Dark Matter Across the Scales

based on : 1607.04278,1705.09455, 1710.02146
in collaboration with Joachim Kopp, Jia Liu and Xiao-Ping Wang

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Outline

- DM in Galaxy clusters (Perseus...) and Galaxies (M31, MW)

  DM candidate : keV-scale fermion (one may refer to it as “sterile neutrino”)

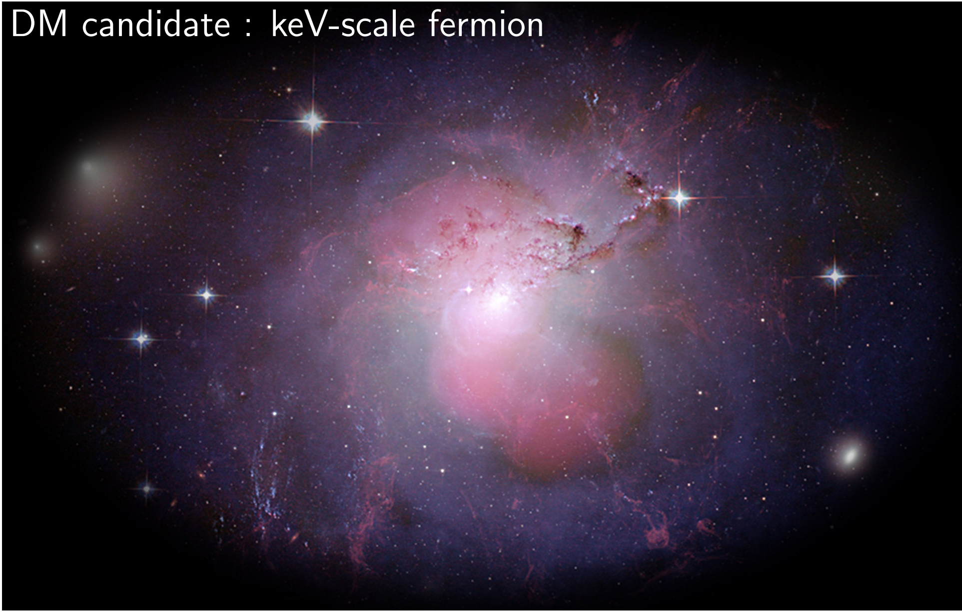
- DM in Galactic Supernovae

  DM candidate : WIMP

- DM at Earth

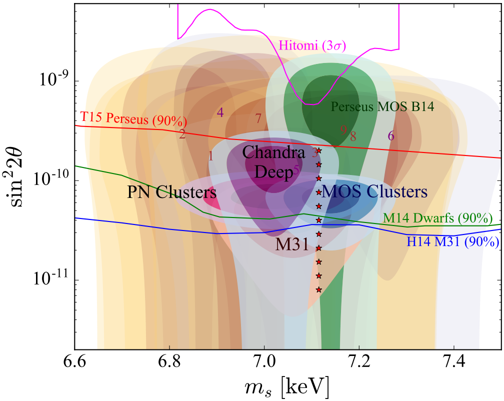
  DM candidate : Ultralight “Fuzzy” DM

DM candidate : keV-scale fermion

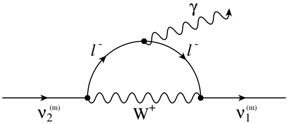


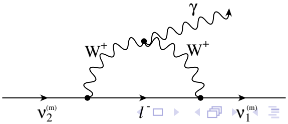
keV-scale sterile neutrino (decaying DM)

K. Abazajian, arXiv:1705.01837



- keV DM proposed originally in hep-ph/9303287 by Dodelson and Widrow
- revival in 2014
- stacked clusters (Bulbul et al. 1402.2301), Perseus and M31 (Boyarski et al. 1402.4119)
- (Cappelluti et al., 1701.07932) – Deep Field search using Chandra satellite





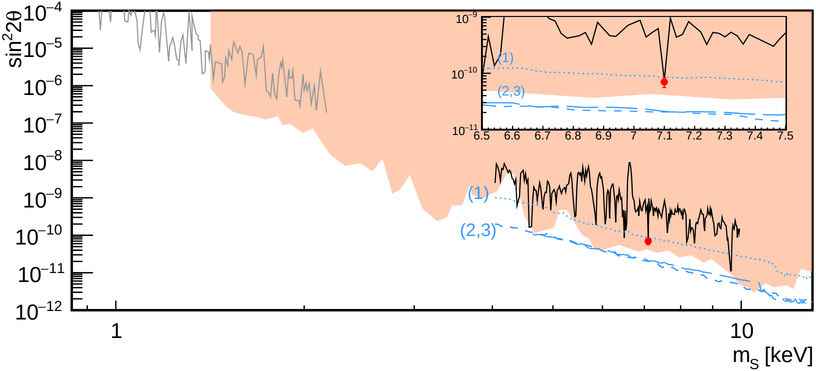
Dark Matter or atomic physics?

- Jeltema, Profumo : "Dark matter searches going bananas" – Potassium contribution
- "Hitomi constraints from Perseus" (1607.07420)

  "We do not find anomalously high fluxes of the nearby faint K line or the Ar satellite line that were proposed as explanations for the earlier 3.5 keV detections."
- x-rays from charge exchange : *"Laboratory measurements compellingly support charge-exchange mechanism for the 'dark matter' 3.5 keV X-ray line"* (1608.04751)
- from Cappelluti et al.
  "According to these measurements and atomic calculations, we can conclude that, at $> 3\sigma$ confidence level, the totality of the 3.5 keV line flux is not produced by charge exchange"

Final answer coming soon?

- Micro-X: A Sounding Rocket Dark Matter Search (1506.05519)



  - 3 eV energy resolution (comparable to Hitomi)
  - launch in 2019

Return of the X-rays: A New Hope for Fermionic Dark Matter at the keV Scale

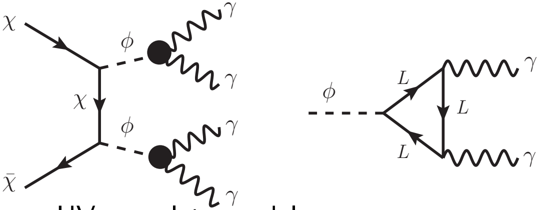
(VB, J. Kopp, J.Liu, X-P Wang 1710.02146)

May the Force Be With DM Annihilation (rather than Decay)

Model and BSM Particle Content

- keV-scale fermion χ and keV scale real scalar ϕ
- effective Lagrangian :

$$\mathcal{L}_{\text{eff}} \supset \frac{\alpha}{4\pi\Lambda} F_{\mu\nu}F^{\mu\nu}\phi + y\phi\bar{\chi}\chi$$



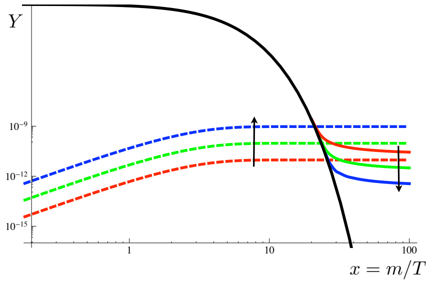
- UV complete model:

$$\mathcal{L} \supset \bar{L} i \not{D} L - m_L \bar{L} L + y\phi\bar{\chi}\chi + g\phi\bar{L}L$$

$$\frac{1}{\Lambda} = \frac{4 g m_L}{\mu^2} f(4m_L^2/\mu^2) \qquad f(\tau) = \begin{cases} 1 - (\tau - 1)(\csc^{-1}\sqrt{\tau})^2) & \tau \geqslant 1 \\ 1 + \frac{\tau - 1}{4}\left[\log\left[\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right] - i\pi\right]^2 & \tau < 1 \end{cases}$$

DM Production

- Freeze-in (Hall et al. 0911.1120)



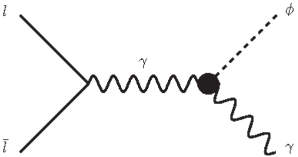
$$\frac{dY}{dT} = -\frac{1}{512\pi^6 H(T)\, S(T)} \int_0^\infty ds\, d\Omega\, P_{\mathrm{AB}} P_{CD}$$

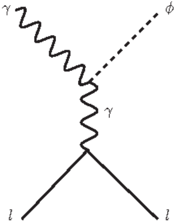
$$\times \frac{\overline{|\mathcal{M}|^2}_{AB\to CD}}{\sqrt{s}} K_1(\sqrt{s}/T)$$

UV freeze-in

- valid in regime $T_{RH} < M_L$
- freeze-in of ϕ followed by a decay to $\chi\bar{\chi}$ $(m_\phi(T) = m_\phi^2 + \lambda T^2)$

  $\mathcal{L}_{\rm eff} \supset \frac{\alpha}{4\pi\Lambda} F_{\mu\nu} F^{\mu\nu} \phi + y \phi \bar{\chi} \chi$





$$Y_{\rm UV} \simeq \frac{20\,400\,\alpha^3\, M_{\rm Pl}\, T_{\rm RH}}{16 \cdot 1.66 \cdot \pi^8 [g_*(T_{\rm RH})]^{3/2} \Lambda^2}$$

$$\Omega h^2\big|_{\rm UV} \simeq 105.31 \times \left(\frac{\rm PeV}{\Lambda}\right)^2 \left(\frac{T_{\rm RH}}{\rm TeV}\right) \left(\frac{100}{g_*(T_{\rm RH})}\right)^{\frac{3}{2}} \left(\frac{m_\chi}{\rm keV}\right)$$

Alternative Production Mechanisms

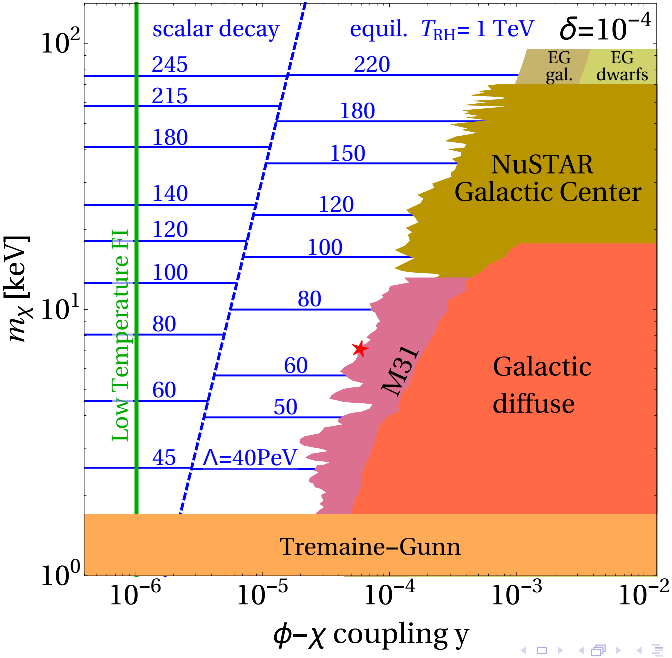
- Low energy Freeze-in valid in regime $T_{RH} > M_L$

$$\Omega h^2 \simeq \begin{cases} 0.1 \times \left(\frac{y}{10^{-6}}\right)^2 \left(\frac{\lambda}{10^{-8}}\right)^{\frac{3}{2}} & (\text{FI via } \phi \to \bar{\chi}\chi) \\ 0.094 \times \left(\frac{y}{10^{-6}}\right)^4 & (\text{FI via } \phi\phi \leftrightarrow \bar{\chi}\chi) \end{cases}$$

- ϕ is thermalized
- N_{eff} constraint from BBN is not violated as the dark sector has been sufficiently diluted by entropy production in the SM sector

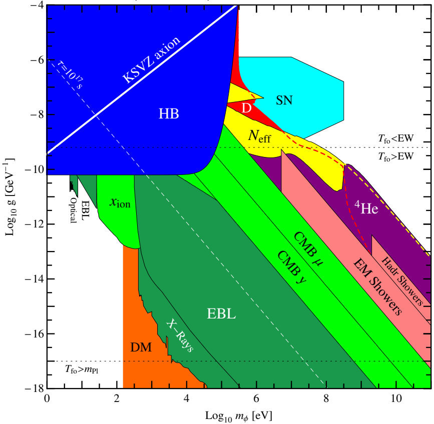
Misalignment mechanism

- after ϕ and χ come into thermal contact, and a fraction of the ϕ energy density is transferred to χ
- very cold DM

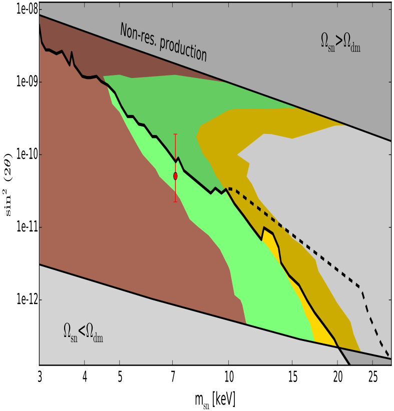

scalar decay
equil. T_{RH}= 1 TeV
$\delta=10^{-4}$
245
215
180
140
120
100
80
60
45
220
180
150
120
100
80
60
50
Λ=40PeV
Low Temperature FI
EG gal.
EG dwarfs
NuSTAR Galactic Center
M31
Galactic diffuse
Tremaine–Gunn
m_χ [keV]
10^0
10^1
10^2
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
$\phi-\chi$ coupling y

Limits on scalar coupling to EM and structure formation

Cadamuro, Redondo, arXiv:1110.2895



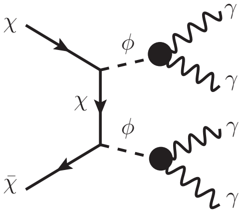
Schneider, arXiv:1601.07553

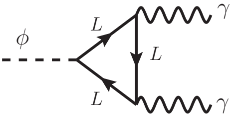


- for freeze-in scenarios, when ϕ and χ come in the thermal contact, new dominant channel for scalar decay required in order to avoid CMB limit
- $L\bar{L} \to \chi\bar{\chi}$ production is disfavored by HB constraints
- effective temperature of the dark sector is reduced by an entropy dilution factor (sizable quartic coupling helps)

DM Annihilation

- the cross section for the DM annihilation process ($\bar{\chi}\chi \to \phi\phi$) depends on the ratio between the relative mass difference $\delta \equiv (m_\chi - m_\phi)/m_\chi$ of χ and ϕ, and the relative velocity $v_{\rm rel}$ of the annihilating DM particles



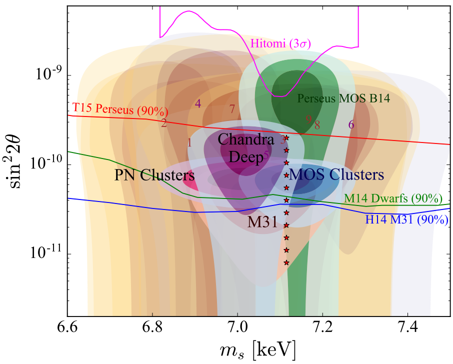


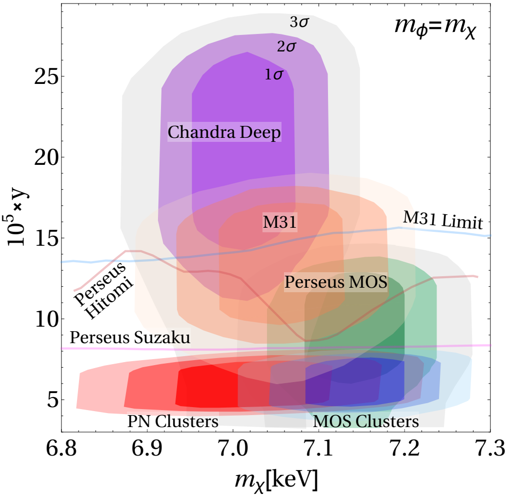
$$|\delta| \ll v_{\rm rel}^2, \quad \sigma_{\rm ann} v_{\rm rel} = \frac{y^4 v_{\rm rel}^3}{16\pi m_\chi^2} \qquad \delta \gg v_{\rm rel}^2, \quad \sigma_{\rm ann} v_{\rm rel} = \frac{\sqrt{\delta}(2\delta(\delta+2)+3)\, y^4 v_{\rm rel}^2}{24\pi(1+\delta)^4\, m_\chi^2}$$

Converting existing limits from decaying DM :

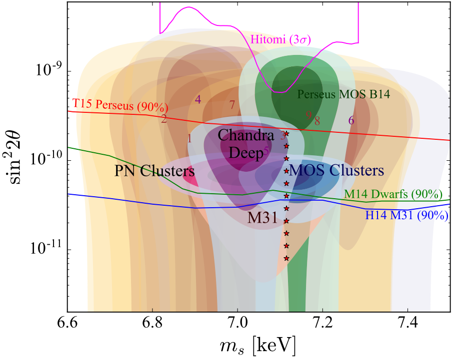
$$\frac{\Gamma_\chi}{4\pi m_\chi} \int dl\, d\Omega\, \rho_{\rm DM}(l,\Omega) = \frac{4}{16\pi m_\chi^2} \int dl\, d\Omega\, d^3 v_{\rm rel}\, \rho_{\rm DM}^2(l,\Omega)\, \sigma_{\rm ann} v_{\rm rel}\, f(l,\Omega,v_{\rm rel})$$

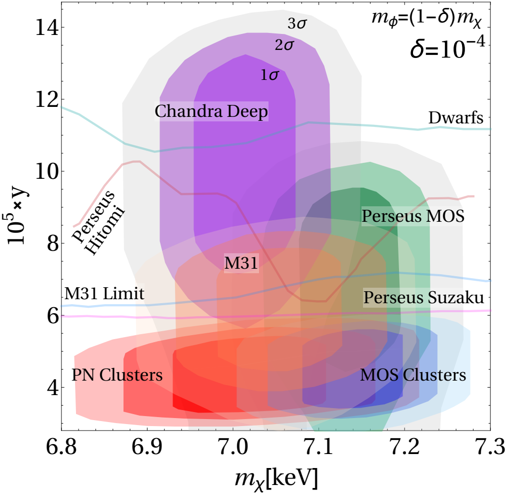
degenerate χ and ϕ masses



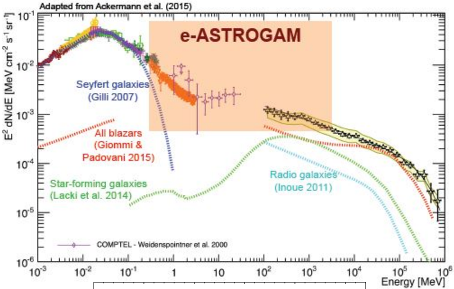


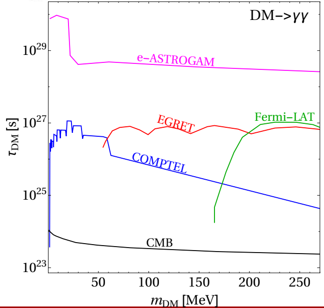
quasidegenerate χ and ϕ masses



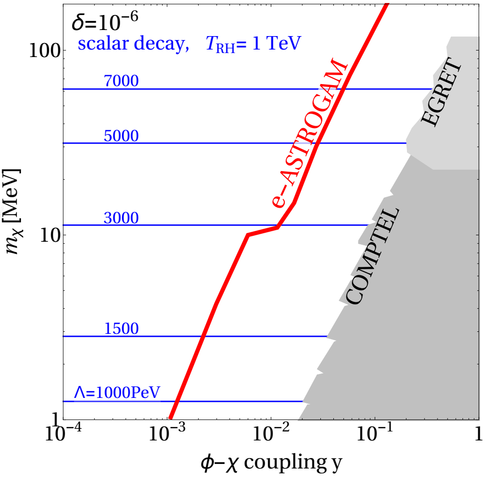


Non-thermally Produced Dark Matter at the MeV scale

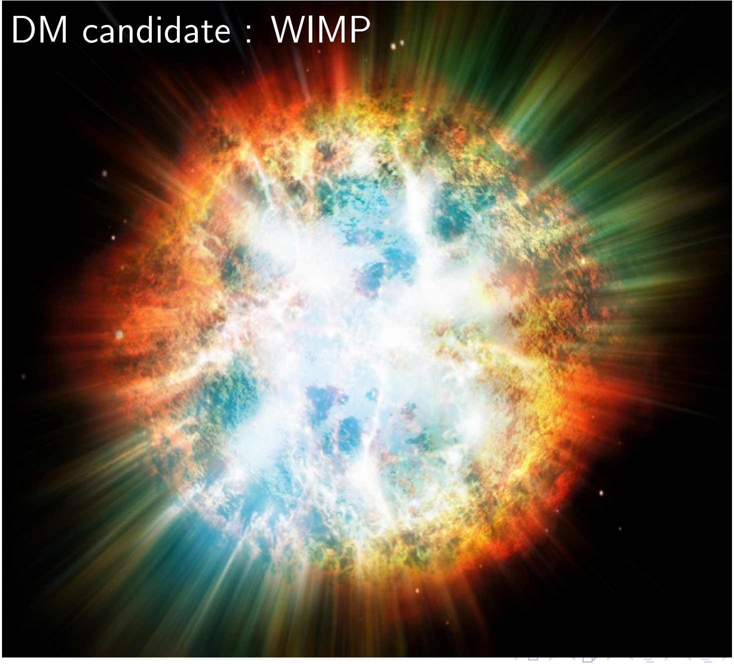

Adapted from Ackermann et al. (2015)



White paper on e-ASTROGAM 1710.xxxxx



DM candidate : WIMP



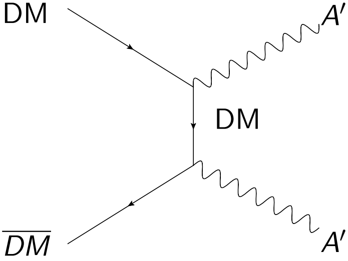
DM annihilation in the Sun

Capture and Annihilation $(dN/dt = C_{cap} - C_{ann} N^2)$

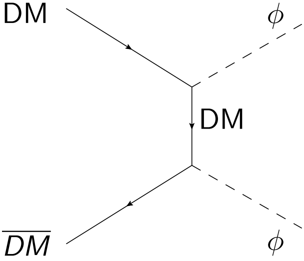
1. Conditions:
    - $C_{ann}^{\rm Sun} \equiv \frac{1}{N^2} \int d^3r \, \langle \sigma v_{\rm rel} \rangle \, n_{\rm DM}^2(r) \sim 10^{-53} s^{-1}$
    - $C_{cap} = \sum_i \int_0^{R_{\rm star}} dr \, 4\pi r^2 \, \frac{dC_i(r)}{dV} \sim 10^{22} s^{-1}$
    - parameters: $m_{DM} = 100 \, GeV$, $\sigma_{SD}^H = 10^{-40} cm^2$ and $\langle \sigma v_{\rm rel} \rangle = 3 \times 10^{-26} cm^3 s^{-1}$
2. Results:
    - $N(t) = \sqrt{\frac{C_{cap}}{C_{ann}}} \tanh \frac{t}{t_{eq}} \rightarrow \sqrt{\frac{C_{cap}}{C_{ann}}} \sim 10^{37}$
    - $t_{eq} \equiv 1/\sqrt{C_{cap} C_{ann}} \sim 10^{15} s$, $t_{Sun} = 10^{17} s$
    - $C_{ann} N^2 = C_{cap} = 10^{22} s^{-1}$
3. Conclusion: **For the case of the Sun, there is an equilibrium!**

BSM particle content

- fermionic (Dirac) DM $\sim$ (1,1,0)
- $\sim \mathcal{O}(1)$ GeV dark photon or scalar coupling to
    - DM
    - SM via kinetic mixing (vector) or higgs portal (scalar)

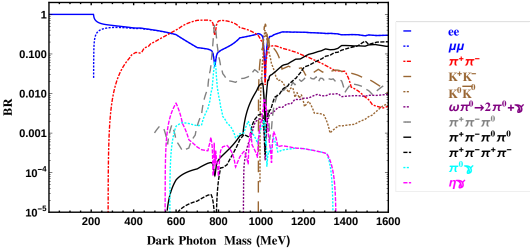


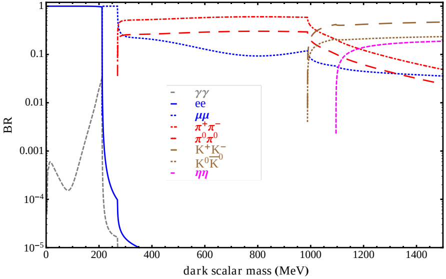
s-wave



p-wave

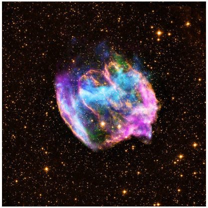
Decay modes of dark mediators





Liu,Weiner, Xue, arXiv:1412.1485

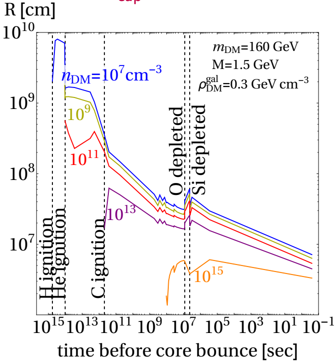
Supernova progenitors versus the Sun

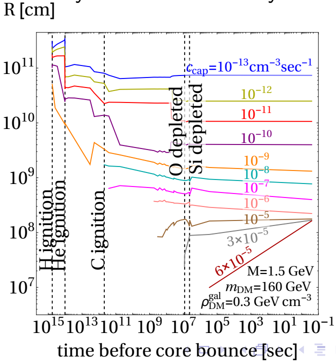


- $\mathcal{O}(10^8)$ further than the Sun, $\sim 1kpc$
- much heavier than the Sun, $\gtrsim 8M_{Sun}$
- $\mathcal{O}(10^{-2})$ shorter lifetime $\sim 10^{15}s$
- density, temperature and chemical composition change in time much faster
- End up with a core collapse Supernova
- Peak annihilation rate (dark gamma ray burst coincident with the supernova) $\mathcal{O}(10^{12})$ larger than the Sun!
- Capture and Annihilation *Not* in Equilibrium!

Capture Rates and DM Distribution in the Star

- $\rho_i(r,t), T(r,t)$ and chemical composition from Heger *et al.*
- $m_{DM} \in [10, 10^3]$ GeV, $\sigma^{SD} = 10^{-40} cm^2$, $\sigma^{SI} = 10^{-46} cm^2$
- DM core contracts along with the baryonic matter
- Quasi-instantaneous thermalization ($n_{\rm DM}(r) = n_0 \exp[-m_{\rm DM}\phi(r)/T_{\rm DM}]$)
- Large $C_{\rm cap}$ at early times due to large σ_{SD} on H
- $C_{\rm cap}$ at later time dominated by H in the outer layers and ^{14}N

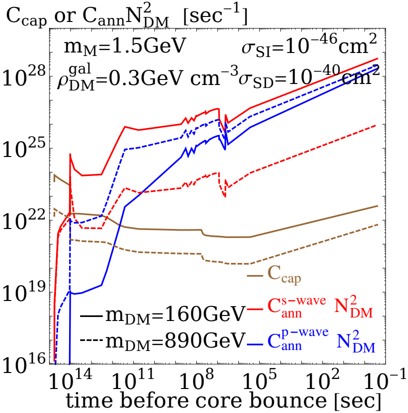


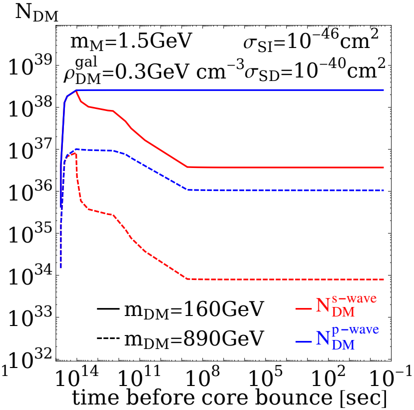


Capture and Annihilation Rates

$$\dot{N}_{\rm DM}(t) = C_{\rm cap}(t) - C_{\rm ann}(t) N_{\rm DM}(t)^2 + C_{\rm self}(t) N_{\rm DM}(t)$$

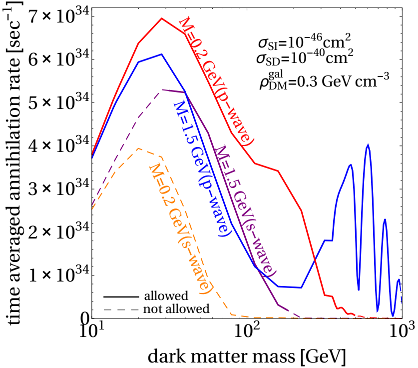
$$C_{\rm cap} = \sum_i \int_0^{R_{\rm star}} dr\, 4\pi r^2 \frac{dC_i(r)}{dV} \qquad C_{\rm ann} N_{\rm DM}^2 \equiv \int d^3r\, \langle \sigma v_{\rm rel} \rangle\, n_{\rm DM}^2(r)$$

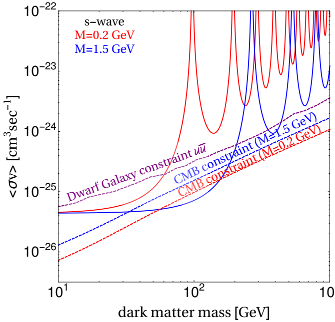




DM Annihilation Burst during Supernova cooling phase

- density and temperature fixed to $10^{14}\ \mathrm{g\,cm}^{-3}$ and 3 MeV
- DM particles within $R_{core} \sim 30km$ (size of proto-neutron star)
- DM gets thermalized within $\sim 10^{-6}$ seconds
- $N_{\mathrm{DM}}(t) = \frac{N_0}{1+t\, C_{\mathrm{ann}}^{SN} N_0}$ $\quad \Delta t_{dur} \sim (C_{\mathrm{ann}}^{SN} N_0)^{-1}$ $\quad C_{\mathrm{ann}}^{SN} = \langle \sigma v_{\mathrm{rel}} \rangle \left(\frac{G_N m_{\mathrm{DM}} \rho_{\mathrm{SN}}}{3 T_{\mathrm{SN}}} \right)^{3/2}$

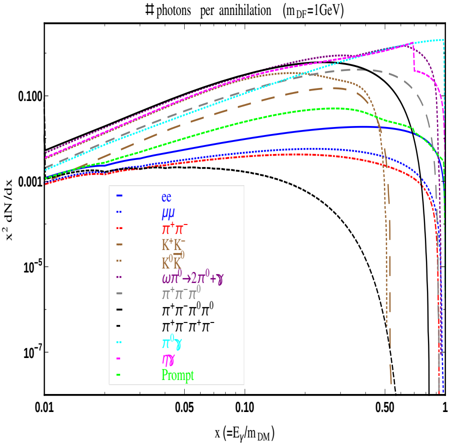




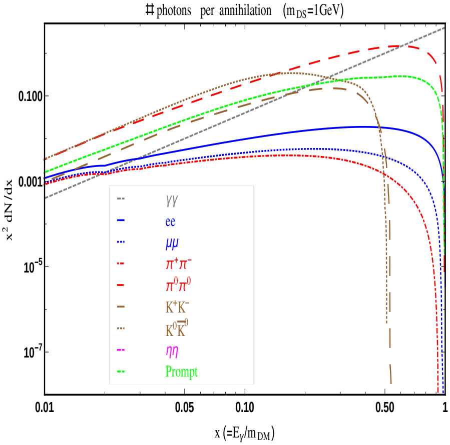
Photon Spectrum

Liu,Weiner, Xue, arXiv:1412.1485

dN/dx for dark photon



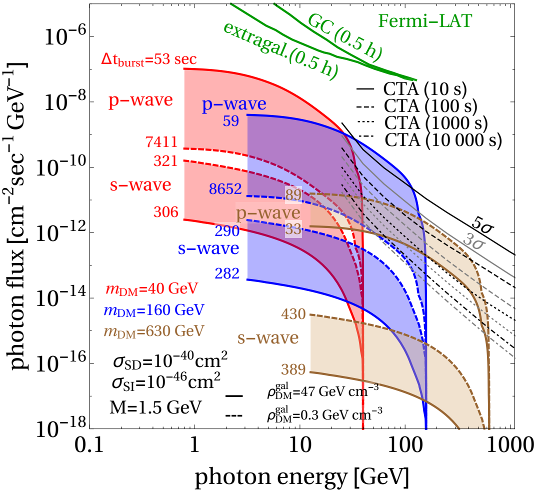
dN/dx for dark scalar



Dark Gamma Ray Burst

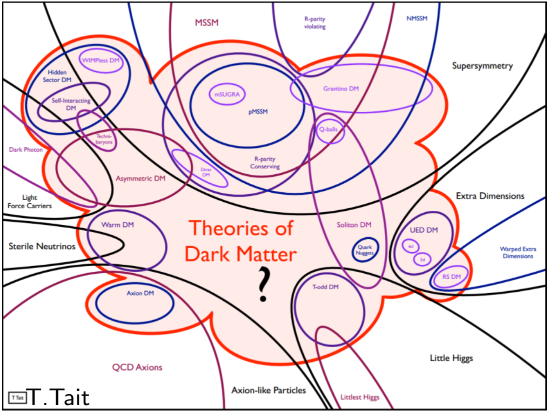
Properties

- An observable gamma ray signal after ν arrival
- $\Delta t_{burst} = (C_{\mathrm{ann}}^{SN} N_0)^{-1}$ related to sensitivity
- $\Delta t_{burst} \in [\mathcal{O}(10), \mathcal{O}(10^3)]$ sec for p-wave, $\mathcal{O}(10^2)$ sec for s-wave
- Benchmark locations: 0.1*kpc* and 8*kpc* from GC



DM candidate : Ultralight DM

Dark Matter - vast number of candidates



T.Tait

- fuzzy DM with mass $\mathcal{O}(10^{-22})\,\mathrm{eV}$
- we consider both scalar and vector ultralight DM

Properties of Fuzzy DM candidate

Fuzzy DM can address:

- “core vs. cusp problem”– DM density profile discrepancy between measurements and simulations

→ DM delocalization
(huge Compton wave length $\lambda = 2\pi/m_\phi \simeq 0.4\,\mathrm{pc} \times (10^{-22}\mathrm{eV}/m_\phi)$)

- “missing satellites problem”–lower than expected abundance of dwarf galaxies

→ higher probability for tidal disruption of DM subhalos and suppression of the matter power spectrum at small scales (Hui et al. 1610.08297)

- “too big to fail problem”– apparent failure of many of the most massive Milky Way subhalos to host visible dwarf galaxies

→ Fuzzy DM predicts fewer such subhalos (Marsh et al. 1307.1705)

- admittedly, better treatment of baryonic physics in simulations (1602.05957,1202.0554) may solve these puzzles but the possibility that DM physics plays a crucial role is not excluded

DM production

Arias et al. 1201.5902
Nelson & Scholtz 1105.2812
Golovnev et al. 0802.2068

Misalignment mechanism

- EOM for real scalar field ϕ

$$\ddot{\phi} + 3\,H\,\dot{\phi} + m_\phi^2 \phi = 0.$$

- while $3\,H \gg m_\phi$, ϕ is “frozen”
- at $3\,H = m_\phi$ damping term stops dominating and the field can start to oscillate
- for vector DM ϕ^μ one introduces coupling to gravity $\sim R\phi_\mu\phi^\mu$
- The mass of ϕ^μ can be generated either through the Stückelberg mechanism or from spontaneous symmetry breaking in a dark Higgs sector
- we consider both polarized and unpolarized vector DM (polarization may be altered during structure formation)

Model

Relevant part of the Lagrangian:

Scalar $$\mathcal{L}_{\text{scalar}} = \bar{\nu}_L^\alpha i\partial\!\!\!/ \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta - \frac{1}{2} y^{\alpha\beta} \phi \, \overline{(\nu_L^c)^\alpha} \nu_L^\beta .$$

The interaction term can be generated in a gauge invariant way by coupling ϕ to heavy right-handed neutrinos N_R (introduced in seesaw type-I)

- we assume $y = y_0(m_\nu/0.1\text{eV})$

Vector $$\mathcal{L}_{\text{vector}} = \bar{\nu}_L^\alpha i\partial\!\!\!/ \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta + g Q^{\alpha\beta} \phi^\mu \bar{\nu}_L^\alpha \gamma_\mu \nu_L^\beta \, .$$

- ϕ^μ as the $L_\mu - L_\tau$ symmetry gauge boson with couplings $Q^{\alpha\beta} = \text{diag}(0, 1, -1)$
- if $L_\mu - L_\tau$ breaking occurs at TeV scale, with $m_\phi \sim 10^{-22}$ eV we require coupling $g \sim 10^{-30}$ which can be probed

Model II

- alternatively, ϕ^μ could couple to the SM via mixing with a much heavier $L_\mu - L_\tau$ gauge boson K^μ (term $\epsilon\phi^{\mu\nu}K_{\mu\nu}$)

$$\mathcal{L}_{\mu-\tau} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \bar{L}^\alpha\left(i\partial\!\!\!/ + g_{\mu-\tau}Q^\alpha_{\mu-\tau}\gamma_\mu K^\mu\right)L^\alpha + \bar{e}^\alpha_R\left(i\partial\!\!\!/ + g_{\mu-\tau}Q^\alpha_{\mu-\tau}\gamma_\mu K^\mu\right)e^\alpha_R$$

$$+ (D^\mu S)^\dagger(D_\mu S) + \mu_S^2 S^\dagger S - \lambda_S(S^\dagger S)^2$$

$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}\epsilon\phi_{\mu\nu}K^{\mu\nu} + \frac{1}{2}\left(\partial_\mu\sigma + m_1\phi_\mu + m_2K_\mu\right)^2$$

kinetic and mass term in matrix form : $V = (\phi, K)^T$

$$\mathcal{L} \supset -\frac{1}{4}V^T_{\mu\nu}\begin{pmatrix}1 & -\epsilon\\ -\epsilon & 1\end{pmatrix}V^{\mu\nu} + \frac{1}{2}V^T_\mu\begin{pmatrix}m_1^2 & m_1m_2\\ m_1m_2 & m_2^2 + (g_{\mu-\tau}v_S)^2\end{pmatrix}V^\mu$$

after two unitary transformations

$$\begin{pmatrix}\phi\\ K\end{pmatrix} = U\begin{pmatrix}\tilde{\phi}\\ \tilde{K}\end{pmatrix} \equiv U_1U_2\begin{pmatrix}\tilde{\phi}\\ \tilde{K}\end{pmatrix}$$

we identify gauge boson masses and the effective coupling $\quad y_1 = \frac{m_i}{g_{\mu-\tau}v_s}$

$$\mathcal{L}_{\text{int}} = \left(-\frac{y_1^2\epsilon}{1-y_1^2} - \frac{y_1y_2}{1-y_1^2}\right)g_{\mu-\tau}Q^\alpha_{\mu-\tau}\tilde{\phi}^\mu\left(\bar{L}^\alpha\gamma_\mu L^\alpha + \bar{e}^\alpha_R\gamma_\mu e^\alpha_R\right)$$

Neutrino Masses

Heeck,Rodejohann 1107.5238

- neutrino masses are generated by introducing 3 RH neutrinos with the following charges under $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{L_\mu - L_\tau}$

$$N_1 \sim (1,1,0)(0), \quad N_2 \sim (1,1,0)(+1), \quad N_3 \sim (1,1,0)(-1)$$

$$\mathcal{L}_{yuk} = \frac{1}{2} a \bar{N}_1^c N_1 + \frac{1}{2} b \left(\bar{N}_2^c N_3 + \bar{N}_3^c N_2 \right) + \lambda_e \bar{L}_e \tilde{H} N_1 + \lambda_\mu \bar{L}_\mu \tilde{H} N_2 + \lambda_\tau \bar{L}_\tau \tilde{H} N_3 + h.c. + \lambda_S^{12} \bar{N}_1^c N_2 S + \lambda_S^{13} \bar{N}_1^c N_3 S^\star + h.c.$$

$$m_D = \begin{pmatrix} m_{\nu_e} & 0 & 0 \\ 0 & m_{\nu_\mu} & 0 \\ 0 & 0 & m_{\nu_\tau} \end{pmatrix}, \quad m_R = \begin{pmatrix} a & s & t \\ s & 0 & b \\ t & b & 0 \end{pmatrix},$$

$m_{\nu_j} \equiv \lambda_i v/\sqrt{2}$, $s \equiv \lambda_S^{12} v_X$ and $t \equiv \lambda_S^{13} v_X$.

$$m_\nu \simeq -m_D \cdot m_R^{-1} \cdot m_D \,.$$

MSW Potential

- Coherent Forward Scattering of Neutrinos on Fuzzy DM
- scalar DM

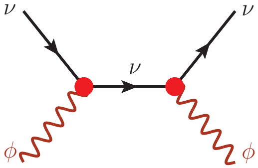
L. Wolfenstein, Phys.Rev. D17 (1978)
S. P. Mikheev and A. Yu. Smirnov, Sov. J. Nucl. Phys. 42 (1985)

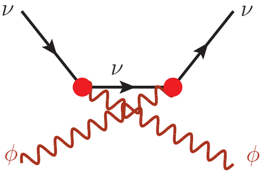
$$V_{\text{eff}} = \frac{1}{2E_\nu}\left(\phi\,(y\,m_\nu + m_\nu\,y) + \phi^2 y^2\right), \qquad \phi = \frac{\sqrt{2\rho_\phi}}{m_\phi}\cos(m_\phi t)\ ,$$

- vector DM

$$V_{\text{eff}} = -\frac{1}{2E_\nu}\left(2(p_\nu \cdot \phi) g Q + g^2 Q^2 \phi^2\right). \qquad \phi^\mu = \frac{\sqrt{2\rho_\phi}}{m_\phi}\xi^\mu \cos(m_\phi t)\,.$$

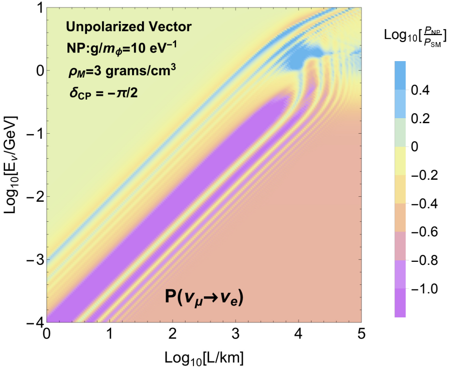
- $V_{\mu\mu}^{(T,U)} = V_{\tau\tau}^{(T,U)} = \frac{g^2\rho_\phi}{E_\nu m_\phi^2}\cos^2(m_\phi t)$
- for polarized DM we evaluate $p_\nu \cdot \phi$ assuming the polarization axis to be parallel to the ecliptic plane





Methods

- We have implemented the potential in GLoBES Huber et al. 0701187,0407333
- the time dependence of matter potential induces time dependent oscillation probabilities
- we evaluate the oscillation probabilities at several fixed times and interpolate using a second order polynomial in $cos(m_\phi t)$

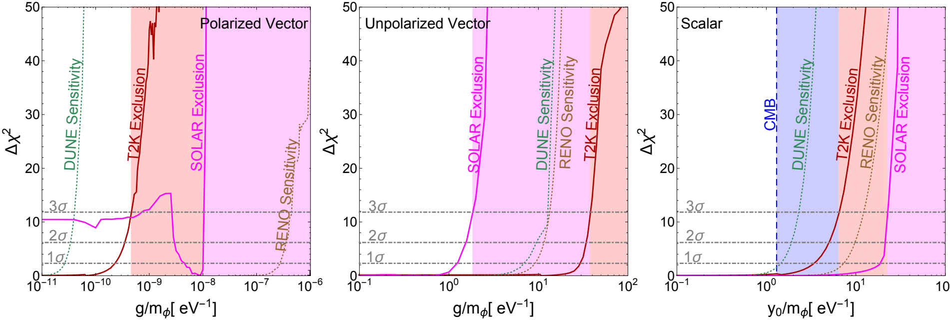


$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = P_0^{\alpha\beta}(E_\nu) + P_1^{\alpha\beta}(E_\nu) \cdot V(t) + P_2^{\alpha\beta}(E_\nu) \cdot V(t)^2 + \ldots$$

- the probability is then averaged in a given time interval T

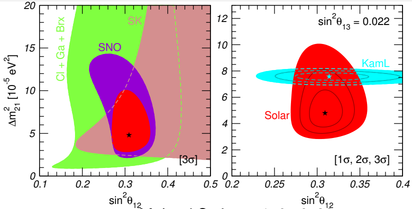
$$\bar{P}(E) = \frac{1}{T}\int_0^T dt P(E_\nu, t)$$

Constraints

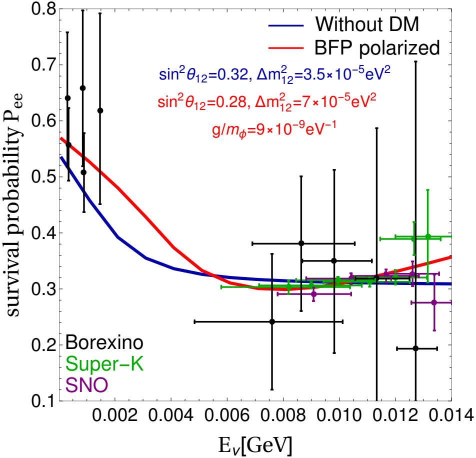


- for vector DM, the sensitivity is more than ten orders of magnitude better in the polarized case
- for scalar and polarized vector DM acceleration-based experiments give stronger limits and sensitivities
- for unpolarized vector DM, experiments at lower energies are better (energy dependence of the potential)

Impact on Solar and Astrophysical neutrinos



Maltoni,Smirnov 1507.05287
Gonzalez-Garcia, Maltoni 1307.3092



Solar

- adiabatic evolution in the sun Sun
- survival probability of electron flavor $P_{ee}(E_\nu) = \sum_i |U^{\odot}_{ei}|^2\, |U^{\oplus}_{ei}|^2$
- fitted data from Borexino, Super-K and SNO

Astrophysical

- obtaining constraints from optical depth $\tau_\nu(E_\nu) = \sigma_{\nu\phi}(E_\nu) X_\phi m_\phi^{-1}$ with $X_\phi \equiv \int_{\text{l.o.s}} dl\, \rho_\phi$
- much weaker limits in comparison to oscillation exp.

Summary I

- Novel proposal for explaining 3.5 keV line relying on annihilating DM
- For exactly degenerate χ and ϕ, the agreement between different searches is at $2-3\sigma$ level
- For quasidegenerate masses, our scenario leads to better statistical agreement between various searches wrt to decaying DM (for annihilating DM the limit from dwarf galaxies is less relevant thanks to the strong dependence of the annihilation cross section on the DM velocity)
- DM production via freeze-in or misalignment
- DM is cold enough, evading structure formation bounds

Summary II

- We have computed the evolution of the DM core in a massive star until core collapse
- If the DM annihilation products are able to leave the exploding star and decay to SM particles later, this may lead to an observable signal
- Such dark gamma ray burst can be detected by CTA for p-wave DM
- p-wave has larger photon flux than s-wave!

  This is a special feature since p-wave annihilation is generally harder to detect than s-wave ($< \sigma v >= \sigma_0 v^2$, with $v \sim 10^{-3}$ for galactic DM)
- The best signal is around $m_{\mathrm{DM}} \sim O(100)$ GeV

Summary III

- fuzzy DM is an interesting alternative to WIMP
- fuzzy neutrinophilic DM has recently received attention (Berlin 1608.01307, Krnjaić et al. 1705.06740)
- we have demonstrated that unique opportunities exist at current and future neutrino oscillation experiments to probe interactions between neutrinos and ultra-light DM particles