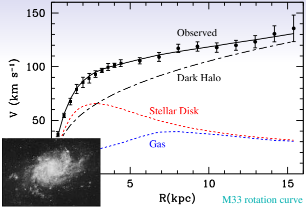
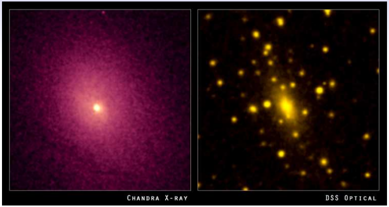
Dark Matter and What Do We Know About It

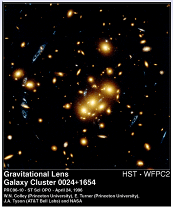
Tbilisi

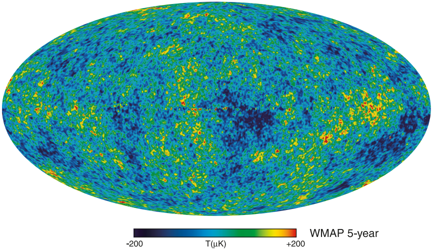
Alexey Boyarsky

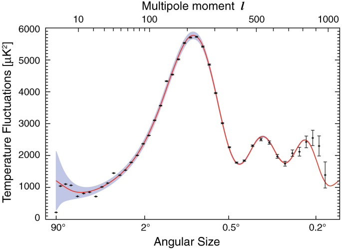
Monday 26th September, 2022


150
100
50
V (km s⁻¹)
Observed
Dark Halo
Stellar Disk
Gas
5
10
15
R(kpc)
M33 rotation curve

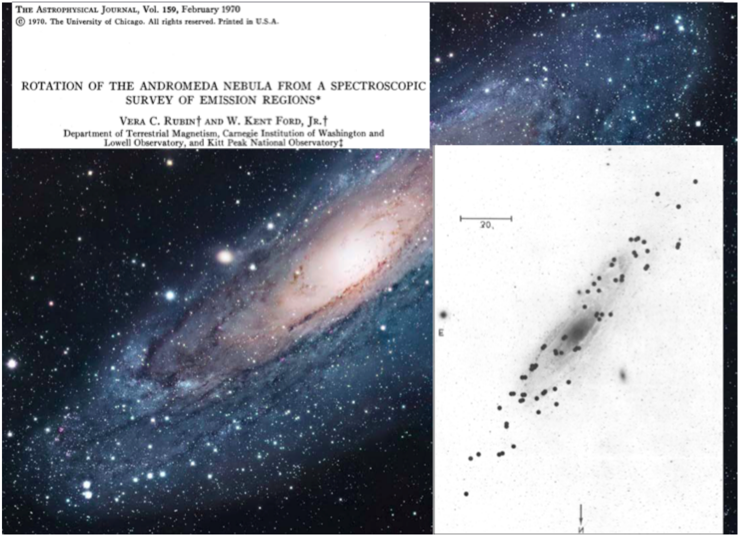

CHANDRA X-RAY
DSS OPTICAL


Gravitational Lens
HST · WFPC2
Galaxy Cluster 0024+1654
PRC96-10 · ST ScI OPO · April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University),
J.A. Tyson (AT&T Bell Labs) and NASA


-200
T(μK)
+200
WMAP 5-year


Multipole moment l
10
100
500
1000
6000
5000
4000
3000
2000
1000
0
Temperature Fluctuations [μK²]
90°
2°
0.5°
0.2°
Angular Size

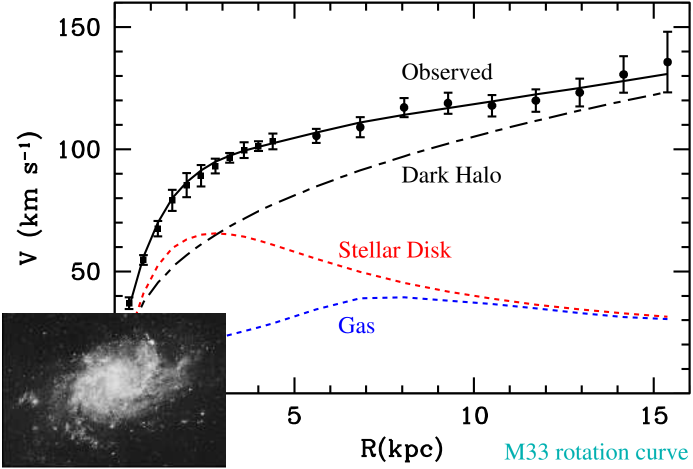
M31 rotation curve


THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

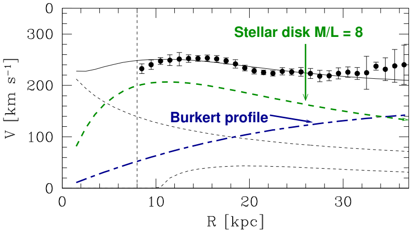
VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

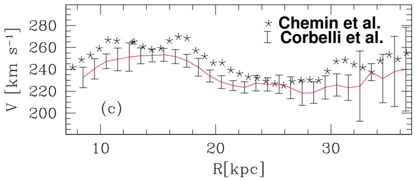
Rotation curve?



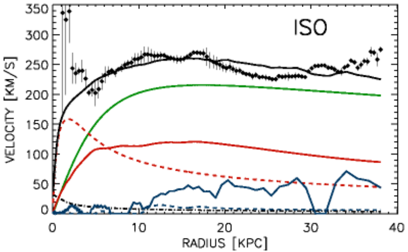
Newton dynamics: $\mathrm{V}(R) \sim \dfrac{1}{\sqrt{R}}$

The same M31 but today (2009)





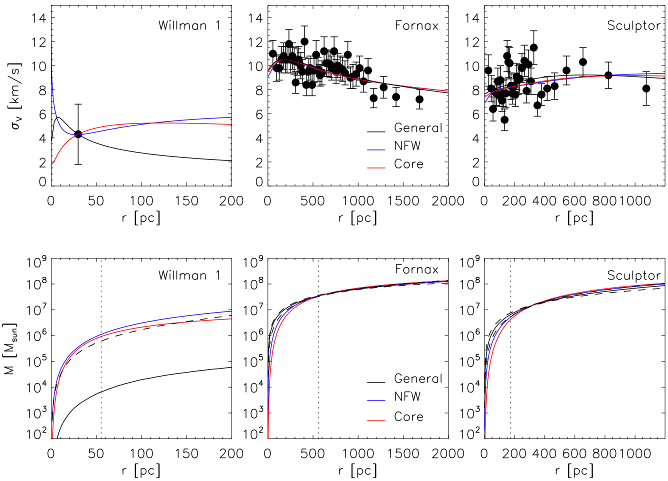
Corbelli et al. A&A 2009 [0912.4133]



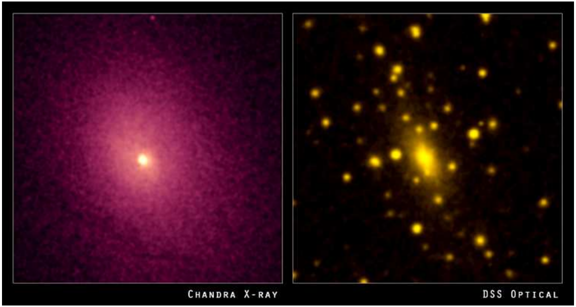
Chemin et al. ApJ 2009 [0909.3846]

- New precise HI data resolve features within inner 5–8 kps
- **Chemin et al.** model this region
- **Corbelli et al.** exclude this region from the analysis

DM in Dwarf Spherodiadals



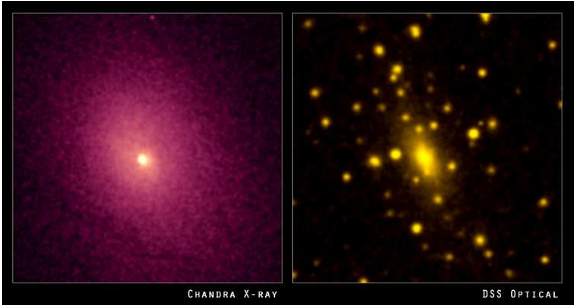
Intracluster gas



Cluster Abell 2029. **Credit: X-ray: NASA/CXC/UCI/A.Lewis et al. Optical: Pal.Obs. DSS**

$$\frac{dp}{d\boldsymbol{r}} = n_{\text{gas}}(\boldsymbol{r})\frac{dT(\boldsymbol{r})}{d\boldsymbol{r}} + T(\boldsymbol{r})\frac{dn_{\text{gas}}(\boldsymbol{r})}{d\boldsymbol{r}} = -\frac{GM(\boldsymbol{r})n_{\text{gas}}(\boldsymbol{r})}{\boldsymbol{r}^2}, \tag{11}$$

Intracluster gas



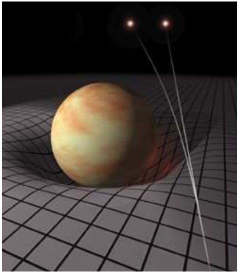
Cluster Abell 2029. **Credit: X-ray: NASA/CXC/UCI/A.Lewis et al. Optical: Pal.Obs. DSS**

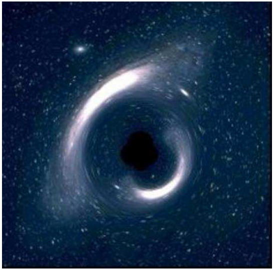
Dark Matter	$\sim 85\%$
Intracluster gas	$\sim 15\%$
Galaxies	$\sim 1\%$

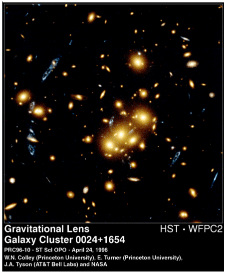
$$\frac{\text{DM in cluster}}{\text{Baryons in cluster}} \approx \frac{\Omega_{\text{DM}}}{\Omega_{\text{baryons}}}$$

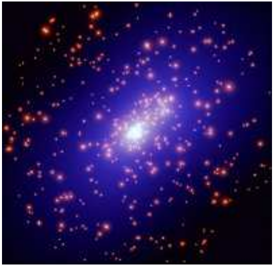
Temperature of ICM: $1 - 10$ keV $\sim 10^7 - 10^8$ K

Gravitational lensing

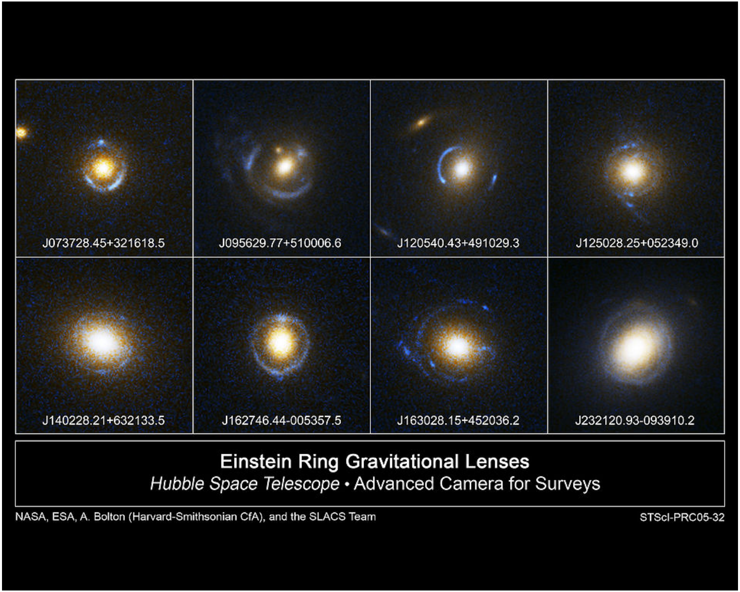




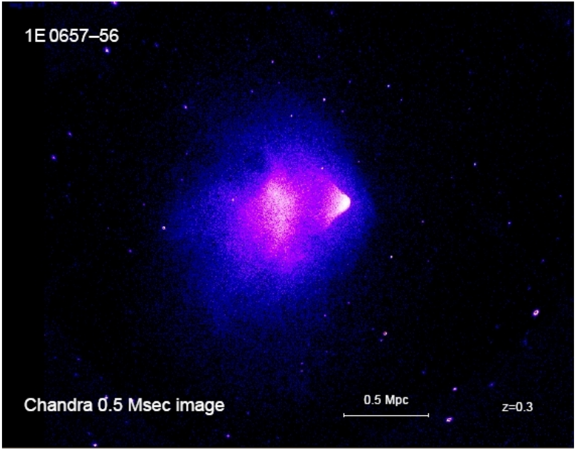




Gravitational lensing



"Bullet" cluster

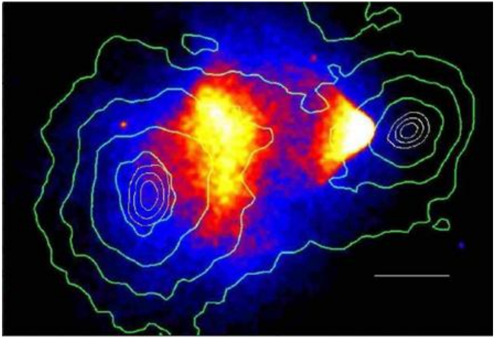


Cluster 1E 0657-56

Red shift $z = 0.296$

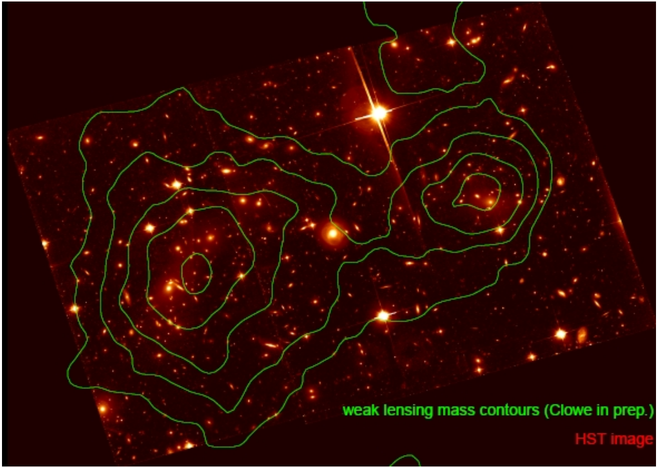
Distance $D_L = 1.5$ Gpc

Merging system in the plane of the sky



- Subcluster passed through the center of the main cluster
- DM and galaxies are collisionless
- Gas has been stripped away (shock wave, Mach number $M = 3.2$ and $T_{\rm shock} \sim 30$ keV)

Merging system in the plane of the sky

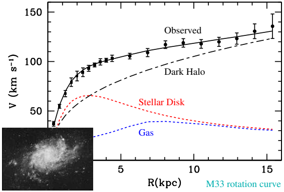


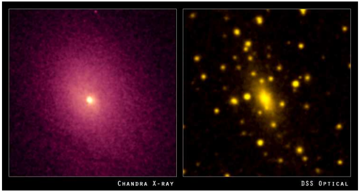
⋆ Comparing the gravitational lensing data with velocity distribution for galaxies

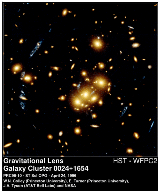
Dark Matter in the Universe

- Rotation curves of stars in galaxies and of galaxies in clusters
- Distribution of intracluster gas
- Gravitational lensing data
- Cosmic microwave background
- Formation of cosmic structures

- These phenomena are **independent tracers** of gravitational potentials in astrophysical systems
- They all show that dynamics is dominated by a matter that is not observed in any part of electromagnetic spectrum.

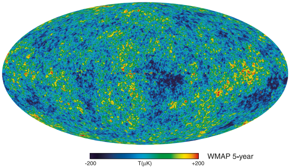


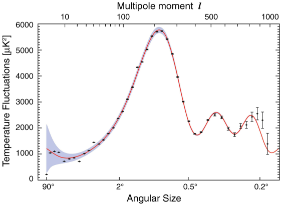




Cosmological evidence for dark matter

- We see the structures today and 13.7 billions years ago, when the Universe was 380 000 years old (encoded in anisotropies of the temperature of cosmic microwave background)
- All the structure is produced from tiny density fluctuations due to gravitational Jeans instability
- In the hot early Universe before recombination photons smeared out all the fluctuations





Structure formation

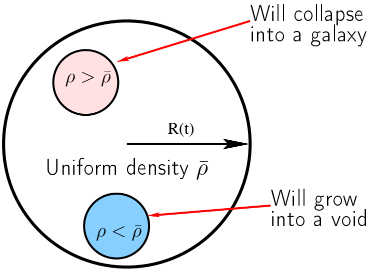
- We have learned that for the matter dominated Universe the Friedmann equation comes from Newton's laws:

$$\frac{m\dot{R}^2(t)}{2} - \frac{Gm\left(\frac{4\pi}{3}\bar{\rho}R^3(t)\right)}{R(t)} = 0$$

$$\Updownarrow$$

$$\boxed{H^2(t) = \frac{\dot{R}^2(t)}{R^2(t)} = \frac{8\pi G}{3}\bar{\rho}}$$

Friedmann equation



- The same can be done for studying of the structure growth

Structure formation

- **Jeans instability** in expanding Universe: interplay of two concurrent processes:
  - Gravitational attraction within an overdense region $\left(\mathcal{U} \sim \frac{GM}{R}\right)$
  - Overall expansion of the Universe $\left(\mathcal{K} \sim \frac{H^2 R^2}{2}\right)$
- Before **recombination** ($e + p \to H$), pressure of photon gas balances gravity and does not allow charged protons to form structures. Jeans instability only happened after recombination, in the matter-dominated epoch
- Each **overdensity** (region with $\rho > \bar{\rho}$) can be thought of as a tiny **closed Universe** (matter-dominated) inside the flat expanding Universe
- Closed Universe reaches its maximal scale factor when the pull of **extra matter** $\rho - \bar{\rho}$ overcomes the kinetic energy of cosmological expansion

$$\frac{\dot{R}^2(t)}{2} - \frac{GM(R)}{R} = -\frac{GM(R)}{R_{max}} \qquad (1)$$

Structure formation

- We can rewrite (1) as an equation for $R(t)$:

$$\frac{dR}{dt} = \sqrt{2GM\left(\frac{1}{R(t)} - \frac{1}{R_{max}}\right)} \qquad (2)$$

- Let us consider the early stages of growth of $R(t)$, when $\rho(t) \approx \bar{\rho}(t)$.
- Eq. (2) gives us

$$R(t) \approx t^{2/3}\left(1 - \left(\frac{t}{t_{max}}\right)^{2/3}\right),$$

where $t_{max} = \left(\frac{R_{max}^3}{2GM}\right)^{1/2} \frac{\pi}{2}$

Structure formation

- Compute average density within the $R(t)$:

$$\rho(t) = \frac{M}{\frac{4}{3}\pi R^3(t)} = \frac{1}{6\pi^2 G t^2}\left(1 + \mathrm{const}\left(\frac{t}{t_{max}}\right)^{2/3}\right),$$

- The first term (in blue) is the evolution of background density in the matter-dominated Universe.
- The second term shows how fast the overdensity (i.e. $\rho - \bar{\rho}$) grows with time. The evolution $t^{2/3}$ is the evolution of scale-factor in the matter-dominated Universe.
- $\Rightarrow$ At linear stage $\delta\rho/\bar{\rho} \ll 1$ the overdensities grow linearly with scale factor $a(t)$

Structure formation

- For successful structure formation, the second term in

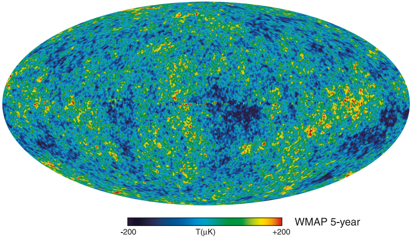
$$\rho(t) = \bar{\rho}(1 + \frac{\delta\rho}{\bar{\rho}})$$

must exceed 1. This condition may be rewritten in the form

$$\left(\frac{\delta\rho}{\bar{\rho}}\right)_{t_{rec}} \frac{a(t)}{a(t_{rec})} \simeq 1, \quad (3)$$

where $t_{rec} \simeq 10^5$ yr is around the recombination time

Structure formation



- What is the value of $(\delta\rho/\rho)_{t_{\rm rec}}$ for baryonic matter? It comes from CMB observations:

$$\left(\frac{\delta\rho}{\rho}\right)_{t_{\rm rec}} \simeq \frac{\delta T}{T} \simeq 10^{-5} \quad (4)$$

- The scale factor has changed in $\sim 10^3$ times. This means that the even now the overdensity is tiny:

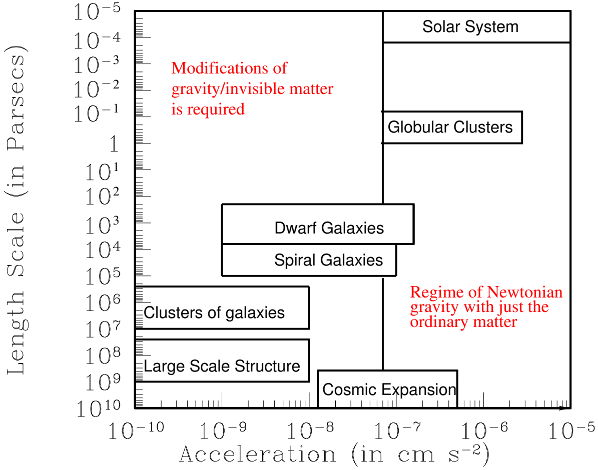
$$\left(\frac{\delta\rho}{\rho}\right)_{t_0} \sim 10^{-2} \ll 1 \quad (5)$$

- To avoid this problem, we need to have particles whose overdensity is not constrained by CMB. **Dark matter?**

The nature of dark matter

Change of fundamental laws?

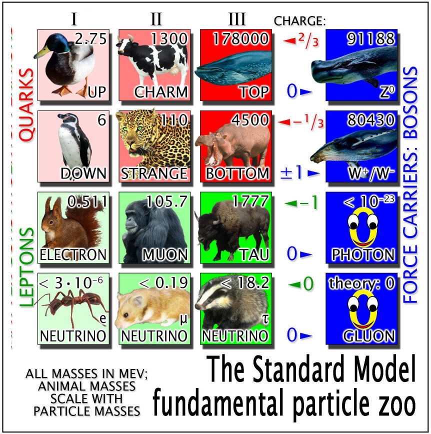
(**From Ferreira & Starkman 0911.1212**)



Disclaimer: In this talk I assume that DM is made of particles and the gravity is not modified.

Properties of Dark Matter particles

- DM particle should be:
  massive (relativistic particles do not cluster)
- If DM particles ever were relativistic – they should have **slow down early** in the history of the Universe
- DM particles should be **neutral** (not to interact with photons)
- DM particles should be **stable** or have cosmologically **long lifetime**



Any candidates in the Standard Model?

Neutrino Dark Matter

Energy density of relic neutrinos

- After neutrino decouple, their comoving number density does not change
- Their momentum decreases

$$\langle p_\nu \rangle \propto T \tag{6}$$

- If neutrinos are massive, at some moment $\langle p_\nu(T) \rangle$ becomes **smaller than** m_ν – neutrinos become non-relativistic
- Their number does not change, but their energy density changes from $\rho_\nu \propto T^4$ to

$$\rho_\nu = \underbrace{\left(\sum m_\nu\right) \times n_{\rm dec}}_{\substack{\text{number density of}\\ \text{non-relativistic particles}}} \quad \text{or numerically} \quad \Omega_\nu h^2 \equiv \frac{\rho_\nu}{\rho_{\rm crit}} \approx \frac{\sum m_\nu}{94\ \text{eV}} \tag{7}$$

Neutrino Dark Matter?

Tremaine-Gunn bound

In 1979 when S. Tremaine and J. Gunn published in Phys. Rev. Lett. a paper *"Dynamical Role of Light Neutral Leptons in Cosmology"*

- The smaller is the mass of Dark matter particle, the larger is the number of particles in an object with the mass $M_{\rm gal}$
- Average **phase-space density** of **any fermionic** DM should be **smaller** than density of **degenerate Fermi gas**
- The density of degenerate Fermi gas is given by

$$\Pi_{deg} = \frac{1}{(2\pi\hbar)^3} \tag{8}$$

Neutrino Dark Matter?

Tremaine-Gunn bound

- The mass density of non-relativistic degenerate fermions is given by

$$\rho_{deg} = m \times \underbrace{\int d^3\boldsymbol{p}\, \frac{1}{(2\pi\hbar)^3}}_{\text{number density}} = m \times \int d^3\boldsymbol{v}\, \frac{m^3}{(2\pi\hbar)^3} \tag{9}$$

  where we took into account that fermions are non-relativistic and so $\boldsymbol{p} = m\boldsymbol{v}$

- Thus, the mass density in the **velocity** (rather than momentum) space is given by

$$\Pi_{deg} = \frac{m^4}{(2\pi\hbar)^3} \tag{10}$$

- If dark matter is made of fermions – **its mass is bounded from below**

Neutrino Dark Matter?

Tremaine-Gunn bound

- Indeed, a galaxy with mass M_{gal} and size R_{gal} has average matter density

$$\rho_{matter} = \frac{M_{gal}}{\frac{4\pi}{3} R_{gal}^3} \tag{11}$$

- It occupies the volume of velocity space with $|\boldsymbol{v}| < v_\infty$, where v_∞ is the **escape velocity** – velocity that is sufficient for a particle to break gravitational attraction of the galaxy and leave it
- Average phase-space density of any system of fermions should be **lower** than the phase-space density of degenerate gas (10)

$$\frac{M_{gal}}{\underbrace{\frac{4\pi}{3} R_{gal}^3}_{\text{volume of space}}} \frac{1}{\underbrace{\frac{4\pi}{3} v_\infty^3}_{\text{volume of } \textbf{velocity} \text{ space}}} \leq \frac{2 {m_{\rm DM}}^4}{(2\pi\hbar)^3} \tag{12}$$

Neutrino Dark Matter?

Tremaine-Gunn bound

Mass of any fermionic dark matter is **bounded from below**

Tremaine-Gunn bound and observations

- Let us put the numbers for M_{gal}, R_{gal} and v_∞ from observations
- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the fermionic DM mass $M_{\mathbf{DM}} \gtrsim 300 - 400$ **eV** **[0808.3902]**
- **However**, as we have seen if you compute contribution to DM density from massive active neutrinos ($m_\nu \lesssim$ MeV), you get

$$\Omega_{\nu\ \mathrm{DM}} h^2 = \boxed{\frac{\sum m_\nu[\mathrm{eV}]}{94\ \mathrm{eV}}}$$

- Using minimal mass of 300 eV you get $\Omega_{\mathrm{DM}} h^2 \sim 3$ (**wrong by about a factor of 30!**)
- Sum of masses to have the correct abundance $\boxed{\sum m_\nu \approx 11\ \mathrm{eV}}$

Tremaine-Gunn bound and observations

Massive Standard Model neutrinos cannot be simultaneously "astrophysical" and "cosmological" dark matter: to account for the missing mass in galaxies **and** to contribute to the cosmological expansion

Hot dark matter

- Next blow to neutrino DM came around 1983–1985 when M. Davis, G. Efstathiou, C. Frenk, S. White, *et al.* "*Clustering in a neutrino-dominated universe*"
- They argued that structure formation in the neutrino dominated Universe (with masses around 100 eV) would be incompatible with the observations

http://www.adsabs.harvard.edu/abs/1983ApJ...274L...1W

Abstract

The nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution has been simulated **The conventional neutrino-dominated picture appears to be ruled out.**

Two obvious generalizations of neutrino DM:

1) Make the "neutrino" **heavier** so that it decouples non-relativistic (and therefore the expression $\Omega_{\rm DM}h^2 = \frac{\sum \mathcal{M}_\nu[\,\rm eV]}{94\ \rm eV}$ is not applicable anymore) but keep the interaction of the same order.

2) Make the "neutrino" interact **weaker-than-weak**, so that it never enters the equilibrium with the plasma in the first place (and therefore the expression $\Omega_{\rm DM}h^2 = \frac{\sum \mathcal{M}_\nu[\,\rm eV]}{94\ \rm eV}$ is not applicable anymore)

- First modification is called . . . . **WIMP**
  large mass and interaction strength of such a particle means that it will be unstable unless there is an exact symmetry, protecting it from decay
- Second modification is called . . . . **super-WIMP**
  mass that can be rather small ($\mathcal{O}(0.5\ \rm keV)$ and super-weak interaction strength of such a particle means that it **can** be unstable but still provide a correct phenomenology

Properties of dark matter particles

- For any dark matter candidate you invent you should answer a number of questions:
  - ? What is its mass?
  - ? How dark matter particles are produced and do they have a correct abundance
  - ? How do they form structures? **(were they produced relativistic?)**
  - ? Dark matter particle **interaction type** & **interaction strength**
    (are they stable or decaying? How they interact with the ordinary matter?)

WIMPs

Weakly interacting massive particles

- Consider weakly interacting neutral particles χ (as neutrinos) **but** with the mass $m_\chi \gg$ MeV
- Consider the situation when these particles are **stable** and the only process that can change their number density is their **annihilation** into the SM particles

$$\chi + \chi \longleftrightarrow \text{SM} + \text{SM} \tag{13}$$

- Both direct and inverse processes (13) go sufficiently fast at high temperatures $T < m_\chi$
- In this case, the number density n_χ at temperatures $T_{dec} \ll T \ll m_\chi$ is given by the Boltzmann distribution:

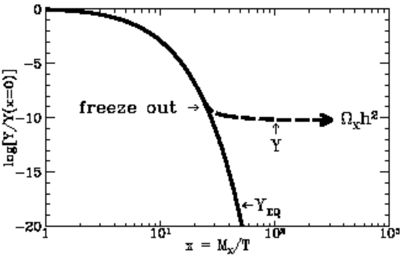
$$n_\chi^{\text{eq}}(T) = \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}, \qquad T \geq T_{dec} \tag{14}$$

Weakly interacting massive particles

- For $T \ll m$ both Fermi-Dirac and Bose-Einstein distributions become "Maxwell-Boltzmann distributions" $f_{\text{M-B}}(p) = e^{-m-\frac{p^2}{2mT}}$. Integrating $f_{\text{M-B}}(p)$ over d^3p we get (14).
- At later times ($T < T_{dec}$) the comoving number density of particles **is conserved:**

$$n_\chi(T) = n_\chi(T_{dec}) \left(\frac{T}{T_{dec}}\right)^3$$

- This number density is **much larger** than the equilibrium number density would be for a temperature T – **freeze-out**



WIMP freeze-out

- We need to find the temperature of decoupling (of freeze-out) T_{dec}, such that

$$H(T_{dec}) = \Gamma(T_{dec}) \equiv \langle \sigma v \rangle n(T_{dec})$$

(**for neutrino we took** $v = c = 1$).

- Assuming $m_\chi \gg T_{dec}$ we can estimate $\langle \sigma v \rangle \sim \sigma_0 \times \sqrt{T/m_\chi}$
- Fermi cross-section of two non-relativistic particles $\sigma_0 \sim G_F^2 E_{cm}^2$ (where in the non-relativistic case $E_{cm} = 2m_\chi + \mathcal{O}(T^2/m_\chi^2)$)
- Therefore

$$\frac{T^2}{M_*} = \sigma_0 \sqrt{\frac{T}{m_\chi}} \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T} \qquad (15)$$

- Right hand side of Eq. (15) is equal to $\frac{\sigma_0 T^2 m_\chi}{(2\pi)^{3/2}} e^{-m_\chi/T}$ and one finds

$$\frac{m_\chi}{T_{dec}} \simeq \log\left(\frac{M_* m_\chi \sigma_0}{(2\pi)^{3/2}}\right) \approx \log\left(\frac{M_* m_\chi^3 G_F^2}{(2\pi)^{3/2}}\right) \qquad (16)$$

WIMP freeze-out

- If we take $m_\chi \sim$ GeV and weak cross-section $\sigma_0 \sim G_F^2 m_\chi^2$ and put the numbers in Eq. (16), we see that, indeed, $m_\chi \gg T_{dec}$ — our initial assumption that these particles decouple **non-relativistically** is justified!
- Because $m_\chi \gg T_{dec}$, the inverse reaction in (13) – pair-creation of χ from two (relativistic) SM fermions – is possible only for very energetic particles whose energy $E \gtrsim m_\chi \gg T$. Their number density is not given by T^3, but rather is suppressed as $T^3 e^{-E/T}$. As a result pair-creation rate is also given by the r.h.s. of Eq. (15)
- We can now compute comoving number density of the particles χ:

$$n_\chi^{co} = \frac{n_\chi(T_{dec})}{T_{dec}^3} = \frac{\log^{3/2}\left(\frac{M_* m_\chi \sigma_0}{(2\pi)^{3/2}}\right)}{m_\chi M_* \sigma_0} \tag{17}$$

so as a result **comoving** energy density

$$\rho_\chi^{co} = m_\chi \times n_\chi^{co} = \frac{\log^{3/2}\left(\frac{M_* m_\chi \sigma_0}{(2\pi)^{3/2}}\right)}{M_* \sigma_0} \tag{18}$$

WIMP freeze-out

depends only logarithmically on the particle mass m_χ!

- The number density of χ-particles at the moment of their decoupling gets diluted due to the expansion of the Universe which gives their present-day number density

$$n_{\chi,0} = \left(\frac{a_f}{a_0}\right)^3 n_\chi(T_{dec}).$$

- Using the conservation of comoving entropy we rewrite it as

$$n_{\chi,0} = \left(\frac{s_0}{s_f}\right) n_\chi(T_{dec}),$$

where $s_0 = 2 \times \frac{4\pi^2}{90}\left(T_\gamma^3 + 3 \times \frac{7}{8} \times T_\nu^3\right) \approx 2.8 \times 10^3 \mathrm{cm}^{-3}$ is the present-day entropy of the Universe, $s_f = g_*(T_{dec}) \times \frac{4\pi^2}{90} T_{dec}^3$ is the entropy at the time of decoupling.

WIMP freeze-out

- Finally, the present-day energy density of χ-particles is

$$\rho_\chi = m_\chi n_{\chi,0} \sim m_\chi \frac{T_{dec}^2}{M_* \sigma_0} \frac{s_0}{T_{dec}^3} \propto \frac{\log(\sigma_0 m_\chi)}{\sigma_0}$$

- and abundance

$$\Omega_\chi = \frac{\rho_\chi}{\rho_{crit}} = 3 \times 10^{-10} \left(\frac{1 \text{ GeV}^2}{\sigma_0} \right) \frac{1}{\sqrt{g_*(T_{dec})}} \log \left(\frac{M_{Pl*} m_\chi \sigma_0}{(2\pi)^{3/2}} \right).$$

Note that this expression depends on m_χ only **logarithmically**. Note also the **strong dependence on** σ_0: the **weaker** is the interaction, the **more** particles survive before decoupling.

WIMP "miracle"

- Taking electroweak cross-section

$$\sigma_0 \simeq \frac{\alpha_W^2}{M_W^2} \simeq 10^{-7}\ \text{GeV}^{-2}$$

  mass $M_\chi = 100$ GeV, $g_*(T_{dec}) = 100$, the log value is $\simeq 30$, so that for electroweak-scale interaction one would obtain $\Omega_\chi \simeq 10^{-2}$. Thus we predict DM abundance within an order of magnitude.

- Thus, **weakly**-interacting massive particles (**WIMPs**) are considered as probable dark matter candidates.
- WIMPs can be searched in direct detection experiments (interaction of galactic WIMPs with laboratory nucleons).

Stability of weakly interacting particles

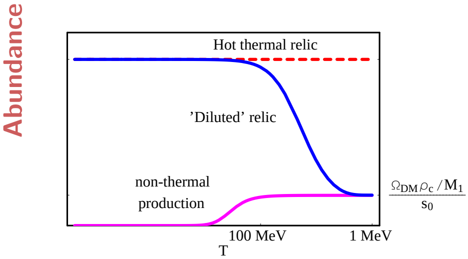
- Among the weakly interacting particles of the Standard Model there are 3 stable: electron, proton, neutrino
- The reason for that: each of these particles is the **lightest** carrier of some quantum number
  - electron: lightest electrically charged particle. Its decay (for example to 3 neutrinos or neutrino and photon) would violate the electric charge conservation
  - neutrino: lightest fermion (no lighter particles with spin 1/2 are known)
  - proton: lightest baryon.
- Neutron which is heavier than proton by only 1.2 MeV (about 2% of its mass) decays $n \to p + e^- + \bar{\nu}_e$
- Muon (next lightest electrically charged fermion after electron) decays $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$. Mass: $m_\mu \simeq 105.6$ MeV, lifetime: 2.2×10^{-6} sec
- Tau-lepton decays in a similar way $\tau^+ \to e^+ + \nu_e + \bar{\nu}_\tau$ (plus many other decays). Its mass: $m_\tau \simeq 1776.82$ MeV and the lifetime is 2.9×10^{-13} sec

Stability of weakly interacting particles

- What makes WIMP stable?
- We need some new symmetry to protect WIMP from decay

Super-WIMPs

Thermal production of light particles in the early Universe

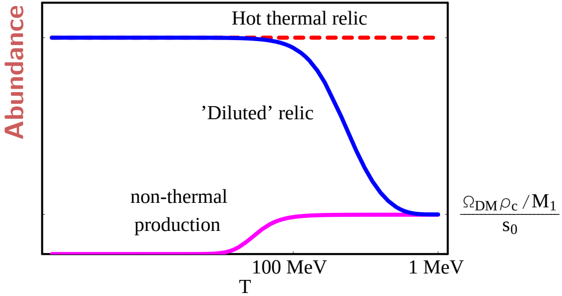


- As we saw before, the particles that decouple with $T_{\rm dec} < m$ (WIMPs) have their abundance dependent on their interaction strength (σ_0)

- The abundance of hot thermal relics $T_{\rm dec} \gg m$ is universal (independent on the interaction strength) and is too high **unless** $M_{\rm DM} = 11$ eV (remind neutrinos)
- Is it possible to make hot (relativistic) relic a DM candidate (if its mass is higher than 11 eV)?

Thermal production of light particles in the early Universe

- Yes! This may be done if the interaction strength is low and particles **never enter thermal equilibrium**
- The concentration of these particles gradually builds up. Such particles are called **Super-WIMPs**
- Non-equilibrium processes can "remember" something about the history of the Universe



Super-WIMP production: main idea

- Consider a massive particle, N ("sterile neutrino"), that interacts with the SM particles like neutrino, but the interaction strength is ϑG_F, where $\vartheta \ll 1$
- The $\vartheta \ll 1$ is so small that particles never enter thermal equilibrium. The interaction rate $\Gamma_N \approx \vartheta^2 G_F^2 T^5$ – similar to neutrino, but suppressed by ϑ^2
- Their number density slowly builds up from interaction with the SM particles (inverse process of DM particles converting into the SM ones is not effective while there are too few DM particles, much less than equilibrium)
- As a result their total number density: $n_N \propto \vartheta^2 n_\nu$ and their abundance $\Omega_N \propto m_N \vartheta^2$. For sufficiently small ϑ particles of any mass can produce the correct DM abundance

Super-WIMP production: main idea

- The distribution is proportional to the equilibrium distribution of SM particles:

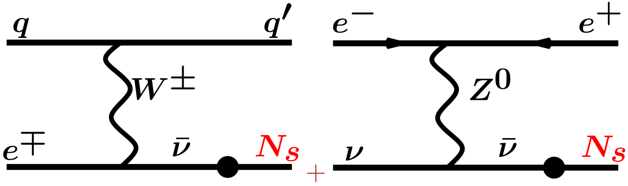
$$f_N(p,t) \sim \frac{\vartheta^2}{\exp(\frac{p}{T_\nu(t)})+1} \qquad (19)$$

— strongly suppressed $f_N(p) \ll f_{\text{eq}}(p)$

- The average momentum of DM particles computed with this distribution is the same as for Fermi-Dirac distribution: $\langle p\rangle = 3.15\,T_\nu$
- It is independent of mass and ϑ!
- Therefore, for some m_N and ϑ one will always have $\langle p\rangle \gg m_N$ – **particles can be produced relativistic!**

Production

- Sterile neutrino is produced in the primordial plasma via processes like



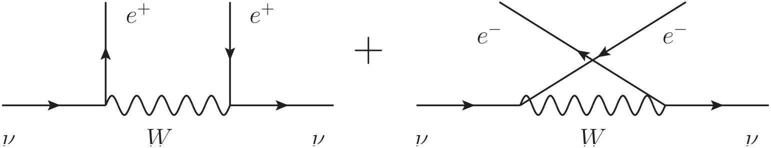
- Let's check first whether sterile neutrinos in plasma are never in thermal equilibrium: compare the reaction rate Γ_N with the Hubble expansion rate

$$\Gamma_N \sim \vartheta^2 G_F^2 T^5 \gtrsim \frac{T^2}{M_*} \tag{20}$$

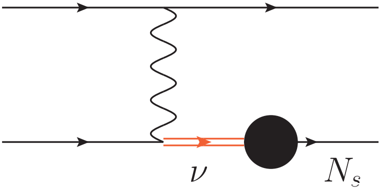
Production

- **Naively** you should conclude that sterile neutrinos were in equilibrium $\Gamma > H$ up until the temperature
$$T_{\text{dec}} \sim \left(M_* G_F^2 \vartheta^2\right)^{-1/3} \approx 90 \text{ MeV} \left(\frac{10^{-5}}{\vartheta^2}\right)^{1/3}$$
- Does this mean that sterile neutrino DM is **not** a super-WIMP, that it was in equilibrium and then decoupled at temperature T_{dec}?
- If it were so, this could not be the dark matter candidate (with the mass above Tremaine-Gunn bound it would lead to Ω_N that is too high)

Where did we do it wrong?

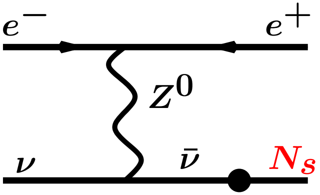


- Equation of motion for neutrinos propagating in thermal medium gets changed



- Neutrinos are an intermediate state in any process with N_s. A change of properties of neutrinos lead to the corresponding change of any matrix element with N_s

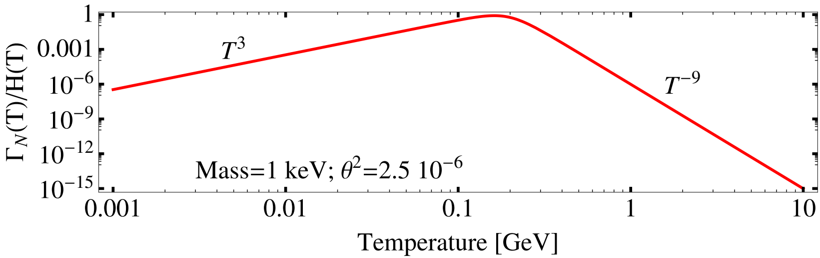
Where did we do it wrong?



- Averaging over the particles from the bath, the mixing angle becomes temperature dependent:

$$\vartheta(T) \approx \frac{\vartheta_0}{1 + c\frac{T^6 G_F^2}{\alpha M_N^2}} \tag{21}$$

Where did we do it wrong?



- The reaction rate $\Gamma_N(T) \sim \vartheta^2(T) G_F^2 T^5$ is strongly suppressed at high temperatures
- The production is the most effective at

$$T_{\text{peak}} \sim 150 \text{ MeV} \left(\frac{M_N}{1 \text{ keV}}\right)^{1/3} \gg M_N \qquad (22)$$

for M_N in keV–MeV range. Because of the suppression it may turn out that always $\Gamma_N \lesssim H$

Where did we do it wrong?

- ...and indeed, the sterile neutrino have phase-space distribution

$$f_N(p,t) \sim \frac{\vartheta^2}{\exp(\frac{p}{T_\nu(t)}) + 1} \tag{23}$$

and their average momentum at production is:

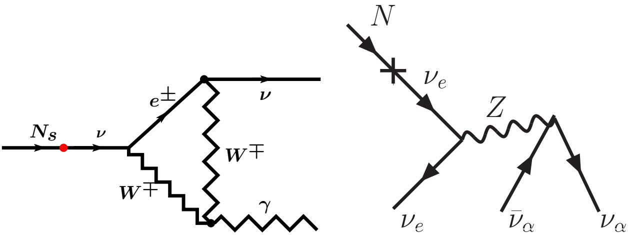
$$\langle p \rangle = 3.15\, T_{peak} \gg M_N \tag{24}$$

for M_N in keV–MeV range.

- With time, the momenta redshift and sterile neutrinos become non-relativistic

Decays of sterile neutrinos

- Interaction of massive particles with the SM particles means that these particles may decay (unless we invent a new symmetry protecting them)
- The decay can always go through the same interaction that produced these particles in the early Universe
- For example, in case of sterile neutrino of keV mass decay channels are $N \to e^+e^-\nu$, $N \to 3\nu$, $N \to \gamma\nu$
- Therefore, sterile neutrinos are decaying warm dark matter candidate



Axions

- Axion is a massive particle interacting with EM field pseudoscalar $F_{\mu\nu}\tilde{F}^{\mu\nu} \sim \mathbf{E}\cdot\mathbf{B}$:

$$\boxed{\mathcal{L}_{\text{axion}} = \frac{(\partial a)^2}{2} - \frac{m_a^2 a^2}{2} - \frac{g_{a\gamma}}{4} aF\tilde{F}} \tag{25}$$

- It may also interact with other pseudoscalar operators constructed from SM particles:

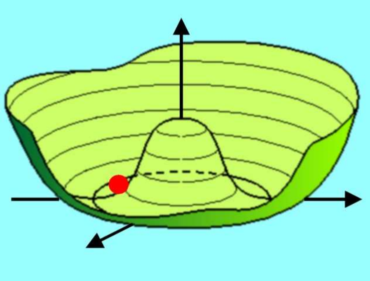
$$\mathcal{L}_{\text{axion,int}} = -\frac{g_{a\gamma}}{4} aF\tilde{F} - g_{aG}\, aG\tilde{G} + \sum_{f=e,\mu,\ldots} g_{af}\, a\bar{f}\gamma_5 f \tag{26}$$

Origin of axions

- Complex scalar field $\Phi = (f + \phi)e^{\frac{ia}{f}}$ with a "Mexican hat"-type potential

$$V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - f^2)^2 \quad (27)$$

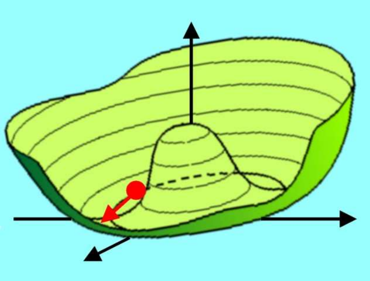
- This $U(1)$ symmetry $\Phi \to \Phi e^{i\alpha}$ is often called **Peccei-Quinn symmetry**



- The symmetry is **spontaneously broken** at high energies $\langle\Phi\rangle \sim f \gg \mathrm{TeV}$
- Axion – Goldstone boson a – settles in a Mexican hat.

Origin of axions

- Because of some other interactions the Mexican hat "tilts" (this means that the $U_{\mathrm{PQ}}(1)$ was not an exact but **approximate** symmetry
- Axions acquire a mass – **pseudo**-Goldstone boson



$$\mathcal{L}_{\text{axion}} = \frac{(\partial a)^2}{2} - \frac{m_a^2 a^2}{2} - \frac{g_{a\gamma}}{4} aF\tilde{F} \qquad (28)$$

Axions in the early Universe

- In the expanding Universe the evolution of the homogeneous axion field is given by

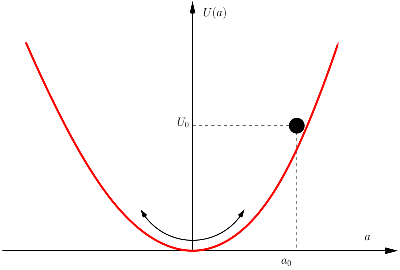
$$\ddot{a} + 3H\dot{a} + \frac{\partial U}{\partial a} = 0 \tag{29}$$

  where $U(a)$ is the axion potential (its quadratic term is just a mass $m^2 a$). It may be zero until high temperatures and then is generated at some temperature T_0

- As far as $U(a) = 0$ (or $\partial U / \partial a \ll 3H\dot{a}$), the solution is $a = a_0$. The value of a_0 has no role – shift symmetry $a \to a + \alpha$

Axions as DM particles

- Once the term with potential becomes relevant, the situation changes
- The initial value a_0 is generically off the minimum of U, so the field starts to oscillate
- The oscillating axion field may be interpreted as a set of particles at rest – viable DM candidates



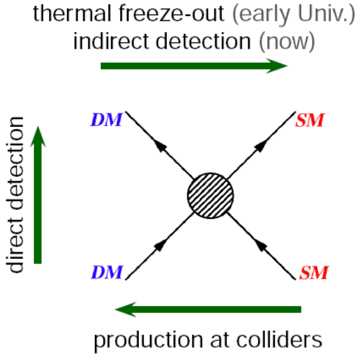
- Axions are unstable particles; they decay into two photons: $a \to 2\gamma$
- Unlike neutrinos, they are bosons, and hence their mass is not constrained from below (no Tremaine-Gunn bound)
- If their masses are very small $m_a \sim 10^{-22}$ eV, their Compton wavelength is as large as the astrophysical scales $\Rightarrow$ **fuzzy dark matter**

Searching for WIMPs and super-WIMPs

Two types of interaction of dark matter particles

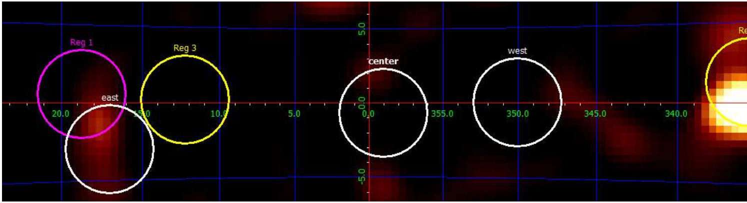
- annihilating
- decaying

WIMP annihilation

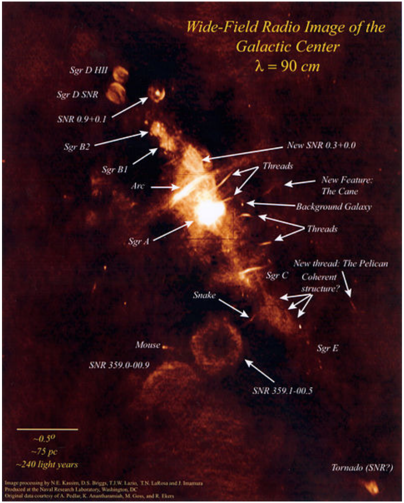


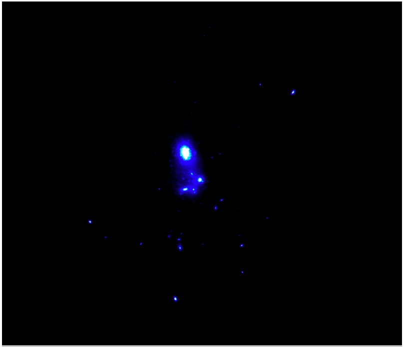
Same is true for WIMP:

- The same interaction that is responsible for WIMP production is responsible for their decay $\Rightarrow$ **annihilating dark matter**
- The annihilation signal is proportional to the **density squared**



Galactic center is a busy place



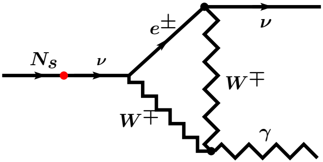


Annihilation signal from the Milky way-like galaxy

Decaying super-WIMPs

Many decaying dark matter candidates posses **two-body decay channel**.
We have learned that

- Axions decay into $a \to \gamma\gamma$ (via $\frac{1}{f_a} a\vec{E} \cdot \vec{B}$)
- Sterile neutrinos decay into $N \to \nu + \gamma$

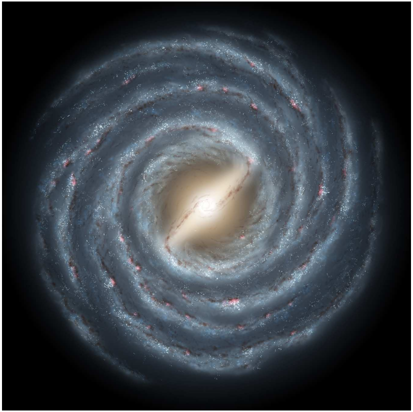


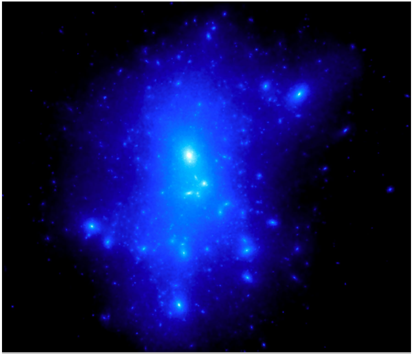
Decaying super-WIMPs

- Two-body decay into two massless particles ($\mathrm{DM} \to \gamma + \gamma$ or $\mathrm{DM} \to \gamma + \nu$) $\Rightarrow$ narrow decay line
$$E_\gamma = \frac{1}{2} m_{\mathrm{DM}} c^2$$
- The width of the decay line is determined by **Doppler broadening**
- Typical virial velocities:
  - A dwarf satellite galaxy: $\sim 30\,\mathrm{km/sec}$
  - Milky Way or Andromeda-like galaxy: $\sim 200\,\mathrm{km/sec}$
  - Typical velocity in the galaxy cluster $\sim 1500\,\mathrm{km/sec}$
- Very characteristic signal: narrow line in all DM-dominated objects with $\dfrac{\Delta E}{E_\gamma} \sim \dfrac{v_{\mathrm{vir}}}{c} \sim 10^{-4} - 10^{-2}$
- Lifetime should be longer than the age of the Universe

Search for DM decay

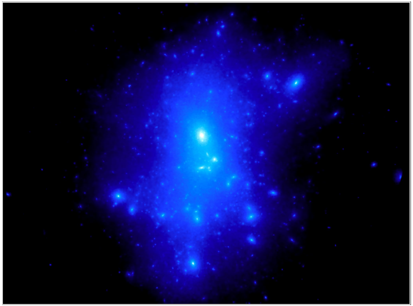
- Can we detect such decay?
- **Yes!** If you multiply a small number (probability of decay) with a large number (typical amount of DM particles in a galaxy $\sim 10^{70}$–10^{100})



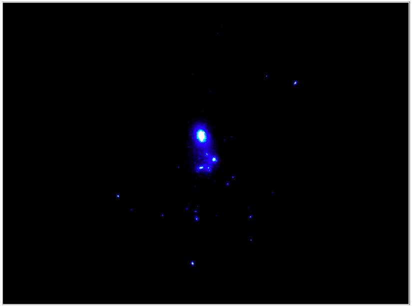


Expected signal from a galaxy at a particular energy (simulation from B. Moore)

Search for DM decay



DM **decay** signal from a galaxy



DM **annihilation** signal from a galaxy

For decaying dark matter astrophysical search is (almost) "**direct detection**" as any candidate line can be unambiguously checked (confirmed or ruled out) as DM decay line

Dark matter decay flux

- Flux from dark matter decay is $\text{Flux} = \frac{1}{4\pi\tau_{\text{DM}} M_{\text{DM}}} \frac{M_{\text{fov}}}{D_L^2}$
- For objects that *cover the whole Field of Vision of the instrument*

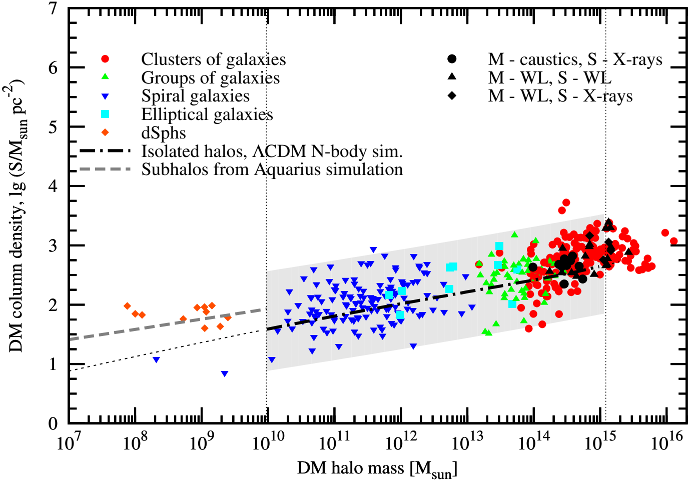
$$\frac{M_{\text{fov}}}{D_L^2} \approx \Omega_{\text{fov}} \int\limits_{\text{line of sight}} \rho_{\text{DM}}(r) dr$$

— does not depend on the distance to the object!

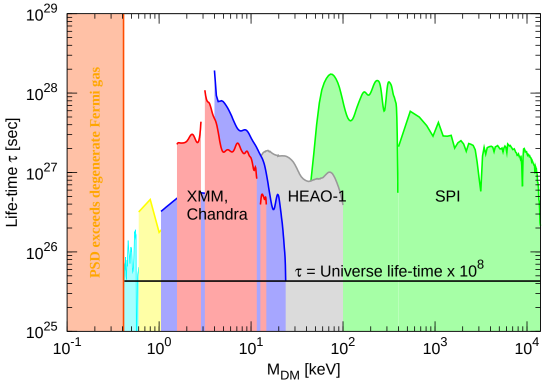
- **column density** $\boxed{\mathcal{S} = \int \rho_{\text{DM}}(r) dr}$ remains **remarkably constant** from one object to another!
-
    - Distance to the Galactic Center: 8 kpc
    - Distance to the Andromeda galaxy: 780 kpc
    - Distance to the Perseus cluster: 73.6 Mpc
    - Distance to the Virgo cluster: 18 Mpc

Signal from different DM-dominated objects

Boyarsky, O.R. et al. PRL'09



Restrictions on lifetime of decaying DM



MW (HEAO-1) Boyarsky, O.R. et al. 2005

Coma and Virgo clusters Boyarsky, O.R. et al.

Bullet cluster Boyarsky, O.R. et al. 2006

LMC+MW(XMM) Boyarsky, O.R. et al. 2006

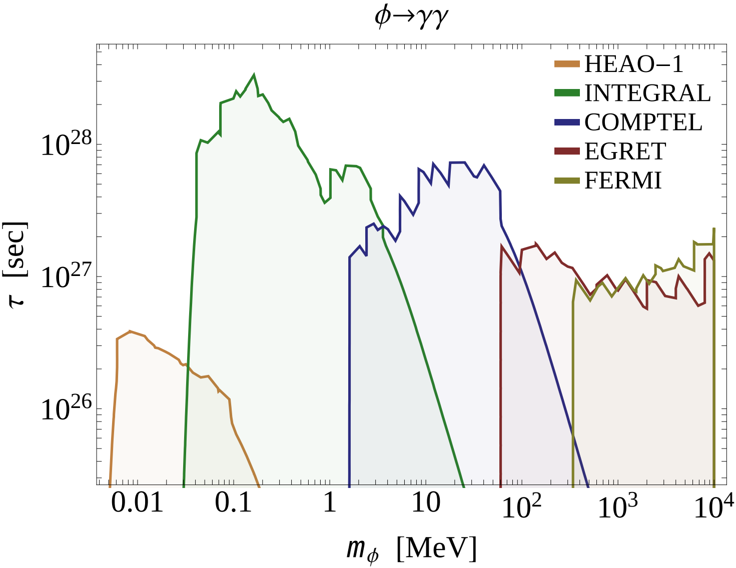
MW Riemer-Sorensen et al.; Abazajian et al.

MW (XMM) Boyarsky, O.R. et al. 2007

M31 Watson et al. 2006; Boyarsky et al. 2007

Many groups, incl. A. Boyarsky with collaborators 2005-2010

Restrictions on lifetime of decaying DM

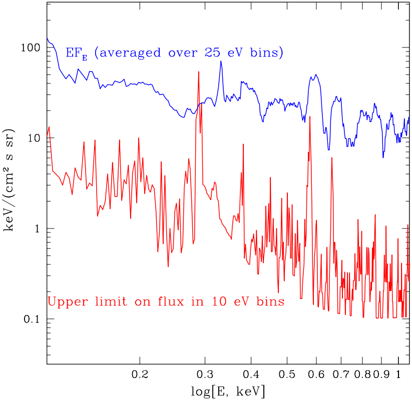


Bertone et al.'07

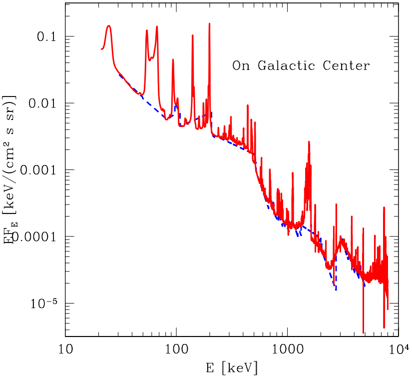
Compilation from Essig et a

Search for dark matter particles

Finding a decaying DM line is not an easy task – most DM-dominated objects have X-ray emission (**are massive enough to confine keV-temperature gas**)



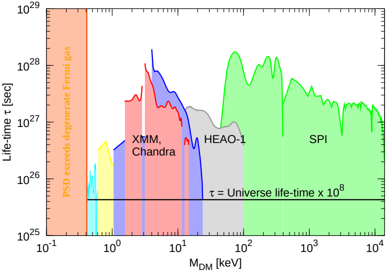
Milky Way in soft X-rays



Milky Way in hard X-rays/γ-rays

Search for Dark Matter decays in X-rays

Available X-ray satellites: Suzaku, XMM-Newton, Chandra, INTEGRAL



MW (HEAO-1) 2005
Coma and Virgo clusters 2006
Bullet cluster 2006
LMC (XMM) 2006
MW (XMM) 2006–2007
M31 (XMM) 2007, 2010

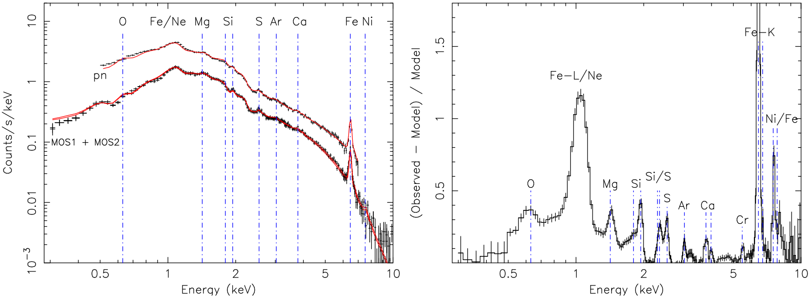
$$\text{Signal-to-noise} \propto \mathcal{S}\sqrt{t_{\text{exp}} \cdot \Omega_{\text{fov}} \cdot A_{\text{EFF}} \cdot \Delta E} \qquad (30)$$

All types of individual objects/observations have been tried: galaxies (LMC, Ursa Minor, Draco, Milky Way, M31, M33,...); galaxy clusters (Bullet cluster; Coma, Virgo, ...) with all the X-ray instruments

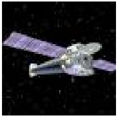
Why clusters do not obviously win?

- Virial theorem: $k_B T \sim \frac{G_N M}{D}$ or $T \sim 10\,\mathrm{keV}\left(\frac{\text{Overdensity}}{10^3}\right)\left(\frac{\text{Size}}{\mathrm{Mpc}}\right)$

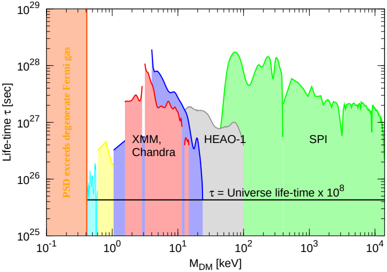
Werner et al.'2006



Improvements



$$\frac{S}{N} \propto S\sqrt{t_{\rm exp}\cdot\Omega_{\rm fov}\cdot A_{\rm EFF}\cdot\Delta E} \qquad (31)$$



MW (HEAO-1) 2005

Coma and Virgo clusters 2006

Bullet cluster 2006

LMC (XMM) 2006

MW (XMM) 2006–2007

M31 (XMM) 2007, 2010

- Individual observation: 50-100 ksec
- One year of XMM-Newton observational programme: 14 Msec
- Only 60-70% of exposure is used (cosmic flares contamination)
- Long exposure $\mathcal{O}(10^3)$ photons/bin $\Rightarrow$ small statistical errors

Detection of An Unidentified Emission Line

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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Submitted to ApJ, 2014 February 10

[1402.2301]

We detect a weak unidentified emission line at E=(3.55-3.57)+/-0.03 keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range 0.01-0.35. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is significantly detected in all three independent MOS spectra and the PN "all others" spectrum. It is also detected in the Chandra spectra of Perseus with the flux consistent with XMM (though it is not seen in Virgo)...

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

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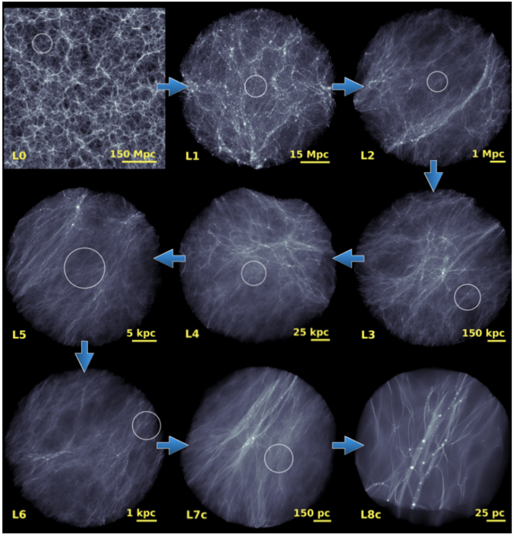
[1402.4119]

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset...

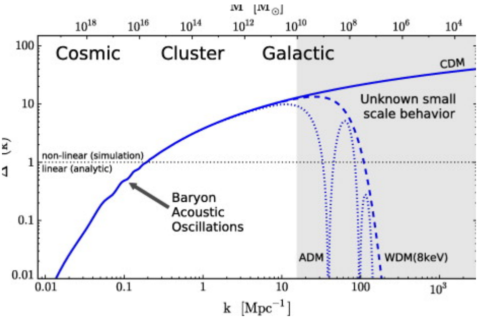
Cold Dark Matter

Cold dark matter – self-similar structure formation

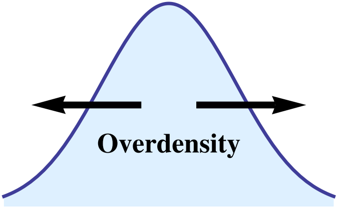


CDM vs. non-CDM

- Example: WDM. Particles are born relativistic $\Rightarrow$ they do not cluster
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

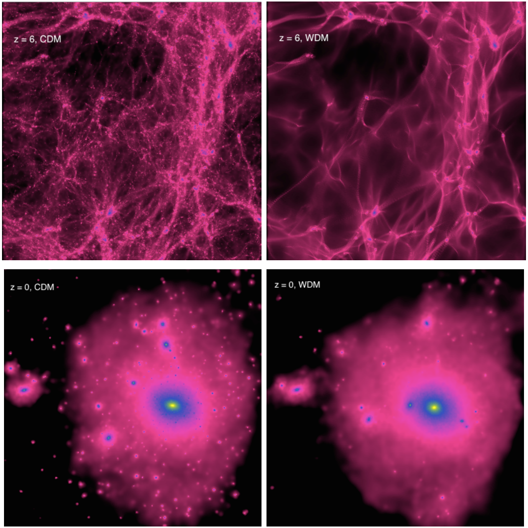


(Kuhlen et al. (2012))



– Particle velocities means that warm dark matter has effective **pressure** that prevents small structure from collapsing

What is "warm dark matter" observationally?

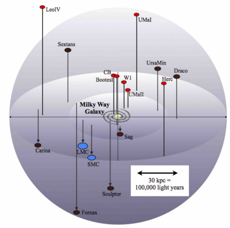


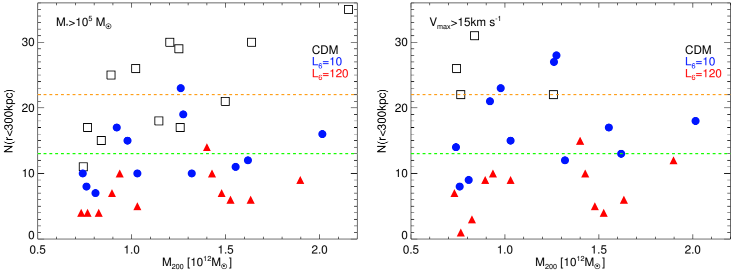
Warm dark matter:

- Same structures as in **CDM** Universe at scales of Mpc and above $\Rightarrow$ no signatures in CMB or galaxy counts
- Decreasing number of small galaxies around Milky Way
- Decreasing number of small satellite galaxies **within** Milky Way halo
- **Can help** with "too big to fail" or "missing satellites" problems

Satellite number and properties

- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with “predictions”
- **Simulations**: The answer depends **how** you “light up” satellites
- **Observations**: We do not know how typical Milky Way is

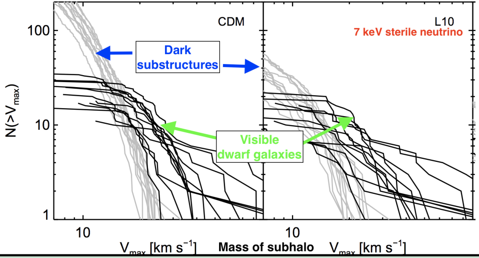


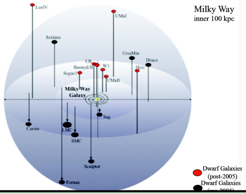


Lovell, Boyarsky+ [1611.00010]

Counting satellites

Boyarsky, Ruchayskiy with Lovell et al. [1611.00010]





The same number of luminous satellites, but different number of dark satellites

- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with "predictions"
- **Simulations**: The answer depends **how** you "light up" satellites
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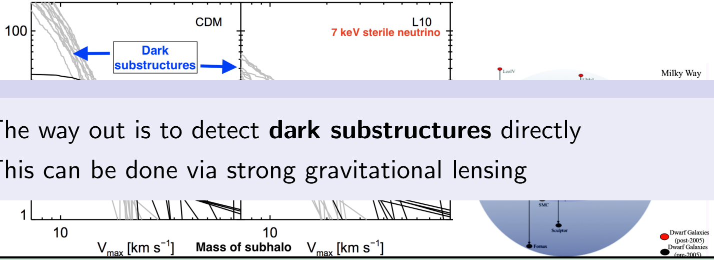
Counting satellites

Boyarsky, Ruchayskiy with Lovell et al. [1611.00010]



- The way out is to detect **dark substructures** directly
- This can be done via strong gravitational lensing

The same number of luminous satellites, but different number of **dark** satellites

- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with "predictions"
- **Simulations**: The answer depends **how** you "light up" satellites
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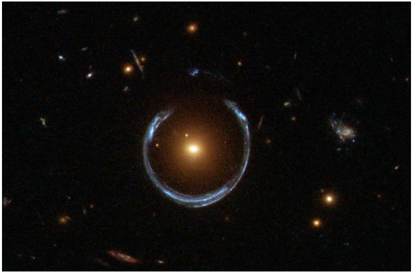
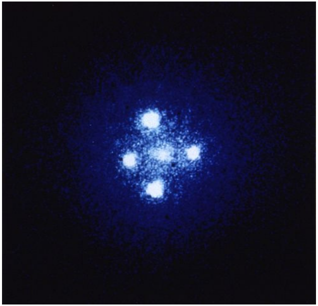
Way 1: Strong gravitational lensing

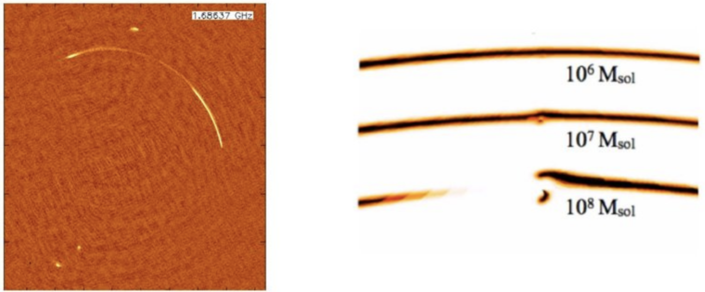


Einstein ring: large red galaxy lenses distant blue galaxy (almost on the line-of-sight).



Einstein cross: 4 images of a distant quasar

Dark substructures detection via arcs

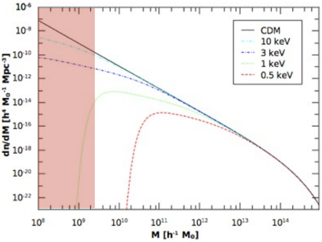


High-resolution gravitational imaging: The image on the left shows VLBI data for the lens system B1938+666. The long arc is a strongly lensed image of a distant background galaxy. The image on the right shows how different mass substructures in the lens galaxy would affect the gravitational arc of B1938+666.

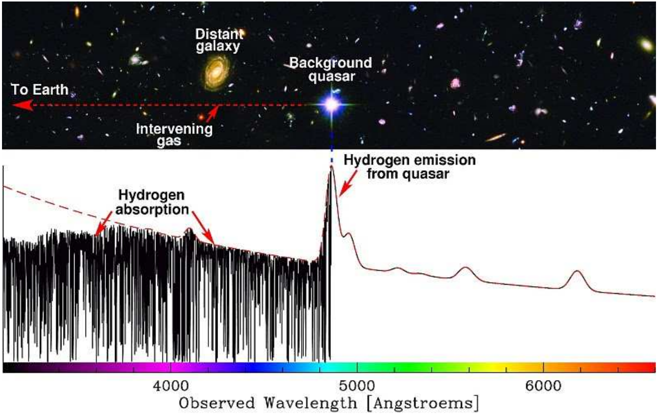
S. Vegetti

Ruling out cold or warm dark matter

- Current detection limits $M_{sub} \sim 10^9 M_\odot$
- Future surveys (more lenses/arcs) will bring the detection limits $M_{sub} \sim 10^6 M_\odot$
- If no substructures of this size will be found $\Rightarrow$ **CDM is ruled out!** Strong impact on direct detection experiments, axion DM searches, etc
- If such substructures are found – WDM strongly disfavoured, no sterile neutrino DM. . .



Way2: Lyman-α forest



- Neutral hydrogen absorption line at $\lambda = 1215.67\text{Å}$

  (Ly-α absorption $1s \rightarrow 2p$)
- Absorption occurs at $\lambda = 1215.67\text{Å}$ in the **local reference frame** of hydrogen cloud.
- Observer sees the **forest**: $\lambda = (1 + z)1215.67\text{Å}$

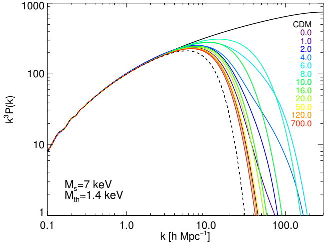
Suppression in the flux power spectrum (SDSS)

What we want to detect

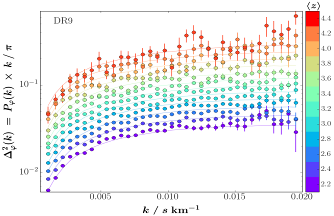
- CMB and large scale observations fix matter power spectrum at large scales
- Based on this we can predict the ΛCDM matter power spectrum at small scales
- WDM predicts suppression (cut-off) in the matter power spectrum as compared to the CDM

What we observe

- We observe **flux power spectrum** – projected along the line-of-sight power spectrum of neutral hydrogen absorption lines

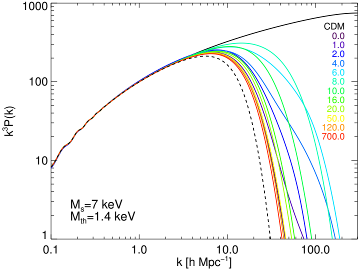


3D linear matter power spectra

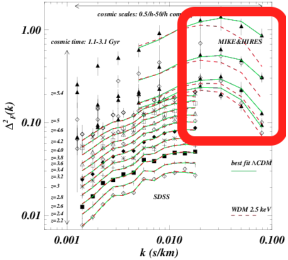


BOSS (SDSS-III) Ly-α [1512.01981]

High-resolution Ly-α forest



Warm dark matter predicts suppression (cut-off) in the flux power spectrum derived from the Lyman-α forest data



Lyman-α from HIRES data (1306.2314)

- HIRES flux power spectrum **exhibits suppression at small scales**
- Is this **warm dark matter?**

But we measure neutral hydrogen!

Lyman-α forest method is based on the underlying assumption

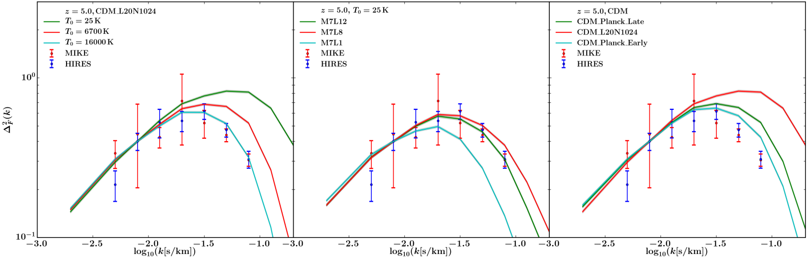
The distribution of neutral hydrogen follows the DM distribution

Baryonic effects

- Temperature at redshift z (Doppler broadening) – **increases hydrogen absorption line width**
- Pressure at earlier epochs (gas expands and then needs time to recollapse even if it cools)

Temperature? Pressure? WDM?

Garzilli, Magalich, Theuns, Frenk, Weniger, Ruchayskiy, Boyarsky [1809.06585]

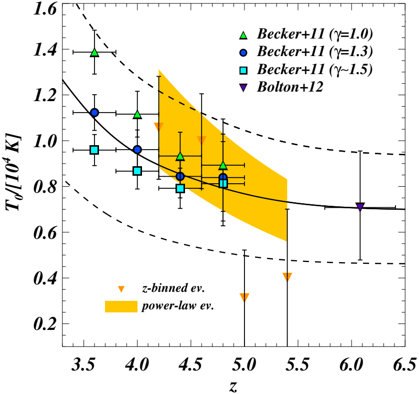


Temperature **WDM** **Pressure**

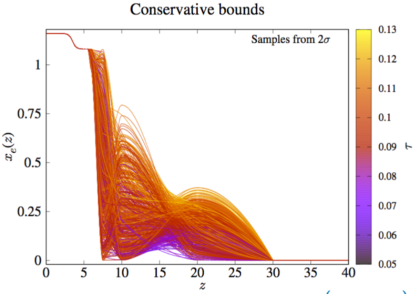
- CDM with the IGM temperature $\sim 10^4$ K is able to explain the MIKE/HIRES flux power spectrum
- Different thermal histories (onset/intensity of reionization) are able to explain power spectra
- ...and so can WDM with a reasonable thermal history

What is known about the IGM thermal history?

Current measurements of IGM temperature



(1306.2314)

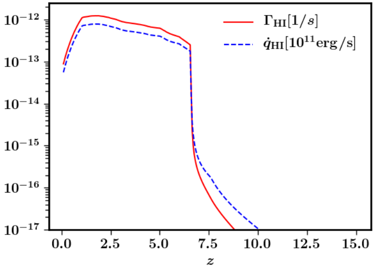


(1708.04913)

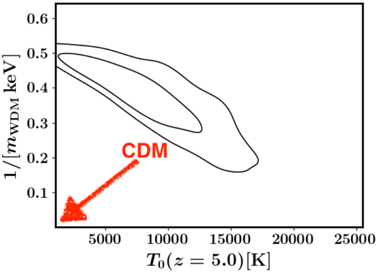
- There are many measurements at $z < 5$
- There is a single measurement **above** $z = 6$
- History of reionization at higher redshifts is poorly constrained

Warm dark matter may have been discovered

Garzilli, Boyarsky, Ruchaiskiy,. . . 2015, 2018, 2019



(**Onorbe et al. 2016**)



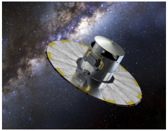
(**Garzilli et al. [1912.09397]**)

- Universe reionizes late
- CDM is ruled out for such reionization scenario (even if instantaneous temperature is varied)

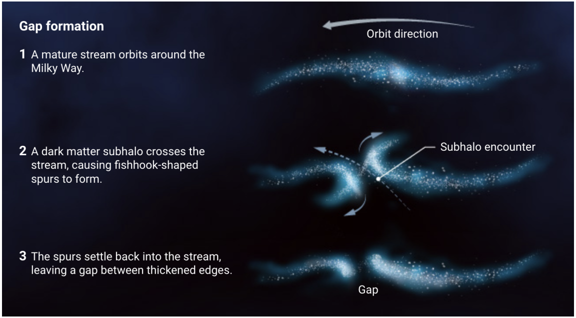
WDM effects and thermal effects have different redshift dependence. More data are on the way, we can distinguish between them!

Way 3: Stellar stream gaps

E.Hand, Science (2018)

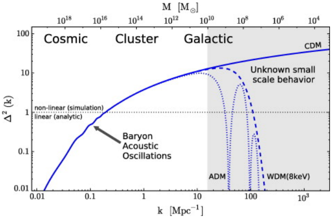


- Thanks to Gaia we know much better the structure of the Milky Way
- In particular many **stellar streams** – distrupted dwarf galaxies – have been discovered



What does this mean for particle physics?

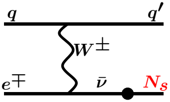
- If one of these methods shows convincing deviation from CDM – what does this mean for particle physics?
- How can particle physics help to identify a microscopic model beyound "non-CDM"?

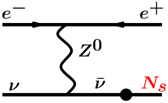


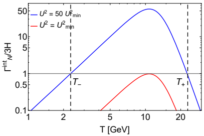
Light new physics

- Although this is not a theorem, but **generically** deviations from CDM would strongly suggest that **new light physics exists**
- This can mean that
    1. Dark matter particles are **light**.
    2. Mediators with the "**dark sector**" are light (mediators)
    3. Both!

Example 1: HNL – "naturally warm" DM.







- Heavy neutral lepton (HNL) – part of the **neutrino portal**
- In the early Universe mixing angle is **temperature dependent**
- Produced via freeze-in

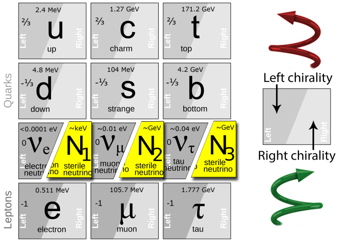
(**Dodelson & Widrow'93; Shi & Fuller'98; Abazajian et al.'00; Asaka, Laine, Shaposhnikov'06-08**)

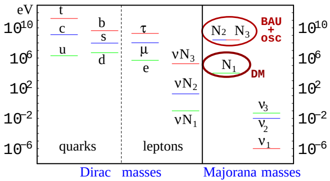
- Production is effective at temperatures

$$T_{max} = 150\,\mathrm{MeV}\left(\frac{M_{dm}}{\mathrm{keV}}\right)^{1/3}$$

- ...and average momentum $p \sim T_{max} \gg M_{dm}$ – **warm dark matter**
- Production is sensitive to the presence of lepton asymmetry in the primordial plasma (MSW-like effect)

HNL DM as a part of full model





Heavy neutral leptons can explain ...

- ... neutrino oscillations

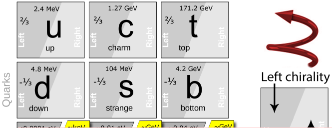
  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80

- ... Baryon asymmetry

  Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05; Shaposhnikov+'05–

- ... Dark matter

  Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00; Abazajian+; Asaka, Shaposhnikov, Laine'06 –



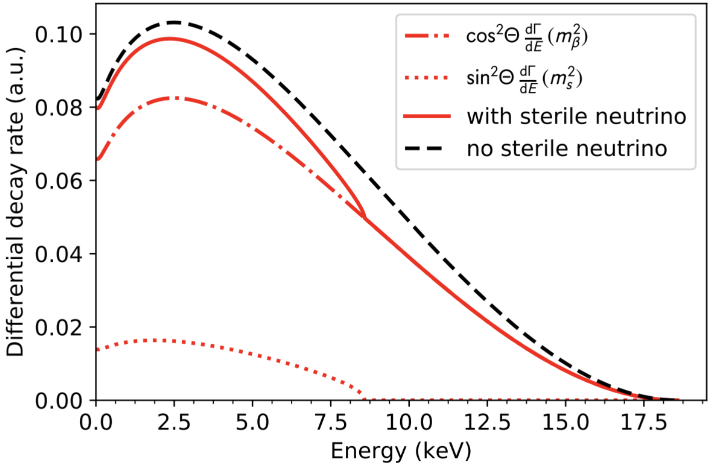
Heavy neutral leptons can explain . . .

Heavy neutral leptons can explain all of it

- **Neutrino Minimal Standard Model (νMSM)**
  Asaka & Shaposhnikov'05 + . . . hundreds of subsequent works
- Minimal complete extension of the Standard Model
- Masses of HNL are of the order of masses of other leptons
- **Reviews: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]**

Signature of keV sterile neutrino detection

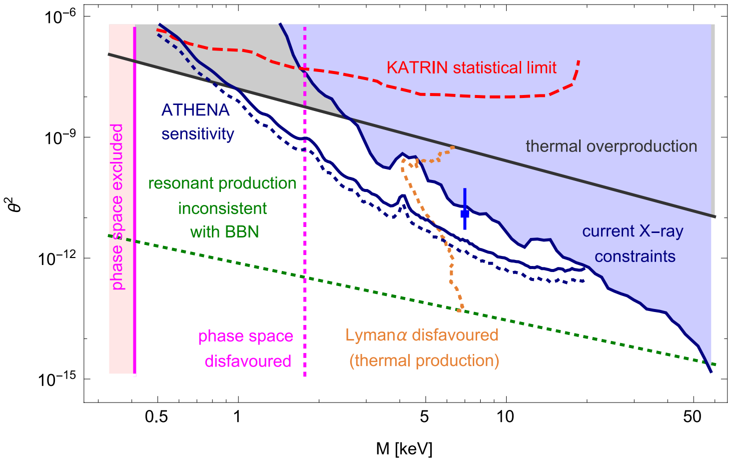
Detection idea: look for a **reaction** $\mathrm{T} \rightarrow^3 \mathrm{He} + e^- + N$



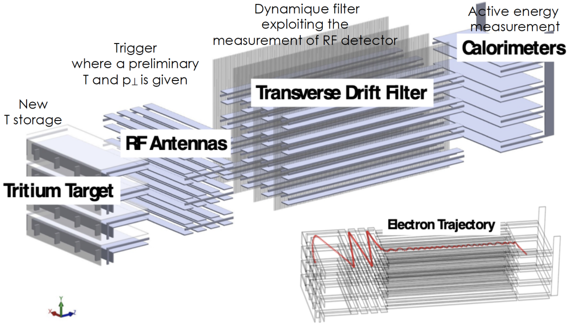
Searching for sterile neutrinos in lab. . .

. . . in the grand scheme of things

Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy [1807.07938]



PTOLEMY experiment



Goals:

1. Detect CNB
2. Accurate measurement of m_ν (anyway necessary before detecting CNB)
3. eV and/or keV sterile neutrino detection (?)

Key challenges:

1. Statistics: extreme amount of tritium
2. Systematics: extreme energy resolution is required
3. Extreme background rates from the target

Constraining sterile neutrino

- Constraining sterile neutrino in the lab is more than challenging
- Fortunately, sterile neutrino has a number of distinct astrophysical/cosmological signatures that can be used to explore its properties
- Together with laboratory searches for heavier sterile neutrinos this may allow to explore parameter space of the minimal sterile neutrino model