Preliminary

第二届北师大暗物质研讨会

Indirect detection signal from dark matter bound state formation

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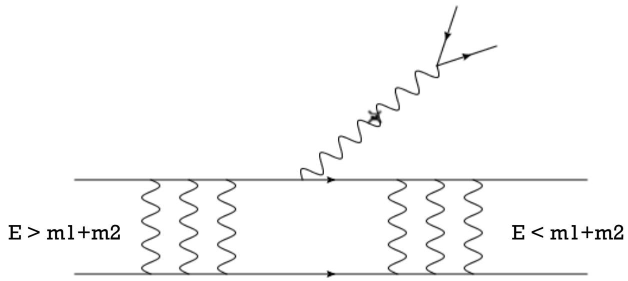
OUTLINE

- Introduction
- Model and parameter space
- Dark recombination and relic ionization fraction
- Photon spectrum from the Galactic center
- Solar signatures of the BS formation
- Summary



银河系中心光子在GeV存在超出

(arXiv:1704.03910 [astro-ph.HE])

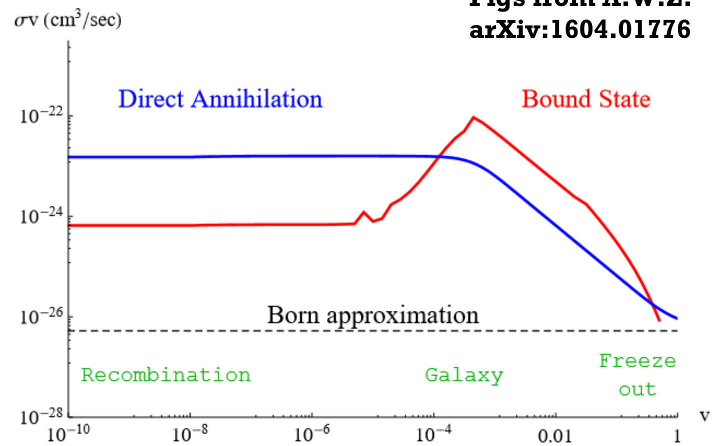
$$\Phi_\gamma(E_\gamma,\psi)=\frac{dN_\gamma}{dE_\gamma}\frac{\langle\sigma v\rangle}{8\pi m_{\rm DM}^2}\int_{\rm los}\rho^2(r)dl,$$

DM annihilation benchmark

$m_\chi = 50$ GeV
$\langle\sigma v\rangle \sim 3\times10^{-26}\ cm^3 s^{-1}$
$\chi\chi\rightarrow b\bar{b}$

To obtain the same signal

Figs from A.W.Z. arXiv:1604.01776

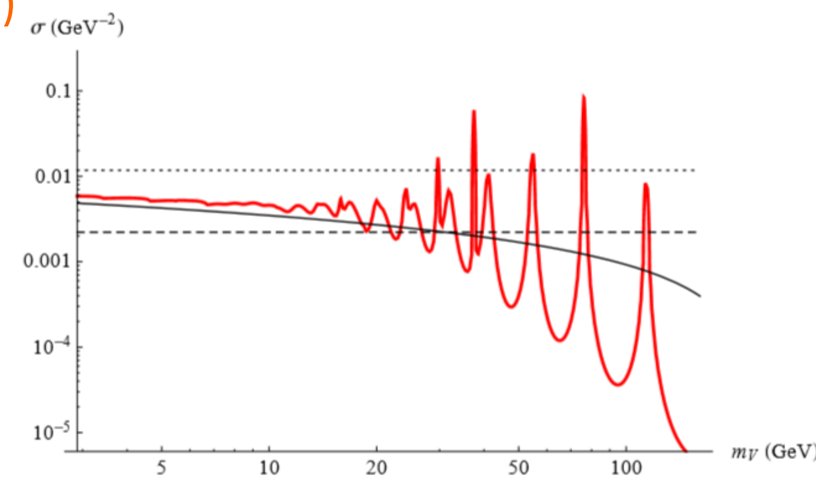


能否用束缚态形成来解释?（简单估计）

Bound state formation benchmark

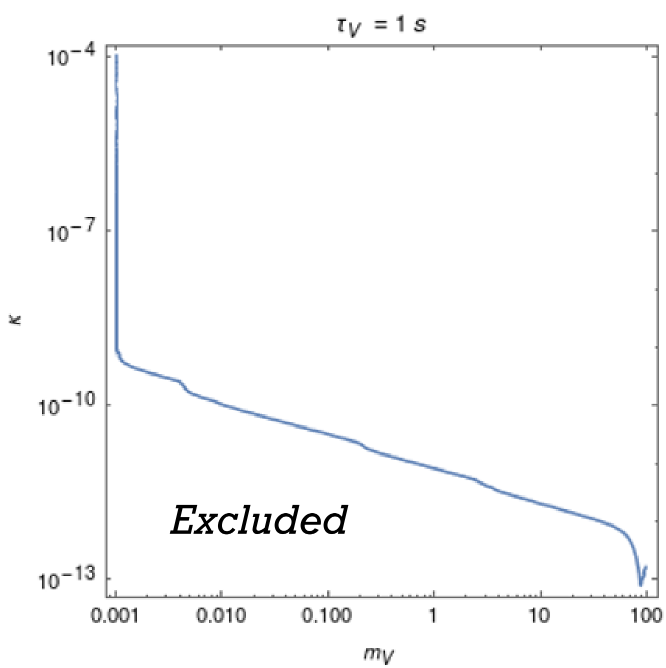
$m_1 = m_2 = 1000$ GeV
$\langle\sigma v\rangle \sim \mathbf{400}\times3\times10^{-26}\ \mathrm{cm^3 s^{-1}}$

- Velocity dependence ~10
- Mediator mass ~5
- Other decay channels ~ 10



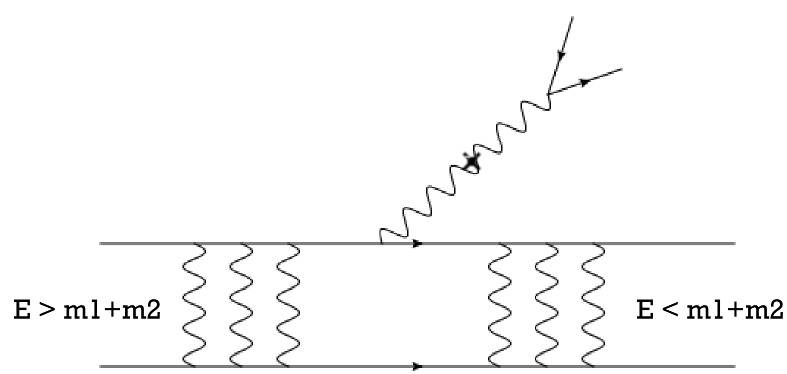
问题及解答

- 不考虑湮灭信号：
  Asymmetric dark matter
- 存在稳定束缚态：
  Long range force
- 束缚态在今天能形成：
  inefficient recombination
- 束缚态结合能~O(10 GeV)：
  m1=m2, maximize
- 满足宇宙学限制
  O(GeV) massive dark photon
  $\tau_V < 1s$



Asymmetric Dark Matter Model (ADM)

- Dark matter today is composed of particles without anti-particles
- SIDM with a primordial dark asymmetry η_D
  (We consider two generations)
- With large enough α_D, the symmetric part can be completely depleted
- Stable bound states
- **In depth studies exist for atomic dark matter, considering massless mediators**
  - **Astrophysicists**: *Cyr-Racine Francis-Yan, Sigurdson Kris, Agrawal Prateek, Randall Lisa, Scholtz Jakub ...*
  - **Particle physicists**: *Petraki Kalliopi, von-Harling Benedict ...*
  - … …
  - A few papers on cosmology indirect detection



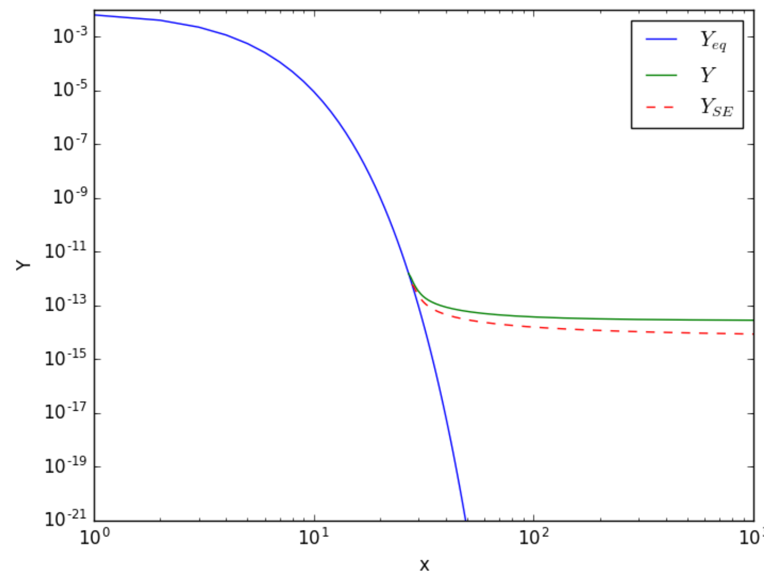
5 MODEL AND PARAMETER SPACE

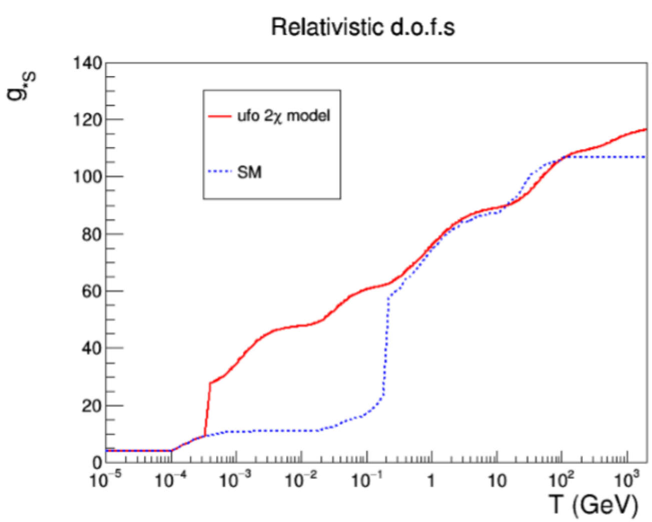
Dark Sector 演 化

- Multi-TeV: UV model generates a primordial dark asymmetry $\eta_D \equiv Y_\chi - Y_{\overline{\chi}}$
- Symmetric part annihilation
- Dark recombination
- Relic density composed of free χ_1, χ_2 and $(\chi_1\chi_2)_{BS}$
- Bound state formation today
  - Galactic center
  - Sun
  - Dwarf galaxies

Symmetric part annihilation and freeze-out

With/without Sommerfeld Enhancement



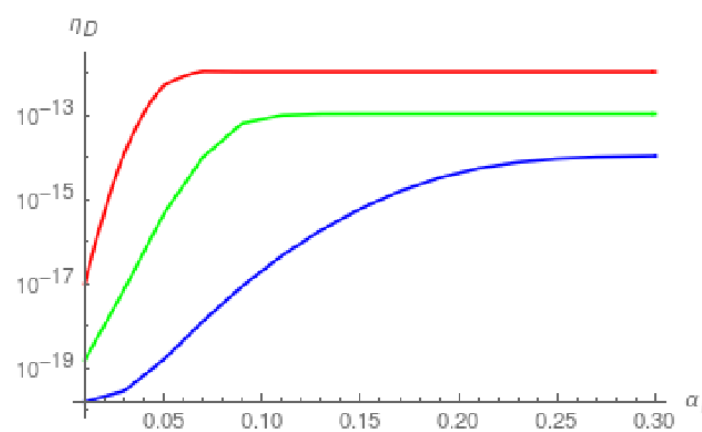


选取右下参数空间使得对称部分完全湮灭

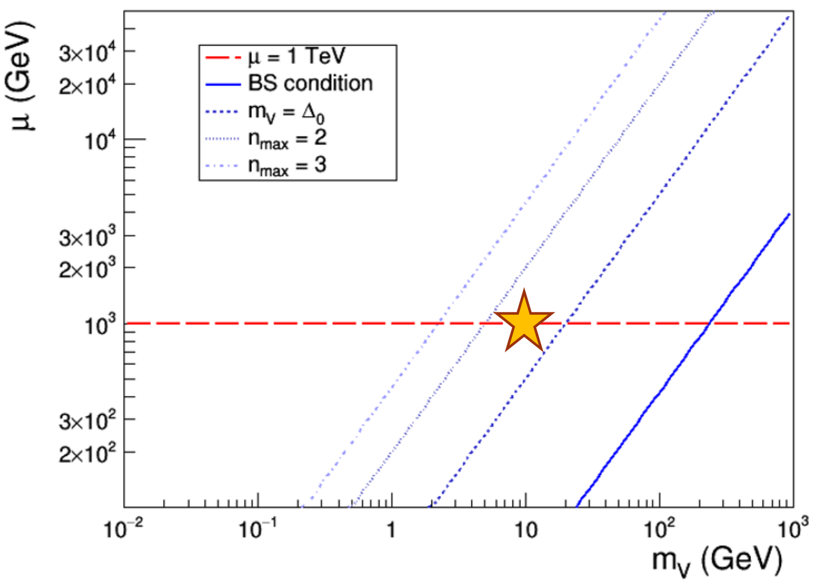
Red : $\mu = 0.1$ TeV

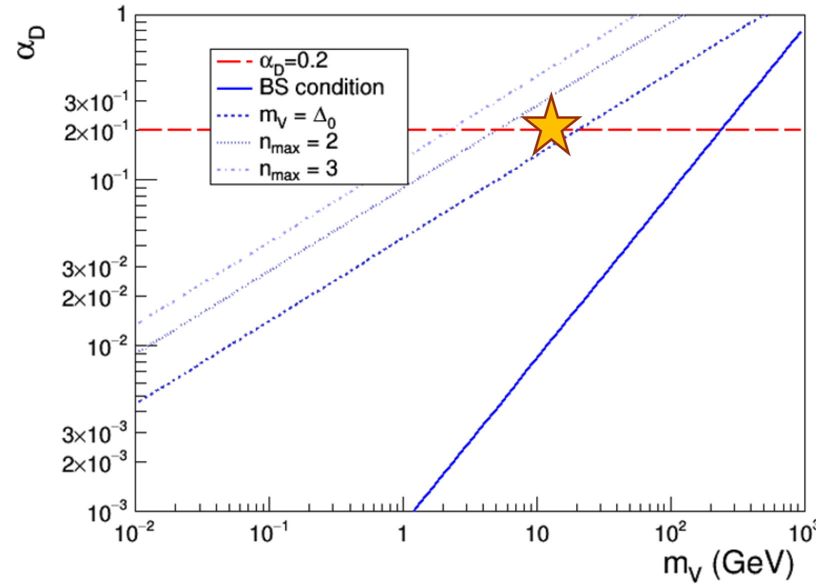
Blue : $\mu = 1$ TeV

Green : $\mu = 10$ TeV



Model and parameter space





The mV is chosen s.t. (discuss later)

- the dark recombination is not efficient
- Bound state formation cross section is large

Size of the bound state: $a_n = \dfrac{n}{\alpha_D \mu}$.

Screening length of the Yukawa potential: $\lambda = \dfrac{1}{\mathrm{m_V}}$.

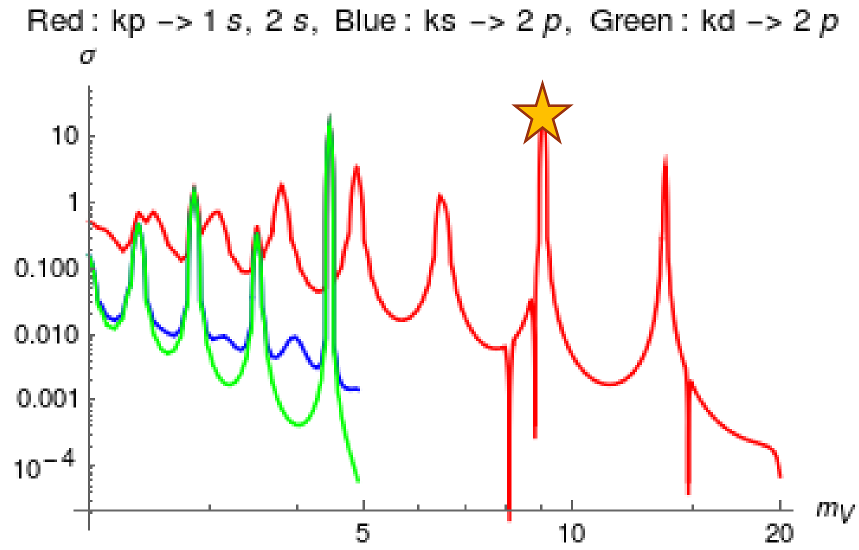
Existence condition: $a_n < \lambda$.

Binding energy: $\Delta_{nl} = E_{nl} \sim \frac{\alpha_D^2 \mu}{2n^2}$.

Mass of bound state: $M^{(n)} = 2m_D - \Delta_n$.

Emitted dark photon energy: $\omega^{(n)} = \Delta^{(n)} + \frac{\mu v_{rel}^2}{2}$.

Model and parameter space



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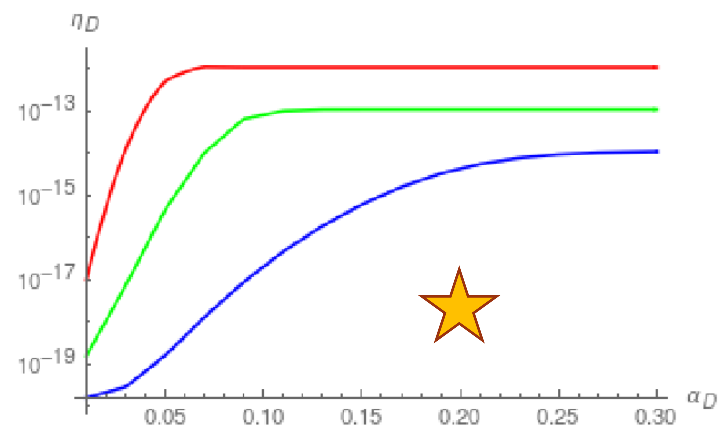

$$\eta = \frac{m_p}{m_1+m_2}\frac{\Omega_{DM}}{\Omega_b}\left(\frac{1-r_\infty(\alpha_D,\eta)}{1+r_\infty(\alpha_D,\eta)}\right)\eta_B$$

- $\alpha_D = 0.2$,
- $\mathrm{m}_\chi = m_1 = m_2 = 2$ TeV, $\mu = 1$ TeV,
- $m_V = 9.08$ GeV.
- η_D chosen such that the DM relic density is completely generated by our model.
- $\kappa = 1 \times 10^{-8}$.

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DARK RECOMBINATION AND RELIC IONIZATION FRACTION

Bound state formation with a massive spin-1 mediator

In the non-relativistic limit:

$$
\begin{aligned}
H &= H_0 + H_{int},\\
H_0 &= -\frac{\nabla^2_{cm}}{2M} - \frac{\nabla^2}{2\mu} + V(r)_{\text{static}},\\
H^T_{int} &= \frac{g_D \mathbf{k}}{m_D}\left(\mathbf{A}^{\mathrm{T}}(\frac{\mathbf{r}}{2}) + \mathbf{A}^{\mathrm{T}}(-\frac{\mathbf{r}}{2})\right),\\
H^L_{int} &= -g_D \frac{m_V}{|\mathbf{q}|}\left(\phi_L(\frac{\mathbf{r}}{2}) - \phi_L(\frac{-\mathbf{r}}{2})\right).
\end{aligned}
$$

The bound and scattering wavefuctions that solve the Schrodinger equation are written as

$$\psi_n(\mathbf{r}) = \sum_{\ell m} R_{n\ell}(r) Y_{\ell m}(\hat{r}),$$

$$\psi_k(\mathbf{r}) = \sum_{\ell m} R_{k\ell}(r) Y_{\ell m}(\hat{r}) Y^*_{\ell m}(\hat{k})$$

Bound state formation cross section as a function of mV.

Red line: kp → 1,2s.

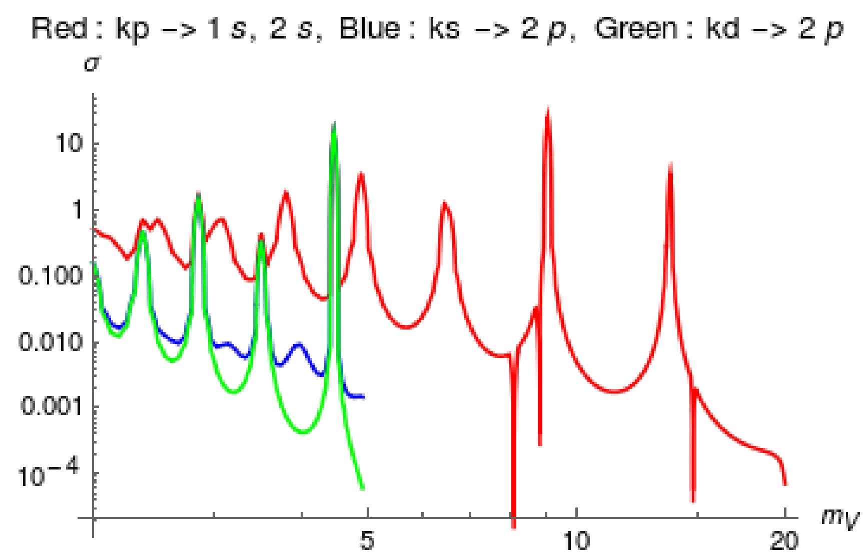
Blue line: ks → 2p.

Green line: kd → 2p.

The amplitudes are calculated using time dependent perturbation theory, with dipole approximation

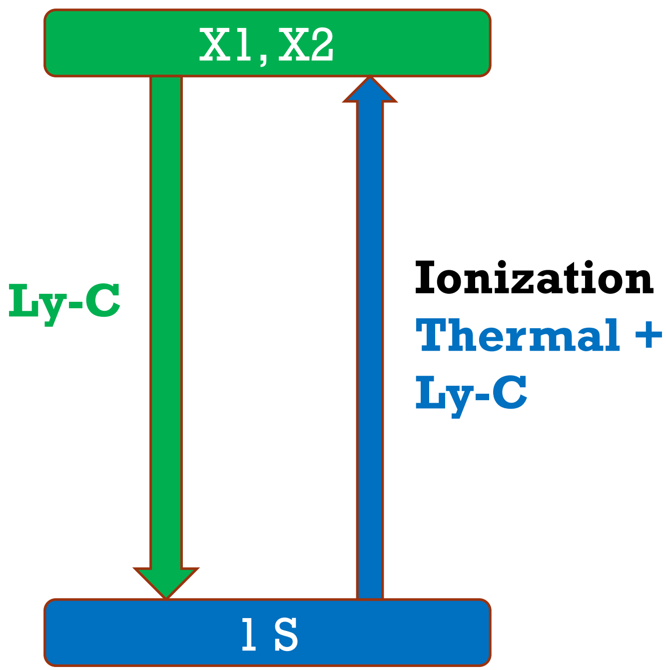
$$
\begin{aligned}
c_T &= g_D \int \mathrm{d}^3\mathbf{r}\Psi^*_f(\mathbf{r})(E_i - E_f)\mathbf{r}\cdot\epsilon_T \Psi_i(\mathbf{r}),\\
c_L &= -i g_D \int \mathrm{d}^3\mathbf{r}\Psi^*_f(\mathbf{r})\mathrm{m_V}\frac{\mathbf{r}\cdot\mathbf{q}}{|\mathbf{q}|}\Psi_i(\mathbf{r}),
\end{aligned}
$$

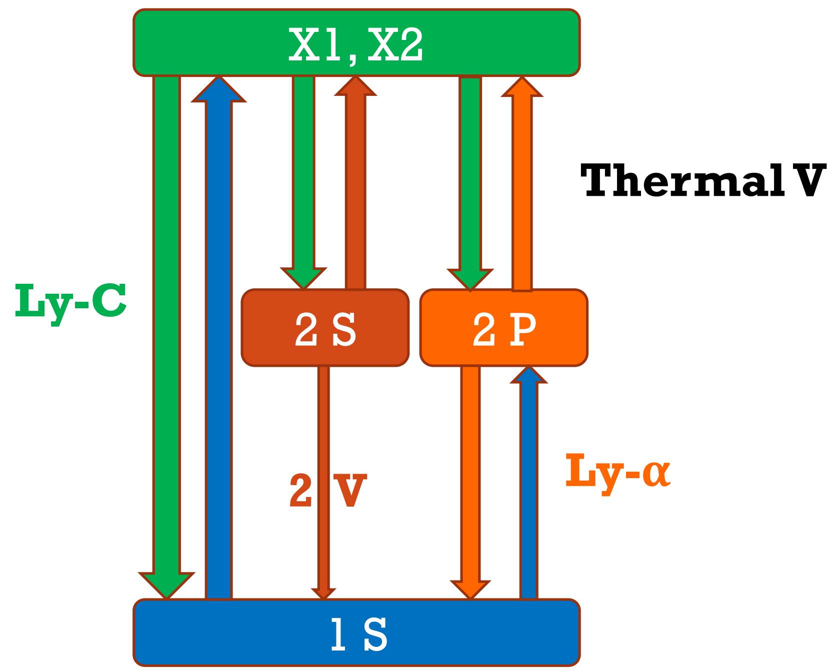
$$
\begin{aligned}
(\sigma v)_B &= \frac{\alpha_D}{3\pi}\sum_{n,l}\left(\omega^2_{nl} + \frac{1}{2}\mathrm{m_V^2}\right)\sqrt{\omega^2_{nl} - \mathrm{m_V^2}}\\
&\times \left[l\left|\int \mathrm{d}r r^3 R_{n,l}(r) R_{k,l-1}\right|^2 + (l+1)\left|\int \mathrm{d}r r^3 R_{n,l}(r) R_{k,l+1}\right|^2\right]
\end{aligned}
$$



Dark recombination and relic ionization fraction

- Temperature of thermal photons $\ll$ Binding energy Δ
- 2S->1S dominant in the standard Hydrogen recombination
- Ly-Continuum photon are non-thermal, can ionize another bound state





Our present benchmark only allows for n=1 bound state

Dark recombination and relic ionization fraction

Assuming that our dark sector constitutes the dark matter energy density today

$$n_c = 2n_{BS} + n_{D1} + n_{D2}$$

$$s(T) = \frac{2\pi^2}{45} g_{\star S}(T) T^3,$$

$$n_c = \frac{n_c(T_0)}{n_B(T_0)} \eta_\gamma \frac{n_\gamma(T_0)}{s(T_0)} s(T).$$

$$X_D \equiv \frac{n_D}{n_c} \qquad x = \frac{\Delta}{T}$$

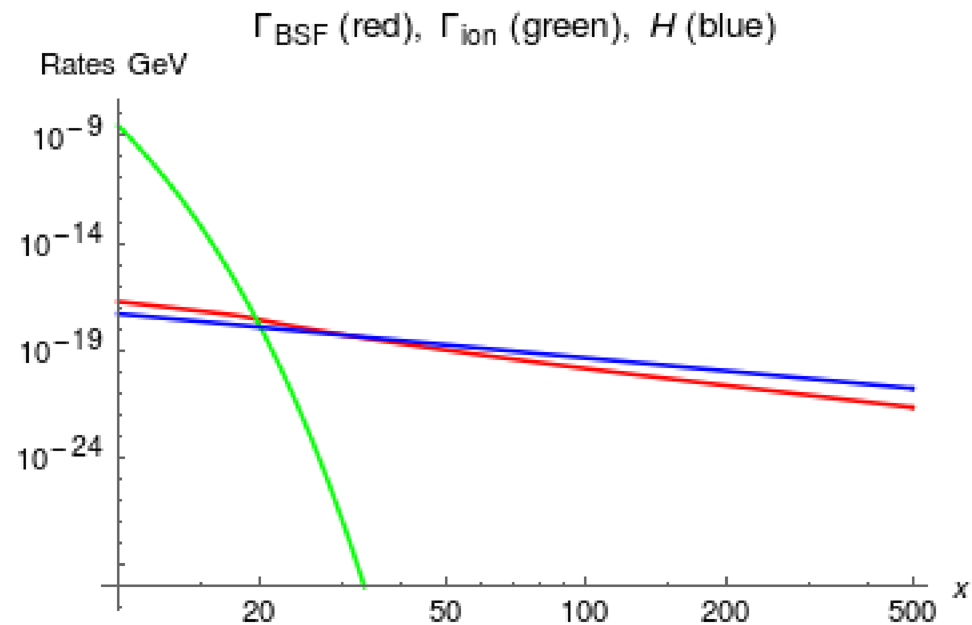
We hope to have a significant relic XD s.t. the BS can still form efficiently today inside galaxies

- Large formation and ionization rate

The ionization cross section can be obtained from the principle of detailed balance

$$(\sigma v)_B n_1^{eq} n_2^{eq} = g_V (\sigma v)_I n_{BS}^{eq} n_V^{eq}$$

$$\Gamma_I(T) = \langle \sigma v \rangle_I \left(n_V^{th} + n_V^{nt}\right)$$



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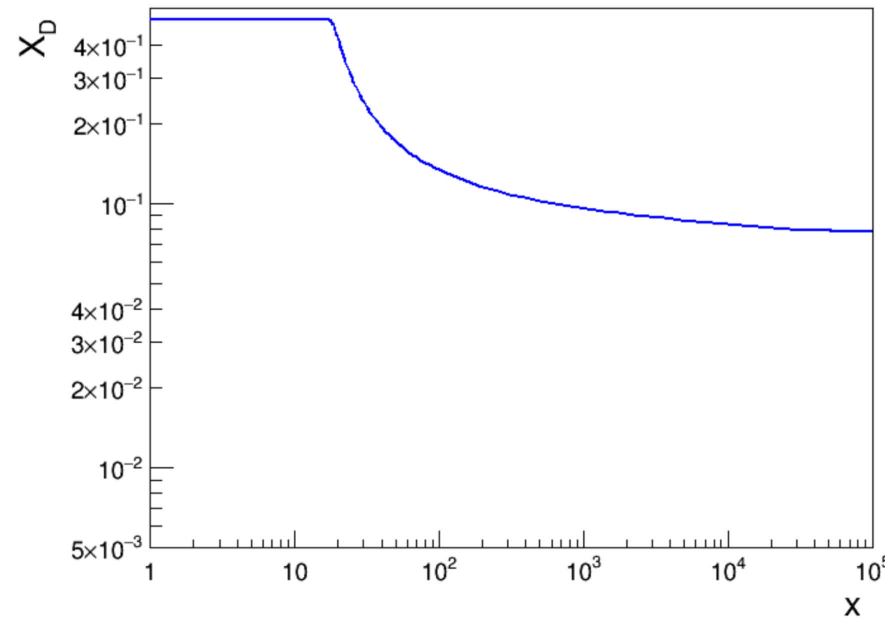
$$n_c = 2n_{BS} + n_{D1} + n_{D2}$$

$$X_D \equiv \frac{n_D}{n_c} \qquad x \equiv \frac{\Delta}{T}$$

- The dark recombination happened at GeV scale
- The recombination is slow
- Ionization fraction can be tuned to order 1: ~20% free states

➢ Non-thermal photons can prolong the recombination, but leads to negligible change in the relic ionization fraction



$$\frac{\mathrm{d}(n_V^{nt}/n_c)}{\mathrm{d}x} = \frac{x}{H(\Delta)}\left[\langle\sigma v\rangle_B\, n_c X_D^2 - \langle\sigma v\rangle_I\, n_V^{nt}\left(\frac{1}{2} - X_D\right)\right]$$

$$\frac{\mathrm{d}X_D}{\mathrm{d}x} = -\frac{x n_c}{H(\Delta)}\langle\sigma v\rangle_B\, X_D^2 + \frac{x}{H(\Delta)}\Gamma_I\left(\frac{1}{2} - X_D\right)$$

14 GALACTIC CENTER GEV EXCESS

Photon flux from the BS formation

- We obtain the photon spectrum using the PPPC program
- The predicted Gamma Ray signal from the DM is strongest in the GC owing to its proximity and the enhanced density of the DM.
- J-factor taken from Ref. [*Astrophys. J. 840, 43 (2017), 1704.03910*], (calculated assuming a local DM density of 0.4 GeV/cm^3)

$$1.53 \times 10^{22} \quad \mathrm{GeV}^2\ \mathrm{cm}^{-5} \quad \gamma = 1$$

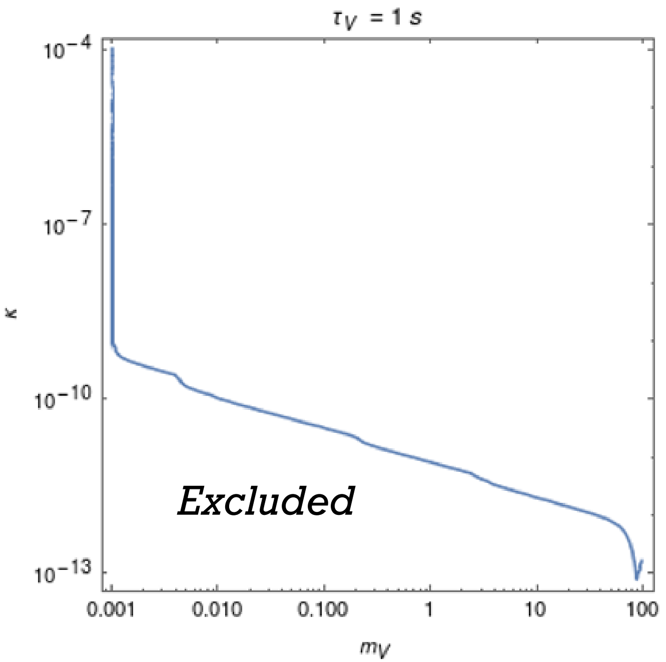
$$\begin{aligned}
\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma}(E_\gamma, \theta) &= \frac{1}{4\pi}\int_{\Delta\Omega} \mathrm{d}\Omega \int_{l.o.s} \mathrm{d}s \sum_{n,l}\left(\frac{\rho(r(s,\theta))}{m_1+m_2}2X_D\right)^2 \langle\sigma v\rangle_{n,l} \times \frac{\mathrm{d}N_\gamma^{n,l}}{\mathrm{d}E_\gamma} \\
&= \frac{X_D^2}{\pi}\sum_{n,l}\frac{\langle\sigma v\rangle_{n,l}}{(m_1+m_2)^2}\frac{\mathrm{d}N_\gamma^{n,l}}{\mathrm{d}E_\gamma} \\
&\times \int_{\Delta\Omega}\int_{l.o.s} \mathrm{d}s\mathrm{d}\Omega\rho^2(r(s,\theta)), \\
J\text{-factor} &= \int_{\Delta\Omega}\int_{l.o.s} \mathrm{d}s\mathrm{d}\Omega\rho^2(r(s,\theta)), \\
\frac{\mathrm{d}N_\gamma^{n,l}}{\mathrm{d}E_\gamma} &= \sum_f \mathrm{Br}(V \to f\bar{f})\frac{\mathrm{d}N_\gamma^f}{\mathrm{d}E_\gamma}.
\end{aligned}$$

$$\rho_{DM}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

$$\begin{aligned}
f(v) &= \frac{1}{N_{esc}}\left(\frac{3}{2\pi\sigma_v^2}\right)^{\frac{3}{2}} e^{-\frac{3v^2}{2\sigma_v^2}}, \ |v| < v_{esc} \\
f(v) &= 0\text{: otherwise} \\
N_{esc} &= erf(z) - \frac{2}{\sqrt{\pi}}ze^{-z^2}, \\
z &\equiv \frac{v_{esc}}{\sigma_v}\sqrt{\frac{3}{2}}, \\
v_{esc} &= 553\ \mathrm{km/s}, \\
\sigma_v &= 150\ \mathrm{km/s}, \\
\sigma_r &= \sqrt{2}\sigma_v.
\end{aligned}$$

Model and parameter space
V boson life time

We choose kappa and mV s.t. there is no impact on the BBN, CMB, and structure formation…



$$\frac{\kappa}{2\cos\theta_W} B_{\mu\nu}V^{\mu\nu} = \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{\kappa\tan\theta_W}{2}Z_{\mu\nu}V^{\mu\nu}$$

$$\Gamma_{V\to f\bar{f}} = \frac{1}{2\mathrm{m_V}}N_c^f\frac{1}{8\pi}\sqrt{1-\frac{4m_f^2}{\mathrm{m_V^2}}}\int\frac{\mathrm{d}\cos\theta}{2}|\mathcal{M}_{L/R}(\cos\theta)|^2$$

$$= \frac{N_c}{24\pi\mathrm{m_V}}\sqrt{1-\frac{4m_f^2}{\mathrm{m_V^2}}}\left(\mathrm{m_V^2}(g_L^2+g_R^2) - m_f^2(-6g_L^2g_R^2+g_L^2+g_R^2)\right)$$

Decay channel	Branching ratio (MadWidth)	**Branching ratio** (analytic)	Mass (MeV)	PDG ID1	PDG ID2
$u\bar{u}$	0.204	0.215901	2.2	2	-2
$c\bar{c}$	0.204	0.209764	1280	4	-4
e^+e^-	0.153	0.161767	0.511	11	-11
$\mu^+\mu^-$	0.153	0.161767	106	13	-13
$\tau^+\tau^-$	0.134	0.14253	1777	15	-15
$d\bar{d}$	0.0511	0.0541345	4.7	1	-1
$s\bar{s}$	0.0511	0.0541345	96	3	-3
$b\bar{b}$	0.0511	0	4180	5	-5
$\nu_e\bar{\nu}_e$	2.953107e-07	3.11121e-07	0	12	-12
$\nu_\mu\bar{\nu}_\mu$	2.953107e-07	3.11121e-07	0	14	-14
$\nu_\tau\bar{\nu}_\tau$	2.953107e-07	3.11121e-07	0	16	-16

TABLE II: Branching ratios for $\mathrm{m_V} = 5$ GeV. The MadWidth considers only τ, t masses. They are listed here for validation.

Photon flux from the BS formation

Validation, spectrum from Pythia (Left) and from PPPC (right)
Electroweak correction has been included in the latter case.

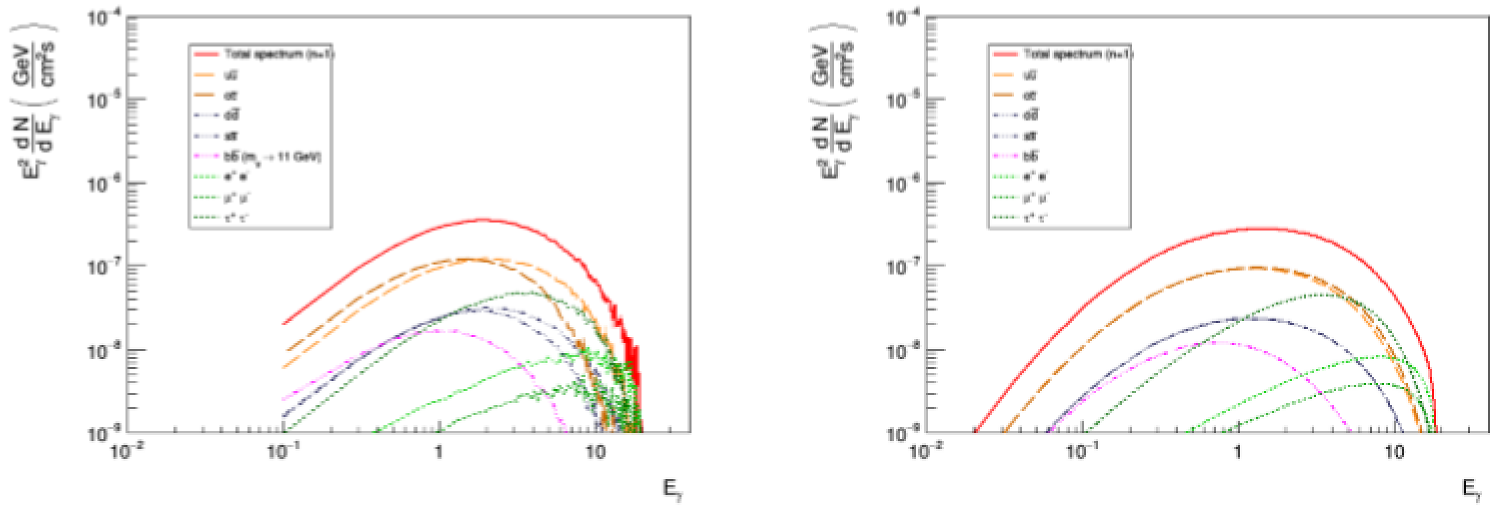
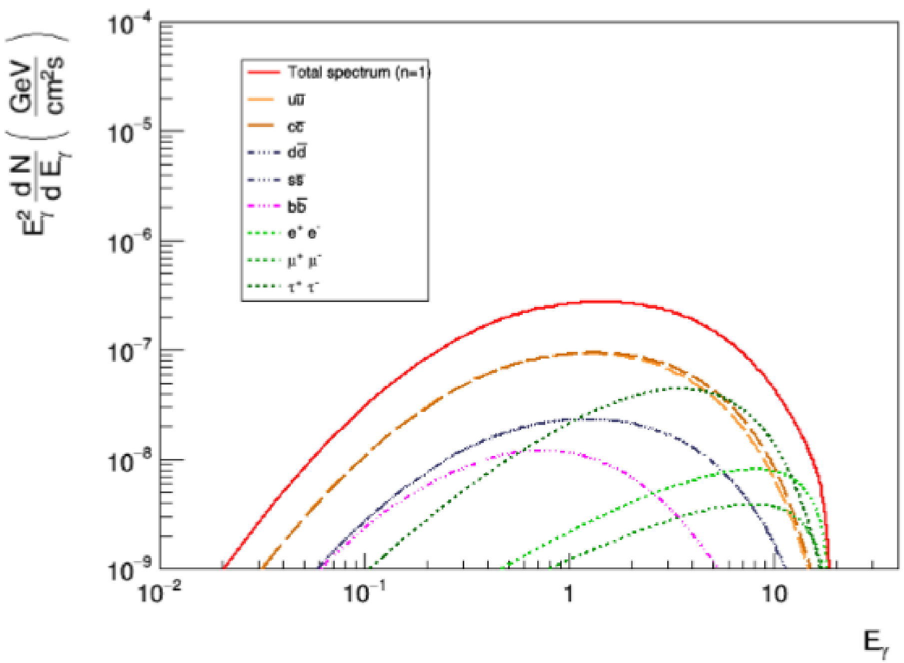


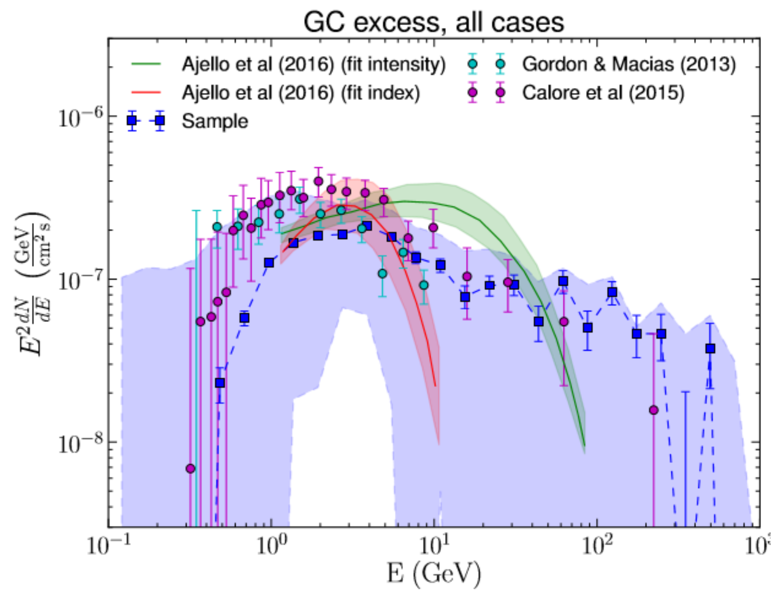
FIG. 16: Comparison of photon energy spectrum between pythia and pppc. The $b\bar{b}$ mode does not appear in pythia until about 11 GeV.

Photon flux from the BS formation

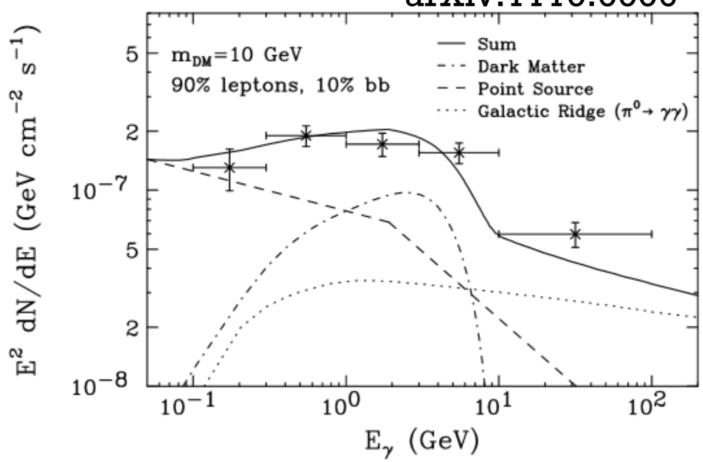
BS formation can generate a photon flux as strong as the GC gamma-ray excess



arXiv:1704.03910 [astro-ph.HE]

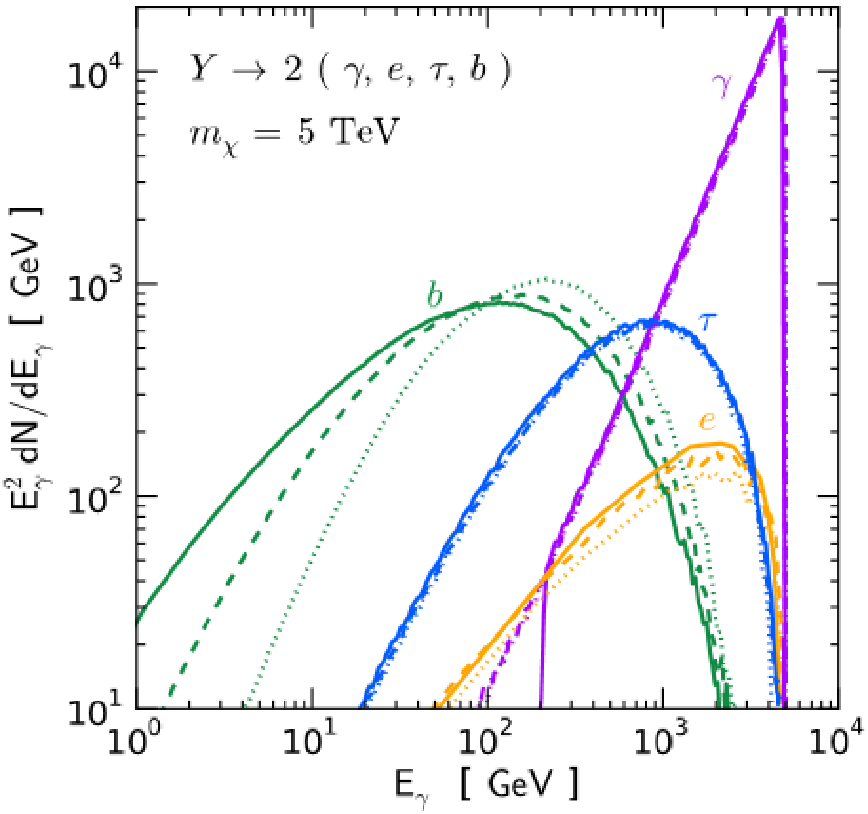


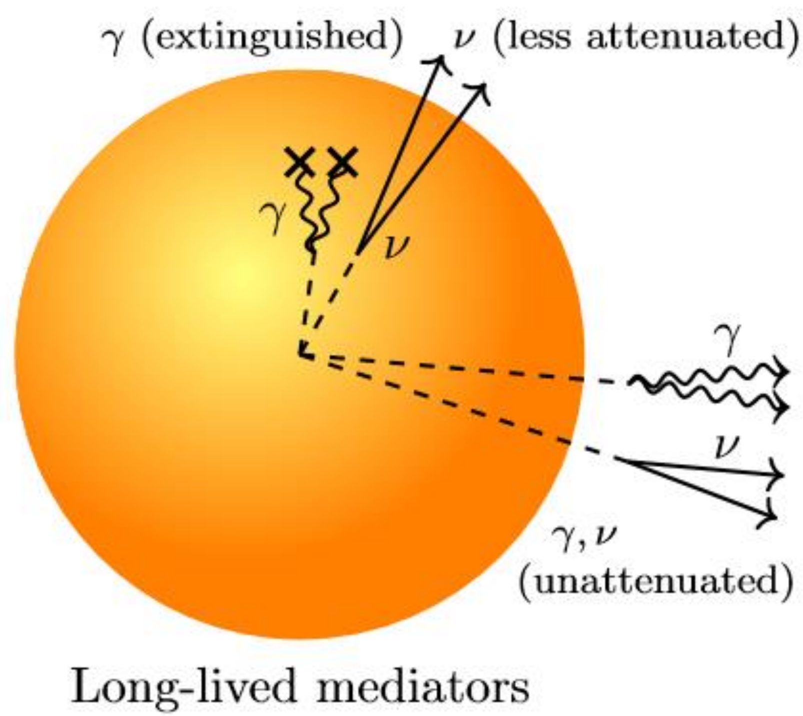
arXiv:1110.0006



Solar signatures of the BS formation

Figs from L.N.B arXiv: 1703.04629:
Powerful Solar Signatures of Long-Lived Dark Mediators





Gamma-ray spectra for various final states, per DM annihilation, with mediator masses mY = 2 TeV (solid), mY = 200 GeV (dashed), and mY = 20 GeV (dotted)

- BBN generally require $\tau < 1$s
- Solar Radius = 2.32 s
- Consider $\bar{p}, \bar{e}$ spectrum to reduce backgrounds

SUMMARY

- Asymmetric Dark Matter model provides a possible way to generate the Galactic Center GeV photon excess through the BS formation process.
- The relic dark recombination can be made inefficient, making the bound state formation possible today.
- If the dark photon has a relatively long life time, there are interesting solar signatures.