Gauge Z’ to Geometric Z’: A New WISP

Durmuş Demir

Sabancı University, İstanbul

http://myweb.sabanciuniv.edu/durmusdemir/

Sabancı Üniversitesi

FACULTY OF ENGINEERING AND NATURAL SCIENCES

Cosmic WISPERs Talk (April 17, 2023)

Experiment:

- Heavy Z’ bosons seem to weigh very heavy (CMS and ATLAS: $M_Z' \gtrsim 5\ \mathrm{TeV}$ for SSM Z’ boson) .
- Light Z’ bosons might exist with mass near the WISP domain (Atomki: $M_Z' \simeq 17\ \mathrm{MeV}$) .

Theory:

- Z’ bosons are often associated with some U(1)’ symmetry beyond the SM.
- Z’ bosons can arise also from beyond-the-GR geometry (non-metricity vector in Palatini gravity).

→ this talk

Gauge-Z’ in SUSY (model building):

- **Electroweak breaking and the mu problem in supergravity models with an additional U(1)**
  Mirjam Cvetic, DD, J.R. Espinosa, L.L. Everett, P.Langacker
  hep-ph/9703317 Phys.Rev.D 56 (1997), 2861

- **One loop effects in supergravity models with an additional U(1)**
  DD, N.K. Pak
  hep-ph/9809357 Phys.Rev.D 57 (1998), 6609-6617

- **Two Higgs doublet models from TeV scale supersymmetric extra U(1) models**
  DD
  hep-ph/9809358 Phys.Rev.D 59 (1999), 015002

- **The Minimal U(1)' extension of the MSSM**
  DD, Gordon L. Kane, Ting T. Wang
  hep-ph/0503290 Phys.Rev.D 72 (2005), 015012

- **Renormalization group invariants in the MSSM and its extensions**
  DD
  hep-ph/0408043 JHEP 11 (2005), 003

Gauge-Z’ in SUSY models (collider searches):

- **e+ e- ---> (h A) ---> bbbb in Abelian extended supersymmetric standard model**
  DD, N.K. Pak
  hep-ph/9809355 Phys.Lett.B 411 (1997), 292-300

- **Higgsstrahlung in Abelian extended supersymmetric standard model**
  DD, N.K. Pak
  hep-ph/9809356 Phys.Lett.B 439 (1998), 309-315

- **LEP indications for two light Higgs bosons and U(1)-prime model**
  DD, Levent Solmaz, Saime Solmaz
  hep-ph/0512134 Phys.Rev.D 73 (2006), 016001

- **Search for Gauge Extensions of the MSSM at the LHC**
  Ahmed Ali, DD, Mariana Frank, Ismail Turan
  0902.3826 Phys.Rev.D 79 (2009), 095001

- **Tevatron Higgs Mass Bounds: Projecting U(1)' Models to LHC Domain**
  Hale Sert, Elif Cincioglu, DD, Levent Solmaz
  1005.1674 Phys.Lett.B 692 (2010), 327-335

Gauge-Z’ in SUSY (dark matter):

- **Scalar Neutrinos at the LHC**
  DD, Mariana Frank, Levent Selbuz, Ismail Turan
  1012.5105 Phys.Rev.D 83 (2011), 095001

Gauge-Z’ in SUSY (CP violation):

- **CP violation in supersymmetric U(1) prime models**
  DD, L.L.Everett
  hep-ph/0306240 Phys.Rev.D 69 (2004), 015008

Gauge-Z’ in extra dimensions (dark matter):

- **Stable Q balls from extra dimensions**
  DD
  hep-ph/0006344 Phys.Lett.B 495 (2000), 357-362

Geometric Z’: A new WISP

Palatini Gravity:

$$S_P[g,\Gamma] = \int d^4x \sqrt{-g} \left\{ \frac{M_{Pl}^2}{2} g^{\mu\nu} \mathbb{R}_{\mu\nu}(\Gamma) + \mathcal{L}(\psi_m, {}^g\Gamma) \right\}$$

affine connection $\Gamma^{\lambda}_{\mu\nu}$ has nothing to do with the LC connection ${}^g\Gamma^{\lambda}_{\mu\nu}$

Levi-Civita connection of the metric $g_{\mu\nu}$

$${}^g\Gamma^{\lambda}_{\mu\nu} = \frac{1}{2} g^{\lambda\rho}\left(\partial_\mu g_{\nu\rho} + \partial_\nu g_{\rho\mu} - \partial_\rho g_{\mu\nu}\right)$$

affine Ricci curvature tensor $\mathbb{R}_{\mu\nu}(\Gamma)$ has nothing to do with the usual metrical Ricci curvature $R_{\mu\nu}({}^g\Gamma)$

M. Tsamparlis, J. Math. Phys. 19, 555 (1978)

Palatini Gravity:

- $\frac{\delta S_P[g,\Gamma]}{\delta \Gamma^{\lambda}_{\mu\nu}} = 0 \Longrightarrow {}^{\Gamma}\nabla_{\lambda}\left(\sqrt{-g}\, g^{\mu\nu}\right) = 0 \;\Longrightarrow \Gamma^{\lambda}_{\mu\nu} = {}^{g}\Gamma^{\lambda}_{\mu\nu}$

- $\frac{\delta S_P[g,\Gamma]}{\delta g^{\mu\nu}} = 0 \Longrightarrow \mathbb{R}_{\mu\nu}(\Gamma) - \frac{1}{2} g^{\alpha\beta}\mathbb{R}_{\alpha\beta}(\Gamma) g_{\mu\nu} = T_{\mu\nu}$

- Einstein field equations in GR arise dynamically:

$$R_{\mu\nu}({}^{g}\Gamma) - \frac{1}{2} g^{\alpha\beta} R_{\alpha\beta}({}^{g}\Gamma) g_{\mu\nu} = T_{\mu\nu}$$

- In metrical theory ($\Gamma^{\lambda}_{\mu\nu} = {}^{g}\Gamma^{\lambda}_{\mu\nu}$ from the scratch) it is not possible to get the Einstein field equations without adding extrinsic curvature to cancel out terms like $\partial_{\lambda}(\delta g_{\mu\nu})$ at the boundary of the manifold.

J. York, Phys. Rev. Lett. 28 (1972) 1082

G. Gibbons & S. Hawking, Phys. Rev. D15 (1977)

Extended Palatini Gravity :

$$S_{EP}[g,\Gamma] = \int d^4x \sqrt{-g} \left\{ \frac{M_{Pl}^2}{2} g^{\mu\nu} \mathbb{R}_{\mu\nu}(\Gamma) + \zeta \mathbb{R}_{[\mu\nu]}(\Gamma) \mathbb{R}^{[\mu\nu]}(\Gamma) + \mathcal{L}(\psi_m, {}^g\Gamma\,) \right\}$$

antisymmetric part of the affine Ricci curvature tensor $\mathbb{R}_{\mu\nu}(\Gamma)$:

$$\mathbb{R}_{[\mu\nu]}(\Gamma) = \partial_\mu \Gamma^\lambda_{\lambda\nu} - \partial_\nu \Gamma^\lambda_{\lambda\mu}$$

antisymmetric affine Ricci acts like field strength tensor of an Abelian vector field:

$V_\mu = \Gamma^\lambda_{\lambda\mu}$ and $\mathbb{R}_{[\mu\nu]}(\Gamma) = \partial_\mu V_\nu - \partial_\nu V_\nu$

V_μ is the source of geometric Z' and can be related to non-metricity for a symmetric affine connection: $\Gamma^\lambda_{\mu\nu} = \Gamma^\lambda_{\nu\mu}$

V. Vitagliano et al., Phys. Rev. D 82 (2010) 084007

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Extended Palatini Gravity with Matter:

$$S_{EPm}[g,\Gamma] = \int d^4x\,\sqrt{-g}\,\left\{\frac{M_{Pl}^2}{2} g^{\mu\nu}\mathbb{R}_{\mu\nu}(\Gamma) + \zeta\mathbb{R}_{[\mu\nu]}(\Gamma)\mathbb{R}^{[\mu\nu]}(\Gamma) + \mathcal{L}(\psi_m, \boldsymbol{\Gamma})\right\}$$

matter sector involves affine connection $\Gamma^\lambda_{\mu\nu}$ (not ${}^g\Gamma^\lambda_{\mu\nu}$)

- in general, affine connection $\Gamma^\lambda_{\mu\nu}$ can be written as:

  $\Gamma^\lambda_{\mu\nu} = {}^g\Gamma^\lambda_{\mu\nu} + \frac{1}{2}\, g^{\lambda\rho}\left({}^\Gamma\nabla_\mu g_{\nu\rho} + {}^\Gamma\nabla_\nu g_{\rho\mu} - {}^\Gamma\nabla_\rho g_{\mu\nu}\right)$

- affine connection appears in the fermion kinetic term:

$$\mathcal{L}(\psi_m, \Gamma) \ni \bar\psi\gamma^\mu\left({}^\Gamma\nabla_\mu\psi\right)$$
$$= \bar\psi\gamma^\mu\left(\partial_\mu - \frac{i}{4} e^a_\alpha\, {}^\Gamma\nabla_\mu e^{\beta b}\,\gamma_a\gamma_b\right)\psi$$
$$= \bar\psi\gamma^\mu\left(\nabla_\mu + \frac{1}{2} Q_\mu\right)\psi$$

non-metricity vector:

$$Q_\mu = -{}^\Gamma\nabla^\alpha g_{\alpha\mu}$$

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L. Fatibene *et al.*, gr-qc/9608003 (1996)

M.Adak, T. Dereli, L. Ryder, Int. J. Mod. Phys. D 12 (2003) 145

Geometric-Z' Field with Matter:

Extended Palatini gravity reduces to the GR + Geometric-Z' field:

$$S_{EPm}[g,Y] = \int d^4x\,\sqrt{-g}\,\left\{\frac{M_{Pl}^2}{2}R({}^g\Gamma) - \frac{1}{4}Y_{\mu\nu}Y^{\mu\nu} - \frac{1}{2}M_Y^2 Y_\mu Y^\mu + g_Y Y_\mu \bar{\psi}\gamma^\mu\psi + \mathcal{L}_{rest}(\psi_m, {}^g\Gamma)\right\}$$

- Canonical geometric field: $Y_\mu = 2\sqrt{\zeta}Q_\mu$
- Z'-mass: $M_Y^2 = \frac{3M_{Pl}^2}{2\zeta}$
- Z'-fermion coupling: $g_Y = \frac{1}{4\sqrt{\zeta}}$

matter is described by the GR (no Y_μ in $\mathcal{L}_{rest}$)

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Geometric-Z' Field → Geometric-Z' Boson:

Geometric-Z' can be quantized along with matter fields
(in the spacetime of flat metric $\eta_{\mu\nu}$ by letting $g_{\mu\nu} \rightarrow \eta_{\mu\nu}$):

$$\hat{Y}_\mu = \sum_{\lambda=1}^{3} \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{1}{\sqrt{2\omega(\vec{p})}} \left\{ \hat{a}(\vec{p},\lambda) \epsilon^{\mu}(\vec{p},\lambda) e^{-ip\cdot x} + \hat{a}^{\dagger}(\vec{p},\lambda) \epsilon^{\star\mu}(\vec{p},\lambda) e^{-ip\cdot x} \right\}$$

- with the commutation relation: $\left[\hat{a}(\vec{p},\lambda), \hat{a}^{\dagger}(\vec{p}',\lambda')\right] = \mathrm{i}\, \delta^3(\vec{p}\text{-}\,\vec{p}')\delta_{\lambda\lambda'}$

- and the polarization sum: $\sum_{\lambda=1}^{3} \epsilon^{\mu}(\vec{p},\lambda)\epsilon^{\star\nu}(\vec{p},\lambda) = \eta^{\mu\nu} - \frac{p^\mu p^\nu}{M_Y^2}$

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Geometric-Z' Boson as WISP:

- Property 1: $\hat{Y}_\mu$ couples only to fermions and $\hat{Y}_\mu$-fermion coupling is universal.

- Property 2: Lighter the $\hat{Y}_\mu$ smaller its couplings to fermions $\left(M_Y^2 \sim \frac{M_{Pl}^2}{g_Y^2}\right)$.

- Lighter the $\hat{Y}_\mu$ boson slower its decay into fermion/anti-fermion pairs.

- If the life-time of $\hat{Y}_\mu$ is longer than the age of the Universe, it can live around as a non-gauge massive Z'-boson and contribute to various processes at the Intensity Frontier.

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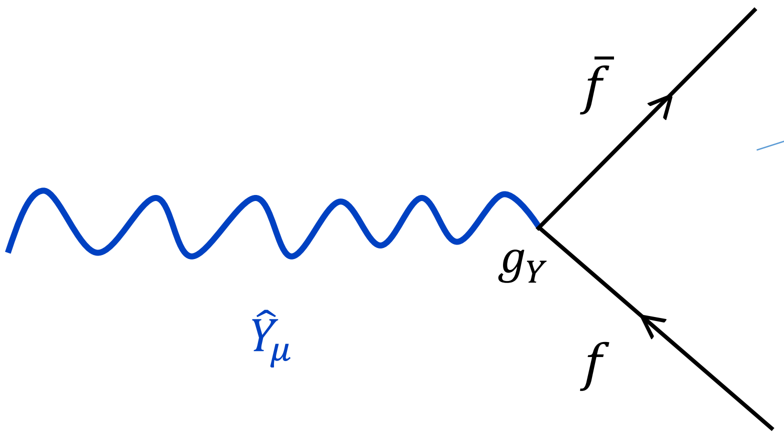
Geometric-Z' Boson as WISP

Life-time of geometric-Z' is a sensitive function of ζ:



no decay into particles other than fermions

- Decay rate: $\Gamma\left(Y \rightarrow f\bar{f}\right) = \frac{N_c^f}{8\pi}\left(\frac{3}{2\zeta}\right)^{\frac{3}{2}}\left(1+\frac{4\zeta m_f^2}{3M_{Pl}^2}\right)\left(1-\frac{8\zeta m_f^2}{3M_{Pl}^2}\right)^{\frac{1}{2}} M_{Pl}$

- Life-time: $\tau_Y = \frac{1}{\sum_f \Gamma(Y\rightarrow f\bar{f})}$

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Geometric-Z’ Boson as WISP (=Feebly-Interacting WISP)

- Y_μ can itself be a WISP: $M_Y = 1\ \mathrm{eV}$

- Y_μ couples feebly to fermons: $g_Y = \frac{1}{24}\left(\frac{M_Y}{M_{Pl}}\right) \approx 10^{-28}$

- Life-time: $\tau_Y = 3\times 10^{24}\ \mathrm{Gyr} \gg \tau_{\mathrm{Universe}}$

- $\hat{Y}_\mu$ is a feebly-interacting dark matter candidate.

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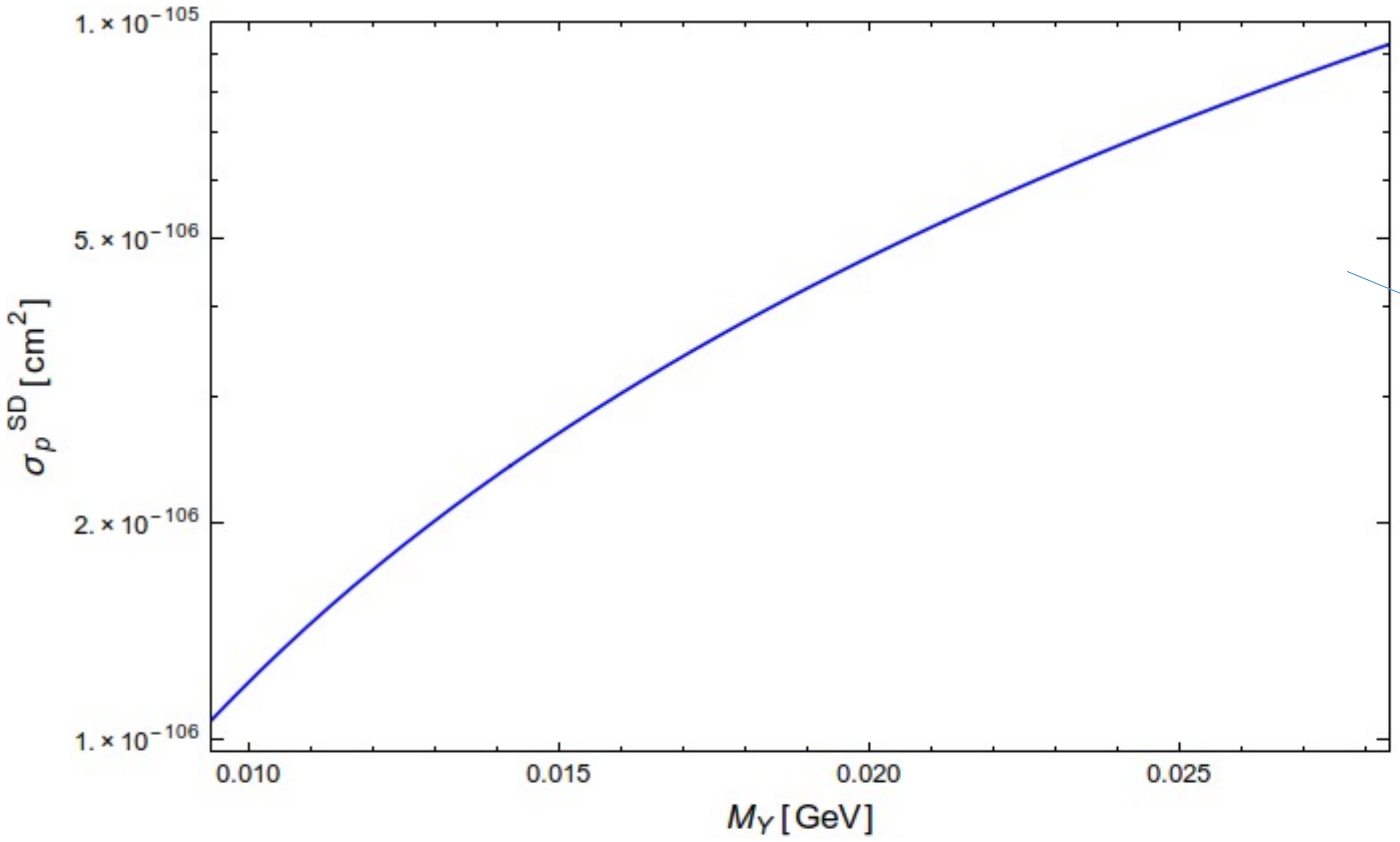
Geometric-Z' Boson as WISP (=Feebly-Interacting WISP)

- Y_μ is undetectable within today's experimental precision limits:



reason for negative results from dark matter searches?

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Geometric-Z' Boson as WISP (=Weakly Interacting WISP)

Extended Palatini gravity augmented with metrical curvature:

$$S_{EPMm}[g,\Gamma] = \int d^4x \sqrt{-g} \left\{ \frac{M^2}{2} g^{\mu\nu} R({}^{g}\Gamma) + \frac{\overline{M}^2}{2} g^{\mu\nu} \mathbb{R}_{\mu\nu}(\Gamma) + \zeta \mathbb{R}_{[\mu\nu]}(\Gamma) \mathbb{R}^{[\mu\nu]}(\Gamma) + \mathcal{L}(\psi_m, \boldsymbol{\Gamma}) \right\}$$

matter curvature sector now involves also the metrical LC connection ${}^{g}\Gamma^{\lambda}_{\mu\nu}$

- main difference from extended Palatini gravity is that affine curvature generates only part of the EH term.

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Geometric-Z’ Boson as WISP (=Weakly Interacting WISP)

In this extended Palatini gravity with metrical curvature, geometric-Z’ possesses the following properties:

$$S_{EPMm}[g, Y] = \int d^4x \sqrt{-g} \left\{ \frac{M_{Pl}^2}{2} R({}^g\Gamma) - \frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} - \frac{1}{2} M_Y^2 Y_\mu Y^\mu + g_Y Y_\mu \bar{\psi} \gamma^\mu \psi + \mathcal{L}_{rest}(\psi_m, {}^g\Gamma) \right\}$$

- Planck scale is composed of the two masses:
  $M_{Pl}^2 = M^2 + \bar{M}^2$

- Z’-mass: $M_Y^2 = \frac{3\bar{M}^2}{2\zeta}$

- Z’-fermion coupling: $g_Y = \frac{1}{4\sqrt{\zeta}}$

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Geometric-Z’ Boson as WISP (=Weakly-Interacting WISP)

In this extended Palatini gravity with metrical curvature, tight bounds on geometric Z’-couplings get lifted:

- Y_μ can be a WISP: $M_Y = 1\ \mathrm{eV}$ → this small value can be achieved without a large ζ: $\overline{M} \sim \mathrm{eV}$ and $\zeta \sim 1$

- Life-time: $\tau_Y \sim \frac{1}{M_Y} \sim 1\ \mathrm{psec}$ since $\Gamma\left(Y \rightarrow f\bar{f}\right) \sim M_Y$

- $\hat{Y}_\mu$ is a weakly-interacting WISP-scale light particle.

- $\hat{Y}_\mu$ can mediate interaction between visible and dark sectors at the WISP scale.

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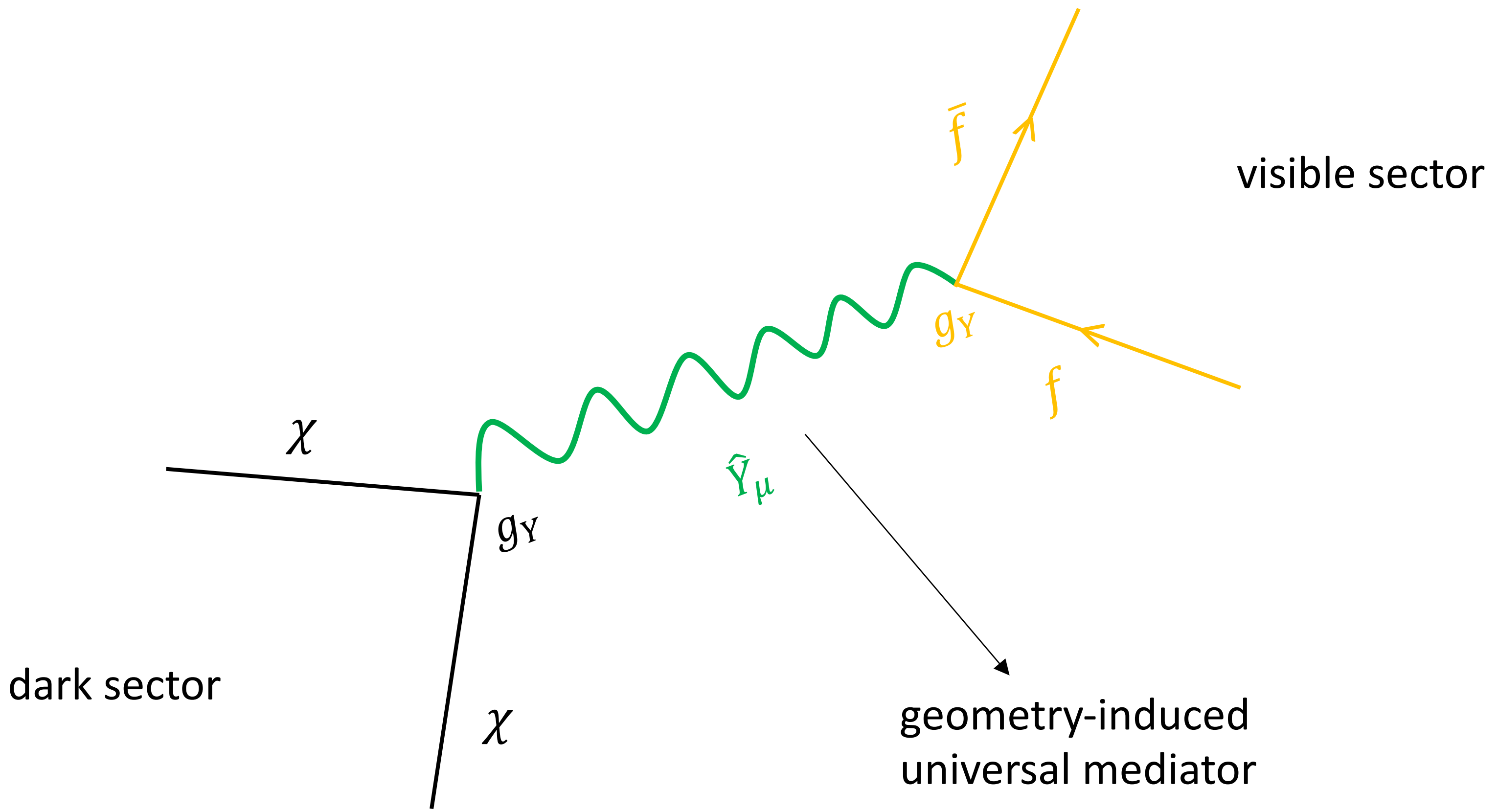
Geometric-Z’ Boson as WISP (=Weakly Interacting WISP)



THANK YOU !