

Přednášky z moderní fyziky

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Gravitační čočky

David Heyrovský

Ústav teoretické fyziky, MFF UK

Stručná (pre-)historie gravitačních čoček

1801 – **Soldner**: newtonovský ohyb světla

1911 – **Einstein**: ohyb paprsků v gravitačním poli Slunce
(princip ekvivalence)

1914 – **Freundlich**: pokus o naměření - neúspěšný

1915 – **Einstein**: OTR (ohyb 2× větší)

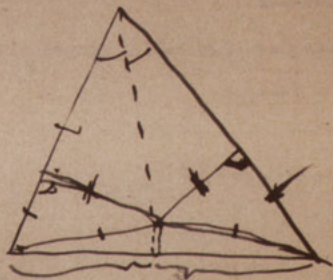
1919 – **Eddington**: experimentální ověření

Průchod světla gravitačním polem jiných hvězd?

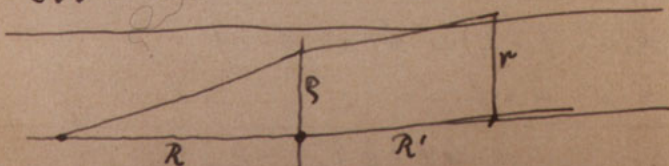
dílčí poznatky: **Eddington** 1920, **Chwolson** 1924

1936 – **Einstein**: odvození hlavních vlastností gravitační čočky

Alle Dreiecke sind gleichschenkelig.



Hebesäule
 Berlin-Hulensee,
 Machin Friedrichsh. 33.



$$r = s \frac{R+R'}{R} - \frac{R'\alpha}{s}$$

s nach unten
 negativer Sinn soll
 auch für stark abgelenkte
 Strahl.

$$r_0 = s_0 - \frac{1}{s_0} \dots (1)$$

$$s_0^2 = s^2 \frac{R+R'}{R R' \alpha}$$

Erdegl. $r = \dots - \frac{R\alpha}{s} = \dots - \frac{R\alpha}{s_0} \sqrt{\frac{R+R'}{R R' \alpha}}$

$$= \dots - \frac{1}{s_0} \sqrt{\frac{R}{R'} (R+R') \alpha}$$

$$\left. \begin{aligned} r_0 &= r \sqrt{\frac{R R'}{R(R+R')\alpha}} \\ s_0 &= s \sqrt{\frac{R+R'}{R R' \alpha}} \end{aligned} \right\} (2)$$

1) gibt zwei Wurzeln für s_0
 von hier ein Index weglassen.

$$2 + r^2 = s^2 + \frac{1}{s^2}$$

$$f = \varphi + \frac{\pi^2}{\varphi}$$

$$df = \left(1 - \frac{\pi^2}{\varphi^2}\right) d\varphi = \left(1 - \frac{1}{s^2}\right) d\varphi$$

$$R df = \pm H d\varphi$$

$$R = \pm \frac{H}{1 - \frac{1}{s^2}}$$

$$R_{tot} = H \left\{ \frac{1}{1 - \frac{1}{s^2}} + \frac{1}{\frac{1}{s^2} - 1} \right\} \dots (3)$$

Klammer gibt relative Helligkeit.
 (im $\infty = 1$)

$$r = \frac{1}{x} - x$$

$$\left\{ \right\} = \frac{1}{1-x^2} + \frac{1}{x^2-1}$$

A. Einstein (1936, Science 84, 506):

“Some time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.”

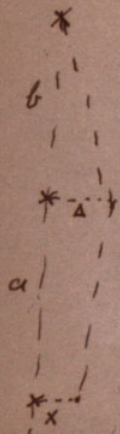
Průvodní dopis editorovi:

“Ich danke Ihnen noch sehr für Ihr Entgegenkommen bei der kleinen Publikation, die Herr Mandl aus mir herauspresste. Sie ist wenig wert, aber diese arme Kerl hat seine Freude davon.”

2. VI. 36.

Brief an Herrn Maull.

$$\xi = \frac{\xi \Delta_0}{\Delta} = \frac{\Delta}{b} + \frac{\Delta - x}{a}$$



Gleichung für Δ

$$\Delta^2 - \underbrace{\left(\frac{x b}{a+b}\right)}_{\xi} - \underbrace{\left(\frac{\xi_0 \Delta_0 a b}{a+b}\right)}_A = 0 \quad (\text{Wurzeln } \Delta_1 (>0) \quad \Delta_2 (<0))$$

für $x=0$ $\Delta = \sqrt{\frac{\xi_0 \Delta_0 a}{1 + \frac{a}{b}}}$ Schwünke $\frac{\Delta}{a} = \sqrt{\frac{\xi_0 \Delta_0}{a(1 + \frac{a}{b})}}$

$$\Delta_1 + \Delta_2 = \xi \quad \Delta_1 \Delta_2 = -A$$

$$\Delta_1 + \Delta_2 = \sqrt{\xi^2 + 4A}$$

Verhältnis der Flächen $\frac{d(\Delta_1^2 - \Delta_2^2)}{d(x^2)}$

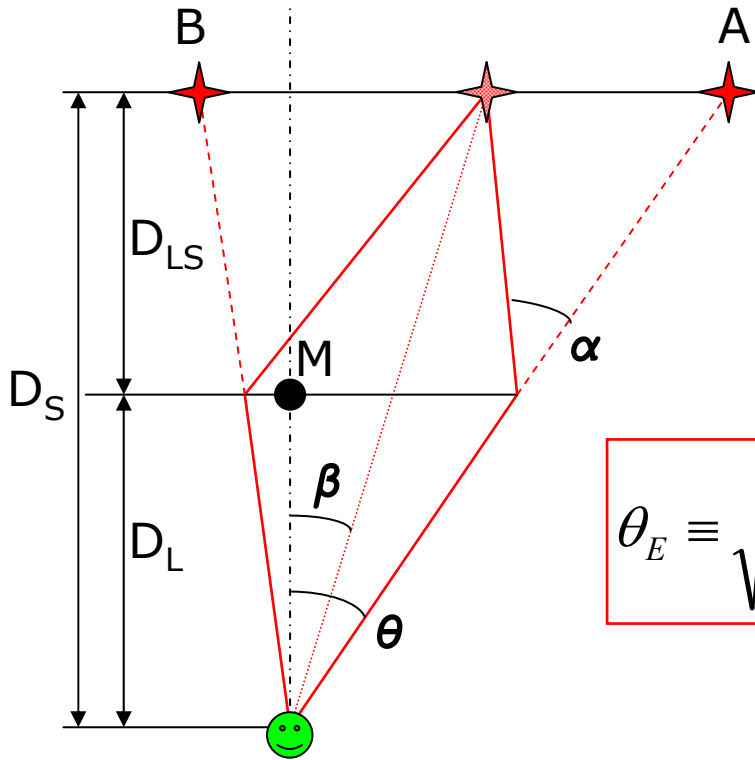
$$V = \left(1 + \frac{a}{b}\right)^2 \frac{d(\Delta_1^2 - \Delta_2^2)}{d(x)^2} = \frac{d(\Delta_1^2 - \Delta_2^2)}{d(\xi^2)} = \frac{d}{d(\xi^2)} \sqrt{(\xi^2)^2 + 4A\xi^2}$$

$$= \frac{1}{\xi} \frac{2\xi^2 + 2A}{2\sqrt{\xi^2 + 4A}} = \frac{\sqrt{A}}{\xi} \frac{1 + \frac{\xi^2}{2A}}{\sqrt{1 + \frac{\xi^2}{4A}}} = \frac{\sqrt{A}}{\xi}$$

Für grosse V

$$V = \frac{\sqrt{A}}{\xi} = \sqrt{\xi_0 \Delta_0 a \frac{a+b}{b}}$$

Gravitační čočka



$$\beta D_S + \alpha(\theta) D_{LS} = \theta D_S$$

Hmotný bod: $\alpha(\theta) = \frac{4GM}{c^2 D_L \theta}$

zobrazovací rovnice:

$$\vec{\beta} = \left(1 - \theta_E^2 / \theta^2\right) \vec{\theta}$$

$$\theta_E \equiv \sqrt{\frac{4GM D_{LS}}{c^2 D_L D_S}}$$

Einsteinův poloměr

poloha obrazů

$$|\vec{\beta}| = 0 \dots |\vec{\theta}| = \theta_E$$

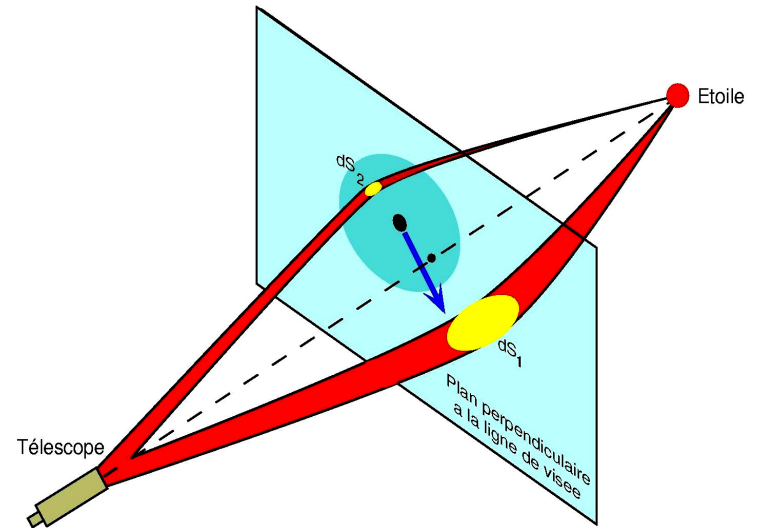
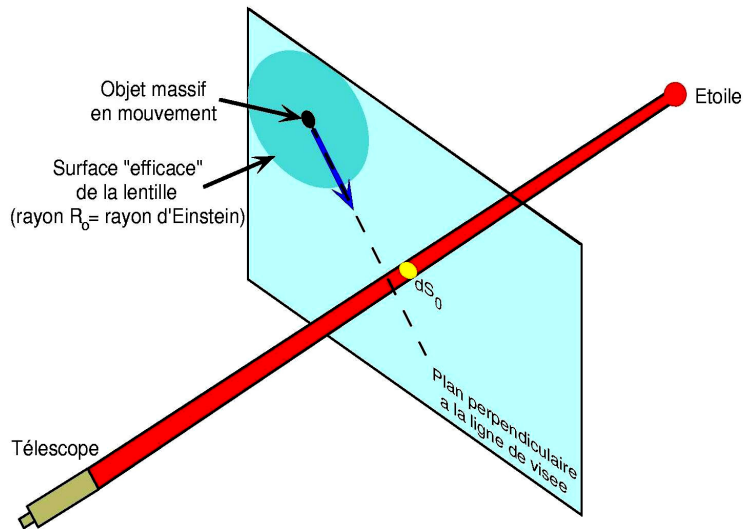
$$|\vec{\beta}| > 0 \dots \vec{\theta}_{A,B} = \left(\frac{1}{2} \pm \sqrt{\frac{1}{4} + \frac{\theta_E^2}{\beta^2}} \right) \vec{\beta}$$





Zjasnění světelného toku bodového zdroje:

$$A_0(\beta) = \frac{F_A + F_B}{F_0} = \left| \frac{\partial \vec{\beta}}{\partial \vec{\theta}} \right|_A^{-1} + \left| \frac{\partial \vec{\beta}}{\partial \vec{\theta}} \right|_B^{-1} = \frac{\beta^2 + 2\theta_E^2}{|\beta| \sqrt{\beta^2 + 4\theta_E^2}}$$



Einstein (1936):

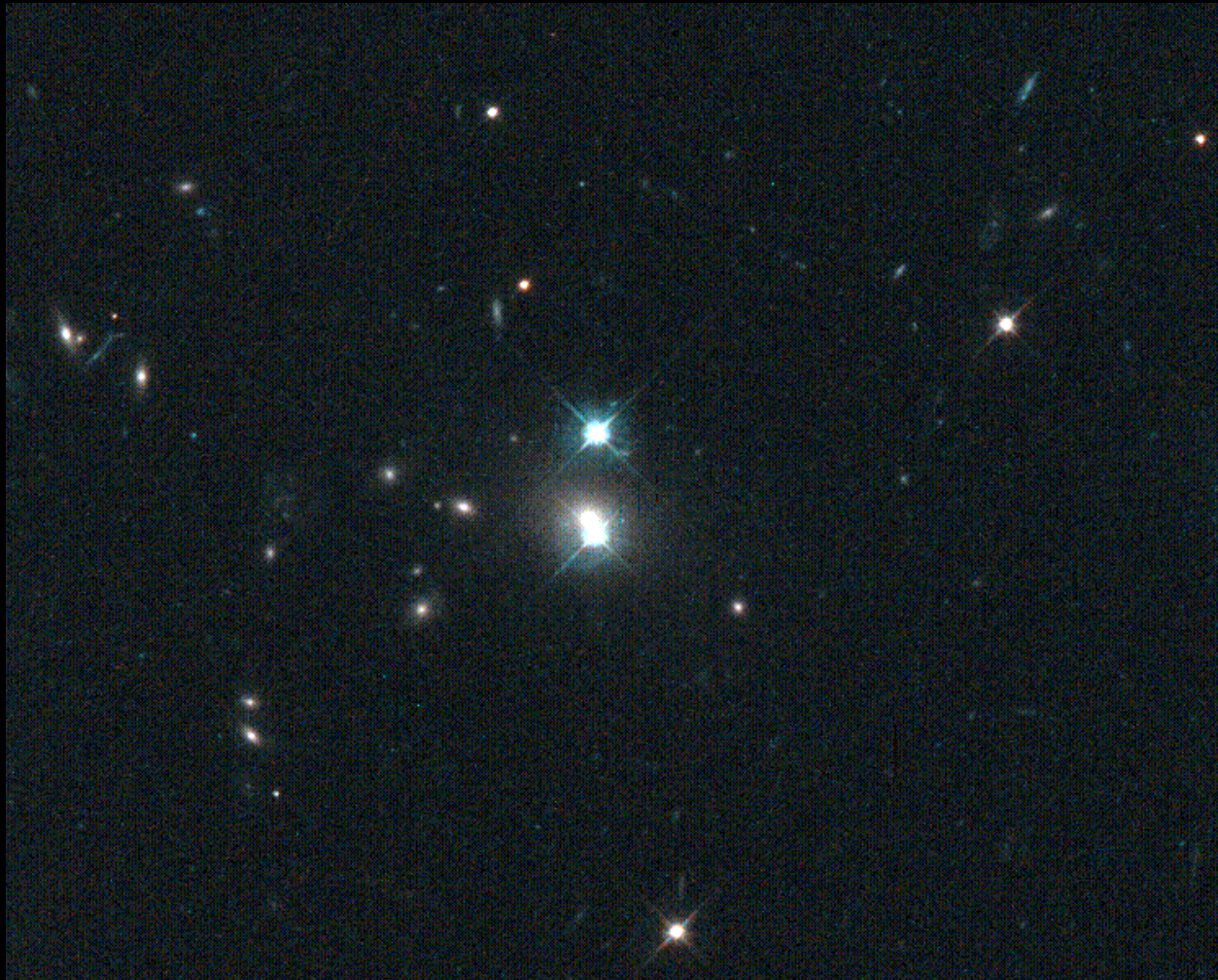
"no great chance of observing this phenomenon"

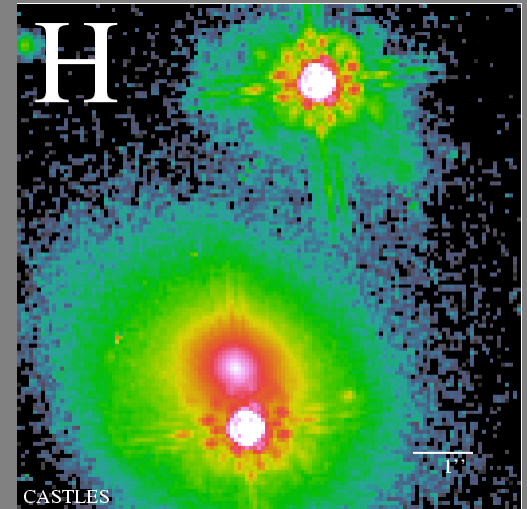
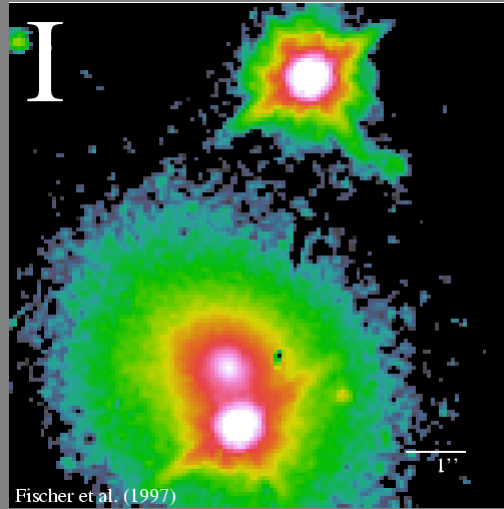
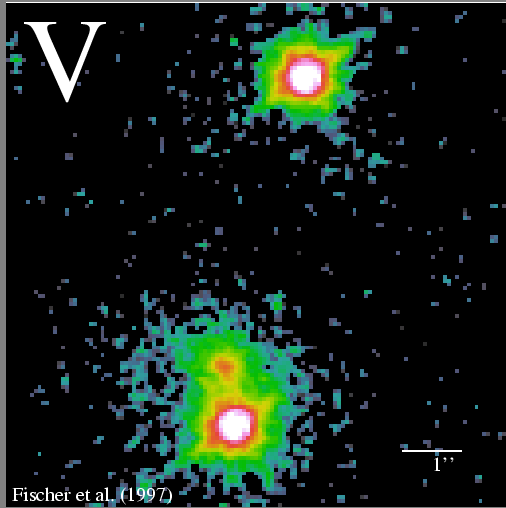
Zwicky (1937):

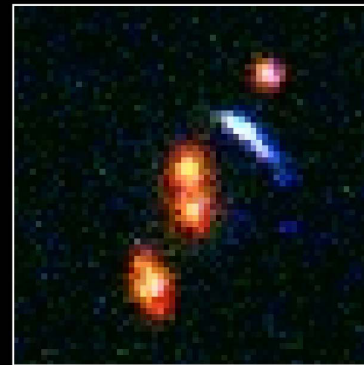
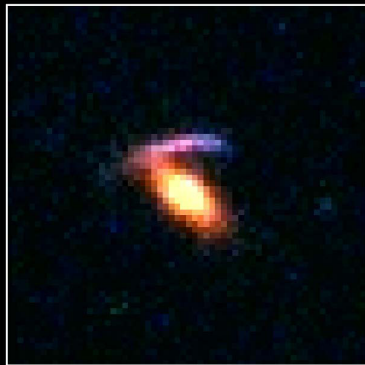
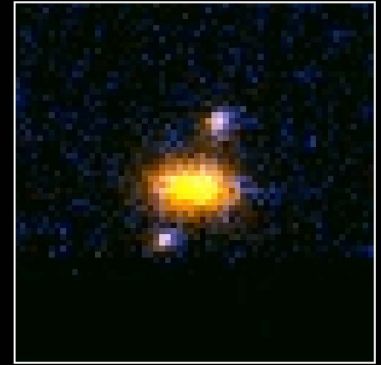
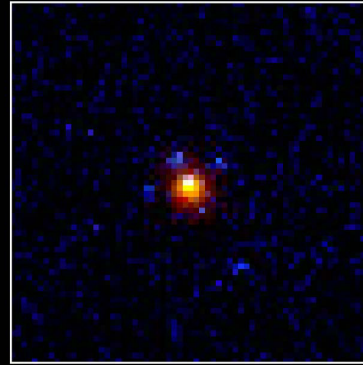
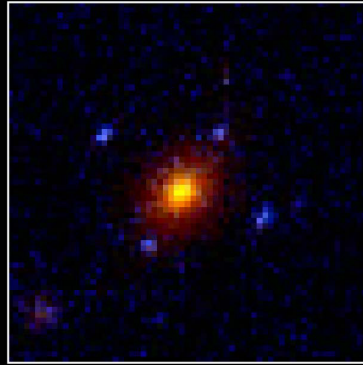
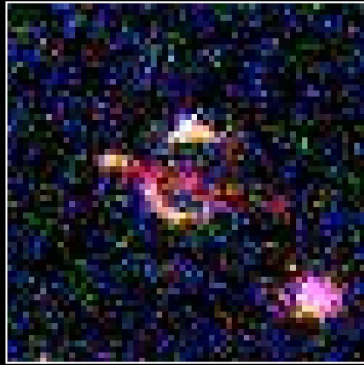
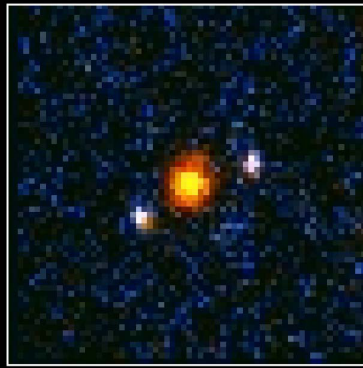
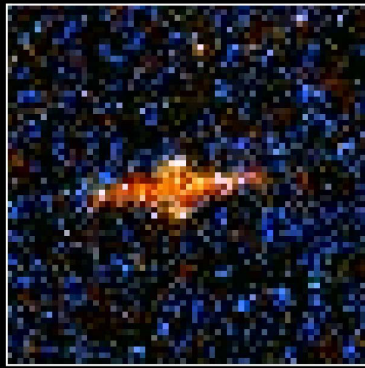
lepší hledat efekt u **galaxií** – realistické!

Kvasar 0957+561

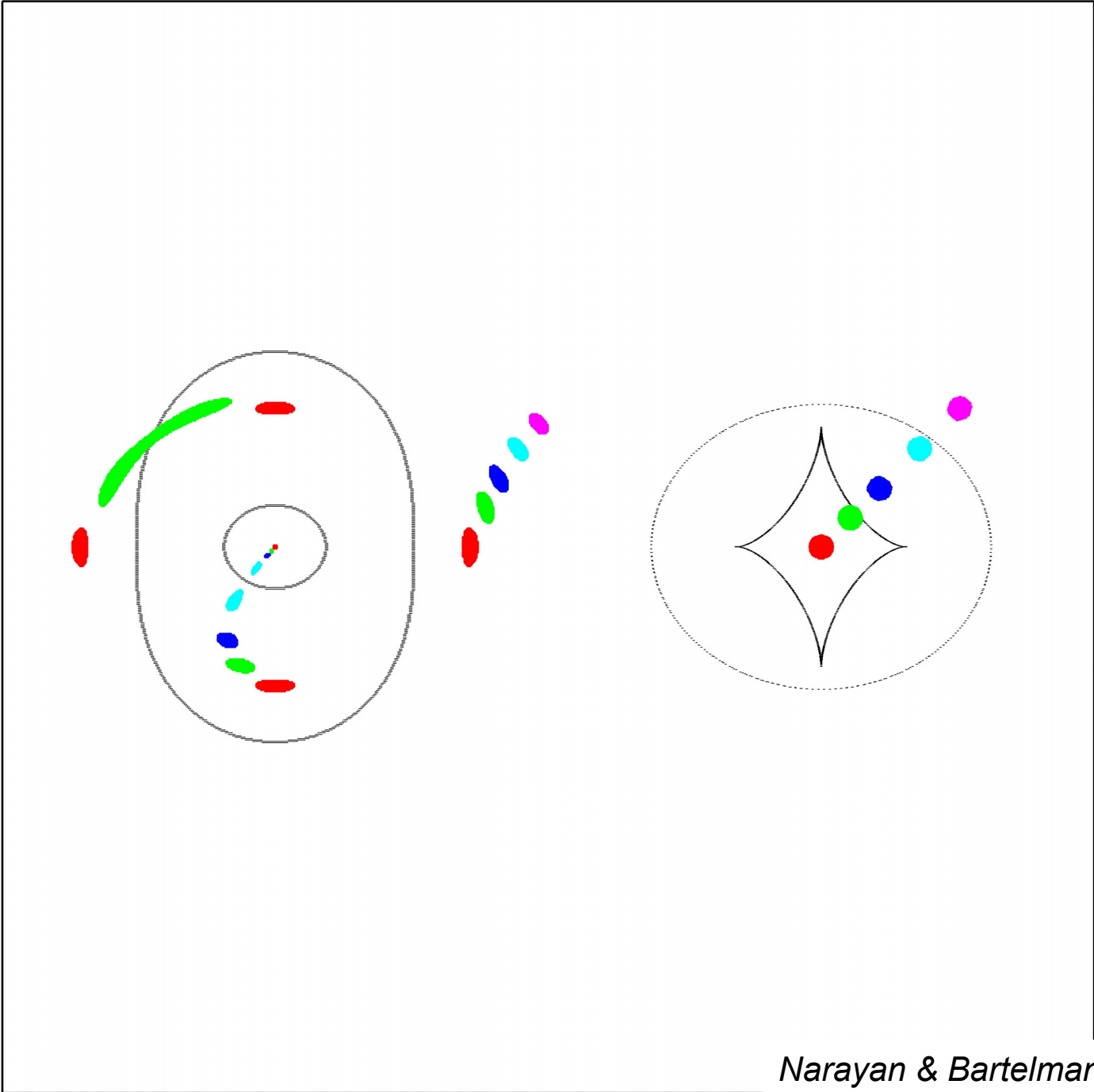
(Walsh, Carswell, Weymann 1979)

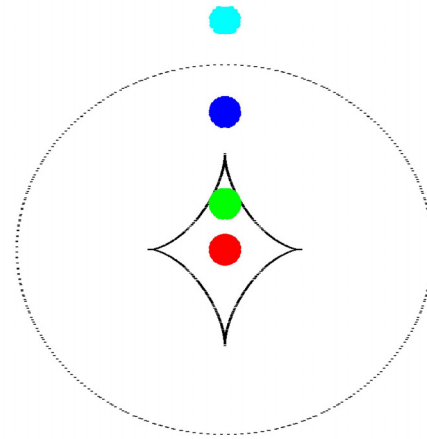
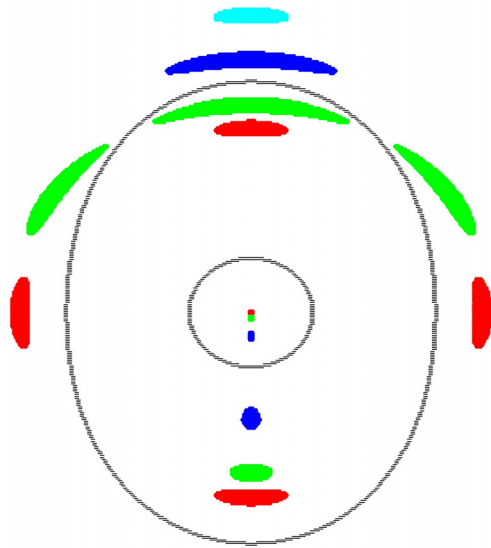


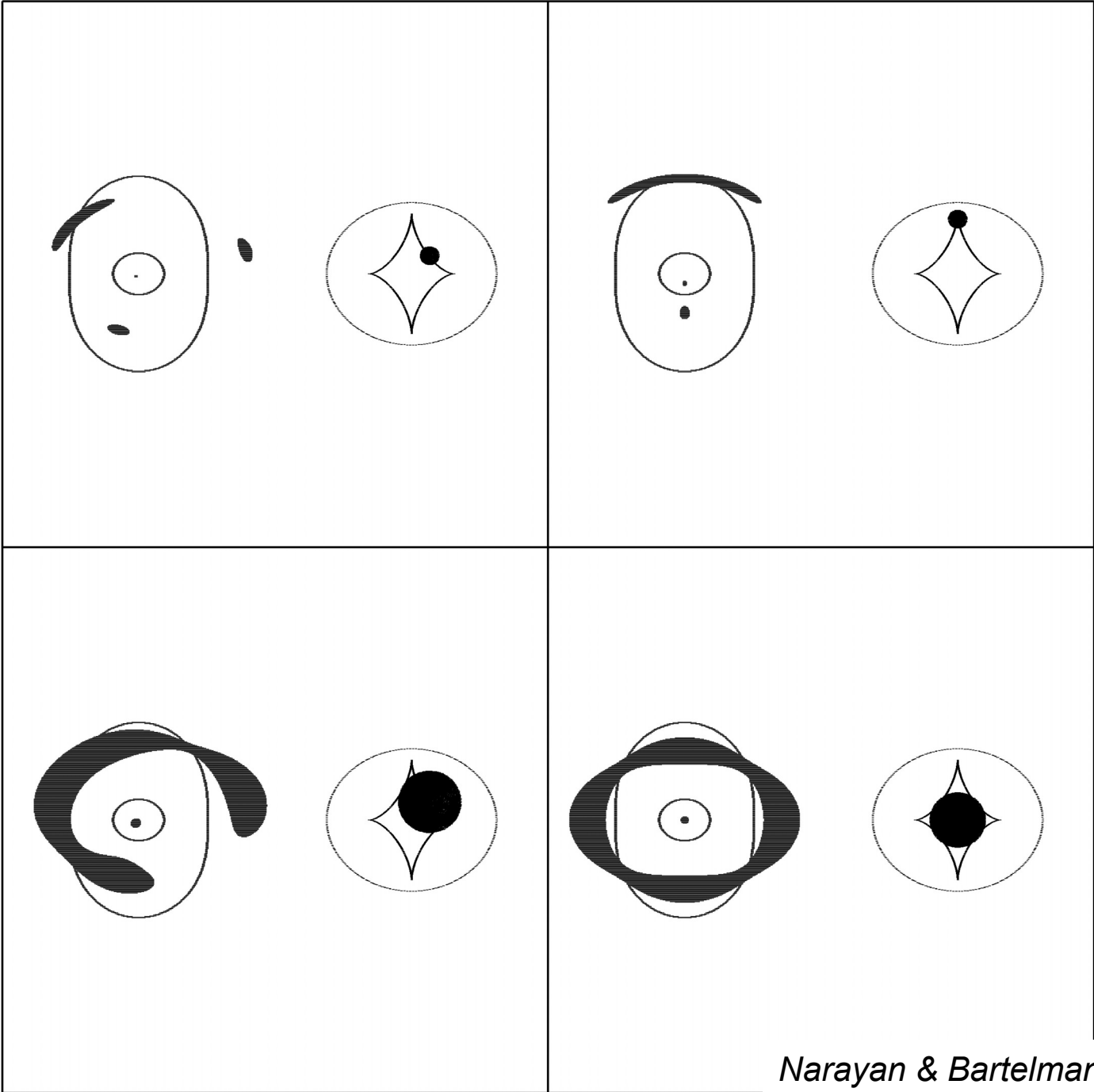


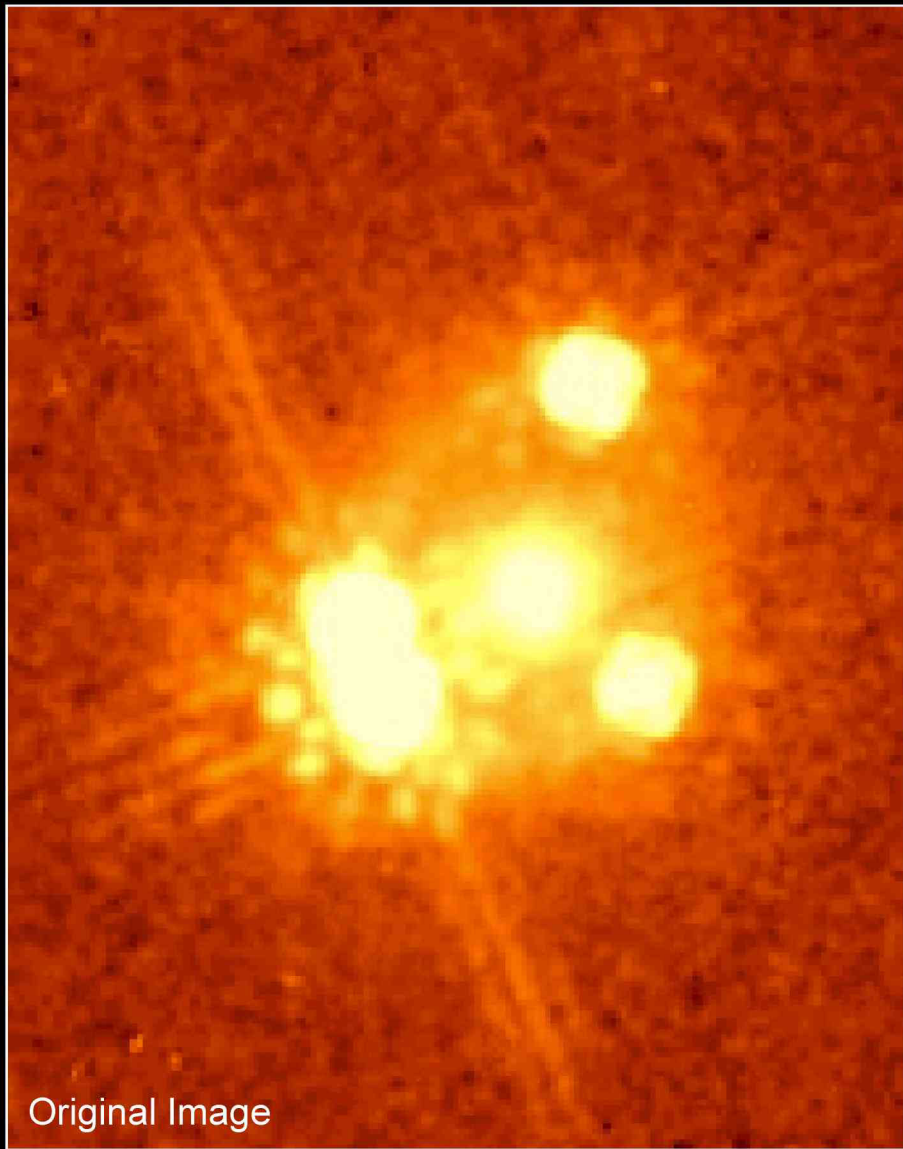


Gallery of Gravitational Lenses
Hubble Space Telescope • WFPC2

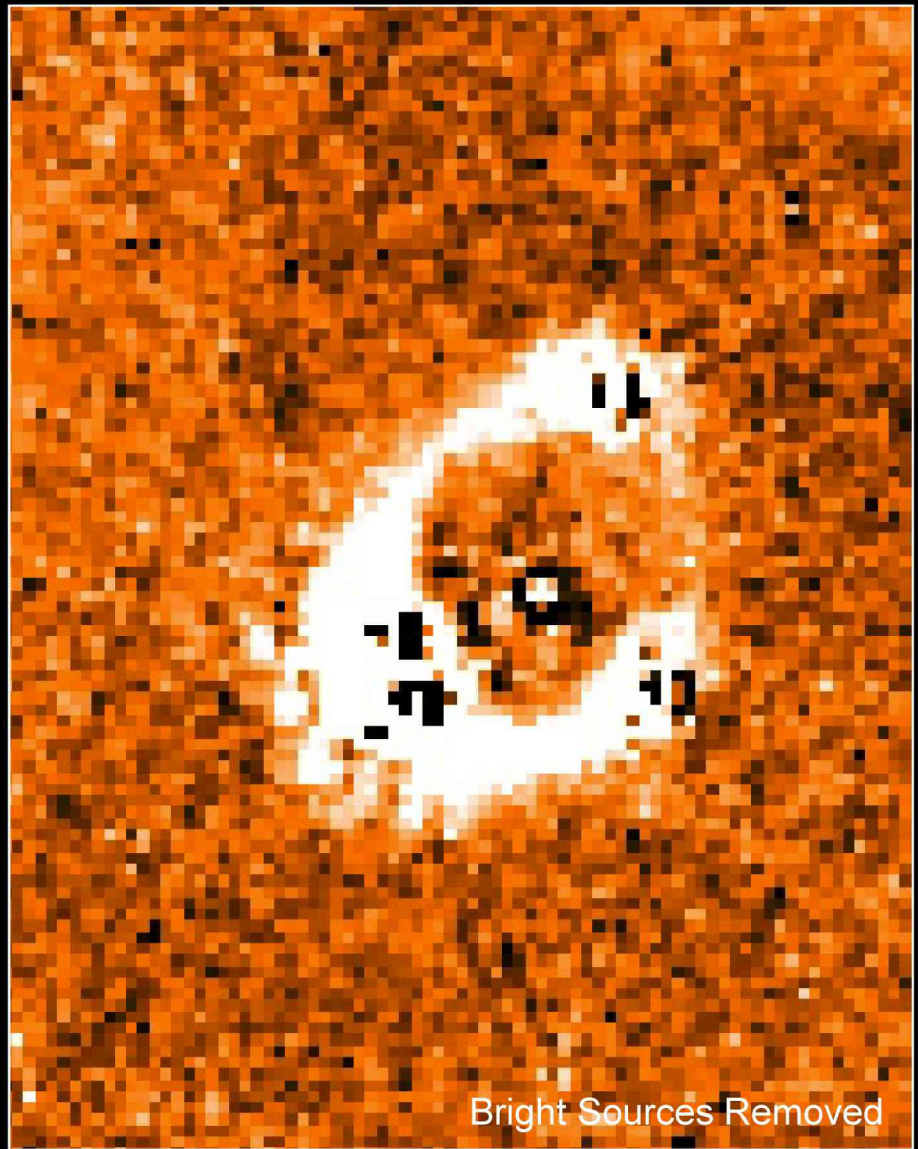






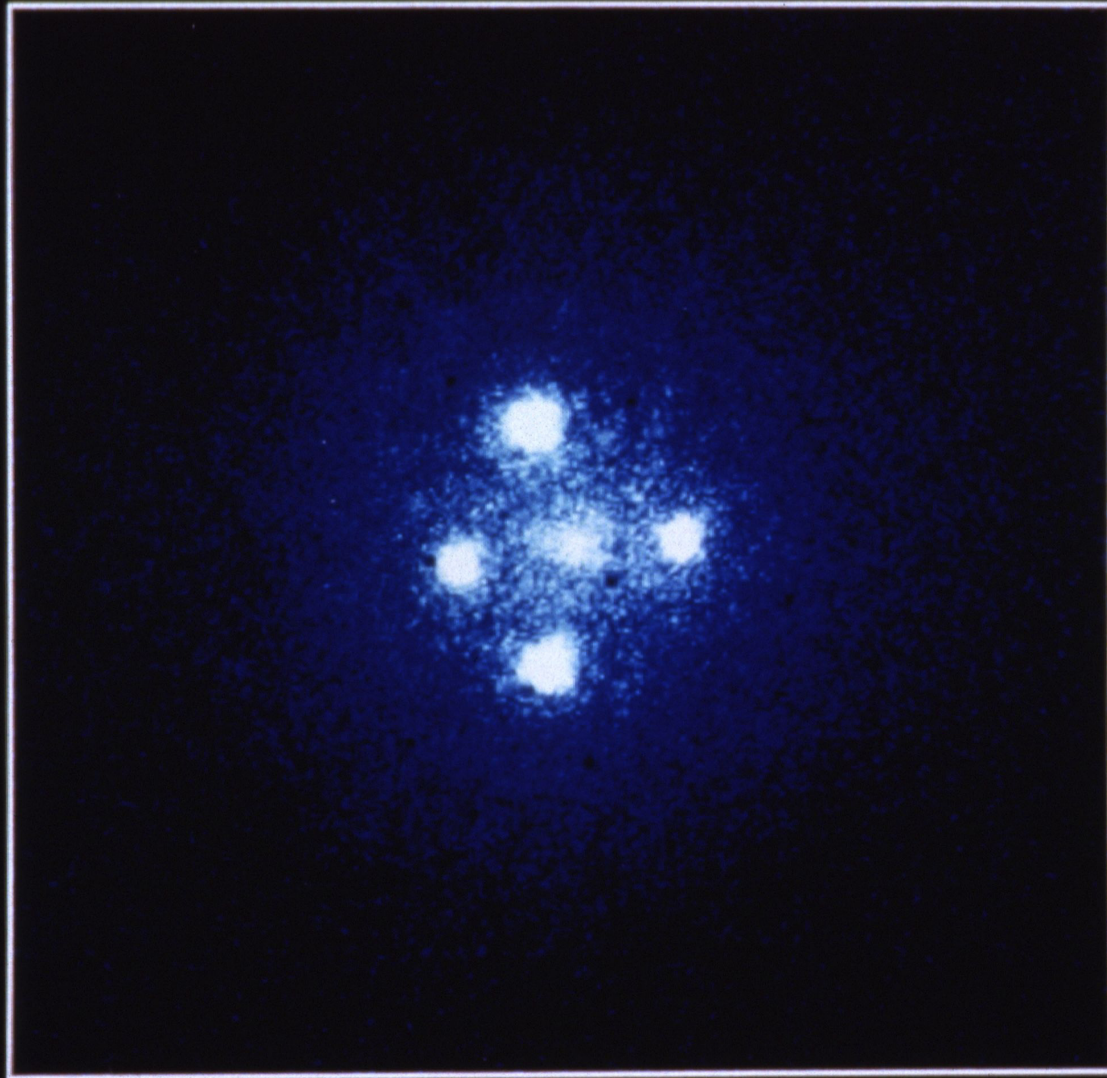


Original Image



Bright Sources Removed

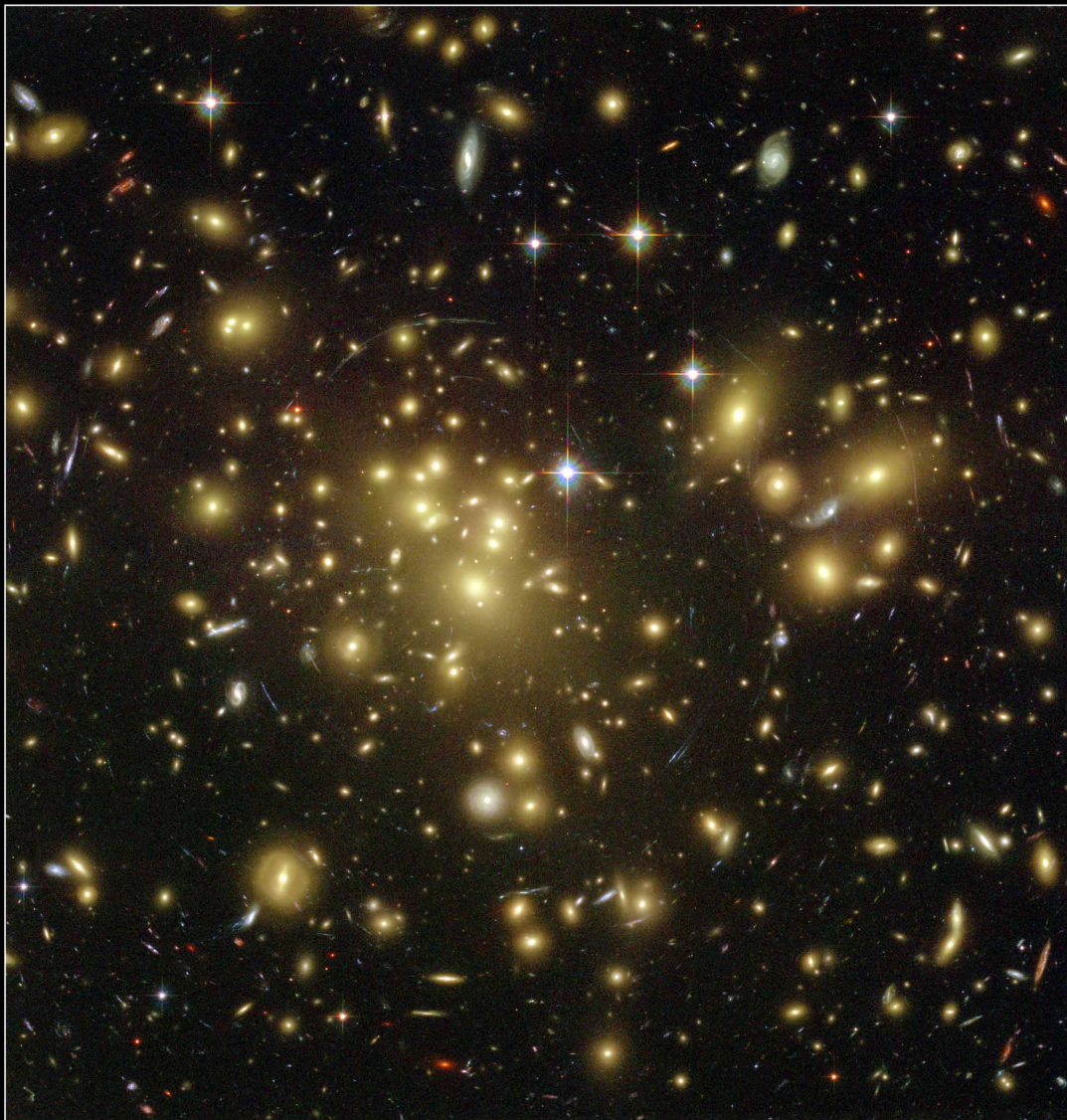
Gravitational Lens and Quasar PG 1115+080
Hubble Space Telescope • NICMOS



Gravitational Lens G2237+0305

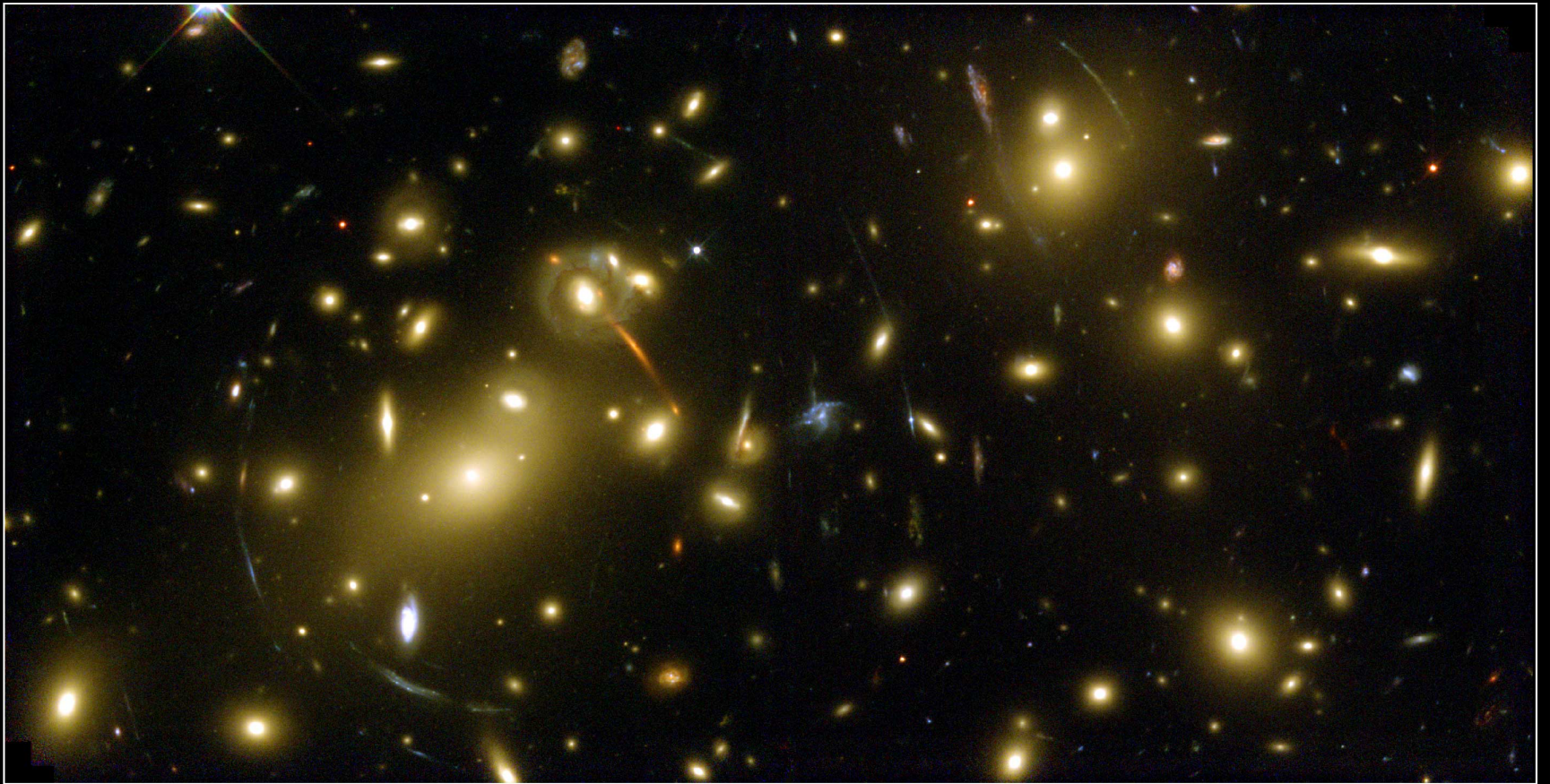


Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope · WFPC2



Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

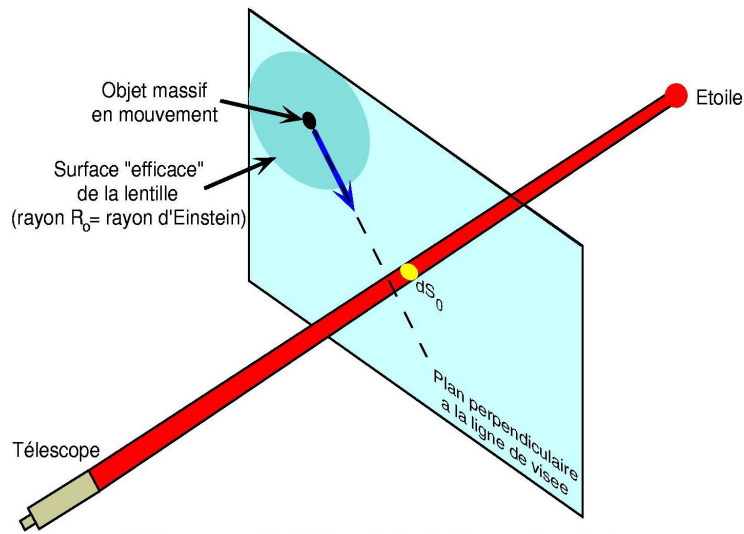


Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

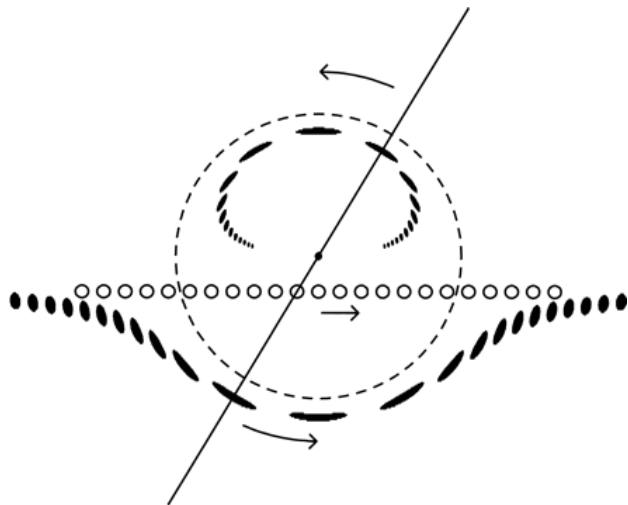


Distant Galaxy Lensed by Cluster Abell 2218
Hubble Space Telescope • WFPC2 • ACS

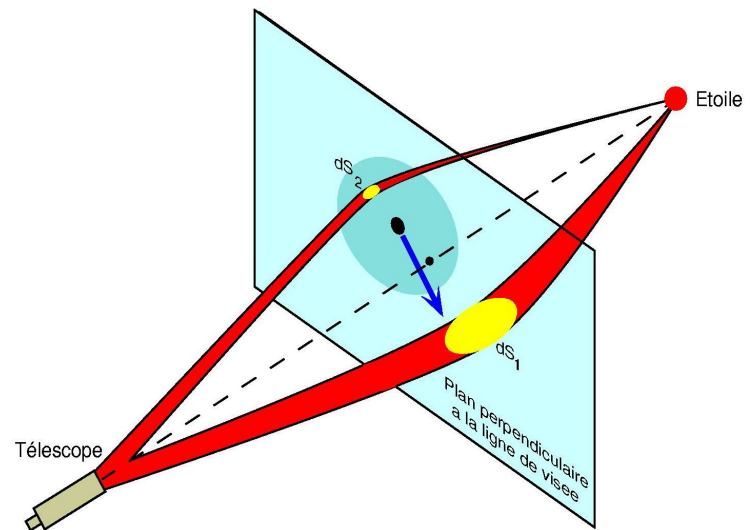


Zjasnění hvězdy mikročočkou

$$A_0(\beta) = \frac{F_A + F_B}{F_0} = \frac{\beta^2 + 2\theta_E^2}{|\beta| \sqrt{\beta^2 + 4\theta_E^2}}$$



Paczynski (1996)



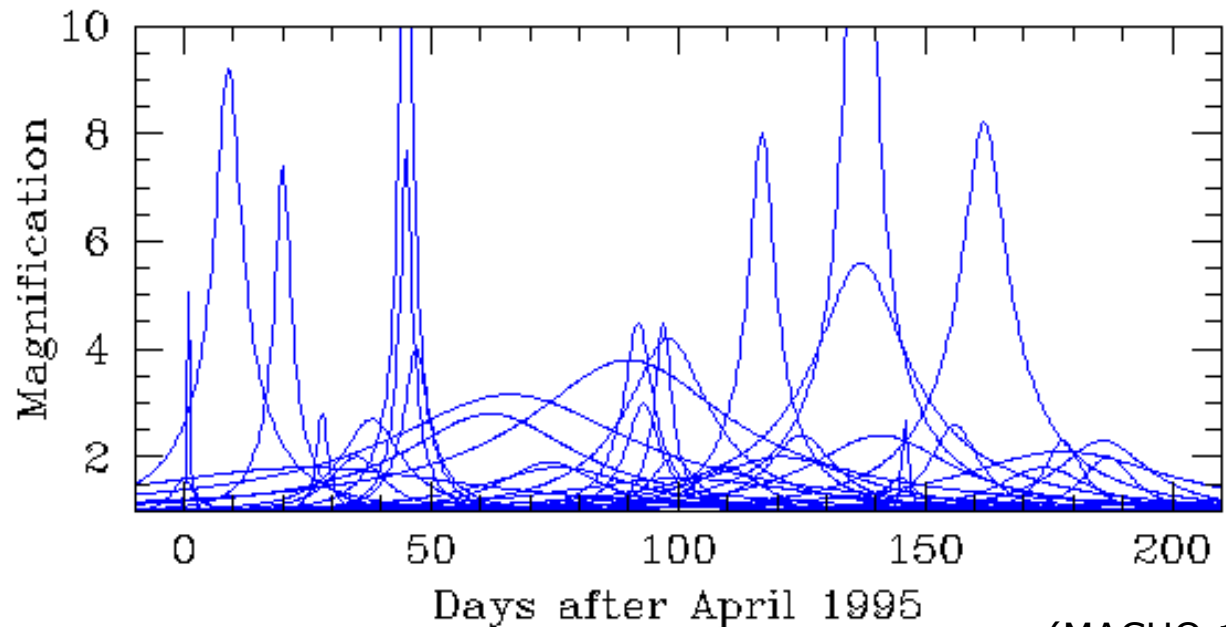
EROS

pravděpodobnost pro jednu hvězdu nízká

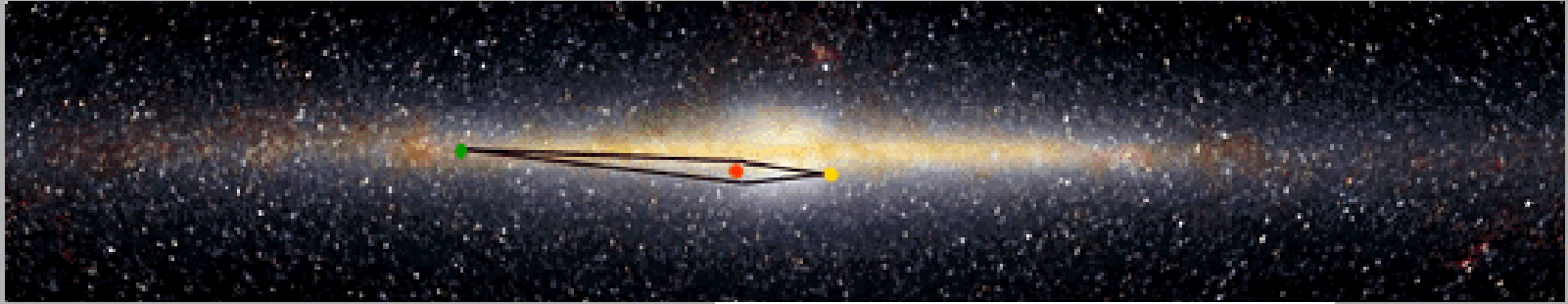
=> potřeba monitorovat dostatek hvězd (Paczynski 1986)

Monitorovací projekty (MACHO, EROS, OGLE, MOA, ...)

- pozorování hlavně směrem ke Galaktické výduti, LMC, SMC
- 1992 – 2004 ~ 2500 mikročoček

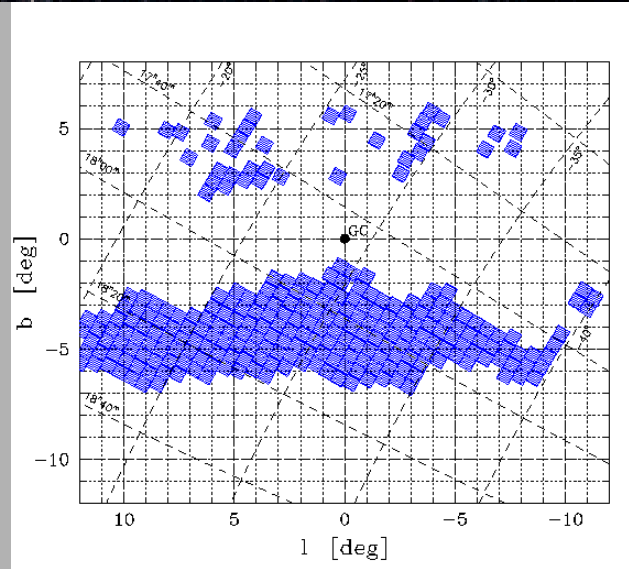
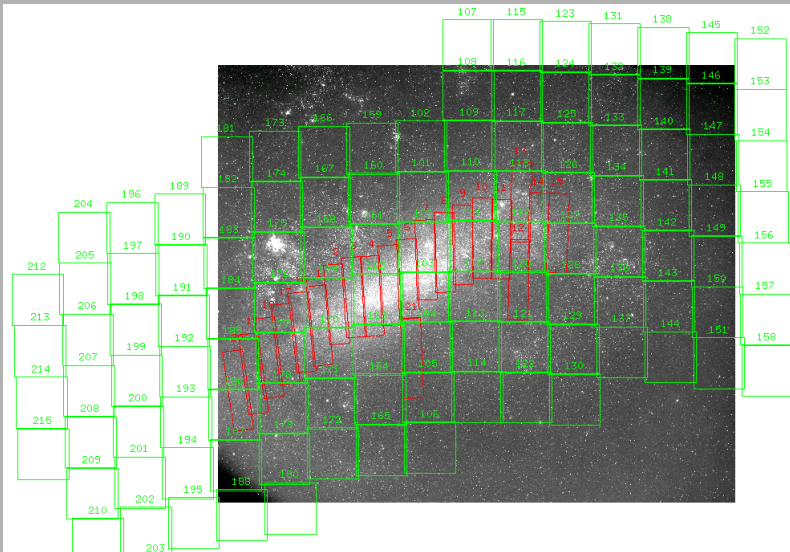


(MACHO 1995)



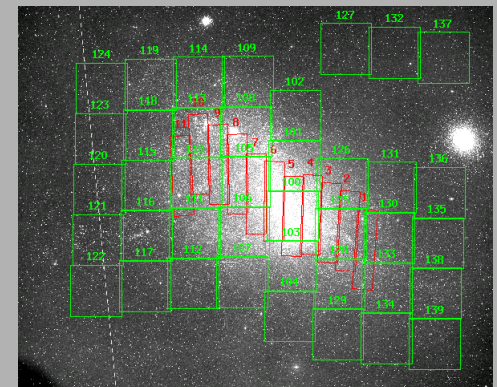
OGLE-III sleduje:

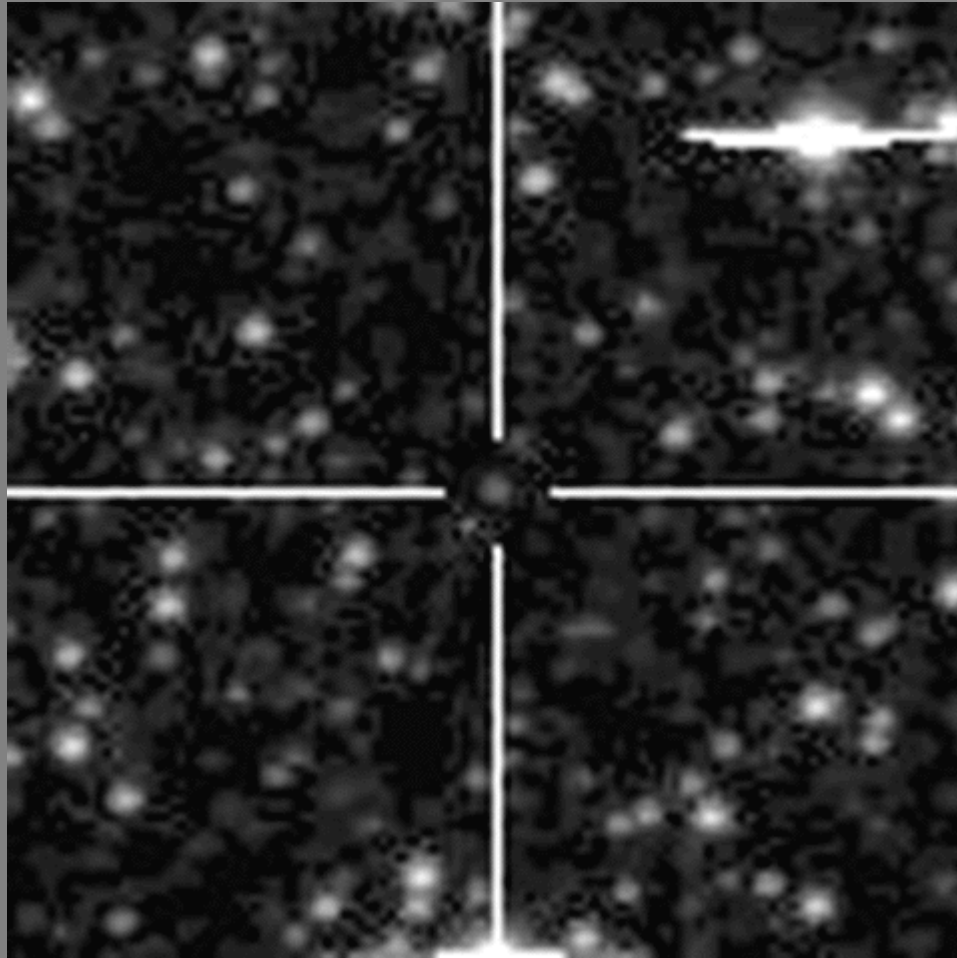
LMC



**Gal.
výduť**

SMC

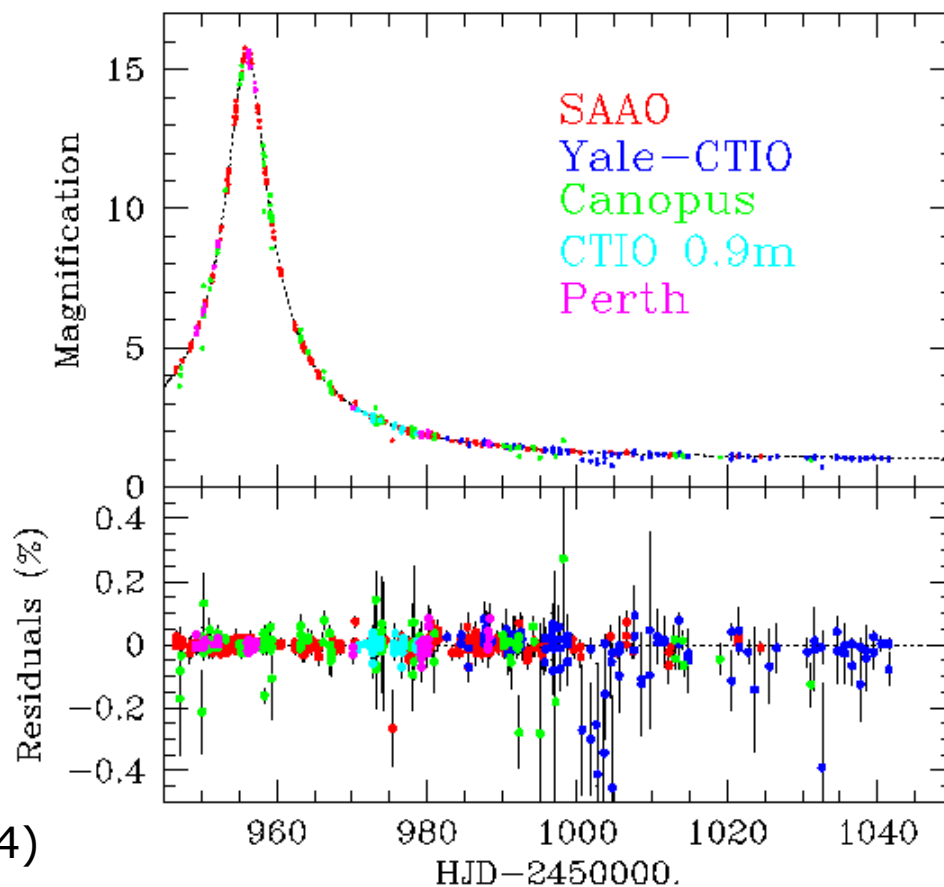




Animace viz <http://www.ctio.noao.edu/~supermacho/lensing3.gif>

Návazné projekty

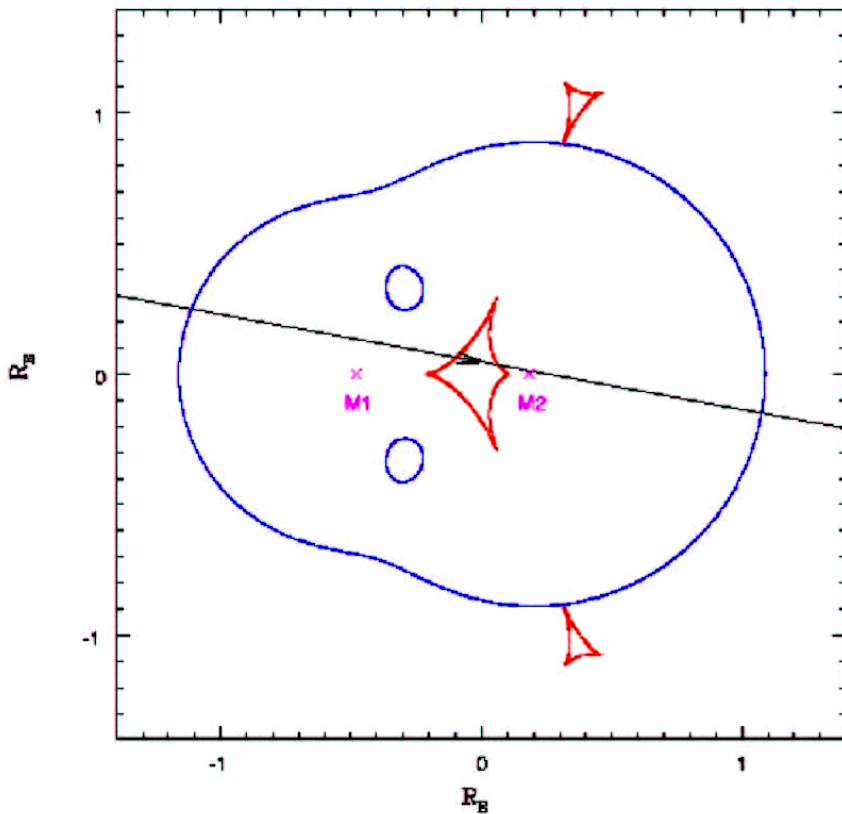
- PLANET, GMAN, MPS, MicroFun, ...
- „nepřetržité“ sledování mikročoček ohlášených monitorovacími projekty
- hledání odchylek od jednoduchého modelu



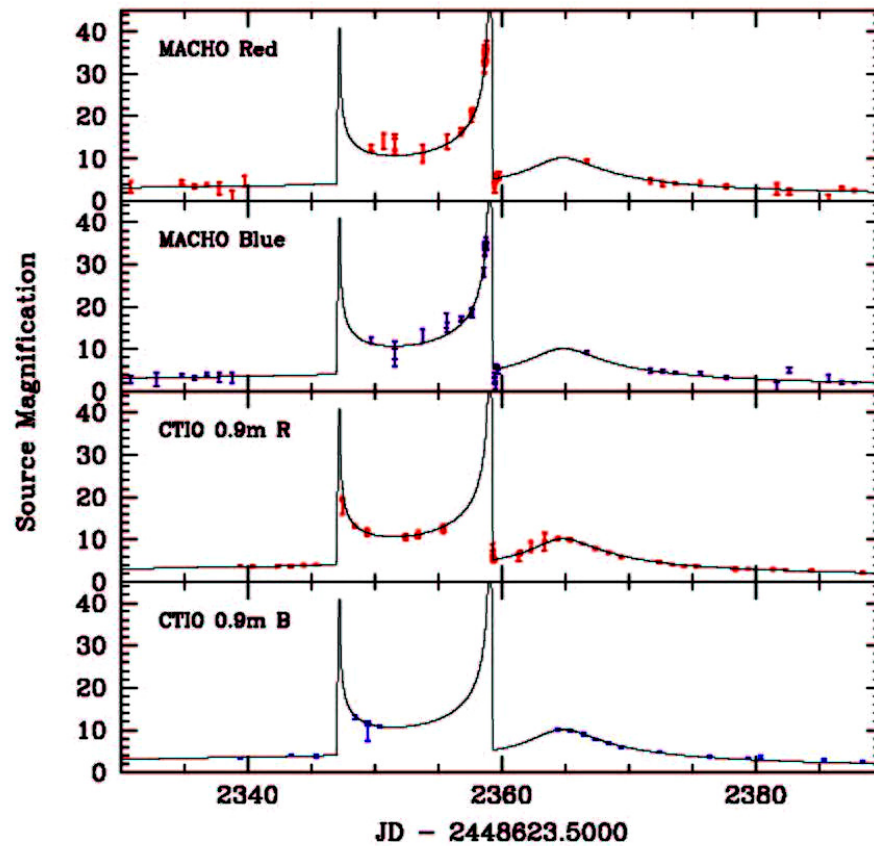
PLANET (OGLE-1998-BUL-14)

Dvojité čočky

MACHO Event 98-SMC-1



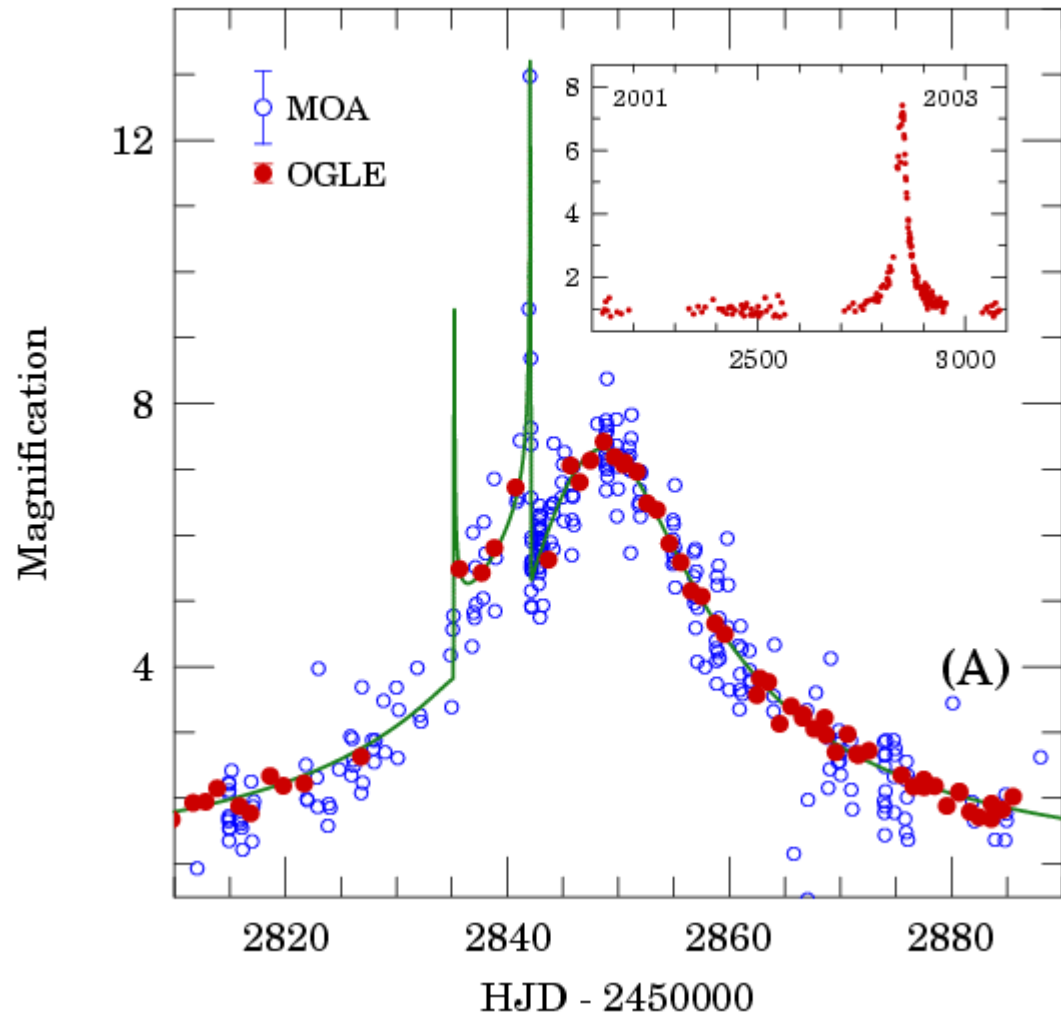
MACHO Event 98-SMC-1

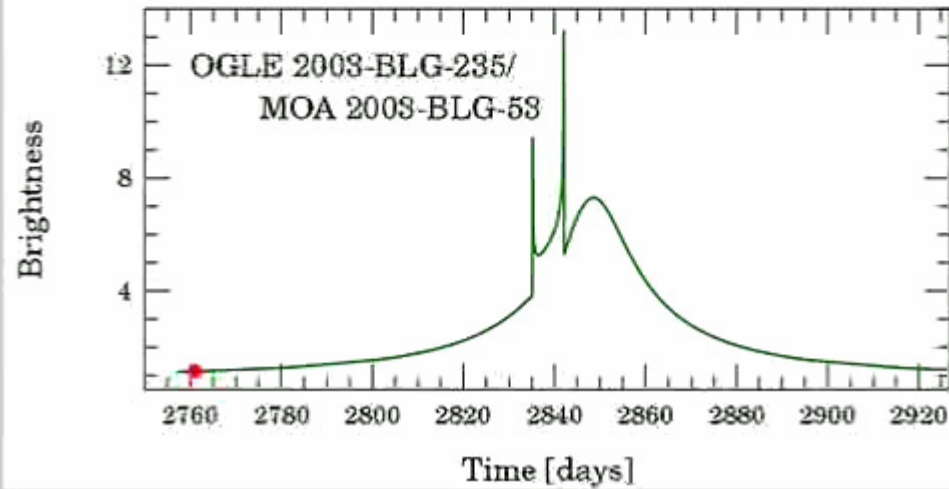
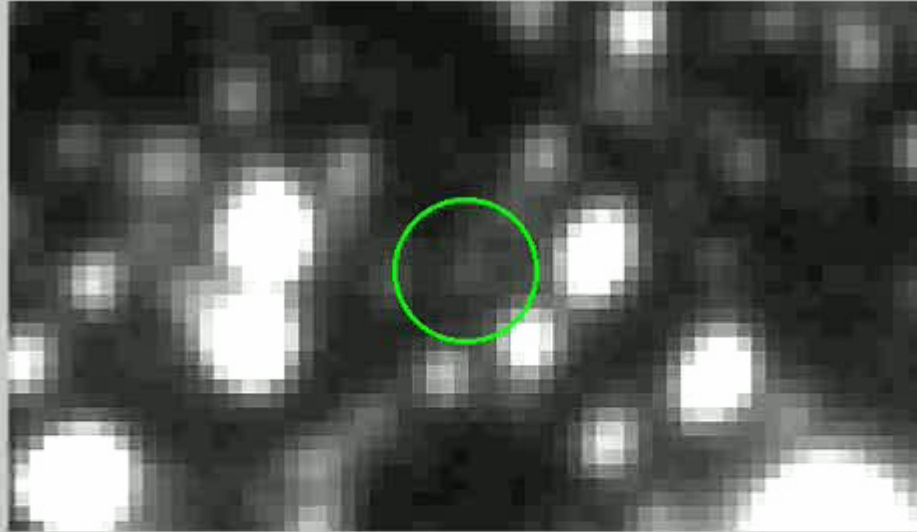


Alcock et al. (2000)

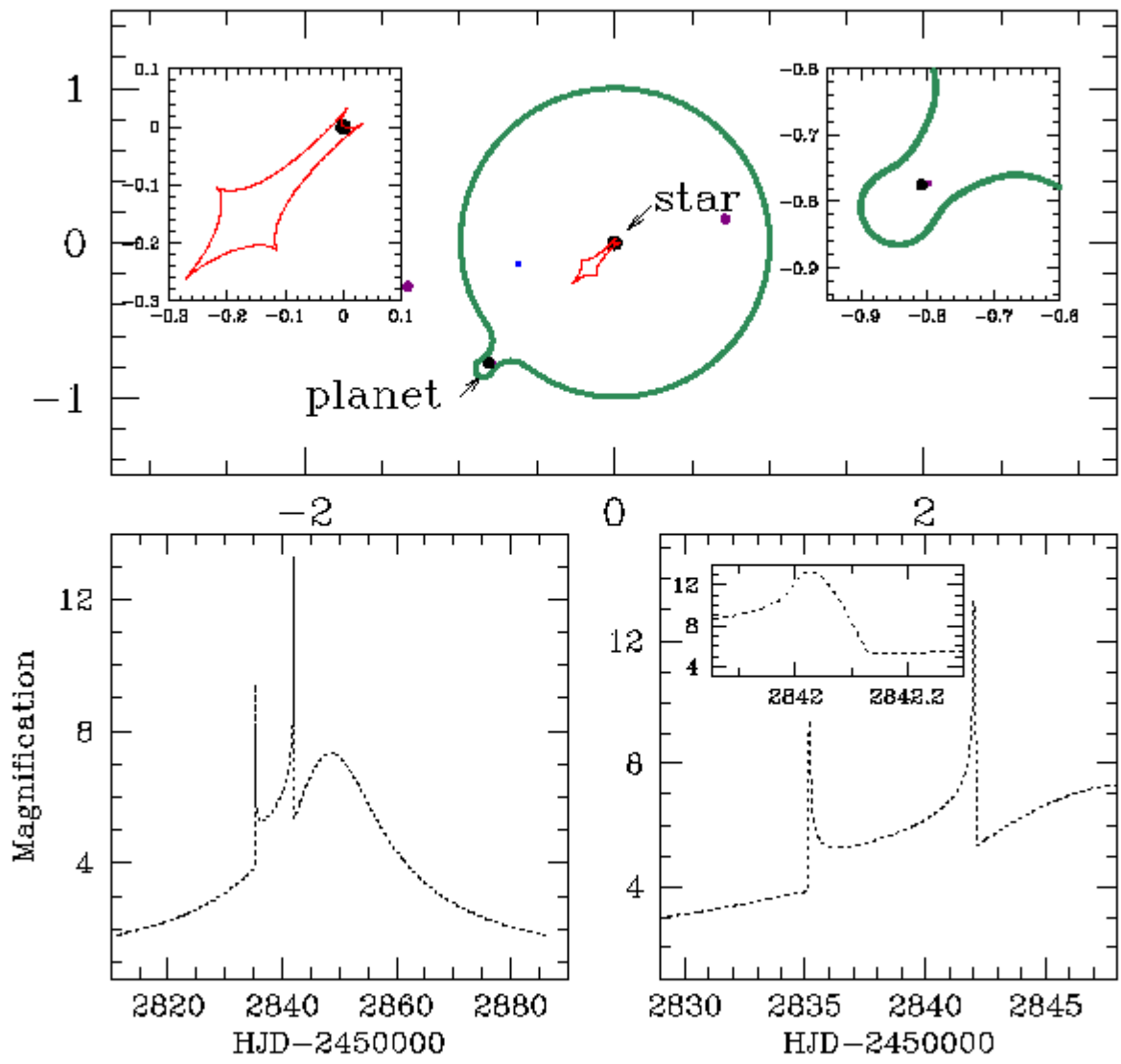
Detekce planety u čocky

MOA 2003-BLG-53





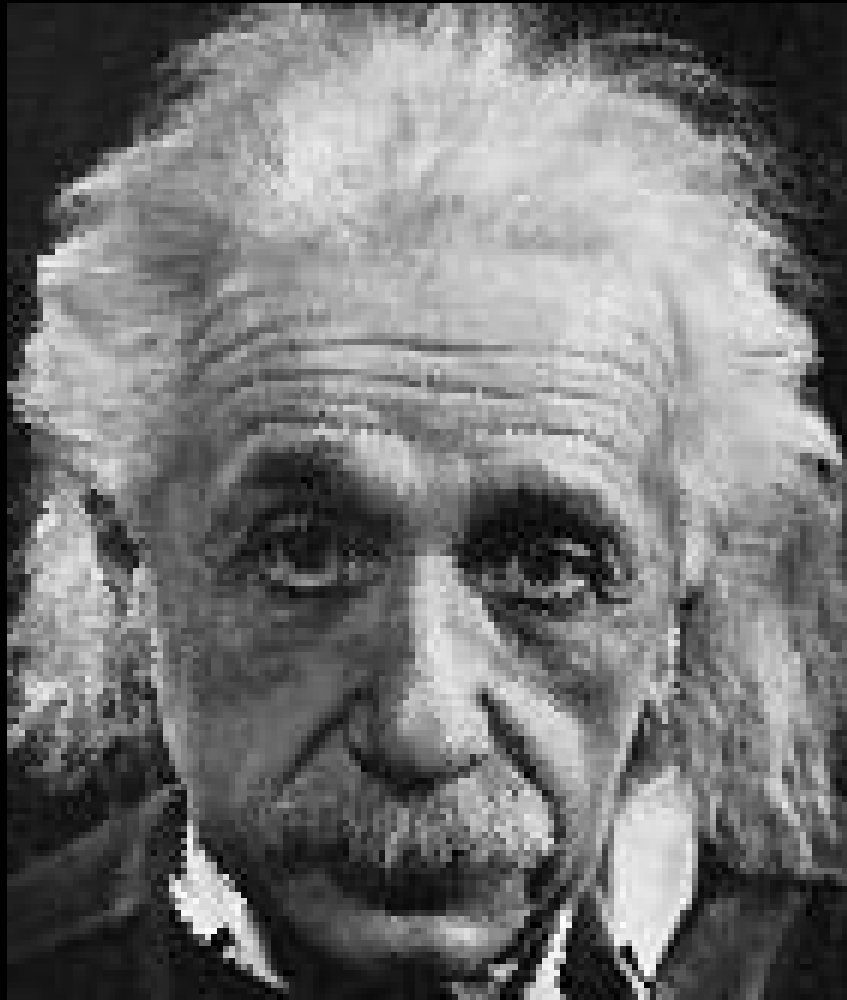
Animace viz <http://www.astrouw.edu.pl/~ogle/ogle3/blg235-53.html>



Animace viz <http://www.astrouw.edu.pl/~ogle/ogle3/blg235-53.html>

Užití gravitačních čoček ?

- *mapování rozložení hmoty ve Vesmíru*
- *pozorování nejvzdálenějších objektů*
- *měření vzdáleností*
- *hledání planet*
- *další (měření hmotností hvězd, studium povrchů hvězd, atd.)*
- *experimentální ověření OTR*



Animace viz <http://people.bu.edu/brainerd/lensconf/einanim.html>