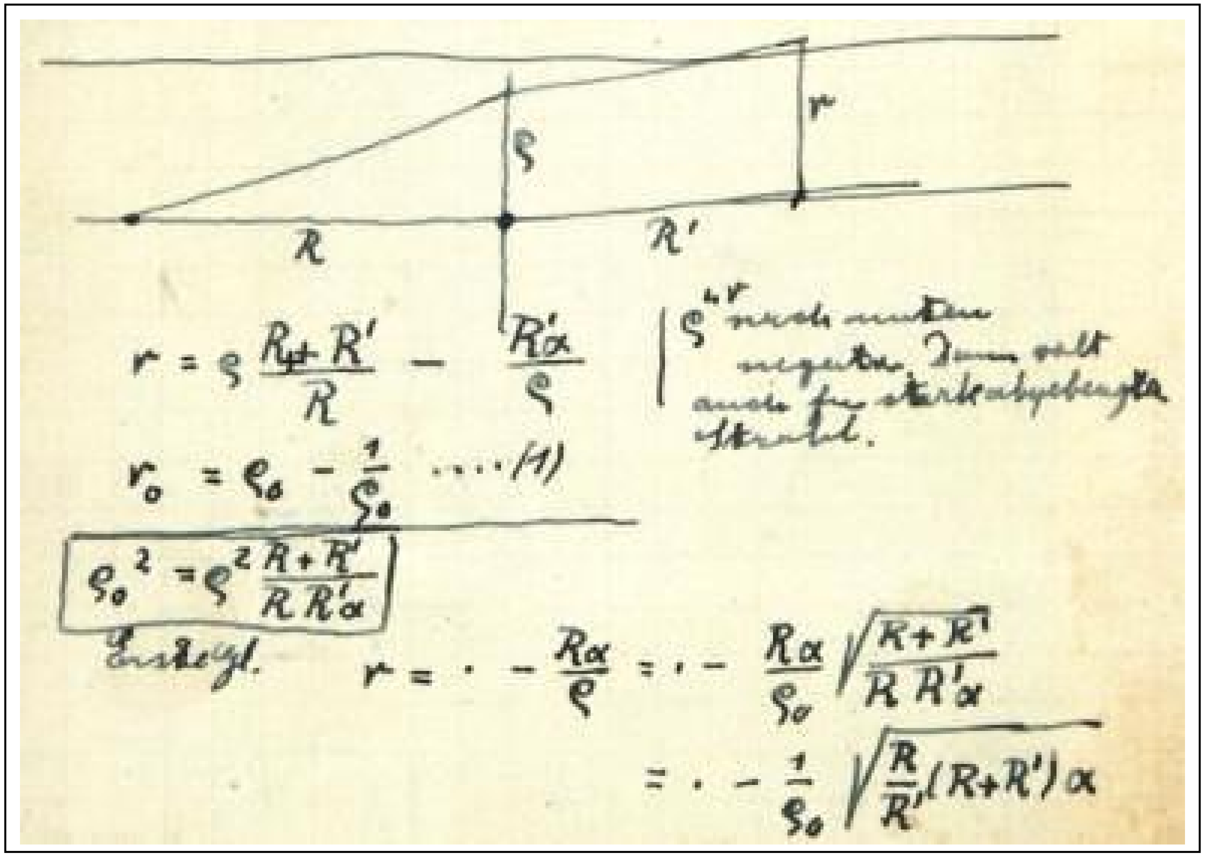
Extragalactic DM Halos and QSO Properties Through Microlensing



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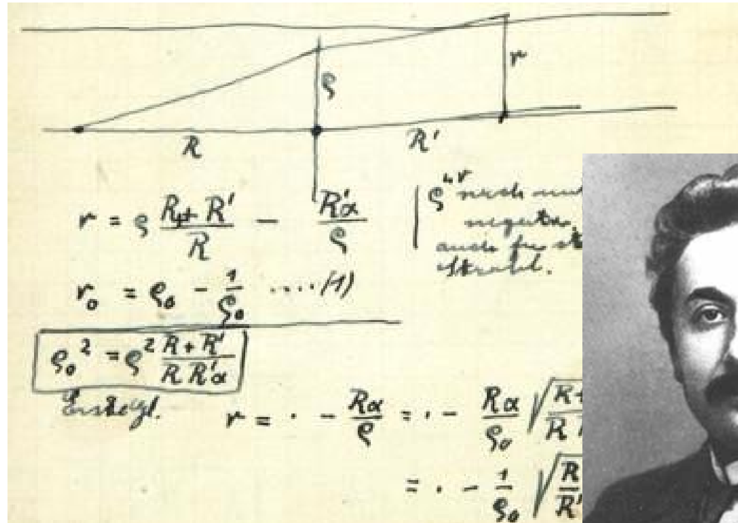
Instituto de Astrofísica de Canarias

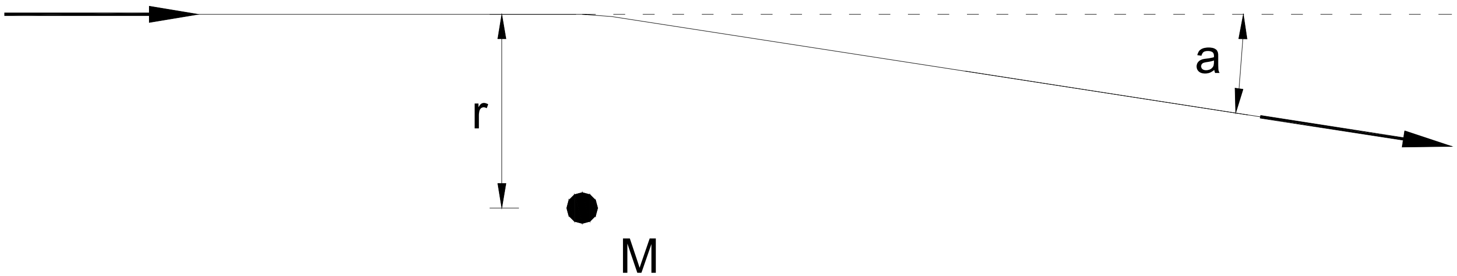
1. Microlensing

1. Microlensing

Photon deflection by gravitating mass

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





1915SPAW.......831E

1. Microlensing

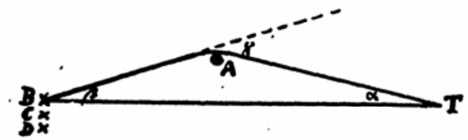
Орест Хвольсон (1852-1934) raised in 1924 the possibility that an alignment could result in a ficticious double star or a ring image

Über eine mögliche Form fiktiver Doppelsterne. Von *O. Chwolson.*

Es ist gegenwärtig wohl als höchst wahrscheinlich anzunehmen, daß ein Lichtstrahl, der in der Nähe der Oberfläche eines Sternes vorbeigeht, eine Ablenkung erfährt. Ist γ diese Ablenkung und γ_0 der Maximumwert an der Oberfläche, so ist $\gamma_0 \geqq \gamma \geqq 0$. Die Größe des Winkels ist bei der Sonne $\gamma_0 = 1''7$; es dürften aber wohl Sterne existieren, bei denen γ_0 gleich mehreren Bogensekunden ist; vielleicht auch noch mehr. Es sei A ein großer Stern (Gigant), T die Erde, B ein entfernter Stern; die Winkeldistanz zwischen A und B, von T aus gesehen, sei α, und der Winkel zwischen A und T, von B aus gesehen, sei β. Es ist dann

$$\gamma = \alpha + \beta\,.$$

Ist B sehr weit entfernt, so ist annähernd $\gamma = \alpha$. Es kann also α gleich mehreren Bogensekunden sein, und der Maximumwert von α wäre etwa gleich γ_0. Man sieht den Stern B von der Erde aus an zwei Stellen: direkt in der Richtung TB und außerdem nahe der Oberfläche von A, analog einem Spiegelbild. Haben wir mehrere Sterne B, C, D, so würden die Spiegelbilder umgekehrt gelegen sein wie in einem gewöhnlichen Spiegel, nämlich in der Reihenfolge D, C, B, wenn von A aus gerechnet wird (D wäre am nächsten zu A).



Der Stern A würde als fiktiver Doppelstern erscheinen. Teleskopisch wäre er selbstverständlich nicht zu trennen. Sein Spektrum bestände aus der Übereinanderlagerung zweier, vielleicht total verschiedenartiger Spektren. Nach der Interferenzmethode müßte er als Doppelstern erscheinen. Alle Sterne, die von der Erde aus gesehen rings um A in der Entfernung $\gamma_0 - \beta$ liegen, würden von dem Stern A gleichsam eingefangen werden. Sollte zufällig TAB eine gerade Linie sein, so würde, von der Erde aus gesehen, der Stern A von einem Ring umgeben erscheinen.

Ob der hier angegebene Fall eines fiktiven Doppelsternes auch wirklich vorkommt, kann ich nicht beurteilen.

Petrograd, 1924 Jan. 28. *O. Chwolson.*

1924AN....221..329C

1. Microlensing

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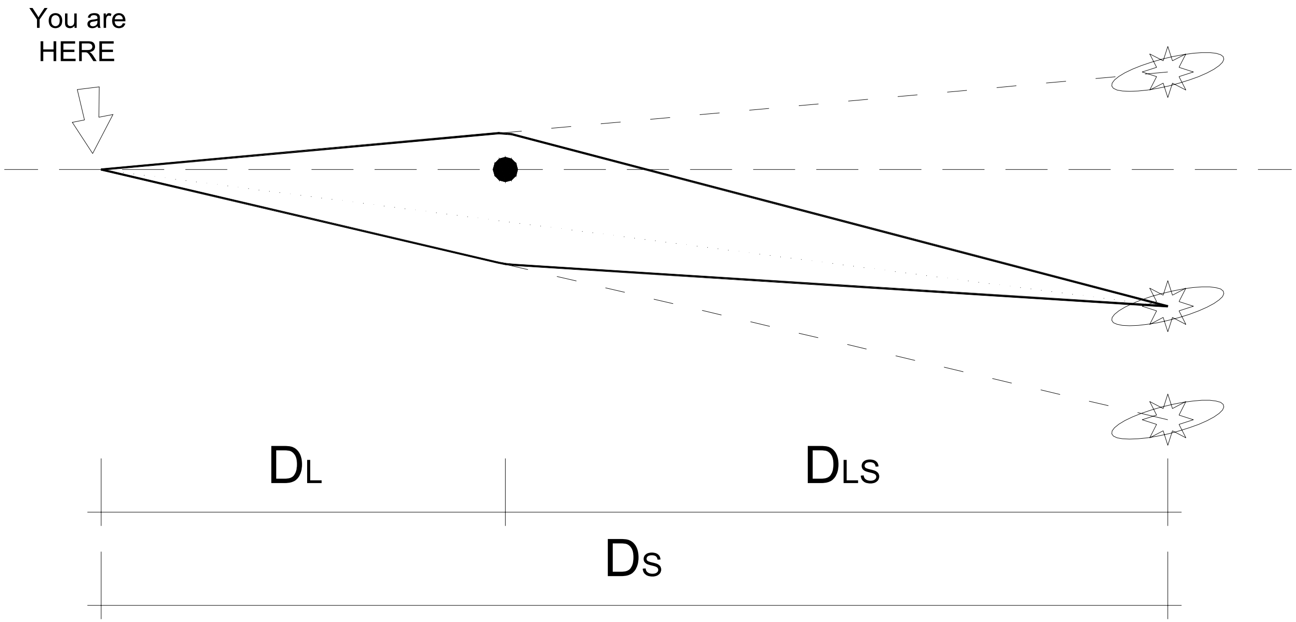

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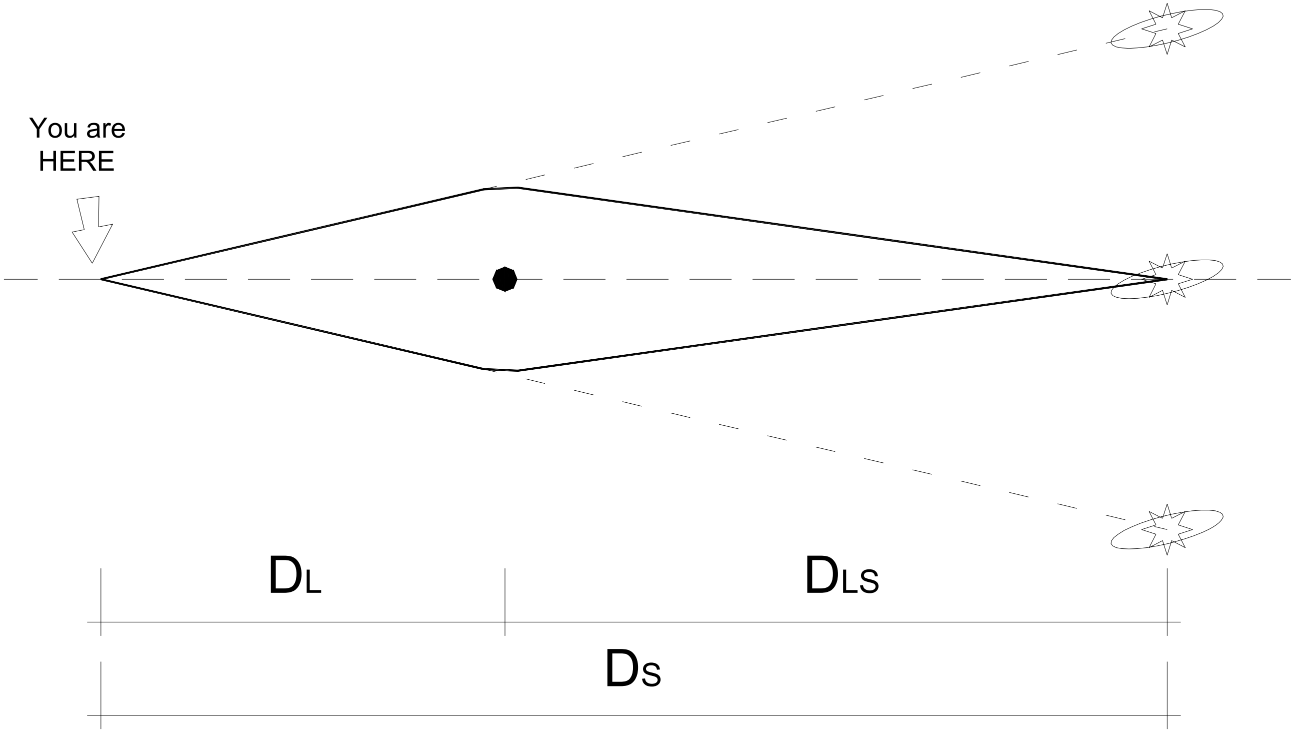

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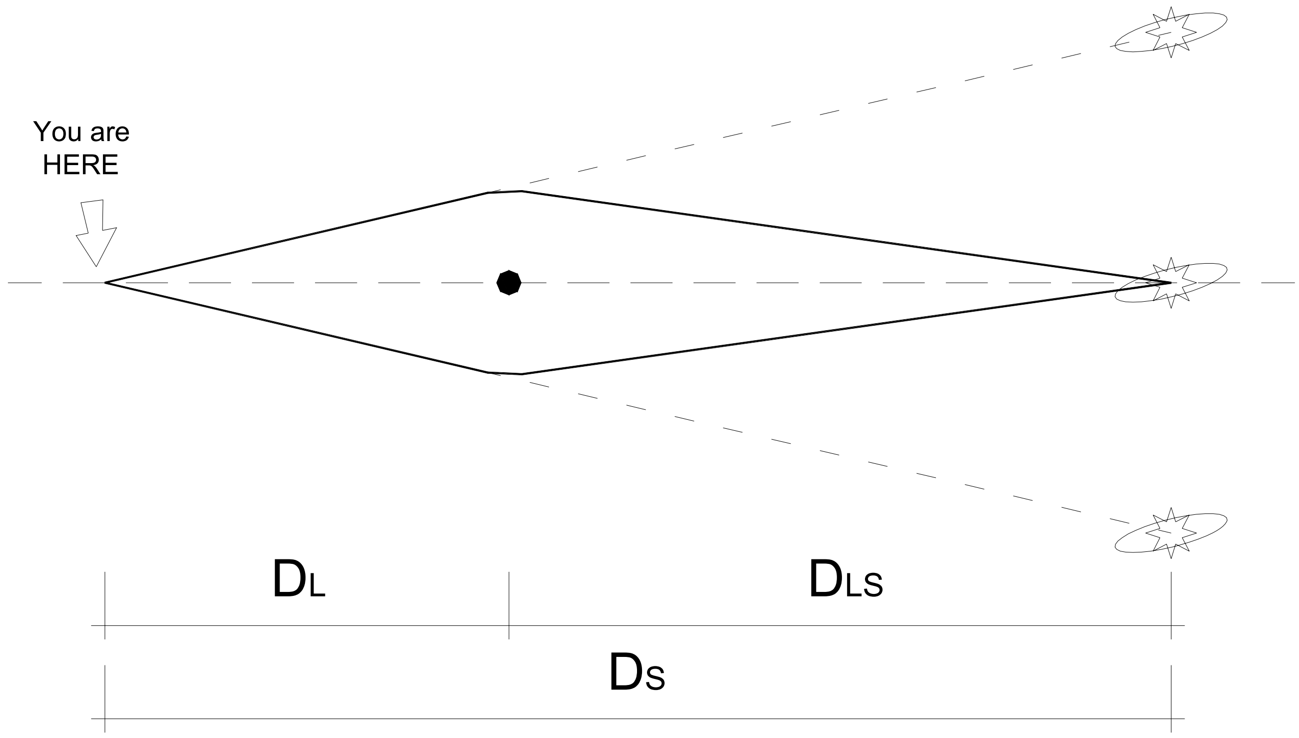


$$R_0 = \sqrt{\frac{4GMD_{LS}}{c^2 D_S D_L}} \approx 1\times10^{-3}\ \text{arcsec}$$

below telescope resolution!

(D_L ,D_{LS} = 5 kpc, M = M_{Sun})

1. Microlensing

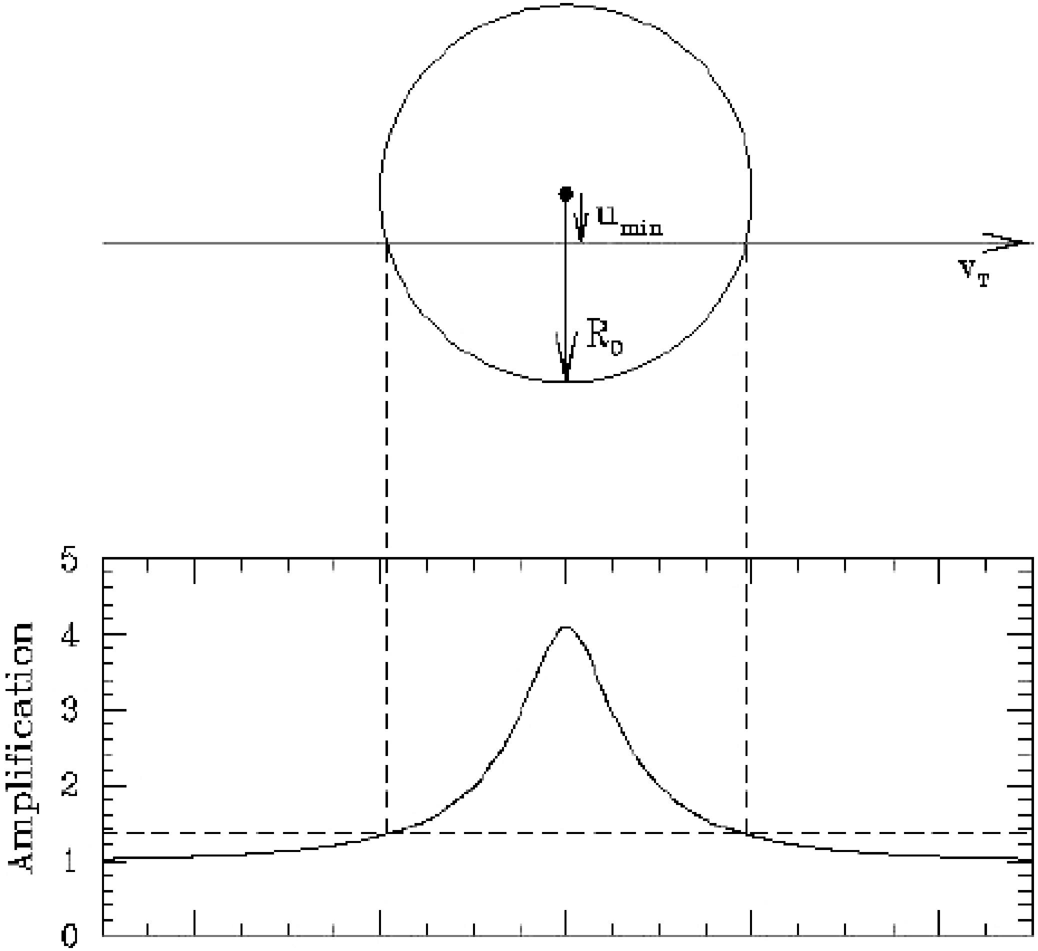
Magnification is position dependent

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

Time span of the event

$$t_E = \frac{R_0}{v_T}$$

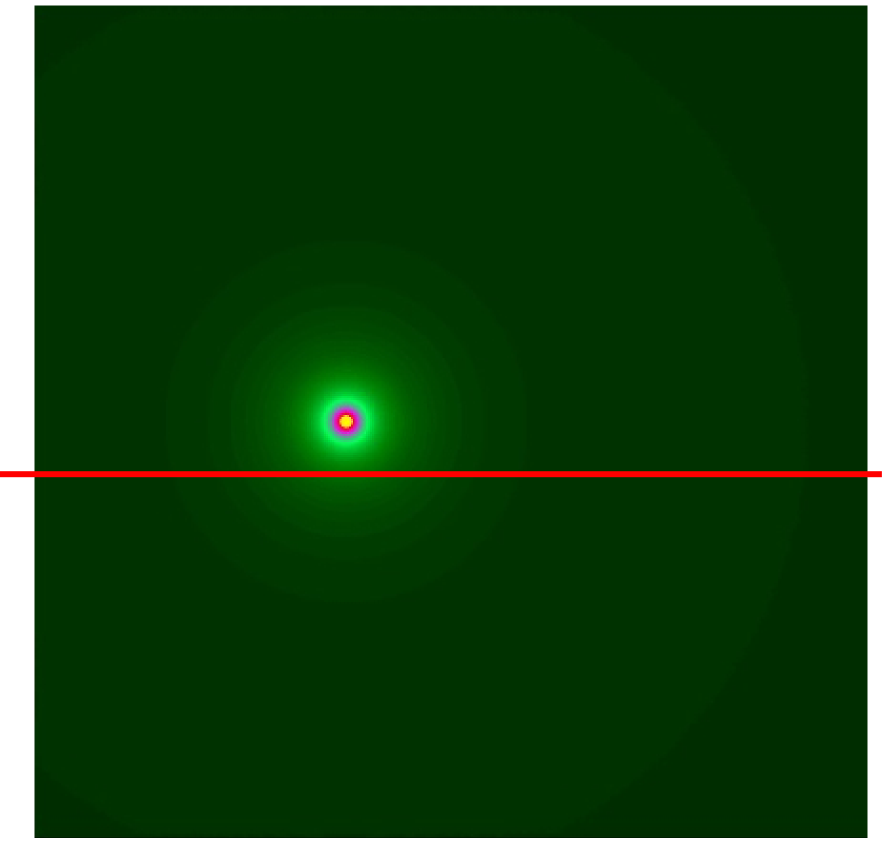
(Point-source-point lens approximation; transversal speed is angular apparent speed)



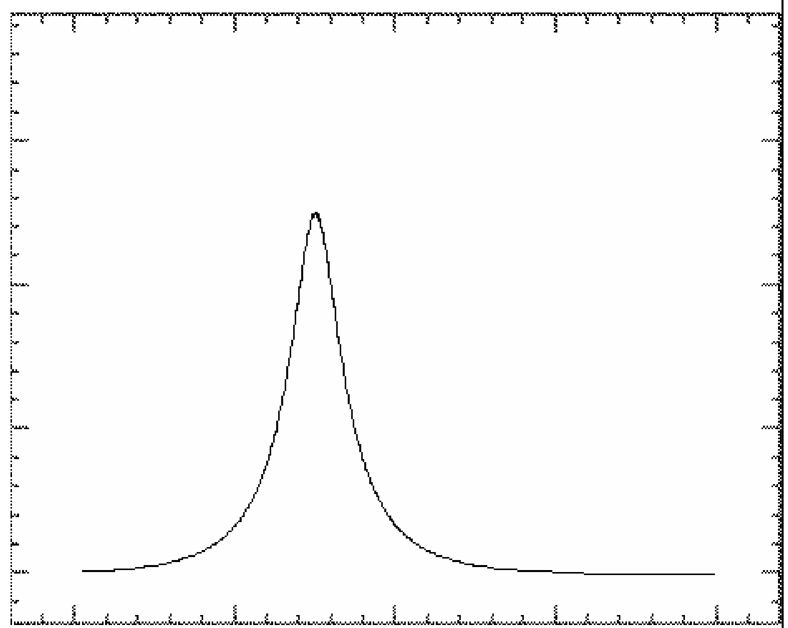
1. Microlensing

Main Tool in microlensig numerical calculations: **Magnification Map**

- Divides source plane in *cells*, (so every pixel represents a square area)
- Assigns value of magnification for hypothetical source *within* every cell
- Does *not* gives information about deflections



Single point-deflector



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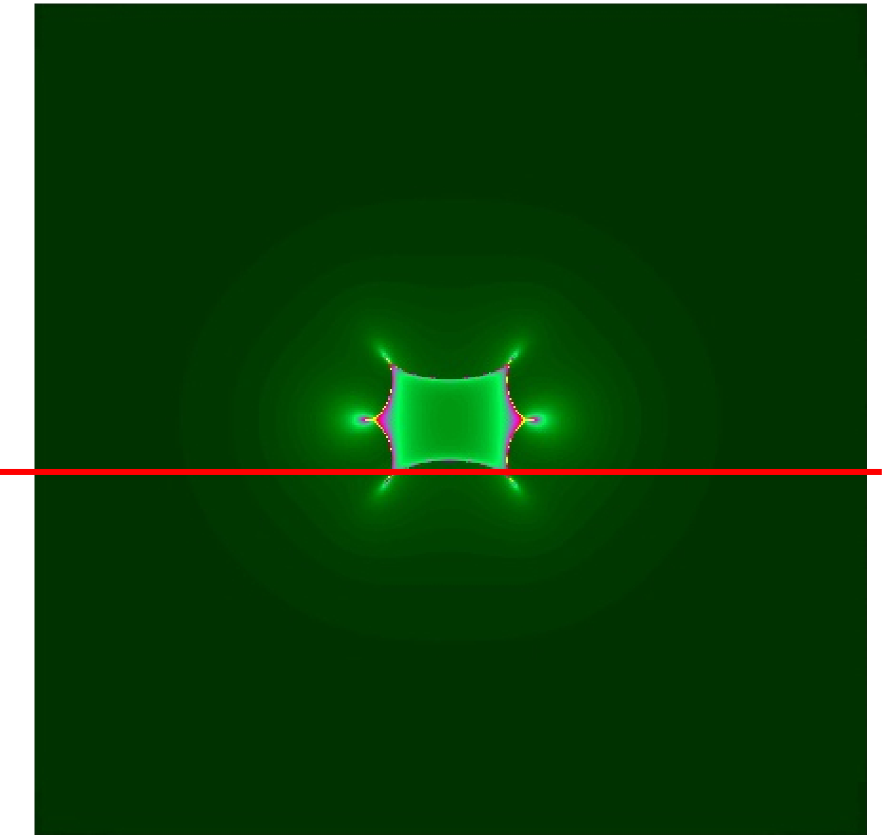
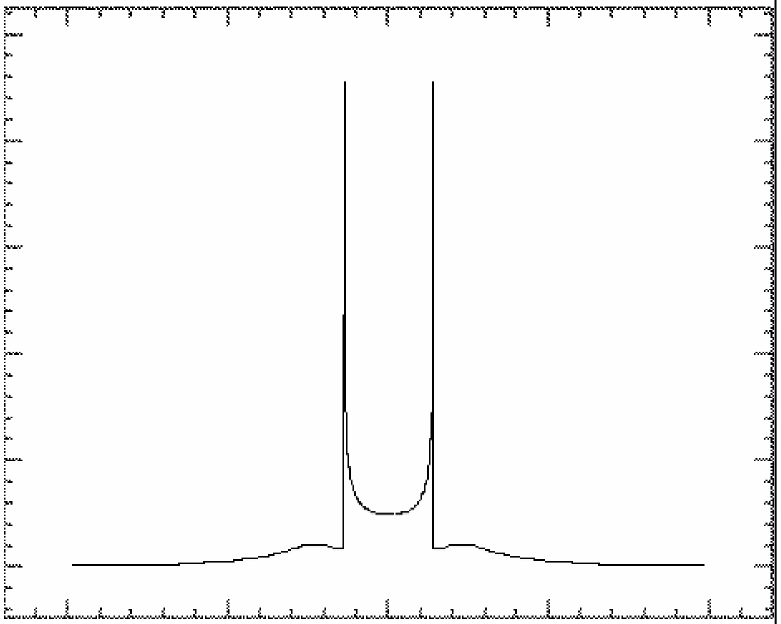
Binary point-deflector





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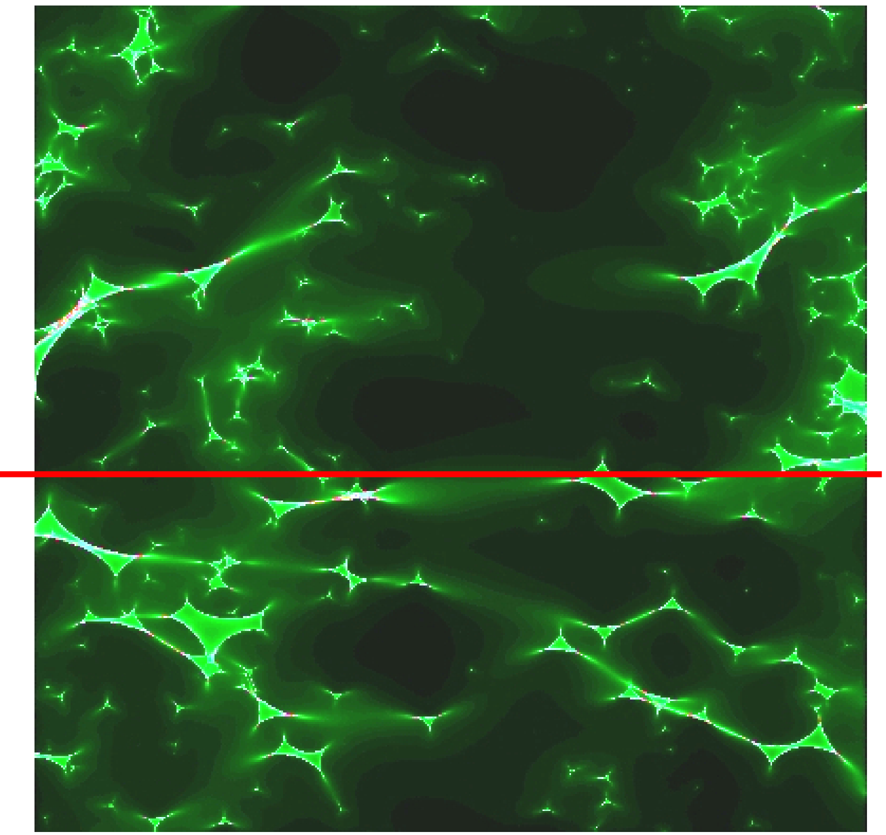
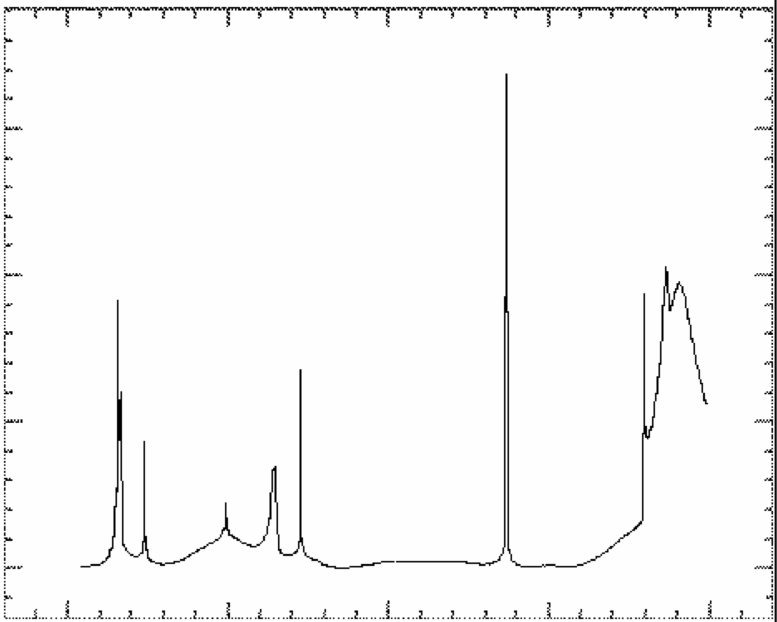


Multiple point-deflector



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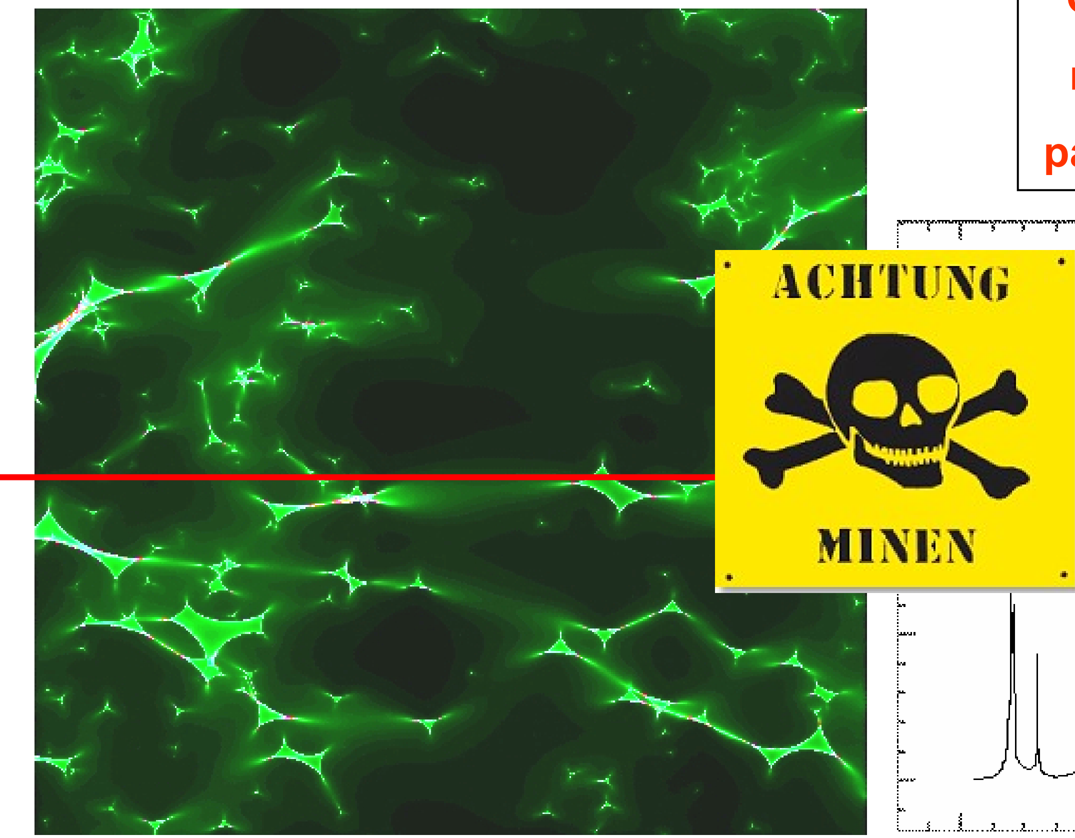
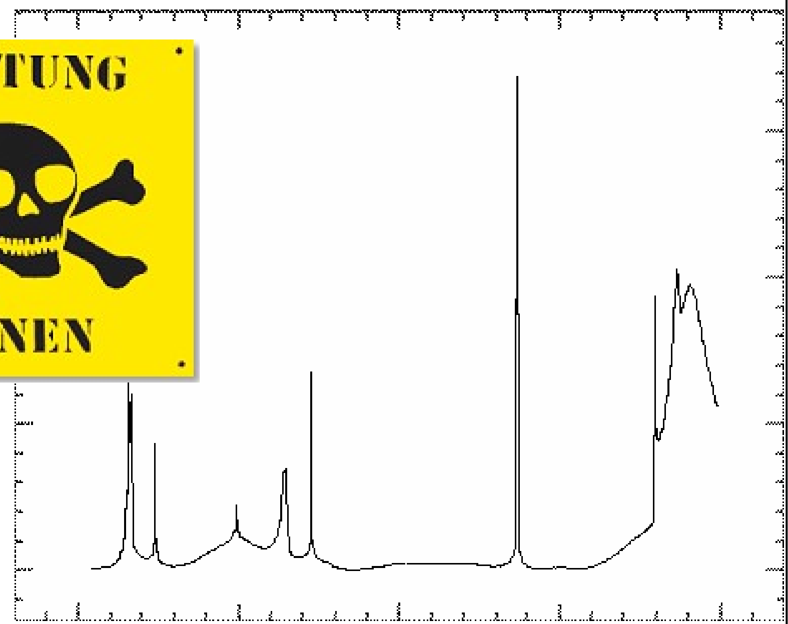
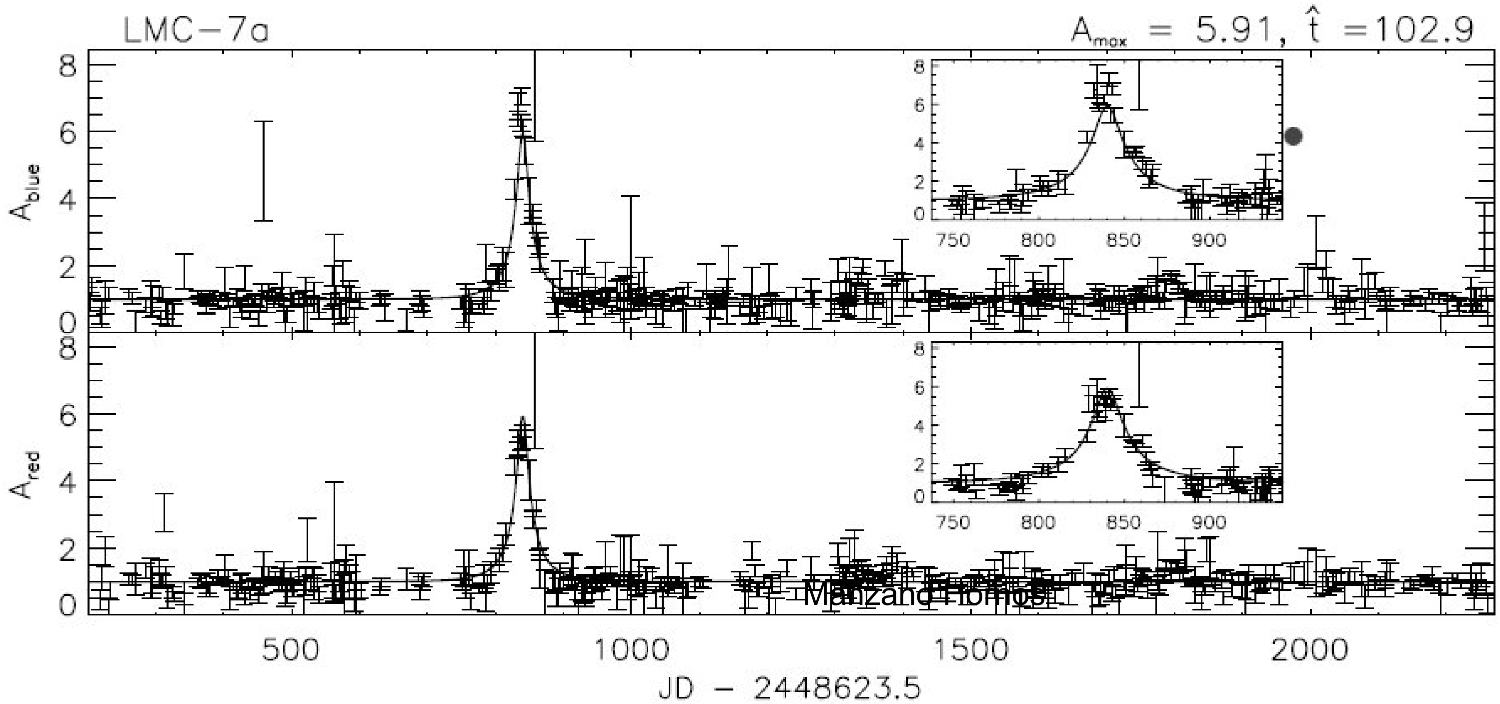
- Divides source plane in *cells*, (so every pixel represents a square area)
- Assigns value of magnification for hypothetical source *within* every cell
- Does *not* gives information about deflections

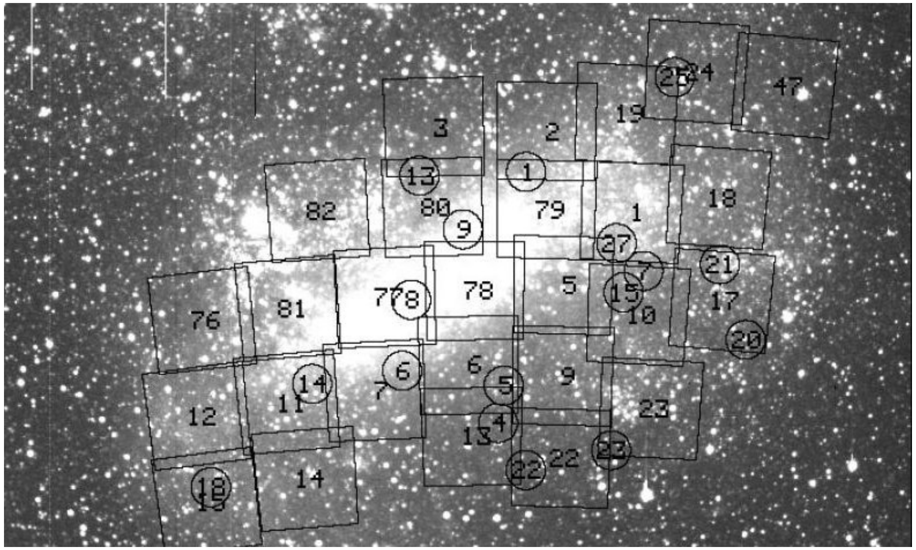
Computational tool: results are strongly parameter dependent !





1. Microlensing





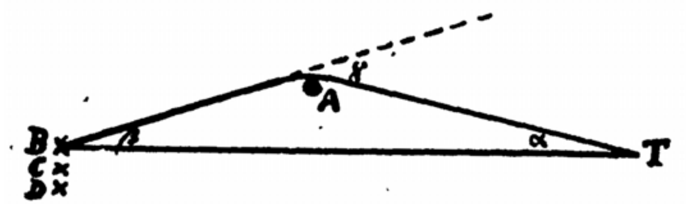
The MACHOs project

Alcock et al, 2000ApJ…542..281A

1. Microlensing

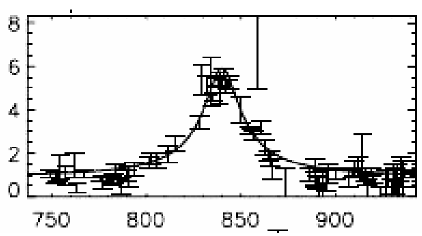
Remarks:

Single star as light deflector: MICROLENSING



- **No change in shape or position**

  of the source image



but a change in brightness during alingment

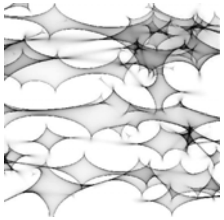
(microlensing event).

- **Time scale dependent on distances scale and deflector mass**

$$R_0 = \sqrt{\frac{4GMD_{LS}}{c^2 D_S D_L}}$$

- **Extended sources bigger than the Einstein radius "dilute" the effect and won't result in meaningful magnification**

- **Numerical Tool: Magnification Map**



2. Strong Lensing

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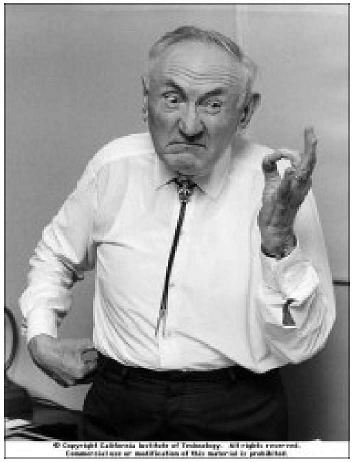


Fritz Zwicky (1898 - 1974) predicted in 1937 the detection of multiple images when extragalactic nebulae instead of stars were involved

(1937PhRv...51..290Z, 1937PhRv...51..679Z)

$$R_0 = \sqrt{\frac{4GMD_{LS}}{c^2 D_S D_L}} \approx 5\,\text{arcsec}$$

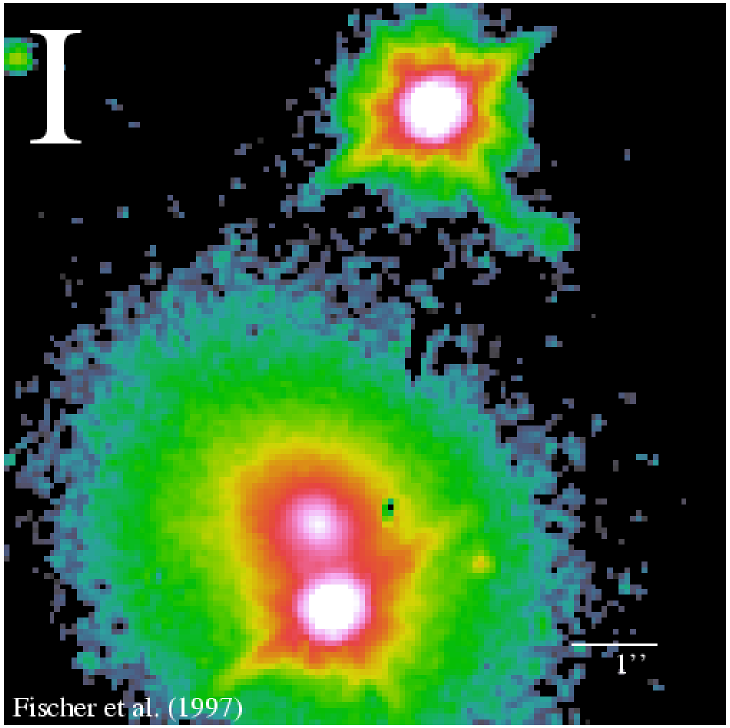
Zwicky's calculations and predictions include:

- **multiple images**
- **ring images**
- **amplification bias**
- **mass determinations**
- **GR test**
- **lens as telescopes**

First detection in 1979:

QSO 0957+561

1979Natur.279..381W



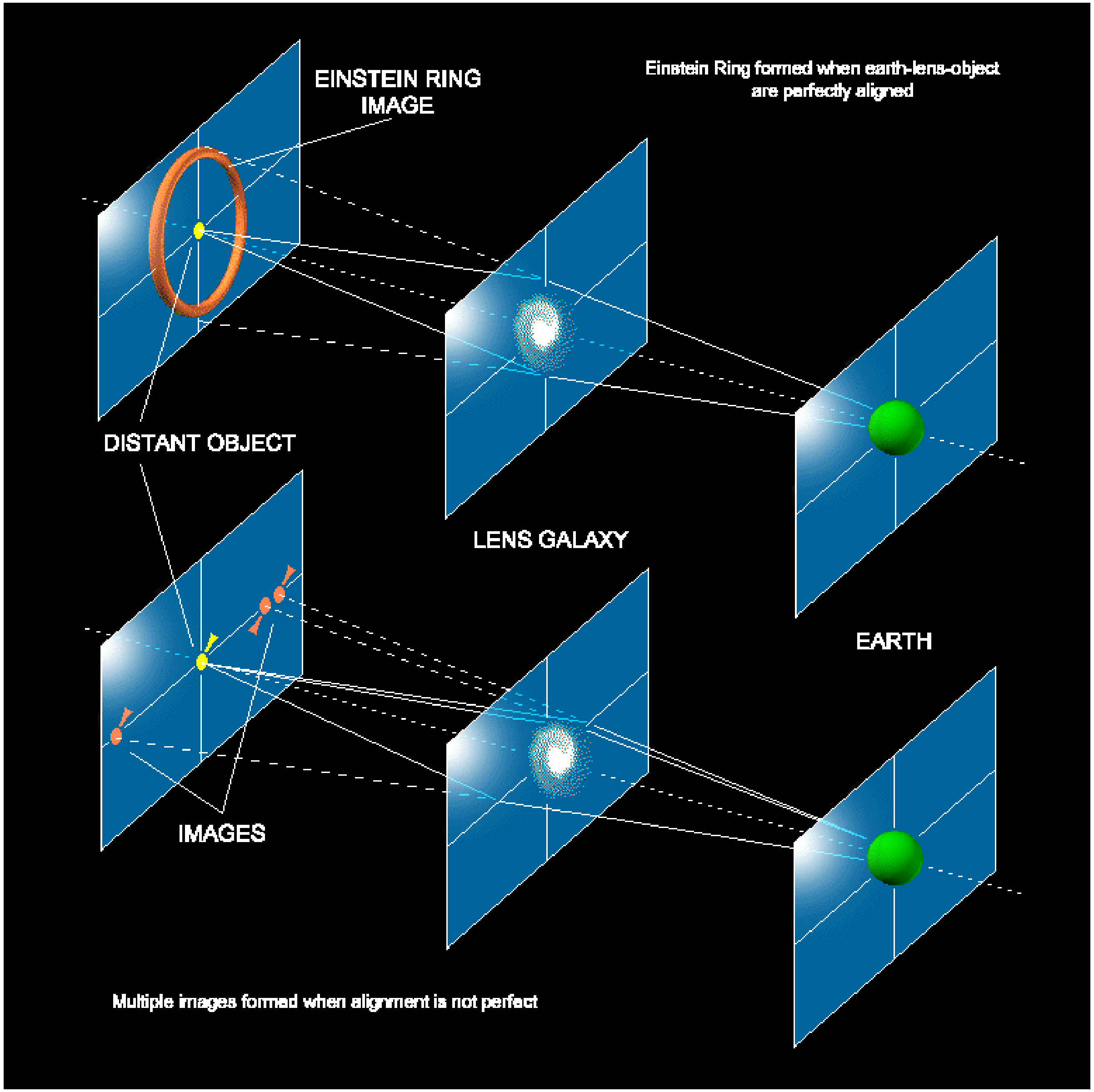
2. Strong Lensing

Galaxy as lens:

- High mass

AGN as sources:

- High luminosity
- Great D_{LS}



2. Strong Lensing

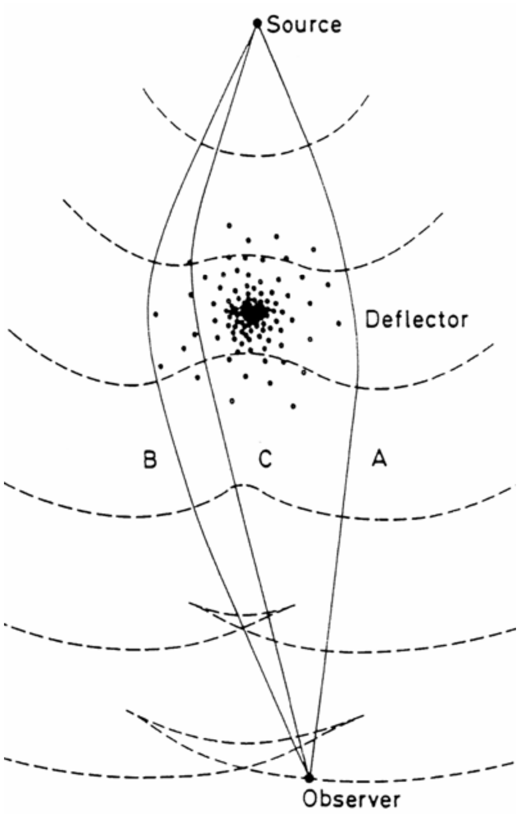
Good old Fermat's principle

δL=0

but in curved spacetime:

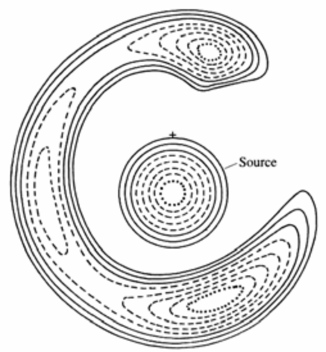
$$\mathcal{L}\left(x^{\alpha},\dot{x}^{\beta}\right)=\frac{1}{2}g_{\alpha\beta}(x^{\gamma})\dot{x}^{\alpha}\dot{x}^{\beta}$$

$$\delta\left\{\frac{1}{2}\int g_{\alpha\beta}\dot{x}^{\alpha}\dot{x}^{\beta}dv\right\}=0$$



A mass model for the lens is required, which leads to the assumption of a deflection potential dependent from several parameters, usually redshifts, angular separations, etc.

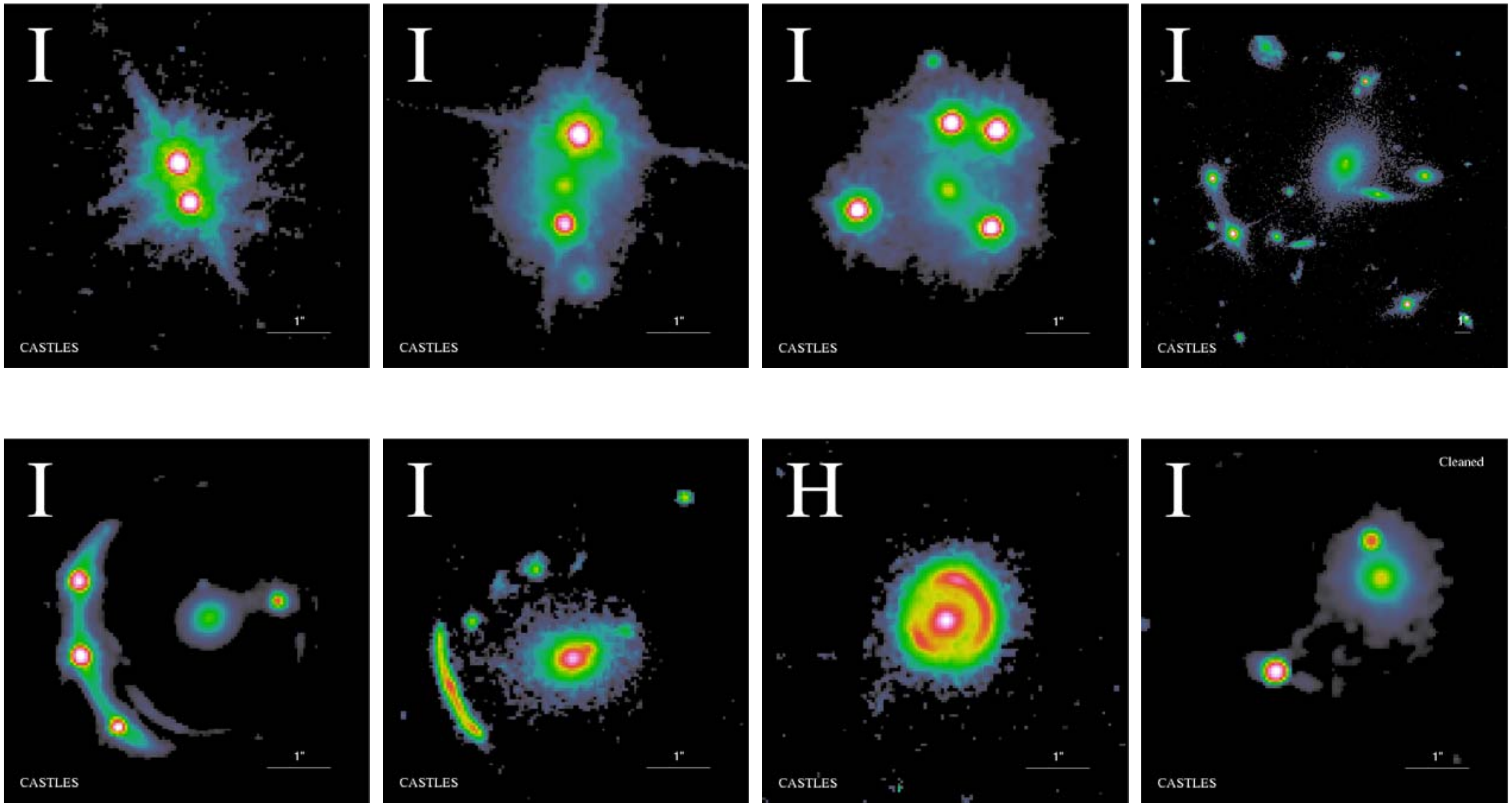
$$f:\mathrm{R}^2\rightarrow\mathrm{R}^2,\ \mathrm{x}\mapsto\mathrm{y}$$



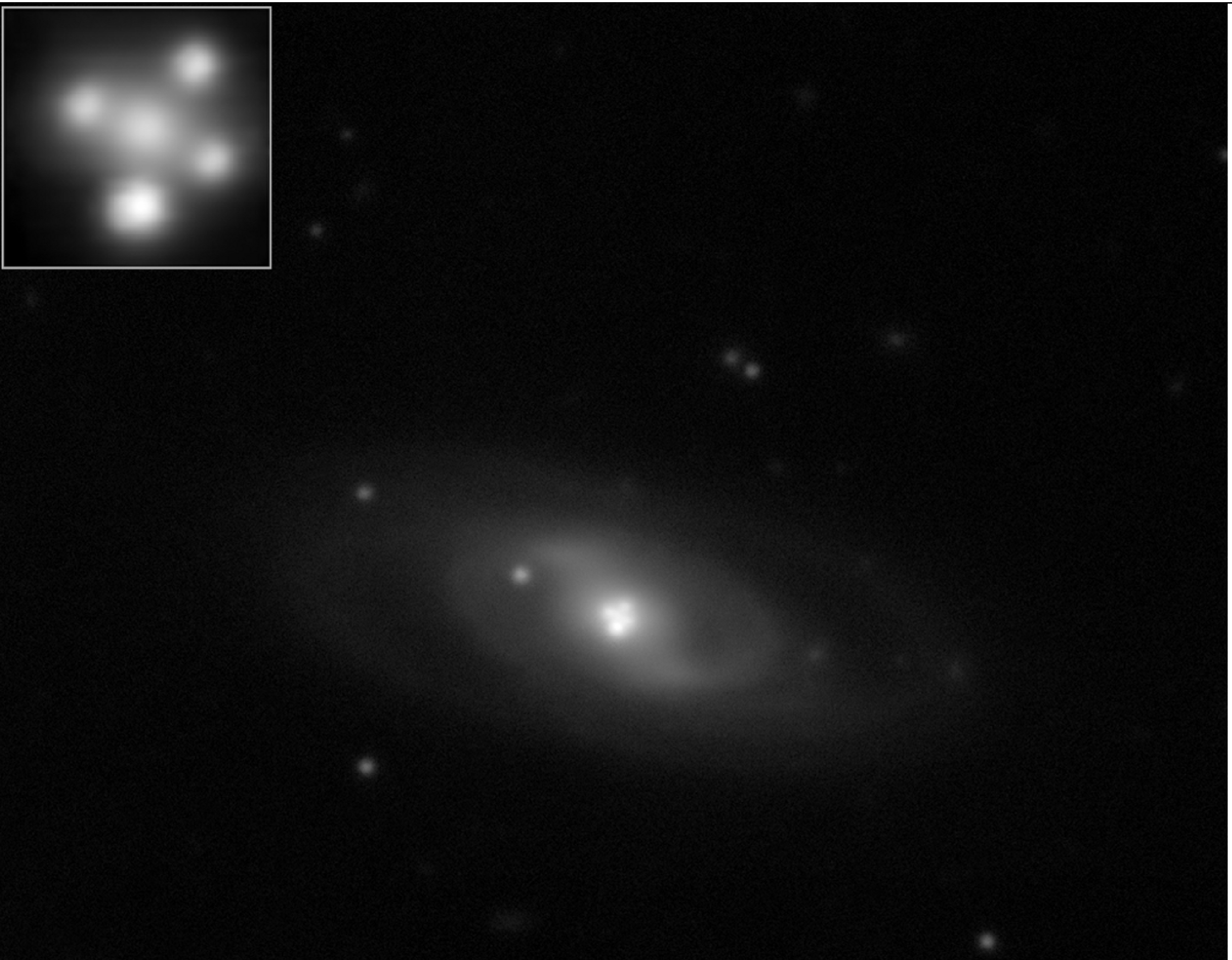
Imaging is modeled as a mapping from the *lens plane* to the *source plane*. which is only *locally* homeomorphic due to image plane domains to whom the jacobian of the transformation diverges.

2. Strong Lensing

Gravitational lens zoo



2. Strong Lensing

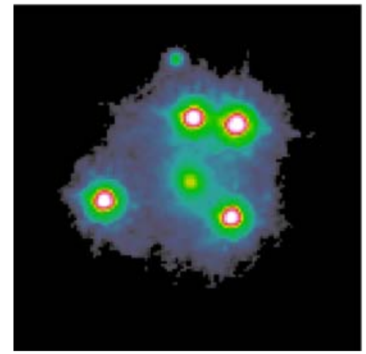


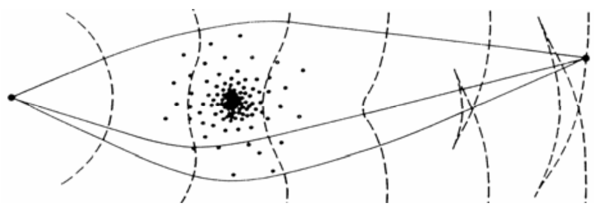
2. Strong Lensing

Therefore:

Galaxy mass deflector and cosmological distances: LENSING

- **Resolved multiple images (Ro 0.3 ~ 3 arcsec)**
  Amplification (some images too faint)

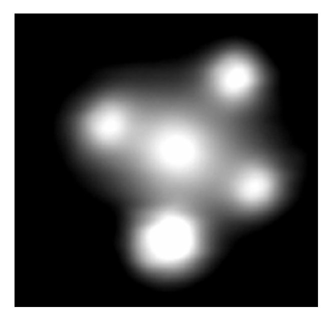




$$\delta\left\{\frac{1}{2}\int g_{\alpha\beta}\dot{x}^{\alpha}\dot{x}^{\beta}dv\right\}=0$$

- **Curved spacetime optics require deflector mass model**

- **Additional microlensing effect in every image (light beams travel across the lens galaxy)**



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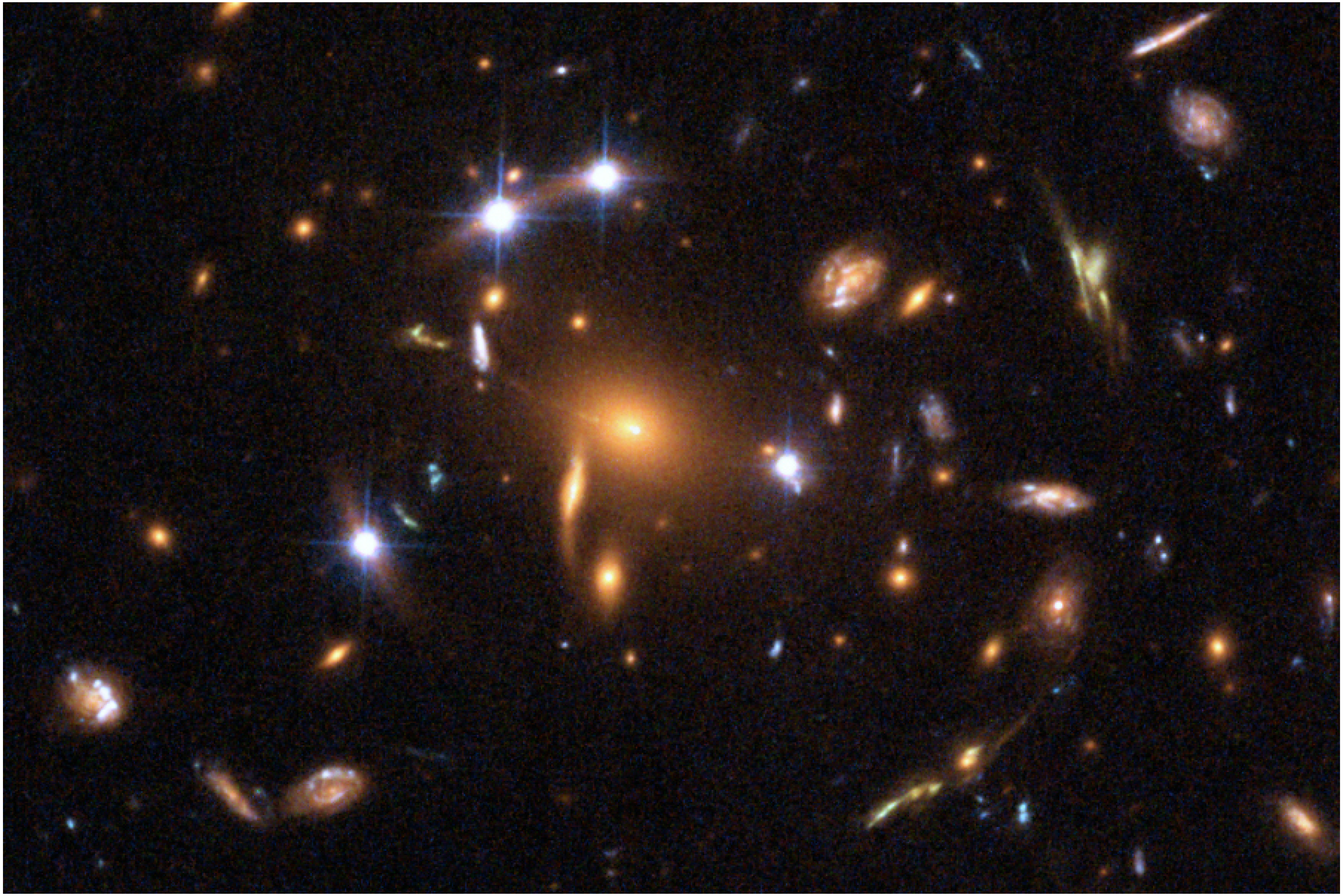

SDSS J1004+4112

3. Extragalactic microlensing: difficulties

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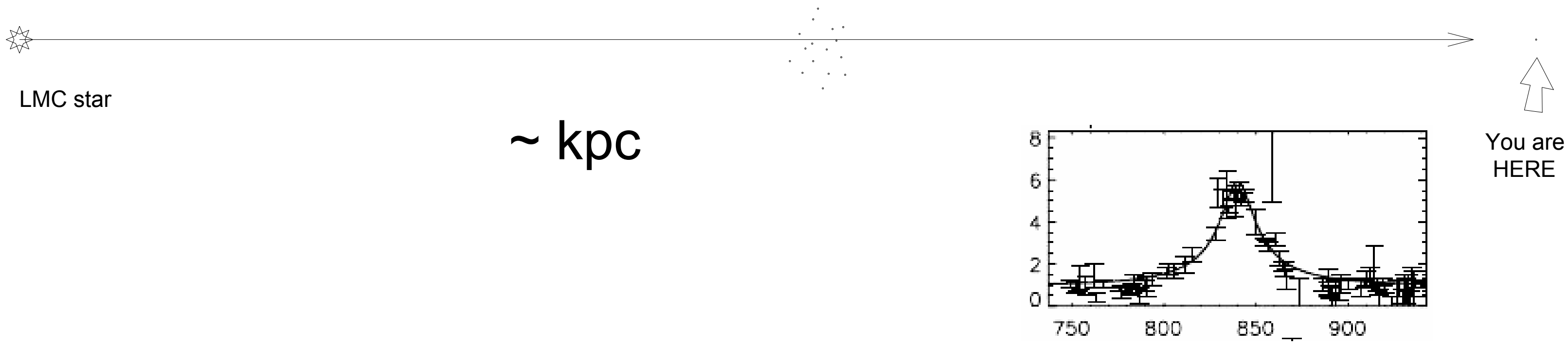
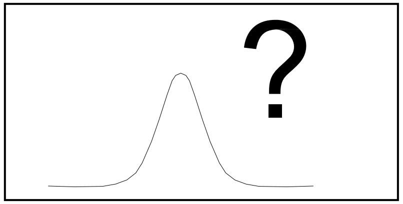
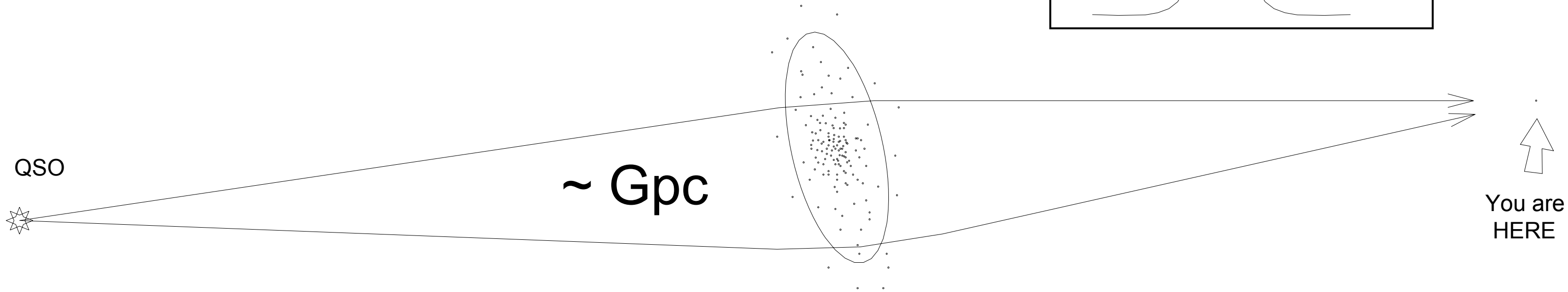


- Analogy between galactic and extragalactic microlensing.
- Is it possible to count individual microlensing events in the extragalactic domain as well ?



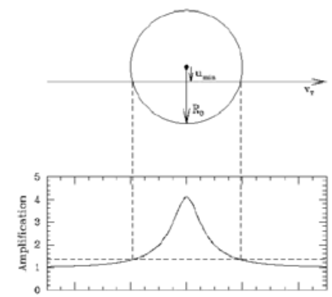


3. Extragalactic microlensing: difficulties

Detecting extragalactic microlensing events is not straightforward:

1. A single event at Gpc scales would take months, even years !

$$\left.\begin{aligned} R_0 &= \sqrt{\frac{4GMD_{LS}}{c^2 D_S D_L}} \propto \frac{1}{\sqrt{D_L}} \\ v_T &\propto \frac{1}{D_L} \end{aligned}\right\} \Rightarrow t_E \left(= \frac{R_0}{v_T} \right) \approx \sqrt{D_L}$$



(assuming deflector at midpoint between source and us)

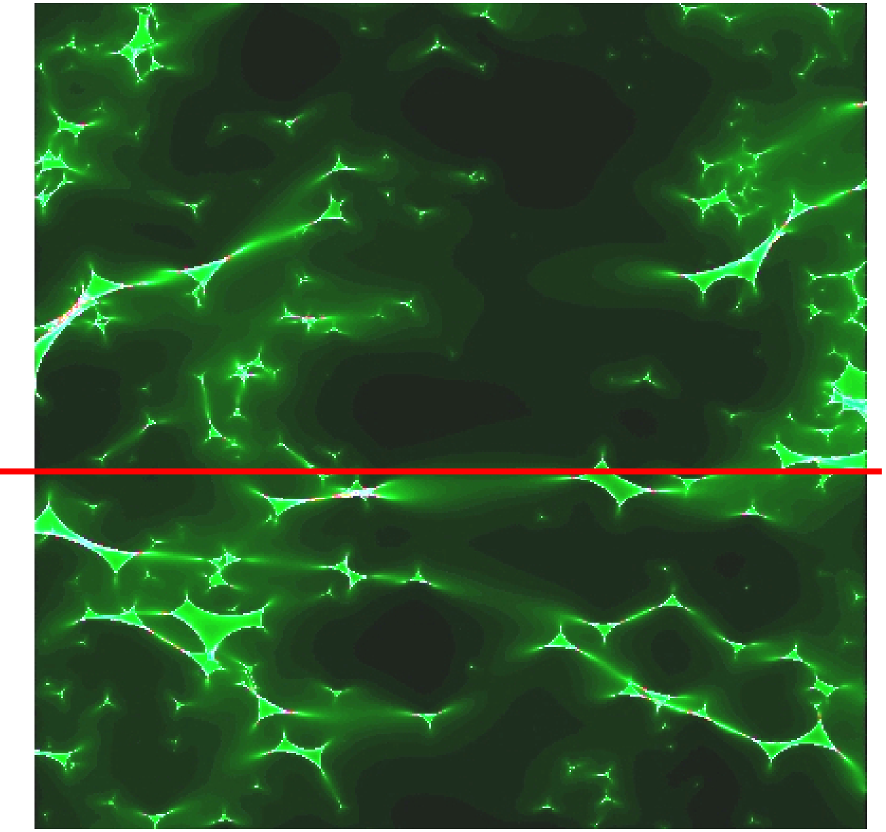
Trasverse speed is angular apparent speed

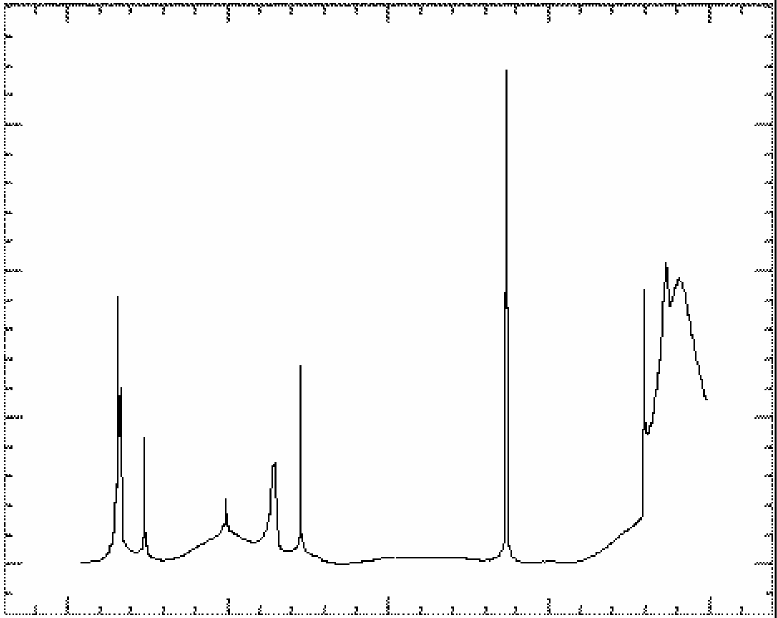
3. Extragalactic microlensing: difficulties

Detecting extragalactic microlensing events is not straightforward:

2. Unknown distribution of multiple deflectors make light curve complex and difficult to interprete (big degeneration).

Multiple point-deflector





3. Extragalactic microlensing: difficulties

Detecting extragalactic microlensing events is not straightforward:

3. Exact macrolens amplification is unknown, since the exact mass distribution in the lens galaxy/ cluster is unknown. We don't know original source flux either.

Therefore, we lack the baseline of no microlensing amplification.

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Summary

- **Timescale of events too long**
- **Lightcurves complex and difficult to interprete**
- **No reference value for absence of microlensing**

Detecting and getting information from extragalactic microlensing requires a different approach

4. Measuring extragalactic microlensing

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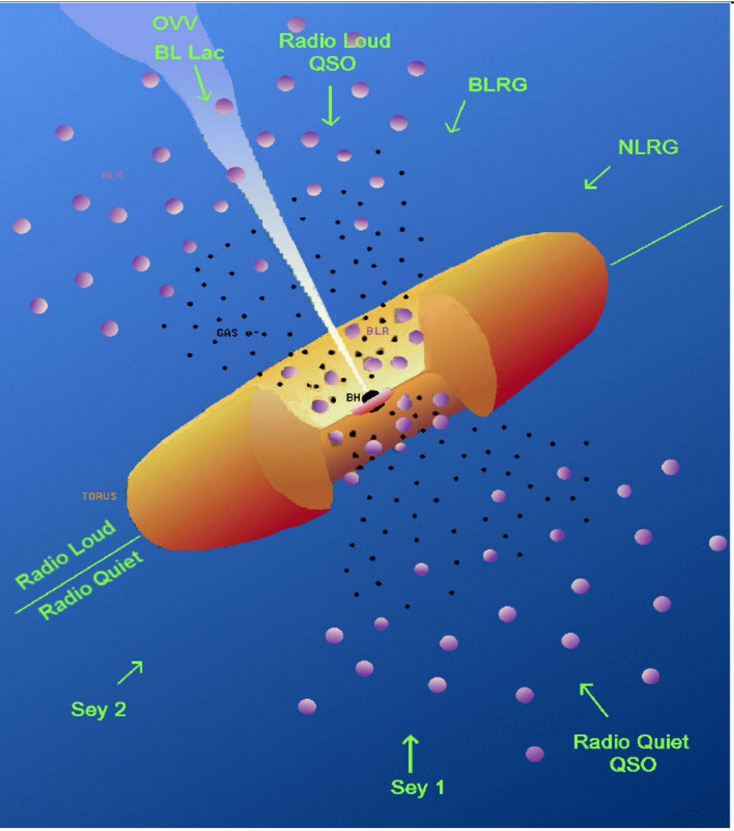
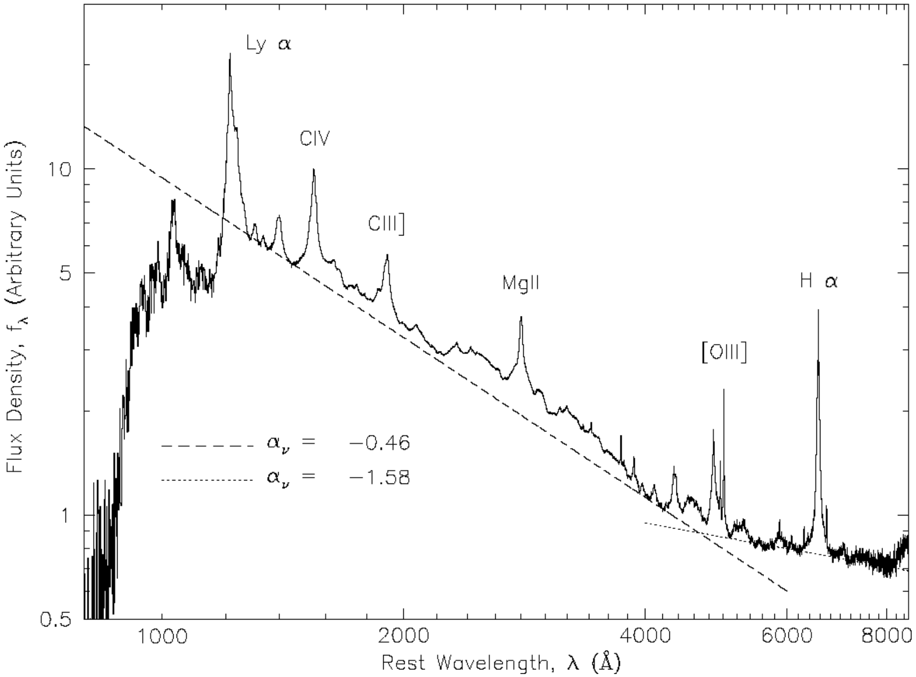


Why QSOs are so good for microlensing

- NEL originate in large regions
  They are not affected by ML
- Continuum source is a small,
  plays the role of source star.



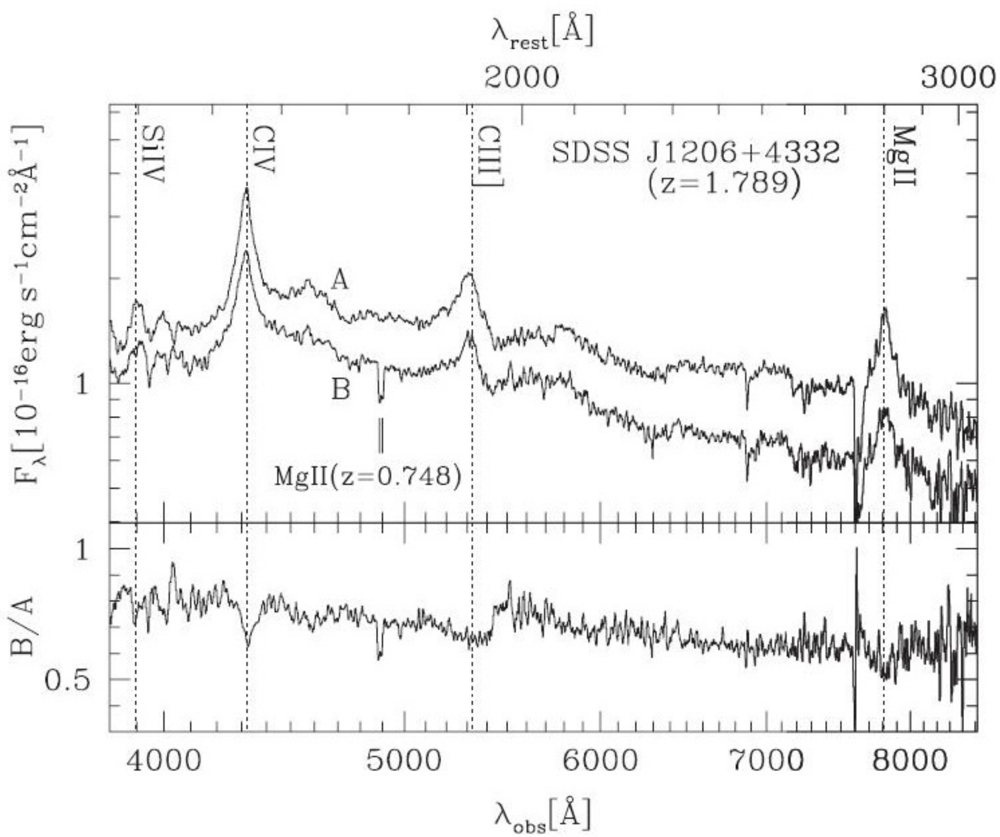
Composite SDSS QSO spectrum

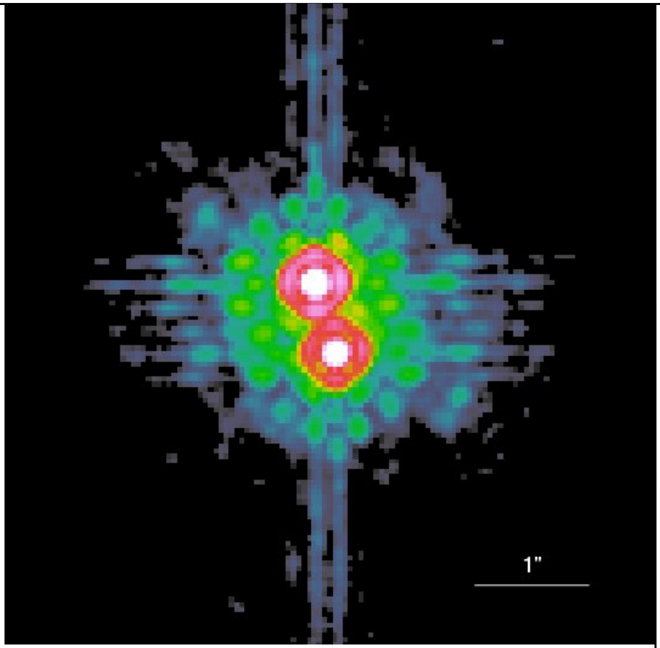
2001AJ....122..549V

4. Measuring extragalactic microlensing

Therefore the clue for an ongoing microlensing event is finding different flux ratios for lines and continua between two images, sinde only continua are affected by microlensing.

- NEL region provides baseline of no microlensing amplification.



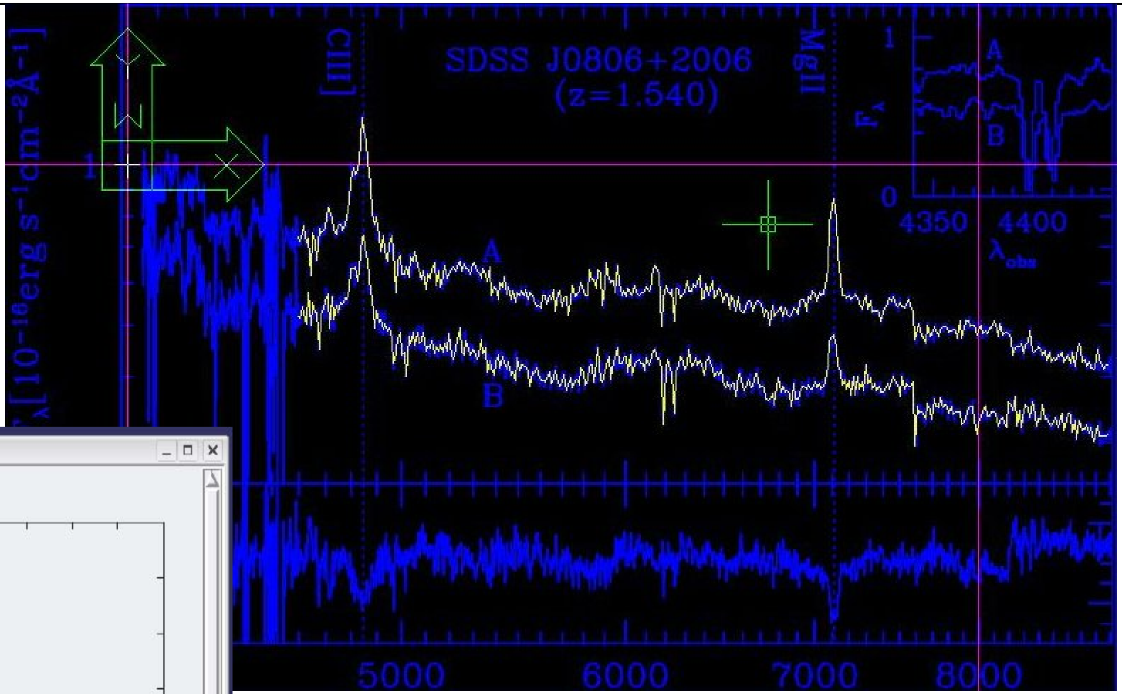


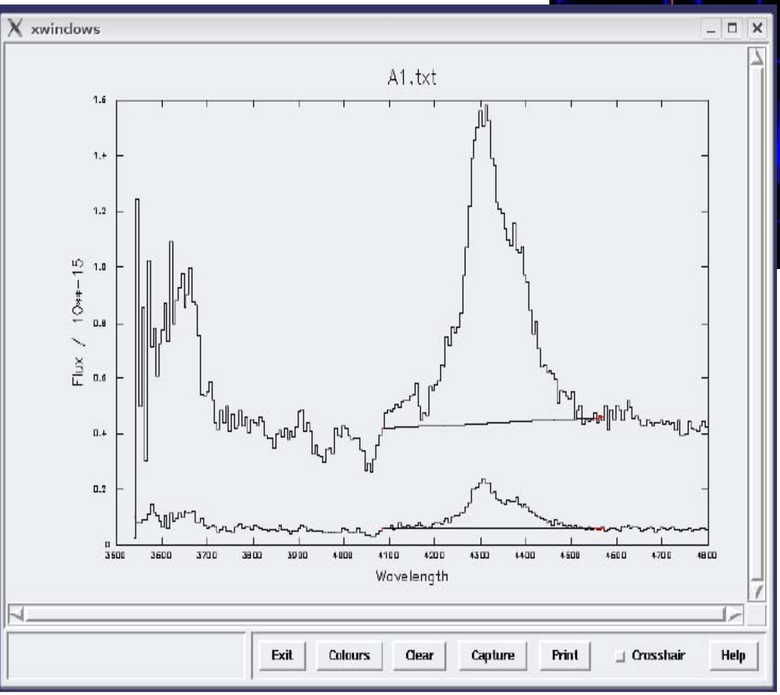
However, only magnification differences between images will be measured

4. Measuring extragalactic microlensing

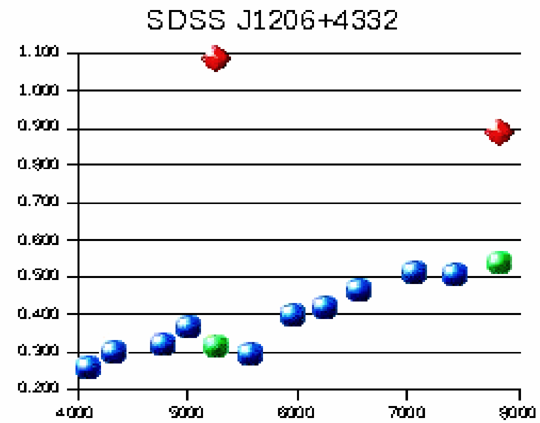
Measuring

Up to now, we have sufficiently good spectra for 29 image pairs seen through 20 lens galaxies





After continuum subtraction is performed, we do calculations for flux ratios among the continuum spectrum and the different lines



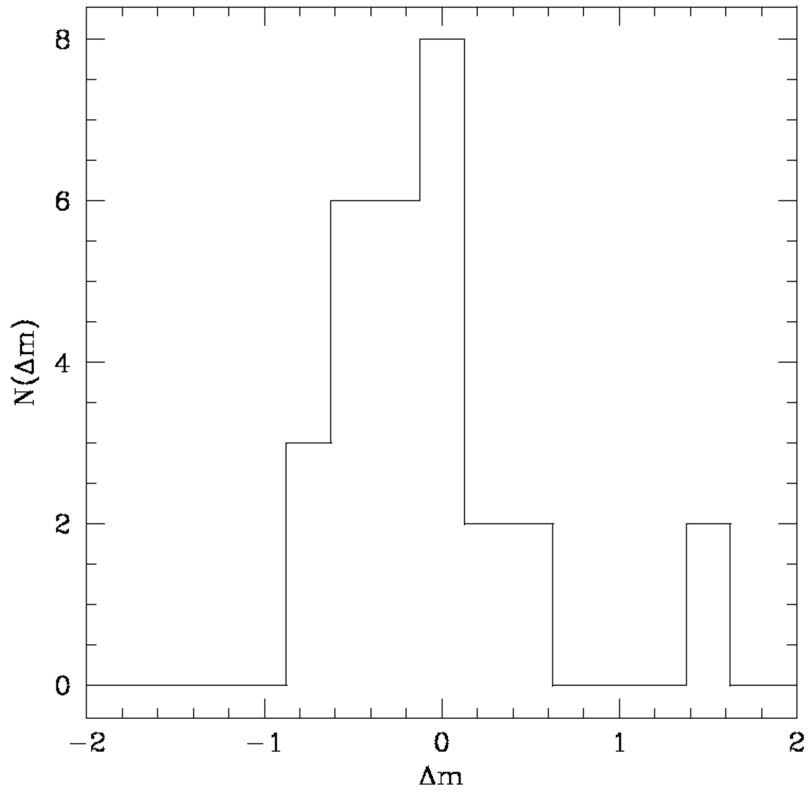
- Available MID-IR data for some systems confirm the reliability of our optical line flux ratios as baseline

1. Microlensing
2. Strong lensing
3. Problems in extragalactic microlensing
4. Measuring extragalactic microlensing
5. Detection of extragalactic MACHOs
6. Next step

4. Measuring extragalactic microlensing

Histogram for the measured *differential* microlensing magnifications:

- It peaks close to no differential magnification
- It is highly concentrated below 0.6 mag



A further study is needed to extract information.

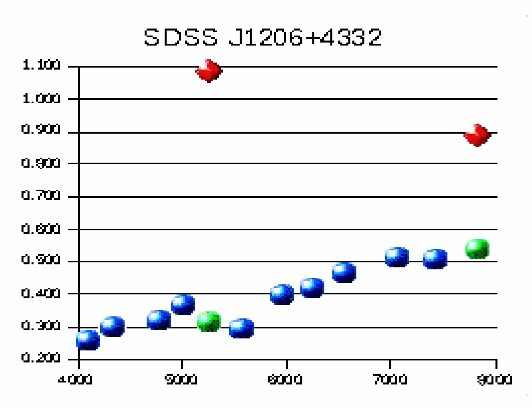
4. Measuring extragalactic microlensing

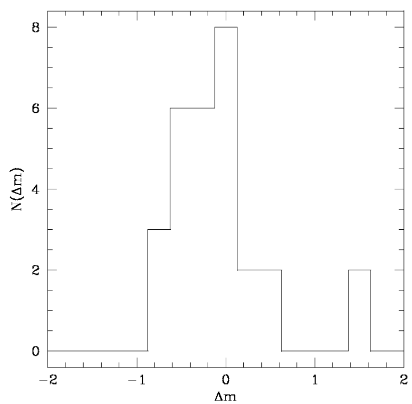
Remarks:

- Statistical method over a QSO sample, rather than measurin single light curves
- Spectroscopic based measures, where

  •NEL flux ratios are unaffected, therefore providing baseline.

  •Continua flux ratios do suffer microlensing amplification





- We get a microlensing amplification differences histogram from the sample, that
  - peaks around no difference of magnification between pairs,
  - and is highly concentrated

4. Measuring extragalactic microlensing

And now, what do we want extragalactic microlensing for ?

<<Stellar mass lenses affect the apparent brightness of the quasar images. Microlens-induced variability can be used to study two cosmological issues of great interest, the size and brightness profile of quasars in one hand, and the distribution of compact (dark) matter along the line-of-sight on the other hand. >>

Wambsganss J (2006), Gravitational microlensing. In: Meylan G, Jetzer Ph and North P (eds) Gravitational lensing: Strong, weak and micro. Saas-Fee Adv Courses vol 33, pp 453-540

We attack both issues with no need for variability !

5. Detection of extragalactic MACHOs

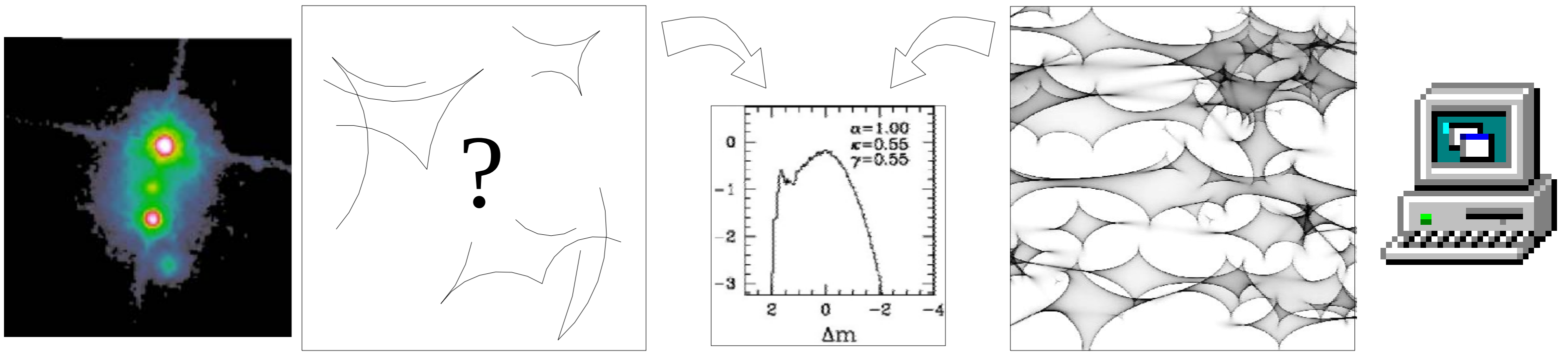
Main idea: modelling realistic magnification difference histograms for a wide range of compact objects densities and comparing them with the observational histogram

Section 5 describes this method and the results obtained. It is a (limited) summary of the work by Mediavilla, E. et al. published in ApJ under the title "*Microlensed-based Estimate of the Mass Fraction in Compact Objects in Lens Galaxies" (2009ApJ…706.1451M)*

5.a: Modelling probability distributions

Starting point:

We cannot know how the "real" magnification maps are, but a simulated map with the same local conditions (density fraction of compact objects and shear parameter) should have the same magnification histogram as the "real" one.

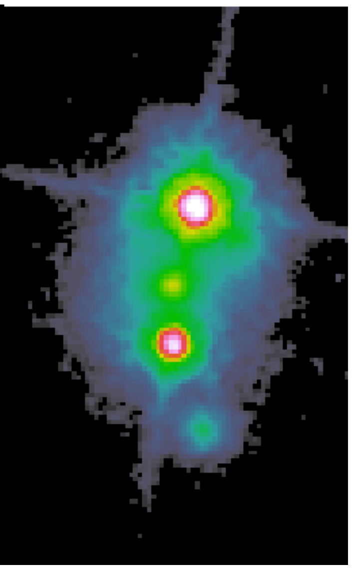


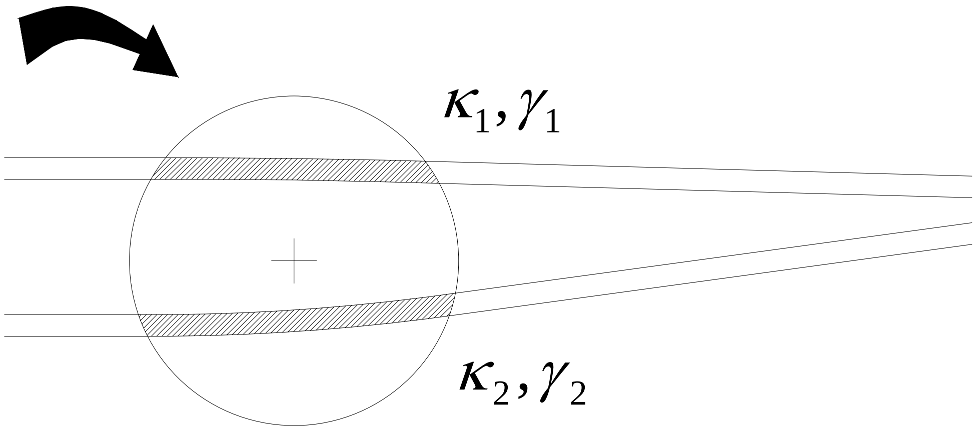
But getting the local conditions requires to assign a macrolens model for each system, from which to obtain the local conditions the simulated maps must resemble.

The mass fraction in compact objects is another parameter that is needed for computing the maps, so we have to make a set of guesses and somehow choose the value that best matches the real data (the observational histogram)

5.a: Modelling probability distributions

By fitting image positions in a singular isothermal sphere plus external shear ($SIS+\gamma_e$) macrolens model we obtain projected matter density κ and shear γ for every image in every system



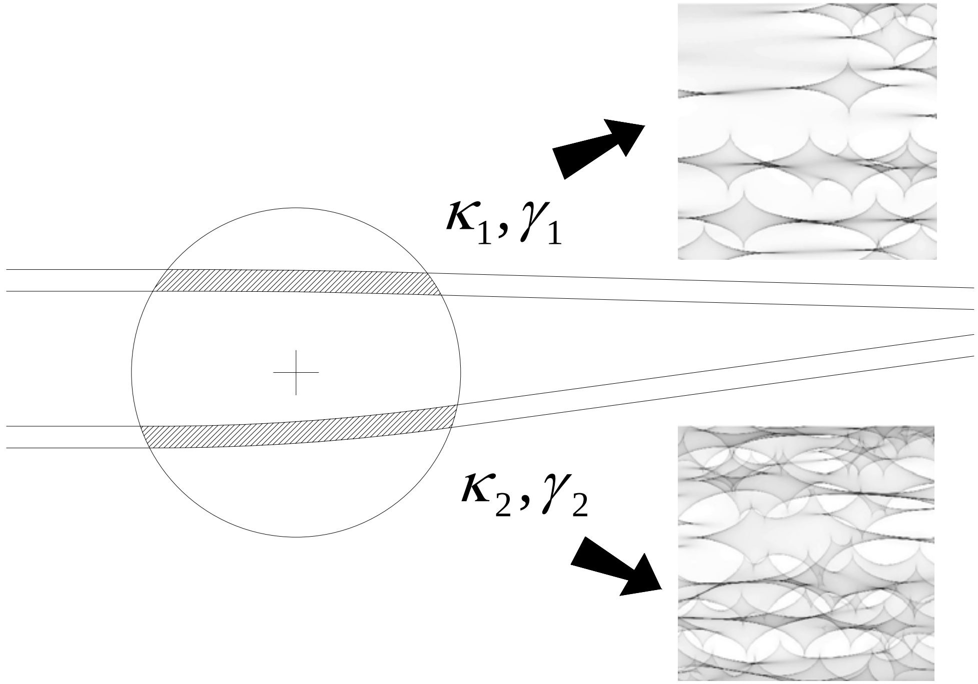


We used the "lensmodel" code by Keeton (2001)

http://www.cfa.harvard.edu/castles/

5.a. Modelling probability distributions

For every par of values *and a given mass fraction in point-deflectors*, a magnification map is computed

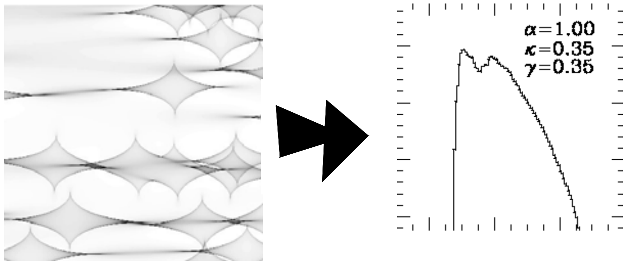


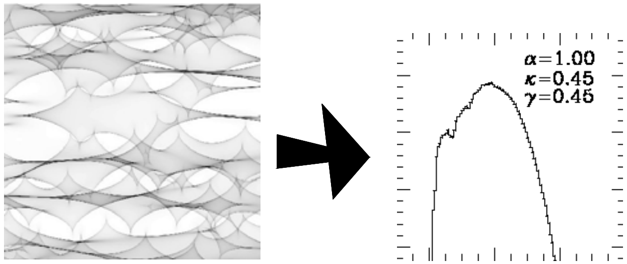
- To compute the magnification maps we use the inverse polygon mapping method (Mediavilla et al. 2006)

(!) To account for the extended (though small) nature of the source we blur every map by means of convolution with a 2D gaussian profile

5.a. Modelling probability distributions

Every magnification map results in a histogram of magnifications



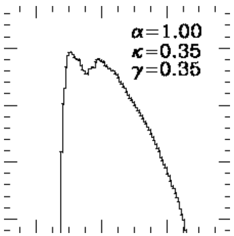


The microlensing magnification at a given pixel is obtained as the ratio of the magnification in the pixel to the average magnification.

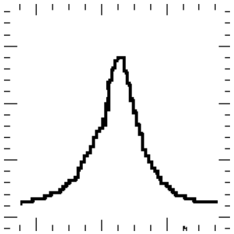
This histograms give the frecuency distribution of microlensing magnifications.

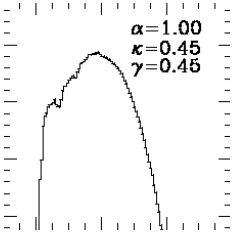
5.a. Modelling probability distributions

Since we are interested in the frequency distribution of the difference in microlensing magnification between pairs, we do a final crosscorrelation of the magnification histograms:



$$f_{\alpha\kappa_1,\alpha\kappa_2,\kappa_1,\kappa_2,\gamma_1,\gamma_2}(\Delta m) =$$
$$\int f_{\alpha\kappa_1,\kappa_1,\gamma}(\Delta m_1)\, f_{\alpha\kappa_2,\kappa_2,\gamma_2}(m_1 - \Delta m)\, dm_1$$





- Everyone of this distributions give the normalized probability for measuring any magnification difference.
- There is one distribution for every set of the five values

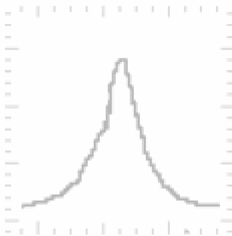
$(\alpha, \kappa_1, \gamma_1, \kappa_2, \gamma_2)$ (α = mass fraction of compact objects)

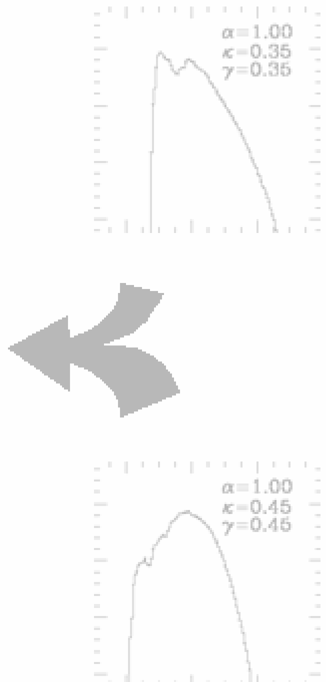
5.a. Modelling probability distributions

Since we are interested in the frequency distribution of the difference in microlensing magnification between pairs, we do a final crosscorrelation of the magnification histograms:

$$f_{\alpha\kappa_1,\alpha\kappa_2,\kappa_1,\kappa_2,\gamma_1,\gamma_2}(\Delta m) =$$

$$\int f_{\alpha\kappa_1,\kappa_1,\gamma}(\Delta m_1) f_{\alpha\kappa_2,\kappa_2,\gamma_2}(m_1 - \Delta m) dm_1$$





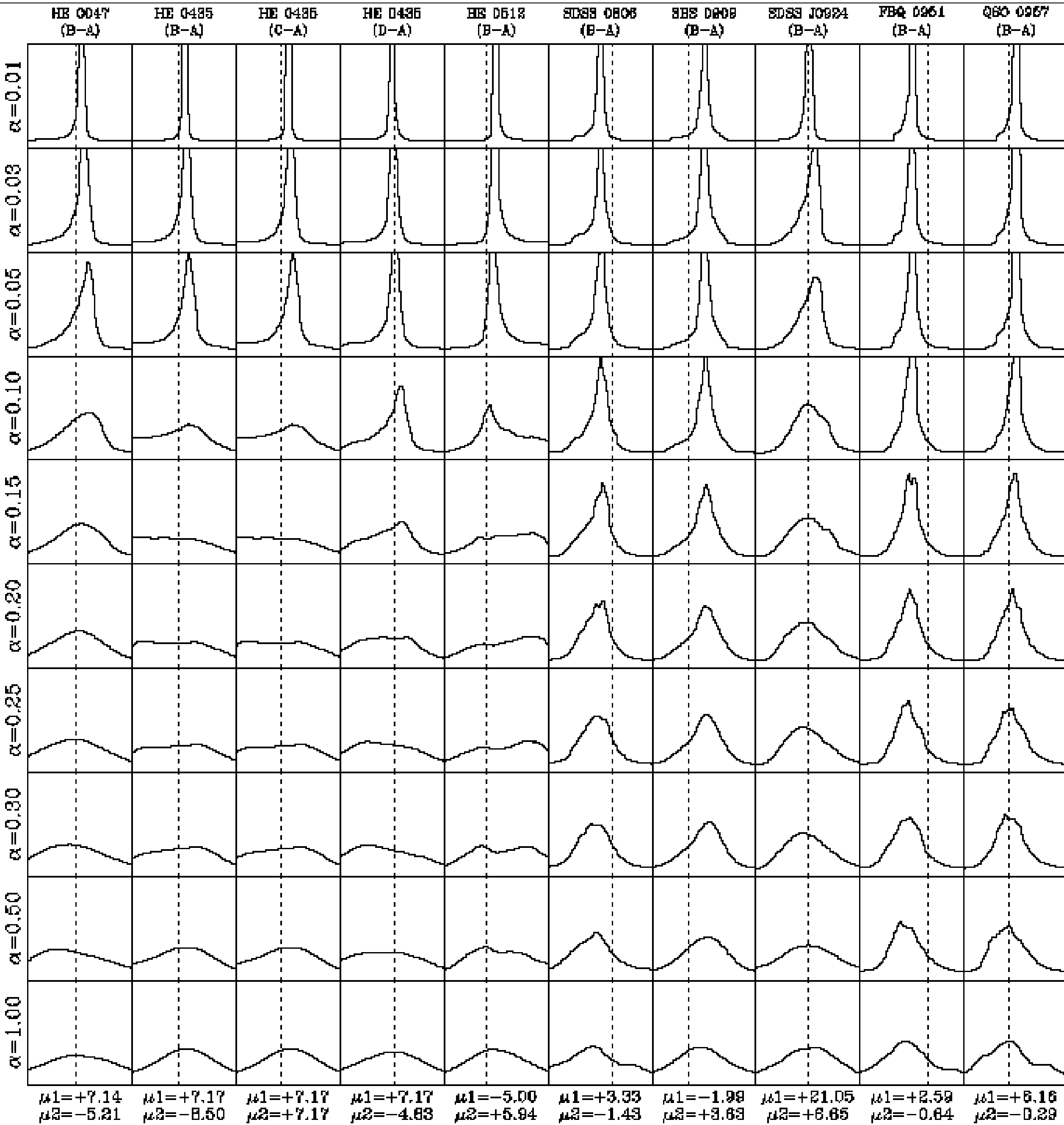
- Everyone of this distributions give the normalized probability for measuring any magnification difference.
- There is one distribution for every set of the five values

(α, κ_1, γ_1, κ_2, γ_2)   (α = mass fraction of compact objects)

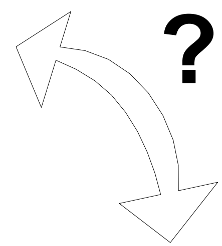
Summary:

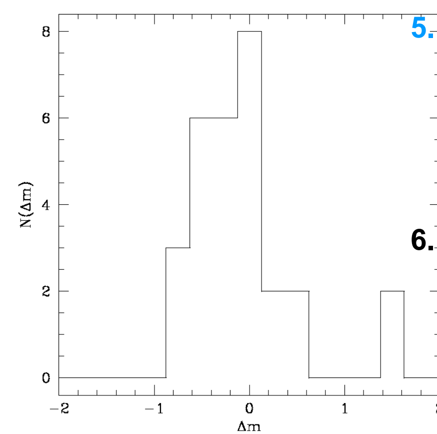
Through computer modelling and simulation, we are able to infer the probability distribution of differences in microlensing magnification for each system, with the mass fraction of compact objects as an input parameter.

5.b. Chi square test



Which distributions best match the observational histogram ?





1. **Microlensing**
2. **Strong lensing**
3. **Problems in extragalactic microlensing**
4. **Measuring extragalactic microlensing**
5. **Detection of extragalactic MACHOs**
6. **Next step**

5.b. Chi square test

- This test tries to find the value for α for which the probability distributions most resemble the observational histogram
- For each value of α, the sum of the cuadratic distances between between modeled and measured values in the observational histogram is computed:

$$\chi^2_\alpha = \sum_i \left(\frac{f_\alpha(\Delta m_i) - f_{obs}(\Delta m_i)}{\sigma_i} \right)^2,$$

5.b. Chi square test

- This test tries to find the value for α for which the probability distributions most resemble the observational histogram
- For each value of α, the sum of the cuadratic distances between between modeled and measured values in the observational histogram is computed:

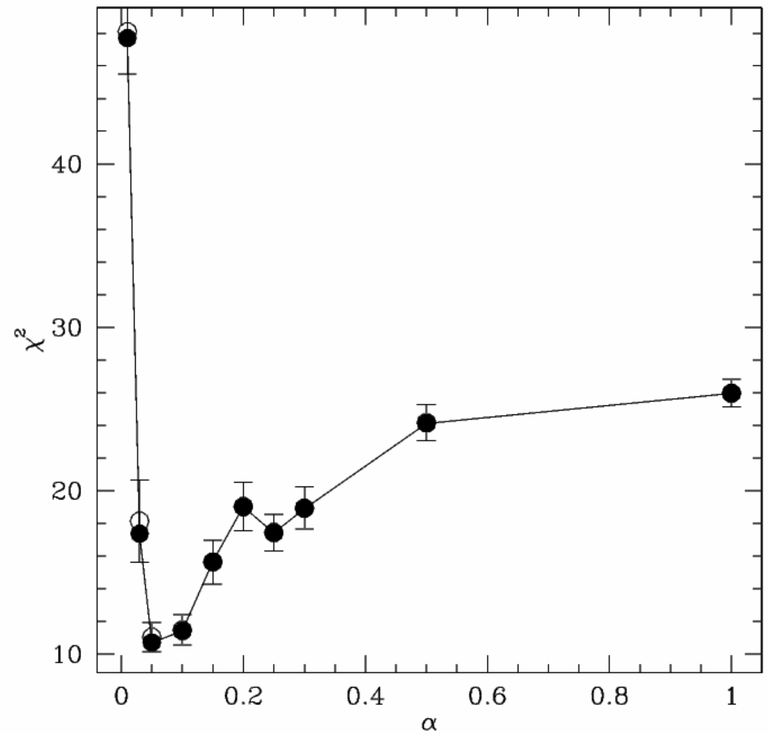
$$\chi^2_\alpha = \sum_i \left(\frac{f_\alpha(\Delta m_i) - f_{obs}(\Delta m_i)}{\sigma_i} \right)^2,$$

Minimum distance corresponds to

α = 5% aprox

of halo mass in compact objects

Errorbars result from a montecarlo algorithm based on permutations of the system values



5.c. Maximum Likelihood Analysis

Our 29 microlensing measurements are a specific realization of the prediction made by the computed distributions. We may ask: *how similar* to the predicted most likely set of values is our realization?

We search the value of α for which that "similarity" is maximum.

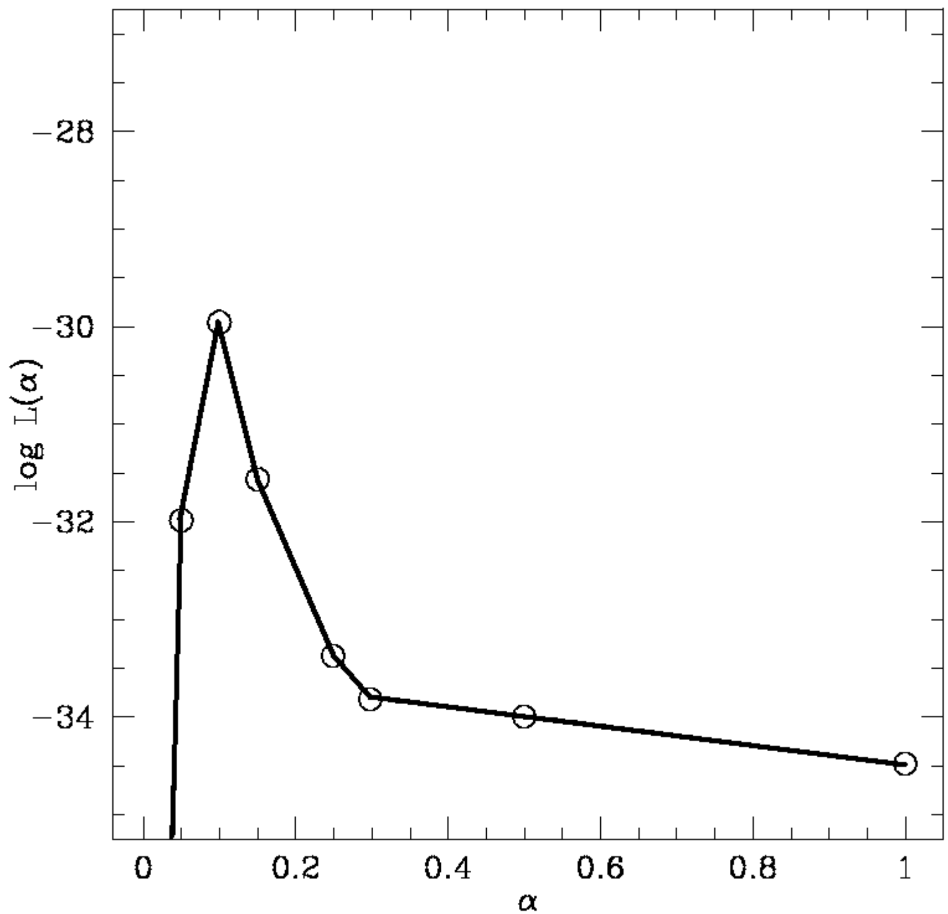
- We get from the distributions which frequency corresponds to the observed magnification difference in each system,

$$f_{\alpha\kappa_1,\alpha\kappa_2,\kappa_1,\kappa_2,\gamma_1,\gamma_2}(\Delta m)$$

- Then we obtain the likelihood function for the 29 measurements of the sample:

$$\log L(\alpha) = \sum_{i=1}^{29} \log f^{i}{}_{\alpha\kappa^i{}_1,\alpha\kappa^i{}_2,\kappa^i{}_1,\kappa^i{}_2,\gamma^i{}_1,\gamma^i{}_2}(\Delta m^i)$$

5.c. Maximum Likelihood Analysis

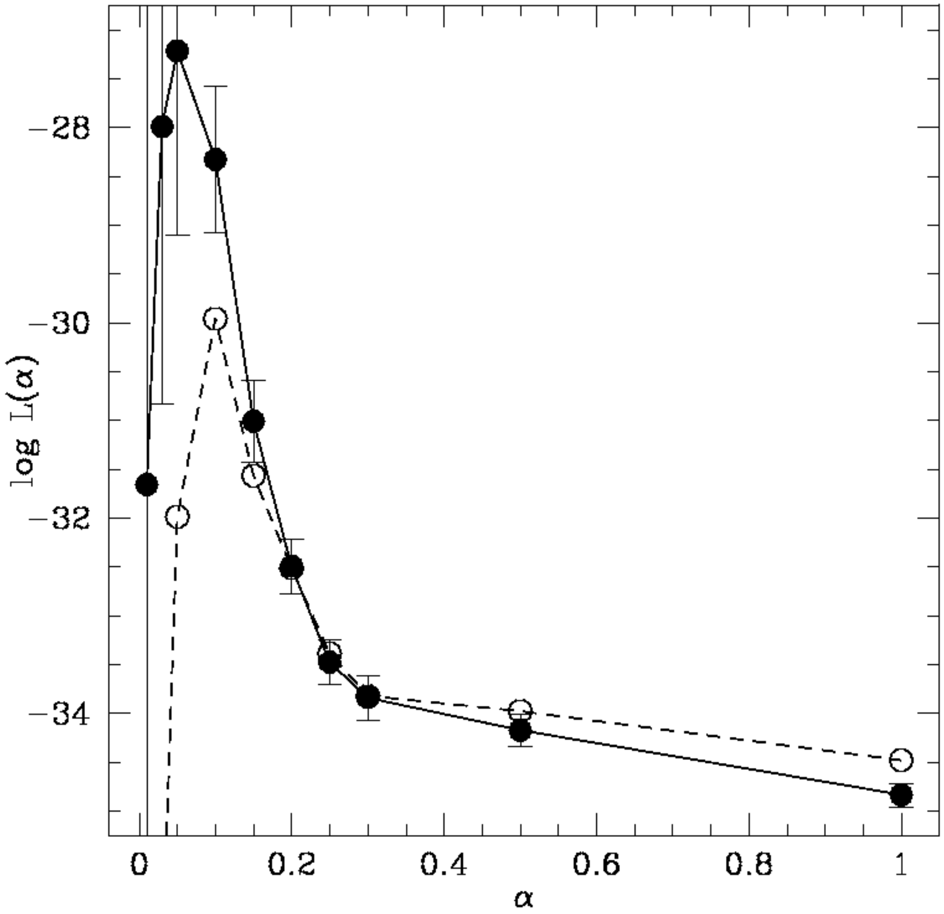


The likelihood function peaks at a value of

α = 0.10± 0.04 at 90% confidence interval

using the log $L(\alpha \pm n\sigma_\alpha) \sim \log L_{max} - n^2/2$ criterion

5.c. Maximum Likelihood Analysis



By considering each microlensing measure as a normal distribution of σ=0.20 we account for realistic errors in the detemination of the microlensing differences.

In that case, the analysis yields a value of 0.05 for the mass fraction in MACHOs

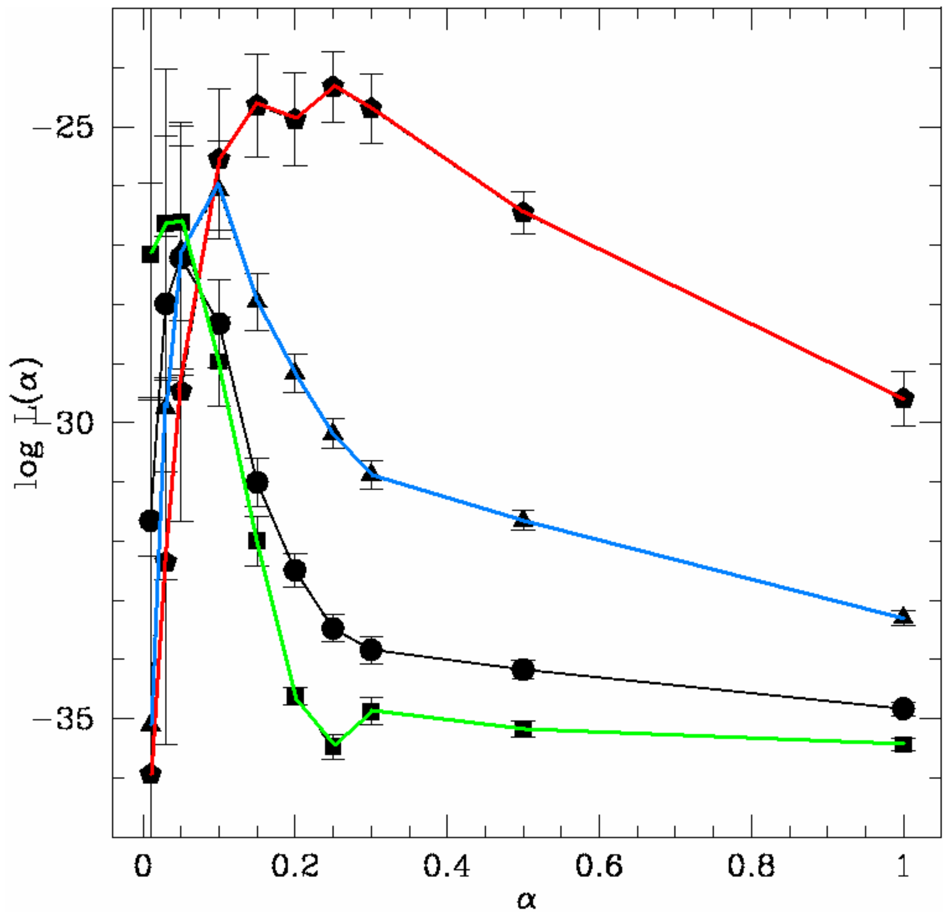
5.d. Fixing the size of the source

$r_{s0} = 0.8\times10^{15}\,cm$ (0.3 ld)

$r_{s0} = 3.9\times10^{15}\,cm$ (1.5 ld)

$r_{s0} = 12.4\times10^{15}\,cm$ (4.8 ld)

$r_{s0} = 40\times10^{15}\,cm$ (15 ld)



Changing the source pixel size or increasing the gaussian representing the continuum source affects by blurring the magnification maps and therefore the probablility distributions. We have chosen to model four sizes for the source plane deprojected size parameter.

Accretion disk size determined by Morgan et al. (2007) and Pooley et al. (2007) matches our range of results for α between 0.05 and 0.10

5.d. Conclusions about extragalactic MACHOs

- We have extended up to the **extragalactic domain** the local (LMC/ LMC/ M31) use of microlensing to probe the properties of the galactic halos.

- Regarding the current controversy about local microlensing DM studies, our work supports the hypothesis of a **very low content in MACHOs (~5%)**

- In fact, QSO microlensing probability arises from the normal star populations and, according to our work, **there is no statistical evidence for MACHOs** in the dark halos.

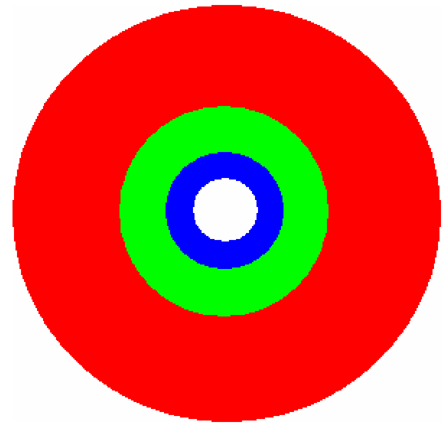
6. Ongoing work: Thermal Structure of the Accretion Disk

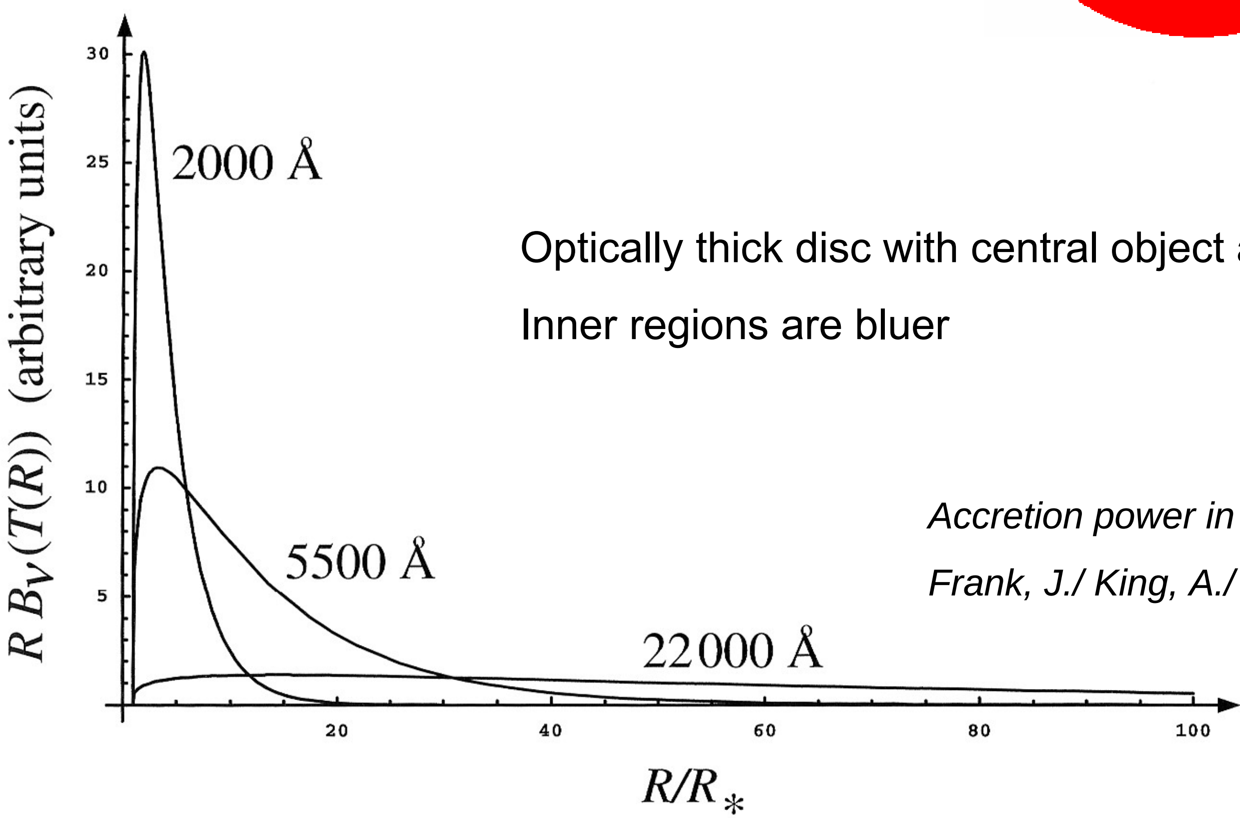
Main idea: to derive the radial dependence of temperature and size of the accretion disk in the case of SBS 0909+532 by measuring the wavelength dependence of the microlensing magnification detected.

In this section we merely mention the underlying principles which the current work of the group is based upon.

6. Thermal structure of the disc

Accretion disks have thermal structure





Optically thick disc with central object at T=7000 K

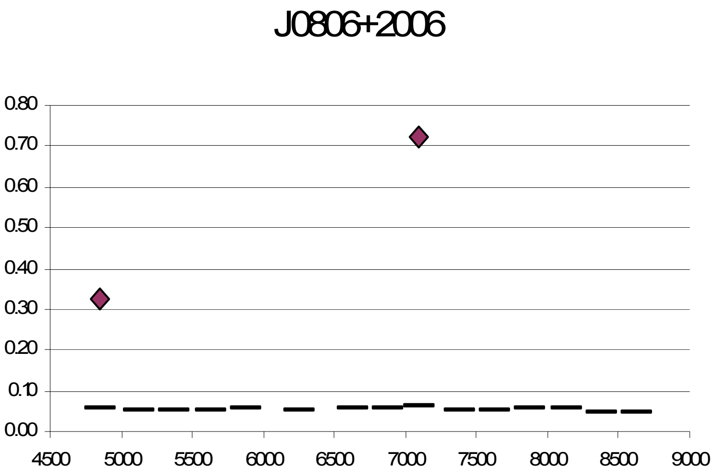
Inner regions are bluer

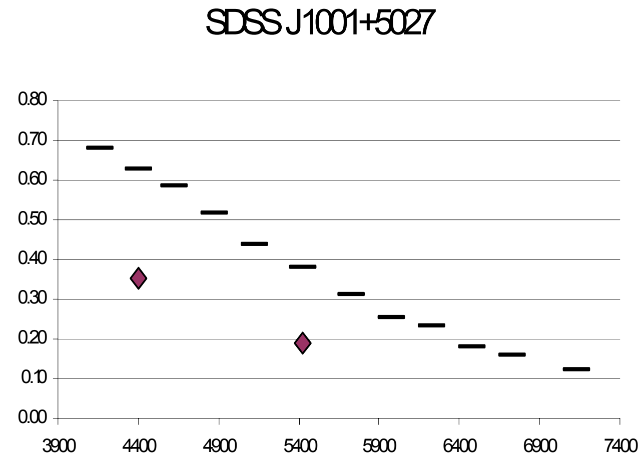
Accretion power in Astrophysics

Frank, J./ King, A./ Raine, D.

9. Next Step

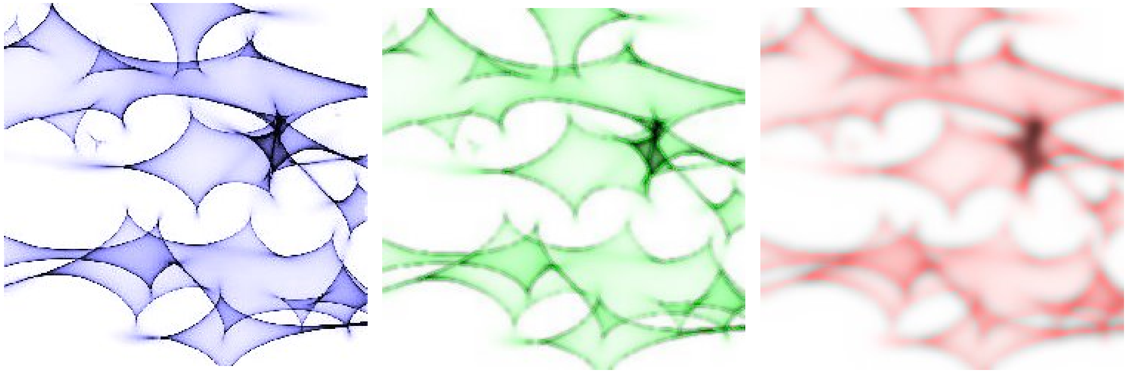
Thermal structure results on cromaticity

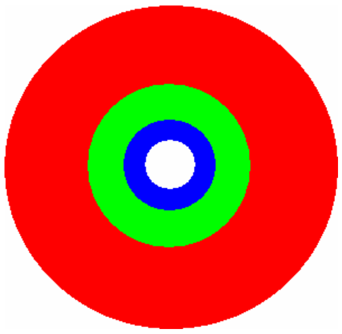




The smaller the source region the more sensitive to microlensing

Cromaticity in the continuum ratio is the microlensing signature of the thermal structure of the accretion disc





Thanks

(You may wake up now)