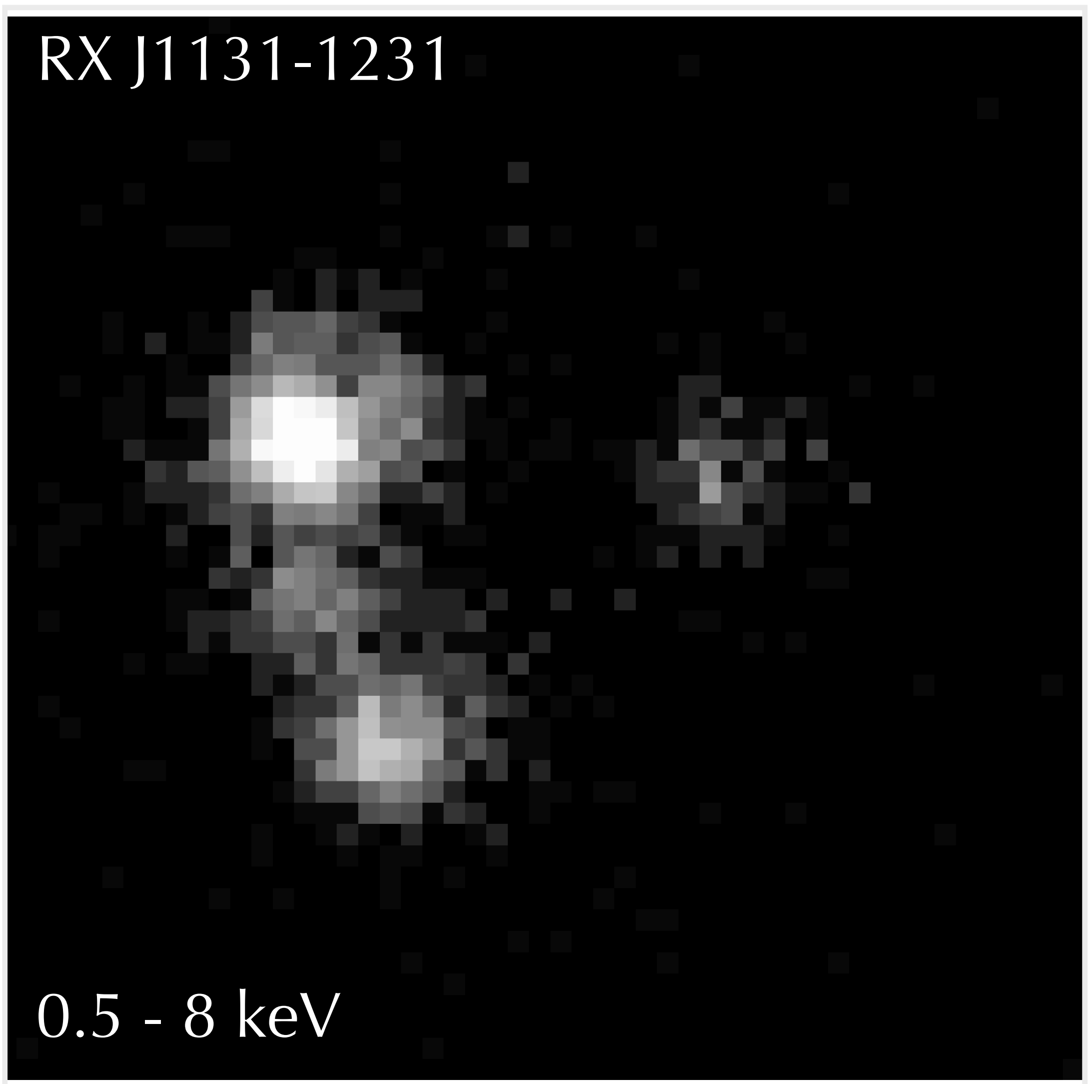
Dark Matter Determinations from *Chandra* Observations of Quadruply Lensed Quasars



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- **Microlensing by stars causes discrepancies with lens models.** *Blackburne, DP, & Rappaport (2006), DP et al. (2006), DP et al. (2007)*

- **X-rays give cleanest microlensing signal.**

- **We have improved the data reduction and analysis.**

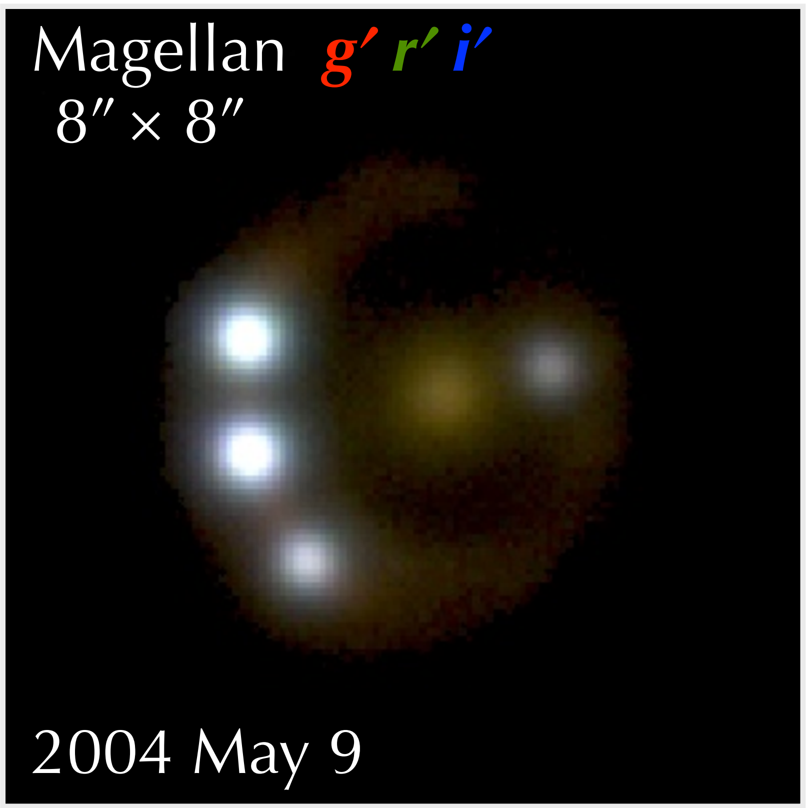
- **Ratio of dark matter to stellar material determines probability of microlensing effects.** *e.g., Schechter & Wambsganss (2004)*

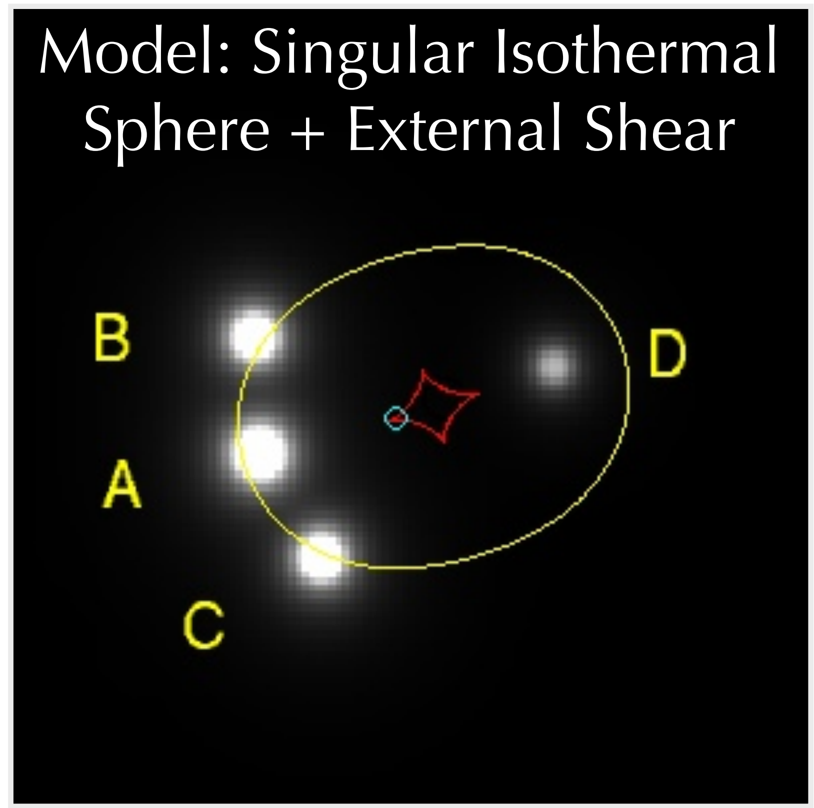
- **Ensemble of 14 systems indicates the integrated mass through lensing galaxies at $R \approx 5$ kpc is 85% – 95% dark matter.**

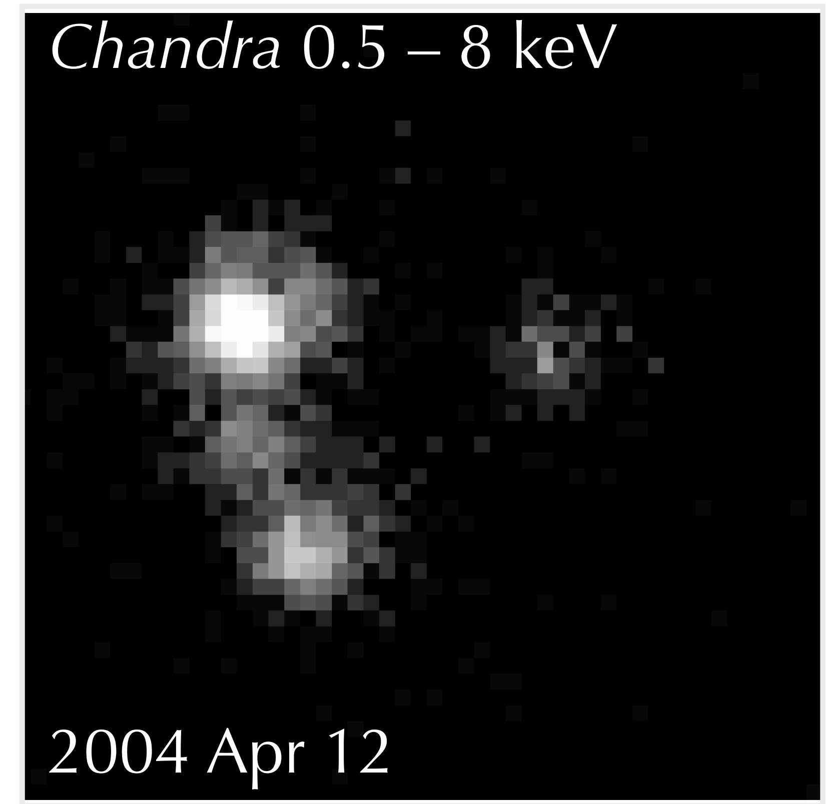
Flux Ratio Anomalies are a result of stellar microlensing

RX J1131–1231

Blackburne, DP, & Rappaport 2006







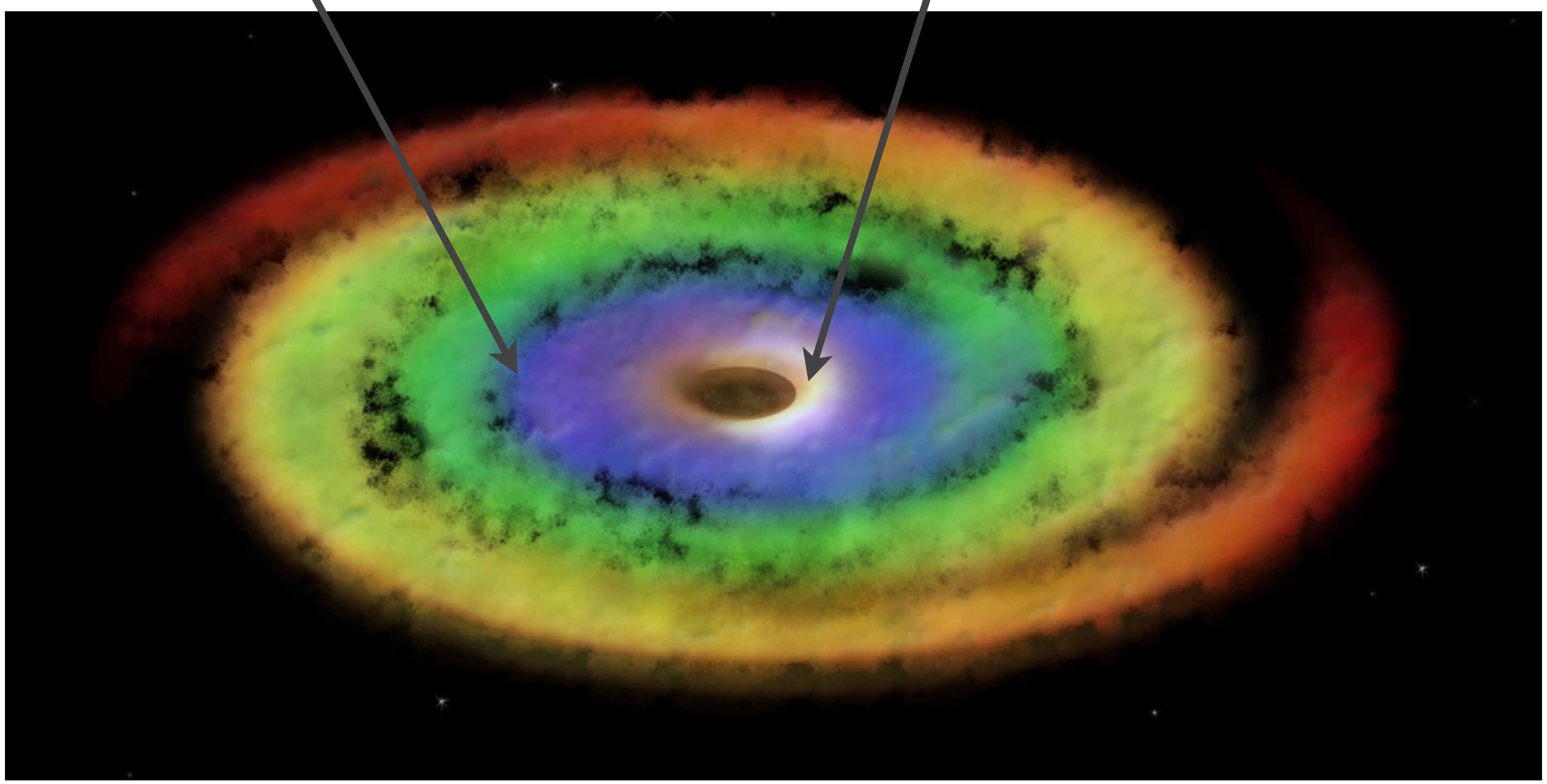
$F_A/F_B = 1.10 \pm 0.16$ $F_A/F_B = 1.7$ $F_A/F_B = 0.10 \pm 0.01$

Similar discrepancies in RX J0911+0551 *Morgan et al. 2001*
and PG 1115+080 *DP et al. 2006*

X-rays give cleanest microlensing signal

Optical region: few × 10^{-7} arcsec

X-ray region: few × 10^{-9} arcsec



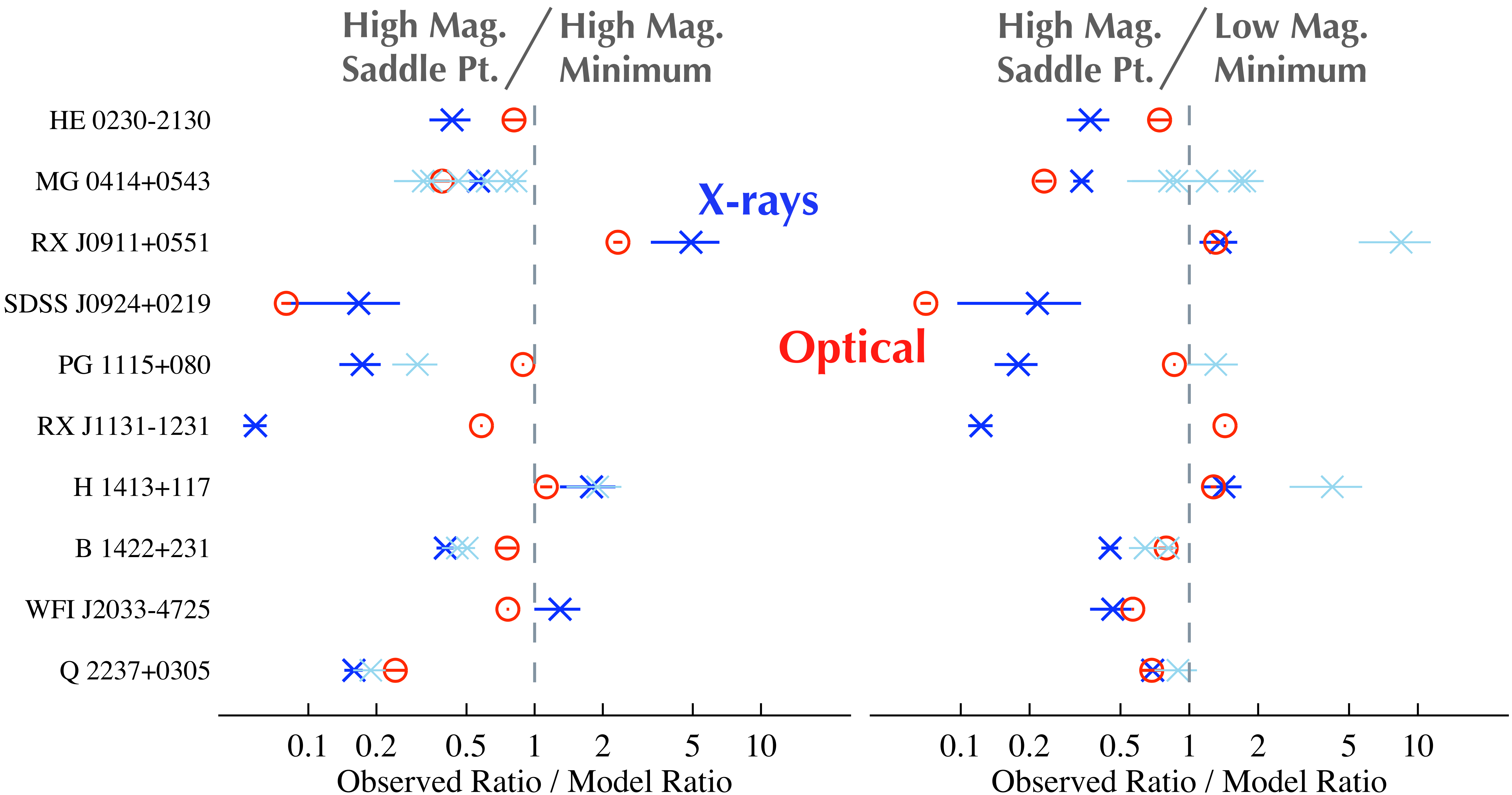
Schematic of quasar accretion disk

Einstein radius of star in typical lensing galaxy:

~ $3 \sqrt{(m/M_\odot)} \times 10^{-6}$ arcsec

(for $D_L \approx 1$ Gpc)

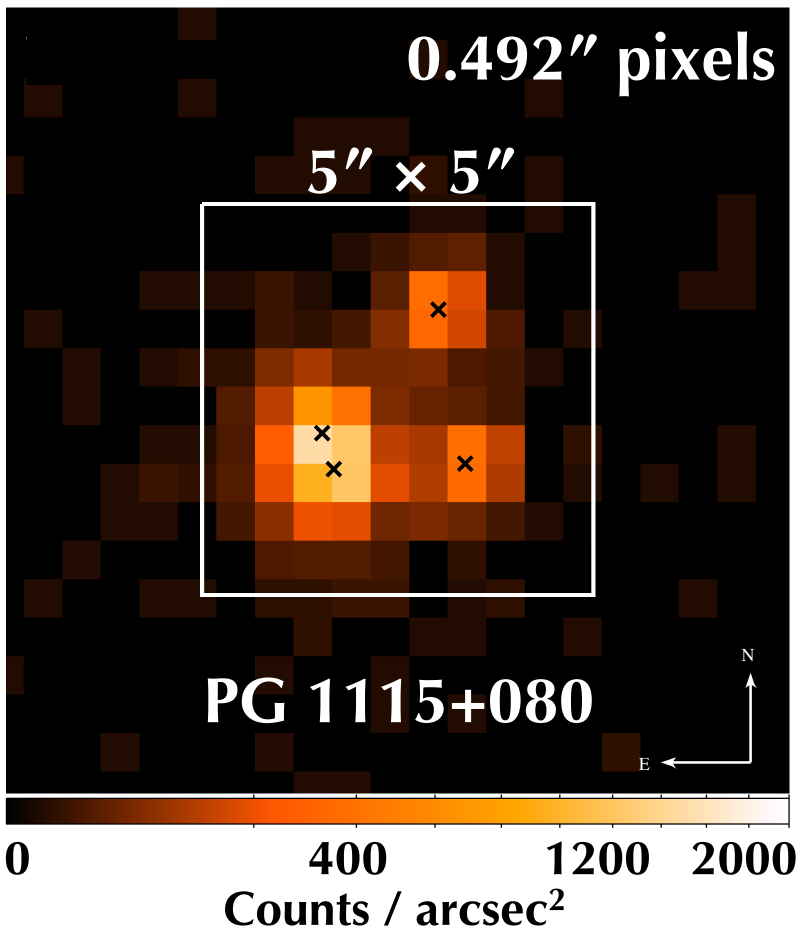
Strong microlensing effects are observed



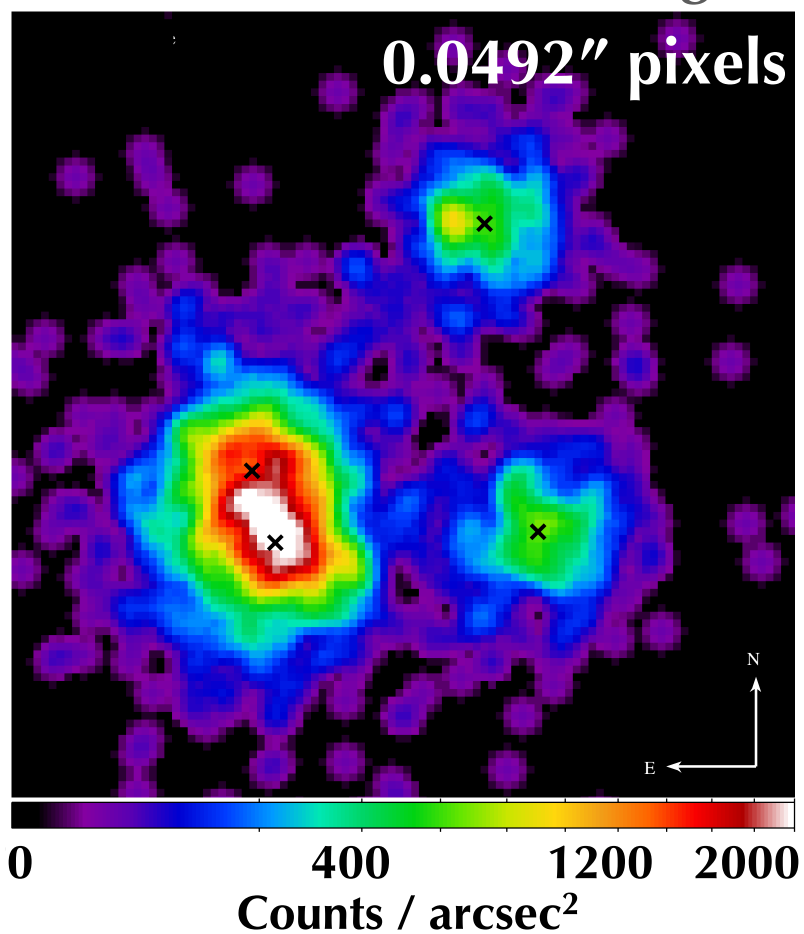
DP et al. 2007

Improved X-ray data reduction gives more precise measurement

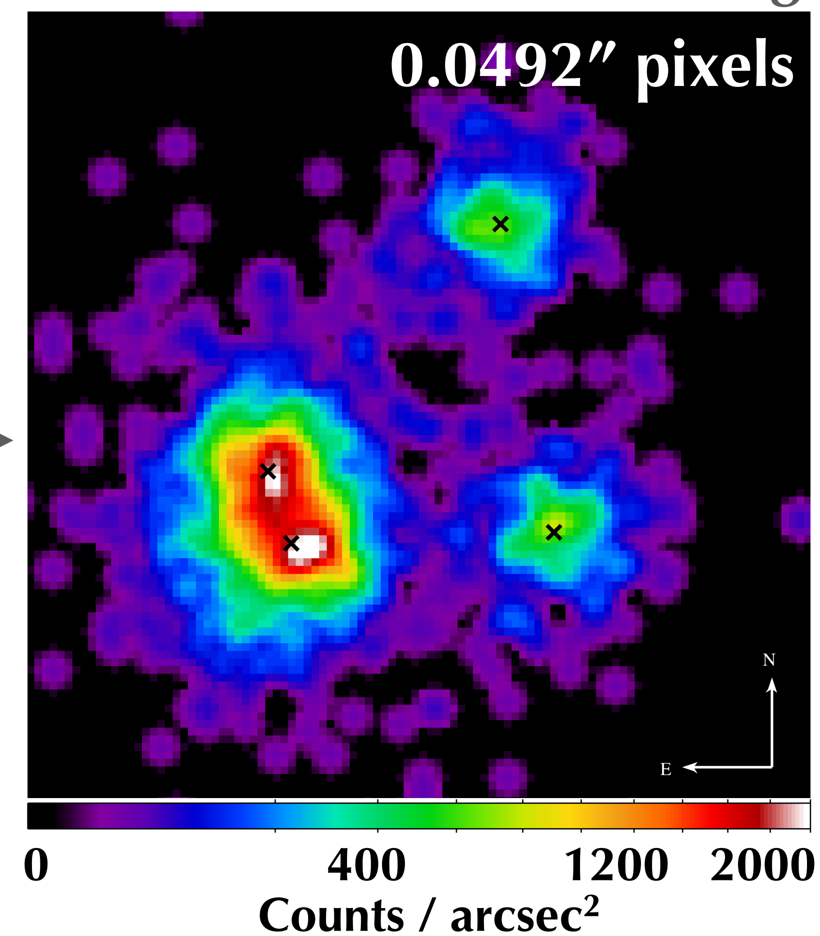
"Standard" *Chandra* image



"Better" *Chandra* image



"Even Better" *Chandra* image

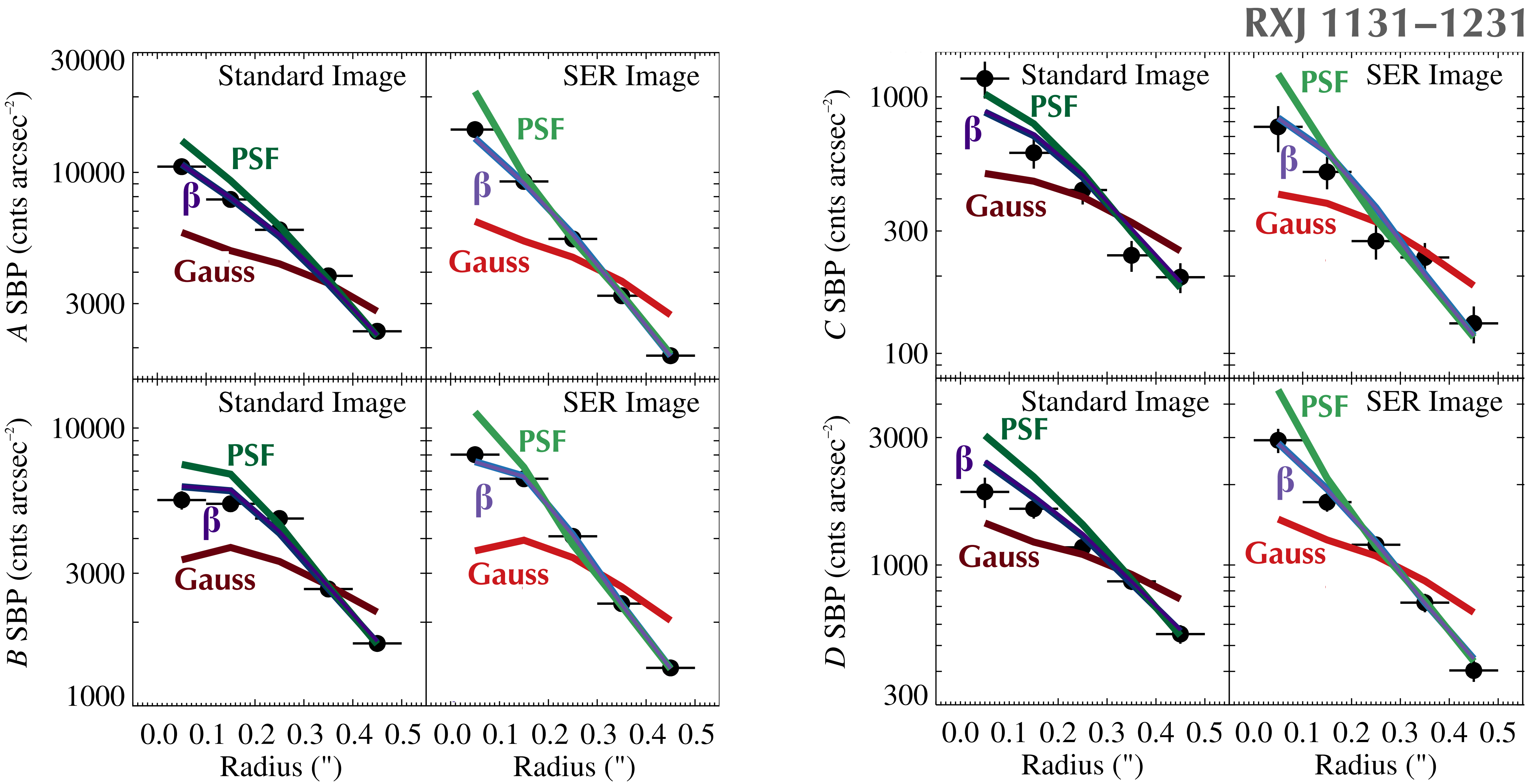


Use dithering of satellite

Use Sub-pixel Event Resolution

Position of an event is based on how charge cloud is split amongst neighboring pixels.

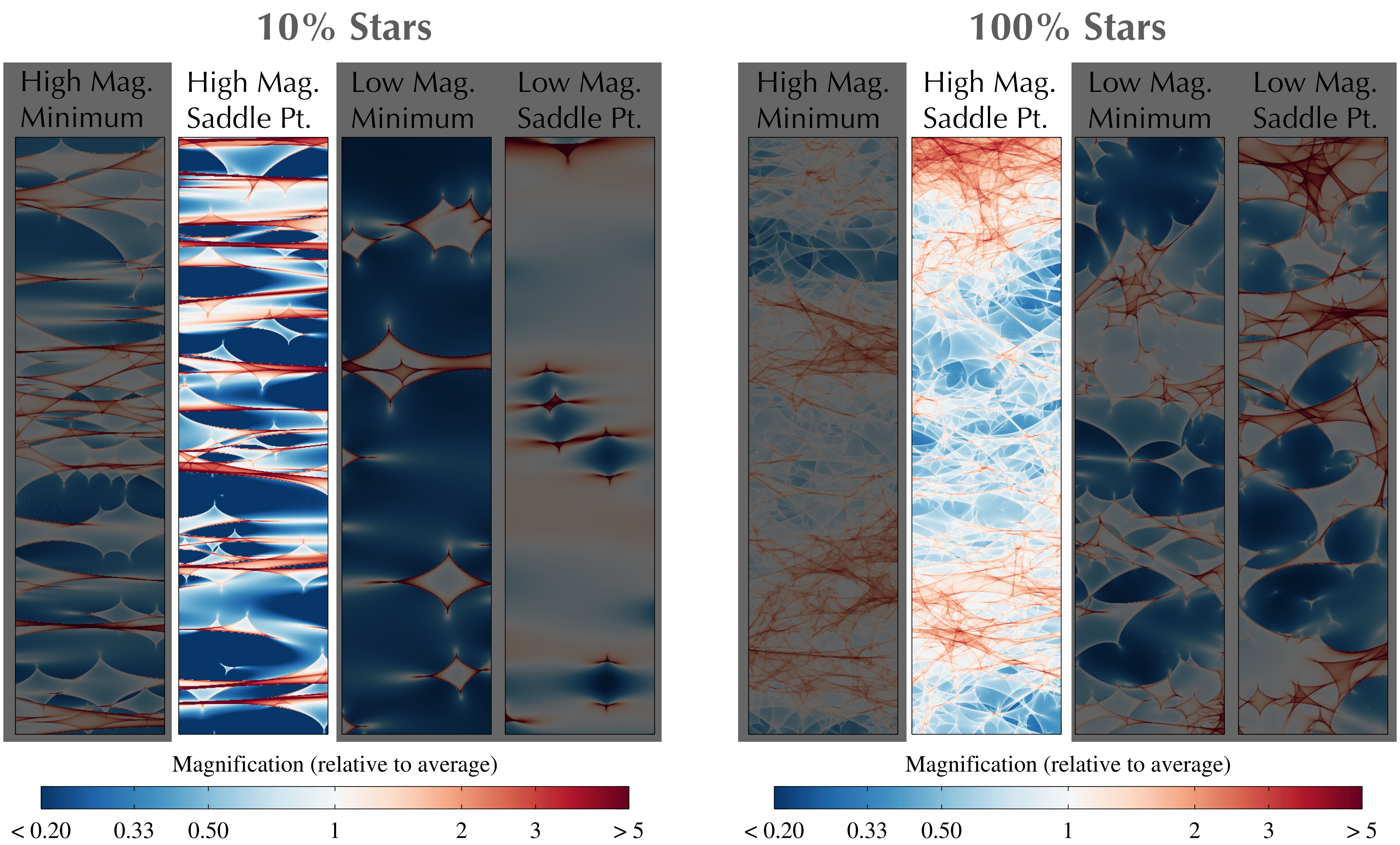
Improved X-ray image modeling gives more precise measurement



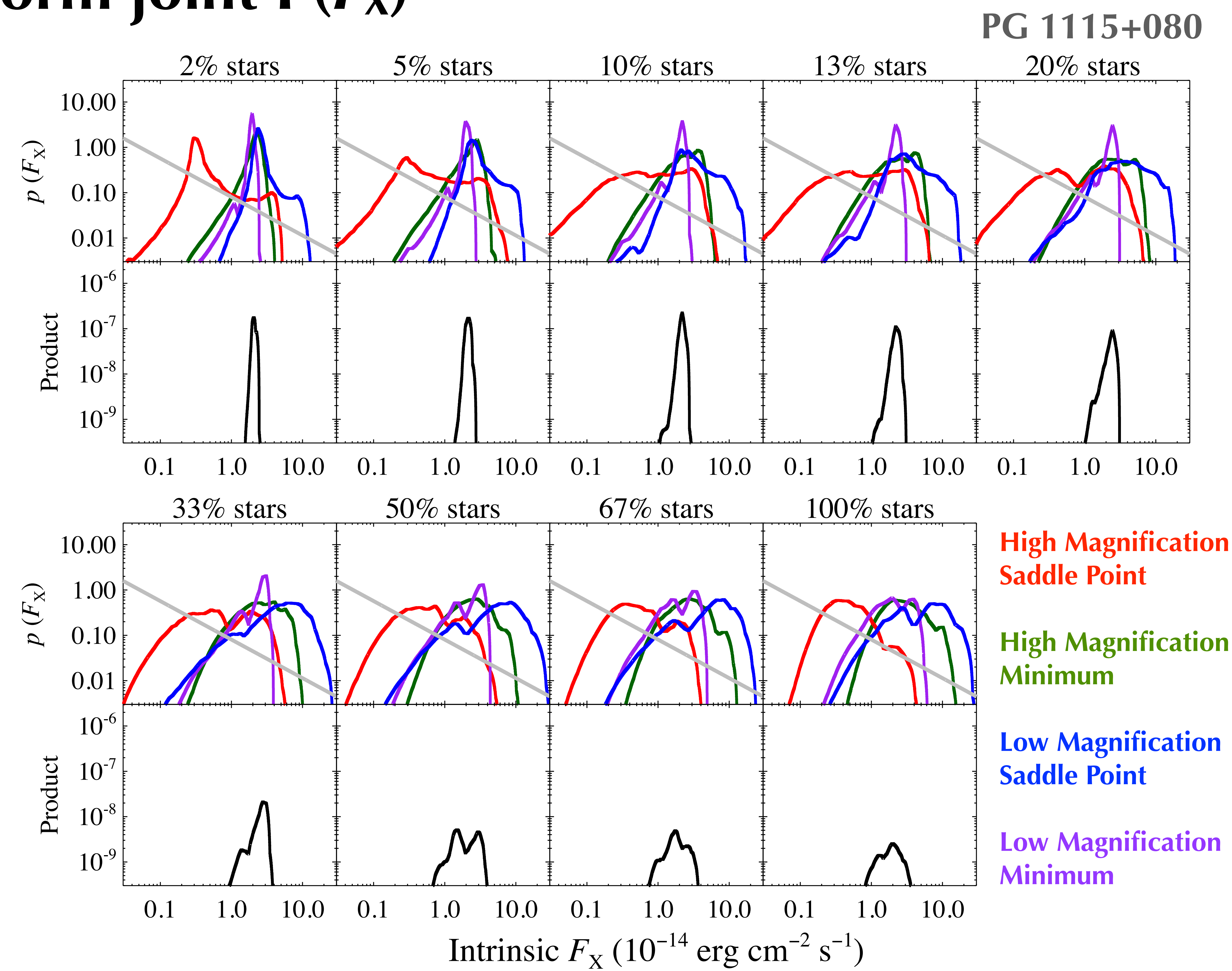
$$\beta \text{ profile: } I(r) = A(1 + (r/r_0)^2)^{-\beta}$$

Probability of microlensing depends on dark/stellar ratio

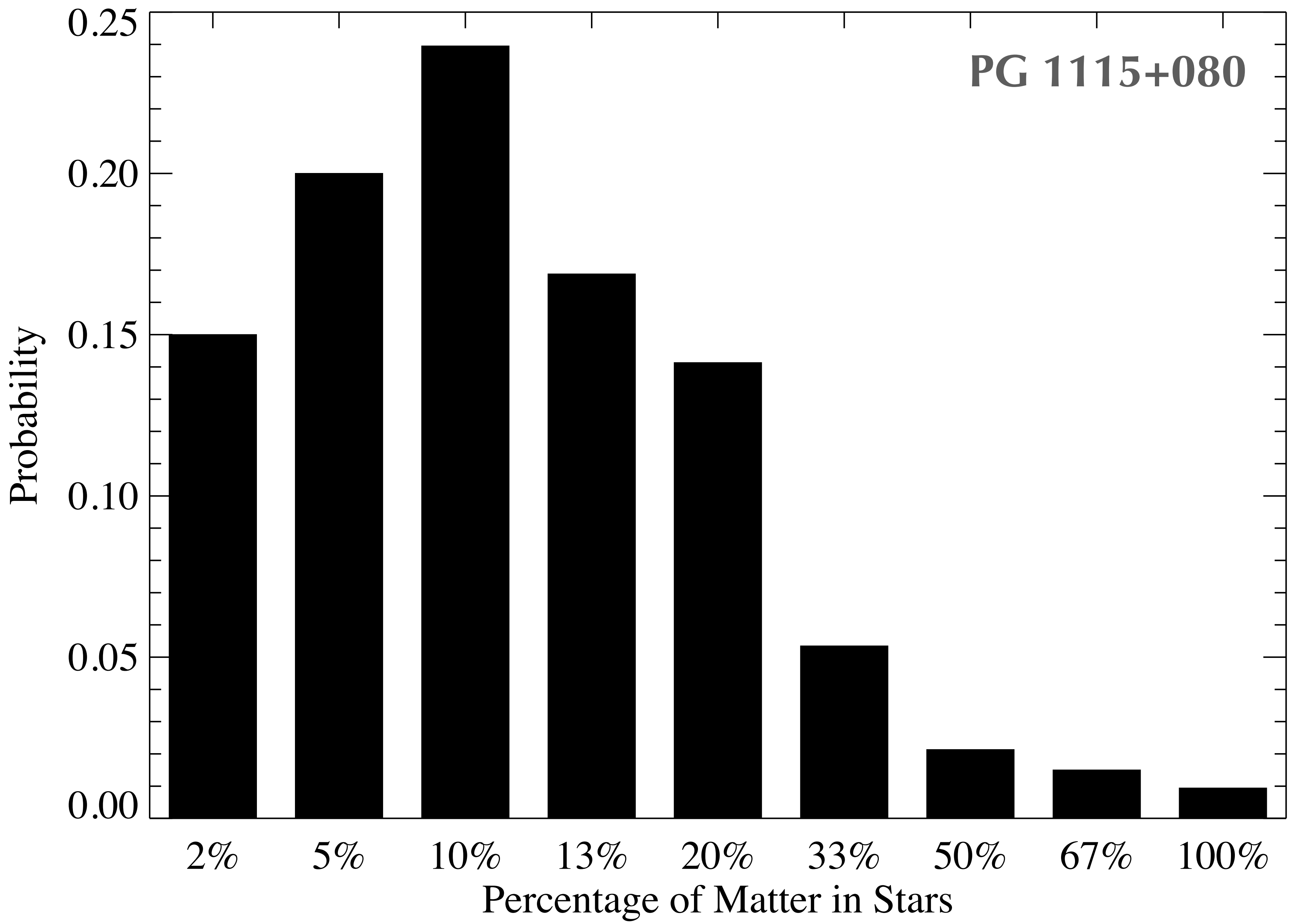
Custom microlensing maps are made for each system for a variety of dark/stellar ratios.
Strong demagnifications are unlikely for very high (100%) and very low (1%) stellar fractions.



Multiply distributions to form joint P(F_X)



Marginalize over F_X to obtain likelihood of stellar fraction



DP et al. 2009

Most parameters are marginalized over

For each system, we marginalize over uncertainties and multiple observations.

$$P(\underline{\mathrm{map}_s}|f_{x,1}, f_{x,2}, f_{x,3}, f_{x,4}) \sim P(f_{x,1}, f_{x,2}, f_{x,3}, f_{x,4}|\mathrm{map}_s)$$

i.e., stellar fraction

Bayes Theroem

Math

$$P(f_{\mathrm{x},1}, f_{\mathrm{x},2}, f_{\mathrm{x},3}, f_{\mathrm{x},4}|\mathrm{map}_s) =$$

$$\sum_i \sum_j \sum_k \sum_l \sum_m \sum_n \sum_o P(f_{\mathrm{x,1,ijn}}, f_{\mathrm{x,2,ikn}}, f_{\mathrm{x,3,iln}}, f_{\mathrm{x,4,imn}}|\mathrm{map}_s, F_{\mathrm{x,o}}) \times$$

$$P(F_{\mathrm{x,o}}) \times P(f_{1,ij}) \times P(f_{2,ik}) \times P(f_{3,il}) \times P(f_{4,im}) \times P(f_{\mathrm{x,tot},in}) \times P(\mathrm{obs}_i)$$

Intrinsic F_X of quasar

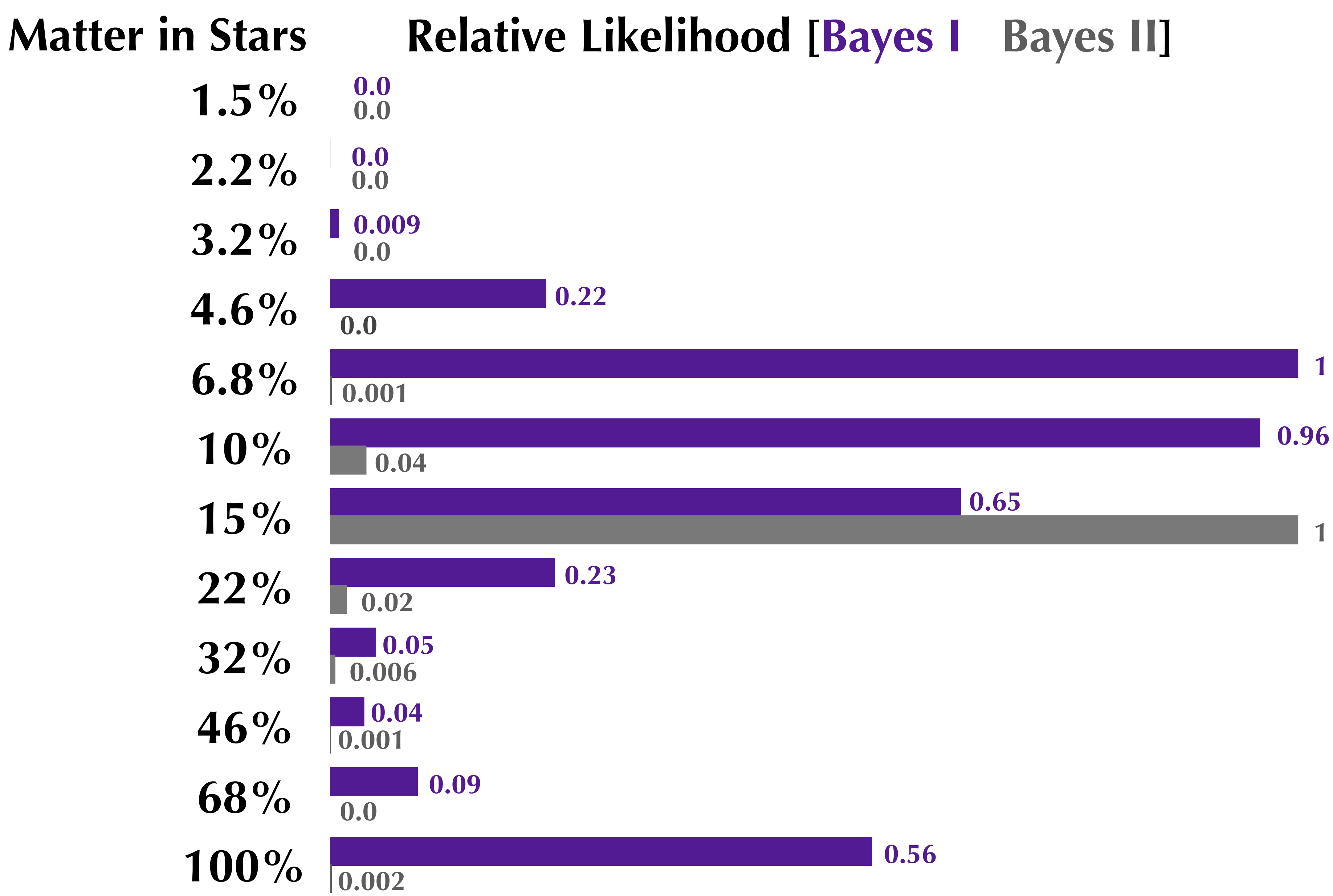
Uncertainties in 2D image fits

Uncertainty in spectral fit

Multiple obs.

Ensemble of quads indicates 85–95% dark matter at $R \approx 5$ kpc

Two Bayesian methods are used to determine most likely dark/stellar ratio — the integrated matter fraction through lensing galaxies at impact parameters between 2 – 8 kpc.



- **Cleanest microlensing signal in X-rays**
- **Strength of microlensing effects depends on composition of matter**
- **85 – 95% dark matter at ~5 kpc impact parameter from galaxy center**
- **Independent evidence for existence of dark matter**
- **Next: *M/L***

Questions? davepooley@me.com