High Resolution Numerical Analysis of Quasar Microlensing

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CCI
From the First Objects to the Cosmic Web

Outline

› Quasar Lensing

› Quasar Microlensing

› Numerical Simulation with Supercomputer code

› Effect of lensing galaxy mass function

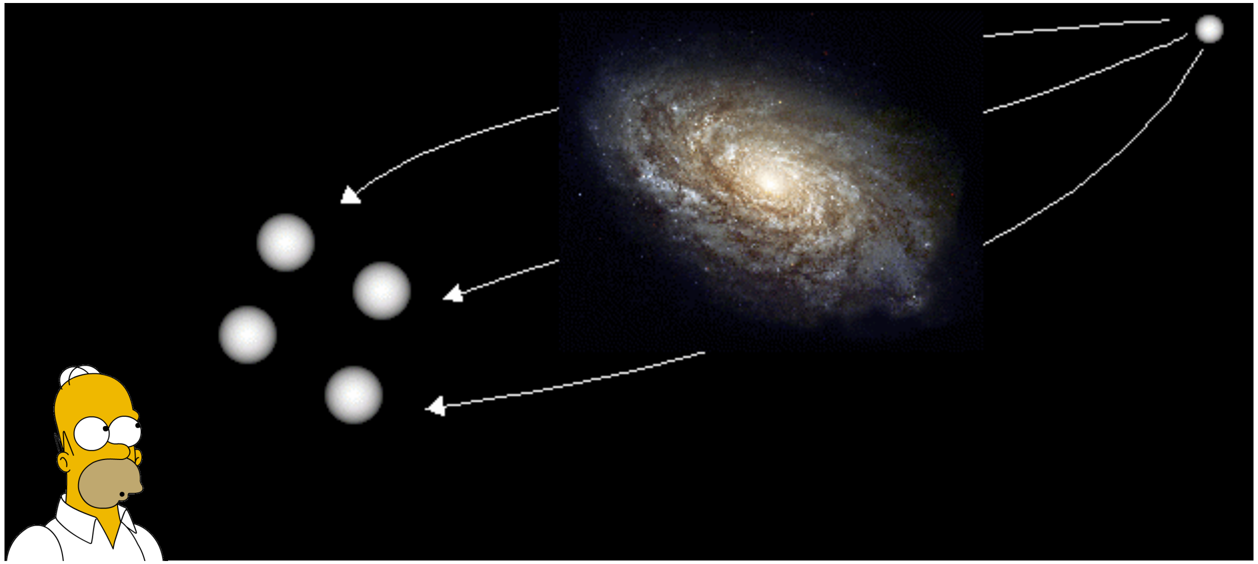
› Broad-line region in quasar Q 2237

› Water Maser in MG 0414

› GPGPUs

› Conclusions

Quasar Lensing Basics



› Gravitational Lensing

› Distant quasar (source), $z_S \sim 2$

› Intervening galaxy (lens), $z_L \sim 0.5$

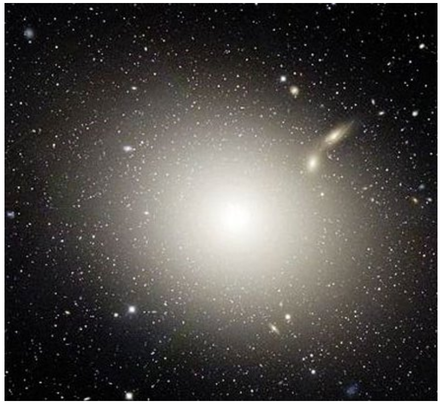
› Multiple magnified images of the quasar are seen

Quasar Lensing Basics

Q 2237 – Einstein Cross
$z_L = 0.0394$, $z_S = 1.695$

- Can't resolve much/anything in the images
- Work with
  - Number, Positions, Flux, Colours/Spectrum, others
- Determined mostly by
  - The lens galaxy mass distribution
  - Observer/lens/source positions
  - These go into model
  - Model is (good) approximation

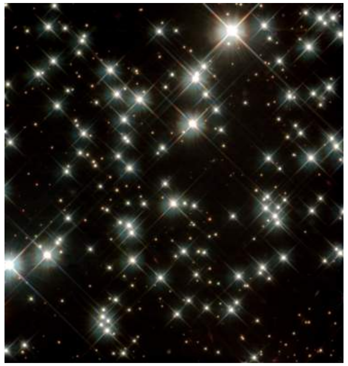
Quasar Microlensing Basics



- Use galaxy models like that are smooth
- What about the small-scale structure (stars, planets, black holes, dark matter) in the lens galaxy?
  - Do they have an effect?
- Yes they can
- *Microlensing*

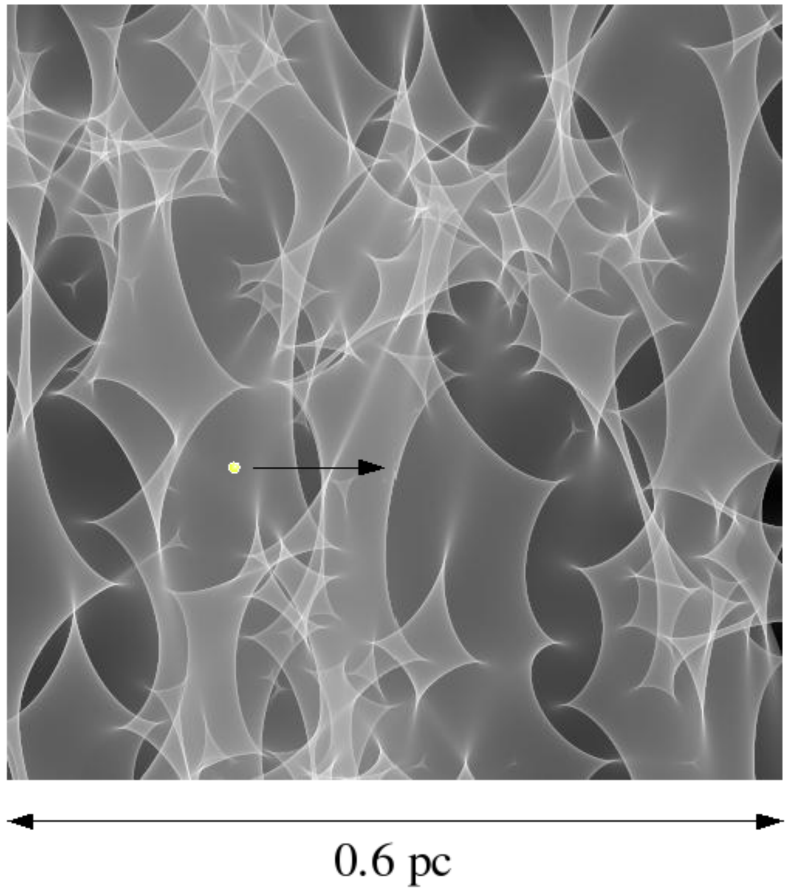
Elliptical Galaxy, M87

Canada-France-Hawaii Telescope, J.-C. Cuillandre (CFHT), Coelum

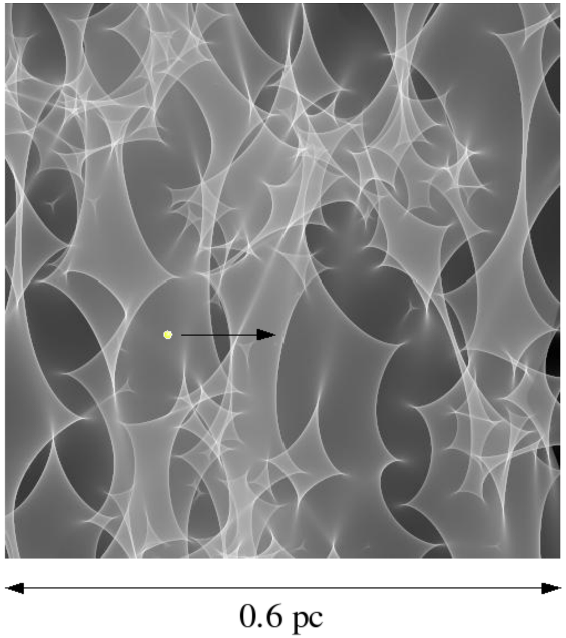


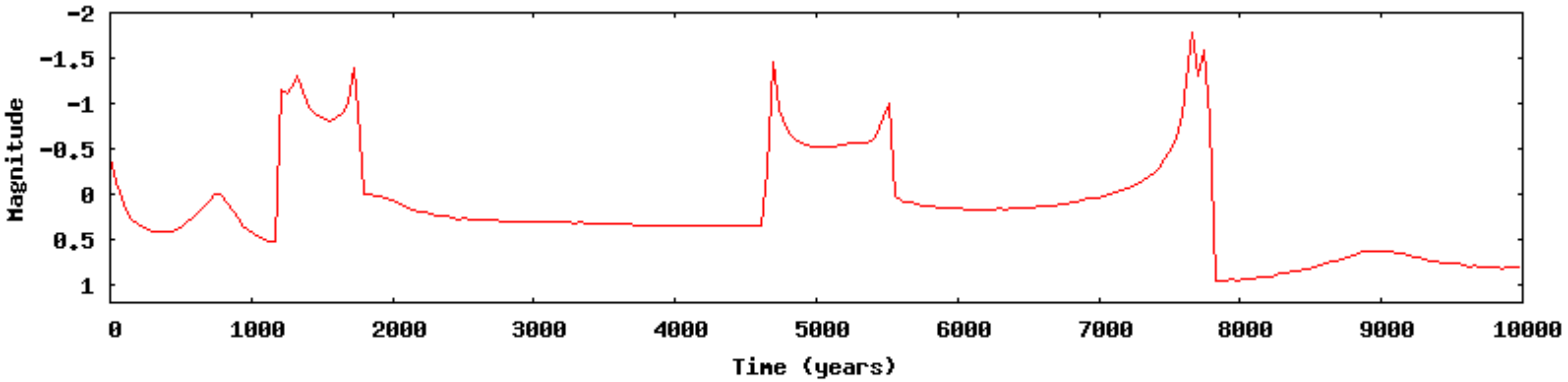
Quasar Microlensing Basics

- For each image add a *magnification map* into the model
  - Has to be numerically generated, by ray-tracing through lensing galaxy
  - Parameters for the map come from the lens model, but different for each image
- Map is representative of plane of quasar
- Map value (brightness) at point indicates relative magnification of quasar
- Quasar moves (relatively)



Quasar Microlensing Basics





Microlensing Simulation Code

- Key representation of microlensing: magnification map
  - Has been code to generate magnification map, Wambsganss, 1990s (others)
  - Out of date, not sufficient for today's problems
- Garsden-Lewis-Wambsganss (GLW) code
  - To limit of what's do-able
  - Parallel, distributed memory, disk caches, supercomputer
  - Huge number of stars in lensing galaxy (~ billion)
  - Huge number light rays (trillions) for ray-tracing
  - Huge resolution magnification maps (50000^2)
  - If these not needed: faster, more data generation

Garsden & Lewis (2010). *Gravitational microlensing: A parallel, large-data implementation*, New Astronomy.

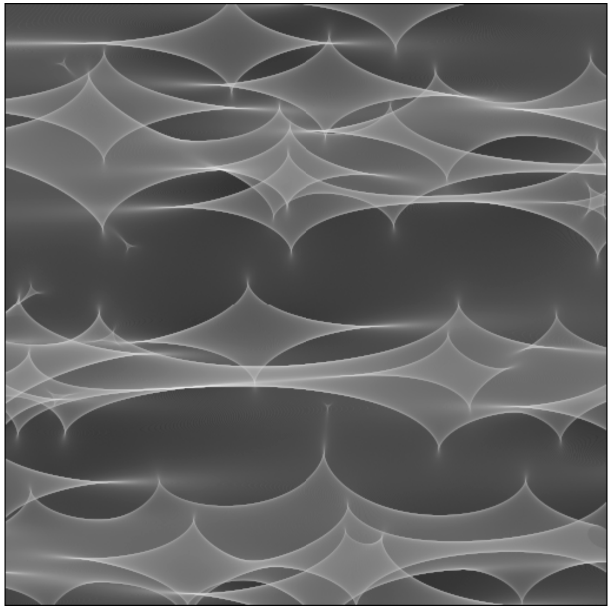
Data Processing

- That's great, but how to process data?
  - New tools need for that as well
- New, more compact data formats and data streaming
- Parallel FFTs of huge maps on supercomputer using distributed memory
- Parallel map analysis on GPGPU

Project 1: Mass in lensing galaxy

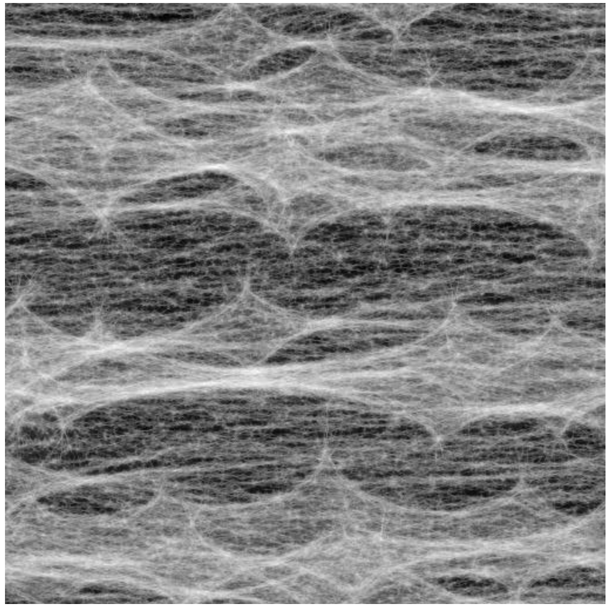
- Mass distribution in lens has an effect on microlensing
- Can we tell smooth matter or small compact matter?
- Investigate "bi-modal" distributions of

Stars + smooth matter



10% $M_\odot$ (N = 1,133) 90% smooth

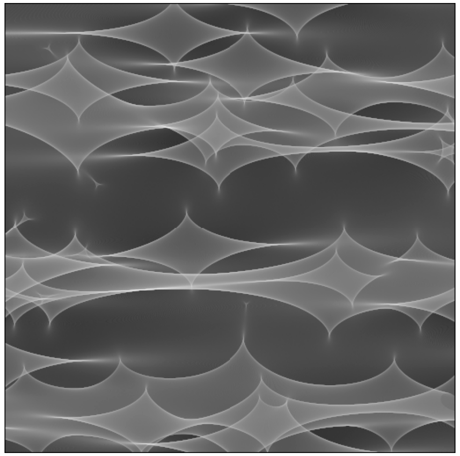
Stars + small compact objects



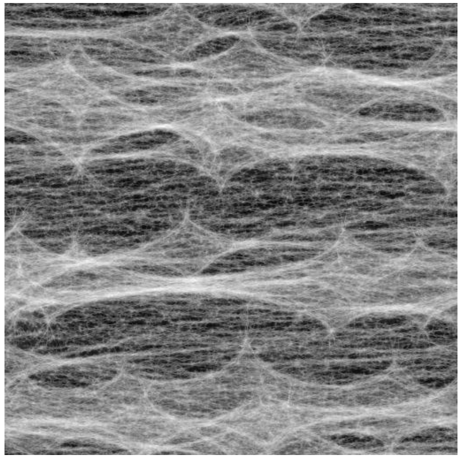
10% $M_\odot$ (N = 1,133) 90% 10^{-3} $M_\odot$ (N = 10,205,331)

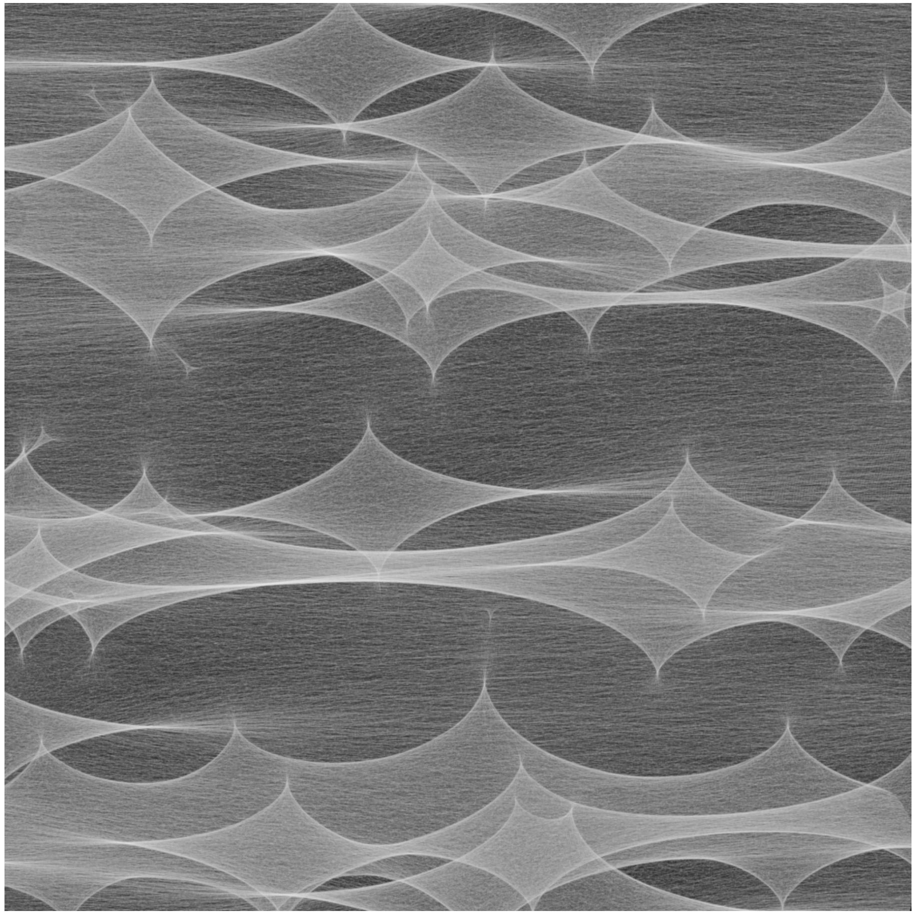
Lewis & Gil-Merino (2006) *Quasar Microlensing: When Compact Masses Mimic Smooth Matter* , ApJ

Smooth vs Very Small Compact Matter



To continue work with smaller masses need billion





10% $M_{\odot}$ (N = 1,133)

90% 10^{-5} $M_{\odot}$ (N = 1,020,533,131)

Quasar Microlensing Basics

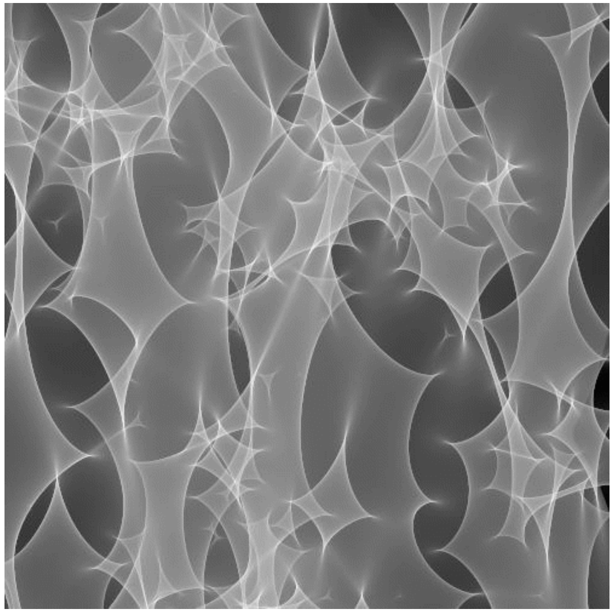
- Other mass distributions studied (not Salpeter)

  Gravitational Nanolensing from Subsolar Mass Dark Matter Halos
  Chen J., Koushiappas S. M., 2010, ApJ, 724, 400

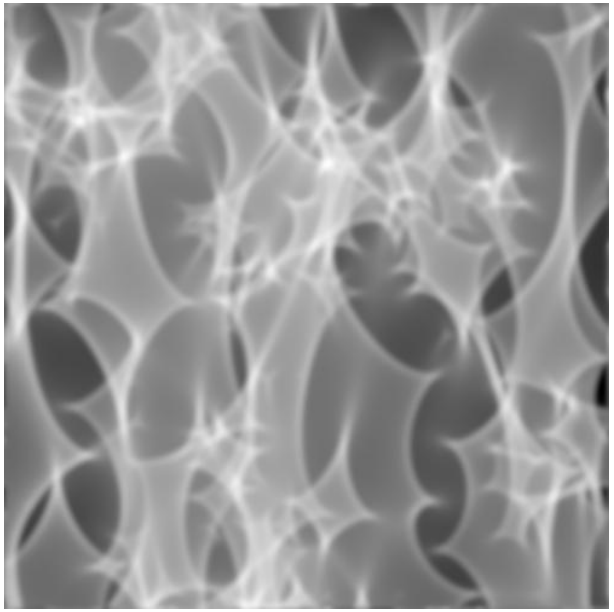
  Masses down to 10^{-4} M. How low can be implemented go?

- Interactions with source size

Small source

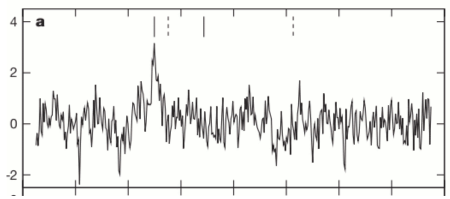


Larger source



Project 2: Water Maser in MG 0414

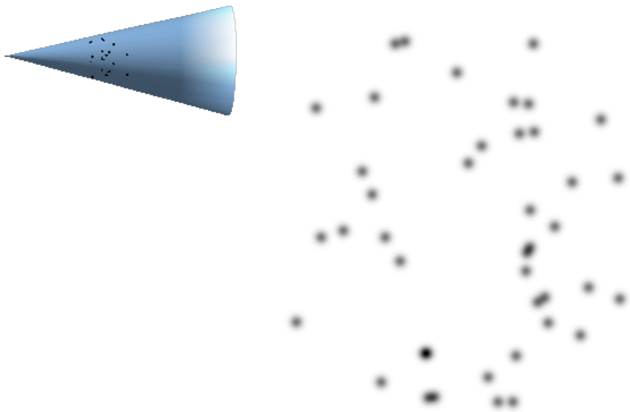
› Pick out quasar substructure

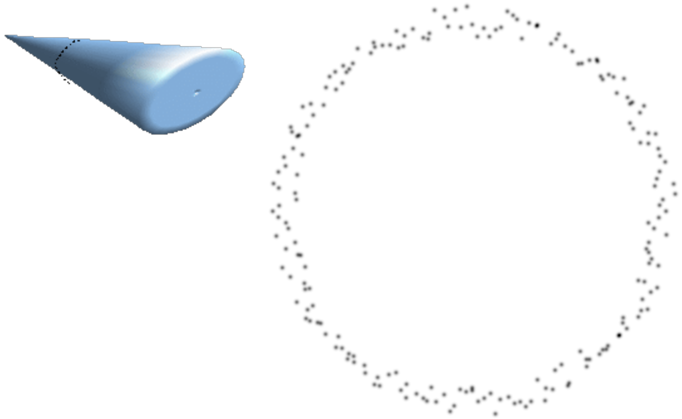


A gravitationally lensed water maser in the early Universe
Impellizzeri et al. Nature 2008

› Observed a single broadened peak

› Assume: Maser spots near to or around an AGN jet



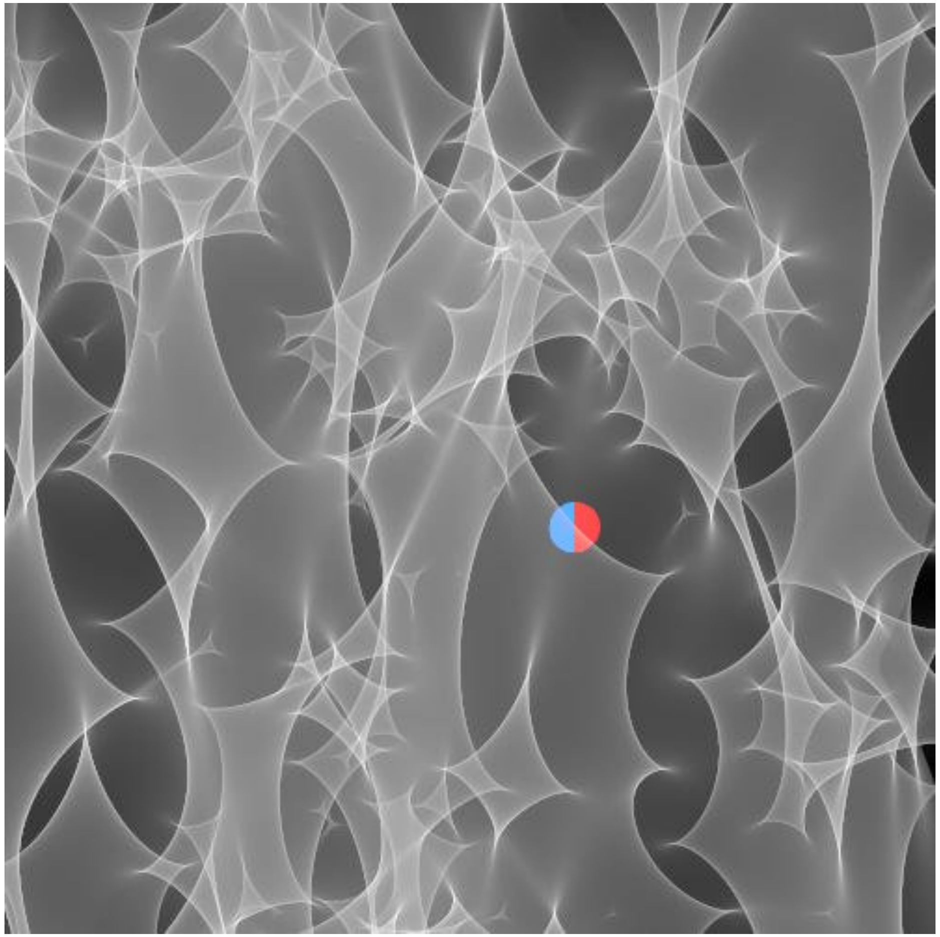


› These have a velocity profile i.e. frequency profile

- gradient vs. oriented ring

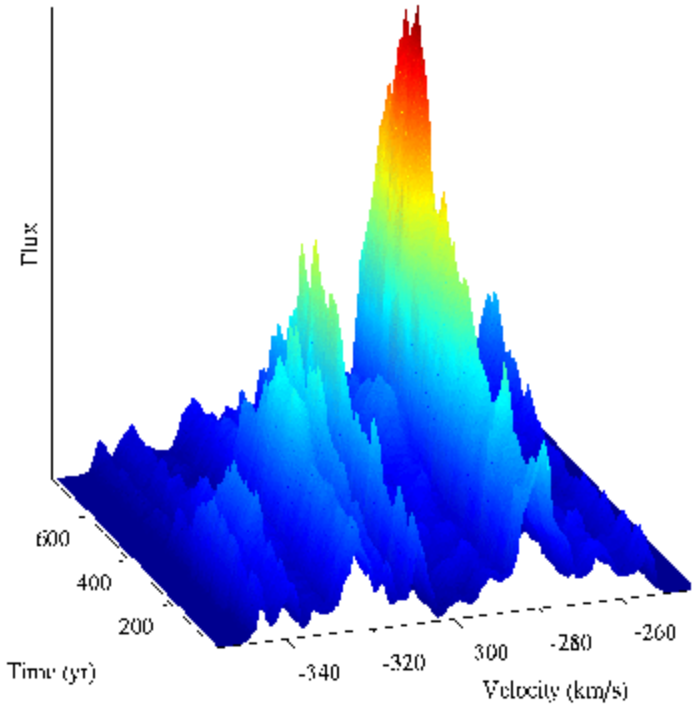
Quasar Microlensing Basics

- Microlensing can change the spectrum of the source
- Huh? Gravitational lensing is achromatic
- Need extended source
  - Different frequencies from different places
  - The different emission *locations* means get differential magnification
- Use microlensing to probe source emission

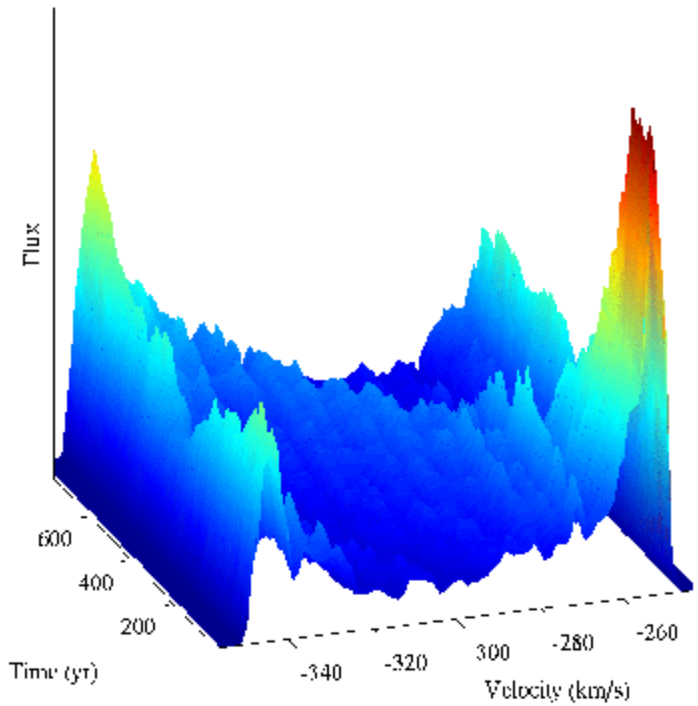


Simulated Microlensed Spectra

Patch



Ring



› Patch fits the observation

› Garsden, Lewis & Harvey-Smith, *The Water Maser in MG 0414+0534: The Influence of Gravitational Microlensing,* MNRAS (to be resubmitted)

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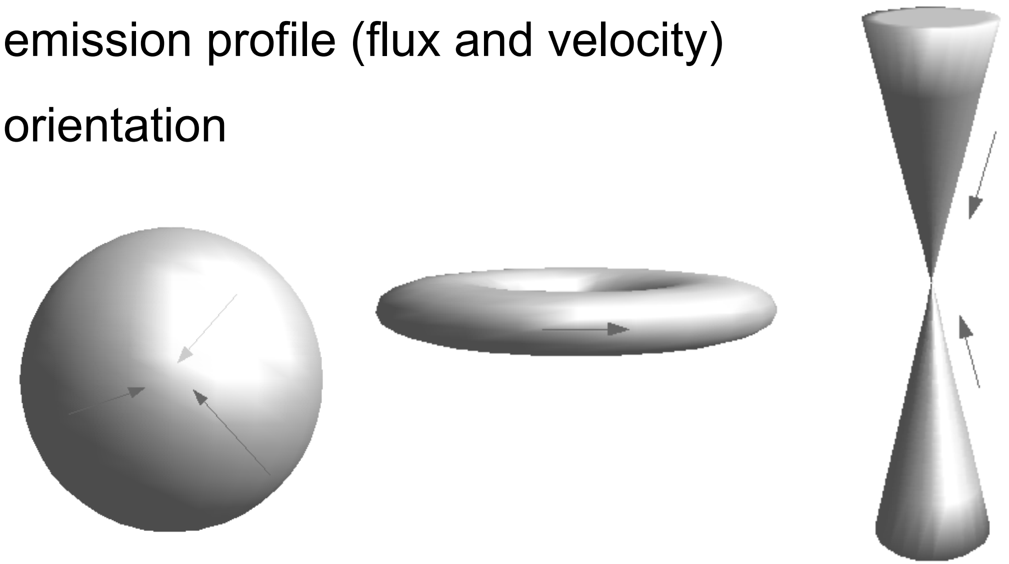
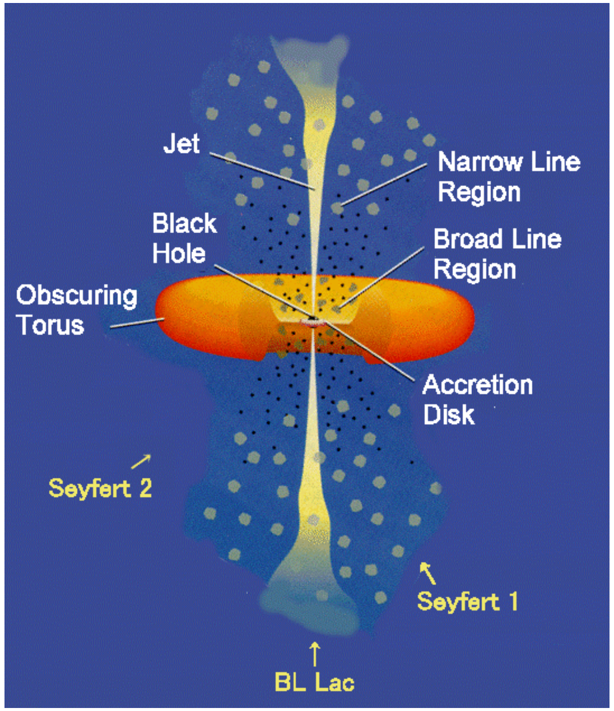
Project 3: Broad Emission Line Regions

› Clouds close to quasar SMBH and accretion disk

› Various models proposed

- source shape
- emission profile (flux and velocity)
- orientation



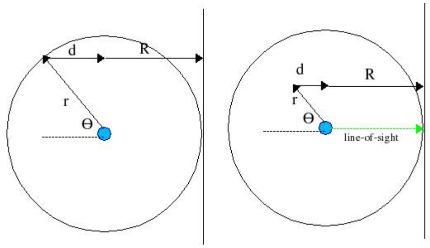


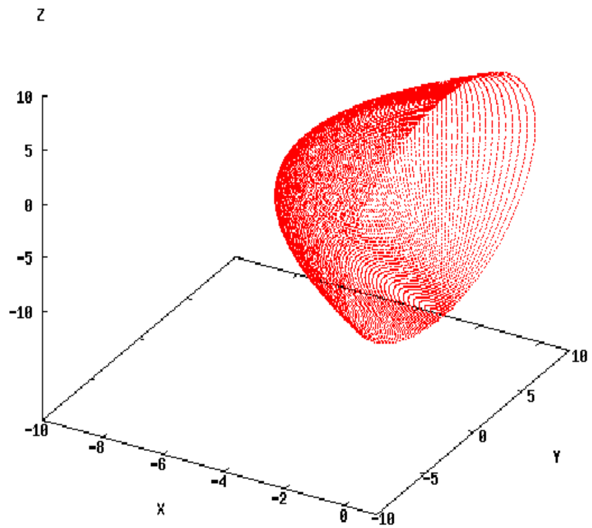
http://heasarc.gsfc.nasa.gov/docs/objects/agn/agn_model.gif

Broad Emission Line Regions

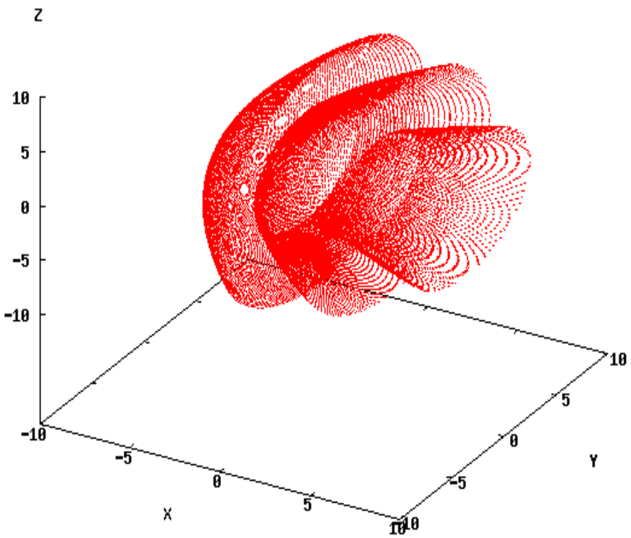
› But there's something else going on: *core flash* and *reverberations*

- Reverberation mapping



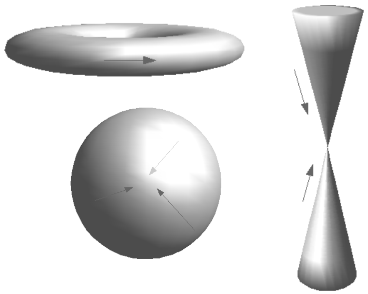


Isodelay surfaces (parabaloids)



Micolensing of Reverberation

- These isodelay surface travel through:



- source shape
- emission profile
  (flux and velocity)
- orientation

- Get spectrum of isodelay surface over time
- Microlens it
- Compare
  - Reverberation with no lensing
  - Reverberation including lensing
  - To see if lensing makes a difference
- More to do
  - This for source (BLR) the source at 1 location

Project 4: GPGPU[1]

Represents the arrival in your PC of a new programming paradigm, in the same sense that multiple CPUs and multiple cores did

- Multi-core CPUs gave you MIMD, parallel processes, parallel threads
- GPUGPU gives you SIMD, parallel threads, lots
  - SIMD? => vectorize array addition

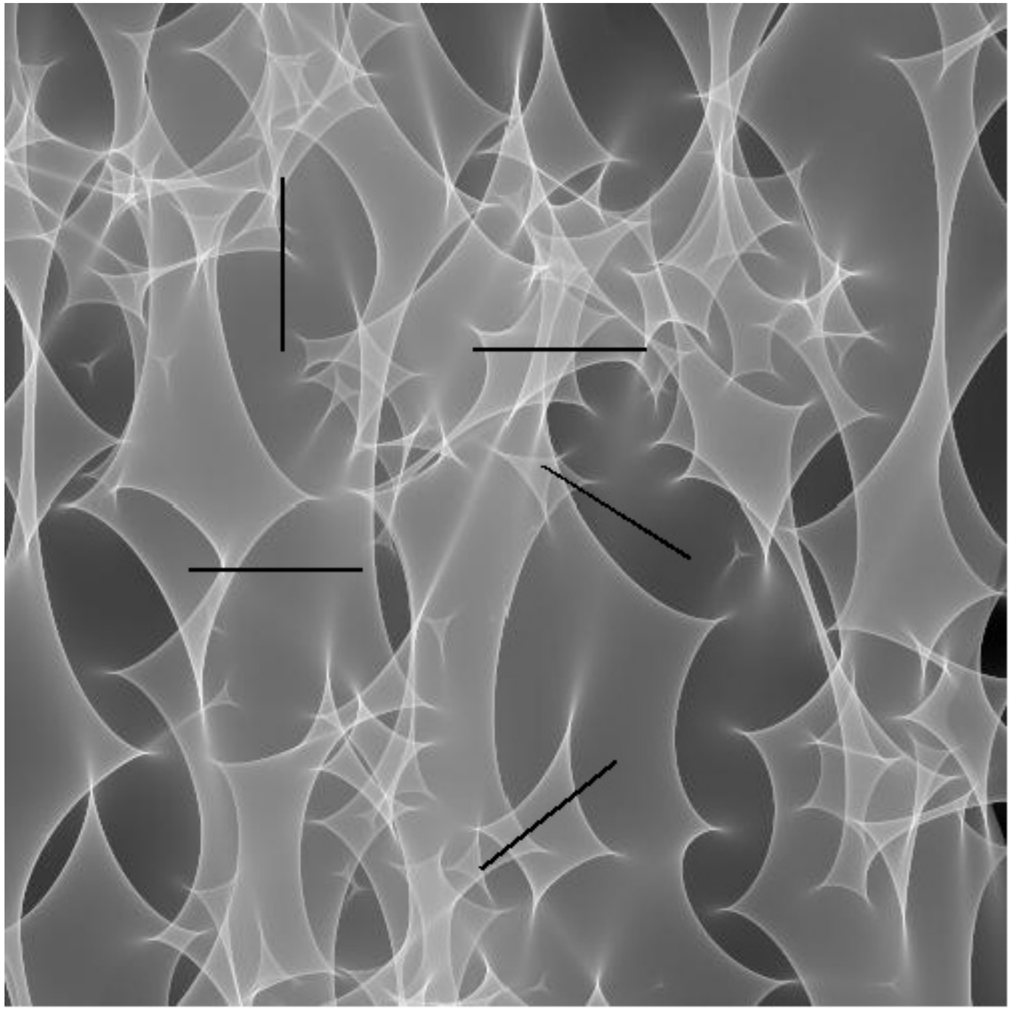
Two paradigms for the price of one!

- GPGPU provides tools to work with huge maps

[1] General Purpose Graphics Processing Unit

Structure Function

- Consider path of length L, i.e time T
- Question: What is the range of magnification?
- Examine all paths of this length to get statistics
- Do the same for paths of other lengths
- Massively parallel operation
- Massively parallel histogram generation and other stats



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Conclusions

- Possible to generate huge maps with billions of lens masses
  - Only I can do this
- Opens up
  - New possibilities for very small masses, many in number
  - Very high resolution maps for statistics like structure function, and for high quality spectra
  - Can do thousands of the “old-size” simulations in reasonable time
- Future of supercomputer code is to incorporate GPGPU code into supercomputer code
  - Work in progress