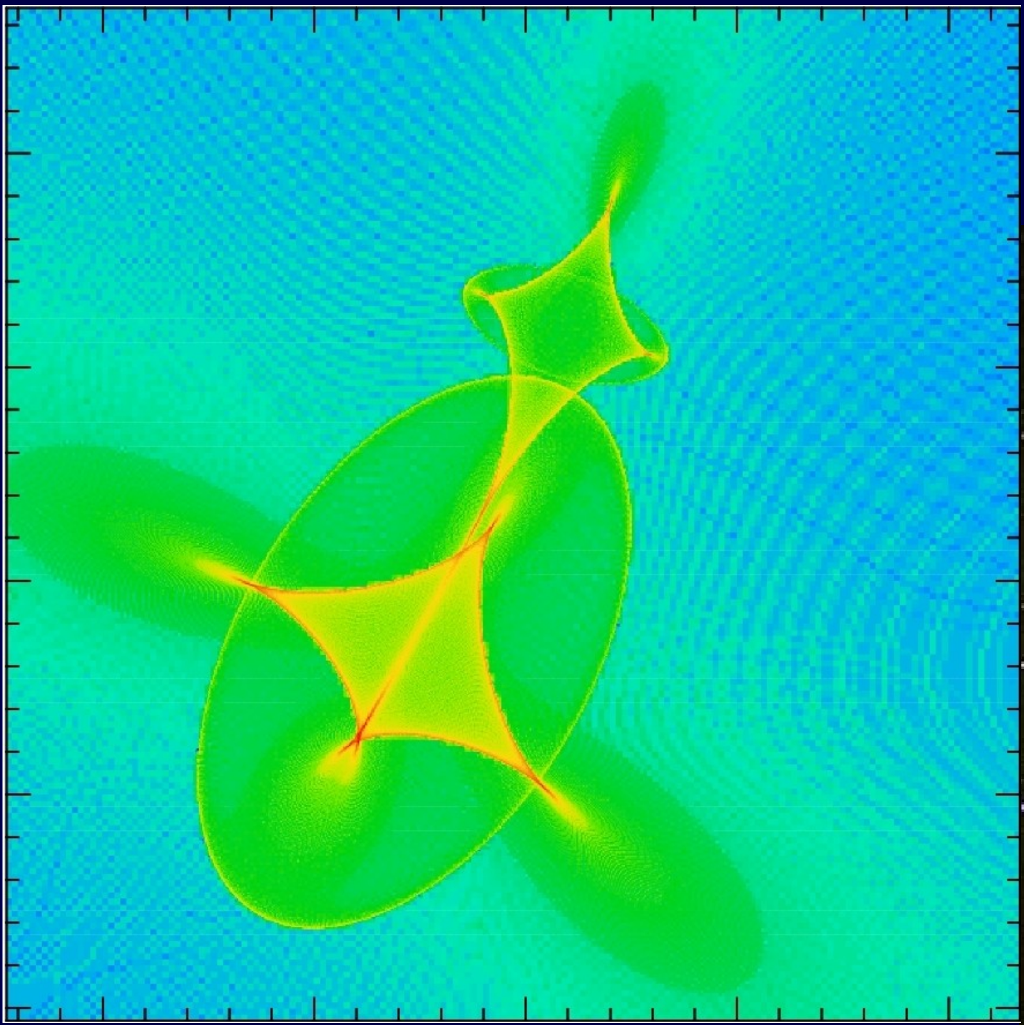
Probing the Dark with Gravitational Lensing



Edward A. Baltz (KIPAC, SLAC)

SCIPP Seminar

March 2nd, 2007

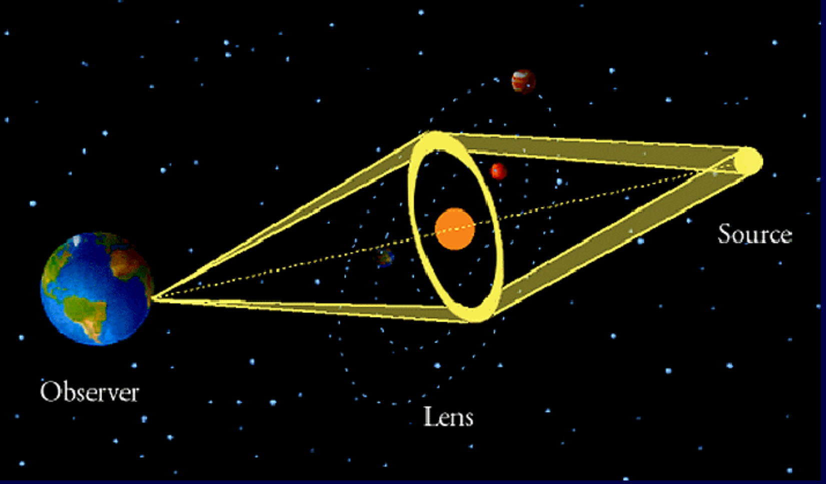
The Dark Matter Problem(s)

- Most (~80%) of the clustering matter in the universe is non-baryonic, “cold” and very weakly interacting
  - CMB + LSS measurements
  - Cluster baryon fraction
  - Spiral galaxy rotation curves
  - Big bang nucleosynthesis + primordial deuterium measurements
- What is this stuff ??? – candidates from particle physics
  - Neutrinos are “hot”
  - Axions (strong CP problem)
  - SUSY particles – neutralinos, gravitinos
  - etc.
- Its worse than that – we are missing roughly half of the baryons in the local (z~0) universe
  - dark baryon problem
- What is the distribution of dark matter in the universe?

Dark Baryons

- Ly-α forest at z~3 seems to have the right baryon density
- At z=0, half have gone missing
- One plausible scenario: warm-hot intergalactic medium
  - known to be an observationally difficult regime
- Focus on another scenario – stellar remnants
- Gravitational microlensing
  - first discussed (and dismissed as too difficult) by Einstein
  - Paczynski pointed out that monitoring campaigns of e.g. the LMC could explore the Milky Way halo for dark solar-mass objects
- MACHO project results from monitoring the LMC: 20% of the Milky Way halo is lens objects
- This can not fully solve the dark matter problem (e.g. primordial black holes) but it may be relevant for the dark baryon problem

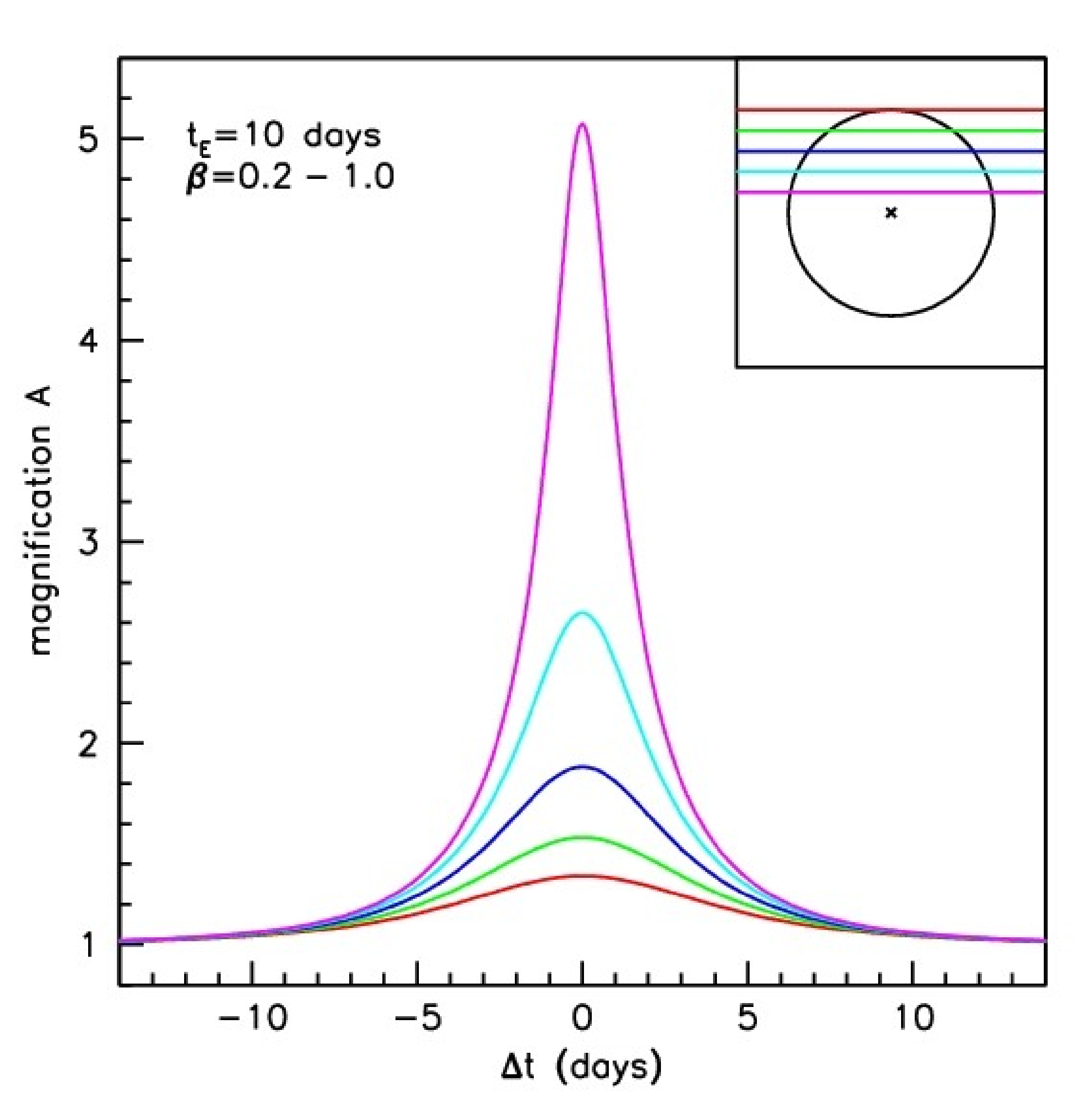
Gravitational Microlensing



- Stellar mass objects can act as transient lenses
- Significant magnification withing the Einstein radius

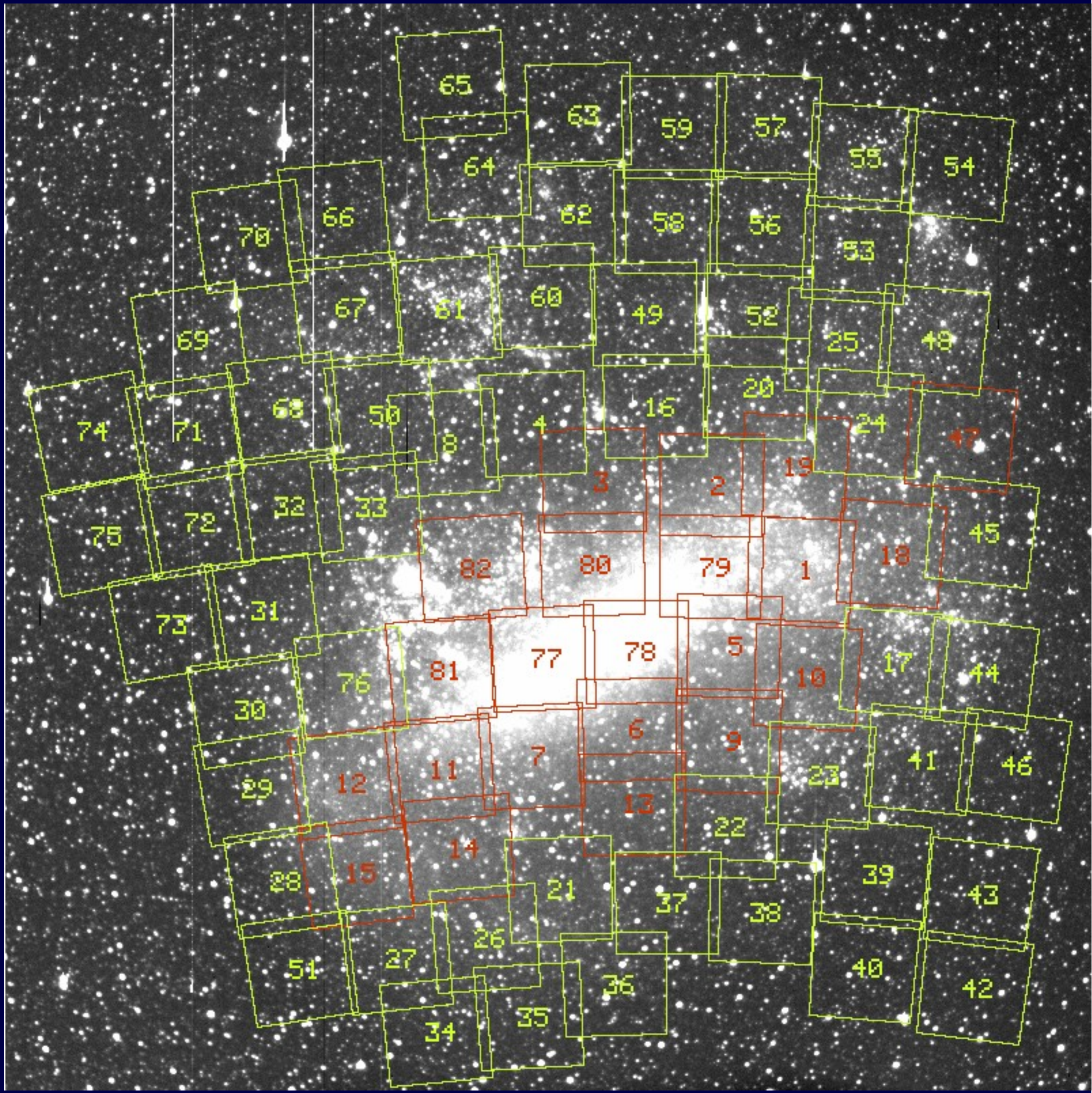
$$R_E = \sqrt{\frac{4\,GM}{c^2}\,\frac{D_L D_{LS}}{D_S}}$$

- Typical value is ~10 AU
- Galactic velocities give a timescale of ~100 days
- Search for dark objects in galactic halos – dim stars, remnants, PBHs
- Find (some of?) the missing baryons



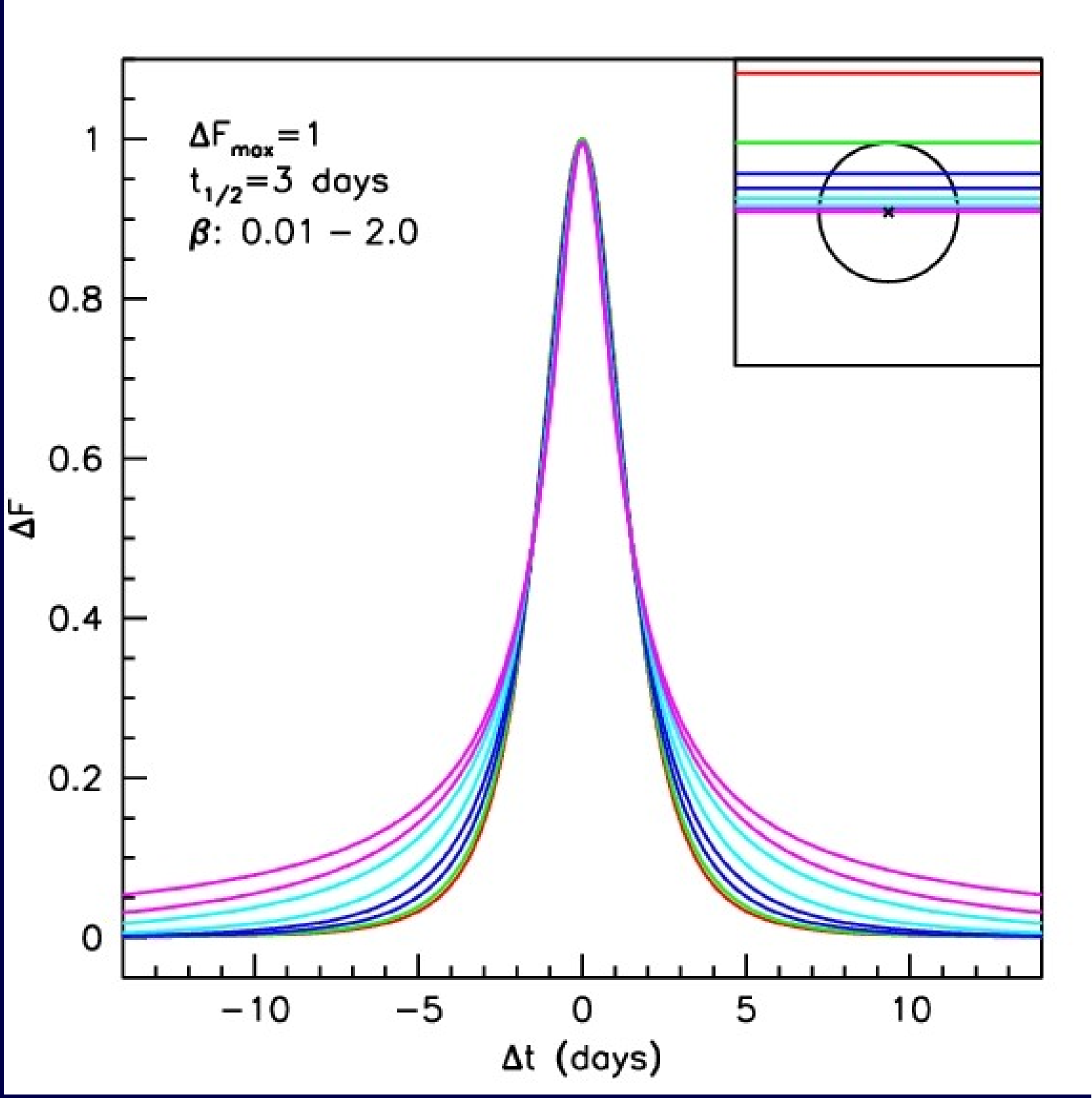
Microlensing in the Milky Way Environs

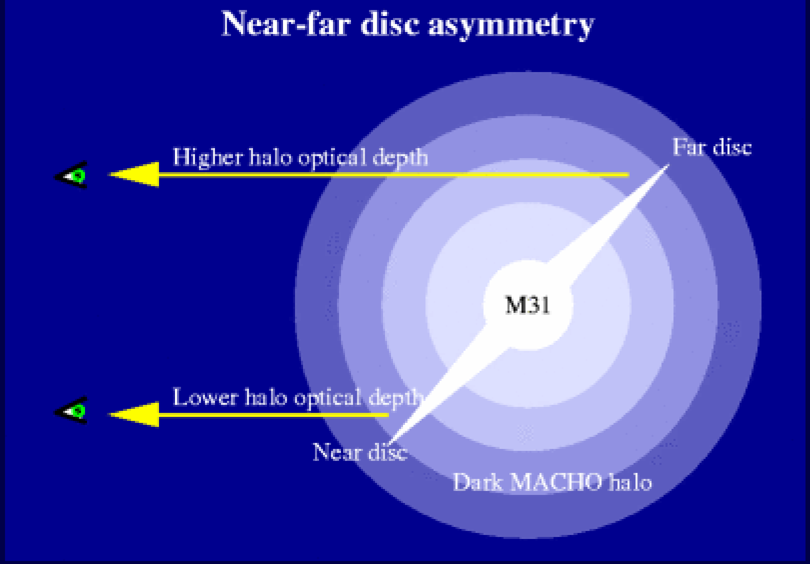
- MACHO project found 20% excess toward the LMC
  - non-virialized population?
  - stellar remnants?
- This is a surprising result!
- EROS project is slightly more sensitive
  - put limits at the 20% level
- SuperMACHO is taking data – follow up the LMC
- Go beyond the Milky Way
  - Andromeda (M31)
  - Virgo Cluster (e.g. M87)
  - cosmologically



"Pixel" Microlensing

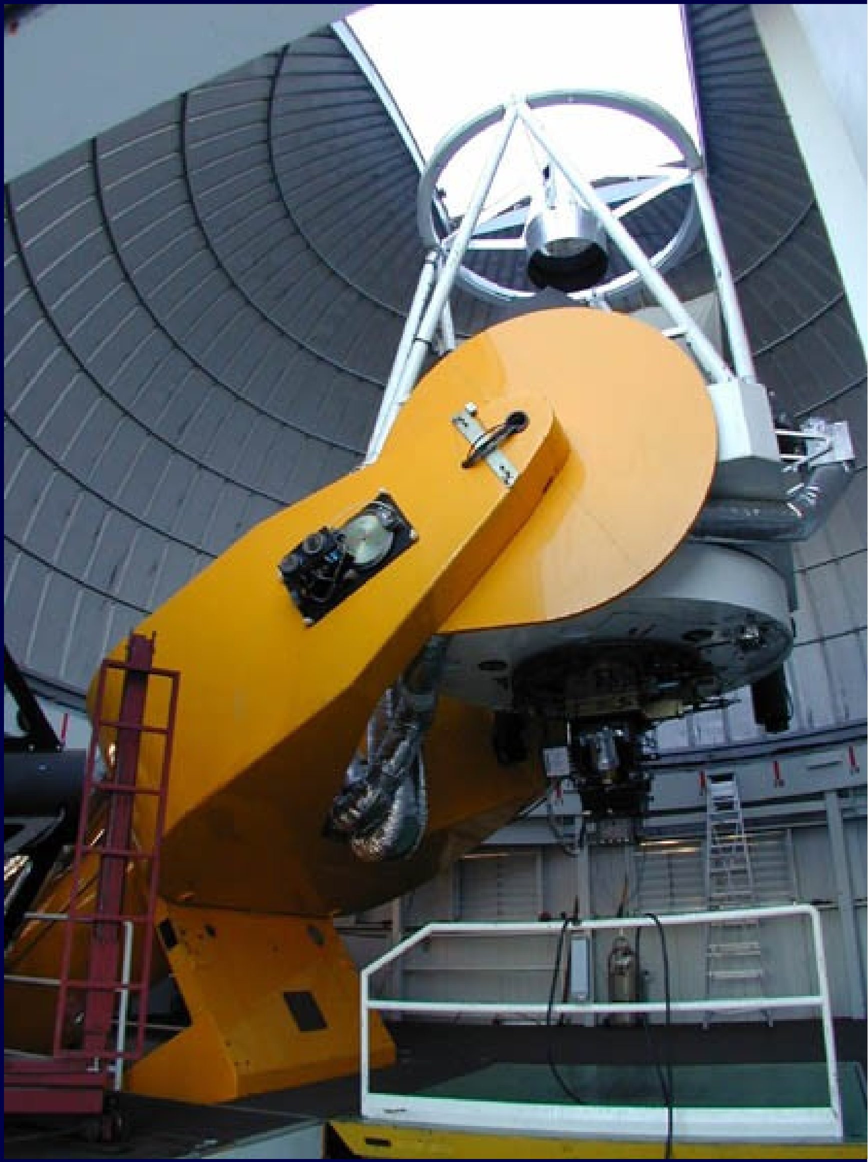
- Sources resolved from the ground only locally (LMC)
- More distant targets require image differencing
- Useful quantities not directly measurable
  - fixing flux increase and FWHM, lightcurve depends very weakly on magnification
- Einstein times recovered only statistically
  - relation between FWHM and lens mass is less direct





Microlensing Surveys of M31

- Nearest large galaxy
  - 750 kpc – few resolved stars
- Nearly edge-on
  - asymmetry in lensing would indicate a halo lens pop.
- VATT / Columbia survey
  - 3 seasons, completed
  - MDM 1.3m and VATT 1.8m
- MEGA survey
  - MDM 2.4m, KPNO 4m, INT, CFHT, Subaru, MDM 1.3m
  - Data taking winding down
  - 5+ seasons of observations
- AGAPE survey



MDM 2.4m @ Kitt Peak

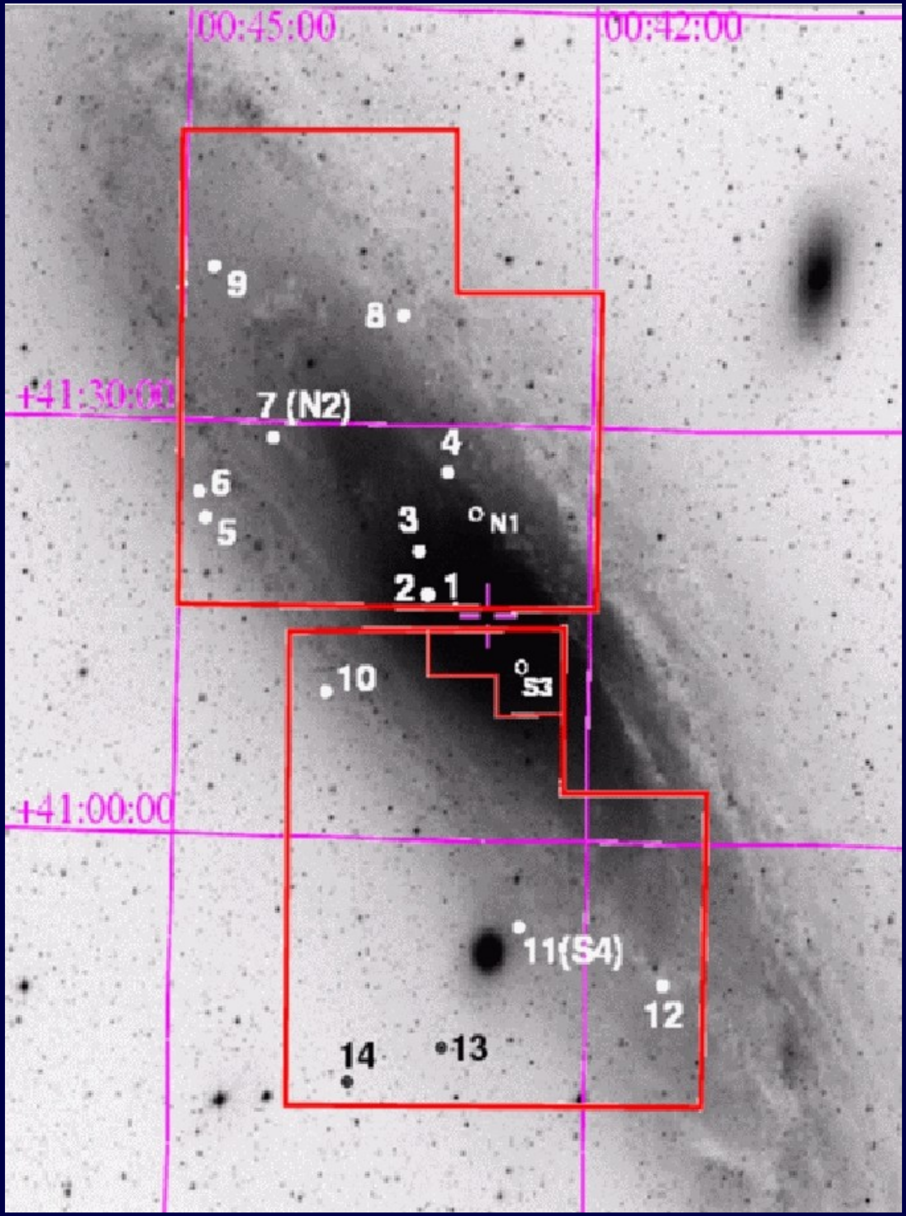
VATT / Columbia Survey of M31

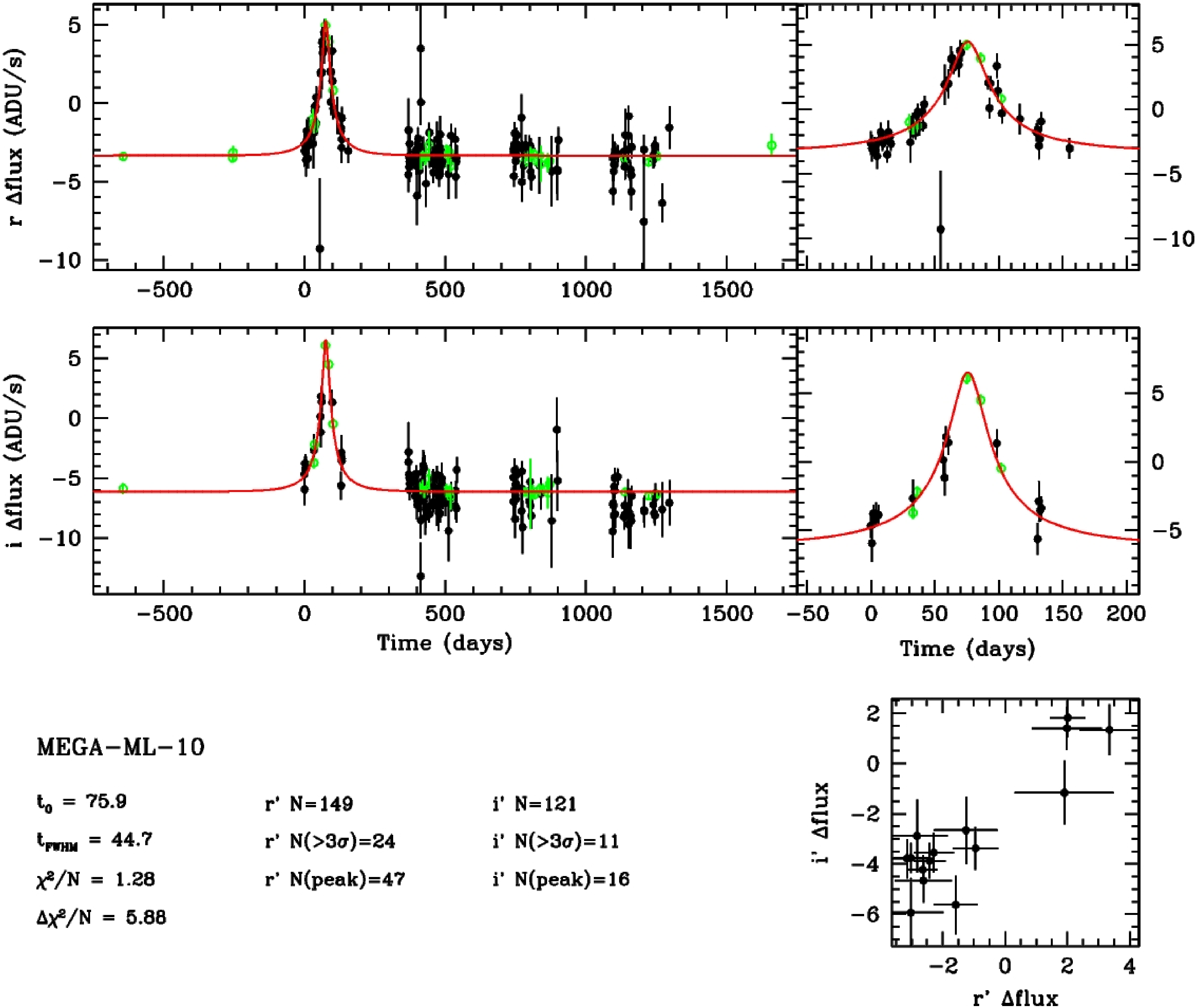
- Three seasons of observations with MDM 1.3m
- Data reduction / analysis was thesis of R. Uglesich, advised by Arlin Crotts
- Three candidate events survive all cuts for variable sources, include checking against INT data of MEGA collaboration
- Events are at large distance along minor axis – indicative of halo lensing
  - detailed analysis confirms this
  - modeling of M31 and the VATT / Columbia survey
  - maximum likelihood calculation
- Final results of VATT / Columbia:
  - weak constraint on mass
  - halo lens fraction > 0.04 at 95% confidence

$$f = 0.17^{+0.36}_{-0.04}$$

The MEGA Survey of M31

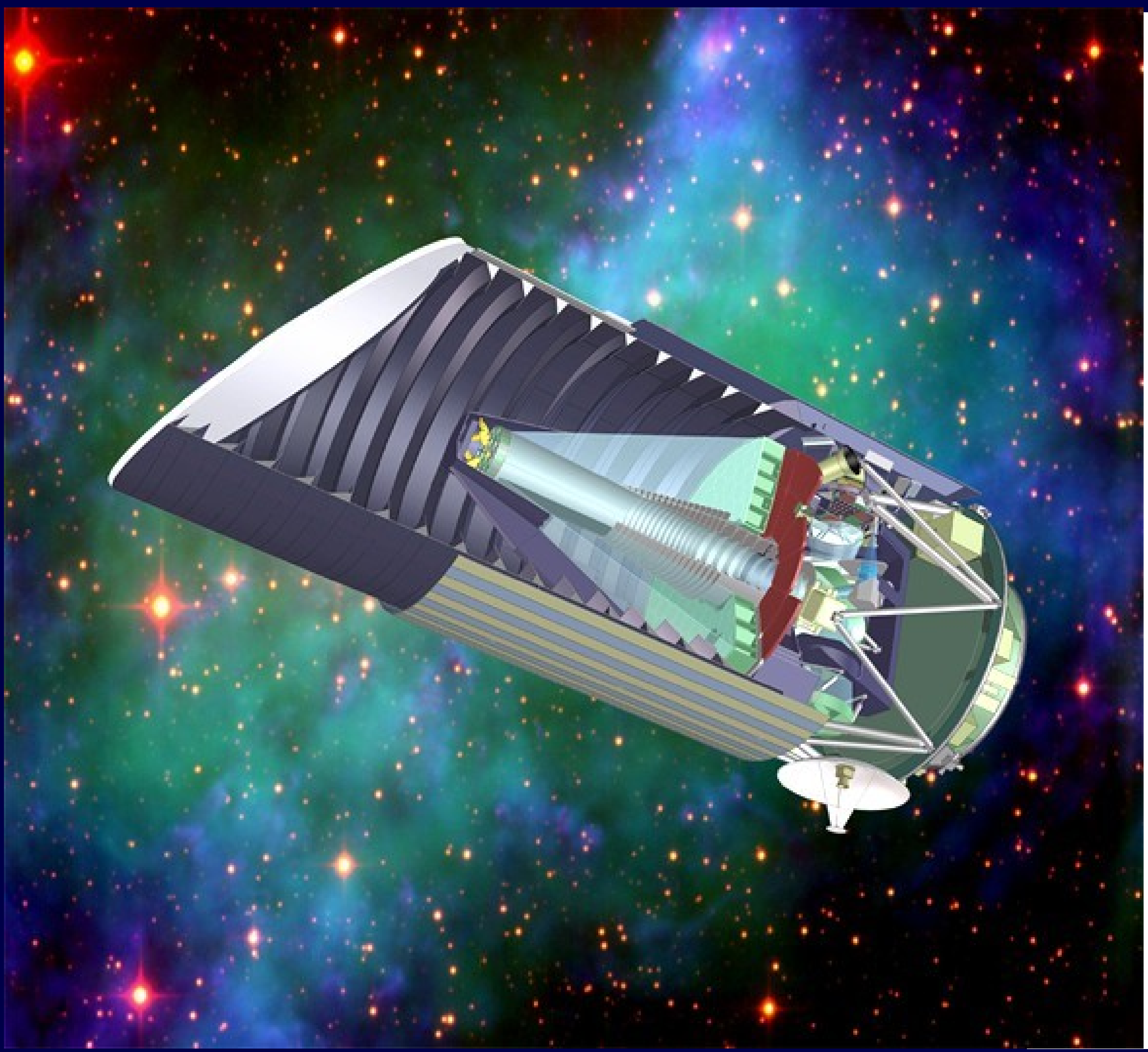
- 5+ years of observations – being analyzed now
- MDM 2.4m, KPNO 4m, INT, CFHT, Subaru, MDM 1.3m
- INT results, J. de Jong et al.
- 14 candidates, near / far asymmetry tentatively observed (at ~80% conf.)
- "Absence of Evidence" but not "Evidence of Absence"
- KPNO 4m data will contain all long timescale events
- MDM 2.4m has much better sampling



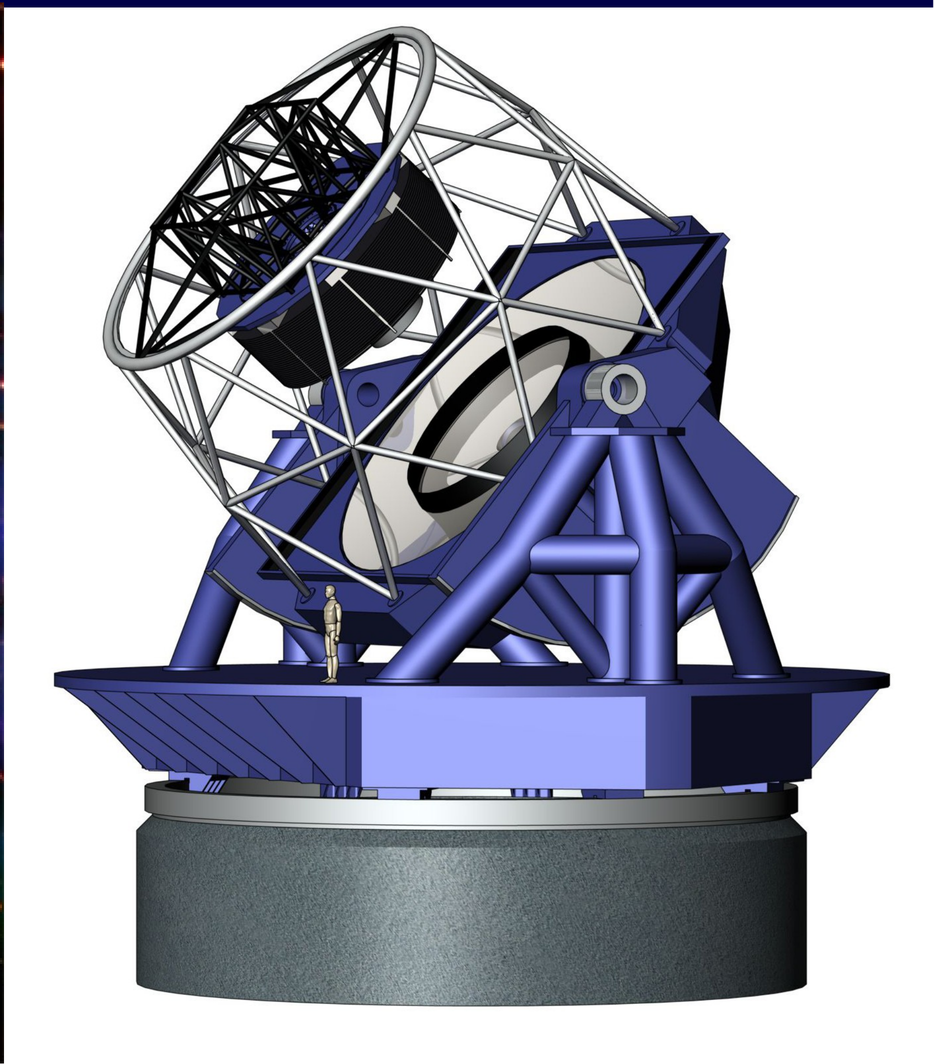


r Δflux (ADU/s)
i Δflux (ADU/s)
Time (days)
Time (days)
MEGA−ML−10
t₀ = 75.9
t_FWHM = 44.7
χ²/N = 1.28
Δχ²/N = 5.88
r' N=149
r' N(>3σ)=24
r' N(peak)=47
i' N=121
i' N(>3σ)=11
i' N(peak)=16
i' Δflux
r' Δflux

Future of M31 Microlensing: Wide Field Imaging



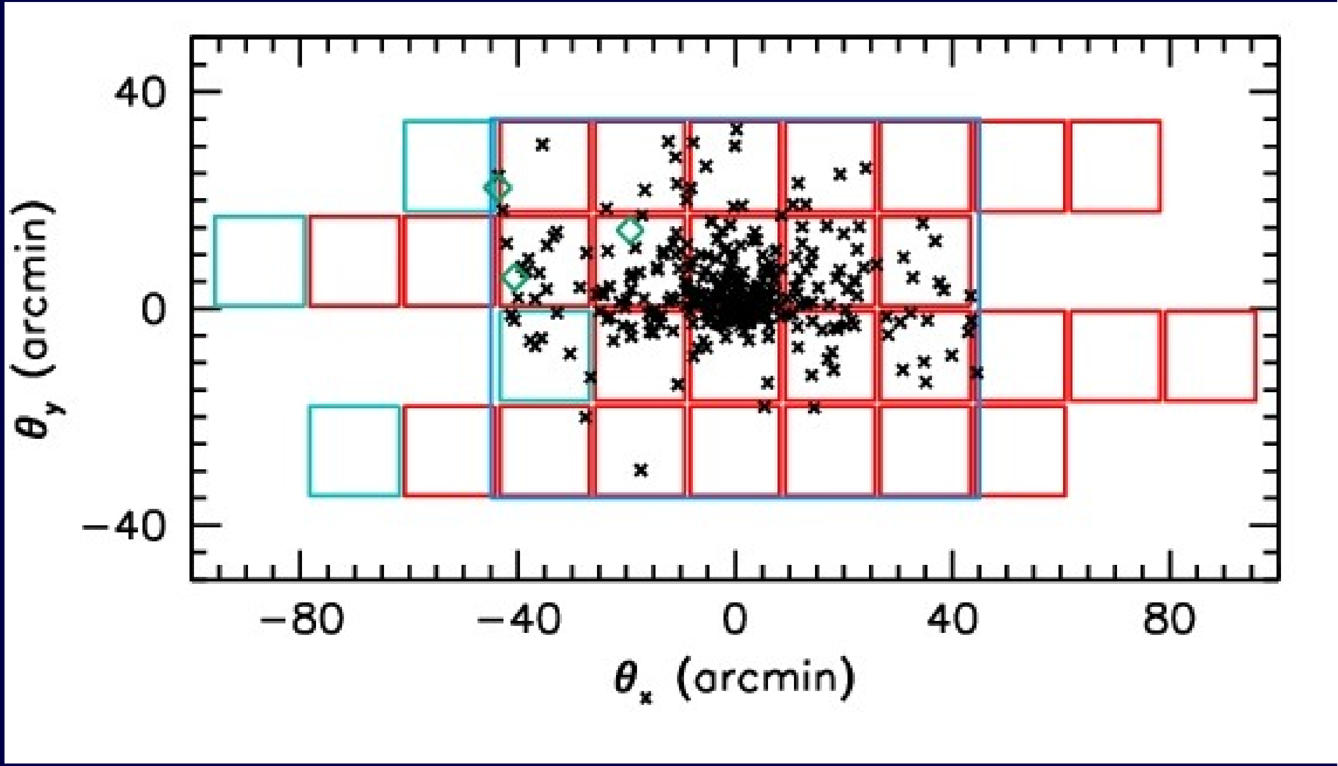
SNAP 2m space telescope concept



LSST 8m concept

Microlensing in M31 with SNAP

- 0.7 square degree imager – optical and NIR CCDs
  - strip of exposures required, 9 filters covering BVRIJ+
- Stable, small PSF – 0.1 square arcsec or better
  - use image differencing, but a few sources will be resolved
- Visible ~ 3 months
- NIR colors for variable rejection
- Improve self lensing model
- Uniform coverage near vs. far side
- Systematics!!!

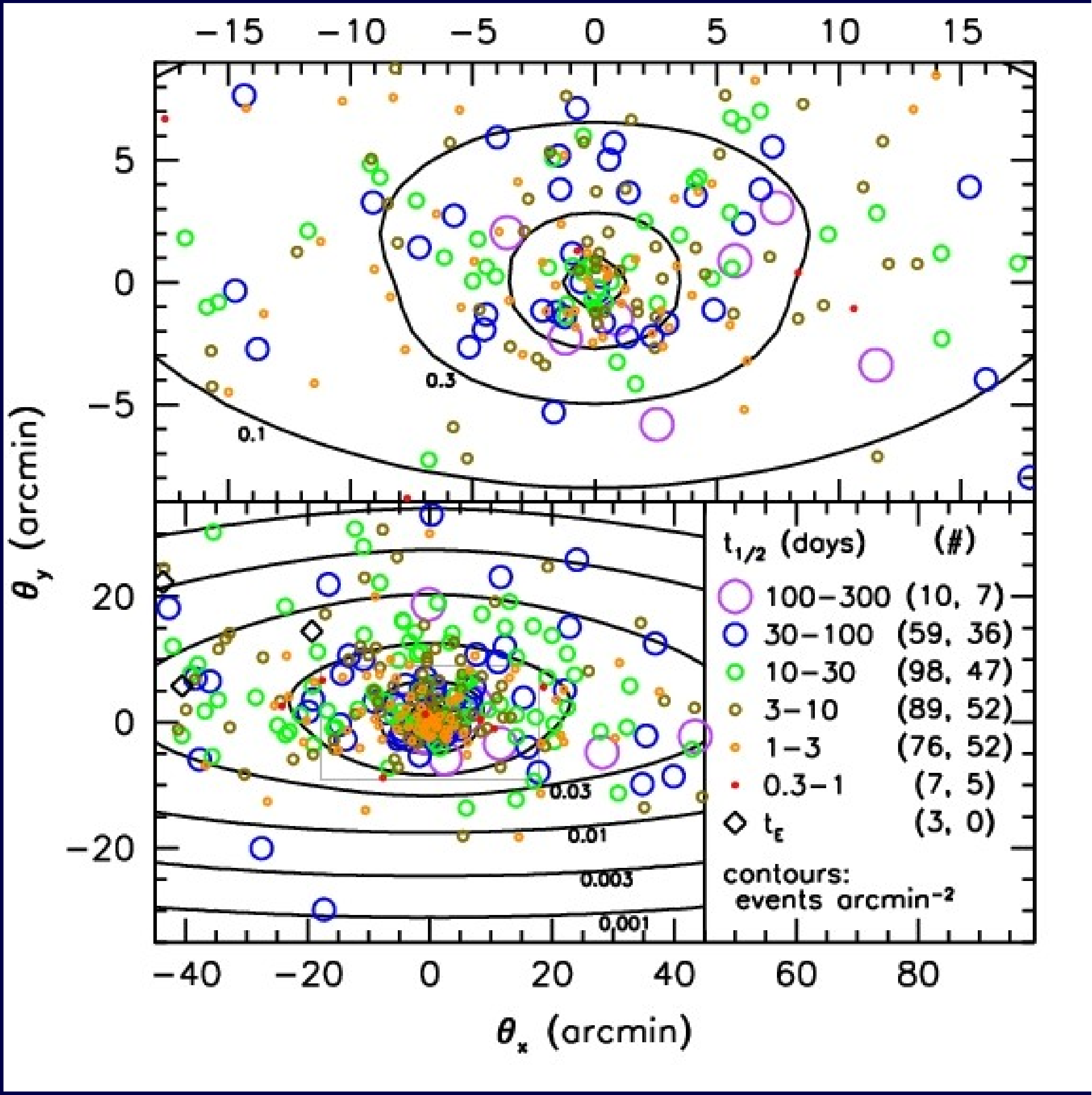


Mock Dataset for SNAP

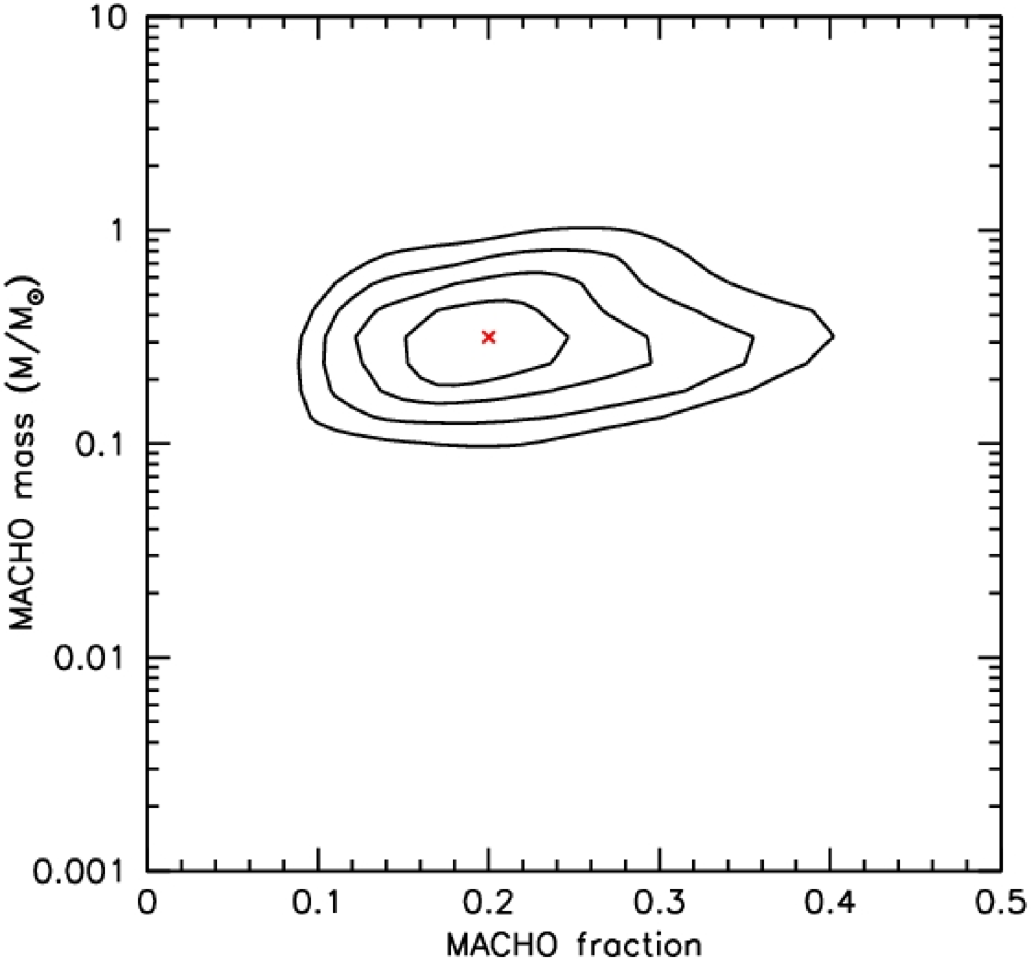
- Assume 2d cadence
  100s exposures x27
  90d total survey
  - optical cadence 4d
- 165 star-star lensing
  - ~10% binaries
- 20% halos give:
  - 50 (MW)
  - 125 (M31)
- Max. likelihood – rate vs. timescale

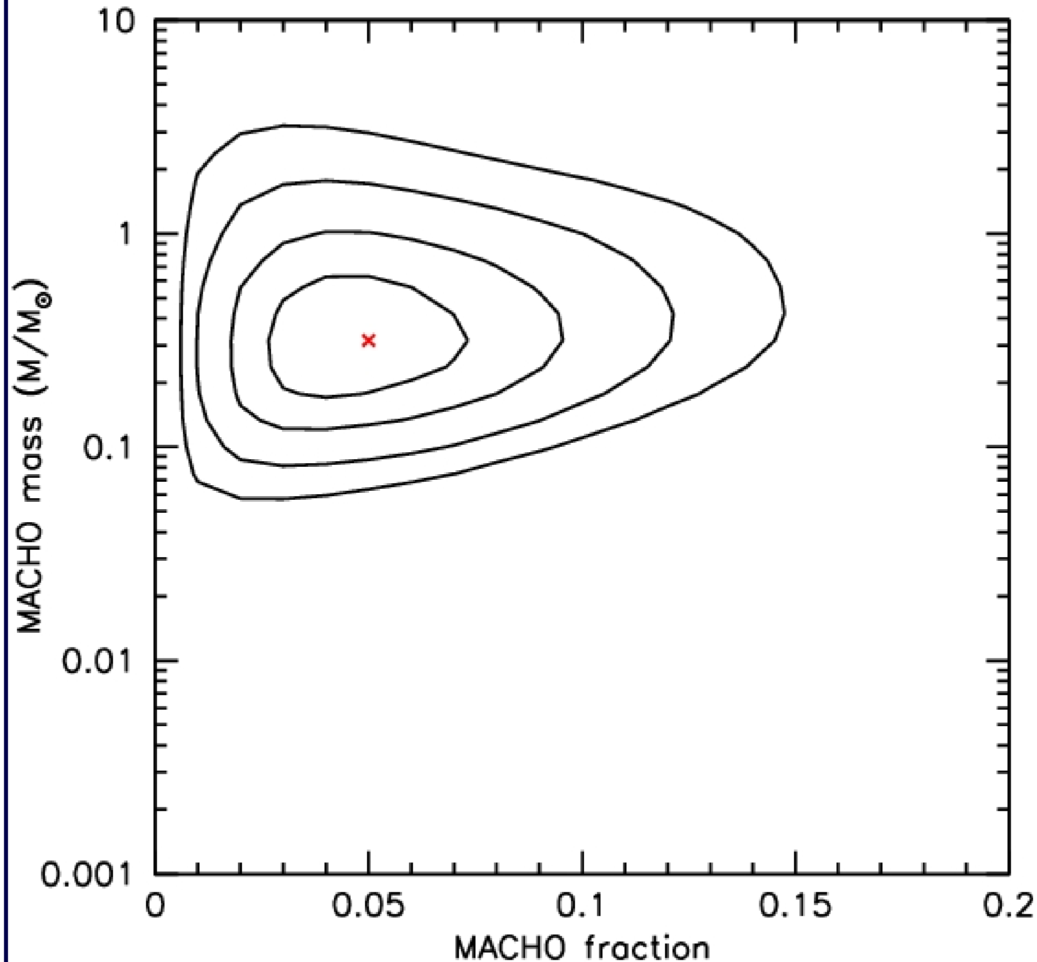
$$L=\prod_i e^{-\tau_i}\frac{\tau_i^{n_i}}{n_i!}$$

- Likelihood contours

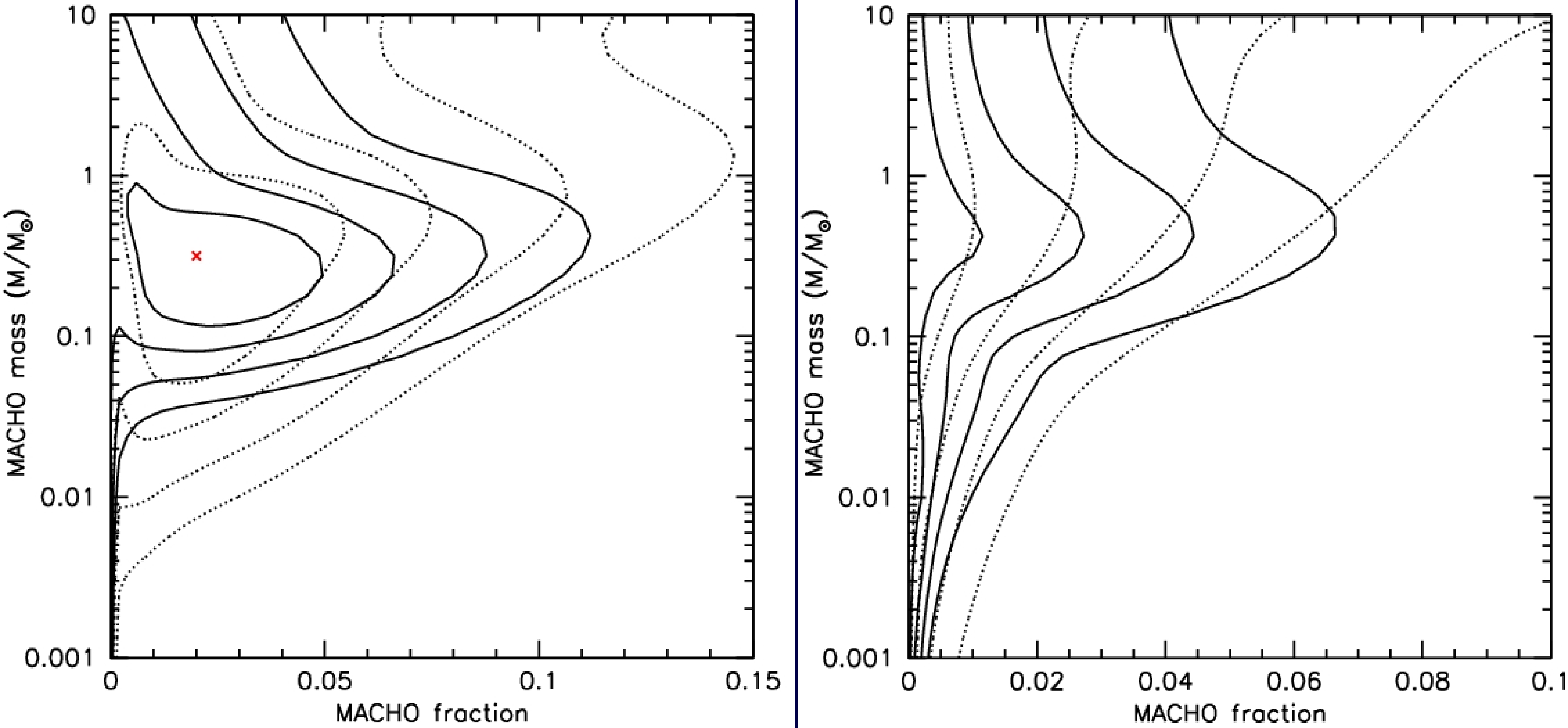


Maximum Likelihood: 20% and 5% Halo





Maximum Likelihood: 2% and 0% Halo

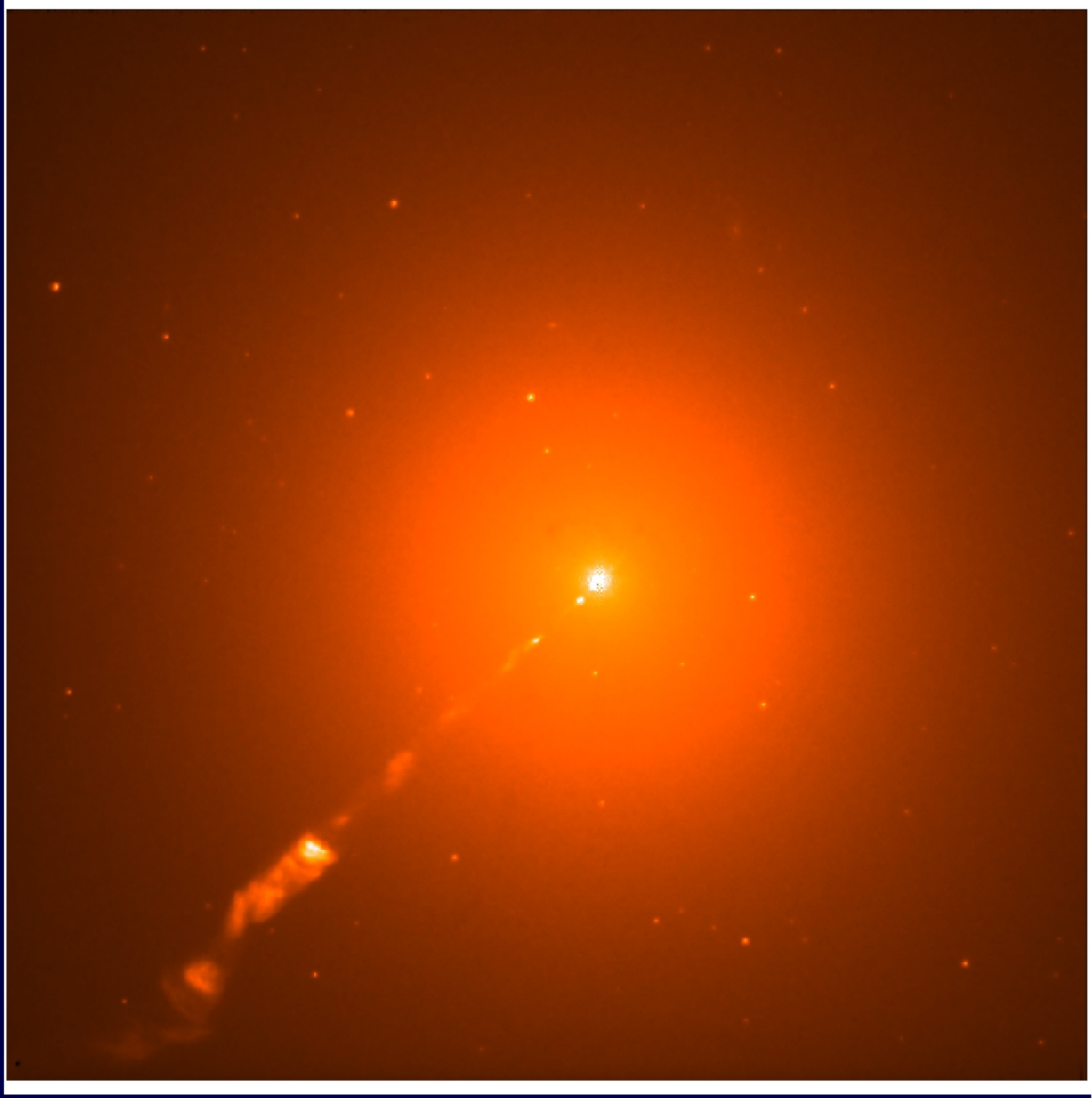


Wide Field Ground Based Surveys of M31

- LSST will have FOV > 3 degree across
  - Single field is more than adequate to cover M31
- 4 day cadence planned, in each of ~4 filters
- Current plan is 10 second exposures in pairs
- Event rates are comparable with SNAP numbers with exposures of several hundred seconds
- LSST FOV is overkill – numbers scale with effective area
  - Any 8m survey of M31 with > 1 square degree FOV
  - Exposures of 300s with 4d cadence
- However, PSF is larger – essentially no resolved star events
- No IR data – variable star rejection is harder

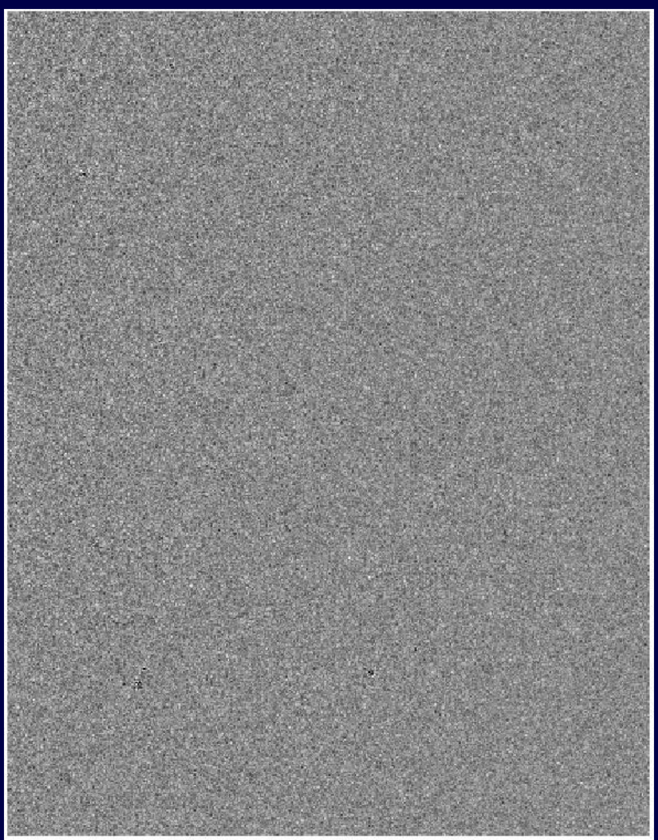
Microlensing in M87 and the Virgo Cluster

- Virgo cluster is massive – microlensing survey with M87 as a backlight
  - 16 Mpc distant
  - HST resolution required even for image differencing
- 30 orbits of WFPC2 data
  - One orbit daily – filters F814W and F606W
- Reference image stack
- Image differences PSF convolved, compared to noise image

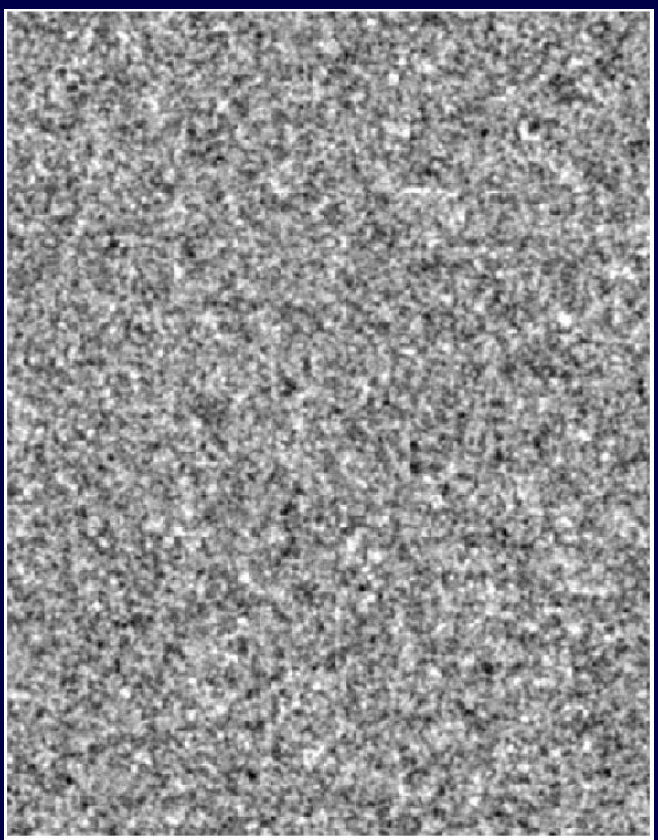


Example Image Subtraction

example field



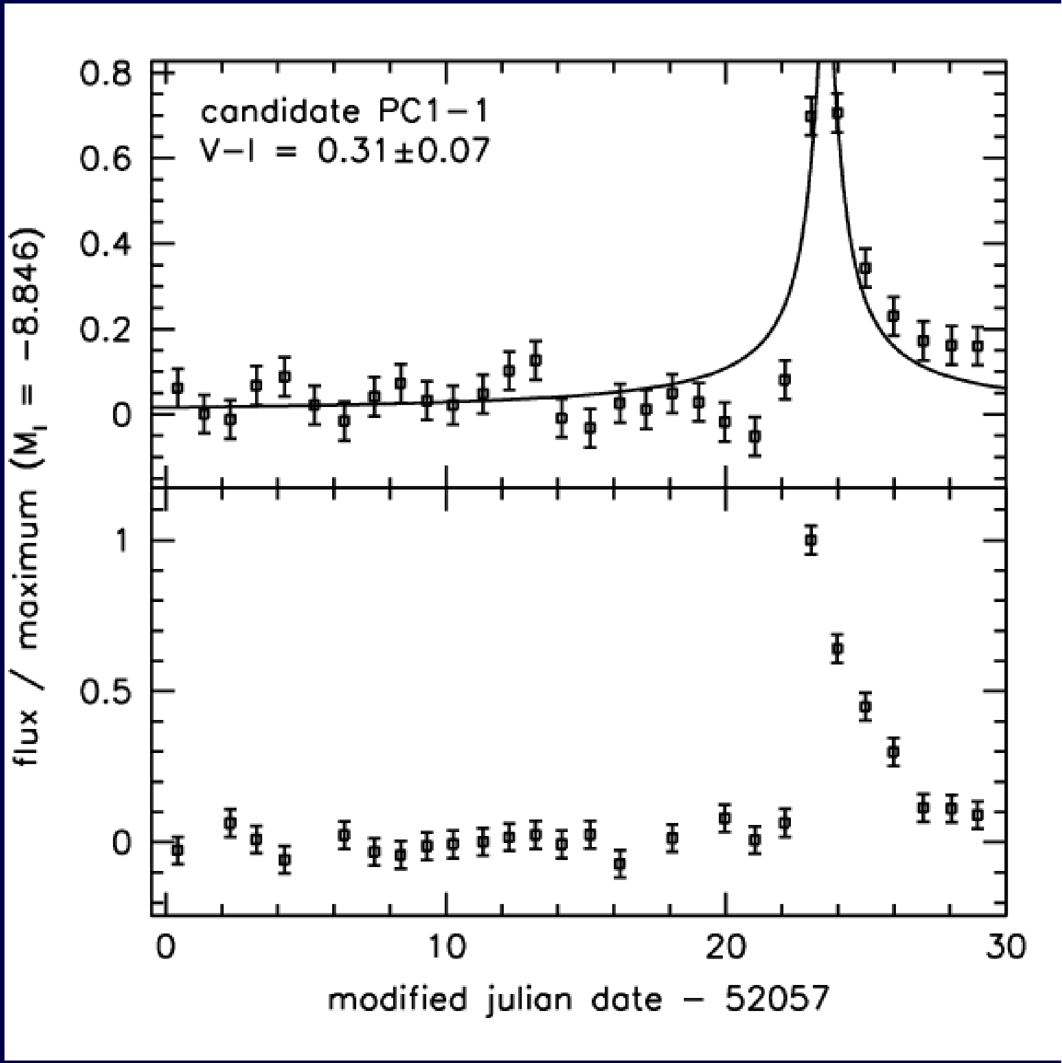
difference image



PSF convolved

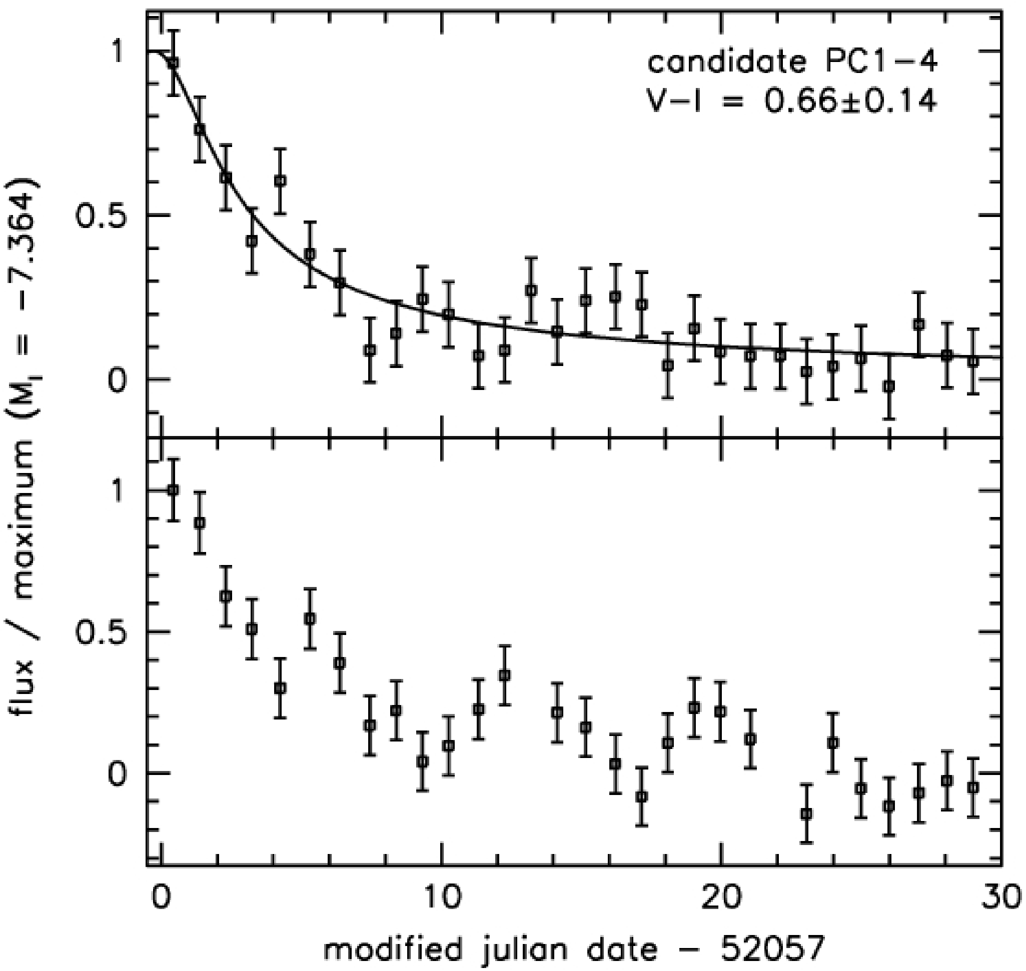
Lightcurve Analysis

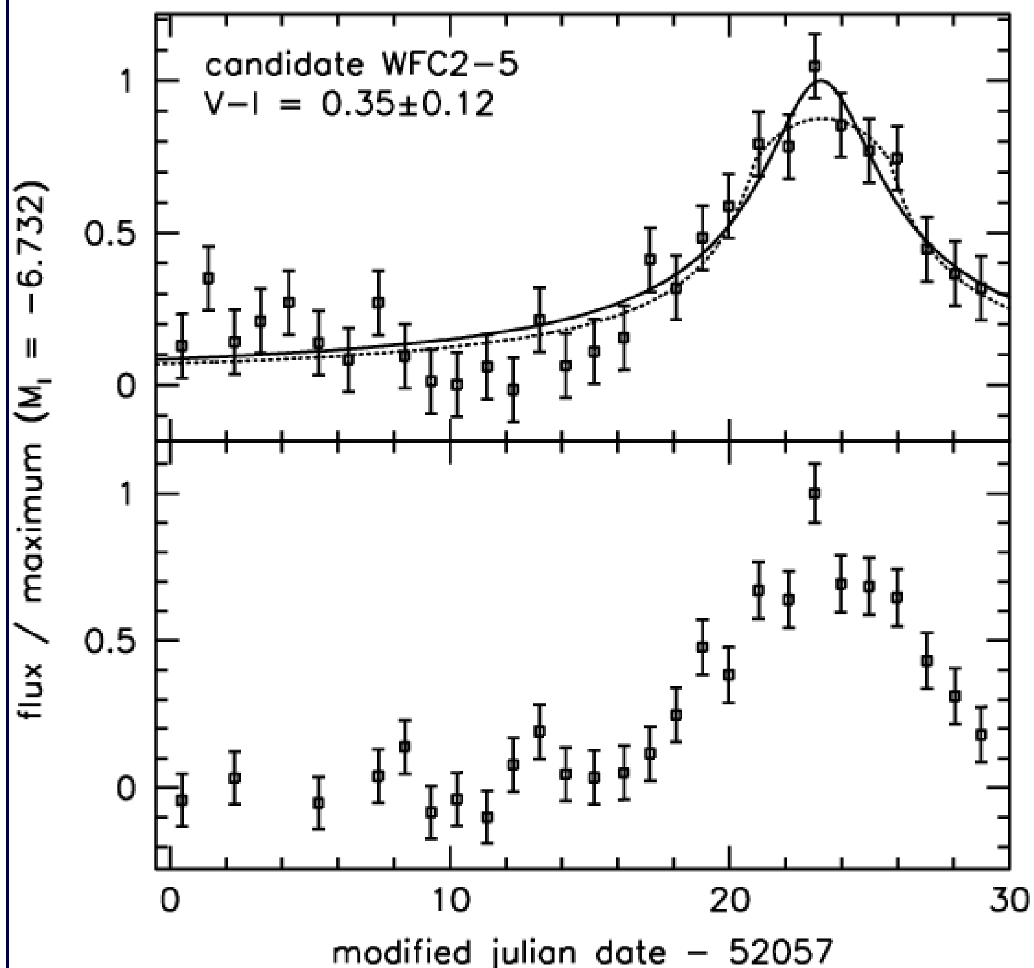
- Set baseline at each pixel
- Consecutive detections
  - total S/N > 10
- Hot pixels found by shape
  - different than PSF
- Fit lightcurves, calculate χ^2
  - step function, linear, degenerate lightcurve
- Visual inspection for subtraction artifacts
  - e.g. high SB gradient
- 7 candidates survive:
  - 3 in WFC2, 4 in PC



nova at 3” from nucleus

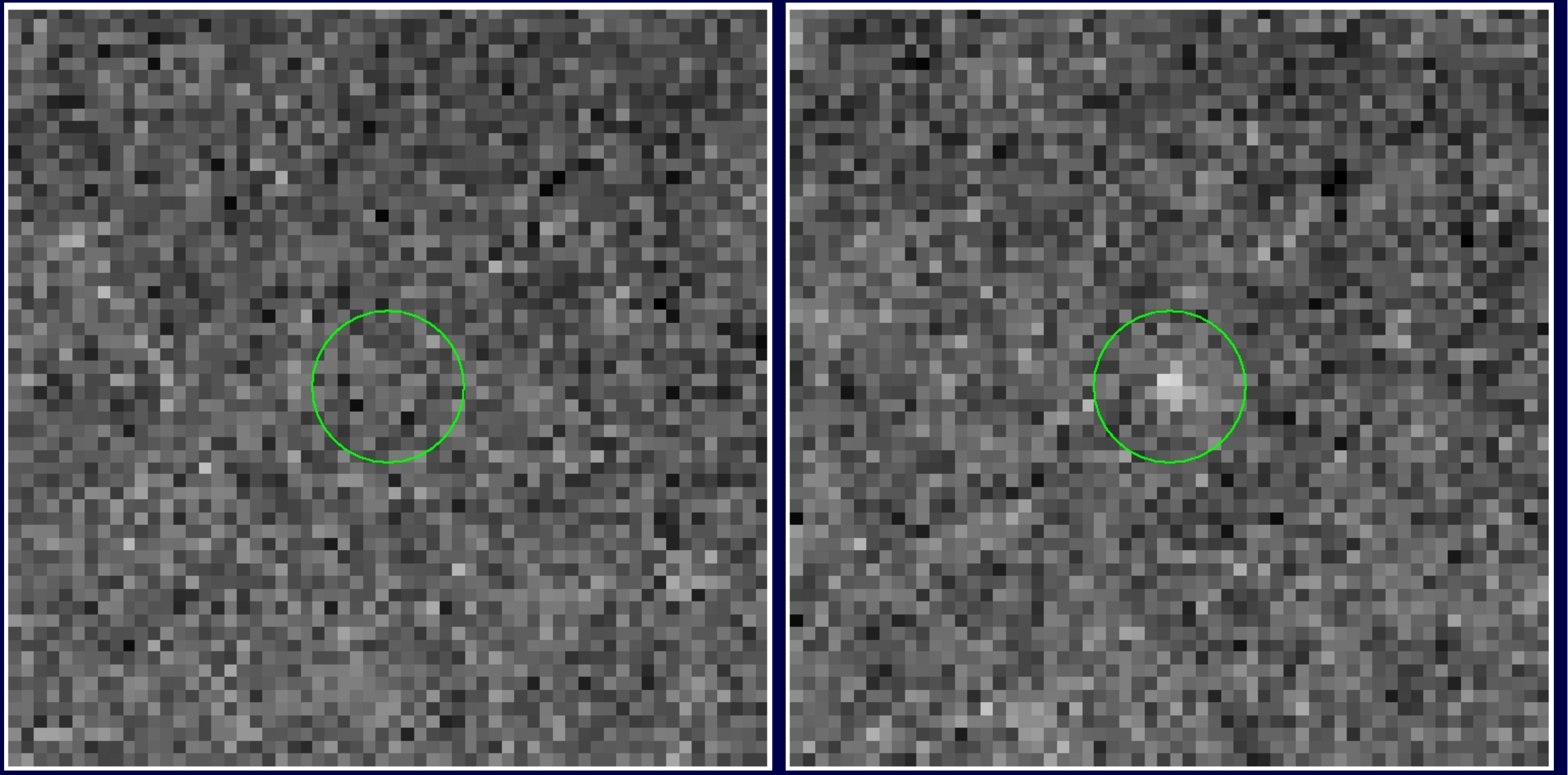
Candidate Events





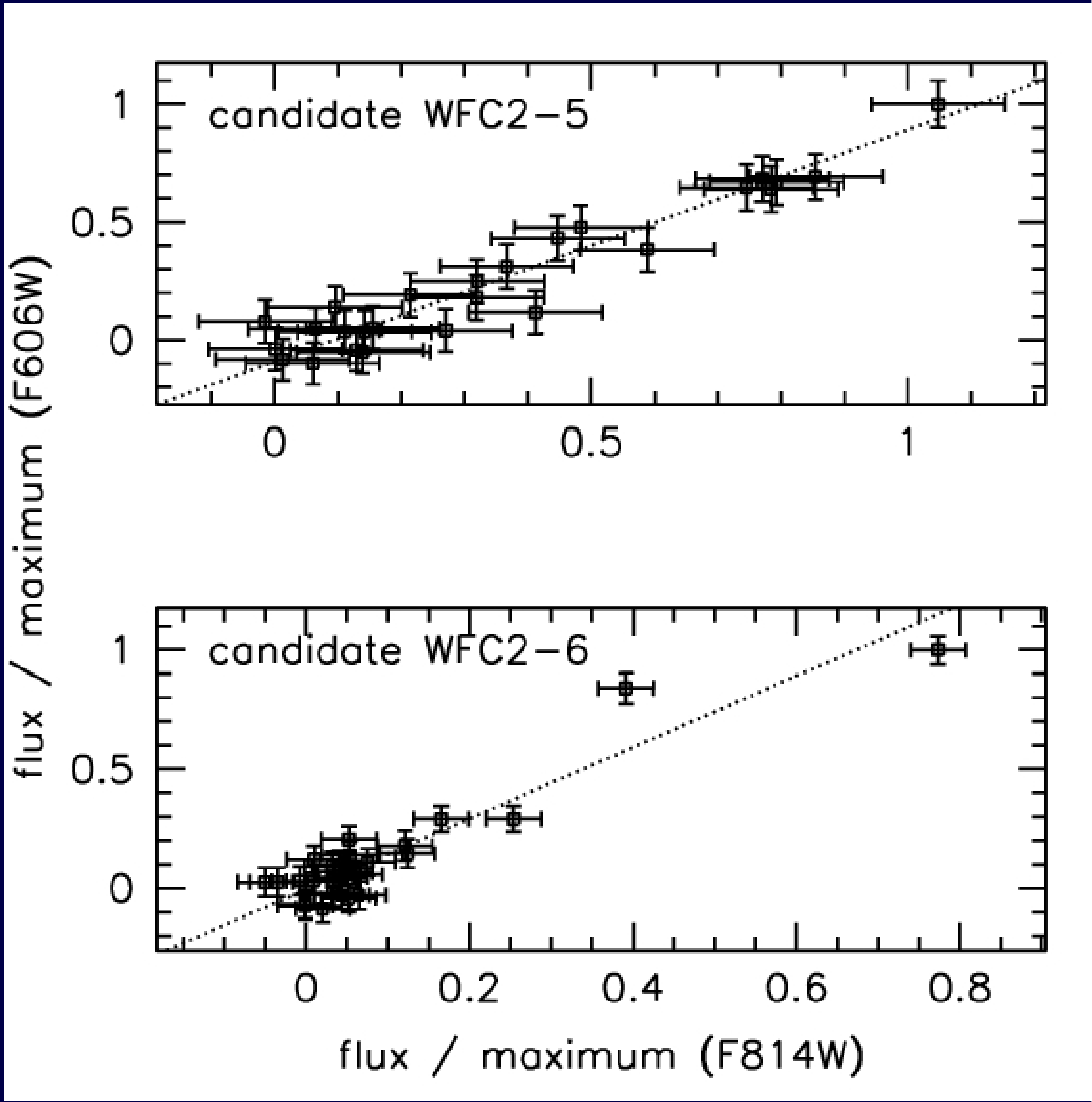
microlensing candidate

Microlensing Candidate



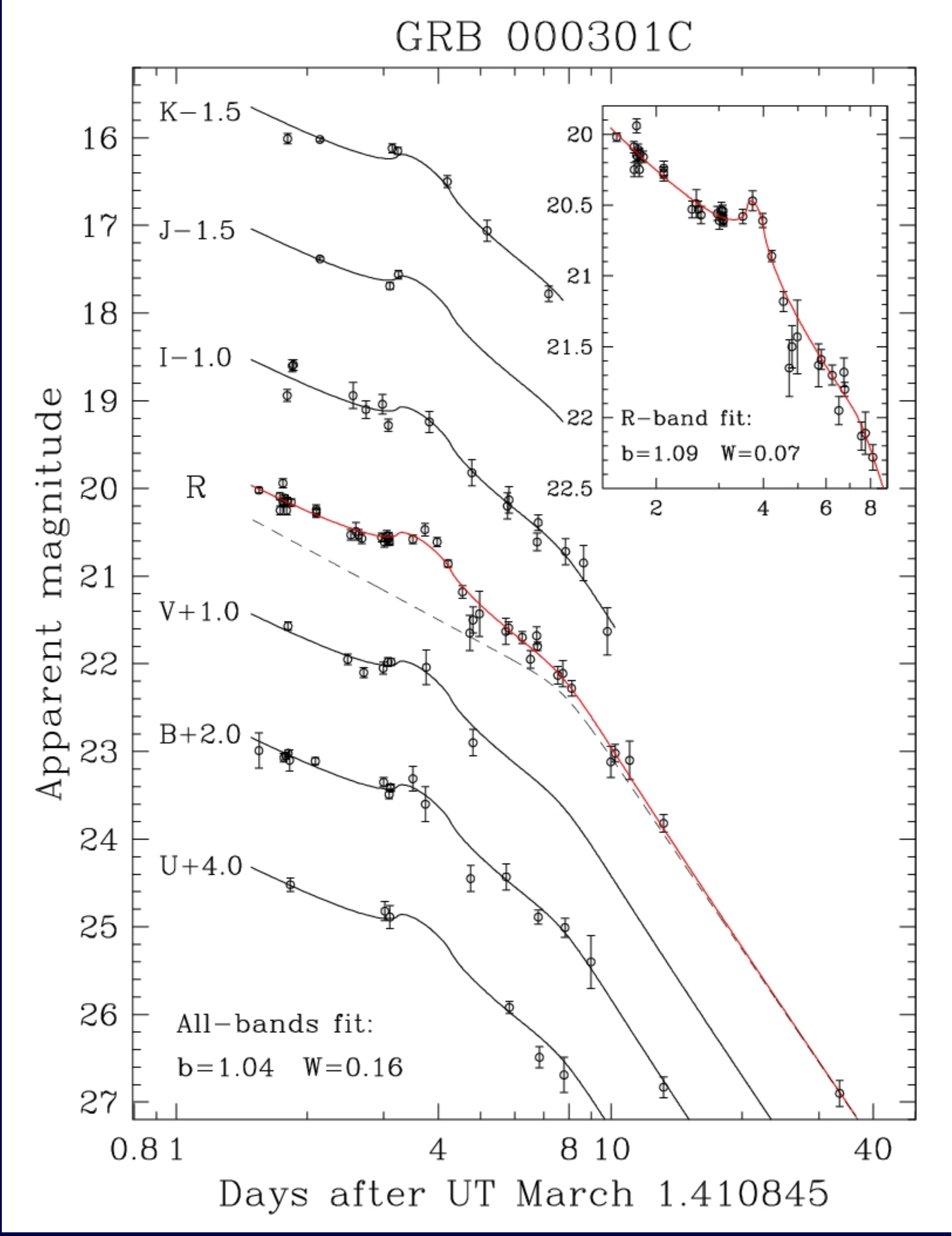
Interpretation of M87 Results

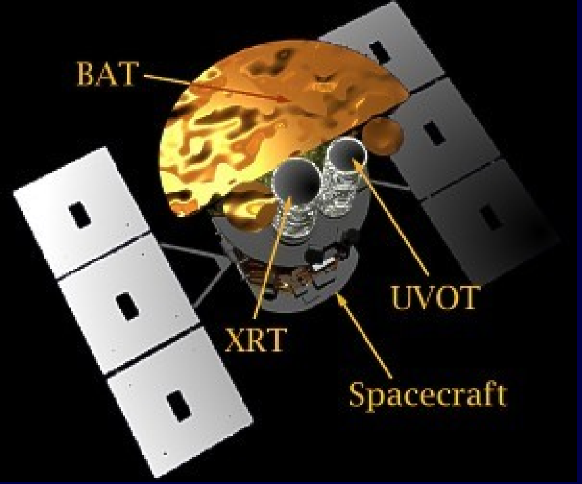
- Two good nova candidates
- Microlensing candidate is likely too blue – HB star?
- Constant flux ratio required
- Simulate event rate
  - 0.6-1 event for 20% Virgo
  - 0.05 self lensing
- With no candidate:
  - f < 0.6 @ 95% confidence
- ACS is 14x better
  - 50 orbit program complete
  - Stay tuned



Microlensing of GRBs

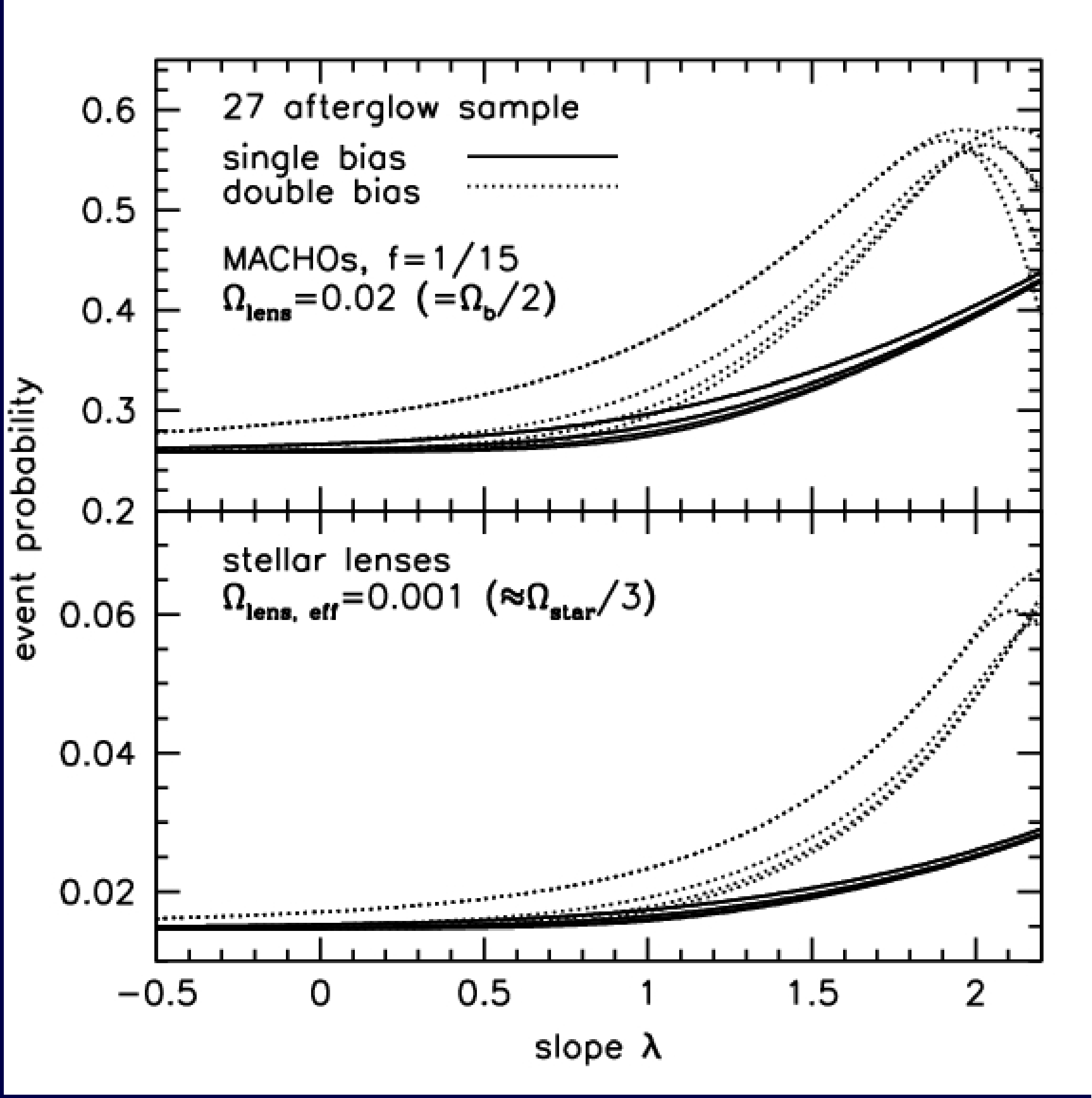
- Relativistic fireball appears as expanding ring
- Superluminal expansion
  - microlensing timescale is days even at z ~ 2
- GRB 00301C afterglow seems to be microlensed
  - Garnavich et al. 2001
- Microlensed GRBs probe stellar objects at high z
- How likely are they?
- What is the cosmological lens density?





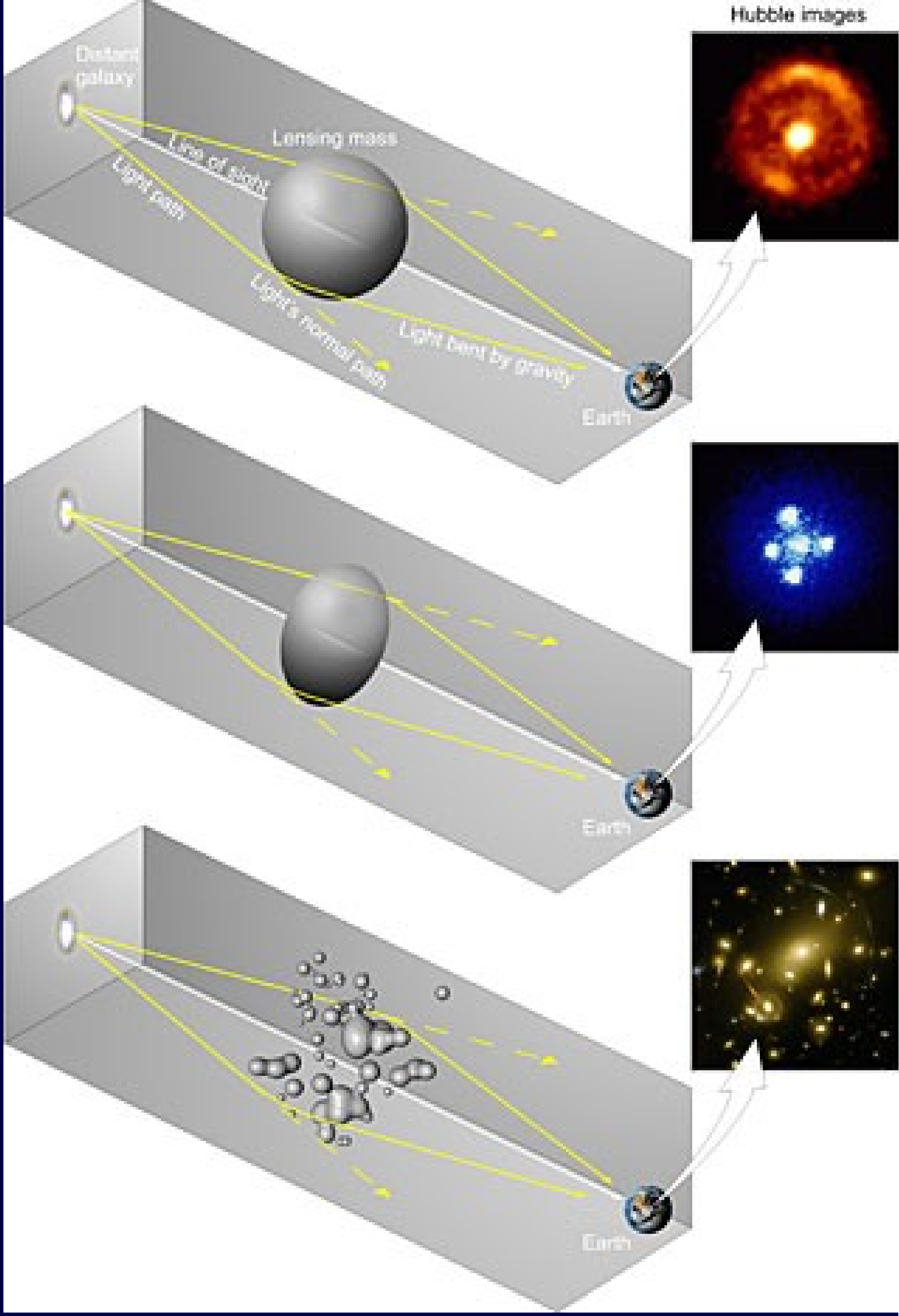
GRB Microlensing Rate

- Double magnification bias
  - gamma ray detection
  - localization in X-rays
  - optical may not correlate
- Halo lenses act uniform
- Stellar lenses are "close"
  - caustic network
- With half of baryons in lenses – significant rates
- SWIFT satellite will measure ~1000 afterglows
  - lower threshold and better time coverage



Strong Lensing

- Galaxies act as lenses
  - multiple resolved images
- Image characteristics constrain the lens potential and its derivatives
  - time delays (0^{th})
  - deflection angles (1^{st})
  - magnification / shear (2^{nd})
  - "flexion" (3^{rd})
- What can we learn about the (dark) matter distribution in the universe?
- Unbiased probe in the sense that all matter has equal lensing power



Mathematics of Strong Lensing

- Single plane lens equation $\vec{y}=\vec{x}-\vec{\nabla}\psi(\vec{x}),\ \boldsymbol{J}=\mathbf{1}-\vec{\nabla}\vec{\nabla}\psi(\vec{x})$
- Magnification (=1/det J) is formally infinite on “critical curves”
- The critical curve is the lowest order “catastrophe” – the fold
- The next order catastrophe is the cusp $\vec{Z}=(\vec{\nabla}\,det\,\boldsymbol{J})_{\perp},\ (\vec{Z}\cdot\vec{\nabla})\vec{y}=\vec{0}$
  - Derivative of source position along critical curve in image plane = 0
- Iterative solution in the case of multiple lens planes

$$\vec{x}_j=\vec{x}_0-\Sigma_{i<j}\beta_{ji}\vec{\nabla}_i\psi_i(\vec{x}_i),\ \ \boldsymbol{J}_j=\mathbf{1}-\Sigma_{i<j}\beta_{ji}\boldsymbol{J}_i\cdot\vec{\nabla}_i\vec{\nabla}_i\psi_i(\vec{x}_i)$$

image plane magnification

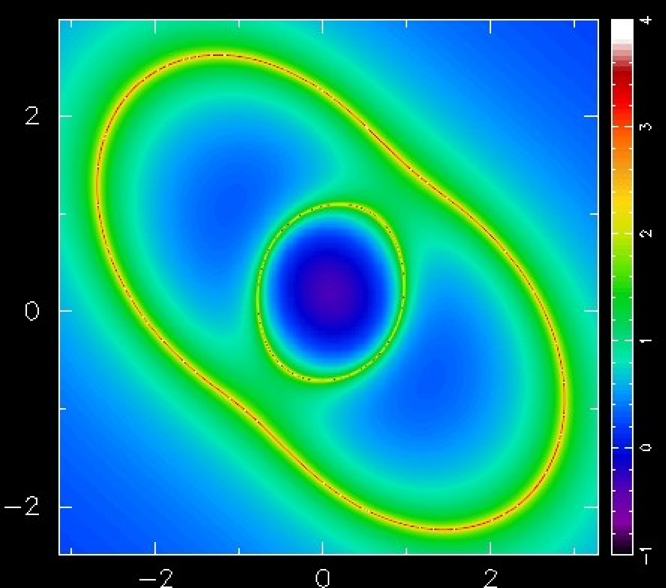
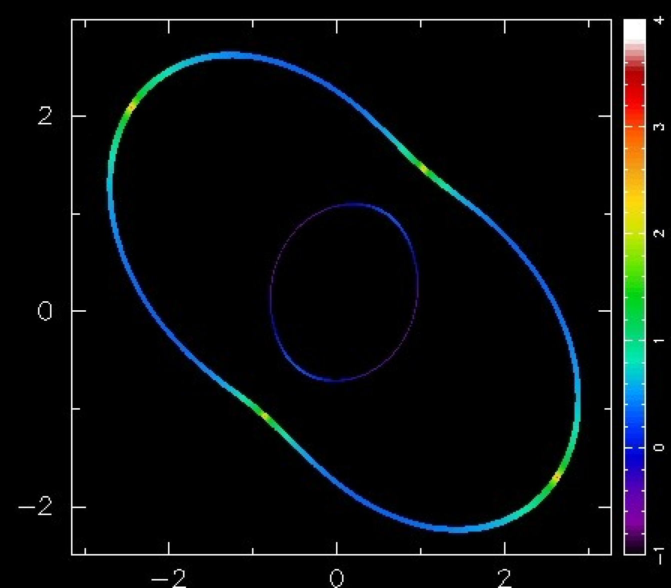
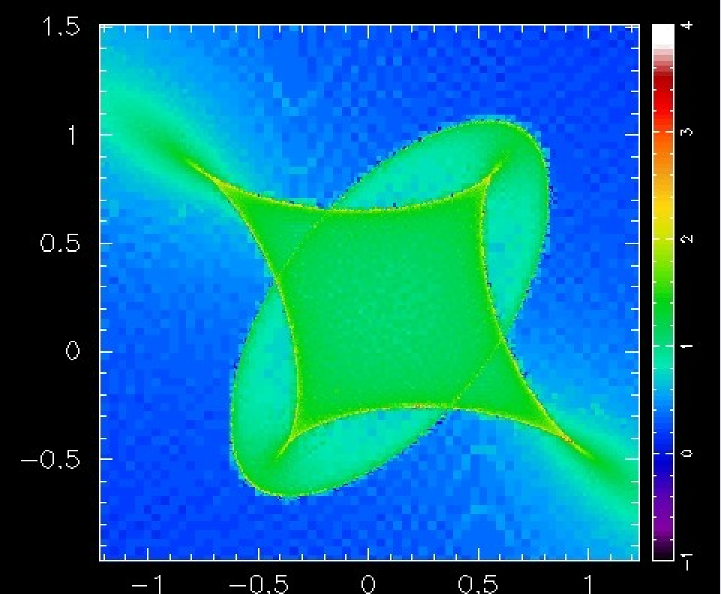


image plane “cuspiness”



source plane magnification



GLAMROC: Gravitational Lens Adaptive Mesh Raytracing of Catastrophes

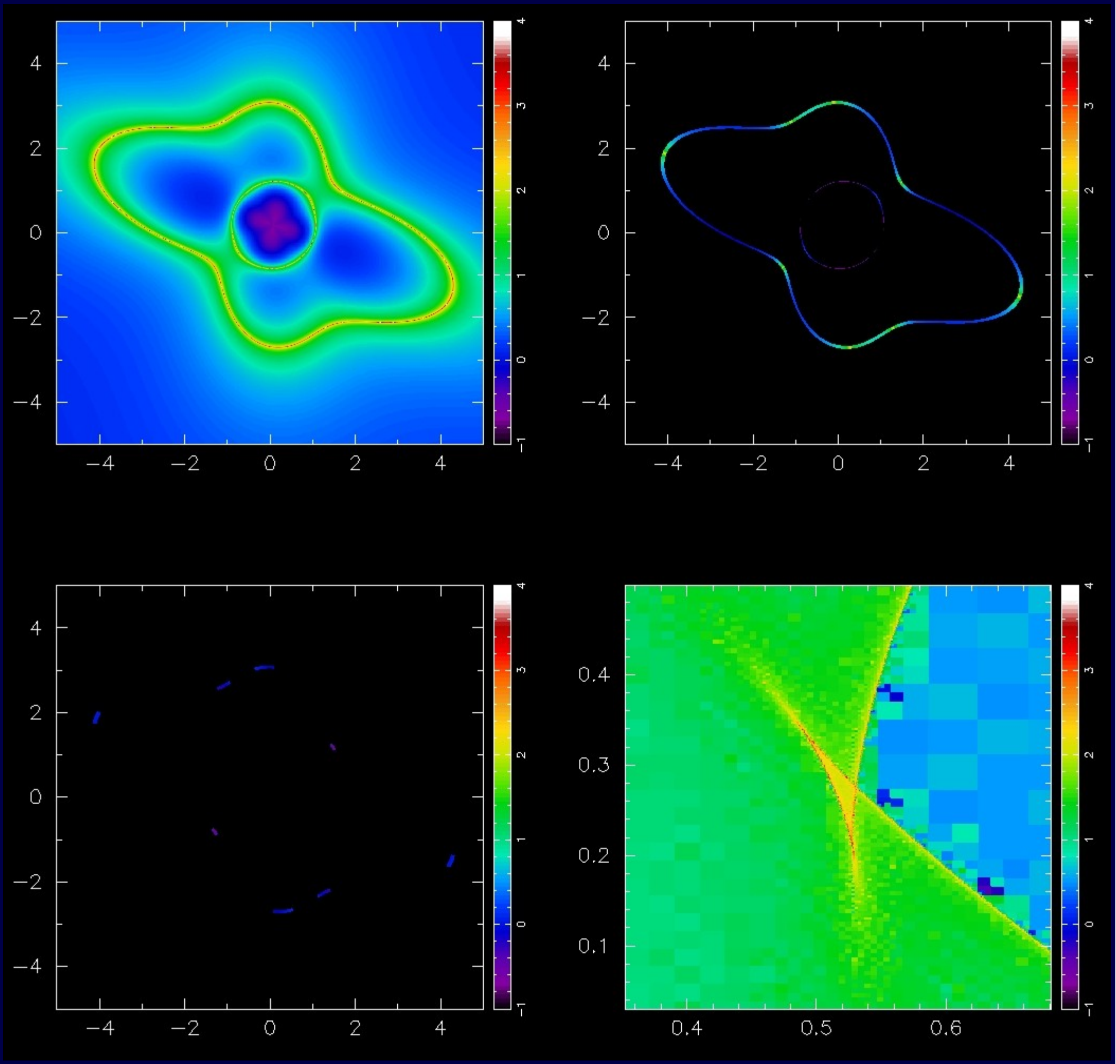
- Use tractable lens "atoms" - all derivatives are done analytically
  - Cored isothermal spheres (isopotentials with ellipticity, boxiness, skew)
  - NFW (elliptical, boxy, skew)
  - Sersic profiles with 2n = integer
- Arbitrary number of lenses on arbitrary number of lens planes
  - Going from 1 to 2 lens planes is a huge mess
  - Going from 2 to N lens planes is simple
- Up to 6th derivative of time delay can be calculated
  - This covers all "elementary" catastrophes
- Image plane adaptive mesh improves resolution where needed
  - Based on magnification to resolve critical curves
  - Based on surface brightness for efficient lens modeling
- **Powerful tool to study questions in gravitational lens theory**

How Generic Are Catastrophes?

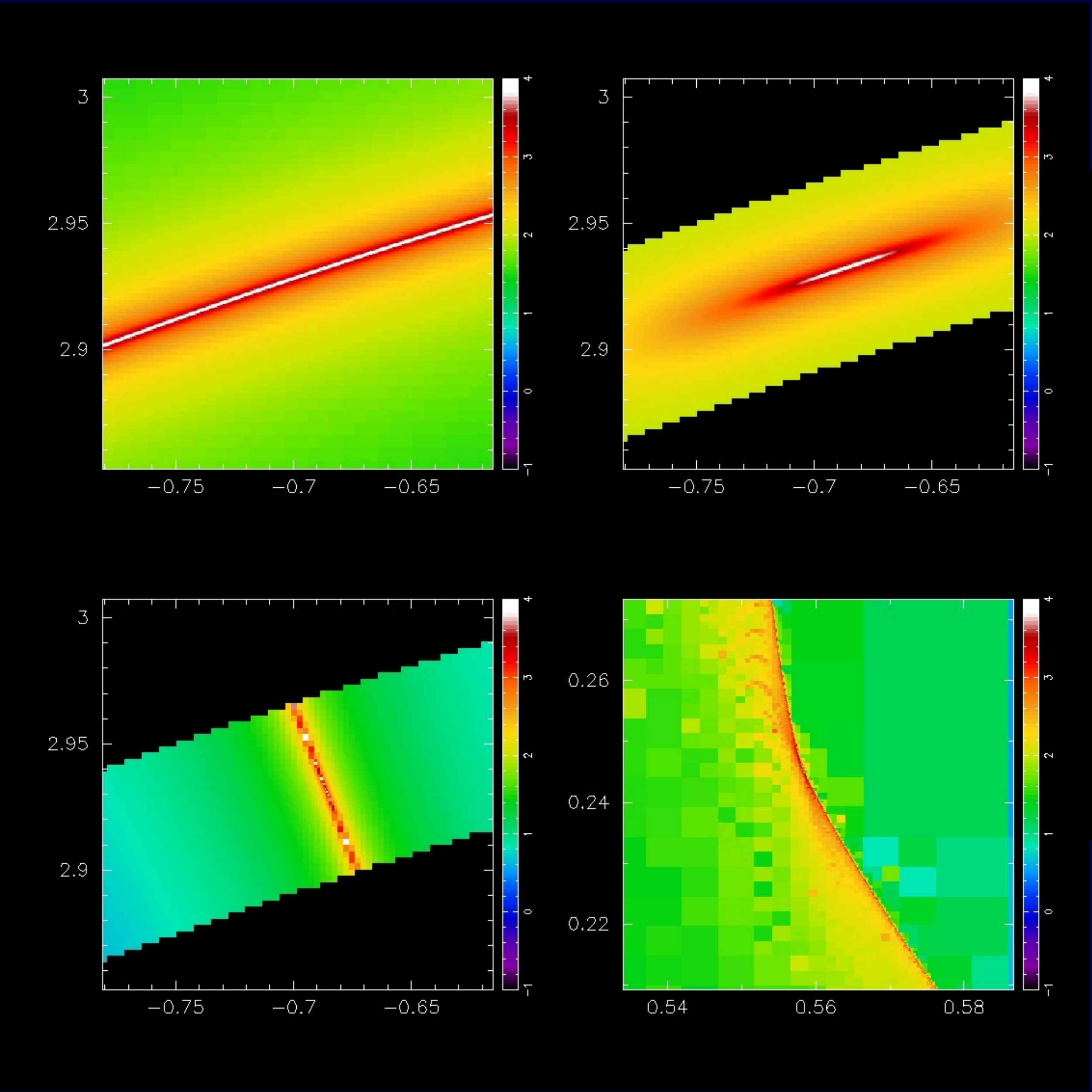
- Fold (critical curve) is one condition on the lens map
  - A given source plane has 1D sets of folds
- Cusp is one additional condition
  - A given source plane has a discrete set of cusp points
- Swallowtail is next order (first and second derivatives = 0)
  - Discrete source planes behind a general lens exhibit swallowtails
- 2D catastrophes: umbilics
  - Fold catastrophe: one eigenvalue of magnification matrix = 0
  - Umbilics have both eigenvalues = 0: $J = 0$
  - Discrete source planes exhibit the lowest-order umbilics
    - Hyperbolic and elliptic umbilics distinguished by sign of Det Hess J
- Higher order catastrophes do not generically appear
  - Butterfly etc. (cusp-like), parabolic umbilic etc.

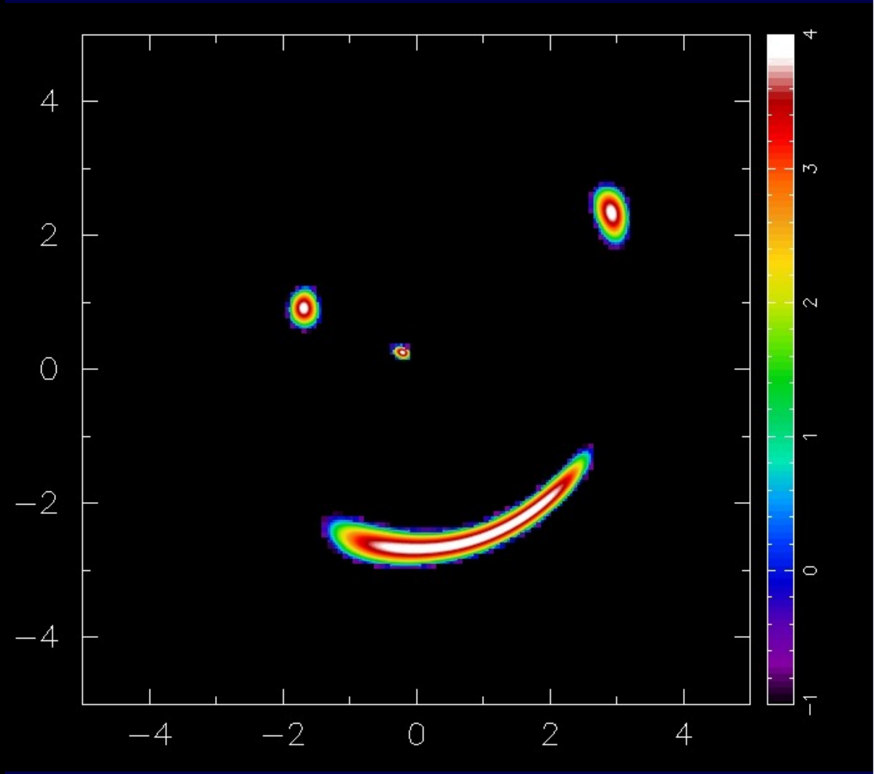
Observing Higher-Order Catastrophes

- Future surveys (SNAP, LSST) will find 1000s of lenses
  - Chance to observe rare systems near swallowtails, etc.
- Precise modeling possible
  - “Golden” lenses?
- Monte carlo simulations:
  - How common are these?
  - Automatic detection in datasets?
- Dark Matter Physics?
  - Substructure?
  - Self interactions?
- Distribution of dark matter

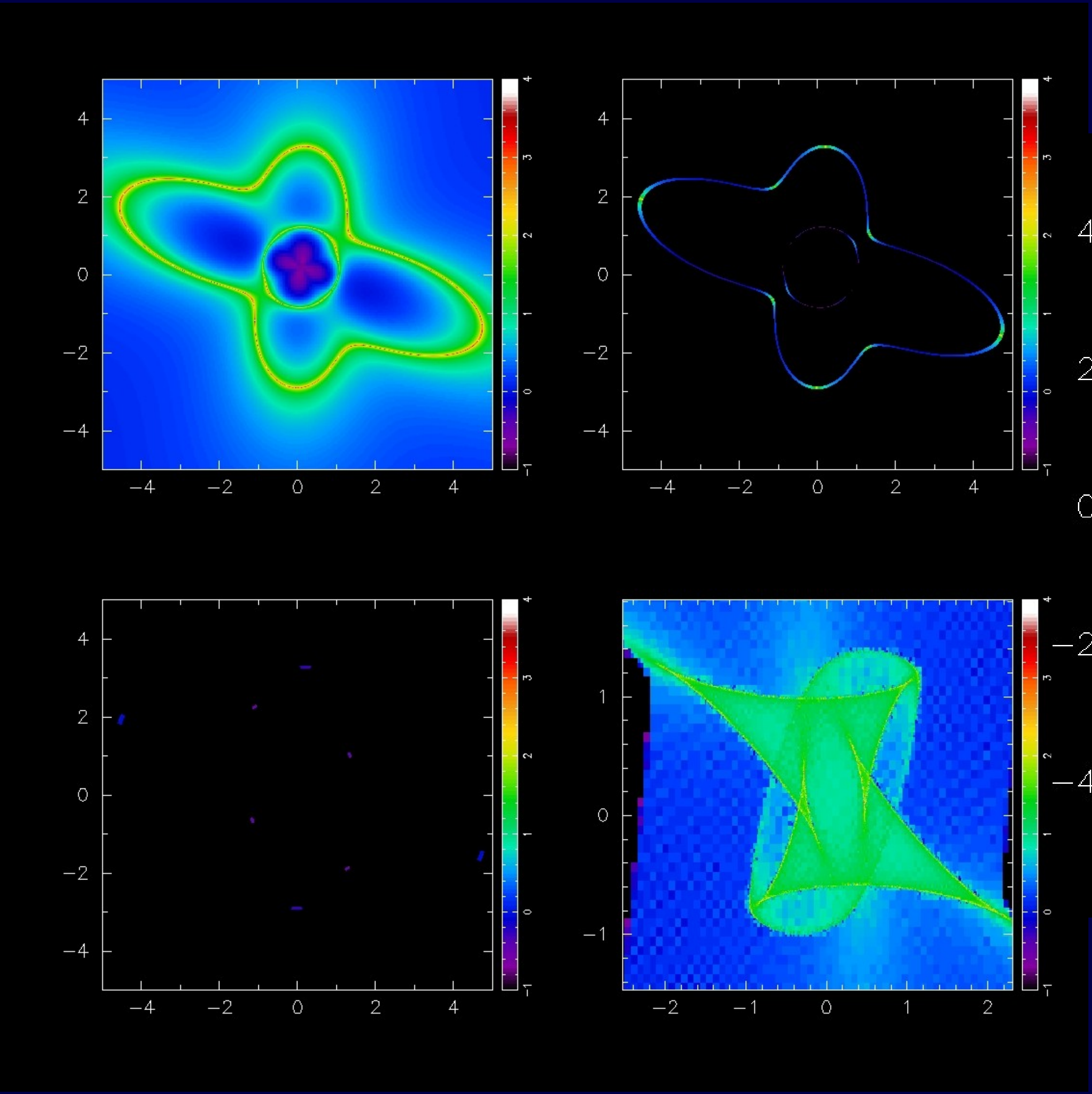


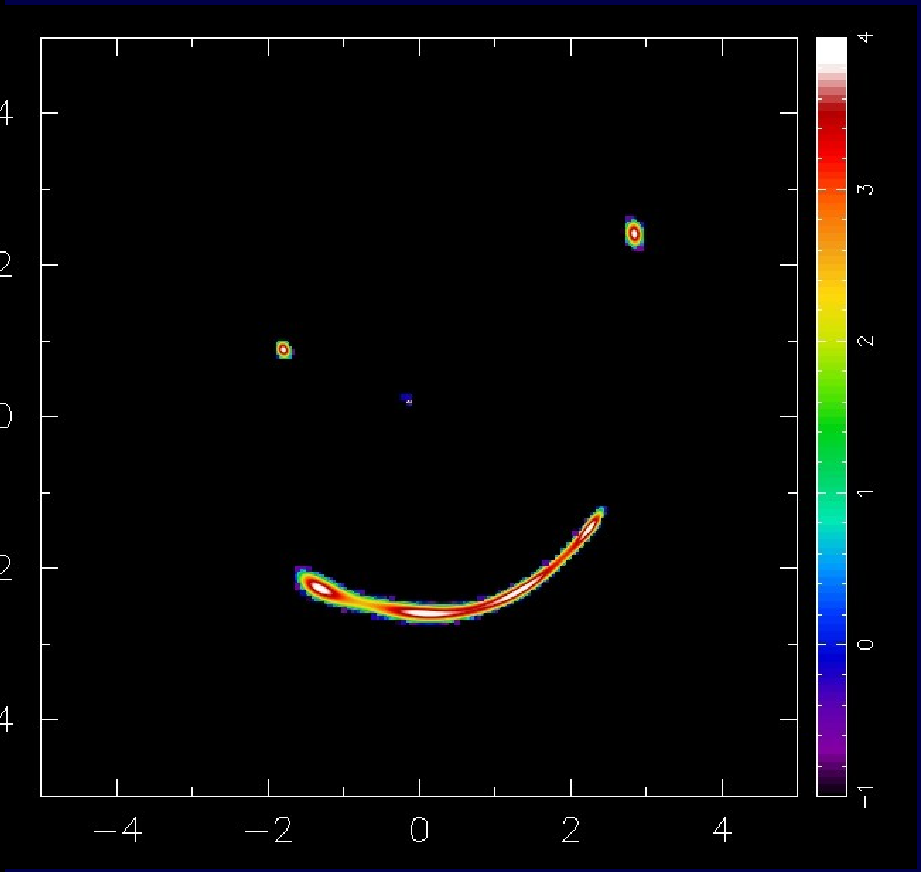
Swallowtail Points: 4 Images Merge





Inside the Swallowtail: Seven Image Configuration



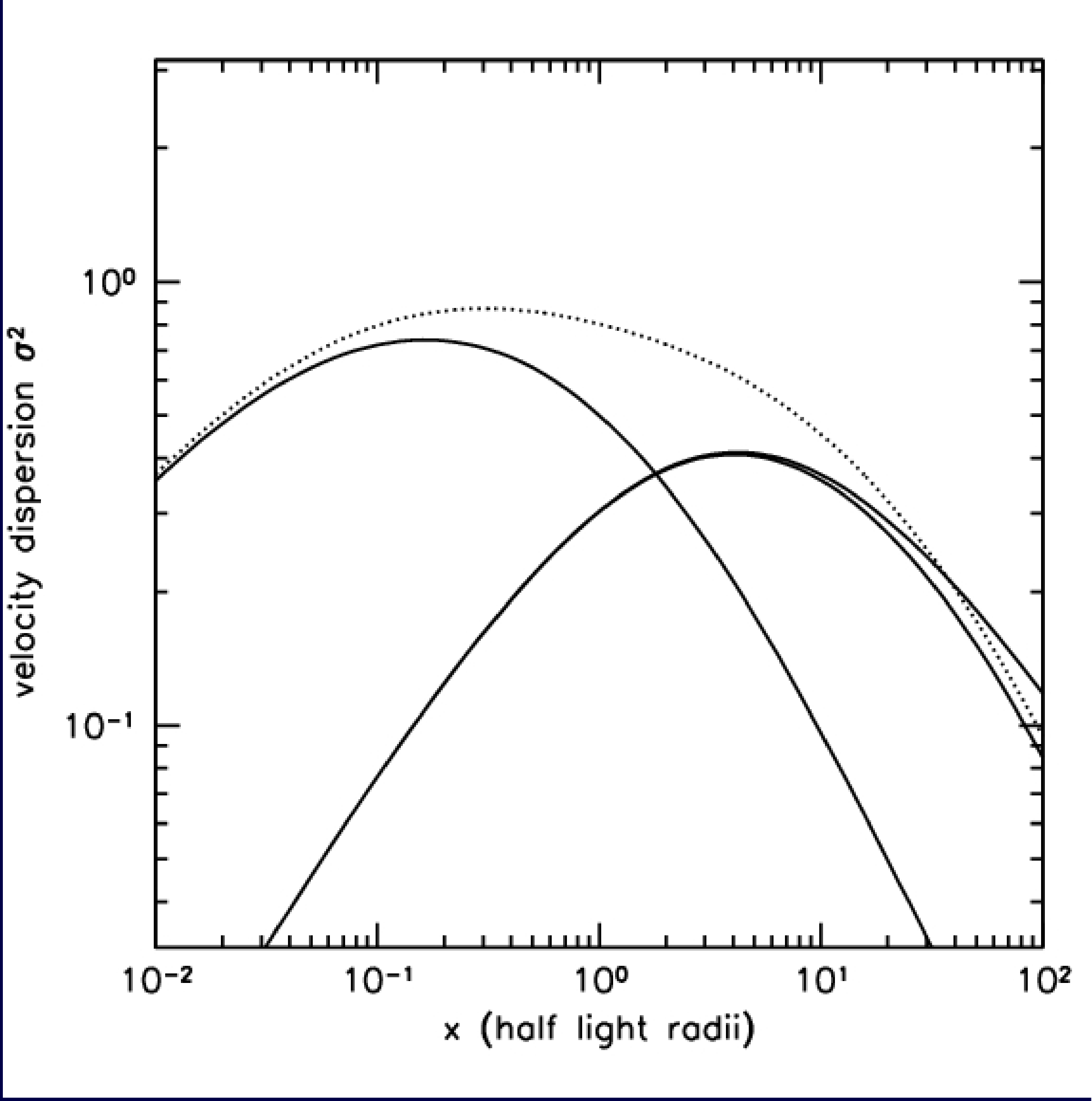


Aside: Finite Mass NFW Profile

- NFW profile has a (logarithmically) infinite mass
- Additional truncation with analytic lens potential

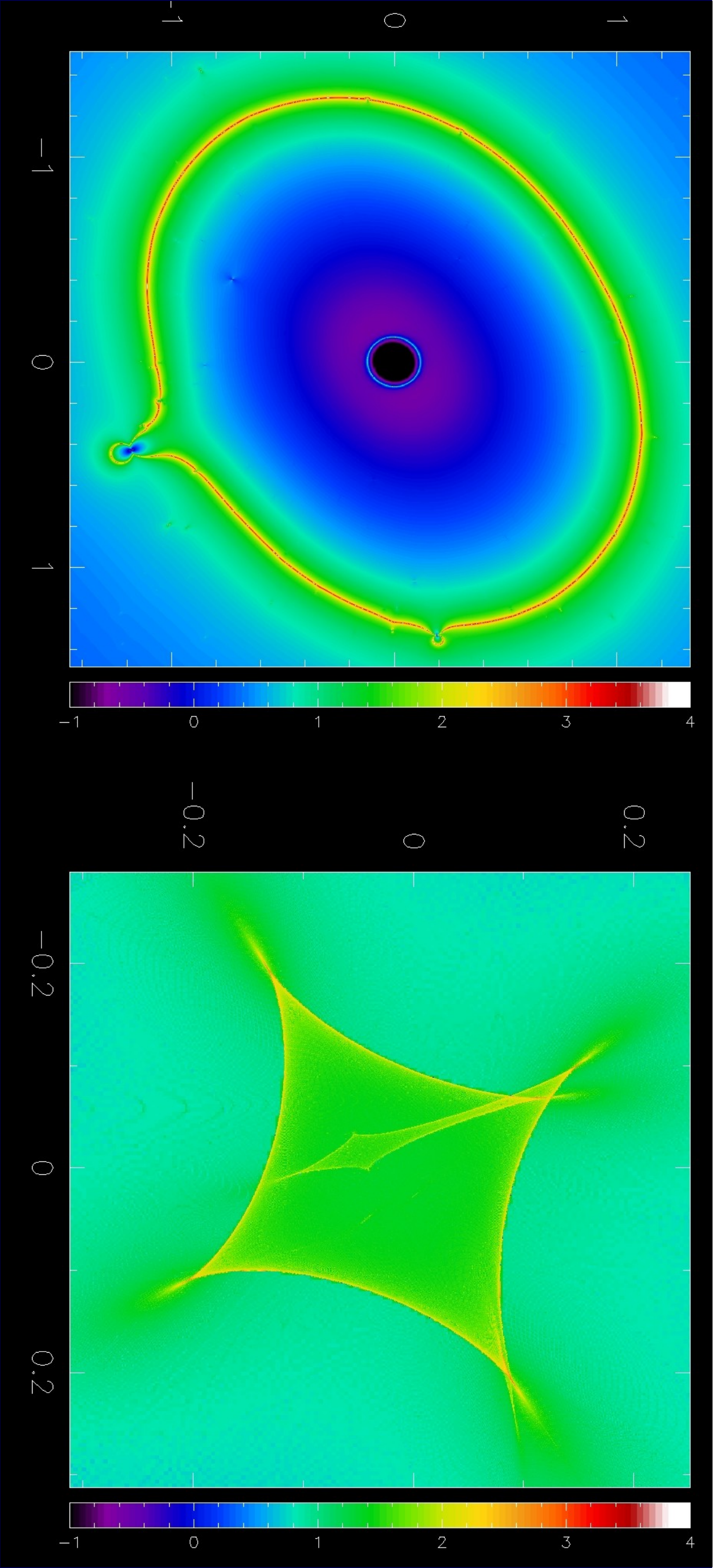
$$\rho(x) = \rho_{NFW}(x)\left(\frac{C^2}{C^2+x^2}\right)^n$$

- Model elliptical galaxy: Sersic profile for stellar component
- With reasonable parameters, combination is ~isothermal
  - agrees with observations
- Combination of elliptical isopotentials can yield elliptical isodensities with 3:1 axis ratio



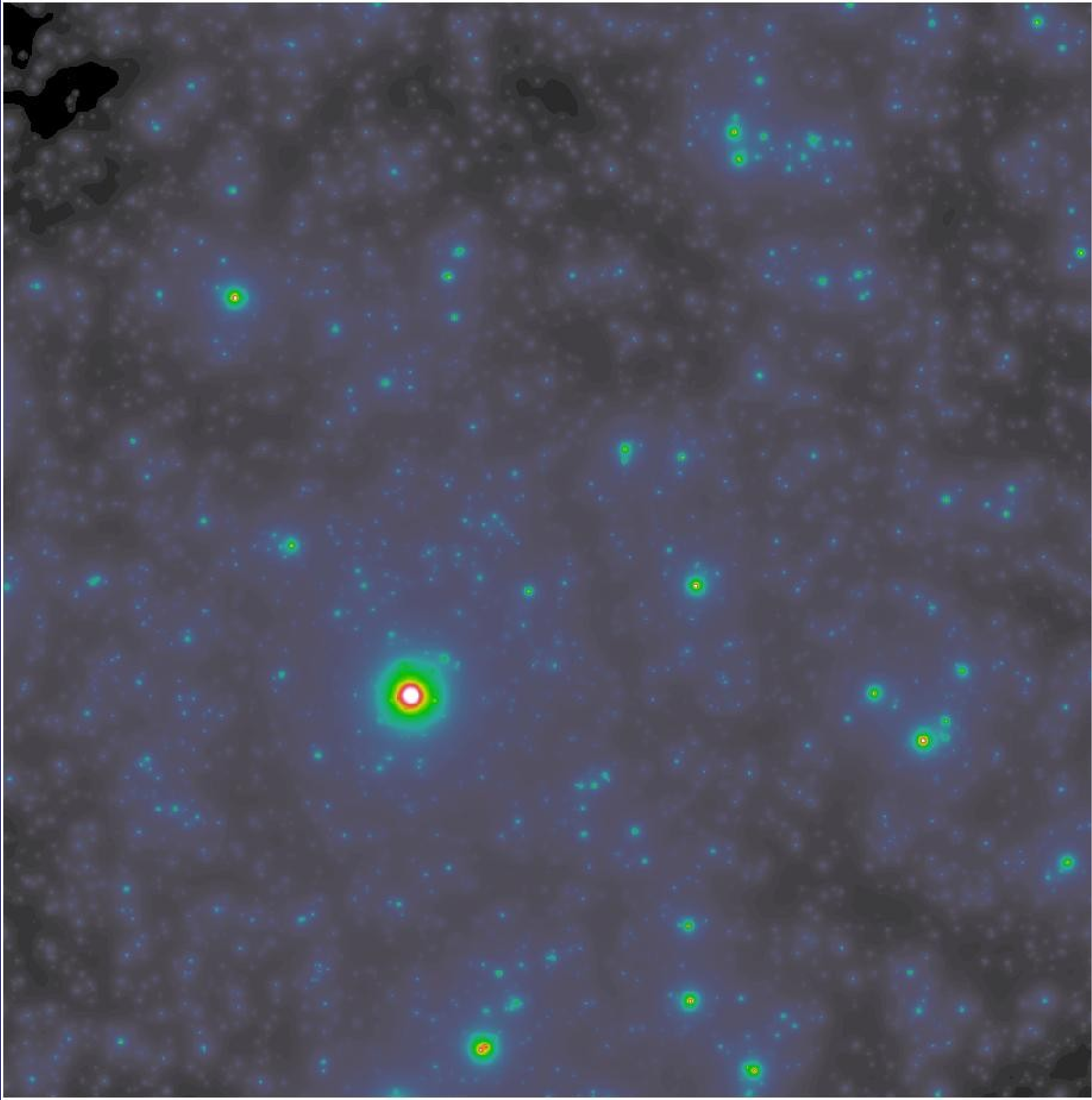
Lens Substructure

- Semi-analytic simulation (Taylor & Babul) of substructure in galactic halos
  - several hundred subhalos within 2 Einstein radii
- Main lens is approximately isothermal
  - e.g. NFW + Sersic
- With isothermal substructure, the effects are easily noticeable
  - 7 and even 9 image configurations seen
- NFW substructure is considerably less powerful for modifying the lens structure



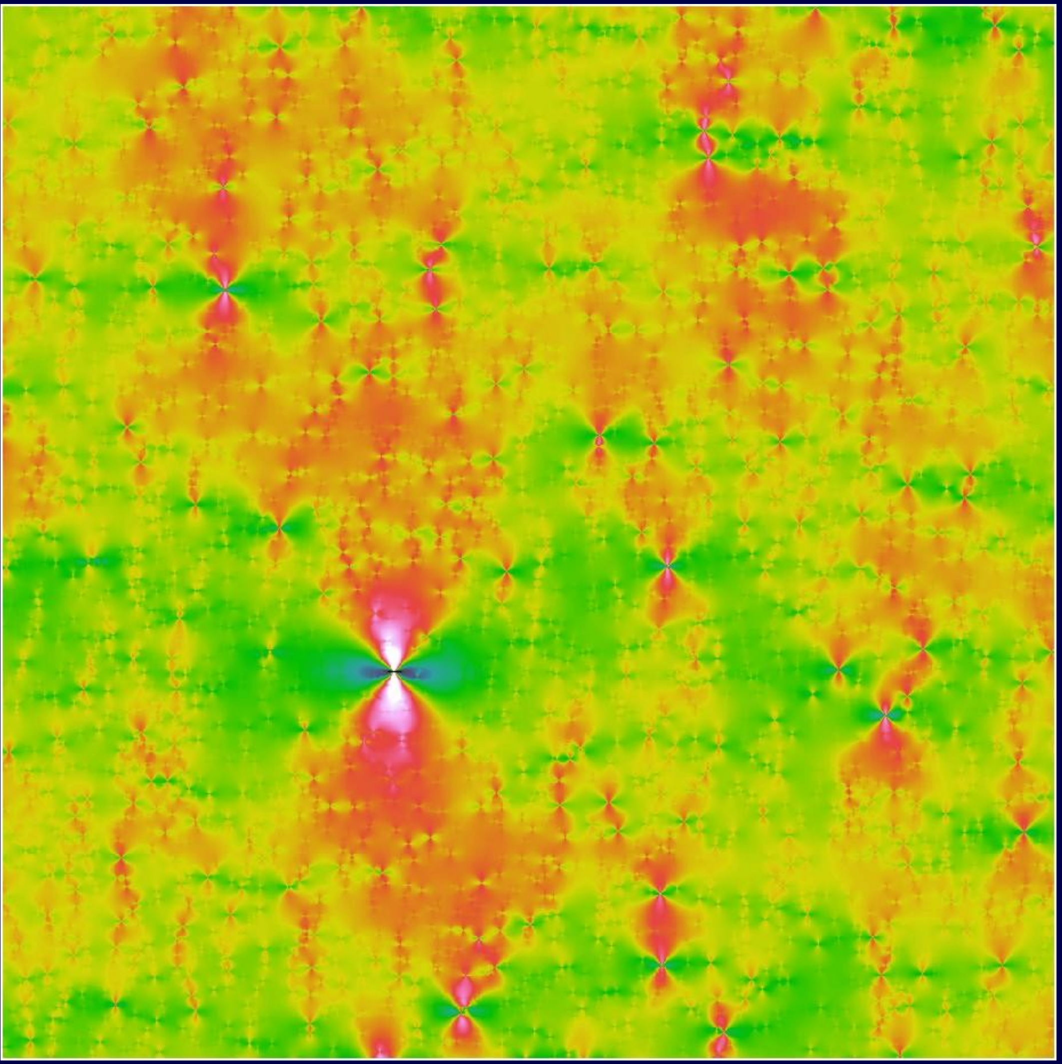
The Mini-Millennium

- Millennium run
  - galaxy catalog
  - light cone output
- Galaxy-galaxy lensing of particular interest
- What's new? Flexion.
  - 3^{rd} derivative of lens map
  - gradient of convergence and shear: 6 terms
- Shear gives ellipses, flexion gives “bananas”
- GLAMROC computes this easily – derivatives of lens map along rays
  - 7500 galaxy lenses
  - 20 lens planes

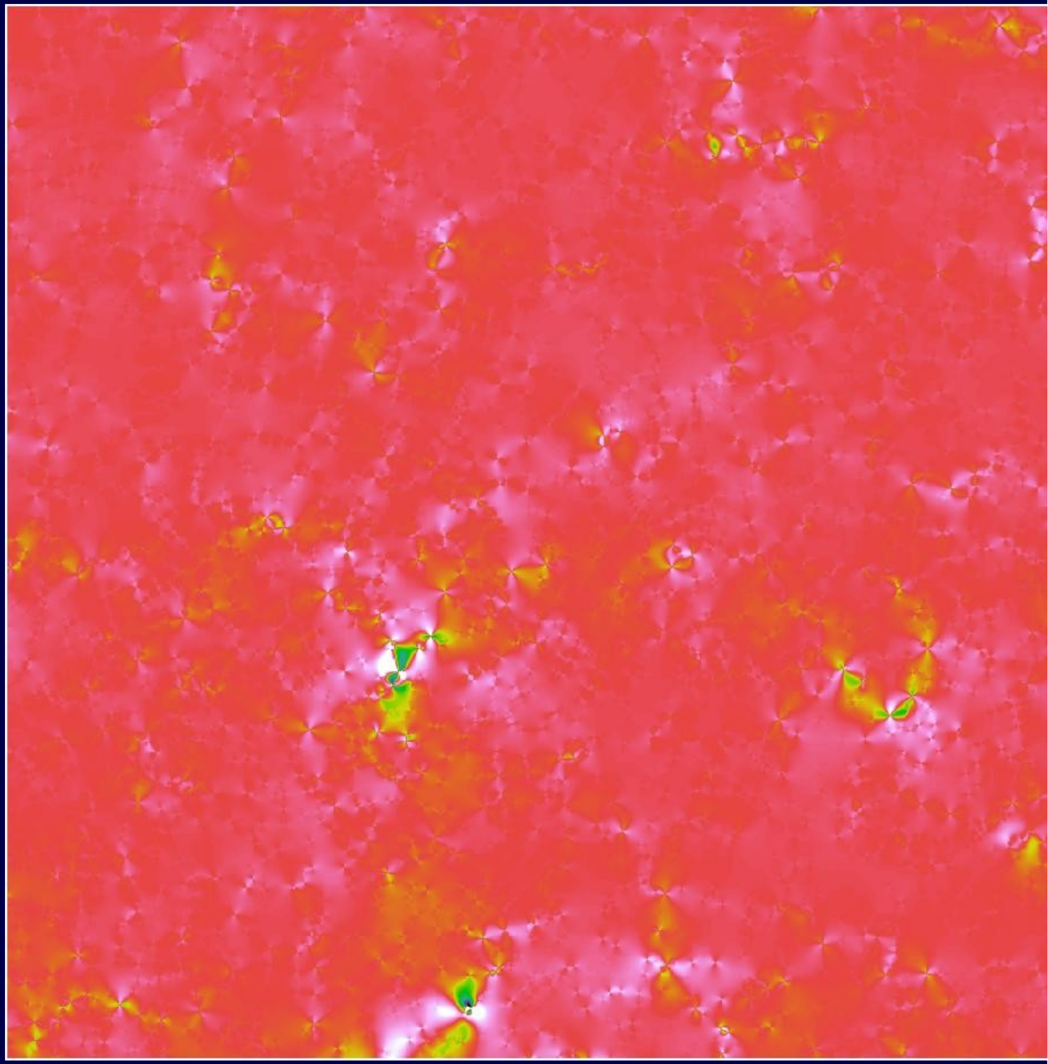


3'x3' convergence map

Shear and Rotation



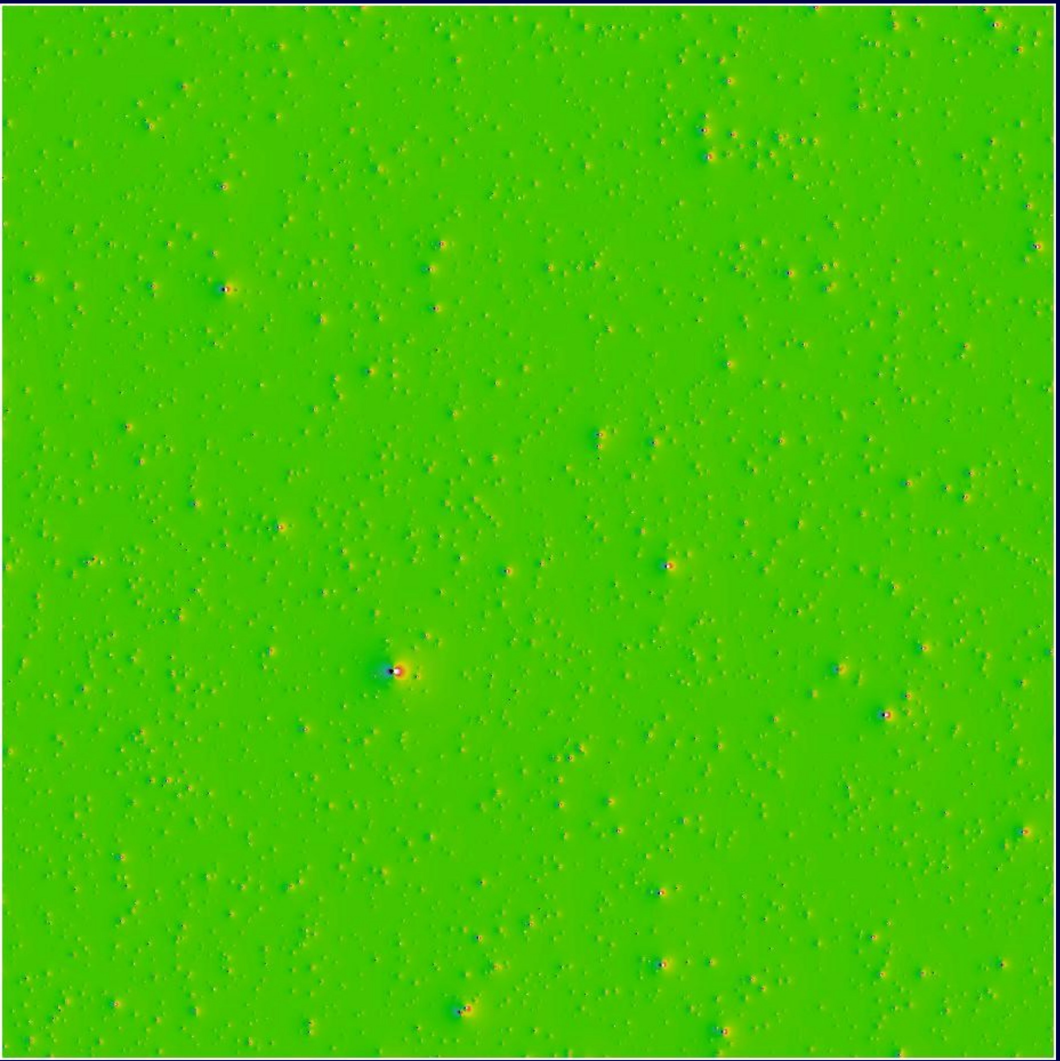
one (of two) shear components



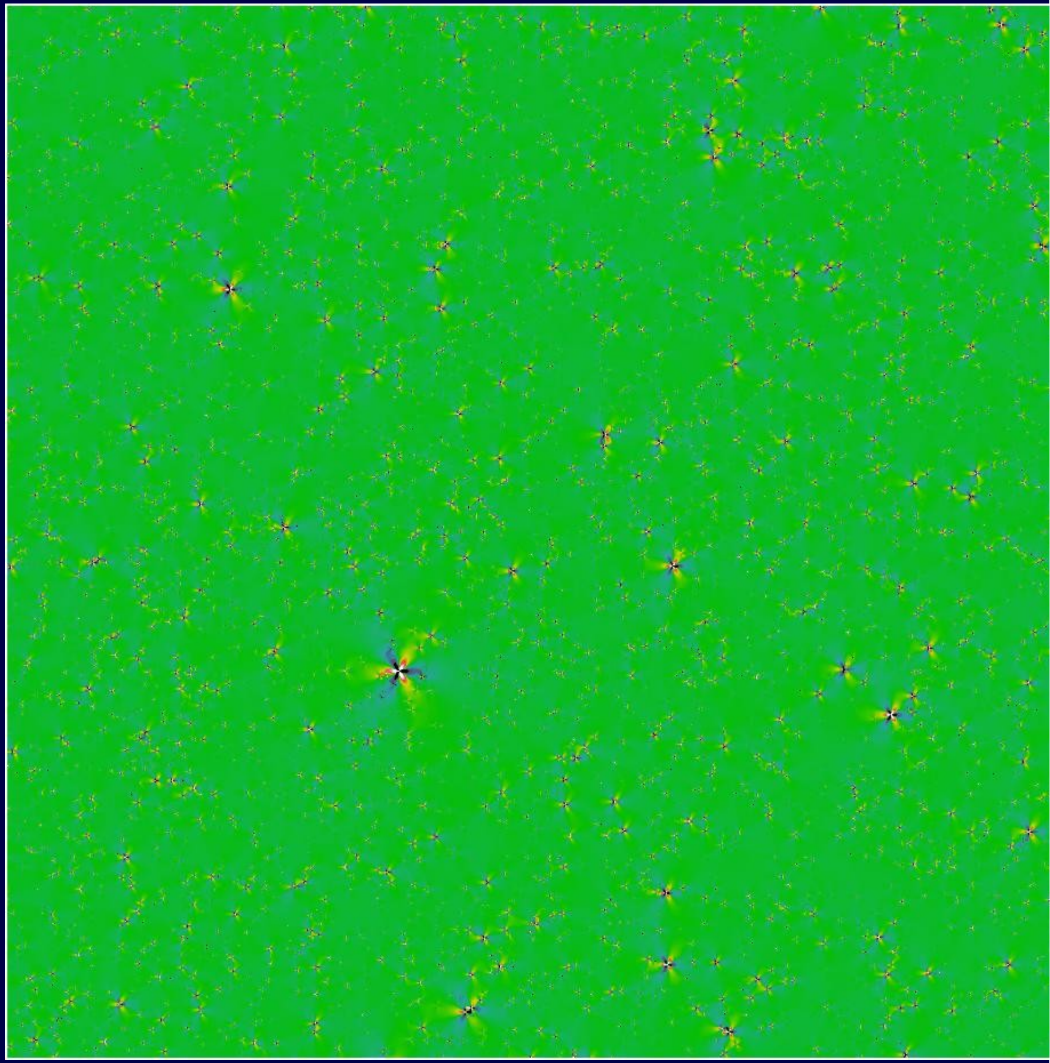
“rotation” induced by multiple lens planes

Flexion

Notice: flexion field is flatter – flexion falls off more rapidly than shear



4 components have "dipole" structure



2 components have "sextupole" structure

Summary

- Ground based microlensing surveys of M31 are ongoing, approaching LMC/SMC sensitivity
- Excellent prospects – both ground and space
- HST WFPC2 survey of M87 limits Virgo MACHOs
  - ACS data in hand will greatly expand reach
- GRB microlensing will have similar sensitivity considering SWIFT data

- Large samples of strong lenses can probe the distribution of dark matter in the universe
  - Higher order catastrophes
  - Substructure in lens galaxies
  - Shear and flexion in galaxy-galaxy lensing