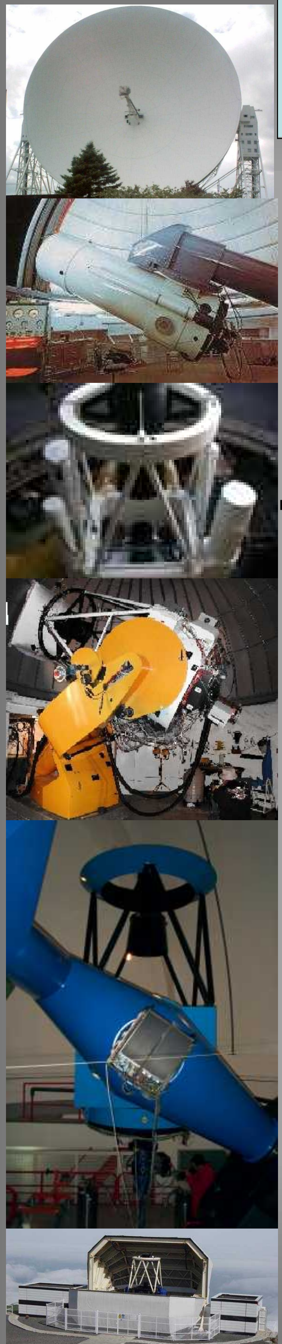
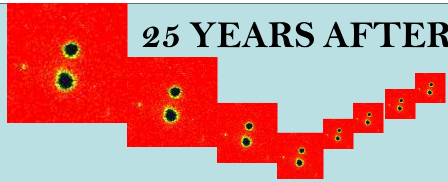




25 YEARS AFTER THE DISCOVERY: SOME CURRENT TOPICS ON LENSED QSOs

Santander (Spain), 15th-17th December 2004

Transverse velocities of QSOs from microlensing parallax

Tyoma Tuntsov, Mark Walker and Geraint Lewis

Sydney Uni

Outline of the talk

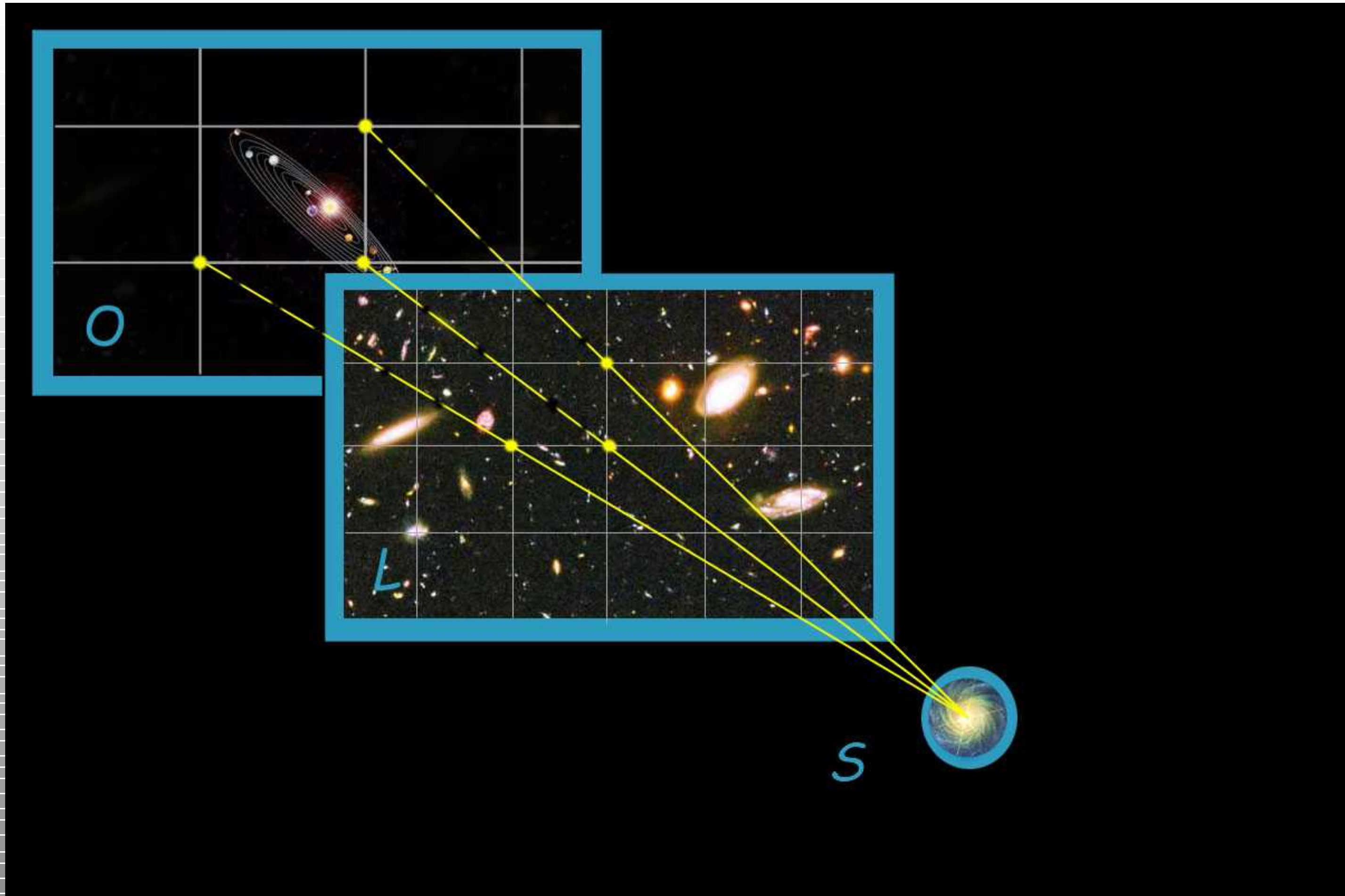
- What is the annual parallax effect?
- How can it be used to determine the transverse velocity in the system?
- Where can we find the effect?
- (Bad) Illustration – QSO2237+0305
- Conclusions and Outlook

Outline of the talk

- **What is the annual parallax effect?**
  - Natural formalism for microlensing
  - What is the annual parallax effect?
  - What is it telling us?
- How can it be used to determine the transverse velocity in the system?
- Where can we find the effect?
- (Bad) Illustration – QSO2237+0305
- Conclusions and Outlook

Natural formalism for microlensing

(Gould, 2000, ApJ, 542, 785)



- All quantities projected onto observer plane
- Coordinate frame is fixed by source and lens
- Many things (those related to observer motion) look simpler!

What is the annual parallax effect?

$$F = F_0(t-\tau)\times\mu(\mathbf{r},t)$$

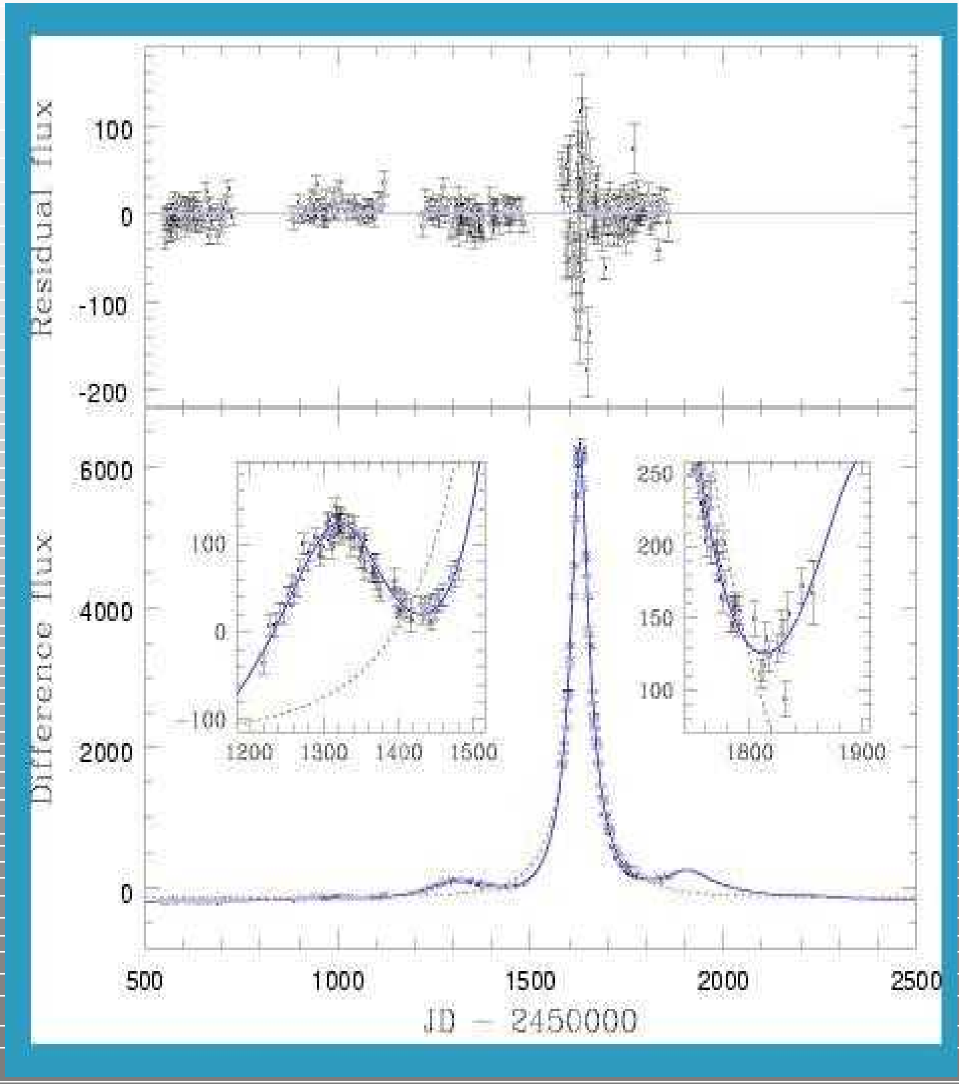
$$F_0 = const$$

$$\Rightarrow$$

$$m = m_0 + 2.5\lg\mu(\mathbf{r},t)$$

$$\mathbf{r}(t) = \mathbf{v}\cdot t + \mathbf{r}_e(t)$$

What is it telling us?



OGLE-1999-Bulge-19
(Smith et al., 2002, MNRAS, 336, 670)

Galaxy: Optical depth τ is low

$\Longrightarrow$ Schwarzschild lens model for $\mu(\mathbf{r},t)$

$$\mu = \mu(\mathbf{r}) = \frac{y^2+2}{y\sqrt{y^2+4}}$$

$$y = \frac{|\mathbf{r}(t)-\mathbf{r}_0|}{r_E}$$

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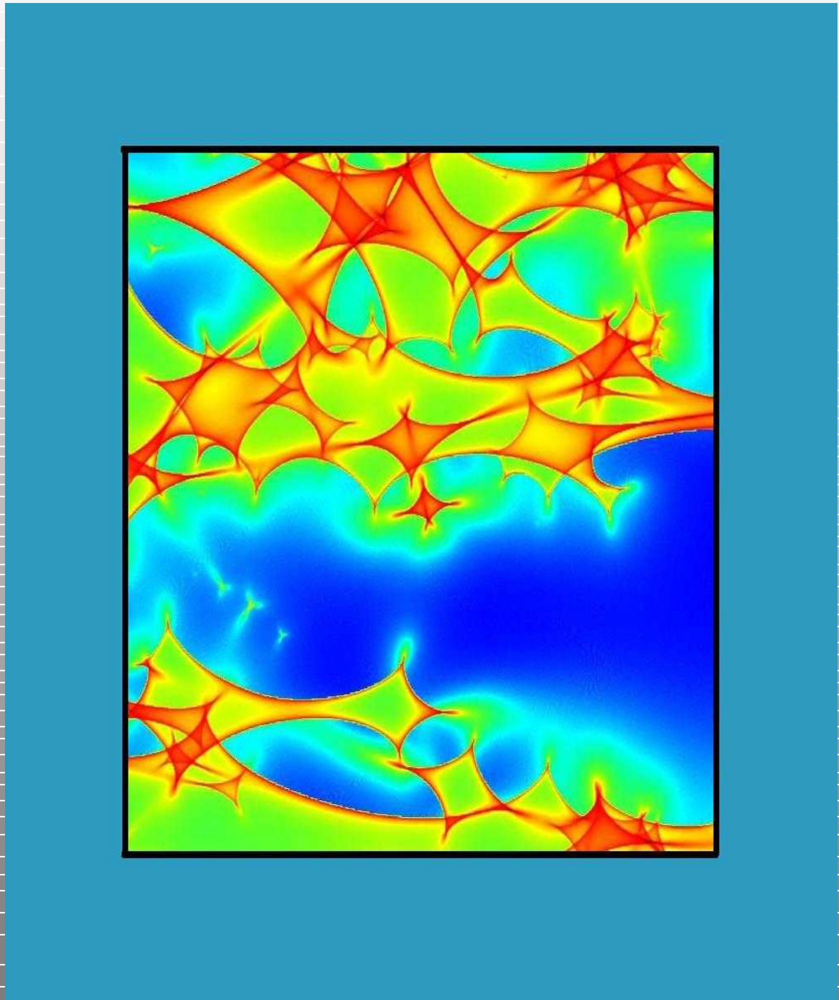

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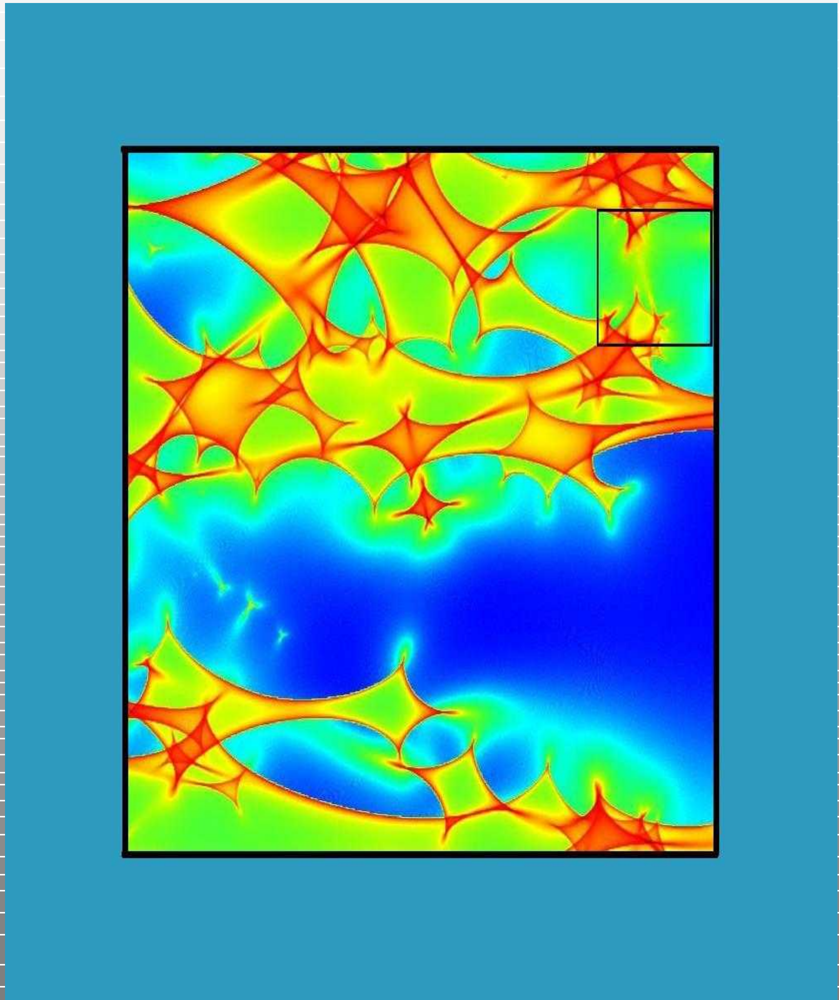
- Microlensed QSOs: $\tau \sim 1$

  $\mu(\mathbf{r},t)$ can be anything

What is it telling us?



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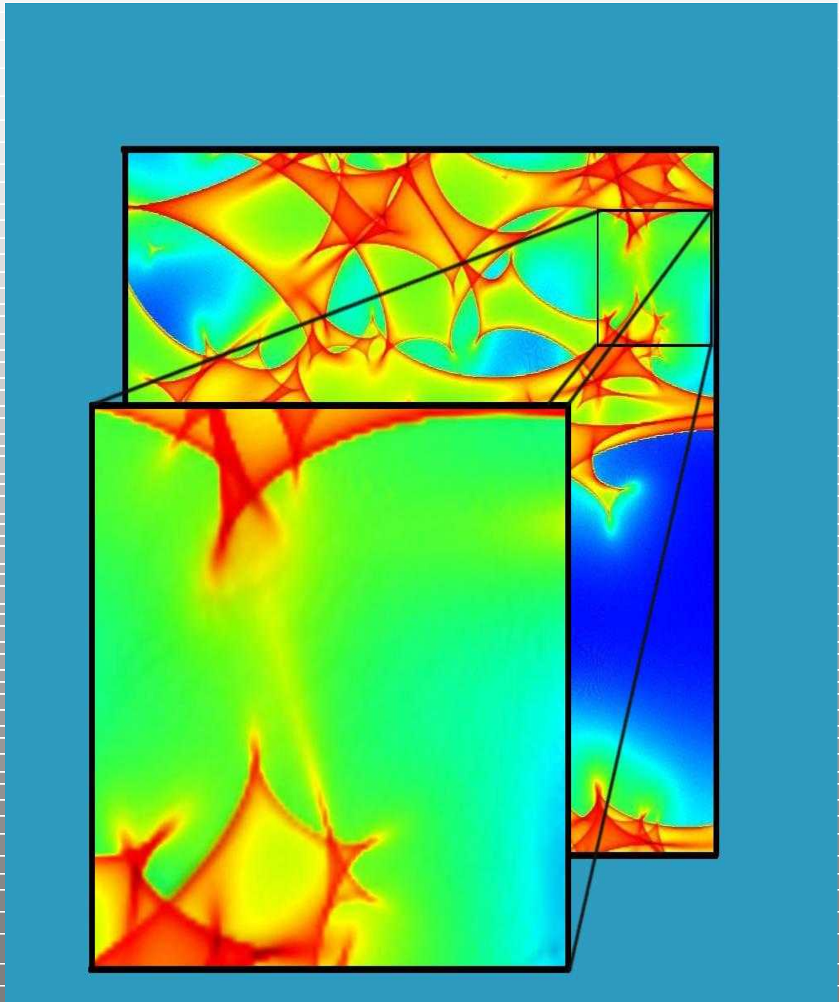

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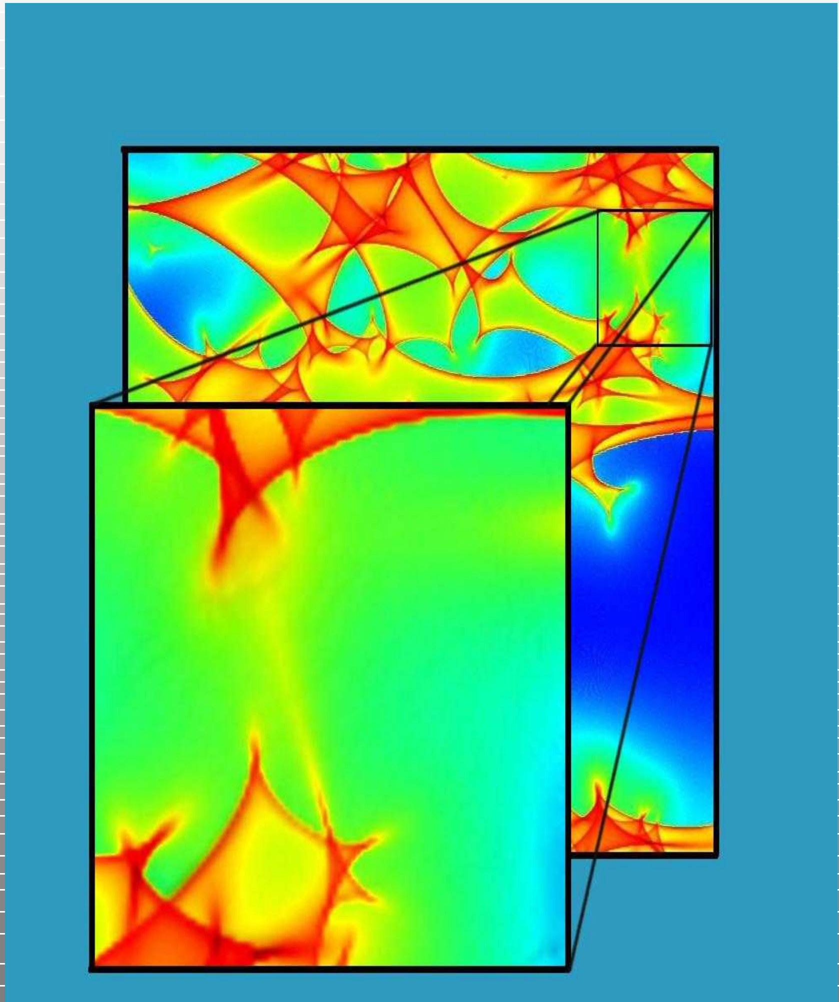

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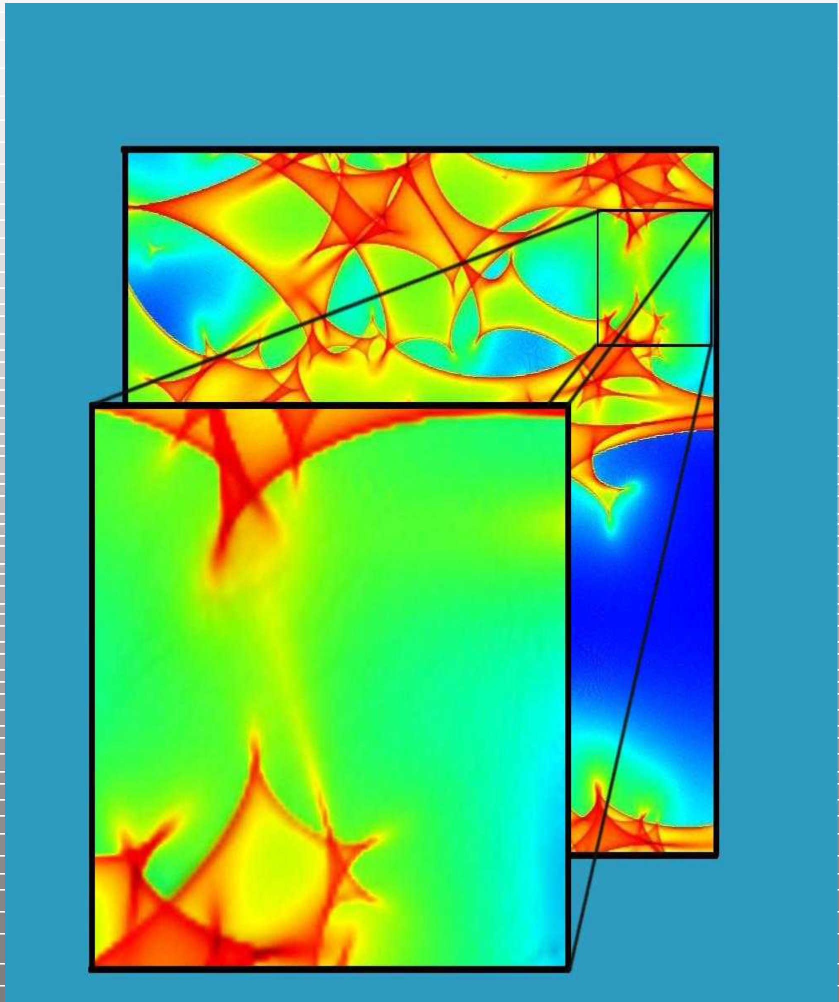
- Microlensed QSOs: $\tau \sim 1$

  $\mu(\mathbf{r},t)$ can be anything

  $\Longrightarrow$ Use Taylor expansion:

$$\mu(t) = \mu_0 + \frac{\partial\mu}{\partial t}(t-t_0) + (\mathbf{r}(t)-\mathbf{r}_0)\cdot\nabla\mu + \Re$$

What is it telling us?



$$m(t) = m_0 + \frac{\partial m}{\partial t}(t - t_0) + (\mathbf{r}(t) - \mathbf{r}_0)\cdot \nabla m + \Re$$

$$\mathbf{r}(t) - \mathbf{r}_0 = \mathbf{v}t + \mathbf{r}_e(t) \quad \mathbf{r}_e = (x, y)$$

$$m_i - m_0 = T(t_i - t_0)$$
$$+ X(x_i - x_0) + Y(y_i - y_0)$$

$$\nabla m = (X, Y)$$

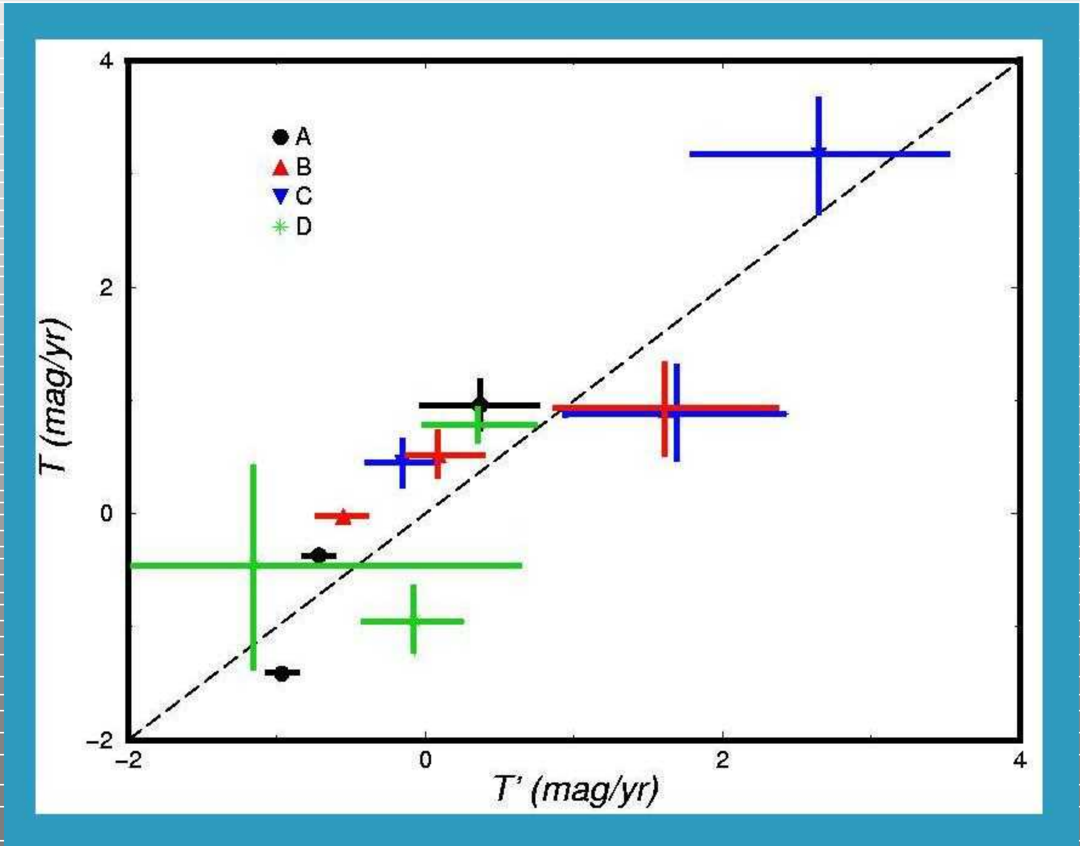
$$T = \frac{\partial m}{\partial t} + \mathbf{v}\cdot\nabla m$$

Outline of the talk

- What is the annual parallax effect?
- **How can it be used to determine the transverse velocity in the system?**
  - Correlation between (T, X, Y) coefficients in different images
  - Individual velocities and magnification matrices
- Where can we find the effect?
- (Bad) Illustration – QSO2237+0305
- Conclusions and Outlook

Correlations between (T, X, Y) coefficients in different images

$$m(t) = m_0 + \frac{\partial m}{\partial t}(t - t_0) + (\mathbf{r}(t) - \mathbf{r}_0) \cdot \nabla m + \Re$$



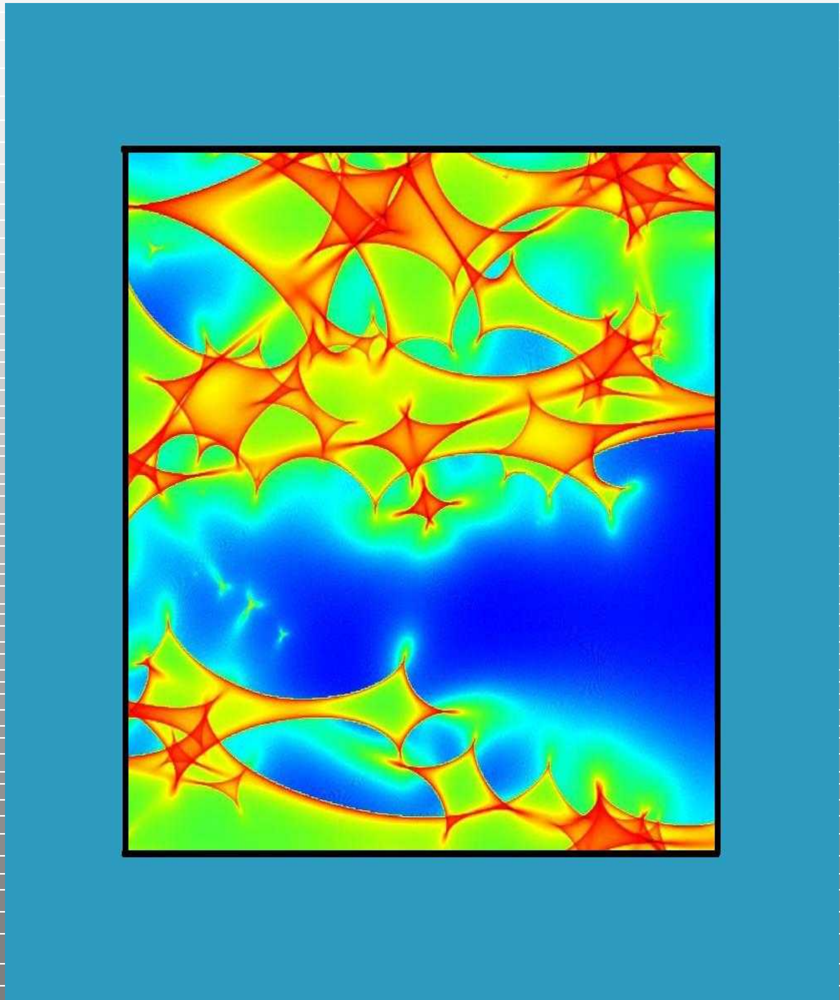
$$T = \frac{\partial m}{\partial t} + \mathbf{v} \cdot \nabla m$$

$$T'_j \approx \mathbf{v} \cdot \nabla m_j$$

$$T'_j \approx \mathrm{v}_\mathrm{x} X_j + \mathrm{v}_\mathrm{y} Y_j$$

Thus, at least three images required

Individual velocities and magnification matrices



$$\mathbf{v}_j = \mathbf{v}_0 + \hat{\mathbf{A}}_j \mathbf{u}_j$$

- Assume $|\hat{\mathbf{A}}_j \mathbf{u}_j| << \mathbf{v}_0$

$$(\mu_j = |\hat{\mathbf{A}}_j|^{-1})$$

OR

- Use independent regions of O-plane plus additional info

Outline of the talk

- What is the annual parallax effect?
- How can it be used to determine the transverse velocity in the system?
- **Where can we find the effect?**
  - Order-of-magnitude argument
  - QSO wish list
- (Bad) Illustration – QSO2237+0305
- Conclusions and Outlook

Order-of-magnitude argument

- How good is linear approximation?

$$m = m_0 + (\mathbf{v}t + \mathbf{r}_e) \cdot \nabla m + \Re + \Delta m \qquad \Re = (\mathbf{v}t + \mathbf{r}_e)^2 D_2$$

- Rescaling to Einstein units:

$$m - m_0 = \frac{\mathbf{v}t + \mathbf{r}_e}{r_E} \cdot \left[r_E \nabla m \right] + \left(\frac{\mathbf{v}t + \mathbf{r}_e}{r_E} \right)^2 \left[r_E{}^2 D_2 \right] + \Delta m$$

Order-of-magnitude argument

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- Rescaling to Einstein units:

$$m - m_0 - \frac{\mathbf{v}t}{r_E}\cdot\left[r_E \nabla m\right] = \frac{\mathbf{r}_e}{r_E}\cdot\left[r_E \nabla m\right] + \left(\frac{\mathbf{v}t + \mathbf{r}_e}{r_E}\right)^2\left[r_E^{\,2} D_2\right] + \Delta m$$

Order-of-magnitude argument

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Signal *S*

Order-of-magnitude argument

- How good is linear approximation?

$$m = m_0 + (\mathbf{v}t + \mathbf{r}_e)\cdot\nabla m + \Re + \Delta m \qquad \Re = (\mathbf{v}t + \mathbf{r}_e)^2 D_2$$

- Rescaling to Einstein units:

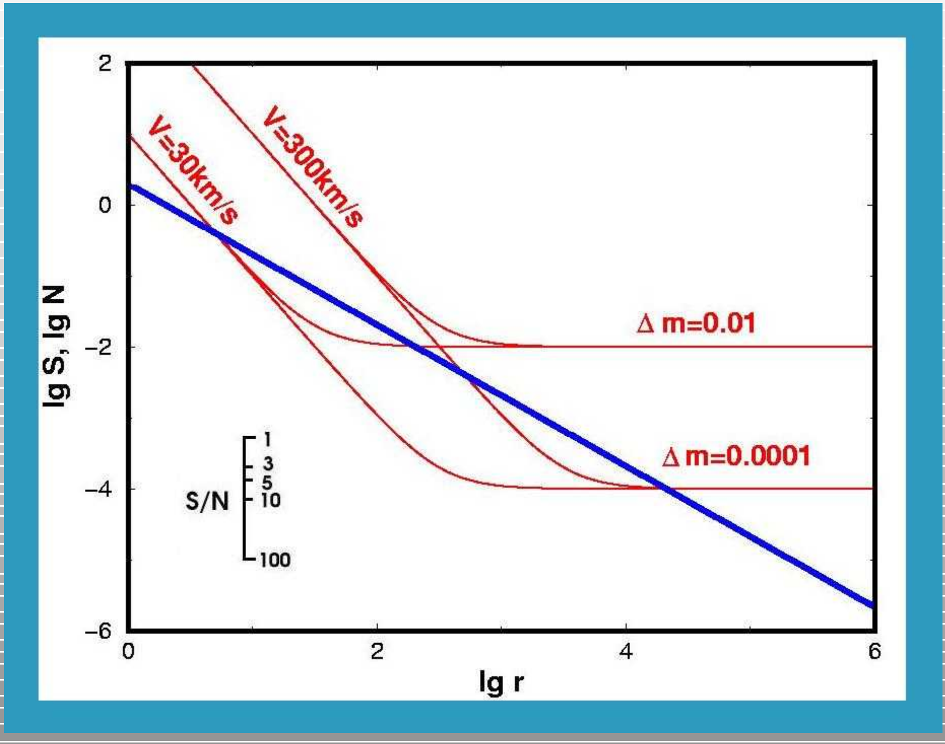
$$m - m_0 - \frac{\mathbf{v}\,t}{r_E}\cdot\left[r_E \nabla m\right] = \frac{\mathbf{r}_e}{r_E}\cdot\left[r_E \nabla m\right]$$

Signal *S*

Noise *N*

$$+\left(\frac{\mathbf{v}\,t + \mathbf{r}_e}{r_E}\right)^2 \left[r_E{}^2 D_2\right] + \Delta m$$

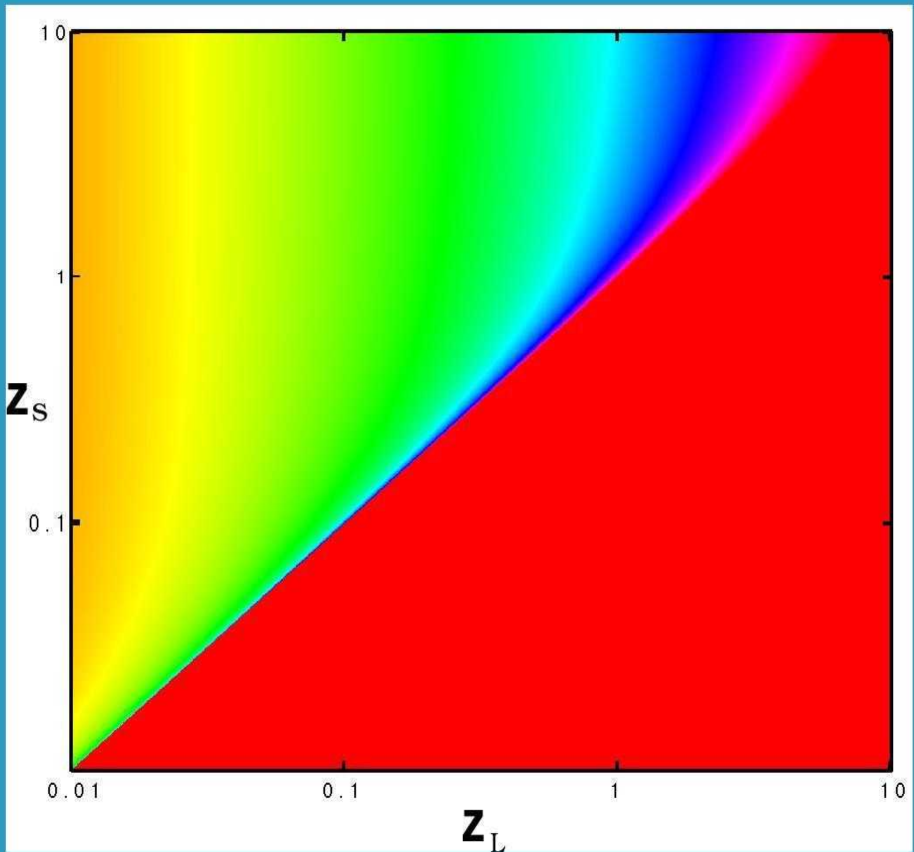
Order-of-magnitude argument



- $\left[r_E \nabla m\right] \sim 1$, $\left\lfloor r_E{}^2 D_2 \right\rfloor \sim 1$
- $S = \dfrac{\mathbf{r}_e(t)}{r_E} \cdot \left[r_E \nabla m\right]$
  - Optimal t ~ 1 year
- $N \approx \left(\dfrac{\mathbf{v}\,t}{r_E}\right)^2 \left[r_E{}^2 D_2\right] + \left|\Delta m\right|$

$$S : N \approx \left(\frac{r_e}{r_E}\right) : \left(\left(\frac{\mathbf{v}\,t}{r_E}\right)^2 \left[r_E{}^2 D_2\right] + \left|\Delta m\right|\right)$$

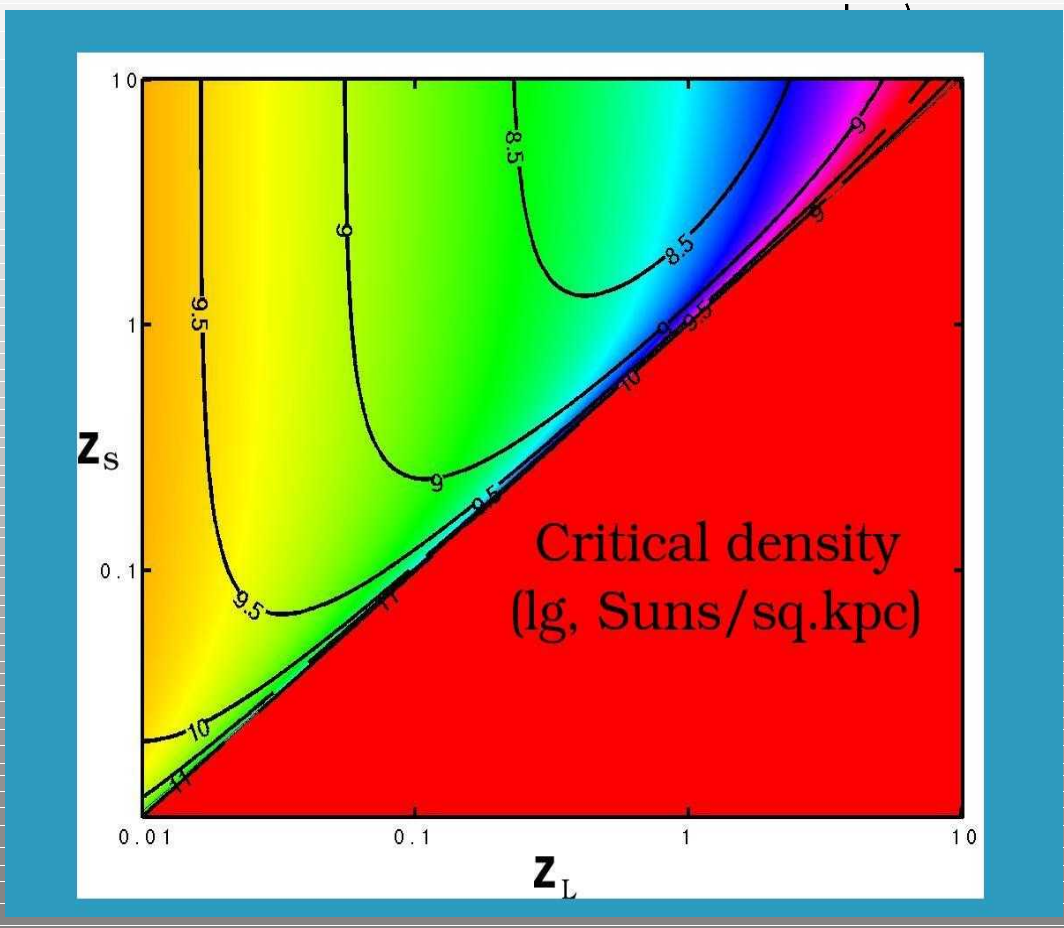
Go Green



$$r_E = (1 + z_L)\sqrt{\frac{4GM}{c^2}\frac{D_L D_S}{D_{LS}}}$$

Go Green

(if it



$$r_E = (1+z_L)\sqrt{\frac{4GM}{c^2}\frac{D_L D_S}{D_{LS}}}$$

$$\Sigma_{cr} = (1+z_L)\frac{c^2}{4\pi G}\frac{D_S}{D_L D_{LS}}$$

Go Green

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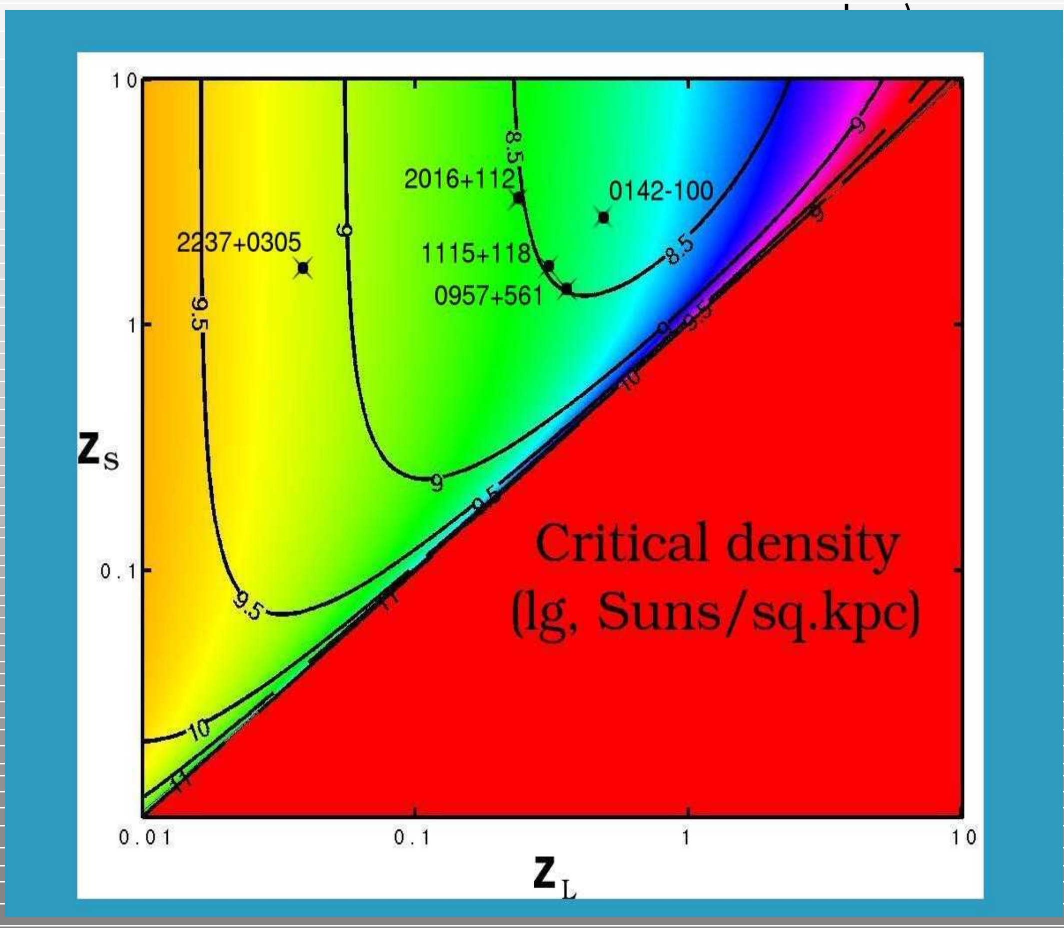

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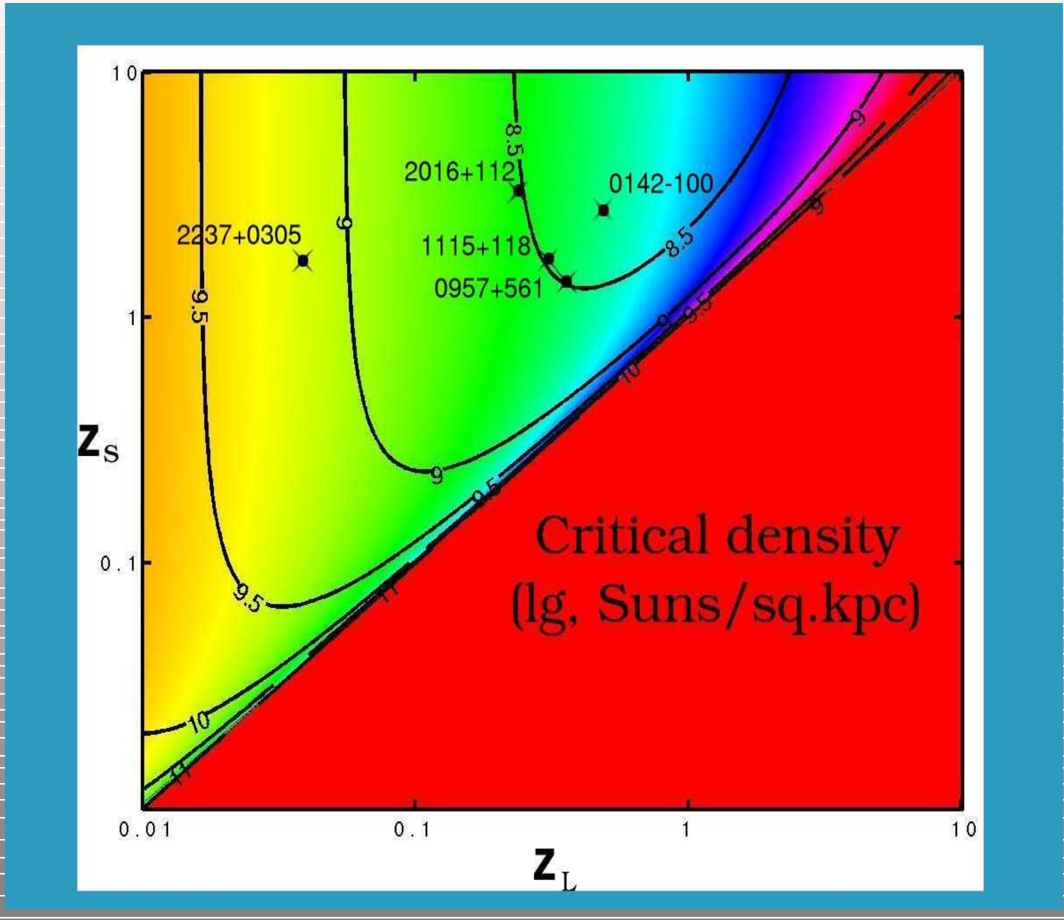
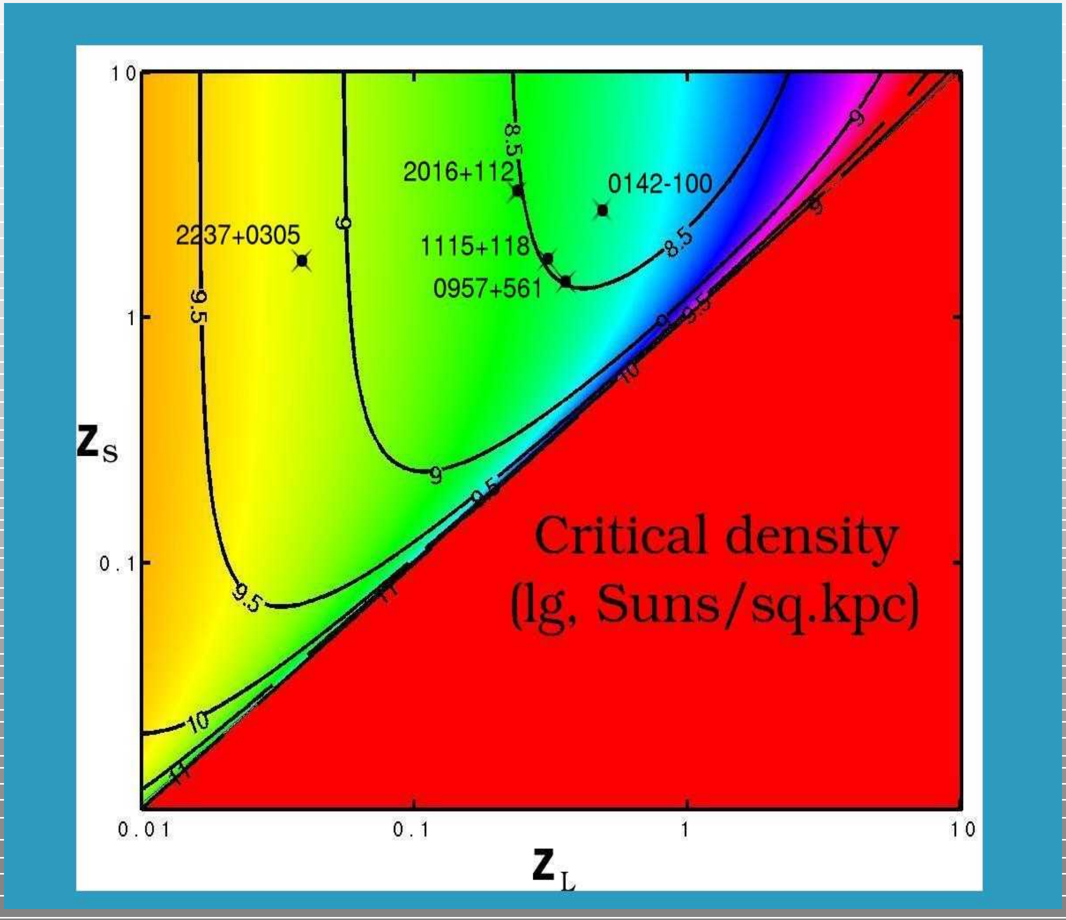
QSO Wish List



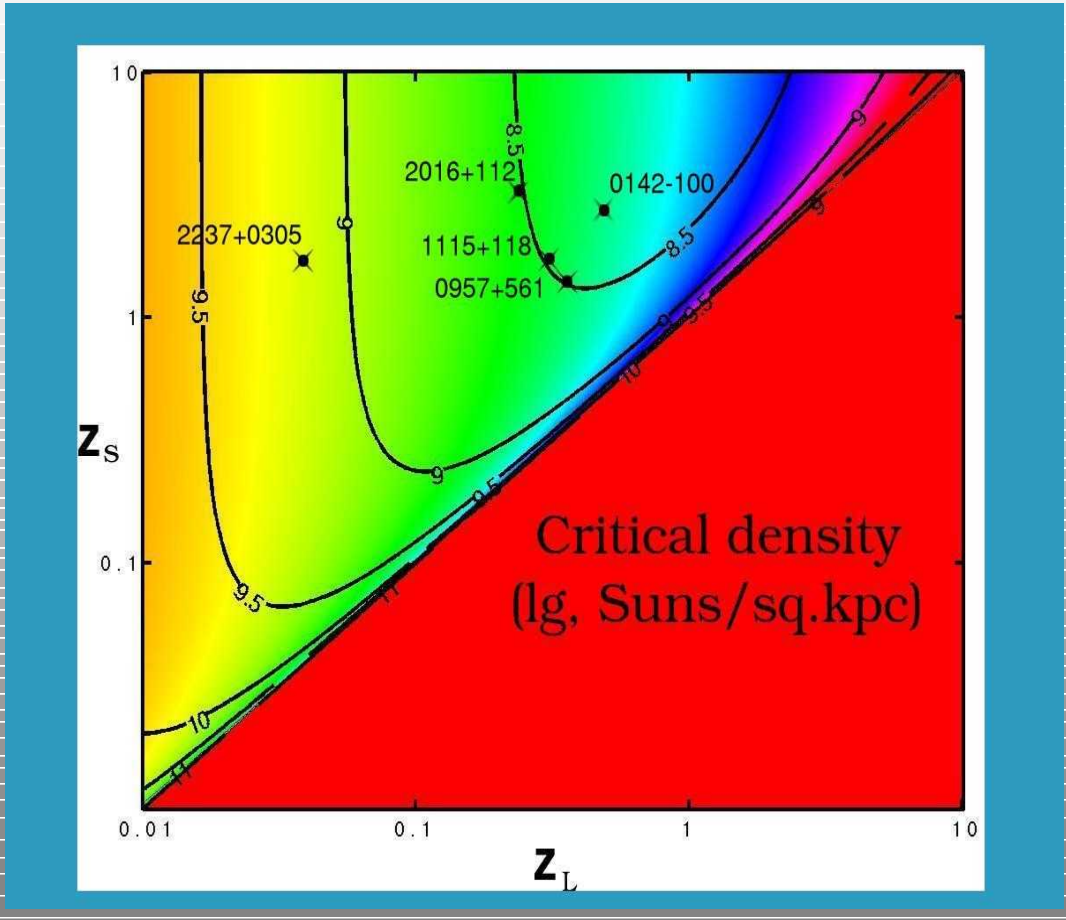
- Redshifts of order unity

QSO Wish List



- Redshifts of order unity
- Highly symmetric configuration
    - Intrinsic variability constraint
    - bulk velocity constraints

QSO Wish List



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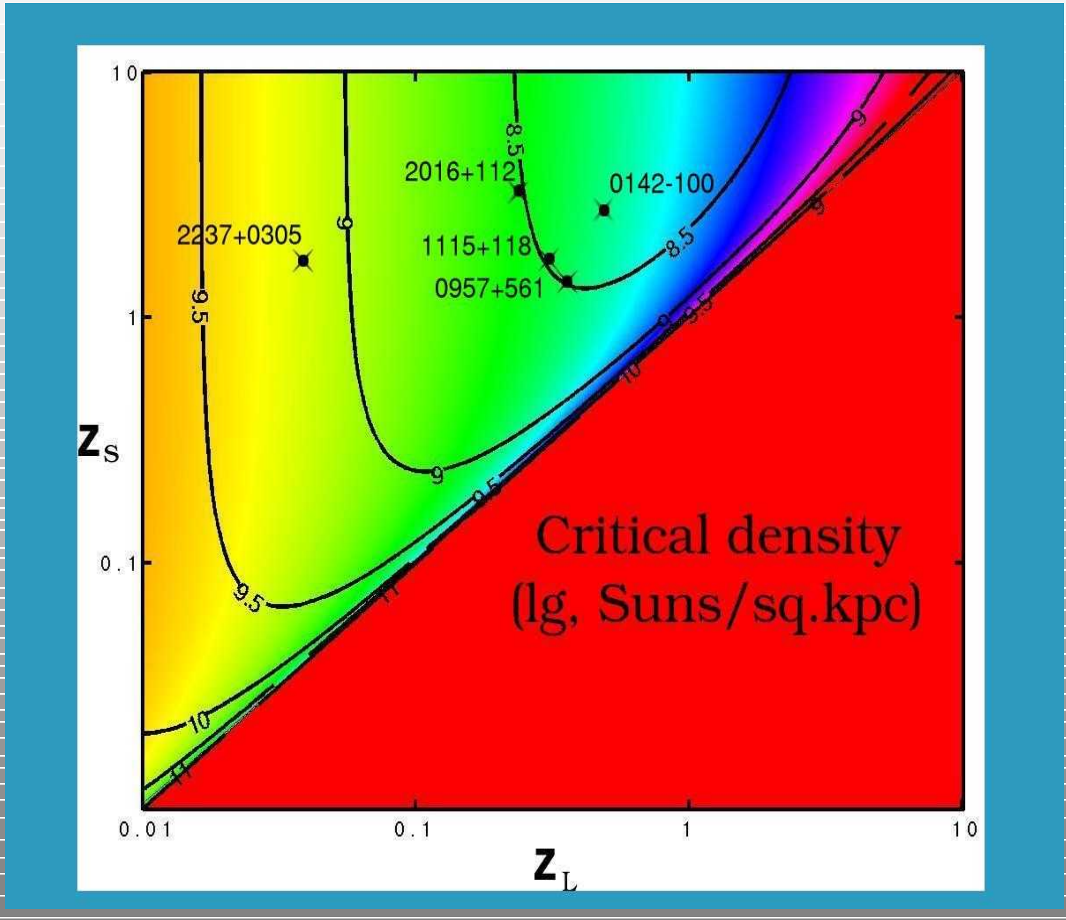
- The lens is NOT:
  - a virialized cluster member
  - massive elliptic galaxy

QSO Wish List



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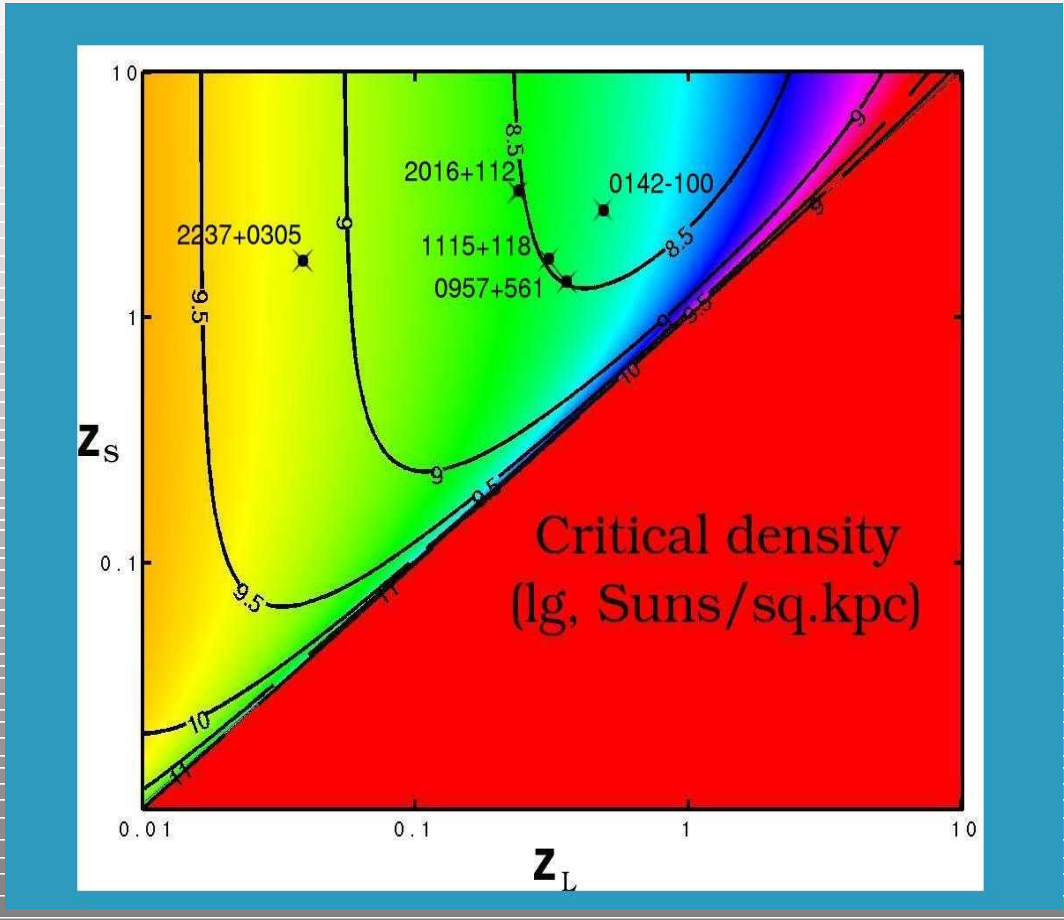
QSO Wish List



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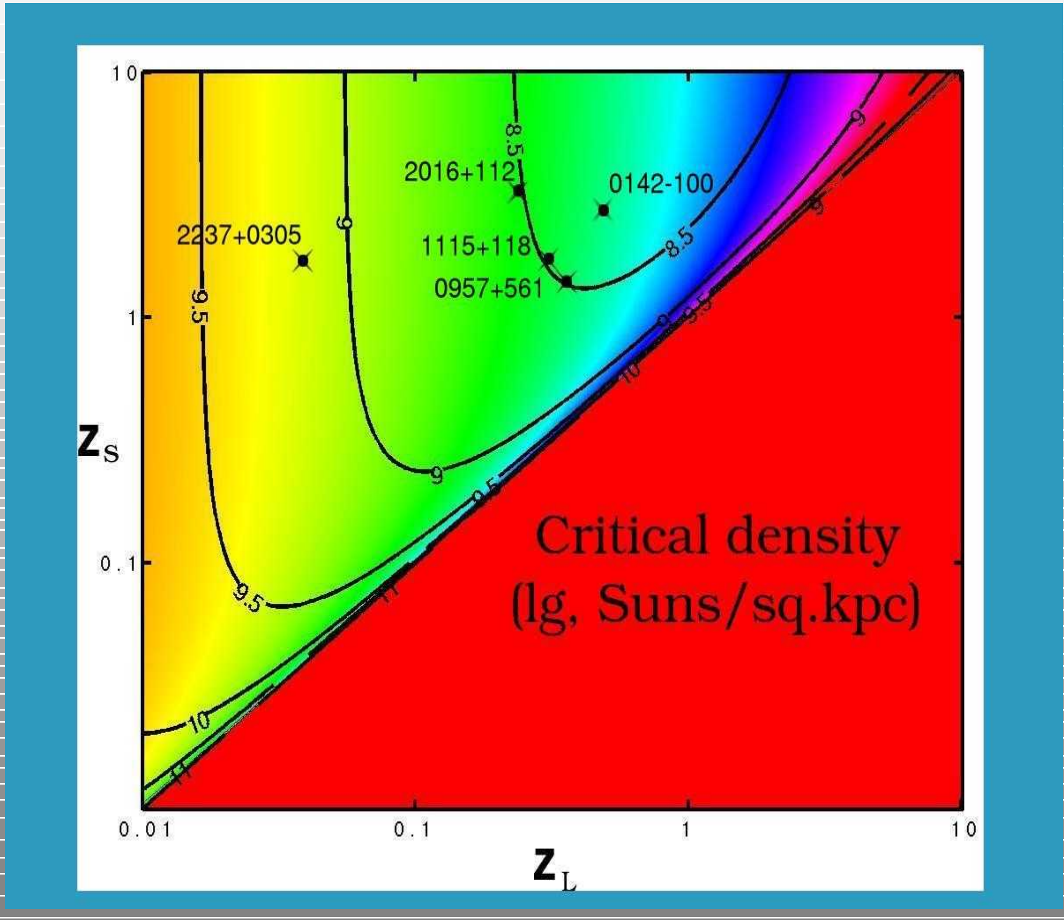
QSO Wish List



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And it should be bright, favourably located on the sky, year-around observable etc..

Outline of the talk

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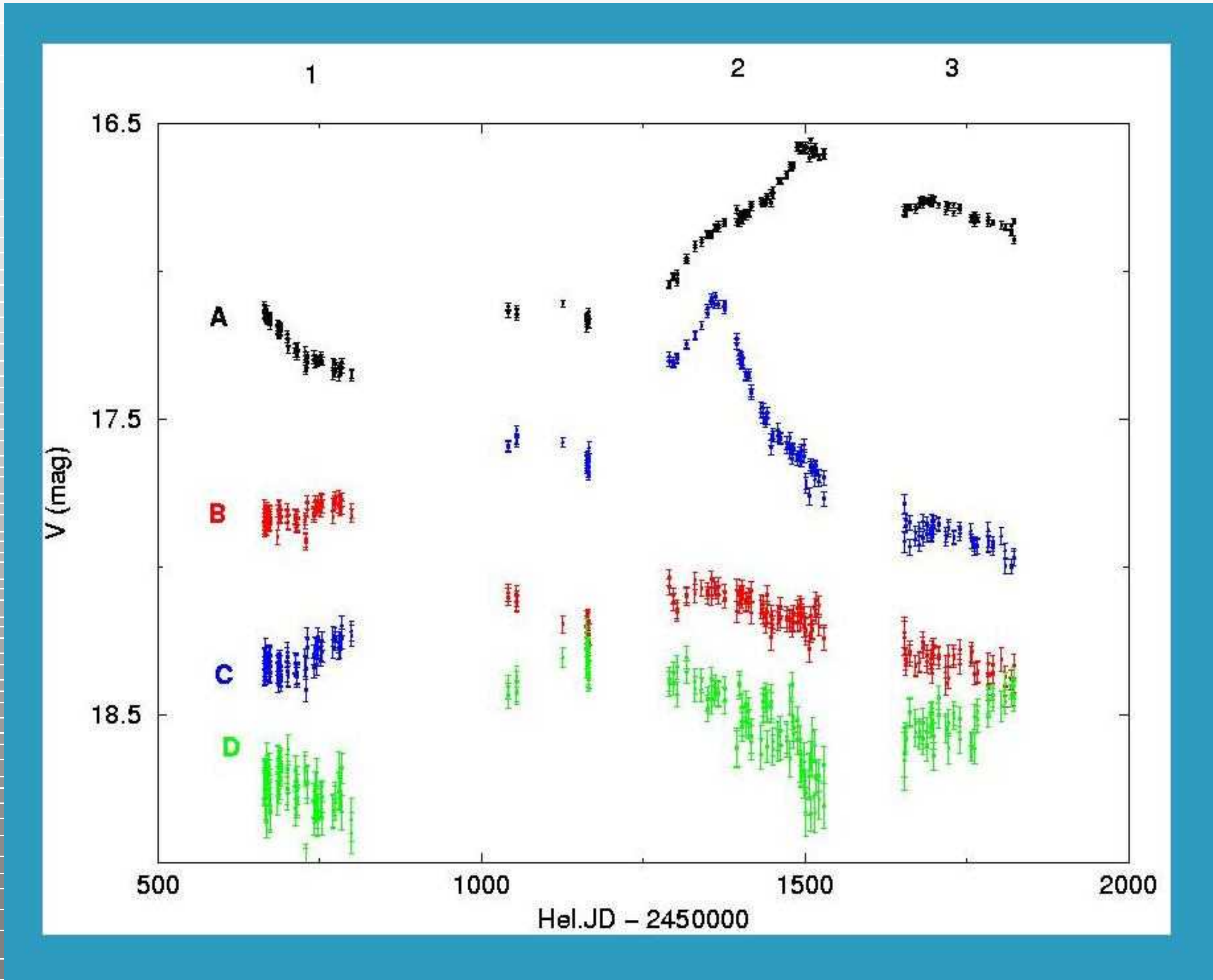
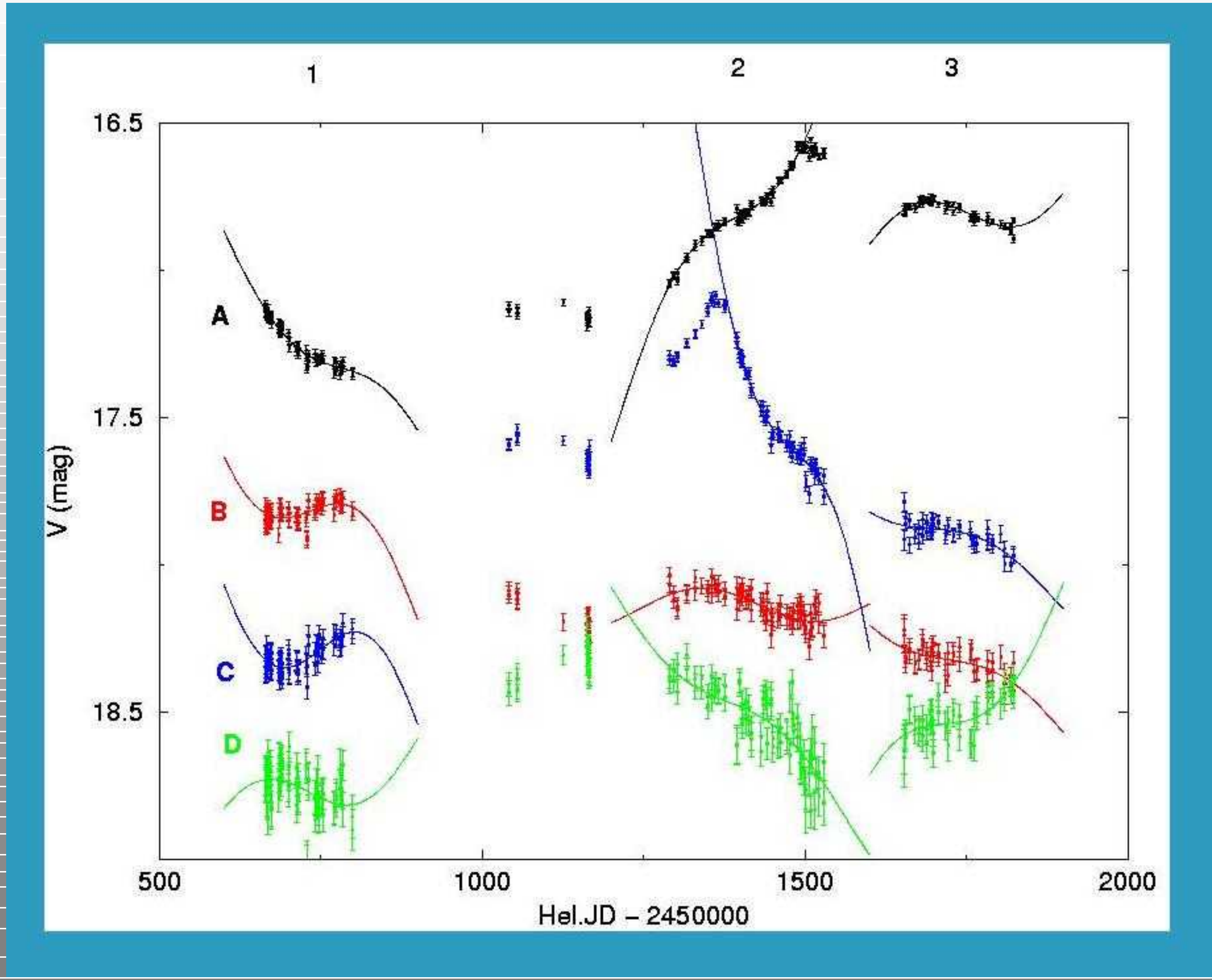
- **(Bad) Illustration – QSO2237+0305**
- Conclusions and Outlook

Application to QSO2237+0305



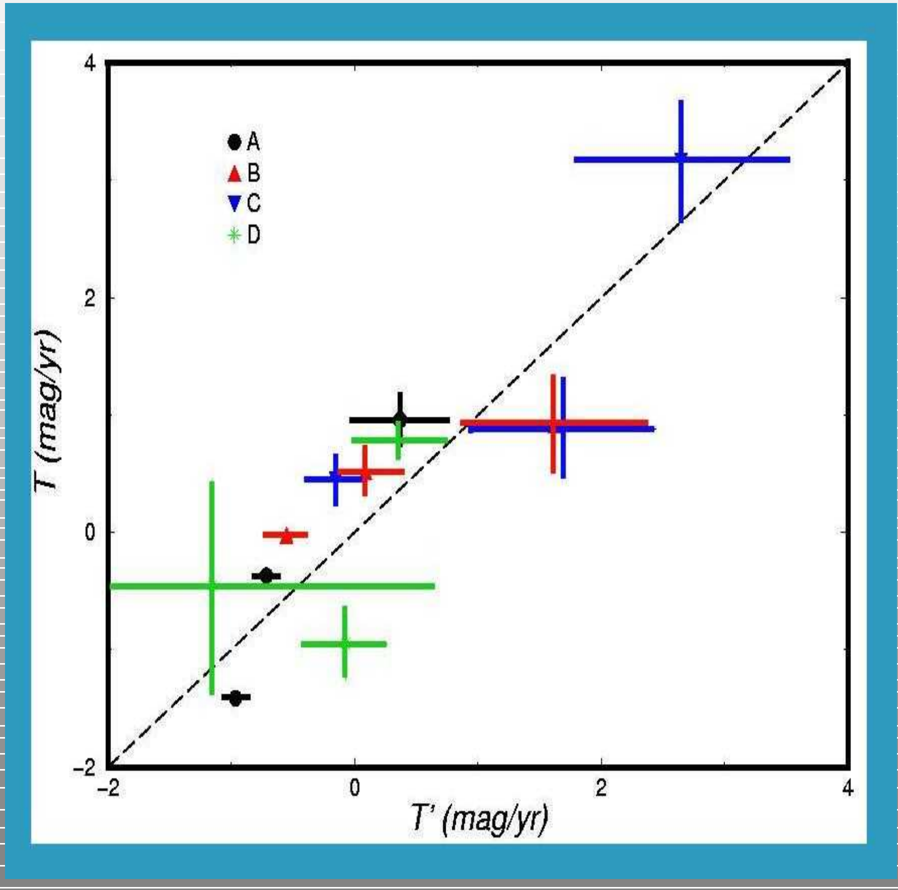
OGLE-II (Wozniak et al., 2000, ApJ, 529, 88)

Application to QSO2237+0305



OGLE-II (Wozniak et al., 2000, ApJ, 529, 88)

Weird velocities



- Effective transverse velocity

$$\mathbf{v}_0 = (-15 \pm 7, -1 \pm 2)\mathrm{km/s}$$

$$\mathbf{v}_A = (5 \pm 20, 2 \pm 4)\mathrm{km/s}$$
$$\mathbf{v}_B = (-24 \pm 20, -4 \pm 6)\mathrm{km/s}$$
$$\mathbf{v}_C = (14 \pm 110, -7 \pm 20)\mathrm{km/s}$$
$$\mathbf{v}_D = (-20 \pm 4, -7 \pm 1)\mathrm{km/s}$$

- Using a different method

$$\mathbf{v}_0 = (-8 \pm 9, -2 \pm 2)\mathrm{km/s}$$

$$\mathbf{u}_A = (42 \pm 20, -4 \pm 5)\mathrm{km/s}$$
$$\mathbf{u}_B = (-49 \pm 17, -12 \pm 7)\mathrm{km/s}$$
$$\mathbf{u}_C = (20 \pm 40, -1 \pm 20)\mathrm{km/s}$$
$$\mathbf{u}_D = (-13 \pm 5, 16 \pm 2)\mathrm{km/s}$$

(Schmidt, Webster & Lewis, 1998, MNRAS, 295, 488)

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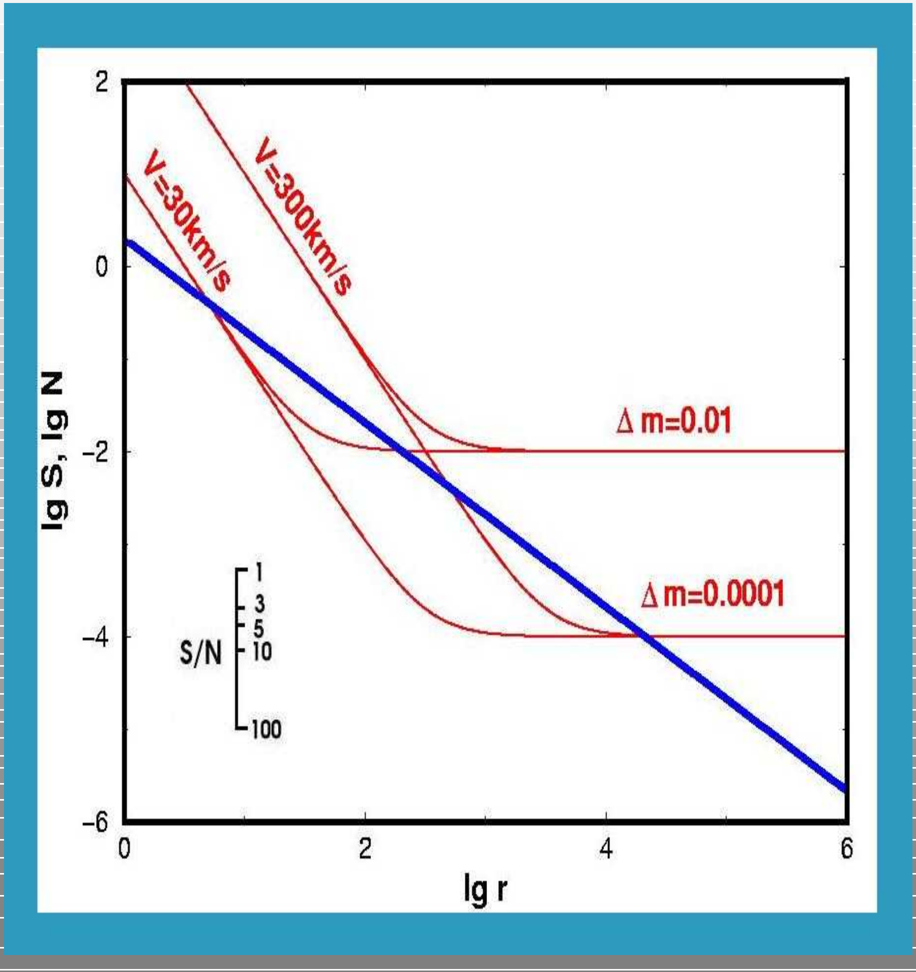
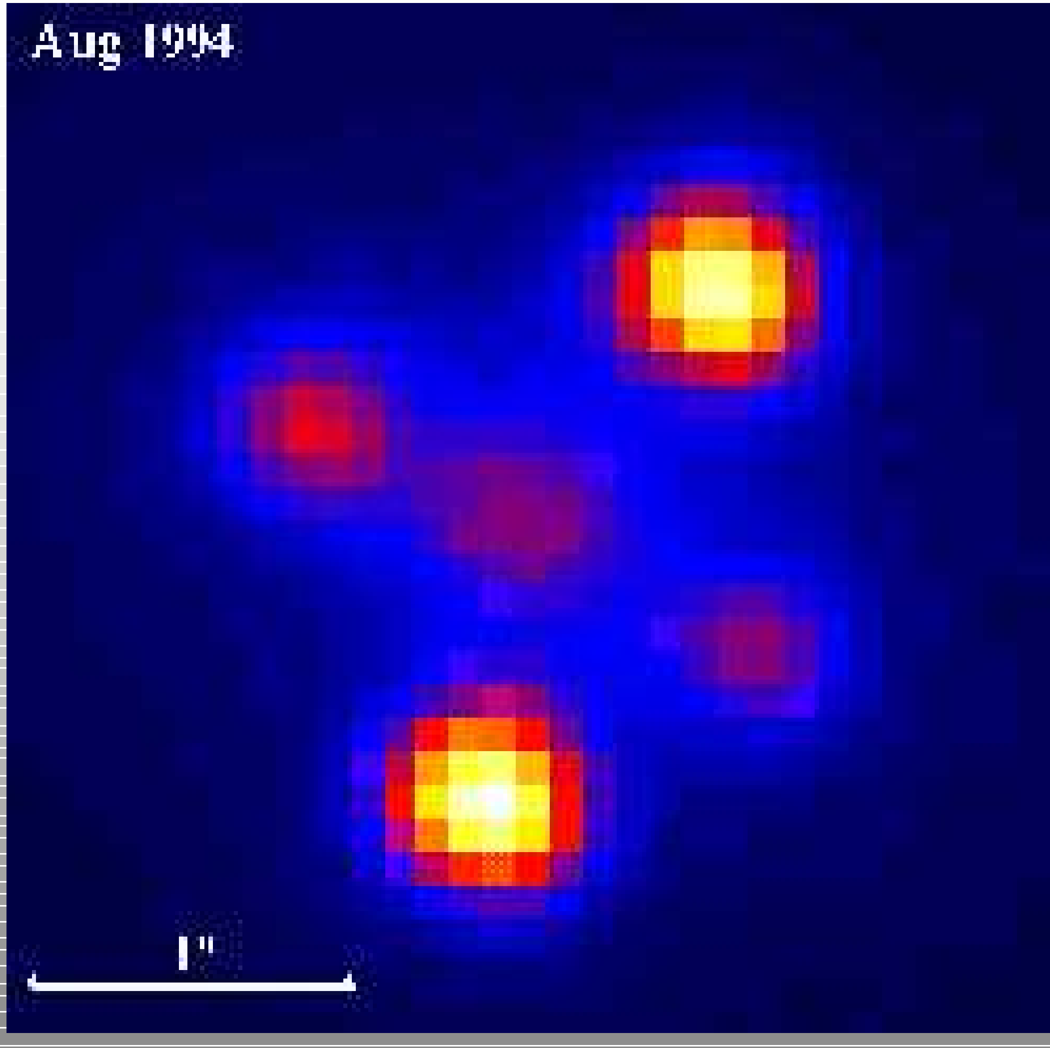
Conclusions and Outlook



- Photometric monitoring of some QSOs can help determine 3D picture of their motion
- Little chance to know *a priori* where the method will work
- Photometric accuracy is most important
- More data are needed
- Try it yourself!



Thank you for your attention!