Dark photons

G. Kozlov
JINR, Dubna

DM

Gravitational

WIMP Miracle
SUSY wimp ? ~ 100 GeV

Why?
DM relic density consistent with weak int's

⇓

No SUSY yet/ experiments??

DM originated as thermal relic from early Universe

If correct, → abundance of DM, once DM has non-gravitational interactions with SM

Clear mass window ~ MeV – 10 GeV for candidates

experimental probe to rule out thermal DM

Need low mass vector state – *MEDIATOR* to be consistent with DM Relic density

$$\Omega_{DM} \sim \frac{m_{\gamma*}^4}{m_\chi^2}$$

Heavy "PHOTON"?
***Dark* Photon state ?**

- ***Hidden sector scenario;***
DM do not interact directly to SM!

○ *Hidden sector scenario*

- *DM charged under new U'(1) gauge field mediator by U'(1) gauge boson.*

- **DP** mixes with $U(1)_Y$ *by* ϵ *(free parameter, mixing angle)*

- **DP** *as a low mass mediator* $DM \longleftrightarrow SM$ (via DP)

Min. cross section $\Omega_{DM} \sim \frac{m_{\gamma*}^4}{m_\chi^2}$

○ If ***DP*** is the mediator, the issues arise:

- *What is the symmetry providing its propagation*
- *The nature of the propagator*
- *Experimental search for mediator -* ***DP***

○ *Kinetic* ϵ^2 *- mixing importance*

- *to estimate indirect/direct detection of DM*

$\langle\sigma v\rangle \sim \alpha_{DM}^2/m_\psi^2$. annihilation rate

- **Indirect** *Annihilation to*

$$l^+l^- : \langle\sigma v\rangle_\epsilon \sim \epsilon^2 \frac{\alpha\,\alpha_{DM}}{m_\psi^2\,P(\Delta)}, \qquad \Delta = \frac{m_{DP} - m_\psi}{m_\psi}$$

- **Direct** *DM scattering against nuclei*

$$\langle\sigma v\rangle_\epsilon \sim \epsilon^2 \frac{\alpha\,\alpha_{DM}\,\mu_{\psi p}^2}{m_{DP}^4}\frac{Z^2}{A^2}, \qquad \mu_{\psi P} = \frac{m_\psi\,m_p}{m_\psi + m_p}$$

❖Heavy photon searches

❖ Fixed target

NA 64 @ SPS, **PRD 97 (2018) 072002** $e^{-}Z \rightarrow e^{-}Z\gamma^{*} \rightarrow e^{-}Z\chi\bar{\chi}$ invisible

$$10^{-5} \leq \epsilon_{\gamma-\gamma^{*}} \leq 10^{-2}$$
$$m_{\gamma*} \leq 1\ GeV$$

HPS @ Jlab, **PRD 98 (2018) 091101** $19 < m_{\gamma*} < 81\ MeV, \varepsilon^{2}{}_{\gamma-\gamma^{*}} \sim 6\ 10^{-6}$

- J-PARC, T2K ?
- DUNE @ FNAL ?

➢ **Low** α_{DM} , $\boldsymbol{low\ m_{DP} \rightarrow longer}$ **lifetime**

○ EM Telescope SHUKET $(\mu eV\ mass\ @\ mixing \sim 10^{-12})$

Detect weak DM-induced electric field $E_{DM} \sim \epsilon\ m\ \overrightarrow{\psi_{DM}}$

○ Colliders

- ***LHC, FASER*** 480 m downstream of ATLAS int. point 2020-21?

LHC: DP experimental signature

Overall signal strength in $gg \to H(\bar{\sigma}) \to \gamma\gamma(\gamma\gamma^*)$

- ***Origin***: - ***SI*** breaking sector of CFT
  - Contribution from DP to BR

$$BR(H \to \gamma\gamma^*) \approx (1 + a\varepsilon^2\Omega) BR^{SM}(H \to \gamma\gamma), \;\; \Omega \sim (1 - m^2 / m_H^2)^3$$

Salient feature: ***DP*** γ^* energy with cont. spectrum vs $H \to \gamma\gamma$ in SM

- By measuring E_γ spectrum in $H \to \gamma\gamma$ one can discriminate the presence of DP or not.
- **Strategy of the analysis:** identify $\gamma^* \to inv$ candidates by precise reconstruction of the initial Higgs state.
- The ***measured rate*** of such events has to be compared to that expected from known sources

✓ ***DP*** signal (exp. signature): detected in missing E and p distribution

Once ***DP*** produced:

E_γ spectrum is NO more δ-function peaked at $0.5m_H$

but rather continuous with $E_\gamma = [0,\ 0.5m_H]$

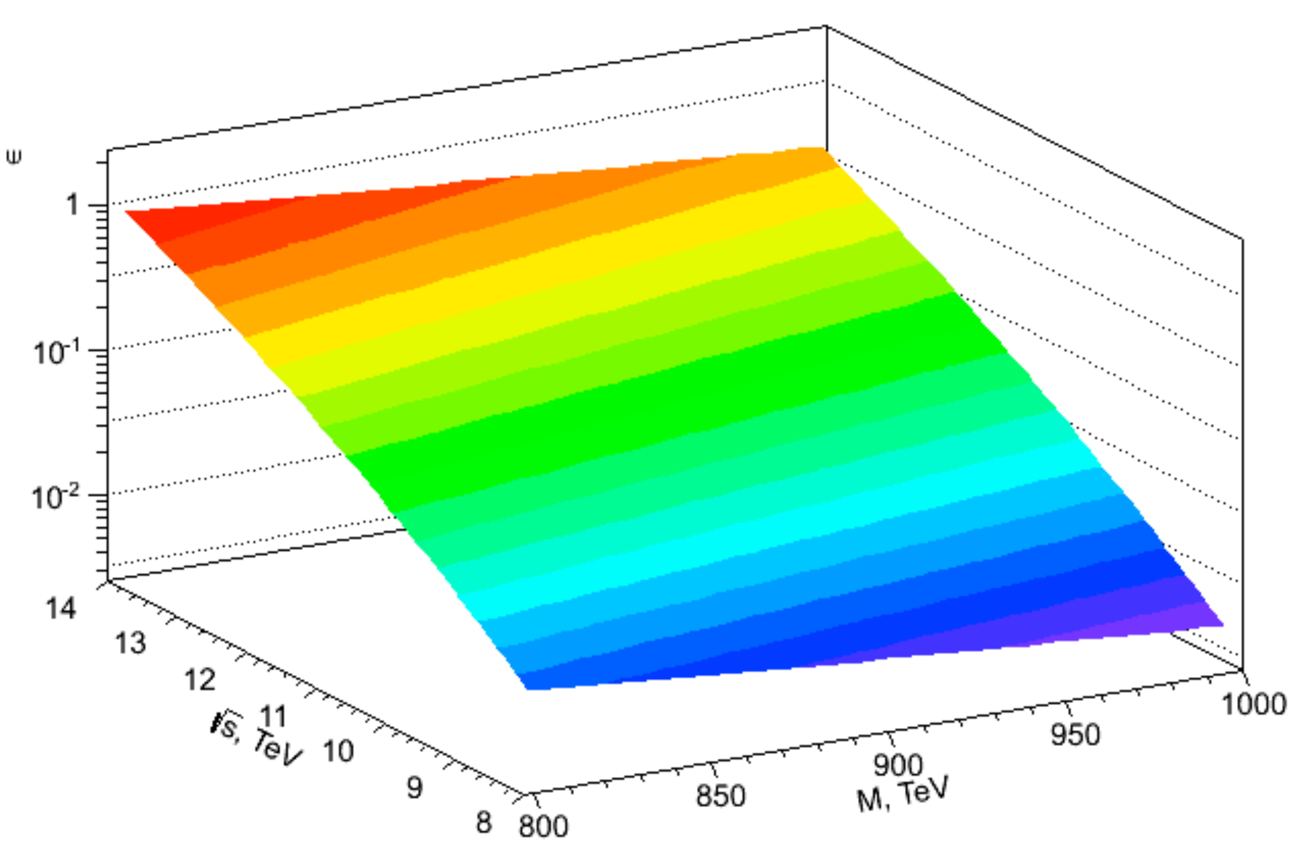
Effect of DM sector on observable(s)

➢ Mixing strength ε is bounded by

$$\varepsilon < \frac{s^d}{\left(v^2 M^{d-2}\right)^2}$$

$\sqrt{s} = 8-14\ TeV,\ \ M = 800-1000\ TeV,\ \ d = 4$

GK Nucl. Phys. B273 (2016)



Upper limit on mixing angle ε

✓ NP signals with DP increase with $\sqrt{s}, \ d$

For $H \to \gamma\gamma^*$: $L \sim O_{SM} \ O_{IR} \sim \varepsilon\bar{\psi}\gamma_\mu\psi H \ B^\mu M^{-1}$

Relevant energy scale $Q \sim m_q, \ q : top, ...$

Result: $\varepsilon < 3 \cdot 10^{-2}, \ q : top, \ d = 4; M > v$

DP visible @ LHC for the ***UV*** scale up to $M < 10^3$ TeV, d=4

If $\varepsilon \to 0$, the only decay $H \to \gamma\gamma$ is appropriate within SM

✓***LHC is a very good facility where the DM Physics can be tested well***

Upper limit on DP mass

$$Am\left(\gamma^* \to \nu\bar{\nu}\right) = \frac{1}{2} f_\nu \bar{\nu}\left(g_{V_\nu}\gamma_\beta + g_{A_\nu}\gamma_\beta\gamma_5\right)\nu\gamma^*_\beta$$

$$f_\nu^2 = 4\sqrt{2}Gm^2, \quad G \sim 10^{-5} GeV^{-2}$$

No final state interactions: (partial decay width)

$$\Gamma\left(\gamma^* \to \nu\bar{\nu}\right) = \frac{2}{3}\bar{\alpha}\cdot\varepsilon^2 m$$

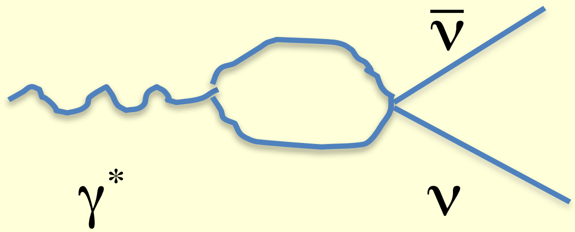
$$\downarrow$$

$$\frac{\sqrt{2}Gg_\nu^2 m^2}{4\pi\bar{\alpha}}, \quad g_{V_\nu}^2 = g_{A_\nu}^2 = g_\nu^2 = \frac{1}{4}$$

For $\varepsilon < 3 \cdot 10^{-2} \to m < 3.3\ GeV$

To predict m, the more detailed calculations need

E.g., EMνFF



$$\Gamma\left(\gamma^* \to \nu\bar{\nu}\right) \sim \alpha^2 m^5 G^2 \left(ln \frac{\Lambda_\nu^2}{m_l^2} - \frac{1}{6} \right)^2$$

DP mass: Combined calculations give

$$m \approx m_\mu \sqrt{\left[\frac{3\sqrt{2}\pi\alpha^{-1}}{\sum_{l:e,\mu}\left(ln\frac{\Lambda_\nu^2}{m_l^2} - \frac{1}{6} \right)} \right]} \to m = 0.83\ GeV \qquad \text{e, } \mu\ loops$$

$$\Lambda_\nu \sim O(m_Z),\ \varepsilon = 7.6\ \cdot 10^{-3}$$

❖ *Higgs-Dilaton Abelian Model*

$$L_{SM+DM+DP} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}\bar{\alpha}F_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\bar{\beta}\,B_{\mu\nu}^2 - b(\partial B) + \frac{1}{2\eta}b^2$$

$$+\bar{\psi}\left(i\widehat{D_\mu} - m_\psi\right)\psi + \left|D_\mu\varphi\right|^2 - \lambda^2|\varphi|^4 + \mu_0^2|\varphi|^2$$

$$\bar{\alpha} = \frac{1}{2}\epsilon(\alpha+\beta), \qquad \bar{\beta} = \epsilon^2\alpha\beta, \qquad D_\mu = \partial_\mu + igB_\mu$$

➢ *Invariance under transformations:*

$$A_\mu \to A_\mu + \partial_\mu\Lambda, \quad B_\mu \to B_\mu + \partial_\mu\Lambda,$$

$$\varphi \to e^{ig\Lambda}\varphi,\ \psi \to \psi e^{ig\Lambda},\ \Delta^2\Lambda(x) = 0$$

❖ Symmetry breaking

Real fields $\phi + f = \frac{1}{\sqrt{2}}(\varphi + \varphi^*), \qquad \chi = \frac{-i}{\sqrt{2}}(\varphi - \varphi^*)$

$$\langle \Omega, \chi\Omega \rangle = 0, \qquad f = \langle \Omega, (\phi + f)\Omega \rangle, \qquad \langle \Omega, \Omega \rangle = 1$$

After symmetry breaking

$$L_R = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}\bar{\alpha}F_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\bar{\beta}\, B_{\mu\nu}^2 - b(\partial B) + \frac{1}{2\eta}b^2 +$$

$$\bar{\psi}\,(i\widehat{D_\mu} - m_\psi)\psi + \boldsymbol{\frac{m^2}{2}B_\mu^2} + mB_\mu\partial^\mu\chi - \frac{1}{2}\mu^2\phi^2 + \frac{1}{2}\left[(\partial_\mu\phi)^2 + (\partial_\mu\chi)^2\right]$$

$$m = gf \ \text{ DP mass}$$

$$\mu = \sqrt{2}\lambda f \ scalar\ dilaton\ mass$$

❑ *Dark* photon field itself

➢ ***Basic Eq.***

$$\Delta^2 B_\mu - p\,\partial_\mu(\partial B) + \frac{m^2}{q} B_\mu + \frac{m}{q}\,\partial_\mu \chi = 0$$

$$p = 1 - \frac{\eta}{q}, \qquad q = -\frac{1}{4}\epsilon^2(\alpha - \beta)^2$$

Solution. DP field

$$\boldsymbol{B_\mu(x) \equiv C_\mu(x) - \frac{\partial_\mu \chi(x)}{m} + \frac{\eta}{m^3}\Delta^2 \partial_\mu \chi(x)}$$

$$\Delta^2\Delta^2\chi(x) = 0, \qquad \Delta^2\chi(x) \neq 0,$$

$$[\chi(x), \chi(0)] = 2\pi i\, sgn(x^0)[b_1\theta(x^2) + b_2\delta(x^2)]$$

$$\left(\Delta^2 + \frac{m^2}{q}\right) C_\mu(x) = (\partial C) = 0, \qquad [C_\mu(x), \chi(y)] = 0$$

❖ *Propagator of Dark Photon field*

$\mathbb{R}_4$:

$$\hat{\tau}(p) \sim \frac{1}{\eta} \lim_{\kappa^2 \to 0} \frac{p_\mu p_\nu}{(p^2 - \kappa^2 + i\varepsilon)^2} + c\left[g_{\mu\nu} - \frac{p_\mu p_\nu}{(p^2 + i\varepsilon)}\right] \frac{1}{p^2 - m^2 + i\varepsilon}$$

- The mixing $\epsilon -$ dependence is through the Eq.

$$\partial^\mu \left[F_{\mu\nu} + \frac{1}{2}\epsilon(\alpha + \beta)B_{\mu\nu}\right] = 0$$

$B_{\mu\nu}$: B_μ is the basic DP field solution

❖ DM field properties. DM propagator.

$$\left(i\partial_\mu\gamma^\mu - m_\psi\right)\psi(x) \approx -gm^{-1}\gamma^\mu N\left[\partial_\mu\chi(x)\cdot\psi(x)\right]$$

$$\psi(x) = N\, e^{ig\chi(x)/m}\, \psi^{(0)}(x)$$

→ Free DM field with mass m_ψ

$$N\left[\partial_\mu\chi(x)\cdot\psi(y)\right] = \lim_{y\to x}\partial_\mu[\chi(x) + ig\omega(x-y)]\,\psi(y)$$

➢ **DM propagator**

$$\tau_\psi(x) = \langle\Omega, T[\psi(x)\bar{\psi}\,(0)]\Omega\rangle = \frac{\left\langle\Omega, T\left[\psi^{(0)}(x)\overline{\psi^{(0)}}\,(0)\right]\Omega\right\rangle}{\left(-\kappa^2 x_\mu^2 + i\varepsilon\right)^{g^2/(4\pi)^2}}$$

- ❑ $DM\ \psi(x)\ picked\ up\ anomalous\ dimension\ \ g^2/(4\pi)^2$
- ○ $\kappa - multiplicative\ normalization\ constant\ of\ DM\ \psi(x)$

❖ *Observables.* DM, DP

Ideal system DM-DP -> *Dynamical system with constraints in phase space* Γ

DM-DP: *Dynamical system with physical space* $\mathcal{M} \subset \Gamma$, *surface* $b(x) = 0$

L. Faddeev, 1969

Observables on $\mathcal{M} \Rightarrow$ *weak equations*

$\downarrow$

quantities $\{\dots,\dots\} \approx 0$ *Poisson*

- ❖ Observables local $\{O(x), O(y)\} = 0,\ (x-y)^2 < 0$
- ❖ Observables relatively local $\{O_1(x_1), O_2(x_2)\} = 0,\ (x_1 - x_2)^2 < 0$

$$(i\hat{\partial} - m - g\hat{B})\psi(x) = 0, \qquad \{b(x), B_\mu(y)\} \neq 0, \qquad \{b(x), \psi(y)\} \neq 0,$$

❖ ***Result:*** Both DM field $\psi(x)$ *and DP field* $B_\mu(x)$ are not ***observables***

❖ *Stochastic forces*

Both ***DM*** and ***DP*** are observables under stochastic forces $h_\mu(x)$ ONLY

DP $B_\mu(x)$ $f$luctuations in medium:

probability $P[B_\mu] \sim exp(-G[h_\mu]\beta)$

$$G[h_\mu] = ln \int dB_\mu e^{-\int dx[L(x)+h_\mu(x)B^\mu(x)]}$$

Free energy averaged over fluctuation h_μ

$$F_h = \int dh_\mu G[h_\mu]\, e^{-\int dx h_\mu^n(x)}, \qquad n = 1,2, \dots\, external\ insertions\ of\ h_\mu(x)$$

$$\partial_\mu h^\mu(x) = \delta(x)$$

❖ *Observables.* DM, DP

$$\psi(x) \to \Psi(x; h_\mu) = \left\{ exp\left[ig \int d^4y\, h_\mu(x-y) \times B^\mu(y) \right] \right\} \psi(x)$$

$$(i\hat{\partial} - m - g\hat{B})\psi(x) \to \left[i\hat{\partial} - m - gB_\mu(x; h_\mu)\gamma^\mu \right] \Psi(x; h_\mu) = 0$$

$$\{b(x), \Psi(y; h_\mu)\} = \{b(x), \overline{\Psi}(y; h_\mu)\} = 0; \quad \{b(x), B_\mu(y, h_\mu)\} = 0,$$

$$B^\mu(x, h_\mu) = \int d^4y [g^{\mu\nu}\delta(x-y) - \partial^\mu h_\nu(x-y)] B^\nu(y)$$

Both *DM field* $\Psi(x; h_\mu)$ and *DP field* $B^\mu(x, h_\mu)$ have advantages of involving *observables* only

❖ *Hidden sector.* How it should be explored?

$$L_{int/med} = \sum_{k,l,m,n}^{k+l+m=n+4} \frac{O_{DM}^{(k)}\ O_{DP}^{(l)}\ O_{SM}^{(m)}}{\Lambda^n}$$

Weak scale barrier

O_{DP}: $B_{\mu\nu}$ ***mediator vector operator*** */ Portal to DM*

$At \sim O(GeV)\ \tau_{DP} \geq \tau_{SM}\ \ (meson\ decays\ due\ to\ weak\ int's)$

Assume interplay between ***DM and SM*** mediated by new operators with $d_{tot} = n + 4$

- *Production cross section* $\sigma \sim \epsilon^2 \frac{\zeta^2}{E^2} \left(\frac{E}{\Lambda}\right)^{2n}, d_{tot} = n + 4$

✓ *Collider or Fixed target?*

❖ Dark photon. **Production rate**

$$R_{FT/Coll} = \frac{N_{FT}}{N_{Coll}} = \frac{L_{FT}}{L_{Coll}} \left(\frac{E_{FT}}{E_{Coll}} \right)^{2n-2}$$

$$R_{FT/Coll} = \begin{cases} 10^{11-6n} & \dfrac{100\ GeV\ (p-beam)}{LHC} \\ 10^{14-9n} & \dfrac{100\ GeV\ (e-beam)\ \ SPS\ CERN}{LHC}, \\ 10^{16-11n} & \dfrac{1\ GeV\ (e-beam)\ \ JLab}{LHC} \end{cases}$$

$$n = 0 \quad R_{FT/Coll} \sim 10^{11} - 10^{16}$$

$$n = 1 \quad R_{FT/Coll} \sim 10^{5}$$

$$n = 2 \quad R_{FT/Coll} \sim 10^{-6} - 10^{-1}$$

Conclusion

1. Abelian conformal-gauge model for DP and interactions.

2. DP solution. DP massive.

3. Upper limit for mixing angle estimated $\varepsilon < 3 \cdot 10^{-2}$, S→ $\gamma\gamma^*$

4. ***Dark photon*** parameters predicted m = 0.83 GeV, ε = 7.6· 10^{-3}

5. DM - SM interactions through DP (***the portal***) as non-trivial combination of the derivatives of dilaton field.

6. Influence of Conformal Sector to SM sector.

7. DP production rate for *collider* and *fixed target* modes.


DM
DP is the conformal portal to DM
Thank you!