Recent progress on searching for dark photons

Haipeng An (Tsinghua University)

上海市粒子物理与宇宙学论坛暨轴子暗光子分数电荷与磁单级新物理前沿研讨会

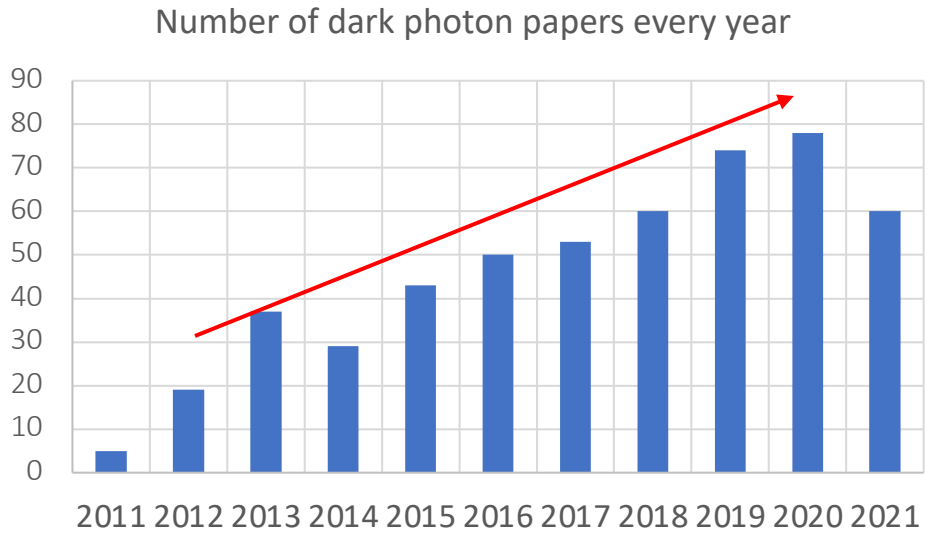
11月19–22日

What is dark photon?

- A new vector boson (usually massive)

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

- It couples to the SM through
  - Kinetic mixing with photon: $-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$
  - Directly interaction to conversed currents: $gV_\mu J^\mu_{B-L}$ $gV_\mu(J^\mu_\mu - J^\mu_\tau)$ …
  - Kinetic mixing with Z boson.



What is dark photon?

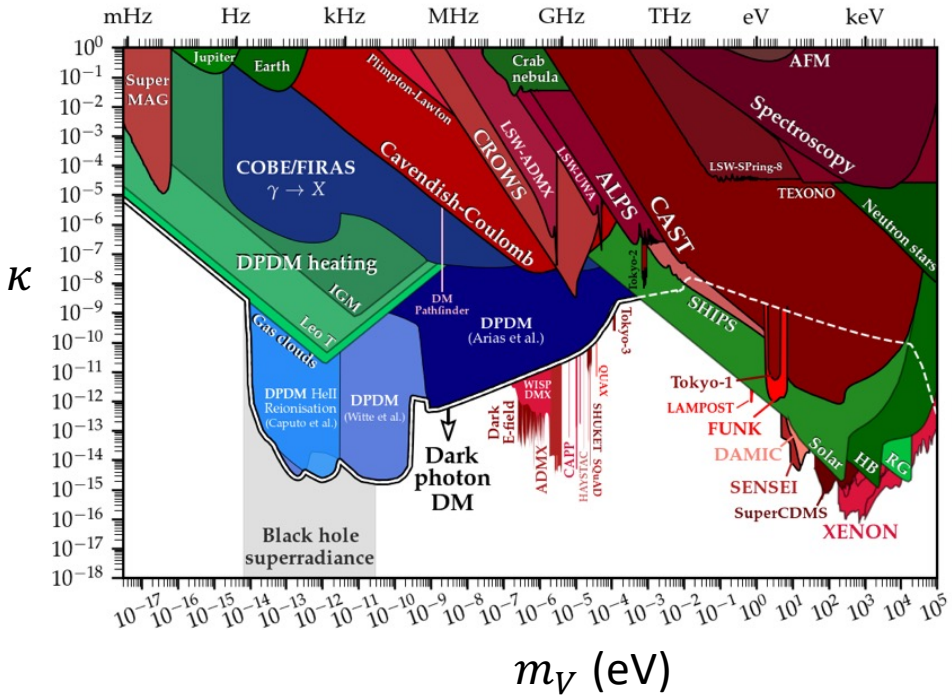
- A new vector boson (usually massive) $\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu$
- It couples to the SM through
  - Kinetic mixing with photon: $-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$
  - Directly interaction to conversed currents: $gV_\mu J^\mu_{B-L}$ $gV_\mu(J^\mu_\mu - J^\mu_\tau)$ …
  - Kinetic mixing with Z boson.

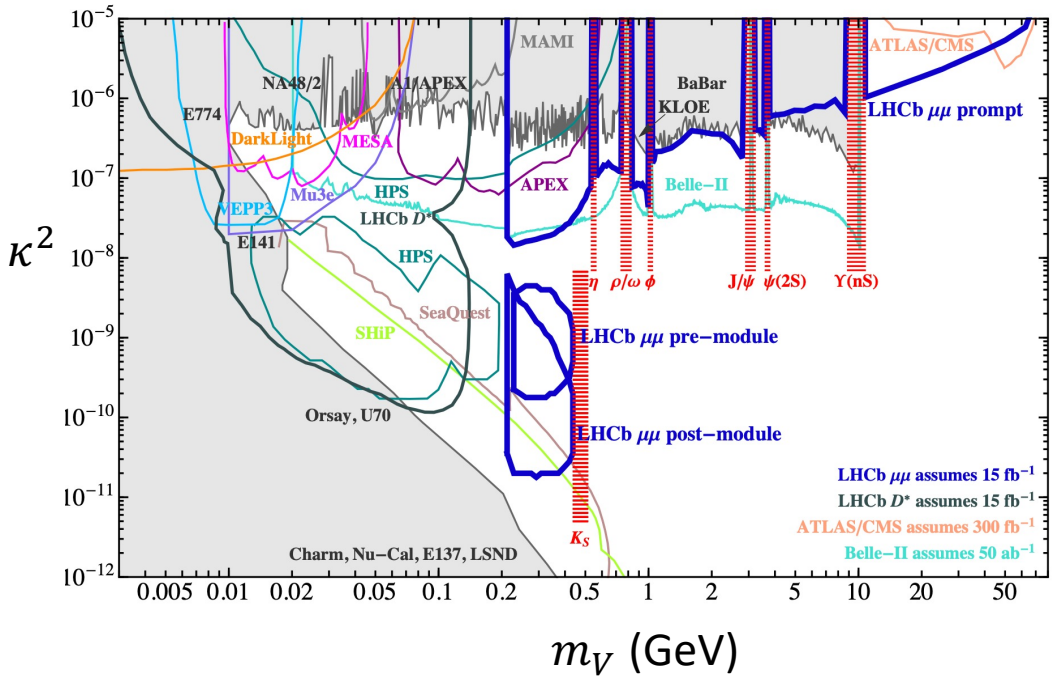
Why it is interesting?

- If $m_V < 1$ MeV, the $V \to e^+e^-$ channel is forbiden.

  $\Gamma(V \to 3\gamma) \sim \kappa^2 m_V^9 / m_e^8$, can be easily cosmologically stable.

- If $m_V > 1$ MeV, V is not stable, can act as dark force.





Production of dark photon dark matter

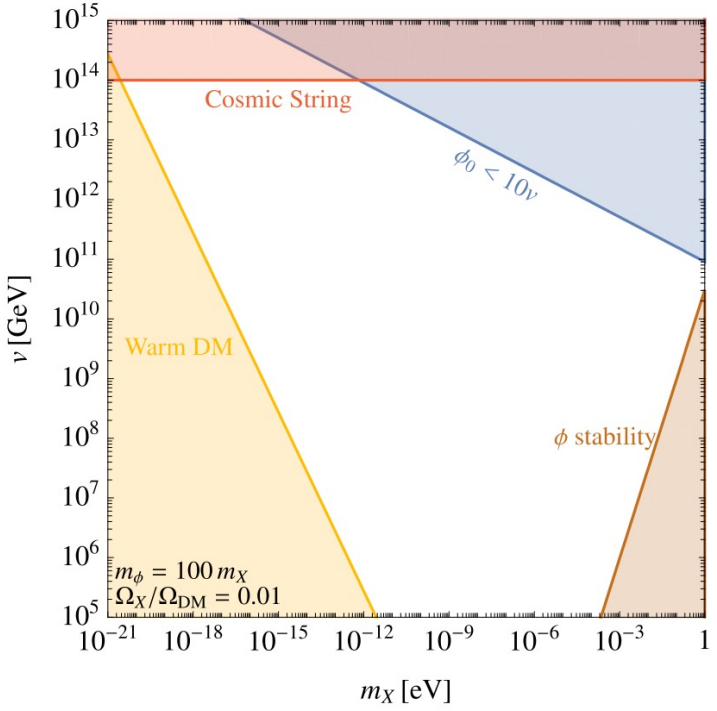
- From quantum fluctuation during inflation

  Graham, Mardon, Rajendra (2015)

$$m_{A'} = 10^{-5}\ \mathrm{eV} \times \left(\frac{10^{14}\mathrm{GeV}}{H_I}\right)^4$$

- From parametric resonant production

  Co, Pierce, Zhang, Zhao (2018)
  Dror, Harigaya, Narayan (2018)
  Bastero-Gil, Santiago, Ubaldi, Vega-Morales (2018)
  Agrawal, Kitajima, Reece, Sekiguchi, Takahashi (2018)



- From decay of cosmic string

  Long, Wang (2019)

- …

From “flavor” eigenstates to mass eigenstates

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

$$\Big\downarrow \quad A \to A - \kappa V$$

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu - \kappa e V_\mu J^\mu$$

- V_μ and A_μ are now mass eigenstates.
- No oscillation between V and A.

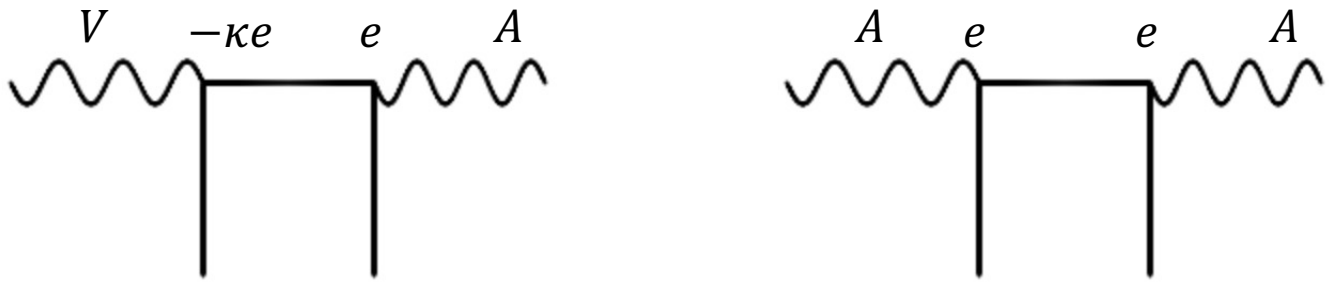
Photon dark photon oscillation

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu - \kappa e V_\mu J^\mu$$

V_μ and A_μ are mass eigenstates.

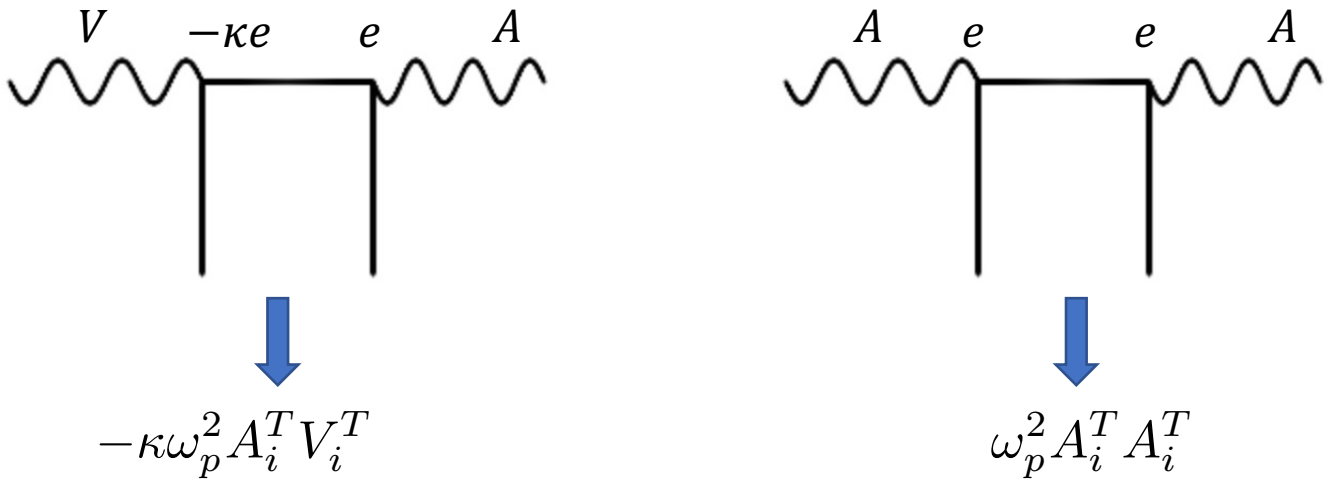
- In the vacuum, V cannot be converted into A, no interaction
- In the plasma, (1) a mixing between V and A is generated.

  (2) a mass for A is also generated.



Photon dark photon oscillation

- Projecting onto the transverse modes



- One to one transition matrix element

$$\mathcal{M}_{V_T \to A_T} = -\kappa\omega_p^2 \epsilon_A \cdot \epsilon_V$$

Polarization vectors

Photon dark photon oscillation

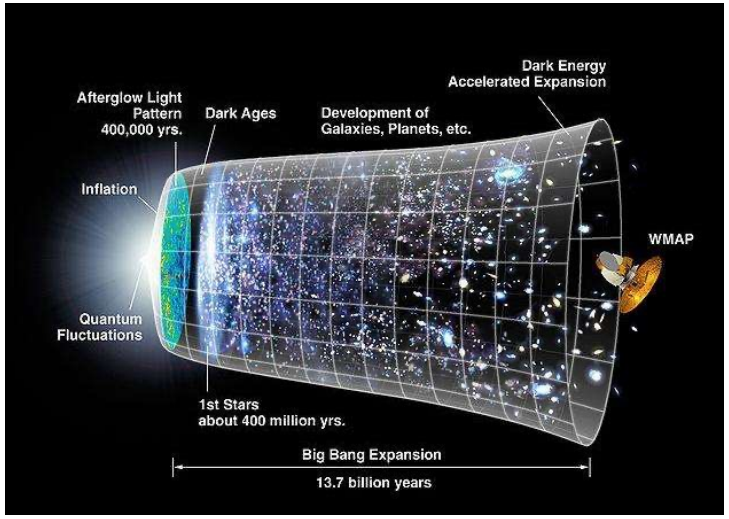
- Inside a homogeneous plasma:

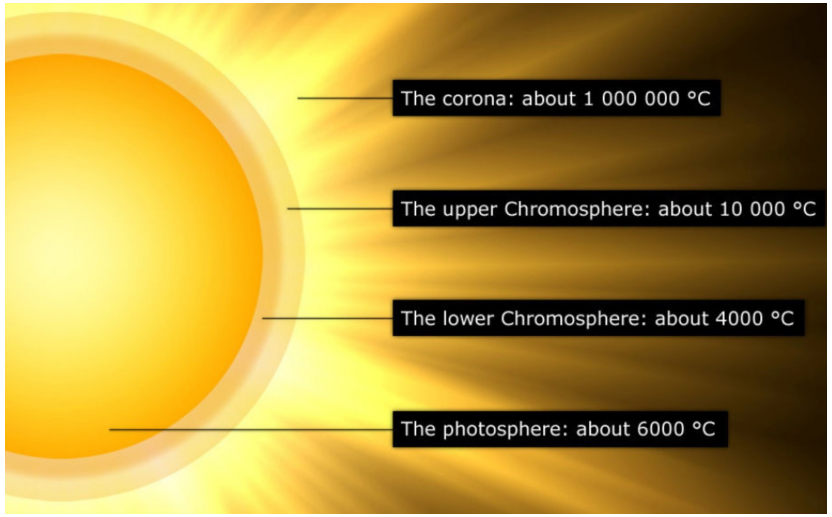
  momentum conservation: $p_V = p_A$

  energy conservation: $E_V = E_A$

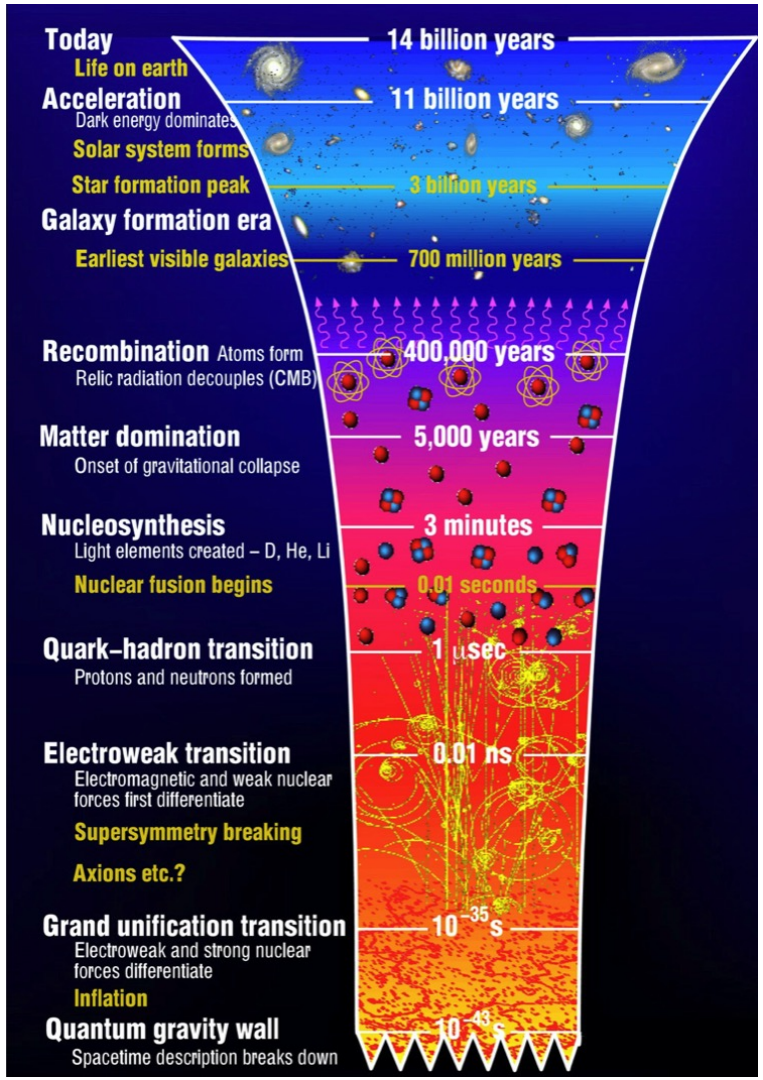
  } Oscillation happens when $m_V = \omega_p$

- Our task: to find a plasma!



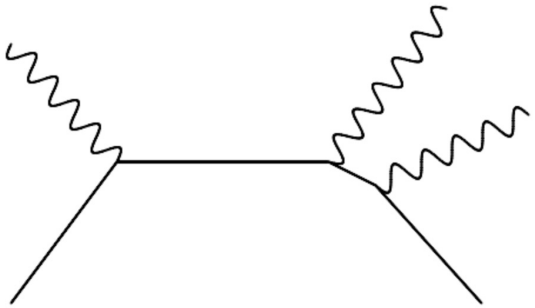


The Universe as a plasma



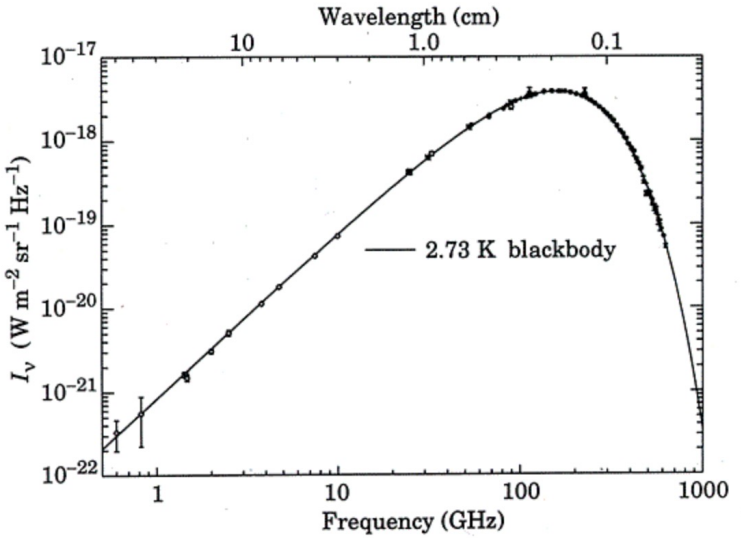
$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

$$n_e \sim 10^{-10} T^3$$

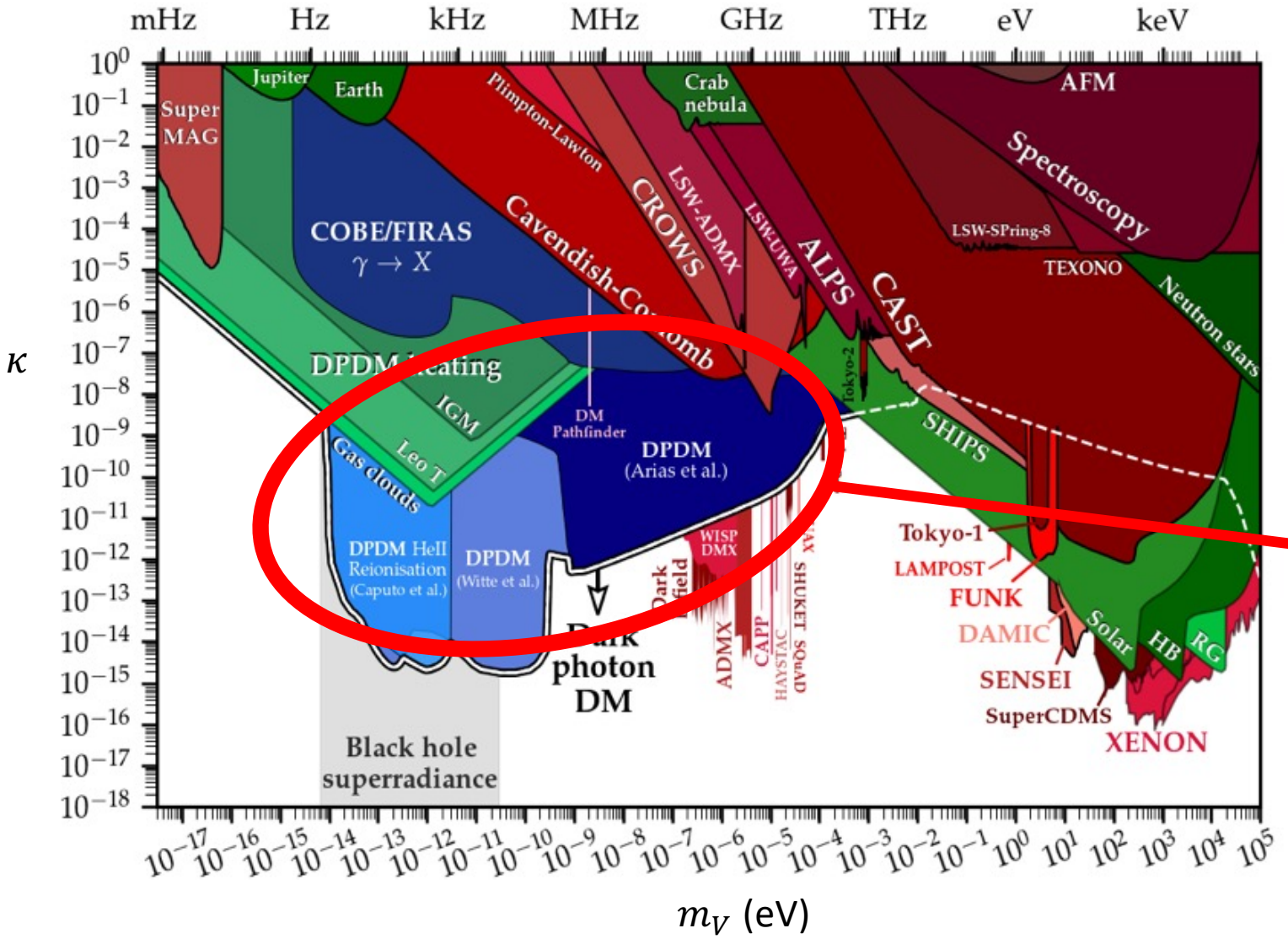


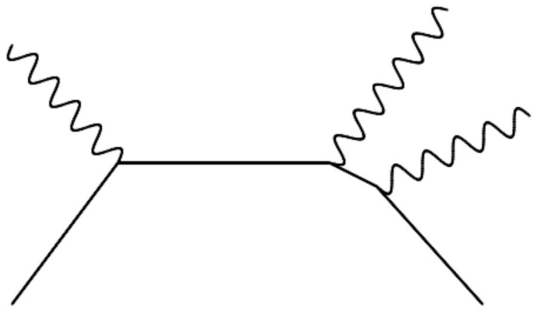
Stops below 1 keV.

→ CMB distortion for 10^{-14} eV < m_V < 10^{-3} eV

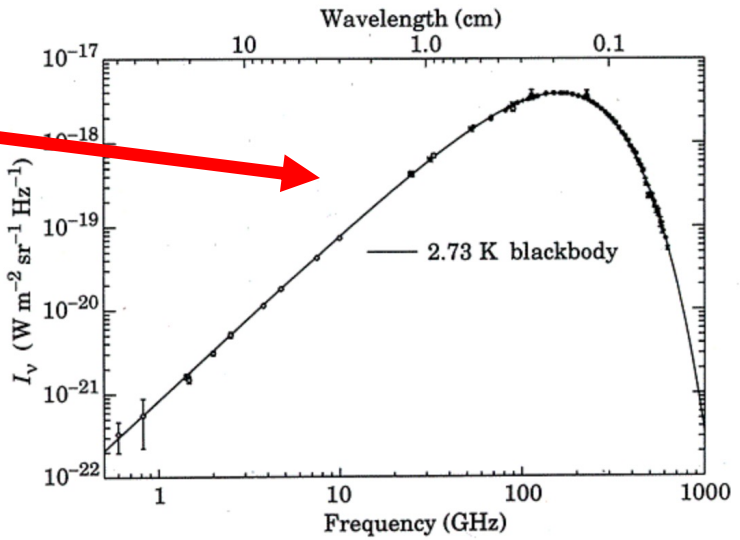


The Universe as a plasma





Stops below 1 keV.



Searching for ultralight DM with radio telescopes

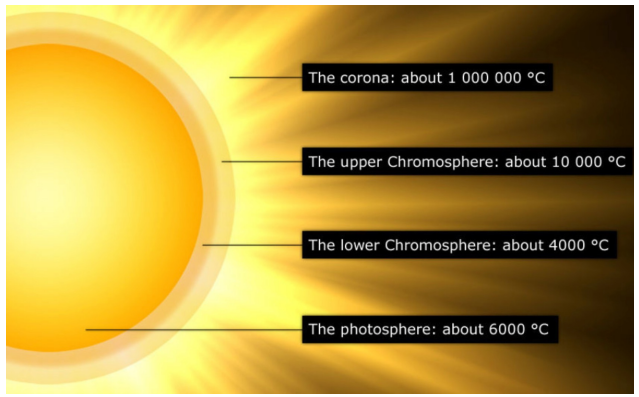
- For dark photon:

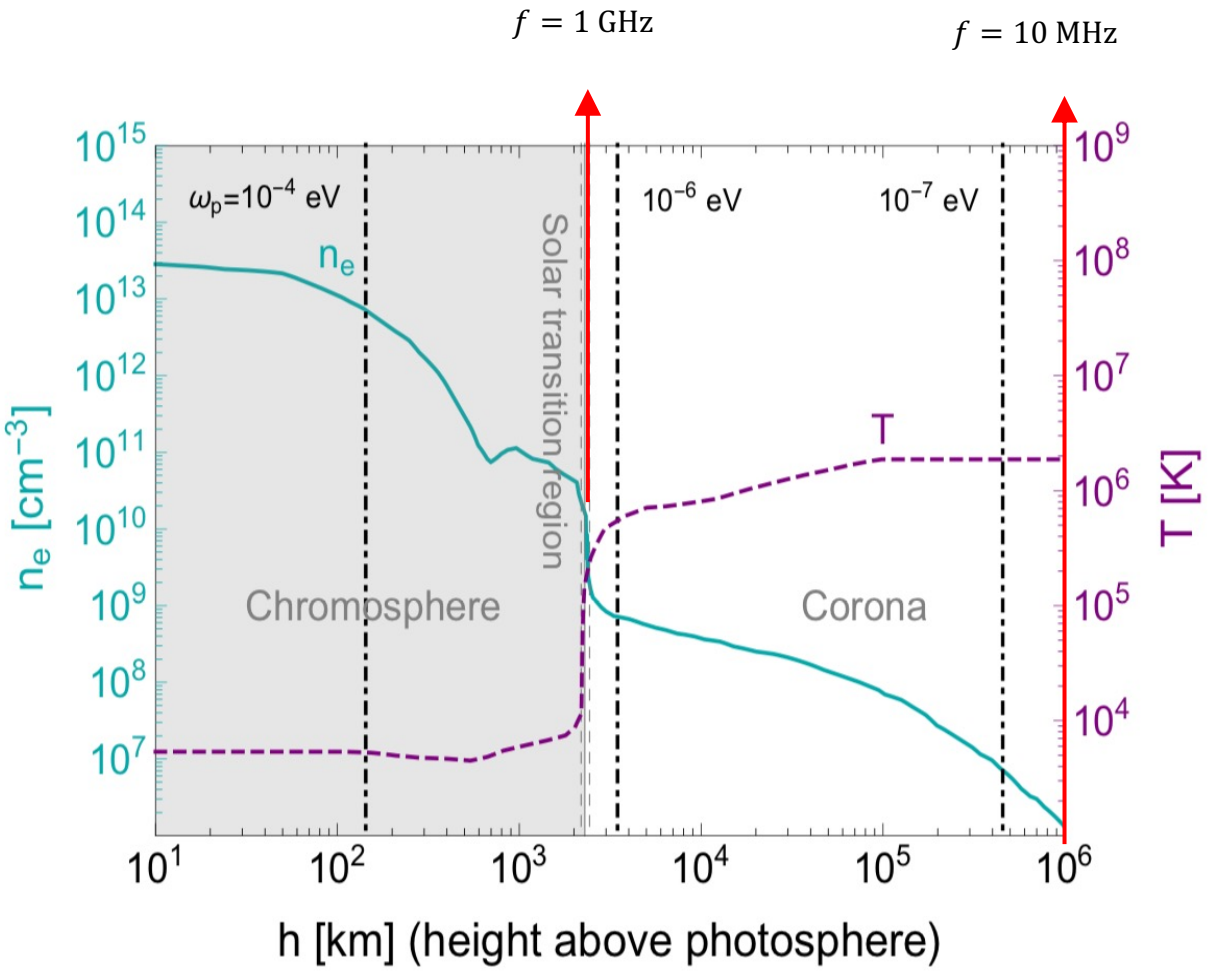
$$\omega^2 - k^2 = m^2$$

- For photon in plasma:

$$\omega^2 - k^2 = \omega_p^2$$

- We need plasma.



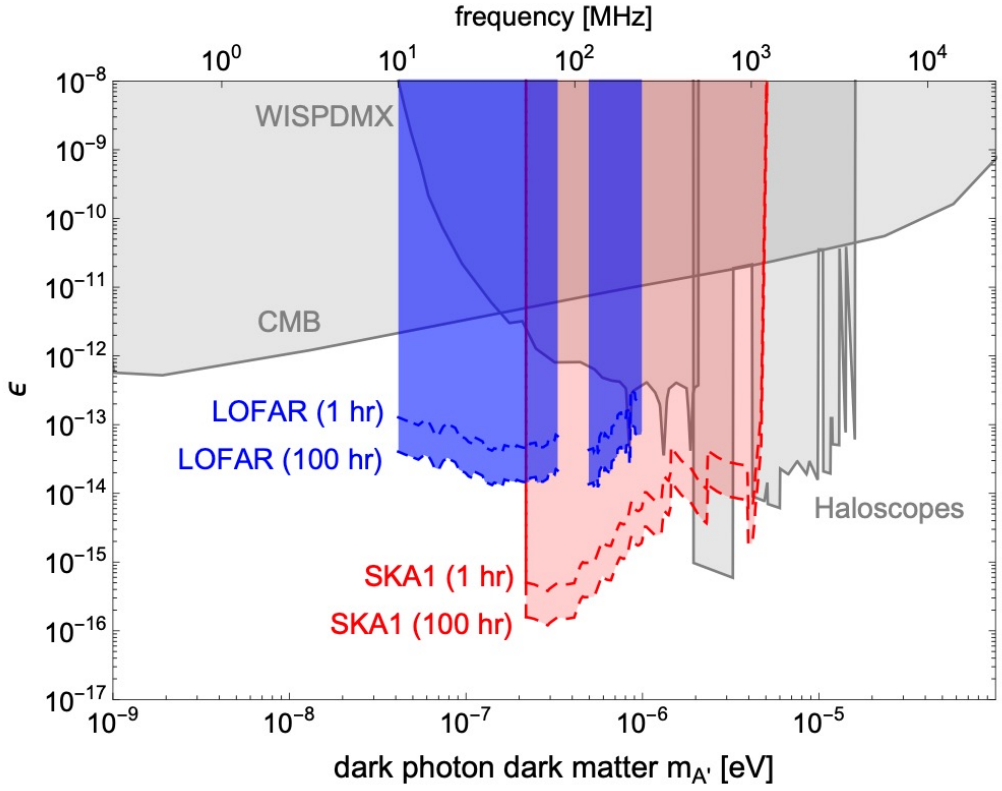


Searching for the converted photon with radio telescopes

- The minimal detectable flux

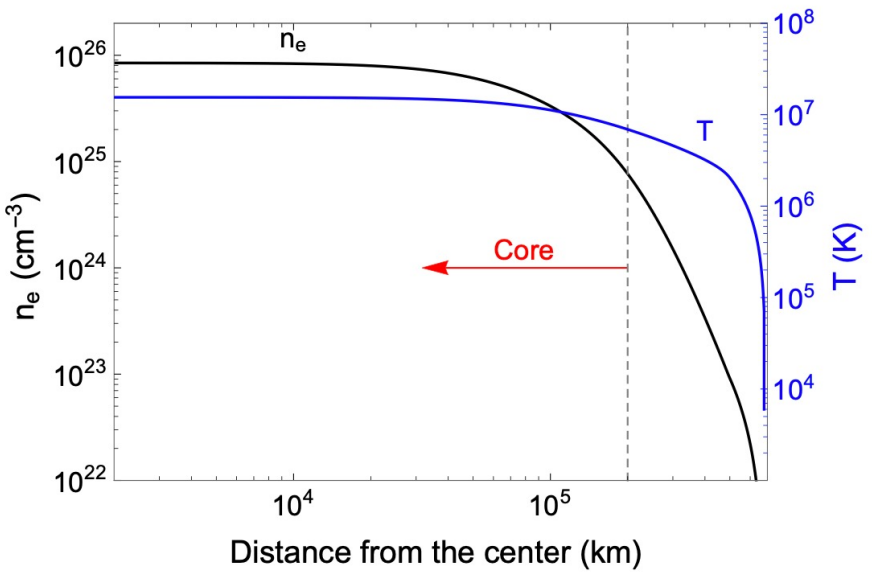
$$S_{\rm min} = \frac{\rm SEFD}{\eta_s \sqrt{n_{\rm pol}\, \mathcal{B}\, t_{\rm obs}}} \qquad {\rm SEFD} = 2k_B \frac{T_{\rm sys} + T_\odot^{\rm nos}}{A_{\rm eff}}$$

Name	f [MHz]	$B_{\rm res}$ [kHz]	$\langle T_{\rm sys} \rangle$ [K]	$\langle A_{\rm eff} \rangle$ [m^2]
SKA1-Low	(50, 350)	1	680	2.2×10^5
SKA1-Mid B1	(350, 1050)	3.9	28	2.7×10^4
SKA1-Mid B2	(950, 1760)	3.9	20	3.5×10^4
LOFAR	(10, 80)	195	28,110	1,830
LOFAR	(120, 240)	195	1,770	1,530



HA, F.P.Huang, J.Liu, W.Xue, 2010.15836, PRL 126 (2021)181102

Dark photon production inside the Sun



$$1\ \text{eV} < \omega_p < 300\ \text{eV}$$

Transverse modes

$$\omega^2 - |\vec{k}|^2 = \omega_p^2 \qquad \omega^2 - |\vec{k}|^2 = m_V^2$$

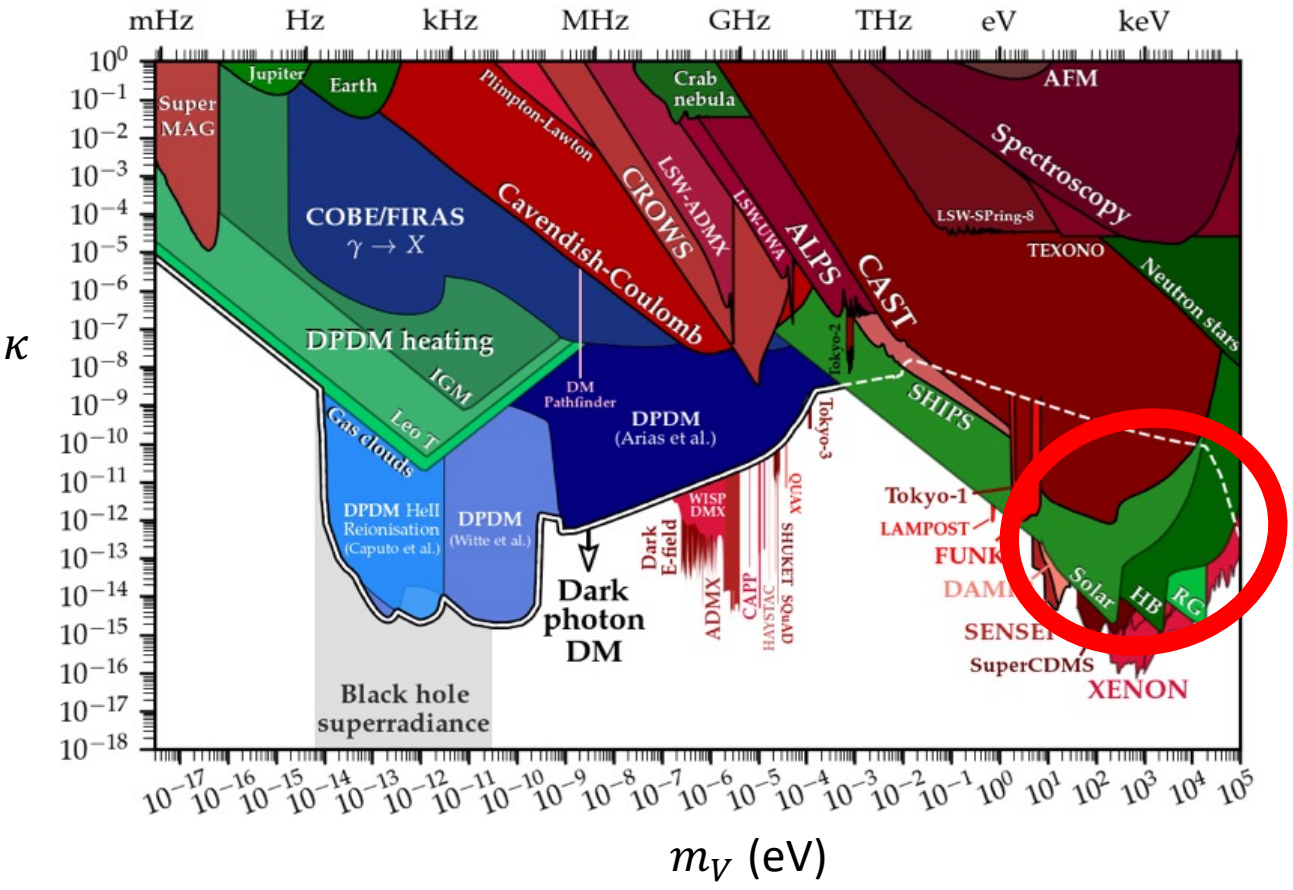
$$m_V^2 = \omega_p^2$$

Longitudinal mode

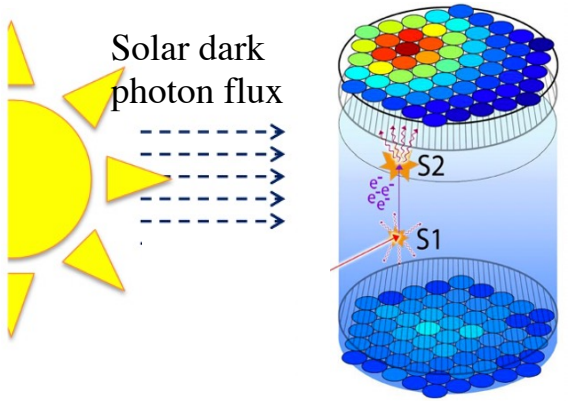
$$\omega^2 = \omega_p^2 \qquad \omega^2 - |\vec{k}|^2 = m_V^2$$

$$\omega^2 = \omega_p^2$$

Dark photon production inside the Sun



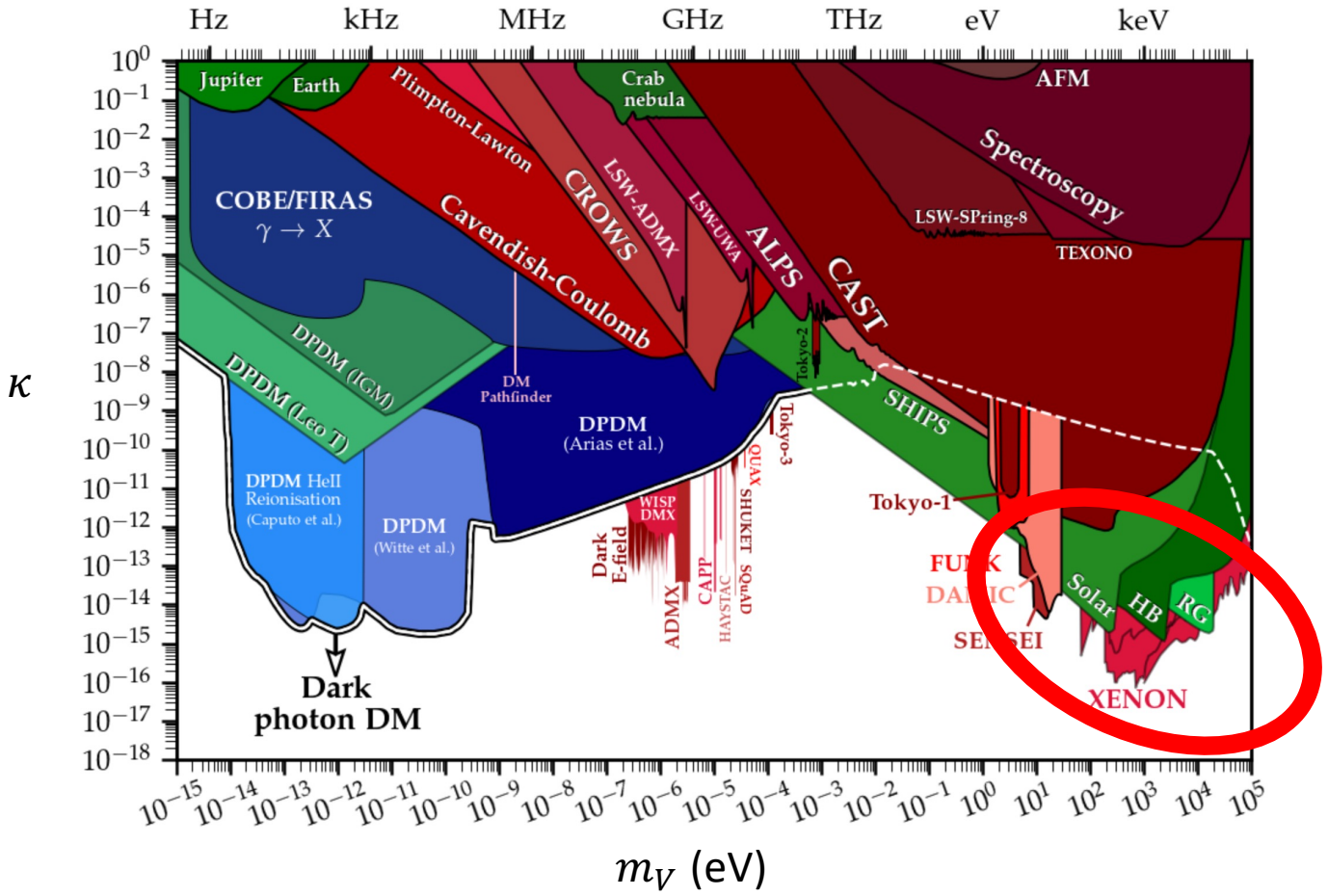
- Shorten the stellar lifetime.
- The dark photon flux can be detected by DM detectors.
- Change the solar neutrino flux.



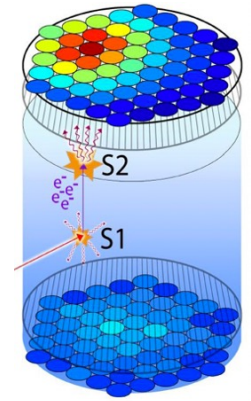
[HA, Pospelov, Pradler, PLB 725 (2013) 190,](#)
[HA, Pospelov, Pradler, PRL 111 (2013) 041302](#)

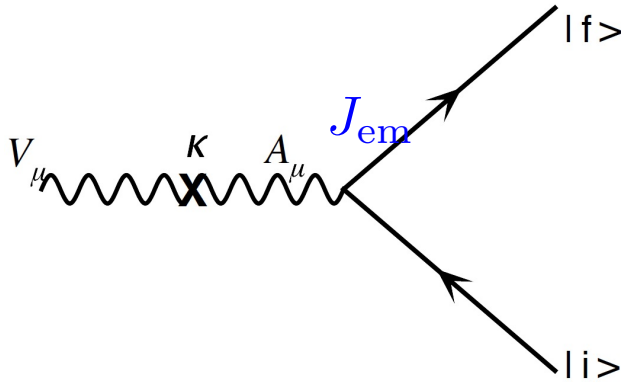
[HA, Pospelov, Pradler, Ritz, PLB 747 (2015) 331](#)
[HA, Pospelov, Pradler, Ritz, PRD 102 (2020) 115022](#)

Convert dark photon dark matter to virtual photons



Dark photon from DM halo





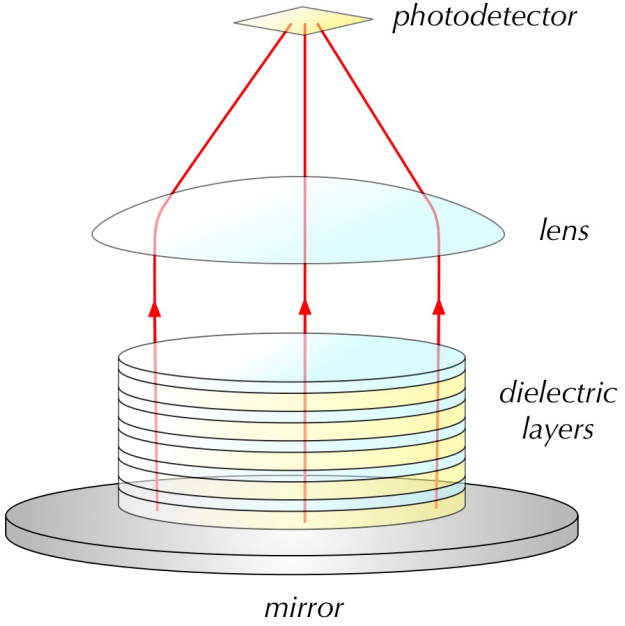
Breaking the spacial translation symmetry

- Inside homogeneous material

$$\omega^2 - |\vec{k}|^2 = \omega_p^2 \qquad \omega^2 - |\vec{k}|^2 = m_V^2$$

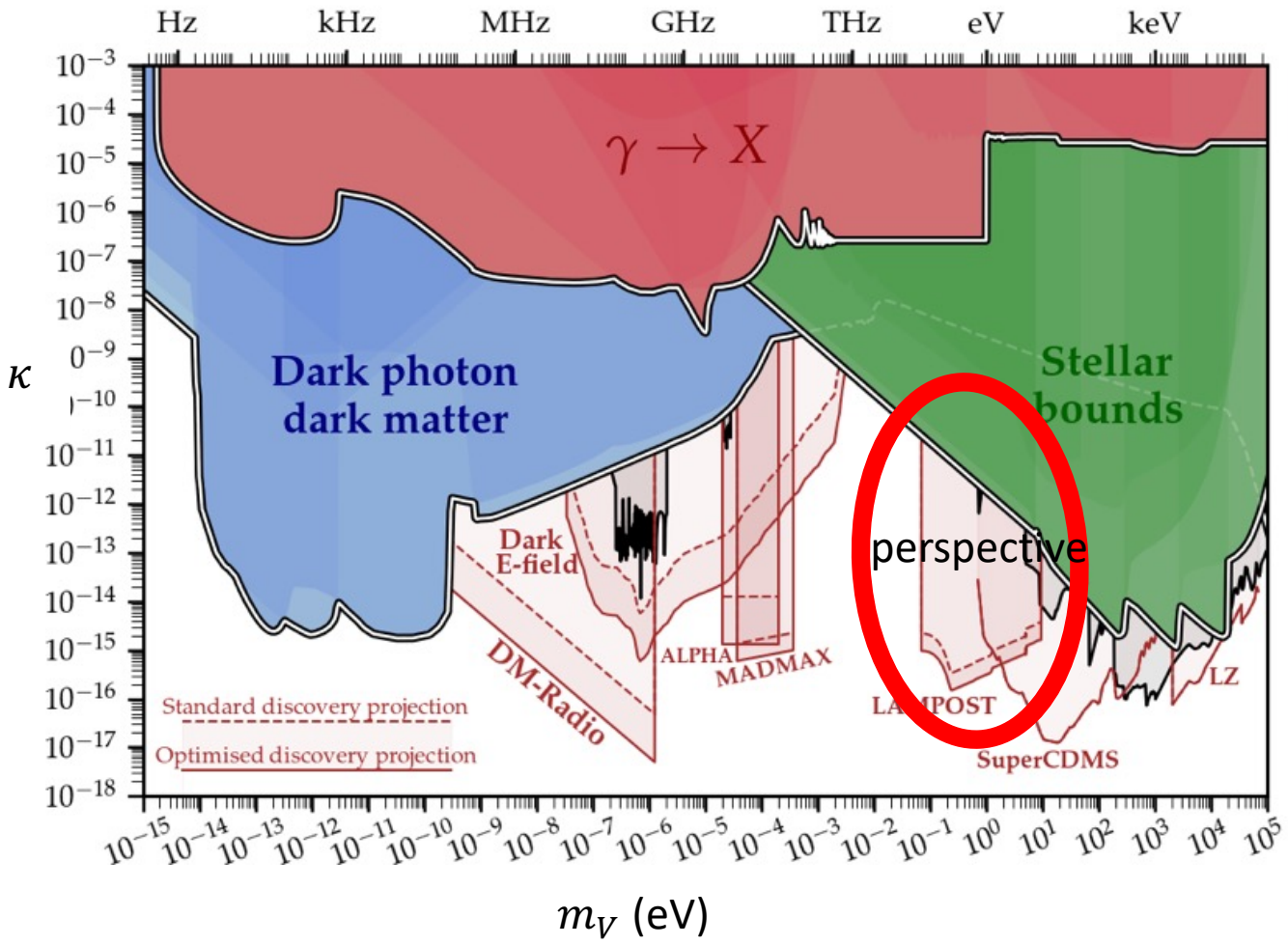
$$m_V^2 = \omega_p^2$$

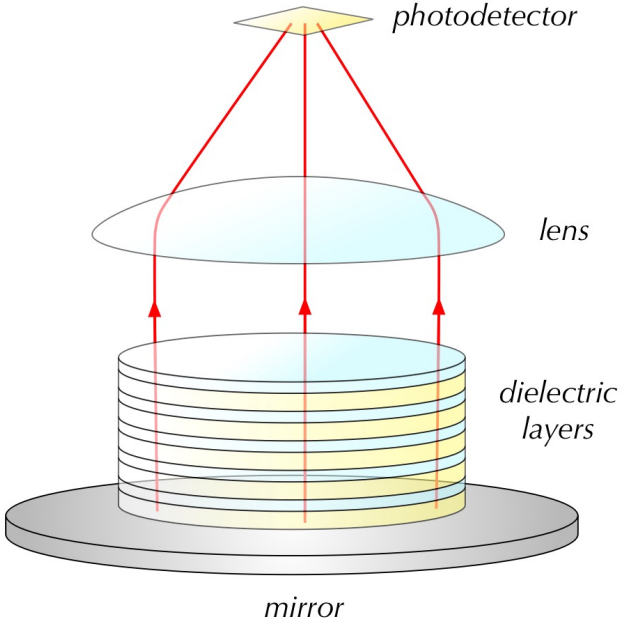
- A stack of dielectric layers, with alternating indices of refraction provide a non-zero momentum for the photon to propagate.



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

Breaking the spacial translation symmetry

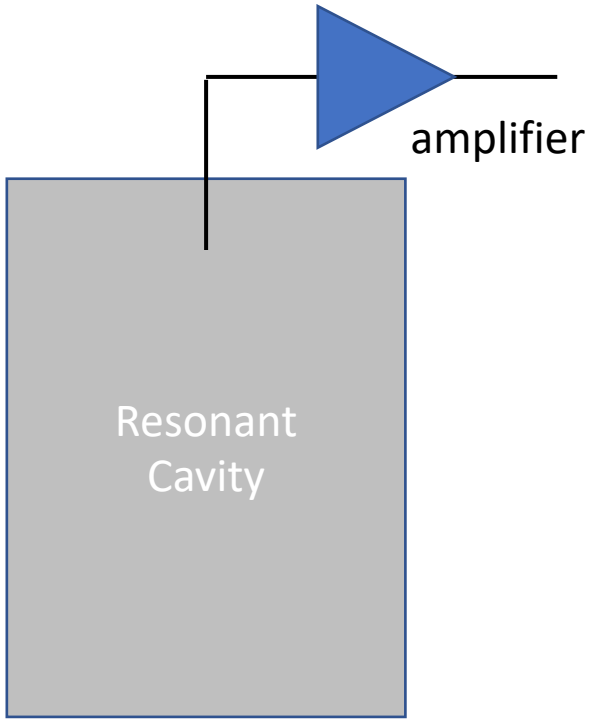


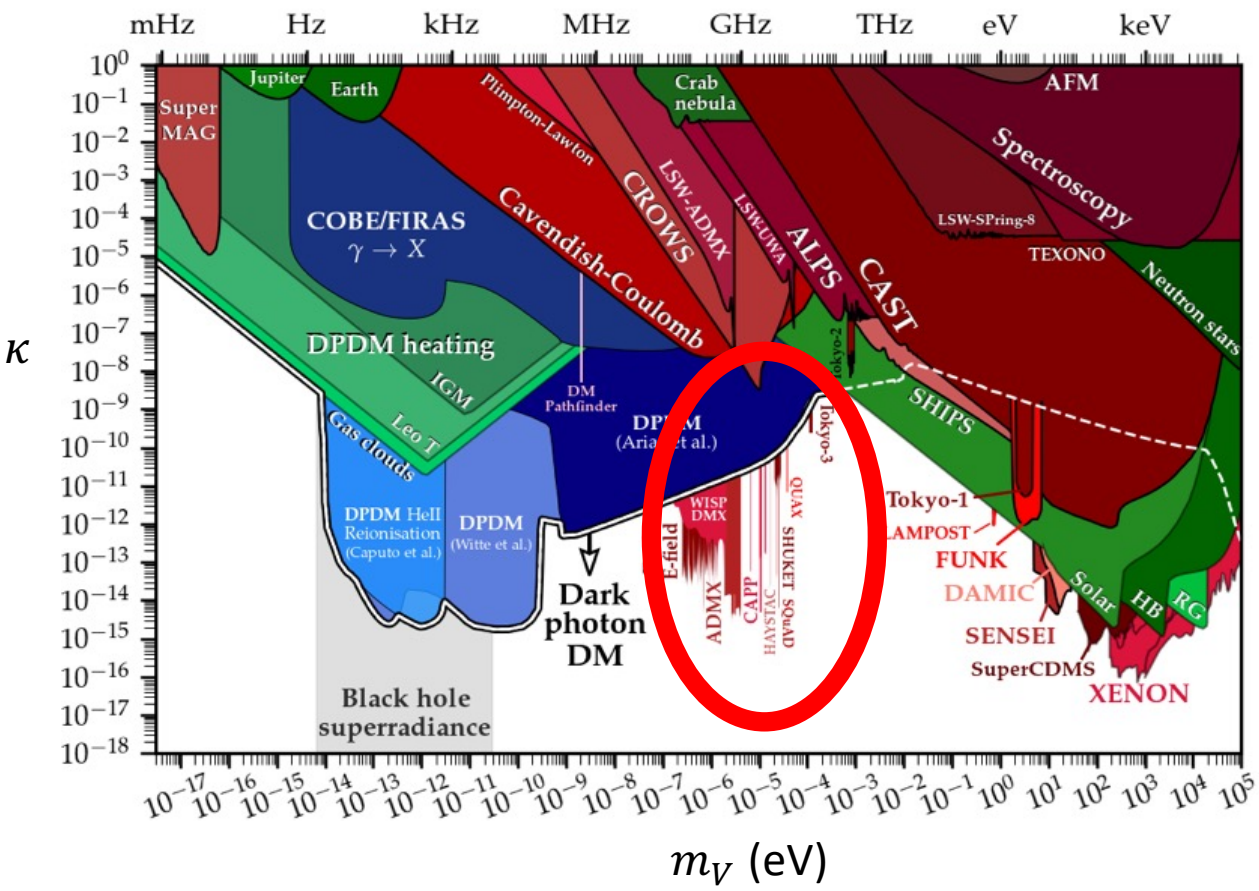


Baryakhar, Huang, Lasenby, PRD 98 (2018) 035006

Breaking the spacial translation symmetry

- Resonant cavities as haloscopes





Stuekelberg vs Higgs

- Restore the U(1) gauge symmetry

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_V^2 \left(V_\mu - \frac{\partial_\mu a}{m_V} \right)^2$$

Would-be Goldstone

- Should there be a dark Higgs mode?

No! (Naturalness)

Yes! A Higgs at weak scale has just been found.

Stueckelberg case

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_V^2 V_\mu^2$$

Higgsed case

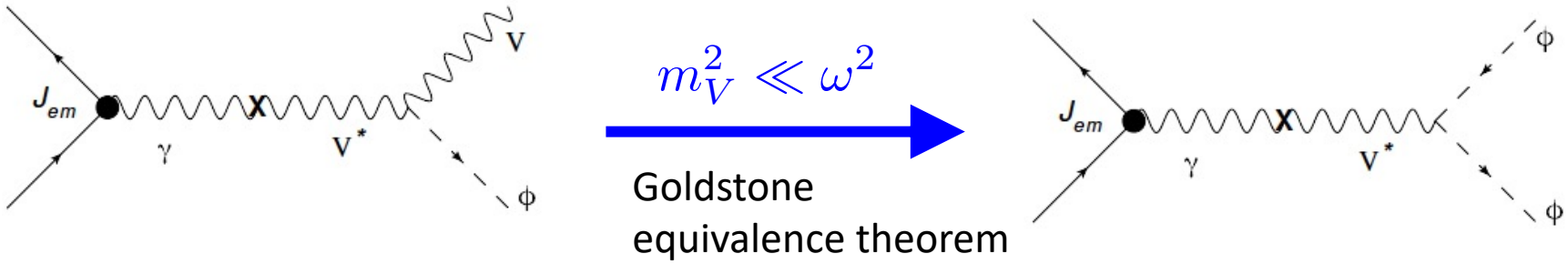
$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_V^2 V_\mu^2$$

$$\mathcal{L}_{\text{int}} = e' m_V h' V_\mu^2 + \frac{1}{2} e'^2 h'^2 V_\mu^2$$

In case of a light dark Higgs

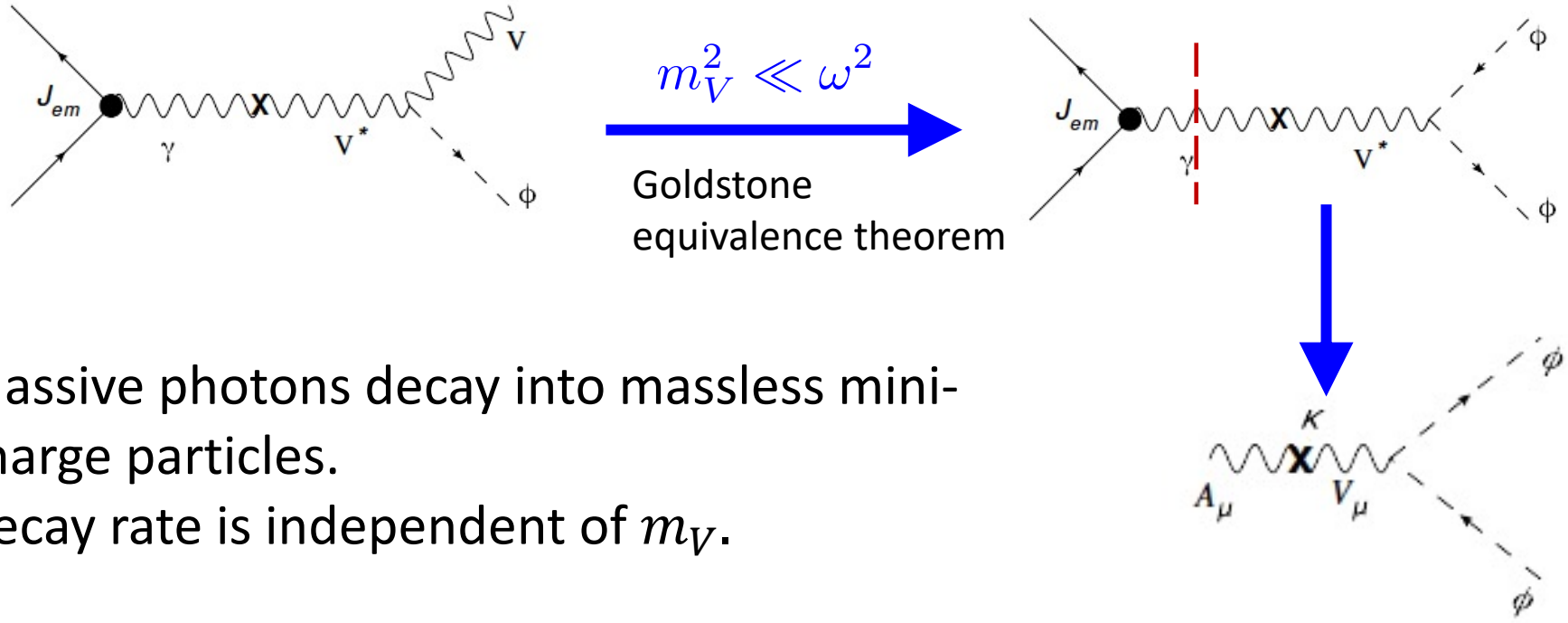
- The Higgs-strahlung process

Higgs modes before SSB



In case of a light dark Higgs

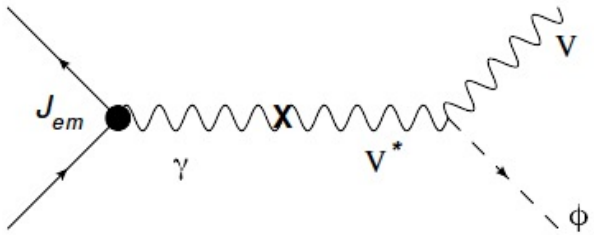
- The Higgs-strahlung process



- Massive photons decay into massless mini-charge particles.
- Decay rate is independent of m_V.

In case of a light dark Higgs

- The Higgs-strahlung process

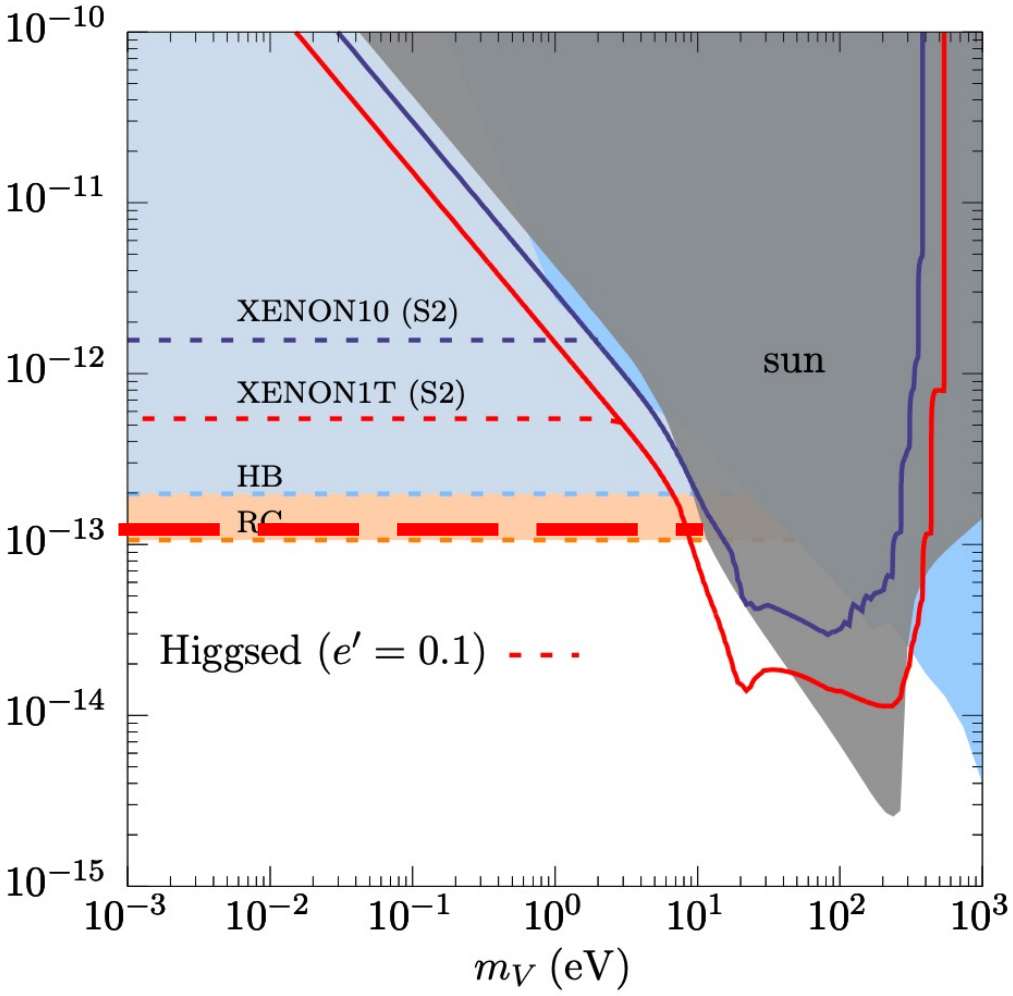


$m_V^2 \ll \omega^2$

Goldstone equivalence theorem

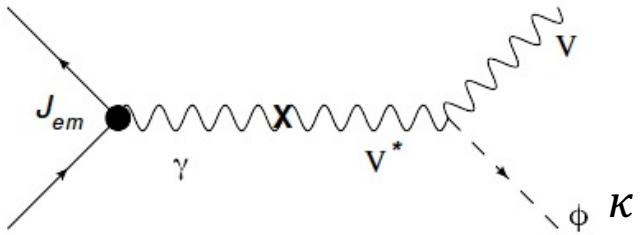
- Massive photons decay into massless mini-charge particles.
- Decay rate is independent of m_V.

HA, Pospelov, Pradler, Ritz, 2006.13929
HA, Pospelov, Pradler, 1304.3461

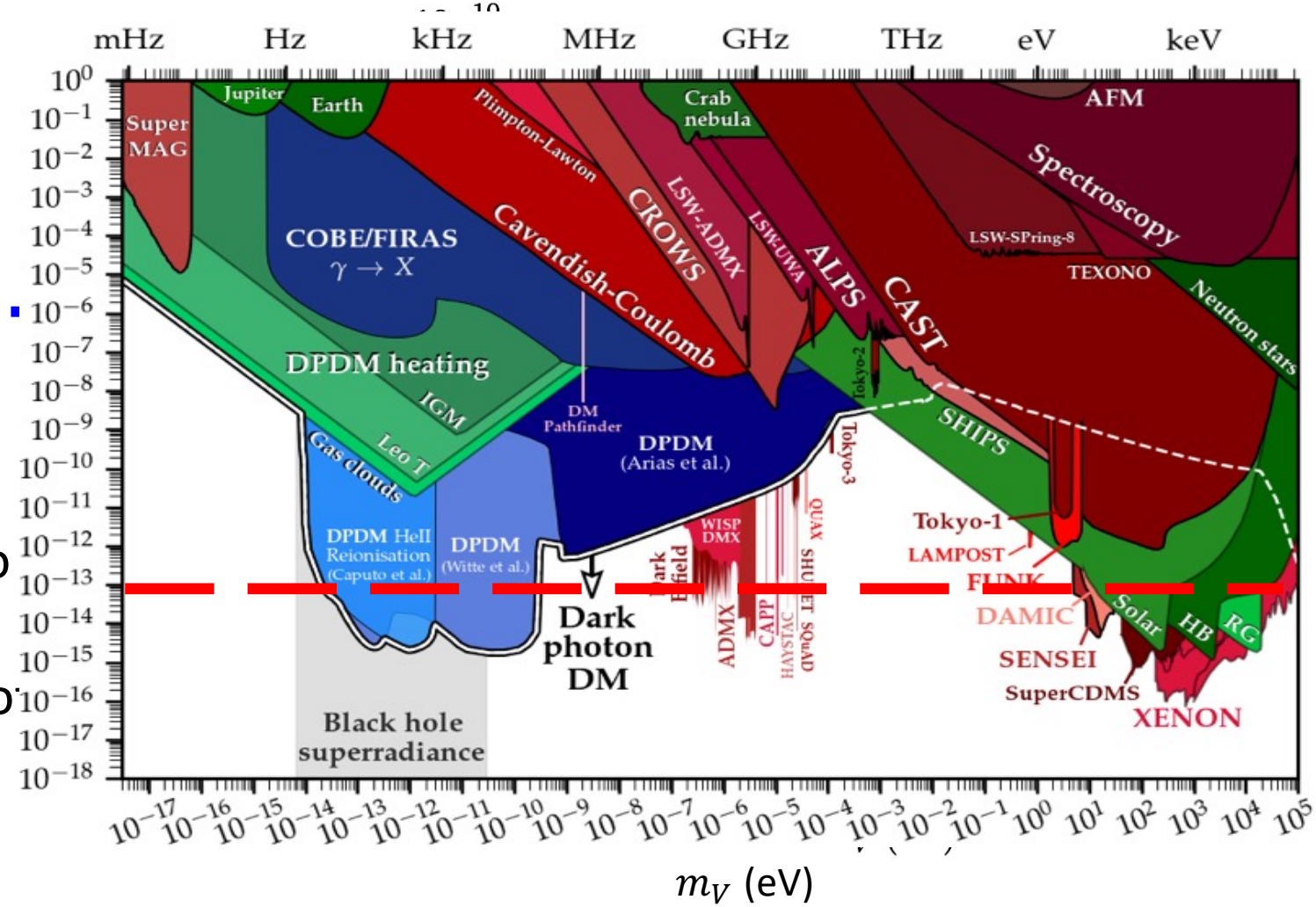


In case of a light dark Higgs

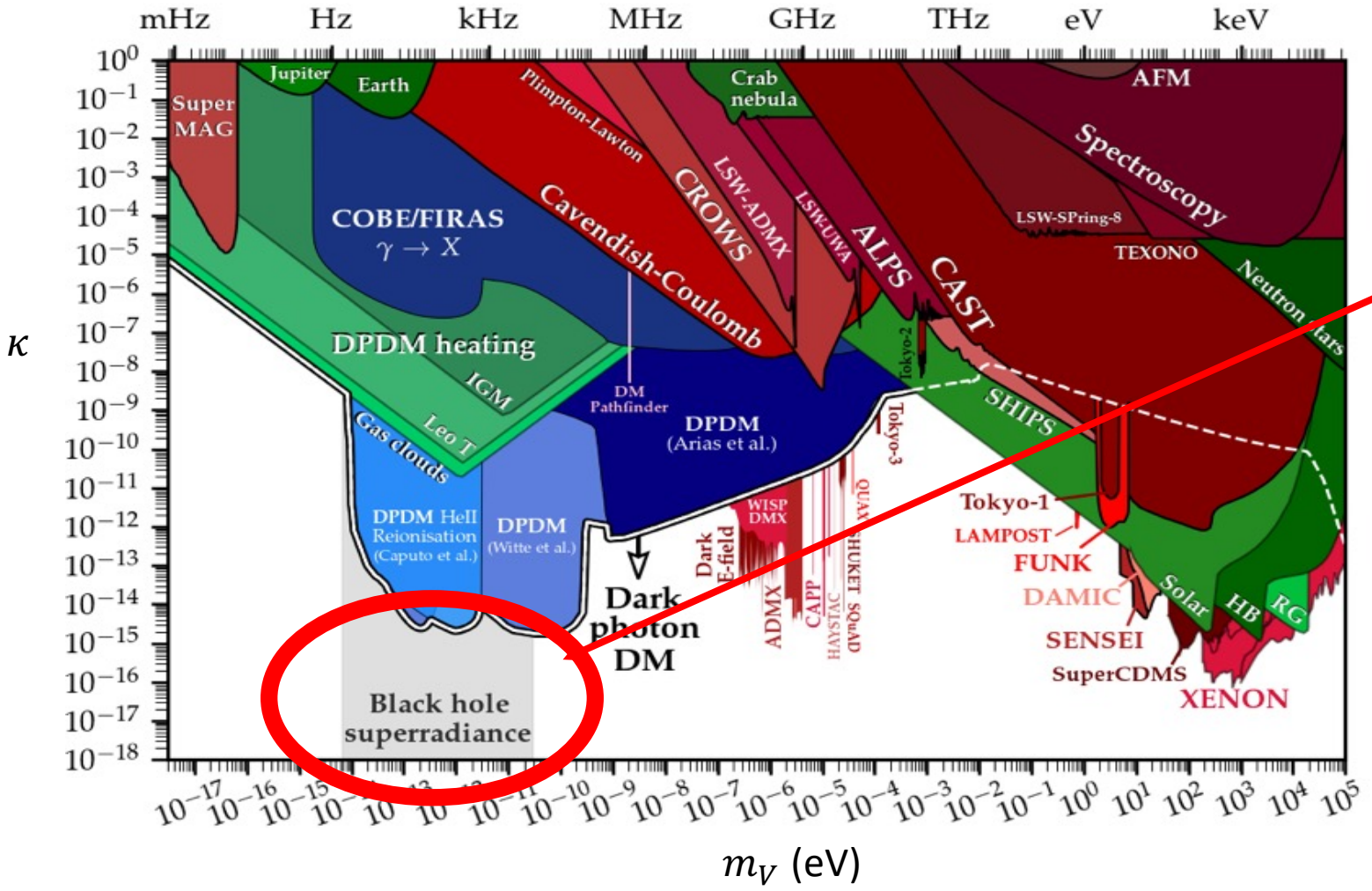
- The Higgs-strahlung process

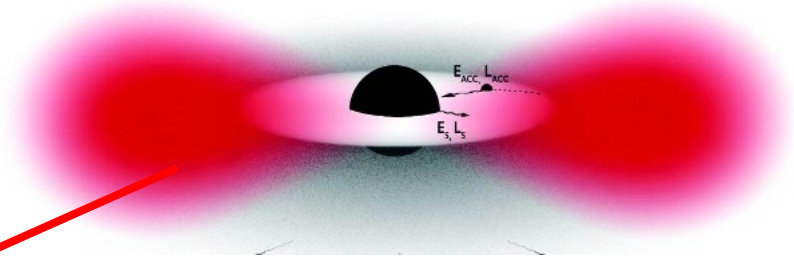


- Massive photons decay into charge particles.
- Decay rate is independent o



Black hole superradiance

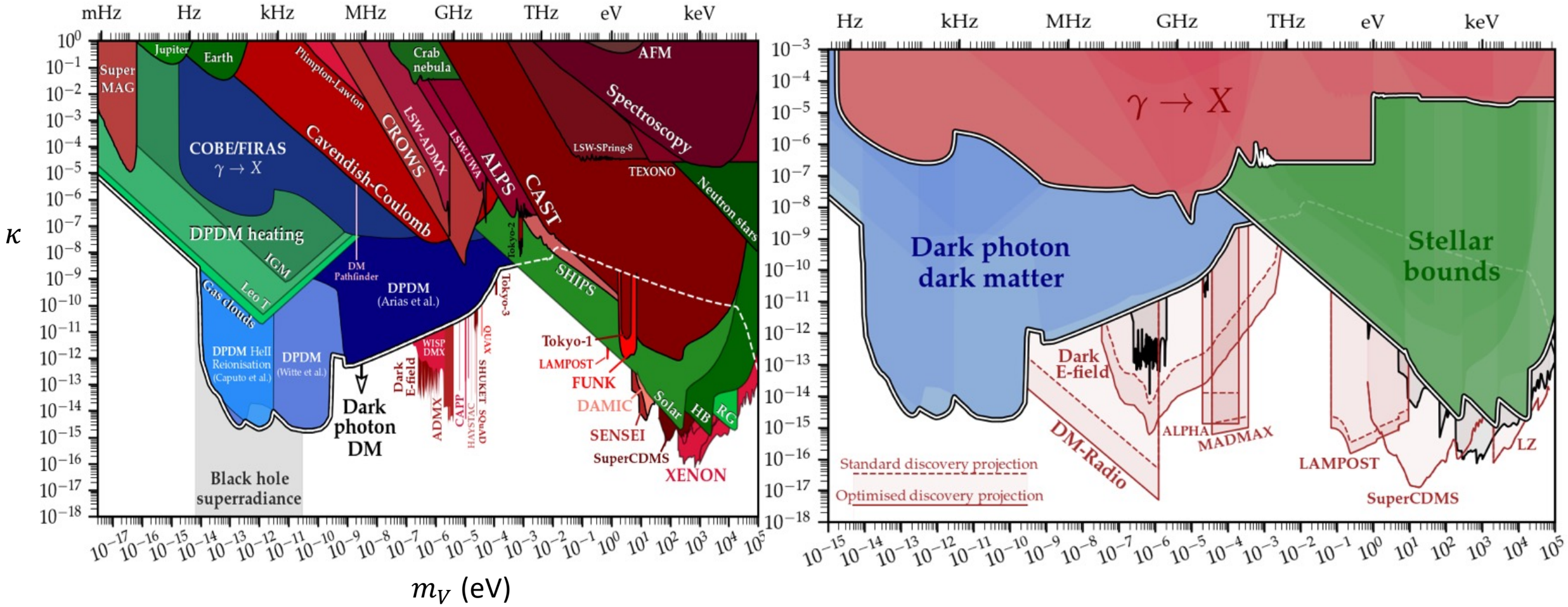




Cardoso et al. 1801.0142

The instability modes of dark photon drain energy from the spin of the black hole.

Summary


mHz
Hz
kHz
MHz
GHz
THz
eV
keV
κ
m_V (eV)
Super MAG
Jupiter
Earth
Plimpton-Lawton
Crab nebula
AFM
Spectroscopy
COBE/FIRAS
$\gamma \to X$
Cavendish-Coulomb
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
LSW-SPring-8
TEXONO
Neutron stars
DPDM heating
IGM
Leo T
Gas clouds
DM Pathfinder
DPDM (Arias et al.)
Tokyo-2
Tokyo-3
SHIPS
DPDM HeII Reionisation (Caputo et al.)
DPDM (Witte et al.)
Dark E-field
WISP DMX
ADMX
CAPP
HAYSTAC
QUAX
SHUKET SOuAD
Tokyo-1
LAMPOST
FUNK
DAMIC
Solar
HB
RG
SENSEI
SuperCDMS
XENON
Dark photon DM
Black hole superradiance
$\gamma \to X$
Dark photon dark matter
Stellar bounds
Dark E-field
DM-Radio
ALPHA
MADMAX
LAMPOST
LZ
SuperCDMS
Standard discovery projection
Optimised discovery projection