Searching for dark photon

Haipeng An
Caltech
Seminar at USTC
The standard model is very successful!
The big challenge

- We just discovered a massless spin-2 particle.

- We don’t know how to write down a quantum field theory for it yet.

- The leading solution is string theory.

- The ultimate form of various string theories is believed to be the $\mathcal{M}$ theory, which is the central topic of ICTS.
But when we look up into the sky …

- The rotation curves of galaxies

![Graph showing observed and predicted rotation curves.](Image)
But when we look up into the sky …

- Either Newtonian gravity (as well as general relativity) needs to be modified or there is more stuff (dark matter) we cannot see.

Bullet cluster

Visible stuffs are displaced from the centers of gravitational potential.

Strong support of dark matter!
Other evidences for dark matter

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What do we know about dark matter?

- Dark (cannot block light)
- Relic abundance $\sim 1/4$
- Cold (non-relativistic)
- Gravitates (like ordinary matter)
What do we know about dark matter?

- Dark (cannot block light)
- Relic abundance ~ 1/4
- Cold (non-relativistic)
- Gravitates (like ordinary matter)

- Do we know its mass? No
- Interactions with us other than gravity? No idea
- Self interaction? Maybe …
- What is the origin of dark matter? Maybe thermal relic …
How to answer these questions?

![Diagram showing direct and indirect detection for Dark Photon (χ) in the Standard Model (SM)]
Dark matter direct detection

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Dark matter indirect detection

PAMELA

Fermi

DAMPE (悟空)

AMS02

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Dark matter production
Any signals from dark matter?

- Direct detection
  - DAMA, CoGeNT (both excluded by larger experiments, CDEX)
- Collider searches
  - Nothing yet …
- Indirect detections?
  - PAMELA positron access later confirmed by Fermi and AMS02
    - (Might be purely from secondary scattering …)
  - Fermi GeV access from the Galactic center
    - (Might be from point-like sources …)
Dark matter indirect detection

0810.4995, Nature 2009

PRL 110, 141102, 2013

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Long range dark force

- One possible origin: dark matter annihilation at the galactic center
  
  $\langle \sigma v \rangle_{\text{GC}} \approx 10^{-23} \text{ cm}^3\text{sec}^{-1}$

- If dark matter relic abundance is from thermal annihilation,
  
  $\langle \sigma v \rangle_{\text{Th}} \approx 3 \times 10^{-26} \text{ cm}^3\text{sec}^{-1}$

- A boost factor is needed.
  
  $S_B \approx \mathcal{O}(100)$
What is the difference?

- At GC, $v \sim 10^{-3} c$;
- During dark matter freeze-out, $v \sim 0.3 c$. 
Long range dark force

- What is the difference?
  - At GC, $v \sim 10^{-3} \, c$;
  - During dark matter freeze-out, $v \sim 0.3 \, c$.
- A long range attractive force can enhance the annihilation rate at low velocity (Sommerfeld enhancement).

Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
Pospelov, Ritz 0810.1502
Small scale structure anomalies

- **Too big to fail problem**  
  - Cold dark matter simulation predicts much more Galactic dwarf satellites than observed.

- **Core/Cusp problem**  
  - Cold dark matter simulation predicts the dark matter distribution has a cusp at the center of dwarf galaxies.
  - What observed is a core.

*Flores, Primack APJ 1994 & Moore, Nature 1994*
Small scale structure anomalies

- People are still debating on if the traditional Lambda CDM model with baryonic feedback can solve these problems or not.

_Hopkins et al 1602.05957_
Small scale structure anomalies

- People are still debating on if the traditional Lambda CDM model with baryonic feedback can solve these problems or not. *Hopkins et al 1602.05957*

Small scale structure anomalies

- People are still debating on if the traditional Lambda CDM model with baryonic feedback can solve these problems or not.
  
  Hopkins et al 1602.05957

- Self interacting dark matter might be the solution to the problem.
  

- The most prominent model for Sommerfeld enhancement and self-interacting dark matter

  ------- the dark photon model
The dark photon model

- Lagrangian \[ \mathcal{L} = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} m_V^2 V^\mu V_\mu - \frac{1}{2} \kappa V^{\mu\nu} F_{\mu\nu} \]

- \( V_\mu \): dark photon vector boson
- \( V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \): dark photon field strength tensor
- \( m_V \): mass of dark photon
- \( \kappa \): kinetic mixing between photon and dark photon
- \( F_{\mu\nu} \): photon field strength tensor
The dark photon model

- **Lagrangian**  \[ \mathcal{L} = -\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}m^2_\nu V^\mu V_\mu - \frac{1}{2}\kappa V^{\mu\nu}F_{\mu\nu} \]

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  \( F_{\mu\nu} \): photon field strength tensor

I am going to explore the parameter space of this model, focusing on the works I have done with my collaborators.
The dark photon model

- Lagrangian: \[ \mathcal{L} = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} m_V^2 V^\mu V_\mu - \frac{1}{2} \kappa V^{\mu\nu} F_{\mu\nu} \]

- \( m_V > 1 \text{ MeV} \)  \hspace{1cm} V \rightarrow e^+ e^-

The dark photon decays fast and can be the mediator of the dark force.
The dark photon model

- **Lagrangian**
  \[ \mathcal{L} = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} m_V^2 V^\mu V_\mu - \frac{1}{2} \kappa V^{\mu\nu} F_{\mu\nu} \]

- **\( m_V > 1 \text{ MeV} \)**
  \[ V \rightarrow e^+ e^- \]
  The dark photon decays fast and can be the mediator of the dark force.

- **\( m_V < 1 \text{ MeV} \)**
  \[ V \rightarrow 3\gamma \quad \text{Landau-Yang theorem} \]
  \[ \Gamma_V \propto \frac{\kappa^2 \alpha^4 m_V^9}{m_e^8} \]
  The dark photon can easily be cosmologically stable, and play the roll of dark matter.
Outline of the talk

- Phenomenology of dark photon as a dark matter candidate
  \[ m_V < 1 \text{ MeV} \]
  - Dark photon from the Sun
  - Dark photon dark matter

- Phenomenology of dark photon as dark force mediator
  \[ m_V > 1 \text{ MeV} \]
  - Collider searches for dark bound states
  - Dark matter annihilation via bound state formation
$m_V < 1$ MeV

- People were using CAST experiment and light-shining-through-the-wall experiment to detect light dark photon
A diagram showing the region of the parameter space $m_V < 1 \text{ MeV}$ where $m_V$ is the mass of a dark photon. The diagram includes regions labeled 'Coulomb', 'Rydberg', and 'Solar Lifetime', with direct searches indicated. The text 'Redondo (JCAP 2008)' is noted on the right side of the diagram.
Solar dark photon

Solar life time
Redondo (JCAP 2008)

New solar dark radiation constraint
HA, M.Pospelov, J.Pradler 1302.3884&PLB
Comparison between photon and dark photon

- Photon: massless, two transverse modes
- Dark photon: massive, two transverse modes, one longitudinal mode.
Solar dark photon

- Matrix element

\[
\begin{align*}
| i \rangle & \quad J_{em} \quad A \\ & \quad V_{\mu} \\ | f \rangle
\end{align*}
\]
Solar dark photon

- Matrix element

\[ \left| f \right> \]

\[ J_{em} \]

\[ \left| i \right> \]

\[ \frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} \rightarrow \kappa A_\nu \partial_\mu V^{\mu\nu} \]

E.O.M

\[ \kappa m_V^2 A_\nu V^\nu \]
Solar dark photon

Matrix element

\[ -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} \rightarrow \kappa A_\nu \partial_\mu V^{\mu\nu} \]

E.O.M

\[ \kappa m_V^2 A_\nu V^\nu \]

Feynman gauge:

\[ \frac{1}{\kappa^2} \]
Solar dark photon

- Matrix element

\[ \left| f \right> \quad J_{em} \quad \left| i \right> \]

\[ \begin{align*}
- \frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} & \rightarrow \kappa A_\nu \partial_\mu V^{\mu\nu} \\
E.O.M & \\
\kappa m_V^2 A_\nu V^\nu & \\
\frac{1}{k^2} & \rightarrow \frac{1}{k^2 - \Pi_{T,L}}
\end{align*} \]

Feynman gauge:
Solar dark photon

- Matrix element

\[ \frac{-\kappa}{2} F_{\mu\nu} V^{\mu\nu} \rightarrow \kappa A_\nu \partial_\mu V^{\mu\nu} \]

E.O.M

\[ \kappa m_V^2 A_\nu V^\nu \]

\[ \Pi^{\mu\nu} = e^2 \langle J_\text{em}^\mu, J_\text{em}^\nu \rangle = \Pi_T \epsilon_i^{T\mu} \epsilon_i^{T\nu} + \Pi_L \epsilon_i^{L\mu} \epsilon_i^{L\nu} \]

Feynman gauge:

Plasma effect

\[ \frac{1}{k^2} \rightarrow \frac{1}{k^2 - \Pi_{T,L}} \]
Solar dark photon

- Matrix element

\[ \langle f | e^2 \langle J^\mu_{\text{em}}, J^\nu_{\text{em}} \rangle | i \rangle = \Pi_T \epsilon^T_i \epsilon^T_\nu + \Pi_L \epsilon^L_\mu \epsilon^L_\nu \]

\[ \mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}} [e J^\mu_{\text{em}}]_{fi} \epsilon^{T,L}_\mu \]

E.O.M

\[ - \frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} \rightarrow \kappa A_\nu \partial_\mu V^{\mu\nu} \]

\[ \kappa m_V^2 A_\nu V^\nu \]

Feynman gauge:

\[ \frac{1}{k^2} \rightarrow \frac{1}{k^2 - \Pi_{T,L}} \]

Plasma effect
Solar dark photon

\[ M = -\frac{\kappa m_{V}^{2}}{m_{V}^{2} - \Pi_{T,L}} [eJ_{\text{em}}^{\mu}]_{fi} \epsilon_{\mu}^{T,L} \]

\[ \Pi^{\mu\nu} = e^{2} \langle J_{\text{em}}^{\mu}, J_{\text{em}}^{\nu} \rangle = \Pi_{T} \epsilon_{i}^{T \mu} \epsilon_{i}^{T \nu} + \Pi_{L} \epsilon_{i}^{L \mu} \epsilon_{i}^{L \nu} \]

- Inside a thermal plasma (with NR electrons)
- For transverse modes

\[ \text{Re}\Pi_{T} = \omega_{p}^{2} = \frac{4\pi \alpha_{\text{em}} n_{e}}{m_{e}} \quad m_{V} \to 0 \quad M_{i\to f+\nu_{T}} \sim \frac{m_{V}^{2}}{\omega_{p}^{2}} \]
Solar dark photon

\[ \mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}} [eJ_{\text{em}}^\mu] f_i \epsilon^T_{\mu} \]

\[ \Pi^{\mu\nu} = e^2 \langle J_{\text{em}}^\mu, J_{\text{em}}^\nu \rangle = \Pi_T \epsilon_i^T \epsilon_i^T + \Pi_L \epsilon^L \epsilon^L \]

- Inside a thermal plasma (with NR electrons)
  - For transverse modes
    \[ \text{Re} \Pi_T = \omega_p^2 = \frac{4\pi \alpha_{\text{em}} n_e}{m_e} \quad m_V \to 0 \quad \Rightarrow \quad \mathcal{M}_{i\to f+V_T} \sim \frac{m_V^2}{\omega_p^2} \]
  - For longitudinal mode
    \[ J_{\text{em}}^\mu \epsilon^L_{\mu} \sim m_V \quad \Rightarrow \quad \Pi_L \sim m_V \quad m_V \to 0 \quad \Rightarrow \quad \mathcal{M}_{i\to f+V_L} \sim m_V \]

\[ \text{Re} \Pi_L = \omega_p^2 \left( 1 - \frac{|\vec{k}|^2}{\omega^2} \right) \]
Solar dark photon

- Inside the Sun, because of the plasma effect
  - Longitudinal flux dominates for $m_v << E$.
  - The previous calculation of the longitudinal flux was completely wrong.

\[
\Gamma_T \propto (m_V/E)^4 \quad \Gamma_L \propto (m_V/E)^2
\]

*HA, M.Pospelov, J.Pradler 1302.3884&PLB*
Solar dark photon

- Why CAST is not sensitive?
  - In the vacuum, photon only has transverse modes
  - In materials, photon develops longitudinal mode.

- The detector should contain a large volume of materials
  ------ the dark matter detector
Solar dark photon

- Resonant production

\[ \mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}} [e J_{\text{em}}^\mu f_i \epsilon_{\mu}^{T,L} \]  

Transverse resonance

\[ m_V^2 = \text{Re}\Pi_T = \omega_p^2 \]

Longitudinal resonance

\[ m_V^2 = \text{Re}\Pi_L = \omega_p^2 m_V^2 / \omega^2 \]

\[ \omega^2 = \omega_p^2 \]
Solar dark photon

- Longitudinal resonant production

\[ \omega \approx \omega_p, \ 1 \text{ eV} < \omega_p < 300 \text{ eV} \]

The detector should be able to detect \( \sim 100 \text{ eV} \) energy deposition.

\[ HA, M.\text{Pospelov, J.\text{Pradler 1309.6599}} \]
We are looking at electron recoils.

Up to now only XENON10 collaboration has published the result in this energy region.

$1 \text{ eV} \lesssim E_r \lesssim 300 \text{ eV}$
Solar dark photon

Constraint from solar dark radiation

HA, M.Pospelov, J.Pradler
1302.3884&PLB

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Dark photon dark matter

- Coherent oscillation

\[ \frac{1}{2} m^2 \nu V^2 \]

- The longitudinal mode of dark photon can be produced during inflation, and keep oscillating till today to be a dark matter candidate.

*Graham, Mardon, Rajendran 1504.02102*
Dark photon dark matter

- Nonrelativistic
  \[ v \sim 10^{-3} \quad \omega \approx m_V \]
- Can be detected by XENON if \( m_V > 12 \) eV.
Dark photon dark matter

HA, M.Pospelov, J.Pradler, A.Ritz 1412.8378
HA, M.Pospelov, J.Pradler, A.Ritz, K.Ni 1510.04530

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Summary for $m_V < 1$ MeV

- We have shown how to detect the solar dark photon and dark matter dark photon with XENON10.

- In principle all the dark matter detectors can used to search for dark photon, it is very important to understand the electron recoil background.

- A lot of new proposals are on the way.
$m_V > 1$ MeV

- Dark photon decays into charged particles
  - Beam damp experiments
  - Bump searches
  - Electron and muon g-2
  - Meson decays
  - Electroweak precision test
  - Supernova
$m_V > 1$ MeV

- Dark photon decays into charged particles

\[ K^\pm \rightarrow \pi^\pm \pi^0, \quad \pi^0 \rightarrow \gamma V, \quad V \rightarrow e^+e^- \]

$K^\pm$ decay, mixing with $Z$ boson

$e^+e^- \rightarrow \gamma V, \quad V \rightarrow e^+e^-, \mu^+\mu^-$

H. AN – Seminar @ USTC – Searching for Dark Photon
$m_V > 1 \text{ MeV}$

- Dark photon decays into charged particles

Very little information from dark matter!
Searching for dark bound states

- Searching for dark photon as the dark force mediator
  - How to know it carries the dark force?
  - If the dark force is strong enough, dark bound states can be produced at the colliders.
  - We propose to use high luminosity B-factories to search for dark bound states.  
    \textit{HA, Echenard, Pespelov, Zhang 1510.05020 & PRL}
Searching for dark bound states

$H$, Echenard, Pespelov, Zhang 1510.05020 & PRL

$\kappa$ vs. $m_V$ (GeV)

- (current limit, $\alpha_D=0.25$)
- (current limit, $\alpha_D=0.5$)
- (future limit, $\alpha_D=0.25$)
- (future limit, $\alpha_D=0.5$)

No bound states
Bound state effects on dark matter indirect detection

- The Sommerfeld enhancement

If the dark photon is light enough, dark bound state can form by emitting a dark photon.
In the limit $m_V \to 0$

- Sommerfeld enhancement

\[ \sigma v = \frac{\pi \alpha_D^2}{m_D^2} \frac{2\pi \alpha_D}{v} \]

- Kramer’s formula

\[ \sigma v = \frac{128\pi \alpha_D^3}{3\sqrt{3}m_D^2v} \log \left( \frac{\alpha_D}{v} \right) \]
Bound state effects on dark matter indirect detection

- In the limit $m_V \to 0$

\[ \frac{\sigma v_{\text{Kramer}}}{\sigma v_{\text{Sommerfeld}}} \approx 4 \times \log \left( \frac{\alpha D}{v} \right) \]

\[ \int \frac{dE}{E} = \sum_n \frac{\alpha^2 \mu/n^3}{\left( \frac{1}{2} \frac{\alpha^2 \mu}{n^2} + \frac{1}{2} \mu v^2 \right)} \approx 2 \log \left( \frac{\alpha}{v} \right) \]
Bound state effects on dark matter indirect detection

- In the limit $m_V \rightarrow 0$

\[ \frac{\sigma v_{\text{Kramer}}}{\sigma v_{\text{Sommerfeld}}} \approx 4 \times \log \left( \frac{\alpha_D}{v} \right) \]

- For gamma rays from the galactic center $v \sim 10^{-3} c$

- The logarithmic factor is from the infrared divergence.

- Famous people sometimes also miss the leading contribution.
Bound state effects on dark matter indirect detection

Bound states do not exist

Bound states cannot form today or during recombination

Focus of this study

Inconsistent with LUX, SN&BBN

CMB

$\alpha_D > 0.3$

Bound states do not exist

Inconsistent with LUX, SN&BBN

Focus of this study

$\alpha_D > 0.3$

 Bound states cannot form today or during recombination

Bound states do not exist
Bound state effects on dark matter indirect detection

$\sigma$ (GeV$^{-2}$)

$m_V$ (GeV)

HA, Wise, Zhang 1604.01776

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Bound state effects on dark matter indirect detection

- Constraints from the Galactic center gamma rays

HA, Wise, Zhang 1604.01776

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Future works for dark bound states

- Collider searches
  - Other high luminosity colliders (SeaQuest, HPS …)

- Cosmic rays
  - Gamma rays from dwarf galaxy
  - Anti-proton constraint from the AMS02
  - Dark matter annihilate inside the Sun & the earth
  - Sensitivity of DAMPE (future)
Summary

- Dark photon model is a well motivated model for dark matter self-interaction and dark matter itself.
- There is still a lot of work to do.

Thank you for your attention!