Review of dark photon searches

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The 3rd BNU dark matter workshop

Dec 7, 2019, Zhuhai

What is dark photon?

- A vector boson coupled to the SM sector only through kinetic mixing with the photon and Z0.

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{1}{2}\kappa' V_{\mu\nu} \underbrace{B^{\mu\nu}}_{F^{\mu\nu} \quad Z^{\mu\nu}}$$

- We are interested in the case $m_V \ll m_Z$.
  - The interaction with Z boson is suppressed by a factor of $({}^{m_V}/{}_{m_Z})^2$

What is dark photon?

- The effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{QED}} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{1}{2}\kappa F_{\mu\nu}V^{\mu\nu}$$

Stueckelberg:

- Without the Higgs mode
- Or $m_{hD} \gg m_V$

Higgsed Case:

- Assuming $m_{hD} \approx m_V$
- $e_D m_V h_D V_\mu V^\mu$

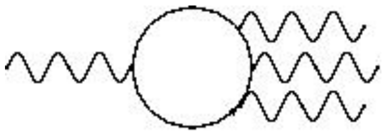
The dark photon model

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

- $m_V > 1\ \mathrm{MeV}$ $\quad V \to e^+e^-$

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

- $m_V < 1\ \mathrm{MeV}$ $\quad V \to 3\gamma$ *Landau-Yang theorem*



$$\Gamma_V \propto \frac{\kappa^2\alpha^4 m_V^9}{m_e^8}$$

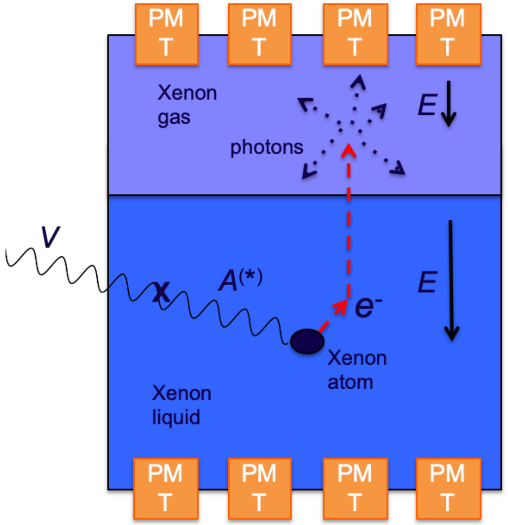
The dark photon can easily be cosmologically stable, and play the roll of dark matter.

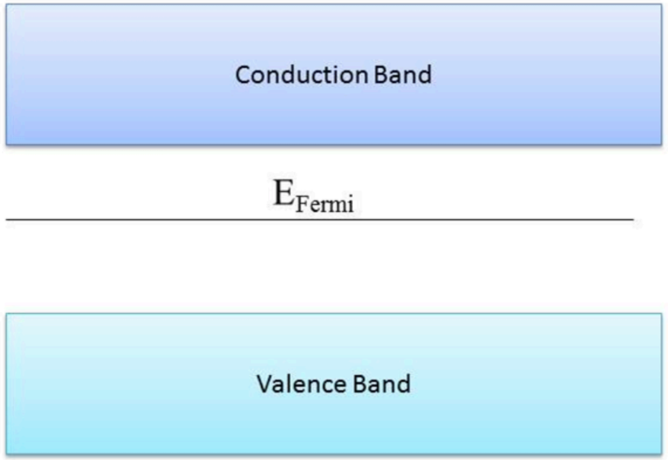
Dark photon dark matter

- It can be absorbed by materials.
- It can be produced inside stars.
- It can be emitted from radio sources.
- It can be converted into real photons.
    - CMB, visible light, radio wave …

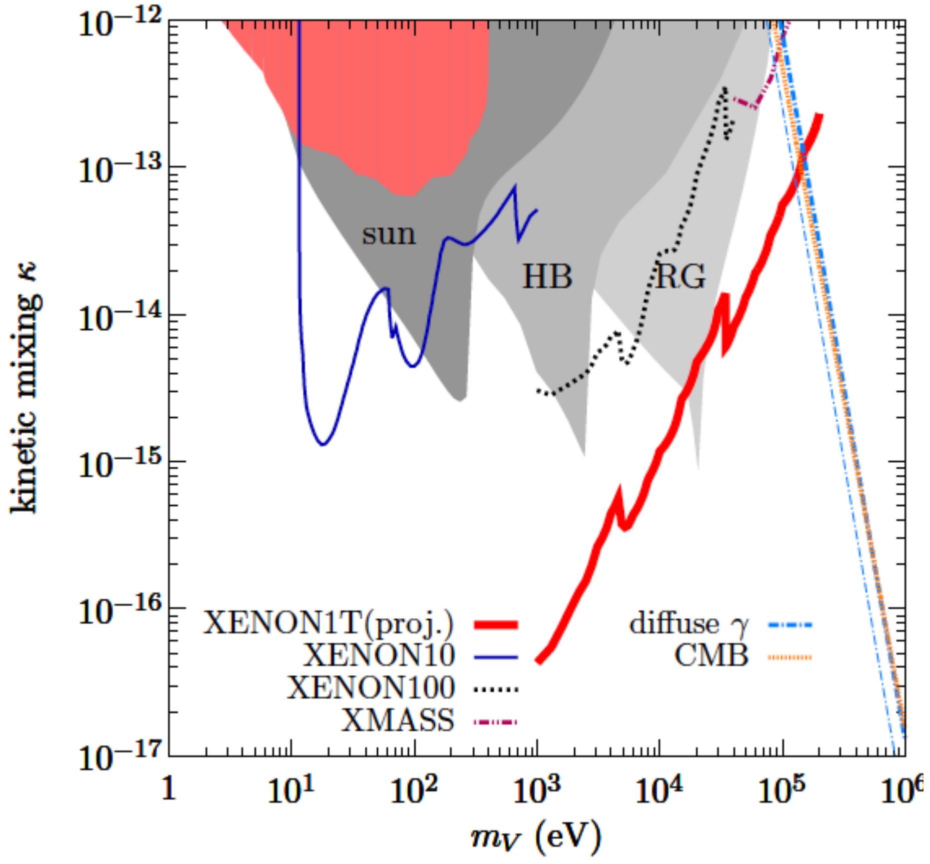
Absorption of dark photon DM

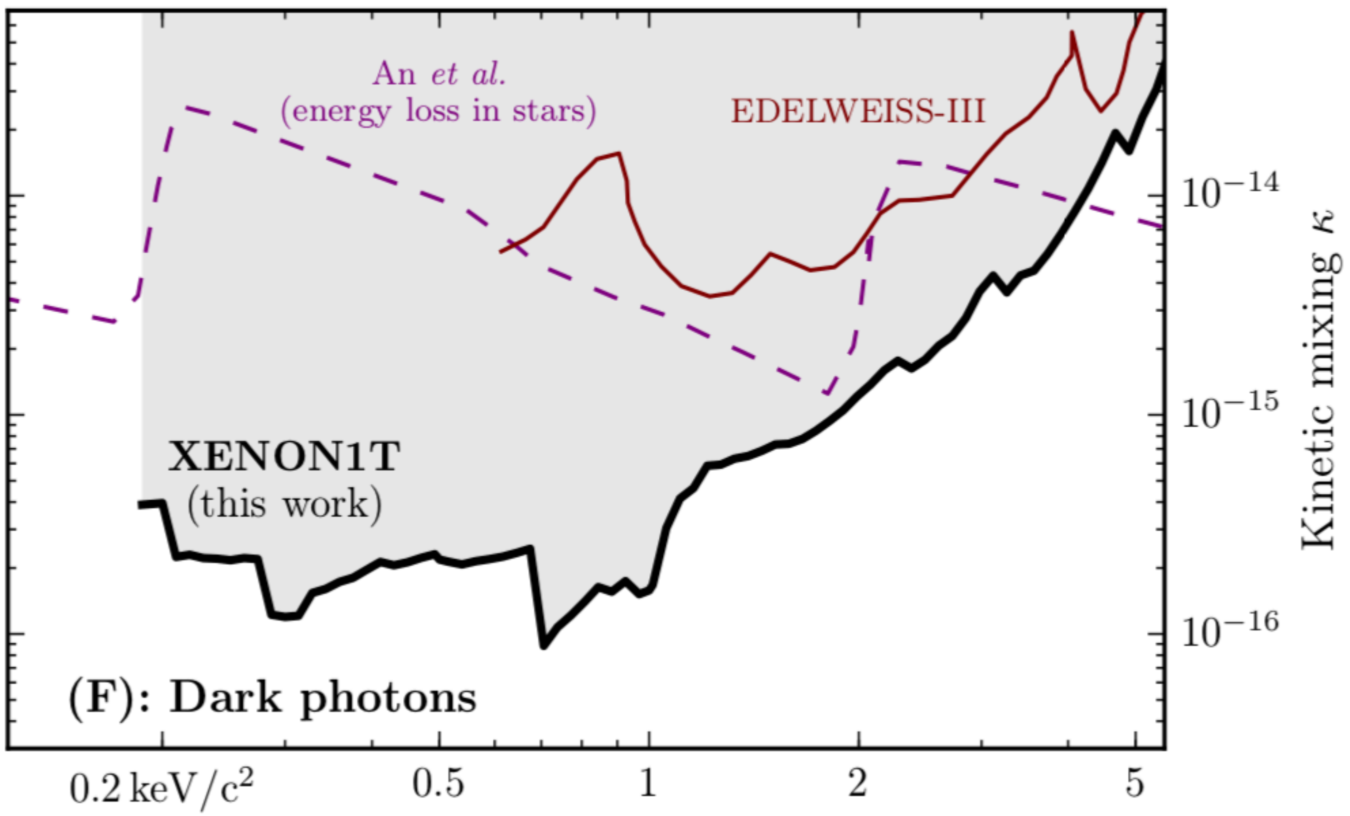
- Electron recoil events.
- The binding energy is at eV scale.
  - 12 eV for XENON10 (signal electron)
  - 400 eV XENON1T
  - 160 eV for CDEX
  - 12.4 eV SENSEI
  - …





Absorption of dark photon DM

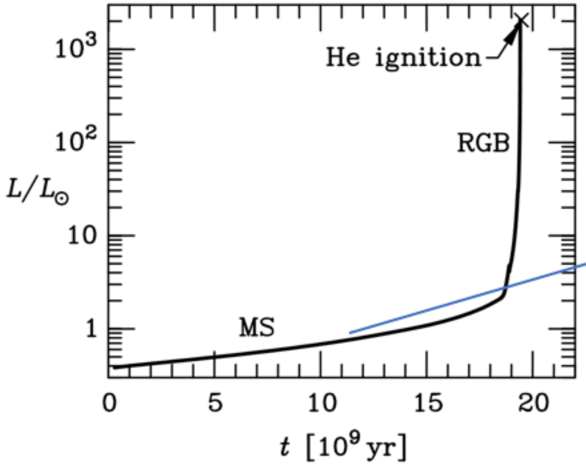


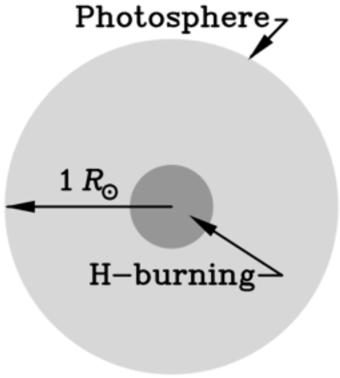


HA, M.Pospelov, J.Pradler, A.Ritz 1412.8378
HA, M.Pospelov, J.Pradler, A.Ritz, K.Ni 1510.04530

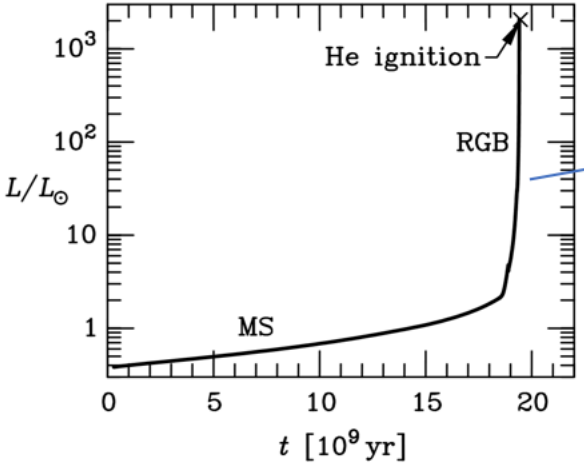
XENON1T, 1907.11485

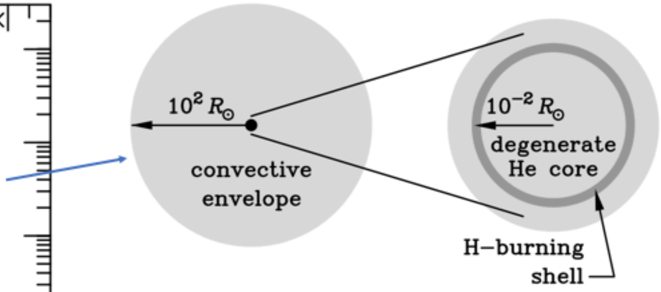
Evolution of stars



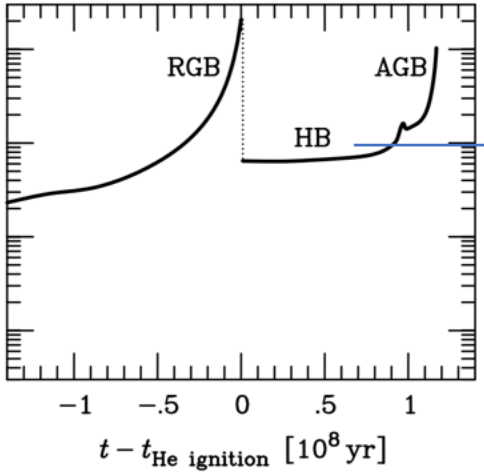


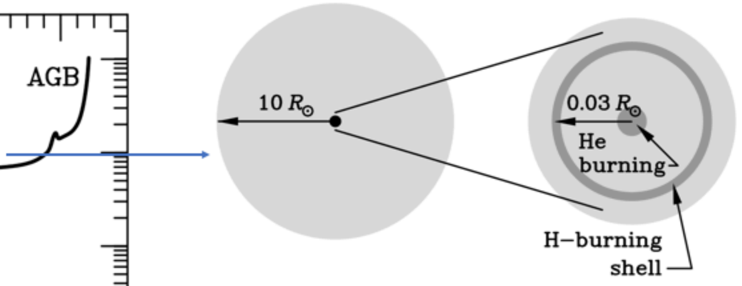
Main sequence



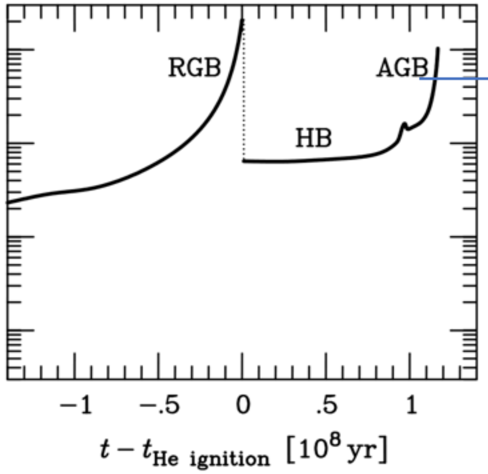


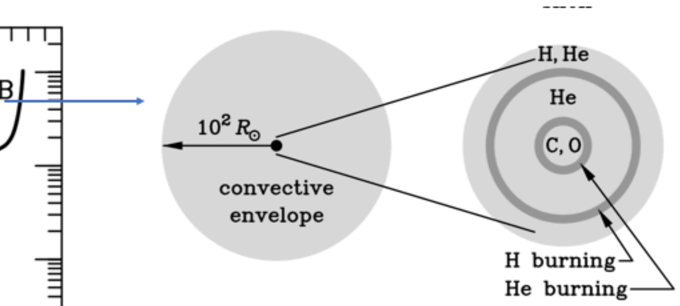
Red Giant Branch





Horizontal branch

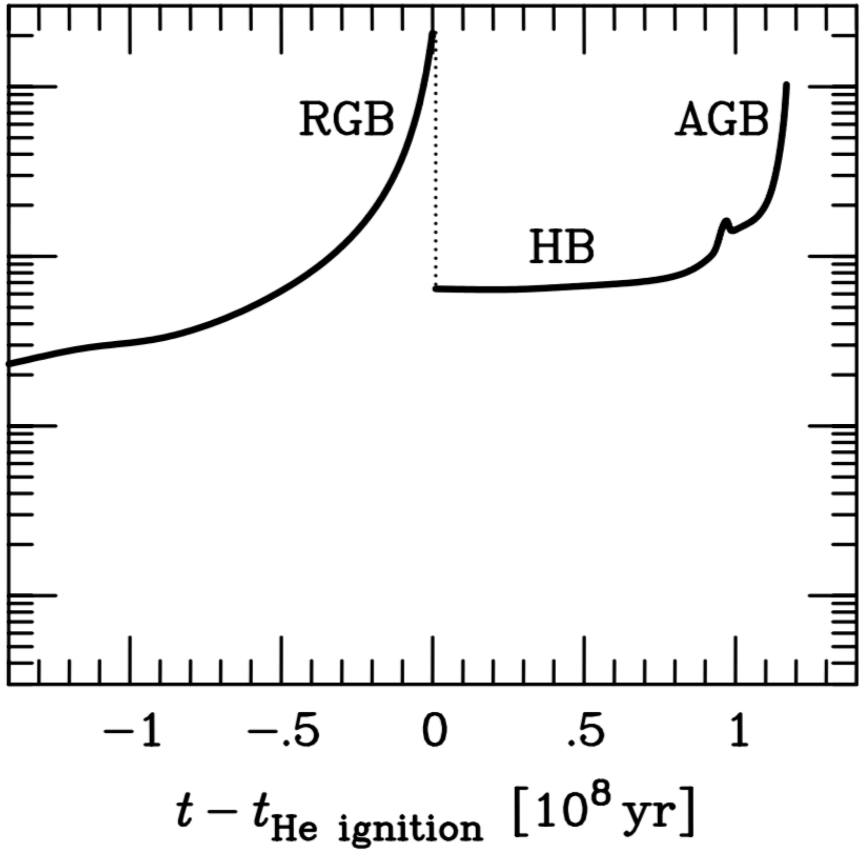




Asymptotic Giant

New channels of losing energy

- The star will lose more energy.
- The burning phases will burn faster and become shorter.
- However, the giant phases will become longer since it cost more time for the temperature to climb up to ignite the next fuel.

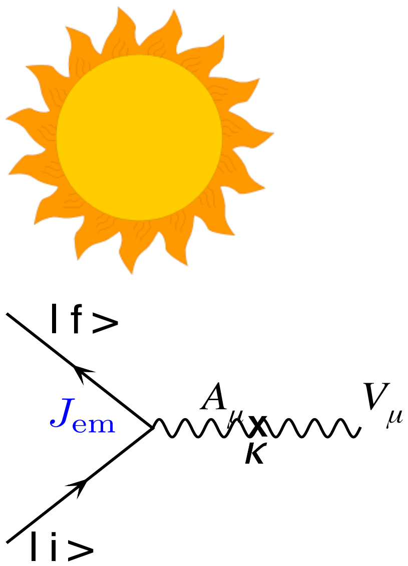


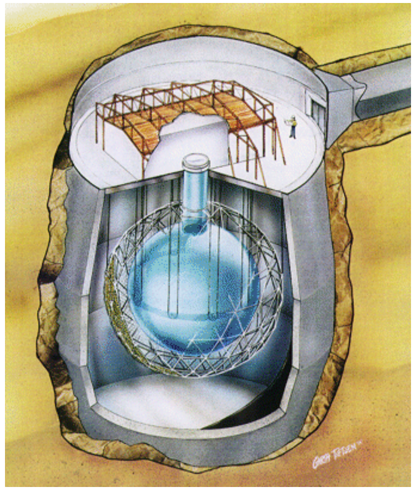
Supernova

- Supernova (especially type II) is important because it core temperature can be as high as 100 MeV and its plasma frequency can be as large as about 10 MeV.
- It can produce heavy dark photons or axions.

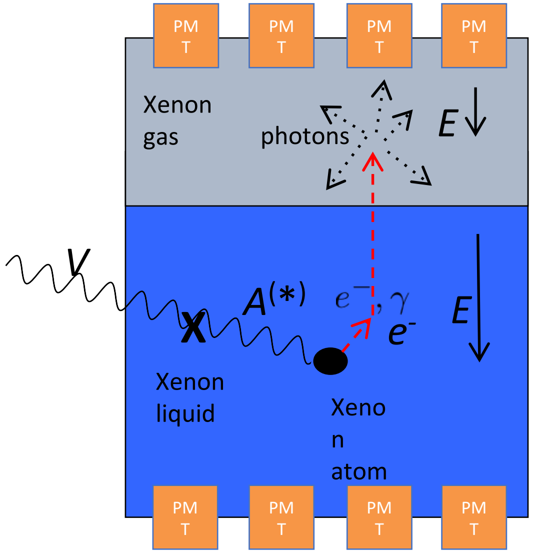
- For light dark photons or axions supernova constraints are weaker than other stars, this is simply because it produces too many neutrinos.

Constraints from the Sun





SNO experiment

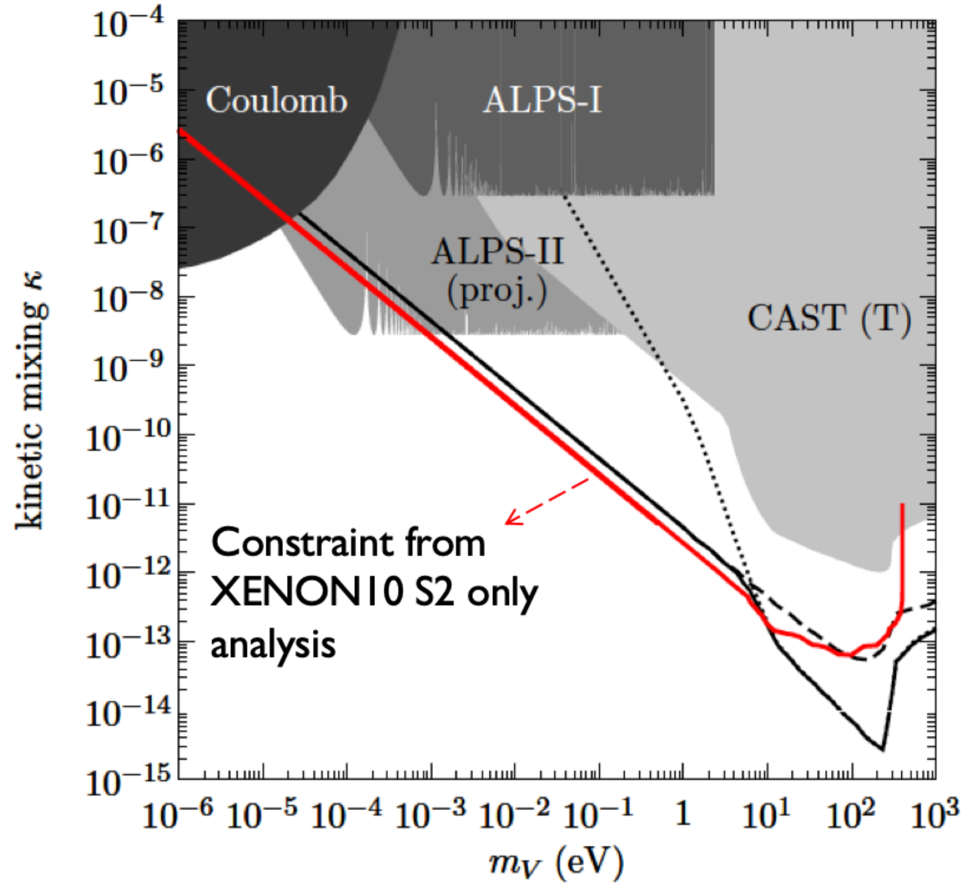


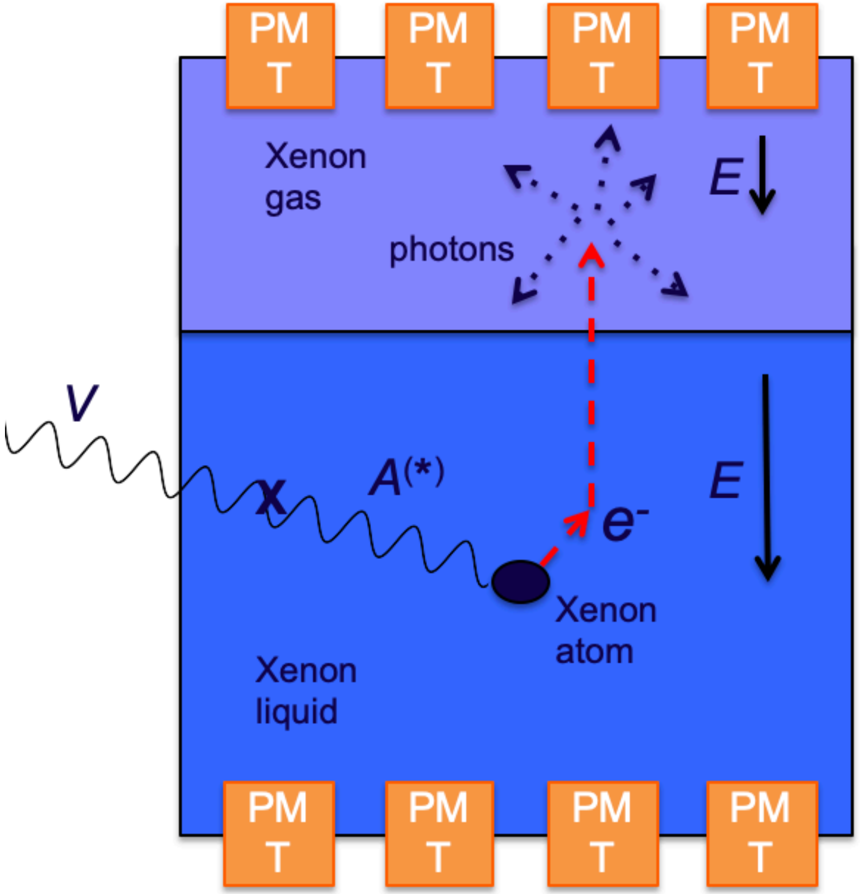
XENON experiment

- Increase the flux of ^{8}B neutrinos constrained by SNO experiment.
- The dark photons or axions can be detected by dark matter detector directly.

Direct detection of the solar flux

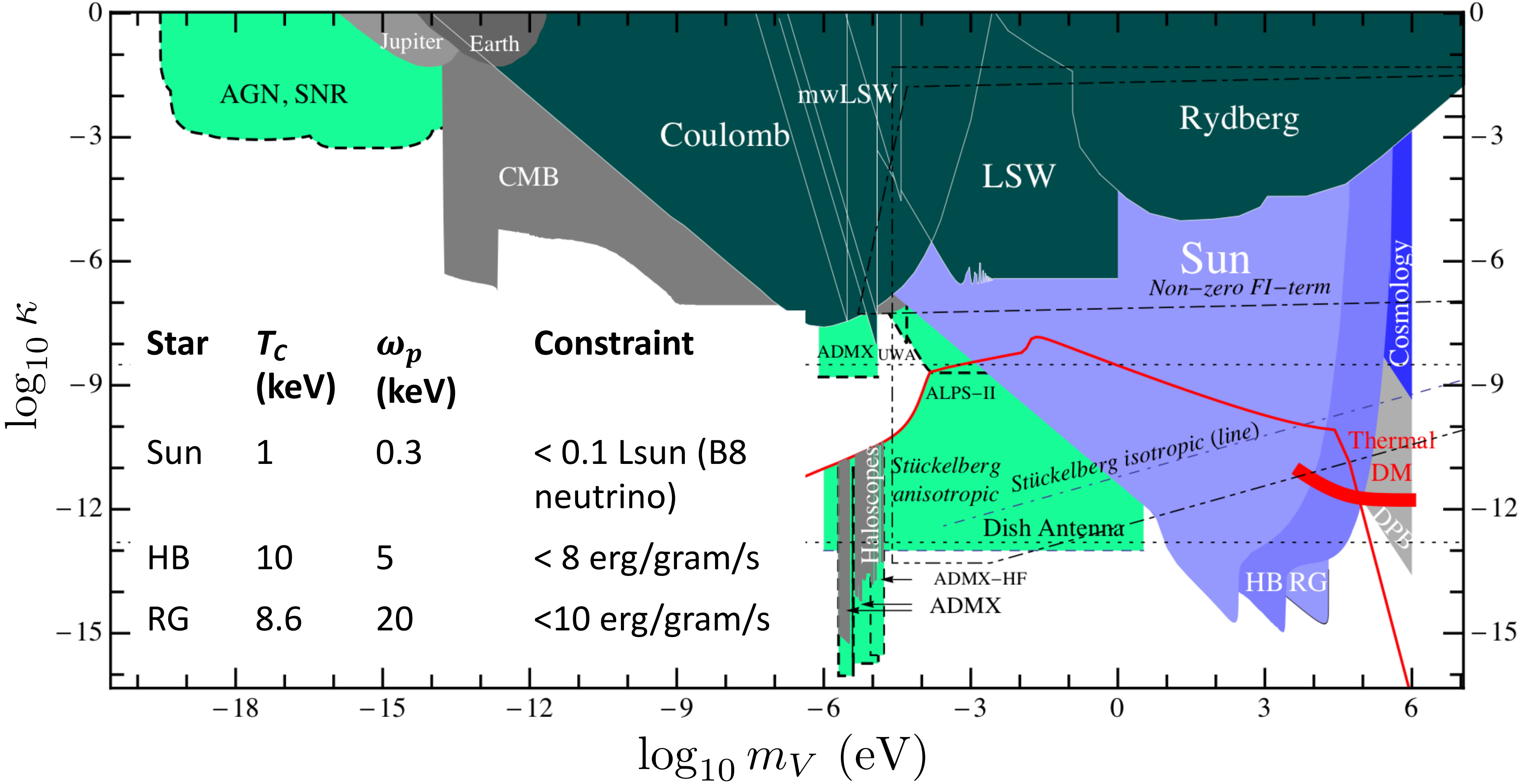
HA, Pospelov, Pradler, PLB 725 (2013) 190,
PRL 111 (2013) 041302





Stellar constraints

Essig, Jaros, Wester 1311.0029



Star	T_C (keV)	ω_p (keV)	Constraint
Sun	1	0.3	< 0.1 Lsun (B8 neutrino)
HB	10	5	< 8 erg/gram/s
RG	8.6	20	<10 erg/gram/s

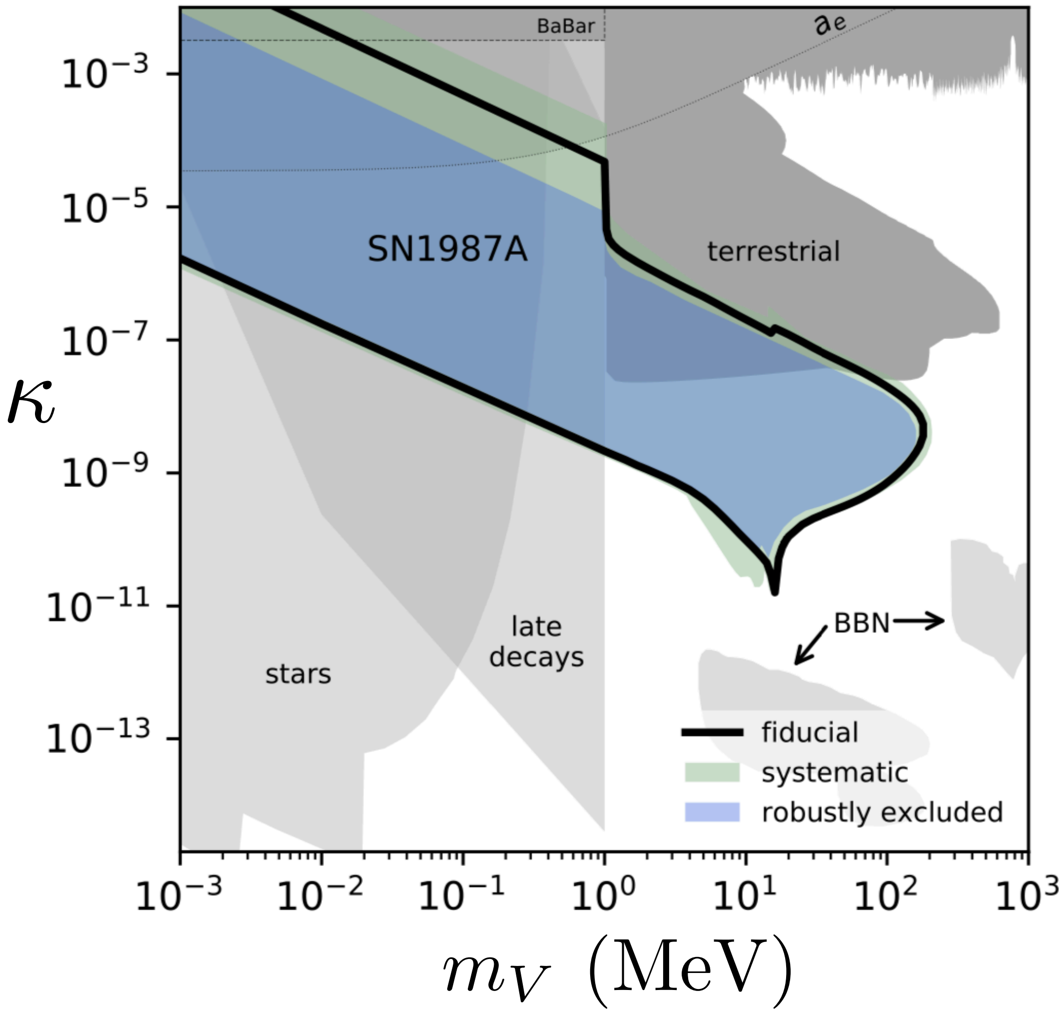
Constraints from supernova

- Supernova 1987A
  - $\omega_p \approx 10$ MeV
  - $T_C \approx 20$ MeV

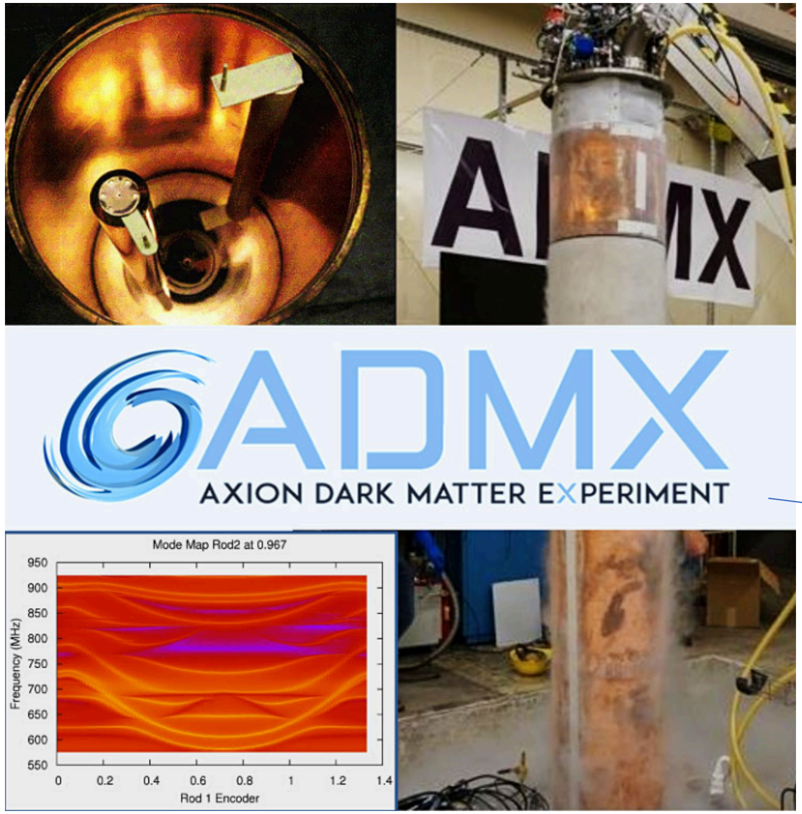
- Compared to the neutrino production

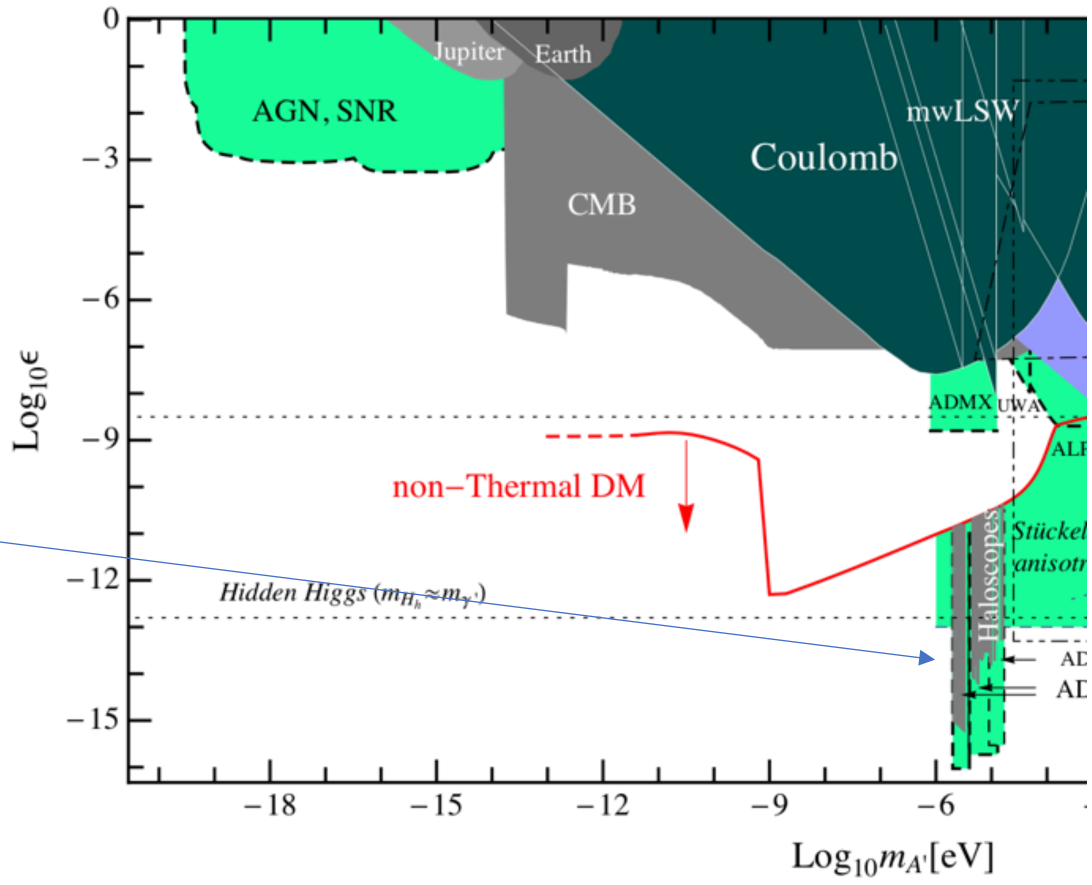
$$\kappa \sim \left(\frac{T_C}{M_W}\right)^2$$

Chang et al, JHEP 1701 (2017) 107

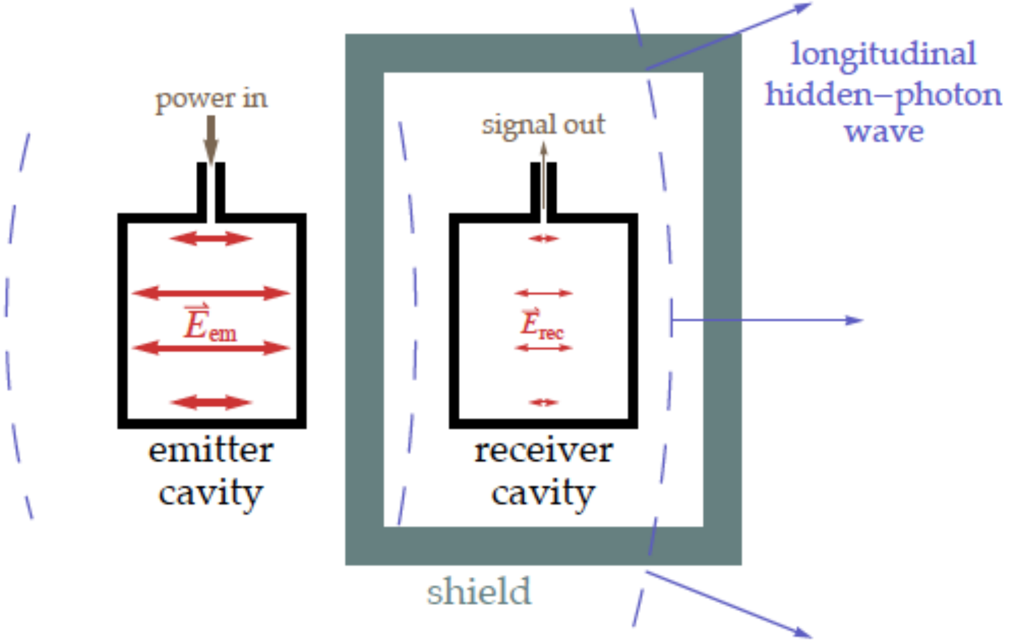


Dark photon converts to photon in resonant cavity

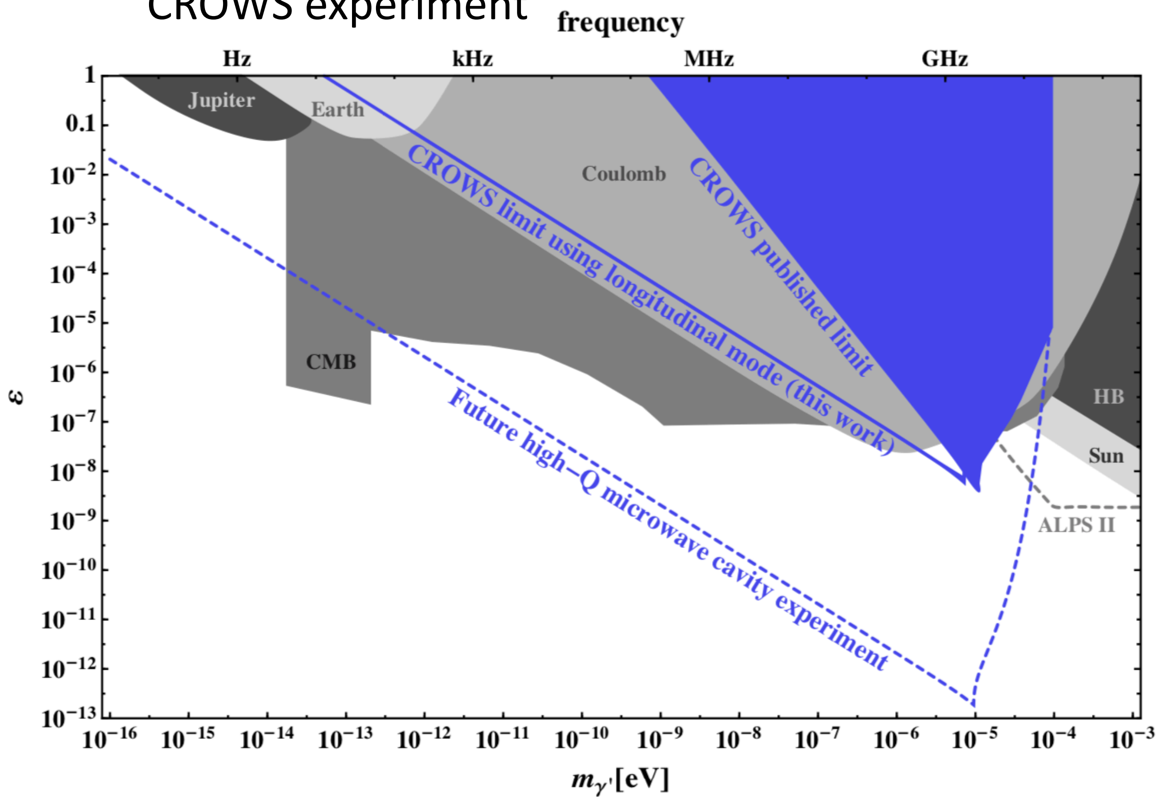




Microwave through the wall



CROWS experiment



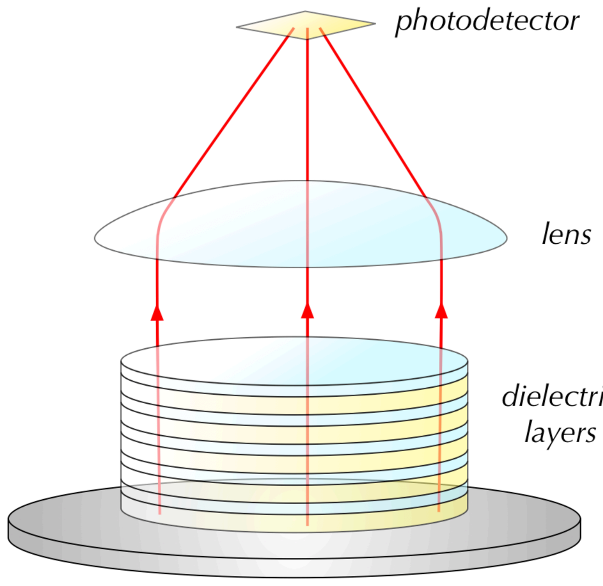
Graham, Mardon, Rajendran, Zhao 1407.4806

Convert dark photon DM into visible light

- Dark photon dark matter oscillate to on-shell photons

Baryakhar, Huang, Lasenby, PRD 98 (2018) 035006

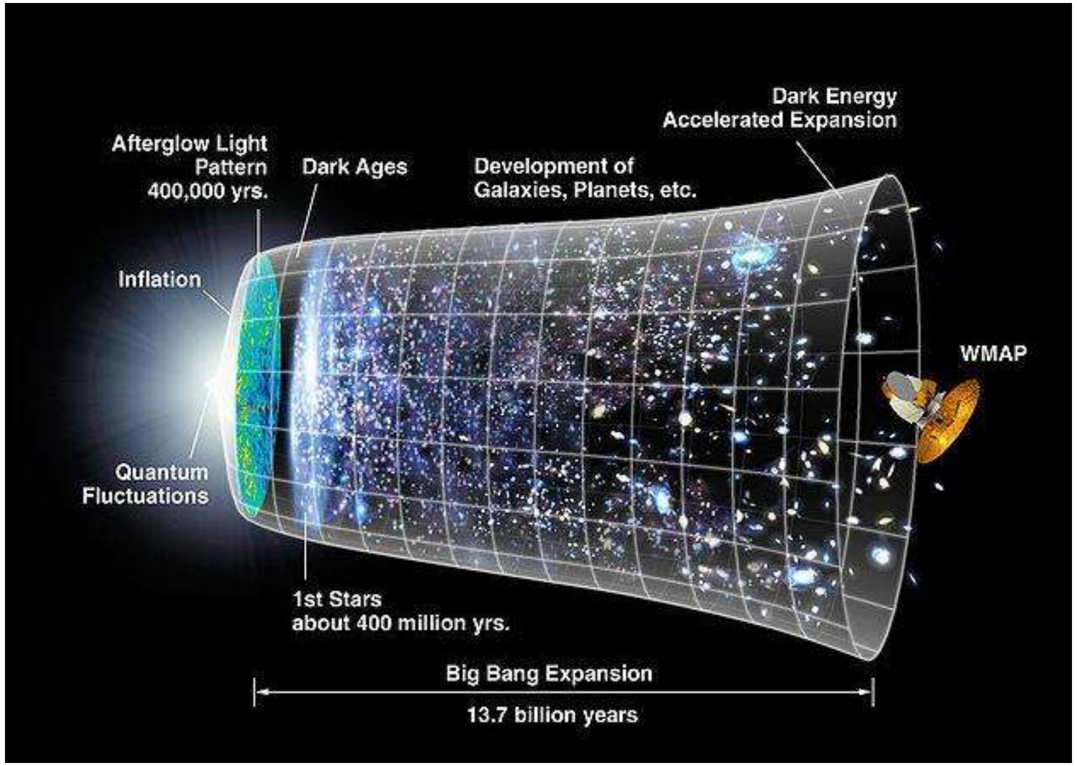
A stack of dielectric layers, with alternating indices of refraction provide a non-zero momentum for the photon to propagate.



Convert dark photon DM into CMB

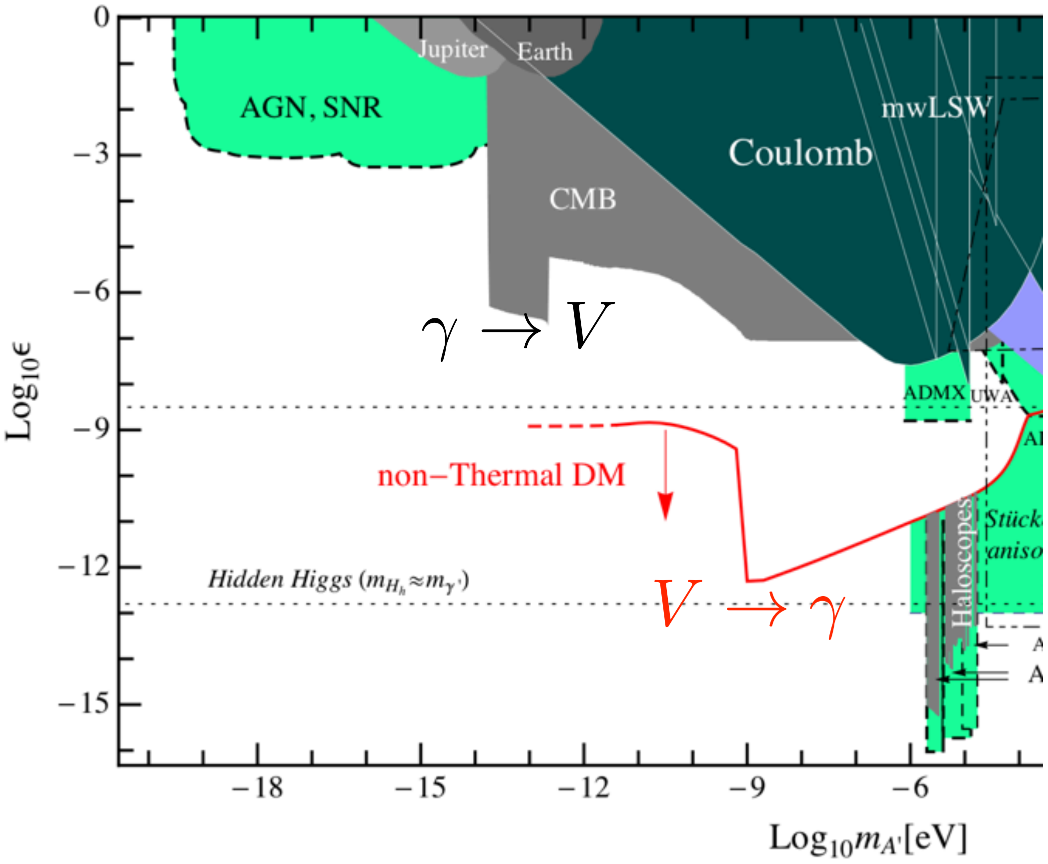
- Our universe is expanding.
- It is thermal plasma.
- $$\omega_p^2 = \frac{4\pi\alpha_{\rm EM} n_e}{m_e}$$
- Resonant transition when

$$\omega_p^2 = m_V^2$$



Convert dark photon DM to CMB photons

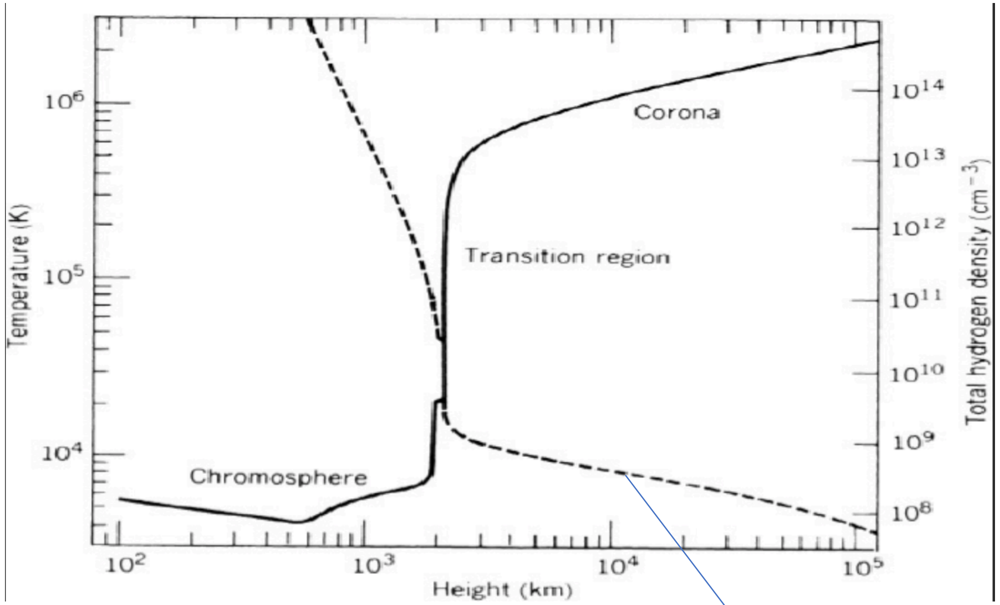
- T < 1 keV
  - $\gamma + e \to 2\gamma + e$ stops
  - photon number is conserved
  - a distortion in the CMB is generated



Where else can we find plasma?

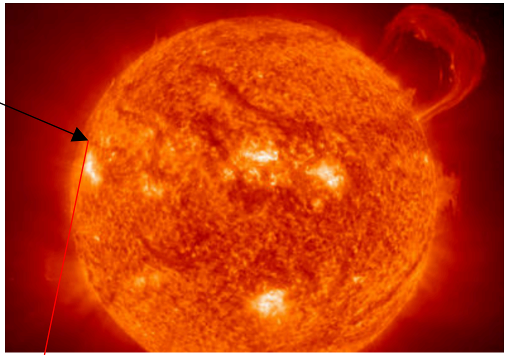
- In the corona sphere of the Sun

With Fapeng Huang, Jia Liu and Wei Xue, in preparation



$$\omega_p \sim \mathrm{GHz}$$

V

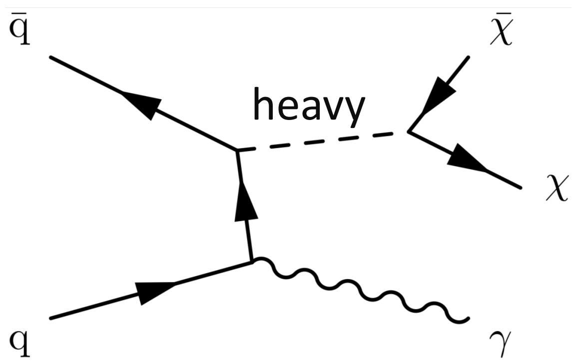


A

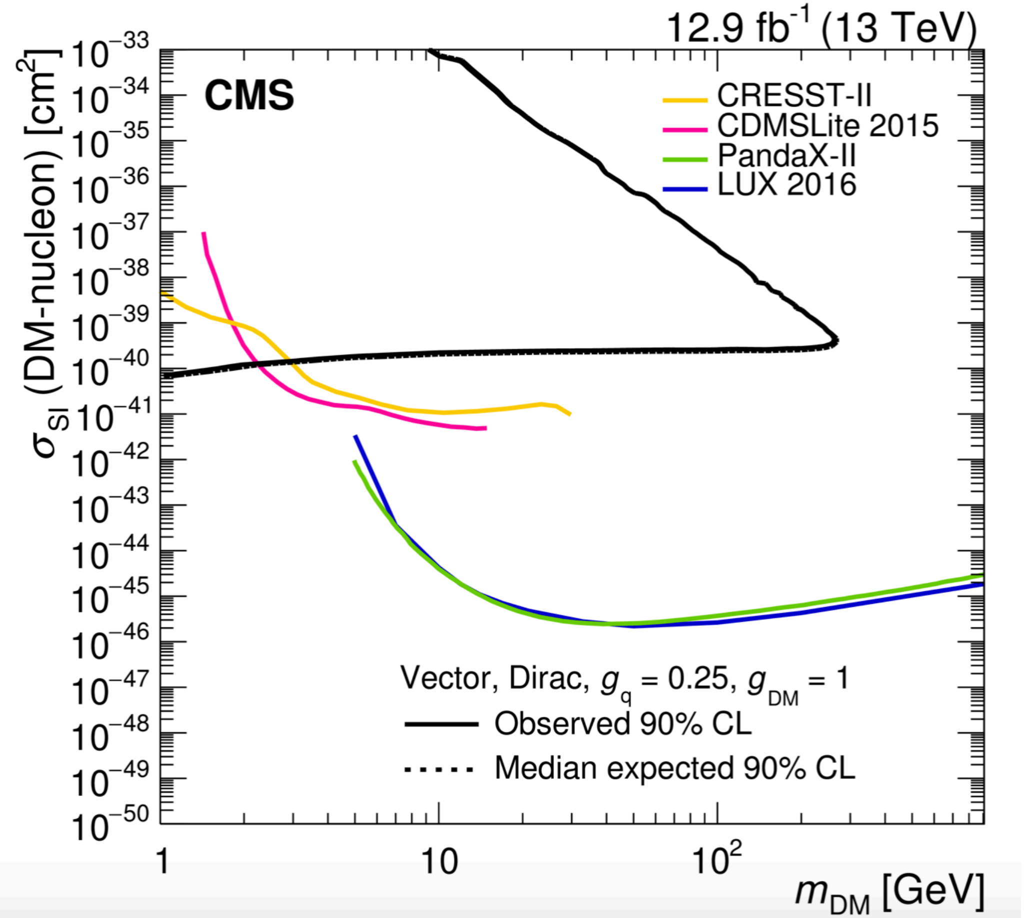
Square Kilometer Array – SKA telescope

Dark mediator search

- Collider search

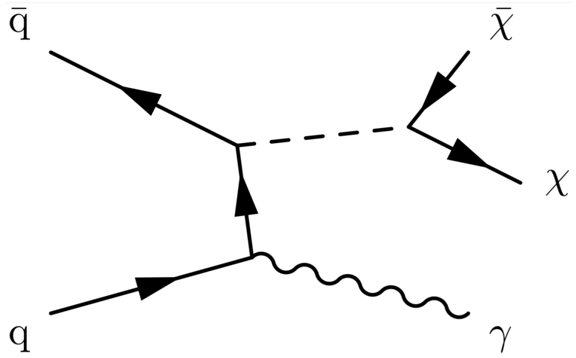


monojet

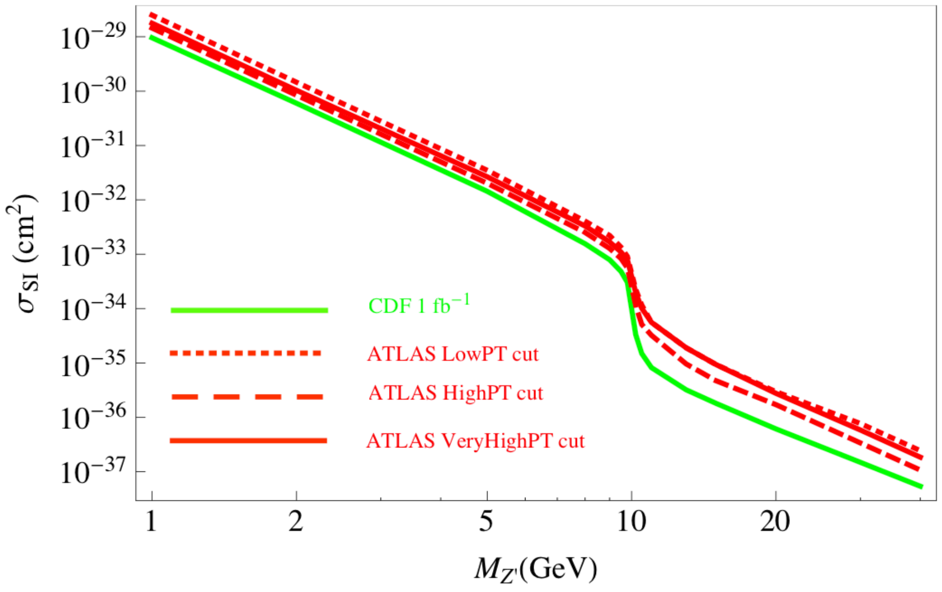


Collider search

- Light mediator case

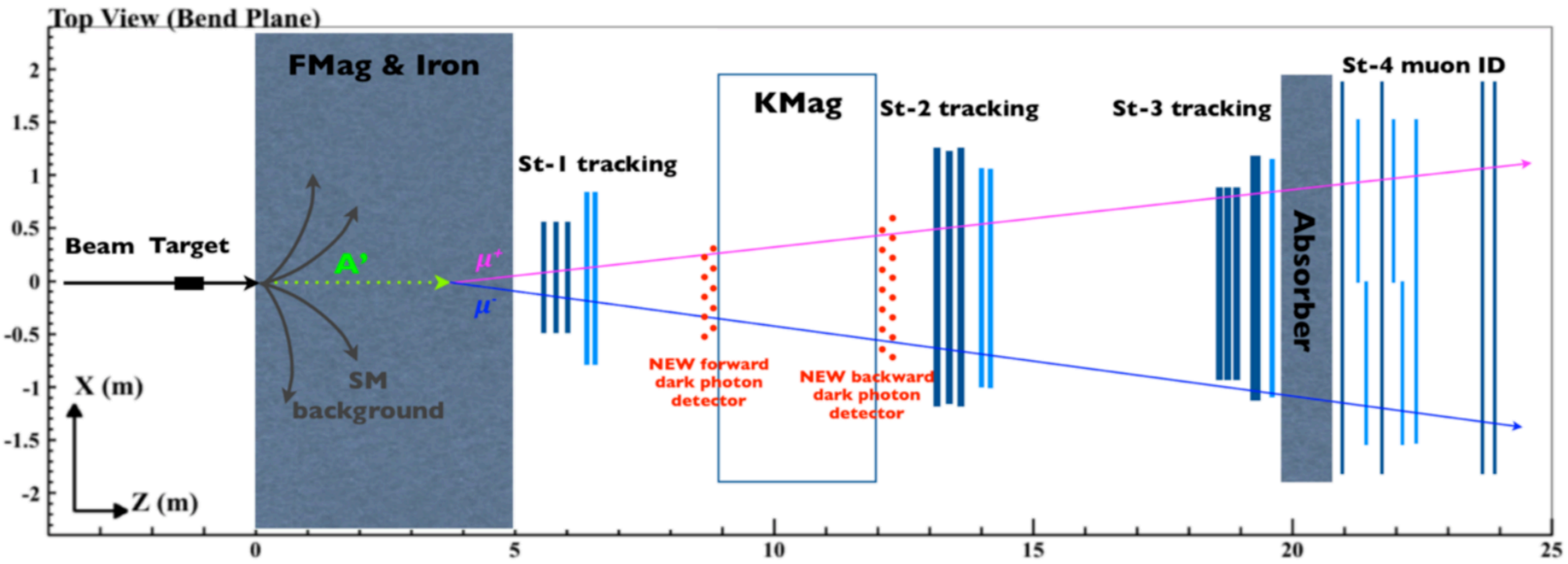


HA, X. Ji, L.-T. Wang, JHEP 1207 (2012) 182

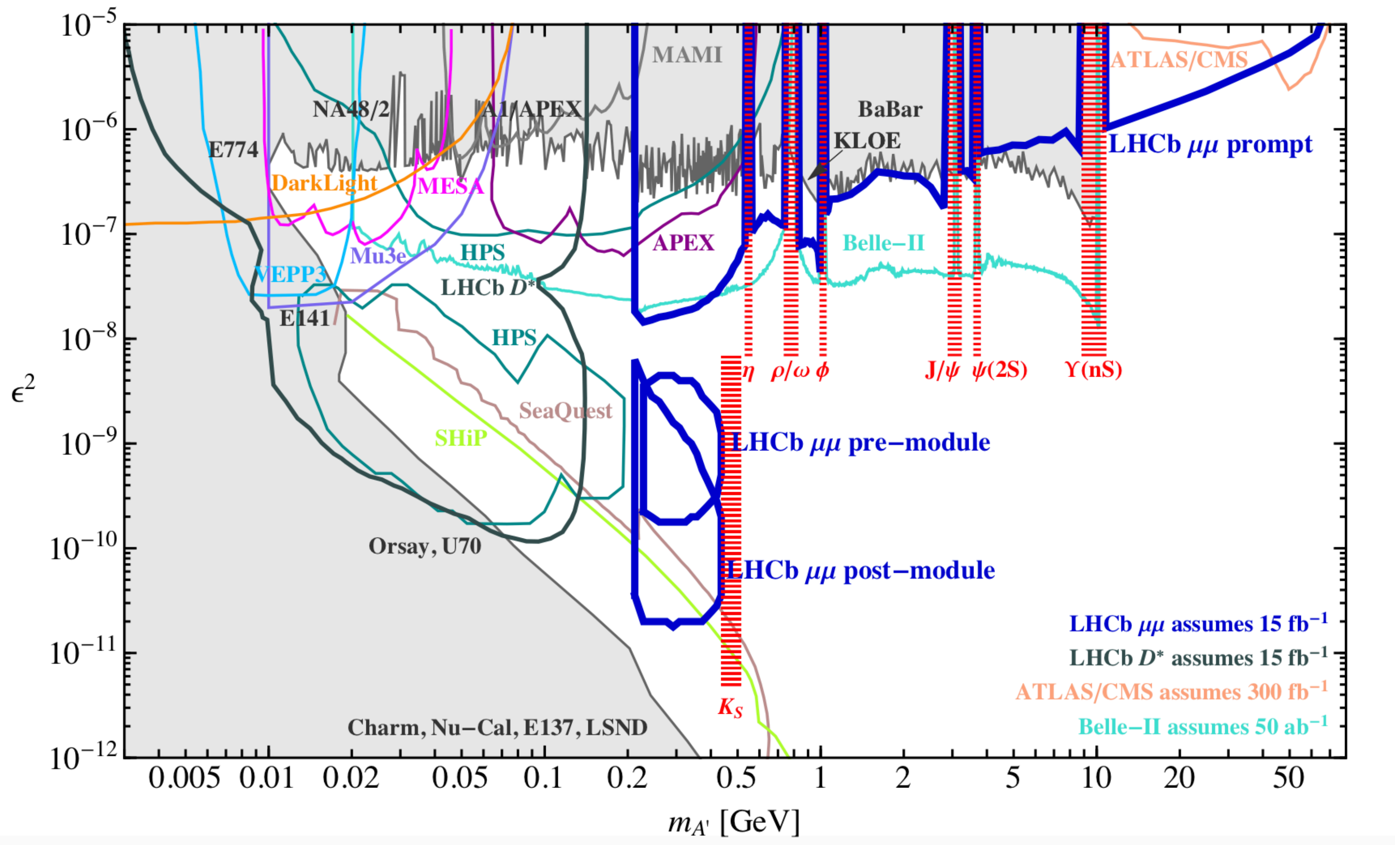


Search for mediator directly

- Beam damp experiments (high luminosity, low energy)



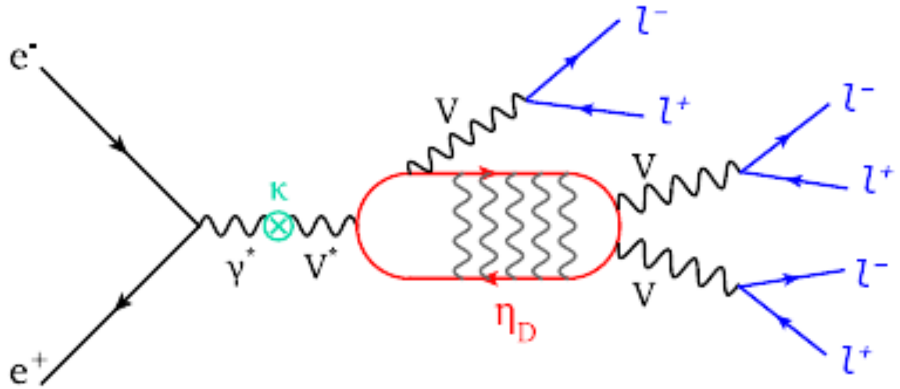
Search for mediator directly



Search for dark bound states

- If DM can form bound state, there will be multiple charged leptons in the final state.
- Production rate is small, but signal is striking.

HA, Echenard, Pospelov, Zhang, PRL 116 (2016) 151801



Indirect searches

- Light mediator provides Sommerfeld enhancement in dark matter annihilation.

- Light mediator may also help to generate dark bound states which will also significantly enhance the annihilation cross section.

Bound state formation of asymmetric DM

- Just like in SM we have

$$e + p \to H + \gamma$$

- In the dark sector we may have

$$e_D + p_D \to H_D + V$$

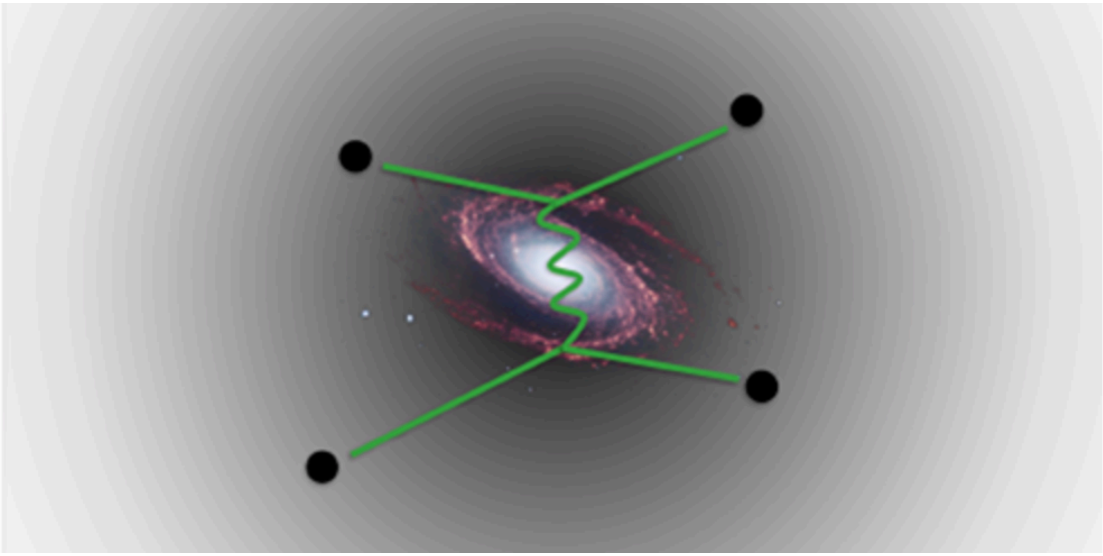
  - Multiple energy levels
  - Distinctive signatures in gamma ray spectrum

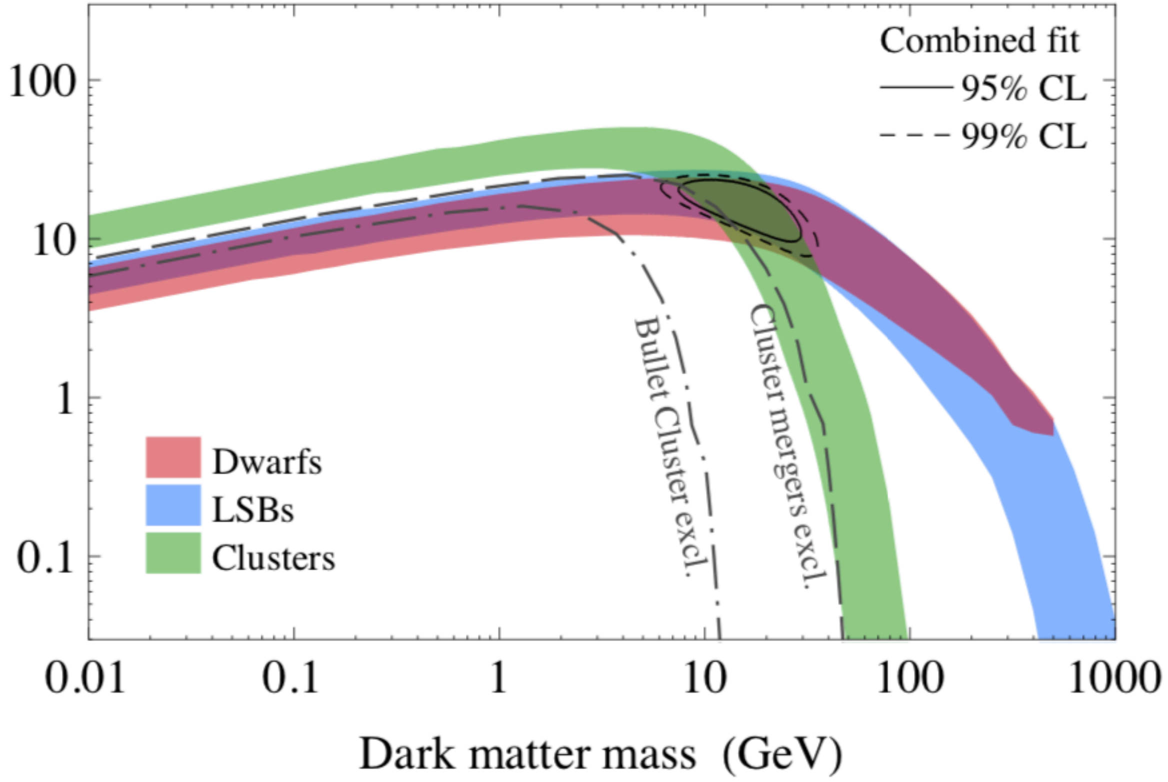
V → SM charged particles

With in progress with Daneng Yang.

Search for long range force from the structure of galaxies

M. Kaplinghat, S. Tulin, H. B. Yu, PRL 116 (2016) 041302





Summary

- For dark photon with mass smaller than 1 MeV, it can be dark matter candidate.
- For dark photon with mass larger than 1 MeV, it can be dark force mediator.
- We are searching for it with all our knowledges.