Dark Matter Theory
Lecture 3

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We reviewed what we know about DM:

- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit $\sigma_{\rm self}/{\rm m} \leq 2$ barn/GeV**
- **6- Mass within some 90 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm** (NR or quasi when $T \sim$ keV)
- **8- Particle DM requires Beyond Standard Model physics**

CAVEAT: Most DM candidates are relics from the pre-BBN era, from which we have no data. We can think of them as the earlier probes of cosmology in the Universe

- **We talked about several particle DM candidates**
  - CDM, WDM, PIDM, DDDM, SIDM?
  - Kinetic mixing, Hidden or dark photons, Atomic DM, Mirror DM, WIMPs, FIMPs, SIMPs, Axions, ALPs, WISPs, sterile neutrinos...?
- **and started with thermal particle DM production**
  - "Thermal" DM: produced via interactions with the thermal bath and reach equilibrium with visible matter. Then"decouple" or "freeze-out".
- **Particle DM production mechanisms continue**
  - "Thermal" DM (WIMP, SIDM)
  - "Non-thermal" DM: particles produced via other mechanics:
  - "freeze-in" due to out of equilibrium annihilations or decays (FIDM)
  - "freeze-in" due quantum mechanical flavor oscillations (sterile neutrinos)
  - boson condensate formation (axions)
  - decay of particles with thermal abundance or not, or the decay of strings,(axions)

Thermal relics

At high T, $\Gamma_A > H$ for particles that are in equilibrium, but Γ_A decreases with decreasing T faster than $H \simeq T^2/M_P$, and crosses H at chemical decoupling or freeze-out $T = T_{fo}$:

$$\Gamma_A(T_{fo}) = \langle \sigma_A v \rangle_{T=T_{fo}} n_{EQ}(T_{fo}) \simeq H(T_{fo})$$

Estimates offer cross sections annihilation into light SM fermions of mass $m_f <<$ T via the exchange of a mediator of mass M and coupling g:

- For relativistic particles, $m < T$: $\sigma_A^R \simeq \dfrac{g^4}{M^4} T^2$.

(For weak interactions $g^4/M^4 \simeq G_F^2$ and $G_F \simeq 10^{-5}$/GeV^2 is the Fermi constant).

- For non-relativistic DM particles, $M > m > T$: $\sigma_A^{NR} \simeq \dfrac{g^4}{M^4} m^2$

- For non-relativistic DM particles, $m >> T, M$: $\sigma_A^{NR} \simeq \dfrac{g^4}{m^2}$

Decoupling of Relativistic Particles $m < T$ (active neutrinos)

Back-of-an-envelope calculation (literarily!) Use $n \simeq T^3$, $\rho_{rad} \simeq T^4$, $\sigma \simeq (g_w^4/m_Z^4)T^2 \simeq G_F^2 T^2$
Thus, at decoupling

$$\Gamma \simeq n\sigma c \simeq T_{fo}^3 G_F^2 T_{fo}^3 \simeq G_F^2 T_{fo}^5 = H = \sqrt{\frac{8}{3}\pi G \rho} \simeq \frac{T_{fo}^2}{M_{Planck}}$$

putting numbers in, this implies

$$T_{fo} \simeq \text{MeV}$$

Recall, the Fermi constant $G_F \simeq 10^{-5}/\text{ GeV}^2$
Gravity const. $G = 1/M_{Planck}^2$, $M_{Planck} \simeq 10^{19}$GeV. RD Universe: $\rho = \rho_{rad} \simeq T^4$.

This is when BBN is starting, so we know the universe is radiation dominated then.
(Since $n_{EQ} \sim T^3$ the frozen species still track the equilibrium density. Just after e^+e^- annihilate, heat-up γ's $T_\nu = (4/11)^{1/3}T$ and $n_{\nu_i} = (3/4)(T_\nu/T)^3 n_\gamma$)

Chemical Decoupling or freeze-out of Non-Relativistic particles $T < m$

Another back of an envelope calculation. Until the moment of freeze-out the DM is in equilibrium $n = n_{EQ}$ and n_{EQ} is a function of T, $n_{EQ}(T)$ thus

$$\Gamma(T_{f.o.}) = \sigma v \; n_{EQ}(T_{f.o.}) = \sigma v \left(\frac{mT_{f.o.}}{2\pi}\right)^{3/2} e^{-m/T_{f.o.}} = H(T_{f.o.}) \simeq T^2_{f.o.}/M_{Planck}$$

Thus $n_{EQ}(T_{f.o.}) \sim T^2_{f.o.}/\sigma v$ To solve this eq. notice that the $e^{-m/T_{f.o.}}$ and the $T^2_{f.o.}$ terms cross when the exp. is of O(1), i.e. $T_{f.o.} \simeq m$, thus when $n_{EQ}(T_{f.o.}) \sim m^2/\sigma v$

After freeze-out the number density only decreases due to the expansion of the Universe: $1/\text{Volume} \sim a^{-3} \sim T^3$. Thus, the DM density at $T < T_{f.o.}$

$$\rho = m \; n(T) = m \; n_{EQ}(T_{f.o.}) \; \frac{T^3}{T^3_{f.o.}} \sim \frac{m^3}{\sigma v}\frac{T^3}{m^3} = \frac{T^3}{\sigma v}$$

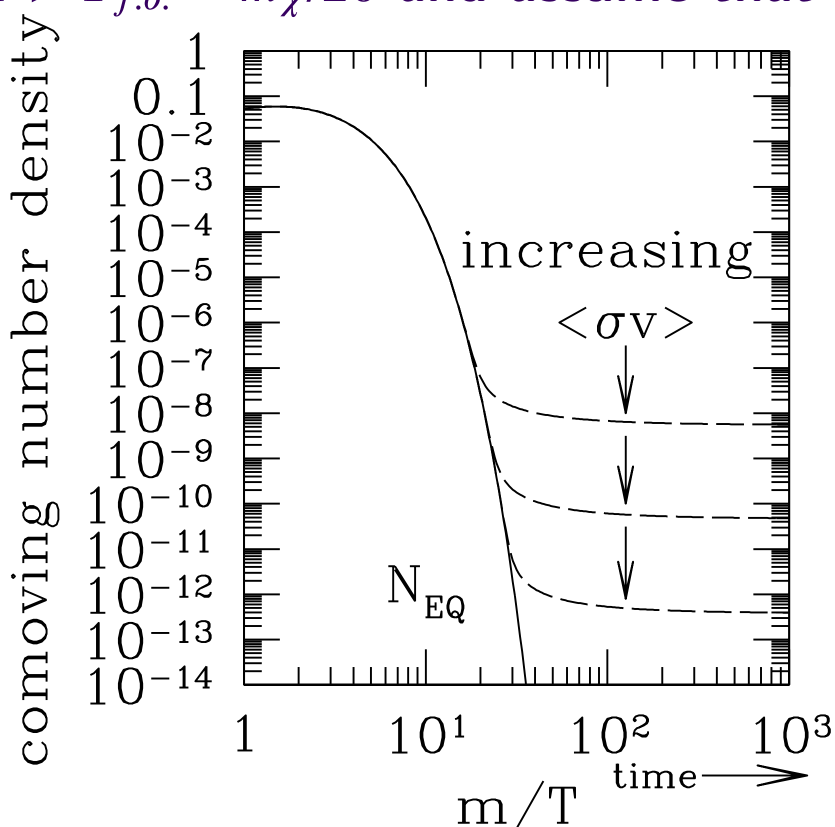
We got the crucial result that the relic density if inversely proportional to the cross section σ (with logarithmic corrections coming from the exponential factor)

"Thermal WIMPs"

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

- WIMPs reach equilibrium while Universe is radiation dominated
- No particle asymmetry
- Chemical decoupling (freeze-out) when $\Gamma_{ann} = \langle\sigma v\rangle\, n \leq H$,
- No entropy change in matter+radiation

$$\Omega_{std} h^2 \approx 0.2\, \frac{3\times 10^{-26} cm^3/s}{\langle\sigma v\rangle}$$



Weak annihilation cross section $\sigma_{annih} \simeq G_F^2 T^2 \simeq 3\times 10^{-26} cm^3/s$ is enough to get $\Omega = \Omega_{DM} \simeq 0.2$!
"WIMP Miracle"

(Fermi-LAT limit on "WIMP Miracle" with s-wave scattering (σv independent of v) m>60 GeV)

$<\sigma v>$= average over a thermal momenta distrib. (aver. over initial and sum over final states)

"Thermal WIMPs"

The freeze-out for weak-strength interactions occurs at $x_{fo} \equiv m/T_{fo} \simeq 20$, when the typical WIMP speed is $v_{fo} = (3T_{fo}/m)^{1/2} \simeq 0.27c$, and the relic density is

$$\Omega h^2 \simeq 0.1\left(\frac{x_{fo}}{20}\right)\left(\frac{60}{g_{eff}}\right)^{1/2}\frac{3\times 10^{-26}\ cm^3/s}{a+(3b/x_{fo})},$$

where $\left\langle \sigma_A^{NR} v\right\rangle \simeq a + b\langle v^2\rangle + O(v^4)$
a and bv^2 correspond to s-wave and p-wave annihilation, respectively.

in the SM: g_{eff} =10.75 at 1MeV $< T <$ 100 MeV
g_{eff} $\simeq$60 above the QCD phase transition
g_{eff} $\simeq$100 at $T > m_{\text{top}}$

Kinetic Decoupling of Non-Relativistic particles $T < m$

At **chemical decoupling or freeze-out**: the number density is fixed.
At **kinetic decoupling**: the exchange of momentum with the radiation bath ceases to be effective. It happens after chemical decoupling:

The fraction of the WIMP momentum lost per collision is small (T/M) thus

$$\Gamma_{E-loss} \simeq n\sigma_{scatt}\frac{T}{M} << \Gamma_{annih}$$

$$T_{k.d.} \simeq 15 \text{ MeV}\left(\frac{m}{100\text{GeV}}\right)^{1/4} << T_{f.o.} \simeq 5 \text{ GeV}\left(\frac{m}{100\text{GeV}}\right)$$

More accurate calculations give a range of 10 MeV to a few GeV for T_{kd} (Profumo, 2006).

At kinetic decoupling, WIMPs are in thermal equilibrium with the radiation, and their characteristic speed is $v(T_{kd}) \simeq \sqrt{T_{kd}/m}$. At $T < T_{kd}$, v redshift: $v \sim a^{-1} \sim T$

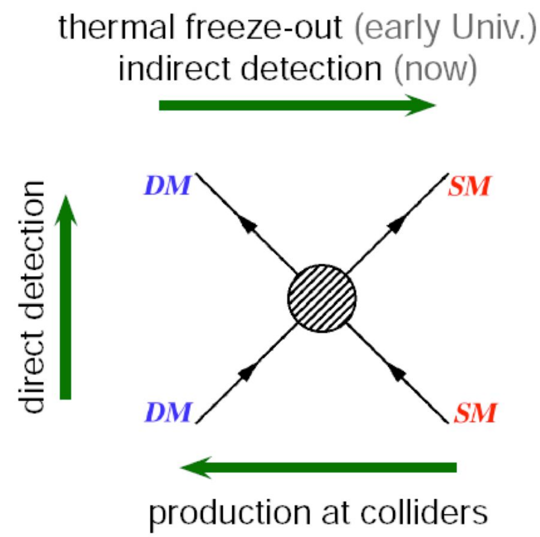
$$v_{\text{WIMP}}(T) \simeq \sqrt{\frac{T_{kd}}{m_\chi}\left(\frac{T}{T_{kd}}\right)}$$

until WIMPs fall into structures and get their viral velocity.

WIMP DM searches:

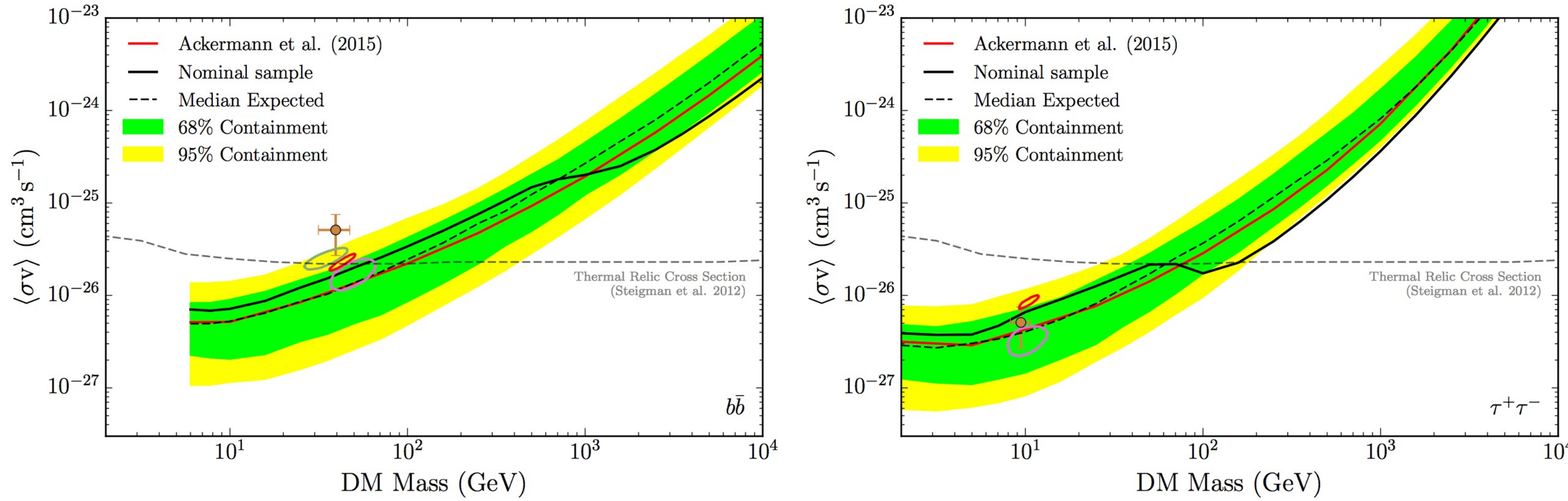
(lectures of Kendall Krauss)

- 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



Notice that indirect detection tests DM annihilation, thus thermal freeze-out

Upper limit on annihilating DM from Fermi ST 95% CL upper limits, 6 y of Fermi Large Area Telescope (LAT)- 15 stacked dwarfs 1611.03184

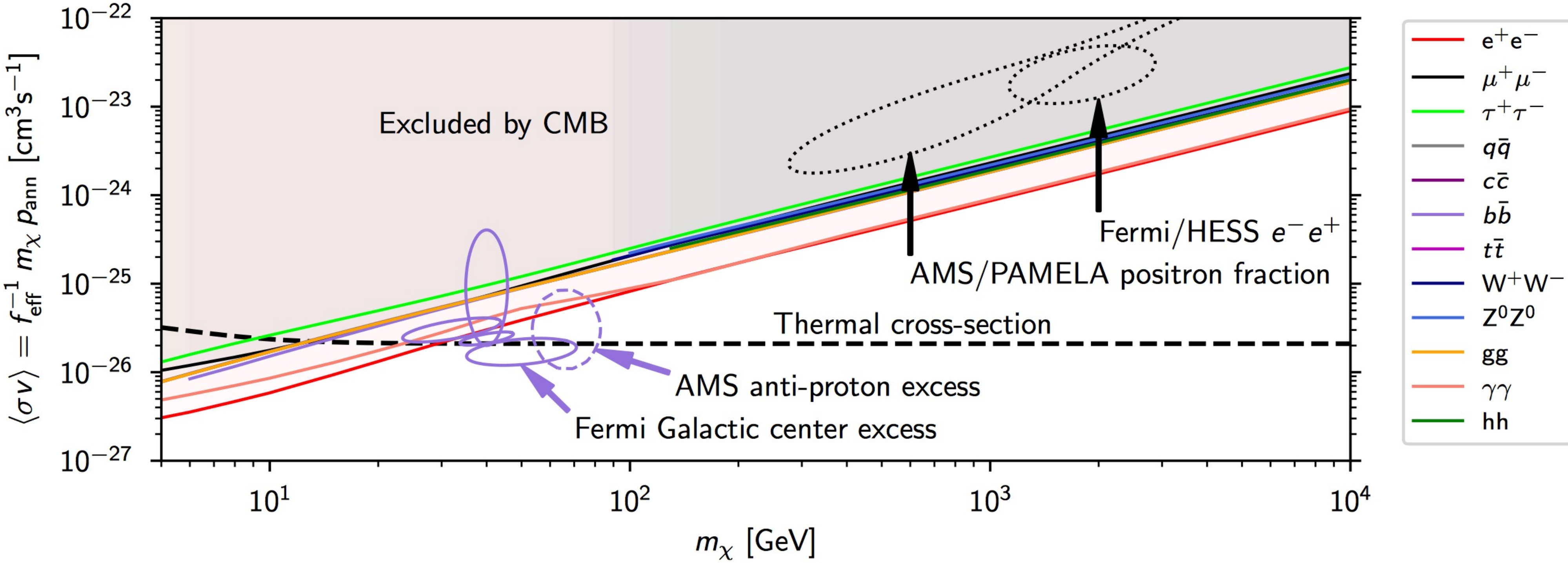


Shown are to the GC excess. They are in tension with the upper limit.

This analyses rules out the "WIMP miracle" benchmark annihilation cross section ($< \sigma_{annih} v > \simeq 2 \times 10^{-26}$ cm^3/s) for masses up to ≃60 GeV for s-wave annihilation, i.e. v-independent $\sigma_{annih} v$. For p-wave annihilation $\sigma_{annih} v \sim v^2$, so it is 10^5 times larger at WIMP decoupling ($v \simeq 0.3$c) than in the galaxy ($v \simeq 10^{-3}$c)

CMB limits on DM annihilation cross sections

Planck 2018, 1807.06209



DM annihilations which would heat up the Universe close to recombination would leave an imprint in the CMB- Limits due to the total electromagnetic power injected, so they extend to lower masses too. Do not apply to p-wave annihilation (e.g. $m = 100$ GeV, at $T = 10$eV, $v \simeq 10^{-8}$- so limit is $\times 10^{16}$)

Indirect limits on DM annihilation cross sections

1- CMB anisotropy precision measurements (Planck and others) Constrain DM annihilations (or decays) at recombination or after

2- FermiLAT observations of stacked dwarf galaxies Constrain annihilation at present of DM particles bound to galactic haloes

3- Positron spectrum measured by AMS-02 (more precise that earlier measurements) Constrain annihilation at present of DM particles close to Earth

They all imply $< \sigma v >< 3 \times 10^{-26}$ cm^3/s $= \sigma_{th} v$ for WIMP $m < O(10)$ GeV (exact limit depends on annih. mode). $\sigma_{th} v$ is the upper limit of thermal WIMPs (so $\Omega \leq \Omega_{DM}$). This rejects thermal WIMPs $m < O(10)$ GeV if annihilation is in s-wave:$< \sigma v >$ is v independent, but not constraining for p-wave annihilation: $< \sigma v > \sim v^2$. This is so because at freeze-out $v \simeq c/3$ and it is much smaller at recombination and within galaxies.

The original WIMP

Notice 2 GeV for $\Omega_{DM} = 1$, now 4 GeV for 0.25

PHYSICAL REVIEW LETTERS

VOLUME 39 25 JULY 1977 NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
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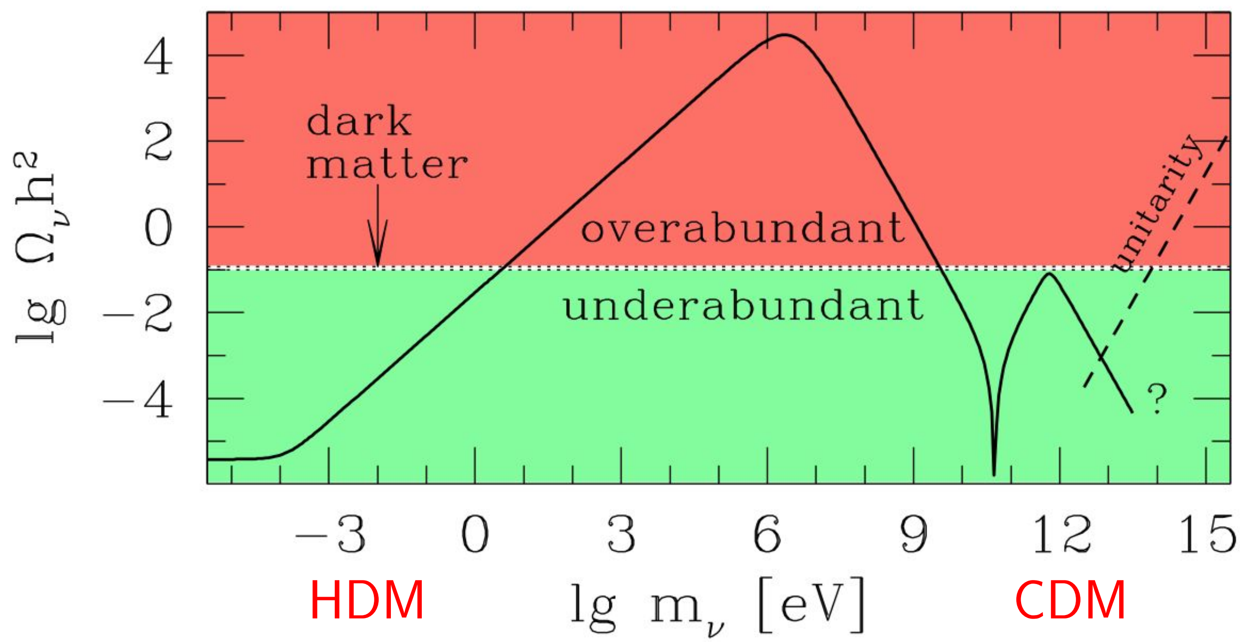
and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

The original WIMP Lee & Weinberg 1977 considered active neutrinos- now 4th generation- took Dirac neutrinos, $\chi \neq \bar{\chi}$ without an asymmetry (Fig from P. Gondolo)



Two solutions for CDM, one at each side of the Z-resonance (dip at 10^{11} eV):
$\sigma \simeq G_F^2 m_\chi^2$ thus $\Omega_\chi h^2 \simeq (GeV/m_\chi)^2$ and $\sigma \simeq g_w^4/m_\chi^2$ thus $\Omega_\chi h^2 \simeq (m_\chi/TeV)^2$
For 4th. gen. active neutrinos, $m < m_Z/2$ forbidden by LEP-but similar for other models

Caveats to Thermal WIMPs as Dark Matter

- Asymmetric DM We owe our very existence to a particle-antiparticle asymmetry so why not also the DM? (Requires non-self conjugated DM candidates- neutralinos are Majorana particles instead) (Nussinov 85; Gelmini, Hall, Lin 87; Kaplan 92; Barr, Chivukula, Fahri 90; Enkvist, MacDonald 98; Gudnason, Kouvaris , Sannino 05; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)
- Non-Standard Pre-Big bang Nucleosynthesis (pre-BBN) cosmology WIMP relic abundance is fixed before BBN, a moment in the Universe from which we have so far no data. (See e.g. Gelmini et al hep-ph/0605016, or Gelmini, Gondolo 1009.3690 and refs. therein)

  $T_{f.o.} \simeq (m/20) > 5$ MeV for $m > 100$ MeV!

  Salas *et al* "Bounds on very low reheating scenarios after Planck" 1511.0067
- WIMPs may be unstable and decay into the dark matter (Super-WIMP scenario). (Feng, Rayaraman, Takayama 03; Feng, Smith 04)
- WIMPs can be produced in decays of other particles (Sigurdson, Kamionkowski 04; Kaplinghat 05)

If DM is Warm, cold WIMP DM could be a subdominant DM component or
WIMPs could be WDM but in this case particle models must be very different from usual- e.g. WIMPs are created late in decays and never reach kinetic equilibrium with the thermal bath

Asymmetric DM (ADM) Idea almost as old as the "WIMP miracle"

For Baryons: if usual decoupling, $\sigma_{strong} \sim 1/m_\pi^2$ emplies $T_{f.o.} \simeq m_N/45$ (but eq. for Ω is very similar- it depends logarithmically on x=20 or x=45).

Predicted: $\Omega_B \simeq 10^{-10}$ and equal numbers of baryons and antibaryons

Observed: $\Omega_B \simeq 0.05$ and only baryons. Thus an early Baryon Asymmetry must exist

$A_B = n_B - n_{\bar{B}}/n_\gamma \simeq 10^{-9}$, and annihilation ceases when no $\bar{B}$ left.

For Dark Matter particles: assume A_{DM} and A_B generated by similar physics,

1985: Nussinov, if technibaryon and baryons have same number density then $\Omega_{DM}/\Omega_B = m_{TB}/1$ GeV (with $\Omega_{DM} \simeq 1$, $m_{TB} \simeq 100$GeV!)

1986: Gelmini, Hall and Lin, proposed model a for "cosmions" ($m_C = 5$ to 10 GeV) with $B - C$ number conserved and the same asymmetry is produced for both (when "cosmions" were abandoned to explain the solar-neutrino problem this paper was largely forgotten!- also we could account "only" for $\Omega_{DM} \simeq 0.2$)

Asymmetric DM (ADM) Idea almost as old as the "WIMP miracle"

assume A_{DM} and A_B generated by similar physics,

$A_{DM} \simeq A_B$ so $n_{DM} \simeq n_B$

$$\frac{\Omega_{DM}}{\Omega_B} \simeq \frac{n_{DM} m_{DM}}{n_B m_N} \simeq \frac{m_{DM}}{m_N}$$

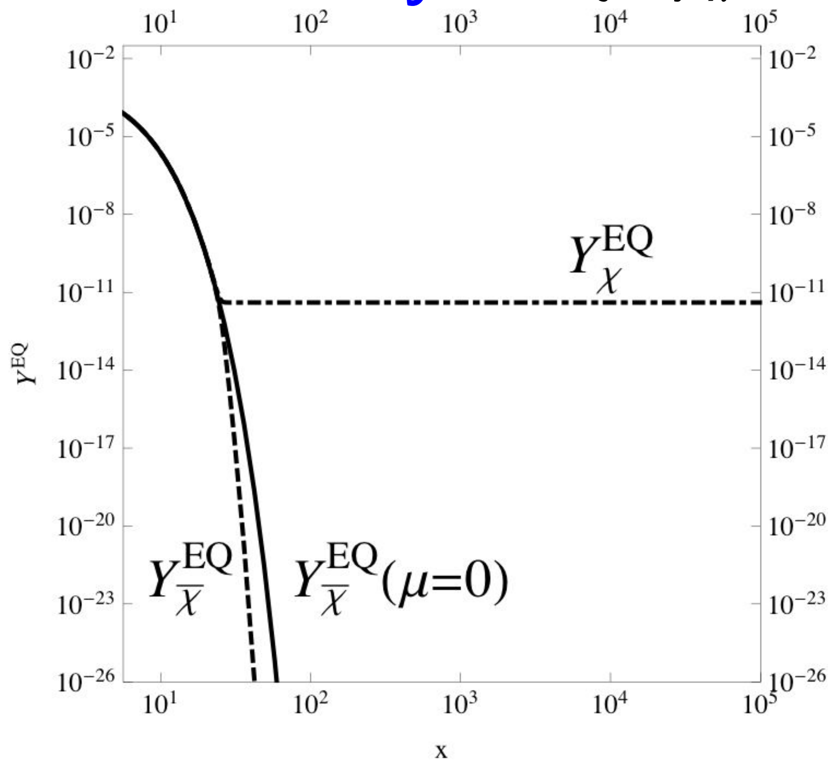
$\Omega_{DM}/\Omega_B \simeq 5$ if $m_{DM} \simeq 5$ GeV. So ADM explains why $\Omega_{DM}/\Omega_B \simeq O(1)$

GeV scale ADM in hidden/mirror sector, or pNGB in Technicolor or low scale strong interactions....
Also possible TeV scale ADM in Technicolor: $A_{DM} \simeq A_B \ (-m_{DM}/T_{weak})$

(Nussinov 85; Gelmini, Hall, Lin 87; Barr, Chivukula, Fahri 90; Barr, 1991; Kaplan 92; Enkvist, MacDonald 98; Dodelson, Greene and Widrow, 1992; Fujii and Yanagida, 2002); Kitano and Low, 2005; Gudnason, Kouvaris , Sannino 05; Kitano, Murayama and Ratz, 2008; Kaplan, Luty, Zurek 09 [which now has 180 citations]; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)

Main characteristic: no annihilation rate after freeze-out.
But this is a pre-BBN cosmology dependent statement Gelmini, Huh, Rehagen 1304.3697

Asymmetric DM relic density with majority χ and minority $\bar{\chi}$ components



If $Y - \bar{Y} = A$, when Y_χ^{EQ} becomes A, $\Gamma_{\bar{\chi}}^{EQ} \sim n_\chi^{EQ} \sim AT^3$ while $n_{\bar{\chi}}^{EQ} \sim \Gamma_\chi^{EQ}$ decreases exponentially small until $\bar{\chi}$ freezes-out, when $\Gamma_{\bar{\chi}}^{EQ} \simeq H$. (Gelmini, Huh, Rehagen 1304.3697

DM as the earliest relic, from before BBN

Relic densities change in non-Standard pre-BBN Cosmologies

- **Increase** the density by increasing the expansion rate at freese-out [e.g. quintessence and scalar-tensor models] or by creating DM from particle (or topological defects) decays [non-thermal production].
- **Decrease** the density by reducing the expansion rate at freese-out [e.g. scalar-tensor models], by reducing the rate of thermal production [low reheating temperature] or by producing radiation after freeze out [entropy dilution].

Non-std scenarios are more complicated (baryon number generation, for example). They contain additional parameters that can be adjusted to modify the DM relic density. However these are due to physics at a high energy scale, and do not change the model at the electroweak scale.

Non std pre-BBN cosmologies

- **Models that only change the pre-BBN Hubble parameter H**

  These models alter the thermal evolution of the Universe without an extra entropy production.

- **Low temperature reheating (LTR) models**

  A scalar field φ oscillating around its true minimum while decaying is the dominant component of the Universe.
  Entropy in matter and radiation is produced: not only the value of H but the dependence of the temperature T on the scale factor a is different.

Models that only change the pre-BBN H

The change in Ω_χ is more modest than in LTR models

- Extra contributions to ρ_U increase H (increases Ω_χ):

  -Brans-Dicke-Jordan cosmological model Kamionkowski, Turner-1990

  -models with anisotropic expansion Barrow-1982; Kamionkowski, Turner-1990; Profumo, Ullio-2003,

  - scalar-tensor models Santiago, Kalligas, Wagoner-1998, Damour, Pichon-1998, Catena, Fornengo, Masiero, Pietroni, Rosati; 2004; Catena, Fornengo, Masiero, Pietroni, Schelke-2007

  -kination models Salati-2002, Profumo, Ullio-2003

  -and other models Barenboim, Lykken-2006 and 2007; Arbey, Mahmoudi-2008

- H may be decreased (decreases Ω_χ) in some scalar-tensor models Catena, Fornengo, Masiero, Pietroni, Schelke-2007

$H(T)$ for several pre-BBN cosmological models

"LTR": Low T_{RH}

.

"K": kination

.

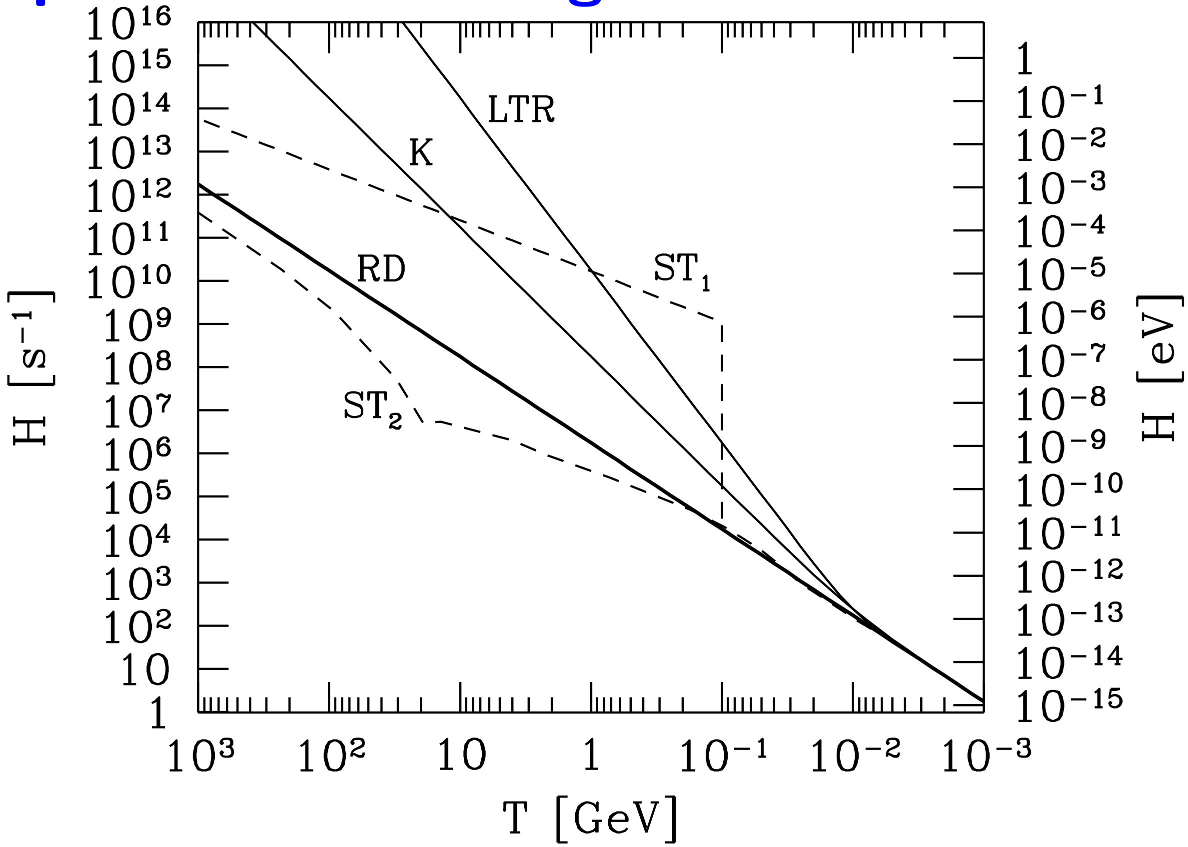
"ST1": scalar tensor with H increase

.

"RD": radiation-dom.

.

"ST2" : scalar tensor with H decrease



e.g old example: 1700 MSSM Models

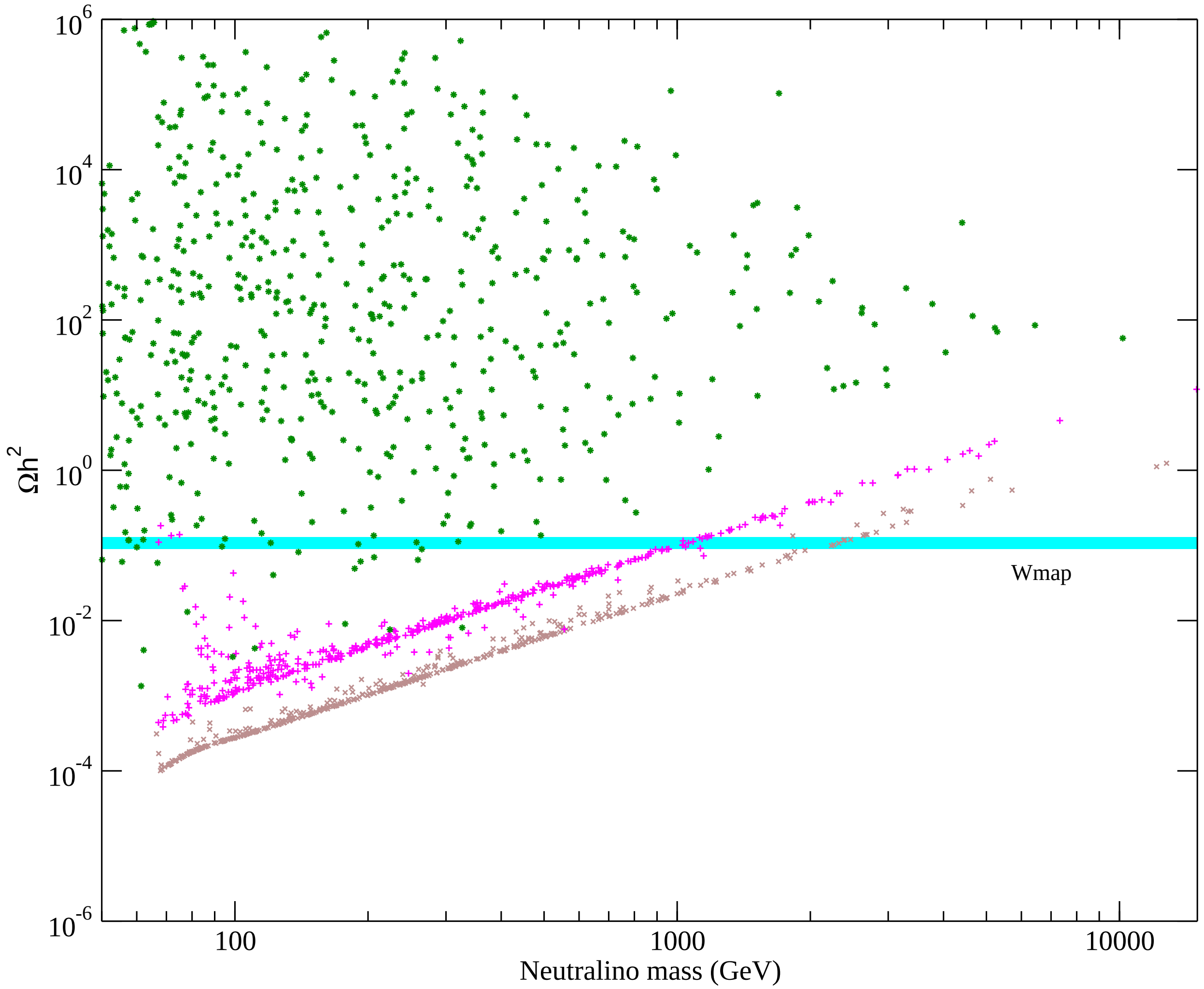
Standard cosmology

Gelmini, Gondolo, Soldatenko and Yaguna,PRD 74: 083514, 2006

bino-like: overdense or tuned

higgsino-like: underdense or m$\simeq$ 1TeV

wino-like: underdense or m$\simeq$ 2TeV



Neutralino LSP relic abundance in the standard pre-BBN cosmology

- LSP= $\widetilde{B}$ (typical in CMSSM) is OVERDENSE
  (σ_{annih} into $f\bar{f}$ through $\widetilde{f}$ exchange is helicity suppressed $\sim m_f$)

- LSP= $\widetilde{H}$ and $\widetilde{W}$ (not GU, AMSB) is UNDERDENSE
  unless $m \simeq$ TeV (large σ_{annih} into W^+W^-, ZZ, or $f\bar{f}$)

- RIGHT ABUNDANCE for $m <$ TeV's requires a special condition
  – Mixed composition (in CMSSM:"focus point"),
  – pole enhancement of σ_a ($m_\chi \simeq m_A/2$: "A-funnel region"- CP-odd Higgs A)
  –"coannihilation" between the LSP and the NLSP (Next to LSP- stop or other squarks)

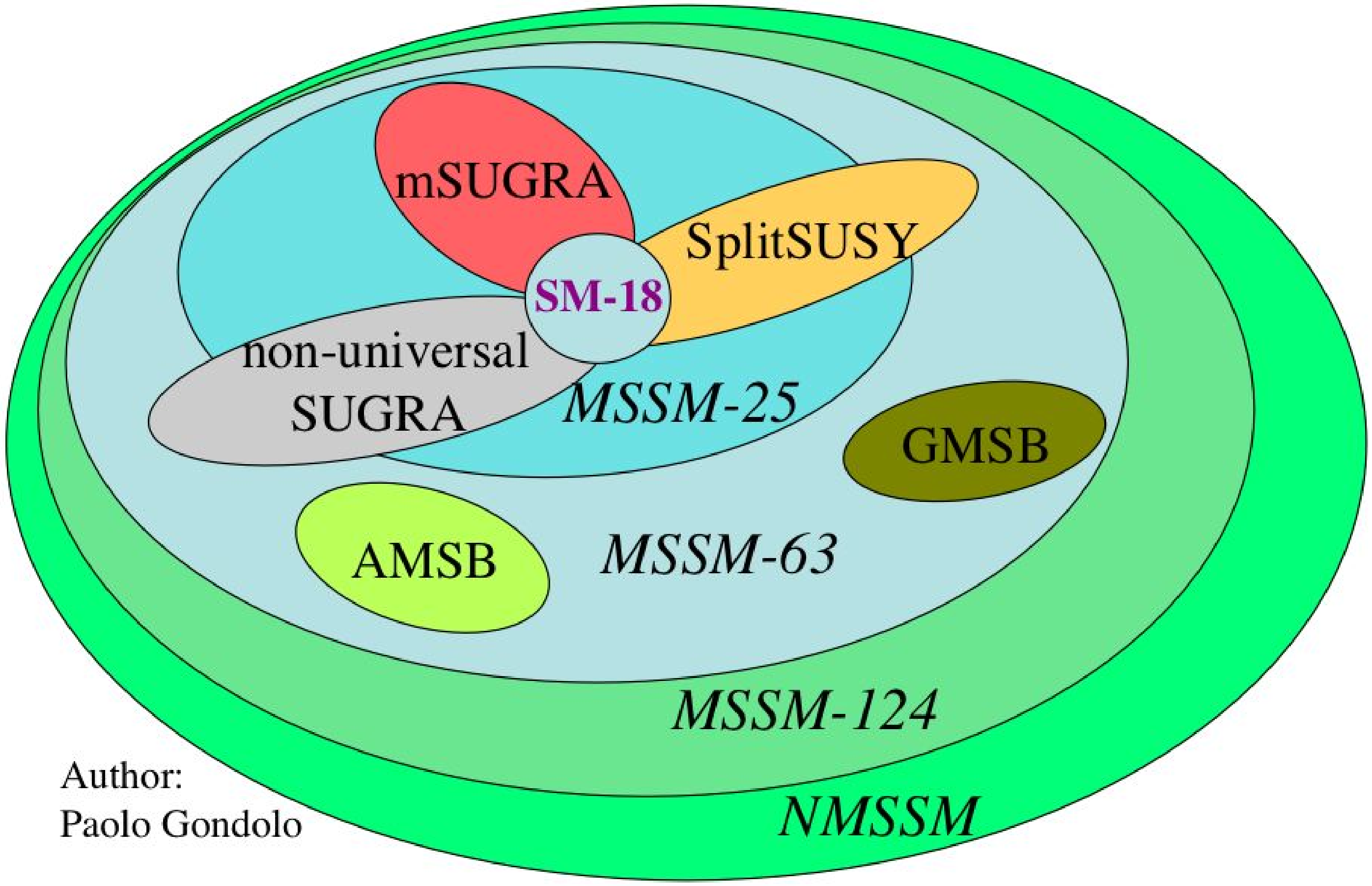
Many many versions of SUSY- Many parameters

MSSM

- Minimum number of particles (SUSY partners+ two Higgs doublets)
- Number of parameters: 18 of the SM + 106!!!
- Parameter reduction:
  - wMSSM: simplified weak-scale MSSM: SM + 7 p. $(M_2, \mu, \beta, m_A, \widetilde{m}, A_b, A_t)$
  - CMSSM: constrained MSSM: SM+5 parameters $(m_0, A_0, m_{1/2}, \beta, \mu)$
  - mSUGRA: minimal supergravity: SM+5 parameters $(m_0, A_0, m_{1/2}, \beta, sign\ of\ \mu)$
  - many more....

NMSSM

- Non Minimum number of particles (extra singlet Higgs, etc)


mSUGRA
SplitSUSY
SM-18
non-universal
SUGRA
MSSM-25
GMSB
AMSB
MSSM-63
MSSM-124
Author:
Paolo Gondolo
NMSSM

MSSM + Late decaying scalar field in Dark SUSY

(G.G., Gondolo, Soldatenko and Yaguna, PRD 74:083514, 2006)

We performed a random scan in 9 parameters in the ranges:

$$10 \text{ GeV} < M_i, m_A, \mu < 50 \text{ TeV}$$

$$10 \text{ GeV} < m_0 < 200 \text{ TeV}$$

$$-3m_0 < A_t, A_b < 3m_0$$

$$1 < \beta < 60$$

The sign of μ was randomly chosen.

Accelerator constraints (as contained in DarkSUSY version 4.1)
1700 models (points) for each η, T_{RH} pair.

mSUGRA, mAMSB or split-SUSY are similar to - though not necessarily coincide with - particular examples of these models

MSSM

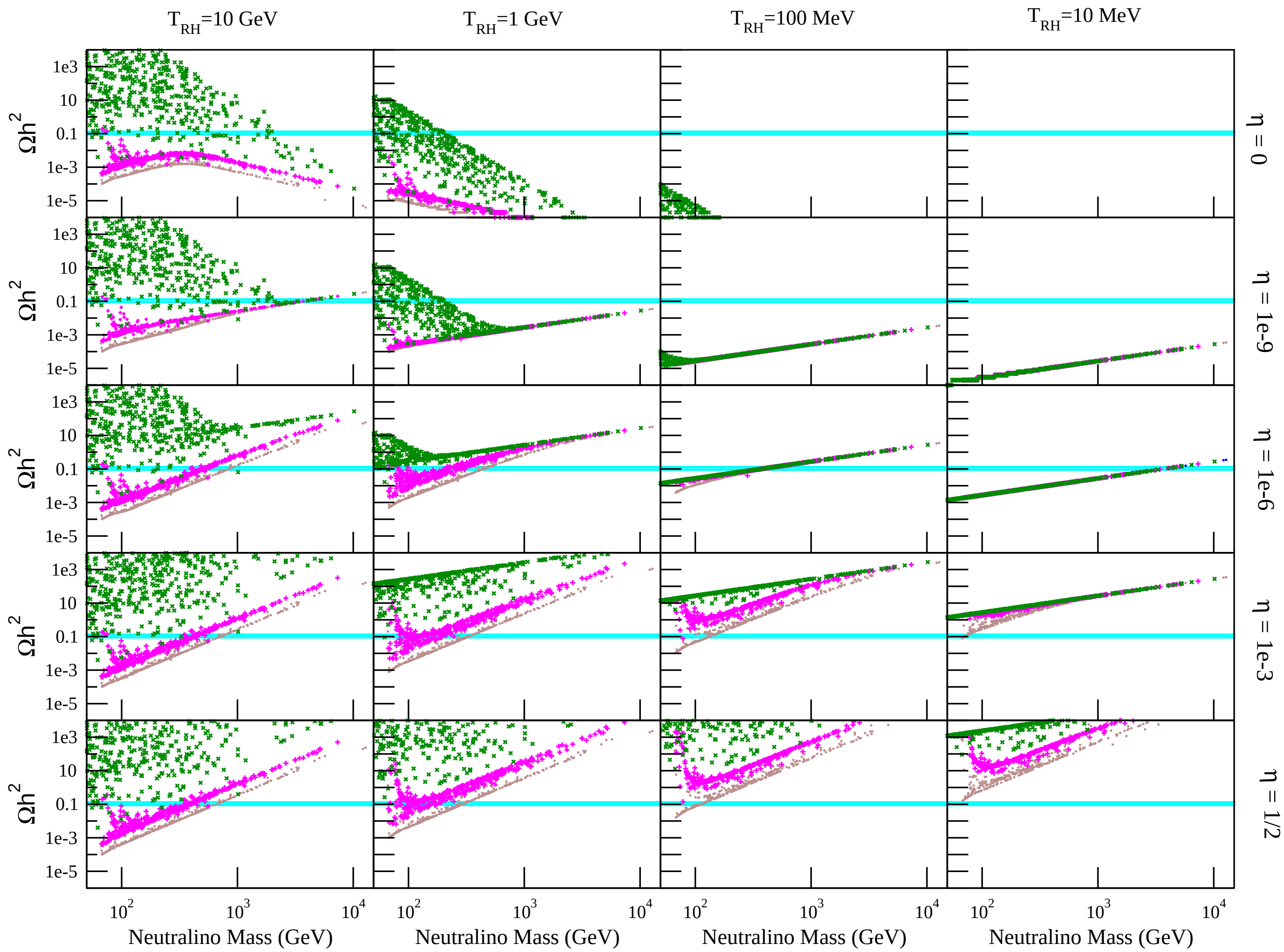
G.G., Gondolo, Soldatenko and Yaguna, 2006

With LTR all points can be brought to cross the DM cyan line with suited T_{RH}, η

bino-like

higgsino-like

wino-like



WIMP density as cosmology probe

Use WIMP properties to find out about the cosmology before BBN...

This is not a new idea

MASSIVE PARTICLES AS A PROBE OF THE EARLY UNIVERSE

John D. BARROW

Astronomy Centre, University of Sussex, Brighton BN1 9QH, UK

Received 29 January 1982
(Revised 30 March 1982)

The survival density of stable massive particles with general annihilation cross section is calculated in a cosmological model that expands anisotropically in its early stages ($t < 1$ s). It is shown that the faster average expansion rate leaves a larger present density of surviving particles than in a model that expands isotropically. This allows particle survival calculations to be employed as a probe of the dynamics of the early universe prior to nucleosynthesis. Several examples of heavy lepton, nucleon and monopole survival are discussed.

WIMP density as cosmology probe

Use WIMP properties to find out about the cosmology before BBN...

This is not a new idea

Thermal relics: Do we know their abundances?

Marc Kamionkowski and Michael S. Turner

Physics Department, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433 and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500

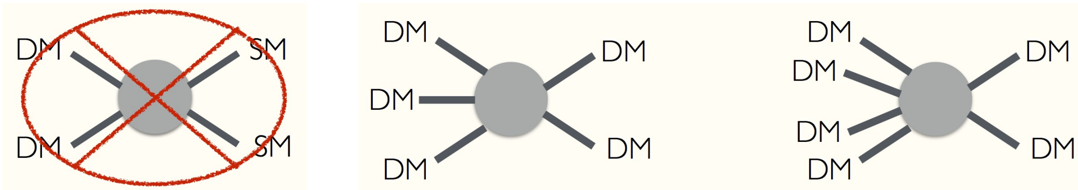
(Received 25 May 1990)

The relic abundance of a particle species that was once in thermal equilibrium in the expanding Universe depends upon a competition between the annihilation rate of the species and the expansion rate of the Universe. Assuming that the Universe is radiation dominated at early times the relic abundance is easy to compute and well known. At times earlier than about 1 sec after the bang there is little or no evidence that the Universe *had* to be radiation dominated, although that is the simplest—and standard—assumption. Because early-Universe relics are of such importance both to particle physics and to cosmology, we consider in detail three nonstandard possibilities for the Universe at the time a species' abundance froze in: energy density dominated by shear (i.e., anisotropic expansion), energy density dominated by some other nonrelativistic species, and energy densi-

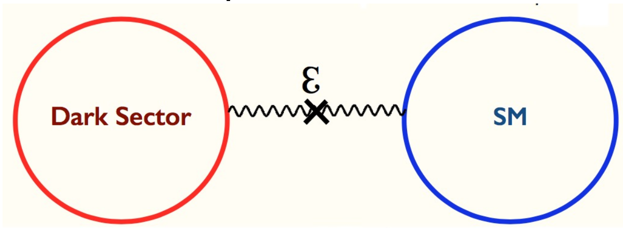
Dark-sector thermal production: Freeze-out of SIMPs

Hochberg, Kuflik, Volansky & Wacker, 1402.5143; Kuflik, Hochberg, Murayama, Volansky & Wacker, 1411.3727

Assumes



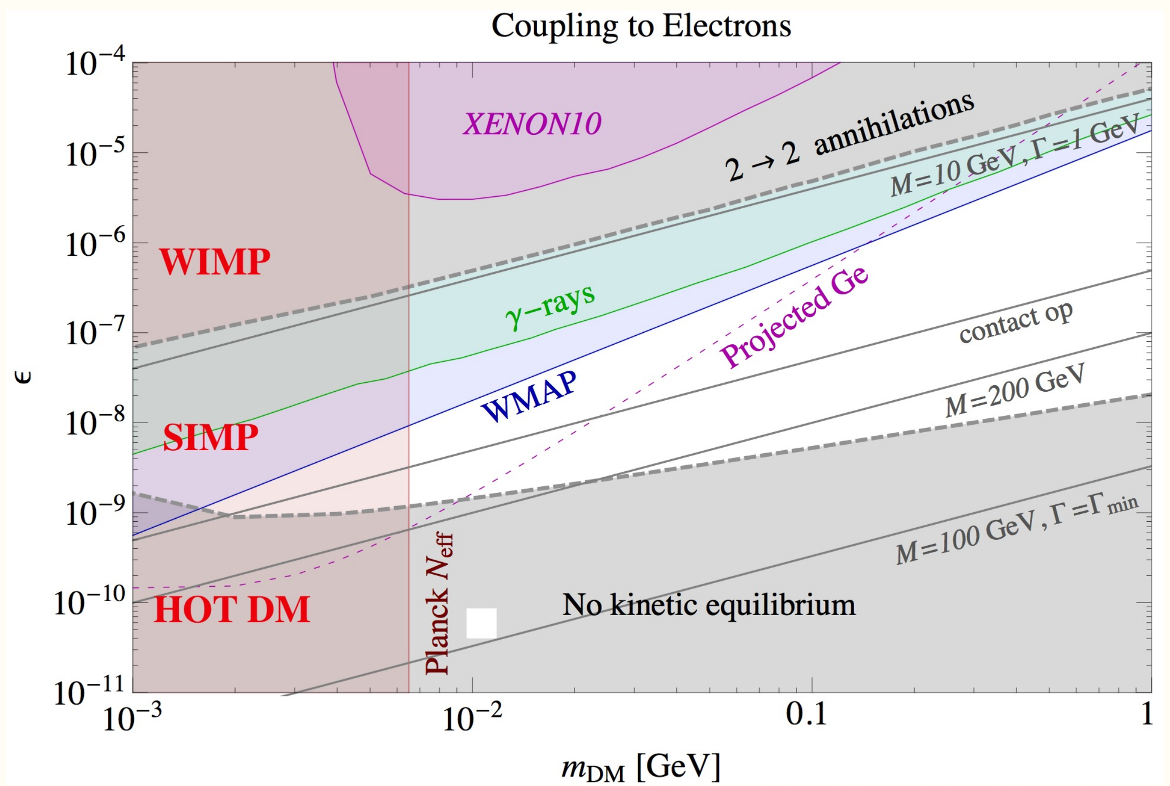
The 3 or 4 DM → 2 DM processes reduce n_{DM} when $T < m_{DM}$ and heat up the DM. So as to not end as Hot DM there must be kinetic coupling (i.e. effective momentum exchange) with visible matter. This also equalizes the temperature in both sectors



3→2 freeze-out: $\Gamma \simeq n_{DM}^2 \left(\alpha_{eff}^3 / m_{DM}^5\right) \simeq H(T)$, with $x_{fo} \simeq 20$, then $m_{DM} \simeq$ 40MeV, $T_{fo} \simeq$ 2MeV
4→2 freeze-out: $\Gamma \simeq n_{DM}^3 \left(\alpha_{eff}^4 / m_{DM}^8\right) \simeq H(T)$ for $x_{fo} \simeq 14$ (from solving the Boltzmann eq.) implies $m_{DM} \simeq$ 100keV and $T_{fo} \simeq$ 7keV (f.o is after BBN)
(The quantities in the large brackets are here obtained just on dimensional grounds).

Dark-sector thermal production: Freeze-out of SIMPs

For $\mathscr{L}_{int} = (m_e/M^2)\ \chi^\dagger \chi\ \bar{e}e$, and ε defined as $<\sigma v>_{kin} = (\varepsilon^2/m^2_{DM})$ so $\varepsilon \simeq (m_e m_{DM}/M)^2$



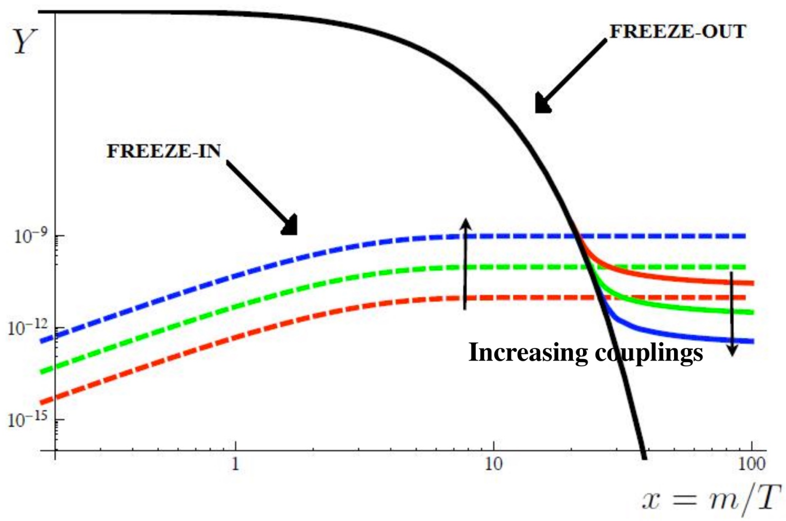
SIMPs are candidates for LDM (sub-GeV to keV or lighter DM) and for Self-Interacting DM (SIDM)

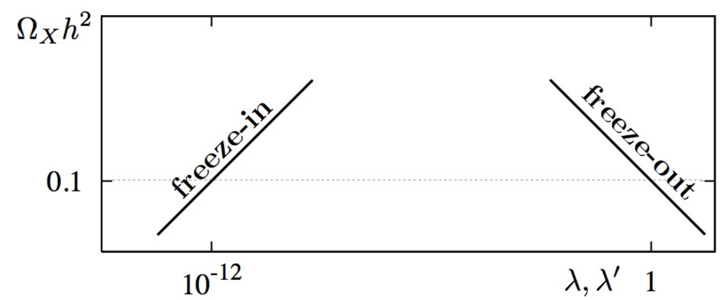
Non thermal mechanism: Freeze-in of FIMPs

Hall, Jedamzik, March-Russell & West, 0911.1120...; see e.g. Bernal, Heikinheimo, Tenkanen, Tuominen &Vaskonen 1706.07442 and refs. therein

FIMPs: produced at a low rate from other particles, never reach equilibrium with the bath. Cannot usually be tested by experiments but by cosmological and astrophysical observations. Ex. of the Higgs Φ portal Lagrangian for a hidden sector FIMP, a real singlet scalar S, $\lambda_{sh} < 10^{-7}$

$$V(\Phi, s) = \mu_h^2 \Phi^\dagger \Phi + \lambda_h (\Phi^\dagger \Phi)^2 + \frac{1}{2}\mu_s^2 s^2 + \frac{\lambda_s}{4} s^4 + \frac{\lambda_{sh}}{2} \Phi^\dagger \Phi s^2$$





Larger couplings lead to larger annihilation rate in freeze-out and larger production rate in freeze-in

Non thermal mechanism: Freeze-in of sterile neutrinos

The 3 (left-handed) neutrinos of the SM are called "active neutrinos" because they have full strength weak interactions, but others with no weak interactions (right-handed) thus called "sterile" (Bruno Pontecorvo- 1967) ν_s, can be easily added (one or more).

ν_s can be created via active-sterile neutrino oscillations, either without (Dodelson & Widrow 1994) or with (Shi & Fuller 1998) a large Lepton Asymmetry L (L-driven MSW conversion), and respectively be Warm DM or "less warm" DM.

For two-neutrino active-sterile mixing where $|\nu_{\alpha,s}\rangle$ are interaction eigenstates (α left handed, s right-handed) and $|\nu_{1,2}\rangle$ are mass eigenstates, $m_1 << m_2 \equiv m_s$
$|\nu_\alpha\rangle = cos\theta\ |\nu_1\rangle + sin\theta\ |\nu_2\rangle$;
$|\nu_s\rangle = -sin\theta\ |\nu_1\rangle + cos\theta\ |\nu_2\rangle$

ν_s can also be produced in the decay of other particles (e.g. new scalar fields or heavier sterile neutrinos).

Non thermal mechanism: Freeze-in of sterile neutrinos

Production of sterile neutrinos with no-extra SM interactions via active-sterile oscillations:

• At $t = 0$: produce $\nu_\alpha = \cos\theta \nu_1 + \sin\theta \nu_2$; $\nu_{1,2}$ evolve with different phases, $\approx e^{-itm_i^2/2E}$ for $E >> m_i$.

• At $t > 0$: $\nu(t) = a(t)\nu_\alpha + b(t)\nu_s$, thus $P(\nu_\alpha \to \nu_s) = \sin^2 2\theta \, \sin^2\left(\frac{t}{\ell}\right)$

$\ell = \frac{\Delta m^2}{2E}$ = vacuum oscillation length.

• Matter effects: ℓ, $\sin^2 2\theta \to \ell_m$, $\sin^2 2\theta_m = \left(\frac{\ell_m^2}{\ell^2}\right) \sin^2 2\theta$,

•Collisions: act as measurements, so $t = t_{coll}$

•"Average regime": $t_{coll} >> \ell_m$ so $\langle \sin^2\left(\frac{t_{coll}}{\ell_m}\right)\rangle = \frac{1}{2}$.

Thus, rate of production of sterile neutrinos:

$\Gamma_s \simeq P(\nu_\alpha \to \nu_s)\,\Gamma_\nu \simeq \left(\frac{\ell_m^2}{\ell^2}\right)\sin^2 2\theta\,\Gamma_\nu$, where for negligible L_ν ($\simeq 10^{-10}$)

$$\ell_m \simeq \frac{\ell}{\left\{\sin^2 2\theta + \left[\cos 2\theta - \frac{2E\,V^T}{\Delta m^2}\right]^2\right\}^{1/2}}$$

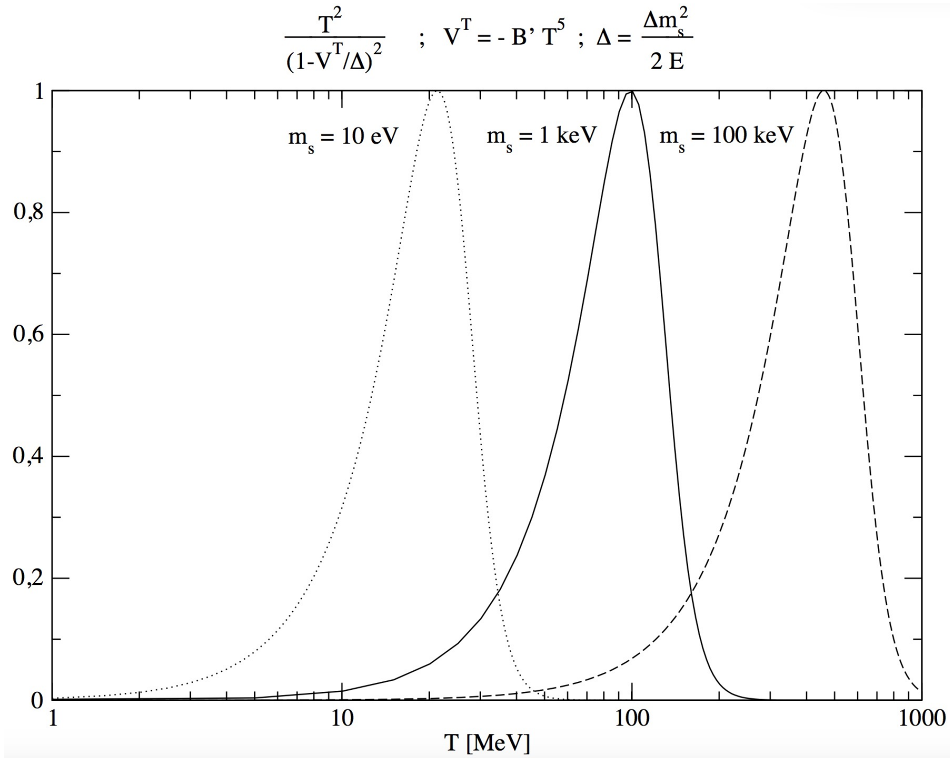
$V^T \sim T^5$: thermal potential due to finite temperature effects

- Low T: $\Gamma_s \simeq \Gamma_\nu \simeq n\sigma \sim T^5$ (V^T term negligible, $\ell_m \simeq \ell$ as in vacuum)
- High T: $\Gamma_s \simeq \left(\frac{\Delta m^2}{V^T 2E}\right)^2 \Gamma_\nu \sim T^{-7}$ (V^T term dominates $\left(\frac{\ell_m}{\ell}\right) \simeq \frac{\Delta m^2}{V^T 2E}$)

So Γ_s is max. at $T_{max} \approx 130\,MeV \left(\frac{m_s}{1\,keV}\right)^{1/3}$

(Dodelson and Widrow, Phys. Rev. Lett. **72**, 17 (1994))

ν_s production is max. at T_{max}: $\frac{1}{f_\nu}\left(\frac{df_s}{dT}\right)_{E/T}$



Non thermal mechanism: Freeze-in of sterile neutrinos

When propagating in a medium with large L_ν the neutrino mixing changes to

$$\sin^2 2\theta_m = \frac{\Delta^2(p)\,{}^2\,2\theta}{\Delta^2(p)\,\sin^2 2\theta + \left[\Delta(p)\cos 2\theta - V^L + |V^T(p)|\right]^2}$$

Where $\Delta(p) = \dfrac{|m_s^2 - m_\alpha^2|}{2p}$, and the potential $V^L \sim L_\nu$,

L_ν is the lepton asymmetry

$$L_{\nu_\alpha} \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma}$$

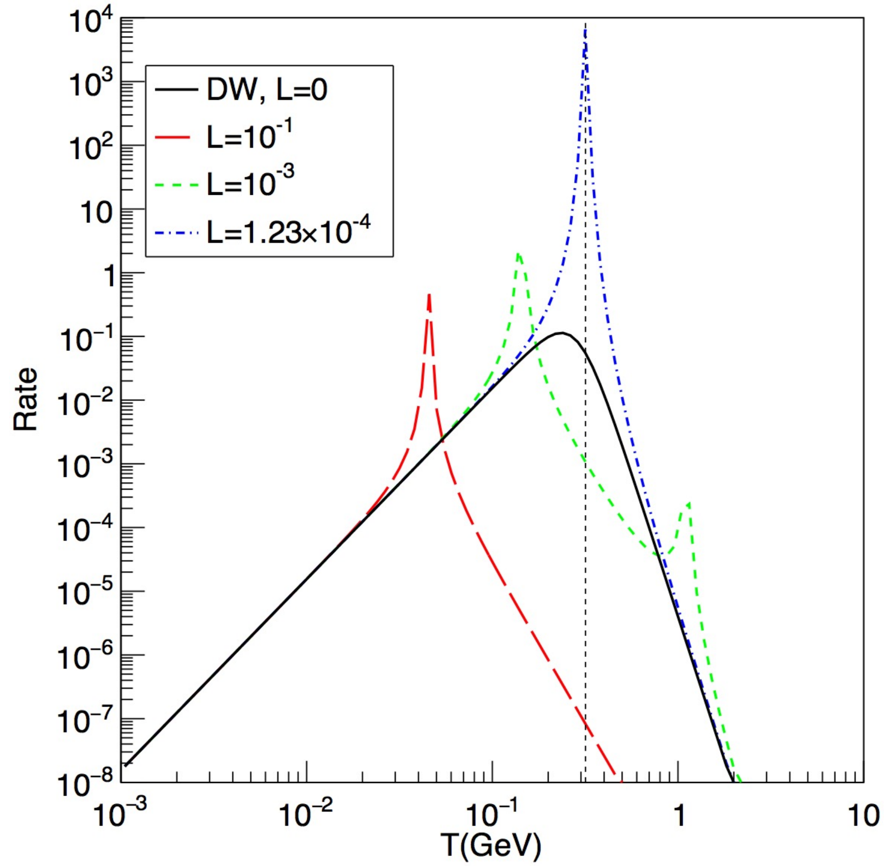
When $\Delta(p)\cos 2\theta - V^L + |V^T(p)| \simeq 0$, $\sin^2 2\theta_m = 1$: resonant production

(similar to the Mikheev-Smirnov-Wolfenstein (MSW) mechanism for active neutrinos in the Sun)

See e.g. Abazajian 1705.01837

Thus, rate of resonant production of sterile neutrinos: m_s =1keV

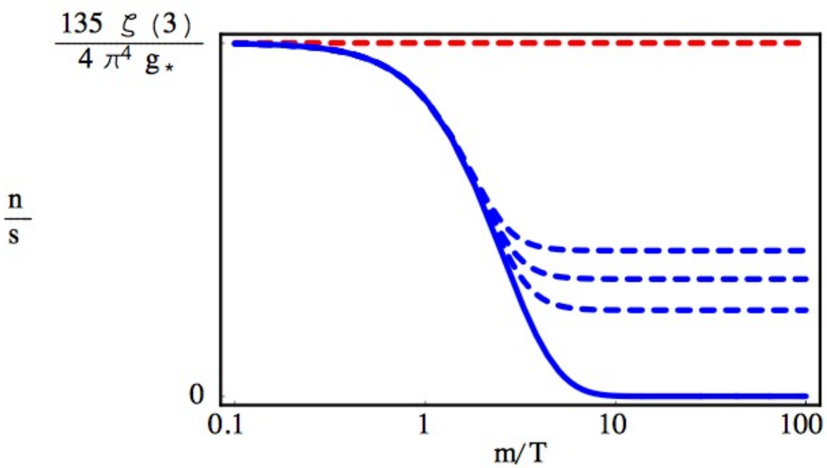
(Fig. from Philip Lu)

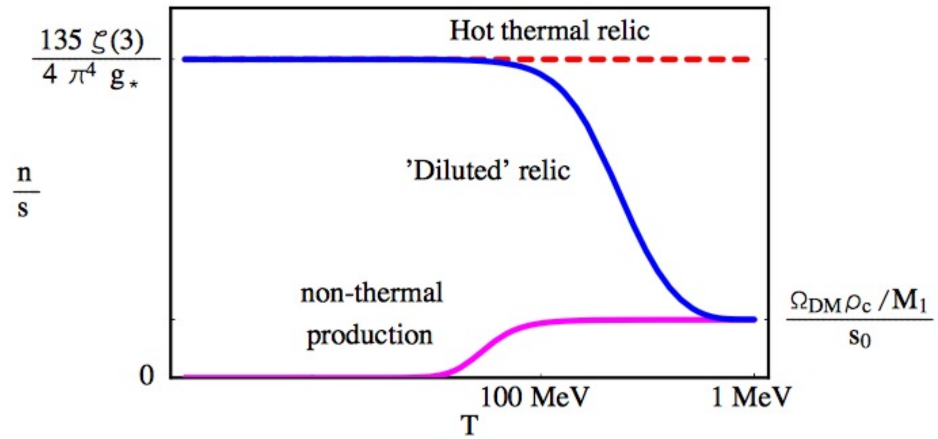


Production of sterile neutrinos

Sterile neutrinos could reach equilibrium. In this case, entropy dilution due to particles annihilating after they decouple reduces their abundance.

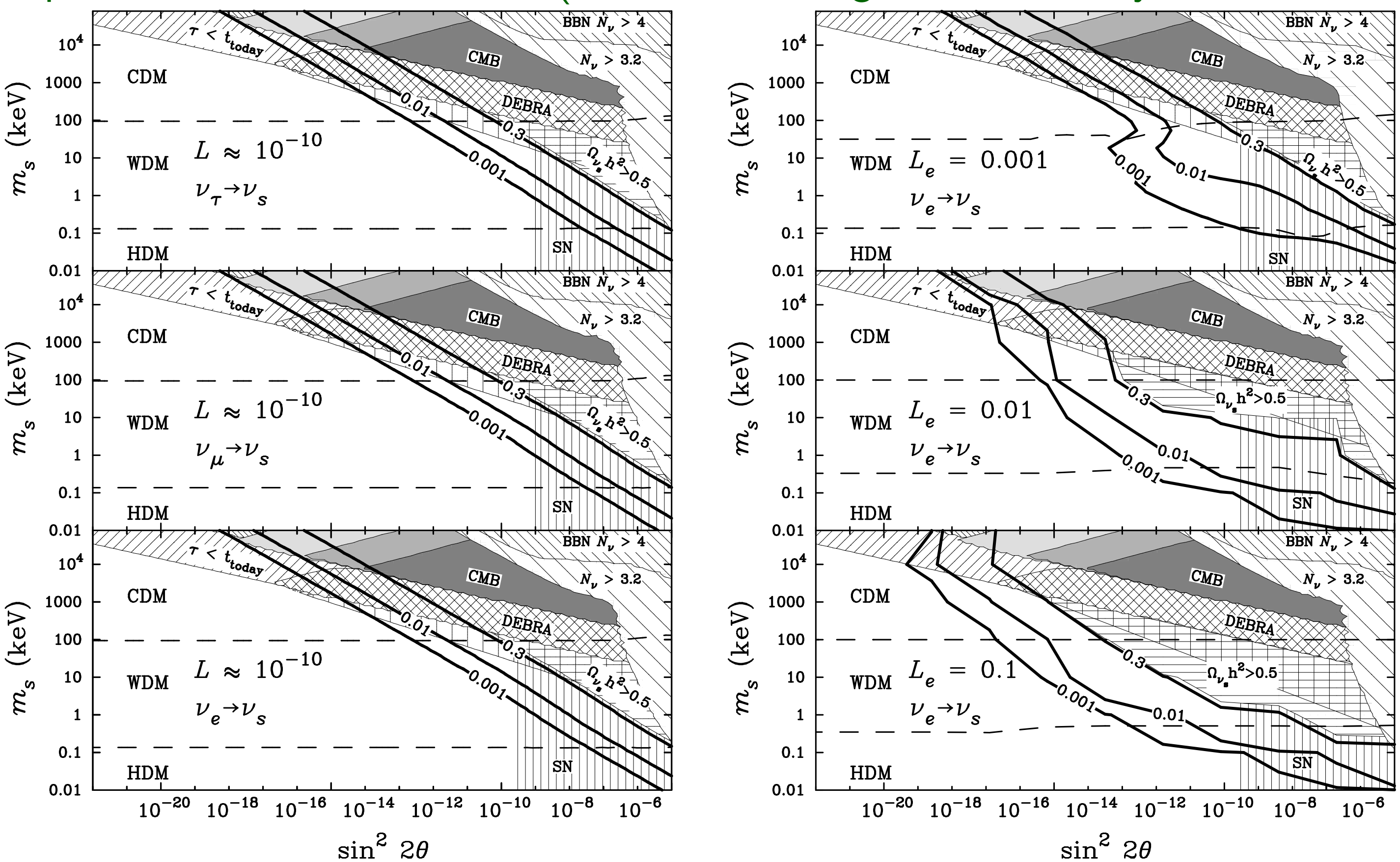
LEFT: Thermal production- RIGHT: Thermal equilibrium+decoupling plus dilution, or freeze-in.





Sterile Neutrino Abundance from Abazajian, Fuller, Pattel 2001

L = net lepton number in the Universe (can be much larger than the baryon number $B = 10^{-10}$)



Solid lines indicate density fraction in ν_s 0.3 (whole DM), 0.01, 0.001

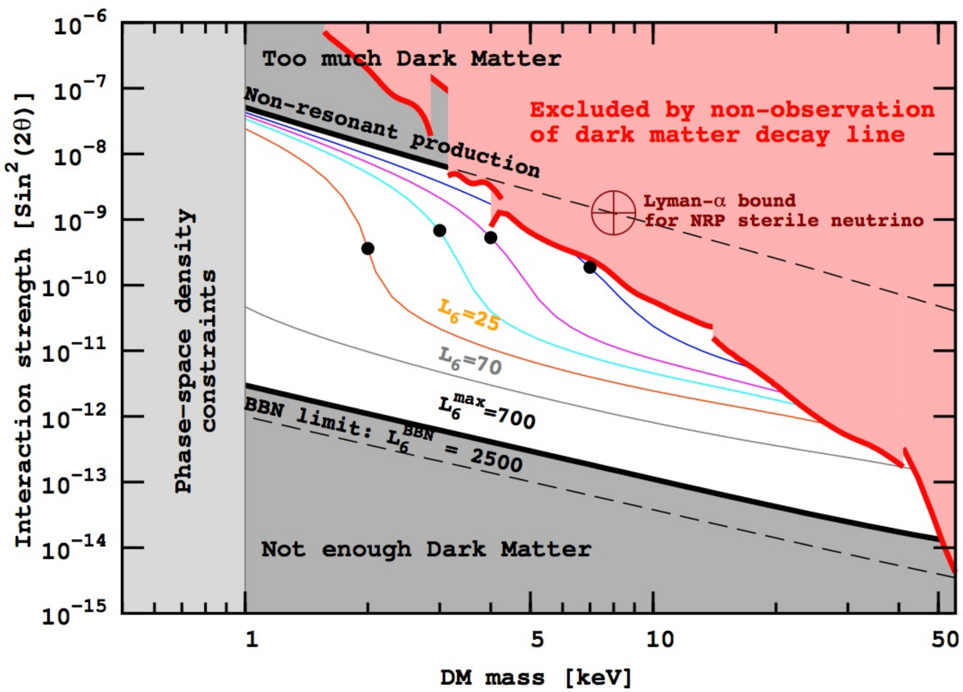
Sterile Neutrinos ("Light Sterile Neutrinos:A White Paper", Abazajian et al. hep-ph/1204.5379)

Non-resonantly produced (Dodelson-Widrow 1994) sterile neutrinos cannot constitute the whole of the DM ($< 20\%$ OK)

Dwarf-Spheroidal Galaxies phase space: $m_s > 1$ keV

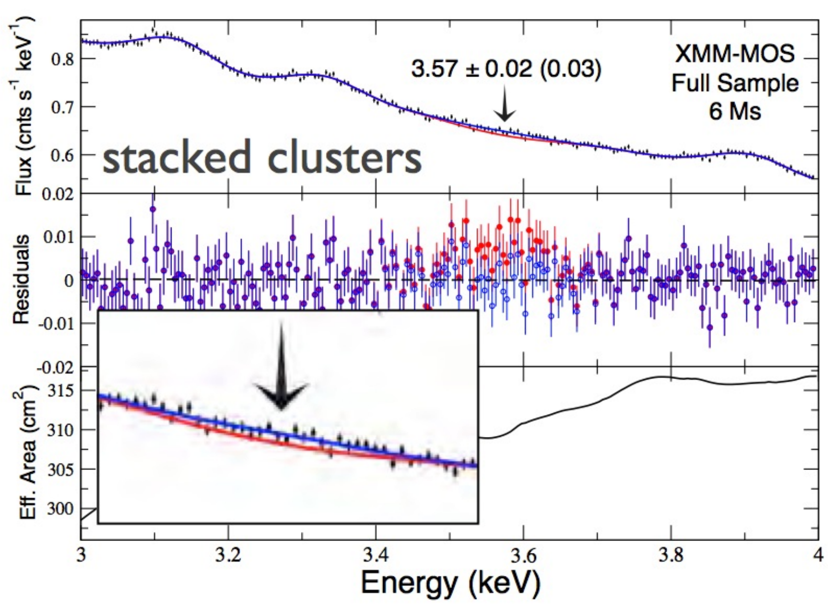
$\nu_s \to \nu\gamma$ would produce X-rays in galaxies and galaxy clusters

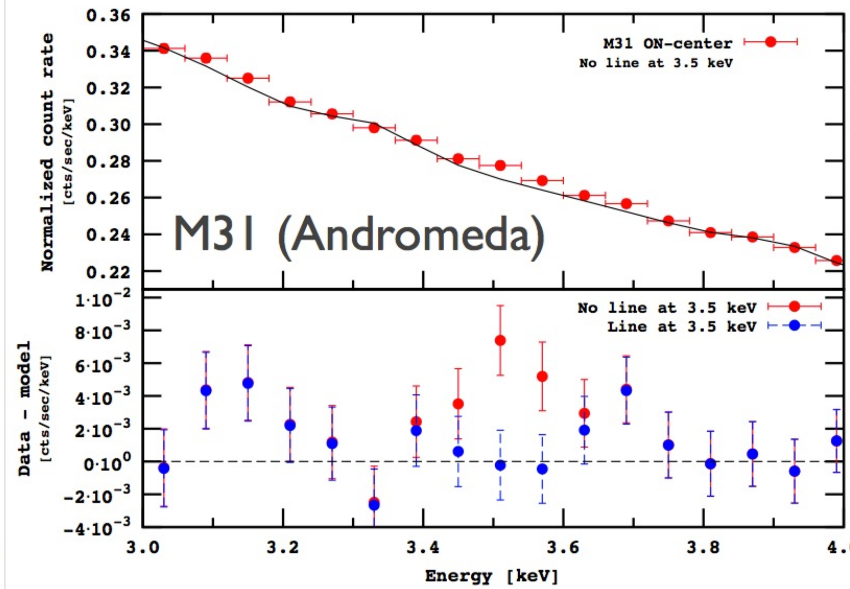
Early structures (Ly-α clouds): $m_s > 5$ keV but not with large L (Cool DM)-black dots are allowed by the Ly-α limits



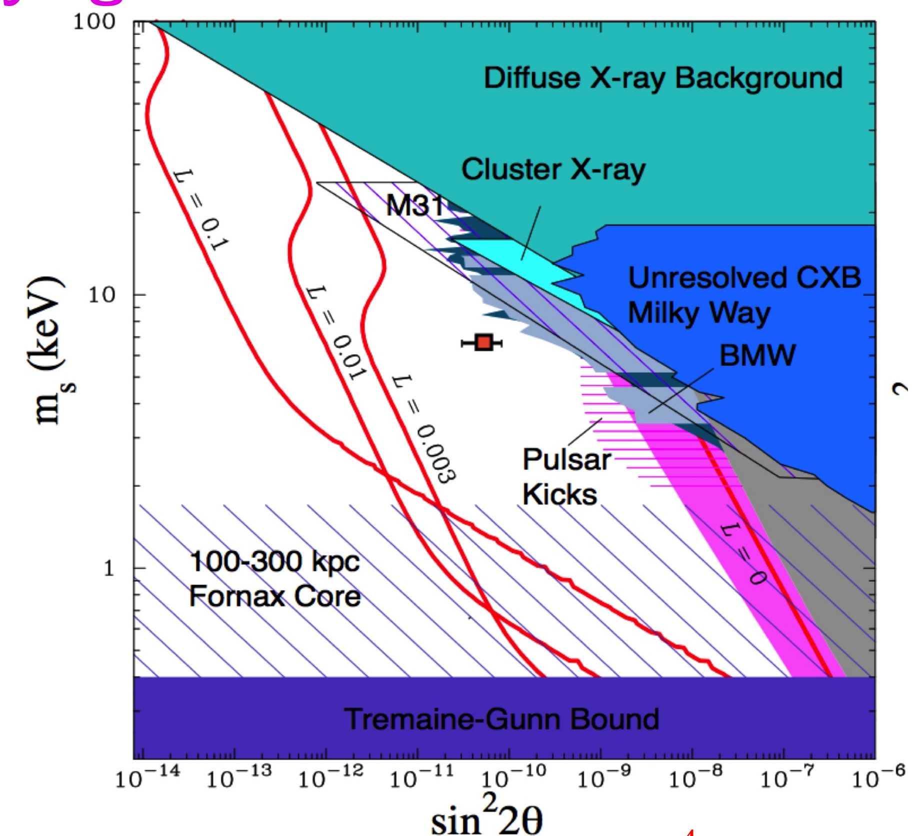
If ν_s are the DM, $\nu_s \to \nu\gamma$ would produce a monochromatic X-ray line in galaxies and galaxy clusters. This line may have been seen at 3.5 keV!

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 ($E_\gamma = m_s/2$)





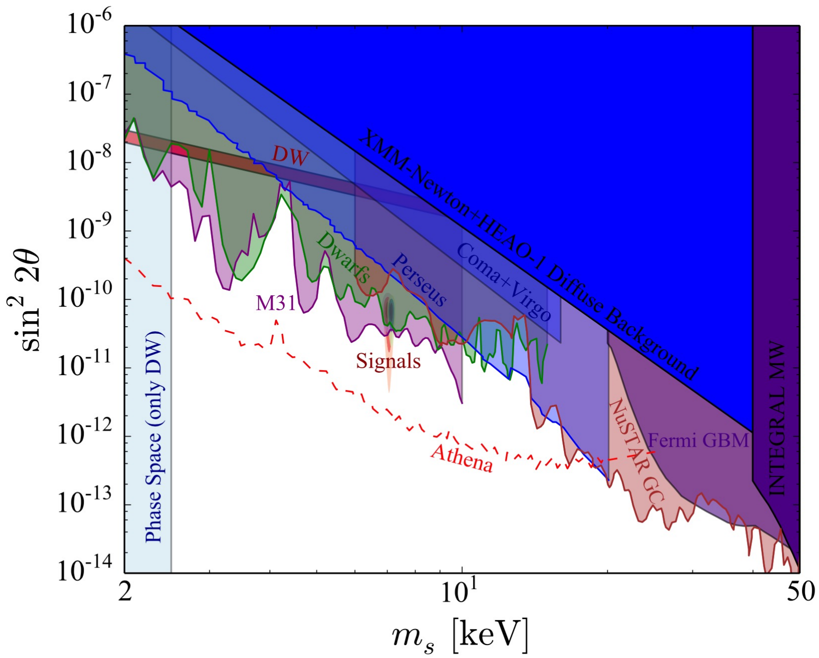
A 7 keV decaying sterile neutrino Bubul et al 2014

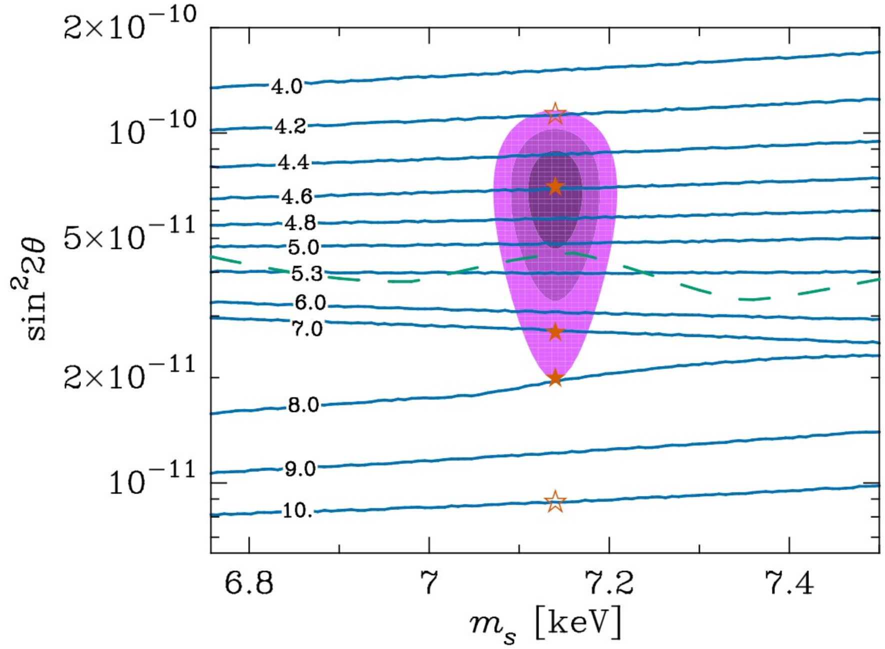


Would require a large Lepton asymmetry $\simeq 5\times10^{-4}$, much larger than the baryon asymmetry (10^{-10})

A 7 keV decaying sterile neutrino

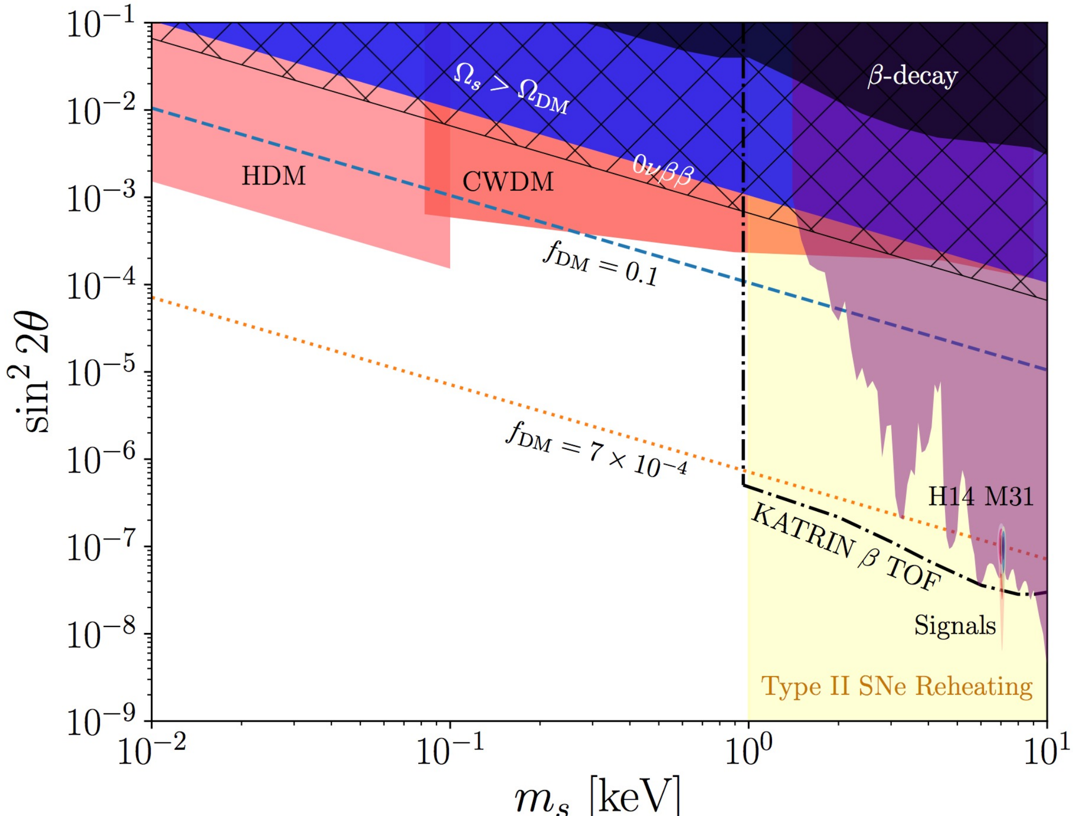
Abazajian 1705.01837, 2017





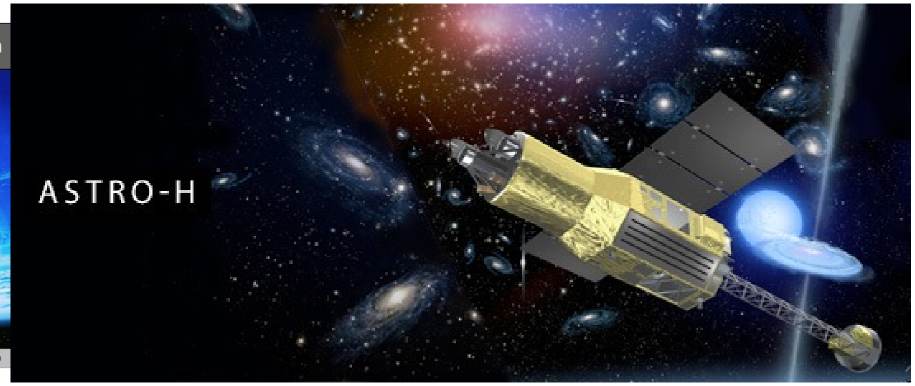
LEFT: assuming this neutrino accounts for all the DM, in the standard cosmology would require a large Lepton Asymmetry L $\simeq 5\times10^{-4}$ RIGHT: L in units of 10^{-4}

A 7 keV decaying sterile neutrino Abazajian 1705.01837, 2017



In the low reheating temperature model of GG, Palomarez and Pascoli, 2004, DW produced neutrinos constituting a fraction 0.7 10^{-3} of the DM and could be detected by KATRIN.

ESA's XMM-Newton & NASA's Chandra do not provide enough energy resolution of the line.

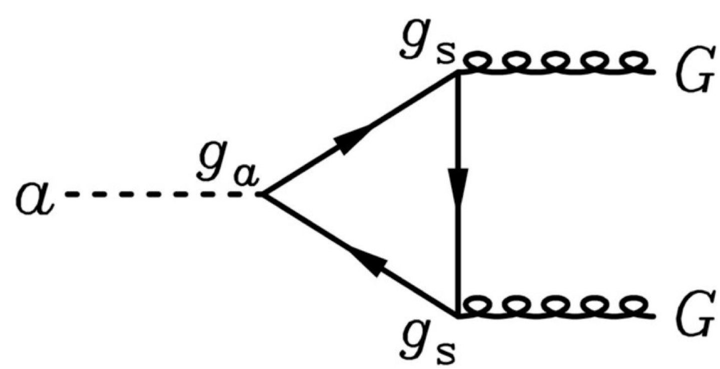


JAXA's ASTRO-H (Hitomi after "first light"), launched on Feb. 17 2016 expected to measure the profile of the line and prove/disprove that it is due to DM in 1 year!
But it was destroyed on March 26, 2016.

Prospect: Will be tested by JAXA-NASA by the X-Ray Astronomy Recovery Mission (XARM) in 2021 (next planned X-ray astronomy satellite is ESA's ATHENA, scheduled for 2028)

Non thermal mechanism: boson condensate formation

AXIONS are hypothetical pseudo-Goldstone Bosons (Wilczek 1978, Weinberg 1978) associated with the spontaneous breaking of an axial U(1) symmetry (Peccei-Queen 1977) of quarks (and optionally of leptons too) at a scale f_a (given by the VEV of a scale field) thus coupled through the chiral triangular anomaly to gluons. The coupling with photons is model dependent (as is that with leptons).



The PQ symmetry is the only viable solution of the "strong-CP" problem of QCD proposed so far.(See e.g. reviews by Peccei and Raffelt on axions)

AXIONS: The Lagrangian of QCD includes a CP violating term

$$L_{QCD} = \theta_{QCD} \frac{g^2}{32\pi^2} G_a^{\mu\nu} \widetilde{G_{a\mu\nu}}$$

Besides, the quark mass matrix is in general complex

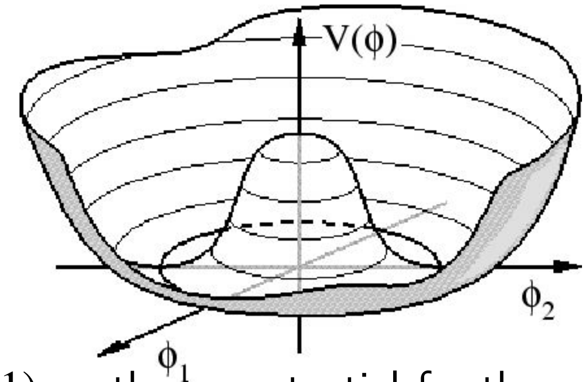
$$L_{Mass} = \bar{q}_{iR} M_{ij} q_{jL} + h.c.$$

A $U(1)_A$, namely one which rotates right and left handed fields separately change the θ value is necessary to diagonalize it

$$-\pi \leq \bar{\theta} = \theta + arg\ det M \leq \pi$$

The experimental limit on the neutron electric moment $d_n \simeq e\theta m_q / M_N^2$ implies $\bar{\theta} < 10^{-11}$! The strong CP problem is why is this $\bar{\theta}$ angle, coming from the strong and weak interactions, so small?.

AXIONS: The only viable solution of the "strong-CP" problem of QCD proposed so far is to augment the SM to make the Lagrangian invariant under
a global chiral symmetry $U(1)_{PQ}$ (Peccei-Queen 1977) spontaneously broken at a high scale f_a, whose Goldstone boson is the AXION a (Wilczek 1978, Weinberg 1978)

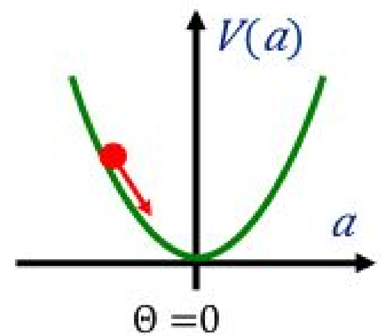


so that now

$$\bar{\theta} + \frac{< a >}{f_a}$$

Effects of the QCD anomaly generates an explicit breaking of $U(1)_{PQ}$, thus a potential for the field a,

$$V_{eff} \sim cos\left(\bar{\theta} + \frac{< a >}{f_a}\right) = cos(\theta)$$



whose minimum is at $< a >= -f_a/\bar{\theta}$, i.e. $\theta = 0$ thus the Lagrangian in terms of $a_{phys} = a- < a >$ no longer has a CP violating θ-term. CP - symmetry is dynamically restored

AXIONS: In this minimum the axion has mass (generic prediction)

$$m_a = \frac{\sqrt{m_u m_d} m_\pi}{(m_u + m_d) f_\pi f_a} \simeq 6.3\ eV \left(\frac{10^6 GeV}{f_a} \right)$$

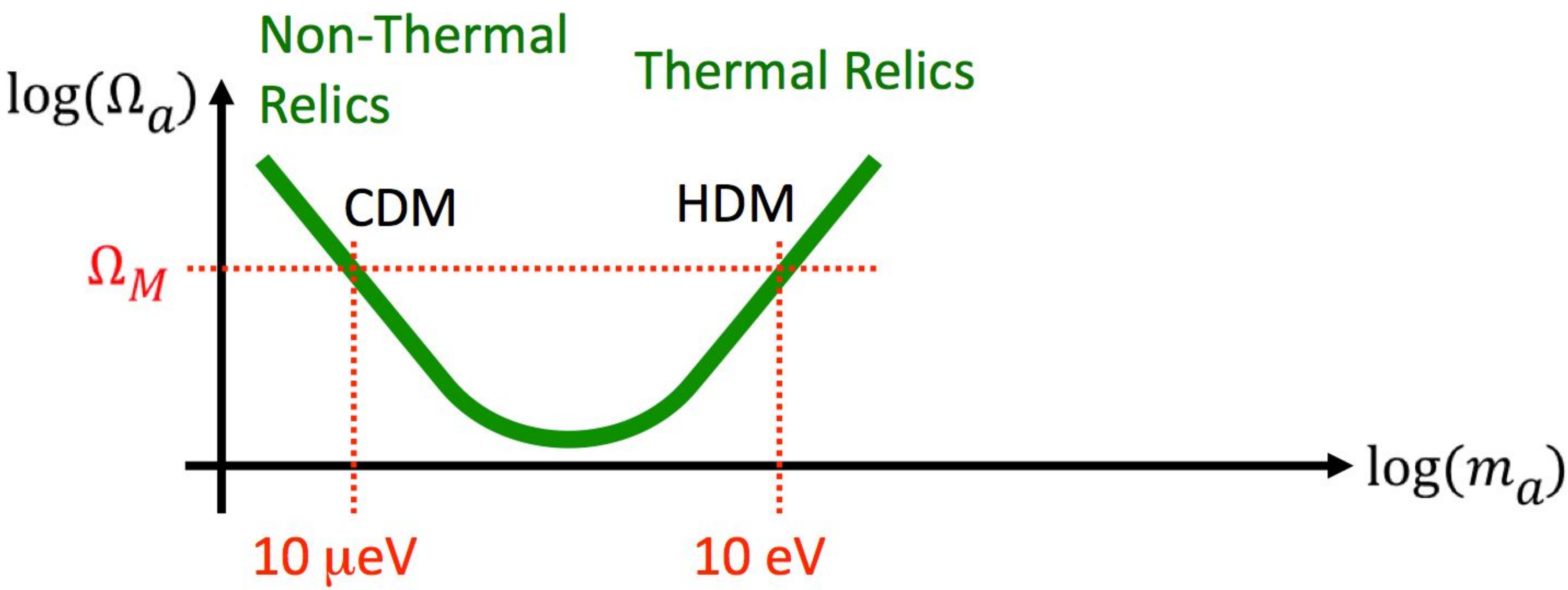
and a coupling with gluons (generic prediction)

$$L_{agg} = \frac{\alpha_s}{8\pi} \frac{a_{phys.}}{f_a} G^{\mu\nu} \widetilde{G_{\mu\nu}}$$

Several models: Shifman, Vainshtein, Zakharov (SVZ) and Dine, Fischler, Srednicki and Zhitnisky (DFSZ) produce different coupling of a with γ's and fermions.

$$L_{a\gamma\gamma} = \frac{\alpha}{4\pi} K_{a\gamma\gamma} \frac{a_{phys.}}{f_a} F^{\mu\nu} \widetilde{F_{\mu\nu}} \qquad\qquad L_{aff} = \frac{C_f}{2 f_a} \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f \partial_\mu a_{phys.}$$

AXIONS can be HDM or CDM



HDM when produced thermally for "large" m_a (large enough coupling with pions $a\pi\pi\pi$)
CDM produced as a Bose-Einstein condensate (very small coupling)

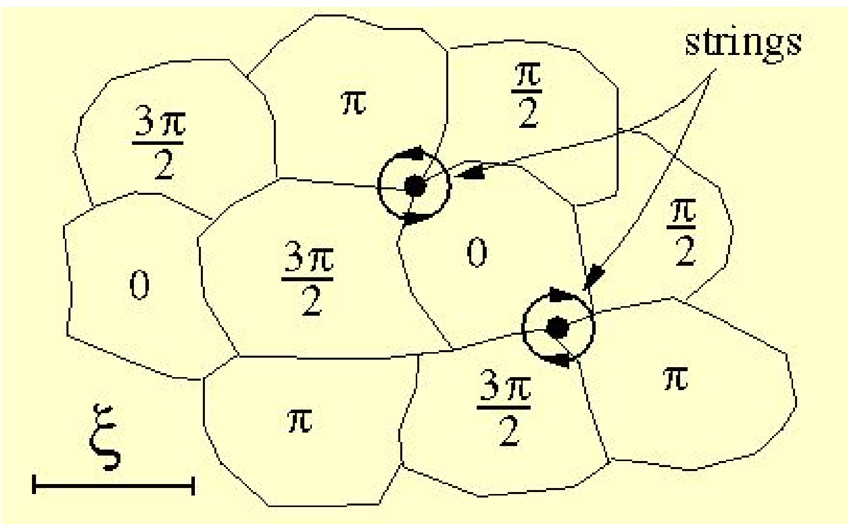
AXIONS as CDM

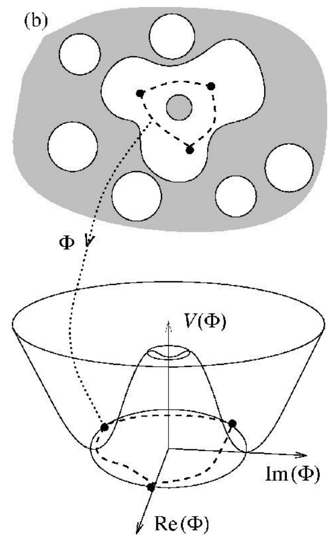
If inflation happens after PQ symmetry breaking $\Omega_a \sim \theta_i^2$, where θ_i is the initial value of a in our patch of the Universe, homogeneous mode stars oscillating when $T < \Lambda_{QCD}$ when V_{eff} develops

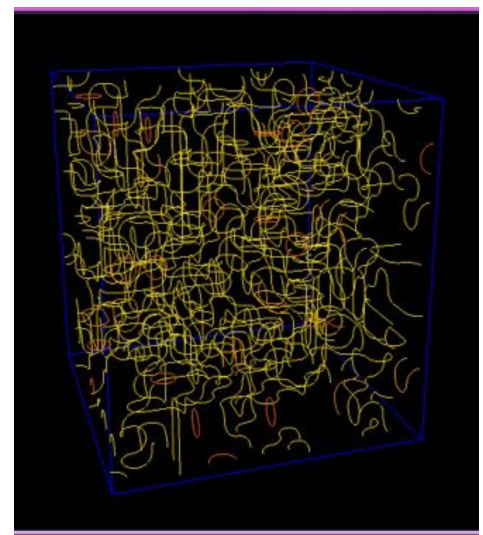
If reheating restores PQ symmetry, much more complicated picture (often a overabundant!)

-Cosmic string form via the Kibble mechanism and then decay(e.g. Harimatsu et al. 1202.5851

-If more than one background also walls could form (e.g. Harimatsu et al.1207.3166)



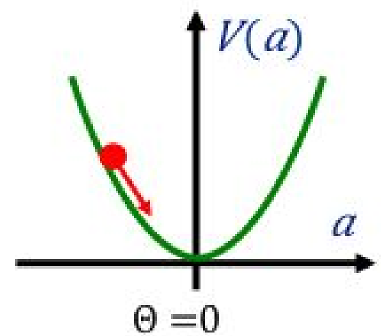




AXIONS as CDM In the coherently oscillating field scenario, present QCD parameters and temperature dependent m_a imply (Bae, Huh & Kim, 0806.0497)

$$\Omega_a h^2 = 0.195\ \theta_i^2 \left(\frac{f_a}{10^{12} GeV}\right)^{1.184} = 0.105\ \theta_i^2 \left(\frac{10\mu eV}{m_a}\right)^{1.184}$$

θ_i is the initial value of a in our patch of the Universe.
If inflation happens after the PQ symmetry spontaneous breaking, there is only one value



If axions account for the whole of the DM $\Omega_a h^2 = 0.11$

$$\theta_i = 0.75 \left(\frac{10^{12 GeV}}{f_a}\right)^{0.592} = 1.0 \left(\frac{m_a}{10\mu eV}\right)^{0.592}$$

$\theta_i \simeq 1$ implies $f_a \simeq 10^{12}$ GeV "classic window"
$\theta_i < 1$ implies $f_a > 10^{12}$ GeV " anthropic window" (e.g. $f_a \simeq 10^{16}$ GeV for $\theta_i \simeq 0.003$)

But also AXIONs could be a subdominant component of the CDM.

A scalar field oscillating in a quadratic potential behaves as CDM

The equation of motion of a spatially homogeneous scalar field in the expanding Universe is

$$\ddot{\varphi} + 3H\dot{\varphi} + V(\varphi)' = 0$$

which for $V = (m^2\varphi^2)/2$ becomes

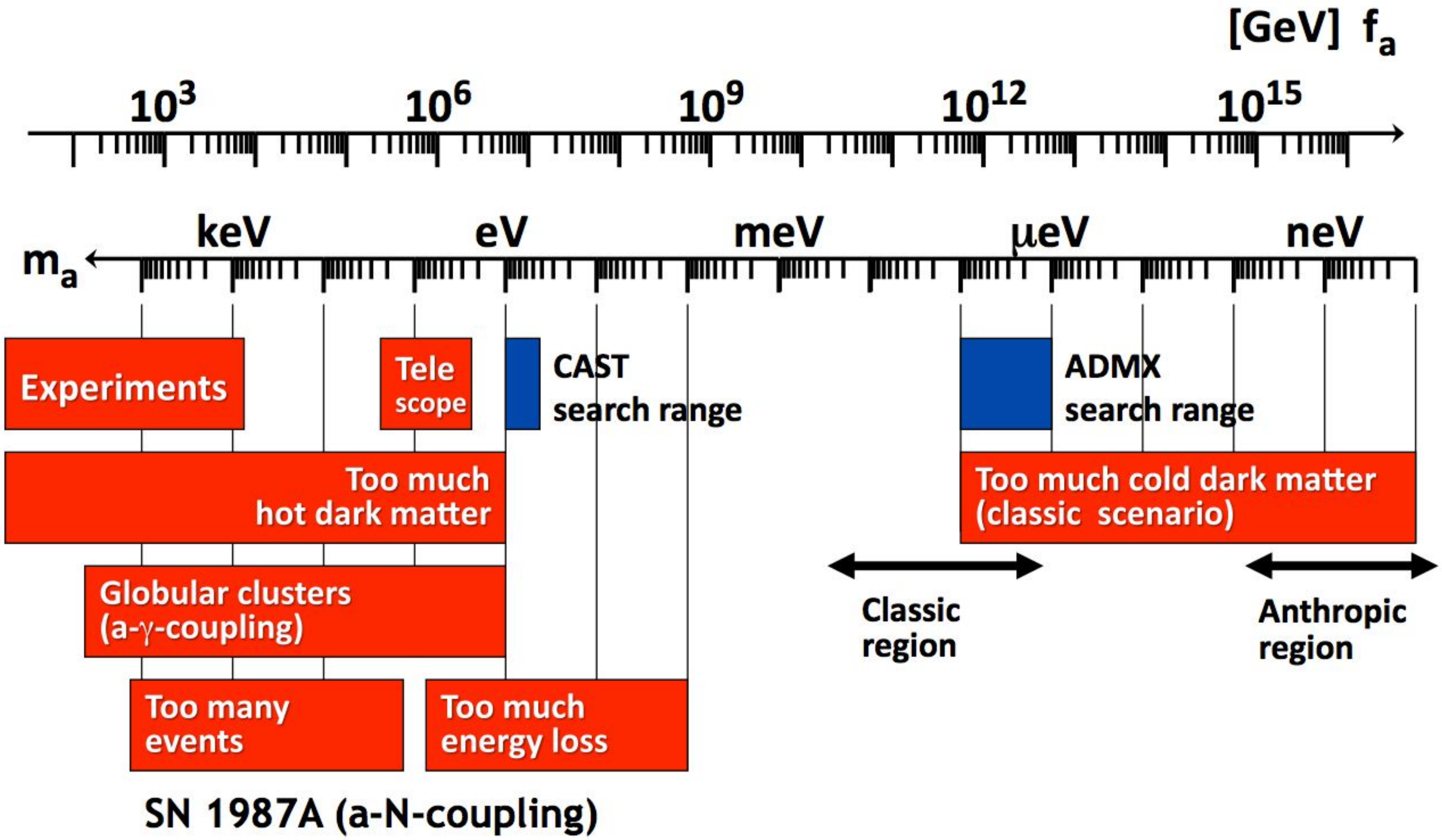
$$\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0$$

The energy density of this field is $\rho = \dot{\varphi}^2/2 + V(\varphi)$. As in any harmonic oscillator the average of the kinetic and of the potential energies over one period are equal: $< \dot{\varphi}^2/2 >=< (m^2/2\varphi^2)/2 >$. Thus $\rho =< \dot{\varphi}^2 > + < m^2/2\varphi^2 >$. Taking the derivative of this expression and $m = m(T)$ to be a slowly varying function of time, we get

$$\dot{\rho} = [< (\dot{m}/m) > -3H]$$

which has as solution $\rho = const.m/a^3$ (a is the scale factor of the Universe and H$=\dot{a}/a$). This has the same form as for matter: $\rho_{matter} = n\ m/a^3$.

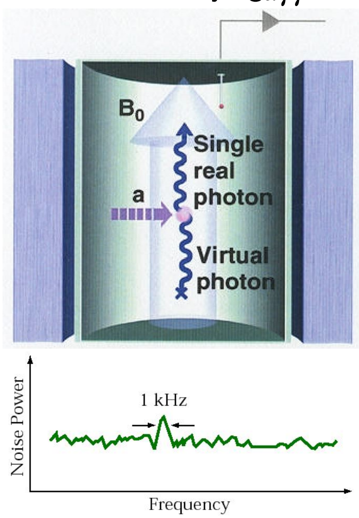
AXIONS Many bounds- fig. from Raffelt- 2011

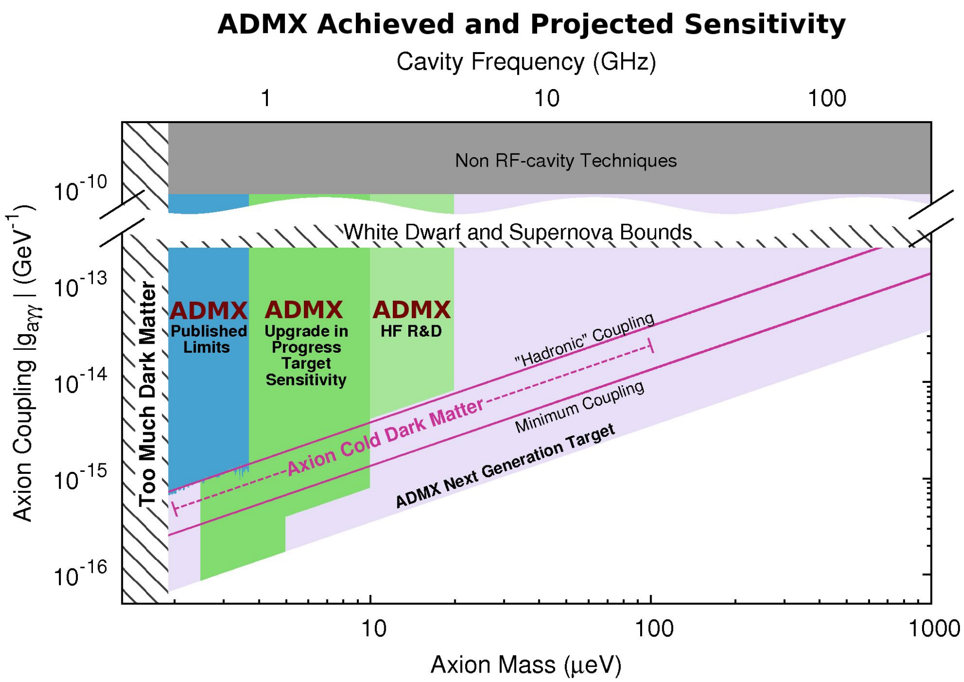


AXIONS as CDM using the axion coupling to photons (model dependent) (Sikivie 1983) ADMX best experiment for the "good CDM candidate range" $1\mu\text{eV} \leq m \leq 1$ meV

ADMX (Axion DM eXperiment)

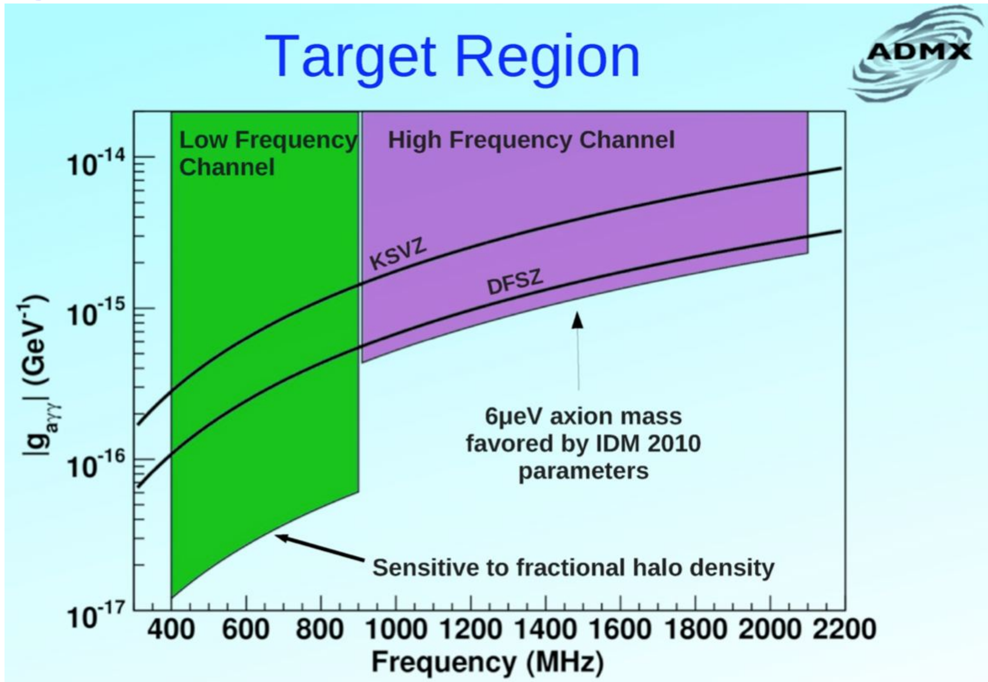
Microwave cavity: $g_{a\gamma\gamma}$





ADMX Phase II-"definitive" axion dark matter search (L. Rosenberg 2013) to start soon

AXIONS as CDM



But vertical axis $\sim \sqrt{Rate} \sim \sqrt{\Omega_a g^2_{a\gamma\gamma}} \sim \theta_i K_{a\gamma\gamma} m_a^{0.4}$ so bound applies to this product of parameters and the coupling $K_{a\gamma\gamma}$ is highly model dependent.

AXIONS as CDM in the "anthropic window" using the model independent axion coupling to gluons, Graham & Rajendran (1101.2691, 1306.6088, 1306.6089) proposed to measure a time varying electric neutron moment as the axion field oscillates. Recall $d_n \sim \theta$ and $\theta(t) = a(t)/f_a$

$$d_n = g_d a \simeq 10^{-16}\ \theta_i\ cos(m_a t)\ \ e\ cm$$

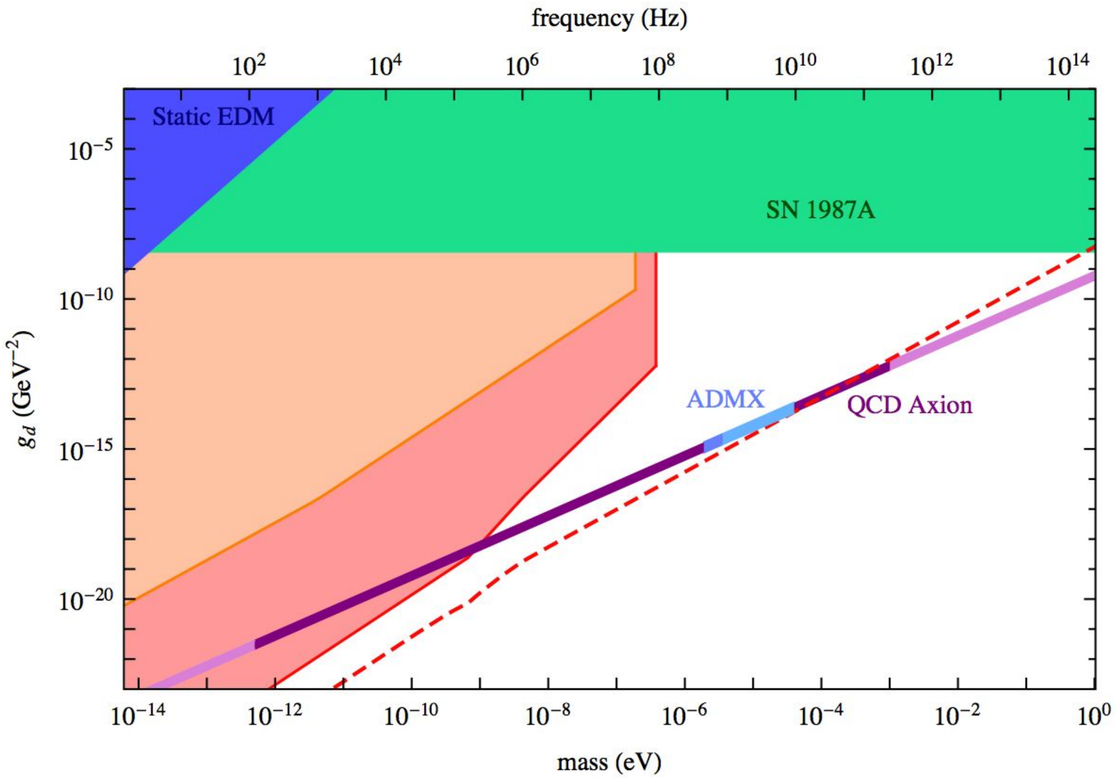
Experimental limit on static EDM $d_n < 0.63 \times 10^{-25}$ e-cm (observation last ≥ 1 second)

Also valid for Axion-Like Particles (ALPs): similar to axions but with QCD replaced by other dynamics

For kHz-GHz, precession of nuclear spins in electric fields changes the magnetization of a sample of material, which could be observed with precision magnetometry.

AXIONS as CDM in the "anthropic window"

from Budker, et al 1306.6089

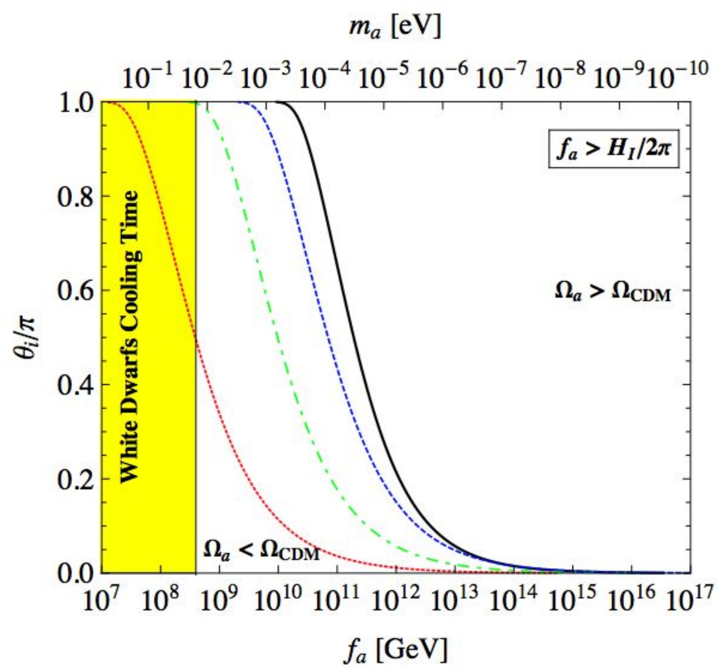


Solid pink and orange: sensitivity regions for phase 1 and 2 proposals, set by magnetometer noise - red dashed line: limit from magnetization noise

AXIONS in non-Standard Pre-BBN Cosmologies

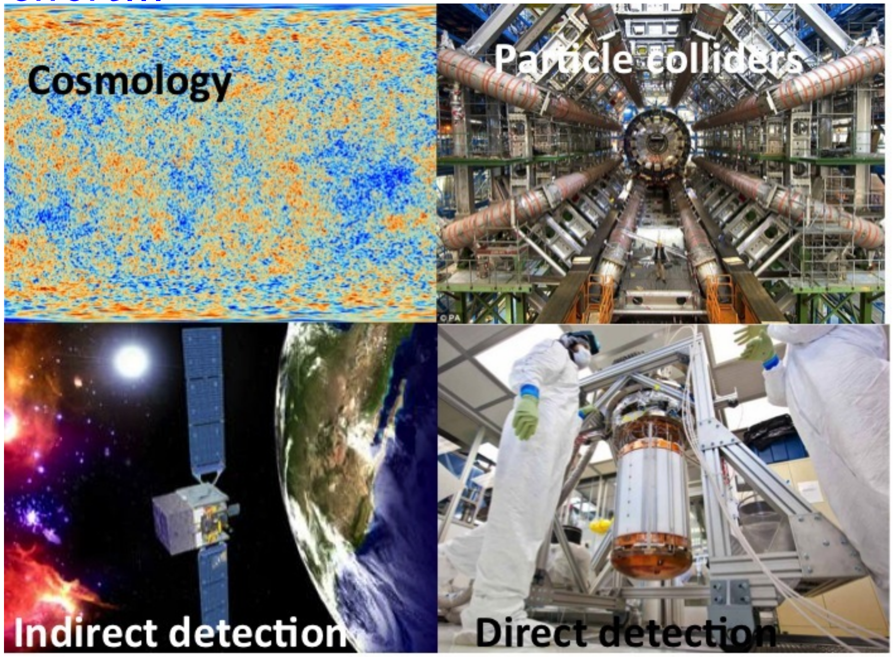
allow for different combination of parameter. Example: the initial misalignment angle θ_i as a function of the Peccei-Quinn scale f_a for the axion to be 100% of the CDM in standard cosmology (black solid line), kination cosmology with transition to standard at 4MeV (red dotted line), 300MeV (green dot-dashed line) or 700MeV (blue dashed line).

from Visinelli and Gondolo 0912.00



Outlook

The nature of the Dark Matter, the most abundant form of matter in the Universe, is one of the fundamental open problems in particle physics astrophysics and cosmology. The search for Dark Matter, is multi-pronged involving a very intense world-wide effort...



Outlook

DM searches are advancing fast in all fronts, astrophysical/cosmological observations and modeling, direct and indirect detection and accelerators. Lots of data necessarily lead to many hints so far unsuccessfully. Hopefully at some point several of them will point to the same DM candidate.

Motto attributed to Einstein:
"Make things as simple as possible, but not simpler.