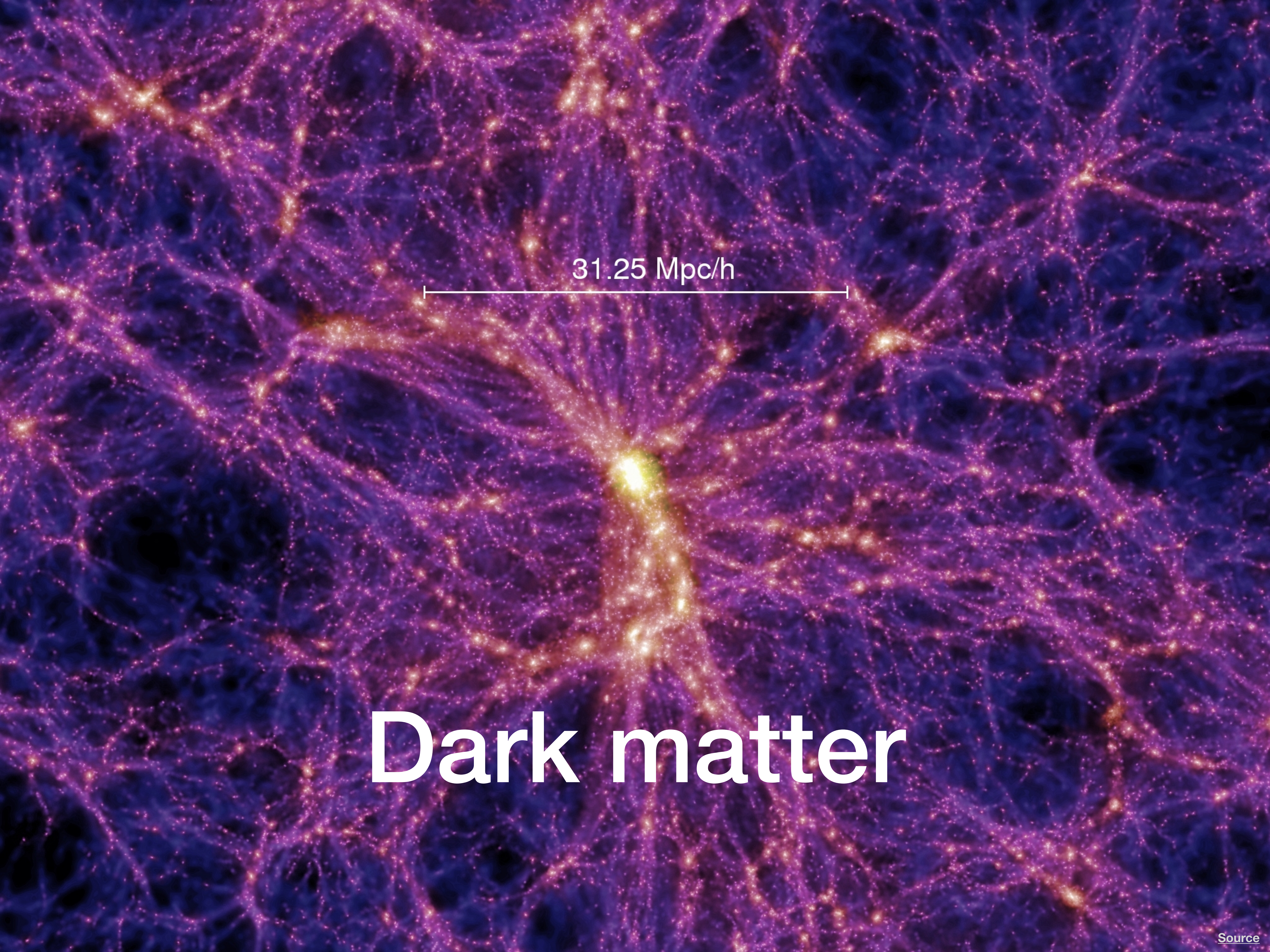
GRAPPA Student Seminar

Shin'ichiro Ando, Gianfranco Bertone,
Adam Coogan, Christoph Weniger

4 june 2019

University of Amsterdam

GRAPPA
GRavitation AstroParticle Physics Amsterdam


31.25 Mpc/h
Dark matter
Source

Lecturers

Adam Coogan
a.m.coogan@uva.nl
Week 1

Shin'ichiro Ando
s.ando@uva.nl
Week 2

Christoph Weniger
c.weniger@uva.nl,
Week 3

Gianfranco Bertone
g.bertone@uva.nl

Dark matter questions

- What is the **evidence** for its existence?
- What is **known** about dark matter?
- How can we identify its **non-gravitational interactions**?
- What are some leading **candidates**?

Seminar overview

- **Week 1:** evidence for dark matter, basic facts, production
- **Week 2:** indirect detection
  - Gamma rays, antimatter, high-z (CMB, 21cm, etc)
- **Week 3:** direct detection
  - DM-nucleus/electron scattering, new directions
- **Week 4:** student presentations

Learning goals

Research skills alongside content

- Write **codes** each week to perform physics calculations
- **Final presentations** on current topics in dark matter

Weekly physics codes

- Programming is a key skill for doing research
- Topics:
    - Relic abundance
    - Indirect detection with gamma rays
    - Direct detection constraints
- Use jupyter notebooks with Python 3; files to be uploaded on GitHub

Final presentations

- You will learn to find and evaluate references, and understand key ideas from papers
- Lectures will give you a broad overview of dark matter, but you will need to study your topic independently in **much more detail**
- See GitHub page for topic list

Tips for finding references

- Some search engines: Google Scholar, INSPIRE, NASA ADS, arXiv, Google, Wikipedia
- Review articles are often helpful. Can be outdated, so may want to search by year.
- There are **lots** of papers: highly cited ones *tend* to be important

Recommended articles

- Particle Dark Matter: Evidence, Candidates and Constraints (Bertone et al 2004)
- WIMP dark matter candidates and searches (Roszkowski et al 2018)
- TASI 2012 Lectures on Astrophysical Probes of Dark Matter (Profumo 2012)
- Lectures on Dark Matter Physics (Lisanti 2015)

These are just a starting point!

Tips for reading references

- Abstract, introduction: is the paper relevant to your topic? What was done before? What did this paper improve?

- Plots, conclusion: what are the main results?

- Body of paper: what is the reasoning? What are the assumptions?

- What **important parts** were confusing?
  → "Read around" the paper: understand argument on paper; look at follow-up works, cited articles, reviews, lecture notes, slides, etc…

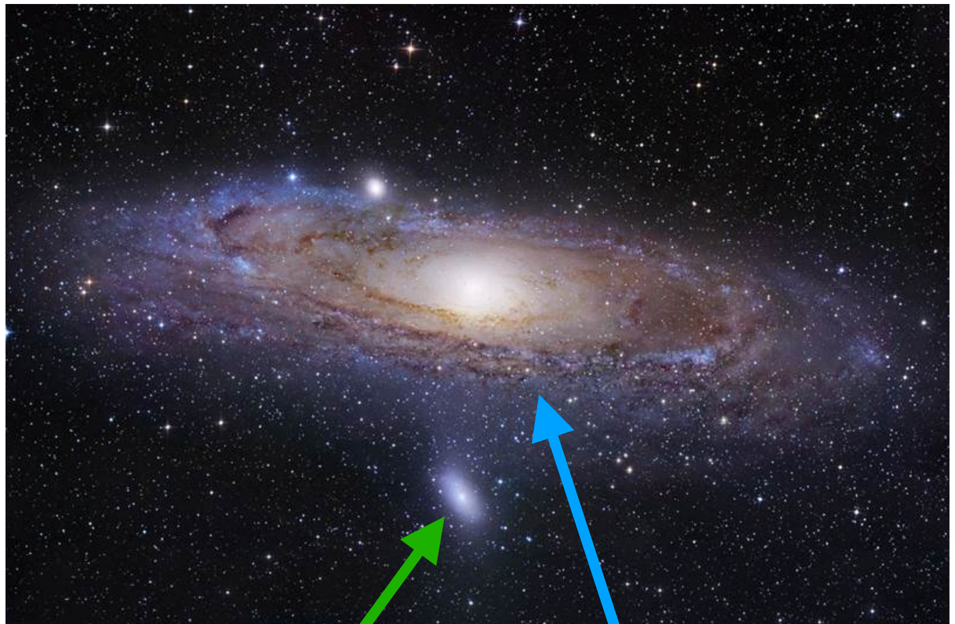
Course schedule

	Tuesday	Wednesday	Friday
Week 1: evidence, facts, production	Lecture 1 (Coogan)	Script 1 introduced	Q&A
Week 2: indirect detection	Lecture 2 (Ando), script 1 due	Script 2 introduced	Q&A
Week 3: direct detection	Lecture 3 (Weniger), script 2 due	Script 3 introduced	Q&A
Week 4	Q&A, script 3 due	—	Final presentations

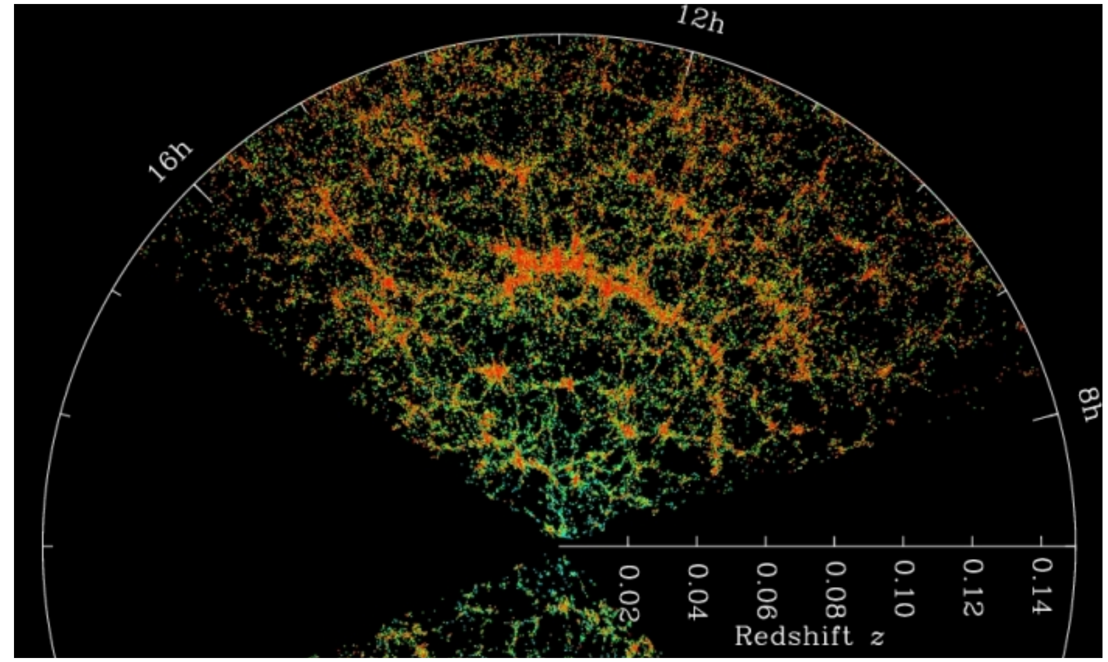
Tonight's homework

- **Install** essential coding tools
- Form groups of **four people;** have one person email me your names
- **Look over presentation topics** (see GitHub wiki) with your group and submit ranked list of preferences
- Start studying **freeze-out calculation** (I'll describe this shortly)

Lecture 1: Evidence for and basic features of dark matter



Andromeda



SDSS

Dwarf spheroidals

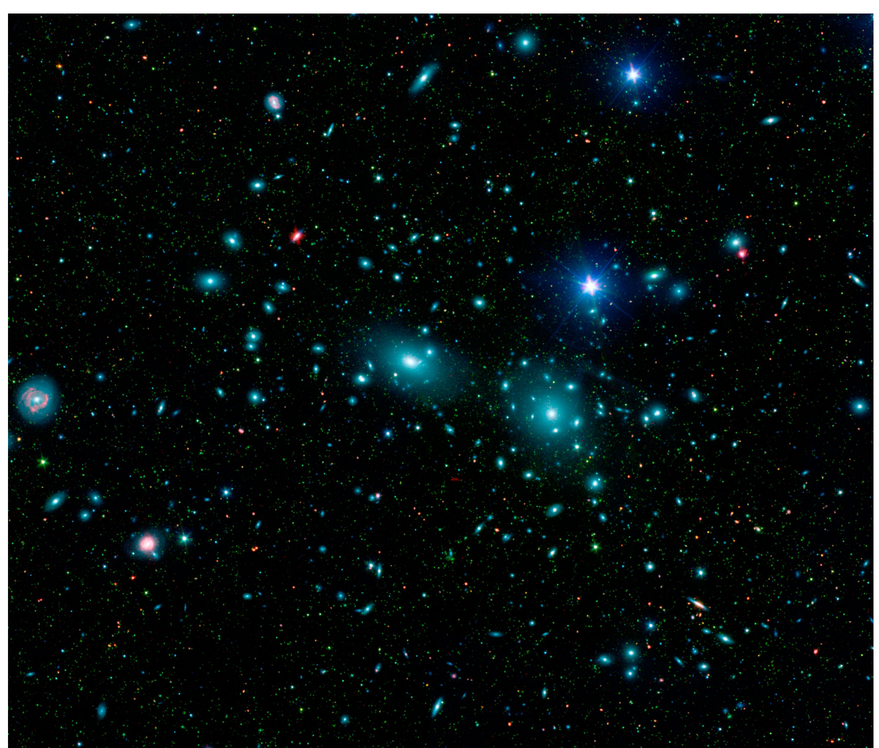
Galaxies

Galaxy clusters

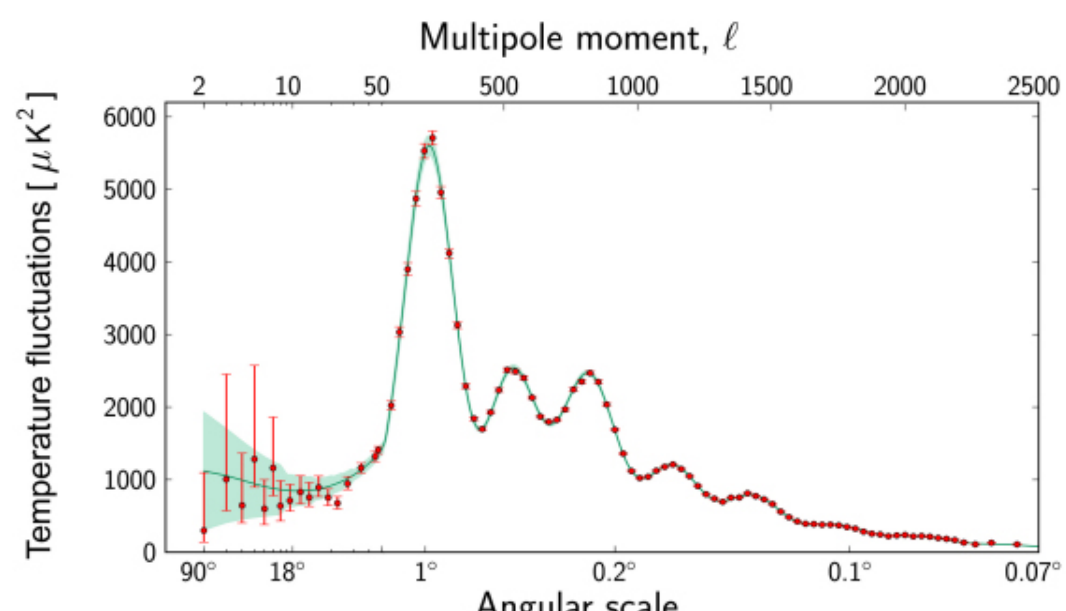
Large-scale structure

CMB

$10^8\ M_\odot$ — $10^{12}\ M_\odot$ — $10^{15}\ M_\odot$ — z ~ a few — z~1100

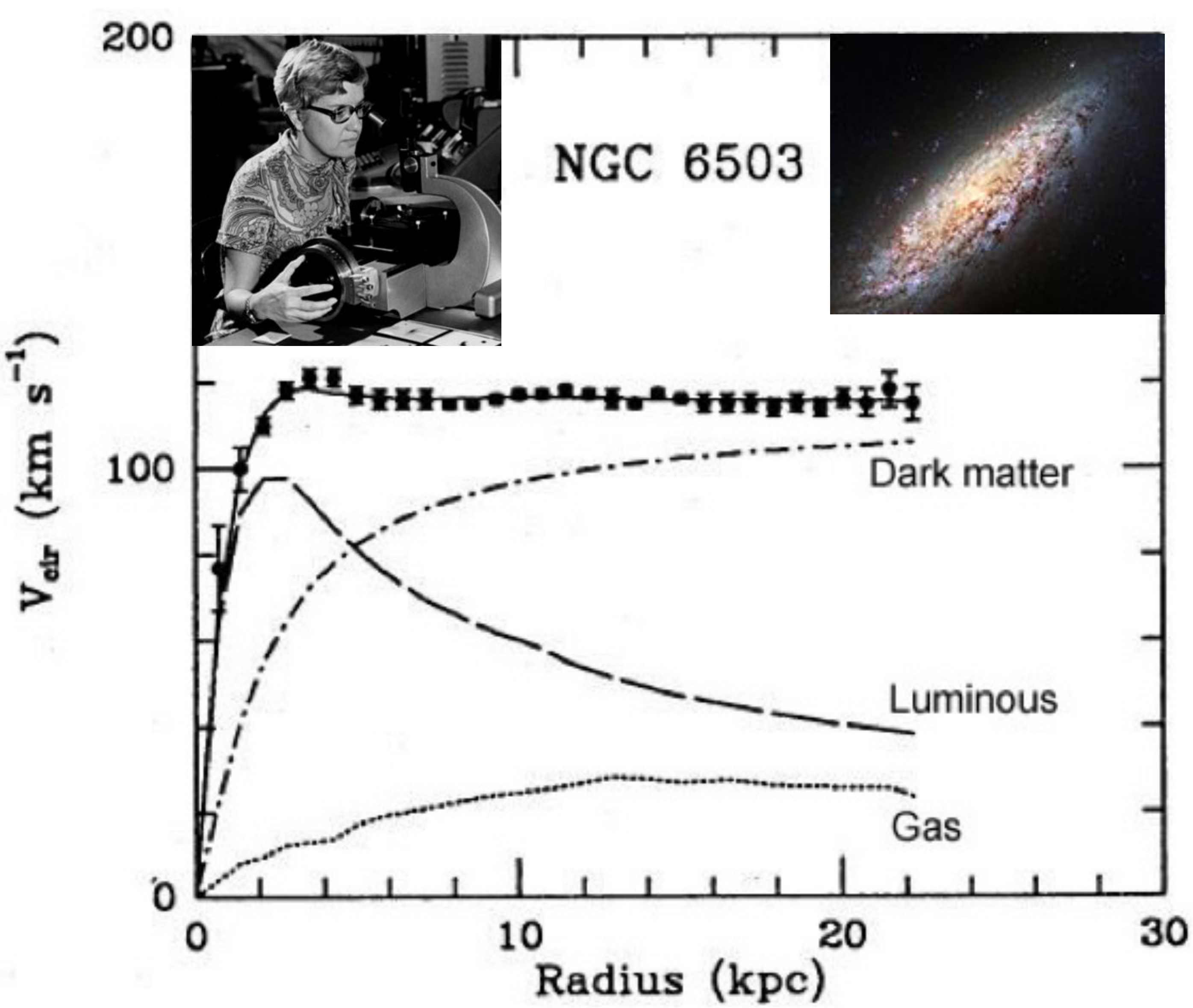


Coma Cluster



Planck

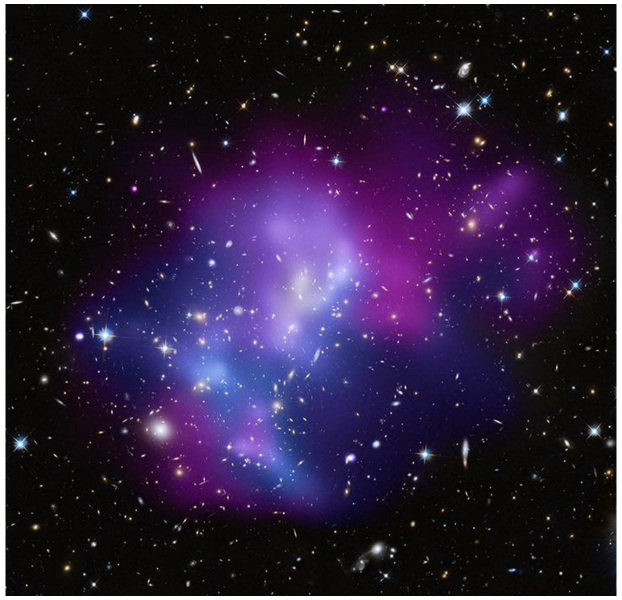
Galactic scale: rotation curves



- Measured using starlight, H emission lines
- Q: why is this evidence?
  → Compute v(r) inside and outside of sphere with constant density
- Q: what do we learn about DM distribution?
  → Find ρ(r) for flat rotation curve, assuming spherical symmetry

Begeman, Broeils, Sanders 1991;
Vera Rubin image;
NGC6503 image

Cluster scale: x-rays



- Gas heats as it falls into potential well, emitting x-rays (blue & purple)
- F=ma: $$\frac{dP}{dr} = -\frac{GM(r)}{r^2}\rho$$
- Q: how can we eliminate pressure (P)?
- Q: how to get T, M_{gas} from spectrum?
- Typical numbers:
  T ~ (1.5 keV) ($M/10^{14}M_\odot$) (1 Mpc/r)
- But T_{obs}~10 keV ⇒ M_{DM}/M_{gas}~0.7

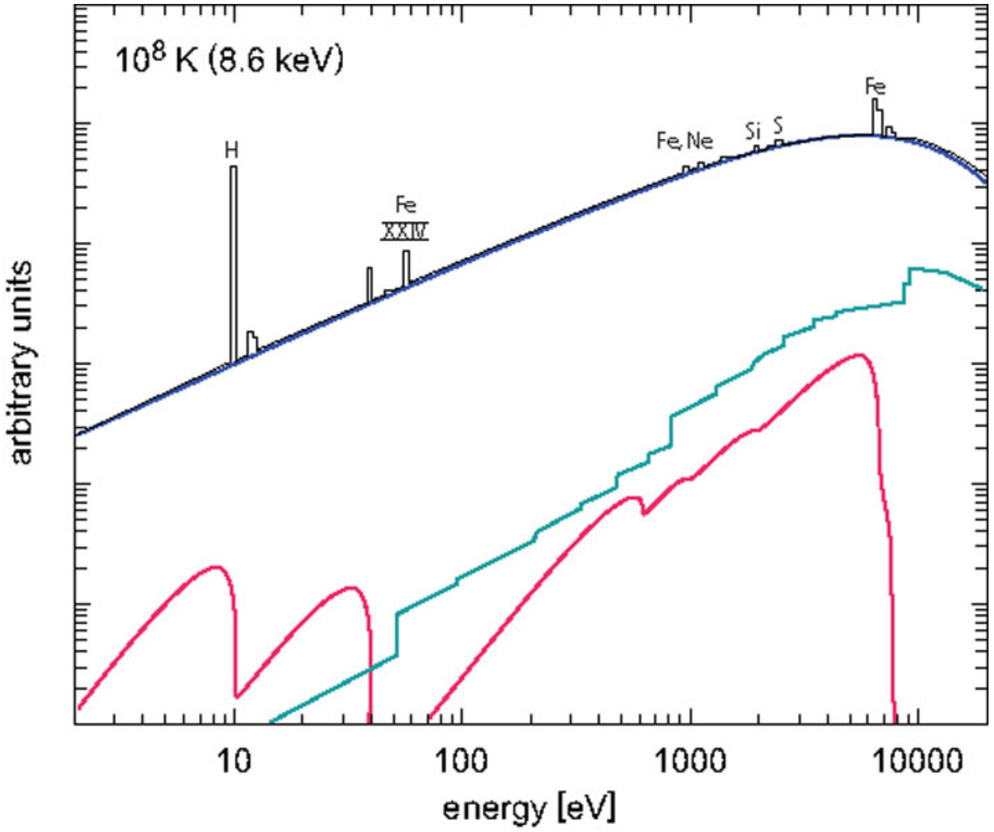
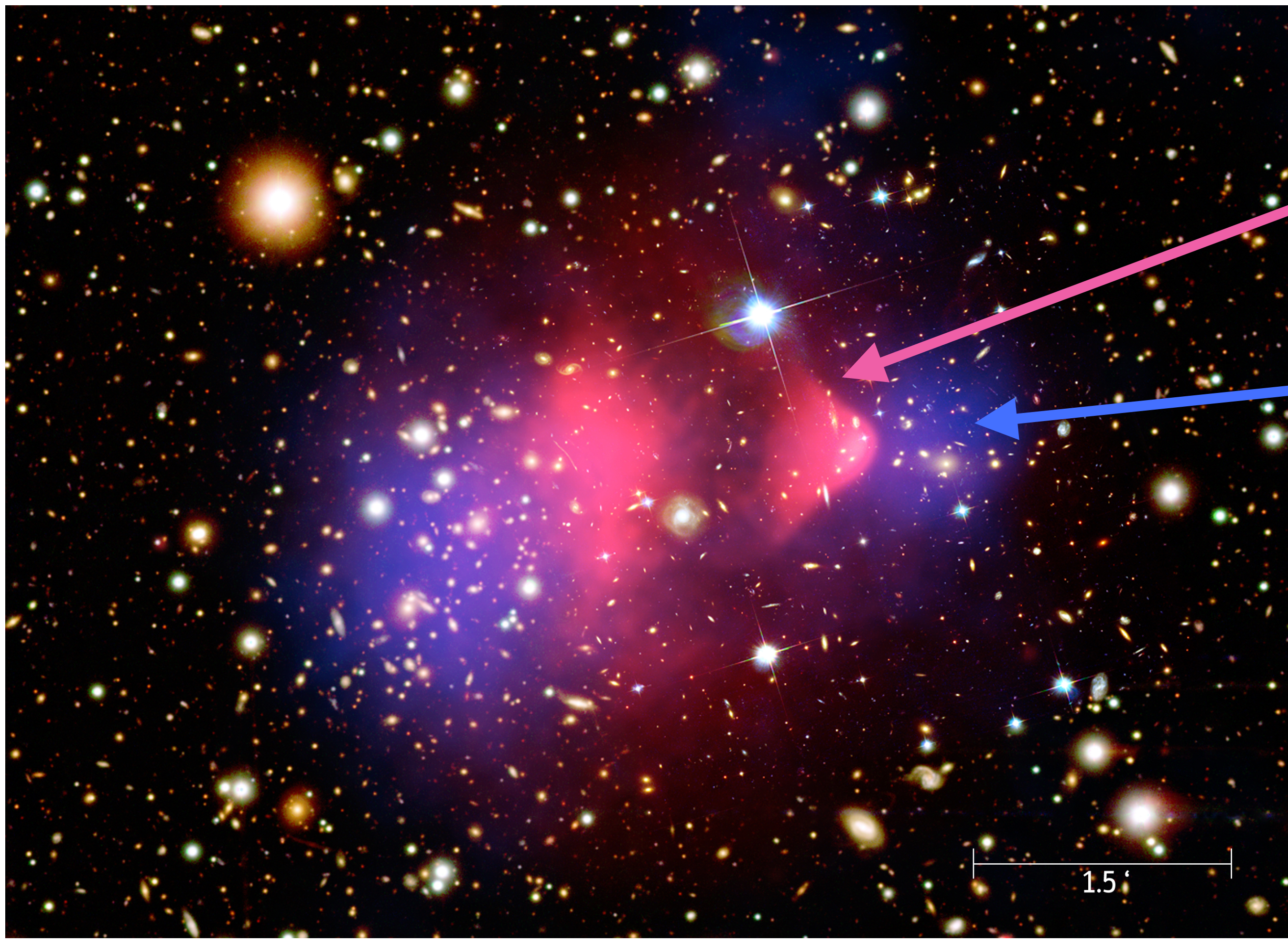


Image source; figure source

Cluster scale: Bullet Cluster



Source

X-rays from gas

Dark matter (detected using lensing)

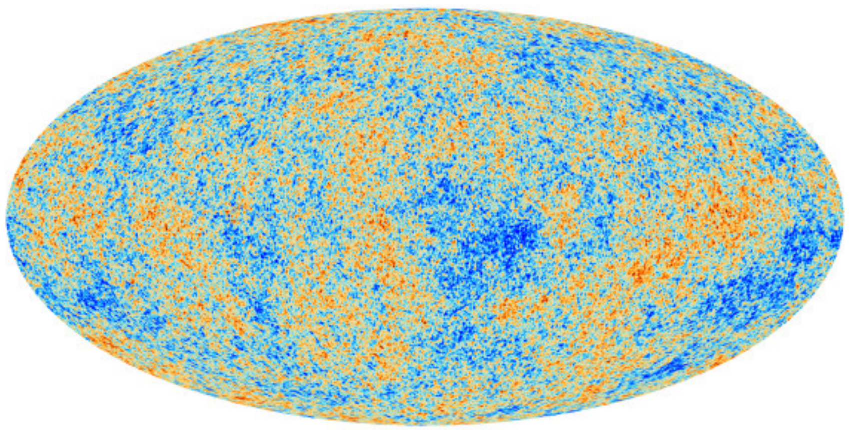
Gas is collisional (Coulomb force), thus slowed by friction; dark matter is not

Bound on DM self-interaction:

$$\frac{\sigma_{\mathrm{DM-DM}}}{m_{\mathrm{DM}}} \lesssim 1\,\mathrm{cm}^2/\mathrm{g} \sim 1\,\mathrm{barn/GeV}$$

Q: how small is this, really? Estimate the proton-proton cross section.

Structure formation



$$\frac{\delta\rho_b}{\rho_b} \sim 10^{-4}$$

z~1100

z~5

Andromeda

$$\frac{\delta\rho_b}{\rho_b} \sim 10^{6}$$

Linear perturbation theory (from Euler, continuity and Poisson eqs):

$$\frac{\delta\rho}{\rho} \propto a$$

$$\Longrightarrow \left.\frac{\delta\rho_b}{\rho_b}\right|_{z=5} = \frac{1101}{6} \times 10^{-4} \sim 0.02 \ll 10^{6}$$

Not enough time for structure to evolve, unless something else seeds structures!

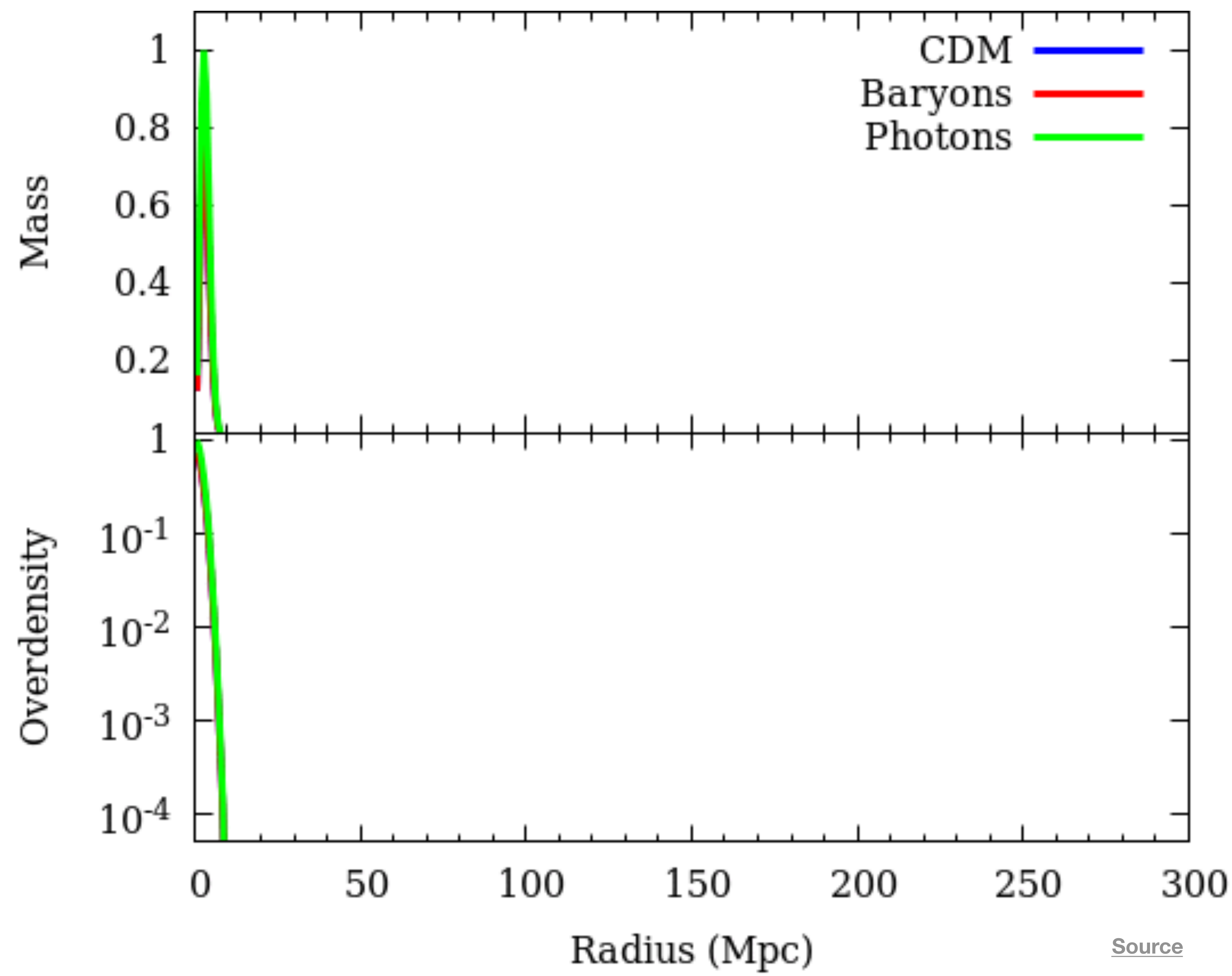
Cosmological scale: baryon acoustic oscillations, CMB

- How initial overdensities evolve?

- Plasma rebounds at ~0.5c off initial overdensity

- Photons decouple and free-stream

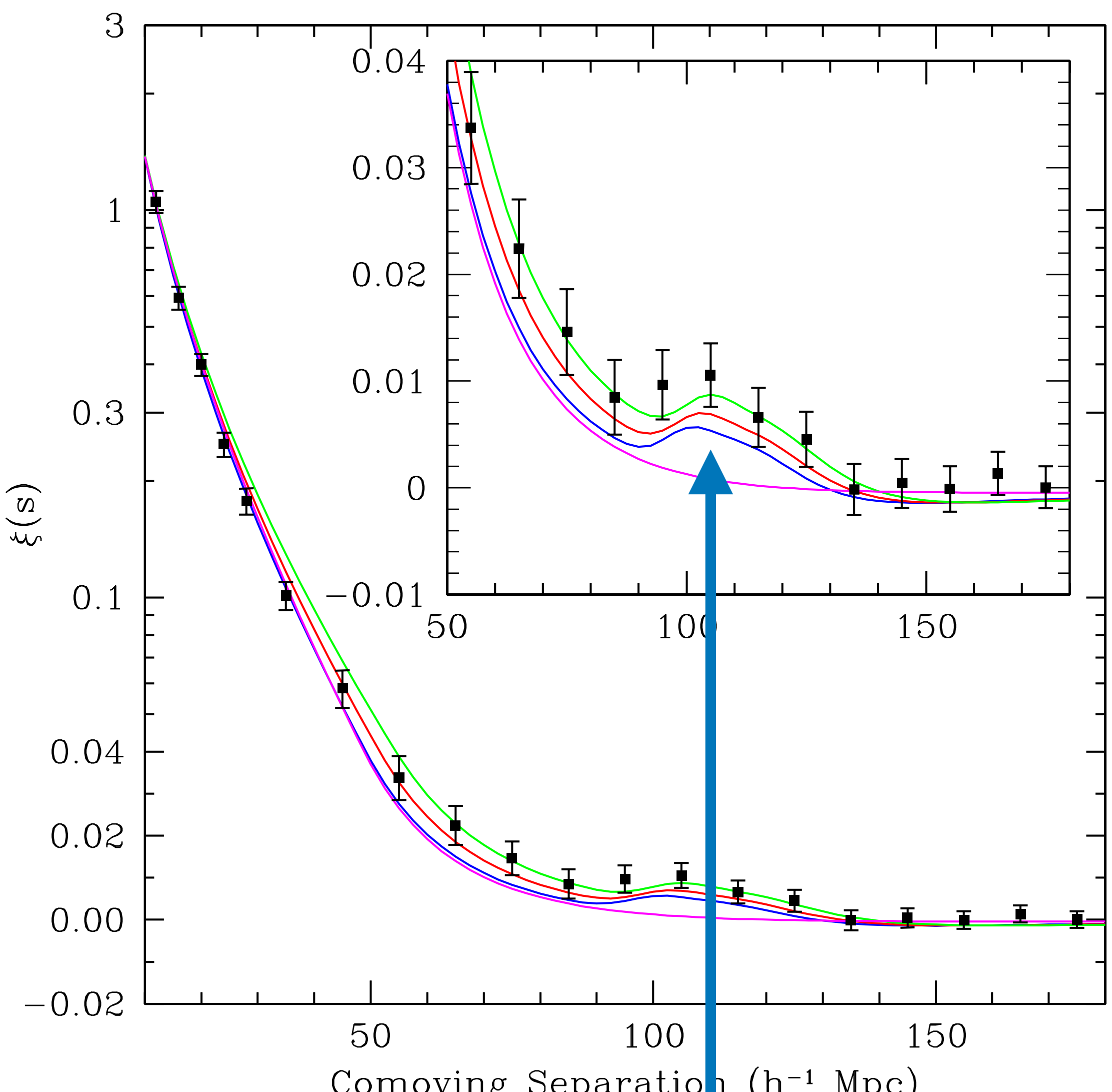
- Baryons slow and perturbations mix



Source

Cosmological scale: baryon acoustic oscillations, CMB

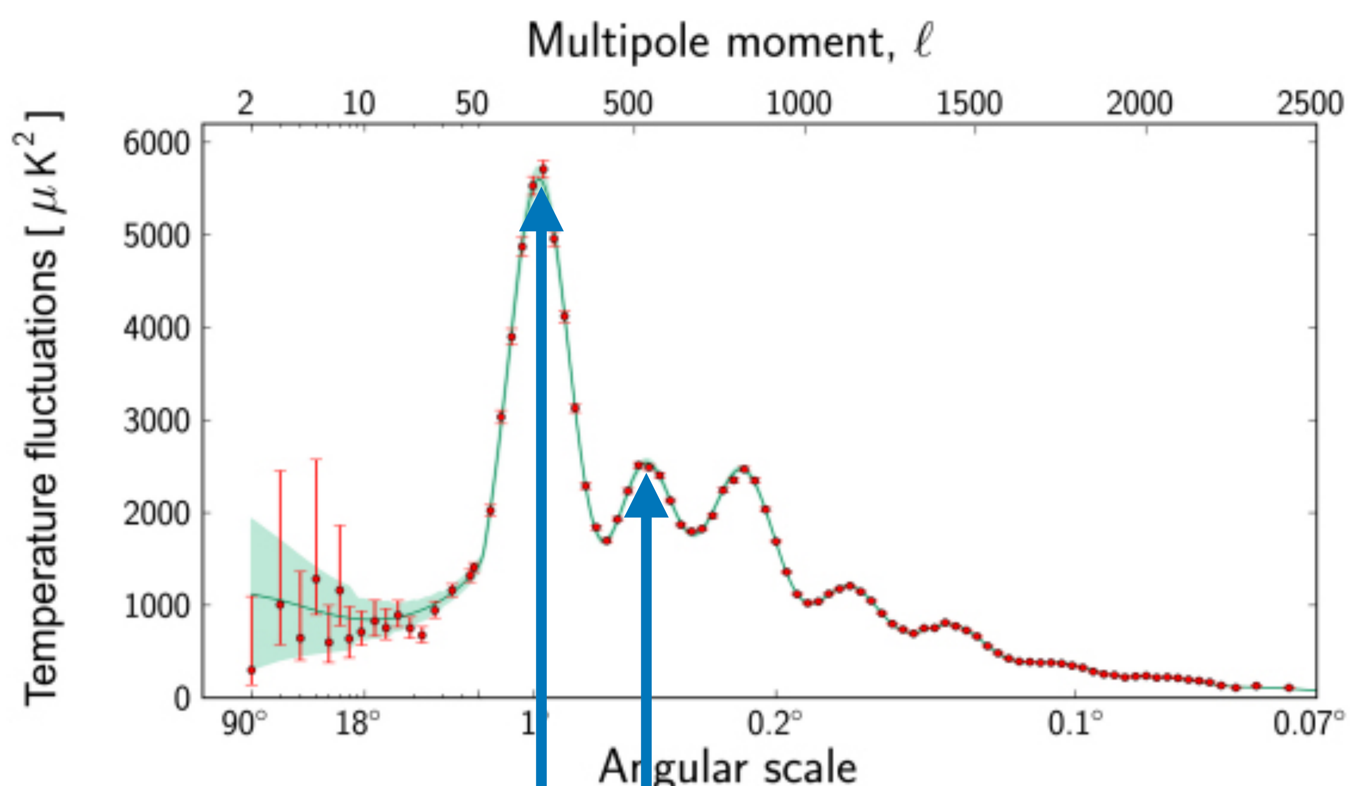
Matter 2-point function



Source

Peak height probes Ω_b/Ω_{DM}

CMB angular power spectrum



Planck

Ratio of peak heights probes Ω_b/Ω_{DM}. Current value is $\Omega_{DM}h^2$~0.18.

Basic features of dark matter

- Makes up 27% of total energy, 85% total matter
- Must be **dark**: interacts only weakly with photons
  - Can have a small fractional electric charge
  - Too much dissipation would lead to disks (possible in some models)
- Collisionless: $\frac{\sigma_{\mathrm{DM-DM}}}{m_{\mathrm{DM}}} \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$
  - Though as we discussed, this is not so small!

Basic features of dark matter

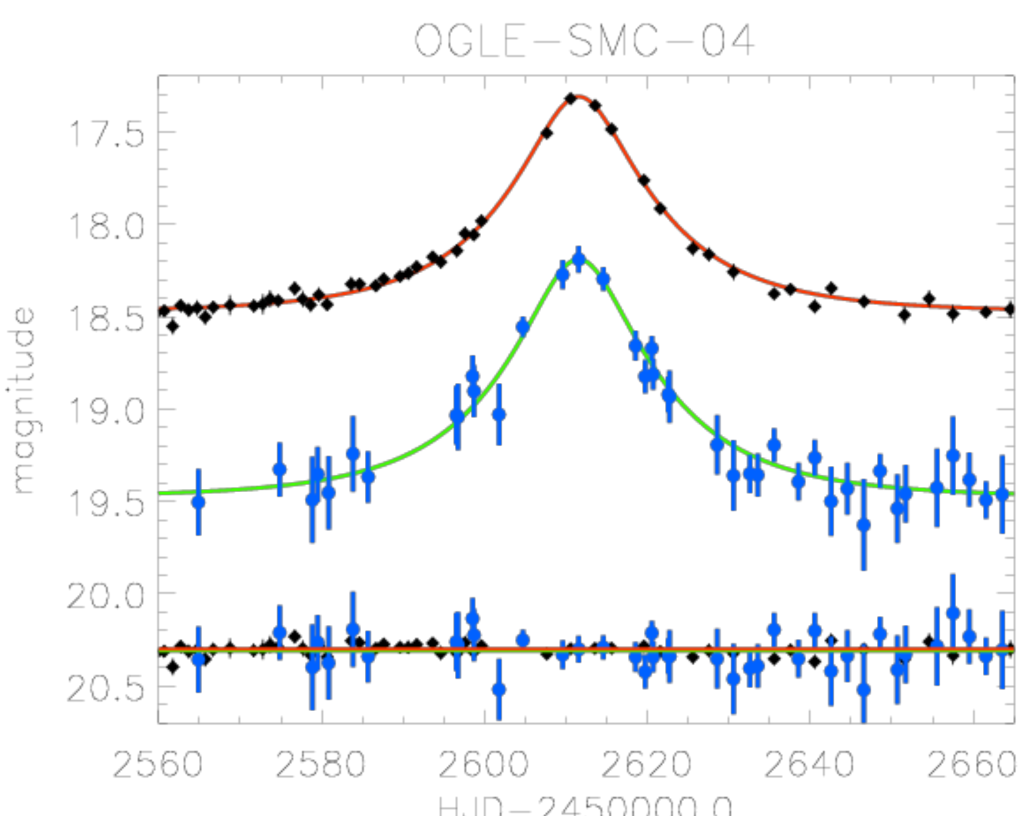
- Classical: must be confined on dwarf-galaxy scales
    - Q: given $M_{\rm dwarf} \sim 10^8\ M_\odot$, $r_{\rm dwarf} \sim 1$ kpc, what is an estimate for the lower bound on $m_{\rm DM}$?
    - Can improve this estimate for fermions:

$$\underbrace{M_{\rm dwarf} = V}_{\textbf{Dwarf's volume}} m_{\rm DM} \int d^3p\, f(p) \lesssim V m_{\rm DM} \int d^3p \sim V m_{\rm DM} (m_{\rm DM} \underbrace{v}_{\textbf{Set to virial velocity}})^3$$

    - Gives $m_{\rm DM} \gtrsim 10$ eV

Basic features of dark matter

- Cannot be massive compact halo objects (MACHOs)
  - Bounds from microlensing: small fluctuations in stars' brightness due to magnification



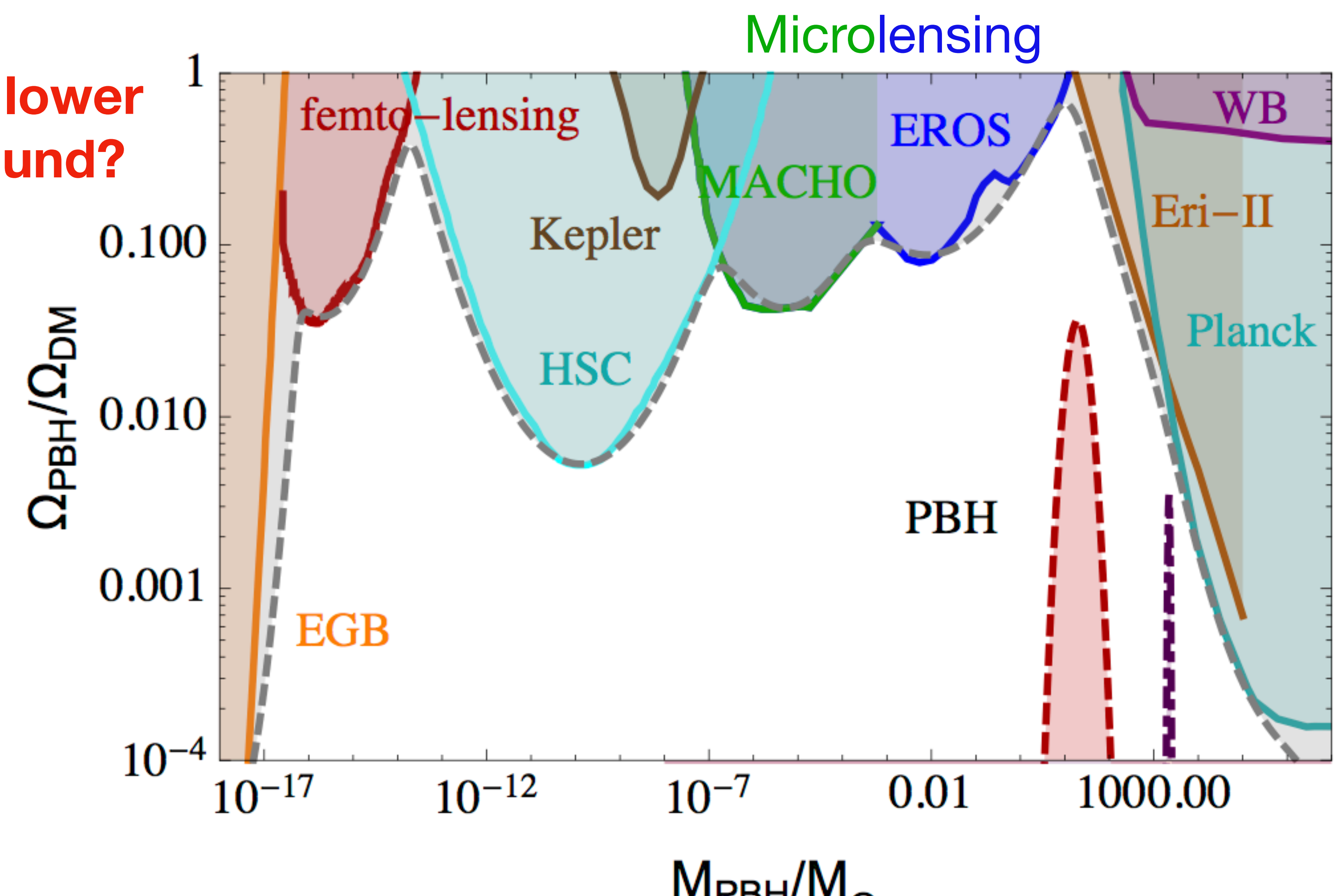
Source

- OGLE: observed 6 million stars for ~8 years; saw only 3 events
- Rules out MACHOs over the mass range ~$10^{-7} < M/M_\odot < 15$ making up all the dark matter

Basic features of dark matter

- A remaining baryonic candidate: primordial black holes
  - Form from very dense regions in the early universe

Q: why a lower mass bound?



Possible presentation topic!

Summary

- Dark matter explains observations on a variety of scales and throughout the universe's history
- Mass: 90 orders of magnitude available for bosons, 70 for fermions
- **Interactions:** self-interactions can be ~strong; interactions with normal matter are the topic of the next lectures!
- Cosmological abundance well known, reasonable knowledge of density and velocity distribution down to galactic scales

Thermal relics

- Particle initially in thermal equilibrium with Standard Model plasma due to reaction with rate $\Gamma = n \sigma v$
- As universe cools, $\Gamma \ll H$ (instantaneous approximation):
  - Particles cannot find each other to annihilate
- Particle drops out of equilibrium (decouples), and its abundance freezes out at T_{fo}
  - Number density redshifts to present value

Thermal relics

- Next, we'll study two types of relics:
  - Hot relic: $T_{fo} \gg m \Rightarrow n_{rel} \sim T^3$
  - Cold relic: $T_{fo} \ll m \Rightarrow n_{non\text{-}rel} \sim (mT)^{3/2}\, e^{-m/T}$
- Useful approximation:
  - $H(T) \sim T^2 / M_P$ in radiation era ($T > 1$ eV $\longleftrightarrow$ $z=3200$)
  - Reasonable since DM density perturbations need to seed structure formation
- Set v~c; can check later using T_{fo} and equipartition

Neutrinos as dark matter

- Example of a hot relic
- Kept in equilibrium by $\bar{\nu} + \nu \leftrightarrow \bar{f} + f$, where f is a light lepton
- Q: estimate cross section for this process (for $T_{fo} \gg m_{\nu}$)

$\sigma \sim \Big|$  $\Big|^2 \sim G_F^2\, T_\nu^2 \sim (10^{-5}\ \mathrm{GeV}^{-2})^2\ T_\nu^2$

- Q: what is the neutrino freeze-out temperature?

Neutrinos as dark matter

- Freeze-out condition:

$$\sigma(T_{\rm fo})\, n(T_{\rm fo}) = H(T_{\rm fo}) \to T_{\rm fo}^3 \cdot G_F^2 T_{\rm fo}^2 = \frac{T_{\rm fo}^2}{M_P} \implies T_{\rm fo} \sim 1 \text{ MeV}$$

- This verifies that $T_{fo} \gg T_\nu$ (hot relic condition)

- Redshift to get present-day abundance:

In general, linear in mass

$$n_0 = \frac{n(T_{\rm fo})}{a^3(T_{\rm fo})} \sim \left(\frac{1\,\text{MeV}}{10^9}\right)^3 \sim 10\,\text{cm}^{-3} \implies \Omega_\nu h^2 = \frac{\rho_\nu}{\rho_c} h^2 \sim \frac{m_\nu}{100\,\text{eV}}$$

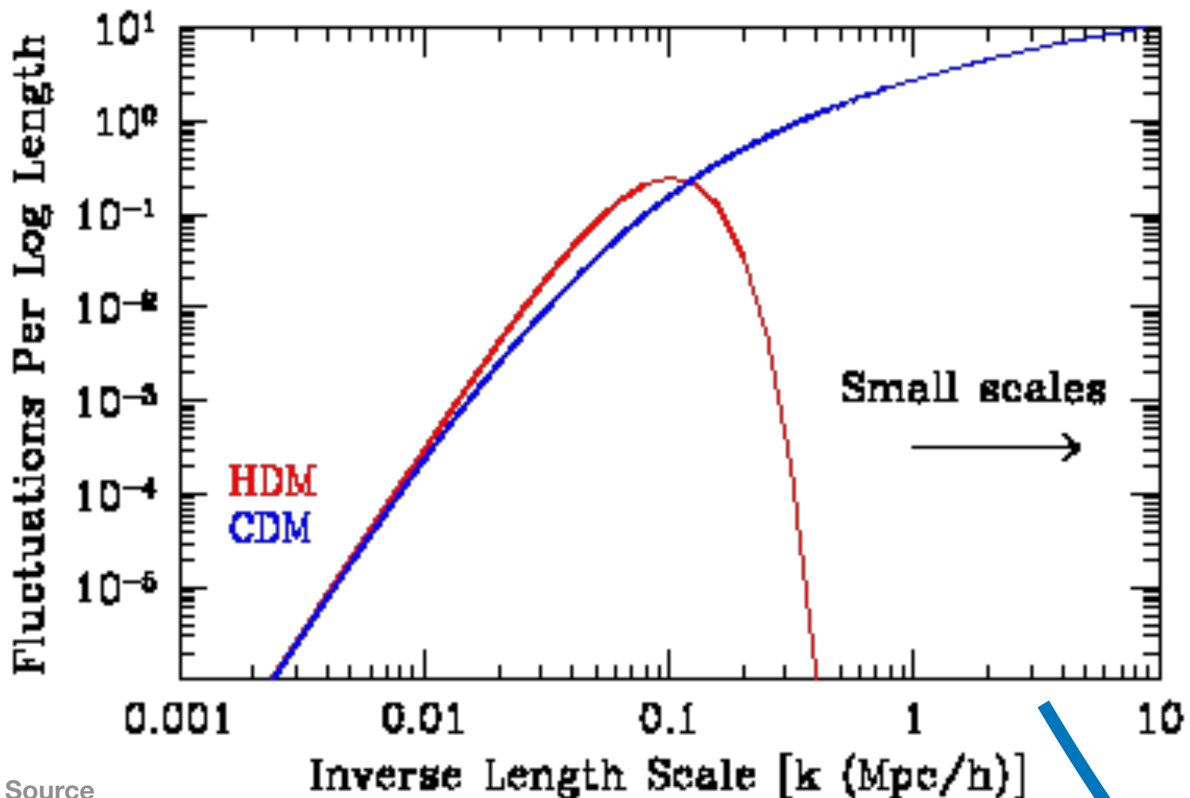
- Tritium β-decay ⇒ $m_\nu < 6$ eV, so $\Omega_\nu h^2 \sim 0.06$

- Much less than $\Omega_{DM} h^2 = 0.12$!

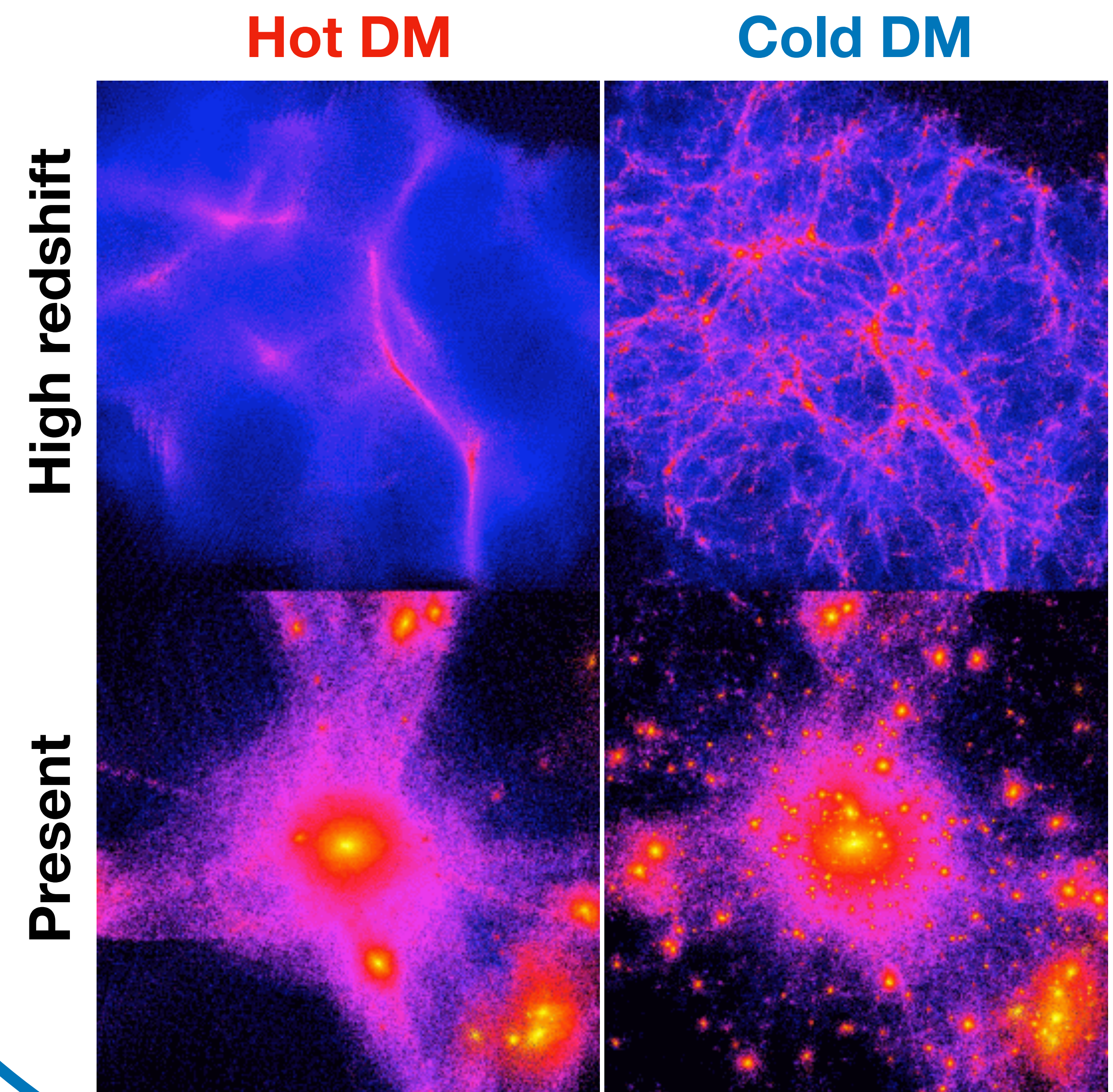
Neutrinos as hot DM

- Neutrinos free-stream out of overdensities until $T \lesssim m_\nu$
- During this time they travel a distance $d \sim 1/H(m_\nu) \sim M_P/m_\nu^2$
- Mass of fluctuation: $M \sim d^3\, m_\nu\, n_\nu(m_\nu) \sim M_P^3/m_\nu^2 \sim 10^{16}\, M_\odot$
- Timescale for gravitational collapse: $t_{\text{free-fall}} \sim (G\rho)^{-1/2}$
- Low $\rho \Rightarrow$ slow collapse: large structures collapse slowly
- No time for galaxies, stars, etc to form!

Neutrinos as hot DM



Source



Source

Neutrinos do not explain observed structure: cannot be the DM!

CDM: the WIMP miracle

- In CDM case, $n \sim (m\,T)^{3/2} \exp\left(-\frac{m}{T}\right) = \frac{m^3}{x^{3/2}} e^{-x}$
- Freeze-out condition: $n_{\rm fo}\,\sigma \sim H(T_{\rm fo}) \sim \frac{T_{\rm fo}^2}{M_P} \to \frac{m^3}{x_{\rm fo}^{3/2}} e^{-x_{\rm fo}} = \frac{m^2}{x_{\rm fo}^2 M_P \sigma}$
- Consider a WIMP, with $\sigma \sim G_F^2 m^2$, m~100 GeV: solving numerically gives x_{fo} ~ 20-50
- Present-day abundance:

$$\Omega_{\rm DM} = \frac{m\,n(T_0)}{\rho_c} = \frac{m\,T_0^3}{\rho_c}\frac{n(T_0)}{T_0^3} \underset{\uparrow}{=} \frac{m\,T_0^3}{\rho_c}\frac{n(T_{\rm fo})}{T_{\rm fo}^3} \underset{\uparrow}{=} \frac{x_{\rm fo}\,T_0^3}{\rho_c}\frac{1}{M_P\sigma} = 0.2\,\frac{x_{\rm fo}}{20}\left(\frac{10^{-8}\,{\rm GeV}^{-2}}{\sigma}\right)$$

$T \sim a^{-1}$, $n \sim a^{-3}$

FO condition

CDM: the WIMP miracle

$$\Omega_{\rm DM} = 0.2\,\frac{x_{\rm fo}}{20}\left(\frac{10^{-8}\,{\rm GeV}^{-2}}{\sigma}\right),\ x_{\rm fo} = \frac{m}{T} \sim 20,\ldots,50$$

- Q: what range of DM velocities does this correspond to?

- This corresponds to a cross section times velocity of

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \frac{\rm cm^3}{\rm s}$$

- The fact that weak-scale m and σ give the correct DM abundance is the WIMP miracle

- But for the right $\sigma \sim g^4/m^2$, other DM masses work fine.

For tomorrow

- **Install** essential coding tools: see the wiki at:

  https://github.com/adam-coogan/GRAPPA_Student_Seminar_2019

- Form groups of **four people;** have one person email me your names (a.m.coogan@uva.nl)

- Look at presentation topics, submit list of preferences

- Start looking at references for freeze-out calculation

Thank you!