Lectures on Dark Matter

Guy D. Moore, TU Darmstadt

- Lecture 1: Evidence for Dark Matter
- Lecture 2: WIMP Dark Matter
- Lecture 3: Axion Dark Matter

Nota bene: not "professional" Dark Matter scientist. Current work on axion cosmology, some past work on composite models for WIMP dark matter. My own idiosyncratic view...

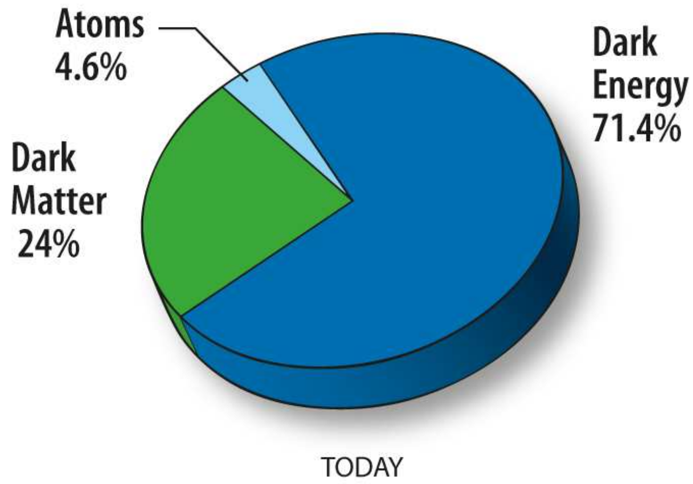
Dark Matter Part I

Evidence for Dark Matter

Guy Moore, TU Darmstadt

- Galaxy clusters
- Microwave Sky
- Galaxy correlation function

Cosmic matter budget



Only 5% “normal” matter

70% “Dark Energy” inferred from expansion history

25% “Dark Matter” inferred from its gravitational effects

We know only 3 things about dark matter:

- it’s matter – it clumps gravitationally
- it’s cold – negligible pressure since $z = 3000$
- it’s dark: negligible interactions with us & itself

You should be skeptical!

Radical departure to say most of Universe's matter is in some form completely different than "us"

Extrordinary claim requires multiple lines of evidence
This lecture will summarize the most compelling arguments.

Missing: galactic rotation curves, Bullet cluster ...

There is a community of people looking for "alternatives," generally ways to modify gravity so DM is not needed.
NO SUCH MODEL WORKS. Some explain one or two phenomena, but there are many phenomena....

History of Science analogy

2500 years ago: How do we know the Earth is a sphere?
People believed it was flat for a good reason:

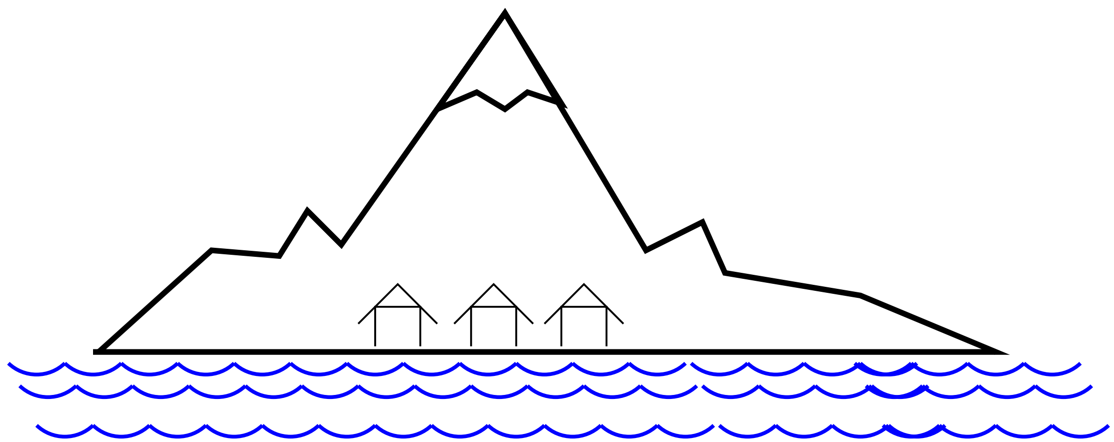
Look out the window! It's flat!

Deeply woven into world view, culture, religion.

One good counterargument is *not enough*:
need several clear arguments to overcome natural suspicion.
Developed by Greeks ~ 2400 years ago.

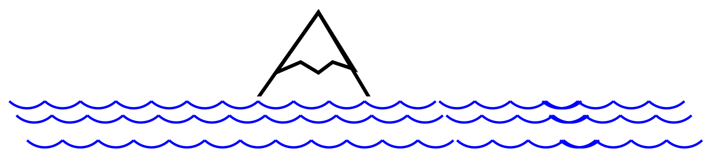
Argument 1: sighting land

Greeks were great sailors. Sighting land: usually a mountain

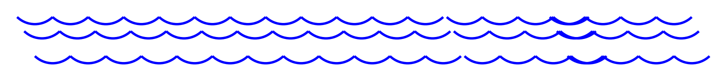


What I expect to see

What I see first:



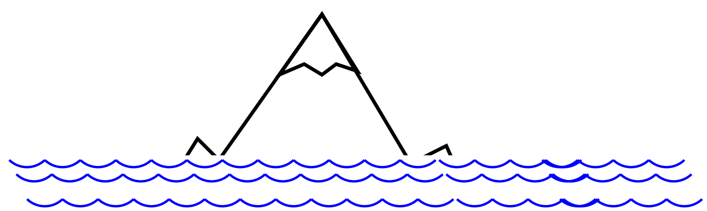
From top of mast



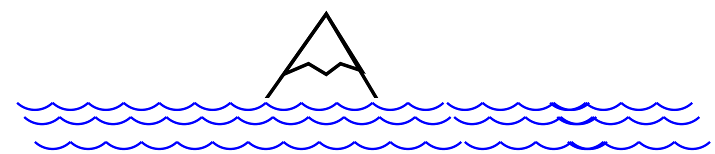
From deck of ship

See only the peak of the mountain, and only when looking from the top of the mast.

What I see as I get closer



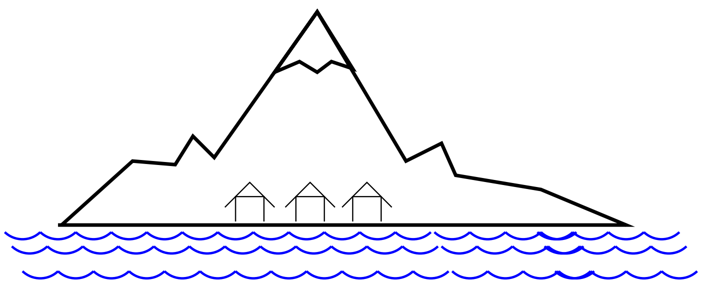
From top of mast



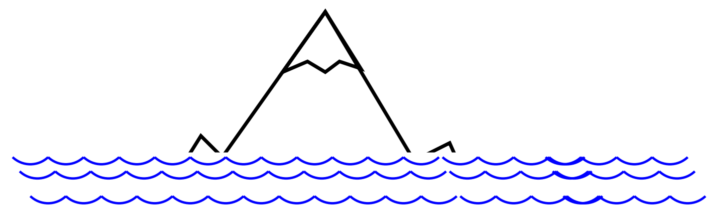
From deck of ship

Mountain appears from peak down, and you see more from the top of the mast than from on deck.

When I get close



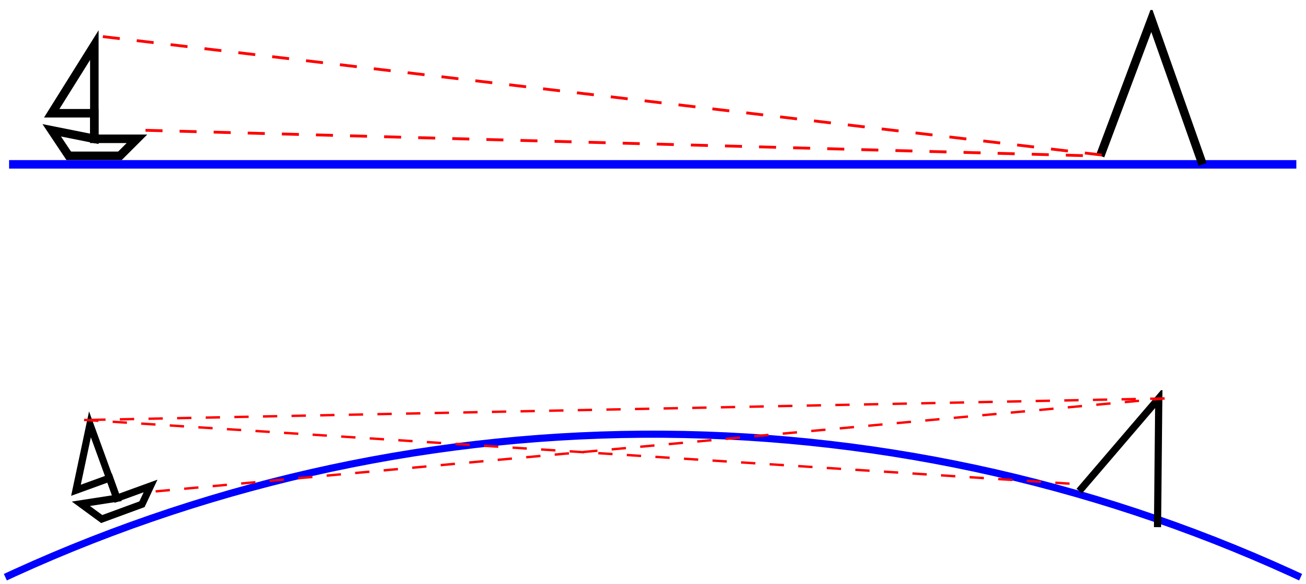
From top of mast



From deck of ship

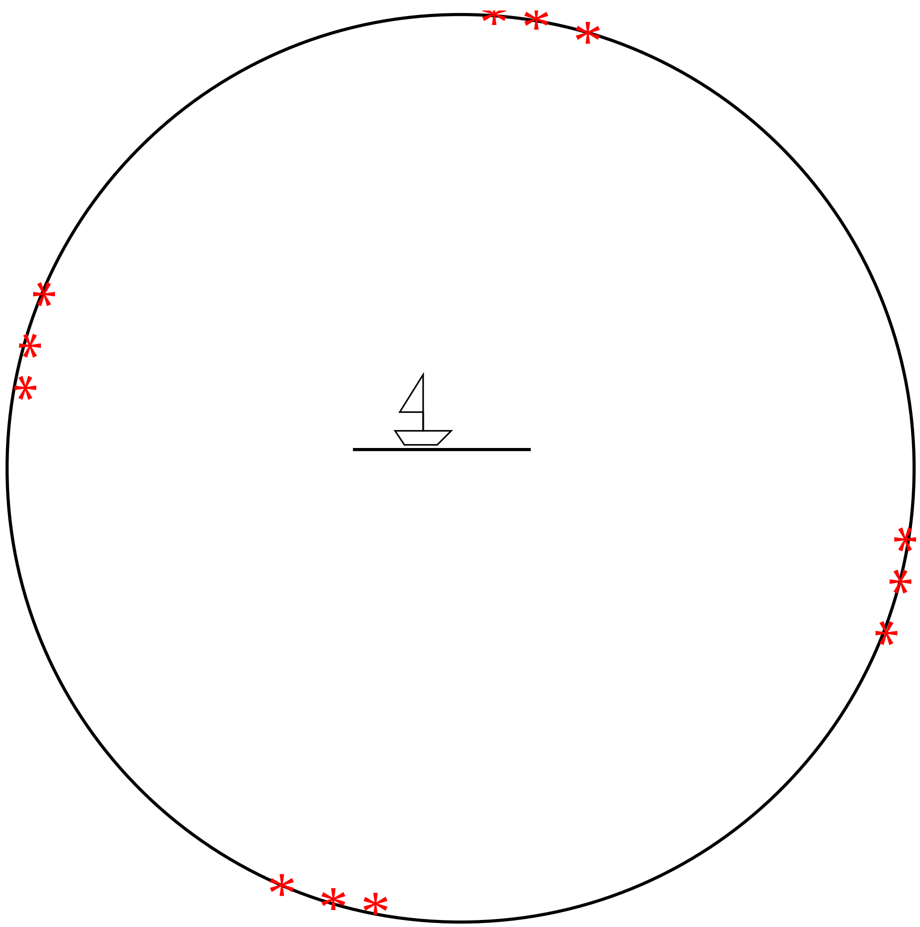
Now I see the whole island, but the houses still hiding from the deck.

Makes sense for sphere but not flat earth



Enough evidence for you or me. But not for the Greeks.

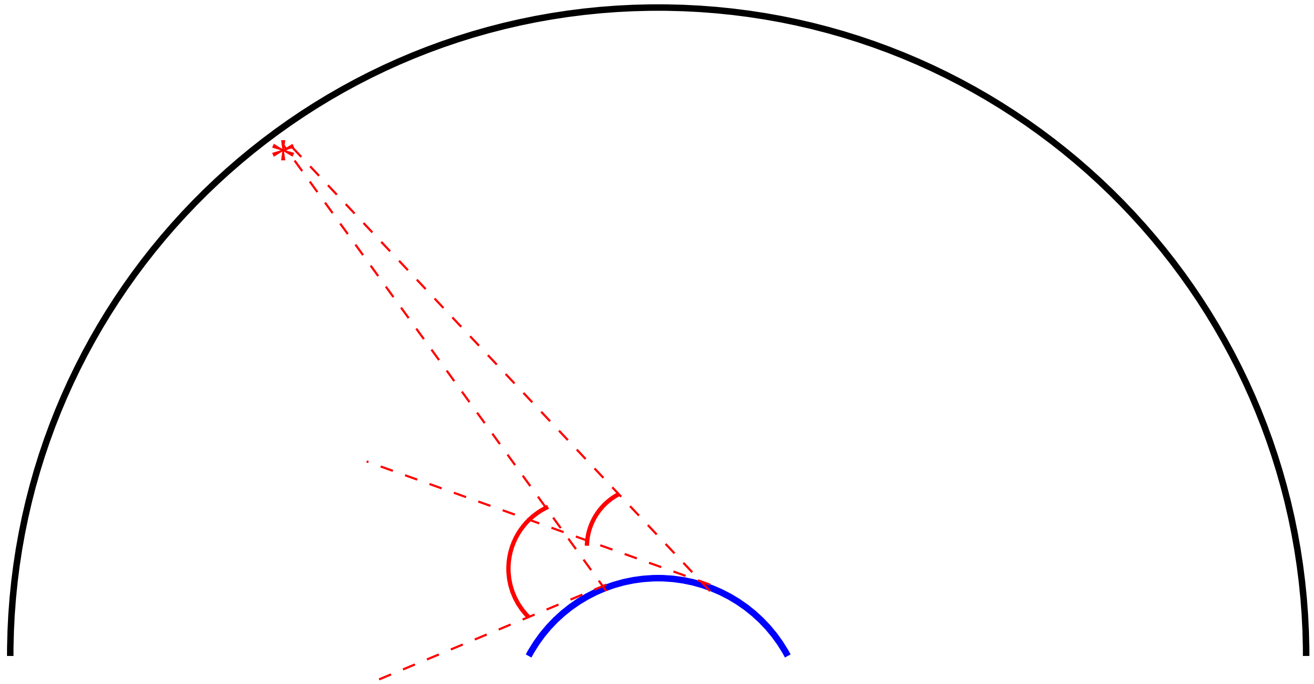
Celestial Sphere



Constellations!
Angles between stars preserved as they move across sky.
Must be on distant celestial sphere

Celestial sphere revolves around Earth or vice versa
Revolves on fixed axis which goes through Polestar.

Now travel to the South



Angles stay exactly same ⇒ Celestial Sphere far away

Polestar sinks in the sky, relative to horizon.

Horizon, not stars, must be changing position!

Third argument

Moon eclipses precisely when moon opposite Sun on Celest. Sphere

Shadow of Earth falls on Moon.

Shadow is always an arc, always same curvature.

Only sphere casts circular arc from any orientation

Having 3 arguments more convincing than one.

Can we do the same for dark matter?

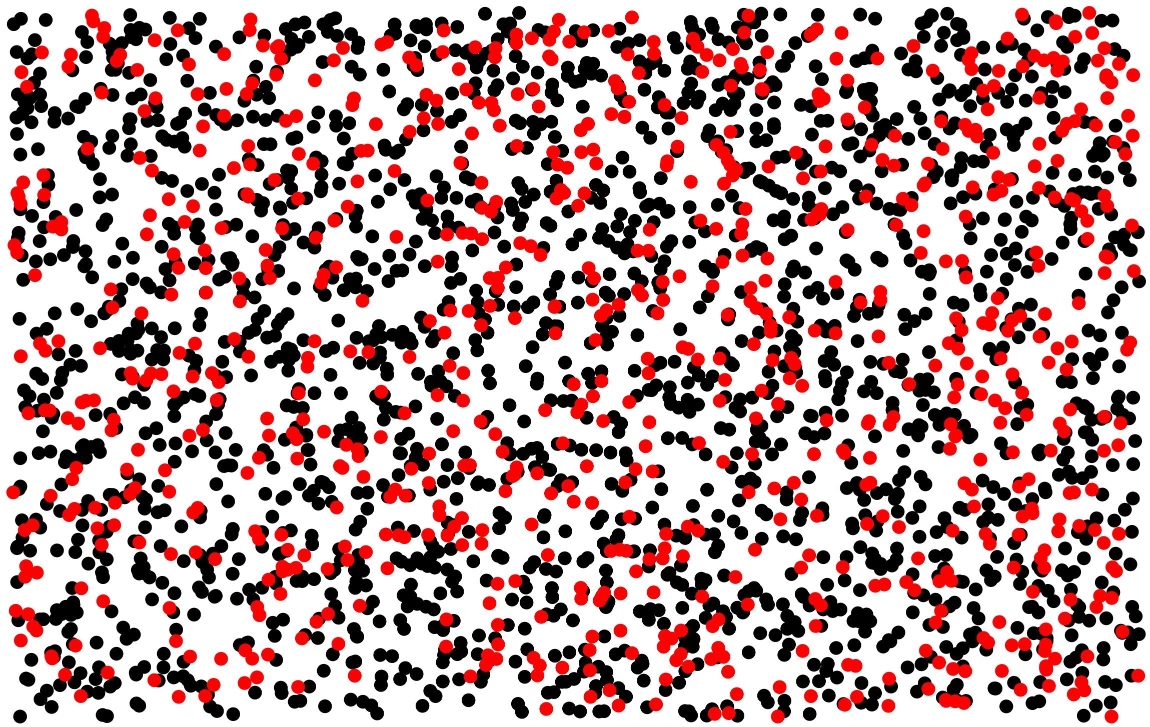
Arguments for Dark Matter

Arguments are of varying quality:

- Galaxy rotation curves: I will skip
- "The Bullet Cluster" I will also skip
- Rich galactic clusters: simple physics, clear answer!
- Microwave sky: lots of complex physics, very precise
- Other modern cosmological probes: show concordance

How would CDM behave?

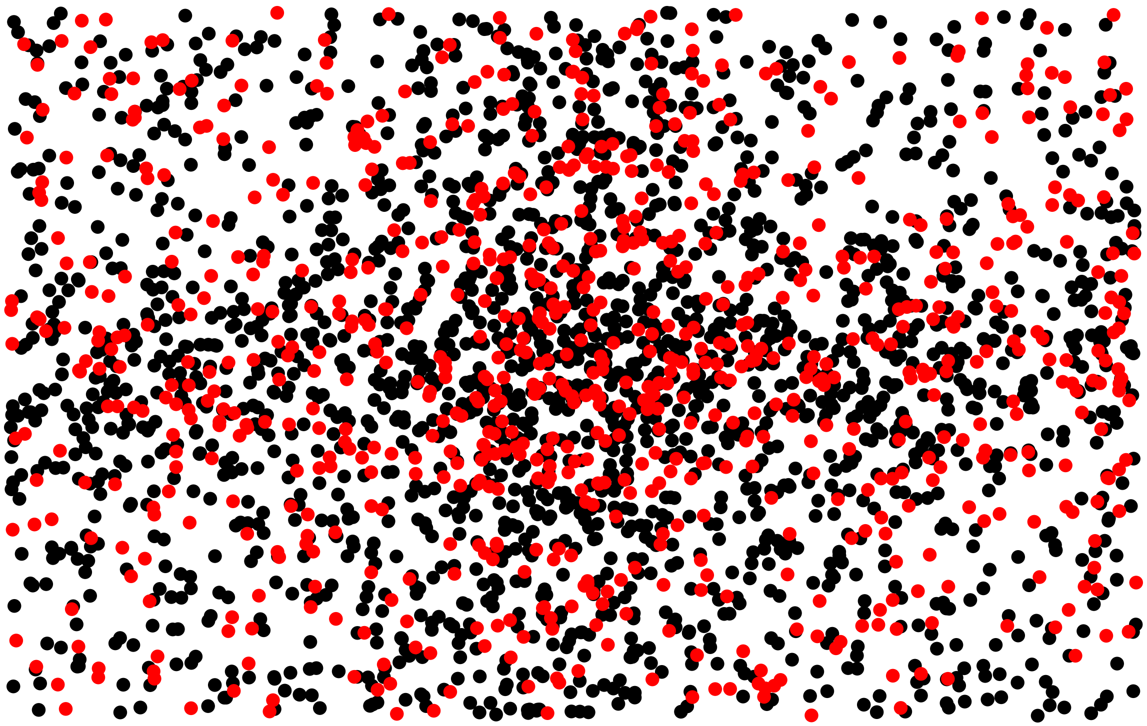
Universe starts with almost uniform mix of CDM and baryons



but some places are overdense

Graviational clumping

Slightly overdense region starts to collapse inward



CDM and baryons both clump equally (Gravity!)

Radiation and interactions

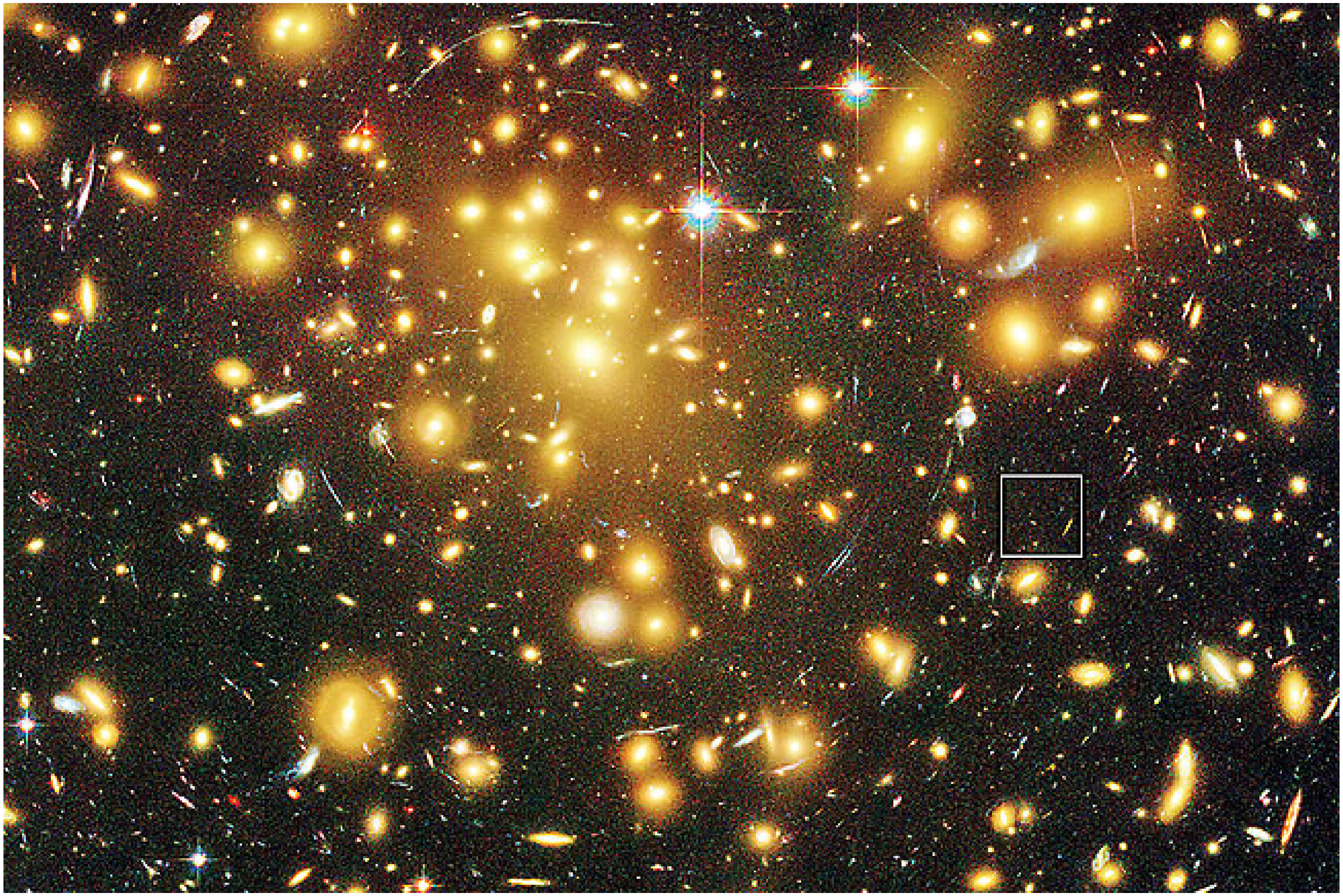
Baryons can lose energy by radiating. Sink to middle

Smaller and more overdense–bigger the effect.

- Stars: complete. Star is only baryons
- Galaxies: large. bulge and disk are baryonic
- Large clusters: small. Physics gravity dominated
- Linear structure: radiation plays no role

Clusters and LSS are good places to look.

Rich galaxy clusters

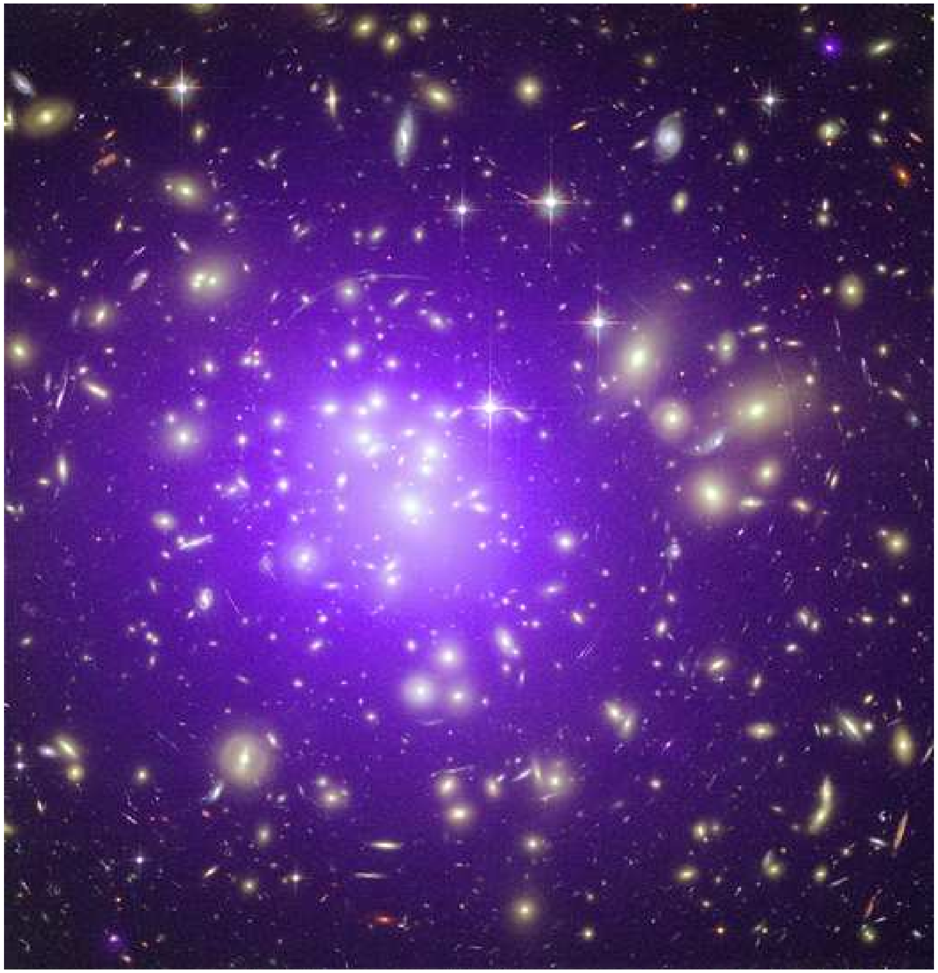


Galaxy Clusters

- 100s to 1000s of galaxies, roughly spherical distrib.
- Held together by gravity
- Dynamical timescale short compared to 10Gyr: must be supported hydrostatically
- Full of $e^- p^+$ plasma: outweighs Galaxies
- Many on the sky $\Rightarrow$ Statistical inference

We will try to weigh the plasma, and the galaxy cluster.
Ratio $M/M_{\rm gas+galaxies} = (M_{DM} + M_B)/M_B$

X-ray appearance



Plasma shines in X-rays

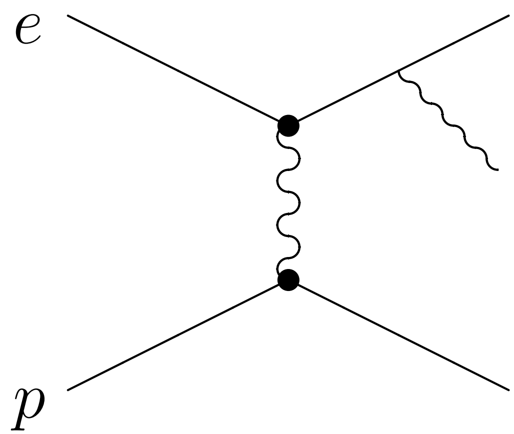
Intensity: density

Spectrum: temperature

X-ray studies–the idea

Mohr et al ApJ 517, 627; Vikhlinin et al astro-ph/0507092; Allen et al astro-ph/0405340...

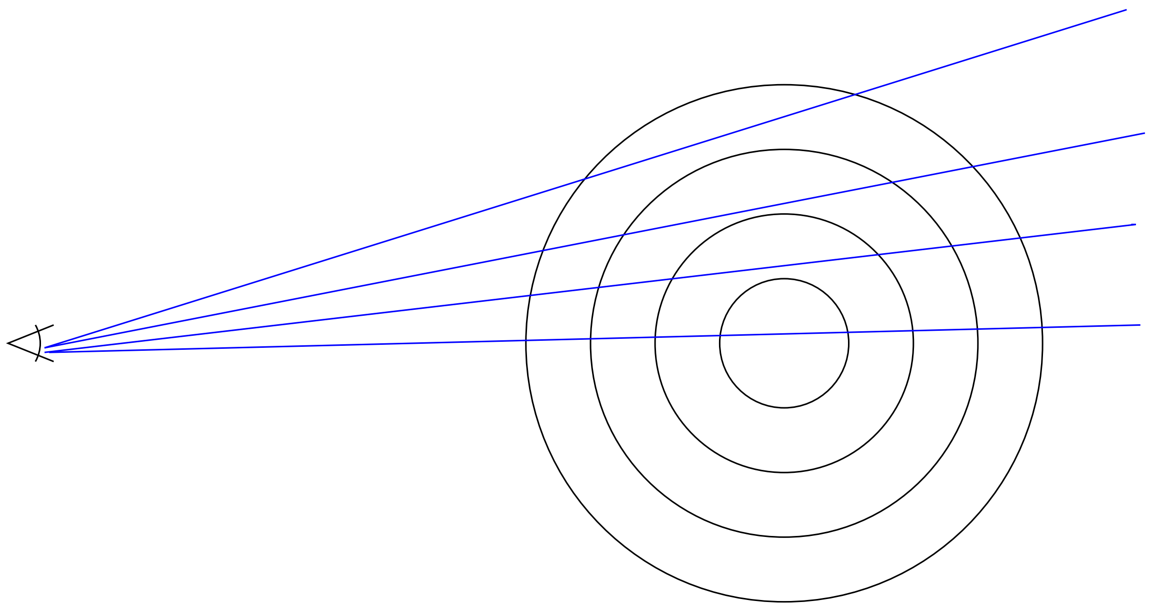
X rays emitted when e^-, p in plasma scatter inelastically



Typical energy determined by temperature of gas

Emission rate goes as collision rate $\propto \rho^2$

X-ray studies: the idea



Different lines of sight sample different spherical shells

X intensity and spectrum: $\int dl \rho_b^2 F(T) \sim \rho_b^2 r F(T)$

Many parameter fit: extract $\rho_b^2 r$, T as function of θ

What it tells us

Intensity $\Rightarrow$ density *of plasma*

Color $\Rightarrow$ Temperature

Temperature $\Rightarrow$ mean velocity $=$ Virial velocity

Virial velocity $\Rightarrow$ total system mass.

X-ray intensity, spectrum combined: *mass of plasma*
and, separately: *total mass*.

In more detail

What you measure: T and $\rho_b^2 r$ as function of θ

Pressure $P_b \propto \rho_b T$ must be in hydrostatic equilibrium:

$$\nabla P_b = \frac{G_\mathrm{N} \rho_b M}{r^2} \quad \rightarrow \quad \frac{\theta d}{d\theta} T \ln \rho \propto \frac{G_\mathrm{N} M}{r}$$

Total mass:

$$M \propto r \frac{1}{G_\mathrm{N}} \frac{\theta d}{d\theta} T \ln \rho$$

Baryonic mass:

$$M_b = \int \rho_b r^2 dr \sim r^{5/2} \sqrt{\rho_b^2 r}$$

Ratio of baryonic to total mass is (almost) measured:

$$\frac{M_b}{M_\mathrm{tot}} = r^{3/2} \times \text{(Measured things)}$$

Reality intrudes

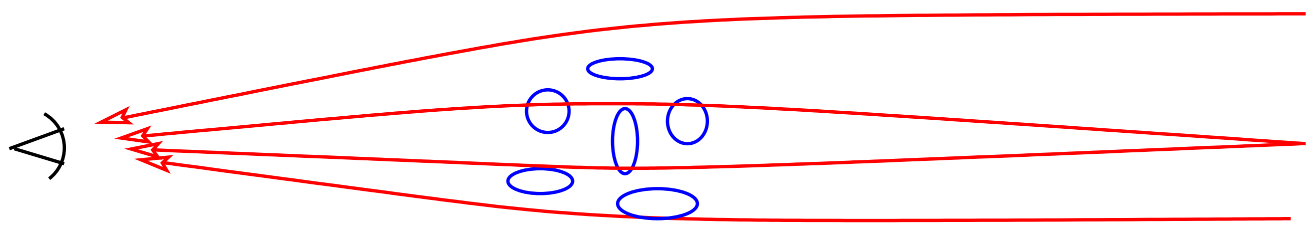
In principle, I measure $h^{3/2}\Omega_b/(\Omega_b+\Omega_{\rm CDM})$. But

- Gas really does settle at center of cluster
- Clusters actually somewhat baryon rich
- Winds from AGN's *etc*. may move around stuff, especially near center

Concentrate on shell around center, put in some modeling.

No longer as clean as hoped. But consistently finds $M \simeq 5M_{\rm gas+galaxies}$ (whereas above corrections are $\sim 20\%$)

Independent check: total mass



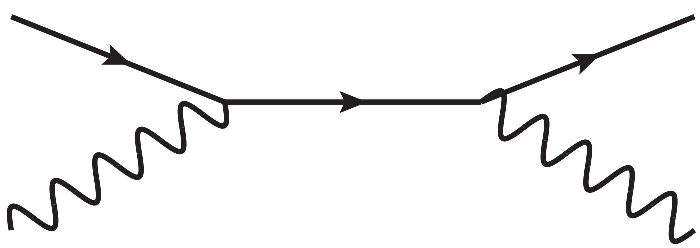
First *pre*diction of GR: gravity bends light.

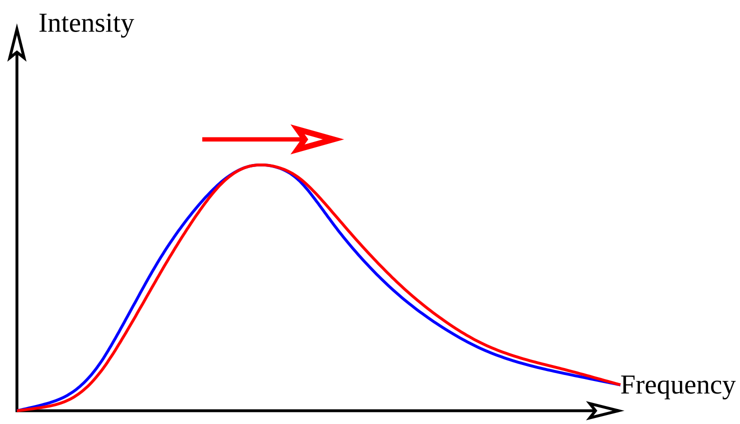
Use light-bending of galaxy cluster to map out its mass distribution

Also takes some modeling. Reproduces determined mass!

Independent check: Weighing Plasma

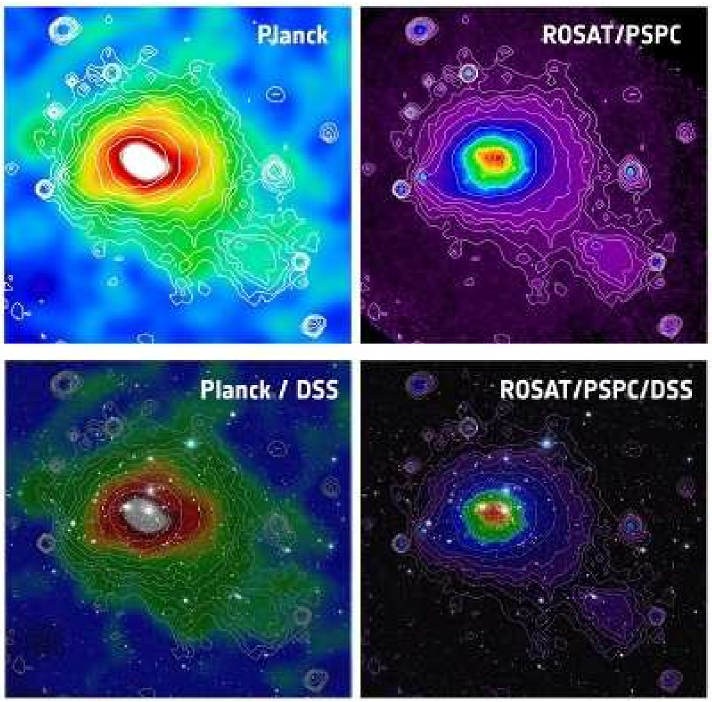
Universe bathed with equilibrium background of microwaves
(Thompson) Scatter from plasma in galaxy cluster





Preserves photon *number*, but doppler effect: $\sim v^2 \sim T/m$
distortion in *spectrum*: Low ω goes down, high ω goes up.

Weighing the Plasma



Sunyaev-Zeldovich effect
Microwave spectrum distorted
Very distinct from "hot/cold" pattern of microwave sky
Determines $\int \rho T d\ell$

Result is consistent with mass found from X-rays

Summary so far

We measure the *mass of plasma* in a galaxy cluster:

- Intensity of X-rays
- Up-scattering of microwave sky photons

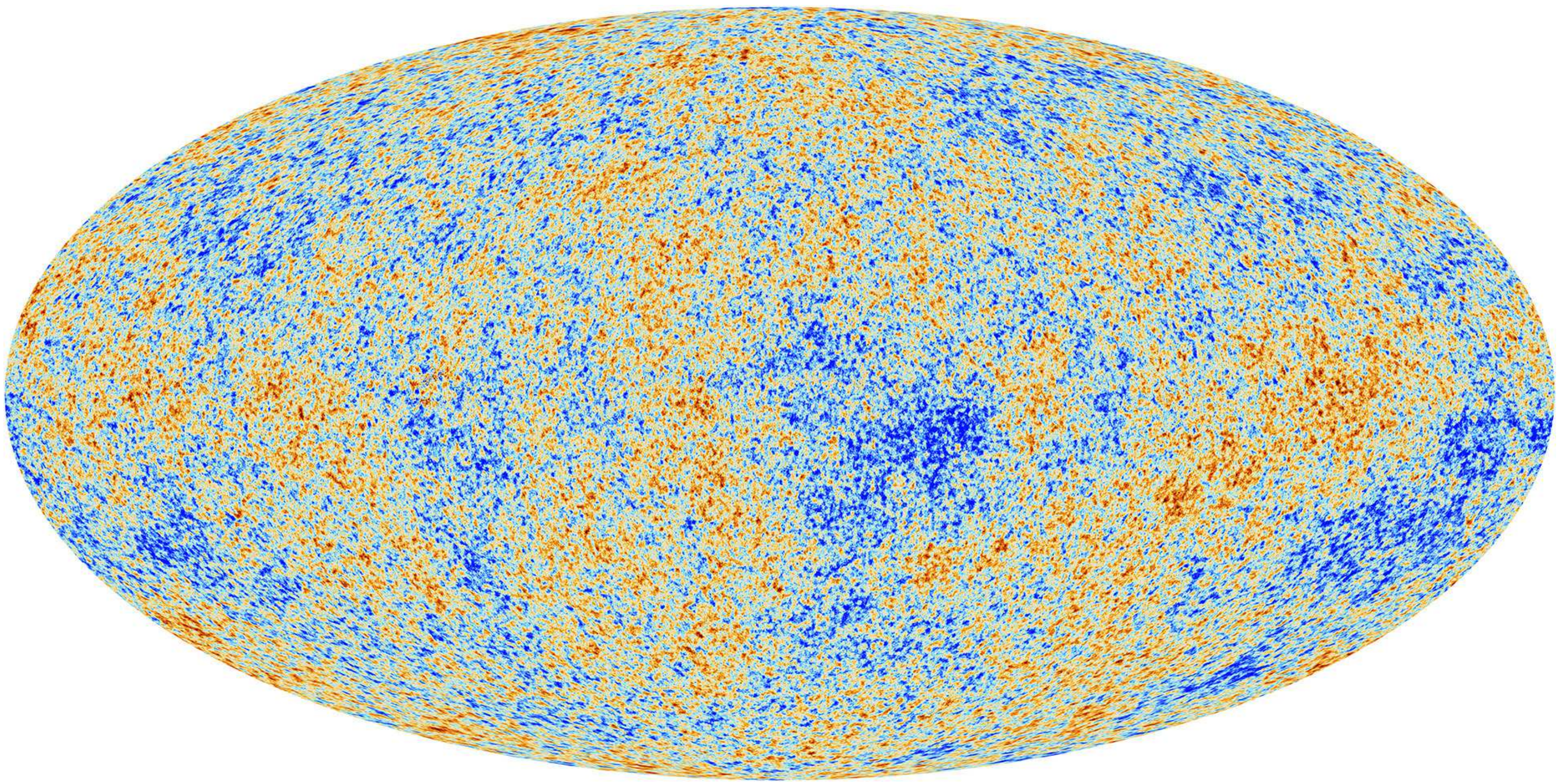
and the *total mass* of the cluster:

- Spectrum of X-rays $\Rightarrow$ Virial velocity
- Gravitational lensing

Over many clusters, consistently find:

$M_{\rm Cluster} \simeq 5 M_{\rm gas-in-cluster}$

Next up: microwave background



Planck Satellite all-sky microwave temperature map

Reminder: cosmic history

Einstein's Relativity: $T^{\mu\nu}$ causes spacetime curvature

Space-sections are flat $\Rightarrow$ curvature in "scale-factor"

Universe *stretches with time*

$$ds^2(x,t) = a^2(t) dx_i dx_j + dt^2 \,, \qquad H^2 \equiv \left(\frac{1}{a} \frac{da}{dt} \right)^2 = \frac{8\pi G_N}{3} \varepsilon$$

with a the "scale-factor" ($\propto$ current size of Universe)

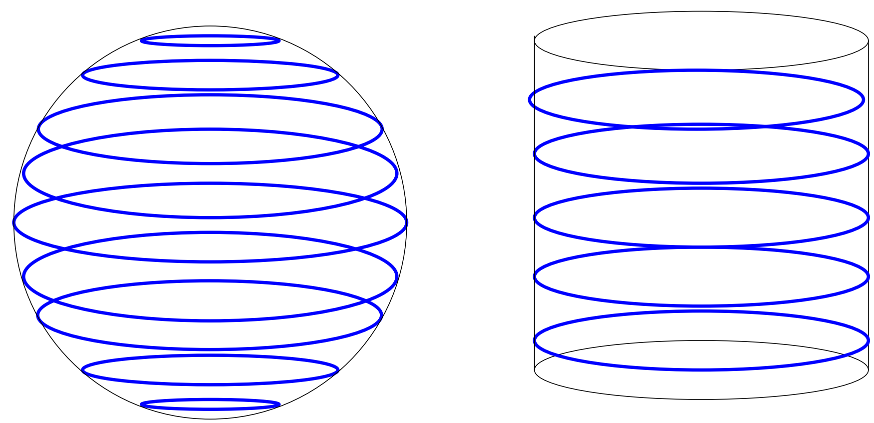
Energy density ε controls stretching rate.

Stretching cools Universe $\Rightarrow$ was much hotter

Current H value: $\varepsilon \sim 5\, m_p / \mathrm{m}^3$.

How can space-sections of curved space be flat?

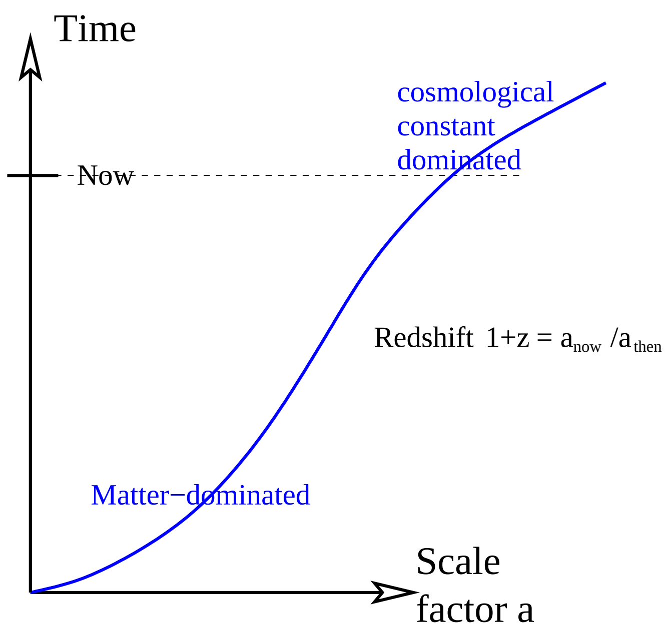
Consider sphere
vs cylinder.
"equal-time" $=$
lines of longitude



"equal-time" curves have no (intrinsic) curvature.
Cylinder: stay same size. Surface not (intrinsically) curved
Sphere: change size. Surface *is* (intrinsically) curved

Analogy: Universe carries (spacetime) curvature as
t-dependence of *size* of space slices, which are flat.

Cosmic expansion



Recent: accel. expansion

Before that, slowing expansion, $a \sim t^{2/3}$ in "matter-dominated era"

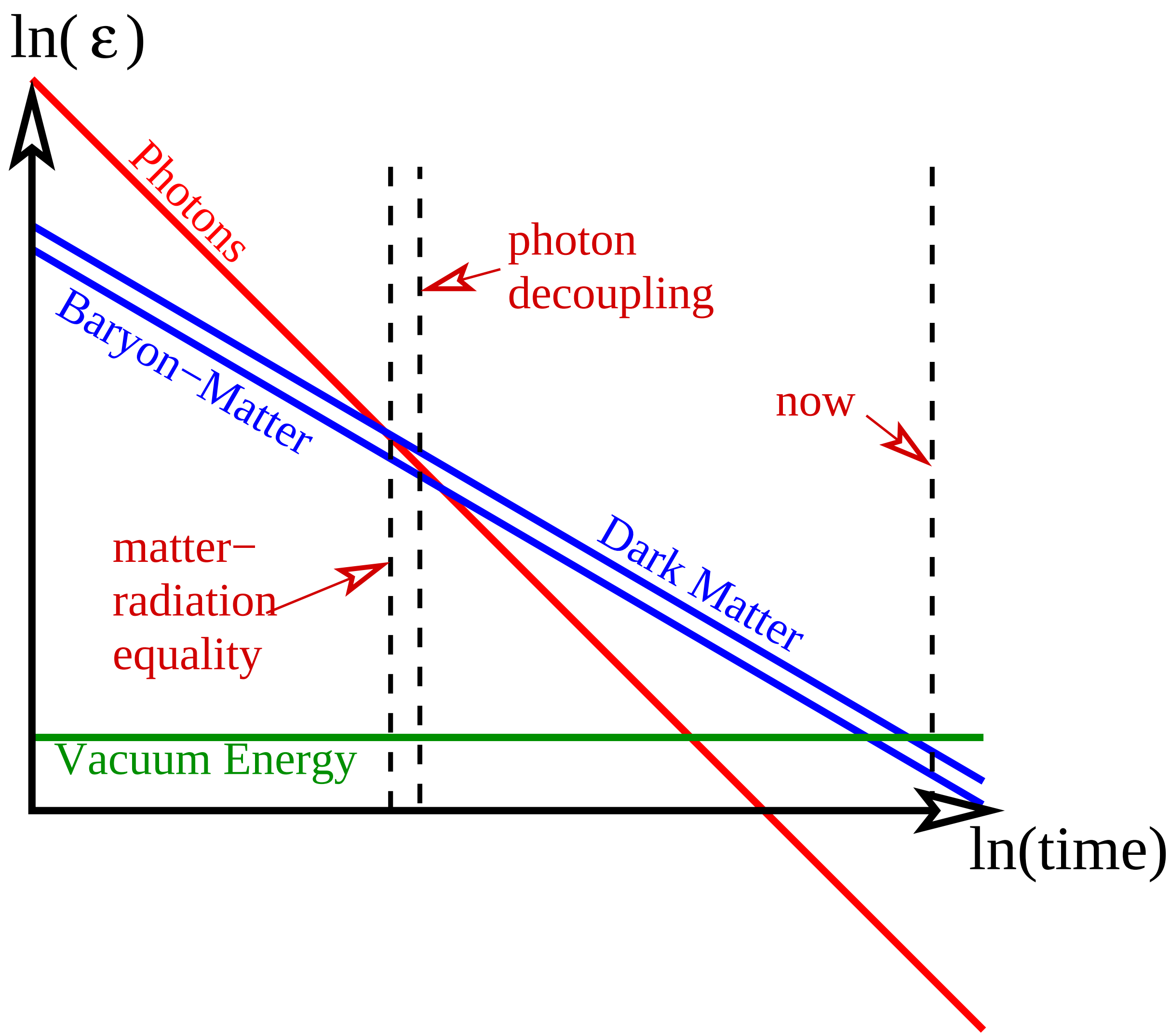
Leaves *total number* of γ, e^-, p^+ fixed: $\frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$

density scales as a^{-3} (shrinks)

Stretch space $\Rightarrow$ stretch γ wavelength, $T \propto a^{-1}$

$\epsilon_\gamma \propto a^{-4}$ but $\epsilon_{p,e} \propto a^{-3}$

Cosmic energy budget



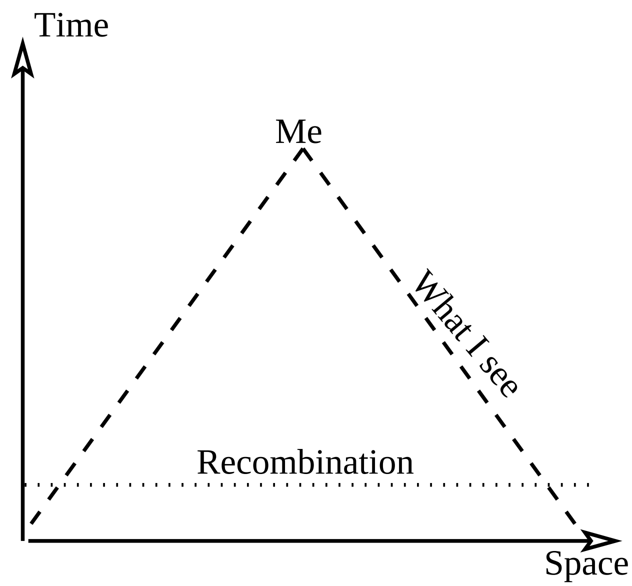
Photon decoupling

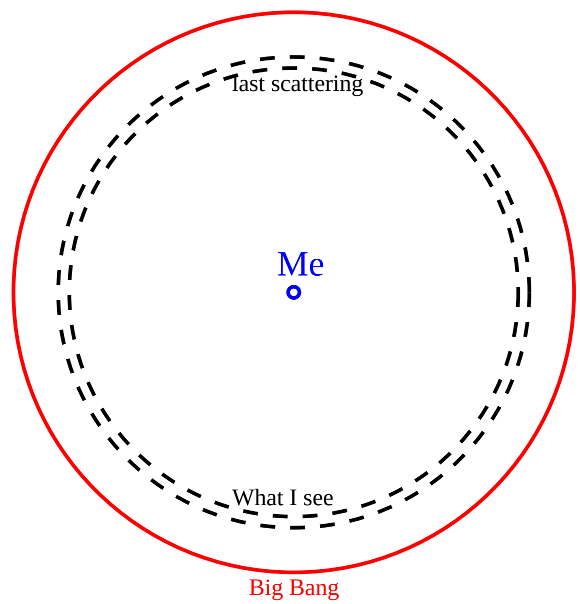
Early on: high temperature $T > 13.6\,\mathrm{eV} = E_{\mathrm{ioniz.}}$.
Hydrogen is $e^- p^+$ plasma. Opaque (Thompson scatt)
Temperature falls: at about $T \sim 0.24\,\mathrm{eV}$,
plasma *re*combines into H atoms.

$$\sigma_{\mathrm{Thompson}} = \frac{8\pi\alpha^2}{3(m_e c^2)^2}\,, \qquad \sigma_{H\gamma} \sim \sigma_{\mathrm{Thompson}} \left(\frac{E}{E_{\mathrm{ioniz.}}}\right)^4 .$$

Redshift $z \sim 1000$: plasma rather abruptly becomes transparent

Surface of Last Scattering





I see a thin surface at $z \simeq 1000$

If it's not all at one T, I see T-inhomogeneities.

Initial inhomogeneities

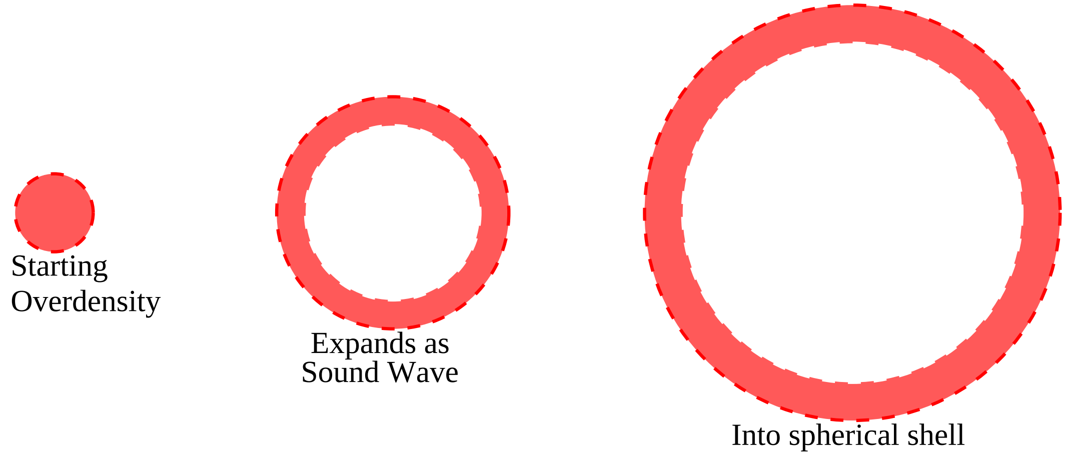
Something (Inflation?) started Universe out with *spectrum* of inhomogeneities:

- *Adiabatic*: all components simultaneously high/low
- *Small (Linear)* and *Gaussian*
- *almost scale-invariant*: almost equal power per log scale (like $1/f$ noise). But not quite: slightly "red"
- *Scalar*: no metric distortion at least, none seen yet

Use Green-function methods to study their evolution

Fluctuation in baryon-photon fluid

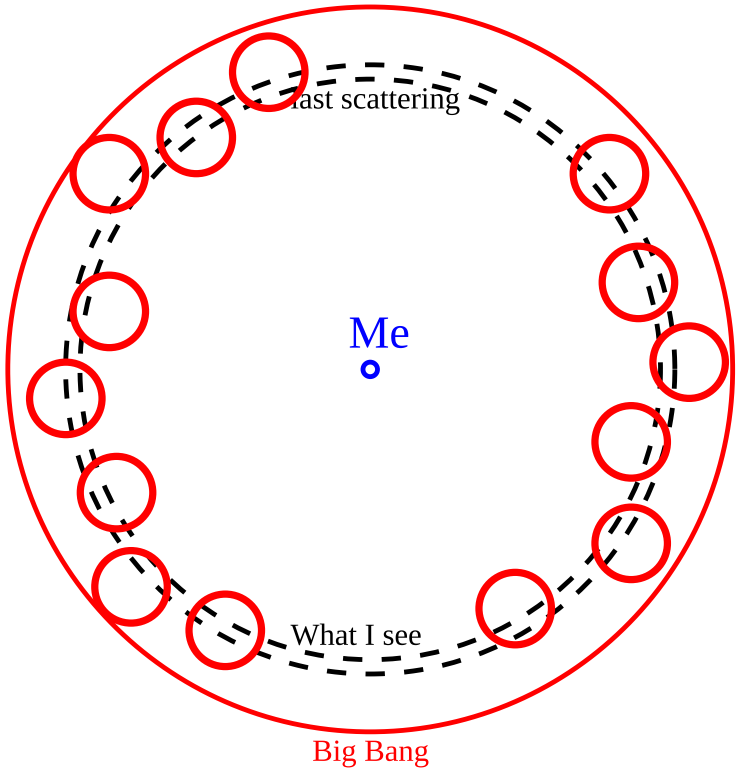
Suppose $e^- p^+ \gamma$
start overdense.
What happens?



Photons, e^- strongly coupled by Thompson scattering.
e^-, p^+ coupled by scattering + Coulomb interactions
Large pressure (γ more energy than $e^- p^+$)
Overdensity = overlapping sound waves.
Expand as spherical shell at $v = v_{\rm sound} \simeq c/\sqrt{3}$

Last scattering surface

What I see: superposition
Each overdensity turns into
a spherical shell
Shell: hot/cold material
Also, fluid flow velocity
And gravitational potential



Convolve initial spectrum with spherical-shell "transfer func"
Don't forget to include red/blue shift of plasma motion
Also, red/blue shift from graviational potential wells

Procedure in full

- Write down initial spectrum of fluctuations
- Convolve with plasma-response transfer function

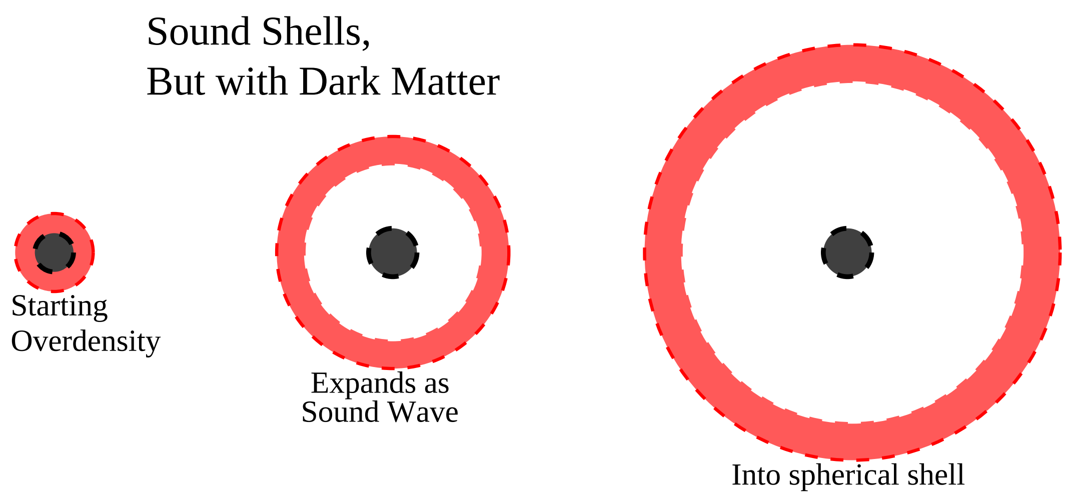
  Easy to do in momentum space

- Project onto spherical shell of last scattering
- Include thickness of shell *silk Damping*
- Y_{lm}-transform into spectrum of Microwave sky

Peaks and troughs, but totally wrong heights!

But if there's Dark Matter...

Consider overdensity again, but this time with Dark Matter.



Photons, e^-, p^+ do the same as before.

Dark matter sits in the middle.

Gravitationally attracts more DM and baryonic matter.

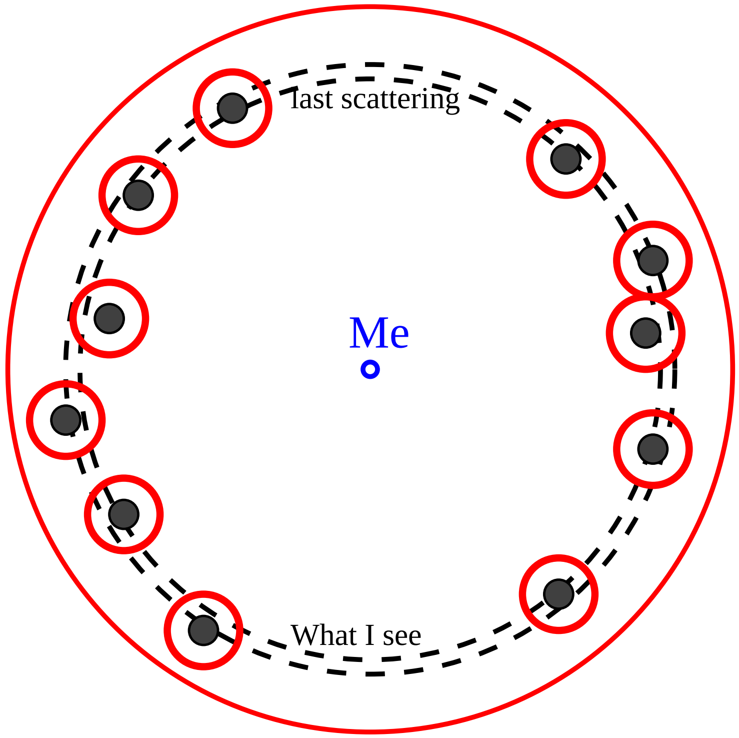
Different pattern: spherical shell + blob in middle

Last Scattering with DM

What I see: superposition

This time, spherical shells

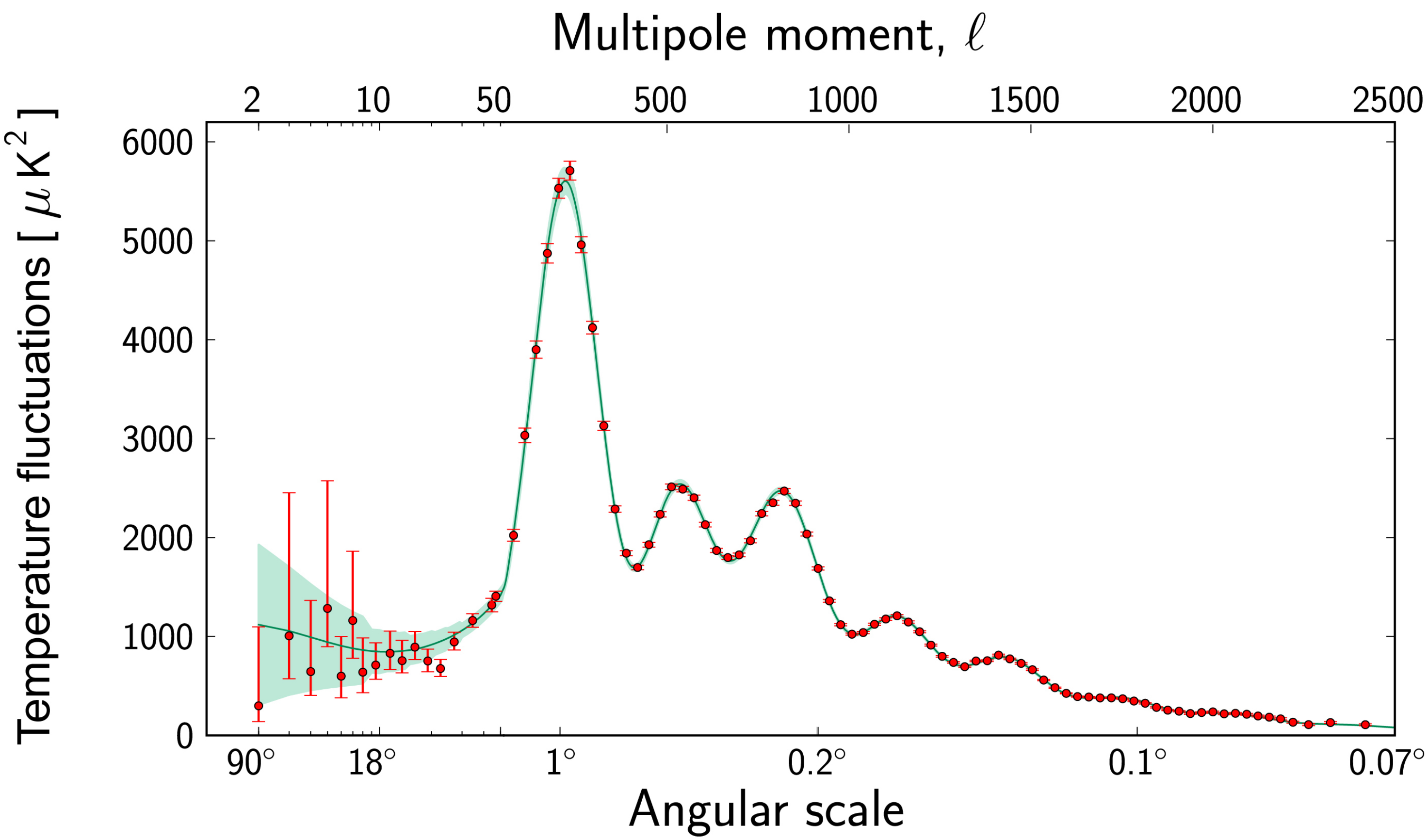
have “cores” at centers



Different transfer function

Leads to different pattern on microwave sky

Recent results: Planck + Ground-Based



Large angles: cosmic variance Planck: arXiv:1807.06205

Middle scales: pattern from filled spherical shells

small scales: Silk damping

Microwave Sky: Results

- Location of peaks: sound horizon at recombination

  Space is flat at $< 1\%$ level

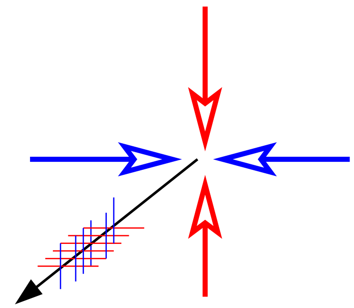
- Relative heights of peaks: relative weights of "sound shell" to "DM core"

- Current precision arXiv:1807.06209:
  $\Omega_c h^2 = 0.11933(91)$ (better than 1%)
  $\Omega_b h^2 = .02242(14)$ (so $M_{\rm DM}/M_{\rm B} = 5.32 \pm .05$)

- Overall scale dependence: slight spectral tilt

- Taper at high ℓ as expected

There's more: Polarization

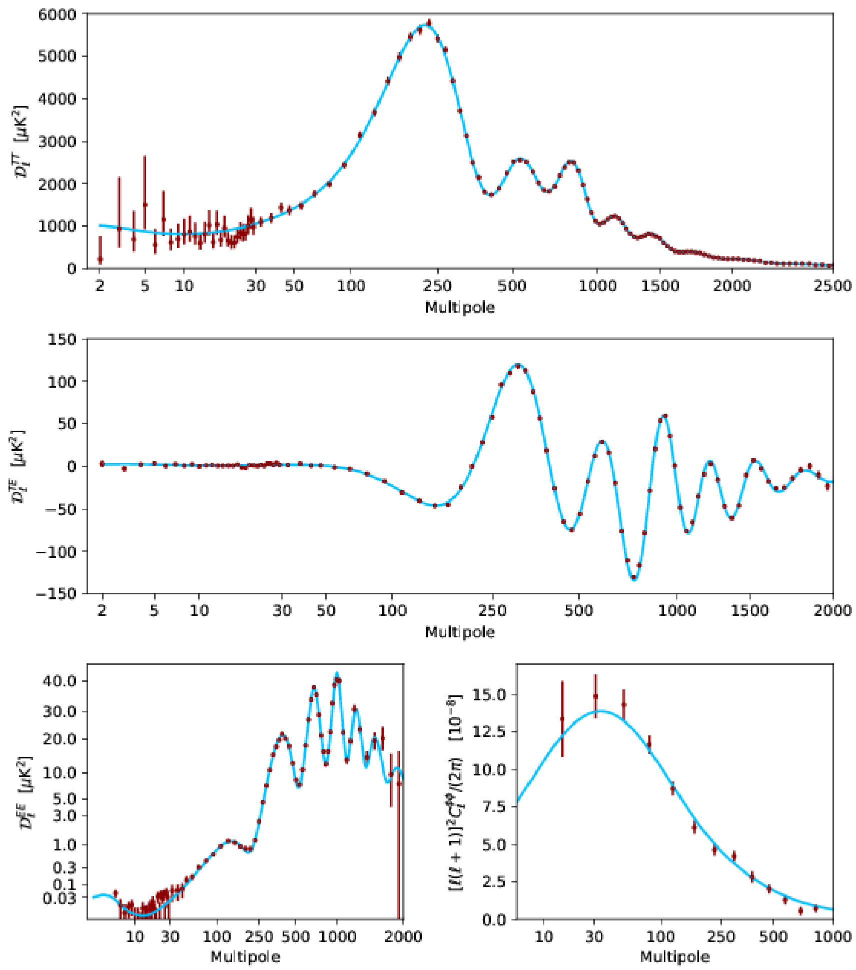


Scattering ends gradually:
Light took last "jump"
before leaving last
scattering surface

Thompson scatt.
polarized:
Dipole T pattern turns
into polarized signal on sky

Temperature: "temperature monopole" on last-scatt-surf.
Polarization: "temperature dipole" on last-scatt-surf

TE correlation



TT, TE, and EE measured.
Predictions of CDM+Matter fit perfectly.

Planck: arXiv:1807.06205

Galaxy-Galaxy Correlations?

Initial overdensity $\Rightarrow$ Spherical shell + peak

Recombination: baryons stop moving

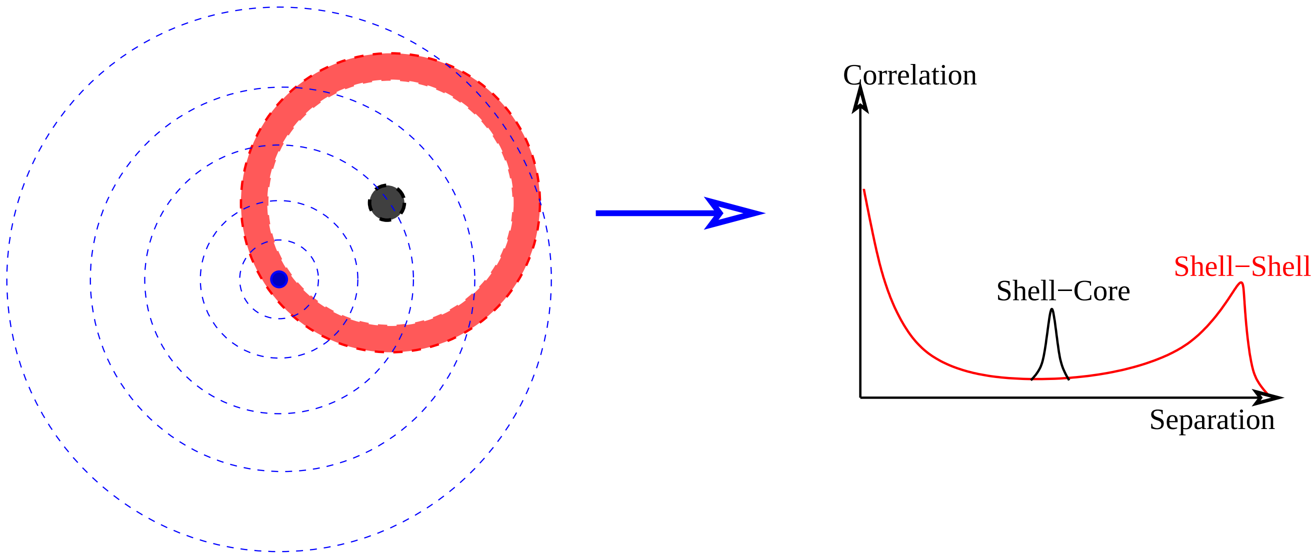
Both shell+peak are overdense: attract more matter

Form the "nucleus" of structure formation

Galaxies today correlated with overdensities then

Should be "echo" of shell+peak structure in modern galaxy-galaxy correlation function!

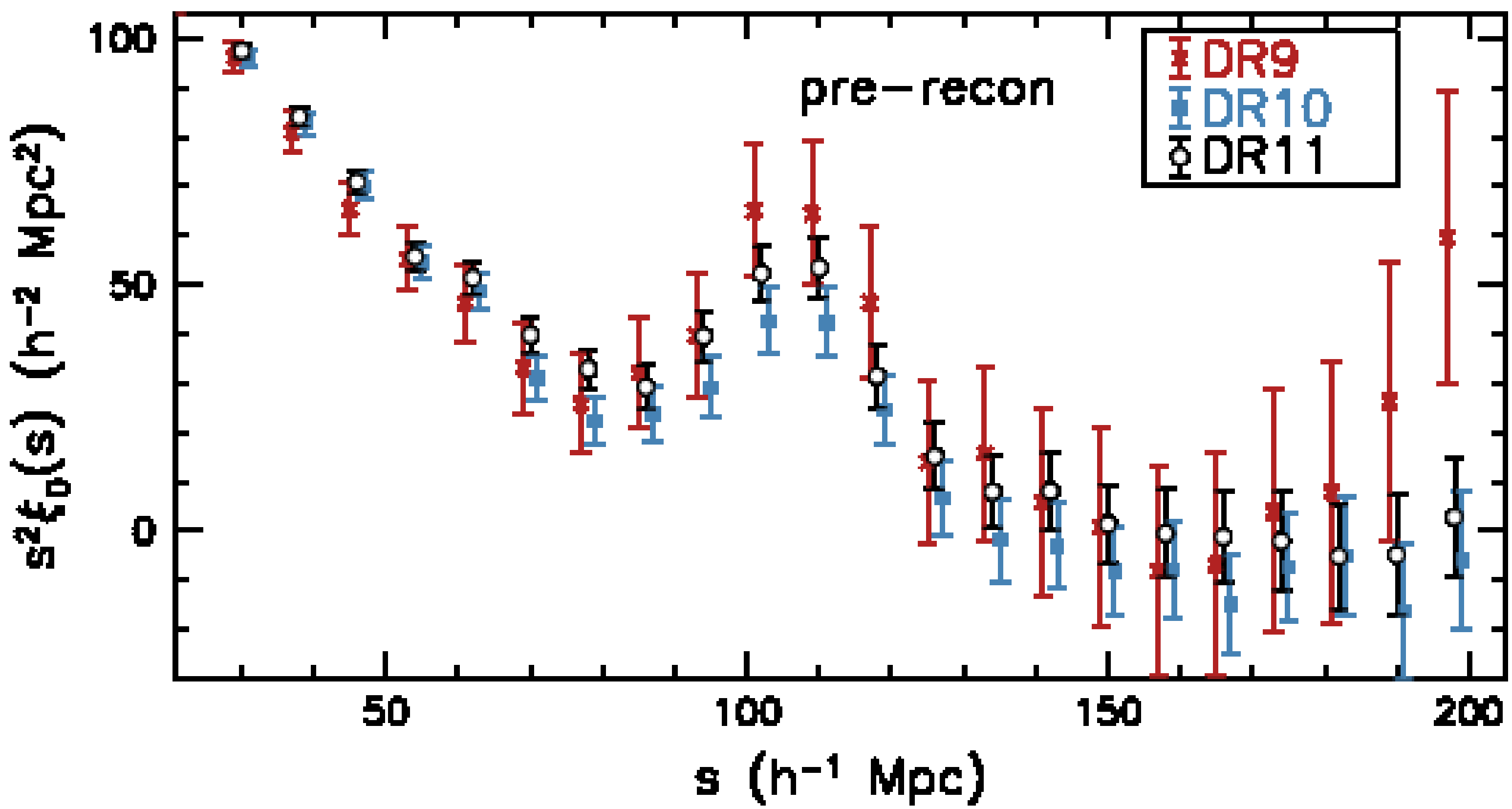
Galaxy Correlation: the Idea



Consider a galaxy in “shell”.

Likely places to find another: “shell” or “core”

“Shell” gives peak at $2r$; “core” at $1r$



Observations

arXiv:1312.4877 “BOSS” many millions of galaxies in 3D...

Peak at $1r = 150\,\mathrm{Mpc}$ as expected.

But wait – there's more

- Baryon abundance independently measured by Deuterium/Hydrogen + Big Bang Nucleosynthesis
  arXiv:1308.3240 Perfect accord with Microwave Sky result

- Supernovae+Hubble constant $\Rightarrow \varepsilon_{\mathrm{matter}}, \varepsilon_{\mathrm{Dark-Energy}}$

- DM initial fluctuations + cosmic evolution
  $\Rightarrow$ Large scale structure in modern Universe.
  Utterly fails without Dark Matter (clusters too late)

Summary

Multiple independent lines of evidence for Dark Matter:

- Galaxy clusters: X-ray temperature, intensity, SZ effect
- Microwave sky: pattern of fluctuations
- Galaxy correlation function: sound-horizon peak
- Other cosmological measurements (n_B, SN1A, H_0)

No alternative theory can explain *all* of these things without invoking dark matter, with $\varepsilon_{DM} \simeq 5\varepsilon_B$.

Do I have to believe in DM?

No. Play with the laws of Gravity,
engineer initial density distributions and correlations,
modify nuclear physics in the early Universe!

But might I also interest you in:

- Geocentrism: Epicycles aren't so bad!
- Young-Earth geology / Flood Theory / Creationism
- Flat-Earth theory
- Crystal healing, Breathairians