On the Inflationary Production of Light Dark Photon Dark Matter

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RIKEN iTHEMS

17th International Workshop on the Dark Side of the Universe

Kigali, Rwanda, 11 July 2023

In collaboration with

Yuichiro Nakai, Ippei Obata & Ziwei Wang

(2212.11516, 2004.10743)

Outline

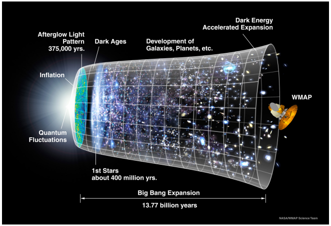
1. Dark matter and light dark photon as a candidate

2. Inflationary production of dark photon

3. Summary & Discussions

Outline

One reason WE need dark matter (a cosmologist's point of view)



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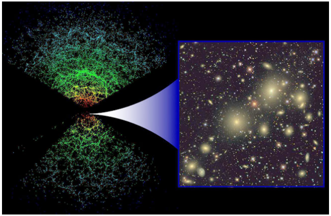

SDSS, adapted from astro.kias.re.kr

- Structure formation is a necessary ingredient for our universe to form

$$\frac{\partial^2 \delta}{\partial t^2} + 2H\,\frac{\partial \delta}{\partial t} + \left(c_s^2\,\frac{k^2}{a^2} - 4\pi G_N \bar{\rho} \right) \delta = 0$$

- $\nearrow$ density contrast $\delta = \delta\rho/\bar{\rho}$
- $\uparrow$ Hubble parameter
- $\uparrow$ sound speed
- $\nwarrow$ background density

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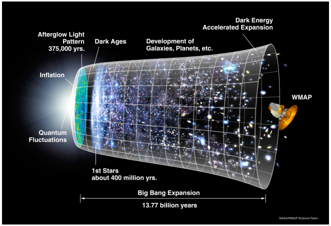

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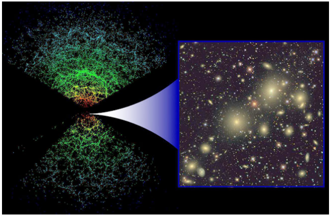

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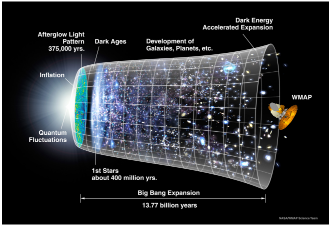
density contrast $\delta = \delta\rho/\bar{\rho}$; Hubble parameter ; sound speed ; background density

- Matter collapses due to gravity by $\bar{\rho} \neq 0$ for wavenumber

$$\frac{k}{a} < \underbrace{\frac{\sqrt{4\pi G_N \bar{\rho}}}{c_s}}_{\text{Jeans wavenumber}}$$



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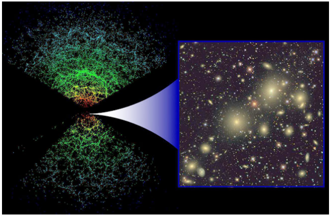

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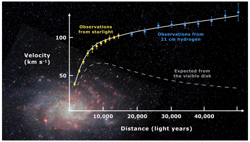
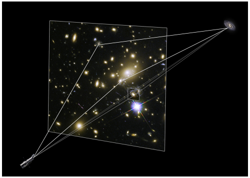
$$\frac{k}{a} < \underbrace{\frac{\sqrt{4\pi G_N \bar{\rho}}}{c_s}}_{\text{Jeans wavenumber}}$$

- Density of visible matter is too small, $\bar{\rho}_{\rm vis} < \bar{\rho}$
- **Dark matter** is necessary for the structure



credit: Mario De Leo, Wikipedia



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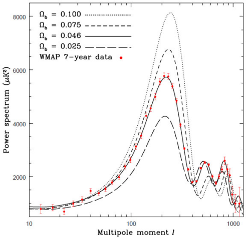
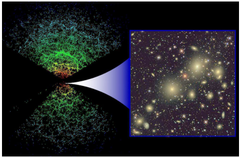


ned.ipac.caltech.edu

- Galaxy rotation curve
- Galaxy clusters
- Gravitational lensing
- Cosmic Microwave Background (CMB)
- Baryon acoustic oscillations (BAO)
- Structure formation
- Bullet Cluster
- Type Ia supernova distance measurements
- Redshift-space distortions
- Lyman-α forest
- ......

Chandra X-ray Observatory



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WHAT IS dark matter?

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A1. We don't know.

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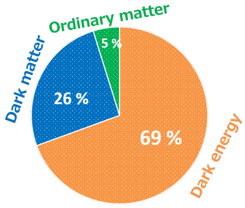
A2. We only know

- Cold: non-relativistic
- Dark: no/very weak interactions
- Matter: pressureless, forms clusters
- Gravitational interaction (at least)
- Abundance is known (under ΛCDM)



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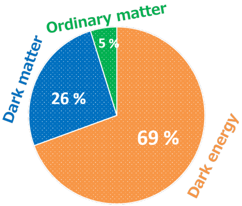


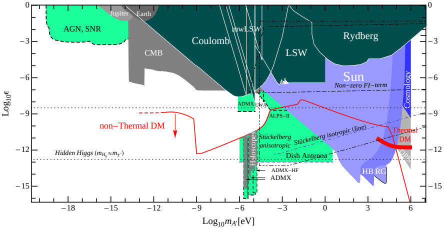
A large number of DM models have been proposed

▷ WIMP, axion DM, sterile neutrinos, condensates, modified gravity, . . .

Bertone & Tait '18

Dark Photon as Dark Matter candidate

$m_{A'} < 2m_e \sim 1\,\mathrm{MeV}$



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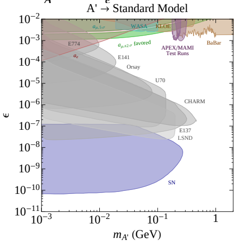

Essig+ '13

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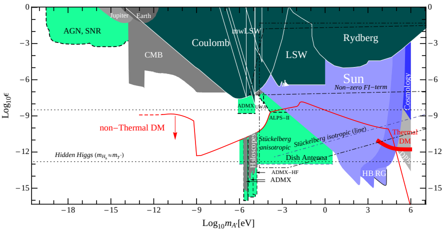

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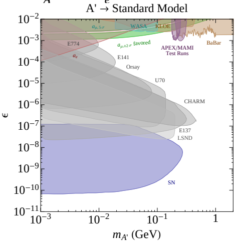

Essig+ '13

Theoretical motivation

- Very common in physics beyond SM
  - ▷ Gauge theories, string theory, . . .
- A wide range of mass is possible
  - ▷ Large mass ⇔ rich pheno
  - ▷ Small mass ⇔ stability against decay
- Kinetic mixing with electromagnetism

$$\mathcal{L}_{\rm mix} = \epsilon F'_{\mu\nu} F^{\mu\nu} \;\Leftrightarrow\; \mathcal{L}_{\rm int} = \epsilon e A'_\mu J^\mu_{\rm EM}$$

  - ▷ Rich playground for new physics
  - ▷ $? < 10^{-12} < |\epsilon| < 1$

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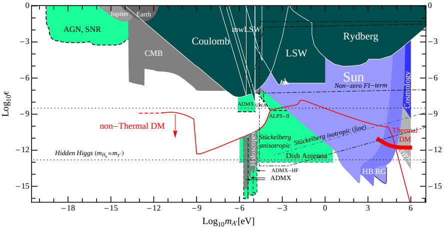

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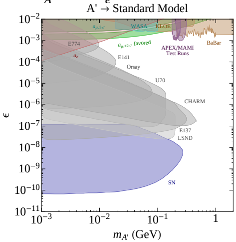

Essig+ '13

Phenomenological motivation

- Dark photon decay to SM for $m_{A'} > 2m_e$
  - ▷ Decays of hidden sector particles
  - ▷ Colliders & fixed-target experiments
- Only slow decays for $m_{A'} < 2m_e$
  - ▷ Stable against decays
- $A_{\mathrm{EM}} \leftrightarrow A'$ oscillation
  - ▷ Like neutrino oscillation
  - ▷ Effective photon disappearance

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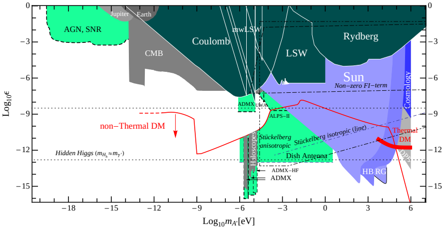

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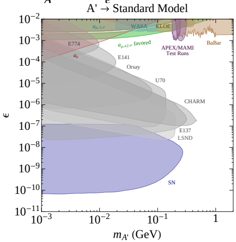

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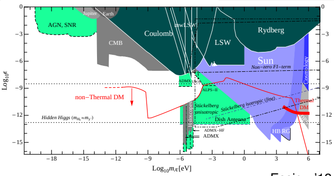
- Light dark photon is stable
  - ▷ Decays are kinematically forbidden
  - ▷ May still oscillate into EM photons



Essig+ ’13

- Ultra-light DM in fuzzy DM paradigm

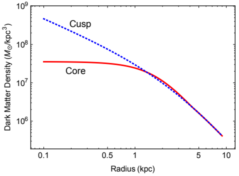
Hu+2000; Hui+ 2016

  - ▷ Might solve small-scale issues:

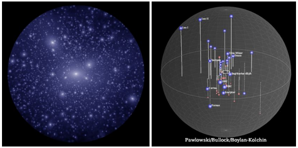
    core-cusp, missing satellites, too-big-to-fail
  - ▷ Wave nature manifests on galactic scales

$$m_{\mathrm{DM}} \sim 10^{-22}\,\mathrm{eV} \;\Leftrightarrow\; \lambda_{\mathrm{dB}} \sim 1\,\mathrm{kpc}$$

Core-cusp problem



Tulin & Yu 2017



V. Robles & T. Kelley, M. Pawlowski

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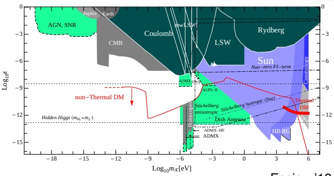
- Cold DM paradigm is favored
  - ▹ Cold ⇔ non-relativistic
  - ▹ $p \ll m_{\rm DM}$

- If DM production is at temperature T
  - ▹ Typically $p \sim T \gg m_{\rm DM}$ for light DM



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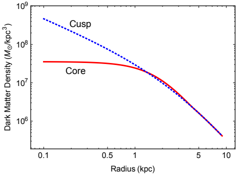

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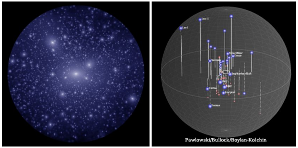

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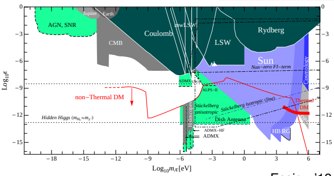

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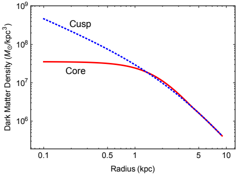

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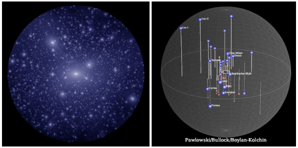
- Potentially **non-thermal production**



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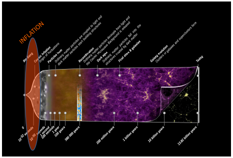
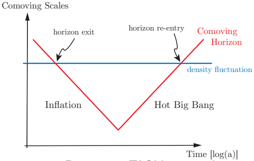
Outline

Inflation



- (Quasi-)exponential expansion of space at the earliest stage of the universe
  - Resolves conceptual problems in hot Big Bang cosmology
- Generation of seeds of fluctuations in the universe
  - Cosmic microwave background
  - Large-scale structure
  - Primordial gravitational waves (yet to be discovered)
- **Long wavelength modes are generated**
  - “Modes are stretched to super-horizon scales”
  - Expansion alone creates perturbations



Baumann, TASI Lecture, ’09

Massless gauge fields are NOT produced by expansion alone

▹ Conformal/Weyl invariance of free gauge field in 4-D

$$g_{\mu\nu} \rightarrow \Omega^2 g_{\mu\nu} \,,$$
$$\mathcal{L}_{\rm free} \propto \sqrt{-g}\, g^{\mu\rho} g^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma} \rightarrow \Omega^{4-2-2} \sqrt{-g}\, g^{\mu\rho} g^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma}$$

Conformal invariance

Y. Nakayama's talk

Weyl invariance and inflationary (non-)production of dark photon

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- **Insensitive to the background expansion**

- In contrast to **cosmological perturbations**
  (density perturbation & gravitational wave)

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Conformal invariance

Y. Nakayama's talk

- **Breaking conformal invariance is essential**

Breaking conformal invariance

By coupling to scalar/pseudo-scalar field σ

Higgs-like mass term

$$\mathcal{L}_{\rm int} = -\frac{m_{\gamma'}^2}{2} A_\mu A^\mu$$

- Longitudinal mode $\sim$ scalar pert'n
- Dark photon mass $m_{\gamma'} \gtrsim 10^{-6}\,\mathrm{eV}$
  Graham+ '15
- $m_{\gamma'} \gtrsim 10^{-18}\,\mathrm{eV}$ with param. resonance
  Dror+ '18

Chern-Simons coupling

$$\mathcal{L}_{\rm int} = \frac{\sigma}{4f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Tachyonic enhancement by $\partial_t \sigma \neq 0$
- Lower H during inflation is possible
- Dark photon mass $m_{\gamma'} \sim \mu\mathrm{eV} - \mathcal{O}(100)\,\mathrm{GeV}$
  Bastero-Gil+ '18

Kinetic coupling

$$\mathcal{L}_{\rm kin/int} = -\frac{I^2(\sigma)}{4} F_{\mu\nu} F^{\mu\nu}$$

- Additional control on the production thanks to $I(\sigma)$ (or thanks to the classical motion of σ)
- Degree of $\partial_t I \neq 0$ is a measure of violation of Weyl inv.
- Dark photon mass $m_{\gamma'} \gtrsim 10^{-13}\,\mathrm{eV}$ is possible
  Nakai, RN & Obata '22

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Consistency checks for production

Energy conservation (continuity eq.)

- Dark photon is produced from vacuum at the cost of kinetic energy of σ
- Production rate is bounded by the energy transfer rate

$$|\partial_t \rho_{\gamma'}| < |\partial_t \rho_\sigma|$$

$\Rightarrow$ **Bound on coupling constant**

Prolonged inflationary period

- Produced dark photon contributes to energy density
- Production needs to be subdominant not to spoil inflation

$$\rho_{\gamma'} < \rho_\sigma \, (< \rho_{\rm total})$$

$\Rightarrow$ **Bound on total energy transfer**

Constraints from CMB

- Produced dark photon dark matter contributes to entropy/isocurvature moes
- CMB observations constrain entropy perturbations at cosmological scales

$$\frac{\rho_{\gamma'} - \langle \rho_{\gamma'} \rangle}{\langle \rho_{\gamma'} \rangle} \lesssim 10^{-5} \ @{\rm Mpc} - {\rm Gpc}$$

$\Rightarrow$ **Production @ largest-scale suppressed**

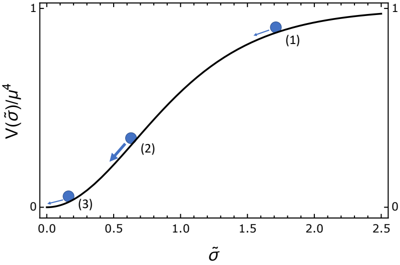
"Cold" dark matter

- Produced dark photon needs to become non-relativistic before matter-radiation equality
- Production rate is bounded by the energy transfer rate

$$p_{\gamma'}(t_{\rm eq}) \ll m_{\gamma'}$$

$\Rightarrow$ **High reheating temperature favored**

Peaked spectrum of dark photon from a (slowly) rolling scalar



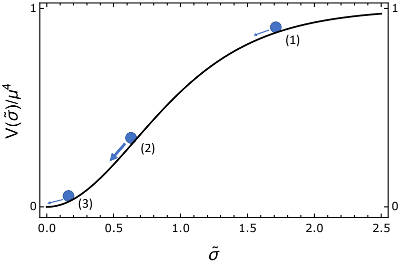
Nakai, RN & Obata '22

Inflecting scalar potential

$$V(\sigma) = \mu^4 \tanh^2\left(\frac{\sigma}{\Lambda}\right)$$

- σ rolls for > 60 e-folds
- Speeds up around the inflection point
- Efficiently enhances DP fluctuations

Nakai, RN & Obata '22



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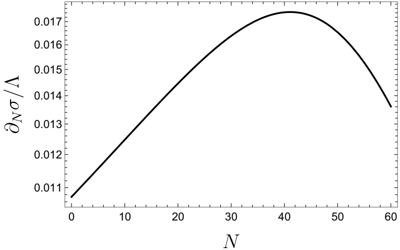
Dilaton-photon-type coupling

$$I(\sigma) = I_0 \exp\left(\frac{\sigma}{M}\right)$$

EoM of dark photon A'_μ (in $\boldsymbol{k}$ space)

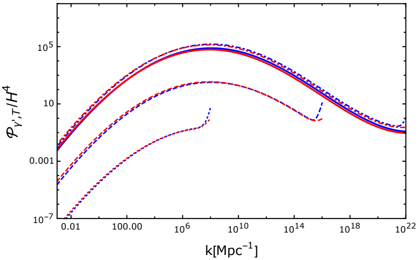
$$\left[\frac{\partial^2}{\partial\tau^2} + k^2 - \frac{n(\tau)\,(n(\tau)+1)}{\tau^2}\right]\left(I\boldsymbol{A}'\right) \simeq 0$$

$$n(\tau) \equiv \frac{\partial I/\partial N}{I} = \frac{\partial\sigma/\partial N}{M}$$



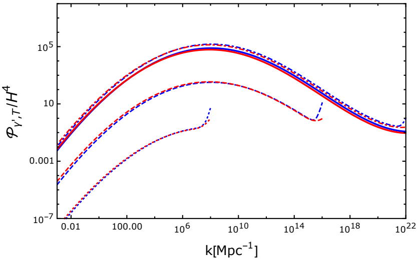
- The spectrum of $\boldsymbol{A}'$ reflects σ's motion at the time each mode exits the horizon

Nakai, RN & Obata '22



- Peak $\simeq$ the mode exiting the horizon at the time when $|\dot{\sigma}|$ is maximum

Resultant spectrum and allowed parameter space



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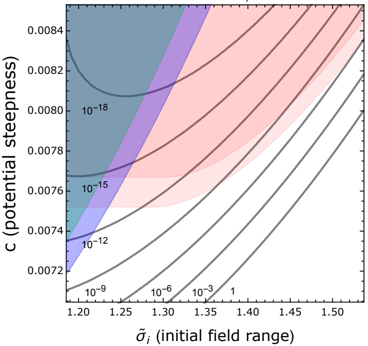

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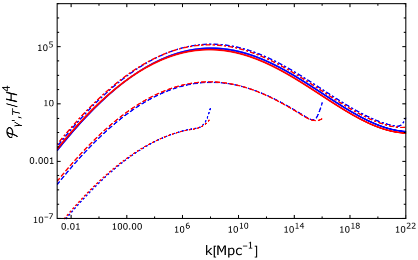

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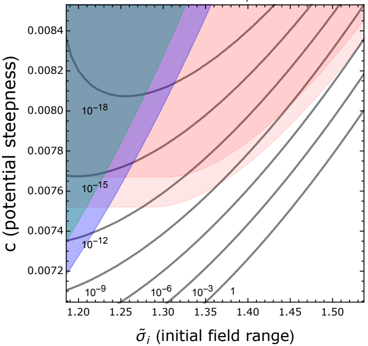

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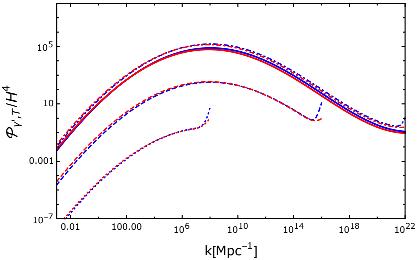

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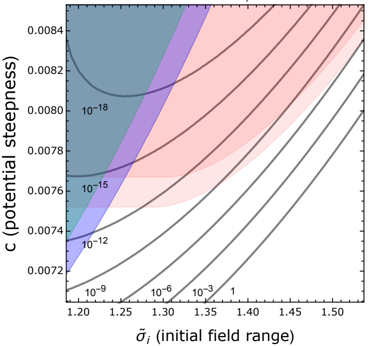

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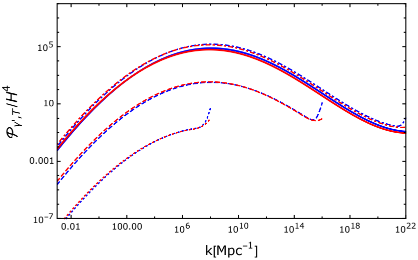

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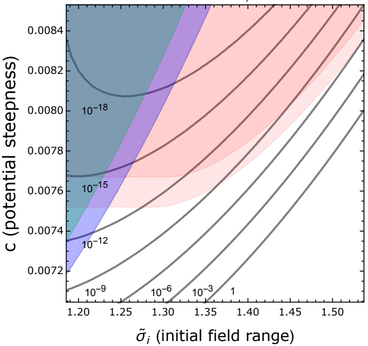

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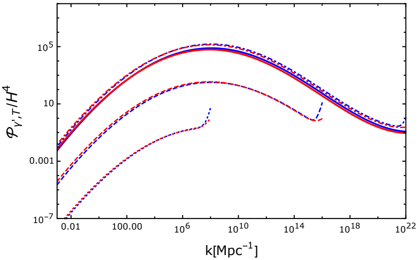

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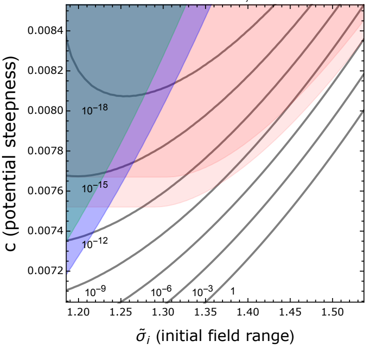

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- **Successful dark photon dark matter for $m_{\gamma'} \gtrsim 10^{-13}\,\mathrm{GeV}$**

Einstein equation

$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

$\Downarrow$ GW

$\Downarrow$ Produced particle/field

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- Produced fields inevitably source GW

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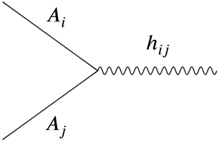
GW ⇔ tensor mode of metric

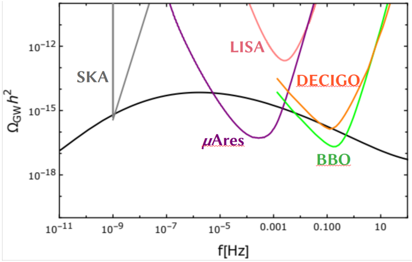
$$g_{ij} = a^2 \left(\delta_{ij} + h_{ij}\right)$$

$$\left(\frac{\partial^2}{\partial\tau^2} - \nabla^2 - \frac{\partial_\tau^2 a}{a}\right)(a\, h_{ij}) = -\frac{2\, a^3}{M_p^2}\left(E_i E_j + B_i B_j\right)$$



$$E_i \equiv -\frac{\bar{I}}{a^2}\partial_\tau A_i\ , \quad B_i \equiv \frac{\bar{I}}{a^2}\epsilon_{ijk}\partial_j A_k$$

Nakai, RN & Obata '22



GW energy density

$$\rho_{\rm GW} = \frac{M_{\rm Pl}^2}{8a^2}\left\langle \partial_\tau h_{ij}\,\partial_\tau h_{ij} + \partial_k h_{ij}\,\partial_k h_{ij}\right\rangle$$

Fractional GW density spectrum:

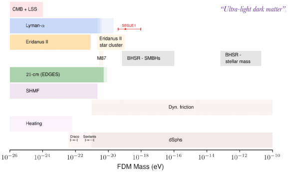
$$\Omega_{\rm GW} = \frac{1}{3M_{\rm Pl}^2 H^2}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln k}$$

$$m_{\gamma'} = 1.64\times 10^{-13}\,{\rm GeV}, \quad c = 7.525\times 10^{-3}, \quad \tilde{\sigma}_i = 1.2525$$

- Peaky spectrum reflects the production feature of dark photon
- Potential GW signature from very light dark photon dark matter
- Future GW missions are wanted!

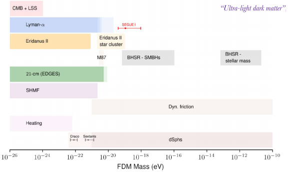
Outline

Summary & discussions



- Dark matter is a necessary ingredient for our universe, albeit unknown identity
- Light dark photon is an interesting candidate
  - Stable against decay
  - Ubiquitous in models beyond SM

Summary & discussions



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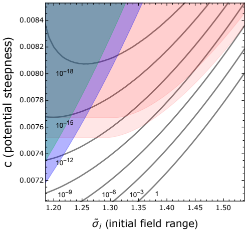
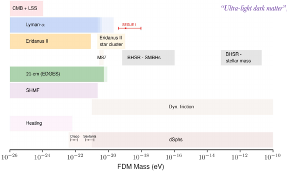
- Inflationary production of dark photon

$$\mathcal{L}_{\mathrm{kin/int}} = -\frac{I^2(\sigma)}{4} F_{\mu\nu} F^{\mu\nu}$$

- Peaked spectrum from the motion of σ
- Open parameter space for $m_{\gamma'} \gtrsim 10^{-13}\,\mathrm{eV}$
- Potential GW signals from very light DPDM for future GW observations





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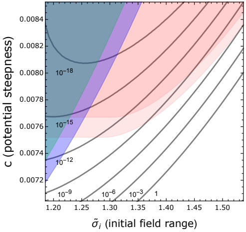

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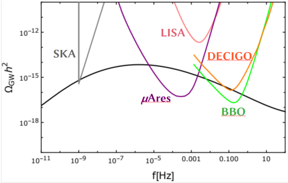

- **Further phenomenology?**
  - – Kinetic mixing with SM photon ⇒ effective coupling to charged particles
  - – Other signals in astrophysical/cosmological experiments?

BONUS SLIDES

Strong coupling issue

- Also the dark sector may have particles charged under the dark $U(1)$

$$\mathcal{L}_{\rm dark} = -\frac{I^2}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{m_{\gamma'}^2}{2} A'_\mu A'^\mu + e' A'_\mu J^\mu_{\rm dark}$$

- By canonically normalizing $A'_\mu = A_\mu^{\rm canonical}/I$, the mass and coupling become

$$m_{\gamma'} \to \frac{m_{\gamma'}}{I}$$
$$e' \to \frac{e'}{I}$$

- For $n > 0$, I increases in time $\Leftrightarrow$ very small I initially
- For $n < 0$, I decreases in time $\Leftrightarrow$ very large I initially
- **Better to have $n < 0$**
  - ▹ To avoid mass suppression of production
  - ▹ To avoid strong coupling in dark sector
- **$n > 0$ is essentially excluded**

Evolution after inflation

- Cold dark matter paradigm is our target
- Produced dark photon must become non-relativistic at time $t_{\rm NR}$, defined by

$$\frac{k_{\rm peak}}{a(t_{\rm NR})} = m_{\gamma'}$$

- We demand that this time is earlier than the matter-dominated era starts

$$t_{\rm NR} < t_{\rm eq}$$

- The dark photon behavior changes from radiation-like to dust-like

$$\langle \rho_{\gamma'} \rangle \propto \begin{cases} a^{-4} \,, & t < t_{\rm NR} \\ a^{-3} \,, & t > t_{\rm NR} \end{cases}$$

- Evaluate the fractional energy density of dark photon at the present time

$$\Omega_{\gamma'} \equiv \left. \frac{\langle \rho_{\gamma'} \rangle}{\rho_c} \right|_{t=t_0} \quad \Leftrightarrow \quad \Omega_{\rm DM} \simeq \frac{0.120}{h^2}$$