## Direct Detection of Dark Photon Dark Matter

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#### Dark Photons

= massive Vector with kinetic mixing to the photon

Two ways to think about 
$$-rac{\kappa}{2}F_{\mu
u}V^{\mu
u}$$

Keep the mixing:



 $eA_{\mu}J^{\mu}_{EM}$ 

Photon-Dark Photon mixing manifest

Or diagonalize kinetic term:



$$eA'_{\mu}J^{\mu}_{EM}-\kappa eV'_{\mu}J^{\mu}_{EM}$$

Ordinary matter has millicharge under new force

#### Dark Photons

#### a simple model - an active field



(g-2) explanation of the muon is now excluded from CERN SPS Kaon facility through  $\pi^0 \rightarrow \gamma e^+ e^-$ 

# Dark Photons bigger picture



(Fig. from Jaeckel 2013)

## Can we make Dark Photon Dark Matter?

Checklist:

- is stable on cosmological timescales
- has the correct relic density
- large scale adiabatic fluctuations
- preferably detectable

## Decay of sub-MeV Dark Photons

Stability:

- 1. Make it light, below  $2m_e$ . Prevents  $V \rightarrow e^+e^-$  decay
- 2. Have small  $\kappa \ll 1$ , to slow down  $V \to 3\gamma$

$$\Gamma_{V \to 3\gamma} = \frac{17\kappa^2 \alpha^4}{2^7 3^6 5^3 \pi^3} \frac{m_V^9}{m_e^8}$$

 $V \sim \gamma$ 

Pospelov, Ritz, Voloshin 2008 (see also Redondo, Postma 2008)

=> Vectors can be have lifetime greater than the Universe

## Thermal abundance

Abundance, early Universe production:

1. thermal production through Compton scattering, e-pair annihilation



For values of the mixing angle that are not already challenged by experiment for  $m_V \gtrsim 1 \,\mathrm{eV}$ , such rates are sub-Hubble.

#### Matter effects



Coupling of V to EM current inside a medium

#### Matter effects



Coupling of V to EM current inside a medium

=> effective mixing angle  $\kappa_{T,L} = \kappa \times \frac{m_V^2}{|m_V^2 - \Pi_{T,L}|}$ 

#### Matter effects

$$\kappa_{T,L} = \kappa \times \frac{m_V^2}{|m_V^2 - \Pi_{T,L}|}$$

$$\operatorname{Re} \Pi_{T,L} \propto \omega_p^2 \sim \alpha T^2 \quad (T \gg m_e)$$
$$\operatorname{Re} \Pi_{T,L} (\omega, T_{r,T,L}) = m_V^2$$

=> effective mixing angle
suppressed at high T
=> production shuts off

=> Resonance may appear

Resonance dominates the production for light vectors at  $T \sim m_e$  but is not efficient to reach a dark matter abundance in ROI  $m_V \gtrsim 1 \,\mathrm{eV}$ 

> see Redondo, Postma 2008 & Arias et al 2012 [for mV > 2 me see also Fradette, Pospelov, JP, Ritz 2014]

## Dark Photon Dark Matter

Abundance, early Universe production:

- 1. thermal production X
- 2. resonant production X
- 3. non-thermal production:

e.g. field can be generated during inflation

Quantum fluctuations yield abundance "for free"

$$\Omega_V \sim 0.3 \sqrt{\frac{m_V}{1\,{\rm keV}}} \left(\frac{H_{\rm inf}}{10^{12}\,{\rm GeV}}\right)$$

Graham, Mardon, Rajendran 2015

with adiabatic fluctuations on large scales

## Dark Photon Dark Matter

Detection:

- 1. Small mass ~ keV means large number density  $n_{\rm DM} = \rho_{\rm DM}/m_{\rm DM}$
- photo-ionization cross sections of ordinary photons can be huge, say, 10<sup>7</sup> bn

Those compensating factors make up for tiny coupling  $\kappa \ll 10^{-10}$  that renders V stable on cosmological timescale!

=> absorption of ~keV vectors can be looked for in electron band

#### Dark Photon Absorption

(including medium effects)

Amplitude: 
$$\mathcal{M}_{i \to f+V_{T,L}} = -\frac{e\kappa m_V^2}{m_V^2 - \Pi_{T,L}(q)} \langle p_f | J_{em}^{\mu}(0) | p_i \rangle \varepsilon_{\mu}^{T,L}(q)$$

Rate: 
$$\Gamma_{T,L} = \frac{e^2}{2\omega} \int d^4x \, e^{iq \cdot x} \kappa_{T,L}^2 \varepsilon_{\mu}^* \varepsilon_{\nu} \langle p_i | [J_{em}^{\mu}(x), J_{em}^{\nu}(0)] | p_i \rangle$$
  
Effective mixing angle Related to the pole inside the medium in the medium in the medium

$$\kappa_{T,L}^2 = \kappa^2 \times \frac{m_V^4}{|m_V^2 - \Pi_{T,L}|^2}$$

arization ohoton 

$$\Pi^{\mu\nu} = \Pi_T \sum_{i=1,2} \epsilon_i^{T\mu} \epsilon_i^{T\nu} + \Pi_L \epsilon^{L\mu} \epsilon^{L\nu}$$

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$$\Gamma_{T,L} = -\frac{\kappa_{T,L}^2 \operatorname{Im} \Pi_{T,L}}{\omega}$$

Absorption rate given by the imaginary part of the polarization functions

An, Pospelov, JP, 2013 An, Pospelov, JP, Ritz 2014

## Absorption in Xenon

Compute absorption rate from refractive index (via tabulated atomic X-ray data, using Kronig-Kramers relations)

$$\Pi_T = \omega^2 (1 - n_{\text{refr}}^2)$$
$$\Pi_L = (\omega^2 - \bar{q}^2)(1 - n_{\text{refr}}^2)$$

In the non-relativistic limit:

$$|\vec{q}| \ll \omega : \Pi_L = \Pi_T = \Pi$$



## Absorption in LXe

Ionization-only S2 analyses amply suited for Dark Photon search.

Drifting charges in an electric field is a powerful amplification mechanism

 $E_{\rm ion}({\rm Xe}) = 12 \, {\rm eV}$ 

Sensitivity to Dark Photons of  $m_V > 12 \,\mathrm{eV}$ 

 $Xe I + V \rightarrow Xe II + e^{-}$ 

Absorption of, say,  $m_V = 300 \,\mathrm{eV}$ can produce ~25 electrons.



## Absorption in XENON10

Ionization-only signal S2 pushes sensitivity for sub-keV signals

Despite uncertainties in electron yield, calibration, and background we can set a robust limit:

- 1. count all events
- 2. do not subtract backgrounds
- 3. infer limit *irrespective* of electron yield



XENON10 collaboration, 2011

## Absorption in XENON100

S1 and S2



predicted Dark Photon scintillation signal (S1)

#### **Direct Detection Limits**



# Astrophysical Limits - I





gamma rays and CMB limits exclude Dark Photon Dark Matter heavier than ~ few x 100 keV

[gamma ray limits quantitatively identical to previous estimates]

10<sup>3</sup>

m<sub>V</sub> (eV)

10<sup>4</sup>

XENON10 XENON100

10<sup>1</sup>

 $10^{-16}$ 

XMASS diffuse γ

CMB

10<sup>2</sup>

10<sup>6</sup>

10<sup>5</sup>

## Astrophysical Limits II - Stars

Particles with mass < O(keV) are kinematically accessible and can be produced. E.g. axions



Stars supported by radiation pressure (active stars):

=> Gravitational potential energy becomes more negative (tighter bound)

=> average kinetic energy increases, star becomes hotter (negative heat capacity)  $\langle E_{\rm kin} \rangle = -\frac{1}{2} \langle E_{\rm grav} \rangle$ 

#### Stellar V-production



Transverse Resonance

$$m_V^2 = \operatorname{Re} \Pi_T = \omega_p^2$$

Longitudinal Resonance

$$m_V^2 = \operatorname{Re} \Pi_L = \omega_p^2 m_V^2 / \omega^2$$
$$\Leftrightarrow \omega^2 = \omega_p^2$$

$$\frac{d\Gamma^{\text{prod}}}{d\omega} \simeq \left(\frac{2r^2}{e^{\omega/T(r)} - 1} \frac{\sqrt{\omega^2 - m_V^2}}{|\partial \omega_P^2(r)/\partial r|}\right)_{r=r_{\text{res}}} \times \begin{cases} \kappa^2 m_V^2 \omega^2 & \text{longitudinal,} \\ \kappa^2 m_V^4 & \text{transverse,} \end{cases}$$

longitudinal: An, Pospelov, JP 2013 transverse: Redondo 2008

## Dark Photon Dark Matter

Position of stellar limits understood from:

Sun  $\omega_P(r=0) \simeq 300 \,\mathrm{eV},$ HB  $\omega_P(r=0) \sim 2.6 \,\mathrm{keV},$ RG  $\omega_P(r=0) \sim 200 \,\mathrm{keV}.$ 

Astrophysical limits are strong, but direct detection can probe unchartered territory

=> improvement potential if experimental e-backgrounds are better understood.



An, Pospelov, JP, Ritz PLB 2015

# "Simplified Models" of super-WIMP absorption

(in contrast to WIMP-nucleon scattering)

(pseudo)scalar (pseudo)vector tensor

$$g_{S}S\bar{\psi}\psi, \quad g_{P}P\bar{\psi}\gamma_{5}\psi, \\ g_{V}V_{\mu}\bar{\psi}\gamma_{\mu}\psi, \quad g_{A}\mathcal{A}_{\mu}\bar{\psi}\gamma_{\mu}\gamma_{5}\psi, \\ g_{T}T_{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi, \quad \cdots$$

If the DM mass is not protected by some symmetry (like for dark photons or axions), loop corrections induce a mass shift

$$\Delta m \sim g_i \Lambda_{\rm UV} \implies g_i \lesssim 10^{-10} \text{ for } m \sim 100 \,\mathrm{eV}$$

As we have just seen, such couplings in the "naturalness regime" are being probed by direct detection!

# Summary

Light (keV and below), very weekly interacting particles ("super-WIMPs") are probed efficiently through stellar cooling or related astrophysical processes.

Dark Photons (hidden photons, A', ...) can be super-WIMPs and they can be dark matter through non-thermally generated abundance.

Liquid scintillator direct detection experiments allow to test for Dark Photon Dark Matter for vector masses > 10 eV.

Thank you.