1.7 Clusters of galaxies

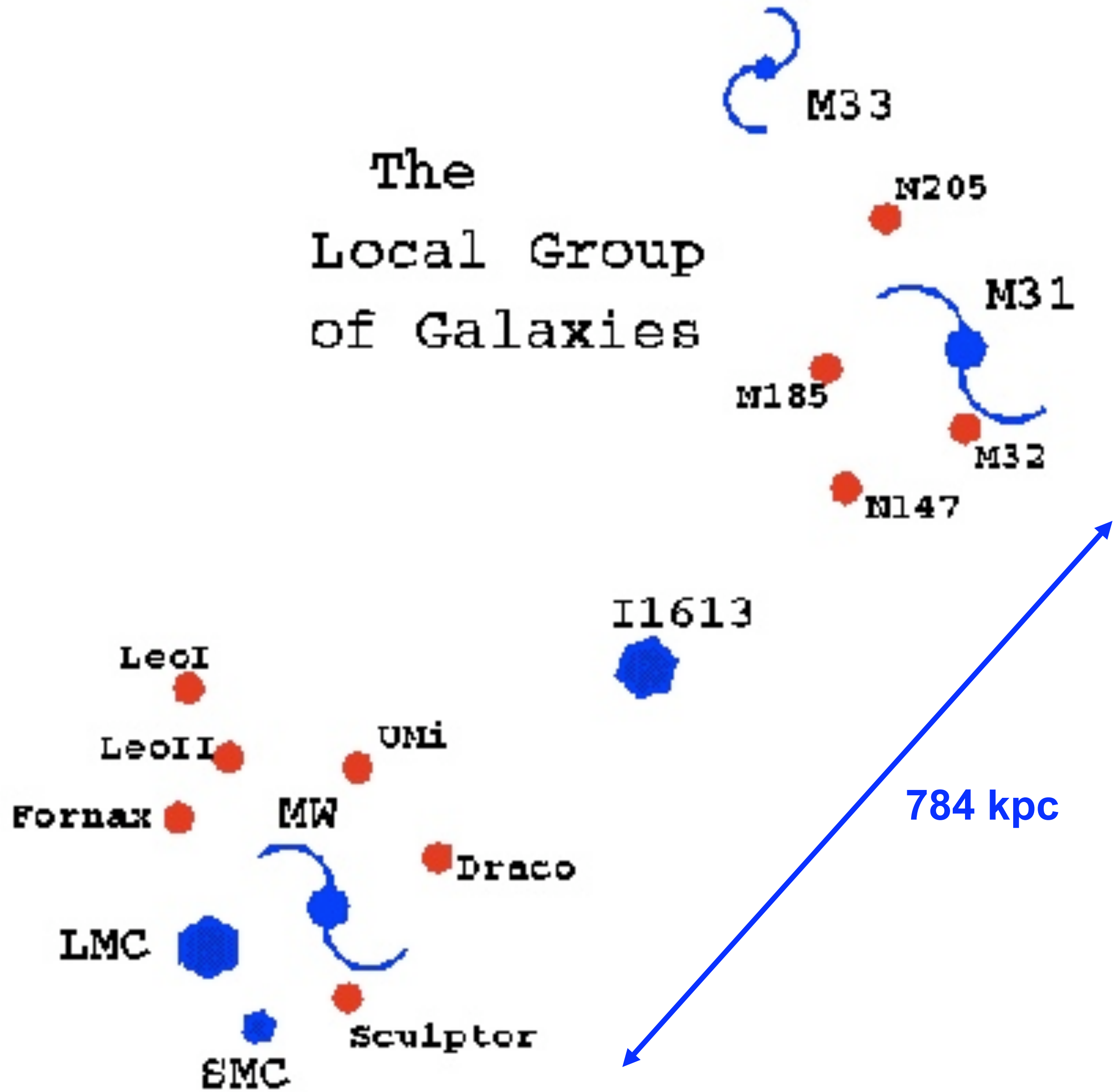
List of topics:

- Our local environment
- What is in a (galaxy) cluster?
- Why are clusters important?
- How do we detect clusters?
- Mass estimates from
  - (a) Velocity dispersions
  - (b) X-ray observations
  - (c) Strong gravitational lensing
  - (d) Weak gravitational lensing

Read JL section 4.3

Our local environment

- We do not live in a cluster of galaxies, but a “group”
  - The “Local group”
  - ~30 members within ~1Mpc
  - sparse and non-symmetrical
- Nearest cluster is Virgo ~15 Mpc away
  - Virgo has 1000s of galaxies
  - Irregular, dominated by 3 cD galaxies
- Coma is larger than Virgo, spherical
  - ~100 Mpc away


M33
The
Local Group
of Galaxies
N205
M31
M185
M32
N147
I1613
LeoI
LeoII
UMi
Fornax
MW
Draco
784 kpc
LMC
Sculptor
SMC

M31, Andromeda

http://antwrp.gsfc.nasa.gov/apod/ap971101.html Copyright Jason Ware

Clusters: summary

- Many elliptical galaxies
- Usually one giant elliptical, or “cD” galaxy
  - giant ellipticals ~ few hundred kpc across
- Composition: (not just galaxies!)

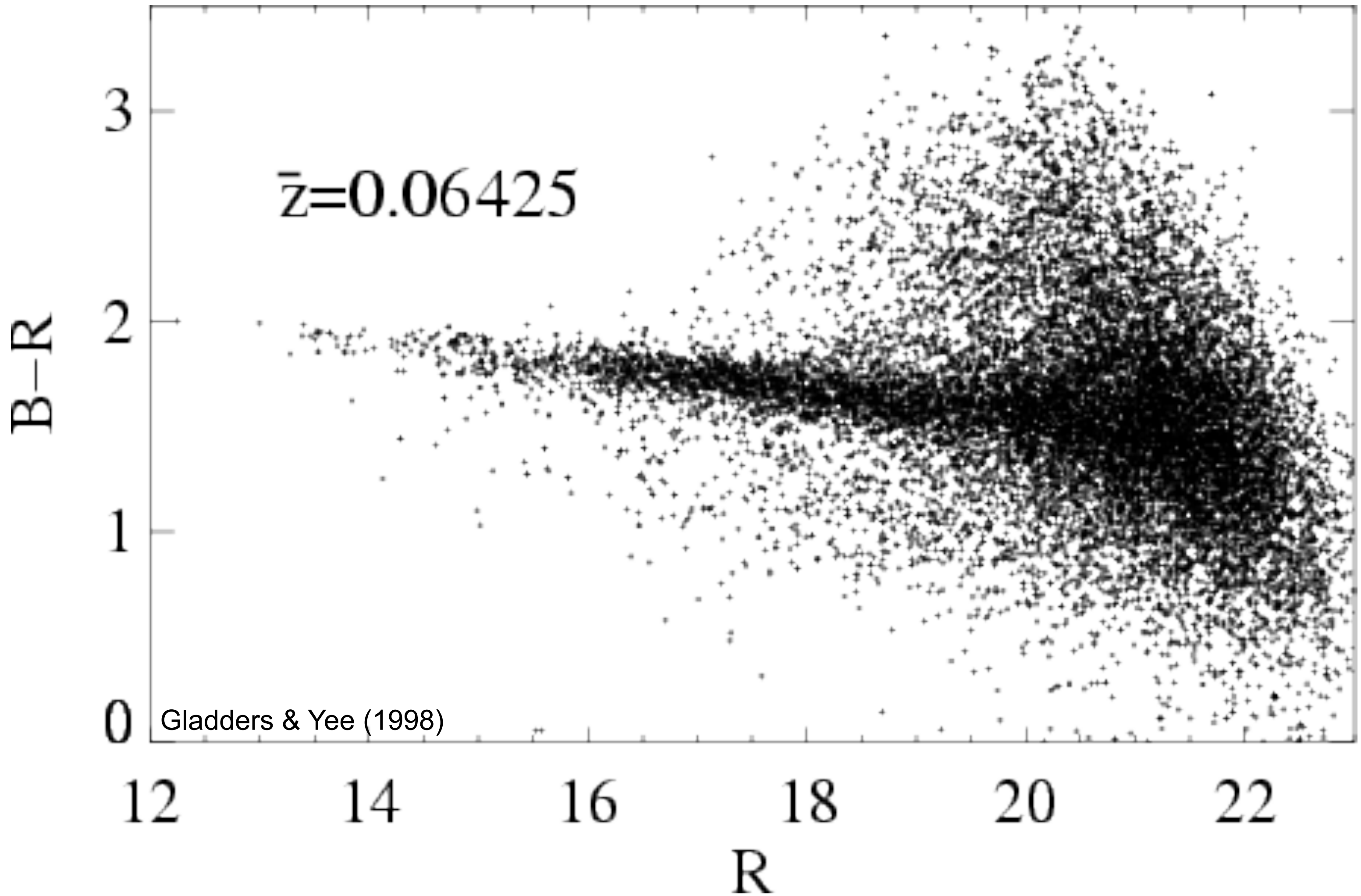
  ~5 % of mass is in galaxies

  ~10 % of mass is hot gas

  the rest is dark matter
- The largest gravitationally bound systems
  - Typical mass is up to a few times 10^{15} M_{solar}
- “Field galaxies”: galaxies not in clusters
  - Most galaxies are not in clusters


Spot the cluster!

The Red Sequence



Combined colour-magnitude diagram for 41 clusters at $z < 0.15$.

Only galaxies in the interior 0.5 Mpc are shown.

Why are clusters important?

1. For Cosmology

They are the largest gravitationally bound structures in the Universe.

Their number density and mass, as a function of redshift, can shed light on:

- initial density fluctuations
- amount of dark matter
- nature and amount of dark energy

Why are clusters important?

2. For Astrophysics

They can be approximated by a “closed-box” environment.

We can study the interaction between galaxies and intracluster gas, e.g.:

- Feedback from Active Galactic Nuclei
- Feedback from Supernovae (galactic winds)

The Abell catalogue

- The first comprehensive cluster catalogue
- Abell (1958) inspected red sensitive photographic plates of Northern sky
  - identified 2712 clusters
  - Used: cluster = overdensity of galaxies in radius 1.7'/z
- Many clusters studied today are in this
  - e.g. A2218 (A stands for Abell)
- Since updated to southern sky
  - contains 4073 clusters

~30 to 300+ galaxies per cluster

THE DISTRIBUTION OF RICH CLUSTERS OF GALAXIES*

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Received September 30, 1957; revised November 13, 1957

ABSTRACT

A catalogue is prepared of 2712 rich clusters of galaxies found on the National Geographic Society–Palomar Observatory Sky Survey. From the catalogue, 1682 clusters are selected which meet specific criteria for inclusion in a homogeneous statistical sample. An investigation of the sample leads to the following conclusions: (1) the distribution function of clusters according to richness, $N(n)$, increases rapidly as n decreases; (2) the data allow no significant decision that the spatial density of cluster centers varies with distance; (3) galactic obscuration of the order of a few tenths of a magnitude (photored) exists at high northern galactic latitudes around galactic longitude 300°; (4) there is a highly significant non-random surface distribution of clusters, both when clusters at all distances and when clusters at various distances are considered. An analysis of the distribution yields evidence that suggests the existence of second-order clusters, that is, clusters of clusters of galaxies. A statistical test reveals no incompatibilities between the observed distribution and one of complete second-order clustering of galaxies.

The red plate for each sky survey field was inspected and searched for clusters of galaxies with a 3.5× magnifying lens. All rich clusters that were recognized and that appeared as possible candidates for inclusion in the statistical sample were noted. Next the records were consulted of earlier routine inspections of the same plate or of other plates of the same field made by either the writer or A. G. Wilson. All but 1 or 2 per

* A portion of a thesis submitted in partial fulfilment of the requirements for the Ph.D. degree in the Department of Astronomy at the California Institute of Technology.

TABLE 6

A CATALOGUE OF RICH CLUSTERS OF GALAXIES

No.	R.A. (1855)	Decl.	Precession R.A. (1900)	Decl.	l	b	Mag.	Dist.	Rich.
1	00 00.1	15 43	0.512	3.34	75.6	-45.4	17.1	5	1
2	00 01.0	-20 27	0.512	3.34	35.9	-78.2	17.3	6	1
3	00 01.8	03 14	0.512	3.34	71.1	-57.6	17.0	5	1
4	00 01.9	05 59	0.512	3.34	72.6	-54.9	17.8	6	1
5*	00 02.8	32 18	0.514	3.34	80.6	-29.2	17.1	5	1
6	00 03.0	16 54	0.513	3.34	77.0	-44.4	17.5	6	2
7	00 04.2	31 37	0.515	3.34	80.8	-30.0	17.1	5	1
8	00 04.7	-12 00	0.511	3.34	59.3	-72.0	17.2	5	1
9	00 04.9	08 40	0.513	3.34	74.9	-52.5	18.0	6	1
10	00 05.4	-06 48	0.511	3.34	65.9	-67.3	17.2	5	2
11	00 05.4	-17 15	0.511	3.34	49.5	-76.6	17.2	5	2
12	00 05.9	-08 25	0.511	3.34	64.6	-68.9	17.2	5	2
13	00 06.3	-20 19	0.510	3.34	40.6	-79.0	16.6	5	2
14*	00 07.9	-24 42	0.508	3.34	20.0	-81.8	15.2	3	0
15*	00 07.9	-26 50	0.508	3.34	5.0	-82.4	17.4	6	0
16	00 09.3	05 57	0.513	3.34	75.7	-55.4	17.0	5	2
17	00 09.5	08 00	0.513	3.34	76.5	-53.4	17.6	6	1
18*	00 09.6	-03 36	0.511	3.34	70.9	-64.7	17.1	5	0
19	00 11.5	-07 00	0.511	3.34	69.5	-68.0	17.8	6	2
20	00 12.3	-23 26	0.507	3.34	31.3	-82.1	17.1	5	1
21*	00 13.0	27 50	0.519	3.34	82.3	-34.0	16.2	4	1
22	00 13.4	-26 31	0.506	3.34	9.4	-83.6	17.5	6	3
23*	00 14.3	-01 42	0.512	3.33	74.6	-63.1	17.0	5	0
24	00 15.0	22 30	0.518	3.33	82.0	-39.3	17.5	6	2
25	00 15.6	-00 58	0.512	3.33	75.7	-62.5	17.8	6	1
26*	00 15.7	36 03	0.523	3.33	84.1	-25.9	17.4	6	2
27*	00 17.5	-21 31	0.505	3.33	47.2	-81.7	16.5	5	0
28	00 17.7	07 20	0.514	3.33	79.7	-54.4	17.6	6	2
29*	00 19.3	37 46	0.527	3.33	85.1	-24.3	17.5	6	0
30	00 19.4	-13 00	0.508	3.33	69.3	-74.4	17.8	6	2
31	00 19.6	21 50	0.520	3.33	83.3	-40.1	17.7	6	2
32	00 19.6	-09 55	0.509	3.33	72.6	-71.4	18.0	6	1
33	00 19.8	-20 19	0.505	3.33	54.8	-81.0	17.9	6	1
34	00 19.9	-09 37	0.509	3.33	73.1	-71.1	18.0	6	2
35	00 20.1	-22 29	0.504	3.33	45.8	-82.8	17.1	5	1
36	00 20.3	-13 36	0.507	3.33	69.4	-75.0	17.6	6	2
37	00 20.6	-11 20	0.508	3.33	72.1	-72.8	18.0	6	1
38	00 20.9	13 08	0.517	3.33	82.3	-48.8	17.6	6	1
39	00 21.0	-12 12	0.508	3.33	71.6	-73.7	18.0	6	1
40	00 21.1	15 36	0.518	3.33	82.8	-46.4	17.5	6	1
41	00 21.3	07 03	0.515	3.33	81.1	-54.9	17.6	6	3
42	00 21.3	-24 27	0.503	3.33	34.5	-84.3	17.1	5	3
43*	00 21.4	16 47	0.518	3.33	83.1	-45.2	15.9	4	0
44	00 22.1	11 14	0.516	3.33	82.3	-50.7	17.0	5	1
45	00 22.5	-13 06	0.507	3.33	71.9	-74.7	17.8	6	2
46	00 22.9	-13 41	0.507	3.32	71.7	-75.3	17.6	6	1
47	00 23.3	-24 58	0.502	3.32	32.8	-85.0	17.5	6	1
48	00 23.7	11 45	0.517	3.32	83.1	-50.3	17.6	6	1
49	00 24.1	-12 14	0.507	3.32	74.2	-73.9	18.0	6	1
50	00 24.1	-23 02	0.502	3.32	48.8	-83.8	17.4	6	2
51*	00 24.3	-24 28	0.501	3.32	38.9	-84.9	17.4	6	0
52	00 24.5	-13 00	0.507	3.32	73.8	-74.7	18.0	6	1
53*	00 25.3	-08 22	0.508	3.32	77.9	-70.2	17.2	5	0
54*	00 26.1	25 57	0.524	3.32	85.6	-36.2	17.7	6	0
55*	00 26.5	05 32	0.515	3.32	83.1	-56.5	17.2	5	0
56	00 26.5	-08 36	0.508	3.32	78.6	-70.5	18.0	6	1
57	00 26.6	-09 43	0.508	3.32	78.0	-71.6	17.6	6	2
58	00 26.7	-07 34	0.509	3.32	79.3	-69.5	17.2	5	1
59	00 26.8	29 29	0.527	3.32	86.1	-32.7	17.5	6	1
60	00 27.3	29 14	0.527	3.32	86.2	-32.9	17.9	6	2
61	00 27.6	-24 00	0.500	3.32	48.8	-85.1	17.7	6	1
62	00 27.7	19 36	0.522	3.32	85.5	-42.5	17.1	5	1
63*	00 27.9	48 54	0.543	3.32	87.7	-13.3	16.1	4	0
64	00 28.9	18 07	0.521	3.31	85.7	-44.0	17.5	6	1
65	00 29.3	18 17	0.521	3.31	85.9	-43.9	17.5	6	2
66*	00 29.3	-05 59	0.509	3.31	81.7	-68.0	17.8	6	0
67	00 29.4	18 28	0.522	3.31	85.9	-43.7	17.5	6	2
68	00 29.5	08 21	0.516	3.31	84.9	-53.8	18.0	6	1
69	00 30.0	17 33	0.521	3.31	86.0	-44.6	17.1	5	2
70	00 30.0	-08 14	0.508	3.31	81.3	-70.3	17.5	6	1
71*	00 30.1	28 48	0.528	3.31	86.9	-33.4	15.6	3	0
72*	00 30.6	44 56	0.542	3.31	87.9	-17.3	16.3	4	0
73	00 30.8	08 38	0.517	3.31	85.4	-53.5	18.0	6	1
74*	00 31.7	-23 07	0.499	3.31	63.2	-84.8	15.9	4	0
75*	00 32.2	20 28	0.524	3.31	87.0	-41.7	16.5	5	0
76*	00 32.3	05 59	0.515	3.31	85.7	-56.2	15.0	3	0
77	00 32.9	28 44	0.529	3.31	87.7	-33.5	16.5	5	1
78	00 32.9	25 57	0.527	3.31	87.5	-36.3	17.9	6	1
79	00 33.0	17 21	0.522	3.31	87.0	-44.9	17.1	5	1
80	00 33.2	-25 29	0.497	3.31	49.1	-87.0	17.1	5	1

Types of cluster surveys

- Optical surveys
- X-ray surveys
- Sunyaev-Zel'dovich effect

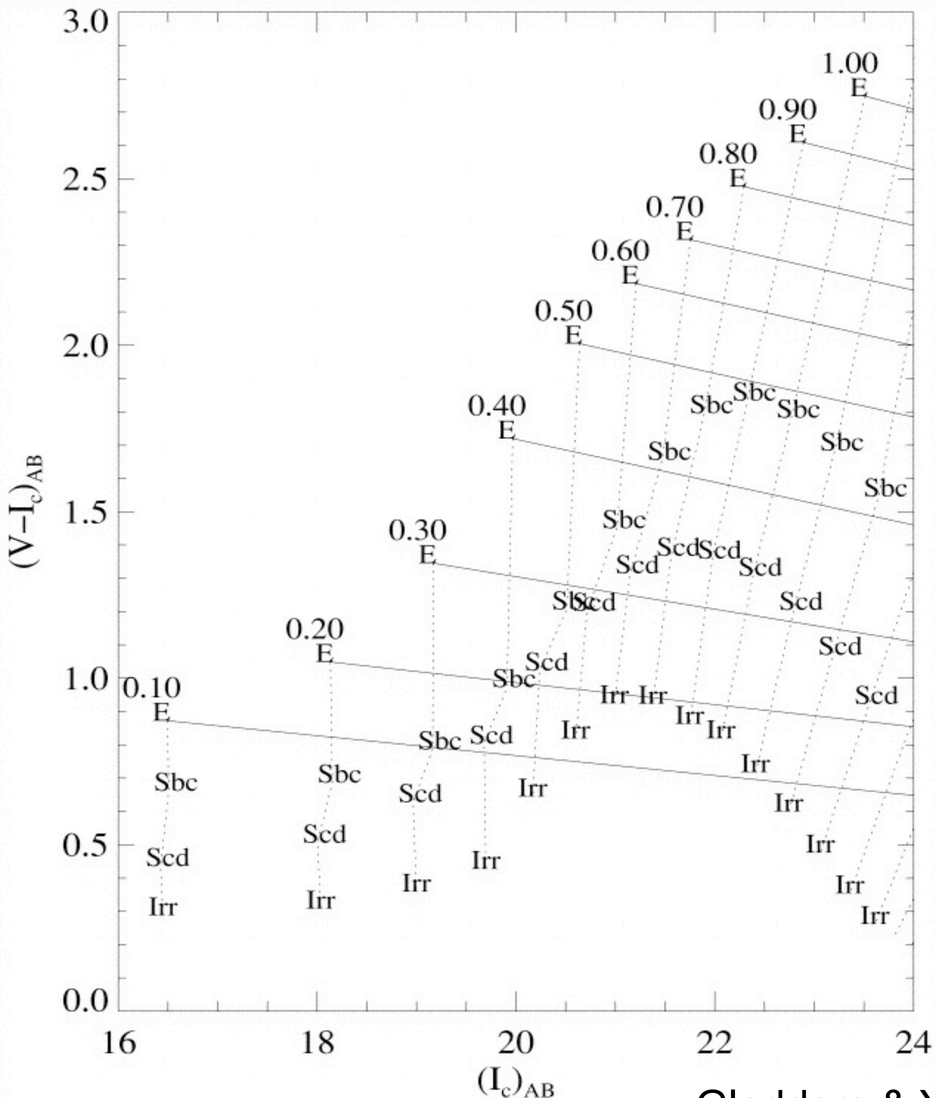
Optical surveys

- Two-dimensional techniques (e.g. Abell)
- Red Sequence technique (Gladders & Yee)
- Using photometric redshifts
- Using spectroscopic redshifts

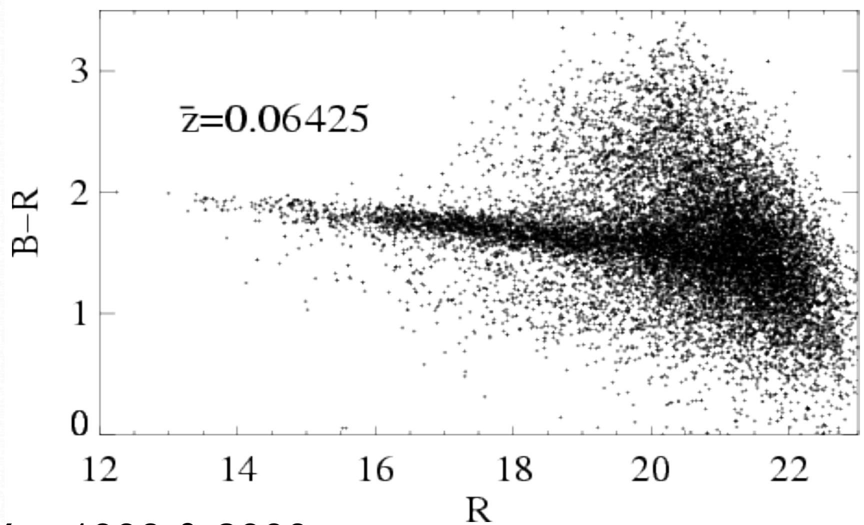
Problems

1. Projection effects, or inefficient
2. Difficult at high redshift

Optical Surveys



The Red Sequence galaxies are the brightest and reddest galaxies at any given redshift



Gladders & Yee 1998 & 2000

X-ray surveys

- Probes the hot intracluster gas
- Emission $\propto$ (density)$^2 \rightarrow$ minimal projection effects
- Temperature given by X-ray spectrum, correlates with cluster mass

Problems

1. Biased towards hot systems
2. Surface brightness declines steeply with redshift

Credit: ESO/ESA/Mullis et al.

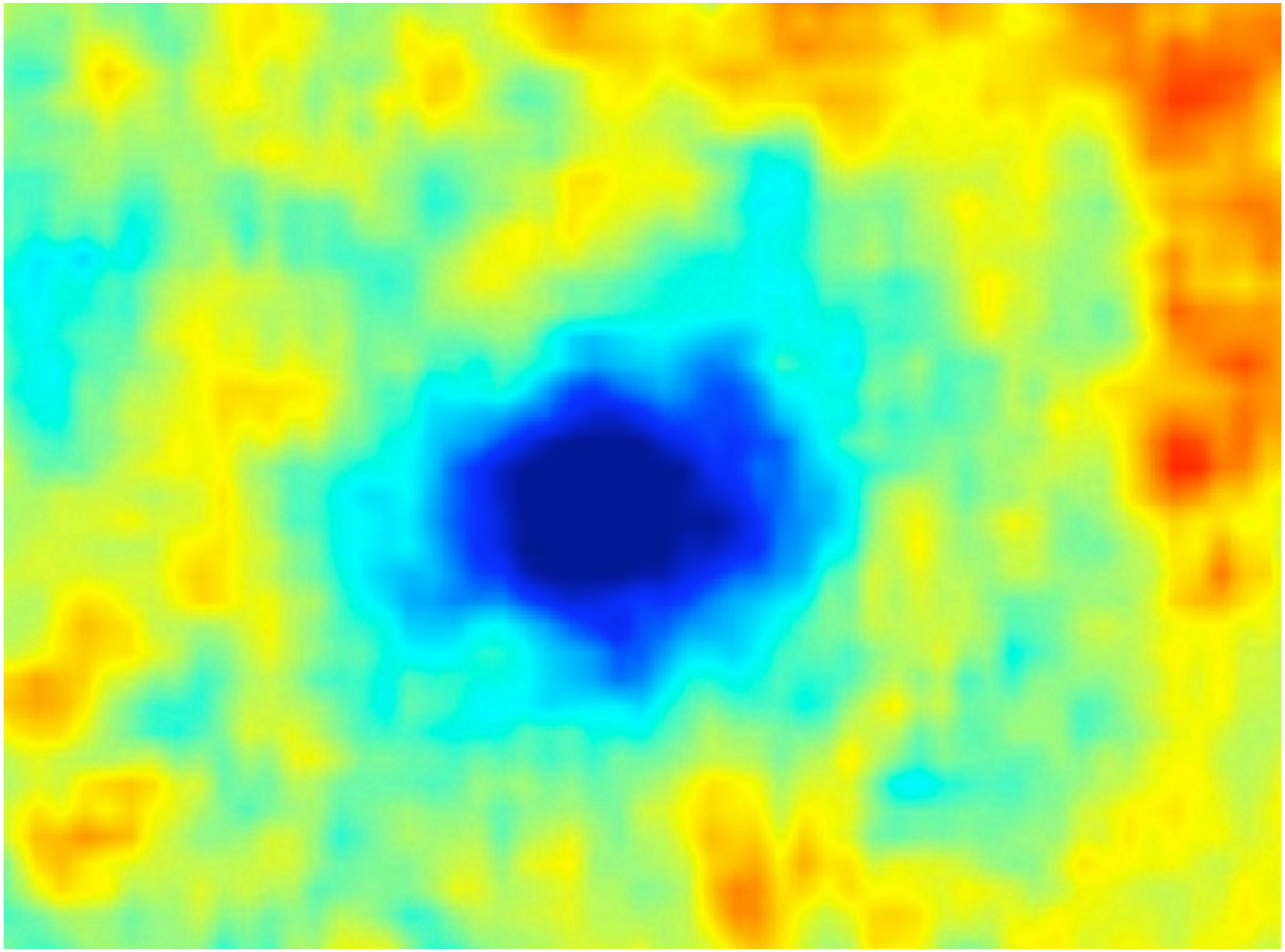
Sunyaev-Zel’dovich effect

- Detects ‘holes’ in CMB through Compton scattering by intracluster medium
- Independent of redshift

Problems

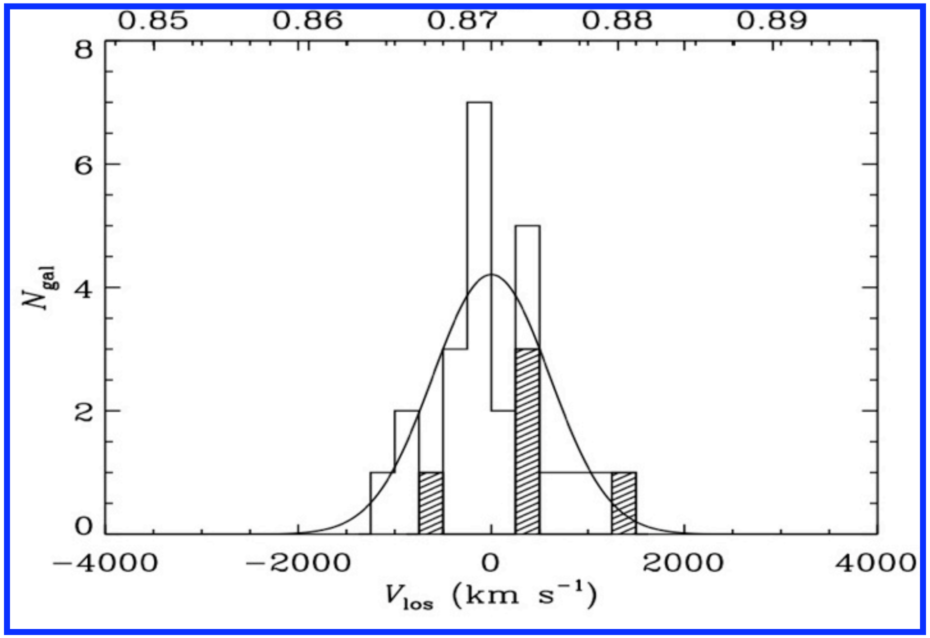
1. Suffers from large projection effects
2. Difficult to determine distance

Sunyaev-Zel'dovich Effect



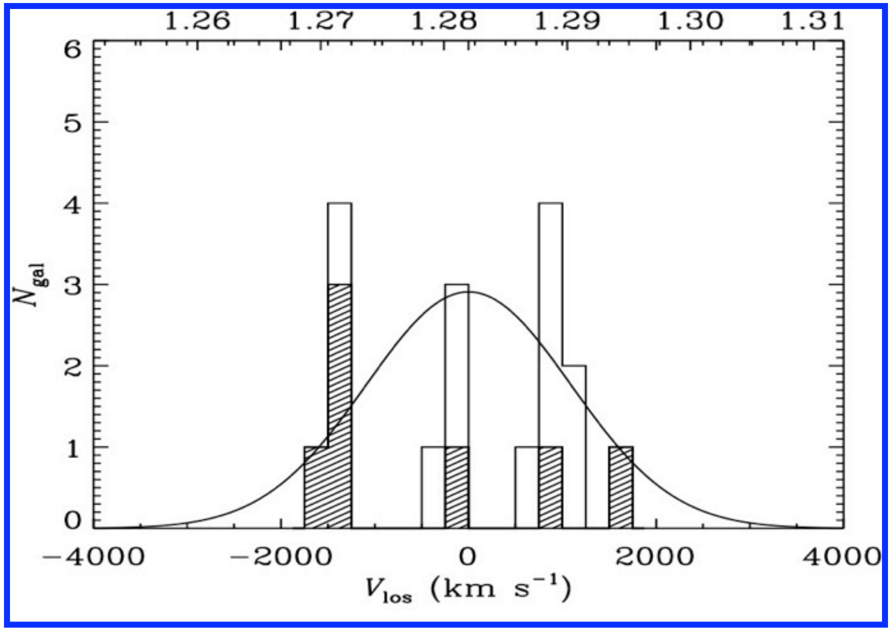
Credit: SuZIE website

Velocity profiles



Virialised

Non-virialised



Van Breukelen et al. 2009

Cluster masses from velocity dispersions

- First applied by Zwicky in 1930s
  - Discovered that Coma had much invisible matter
- Virial theorem

  2 K.E. ~ | P.E.|
- $\boxed{M = 3\,\sigma_v^2\, r / G}$
  - This time σ_v is that for the galaxies
  - Measure from distribution of redshifts
- How reliable is the virial theorem for clusters?
  - Many clusters are believed to be merging
- Virgo has a velocity dispersion of 550 km s^{-1}
  - Estimate its mass

Estimate the mass of Virgo (σ_v = 550 km s^{-1})

Summary Lecture 1

- The Milky Way is part of the Local Group
- Nearest cluster is Virgo, more distant is Coma

- Clusters consist of galaxies, hot gas, and dark matter
- There are many ellipticals in clusters (Red Sequence)

Clusters are important for:

- Cosmology (e.g. $\Omega_{M,}$ Ω_{Λ})
- For Astrophysics (interaction galaxies & gas)

Clusters are detected using:

- Optical/Infrared surveys
- X-ray surveys
- Radio surveys (Sunyaev-Zel'dovich effect)

- Cluster mass can be calculated using the Virial Theorem

Cluster masses from X-rays

- Hot gas (10^7-10^8 K) in clusters emits lots of X-rays
  - thermal bremsstrahlung
- X-ray observations are good for finding clusters
  - can observe luminosity and T as fn of position
- If spherically symmetric and stationary:
  - can apply hydrostatic eqn to find mass

Hydrostatic equilibrium equations

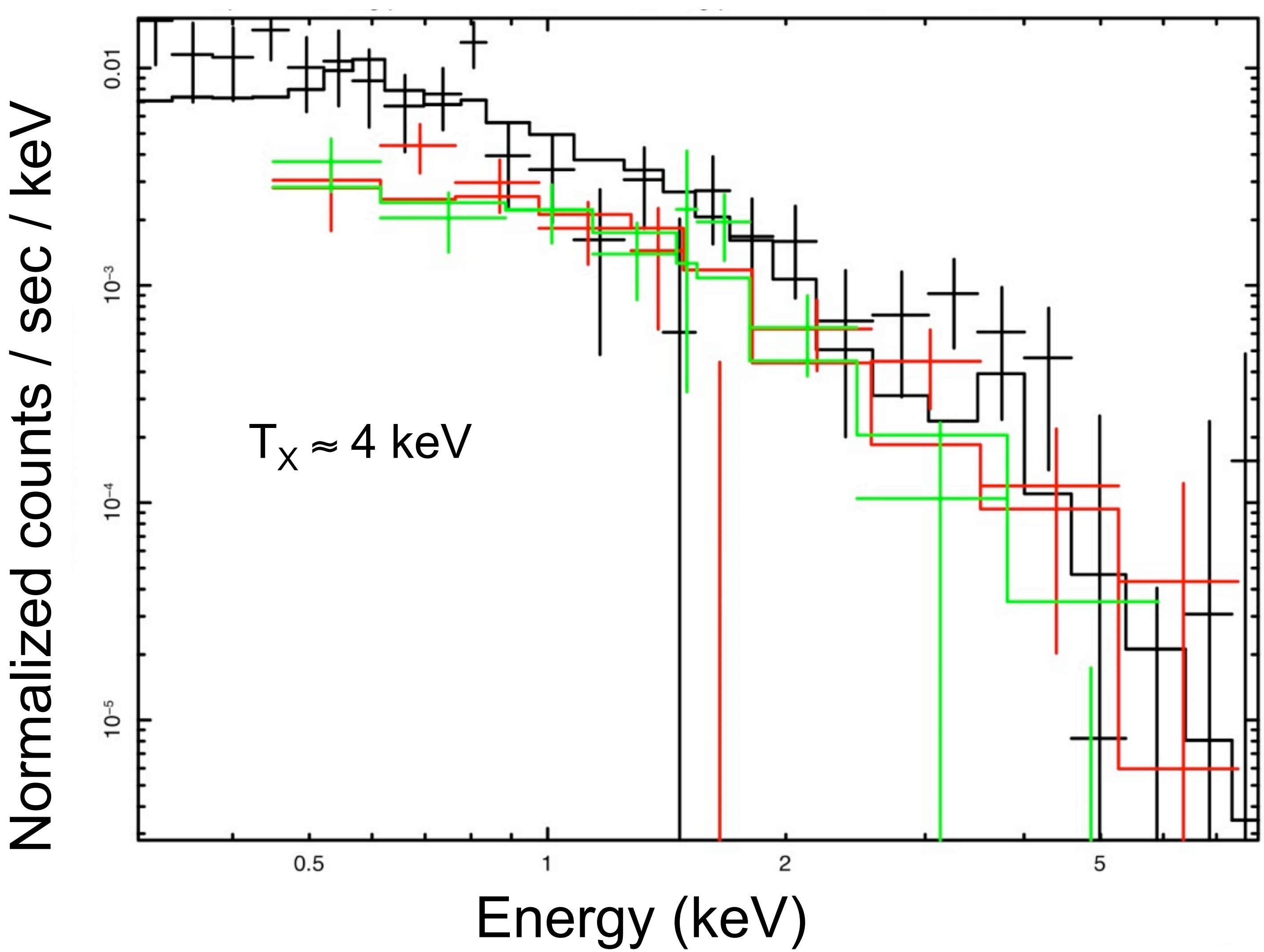
$$\frac{dp}{dr} = -\frac{GM(r)}{r^2}$$

$$p = n k_B T = \frac{\rho_g k_B T}{m}$$

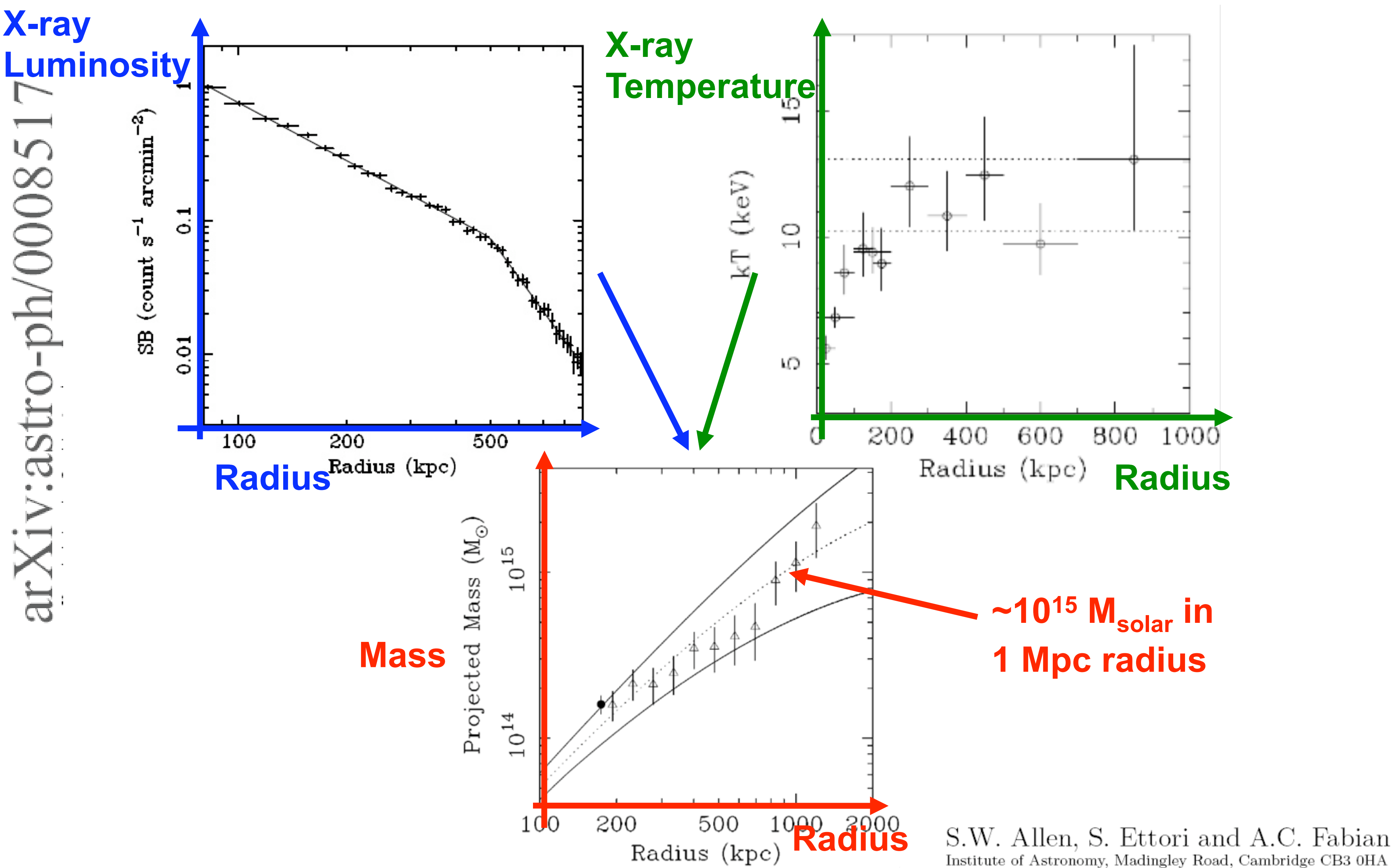
$$M(r) = -\frac{k_B T r}{Gm}\left(\frac{d\ln\rho_g}{d\ln r} + \frac{d\ln T}{d\ln r}\right)$$

- Observe $T(r)$ and $\rho_g(r)$ from X-rays
  - T from spectra; ρ_g from X-ray luminosity

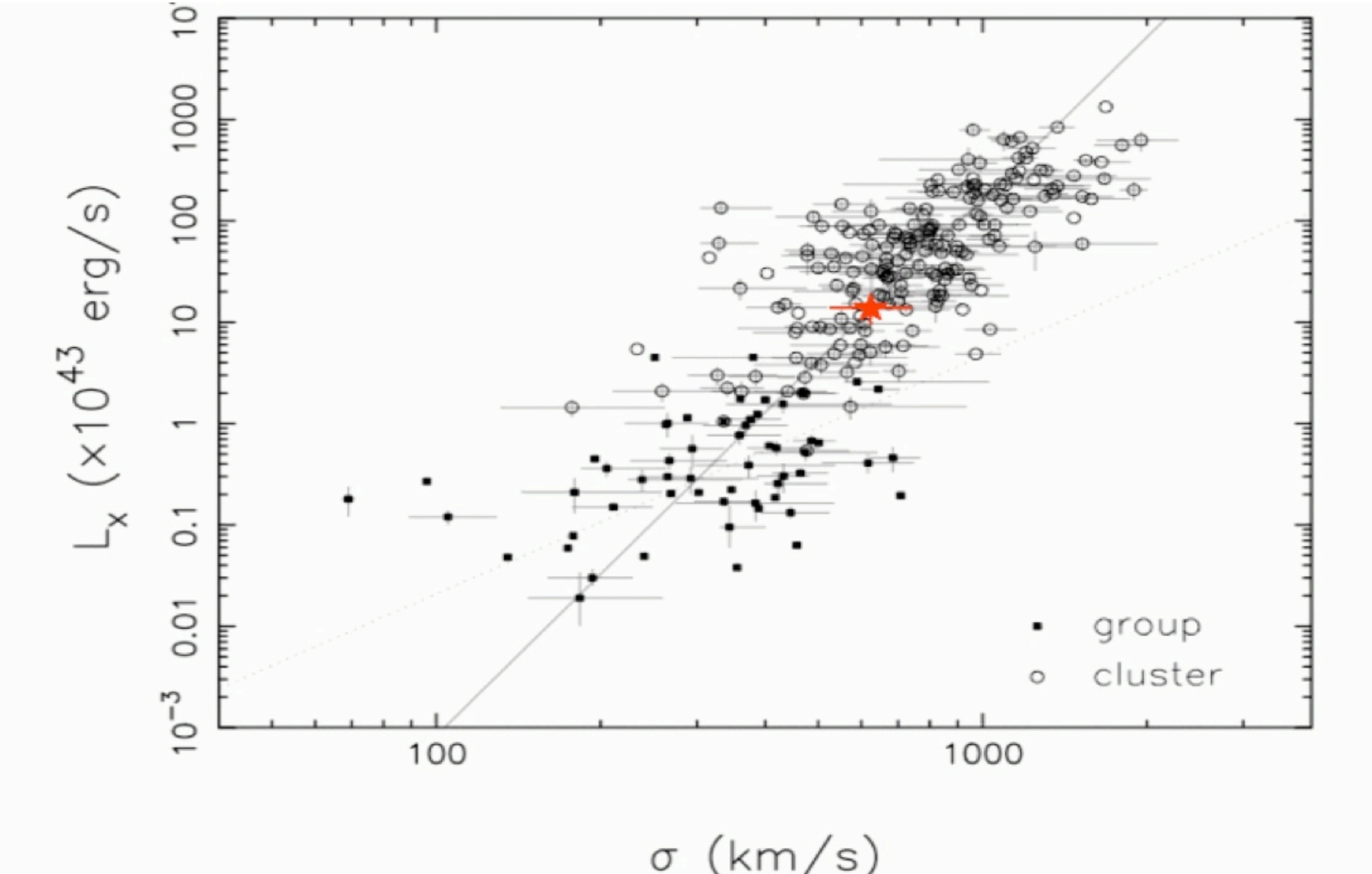
X-ray spectrum yields T_X



Mass of Abell 2390 from X-rays

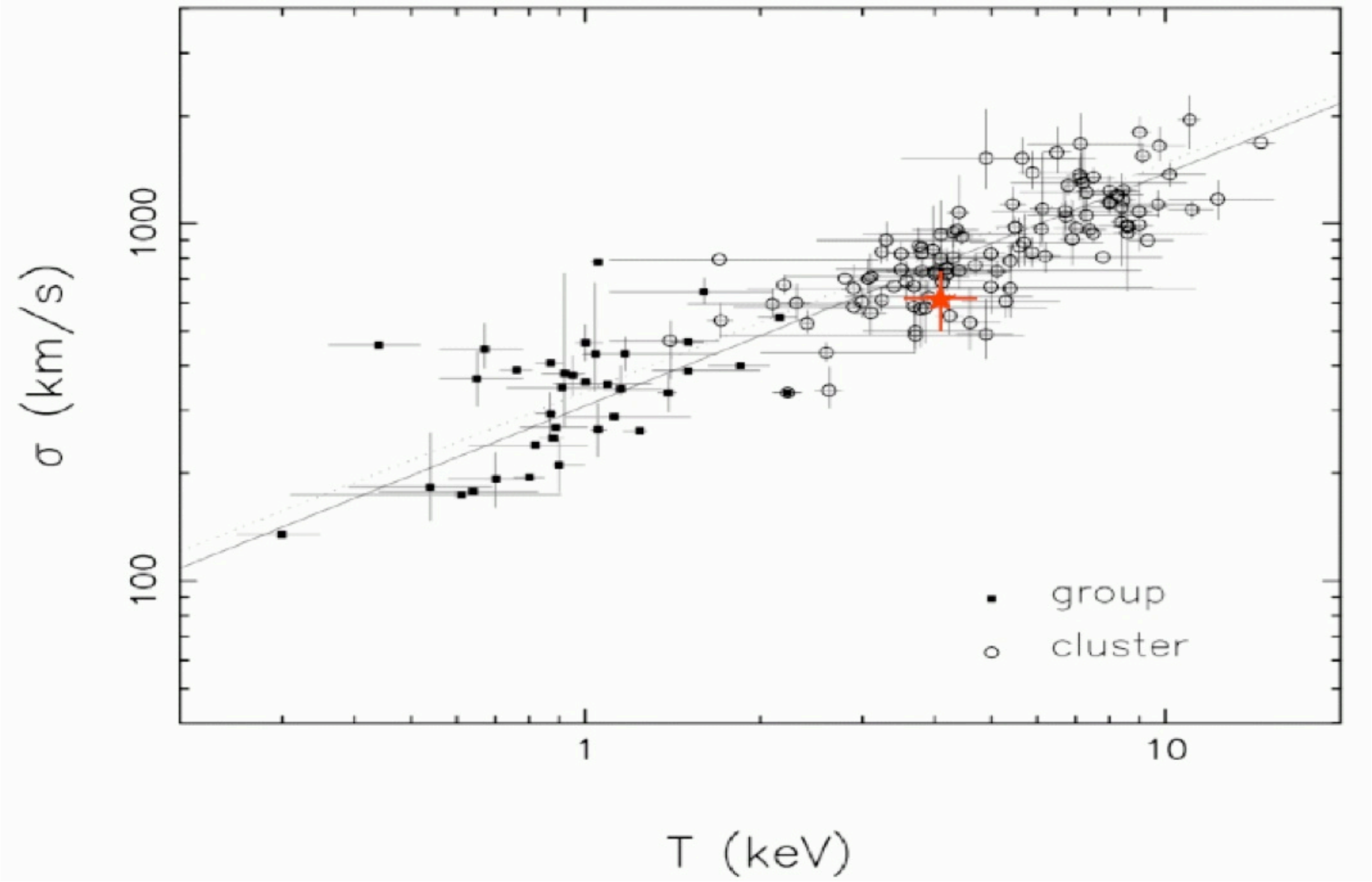


X-ray scaling relations



Xue & Wu 2000

X-ray scaling relations



Xue & Wu 2000

Cluster masses from gravitational lensing

1. Strong lensing: highly distorted images
   - Einstein radius

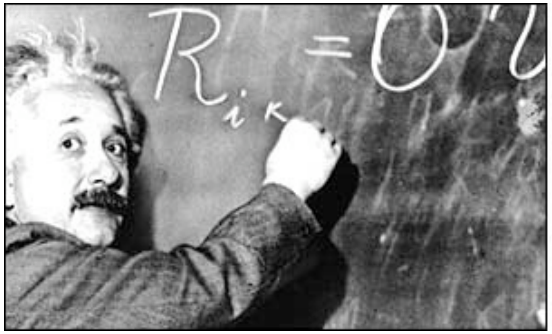
$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{ds}}{D_d D_s}}$$

2. Weak lensing: have to average over many galaxies
   - weak shear

$$\text{"shear"} \equiv \frac{a_e - b_e}{a_e + b_e} = \frac{4GM}{c^2}\frac{D_d D_{ds}}{D_s}\frac{1}{b^2}$$

History of light deflection

- Suspected by Newton and Laplace
  - Soldner (1804) calculated deflection angle
- Einstein (1915) applied GR
  - twice the deflection angle
- Eclipse experiment (1919)
  - confirms Einstein's result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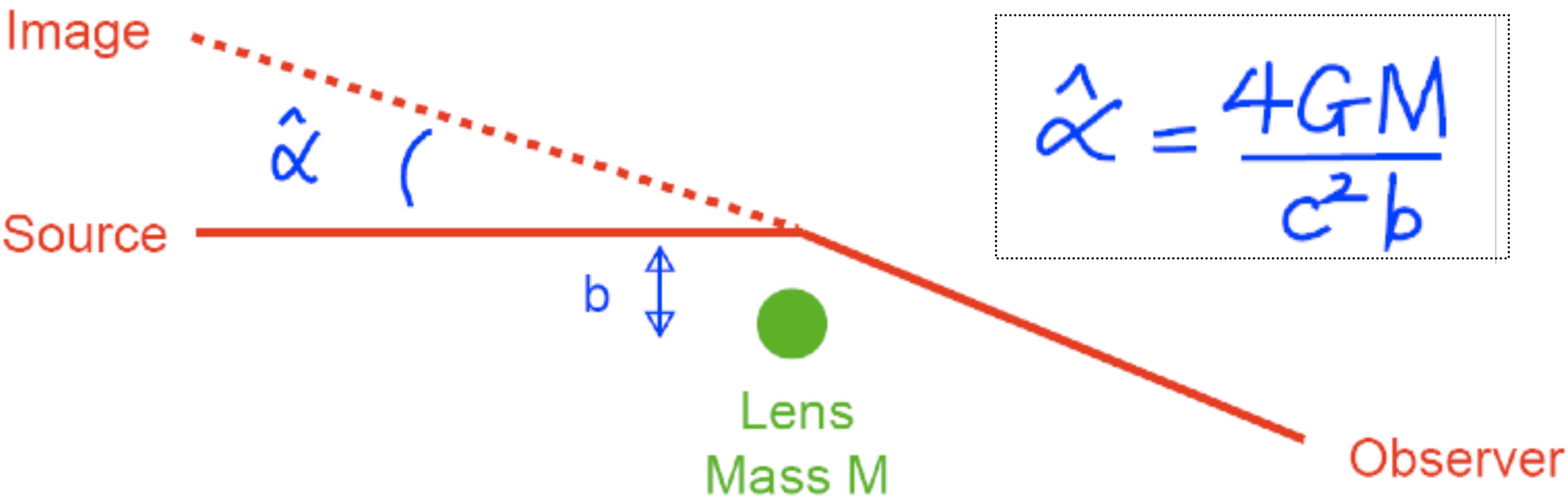
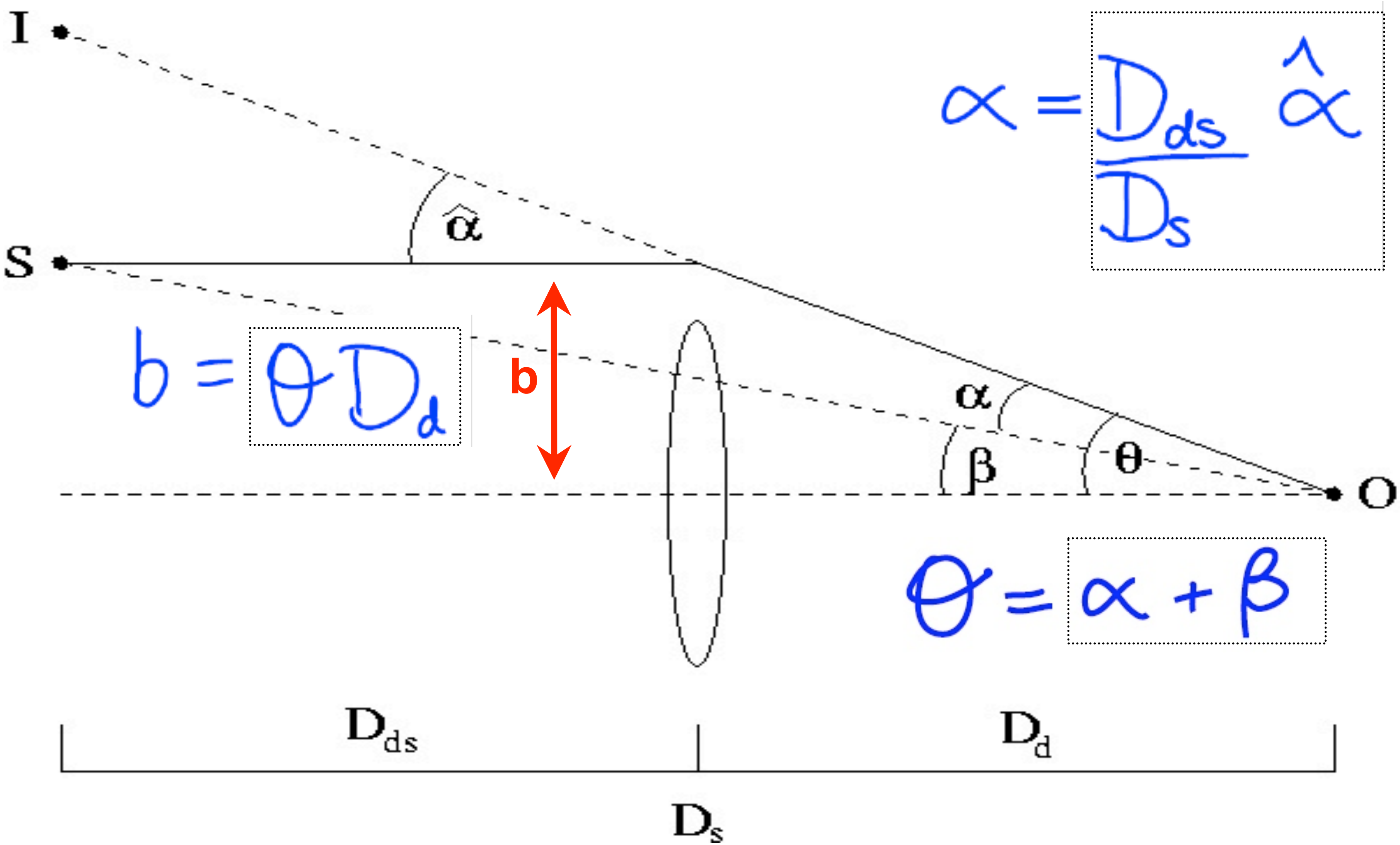
Just one equation from GR



$$\hat{\alpha} = \frac{4GM}{c^2 b}$$

- NB. Independent of light wavelength

Apparent deflection angle, α



$$\alpha = \frac{D_{ds}}{D_s}\hat{\alpha}$$

$$b = \boxed{\theta D_d}$$

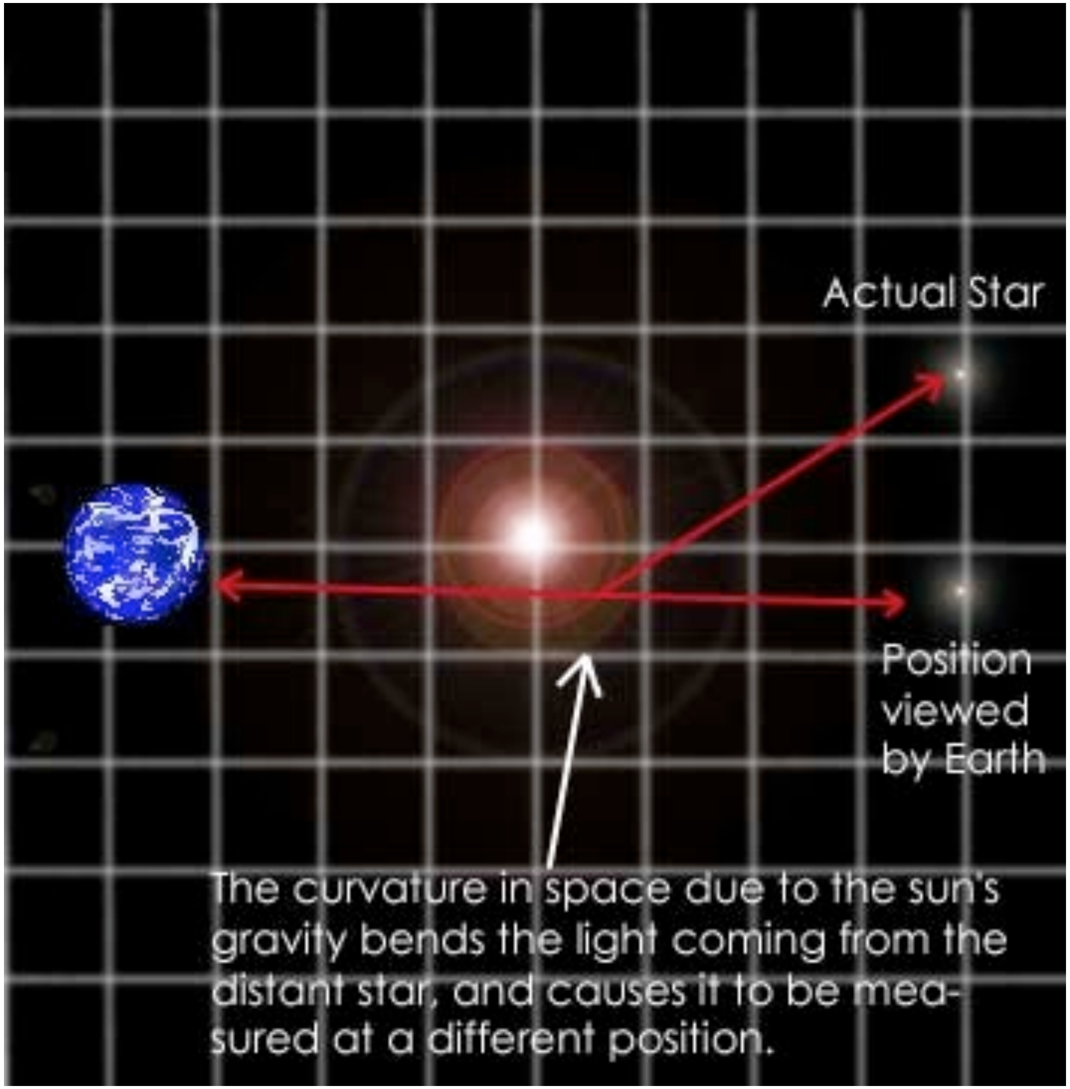
$$\theta = \boxed{\alpha + \beta}$$

Deflection by the sun

$D_{ds} \sim D_s$ so

$$\alpha \simeq \hat{\alpha} = \frac{4GM}{c^2 b}$$

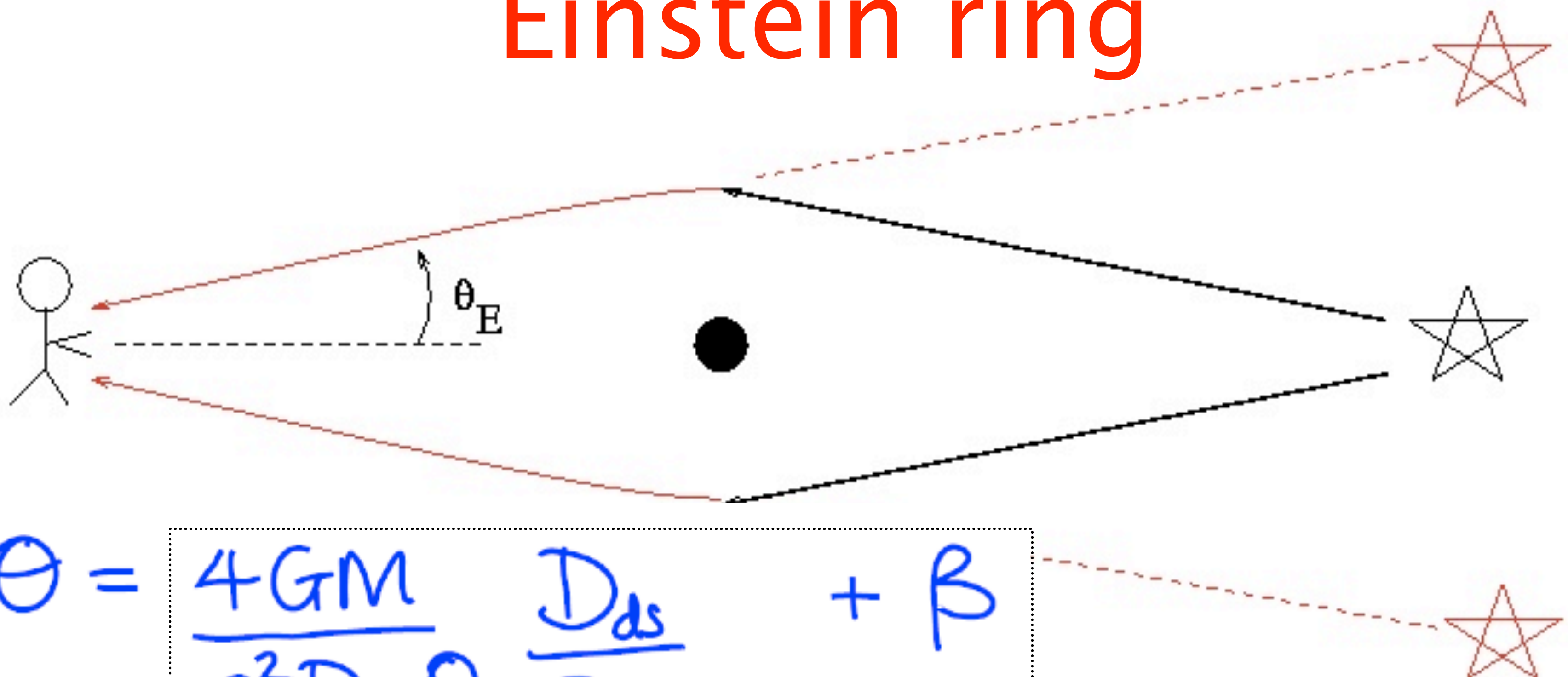
$\alpha = 1.75''$



Eclipse Experiment

- Eddington et al.
  - 29 March 1919
  - Principe Island off west coast of Africa
- Agrees with Einstein
- Einstein becomes a celebrity
  - Within 1 year more than 100 books written on GR!

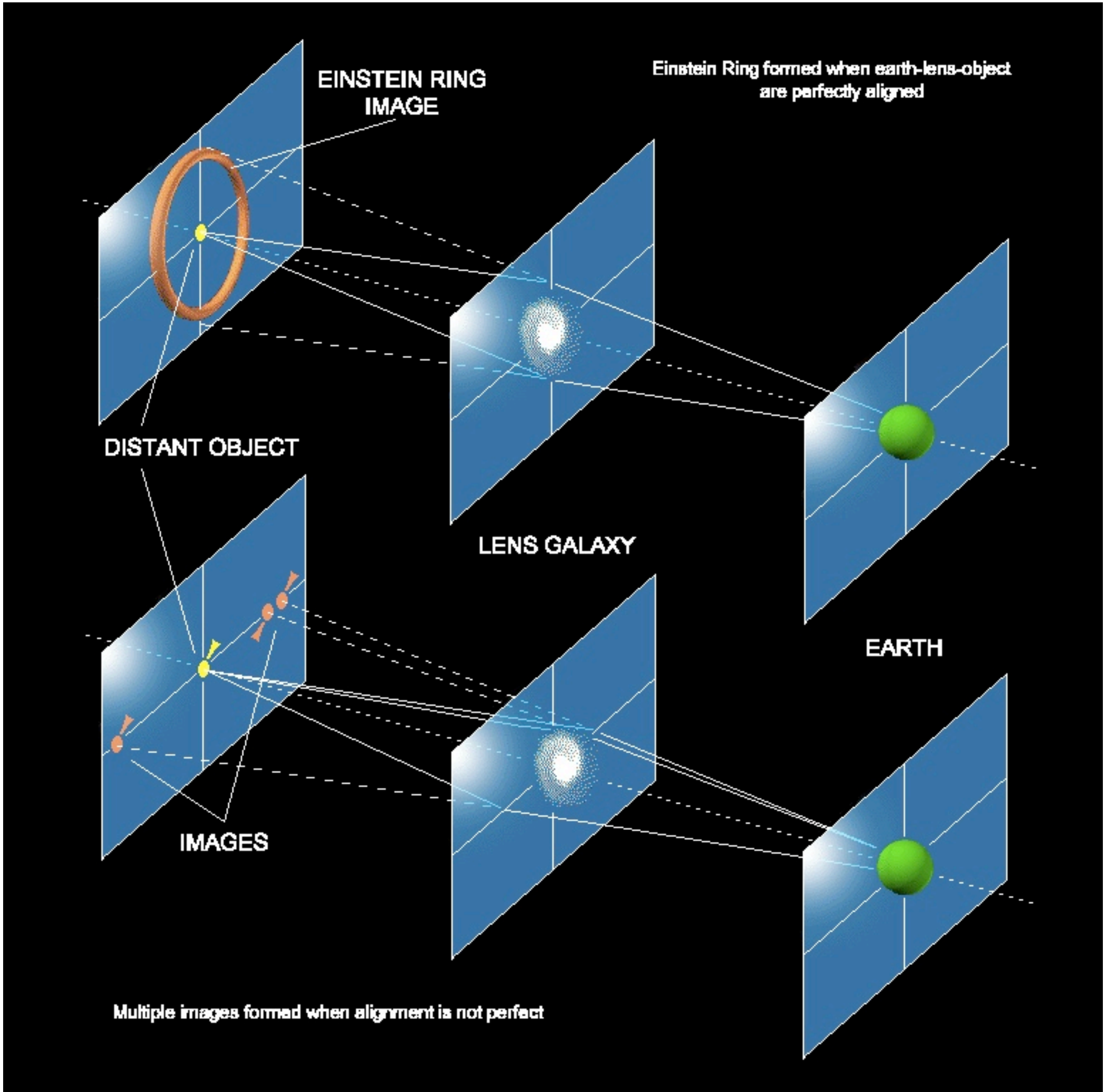
Einstein ring

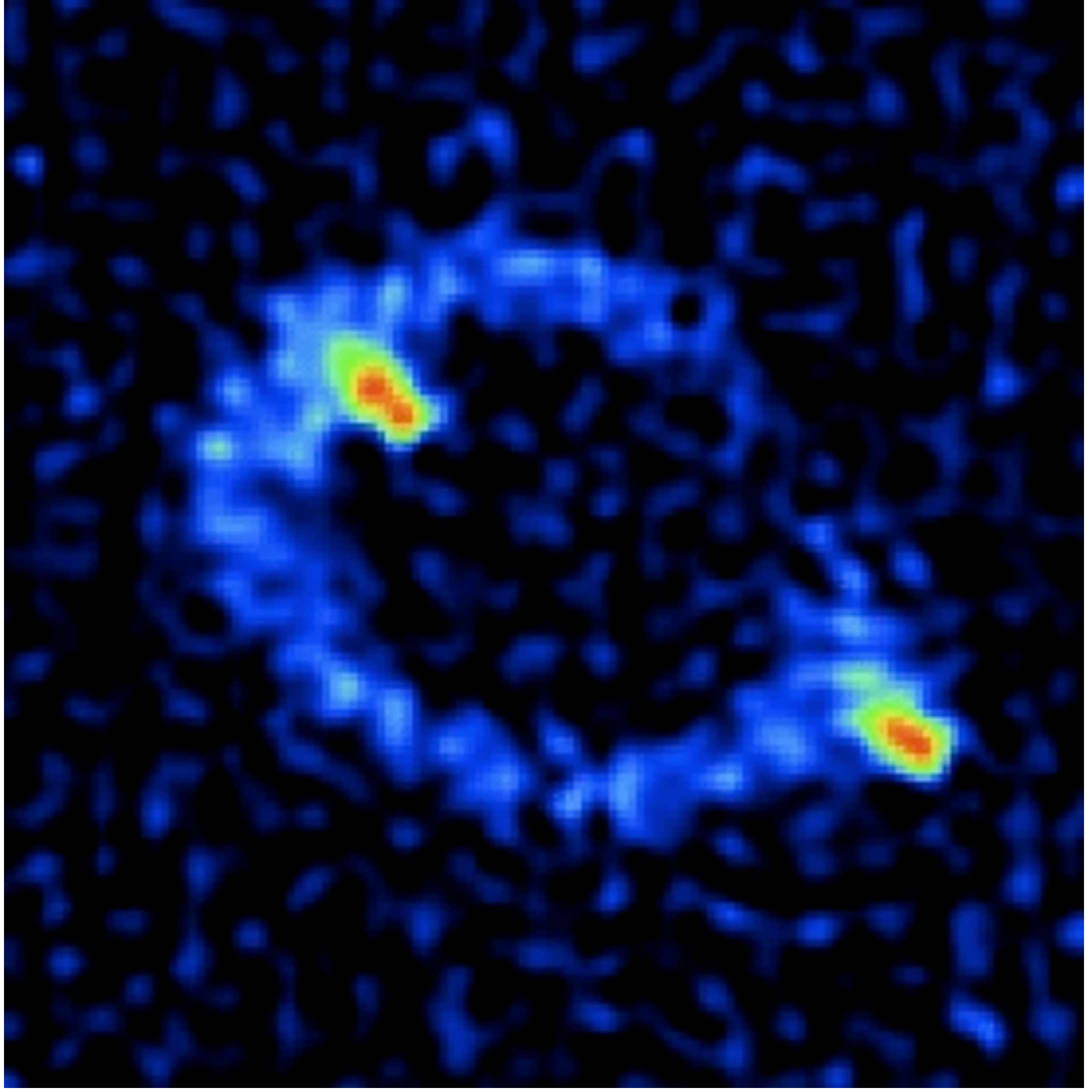


$$\theta = \boxed{\frac{4GM}{c^2 D_d \theta}\frac{D_{ds}}{D_s} + \beta}$$

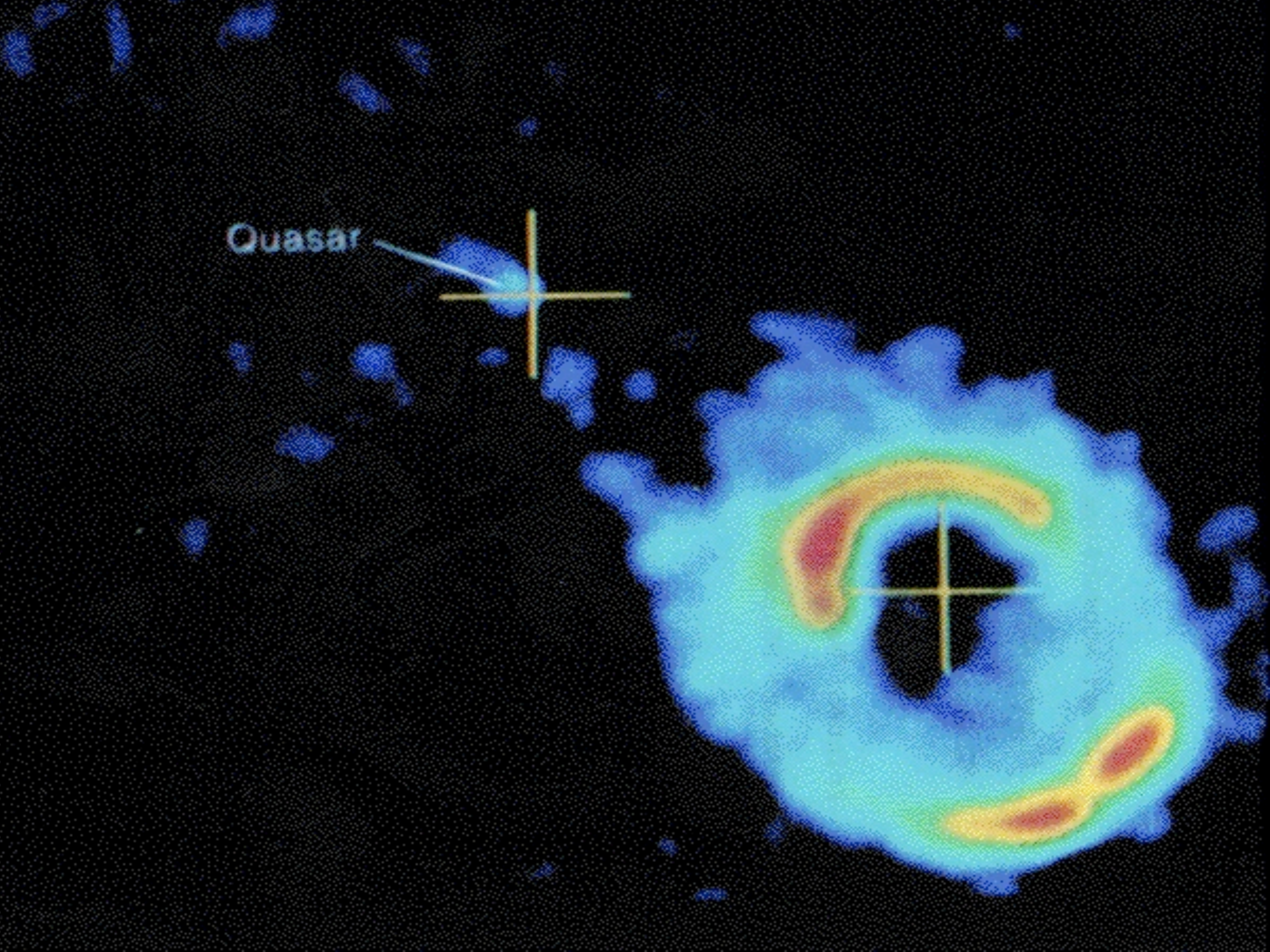
Einstein ring $\beta = \boxed{0}$ $\quad \theta = \boxed{\theta_E}$

$$\theta_E = \boxed{\sqrt{\frac{4GM}{c^2}\frac{D_{ds}}{D_d D_s}}}$$

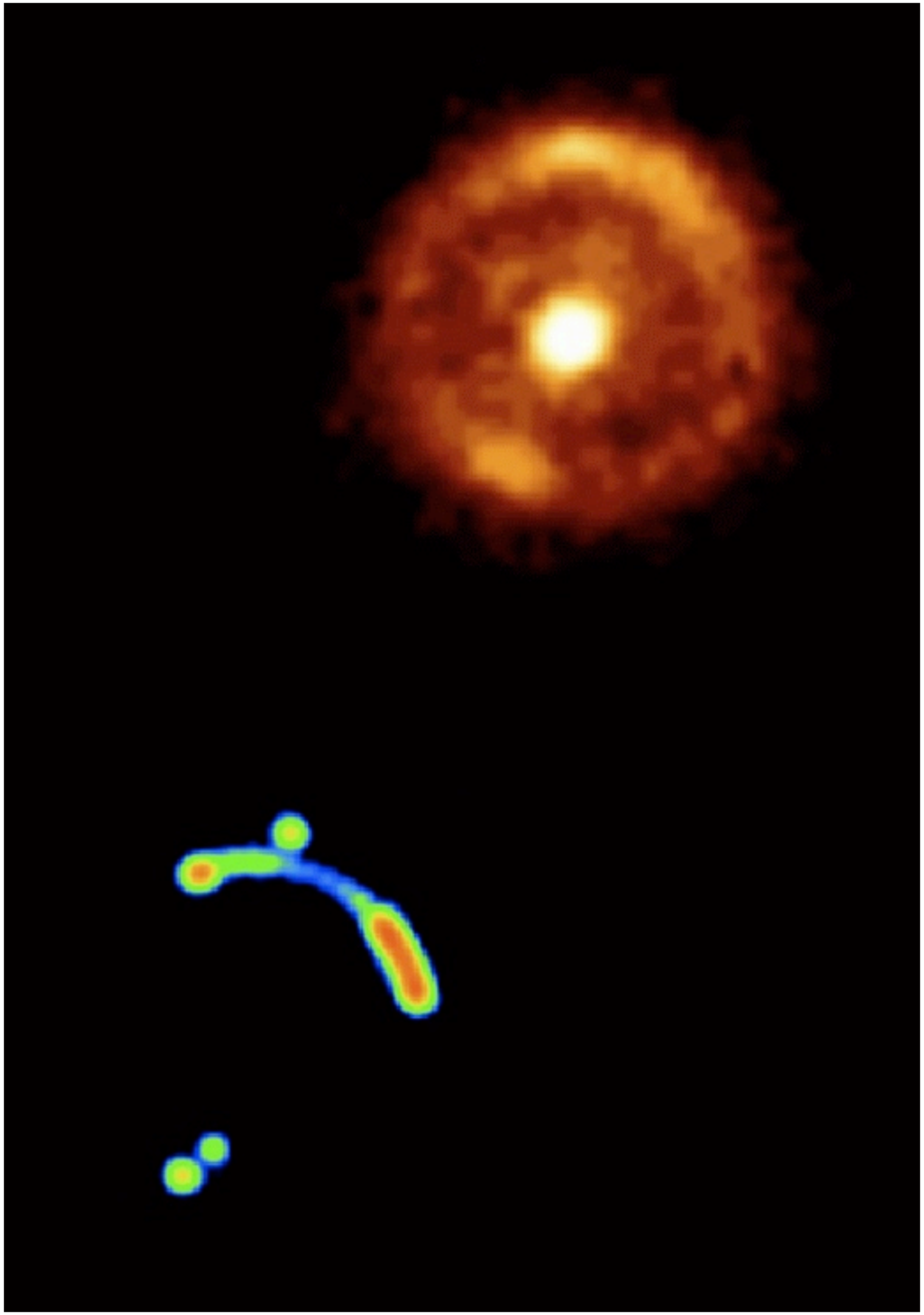

EINSTEIN RING IMAGE
Einstein Ring formed when earth-lens-object are perfectly aligned
DISTANT OBJECT
LENS GALAXY
EARTH
IMAGES
Multiple images formed when alignment is not perfect



- First Einstein ring observed by VLA
- Quasar lensed by galaxy


Quasar

- upper: Hubble
- lower: Merlin



Lens a Picture From the Web - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://theory2.phys.cwru.edu/~pete/GravitationalLens/mypic.cgi

standard candle

Lens a Picture From the Web | [astro-ph/0701671] Intrinsic galaxy align... | standard candle - Google Image Search

URL to lens: http://www.sarahbridle.net/sarah07.jpg

Lens It

Lens a Picture from the Web!

If you want to try a picture off the web, enter the full URL above, as in *http://www.phys.cwru.edu/research/sn1a.jpg* and click on "Lens It" note: the *http://* part of the URL is important. The point is that 1) the URL must be fully qualified including the protocol part, (the http://, ftp:// or whatever-- not *file:/* because of the applet security model) and 2) there must be a gif or jpeg image on the other end. Also, things look best if one keeps the maximum image size in pixels below about 500x450

Here is the link to your image (if you cannot click on this and view it directly, neither can this applet-- the exception being a file on your own computer, even though you can view it this applet cannot, believe me you wouldn't want it to be able to): http://www.sarahbridle.net/sarah07.jpg

---

mass/2 | 2*mass | default

up

left | 1 | right

down

Done

Lens a Picture From the Web - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://theory2.phys.cwru.edu/~pete/GravitationalLens/mypic.cgi

gravitational lens movie

Lens a Picture From the Web | [astro-ph/0701671] Intrinsic galaxy align... | sarah07.jpg (JPEG Image, 240x225 pixels)

URL to lens: http://www.sarahbridle.net/sarah07.jpg

Lens It

Lens a Picture from the Web!

If you want to try a picture off the web, enter the full URL above, as in *http://www.phys.cwru.edu/research/sn1a.jpg* and click on "Lens It"
note: the *http://* part of the URL is important. The point is that 1) the URL must be fully qualified including the protocol part, (the http://, ftp:// or whatever-- not *file:/* because of the applet security model) and 2) there must be a gif or jpeg image on the other end. Also, things look best if one keeps the maximum image size in pixels below about 500x450

Here is the link to your image (if you cannot click on this and view it directly, neither can this applet-- the exception being a file on your own computer, even though you can view it this applet cannot, believe me you wouldn't want it to be able to): http://www.sarahbridle.net/sarah07.jpg

---

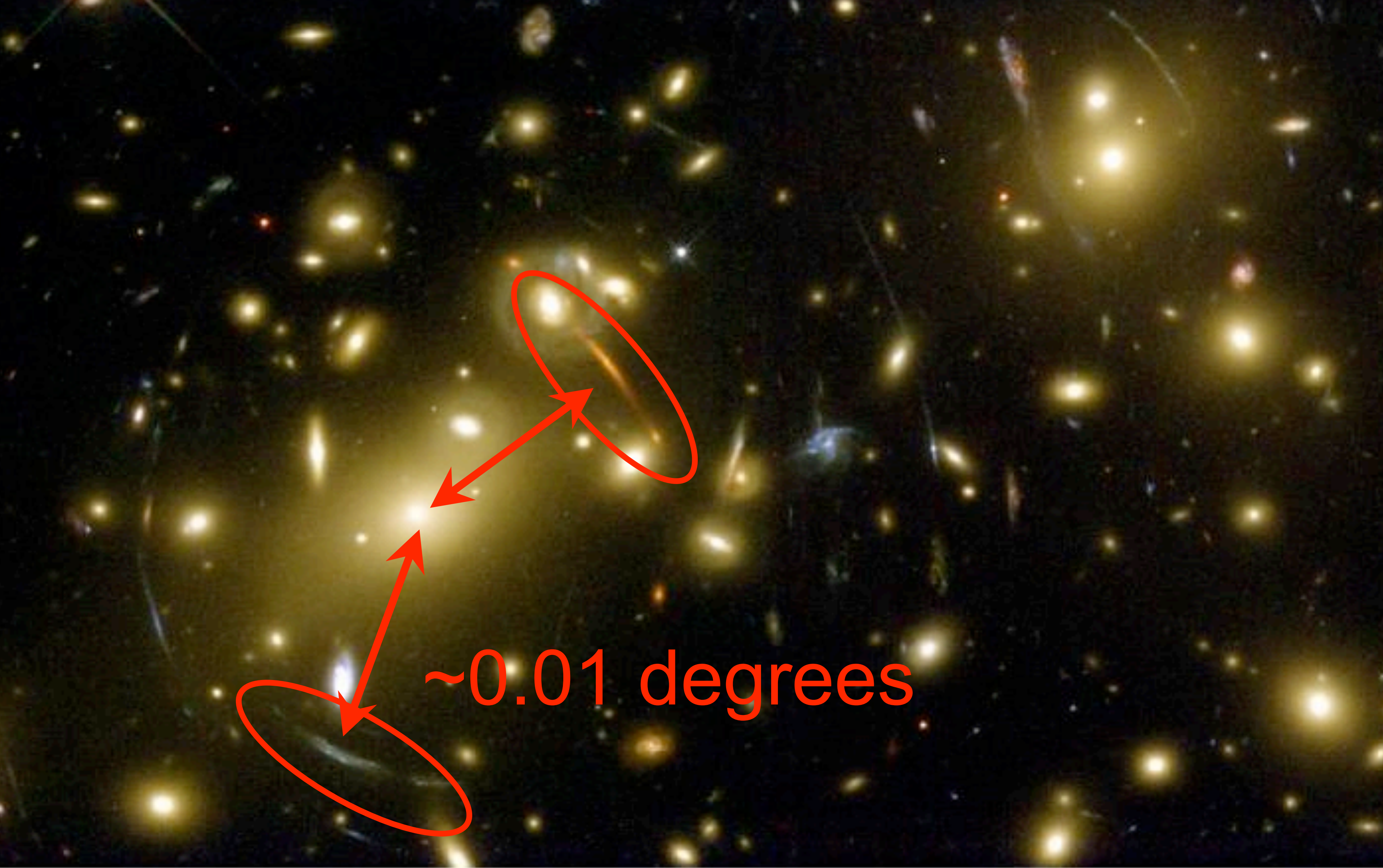
mass/2 | 2*mass | default

up

left | 1 | right

down

Applet GravitationalLens started

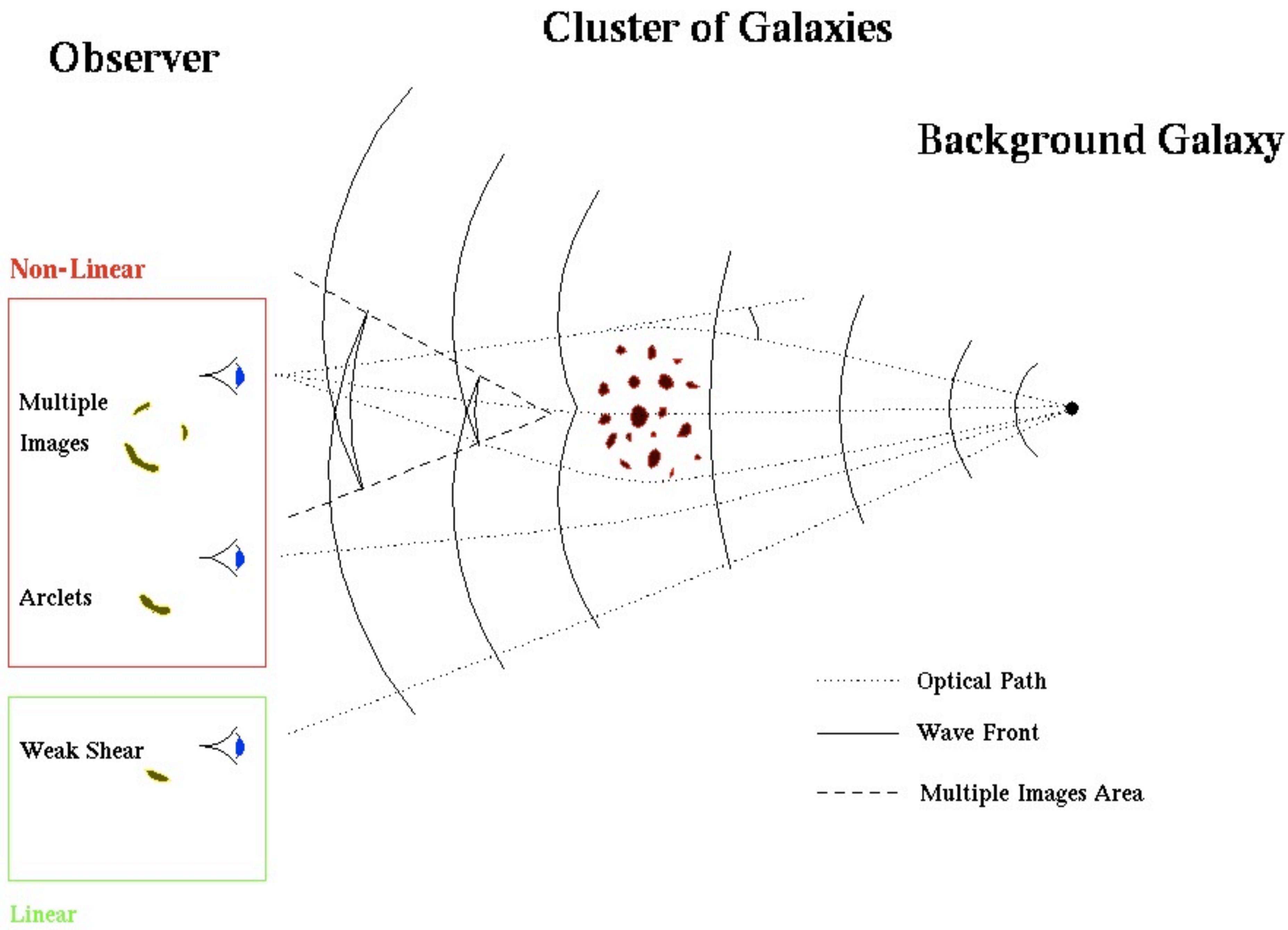


Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

Estimate the mass of A2218

- θ_E ~ 0.01 degrees
  - Assume is a point mass
  - Assume background galaxy is very far
  - Assume distance ~700 Mpc
- If another cluster has arcs of size 0.02 degrees, how massive is it relative to A2218?

Read JL p185

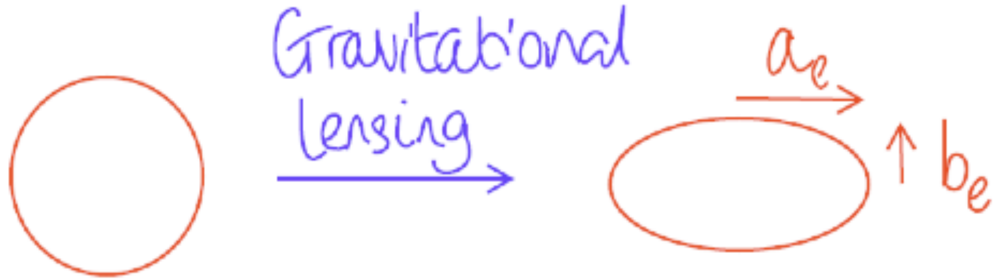


Observer
Cluster of Galaxies
Background Galaxy
Non-Linear
Multiple
Images
Arclets
Weak Shear
Linear
Optical Path
Wave Front
Multiple Images Area

Weak versus strong lensing

- Strong lensing:
  - multiple images
  - banana shaped arcs
  - inner parts of massive clusters/ galaxies
- Weak lensing
  - ellipse orientation is changed
  - low-mass clusters, outer parts of massive clusters
  - have to average over many galaxies to measure mass

Weak lensing shear



Circular galaxy

$\boxed{\text{Ellipse}}$

"shear" $\equiv \boxed{\dfrac{a_e - b_e}{a_e + b_e}}$

For point mass lens (e.g. cluster):

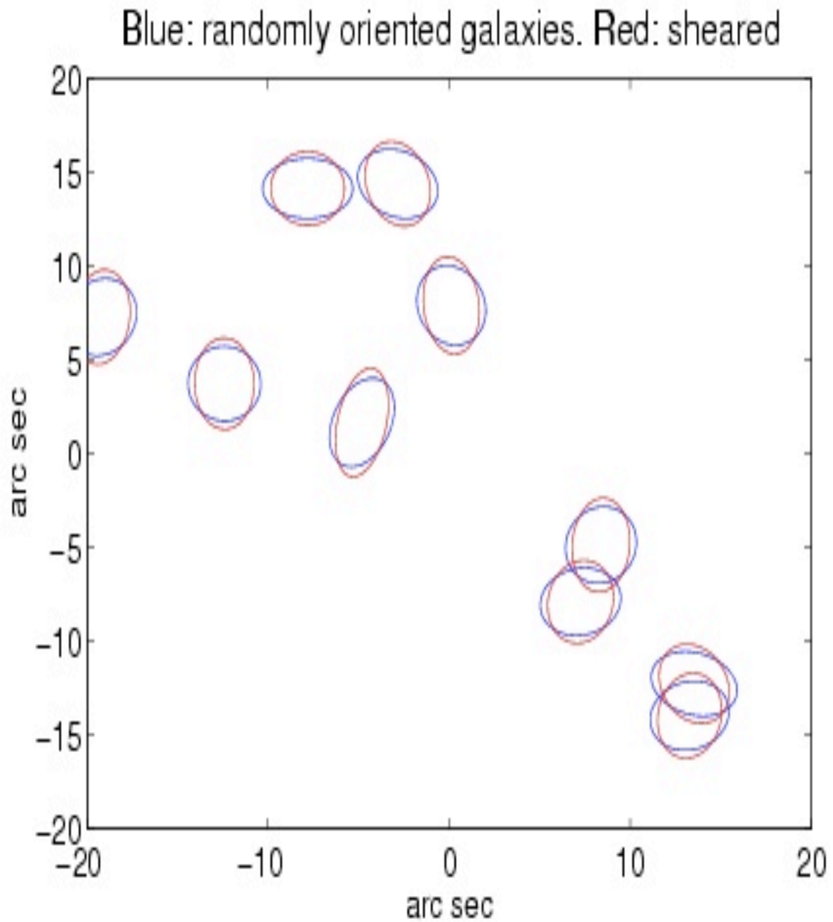
$$\frac{a_e - b_e}{a_e + b_e} = \frac{4GM}{c^2} \frac{D_d D_{ds}}{D_s} \frac{1}{b^2}$$

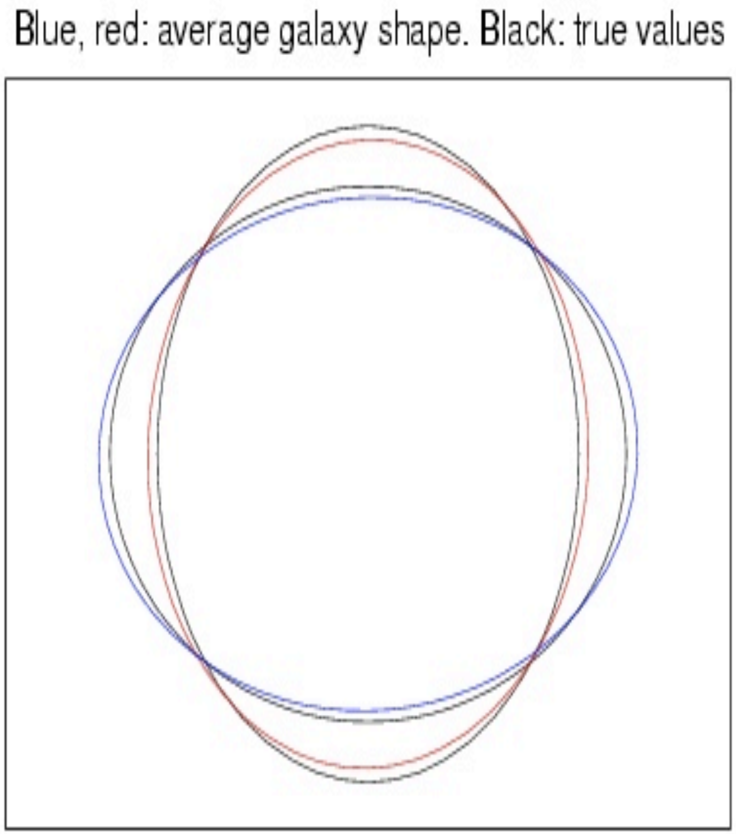
Impact parameter

(Proof beyond this course)

stretch is always $\boxed{\text{tangential around}}$ mass

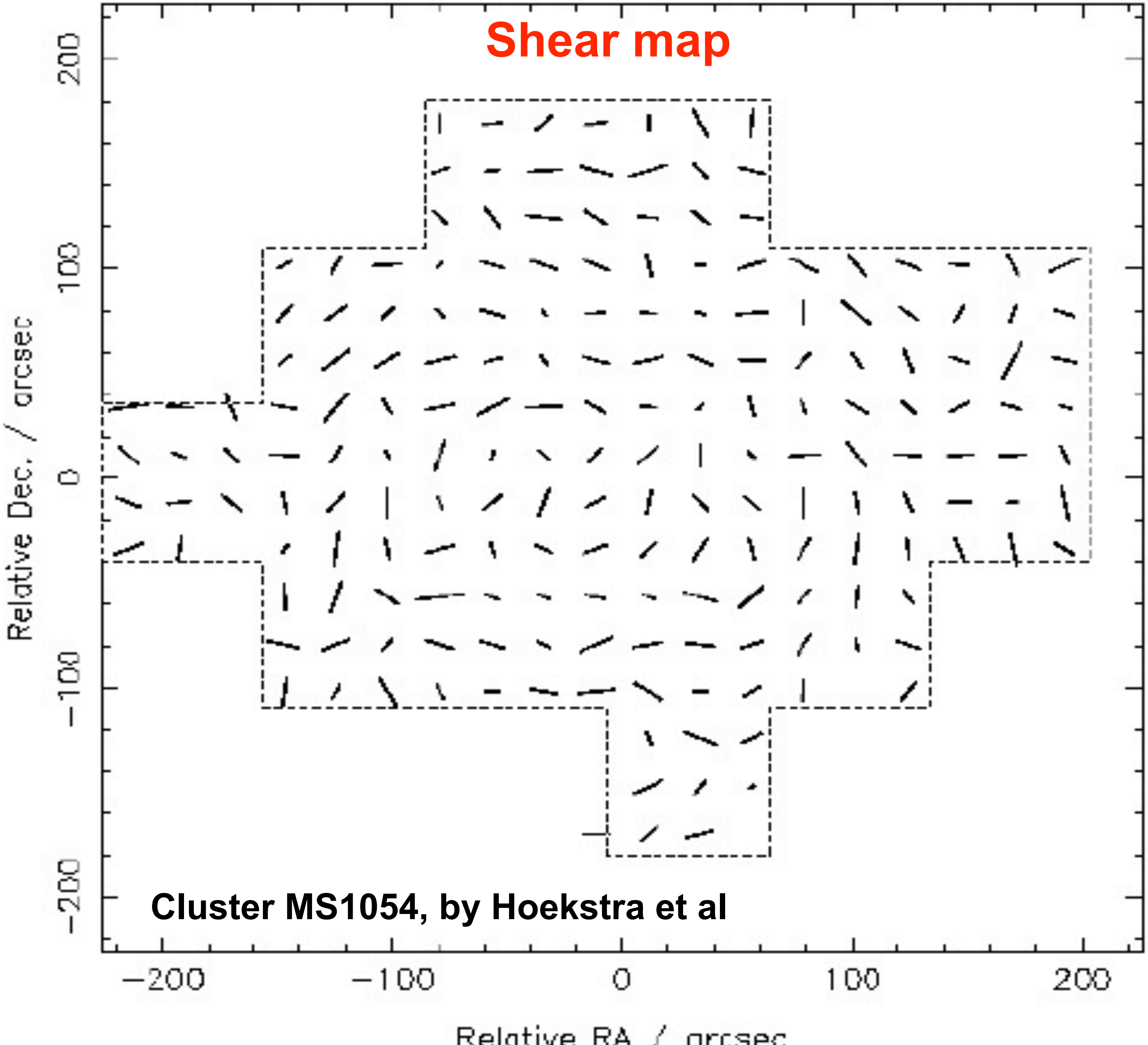
Galaxies are only circular on average



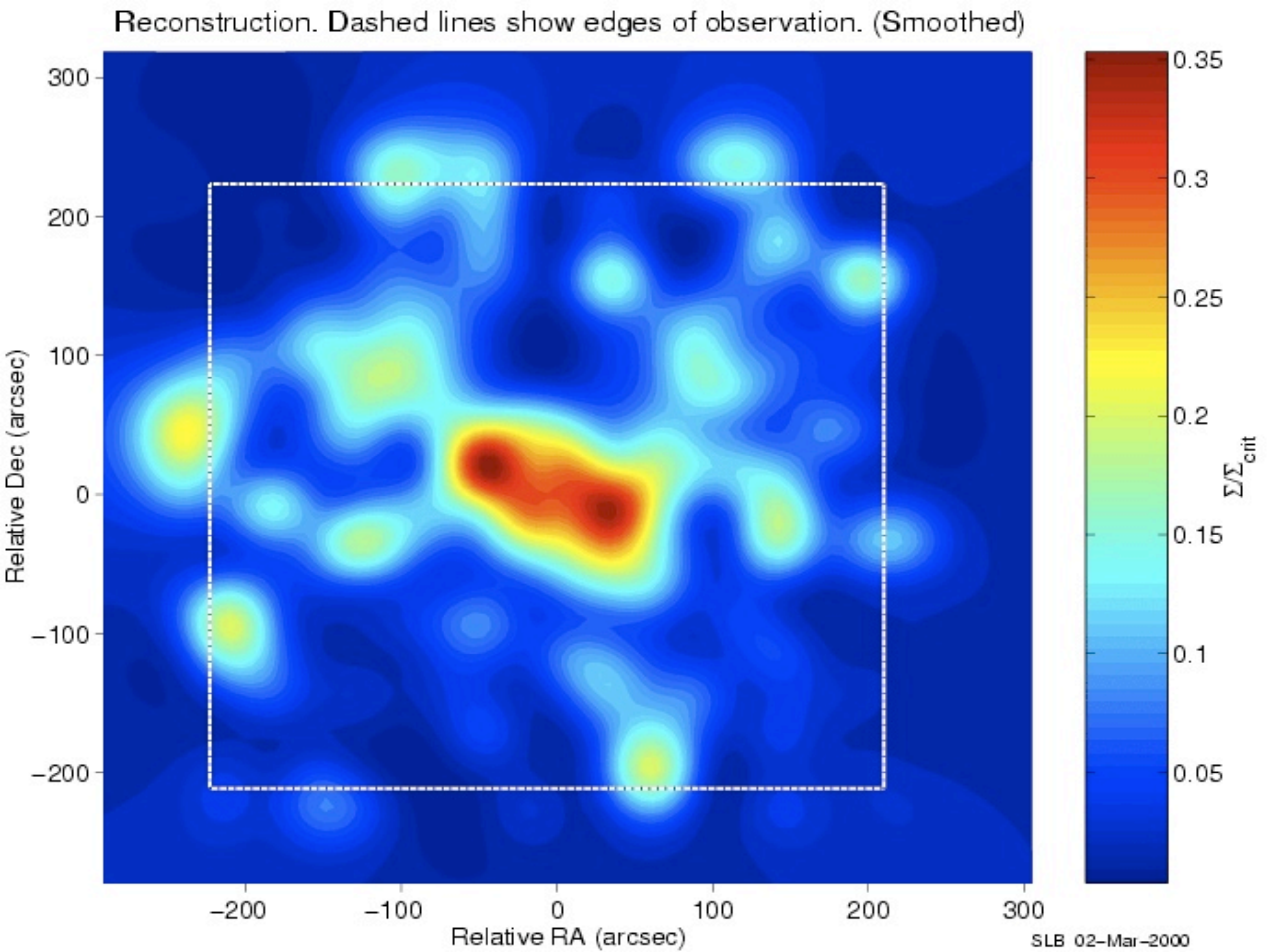


Weak lensing method

- Divide image up into boxes containing ~10 galaxies in each
- Average galaxy images together
  - shear map
- Guess mass map
  - predict shear map
  - compare to observed shear map
  - repeat until fit the observations



Shear map
Cluster MS1054, by Hoekstra et al
Relative Dec. / arcsec
Relative RA / arcsec
200
100
0
−100
−200
−200
−100
0
100
200


Reconstruction. Dashed lines show edges of observation. (Smoothed)
Relative Dec (arcsec)
Relative RA (arcsec)
300
200
100
0
−100
−200
300
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Σ/Σ_{crit}
SLB 02−Mar−2000

Conclusion on cluster masses

- 4 different methods for determining them
  - Galaxy velocity dispersions and X-rays assume thermodynamic equilibrium
  - Strong lensing looks at central parts
  - Weak lensing looks at outer parts

- When all methods are carried out on the same cluster, they agree well.