Gravitational Lensing

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॥ सा विद्या या विमुक्तये ॥

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From Reionization to large scale Structures:

A multiwavelength approach

IUCAA, Pune, February 11–17, 2018

Lens in Optics

Velocity of light changes due to **Refractive Index** – an Electromagnetic property of the medium.

You make Lens surface Curved – Light Bends while crossing from one medium to another through this surface.

Result: Magnified, Distorted Image.

You can achieve same by changing the properties of the **Space–Time**.

But the effective focal length will be varying.

General Relativity: Energy of
Matter determines the Structure of **Space Time**.

What it implies:

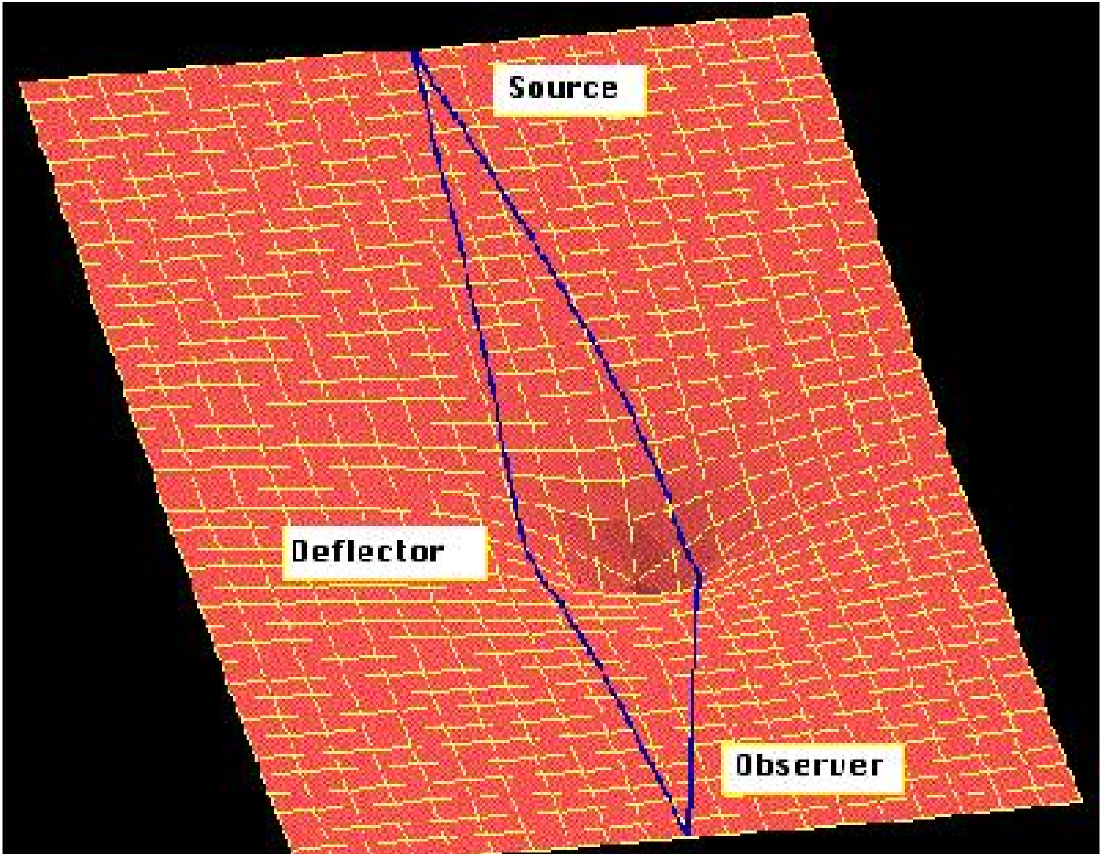
1. Space is Curved.
2. Photon slows down due to Matter.

Result:

Photon Path will be bent by the **Mass** of an object.

A massive object en route a source can act as a lens.

Check **scitechdaily.com/tag/gravitational-lensing/** and **astronomynow.com** to find out exciting results for some of the objects I am going to show now.


Source
Deflector
Observer

PostNewtonian

Bending Angle of Point Mass

$$\alpha = \frac{4GM}{bc^2}$$

G = Gravitational constant

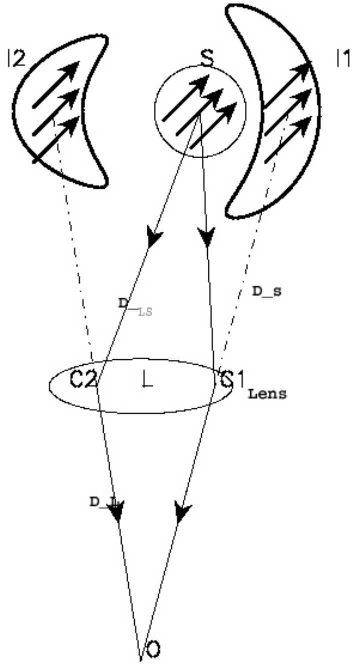
c = velocity of light in vacuum

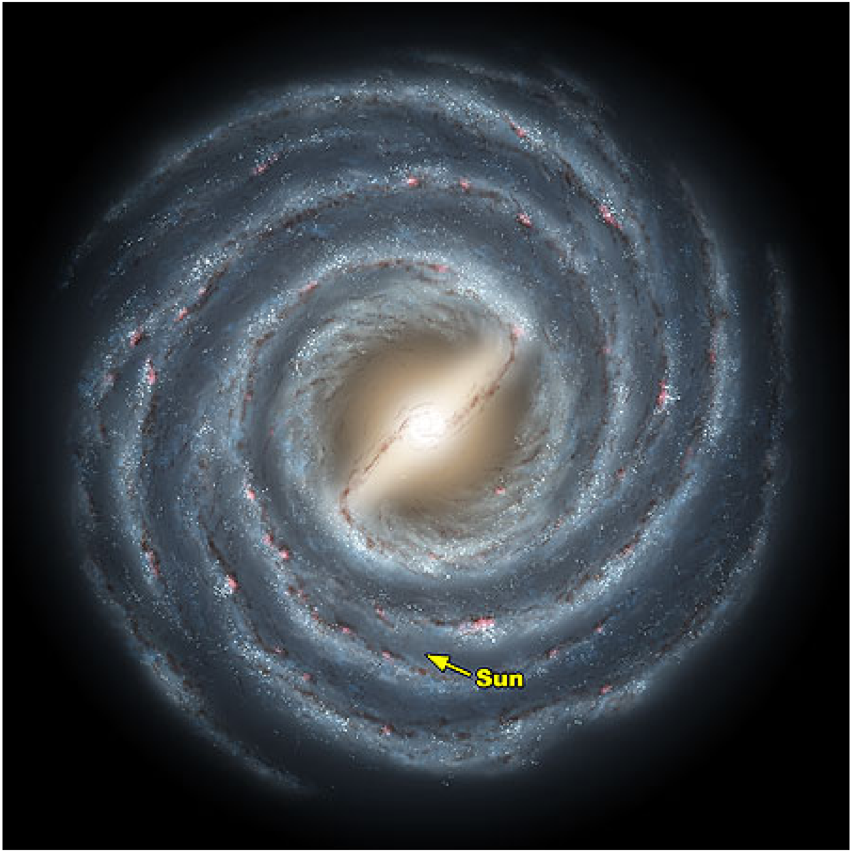
M = Mass of the Object

b = “Impact parameter ”

A solar mass object at an impact parameter of solar radius produces a bending angle of 1.8 arcsecond

Schematic Lens Configuration




Sun

Gravitational Lens in Abell 2218 HST • WFPC2

PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA

An inventory of the Universe:

Only 5% - ordinary matter: **Baryons**
Hydrogen, Helium, Oxygen, Iron........
Out of this, only ${\frac{1}{10}}^{th}$ **can be traced to Galaxies & Galaxy–Clusters.**

26% Dark Matter - unseen but we can probe it.
${\frac{2}{3}}^{rd}$ **of the Universe "Dark Energy": we infer.**

Milky Way: Ordinary Matter: $\mathbf{6\times10^{10}M_\odot}$
Dark Matter: $\mathbf{3\text{–}16\times10^{11}M_\odot}$

In Dwarf Galaxies, the ratio is worse than 0.1

So, Does Luminosity trace Galaxies?

Gravitational Lensing

All massive objects, luminous and DARK, act as lenses.

Lens cannot influence the source location. Hence it is an *unbiased tracer* **of matter.**

Galaxies and Galaxy–Clusters at hundreds crore light year distance are powerful Lenses.

They form Eye–catching images of sources behind them.

Signatures of Lensing

Multiple Images with identical *Intrinsic* properties.

Distortion and Magnification of Images

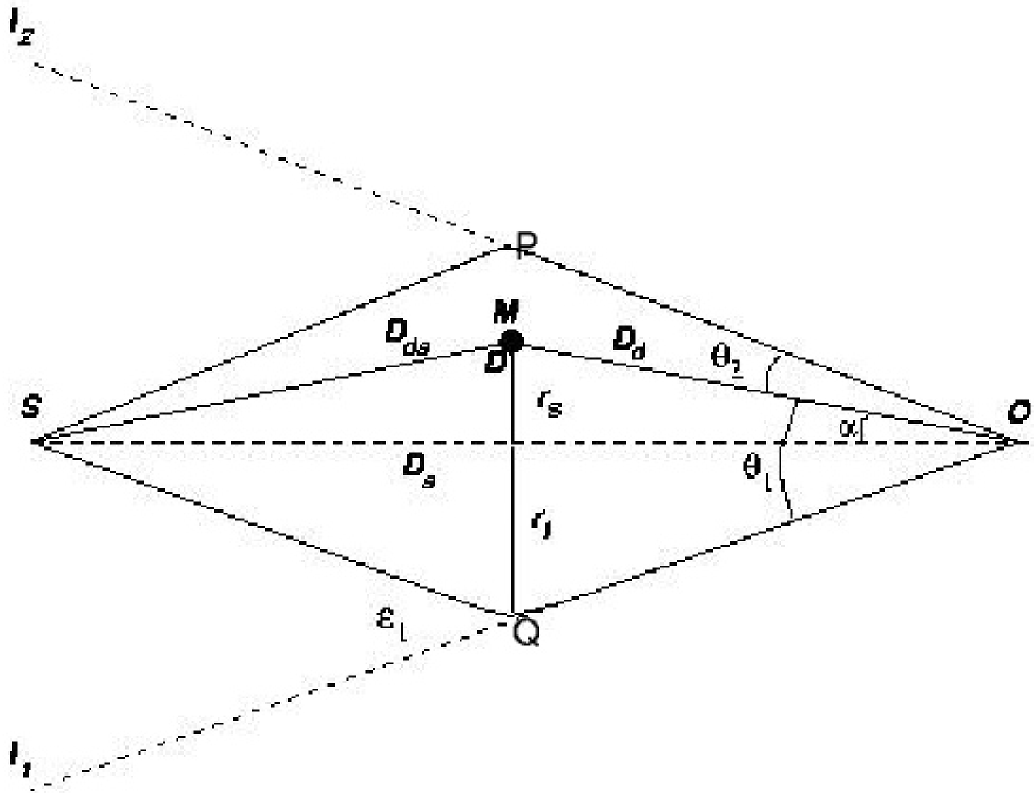
Giant Arcs, *arclets*, Rings

Time Delay

Characteristic Microlens change in light we receive.

Galaxy lenses: arcsecond scale Rings

Cluster lenses: giant arcs of ten arcseconds



I2
P
M
Dds
Dd
D
θ2
S
rs
O
α
Ds
θ1
r1
ε1
Q
I1

Point Gravitational Lens

A Point Lens produces two images collinear with the source and lens position on the sky (say, at angular positions θ_1 and -θ_2 with respect to the lens)
Separation = $\Delta = \theta_1 + \theta_2$.

If α is the angular position of the source with respect to the lens, two images will be at

$$\theta_i = \sqrt{\mu + \left(\frac{\alpha}{2}\right)^2} \pm \frac{\alpha}{2},$$

μ is a measure of the Strength of the Gravitational lens.
For a point lens

$$\mu = \frac{4GM}{D_{eff}c^2}$$

where G=Gravitational constant,
M=mass of the lens,
c=velocity of light.
Effective Distance to the lens system is

$$D_{eff} = \frac{D_{lens}D_{source}}{D_{ds}}.$$

If the source is just behind the lens, Einstein Ring centred around the lens: Einstein Radius: R_E.

$$\mu = R_E^2 = \frac{4GM}{D_{eff}c^2}$$

Magnification of the images A_i are given by,

$$A_i^{-1} = 1 - \frac{\mu^2}{\theta_i^4}$$

Tangential Magnification $= 1/\left(1 - \frac{\mu}{\theta_i^2}\right)$

Radial (de)magnification $= 1/\left(1 + \frac{\mu}{\theta_i^2}\right)$**.**

If magnification ratio of the Images is A,

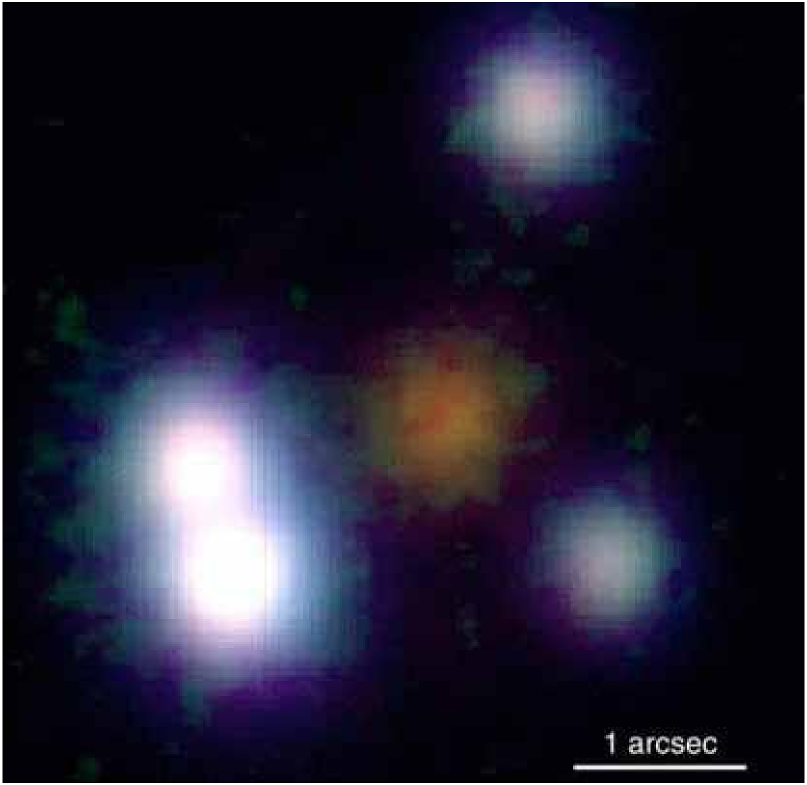
$$\mu = \sqrt{A}\left[\frac{\Delta}{(1+\sqrt{A})}\right]^2$$

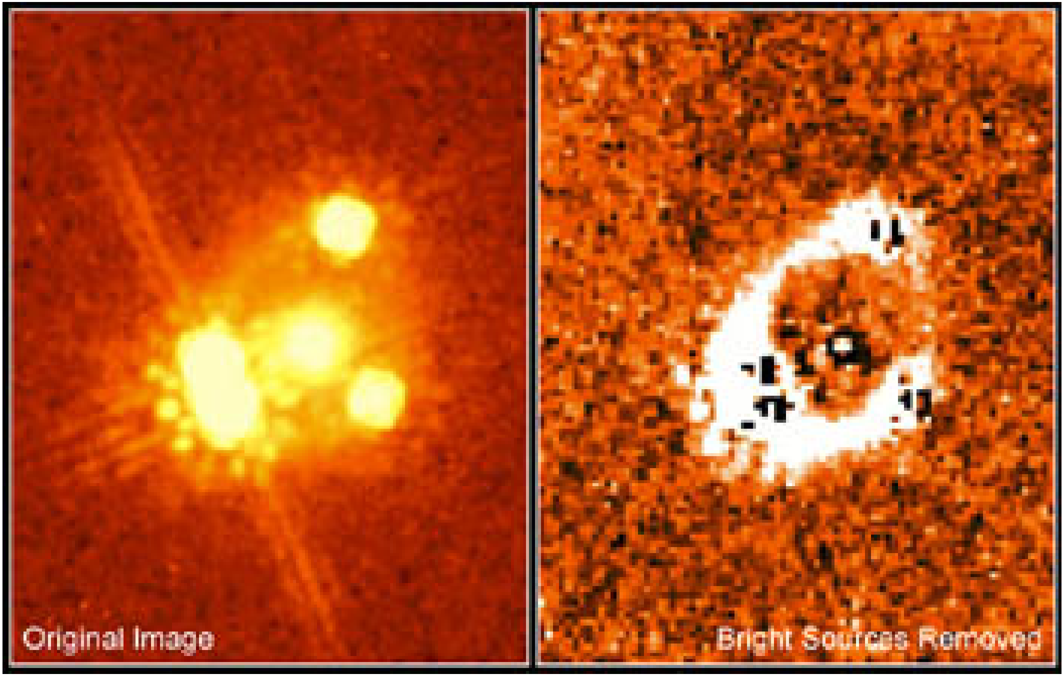
Time–Delay

If the source is variable, variability will not be seen simultaneously in the images, because of the time delay both due to the path length difference and the ravitational Potential along the photon path. The Time–Delay between the Images,

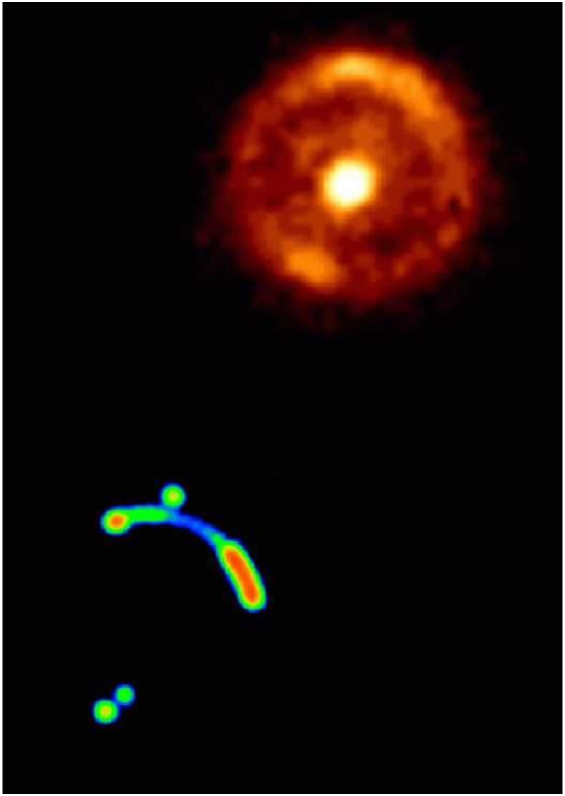
$$\tau = \frac{D_{eff}}{2c}\left[(\theta_1^2 - \theta_2^2) + \mu * \ell n \frac{\theta_1}{\theta_2}\right]$$

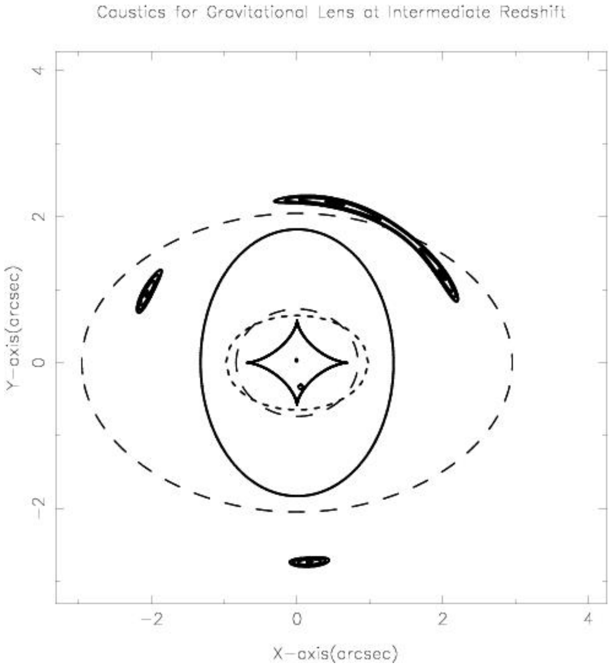
has a geometrical (first term) and potential (second term) component.
Signal arrives at Image 1 first.
If we know the strength of the lens μ from the Image Positions and magnification ratios, the Time–delay tells us the Distance scale through the combination D_{eff} .
Realstic lenses will not be point objects, but
In this first part of my talk, I have explained
The basic diagnostic value of Gravitational Lens.


1 arcsec

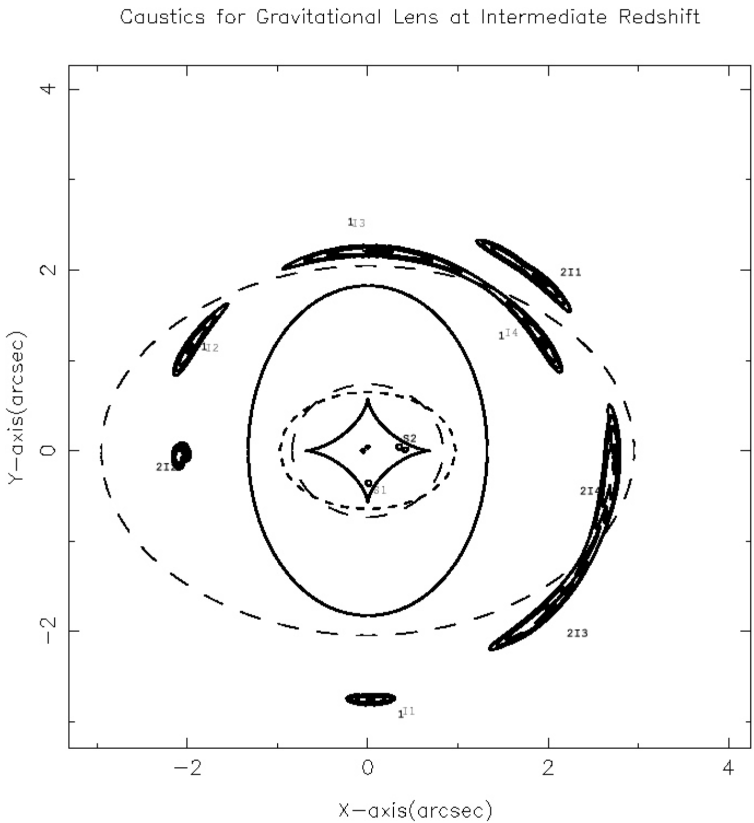


Original Image
Bright Sources Removed

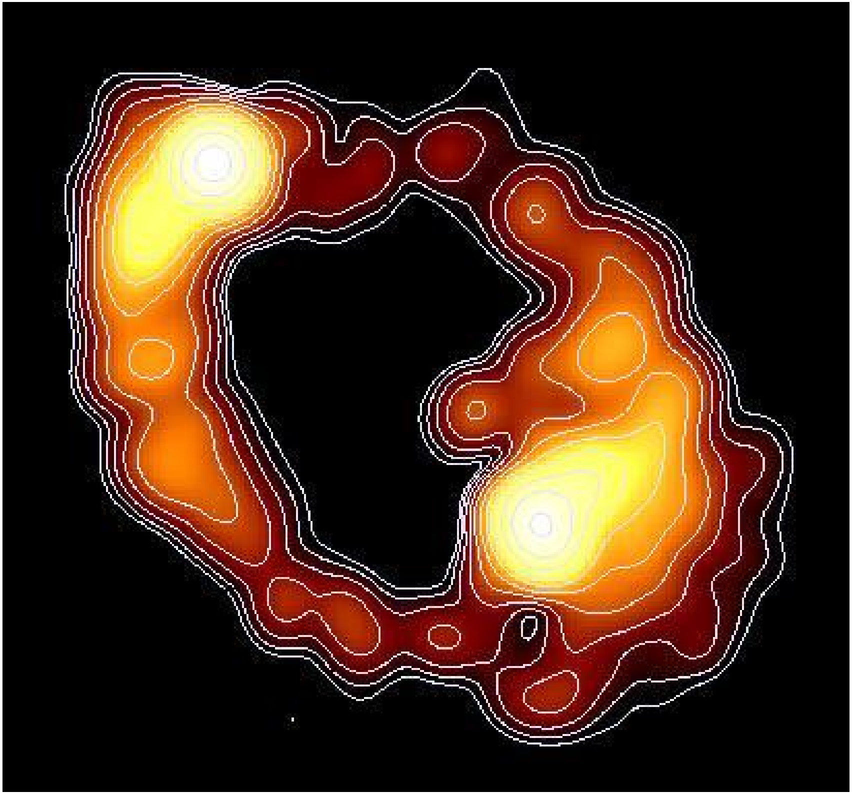


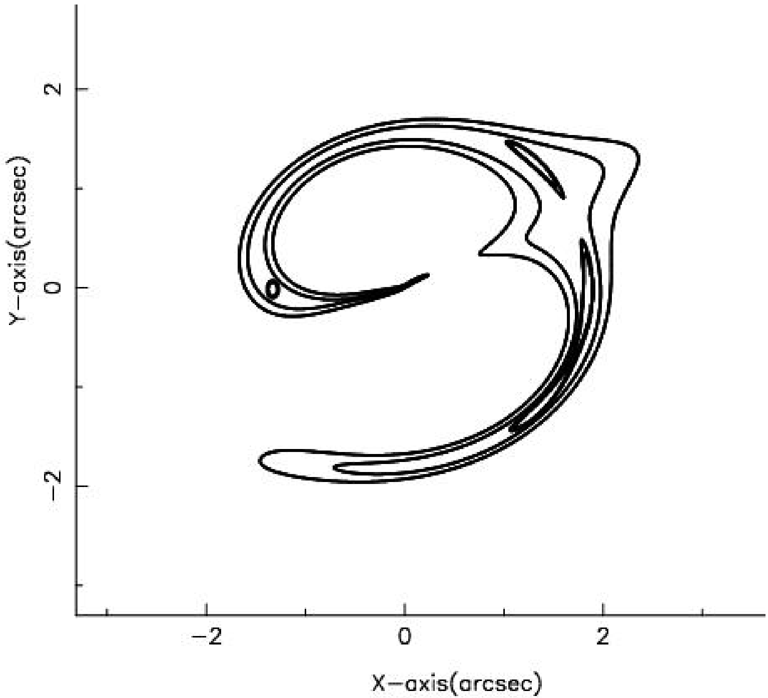


Caustics for Gravitational Lens at Intermediate Redshift
Y−axis(arcsec)
X−axis(arcsec)
−2
0
2
4



Caustics for Gravitational Lens at Intermediate Redshift
Y−axis(arcsec)
X−axis(arcsec)
4
2
0
−2
−2
0
2
4
1I3
2I1
1I2
1I4
S2
2I2
S1
2I4
2I3
1I1





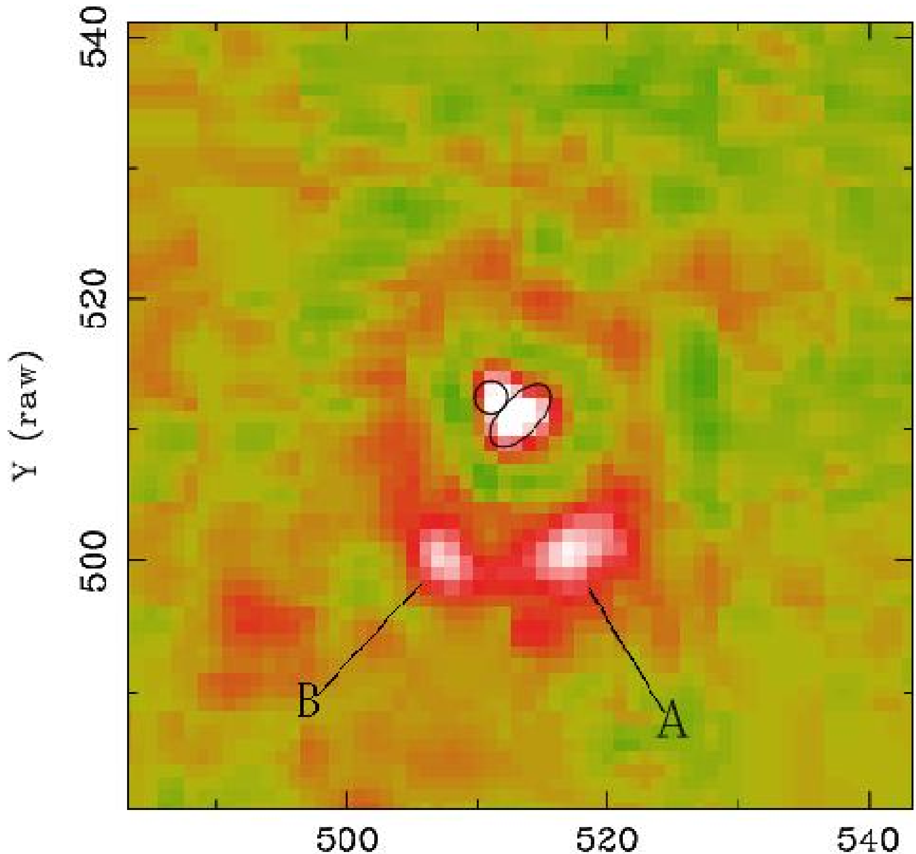
2
0
−2
Y−axis(arcsec)
−2
0
2
X−axis(arcsec)

Why Einstein Ring is a model independent tracer of Mass of the Lens:

Area of the Ring multiplied by its Distance is the Enclosed Mass of the Lens.

Astronomers measure cosmological distances from "Spectral Lines".

We can trace Dark Matter and its concentration by this method.


540
520
500
Y (raw)
B
A
500
520
540

SDSS J091949.16+342304

Ghosh & Narasimha (2009)

Quasar at a redshift of 0.68

Lens: Dwarf Galaxy at redshift 0.0375?

Lens needs atleast $5 \times 10^{11} M_{\odot}$ mass AND
5 gm/cm^2 surface mass density
to produce 6" image seperation.

Are groups of Dwarf Galaxies just visible matter in Massive Dark Halos?

I have described lensing by Galaxies.

I have explained how mass of these galaxies can be reliably estimated in some cases.

I have argued for Dark Matter Halos.

The take home message:

Maximum IMAGE SEPARATION is a measure of

MASS of CENTRAL REGION of Lens Galaxy.

If there is a Gravity Ring:

RING RADIUS gives a Reliable estimate of the

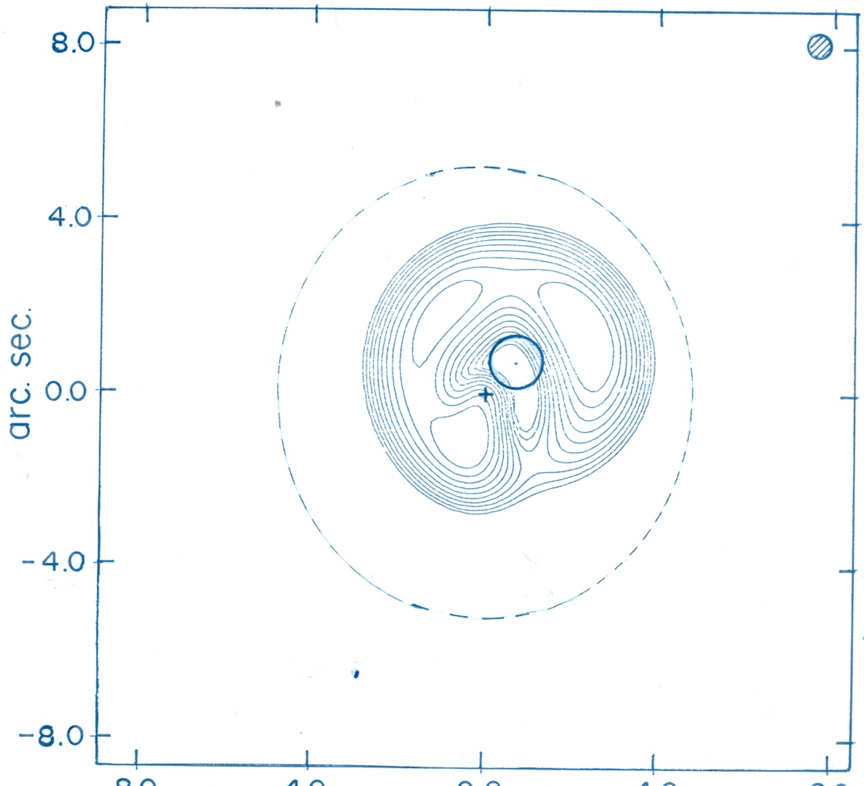
ENCLOSED MASS in the lens (Galaxy).

In the next two figures, I shall show some curious features observable due to lensing of a galaxy by a foreground galaxy.

I generated it out of curiosity more than 35 years ago!

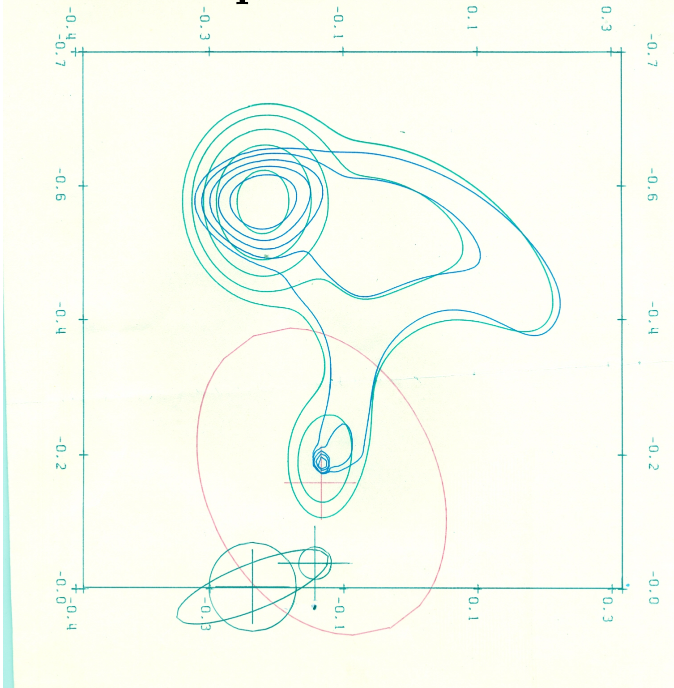
Observe the multiple images of a galaxy due to the lens effect of a dark halo of a foreground galaxy.

The second figure shows how a jet might artifically appear to connect a distant galaxy with a foreground galaxy a few arcseconds away.



8.0
4.0
0.0
-4.0
-8.0
arc. sec.

Arp's Problem



Lensing by Galaxy–Clusters

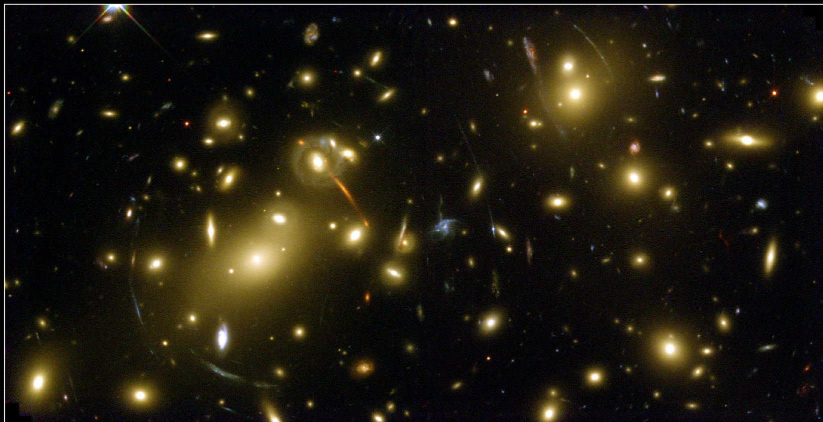
Rich Clusters of Galaxies at "Intermediate Redshifts" (z= 0.2–0.8) are powerful lenses.

They have sufficient "Surface Mass Density" to form multiple images of suitably located background sources in their field.

Background galaxies can be magnified by factor of even 100 and stretched into linear structures of tens of arcseconds called Giant Arcs.

They act as Giant Telescopes.
Flux variation and width of Giant arcs as well as magnification of point objects are important diagnostic tools.

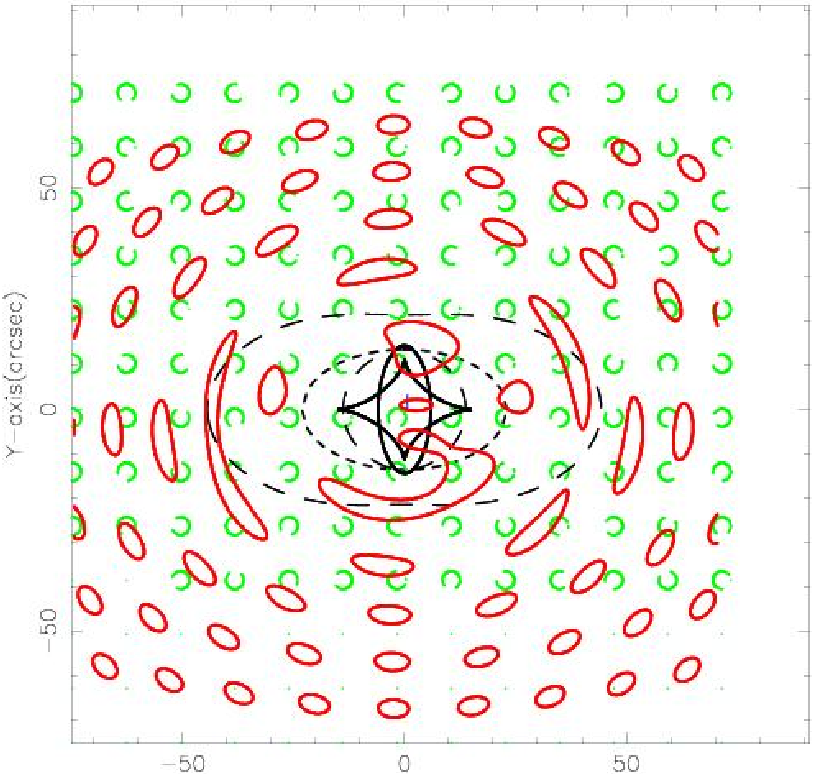
Lensing by Galaxy–Clusters: **Giant Arcs**

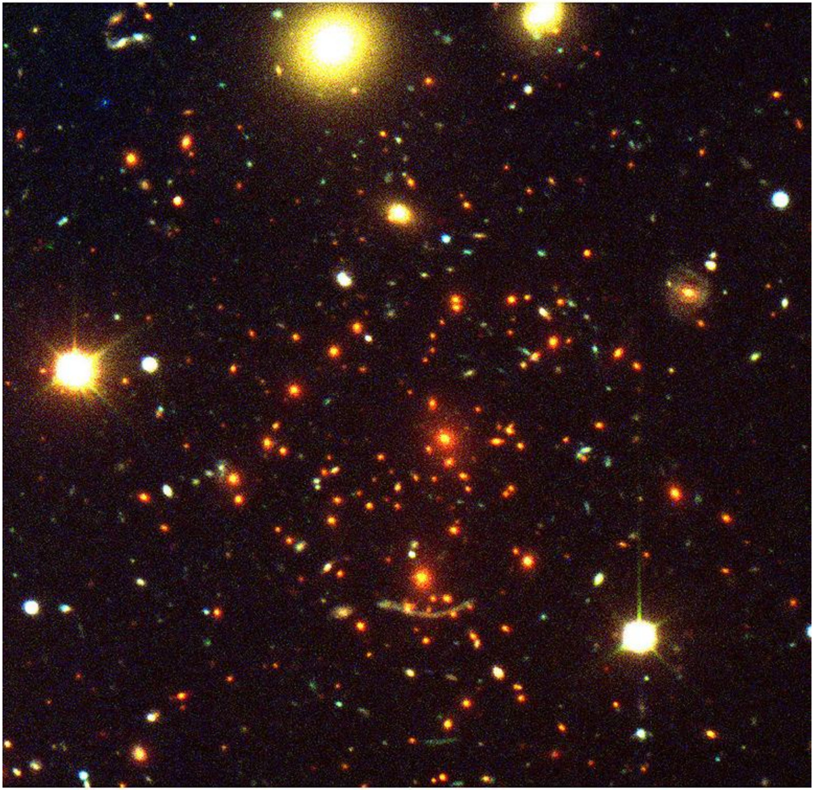


Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Weak Lens pattern due to a Galaxy Cluster



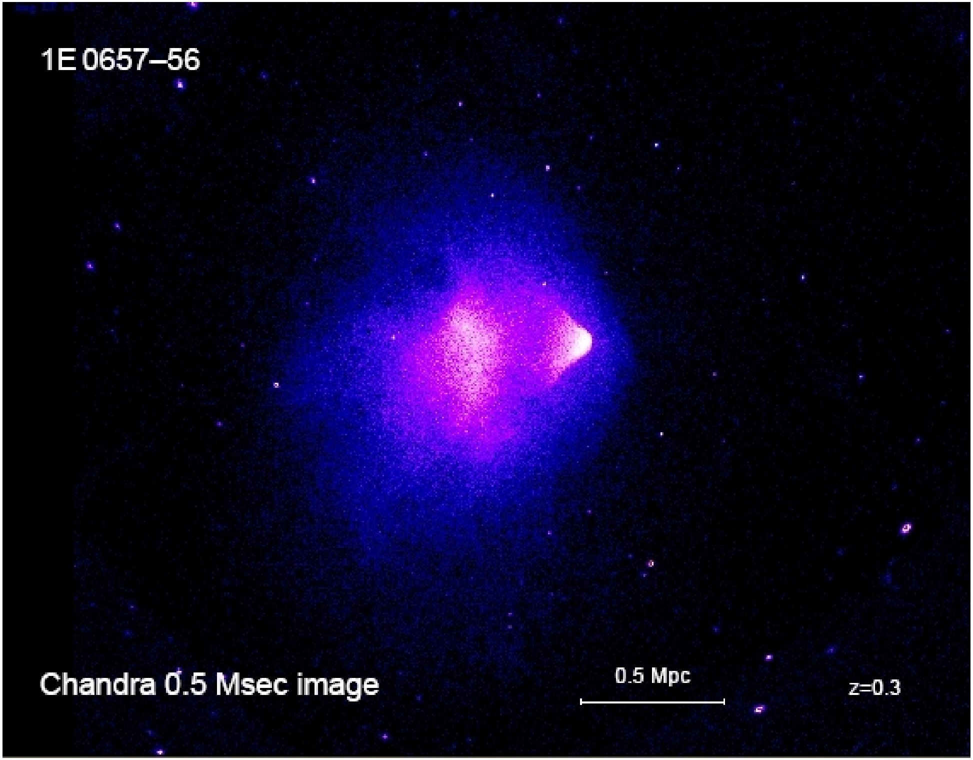


In the third part of my talk I have explained Galaxy-Clusters as lenses.

Galaxy–clusters located at billions of light years are powerful lenses which magnify background galaxies by 10–100 times and produce characteristic images like Giant Arcs.

These giant natural telescopes have importance as cosmological probes.

Now I shall describe a concrete case of what we can infer about Dark Matter in Galaxy–Clusters
The BULLET–CLUSTER


1E 0657–56
Chandra 0.5 Msec image
0.5 Mpc
z=0.3

Bullet Cluster: 1E 0657-558

(M. Markevitch et al 2003 ApJ)

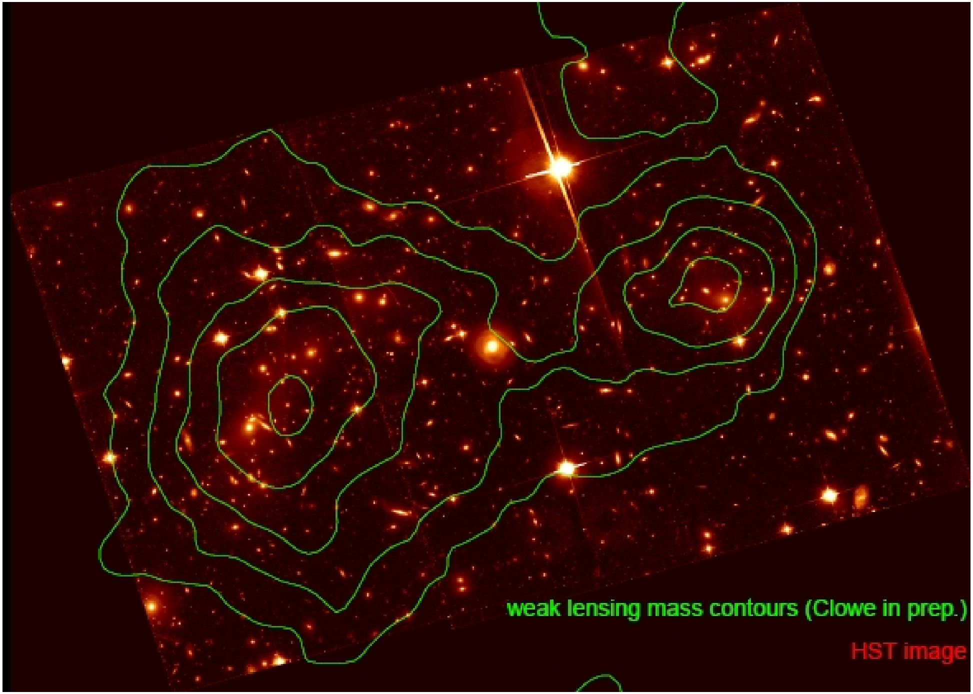
Two colliding massive galaxy–clusters at a distance of 370 crore light years (redshift 0.296)

Very hot clump of Gas emitting X-rays. The gas of the two clusters has Merged

Gravitational lensing of background galaxies allows to map the Total Mass of the clusters

It shows that Dark Matter of the clusters has just passed each other

We *see* the Dark Matter which can pass without other Interaction unlike normal gas.


weak lensing mass contours (Clowe in prep.)
HST image

I have shown that galaxy–clusters have

Two separate components of matter.

Normal Hydrogen type matter which shines in X-rays and as Stars in Galaxies

Dark Matter which can penetrate through each other without much scattering

Can we use Multiply–imaged Supernova at

redhsifts of above 3, in the field of

Galaxy–Clusters to test Cosmology?

(Narasimha & Chitre, 1989; Narasimha 2015, 2017)

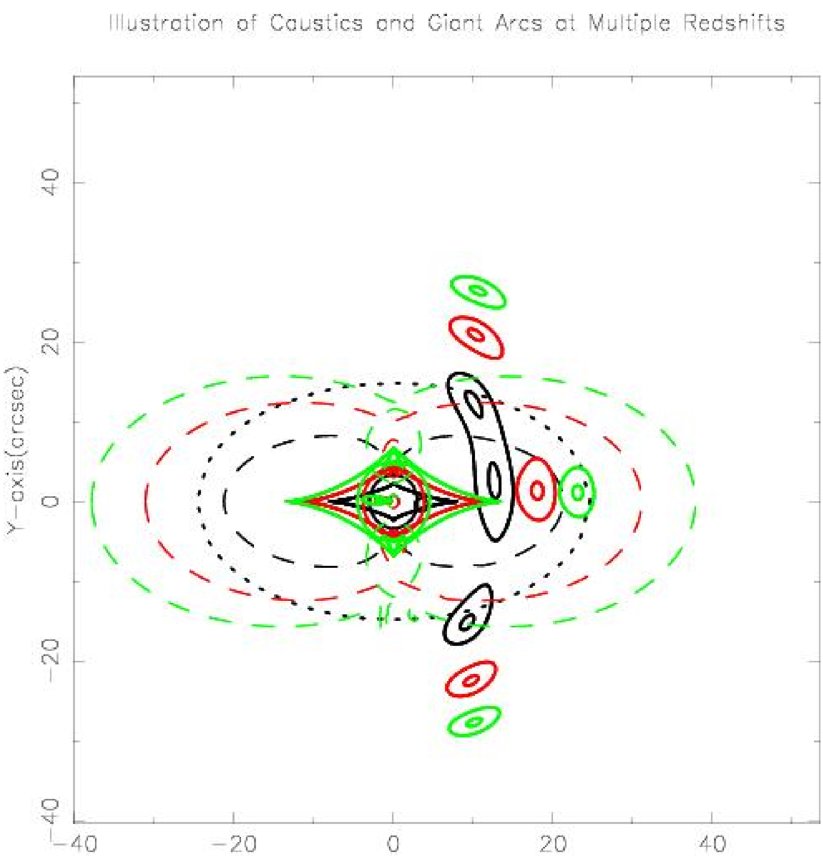


Illustration of Caustics and Giant Arcs at Multiple Redshifts
Y−axis(arcsec)
40
20
0
−20
−40
−40
−20
0
20
40

Summary

- **Galaxies and Galaxy–clusters at cosmological distance are powerful Gravitational Lenses.**
- **We can trace LUMINOUS & DARK matter in the lens.**
- **Now Dark Matter and Luminous Gas have been separately seen through the Eyes of Gravity.**
- **Way back in 1989 Narasimha & Chitre argued that Supernova in lensed galaxies can be powerful probe of the distant Universe.**
- **Can we use Lens to test Accelerating Universe?**