Dark matter

in the light of the ΛCDM paradigm

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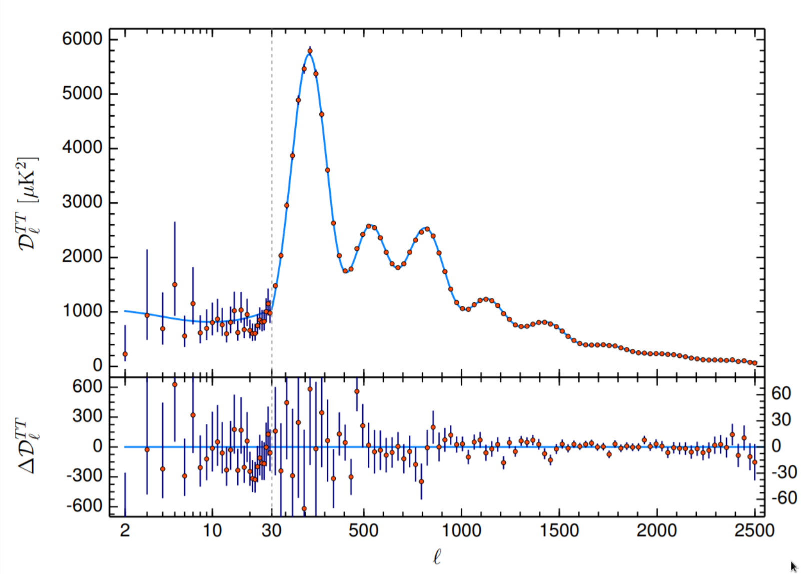
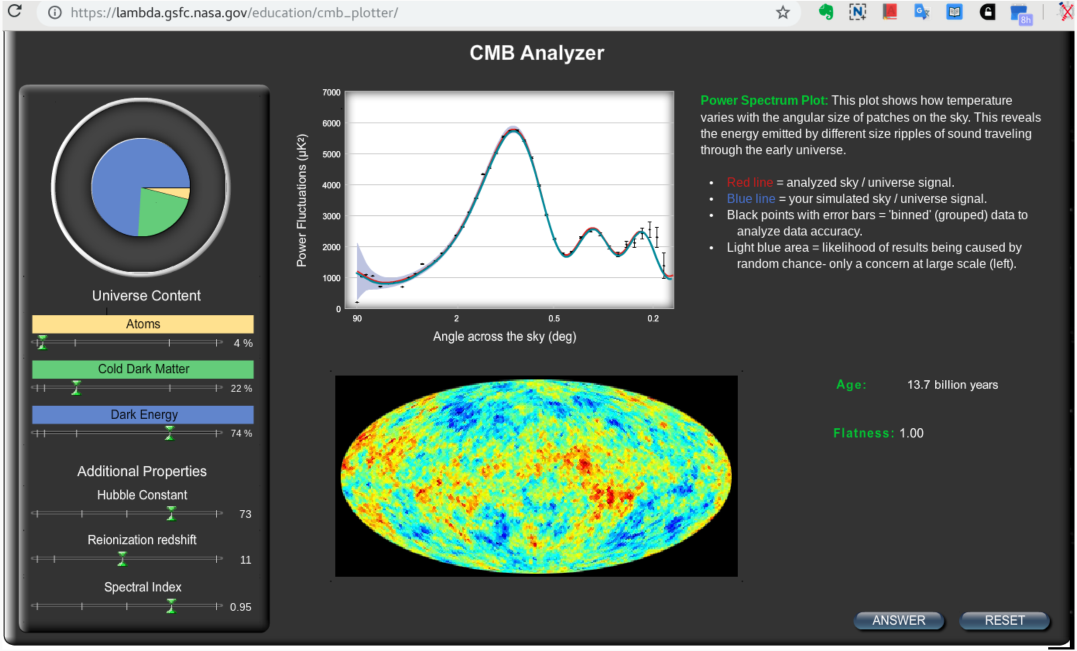
GRUPO DE
FENOMENOLOGÍA DE INTERACCIONES FUNDAMENTALES

ΛCDM paradigm

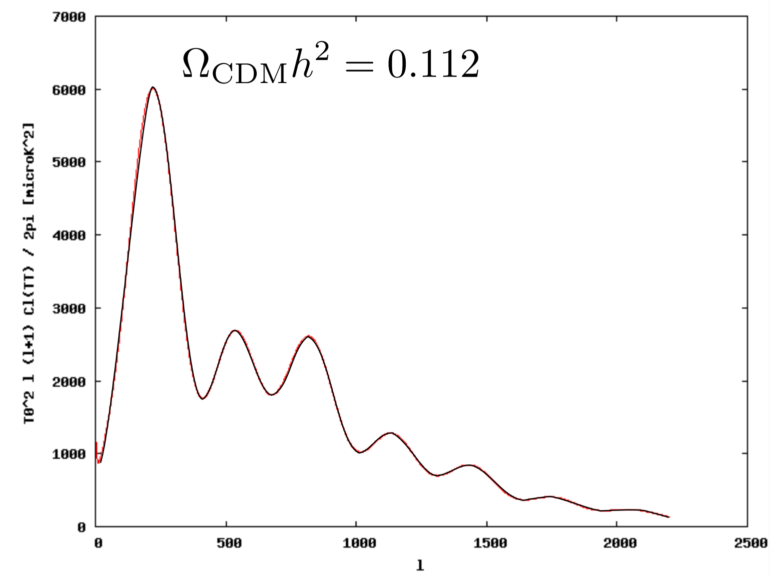


Credit: Planck 2018

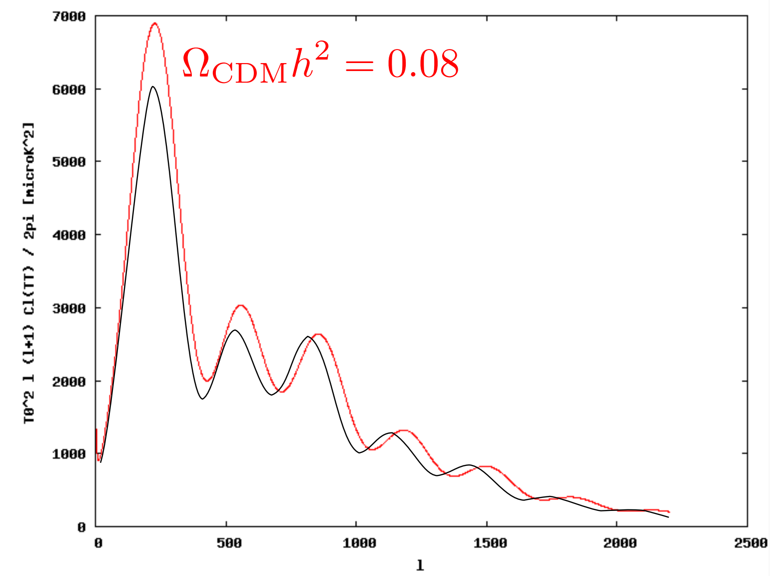
Why was the temperature of the CMB the same in all directions?
What was the origin of the small temperature fluctions?



See also `https://lambda.gsfc.nasa.gov/toolbox/tb_camb_form.cfm`



$\Omega_{\rm CDM}h^2 = 0.112$
T0^2 l (l+1) Cl(TT) / 2pi [microK^2]
l
7000
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500


$\Omega_{\mathrm{CDM}} h^2 = 0.08$
T0^2 l (l+1) Cl(TT) / 2pi [microK^2]
l
0
1000
2000
3000
4000
5000
6000
7000
0
500
1000
1500
2000
2500

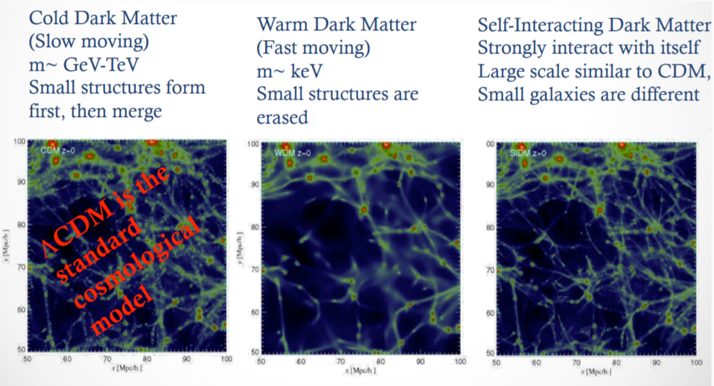
Credit: Komatsu, ICTP Summer School on Cosmology 2018[1]

[1] Video avalaible

Credit: Komatsu, ICTP Summer School on Cosmology 2018[1]

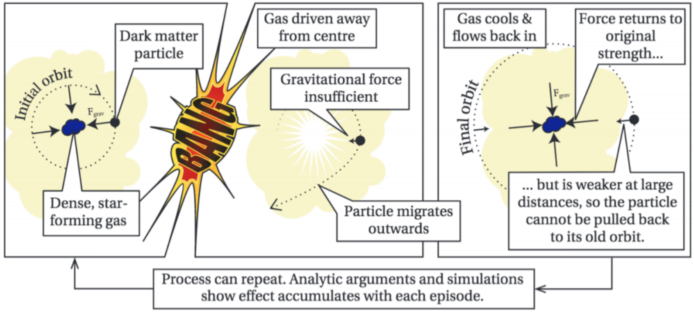
[1] Video avalaible

Dark matter simulations



Credit: Arianna Di Cintio (Conference on Shedding Light on the Dark Universe with Extremely Large Telescopes, ICTP - 2018)

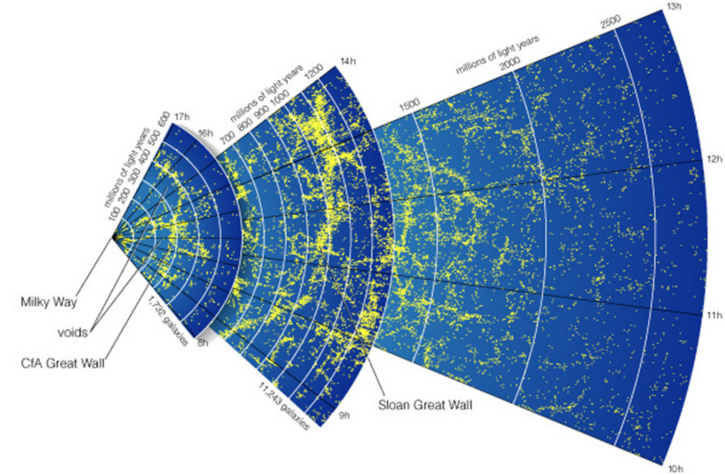
Baryonic effects



Pontzen & Governatp 14

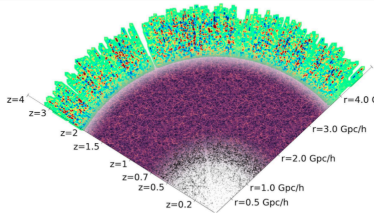
Once the effect of baryonic physics is included, it is hard to distinguish between WDM/SIDM/CDM

Goal



Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***

The DESI experiment

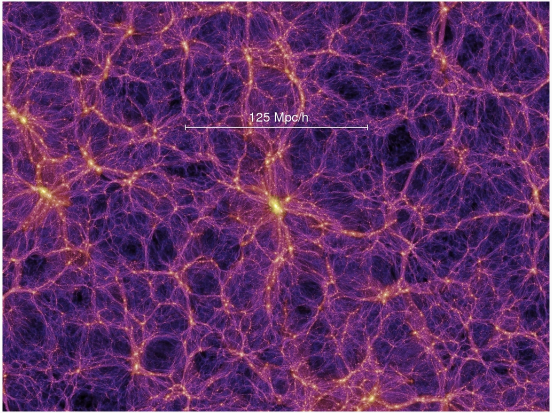


J. Forero `http://cosmology.univalle.edu.co/`

Cooking the soup: Cosmic web

Dark matter in the universe evolves through gravity to form a complex network of halos, filaments, sheets and voids, that is known as the cosmic web [arXiv:1801.09070]

An excess of a gas is observed between Milky Way and Andromeda



Milenium simulation: `https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/`

Cosmic Anatomy

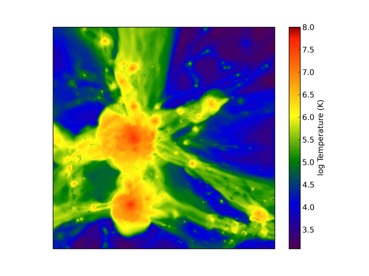
Baryons Missing Baryons Dark Matter

The muscles

Direct observations of filaments

Where are the Baryons? (Cen, Ostriker, astro-ph/9806281 [AJ])

> *Thus, not only is the universe dominated by dark matter, but more than one half of the normal matter is yet to be detected. (the muscles)*



Credit: Cen, arXiv:1112.4527 [AJ]

Warm-hot intergalactic medium (WHIM)
Density-weighted temperature projection of a portion of the refinement box of the C run of size $(18\,h^{-1}\text{Mpc})^3$.
Low temperature WHIM confirmed by O VI line that peak at $T \sim 3 \times 10^5$ K

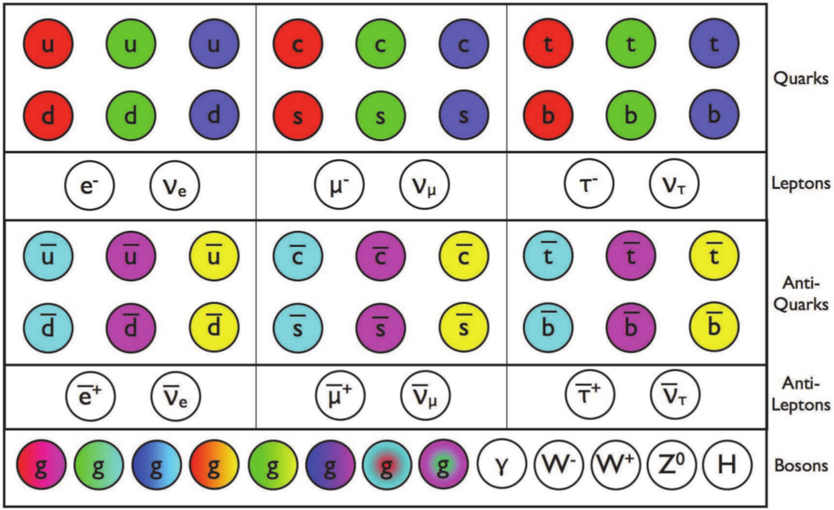
Hotter phases of the WHIM: **Observations of the missing baryons in the warm-hot intergalactic medium** (Nicastro, *et al.* arXiv:1806.08395 [Nature]).

The skeleton

Credit: `https://www.disnola.com`

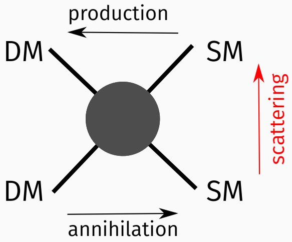
Dark matter interpretations

SM

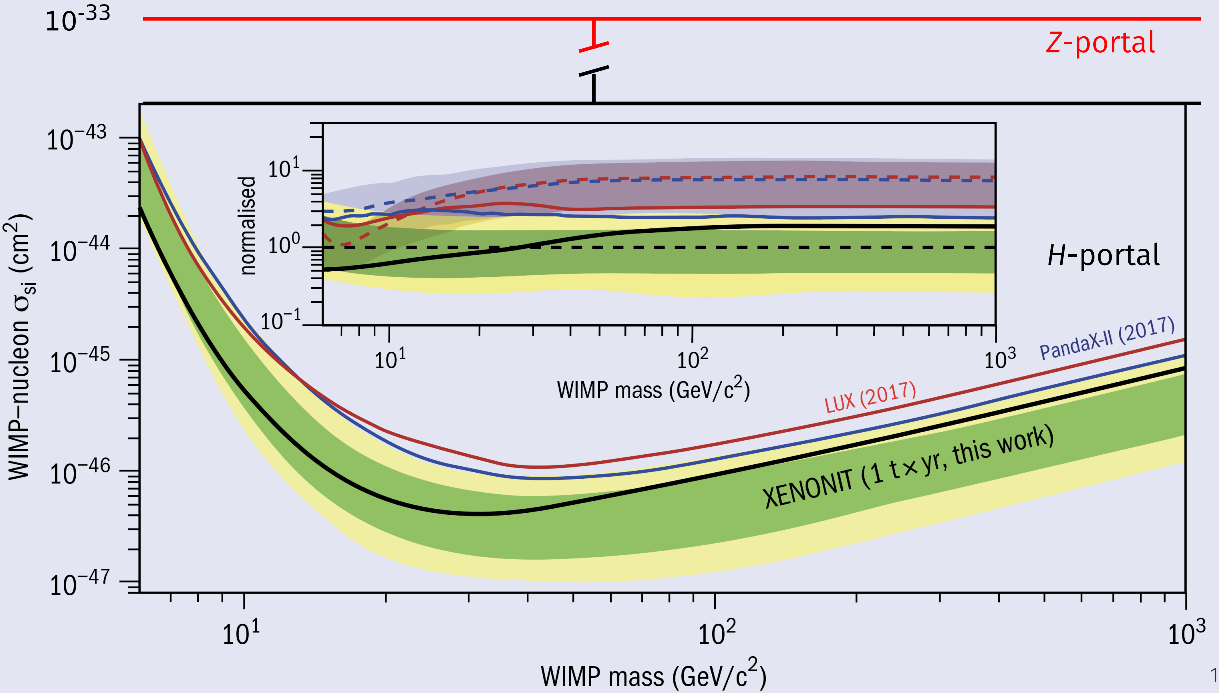


E. SIEGEL / BEYOND THE GALAXY

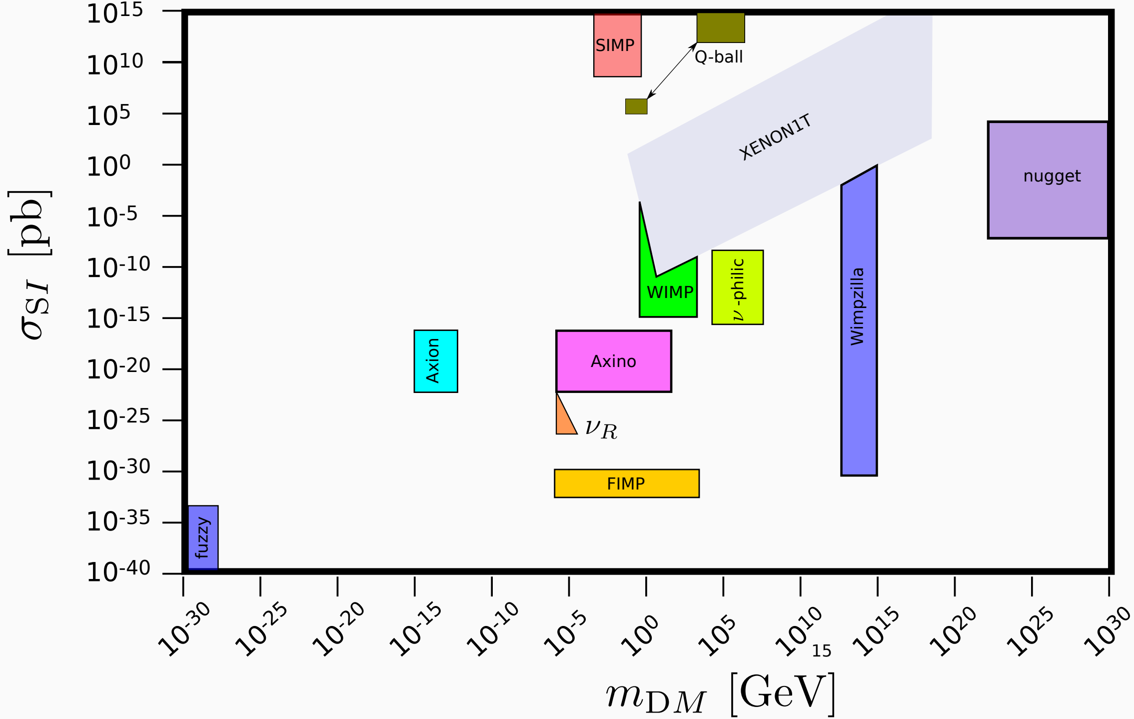

WIMP


production
DM
SM
scattering
DM
SM
annihilation

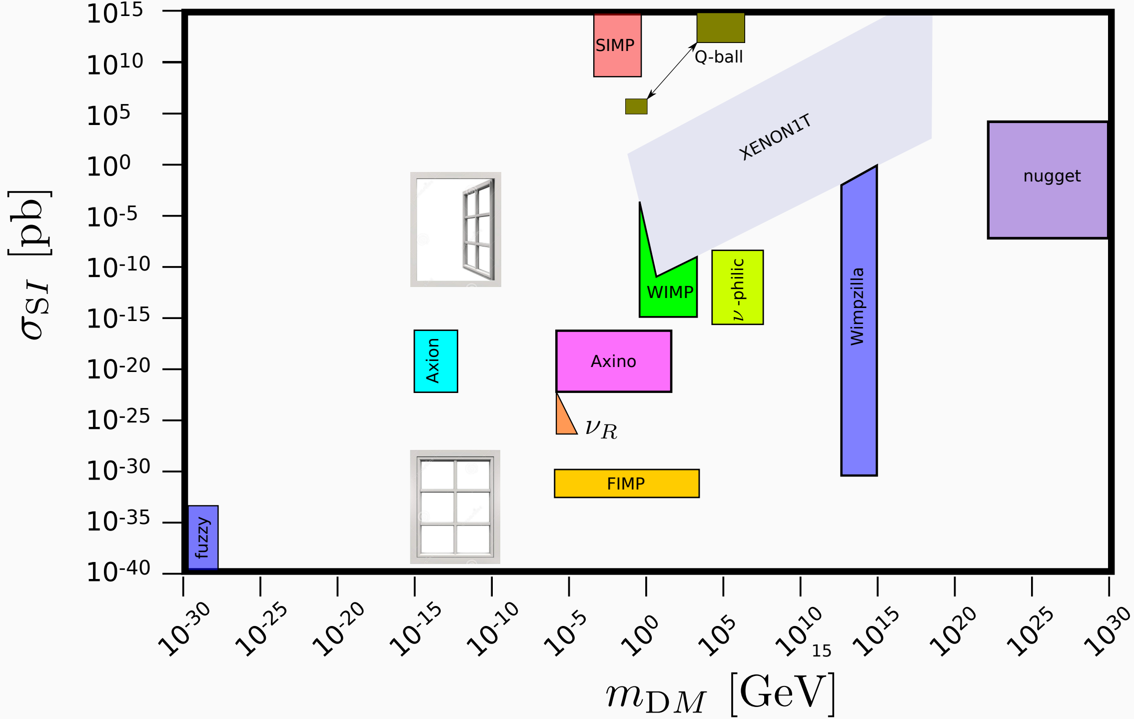

WIMP



10^{-33}
Z-portal
H-portal
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
WIMP–nucleon σ_{SI} (cm^2)
normalised
10^1
10^0
10^{-1}
10^1
10^2
10^3
WIMP mass (GeV/c^2)
PandaX-II (2017)
LUX (2017)
XENON1T (1 t × yr, this work)
10^1
10^2
10^3
WIMP mass (GeV/c^2)



σ_{SI} [pb]
m_{DM} [GeV]
SIMP
Q-ball
XENON1T
nugget
WIMP
ν -philic
Wimpzilla
Axion
Axino
ν_R
FIMP
fuzzy


σ_{SI} [pb]
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
SIMP
Q-ball
XENON1T
nugget
WIMP
ν -philic
Wimpzilla
Axion
Axino
ν_R
FIMP
fuzzy
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
15
10^{15}
10^{20}
10^{25}
10^{30}
m_{DM} [GeV]

Z_2 Singlet scalar dark matter

Minimal number of fields:

SM (even) + Real Scalar singlet (odd)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \lambda_{HS} H^\dagger H \, S^2 - {M_S}^2 \, S^2 - \lambda_S S^4 \, .$$

S is stable and a dark matter particle

WIMP

At some high temperature after reheating the scalar dark matter particle is in thermal equilibrium with the standard model plasma. With rather high yield. We need the Higgs portal interaction to exponetial decrease the abundance until the correct relic density value. Freeze-out at $M_S/T \sim 20$

See `http://bit.ly/singletscalar`

requieres $\lambda_{HS} \sim 0.1$ (weak-like annihilation cross sections)

```
[ ] %pylab inline
    import numpy as np
    from numpy import arange
    from scipy.integrate import odeint
```

```
[ ] # parameters

    Ms = 100                                        #GeV Singlet Mass
    Mp = 1.22e19                                    #GeV Planck Mass
    g = 100                                         # Degrees of freedom
    gs = 106.75                                     # Entropy degrees of freedom
    H0 = 2.133*(0.7)*1e-42                           # GeV Hubble parameter (unused)
```

Boltzmann equation

The general expresion for the thermal evolution of DM is as follows (see eq (5.26) Kolb and Turner):

$$\frac{x}{Y_{EQ}(x)}\frac{dY}{dx} = -\frac{n_{EQ}(x)\langle\sigma v\rangle}{H(x)}\left[\left(\frac{Y}{Y_{EQ}(x)}\right)^2 - 1\right],$$

donde

$$n_{EQ}(x) = 2\left(\frac{M^2}{2\pi x}\right)^{3/2} e^{-x}$$

and []see (eq 5.16) Kolb & Turner]

$$H(x) = 1.67x^{-2}g_*^{1/2}\frac{M^2}{Mp}$$

WIMP

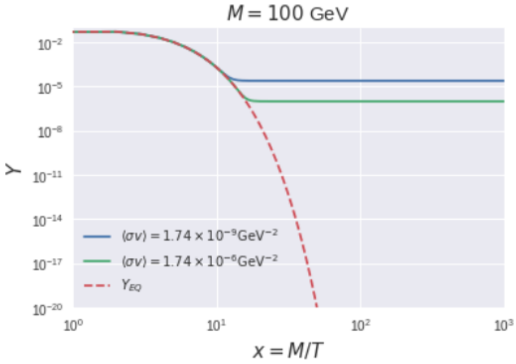
The initial condition to solve the evolution equation is $Y(x_i) = Y_{EQ}$, where $x_i = 0.01$, such that $T_i = M/x_i = 10^4$ GeV.

```
[7] def Yeq(x):
        return 0.145*(g/gs)*(x)**(3/2)*np.exp(-x)

    xi=1E-4
    xe=1000
    npts=3000
    # For several order of magnitude:
    x = np.linspace(0.01, 1000, 1000)
```

```
sigmav=[1.7475568196239999e-09,1.7475568196239999e-06]
def eqd(yl,x,Ms = 100,σv = sigmav[0]):
    '''
    Ms  [GeV]      : Singlet Mass
    σv: [1/GeV^2] : ⟨σv⟩
    '''

    Mp = 1.22e19
    g = 100                                 # Degrees of freedom
    gs = 106.75                             # Entropy degrees of freedom

    H = 1.67*g**(1/2)*Ms**2/Mp

    dyl = -2*(((Ms**2/(2*np.pi*x))**(3/2)*np.exp(-x))*σv/(x**(-2)*H*x))*(yl**2 - (0.145*(g/gs)*(x)**(3/2

    return dyl
```

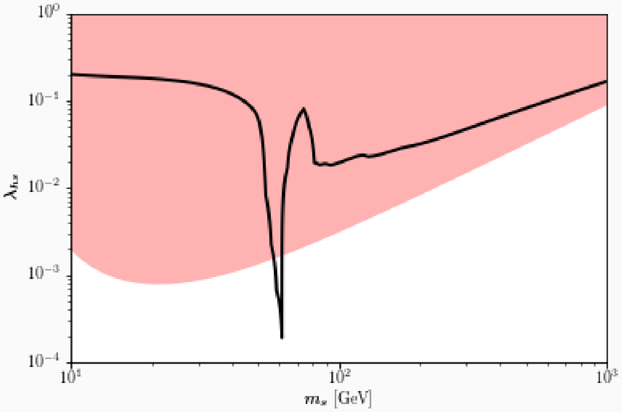
The following plot can be find in the reference book (Figure 5.1)

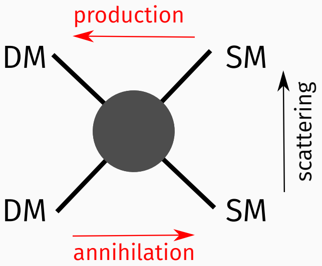
```
[10] plt.loglog(x,yl, label = r'$\langle σ v\rangle = 1.74 \times 10^{-9} {\rm GeV}^{-2}$')
     plt.loglog(x,yl1, label = r'$\langle σ v\rangle = 1.74 \times 10^{-6} {\rm GeV}^{-2}$')
     plt.loglog(x,Yeq(x), '--', label = '$Y_{EQ}$')
     plt.ylim(ymax=0.1,ymin=1e-20)
     plt.xlim(xmax=1e3,xmin=1)
     plt.xlabel('$x = M/T$', size= 15)
     plt.ylabel('$Y$', size= 15)
     plt.title('$M = 100$ GeV', size= 15)
     plt.legend(loc='best',fontsize=10)
     plt.grid(True)
```



Full wimp parameter space

Restricted by direct detection cross section Xenon1T (arXiv:1805.12562)



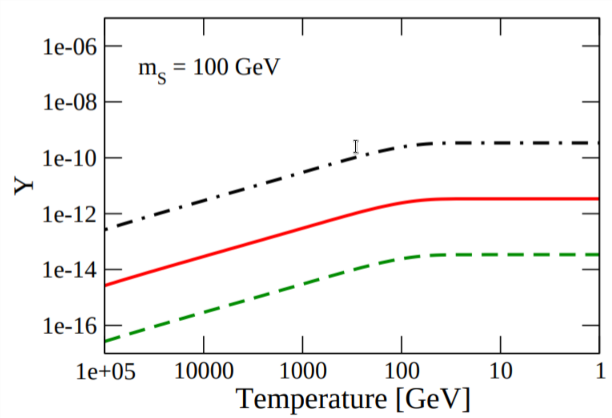


$\Omega h^2 = 0.112$


Hard To
KILL

FIMP

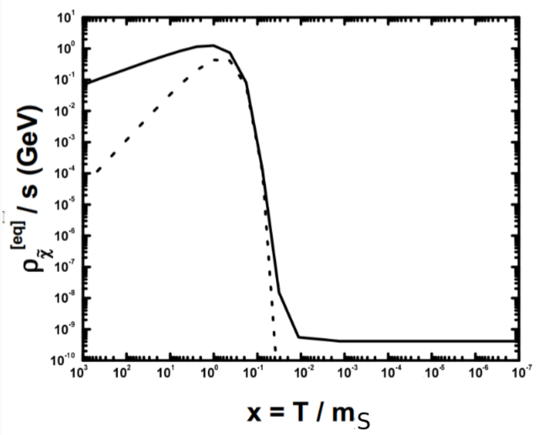
At some high temperature after reheating the abundance of scalar dark matter particle is zero. A feebly interaction allows the Higgs to produce dark matter particles until $M_S/T \sim 1$ where the freeze-in is reached. See C. Yaguna arXiv:1105.1654 [JHEP]



$\lambda_{HS} = 10^{-10}$, 10^{-11} , 10^{-12}. Not signals at all!

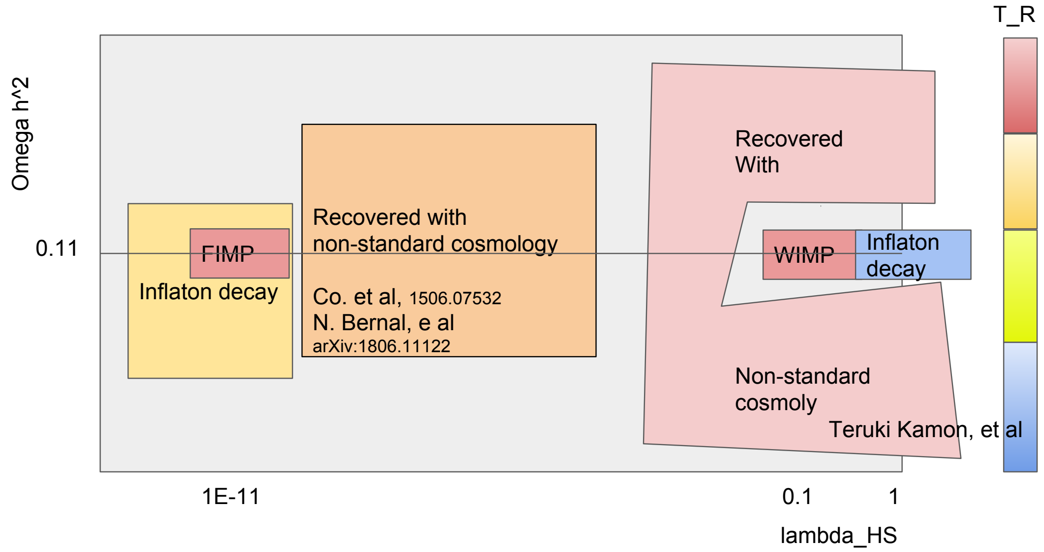
WIMP during reheating

The freeze-out occurs at $M/T_{\mathrm{RH}} \sim 10^3$. Very slow reheating for $M \sim 1TeV$- After reheating the dark matter particle not longer termalize and the freeze out is kept. See C. Pallis hep-ph/0402033 [APP]



$M_\phi = 10^6$ GeV, $M_S = 350$ GeV $T_{\mathrm{RH}} = 5$ GeV $N_S^i = 1.4 \times 10^{-7}$. λ_{HS} fixed to be compatible with direct dection constrains

Recovered parameter space



Alternative WIMP portals

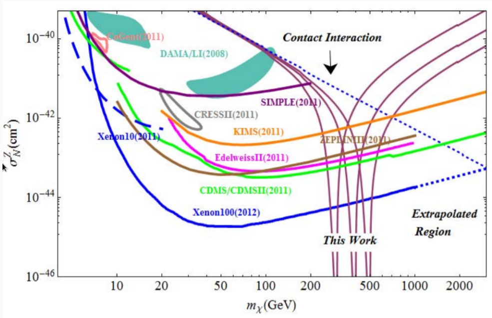
- One-loop direct cross-section
- Z'-portal (Dirac fermion dark matter)
- $\vdots$

Isosinglet dark matter candidate

ψ as a isosinglet Dirac dark matter fermion charged under a local U(1)$_X$ (SM) cuples to a SM-singlet vector mediator X as

$$\mathcal{L}_{\text{int}} = -\, g_\psi \,\overline{\psi}\gamma^\mu \psi X_\mu - \sum_f g_f \bar{f}\gamma^\mu f X_\mu \,,$$

where f are the Standard Model fermions

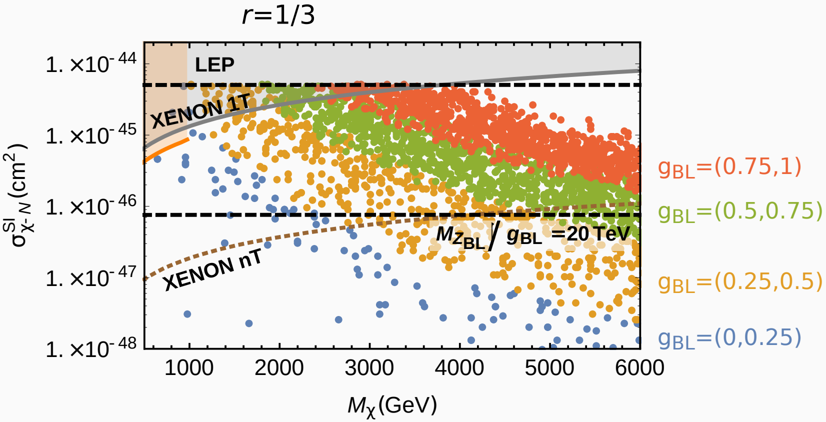


1305.7008. Chua, Hsieh

Isosinglet Dirac fermion dark matter model

Left Field	$U(1)_{B-L}$
$(\nu_{R_1})^\dagger$	$+1$
$(\nu_{R_2})^\dagger$	$+1$
$(\nu_{R_2})^\dagger$	$+1$
ψ_L	$-r$
$(\psi_R)^\dagger$	r
ϕ	2

$$\chi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

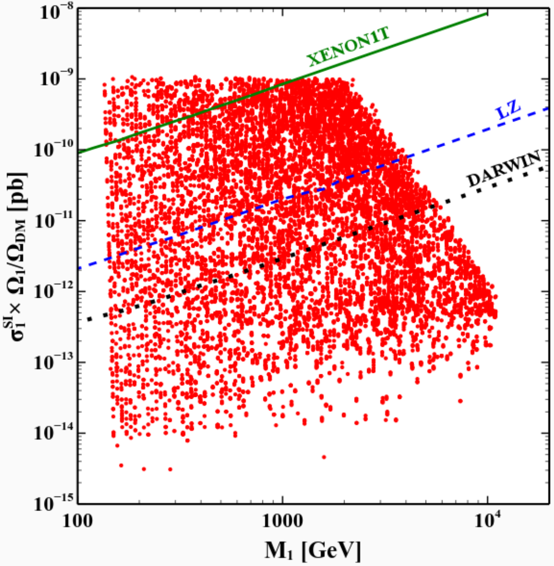


Duerr et al: 1803.07462 [PRD]

Two component Dirac fermion dark matter model

Field	$U(1)_{B-L}$
$(\nu_{R_1})^\dagger$	$+1$
$(\nu_{R_2})^\dagger$	$+1$
ξ_1	$10/7$
η_1	$4/7$
ξ_2	$-9/7$
η_2	$2/7$
ϕ_1	2
ϕ_1	1

$$U(1)_{B-L} \to Z_7 \,.$$



with N. Bernal, C. Yaguna and C. Zapata, 1808.03352

Colored Dirac fermion dark matter

Colored Dirac fermion dark matter

$SU(3)_c = 8$

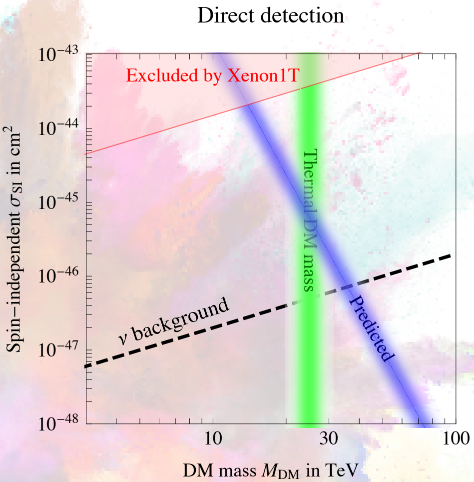
Field	$U(1)_{\mathcal{Q}}$
$\mathcal{Q}_L$	r
$(\mathcal{Q}_R)^\dagger$	$-r$

$$\mathcal{Q} = \begin{pmatrix} \mathcal{Q}_L \\ \mathcal{Q}_R \end{pmatrix}$$

$$\mathcal{L} = i\overline{\mathcal{Q}}\gamma^\mu \mathcal{D}_\mu \mathcal{Q} - M_{\mathcal{Q}}\overline{\mathcal{Q}}\mathcal{Q}\,.$$

$$\chi = |\mathcal{Q}\mathcal{Q}\rangle, \qquad \overline{\chi} = |\overline{\mathcal{Q}\mathcal{Q}}\rangle.$$

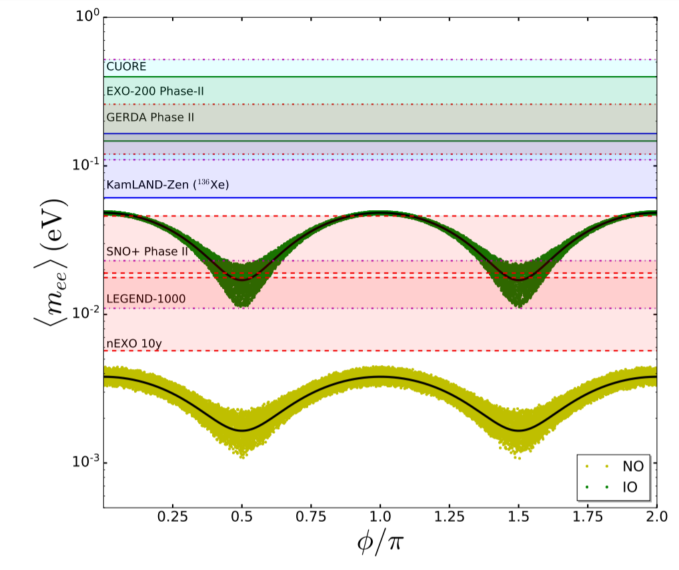
$M_{DM} \approx 2M_{\mathcal{Q}}$



V. De Luca, *et al*, 1801.01135 [PRD]]

Dirac neutrino masses

NLDBD prospects for a model with a massless neutrino (arXiv:1806.09977 with Reig, Valle and Zapata)



with M.Reig, J.W.F Valle, O. Zapata, arXiv:1806.09977

Small Dirac neutrino masses

$$\text{SM} \times \text{U}(1)_{B-L} \underbrace{\longrightarrow}_{\langle S \rangle} \text{SM} + Z_N\,.$$

- Avoids tree-level mass (TL) term ($Y(H) = +1/2$)

$$\begin{aligned}\mathcal{L}_{\text{T.L}} =& h_D \epsilon_{ab} \left(\nu_R\right)^\dagger L^a H^b + \text{h.c} \\ =& h_D \left(\nu_R\right)^\dagger L H + \text{h.c}\end{aligned}$$

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- Forbids Majorana term: $\nu_R \nu_R$

Small Dirac neutrino masses

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- Forbids Majorana term: $\nu_R \nu_R$
- Realization of the 5-D operator which conserves total lepton number in $\text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y \times \text{U}(1)_{B-L}$:

$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} \left(\nu_R\right)^\dagger LHS + \text{h.c}$$

Small Dirac neutrino masses

$$\mathrm{SM} \times \mathrm{U}(1)_{B-L} \underbrace{\longrightarrow}_{\langle S \rangle} \mathrm{SM} + Z_N \,.$$

- Avoids tree-level mass (TL) term ($Y(H) = +1/2$)

$$\begin{aligned} \mathcal{L}_{\mathrm{T.L}} =& h_D \epsilon_{ab} \left(\nu_R\right)^\dagger L^a H^b + \mathrm{h.c} \\ =& h_D \left(\nu_R\right)^\dagger L H + \mathrm{h.c} \end{aligned}$$

- Forbids Majorana term: $\nu_R \nu_R$
- Realization of the 5-D operator which conserves total lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

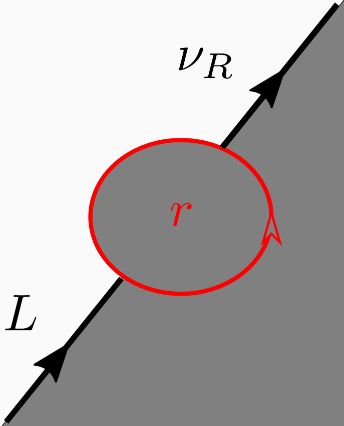
$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} \left(\nu_R\right)^\dagger L H S + \mathrm{h.c}$$

- Prediction of extra relativistic degrees of freedom N_{eff}

One-loop realization of $\mathcal{L}_{5-D}$ with total L

$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter



$$\mathrm{U}(1)_X$$

Dirac neutrino masses + Dirac fermion dark matter

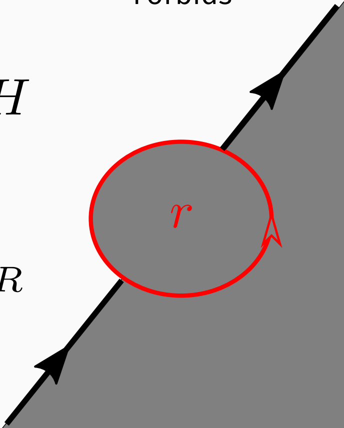
Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$



$\psi_R \psi_R$

$\psi_L \psi_L$

$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

$(\nu_R)^\dagger L H S$

$(\psi_R)^\dagger \psi_L$

$(\psi_R)^\dagger \psi_L S$

$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

$X(L) \neq 0$

$(\nu_R)^\dagger L H S$

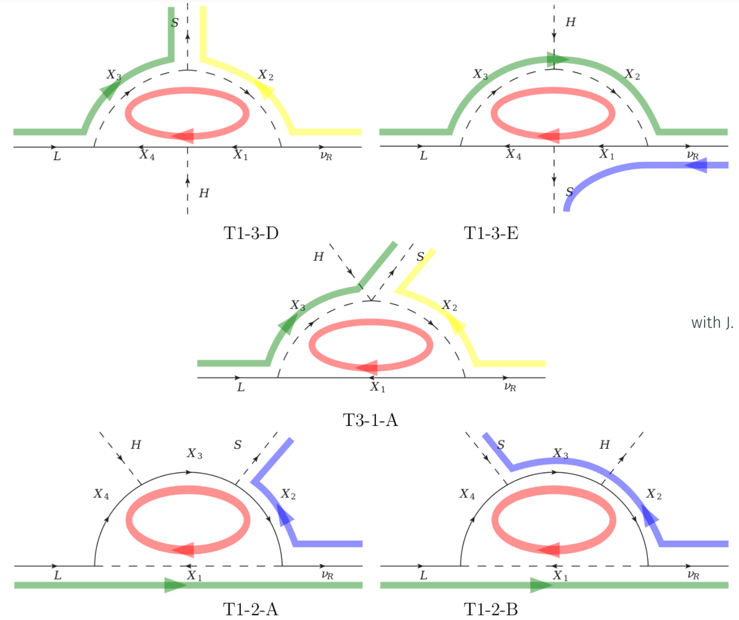
$(\psi_R)^\dagger \psi_L$

$(\psi_R)^\dagger \psi_L S$

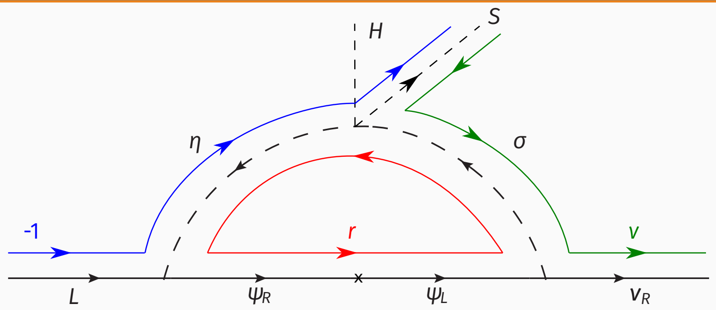
$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N$ $\quad N \neq 2$

normalized to $X(L) = -1$

One loop topologies



with J. Calle, C. Yaguna, and O. Zapata, arXiv:1811.XXXXX

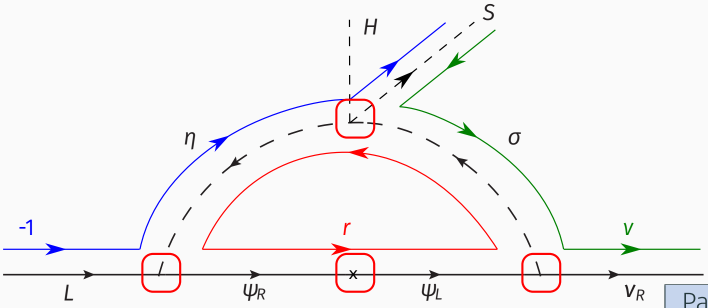


Soft breaking term induced:

$$\mathcal{L} \supset \kappa \sigma \eta^{\dagger} H \,,$$

where $\kappa = \lambda \langle S \rangle$.

Exotic $(\nu_R)^\dagger$ with $\nu \neq -1$, and vector-like Dirac fermion with $r \neq 1$



$$-1 + \eta = -r$$

$$-r = -r$$

$$-r = -\nu + \sigma$$

$$\sigma = \eta + S$$

$$N_C = 1\,.$$

Soft breaking term induced:

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where $\kappa = \lambda \langle S \rangle$.

Particles	$U(1)_{B-L}$	$(SU(3)_c, SU(2)_L)_Y$
L_i	-1	$(1,2)_{-1/2}$
H	0	$(1,2)_{1/2}$
$(\nu_{Ri})^\dagger$	ν	$(1,1)_0$
ψ_L	$-r$	$(N_c,1)_0$
$(\psi_R)^\dagger$	r	$(N_c,1)_0$
σ_a	$\nu - r$	$(N_c,1)_0$
η_a	$1 - r$	$(N_c,2)_{1/2}$
S	$\nu - 1$	$(N_c,2)_{1/2}$

Neutrino masses and mixings

- ν_i are free parameter and could be fixed if we impose $\mathrm{U}(1)_{B-L}$ to be local

$$r \neq 1 \,, \qquad \sum_i \nu_i = 3 \,, \qquad \sum_i \nu_i^3 = 3$$

	$(\nu_R)_1^\dagger$	$(\nu_R)_2^\dagger$	$(\nu_R)_3^\dagger$
$\mathrm{U}(1)_{B-L}$	$+4$	$+4$	-5
$\mathrm{U}(1)_{B-L}$	-6	$+\frac{10}{3}$	$+\frac{17}{3}$

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  - At least two heavy Dirac fermions Ψ_a, $a = 1, 2, \ldots$
  - At least two sets of scalars η_a, σ_a

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$$\mathcal{L} \supset \left[M_\Psi\, (\psi_R)^\dagger\, \psi_L + h_i^a\, (\psi_R)^\dagger\, \widetilde{\eta}_a^\dagger L_i + y_i^a \overline{\nu_{Ri}}\, \sigma_a^* \psi_L + \text{h.c} \right] + \kappa^{ab}\, \sigma_a \eta_b^\dagger H + \ldots$$

Neutrino masses and mixings (with M.Reig, J.W.F Valle, O. Zapata, arXiv:1806.09977)

$$(\mathcal{M}_\nu)_{ij} = N_c \frac{M_\Psi}{64\pi^2} \sum_{a=1}^{2} h_i^a y_j^a \frac{\sqrt{2}\kappa_{aa} v}{m^2_{S^a_{2R}} - m^2_{S^a_{1R}}} \left[F\left(\frac{m^2_{S^a_{2R}}}{M^2_\Psi} \right) - F\left(\frac{m^2_{S^a_{1R}}}{M^2_\Psi} \right) \right] + (R \to I) \qquad (1)$$

where $F(m^2_{S_\beta}/M^2_\Psi) = m^2_{S_\beta} \log(m^2_{S_\beta}/M^2_\Psi)/(m^2_{S_\beta} - M^2_\Psi)$. The four CP-even mass eigenstates are denoted as $S^1_{1R}, S^1_{2R}, S^2_{1R}, S^2_{2R}$, with a similar notation for the CP-odd ones.

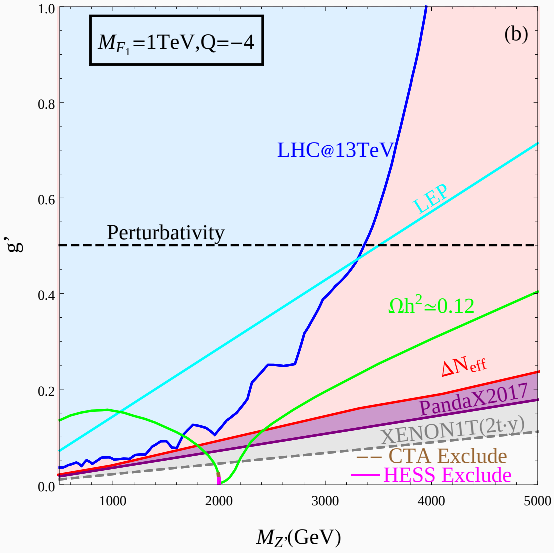
T3-1-A with only $U(1)_{B-L}$

Field	$U(1)_{B-L}$
$(\nu_{R_i})^\dagger$	$+4$
$(\nu_{R_j})^\dagger$	$+4$
$(\nu_{R_k})^\dagger$	-5
ψ_L	$-r$
$(\psi_R)^\dagger$	r
η_a	$r-4$
σ_a	$r-1$
S	-3

$a = 1, 2$, $i \neq j \neq k$.

$m = 0$: ν_{L_k}, and $\nu_{R_k} \to N_{\text{eff}}$

$$F_1 = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$



Extra Z_2: Han, Wang, 1808.03352 [EJPC]

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ψ_L	$-r$
$(\psi_R)^\dagger$	r
η_a	$r-4$
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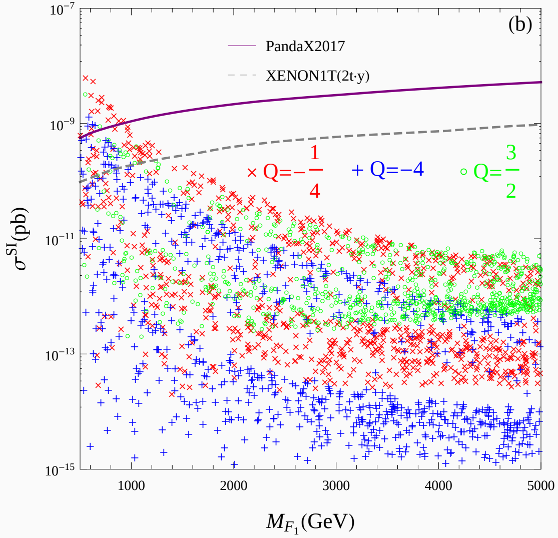

Extra Z_2: Han, Wang, 1808.03352 [EJPC]

Conclusions

Only gravitational evidence of dark matter so far which is fully compatible with the ΛCDM-paradigm without simulation problems (~~cups vs core~~, ~~etc~~)

Not convincing signal at all

- ~~Galatic center excess~~
- ~~KeV lines~~
- ~~Positron excess~~
- ~~DAMA oscillation signal~~

Direct detection and LHC null results suggest to look

- Other (CDM) windows (Axion, FIMP, SIMP, . . .)
- Non-standard cosmology
- Other portals . . .

Z'-portal: A single $U(1)$ symmetry to explain both the smallnes of Dirac neutrino masses and the stability of Dirac fermion dark matter

Thanks!