# X-ray and Optical Flux Ratio Anomalies in Quadruply Lensed Quasars:

## *Zooming in on Quasar Emission Regions*

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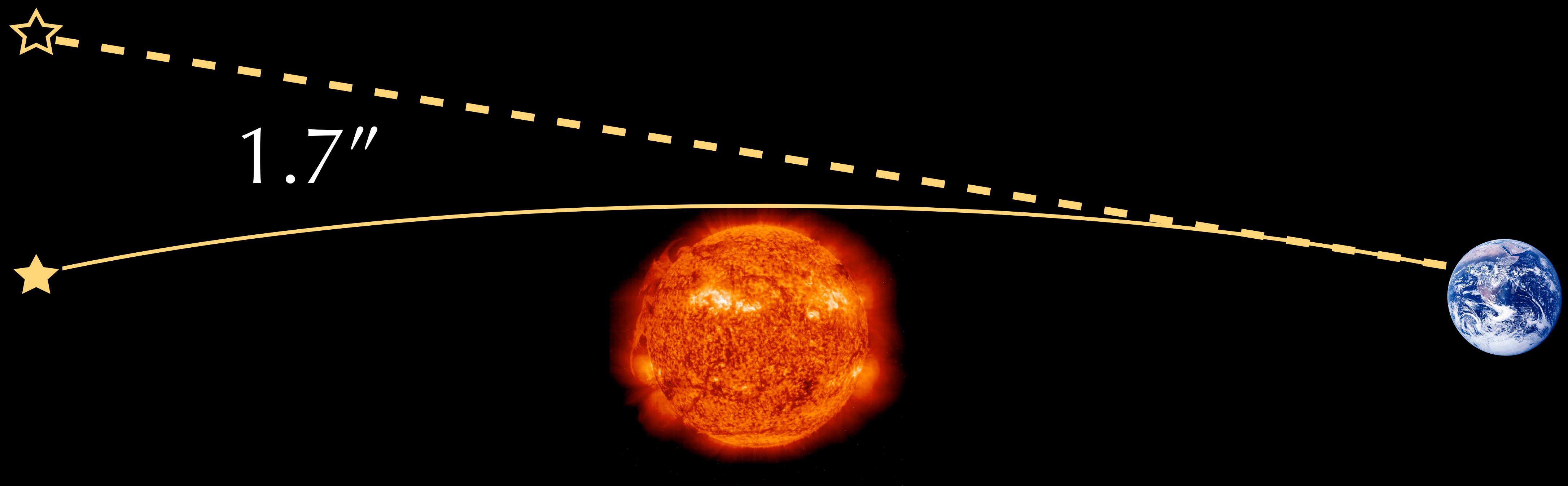
*ApJ*, in press, astro-ph/0607655

UC Santa Cruz 2007 Feb 14

# Quadruply Gravitationally Lensed Quasars



# Quadruply Gravitationally Lensed Quasars

Black hole ~ $10^{8-9}\ M_\odot$

L ~ $10^{45}$ erg $s^{-1}$

Optical

$2\times10^{15}$ cm

≈ 100 $R_g$

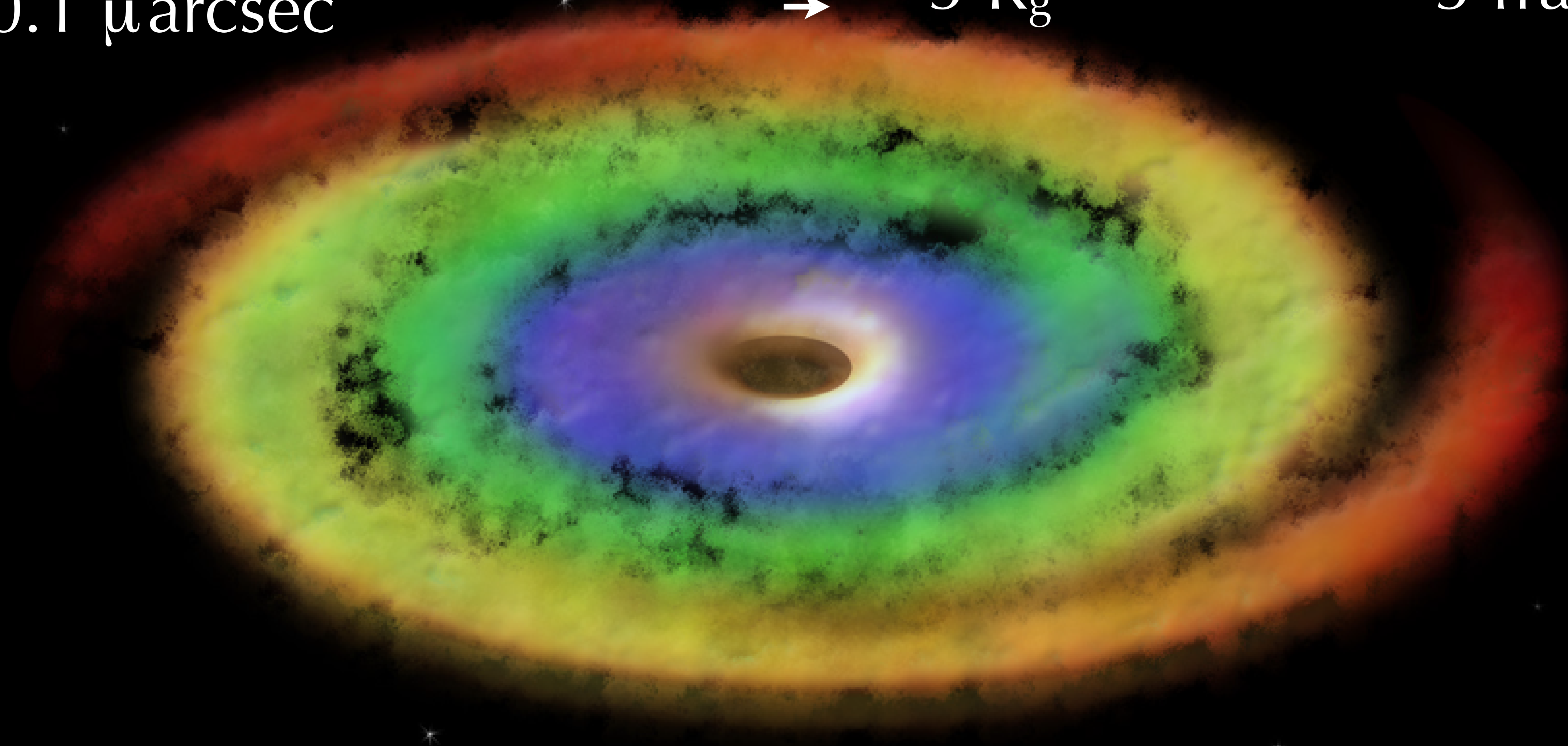
≈ 0.1 μarcsec

$10^{14}$ cm

≈ 5 $R_g$

X-ray

≈ 5 narcsec



$$T(r) = \left[\frac{3GM_{\rm BH}\dot{M}}{8\pi\sigma r^3}\right]^{1/4}\left(1-\sqrt{r_0/r}\right)^{1/4}$$

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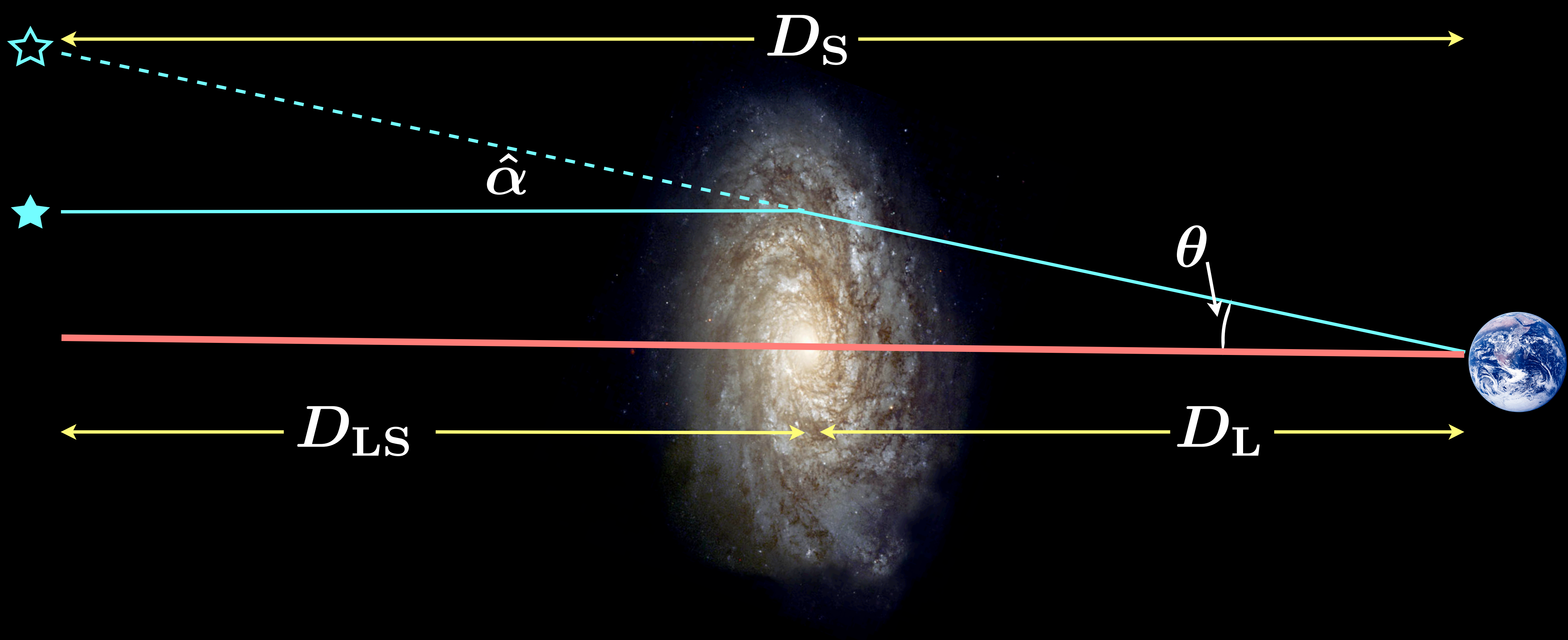
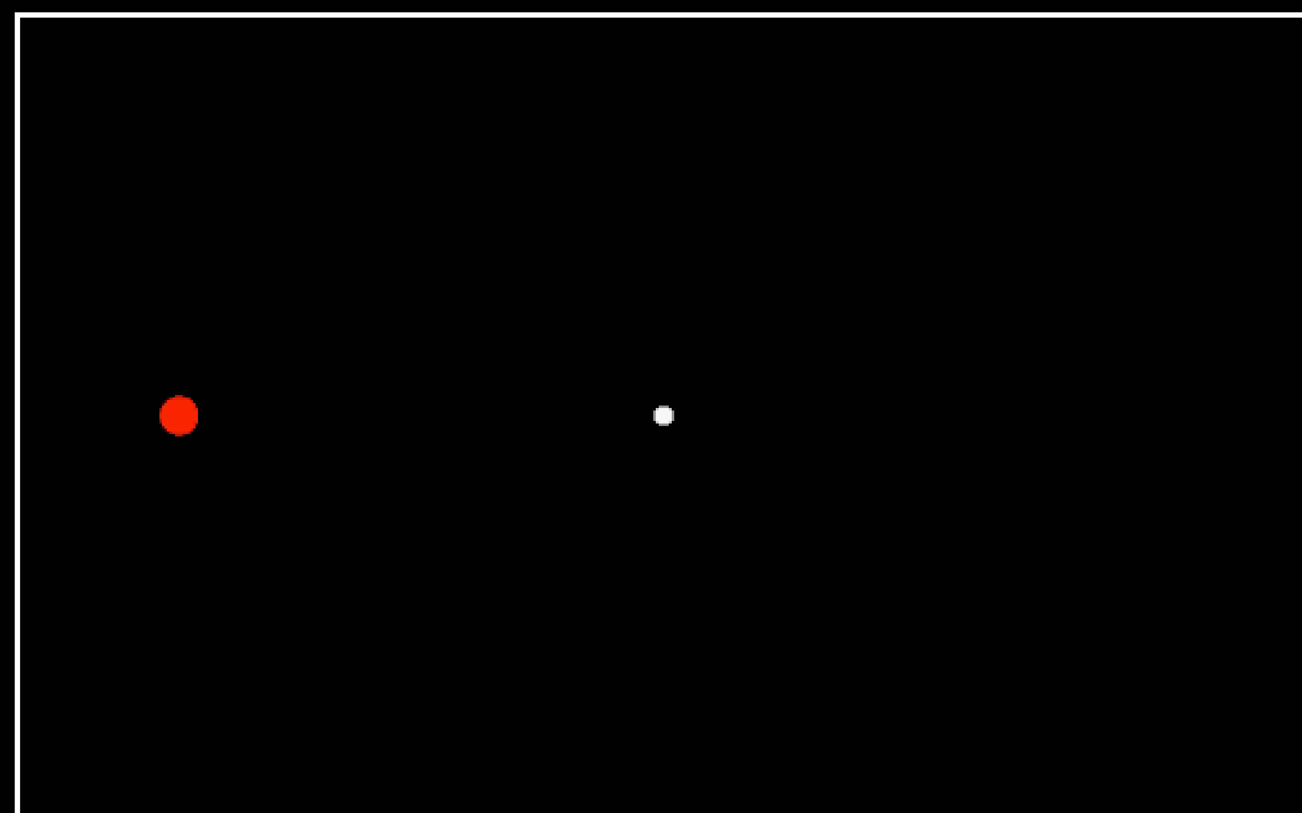



$$\theta_{\mathrm{Ein}} = \sqrt{\frac{4GM(\theta_{\mathrm{Ein}})}{c^2}\frac{D_{\mathrm{LS}}}{D_{\mathrm{L}}D_{\mathrm{S}}}}$$

# Quadruply Gravitationally Lensed Quasars

Singular Isothermal Sphere: $\rho(r) = \frac{\sigma_v^2}{2\pi G}\frac{1}{r^2}$

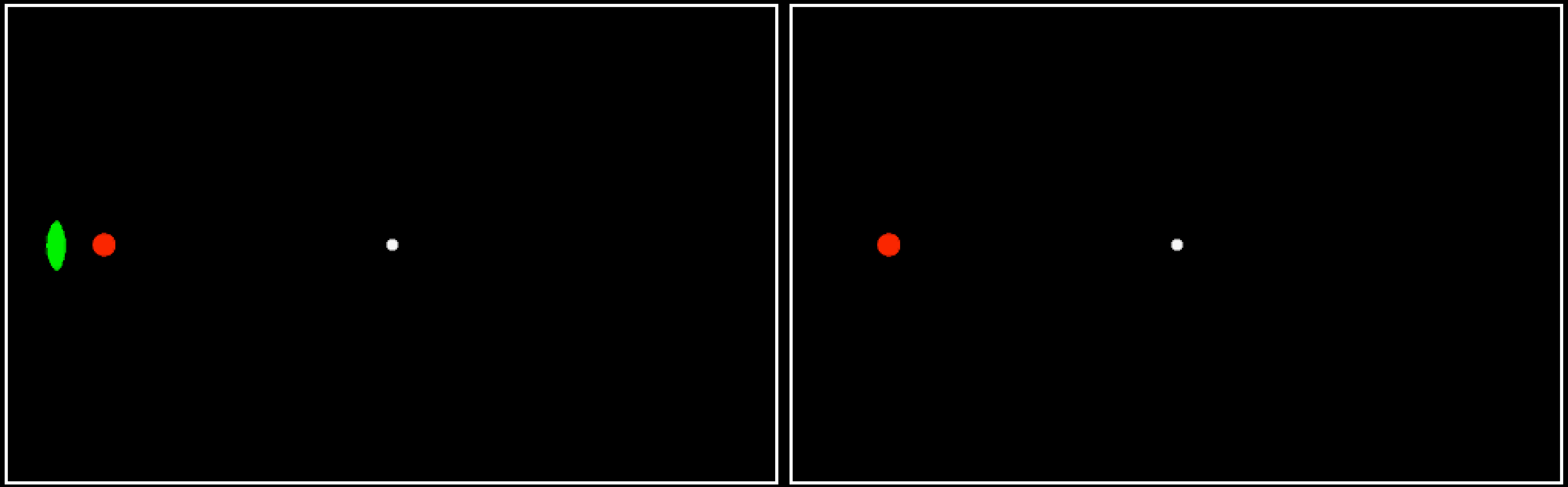


*courtesy Josiah Schwab*

● True source position ● Image position(s)

# Quadruply Gravitationally Lensed Quasars

SIS with Shear (0°) SIS with Shear (45°)



*courtesy Josiah Schwab*

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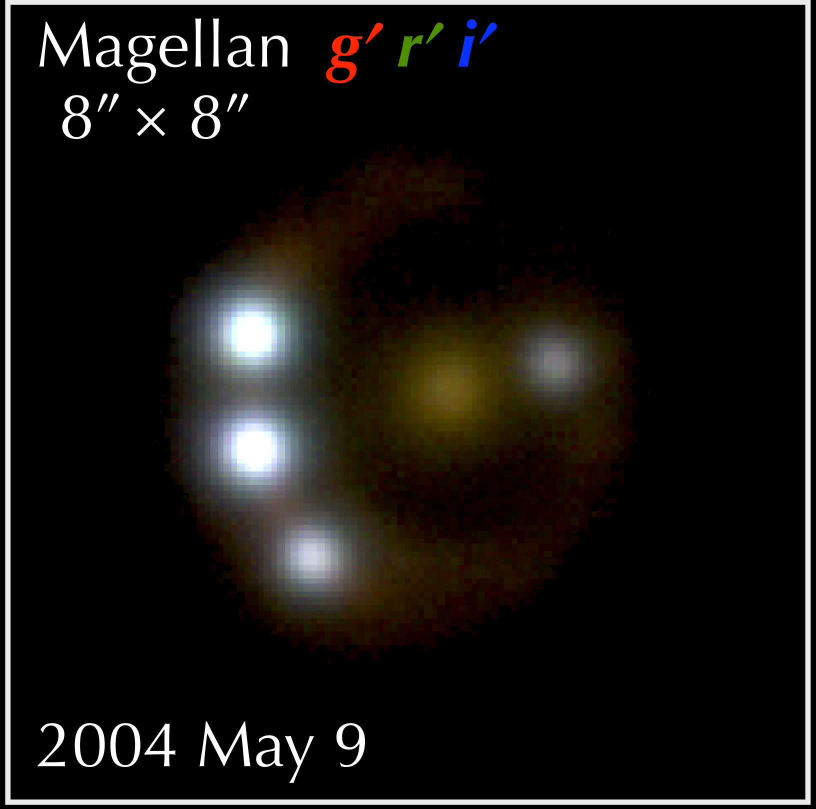
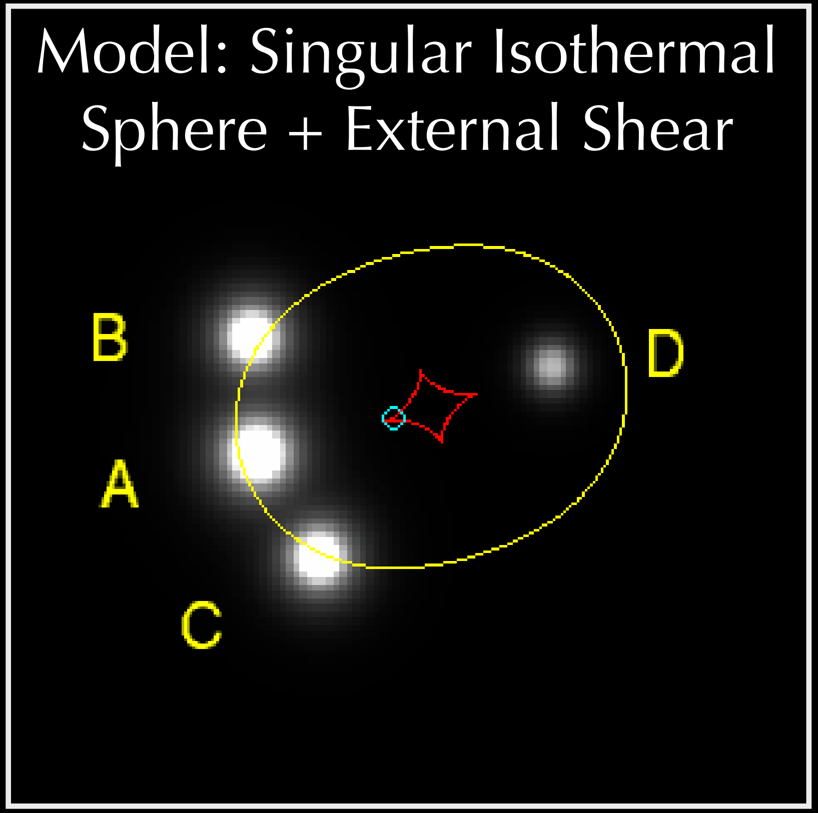
# Flux Ratio Anomalies: What are they?

## RX J1131-1231

*Blackburne, DP, & Rappaport 2006*




$F_A/F_B = 1.10 \pm 0.16$

$F_A/F_B = 1.7$

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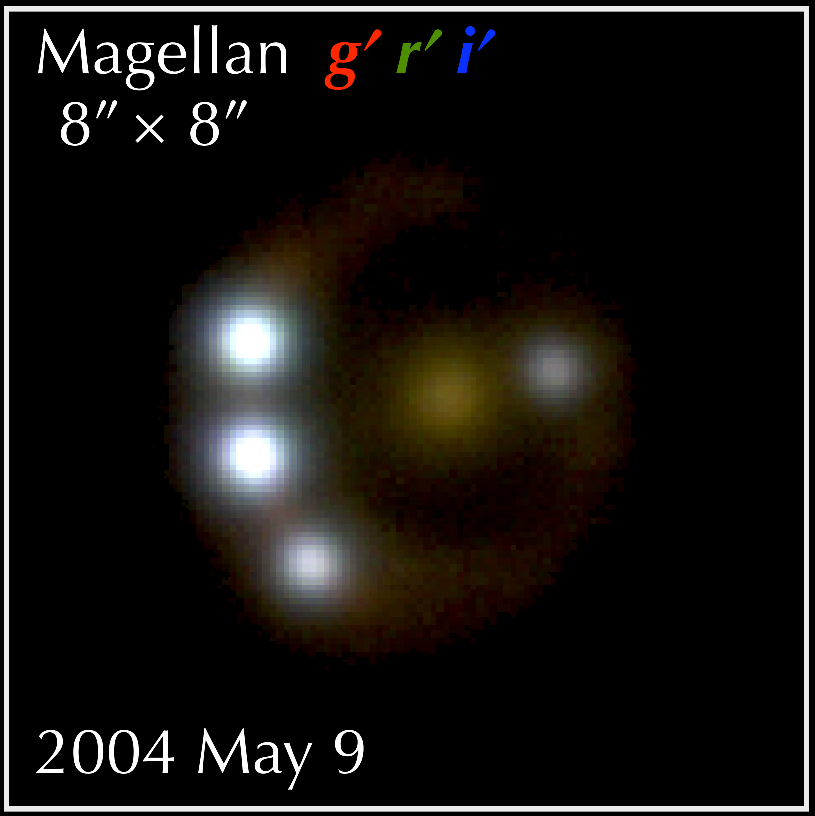


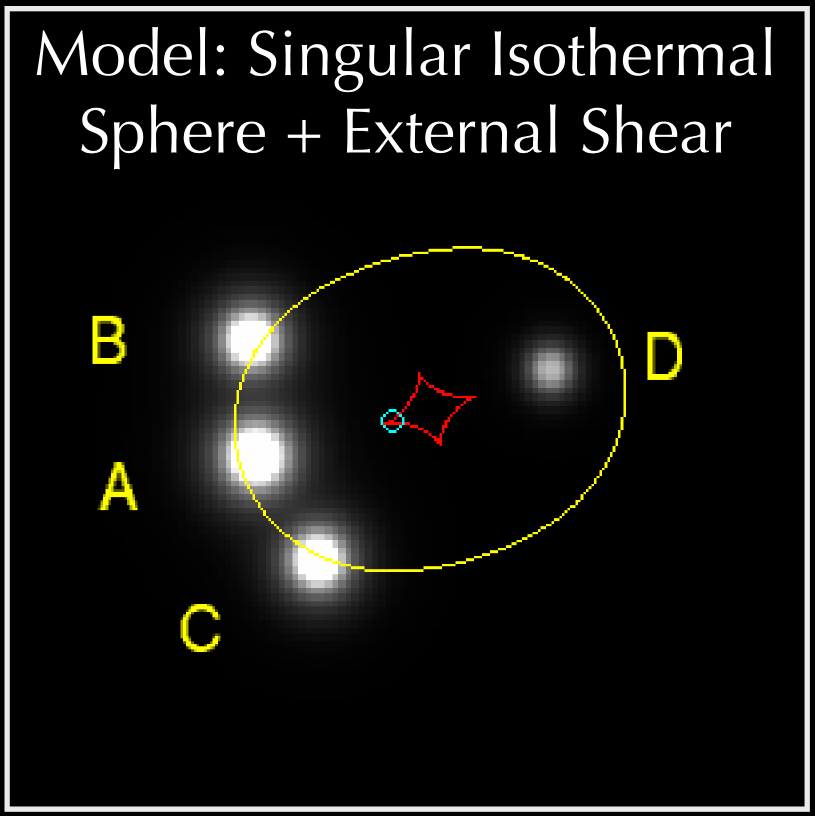


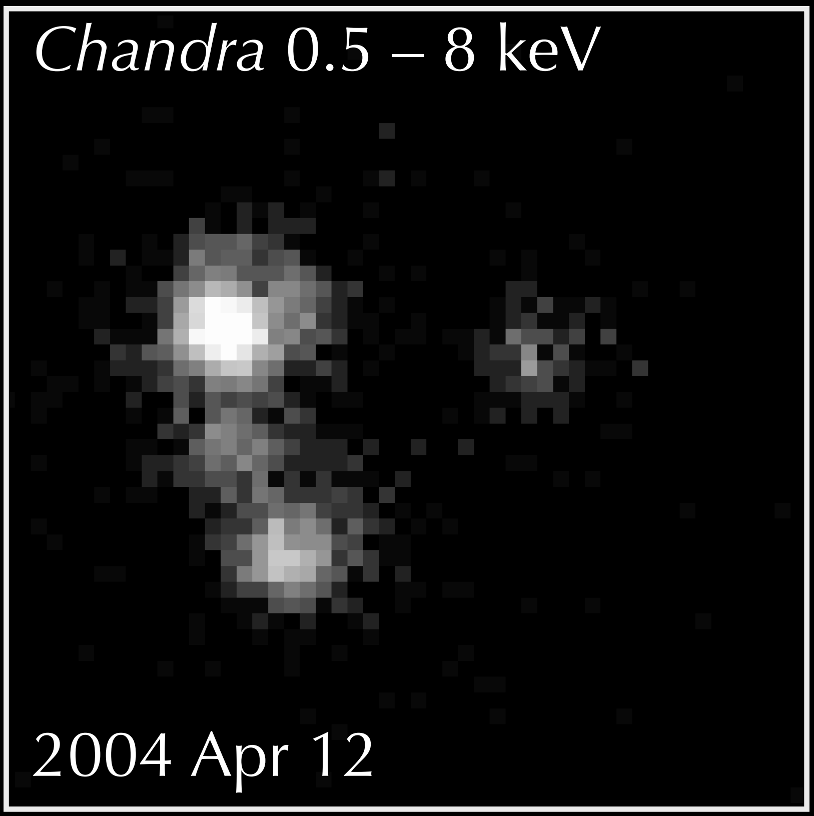


$F_A/F_B = 1.10 \pm 0.16$

$F_A/F_B = 1.7$

$F_A/F_B = 0.10 \pm 0.01$

Similar discrepancies in RX J0911+0551 *Morgan et al. 2001*

and PG 1115+080 *DP et al. 2006*

# Flux Ratio Anomalies: What causes them?

- Smooth lens models cannot account for them
  - *Micro*lensing by stars (~1 $M_\odot$) *e.g., Witt, Mao, & Schecter 1995*
  - *Milli*lensing by dark matter clumps (~$10^4$–$10^6$ $M_\odot$)
    *Mao & Schneider 1998, Metcalf & Madau 2001, Chiba 2002, Dalal & Kochaneck 2002*
- Einstein radius of perturber in typical lensing galaxy:
  $\sim 3 \sqrt{(m/M_\odot)\,(\mathrm{Gpc}/D_L)}$ $\mu$-arcsec
- If millilensing, X-ray and optical should be affected the same
- Differences in X-ray and optical ⇒ microlensing

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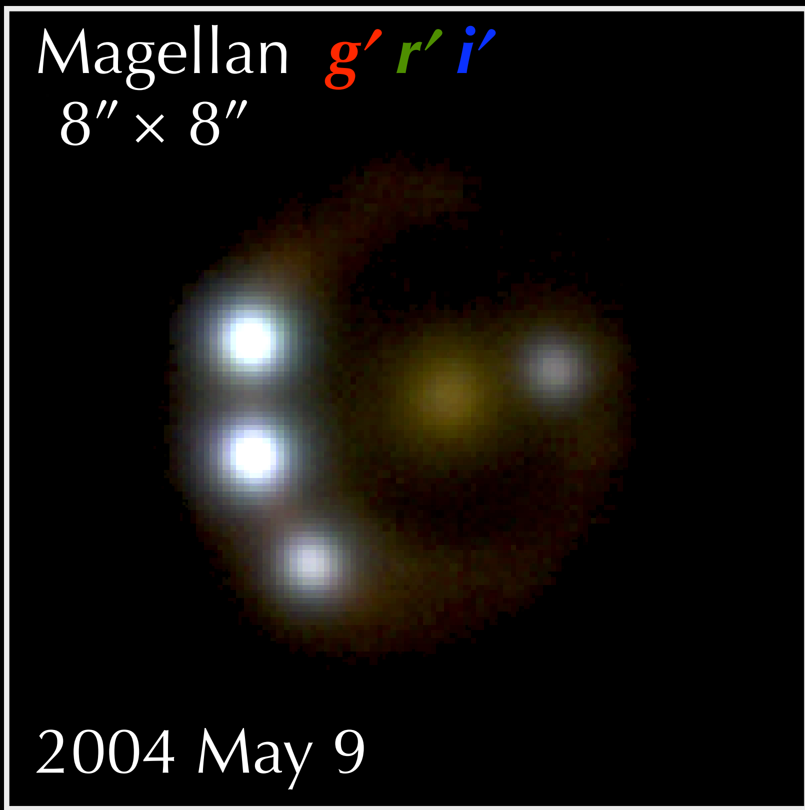


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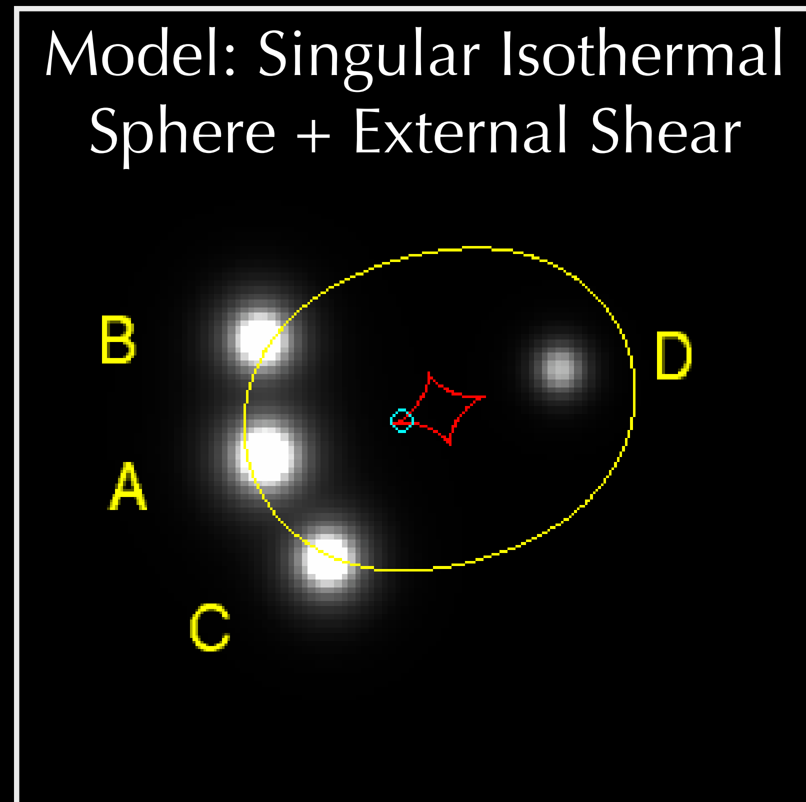


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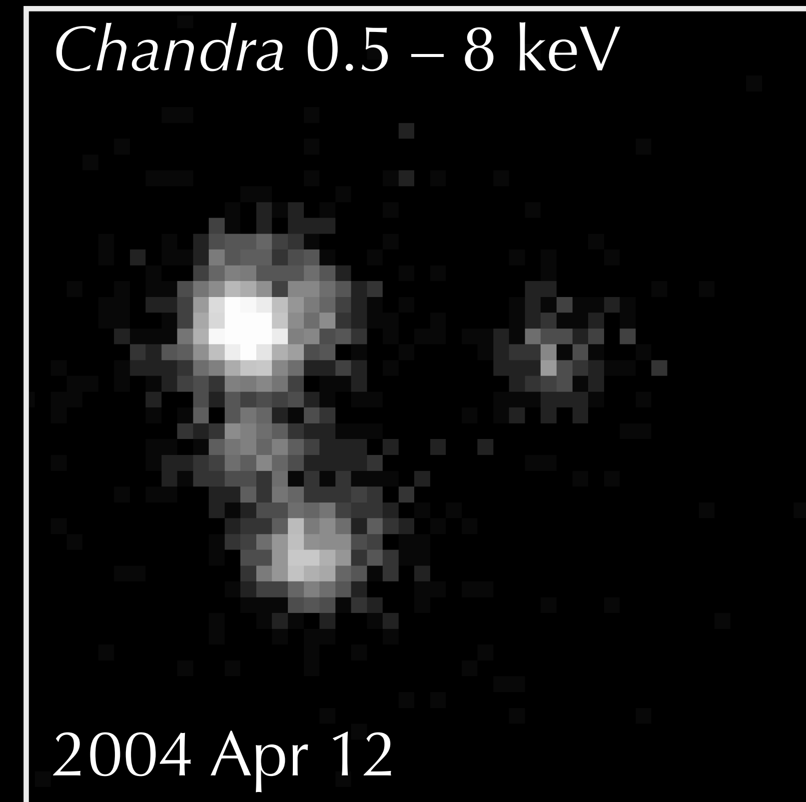


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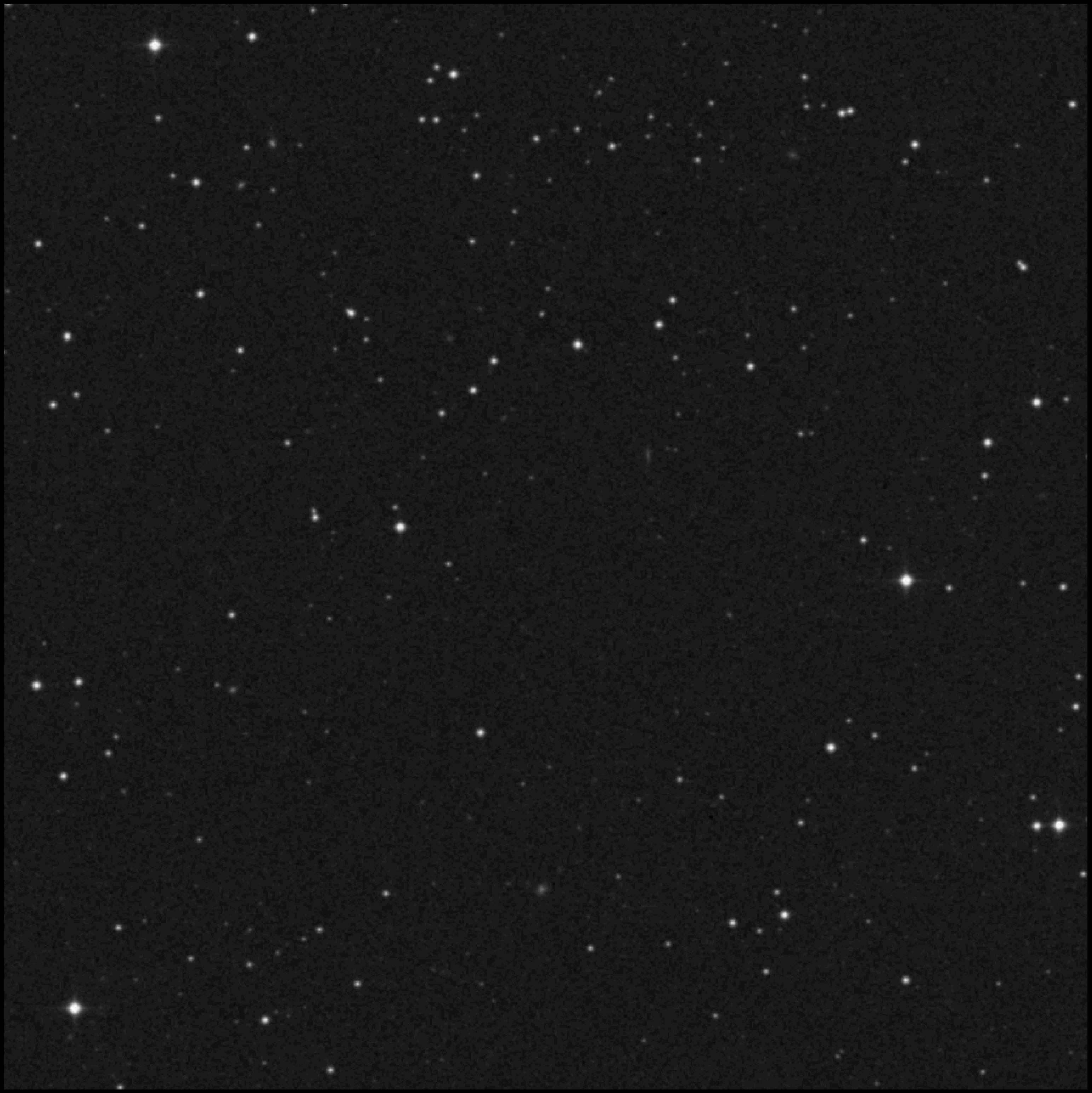
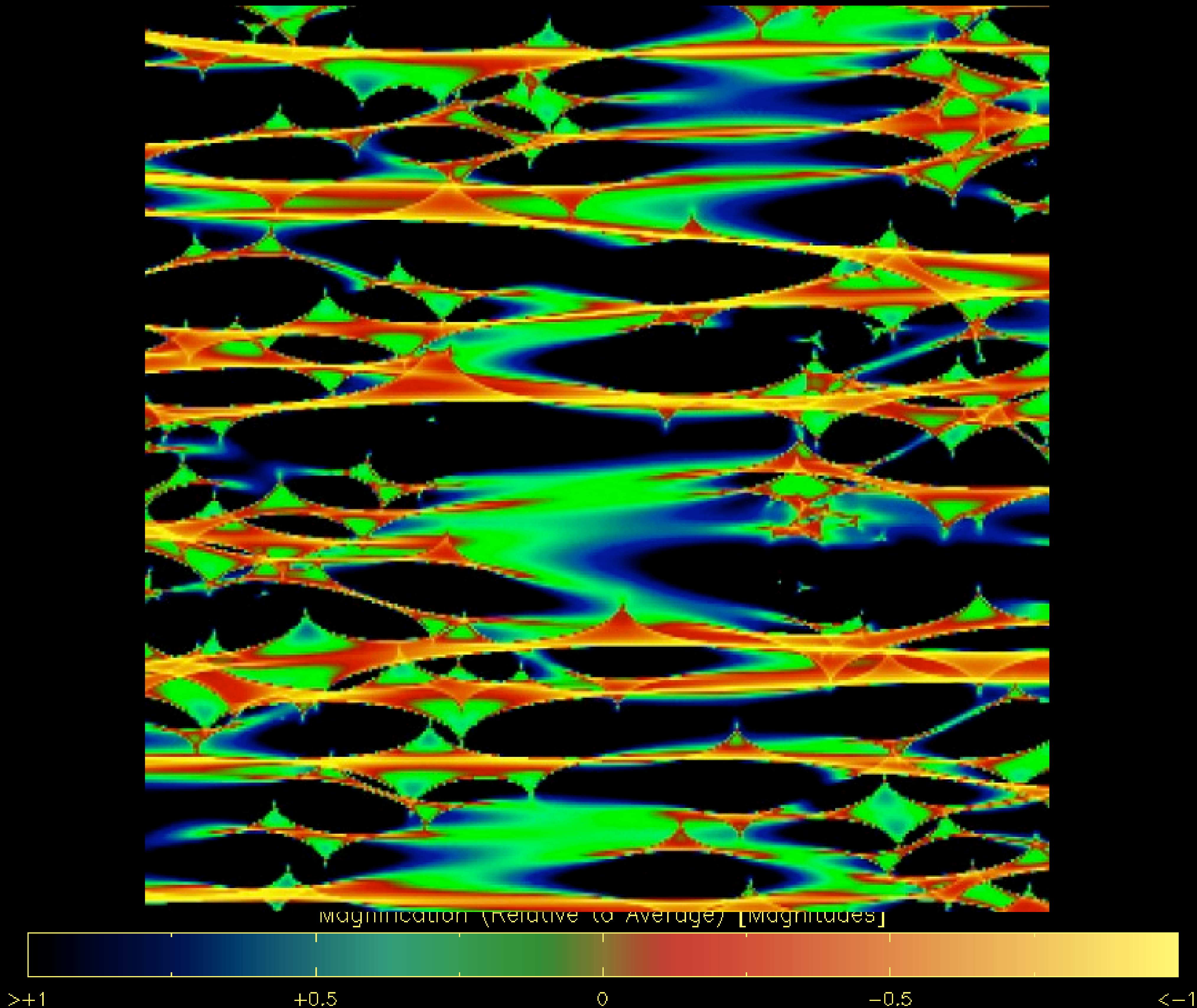
# Microlensing



# Microlensing




*Schechter & Wambsganns 2002*

# Microlensing

*courtesy Svetlin Tassev*

# Flux Ratio Anomalies: How common are they?

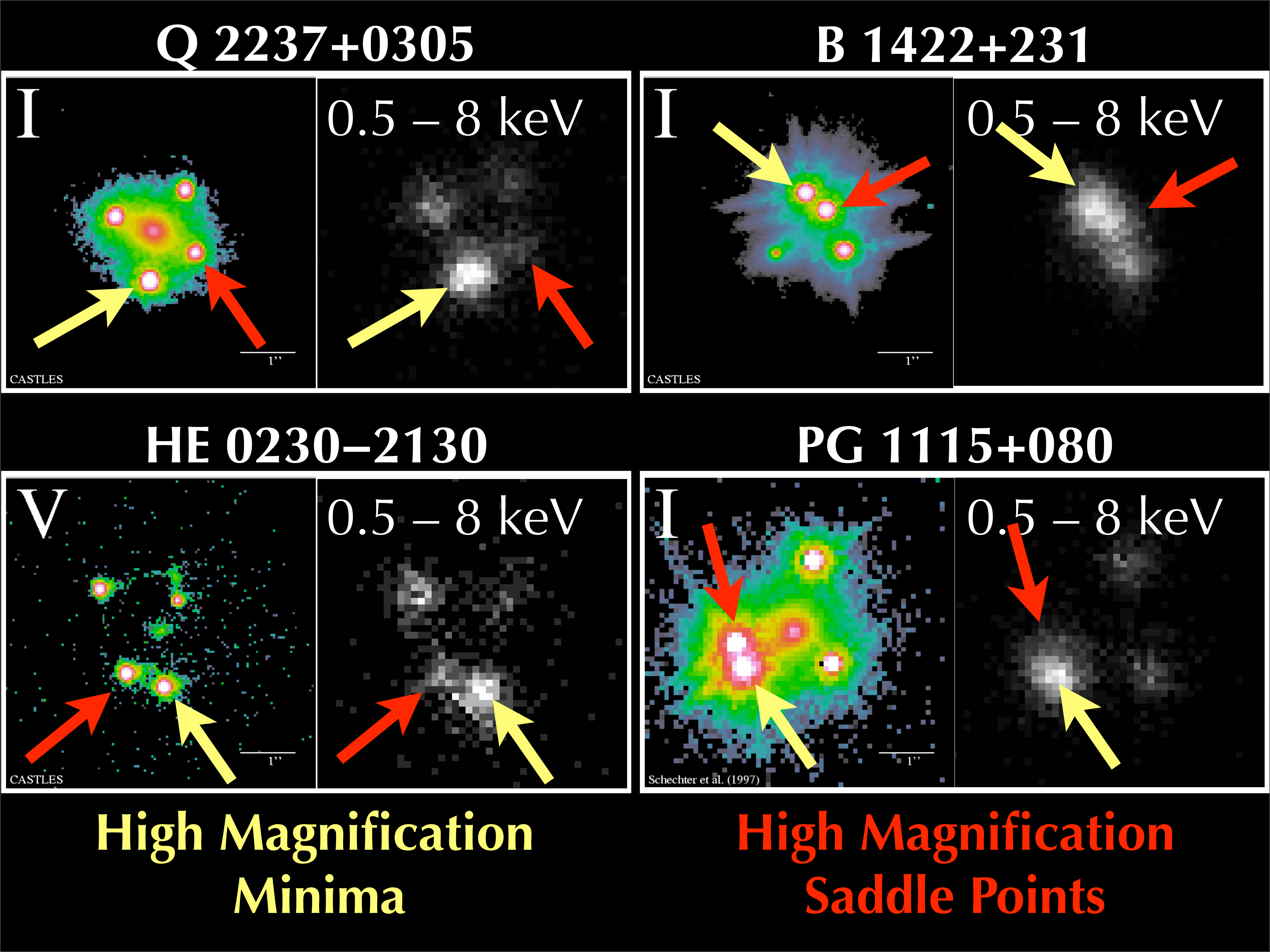
- ✦ Systematic study of 10 quadruply lensed quasars
  - ✦ Re-analysed archival *Chandra* data
  - ✦ Optical fluxes from the literature (near IR band)
  - ✦ Simple lens models (SIS + external shear)

- ✦ Emphasis on high-magnification saddle point (HS)
  - ➡ Should be most susceptible to microlensing

*Schechter & Wambsganns 2002*

  - ✦ Compare it to high-magnification minimum (HM)
    - ‣ In many cases, should be about equal
  - ✦ Compare it to low-magnification minimum (LM)
    - ‣ Should be least susceptible to microlensing

*Kochanek & Dalal 2004*



Q 2237+0305
I
0.5 – 8 keV
1''
CASTLES
B 1422+231
I
0.5 – 8 keV
1''
CASTLES
HE 0230–2130
V
0.5 – 8 keV
1''
CASTLES
PG 1115+080
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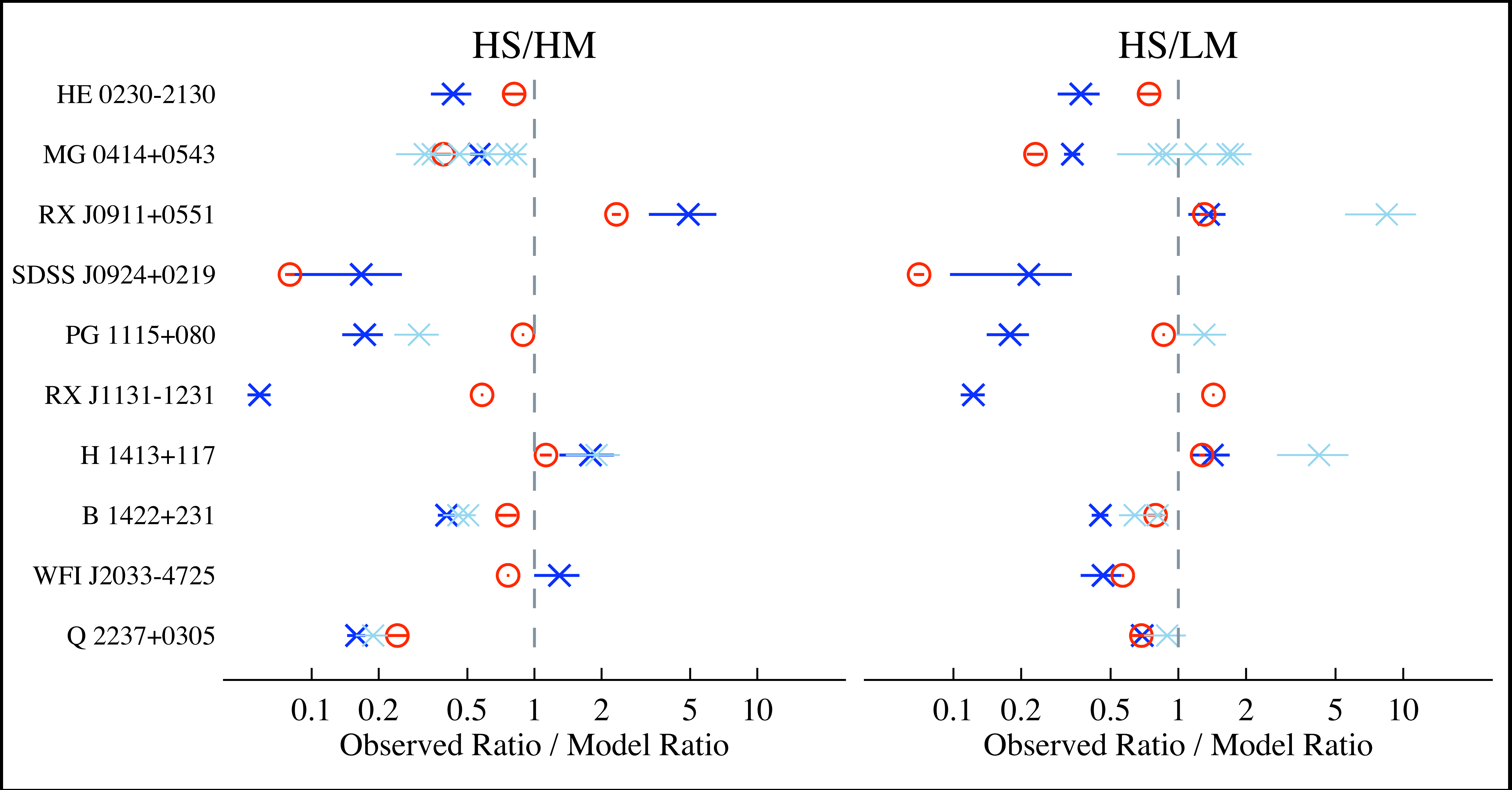
1''
Schechter et al. (1997)
High Magnification Minima
High Magnification Saddle Points

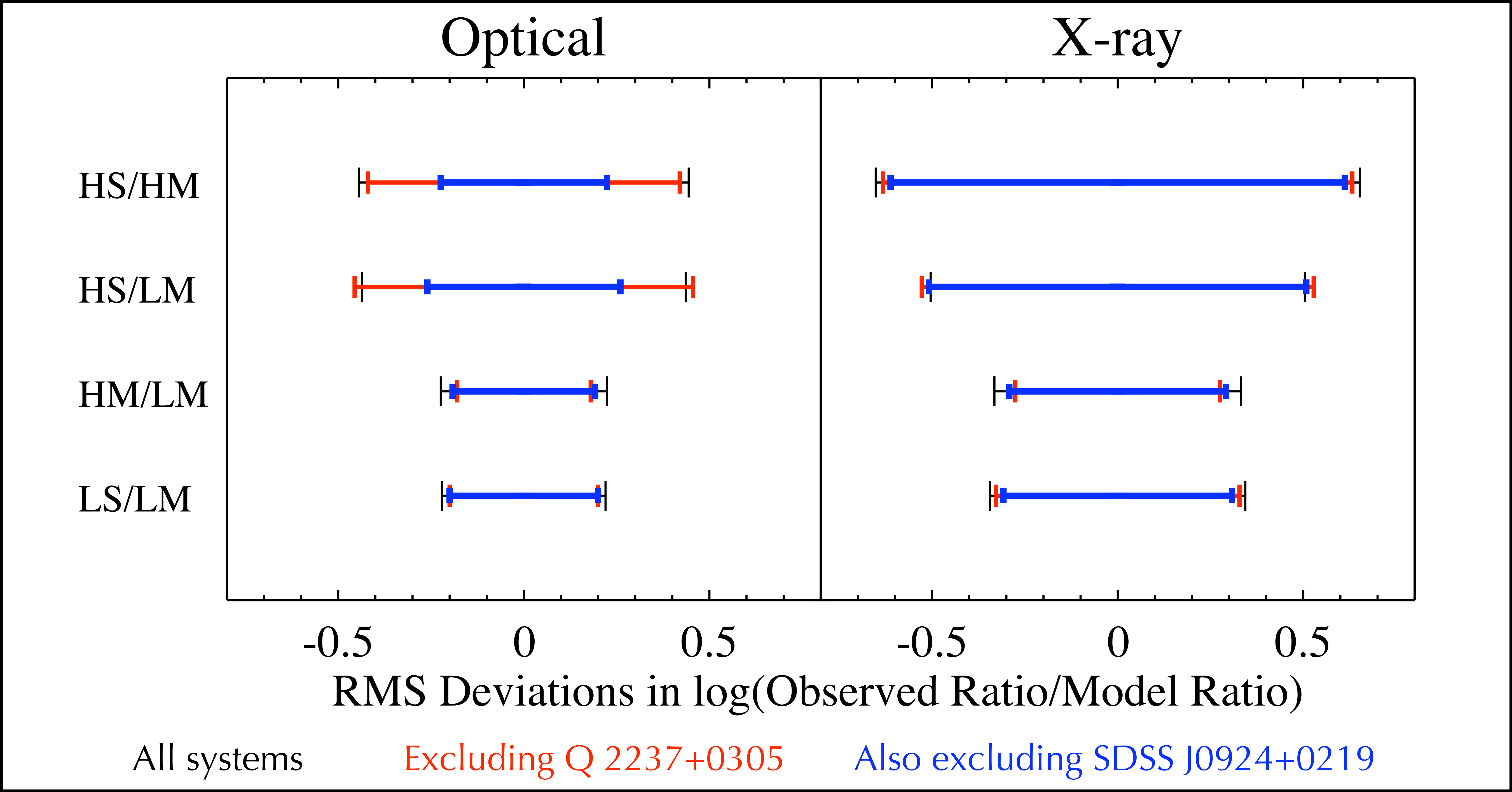
# Flux Ratio Anomalies: How common are they?




*DP et al. 2006*

**HS** = **H**igh magn. **S**addle point
**HM** = **H**igh magn. **M**inimum
**LM** = **L**ow magn. **M**inimum

# Flux Ratio Anomalies: Optical vs. X-ray




*DP et al. 2006*

**HS** = **H**igh magn. **S**addle point

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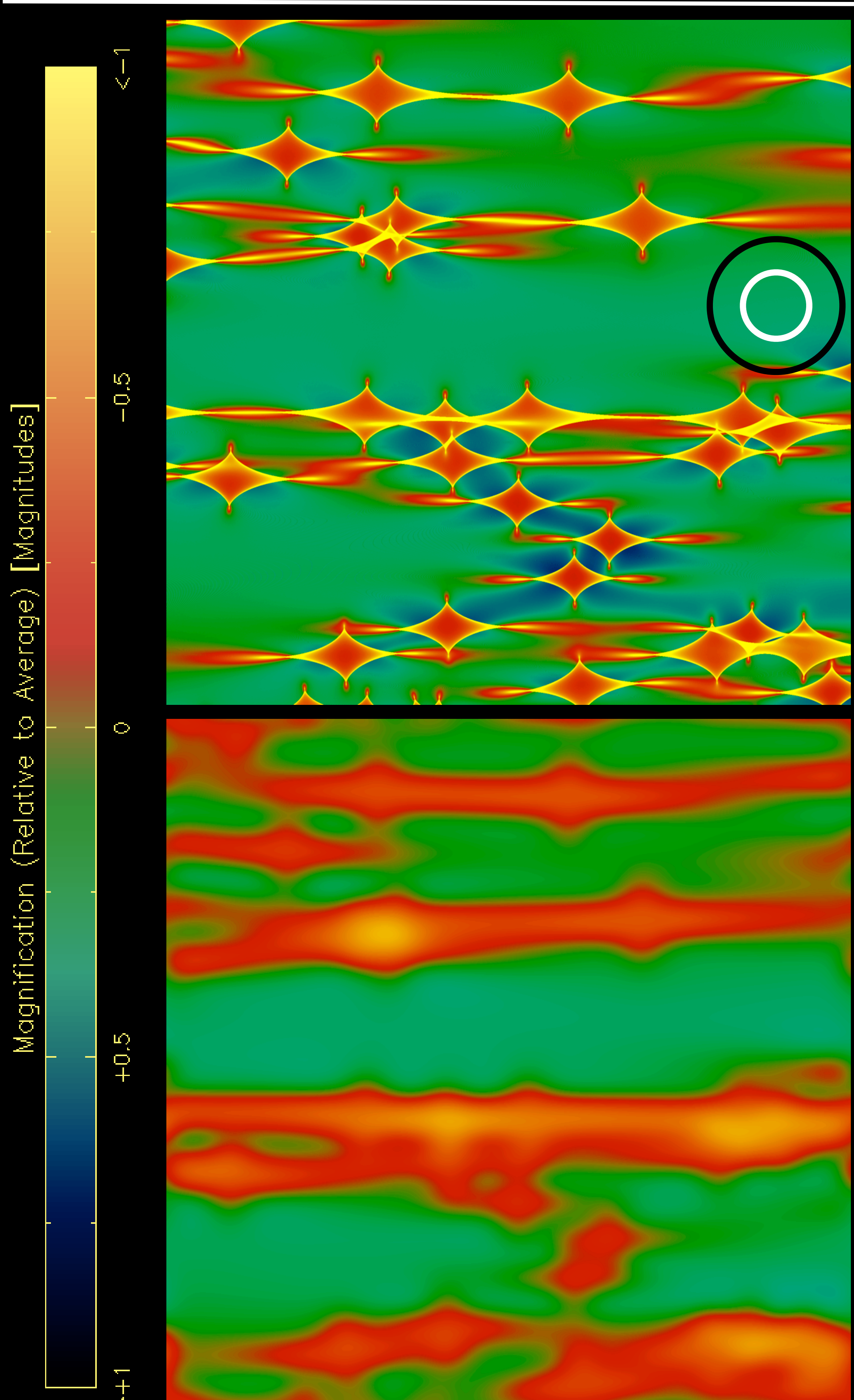
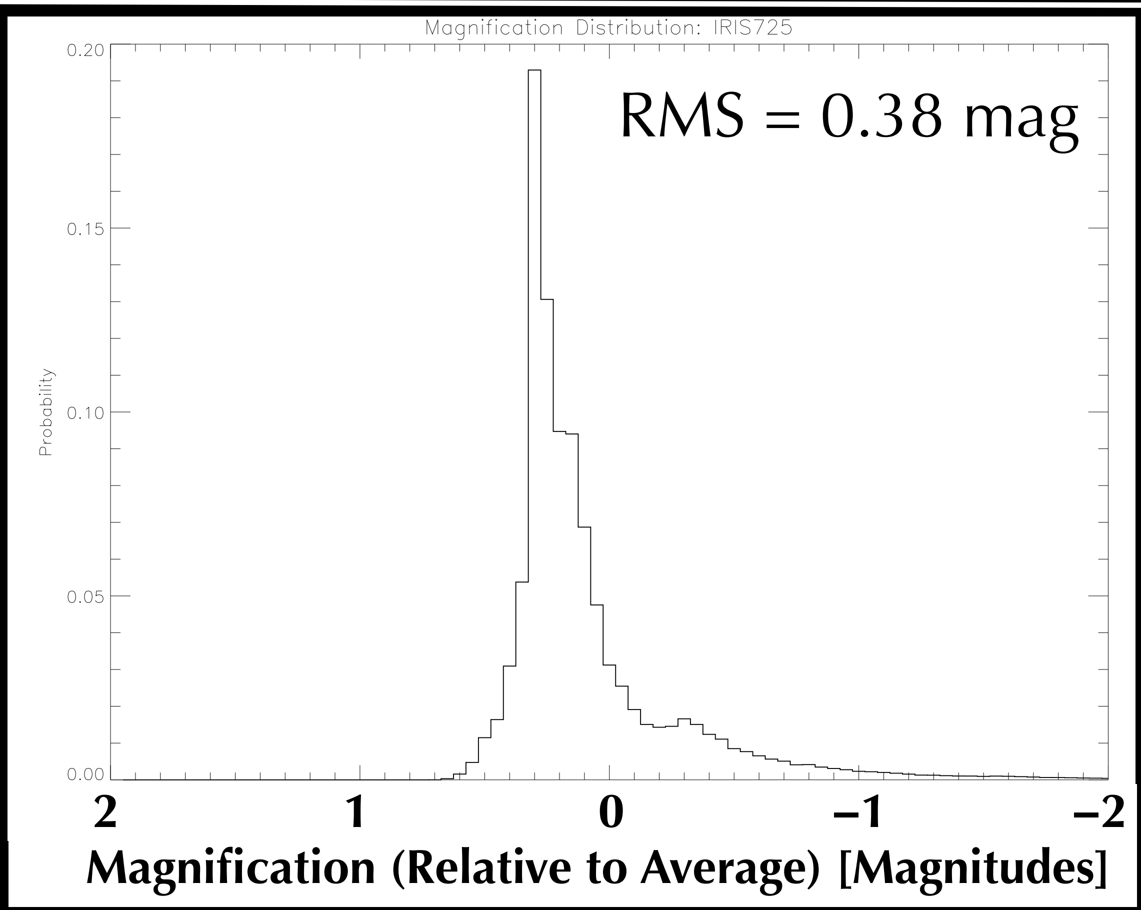
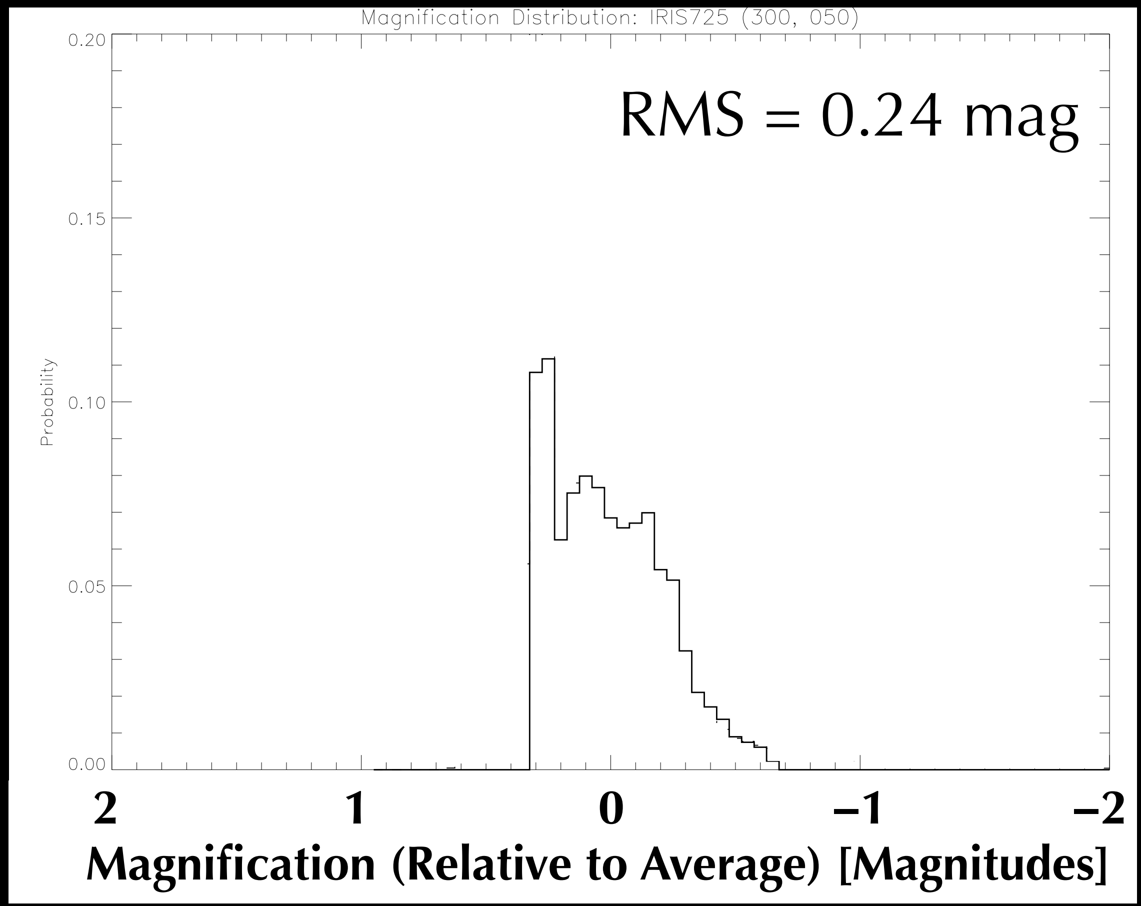
# Flux Ratio Anomalies: The effects of source size

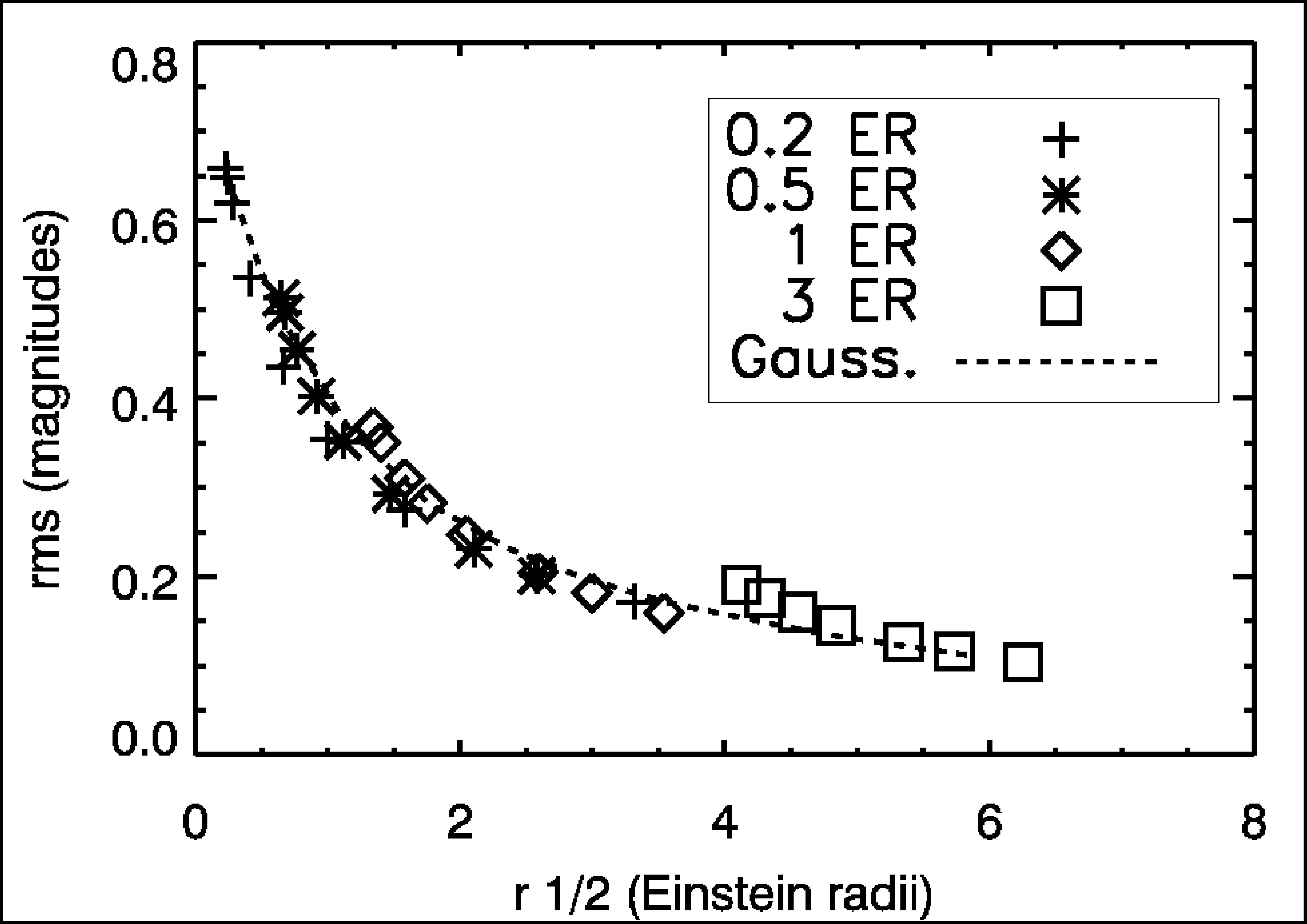



*courtesy Josiah Schwab*



# Flux Ratio Anomalies: The effects of source shape




*Mortonson, Schechter, & Wambsganns 2005*

Conclusion:

Our optical anomalies are roughly half the amplitude of the X-ray anomalies

$\Rightarrow$ **optical $R_{1/2} \gtrsim 1/3\ R_{Ein}$**

# The Sizes of Quasar Emission Regions

We calculate the optical $R_{1/2}$ for Shakura-Sunyaev disks and compare to the microlens Einstein radii:

| Quasar | $L_{\rm bol,opt}$[a] ($10^{45}$ erg s$^{-1}$) | $L_{\rm bol,X}$[b] ($10^{45}$ erg s$^{-1}$) | log $M_{\rm BH}$[c] ($M_\odot$) | $r_{1/2}$[d] ($10^{15}$ cm) | $r_{1/2}$[d] ($R_g$) | stellar $r_{\rm Ein}$[e] ($10^{15}$ cm) | log $r_{1/2}/r_{\rm Ein}$ |
|---|---|---|---|---|---|---|---|
| HE 0230−2130 | 2.9 | 6.3 | $7.95 \pm 0.24$ | 0.93 | 70 | 43 | $-1.66 \pm 0.16$ |
| MG J0414+0534 | 36 | 28 | $9.04 \pm 0.17$ | 3.8 | 23 | 31 | $-0.91 \pm 0.11$ |
| RX J0911+0551 | 13 | 13 | $8.60 \pm 0.18$ | 1.9 | 32 | 35 | $-1.26 \pm 0.12$ |
| SDSS J0924+0219 | 0.6 | 0.3 | $7.27 \pm 0.56$ | 0.42 | 152 | 48 | $-2.06 \pm 0.37$ |
| PG 1115+080 | 11 | 6.6 | $8.53 \pm 0.37$ | 2.5 | 50 | 55 | $-1.35 \pm 0.25$ |
| RX J1131−1231 | 0.80 | 1.3 | $7.39 \pm 0.19$ | 0.84 | 230 | 38 | $-1.65 \pm 0.13$ |
| H 1413+117 | 56 | 6.5 | $9.24 \pm 0.51$ | 5.4 | ... | ... | ... |
| B 1422+231 | 250 | 135 | $9.89 \pm 0.18$ | 13 | 11 | 47 | $-0.55 \pm 0.12$ |
| WFI J2033−4723 | 5.7 | 3.8 | $8.24 \pm 0.12$ | 1.6 | 62 | 36 | $-1.35 \pm 0.08$ |
| Q 2237+0305 | 32 | 2.7 | $8.99 \pm 0.76$ | 5.5 | 38 | 150 | $-1.43 \pm 0.51$ |

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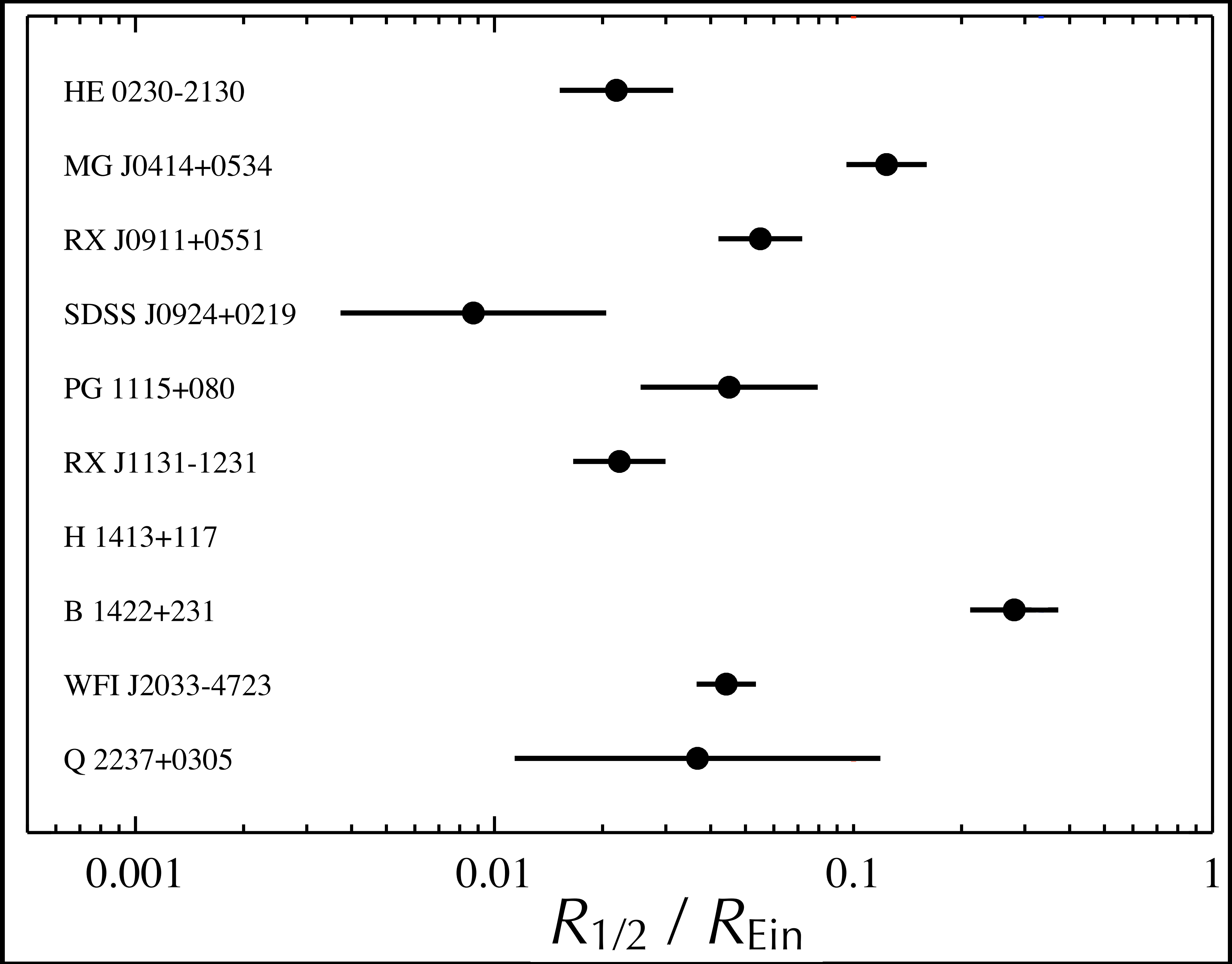


*DP et al. 2006*

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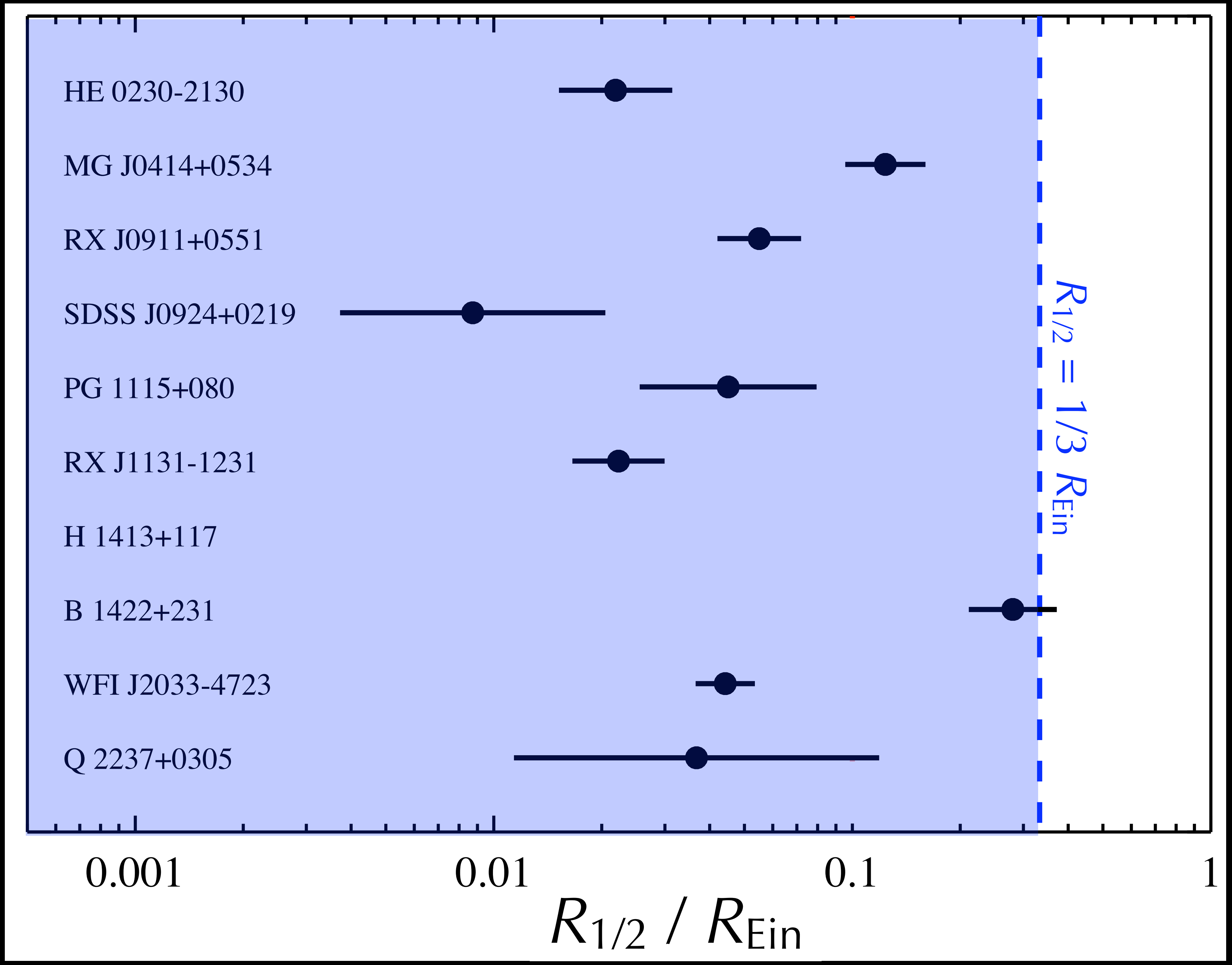


*DP et al. 2006*

# Summary & Outlook

- ✳ Microlensing is the primary cause of the flux ratio anomalies
- ✳ Optical emitting regions of these quasars have sizes $\gtrsim$1/3 of a stellar Einstein radius, i.e., a few $\mu$-arcsec, corresponding to ~$10^{16-17}$ cm
- ✳ Standard accretion disks are too small
- ✳ Four new systems coming in *Chandra* Cycle 8
- ✳ These same flux ratio anomalies can be used to determine the ratio of stellar matter to dark matter in the lens galaxy

# Stellar/Smooth Matter Fraction

*Schechter & Wambsganns 2002*