GRAVITATIONAL LENSING QUASARS - WHAT CAN WE LEARN FROM…

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special thanks to

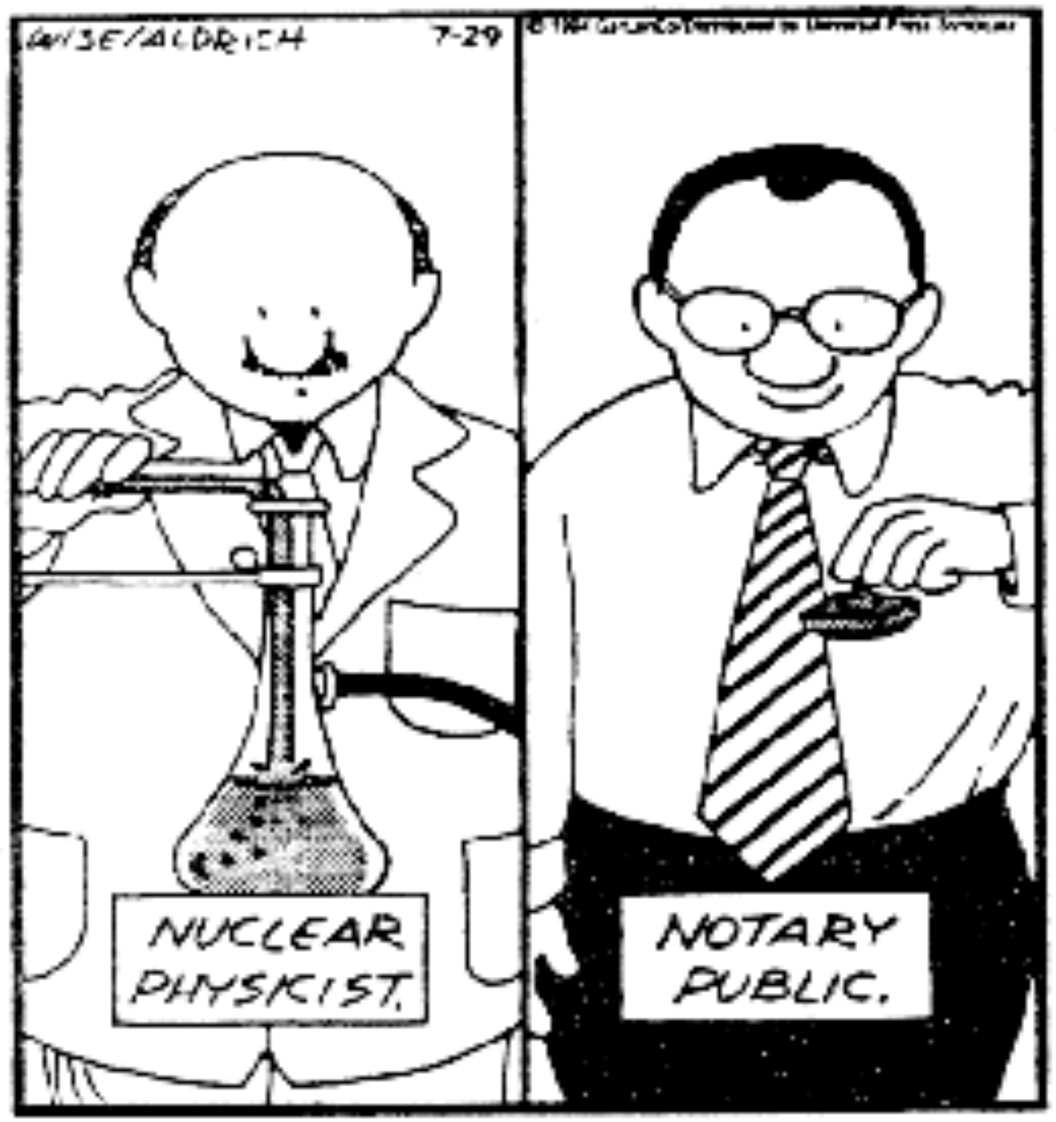
Carina Fian

Evencio Mediavilla

IAC

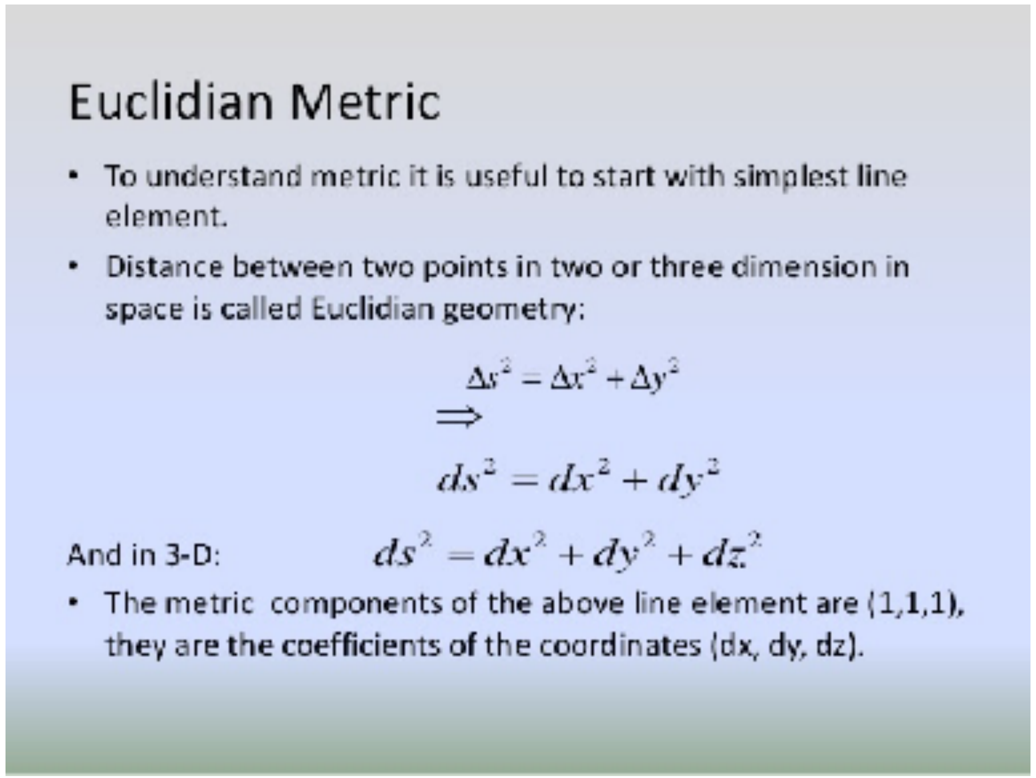
HOW TO DO PHYSICS??

Real Life Adventures



Jobs in which nobody understands what you do.

How to do physics??



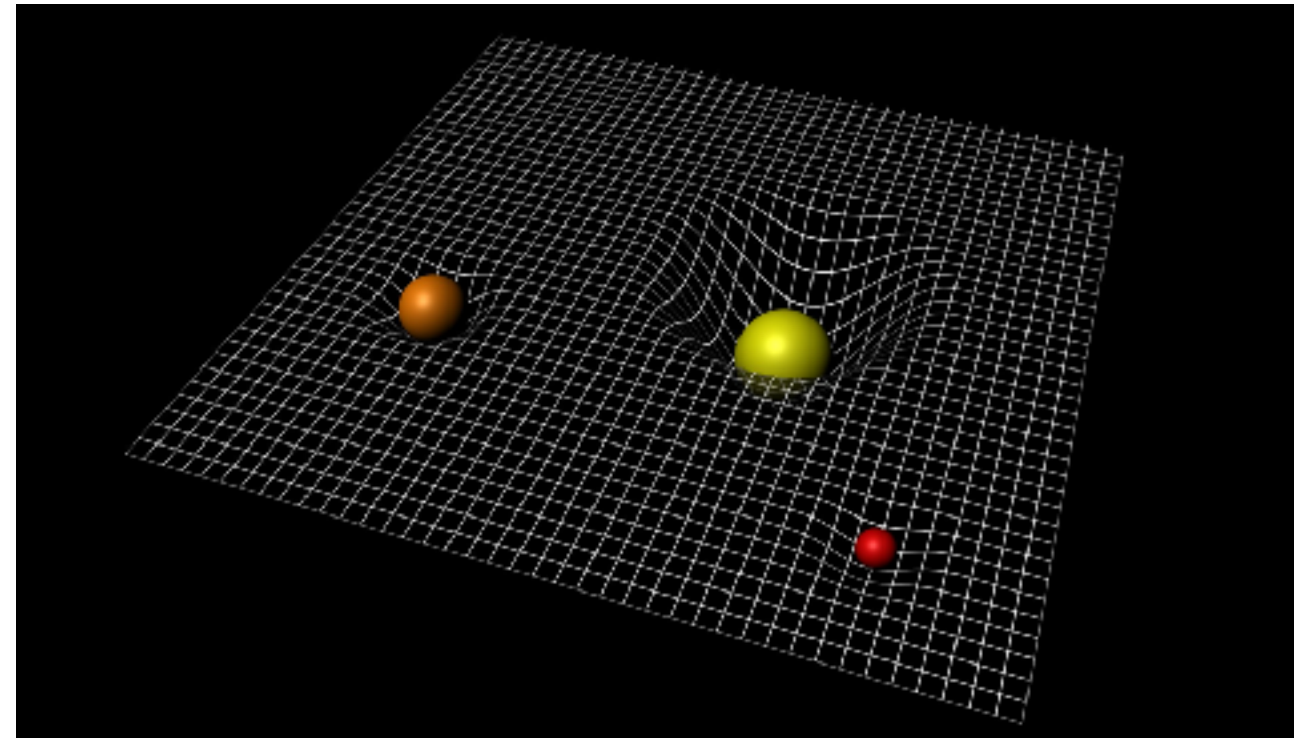
Euclidian Metric

- To understand metric it is useful to start with simplest line element.
- Distance between two points in two or three dimension in space is called Euclidian geometry:

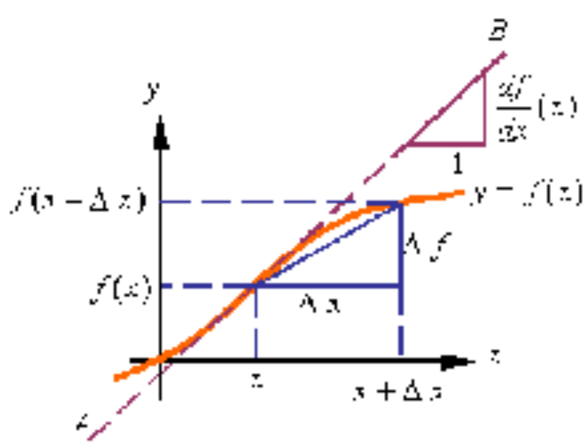
$$\Delta s^2 = \Delta x^2 + \Delta y^2$$
$$\Rightarrow$$
$$ds^2 = dx^2 + dy^2$$

And in 3-D: $$ds^2 = dx^2 + dy^2 + dz^2$$

- The metric components of the above line element are (1,1,1), they are the coefficients of the coordinates (dx, dy, dz).



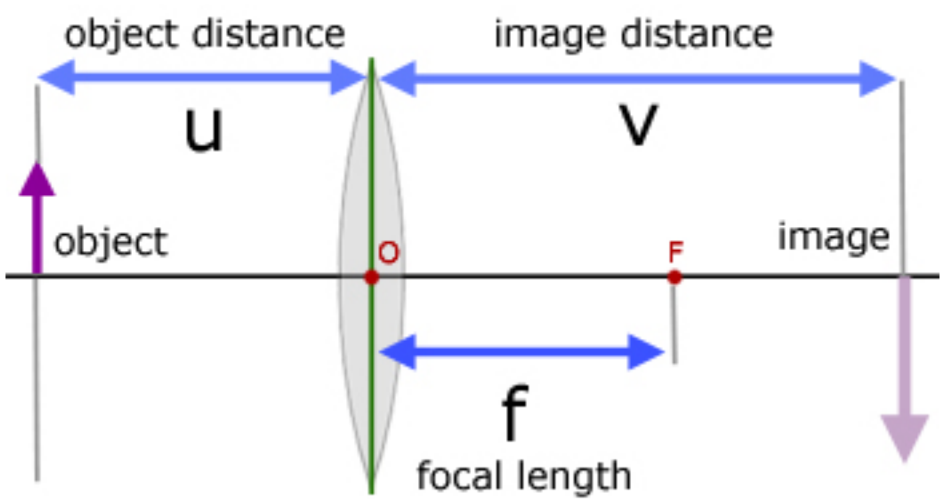
$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

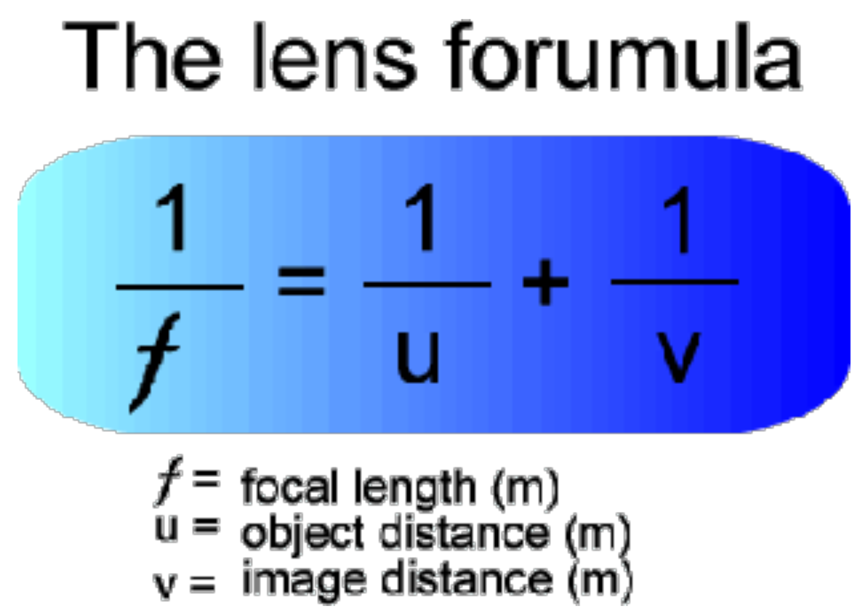


$$g_{\mu\nu} = \begin{pmatrix} -\left(1 - \frac{r_s}{r}\right) & 0 & 0 & 0 \\ 0 & \frac{1}{\left(1 - \frac{r_s}{r}\right)} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2 \sin^2\theta \end{pmatrix}$$

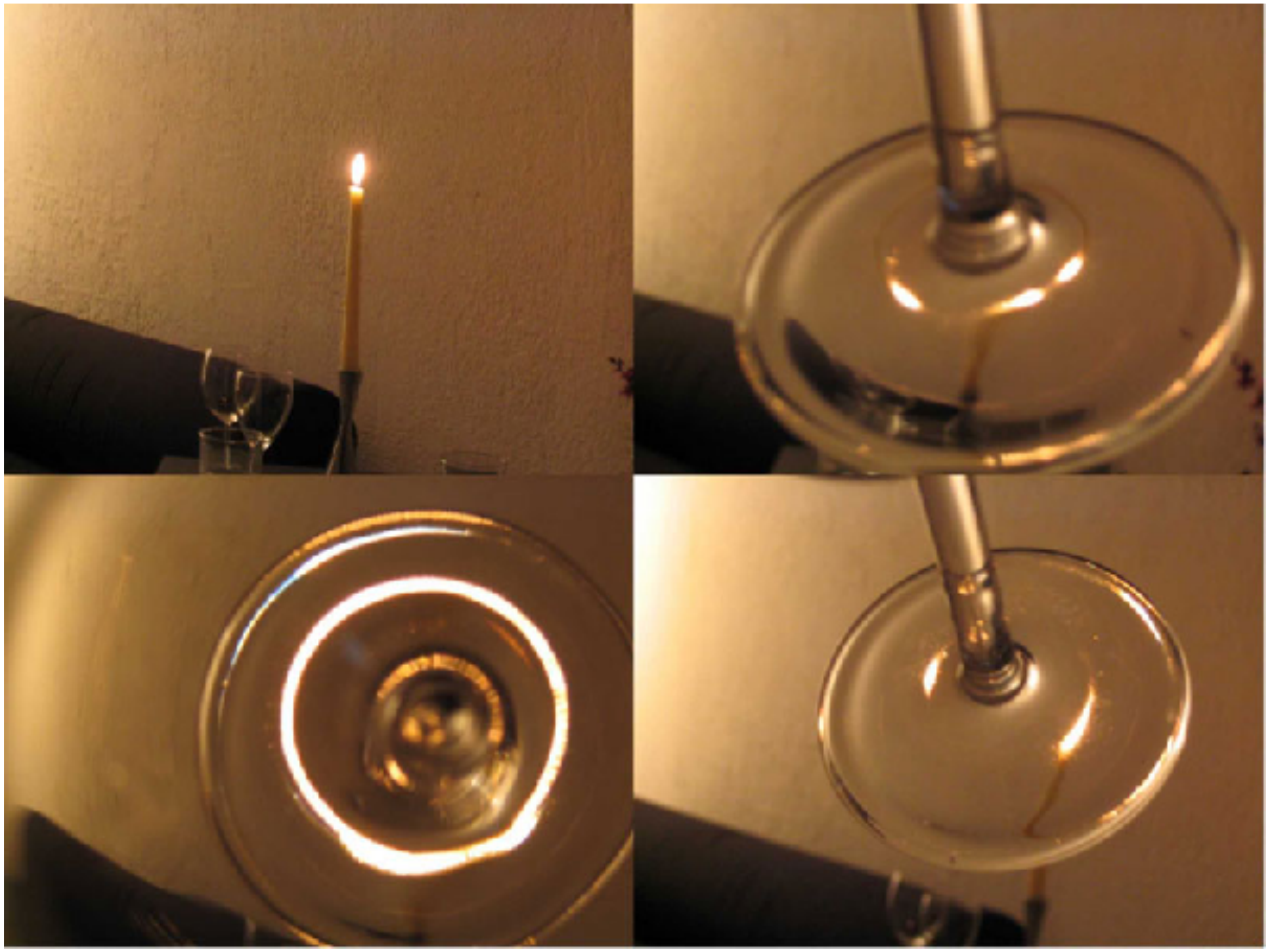
GRAVITATIONAL LENSING PRINCIPLES

- Common: bending of light by optics
- linear lenses: one sees only a single image of the object of interest.

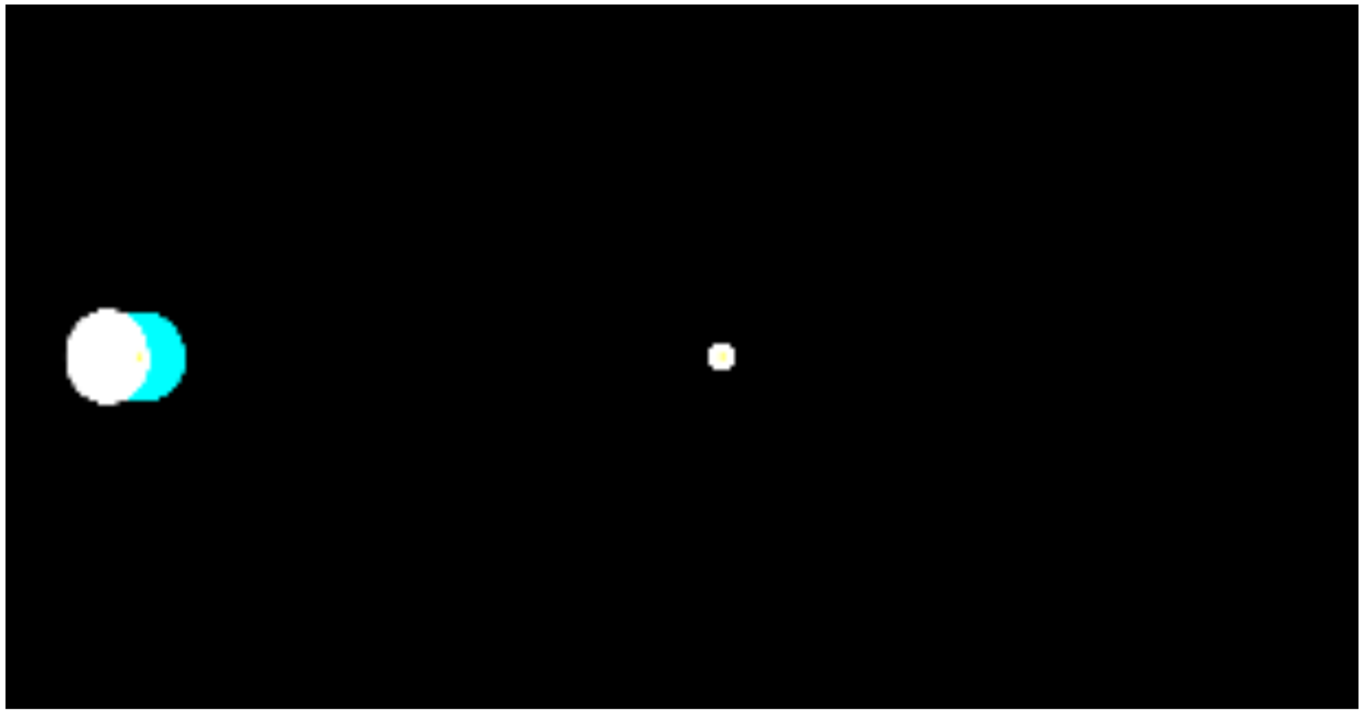




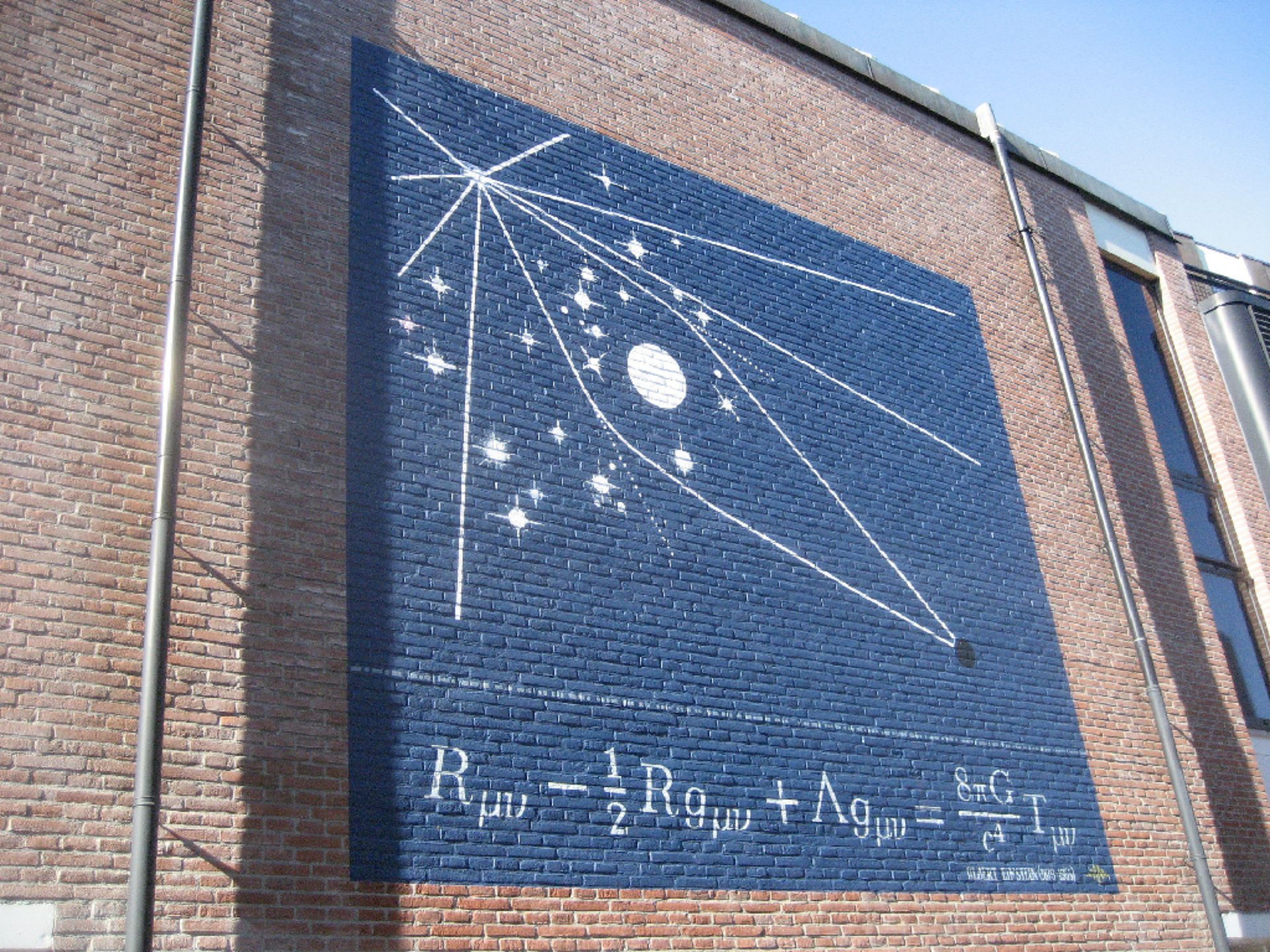
- non linear lenses: wine glass, candle example



- by tilting the base of the wine glass we change the properties of the optical lens and thus the light path we see.

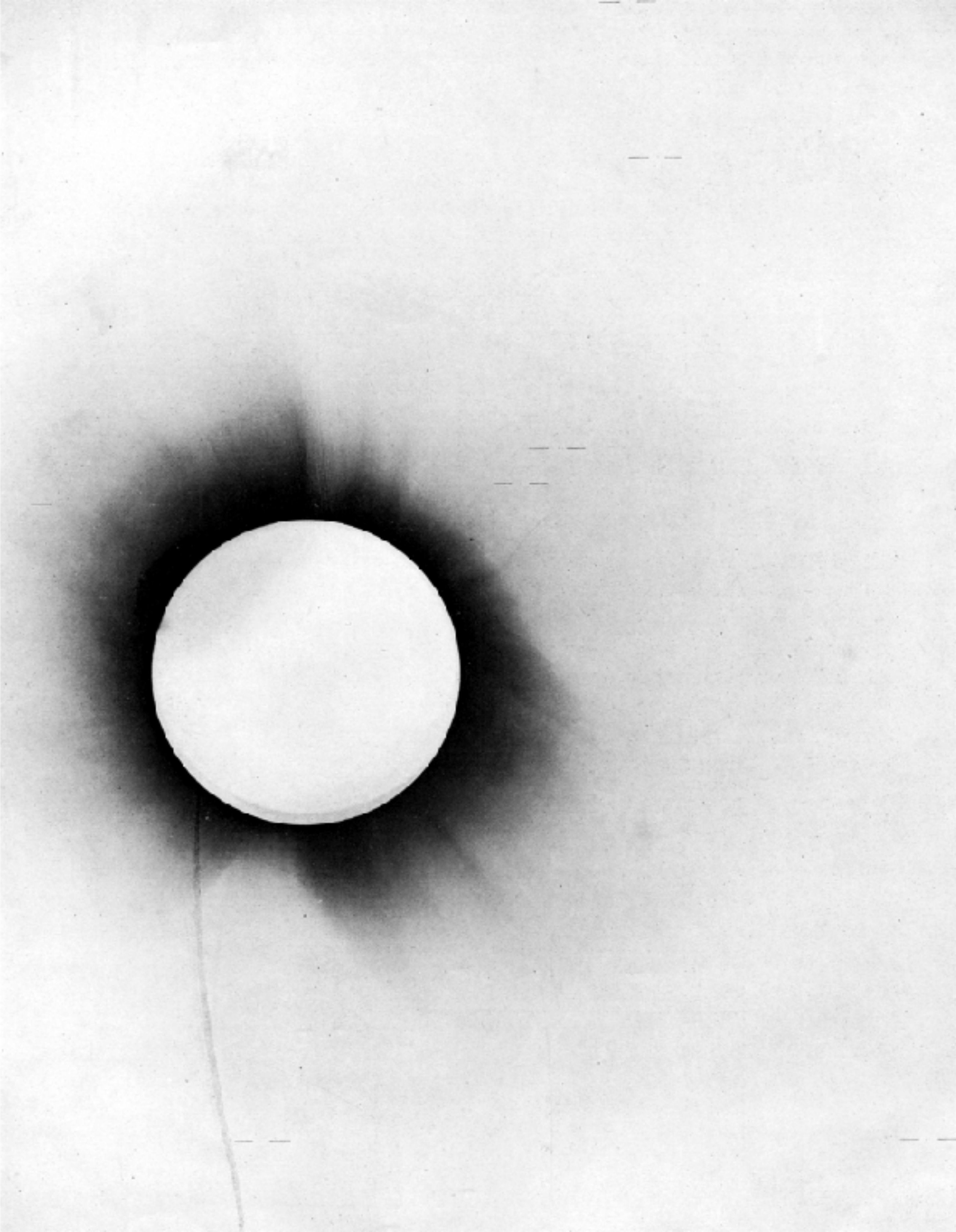


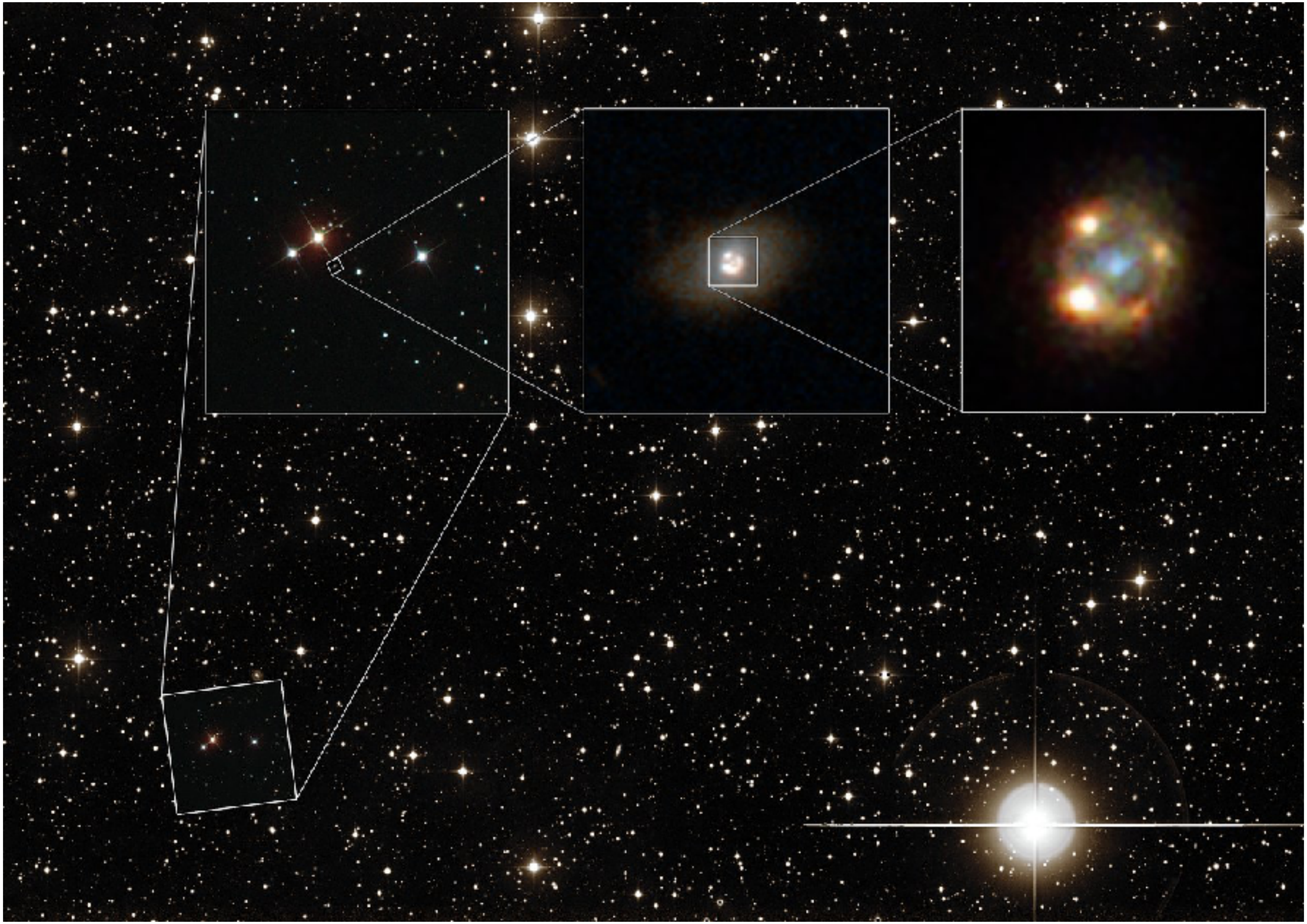
A light source passes behind a gravitational lens (point mass placed in the center of the image). The aqua circle is a source as it would be seen if there was no lens; white spots are the multiple images of the source.


$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$

Testing general relativity

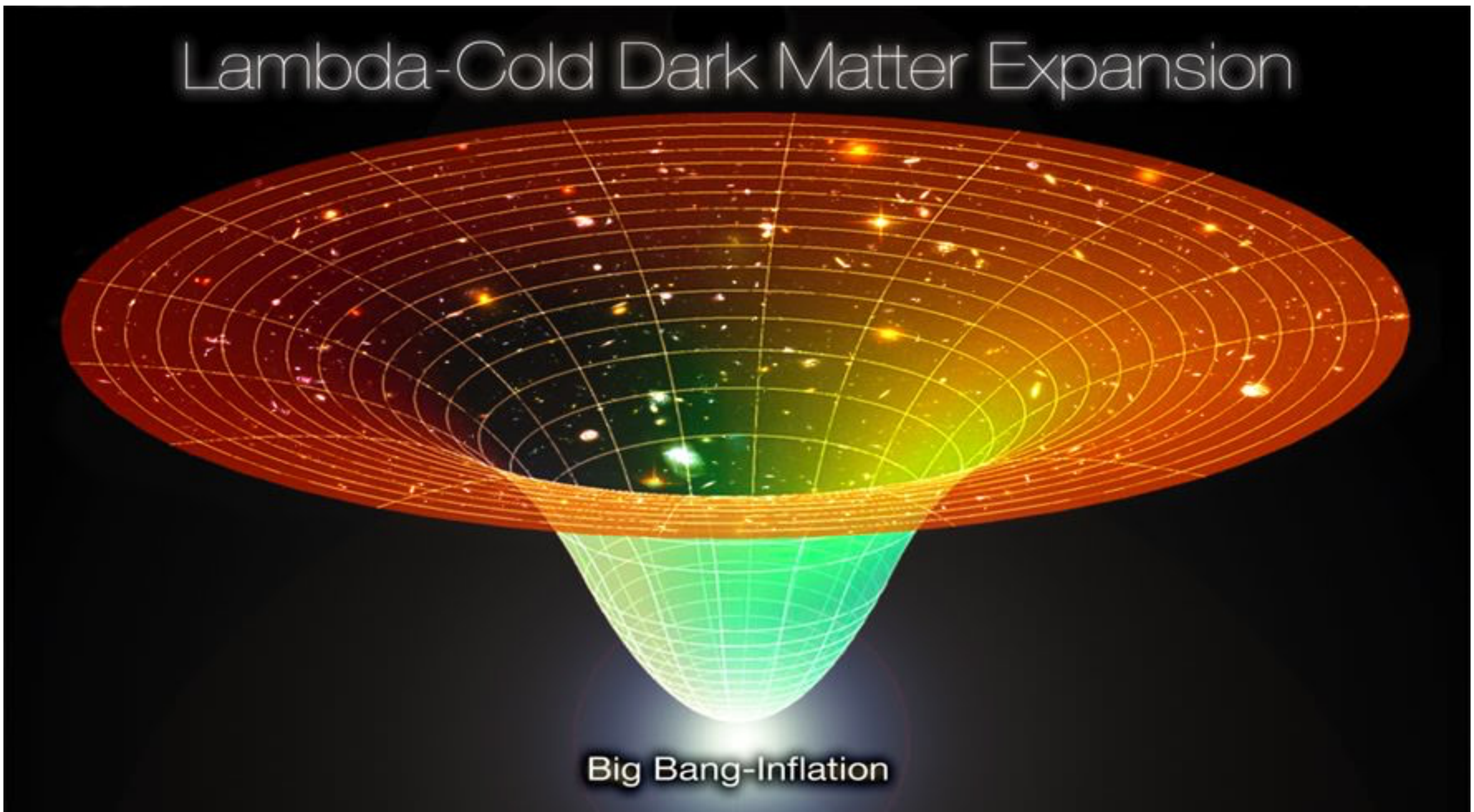
Eddington 1919, total solar eclipse



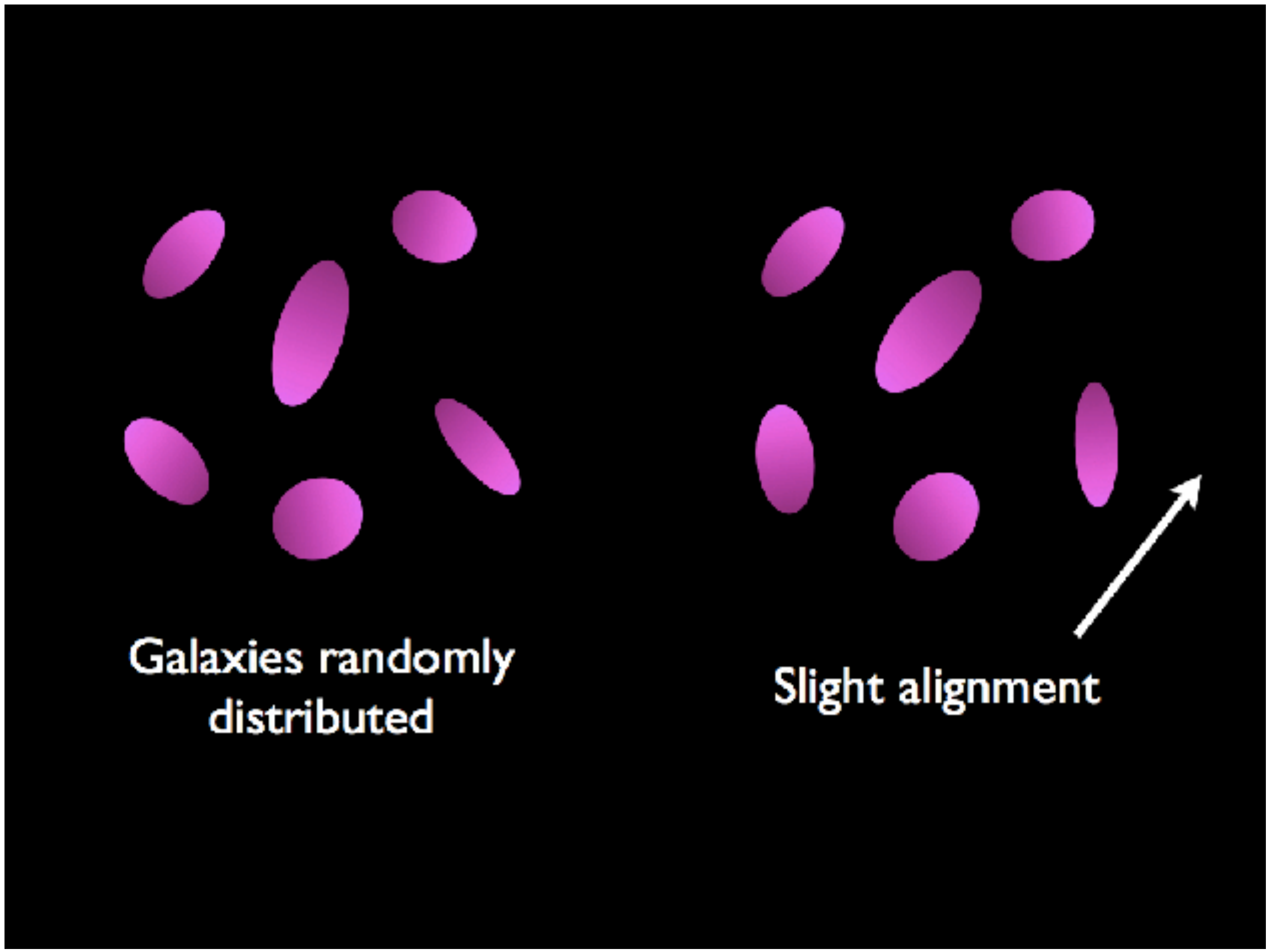


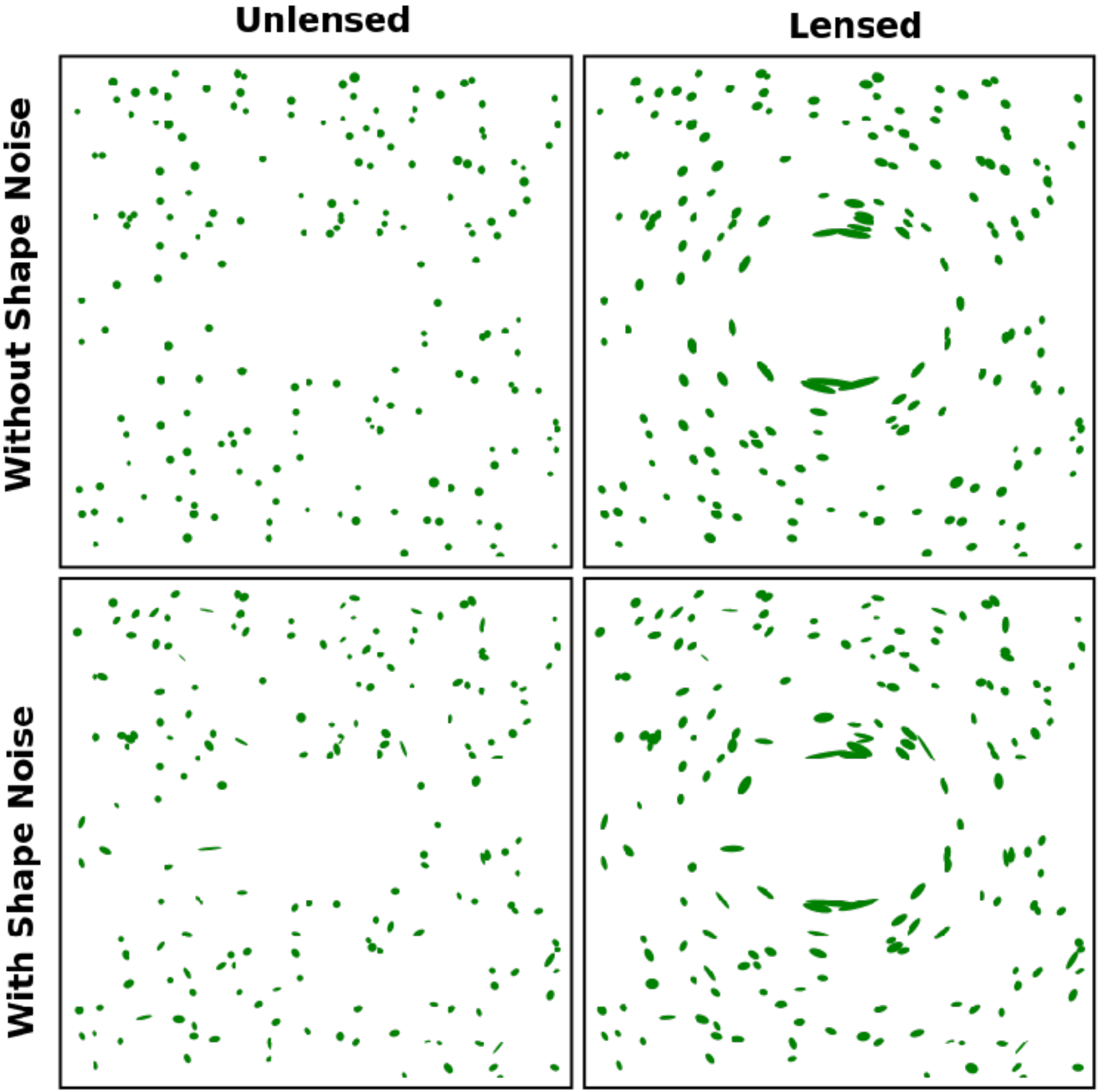
Gravitationally lensed Supernova Ia

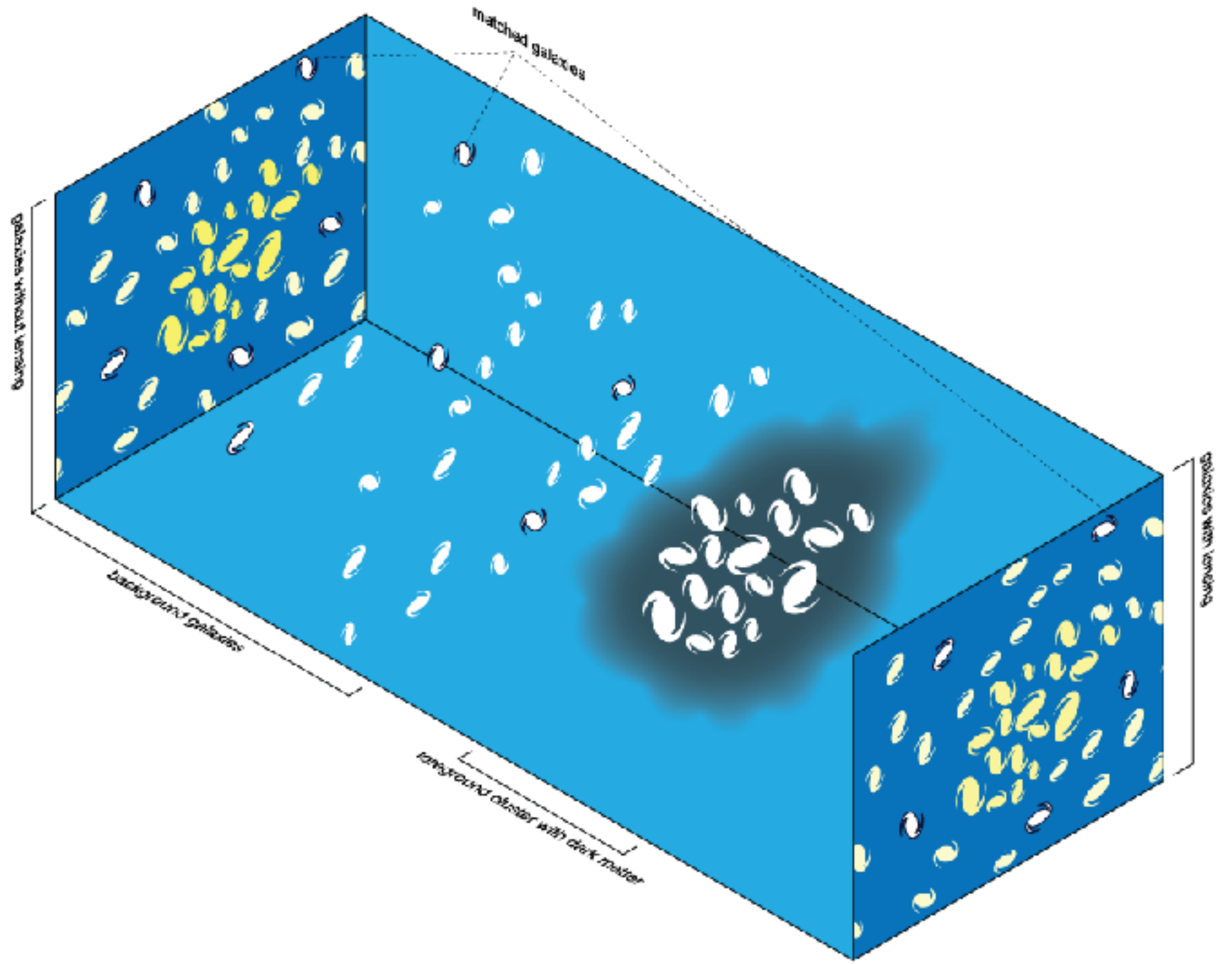
- strong lensing: visible distortions, Einstein rings, multiple images
- weak lensing: analyzing large numbers of objects —> distortions; stretching of background objects; large number of distant galaxies:
  - shapes, orientation —> distribution of matter in that area —>dark matter distribution. Lambda DCM Model



weak lensing

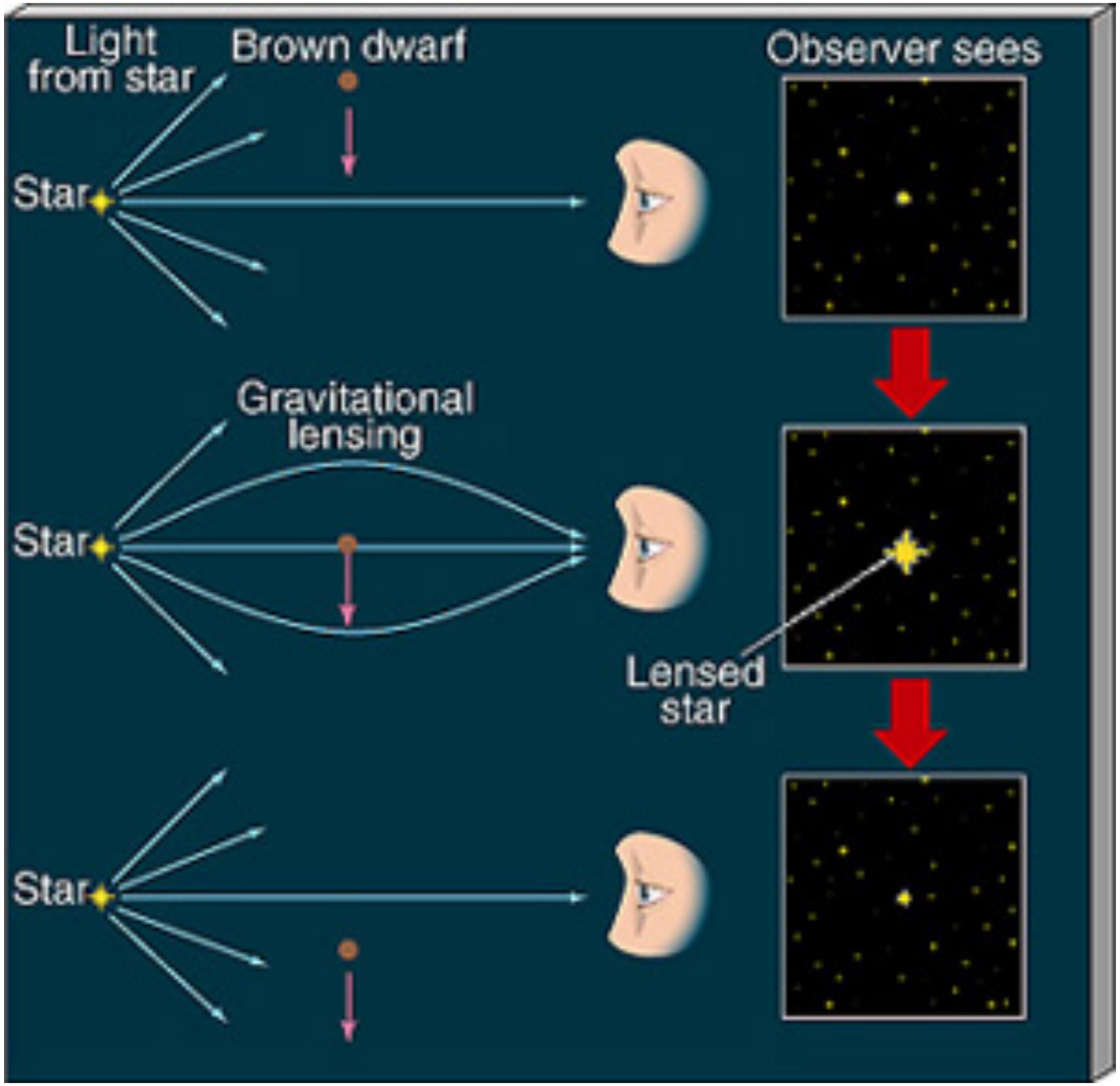



Unlensed
Lensed
Without Shape Noise
With Shape Noise

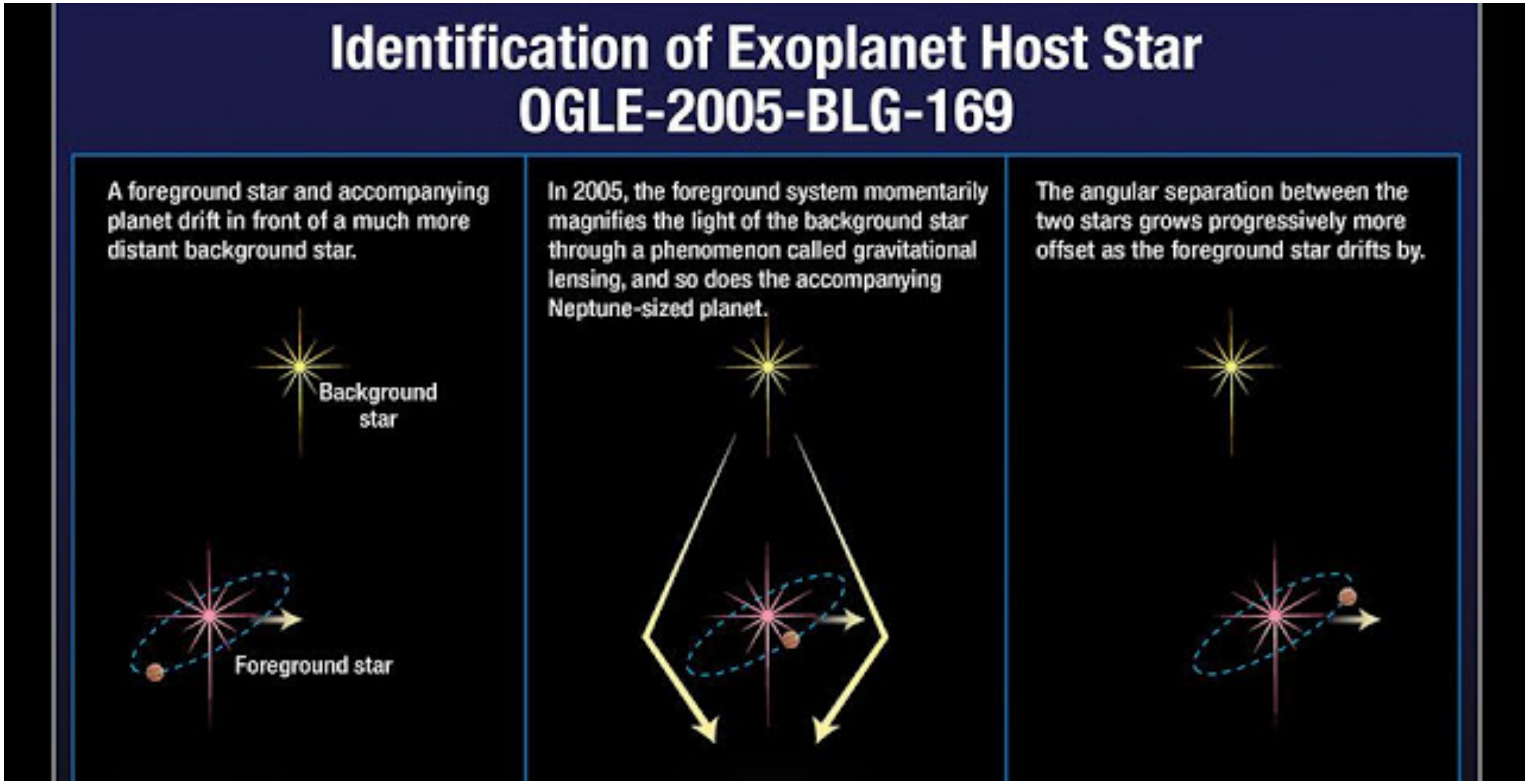


The effects of foreground galaxy cluster mass on background galaxy shapes. The upper left panel shows (projected onto the plane of the sky) the shapes of cluster members (in yellow) and background galaxies (in white), ignoring the effects of weak lensing. The lower right panel shows this same scenario, but includes the effects of lensing. The middle panel shows a 3-d representation of the positions of cluster and source galaxies, relative to the observer. Note that the background galaxies appear stretched tangentially around the cluster.

- Microlensing: where no distortion in shape can be seen but the amount of light received from a background object changes in time.
- The lensing object may be stars in the Milky Way with the background source being stars in a remote galaxy,
- or even more distant quasar.
- The effect is small, such that (in the case of strong lensing) even a galaxy with a mass more than 100 billion times that of the Sun will produce multiple images separated by only a few arcseconds.
- Galaxy clusters can produce separations of several arcminutes.
- In both cases the galaxies and sources are quite distant, many hundreds of megaparsecs away from our Galaxy.



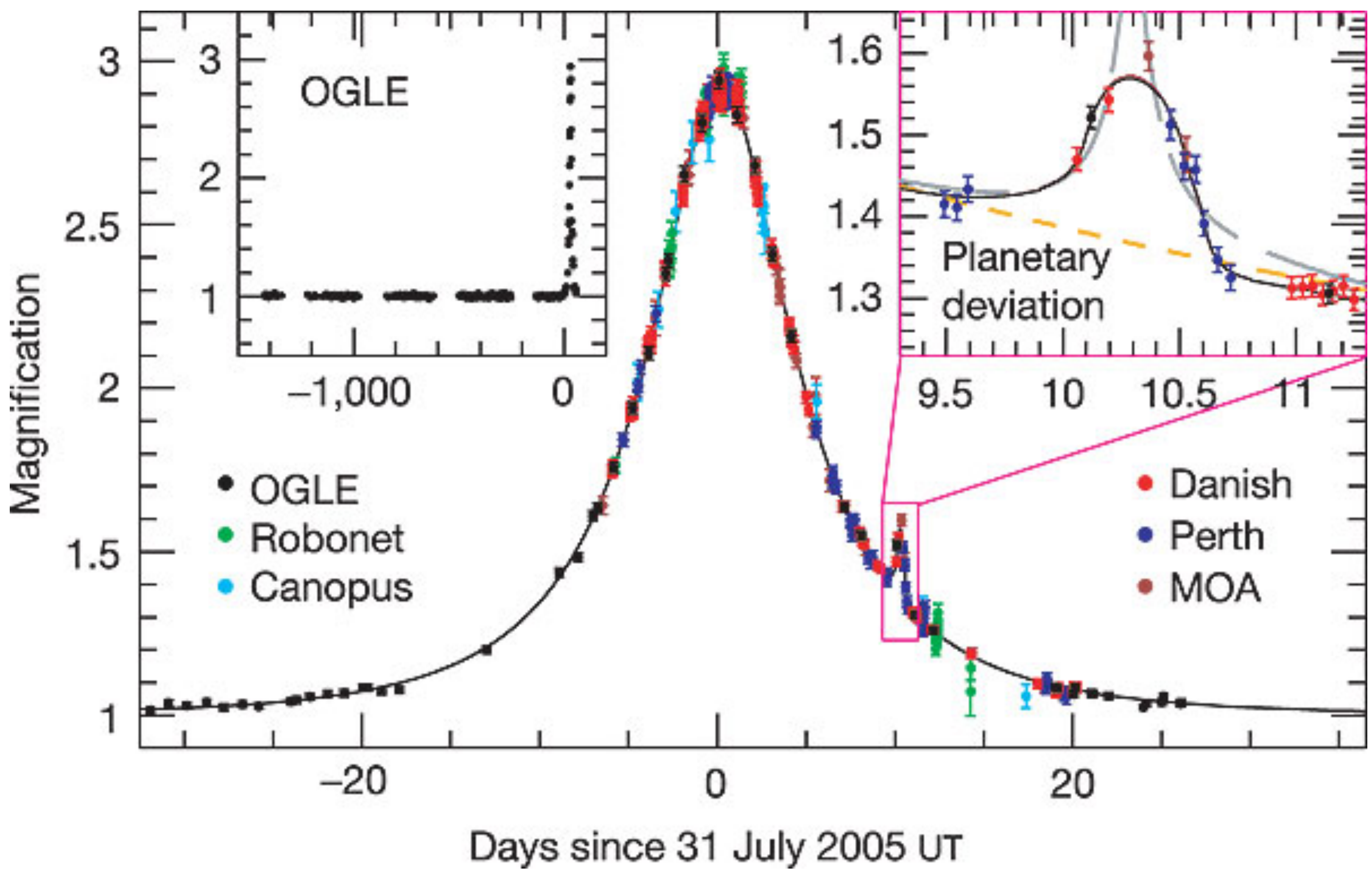
Light from star
Brown dwarf
Observer sees
Star
Gravitational lensing
Star
Lensed star
Star


Identification of Exoplanet Host Star
OGLE-2005-BLG-169
A foreground star and accompanying planet drift in front of a much more distant background star.
Background star
Foreground star
In 2005, the foreground system momentarily magnifies the light of the background star through a phenomenon called gravitational lensing, and so does the accompanying Neptune-sized planet.
The angular separation between the two stars grows progressively more offset as the foreground star drifts by.

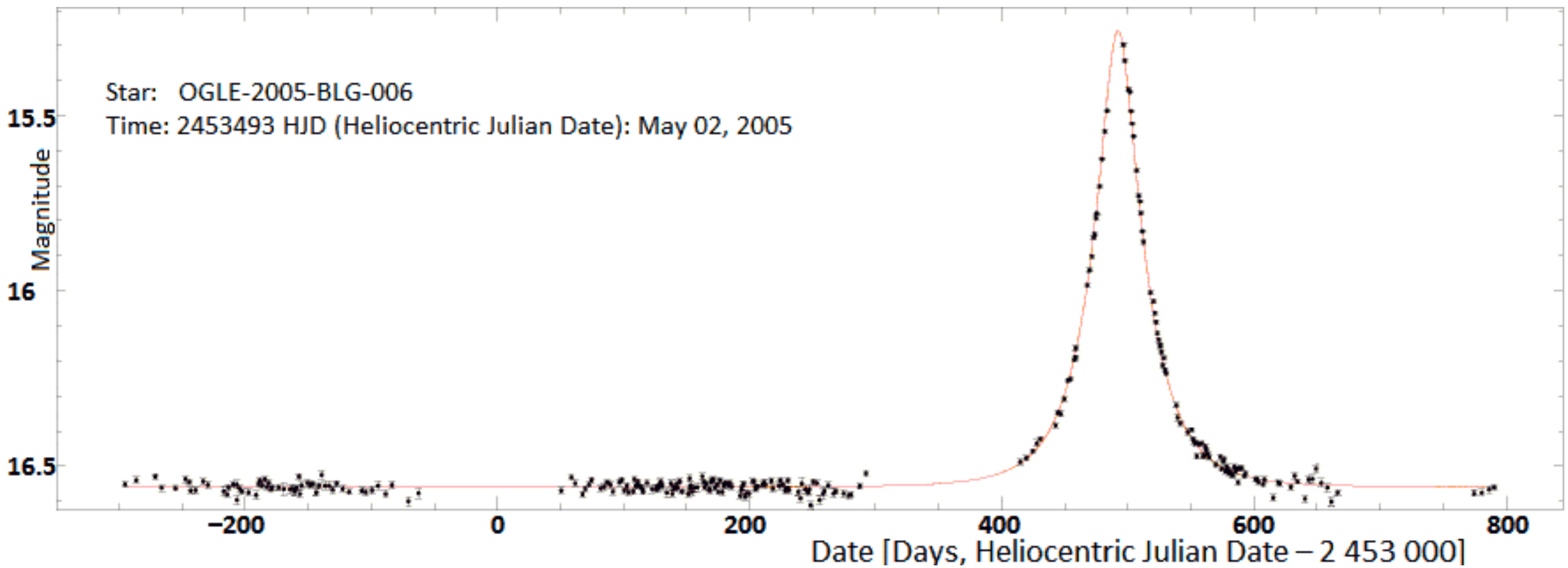
OGLE

Optical **G**ravitational **L**ensing **E**xperiment

Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing

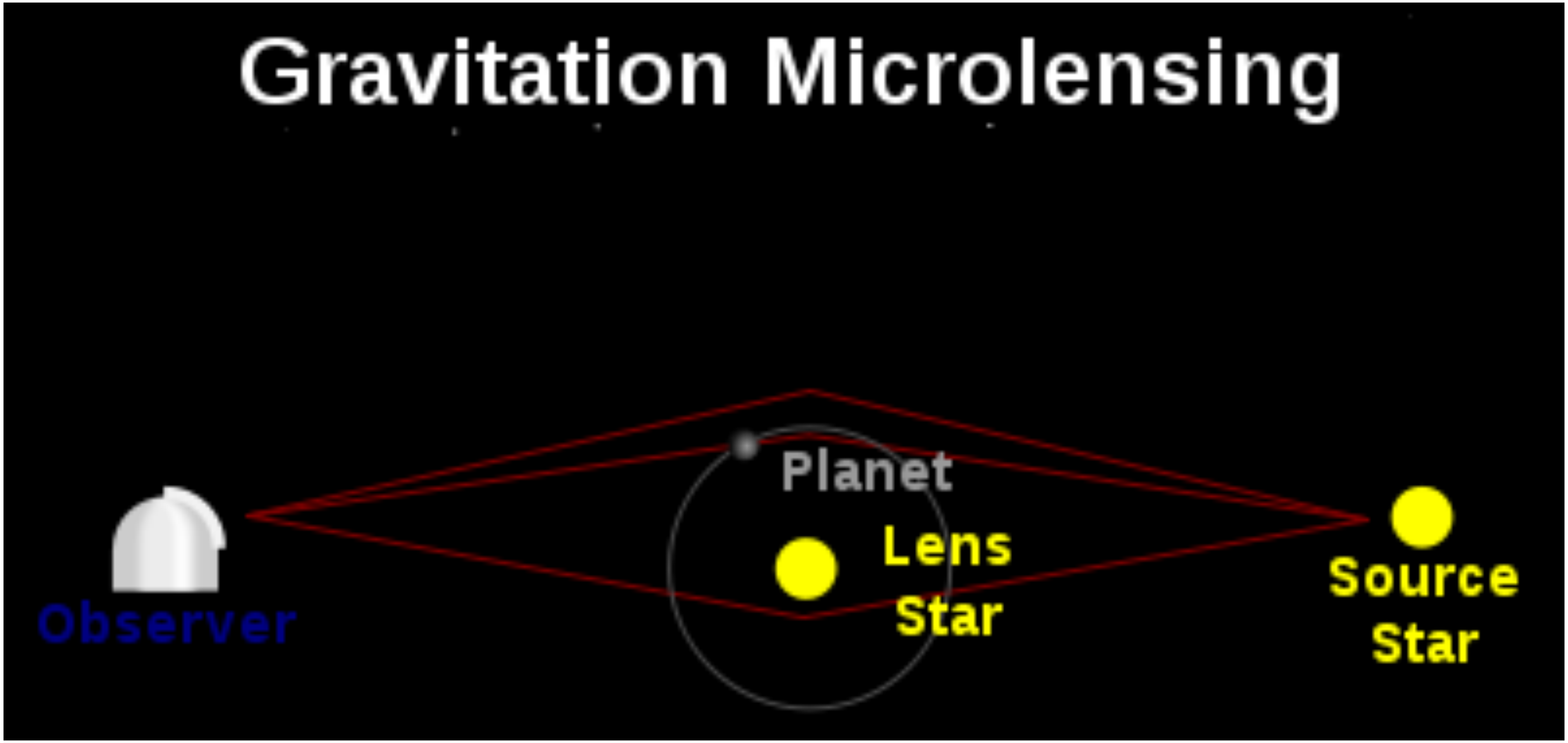


Object at a distance > 6.5 kpc



Typical light curve of gravitational microlensing event (OGLE-2005-BLG-006) with its model fitted (red)

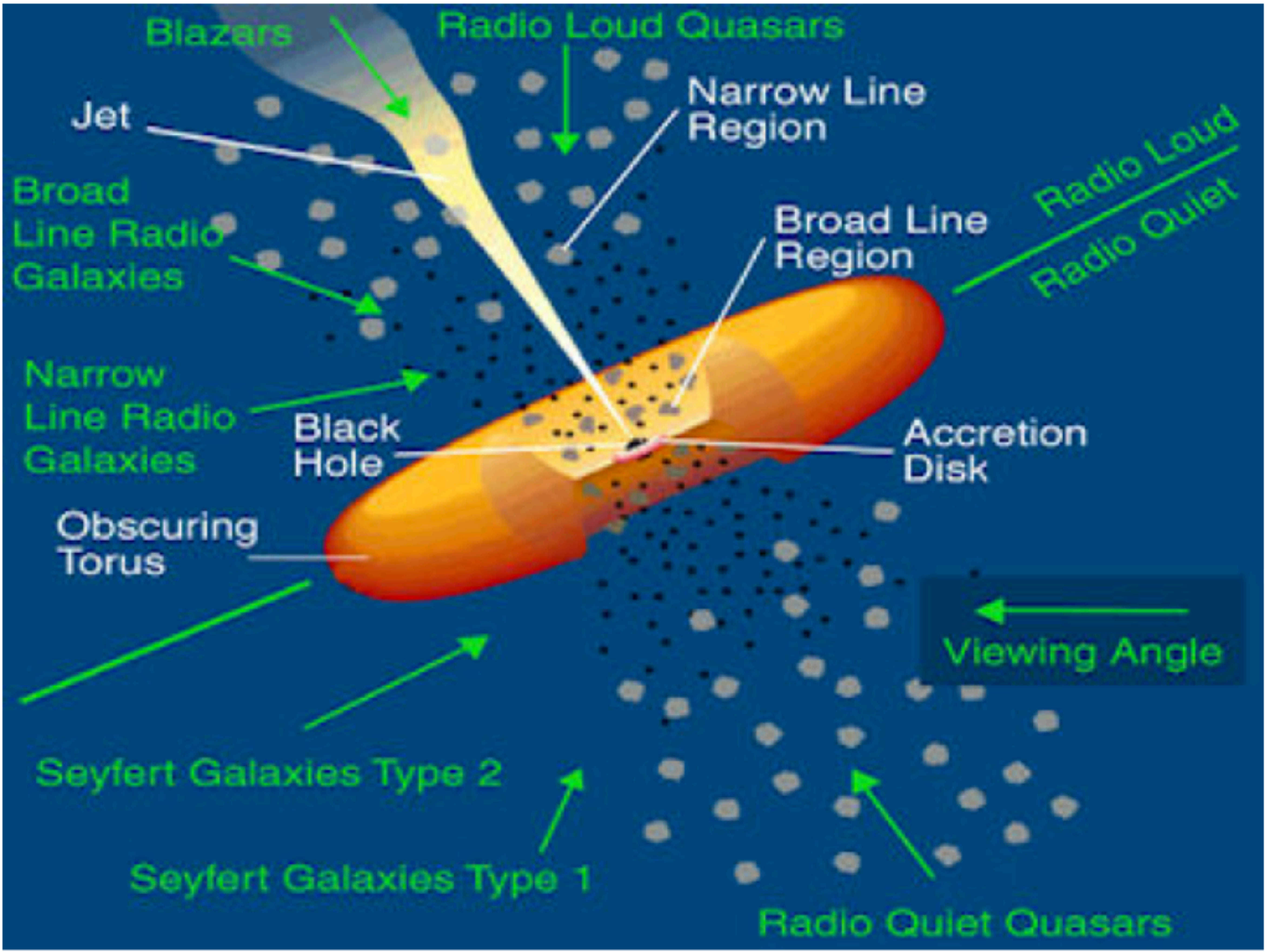
- Lens mass distribution. If the lens mass is not concentrated in a single point, the light curve can be dramatically different, particularly with caustic-crossing events, which may exhibit strong spikes in the light curve. In microlensing, this can be seen when the lens is a binary star or a planetary system.
- Finite source size. In extremely bright or quickly-changing microlensing events, like caustic-crossing events, the source star cannot be treated as an infinitesimally small point of light: the size of the star's disk and even limb darkening can modify extreme features.
- Parallax. For events lasting for months, the motion of the Earth around the Sun can cause the alignment to change slightly, affecting the light curve.


Gravitation Microlensing
Planet
Lens
Star
Source
Star
Observer

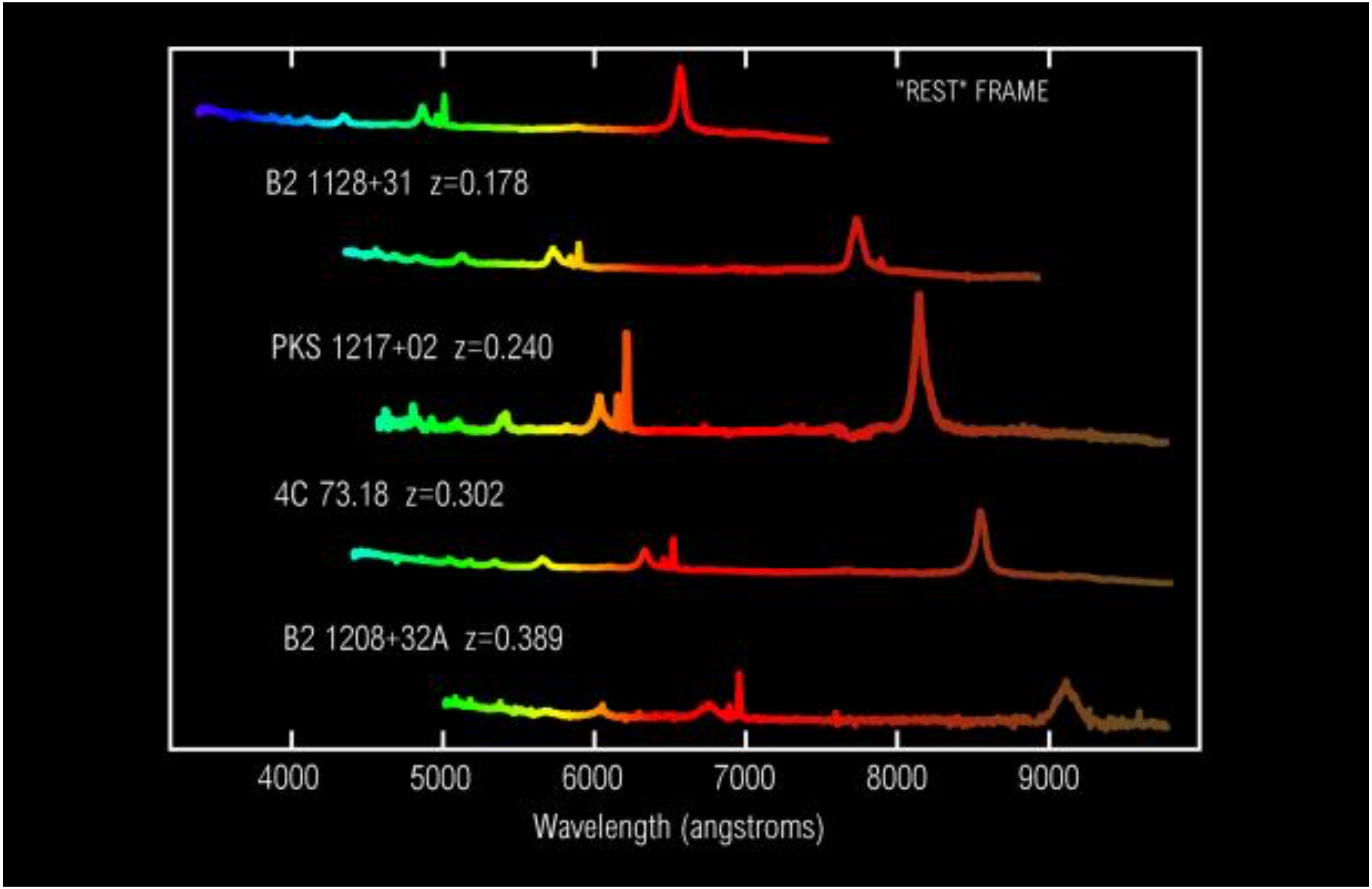
QUASARS - DETECTION

- Discovery in the 1960s, as radio sources
- counterparts in the visible, point-like blemish objects, similar to stars
- spectra: strange not stellar like broad emission lines
- 1963 Maarten Schmidt: wavelengths of emission lines make sense <—>strong redshift
- Quasar redshifts: extremely high receeding velocities.

Quasars are extremely luminous objects at great distances



Blazars
Radio Loud Quasars
Narrow Line Region
Jet
Radio Loud
Radio Quiet
Broad Line Radio Galaxies
Broad Line Region
Narrow Line Radio Galaxies
Black Hole
Accretion Disk
Obscuring Torus
Viewing Angle
Seyfert Galaxies Type 2
Seyfert Galaxies Type 1
Radio Quiet Quasars



"REST" FRAME
B2 1128+31 z=0.178
PKS 1217+02 z=0.240
4C 73.18 z=0.302
B2 1208+32A z=0.389
4000
5000
6000
7000
8000
9000
Wavelength (angstroms)

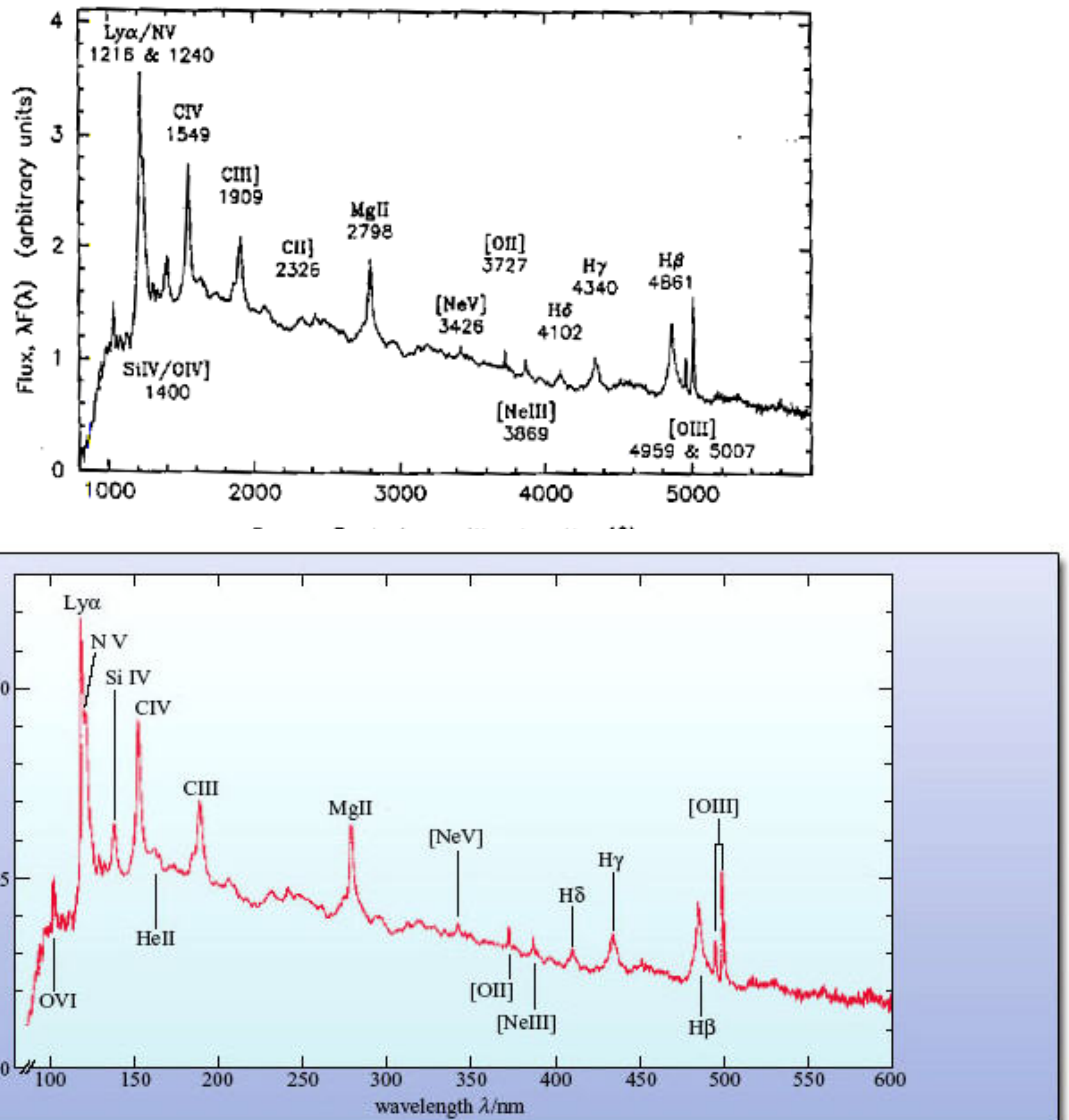


Figure 16: The mean optical spectrum of a sample of more than 700 quasars. The individual spectra were all corrected to remove the effect of red-shift before the spectra were averaged. Note the broad emission lines

PROPERTIES OF QUASARS

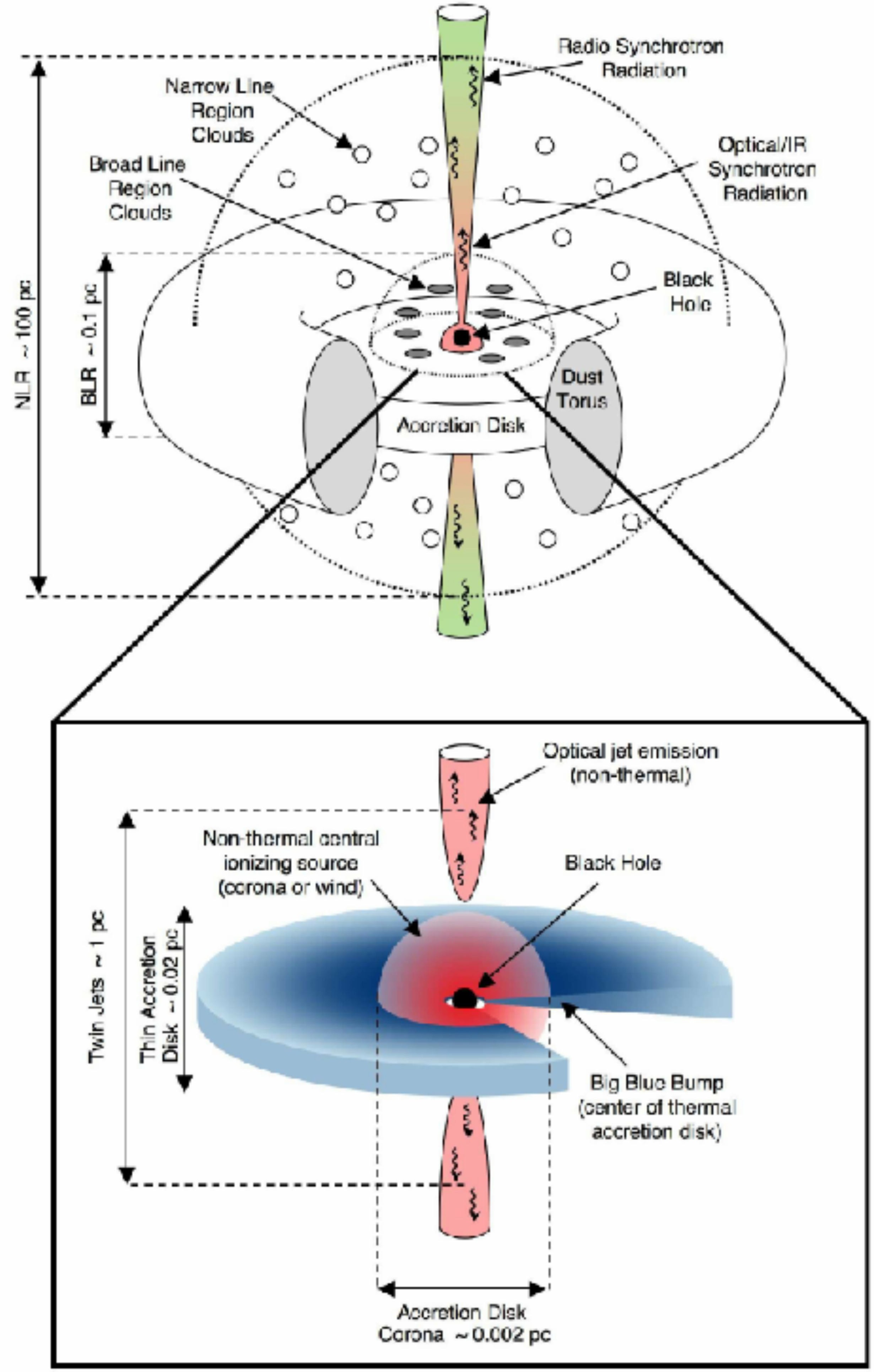
- innermost very compact region of a very distant galaxy in active state
- enormous amounts of energy emitted within a small spatial region
- Quasar's host galaxy can be only detected in very deep exposures
- Variability: from days to decades of years
- broad emission lines, also small emission lines and sometimes absorption lines.
- SDSS (Sloan digital sky survey): approx. 200.000 QSO's

ENERGY PRODUCTION

- Accretion of matter on a supermassive black hole
- Mass of the SMBH: 10^7…10^9 M_Sun
- release of gravitational energy
  - matter falling towards a SMBH
  - up to 10% of rest energy is converted into radiation.
- Luminosity: approx 100 L_Galaxy=10^40 W/s.
- Peak luminosity in UV; but emit from gamma ray to Radio
- Cosmological evolution: quasars were more common in the past. ; highest density at redshift z=2.

TYPICAL STRUCTURE OF A QSO

- supermassive black hole, SMBH
- continuum emission region, accretion disk
- broad line region, BLR
- narrow line region NLR
- occasional one or two jets are seen.



The black hole in QSO

The gravitational force F_{grav} of the black hole can be calculated using:

$$F_{grav} = \frac{GM_{BH}m_p}{r^2}$$

where G is gravitational constant, m_p is the proton mass and M_{BH},r are the mass and radius of the black hole respectively.

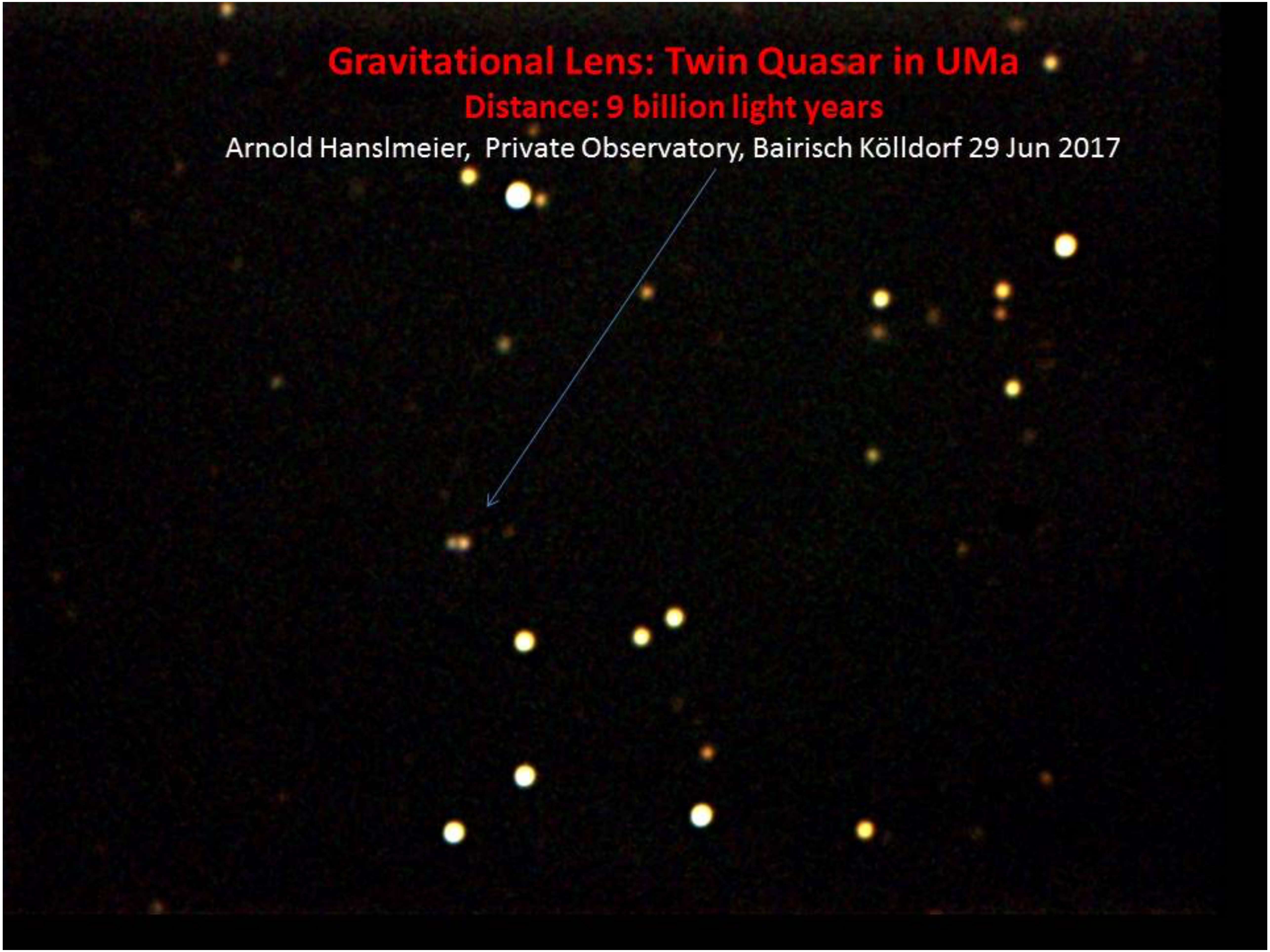
$$F_{rad} = \frac{dp}{dt} = \frac{1}{c}\frac{dE}{dt} = \frac{1}{c}\sigma_t \frac{L}{4\pi r^2}$$

where p is momentum, t is time, c is the speed of light, E is energy, σ_t is the Thomson cross-section and L is luminosity.
The luminosity of the black hole must be less than the Eddington luminosity $L_{Eddington}$, which is given when:

$$F_{rad} = F_{grav} \rightarrow L < L_{Eddington} = \frac{4\pi c G M_{BH} m_p}{\sigma_t} = 1.3 \times 10^{38} \frac{M_{BH}}{M_{solar}} erg/sec$$
$$= 30000 \frac{M_{BH}}{M_{solar}} L_{solar}$$

QUASARS AND GRAVITATIONAL LENSING

- normal lensing
- microlensing


Gravitational Lens: Twin Quasar in UMa
Distance: 9 billion light years
Arnold Hanslmeier, Private Observatory, Bairisch Kölldorf 29 Jun 2017

QUASARS AND GRAVITATIONAL LENSING

- relatively rare phenomenon
- multiple imaging occurs in 1 out of every 500 quasars
- To identify a quasar-lens system:
  - two or more point-like images of the same color with separation angle 1-10 arcsec
  - identical z

Textbook case multiple quasar

  - identical (very similar) spectra
  - lensing galaxy visible in between with lower z
  - identical or very similar change of brightness after certain time delays, parallel light curves

Gravitational lens effect

2. *The gravitational lens effect.*—We assume that the deflection of light is given by Einstein's expression, so that a ray of light passing B at a distance r is deflected towards B by an angle

$$v = 4G\mathscr{M}c^{-2}r^{-1} \equiv Kr^{-1} \qquad (1)$$

this is 2 times the classical value (escape vel=speed of light)

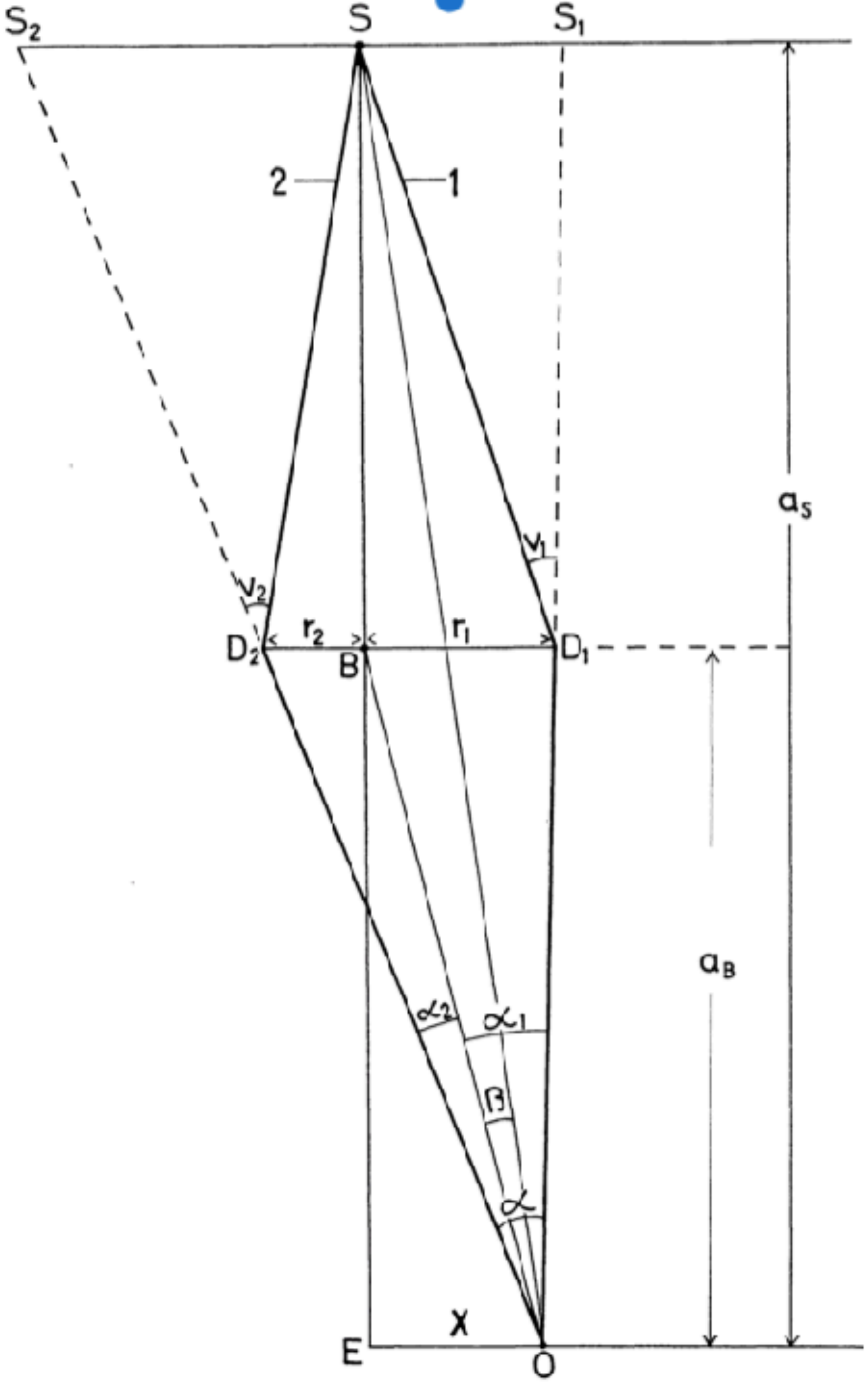


FIG. 1.—*The two light rays from S to O.*

From (2) we then obtain

$$L_1 = \tfrac{1}{4}\left(2 + \frac{\alpha}{\beta} + \frac{\beta}{\alpha}\right)L_N.$$

In a similar way we find

$$L_2 = \tfrac{1}{4}\left(-2 + \frac{\alpha}{\beta} + \frac{\beta}{\alpha}\right)L_N.$$

Magnification of the two images!!!
LN normal intensity

$$\frac{L_1}{L_2} = \frac{r_1^2}{r_2^2} = \frac{\alpha_1^2}{\alpha_2^2}.$$

$$\alpha_0 = \frac{2r_0}{a_B} = 2\sqrt{\frac{K}{na_B}}.$$

where $n = a_S/(a_S - a_B)$.

where $r_0 = \sqrt{Ka_B n^{-1}}$

double stars, this condition will usually be satisfied. Assuming B to be spherically symmetric, no more changes due to the extent of B are necessary. Correction terms for the extent of S must be introduced when β is less than, or of the same order of magnitude as the angular radius of $S, u=r_S/a_S$, r_S being the radius of S. Usually α_0 will be larger than u by several orders of magnitude.

$$L_T(\max) \approx \frac{\alpha_0}{u} L_N. \tag{25}$$

We shall give an example:

Let $a_S = 100$ pc, $a_B = 10$ pc, $\mathcal{M} = \mathcal{M}_\odot$, $r_S = r_\odot$. We then obtain $\alpha_0 = 5{\cdot}5 \times 10^{-2}{}''$ and $u = 5{\cdot}7 \times 10^{-5}{}''$, hence

$$L_T(\max) \approx 1100 L_N. \tag{26}$$

$, u=r_S/a_S,$

Correction terms for the extent of S must be introduced when β is less than, or of the same order of magnitude as the angular radius of $S, u=r_S/a_S$, r_S being the radius of S. Usually α_0 will be larger than u by several orders of magnitude.
The total intensity is of the most interest for us, and we shall therefore only give the correction terms for L_T. The angle β no longer has a precise meaning, but it is natural to define it by $\beta = \angle C_S O C_B$ where C_S and C_B are the respective centres of S and B.

DETERMINATION OF MASSES AND THE HUBBLE PARAMETER

2. *Determination of Hubble's parameter and the masses of galaxies.*—We consider a supernova S lying far behind and close to the line of sight through a distant galaxy, B, which will then act as a gravitational lens. For simplicity, we assume

1. The deflecting galaxy is spherically symmetric.
2. The red-shifts of S and B are small.

We can then apply the results previously obtained in the case of a star acting as a gravitational lens (Refsdal 1964). Using the same notation, we have

$$\alpha = \sqrt{\alpha_0^2 + \beta^2} \approx \alpha_0\left(1 + \tfrac{1}{2}\frac{\beta^2}{\alpha_0^2}\right) \approx \alpha_0 \tag{1}$$

$$\alpha_0 = \frac{4}{C}\frac{\sqrt{G\mathcal{M}}}{\sqrt{na_B}} \tag{2}$$

$$\alpha_1 - \alpha_2 = \beta \tag{3}$$

$$\frac{L_1}{L_2} = \frac{\alpha_1^2}{\alpha_2^2} \tag{4}$$

$$\Delta t \approx na_B\alpha\beta C^{-1}\left(1 - \tfrac{1}{3}\frac{\beta^2}{\alpha^2}\right) \approx na_B\alpha\beta C^{-1} \approx na_B\alpha_0\beta C^{-1}. \tag{5}$$

speed of light

From (2) and (5) we obtain

$$\Delta t = \frac{16G}{C^3}\frac{\beta}{\alpha_0}\mathscr{M}. \tag{6}$$

With $\beta/\alpha_0 = 0{\cdot}2$ and $\mathscr{M} = 3 \times 10^{11}\mathscr{M}_\odot$ we obtain $\Delta t = 55$ days. Due to the rapid change in the magnitude of S, it should then be possible to determine Δt. To be precise, (4) has to be changed to

$$\frac{L_1(t)}{L_2(t+\Delta t)} = \frac{\alpha_1^2}{\alpha_2^2}. \tag{7}$$

Our second assumption involves that the linear distance–red-shift relation is valid.

$$a_B = Z_B C H^{-1}, \quad a_S = Z_S C H^{-1} \tag{8}$$

where Z_B and Z_S are the red-shifts of S and B, respectively, and H is Hubble's, parameter. Hence,

$$n = Z_S/(Z_S - Z_B). \tag{9}$$

From (2), (5), (8) and (9) we obtain

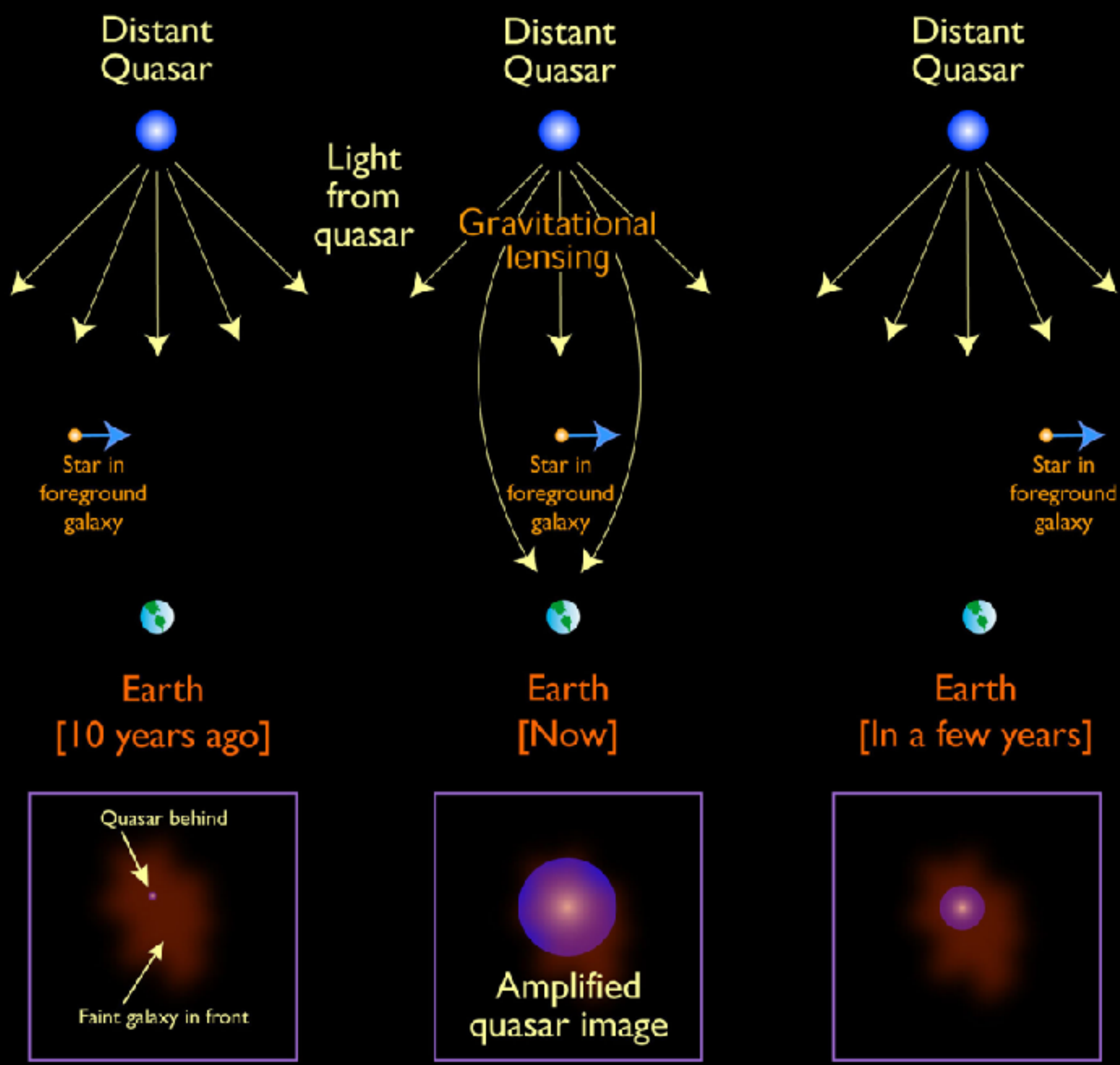
$$H = \frac{Z_S Z_B \alpha(\alpha_1 - \alpha_2)}{\Delta t(Z_S - Z_B)}. \tag{10}$$

From (3) and (6) we get

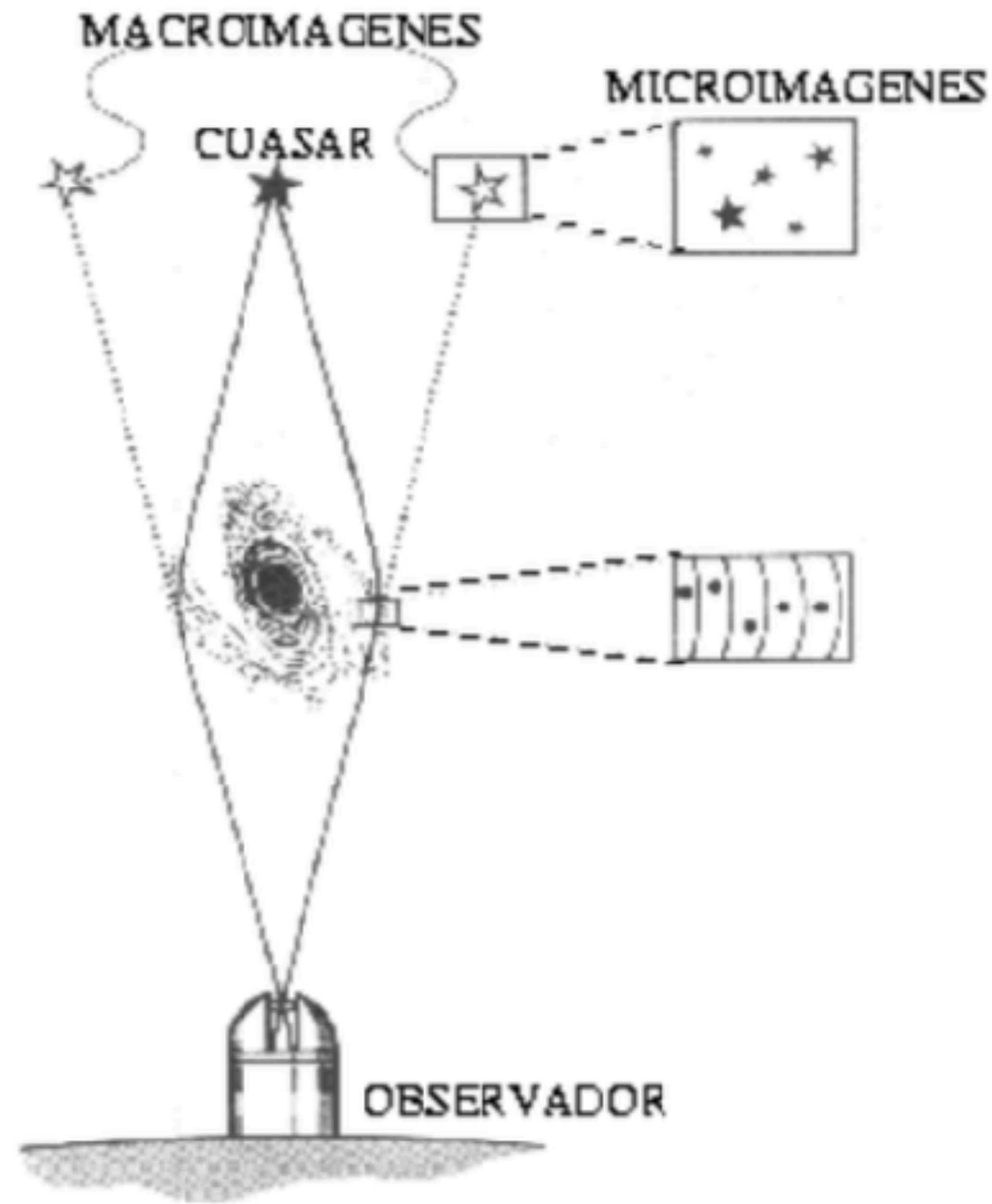
$$\mathscr{M} = \frac{\Delta t \alpha C^3}{16G(\alpha_1 - \alpha_2)}. \tag{11}$$

We note that H and $\mathscr{M}$ depend only on observable quantities. The quantity most difficult to determine experimentally seems to be $\alpha_1 - \alpha_2$, because α_1 and α_2 are nearly equal. Using (7), and noting that $\alpha_1 + \alpha_2 = \alpha$, we get

Quasar Microlensing



- stars behave like small lenses
- affect light curves
- image separation too small to be resolved
- whole galaxy: smooth potential, produces macro-images
- stars: introduce graininess, produce additional magnification
- information about size

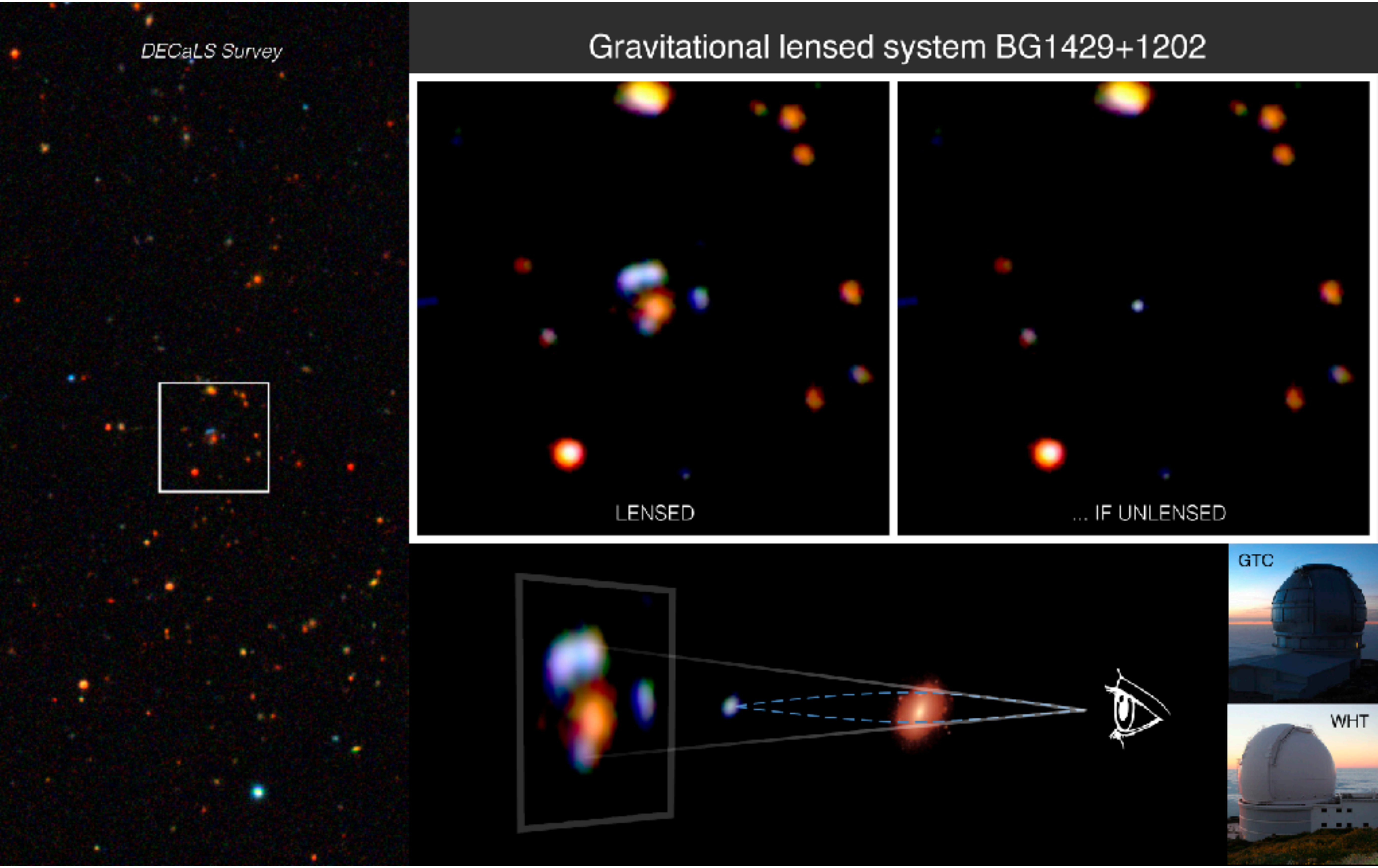


Refsdal & Surdej 1994

Own observations

- **IAC 80**: Photometry (1 object)
- **WHT**: Spectroscopy (13 objects)
- **Literature**: many spectra (28 objects)

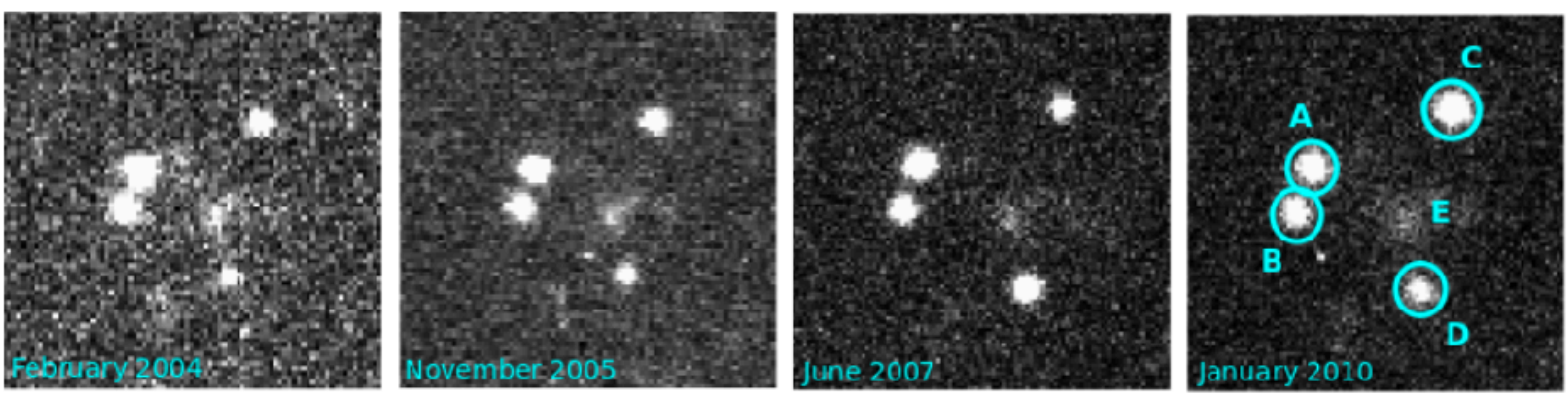
ORM WHT


DECaLS Survey
Gravitational lensed system BG1429+1202
LENSED
... IF UNLENSED
GTC
WHT

Size of the Accretion Disk in the Gravitationally Lensed Quasar SDSS J1004+4112 from the Statistics of Microlensing Magnifications

Fian et al. 2016, ApJ 830, 149

- monitoring between December 2003 and October 2010
- observation in r-band
- 8 observing seasons spanning 2505 days
- 109 epochs



rare example of a quasar lensed by galaxy cluster!

$Z_s=1.73$

$Z_l=0.68$

max separation 14.6 arcsec

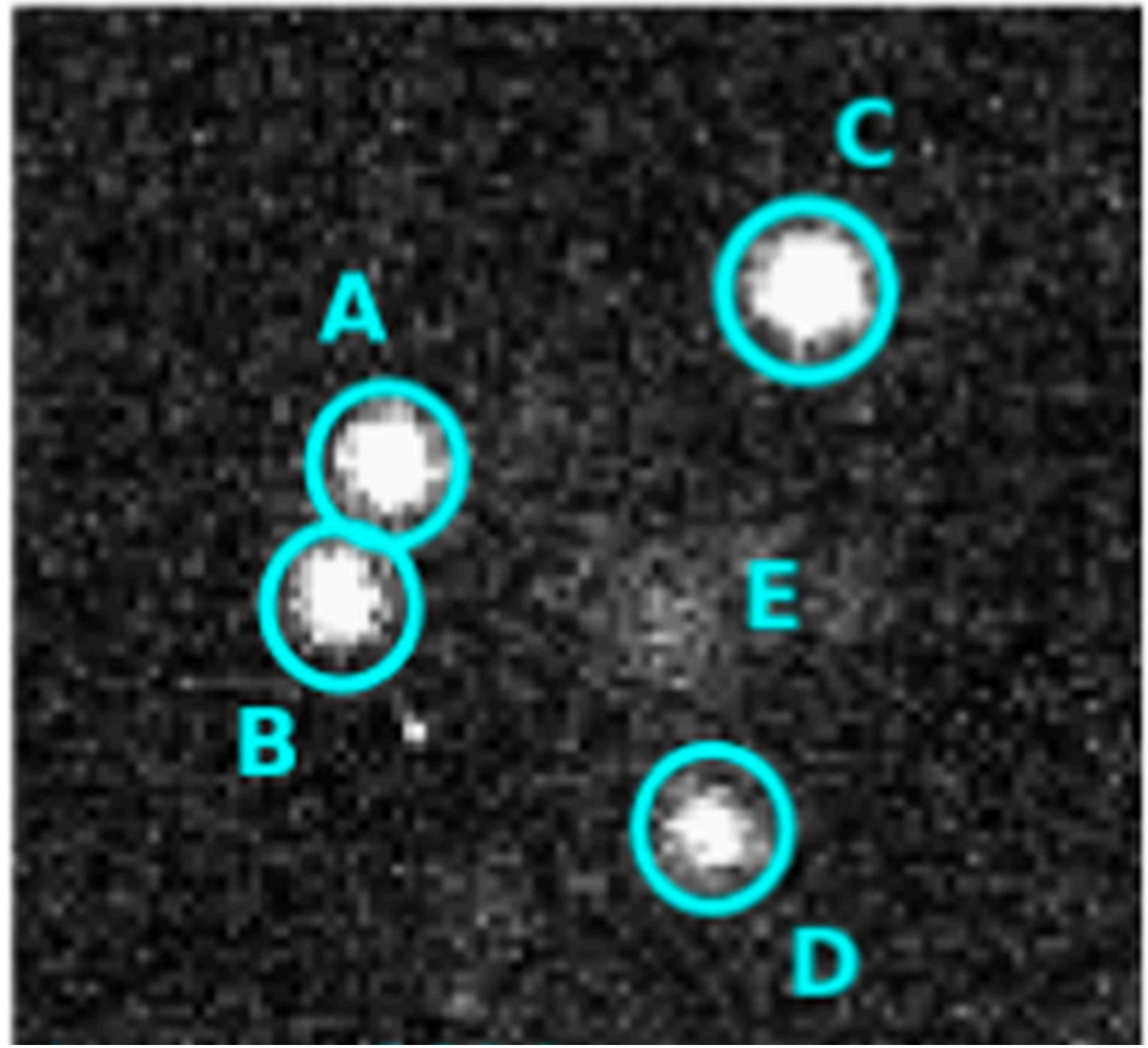
time delay:

between A and B: 40.6 days

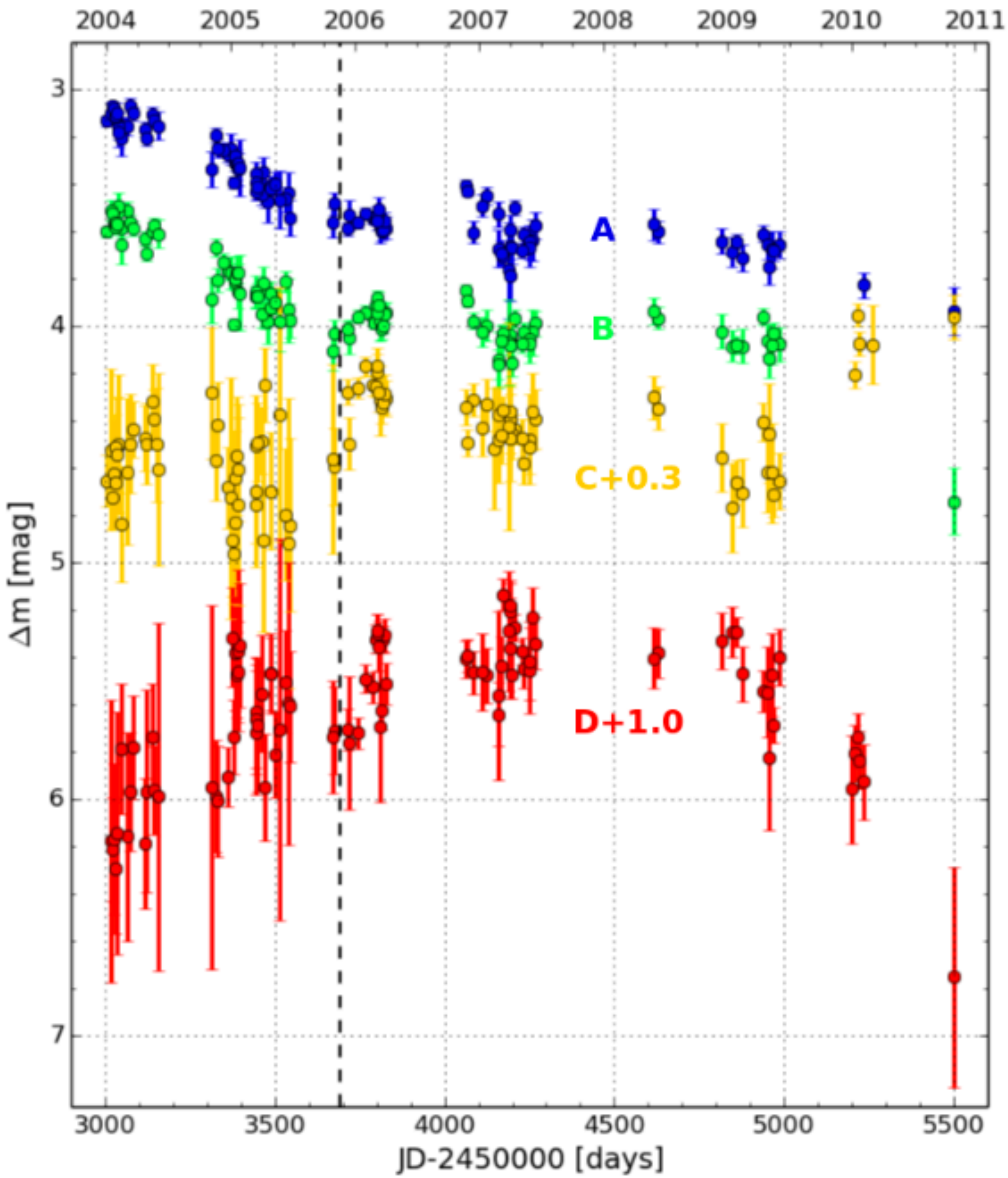
between A and C: 822 days

To obtain microlensing:

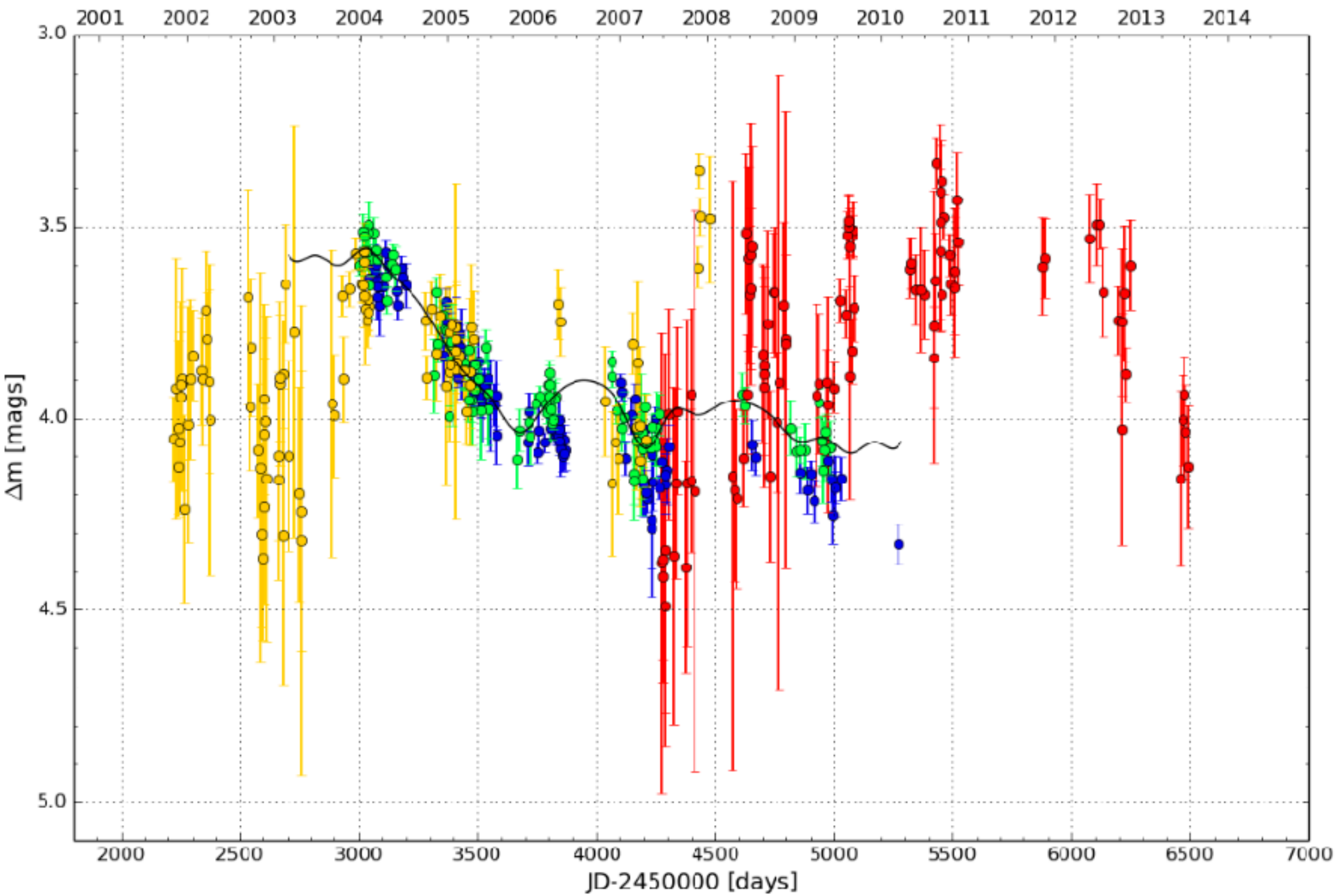
correct for the time delay, calculate residuals



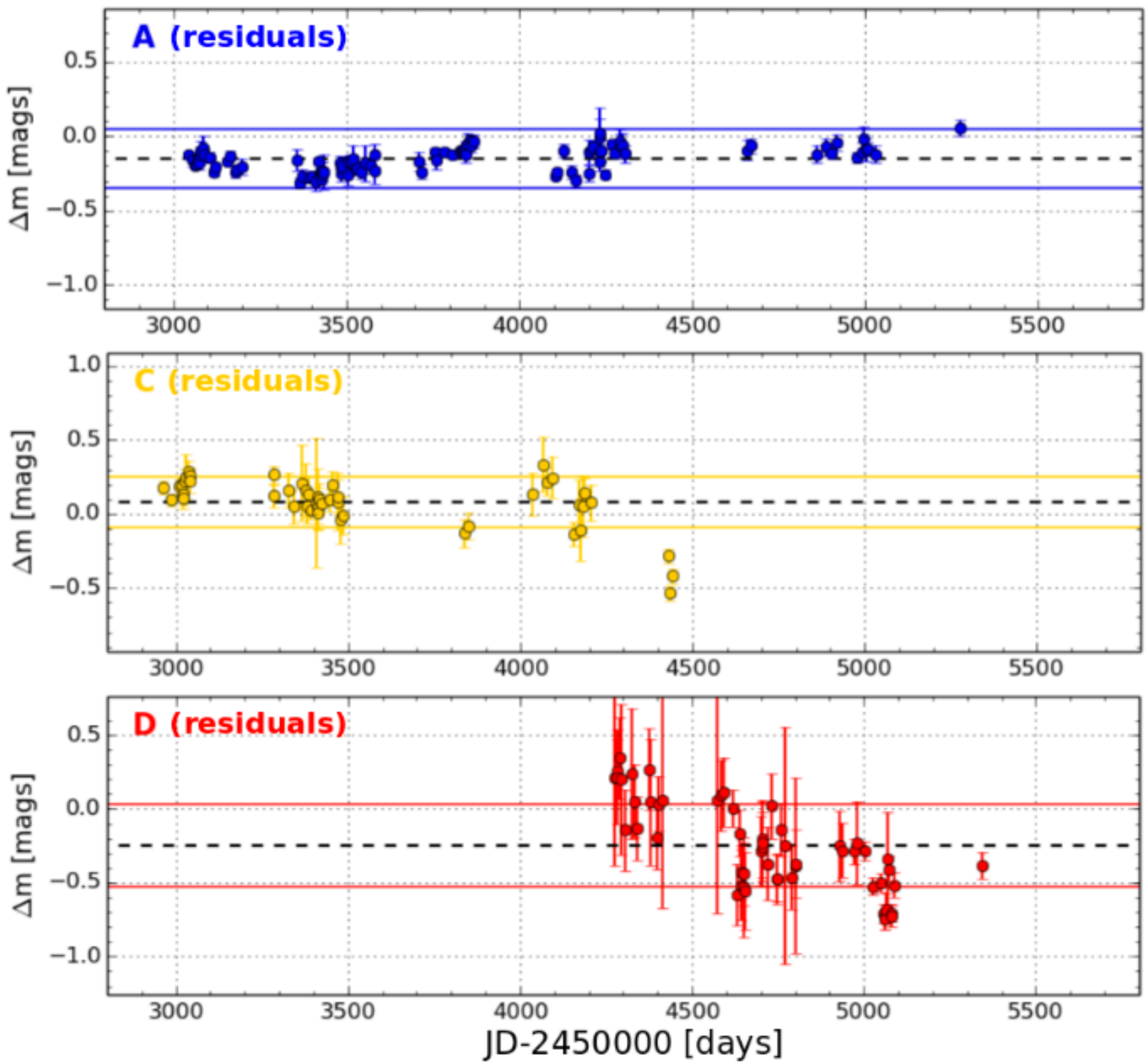
Analysis of lightcurves



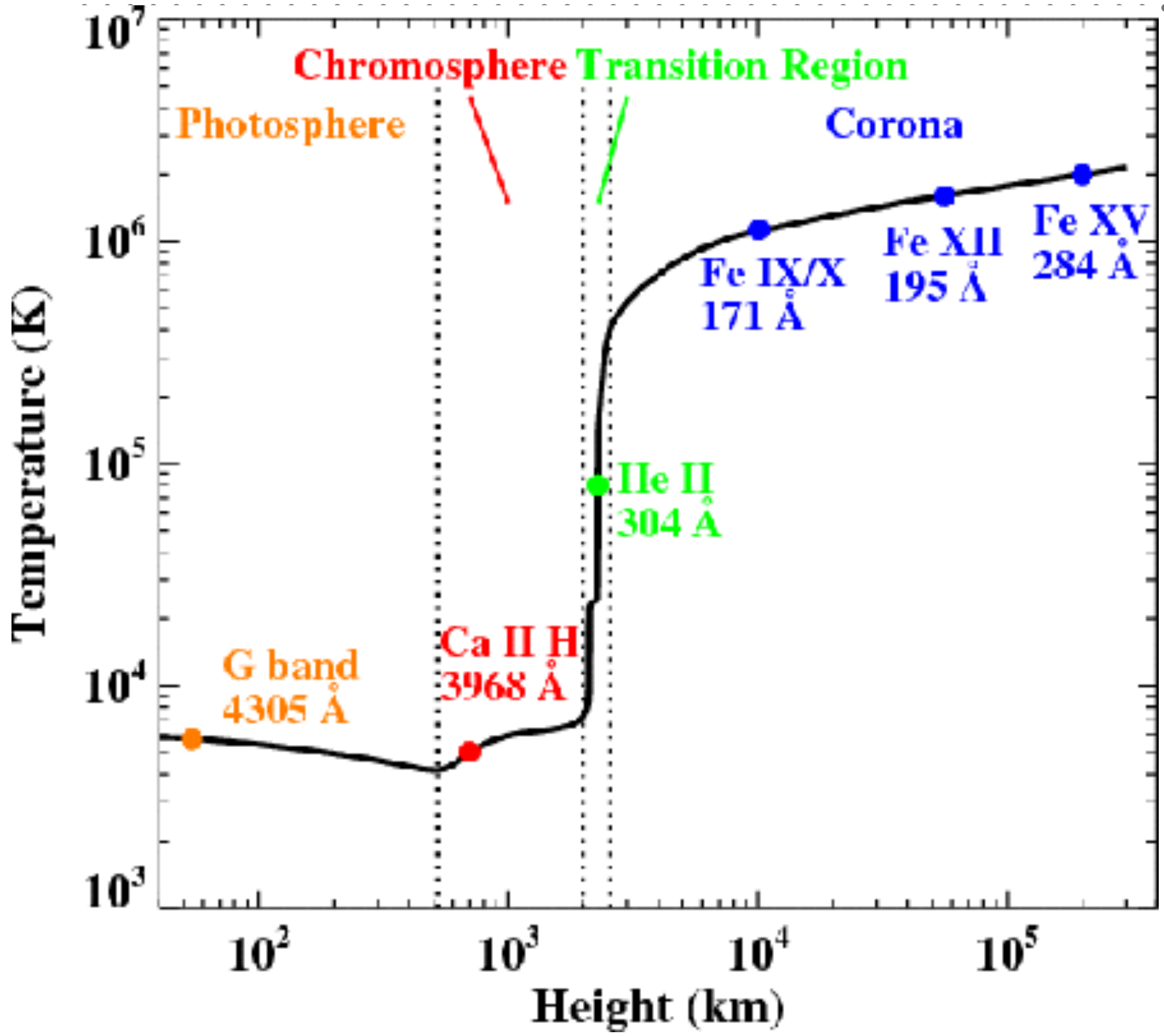
Intrinsic Variability

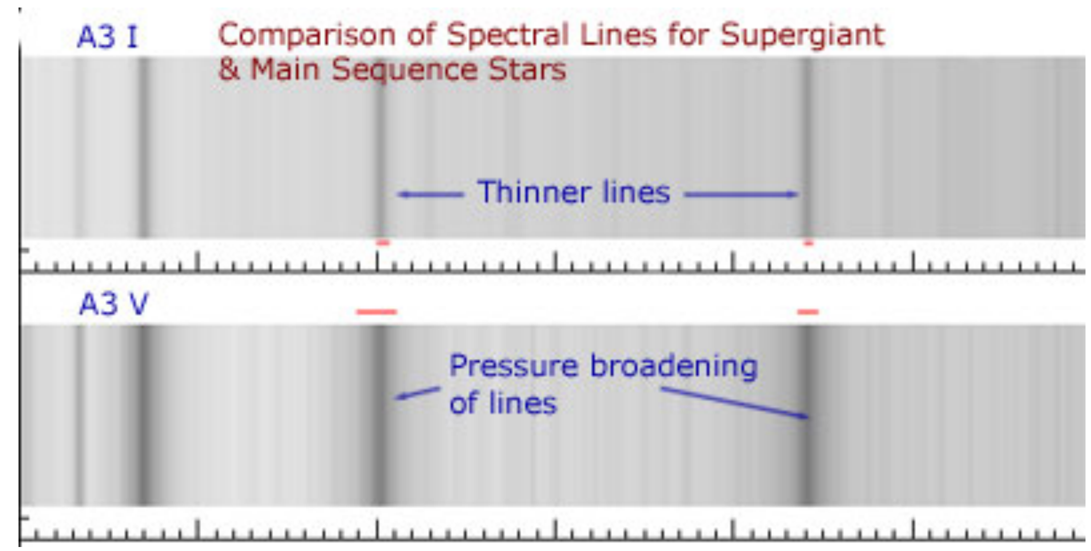


Microlensing, variability residuals



WHAT HAVE GRAVITATIONALLY LENSED QSO AND THE SUN IN COMMON?





Spectral line formation

Temperature

pressure

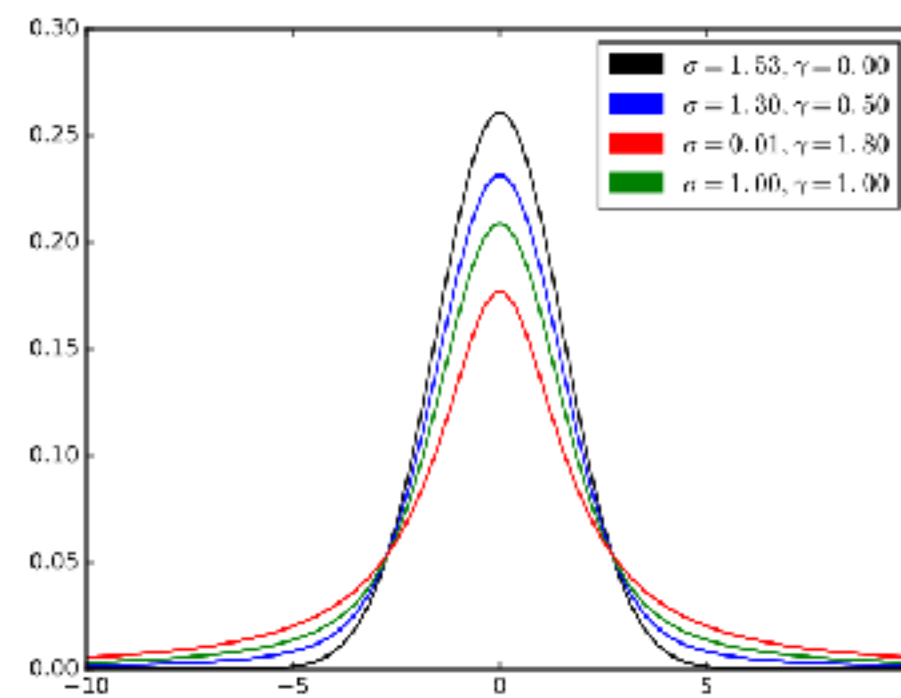
turbulence

$$G(x;\sigma) \equiv \frac{e^{-x^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}},$$

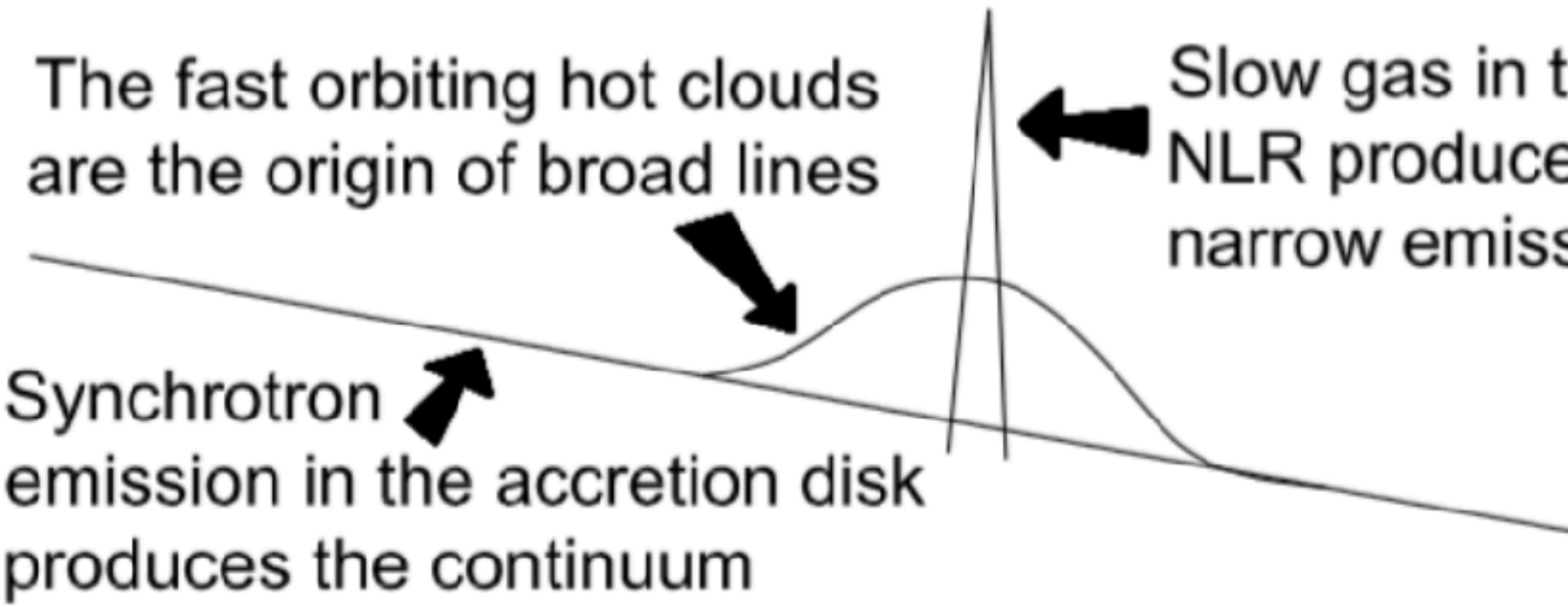
Gauss profile

$$L(x;\gamma) \equiv \frac{\gamma}{\pi(x^2+\gamma^2)}.$$

Lorentz profile

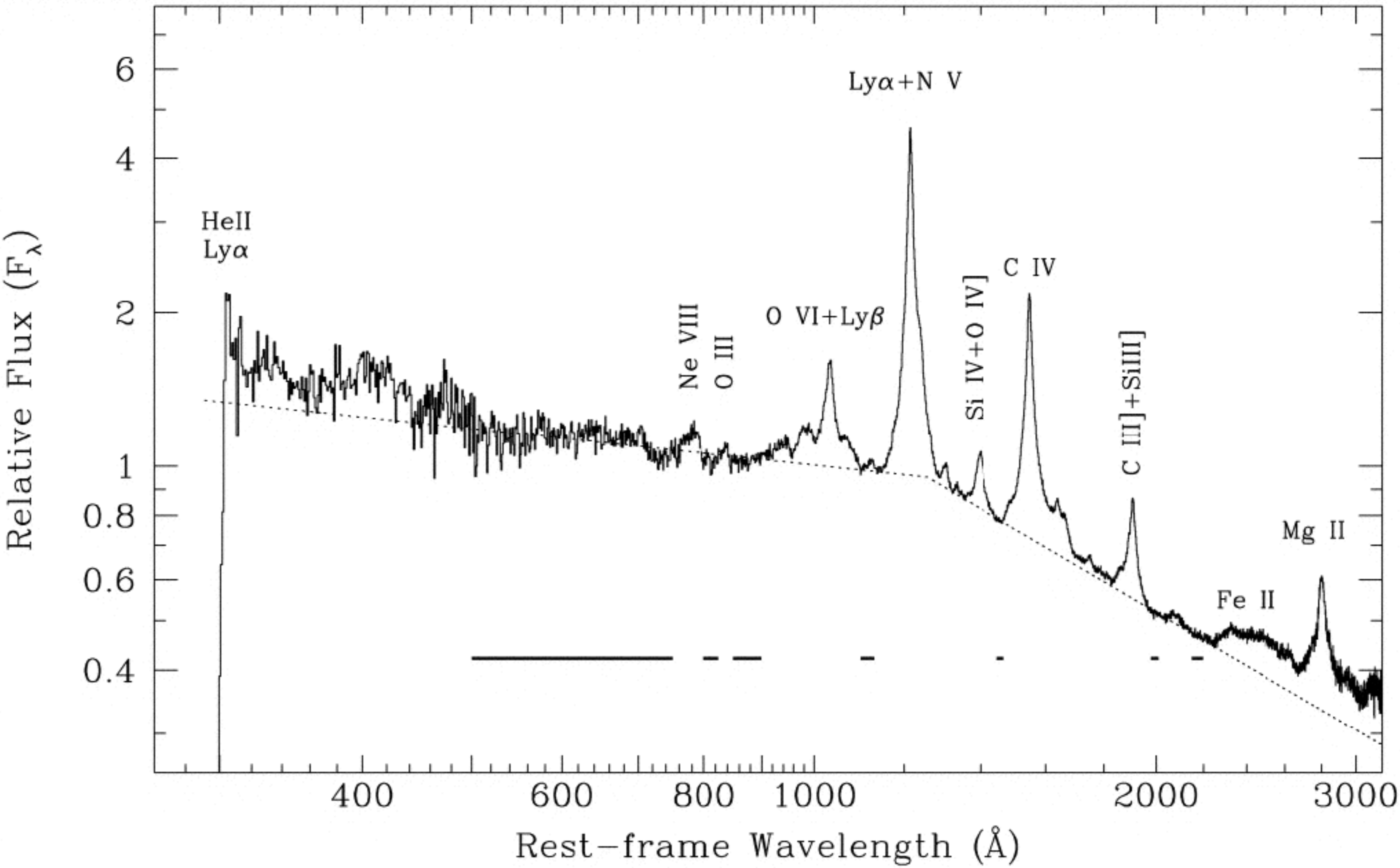


Analysis of spectra: from WHT



BLR: broad line region

NLR: narrow line region

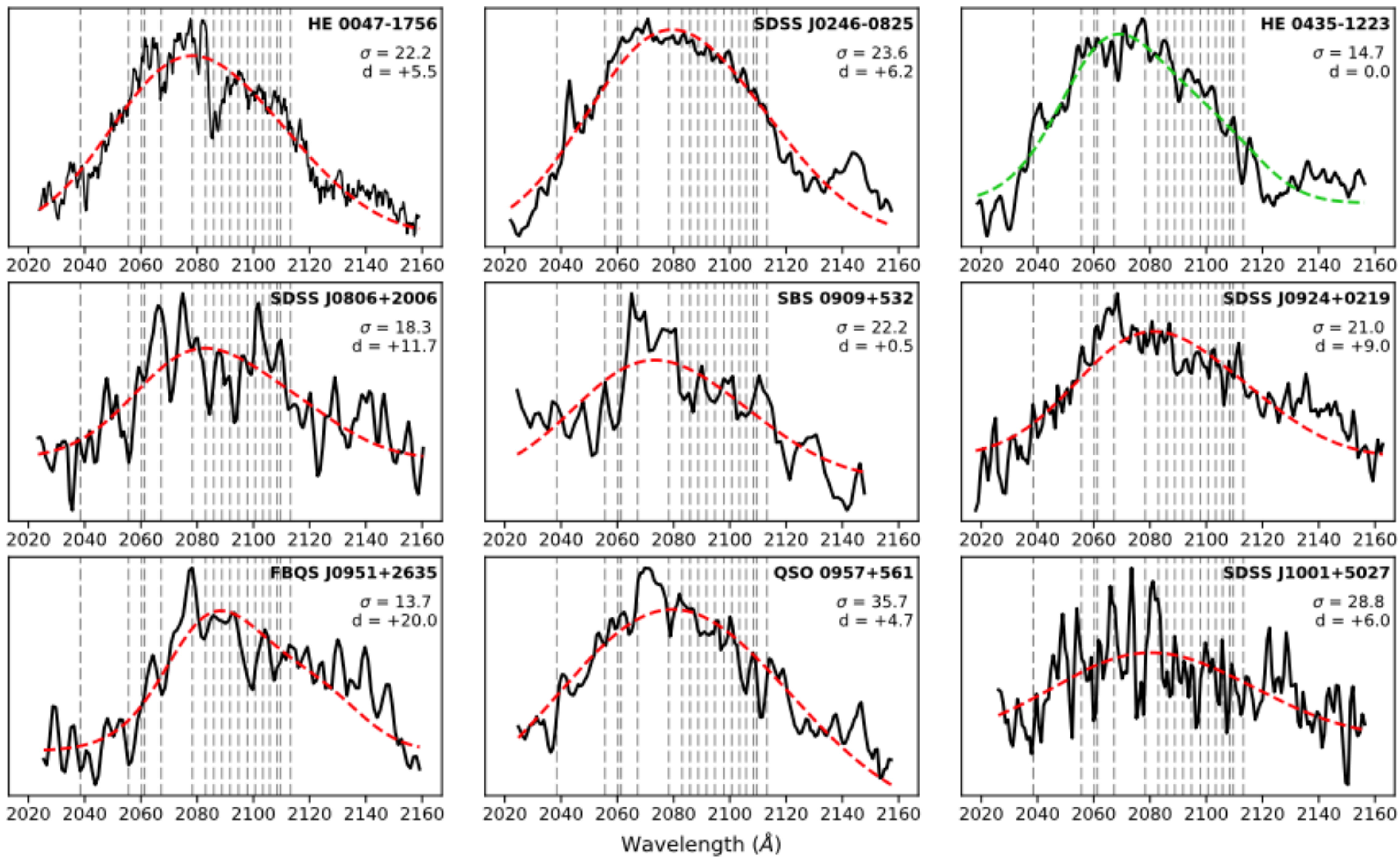

HeII
Lyα
Ne VIII
O III
O VI+Lyβ
Lyα+N V
Si IV+O IV]
C IV
C III]+SiIII]
Mg II
Fe II
6
4
2
1
0.8
0.6
0.4
400
600
800
1000
2000
3000
Relative Flux (Fλ)
Rest−frame Wavelength (Å)

WHAT CAN WE LEARN FROM QUO SPECTRAL LINES?

- Seyfert Galaxies
  - emission lines are formed (a) in the accretion disc (b) in clouds of gas illuminated by AGN
  - each part of emission disc has different velocity—> line broadening
  - the faster the gas is rotating around the black hole the larger the broadening
  - narrow lines appear in outer parts where velocities are lower
  - narrow lines do not show a variability—> large emitting region
  - broad lines can vary on short time scales

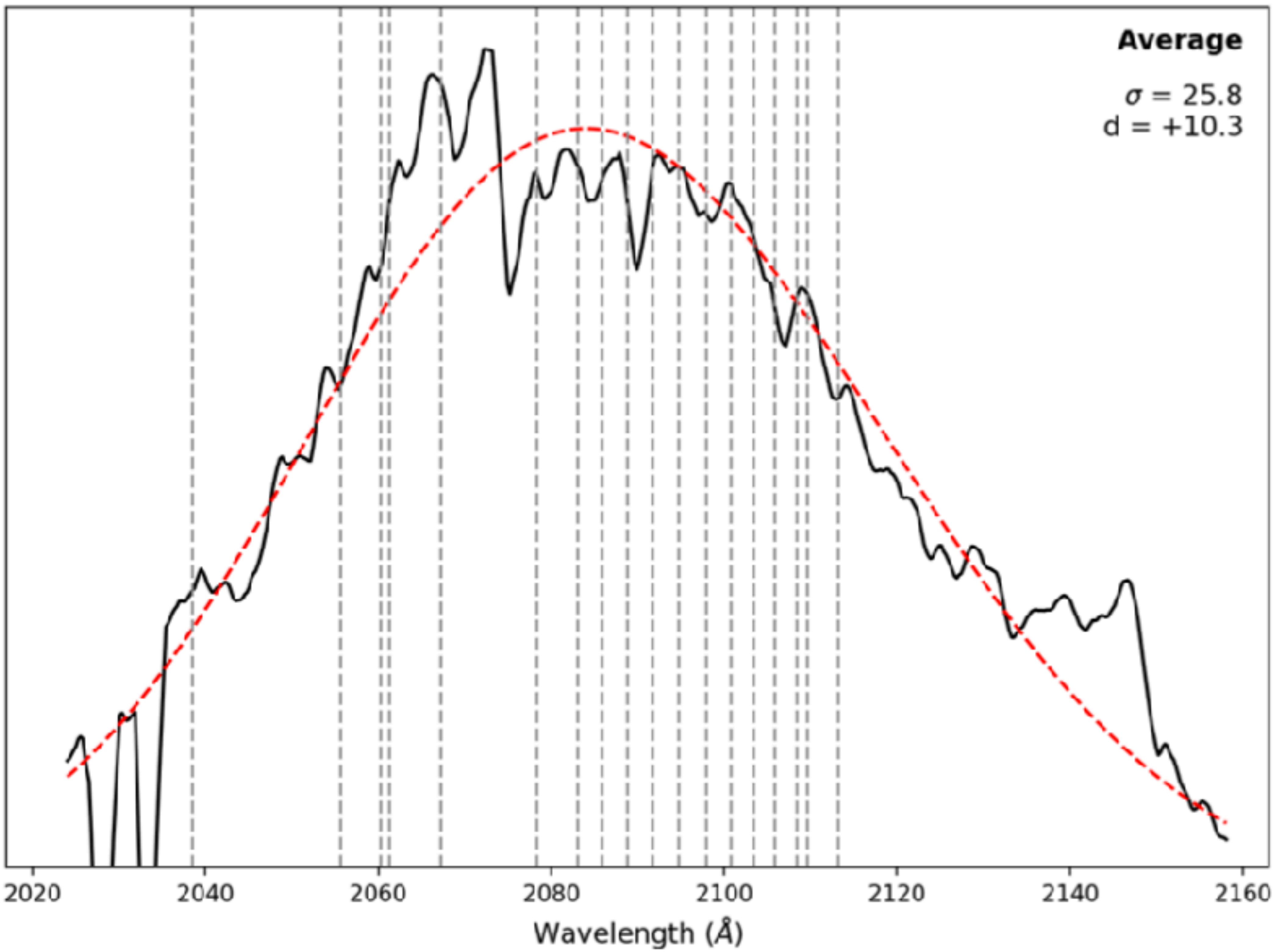
FE III COMPLEX

- Fe III complex formed by many lines
- fit: sum of 18 Gaussians
- fixed parameters: position and flux
- free parameters:
    - shift (position)
    - factor (flux)
    - sigma (broadening)
- very interesting result: line is shifted $\rightarrow$ relativistic effect
- from shift and broadening $\rightarrow$ size and SMBH mass



HE 0047-1756
σ = 22.2
d = +5.5
SDSS J0246-0825
σ = 23.6
d = +6.2
HE 0435-1223
σ = 14.7
d = 0.0
SDSS J0806+2006
σ = 18.3
d = +11.7
SBS 0909+532
σ = 22.2
d = +0.5
SDSS J0924+0219
σ = 21.0
d = +9.0
FBQS J0951+2635
σ = 13.7
d = +20.0
QSO 0957+561
σ = 35.7
d = +4.7
SDSS J1001+5027
σ = 28.8
d = +6.0
2020 2040 2060 2080 2100 2120 2140 2160
Wavelength (Å)

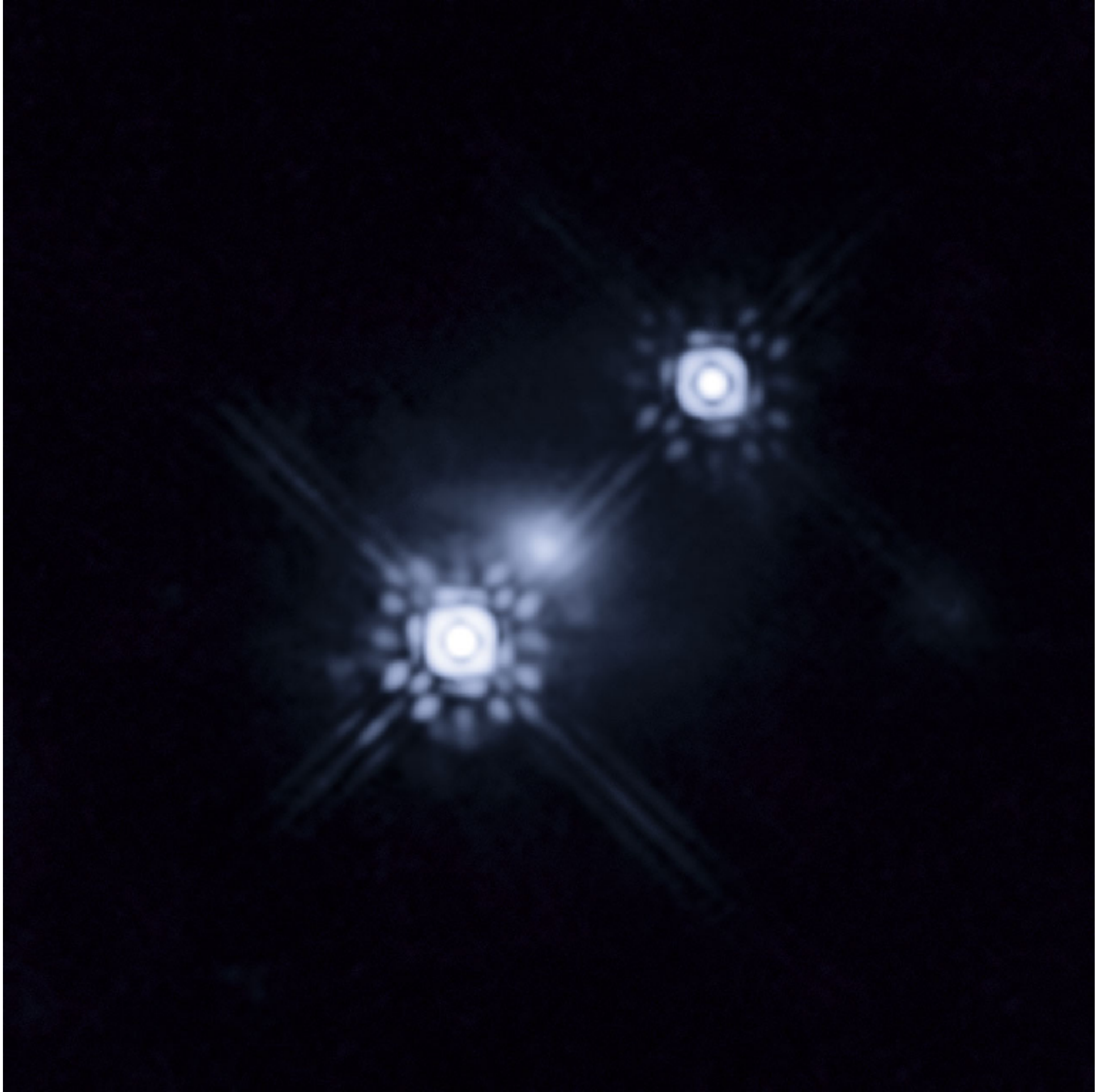
Fe III Line Average + Fit

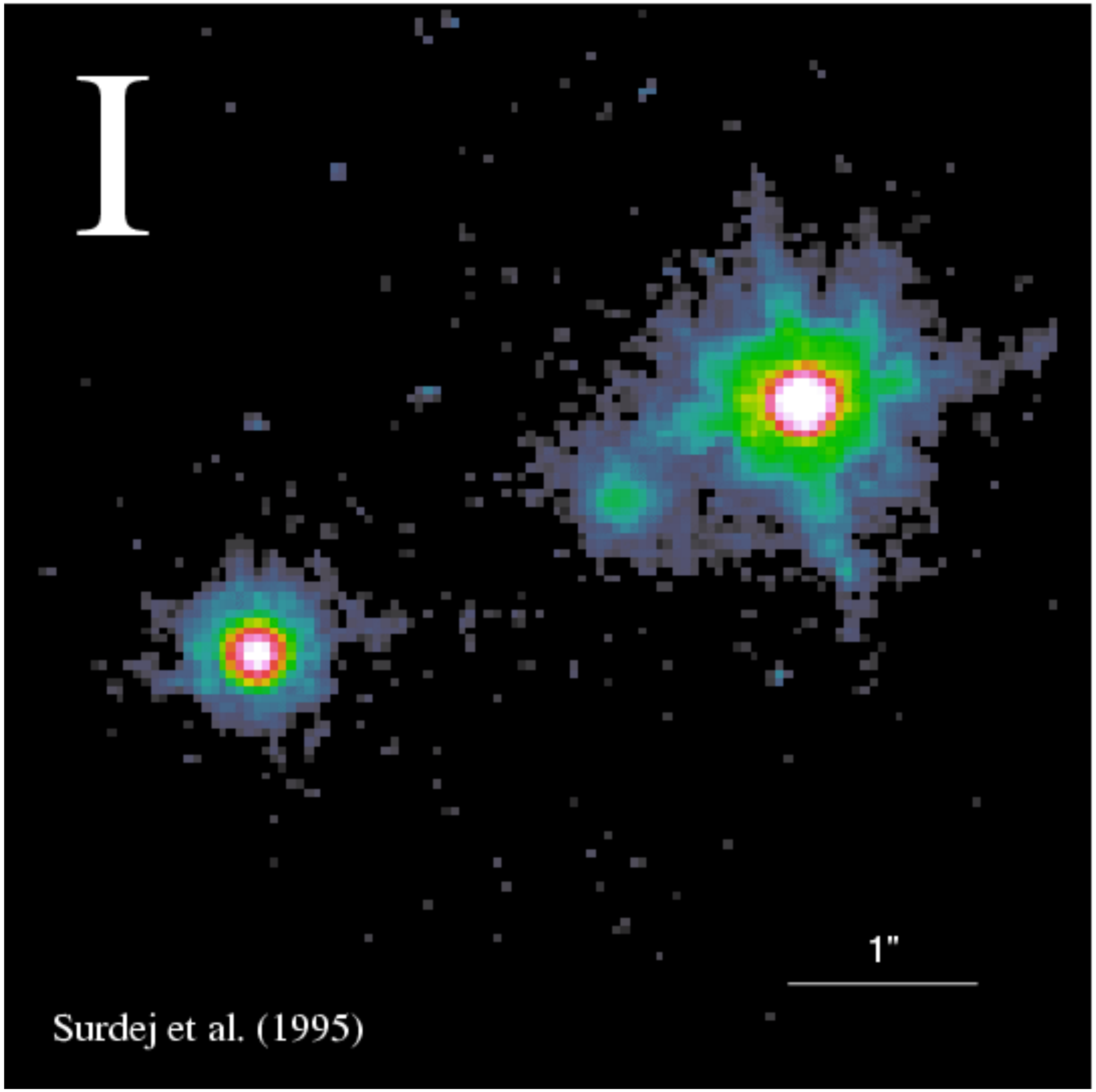


- Observation at WHT in La Palma (March 2016)
- in total: 13 systems
- problem: in most of the systems very small separation between images ($<$1.5")

Example

He 1104… HST



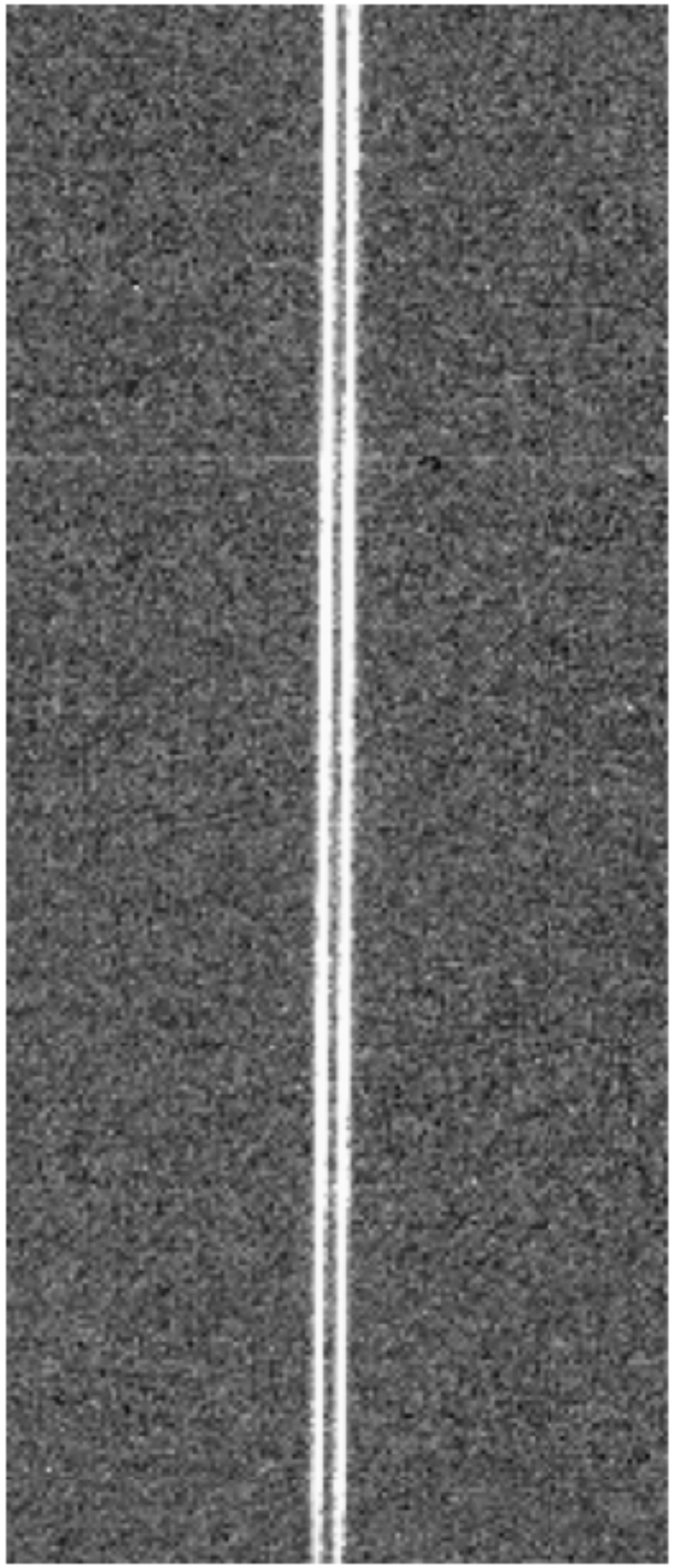


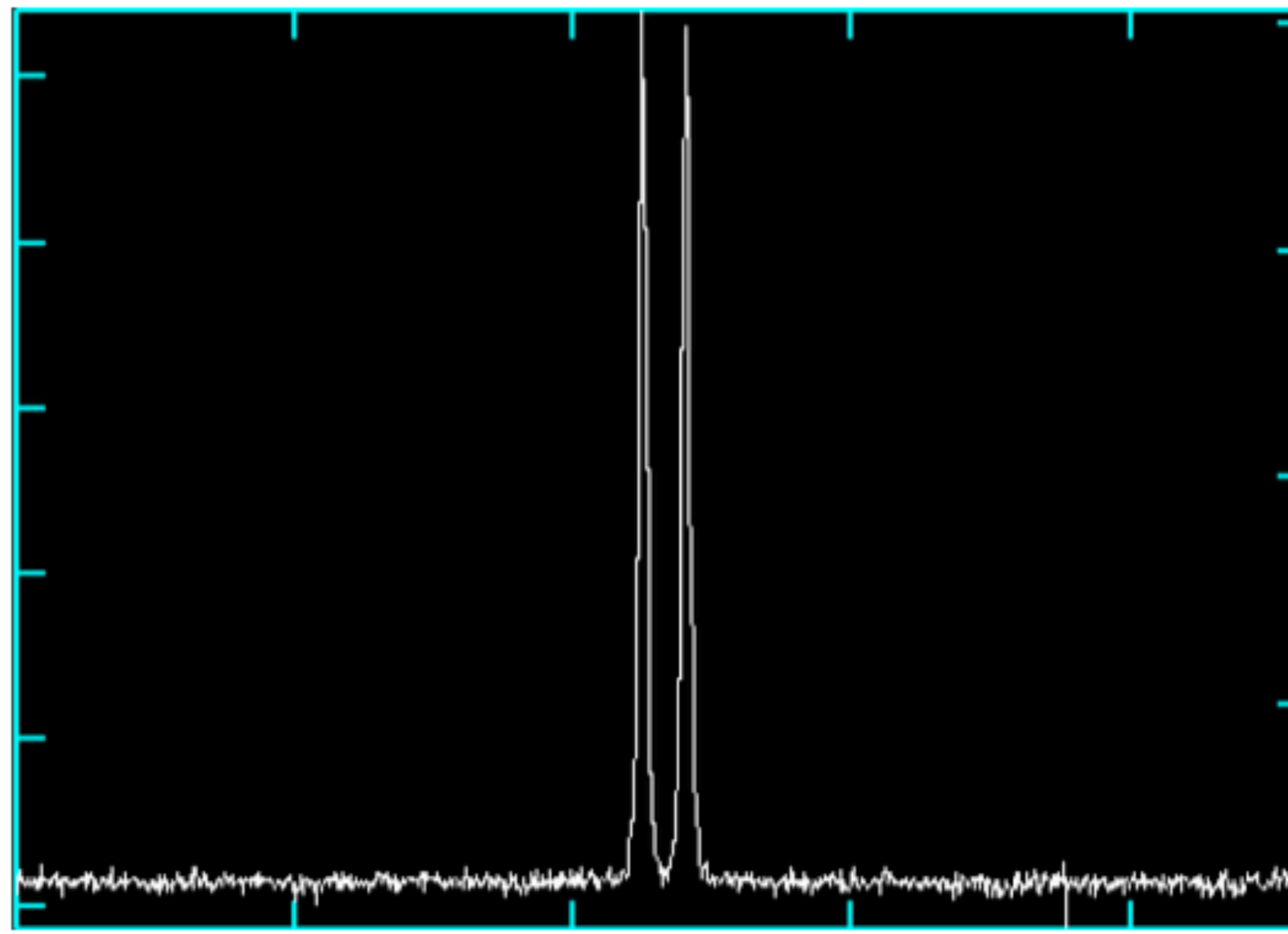
I
1"
Surdej et al. (1995)


Hubble Image

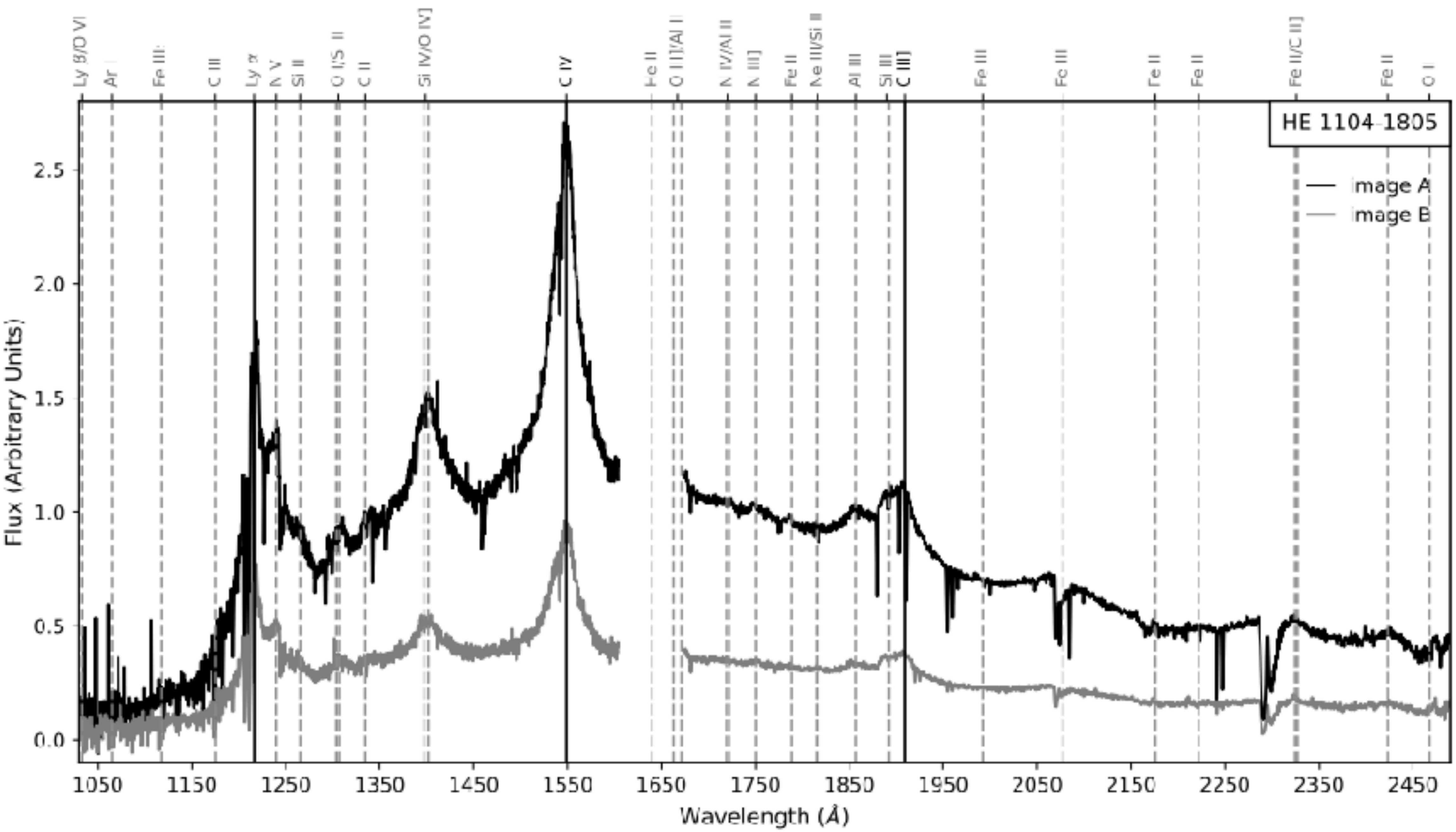
HE1104-1805 - The light from this quasar 20 billion light-years away in the constellation, Crater, is being lensed by the galaxy WKK93, which is 10 billion light-years away. WKK93G is directly between us and HE1104-1805 so that the light from the quasar reaches us via two paths, thus producing two images. The two images are about 3 arcsec apart, which is below the resolution of my telescope, though they are nicely separated in the Hubble image. My image shows that there are two images, and by counting pixels between the centers of the lobes I can confirm that they are 3 arcsec apart. This is the smallest object I have imaged that shows some structure. The lengths of the light paths for the two quasar images differ so that one image reaches us a little over 5 months before the other.

Because of the expansion of the universe, we are moving away from the quasar as its light heads toward us. When you observe such an object, you are looking back in time. The universe was only 2.8 billion years old when the light I captured left the quasar. In the intervening 11 billion years the universe has been expanding so that currently the quasar is 20 billion light-years away as determined by its red shift. Also, by the same reasoning the edge of the observable universe, i.e. the part of the universe that has had time for its light to reach us since the Big Bang, is about 46 billion light-years away. So the light I captured in those two connected blobs came from almost half the distance to the edge of the observable universe.





Spectrum HE 1104-1805



Microlensing magnification -Theory

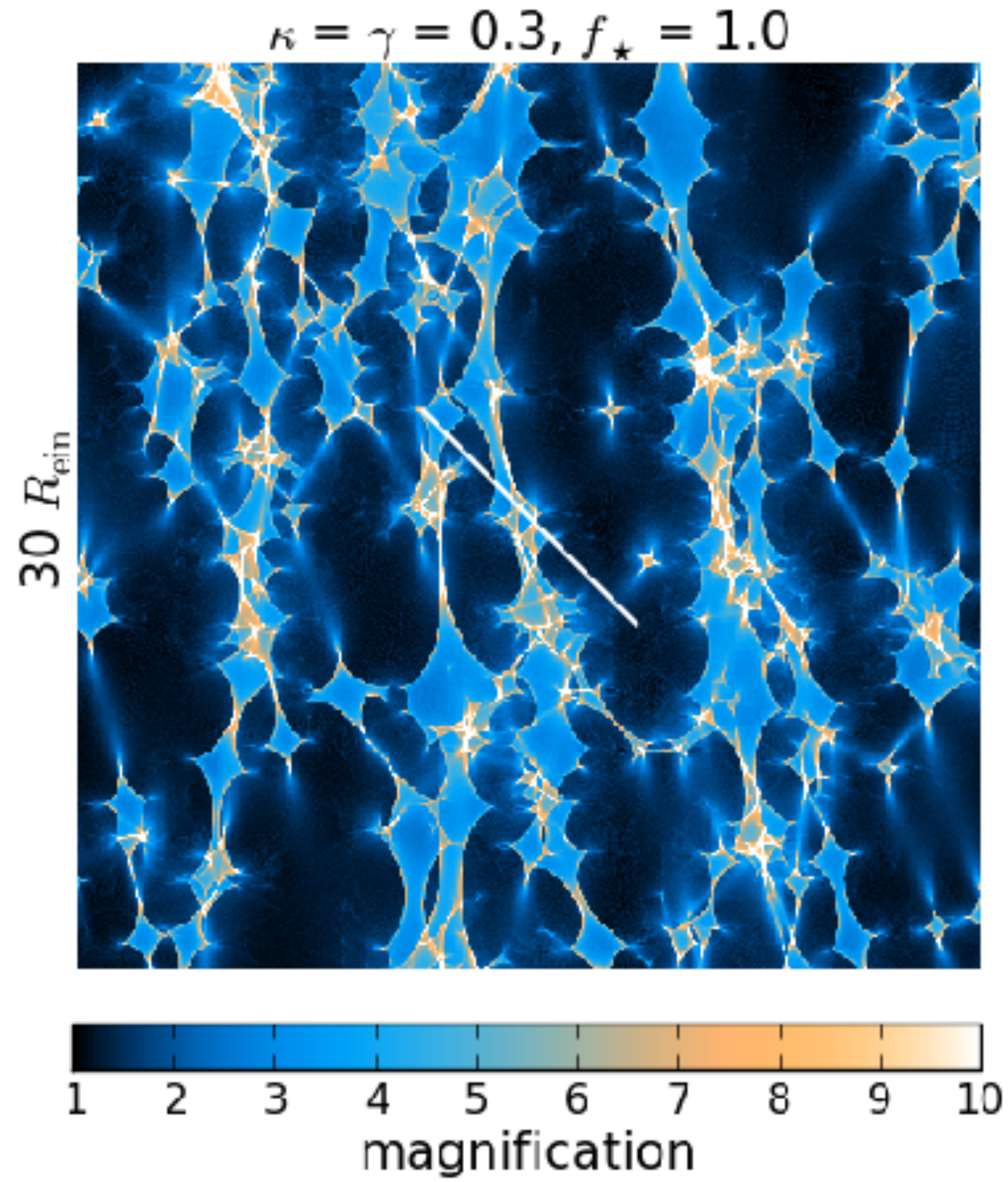
Problem: uncorrelated variability between different images of a lensed source

Reason: mass distribution (granulation) of the lens galaxies

Effects of microlensing on the light curves of a lensed object are studied by finding configurations of

- compact objects in lens galaxy
- source trajectories

should match observations!



Magnification maps

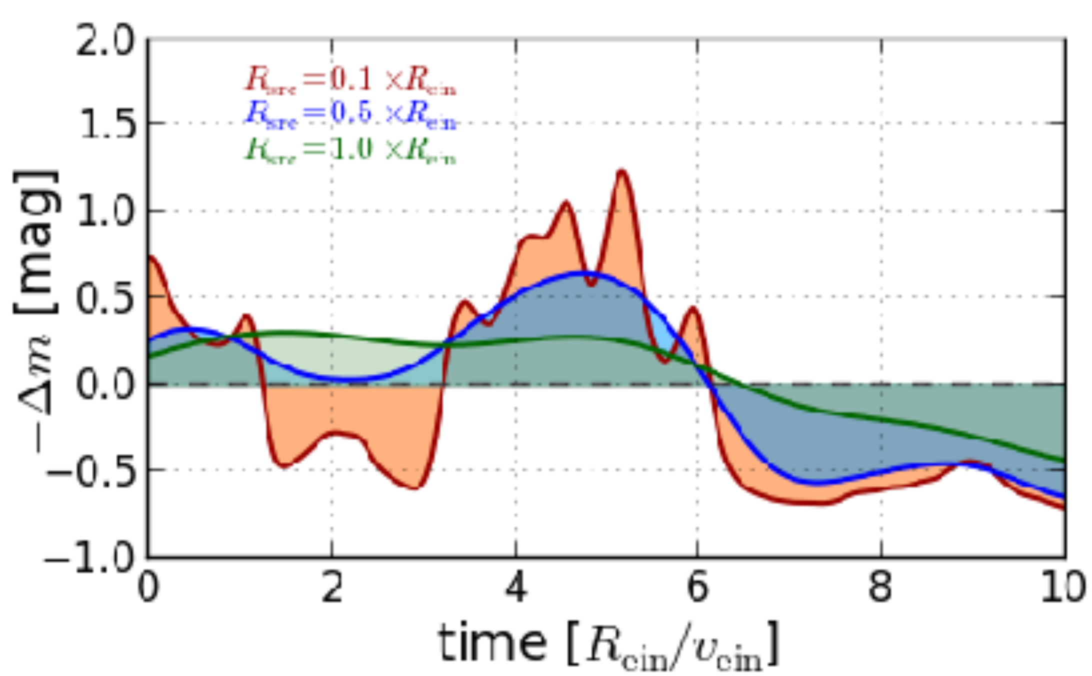
ray tracing; show how caustics are influenced by stars of lensing galaxy; shown is the source plane

As the background quasar and foreground galaxy move relative to each other, the source traverses this pattern (white solid line), resulting in brightness fluctuations due to microlensing.

$$y^i(x^i) = x^i - \alpha^i(x^i),$$

transformed coordinates of the cell center at the source plane

$$y^i(x^i + \Delta x^i) = y^i(x^i) + \Delta x^i - \sum_j \frac{\partial \alpha^i}{\partial x^j} \Delta x^j,$$



$$\Delta y^i = y^i(x^i + \Delta x^i) - y^i(x^i) = \Delta x^i - \sum_j \frac{\partial \alpha^i}{\partial x^j} \Delta x^j.$$

$$\begin{pmatrix} \Delta y^1 \\ \Delta y^2 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} \Delta x^1 \\ \Delta x^2 \end{pmatrix},$$

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SIZE OF THE ACCRETION DISK IN THE GRAVIATIONALLY LENSED QUASAR SDSS J1004+4112 FROM THE STATISTICS OF MICROLENSING MAGNIFICATIONS

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2 bachelor theses completed

Paper II: Fe II/ FeIII to be completed end of August 2017

Paper III: WHT Data to be completed end of 2017

work for Master students, doctorands…