Indications of dark matter
17/10/2018

- **Program**
  - Dispersion velocities in galaxy-clusters
  - Rotation curves
  - Gravitational lensing
  - Galaxy-cluster collisions
  - Large structure formation
  - Cosmic microwave background

- **Literature:**
  - F. Zwicky, *Die Rotverschiebung von extragalaktischen Nebeln*, Helvetica Physica Acta, 6 (1933) 110
  - V. Rubin *et al.*, *Extended rotation curves of high luminosity spiral galaxies*, Astrop. J. 255 (1978) 107
  - E. E. Richards *et al.*, *Baryonic Distributions in the Dark Matter Halo of NGC5005*, arXiv:1503.05981
  - R. Massey *et al.*, *The dark matter of gravitational lensing*, Rep. Prog. Phys. 73 (2010) 086901, arXiv:1001.1739
  - A. Einstein, *Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field*, Science 84 (1936) 506
  - D. Clowe *et al.*, *A direct empirical proof of the existence of dark matter*, Astrophys. J. **648** (2006) L109, astro-ph/0608407
  - D. Harvey *et al.*, *The non-gravitational interactions of dark matter in colliding galaxy clusters*, Science 347 (2015) 1462, arXiv:1503.07675
  - N. Aghanim *et al.* [Planck Collaboration], *Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters*, arXiv:1507.02704
  - R. Adam *et al.* [Planck Collaboration], *Planck 2015 results. X. Diffuse component separation: Foreground maps*, arXiv:1502.01588
  - Springel, Frenk & White, *The large-scale structure of the Universe*, Nature **440** (2006)
  - H. V. Klapdor-Kleingrothaus and K. Zuber, *Particle Astrophysics*, IoP (2000)

- **Material for the lecture:**

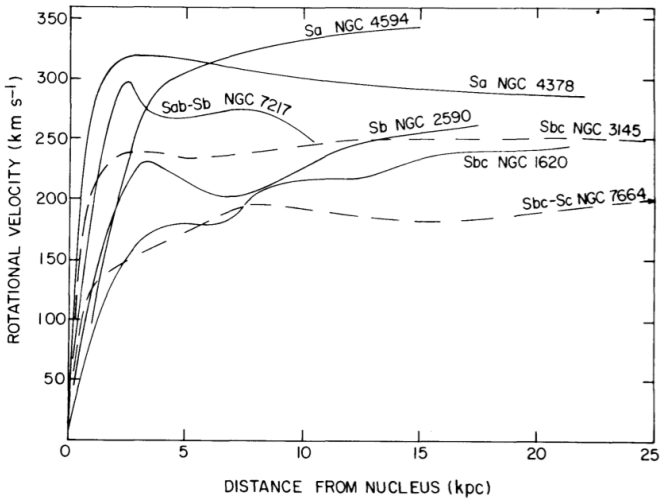

Figure 1: Examples of rotation curve measurements. Figure from V. Rubin *et al.*, 1978.

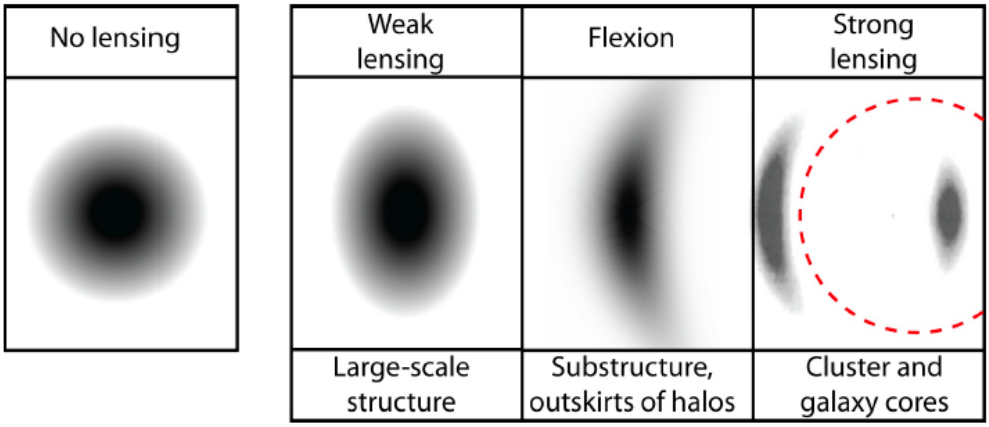

Figure 2: Various regimes of gravitational lensing image distortion. A circular source is distorted into an ellipse by weak lensing being the typical resulting axis ratio $\sim 2\,\%$ (exaggerated for illustration). For most curved space-time (most massive objects), strong gravitational lensing produces multiple imaging and giant arcs. Figure from R. Massey *et al.* (2010), arXiv:1001.1739.

Figure 3: (Left) Strong lensing: Einstein ring. Figure from ESA/Hubble & NASA. (Right) Weak lensing in Abell 2218. Figure from NASA.

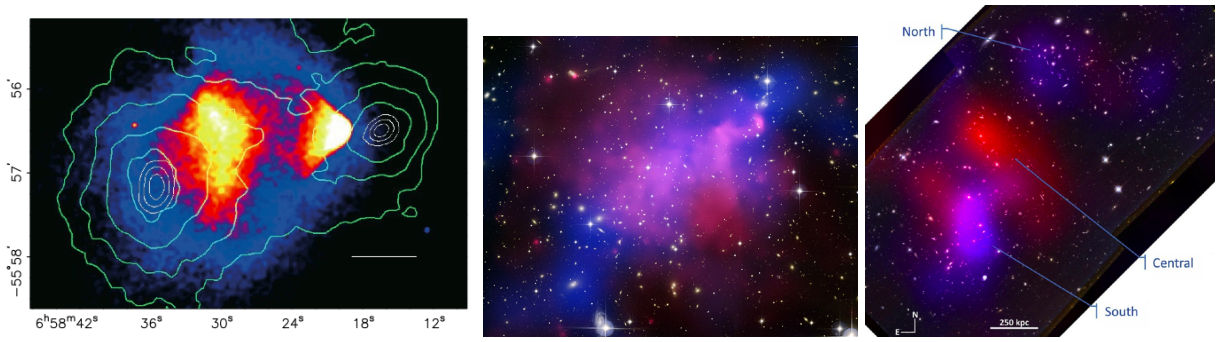

Figure 4: Galaxy-cluster collisions: bullet cluster, Abell 520 and DLSCL J0916.2+2951, respectively. Figures from astro-ph/0608407, X-ray: NASA / CXC/ U. Victoria/ A. Mahdavi et al. and arXiv:1110.4391.

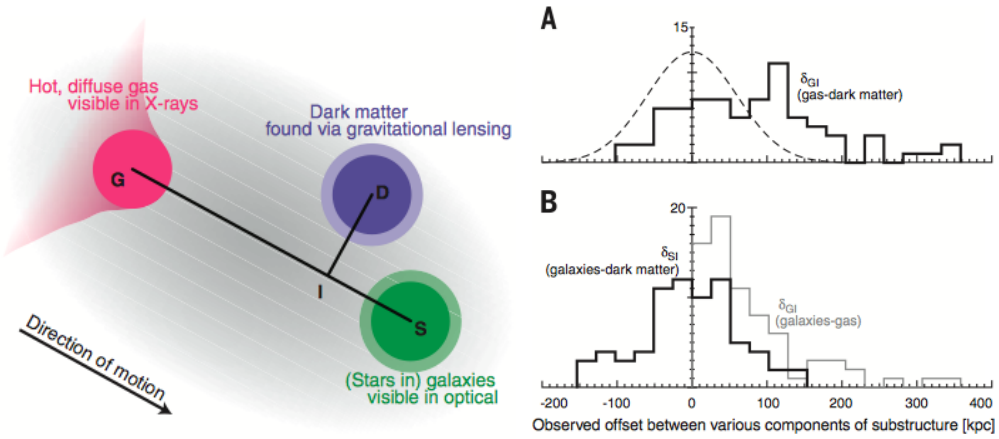

Figure 5: Galaxy-cluster collisions: (Right) Diagram of the displacement between gas (red), dark matter (blue) and the stars (green). (Left) Displacement results for 72 collisions. Figure from D. Harvey *et al.* Science 347 (2015) 1462, arXiv:1503.07675.

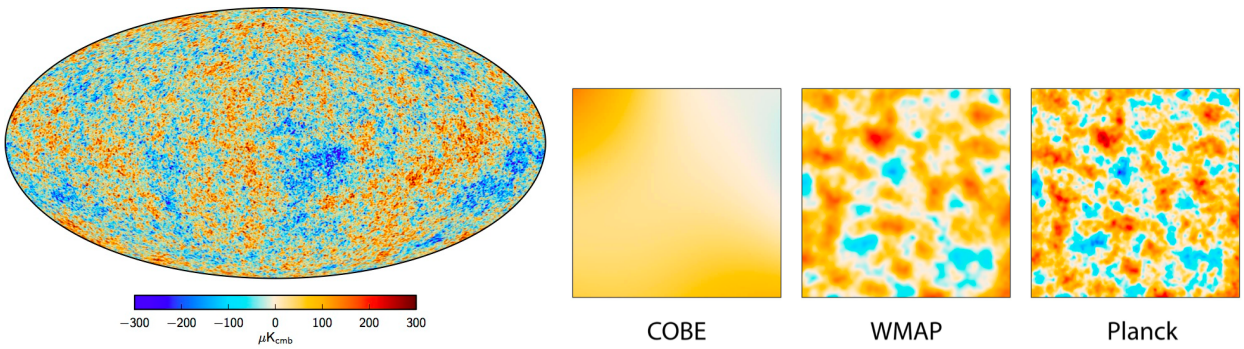

Figure 6: Cosmic microwave background maps. (left) Figure Planck Collaboration, arXiv:1507.02704. (Right) CMB resolution for different satellite measurements.

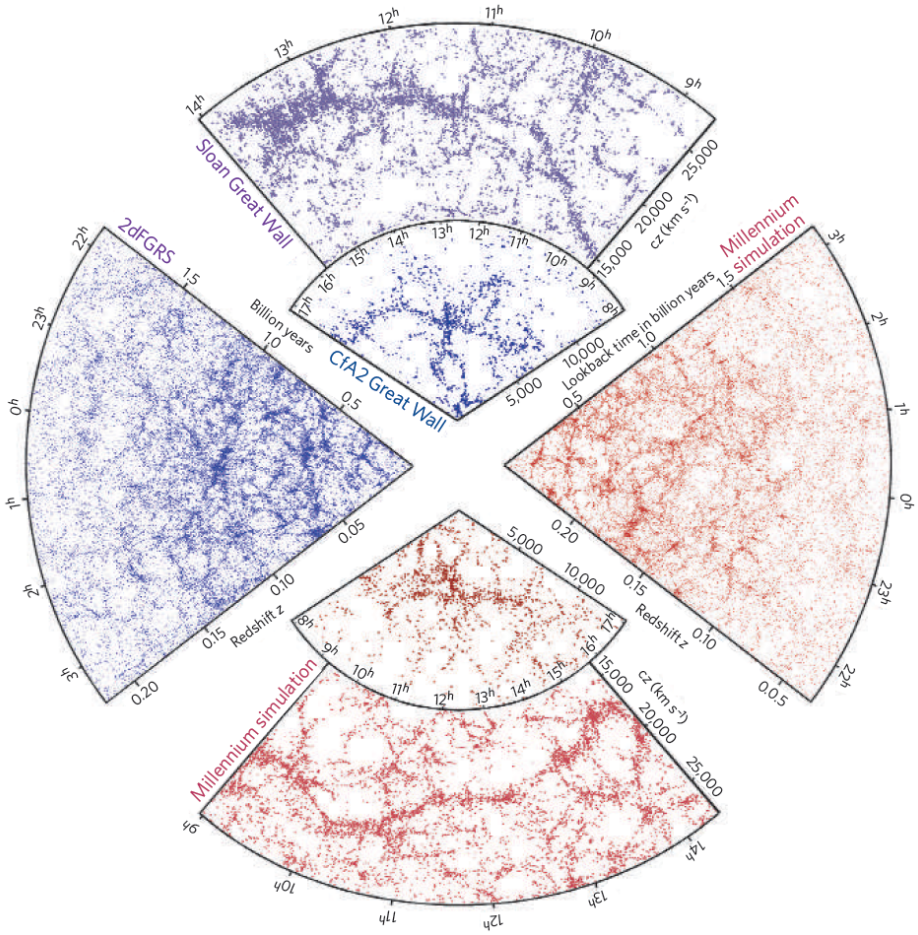

Figure 7: Comparison of clustering in observations of galaxy surveys (in blue) and in dark matter simulations (red). From Springel, Frenk & White, Nature **440** (2006).

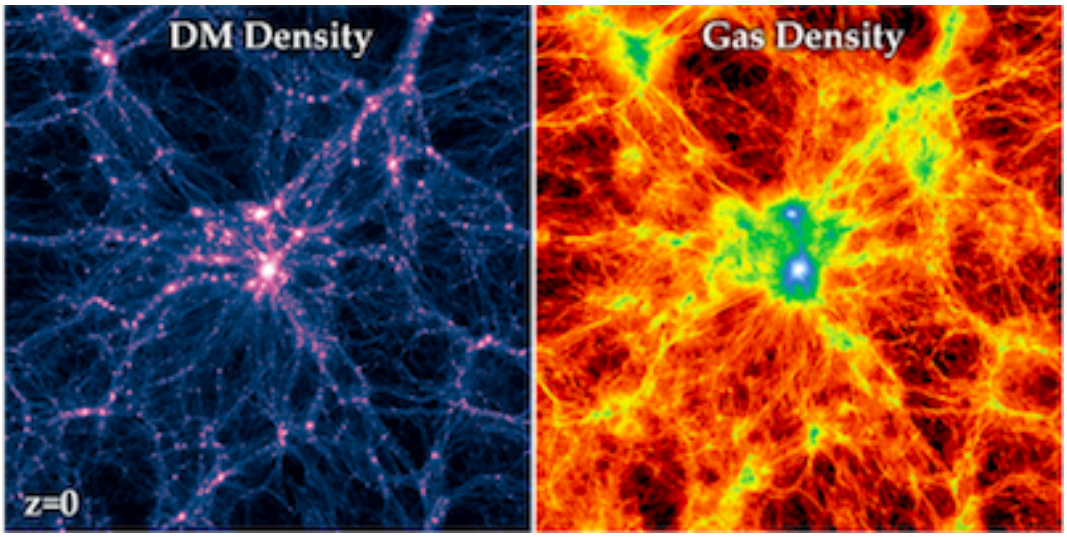

Figure 8: Comparison of the large scale dark matter and gas density fields. Figure from the Illustris simulation.

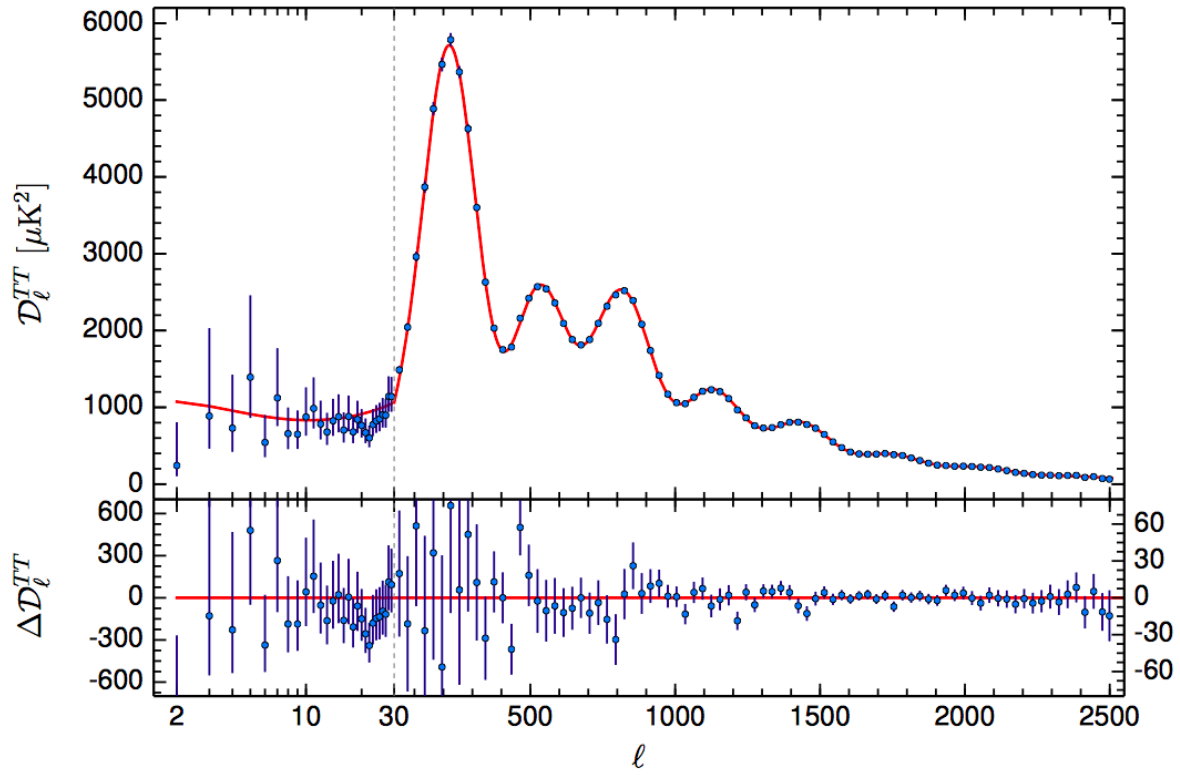

Figure 9: Temperature angular power spectrum of the primary CMB map by Planck. Figure Planck Collaboration, arXiv:1502.01589.