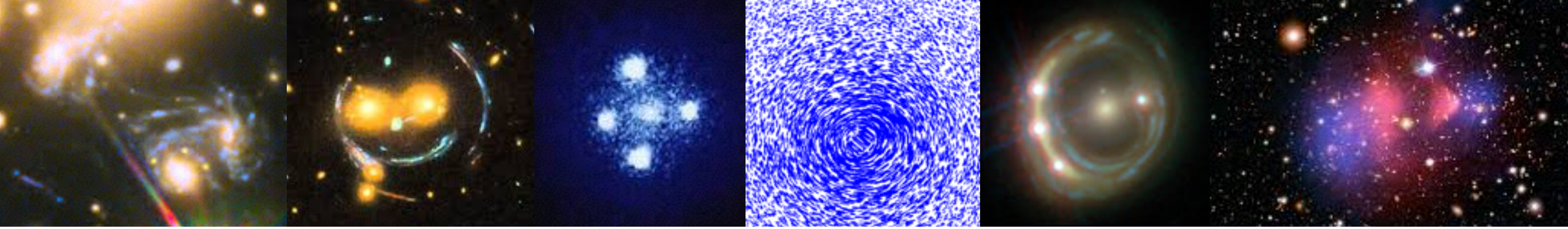


PHY-765 SS18 Gravitational Lensing Week 1

Introduction
&
The History of GL

Kasper B. Schmidt

Leibniz-Institut für Astrophysik Potsdam (AIP)

What’s the aim of today?

- Who is who?
- Course logistics and plan for the semester
- What is gravitational lensing - a quick overview.
- History - The Early Days of Gravitational Lensing
- Worksheet Week 1
  - Details later

Who is Who?

- Name?
- Focus of studies / topics of interest?
- Background, i.e., “Journey to Potsdam University”?

Course Structure:

- Lasts for 15 weeks
- 1V1S setup, i.e., 45min. “lecture” + 45min, “seminar” each week
- Introduction to basics of Gravitational Lensing (GL)
    - From a theoretical side
    - From an observational side
- Focus on general “astronomer skills” used daily in research
    - Science communication
    - Feedback and evaluation
    - Topic condensation
- Weekly worksheets to reflect topic of the week
- Slides and Worksheets available at course web-page
    - https://kasperschmidt.github.io/teaching/SS18_GravLens_UP765

kasperschmidt.github.io/teaching/SS18_GravLens_UP765

K. B. Schmidt, AIP   Research   Software   Travel   CV & Publications   Theses   Teaching

Gravitational Lensing

PHY-765, Summer Semester, *Potsdam University*, 2018

On this page you'll find information about the course on Graviational Lensing (PHY-765) at Potsdam University, summer semester 2018.

If you are interested in the course, please fill out this short google questionnaire. This will help for preparing and focusing the lectures and seminars througout the semester.

Page Content

- Course-Description
- Basic Info
- Course Plan
- Lecture Slides
- Seminar Worksheets
- Literature

Course Description

The theory of gravitational lensing (GL) is one of the three fundamental observational consequences of Einstein's theory of general relativity. GL describes how rays of light are bent by massive astronomical objects like stars, galaxies and galaxy clusters. This results in magnification and potentially in multiple images on the sky of lensed sources.

These unique consequences of GL have been instrumental and of growing importance in modern extragalactic astronomy. Laying out the theoretical framework describing the principles

Course Plan on Webpage (updated along the way)

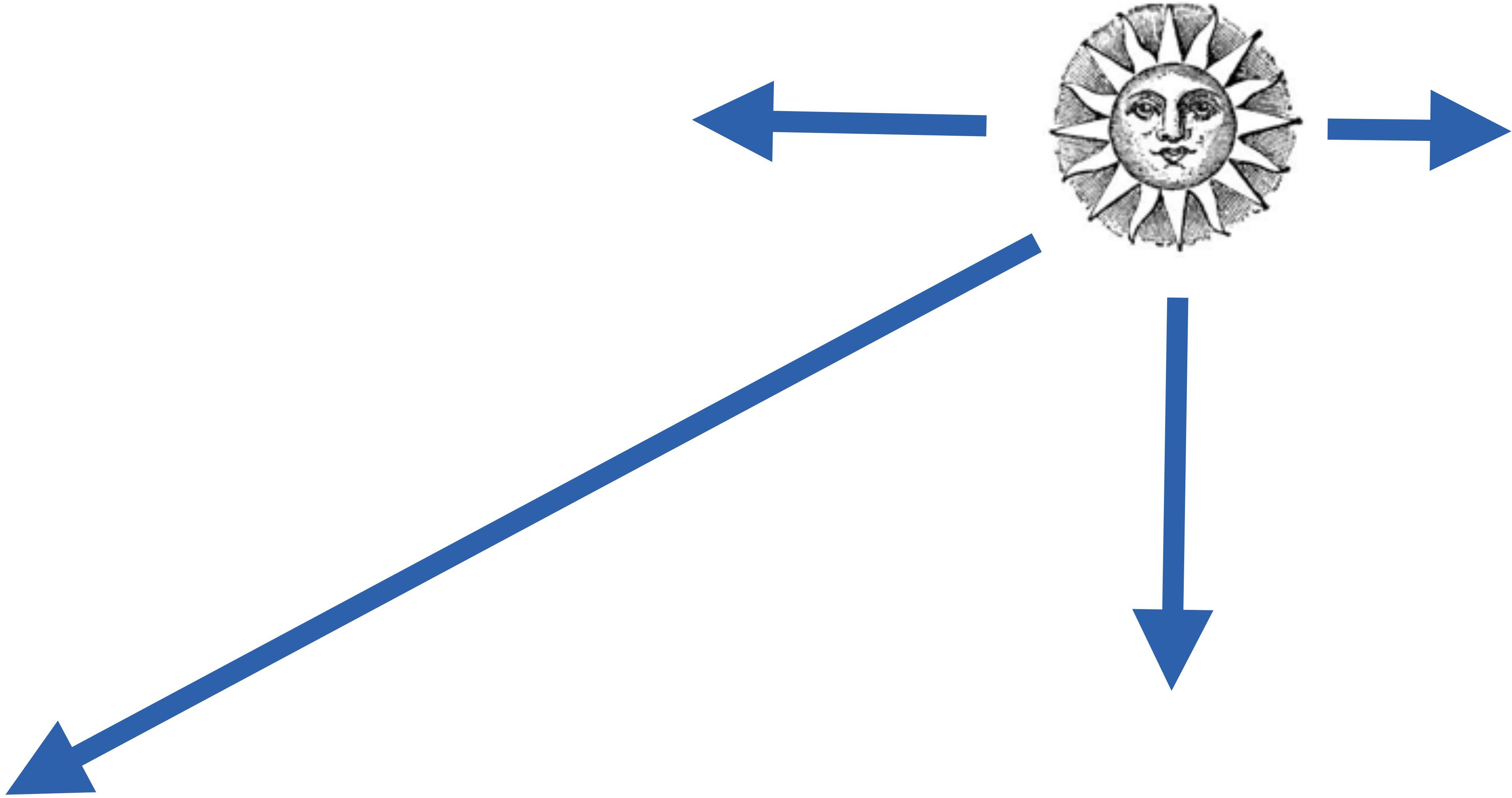
Course Plan: PHY-765 - Gravitational Lensing (GL)

version: April 10, 2018

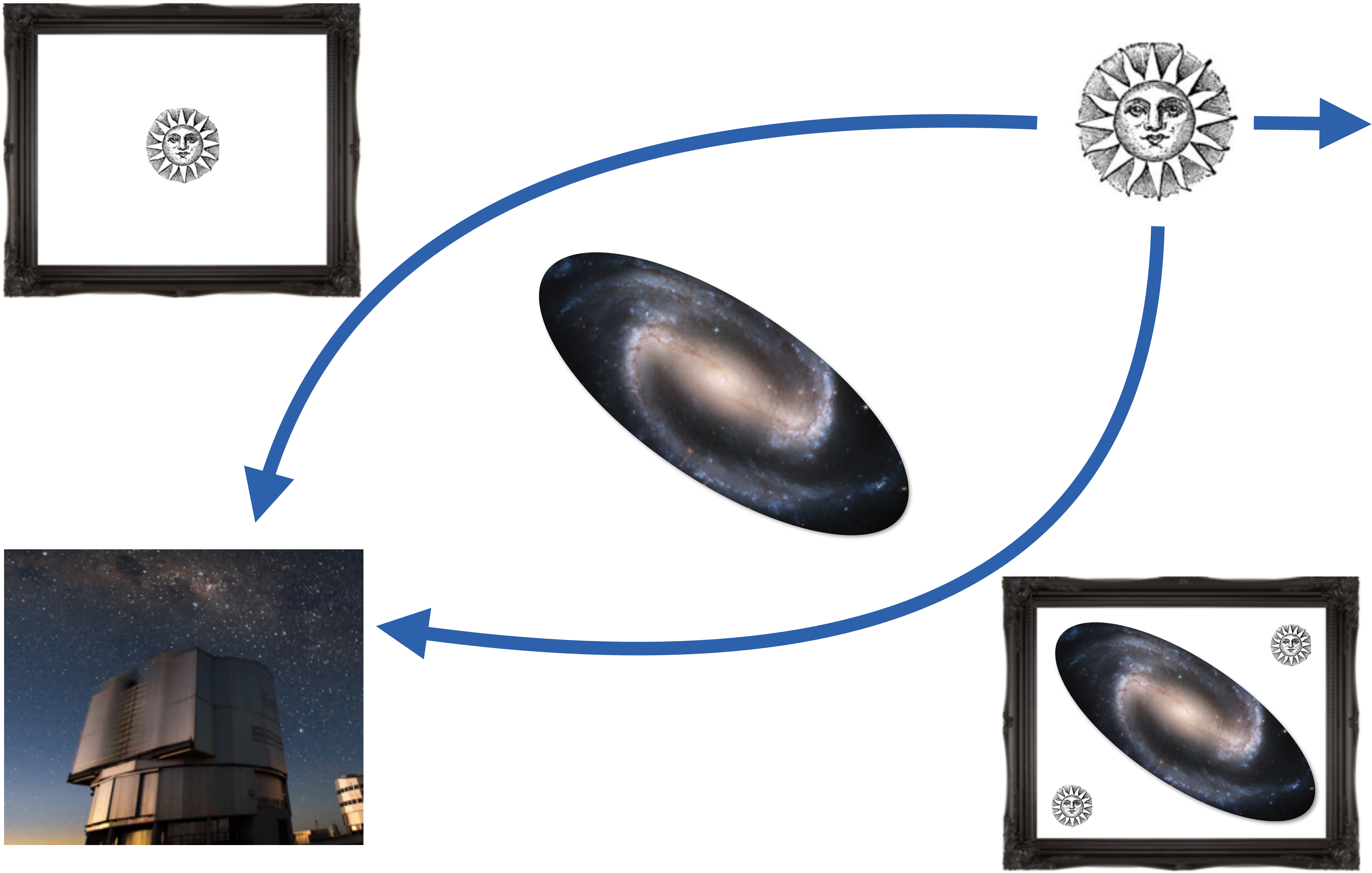
Lecture plan subject to change. See https://kasperschmidt.github.io/teaching/SS18_GravLens_UP765 for details.

W	Lecture (Wed.'s 08:15-09:00)	Exercise/Seminar (Wed.'s 09:00-09:45)	Location
1	Slides 01 Intro & Early days of GL	Worksheet 01 (Literature searches and first lenses)	2.28.2.011
2	Slides 02 Light deflection and basic GL geometry	Worksheet 02 (Select poster topic for presentation)	2.28.2.011
3	Slides 03 Multiple images	Worksheet 03 (TBD)	2.28.2.011
4	Slides 04 The lens equation	Worksheet 04 (Poster presentations)	2.28.2.011
5	Slides 05 Magnifying sources	Worksheet 05 "Journal club" allocations 1	2.28.2.011
6	Slides 06 GL time delays	Worksheet 06 (Present "journal club" papers 1) Essay allocation	2.28.2.011
7	Slides 07 Finding gravitational lenses	Worksheet 07 (TBD)	2.28.2.011
8	Slides 08 Micro GL	Worksheet 08 (Finishing essay)	2.28.2.011

What is Gravitational Lensing?



What is Gravitational Lensing?



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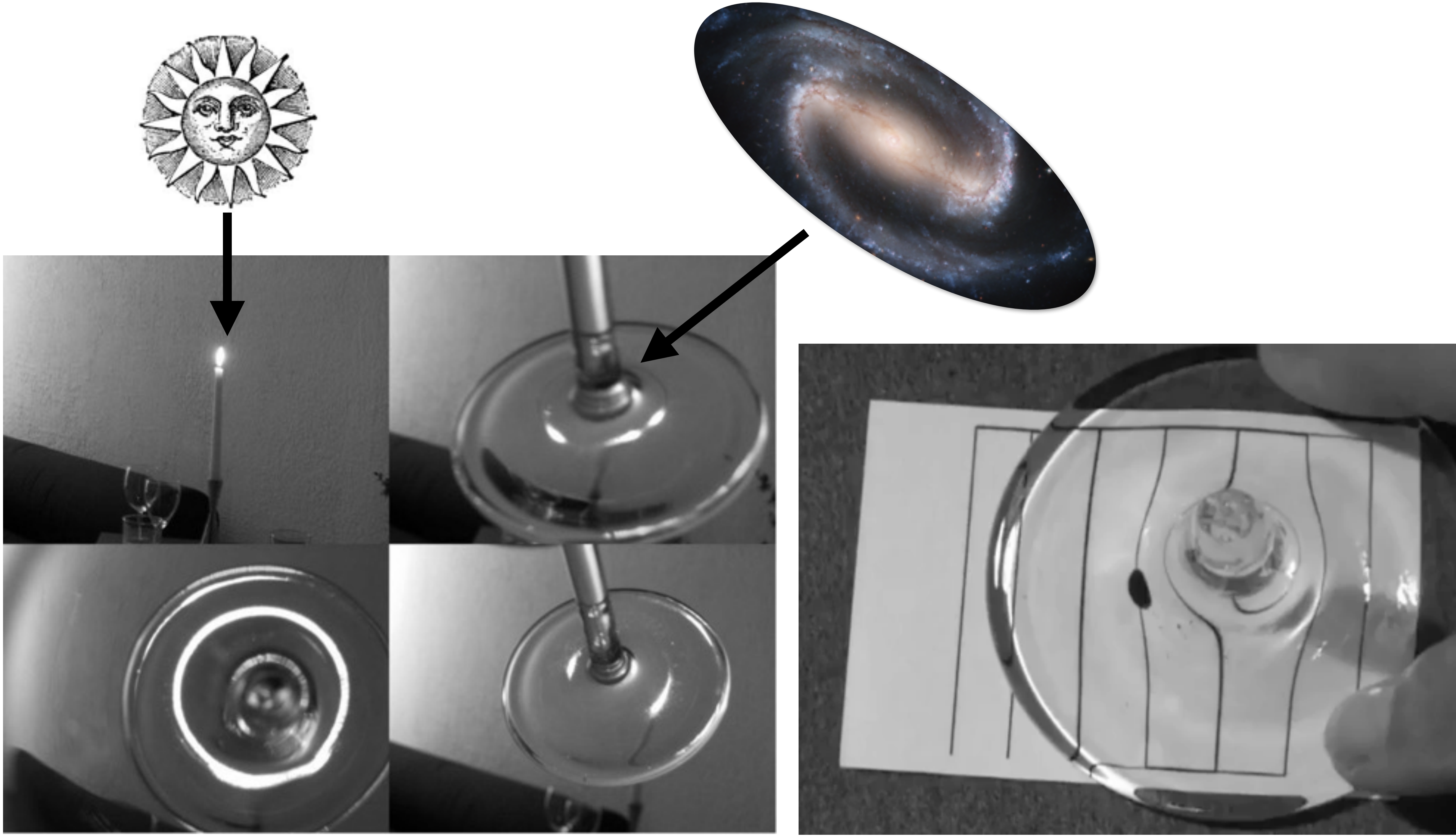
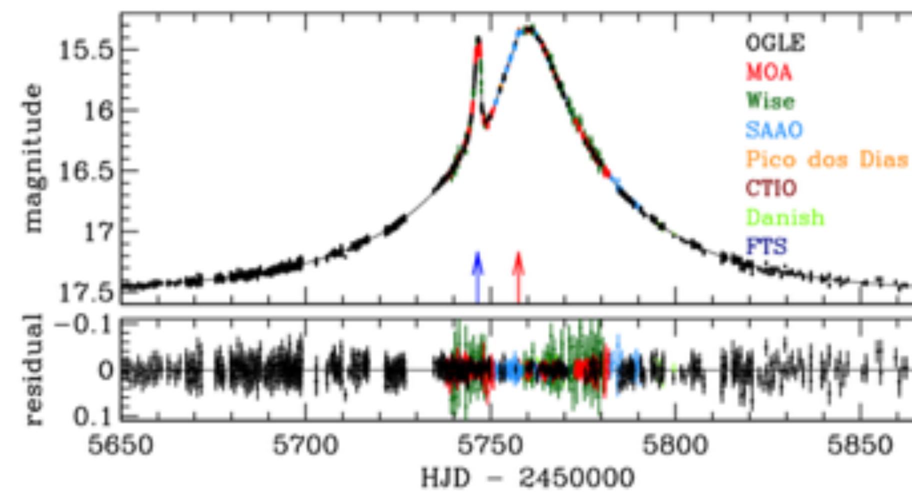


What is Gravitational Lensing?

- Strong
  - Extended & point sources
  - Most extreme distortion of source
  - Multiple images
- Micro (μ-arcsec scales)
  - Strong lensing regime
  - Point source vs. point source
- Weak
  - Lens and/or source is often diffuse
  - Statistical assessment of effect

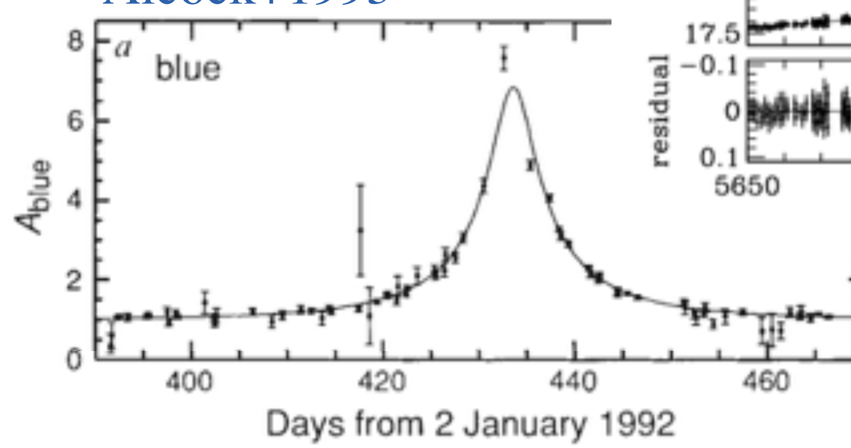
The Cheshire Cat

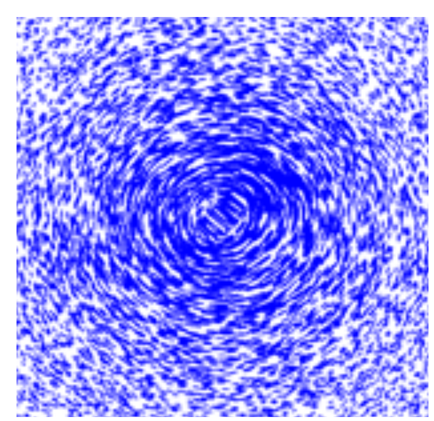
RXJ1131-1231



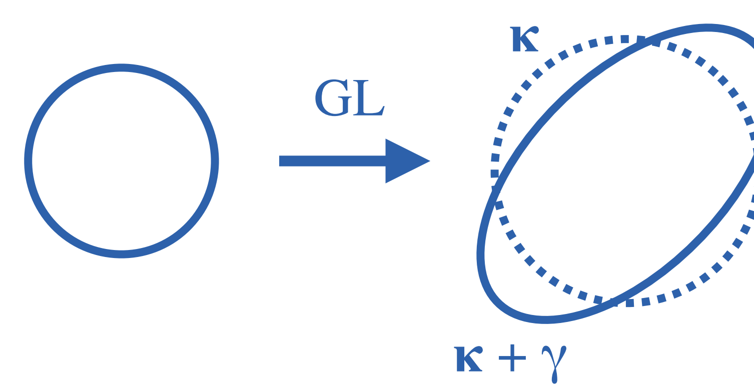
Skowrun+2015

Alcock+1993





Maturi & Merten 2013



What is Gravitational Lensing Good For?

• Multiple images	Improved S/N and multiple sight lines
• Magnification of light	Reach intrinsically fainter objects
• Improved resolution	Resolve high-z
• $\Delta t \neq 0$ in light travel times	Probing cosmological parameters
• Probing mass of lens	BH, planet, galaxy, galaxy cluster
• …	

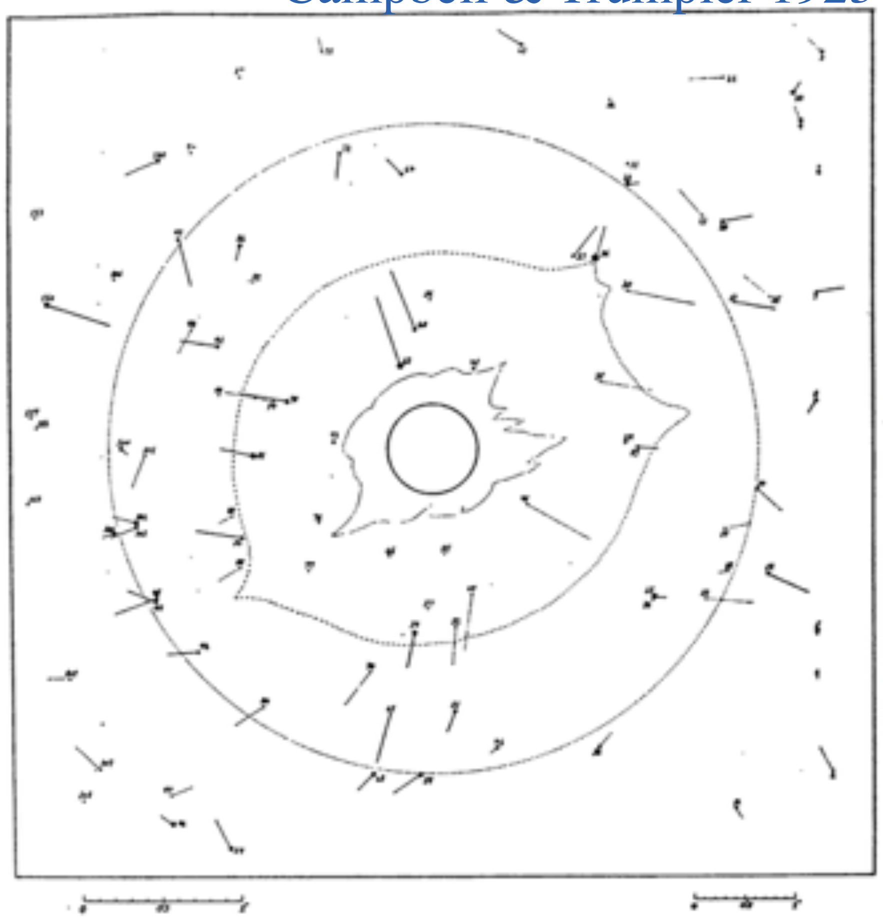
The Early Days of GL

- Before Einsteins GR people already speculated about gravity's affect on light
- Already in Newton+1704, Sir IsaacNewton asked:
  - *"Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action strongest at the least distance?"*
- In 1784 Mitchell wrote Cavendish about "black" bodies' affect on light particles
- Cavendish estimated the deflection using Newtons gravity but never published
- In 1796 Laplace (independently) noted:
  - *"that the attractive force of a heavenly body could be so large, that light could not flow out of it"*
- This lead to the definition of the Schwarzschild radius: $R_s = 2GM / c^2$
- Soldner+1804 derived the Newtonian deflection angle:
  - $\tan \alpha/2 = GM / v^2 r \quad \rightarrow \quad \alpha_N = 2GM / c^2 r$ if $v = c$ and α is small

The Early Days of GL

- Using this equation the prediction is that a star behind the sun should be shifted by 0.85 arcsec
- In 1911 Einstein independently derived the same value (before GR)
- Freundlich initiated expedition to Russia for the solar eclipse in 1914
  - WWI broke out and the expedition was captured.
- Einstein+1915's GR provided the correct deflection angle
  - $\alpha = 4GM / c^2 r \sim 2 \times \alpha_N = 1.75$ arcsec
- Was confirmed with 1919 and1922 expeditions
- Lodge 1919 used the term 'lens' for the first time
  - Noting bad comparison without focal length
- Chwolson+1924 predicted "fictive double stars" and "ring of light" for perfect alignment

Campbell & Trumpler 1923



The Early Days of GL

- After discussions with Mandl, Einstein published calculations of deflections for a star-star lens in 1936

- Zwicky suggested “Nebulae as Gravitational Lenses” in 1937a,b
  - Estimating 1/400 distant sources would be affected by lensing
  - Predicting deflections of up to 0.5 arc minutes
  - Foreseeing such lenses as powerfull estimators of lens masses
  - Predicting magnification allow studies of object at higher redshift
  - And that this leads to a bias when estimating numbers of high-z sources
  - Pointed out the importance of spectroscopic redshift in determining lenses

The Early Days of GL

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).

Emergence of Low Energy Protons from Nuclei

In some experiments recently described[1] the emission of protons in alpha-particle induced transmutations has been studied. In several cases the interesting fact was noticed that protons of relatively low energy were emitted in considerable numbers. Thus for each of the reactions

$$Al^{27}+He^4\rightarrow Si^{30}+H^1,$$
$$P^{31}+He^4\rightarrow S^{34}+H^1,$$
$$Cl^{35}+He^4\rightarrow A^{38}+H^1,$$
$$Ca^{40}+He^4\rightarrow Sc^{43}+H^1,$$

a group of protons of maximum range 20 cm or less is found and the yield is in general large (more than one-third of the total number of protons emitted). In each case protons of range 10 cm are observed with no apparent diminution of the probability of emission. The question arises as to how these low energy protons get out of the composite nucleus.

In recent experiments in this laboratory the excitation curve for the emission of neutrons from argon under alpha-particle bombardment has been plotted and the nuclear radius found to be 7.3×10^{-13} cm which is in accord with Bethe's revised radii for the radioactive elements[2] and may be taken as a basis for calculation of the nuclear radii of Si^{30}, S^{34}, A^{38}, Ca^{43} and Sc^{43}. Other evidence (e.g., scattering experiments) indicates, if anything, smaller radii than those found in this way. In Table I are given the radii so calculated, together with the heights of the corresponding proton barriers and the range of a proton just able to surmount them. It will be seen that in every case the experimentally observed ranges are smaller than necessary to scale the barrier. It therefore appears that we can draw one of two significant conclusions from the experimental data. Either *barriers to emerging protons are abnormally low or the composite nucleus containing the final product element and the proton has a finite lifetime sufficiently long to enable the proton to leak through the barrier*. The latter view, which is in accordance with Bohr's conception of transmutation,[3]

Table I.

Product Nucleus	Nuclear Radius ($\times10^{13}$cm)	Proton Barrier Height (Mev)	Range to Scale Barrier (cm)	Experimentally Found Range
Si^{30}	6.7	3.0	14.0	<10
S^{34}	6.9	3.3	16.5	<10
A^{38}	7.2	3.6	19.0	<10
Ca^{43}	7.4	3.9	22.0	14
Sc^{43}	7.5	4.0	23.0	<10

this description, to an analogous variety of currents in the superconductor. It could be shown that this description provides just as many possible currents as are required in order to satisfy uniquely the macroscopic boundary conditions for current and field. All currents observed in the conductivity experiments can be conceived as produced by the magnetic field. The new relation between current J and magnetic field H derived on this basis is

$$\mathrm{rot}\,\Lambda J=-H,$$

where Λ is a constant characteristic of the superconductor.

This mechanism of conduction is entirely different from that discussed in customary theories of conductivity: The transport of electricity is not based, as usually, on *progressive* waves (or wave packets) but on *stationary* waves. By these a transport of electricity can only be effected *in the presence of a magnetic field* and just this is our assertion as to the nature of the supercurrents.

Though in such a way a serious difficulty could be removed which seemed hitherto to render impossible any theory of superconductivity, the problem remained yet unsolved as to *which kind of interaction* could be made responsible for the appearance of such separated diamagnetic states.

In a paper just published by Slater[3] attention has been drawn to a mechanism which seems to be able to explain the appearance of such a separation of the lowest Bloch eigenvalues as characterized by (1) and it is therefore of interest to examine whether this mechanism is able to fill up the gap still left in the theory of superconductivity. Actually, Slater seems not to have thought of the particular possibility, mentioned above, of a magnetic interpretation of the phenomena of conductivity. In any case, he did not undertake to make plausible a property like that formulated under (2). Instead he refers rather to the notorious difficulties in dealing with the resistance problem at low temperatures. It appears doubtful, indeed, whether such a proof of the superconductivity of the model can be given. Moreover, proof of an infinitely high conductivity would not imply the fact that a superconductor, when formed in a magnetic field, has a magnetic induction zero. The reference in Slater's paper to the parallelism between specific heat and resistance seems to be rather misleading: there are superconductors with a high specific heat in the normal phase and nevertheless a high critical temperature (e.g., *Ta* has a high specific heat and a critical temperature of 4.4°).

The construction of such isolated states is certainly of greatest interest, and perhaps the indications given here may be found useful for discussing this or similar models.

F. London

Institut Henri Poincaré,
Paris, France,
March 7, 1937.

[1] F. and H. London, Proc. Roy. Soc. **A149**, 71 (1935); Physica **2**, 341 (1935). M. v. Laue, F. and H. London, Zeits f. Physik **96**, 359 (1935). F. London, Proc. Roy. Soc. **A152**, 25 (1935). E. Schrödinger, Nature **137**, 824 (1936). H. London, Proc. Roy. Soc. **A152**, 650 (1935); **155**, 102 (1936). F. London, Physica **3**, 450 (1936). Nature **137**, 991 (1936). For a general review see F. London, *Une conception nouvelle de la supraconductibilité*. Actualités scientifiques et Industrielles No. 458 Paris (Hermann & Cie) 1937.
[2] See e.g., Proc. Roy. Soc. **A152**, 31–33 (1935).
[3] J. C. Slater, Phys. Rev. **51**, 195 (1937).

On the Probability of Detecting Nebulae Which Act as Gravitational Lenses

Recently various authors[1,2] have again[3] considered the possibility of observing the image of a distant star A whose light is bent around some nearer star B. For reasons discussed by these authors, the probability that the mentioned effect will ever be observed with *stars* is vanishingly small. The general feeling therefore was that the idea of gravitational lenses affords "perfect tests of general relativity that are unavailable," as Professor H. N. Russell[2] puts it.

The problem in question, however, takes on a radically different aspect, if, instead of in terms of stars we think in terms of *extragalactic nebulae*.[4] Provided that our present estimates[5] of the masses of *cluster nebulae* are correct, the probability that nebulae which act as gravitational lenses will be found becomes practically a *certainty*. The reasoning which leads to this optimistic view is as follows.

Let us consider only the least probable but perhaps most spectacular case in which the straight line which joins the observer in O with the gravitational center of the lens-nebula B passes through a distant nebula A. What is the probability that for a specified nebula B this "coincidence condition" is satisfied? Clearly, if all of the distant nebulae whose apparent magnitude is brighter than m cover a total solid angle ω_m, the probability p for OB to intersect one of these nebulae is $p=\omega_m/4\pi$. Consequently, among $n=1/p$ nearby nebulae B, one satisfies on the average the coincidence condition.

On limiting exposures with the 100-inch telescope about 1/400 of the photographic plate is on the average covered by nebular images. Thus for a limiting magnitude of about $m=21.5$ we have approximately $n=400$. With gravitational focusing, nebulae considerably fainter than $m=21.5$ will be observable. Thus around one in about one hundred nebulae B the ring-like image of a distant nebula should be expected, *provided* that the chosen nebula B has an apparent angular radius ρ smaller than the angles γ through which light is deflected on grazing the surface of this nebula. Present estimates of masses and diameters of cluster nebulae are such that the observability of gravitational lens effects among the nebulae would seem insured. In any case, whatever the outcome, the search for such effects will provide us with valuable information regarding the masses of nebulae.

In searching through actual photographs, a number of nebular objects arouse our suspicion. It will, however, be necessary to investigate certain composite objects spectroscopically, since differences in the red shift of the different components of such objects will immediately betray the presence of gravitational lens effects. Until such tests have been made, further discussion of the problem in question may be postponed.

F. Zwicky

California Institute of Technology,
Pasadena, California,
March 18, 1937.

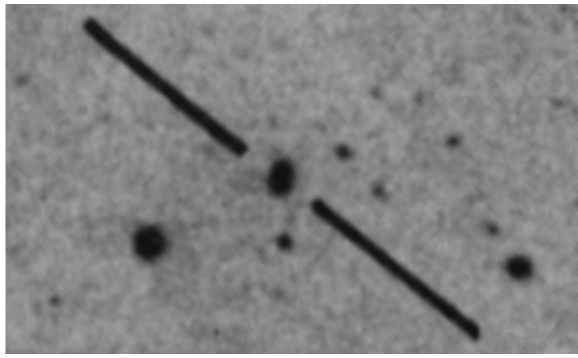
[1] A. Einstein, Science **84**, 506 (1936).
[2] H. N. Russell, Scientific American, p. 76, Feb. (1937).
[3] Dr. G. Strömberg of the Mt. Wilson Observatory kindly informs me that the idea of stars as gravitational lenses is really an old one. Among others, E. B. Frost, late director of the Yerkes Observatory, as early as 1923 outlined a program for the search of such lens effects among *stars*.
[4] F. Zwicky, Phys. Rev. **51**, 290 (1937).
[5] F. Zwicky, Helv. Phys. Acta **6** 124 (1933).

The Early Days of GL

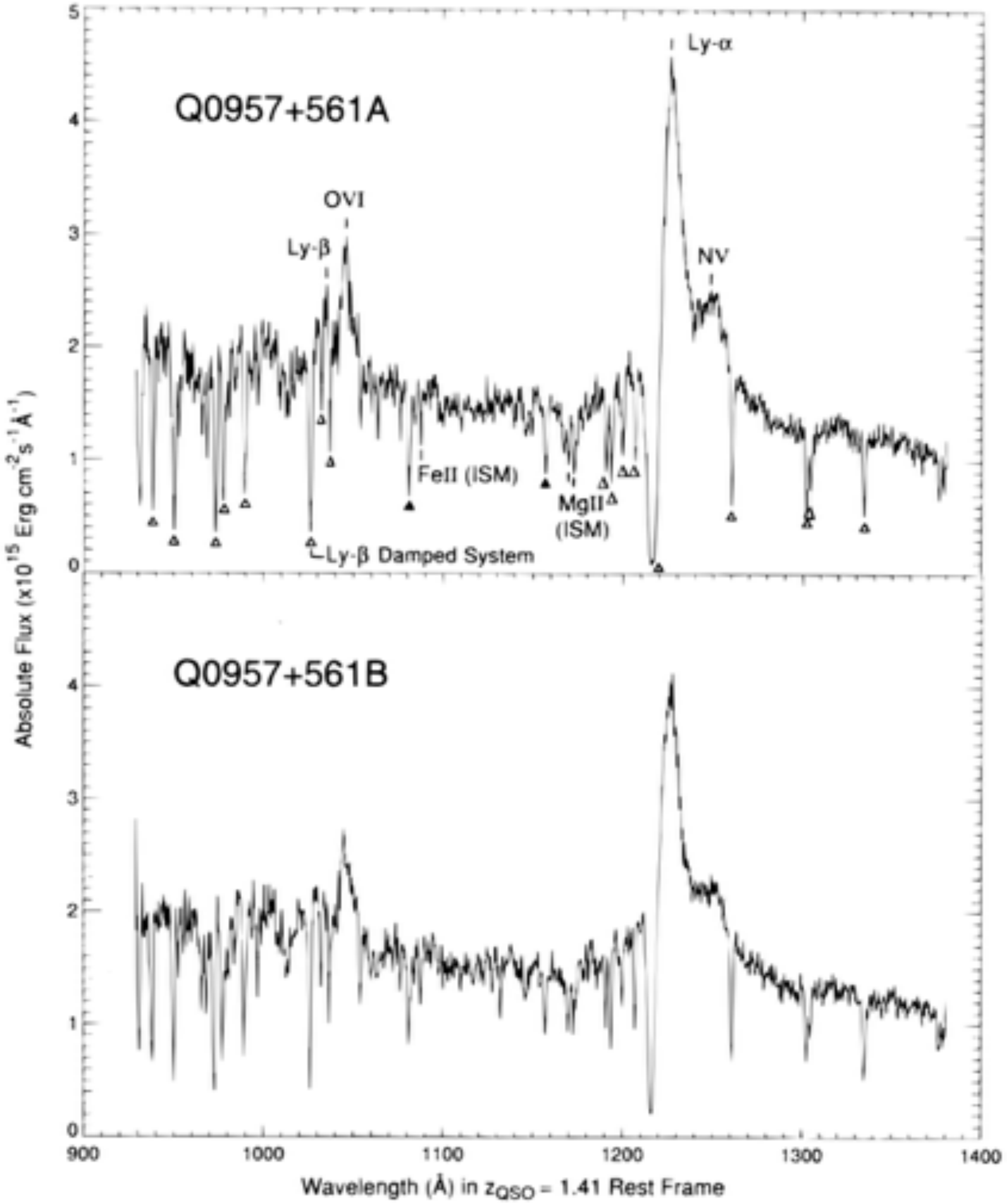
- In 1963, Schmidt presented the first stellar-like extragalactic object, QSO
- Early 1960s several authors "revived" the dormant studies of lensing
  - Klimov 1963: Looking at Einstein rings and multiple images
  - Liebes 1964: Looking at star-star (MW star - M31 star) lensing
  - Refsdal 1964a,b: Difference in light travel times of multiple images and the use of these to determine H_0
- Hence, point-sources were now available for lensing of galaxies…

The Discovery of the First Lens(es)

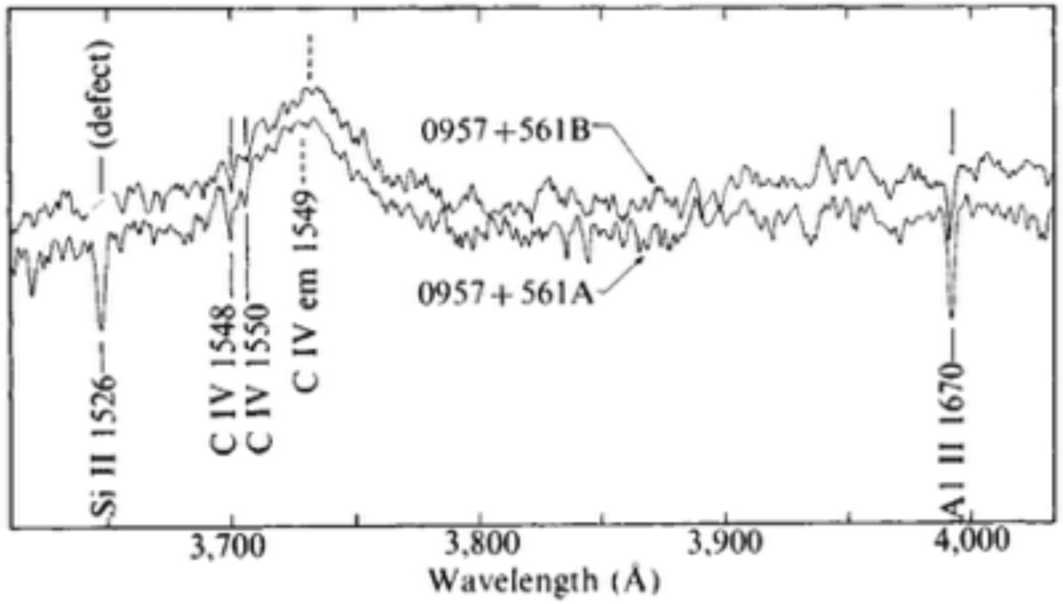
- Walsh+1979 discovered the first QSO lens: QSO 0957+561
- Has been confirmed from multiple observations since then



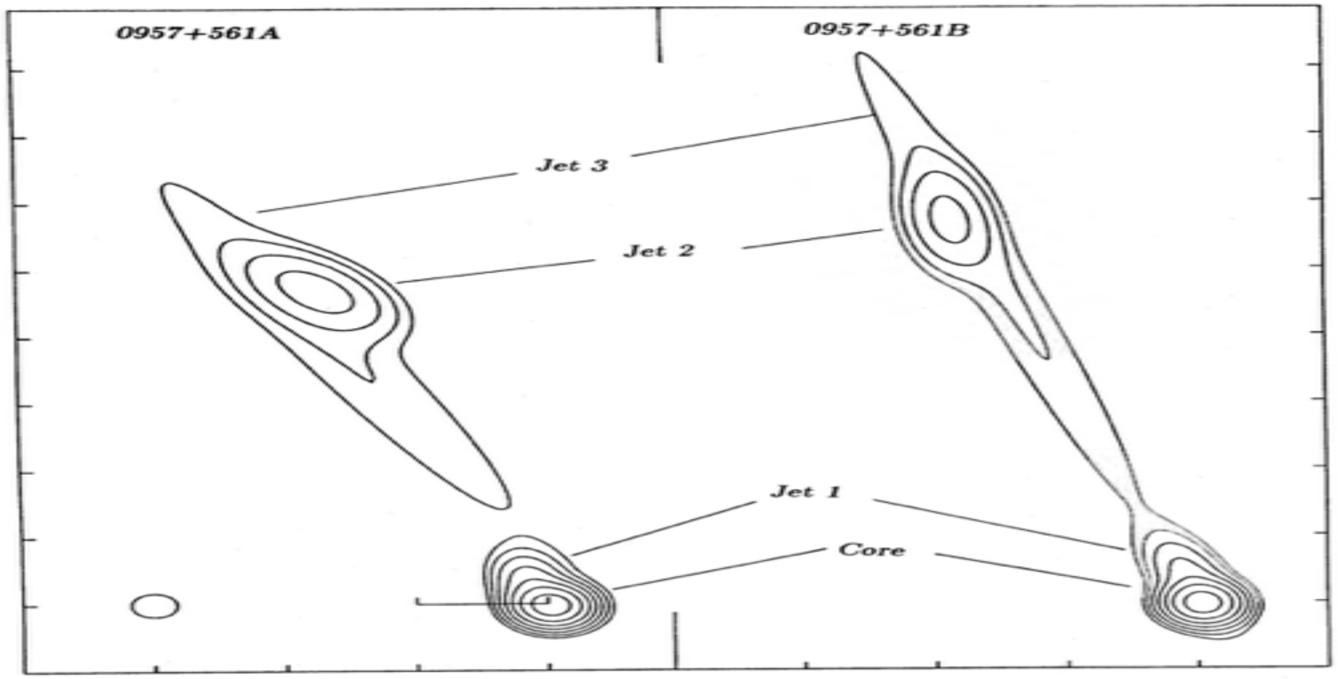
Michalitsianos+1997



Walsh+1979



Gorenstein+1988



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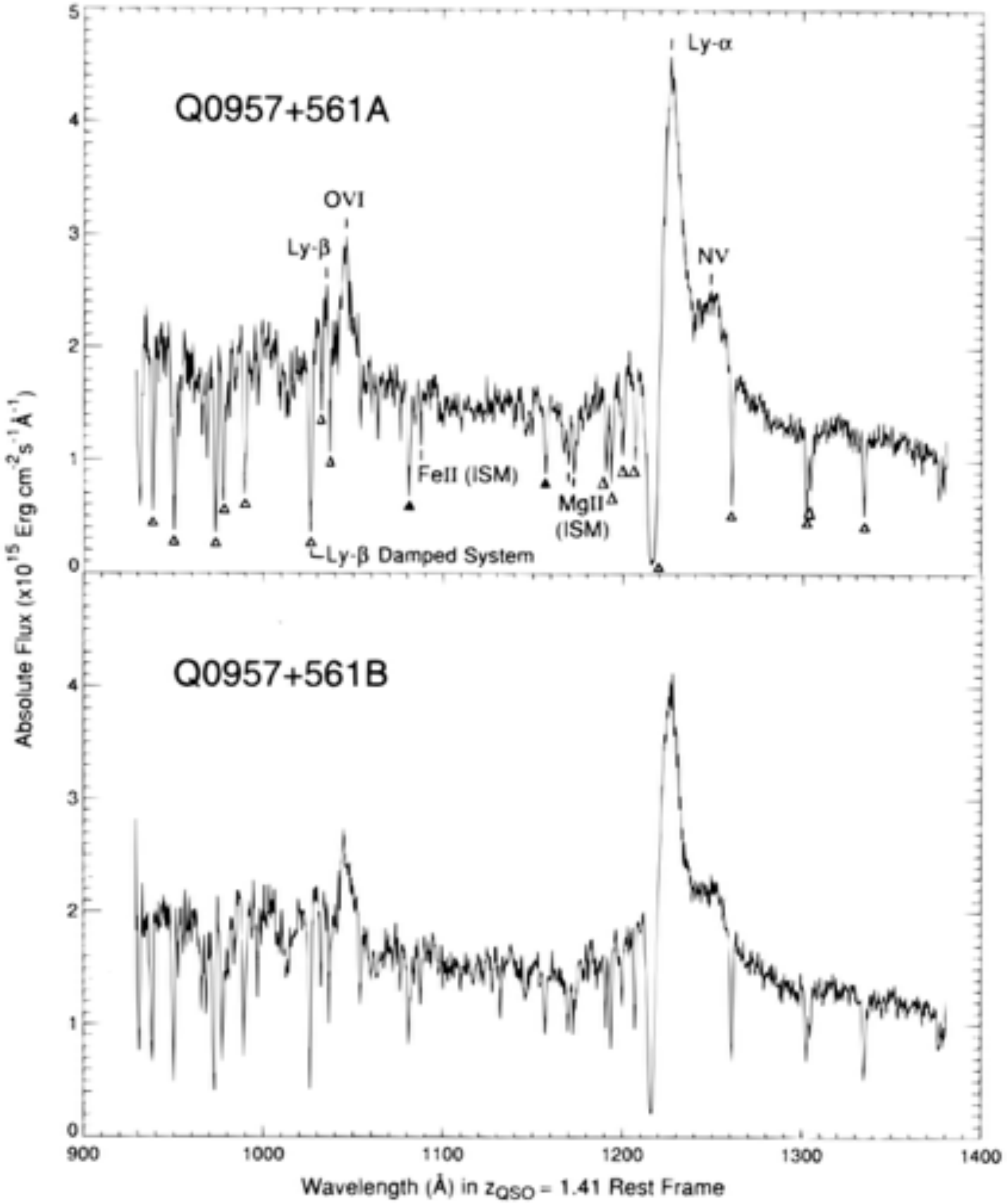
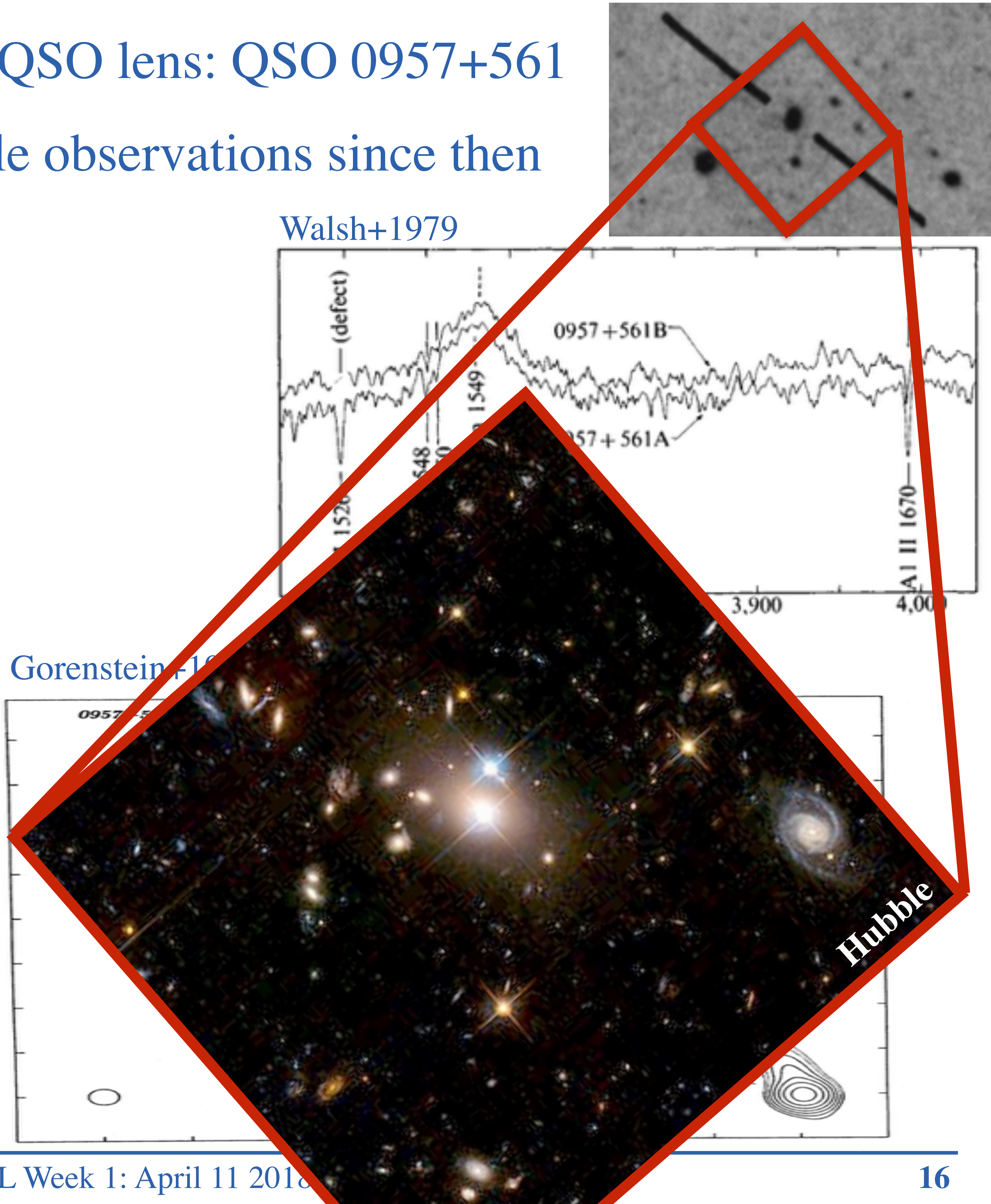


Walsh+1979

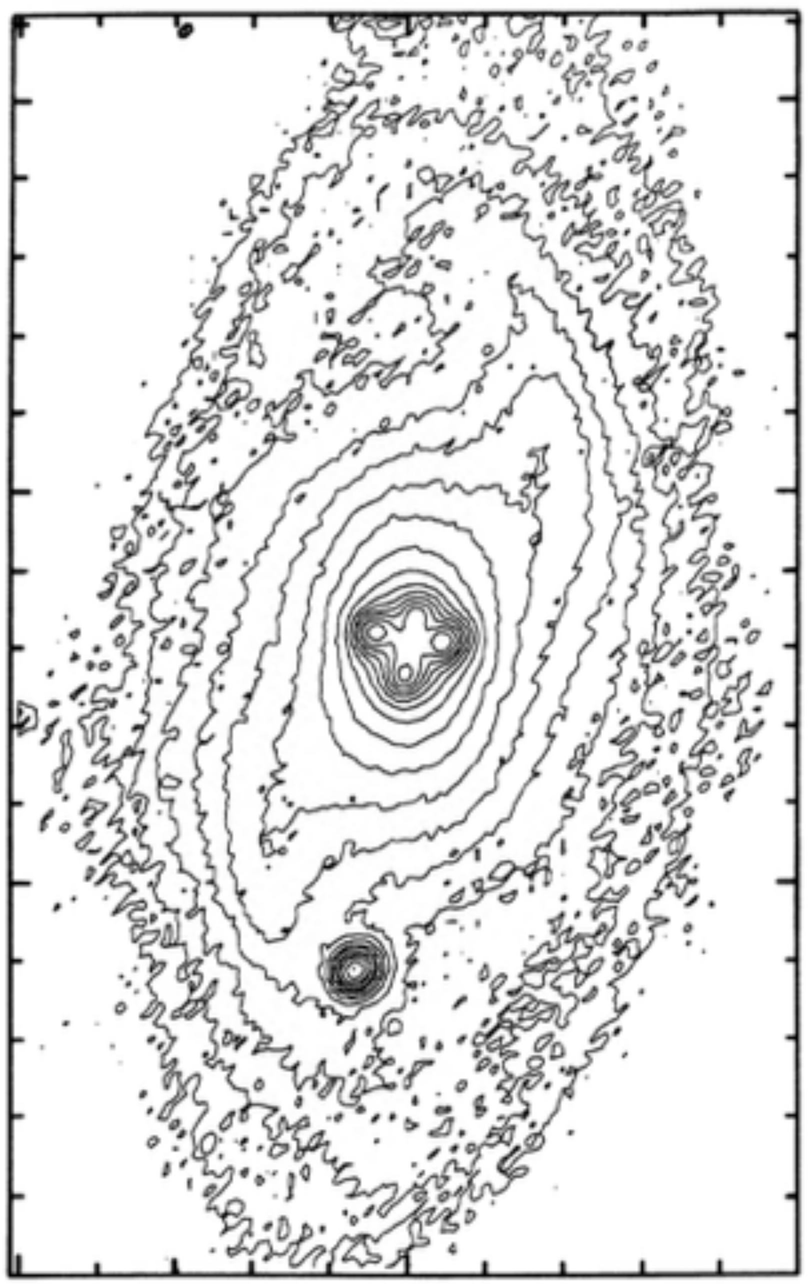
Gorenstein+1



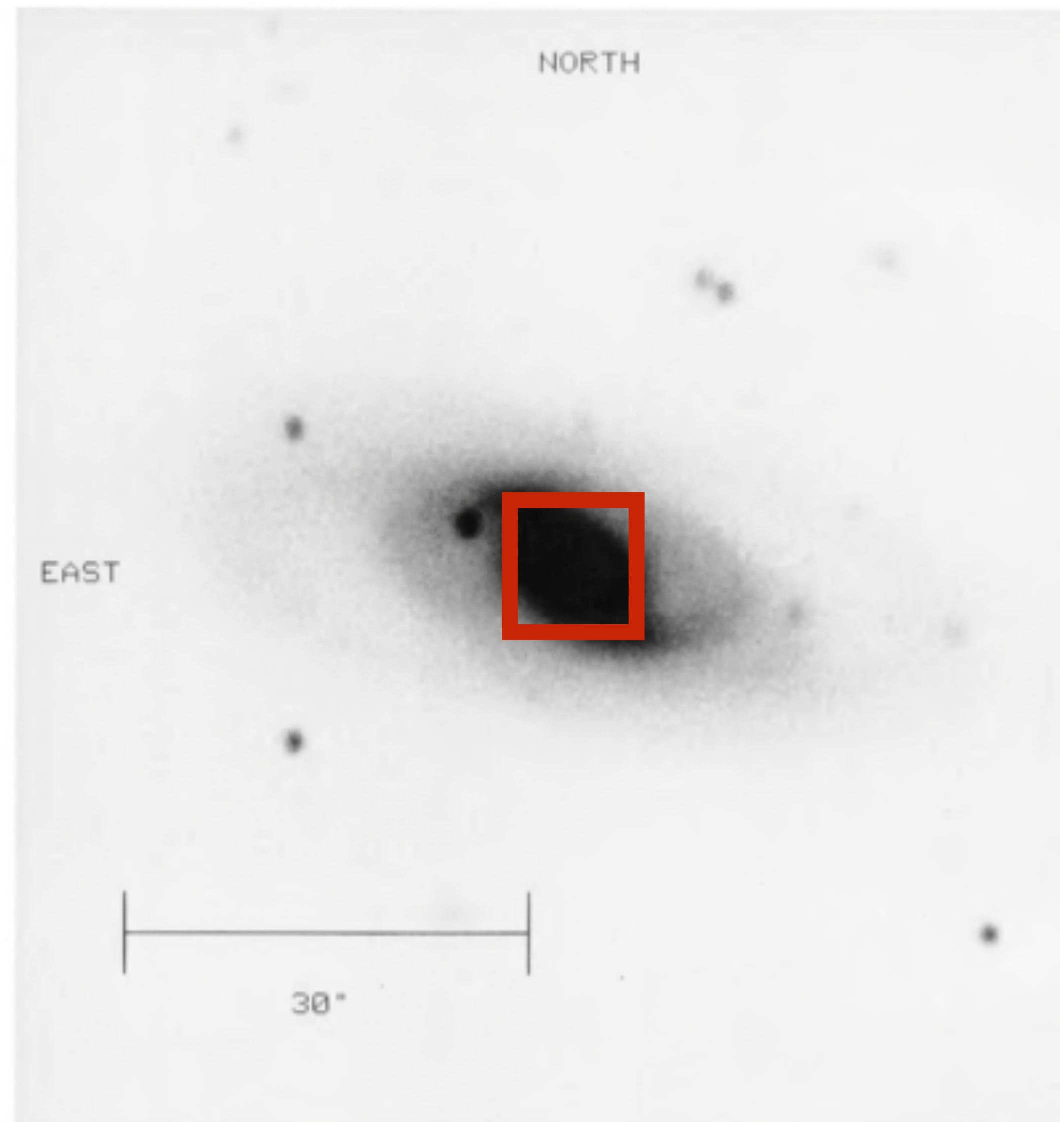
The Discovery of the First Lens(es)

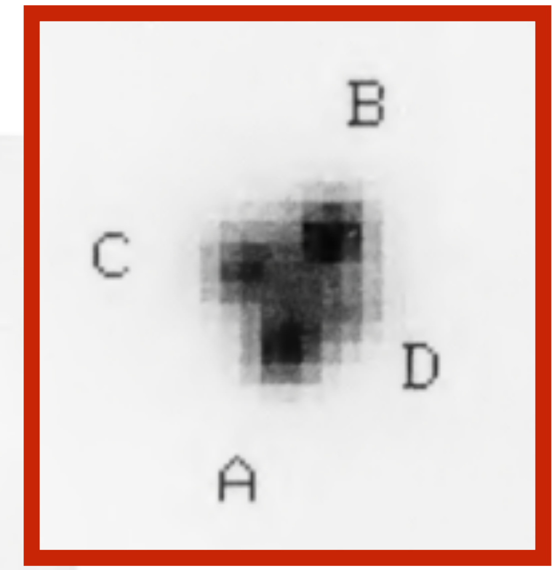
- The Einstein Cross was presented by Huchra+1985

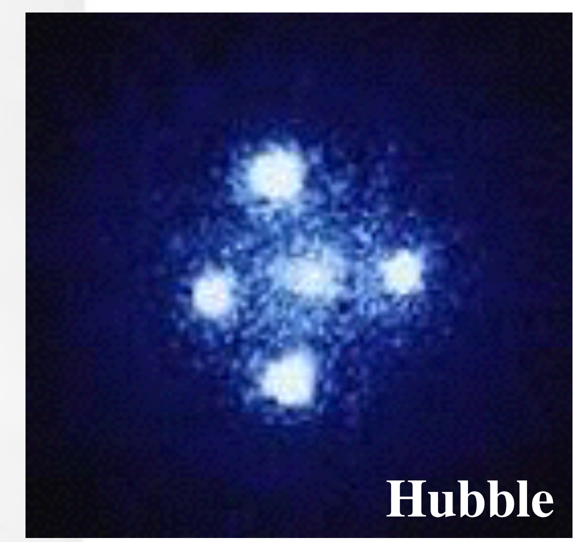
Yee+1988



Schneider+1988

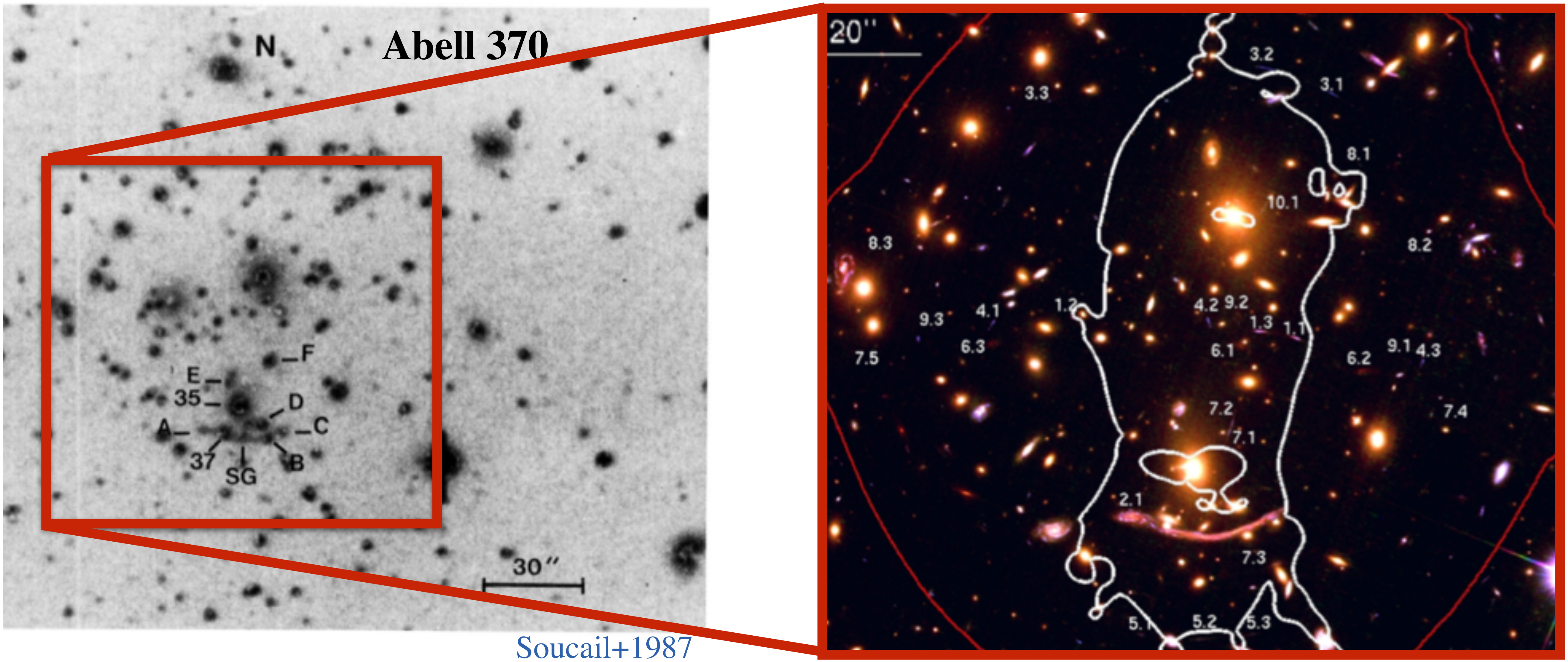




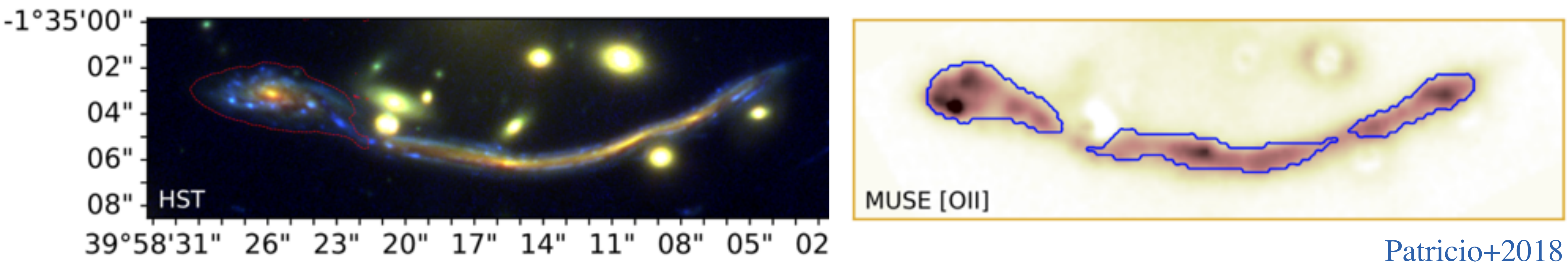


The Discovery of the First Lens(es)

- Discovery of luminous arc in clusters of galaxies occurred in 1986/1987



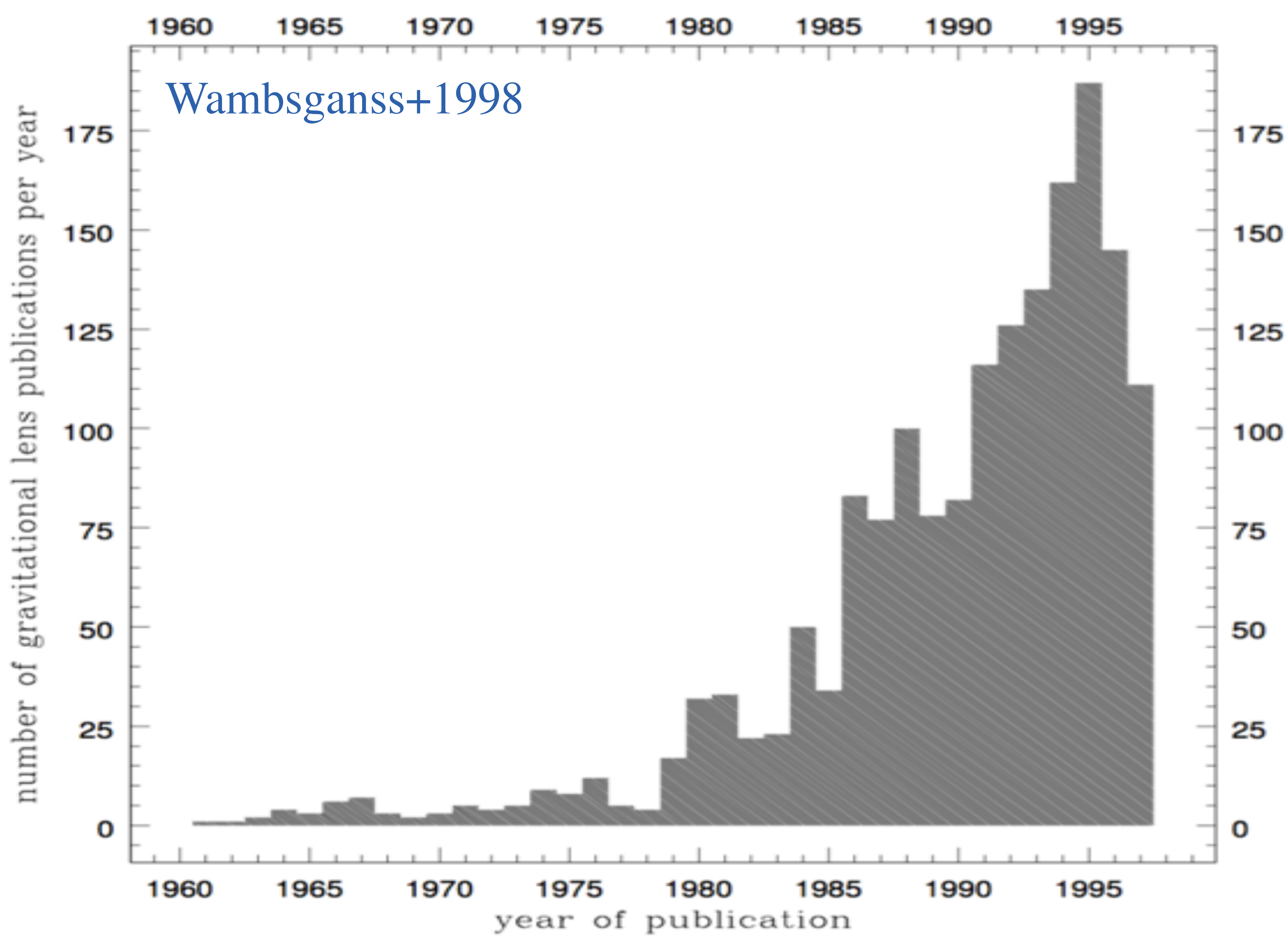
Soucail+1987



Patricio+2018

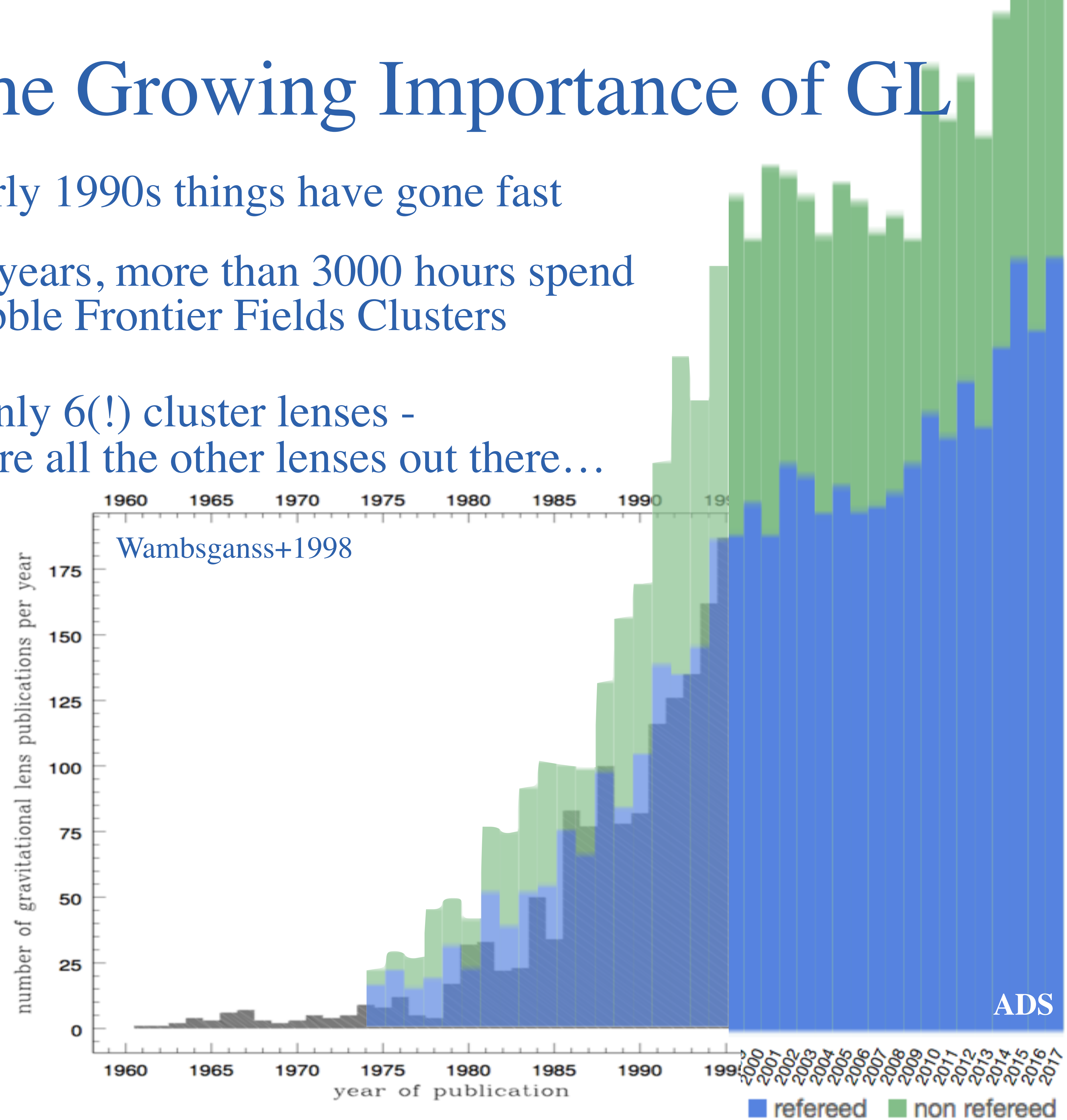
The Growing Importance of GL

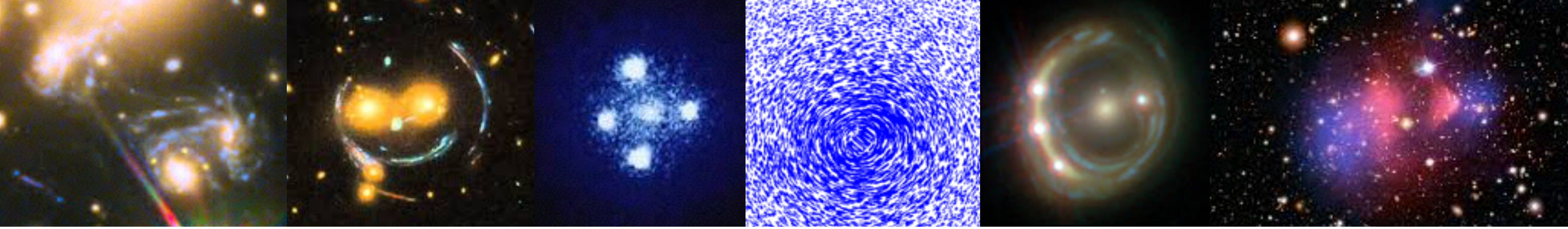
- Since the early 1990s things have gone fast



The Growing Importance of GL

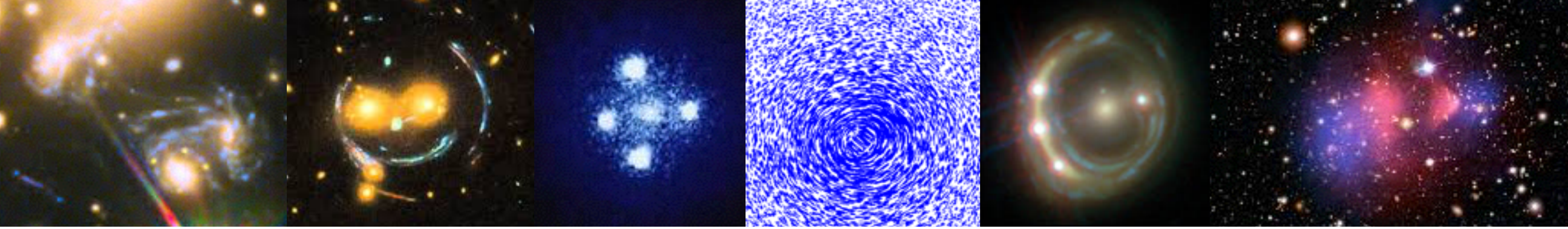
- Since the early 1990s things have gone fast
- In the last 5 years, more than 3000 hours spend on the 6 Hubble Frontier Fields Clusters
- And that's only 6(!) cluster lenses -
  Then there are all the other lenses out there…





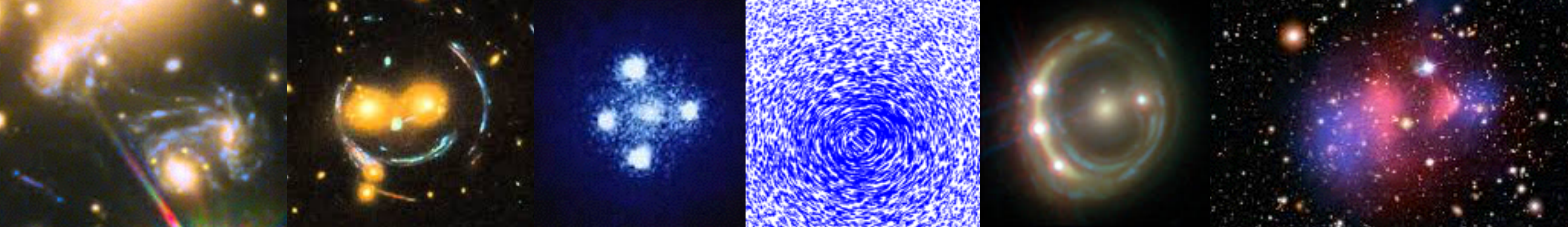
PHY-765 SS18 Gravitational Lensing Week 1

Questions?



The Weekly Worksheets

- New Worksheet every week
- A mix of:
  - “astronomer skill development” exercises
  - classic problem solving
  - instructions for task/assignments to be presented at later stages



PHY-765 SS18 Gravitational Lensing Week 1

This Week’s Worksheet