Dark Matter
Lecture 1: historical overview + cosmology

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Goals for these lectures

- Summarize the evidence for dark matter (DM)
- Understand the broad space of possibilities for DM and how they are bounded by cosmology
- Understand classic benchmark scenarios + production mechanisms, spanning the full range of possible DM masses
- Describe a range of strategies for experimentally detecting dark matter
- Today: historical overview of how the puzzle of DM developed + what you need to know about cosmology

The missing mass

- Zwicky, 1933: estimated the mass in a galaxy cluster in two ways.

Method 1

Estimate mass from mass-to-light ratio, calibrated to local system.

- Count galaxies
- Add up total luminosity
- Convert to mass using mass-to-light ratio of ~3, calibrated from local Kapteyn stellar system.

Mass estimate 1

Method 2

Use virial theorem + measurements of galaxy velocities to estimate gravitational potential, and hence infer mass.

Galactic velocities measured by Doppler shifts

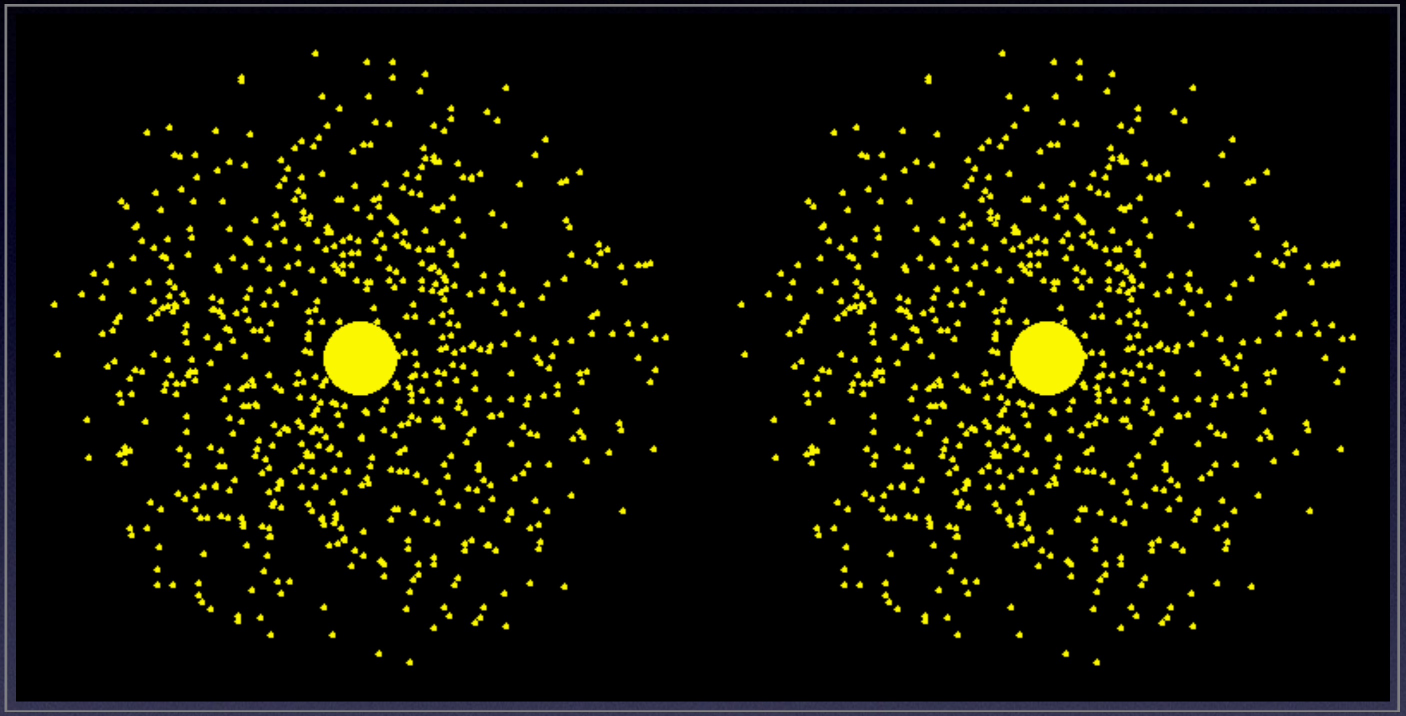
$$\mathrm{KE} = -\frac{1}{2}\mathrm{PE}$$ in equilibrium

Mass estimate 2

- These numbers are different by 2+ orders of magnitude (second one is larger).
- One possibility: there is (lots of) gravitating non-luminous matter.

Rotation curves

Expected



Actual

- Rubin, Ford & Thonnard 1980 (following work in the 1970s): galactic rotation curves are flat, not falling as one would expect if mass was concentrated in the bulge at the Galactic center.
- Modified gravity? Or some "dark" unseen matter? If the latter, needs to extend to much larger radii than the observed Galactic disk - "dark halo".

$$\frac{v^2}{r} = \frac{GM(r)}{r^2}$$

$$M(r) = M \Rightarrow v \propto \frac{1}{\sqrt{r}}$$

$$M(r) \propto r \Rightarrow v \,\mathrm{constant}$$

Rotation curves

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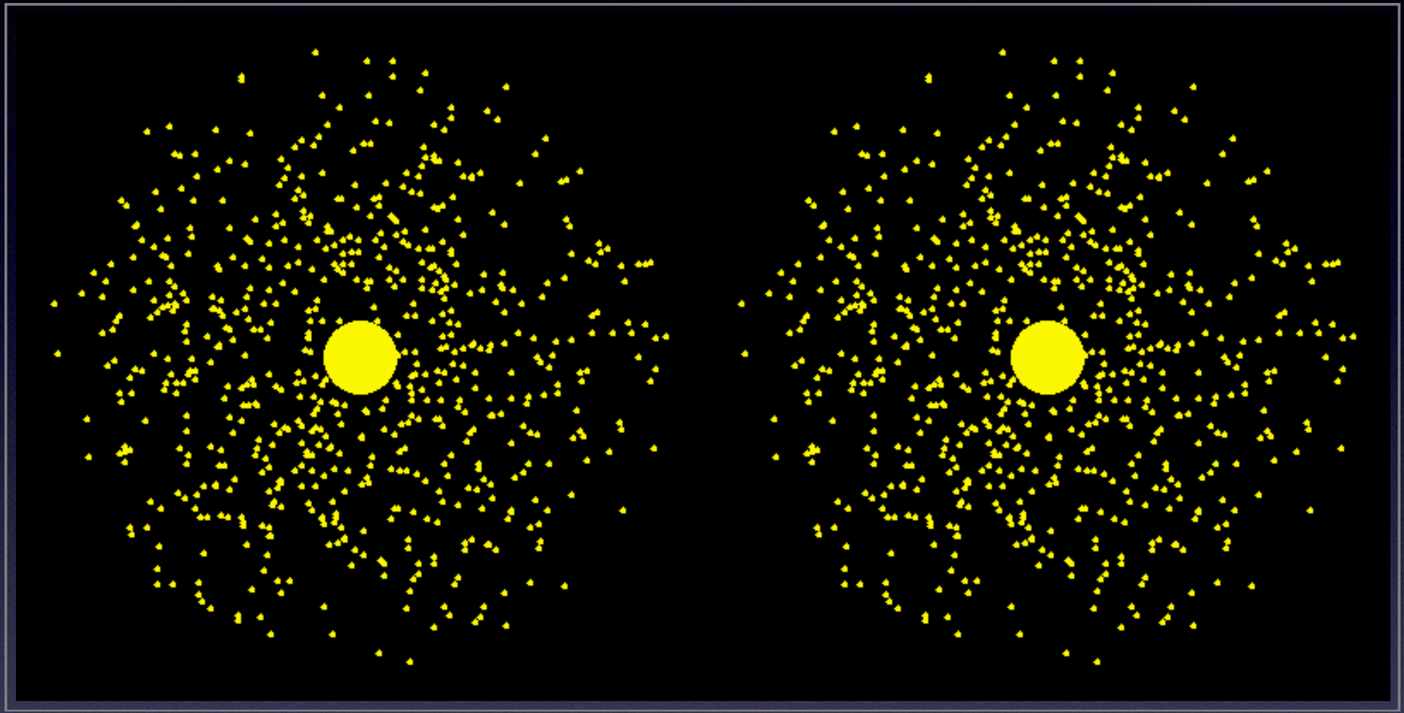

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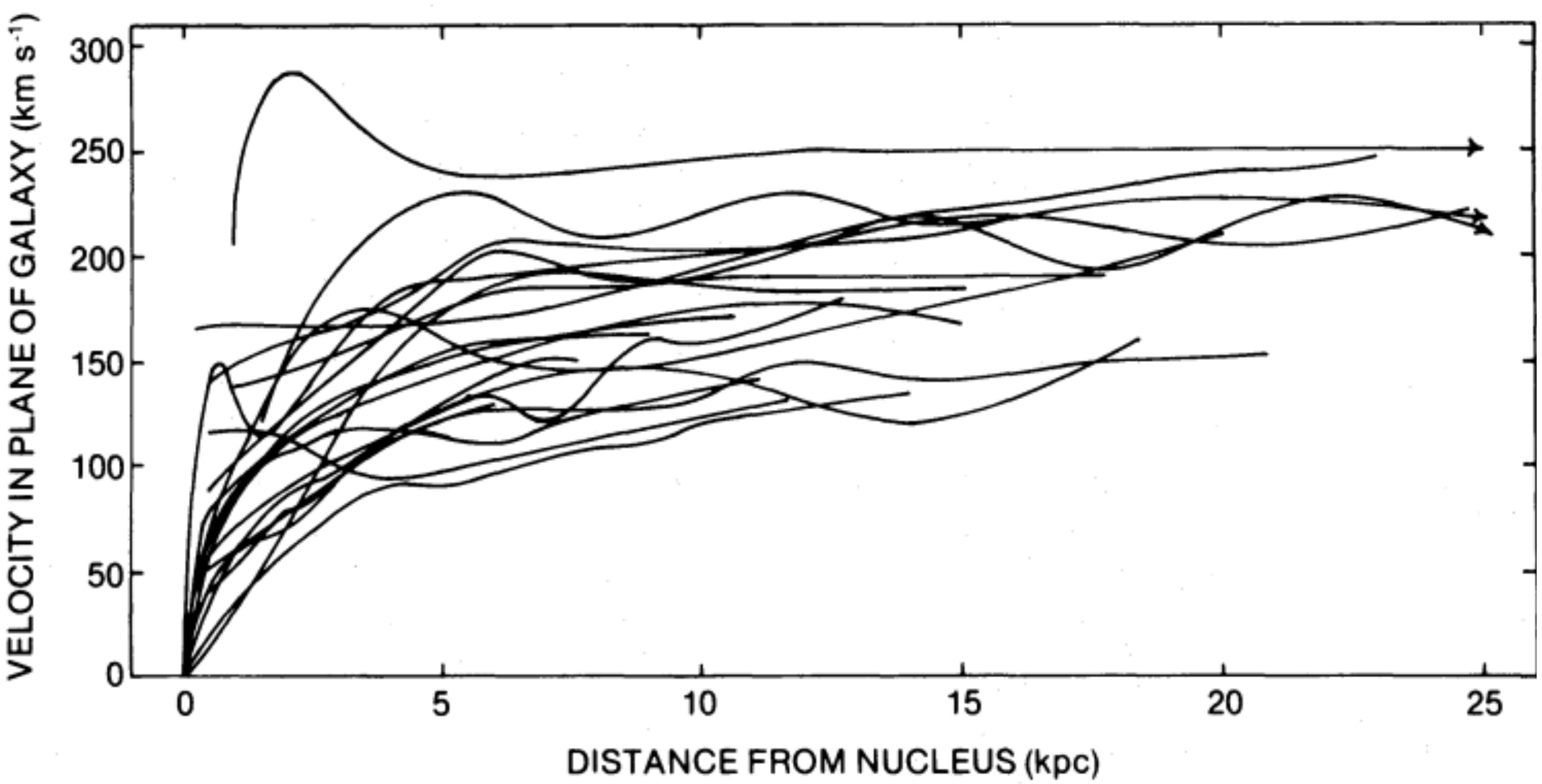

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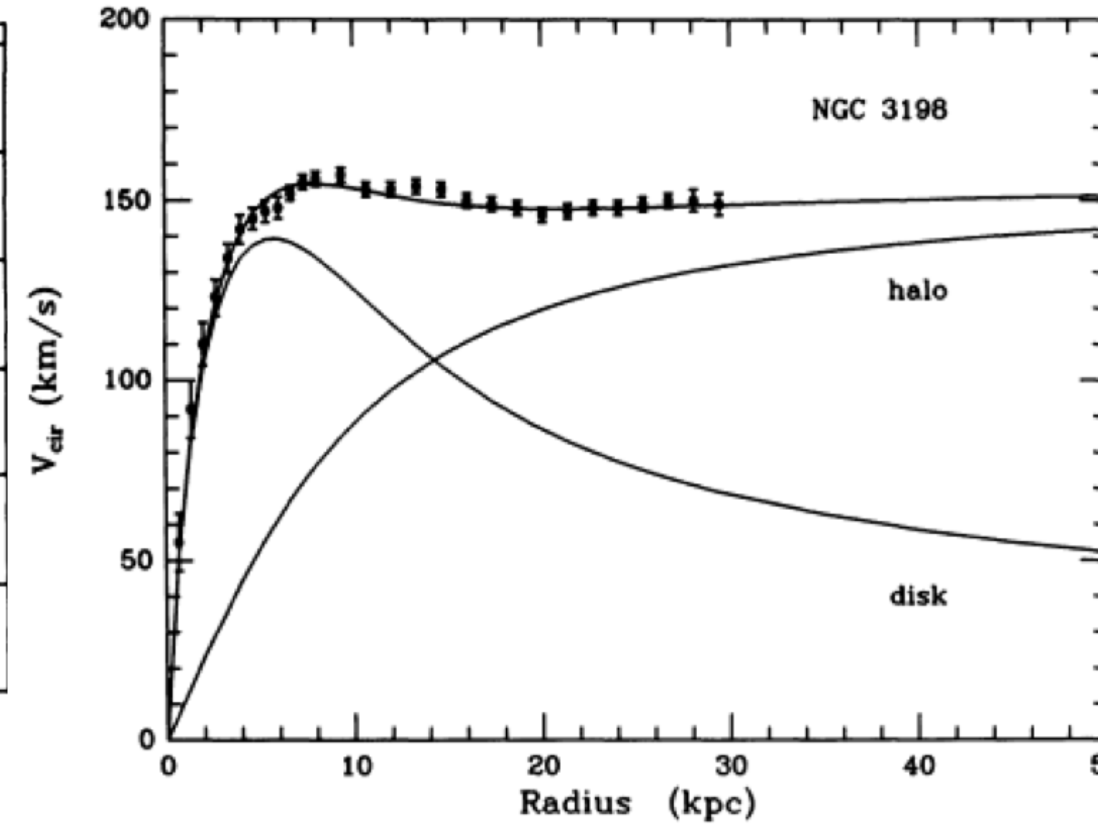

van Albada, T. S., Bahcall, J. N., Begeman, K., & Sancisi, R., 1985

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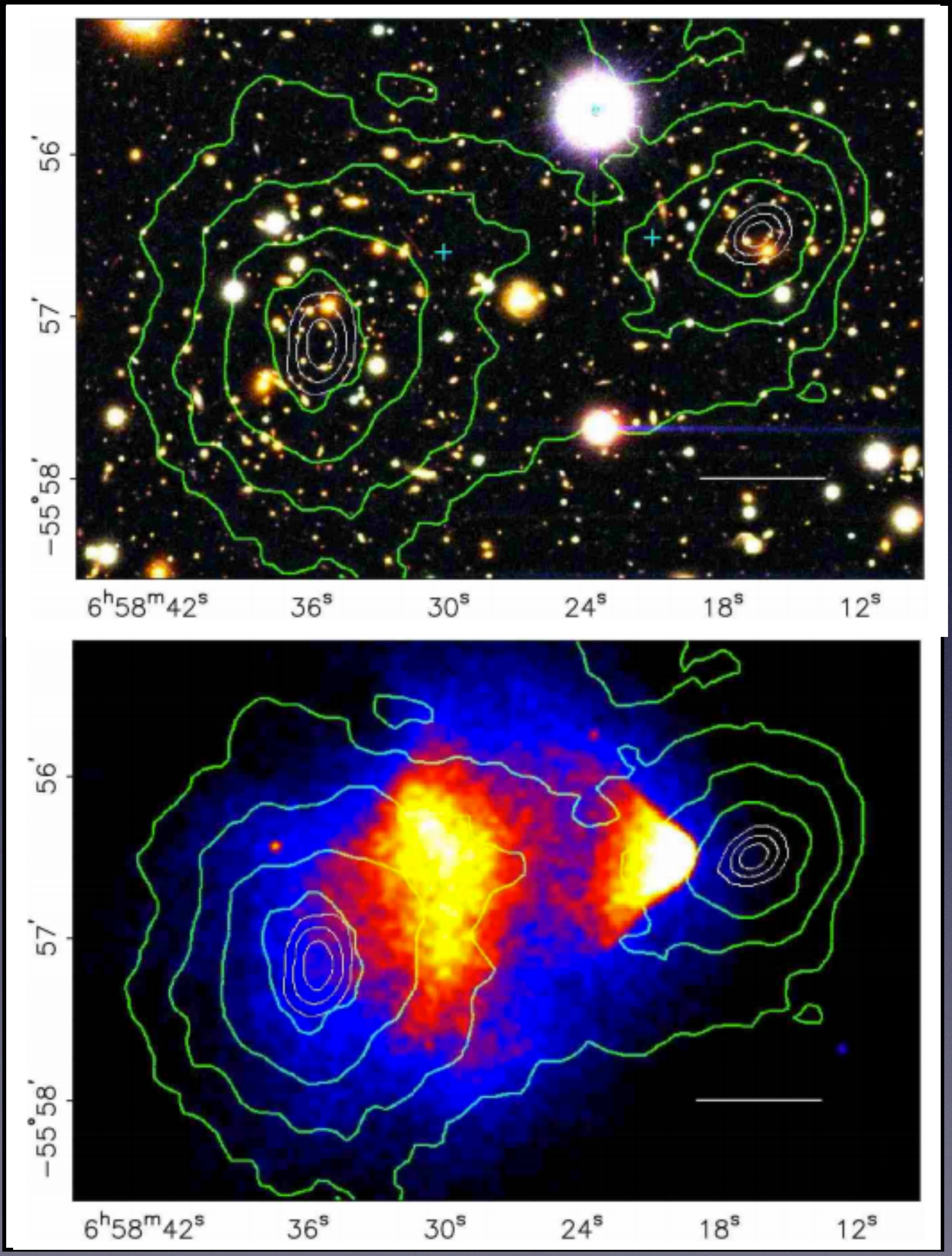
New matter or modified gravity?

- Clowe et al 2006: studied the Bullet Cluster, system of two colliding clusters.
  - X-ray maps from CHANDRA to study distribution of hot plasma (main baryonic component).
  - Weak gravitational lensing to study mass distribution.
- Result: a substantial displacement between the two.
- Attributed to a collisionless cold dark matter component. When the clusters collided, the dark matter halos passed through each other without slowing down - unlike the gas.



Interpreting the Bullet Cluster

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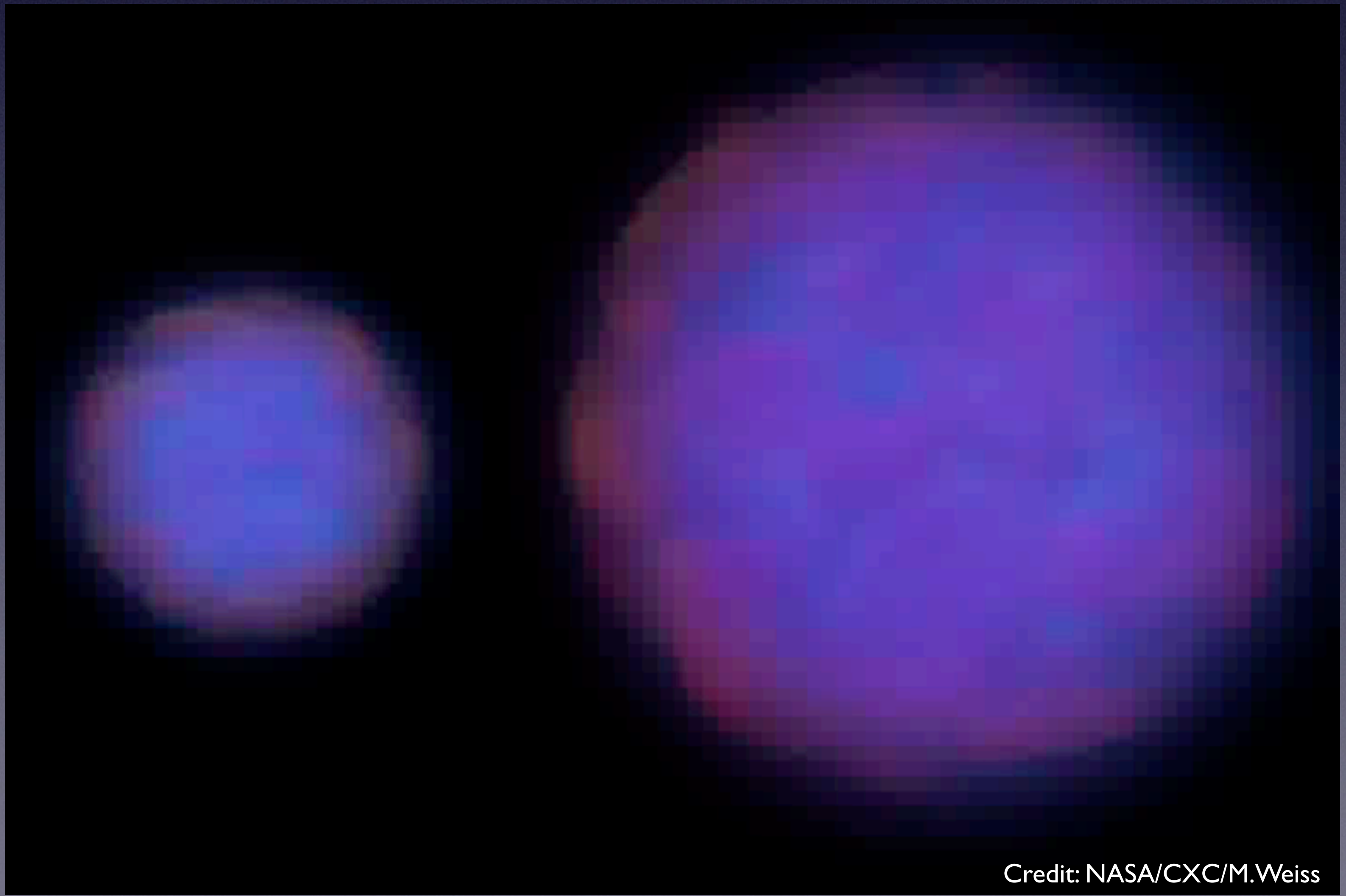
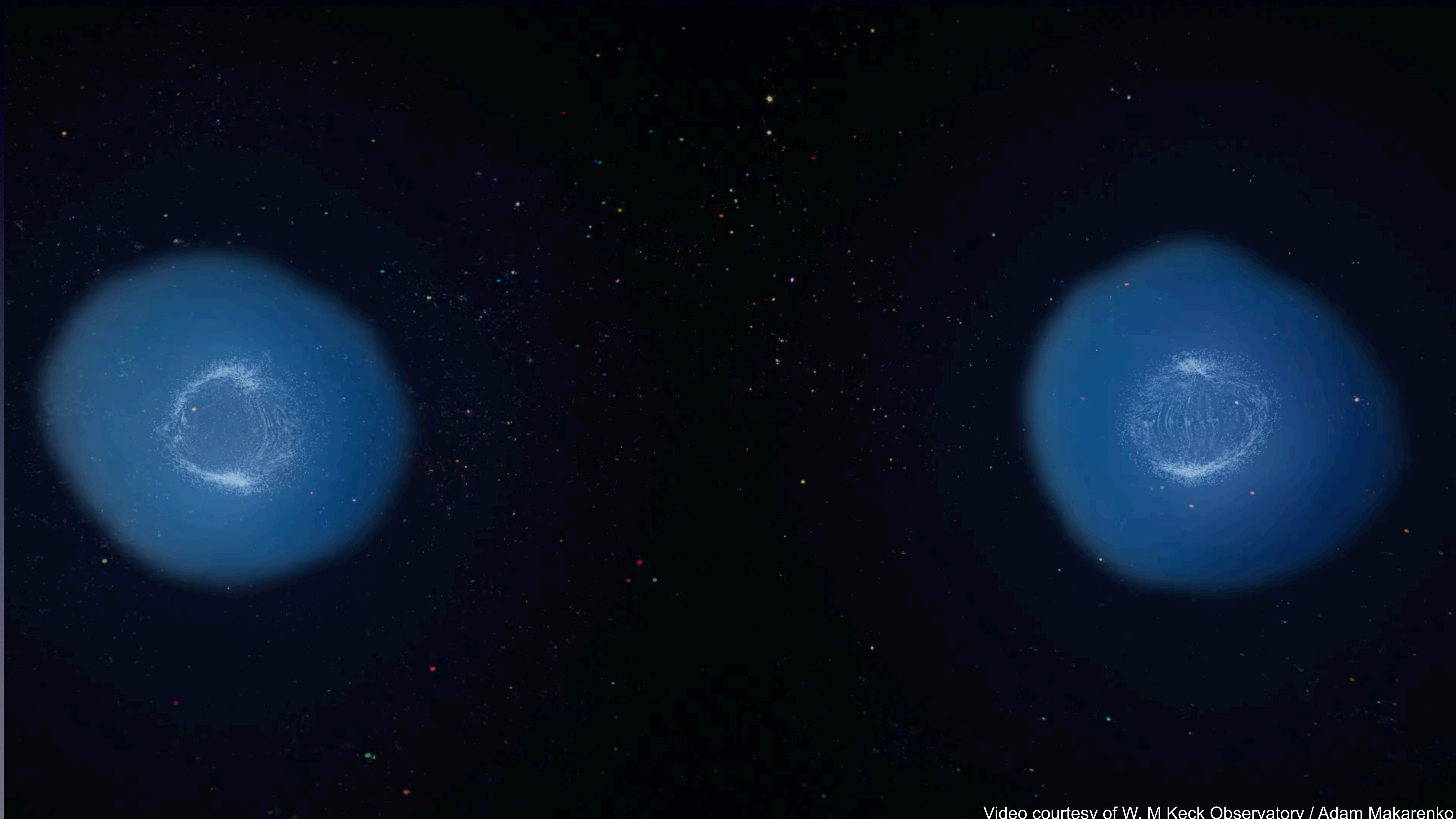
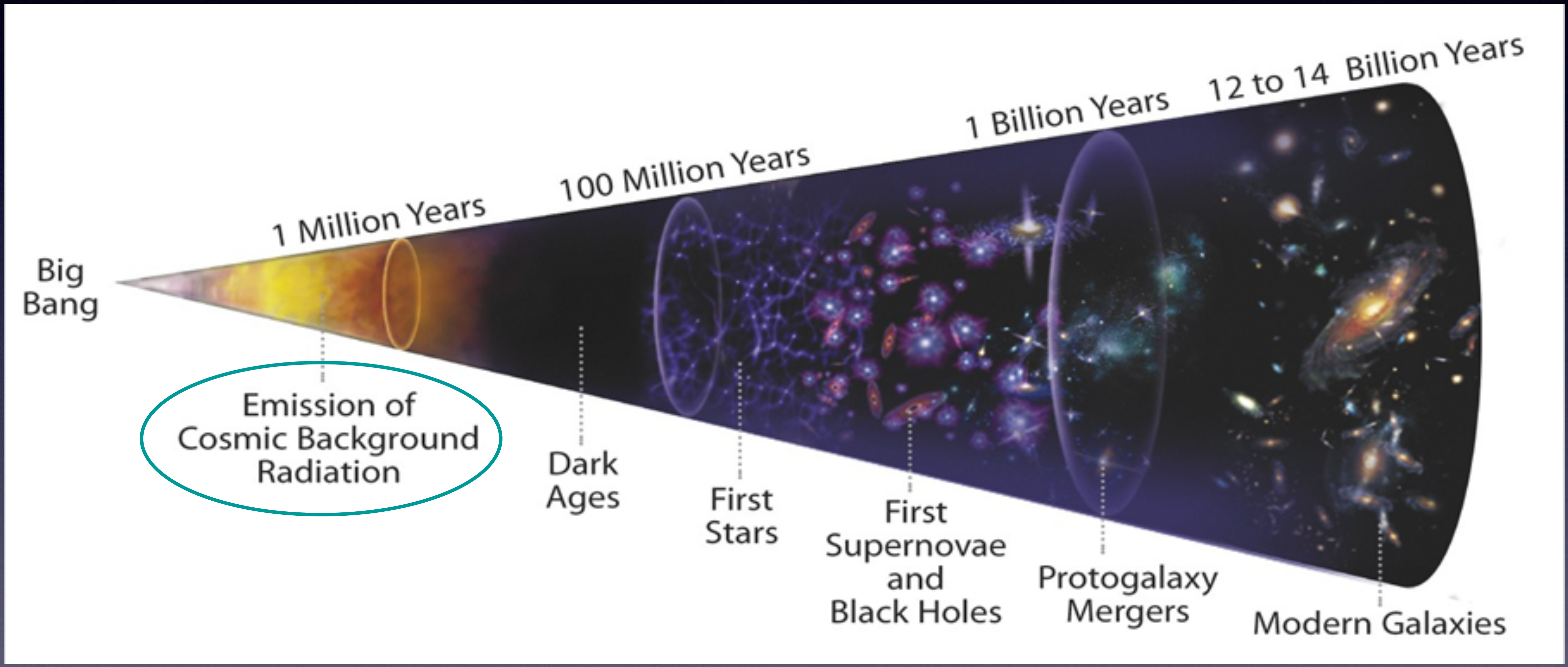


- More recently, we have some evidence for very-low-dark-matter galaxies - thought to have lost their dark matter halos in similar encounters [e.g. Keim et al 2603.15860]

Are we seeing collision remnants?



The cosmic microwave background



- When the universe was ~400 000 years old (redshift = z ~ 1000), H gas became largely neutral, universe transparent to microwave photons.
- Cosmic microwave background (CMB) radiation was last scattered at that time. We can measure that light now.

CMB anisotropies

- Universe at z~1000 was a hot, nearly perfectly homogeneous soup of light and atoms.
- Oscillations in temperature/density from competing radiation pressure and gravity.
- Photon temperature anisotropies today allow measurement of temperature/density inhomogeneities at recombination.
- Peaks occur at angular scales corresponding to a harmonic series based on the sound horizon at recombination.

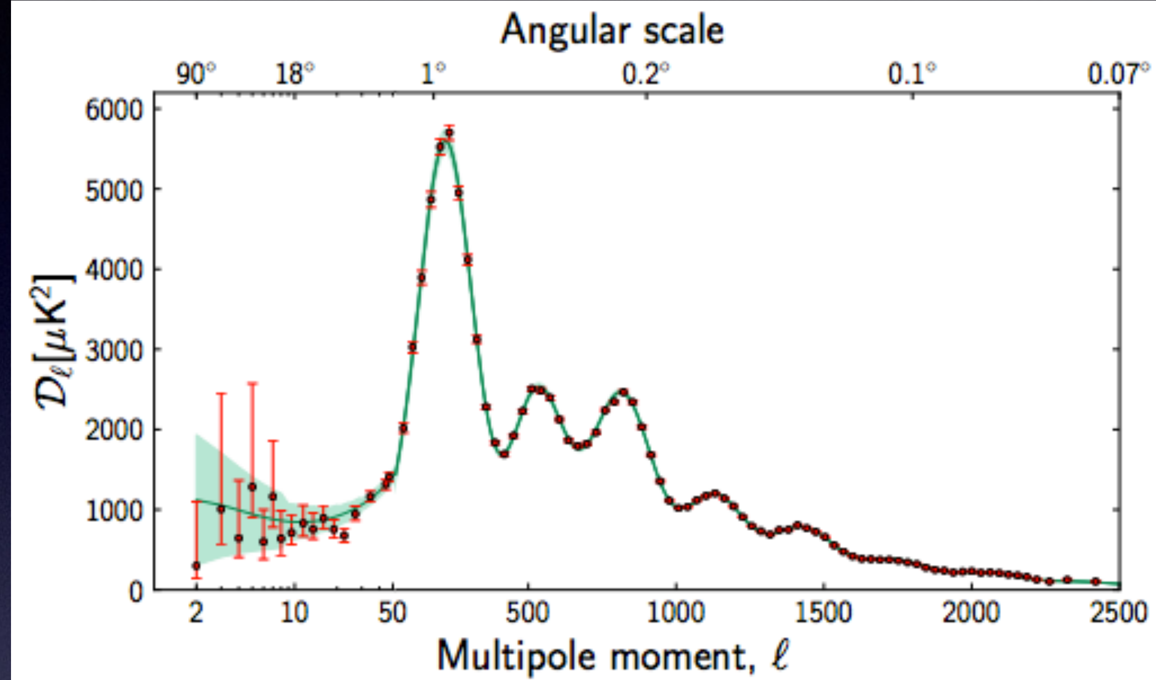


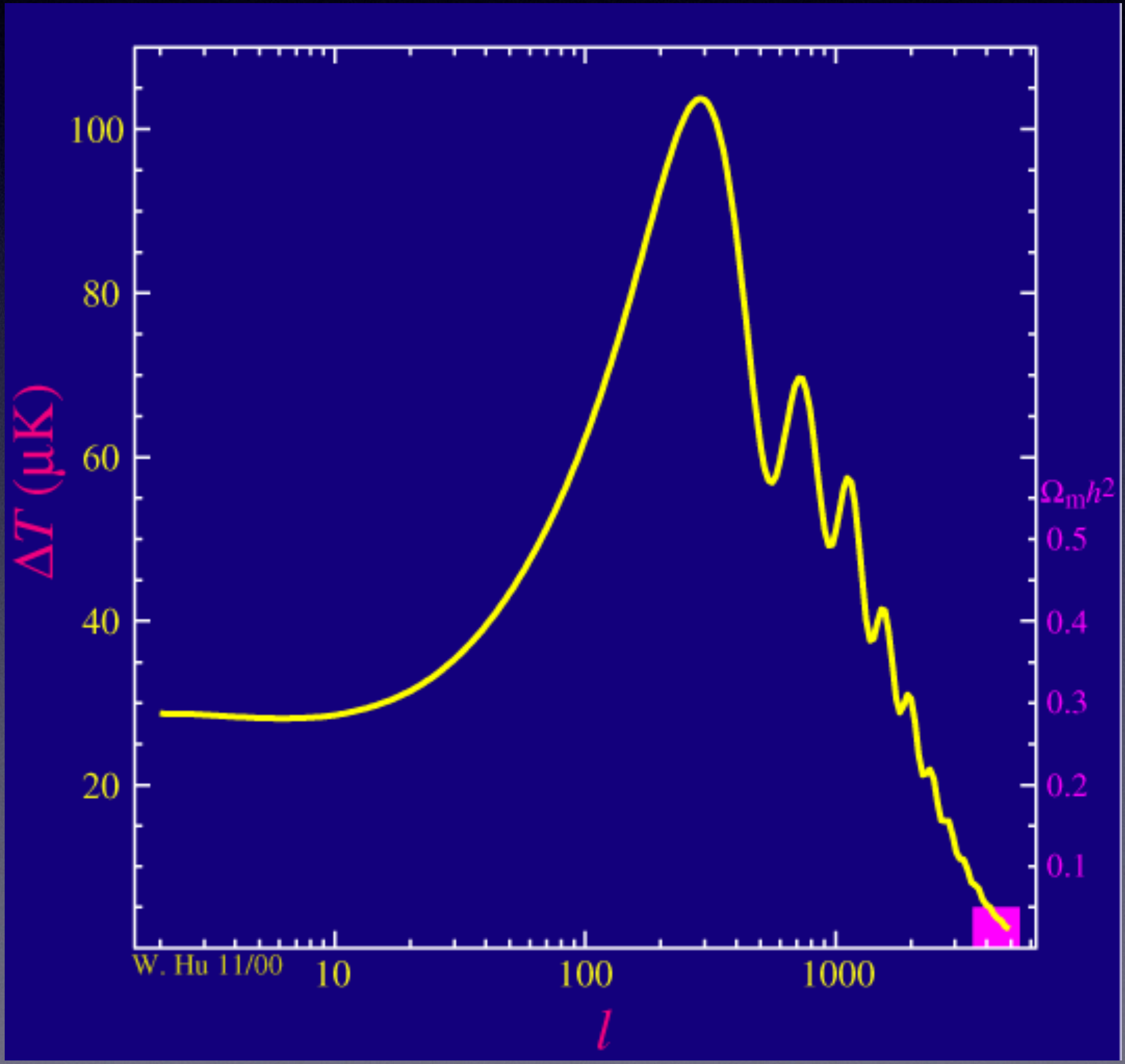
Figure 37. The 2013 *Planck* CMB temperature angular power spectrum. The error bars include cosmic variance, whose magnitude is indicated by the green shaded area around the best fit model. The low-ℓ values are plotted at 2, 3, 4, 5, 6, 7, 8, 9.5, 11.5, 13.5, 16, 19, 22.5, 27, 34.5, and 44.5.

Table 8. Constraints on the basic six-parameter ΛCDM model using *Planck* data. The top section contains constraints on the six primary parameters included directly in the estimation process, and the bottom section contains constraints on derived parameters.

	Planck		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14305	0.1426 ± 0.0025
Age/Gyr	13.819	13.813 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.48	1090.43 ± 0.54
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{eq}	3402	3386 ± 69	3403	3391 ± 60

Measuring dark matter from the CMB

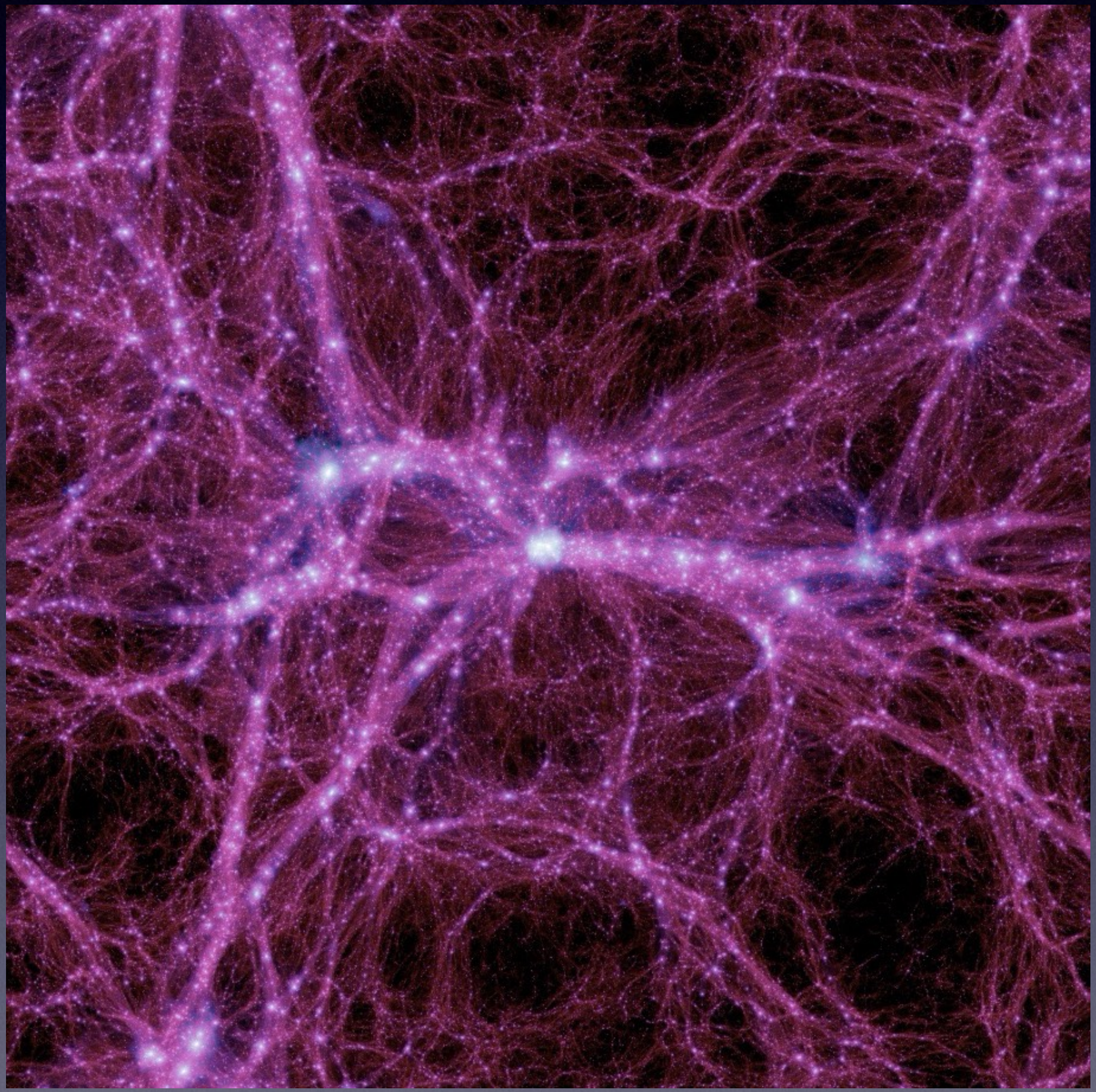
- Model universe as photon bath + coupled baryonic matter fluid + decoupled “dark” matter component (+ “dark” radiation, i.e. neutrinos).
- Dark component: does not experience radiation pressure, effects on oscillation can be separated from that of baryons.
- Result: this simple model fits the data well with a dark matter component about 5x more abundant than baryonic matter (total matter content is ~0.3 x critical density).



Wayne Hu, http://background.uchicago.edu/~whu/

Structure formation

- CMB also maps out initial conditions for cosmic structure formation.
- After the photons decouple from the baryons, overdensities continue to grow under gravity, eventually collapsing into virialized (equilibrated) structures.



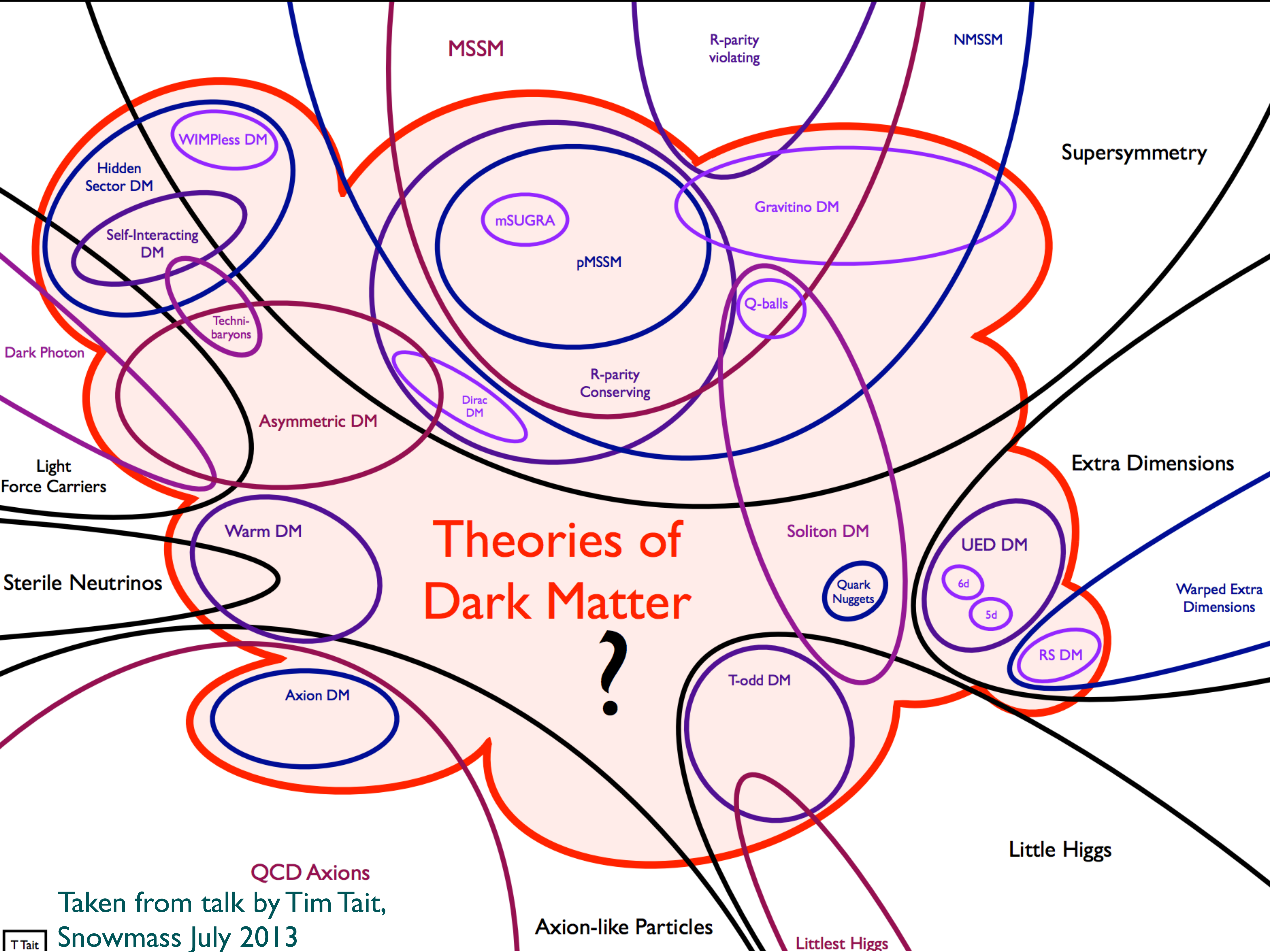
Could it be neutrinos?

- Structure formation varies markedly according to the kinematics of the dark matter, in particular whether it can free-stream during the growth of perturbations.
- If most DM is "hot" (relativistic during the early phases of structure formation), free-streaming erases structures on small scales. Large structures form first, then fragment.
- If most DM is "cold" (non-relativistic throughout this epoch), small clumps of DM form first, then accrete together to form larger structures.
- The relative ages of galaxies and clusters tell us that most DM must be cold.
- Neutrinos <u>are</u> hot dark matter - but cannot be all the DM.

DM as new physics

- Standard Model (SM) of particle physics has been spectacularly successful - but no particle dark matter candidate to our current knowledge. We need something:
  - Stable on cosmological timescales
  - Near-collisionless, i.e. electrically neutral
  - “Cold” or “warm” rather than “hot” - not highly relativistic when the modes corresponding to the size of Galactic dark matter halos first enter the horizon (around $z \sim 10^6$, temperature of the universe around 300 eV).
- Only stable uncharged particles are neutrinos, and they would be hot dark matter.

- DM is one of the most powerful pieces of evidence for physics beyond the SM.
- Everything we have learned so far has come from studying the gravitational effects of dark matter, or from its inferred distribution.



Taken from talk by Tim Tait,
Snowmass July 2013