Particle physics aspects of Dark Matter

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Preamble: general properties of the DM particle

The DM particle must:

- be dark (neutral)
- be stable
- account for 26% of the energy content of the Universe: $\Omega_{DM} \simeq 26\%$
- be 'cold'
- have a small cross section on nucleons: DM direct detection
- not produce too large fluxes of cosmic rays: DM indirect detection
- be able to escape detection at colliders so far
- have not too large self-interactions
- ...

Outline

1) DM neutrality and stability

2) DM relic density

- generalities on early Universe hot plasma
- thermal hot relic
- thermal cold relic: non-relativistic freeze out
- freeze-in
- asymmetric DM

3) DM direct detection

4) DM indirect detection

5) Phenomenology of a few illustrative models

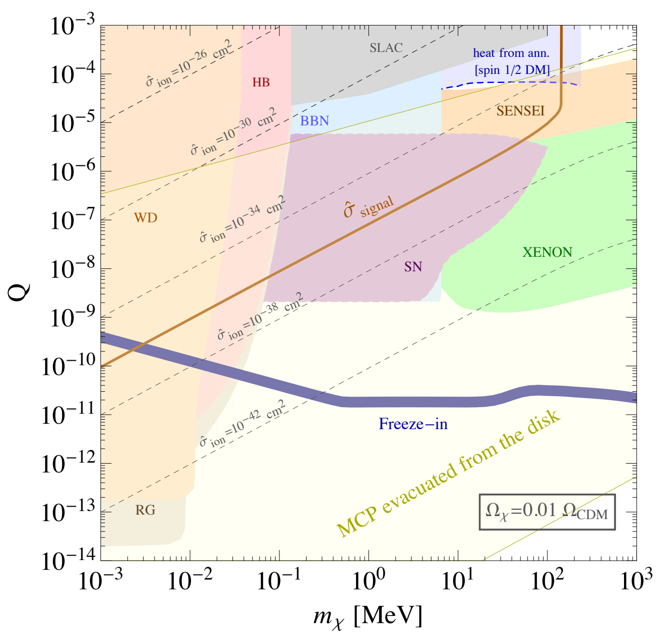
6) DM self-interactions (if time allows)

Part I
DM neutrality and stability

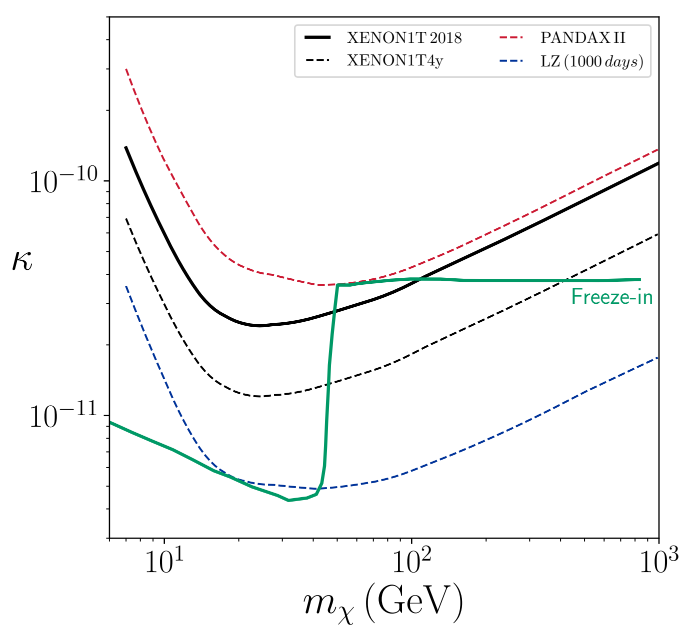
Dark Matter must be dark

A non electrically neutral DM particle would « shine » unless:

- it forms neutral bound states, but basically excluded (ionized population, annihilation into 2 photons, …)
- its electric charge is tiny: strong constraints but not excluded:



Barkana et al 18



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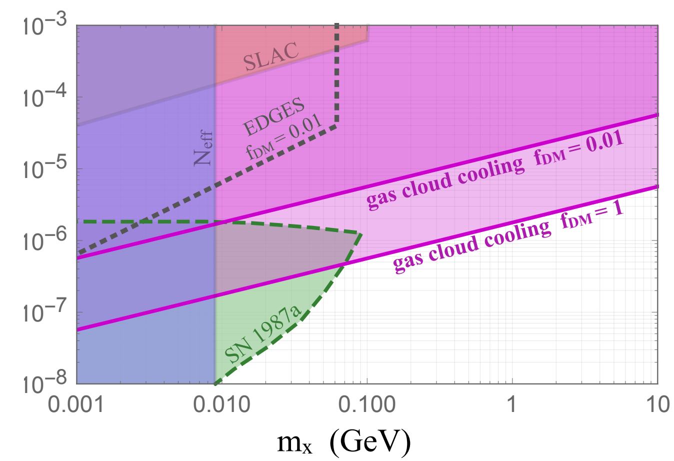

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………………..

Dark Matter stability

- DM is around today $\tau_{DM} > \tau_{universe} \simeq 10^{18}\,\mathrm{sec}$

- Given its relic density today one needs in general much larger lifetimes not to produce fluxes of cosmic rays we should have seen already: $\tau_{DM} > \tau_{universe} \simeq 10^{25-28}\,\mathrm{sec}$

unless very light or invisible decay
see indirect detection part below

To have a particle with at least those lifetimes is the most constraining property for the general structure of the DM model!

Stability of DM particle: general considerations on decay

if DM decays the coupling causing the decay must be tiny

for example a 2-body decay: $\Gamma(DM \to A + B) \sim \frac{1}{8\pi} g^2 m_{DM}$

tree level coupling

$$\tau_{DM} = 1/\Gamma(DM \to A + B) > \tau_{universe} \leftrightarrow g \lesssim 10^{-20} \cdot \sqrt{1\,\mathrm{GeV}/m_{DM}}$$

$$\Updownarrow$$

$$g \lesssim 10^{-10} \cdot \sqrt{10^{-11}\,\mathrm{eV}/m_{DM}}$$

$$\Updownarrow$$

$$g \lesssim 1 \cdot \sqrt{10^{-31}\,\mathrm{eV}/m_{DM}}$$

$\Rightarrow$ to have a long enough lifetime:

- the coupling could be very tiny just so ….. but weird
- or DM mass very tiny but still a tree level coupling of order unity is excluded because $m_{DM} > 10^{-22}\,\mathrm{eV}$ is anyway needed to have DM galactic halo: i.e. to have a wavelength smaller than galaxy size

$\Rightarrow$ clearly this suggests a symmetry:

-to forbid the decay: absolute DM stability: $g = 0$

-or at least to provide an explanation for a so tiny coupling

Stable SM particles: there is always a deep symmetry reason

- γ : stable because massless (due to unbroken $U(1)_{em}$ gauge symmetry)
- lightest ν : lightest fermion of the SM: stable due to Lorentz invariance
- e^- : stable because lightest particle charged under conserved electric charge

due to unbroken $U(1)_{em}$ gauge symmetry

- p : stable due to an accidental symmetry: $U(1)_B$: baryon number conservation

stems from gauge sym. of the SM and charges of particles under them

$SU(3)_c$ gauge invariance

$\mathcal{L}_{quarks} \propto \bar{q} \dots q$

each time a quark is annihilated another one is created

$U(1)_B$ symmetry: $q \rightarrow e^{i\phi} q$

accidental symmetry: $U(1)_B$ not subgroup of $SU(3)_c$

⇒ for DM particle stability one could invoke similar mechanisms or other ones....

Do we need a new symmetry beyond SM for DM stability?

there are no DM candidates in SM (neutrinos are excluded as we will see) but does it means that we need a new symmetry beyond SM for DM stability?

there exists at least one possibility: through an accidental symmetry and a large electroweak multiplet

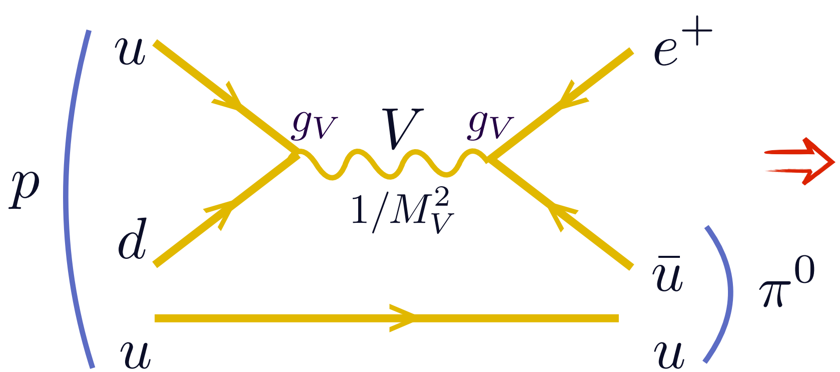
DM stability without new symmetry: accidental symmetry
the proton decay example

A particle which has no dim-4 interactions because its gauge quantum numbers do no match to have such an interaction $\Rightarrow$ accidental symmetry

example in SM: proton: stable due to accidental $U(1)_B$ (see above)

however suppose there exists new physics beyond the SM: this physics has no reason to respect this symmetry: induce higher dimensional operator which leads to proton decay

example: grand unification: has gauge boson coupling to a quark and a lepton



$$\Rightarrow \mathcal{L}_{eff} \ni \frac{g_V^2}{M_V^2} \cdot u\,u\,d\,l \equiv \frac{1}{\Lambda^2} \cdot u\,u\,d\,l$$

$$\Downarrow$$

$$\Gamma(p^+ \to \pi^0 + e^+) \propto \frac{m_p^5}{M_V^4}$$

$$\Downarrow$$

$$\text{if } M_V \gtrsim 10^{16}\,\text{GeV one gets } \tau_p \gtrsim 10^{34}\,\text{years}$$

DM stability without new symmetry: accidental symmetry the minimal DM example

example:

a fermion DM particle ψ_{DM} with given quant. number under $SU(3)_c \times SU(2)_L \times U(1)$:

- a fermion singlet: not expected to be stable automatically:

$\mathcal{L} \ni Y \, \bar{L} \psi_{DM} H \longleftarrow$ not forbidden by anything

$\Downarrow$

$\psi_{DM} \to l^- H^+, \nu H^0$ decays expected!

$\Downarrow$

no accidental sym. forbidding this decay

- a fermion doublet containing a neutral particle: $\psi_{DM} = \begin{pmatrix} \psi^0_{DM} \\ \psi^-_{DM} \end{pmatrix}$

$\mathcal{L} \ni Y \, \overline{l_R} \psi_{DM} H \longleftarrow$ not forbidden by anything

$\Downarrow$

$\psi^0_{DM} \to l^- H^0$ decay expected!

$\Downarrow$

no accidental sym. forbidding this decay

DM stability without new symmetry: accidental symmetry
the minimal DM example

- a fermion triplet containing a neutral particle:

$$\psi_{DM} = \begin{pmatrix} \psi^+_{DM} \\ \psi^0_{DM} \\ \psi^-_{DM} \end{pmatrix} \qquad\qquad \psi_{DM} = \begin{pmatrix} \psi^0_{DM} \\ \psi^-_{DM} \\ \psi^{--}_{DM} \end{pmatrix}$$

$$\mathcal{L} \ni Y\,\bar{L}\psi_{DM}H \qquad\qquad \mathcal{L} \ni Y\,\bar{L}\psi_{DM}H^\dagger$$

not forbidden by anything   not forbidden by anything

$\psi_{DM} \to l^- H^+, \nu H^0$ decay expected! $\psi_{DM} \to \nu \bar{H}^0$ decay expected!

no accidental sym. forbidding this decay   no accidental sym. forbidding this decay

DM stability without new symmetry: accidental symmetry
the minimal DM example

- a fermion quadruplet containing a neutral particle: $\psi_{DM} = \begin{pmatrix} \psi^{+}_{DM} \\ \psi^{0}_{DM} \\ \psi^{-}_{DM} \\ \psi^{--}_{DM} \end{pmatrix}$

$\downarrow$

$\mathcal{L} \ni Y \bar{L} \psi_{DM} H$ not possible

$\downarrow$

no dimension-4 interaction possible

$\bar{L}H$: can only form a singlet or a triplet

$\downarrow$

no decay to a lepton and a scalar

$\downarrow$

has an accidental symmetry forbidding the decay: $U(1): \psi_{DM} \to e^{i\phi} \psi_{DM}$

However: the exchange of a UV particle could induce a dim-5 operator:

$$\mathcal{L} \ni \frac{1}{\Lambda} \bar{L} \psi_{DM} H H \quad \Rightarrow \quad \Gamma(\psi^0_{DM} \to L + H) \sim \frac{1}{8\pi} \frac{v^2 m_{DM}}{\Lambda^2}$$

$m_{DM} = 100\,\text{GeV}$

$\Rightarrow \quad \tau_{DM} > \tau_{universe}$ only if $\Lambda > 10^{21}\,\text{GeV} > M_{Planck}$

$\tau_{DM} > (10^{26}\,\text{sec})$ only if $\Lambda > 10^{25}\,\text{GeV} > M_{Planck}$

Any new physics below the Planck scale would destabilize it easily!! $\Rightarrow$ not that nice

DM stability without new symmetry: accidental symmetry
the minimal DM example

- a fermion quintuplet containing a neutral particle: $\psi_{DM} = \begin{pmatrix} \psi_{DM}^{++} \\ \psi_{DM}^{+} \\ \psi_{DM}^{0} \\ \psi_{DM}^{-} \\ \psi_{DM}^{--} \end{pmatrix}$

$\downarrow$

no possible dimension-4 and dimension-5 interactions

$\downarrow$

Cirelli, Fornengo, Strumia

the exchange of a UV particle could induce only a dim-6 operator:

$$\mathcal{L} \ni \frac{1}{\Lambda^2} \overline{L} \psi_{DM} H H H^\dagger \Rightarrow \Gamma(\psi_{DM}^0 \to L + H) \sim \frac{1}{8\pi} \frac{v^4 m_{DM}}{\Lambda^4} \quad m_{DM} = 100\,\mathrm{GeV}$$

$$\Rightarrow \quad \tau_{DM} > \tau_{universe} \text{ only if } \Lambda > 3 \cdot 10^{13}\,\mathrm{GeV} < m_{Planck}$$

$$\tau_{DM} > (10^{26}\,\mathrm{sec}) \text{ only if } \Lambda > 3 \cdot 10^{15}\,\mathrm{GeV} < m_{Planck}$$

as long as there is no new physics inducing this operator below these scales: fine

but this requires an object as large as a quintuplet

DM stability without new symmetry?

To have a stable particle on top of SM without any extra symmetry is not automatical at all even if not impossible!!

⇓

DM strongly suggests the existence of a new symmetry in Nature!

Stability of DM due to a new symmetry beyond the SM

Various possibilities:

-DM stability due to new unbroken gauge symmetry

-DM stability due to new broken gauge symmetry

-DM stability due to accidental symmetry resulting from new gauge symmetry

-DM stability due to new discrete or global symmetry

DM stability from new gauge symmetry

simplest example: lightest charged particle under a new $U(1)$: " $U(1)_X$ "

- a fermion: a e' which has no charge under SM

  with SM particles chargeless under $U(1)_X$

Pospelov 07,....

"secluded DM"

Standard Model

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$l,\ \nu,\ q,\ \gamma,\ W,\ Z,\ g,\ H$

Hidden sector

$U(1)_X$

$e',\ \gamma'\ +\ \ldots$

portal

kinetic mixing

$\mathcal{L} \ni -\frac{\epsilon}{4} F^Y_{\mu\nu} F^{\mu\nu}_X$

(see later)

"hidden electron"

gauge boson of $U(1)_X$

"hidden photon"

If the $U(1)_X$ is unbroken: the e' DM candidate is stable just as the electron:

lightest particle charged under a conserved charge

If the $U(1)_X$ is spontaneously broken: still the e' DM candidate is stable because of

remnant $Z_2 \in U(1)_X$, because still e' in pairs in $\mathcal{L}$

DM stability from new gauge symmetry

simplest example: lightest charged particle under a new $U(1)$: " $U(1)_X$ "

- a scalar: a ϕ_{DM} which has no charge under SM

  with SM particles chargeless under $U(1)_X$

"secluded DM"

Standard Model

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$l,\ \nu,\ q,\ \gamma,\ W,\ Z,\ g,\ H$

Hidden sector

$U(1)_X$

ϕ_{DM}, γ'

portal

Higgs portal

$\mathcal{L} \ni -\lambda_m \phi^{\dagger}_{DM}\phi_{DM} H^{\dagger} H$

(see later)

"hidden scalar"

gauge boson of $U(1)_X$

"hidden photon"

If the $U(1)_X$ is unbroken: the ϕ_{DM} DM candidate is stable just as the electron:

lightest particle charged under a conserved charge

If the $U(1)_X$ is spontaneously broken: the ϕ_{DM} could decay if gets a vev for instance

or stay stable if no vev but not automatic...

DM stability from accidental symmetry resulting from new gauge symmetry

well known example: conservation of mirror baryon number in a mirror hidden sector

other example: hidden vector DM: it is possible to have gauge boson to be the DM, even a non-abelian one

Standard Model
$SU(3)_c \times SU(2)_L \times U(1)_Y$
$l,\ \nu,\ q,\ \gamma,\ W,\ Z,\ g,\ H$

Hidden sector
$SU(2)_X$
$\phi,\ A^{\mu}_{1,2,3}$

portal
Higgs portal
$\mathcal{L} \ni -\lambda_m \phi^\dagger \phi H^\dagger H$

a doublet of $SU(2)_X$

3 gauge bosons of $SU(2)_X$

TH 07
TH, Tytgat 09
TH, Strumia 12

⇒ after $SU(2)_X$ sym. breaking:
- 3 massive $SU(2)_X$ gauge bosons: stable: DM candidates
- one real scalar boson
- a remnant $SU(2)_C$ accidental custodial symmetry

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ \frac{v_\phi}{\sqrt{2}} \end{pmatrix}$$

DM = hidden forces!

⇒ accidental symmetry: interesting phenomenology from naturally slow decay

DM stability from discrete symmetry: real scalar singlet

- a real scalar singlet S odd under Z_2 parity: $S \to -S$ ← "ad-hoc" symmetry

Standard Model
$SU(3)_c \times SU(2)_L \times U(1)_Y$
$l,\, \nu,\, q,\, \gamma,\, W,\, Z,\, g,\, H$

$\longleftrightarrow$

Hidden sector
Z_2
S

Higgs portal
$\mathcal{L} \ni -\frac{1}{2}\lambda_m S^2 H^\dagger H$

a real scalar singlet odd under Z_2

McDonald,...

⇒ S is stable: the Z_2 symmetry makes sure that all terms involve an even number of S:

$$\mathcal{L} \ni -\frac{1}{2}\mu_S^2 S^2 - \frac{1}{24}\lambda_S S^4 - \frac{1}{2}\lambda_m S^2 H^\dagger H$$

⇒ extremely simple: only 2 relevant parameters: $m_S,\ \lambda_m$

$$m_S^2 = \mu_S^2 + \frac{1}{2}\lambda_m v^2$$

⇒ more generally from a discrete Z_2 sym. one can stabilize any scalar or fermion SM multiplet (or abelian gauge boson)

DM stability from discrete symmetry: fermion triplet

- a fermion triplet under $SU(2)_L$ odd under Z_2 parity: $\psi_{DM} \to -\psi_{DM}$

$$\psi_{DM} = \begin{pmatrix} \psi^+_{DM} \\ \psi^0_{DM} \\ \psi^-_{DM} \end{pmatrix}$$

this is a visible sector DM model: ψ_{DM} has gauge SM interactions

(no hidden sector)

only interactions it can have in fact

DM stability from discrete symmetry: Susy neutralino

- Susy: has many new neutral particles beyond the SM: neutral superpartners;

$$\begin{array}{ccccl} B_Y^\mu & \leftrightarrow & \tilde{B} & : & \text{“Bino”} \\ W_3^\mu & \leftrightarrow & \tilde{W} & : & \text{“Wino”} \\ H_u & \leftrightarrow & \tilde{H}_u & : & \text{“Higgsino”} \\ H_d & \leftrightarrow & \tilde{H}_d & : & \text{“Higgsino”} \\ \nu_{L_i} & \leftrightarrow & \tilde{\nu}_i & : & \text{“sneutrinos”} \\ G & \leftrightarrow & \tilde{G} & : & \text{“gravitino”} \end{array}$$

$\hookrightarrow$ if one assume a Z_2 symmetry so that SM particles are even under it and superpartners are odd under it, "R-parity", the lightest superpartner (LSP) is stable

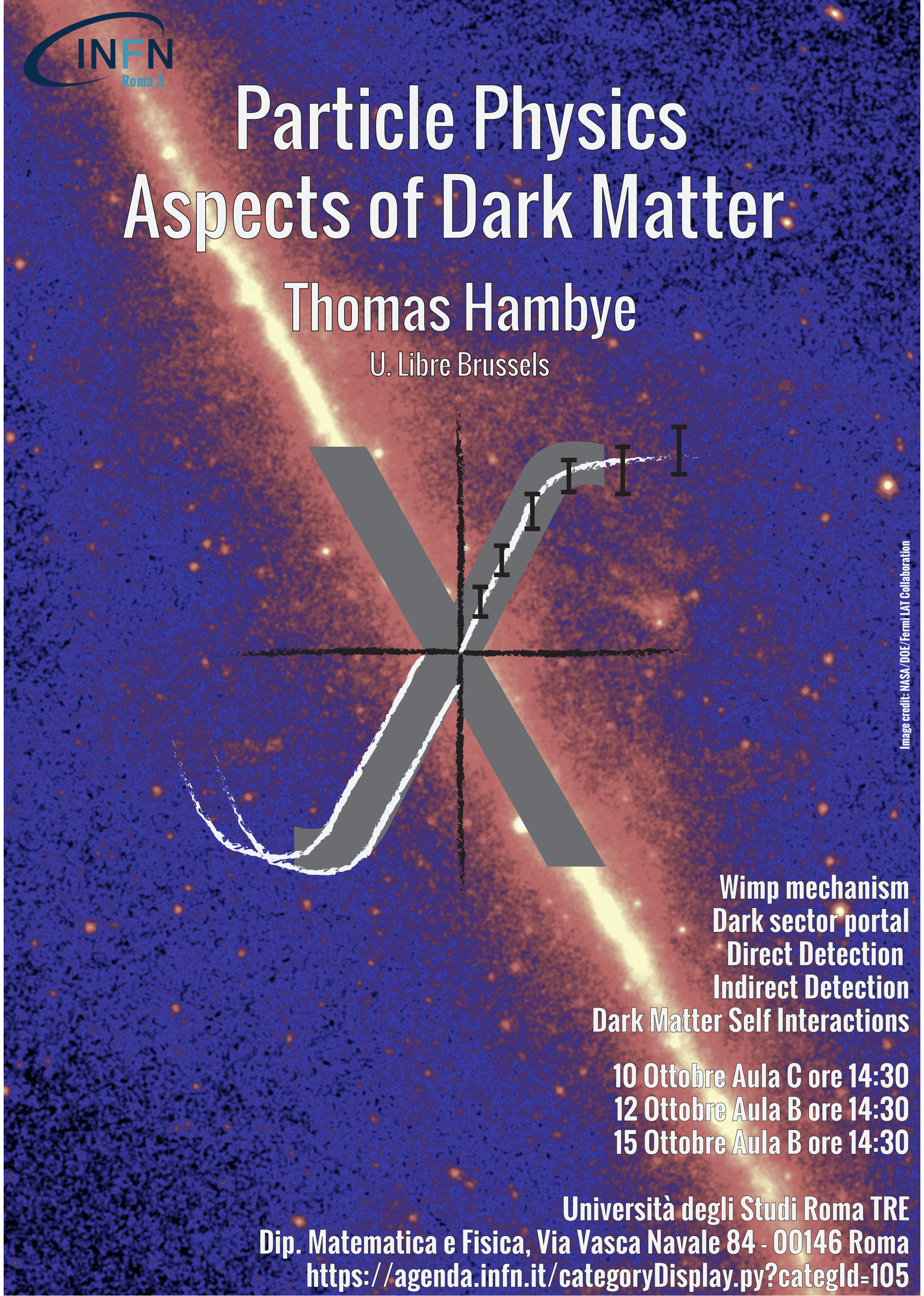
the 4 neutralinos (2 gauginos and 2 Higgsinos) mix: the lightest mass eigenstate, χ , is stable if LSP

R-parity is motivated by proton decay but still totally ad-hoc in MSSM

$\hookrightarrow$ but turns out to be subgroup of $U(1)_{B-L}$ $\Rightarrow$ could derive from gauge symmetry remnant subgroup

This is the χ of this psychedelic poster (thanks Roberto…)

welcome to the DM sect !



Epilogue on DM stability

- DM stability is the most constraining property for the general structure of the DM model!
- DM stability strongly suggests the existence of a new symmetry in Nature!

even if not absolutely mandatory

perhaps it is the result of new forces in Nature (gauge symmetries)
perhaps not if discrete or global symmetry, which is boring
unless directly related to solution of other problem (as axion)

whose stability is due to a mixture of several reasons: due to global symmetry and the fact that it is very light and that it's decay occurs at loop level and suppressed by high scale will not be discussed here

- Depending on stabilization mechanism several possibilities:

Fermion DM candidate <-> Boson DM candidate: scalar, vector

Visible DM candidate <-> Hidden sector DM candidate

Minimal model of DM <-> DM out of more global model

=> different phenomenologies!

A wide variety of DM models!

Illustrative examples:

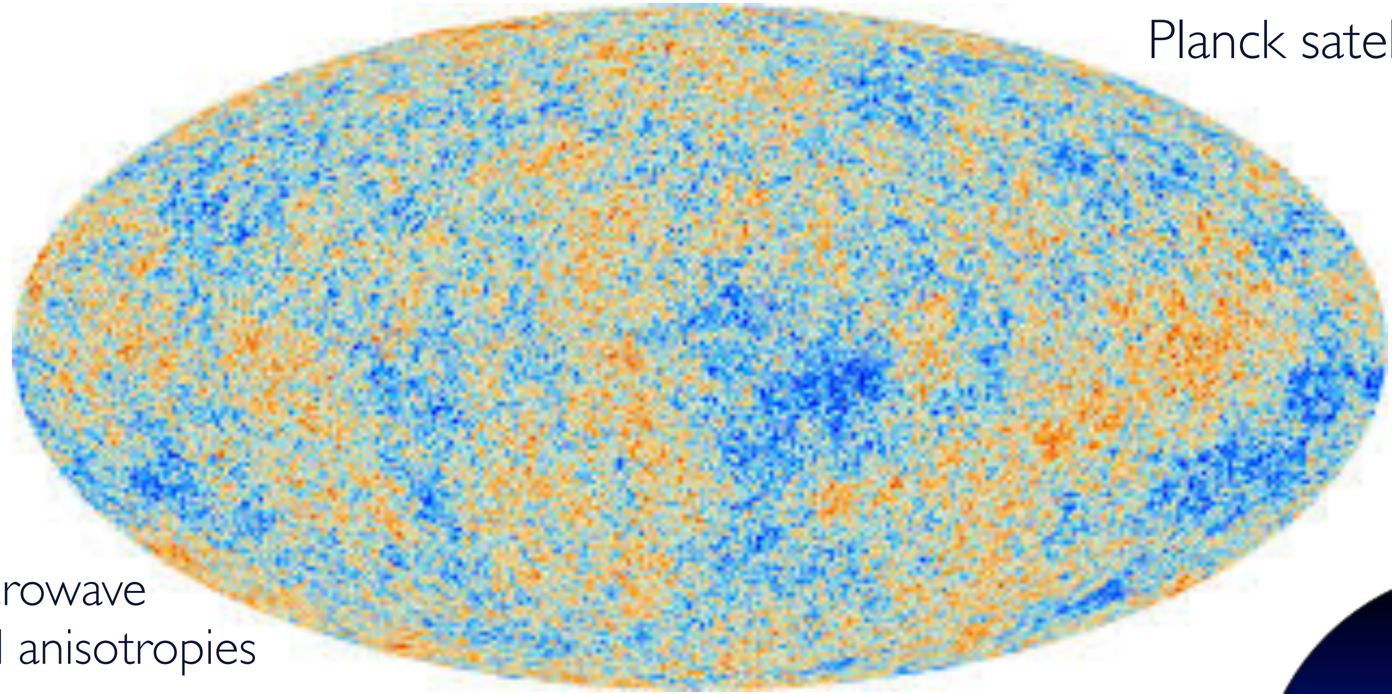
- A real scalar singlet odd under a Z_2 : the simplest DM model
- A fermion triplet odd under a Z_2 ("Wino model " if Majorana)
- A fermion quintuplet stable in an accidental way only on the basis of SM symmetries
- A hidden fermion or scalar charged under a new $U(1)_X$ gauge symmetry
- Hidden gauge bosons of a new $SU(2)_X$ gauge symmetry accidentally stable
- The MSSM neutrino stable due to R-parity
- ……..

Part 2
DM relic density

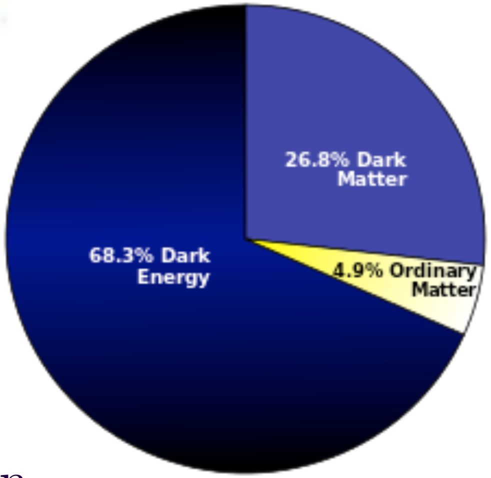
DM relic density: $\Omega_{DM} = 26\%$

$$\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_{crit}}\Big|_{today} \quad \Omega_B \equiv \frac{\rho_B}{\rho_{crit}}\Big|_{today}$$

Planck satellite



Cosmic Microwave Background anisotropies



$$\Rightarrow \quad \Omega_{DM}h^2 = 0.1199 \pm 0.0027 \qquad \Omega_{DM} \simeq (26 \pm 1)\%$$

$$\Omega_B h^2 = 0.02205 \pm 0.00028 \qquad \Omega_B \simeq (4.9 \pm 0.2)\%$$

$$h = 0.673 \pm 0.012$$

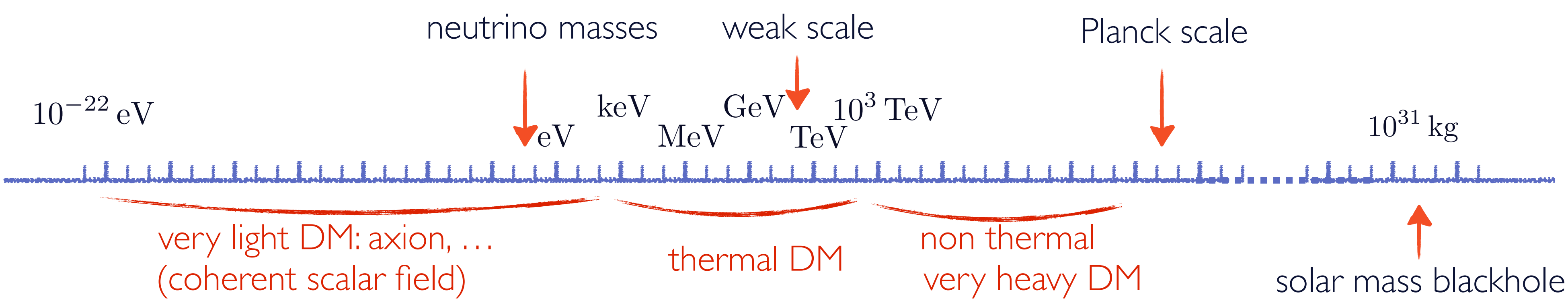
$$\Omega_{rad}h^2 = 4.31 \cdot 10^{-5} \leftarrow 2.7\,\mathrm{K\ black\ body\ CMB\ radiation}$$

DM relic density: $\Omega_{DM} = 26\%$

can be obtained for m_{DM} all the way from $\sim 10^{-22}\,\mathrm{eV}$ to $\sim 10^{31}$ kg

to have wavelength smaller than galactic size

black hole with $\sim$ solar mass



in the following we will consider the thermal DM scenarios

$$\mathrm{keV} \lesssim m_{DM} \lesssim 100\,\mathrm{TeV}$$

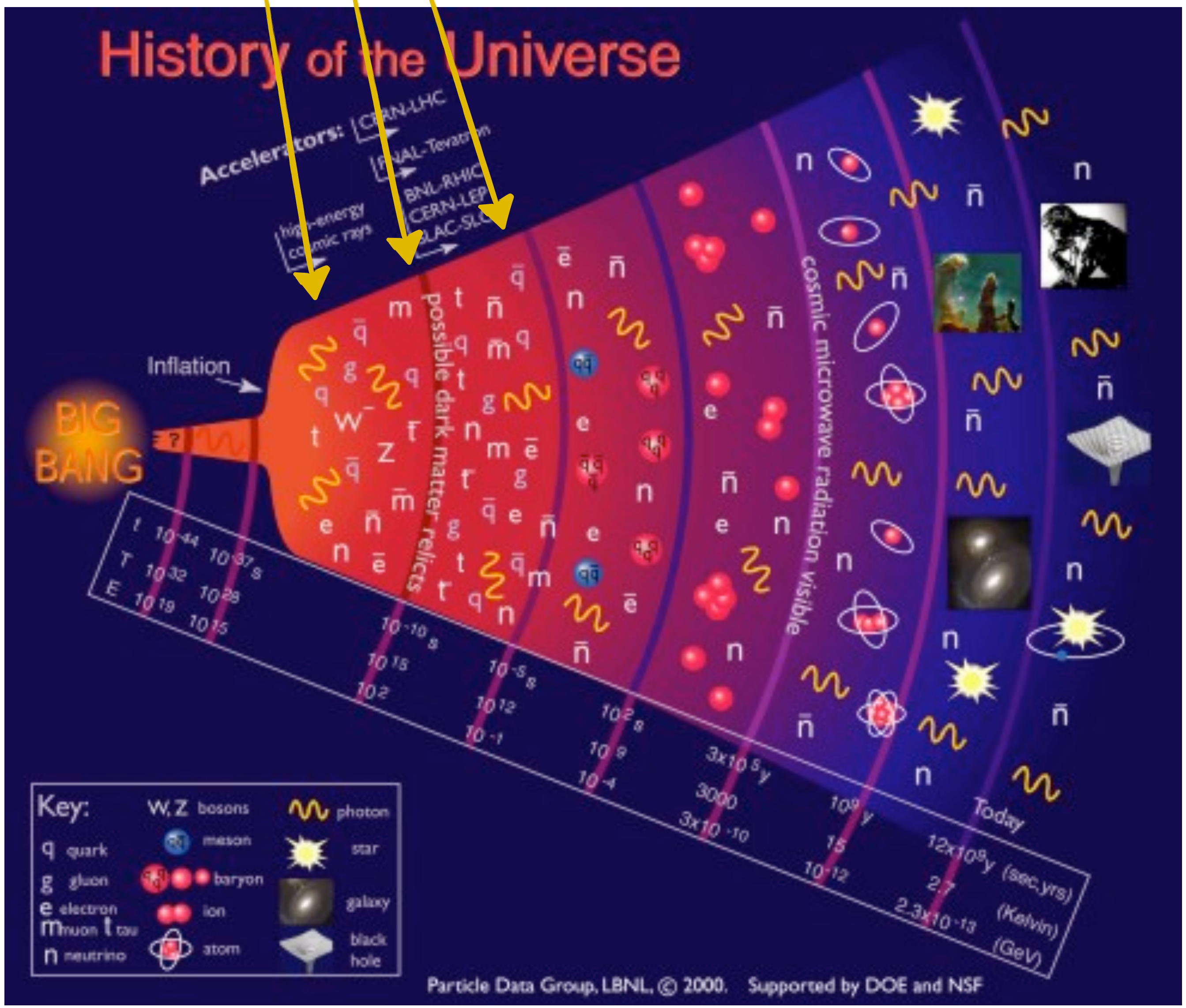
2 general classes of models:

- symmetric DM thermal freezout: no DM matter-antimatter asymmetry
- asymmetric DM

Generalities on early Universe hot thermal bath

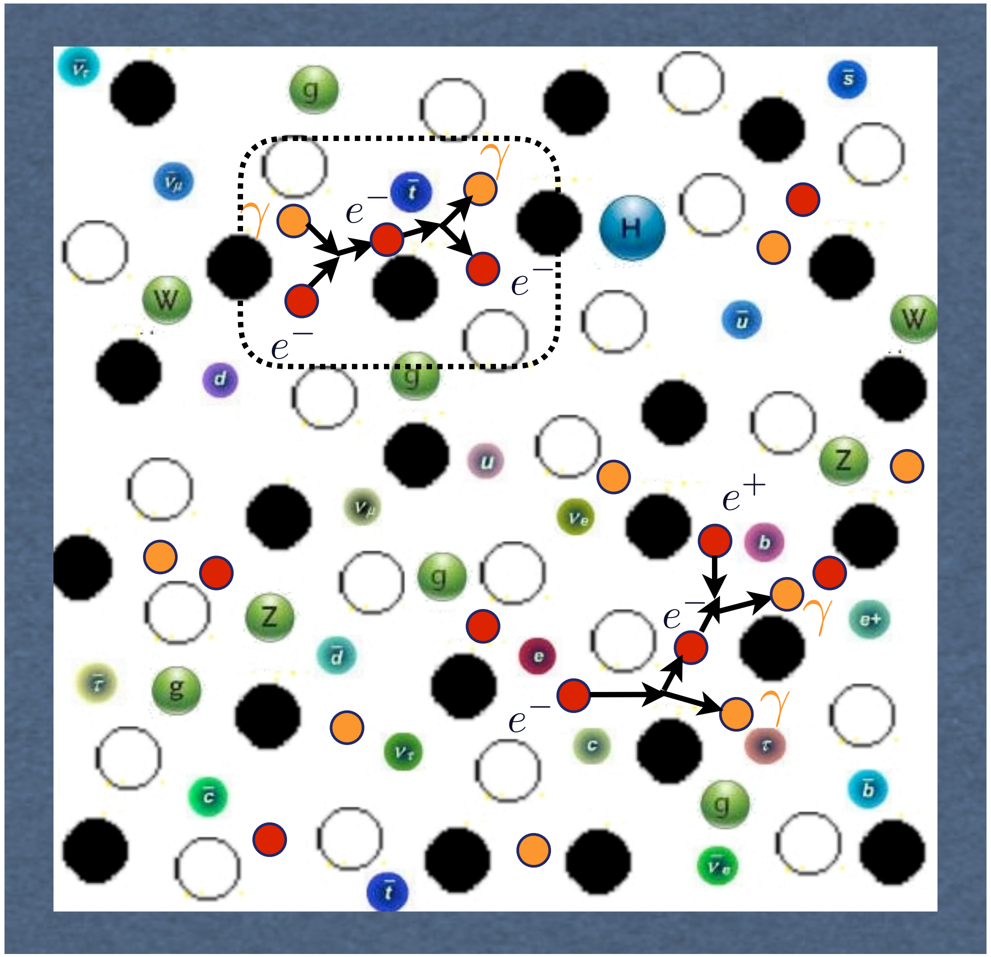
we consider the « radiation domination » epoch when all SM particles were forming a hot thermal soup: plasma

$T \gtrsim 1\,\mathrm{eV}$



Generalities on early Universe hot thermal bath

⇒ hot plasma:



Example with e^- and γ:

2 relevant processes

$$e^{\pm} + \gamma \to e^{\pm} + \gamma$$

$$e^{+} + e^{-} \leftrightarrow \gamma + \gamma$$

if many $e^- + \gamma \to e^- + \gamma$ processes:

⇒ e^- and γ equilibrate their kinetic energy

e^- and γ are in "kinetic equilibrium"

probability that e^- has a given energy is given by a Fermi-Dirac distribution characterized by a temperature T

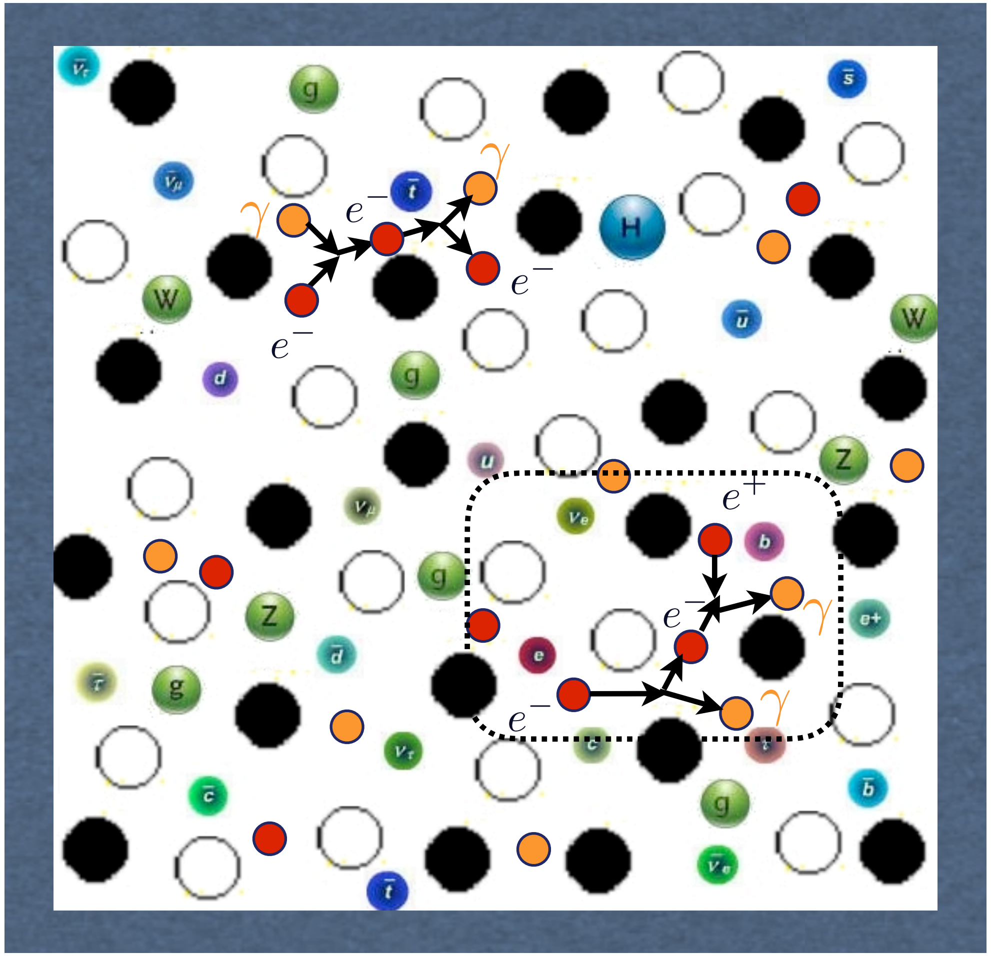
~averaged e^- kinetic energy

and similarly for γ given by a Bose-Einstein distribution characterized by same temperature: $T_{e^-} = T_{e^+} = T_\gamma \equiv T$

~averaged γ kinetic energy

Generalities on early Universe hot thermal bath

⇒ hot plasma:



Example with e^- and γ :

2 relevant processes

$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma$$

$$e^+ + e^- \leftrightarrow \gamma + \gamma$$

if many $e^+ + e^- \leftrightarrow \gamma + \gamma$ processes:

⇒ $e^{\pm}$ and γ equilibrate their numbers

$$n_{e^-} + n_{e^+} \leftrightarrow n_\gamma$$

$e^{\pm}$ and γ are in "chemical equilibrium"

in this case not only the energy distribution is known but also its normalization: how many particles have a given energy

⇒ $f_{FD}^{e^{\pm}} = \dfrac{1}{e^{E_{e^{\pm}}/T} + 1}$ ⇒ $n_{e^{\pm}} = g_{e^{\pm}} \displaystyle\int \frac{d^3 p_{e^{\pm}}}{(2\pi)^3} f_{FD}^{e^{\pm}}$ $\quad \rho_{e^{\pm}} = g_{e^{\pm}} \displaystyle\int \frac{d^3 p_{e^{\pm}}}{(2\pi)^3} f_{FD}^{e^{\pm}} \cdot E_{e^{\pm}}$

assuming here no e^+-e^- asymmetry: $n_{e^+} = n_{e^-}$ $\quad g_\gamma = g_{e^-} = g_{e^+} = 2$

⇒ $f_{BE}^{\gamma} = \dfrac{1}{e^{E_\gamma/T} - 1}$ ⇒ $n_\gamma = g_\gamma \displaystyle\int \frac{d^3 p_\gamma}{(2\pi)^3} f_{BE}^{\gamma} = \frac{\zeta(3)}{\pi^2} g_\gamma T^3$ $\quad \rho_\gamma = g_\gamma \displaystyle\int \frac{d^3 p_\gamma}{(2\pi)^3} f_{BE}^{\gamma} \cdot E_\gamma = \frac{\pi^2}{30} g_\gamma T^4$

Relativistic and non relativistic thermal equilibrium regimes

$$n_{e^\pm} = g_{e^\pm} \int \frac{d^3 p_{e^\pm}}{(2\pi)^3} f_{FD}^{e^\pm} = \begin{cases} \dfrac{3}{4}\dfrac{\zeta(3)}{\pi^2} g_{e^\pm} T^3 & (T >> m_e) \quad \text{relativistic } e^- \\ g_{e^\pm}\left(\dfrac{m_e T}{2\pi}\right)^{3/2} e^{-m_e/T} & (T << m_e) \quad \text{non-relativistic } e^- \end{cases}$$

If no interactions: $n_{e^-} = \dfrac{const}{V}$

to see the variation of n_{e-} due to interactions we look at "comoving number density":

$n_{e-} \cdot V$ or $Y_{e^-} = n_{e^-}/s$

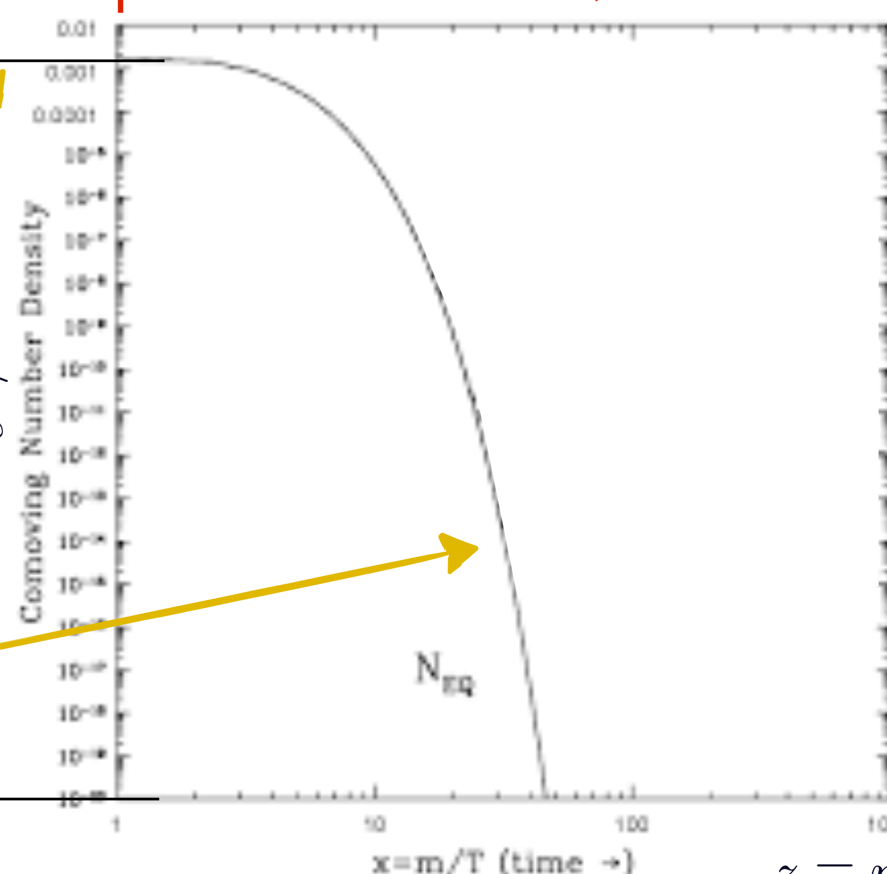
entropy density is conserved:

$$s = \frac{2\pi^2}{45} g_*^s T^3 \propto 1/V$$

$T > m_e$:
comoving number density is constant!

$T < m_e$:
comoving number density is exponentially suppressed:
Boltzmann suppression $\propto e^{-m_e/T}$

relativistic | non-relativistic



n_{e-}/s

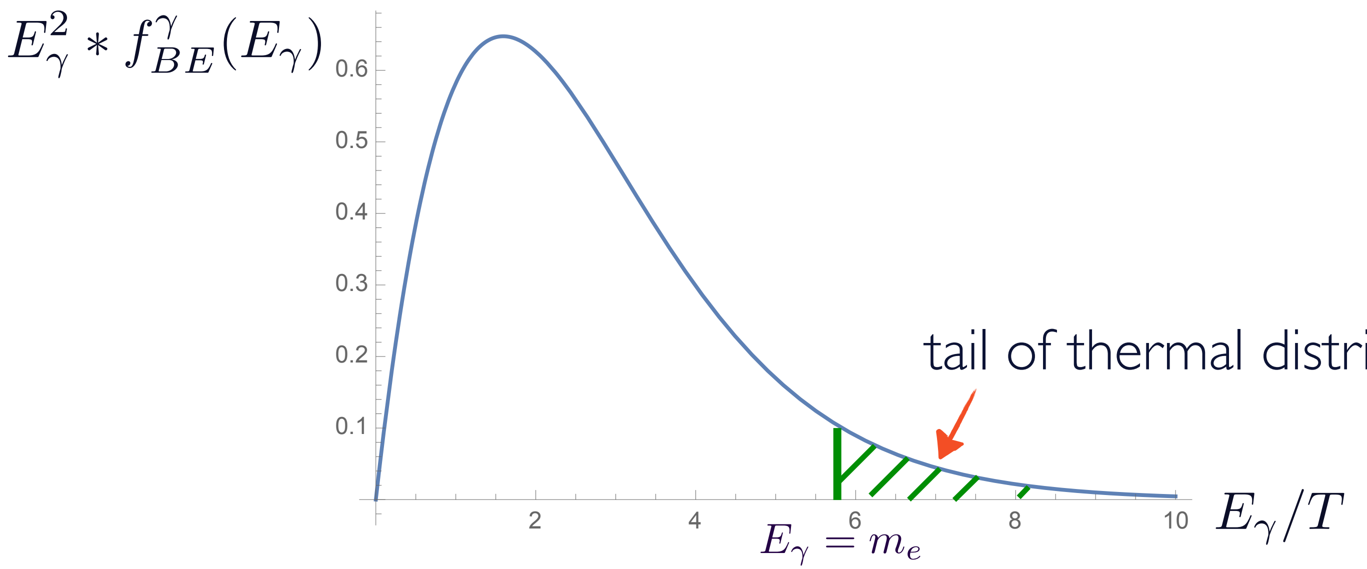
$z \equiv m_e/T$

Boltzmann suppression in non-relativistic regime

when a e^- encounters a e^+, they can always go to 2 γ

when a γ encounters another γ , they can go to e^+e^- only if they have enough energy

at $T < m_e$ only a small proportion of photons have enough energy:



for a fixed temperature thermal equilibrium means same number of interact. in both directions in order that number densities do not change (i.e. to give the equilibrium distribution fixed by temperature only)

$\Rightarrow$ for $T < m_e$: this means basically: $n_{e^-}^{Eq} \sim n_\gamma^{Eq}(E_\gamma > m_e) \propto e^{-m_e/T}$

$\Rightarrow$ as T decreases with expansion $n_{e^-}^{Eq}$ more and more exponentially suppressed

More generalities on early Universe thermodynamics: radiation energy density

- For a relativistic fermion particle:

$$\rho_f = g_f \int \frac{d^3p_f}{(2\pi)^3} f_{FD}^f \cdot E_f = \frac{\pi^2}{30}\frac{7}{8} g_f T_f^4$$

For a relativistic boson particle:

$$\rho_b = g_b \int \frac{d^3p_b}{(2\pi)^3} f_{BE}^b \cdot E_b = \frac{\pi^2}{30} g_b T_b^4$$

For a plasma with several species with same temperature $\leftarrow$ if kinetic equilibrium

$$\rho_{rad}^{Tot} = \frac{\pi^2}{30} g_* T^4 \qquad g_* = \sum_{b_i} g_{b_i} + \frac{7}{8}\sum_{f_i} g_{f_i}$$

$$\Rightarrow H \equiv \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G\rho}{3}} \sim 1.7\sqrt{g_*}\frac{T^2}{m_{Planck}} \qquad a = \text{Universe scale factor}$$

- Remember also that in expanding Universe, all momentum scales as $1/a \sim 1/V^{1/3}$

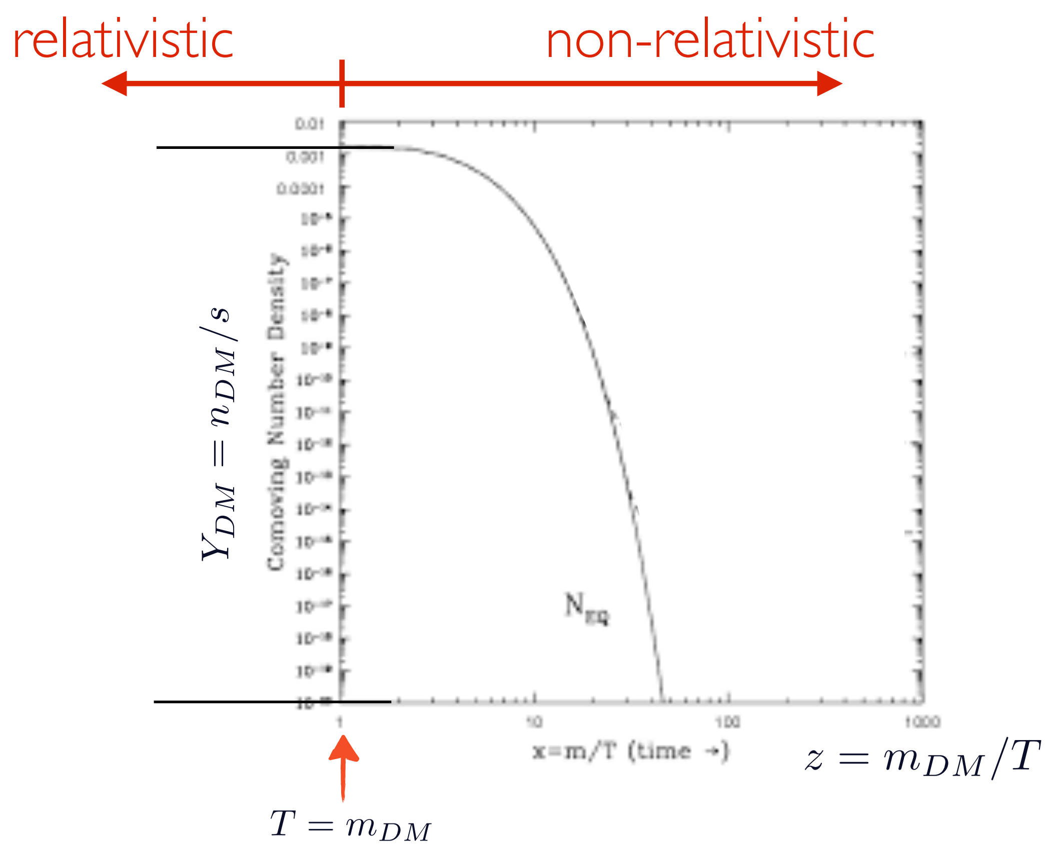
$$\Rightarrow T \sim p_\gamma \propto 1/a \Rightarrow n \propto T^3 \propto 1/V \propto 1/a^3 \Rightarrow \rho_{rad} = n \cdot < E > \propto T^3 \cdot T \propto T^4 \propto a^{-4}$$

- Entropy density: totally dominated by radiation: $s = \frac{4}{3}\frac{\rho_{rad}^{Tot}}{T} = \frac{2\pi^2}{45} g_* T^3 \quad \leftarrow \propto 1/V$

DM thermal equilibrium comoving number density

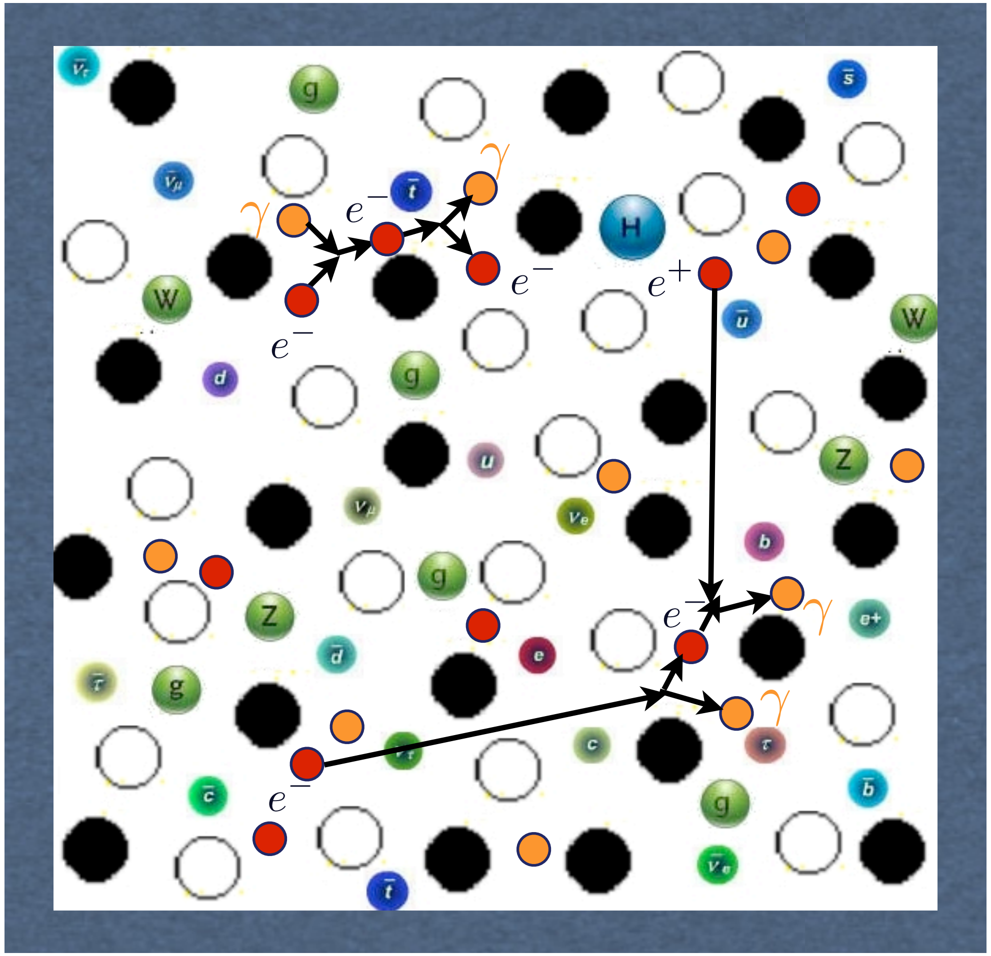
Comoving DM number density is constant when relativistic and becomes Boltzmann suppressed when becoming non-relativistic when $T < m_{DM}$ in the same way as e^- if DM is in kinetic equilibrium and chemical equilibrium

$DM\, SM \leftrightarrow DM\, SM$ $\qquad$ $DM\, DM \leftrightarrow SM\, SM$



No expansion : no thermal decoupling

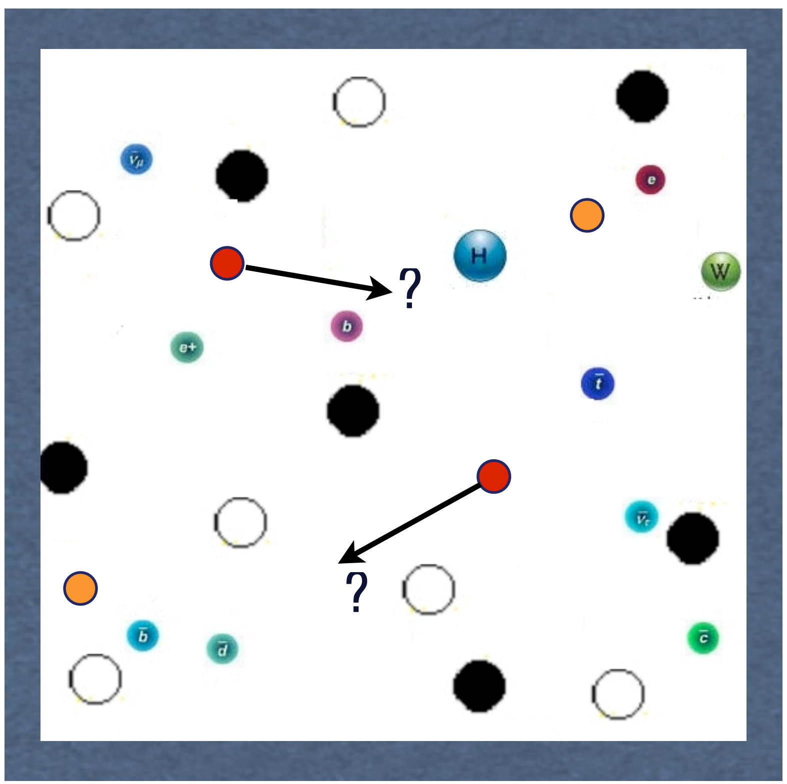
If no expansion: e^+ and e^- or
2 DM particles will always
finish by encountering
$\Rightarrow$ will still equilibrate numbers
and energies $\Rightarrow$ no decoupling



DM thermal decoupling due to expansion

Clearly DM cannot remain in thermal equilibrium for ever: if it has not already decoupled when it was relativistic it will anyway when it is non-relativistic: as Universe expands the DM number density becomes more and more exponentially suppressed: at some point too few DM particles for them to annihilate

⇒the annihilation $DM\,DM \leftrightarrow SM\,SM$ process doesn't occur anymore and n_{DM}/s freezes



⇒When??????

particles couple as long as:

$$\delta t <\sim 1/H \qquad\qquad H = \frac{\dot{a}}{a}$$

average time for a DM particle to undergo an interaction

inverse of rate of Universe expansion $\sim$ age of the Universe

Thermal decoupling condition

Particle decouples when: $\delta t \; > \sim 1/H$ $\Longleftrightarrow$ $\Gamma \equiv 1/\delta t \; < \; H$

interaction rate

rate of Universe expansion

For a decay: $\delta t = 1/\Gamma_D$

decay width

For an annihilation $i + j \rightarrow k + l$

$$\sigma(i+j \rightarrow k+l) = \frac{\text{number of transition a single i particle undergoes per unit time}}{\text{incoming flux of j particles}}$$

$$= \frac{\text{number of transition a single i particle undergoes per unit time}}{\text{number of j particles crossing a unit surface per unit time}}$$

$$= \frac{\text{number of transition a single i particle undergoes per unit time}}{n_j \cdot v_{rel}}$$

relative velocity between i and j

$$\Gamma_i = 1/\delta t_i = \text{number of transition a single i particle undergoes per unit time} = n_j \left\langle \sigma_{i\,j \rightarrow k\,l} \cdot v_{rel} \right\rangle$$

average over i and j momentum distribution

$$\Rightarrow \Gamma_i = n_j \left\langle \sigma_{i\,j \rightarrow k\,l}\, v_{rel} \right\rangle \leftarrow \neq \gamma_{i\,j \rightarrow k\,l} \equiv n_i n_j \left\langle \sigma_{i\,j \rightarrow k\,l}\, v_{rel} \right\rangle$$

$$= \text{number of transitions per unit time per unit volume}$$

Relativistic DM thermal decoupling: "hot relic"

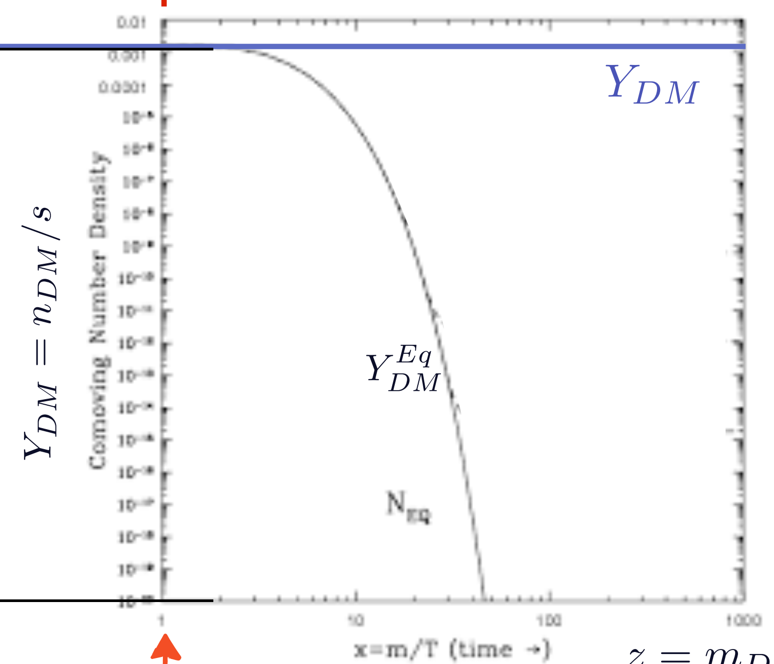
$$\Gamma_{DM} = n_{DM}^{Eq} \langle \sigma_{DM\,DM \to SM\,SM}\, v_{rel} \rangle \; < \; H$$

if this occurs when $T > m_{DM}$:

$$\left.\frac{n_{DM}}{s}\right|_{T_{today}} = \left.\frac{n_{DM}}{s}\right|_{T_{dec}} = \text{constant number it has when relativistic}$$

relativistic | non-relativistic

decoupling here



$T = m_{DM}$

$z = m_{DM}/T$

$$\Rightarrow Y_{DM} = \left.\frac{n_{DM}}{s}\right|_{T_{dec}} = \frac{\frac{3}{4}\frac{\zeta(3)}{\pi^2} g_{DM} \cancel{T_{dec}^3}}{\frac{2\pi^2}{45} g_*^s \cancel{T_{dec}^3}}$$

$E_{DM} = m_{DM}$

today (redshift)

$$\Omega_{DM} = \frac{n_{DM}\, m_{DM}}{\rho_{crit}}$$

$$= \frac{(Y_{DM})_{today}\; s_{today}\, m_{DM}}{\rho_{crit}}$$

$$= \frac{Y_{DM}(T_{dec})\; s_{today}\, m_{DM}}{\rho_{crit}}$$

$$\Omega_{DM} = 0.024\, \frac{g_{DM}}{2}\, \frac{m_{DM}}{\text{eV}}\, \frac{0.7^2}{h^2}$$

$(g_{DM} = 2)$

$\Rightarrow$ $\Omega_{DM} = 26\%$ requires $m_{DM} \simeq 10\,\text{eV}$

Why a hot DM relic points towards eV scale?

because each DM particle today has much more energy than each γ today: $E_{DM} \simeq m_{DM}$

$$E_\gamma \simeq T_{today} \sim 10^{-3}\,\mathrm{eV}$$

at decoupling $T > m_{DM} \Rightarrow E_{DM} \sim E_\gamma \sim T$

but once $T < m_{DM}$ the energy per DM particle freezes to $E_{DM} \simeq m_{DM}$ whereas the energy per γ goes on to decreases as T : the Universe is matter dominated today!

and since the hot relic DM scenario predicts $n_{DM} \sim n_\gamma$ at decoupling $\Rightarrow$ $n_{DM} \sim n_\gamma$ still today

this means that to have Ω_{DM} not larger than 26% today we need DM to be very light!

numerically it is an experimental fact that today: $\Omega_{rad} = 9.6 \cdot 10^{-5}$

$$\Omega_{DM} = 26\%$$

$$\rho_{rad}^{Tot} = \frac{\pi^2}{30} g_* T^4$$

$$T_\gamma = 2.7\,\mathrm{K} \sim 10^{-3}\,\mathrm{eV}$$

$$\Rightarrow \frac{\Omega_{DM}}{\Omega_{rad}} \sim 3000 \sim \frac{E_{DM}}{E_\gamma}\Big|_{today} \sim \frac{m_{DM}}{10^{-3}\,\mathrm{eV}} \Rightarrow m_{DM} \sim \mathcal{O}(10\,\mathrm{eV})$$

if $n_{DM} \sim n_\gamma$

Why a hot DM relic points towards eV scale?

$\Rightarrow$ unless $m_{DM} \lesssim \mathcal{O}(10\,\mathrm{eV})$ the relic density constraint requires a mechanism which gives: $\frac{n_{DM}}{n_\gamma} << 1$

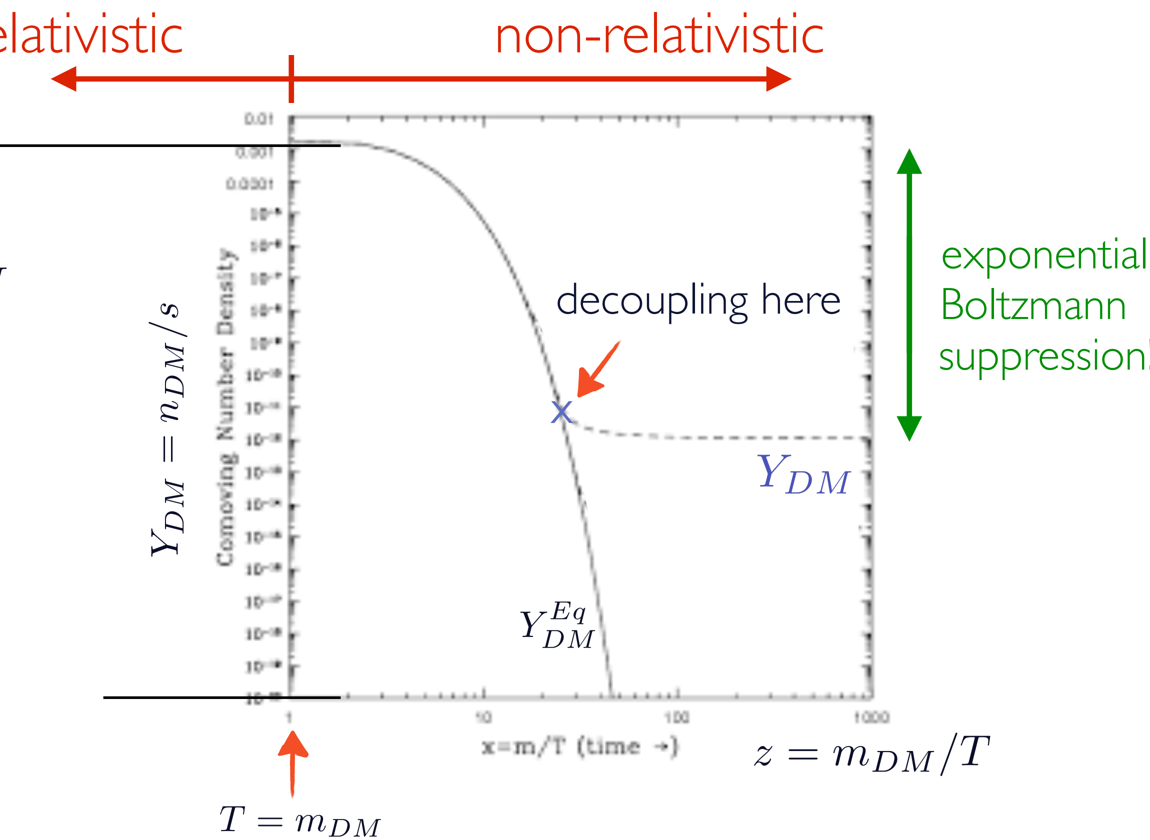
this is similar to the baryon case $\Omega_B = 5\%$ and $m_p \simeq 1\,GeV \;\rightarrow\; \left.\frac{n_B}{n_\gamma}\right|_{today} \sim 10^{-9}$

Non-relativistic DM thermal decoupling: "cold relic"

gives naturally $\frac{n_{DM}}{n_\gamma} << 1$ $\Rightarrow$ points towards heavier values of m_{DM}

$\Gamma_{DM} = n_{DM}^{Eq} \langle \sigma_{DM\,DM \to SM\,SM}\, v_{rel} \rangle \; < \; H$

occurs when $T < m_{DM}$:



approximation of instantaneous decoupling: for $T > T_{dec}$: $n_{DM} = n_{DM}^{Eq}$

for $T < T_{dec}$: no more annihilation at all:

$n_{DM}/s = const$

$\Rightarrow$ $\left.\frac{n_{DM}}{s}\right|_{today} = \left.\frac{n_{DM}}{s}\right|_{T_{dec}} = \left.\frac{n_{DM}^{Eq}}{s}\right|_{T_{dec}}$ $\Rightarrow$ all we just need to know is T_{dec}

Non-relativistic DM thermal decoupling: "cold relic"

T_{dec} is given by: $\frac{\Gamma}{H}\Big|_{T_{dec}} = \frac{n_{DM}^{Eq}\langle\sigma_{DM\,DM\to SM\,SM}\,v_{rel}\rangle}{H}\Big|_{T_{dec}} = 1$

$$n_{DM}^{Eq} = g_{DM}\left(\frac{m_{DM}\,T}{2\pi}\right)^{3/2} e^{-m_{DM}/T}$$

$g_* =$ number of relativistic degrees of freedom in thermal bath

$$H = \sqrt{\frac{8\pi G\rho}{3}} \sim 1.7\,\sqrt{g_*}\,\frac{T^2}{m_{Planck}}$$

$$\Rightarrow\quad z_{dec} \equiv \frac{m_{DM}}{T_{dec}} = \ln[0.038\,\frac{g_{DM}}{\sqrt{g_*}}\,m_{DM}\,m_{Planck}\langle\sigma_{DMDM\to SMSM}\,v_{rel}\rangle]$$

$$\Rightarrow\quad Y_{DM}|_{today} = \frac{n_{DM}}{s}\Big|_{today} = \frac{n_{DM}}{s}\Big|_{T_{dec}} = \frac{n_{DM}^{Eq}}{s}\Big|_{T_{dec}} = \frac{H(T_{dec})}{\langle\sigma_{DMDM\to SMSM}\,v_{rel}\rangle}\,\frac{1}{s(T_{dec})}$$

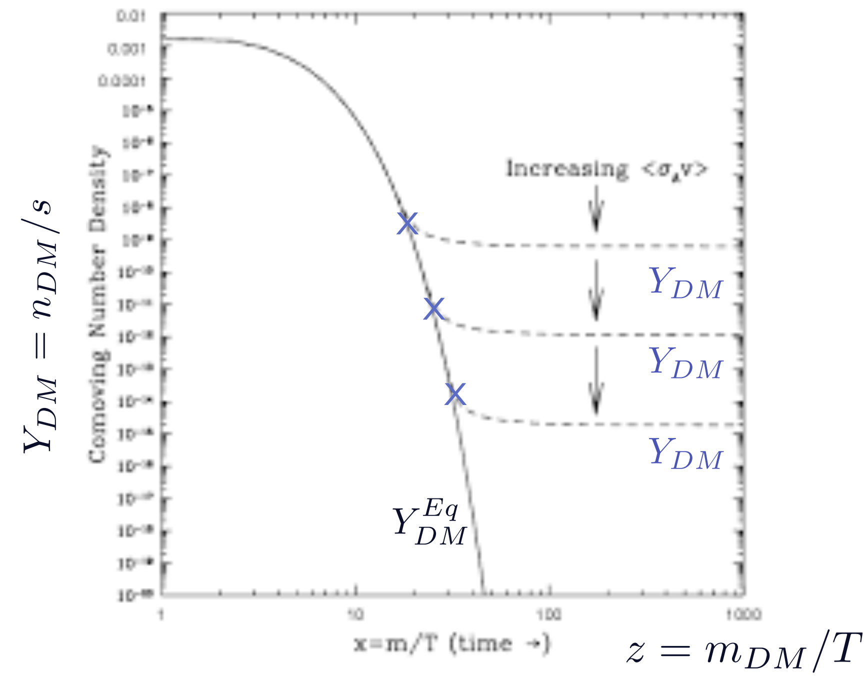
$$= \frac{1.7\pi^2}{4}\,\frac{\sqrt{g_*}}{g_{DM}}\,\frac{z_{dec}}{m_{Planck}m_{DM}}\,\frac{1}{\langle\sigma_{DMDM\to SMSM}\,v_{rel}\rangle}$$

$$= \text{const}\,\frac{1}{m_{DM}}\,\frac{z_{dec}}{\langle\sigma_{DMDM\to SMSM}\,v_{rel}\rangle}$$

$$\Rightarrow\quad \Omega_{DM} = \frac{(n_{DM})_{today}\,m_{DM}}{\rho_{crit}} = \frac{(Y_{DM})_{today}\,s_{today}\,m_{DM}}{\rho_{crit}} = \text{const'}\,\frac{z_{dec}}{\langle\sigma_{DMDM\to SMSM}\,v_{rel}\rangle} \simeq \text{const''}\,\frac{1}{\langle\sigma_{DMDM\to SMSM}\,v_{rel}\rangle}$$

Non-relativistic DM thermal decoupling: "cold relic"

the larger is the annihilation cross section the longer DM will remain in thermal equilibrium, the smaller will be the equilibrium number density when DM decouples, the smaller will be Ω_{DM}



the relic density fixes the value of the cross section to a value basically independent of m_{DM} $\quad \Omega_{DM} = \text{const'} \dfrac{z_{dec}}{\langle \sigma_{DMDM\to SMSM}\, v_{rel} \rangle} \simeq \text{const''} \dfrac{1}{\langle \sigma_{DMDM\to SMSM}\, v_{rel} \rangle}$

$\Rightarrow$ $\Omega_{DM} = 26\% \leftrightarrow \langle \sigma_{DMDM\to SMSM}\, v_{rel} \rangle \simeq 3 \cdot 10^{-26} \text{cm}^3/\text{sec} \simeq 10^{-9}\, \text{GeV}^{-2} \simeq 1\, \text{pb}$

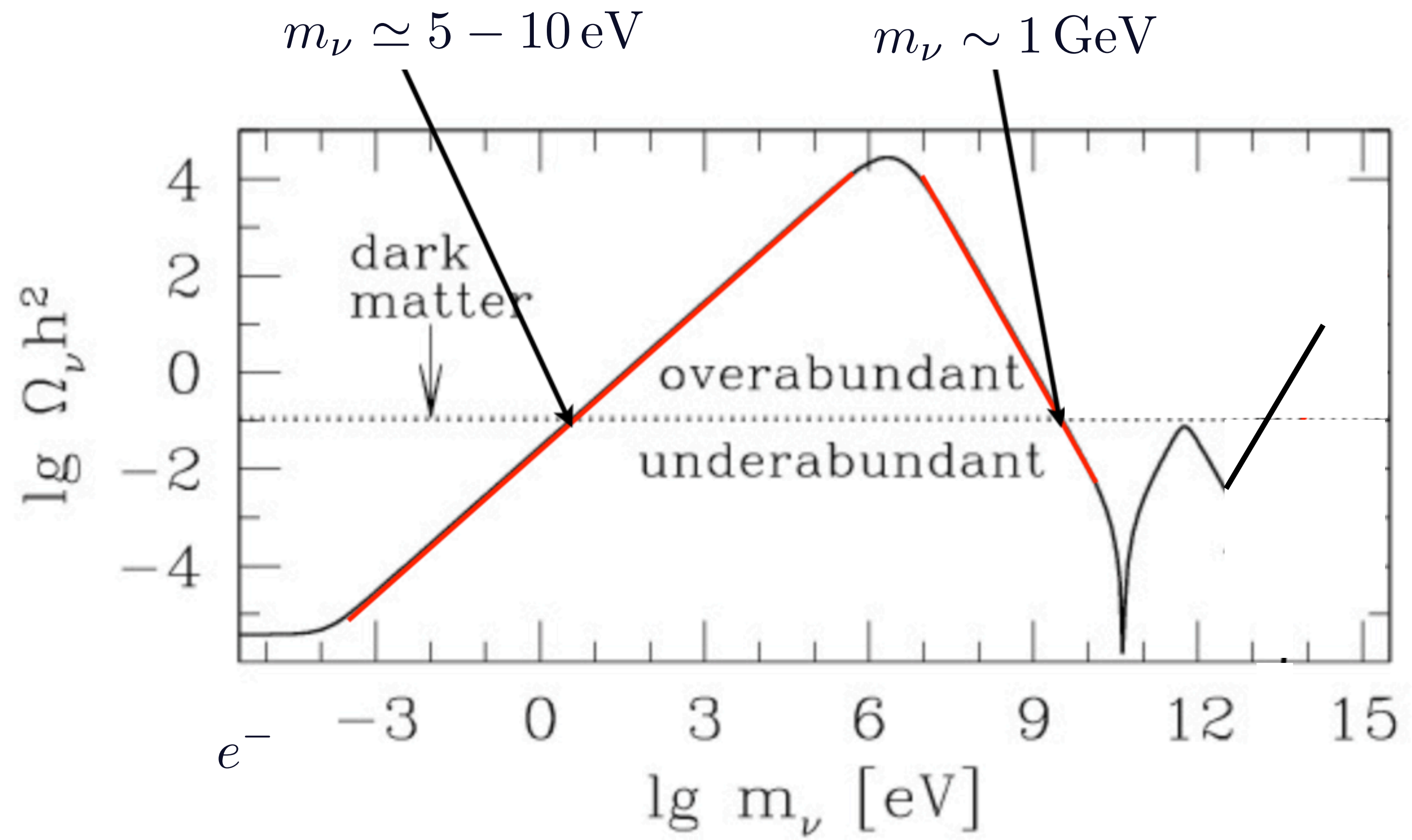
$\Rightarrow$ if $\langle \sigma_{DMDM\to SMSM}\, v_{rel} \rangle \propto \dfrac{g^4}{m_{DM}^2}$ and $g \sim 1 \sim g_{EW}$ one needs $m_{DM} \sim 1\, \text{TeV}$

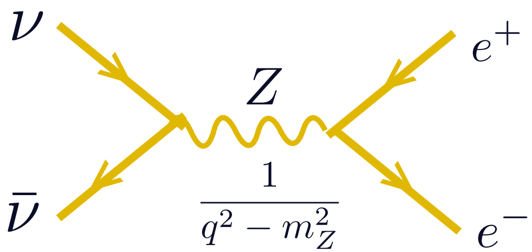
$z_{dec} \simeq 22$

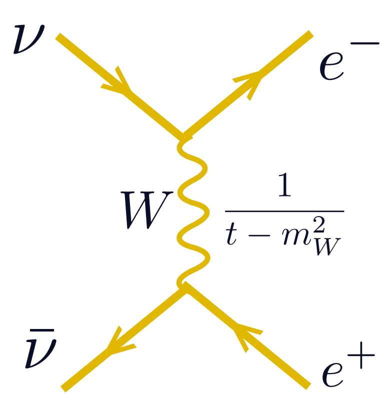
"WIMP miracle"

The example of a Dirac neutrino with mass m_ν

$g_\nu = 4$

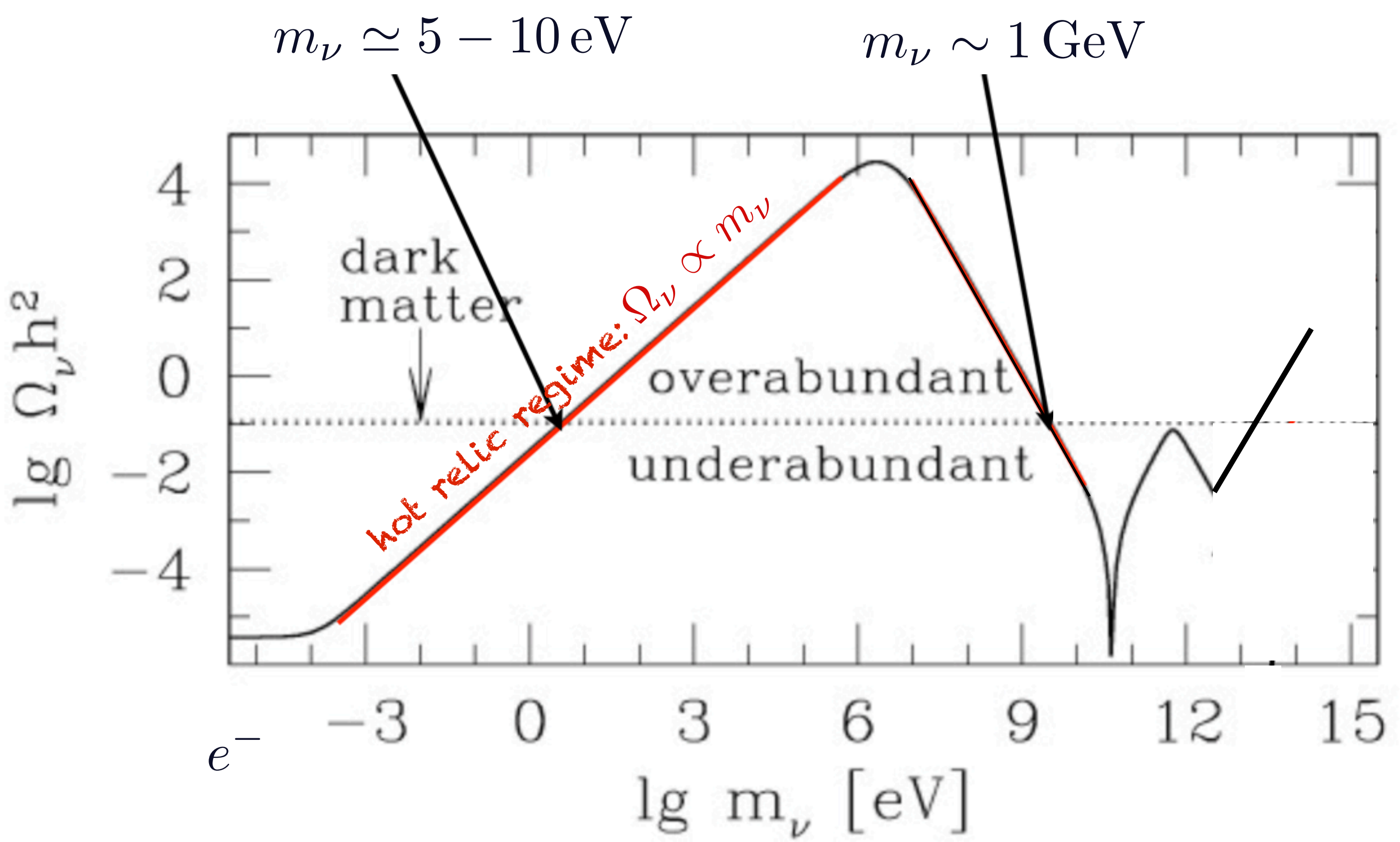






$$\Gamma_\nu = n_\nu \langle \sigma_{\nu\bar{\nu}\to e^+e^-}\, v_{rel} \rangle$$

The example of a Dirac neutrino with mass m_ν: hot relic regime

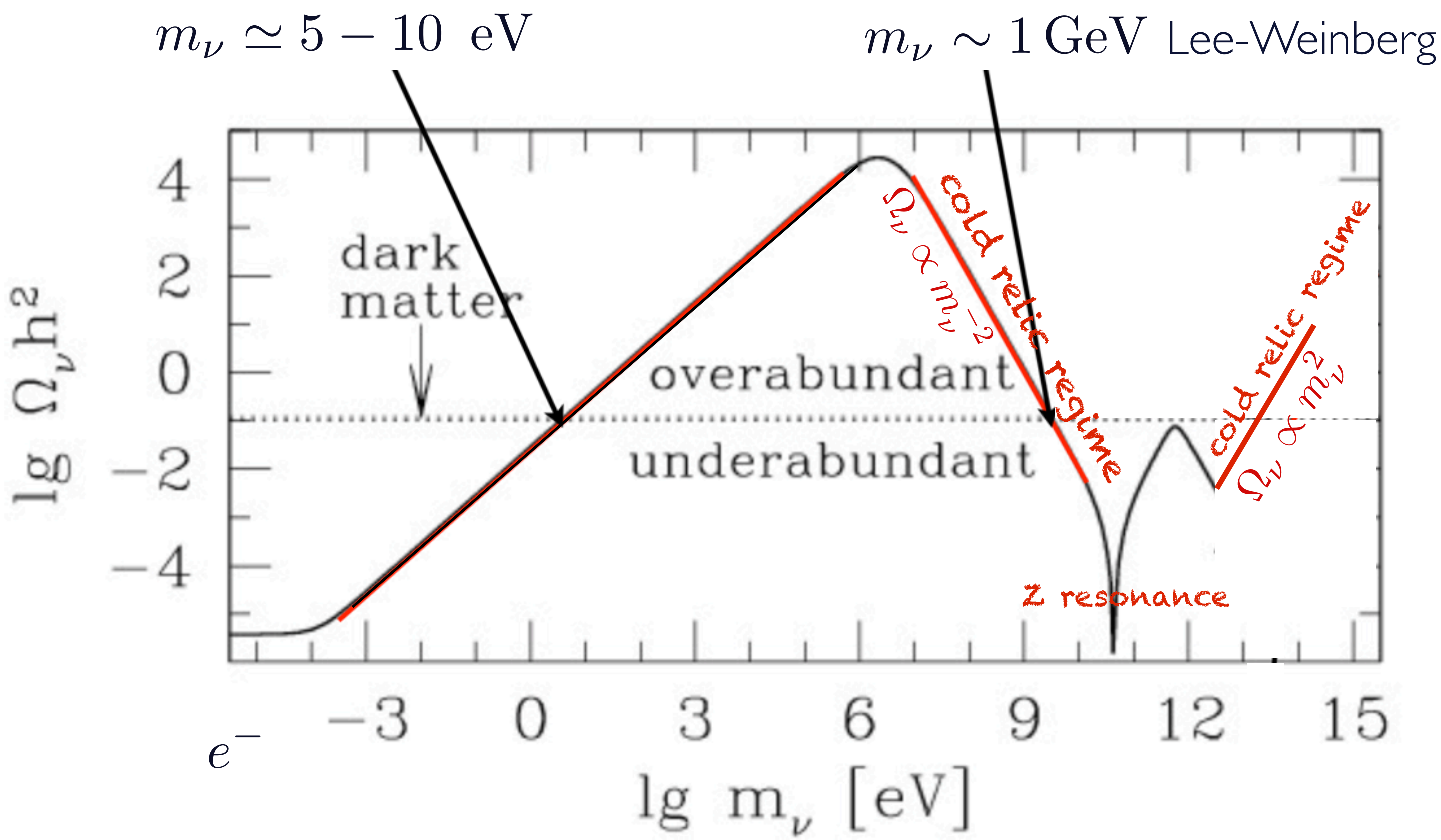


we consider $m_\nu << m_{Z,W}$ and assume $T_{dec} > m_\nu$: $\rightarrow n_\nu^{Eq} \sim g_\nu T^3$ $\rightarrow \langle \sigma_{\nu\bar{\nu}\to e^+e^-} v_{rel} \rangle \sim \alpha_W^2 \frac{T^2}{m_{Z,W}^4}$

$$\frac{\Gamma_\nu}{H}\Big|_{T_{dec}} = \frac{n_\nu^{Eq} \langle \sigma_{\nu\bar{\nu}\to e^+e^-} v_{rel} \rangle}{1.7\sqrt{g_*}\frac{T^2}{m_{Planck}}}\Big|_{T_{dec}} \sim \frac{g_\nu \alpha_W^2 \frac{T_{dec}^5}{m_{W,Z}^4}}{\sqrt{g^*}\frac{T_{dec}^2}{m_{Planck}}} = 1 \Rightarrow T_{dec} \simeq 1\,\mathrm{MeV}$$

$\Rightarrow$ if $m_\nu \lesssim 1\,\mathrm{MeV}$ the ν is a hot relic and $\Omega_\nu \propto m_\nu \Rightarrow \Omega_\nu = 26\%$ for $m_\nu \sim 5-10$ eV

The example of a Dirac neutrino with mass m_ν: cold relic regime



if $m_\nu > 1$ MeV: cold relic

$$\Rightarrow\ z_{dec} \equiv \frac{m_\nu}{T_{dec}} = \ln[0.038\,\frac{g_\nu}{\sqrt{g_*}}\,m_\nu\,m_{Planck}\langle\sigma_{\nu\bar\nu\to e^+e^-}\,v_{rel}\rangle] \sim 22$$

$$\Omega_\nu \simeq \mathrm{const}\,\frac{1}{\langle\sigma_{\nu\bar\nu\to e^+e^-}\,v_{rel}\rangle}$$

$$\propto 1/{m_\nu}^2 \text{ if } m_\nu << m_{W,Z} \quad \leftarrow \quad \langle\sigma_{\nu\bar\nu\to e^+e^-}\,v_{rel}\rangle \propto \frac{m_\nu^2}{m_{W,Z}^4}$$

$$\propto {m_\nu}^2 \text{ if } m_\nu >> m_{W,Z} \quad \leftarrow \quad \langle\sigma_{\nu\bar\nu\to e^+e^-}\,v_{rel}\rangle \propto \frac{1}{m_\nu^2}$$

Thermal DM relic density so far

Thermal decoupling way highly depends on mass of mediator in annihilation process:

for $g \sim 1$

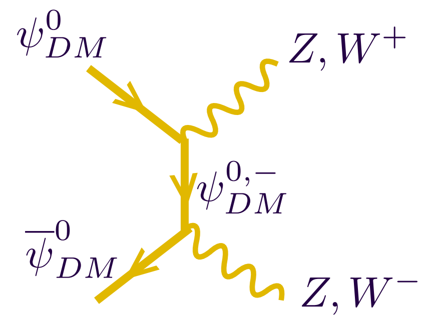
if $m_{med} << m_{DM}$: $\sigma \propto 1/m_{DM}^2$: DM is a cold relic and $\Omega_{DM} = 26\%$ requires $m_{DM} \sim \mathrm{TeV}$

"WIMP miracle"

a true "WIMP" is for example a fermion triplet (see above):

only EW interactions

$\Rightarrow$ $m_{DM} = 2.7\,\mathrm{TeV}$



if $m_{med} >> m_{DM}$: DM can be cold or hot relic depending on cross section

in all cases thermal decoupling gives relic density independent of initial conditions!

hot relics: $m_{DM} \sim \mathcal{O}(10\,\mathrm{eV})$

$\Rightarrow$ what is maximum and minimum value of m_{DM} for a cold relic???

$$1\,\mathrm{keV} \lesssim m_{DM} \lesssim 100\,\mathrm{TeV}$$

Maximum mass allowed for a thermal cold relic

thermal freezeout requires: $\langle \sigma_{DMDM\to SMSM}\, v_{rel} \rangle \simeq 3 \cdot 10^{-26}\, \mathrm{cm}^3/\mathrm{sec}$

but unitarity of S matrix requires: $\sigma_{DMDM\to SMSM} \leq \dfrac{\pi(2J+1)}{\vec{p}^{\,2}_{DM}}$

$$\vec{p}^{\,2}_{DM} = p^2_{DM} - m^2_{DM} = m^2_{DM} v^2_{rel}/4$$

$\Rightarrow$ for $J=0$: $\sigma_{DMDM\to SMSM}\, v_{rel} \leq \dfrac{4\pi}{m^2_{DM} v_{rel}}$ $\Rightarrow$ $\underline{m_{DM} \leq 110\, \mathrm{TeV}}$

$$v^2_{rel} \simeq \frac{6\, T_{dec}}{m_{DM}} \sim \frac{6}{22}$$

Minimum mass allowed for a thermal relic: Cold DM constraint

in principle if one reduces the DM mass and the couplings together one can always get: $\langle \sigma_{DMDM \to SMSM} \, v_{rel} \rangle \simeq 3 \cdot 10^{-26} \, \mathrm{cm}^3/\mathrm{sec}$

$\propto g^n/m^2$

but one cannot go below $\sim \mathrm{keV}$ due to structure formation constraints:

DM must be cold!

$\neq$ DM is a cold relic!

large scale structure formation begins to largely develop themselves when matter begins to dominate the Universe at $T \sim eV$ but to grow from this time they need seeds at this time: anisotropies of energy density at this time

if within the comoving scale which corresponds to a supercluster there are no anisotropies at this time:

-less smaller structure (i.e. galaxies) will form

-galaxies will form only much later

galaxies younger than superclusters

contrary to observations!

Minimum mass allowed for a thermal relic: Cold DM constraint

⇒ by the time matter begins to dominate the Universe, we need anisotropies at scales smaller than supercluster scale!

"free streaming length"

however this will be not the case if $m_{DM} \lesssim 1\,\mathrm{keV}$ because in this case one can calculate that the comoving distance that DM would have done is larger than supercluster comoving size → erase anisotropies at smaller distance

since DM becomes non-relativistic only when $T \lesssim m_{DM}$
the lightest it is the more distance it will have done

⇒ $m_{DM} \gtrsim 1\,\mathrm{keV}$: DM is cold!

⇒ $m_{DM} >> 1\,\mathrm{keV}$: DM is cold

$m_{DM} << 1\,\mathrm{keV}$: DM is hot

$m_{DM} \sim 1\,\mathrm{keV}$: DM is warm

$\neq$

DM is a cold relic: decouple non-relativistic

DM is a hot relic: decouple relativistic

for example a ν with $m_\nu = 30\,\mathrm{keV}$ is cold but a hot relic!

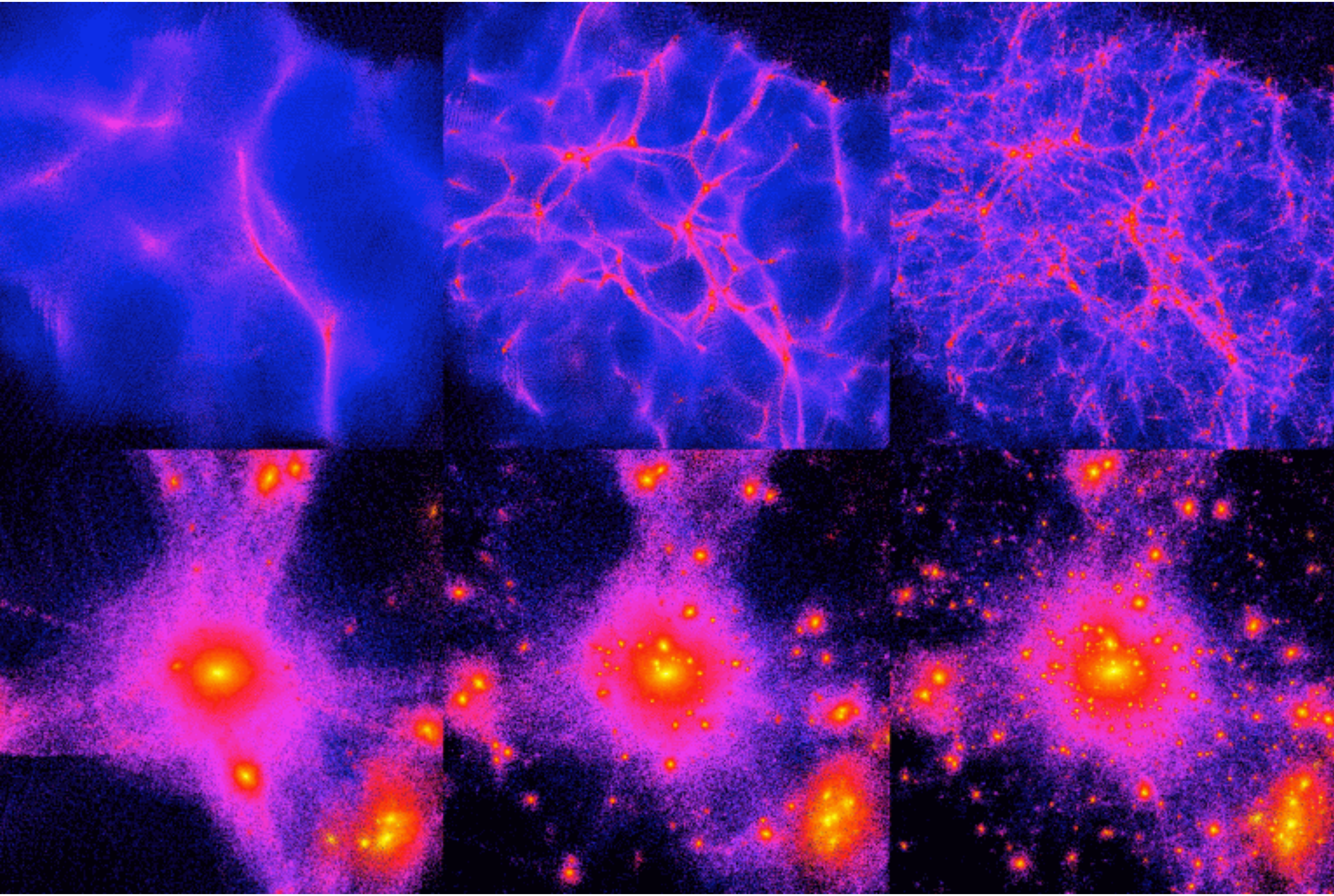
excluded because gives $\Omega_\nu >>> 26\%$

in practice all hot relics excluded because if cold they overclose the Universe!

for example a ν with $m_\nu \sim 10\,\mathrm{eV}$ is hot and a hot relic!

excluded because hot

HOT WARM COLD



Accurate calculation of the DM relic density: Boltzmann equations

equation giving the variation of the DM number density per unit time

if no interactions: $n_{DM} = \dfrac{\text{const}}{V} \propto \dfrac{const}{a^3}$

$$\Rightarrow \frac{dn_{DM}}{dt} \equiv \dot{n}_{DM} = -3\,\frac{\dot{a}}{a} \cdot \frac{const}{a^3} = -3\,H\,n_{DM}$$

$$\Rightarrow \dot{n}_{DM} + 3\,H\,n_{DM} = 0$$

if interactions: $DMDM \leftrightarrow SMSM$

$$\Gamma_{DMDM\to SMSM} = n_{DM}\,\langle \sigma_{DMDM\to SMSM} v_{rel} \rangle$$

$=$ number of $DMDM \to SMSM$ transitions a single DM part. has per unit time

$$\gamma_{DMDM\to SMSM} = n_{DM}^2\,\langle \sigma_{DMDM\to SMSM} v_{rel} \rangle$$

$=$ number of $DMDM \to SMSM$ transitions per unit time per unit volume

$$\Rightarrow \dot{n}_{DM} + 3\,H\,n_{DM} = (\gamma_{SMSM\to DMDM} - \gamma_{DMDM\to SMSM}) \cdot 2$$

ΔN_{DM} per reaction

number of $SMSM \to DMDM$ reactions per unit time per unit volume

number of $DMDM \to SMSM$ reactions per unit time per unit volume

Accurate calculation of the DM relic density: Boltzmann equations

7 steps ahead:

(1)

$$d^3\tilde{p} \equiv \frac{d^3p}{(2\pi)^3}$$

$$\dot{n}_{DM} + 3\,H\,n_{DM} = \int d^3\tilde{p}_{DM_1} d^3\tilde{p}_{DM_2} d^3\tilde{p}_{SM_1} d^3\tilde{p}_{SM_2} (2\pi)^4 \delta^4(p_{DM_1} + p_{DM_2} - p_{SM_1} - p_{SM_2})$$

$$\cdot \left[f_{SM_1} f_{SM_2} |\mathcal{M}_{SM_1 SM_2 \to DM_1 DM_2}|^2 - f_{DM_1} f_{DM_2} |\mathcal{M}_{DM_1 DM_2 \to SM_1 SM_2}|^2 \right] \cdot 2$$

(2) $\text{SM particles are in thermal equilibrium} \rightarrow f_{SM_{1,2}} = f^{Eq}_{SM_{1,2}}$

(3) $\text{Maxwell Boltzmann statistic approximation} \rightarrow f^{Eq} = \dfrac{1}{e^{E/T} \pm 1} \simeq e^{-E/T}$

$$f^{Eq}_{SM_1} f^{Eq}_{SM_2} = e^{-(E_{SM_1} + E_{SM_2})} = e^{-(E_{DM_1} + E_{DM_2})} = f^{Eq}_{DM_1} f^{Eq}_{DM_2}$$

(4) $|\mathcal{M}_{SM_1 SM_2 \to DM_1 DM_2}|^2 = |\mathcal{M}_{DM_1 DM_2 \to SM_1 SM_2}|^2 \equiv |\mathcal{M}|^2$

CP conservation assumed here

Accurate calculation of the DM relic density: Boltzmann equations

(5) $\dot{n}_{DM} + 3\,H\,n_{DM} =$

$$\int d^3\tilde{p}_{DM_1} d^3\tilde{p}_{DM_2} d^3\tilde{p}_{SM_1} d^3\tilde{p}_{SM_2} (2\pi)^4 \delta^4(p_{DM_1} + p_{DM_2} - p_{SM_1} - p_{SM_2})\, f^{Eq}_{DM_1} f^{Eq}_{DM_2} |\mathcal{M}|^2 \quad \leftarrow\equiv \gamma^{Eq}_{DM_1 DM_2 \to SM_1 SM_2}$$

$$\cdot 2 \cdot \left(1 - \frac{f_{DM_1} f_{DM_2}}{f^{Eq}_{DM_1} f^{Eq}_{DM_2}}\right)$$

kinetic equilibrium of all particles $\rightarrow \dfrac{f_{DM_1} f_{DM_2}}{f^{Eq}_{DM_1} f^{Eq}_{DM_2}} = \dfrac{n^2_{DM}}{n^{Eq\,2}_{DM}}$

(6) $n_{DM} \rightarrow Y_{DM} = \dfrac{n_{DM}}{s}$ $\qquad s \propto T^3 \propto t^{-3/2} \qquad \dfrac{ds}{dt} = -3Hs$

$$\dot{Y}_{DM} = \frac{\dot{n}_{DM}}{s} + 3\,H\,\frac{n_{DM}}{s}$$

(7) $t \rightarrow z = m_{DM}/T$ $\qquad$ radiation epoch: $H = \dfrac{1}{2t}$ $\Rightarrow$ $\dfrac{dz}{dt} = zH$

$$\Rightarrow \boxed{szH(z)\frac{Y_{DM}}{dz} = 2 \cdot \gamma^{Eq}_{DMDM \to SMSM} \cdot \left(1 - \frac{Y^2_{DM}}{Y^{Eq2}_{DM}}\right)}$$

$\Rightarrow$ integrating this equation over z one finds $Y_{DM}|_{today}$

shows that instantaneous decoupling approximation above very good

Beyond thermal freezeout: a few other possibilities

Freezein

it might be that DM has never been in thermal equilibrium with SM thermal bath

example: - a $SM \to DM\, DM$ decay:

$$\frac{\Gamma_{decay}}{H}\Big|_{T\sim m_{DM}} \sim \frac{\frac{1}{8\pi} g^2 m_{DM}}{H}\Big|_{T\sim m_{DM}} < 1 \quad \Leftrightarrow \quad g \lesssim 10^{-6}$$

$m_{DM} \sim \mathrm{TeV}$

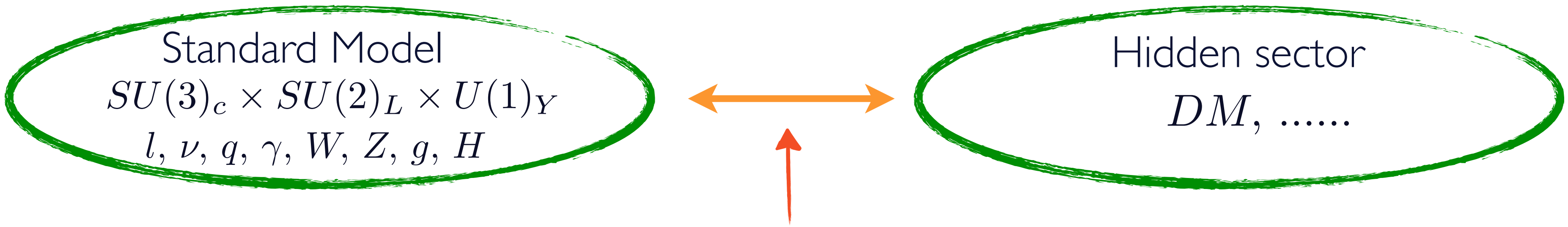
- a $DMDM \to SMSM$ annihilation:

$$\frac{\Gamma_{annih}}{H}\Big|_{T\sim m_{DM}} \sim \frac{\frac{\alpha^2}{m_{DM}^2}}{H}\Big|_{T\sim m_{DM}} < 1 \quad \Leftrightarrow \quad g \lesssim 10^{-3.5}$$

$m_{DM} \sim \mathrm{TeV}$

Freezein

- if the DM particle doesn't thermalize with the SM thermal bath clearly DM lies in a Hidden sector



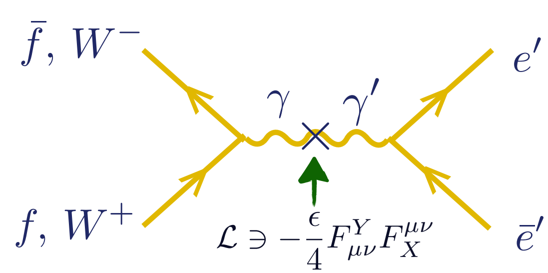
small portal interaction: $\Gamma_{portal} < H$ always

for example with a Higgs portal, $\mathcal{L} \ni -\lambda_m \phi^\dagger \phi H^\dagger H$, both sectors do not thermalize with each other if : $\lambda_m \lesssim 10^{-6} \quad \leftarrow \quad m_\phi \sim TeV$

$H^\dagger H \leftrightarrow \phi^\dagger \phi$

for example with a kinetic mixing portal, $\mathcal{L} \ni -\frac{\epsilon}{4} F^Y_{\mu\nu} F^{\mu\nu}_X$, both sectors do not thermalize with each other if : $\epsilon \lesssim 10^{-6} \quad \leftarrow \quad m_{e'} \sim TeV$

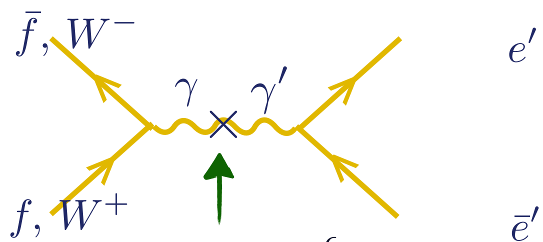
$(\alpha = \alpha')$



Freezein

- in this case even if no thermalization the SM thermal bath can still produce very slowly (out-of-equilibrium) pairs of DM particles to get the right amount of DM: freeze-in

remember the n_{DM}/n_γ we need to get is much smaller than the relativistic thermal value: $n_{DM}/n_\gamma \sim 1$: no need for DM to necessarily thermalize



$\mathcal{L} \ni -\frac{\epsilon}{4} F^Y_{\mu\nu} F^{\mu\nu}_X$

Mc Donald 02'
Hall, Jedamzik, March-Russell, West 09',
Yaguna 11',
Frigerio, TH, Masso 11',...

$$\frac{dn_{DM}}{dt} = n^2_{SM_i}(T)\langle\sigma_{SM_i SM_i \to DM DM}\, v\rangle$$

$$\Downarrow$$

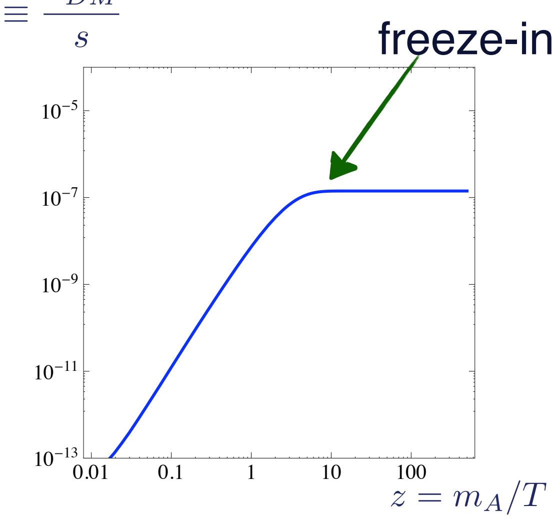
$$\frac{dY_{DM}}{dT} = \frac{n^2_{SM_i}(T)\langle\sigma_{SM_i SM_i \to DM DM}\, v\rangle}{T H(T) s(T)} \propto 1/T^2 \leftarrow Y_{DM} \equiv \frac{n_{DM}}{s}$$

$T > m_{DM}$

$$\Downarrow$$

$Y_{DM} \propto 1/T$ down to $T \sim m_{DM}$ ← where $n^{eq}_{SM_i}$ becomes Boltzmann suppressed

$$Y_{DM} \equiv \frac{n_{DM}}{s}$$



→ DM production IR dominated as for freezeout

→ production depends only on interactions at $T \sim m_{DM}$ and not on physics at higher scales

→ but unlike freezeout it depends on the DM number initial conditions

$$\Omega_{DM} = \Omega_{DM}^{''end\,of\,inflation''} + \Omega_{DM}^{freezein}$$

Freezein

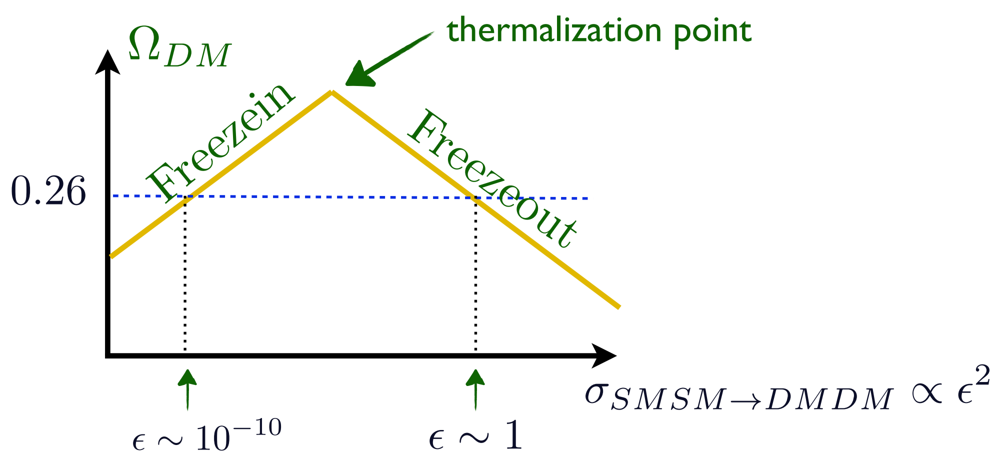
$$Y_{DM} \sim \frac{n_{SM}^2 \langle \sigma_{SMSM \to e'\bar{e}'} v_{rel} \rangle}{s}\Big|_{T \sim m_{DM}} \cdot \frac{1}{H(T \sim m_{DM})} \propto \epsilon^2$$

$$\alpha = \alpha'$$

number of DM particles created per unit time per unit volume over entropy

age of the Universe

⇒ $\Omega_{DM} = 26\%$ requires a tiny coupling: $\epsilon \sim 10^{-10}$



Mc Donald 02'
Hall, Jedamzik, March-Russell, West 09',
Yaguna 11',
Frigerio, TH, Masso 11',...

⇒ so far we got 3 ways to get Ω_{DM} to be only 26% despite of the fact that DM is matter:

or $n_{DM} \sim n_\gamma$ ⇒ DM must be very light but excluded (hot)

or $n_{DM} << n_\gamma$ ⇒ DM must be heavier (cold)

from freezeout (Boltzmann suppression)
or freezein (tiny coupling suppression)

Going more general: general hidden sector structure

Visible Sector

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$l,\ \nu,\ q,\ \gamma,\ W,\ Z,\ g,\ H\ +....?$

$\longleftrightarrow$

Hidden Sector

with its own particle zoology

gauge groups, DM, ...

portals

$SM + SM \leftrightarrow HS + HS$

$SM + SM \leftrightarrow DM + DM$

with purely HS annihilation channel(s):

$DM + DM \leftrightarrow HS + HS$

$\Rightarrow$ DM can annihilate in the HS sector and/or to SM particles and/or be produced from the visible sector through freezein, …

A prototype Hidden Sector model: hidden photon + hidden electron

the QED' model already considered above: $\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}'(i\not{D}' - m_\psi)\psi'$

a e' charged under a new $U(1)_X$ with no charge under SM
with SM particles chargeless under $U(1)_X$

Standard Model
$SU(3)_c \times SU(2)_L \times U(1)_Y$
$l,\ \nu,\ q,\ \gamma,\ W,\ Z,\ g,\ H$

Hidden sector
$U(1)_X$
$e',\ \gamma'\ +\ \dots$

portal
kinetic mixing
$\mathcal{L} \ni -\frac{\epsilon}{4} F^Y_{\mu\nu} F^{\mu\nu}_X$

"hidden electron"

gauge boson of $U(1)_X$
"hidden photon"

+ whatever you want in UV
(irrelevant: freezout and
freezein: infrared dominated!)

A prototype Hidden Sector model: hidden photon + hidden electron

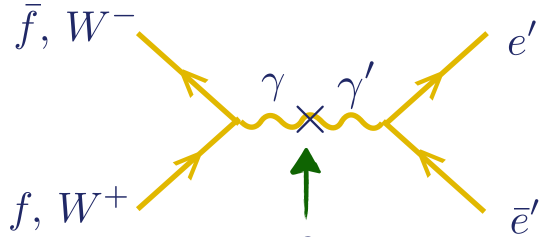
$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}'(i\not{D}' - m_\psi)\psi' \;\; -\frac{1}{4}F^{Y}_{\mu\nu}F^{\mu\nu}_{X}$$

3 parameters: m_{DM}, α', ϵ

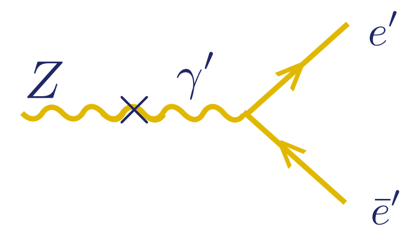
DM electric charge : $\kappa = \sqrt{\alpha'/\alpha}\,\epsilon$

$+$

Connector processes:

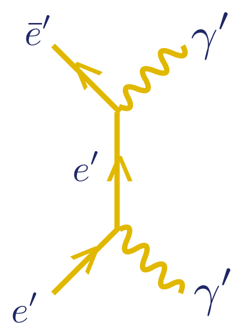


$\mathcal{L} \ni -\frac{\varepsilon}{2}F^{\mu\nu}_{Y}F'_{\mu\nu}$



$\sigma(SMSM \to e'\bar{e}') \propto \alpha^2\kappa^2$

Hidden sector process:



$\sigma(e'\bar{e}' \to \gamma'\gamma') \propto \alpha'^2$

$$z\frac{H}{s}\frac{dY_{DM}}{dz} = \sum_i \langle\sigma_{connect}v\rangle_i (Y^2_{eq}(T) - Y^2) + \langle\sigma_{HS}v\rangle(Y^2_{eq}(T') - Y^2)$$

$SM_iSM_i \to DMDM$

$DMDM \to SM_iSM_i$

$\gamma'\gamma' \to DMDM$

$DMDM \to \gamma'\gamma'$

Visible sector/Hidden sector/Connector structure: 5 basic ways to get the observed relic density

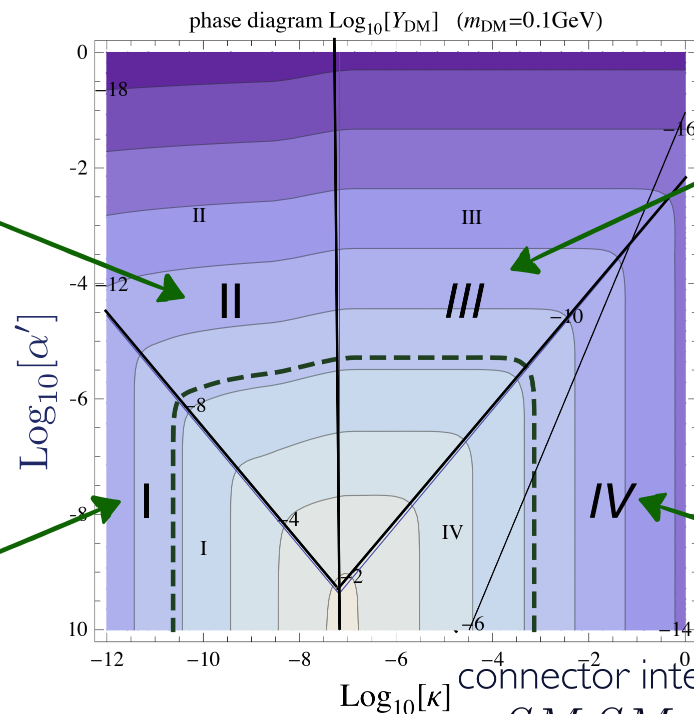
Chu,T.H.,Tytgat 11

hidden sector interaction:
$e'\,\bar{e}' \leftrightarrow \gamma'\gamma'$

Reannihilation regime
(DM thermalizes within the HS)

regimes without thermalization of HS with SM sector

Freeze-in regime
(DM doesn't thermalize with anything)
slow DM pair production $SM\,SM \rightarrow e'\,\bar{e}'$
$\kappa \sim 10^{-10}$



Hidden sector freeze-out regime
from $e'\,\bar{e}' \leftrightarrow \gamma'\gamma'$

regimes with thermalization of HS with SM sector

connector interaction:
$SM\,SM \leftrightarrow e'\,\bar{e}'$

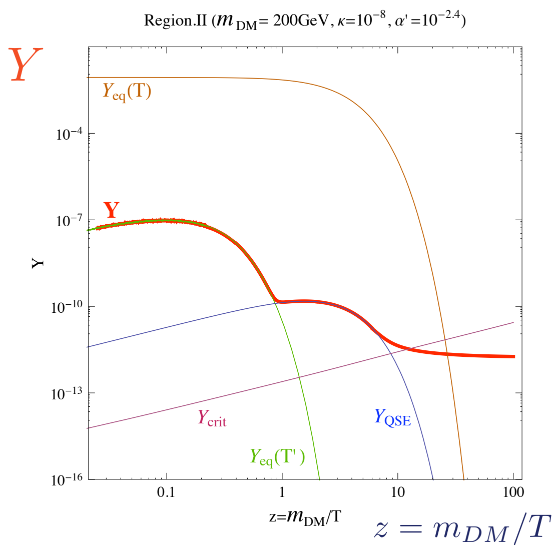
Connector freeze-out regime
from $SM\,SM \leftrightarrow e'\,\bar{e}'$

Visible sector/Hidden sector/Connector structure:
5 basic ways to get the observed relic density

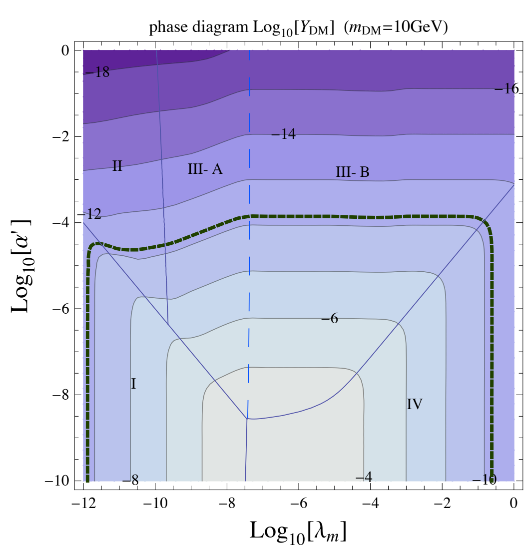
Regime II is new: reannihilation: the connector $SM\,SM \leftrightarrow e'\,\bar{e}'$ process is out of equilibrium
but the HS $e'\,\bar{e}' \leftrightarrow \gamma'\gamma'$ process is in equilibrium

$\Rightarrow$ hidden sector has its own temperature $T' \neq T$

freezeout in HS with $T' \neq T$ and with still at same time slow $SM\,SM \to e'\,\bar{e}'$ DM production



NB: with (massive) Higgs portal: a fifth regime: Dark Freezeout:



freezeout in HS with $T' \neq T$ and at this time no more slow $SM\,SM \to e'\,\bar{e}'$ DM production

more details in Chu, T.H., Tytgat 11

Asymmetric DM

above we have assumed no DM matter-antimatter asymmetry but there could be one

2 asymmetric relics do exist already in Nature: protons and electrons!

The proton asymmetric relic example

at $T \sim m_p$: protons number density becomes to be Boltzmann suppressed from $p\,\bar{p} \to \pi\,\pi$

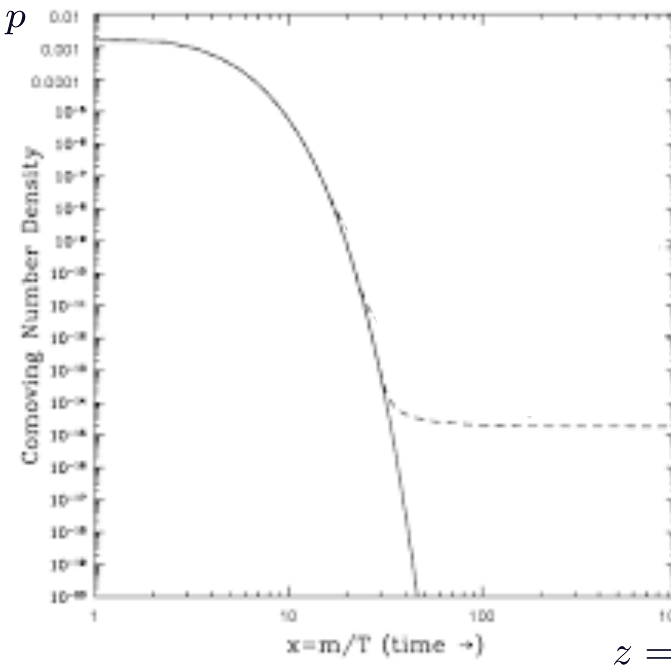
if the number of p was at this time the same than the number of $\bar{p}$ one would have a symmetric freezeout just as DM above but driven by a strong process rather than a weak size one $\Rightarrow$ very strong suppression:

$$\frac{n_p}{s} = \frac{n_{\bar{p}}}{s} \propto \frac{1}{\langle \sigma_{p\bar{p}\to\pi\pi} \cdot v_{rel} \rangle} \sim 10^{-18}$$

"annihilation catastrophy"

we would not be here to talk about!

Y_p^{Eq}



$\frac{n_p}{s} \sim 10^{-18}$

$z = m_p/T$

The proton asymmetric relic example

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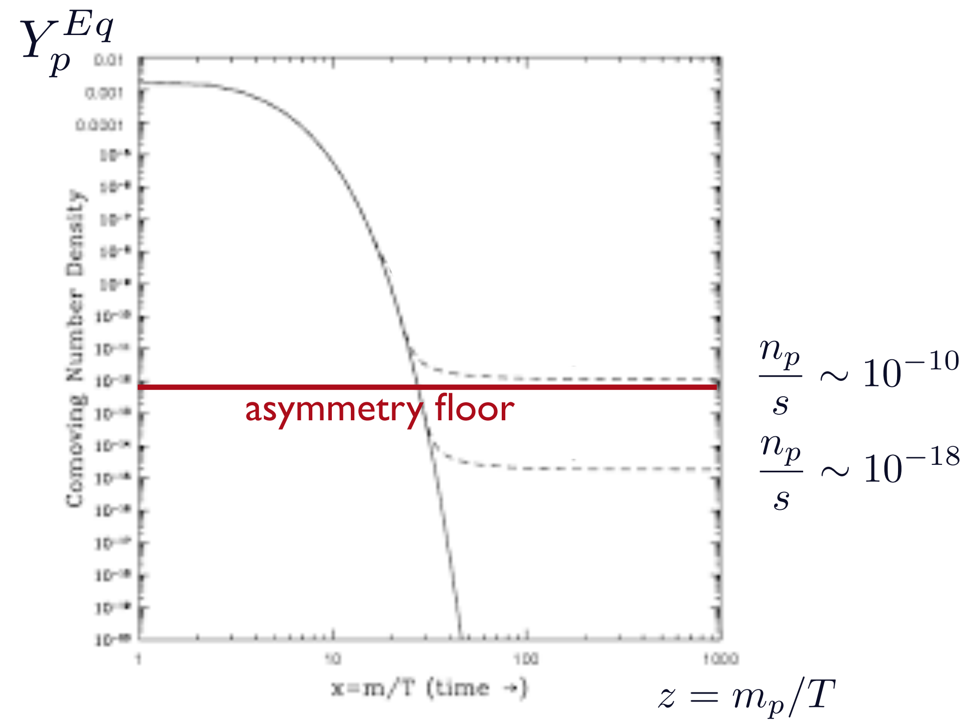
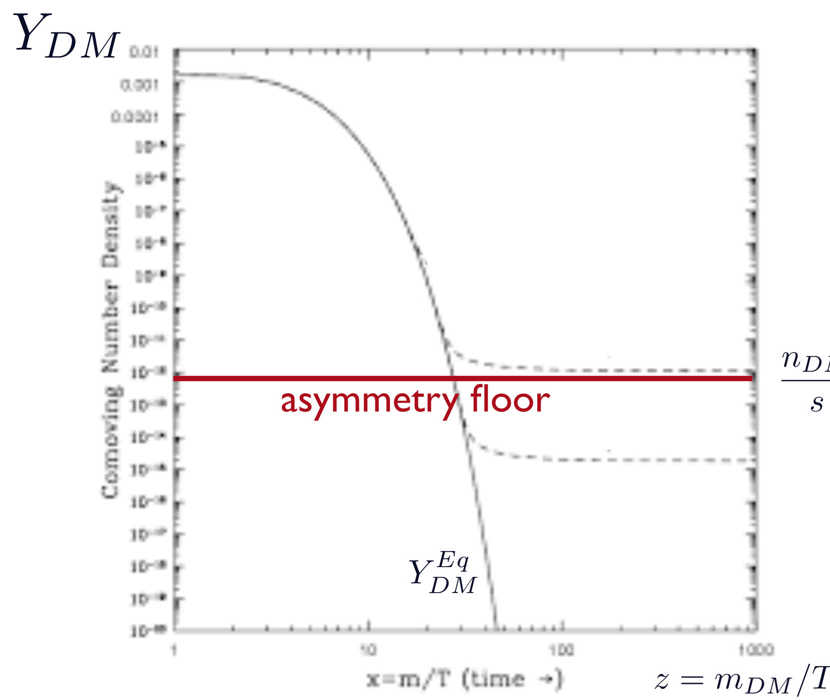


but if at this time $n_p > n_{\bar{p}}$ then the efficient $p\,\bar{p} \to \pi\,\pi$ process cannot annihilate so many p because once it will have annihilated (almost) all $\bar{p}$ still we will be left with a p population: $\left.\frac{n_p}{s}\right|_{today} = \left.\frac{n_p - n_{\bar{p}}}{s}\right|_{preexisting} \simeq 10^{-10}$

Asymmetric DM: same story as baryons

(in simplest version)



$$\frac{n_{DM}}{s}\bigg|_{today} = \frac{n_{DM} - n_{\overline{DM}}}{s}\bigg|_{preexisting} \simeq 10^{-11}$$

$m_{DM} \sim 100$ GeV

- we still need an DM annihilation to put DM in equilibrium and to Boltzmann suppressed it at $T \lesssim m_{DM}$

  the annihilation cross section must be larger than for symmetric freezeout to get rid of the symmetric component

- we need a preexisting asymmetry: $\frac{n_{DM} - n_{\overline{DM}}}{s}\bigg|_{preexisting} \simeq 10^{-11}$ $\quad m_{DM} \sim 100$ GeV

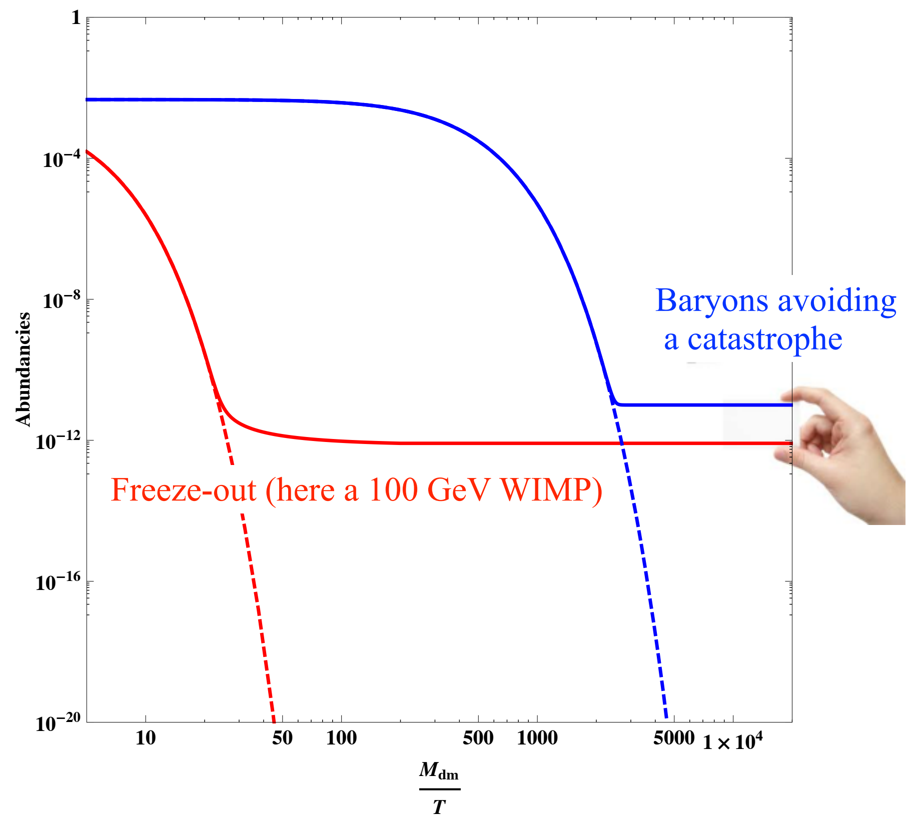
created before from other interactions

$\Rightarrow$ we loose a lot in predictivity % symmetric freezeout!

$\Omega_B \leftrightarrow \Omega_{DM}$ *similarity* $\Rightarrow$ *asymmetric DM?*

Observationally: $\dfrac{\Omega_{DM}}{\Omega_B} \sim 5$ ← coincidence or deep reason???

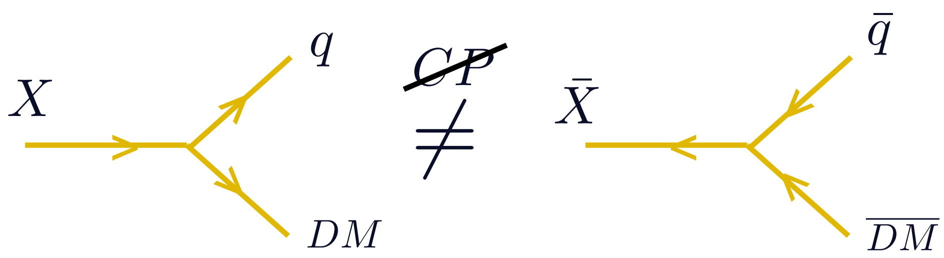
No explanation for such a similarity along the symmetric thermal freezeout scenario:



Suggests that maybe DM is asymmetric and DM asymmetry created from the same process as baryon asymmetry

$\Omega_B \leftrightarrow \Omega_{DM}$ *similarity* $\Rightarrow$ *asymmetric DM?*

Common creation of both asymmetries from a same process: "Co-genesis"



$\Rightarrow$ $$\frac{n_{DM} - n_{\overline{DM}}}{s} = \frac{n_q - n_{\bar{q}}}{s} = \frac{1}{3}\frac{n_p - n_{\bar{p}}}{s} \Rightarrow m_{DM} \sim 3\,\frac{\Omega_{DM}}{\Omega_B}\cdot m_p \sim 15\,\mathrm{GeV}$$

$\Rightarrow$ we trade the $\Omega_{DM} \leftrightarrow \Omega_B$ coincidence for a $m_{DM} \leftrightarrow m_p$ mass coincidence

we should have be seen already in general $\Rightarrow$ need to complicate the model, ...

but remains certainly is a possibility

Part 3
DM direct detection

Flux of DM particles crossing the earth

$\rho_{DM} \simeq 0.3\,\mathrm{GeV/cm^{-3}}$ ← simulations of DM halo formation fitting the observations

$v_{DM} \simeq 220\,\mathrm{km/sec}$ ← orbit velocity of Sun in galaxy

with distribution of velocity around: Maxwellian: $f(v_{DM}) = \frac{1}{\sqrt{2\pi\sigma}}\, e^{-v_{DM}^2/2\sigma^2}$

$\sigma \simeq 270\,\mathrm{km/sec}$

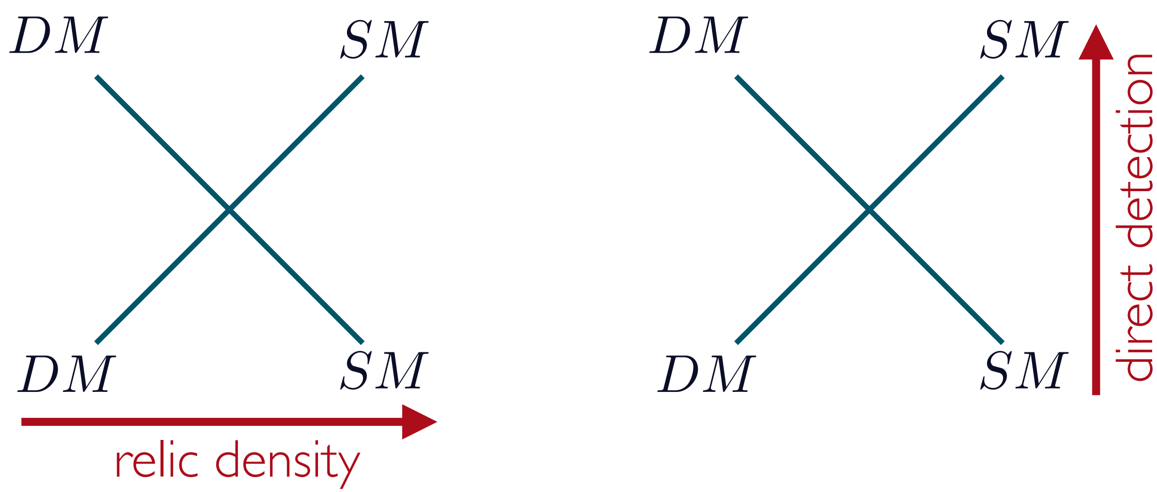
⇒ DM particle flux: $\mathcal{O}(10^5\,\mathrm{cm^{-2}\,sec^{-1}}) \cdot \left(\frac{100\,\mathrm{GeV}}{m_{DM}}\right)$

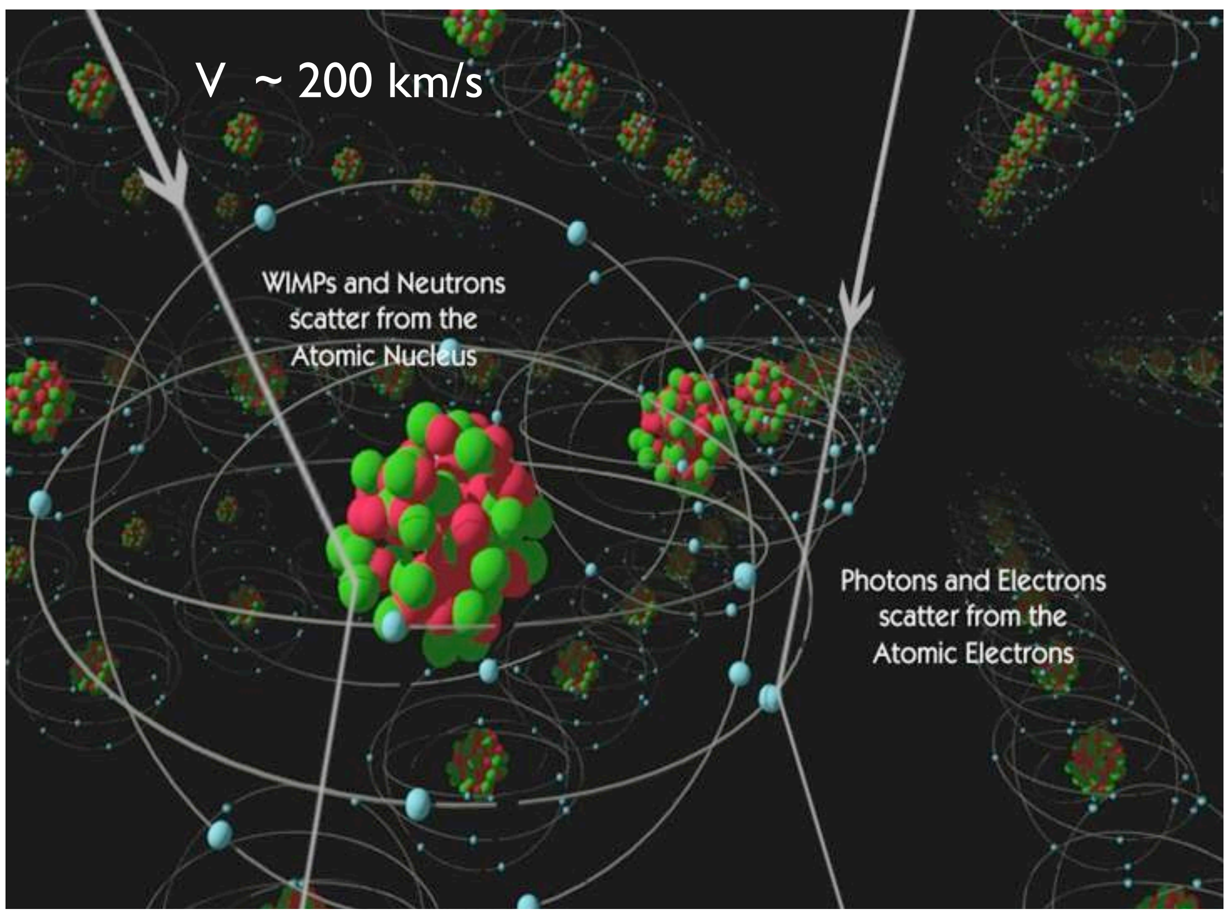
10^5 more than μ flux

10^5 less than total solar ν flux

100 less than $E_\nu > \mathrm{MeV}$ solar flux

Search for a DM-nuclei or DM-electron scattering: direct detection





Search for a recoil of a nuclei or electron from DM hit: direct detection

Event rate (on nuclei): $\frac{dR}{dE_R} = \frac{\rho_{DM}}{m_{DM}} \frac{1}{m_N} \int_{v_{min}}^{\infty} v_{DM} f(v_{DM}) \frac{d\sigma}{dE_R} d^3 v_{DM}$

DM flux

velocity distribution

nucleus recoil energy

rate per mass of nuclei

cross section

$v\cos\theta = \sqrt{\frac{m_N E_R}{\mu^2}}$

$\mu = \frac{m_N\, m_{DM}}{m_N + m_{DM}}$

for a given v_{DM} there is a kinematic upper bound: $E_R < \mu^2 v_{DM}^2 / m_N \sim 0 - 100\,\mathrm{keV}$

$\Rightarrow$ exponential fall-off of $f(v_{DM})$ for large v_{DM} gives an exponential fall-off for large E_R

$$\frac{dR}{dE_R} \sim \left(\frac{dR}{dE_R}\right)_{E_R=0} F^2(E_R)\, e^{-E_R/E_c}$$

$E_c \sim 10^{-6} \mu^2 / m_N$

nuclear form factor

$\Rightarrow$ need for detectors with sensitivity to low $E_R \sim$ few keV and low noise

Search for a recoil of a nuclei or electron from DM hit: direct detection

$\frac{d\sigma}{dE_R}$: depending on the DM candidate the cross section is:

spin-independent:

$$\sigma_{N-DM} \propto A^2$$

couples coherently to nucleons in nuclei

$\Downarrow$

much better sensitivity, especially for large A
(even if suppression of form factor for large E_R is larger for large A)

$\rightarrow$ applies to scalar DM or fermion DM with vector coupling, ...

spin-dependent:

$$\sigma_{N-DM} \propto J(J+1)$$

need for nuclei with a spin, e.g. with odd number of nucleons
coupling only to spin of the last nucleon

$\rightarrow$ applies to fermion DM with axial vector coupling, ...

Spin independent direct detection

$$\frac{d\sigma}{dE_R} = \frac{1}{v^2}\frac{m_N\sigma_n^0}{2\mu^2}\frac{[Zf_p + (A-Z)f_n]^2}{f_n^2}F^2(E_R)$$

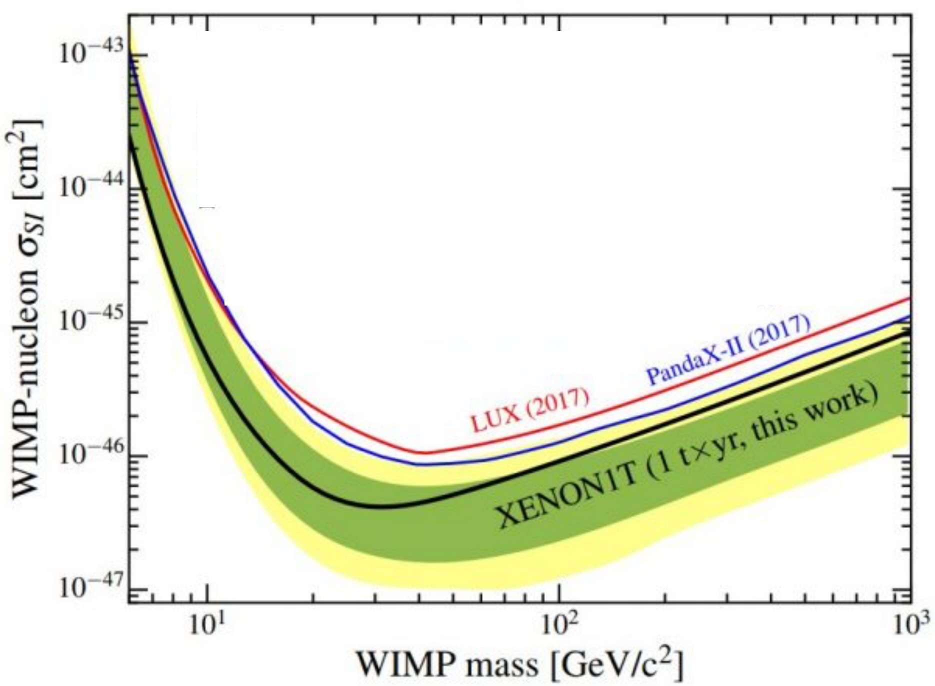
DM-neutron cross section

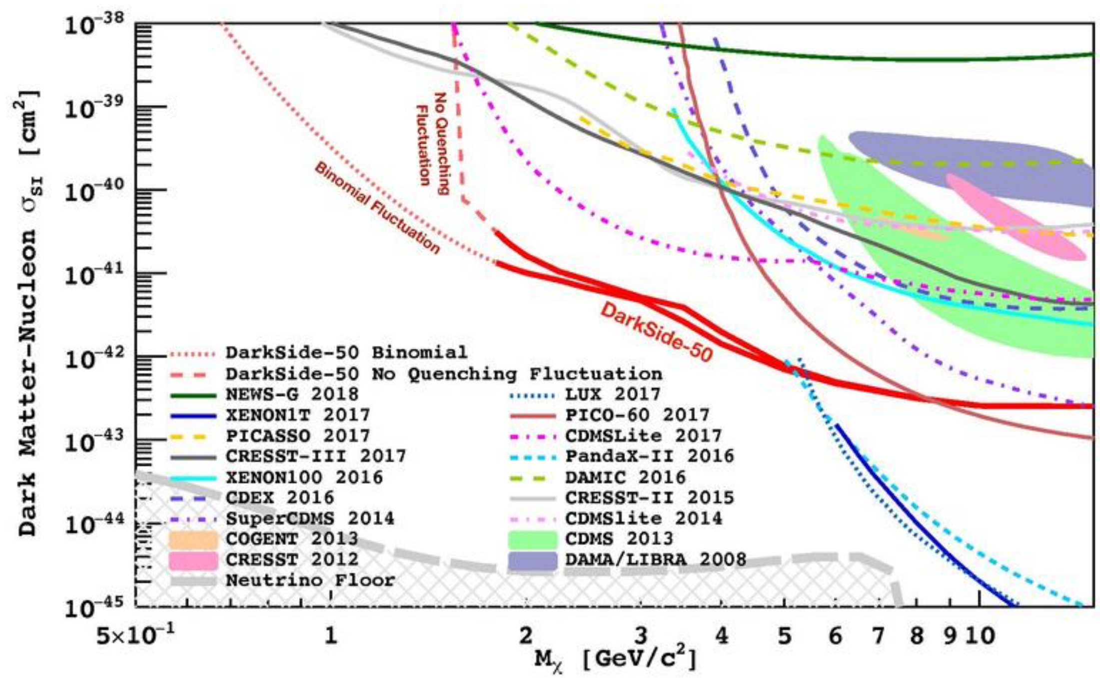
coupling of proton to the mediator

nuclear form factor

coupling of neutron to mediator

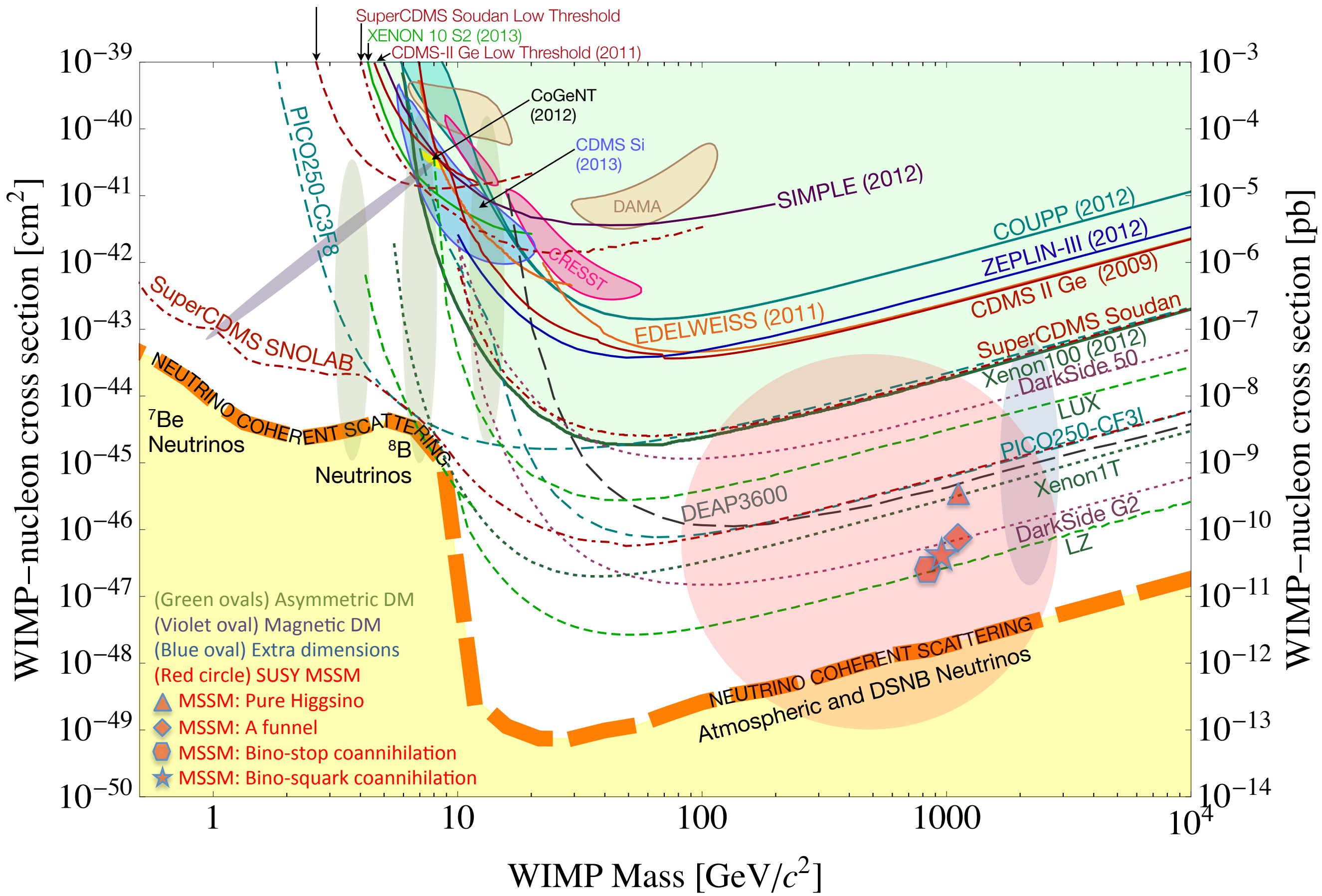
Xenon1T (2018): best limit for $m_{DM} >$ a few GeV



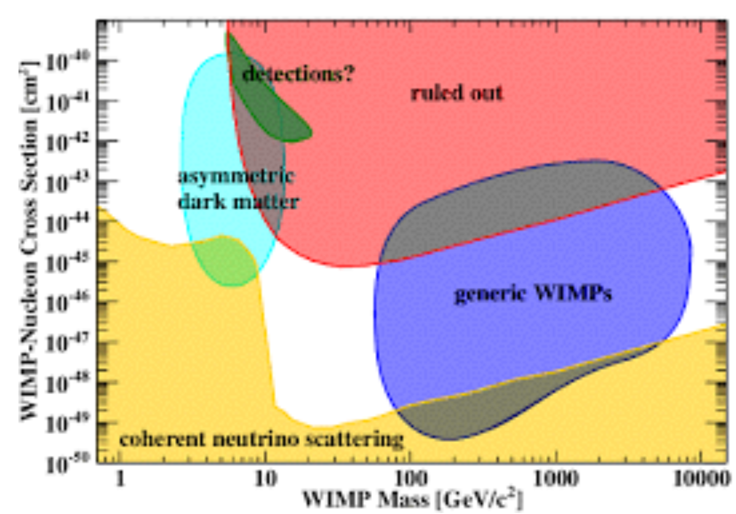


arXiv: 1802.

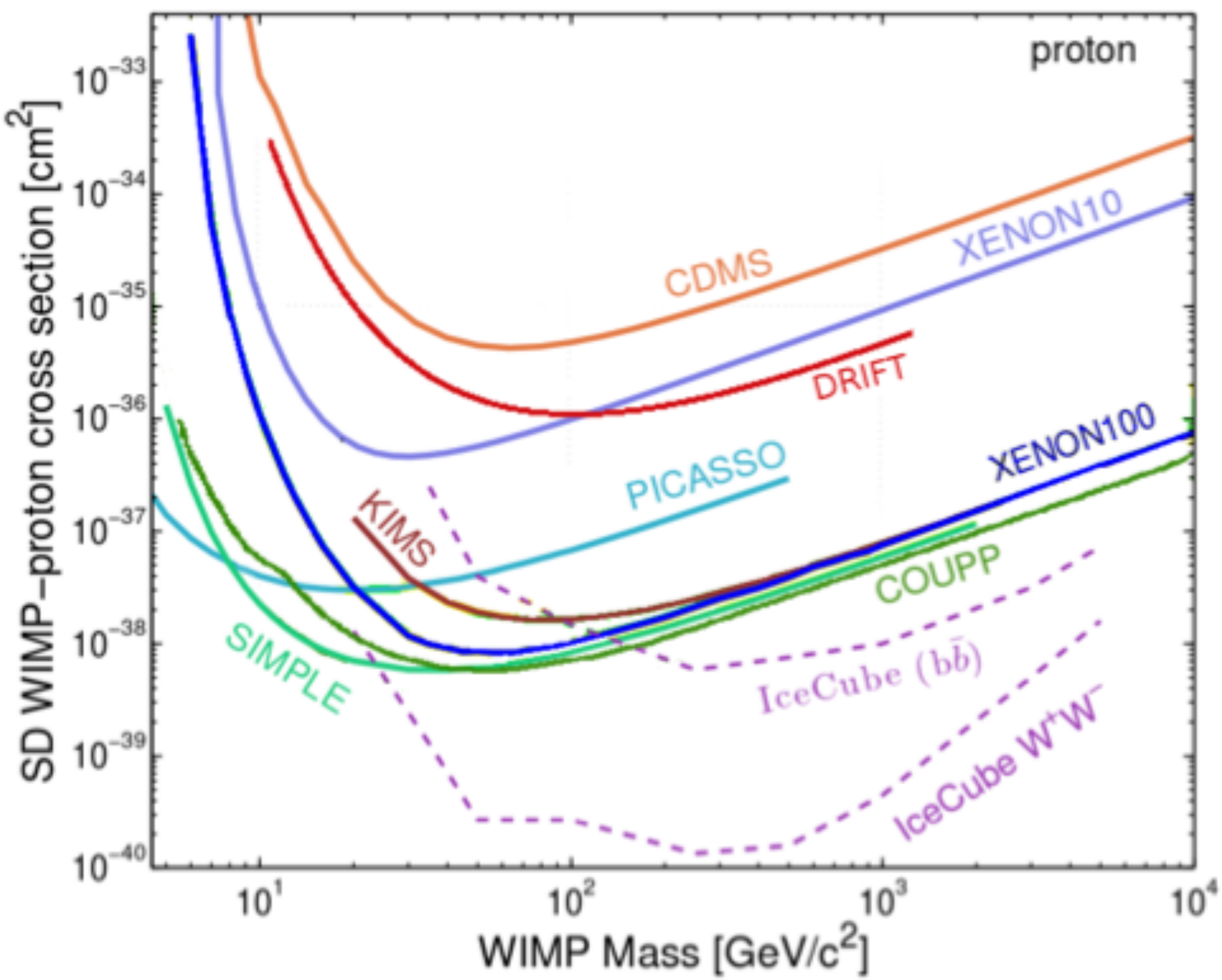
Spin independent direct detection: neutrino floor



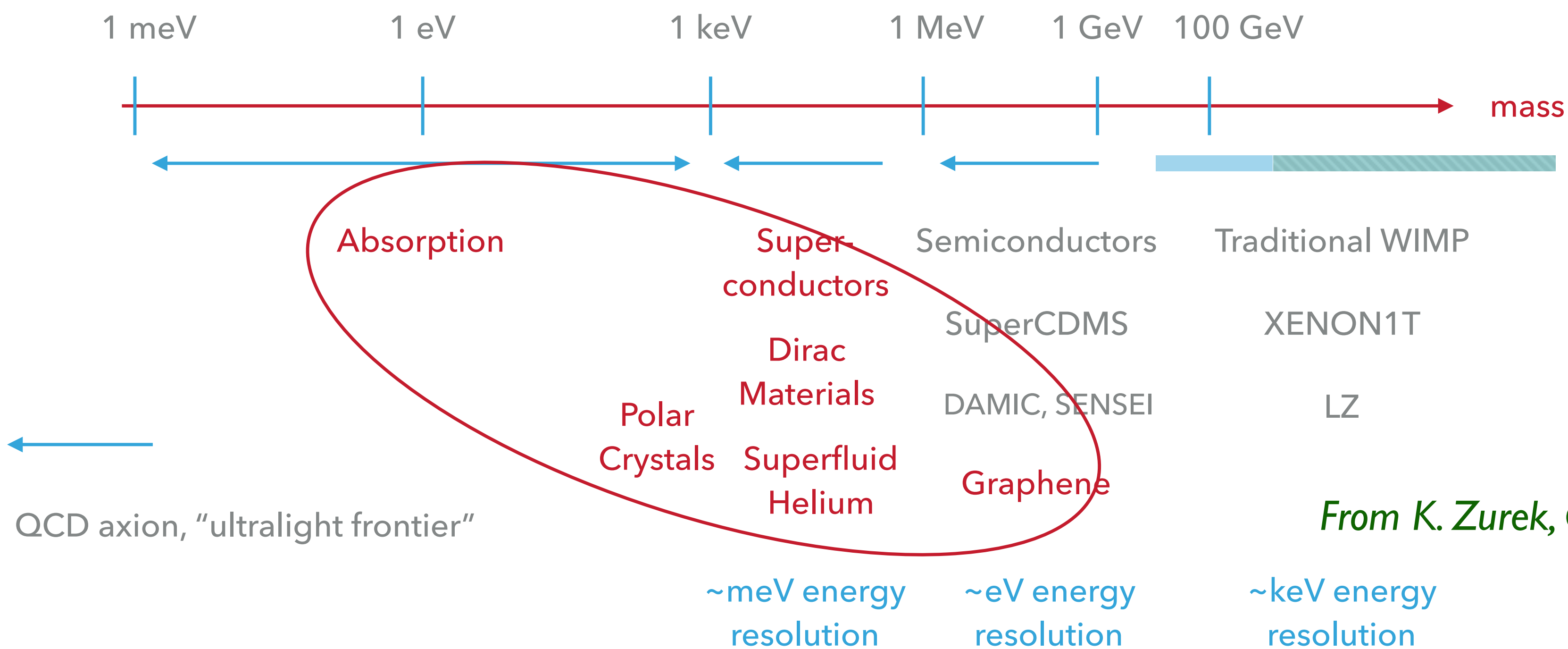
APS Physics Today



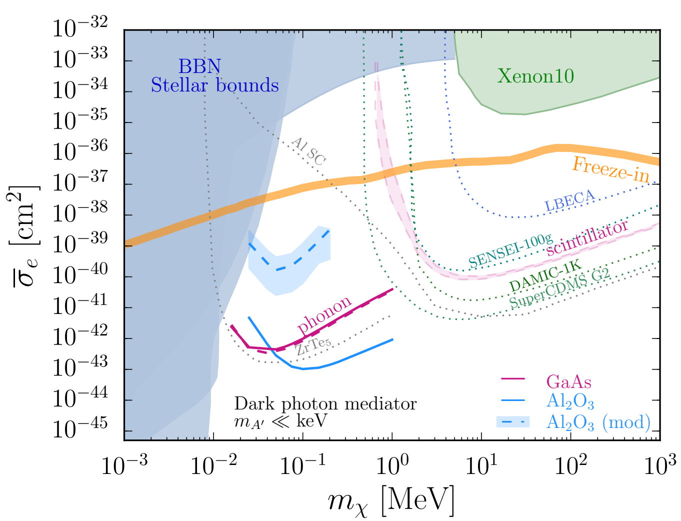
Spin dependent direct detection

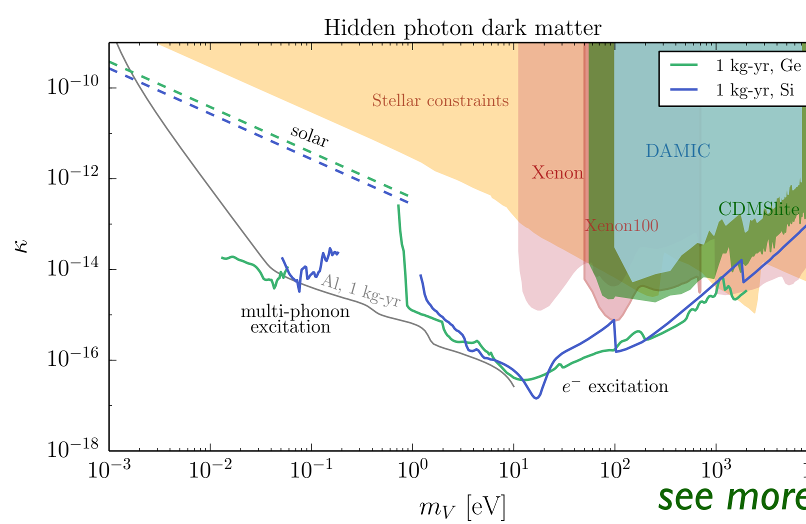


A new trend for the future: direct detection of sub-GeV DM



From K. Zurek, GGI2018 talk

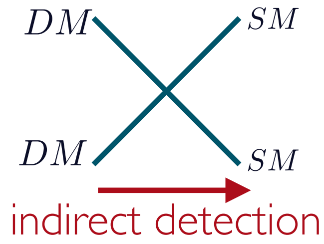




see more in K. Zurek and
T. Volansky talks at GGI2018

Part 4
DM indirect detection

DM indirect detection: a huge field!



search for fluxes of cosmic rays produced today by DM annihilation or decay

1) Gamma-rays:

- radiation from charged particles produced by DM: diffuse flux
- or created directly at loop level (DM is neutral): monochromatic flux

2) anti-protons

3) electron and positron

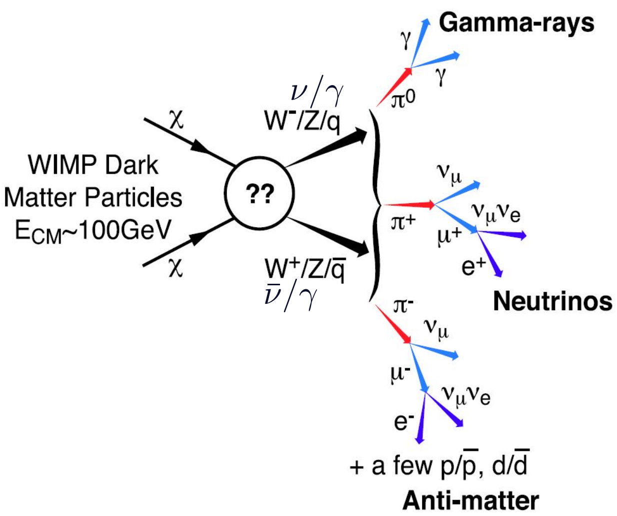
4) neutrinos

5) anti-nuclei

6) effect on synchrotron radiation flux

7) heat deposited by DM products on CMBR,
effects of DM products on BBN, $\lambda = 21$ cm , ...

8) .....



DM indirect detection: regions of production

annihilation: many more in dense DM region: galactic center and dwarf galaxies

number of annihilation $\propto n_{DM}^2$

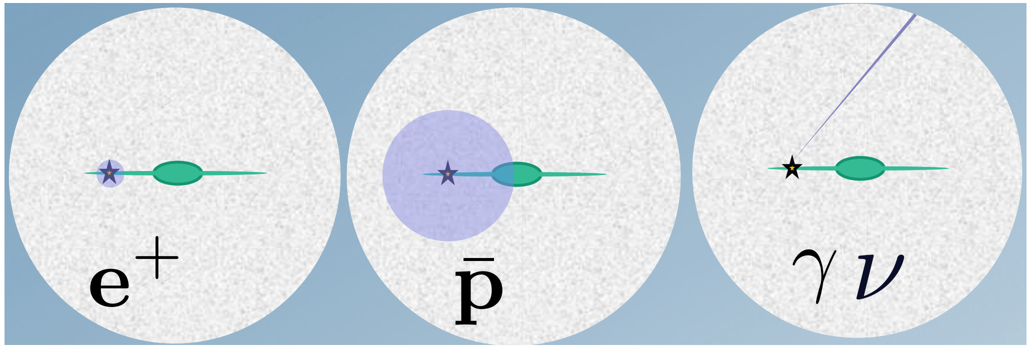
decay: also many from less dense DM region

number of decays $\propto n_{DM}$

$\gamma,\ \nu$: flux, energy spectra and direction basically unaffected during propagation $\Rightarrow$ points to the source and the many ones produced in the galactic center reach us!

$e^{\pm}$: very local: magnetic field + absorption

$\bar{p}$: less local but still the ones from galactic center do not reach us much



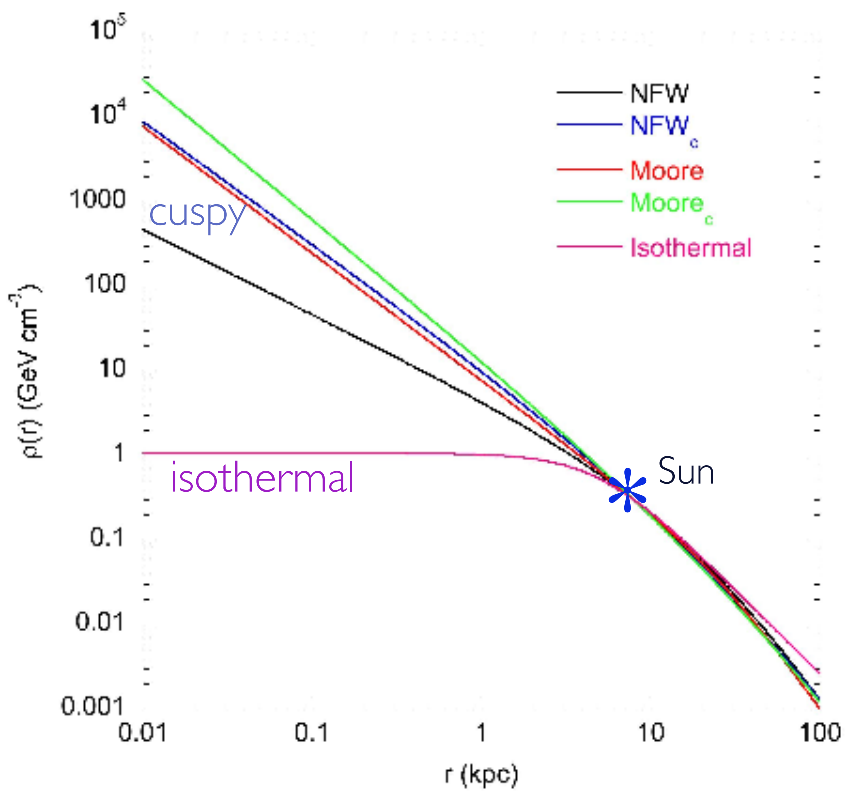
diffuse flux: astrophysical backgrounds! $\Rightarrow$ provides interesting upper limits but interpretation of excesses in general difficult

Pamela, Fermi, Integral, AMS,... excesses

monochromatic γ and ν : no astrophysical backgrounds + flux, energy spectra and and direction unaffected!

Uncertainty on the DM density profile towards the galactic center

Simulation of DM galactic halo formation predicts somewhat cuspy galactic DM density profile:



Observations give some indications for a somewhat more "cored" profile ("isothermal") profile but not precise at all so far

Calculation of the flux on earth: example of γ-rays

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{dN_\gamma}{dE_\gamma}\frac{\sigma v}{m_\chi^2}\int_{V_{ann}}\frac{1}{r^2}\frac{\rho_{DM}^2}{2}d^3x$$

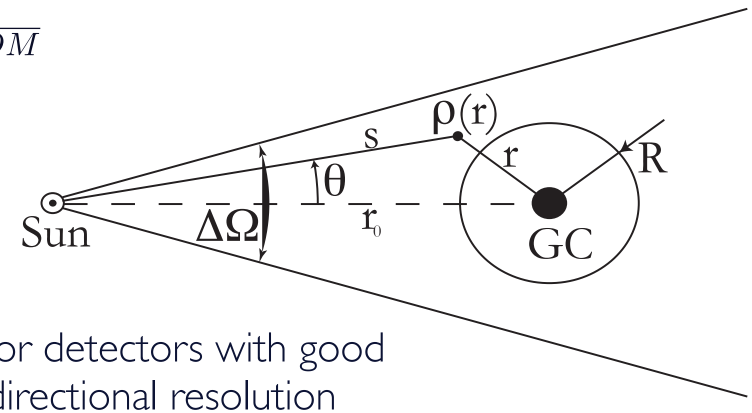
integration over galactic DM halo profile

flux on earth

spectrum

$DM = \overline{DM}$

$$\frac{d\Phi_\gamma}{dE_\gamma d\Omega} = r_0\rho_s^2\frac{dN_\gamma}{dE_\gamma}\frac{\sigma v}{8\pi m_\chi^2}J(\Theta)$$



for detectors with good directional resolution

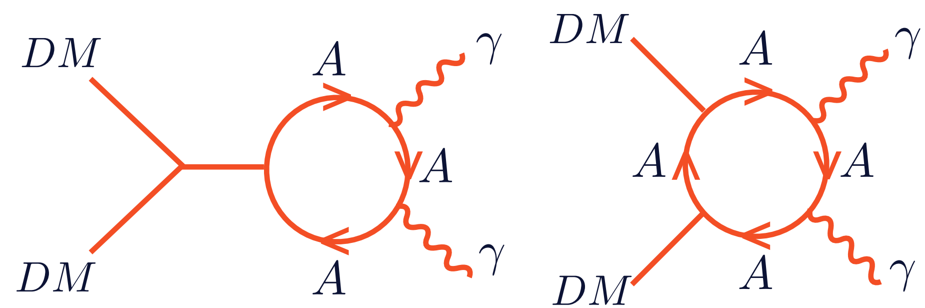
$$J(\Theta) = \int_{los}\frac{ds}{r_0}\left(\frac{\rho_{DM}(r(s,\Theta))}{\rho_s}\right)^2$$

J-factor

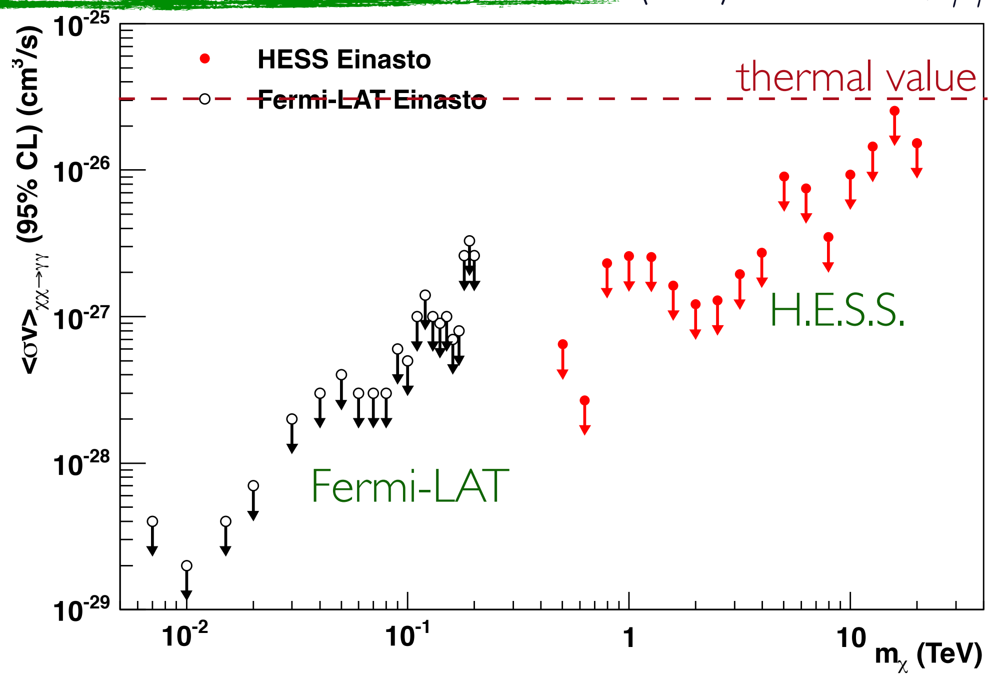
⇒ for monochromatic photons: $\frac{dN_\gamma}{dE_\gamma} = 2\delta(E_\gamma - m_{DM})$

for $\bar{p}$ and $e^\pm$: much more complicated: propagation effects

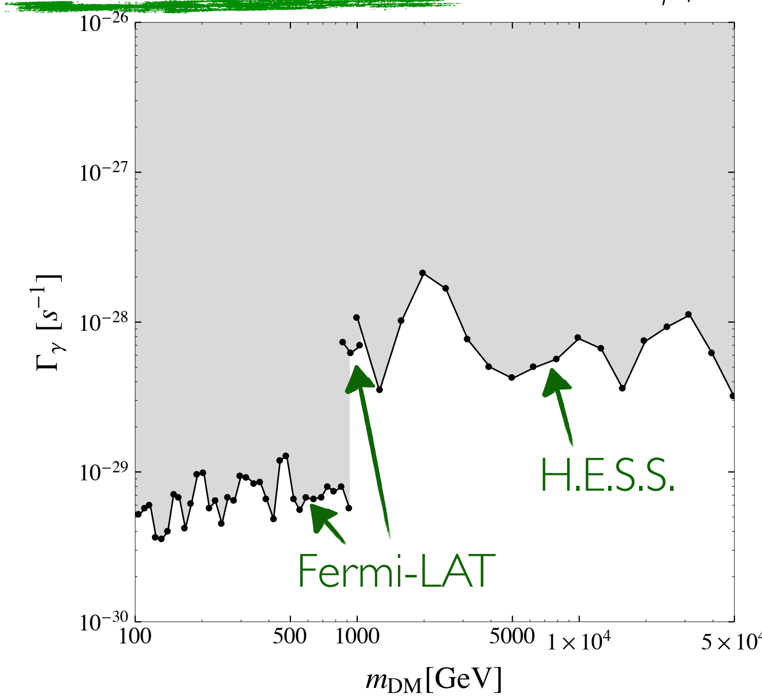
Search for γ-lines: DM smoking gun



Annihilation cross section upper limit: $\langle\sigma\, v\rangle_{DM\,DM\to\gamma\gamma}$



Decay width upper limit: $\Gamma_{DM\to\gamma+X}$



See also recent Hawc results 1301.1173

Sensitivity to cross sections better than thermal value!

~ of order what could be expected given the loop suppression

Sensitivity to γ-line cross sections 2-3 orders of magnitude better than to diffuse γ cross sections

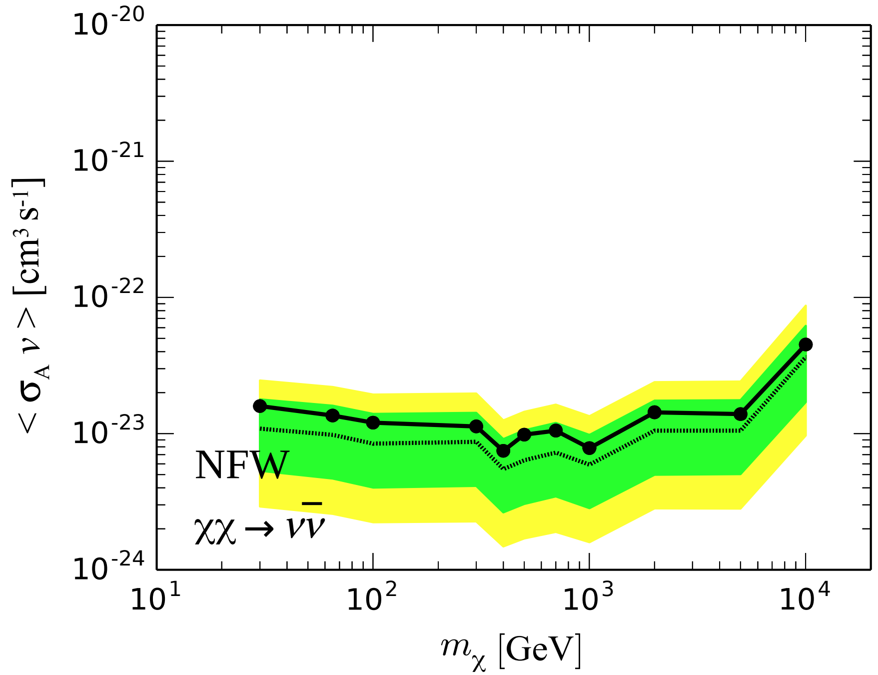
Sensitivity to $10^{(28-29)}$ sec lifetimes!

Search for ν-lines: the other DM smoking gun

from DM annihilation or decay

Annihilation cross section upper limit:

$$\langle \sigma v \rangle_{DM\,DM \to \nu\nu}$$

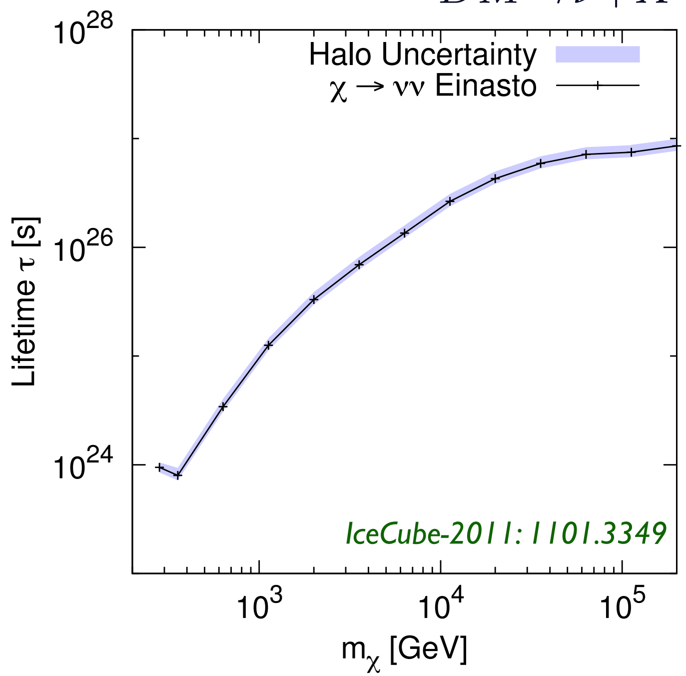


IceCube 1606.00209 (2011-2012)

Still far from thermal value but large improvements to be expected

Decay width upper limit:

$$\Gamma_{DM \to \nu + X}$$



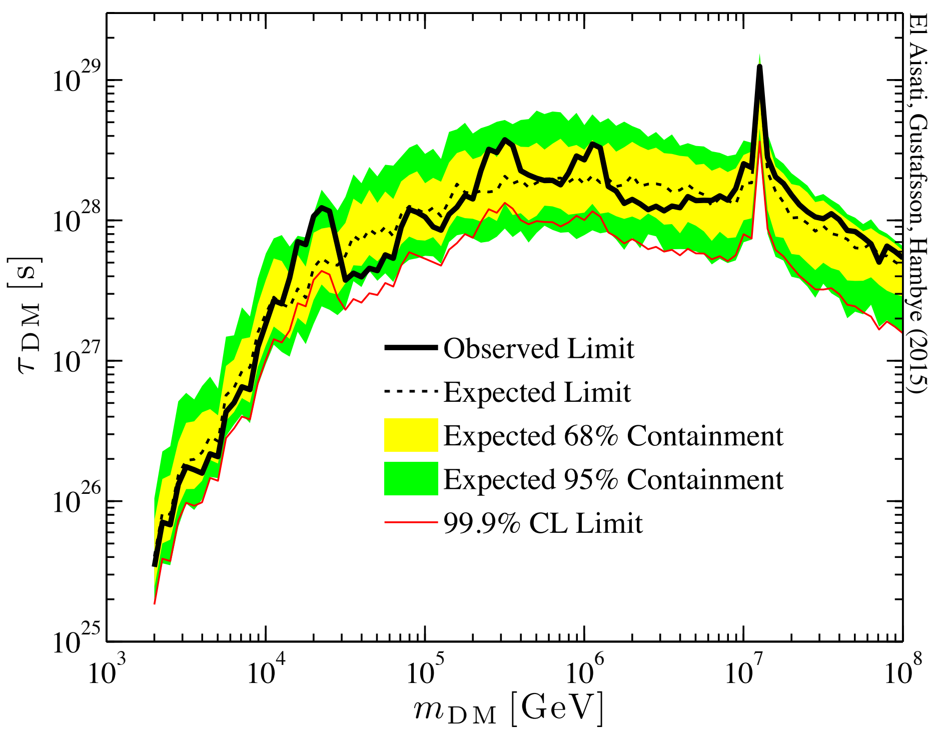
Above 100 TeV there are other limits: Rott, Kohri, Park , 14'
Esmaili, Kang, Serpico 14'

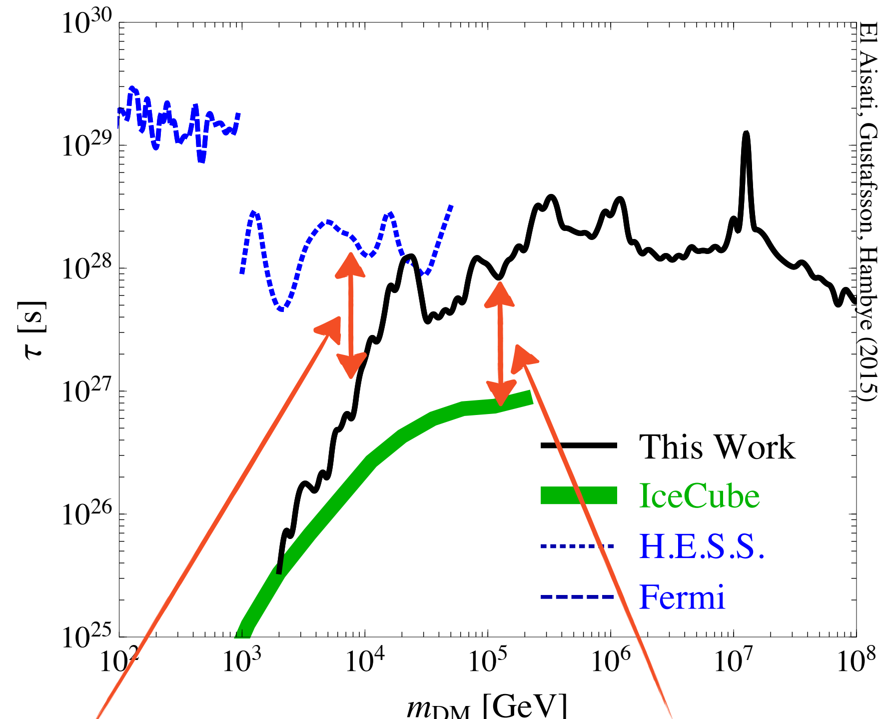
Search for ν-lines: the other DM smoking gun

from DM annihilation or decay

using a 2010-2012 public IceCube data sample: for DM decay: $\Gamma_{DM \to \nu + X}$

dedicated line search using Fermi-LAT statistical techniques, ... *El Aisati, Gustafsson, TH 15'*





between few TeV and 50 TeV,
γ and ν line sensitivities are similar!

~ an order of magnitude improvement from few TeV to 100 TeV

$\Rightarrow$ neutrino are coming into the game and also for an annihilation....

monochromatic neutrino production not loop suppressed, Sommerfeld boost, ...

Part 5
Phenomenology of example scenarios and models
(briefly)

3 different phenomenological approaches

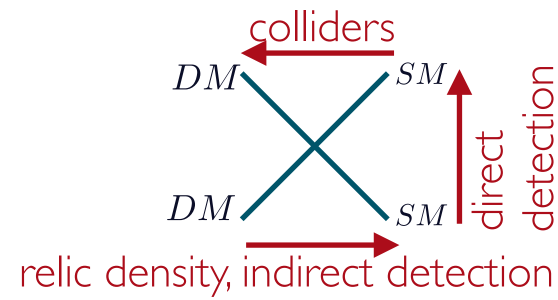
Effective operators: most model independent approach

Explicit DM-SM mediator setups

Explicit DM models

Effective operators and explicit mediators

Effective operator approach



examples: vector and axial operators

induced by heavier particles whose mass and coupling are not specified

$$\mathcal{O} = \frac{1}{\Lambda^2}\bar{\psi}_{DM}\gamma_\mu\psi_{DM}\,\bar{q}\,\gamma^\mu q$$

spin-independent direct detect.

$$\mathcal{O} = \frac{1}{\Lambda^2}\bar{\psi}_{DM}\gamma_\mu\gamma_5\psi_{DM}\,\bar{q}\,\gamma^\mu\gamma_5 q$$

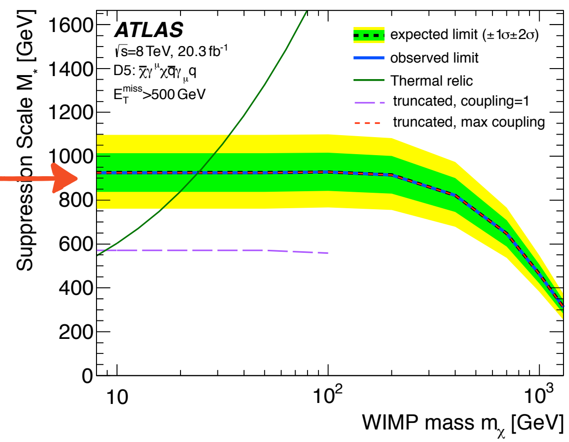
spin-dependent direct detect.

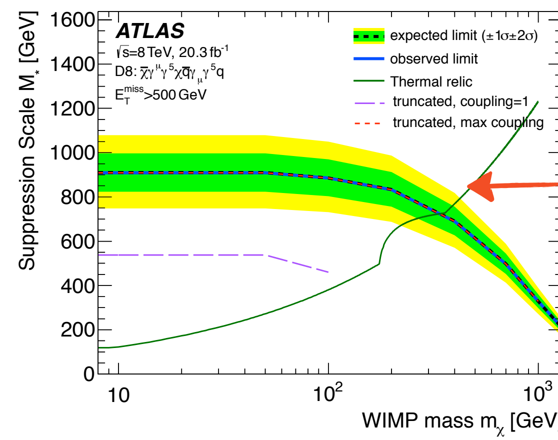
LHC-Run-I:

Colliders: $\Lambda \gtrsim 1\,\mathrm{TeV}$

for m_{DM} up to $\sim 500\,\mathrm{GeV}$

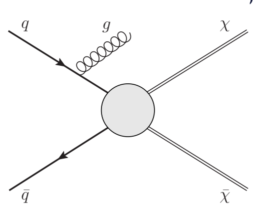
from monojets, mono-photon, mono-W, ...





Colliders: $\Lambda \gtrsim 1\,\mathrm{TeV}$

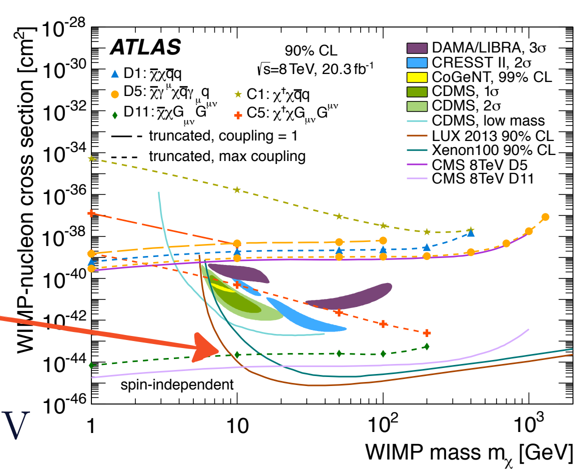
for m_{DM} up to $\sim 500\,\mathrm{GeV}$

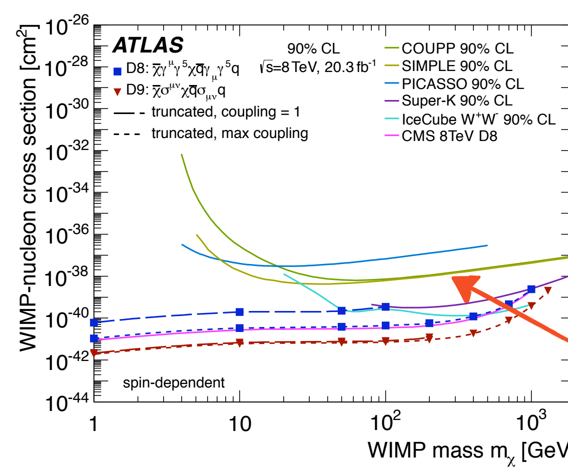


Direct Detect. (2014):

$\Lambda \gtrsim 10\,\mathrm{TeV}$

for $10\,\mathrm{GeV} \gtrsim m_{DM} \gtrsim 1\,\mathrm{TeV}$





Direct Detect. (2014):

$\Lambda \gtrsim 600\,\mathrm{GeV}$

$10\,\mathrm{GeV} \gtrsim m_{DM} \gtrsim 1\,\mathrm{TeV}$

Effective operator approach

examples: vector and axial operators

$$\mathcal{O} = \frac{1}{\Lambda^2} \bar{\psi}_{DM} \gamma_\mu \psi_{DM}\, \bar{q}\, \gamma^\mu q$$

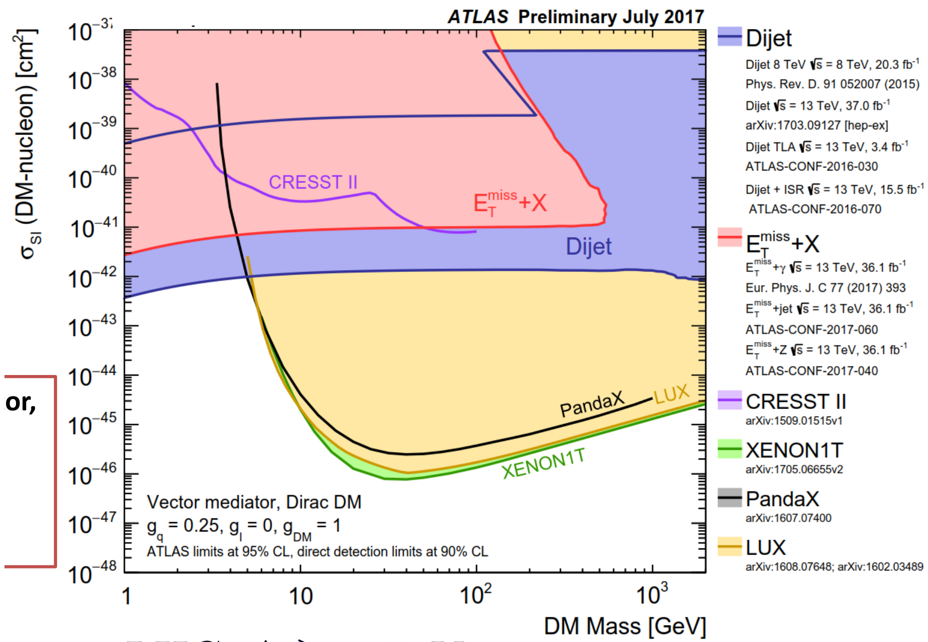
spin-independent direct detect.

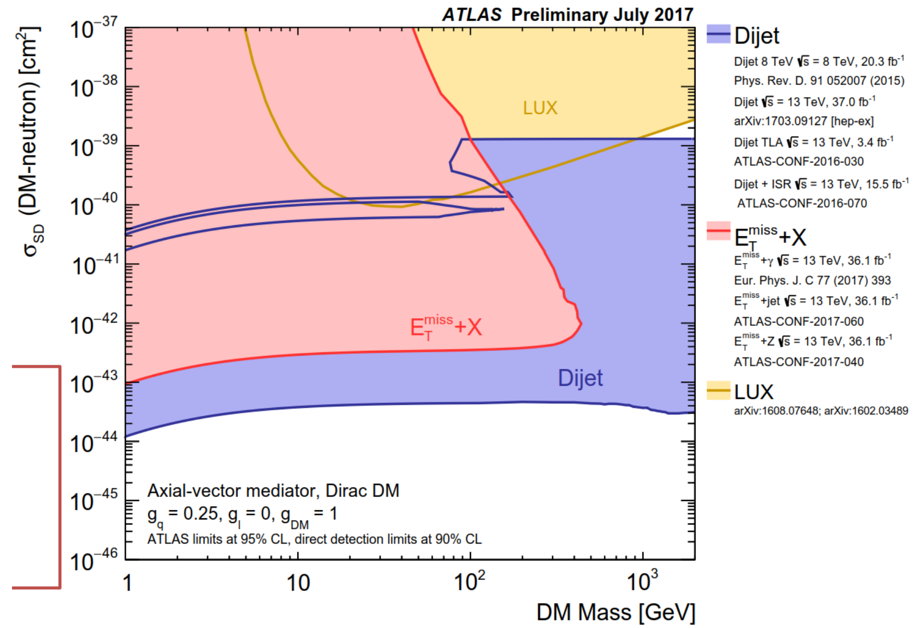
$$\mathcal{O} = \frac{1}{\Lambda^2} \bar{\psi}_{DM} \gamma_\mu \gamma_5 \psi_{DM}\, \bar{q}\, \gamma^\mu \gamma_5 q$$

spin-dependent direct detect.

LHC-Run-II:

or,





LHC: $\Lambda \gtrsim 3$ TeV
Xenon1T: $\Lambda \gtrsim 25$ TeV

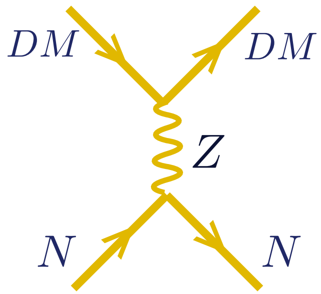
LHC: $\Lambda \gtrsim 7$ TeV

NB : for operators with 2 DM and 2 leptons colliders very competitive % direct detection

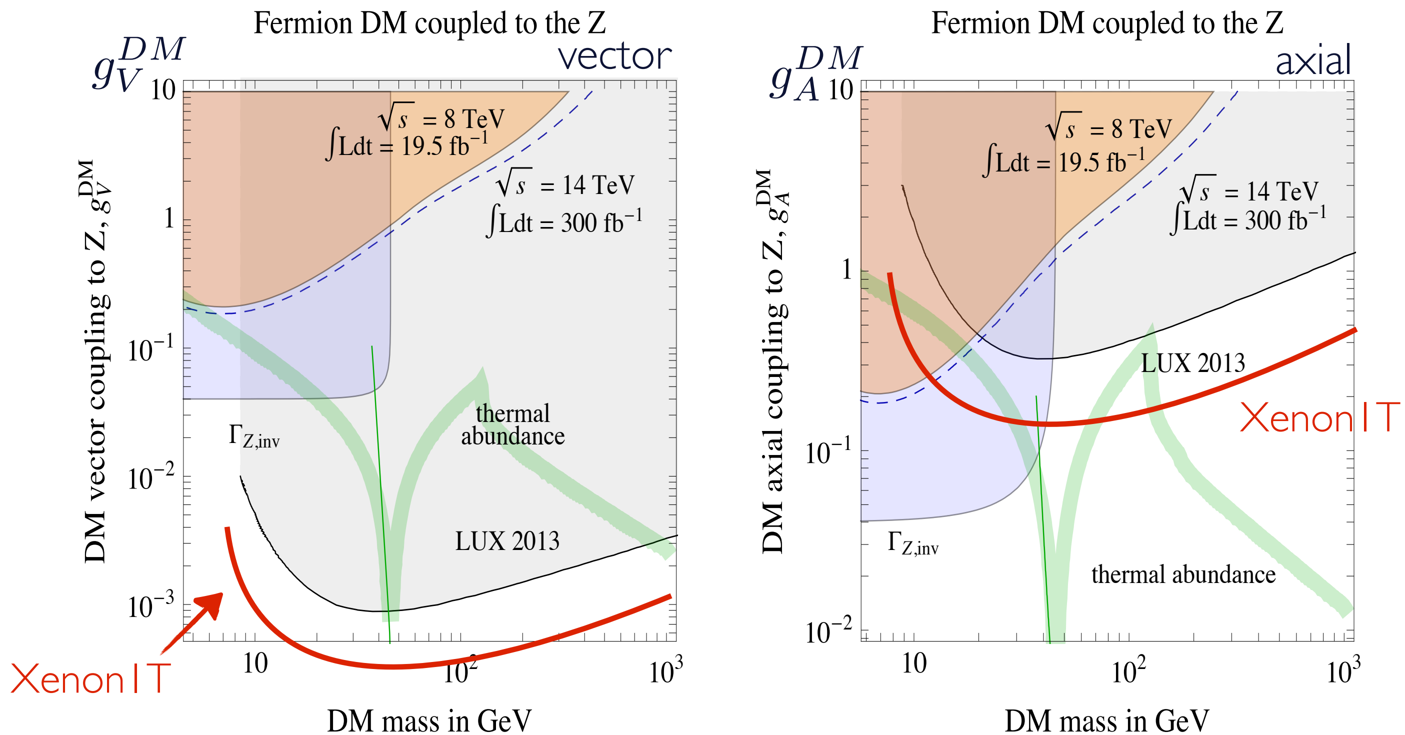
Explicit mediator approach: Z mediator for fermion DM

e.g. assuming DM/SM specific mediator with given coupling and masses:

- Z mediator: fermion DM: vector and axial DM coupling to the Z



$$\mathcal{L} \ni -Z_\mu \frac{g}{\cos\theta_W} \bar{\psi}_{DM} (g_V^{DM} + g_A^{DM} \gamma_5) \gamma^\mu \psi_{DM}$$



DM candidates which have hypercharge of $\mathcal{O}(1)$: totally excluded by direct detection

except for fermion axial coupling case above 10 TeV

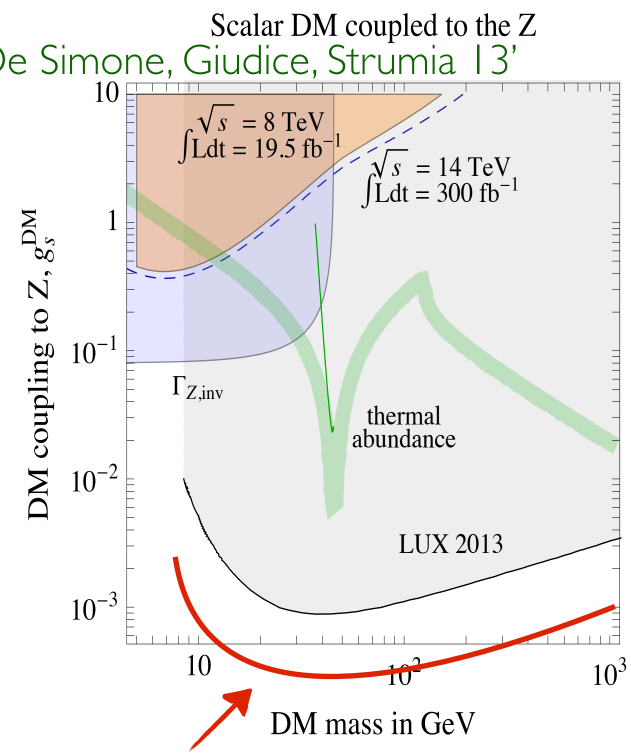
DM candidates with vanishing hypercharge but still small coupling to Z through mixing:
coupling to Z must be small and relic density allows only candidates above ~ 2 TeV and ~ 150 GeV respectiv.

Explicit mediator approach: Z mediator for scalar DM

$$\mathcal{L} \ni -Z_\mu \frac{g}{\cos\theta_W} g_\phi \left[\phi^*_{DM}\partial^\mu\phi_{DM} - \partial^\mu\phi^*_{DM}\phi_{DM}\right]$$

similar to fermion DM vector case

De Simone, Giudice, Strumia 13'



Xenon1T

allowed above $\sim 10\,\mathrm{TeV}$

similar to fermion DM with vector coupling $\Rightarrow$ totally excluded for "standard" Z couplings

Possible kinematical way to avoid Z exchange strong constraint

example: a scalar doublet H_2 odd under a Z_2 symmetry: $H_2 \to -H_2$

$$H_2 = \begin{pmatrix} H^+ \\ \frac{H_0 + iA_0}{\sqrt{2}} \end{pmatrix} \leftarrow Y = 1 \neq 0$$

"inert scalar doublet DM"

Deshpande, Ma 78, Barbieri, Hall, Ryshkov 06, Lopez-Honorez, Nezri, Oliver, Tytgat 07, TH, Lin, Lopez-Honorez, Rocher 08

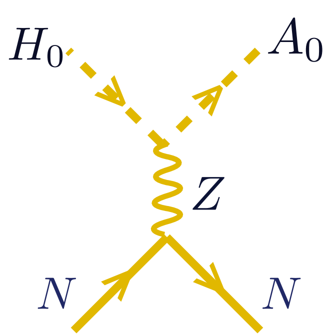
from the most general scalar potential H_0 and A_0 do not have the same mass

$$V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4$$
$$+ \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left[(H_1^\dagger H_2)^2 + h.c. \right]$$

$\Rightarrow$ $m^2_{H_0} - m^2_{A_0} = \lambda_5 \, v^2$ $\Rightarrow$ the lightest neutral component is the DM

$\hookrightarrow$ if splitting larger than $\sim 100 \text{ keV}$: no direct detection through Z exchange!

$\hookrightarrow$ DM is highly non-relativistic today: $E_{kin} \lesssim 100 \text{ keV}$

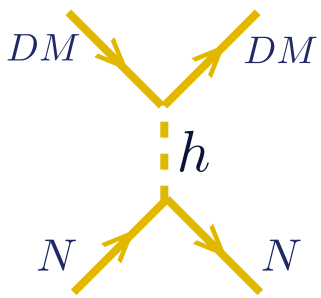


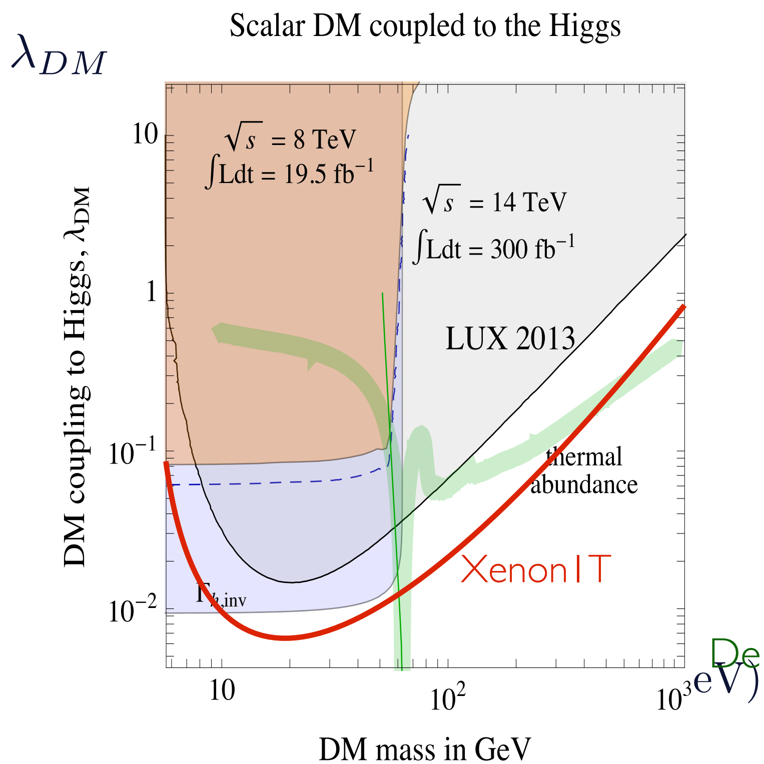
mechanism also possible for a fermion doublet, more demanding for higher multiplets

Explicit mediator approach: Higgs boson mediator: scalar DM

- Scalar DM: Higgs portal interaction: $\mathcal{L} \ni \lambda_{DM} H^\dagger H \, \phi^*_{DM}\phi_{DM}$

"Higgs portal"





De Simone, Giudice, Strumia 13'

$\Downarrow$

excluded below ~ 600 GeV (except around h resonance)

N.B.: Xenon1T probes it up to $\sim 1\,\mathrm{TeV}$ for $\lambda_{DM} \sim 1$

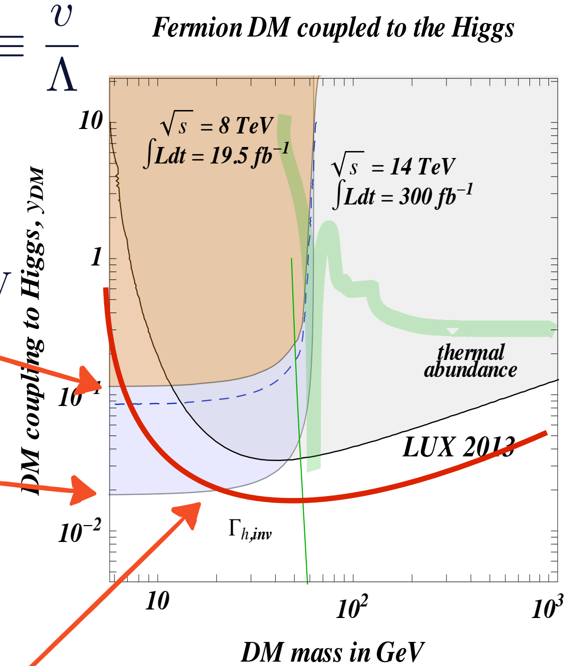
Explicit mediator approach: Higgs boson mediator: fermion DM

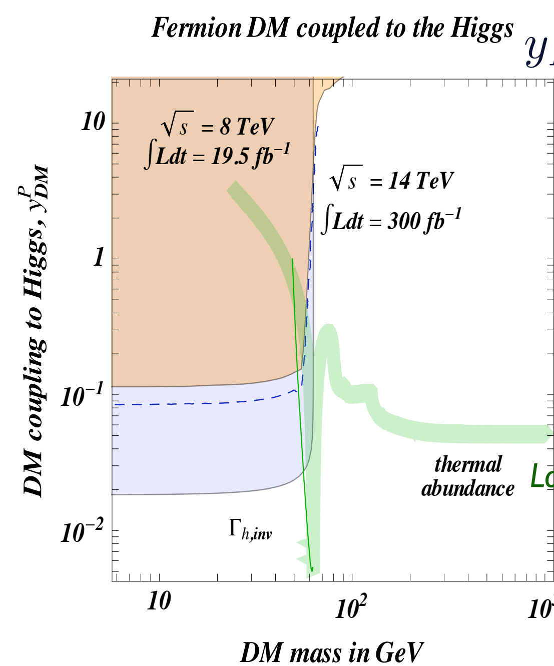
- Fermion DM: lowest gauge invariant interaction: dim-5

$$\mathcal{O} = \frac{1}{\Lambda} H^\dagger H \, \bar{\psi}_{DM} \psi_{DM} \qquad\qquad \mathcal{O} = \frac{1}{\Lambda} H^\dagger H \, \bar{\psi}_{DM} i\gamma_5 \psi_{DM}$$

spin-independent direct detect.   spin-dependent direct detect.

$$y_{DM} \equiv \frac{v}{\Lambda}$$





$$y_{DM} \equiv \frac{v}{\Lambda}$$

LHC monojets (2014)
for m_{DM} up to $\sim 60\,\mathrm{GeV}$

LHC: Higgs boson
invisible decay width

Direct Detect.:
$\Lambda \gtrsim 30\ \mathrm{TeV}$
for $10\,\mathrm{GeV} \gtrsim m_{DM} \gtrsim 1\,\mathrm{TeV}$

....
Lopez-Honorez, Schwetz, Zupan 12
De Simone, Giudice, Strumia 14
....

Direct Detect.:
no relevant bound

Explicit models

(briefly)

The simplest example: real scalar singlet DM

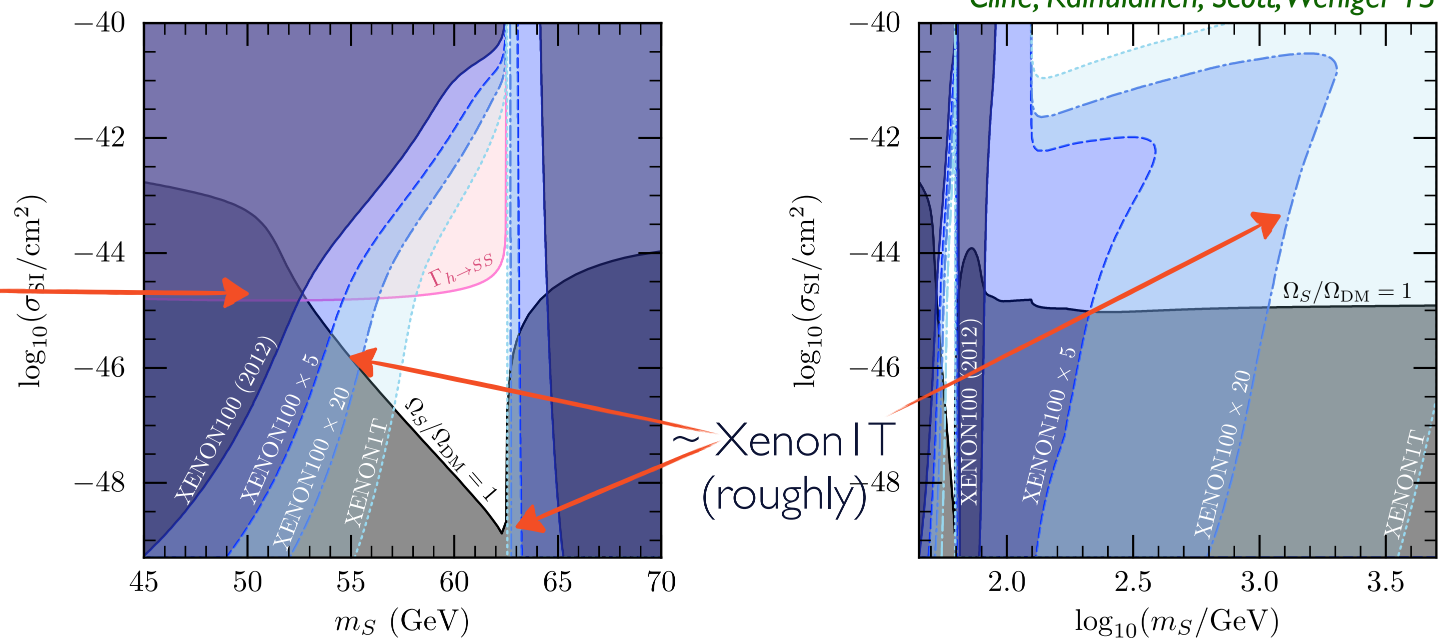
a real singlet S odd under Z_2 parity: $S \to -S$

$$\mathcal{L} \ni -\frac{1}{2}\mu_S^2 S^2 - \frac{1}{24}\lambda_S S^4 - \frac{1}{2}\lambda_{hs} H^\dagger H S^2 \qquad m_S^2 = \mu_S^2 + \frac{1}{2}\lambda_{hs} v^2$$

For m_S fixed, λ_{hs} can be fixed by $\Omega_{DM} \simeq 26\%$ constraint

Cline, Kainulainen, Scott, Weniger 13

Higgs invisible width



~Xenon1T (roughly)

Xenon1T direct detection requires: $55\ \mathrm{GeV} \lesssim m_{DM} \lesssim 63\ \mathrm{GeV}$
or $m_{DM} \gtrsim 800\ \mathrm{GeV}$

GAMBIT collaboration 18

Future: CTA should probe m_{DM} up to $5\ \mathrm{TeV}$

Dwarf galaxies γ-ray flux requires: $m_{DM} \gtrsim 50\,\mathrm{GeV}$

⇒ shows how a model is getting very squeezed when it depends on only very few parameters

$SU(2)_L$ multiplet DM: should we have seen already it in direct detection experiments if thermal????

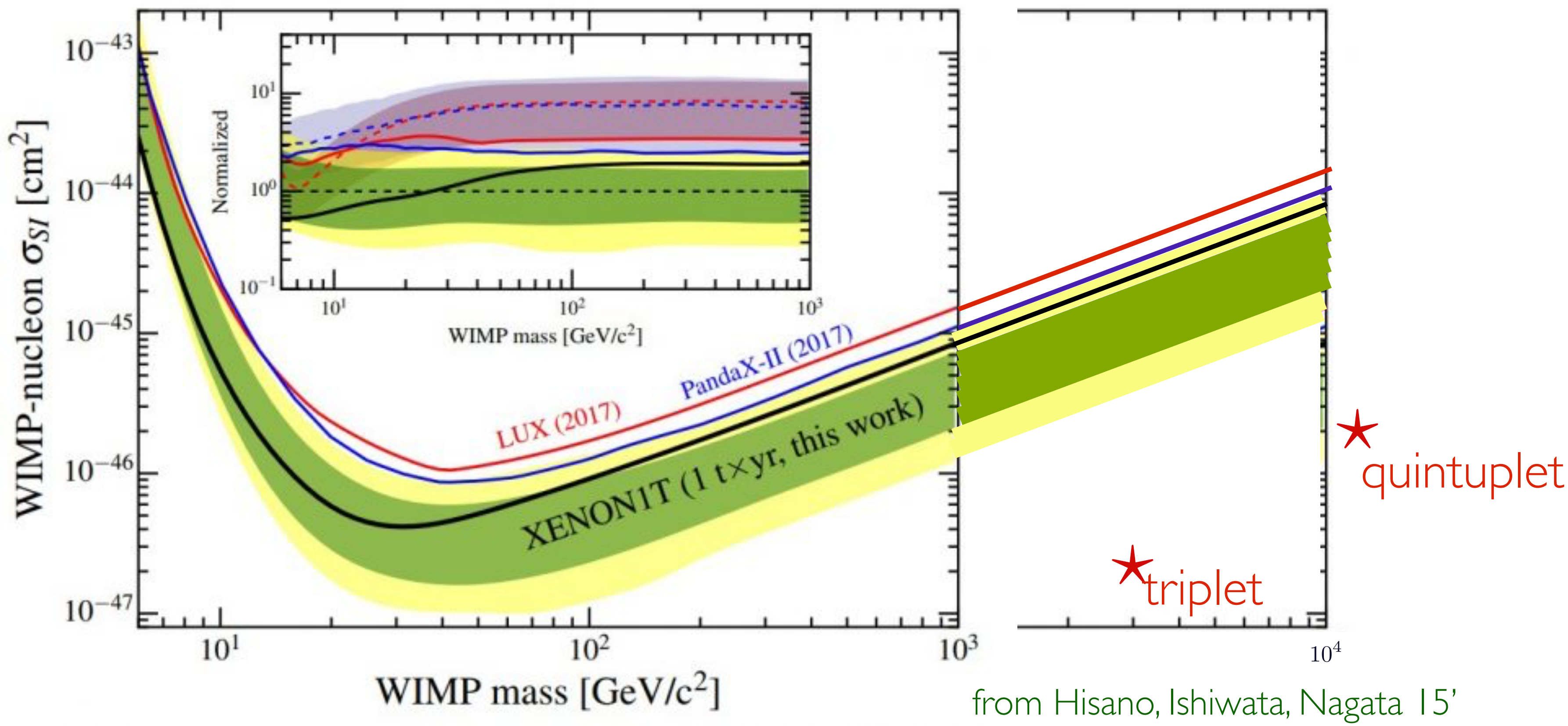
other examples of models with very few parameters

let's take the examples above with $Y=0$ to avoid ruled-out Z exchange

e.g. a $Y=0$ fermion triplet, quintuplet, $\dots$ ``minimal dark matter''

have only gauge interactions with SM fields:

relic density totally fixed by value of m_{DM} $\Rightarrow$ $m_{DM} \simeq 3.0$ TeV
$m_{DM} \simeq 11$ TeV



from Hisano, Ishiwata, Nagata 15'
Mitridate, Redi, Smirnov, Strumia 17'

multi-TeV domain still very open for direct detection

$SU(2)_L$ *multiplet DM: should we have seen already it in indirect detection experiments if thermal????*

let's consider the $SU(2)_L$ triplet DM example again: "wino"

have only gauge interactions with SM fields:

relic density totally fixed by value of m_{DM}

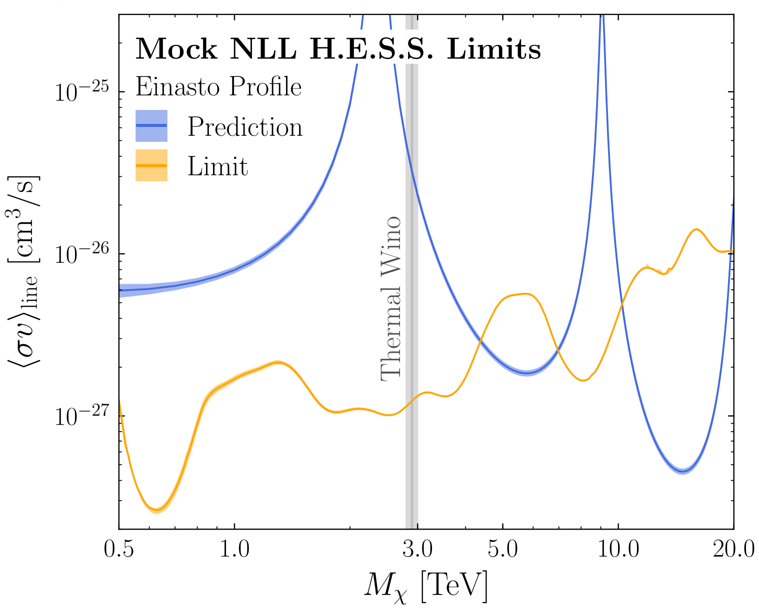
$\Omega_{DM} \simeq 26\%$ requires $m_{DM} \simeq 3.0$ TeV too high for LHC

Hisano et al. 03-09

Indirect detection very efficient here!! production of γ-line is Sommerfeld enhanced

$\sigma(DM DM \to \gamma\gamma)$

Baumgart, Cohen, +7 people 18



m_{DM} (TeV)

HESS upper limit

we should have seen a signal or isothermal profile!

The MSSM neutralino:

example of DM candidate within a more global model with lots of indirect constraints

the lightest neutralino is in general a mixture of Bino, Higgsinos and Wino

if it is the lightest Susy particle (LSP): DM candidate

the direct constraints on the neutralino are mild: m_χ as light as ~few tens of GeV still allowed

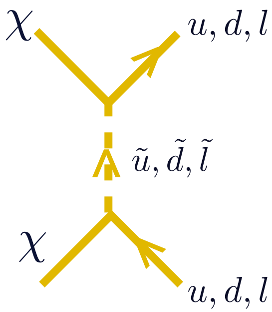
the partners and interactions entering in its annihilation are nevertheless constrained

- a pure bino neutralino:

annihilation through squarks and leptons:

but $\Omega_{DM} = 26\%$ requires squarks and sleptons lighter than allowed experimentally

$m_{\tilde{l}} \lesssim 100$ GeV



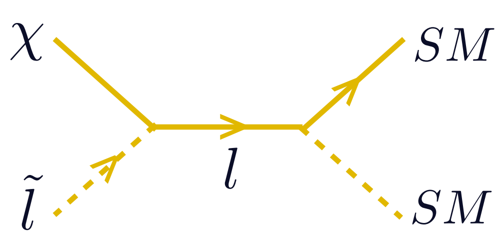
$m_{\tilde{u},\tilde{d}} \gtrsim 1$ TeV

need for other channels having larger annihilation cross section:

co-annihilation channels or channels close to a resonance

for instance if slepton not more than ~10% heavier than Bino it is still around in

thermal bath when Bino is about to decouple $\Rightarrow$ co-annihilation dominates the Bino decoupling



The MSSM neutralino

- a pure Wino neutralino:

annihilation through gauge interactions: $m_{DM} \simeq 3.0 \text{ TeV}$

was not much considered as attractive because sets the Susy scale quite high

$\Rightarrow$ excluded by γ-line search or isothermal profile!

- a pure Higgsino neutralino:

annihilation through gauge interactions are too fast unless it is heavy (as Wino) $m_{DM} \simeq 1 \text{ TeV}$

was not much considered as attractive because sets the Susy scale quite high and not obtained as LSP in many Susy breaking framework

can escape Z exchange direct detection constraint despite it has $Y \neq 0$ because the Z couples to 2 different neutral Higgsino component which can have mass splitting forbidding kinematically the Z exchange

as "inert scalar doublet DM" above

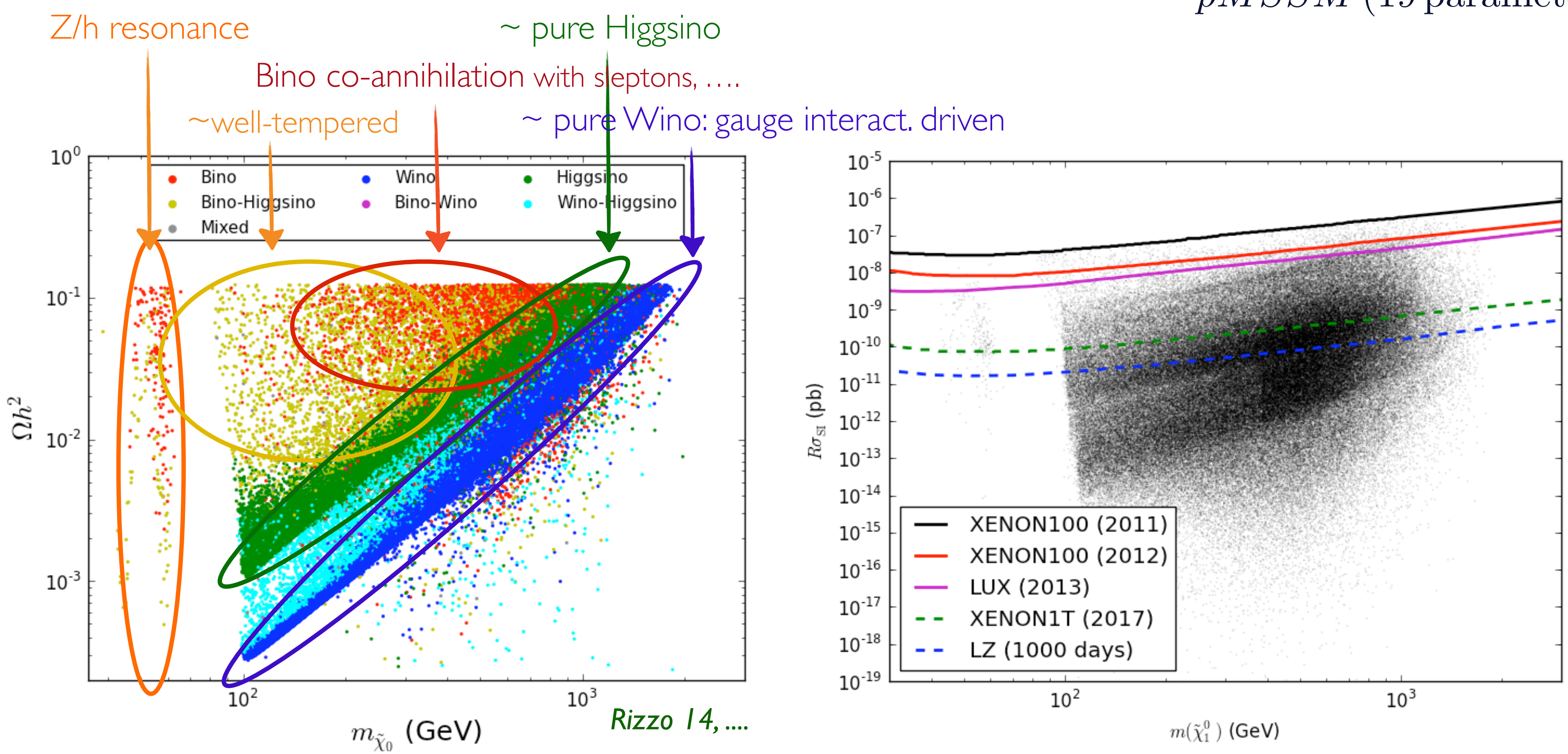
Higgs boson mass measured at LHC requires typically a large stop mass which indirectly typically requires a large Higgsino mass which fits with the mass a Higgsino must have if DM

- a mixed neutralino:

offers more possibility playing around (as "well-tempered neutralino")

The MSSM neutralino

$pMSSM$ (19 parameters)



relic density point out a neutralino below ~3 TeV (i.e. gauge driven, ...) but could be higher

already partly probed by direct detection

still many possibilities to get the relic density in itself but need typically mass similarities, resonances, cancellations, ….

moreover if one adds some naturalness considerations into the game, not much is left

$m_{\tilde{g}} \gtrsim 1\,\mathrm{TeV}$ $\quad m_{\tilde{u},\tilde{d}} \gtrsim 1\,\mathrm{TeV}$

Low scale susy probably does not exists but DM still does!!!

Hidden sector DM

Standard Model
$SU(3)_c \times SU(2)_L \times U(1)_Y$
$l,\ \nu,\ q,\ \gamma,\ W,\ Z,\ g,\ H$

Hidden sector
DM

portal

Testability all depends on size and mass of portal and on whether DM communicates directly to visible sector through portal

example: Higgs portal: $\mathcal{L} \ni -\lambda_m \phi^\dagger_{DM} \phi_{DM} H^\dagger H$ or $\mathcal{L} \ni -\lambda_m \phi^\dagger \phi H^\dagger H$

see real scalar singlet DM and Higgs portal direct detection above

in both cases invisible Higgs decay width constraints if HS particles light enough

$Br(h \to \phi_{DM}\phi_{DM},\ \phi\phi) \leq 20\%$

for massive connector the upper bounds on connector coupling typically are typically of order $\sim 1 - 10^{-2}$

for light connector the bounds can be much more stringent!

Hidden sector DM: direct detection is already testing the freezein regime for light mediator

Let's consider again the hidden electron/photon QED' model above:

Standard Model

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$l,\ \nu,\ q,\ \gamma,\ W,\ Z,\ g,\ H$

Hidden sector

$U(1)_X$

$e',\ \gamma'\ +\ \ldots$

portal

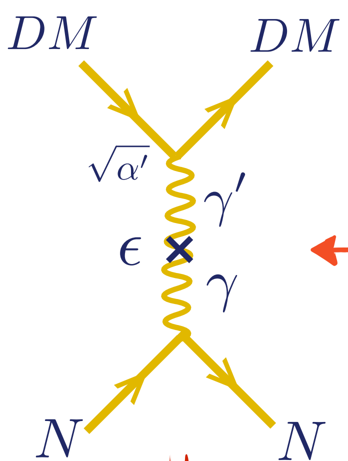
kinetic mixing

$\mathcal{L} \ni -\frac{\epsilon}{4} F^Y_{\mu\nu} F^{\mu\nu}_X$

"hidden electron"

"hidden photon"

gauge boson of $U(1)_X$



$$\frac{1}{q^2} \rightarrow \frac{1}{E_r^2}$$

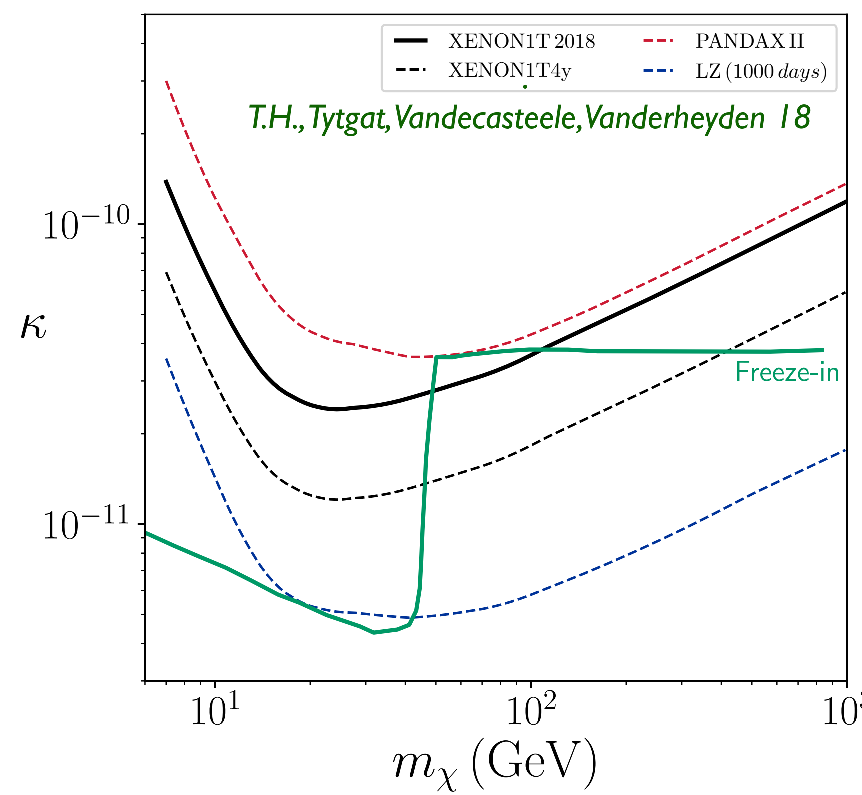
$E_r \sim$ few KeV

$$\frac{d\sigma}{dE_r} = \frac{1}{E_r^2}\frac{1}{v^2}\frac{2\pi\kappa^2 Z^2\alpha^2}{m_A} F_A^2(qr_A)$$

huge enhancement

Chu, T.H., Tytgat 11

direct detection sensitive to very small connector values



Phenomenology trends….

It is true that some thermal models become to be very squeezed experimentally or even excluded:

- all models which allow a (standard) kinematically allowed Z exchange in direct detection process (except pure axial case), h exchange begins to be seriously probed by direct detection experiments

- fermion thermal candidates which have only gauge interactions: triplet (Wino), quintuplet pure electroweak multi-TeV models: excluded by indirect detection: γ-lines (except for isothermal DM halo profile)

  unlike scalar multiplets: more freedom due to possible scalar quartic couplings, mass splittings,….

- models with very few parameters: example: real scalar singlet (except at h resonance and at high mass)

- very global models with many constraints on partner particles entering the DM annihilation , direct detection, …, processes: example: MSSM: needs mass similarities (co-annihilation), resonances, cancellations, …

Phenomenology trends....

but as soon as we go away from these global models (not much favored any-more by LHC data), ..., and away from very minimal visible models, thermal candidates (and beyond) are still largely allowed:

- many visible sector DM models
- hidden sector models: new trend! <- DM is the tip of an all hidden sector world!

→ with clear possibilities of signatures:

- new generation of direct detection experiments: - at high mass
  - at low masses (new!)

with even possibilities to test the freezein scenario

- new generation of indirect detection (CTA, ...), especially for still quite open multi-TeV range, including from still unexplored high energy neutrinos, ...

Thank you