Title: Strong Lensing and Small Scale Structure

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Abstract:

Strong Lensing and Small Scale Structure

Greg Dobler

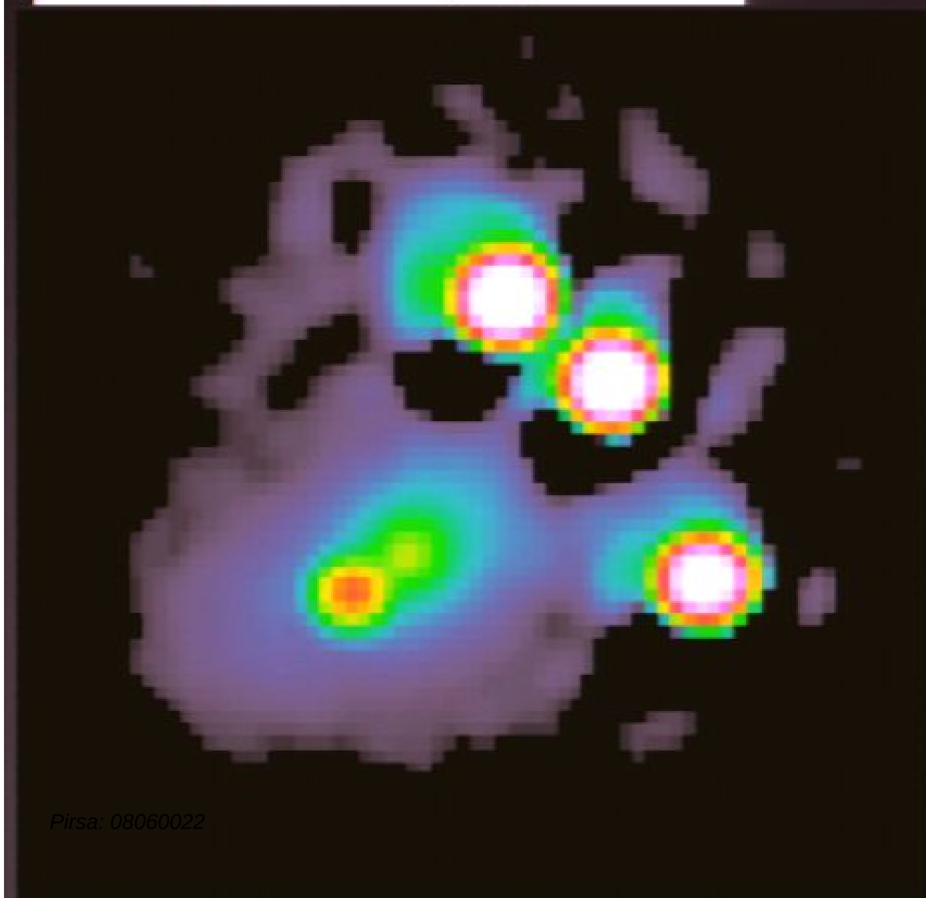
Harvard, CfA

June 8th, 2008 - Perimeter Institute

Length Scales in Strong Lensing

Mass $\longleftarrow R_E \longrightarrow$ Length

$$R_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}} \propto \sqrt{M}$$



"Macro"-lensing:

$R_E \sim 10^0{}''$, $M \sim 10^{12} M_0$

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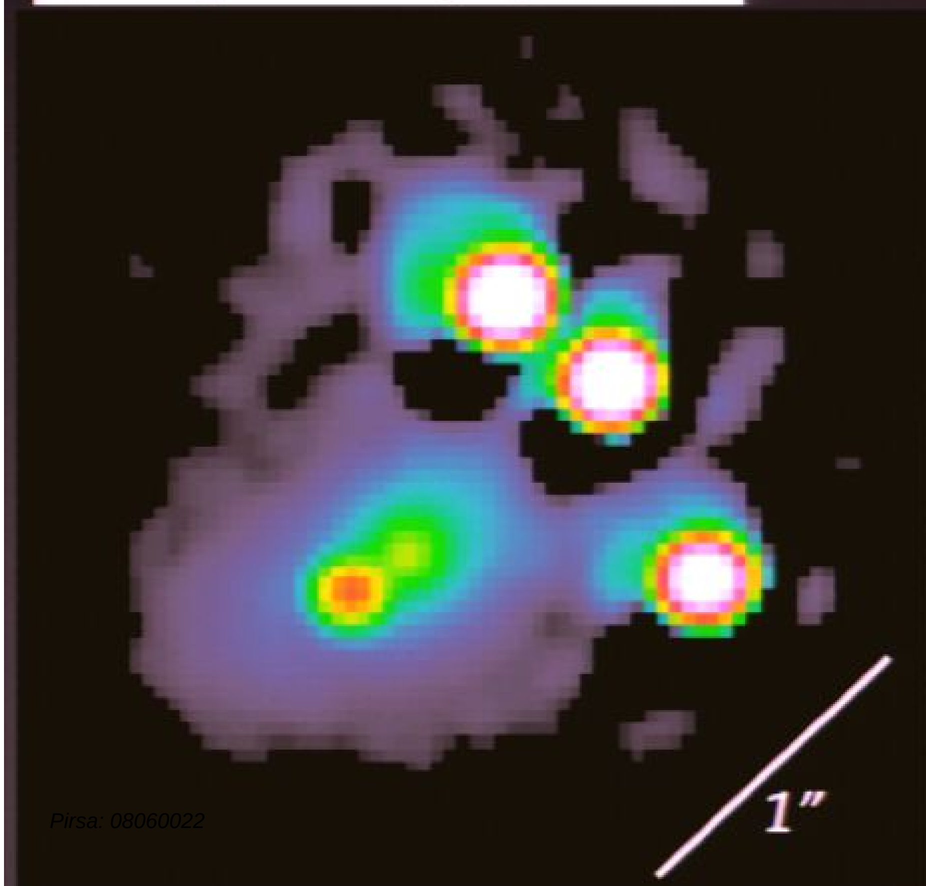

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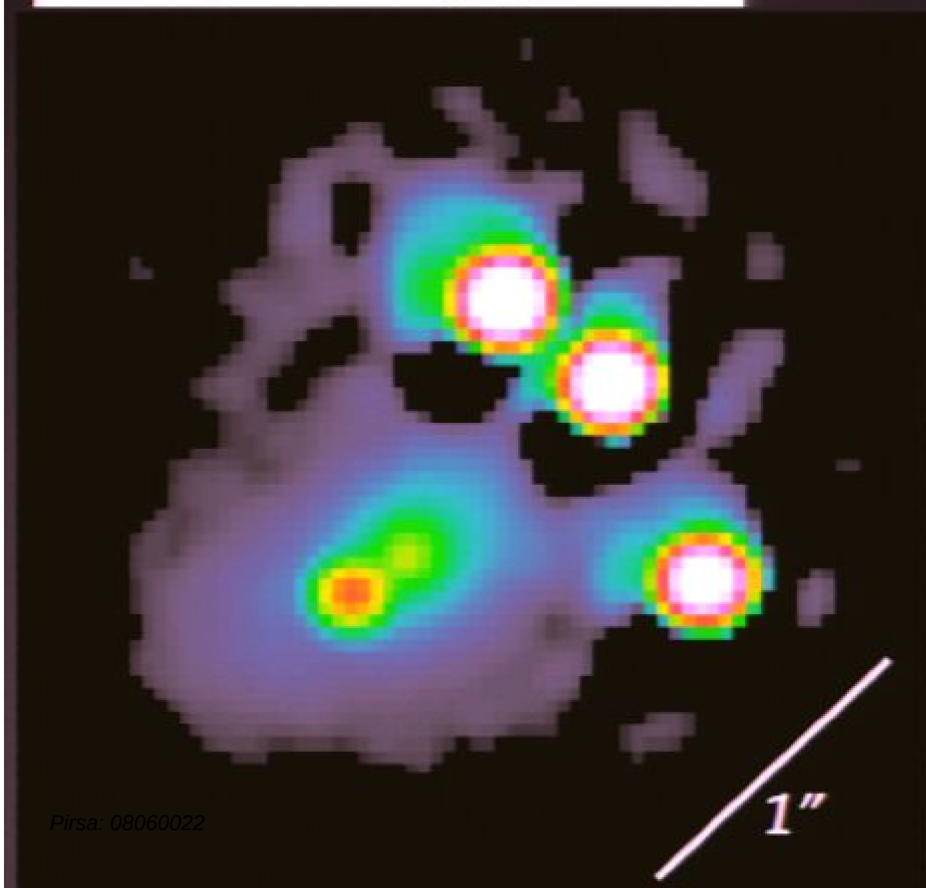

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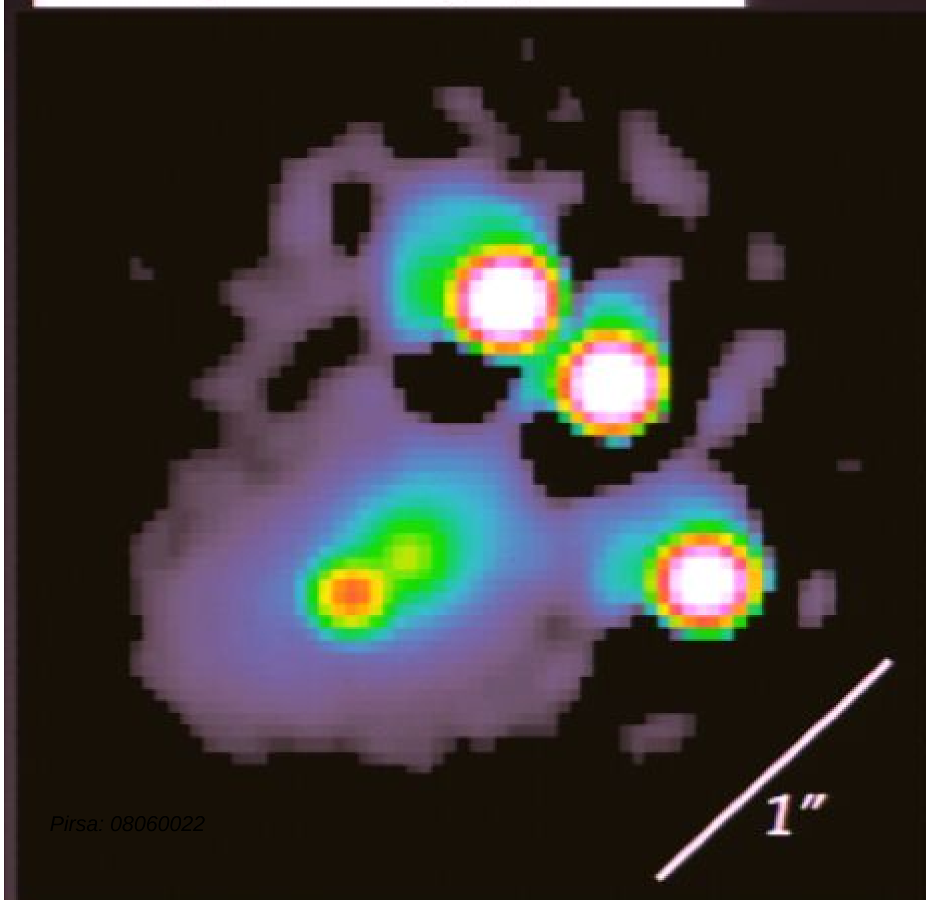

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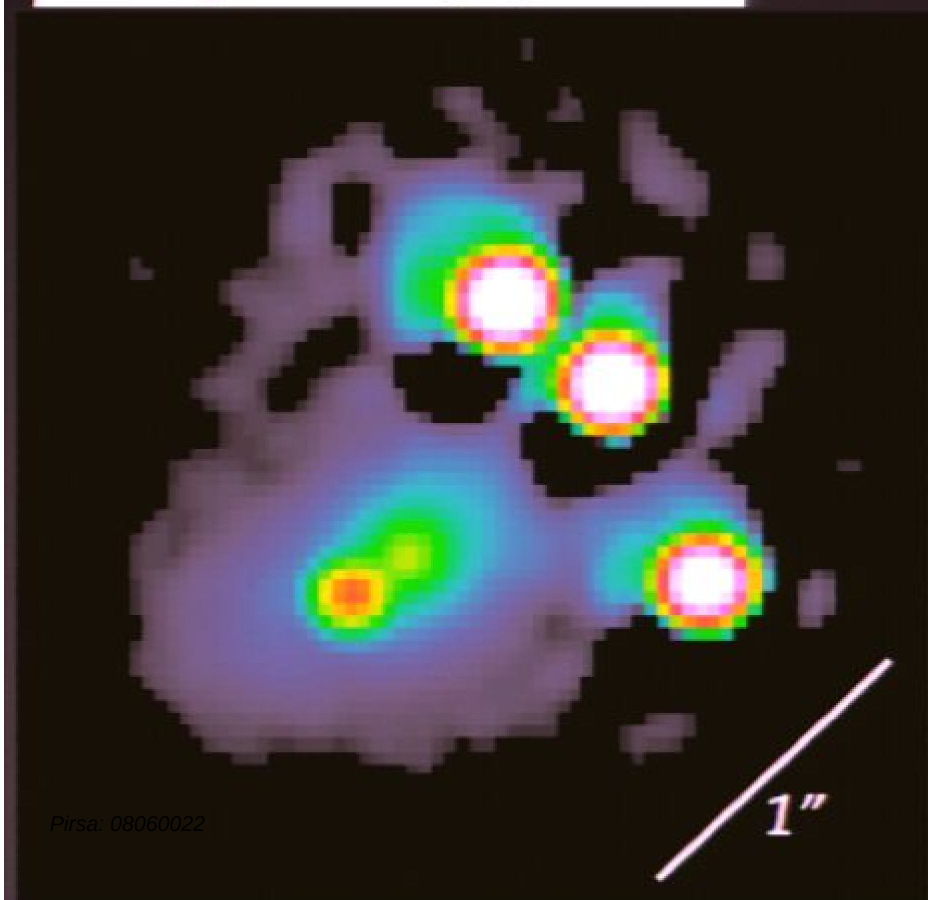

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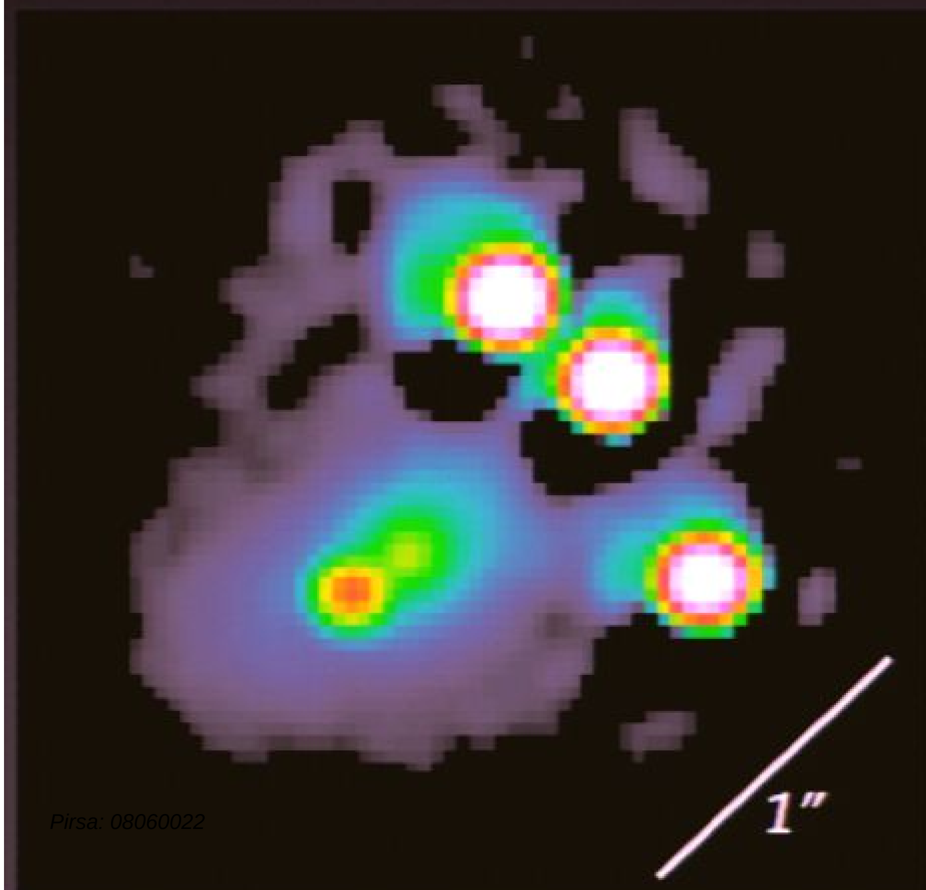

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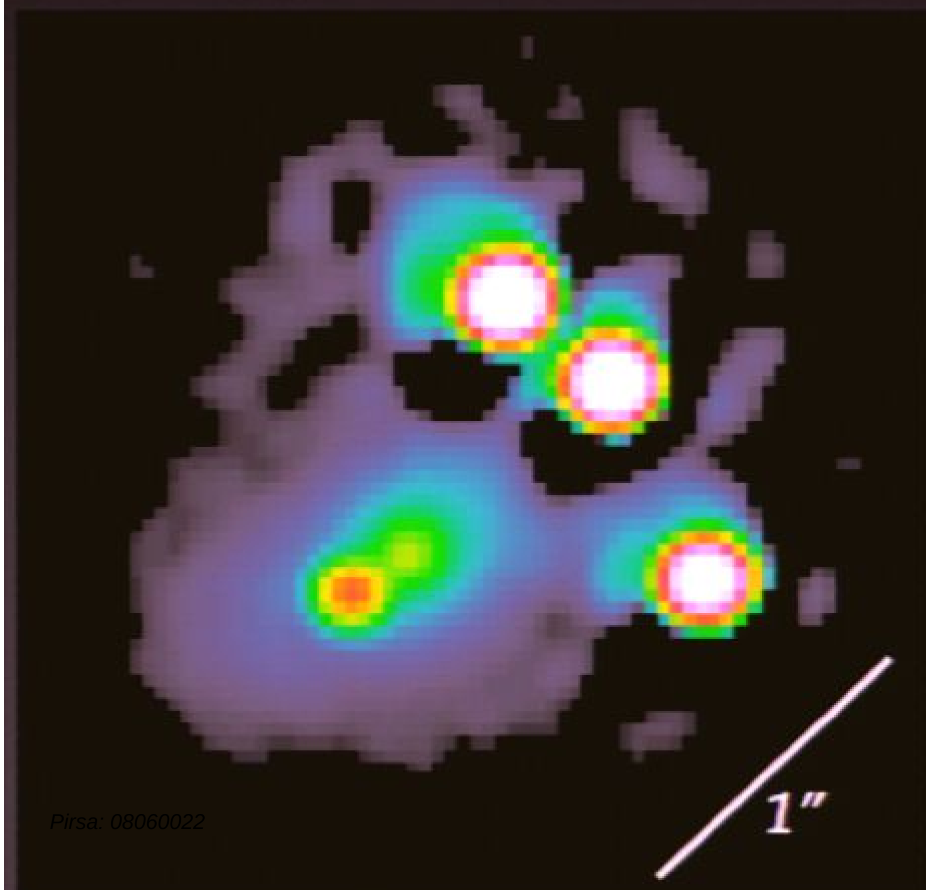

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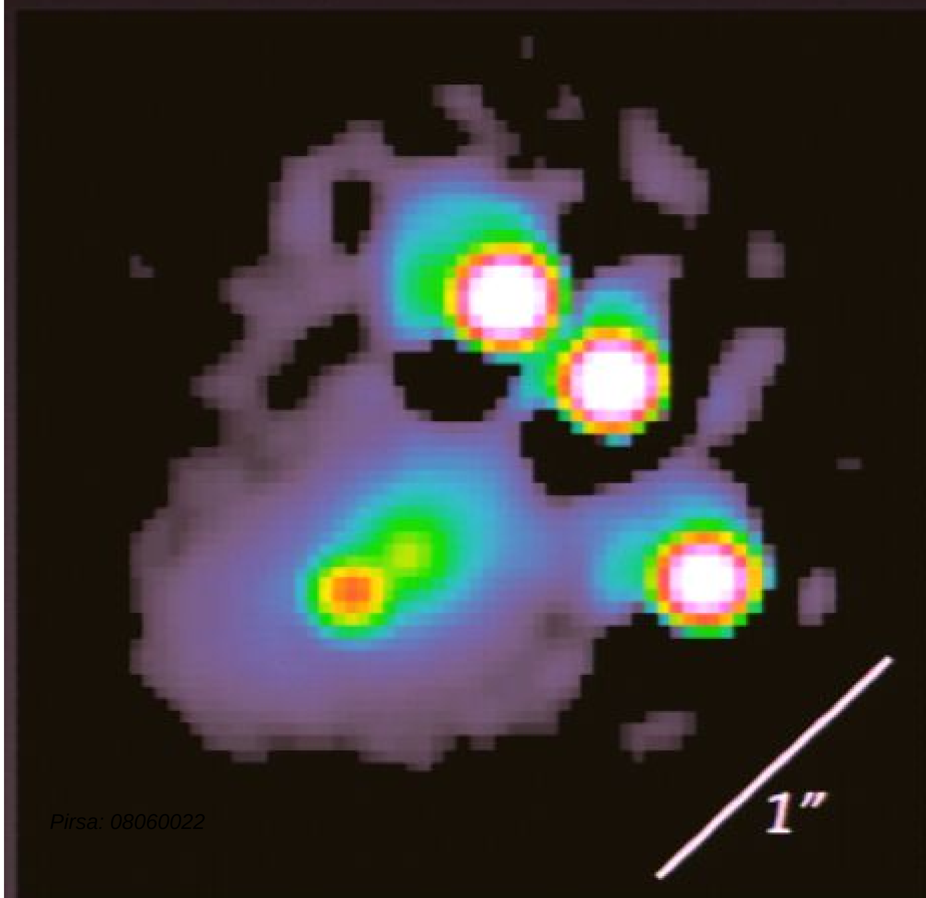

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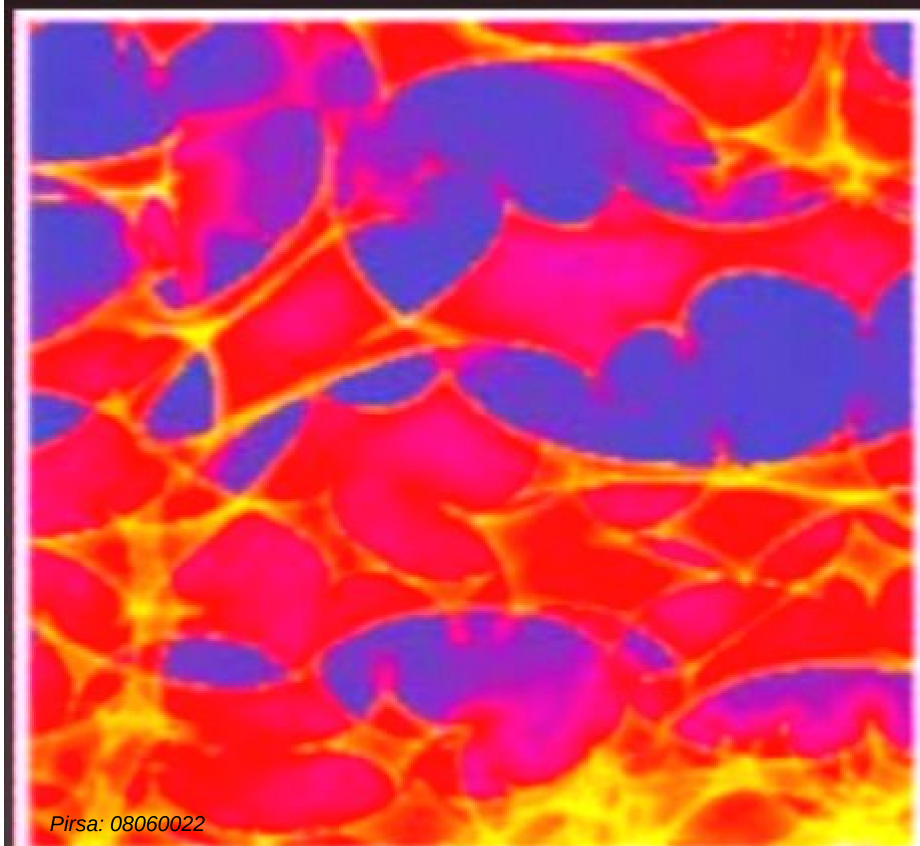

Dobler, Keeton, & Wambsganss (2007)

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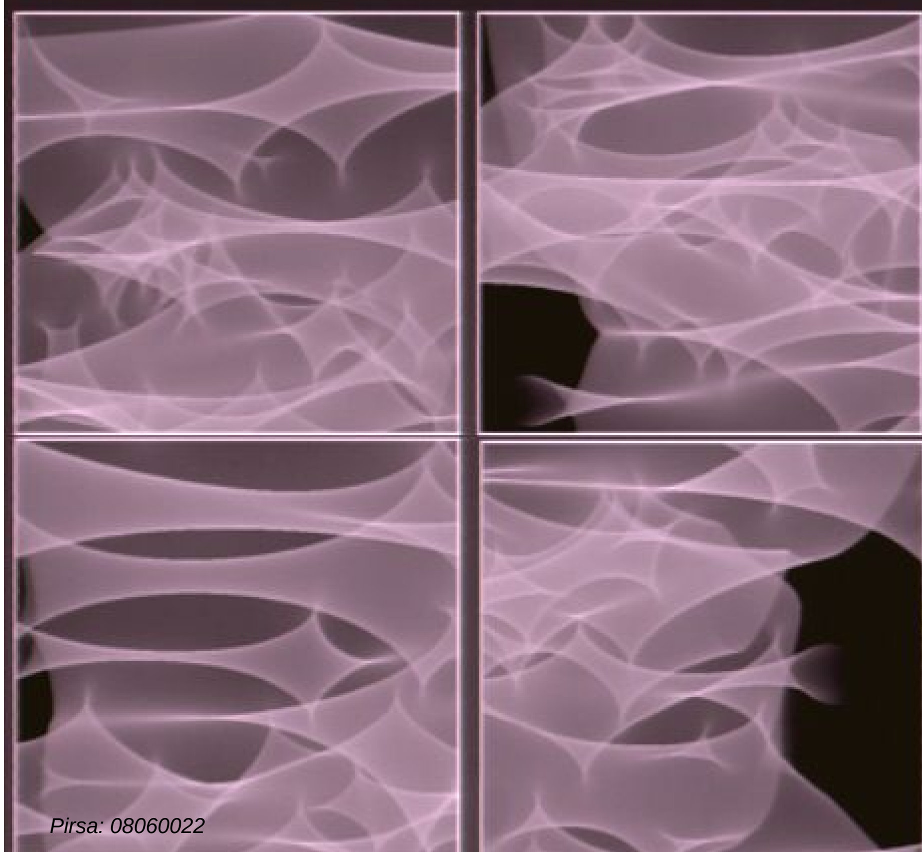

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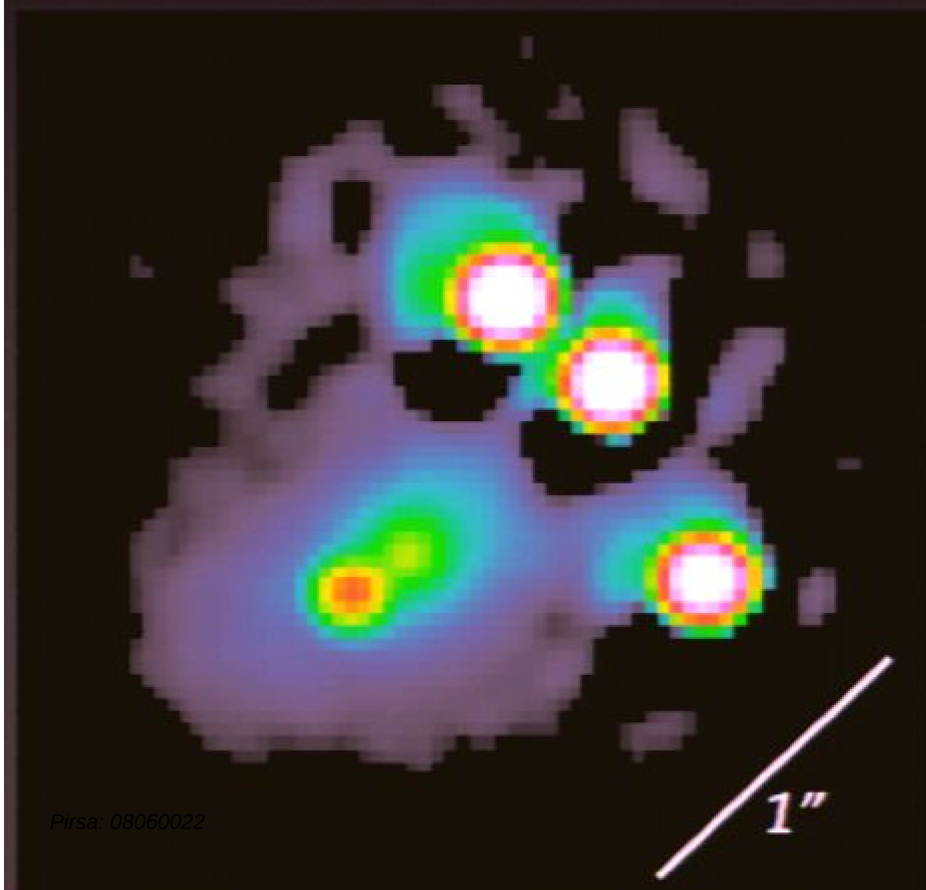

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But how do we **know** if an image is perturbed?

...we don't (typically) know f_{src}

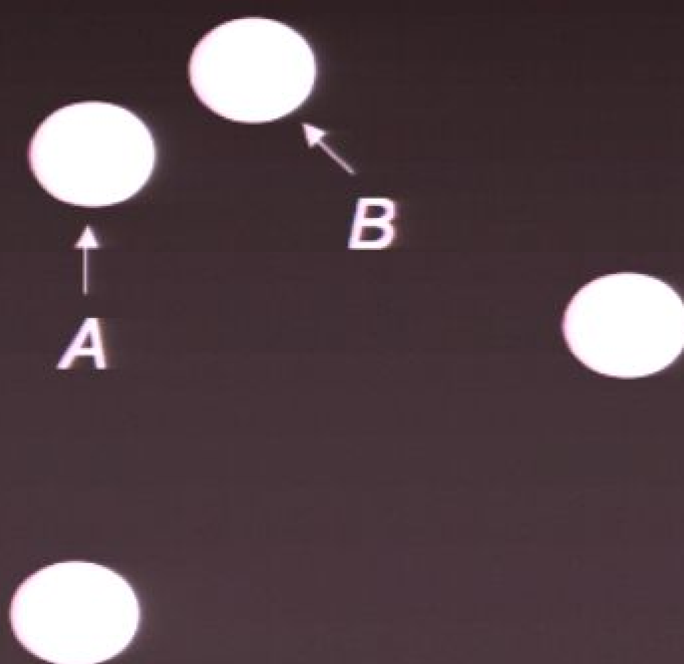
“Cusp” and “Fold” Relations

Mao (1992); Schneider & Weiss (1992)

Cusp: $f_A - f_B + f_C \approx 0$

e.g., B2045+265

Fold: $f_A - f_B \approx 0$



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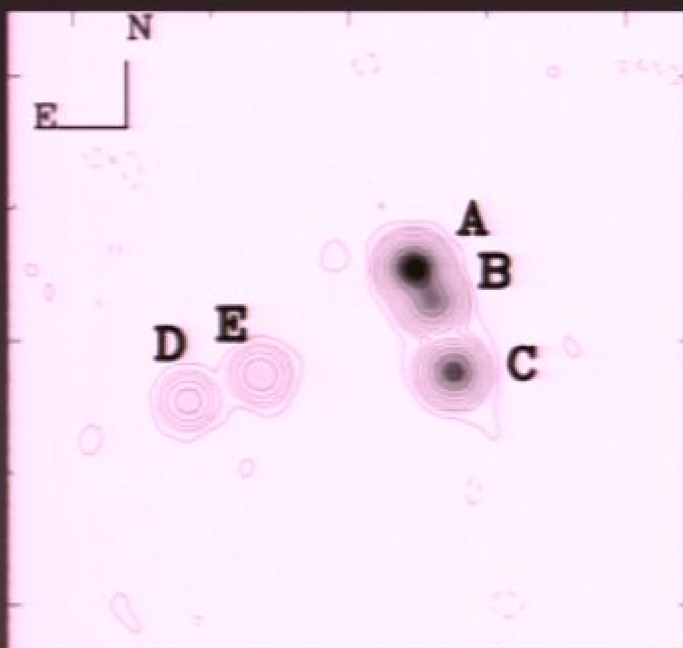

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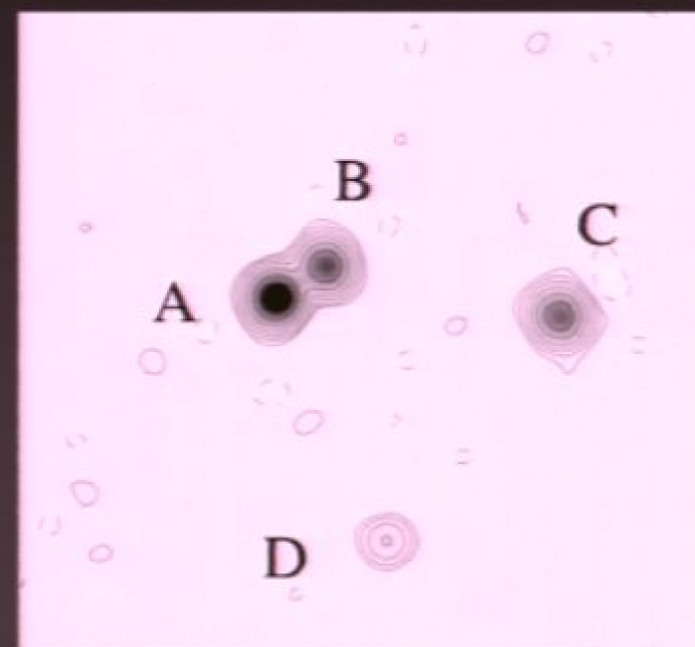

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First Hints of Substructure

Mao & Schneider (1998)

- Smooth lens models fail to predict the observed fluxes (e.g., *B1422+231*)
- Phrase the lack of consistency in terms of $r \equiv \dfrac{\mu_A + \mu_B + \mu_C}{|\mu_A| + |\mu_B| + |\mu_C|}$

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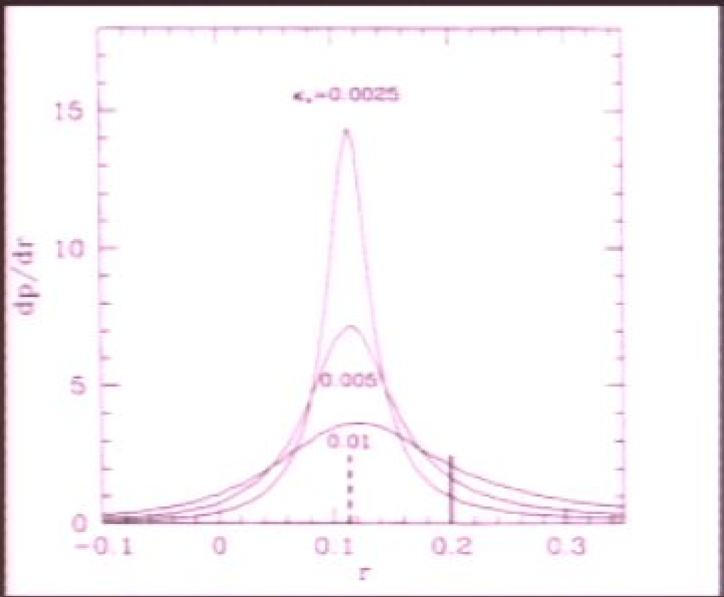

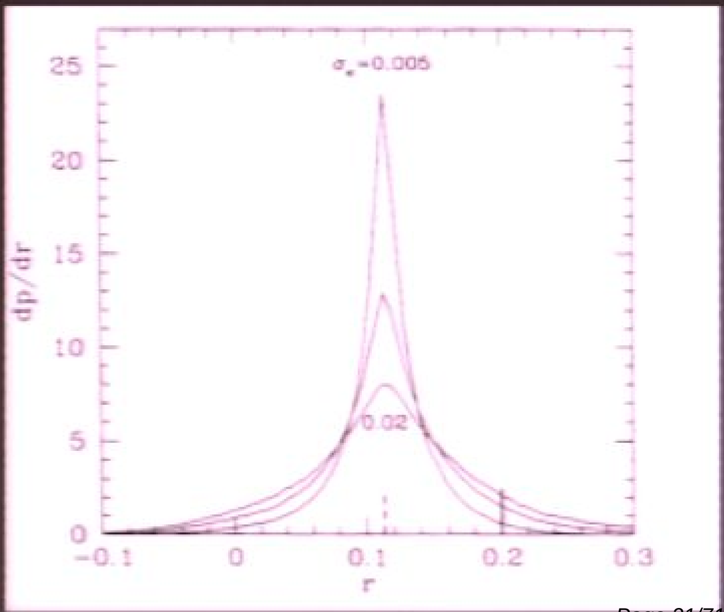

Point mass perturbations

Plane wave perturbations

“Direct Detection” of Substructure

Dalal & Kochanek (2002)

- 7 radio loud quads
- Statistically fit lenses with potential perturbation
  - measurement errors (systematics dominated)
- Re-interpret perturbation in language of substructure model
  - Monte Carlo simulations
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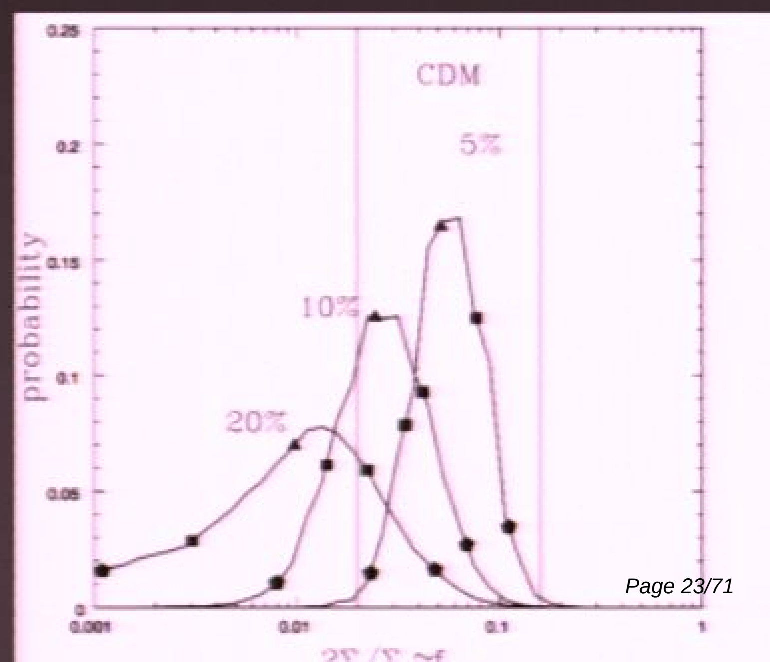

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($0.006 < f_{\text{sat}} < 0.07$, 90% confidence)

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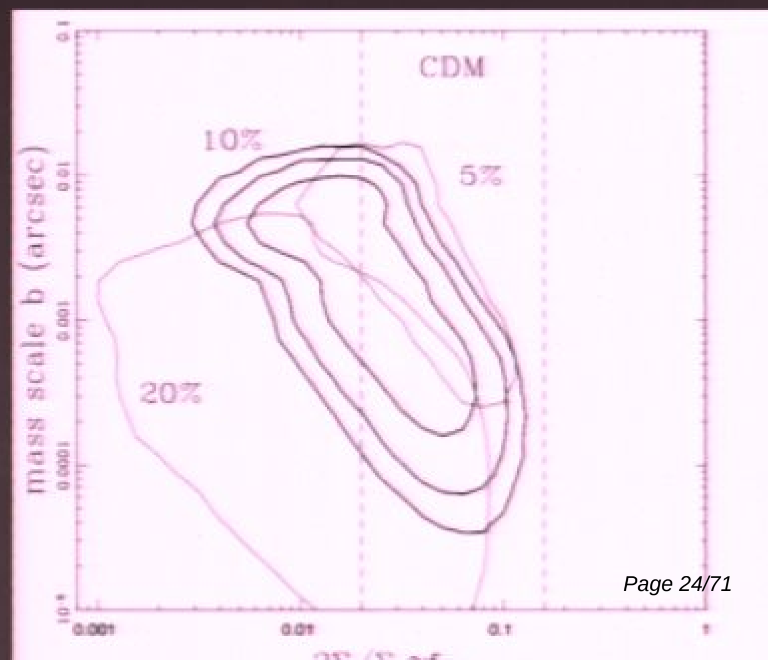

Substructure mass scale less well constrained, but broadly consistent with millilensing a brief *(but important!)* aside:

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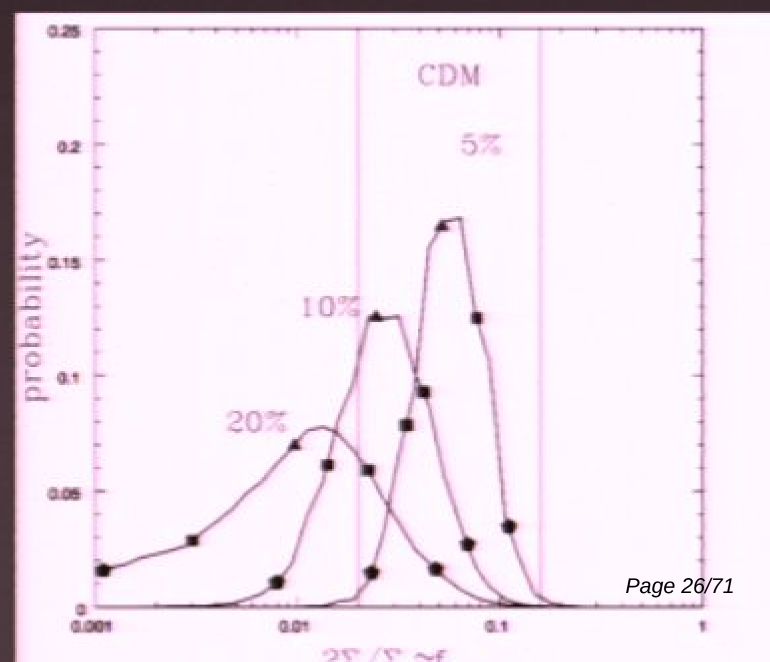

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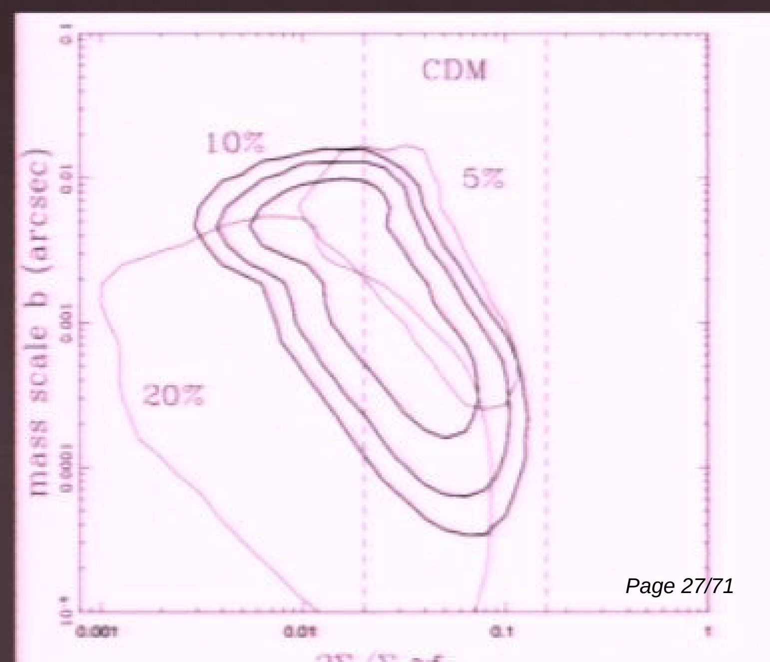

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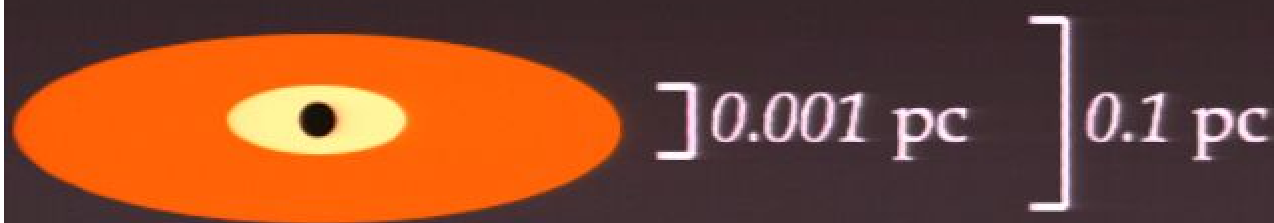

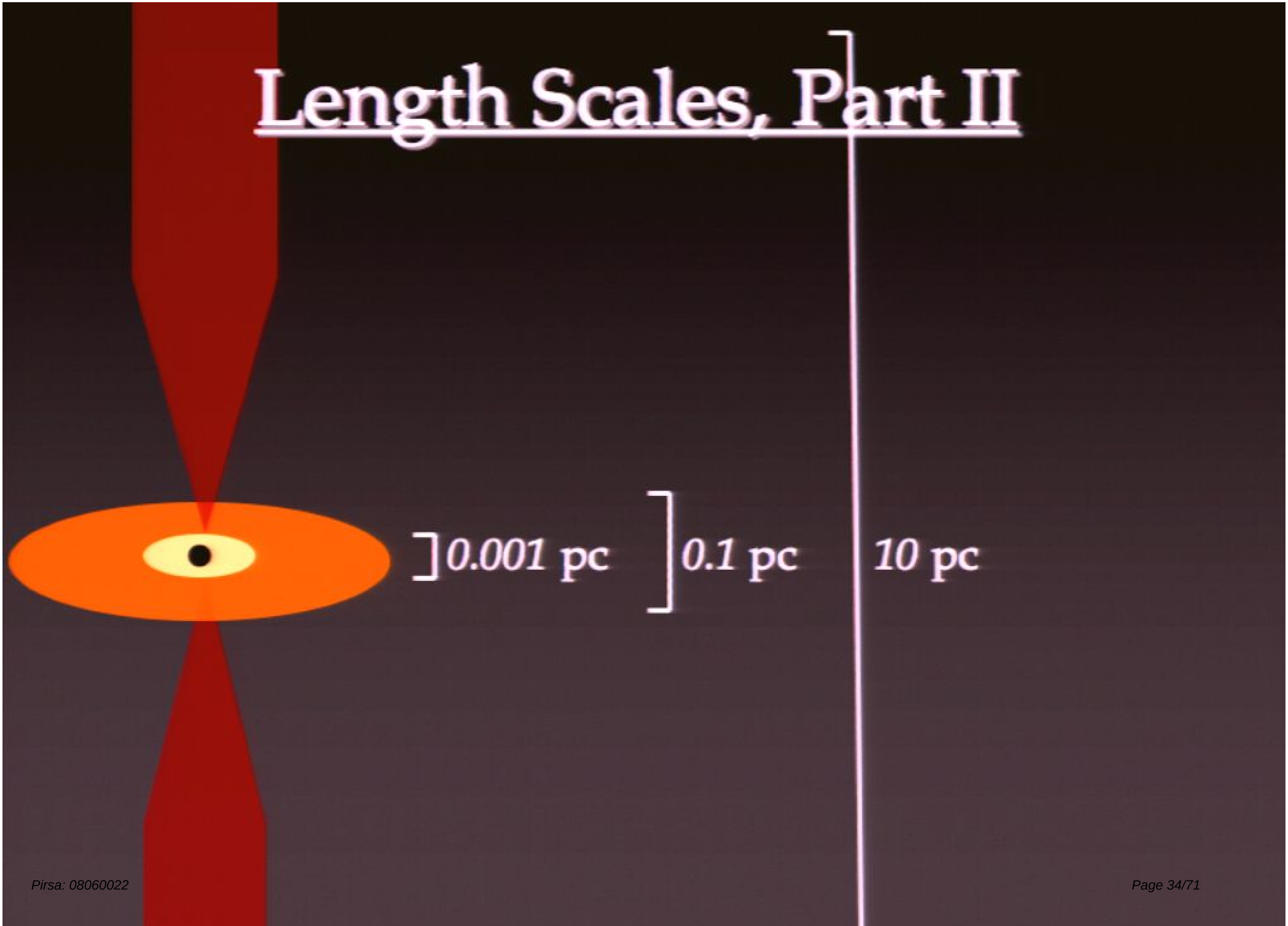
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0.1 pc
10 pc

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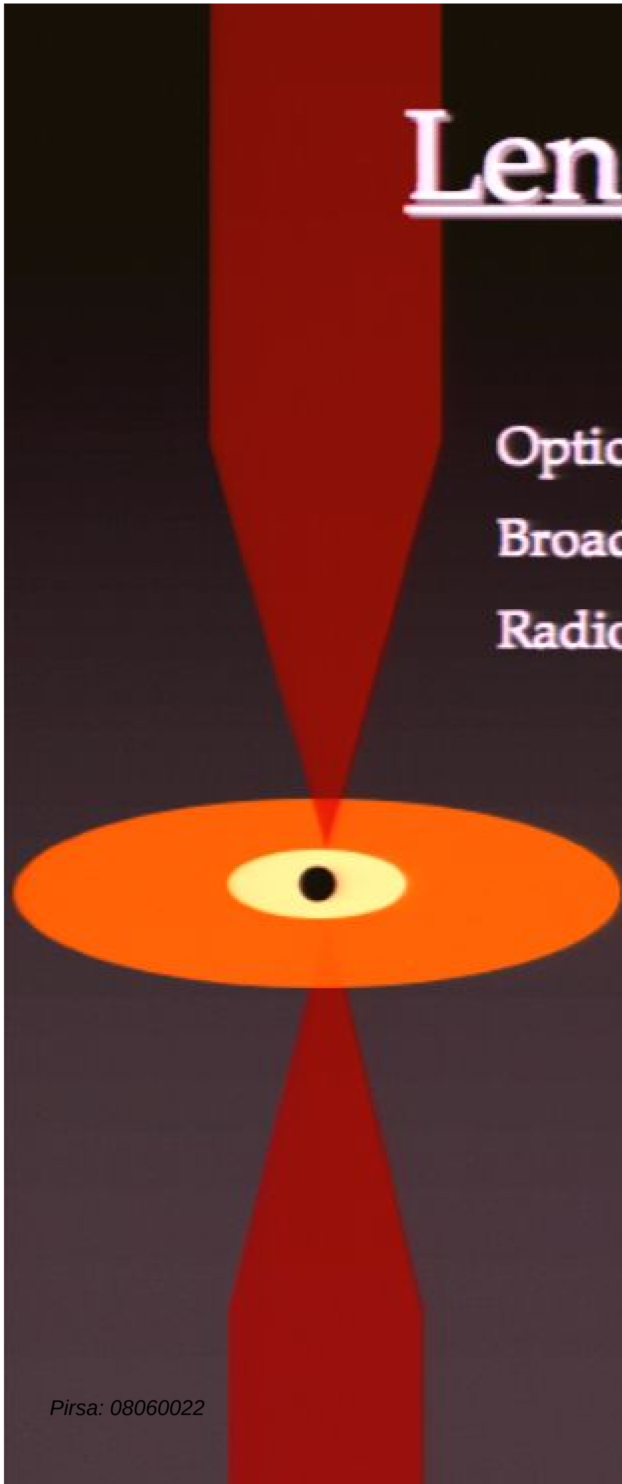

at z~2 …

Optical continuum - compact core ≤ *10^{15}* cm ~ *0.1* μas

Broad line emission region ≤ *10^{16}* - 10^{17} cm ~ *10* μas

Radio emission region > *10^{19}* cm ~ *1* mas

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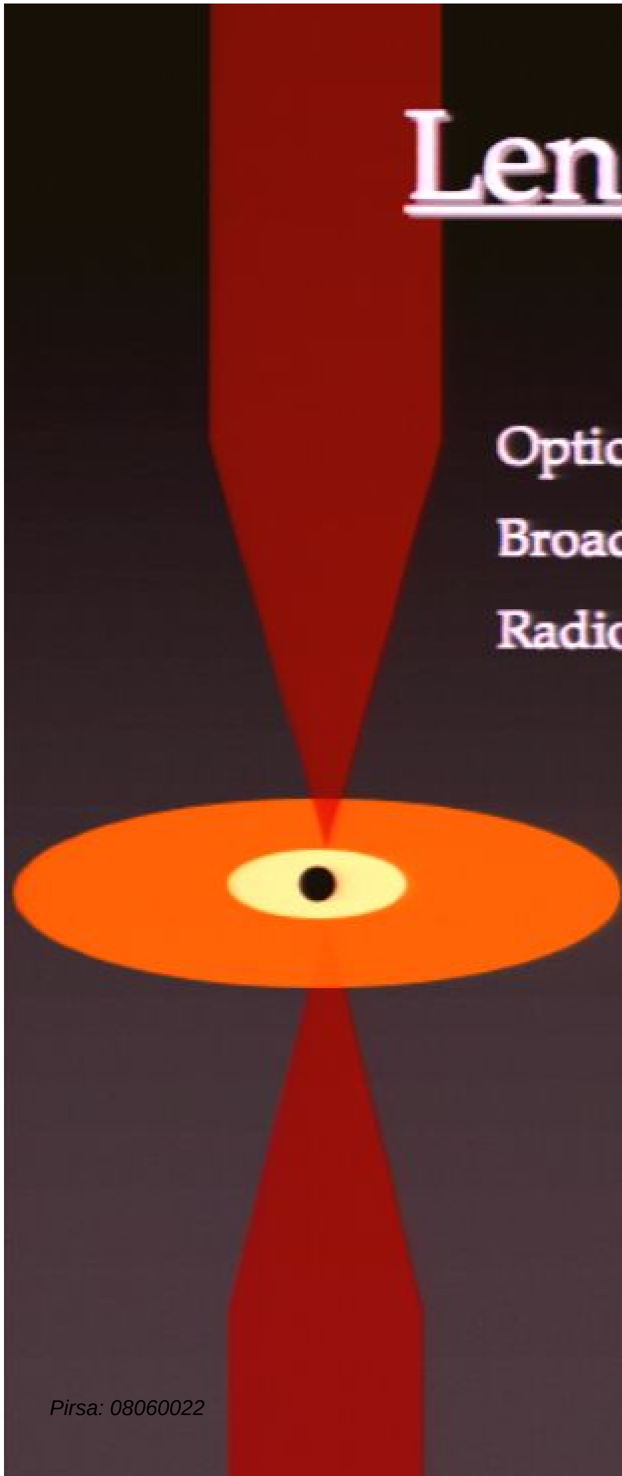
Broad line emission region $\leq 10^{16}$ - 10^{17} cm ~ 10 μas $\Rightarrow$ sub/stars

Radio emission region > 10^{19} cm ~ 1 mas $\Rightarrow$ substructure



Length Scales, Part II

Magnifications only sensitive to mass/length scales $\geq R_{src}$ (finite source lensing)

- need ***radio*** to study substructure ⇒ *~10* systems
- could use multiple λ to probe multiple mass scales *(Metcalf et al 2004; Dobler & Keeton 2006)*

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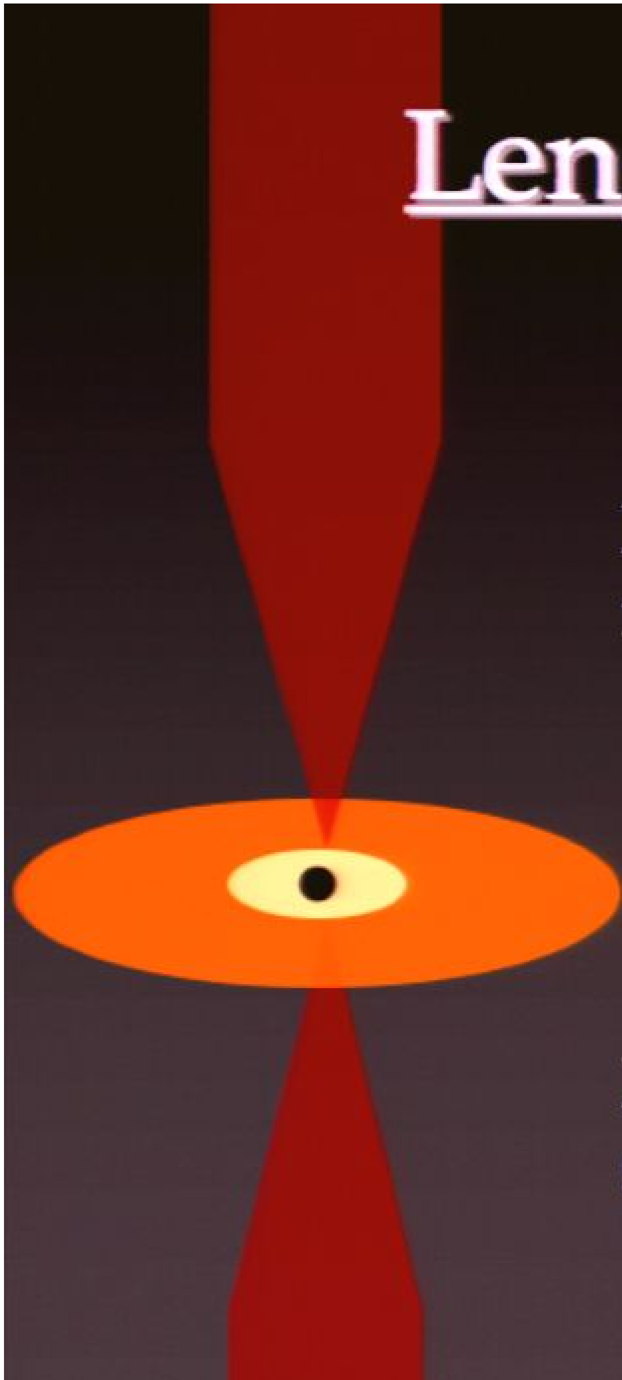

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Flux ratios provide information about structure ~ image separation

- need cusp or fold configurations
- leads to ambiguity with macromodel

Macromodel Uncertainties

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B2045+265

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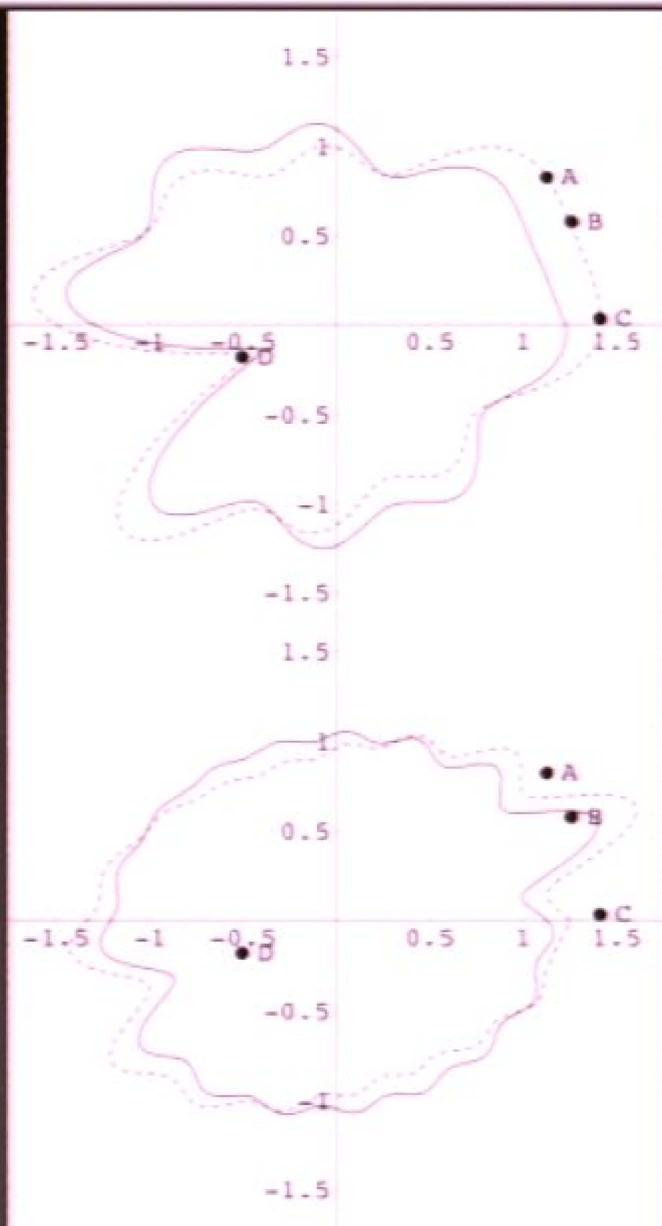

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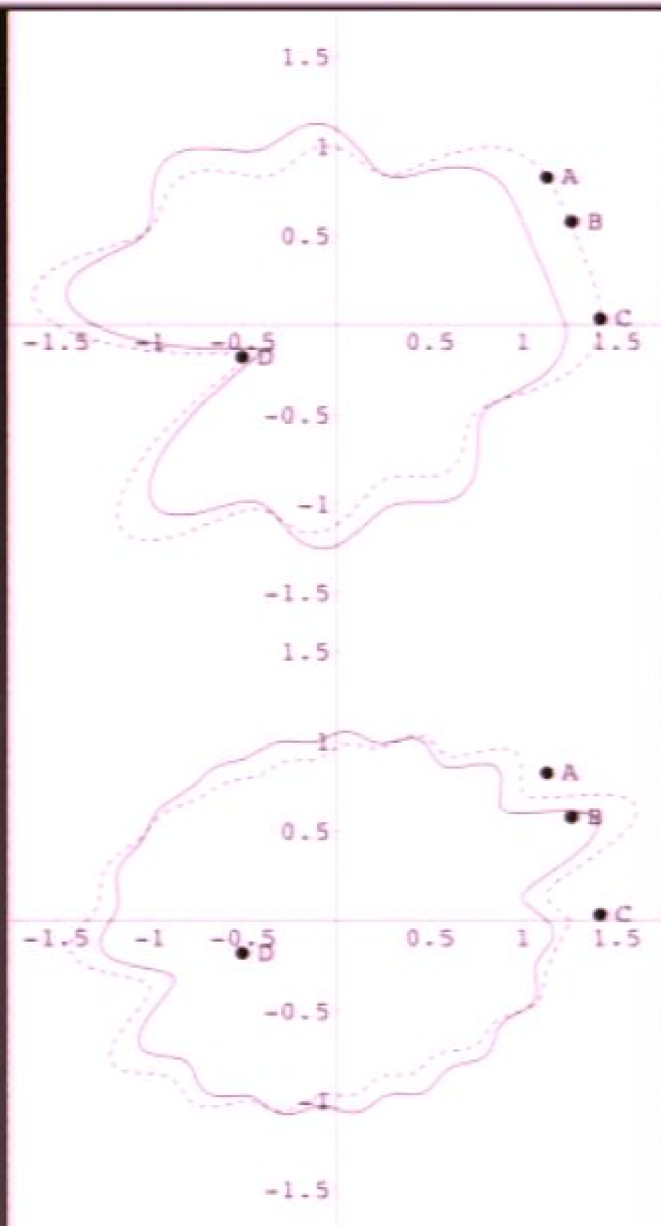
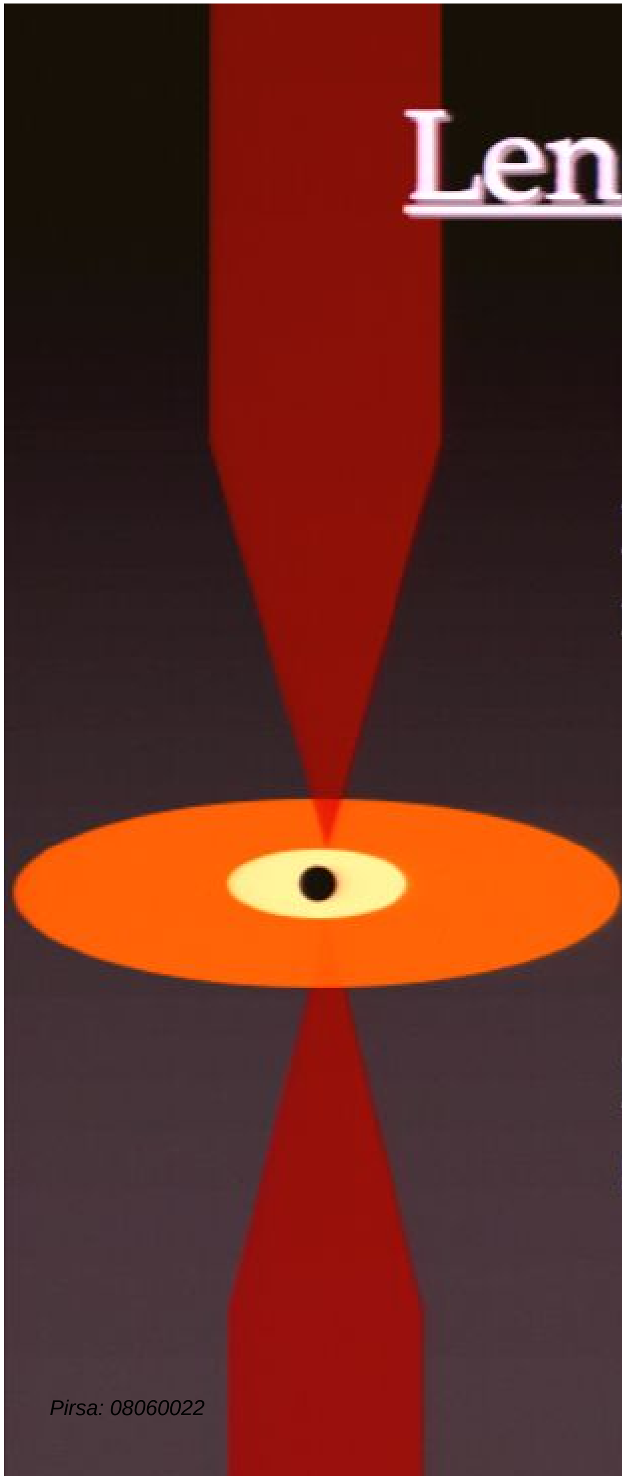


Parameterize the mass model with multipole expansion

- Unphysically large amount of power in low order multipoles
- Requires high order multipoles to get realistic models (substructure)
- Models vary with wavelength (*Evans & Witt 2003*)

Length Scales, Part II



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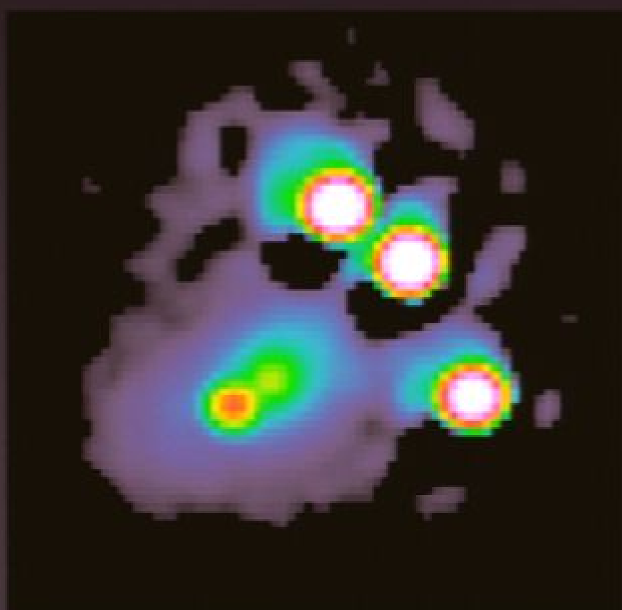

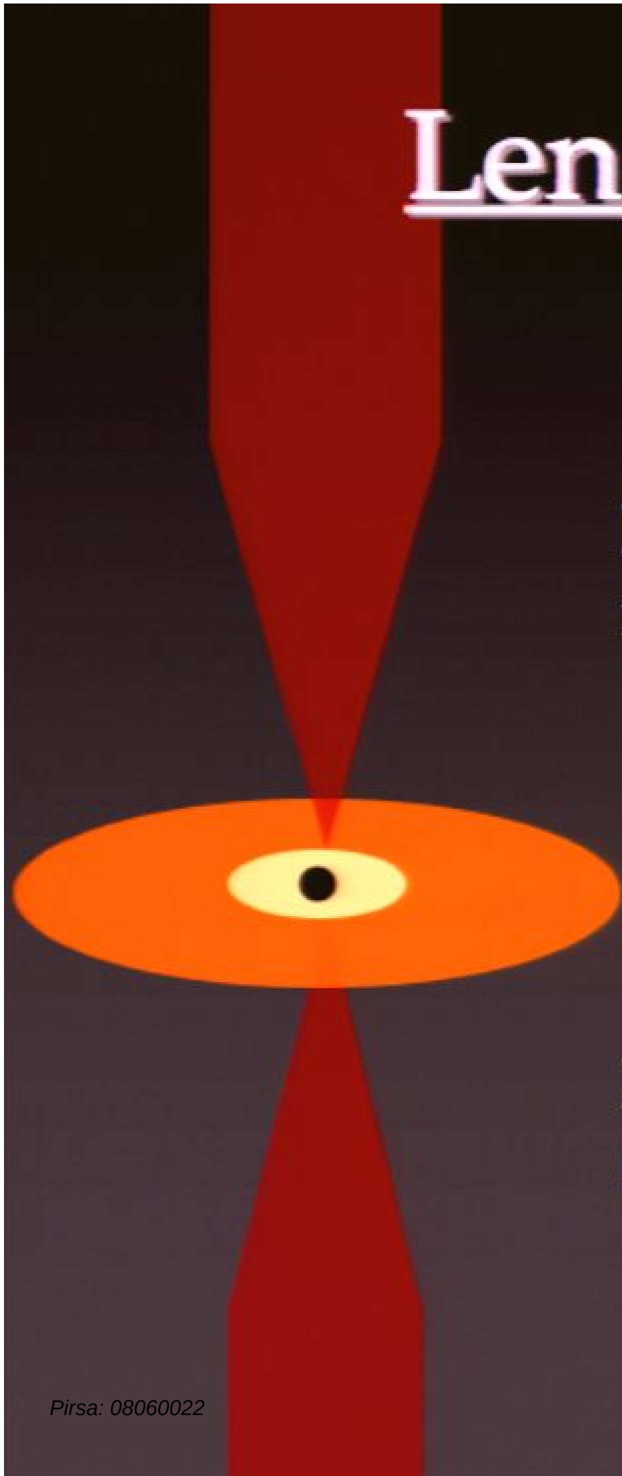

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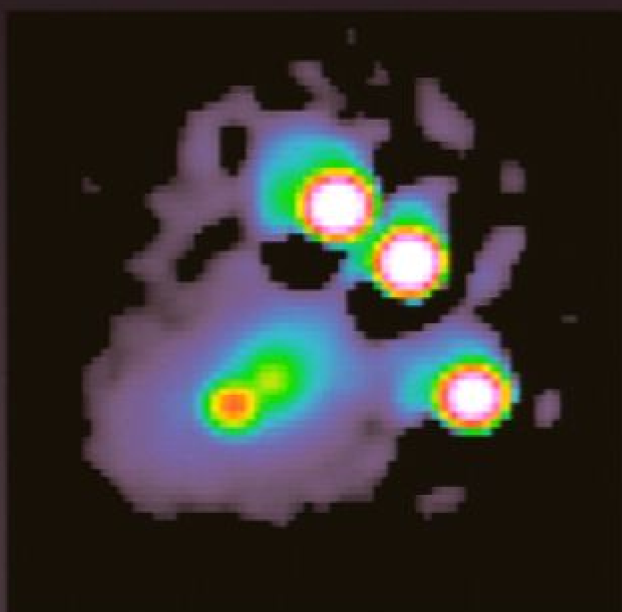

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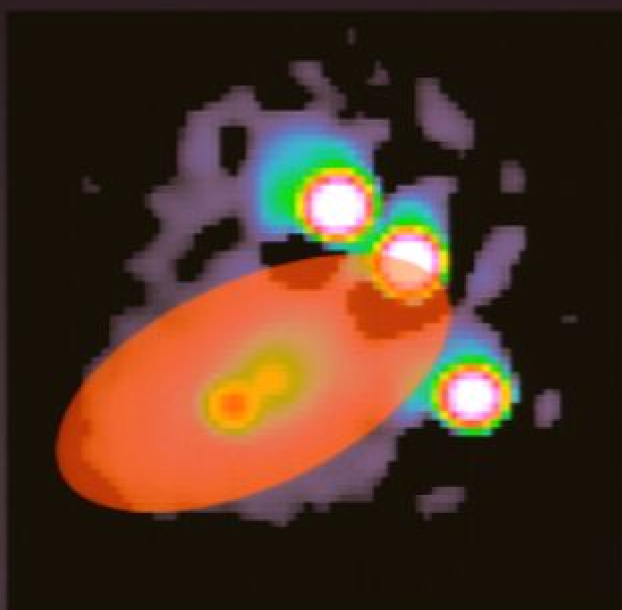

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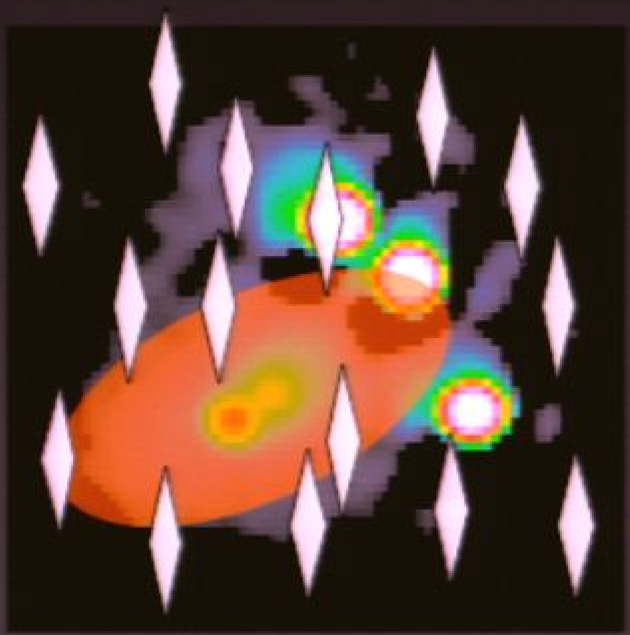

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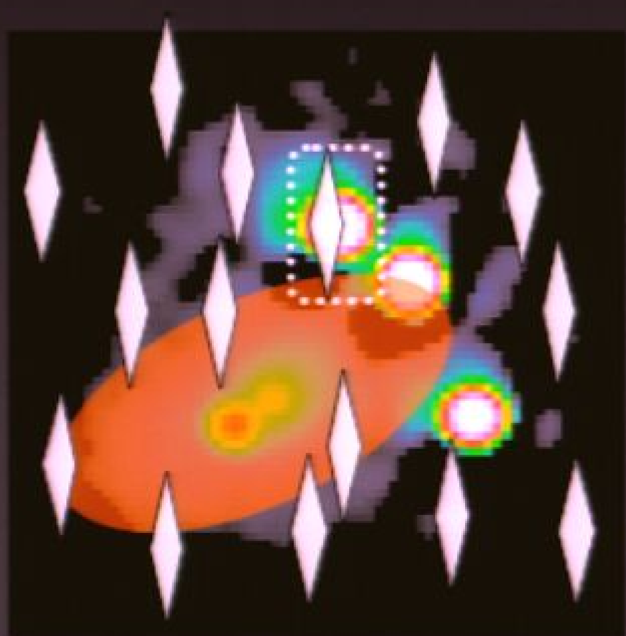

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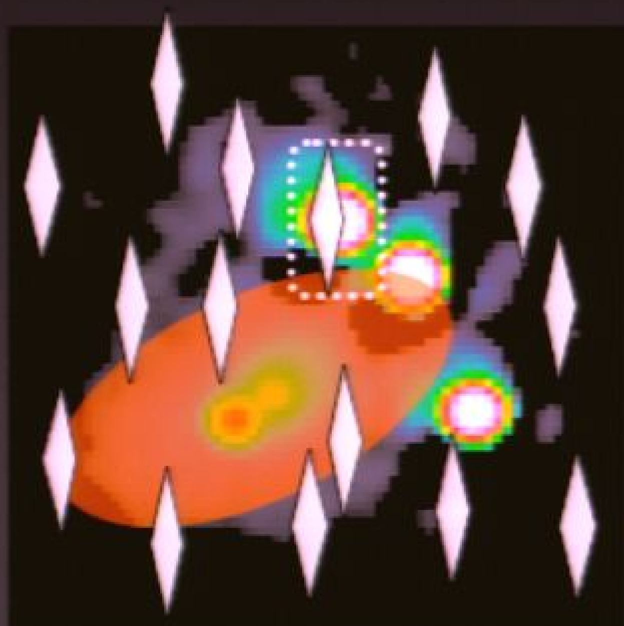

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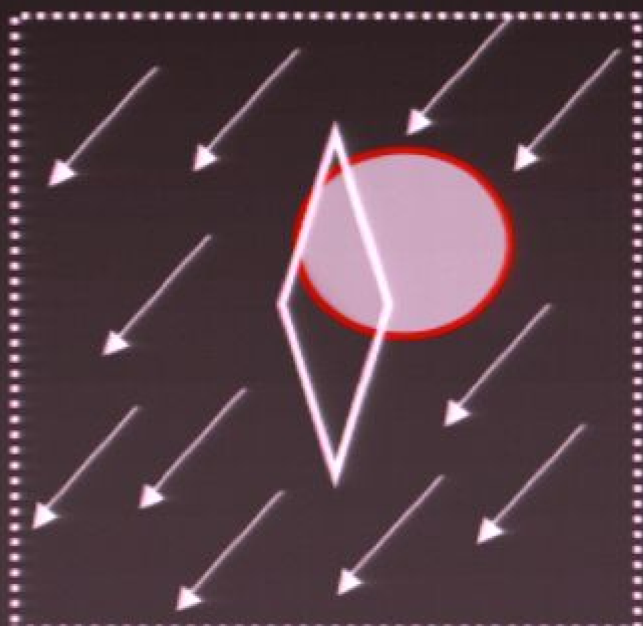

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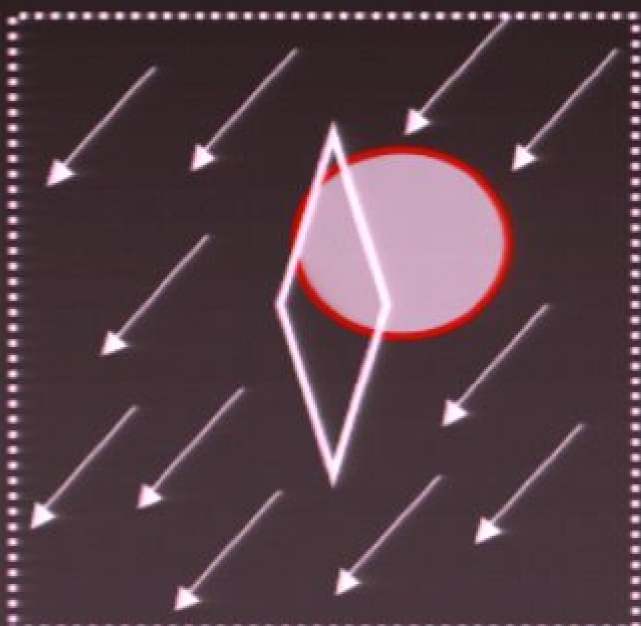

Substructure Model:

$$\mathrm{SIS} + (\kappa + \gamma)$$

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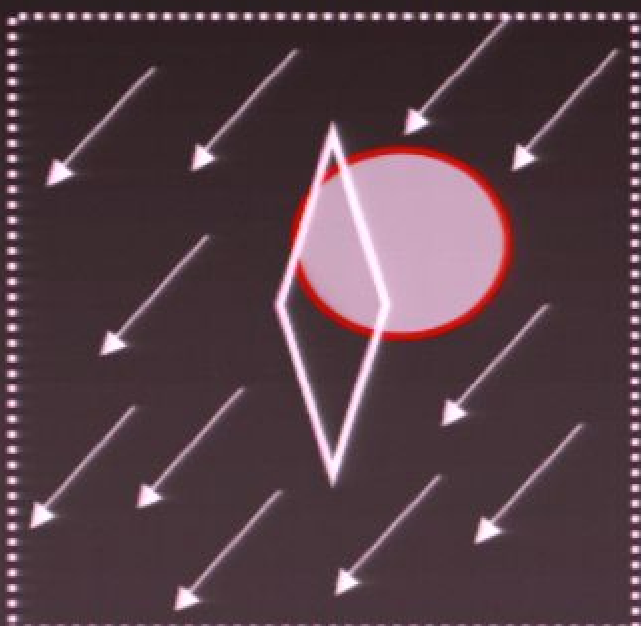
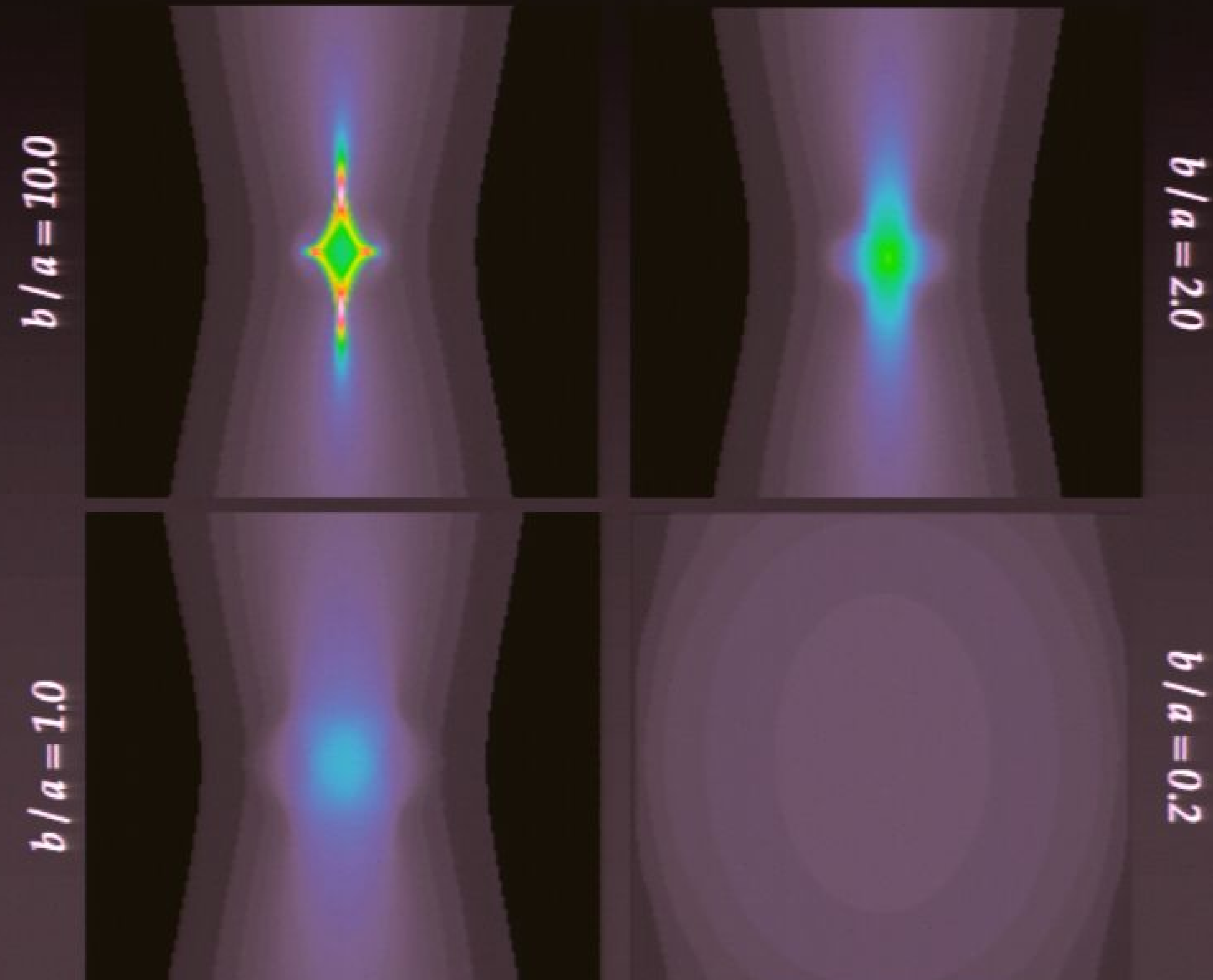


Substructure Model:

$$SIS + (\kappa + \gamma)$$

- allows for semi-analytic analysis
- conservative lower bounds

Magnification Maps ($\kappa=\gamma=0.3$)



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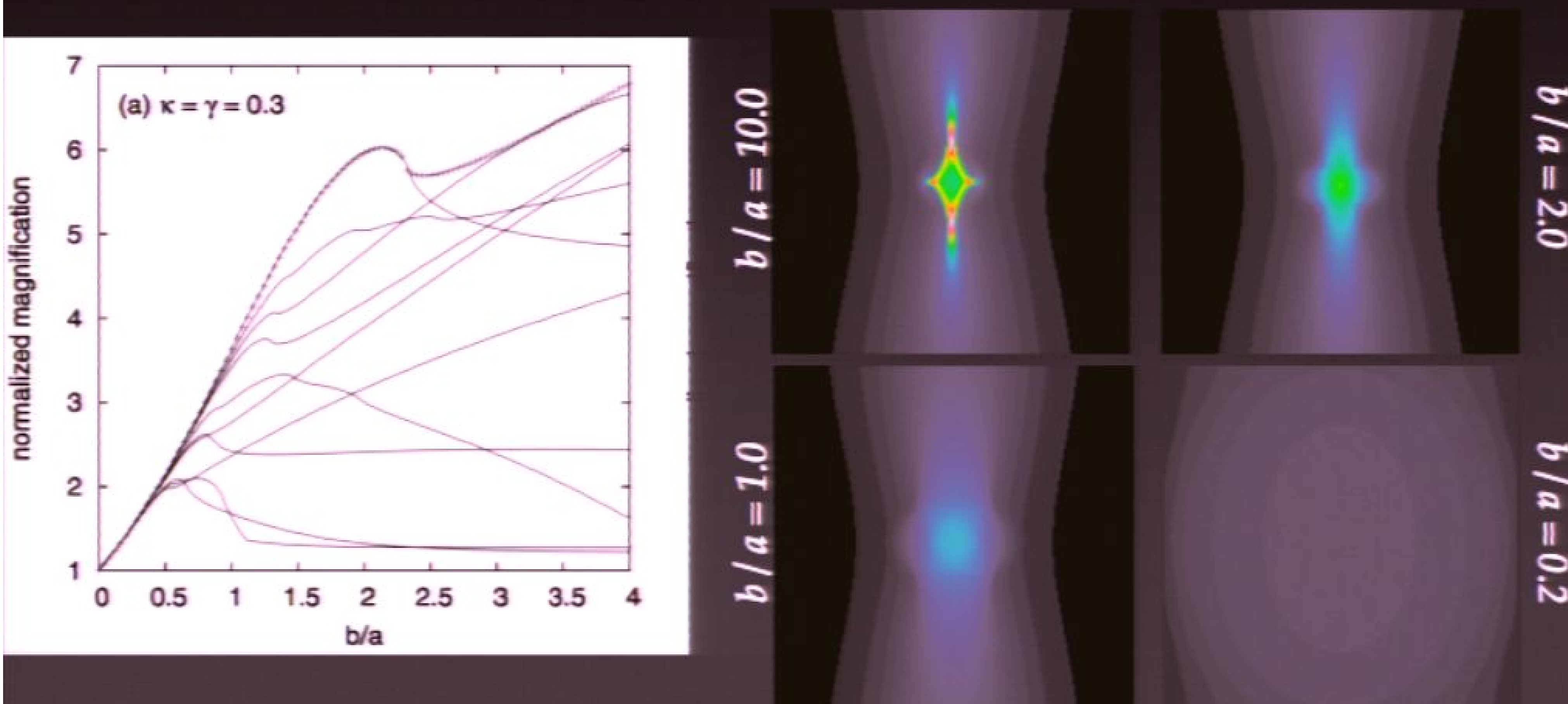


Dobler & Keeton (2006)

Setting Limits on the Substructure Mass Scale

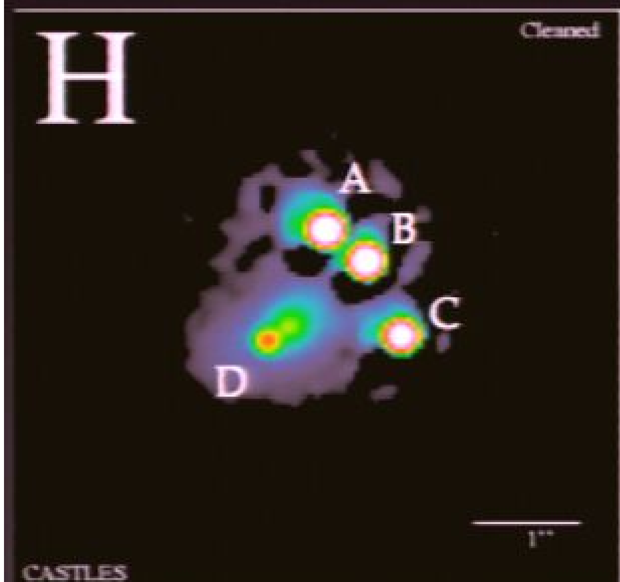
1) Attempt to fit the observed position measurements (for the images and the galaxy) and flux measurements (for the images).

2) Relax the flux constraints on one (or more) images to find a better fit model.

3) Calculate the local convergence and shear at this "perturbed image" and use the finite source method to place a lower limit on b/a.

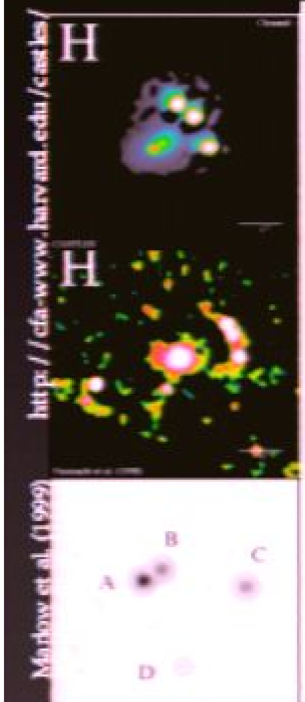
4) Taking $a \sim 10$ pc, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, convert b/a_{min} to $M(b)_{min}$.

Dobler & Keeton (2006)



B1422+231 SIE+γ_{ext}						
	Normalized Magnification					
case	Image A	Image B	Image C	Image D	χ^2_{mod}	χ^2_{flux}
abcd	1.02	0.99	0.94	0.75	112.97	48.08
abc	1.02	1.00	0.94	0.70	98.34	34.59
abd	1.01	0.99	0.83	0.70	35.08	19.81
acd	1.02	0.96	0.94	0.76	111.19	49.17
bcd	1.21	1.01	1.00	0.93	3.07	0.89
ab	1.00	0.99	0.82	0.65	12.91	0.90
ac	1.02	0.98	0.94	0.70	97.99	35.69
ad	1.00	0.83	0.82	0.79	10.29	6.83
bc	1.21	1.01	0.99	0.91	2.40	0.56
bd	1.19	1.00	0.98	0.91	2.41	1.16
cd	1.23	1.04	1.00	0.91	1.71	0.94

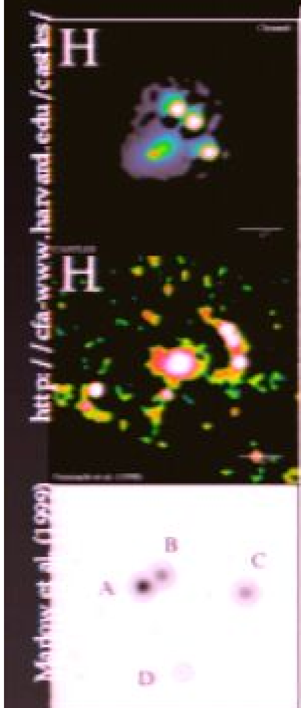
Dobler & Keeton (2006)



Lens	Macromodel	Perturbed Image(s)	χ^2/ν	Image	$M(b)_{min}$ ($M_\odot$)	σ_{min} (km s^{-1})
B1422+231	ellipsoid+shear	A	3.073/3	A	2.07×10^3	2.24
B2045+265	internal+external shear	A and C	7.051/2	A	2.29×10^6	15.51
				C	1.58×10^7	25.12
		B and C	6.320/2	B	4.77×10^5	10.48
				C	3.71×10^5	9.84
B1555+375	internal+external shear	A and C	1.045/0	A	1.96×10^5	7.14
				C	3.54×10^6	14.72
		B and C	0.000/0	B	1.19×10^5	6.30
				C	5.08×10^4	5.09

- More than one image may be perturbed in a given lens system
- Minimum mass to produce the observed perturbations > 10^3 M_0

Dobler & Keeton (2006)



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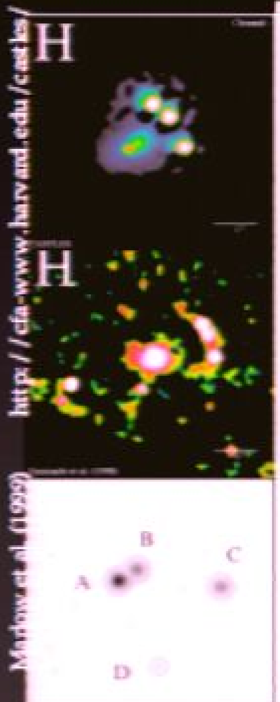
Source geometry - ellipse, jets, ...



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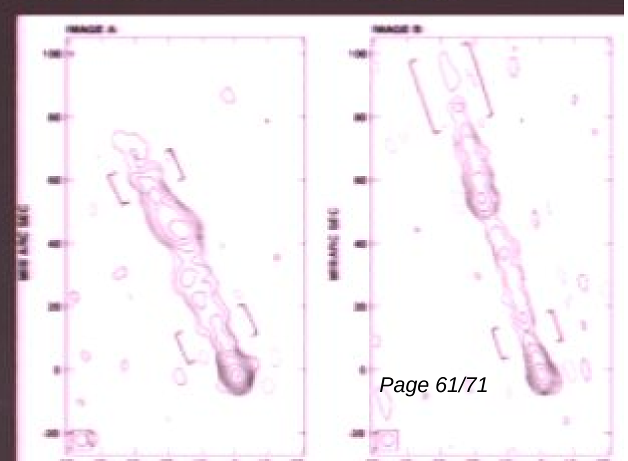
Haraasma et al (2008)



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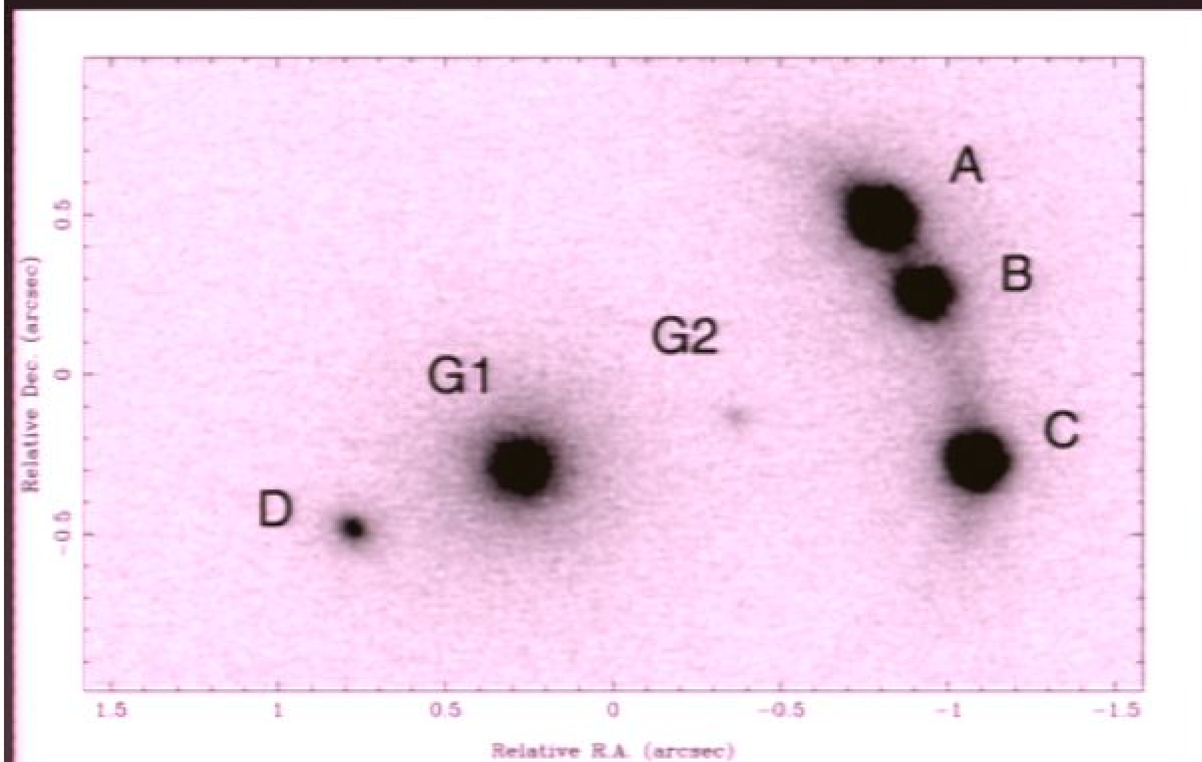
The Future is Here

McKean et al (2007)

Adaptive optics a 2.2 μm



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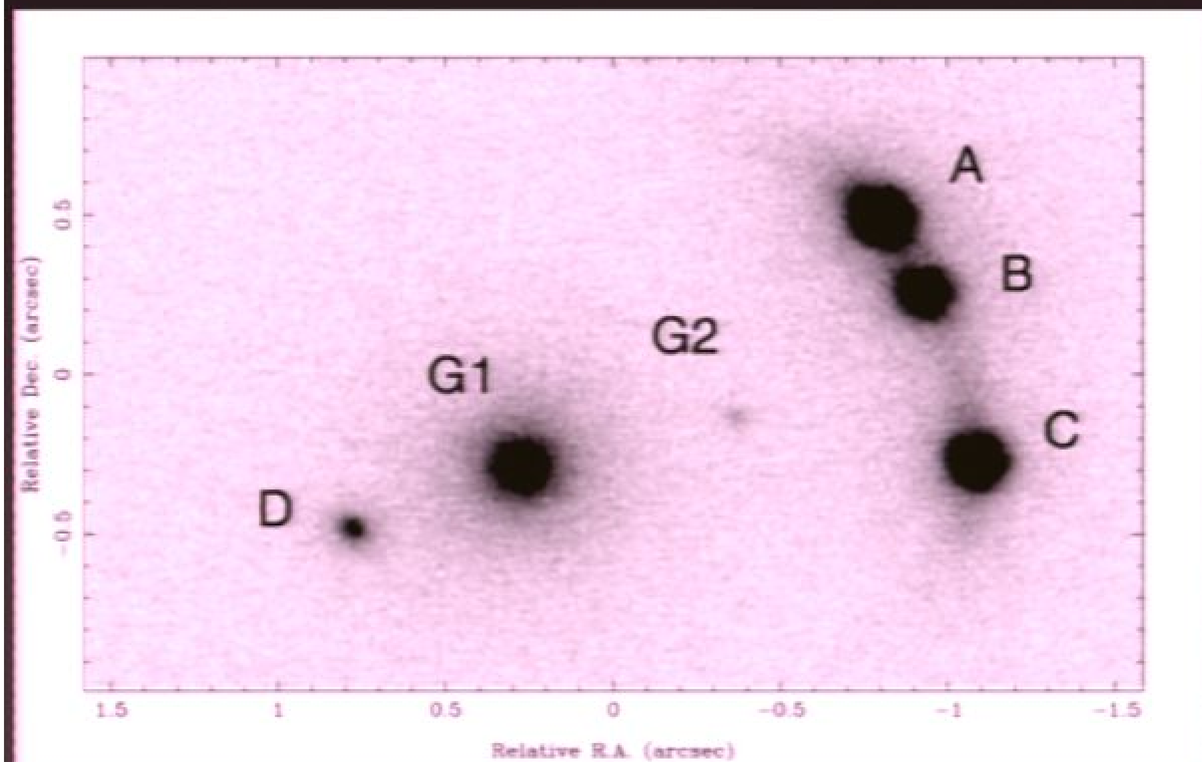
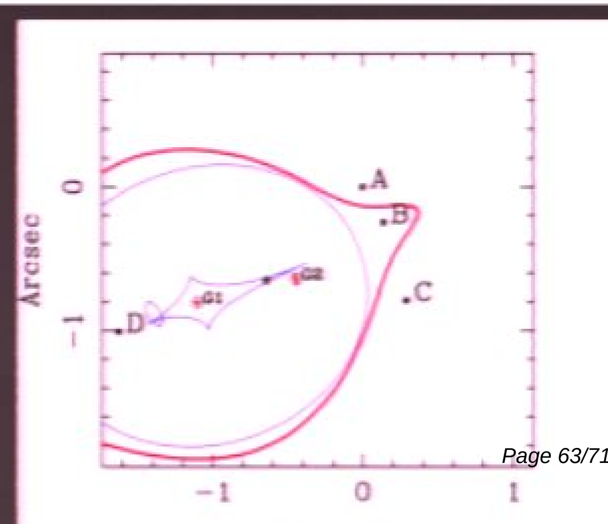


b_{G1}	1.060	1.060 ± 0.002
θ_{G1}	22.3	22.4 ± 0.1
q_{G1}	0.66	0.66 ± 0.01
b_{G2}	0.087	0.087 ± 0.003
θ_{G2}	120.87	120.87 ± 0.03
q_{G2}	0.133	0.133 ± 0.003
γ_{ext}	0.215	0.215 ± 0.002
θ_{ext}	110.05	110.06 ± 0.09
x_s	−0.641	-0.641 ± 0.001
y_s	−0.654	-0.654 ± 0.001
F_s	0.104	0.104 ± 0.003



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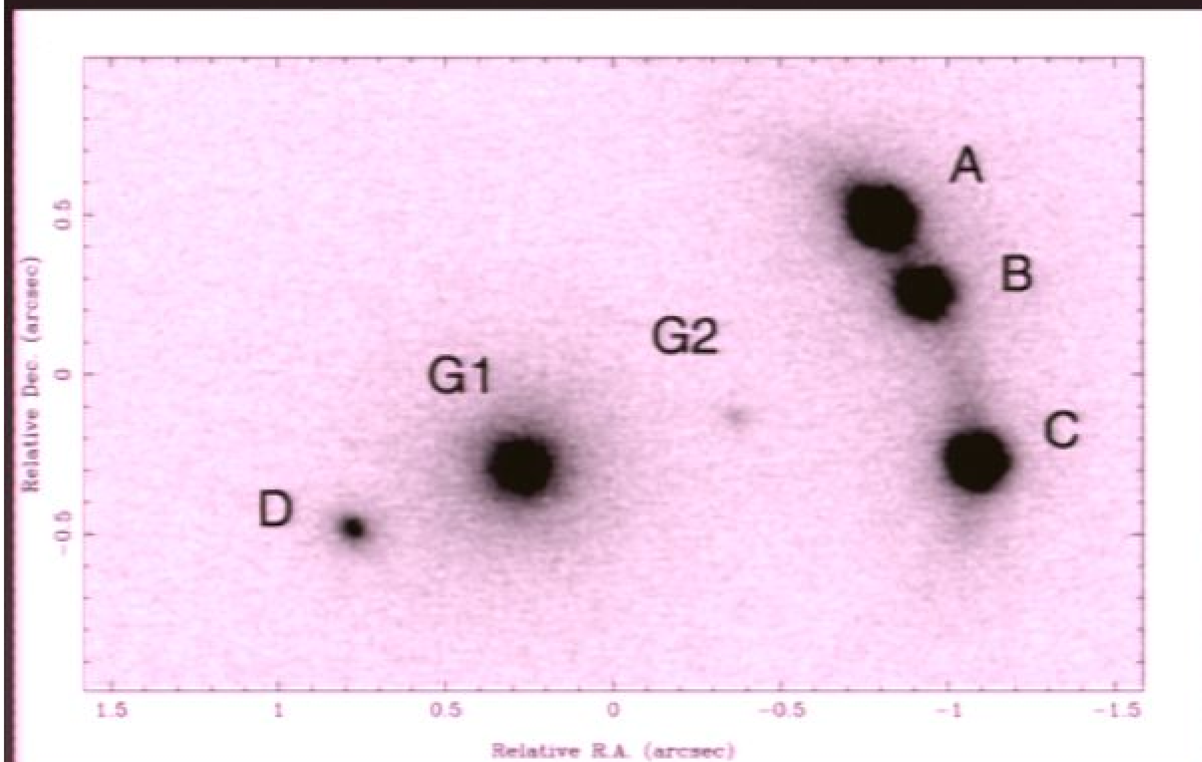

fit with only 1 satellite???

… maybe a little disconcerting

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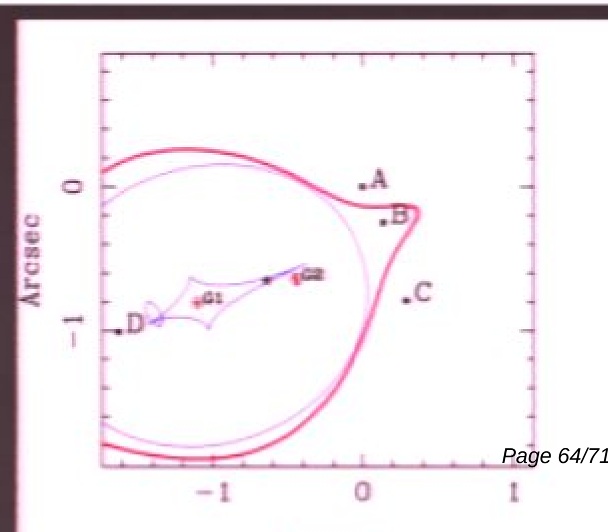

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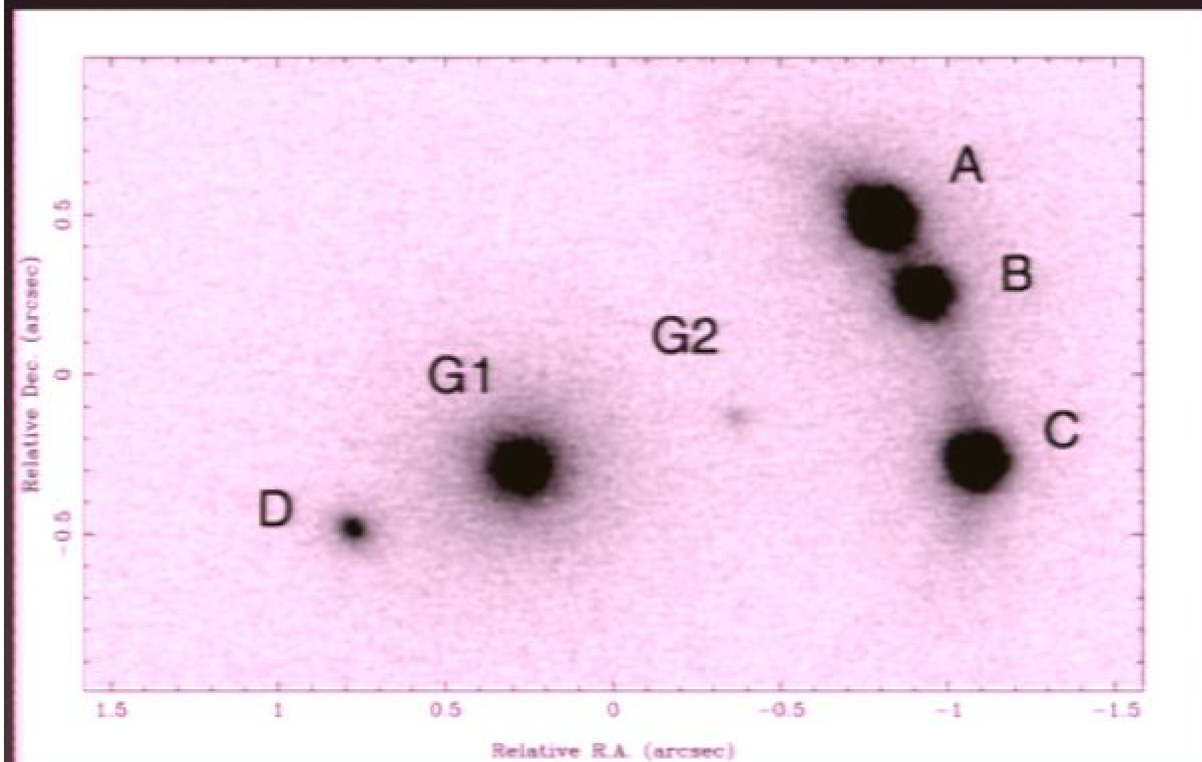

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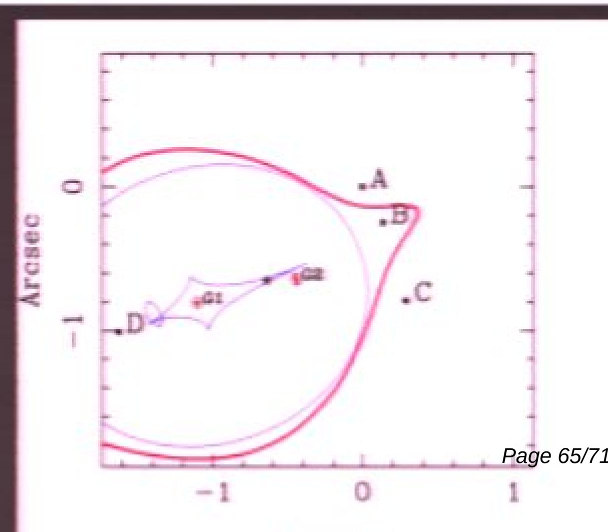

$$\tau \propto \int R_E^2\, dN/dm \propto \int m\, dN/dm$$

The Future is Coming

Pan-STARRS:

- *30,000* deg^2
- down to ~24 mag

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$\Rightarrow$ ~~~5,000~~ *500* new radio lenses!

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image subtract

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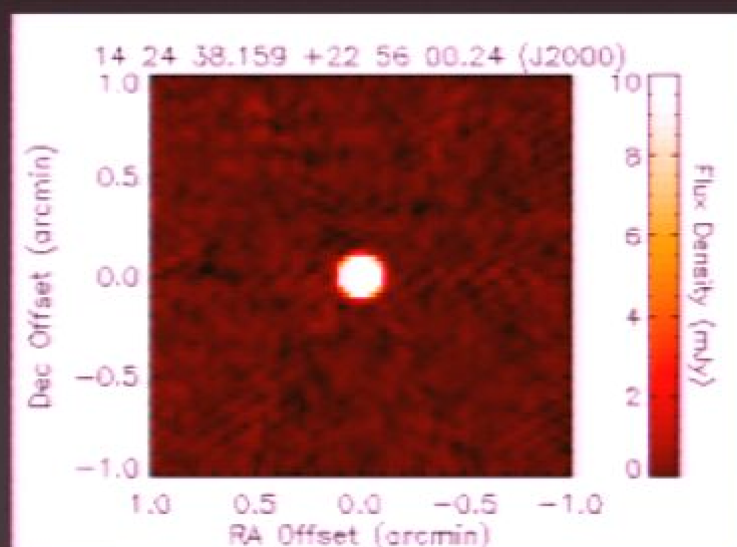

image subtract

radio survey

The Future is Coming

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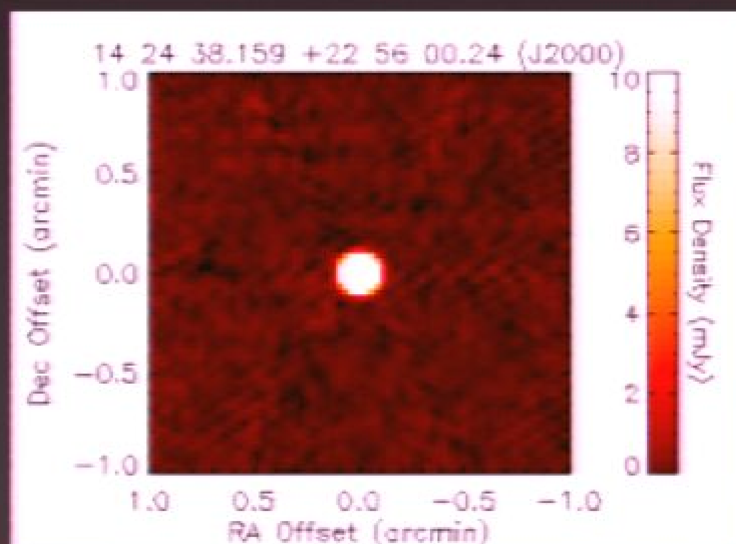

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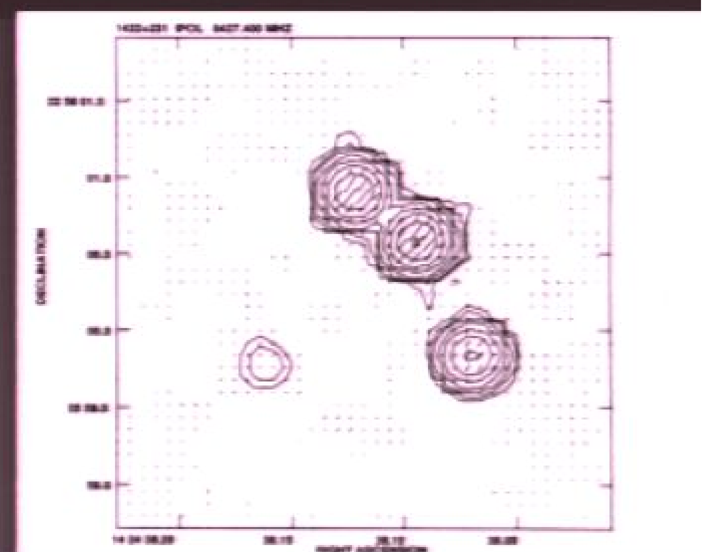

VLA follow-up