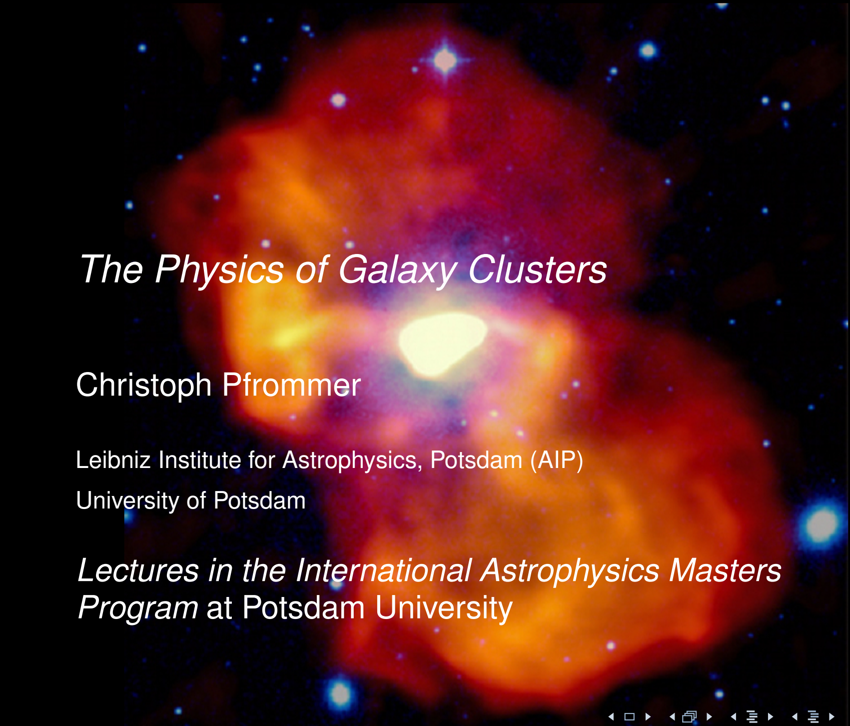

The Physics of Galaxy Clusters

Christoph Pfrommer

Leibniz Institute for Astrophysics, Potsdam (AIP)
University of Potsdam

Lectures in the International Astrophysics Masters Program at Potsdam University

The Physics of Galaxy Clusters

Modus operandi

- I provide you with a full set of lecture notes, freely available at: `https://pages.aip.de/pfrommer/Lectures/galaxy_clusters.html`
- weekly reading assignments, which help you to prepare the class for the upcoming week
- $\sim$10-12 questions about the reading assignment: answers to be handed in every Tuesday at noon

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- exercise sheet with order-of-magnitude estimates, derivations, some problems: due on Tuesday every second week at noon
- in-person lecture every week: derivations and discussions about the material that you prepared

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- in-person lecture every week: derivations and discussions about the material that you prepared
- this won't be a 90-min class the way I would have normally taught it, but rather interactive sessions where
  - **you** can ask questions
  - **we** discuss the concepts of the lectures
  - **we** do order of magnitude physics

- ***Contact:*** `cpfrommer@aip.de`
- ***Literature:*** lecture notes on lecture web page
- ***Background:***
  cosmology part from *Galaxies & Cosmology* useful but not required
- ***Credits:*** 50% of weekly questions and 50% of exercises, oral exam after the course
- ***Success:***
  talk to your fellow students and discuss! Connect online and in real life!

The Physics of Galaxy Clusters

Outline of the lectures

- ***Overview***
- ***Evolution of the dark component***
- ***Evolution of the baryonic component***
- ***Cluster physics informed by different observables***

The Physics of Galaxy Clusters

Outline of the lectures

- ***Overview***
  - What is a galaxy cluster?
  - Why are clusters interesting?
- ***Evolution of the dark component***
  - When, where, and how do clusters form?
  - How many clusters are there?
  - Structure of a cluster?
- ***Evolution of the baryonic component***
  - Non-radiative physics
  - Radiative physics
  - Non-thermal processes
- ***Cluster physics informed by different observables***
  - Optical, X-rays, Sunyaev-Zel'dovich effect, radio

The Physics of Galaxy Clusters

My own motivation to study galaxy clusters

- ***Fascinating science***
    - clusters are largest collapsed objects in the universe
    - clusters are extremely rare: opportunity to study large-scale structure, dark energy and dark matter
    - clusters reveal rich astrophysics: laboratories for physics, including plasma processes to collisionless dynamics

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  - we will assemble a cluster by starting simple and adding consecutively more complex physics

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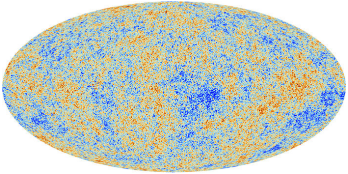
- ***Plan of the lectures***
  - start with overview today and next week
  - we will assemble a cluster by starting simple and adding consecutively more complex physics
- ***Main take-away points***
  - theoretical astrophysics connected to multi-frequency observations
  - order of magnitude physics

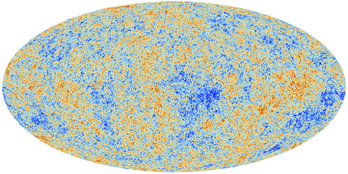
Cosmological structure formation



ESA/Planck Collaboration (2013)

- small fluctuations in cosmic microwave background are initial conditions for structure formation

Cosmological structure formation

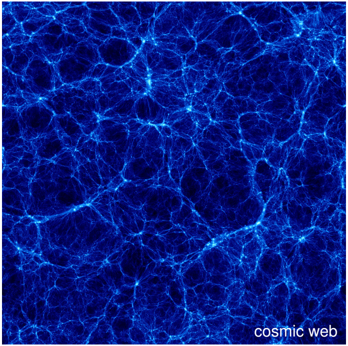


ESA/Planck Collaboration (2013)

dropping pebbles into the pond generates expanding waves that interfere with each other

- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves

Cosmological structure formation



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- cosmic matter assembles in the "cosmic web" through gravitational instability
- galaxies form as "beats on a string" along the cosmic filaments
- galaxy clusters form at the knots of the cosmic web by mergers of galaxies and galaxy groups

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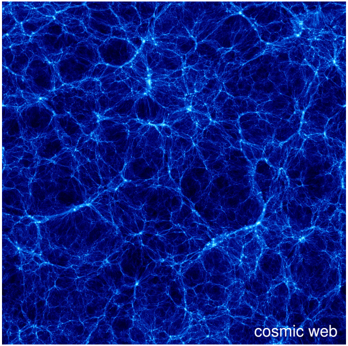

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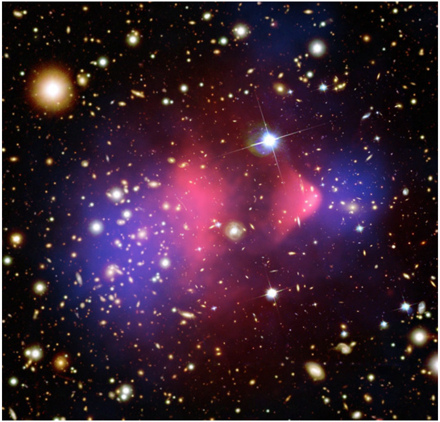
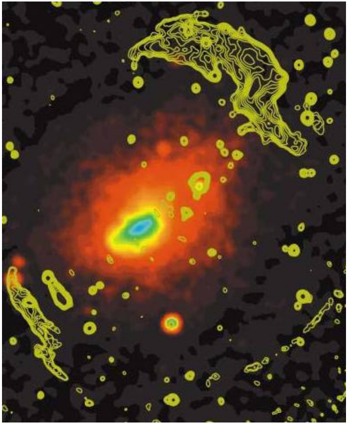
Cluster mergers: *the* most energetic cosmic events



1E 0657-56 (“Bullet cluster”)

(X-ray: NASA/CXC/CfA/Markevitch; Optical: NASA/STScl; Magellan/U Arizona/Clowe; Lensing: NASA/STScl; ESO WFI; Magellan/U Arizona/Clowe)



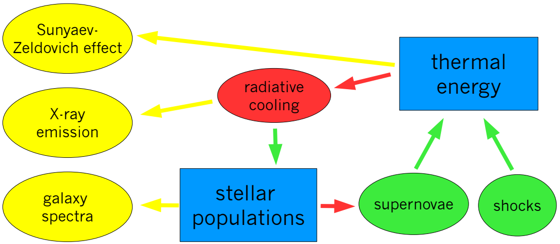
Abell 3667

(radio: Johnston-Hollitt; X-ray: ROSAT/PSPC)

Cosmological simulations – flowchart

Cluster observables:

Physical processes in clusters:



Sunyaev-Zeldovich effect

X-ray emission

galaxy spectra

radiative cooling

thermal energy

stellar populations

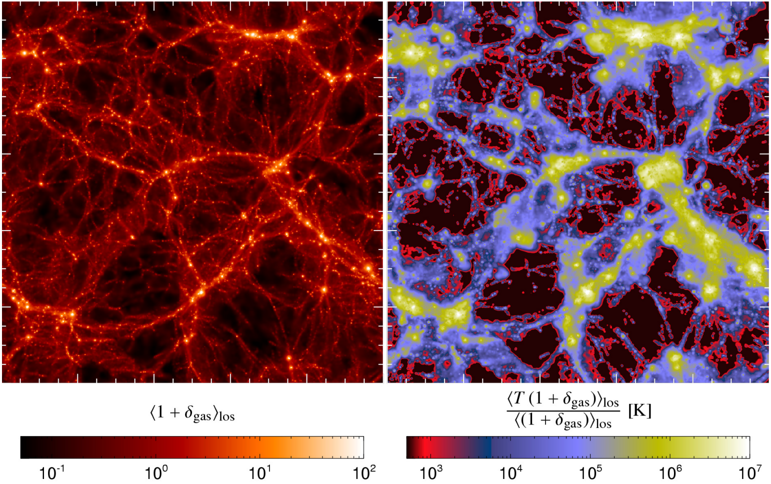
supernovae

shocks

CP, Enßlin, Springel (2008)

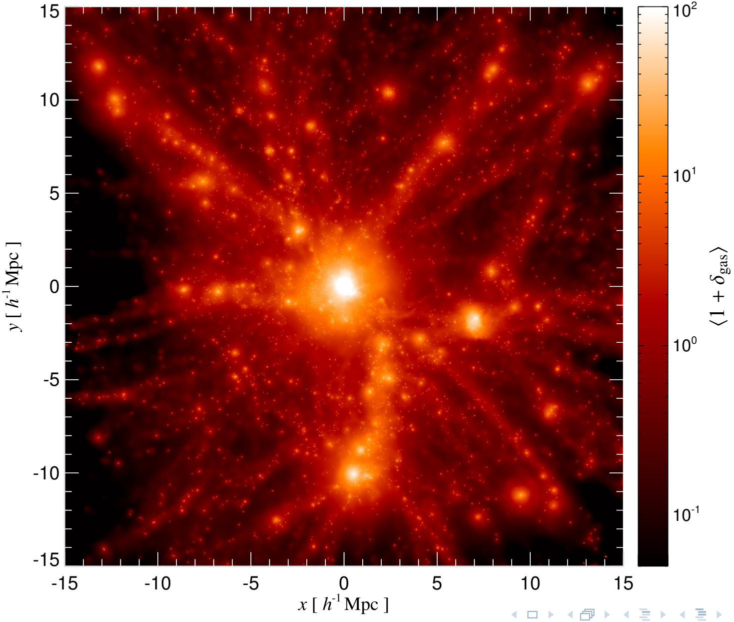
loss processes
gain processes
observables
populations

The structure of our Universe



The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intergalactic medium (CP+ 2006).

Cosmological cluster simulation: gas density



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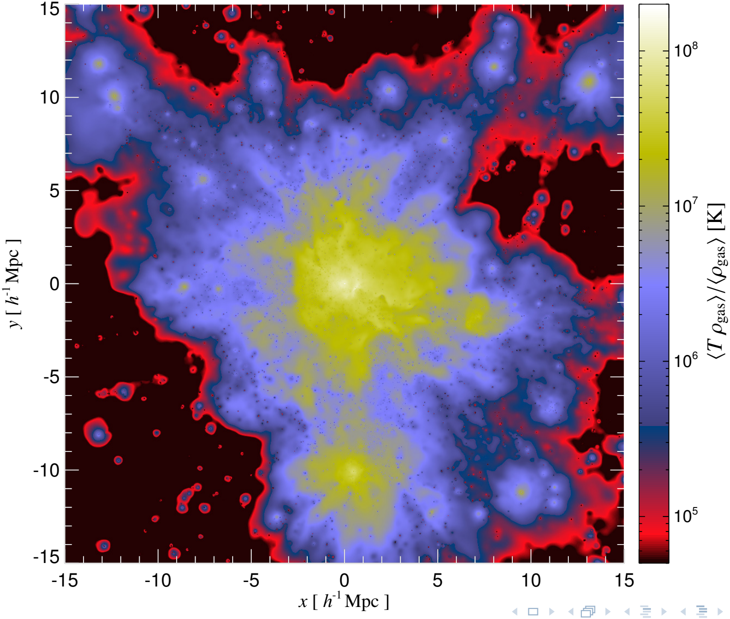
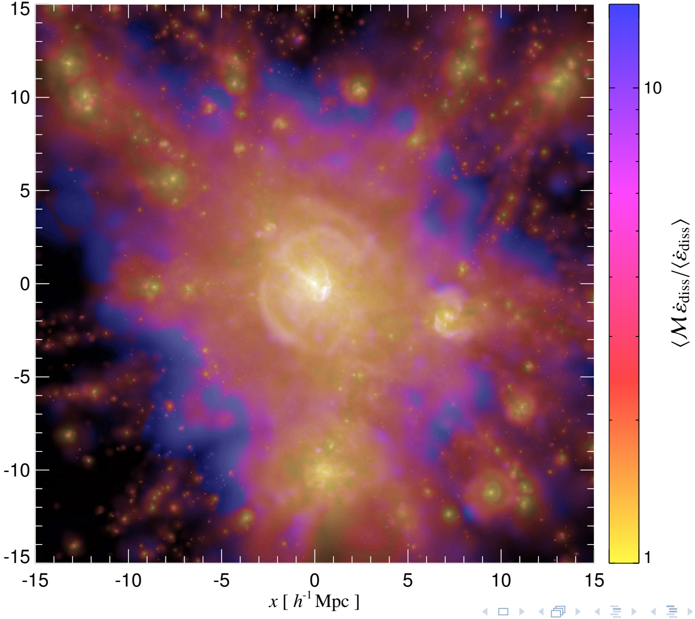
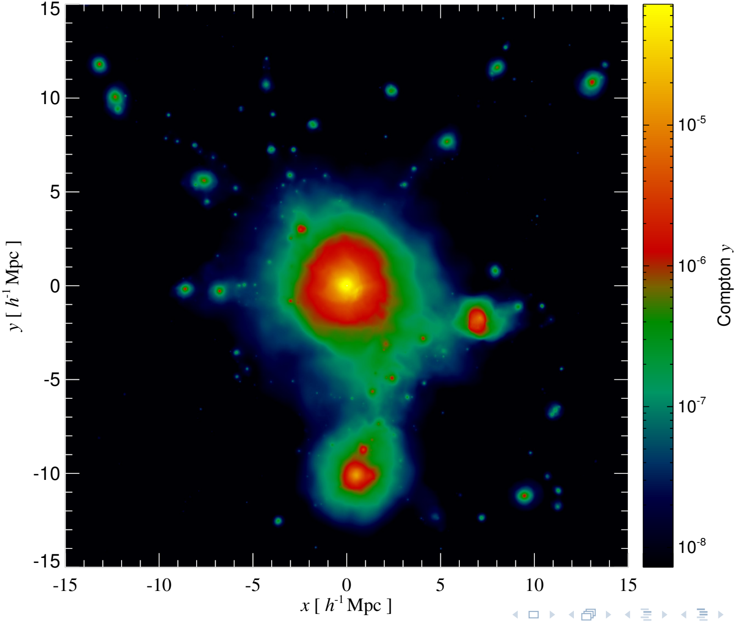
Mass weighted temperature



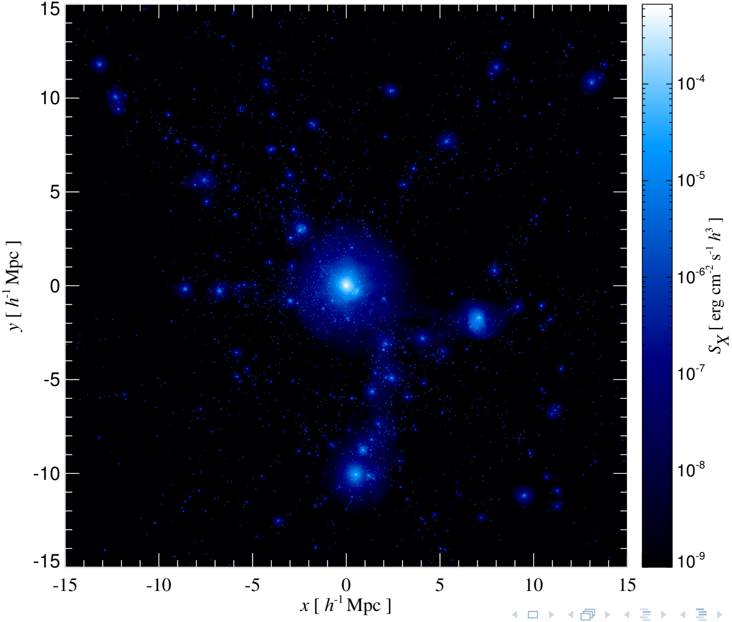
Shock strengths weighted by dissipated energy



Sunyaev-Zel'dovich effect: integrated thermal pressure



Thermal X-ray emission: gas density squared



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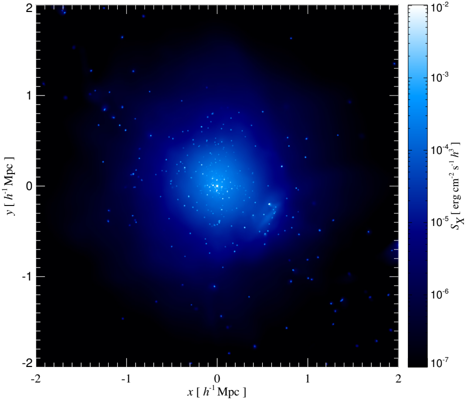
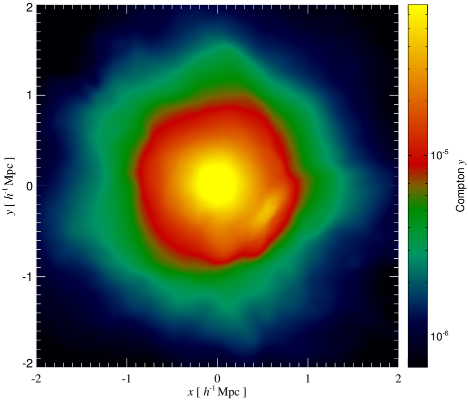
Zooming on the cluster: thermal cluster gas



Thermal bremsstrahlung emission,

merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_\odot / h$



Sunyaev-Zel'dovich effect,

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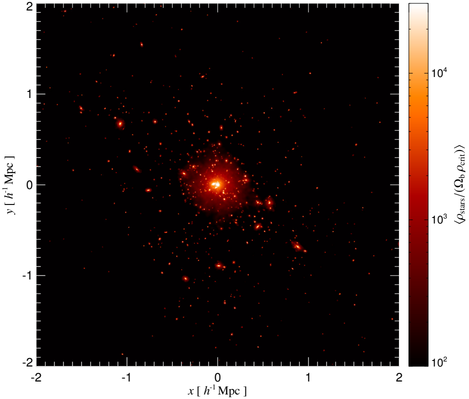
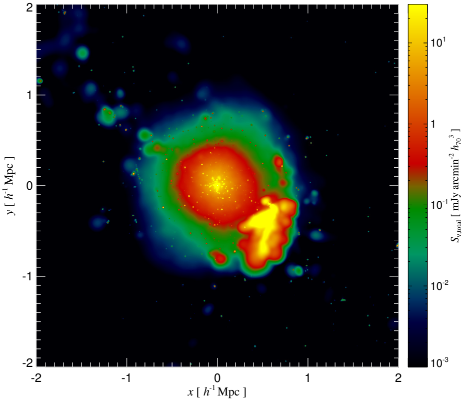
Zooming on the cluster: optical vs. radio synchrotron



Stellar mass density (“cluster galaxies”),

merging cluster, $M_\mathrm{vir} \simeq 10^{15} M_\odot/h$



Radio halo and relic emission,

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Order of magnitude physics

- cgs system of units: cm, gram, second

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- *charge:* balancing electron rest mass and potential energy, $\dfrac{e^2}{r_0} = m_\mathrm{e} c^2$ $\quad 1\,\mathrm{esu} = 1\mathrm{erg}^{1/2}\,\mathrm{cm}^{1/2} = 1\mathrm{cm}^{3/2}\mathrm{g}^{1/2}\mathrm{s}^{-1}$

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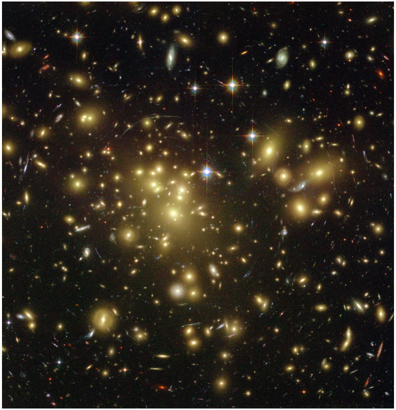
  defines classical electron radius:

  $$r_0 = \frac{e^2}{m_\mathrm{e} c^2} \approx \frac{(4.8\times 10^{-10})^2\mathrm{cm}^3\mathrm{g}}{10^{-27}\mathrm{g}10^{21}\mathrm{cm}^2\mathrm{s}^{-2}\mathrm{s}^2} \approx \frac{2.3\times 10^{-19}}{10^{-6}}\mathrm{cm} \approx 3\times 10^{-13}\,\mathrm{cm}$$

Galaxy clusters: optical window – 1



- rich galaxy clusters have $\sim 10^3$ galaxies
- galaxies have Gaussian velocity distribution with a dispersion $\sigma_v = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \approx 1200\,\mathrm{km\,s}^{-1}$
- the typical cluster radius is

$$r_{\mathrm{cl}} \approx 3\ \mathrm{Mpc} \approx 10^7\ \mathrm{lyr} \approx 10^{25}\ \mathrm{cm}$$

- this defines a dynamical cluster timescale, $t \approx r_{\mathrm{cl}}/\sigma_v \approx 2$ Gyr

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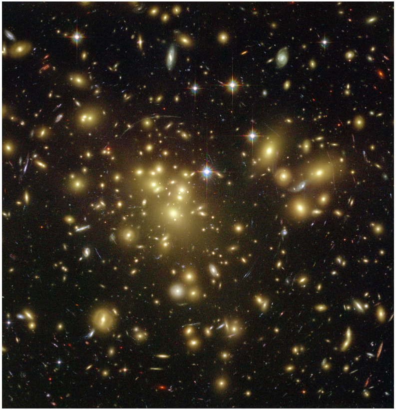
Galaxy clusters: optical window – 2

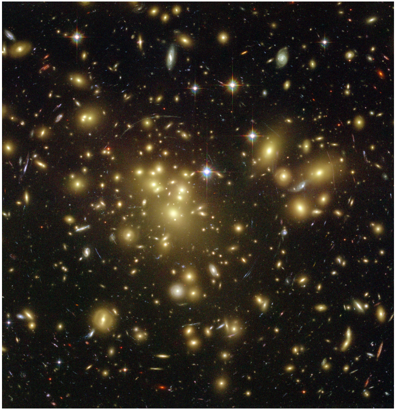


- assuming that the cluster is a closed system in dynamical equilibrium
- virial theorem relates the kinetic energy, E_{kin}, of a galaxy of mass M_{gal} to its potential energy, E_{pot},

$$\begin{aligned} 2E_{\text{kin}} + E_{\text{pot}} &= 0, \\ M_{\text{gal}}\sigma_v^2 - \frac{G M_{\text{cl}} M_{\text{gal}}}{r_{\text{cl}}} &= 0, \end{aligned}$$

G is Newtons gravitational constant

Galaxy clusters: optical window – 2



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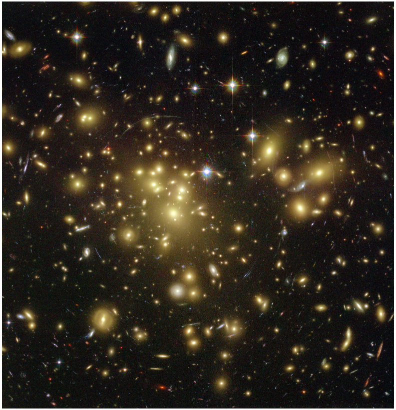
  G is Newtons gravitational constant
- gravitating cluster mass, $M_{\rm cl}$:

$$\begin{aligned} M_{\rm cl} &= \frac{r_{\rm cl}\sigma_v^2}{G} \\ &\approx \frac{10^{25}\,\mathrm{cm}\; 1.4\times10^{16}\,\mathrm{cm}^2\mathrm{s}^{-2}}{7\times10^{-8}\,\mathrm{erg\;cm\;g}^{-2}} \\ &\approx 2\times10^{48}\,\mathrm{g} \approx 10^{15}\,\mathrm{M}_\odot \end{aligned}$$

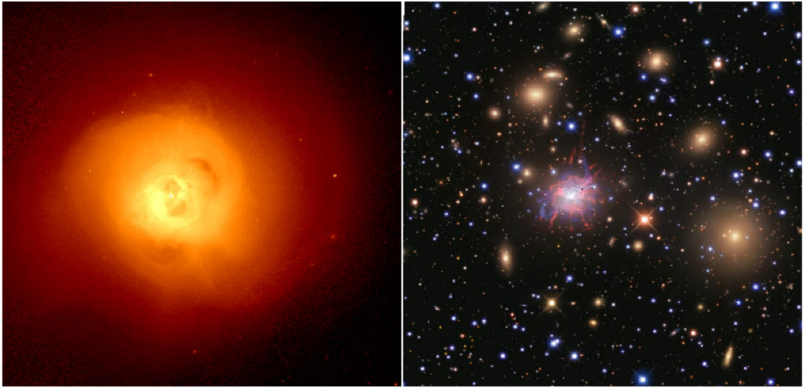
Galaxy clusters: optical window – 3



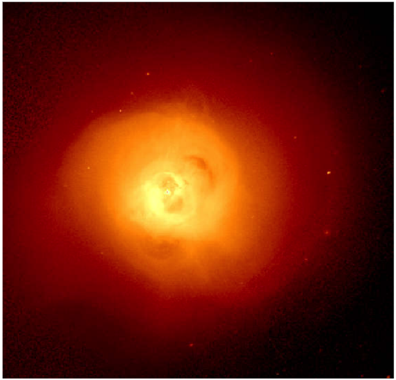
- $M_{\rm cl}$ sources the high velocity dispersion of galaxies
- a typical mass range for clusters is $(10^{14} \dots 10^{15})\,M_\odot$
- however, by adding up the all the luminous stellar mass within the galaxies, we only get $M_* \approx M_{\rm cl}/50$
- this discrepancy of the gravitating and luminous mass in galaxy clusters was already noted by Fritz Zwicky in the 1930s:
  he postulated the existence of dark matter more than 80 years ago!
- to be precise, back then the “dark matter” could have been baryonic in form of compact objects (such as planets) or in form of diffuse gas

Galaxy clusters: X-ray vs. optical window

Perseus galaxy cluster

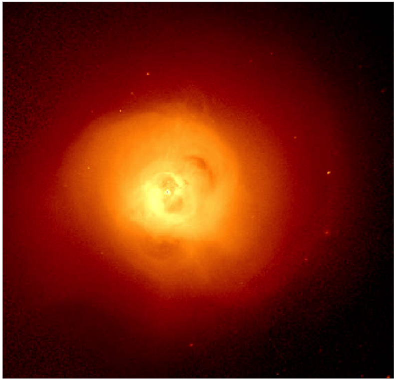


Galaxy clusters: X-ray window – 1



- 1970s: X-ray astronomy that galaxy clusters are among the brightest X-ray sources
- improved angular resolution: the entire galaxy cluster glows in X-rays, filling in the volume in between the galaxies
- which emission process produces X-rays?

Galaxy clusters: X-ray window – 1



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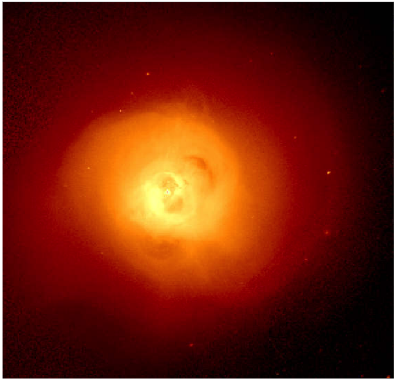
1. bremsstrahlung emission of hot thermal electrons,
2. line emission from recombination of atoms, or
3. inverse Compton emission by relativistic electrons interacting with low-energy photons: electrons cool by upscattering these photons into the X-ray regime ⇒ power-law X-ray spectra

Galaxy clusters: X-ray window – 2



- observed X-ray spectrum is flat with an exponential decline ⇒ thermal bremsstrahlung emission
- bremsstrahlung emissivity scales as $j_X \propto n_e n_i \sqrt{T_e}$, where T_e, n_e, and n_i are the electron temperature, density and the ion density
- additionally, spectral lines

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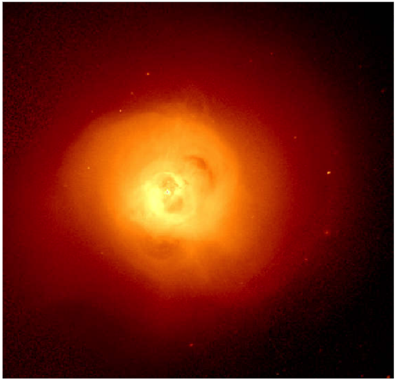

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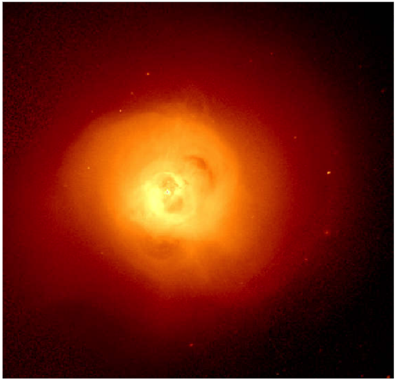
- amount of X-rays and location of the exponential break (as well as individual lines) characterize the plasma:

$$n \approx (10^{-4} \dots 10^{-3})\,\mathrm{cm}^{-3}$$

$$T \approx (10^{7} \dots 10^{8})\,\mathrm{K}$$

⇒ hot, dilute, and thermal gas

Galaxy clusters: X-ray window – 3

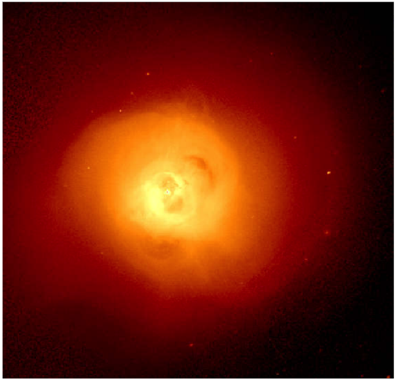


- we talk about gas temperature in terms of particle energies,

$$\begin{aligned} k_\mathrm{B} T &\approx (1 \dots 10)\,\mathrm{keV} \\ &= (10^3 \dots 10^4)\,\mathrm{eV} \end{aligned}$$

- most elements are fully ionized, except for highly-ionized iron, e.g., hydrogen-like iron (iron nucleus with one bound electron, Fe XXVI)

Galaxy clusters: X-ray window – 3



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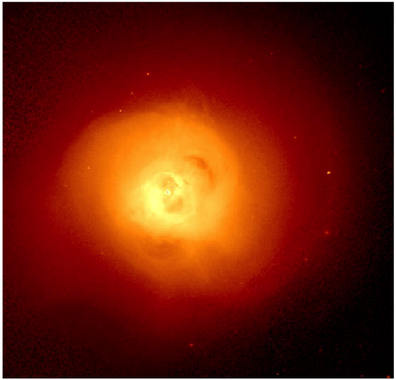
- the transition energy of such highly ionized iron is

$$\text{Fe XXV}: \quad h\nu \approx Z(Z-1)\,\mathrm{Ry} = 26 \times 25 \times 13.6\,\mathrm{eV} \approx 8.8\,\mathrm{keV}$$
$$\text{Fe XXVI}: \quad h\nu \approx Z^2\,\mathrm{Ry} = 26^2 \times 13.6\,\mathrm{eV} \approx 9\,\mathrm{keV},$$

i.e., the higher the temperature, the higher the ionization state

Galaxy clusters: X-ray window – 4



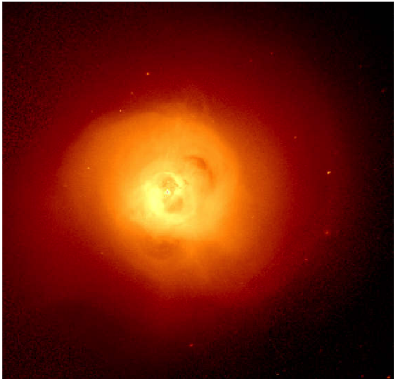
- assuming that hot gas with energy E_{th} is in hydrostatic equilibrium with the cluster potential, we have

$$E_{\mathrm{th}} = E_{\mathrm{pot}},$$

$$\frac{3}{2} k_{\mathrm{B}} T = \mu m_{\mathrm{p}} \frac{G M_{\mathrm{cl}}}{r_{\mathrm{cl}}},$$

m_{p} is the proton mass and $\mu = 4/(5X+3) \approx 0.6$ is mean molecular weight with $X = 0.24$

Galaxy clusters: X-ray window – 4



- assuming that hot gas with energy $E_{\rm th}$ is in hydrostatic equilibrium with the cluster potential, we have

$$E_{\rm th} = E_{\rm pot},$$

$$\frac{3}{2} k_{\rm B} T = \mu m_{\rm p} \frac{G M_{\rm cl}}{r_{\rm cl}},$$

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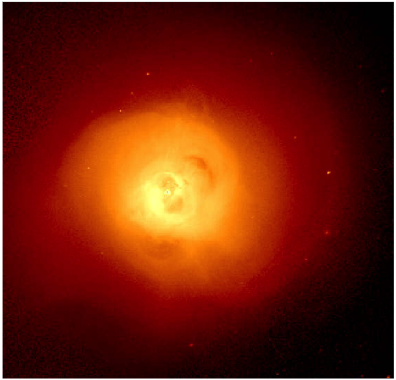
- solving for the gravitating cluster mass with $k_{\rm B} T = 6$ keV yields

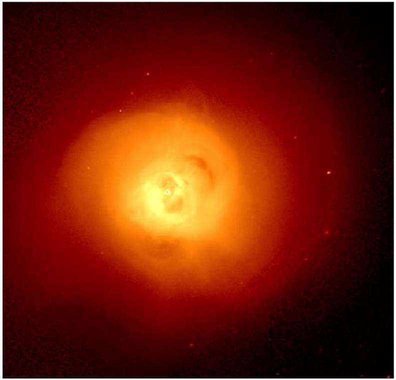
$$M_{\rm cl} = \frac{3}{2} \frac{k_{\rm B} T r_{\rm cl}}{\mu m_{\rm p} G} \approx \frac{1.5 \times 10^{-8}\,\mathrm{erg}\,10^{25}\,\mathrm{cm}}{0.6 \times 1.7 \times 10^{-24}\,\mathrm{g}\,7 \times 10^{-8}\,\mathrm{erg\,cm\,g^{-2}}}$$
$$\approx 2 \times 10^{48}\,\mathrm{g} \approx 10^{15}\,\mathrm{M}_\odot.$$

Galaxy clusters: X-ray window – 5



- resolved X-ray imaging of a galaxy cluster produces an X-ray surface brightness map
- deprojection enables us to back out the mass density profile
- integrating over the cluster volume yields the total gas mass, $M_{\mathrm{gas}} \approx M_{\mathrm{cl}}/7$

Galaxy clusters: X-ray window – 5



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- deprojection enables us to back out the mass density profile
- integrating over the cluster volume yields the total gas mass, $M_{\mathrm{gas}} \approx M_{\mathrm{cl}}/7$
- we found some of the matter that was “dark” in the optical by looking at a different waveband
- the rest cannot be directly seen in any other waveband, only indirectly through its gravitational interaction $\Rightarrow$ “dark matter”
- it dominates the total cluster mass and is mostly responsible for the gravitational cluster potential

Galaxy clusters: inventory

- We can now summarize an inventory of cluster mass

$M_* \approx \;\; 2\% :$	stars in galaxies
$M_{\text{gas}} \approx 13\% :$	hot gas ($1 - 10\,\text{keV}$)
$M_{\text{dm}} \approx 85\% :$	dark matter

- the value of the baryon fraction in a cluster of $f_{\text{b,clus}} \approx 0.15$ is somewhat smaller than the cosmic mean of $f_{\text{b,clus}} \approx 0.166$

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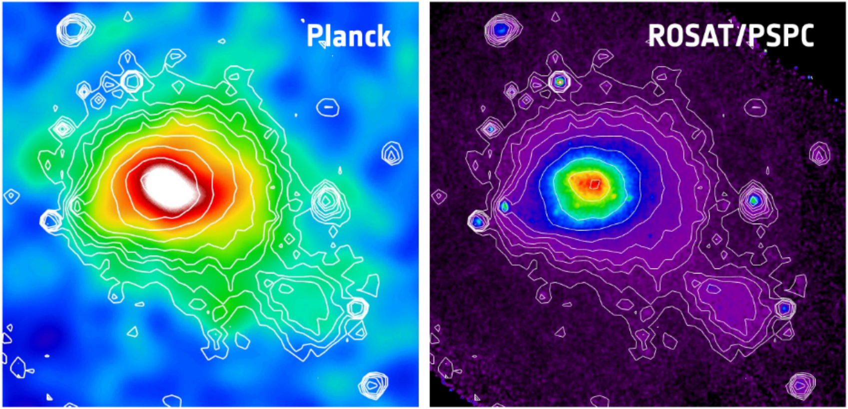
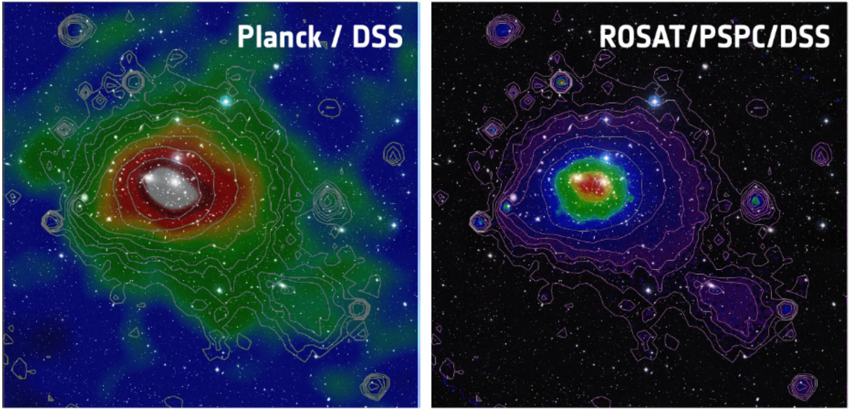
- the value of the baryon fraction in a cluster of $f_{\rm b,clus} \approx 0.15$ is somewhat smaller than the cosmic mean of $f_{\rm b,clus} \approx 0.166$
- this points to interesting physics, including non-gravitational energy input from supernovae and super-massive black holes
- interestingly, $f_{\rm b,clus}$ declines toward less massive clusters in which those feedback processes have a comparably larger impact because of the shallower cluster potential

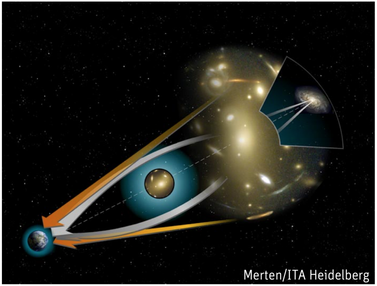
Coma galaxy cluster: Sunyaev-Zel'dovich vs. X-rays



Coma galaxy cluster: SZE/X-rays vs. optical



Gravitational lensing: idea



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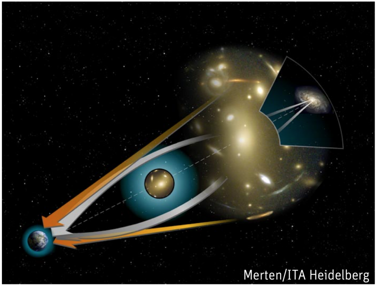
Gravitational lensing: idea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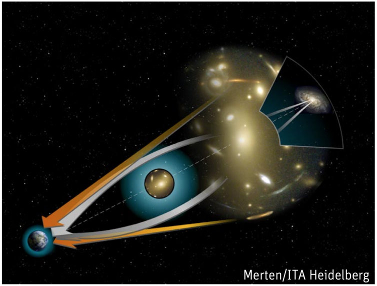
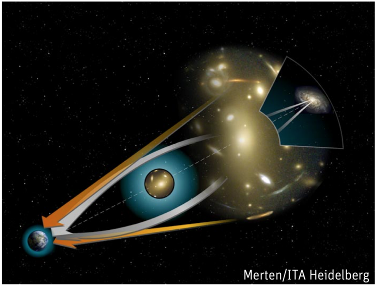
- according to general relativity, light travels on geodesics (straightest possible lines) through curved space time

Gravitational lensing: idea



- according to general relativity, light travels on geodesics (straightest possible lines) through curved space time
- mass acts as a source of gravity, curving space time at the location of a lensing galaxy cluster ⇒ this causes the light rays to be deflected by the gravitational potential of the lensing object

Gravitational lensing: idea



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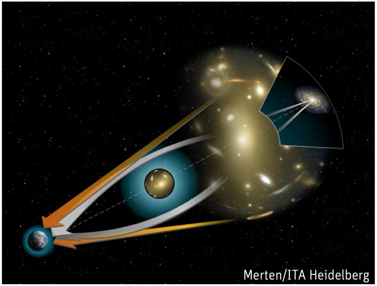
- galaxy clusters (or galaxies) can act as gravitational lenses for galaxies behind them

Gravitational lensing: idea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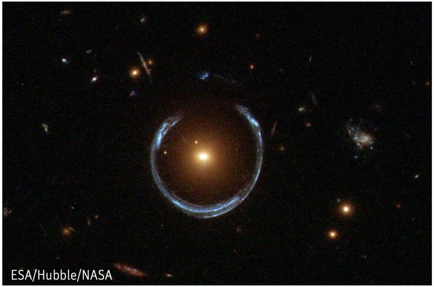
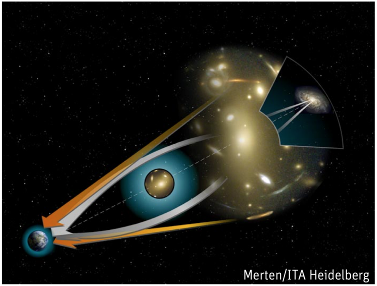
- this causes a single galaxy to be mapped onto multiple images (or even a so-called Einstein ring, provided that we have a very symmetric configuration and a point-like source)

Gravitational lensing: idea



ESA/Hubble/NASA



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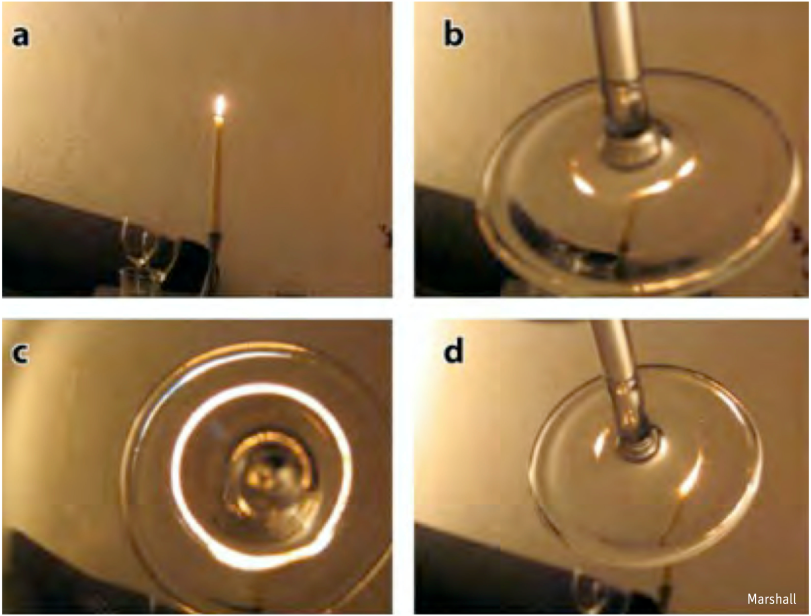
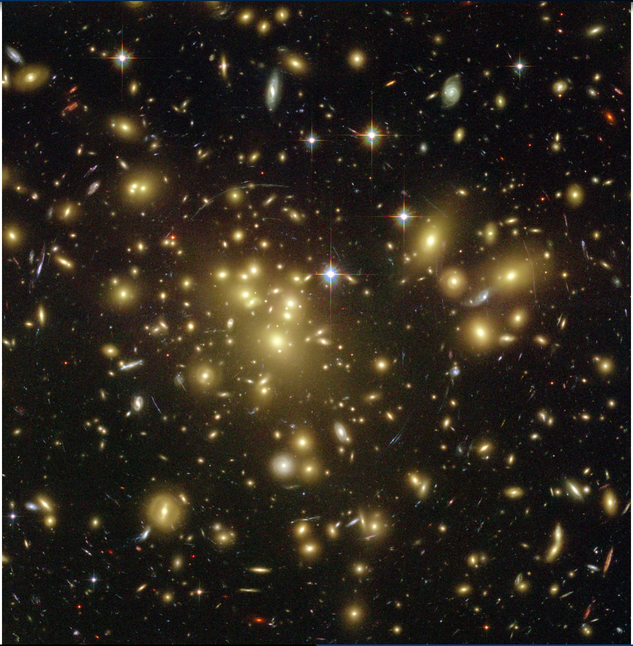
Analogy: light deflection at a wine glass

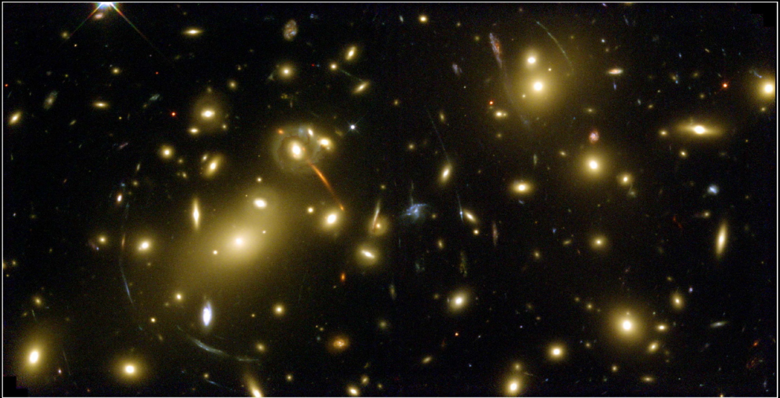


Marshall

Gravitational lensing: Abell 1689



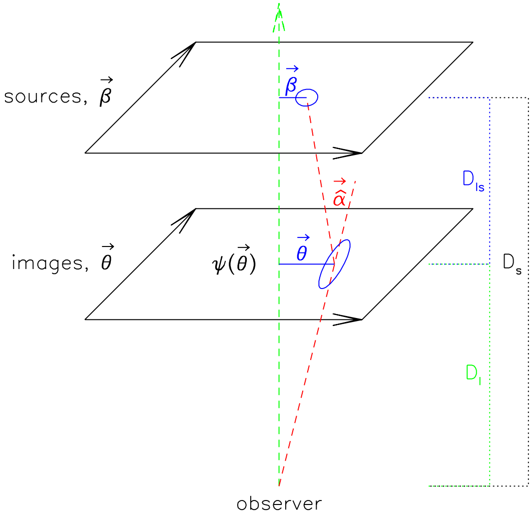
Gravitational lensing: Abell 2218



Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

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

Gravitational lensing: geometry



- D_l is the angular diameter distance to the light-deflecting cluster or galaxy
- D_s is the distance to the source galaxy
- D_{ls} is the angular diameter distance between deflector and source

Gravitational lensing: order of magnitudes

- later, we will derive the Einstein radius θ_E; we state the result and insert some values to estimate the involved angular scales:

$$\begin{aligned}\theta_\mathrm{E} &= \left[\frac{4GM(\theta_\mathrm{E})}{c^2}\,\frac{D_\mathrm{ls}}{D_\mathrm{l}D_\mathrm{s}}\right]^{1/2}\\ &\approx 3''\left(\frac{M}{10^{12}\,M_\odot}\right)^{1/2}\left(\frac{D}{1\,\mathrm{Gpc}}\right)^{-1/2}\quad\text{(galaxy lensing)}\\ &\approx 30''\left(\frac{M}{10^{14}\,M_\odot}\right)^{1/2}\left(\frac{D}{1\,\mathrm{Gpc}}\right)^{-1/2}\quad\text{(cluster lensing),}\end{aligned}$$

where $D = D_\mathrm{l}D_\mathrm{s}/D_\mathrm{ls}$ is the lensing efficiency distance

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&\approx 30'' \left(\frac{M}{10^{14}\,M_\odot}\right)^{1/2}\left(\frac{D}{1\,\mathrm{Gpc}}\right)^{-1/2} \quad \text{(cluster lensing)},
\end{aligned}$$

  where $D = D_\mathrm{l}D_\mathrm{s}/D_\mathrm{ls}$ is the lensing efficiency distance

- in the case of galaxy lensing, the approximation of a point lens is justified whereas for cluster lensing, the size of the lens is much larger than the size of the source

  $\Rightarrow$ requires detailed mass modeling because only the fraction of cluster mass within θ_E contributes to the lensing potential

- $\theta_\mathrm{E} \approx 30''$ corresponds to observed giant (tangential) arcs

Gravitational lensing: two regimes

We distinguish two types of lensing:

- **strong lensing** is sensitive to the projected mass within θ_E and leads to radial arcs that are clearly visible in optical images; in this regime, a source can be imaged onto multiple different images
- **weak lensing** causes weaker distortions of a galaxy image in the tangential direction that cannot be detected on a individual basis because the effect is very small; we need to assume that the orientation of the neighboring galaxies is random and average over an aperture to detect a weak shear signal that is induced by the gravitational tidal field of the cluster lens

Recap of today's lecture

Overview of galaxy clusters: observations and simulations of different observational probes of clusters

- Order of magnitudes
- Optical window: galaxies probe cluster masses; clusters provide a great "magnifying glass" for studying transformational processes of galaxies
- X-ray emission: intracluster plasma probes cluster masses and hydrodynamical flows and instabilities
- Gravitational lensing directly probes cluster potential

The Physics of Galaxy Clusters

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- Sunyaev-Zel’dovich effect
- Relation to the average universe