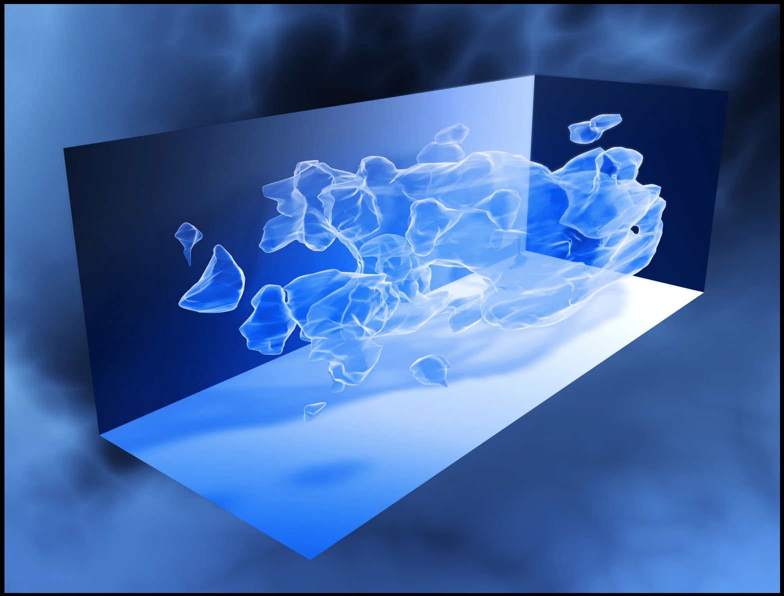


Dark Matter: What Do We Know From Cosmological Observations?

James E. Taylor
University of Waterloo

CAP Congress . Laurentian University, Sudbury . June 19, 2014

Outline:

I Astrophysical Dark Matter: Why and How?

II Particle Dark Matter: Why and How?

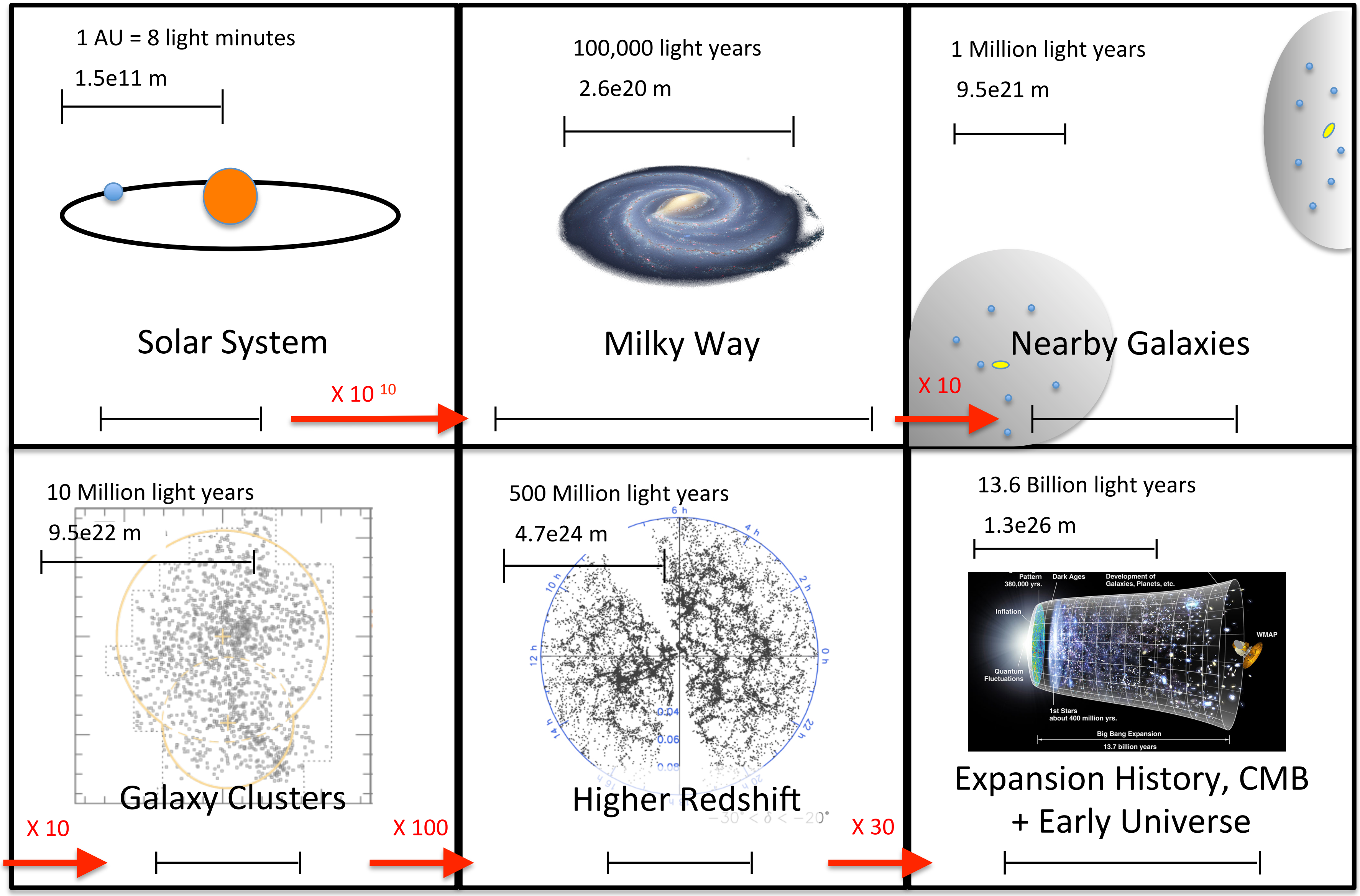
III Cosmological Evidence For Dark Matter –
a Few (Less Common) Examples

IV Outstanding Problems

V The (Near) Future

I: Astrophysical Dark Matter: Why and How?

What we see: visible light from stars & gas; IR/mm from dust & the CMB; + radio/high energy from compact objects



1 AU = 8 light minutes

1.5e11 m

Solar System

X 10^{10}

100,000 light years

2.6e20 m

Milky Way

1 Million light years

9.5e21 m

Nearby Galaxies

X 10

10 Million light years

9.5e22 m

Galaxy Clusters

X 10

X 100

500 Million light years

4.7e24 m

Higher Redshift

X 30

13.6 Billion light years

1.3e26 m

Expansion History, CMB + Early Universe

Can trace luminous structure organized by gravity over a wide range of scales
(from 1 AU to our current horizon, a factor of 10^{15})

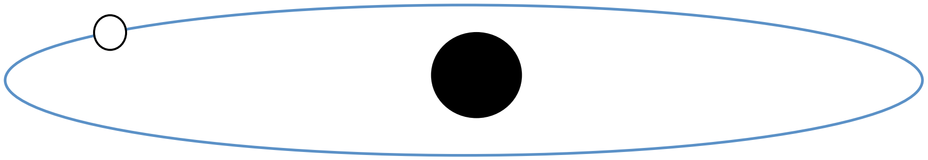
What we measure:

Dynamics:

centrifugal force: $F_c = mV^2/r$ gravitational force: $F_g = -GMm/r^2$

so balancing forces, $V^2 = GM/r$

or $M_{est} = rV^2/G$

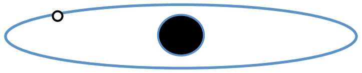


In practice, usually only measure a single velocity component along the line of sight from the Doppler shift: $V_{los} \sim c(\Delta\lambda/\lambda)$

=> geometric dependence

What we measure:

$M_{est} = rV^2/G$



Dynamics:

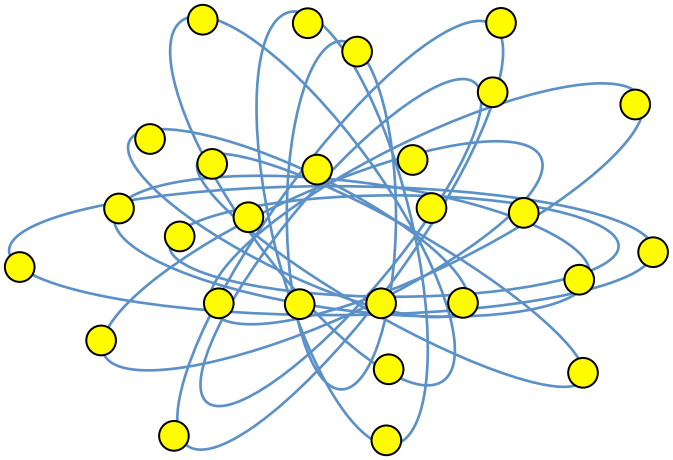
More complex (non-circular, inclined, non-planar) orbits:

in statistical equilibrium, isolated systems satisfy virial theorem:

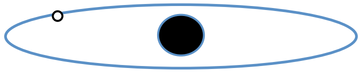
$$2\langle K\rangle = -\langle W\rangle$$

where $\langle K\rangle \sim \alpha M(V_{los})^2$ and $W = -\beta\,(GM^2/r)$

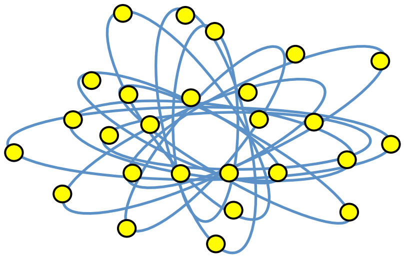
so $M_{est} = 2(\alpha/\beta)\, r\, (V_{los})^2/G$



What we measure:

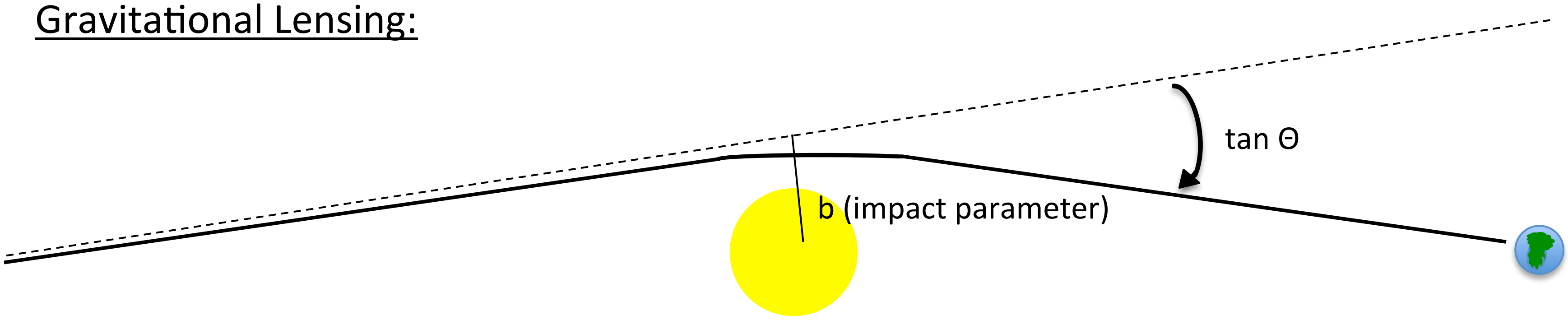


$M_{est} = rV^2/G$



$M_{est} = (2\alpha/\beta)\, rV^2/G$

Gravitational Lensing:



Light deflected by gravitational potential: $\tan\Theta \sim [GM/b]/[1/2\ c^2]$ (Newtonian)

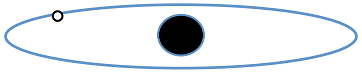
$= 4GM/bc^2$ (GR)

so $M_{est} = (\tan\Theta/4)\, bc^2/G$

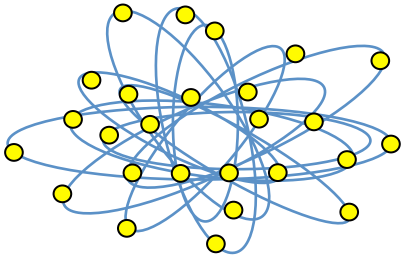
(but note this is a <u>different component</u> of gravitational potential: $(\Psi+\Phi)$ vs. (Φ))

What we measure:

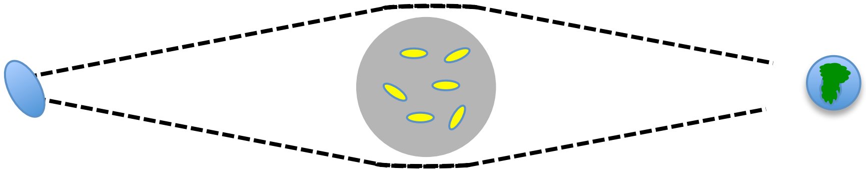
$M_{est} = rV^2/G$

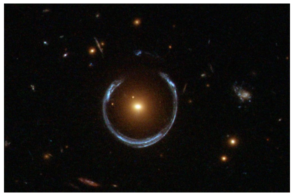


$M_{est} = (2\alpha/\beta)\, rV^2/G$



<u>Strong Lensing:</u> Θ is large enough that we can see multiple images of a single source



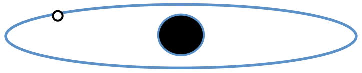


Get excellent estimate of mass enclosed within Einstein radius Θ_E:

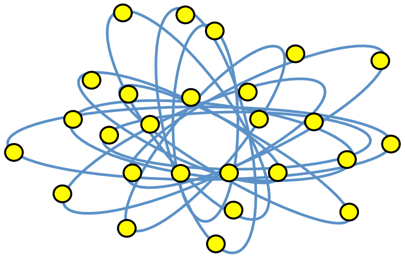
$$M_{est} = (\Theta^2_E/4)(d_L\, d_S/d_{LS})\, c^2/G,$$

What we measure:

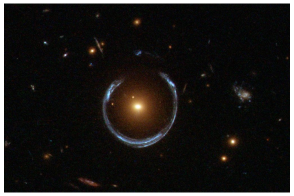
$M_{est} = rV^2/G$



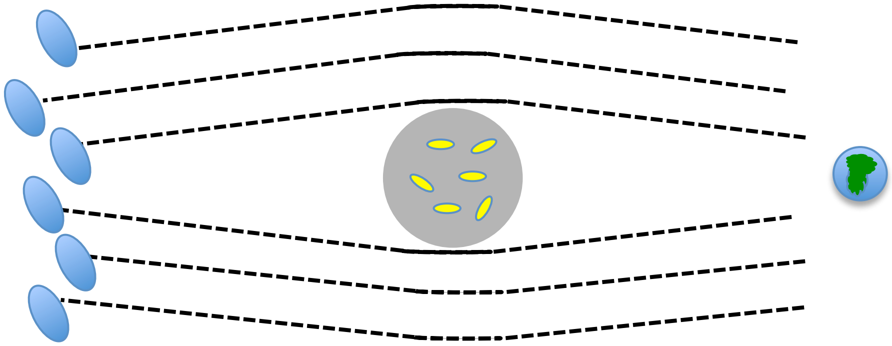
$M_{est} = (2\alpha/\beta)\, rV^2/G$

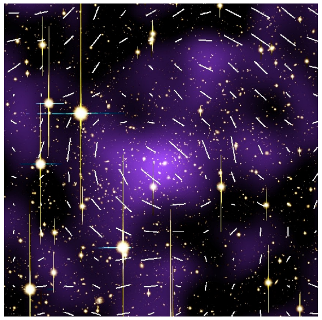


$M_{est} = (\Theta^2_E/4)(d_L\, d_S/d_{LS})\, c^2/G$



<u>Weak Lensing:</u> deflection/distortion is at the percent level; have to measure shapes of 100s of background galaxies to map this out





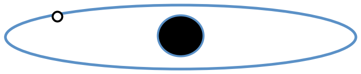
Get very noisy estimate of mass surface density:

$$\Sigma_{est} = (1/4\pi)\, \kappa\, (d_S/d_L\, d_{LS})\, c^2/G$$

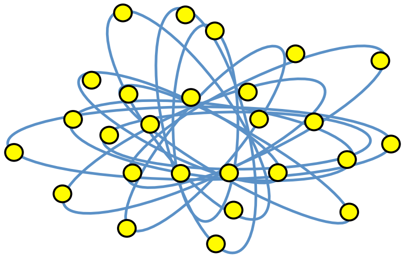
(where the convergence κ is a dimensionless measure of how magnified the region is)

What we measure:

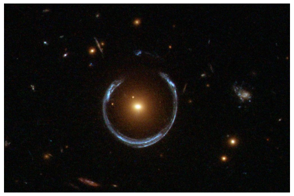
$M_{est} = rV^2/G$



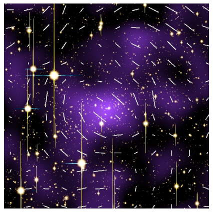
$M_{est} = (2\alpha/\beta)\, rV^2/G$



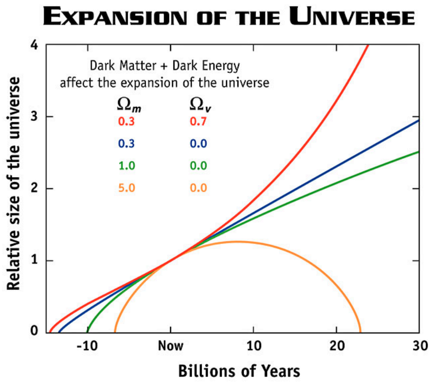
$M_{est} = (\Theta^2_E/4)(d_L\, d_S/d_{LS})\, c^2/G$



$\Sigma_{est} = (1/4\pi)\, \kappa\, (d_S/d_L\, d_{LS})\, c^2/G$



Other (Global) Techniques:



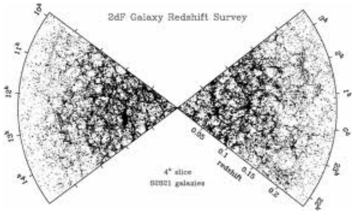
Global mass density ⇔ expansion rate (Friedmann equation)

$$\left(\frac{\dot{a}}{a}\right)^2 = \boxed{\frac{8\pi G}{3}\rho} - \boxed{\frac{kc^2}{a^2}} + \boxed{\frac{\Lambda}{3}c^2}$$

expansion rate (Hubble parameter)   matter   curvature   cosmological constant

Perturbation growth ⇔ number of galaxy clusters, large scale structure, peculiar velocities:

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4\pi G\bar{\rho}\delta$$



The Punchline:

Comparing what we see and what we measure, can estimate the mass-to-light ratio, M/L, in solar units:

$$M_{\odot}/L_{\odot} = 2 \text{ x } 10^{30} \text{ kg}/3.846 \text{ x } 10^{26} \text{ W} = 5133 \text{ kg/W in the visible}$$

Observationally, we find

the Solar System	M/L = 1
older, low-mass stars	M/L ~3-4
the Milky Way (to solar radius)	M/L ~ 10
the extended halo of the Milky Way	M/L ~ 60-80
nearby dwarf galaxies	M/L > 100-200
the local universe	M/L ~ 60-80

So overall we are missing a factor of 5-20+ in the mass budget.

To fill in the gap, we need matter with a much larger mass-to-light ratio:

“dark matter”

(Zwicky 1933: “dunkle Materie”)

What Properties Does (Astrophysical) Dark Matter Need?

Consider a mass N objects of total mass M, individual masses m, sizes r:
At fixed density (e.g. 1 g/cc)

size: $r = (M/N)^{1/3}$ but $N = M/m$, so $r = m^{1/3}$
individual cross-section: $\sigma \sim r^2 = m^{2/3}$
total cross section $\Sigma = N \sigma \sim m^{-1/3}$
total surface area $A = N r^2 \sim m^{-1/3}$
total BB emission $L = m^{-1/3} T^4$

For matter to be dark (large M/L), emission L must be small relative to M ⬄
either cold (w.r.t Sun, 6000 K) and/or relatively large (w.r.t. dust, r ~ 1 micron)
Also doesn't scatter/absorb light -> Σ small
- * either because compact, massive ⬄ m large
- * or because individual σ small (relative to Thomson cross-section)
  ⬄ fundamentally neutral, at most weakly interacting

Overall, distinguish 3 possibilities for matter, based on total cross-section Σ:
- **Σ large**: normal fluid with pressure (e.g. fully ionized gas in galaxies, clusters)
- **Σ small**: pressure negligible, but Σ large enough to produce absorption/scattering ("dust")
- **Σ very small**: <u>dark matter</u> (no pressure, nor scattering/absorption)
  either MACHOS (massive compact halo objects) e.g. black holes
  or WIMPs (weakly interacting massive particles, e.g. neutralinos)

(Note we can relax the “massive” assumption if the particles are non-thermal, e.g. axions)

II: Particle Dark Matter: Why and How?

First, Could Dark Matter be Baryonic?

The nature and cosmic density of dark matter is constrained by a series of interlocking measurements:

1) angular size of CMB features tells us universe is flat to ~1%, so $\Omega_{tot} = \rho/\rho_{crit} = 1$.

2) the Friedmann equation + SNe distances, as well as local structure, tell us that $\Omega_m \sim 0.32$

3) Big Bang nucleosynthesis fixes the proton density of the universe, so that $\Omega_{bar} \sim 0.049$ (where Ω_{bar} is the density of protons + neutrons)

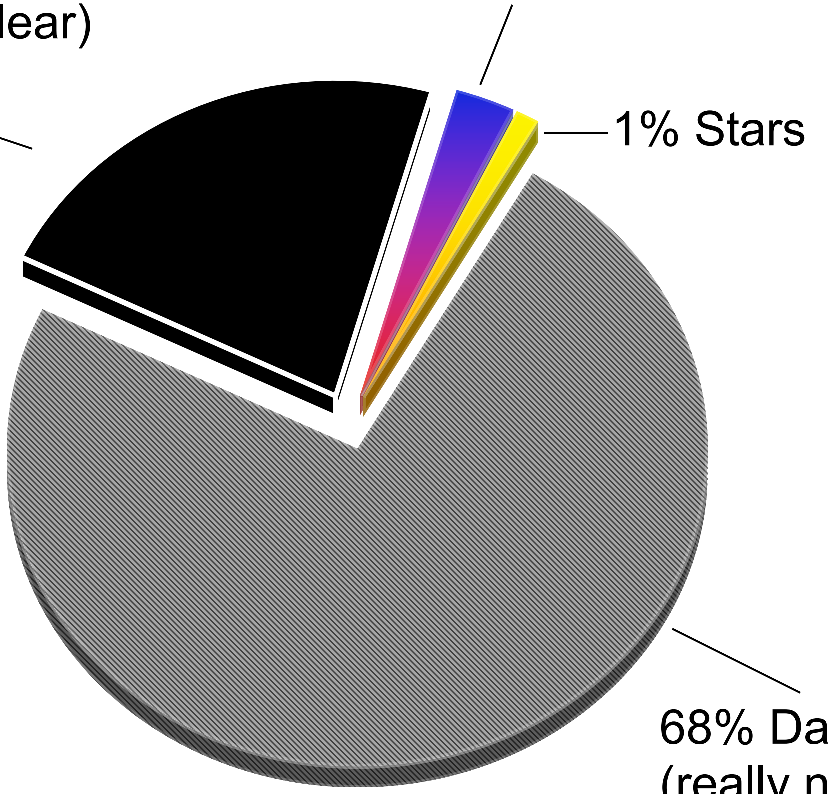
4) the CMB power spectrum also confirms that $\Omega_{bar}/\Omega_m \sim 0.15$

All this indicates that: $\Omega_{tot} \sim 1.0 \;\; >> \;\; \Omega_m \sim 0.32 \;\; >> \;\; \Omega_{bar} \sim 0.049$.

Thus there must be a non-baryonic matter component 6-7 times more abundant than normal matter.

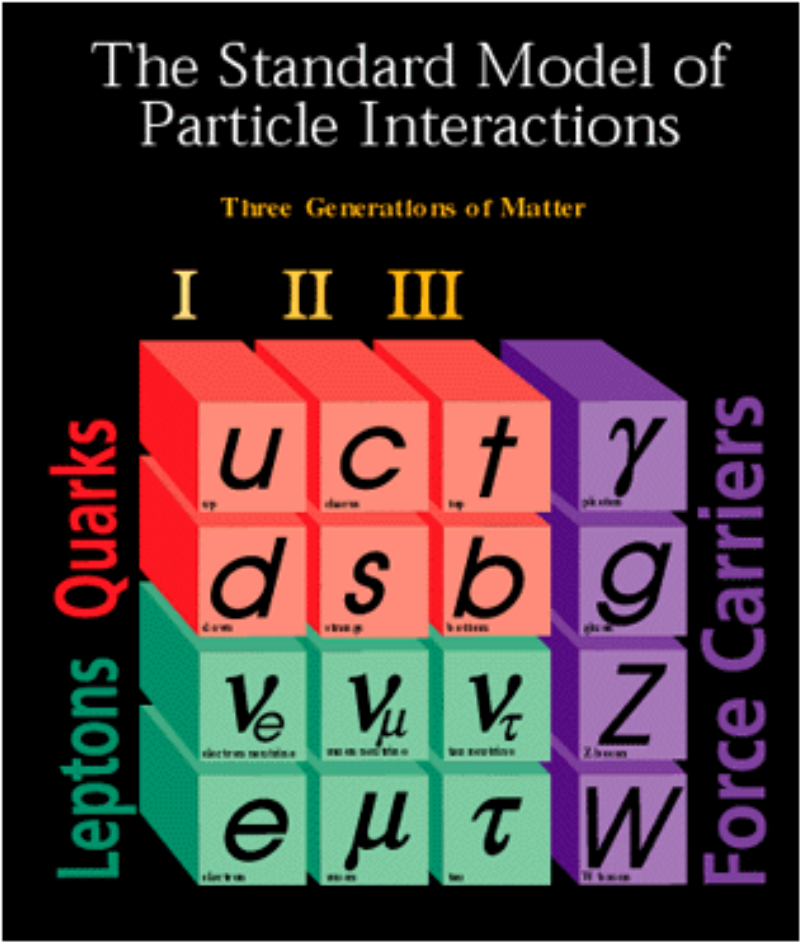
*(Note that even some of the baryonic matter must be dark: at the present day only 30-50% of Ω_{bar} is visible.)

Summary: The Composition of the Universe (2014, post-Planck)



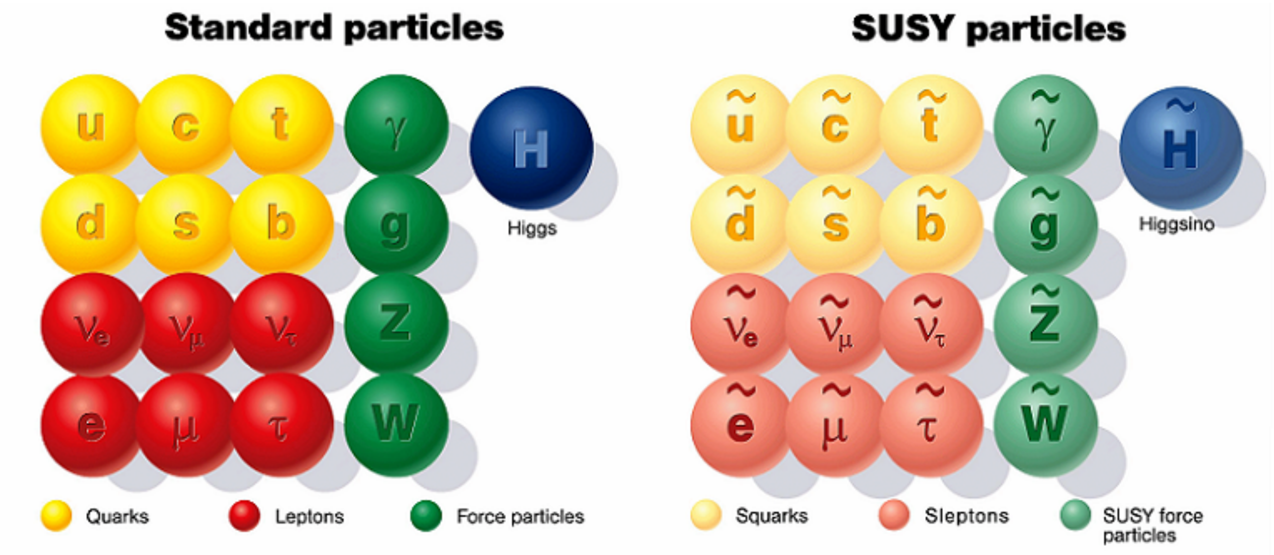
+ need one or more scalar fields?

The Standard Model: No room for WIMPS!



so how do we add to this?

So do we need new symmetries?



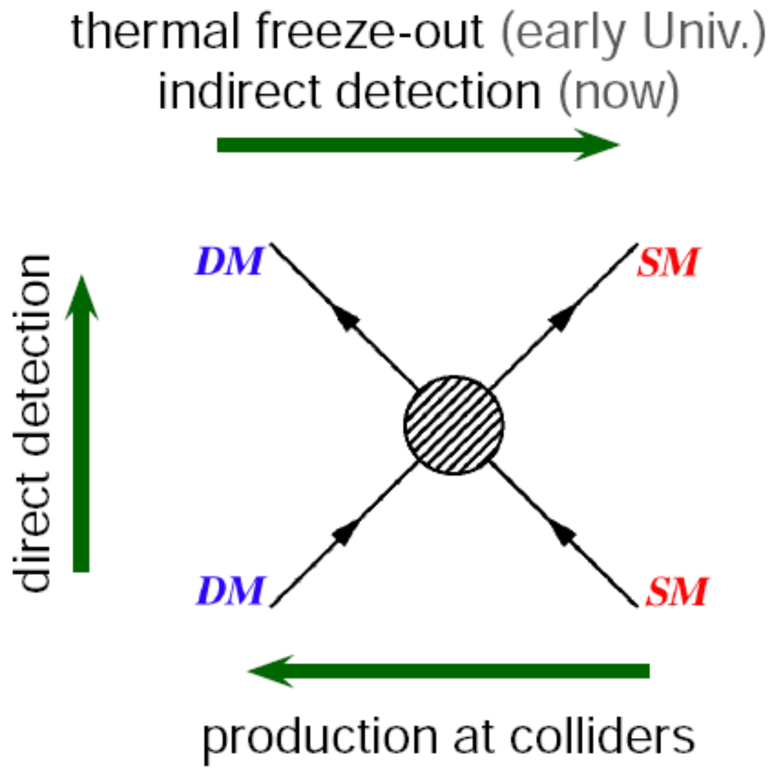
"Supersymmetry" (SUSY):
for every fermion (1/2 spin), a boson (integer spin); for every boson, a fermion

To get more particles,

- could introduce a new symmetry (supersymmetry), doubling SM particles
- could introduce multiple generations, e.g. by adding extra dimensions
  with non-trivial topology ⇔ many copies of SM particles
- could introduce a whole dark sector, mainly decoupled from SM

+ other possibilities:
  axions
  sterile neutrinos
  ...

Dark Matter Searches: Three Strategies



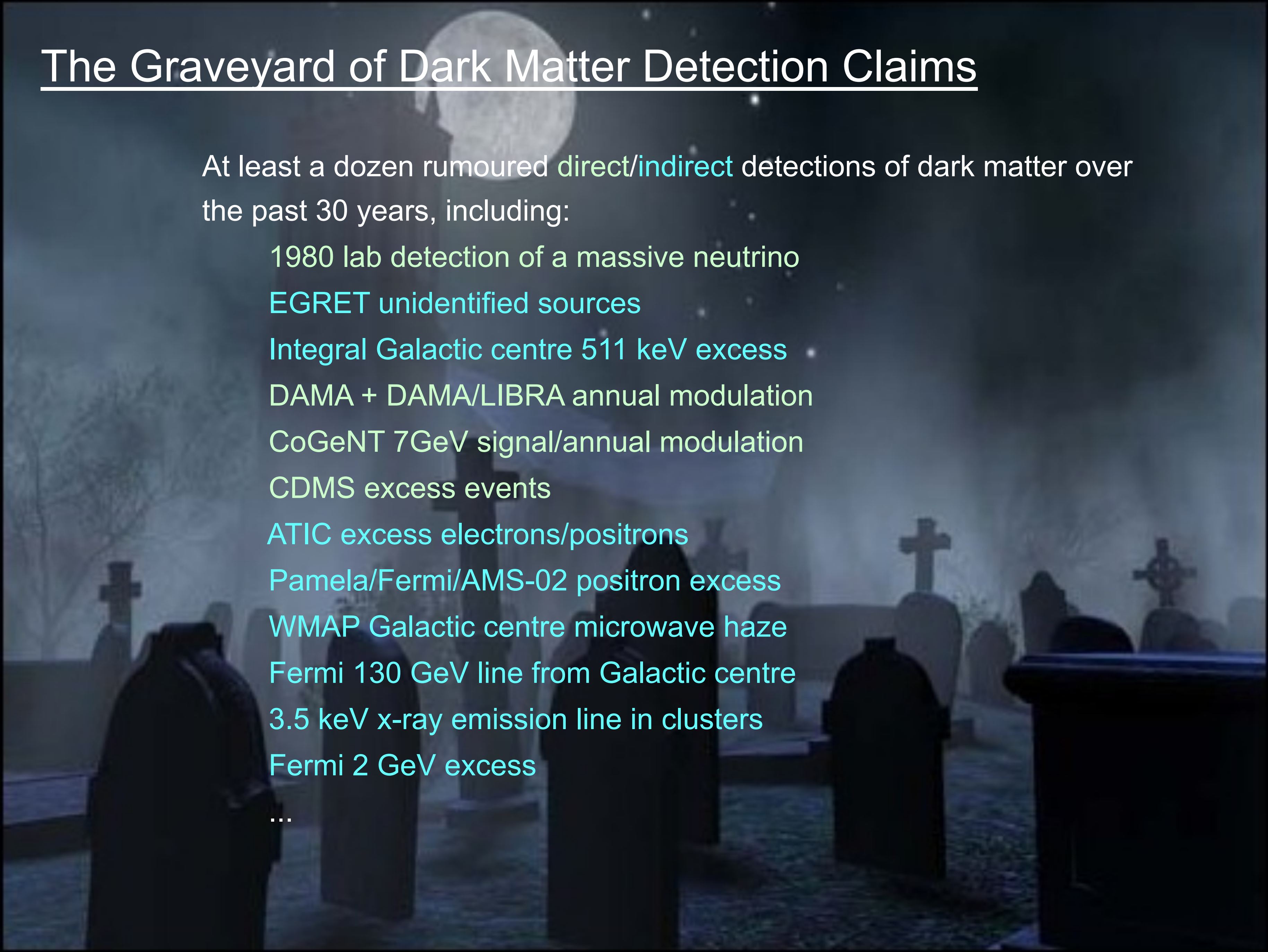
thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

production at colliders

Beyond production at colliders, two other strategies are:
* **“direct” detection** of collisions with SM particles
(normally nucleons in lab experiments),
* or **“indirect” detection** of SM decay/annihilation products, including
gammas, electrons (via synchrotron), positrons or other antimatter,
and neutrinos

The Graveyard of Dark Matter Detection Claims

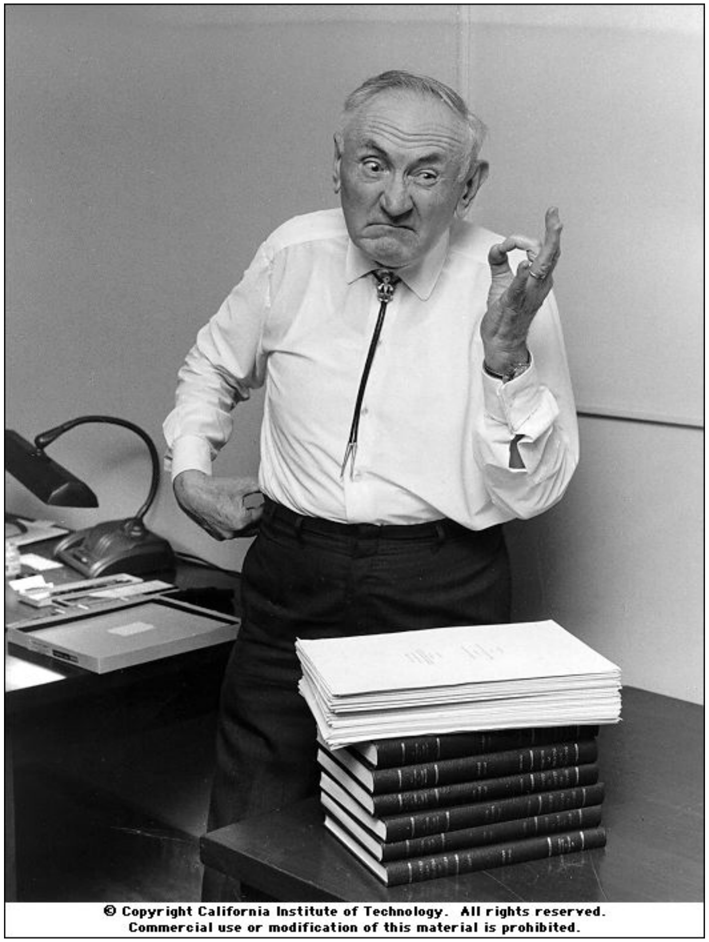


At least a dozen rumoured direct/indirect detections of dark matter over the past 30 years, including:

1980 lab detection of a massive neutrino
EGRET unidentified sources
Integral Galactic centre 511 keV excess
DAMA + DAMA/LIBRA annual modulation
CoGeNT 7GeV signal/annual modulation
CDMS excess events
ATIC excess electrons/positrons
Pamela/Fermi/AMS-02 positron excess
WMAP Galactic centre microwave haze
Fermi 130 GeV line from Galactic centre
3.5 keV x-ray emission line in clusters
Fermi 2 GeV excess
...

III: Cosmological Evidence For Dark Matter – a Few (Less Common) Examples

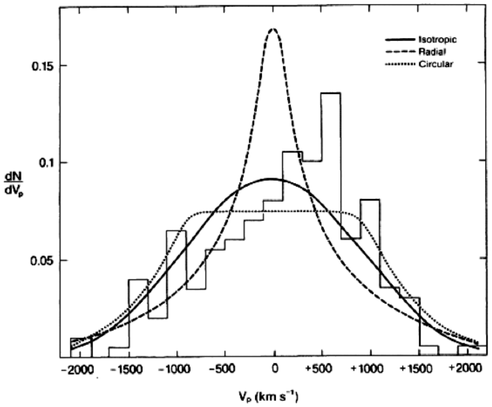
1933: The first evidence for dark matter, in the Coma cluster



Fritz Zwicky (1898-1974)

- Irascible
- Swiss
- Physicist
- Doubled the number of known supernovae
- Also worked on solid state physics, ionized gases, jet propulsion
- Referred to his colleagues as “spherical bastards”

- Measured the velocity dispersion of the Coma cluster to be 1200 km/s; inferred that the mass-to-light ratio was at least 50 times that of the Sun
- Suggested this light deficit was due to “dark matter”



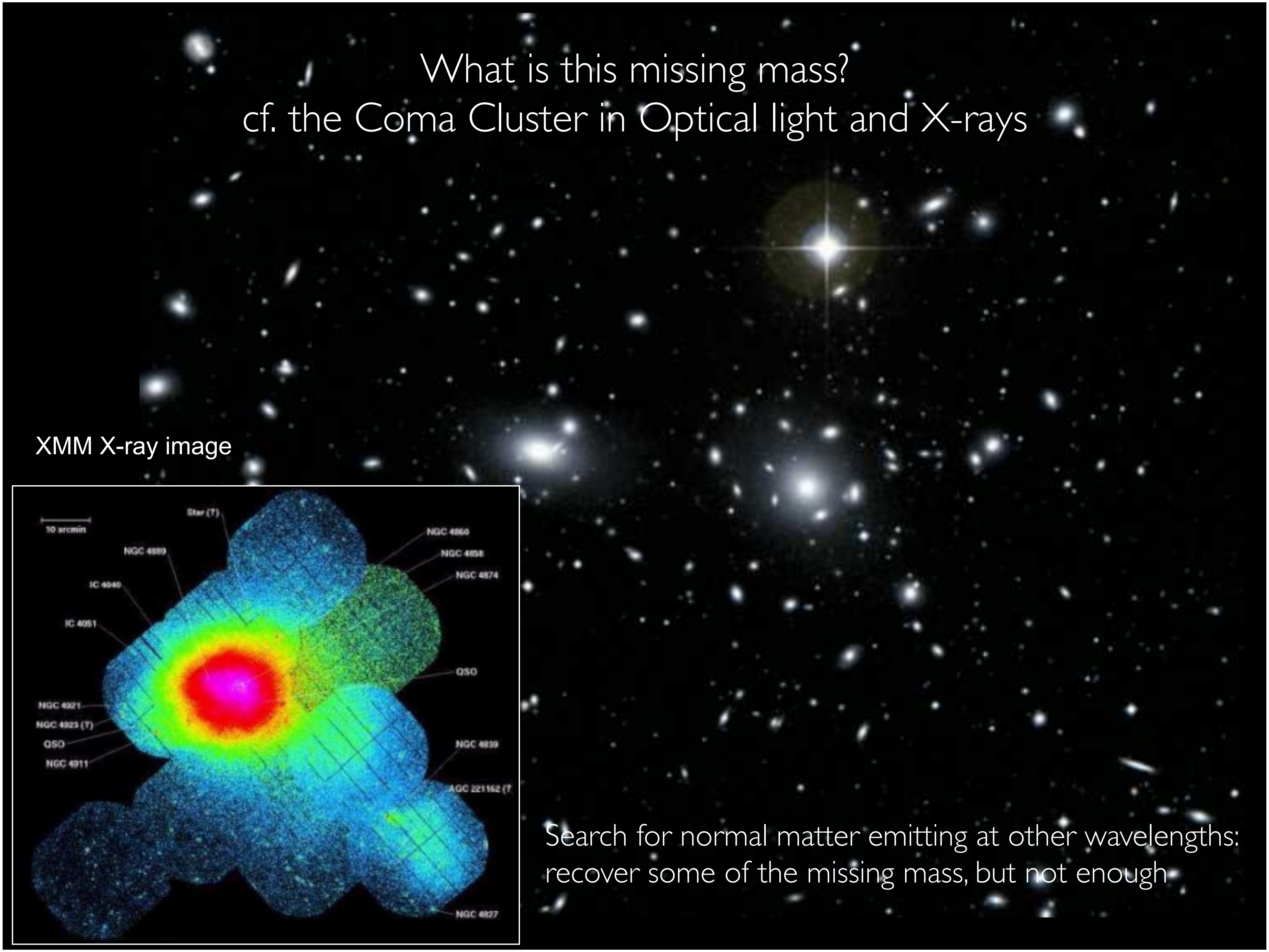
The virial theorem:

$\langle T \rangle = -\langle U \rangle/2$

so $M_{est} \sim RV^2/G$

assuming Coma is isolated and in equilibrium

What is this missing mass?
cf. the Coma Cluster in Optical light and X-rays



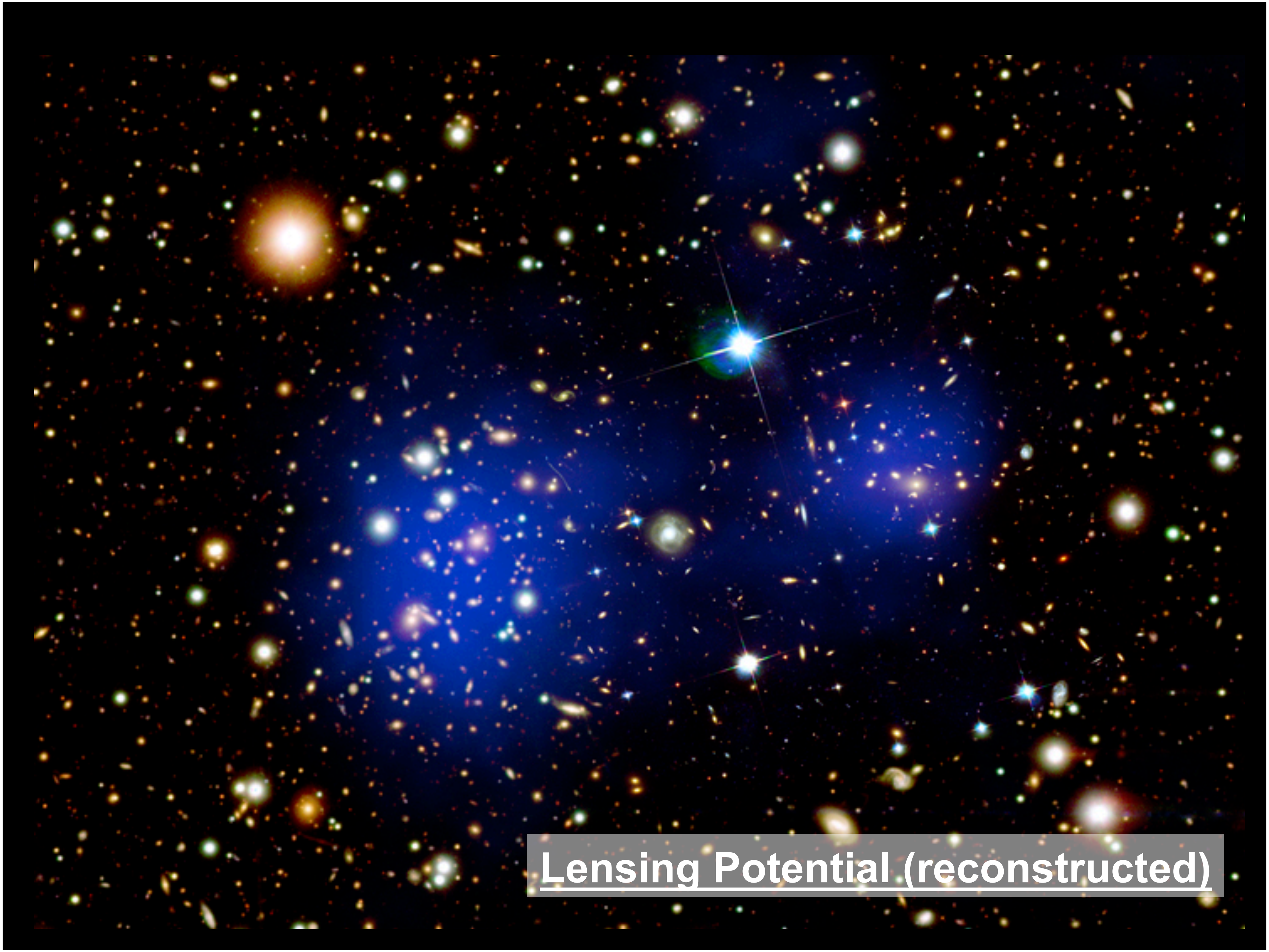
Search for normal matter emitting at other wavelengths:
recover some of the missing mass, but not enough

A modern example: the “Bullet” cluster

DARK MATTER

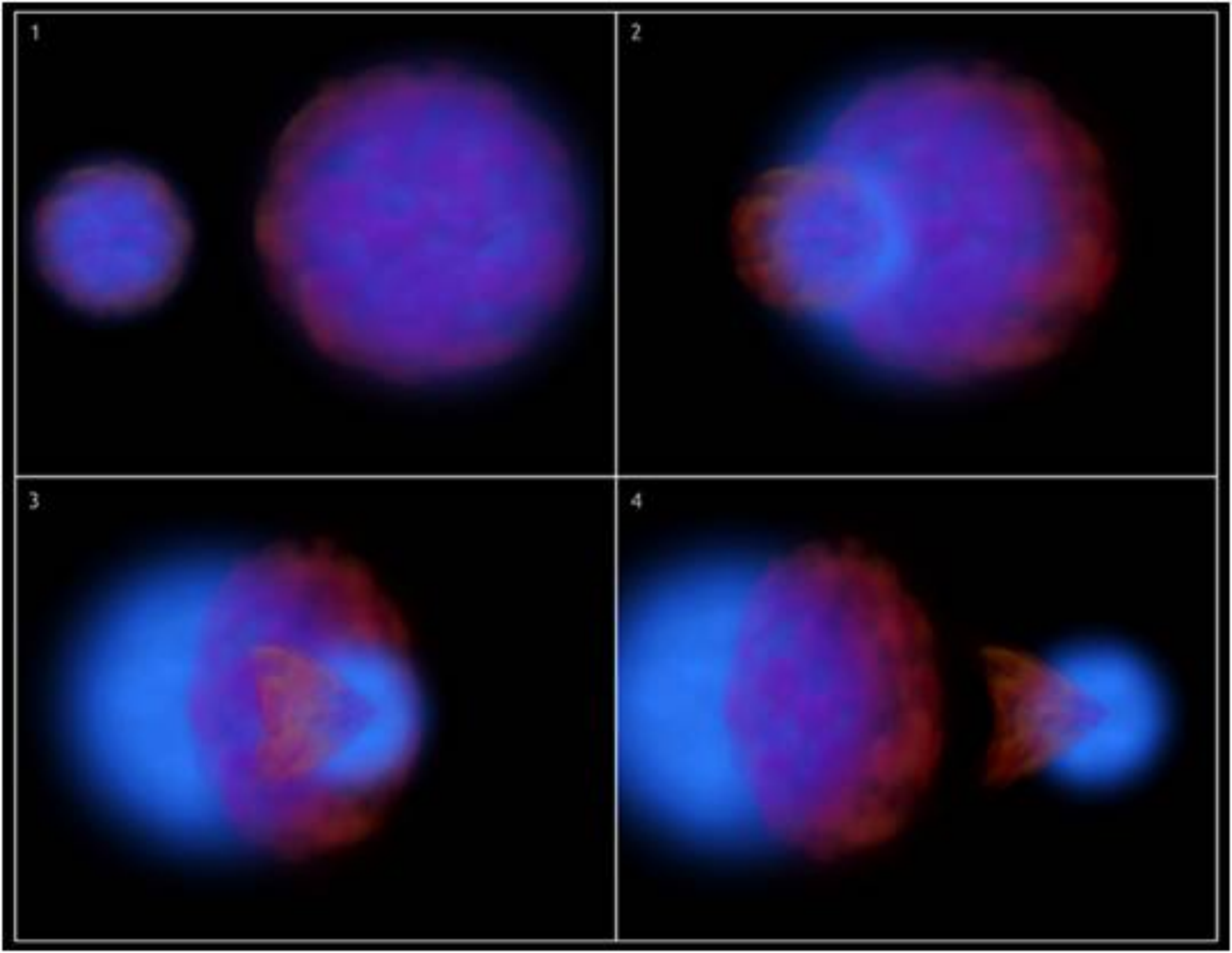
Most of the universe can't even be bothered to interact with you.


Galaxies



Lensing Potential (reconstructed)


Hot Gas (in X-rays)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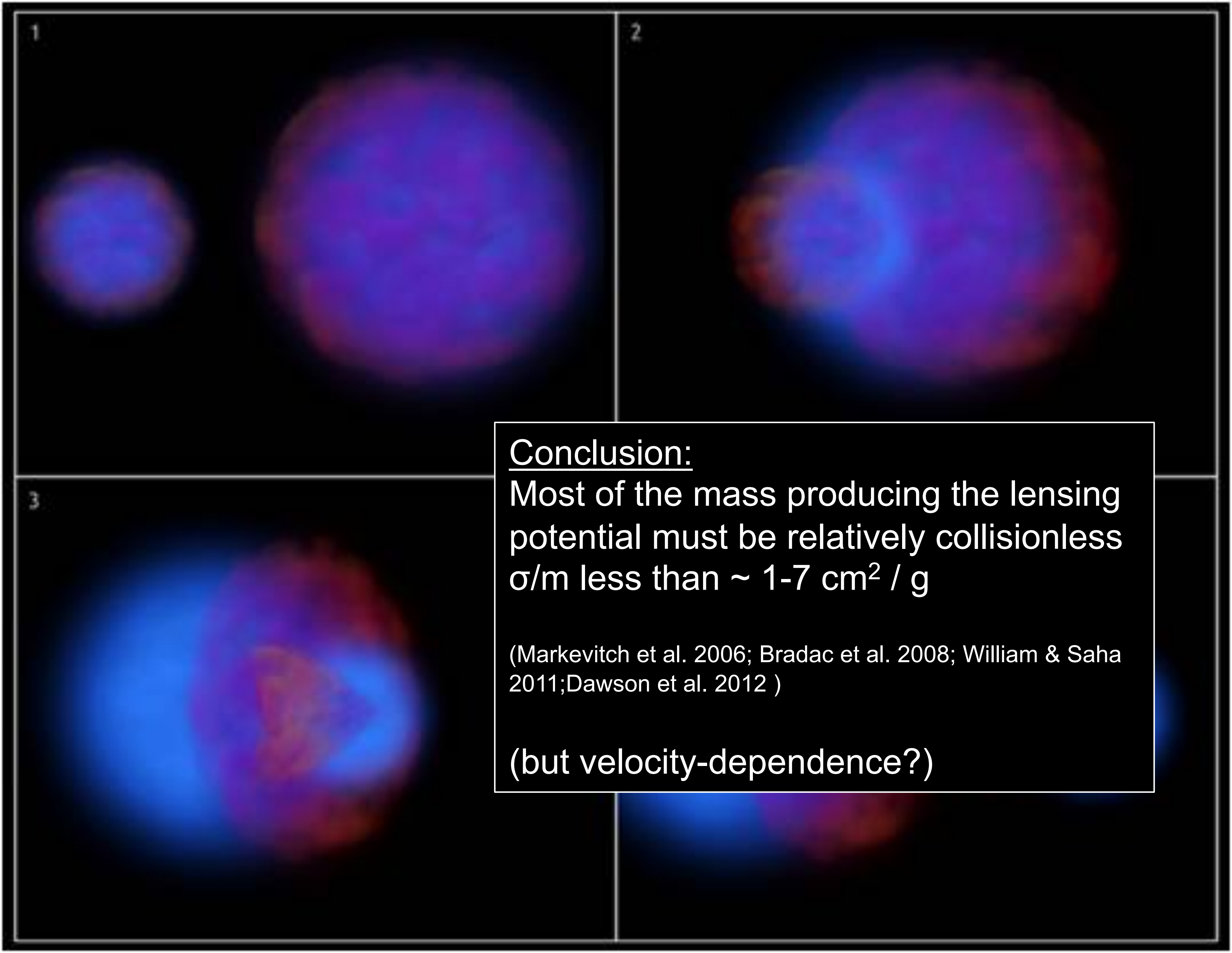


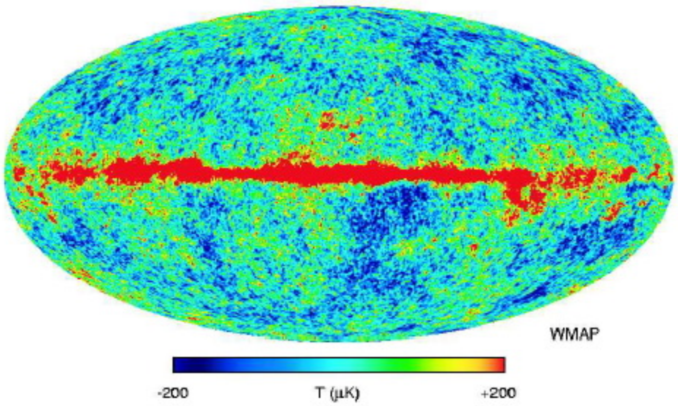
Conclusion:

Most of the mass producing the lensing potential must be relatively collisionless σ/m less than ~ 1-7 cm^2 / g

(Markevitch et al. 2006; Bradac et al. 2008; William & Saha 2011;Dawson et al. 2012)

(but velocity-dependence?)

Another example: Evidence for dark matter from the CMB



A basic argument:

As long as their amplitude is <<1, fluctuations in the matter density grow as 1/(1+z) in a matter-dominated universe.

The fluctuations we see in the CMB at z=1100 have an amplitude of 10^{-5}. Thus by the present day we would expect them to have an amplitude of ~1%, whereas clusters etc. represent overdensities of many 100s.

In fact, the problem is even worse since all baryonic fluctuations below some (large) scale are wiped out until the time of last scattering.

Constraining the dark matter to baryonic matter ratio at z=1100

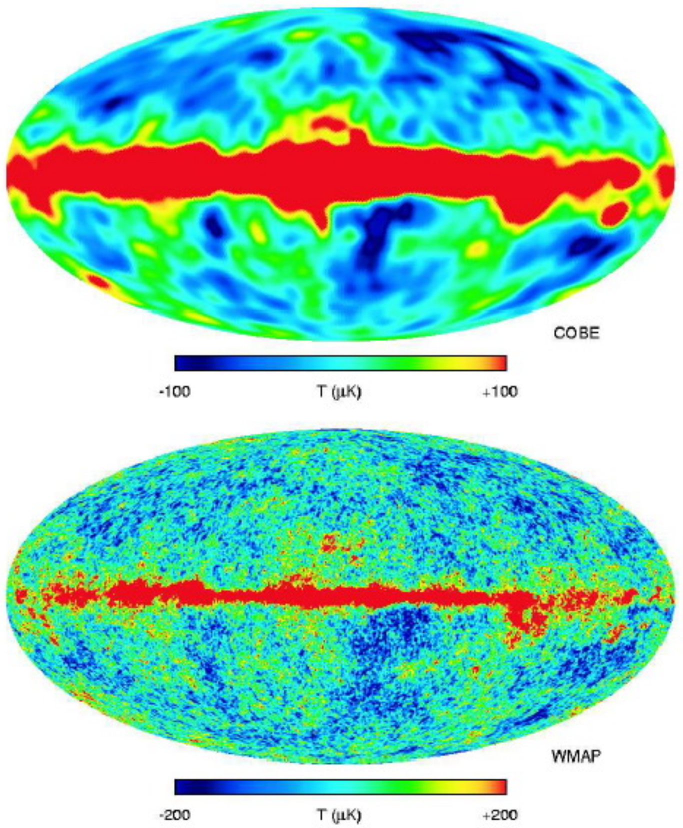
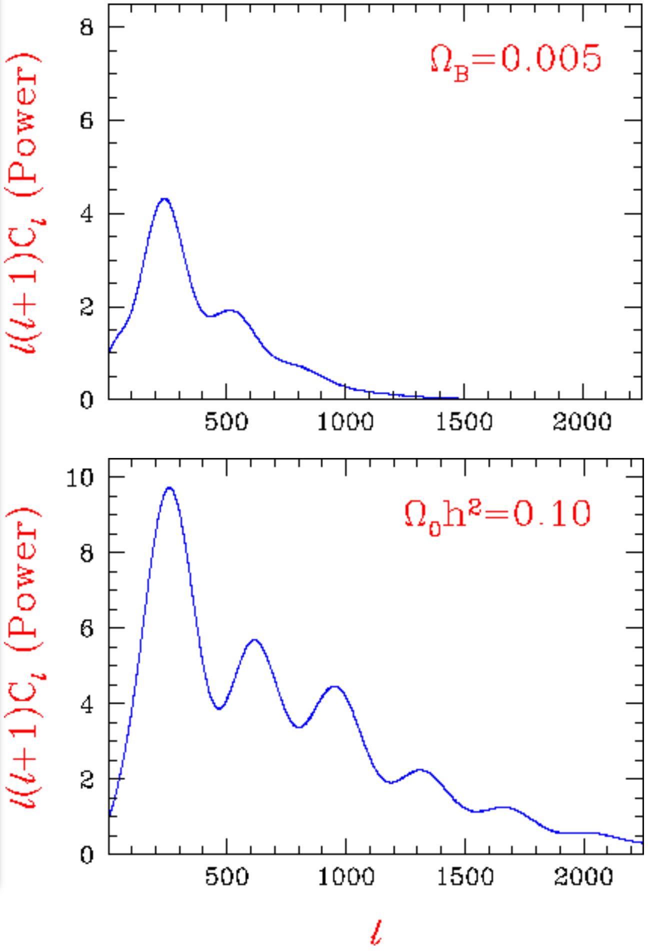


Fig. 7.— A comparison of the *COBE* 90 GHz map (Bennett et al. 1996) with the W-band *WMAP* map. The *WMAP* map has 30 times finer resolution than the *COBE* map.

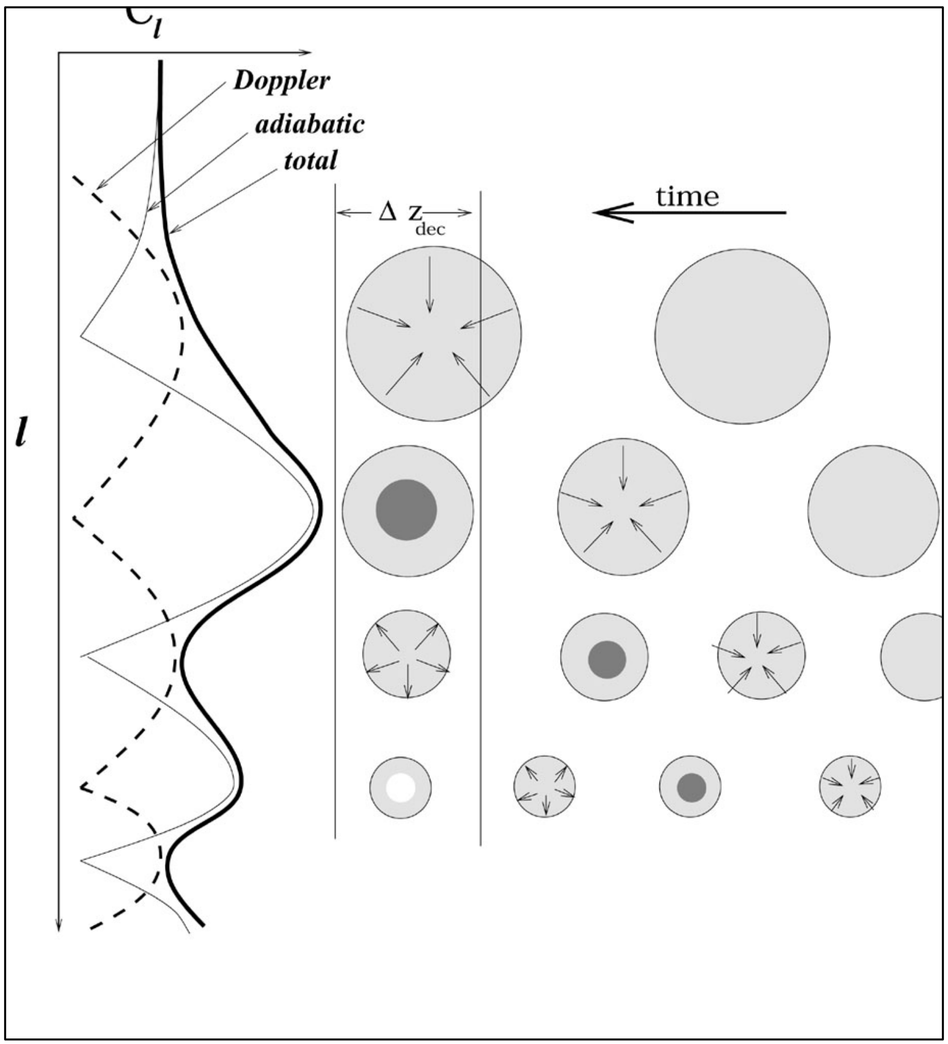
See peaks in angular power spectrum from acoustic oscillations in photon-baryon-dark-matter fluid

Height and shape of peaks depends on equation of state (e.g. **sound speed**)

Simple test of **overall composition** of the universe at redshift z=1000 (380,000 years after the Big Bang)



Constraining the dark matter to baryonic matter ratio at z=1100



First PS peak: compression in wells/rarefaction in peaks

Second PS peak: rarefaction in wells/compression in peaks

get photon pressure + gravity in wells, photon pressure – gravity in peaks

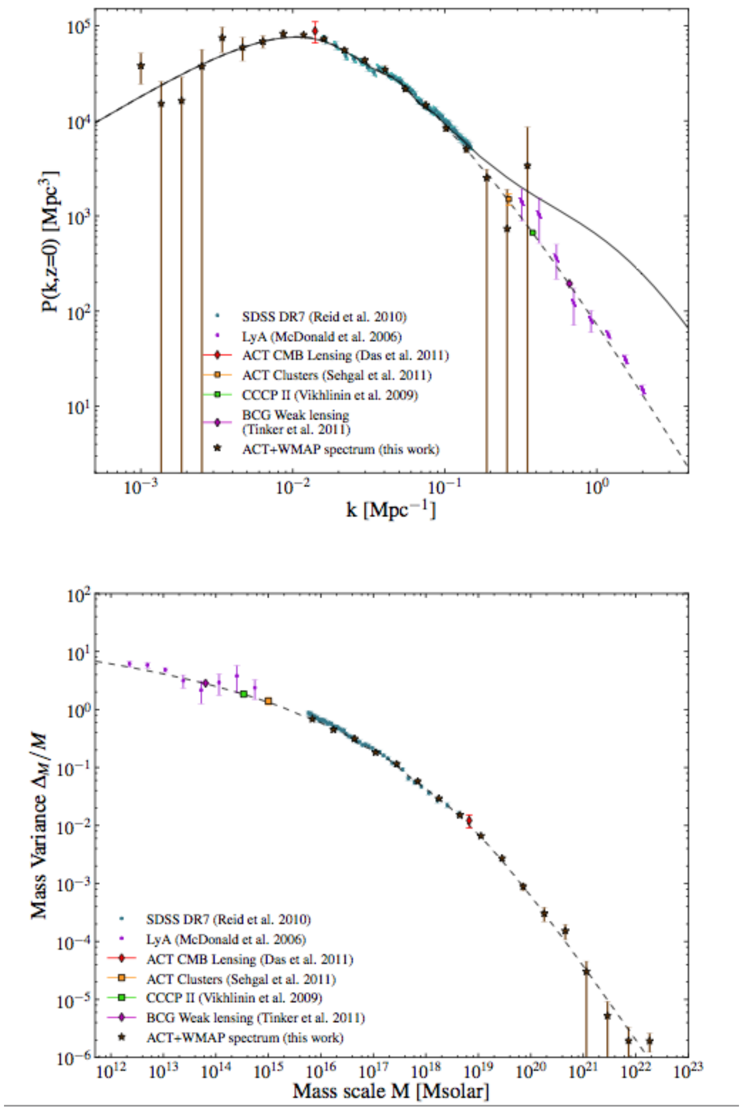
So comparison of PS peaks gives baryonic and total densities separately

Final Results:

Total Matter density:
$\sim 0.3\ \rho_{crit}$

Baryonic Matter density:
$\sim 0.049\rho_{crit}$

Finally, tying it all together: Matter Fluctuations from the CMB to the Local Universe



Hlozek et al. 2012 (the ACT collaboration)

Power spectrum P(k) and/or mass variance $\sigma^2(M)$ express fluctuations in the matter distribution.

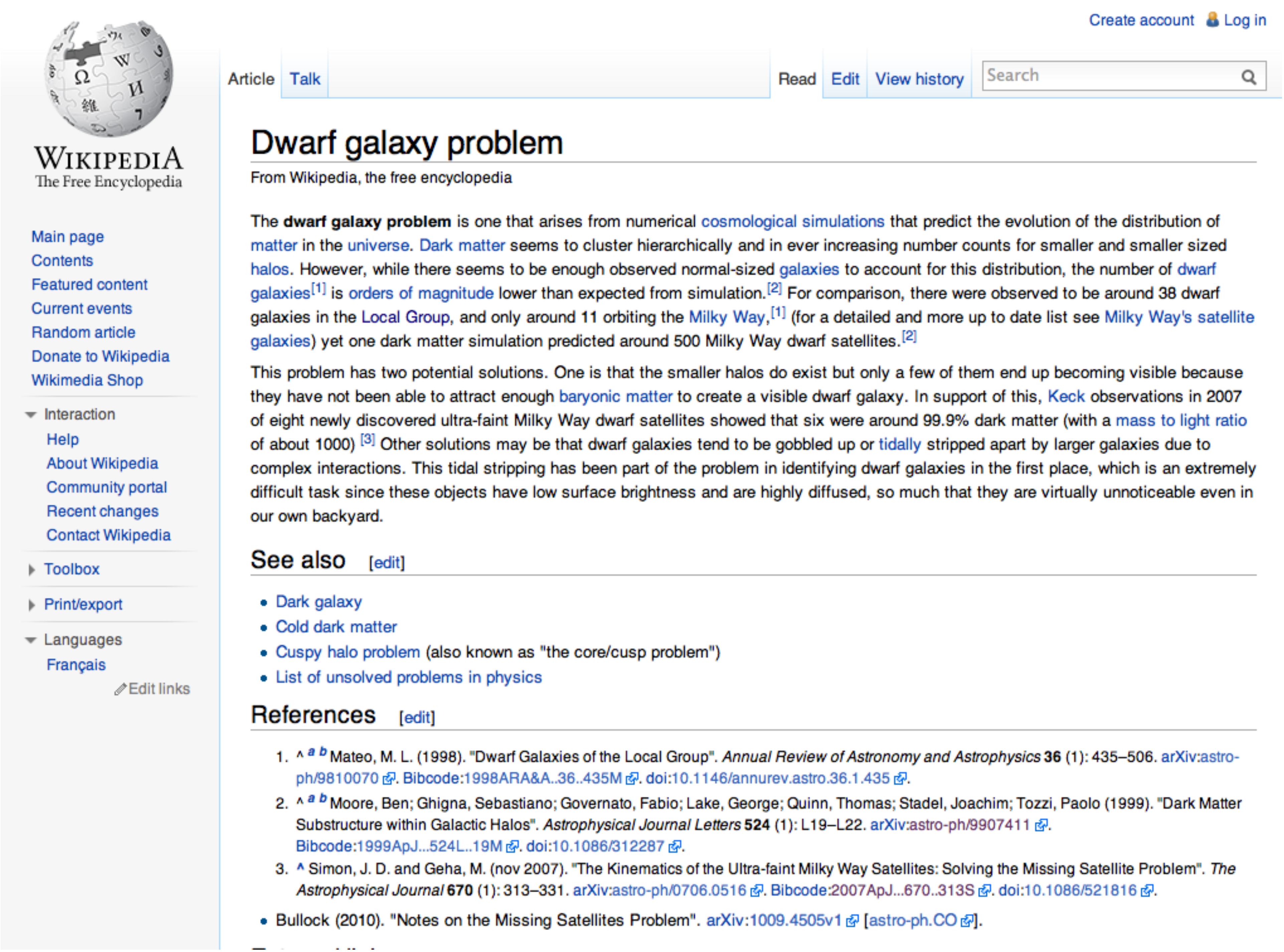
In practice, measured at different redshifts for different scales

Thus, consistency with theory requires both the right initial power spectrum (⇔ correct physics prior to recombination) and the right growth of structure

Current results match prediction for a "cold" (non-relativistic) dark matter component dominating the matter density.

Any significant "warmth" (thermal velocities, e.g. due to a mass < 2keV) would reduce small scale/high k power spectrum ⇔ mismatch with Ly alpha forest

III: A Few Outstanding Problems



Dwarf galaxy problem

From Wikipedia, the free encyclopedia

The **dwarf galaxy problem** is one that arises from numerical cosmological simulations that predict the evolution of the distribution of matter in the universe. Dark matter seems to cluster hierarchically and in ever increasing number counts for smaller and smaller sized halos. However, while there seems to be enough observed normal-sized galaxies to account for this distribution, the number of dwarf galaxies[1] is orders of magnitude lower than expected from simulation.[2] For comparison, there were observed to be around 38 dwarf galaxies in the Local Group, and only around 11 orbiting the Milky Way,[1] (for a detailed and more up to date list see Milky Way's satellite galaxies) yet one dark matter simulation predicted around 500 Milky Way dwarf satellites.[2]

This problem has two potential solutions. One is that the smaller halos do exist but only a few of them end up becoming visible because they have not been able to attract enough baryonic matter to create a visible dwarf galaxy. In support of this, Keck observations in 2007 of eight newly discovered ultra-faint Milky Way dwarf satellites showed that six were around 99.9% dark matter (with a mass to light ratio of about 1000) [3] Other solutions may be that dwarf galaxies tend to be gobbled up or tidally stripped apart by larger galaxies due to complex interactions. This tidal stripping has been part of the problem in identifying dwarf galaxies in the first place, which is an extremely difficult task since these objects have low surface brightness and are highly diffused, so much that they are virtually unnoticeable even in our own backyard.

See also [edit]

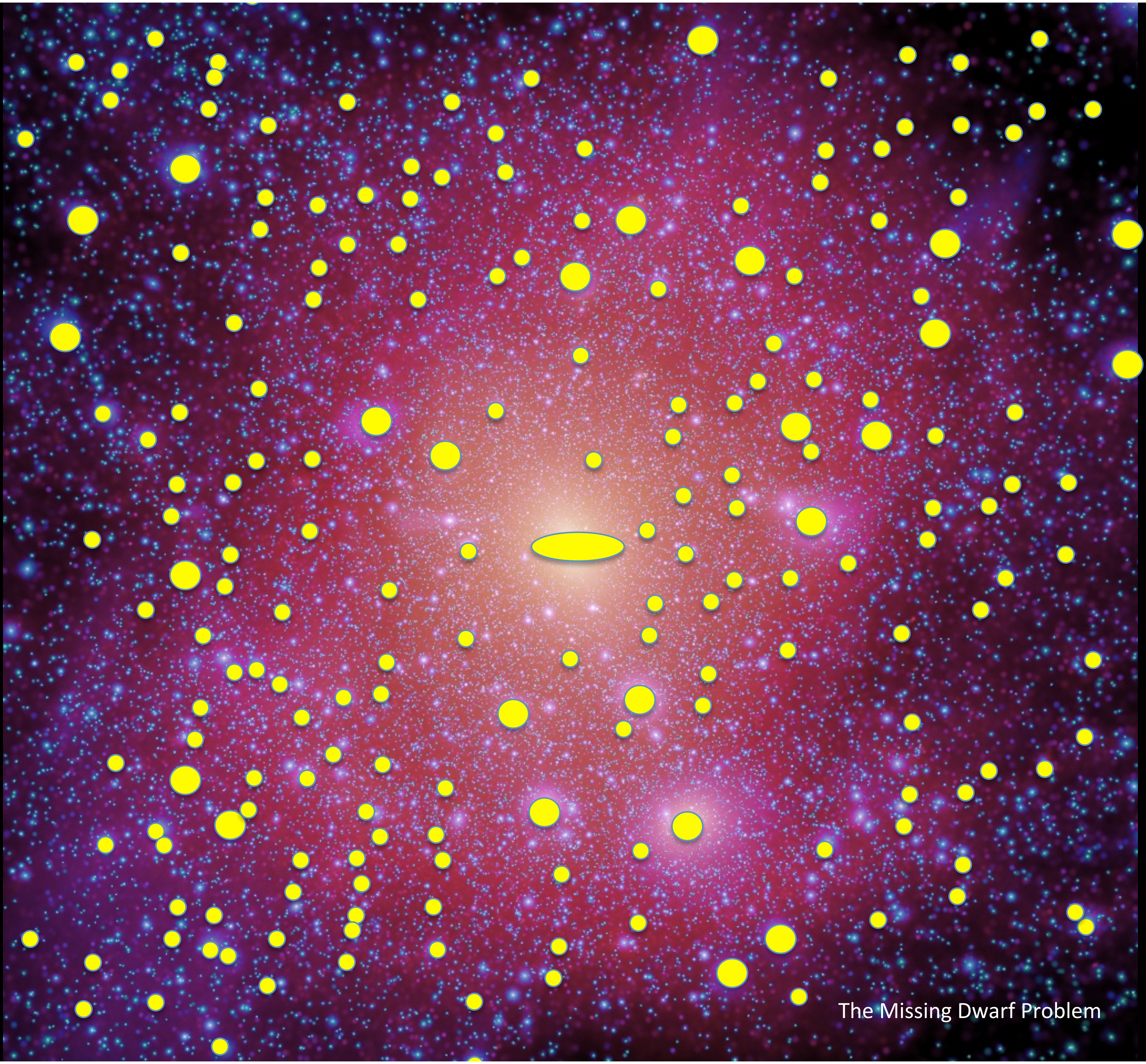
- Dark galaxy
- Cold dark matter
- Cuspy halo problem (also known as "the core/cusp problem")
- List of unsolved problems in physics

References [edit]

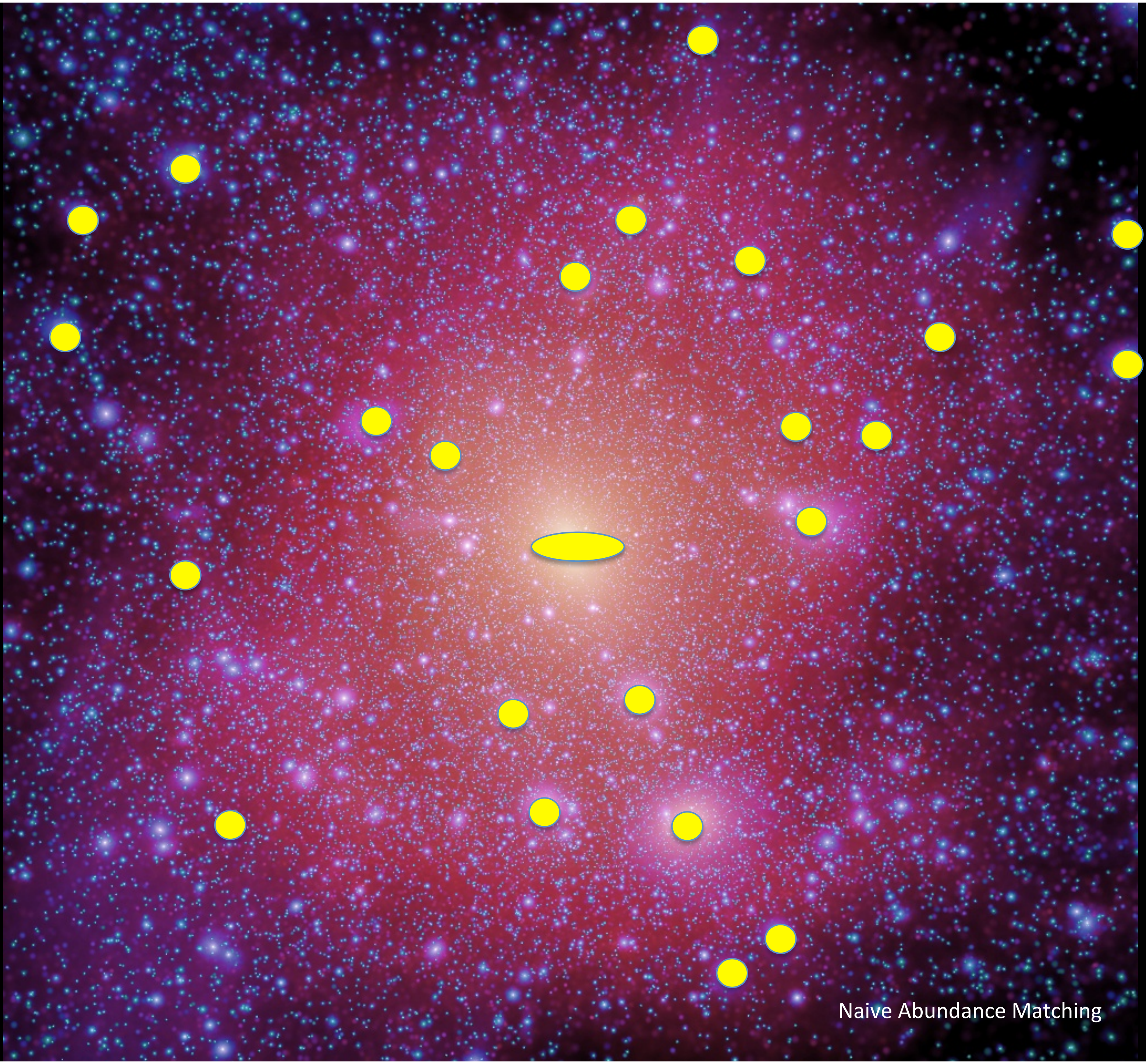
1. ^ *a* *b* Mateo, M. L. (1998). "Dwarf Galaxies of the Local Group". *Annual Review of Astronomy and Astrophysics* **36** (1): 435–506. arXiv:astro-ph/9810070. Bibcode:1998ARA&A..36..435M. doi:10.1146/annurev.astro.36.1.435.
2. ^ *a* *b* Moore, Ben; Ghigna, Sebastiano; Governato, Fabio; Lake, George; Quinn, Thomas; Stadel, Joachim; Tozzi, Paolo (1999). "Dark Matter Substructure within Galactic Halos". *Astrophysical Journal Letters* **524** (1): L19–L22. arXiv:astro-ph/9907411. Bibcode:1999ApJ...524L..19M. doi:10.1086/312287.
3. ^ Simon, J. D. and Geha, M. (nov 2007). "The Kinematics of the Ultra-faint Milky Way Satellites: Solving the Missing Satellite Problem". *The Astrophysical Journal* **670** (1): 313–331. arXiv:astro-ph/0706.0516. Bibcode:2007ApJ...670..313S. doi:10.1086/521816.

- Bullock (2010). "Notes on the Missing Satellites Problem". arXiv:1009.4505v1 [astro-ph.CO].

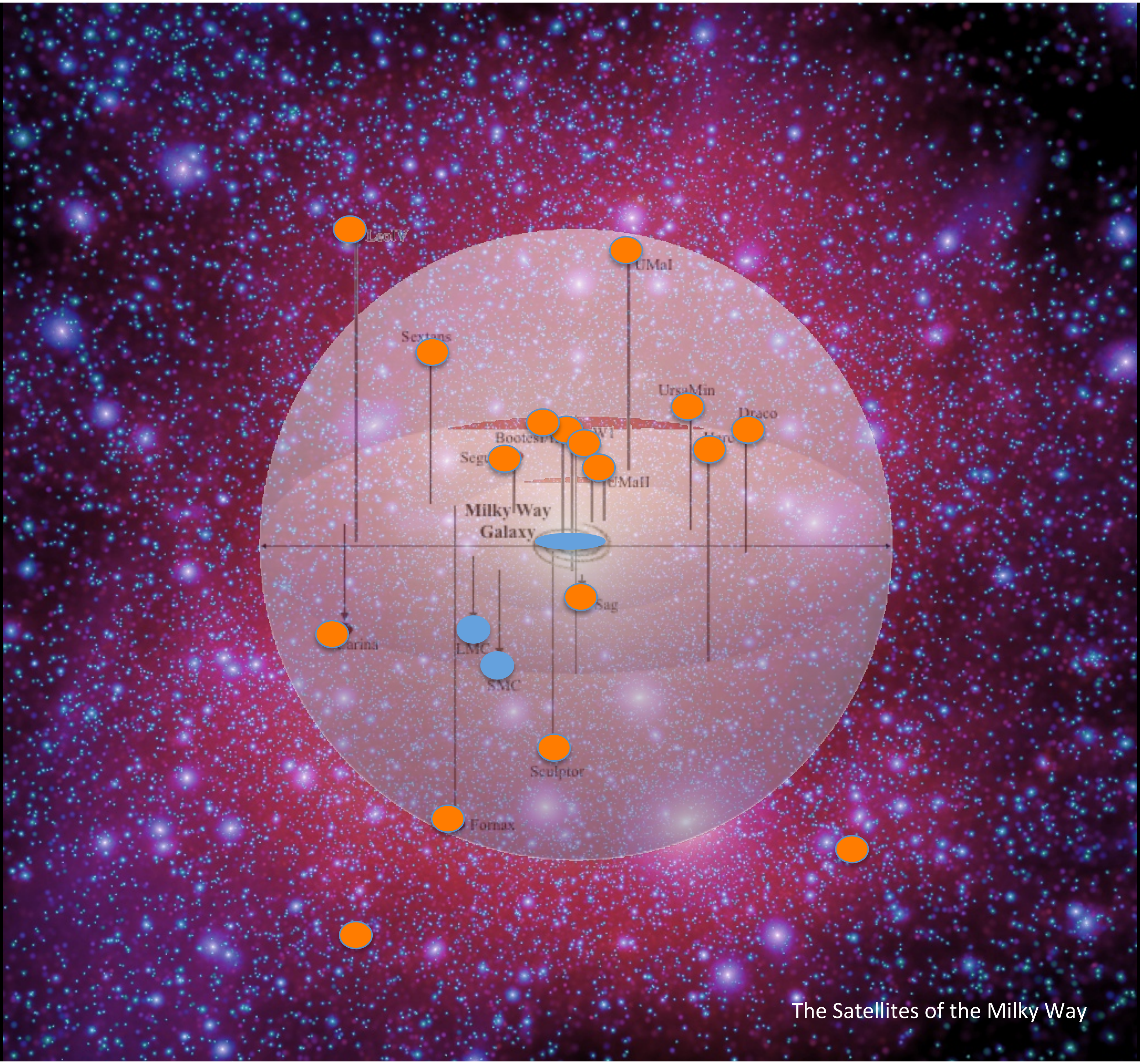
The Aquarius simulation: Springel et al.



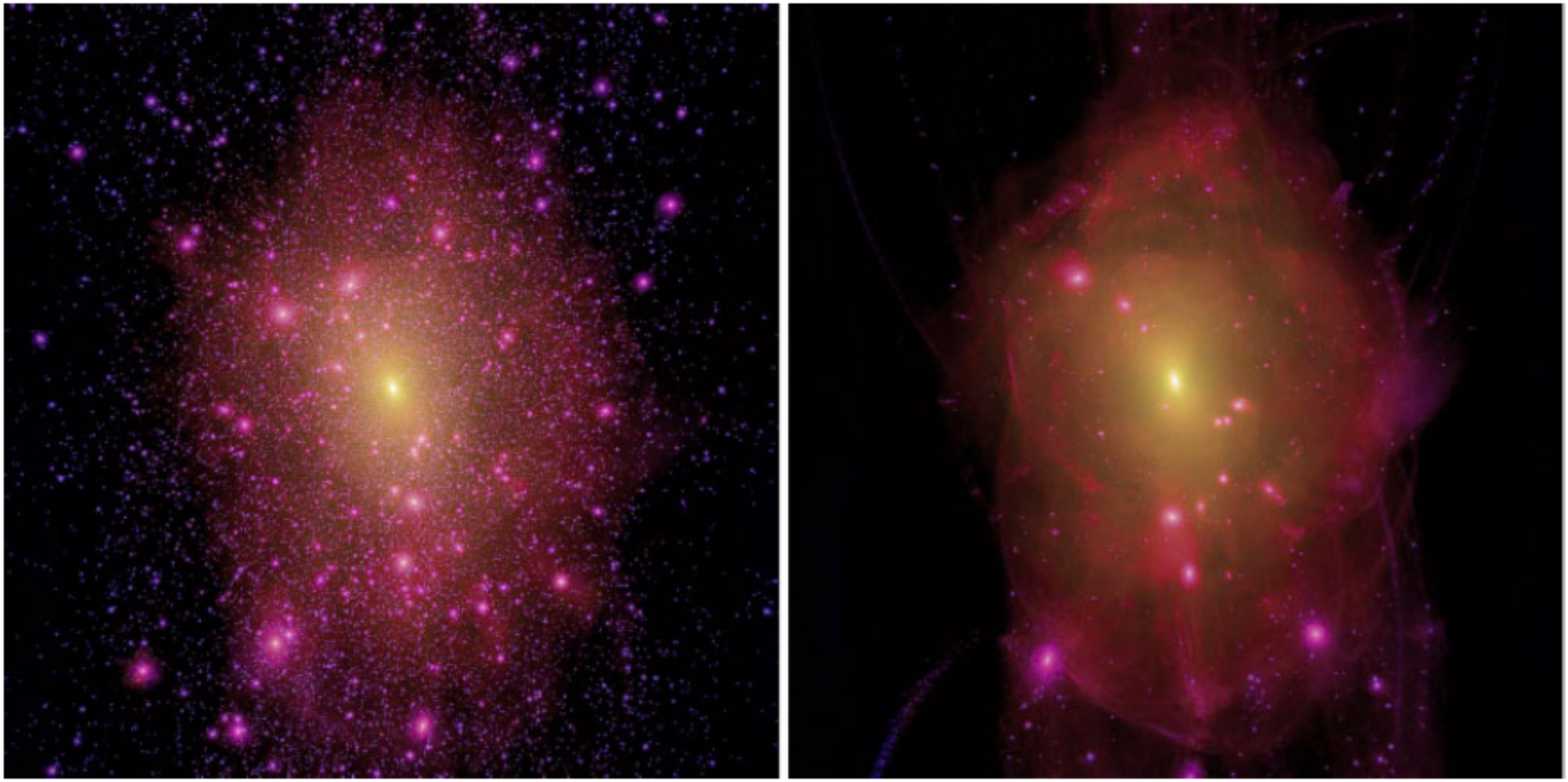
The Missing Dwarf Problem



Naive Abundance Matching



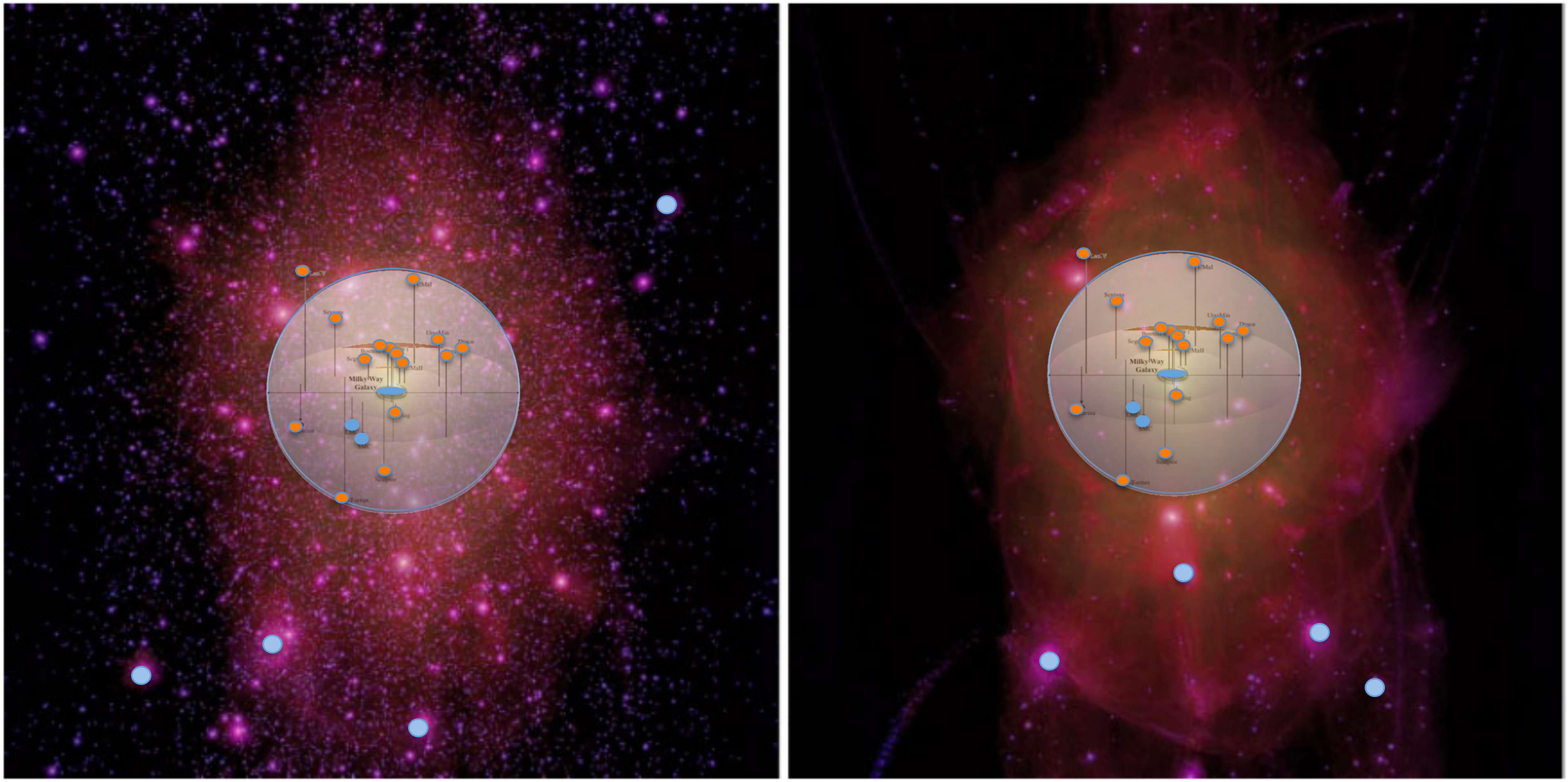
The Satellites of the Milky Way



Cold Dark Matter

Warm Dark Matter

1.5 Mpc box in CDM and WDM simulations – Frenk & White 2012

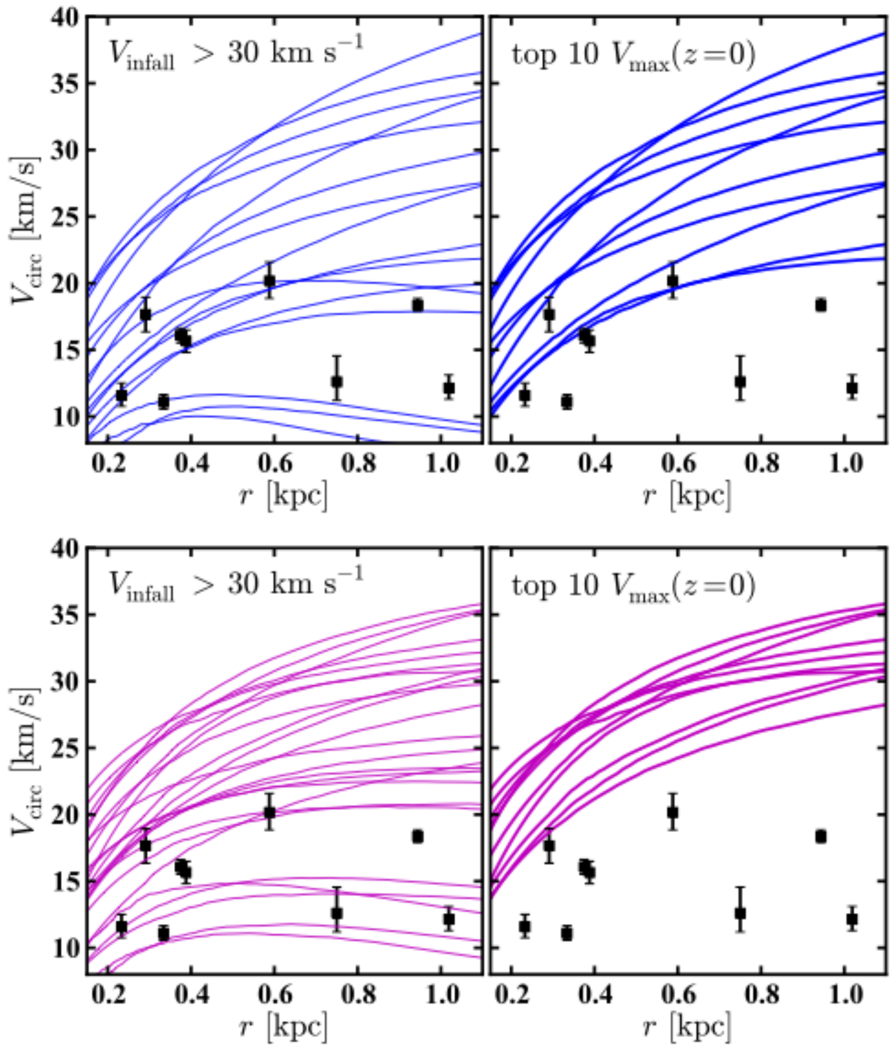


Cold Dark Matter

Warm Dark Matter

1.5 Mpc box in CDM and WDM simulations – Frenk & White 2012

The "Too Big to Fail Problem"
(Boylan-Kolchin et al. 2011, 2012)

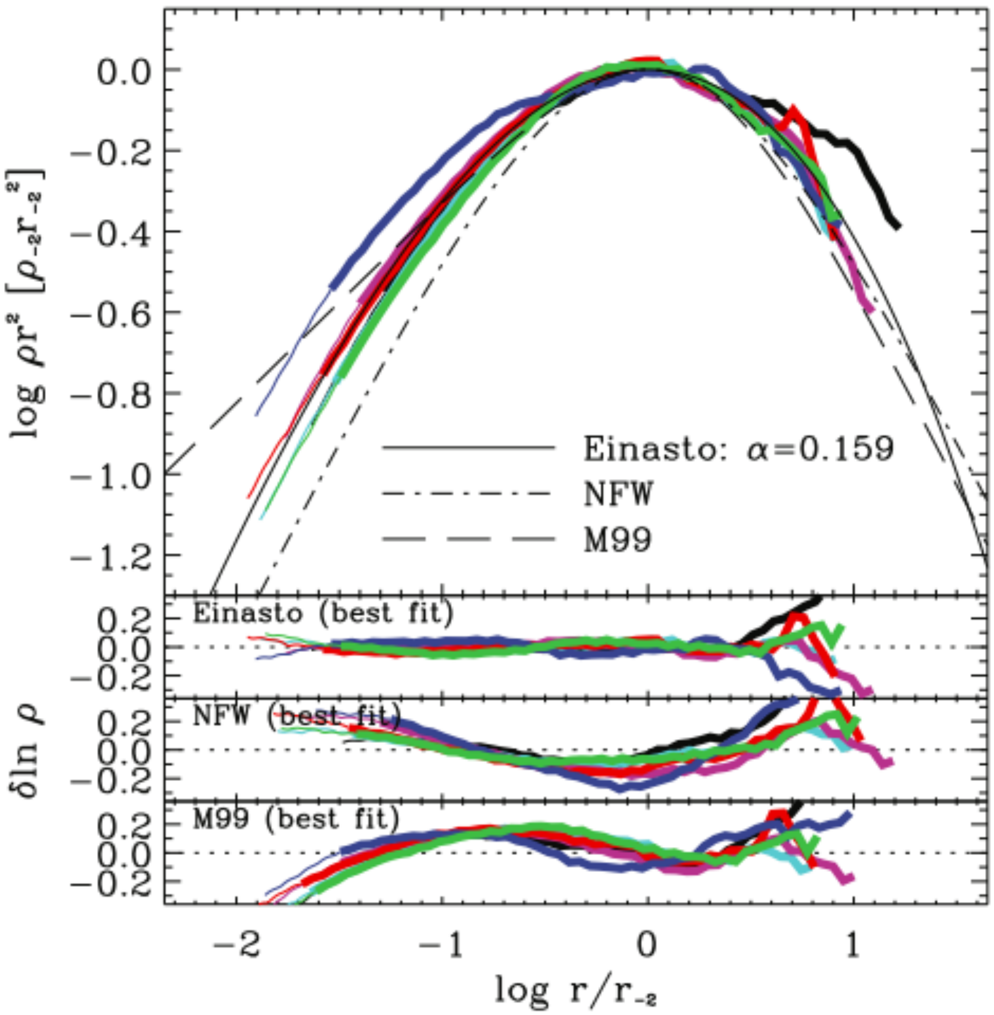


An interesting new twist on the dwarf galaxy problem: simulated CDM subhalos appear to be too dense compared to observations

⇔ either the biggest subhalos have failed to make luminous galaxies, or their central density has somehow been reduced

Possible evidence for WDM or dark matter-self interaction?

The Halo Density Profile



Navarro et al. 2010

Numerical simulations now agree on a (new) general form for the average halo density profile – the Einasto profile:

$$\ln[\rho(r)/\rho_{-2}] = (-2/\alpha)[(r/r_{-2})^{\alpha} - 1]$$

- Its origin is still unclear however (nor is it completely universal)
- Also current analytic fit goes to zero slope as r -> 0; not clear what the real asymptotic slope is
- Also what effect do baryons have?
- Also, what is the profile of the first generation of subhalos? Could it be cuspier?

IV: The (Near?) Future

Future Directions

Theory:

What is the origin of universal halo properties?

How much substructure survives?

What is the central density of halos?

Observations:

Weak Lensing

Can we map out the shape of dark matter halos

Can we detect the cosmic web?

Dwarf Galaxies

Are we missing dwarfs?

Is the Local Group typical?

How do other environments compare?

Lensing Substructure

In principle, strong lensing systems sensitive to small perturbations

⇔ test DM power down to $10^6\ M_\odot$ or less? (cf. Dalal & Kochanek, Moustakas et al.)

subsequent challenges with microlensing & other false positives

in future, much larger samples e.g. from SKA

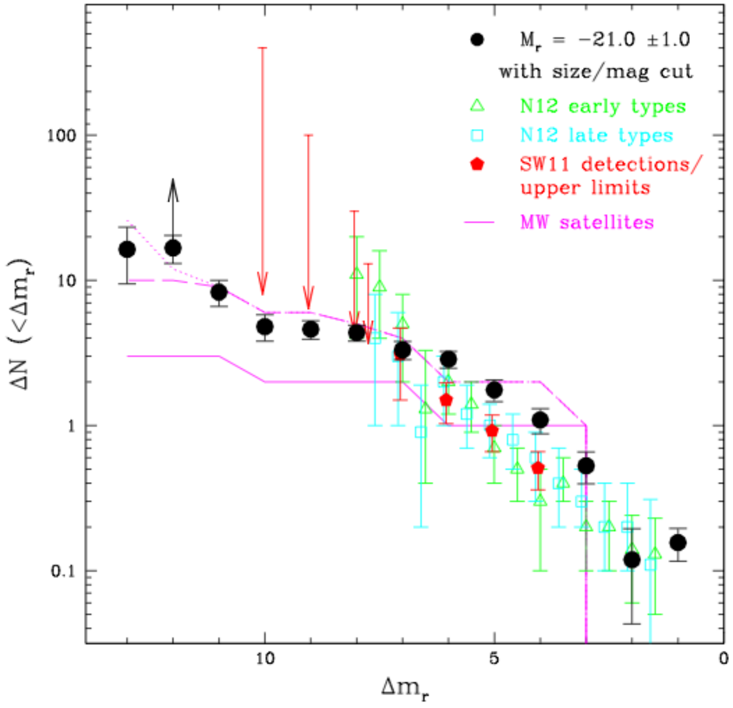
Pulsar Timing:

Differential timing signals from arrays of pulsars have been proposed to detect gravitational waves, but could also be sensitive to mechanical effects of halo substructure?
(e.g. Siegel et al. 2007, Baghram et al. 2011)

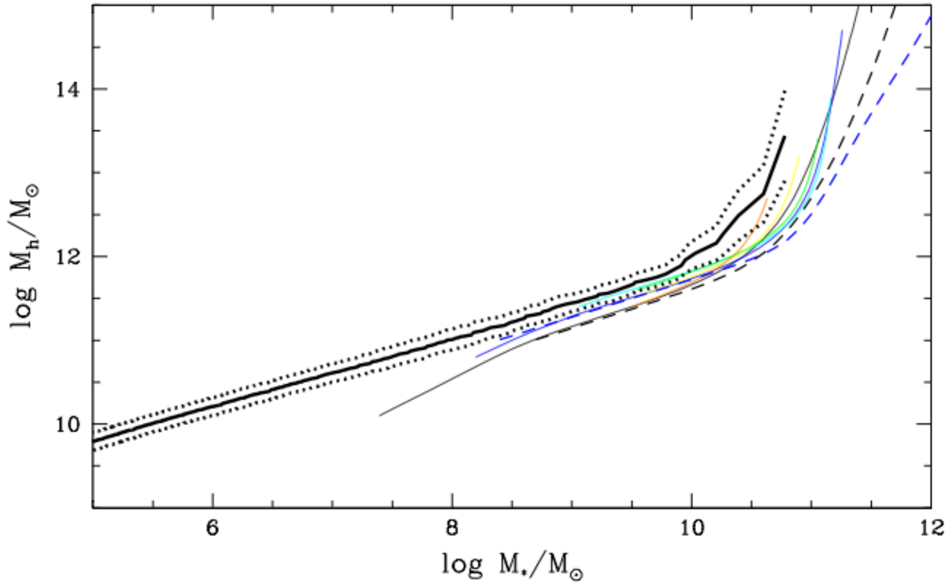
Overall, the push is to test cold, collisional, scale-independent properties of plain vanilla CDM

Some Recent Work

Are the Local Group Dwarfs Representative?
w. Ryan Speller (Speller & Taylor 2014):



How Does Mass Trace Light
on the Smallest Scales in Virgo?
w. Jonathan Grossauer and
the NGVS collaboration
(Grossauer et al. in prep.)



Conclusions

The cosmological evidence for dark matter:

- ✧ best evidence probably from the CMB (1st/2nd/3rd peaks) and/or the growth of structure
- ✧ historically, the first evidence was from galaxy clusters (Zwicky)
- ✧ galaxy rotation curves simplest to explain, but neither first nor best evidence for DM

Some interesting and justifiable statements:

- ✧ there is at least some baryonic dark matter
- ✧ there is at least some non-baryonic dark matter
- ✧ astrophysical observations are completely consistent with plain vanilla cold dark matter (CDM), albeit with some puzzles, e.g. dwarf galaxies
- ✧ any alternative to particle dark matter has to “walk and quack” almost exactly like CDM; only freedom to be different is on scales/redshifts we have not yet explored, e.g. very small scales, very high redshifts, or very high densities

The way forward:

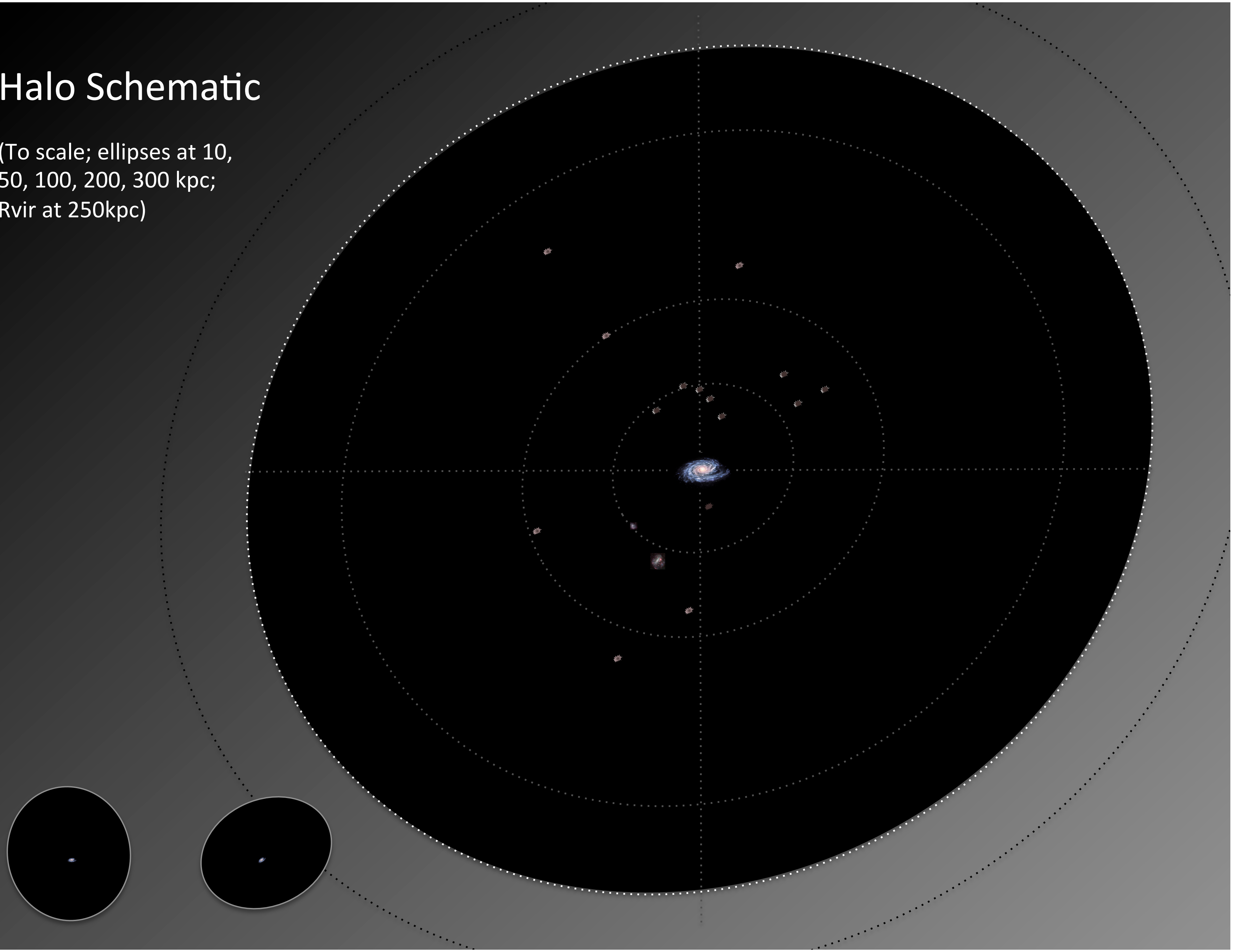
- ✧ follow-up new theoretical (particle DM) possibilities
- ✧ more serious theoretical work on gravitational alternatives,
  e.g. derive perturbation theory, construct well-founded cosmological models, etc.
- ✧ work on observationally testable particle properties:
  - behaviour on small scales
  - indirect detection signals
  - detailed halo properties from lensing

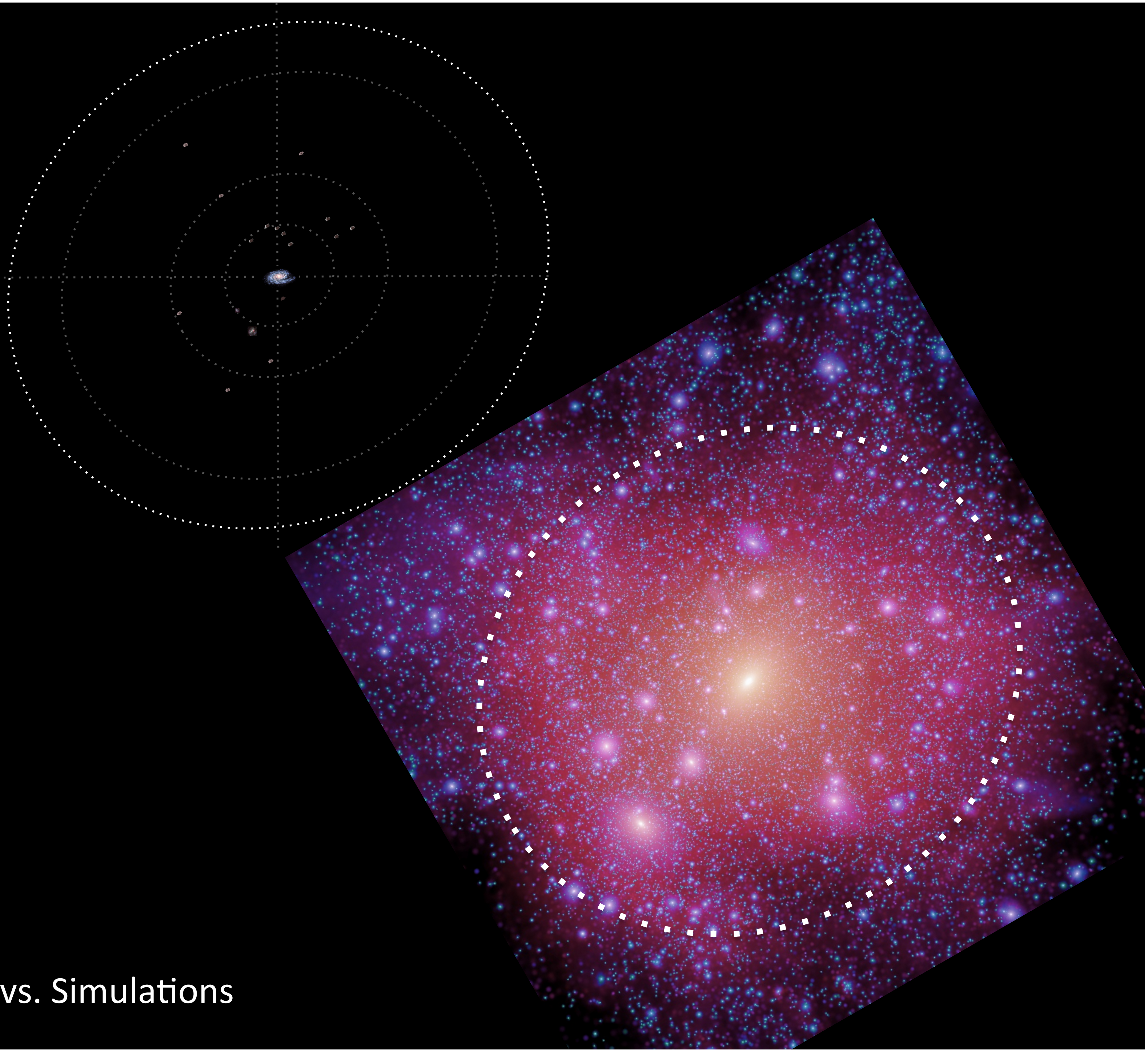
Overall, dark matter remains an exciting field because of the possible synergies:
theory/experiment/observation, high-energy/gravitation/astrophysics.

[redacted]

Halo Schematic

(To scale; ellipses at 10, 50, 100, 200, 300 kpc; Rvir at 250kpc)





Observations vs. Simulations