Galaxies: Structure, formation and evolution

Lecture 8

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FP and the virial theorem

$$\frac{GM}{\langle R\rangle} = k_E \frac{\langle V\rangle^2}{2}$$

the 3D velocity and radius will be some scaled version of the projected version. $R = k_R\langle R\rangle$, $V^2 = k_V\langle V\rangle^2$, $L = k_L I R^2$ Then one can write:

$$R = K_{SR} V^2 I^{-1} (M/L)^{-1}, L = K_{SL} V^4 I^{-1} (M/L)^{-2}$$

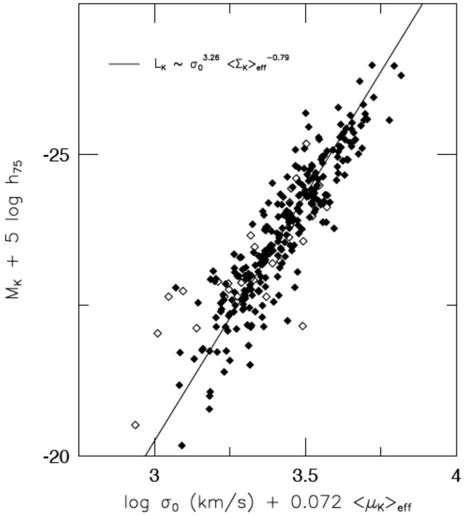
where the structure coeffients

$$K_{SR} = \frac{k_E}{2Gk_R k_L k_V}, K_{SL} = \frac{k_E^2}{4G^2 k_R^2 k_L k_v^2}$$

Question

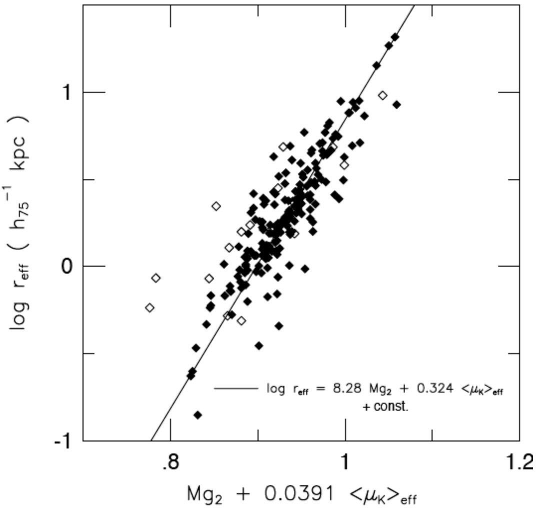
What do deviations of the observed relations from these scalings indicate?

Alternate FP - Luminosity instead of size



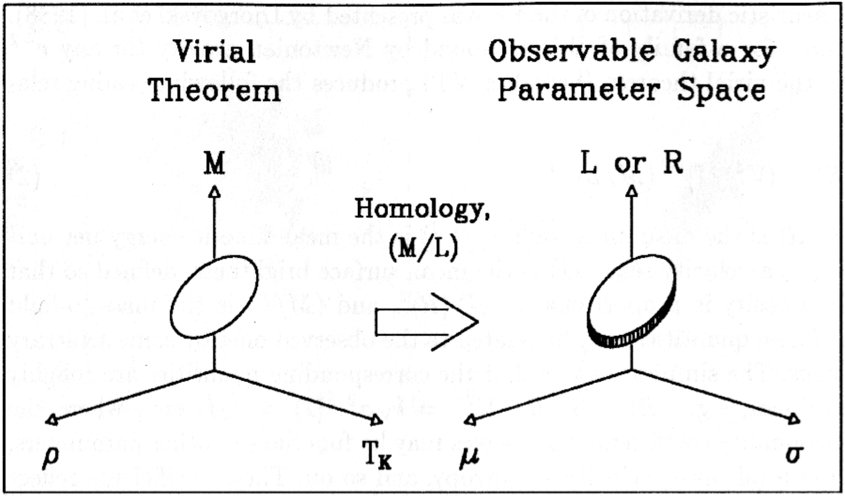
Star formation history connected to structural and dynamical properties

Alternate FP - Metallicity instead of σ



Chemical evolution connected to structural properties

Virial Theorem and the Fundamental Plane



Measuring M/L via the fundamental plane

If we assume homology and attribute all of the FP tilt to the changes in (M/L),

$$(M/L) \sim L^{\alpha}, \alpha \sim 0.2(vis) or \sim 0.1(IR)$$

List two ways of changing M/L in a systematic way

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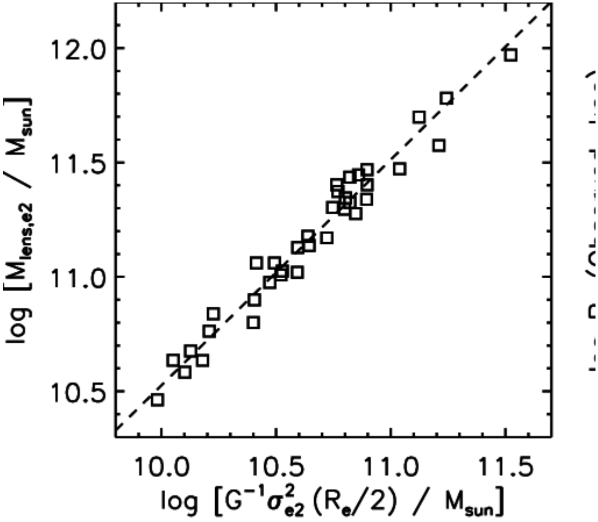
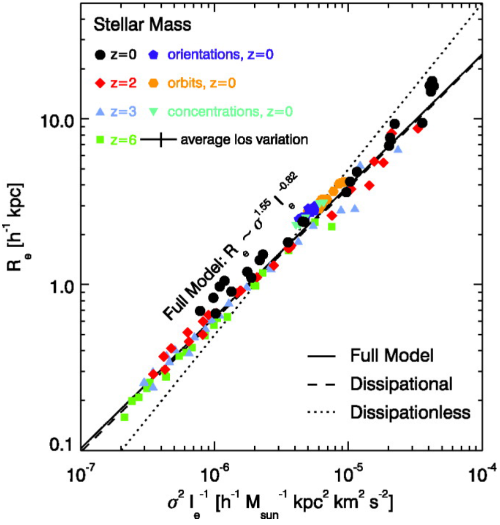
List two ways of changing M/L in a systematic way

1. change the IMF
2. change $M_{\rm visible}/M_{\rm dark}$

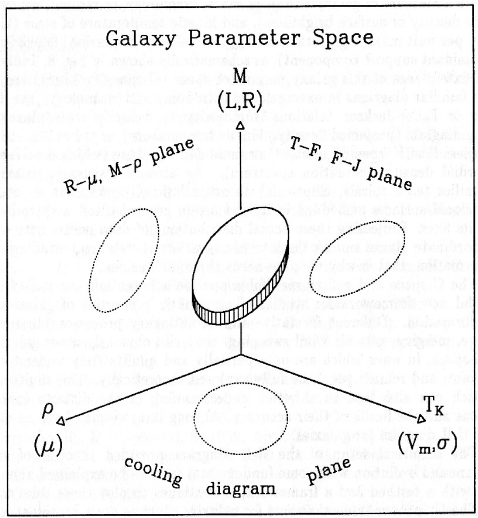
Mass based fundamental plane



FP from numerical simulations



Projections of the FP



For galaxies that fall on FP, just two numbers

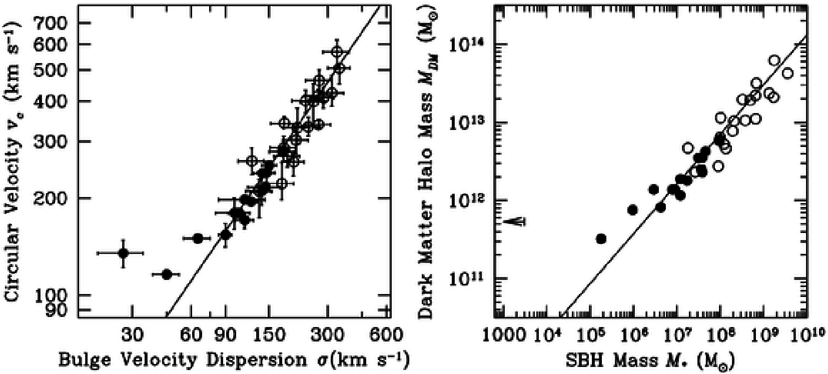
determine to within a few percent or less:

- Mass, luminosity (in any OIR band)
- Any consistently defined radius
- Surface brightness or projected mass density
- Derived 3-d luminosity, mass, or phase-space density
- Central projected radial velocity dispersion
- OIR colors, line strengths, and metallicity
- **Mass of the central black hole**

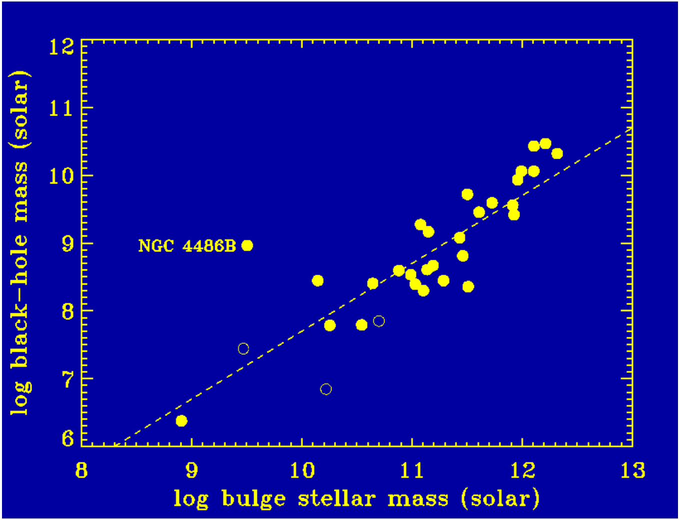
And things that don't matter ...

- Star formation and merging formative/evolutionary history
- Large-scale environment (to within a few %)
- Details of the internal structure and dynamics (including S0's)
- Projection effects (the direction we are looking from)

Central black hole and the bulge



and most interestingly



Dark matter haloes

- Many of galaxy scaling relations may be driven by the properties of their dark halos
- It is possible to infer their properties from detailed dynamical profiles of galaxies and some modeling
- Numerical simulations suggest a universal form of the dark halo density profile (NFW = Navarro, Frenk & White):

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}$$

where ρ_0 and the scale radius r_s are parameters that vary from halo to halo.

Dark matter discovered in 1937 by Zwicky

He calculated the mass of the Coma cluster using the virial theorem. $M_{\rm cl} = \sigma^2 R_{\rm cl}/G$. For typical clusters $\sigma \sim 500 - 1500$ km s^{-1},$R{\rm cl} \sim 3 - 5$ Mpc. This gives $M_{\rm cl} \sim 10^{14} - 10^{15} M_{\odot}$. Typical clusters have 100-1000 galaxies and $L_{\rm cl} \sim 10^{12} L_{\odot}$ and $(M/L) \sim 200 - 500$ in solar units.

Dark matter candidates

- Massive neutrinos: Known to exist and to have mass, but how much?
- Weakly Interacting Massive Particles (WIMPs): Not found yet, but possible . A generic category, e.g., the neutralino = the least massive SUSY particle; also include gravitinos, photinos, and higgsino. Possible masses > 10 GeV
- Axions: predicted in some versions of quantum chromodynamics, Could interact electromagnetically, Possible masses 10^{-12} eV to 1 MeV
- Many (many!) other speculative possibilities ...

Two types of dark matter

- Hot (HDM): matter is relativistic, so must involve low-mass particles such as neutrinos. Their streaming erases the small-scale density fluctuations, so big structures form first, then later fragment. This is “top-down” structure formation
- Cold (CDM): matter moves more slowly; includes exotic as yet unknown particles such as axions, WIMPs, etc. Density fluctuations at all scales survive. Small fluctuations collapse first, then larger ones (pulling in the littler ones along the way). This is “bottom-up” structure formation and this is the best match to what we observe.
- There is probably a little bit of HDM and a lot of CDM

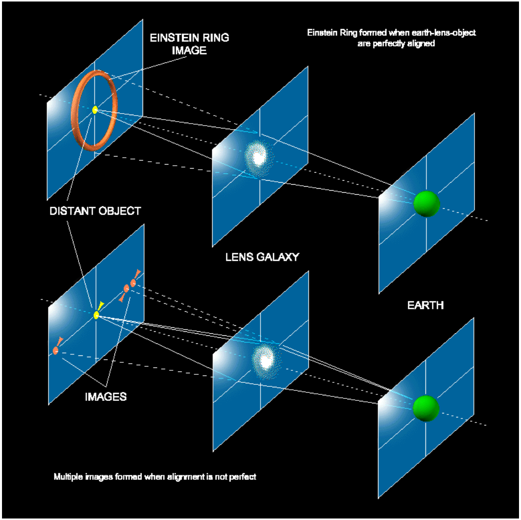
Gravitational lensing

Bending of light is similar to deflection of massive particles, except that GR predicts that for photons the bending is exactly twice the Newtonian value:

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

where R_s is the Schwarzschild radius of a body of mass M, and b is the impact parameter. This formula is valid if $b >> R_s$: The deflection angle α will be small e.g., for the stars near the Solar limb, $\sim$ 2 arcsec

Lensing Geometry



Question

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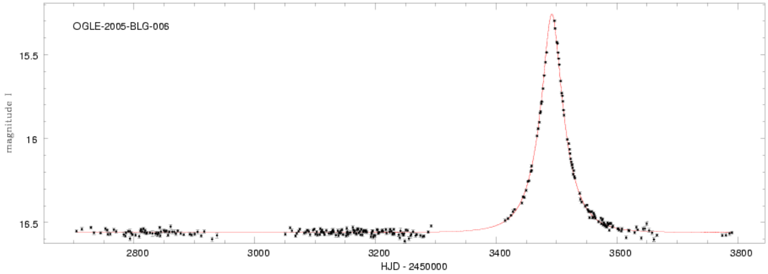
- photons only provide information about objects that emit/absorb/reflect light - what about dark matter?
- probing dark matter requires additional assumptions - with lensing no need for knowledge of orbits (spiral galaxies or stars around a supermassive black hole) or of virialised state (ellipticals) to convert velocity (dispersion) measurements to mass measurements.

Microlensing

There are ongoing searches to use lensing to find a type of dark matter called MACHOs (massive compact halo objects). Although MACHOs, as dark matter, cannot be seen themselves, if they pass in front of a source (e.g. a star nearby), they can cause the star to become brighter for a while, e.g. days or weeks. This effect has been observed but determinations of the dark matter are not yet conclusive. Microlensing observations are underway by many groups.

Gravitational microlensing

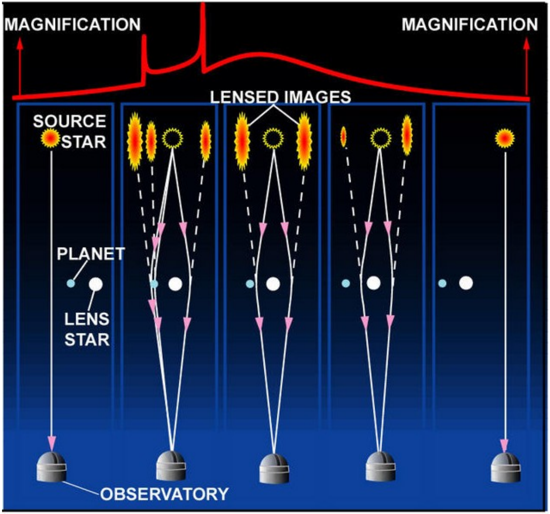


Paczynski (1986)

Question

How can we distinguish a microlensing event from a variable star?

Planet star binary lens geometry



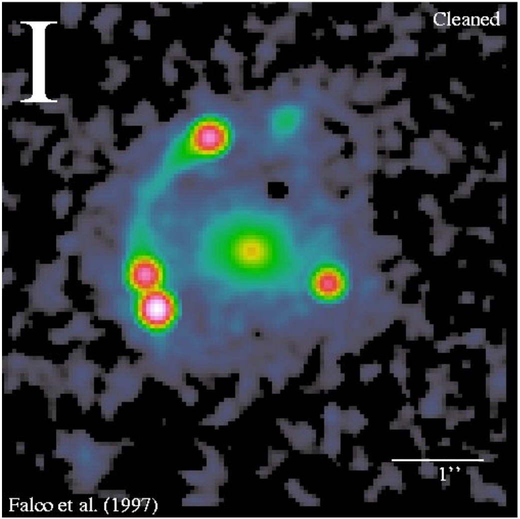
Microlensing in the synoptic era

Rubin/LSST: An optical/near-IR survey of half the sky in *ugrizy* bands to $r \sim 27.5$ based on ~ 1000 visits over a 10-year period

LSST Observing strategy

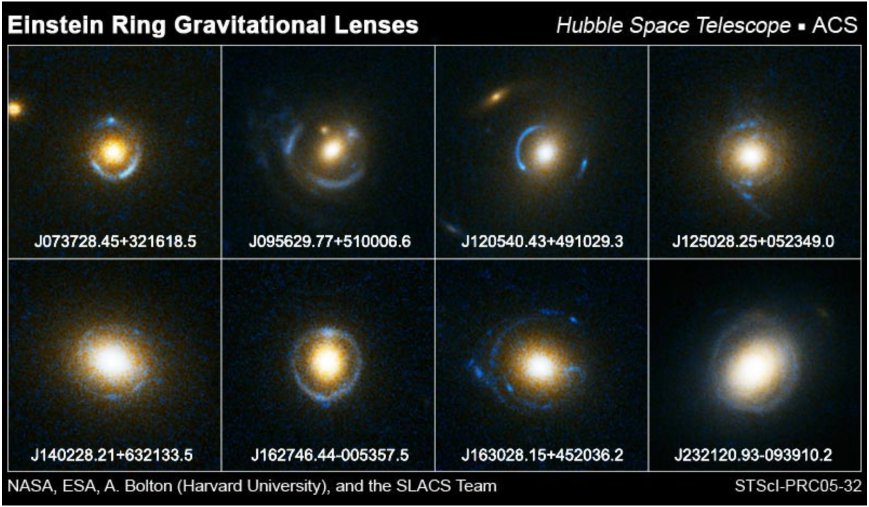
- The main wide-fast-deep survey will use about 90% of the observing time and will be simultaneously optimized for the homogeneity of depth and number of visits, and for time- domain science (e.g., asteroids, supernovae, variable stars).
- The remaining observing time will be used to obtain improved coverage of parameter space such as very deep observations, observations with very short revisit times, and observations of "special" regions (e.g., the Ecliptic, the Large and Small Magellanic Clouds).

quasar lensed by galaxies

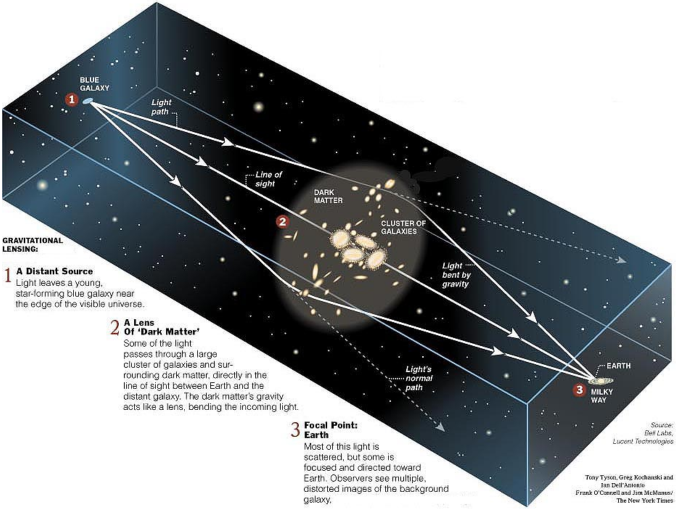


first lens discovered in 1979. Why was it not discovered sooner?

Galaxies lensed by single galaxies

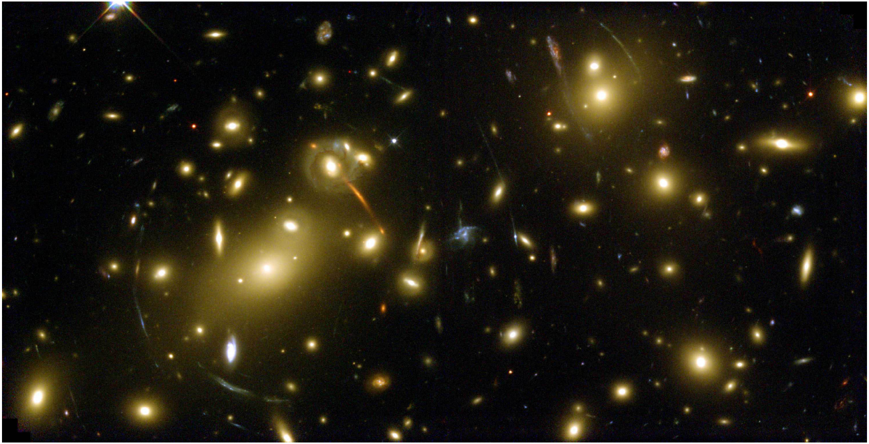


Gravitational Lensing by a cluster



many galaxies lensing one or more galaxies

Abell 2218

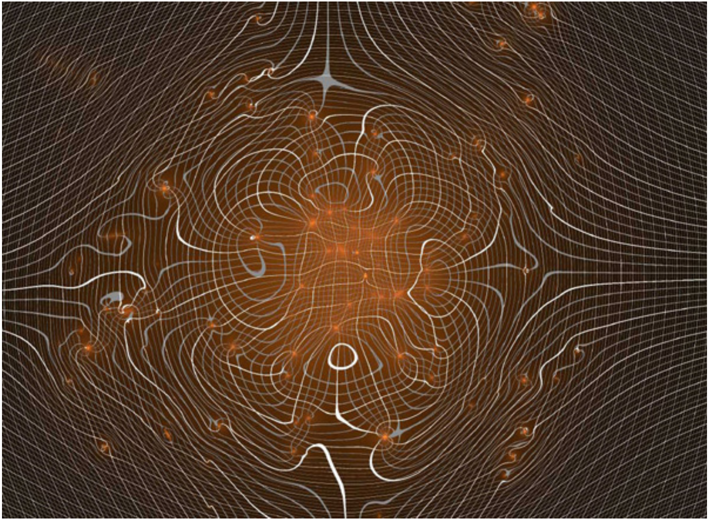


arcs - single galaxy may form multiple images.

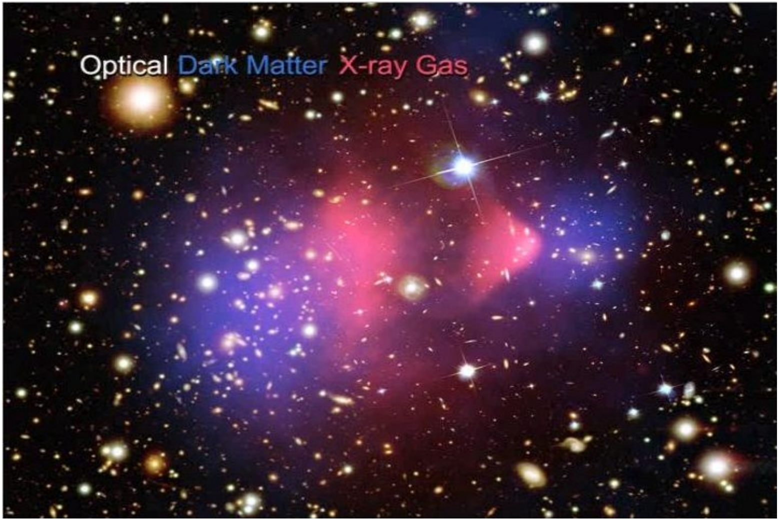
Main characteristics of lensing

- sensitive to matter of all kinds - dark matter + baryonic matter in any form - molecular, atomic, ionized
- bending of light in GR is wavelength independent - can be observed from optical to radio.

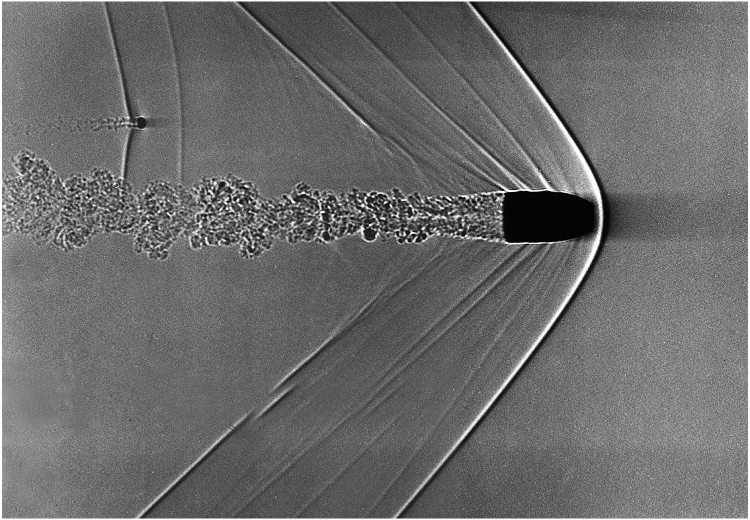
Mass model for a cluster



The bullet cluster



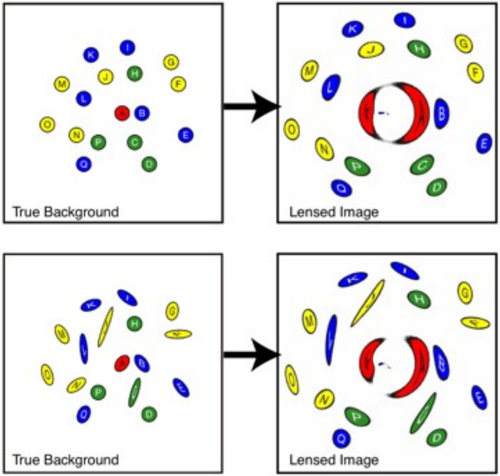
Bullet shock



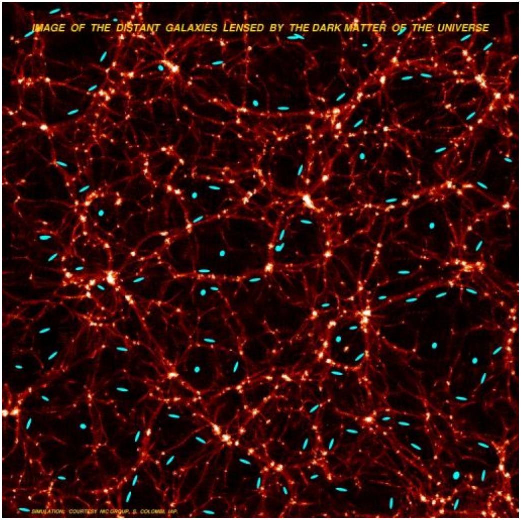
difference between weak and strong lensing

- weak lensing statistical in nature - we look for distortions in shape that affect the average shape of galaxies. Probe large scale structure of very large scales - 0.1 - 10 GPc.

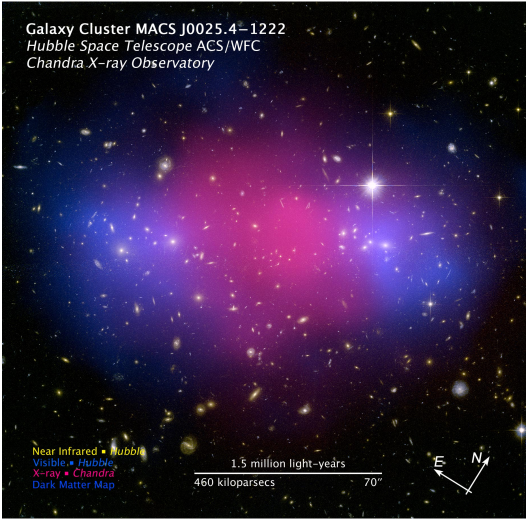
Why is weak lensing statistical?



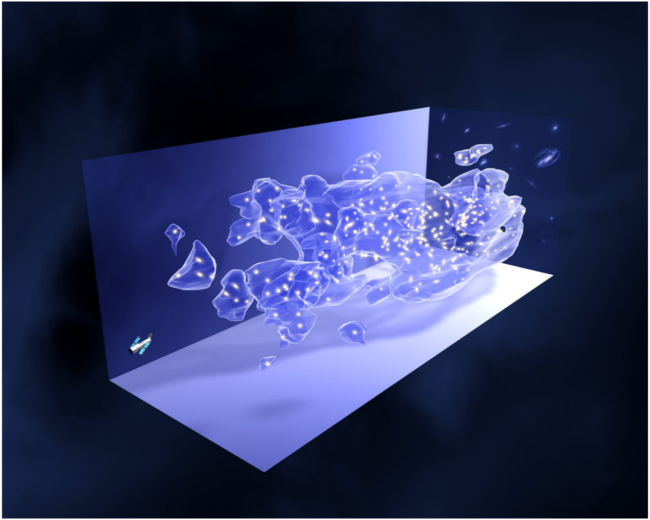
Weak lensing by large scale structure



Does weak lensing really work?



COSMOS survey mass model



Weak lensing for cosmology

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- lensing of diffuse radiation - CMB, 21 cm
- lensing so far has mostly been done in optical. Why? Can also be done in done in radio (with SKA).

How does starlight from 10^{11} stars add up to form galaxy light?

If you want to construct a galaxy spectrum by summing up the spectra of stars what do you need to know?

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- dust - attenuation needs to be modeled.

After that, it is just arithmetic to get the galaxy spectrum