Observational cosmology

More evidence for Dark Matter

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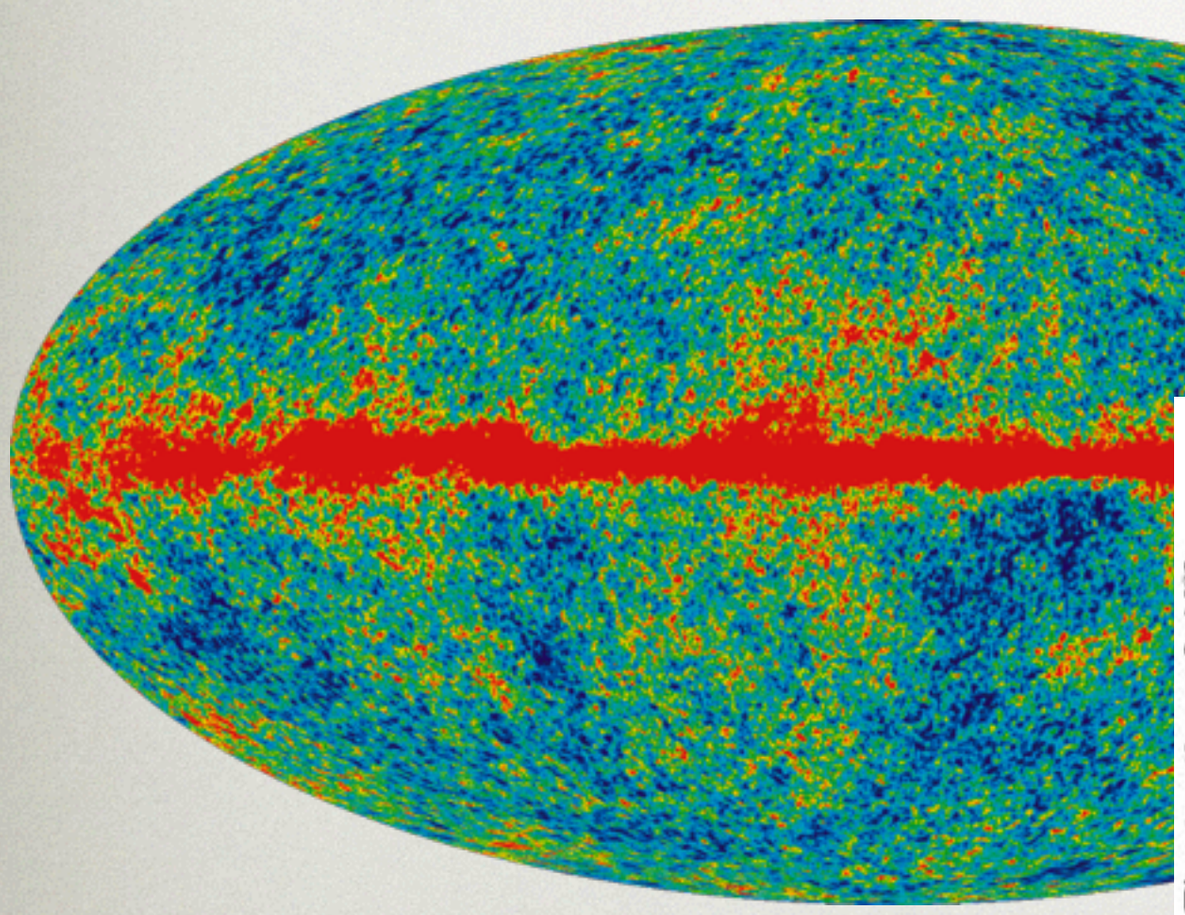
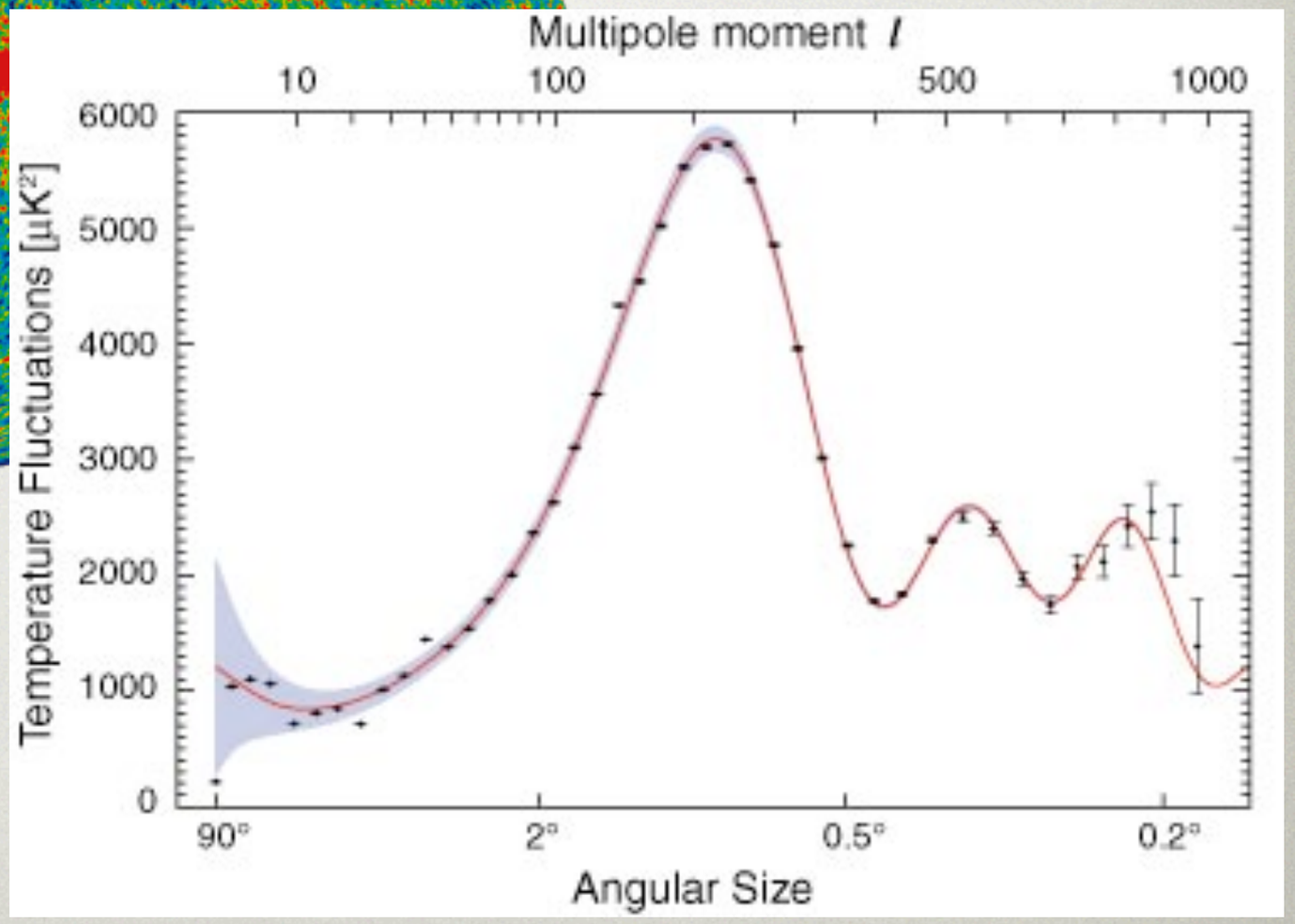
Portsmouth

Cosmic Microwave Background





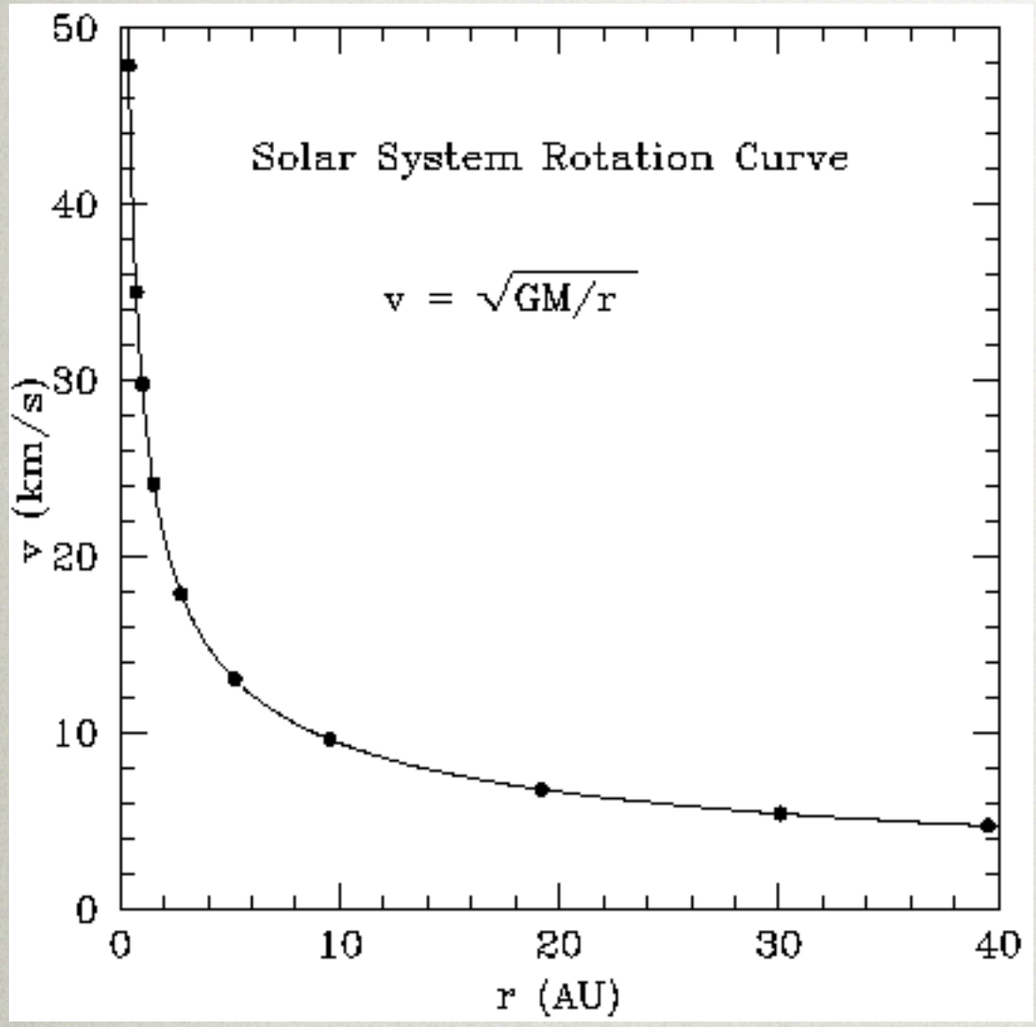
$$-0.0179 < \Omega_k < 0.0081$$

$$\Omega_b h^2 = 0.02267^{+0.00058}_{-0.00059}$$

$$\Omega_c h^2 = 0.1131 \pm 0.0034$$

Komatsu et al. 2008

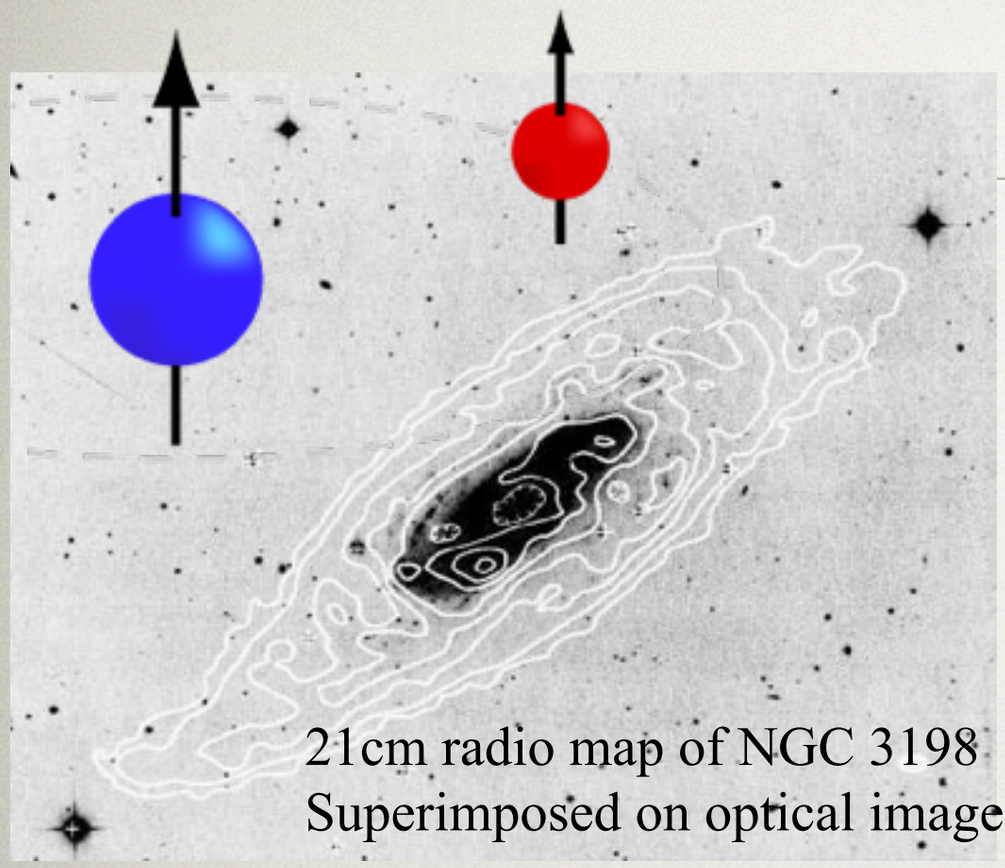
ROTATION CURVES



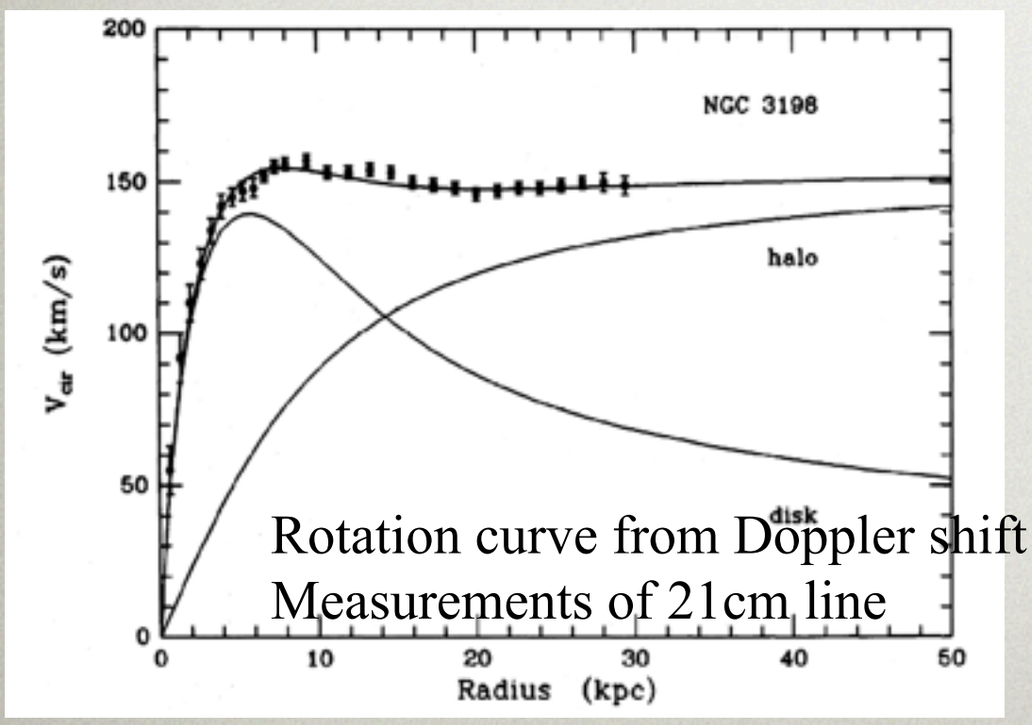
- Newtonian gravity
- v is orbital velocity, r is radius, M is interior mass
- For solar system, interior mass is constant
- Can measure the mass interior to r from velocity measurement

See http://bustard.phys.nd.edu/Phys171/lectures/dm.html

Galactic rotation curves



21cm radio map of NGC 3198
Superimposed on optical image



Rotation curve from Doppler shift
Measurements of 21cm line

- We'd like to measure galaxy mass: ie. look sufficiently far out to see $v=\sqrt{GM/r}$
- But no stars: look at neutral gas
- 21cm emission from small magnetic energy difference between proton spinning parallel or anti-parallel to electron
- At large r, galactic rotation curves are flat
- Implies M grows beyond extent of visible stars

Mass to light for galaxies is typically 2 to 10

See http://bustard.phys.nd.edu/Phys171/lectures/dm.html

Dark matter in clusters

Virial arguments for galaxies

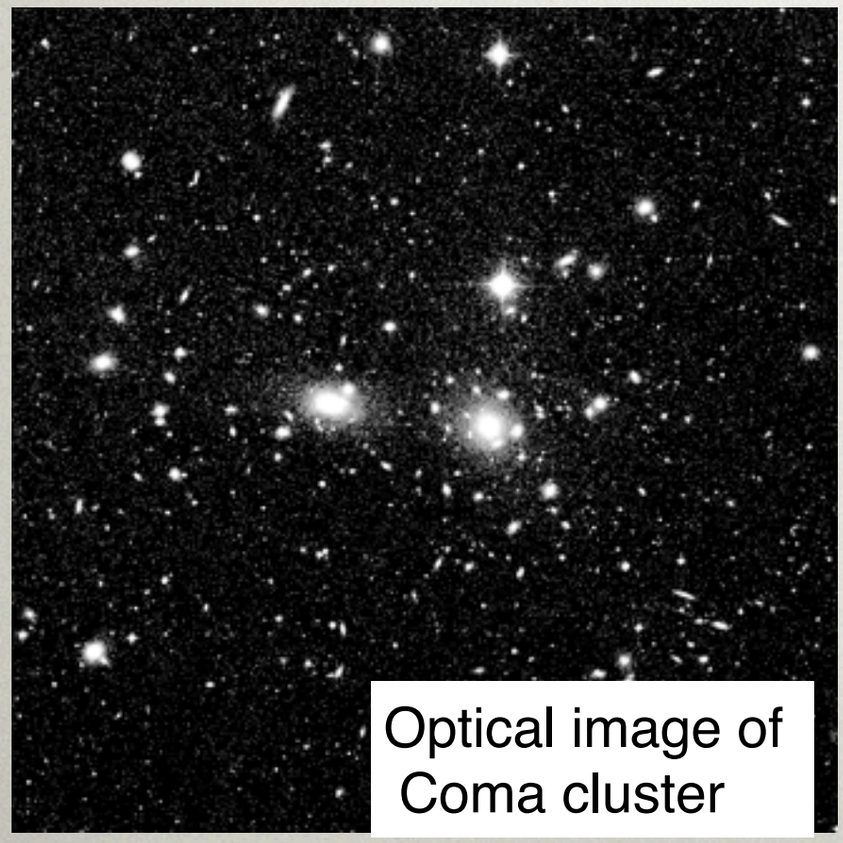
For self-gravitating system in equilibrium

$$\mathrm{KE}_{\mathrm{avg}} = -\frac{1}{2}\mathrm{GPE}_{\mathrm{avg}}$$

$$\mathrm{KE}_{\mathrm{avg}} = \frac{1}{2}\sum_i m_i v_i^2 \qquad \mathrm{GE}_{\mathrm{avg}} = -\frac{1}{2}\sum_i \sum_{j\neq i} \frac{G m_i m_j}{r_{ij}}$$

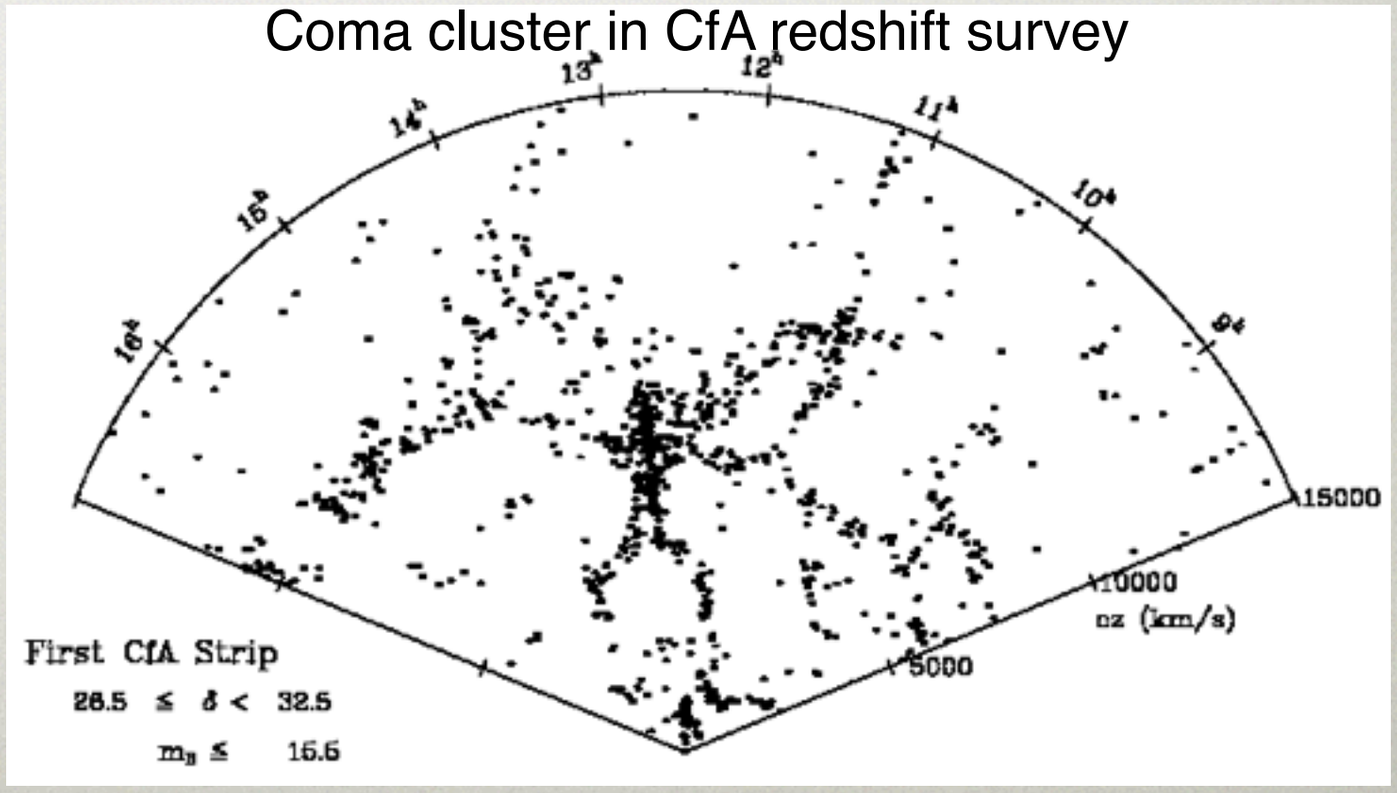
measure

measure



Optical image of Coma cluster

Coma cluster in CfA redshift survey



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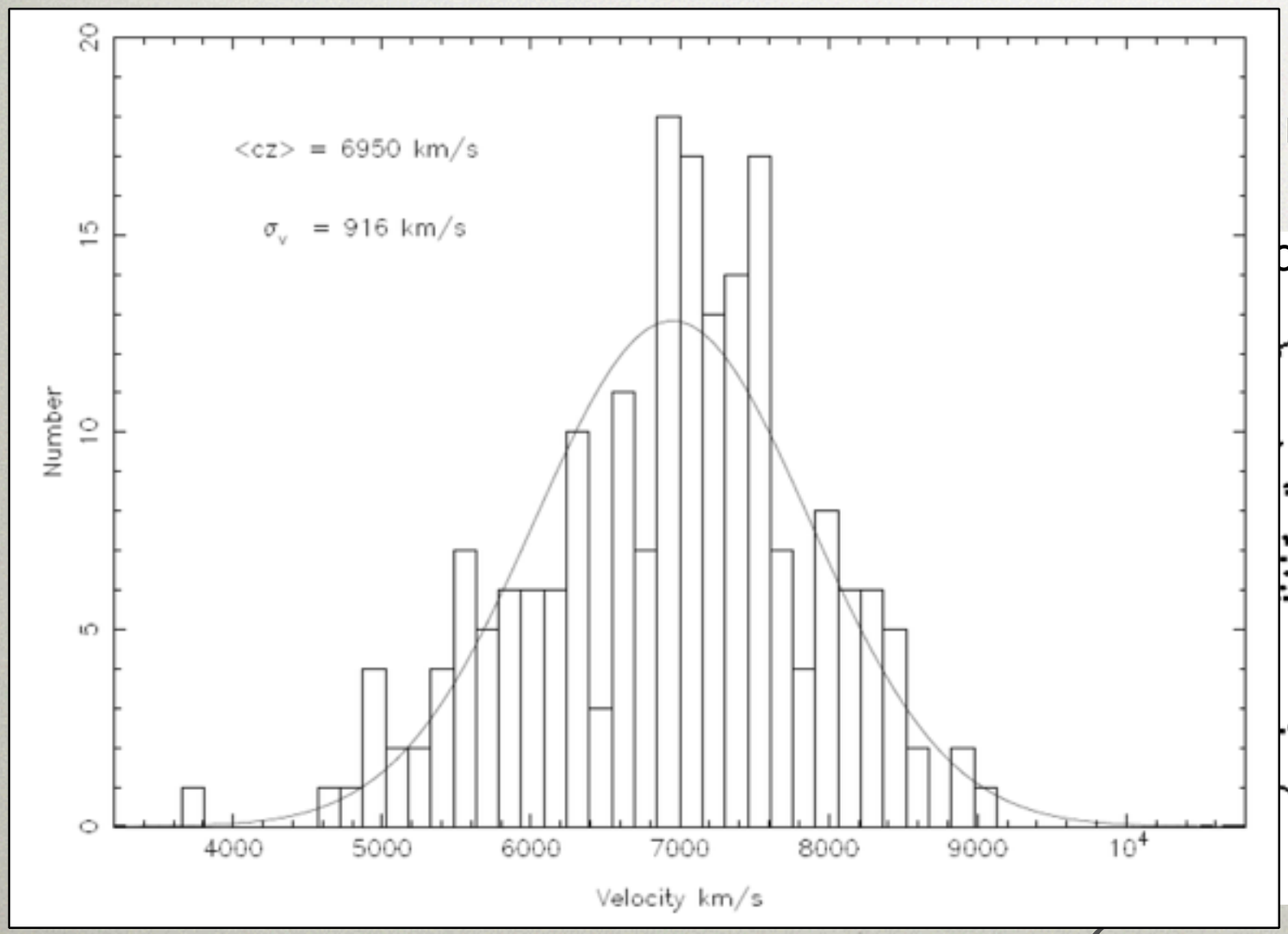
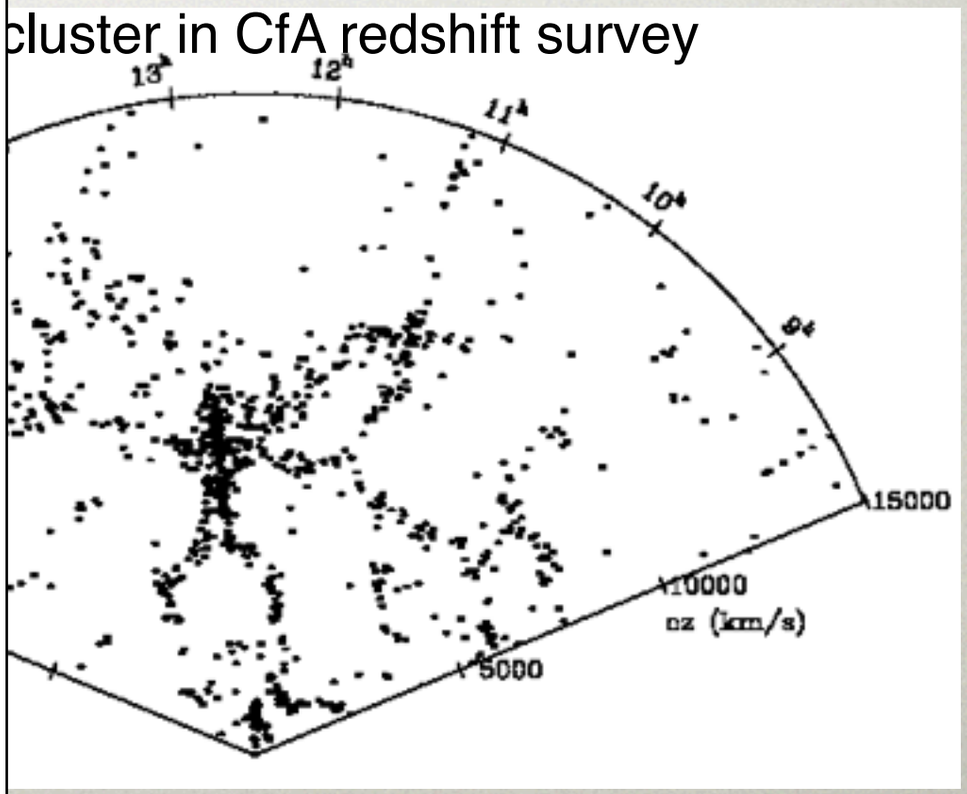
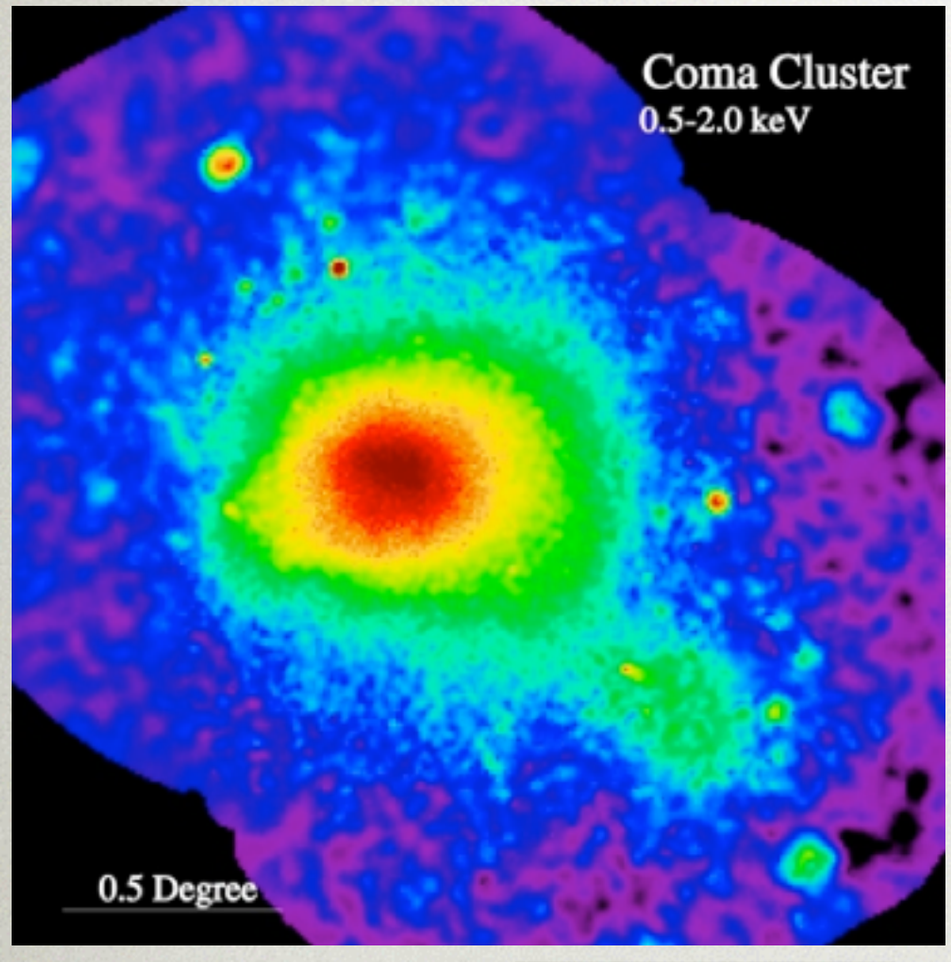


cluster in CfA redshift survey



Dark matter in clusters



ROSAT image

Hydrostatic equilibrium argument for hot gas:

Gas temperature is proportional to v^2, so can use to estimate total mass

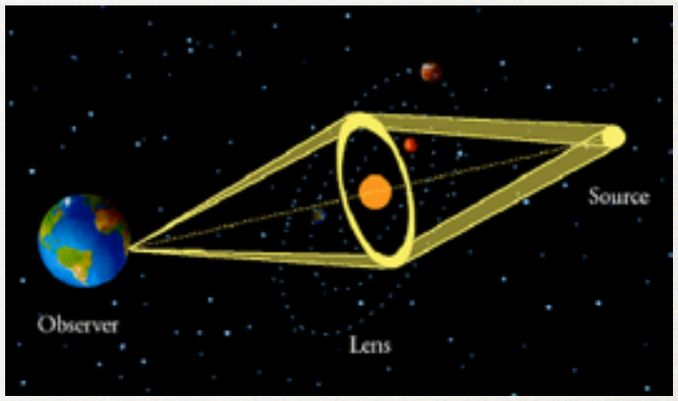
$$\frac{kT_g}{\mu m_p} \approx \sigma_r^2,$$

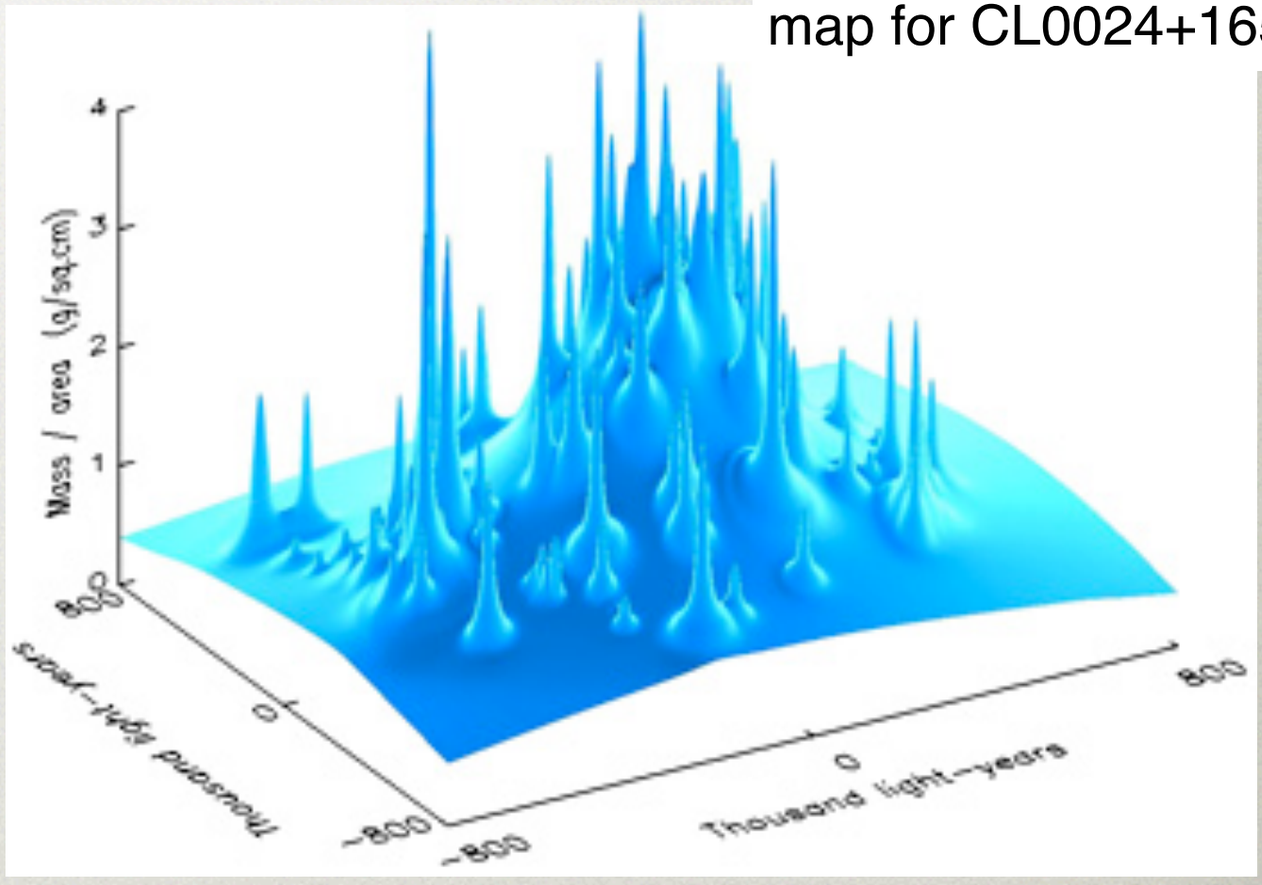
$$T_g \approx 7 \times 10^7\,\mathrm{K} \left(\frac{\sigma_r}{1000\,\mathrm{km/s}}\right)^2$$

- Gas plus galaxies accounts for only 15% of observed mass
- Mass to light can be as high as 100 for massive clusters

Strong lensing by clusters: CL0024+1654

Optical image of CL0024+1654





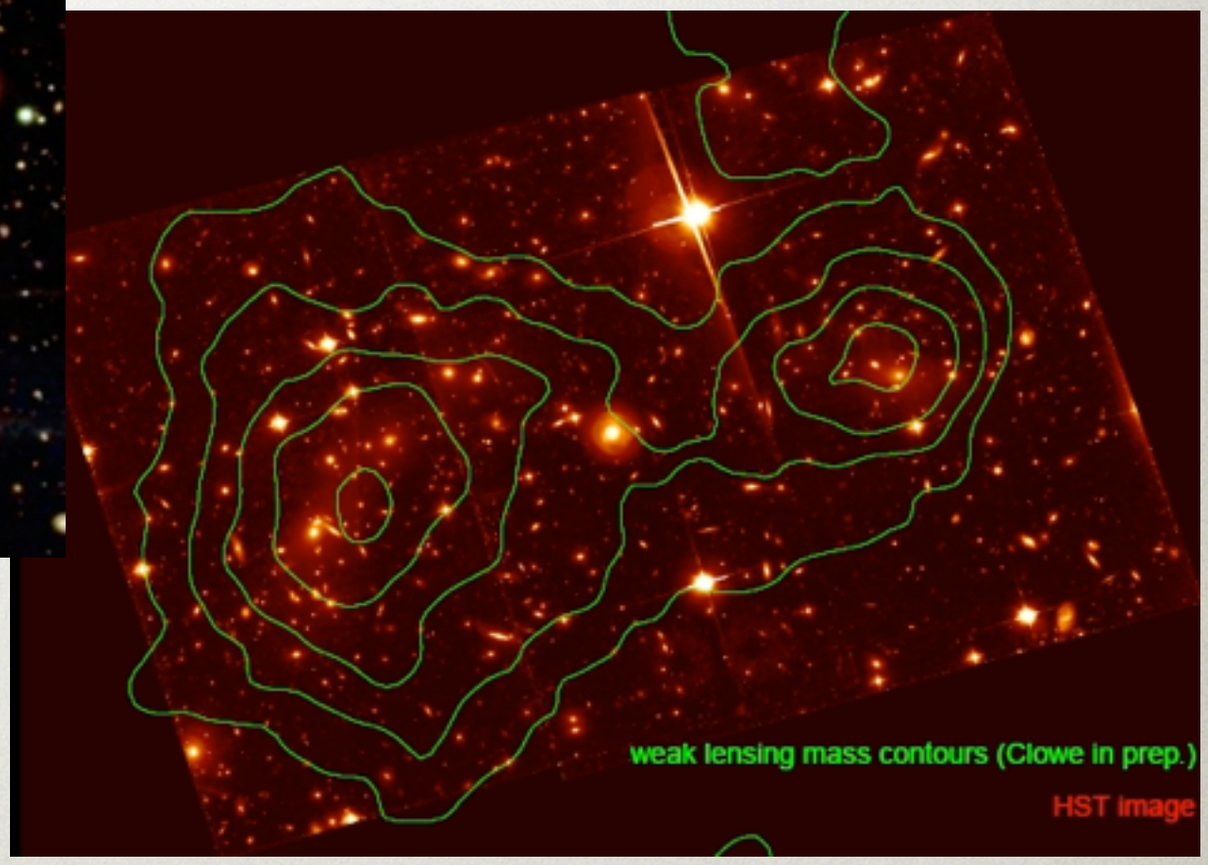
Reconstructed mass map for CL0024+1654

Strong-lensing mass reconstruction tend to give mass-to-light ratios of order ~100, consistent with virial estimates

Tyson et al. 1998

The Bullet cluster

Chandra observations show that dark matter (from lensing) and galaxies are not in the same place as the hot gas

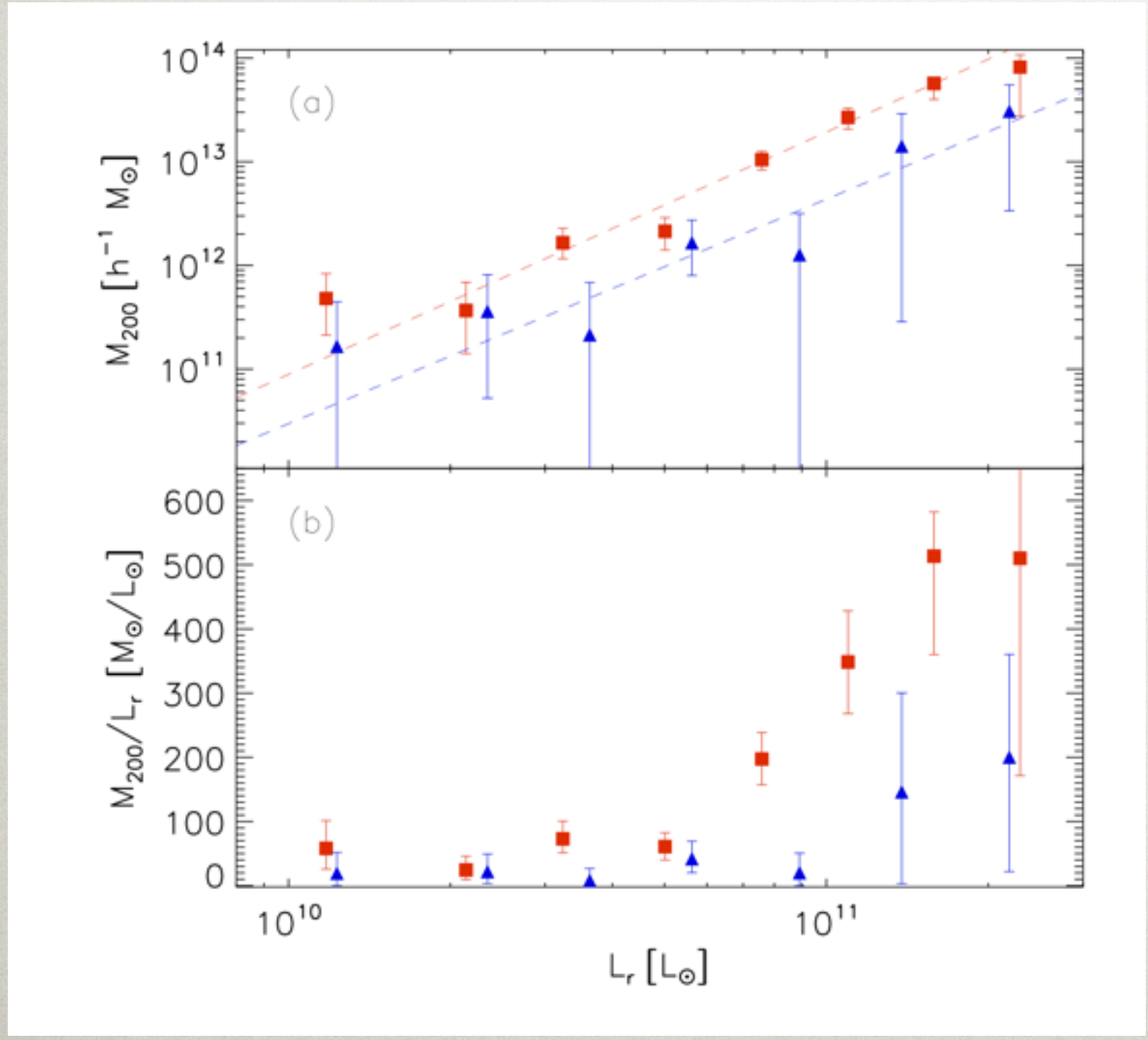


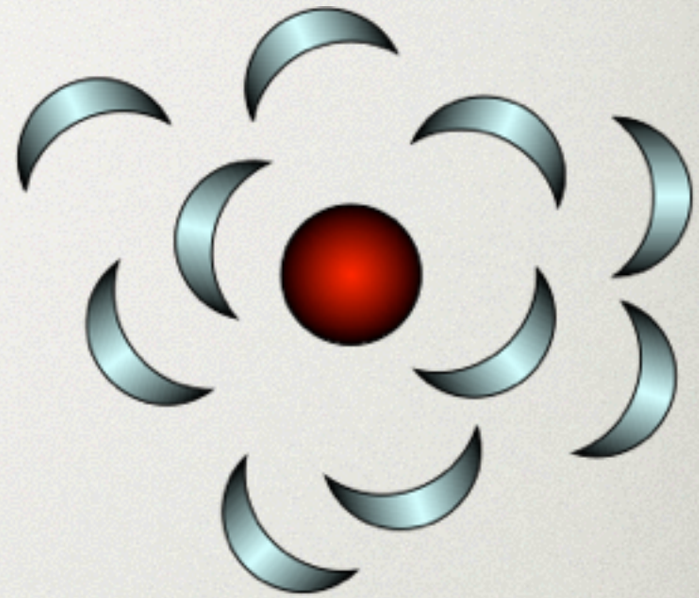
Explaining these observations is a big challenge for theories without dark matter (e.g. modified gravity theories)

There are other “bullet” clusters

Clowe et al. 2004

Weak Lensing



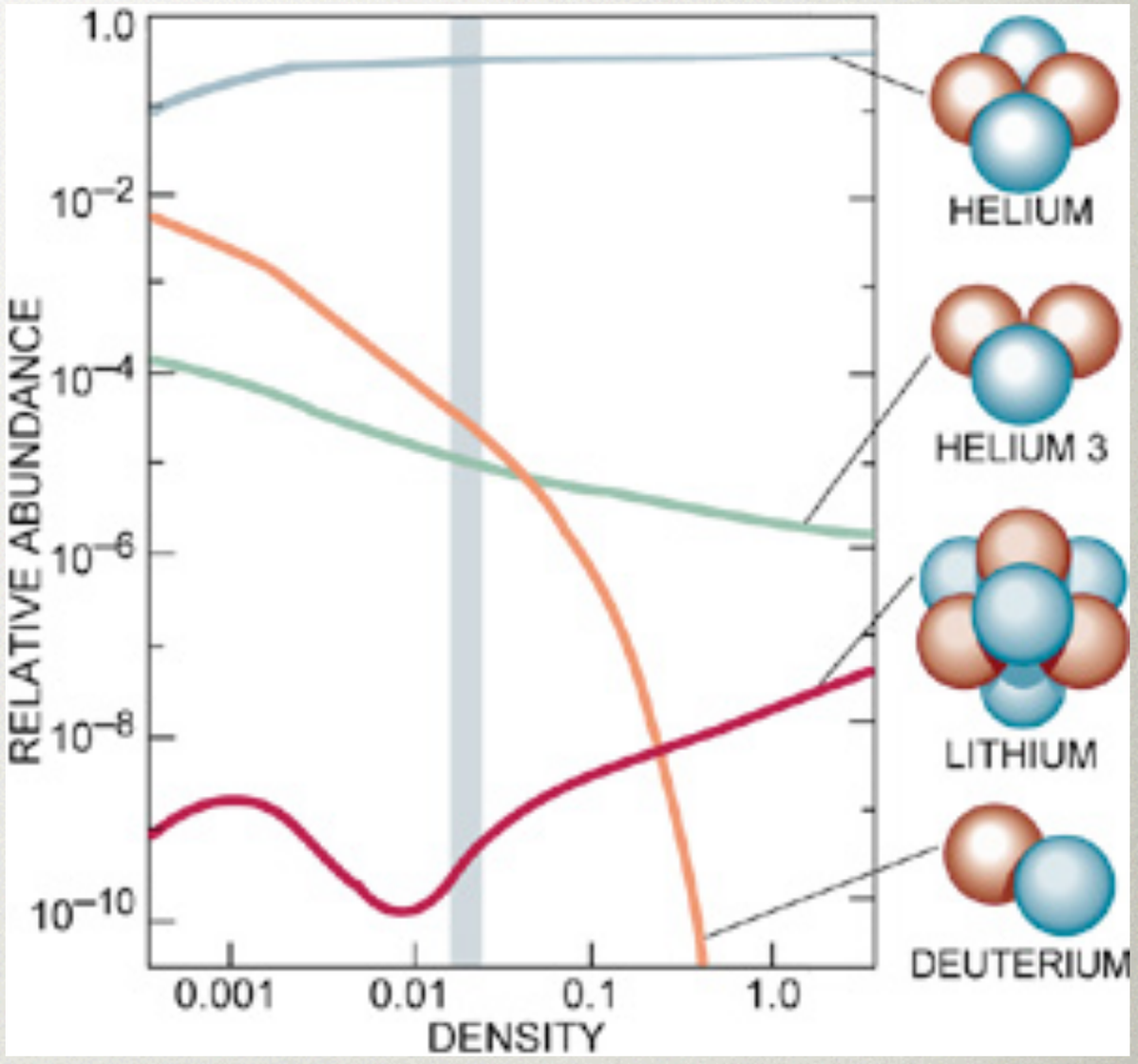


van Uitert et al 11, RCS2

So what is Dark Matter? Hidden baryons?

- DM cannot be baryonic as this causes problems for nucleosynthesis

- Also CMB / LSS arguments require non-baryonic DM



WMAP

$$\Omega_b h^2 = 0.02267^{+0.00058}_{-0.00059}$$

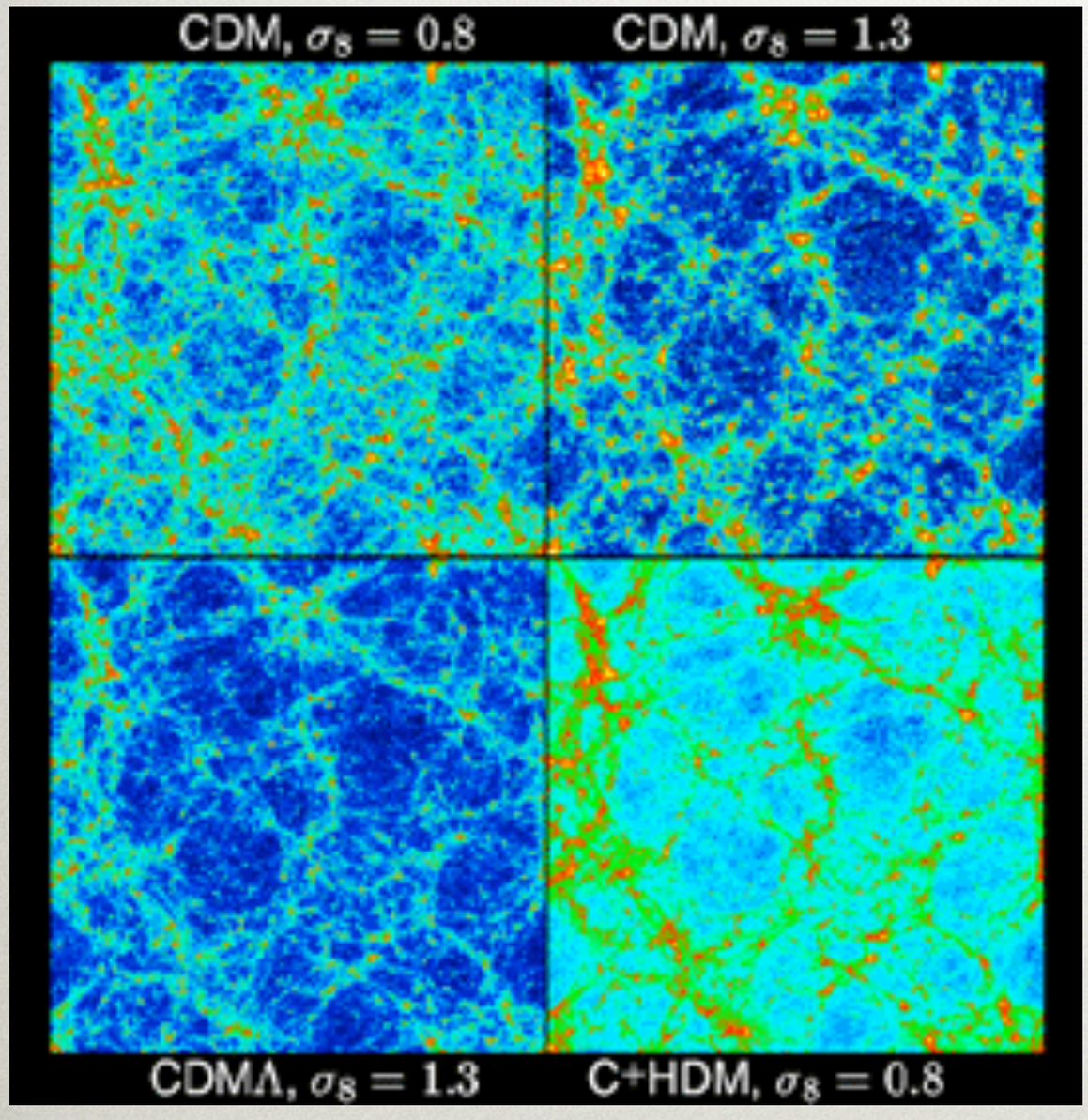
$$\Omega_c h^2 = 0.1131 \pm 0.0034$$

A NEW PARTICLE?

	at freeze-out	if weakly interacting
hot dark matter (e.g. neutrinos)	relativistic	m < 1 keV
warm dark matter (e.g. sterile neutrino)	quasi-relativistic	1 keV < m < 10 keV
cold dark matter (e.g. WIMP)	non-relativistic	m > 10 keV

HDM cannot account for small scale structures.

Limits on neutrino mass (hot dark matter)



Warren et al.

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94\,\mathrm{eV}}$$

Cosmological constraints

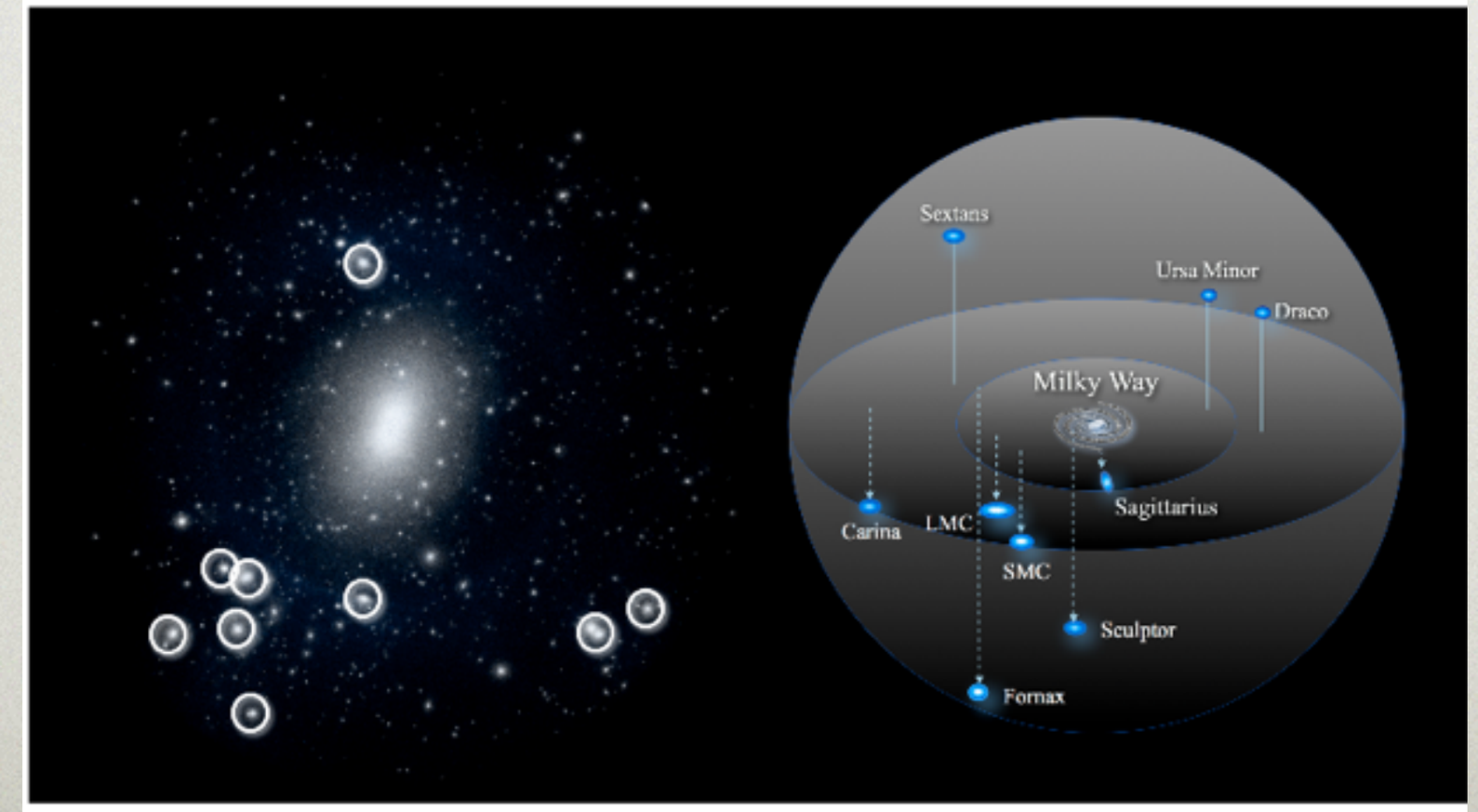
Ω_ν<0.2…2eV

(depends on priors and other assumptions)

Warm dark matter

- Missing Satellites problem: Many more (~500) satellites in CDM simulations than observed

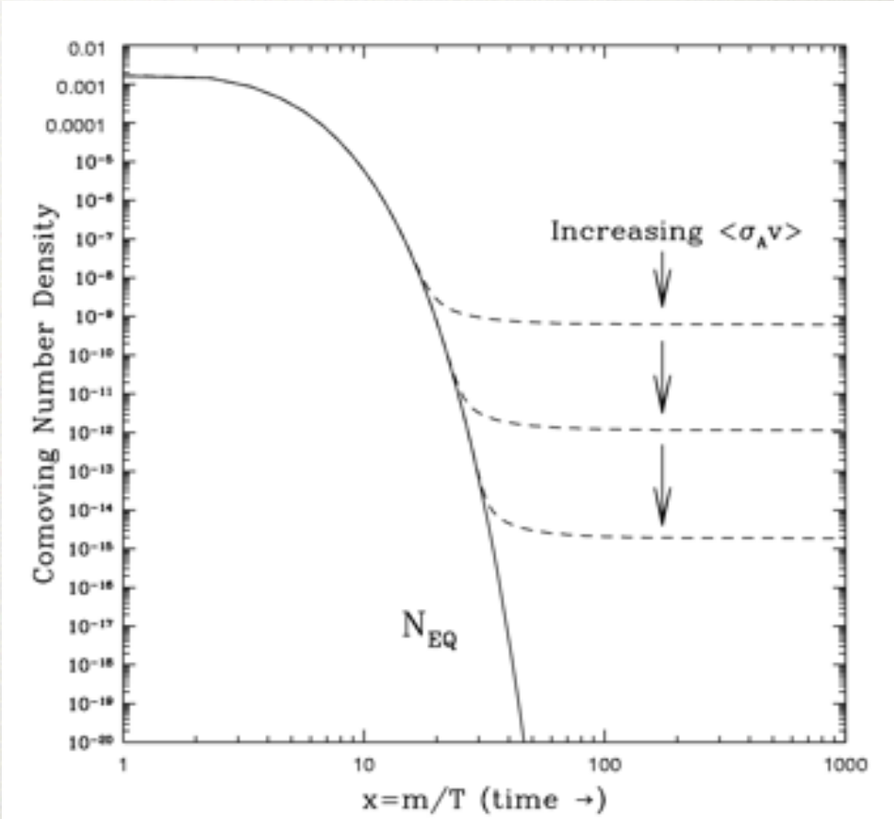
  - Warm dark matter would suppress formation of satellites
  - Satellites may be too faint or contain only dark matter



Cold dark matter?

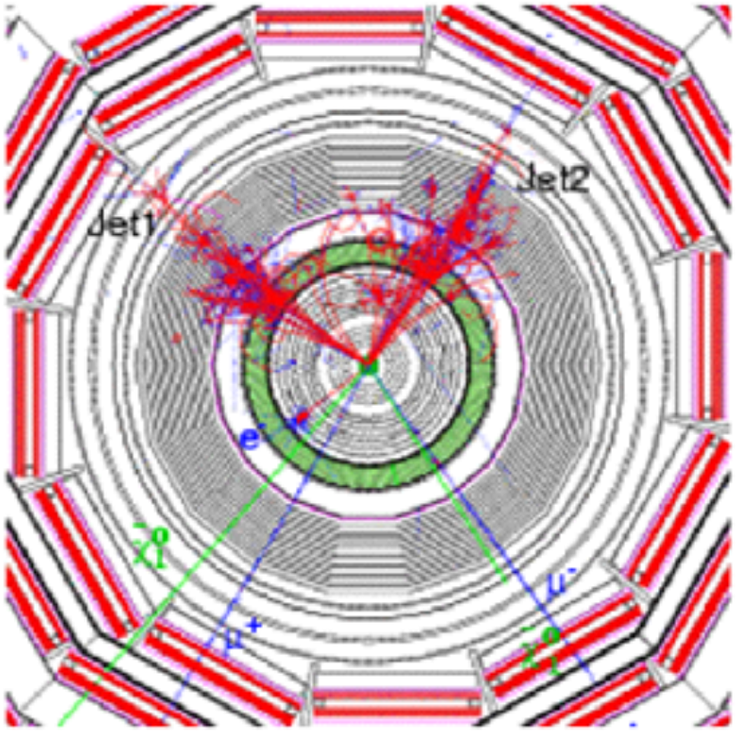
- WIMP = weakly interacting massive particle
  - SUSY predicts as lightest super-symmetric particle
  - But SUSY disfavoured by LHC?

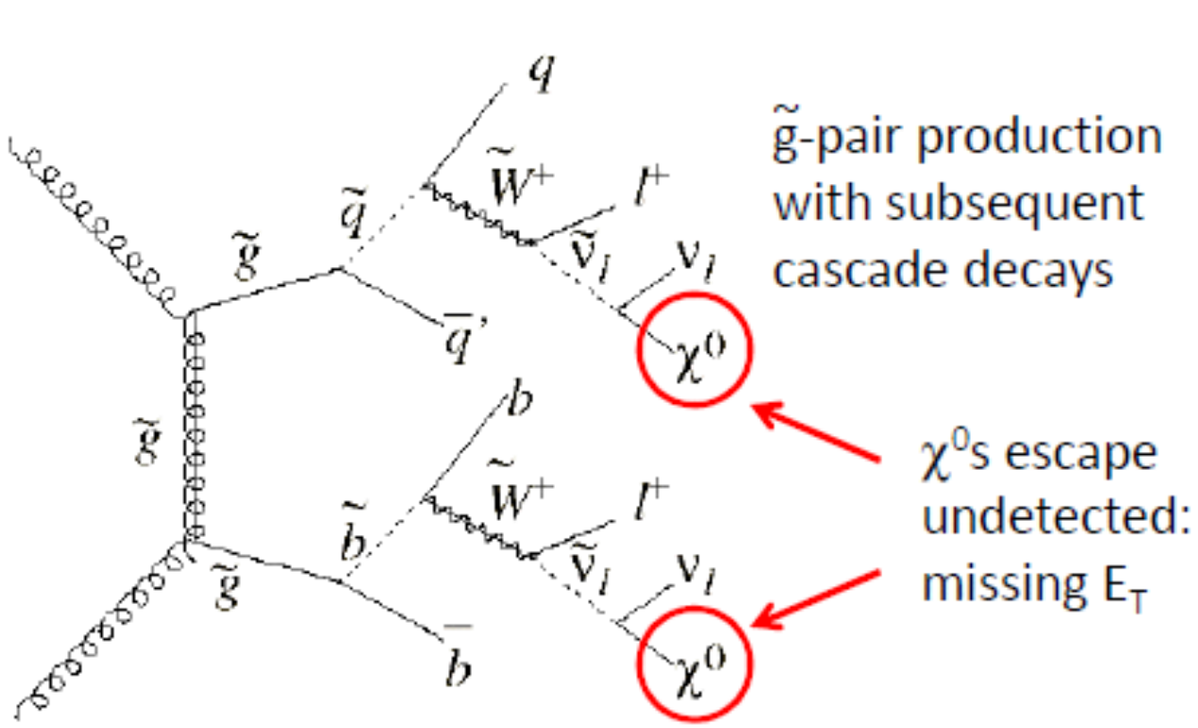
- "WIMP miracle" – correct abundance requires cross-section which is roughly what's expected for weak scale particle ~ 100 GeV



100 GeV predicts $\Omega_m \sim 0.3$

Collider experiments (LHC)





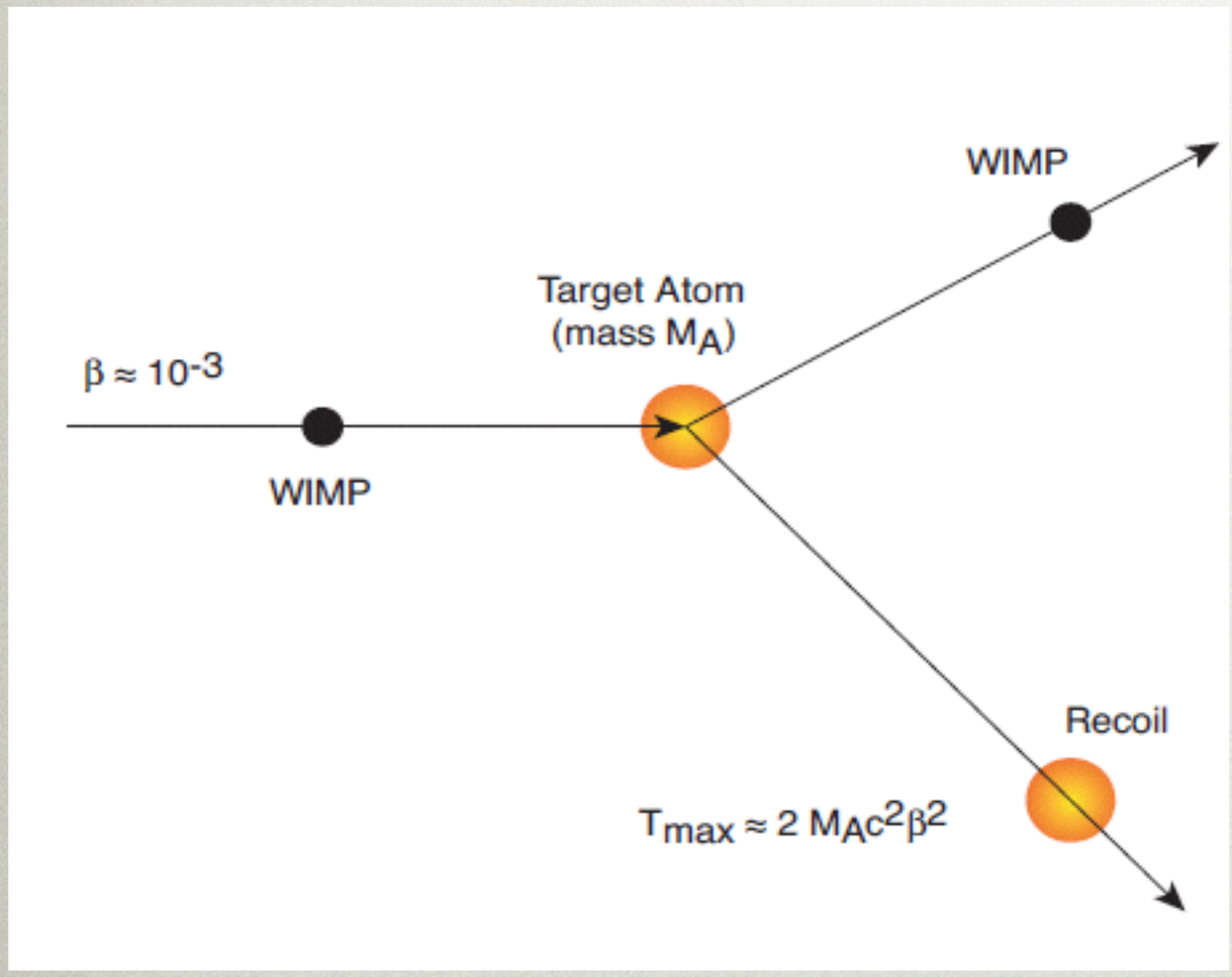
multiple measurements of SUSY observables → cMSSM Parameters: m_0, $m_{1/2}$, tanβ, A_0, sign(μ): SUSY masses, couplings →

$$\frac{dn_\chi}{dt} = -3Hn_\chi - <\sigma v>(n_\chi^2 - n_{\chi(eq)}^2)$$

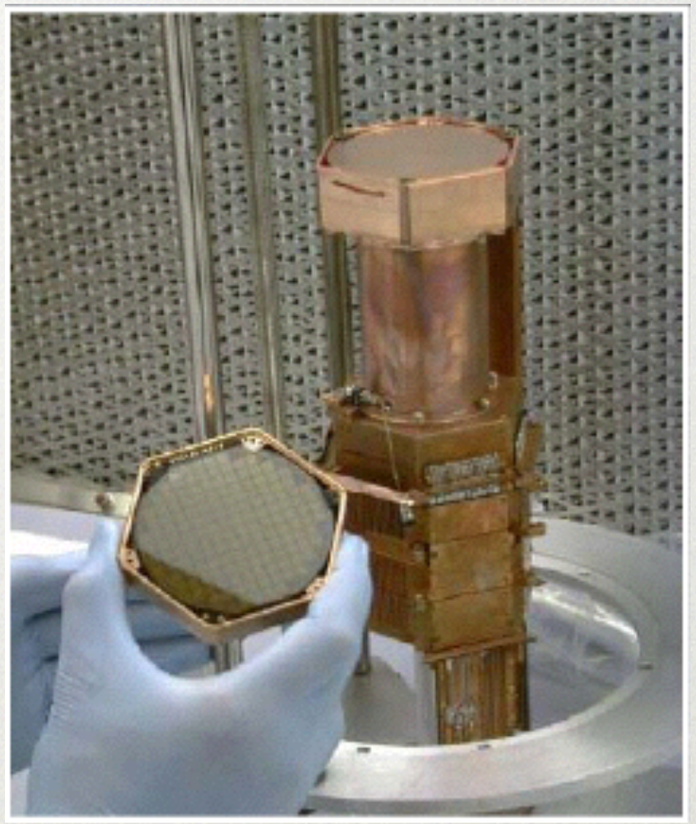
→ $\Omega_\chi h^2$

No ATLAS excesses found yet at 13TeV 3.2fb^{-1}

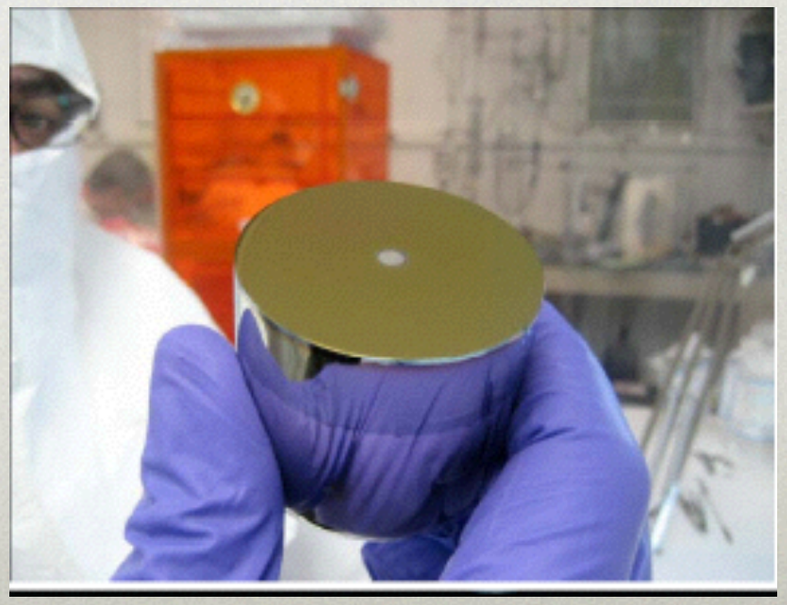
Direct detection



Try to detect ionization and phonons from very cold semiconductors underground

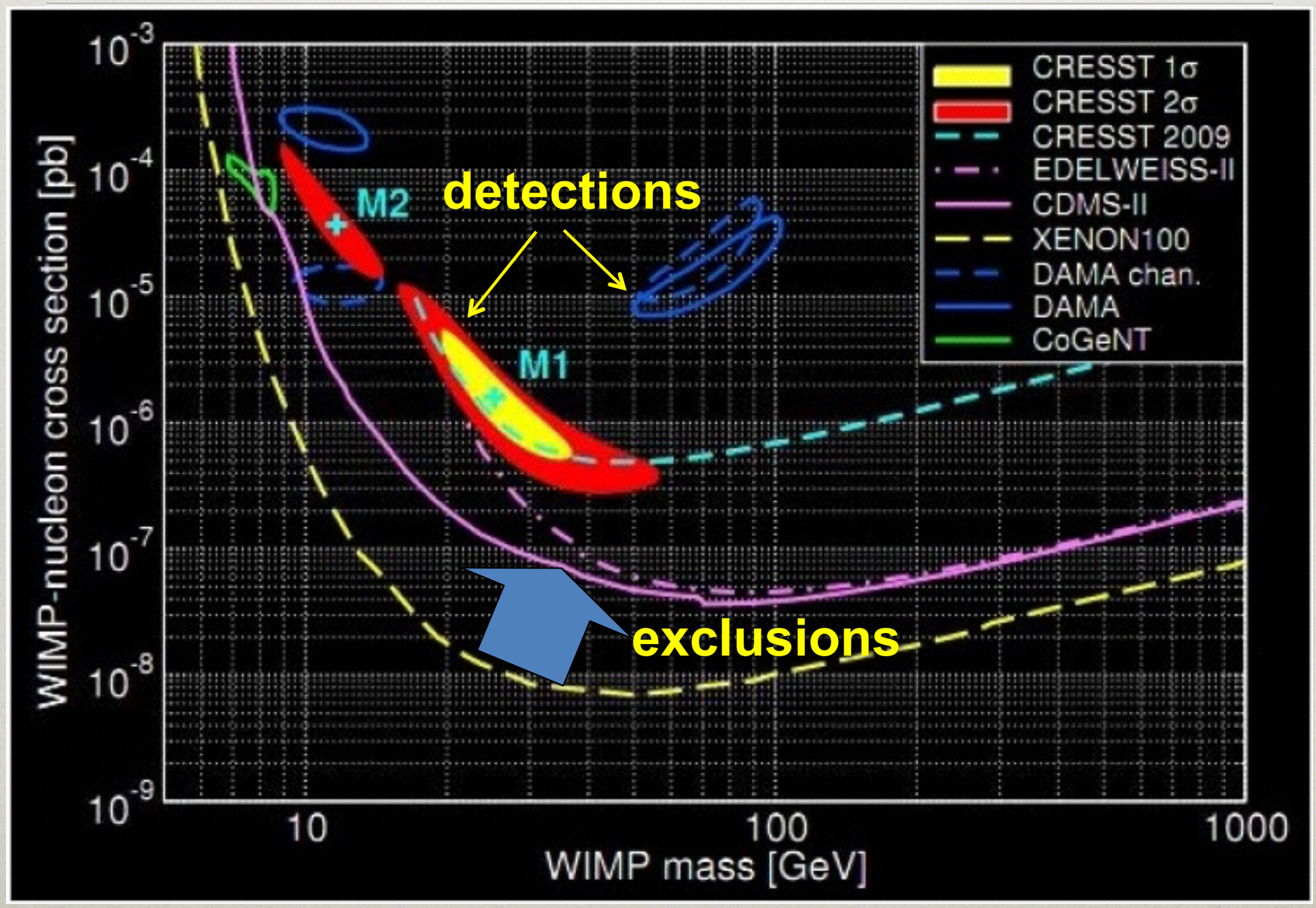


CDMS



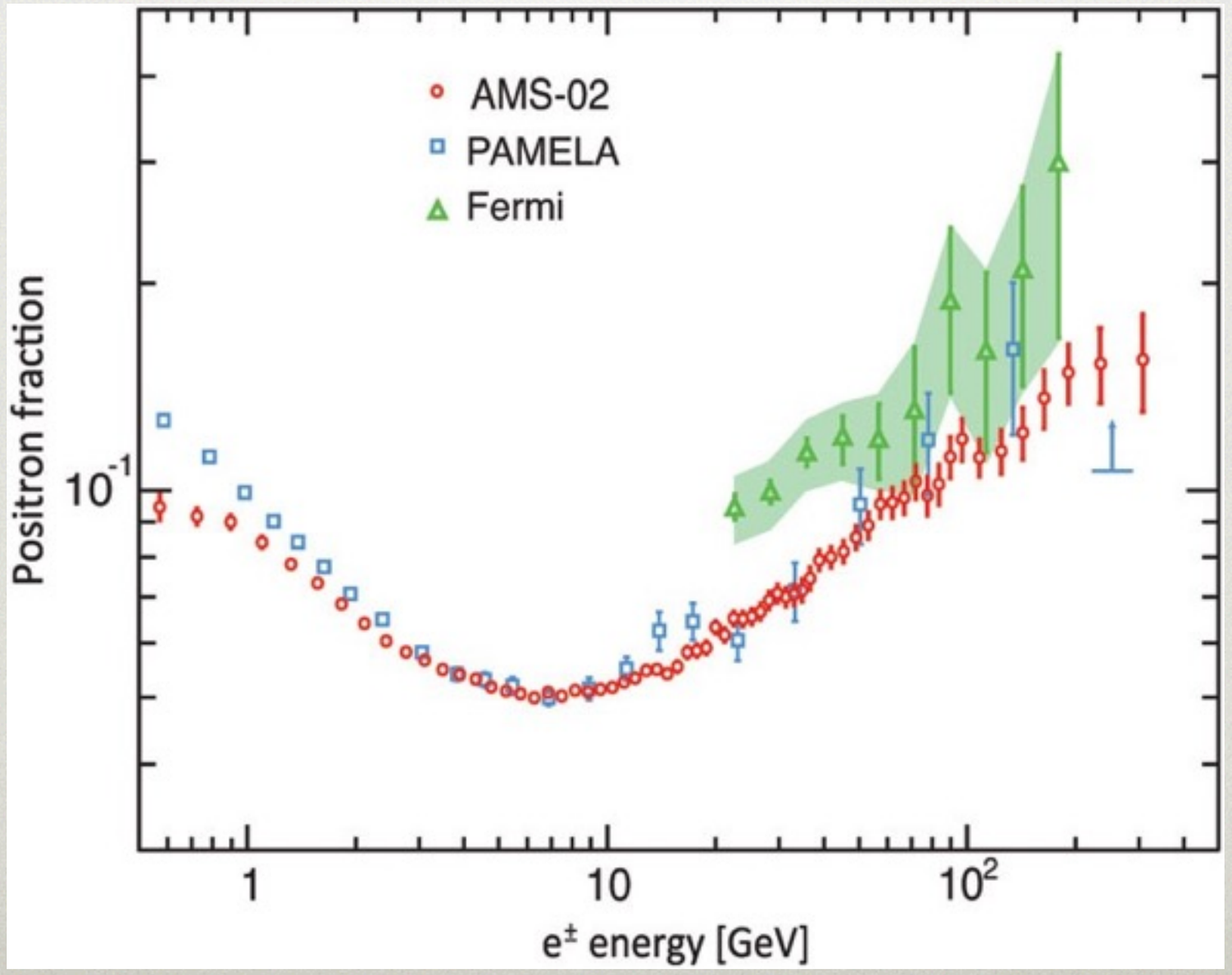
CoGeNT

Confusing results...



Indirect detection

Positron excess a hint of DM annihilation or local pulsars?



AXIONS

NB another DM candidate:

Axion - particle introduced to ensure QCD doesn't violate CP symmetry.

Non-relativistic, collisionless, but small mass (10^{-5} - 10^{-3} eV)

Exciting possibilities for lab tests!
e.g. ADMX, detect axions converting into microwaves in presence of magnetic field.

Summary

Dark matter seems to be there (a lot).

Can't be baryonic (CMB, nucleosynthesis)

Not hot (LSS)

Not weird gravity?? (Bullet cluster)

Don't see cold particle (LHC)

Hmm.