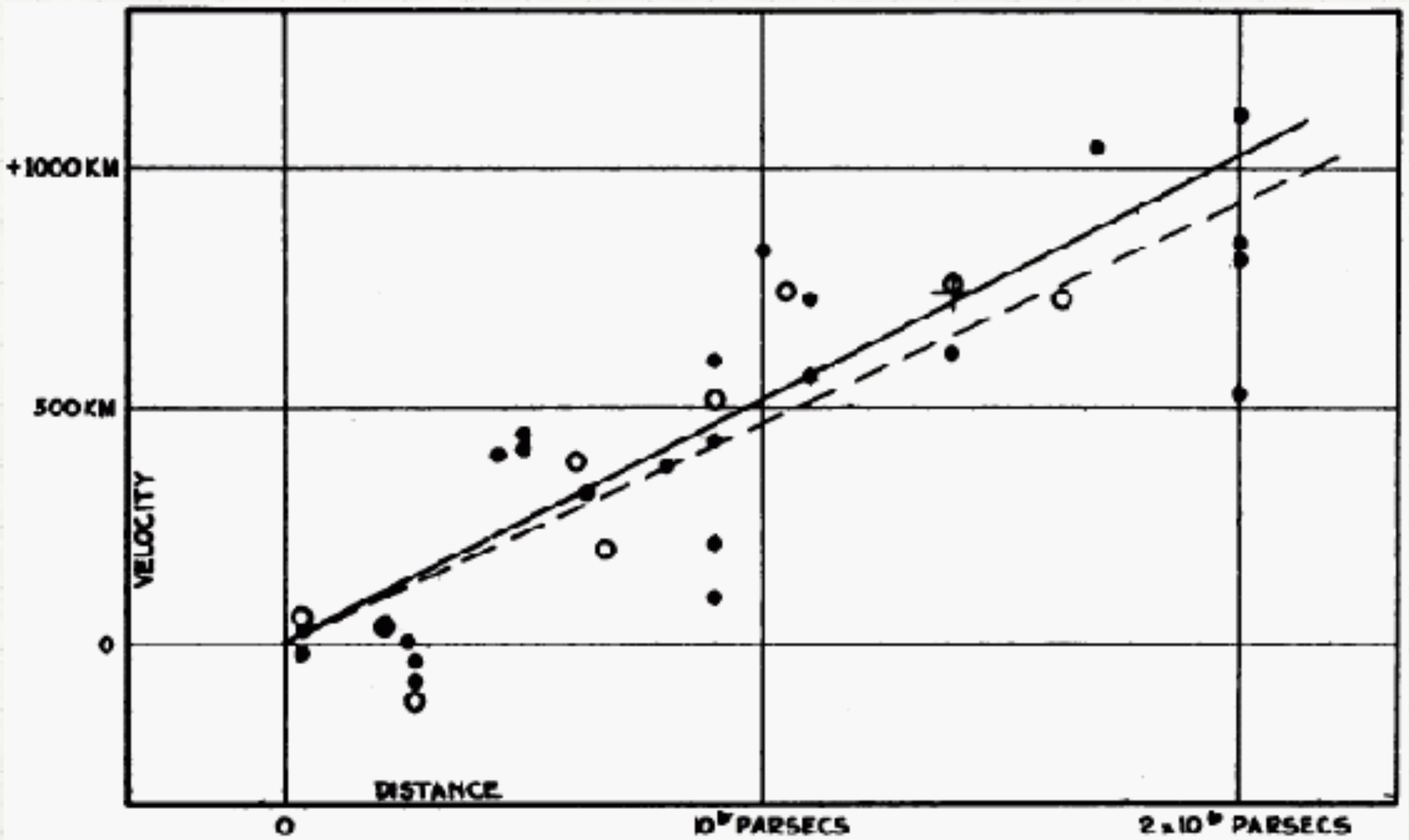
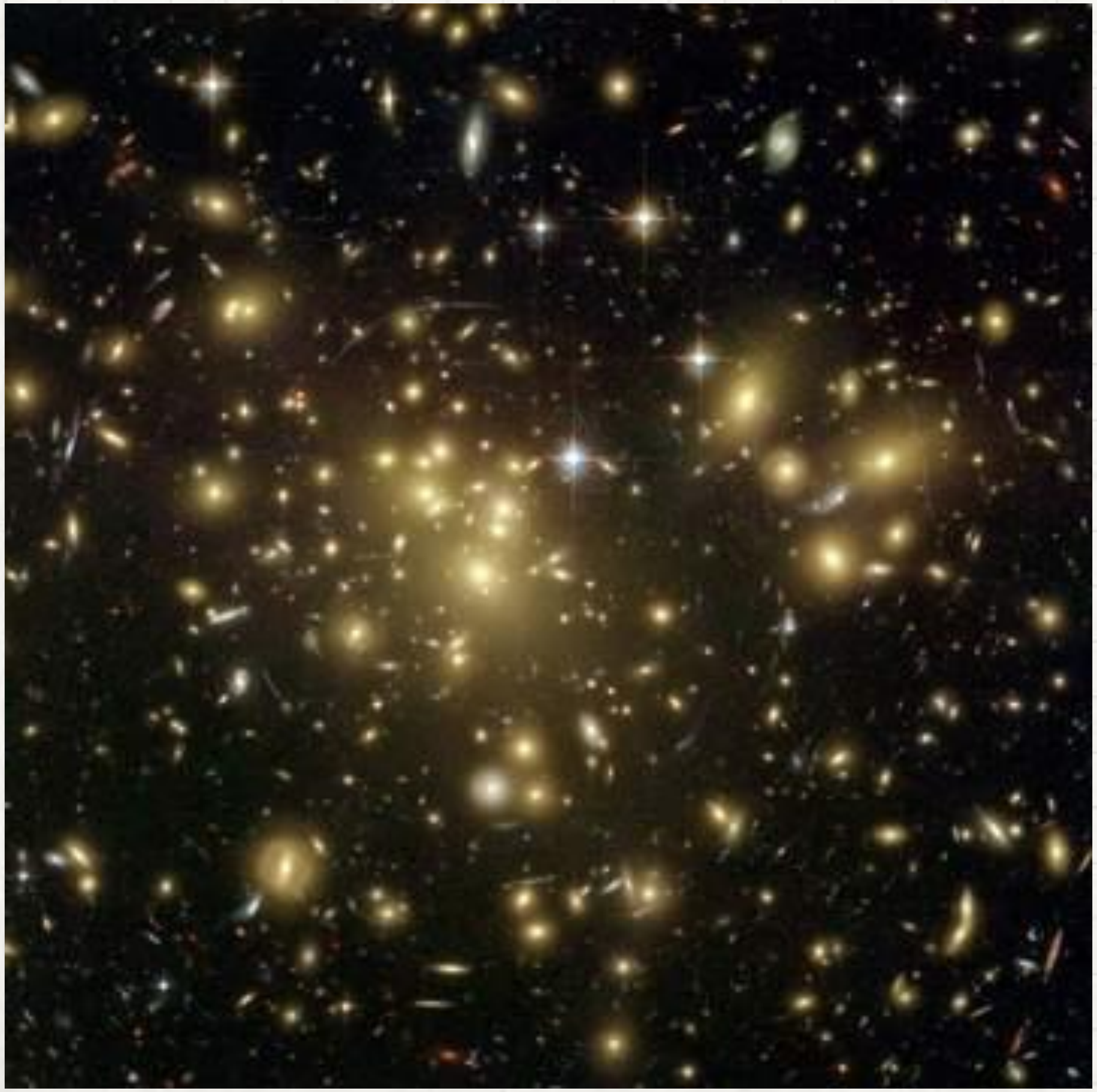


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

2. Zwicky 1937 - missing mass / DM



$$\frac{3}{5}\frac{GM}{R} = \frac{3}{2}\frac{k_B T}{m_p} = \frac{1}{2}v^2,$$

$$T = (1/2)v^2 \sim (3/2)\sigma^2$$

(sigma is 1D therefore 3sigma^2 is ~v^2)

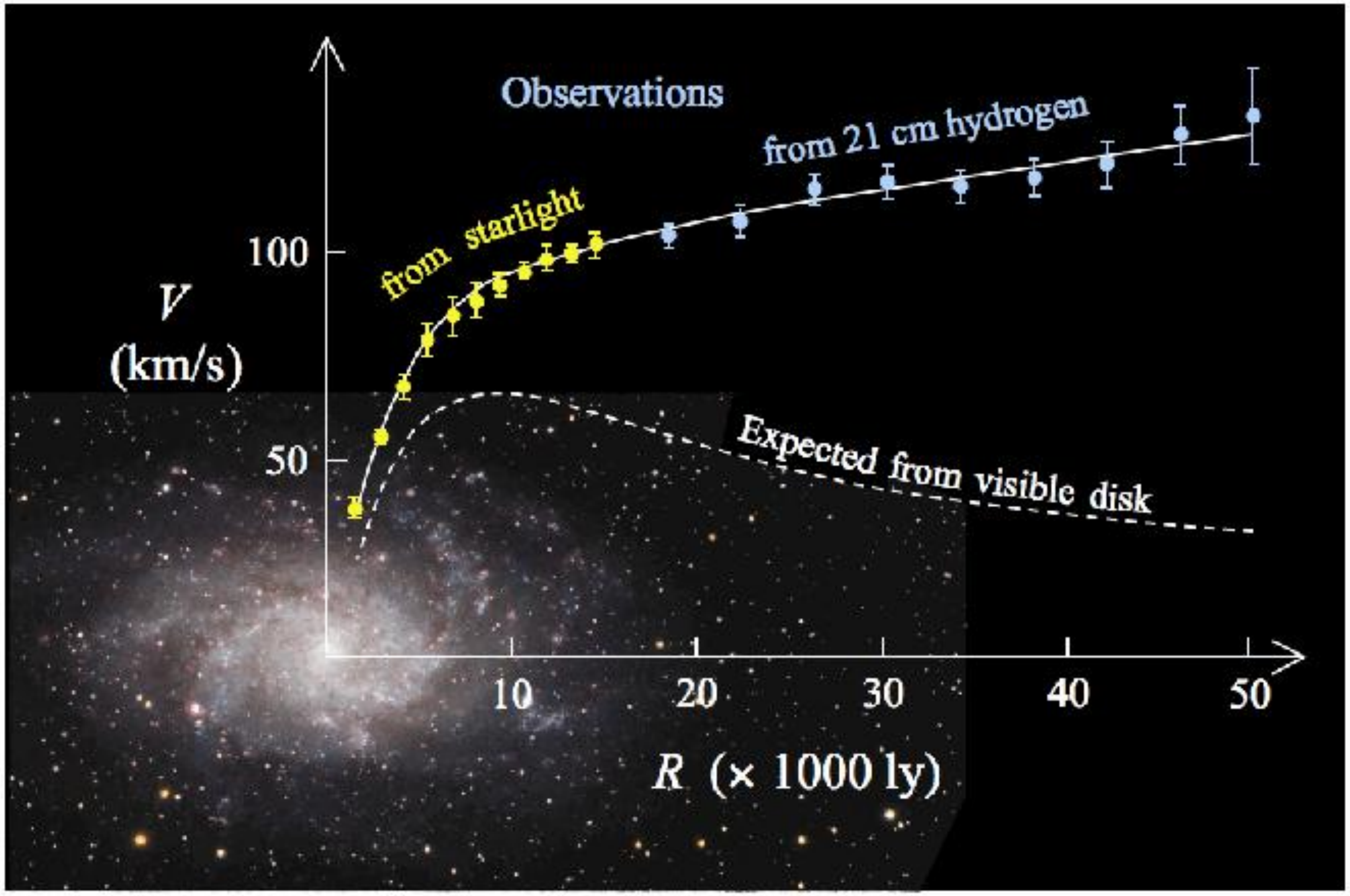
$$\frac{GM}{R} \approx \sigma^2.$$

The virial mass and radius are generally defined for the radius at which the velocity dispersion is a maximum, i.e.

$$\frac{GM_{\rm vir}}{R_{\rm vir}} \approx \sigma^2_{\rm max}.$$

HST image of A1689

3. Rubin 80's- missing mass / DM



F=GM(r)m/r^2

Should equal:
V^2/r centripetal acceleration

V=sqrt(GM/r)

Beyond R_gal, M fixed,
V \propto r^(-1/2)

DARK MATTER

YET UNKNOWN

Dominated the mass budget in the universe!

As far as we know only interacts gravitationally

Does not radiate

Invisible

Collisionless

Various candidates

Still no detection

Don't know what it is

OK, back to lensing history

First cosmological lensing configuration discovered / multiple images

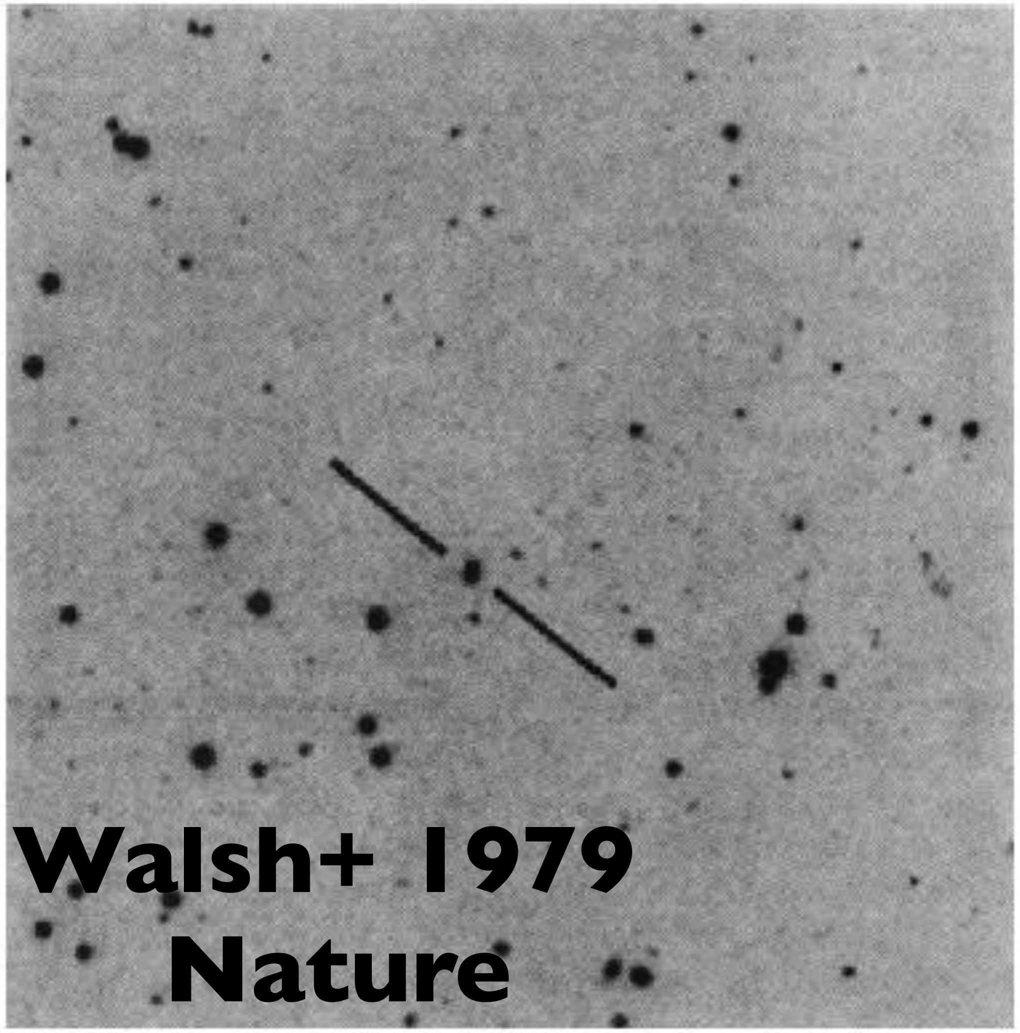
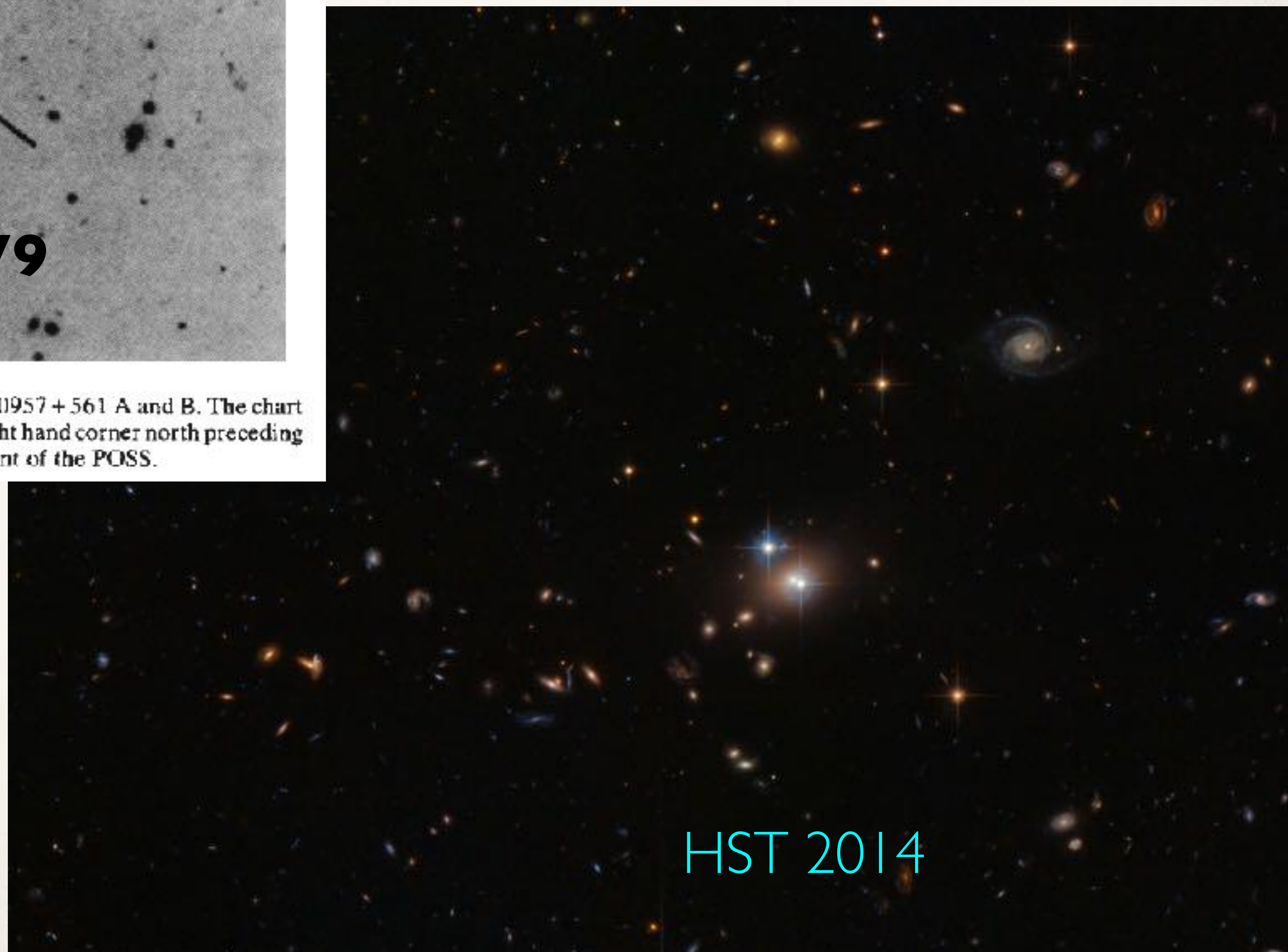


Fig. 1 Finding chart for the QSOs 0957 + 561 A and B. The chart is 8.5 arc min square with the top right hand corner north preceding and is from the E print of the POSS.



Blue giant ring-like structure

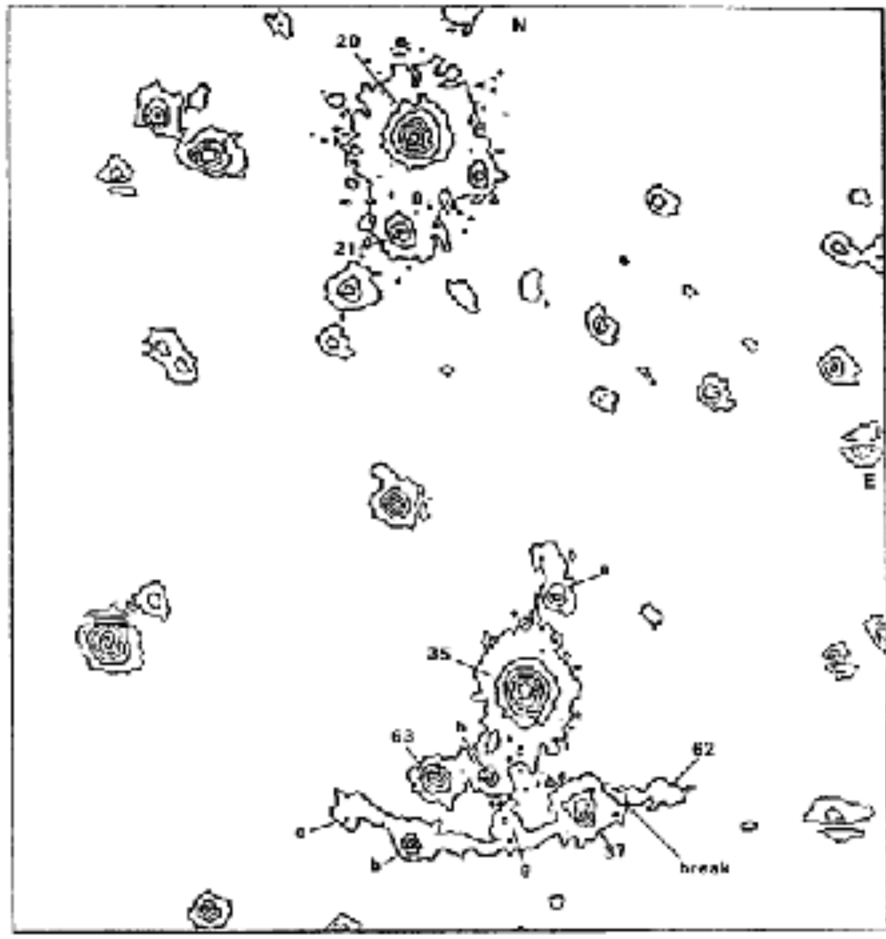
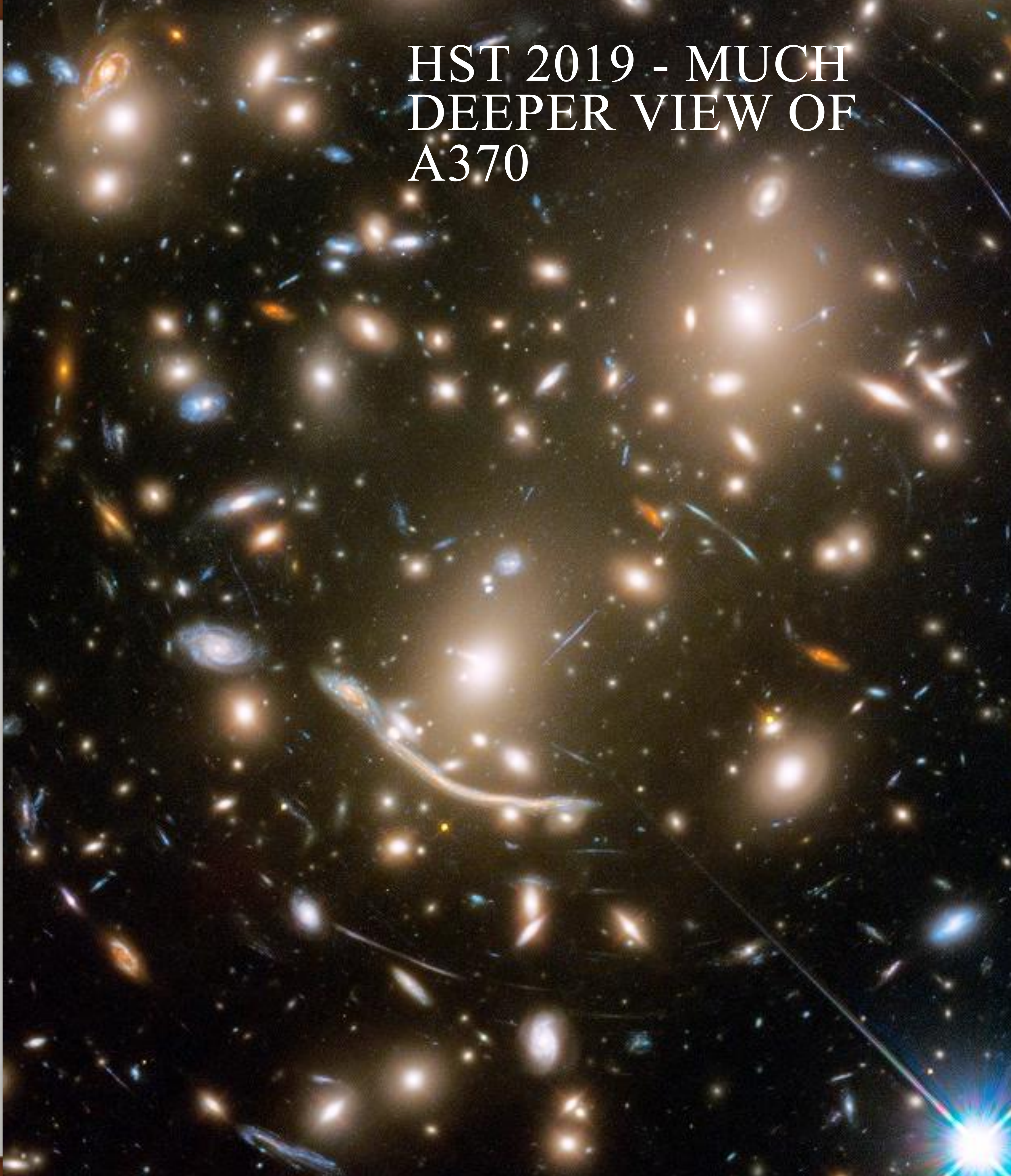


Fig. 1a : The core of the cluster of galaxies Abell (z = 0.374), dominated by both giant galaxies ##35 20, taken with the RCA2 CCD at CFHT. 4 galaxies are superimposed on the blue ring-like structure which widens eastward to give the blue object #62

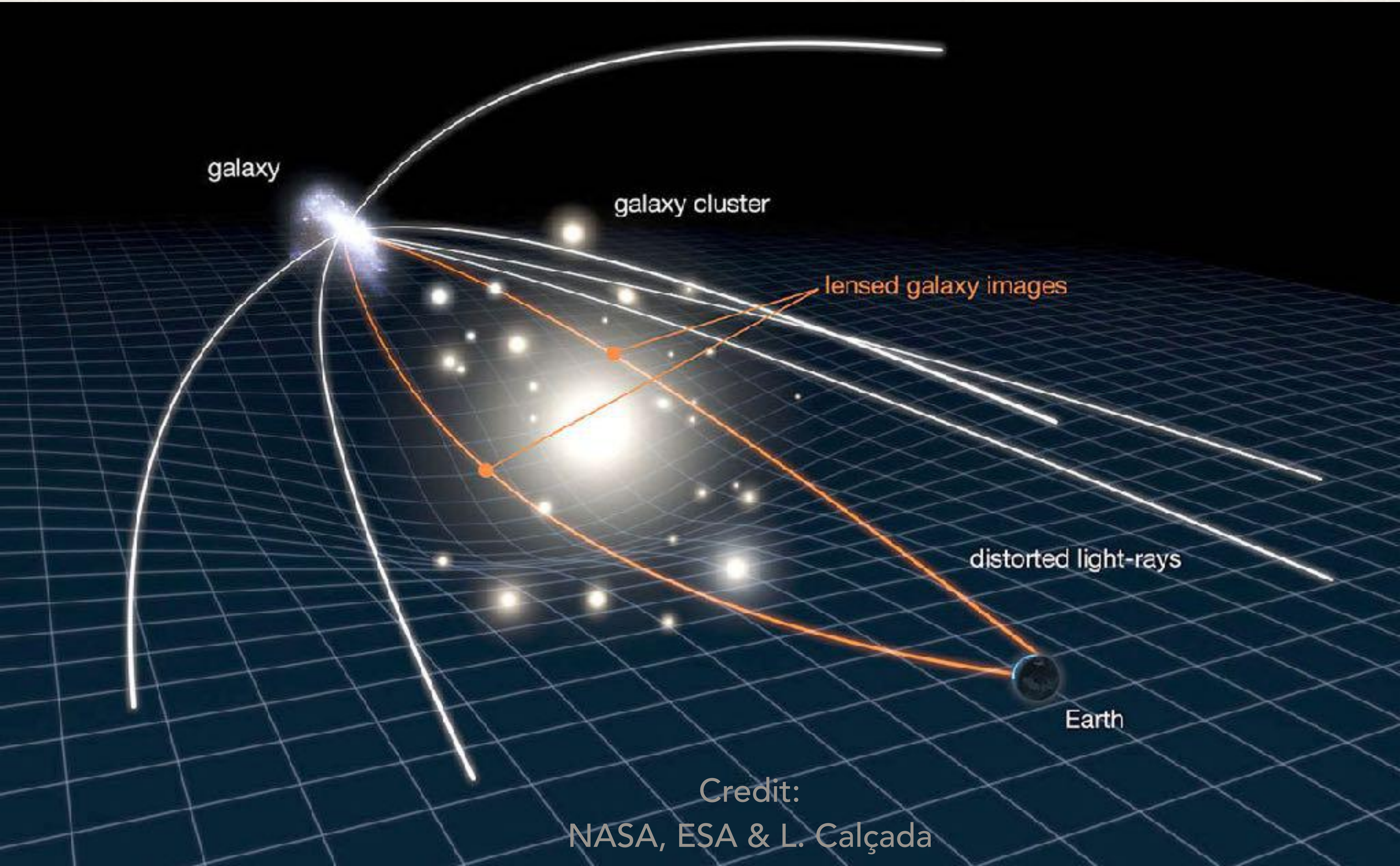
1986/7

Soucail+,
Lynds & Petrosian

End of
historical briefing,
now
let us understand
what is lensing



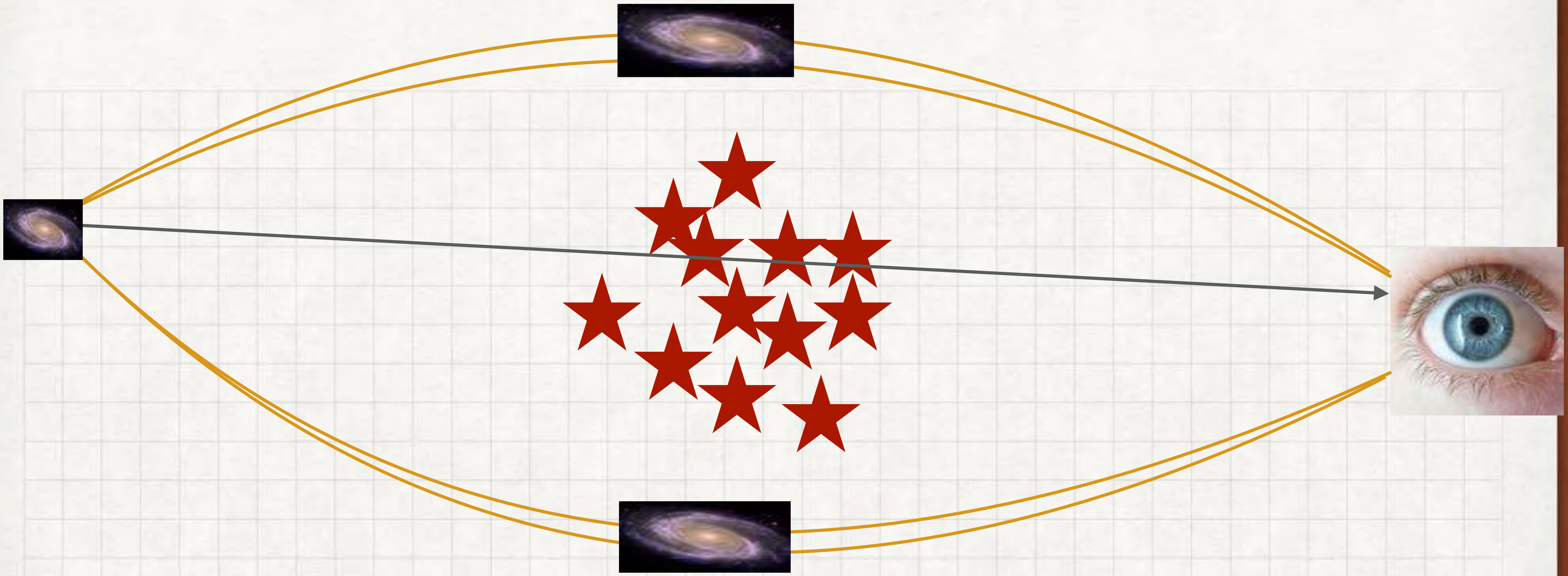
What is Gravitational Lensing?



Credit:
NASA, ESA & L. Calçada

So what is lensing?

Strong lensing



Few noticeable things happen (SL):

1. **background object is magnified, and sheared**
2. **background object is seen shifted**
3. **multiple images of the source appear**
4. **because of different paths, time delay**

Weak lensing

Few noticeable things happen (WL):
sources more distant from LOS, are only slightly shifted, slightly magnified, and slightly sheared
An effect that can only be measured statistically

A nice illustration video:

Credit: NASA, STScI/Frank Summers

Size of strong lens
(Einstein radius)

$$\theta_{\rm E} = \left(\frac{4GM}{c^2} \frac{D_{\rm ds}}{D_{\rm d} D_{\rm s}} \right)^{1/2} .$$

SOME EXAMPLES FOR LENSING

GALAXY GALAXY (STRONG) LENSING

SDSS J120540.43+491029.3
Image by the HST

Galaxy lensed by a galaxy

Quasar lensed by a galaxy

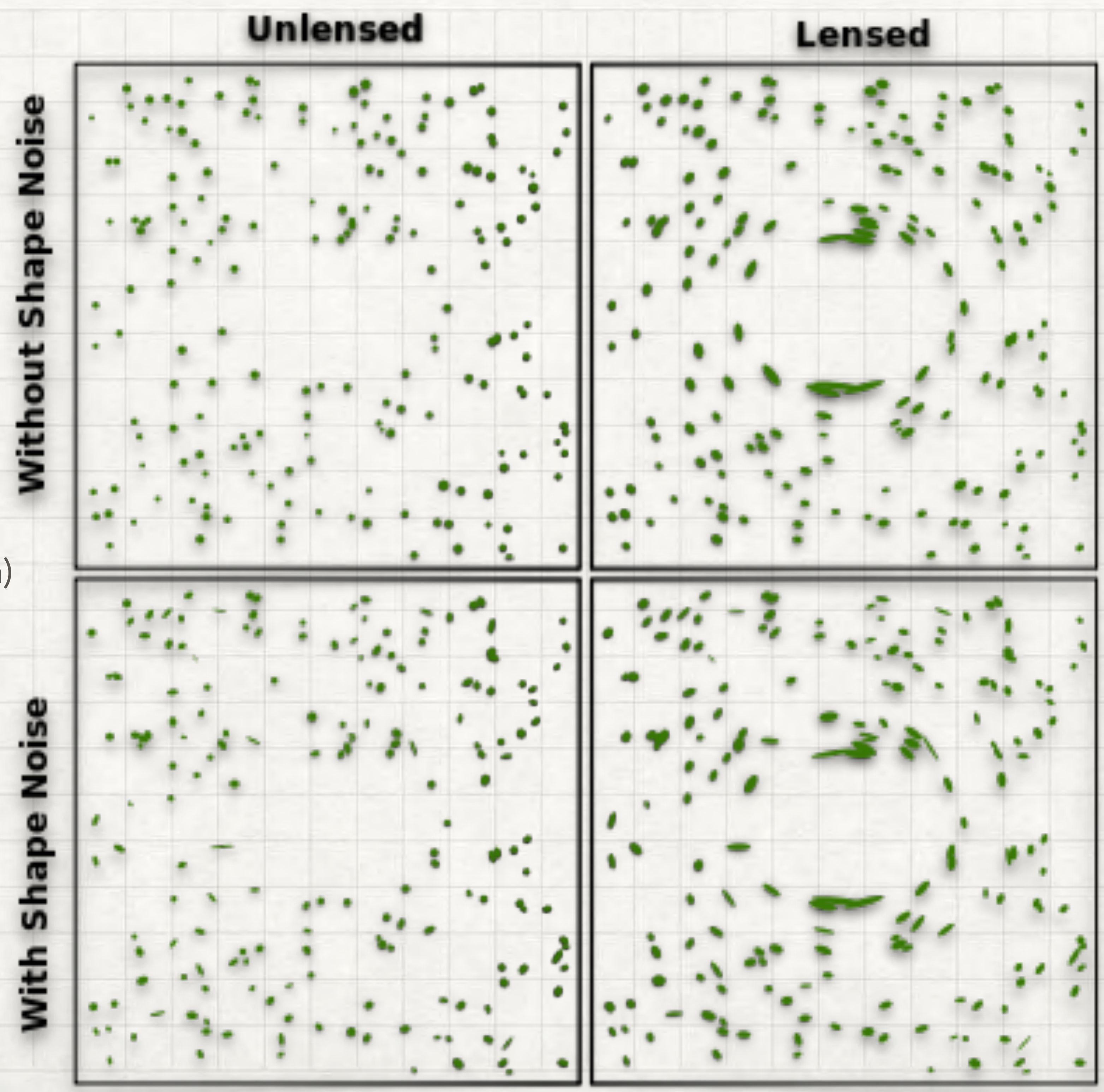
RXJ1131-1231 Image credit:
NASA / ESA / Hubble / S.H. Suyu et al.

SDSS J0252+0039
NASA/HST Bayer et al.

CLUSTER STRONG LENSING

CLUSTER WEAK LENSING (+ARCLETS)

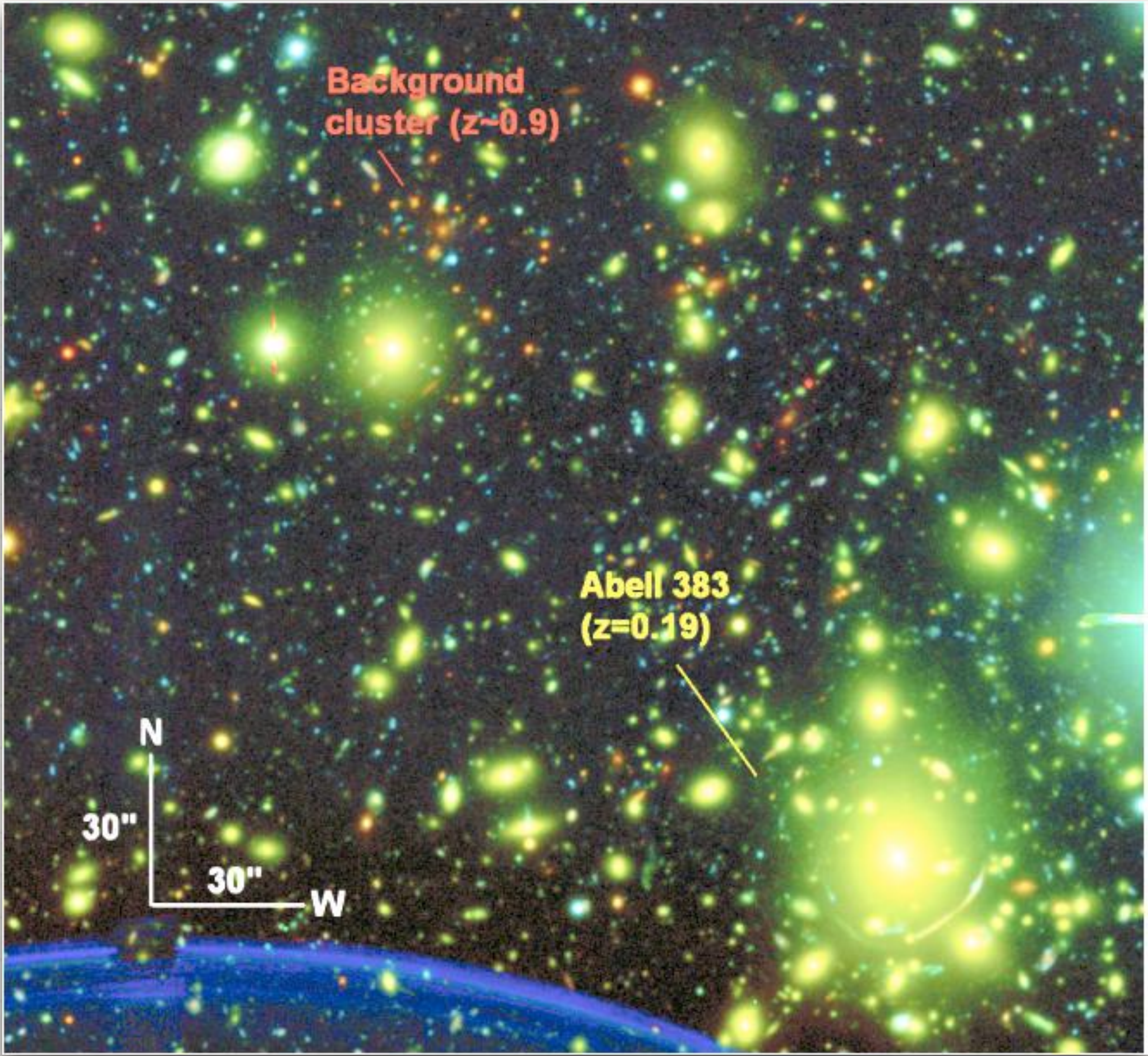
CLUSTER STRONG/WEAK LENSING



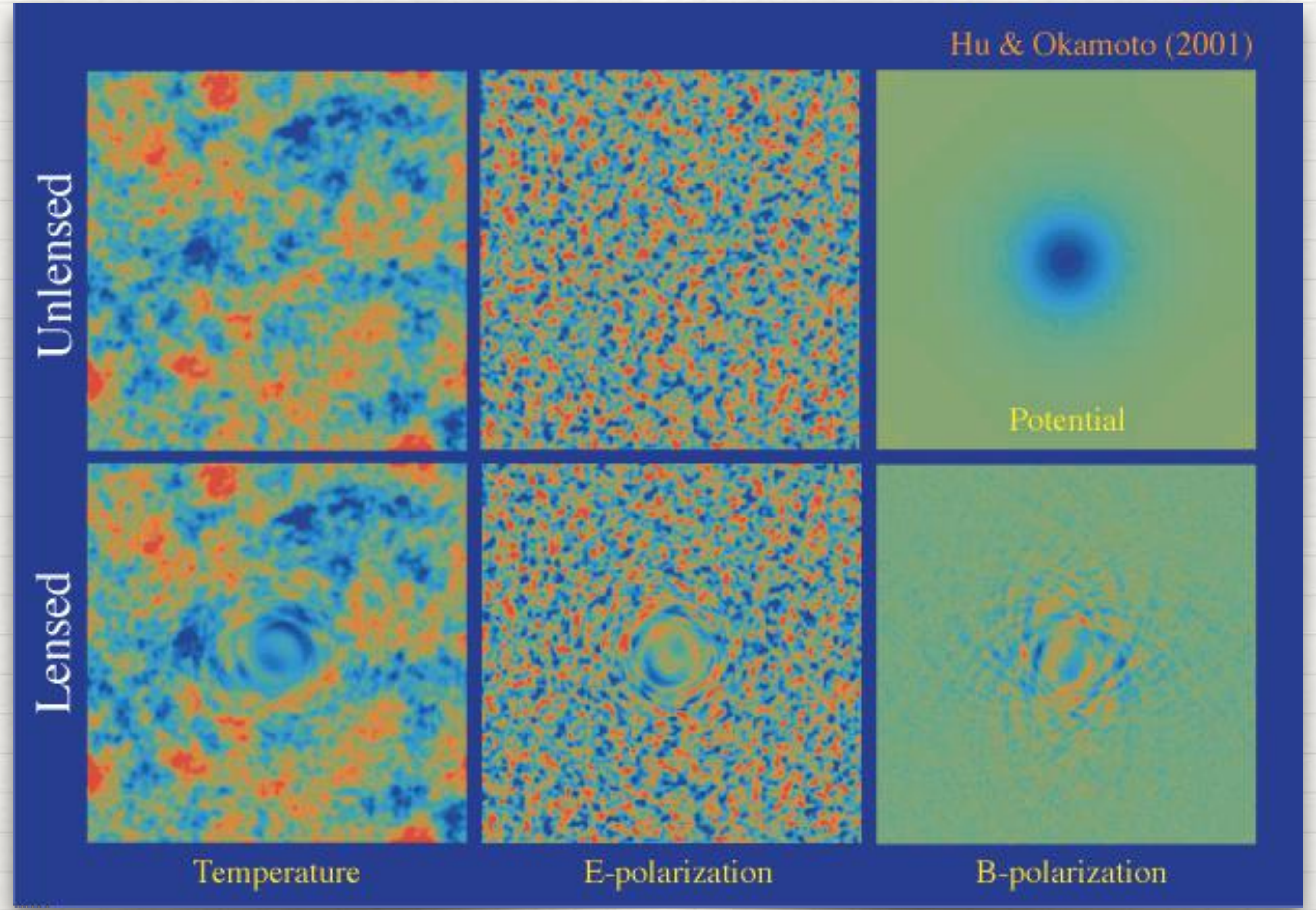
(fig from wikipedia)

CLUSTER CLUSTER LENSING

Zitrin+

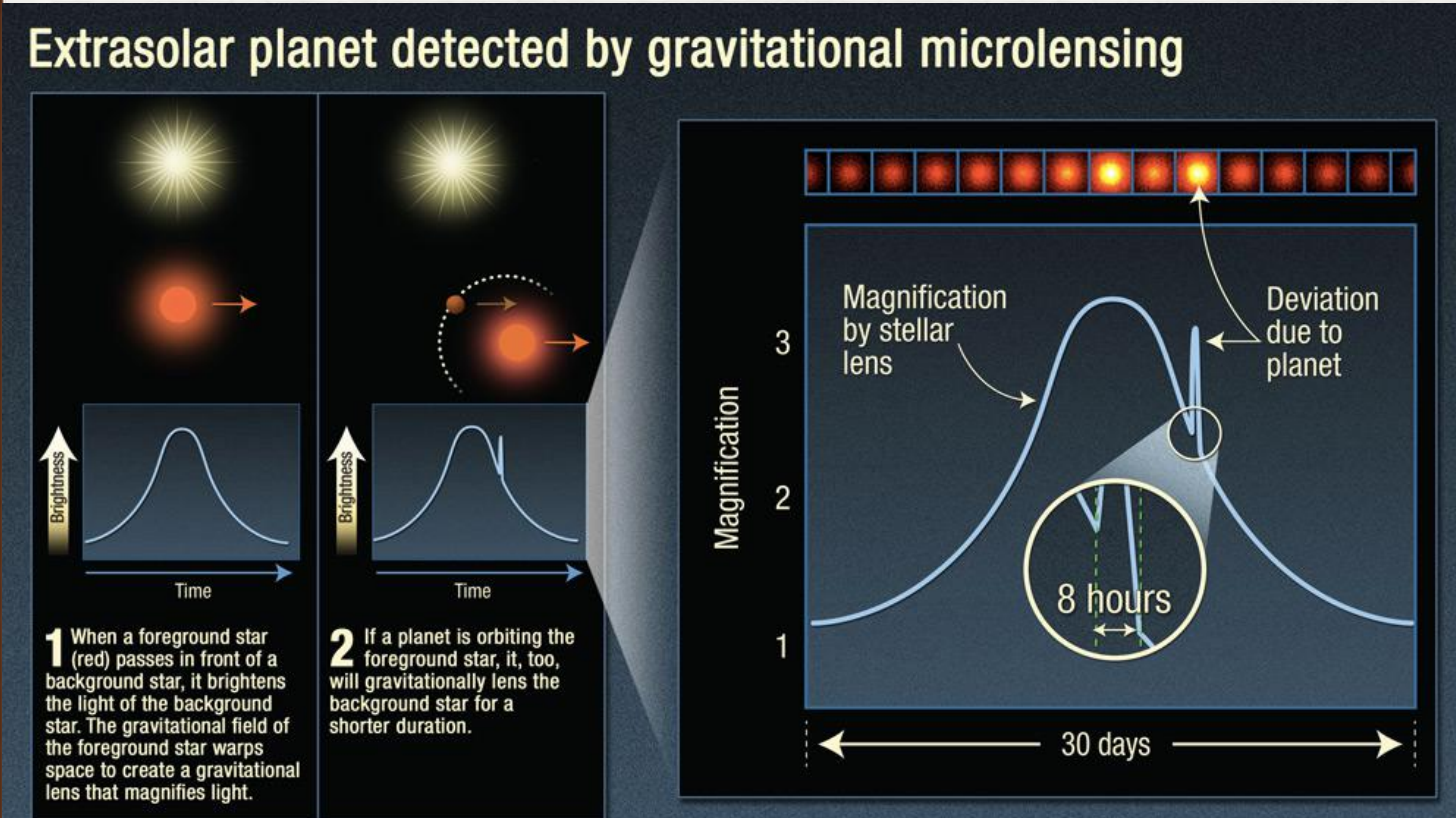


LENSING OF CMB



MICROLENSING

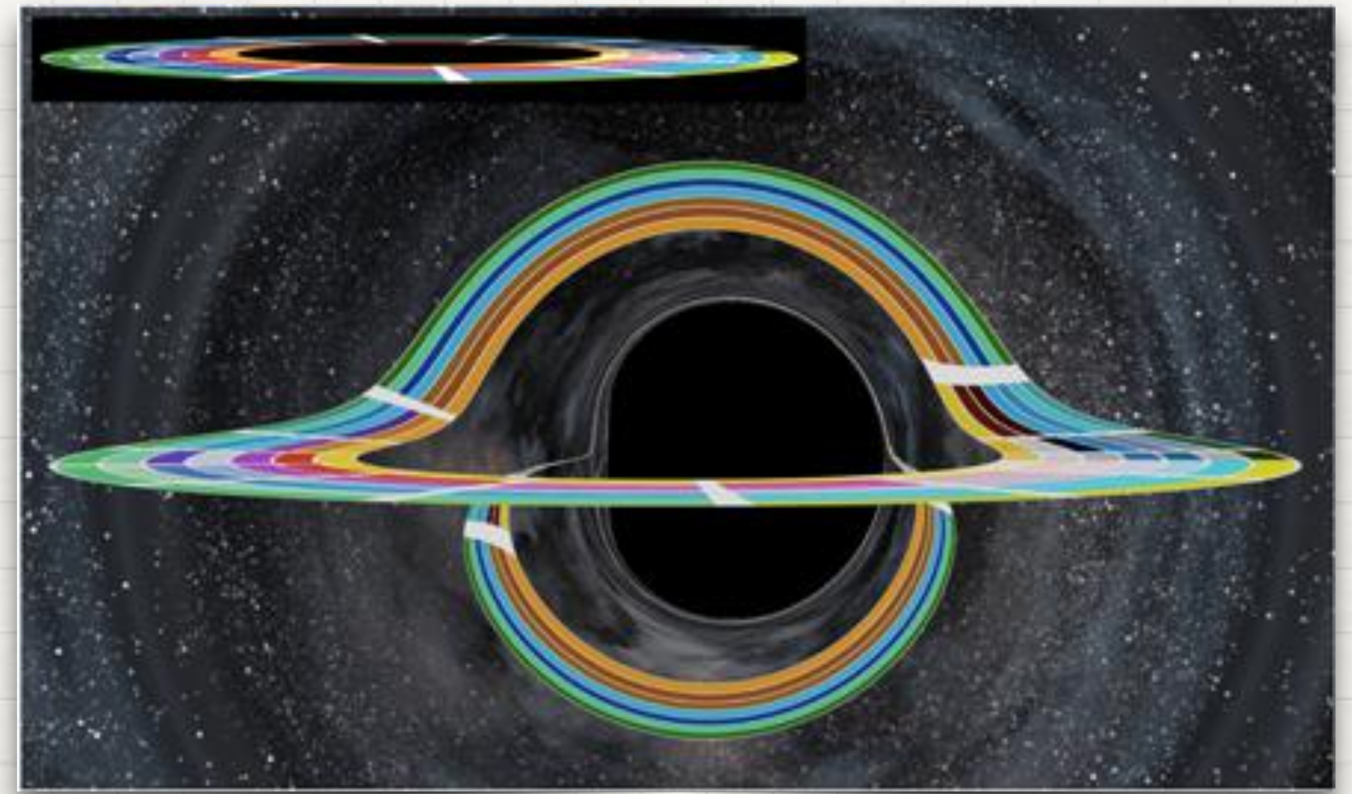
(STAR-STAR / PLANET)



NASA, ESA, and A. Feild

(SPINNING) BLACK HOLE LENSING

SIMULATION, *INTERSTELLAR* MOVIE;

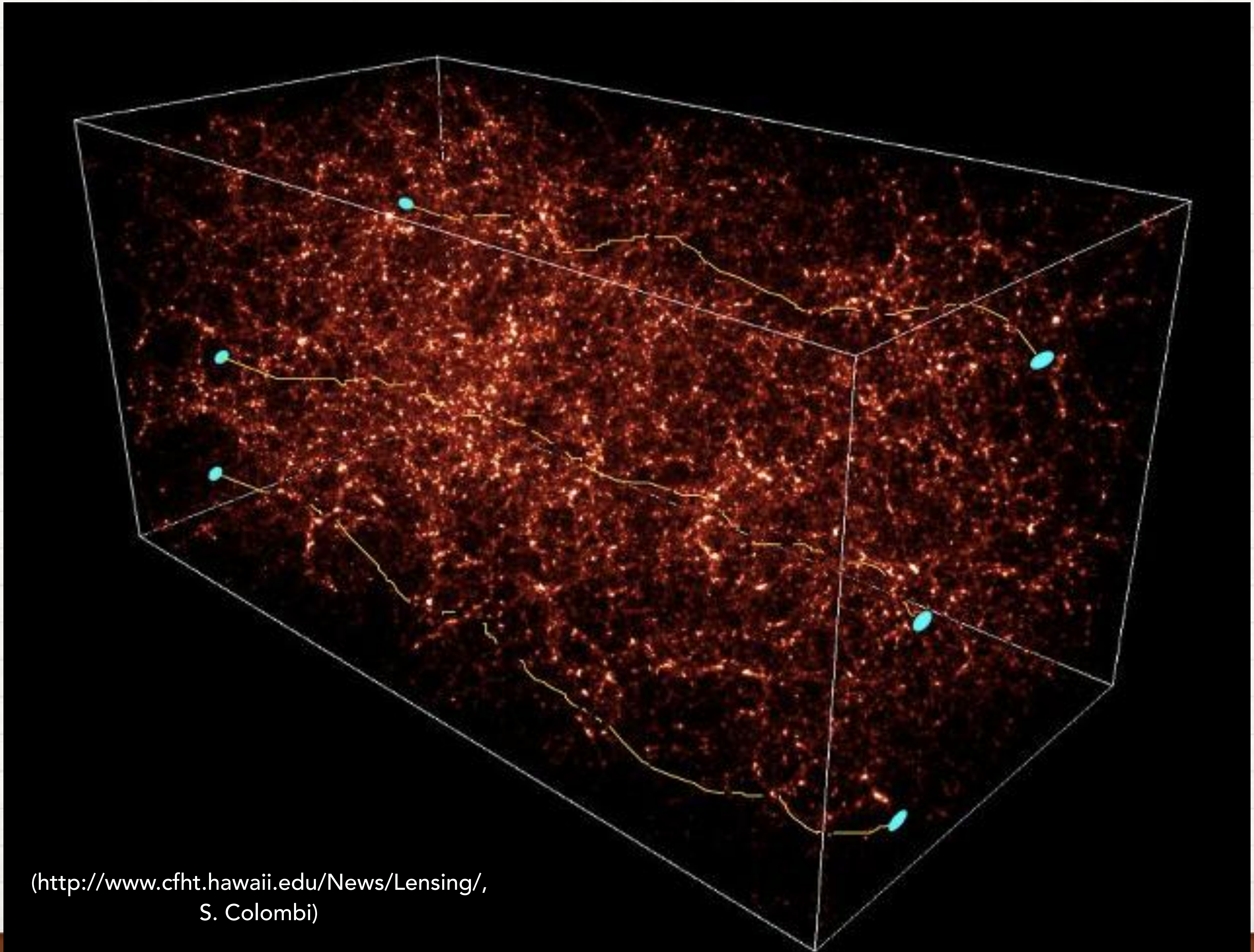


James et al. 2015 (w/ Kip Thorne,
good read: The Science of Interstellar)

BH dubbed Gargantua in movie

fig available in wikipedia

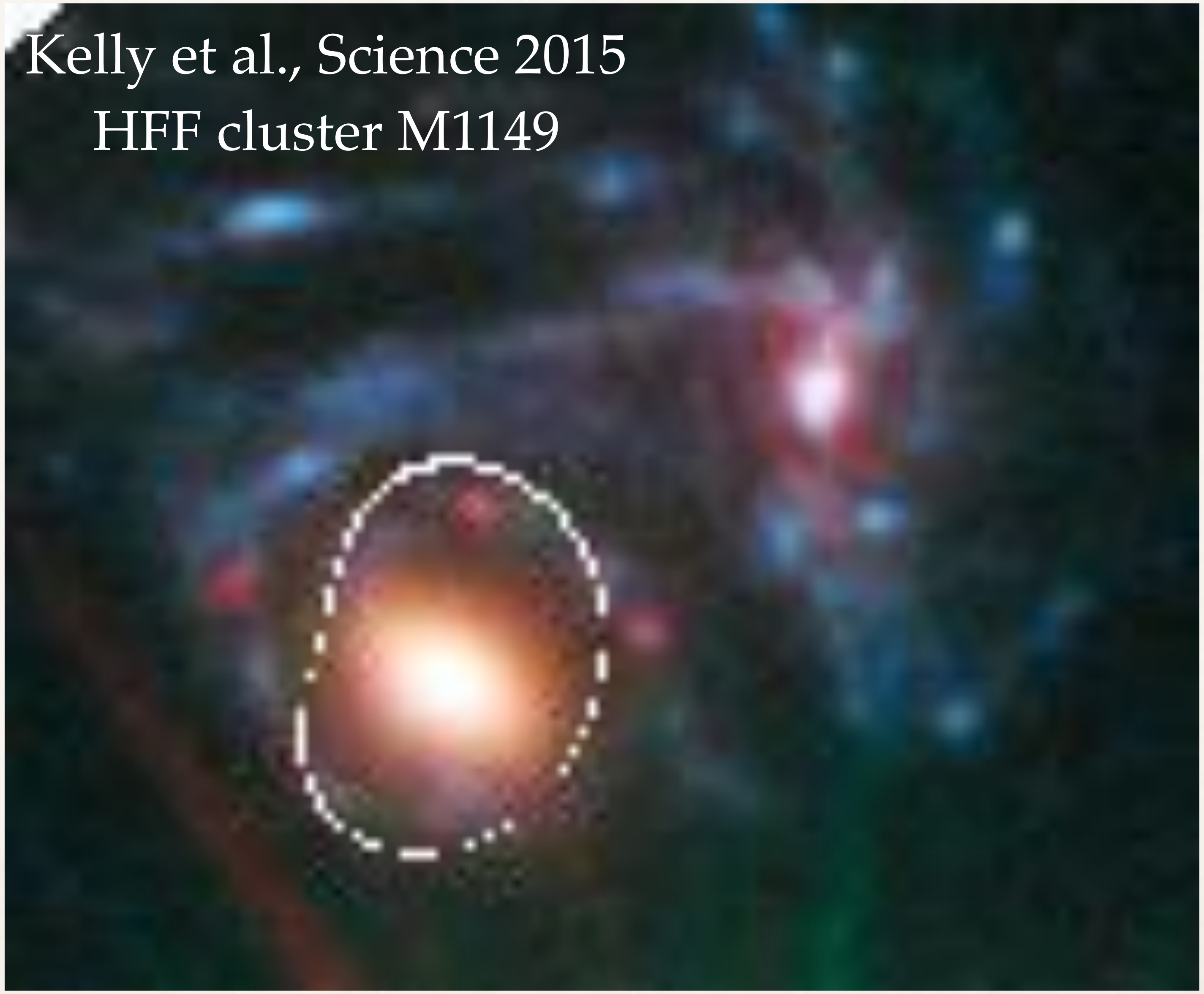
COSMIC SHEAR (WEAK LENSING)



(http://www.cfht.hawaii.edu/News/Lensing/,
S. Colombi)

Lensing of Supernovae (first multiply-imaged SN!)

Exactly 50 years
after prediction



Zitrin+ lensing model

Lensing of Gravitational Waves

(possibly observed already?)

From Broadhurst, Diego and Smoot 2018

The distances published for the LIGO/Virgo events are instead obtained by comparing the observed GW signal strength to the intrinsic strength predicted by General Relativity as a function of m_1, m_2, where the measured strain $h(t)$, is inversely proportional to the luminosity distance d_L allowing an indirect estimate of the redshift, z_{est}, to be inferred:

where $F(t, M_{obs}, \Theta)$ combines the angular sky sensitivity, orbital inclination, spin and polarization of the binary source and its distribution is numerically estimated with a $\simeq 40\%$ dispersion[6,23].

Firstly it is important to appreciate that the redshift of BBH events cannot be derived directly from the inspiral wave frequencies because cosmological stretching of the wave train by $(1+z)$ is exactly compensated by reducing the source frame chirp mass, M_{chirp}, by the same factor[27]. In terms of the observed "chirp mass", M_z, in the detector frame this means:

$$M_z = (1+z)M_{chirp} = (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \quad (1)$$

where m_1, and m_2 are rest frame masses, so: $M_z = (1+z)M_c$. Because gravitation is scale free, GWs from a local binary with masses (m_1, m_2) are indistinguishable by frequency dependence from distant masses $(\frac{m_1}{1+z}, \frac{m_2}{1+z})$. The cosmological time dilation ensures that the waveforms are shifted by precisely the necessary amount to preserve the chirp frequency profile.

minosity distance, $d_{inferred}$ underestimates the real source distance, d_s by the square root of the magnification[23,32]: $d_L = d_s/\sqrt{\mu}$. For example, a lensed source at $z_s = 2.0$ will be assigned a low redshift of $z_{inferred} = 0.15$ when magnified by a factor of $\simeq 200$, and hence an intrinsic chirp mass of $10M_\odot$ is overestimated by a factor of 3.0/1.15, becoming $M_{chirp} \simeq 30M_\odot$, similar to the

*Our lensing kernel predicts a slightly larger value of 7×10^{-5} for $\mu = 10$ at $z = 1$

Credit NSF
(from endgadget)

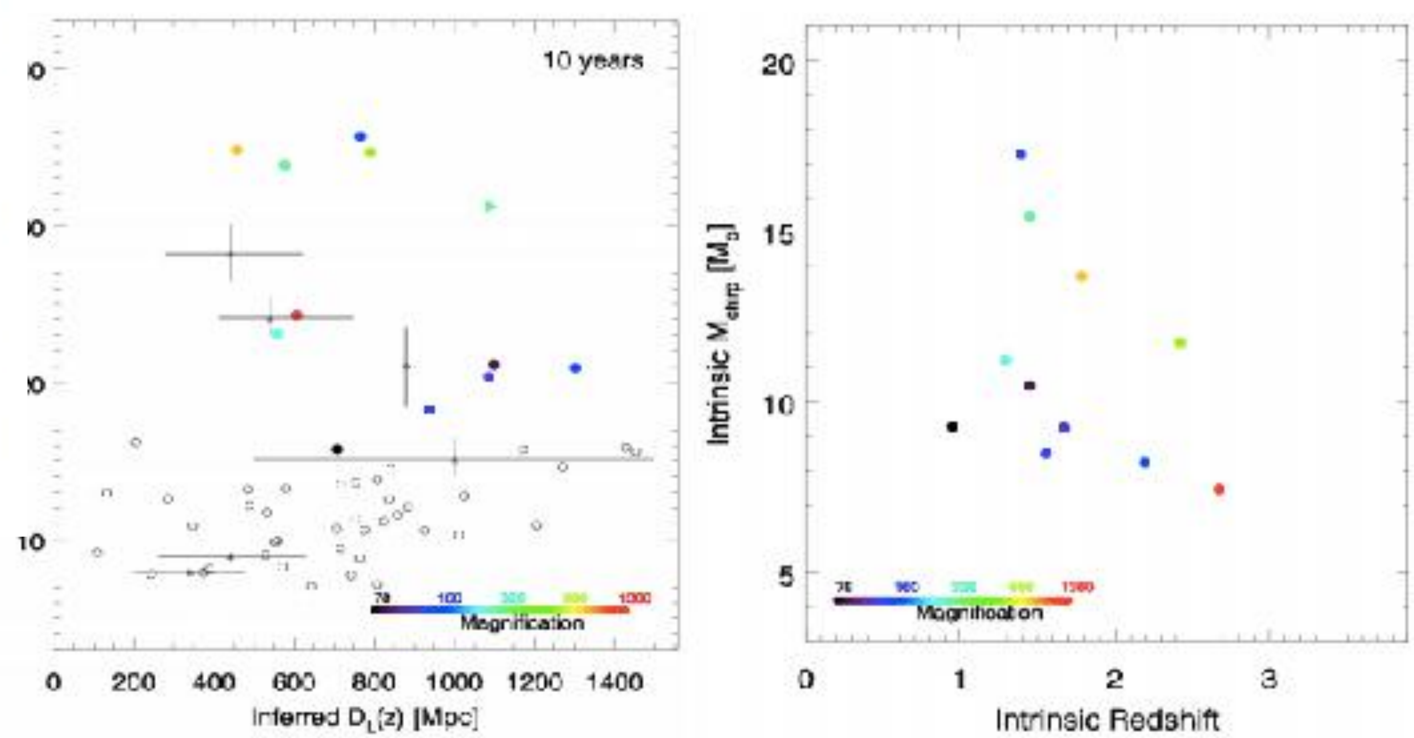
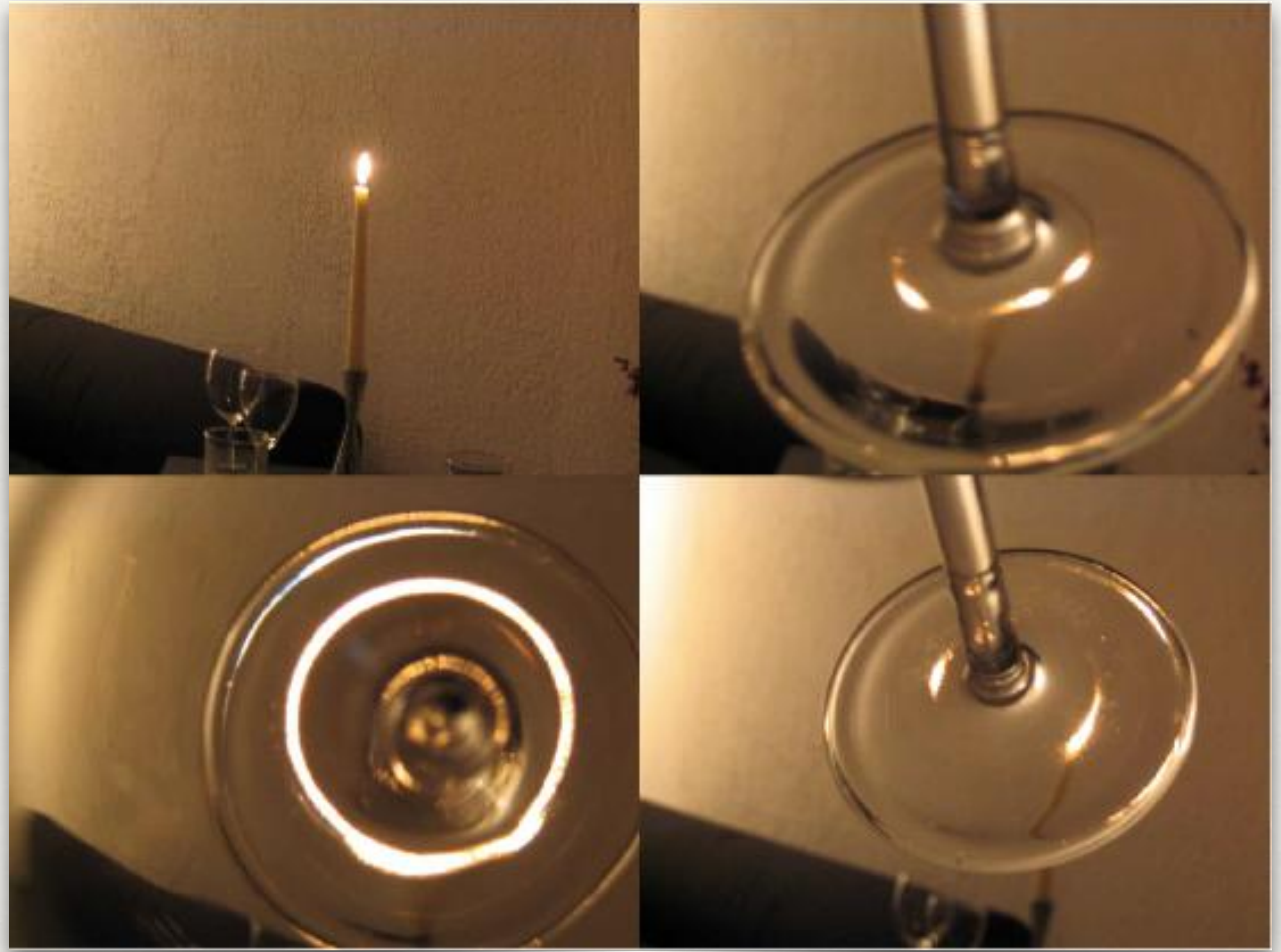


Figure 1: **The observed plane of distance and chirp mass:** The six BBH data points with in-

LENSING OF A CANDLE LIGHT BE A WINE GLASS



Credit: T. Treu / P. Marshall

OK - NOW THAT WE HAVE SEEN LENSING, LET'S REVIEW THE MAIN THEORY

THE LENS EQUATION

THIN LENS APPROXIMATION

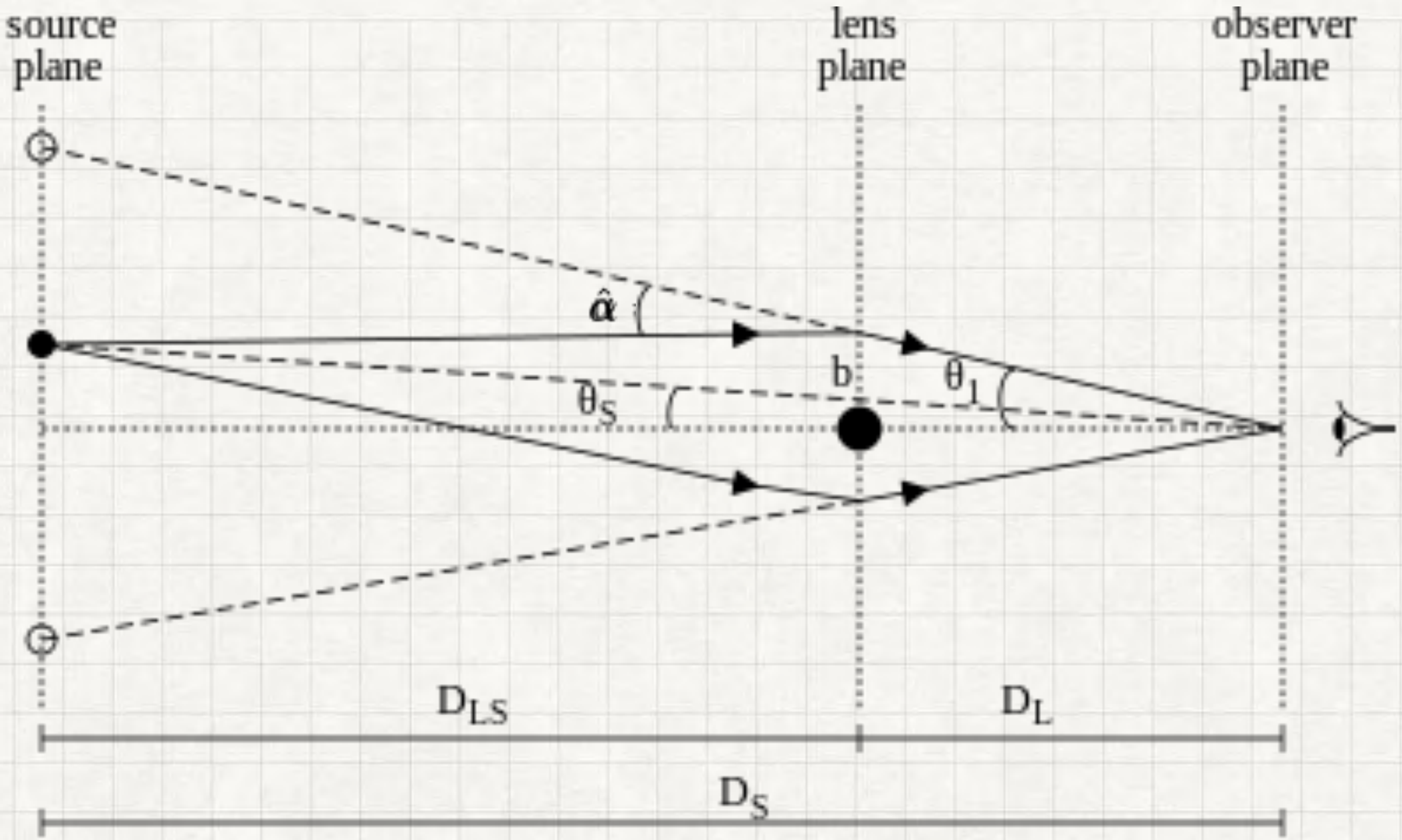


figure from wikipedia

THE LENS EQUATION:

$$\beta = \theta - \frac{D_{LS}}{D_{OS}} \hat{\alpha} \, .$$

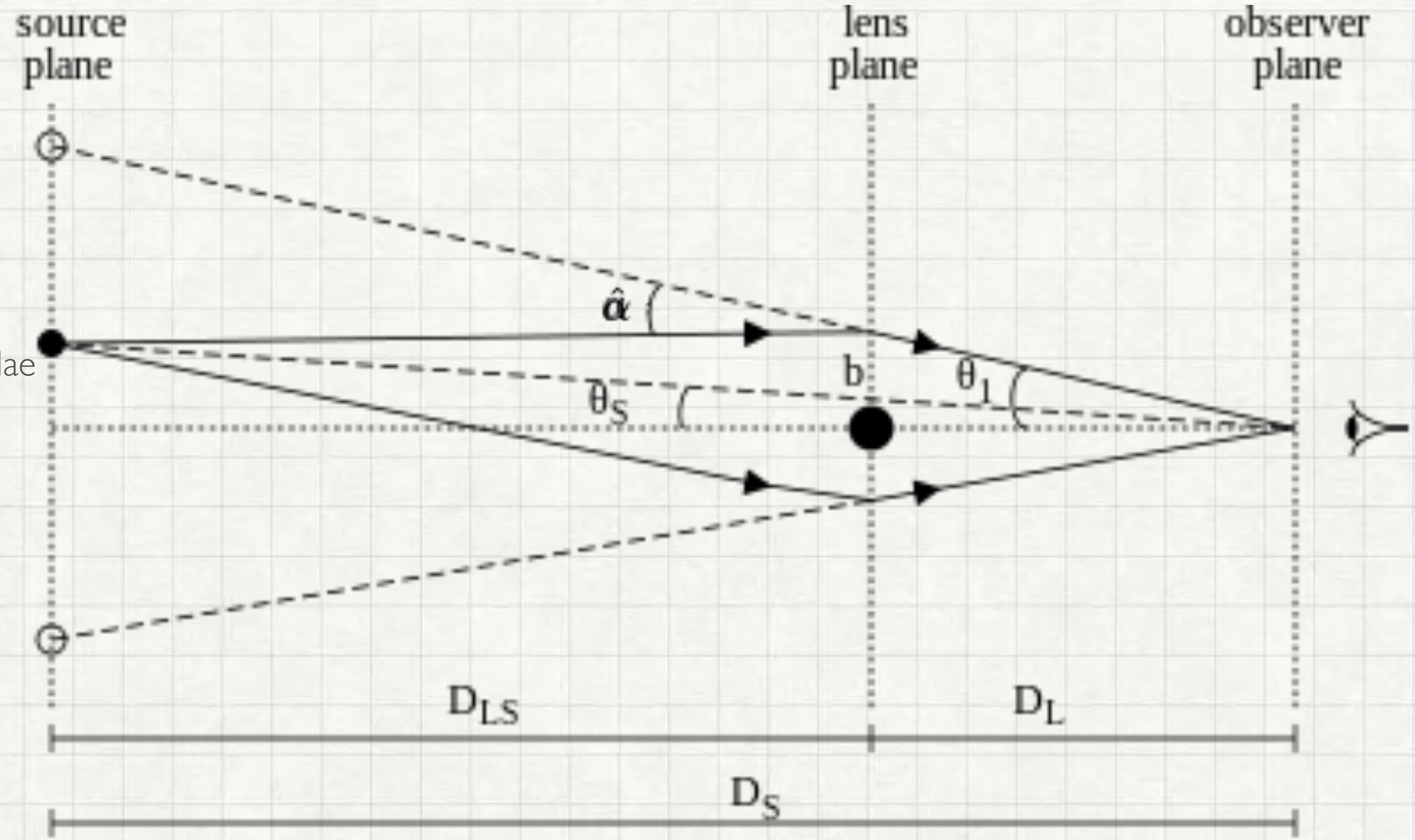
$\hat{\alpha}$: is called the *deflection angle.*

$\frac{D_{LS}}{D_{OS}} \hat{\alpha}$: is the *reduced deflection angle.*

THE DEFLECTION ANGLE

THIN LENS APPROXIMATION

figure and some formulae to follow from wikipedia



THE LENS EQUATION:

$$\beta = \theta - \frac{D_{LS}}{D_{OS}}\hat{\alpha}\,.$$

THE DEFLECTION ANGLE:

$$\hat{\alpha} = \frac{4GM}{c^2 b}$$

(GENERAL RELATIVITY)

THE DEFLECTION ANGLE

THIN LENS APPROXIMATION

$$\hat{\alpha} = \frac{4GM}{c^2 b}$$

is for a point mass. For an ensemble of lenses the deflection angle can be usually written as a linear sum of point masses.

If we have (as is often the case) a continuous mass distribution, it can be written as:

$$\vec{\hat{\alpha}}(\vec{\xi}) = \frac{4G}{c^2} \int \frac{(\vec{\xi} - \vec{\xi}')\Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2} d^2\xi'$$

where $\vec{\xi}'$ is a vector on the sky, and $\Sigma(\vec{\xi}')$ the surface mass density.

It is often comfortable to write the reduced deflection angle $\vec{\alpha}(\vec{\theta})$ as:

$$\vec{\alpha}(\vec{\theta}) = \frac{1}{\pi} \int d^2\theta' \frac{(\vec{\theta} - \vec{\theta}')\kappa(\vec{\theta}')}{|\vec{\theta} - \vec{\theta}'|^2}$$

where $\vec{\theta}' = \vec{\xi}' D_{LS}$ and $\kappa(\vec{\theta}')$ is the *convergence.*

THE CONVERGENCE AND POTENTIAL

$\kappa(\vec{\theta}')$, the convergence, is simply the surface mass density in units of the *critical density for lensing.* Only if a projected mass distribution exceeds the critical density for lensing (kappa>1) will multiple images appear (strong lensing).

$$\kappa(\vec{\theta}) = \frac{\Sigma(D_d\vec{\theta})}{\Sigma_{cr}}$$

Note: D_d (D_{ds}) is other notation for D_L (D_{LS})

This critical density is defined as: $$\Sigma_{cr} = \frac{c^2 D_s}{4\pi G D_{ds} D_d}$$

We can also define a lensing *potential:* $$\psi(\vec{\theta}) = \frac{1}{\pi}\int d^2\theta' \kappa(\vec{\theta}') \ln|\vec{\theta} - \vec{\theta}'|$$

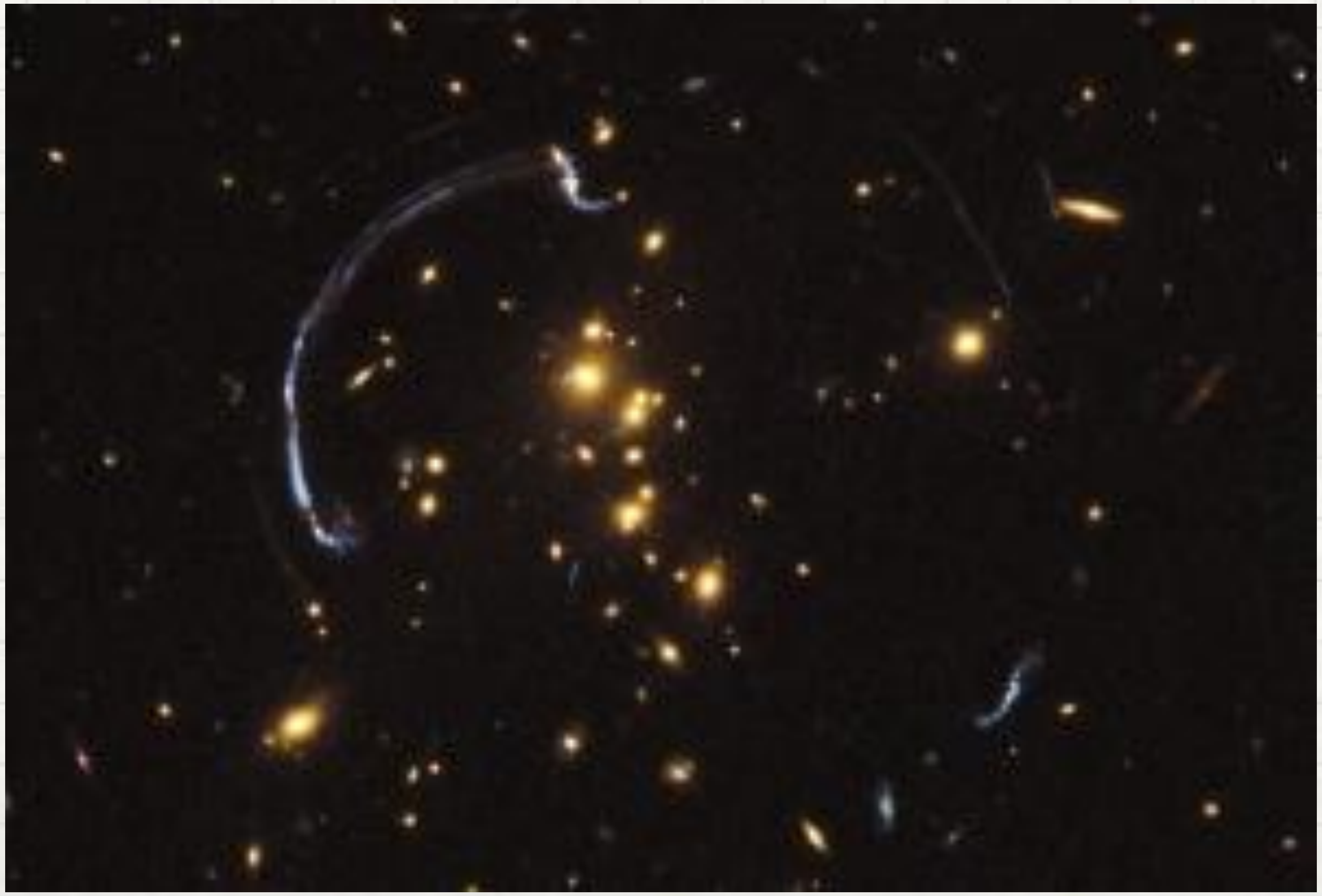
Such that the gradient of the potential is the deflection angle: $$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi(\vec{\theta})$$

And the divergence of the deflection angle is the mass distribution: $$\kappa(\vec{\theta}) = \frac{1}{2}\nabla^2\psi(\vec{\theta})$$

(Possion's eq.)

*CONSEQUENCE

Let’s understand what we have just written (Strong Lensing): suppose I see multiple images of the same source. Using the **reduced deflection angle** and the **lens equation (a set of linear equations, source position same for all images)**, we can now constrain the projected surface mass density!



Credit: NASA, ESA, J. Rigby (NASA GSFC), K. Sharon (KICP, U Chicago), and M. Gladders and E. Wuyts (U Chicago)

EINSTEIN RING AND EINSTEIN RADIUS

When a source is (nearly) exactly behind a circular mass,
the source will be lensed into (nearly) a ring, known as the *Einstein ring.*

ALMA obs.
from wikipedia

The radius of the ring is called the *Einstein radius*,
and it gives a direct measurement of lensing mass:

$$\theta_{\mathrm{E}} = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}}$$

Even if the lens is not circularly symmetric, one can still define an effective Einstein radius as an indicator for the size of the lens

MAGNIFICATION AND DISTORTION

"One of the main features of gravitational lensing is the distortion which it introduces into the shape of the sources…The distortion arises because light bundles are deflected differentially. Ideally the shape of the images can be determined by solving the lens equation for all the points within the extended source. *In particular, if the source is much smaller than the angular size on which the physical properties of the lens change, the relation between source and image positions can locally be linearized*. In other words, the distortion of images can be described by the Jacobian matrix" (**M. Meneghetti's review**).

$$A_{ij} = \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial \alpha_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial^2 \psi}{\partial \theta_i \partial \theta_j} \qquad A = (1-\kappa)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \gamma \begin{bmatrix} \cos 2\phi & \sin 2\phi \\ \sin 2\phi & -\cos 2\phi \end{bmatrix}$$

γ is *shear*, ϕ an angle between alpha and say the x axis

The magnification μ is 1 over the determinant of A.

$$\mu = \frac{1}{\det A} = \frac{1}{[(1-\kappa)^2 - \gamma^2]}$$

This allows us to define the pseudo-vector $\vec{\gamma} = (\gamma_1, \gamma_2)$ on the lens plane, whose components are

$$\gamma_1(\vec{x}) = \frac{1}{2}(\Psi_{11} - \Psi_{22}) \qquad (2.38)$$

$$\gamma_2(\vec{x}) = \Psi_{12} = \Psi_{21} \; , \qquad (2.39)$$

This is called the *shear*.

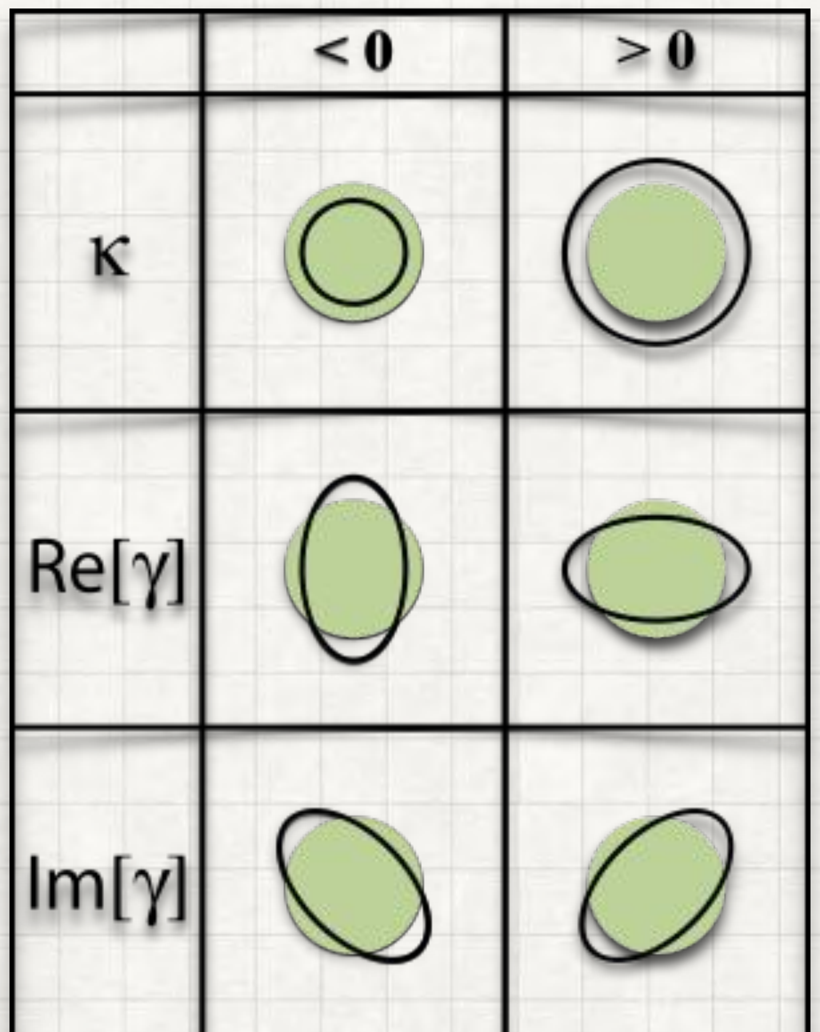
from Meneghetti's

MAGNIFICATION AND DISTORTION

Let's see what this means:

We can define a complex shear:

$$\gamma = |\gamma| \, e^{2i\phi}$$



from wikipedia

Notice both increase in size and change of shape , **turning a circle of radius r to an ellipse** with SMJA and SMNA of r/(1-kappa-gamma) and r/(1-kappa+gamma) , respectively. These factors multiplying r also describe the tangential and radial distortions.

We can define a reduced shear, which, in the weak lensing limit where kappa <<1, relates to the average image ellipticities:

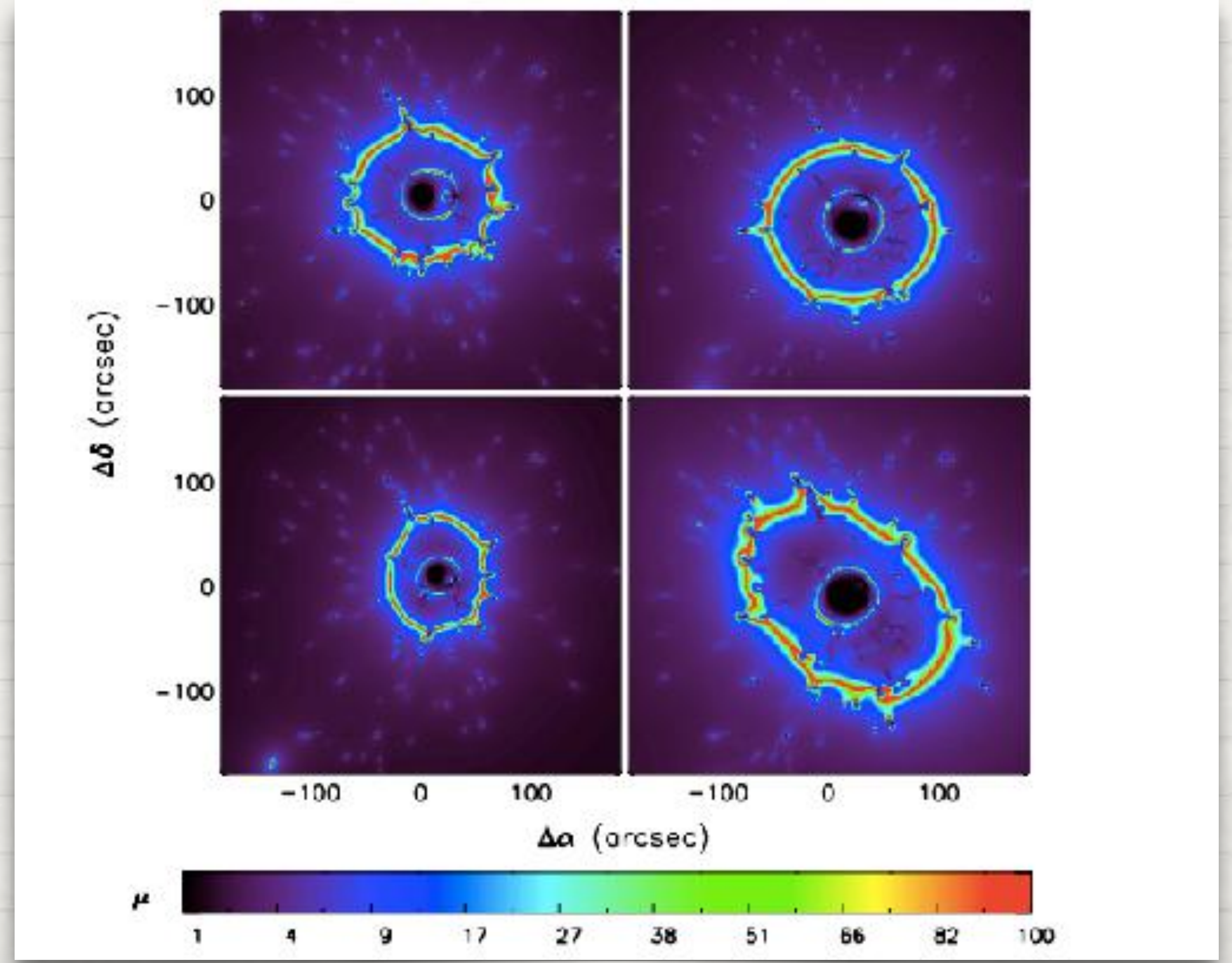
$$g \equiv \frac{\gamma}{1-\kappa}$$ ~ <e>

Because of random intrinsic ellipticities, this can only be measured statistically by averaging over many galaxies.

The shear field can then be inverted into a surface mass distribution (up to some degeneracies)

CRITICAL CURVES/LINES

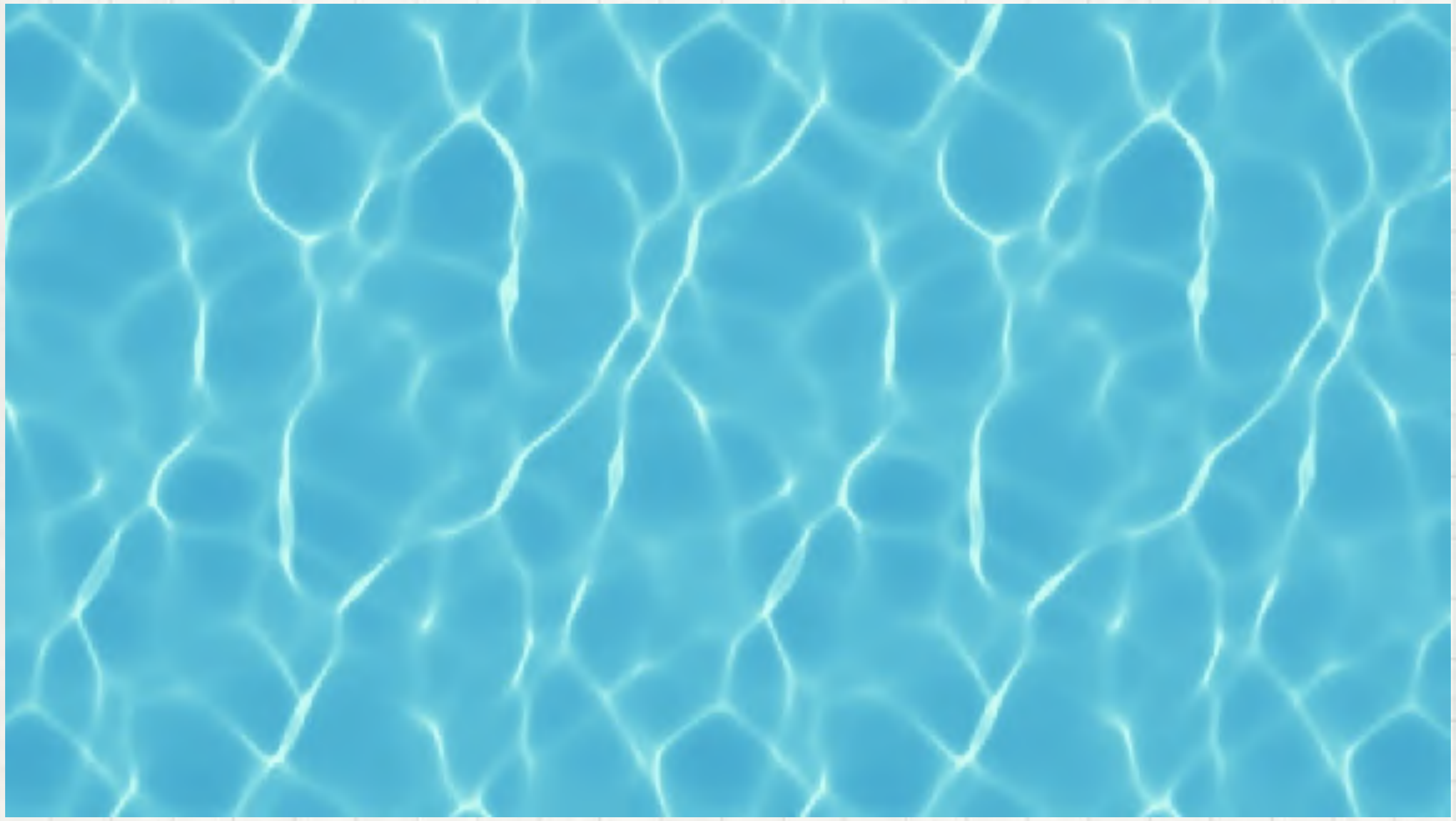
When the determinant of the Jacobian is zero, the magnification diverges. This forms a close curve called critical curves or critical line. In fact, this happens when each of the tangential and radial magnification expressions zeros out, yielding a tangential and radial critical curves. The critical curves separates regions where the Jacobian determinant has opposite signs (see also Scheinder, Ehler, Falco's book).



Ammons+ 2018

CAUSTICS

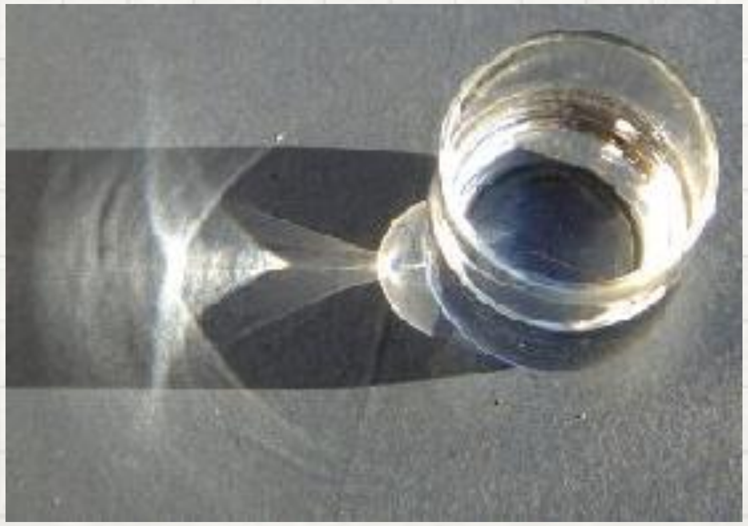
Critical curves describe the det(A)=0 in the image plane. In the source plane, these are called *caustics*. These for example can be achieved by projecting the critical curves to the source plane, via the lens equation. Why caustics?



(these caustics are essentially in the observer's plane)

Credit: Shutterstock/De Reshavskyi

Credit: lumenlearning



Credit: Wikipedia / Heiner Otterstedt

SOME LENSING CONFIGURATIONS

Let's see what happens to images when crossing (*fold, cusp*) caustics. Before that let's notice that the magnification - even if abs(mu)>1 so that the source is magnified indeed, can have mathematically either a position of negative signs, marking the parity of the images. The parity flips when crossing a critical curve.

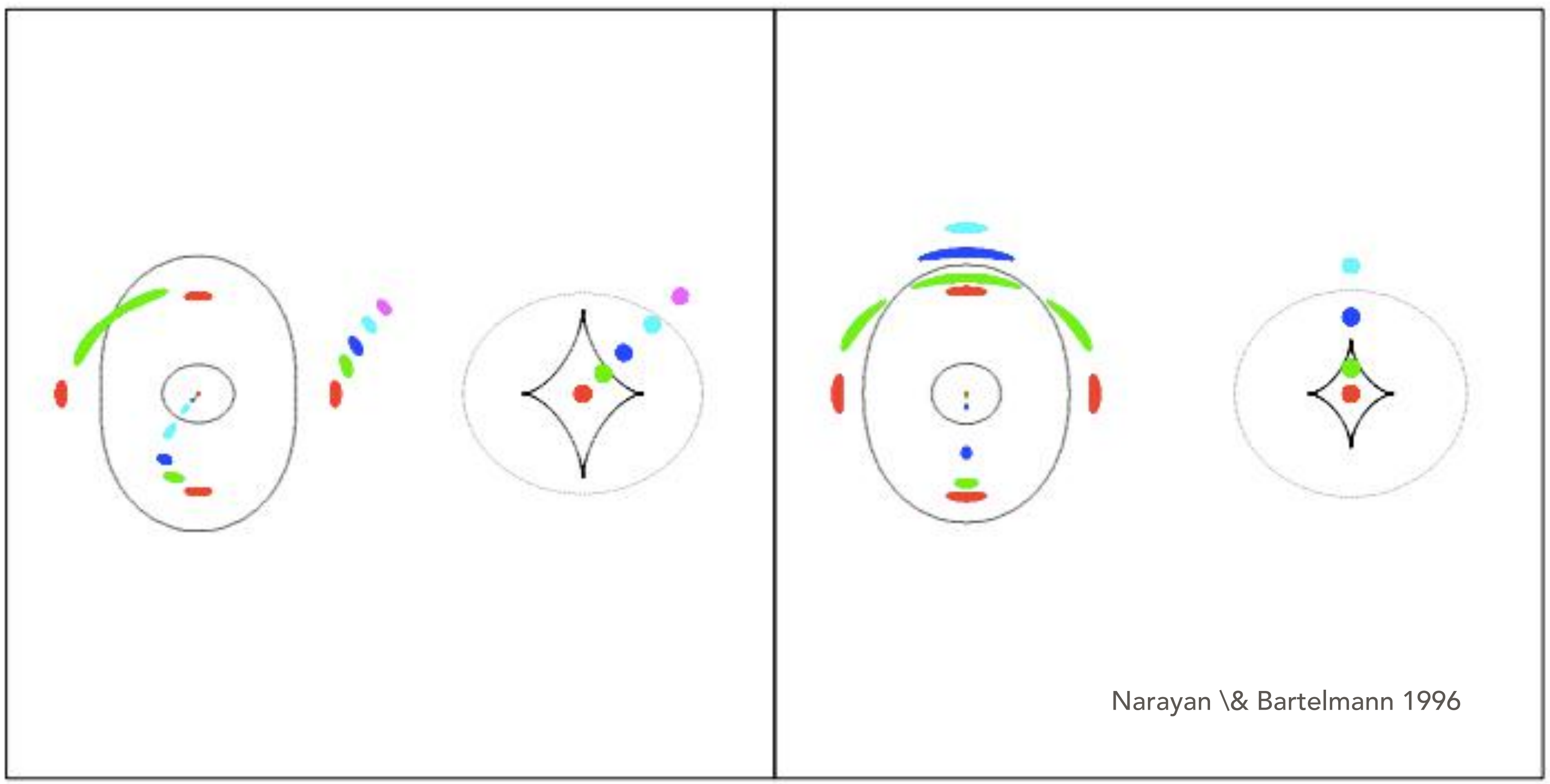


FIG. 19.—Compact source moving away from the center of an elliptical lens. Left panel: source crossing a fold caustic; right panel: source crossing a cusp caustic. Within each panel, the diagram on the left shows critical lines and image positions and the diagram on the right shows caustics and source positions.

FERMAT SURFACE AND TIME DELAY

The arrival time of a light bundle from the source to the observer is increased by the presence of a mass (lens). The increase is a sum of two contributions: an extra geometrical path the light has to pass, and a gravitational delay (can be thought of perhaps as light having to go also down and up the potential well of the lens).

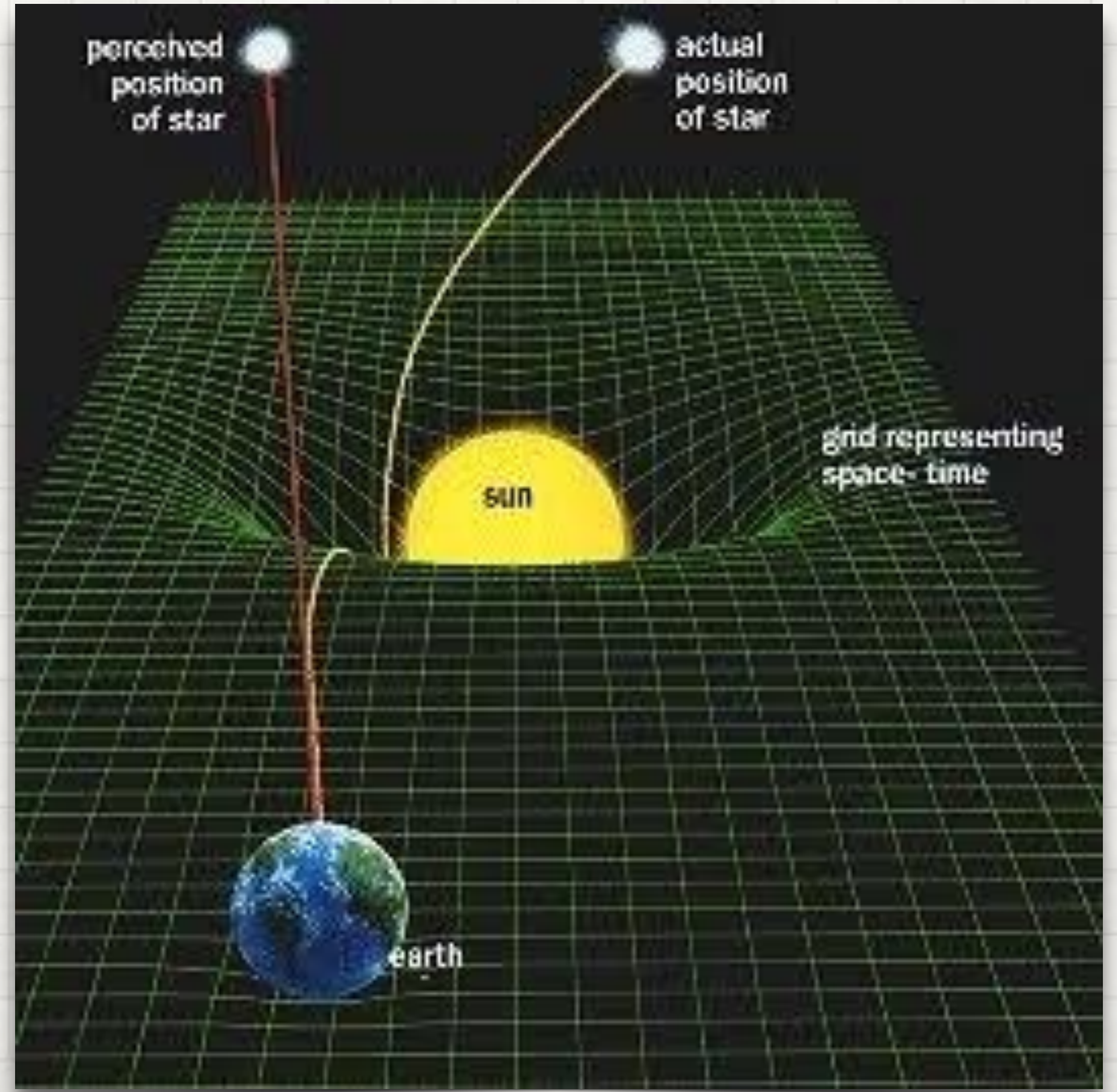


image from Quora

FERMAT SURFACE AND TIME DELAY

Fermat's principle: the principle that the path taken between two points by a ray of light is the path that can be traversed in the least time.

It turns out that we can define a surface describing the arrival time (Fermat's surface). Multiple images form at the extreme of this surface, which is essentially the lens equation.

$$(\vec{\theta} - \vec{\beta}) - \vec{\nabla}_\theta \psi = 0 \,. \tag{61}$$

This equation can be written as a gradient,

$$\vec{\nabla}_\theta \left[\frac{1}{2} (\vec{\theta} - \vec{\beta})^2 - \psi \right] = 0 \,. \tag{62}$$

The physical meaning of the term in square brackets becomes more obvious by considering the time-delay function,

$$\begin{aligned} t(\vec{\theta}) &= \frac{(1 + z_d)}{c} \frac{D_d D_s}{D_{ds}} \left[\frac{1}{2} (\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta}) \right] \\ &= t_{geom} + t_{grav} \,. \end{aligned} \tag{63}$$

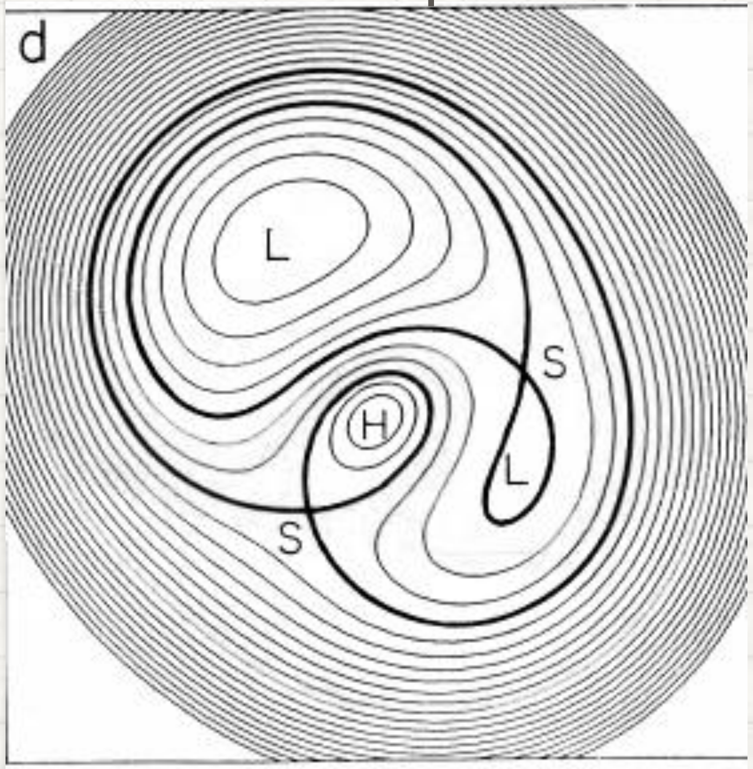
Narayan \& Bartelmann 1996

FERMAT SURFACE AND TIME DELAY

Fermat's principle: the principle that the path taken between two points by a ray of light is the path that can be traversed in the least time.

It turns out that we can define a surface describing the arrival time (Fermat's surface). Multiple images form at the extreme of this surface, which is essentially the lens equation.

example:



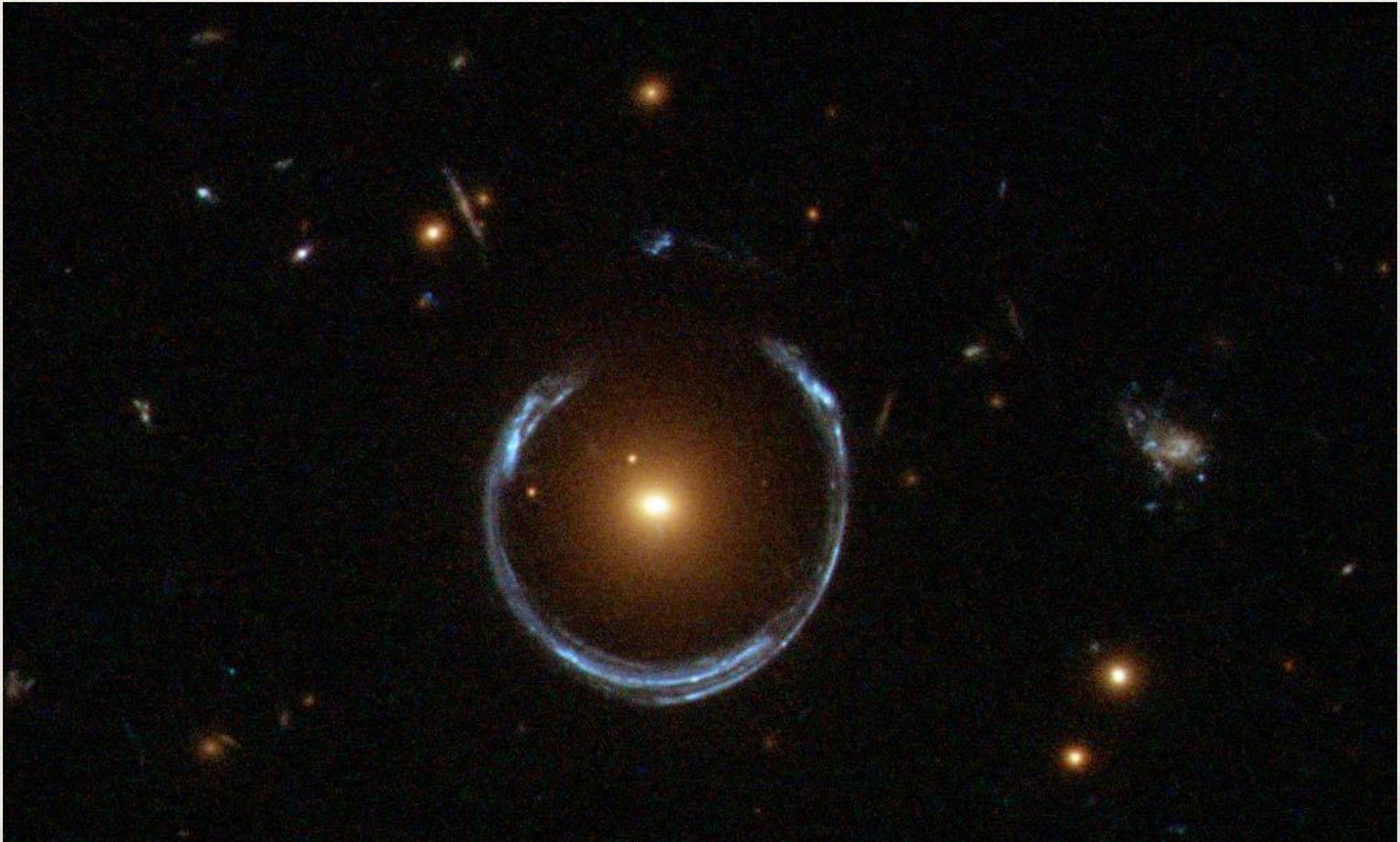
Blandford \& Narayan 1986

FEW OTHER ANECDOTES

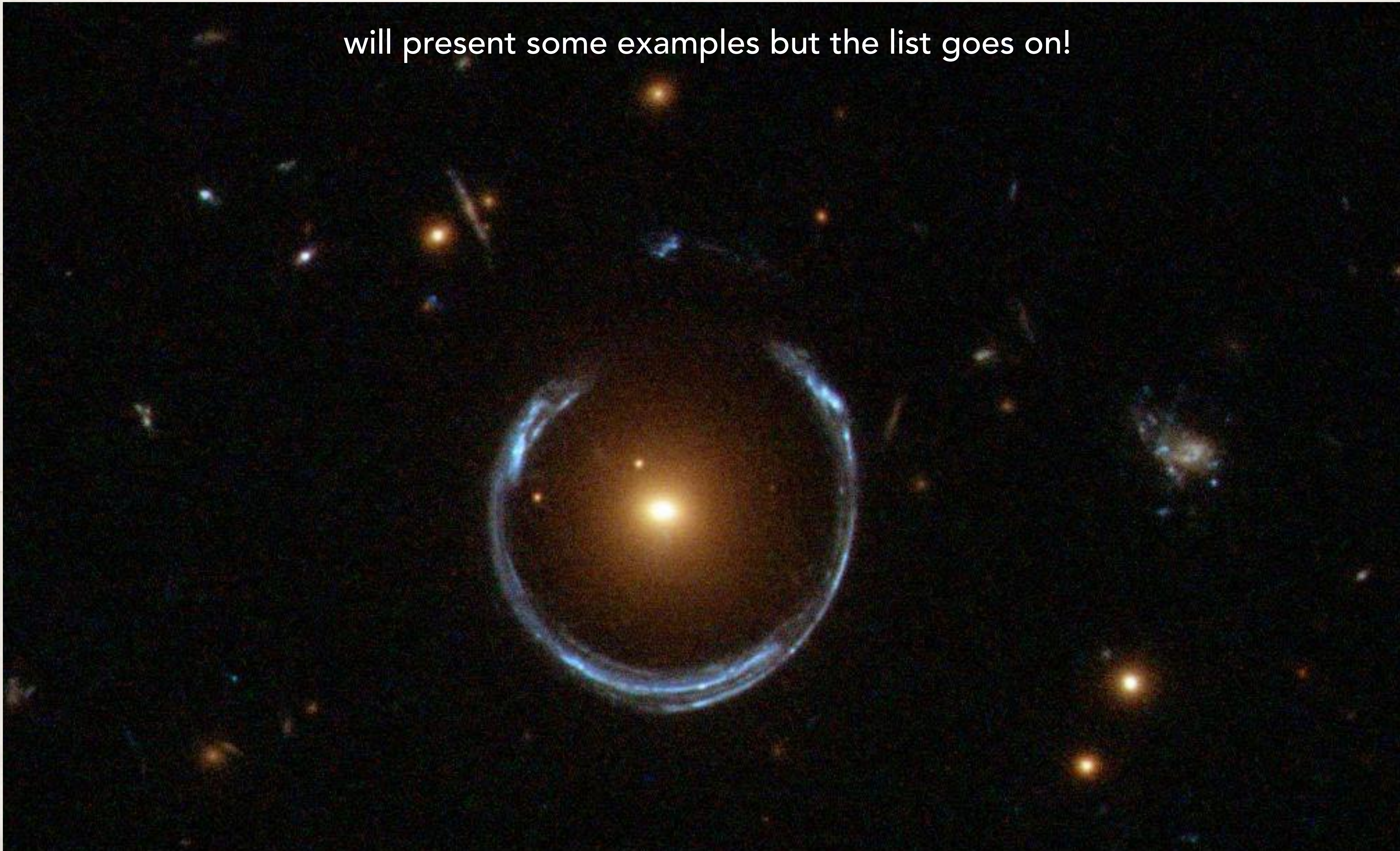
WITHOUT GETTING INTO DETAILS

- Lensing preserves surface brightness! makes objects larger and brighter, but increases both size and flux in same magnification factor mu.
- The distortion caused by gravitational lensing cannot have a curl component because of its origin in a scalar potential (only E-modes, no B-modes).
- Mass-sheet degeneracy. Lensing has some inherent degeneracies. This is one famous one - especially relevant for weak lensing.
- Lens modeling: parametric versus free-form
- The higher the magnification in the image plane, the smaller is the source plane area with that magnification, by that factor.

OK. So now we know what lensing is...



Now, (briefly) what do we do with it?



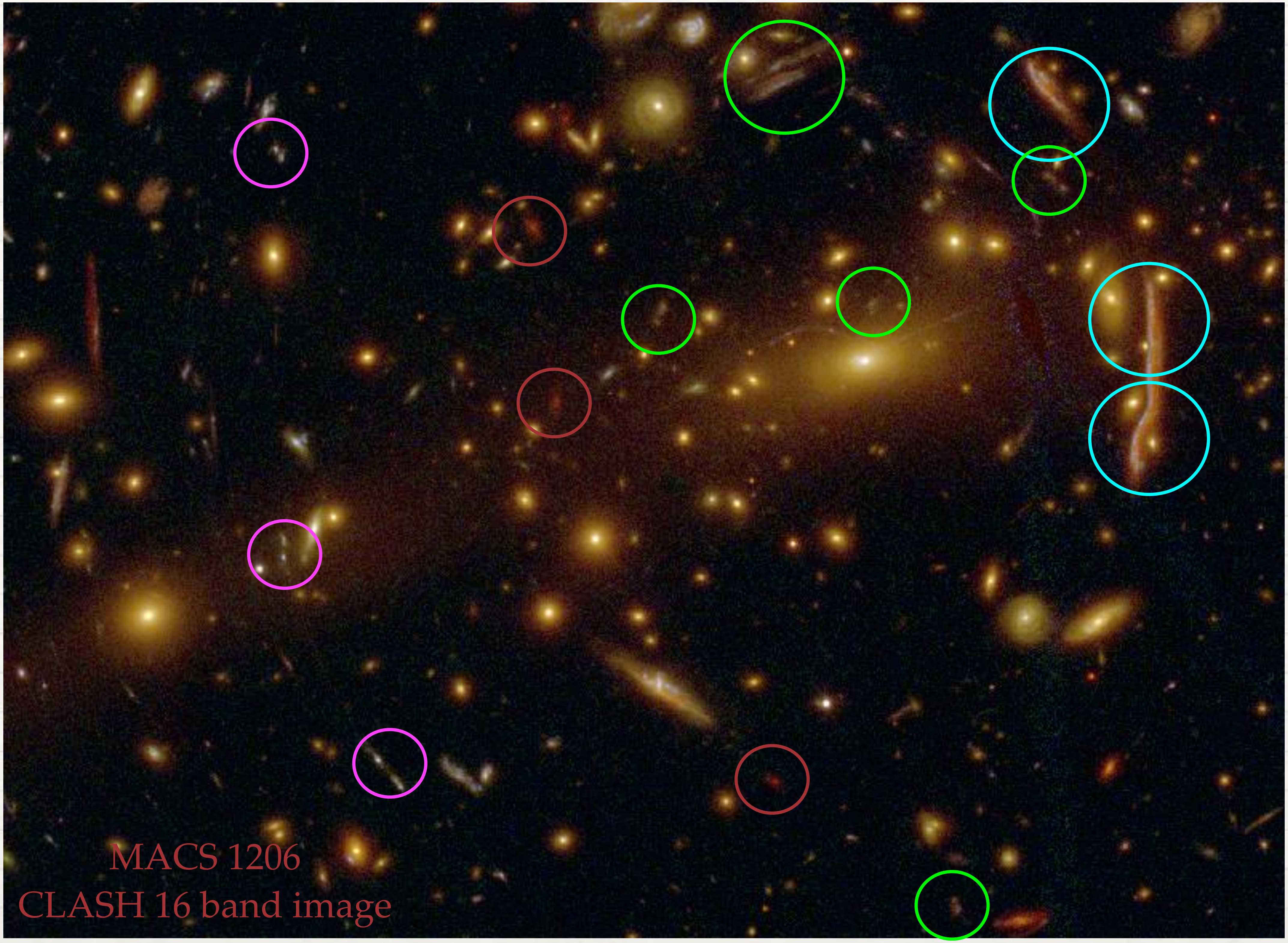
The science of lensing:

MAPPING DARK MATTER

- Lensing tells us about the underlying projected matter distribution
- Matter distribution is dominated by Dark Matter
- We don't know what DM is, hence
- Lensing provides a unique way to learn about and map(!) the otherwise invisible DM

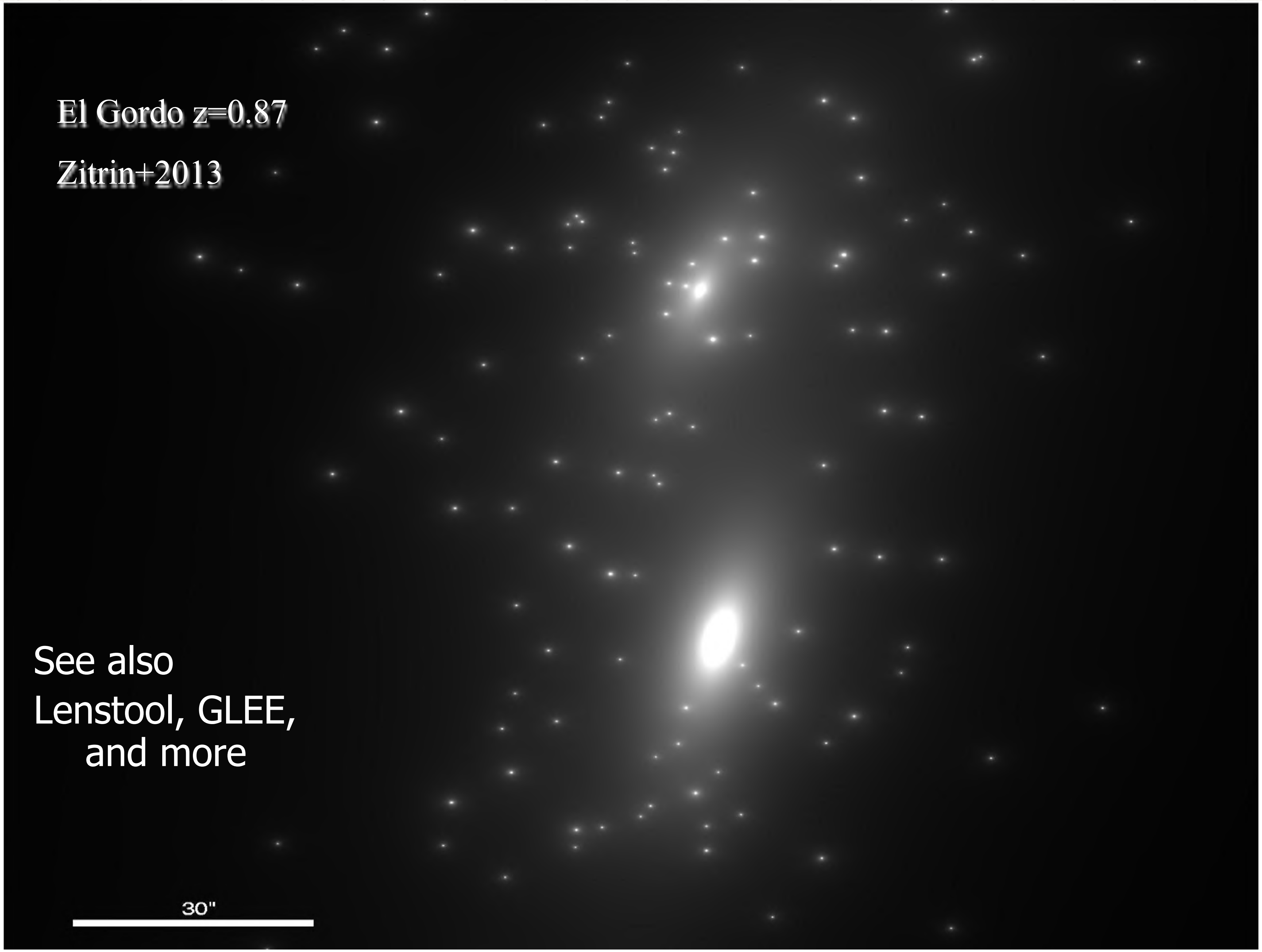
THE SCIENCE OF LENSING

MASS MAPPING: STRONG LENSING



THE SCIENCE OF LENSING

MASS MAPPING: STRONG LENSING



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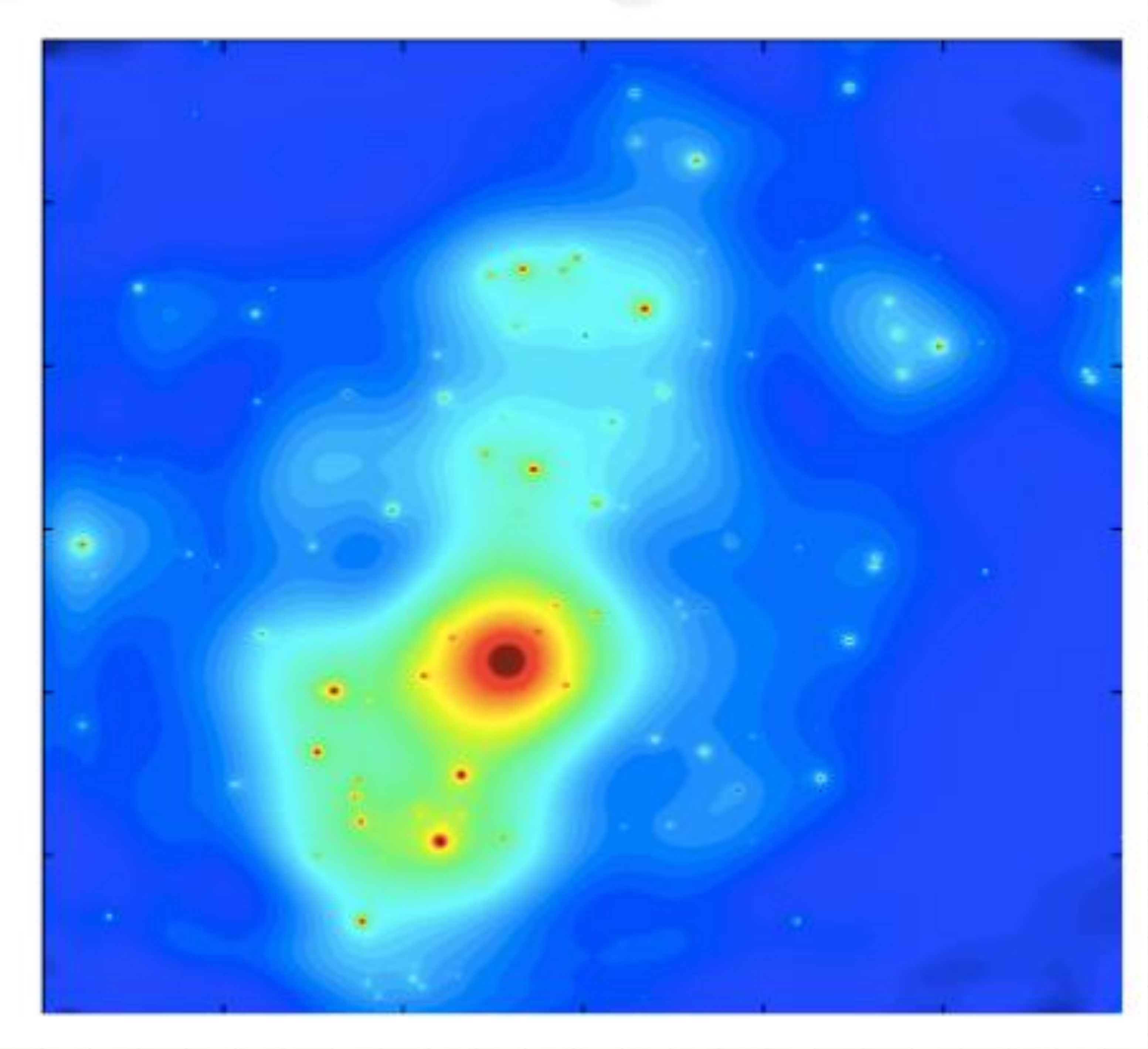
MASS MAPPING: STRONG LENSING



THE SCIENCE OF LENSING

MASS MAPPING: STRONG LENSING

How to model a cluster (will see in Lecture III)?

(Goal: mass map, DM, magnification, slope etc.)

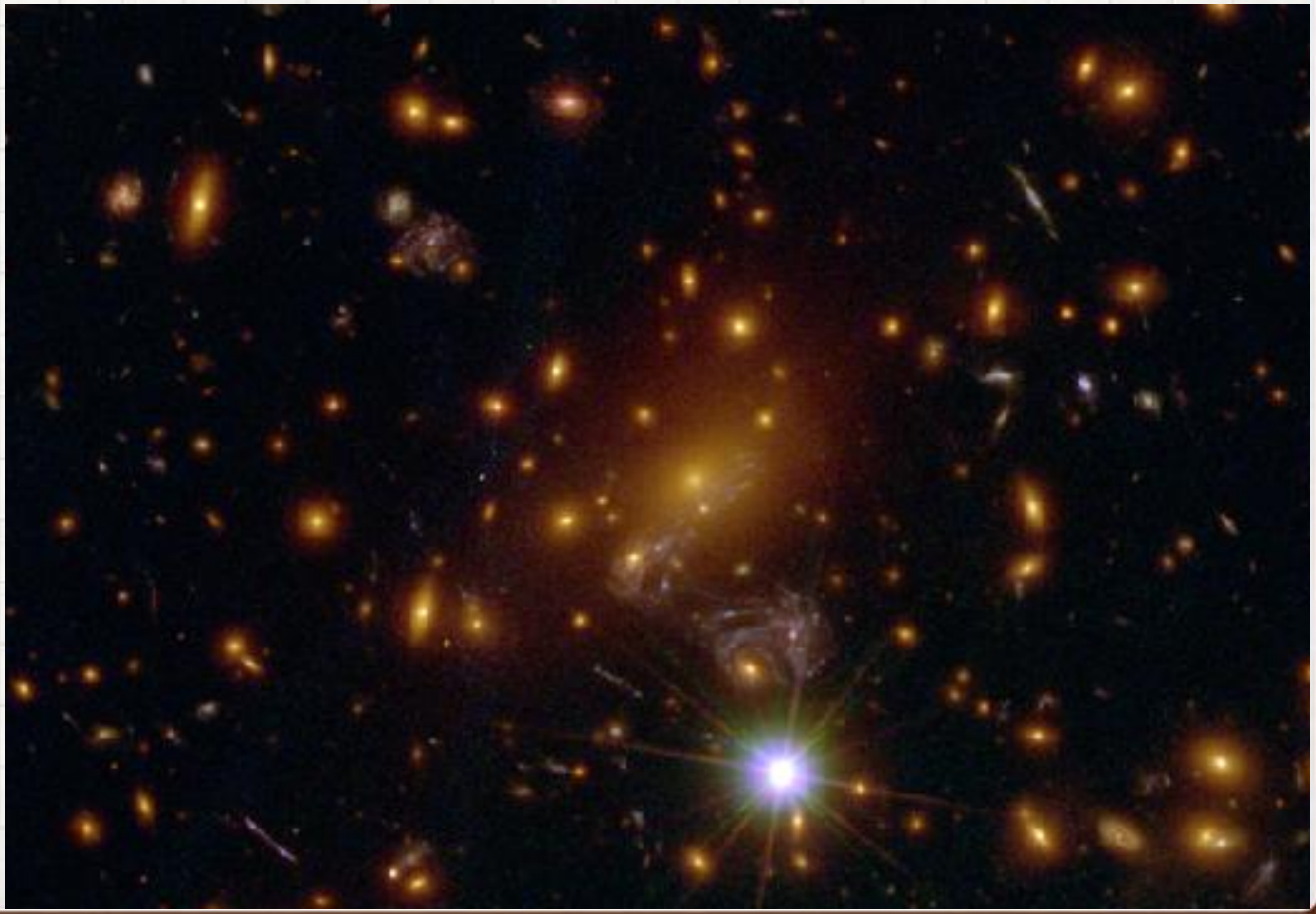
-Multiple images

-Assume a model (galaxies+dark matter, perhaps + gas)

-Check through lens equation

reproduction of images

-Iterate for best-fit model



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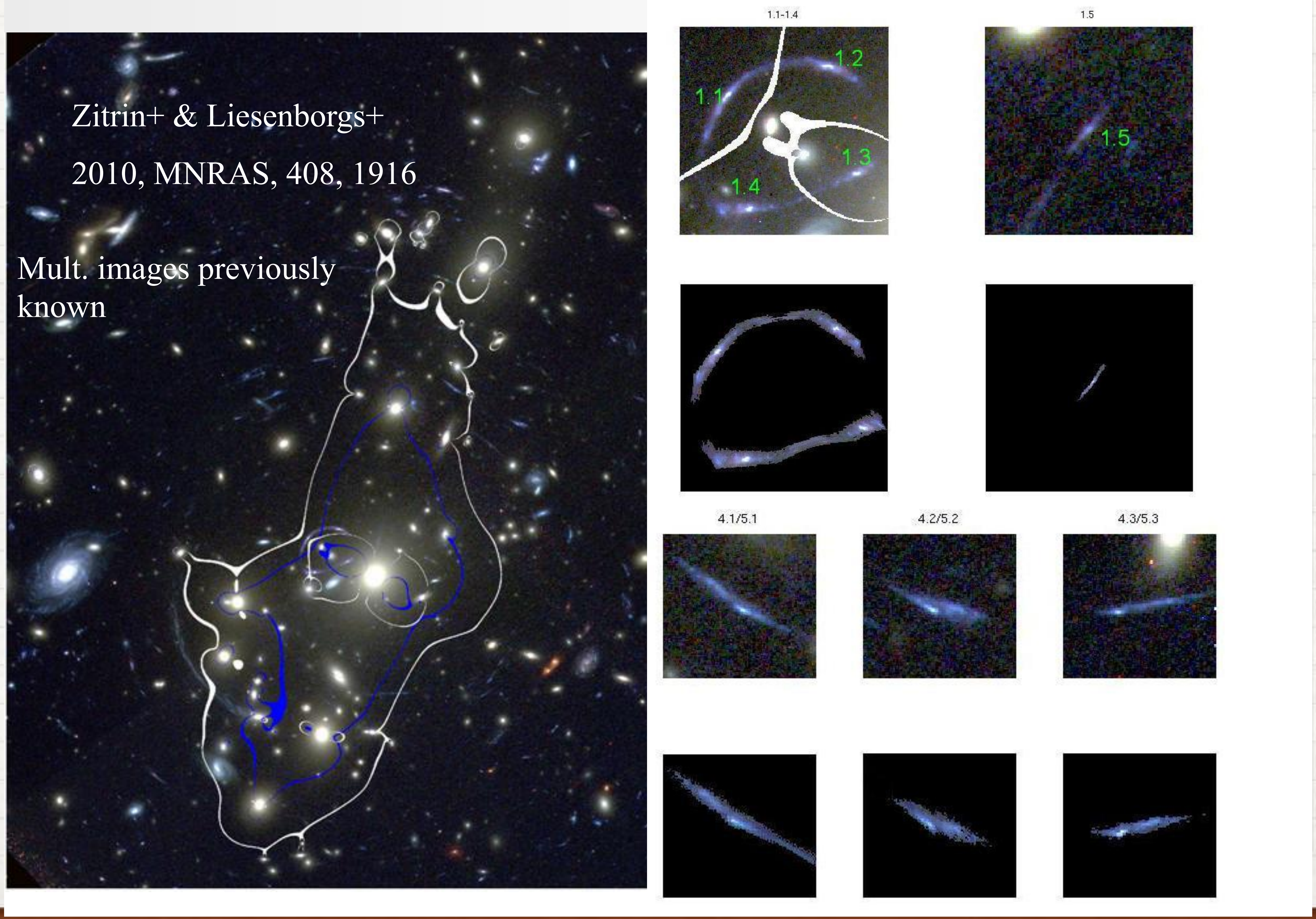
MASS MAPPING: STRONG LENSING

How do we know model works well?



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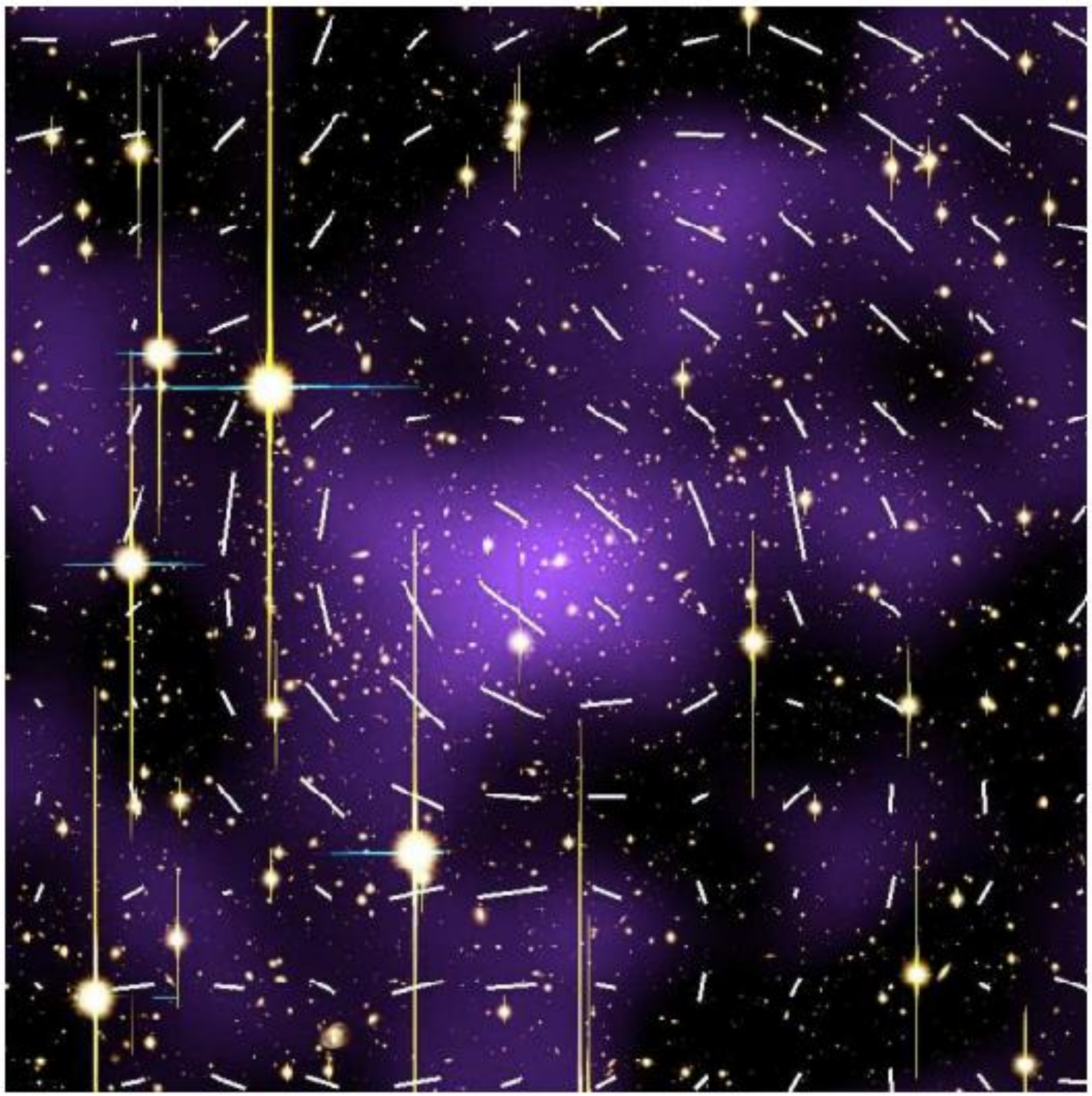
MASS MAPPING: WEAK LENSING

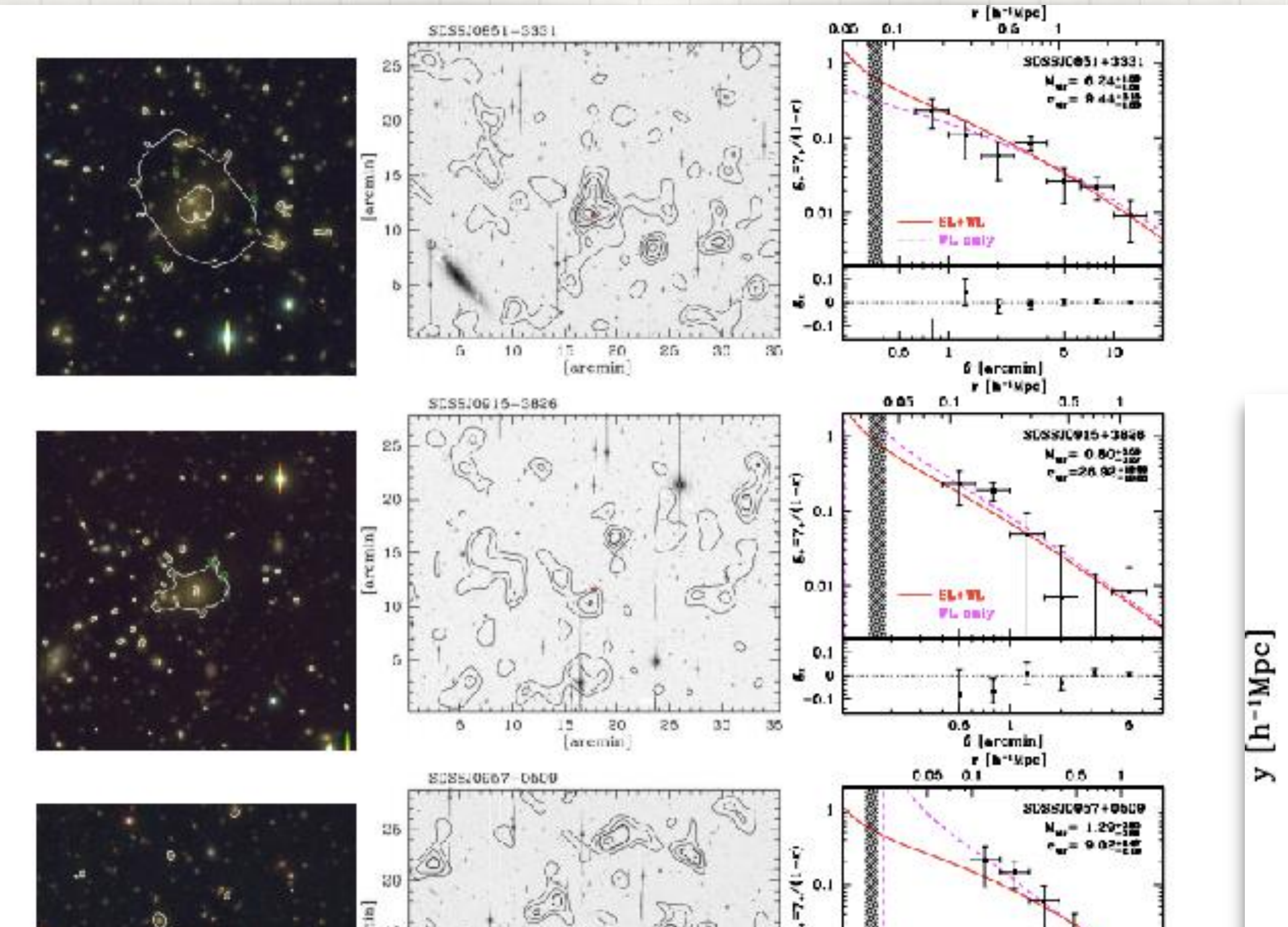
4 *M. Oguri et al.*



How?
one way is similar to before:
assume a model,
compare shear,
optimize

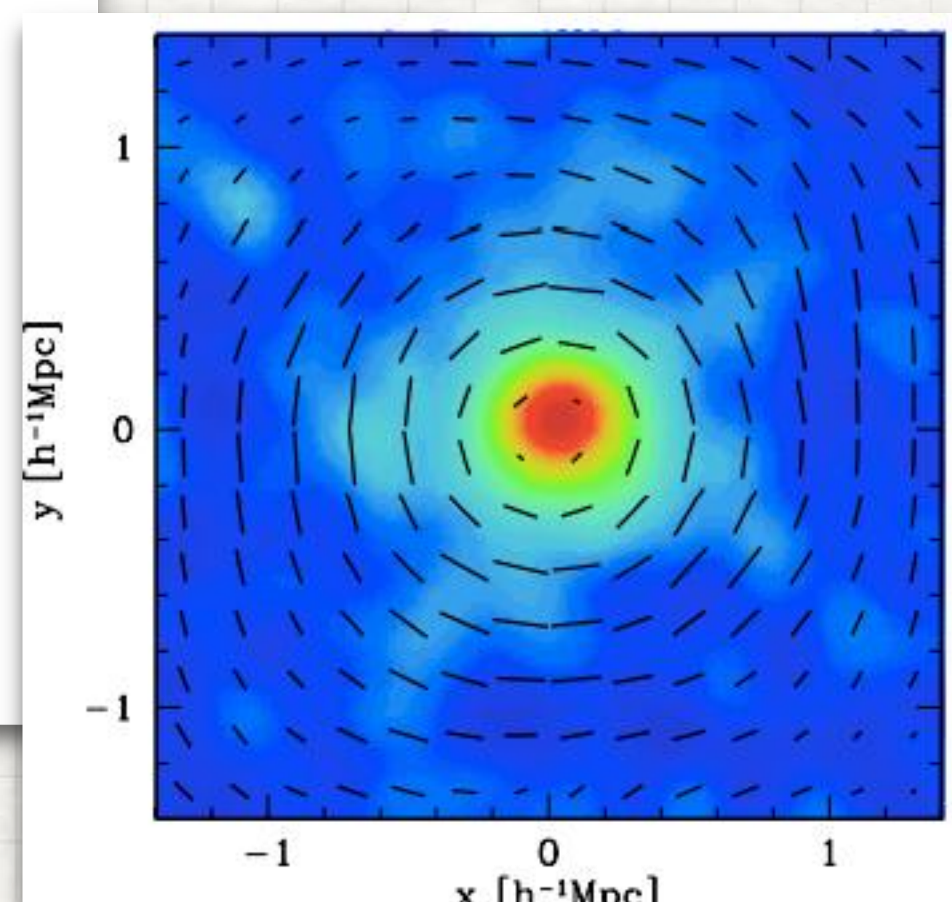
THE SCIENCE OF LENSING

MASS MAPPING: STRONG+WEAK LENSING AND ANALYSIS OF STATISTICAL SAMPLES



E.g., Oguri+2010

Stack of 28 clusters



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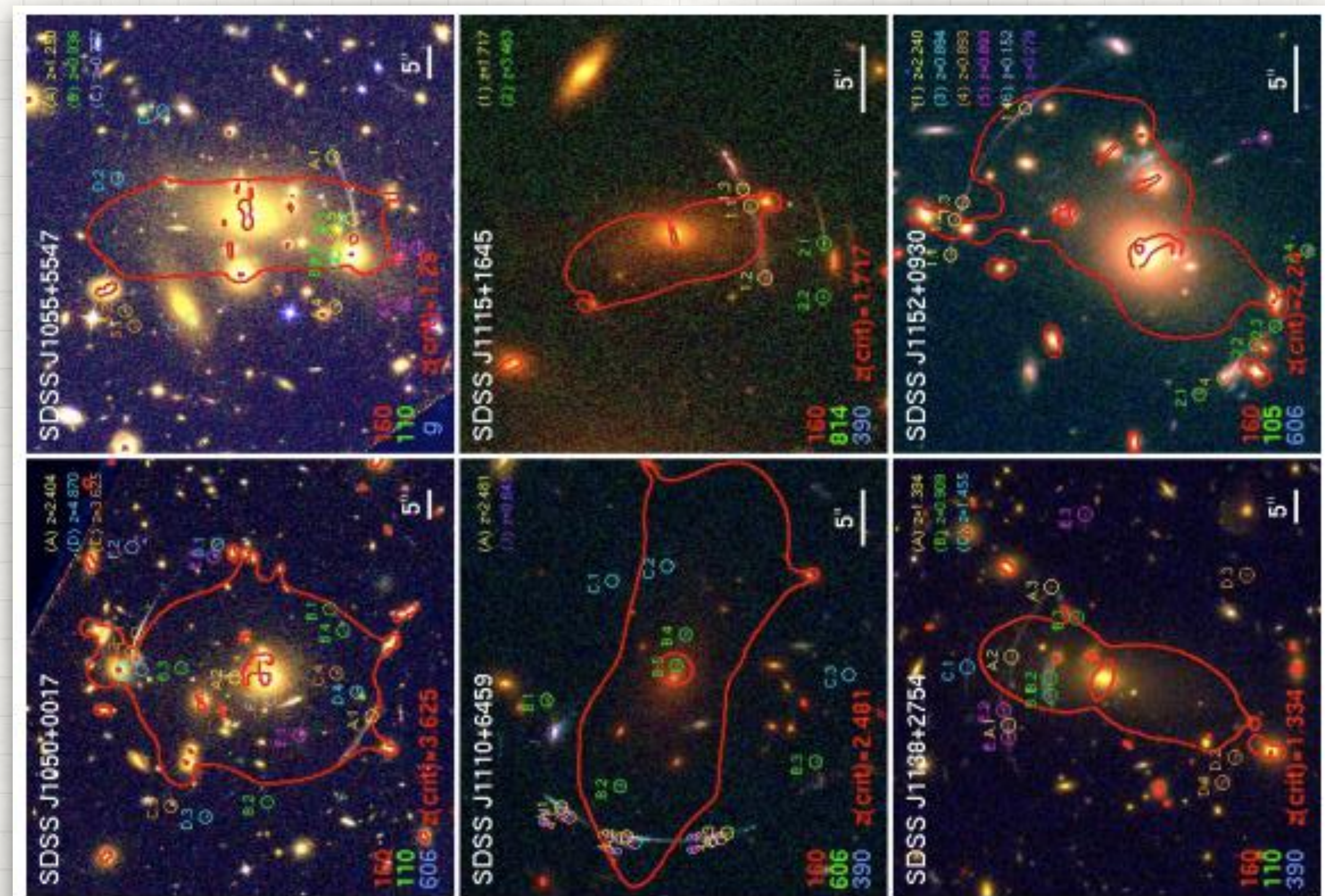
ANALYSIS OF STATISTICAL SAMPLES

Sharon+2019



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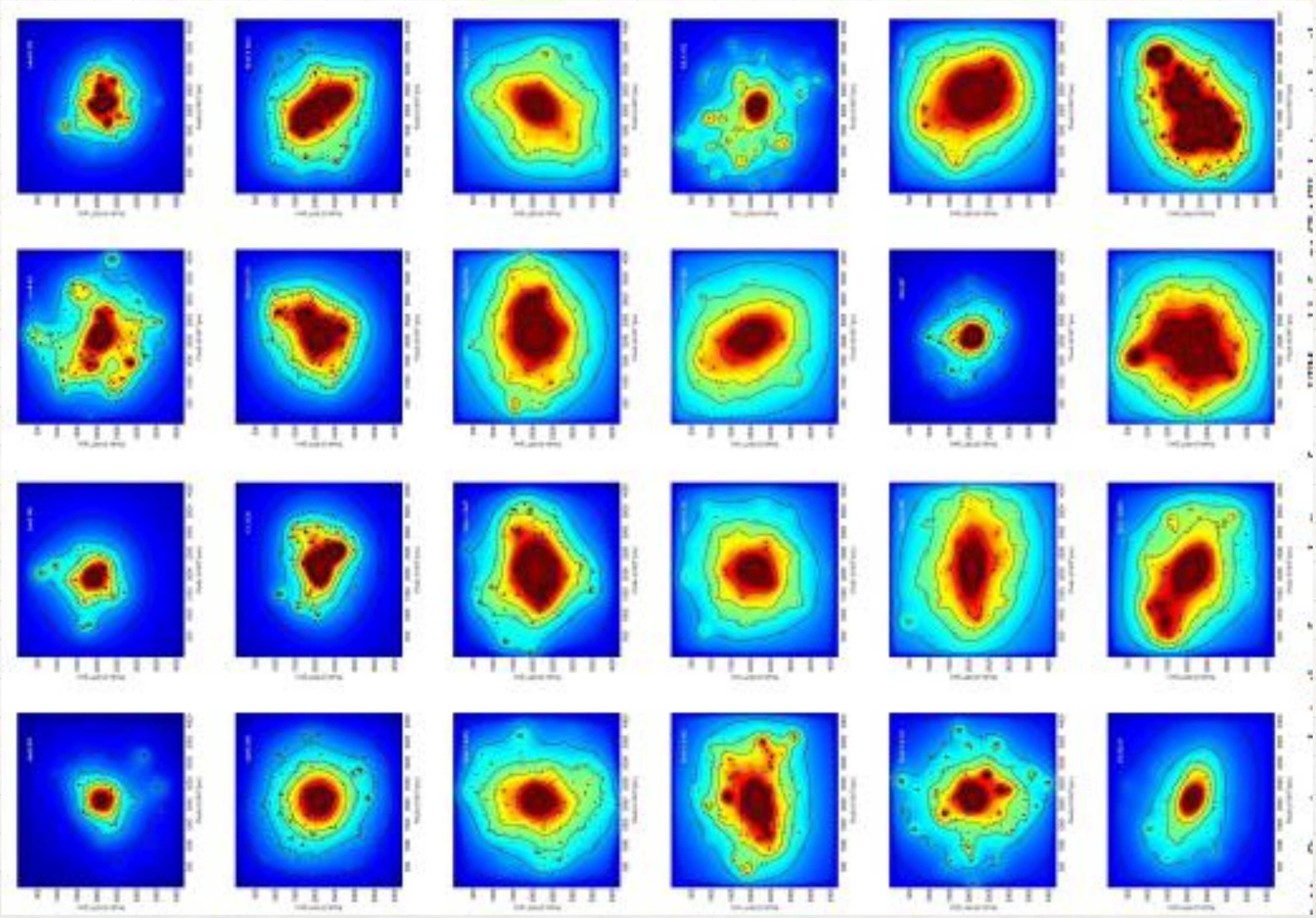
ANALYSIS OF STATISTICAL SAMPLES

MASS MAPPING: STRONG+WEAK LENSING

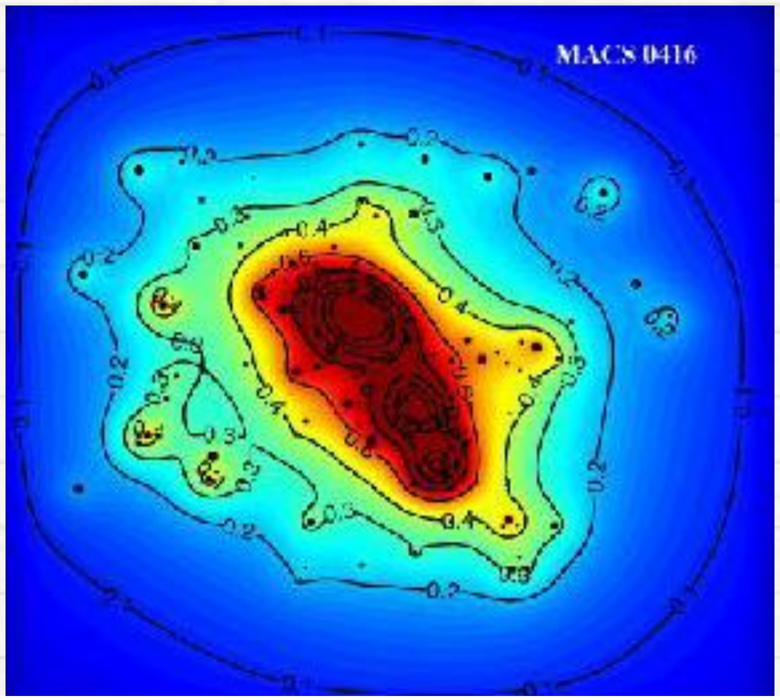
Zitrin+2015

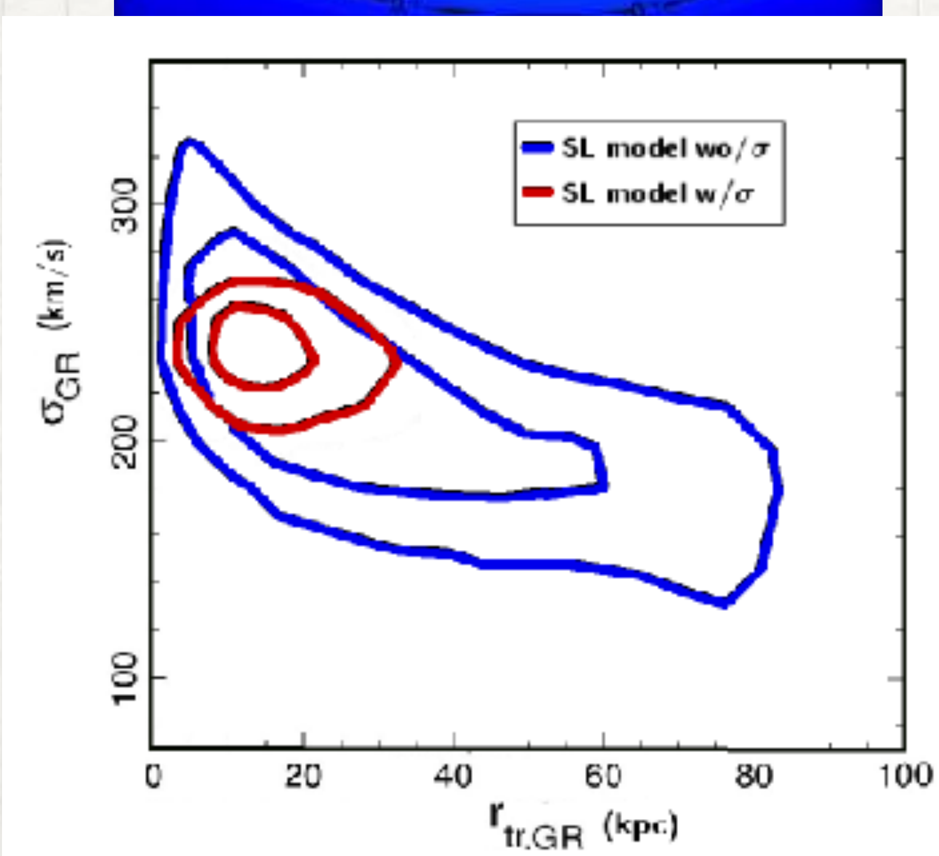


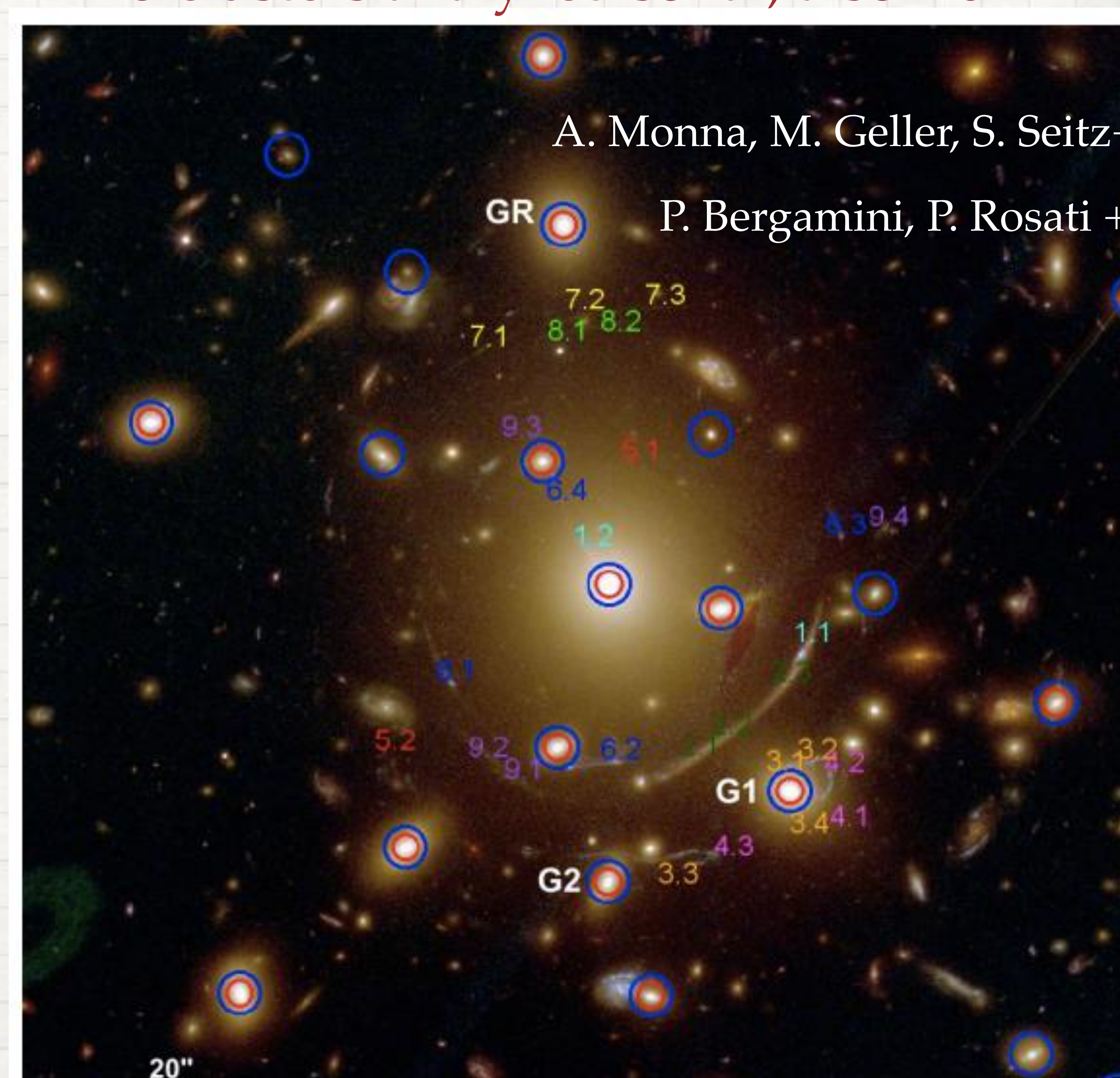
THE SCIENCE OF LENSING

MASS MAPPING: SEPARATING BARYONS FROM DM

2-3 clusters analyzed so far, also A611





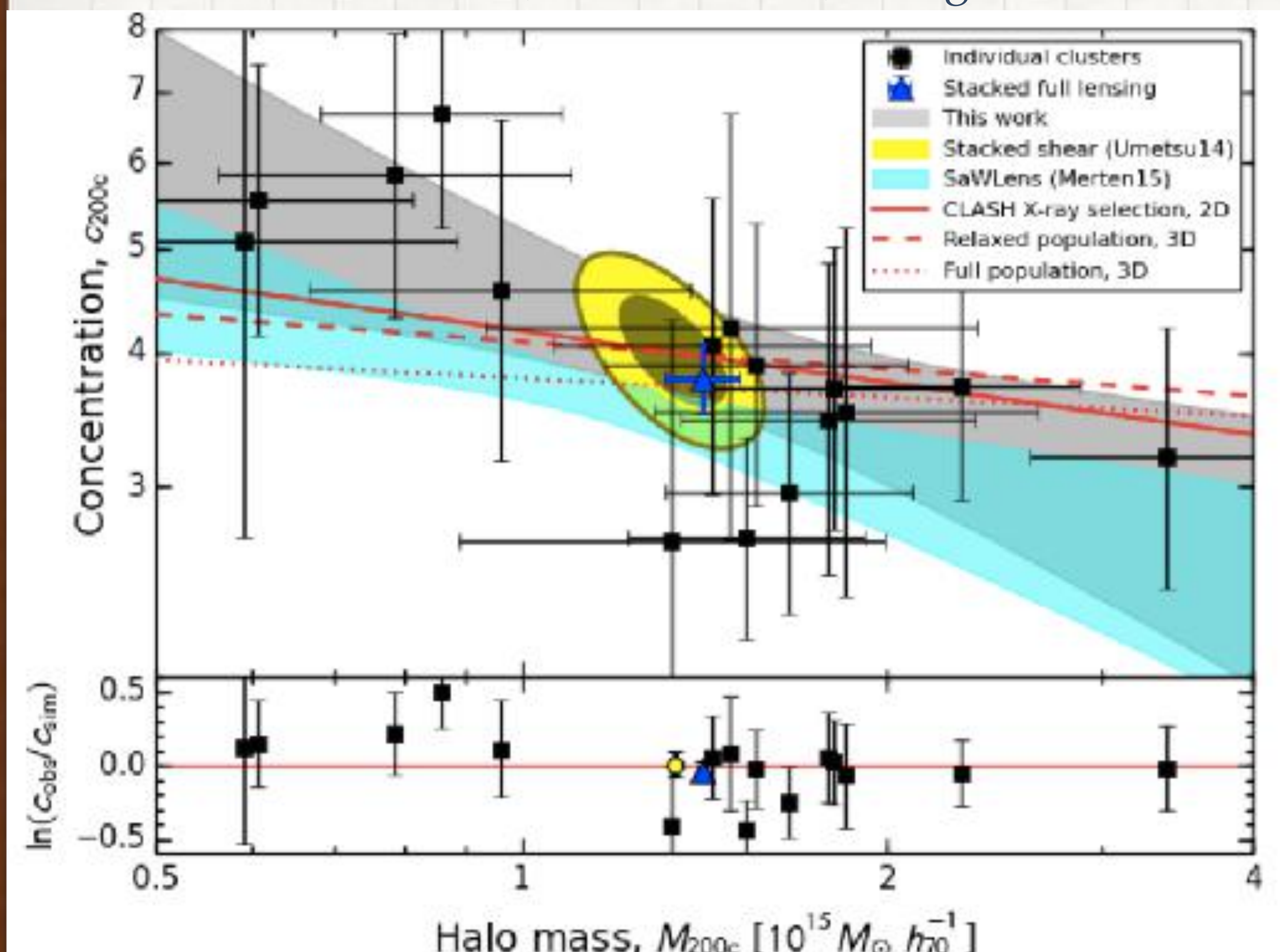


THE SCIENCE OF LENSING

COSMOLOGICAL CONSTRAINTS

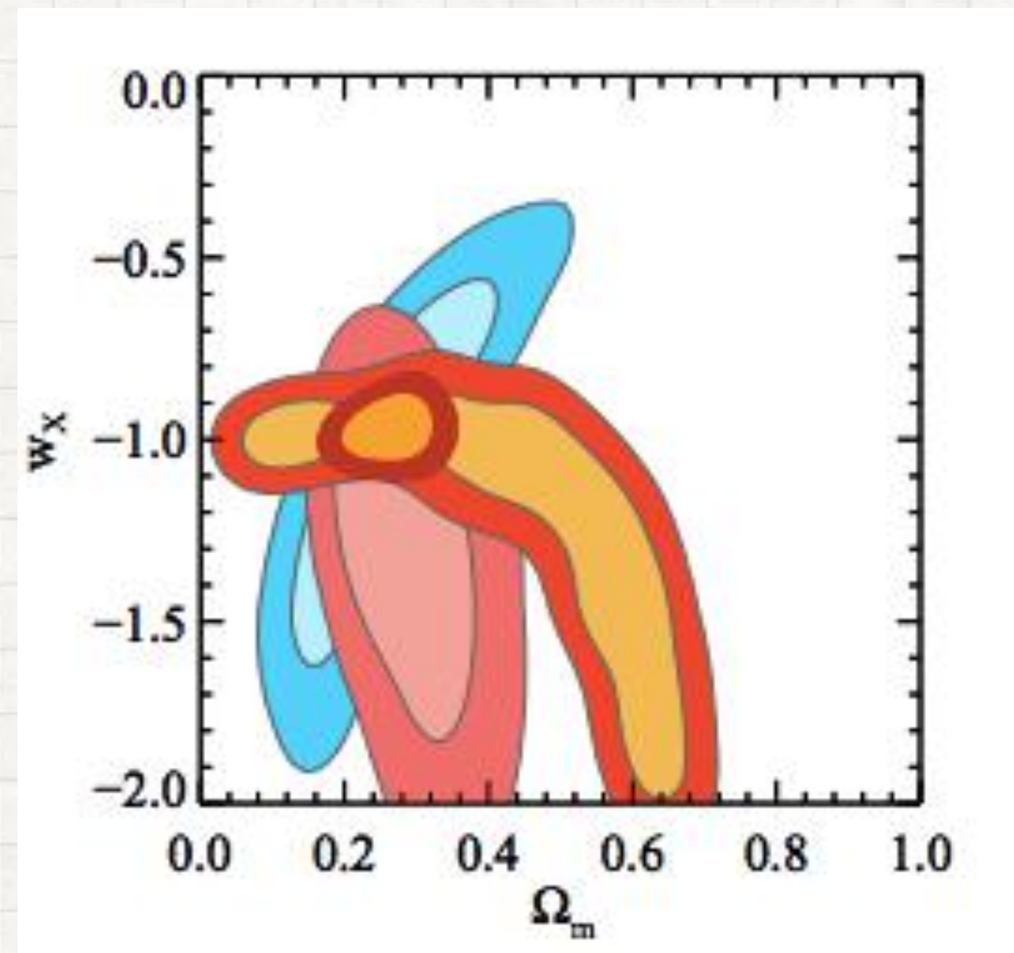
Constraints on Structure formation, shape

Umetsu+ 2015, Merten+2015, Mengehetti+2015



Lensing depends on distance to sources, distance depends on cosmology

A. Monna, M. Geller, S. Seitz+



Jullo+2007

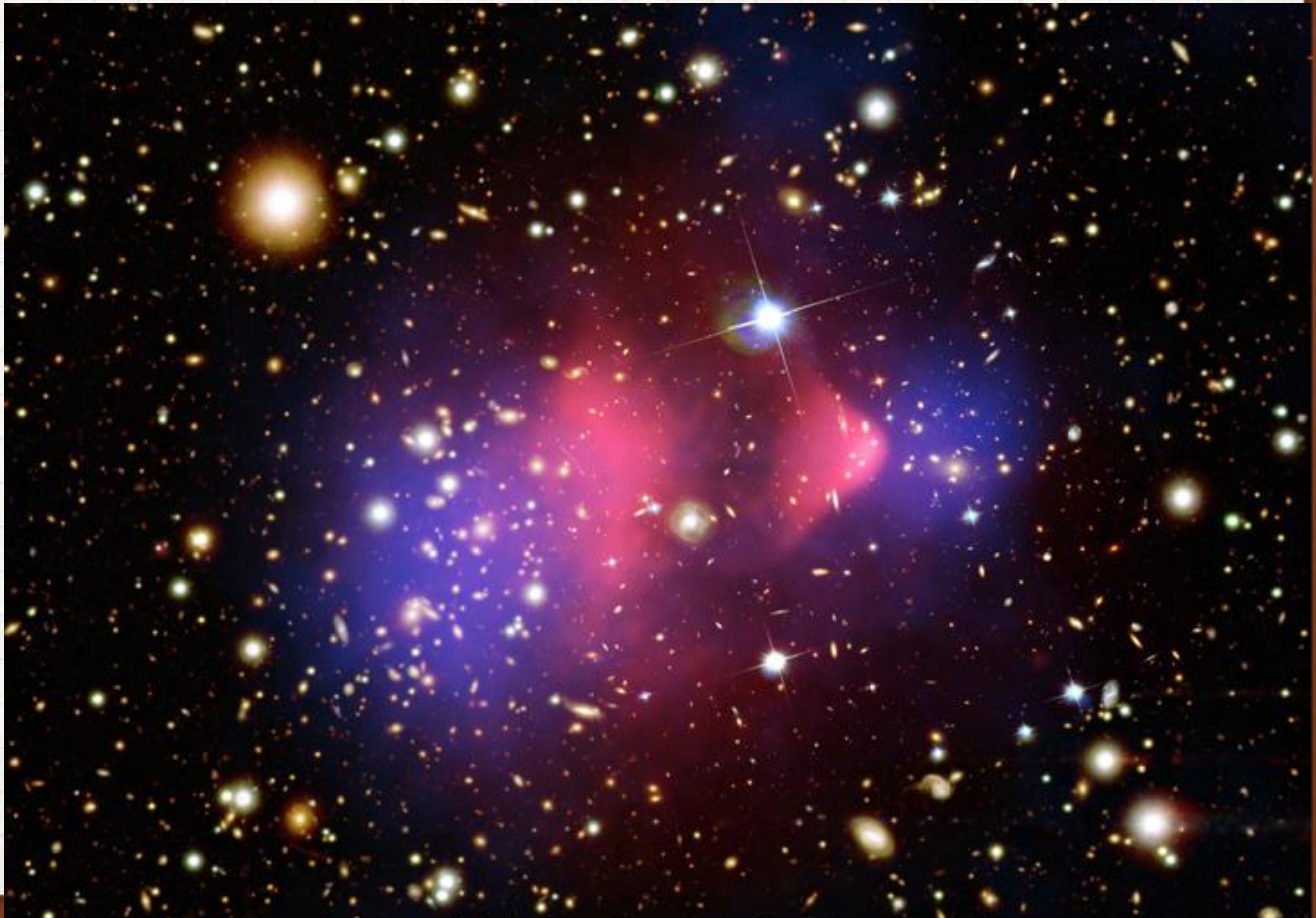
THE SCIENCE OF LENSING

FUNDAMENTAL FEATURE OF DM FROM LENSING

- Merging clusters: DM cross section —> collisionless

Bullet clusters, Clowe, Baradac, Marekevitch+

substantial gap
—>
scattering depth
$\tau = \Sigma\sigma/m \lesssim 1$
σ is self interaction cross section
Lensing gives us Σ
$\sigma/m <$ few cm2/g
—>
DM collisionless



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COSMOLOGICAL CONSTRAINTS: H_0

Each image arrives at a different time

$$t(\vec{\theta}) = \frac{(1+z_{\mathrm{d}})}{c}\frac{D_{\mathrm{d}}D_{\mathrm{s}}}{D_{\mathrm{ds}}}\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2-\psi(\vec{\theta})\right]$$
$$= t_{\mathrm{geom}} + t_{\mathrm{grav}}\ .$$

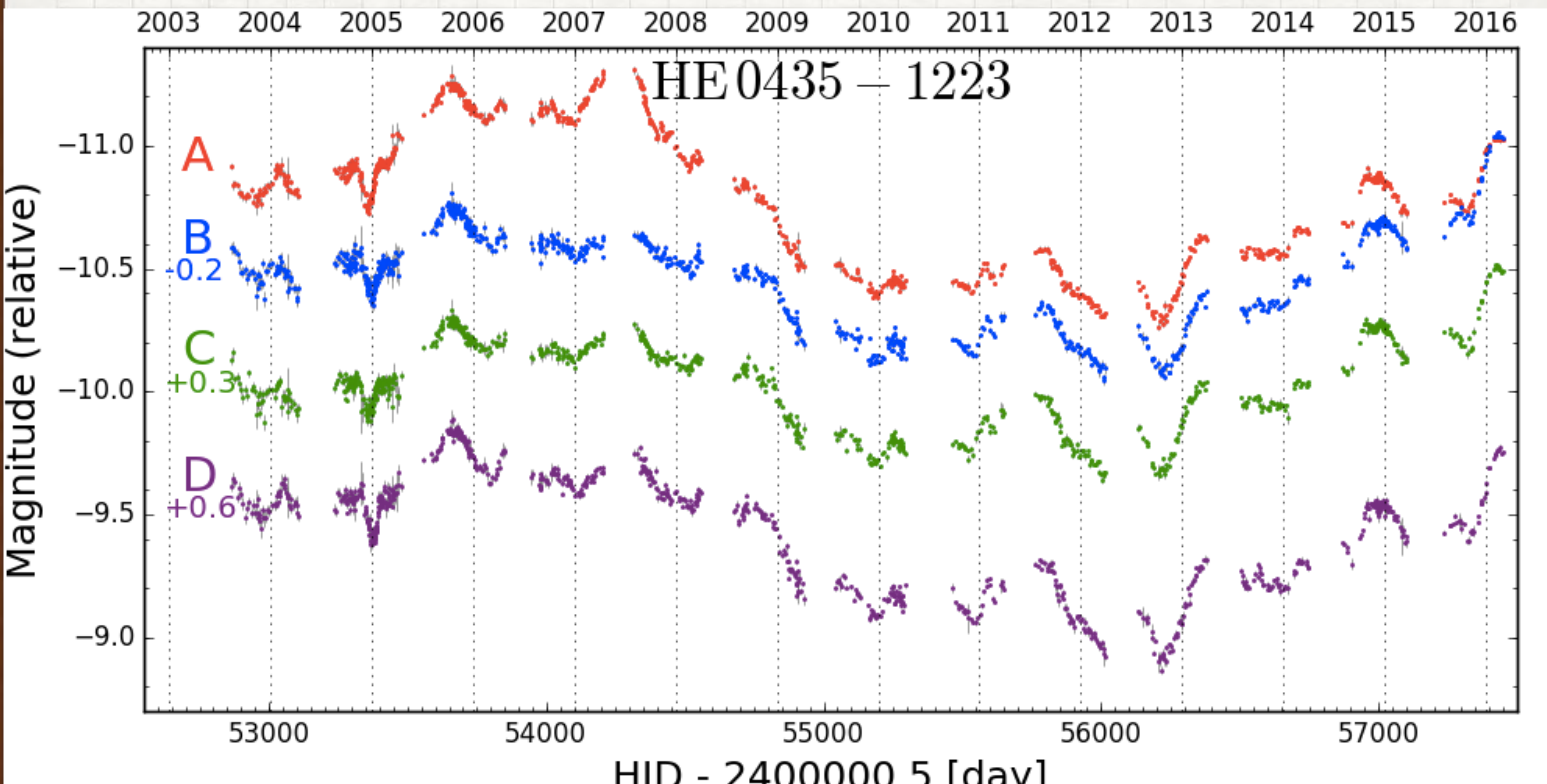
where D_i (and thus)
Delta_t is proportional to 1/H_0
(Hubble parameter today)
from this we know that
H_0 ~70 km/s/ Mpc

Anecdote: tension with CMB results

THE SCIENCE OF LENSING

COSMOLOGICAL CONSTRAINTS: H_0

Cosmograil



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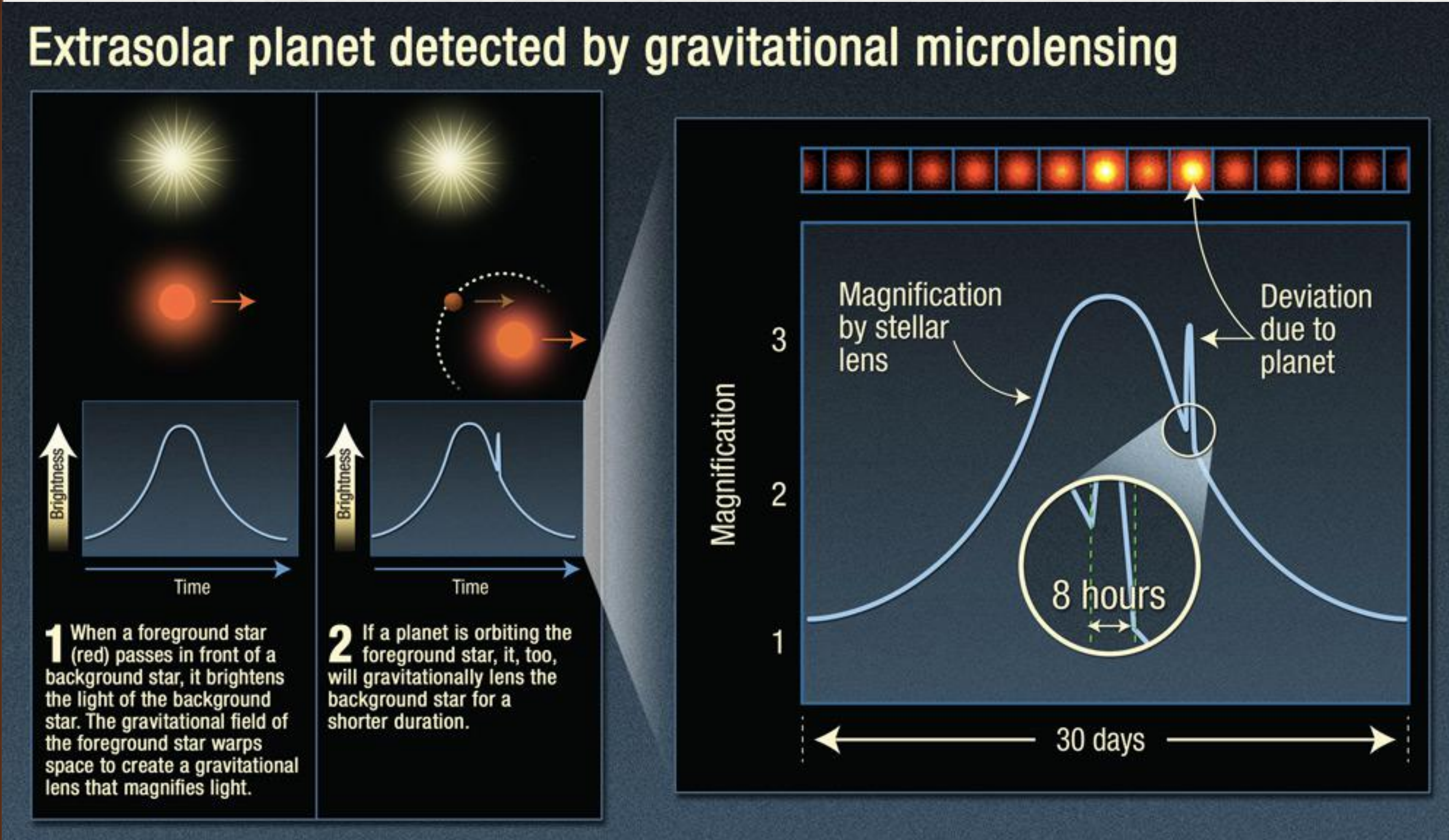
MICROLENSING



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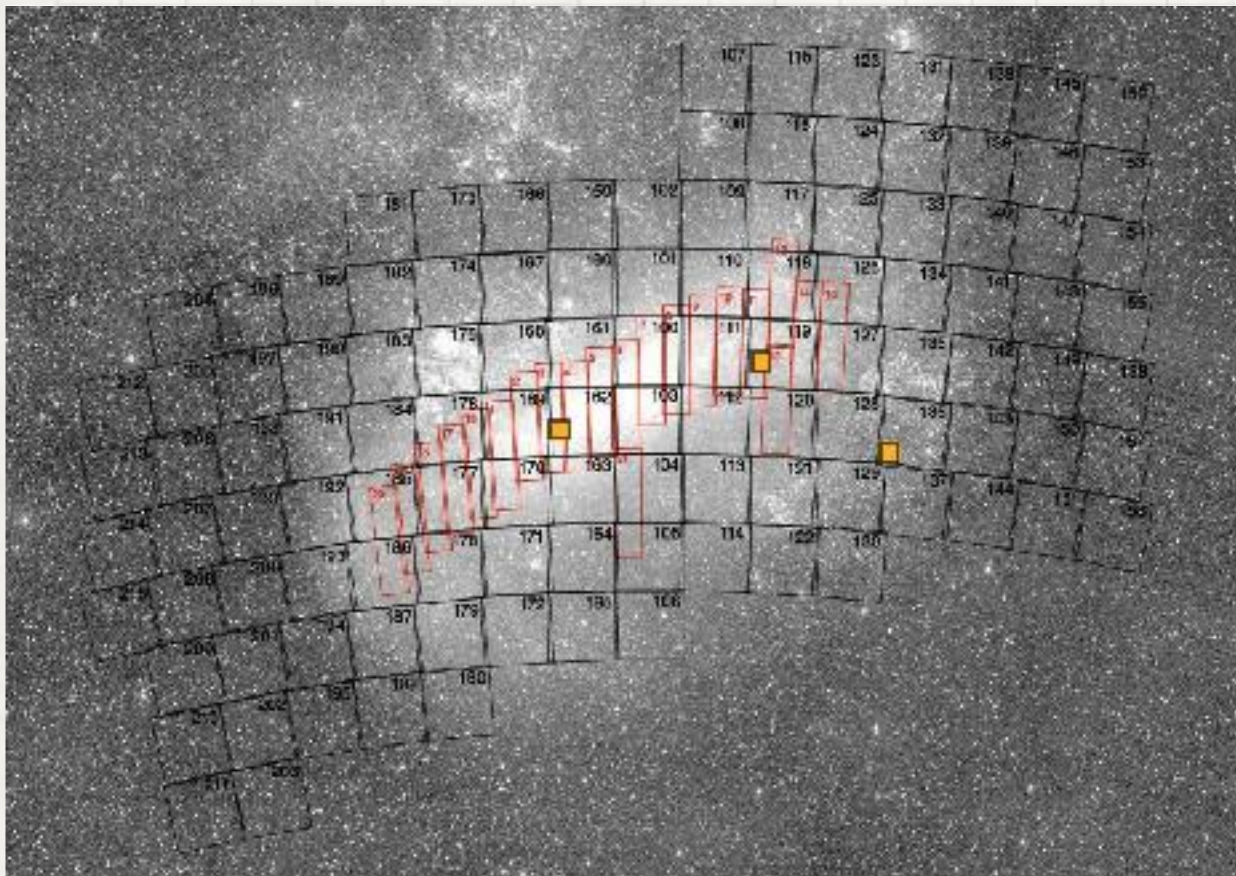
PROBING DM WITH MICROLENSING

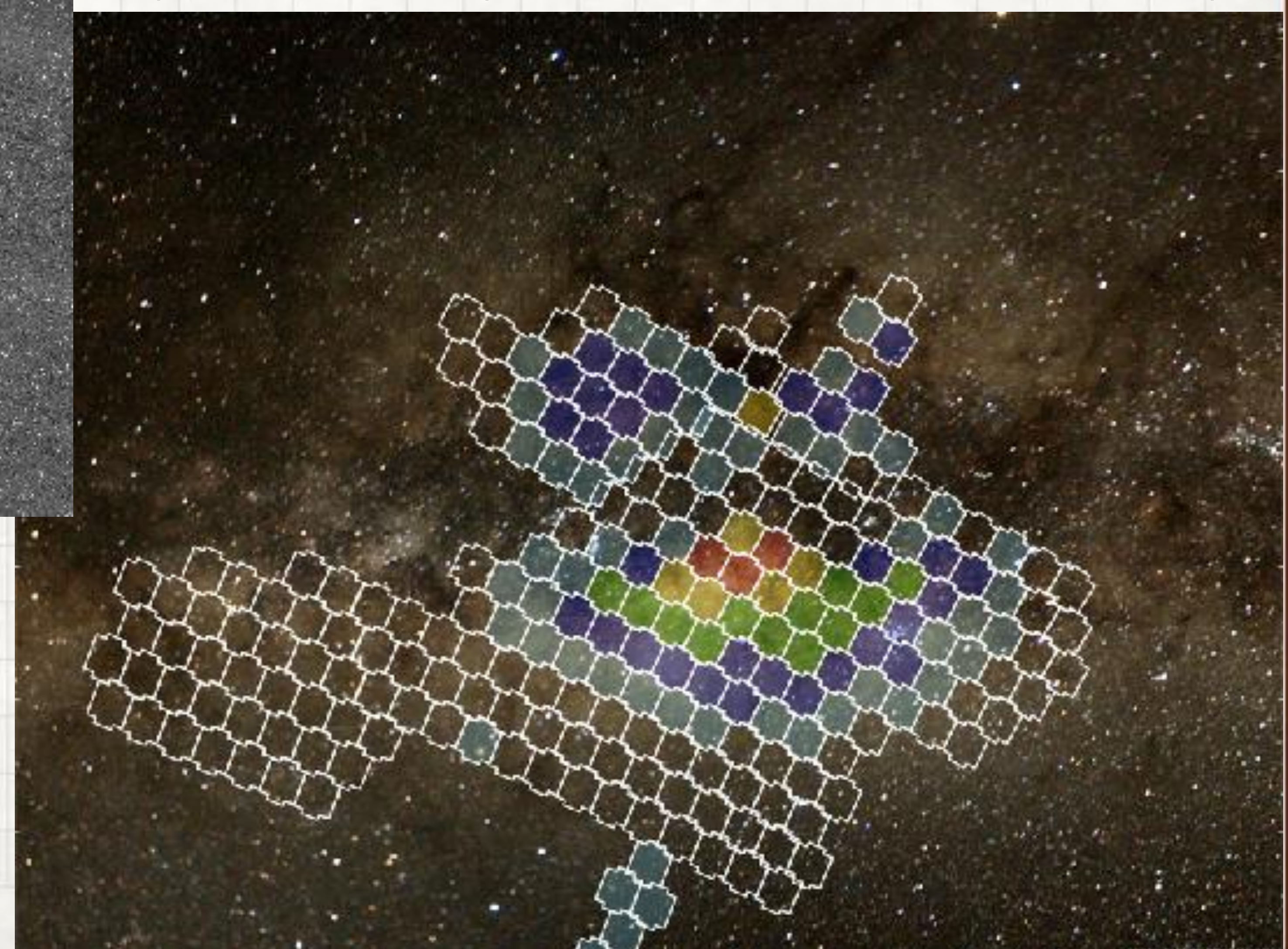
E.G., OGLE, Eros, MOA



L. Wyrzykowski+ 2010

Large Magellanic Cloud
or MW bulge

https://enacademic.com/pictures/enwiki/79/OGLE-IV-BLG-fields-overview.png

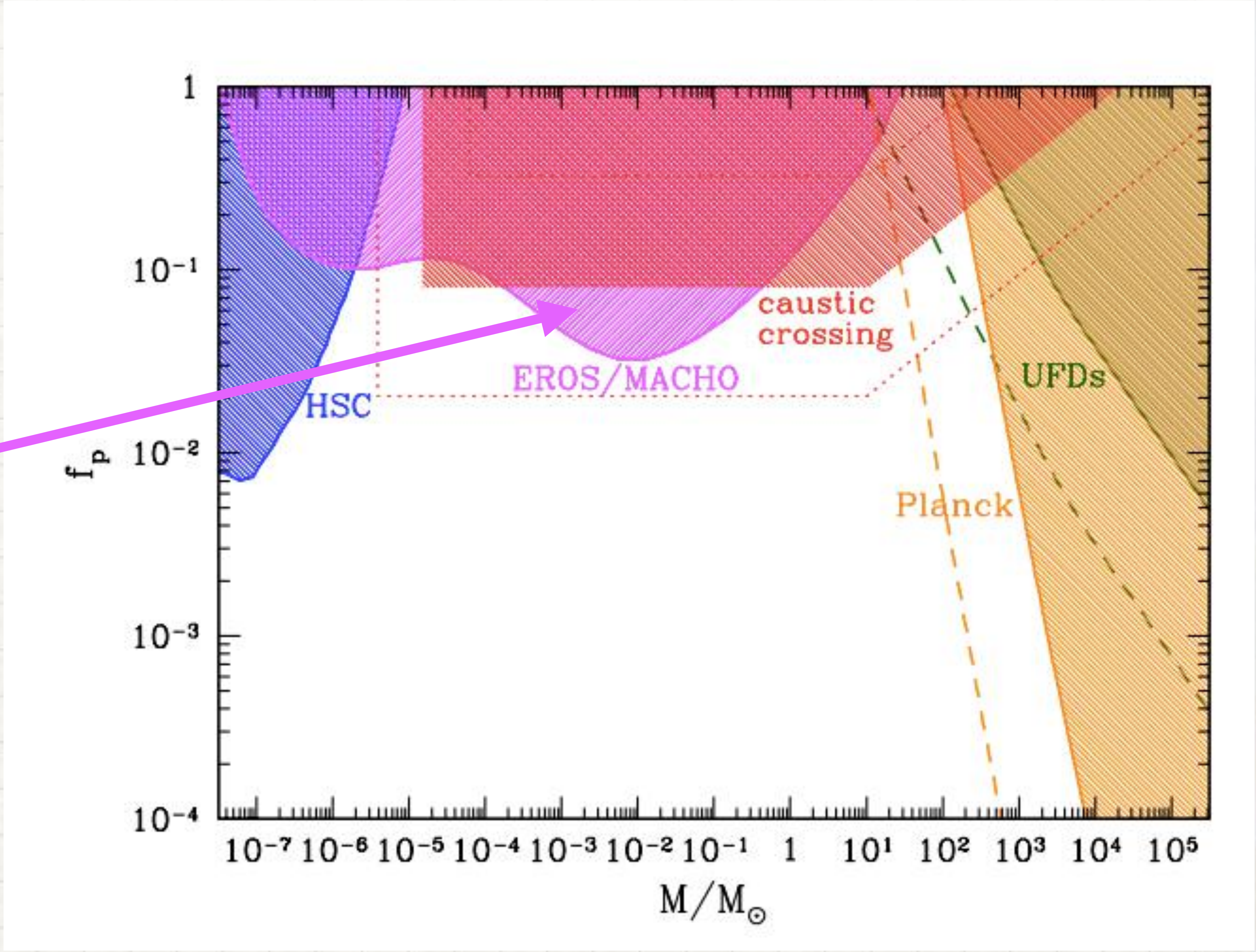


THE SCIENCE OF LENSING

MICROLENSING: CONSTRAINTS ON DM

Oguri+ 2018

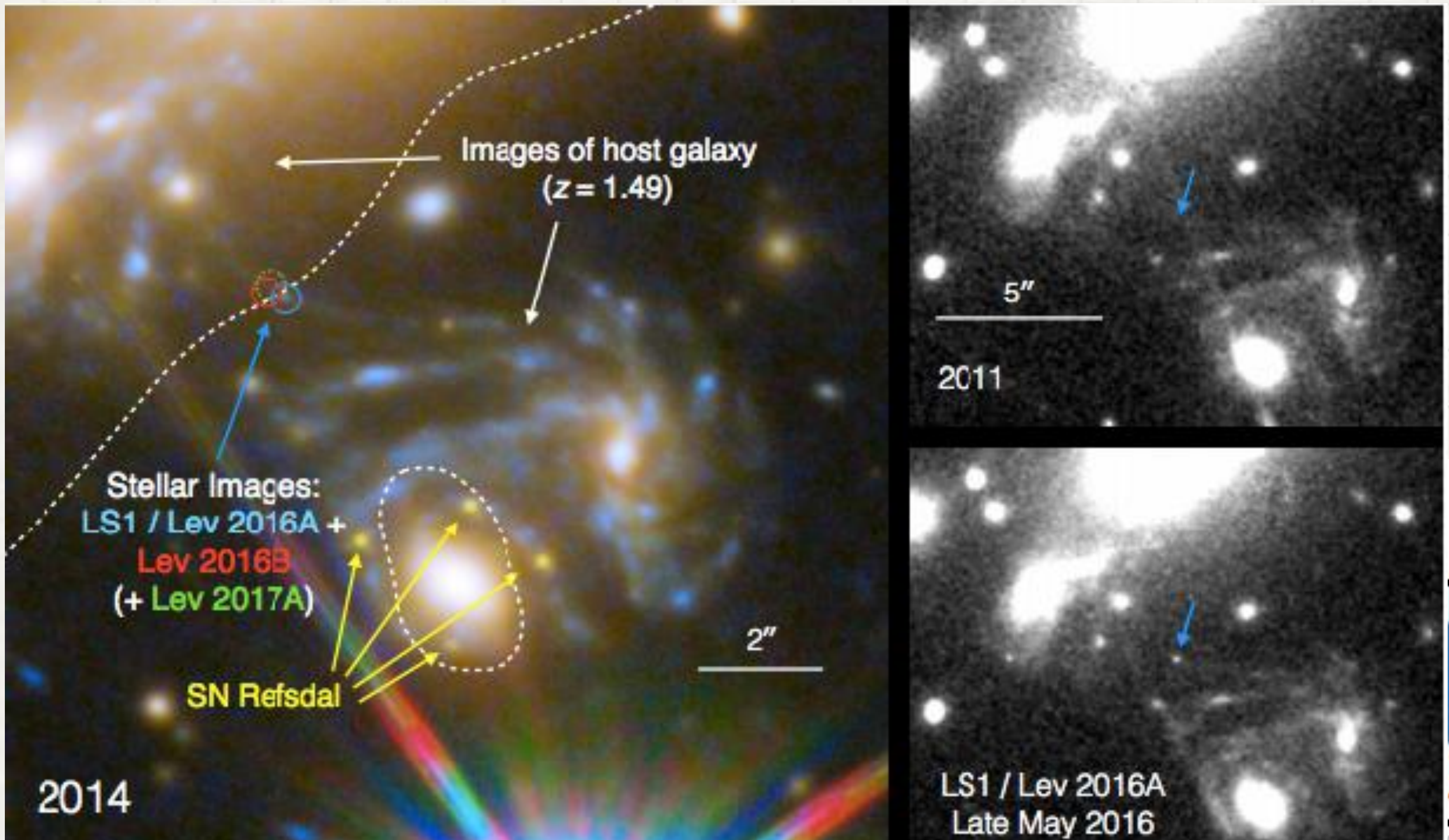
"massive astrophysical compact halo object"

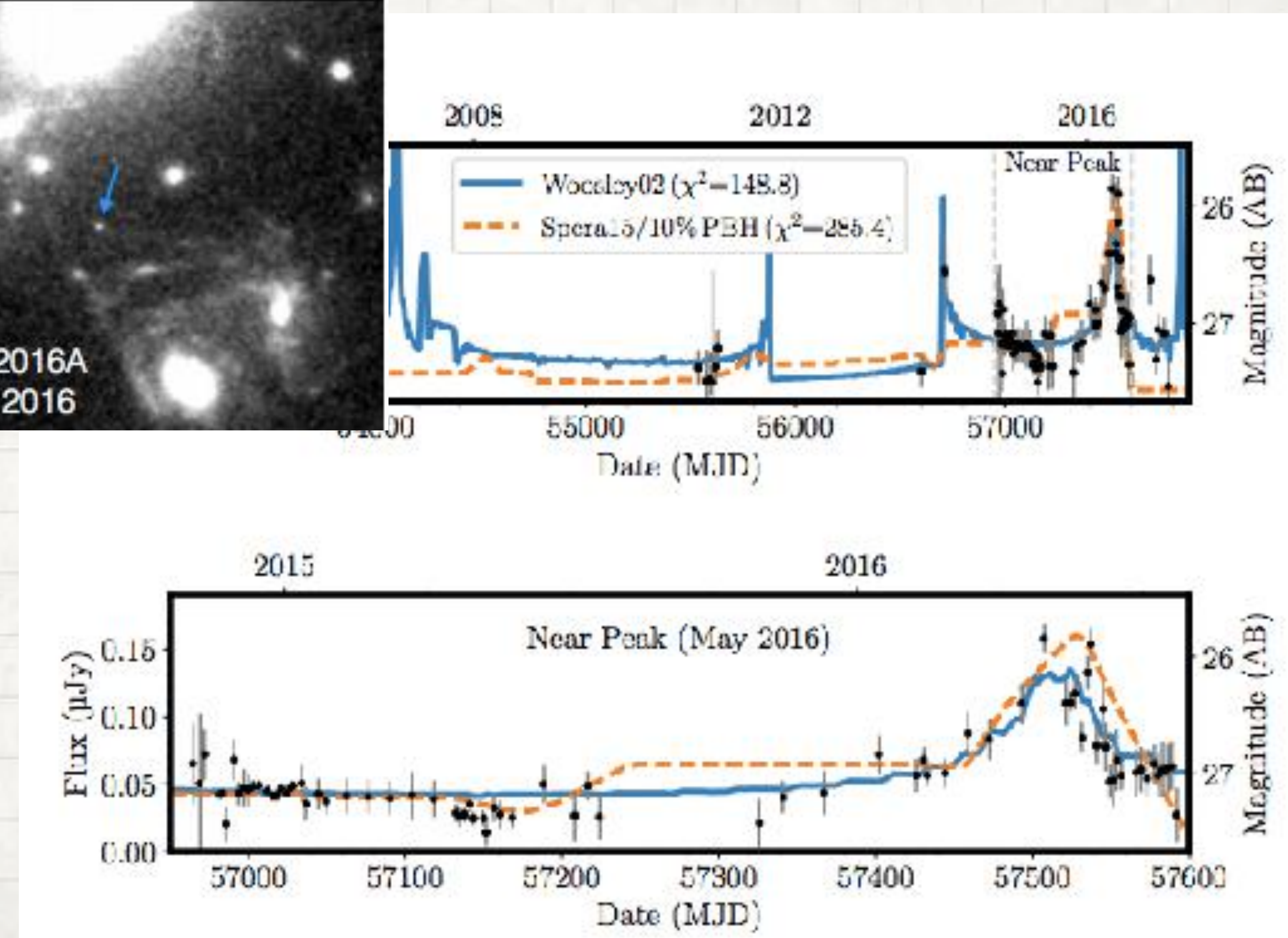


THE SCIENCE OF LENSING

COSMOLOGICAL MICROLENSING AND CAUSTIC CROSSING EVENTS

CONSTRAINTS ON IMF AND DM

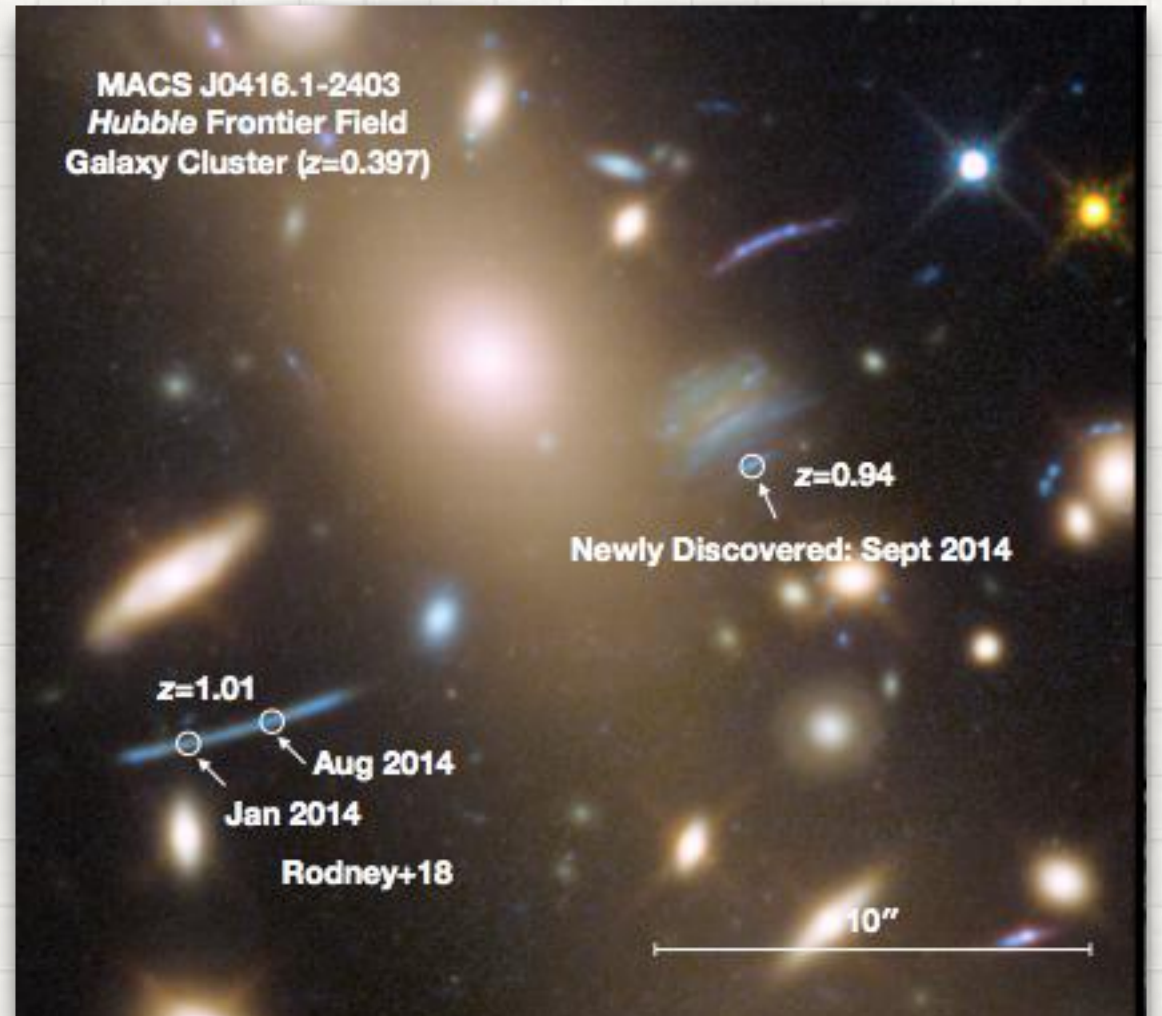




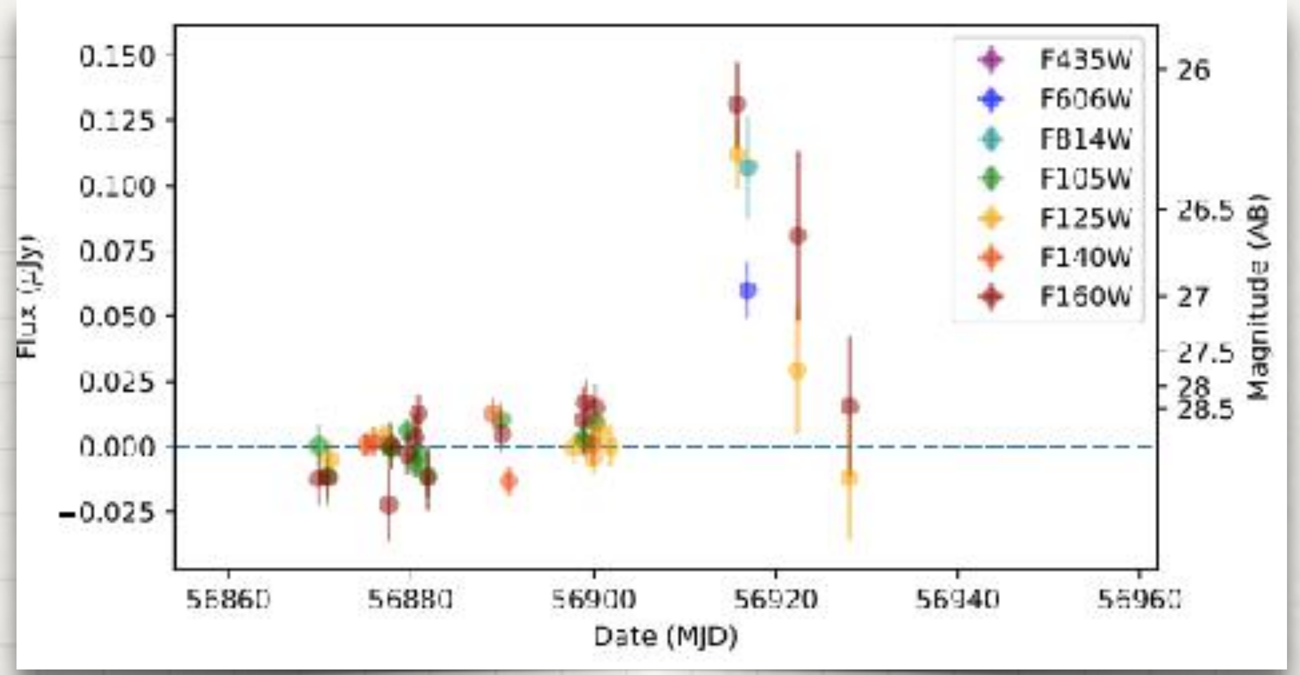
Kelly et al. 2018

THE SCIENCE OF LENSING

COSMOLOGICAL MICROLENSING AND CAUSTIC CROSSING EVENTS
CONSTRAINTS ON IMF AND DM

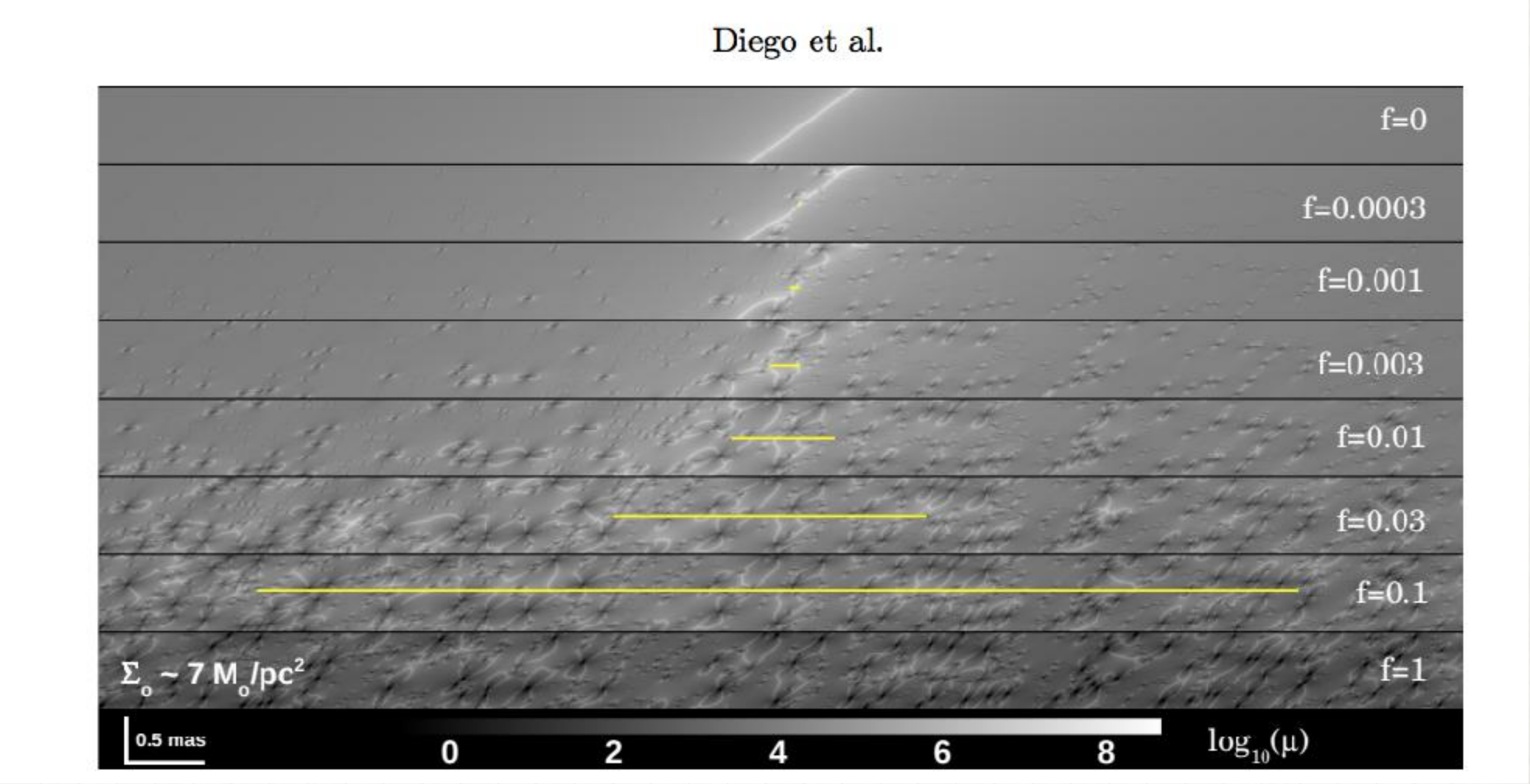


Rodney+2018, Cheng+2019, Kaurov+2019



THE SCIENCE OF LENSING

COSMOLOGICAL MICROLENSING AND CAUSTIC CROSSING EVENTS
CONSTRAINTS ON IMF AND DM

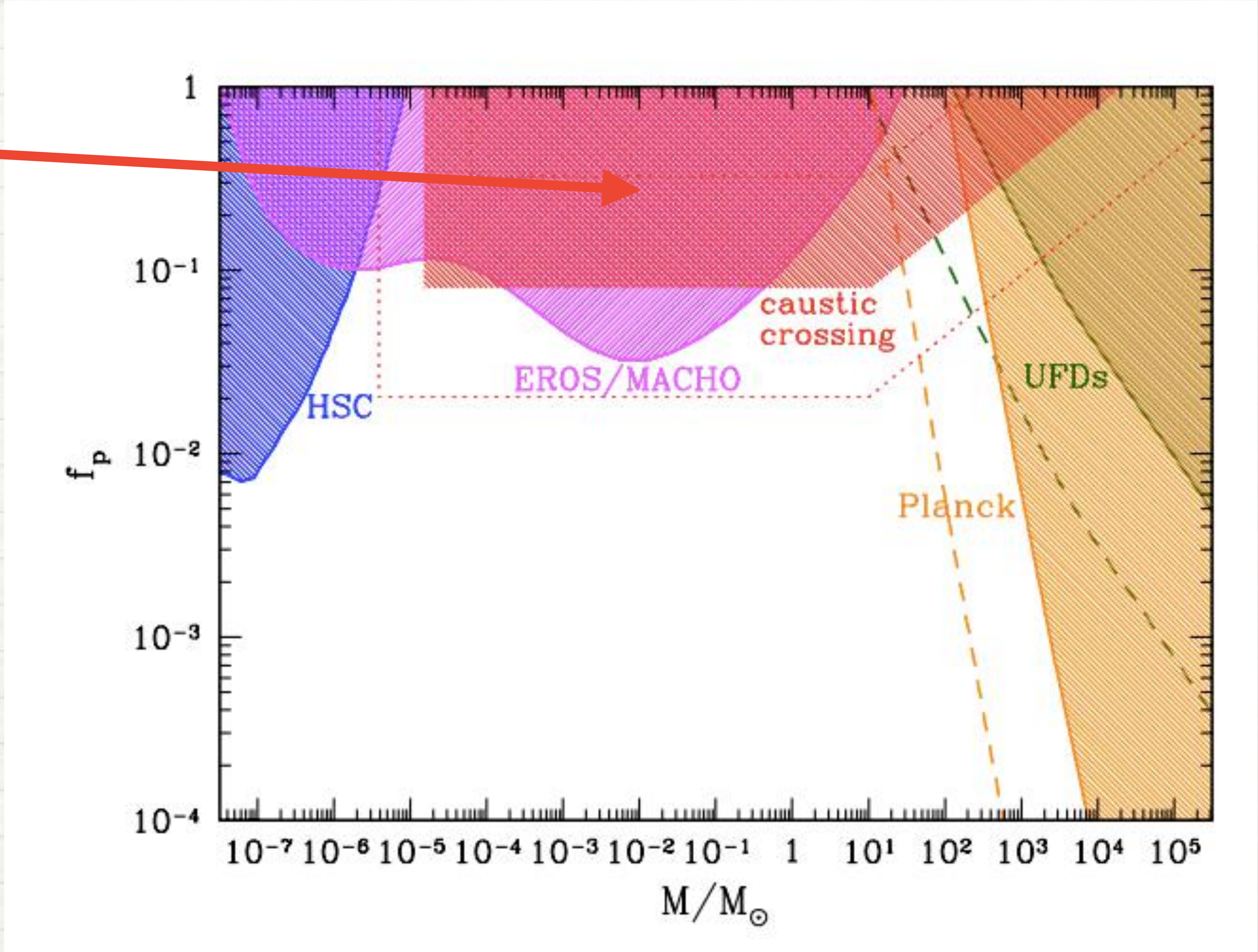


THE SCIENCE OF LENSING

MICROLENSING: CONSTRAINTS ON DM

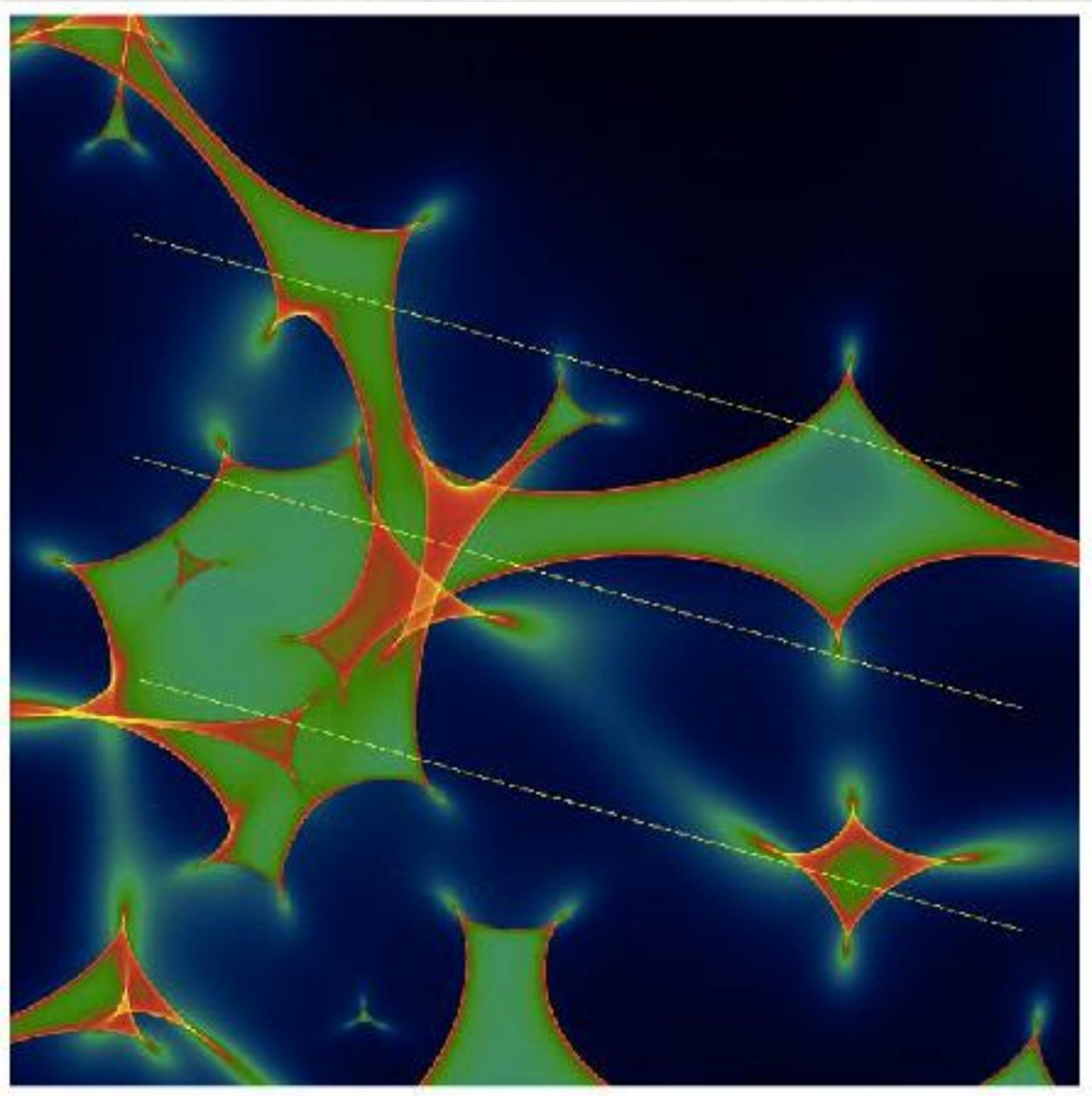
Oguri+ 2018

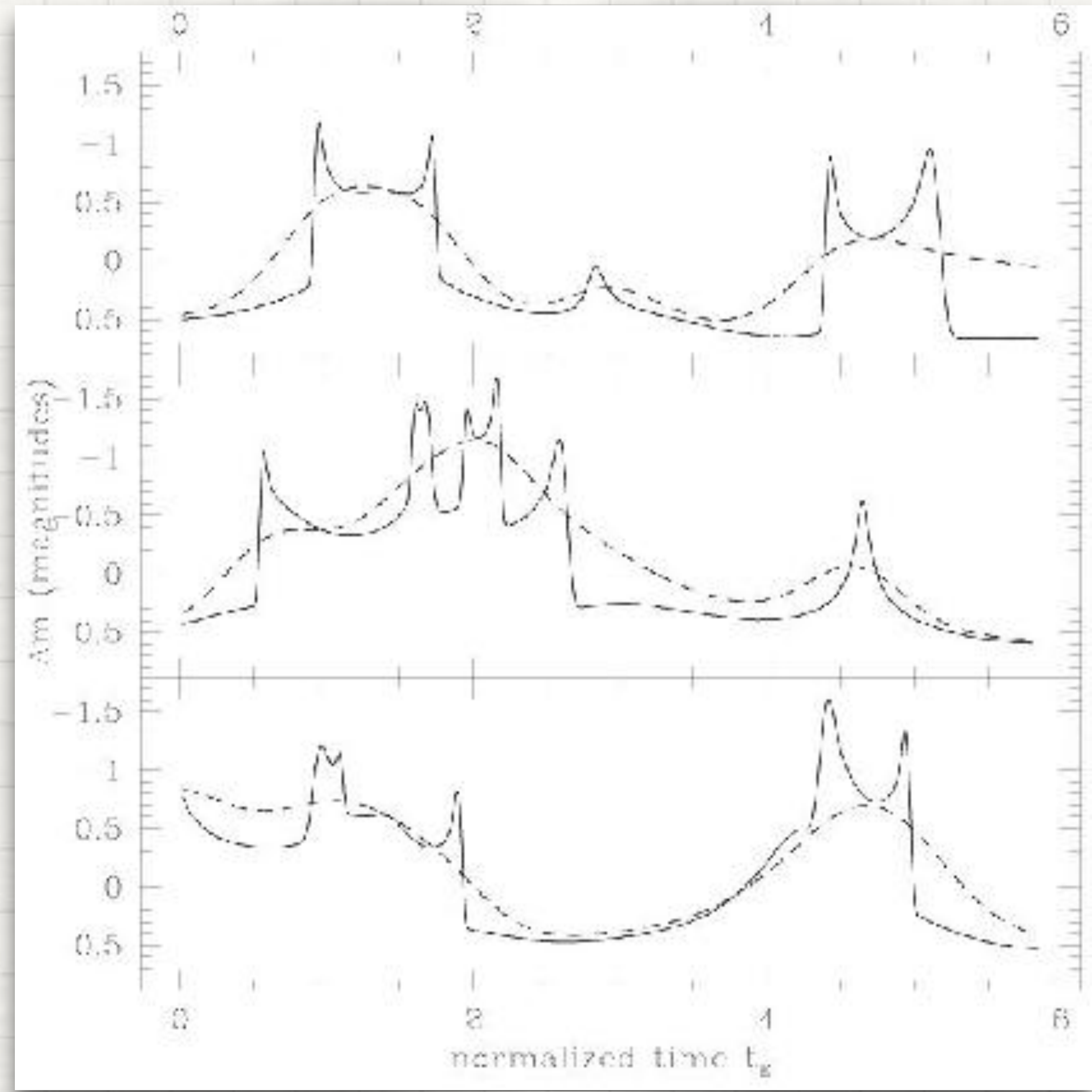
“massive astrophysical compact halo object”



THE SCIENCE OF LENSING

QUASAR MICROLENSING: CONSTRAINTS ON DM





Wambsganss 1998

https://link.springer.com/article/10.12942/lrr-1998-12

HIGH REDSHIFT GALAXIES (or the first galaxies in the universe)

Second main science with SL/WL

Thanks to magnification effect

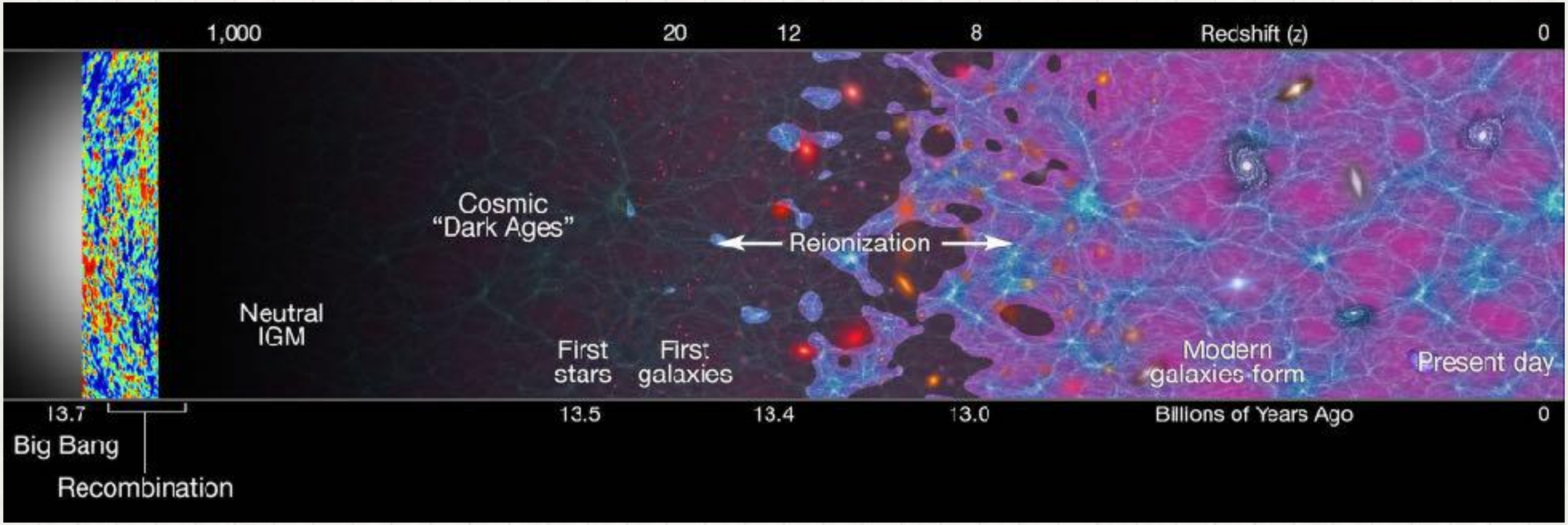
Topic of Lecture II

https://link.springer.com/article/10.12942/lrr-1998-12

THE SCIENCE OF LENSING

HIGH REDSHIFT GALAXIES

History of Universe Timeline

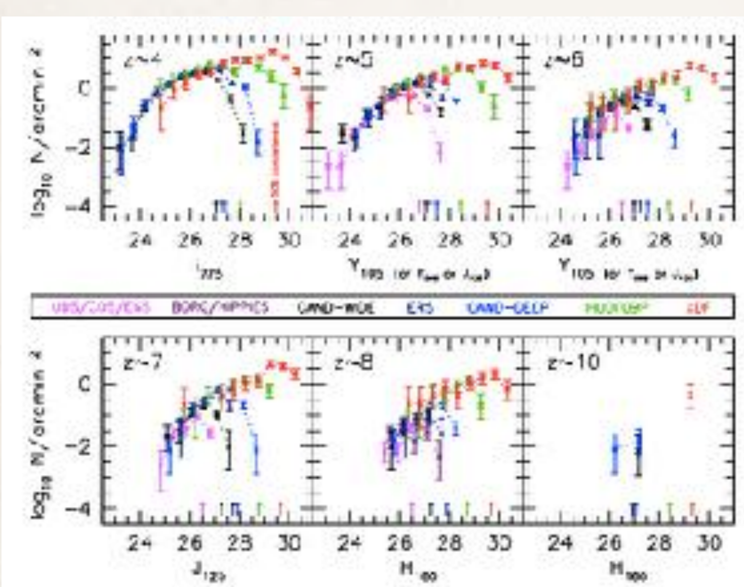


Robertson+2010

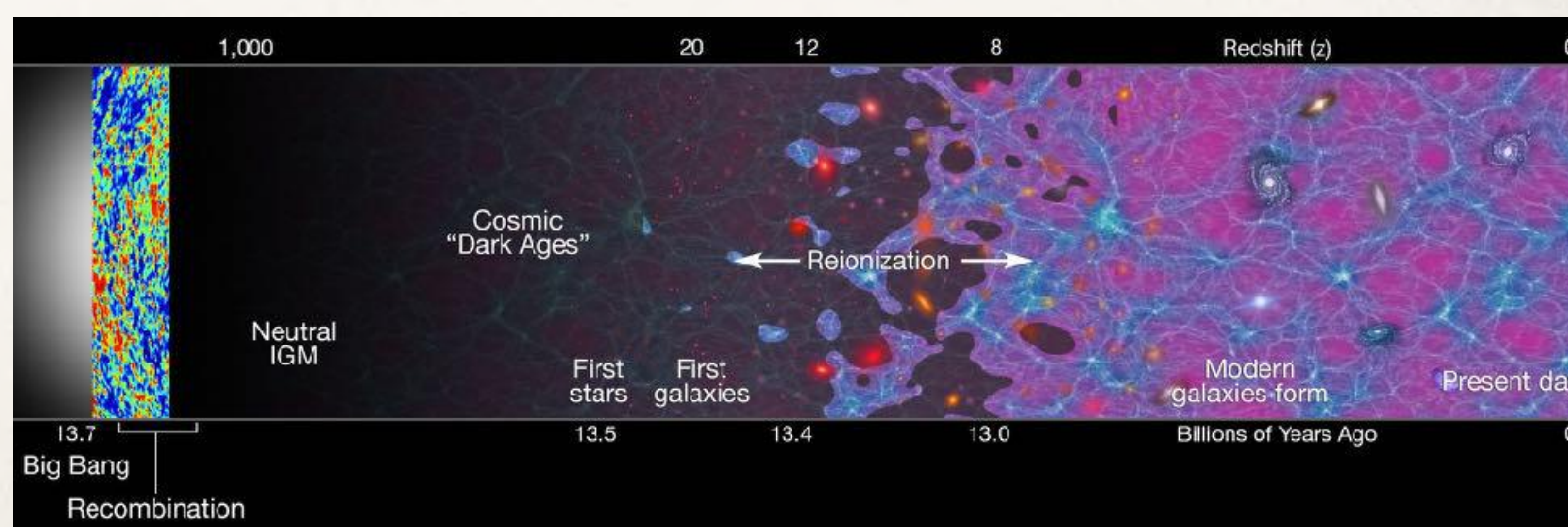
Goals: High-Redshift

- Want to **learn about the first galaxies**, their individual (physical) properties such as SF, gas content, escape fraction, sizes, etc, and as a population (LF)
- How did the first galaxies form? made stars? evolved? on what timescale?
- Understand the reionization process, and important evolutionary phase of the Universe. Could galaxies have even reionized the Universe, or does one need a more exotic form of reionization? when did this happen? how smooth/patchy?

Bouwens+ 2015



Robertson+

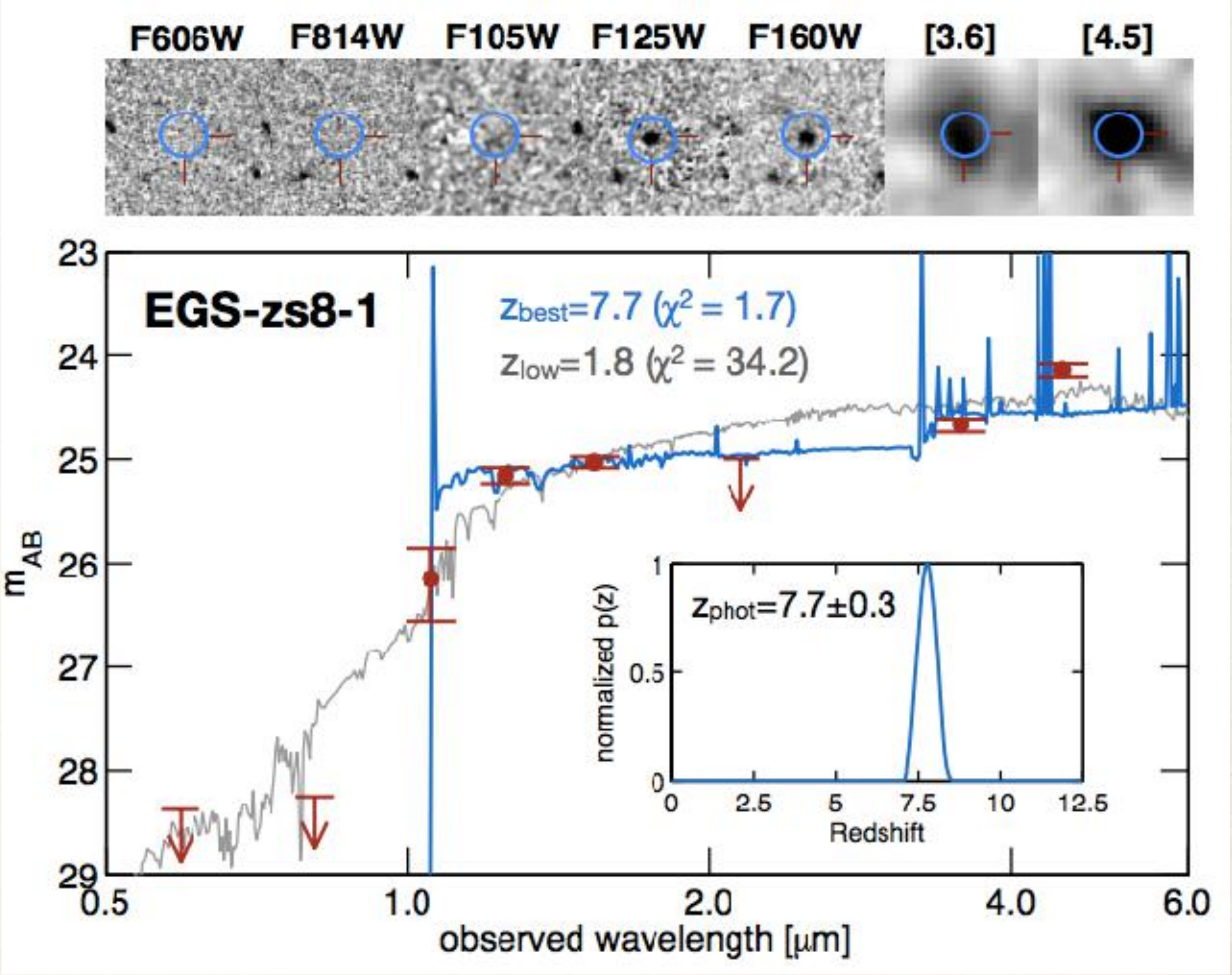


Tools for High-Redshift Route 1: Photometry

Lyman break tells us the redshift

Oesch+ 2015

No flux below 912A

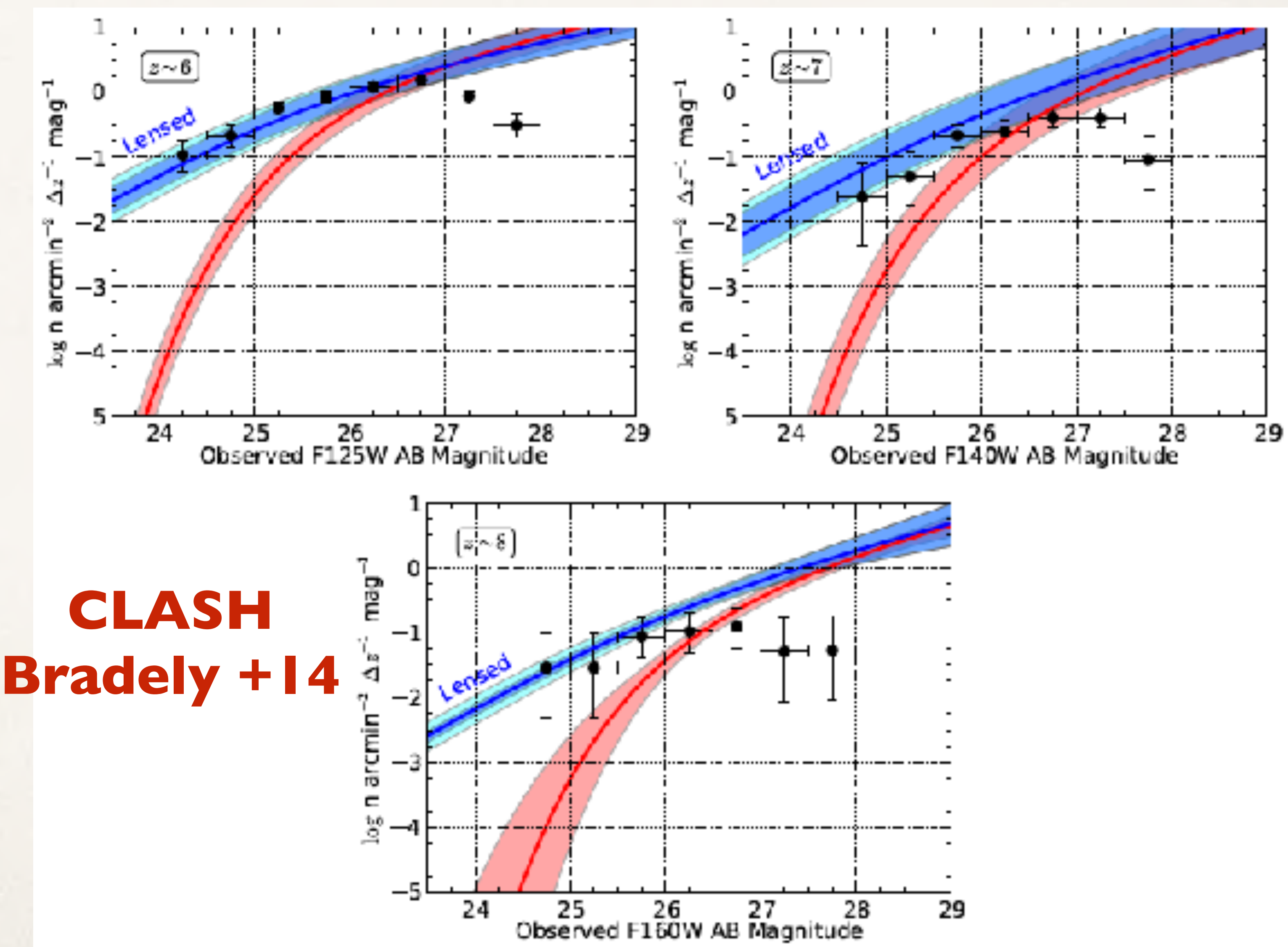


Through the looking glass

Observing the high-z universe through lensing

- We can take advantage of the magnification power of gravitational lenses (especially galaxy clusters) to study the high redshift universe —> can see deeper!

thepoetryquestion.com



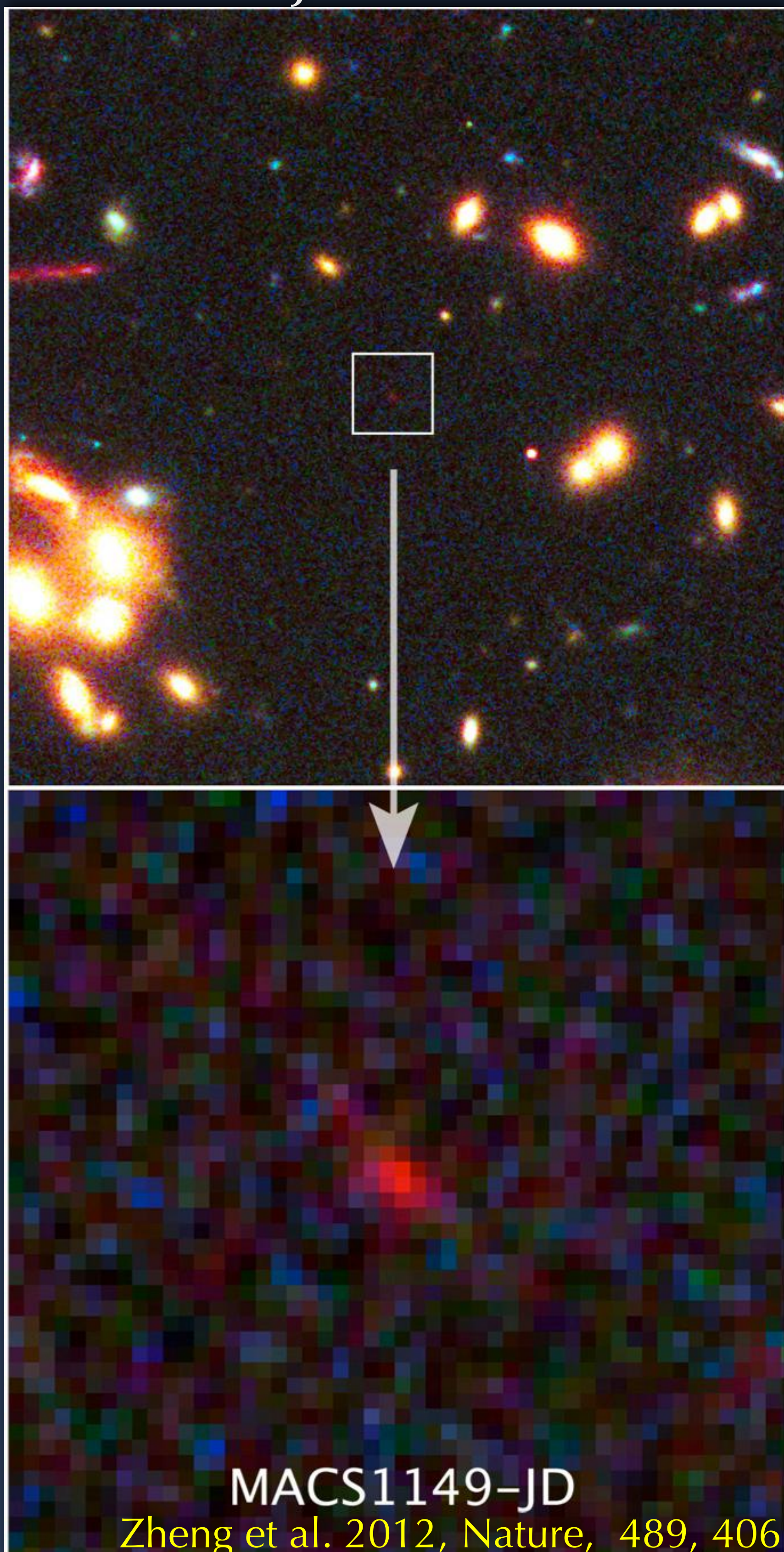
CLASH Bradely +14

Two z > 9 Lensed Galaxies

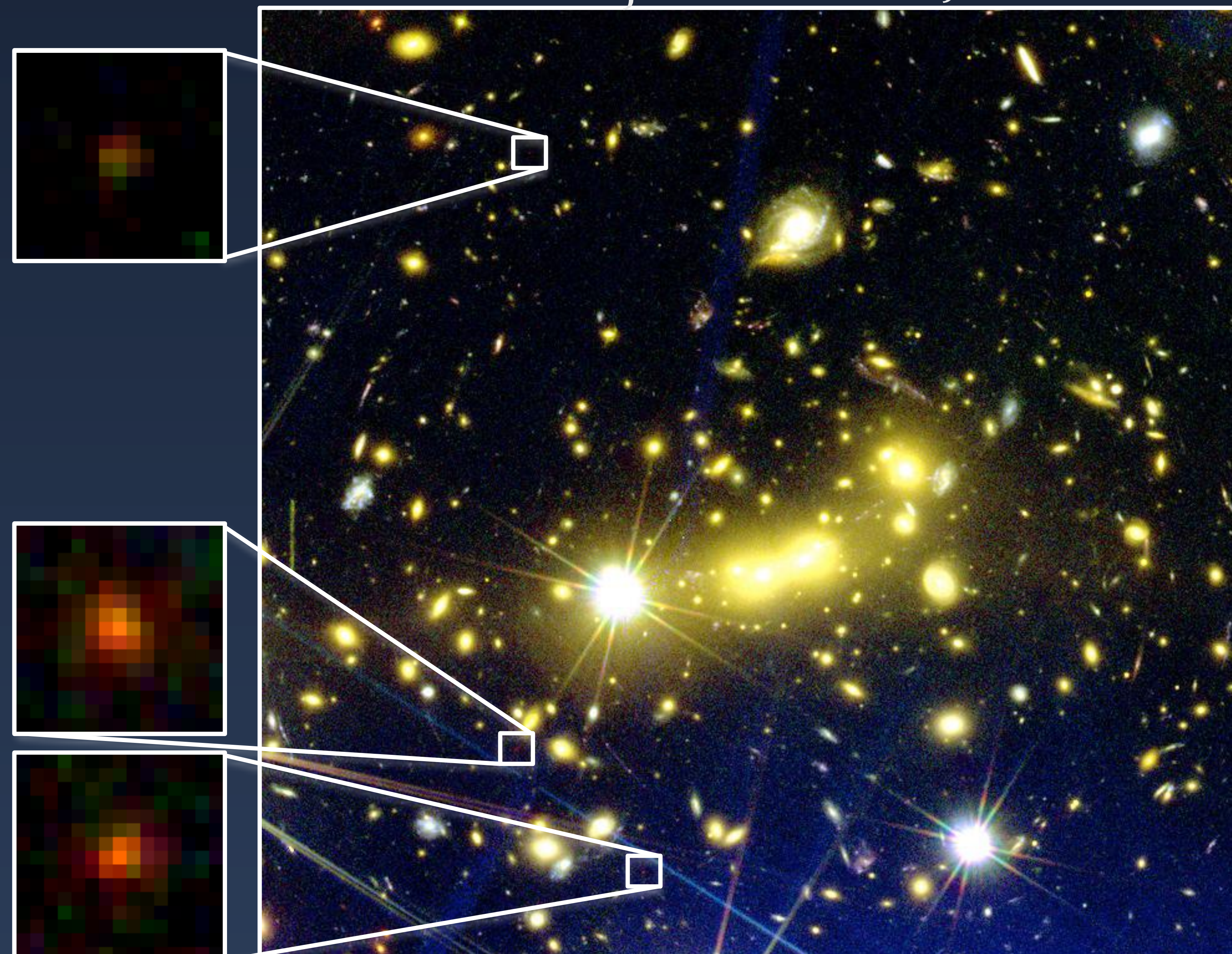
z = 9.6 object in MACSJ1149+2223

SFR~few M_0/yr HLR<100pc

M*~ few10^8 M_0/yr Age: < 200 Myr

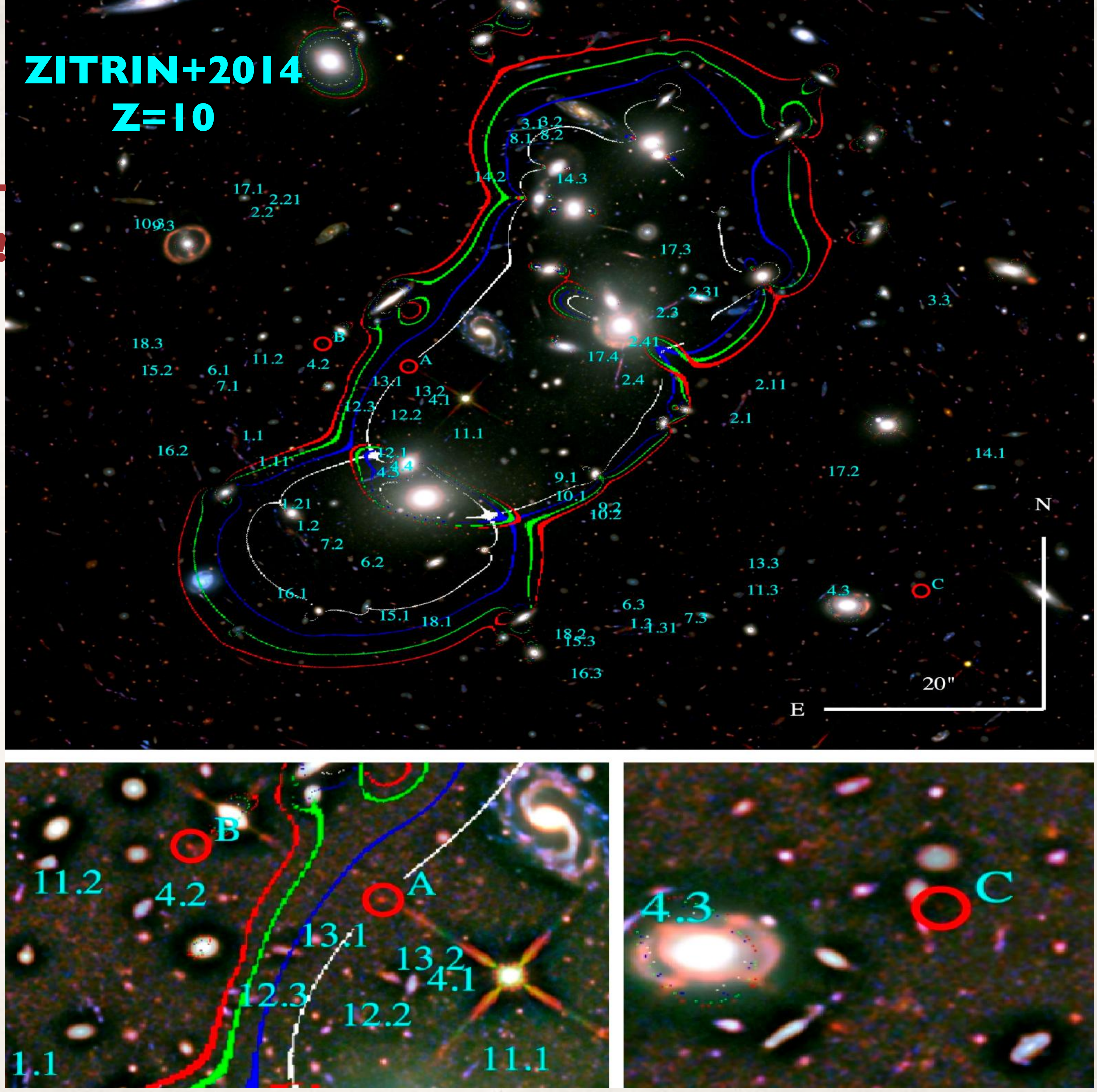


z = 10.8 object in MACSJ0647+7015

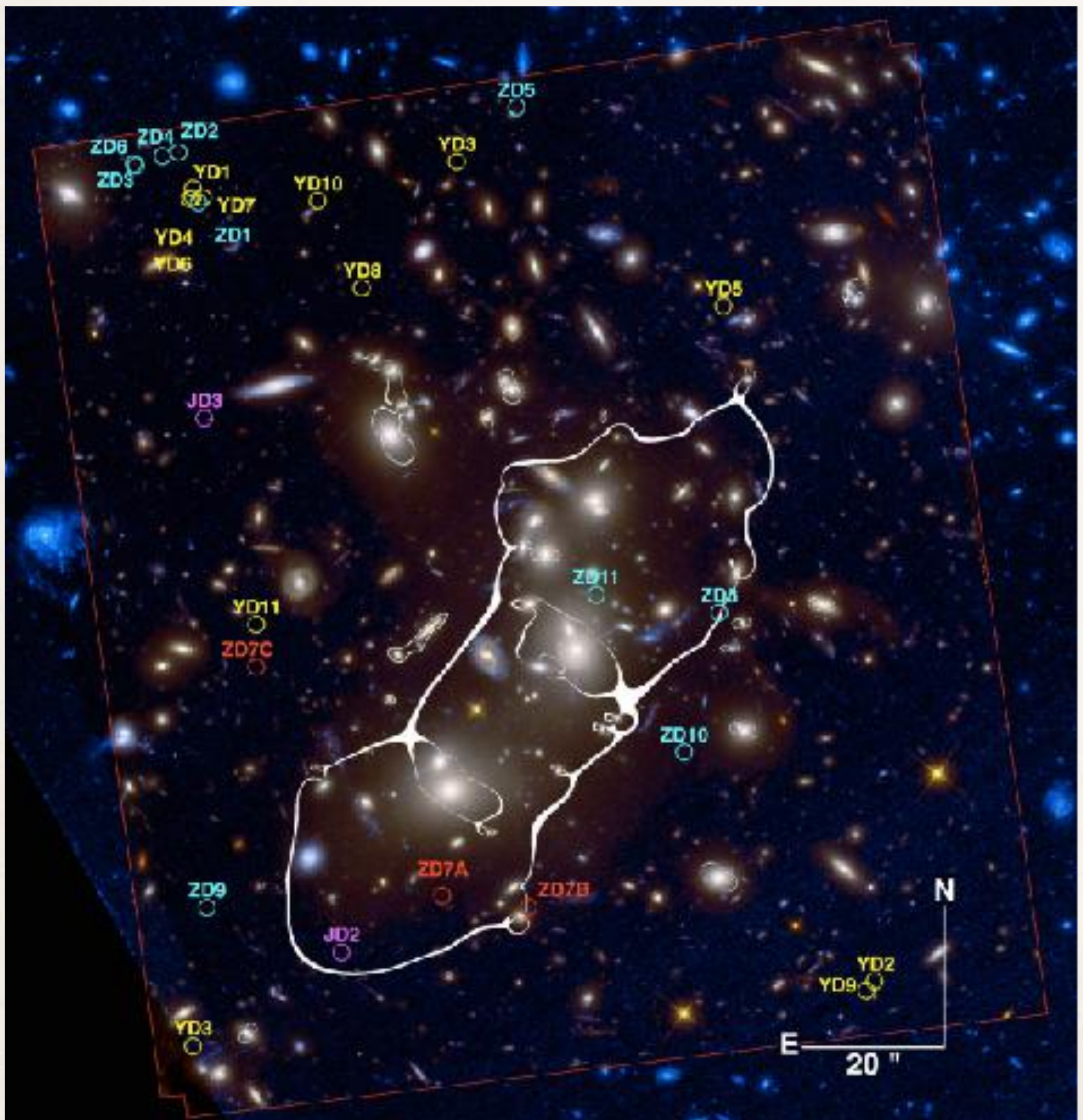


Coe et al. 2013, ApJ, 762, 32

FAINTEST Z~10 OBJ! 0.1L*



Point is: Lensing helps us see deeper!



Zheng et al. 2014

With Lensing,
we see deeper
finding large numbers of
high redshift
galaxies (reionization era)

THE SCIENCE OF LENSING

HIGH REDSHIFT GALAXIES

STAY TUNED FOR LECTURE II

TAKE HOME

SUMMARY

- All background is lensed to some extent
- Lensing effects and size of lens depend on mass and on distances, and position of source
- By how much something is lensed? Deflection angle formula for point mass:

$$\hat{\alpha} = \frac{4GM}{c^2 b}$$

- Alpha is constrained with multiple images through lens equation (SL): $\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{D_{LS}}{D_{OS}} \hat{\boldsymbol{\alpha}}$.
- Alpha is then related to the mass distribution through: $\vec{\nabla}_\theta \vec{\alpha}(\vec{\theta}) = 2\kappa(\vec{\theta})$
- Shear is constrained in WL regime through ellipticity measurements, also invertible to kappa
- Magnification is given by $\mu = \frac{1}{\det A} = \frac{1}{[(1-\kappa)^2 - \gamma^2]}$

TAKE HOME

SUMMARY

- With lensing we can:

- **Map the mass distribution of lens, including dark matter** (via multiple images, shear), probe cosmological parameters (via distances), H_0 (via time delays), constraints on DM particles (microlensing and caustic crossing events), other transient phenomena (lensed SNe, gravitational waves)

- Study **high-redshift galaxies** and reionization (magnification, spectroscopy of high redshift galaxies) —> our next talk, Lecture II.

- Questions, + If anyone feels they still don’t know what lensing is or what we do with it - come see me!