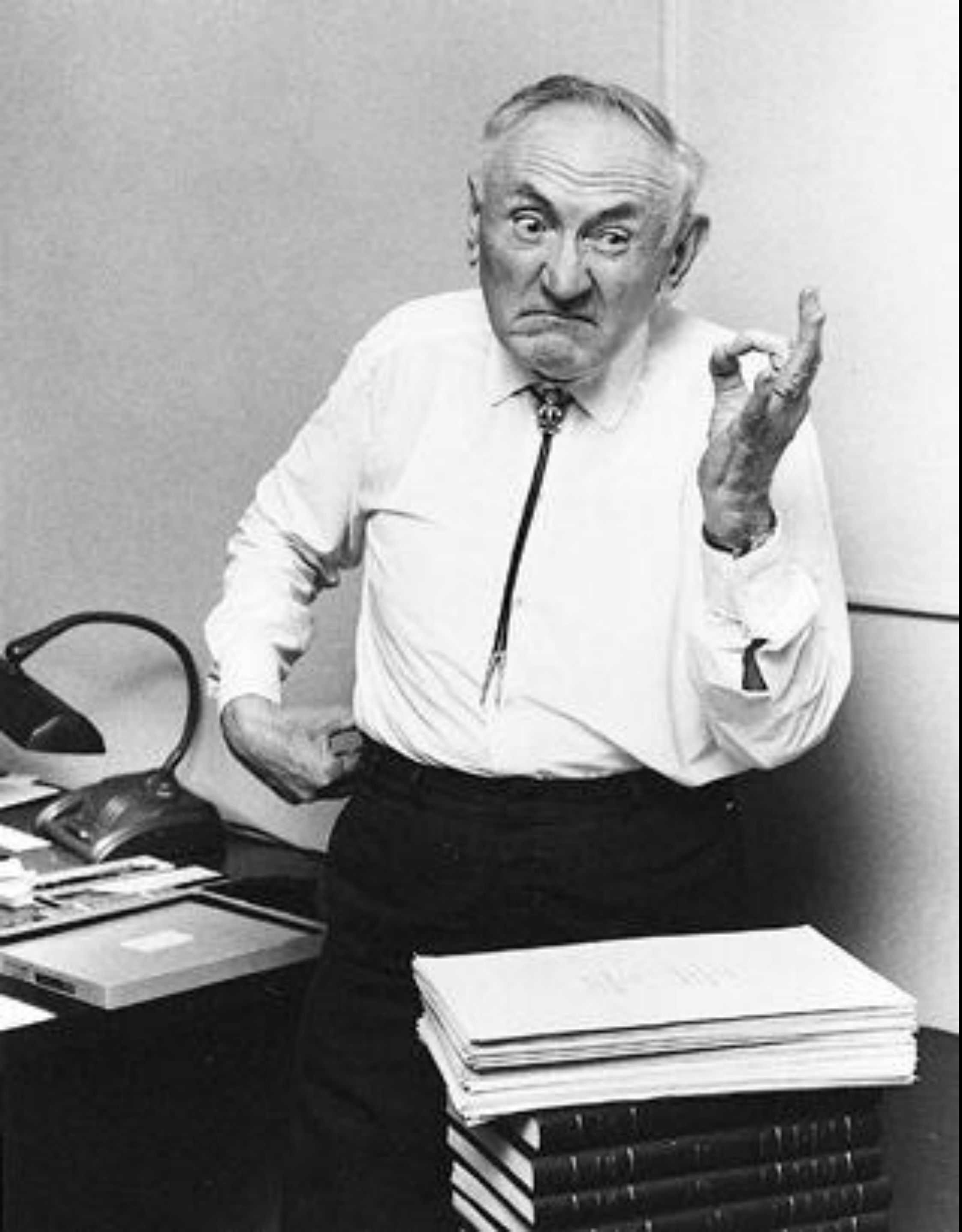
Chap 22: Dark Matter!

- First clue came way back in the 1930's. Fritz Zwicky studied the motions of galaxies in the Coma Cluster of galaxies – the nearest dynamically "relaxed" rich cluster of galaxies.
- "Relaxed" means: the galaxies have had enough time to at least roughly approximate an equilibrium distribution of positions and velocities. Most galaxies presumed to have crossed the cluster a couple of times, or more.



- Fritz Zwicky, in his iconic pose which seemed to match his personality according to those who knew him.
- But he was a pioneering mind who contributed much to astronomy

How do we measure the mass of star clusters and galaxy clusters?

- These objects are moving randomly around and past each other like a swarm of bees.
- (Star cluster (1min),) (Globular cluster 0:41)
- Higher average velocity must mean higher gravity in order to keep them all corral’ed together, means higher mass
- Bottom line – you measure the ***velocity dispersion*** of the stars or galaxies in the cluster to determine the mass

The Virial Theorem

- A generalization of Kepler's 3rd Law can be derived … the Virial Theorem…

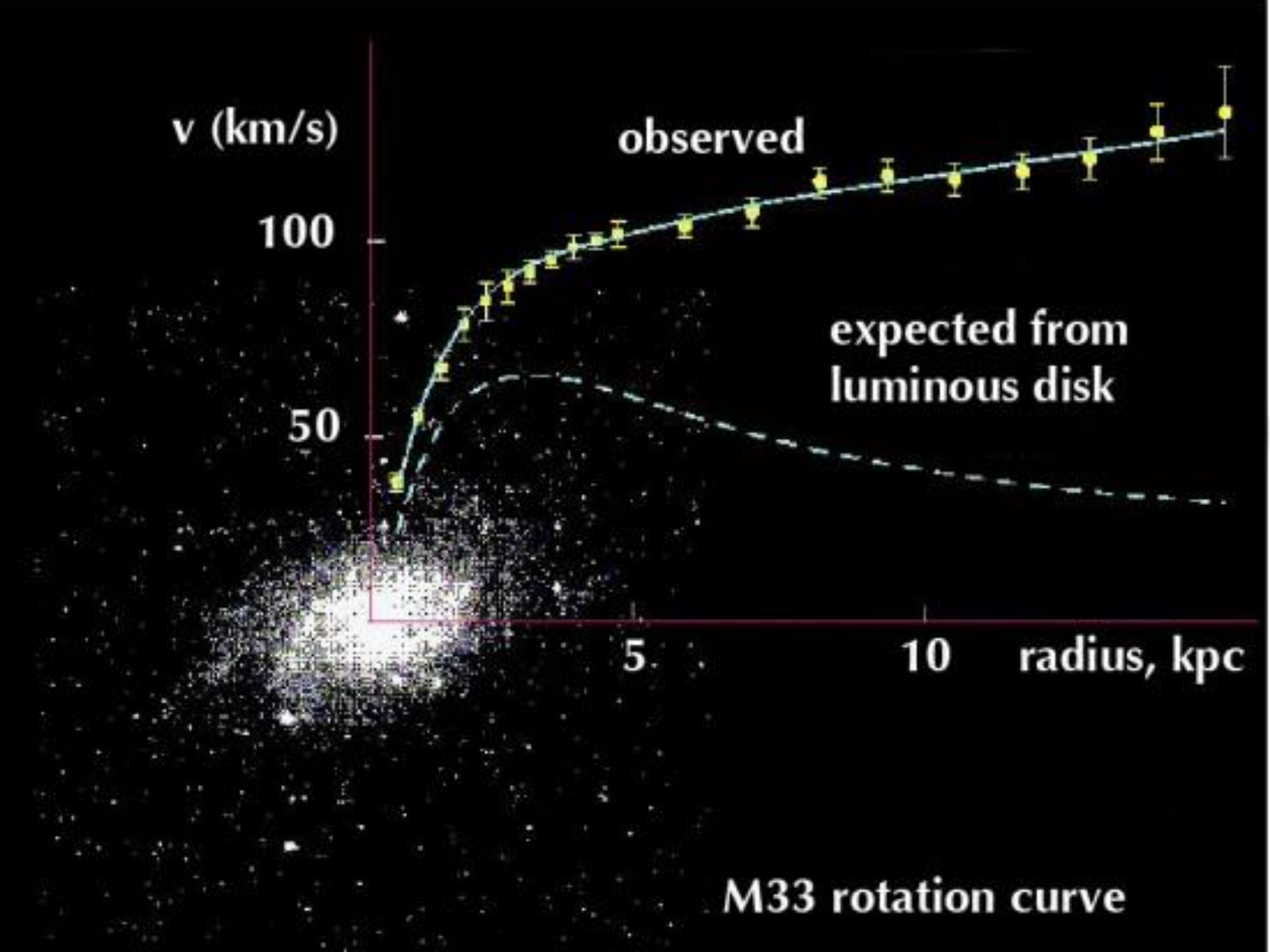
- Kinetic E = -1/2 x Grav Potential Energy
- Kinetic E = ½ M <v2> where v2 is averaged over each galaxy in cluster of mass M
- Grav Potential Energy ~ GM/R for a galaxy cluster of size R
- From this, can solve for cluster mass, given the observed size and also the velocities of the member galaxies
- Only strictly true if the cluster is "relaxed"; meaning the galaxies have moved through the cluster at least a couple of times

What did Zwicky Find?

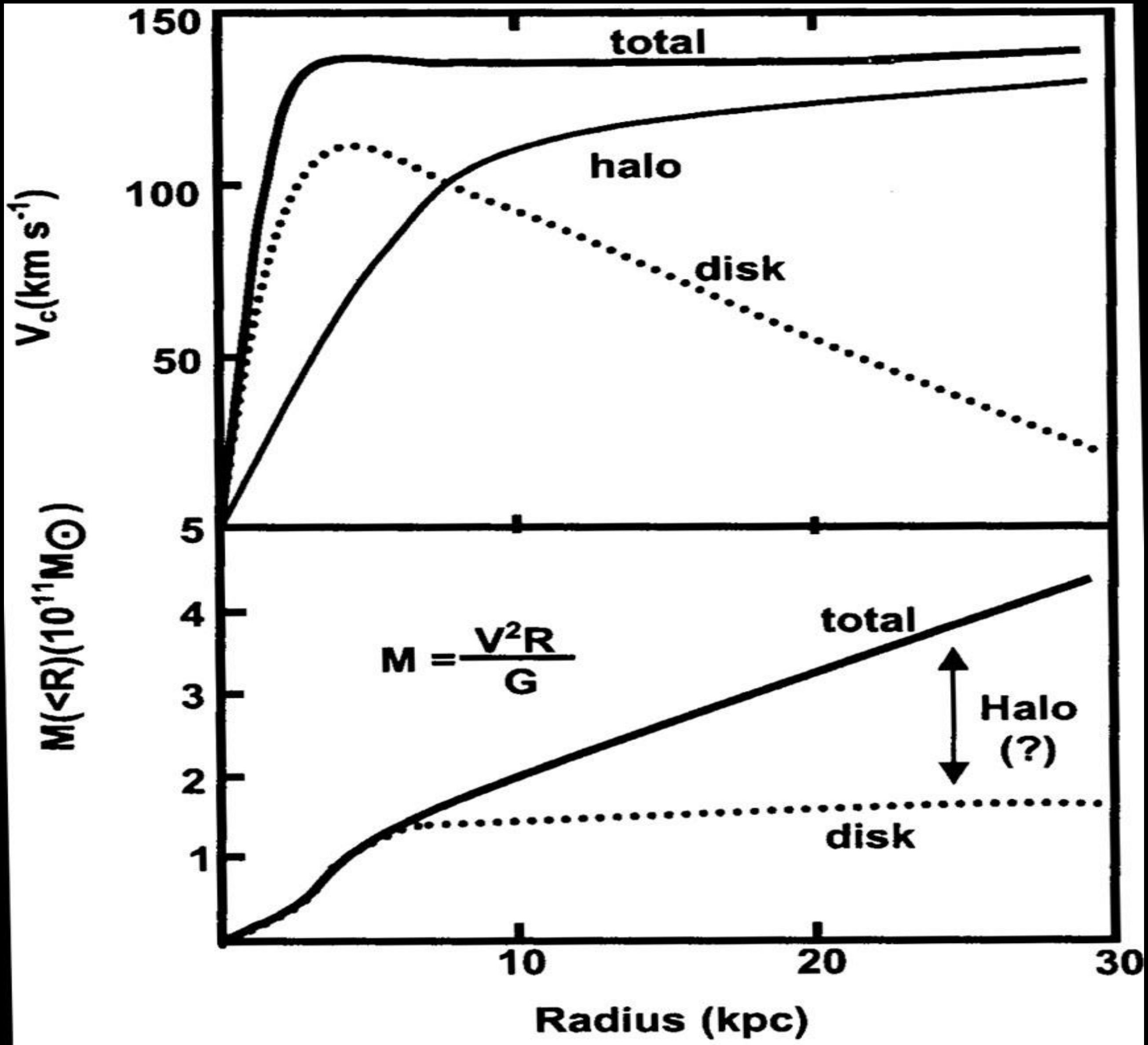
- The mass outweighed the light of the Coma Cluster by a factor of about 160 when compared to that of typical Milky Way stars! (His estimate was based on a cosmic distance scale that was too small, underestimating both the mass and the starlight, however)
- Modern estimates show Coma has ~10x the dark matter of individual galaxies, which already have high dark matter fractions. Coma also has at least half of its ordinary matter in the form of hot X-ray emitting gas, not stars or cold gas.
- **Without getting lost in the numbers – Coma has a LOT of dark matter that neither emits nor interacts with light in any detectable way.**
- **So What IS this stuff?** Hard to answer, but first…
- Remember Sagan's Corollary - *"Extraordinary Claims Require Extraordinary Evidence"*. The claim that the universe is dominated by an unseen mass that has no interaction with light is an extraordinary claim…. We MUST insist on more evidence.

Vera Rubin in the 1970's Measured Rotation Curves of Spiral Galaxies

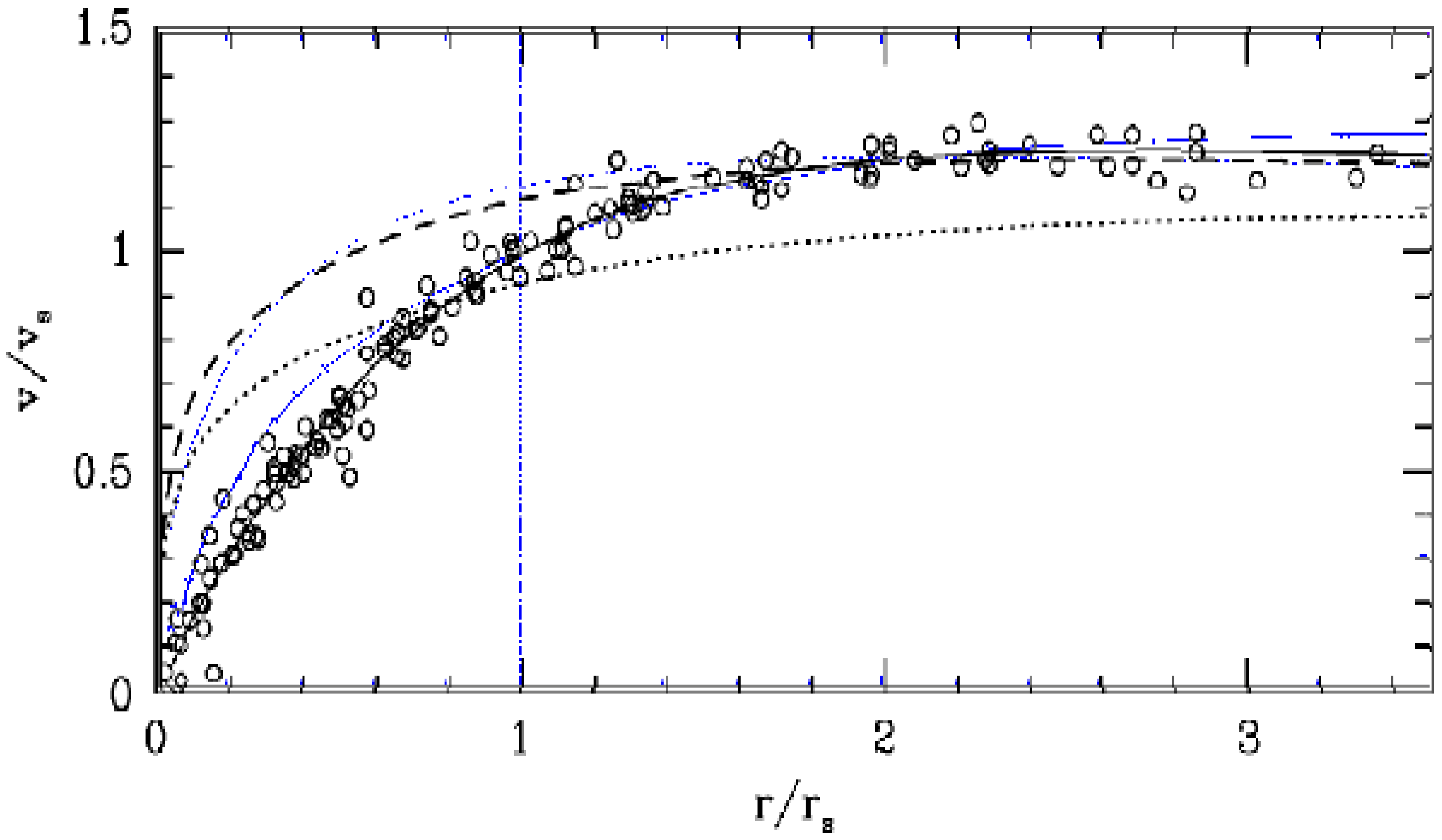
- **Rotation curve** = the graph of rotation speed *vs.* distance from the center of the galaxy
- We had our first electronic detectors in the 1970's, now could measure spectra of very faint things – like the outskirts of distant spiral galaxies
- If mass follows light, here's what you'd expect…follow Rick's reasoning on the whiteboard.


v (km/s)
observed
100
expected from
luminous disk
50
5
10
radius, kpc
M33 rotation curve

The disk is made of stars whose density clearly falls off with distance. It is the spheroidal halo of mostly Dark Matter which comes to dominate the mass budget far out, so that the rotation curves end up roughly flat



A Typical Spiral Galaxy Rotation Curves; Measurements and disk+Dark Matter Halo models

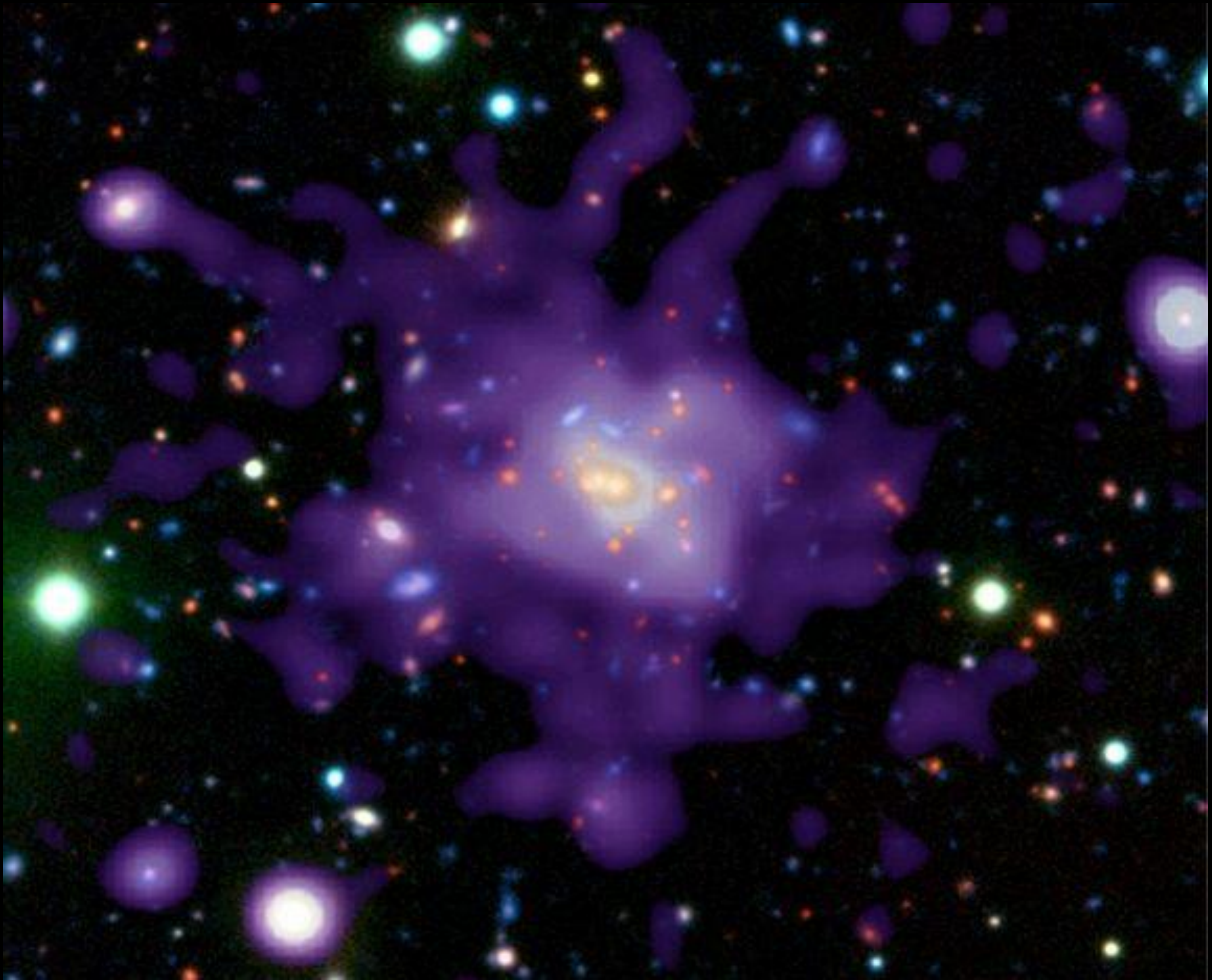


There's two other means to measure the mass of Galaxy Clusters…

- **1. X-rays from the gas in the cluster**. The idea is this – If the gas is well mixed and in equilibrium with the gravity field, high mass means high speeds of gas particles, means HOT, means gas gives off X-rays (remember your Wien's Law)

- **2. Gravitational lensing** of background objects. Gravity bends light! The optical laws of lensing allow determination of the mass doing the lensing

Purple is X-ray hot gas in Coma Cluster



Orange foreground galaxies, blue background lens’ed galaxies distorted into “arcs”

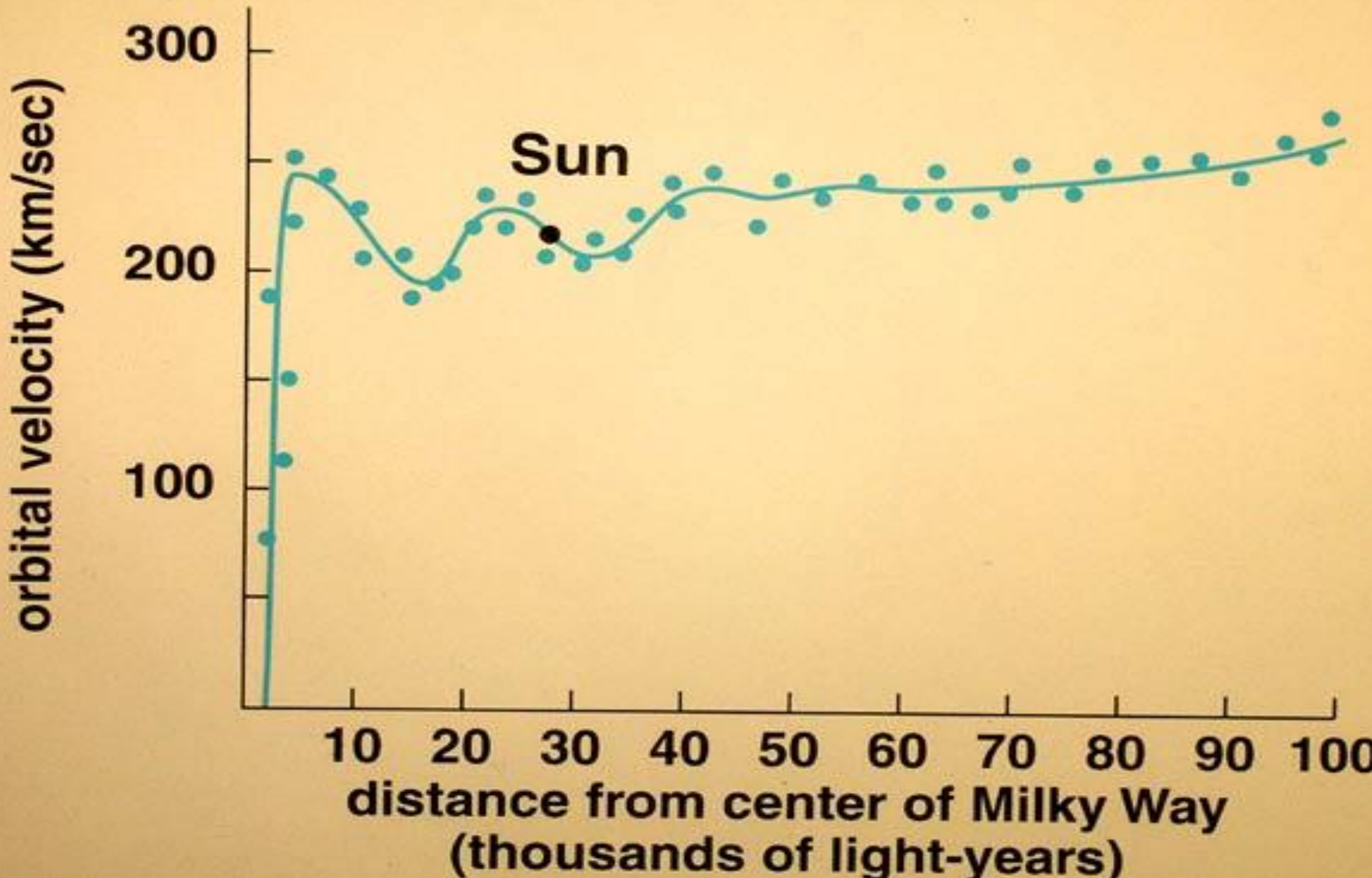
More complex gravitational lensing

Dark Matter in Ellipticals Too

- There's no disk in E galaxies so can't use rotation curves. Its stars are more like a swarm of bees.
- Instead, you measure the **Doppler-broadening of spectral lines**, since the spectrograph is getting the light of billions of stars going in all directions when you take a spectrum of a galaxy. "All directions" means there's Doppler Effect red-shifting and blue-shifting of the lines of each individual star, adding up over the billions ot stars to make a "blurry" (broadened) galaxy spectral line
- When done carefully, you can measure the broadening vs distance from the center of the galaxy, and again find the DM density falls off much more gradually than does the starlight, just as in disk galaxies
- **So: the "Velocity Dispersion" as seen in the width of spectral lines, tells us the mass of the Elliptical Galaxy**

Even our own Milky Way Galaxy is Dominated by …**Dark Matter!**

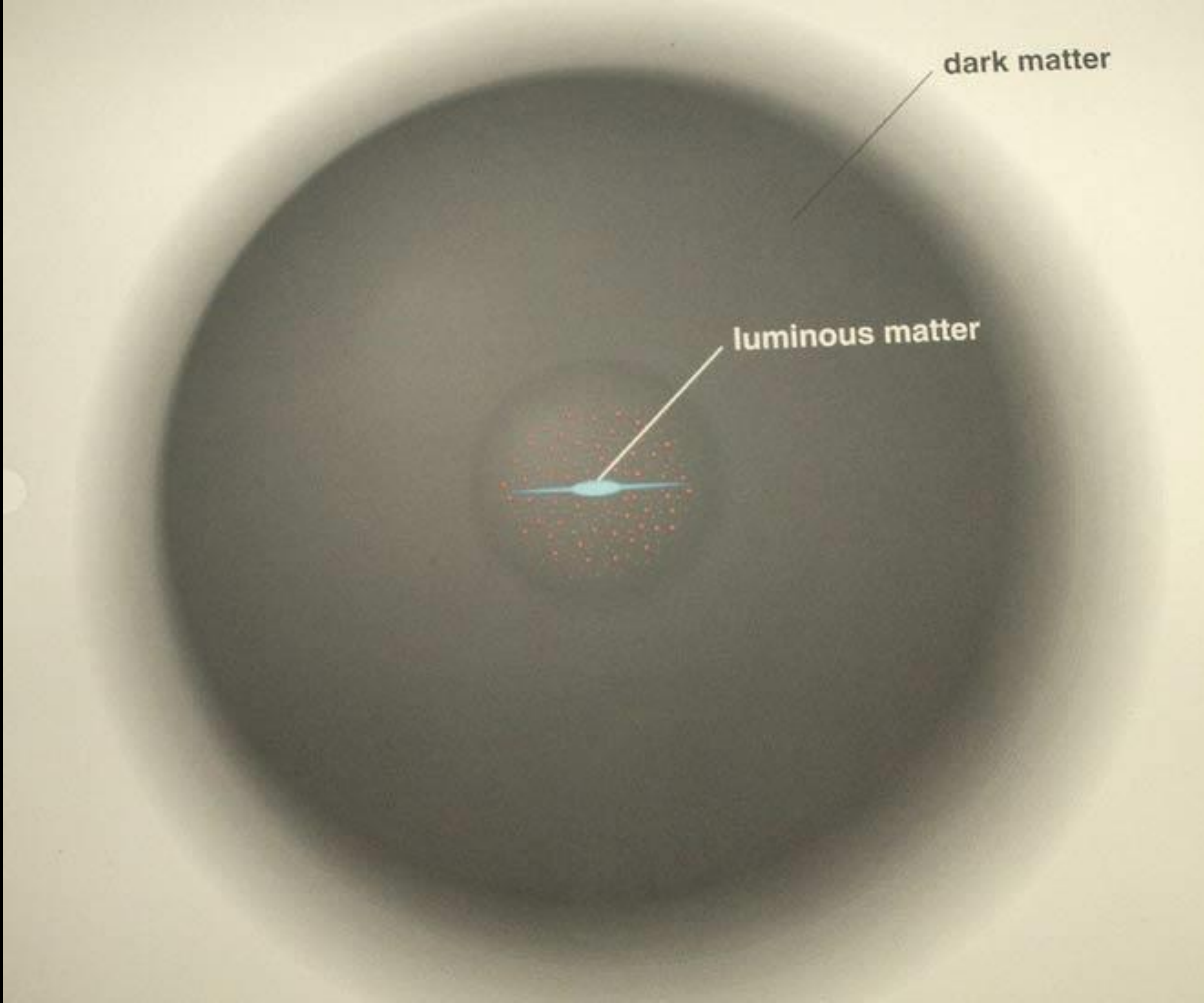
Our Rotation Curve Rises, even far beyond the farthest orbits of the stars



Wesley Longman, Inc.

Conclusion - The Evidence is Strong…

Our Galaxy is deep inside a huge spherical cloud of… ***Dark Matter***


dark matter
luminous matter

What Could The Dark Matter Be?????

- Now it’s your turn…
- Come up with some possibilities. Like good scientists, let’s not reach for the bizarre until and unless we’ve ruled out the well-known things such as we’ve already discussed in this class
- Your list?....

1. Could it be gas?

No!

- We’d see new absorption lines when we look through our halo at stars from the Large Magellanic Cloud (LMC). There’s virtually no cold gas there, and precious little hot ionized gas either. The required absorption lines and strengths are just not there!

2. Well then, could it be Dust?

No.

- Dust would redden background starlight in galaxies beyond our halo. We could compare the spectral types of the starlight with the color we observe and see if the color matches the spectral type.
- Instead, color DOES match spectral type.
- Ergo, there's no significant dust

Could it be
Rocks?
Asteroids?
Comets?

No.

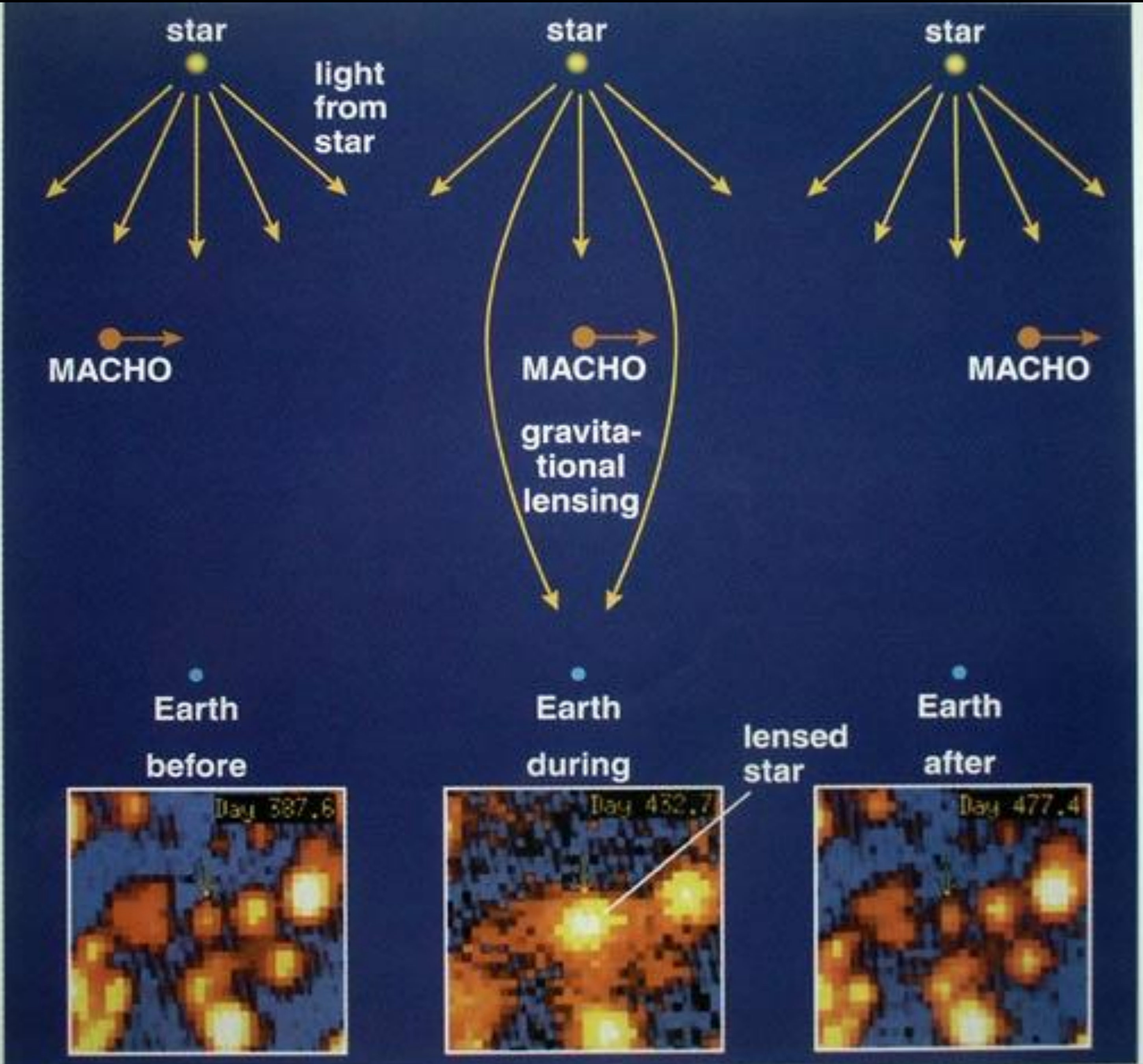
- These are all made mostly of heavy elements.
- How could ~90% of the halo be made up of heavy elements yet the stars, the most gravitating things out there, be pristine hydrogen and helium Pop II stars with ~no heavy elements? Makes no sense – gravity attracts ALL mass regardless of its nature.
- **Ergo, it's not rock, asteroids, or comets**
- **This same reasoning also rules out dust, which is made of heavy elements too.**

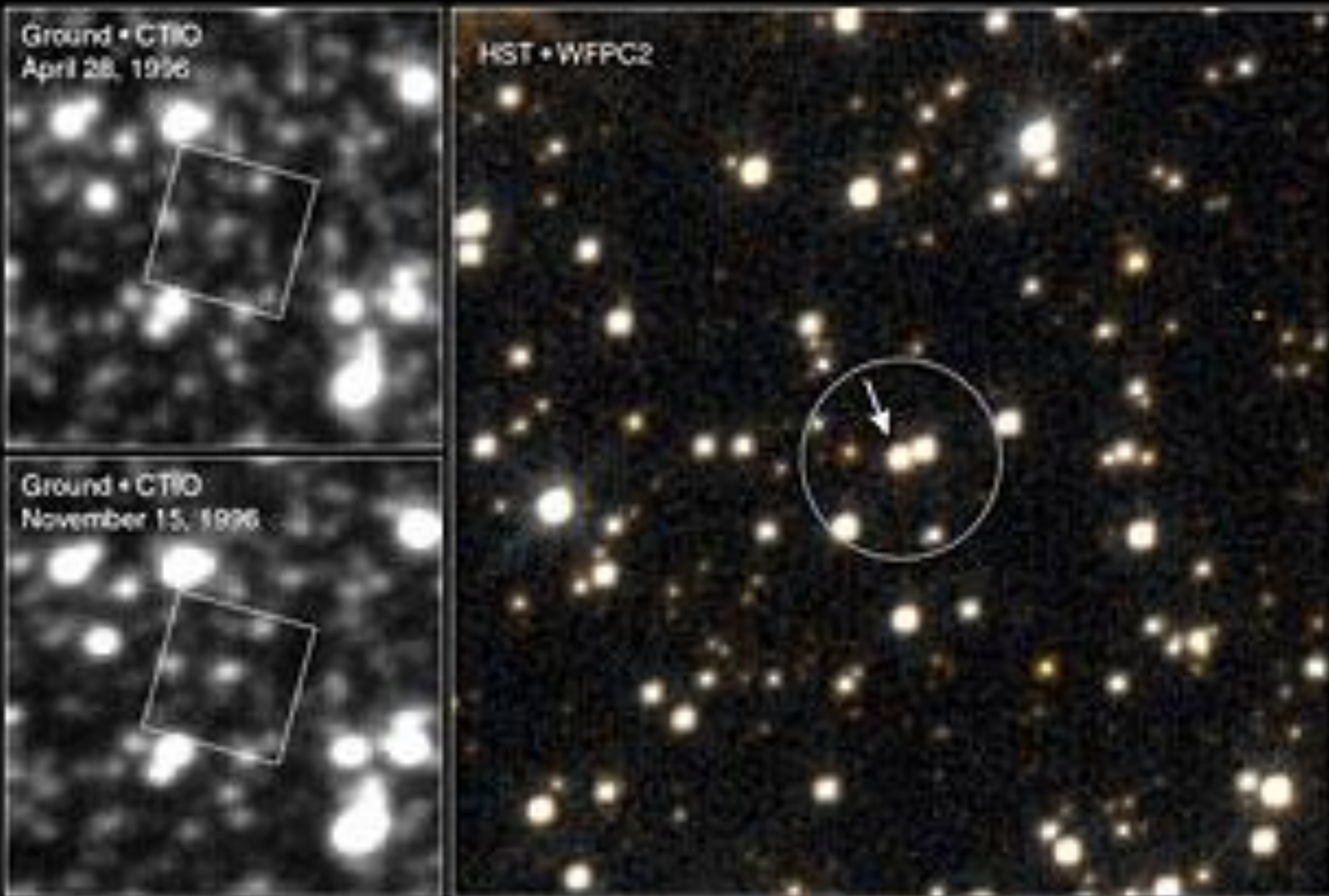
What about Heavier Things? All Self-Gravitating Objects can be Detected by a Particularly Clever Test…

- First- these things need a name:
- They’re massive (not elementary particles), they’re clumped into big things, and they’re in the halo of our galaxy…
- So let’s call them ***M***assive ***C***ompact ***H***alo ***O***bjects
- ***MACHO***’s!
- Look for gravitational lensing of distant stars as a MACHO passes in front of it.

Starfield in the Large Magellanic Cloud

Hubble


star
light from star
star
star
MACHO
MACHO
gravitational lensing
MACHO
Earth
Earth
Earth
before
during
lensed star
after
Day 387.6
Day 432.7
Day 477.4



Microlens Event MACHO-96-BLG-5
Hubble Space Telescope • WFPC2

NASA and D. Bennett (University of Notre Dame) • STScI-PRC00-03

What did the Gravitational Lensing Experiments Find?

- The MACHO project ran from 1994 to 1999. That's 6 years of observations of 12 million LMC stars, and it yielded only ~15 MACHO events.
- A similar study using the background bulge stars from the Milky Way (the OGLE project) is even more sensitive – about 20x that of the MACHO project towards the LMC.
- OGLE has found over 600 candidate lensing events – still many times smaller than needed for the Dark Matter to be MACHO's

OGLE Today: After 19 years of data, not nearly enough lensing events for the dark matter to be MACHO's.

- We can say with good confidence – **the Dark Matter is NOT MACHO's (stars, planets, black holes…).**
- **A new study (Nikura *et al.* 2019) rules out even low-mass "primordial" black holes, through gravitational lensing of stars in the Andromeda Galaxy**
- So, we've now RULED OUT all forms of ordinary matter, from atoms and known elementary particles all the way up to self-gravitating things like stars and planets.

NOW (and only now) is it time to GET CRAZY!

- It must be some form of matter that only interacts by gravity and, perhaps, the Weak Force. Both forces are very WEAK compared to the forces giving rise to atoms and light…
- We need a cute name: ***W***eakly ***I***nteracting ***M***assive ***P***articles = **WIMP**'s!

Yeah, you might have preferred to think our Universe was dominated by MACHO's,

- but instead it turns out we're dominated by WIMP's.
- Sad! A Bummer!

What WIMPs Do We Know for Sure Actually Exist in Nature?

- **The Neutrino** is the only WIMP we know of, which for sure actually exists in Nature.

…But alas…

- Pure standard neutrino dark matter won't work as the Dark Matter.
- To see why, we need to talk about another strategy for figuring out the **Dark Matter**. And that strategy is…

Dark Matter : Hot, Cold, or Warm. Affects the Formation of Large Scale Structure of the Universe

- **It's useful to classify Dark Matter candidates as being either "Hot" or "Cold"**
- **Hot Dark Matter** – particles that have a high random velocity in addition to their normal expansion with the rest of the universe and any tugging supplied by gravity. To be precise, they had speeds not much less than that of light, right up to the time of the formation of the first hydrogen atoms ~300,000 years after the Big Bang – when the Cosmic Background Radiation was freed. They would "free stream" away from any overdensity destined to be a galaxy or even a galaxy cluster, in the early universe.
- A rough analogy for hot dark matter might be the molecules of air in this room, which zip around at about 500 m/sec would be considered "hot" relative to the bulk motion of the air (~0 m/sec).

Hot Dark Matter

- There's only one candidate, but it's a good one because we know these actually exist!
- It's – the neutrino!
- **ALAS! The Dark Matter can't be Hot Dark Matter…**
- Known neutrino species (electron neutrino, tau neutrino, muon neutrino) are zipping around way too fast, especially in the early universe.
- In such a hot dark matter dominated universe, only structures large enough that these zippy neutrinos couldn't escape them - supercluster sized objects - could gravitate together at first, separating from the universal expansion

Only later would velocity sorting allow smaller things to turn around from the universal expansion

- So, next to separate out would be clusters of galaxies, then galaxies, then stars, as velocity sorting made for smaller relative neutrino velocities locally.
- **This is a "top down" scenario (Structure built chronologically from Big to Small)**
- **Such a universe would have sharply defined superclusters, less sharply defined clusters, galaxies would be barely forming, and stars perhaps not at all yet**

But Galaxies are Lumps, separated by many diameters. And Stars are smaller and even more lumpy, separated by millions of diameters


And this is Opposite of What a Hot Dark Matter Universe Predicts!

- **Stars are in fact seen to be the oldest things, and galaxy clusters are very young, and**
- **super clusters are barely starting to separate themselves out from the expansion today. A map of the sky barely suggests clumpiness of those large scales.**
- **But on small scales the universe is VERY lumpy. Galaxies are obvious, with black space between them**
- **The universe must instead be built "Bottom Up", with small things collapsing and forming first**

<u>Cold</u> Dark Matter (CDM) – Particles that are created with very low or zero velocity.

- To be more precise, their velocities were much slower than the speed of light long before the time hydrogen atoms first combined from the available protons and electrons (~300,000 years after the Big Bang).
- They were thus not able to diffuse to any significant extent.
- Essentially all their velocities were acquired by being pulled on by gravity as smaller over-dense areas collapsed within the larger expanding universe.

Cold Dark Matter Candidates?

- If the DM is pure CDM, then structure forms "bottom up" – first stars form, then galaxies, then galaxy groups and clusters, and finally superclusters.
- **This IS what we see**! **So the Dark Matter is believed to ~all be Cold Dark Matter**
- There's a bunch of candidates – **A favorite is** super-symmetric partners to ordinary matter particles – photinos, gravitinos… bunched together we call them "neutralinos" (little neutral ones),
- Other candidates: axions and sterile neutrinos.
- So the good news is there's lots of candidates.
- The bad news is, they're all only hypothetical, none of them are actually yet known to exist in Nature. They're possibly predicted by some unverified but attractive theories in particle physics. More to say on candidates shortly…

What about "Warm" Dark Matter?

- To be considered "warm", they would have primordial velocities comparable to the size of dwarf galaxy-sized overdensities – this would help them "solve" the problem (if it indeed a problem exists – it probably does not) of too few dwarf galaxies.
- Large scale structure in this case would otherwise still grow just like for Cold Dark Matter
- **Problem:** There are no known or hypothesized elementary particles which would behave as "warm dark matter".
- **Warm Dark Matter is NOT favored at this time**

What <u>is</u> the Dark Matter?

- Because the MACHO results show it is not clumped large enough to be self-gravitating, we believe it's <u>**some form of elementary particle.**</u>
- If so, there's been hope we can detect them in the particle physics experiments at big particle accelerators.
- In particular – the BIG one – the Large Hadron Collider, at CERN or perhaps in a specialized detection experiment elsewhere.

Before considering candidate particles, let's review and explore what constraints we can make on the Dark Matter Candidate particles…

1. The Particles are Essentially Dissipationless

- Spiral galaxy rotation curves show the DM distribution is roughly spherical with density falling roughly as $1/r^2$, this shows the particles are essentially dissipationless
- That means they do not give up their kinetic energy by interacting with other particles or photons through anything but gravity and perhaps the Weak force. They do not feel the strong or electromagnetic forces to any measurable extent
- So they stay puffed out, unable to give up energy so they might fall to the middle, they remain puffy cotton ball halos.
- The "Bullet Cluster" shows this very well

The "Bullet Cluster" – Two colliding galaxy clusters. The visible light image shows the galaxies, pink shows the X-ray emitting hot gas, and <u>blue shows the Dark Matter</u>. This collision can be modelled successfully only if the DM is dissipationless and passes right through each other. The hot gas feels the EM force and dissipates (goes "splat!") against that of it's neighbor, and is left in the middle. DM does not.

2. Stable, Or at Least Very Long-Lived

- Dark matter evidence from galaxies and large scale structure shows that the amount of dark matter in the universe has not changed much (and likely not at all) for the ~14 billion years since the Big Bang.
- Stability of the proton, which is measured to be longer than ~10^{34} years, argues there are likely no new forces beyond the Standard Model of particle physics

3. The Particles are "Cold" or at least "Cool"

- Actually, it is the ability to gravitationally clump on down to the smallest dwarf galaxy scales which DEFINES "cold" in this context.
- "Cold" means the particles were moving much much less than the speed of the photons since long before the era when matter and radiation de-coupled (birth of the Cosmic Background Radiation (CMB), more on the CMB in later lectures).

Being "Cold" Allows the Particles to Gravitationally Clump on All Scales, Even Scales Much Smaller than Typical Galaxies

- That means we can put observational limits on the "temperature" (really, the speed) of the DM particles when they de-coupled from the hot Big Bang matter/radiation.
- The result: This speed must be much less than the speed of light, so that decent galaxy-sized over-densities could be bound by gravity before the particles "free streamed" away.
- (In case you are wondering – we can't put a limit in terms of km/sec *vs.* cosmic time without better data on the abundances of dark dwarfs and the density profile of DM in galaxy cores.)

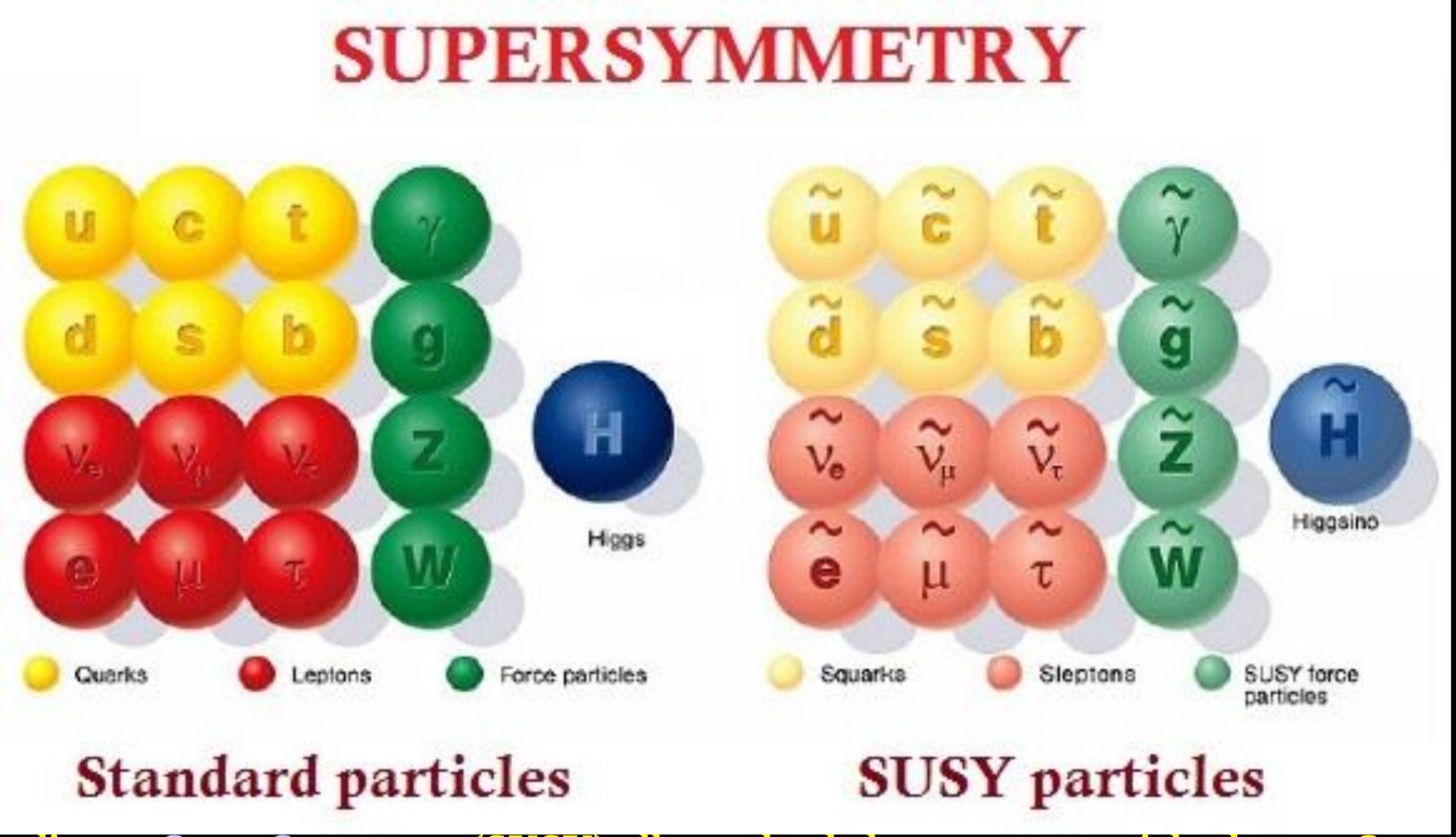
High resolution numerical simulation - Dark Matter clumps within a Milky Way sized Dark Matter Halo – Do we **see** this many corresponding dwarf galaxies around the Actual Milky Way?

No. Observations Find Too Few of the CDM-predicted Dwarfs Corresponding to the Small DM Halos. Why?

- **A.** Many astrophysicists find this not a problem – maybe ordinary but poorly understood mechanisms in these dwarf galaxies prevents stars from forming? (stars, gas, is what we need in order to observe them, remember).
- Supernova-driven winds can blow away ordinary gas and shut off star formation in DM dwarf galaxies, but this mechanism might? have trouble accounting for the too few number of mid-sized Dark Matter dwarf galaxies, perhaps, not clear yet.
- **Or B.** The Dark Matter simply doesn't clump as well on such small scales, which indicates the DM isn't truly "cold", but instead "luke warm". Not a favored idea at the moment.
- **Let's Look at Candidate Particles and their Motivation…**

1. Supersymmetric Partner Particles to Ordinary Particles…

- SuperSymmetry (SUSY): a proposed symmetry obeyed by Nature, whereby the force-carrying massless quanta (photons, gravitons e.g.) have mass-carrying partners, and vice-versa.
- SuperSymmetric partners to ordinary particles (they're given "…ino" names.
- Examples: the superSymmetric partner of the photon is the PHOTINO, and the partner of the quantized gravitational wave (graviton) is called a GRAVITINO.



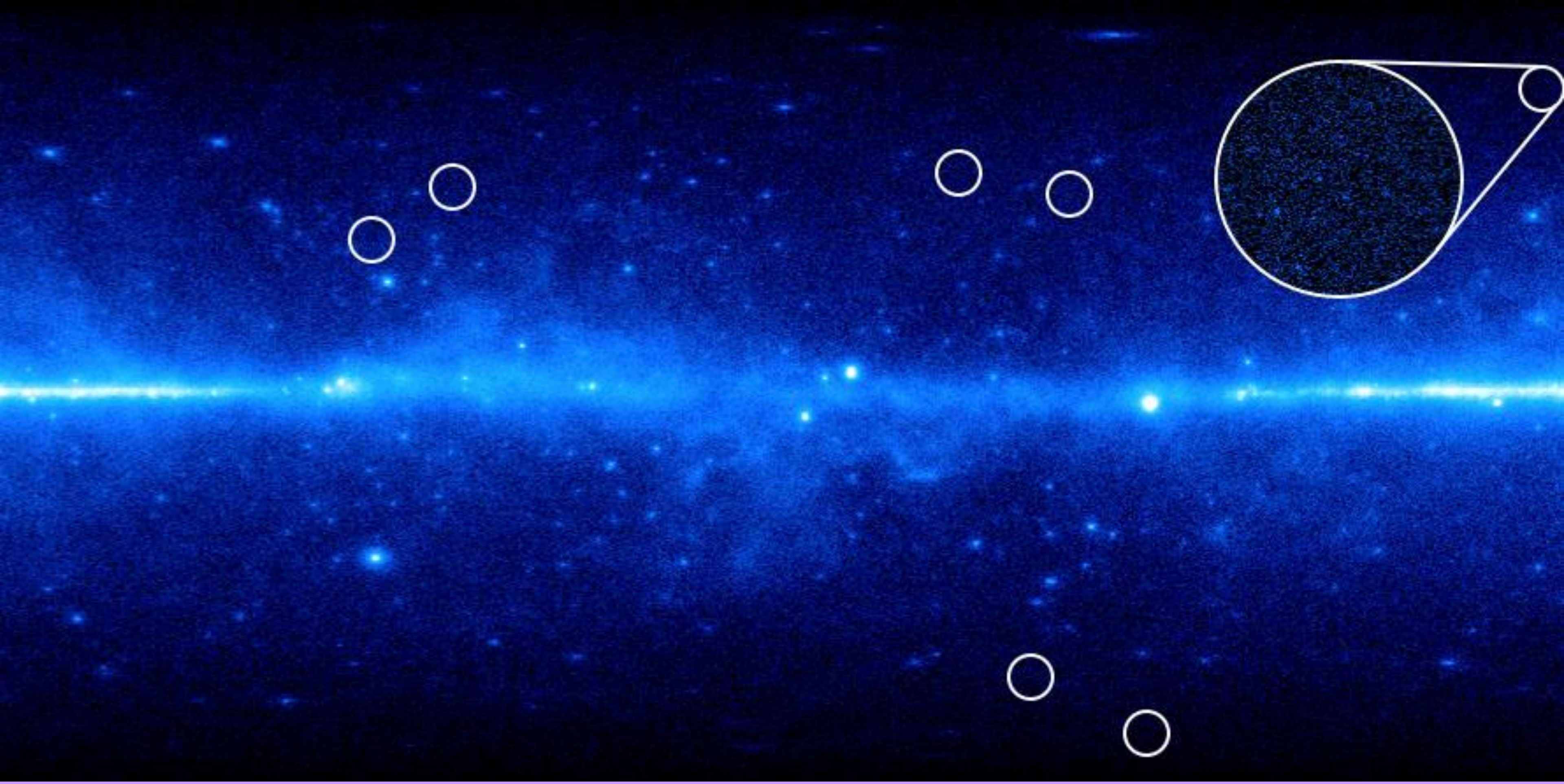
- According to SuperSymmetry (SUSY) all standard elementary particles have a SuperSymmetry partner.
- All Fermions have a Boson SUSY partner and vice versa. (and what does THAT mean??). Look up definitions of Fermions and Bosons in general, but here…
- The Fermions are elementary particles of matter. the Bosons are elementary particles of force (yes, force is quantized too!)
- EXACT SUSY says the partner has the same mass. But this was observationally ruled out long ago, and also solves no problems in physics (including Dark Matter), so we assume that SUSY is a broken symmetry. Then the Force partners instead of being massless, would have mass, and therefore could be DM candidates (Photinos, Gravitinos) – NEUTRALINO's, in general!
- Do these new Bosons have to be carriers of some new force? That would imply the proton should decay, and observationally we see that it does not. Imposing a new parity conservation law (R-Parity) on SUSY mean the new particles would NOT imply new forces.

A Beautiful Theory Murdered by Ugly Facts?

- But – data (Nov ’12) from the LHC has now observed the rare, sought after decay of B particles, into 2 muons. The observations agree very well with the Standard Model, and not with SuperSymmetry.
- More, we find that as we continue to design higher energy particle accelerators which can search for heavier and heavier new elementary particles, the SUSY particles are NOT showing up in the data.
- **That’s BAD news for SUSY, and as a Dark Matter candidate it is not looking so good any more**
- More complicated, less aesthetic, and more contrived versions of SUSY can be concocted, and are not ruled out…. But at this point, according to Chapter 0’s explanation of the scientific process… it might be time to look elsewhere for beautiful and elegant solutions to the problems SUSY was hoped to solve.

More Bad News for SUSY Dark Matter…

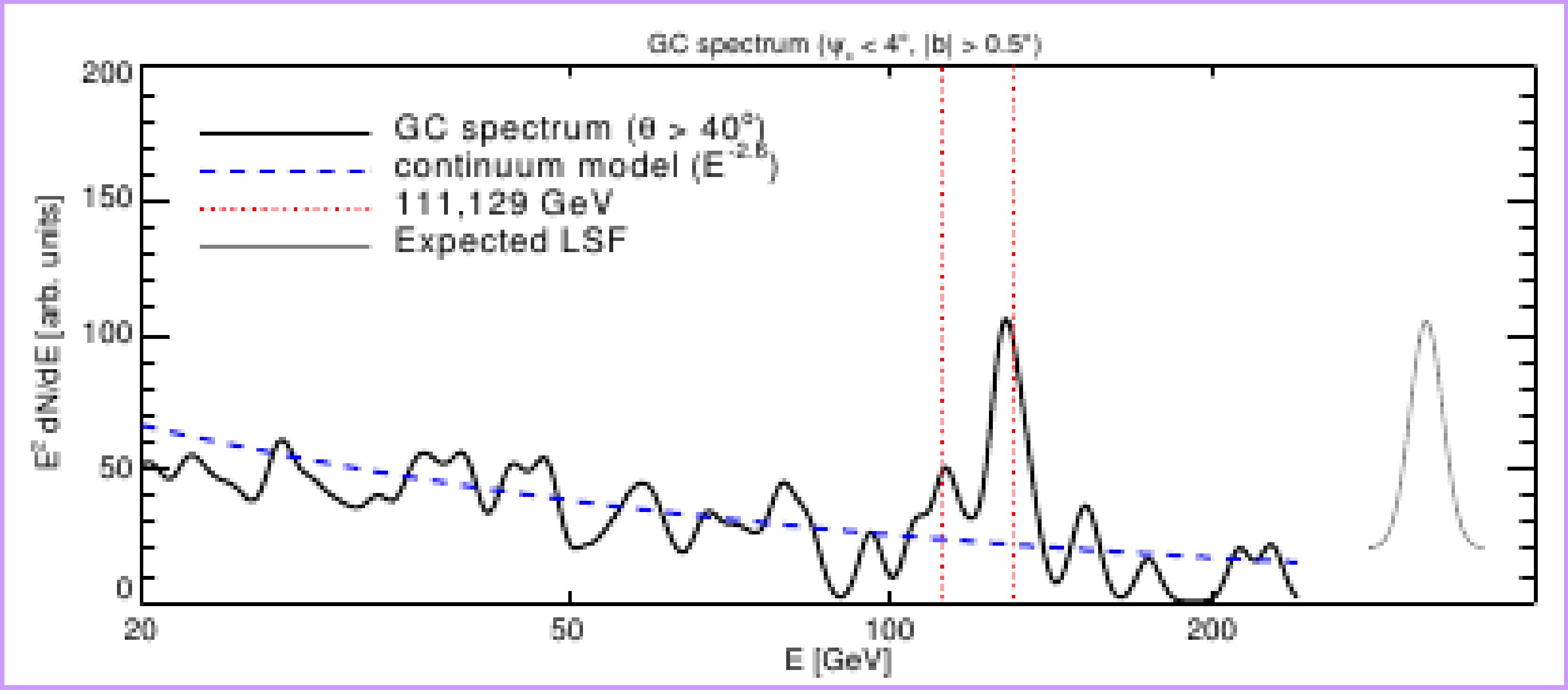
- If the DM particles are uncharged SUSY particles (neutralinos), they are their own anti-particle and therefore can annihilate with each other in collisions and become gamma rays. Gamma rays are light, which we CAN look for.
- **Test:** Look towards places where there's no competing gamma rays from astrophysical processes – places like DM-dominated "dark dwarfs" which exist by the dozens around the Milky Way and look for excess gamma rays.



- Two studies find - The Fermi satellite's gamma ray telescope observes no such gamma rays from ~2 dozen DM dominated Milky Way halo dwarf galaxies
- This puts an UPPER limit on the space density of the neutralino particles and a LOWER limit on the mass of the individual particles – about 40 GeV – when you factor in the gravitationally determined DM total mass of these dwarf galaxies.

Gamma Rays from DM Annihilation from the Milky Way Core?

- In 2012, data from the Fermi satellite showed a slight excess of gamma rays from near the galactic core with an energy of 130 GeV



But…

- **A few months later, re-calibration of the data reduced the signal to a value less than statistically significant**
- **In other words, it may just be noise.**
- **Or it might be real, and very weak.**
- **We don’t know, but papers are already appearing trying to model what it means if it is not noise.**
- **As of 2015, the signal seems to have gone away, and local astronomer Stefano Profumo (and star Santa Cruz Track Club triathlete!) put together a strong case that this signal is not there.**

2. Sterile Neutrinos

- Sterile Neutrinos are proposed massive neutrinos which do not interact via the strong, weak, or EM forces – only gravity. Their motivation in terms of particle physics is poorly understood and out of our depth in this class, but you can read on if you would like…
- **Detection attempts:**
- The production and decay of sterile neutrinos could happen through the mixing with virtual neutrinos. There were several experiments set up to discover or observe NHLs, for example the NuTeV (E815) experiment at Fermilab or LEP-l3 at CERN. They all lead to establishing upper limits to observation, rather than actual observation of those particles. If they are indeed a constituent of dark matter, sensitive X-ray detectors would be needed to observe the radiation emitted by their decays.[1]
- Sterile neutrinos may mix with ordinary neutrinos via a Dirac mass[*citation needed*][*clarification needed*]. Sterile neutrinos and ordinary neutrinos may also have Majorana masses. In certain models[*which?*], both Dirac and Majorana masses are used in a Seesaw mechanism, which drives ordinary neutrino masses down and makes the sterile neutrinos much heavier than the Standard Model interacting neutrinos. In some models[*which?*] the heavy neutrinos can be as heavy as the GUT scale (≈10^{15} GeV). In other models[*which?*] they could be lighter than the weak gauge bosons W and Z as in the so-called *ν*MSM model **where their masses are between GeV and keV. A light sterile neutrino (with the mass ≈1 eV) was suggested as a possible explanation of the results of the LSND experiment.**

But Sterile Neutrinos are Faring Mixed-to-Badly with Observations Now Too…

- **On April 11, 2007, researchers at the MiniBooNE experiment at Fermilab announced that they had not found any evidence supporting the existence of such a sterile neutrino.[2] More recent results and analysis have provided some support for the existence of the sterile neutrino.[3][4][5] Two separate detectors near a nuclear reactor in France found 3% of anti neutrinos missing. They suggested the existence of a 4th neutrino of mass 0.7 Kev**
- **The new (2013) Planck Mission data on the Cosmic Microwave Background shows the expansion rate of the Universe fits well with that predicted from only the known 3 flavors of neutrinos, so a 4th (such as the hypothetical "sterile" neutrino) is dis-favored. (see Scientific American summary)**

More Trouble for Sterile Neutrinos. Matter/anti-matter annihilations – Not there?

- A Majorana sterile neutrino should still be able to annihilate with it's identical partner in a matter/anti-matter reaction
- If sterile neutrinos are the Dark Matter, we might expect to see neutrino/anti-neutrino annihilation products from our Galaxy.
- 2013 new results of an ongoing study to find such annihilations – finds none (Lindner 2013). Will wait for a few more years of data before we can rule out this version of Sterile Neutrino.

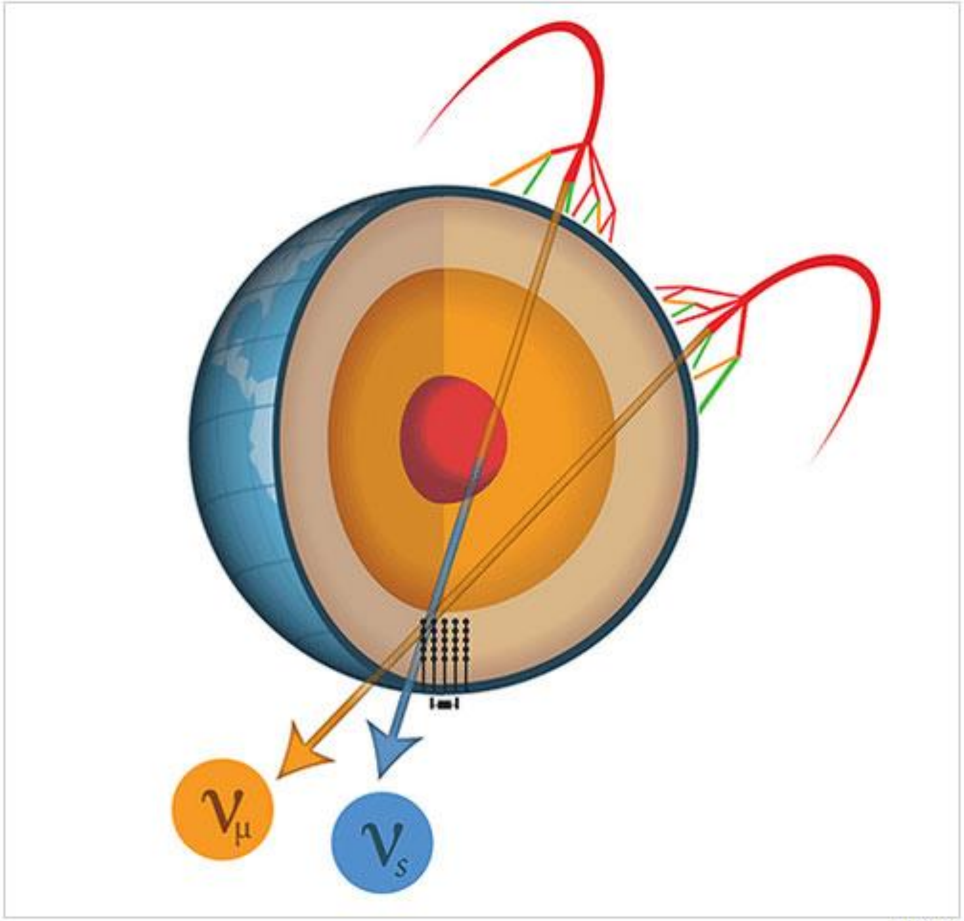
OK. It's 2020, and "A Few More Years" Have Passed.

- Another nail in the Sterile Neutrio coffin? Dessert *et al*. 2020 find after integrating an X-ray satellite's data of blank sky, that the Sterile Neutrino supposed to exist (if it's a Majorana particle) causing a 3.5 keV emission, isn't there.
- The data rules out such Sterile Neutrinos at an amount needed to account for the Dark Matter.

And Now, the Final Stake in the Heart for Sterile Neutrinos?

- Whether Majorana particle or not, even if sterile neutrinos ONLY interact by gravity and do not neutrino+antineutrino annihilate, a new experiment has ruled them out.
- Since neutrinos can oscillate between their different "flavors" (electron, tau, muon, and hypothesized sterile), we can look for missing neutrinos at **Ice Cube**, which looked at 100,000 Cerenkov flashes from standard neutrinos over a year, searching for missing flashes due to oscillations into the sterile neutrino flavor from atmospheric muon-induced neutrinos
- The energy distribution was well matched by predictions of just the 3 flavors and no sterile neutrino (good description)

All but a tiny range of possible masses for the hypothetical Sterile Neutrino have been ruled out



IceCube

Figure 1: To search for sterile neutrinos, the IceCube experiment looks for the disappearance of atmospheric muon neutrinos (ν_μ) that have traveled to its detector (black dots) through the Earth. If sterile neutrinos exist, then the matter in Earth's core shou... **Show more**

3. Axions

- No, not the laundry detergent, woman's hockey team, cable TV provider, internet service provider, tractor built by LeMans, nor the guitar brand!
- It's a sub-atomic particle! (well, if it exists)
- The **Standard Model** allows violation of charge-parity symmetry, yet the unobservably small electric dipole moment of the neutron shows that the violation parameter must be very close to zero. Why? If there is a new symmetry (Pecci-Quinn symmetry) which is broken, it results in a particle – the Axion – which naturally explains the absent electric dipole moment.
- Axions interact with photons in strong magnetic fields (the inverse Primakov Effect), so may be detectable when sensitive detectors go online soon.

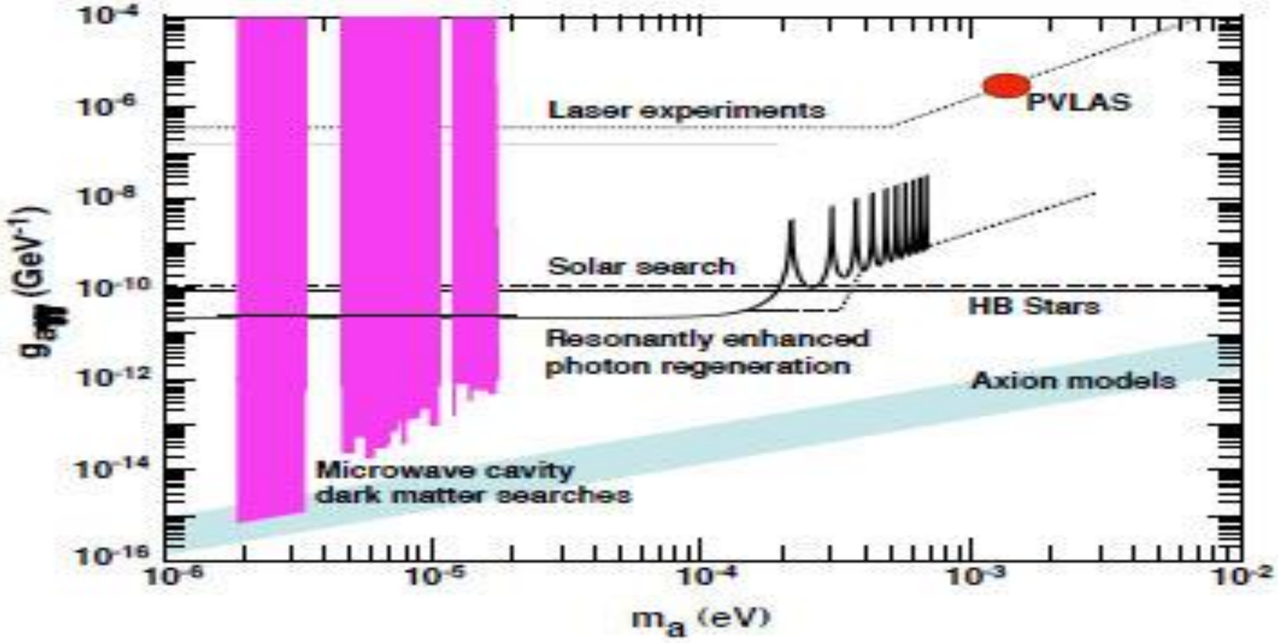


FIG. 2: (color) Current exclusion plot of mass and photon coupling $(m_a, g_{a\gamma\gamma})$ for the axion, and the 5 σ discovery potential for the resonantly enhanced photon regeneration experiment calculated for a configuration of 4 + 4 LHC dipole magnets. The existing exclusion limits indicated on the plot include the cavity microwave experiments assuming axions saturate the dark matter halo density [1], the best direct solar axion search (CAST collaboration) [6], the Horizontal Branch Star limit [13], and previous laser experiments [9]. The red error ellipse indicates the positive result of the PVLAS collaboration, if interpreted as a light pseudoscalar, based on measurements of magnetically-induced dichroism of the vacuum [4]. For the estimated limits of resonantly enhanced photon regeneration presented here, the solid curve corresponds to the $\uparrow\uparrow\uparrow\uparrow$ configuration of the individual LHC dipole magnets in both the production and regeneration strings; the dotted curve indicates the extension of the mass reach by additionally running in the $\uparrow\uparrow\downarrow\downarrow$, and $\uparrow\downarrow\uparrow\downarrow$ configurations.

Best Hope of Axion Detection May be Astrophysical…

- – tell-tale absorption lines in pulsars from photon/axion conversions in strong mag fields, and they are a proposed solution to the question of why the universe is so transparent to TeV gamma rays.
- Axions could, in principle, be heavy, but in this case, they would have decayed long ago, and this violates the evidence of Dark Matter in today's universe (K. Greist).
- But…The light axions proposed (micro eV masses) generate a "fine tuning" problem worse than the "fine tuning" problem they were hired to solve! (Mack & Steinhardt 2009).
- So, axions solve several problems if they exist, but perhaps suffer from a fine-tuning problem (anthropic principle in the Multi-verse solves this?? We'll talk about this a bit at the end of the course)

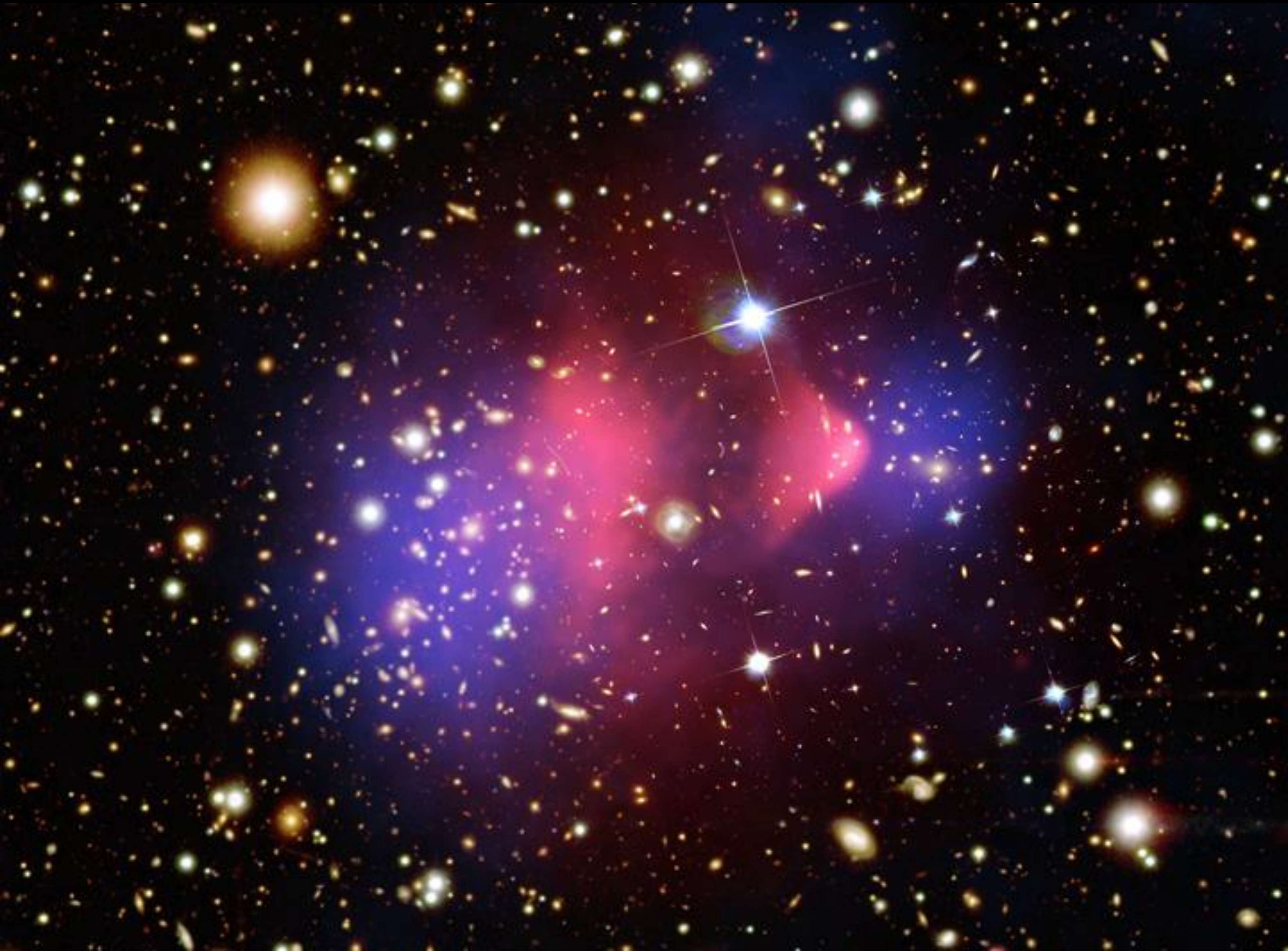
Still - With SUSY particles and sterile neutrinos now looking less likely, perhaps the Axion takes over as the Least Unlikely Candidate for the Dark Matter, at this moment in 2016

So That's the Way It Stands…

- We don't have any observationally well-motivated candidates for the dark matter particle. Sterile neutrinos: now appear almost ruled out, SUSY particles: in conflict with LHC new particle mass limits, **and new 2017 work** and any SUSY variant looks increasingly complex and therefore "ugly". Axion: looks theoretically unmotivated according to some, but perhaps less ugly than the others…
- So, is it back to the drawing board?? Not yet, too soon. SUSY still not completely ruled out, Axions the same, maybe a bright mind will come up with more possibilities…. But to be fair –

Can we make Dark Matter go away by just re-writing the Law of Gravity??

- Beginning in the 1980's (Milgrom *et al.)* has tried re-writing a law a gravity to make the evidence for DM go away
- His **MOND** (MOdified Newtonian Dynamics, later made covariant and consistent with General Relativity) idea was tough to rule out by observations for quite some time.
- **MOND** was always ugly to theorists (it not only makes equations "ugly", but also can be used to account for only about half the observationally determined Dark Matter, and wrecks the beauty of Einstein's gravity, according to many.
- But, ugly doesn't mean it was necessarily wrong.
- **However, the Bullet Cluster shows there certainly exists dissipationless Dark Matter. So MOND is indeed pretty unlikely to be right.**



Ch 22: Dark Matter - Key Points

- First solid evidence: Zwicky's observations of velocity dispersion of galaxies in the Coma Cluster in 1933, followed by Rubin's observations of spiral galaxies' flat rotation curves staying high even after all visible matter was inside the farthest sampled distances
- Methods of measuring mass of Galaxy Clusters: velocity dispersion, X-ray gas temperatures, and gravitational lensing. All show existence of DM.
- Methods of measuring mass of galaxies: broad spectral lines in Ellipticals, rotation curve for disk galaxies.
- DM cannot be gas, dust, rocks, comets, "Jupiters", dead or live stars, black holes. All are ruled out by observations. Know the reasoning.
- DM must be "cold", to explain structure formation observed to be "bottom-up" i.e. DM=CDM
- DM can't be known neutrinos because they are "hot" (fast).
- DM is dissipationless, to explain puffed galaxy halos, and the Bullet Cluster.
- DM does not produce or interact with light in any detectable way. Only feels gravity, and maybe the Weak Force. Therefore it is believed to be an elementary particle
- CDM candidate particles: SUSY particles, Axions are looking increasingly disfavored by particle accelerator data and astrophysical observations, sterile neutrino virtually ruled out
- We have NO clear favored candidate. Axions are the least ugly and the least observationally disfavored of the candidates we have