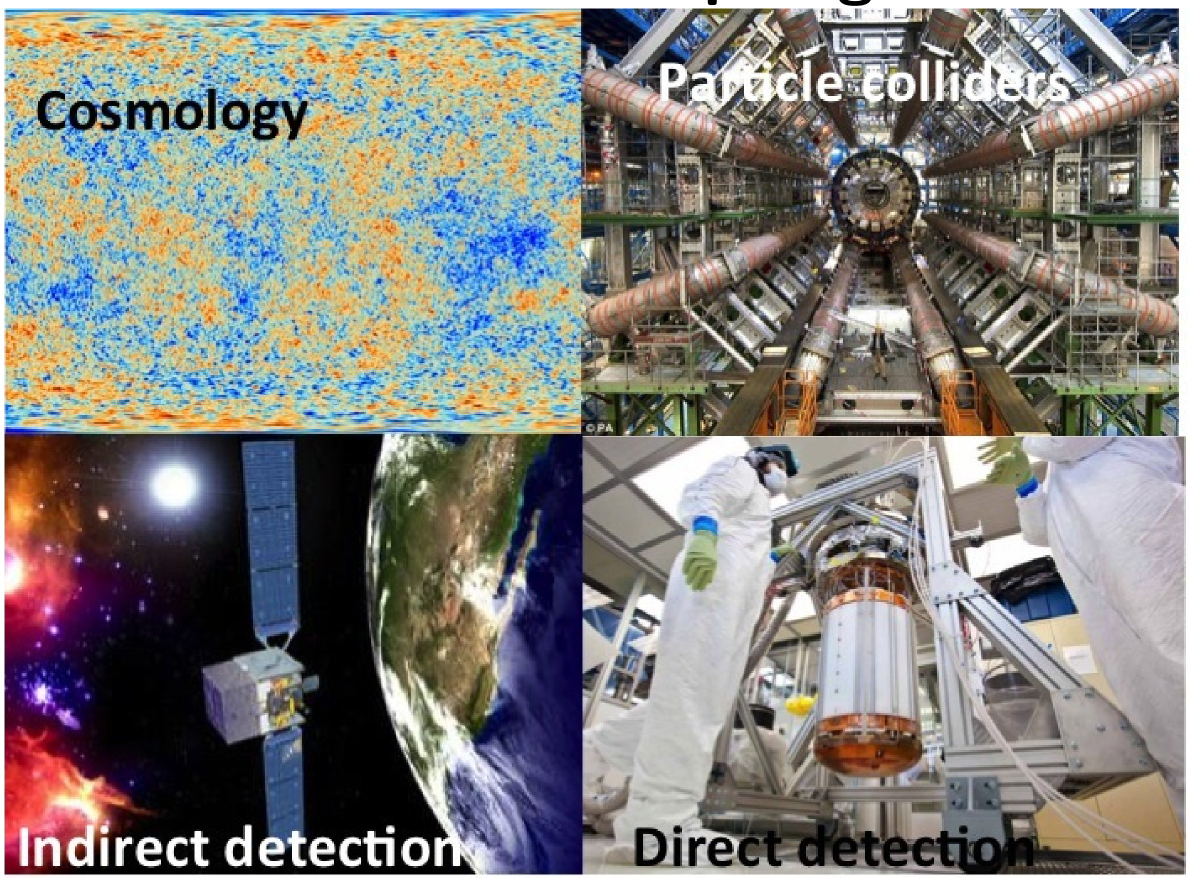
The Hunt for Dark Matter

Graciela Gelmini - UCLA

UAM, Madrid, February 10, 2016

The Hunt for Dark Matter, the most abundant form of matter in the Universe is multi-pronged involving ...



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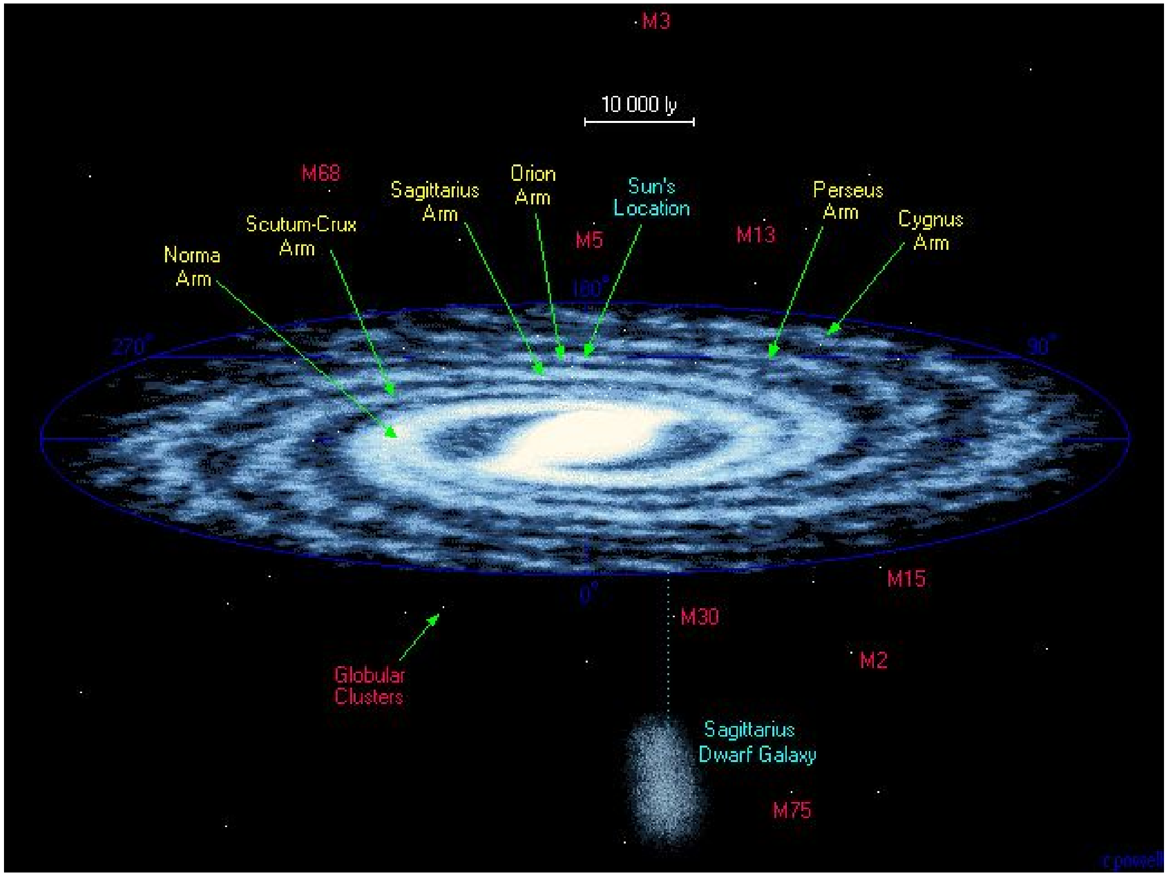
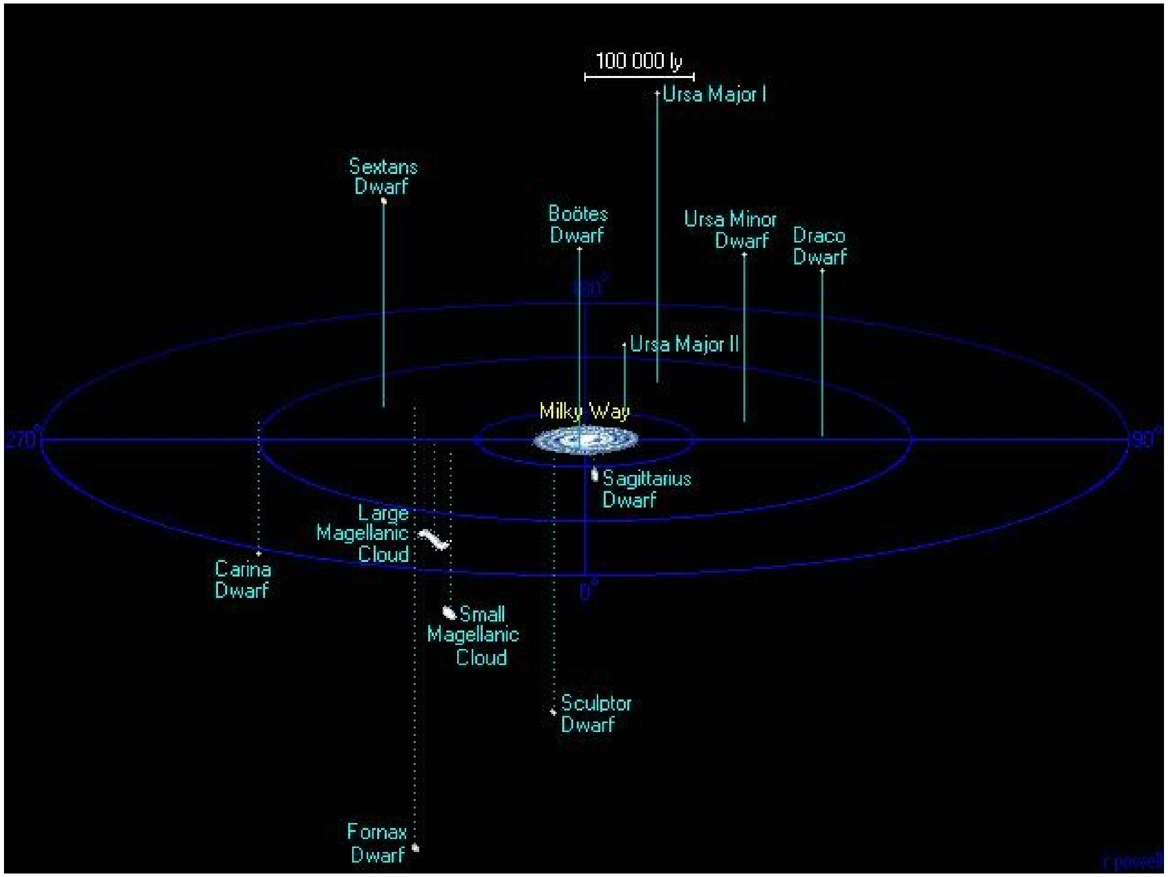
What we are looking for

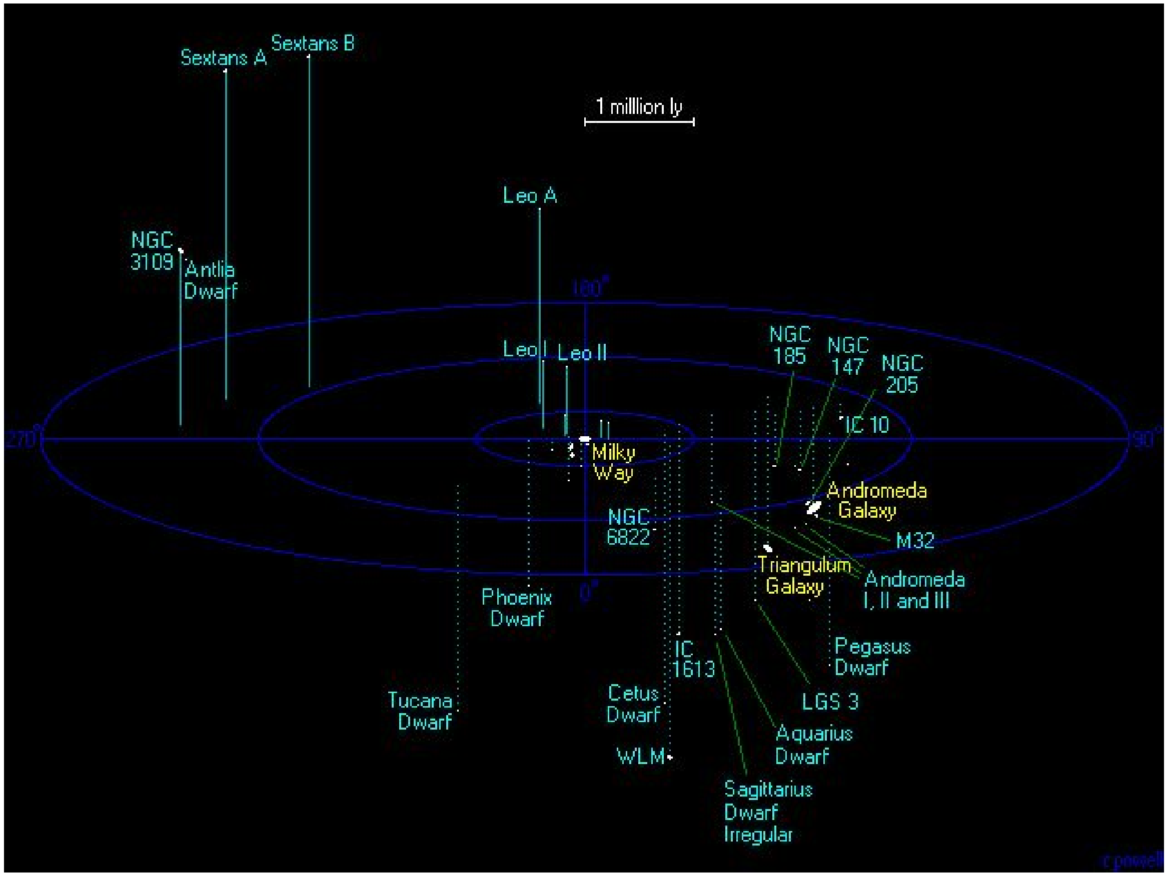
The Universe around us: Galaxies are the building blocks of the Universe. The Milky Way and the Sagittarius Dwarf galaxy its nearest satellite galaxy



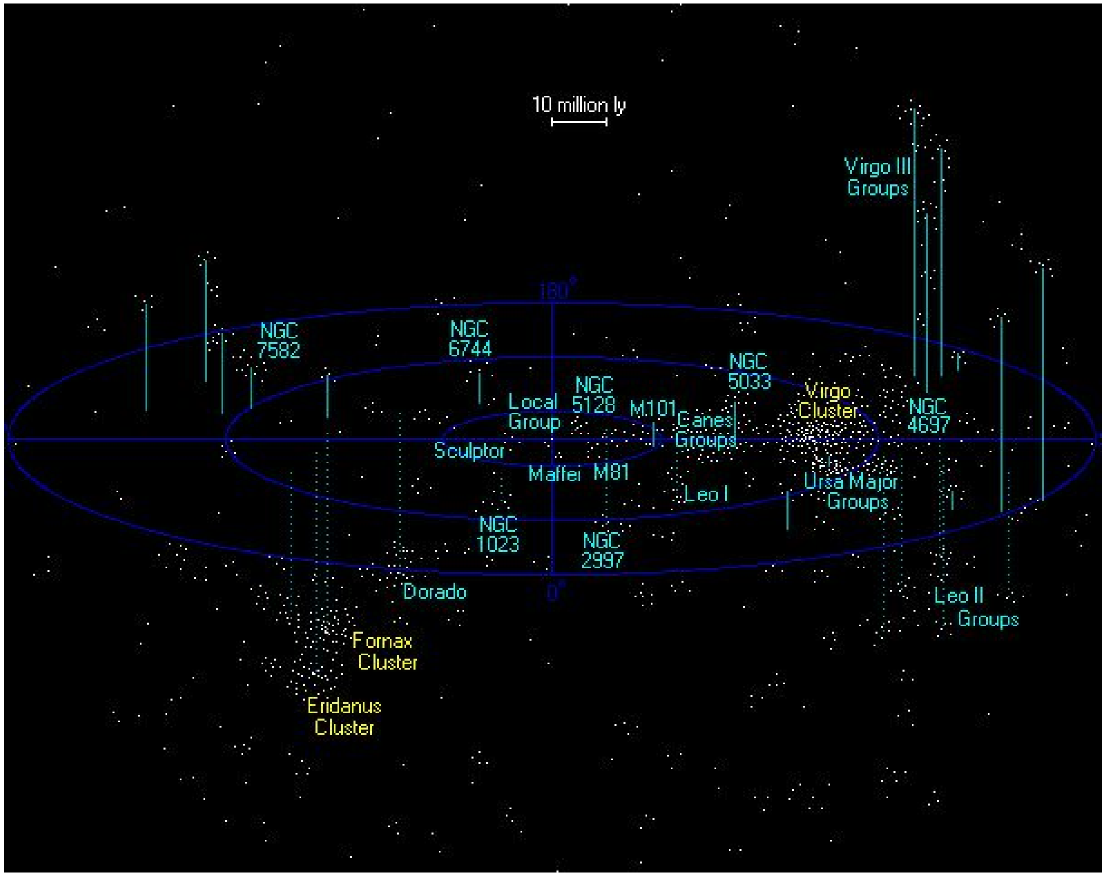
The Milky Way has many small satellite galaxies 35 dwarf galaxies have been found so far (9 in 2015 by DES)



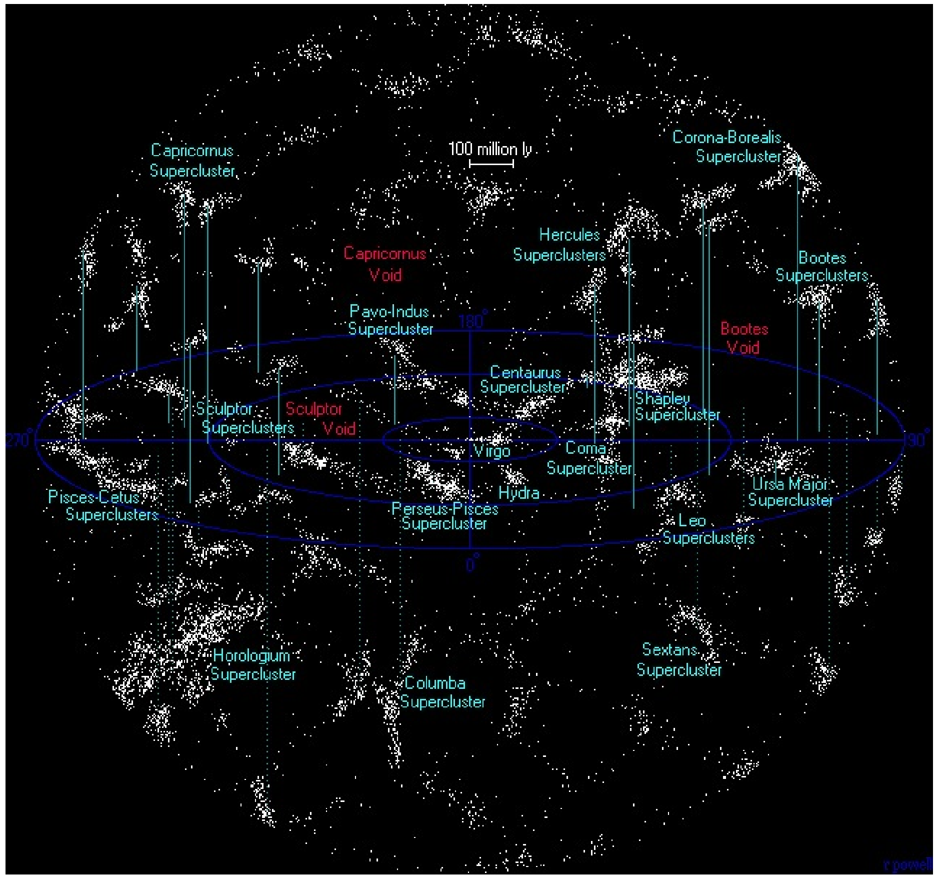
Galaxies come in groups, clusters, superclusters......Our Local Group of galaxies



Galaxies come in groups, clusters, superclusters...... Our Local Group of galaxies is in the outskirts of the Virgo Cluster



Galaxies are the building block of the Universe: they come in groups, clusters, (which form "filaments, walls and voids")



‘Weighing’ galaxies, clusters, the visible Universe

Around us:

- atoms, i.e. protrons and neutrons (baryons) and electrons...

- light ...

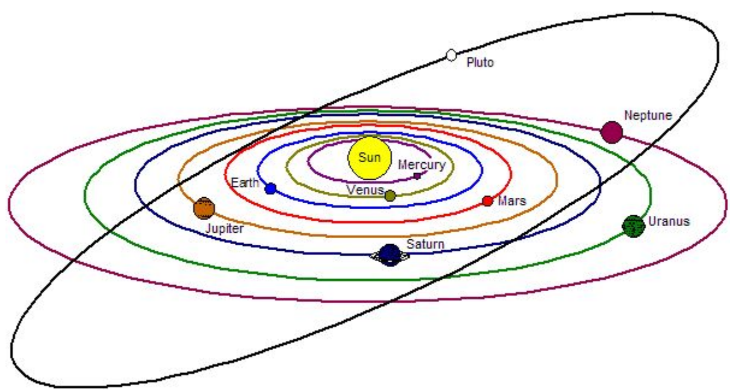
- also neutrinos and unstable particles...

but we weigh galaxies and galaxy clusters and the Universe
and find that

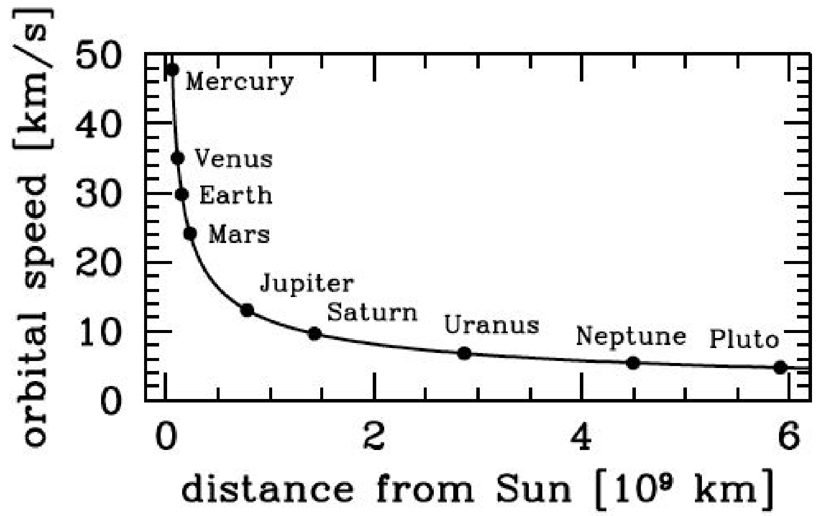
most of the Universe consists of none of these....

Start by 'weighing' the Sun

$$\frac{GM_{\odot}m}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM_{\odot}}{r}}$$



Rotation curve

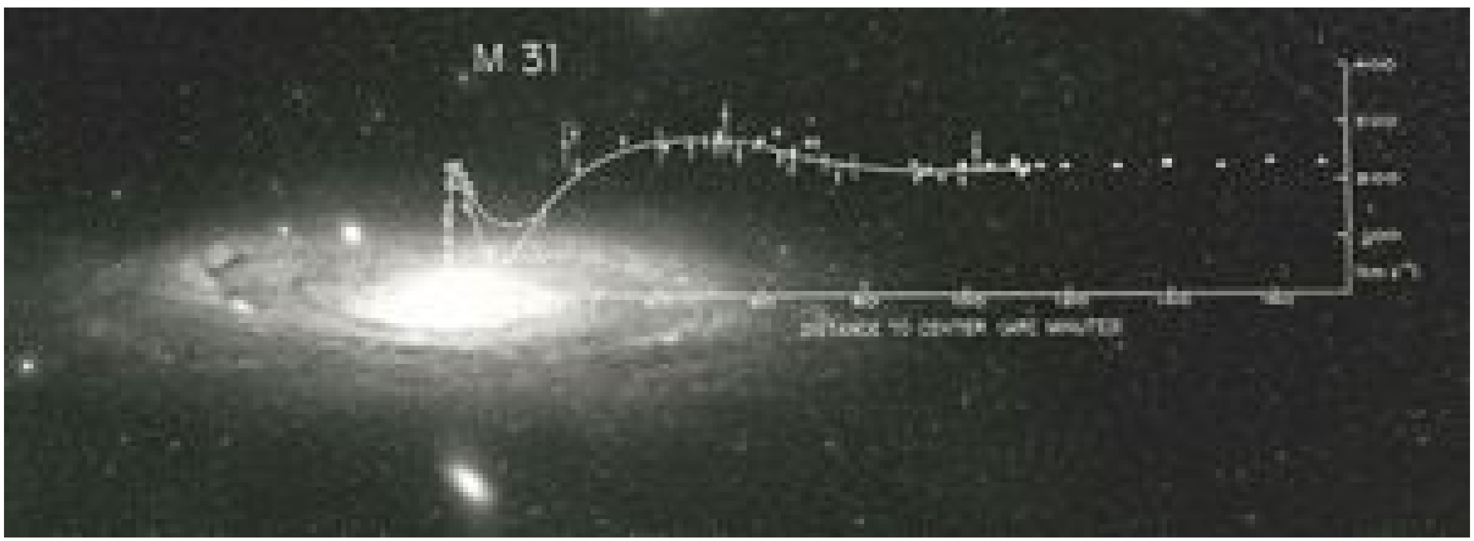


$$\Rightarrow M_{\odot} = 1.9889 \times 10^{30}\, kg$$

‘Weighing” galaxies:

In the 1970’ Vera Rubin et al used the same method of rotation curves in spiral galaxies, expecting $v \sim 1/\sqrt{r}$ at r larger than the disk radius

They found...

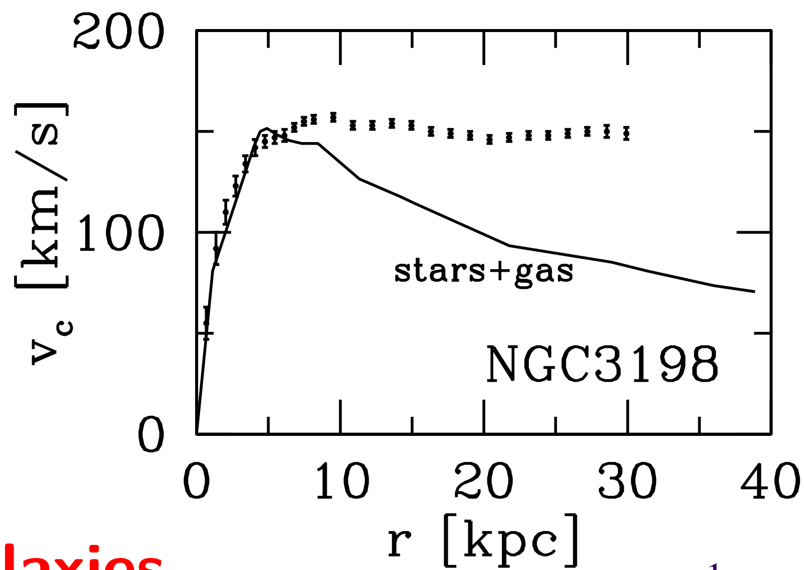


Rotation curves of galaxies ARE FLAT!

$$v = \sqrt{\frac{GM(< r)}{r}} = \text{const.}$$

$$\Rightarrow M(< r) \sim r$$

even where there is no light!



$1pc = 3.2\ell y$

Dark Matter dominates in galaxies

e.g. in NGC3198

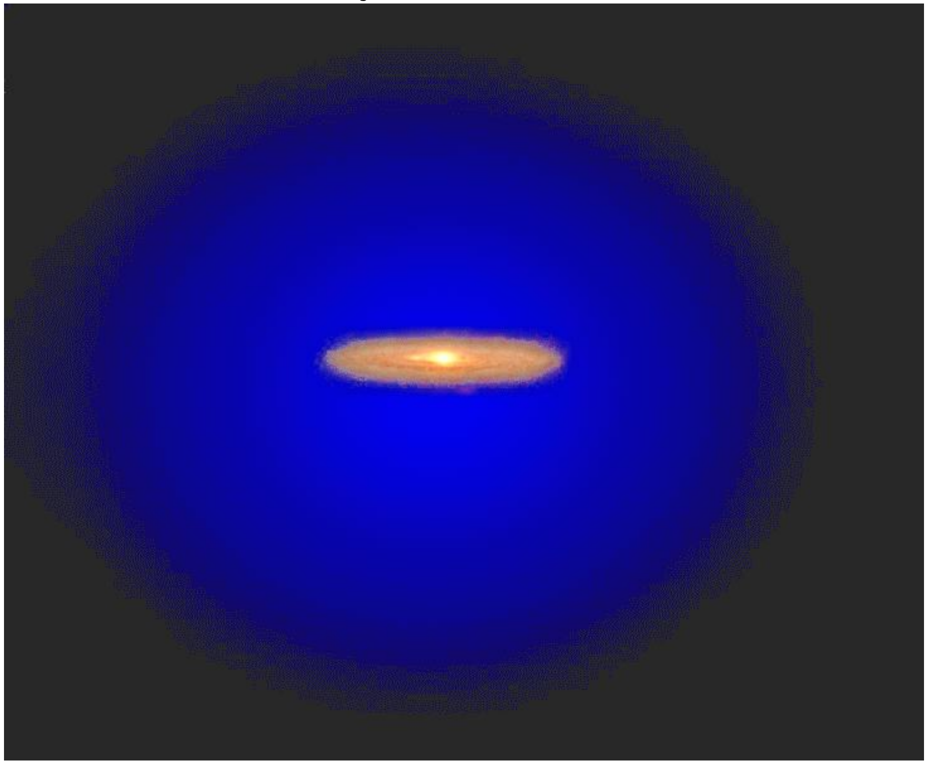
$$M = 1.6 \times 10^{11} M_{\odot} (r/30kpc)$$

$$M_{stars+gas} = 0.4 \times 10^{11} M_{\odot}$$

$$\frac{M}{M_{vis}} > 4$$

Galaxies have a Dark Halo containing about 80% of its mass

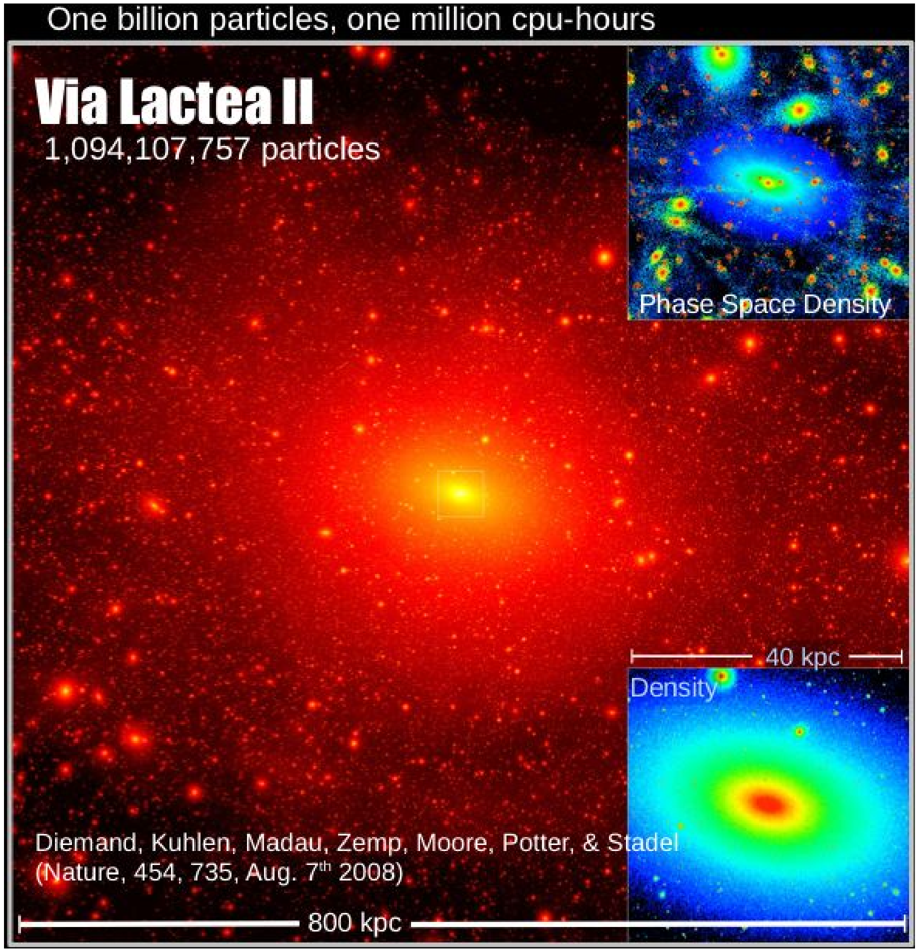
Artist view: visible MW disk surrounded by a DM halo



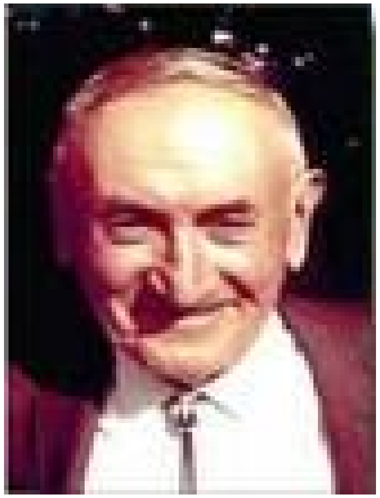
A simulation of a Dark Halo No baryons included (so no disk)!

800 kpc cube.
Lower inset shows density in inner 40 kpc- Sun at 8kpc from the center

Lots of subhalos and tidal streams at large distances from the galactic center.



‘Weighing’ galaxy clusters?



In the 1930’s Fritz Zwicky found the first indication of the DM.
He used the “Virial Theorem”

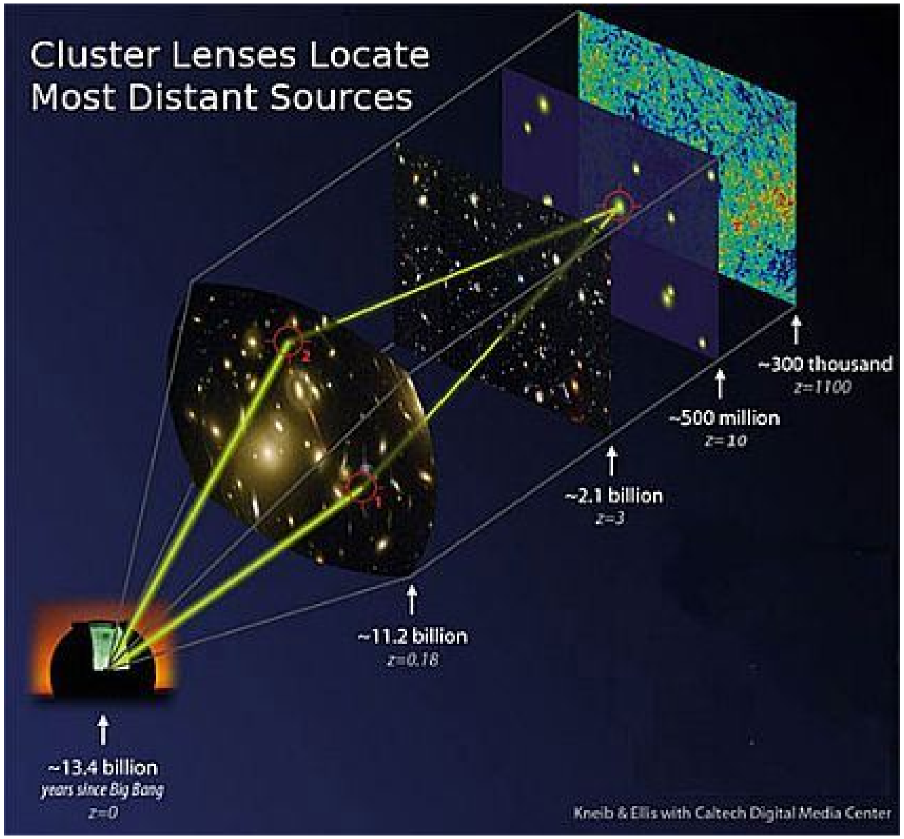
Example: for planets $\frac{GM_{\odot}m}{r} = mv^2$

|Gravitational Potential Energy|=2×Kinetic Energy

in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only

Later: also gas in clusters moves too fast (is too hot - as measured in X-rays) to remain in it, unless there them DM.

Another method to'Weigh' galaxy clusters: gravitational lensing

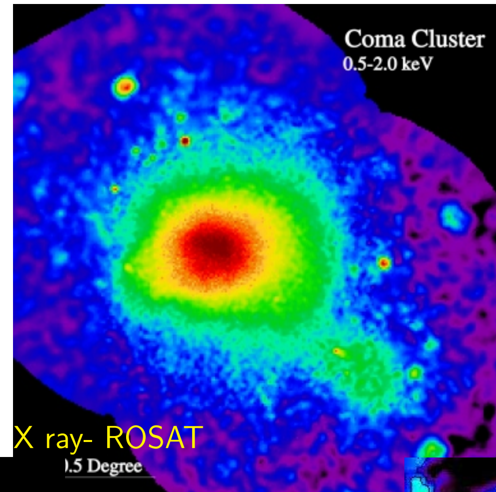


Gravitational attraction
bends light as does
a particle trajectory

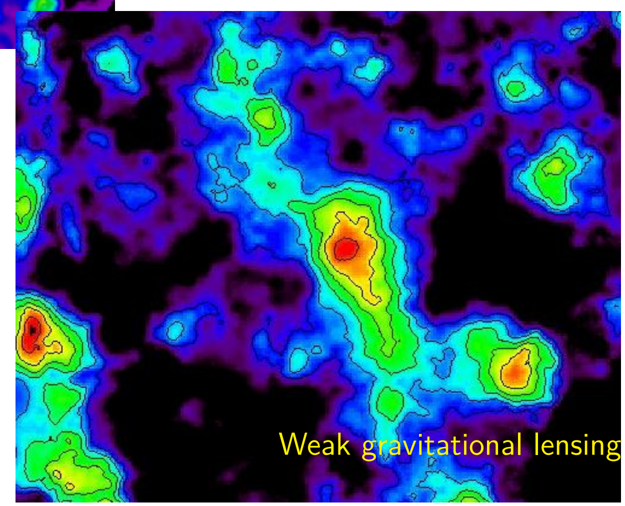
Gravitational lens:
depends on ALL
the intervening mass

Conclusion...

DM dominates in galaxy clusters



$$\frac{M}{M_{vis}} > 5$$



At the largest scales:

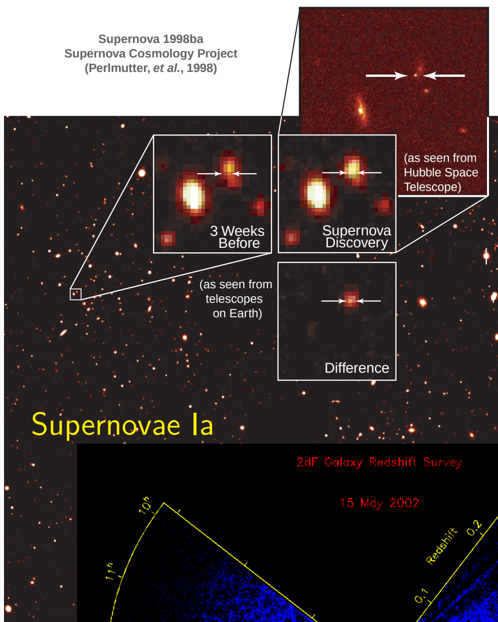
Use General Relativity

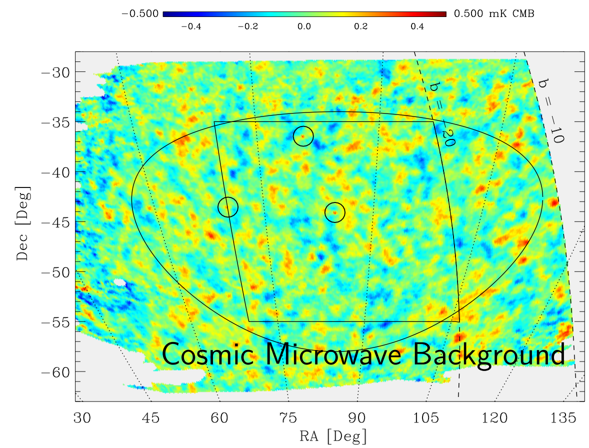
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \left(+ \Lambda g_{\mu\nu} \right)$$

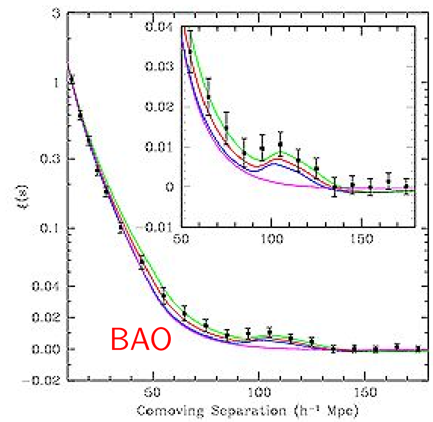
To relate:

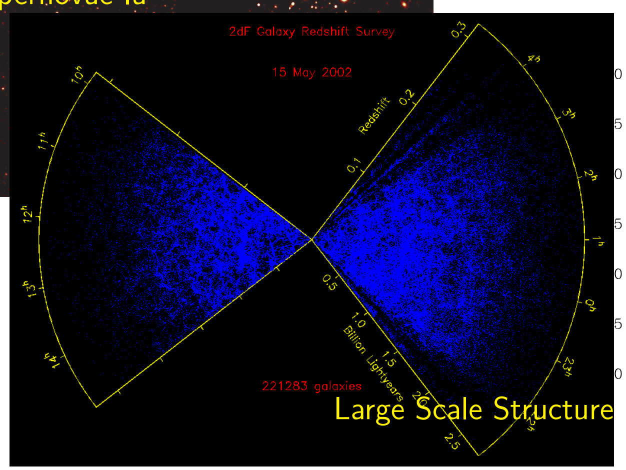
Spacetime geometry $\longleftrightarrow$ Mass-energy density

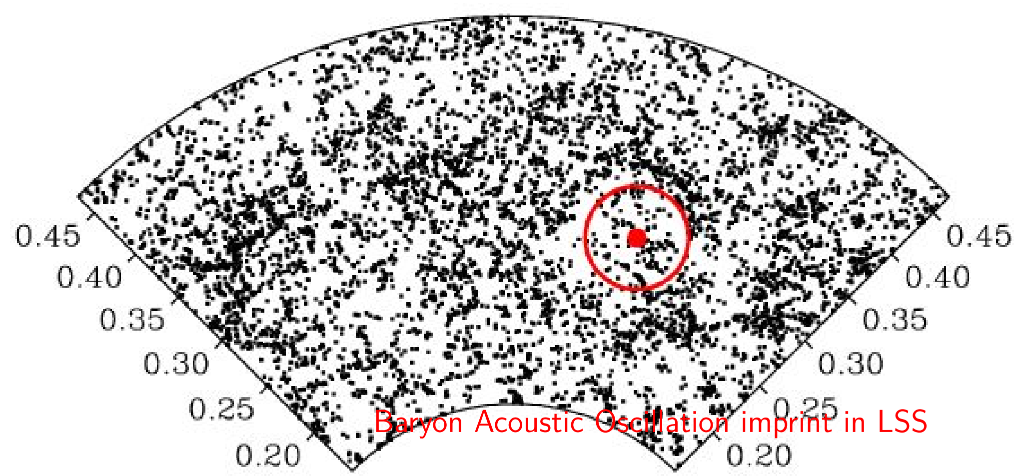
At the largest scales



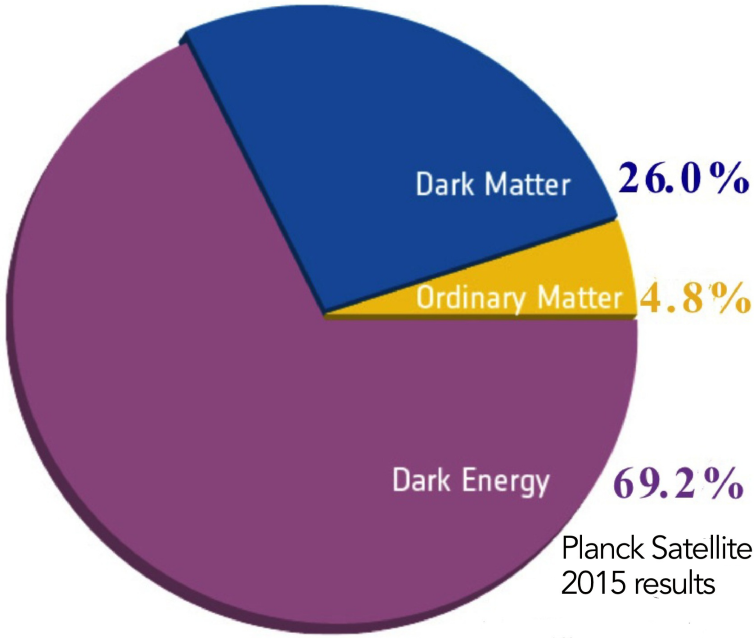


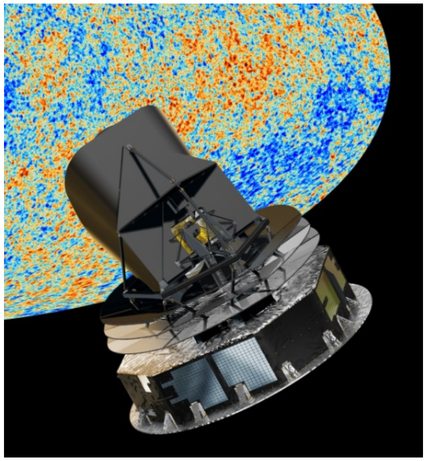






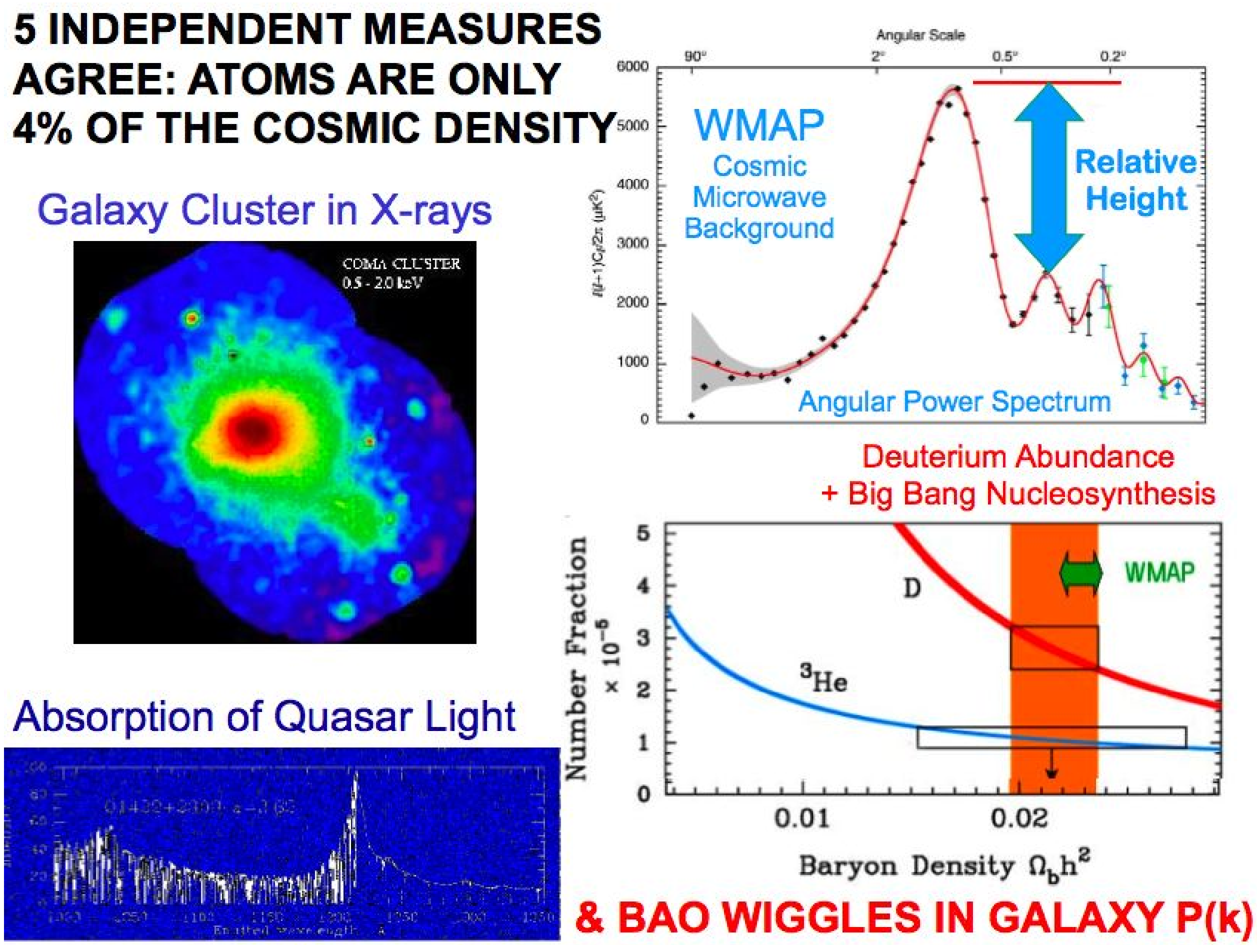
At the largest scales: the "Double-Dark" model





"DARK ENERGY" 69%(with repulsive gravitational interactions)
"MATTER" 31% (with usual attractive gravitational interactions- forms gravitational bound objects) and most of it is "DARK MATTER"

Our type of matter is only $< 5\%$.... Fig: from J. Primack 2010

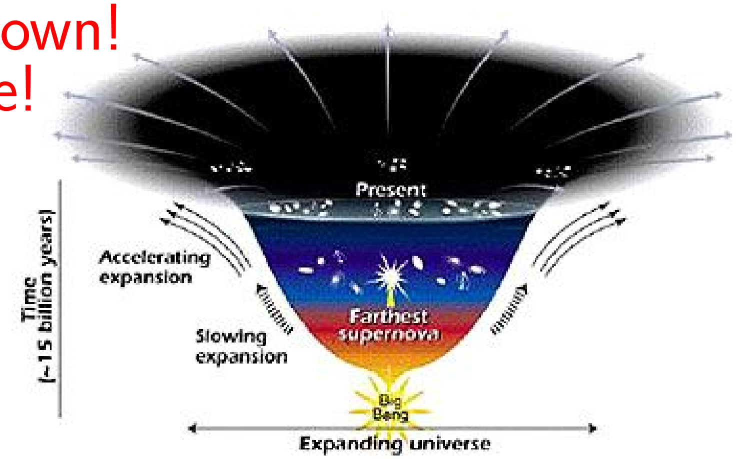


The content of the Universe is

- 69% Dark Energy
- 26% Dark Matter
- 5% nuclei, atoms- our type of matter [the ultimate Copernican Revolution!]
- 10^{-5} radiation [dominated by the Cosmic Microwave Background]

95% of the content of the Universe is unknown!
Lots of fascinating work remains to be done!

We may turn out to be the first humans
to know what the Universe consists of,
and what its fate will be!



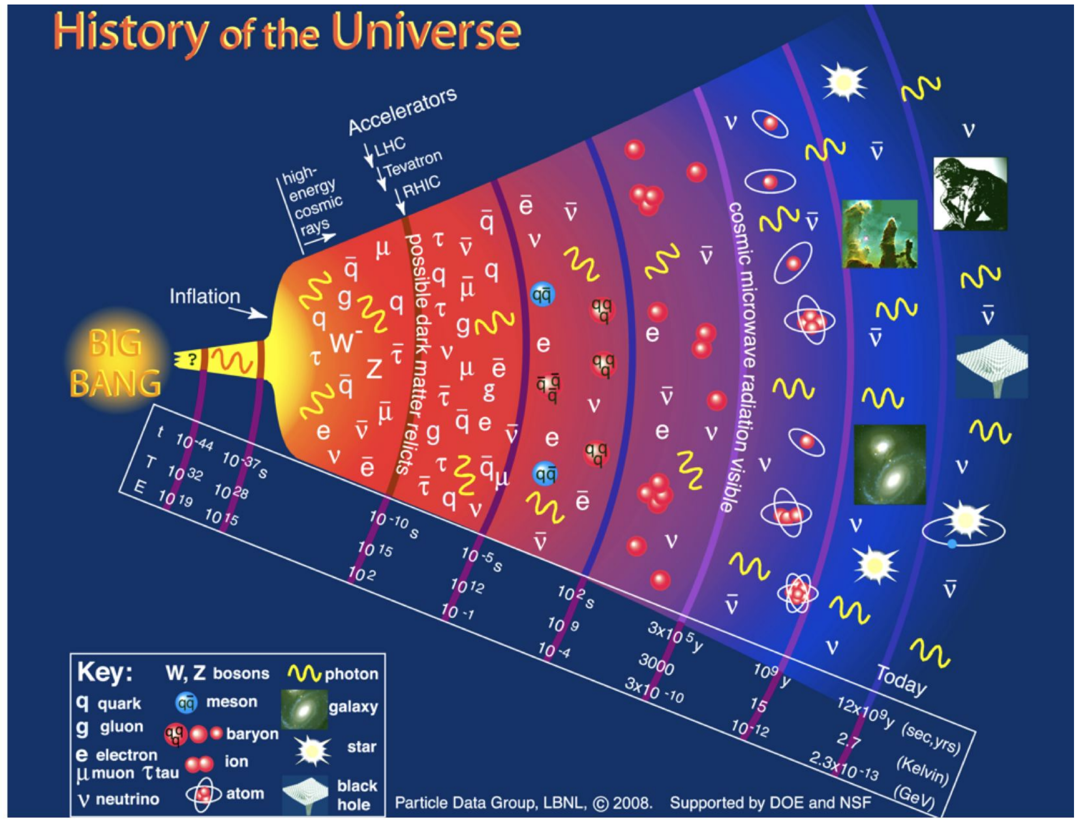
All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically (so T decreases inversely to the size of the Universe)

Earliest data (D, ^{4}He and ^{7}Li):
BBN (Big-Bang Nucleosynthesis)
t$\simeq$3-20min T$\simeq$MeV (blue line)

Radiation domination to Matter domination
t$\simeq$100kyr T$\simeq$3 eV

CMB emitted (atoms form)
(Cosmic Microwave Background)
t$\simeq$380kyr T$\simeq$eV

Now (Planck + other)
t=13.798$\pm$ 0.037$\times 10^9$ys



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What we know about dark matter

After 80 years, what we know about DM:

- **1- Has attractive gravitational interactions and is stable (or has a lifetime $>> t_U$)**

  We have no evidence that DM has any other interaction but gravity. Could departures from the law of gravity itself explain the data instead of DM?

  Modified Newtonian Dynamics: MOND (Mordehai Milgrom,1983) at very small accelerations $a < a_0 \simeq 10^{-8}$cm/s^2.

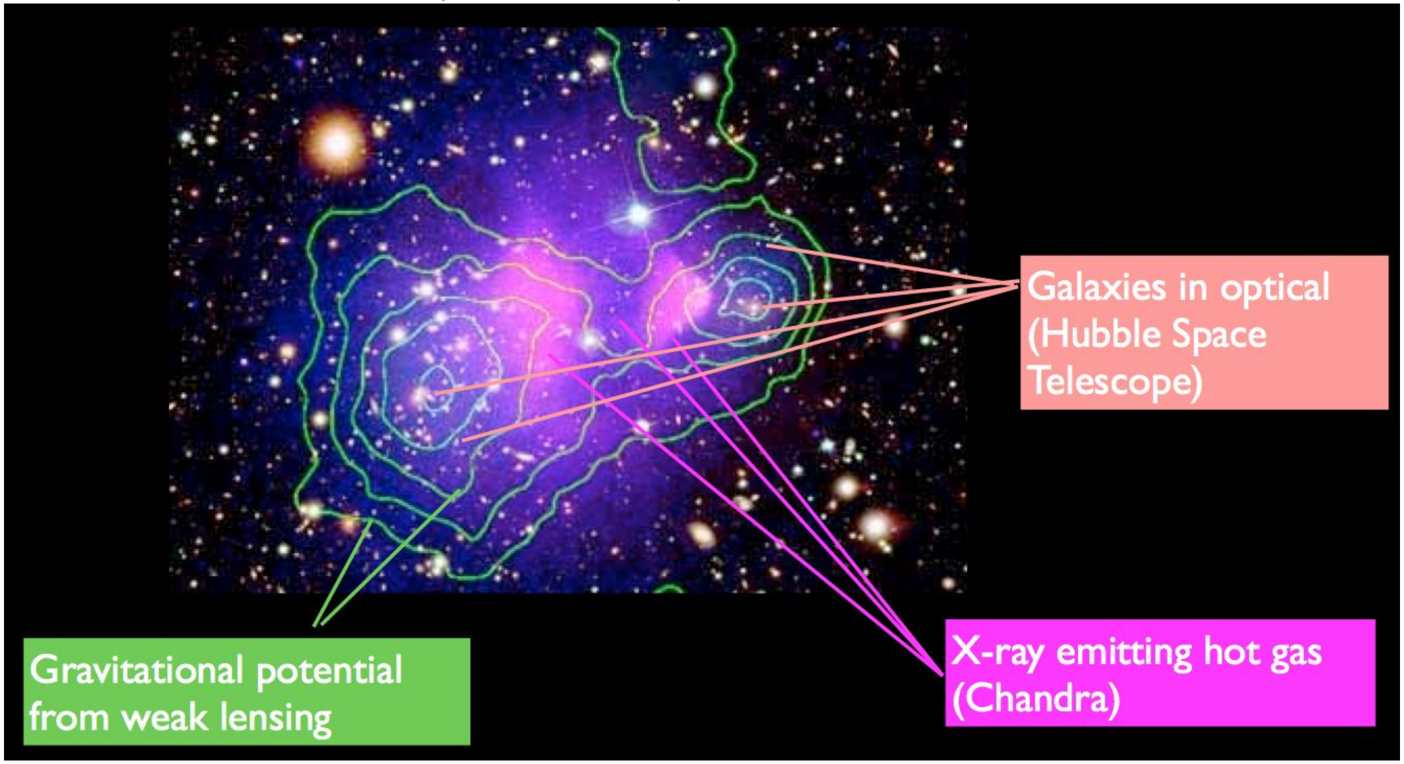
  $$F_{Gravity} = \frac{GMm}{r^2} = ma\frac{a}{a_0} = \frac{mv^4}{a_0 r^2} \Rightarrow v = \text{constant independent of } r$$

  We used the centripetal acceleration $a = \dfrac{v^2}{r}$

- **2-MOND and covariant extensions with only visible matter are not enough at scales larger than galactic** some kind of extra matter is necessary (so still DM!). Do no explain consistently all the data as DM does.

Evidence for DM and not just [MOND+ visible matter]

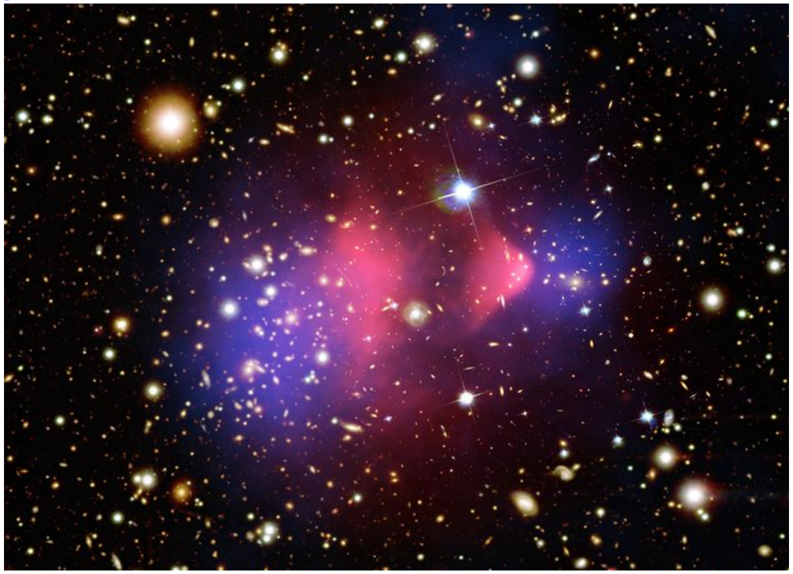
"Bullet Cluster"- 2004 (Fig from Gondolo)



Baryons are at the center but gravitational potential has two lateral wells

Evidence for DM and not [MOND+ only visible matter]

"Bullet Cluster"- 2004



Two galaxies collided and passed through each other leaving behind the visible (interacting) matter (hot gas seen by Chandra in X-rays -pink) which is not where most of the mass of the cluster (seen via gravitational lensing-blue) is. MOND with only visible matter cannot explain this system: needs 2-3×more matter - i.e. some form of Dark Matter(Dark Cluster Baryonic Matter?)

After 80 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- DM and not [MOND + only visible matter]**
- **3- DM is not observed to interact with light** i.e. it is either neutral or with a very small electromagnetic coupling such as:

  "Milli-Charged DM"

  or "electric or magnetic dipole DM", or"anapole DM"

  An important consequence of the small interaction of DM with light is that the DM cannot cool by radiating photons during galaxy formation.

- **4- The bulk of the DM must be nearly dissipationless, but part of it could be dissipative.** i.e. cannot cool by radiating as baryons do to form disks in the center of galaxies. Otherwise, their extended dark halos would not exist.

  But $< 10\%$ could be (radiating "dark photons" or other light dark particles): "Double Disk DM" (DDDM) Fan, Katz, Randall & Reece 1303.1521-1303.3271

After 80 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- DM and not [MOND + only visible matter]**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless, but ≤10% of it could be dissipative.**
- **5- The mass of the major component of the DM has only been constrained within some 80 orders of magnitude!**

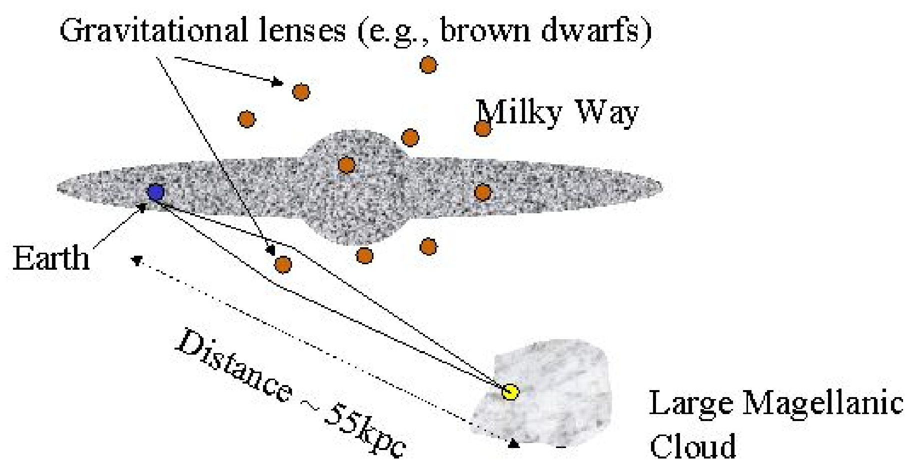
  10^{-31} GeV ≤ **mass** ≤ $2\times10^{-9}M_\odot$ =2 $\times10^{48}$GeV

Limits on MACHOS (Massive Astrophysical Compact Halo ObjectS):

Cannot be the bulk of the DM if **mass** $\geq 2 \times 10^{-9} M_{\odot} \simeq 2 \times 10^{48}$GeV

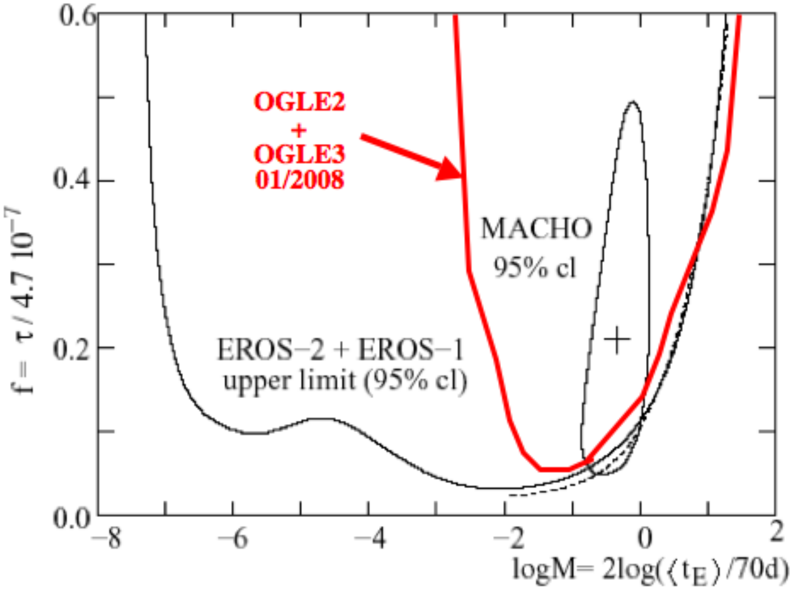
MACHO and EROS collaborations 2009 M. Moniez arXiv:0901.0985 [astro-ph.GA], Griest, Cieplak and Lehner 1307.5798

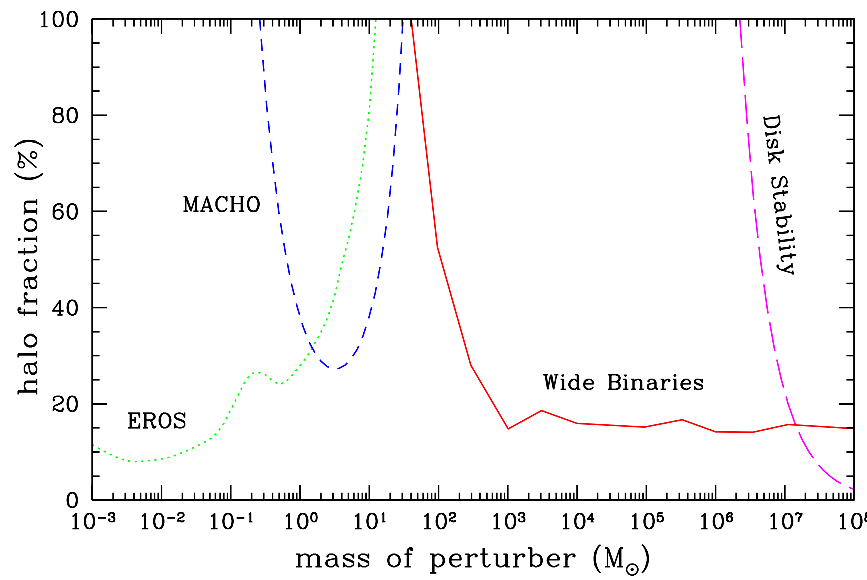
Searched for using gravitational "microlensing" of stars in satellite galaxies and the Galactic Center: multiple images are superposed producing an "anti-eclipse" (star becomes brighter for a while).



Dark Matter: not MACHOS

M. Moniez arXiv:0901.0985 [astro-ph.GA] Combined with older results for larger masses: Yoo, Chaname, Gould, ApJ**601**, 311, 2004 Griest, Cieplak and Lehner 1307.5798





2009 limit: $m > 10^{-7}$ M_{Sun} cannot be the bulk of the DM.
2013 limit: (using Kepler satellite data) $m > 2 \times 10^{-9}$ M_{Sun}.
Problem with MACHOS: how would they form? Could be Primordial Black Holes but limits constrain them to be only a fraction of the DM for almost any mass.

Dark Matter: could be Primordial Black Holes?

A PBH is a hypothetical type of black hole not form by the gravitational collapse of a large star but in an early phase transition Carr and Hawking, 1974

- $m_{PHB} > 10^{15}$g $= 6 \times 10^{38}$ GeV lighter would have evaporated by now

- $m_{PHB} > 10^{17}$g or evaporating BH would have been observed

-10^{17}g$< m_{PHB} < 10^{20}$g excluded by non-observation of "femtolensing" of Gamma-Ray Bursts.

- 10^{16}g$< m_{PHB} < 10^{22}$g excluded- its accretion would destroy neutron stars

Only narrow window remaining for PBH to make up all the DM,

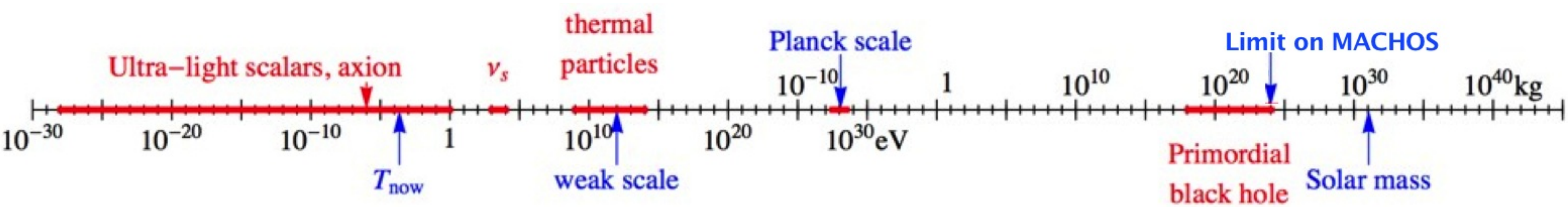
$$6 \times 10^{45} \text{ GeV to } 2 \times 10^{48} \text{ GeV (i.e. } 10^{22}\text{g to } 4 \times 10^{24}\text{g)}$$

is being challenged by less certain excluding arguments too.

- **5- The mass of the major component of the DM has only been constrained within some 80 orders of magnitude.**

$$10^{-31}\ \text{GeV} \leq \textbf{mass} \leq 2\times10^{-9}M_{\odot} = 2\times10^{48}\text{GeV}$$

Lower limit: "Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000 or
0.2-0.7×10^{-6} GeV $\leq$ **mass** for particles which reached equilibrium - depending on boson-fermion and d.o.f. Tremaine-Gunn 1979; Madsen, astro-ph/0006074



The limits just presented, and the fact that particle candidates can have the right relic abundance to be the DM, constitute the only observational arguments we have in favor of DM elementary particles candidates.

After 80 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- DM and not [MOND + only visible matter]**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless, but ≤10% of it could be dissipative.**
- **5- Mass within 80 orders of magnitude.**
- **6- DM has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is huge**

Bullet cluster + non-sphericity of galaxy and cluster halos
$\boldsymbol{\sigma_{\mathrm{self}}/\mathrm{m}} \leq 1\ \mathrm{cm}^2/\mathrm{g} = 2\ \mathrm{barn/GeV} = 2\times10^{-24}\ \mathrm{cm}^2/\ \mathrm{GeV}$
by comparison e.g. ^{235}U-neutron capture cross section is a few barns!
Self Interacting DM (SIDM) just below limit

(Limit on σ_{self}/m ratio comes from requiring self-interaction mean free path $\lambda_{mfp} \simeq 1/n\sigma_{self} = m/\rho\sigma_{self}$ be long enough, $n = \rho/m$ is the DM number density)

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- **5- Mass within 80 orders of magnitude.**
- **6- DM has been mostly assumed to be collisionless, but huge self interaction upper limit** $\sigma_{\rm self}/{\rm m} \leq$ **2 barn/GeV**
- **7- The bulk of the DM is Cold or Warm, thus particle DM requires physics beyond the SM** (Standard Model of Elementary Particles)

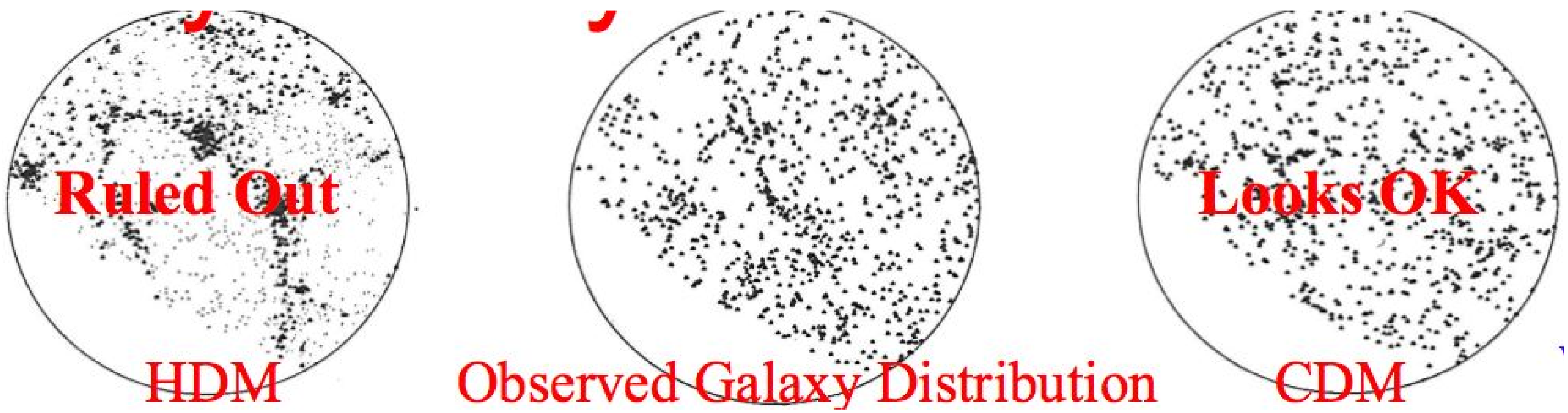
Dark Matter is "Cold" or "Warm"

Dark Matter is classified as "HOT" or "WARM" of "COLD" if it is

RELATIVISTIC (moves with c), SEMI-RELATIVISTIC or NON-RELATIVISTIC

at the moment dwarf galaxy core size structures start to form (when $T \sim 1keV$).

We know since the 1980's that these structures (or smaller ones) form first and structure cannot form with relativistic matter.



Dark Matter is "Cold" or "Warm"

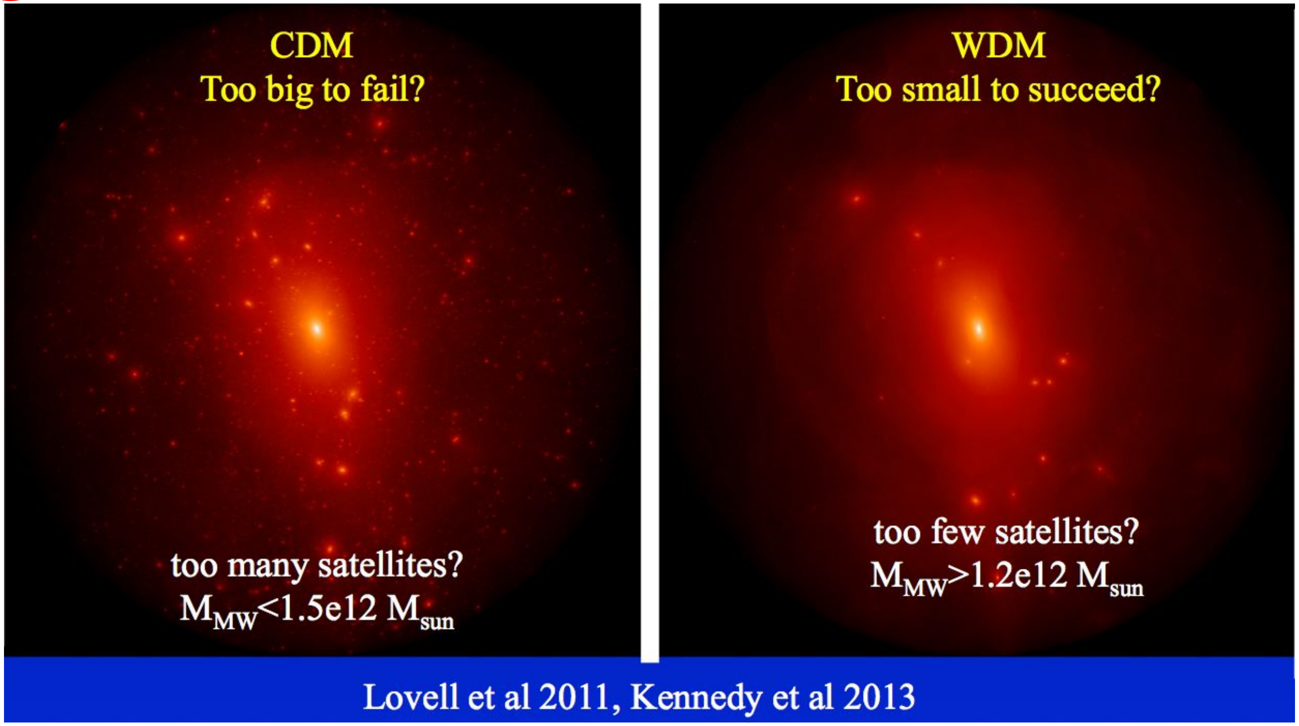
Both work well at scales larger than dwarf galaxies.

The differences are at smaller scales where observations and their interpretation are still not conclusive.

With WDM only structures of dwarf-galaxy cores size and larger survive.

With CDM structures much smaller than galaxy size survive. Galaxies form "bottom-up", by coalescence of smaller structures. Some of the small structures remain in the larger ones (many DM mini-haloes within galactic haloes).

Too-Big-to-Fail or Too-Small-to-Succeed? Fig. from Julio Navarro



Estimates of the Milky Way mass M_{MW} allow for both! But CDM TBTF problem also in Andromeda and the local group? Dwarf Galaxies cored instead of cuspy? Solution could be in the addition of baryons (gas, stars) or WDM of Self-interactingDM?

"Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales

Fig: from Tegmark ("Standard model" with ΛCDM: with Cold DM)

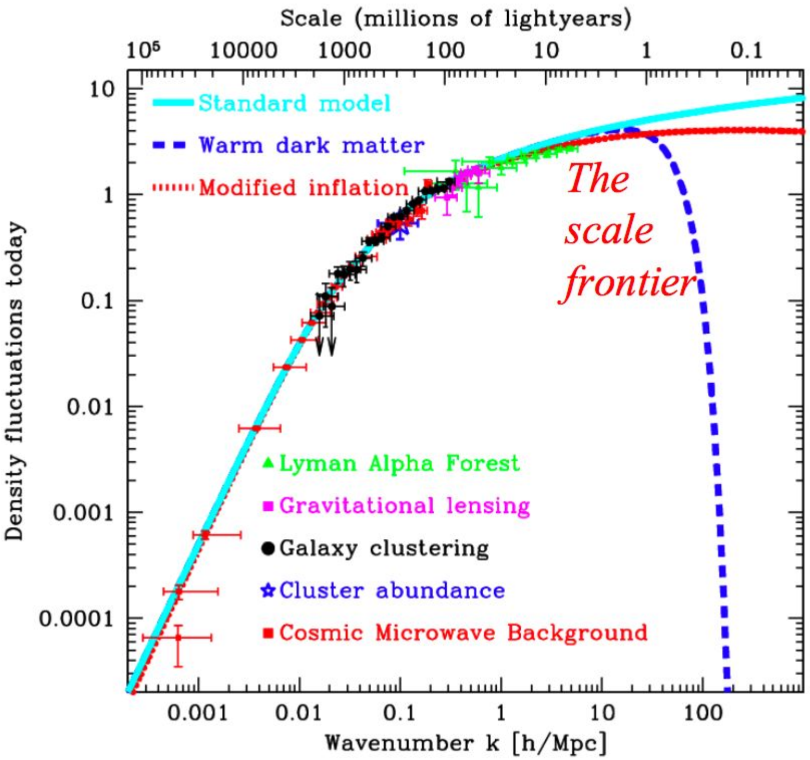
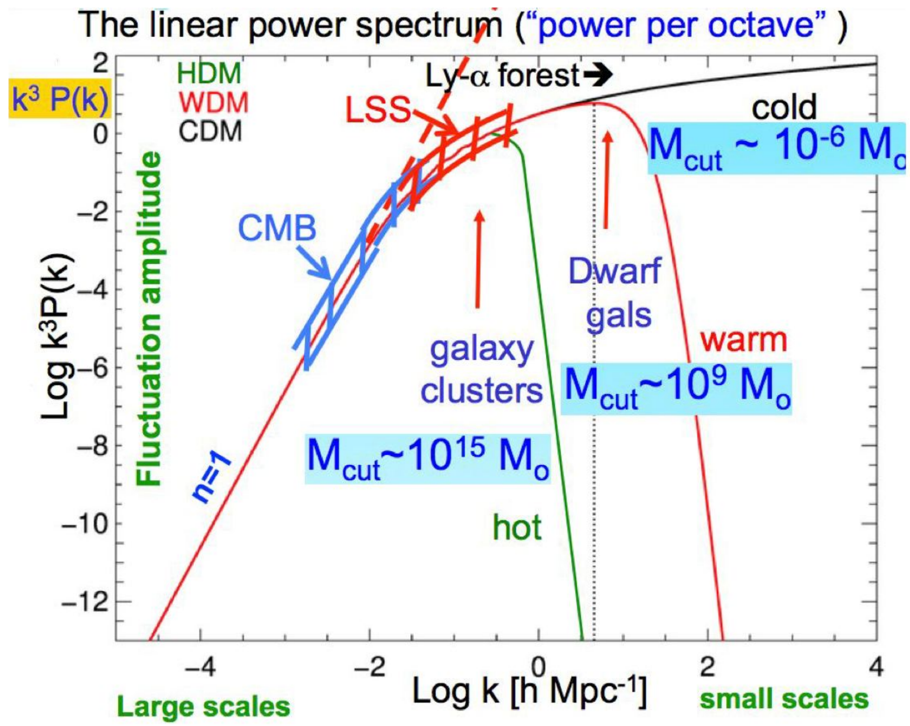


Fig: from Carlos Frenk



No CDM or WDM particle candidate in the SM!

In the SM only **neutrinos** are part of the DM- the are light m< 10^{-1} eV and in equilibrium until BBN, $T \simeq 1$ MeV thus they are **Hot DM (HDM)**

But many in extensions of the SM!

Warm dark matter (WDM):

- sterile neutrino, gravitino, non-thermal WIMPs...

Cold dark matter (CDM):

- WIMPs, axions, gravitinos, WIMPZILLAs, solitons (Q-balls) and many more...

Instead of "The Fifty Shades of Gray" we have here "The 500 shades of dark"...

(WIMPs, Weakly Interacting Massive Particles
but wimp = a weak, cowardly, or ineffectual person *(Merriam-Webster Dictionary)*)

Particle DM requires new physics beyond the SM!

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- **7- The bulk of the DM is Cold or Warm, thus particle DM requires physics beyond the SM**
- **8- Most DM candidates are relics from the pre-BBN era, from which we have no data.** The computation of the relic abundance and velocity distribution of particle DM candidates produced before $T \simeq 4$ MeV depends on assumptions made regarding the thermal history of the Universe.

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Particle candidates and how we search for them

Two examples of many: WIMPs and sterile neutrinos

WIMPs require new physics at the EW scale

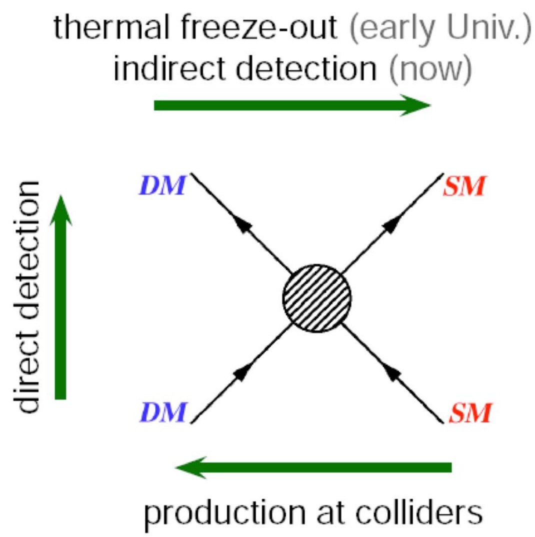
WIMPs: particles with GeV to 100 TeV mass and with weak scale interactions.

New physics is expected at O(TeV) scale because of problems in the SM (totally independently of the DM issue) Usual Beyond SM models such as Supersymmetry, Technicolor, large extra spatial dimensions (possibly warped), "Little Higgs" model...

But the new physics to explain DM may be different....,

e.g. many new models trying to account for "hints" of DM in direct and indirect DM searches ("boutique models") Made to be DM-not to solve any SM problem (attest to the ingenuity of theorists to explain everything)... may or not provide novel signatures for the LHC

WIMP DM searches:



- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.

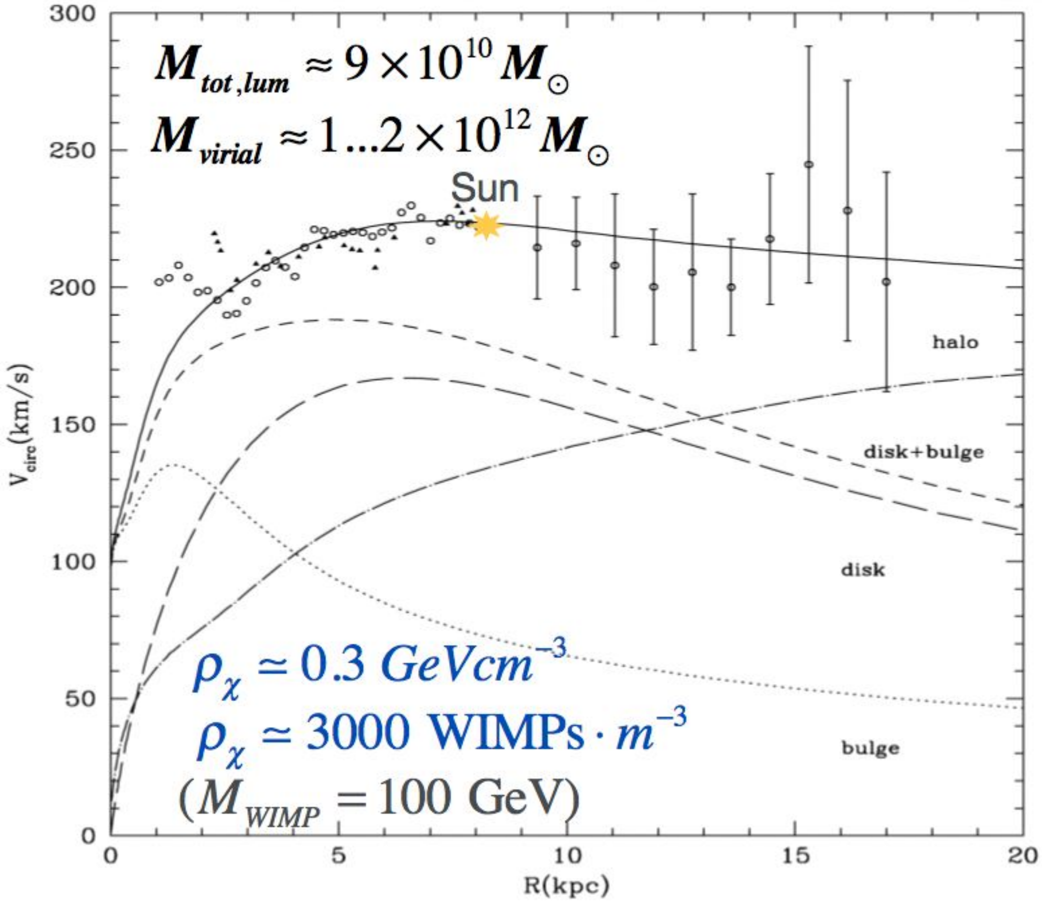
- Indirect Detection- looks for WIMP annihilation (or decay) products.

- At colliders (the LHC) as missing transverse energy, mono-jet or mono-photon events

All three are independent and complementary to each other!

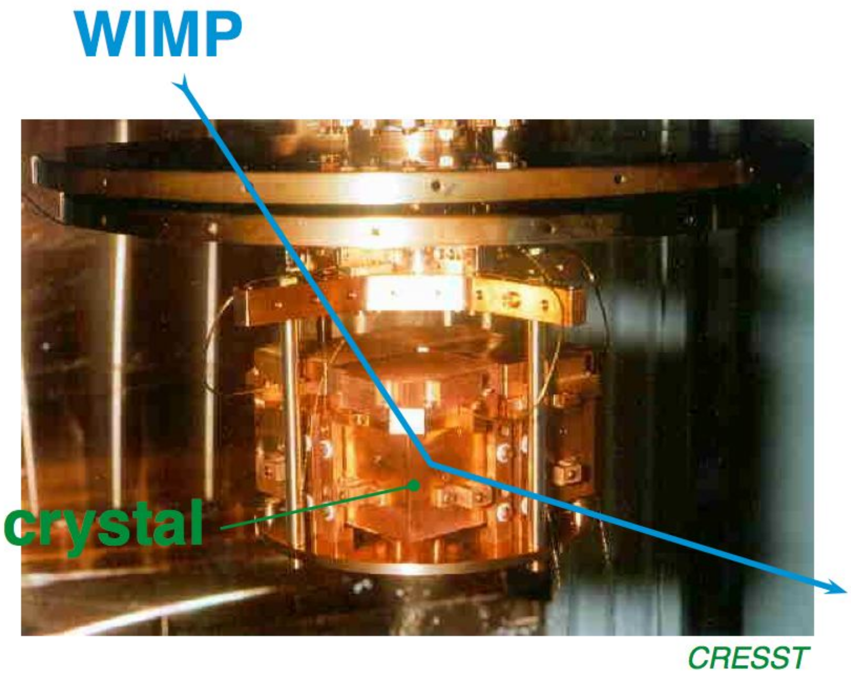
Milky Way's Dark Halo

Fig. from L.Baudis; Klypin, Zhao and Somerville 2002

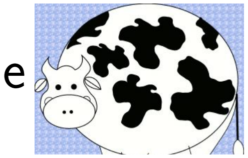


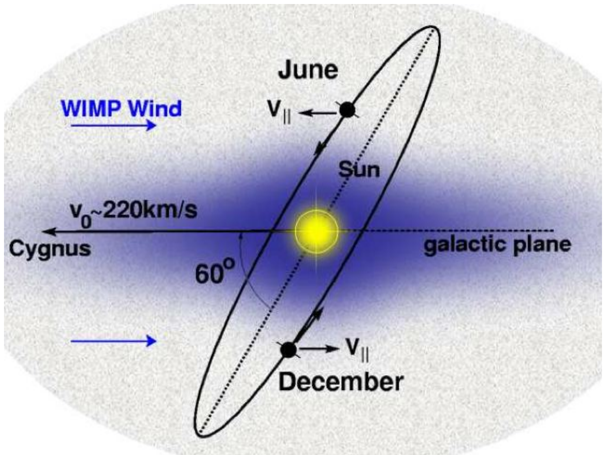
10^7(GeV/m_χ) WIMP's passing through us per cm^2 per second!

Direct DM Searches:

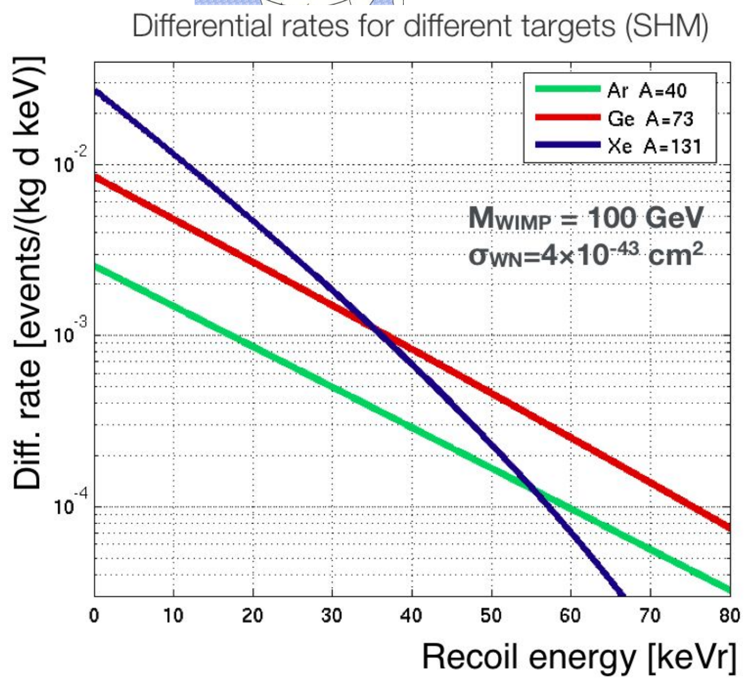


- WIMP interacts with a nucleus in the detector and it recoils
- Small $E_{Recoil} \leq 50\text{keV}(m/100\ \text{GeV})$
- Rate: depends on WIMP mass, cross section, dark halo model, nuclear form factors... typical... < 1 event/ 100 kg/day requires constant fight against backgrounds, must be underground to shield from cosmic rays.
- Annual rate modulation due to the rotation of the Earth around the Sun (few % effect)
- Most searches are non-directional but some in development are (try to measure the recoil direction)

Standard Halo Model (SHM) The  of halo models

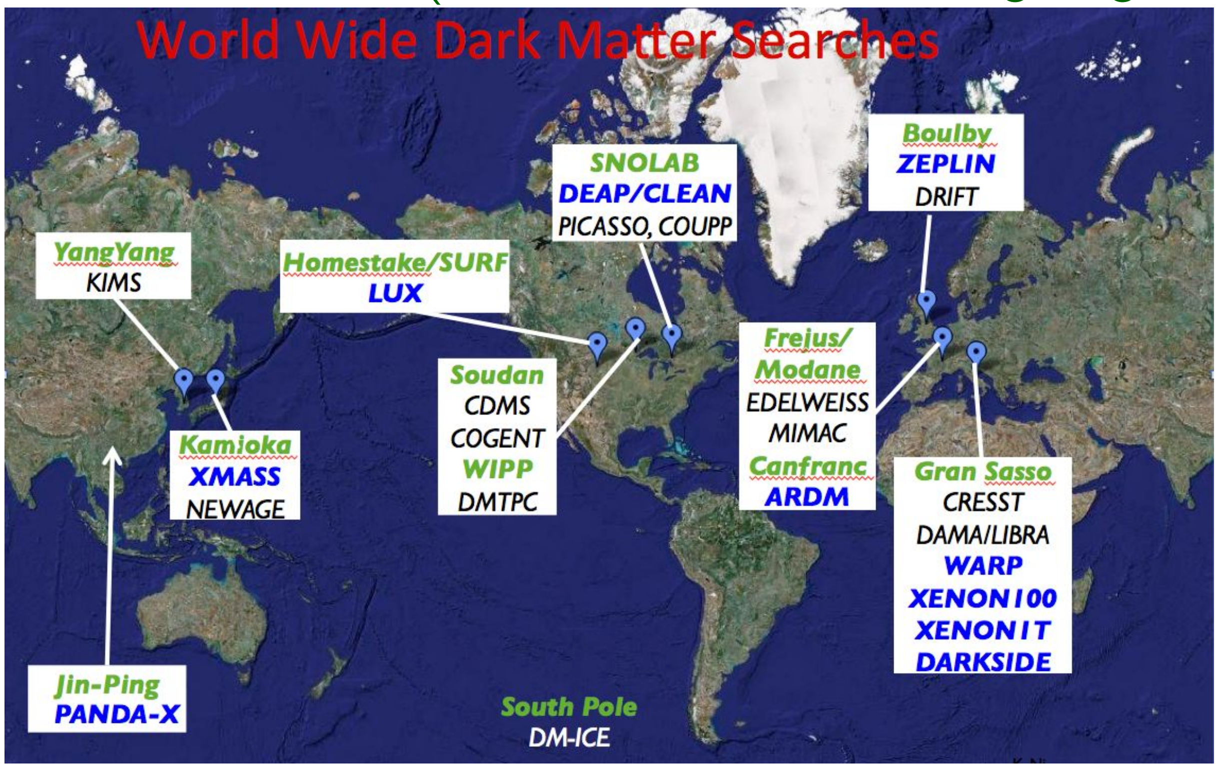


- $\rho_{SHM} = 0.3^{+0.2}_{-0.1}$ GeV/cm^3
- $f(v,t)$: Maxwellian $\vec{v}$ distribution
at rest with the Galaxy $v_\odot \simeq$220km/s
(190 to 320km/s), $v_{esc} \simeq$500-650km/s

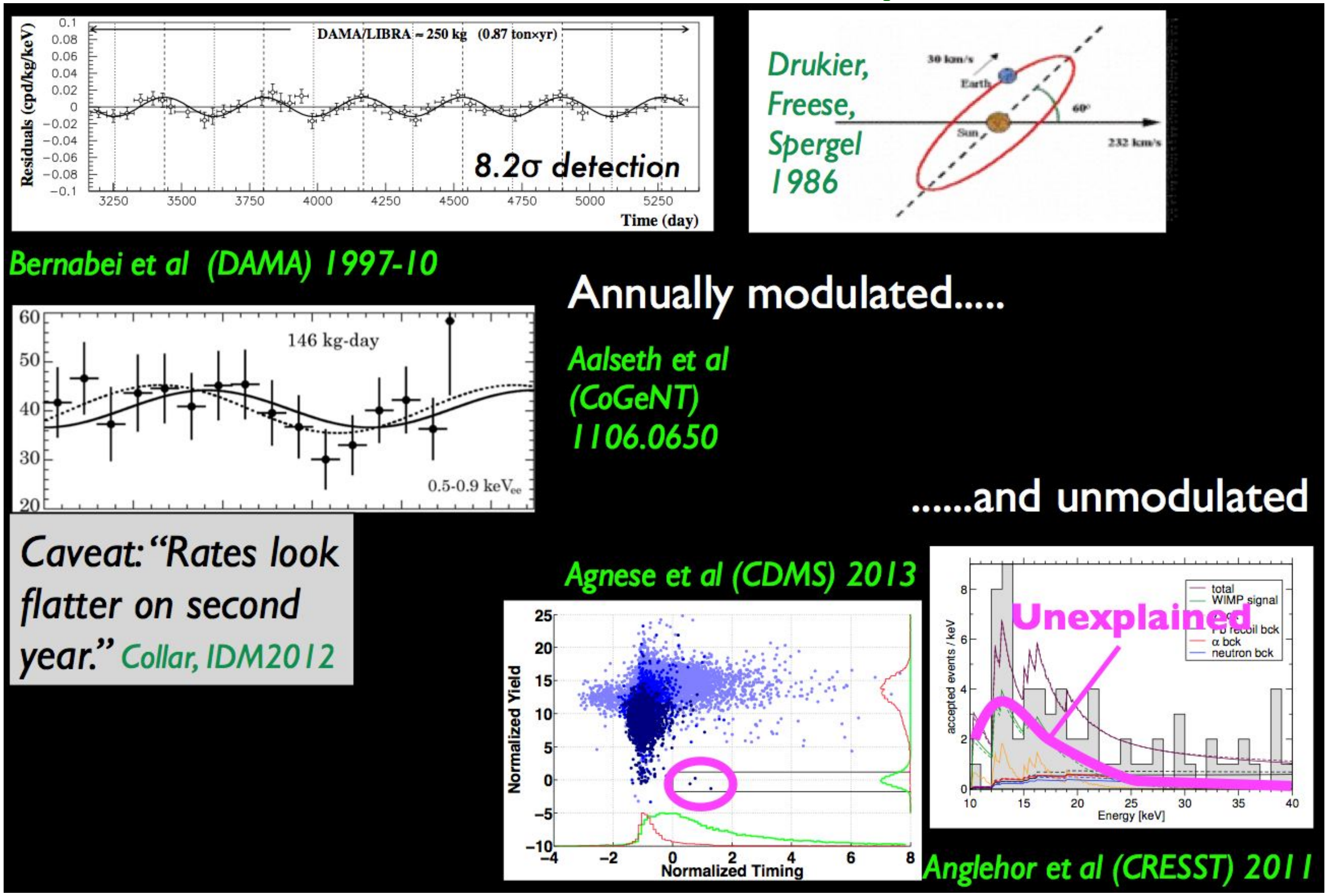


Earth rotation causes an annual rate modulation (Drukier, Freese, Spergel 1986) Local ρ, v, modulation phase/amplitude change if Earth is within a DM clump or stream or a "Dark Disk", or with anisotropies e.g due to Gravitational Focussing by the Sun, or by debris flows...

Direct DM Searches: Many experiments! in mines (Soudan, Boulby, Kamioka) or mountain tunnels (Gran Sasso, Modane, YangYang, Jin-Ping)

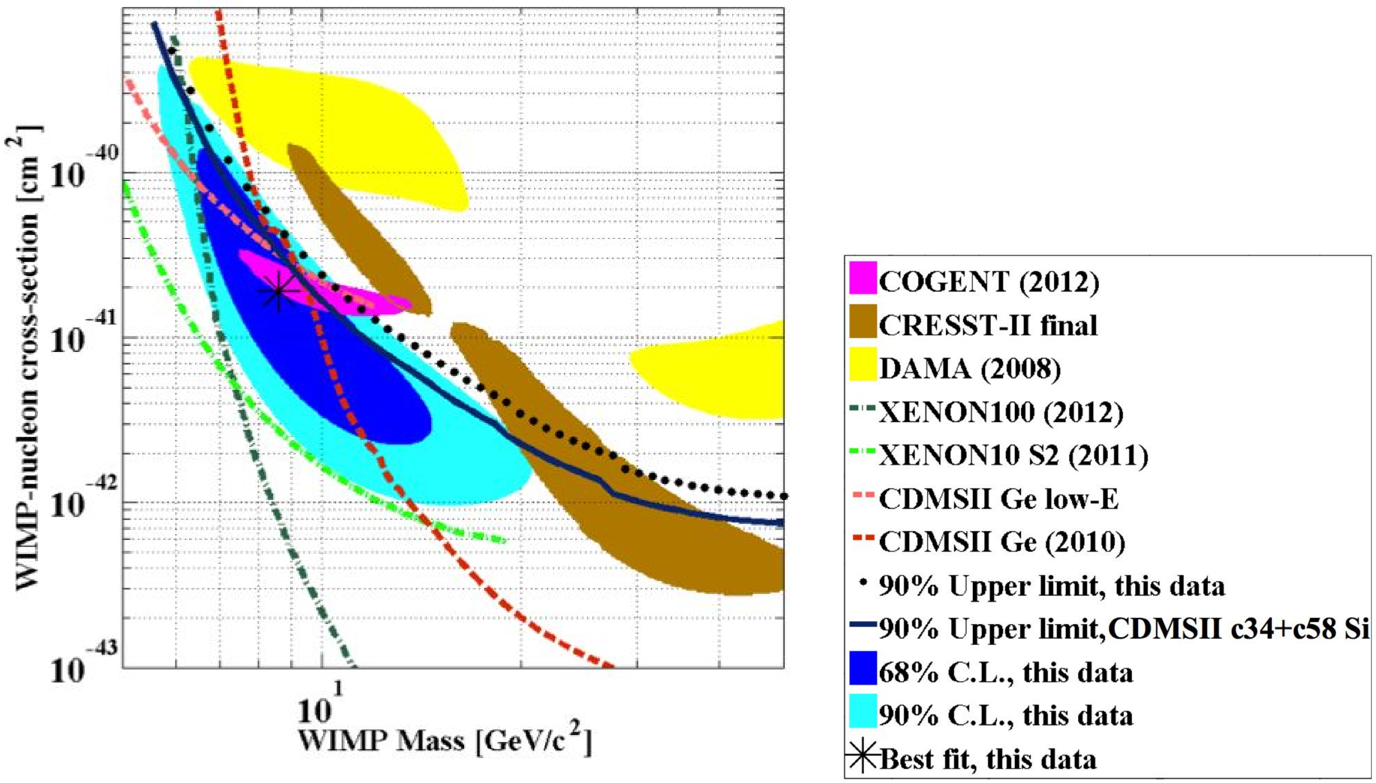


DM hints in four direct detection experiments (Fig. from P. Gondolo)



All point to "Light WIMP's" with mass of few to 10 GeV?

As of 2013- for a particular particle candidate and the Standard Halo Model



All point to "Light WIMP's" with mass of few to 10 GeV?

However:

- some data were not confirmed by the further data of the same collaboration (CRESST)
- some lost significance with more data (CoGeNT)
- no particle candidate of many tried seems to make compatible any two hints with all upper limits of direct searches with negative results. One can make one hint at a time compatible with all negative results, but this is not enough.

Extraordinary claims require extraordinary evidence! So several experiments must find the same DM candidate to believe it is there.

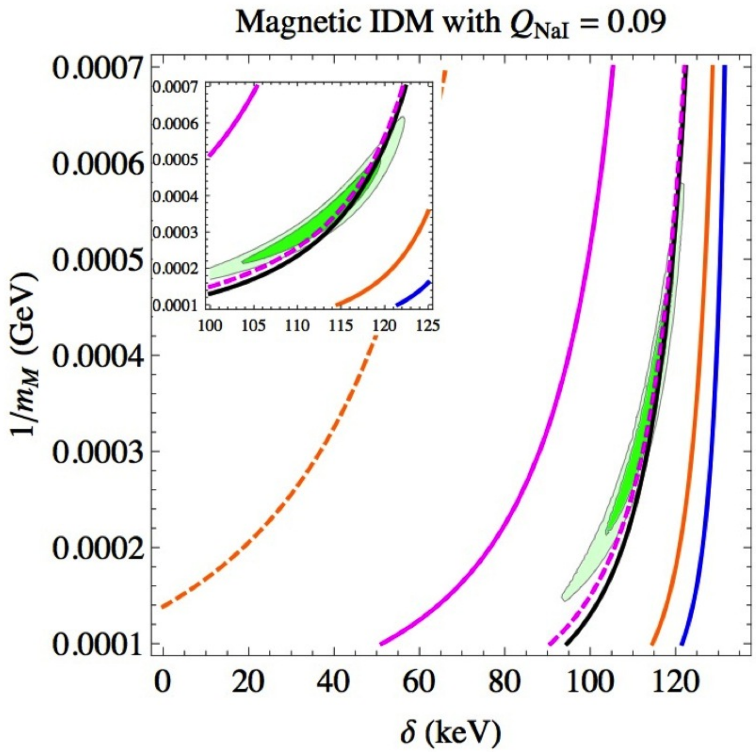
Situation is confusing, many uncertainties and possibilities and data changing all the time. Future data will clarify the situation.

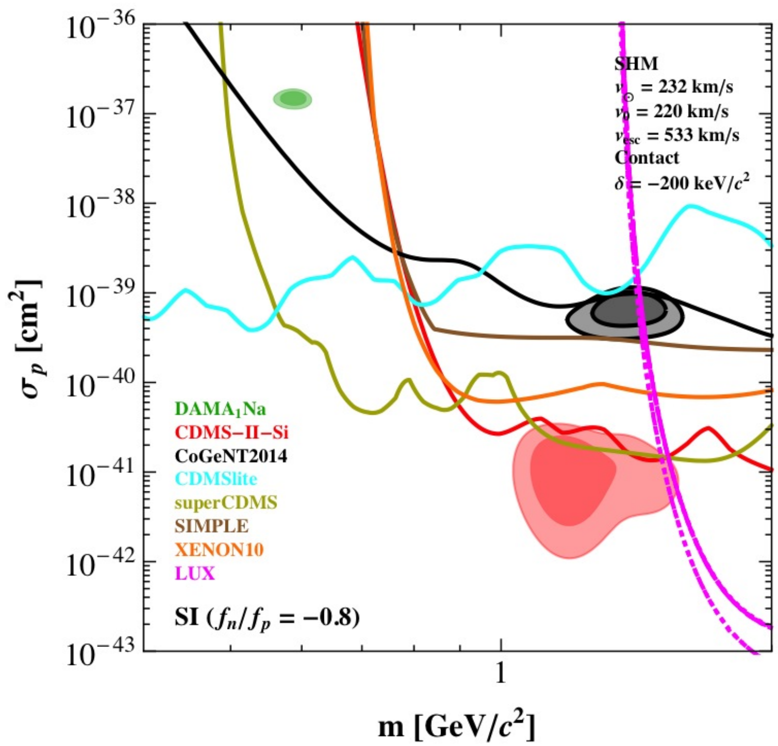
Either DAMA or CDMS-Si compatible with all limits?

Inelastic DM scatters to another state with a mass-difference $\delta = m_{final} - m_{initial}$

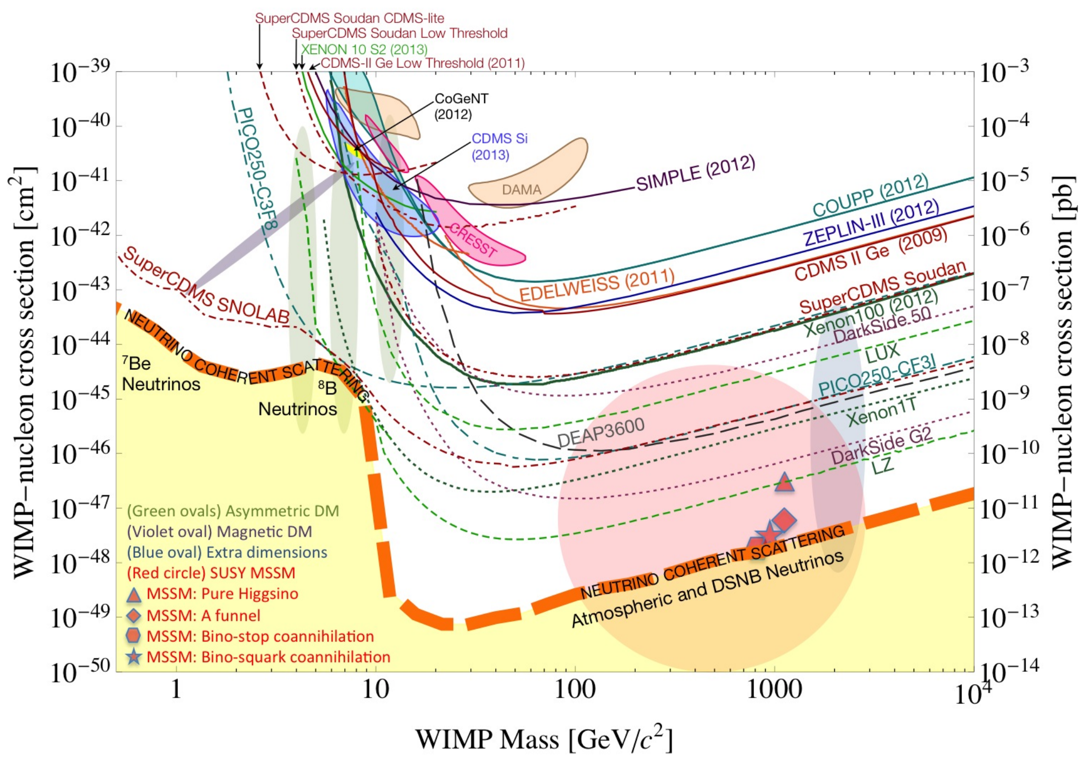
Left:DAMA, Magnetic IDM $m_{initial} = 58$GeV, $1/m_M = e\mu$ Barello, Chang, Newby 1409.0536

Right: CDMS-Si, $\delta = -200$keV Spin-Independent DM with $f_n/f_p = -0.8$ GG, Georgescu, Huh 1404.7484



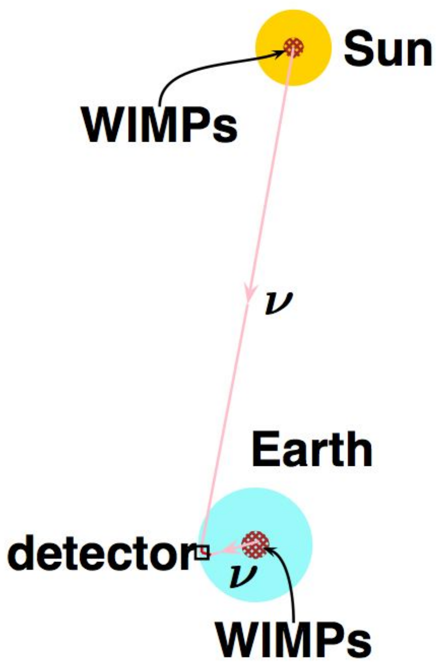


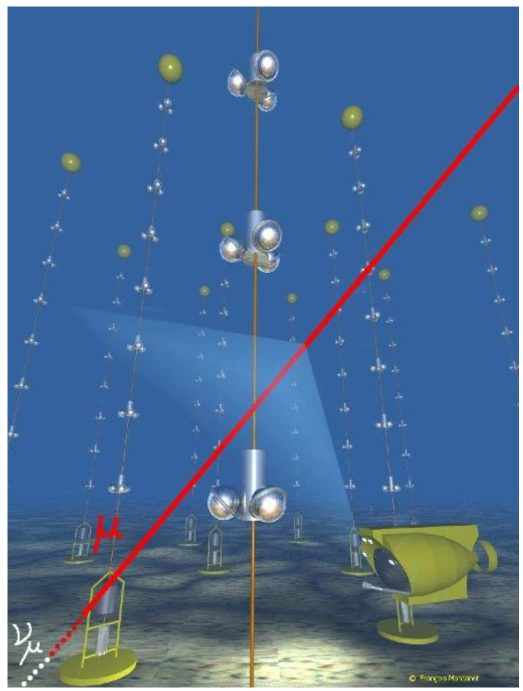
The future of Direct DM detection several ton-scale detectors will reach the irreducible background (“neutrino floor”) others extend to low masses



Indirect DM detection: neutrinos from the Sun and Earth

As the Sun and Earth move through the dark halo, WIMPs scatter, lose energy and become gravitationally bound. When they annihilate only neutrinos escape from the Sun or the center of the Earth and reach **Neutrino Telescopes**





Antares (Mediterranian)

Ice-Cube(Antarctica)

Indirect DM detection: photons and antiparticles

Main detectors: PAMELA, AMS, Fermi ST, HESS, VERITAS, CANGAROO, MAGIC

Look for an excess of γ, e^+, $\bar{p}$ over expected and a bump at $E \sim m$

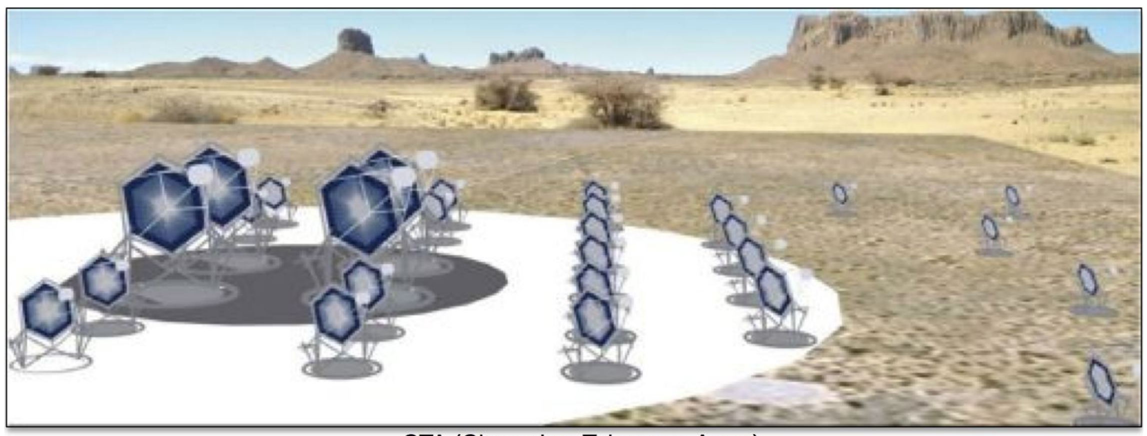
PAMELA

AMS

Fermi-LAT (Fermi Large Area Telescope)

H.E.S.S. & H.E.S.S.-2

In planning stage CTA



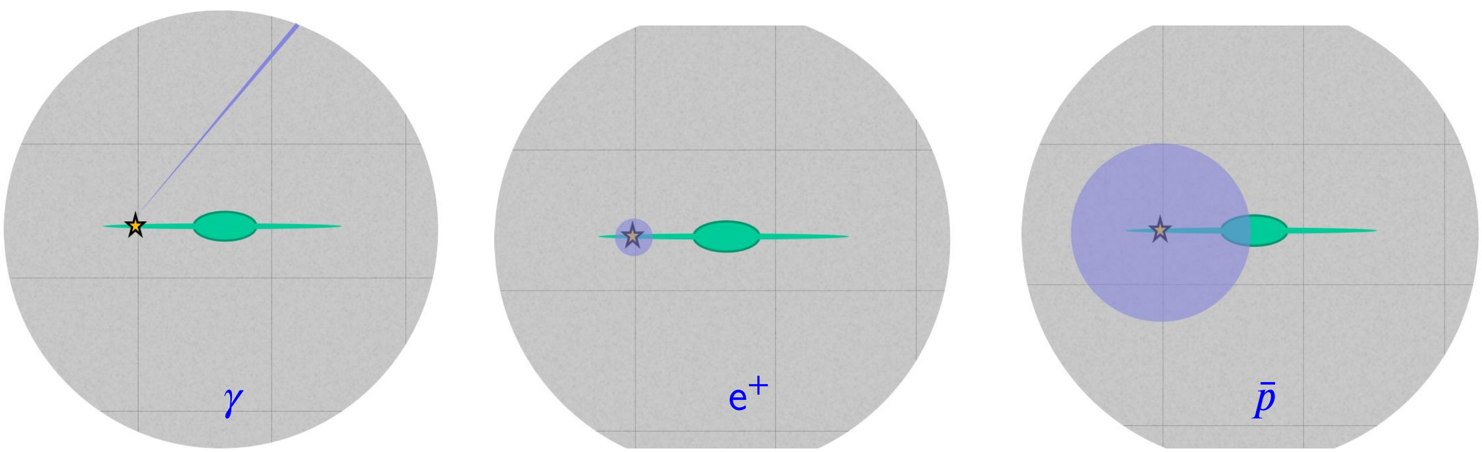
CTA (Cherenkov Telescope Array)

Propagation of γ and Anomalous Cosmic Rays e^+ $\bar{p}$

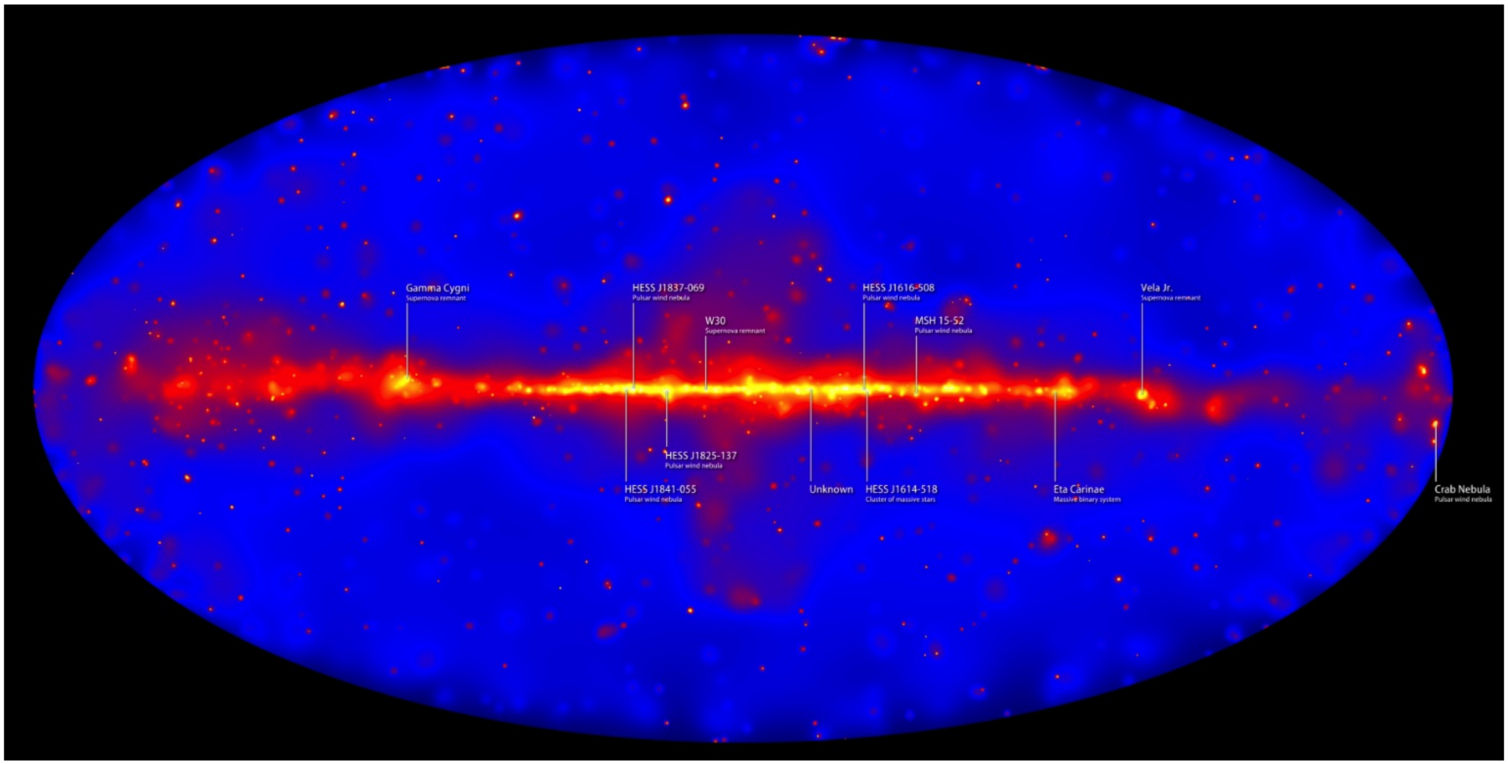
Photons (γ-rays) travel in straight line and are not absorbed (for $E < 100$ TeV) thus point to sources. More production where DM density is largest (e.g. the Galactic Center)

e^+,e^-: are deflected in the magnetic fields of the galaxy and rapidly (few kpc) loose energy through the emission of synchrotron radiation and Inverse Compton (IC) Scattering interactions with photons ($e_{High\ E} + \gamma_{Low\ E} \rightarrow e_{Low\ E} + \gamma_{High\ E}$). Come from nearby.

p, $\bar{p}$: come for further out than e, from a fraction of the size of the galaxy - suffer convecting mixing and spallation-



NASA's Fermi Telescope gamma-ray sky 6 years of data, 50GeV to 2TeV photons. Most energetic point sources indicated. Plane of the galaxy at the center. Notice the "Fermi Bubbles", first detected in 2010.

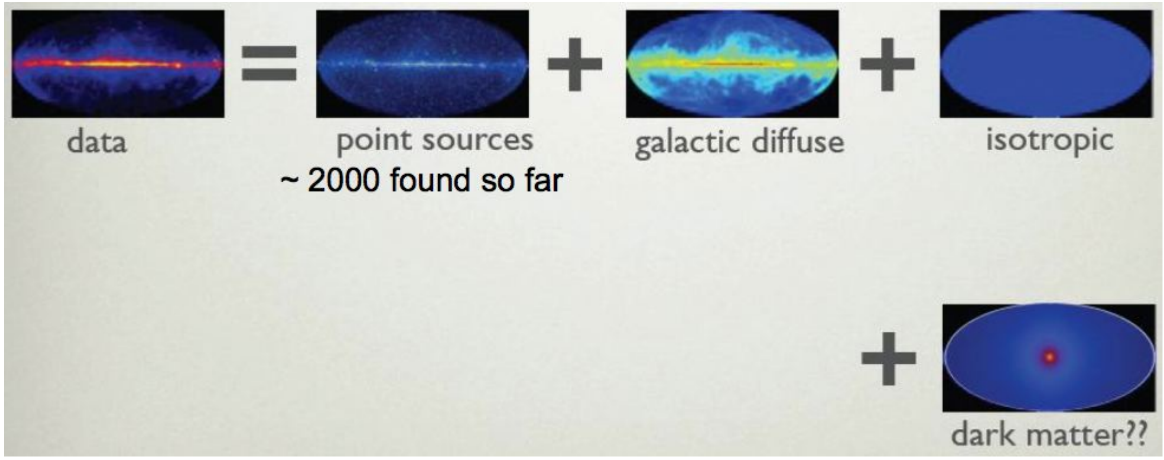


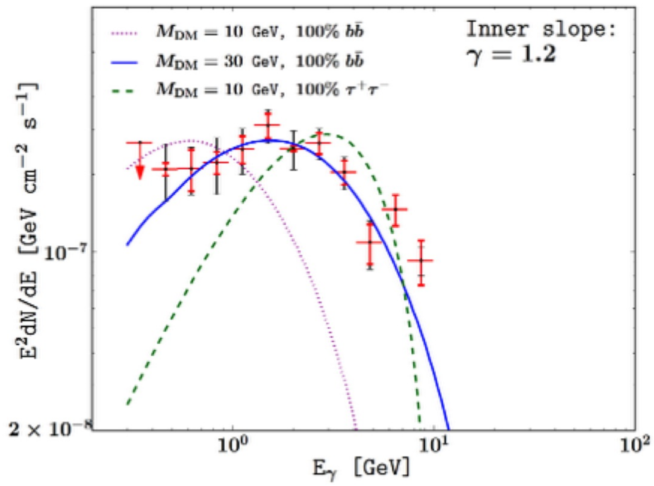
Graciela Gelmini-UCLA

GeV γ's from extended region at the Galactic Center and Inner Galaxy

Signals of 10-40 GeV mass Light WIMPs too?

(Hooper, Linden 1110.0006; D.Hooper 1201.1303; Abazajian & Kaplinghat 1207.6047, Hooper et al 1305.0830, Macias& Gordon, 2013, Dayland et al. 1402.6703)

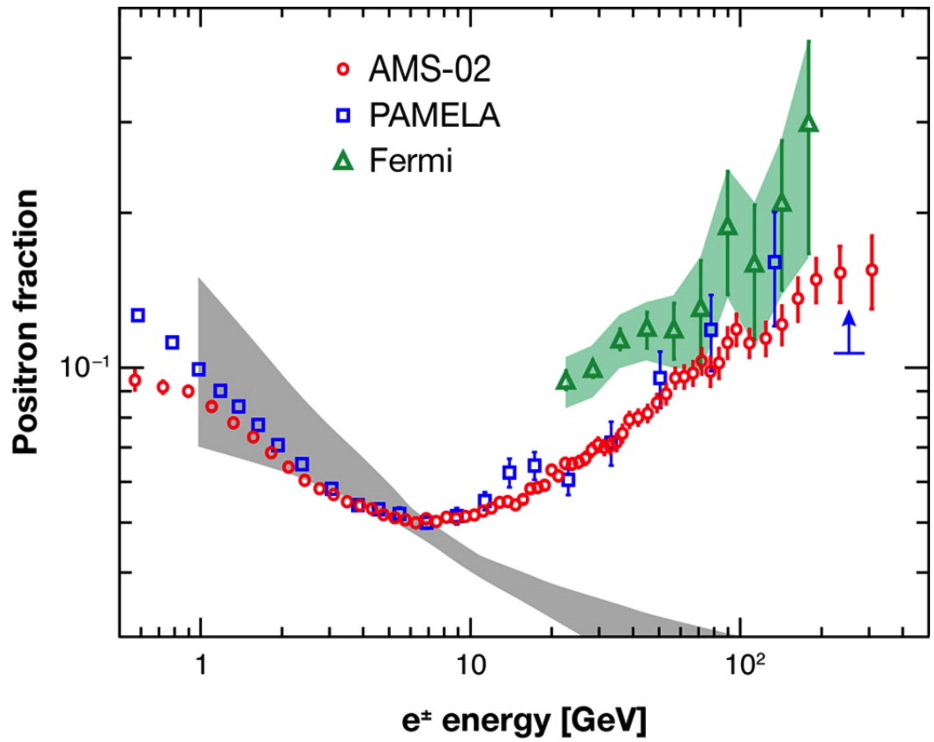




Extended spherically symmetric excess in GeV's gamma rays! Confirmed in several papers-

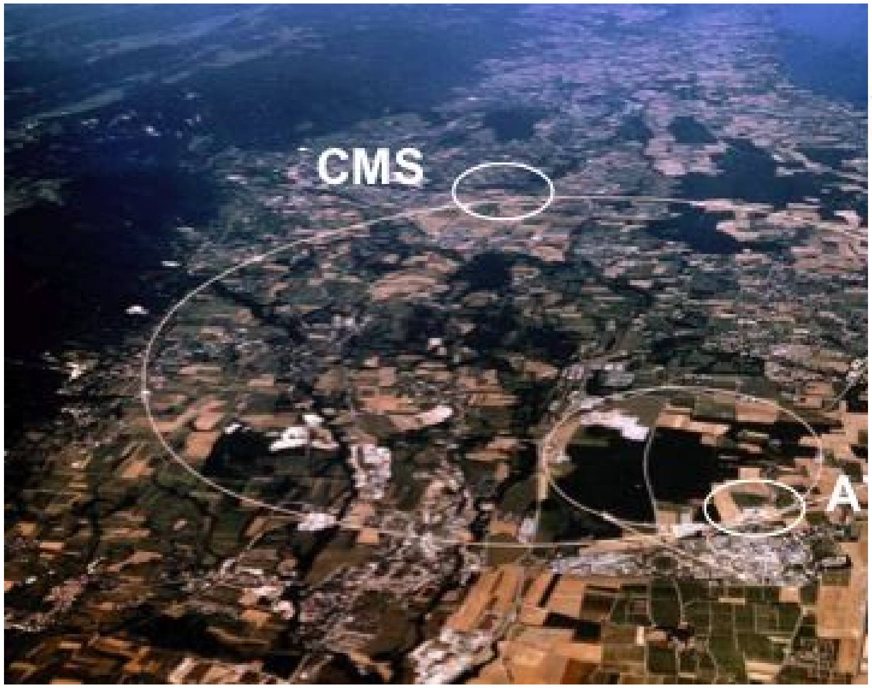
DM or millisecond pulsars? Still not clear

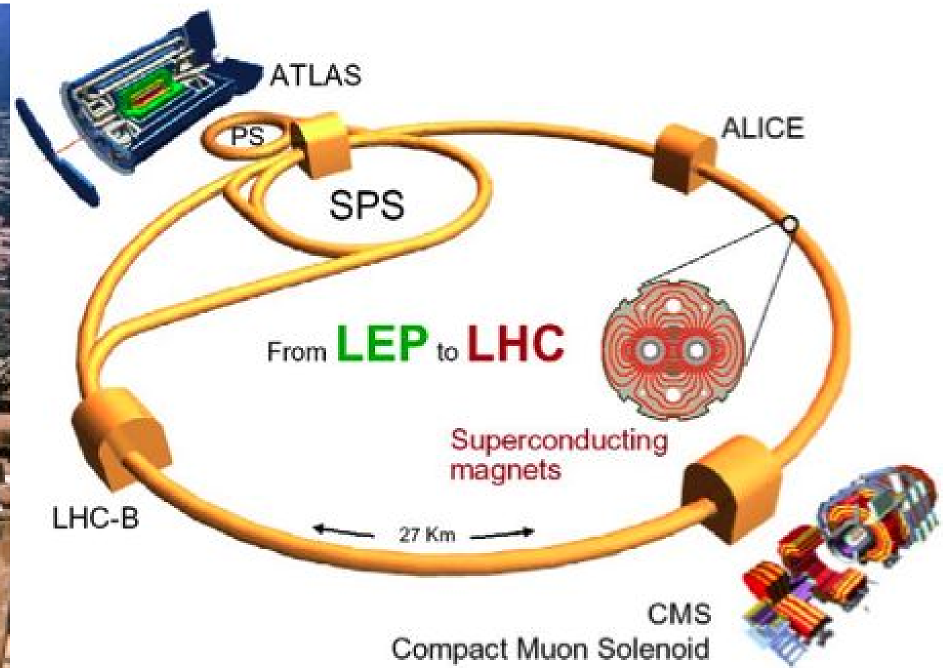
PAMELA e^+ excess 1 to 100 GeV In gray expected from cosmic rays
Announced in 2008 (earlier "HEAT excess") Confirmed by the Fermi Space Telescope-LAT and AMS (Alpha Magnetic Spectrometer) in (2013)



Either $m >$TeV "Leptophilic DM" (no $\bar{p}$ excess) or pulsars?

Large Hadron Collider at CERN



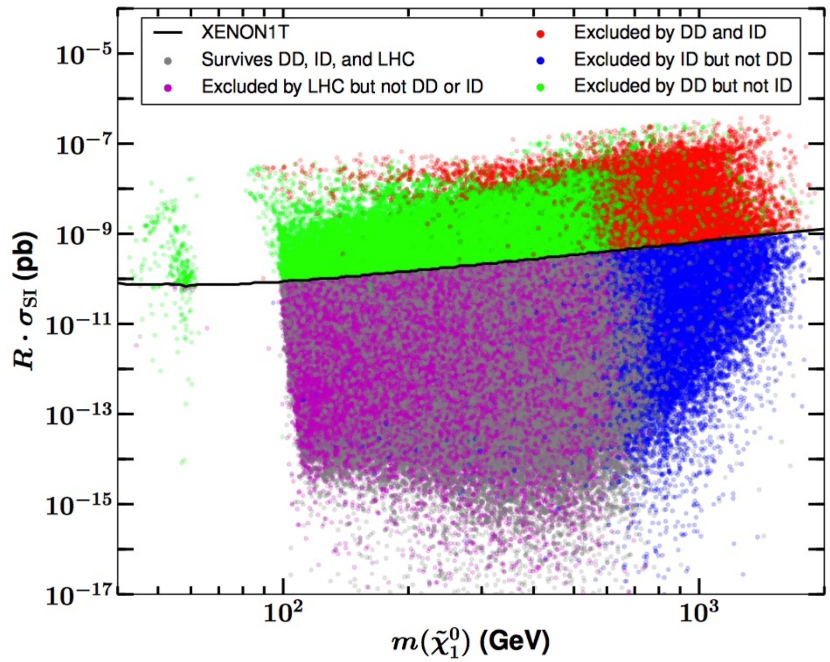


May find new physics Beyond the SM which will give a framework for DM candidates and may even find DM candidates of up to ~ 2 TeV in "missing energy" events.

Viable particle candidates- Complementarity of Searches

neutralino in the p(phenomenological) MSSM with 19 free parameters, for 50 GeV<m< 4 TeV

-Cahill-Rowley et al. 1405.6716



Excluded by: direct detection, indirect detection, direct and indirect detection, only LHC searches.

Gray regions will survive all searches in the forceable future.

Sterile Neutrino DM

The SM has 3 neutrinos with different "flavors", and they are MASSLESS

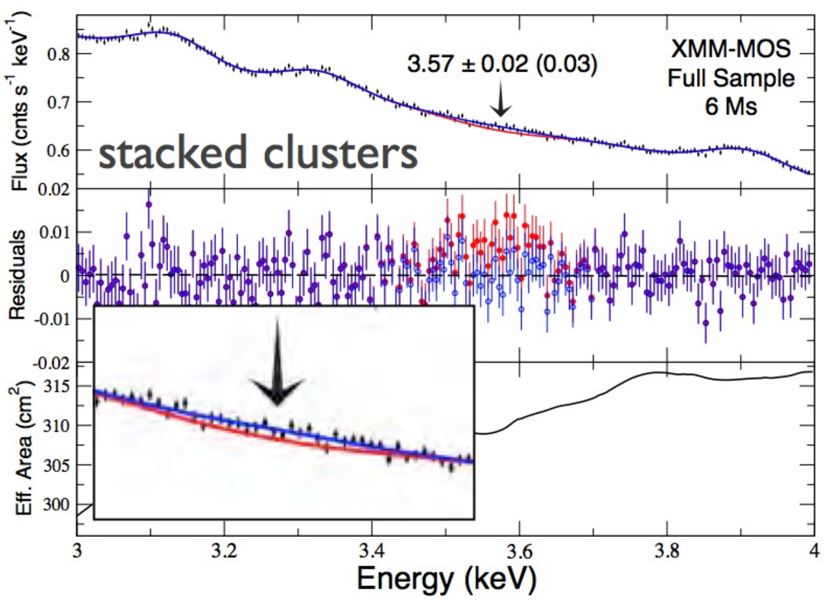
"Neutrino flavor oscillation": similar to beating of sound of two tones very close in pitch. In quantum mechanics energy E plays the role of the pitch in sound, and a small difference in E produce "beating" in the neutrino type.
For relativistic neutrinos $E = p + m^2/2p$ thus $|E_1 - E_2| \sim |m_1^2 - m_2^2| = \Delta m^2$.

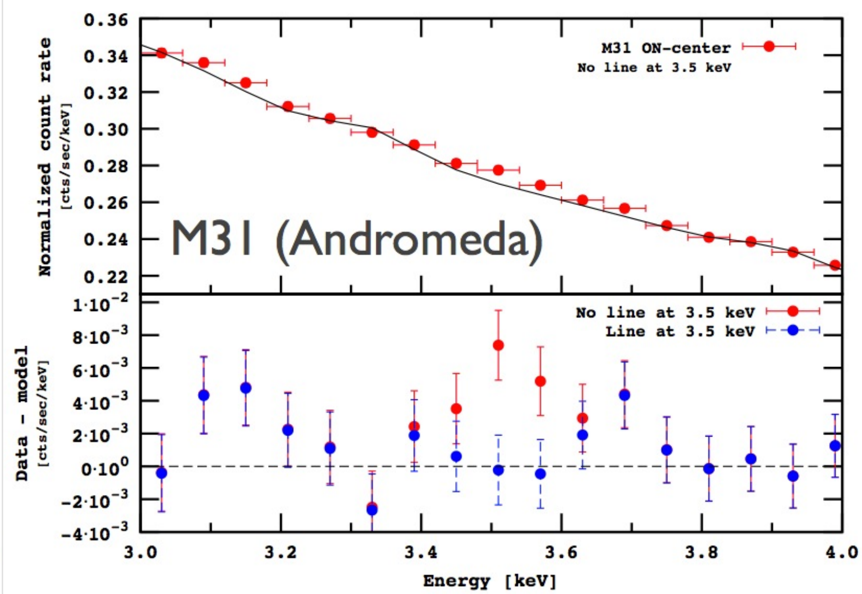
In neutrino oscillations we have measured 2 different Δm^2. Thus neutrinos HAVE MASS although small. Planck 2015 bound is $\Sigma m_\nu < 0.17$ eV (95%).

One way to obtain neutrino masses is to add to the SM new particles called "sterile neutrinos" ν_s. If one of these has mass $m_s \simeq$ few keV it could be WDM and it can decay into a SM neutrino ν and a photon γ with energy is $m_s/2$

If ν_s are the DM, $\nu_s \to \nu\gamma$ would produce a monochromatic X-ray line in galaxies and galaxy clusters. This line may have been seen!

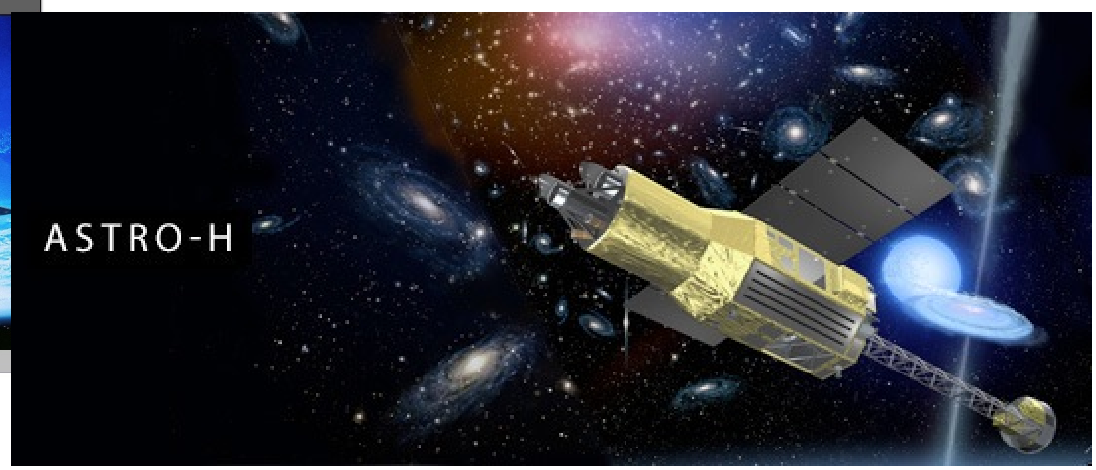
A 3.5 keV X ray line found in X-rays from 74 stacked Galaxy Clusters E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall, 1402.2301 and from the Andromeda galaxy and Perseus cluster A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse, 1402.4119. Could correspond to a 7 keV mass sterile neutrino!





They used the data of ESA's XMM-Newton ("X-ray Multi-Mirror") satellite, launched in 1999, which does not provide enough resolution of the line.

The ASTRO-H satellite of the Japan Aerospace Exploration Agency JAXA, in coll. with NASA and ESA, will be launched on Feb. 12 2016. It will allow to measure the profile of the line and prove/disprove that it is due to DM in 1 year!



To conclude

There is no compelling observational or experimental evidence in favor of any of our DM candidates. Only through experiments and observations we are going to elucidate the nature of the DM and the next decades will be a very exciting time for DM research, for searches at colliders and direct and indirect detection.

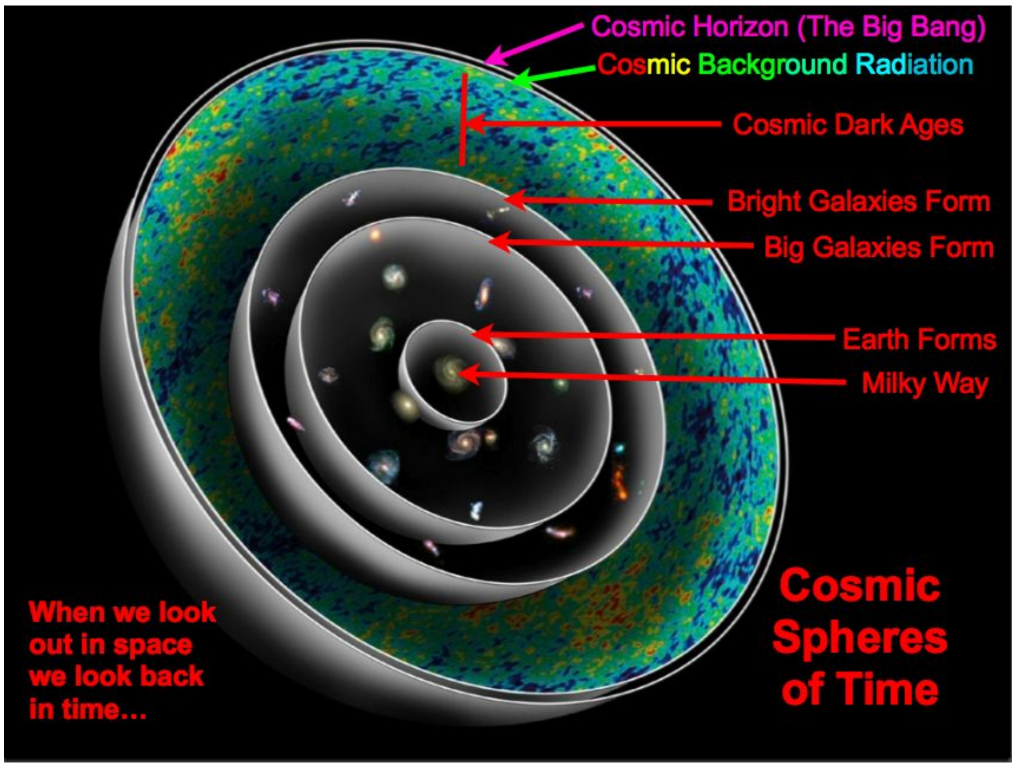
The importance of the possible payoff of these searches is enormous. A confirmed detection of a DM candidate would open the doors to the age of precision DM studies to determine its properties, and to do DM astronomy.

The quest for knowledge and fascination with the mysteries of the Universe have always characterized humanity. We may soon finally understand the what the Universe is made of, and what its fate will be.

We live in a privileged time of exploration of the Universe!
I feel tremendously fortunate to be part of this exploration... and for the junior people here, I hope you will too.

EXTRA SLIDES

Far away is long ago We see the galaxies within the distance light took to come to us since the first moment bright galaxies formed, before there was the "Cosmic Dark Ages" with no stars, and before then the CMBR was emitted at "Recombination", when atoms became stable. Fig frm J. Primack



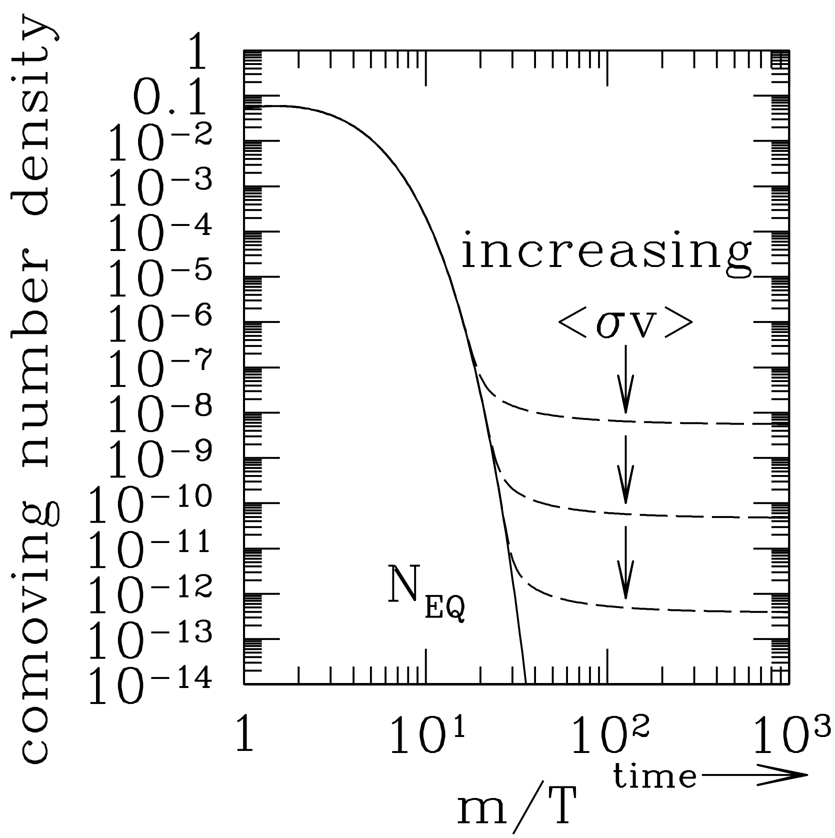
Thermal WIMPs as Dark Matter

Standard calculations: start at $T > T_{f.o.} \simeq m_\chi/20$ and assume that

- WIMPs reach equilibrium while Universe is radiation dominated , $n \sim e^{-m/T}$
- No particle asymmetry
- Chemical decoupling (freeze-out) when $t_{ann} = (\langle \sigma v \rangle\, n)^{-1} \geq t_U \sim H^{-1}$
- No entropy change in matter+radiation

$$\Omega_{std} h^2 \approx \frac{0.2 \times 10^{-9} GeV^{-2}}{\langle \sigma v \rangle}$$

Weak annihilation cross section
$\sigma_{annih} \simeq G_F^2 T^2 \simeq 10^{-9} GeV^{-2}$
is enough to get $\Omega_{DM} h^2 \simeq 0.1$!
"WIMP Miracle"!



Caveats to Thermal WIMPs as Dark Matter

the standard assumptions may not be correct.

- Non-Standard Pre-Big bang Nucleosynthesis (pre-BBN) cosmology e.g. Thermal WIMP relic abundance fixed at $T_{f.o.} \simeq m_\chi/20$ above the 4 MeV BBN limit, for $m > 80$MeV.

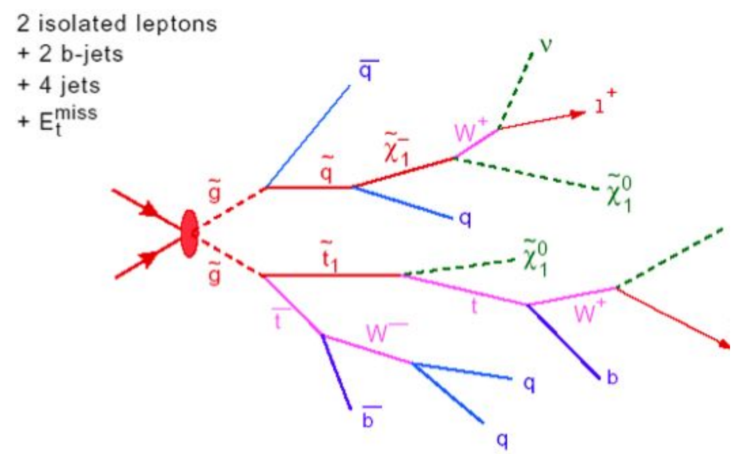
- Asymmetric DM We owe our very existence to a particle-antiparticle asymmetry so why not also the DM? (Requires non-self conjugated DM candidates, i.e. particles differ from antiparticles)

- WIMPs may be unstable and decay into the DM ("Super-WIMP" scenario).

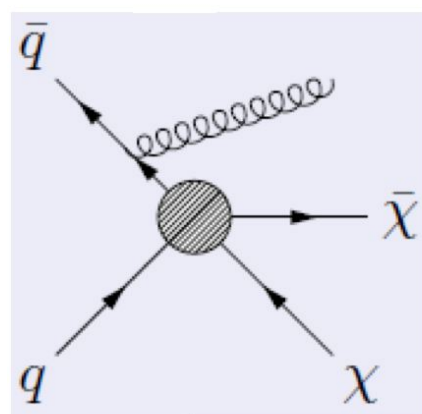
Searches at the LHC

DM particles escape the detector: missing energy and momentum

Either in known decay chains
(specific models, SUSY, simplified)



or direct DM production
plus a single photon or gluon:
monophoton or monojet signal



qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$