Dark matter in astrophysics/cosmology

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1. A brief introduction to cosmology
2. **Observational evidence for dark matter**
3. Dark matter distribution
4. Constraints on the properties of dark matter
5. Overspill + what would you like to hear more about?

Observational evidence for dark matter

Galaxies

Galaxy clusters

Cosmic Microwave Background anisotropies

Large scale structure

Recommended further reading

- chapter 2 of 'Particle dark matter: evidence, candidates & constraints', Bertone, Hooper & Silk, Phys. Rep. hep-ph/0404175.
- chapter 1 of 'An introduction to particle dark matter', Profumo, World Scientific.
- Particle Data Group review of Particle Physics
  - Dark matter, Baudis & Profumo
  - Cosmic microwave background, Scott & Smoot
  - Cosmological parameters, Lahav & Liddle

Historical perspectives:

- 'The dark matter problem a historical perspective', Sanders, Cambridge University Press.
- 'History of dark matter', Bertone & Hooper, arXiv:1605.04909.
- chapters 6 & 7 of 'Cosmology's century: an inside history of our modern understanding of the universe', Peebles, Princeton University Press.

Useful broader textbooks:

- 'Galactic dynamics', Binney & Tremaine, Princeton University Press.
- 'Dynamics and astrophysics of galaxies', Bovy, Princeton University Press (in preparation)
- 'Introduction to cosmology', Ryden, Cambridge University Press.

Galaxies

Rotation curves   Rubin & Ford; Freeman;…

Stars and neutral hydrogen gas in spiral galaxies, move in circular orbits due to the force of gravity.

Speed measured from Doppler shift of hydrogen 21cm line.

NASA

Using Newton’s law of gravity (and also Newton’s Second Theorem: the gravitational force outside a closed spherical shell of matter is the same as if all the matter were concentrated at a point at its centre):

$$\frac{v_{rot}^2}{r} = \frac{GM(< r)}{r^2}$$

$M(< r)$ = mass enclosed within a radius r.

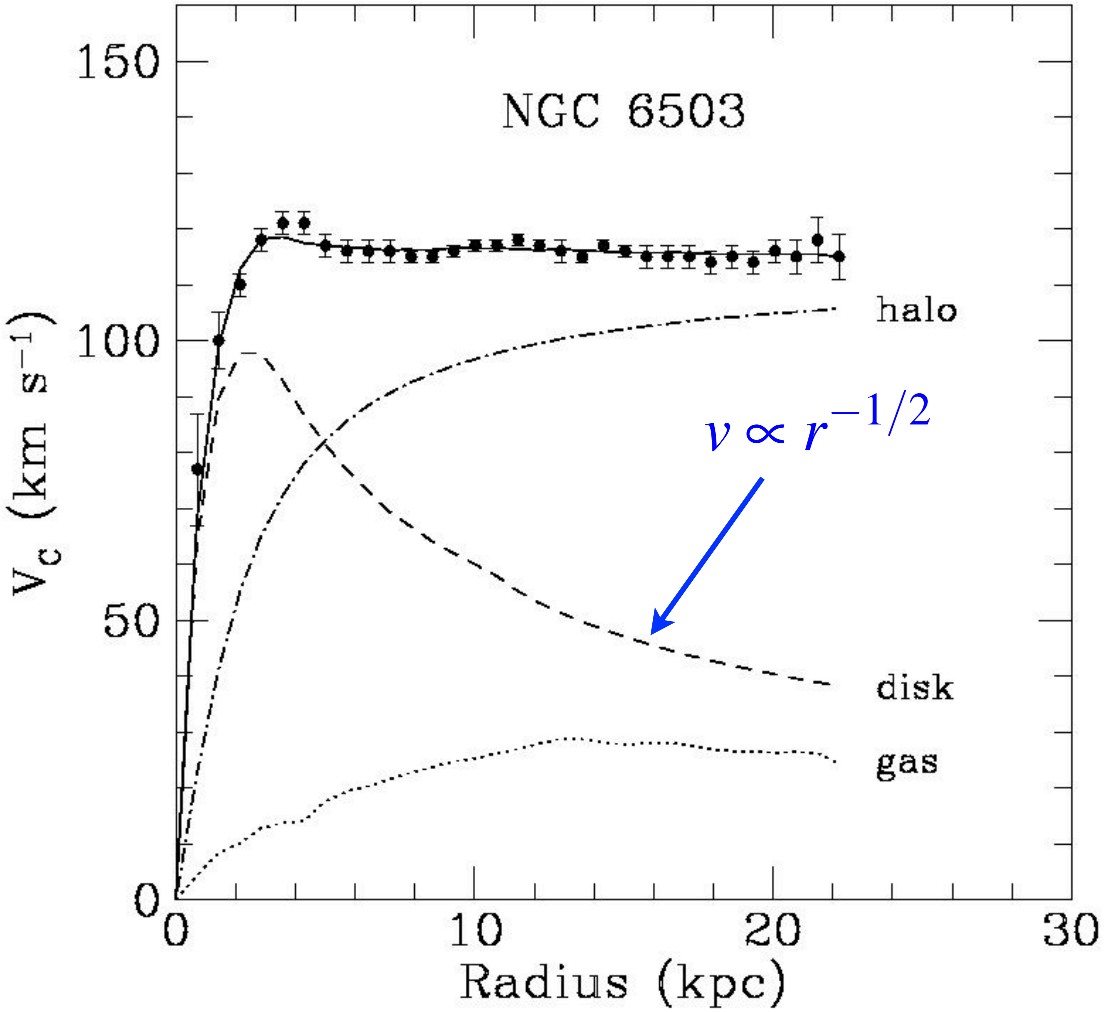
$$= \int_0^r 4\pi r^2 \rho(r)\,\mathrm{d}r$$

$$v_{\mathrm{rot}} = \sqrt{\frac{GM(< r)}{r}}$$

Outside of matter distribution:

$M(< r)$ is constant and $v_{\mathrm{rot}} \propto r^{-1/2}$

‘Keplerian fall-off’



$v \propto r^{-1/2}$

Begeman, Broeils & Sanders

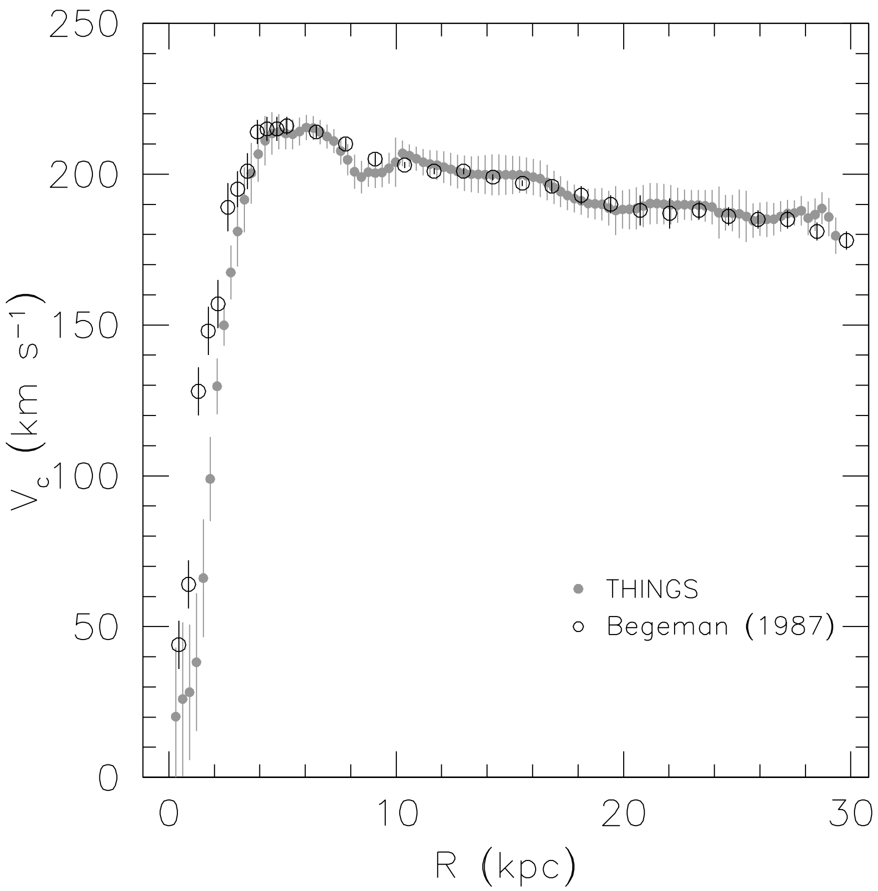
$$v_{\rm rot} = \sqrt{\frac{GM(<r)}{r}}$$

$$v_{\rm rot} \sim \text{const} \quad \rightarrow \quad M(<r) \propto r \quad \rightarrow \quad \rho(r) \propto r^{-2}$$

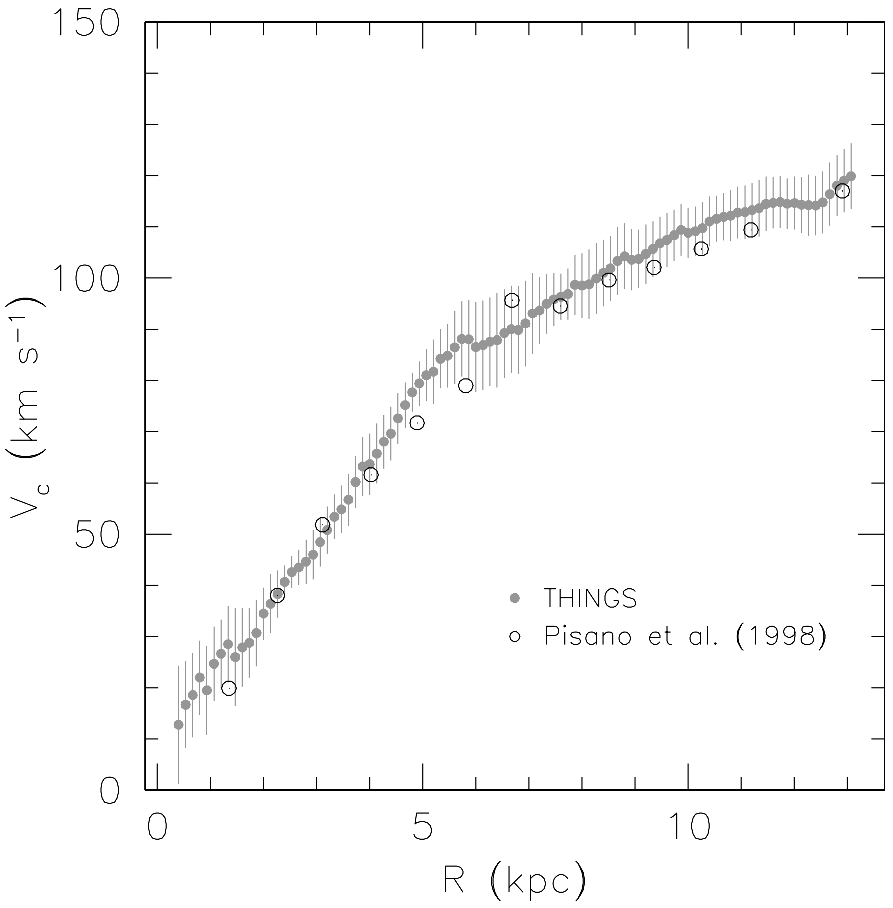
(Assuming Newtonian gravity is correct) galaxies are surrounded by extended halos of invisible dark matter.

N.b. (more in section 3):

i) Not all rotation curves are exactly flat.



NGC 2903



NGC 925

de Blok et al. from The HI Nearby Galaxy Survey

ii) Dark matter halos extend to larger radii than ‘luminous’ components and simulated halos have density profiles, $\rho(r)$, that are shallower (steeper) than r^{-2} at small (large) radii.

Disk stability Ostriker & Peebles

Self-gravitating disks form bars (‘bar instability’) unless they have large velocity dispersion.

Embedding disks in a massive, more extended, ~spherical halo is a solution to this.

Galaxy clusters

Contain 100s or 1000s of galaxies plus hot X-ray emitting gas.

Largest gravitational bound objects in Universe, therefore expect that the material they contain is roughly representative of the Universe as a whole.

Coma cluster

Misti Mountain Observatory

Total mass from virial theorem Zwicky; Smith

For a self-gravitating system in equilibrium, kinetic energy (T) and potential energy (V) are related by the virial theorem (see e.g. Binney & Tremaine): $2T + V = 0$

kinetic energy: $T = \frac{1}{2}\sum_i m_i v_i^2$

mean square velocity: $\langle v^2 \rangle = \frac{\sum_i m_i v_i^2}{\sum_i m_i} = \frac{2T}{M}$

potential energy: $V = -\frac{1}{2}\sum_i \sum_{j \neq i} \frac{G m_i m_j}{r_{ij}}$

define gravitational radius: $R_G = 2\left(\sum_i m_i\right)^2 \left(\sum_i \sum_{i \neq j} \frac{m_i m_j}{r_{ij}}\right)^{-1}$

$$V = -\frac{GM^2}{R_\mathrm{G}}$$

then, from 2T + V =0, total mass, M: $M = \sum_i m_i = \frac{R_\mathrm{G}\langle v^2 \rangle}{G}$

estimate R_G from projected positions of galaxies and $\langle v^2 \rangle$ from speeds.

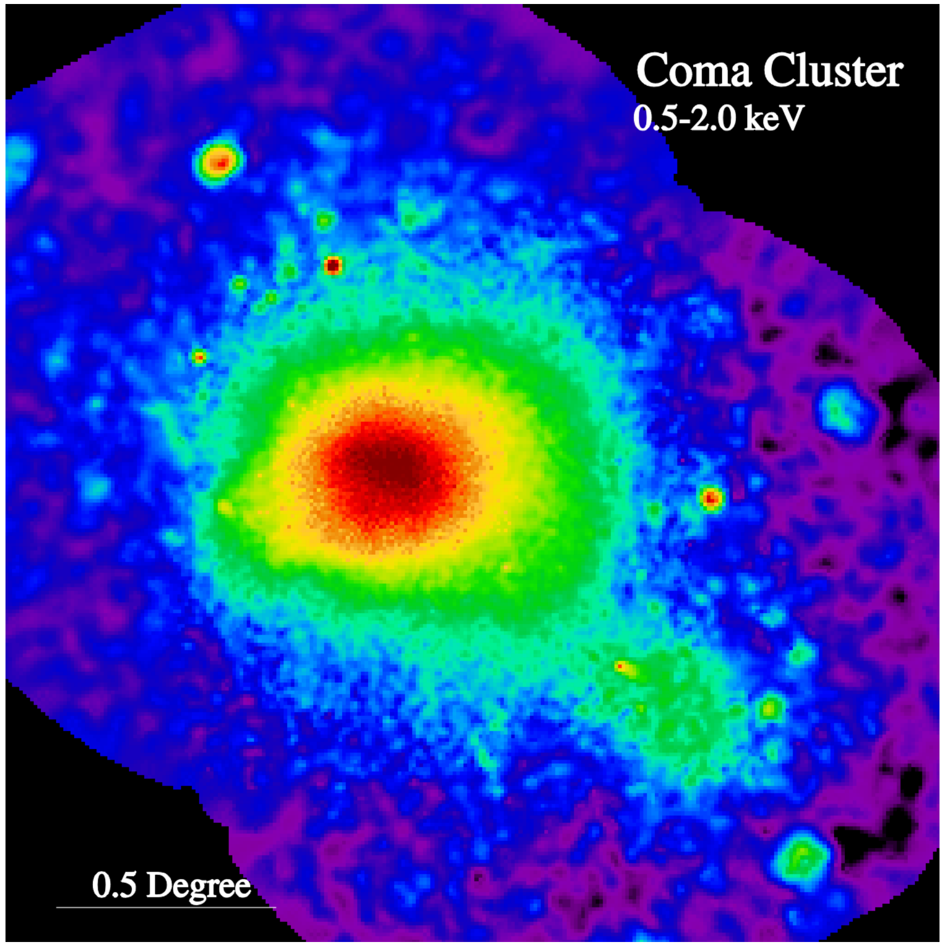
$$\rightarrow \quad \frac{M}{L} \sim 400 \frac{M_\odot}{L_\odot}, \qquad \equiv \quad \Omega_\mathrm{m} \sim 0.3$$

(see e.g. Ryden for more details)

Baryon fraction from X-ray emitting gas

optical image

ROSAT X-ray image



Snowden USRA, NASA/GSFC

Baryon fraction:

$$f_\mathrm{b} = \frac{M_\mathrm{b}}{M_\mathrm{tot}}$$

$$= \frac{\Omega_\mathrm{b}}{\Omega_\mathrm{m}}$$ assuming clusters are a ‘fair sample’ of Universe

Assuming the gas is spherically symmetric and in hydrostatic equilibrium (so that the pressure gradient force and gravity balance):

$$\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM(<r)}{r^2}$$

using ideal gas law:

$$P = \frac{k_{\mathrm{B}}}{\mu m_{\mathrm{p}}}\rho T$$

$$\frac{k_{\mathrm{B}}T}{\mu m_{\mathrm{p}}}\left(\frac{\mathrm{d}\ln T}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}\right) = -\frac{GM(<r)}{r}$$

from X-ray spectra

from X-ray surface brightness

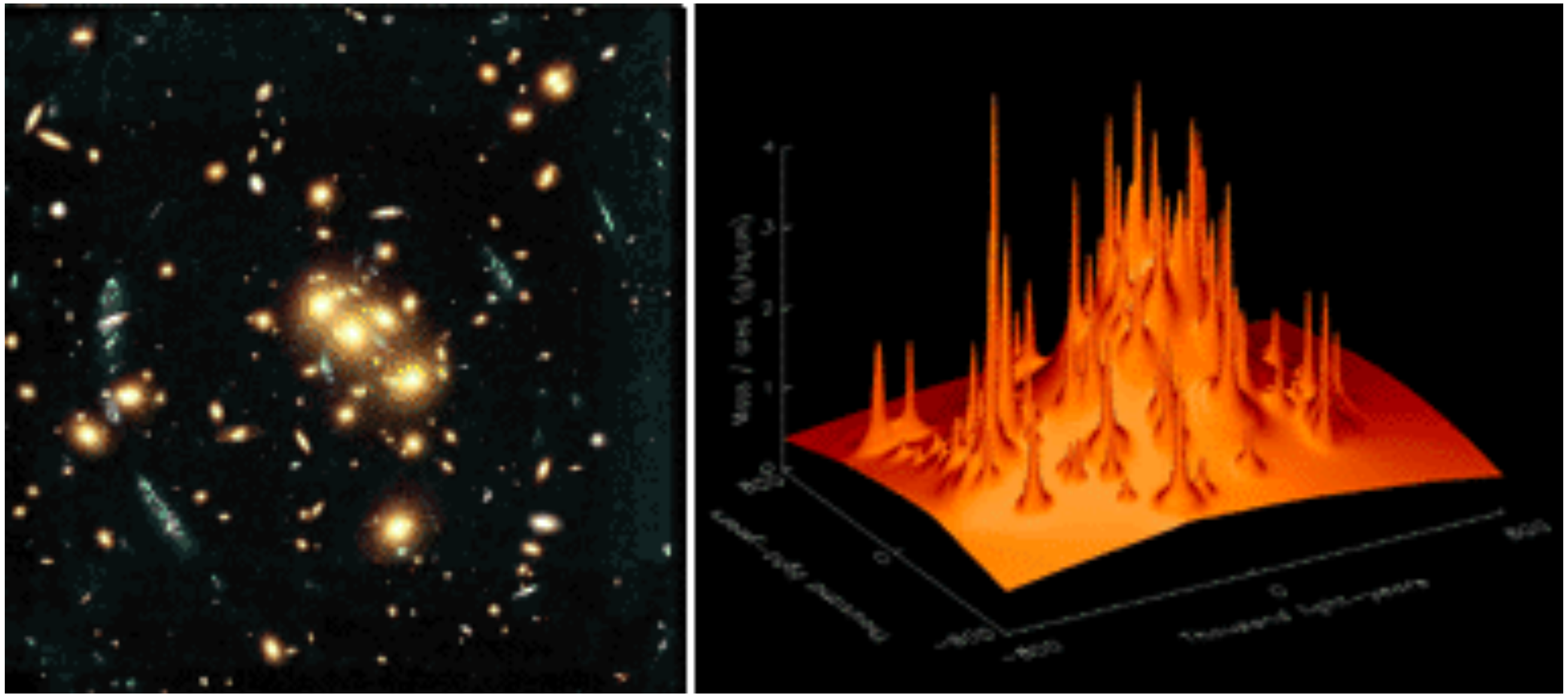
$$f_{\mathrm{b}} = 0.144 \pm 0.005$$

Gonzalez et al.

n.b. systematic from e.g. deviations from hydrostatic equilibrium, uncertainties in cluster temperature-mass relation.

mass distribution from gravitational lensing

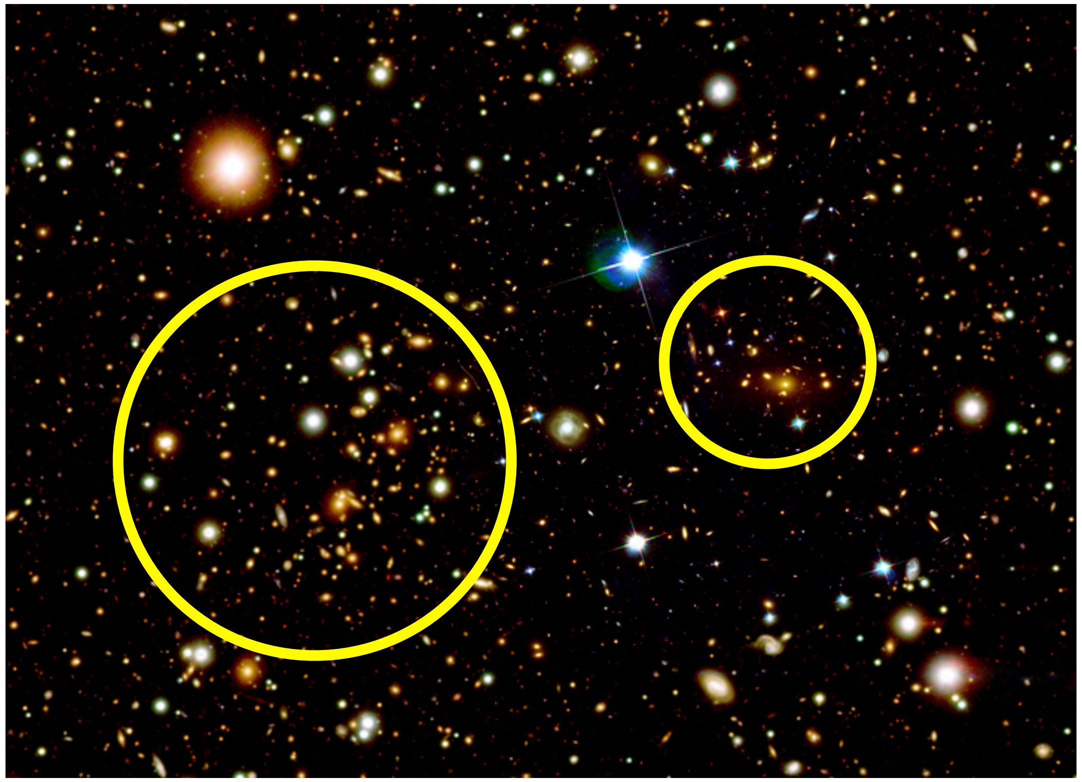
Strong lensing of galaxy behind galaxy cluster CL0024+1654:



Tyson, Kochanski & Dell’Antonio

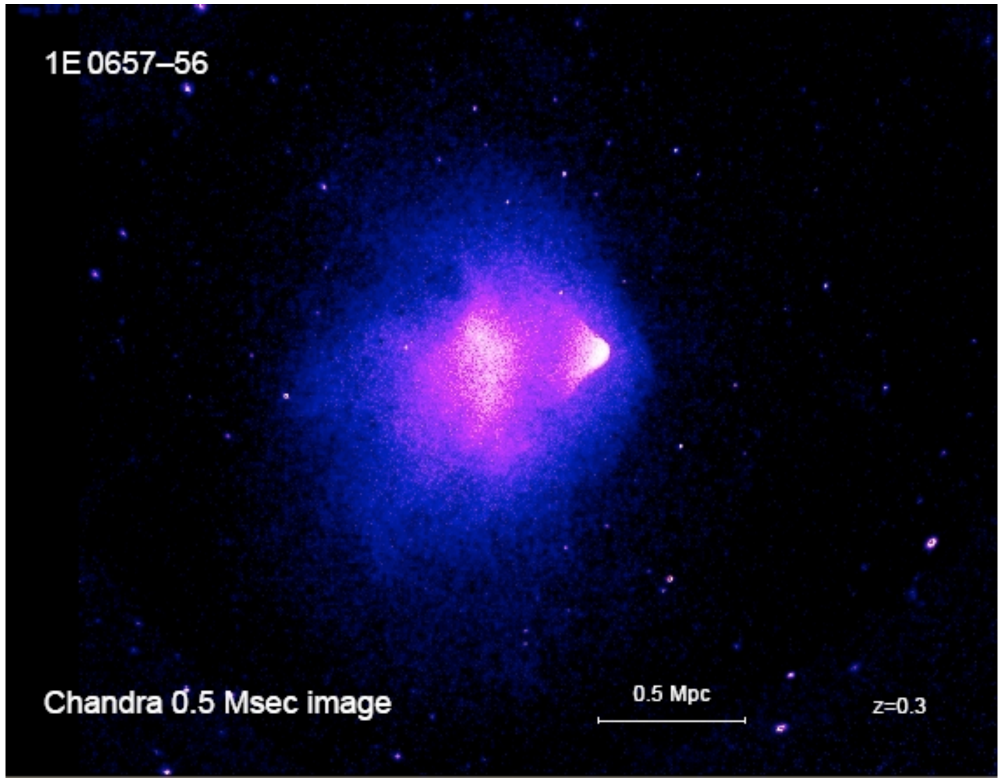
the bullet cluster Clowe et al.

optical image

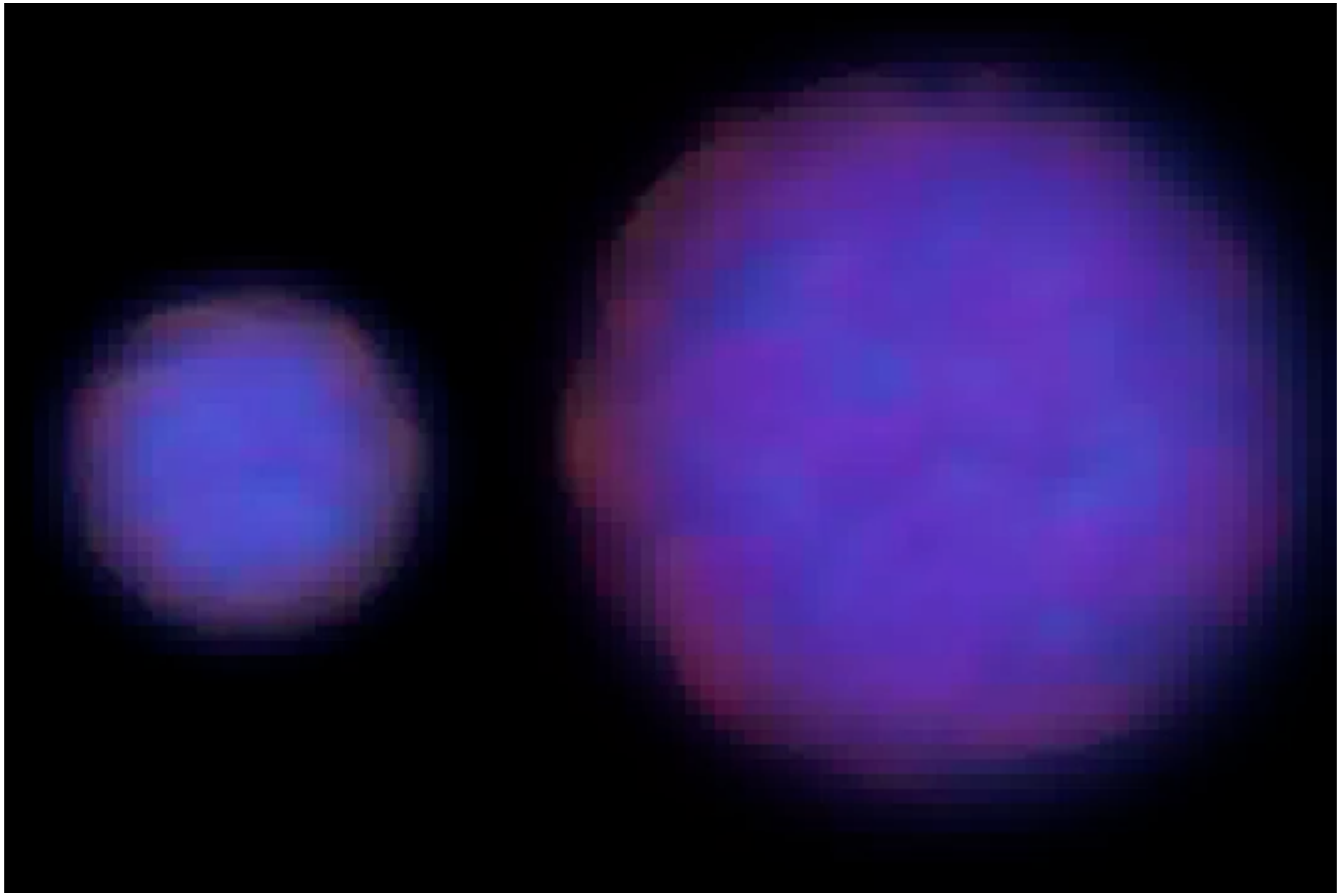


NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

X-ray image

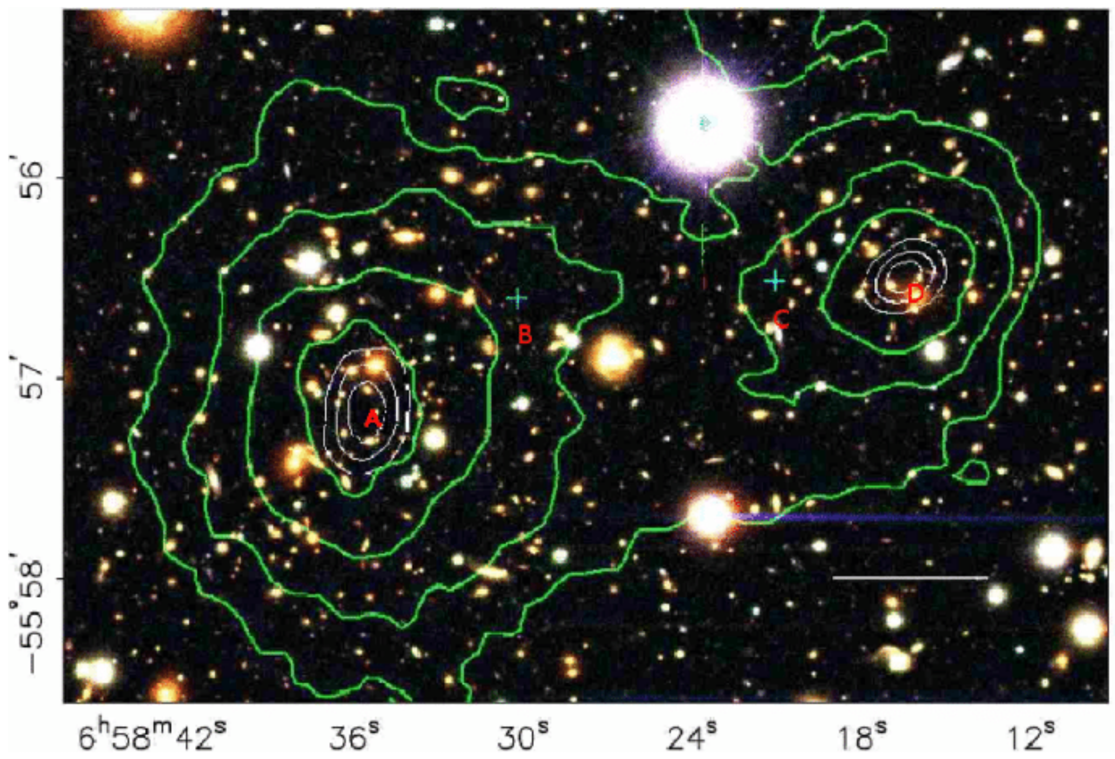


NASA/CXC/M.Markevitch et al.



NASA/CXC/M.Weiss

weak lensing mass contours



NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

composite image

X-ray: NASA/CXC/M.Markevitch et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.
Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Separation of gravitational potential (reconstructed from weak lensing obs.) and dominant baryonic mass component (hot gas, X-ray emission imaged by Chandra).

→ dark matter

n.b. lensing analysis assumes GR, however explaining these observations is a big challenge for modified gravity theories.

Cosmic microwave background anisotropies

Amplitude of perturbations:

On large angular scales: $$\frac{\Delta T}{T} \sim 10^{-5}$$

density fluctuations

↓

fluctuations in gravitational potential $$\nabla^2(\delta\Phi) = 4\pi G \delta\epsilon$$

↓

red/blue shift of photons $$\frac{\delta T}{T} = \frac{1}{3}\delta\Phi$$

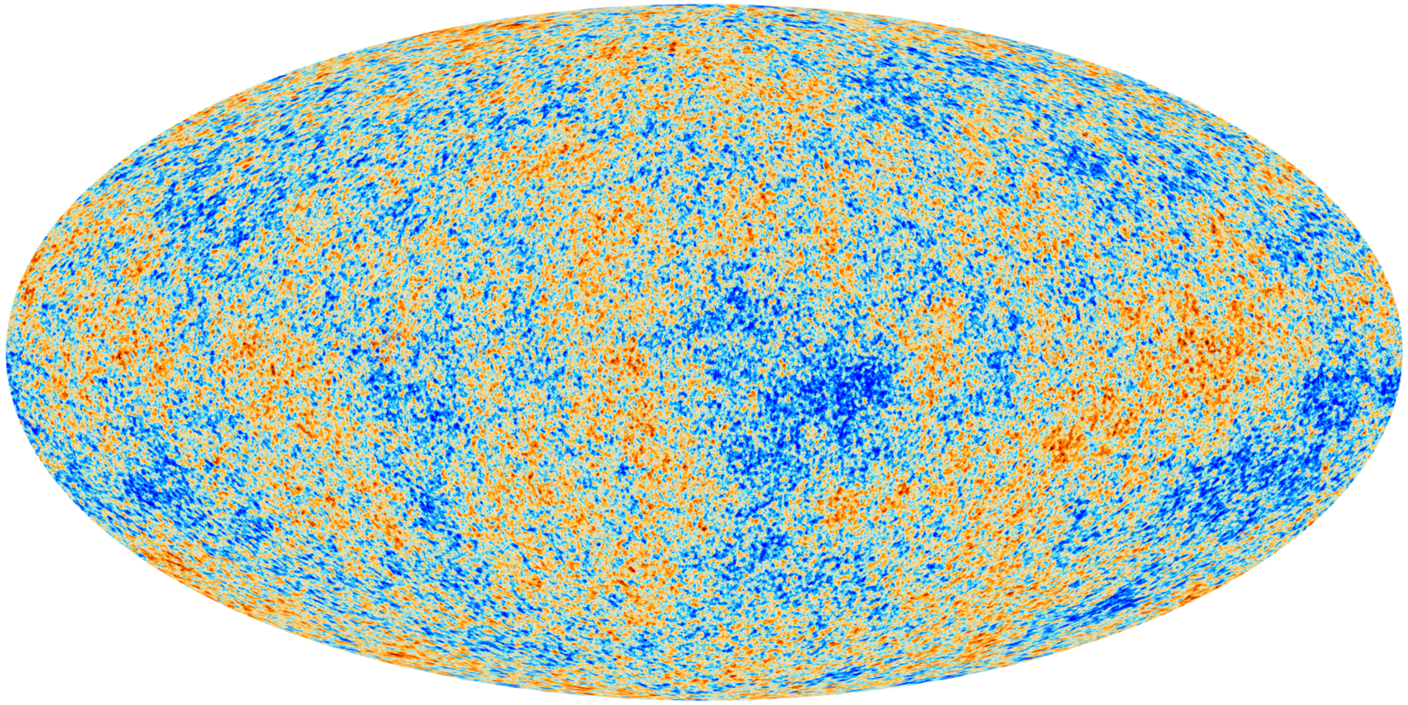
(sub-horizon) Density perturbations in dark matter grow ∝ a from radiation-matter equality (t ~ 0.05 Myr).

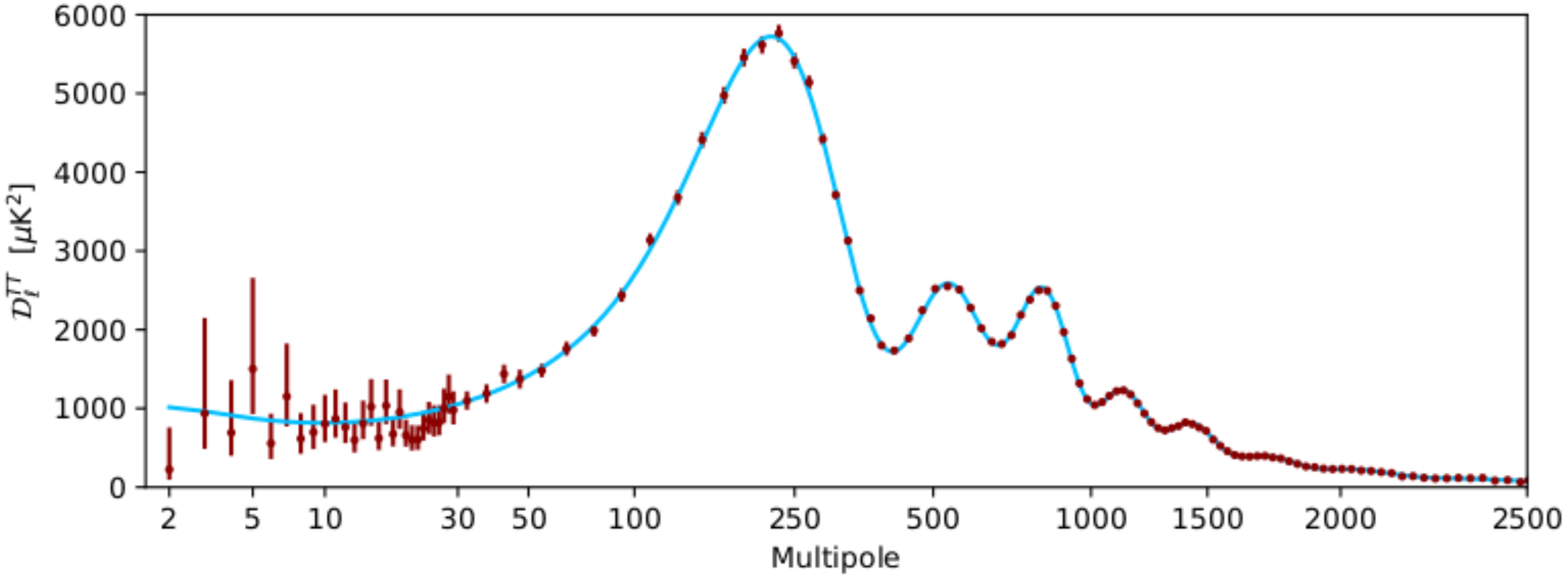
Baryons are tightly coupled to photons until decoupling (t ~0.4 Myr) and perturbations in baryons can only grow after decoupling.

Therefore in a universe without non-baryonic DM initial perturbations have to be larger ($\Delta T/T \sim 10^{-4}$) for observed structures to form.

For perturbations to grow sufficiently from initial measured amplitude, requires non-baryonic DM.

Characteristic angular scale (in particular position of first peak):





Planck 2018

Characteristic angular scale (in particular position of first peak):

Positions of peaks/characteristic size of hot/cold spots determined by ratio of sound horizon at last scattering ('standard ruler') to angular diameter distance (distance an object of known length appears to have)

$$\theta_{\rm hor} = \frac{d_{\rm hor}(t_{\rm ls})}{d_{\rm A}}$$

horizon distance at last scattering:

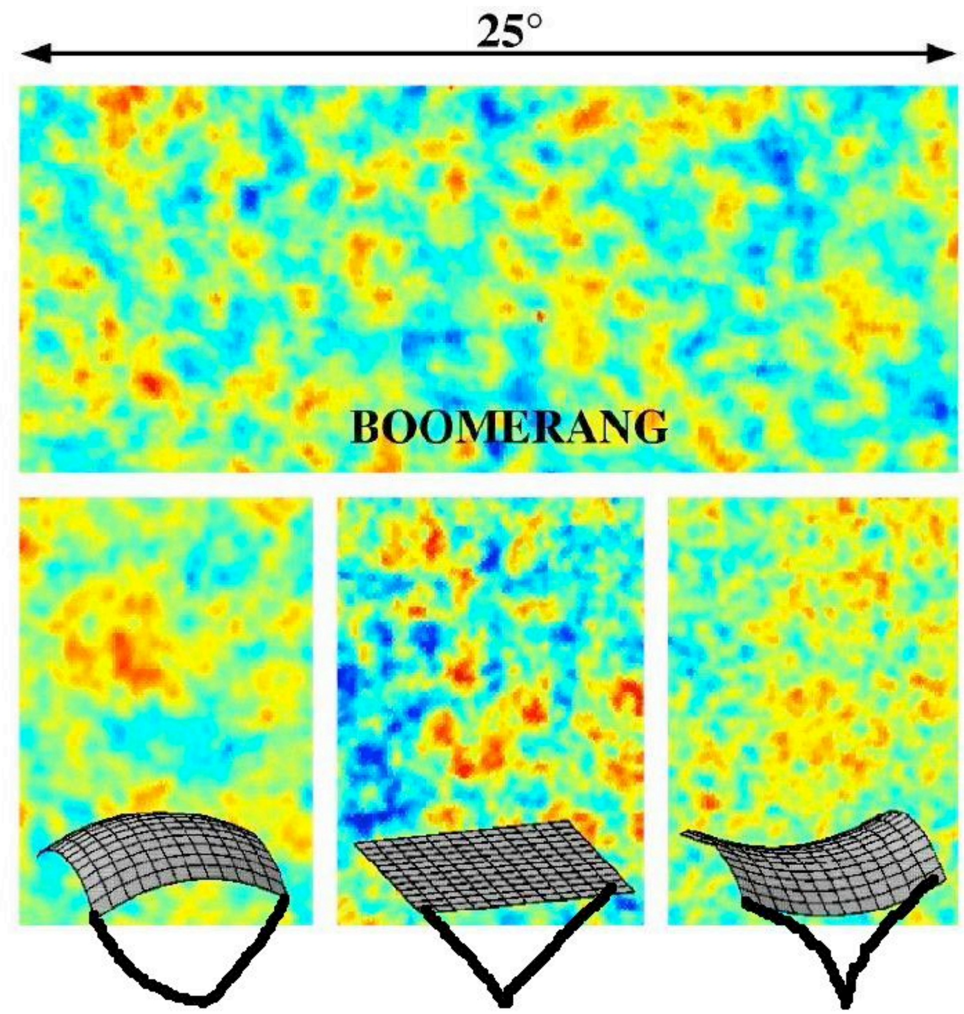
$$d_{\rm hor} = a(t_{\rm ls}) \int_0^{t_{\rm ls}} \frac{{\rm d}t}{a(t)}$$

angular diameter distance (flat k=0):

$$d_{\rm A} \equiv \frac{l}{\delta\theta} = \frac{ar\delta\theta}{\delta\theta} = \frac{r}{(1+z)}$$

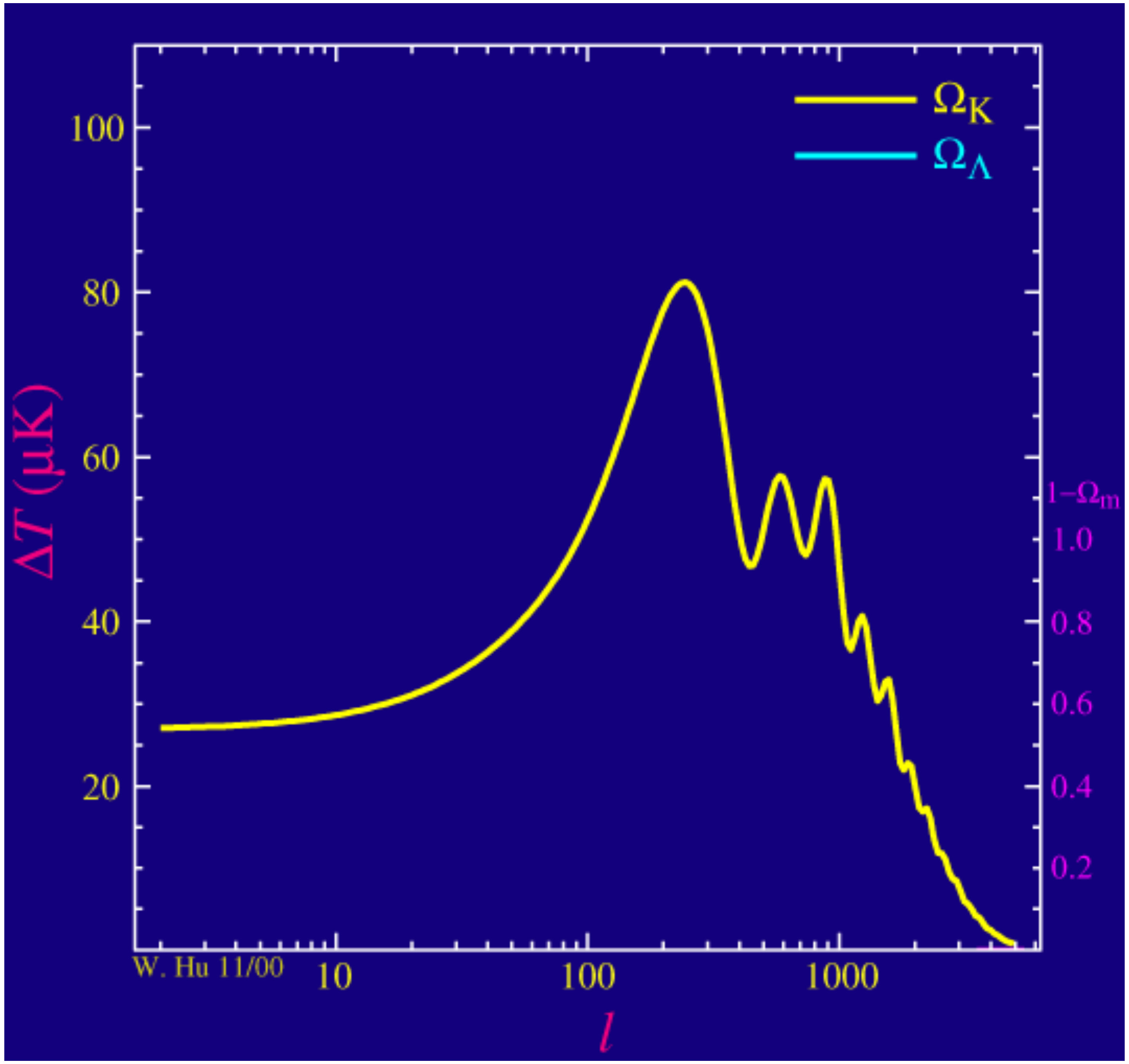
$$d_{\rm A} = \frac{1}{1+z} \int_{t_{\rm ls}}^{t_0} \frac{{\rm d}t}{a(t)}$$

For large z: $d_{\rm A} \approx \dfrac{d_{\rm hor}(t_0)}{z}$



BOOMERANG

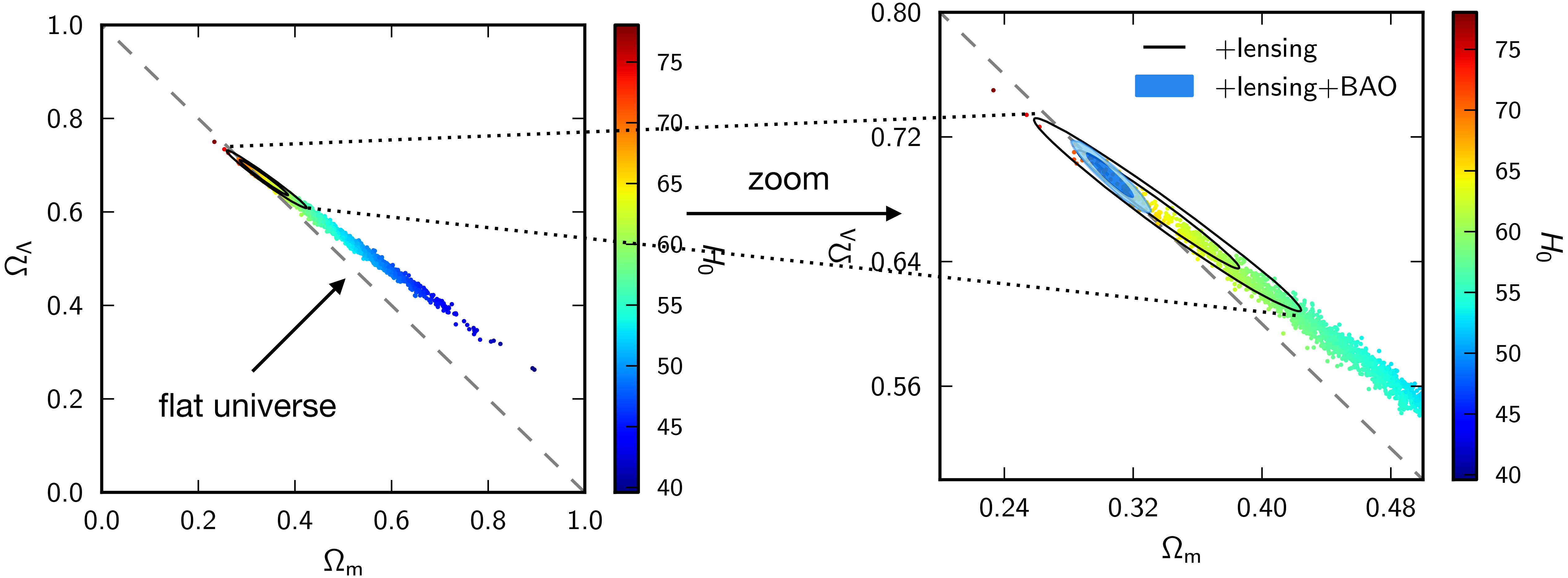
Positions of peaks (mostly) depends on geometry of Universe:



Wayne Hu's web-page

CMB temperature & polarisation + lensing

+ BAO



Planck 2013

Planck 2018:

From temperature, polarisation and (CMB) lensing data:

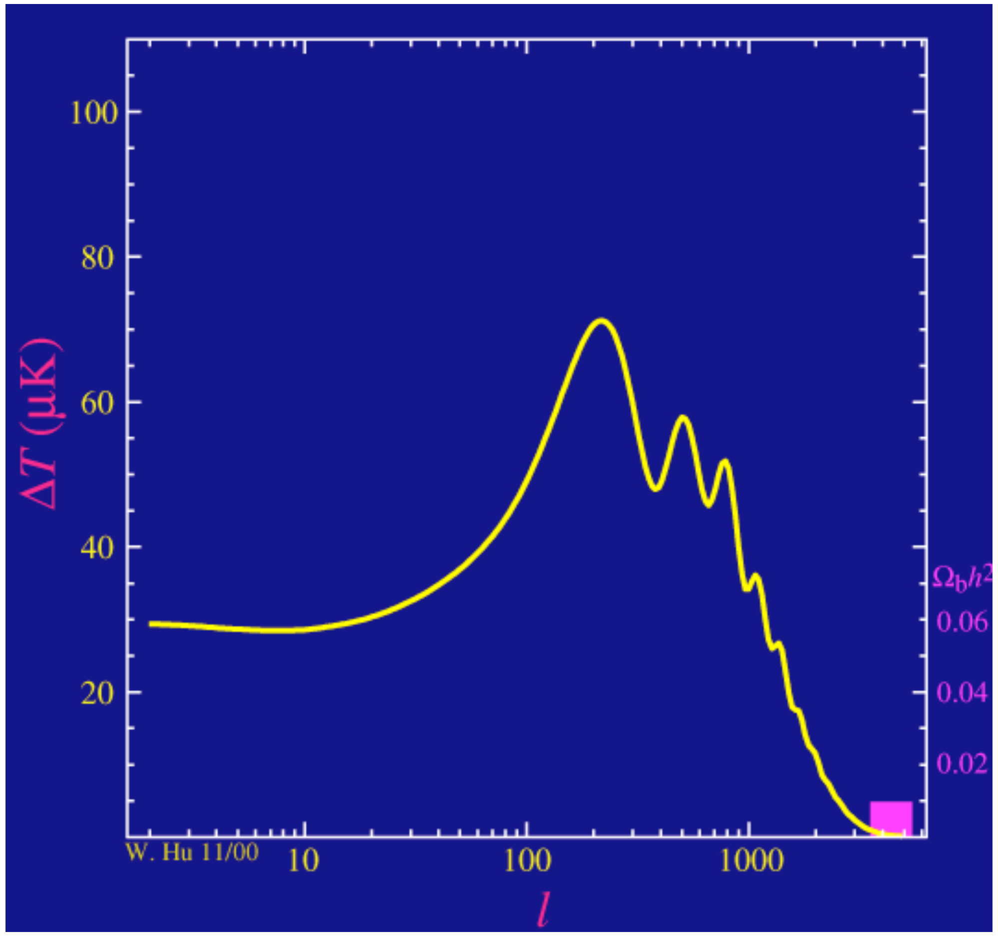
$$\Omega_k = 1 - (\Omega_m + \Omega_\Lambda) = -0.0106 \pm 0.0065$$

Total energy density very close to critical density for which geometry of Universe is flat.

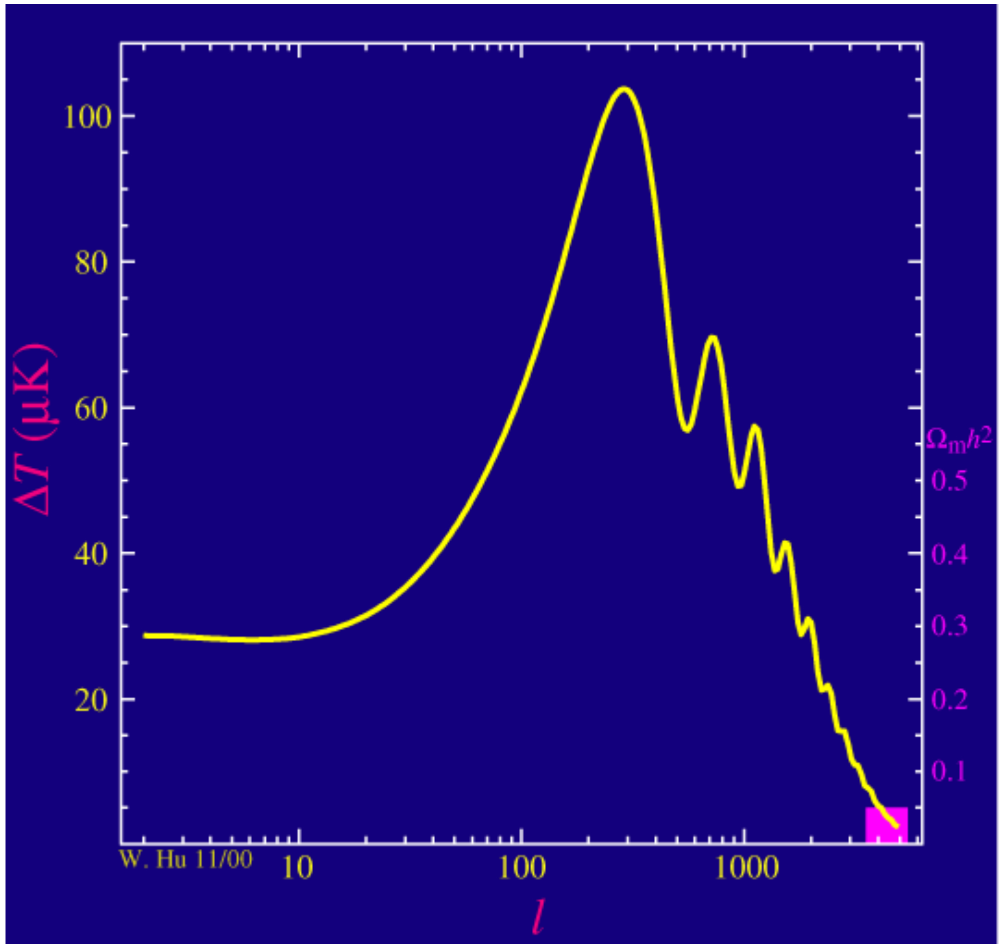
Heights of peaks:

depends on baryon and matter densities:

increased baryon density increases loading of oscillations and enhances odd peaks



increased matter density increases height of 3rd peak



Wayne Hu's web-page

Planck 2018:

From temperature, polarisation and (CMB) lensing data:

$$\Omega_b h^2 = 0.02237 \pm 0.00015$$

cold dark matter →

$$\Omega_c h^2 = 0.1200 \pm 0.0012$$

Large scale structure

Typically not as powerful/clean a probe of cosmological parameters alone, as the CMB (galaxies are biased tracers of the matter distribution, redshift is combination of expansion and peculiar velocity,…).

However different observables have different degeneracies (combinations of parameters they're insensitive to), so combining data sets can lead to more precise constraints (but need to check data sets are consistent first…).

latest results from Dark Energy Survey (DES)

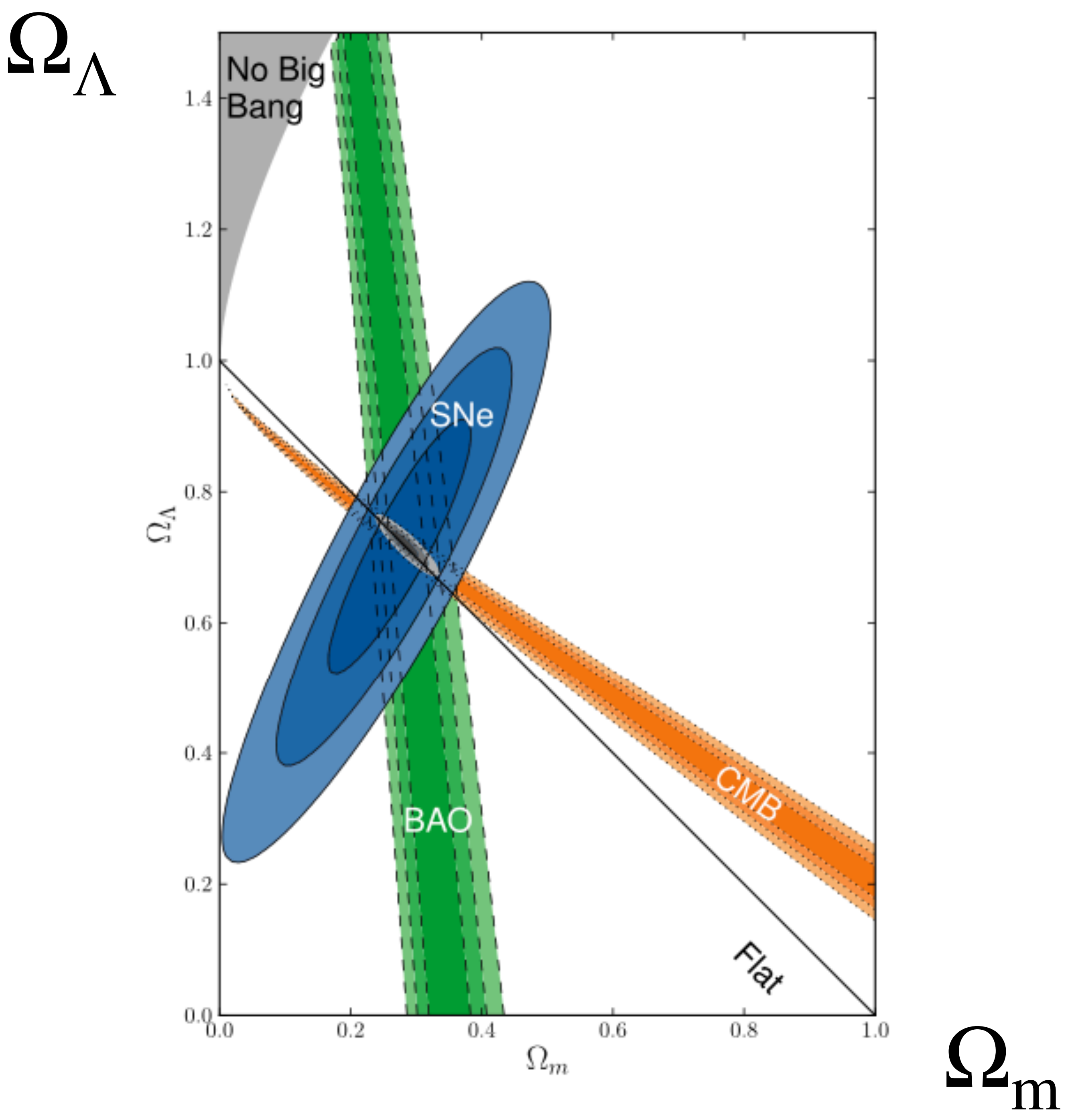
Analysis combining
  i) cosmic shear (weak lensing)
  ii) galaxy clustering
  iii) galaxy-galaxy lensing

$$\Omega_{\rm m} = 0.34 \pm 0.03$$

Combined with other cosmological datasets (including Planck, BAO, BBN, h,):

$$\Omega_{\rm m} = 0.306^{+0.004}_{-0.005}$$

Cosmic concordance



Supernova cosmology project [Suzuki et al.]

n.b. BAO errors have shrunk since this plot (2012)
SNe: statistical errors only

What about modified gravity?

All the evidence for dark matter to date comes from its gravitational effects.

Could the observations be explained by instead modifying the laws of gravity?

Newton’s laws have been tested to high accuracy on terrestrial scales. The laws of gravity could, in principle, be different on astronomical/cosmological scales. But hard to explain all of the diverse (nature and scale) evidence.

See lectures by Justin Khoury.

Summary

There's lots of cosmological and astronomical evidence that non-baryonic cold dark matter makes up ~25% of the total energy density of the Universe.

All of the evidence for DM comes from its gravitational effects-could the observations be explained by modified gravity instead?
See lectures by Justin Khoury.

Next section: how is DM distributed within galaxies?
(theory, simulations, observations)

Backup slides