Title: Cosmological dynamics of light dark bosons

Speakers: Junwu Huang

Series: Colloquium

Date: February 28, 2024 - 2:00 PM

URL: https://pirsa.org/24020048

Abstract: Light bosons, including light axions, dark photons, and dilaton/moduli, are well motivated extensions to the Standard Model of particle physics and intriguing dark matter candidates. Much progress has been made in recent years in both astrophysical and lab searches for these light bosons with the understanding that these light bosons act like weak classical waves which permeate the space we occupy.

In this talk, I will discuss some novel phenomenon of light bosons in the dark sector, based on important in medium effects of these particles. I will show how to take advantage of medium effects of the photon to optimize searches for these light bosons with data coming from cosmic microwave background (CMB) experiments, and improve sensitivity to light dark photons and axions by orders of magnitude. I will also show how thinking of dark photon as weak classical waves breaks down during production of light bosons in both early and late universe, when gauged strings are produced in an event we call the string Bosenova, as well as the resulting observable consequences.

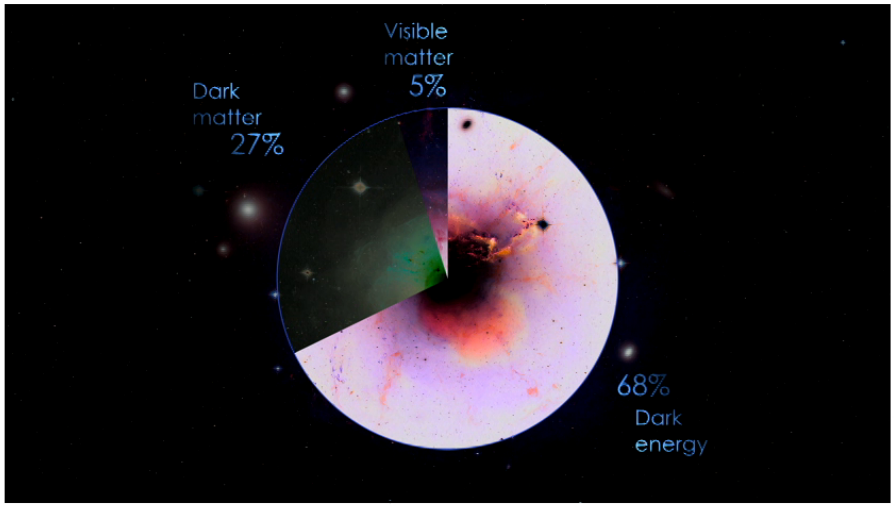
Zoom link

Light dark bosons in the cosmos

Junwu Huang
Feb 28, 2024

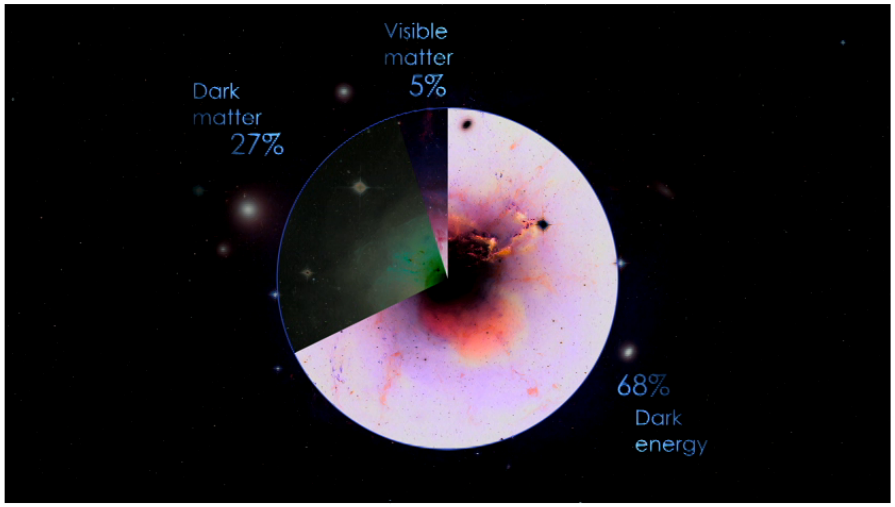
Beyond standard model

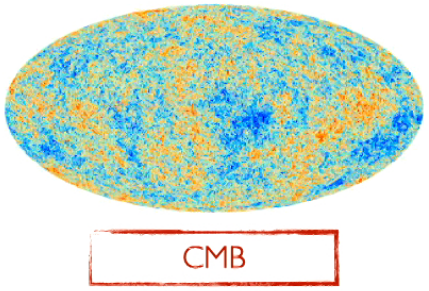
- We have evidence for physics beyond the Standard Model

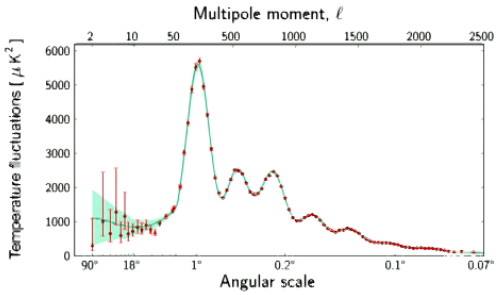


Beyond standard model

- We have evidence for physics beyond the Standard Model
- We know Dark Matter exist, gravitationally







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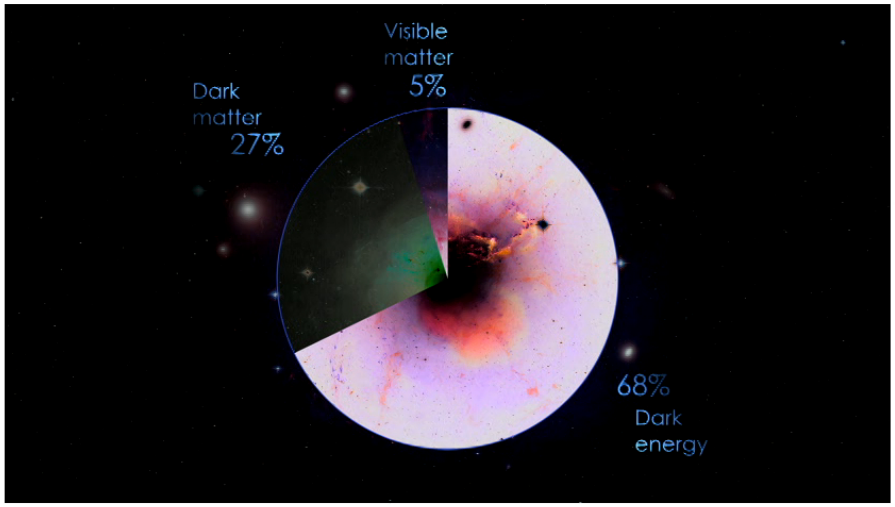
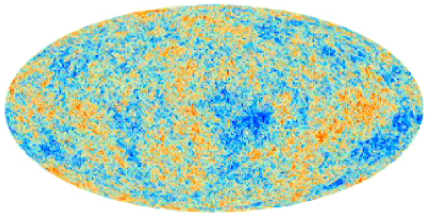
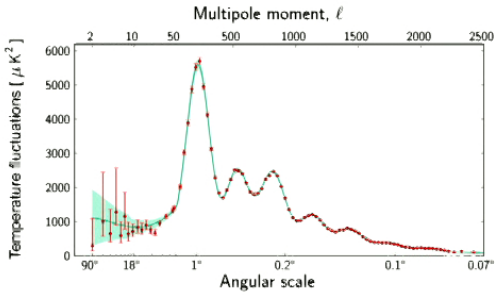
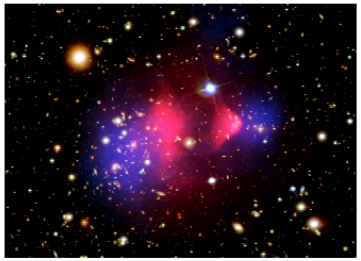


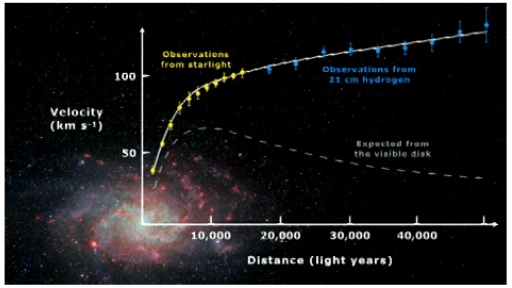


CMB





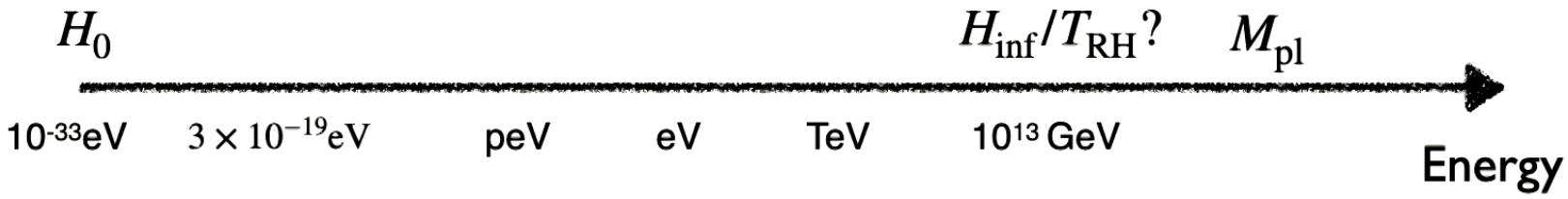
Bullet Cluster



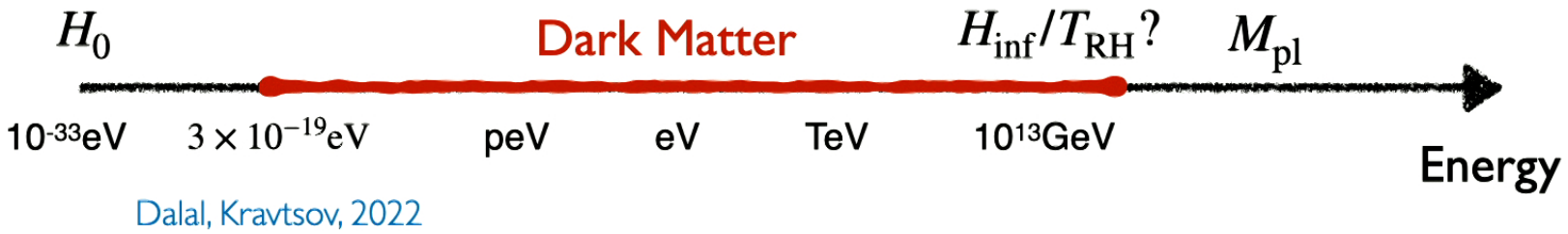
Galaxy Rotation Curve

Dark Matter

- We have evidence for physics beyond the Standard Model
- We know Dark Matter exist, gravitationally
- But where do we start?



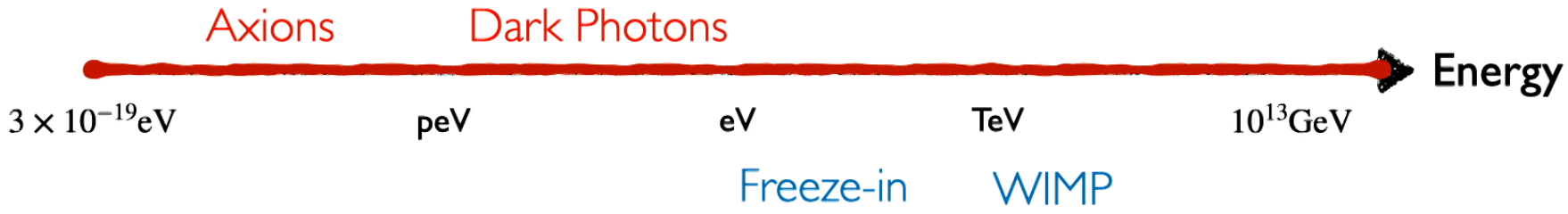
Dark Matter



Dalal, Kravtsov, 2022

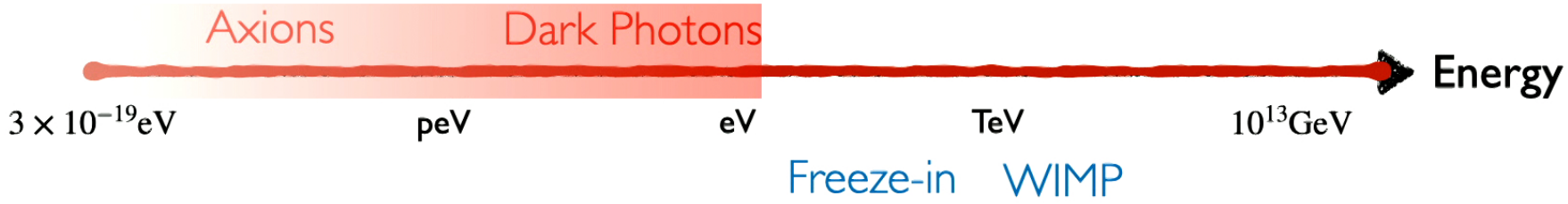
- A model that is not excluded?

Dark Matter



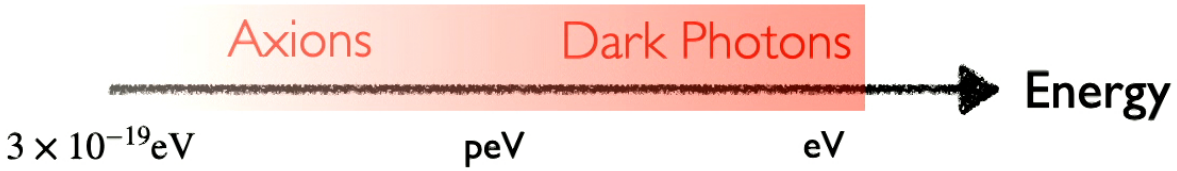
- A model that is not excluded?
- Production in the early Universe?
  - Thermal production
  - Gravitational production

Dark Matter

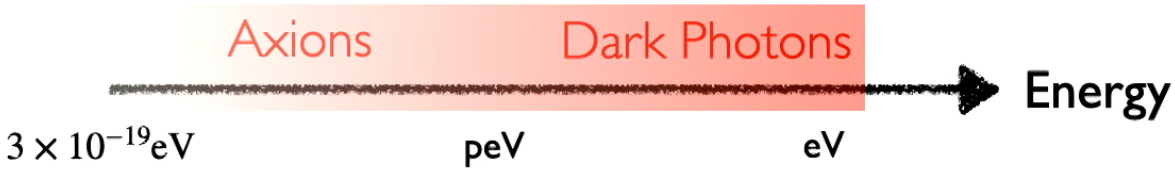


- A model that is not excluded?
- Production in the early Universe?
- Are these targets theoretically motivated?

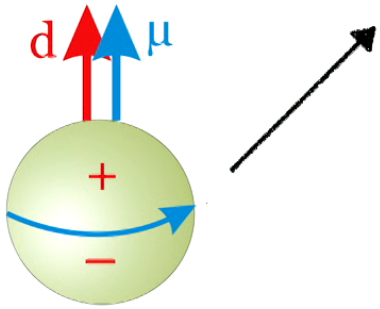
Light Bosons



Light Bosons

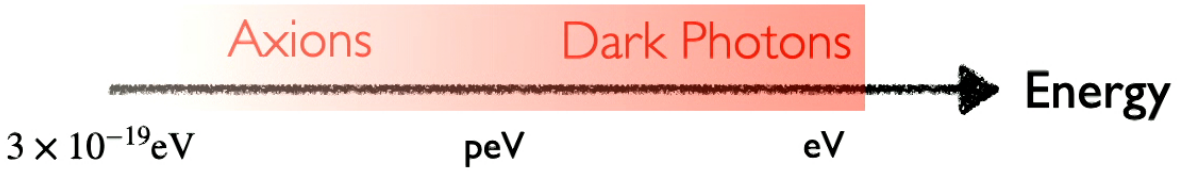


- The QCD Axion is initially proposed to solve to the Strong CP problem



Theoretical expectation:
$|d_n| \sim 2 \times 10^{-16} \theta \cdot e \cdot \mathrm{cm}$

Light Bosons



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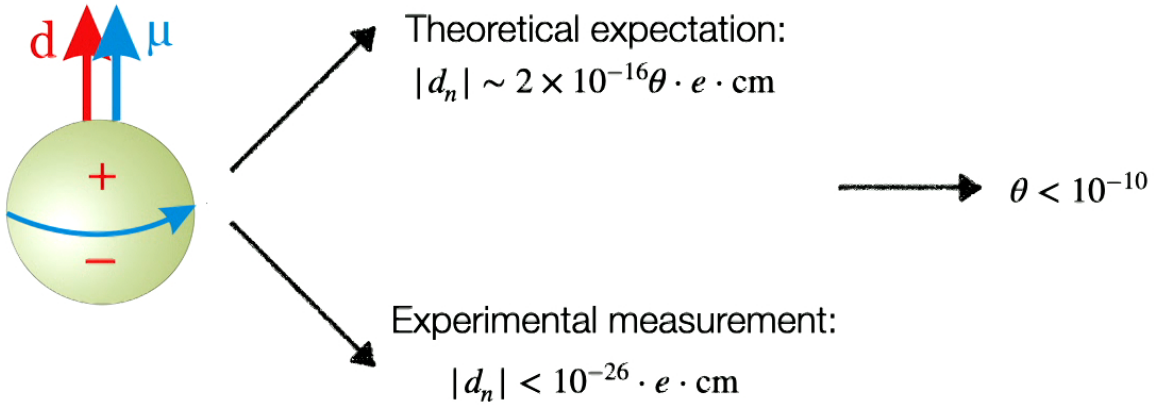
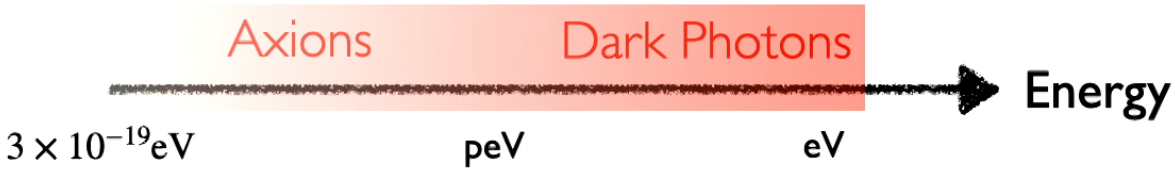


Light Bosons



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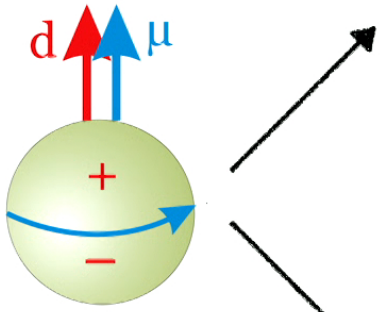
Peccei and Quinn, PRL 38, 1440, 1977
Weinberg, PRL 40, 223, 1978
Wilczek, PRL 40, 279, 1978



Theoretical expectation:

$$|d_n| \sim 2 \times 10^{-16} \theta \cdot e \cdot \text{cm}$$

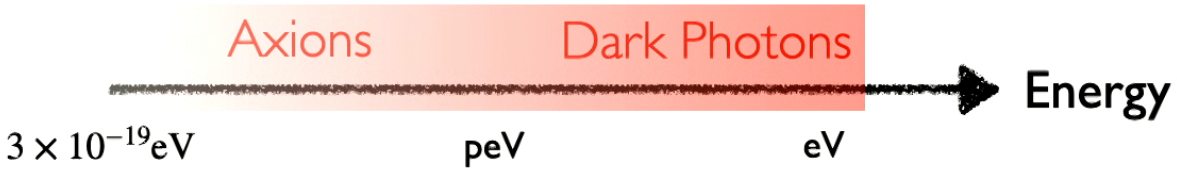
$$\rightarrow \quad \theta < 10^{-10}$$

QCD axion
$\theta(t) \rightarrow 0$

Experimental measurement:

$$|d_n| < 10^{-26} \cdot e \cdot \text{cm}$$

Light Bosons

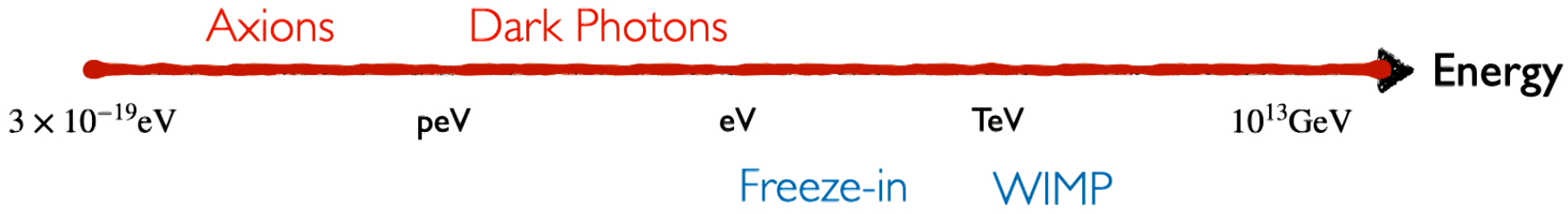


- The QCD Axion is initially proposed to solve to the Strong CP problem
- String axiverse and photiverse

  Svrcek, Witten (2006), Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell (2009)

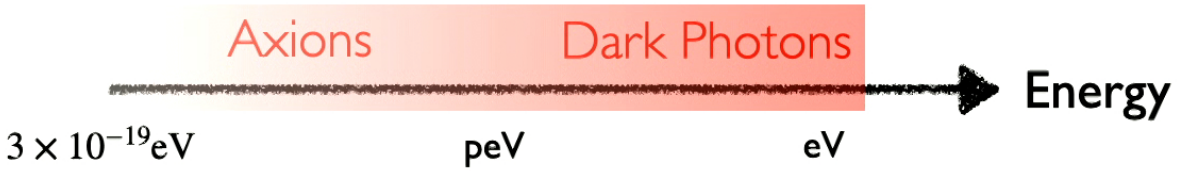
  - Axions (QCD Axion)
  - Dark photon
  - Moduli/Dilaton

Light Bosons



- The QCD Axion is initially proposed to solve to the Strong CP problem
- String axiverse and photiverse
  - Axions (QCD Axion) — Axion dark matter
  - Dark photon — Dark photon dark matter; Mediator of interactions to the dark sector
  - Moduli/Dilaton

Dark Matter



- A model that is not excluded?
- Production in the early Universe?
- Are these targets theoretically motivated?
- Searching for these states?

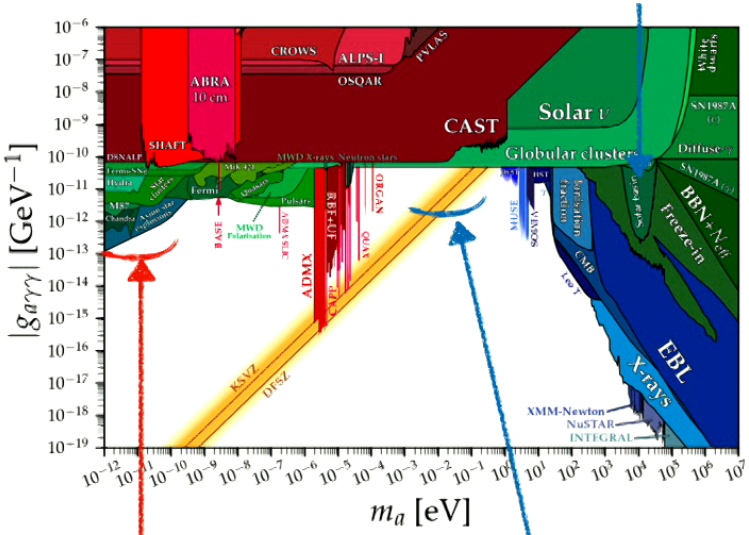
Axions

https://cajohare.github.io/AxionLimits/

Axion photon coupling: $g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$

Agrawal, Hook, JH, 1912.02823

DeRocco, et. al. (JH), 2205.05700

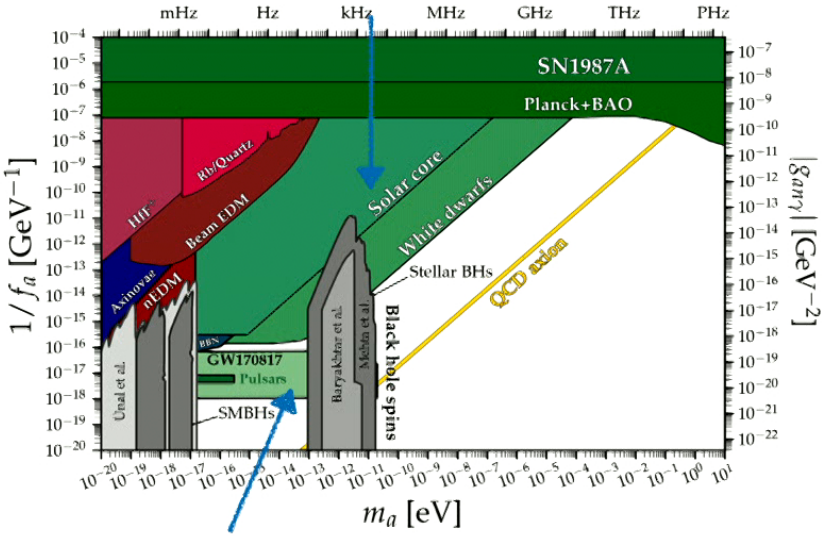


Baryakhtar, JH, Lasenby, 1803.11455

Pirvu, Mondino, JH, Johnson, 240X.XXXXX

Axion gluon coupling: $\frac{a}{f_a} G^{\mu\nu}\tilde{G}_{\mu\nu}$

Hook, JH, 1708.08464



JH, et. al.1807.02133

Zhang, et. al. (JH), 2105.13963

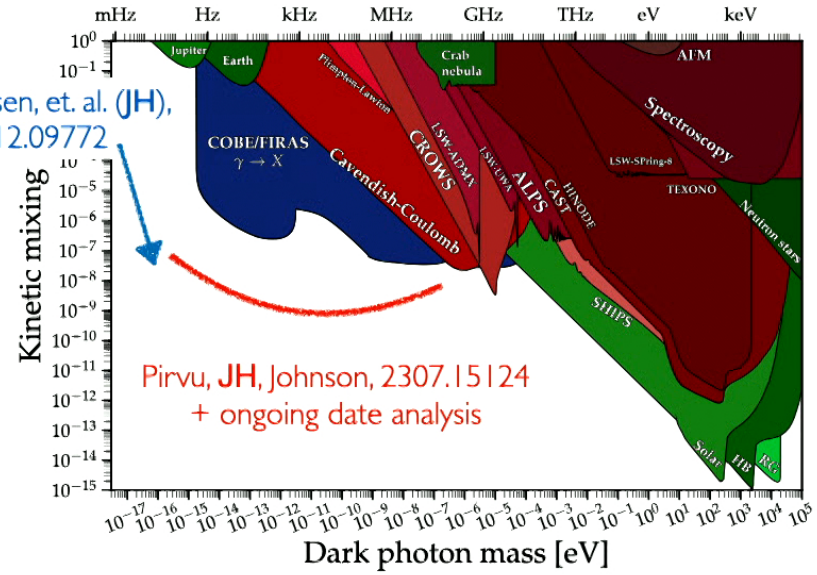
Dark photon

https://cajohare.github.io/AxionLimits/

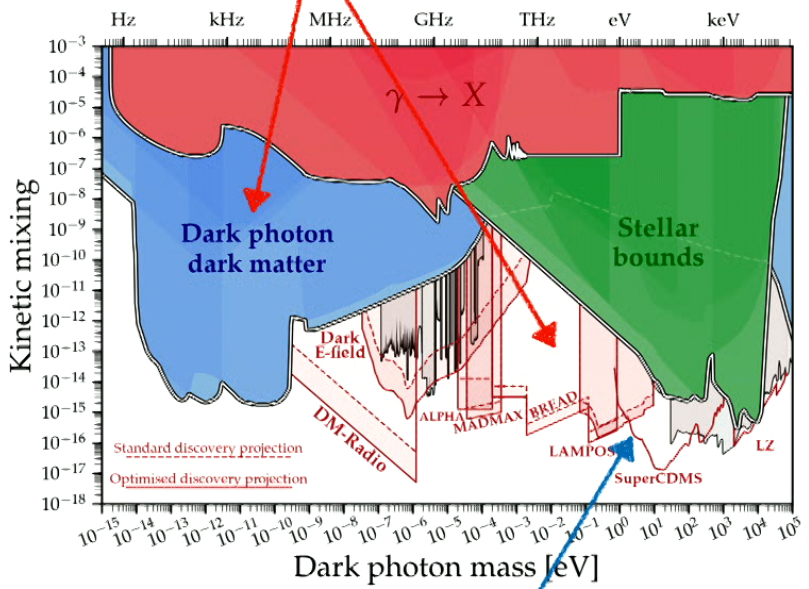
- The dark photon action: (Okun 1982, Holdom 1985)

$$\mathcal{S} = \int \mathrm{d}^4x \left(-\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + \epsilon F^{\mu\nu} F'_{\mu\nu} \right)$$

Siemonsen, et. al. (JH), 2212.09772

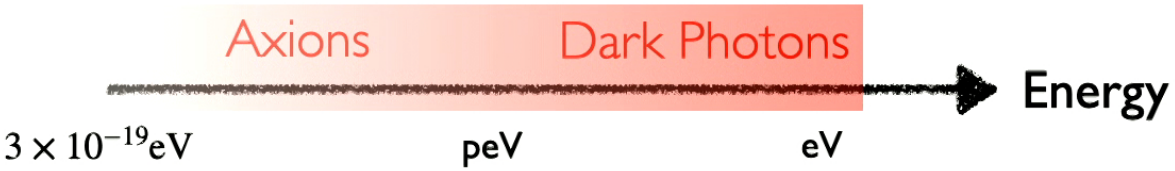


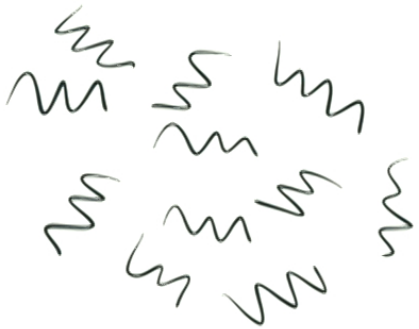
East, Huang, 2206.12432



Baryakhtar, JH, Lasenby, 1803.11455
Chiles & Charaev, et. al. (JH), 2110.01582

Light boson as waves





Overlapping
wave-functions

(Figure Credit: Mina)

We are immersed in light Bosons
as a classical wave as a weak field

Manipulating a photon

- Light Bosons' properties are easily affected by the environment

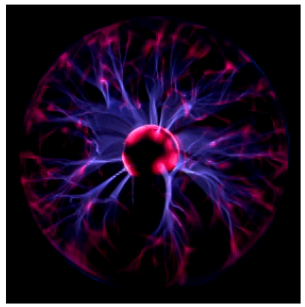
Light

Manipulating a photon

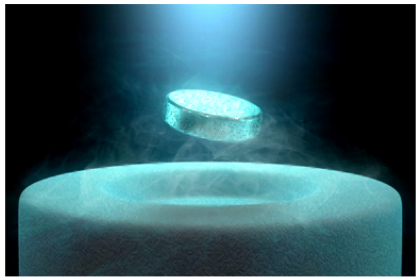
- Light Bosons' properties are easily affected by the environment

Light

Plasma



Superconductor



Light bosons, photon and the dark sector bosons, can have properties that depend on the medium

Light bosons manipulated

- In-Medium Effect:
  - Take advantage of these effects of both photon and/or light bosons
  - …to (find or create) the correct medium to improve our searches for light bosons

    Pirvu, **JH**, Johnson, 2307.15124 + ongoing date analysis

    Pirvu, Mondino, **JH**, Johnson, 240X.XXXXX
  - How the in-medium effects shape the parameter space we probe
  - …as well as producing striking new signatures

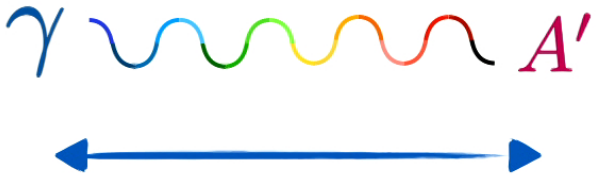
    East, **Huang,** 2206.12432

Patchy Dark Screening

Dalila Pirvu, **Junwu Huang**, Matthew Johnson
2307.15124

Dark photon conversion

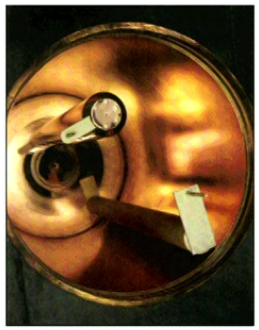
- Resonant conversion to search for photon to dark photon conversion



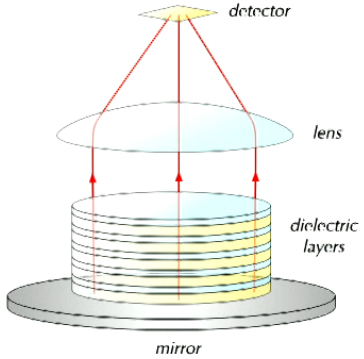
Conversion in the lab

- Resonant conversion to search for photon to dark photon conversion

- In the lab:



ADMX (Cavity)



LAMPOST
(Baryakhtar, **JH**, Lasenby, 1803.11455)

Dark photon conversion

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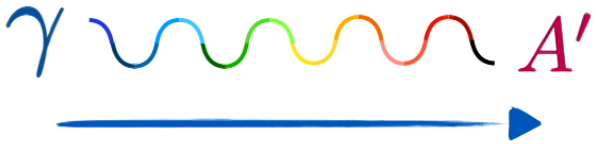


- Ionized medium in the cosmos $\omega_p^2 = \frac{e^2 X_e n_e}{m_e}$

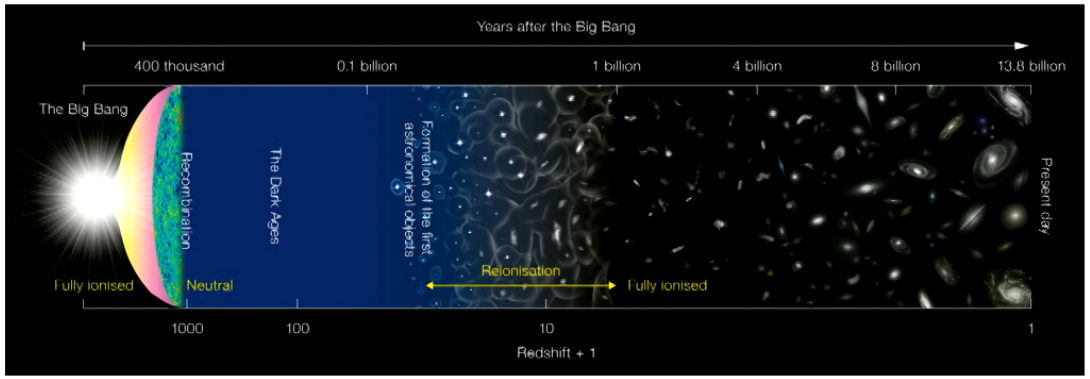
$$\omega_p^2 = m_{A'}^2$$

Conversion in cosmology

- Resonant conversion to search for photon to dark photon conversion
  - $\omega_p^2 = m_{A'}^2$

Cosmology provides natural scanners

$$\omega_p^2 = \frac{e^2 X_e n_e}{m_e}$$



Mirizzi, et. al., 0901.0014, Caputo, et. al., 2002.05165

Conversion in cosmology

- Resonant conversion to search for photon to dark photon conversion
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Cosmology provides natural scanners

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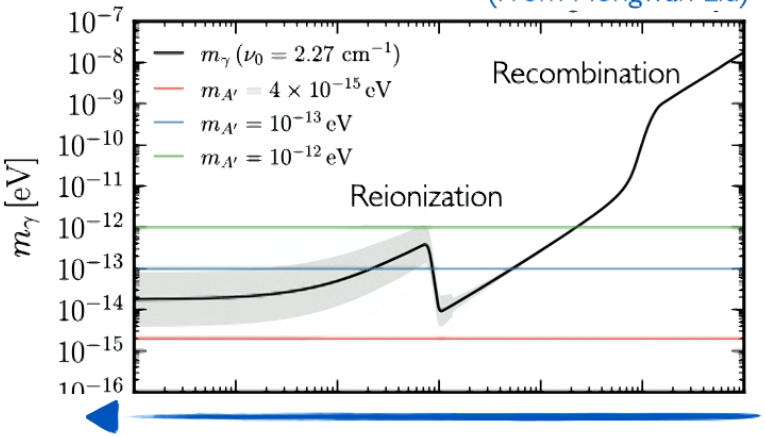
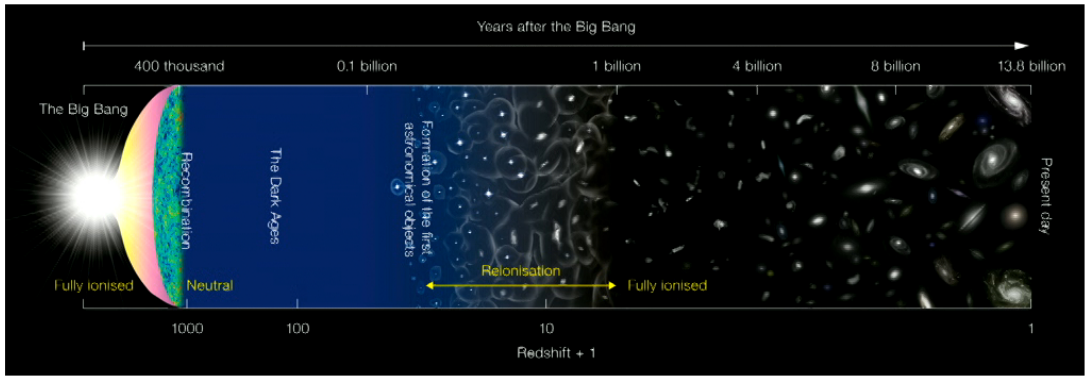
(From Hongwan Liu)



Time



Mirizzi, et. al., 0901.0014, Caputo, et. al., 2002.05165

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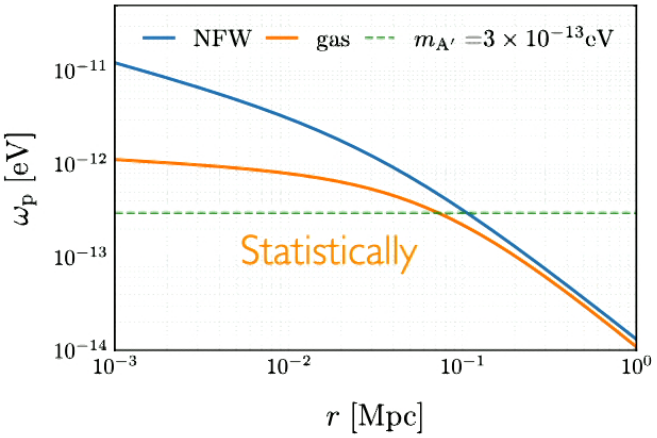
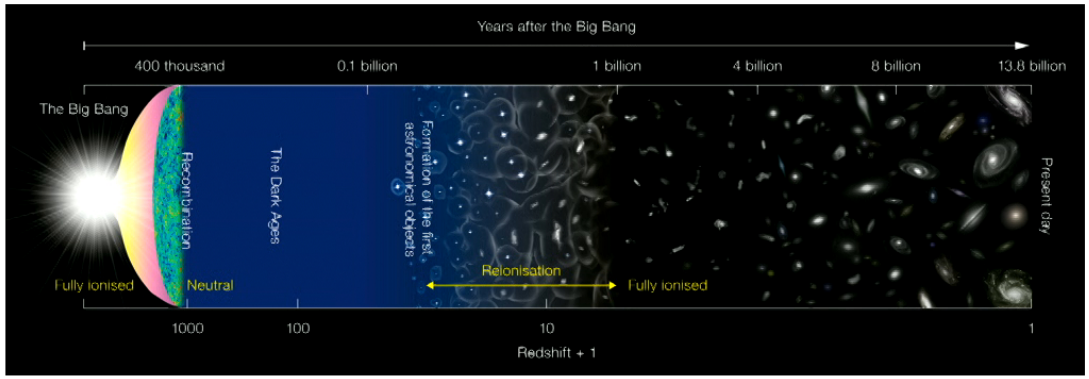
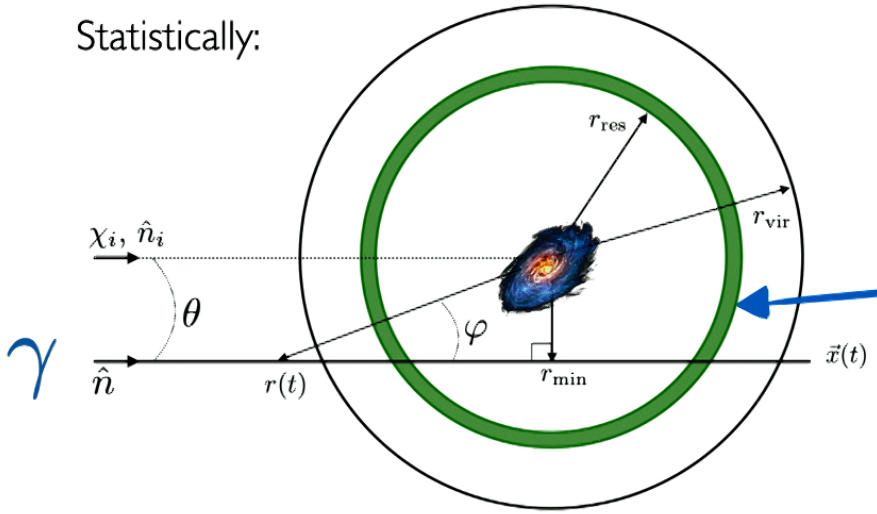
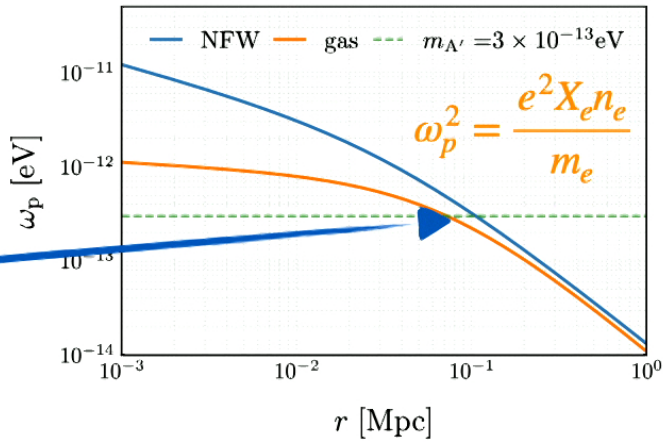




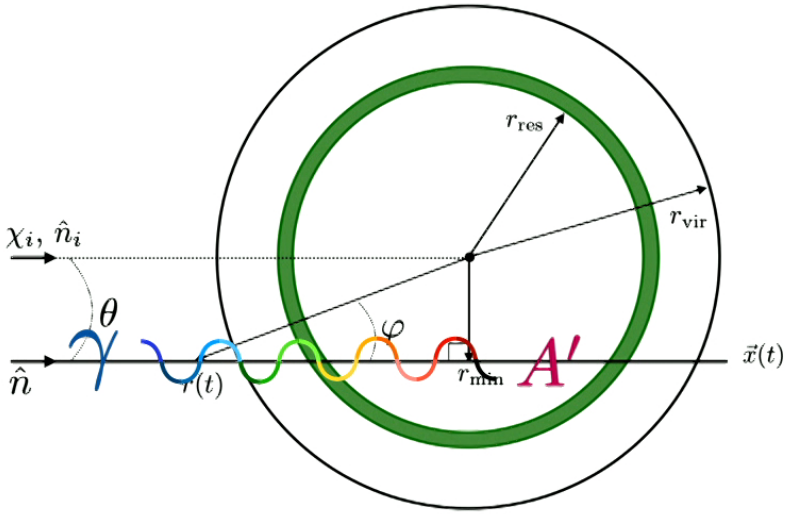
Inside a galactic halo

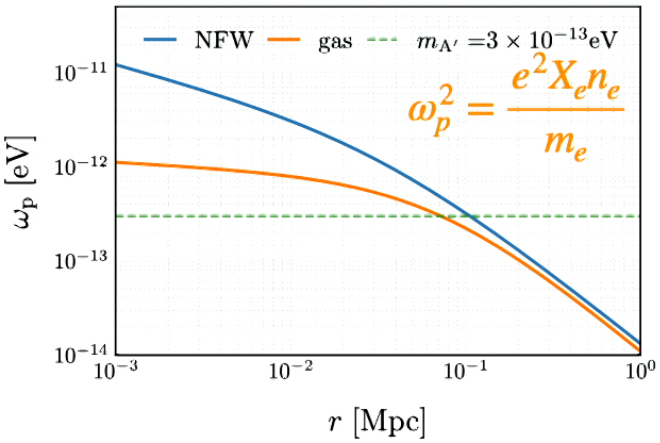
Statistically:





Inside a galactic halo



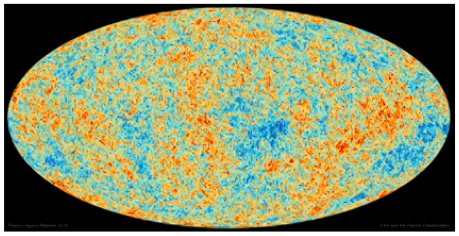


$$\tau(\hat{n},\omega) \equiv P_{\gamma\to A'} = \sum_{t_{\rm res}} \frac{\pi\varepsilon\, m_{A'}^2}{\omega(t_{\rm res})} \times \varepsilon \left|\frac{\rm d}{{\rm d}t} \ln m_\gamma^2(\vec{x}(t))\right|^{-1}_{t=t_{\rm res}}$$

Frequency dependence

Position/Angular dependence

Map of photon conversion



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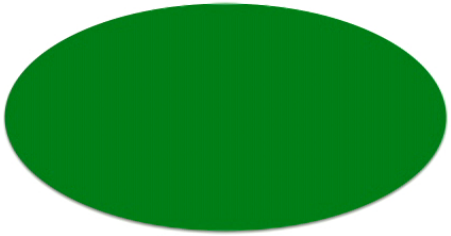
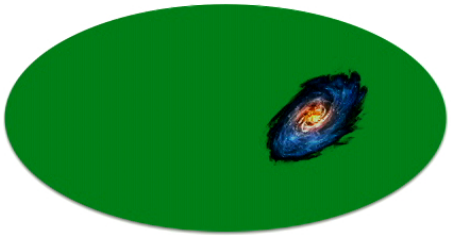
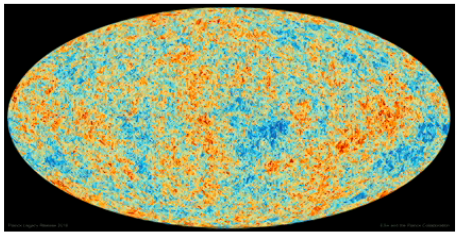


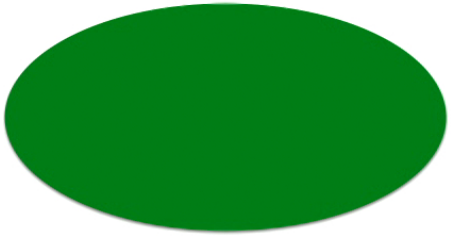
$\bar{T} = 2.726K$



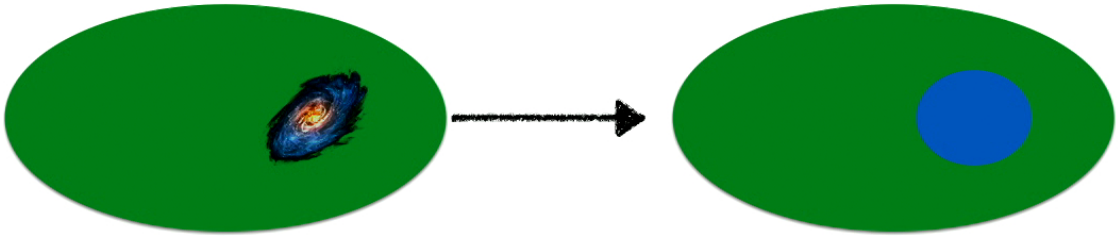
Map of photon conversion



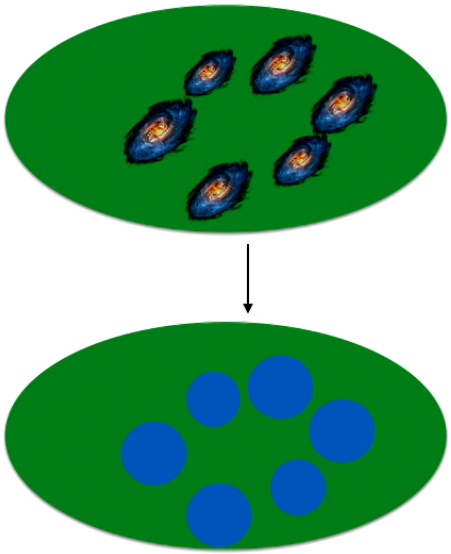
+



$\bar{T} = 2.726K$



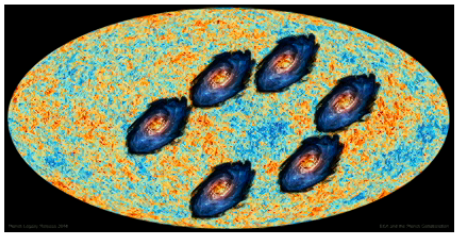
Many halos



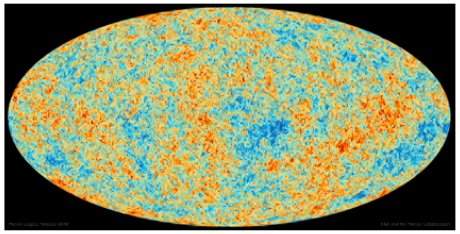
$\bar{T} + \text{halo}$

$T^{\text{dsc}}(\hat{n}, \omega)$

Screening and dark screening maps

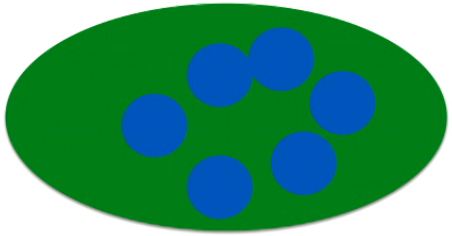


$\bar{T}$ + halo



$T^{\mathrm{CMB}}(\hat{n})$

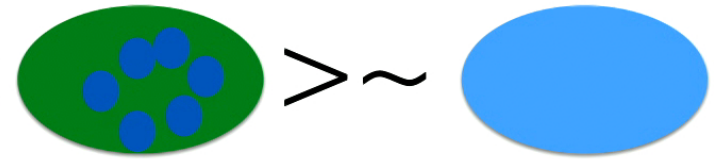
+



$T^{\mathrm{dsc}}(\hat{n}, \omega)$

- How do I separate the two maps?
- How to use this map?

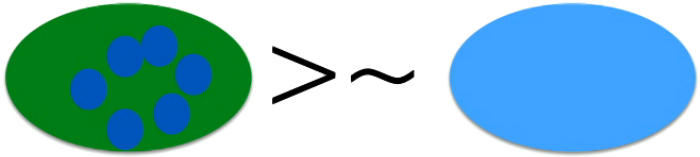
Monopole = Spectral distortion

- Monopole: $\left\langle \right\rangle \sim$ 

$T^{\mathrm{dsc}}(\hat{n}, \omega)$

Monopole = Spectral distortion

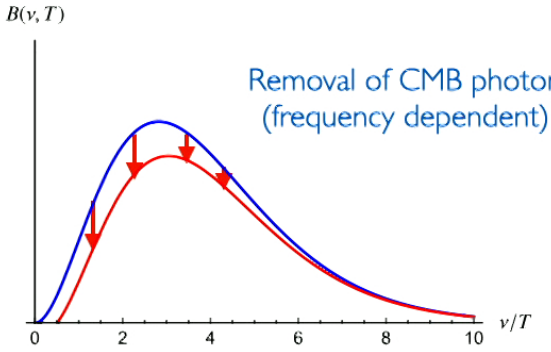
- Monopole: $\left\langle \quad \right\rangle \sim$



$T^{\rm dsc}(\hat{n},\omega)$

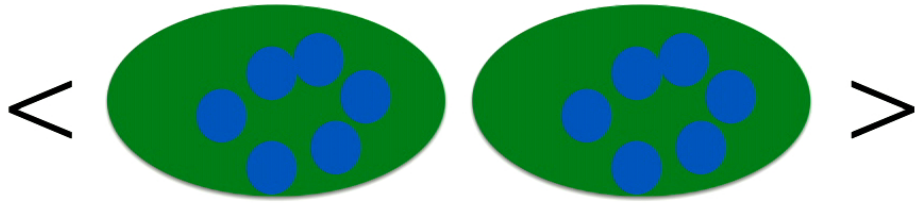
- COBE/FIRAS constraints.

Mirizzi, et. al., 0901.0014,
Caputo, et. al., 2002.05165



Auto-correlation

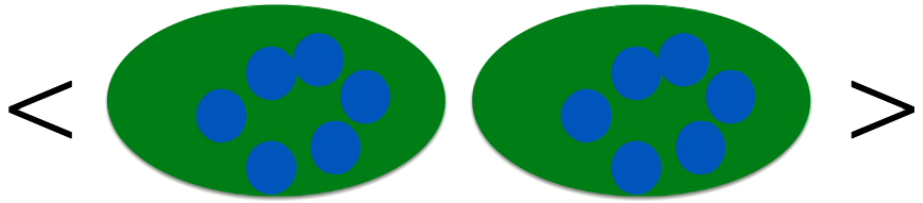
- Auto-correlation $\langle T^{\rm dsc} T^{\rm dsc} \rangle = \overline{T}^2 C_\ell^{\tau\tau}$



Auto-correlation

- Auto-correlation $\langle T^{\rm dsc} T^{\rm dsc} \rangle = \overline{T}^2 C_\ell^{\tau\tau}$

Scales as ε^4

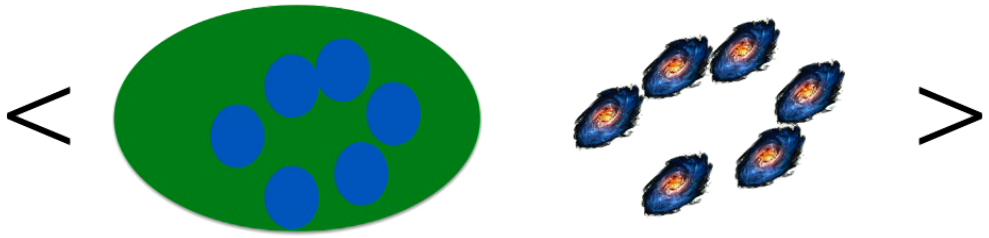


Cross-correlation

- Cross-correlation with LSS survey

$$\langle T^{\rm dsc}\hat{\tau}_g\rangle = \bar{T}C_\ell^{\tau\hat{\tau}^g}$$

Scales as ε^2



Cross-correlation

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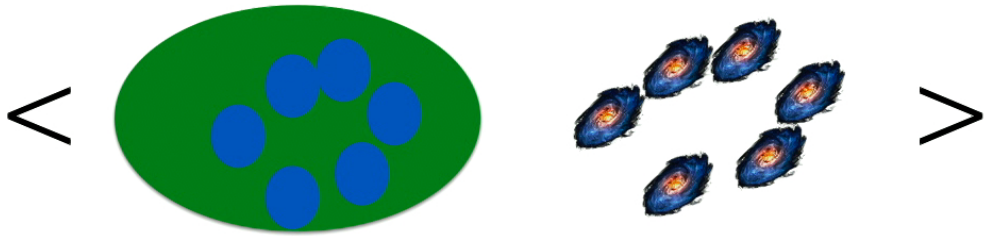
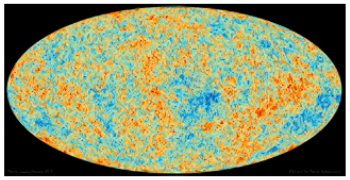
Scales as ε^2

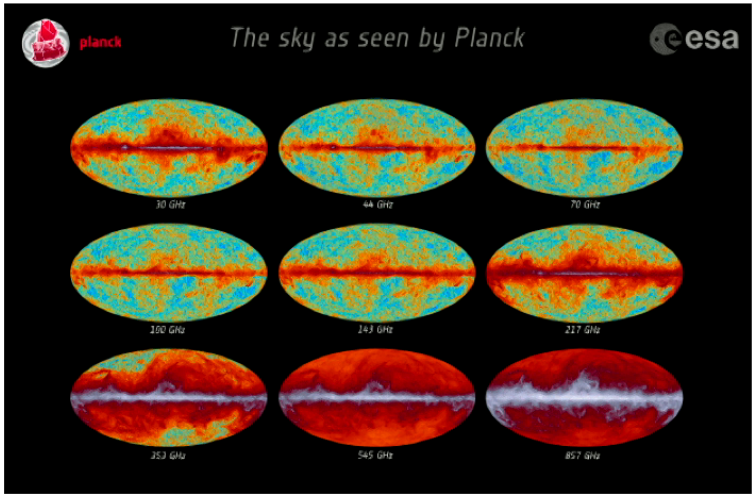


$\langle \text{BSM} \times \text{SM} \rangle$ type operators

$\langle \text{CMB} \times \text{LSS} \rangle$

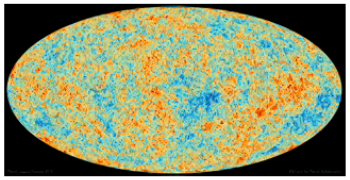
Map separation

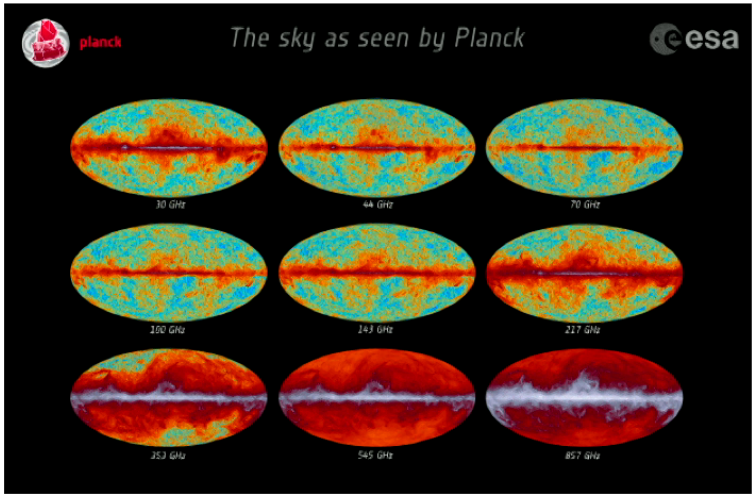




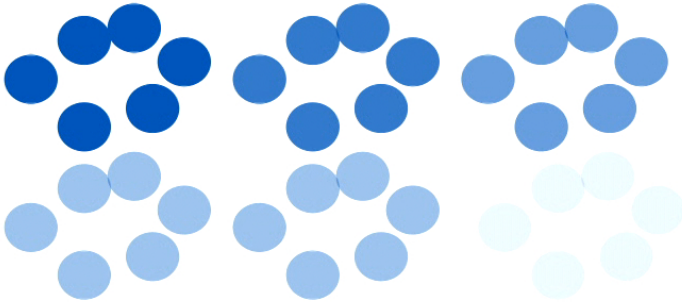
(Taken from Planck website)

Map separation



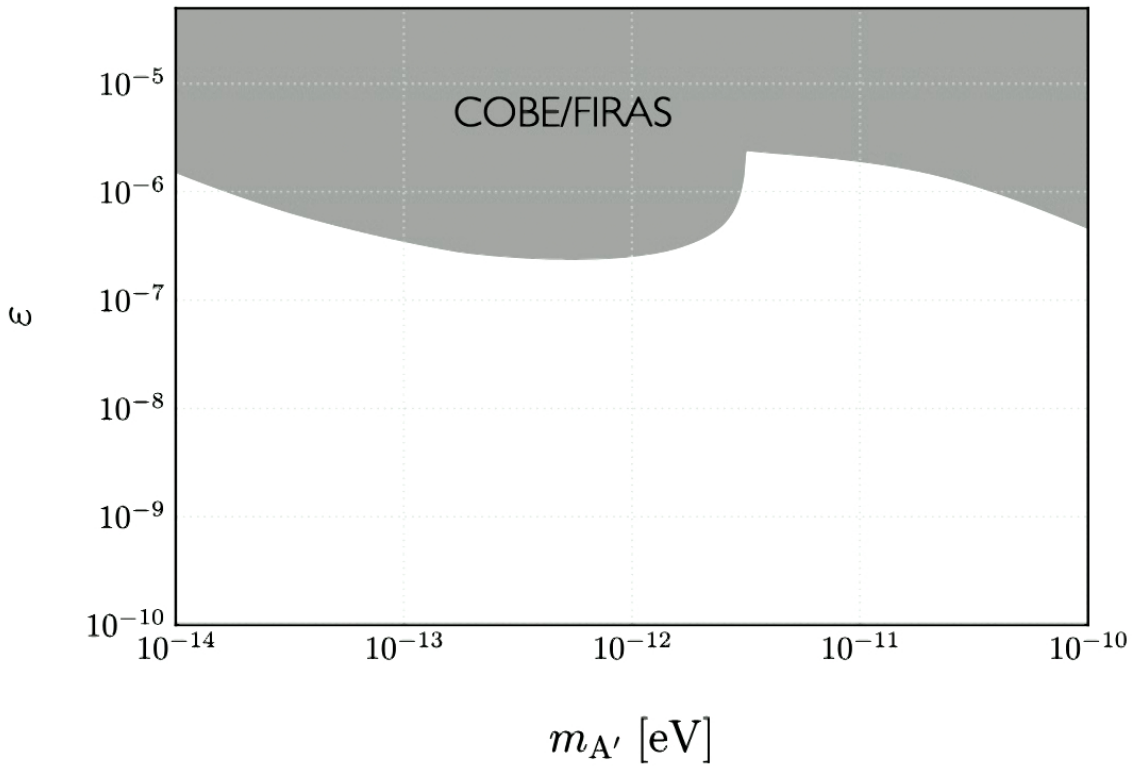


(Taken from Planck website)

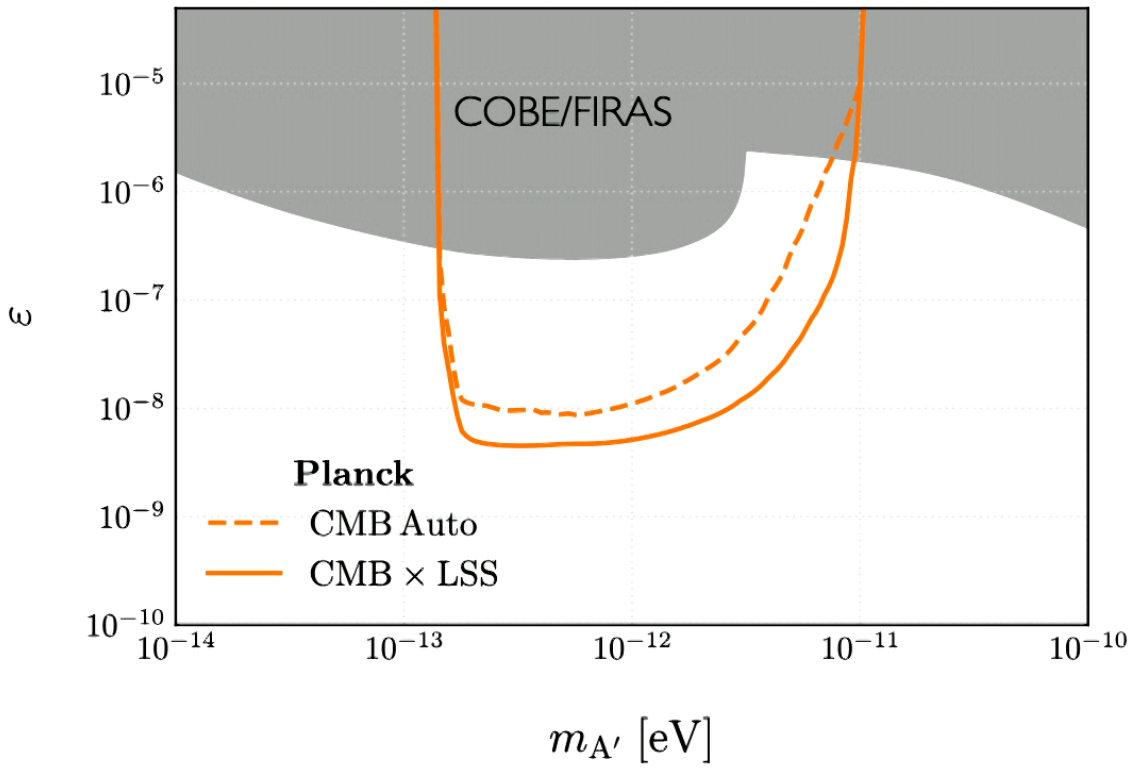


$$\tau(\hat{n}, \omega) \propto \frac{1}{\omega}$$

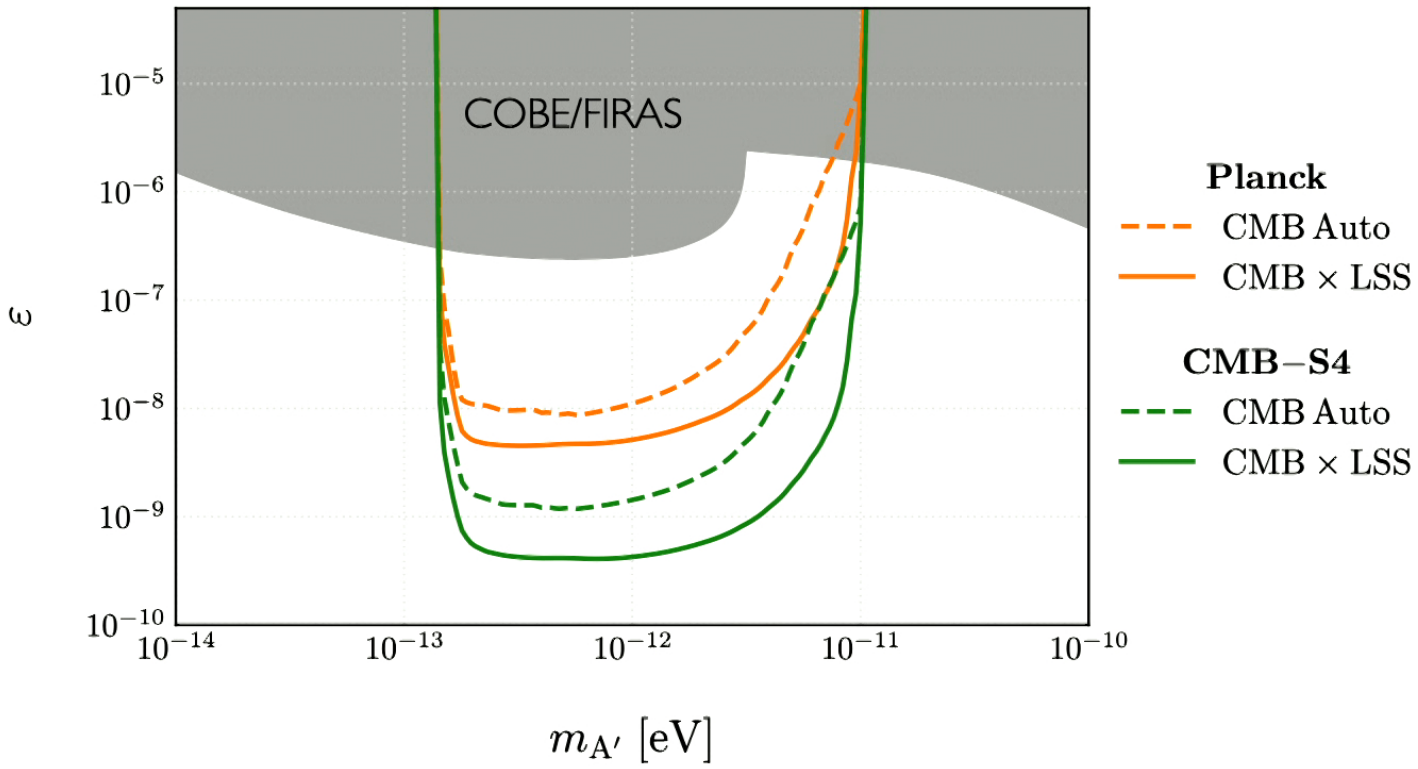
Projection


COBE/FIRAS
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
ϵ
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
$m_{\mathrm{A}'}$ [eV]

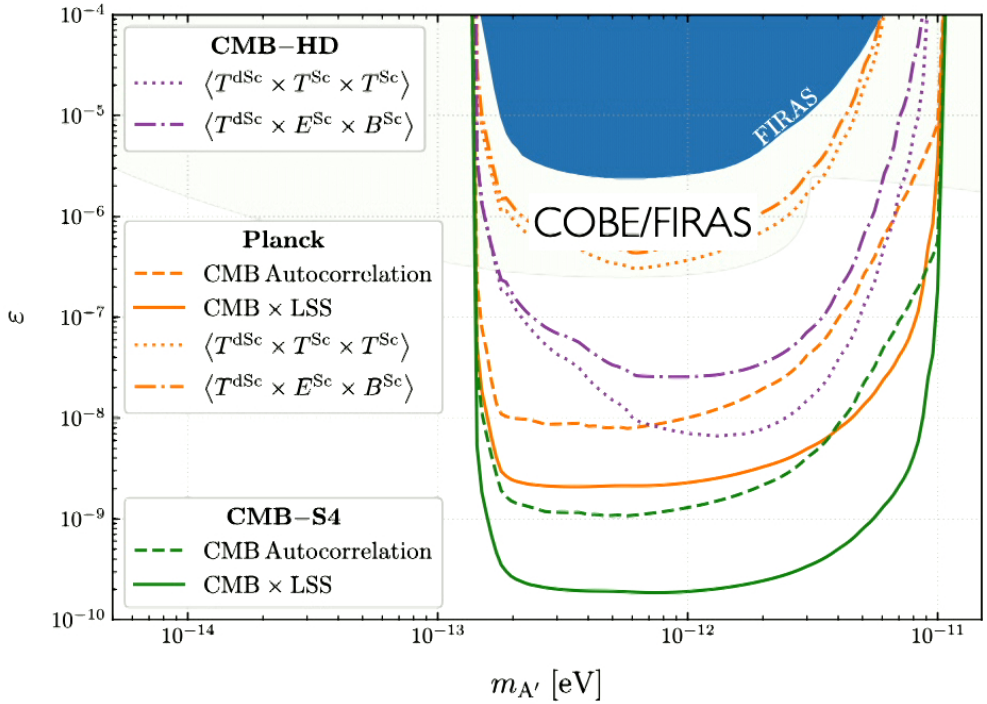
Projection


COBE/FIRAS
Planck
CMB Auto
CMB × LSS
ϵ
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
$m_{A'}$ [eV]

Projection

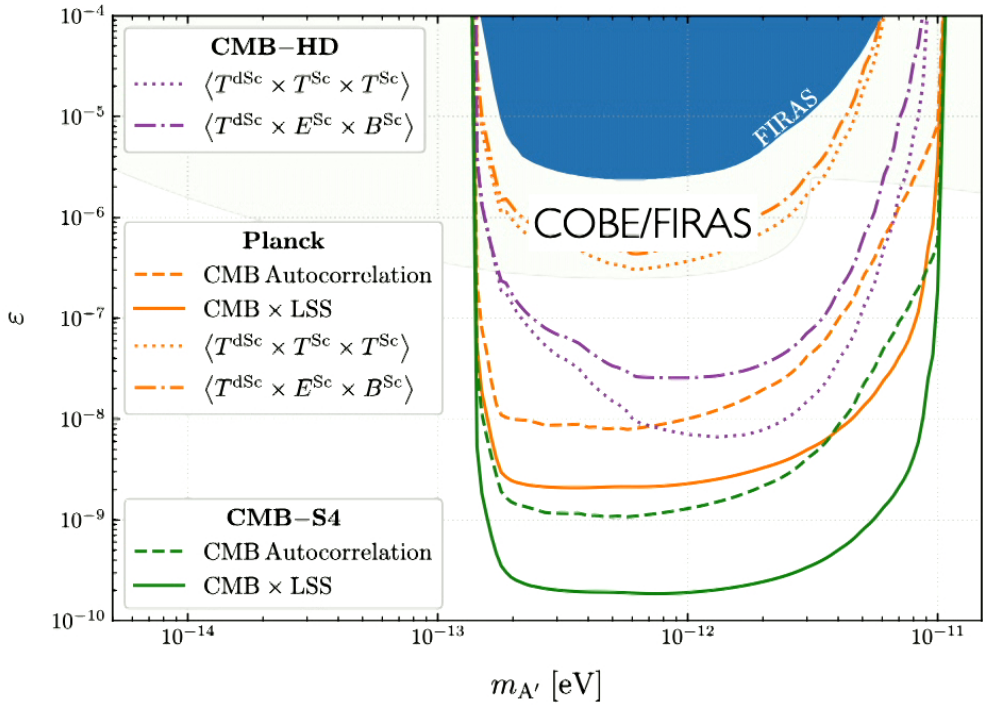

COBE/FIRAS
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
ϵ
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
$m_{A'}$ [eV]
Planck
CMB Auto
CMB × LSS
CMB−S4
CMB Auto
CMB × LSS

Dark photon



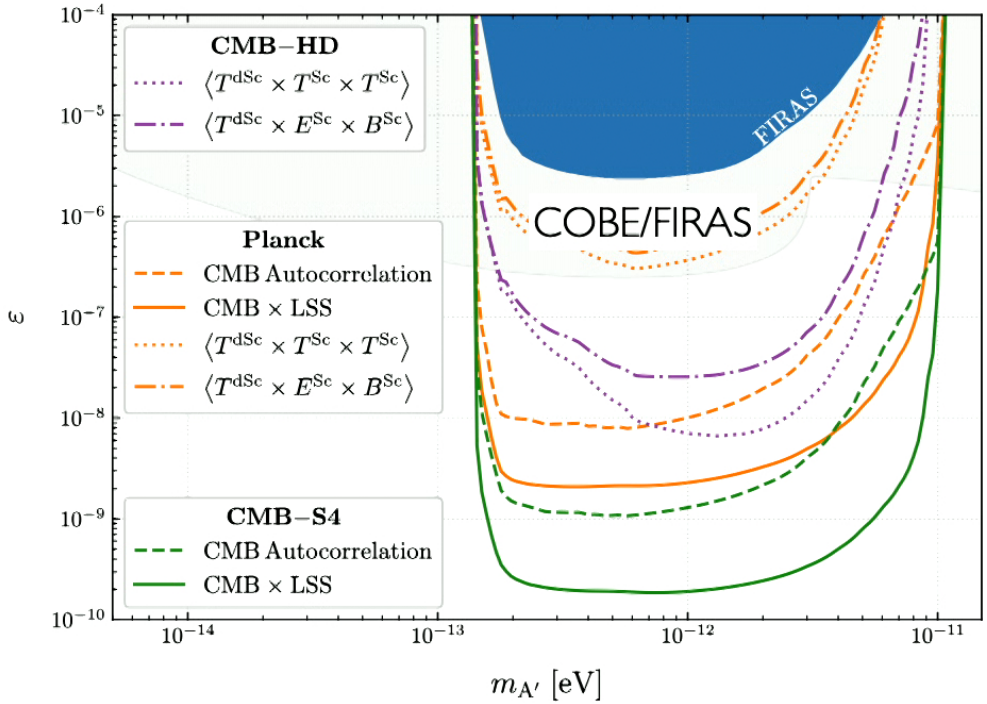
Pirvu, **JH**, Johnson, 2307.15124 + ongoing date analysis

Dark photon



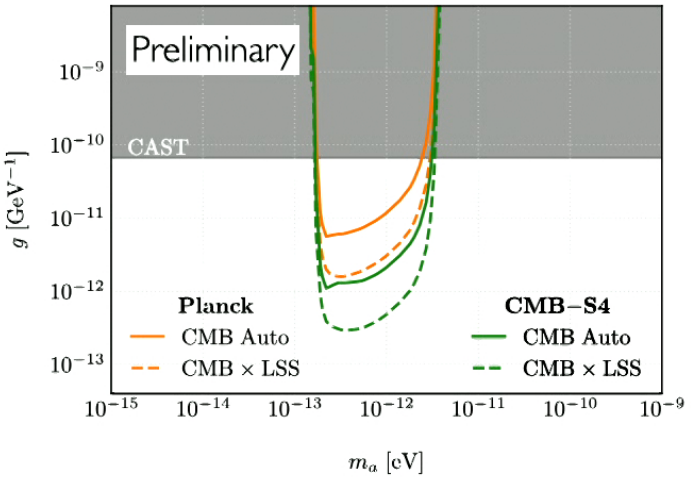
Pirvu, **JH**, Johnson, 2307.15124 + ongoing date analysis

Dark photon



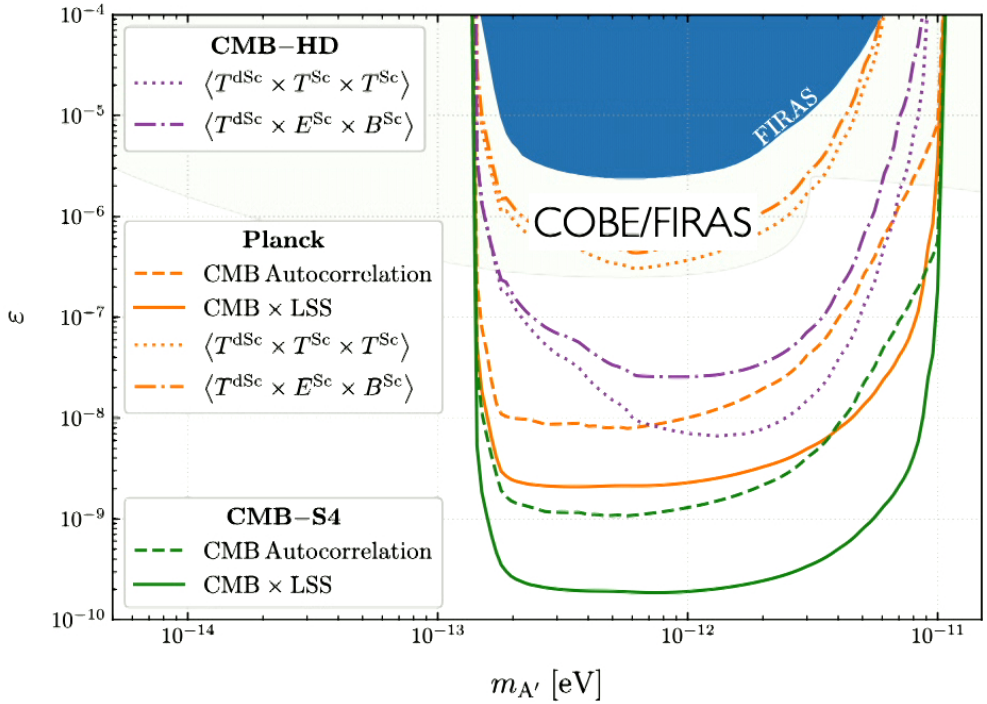
Pirvu, **JH**, Johnson, 2307.15124 + ongoing date analysis

Axion



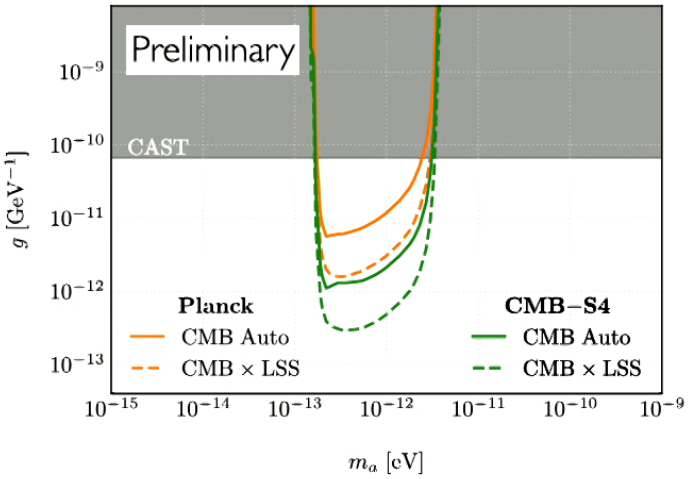
Pirvu, Mondino, **JH**, Johnson, 240X.XXXXX

Dark photon



Pirvu, **JH**, Johnson, 2307.15124 + ongoing date analysis

Axion



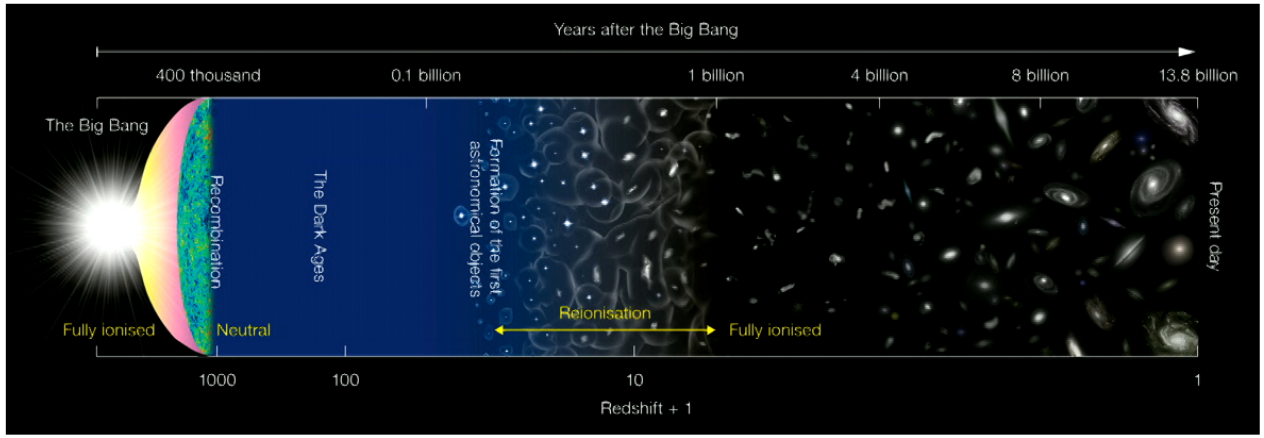
Pirvu, Mondino, **JH**, Johnson, 240X.XXXXX

Summary

Background light

Effect of Dark Sector

Observer



CMB, 21cm, LIM…

Dark photon, axion, freeze-in…

Linear perturbations, Halos, Voids, Bubbles…

$\langle \mathrm{BSM} \times \mathrm{SM} \rangle$

In collaboration with Cristina Mondino, Dalila Pirvu, Matt Johnson, and Hongwan Liu, Fiona McCarthy, Colin Hill, Selim Hotinli, Keir Rogers…

String Bosenova

Will East, **Junwu Huang**, 2206.12432

Packing too much energy?

- Is it actually weak classical wave?

- Dark photon occupation number:
  - At earliest time accessible with CMB ($10^{-5}\,\mathrm{eV}$)

$$N = \frac{\rho_{A'}}{m_{A'}^4} \approx 10^{29}$$

  - At inflationary production ($10^{-5}\,\mathrm{eV}$):

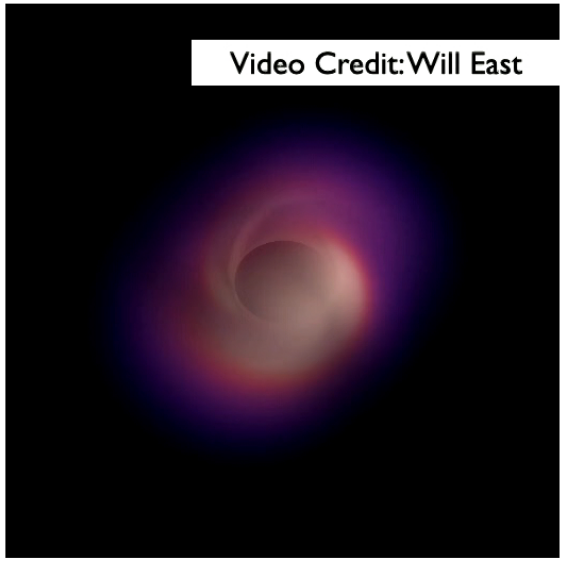
$$N \simeq H_I^2/m_{A'}^2 \simeq 10^{54}$$

  - In superradiance cloud ($10^{-12}\,\mathrm{eV}$):

$$N = \frac{\rho_{A'}}{m_{A'}} R_c^3 \simeq 10^{76}$$

Simulation

- Vortex formation in Superradiance cloud



Simulation

- Vortex formation in Superradiance cloud

- Abelian Higgs model:

$$\mathcal{S} = \int \mathrm{d}^4x \left[\frac{1}{2} \left| D'_\mu \Phi \right|^2 - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\lambda}{4} \left(|\Phi|^2 - v^2 \right)^2 \right],$$

- Stuckelberg limit:

$$m_\Phi^2 / m_{A'}^2 = \lambda / g_D^2 \to \infty$$ Heavy higgs, light dark photon

Simulation

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$$\mathcal{S} = \int \mathrm{d}^4x \left[\frac{1}{2} \left| D'_\mu \Phi \right|^2 - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\lambda}{4} \left(|\Phi|^2 - v^2 \right)^2 \right],$$

- Stuckelberg limit:

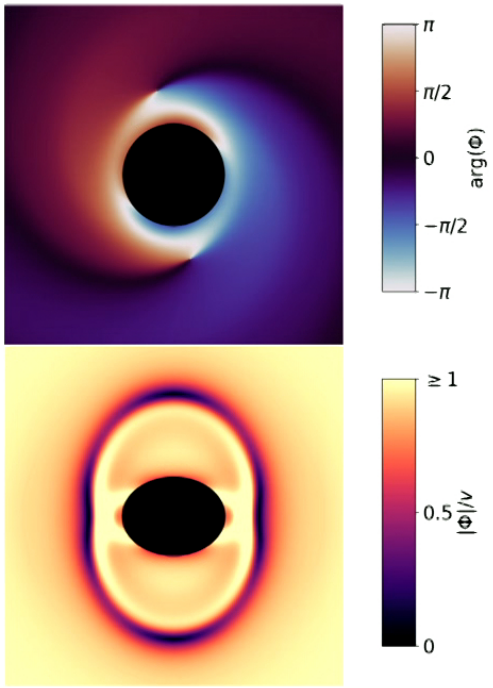
$$m_\Phi^2 / m_{A'}^2 = \lambda / g_D^2 \to \infty$$ Heavy higgs, light dark photon

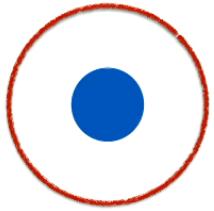
- Low energy action?

$$\mathcal{S} = \int \mathrm{d}^4x \left(-\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu \right)$$

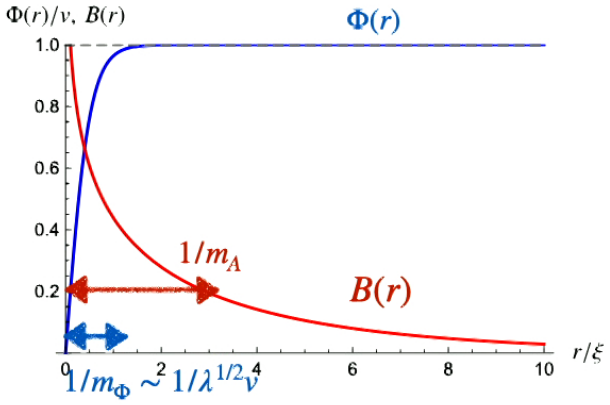
Vortices

Abrikosov 1957



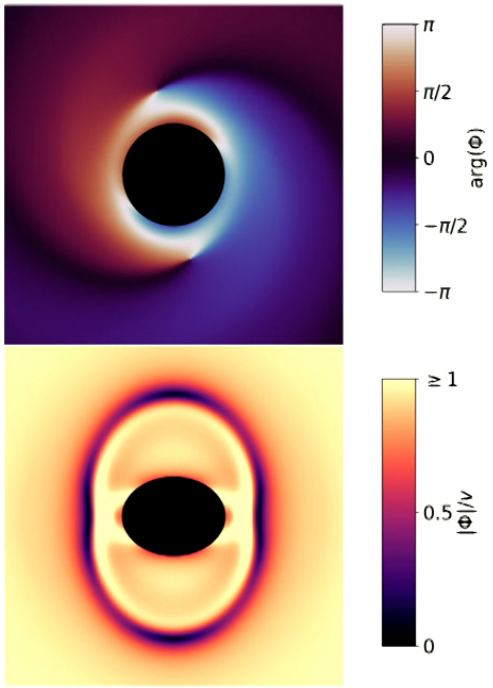


$$\oint A_\mu dx^\mu = \Phi_0$$

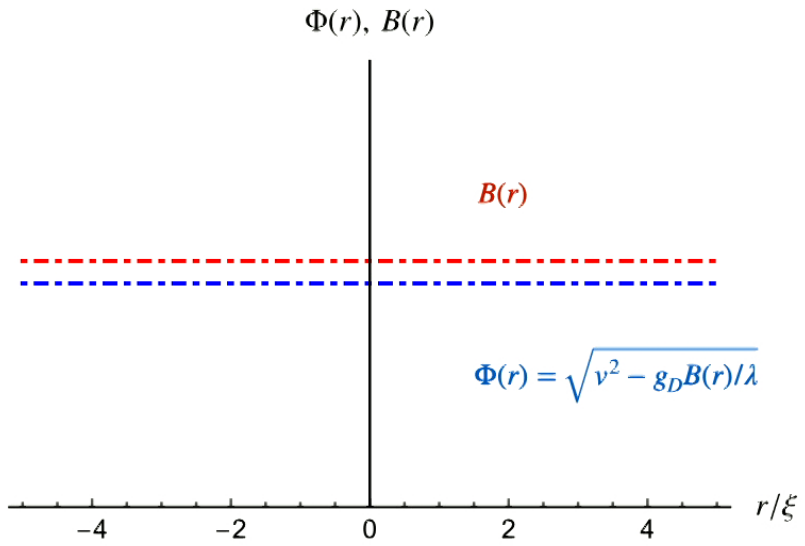


A single vortex

Vortex Formation

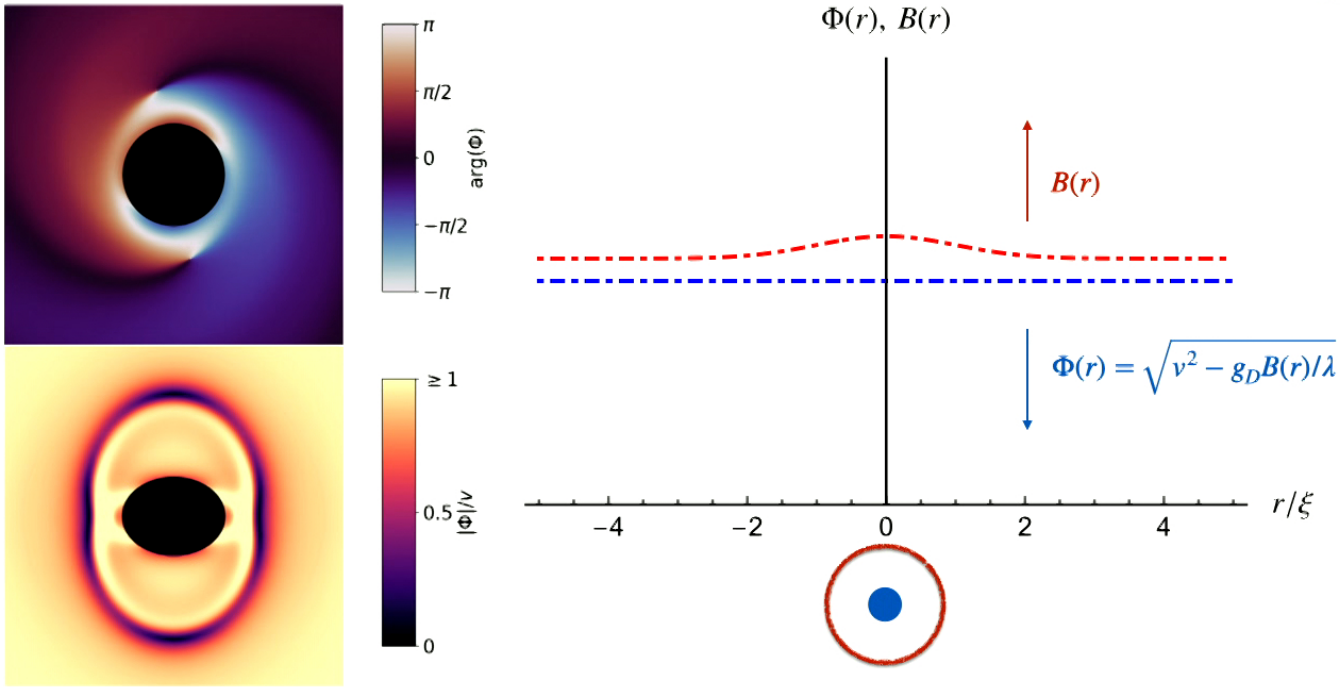


Galaiko 1966



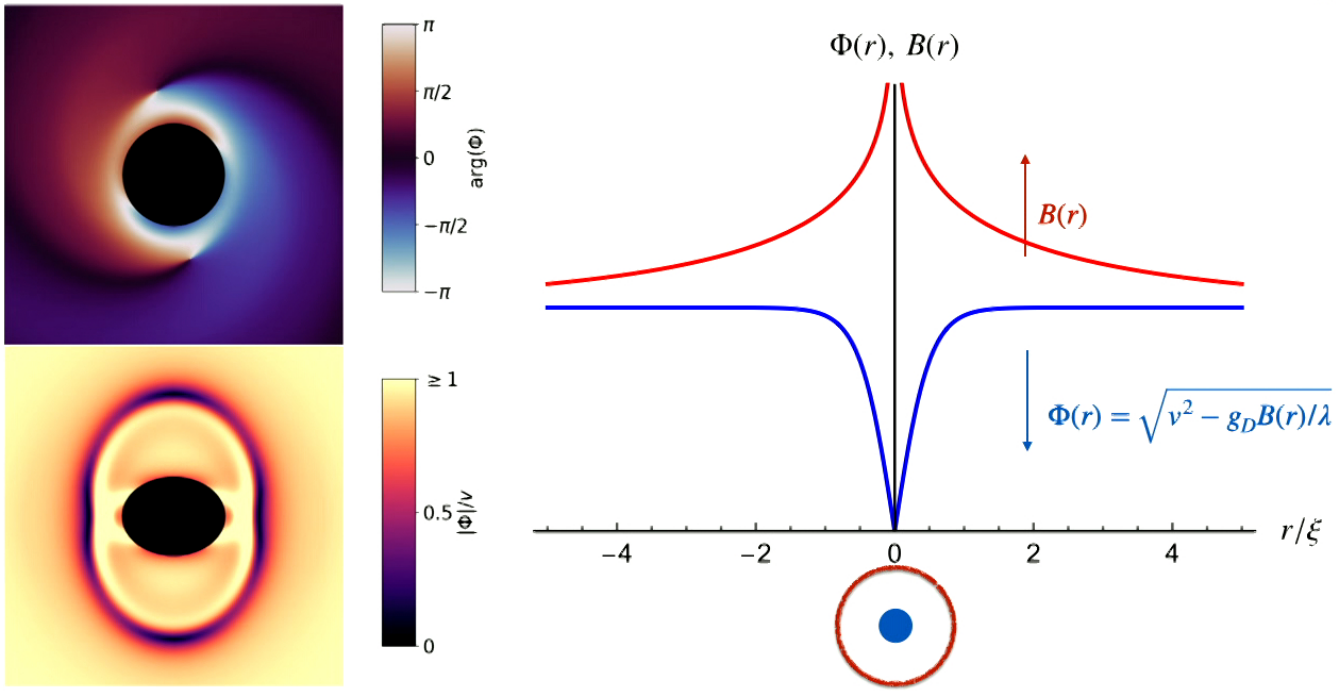
Vortex Formation

Galaiko 1966

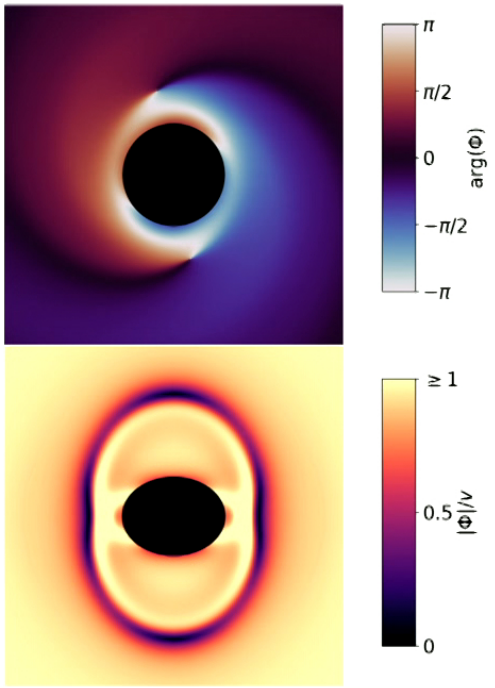


Vortex Formation

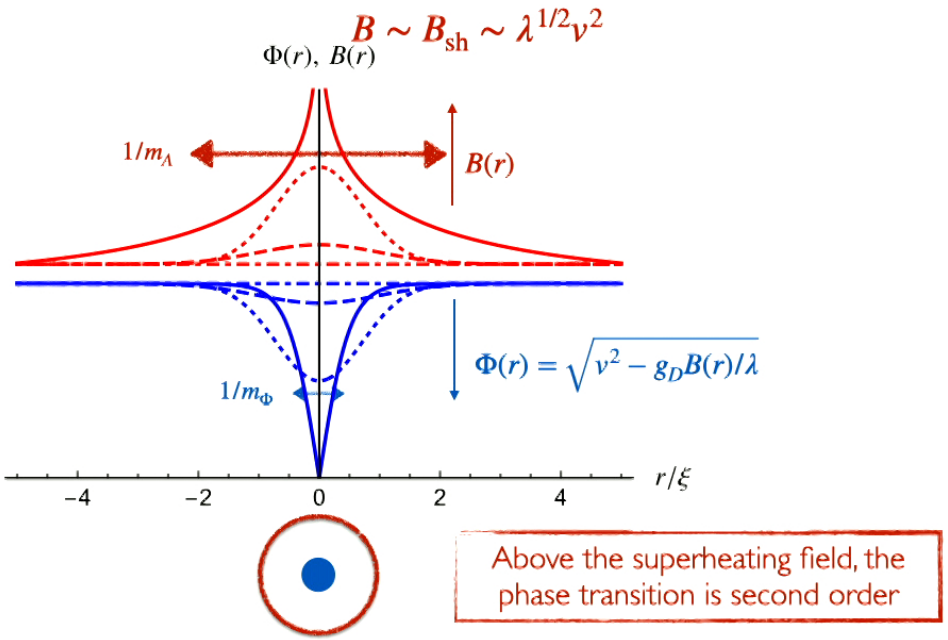
Galaiko 1966



Vortex Formation

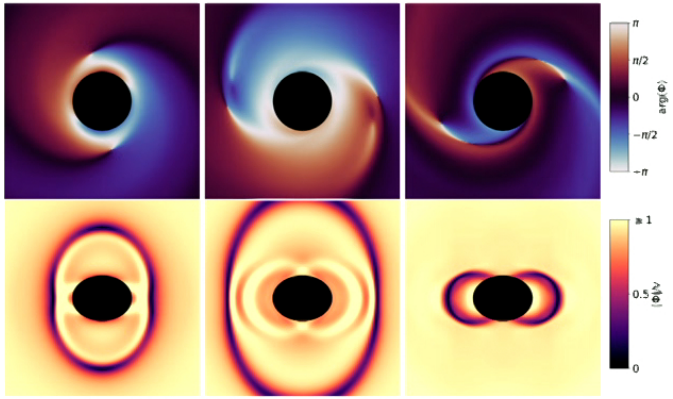


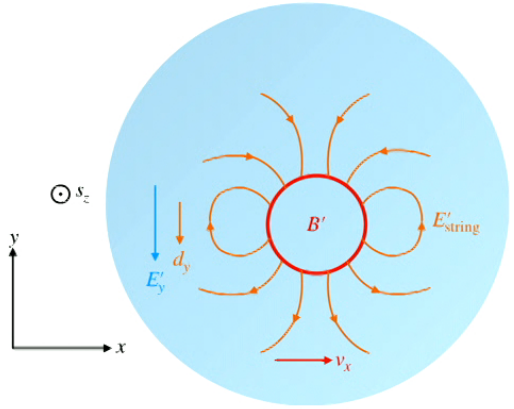
Galaiko 1966



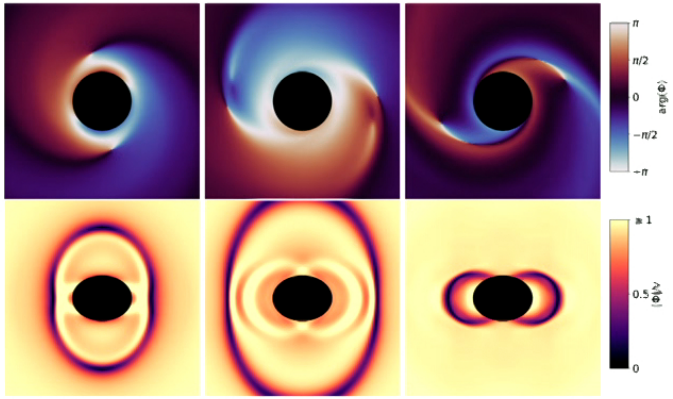
Above the superheating field, the phase transition is second order

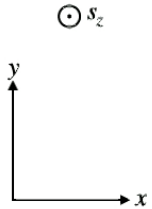
Vortex dynamics

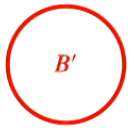




Vortex dynamics

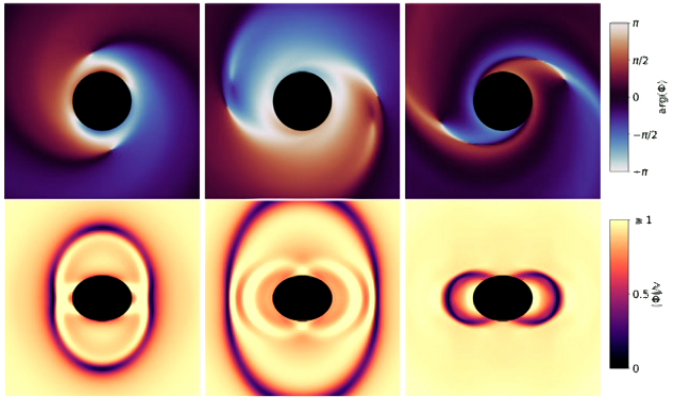


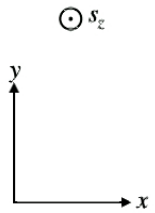


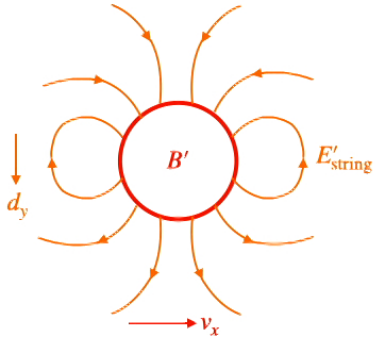


Vortex: $\vec{A} = \frac{\hat{\theta}}{g_D r}$

Vortex dynamics





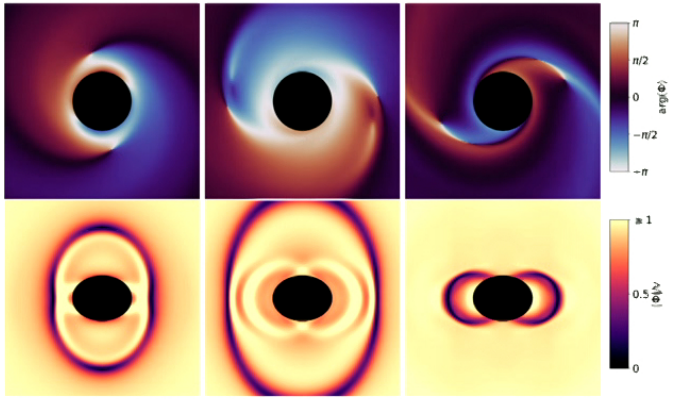


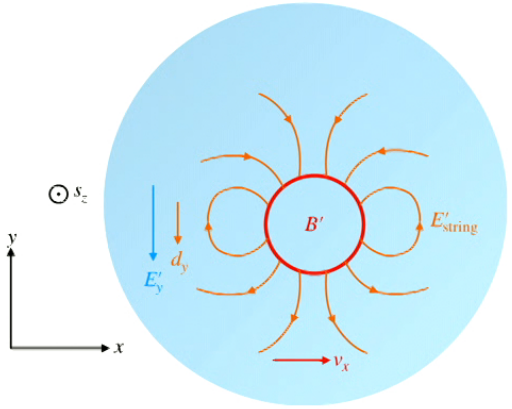
Vortex: $\vec{A} = \dfrac{\hat{\theta}}{g_D r}$

$$\vec{E} = \frac{d\vec{A}}{dt} = \vec{v} \cdot \nabla \vec{A}$$

$$\frac{d\vec{d}}{dl} = \frac{\vec{v}}{g_D}$$

Vortex dynamics



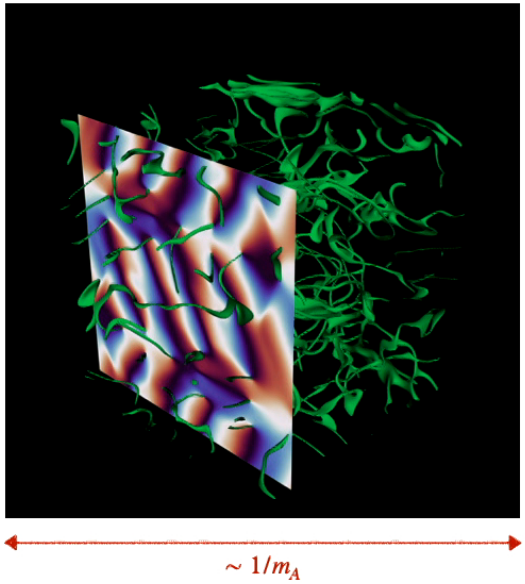


Vortex: $\vec{A} = \frac{\hat{\theta}}{g_D r}$

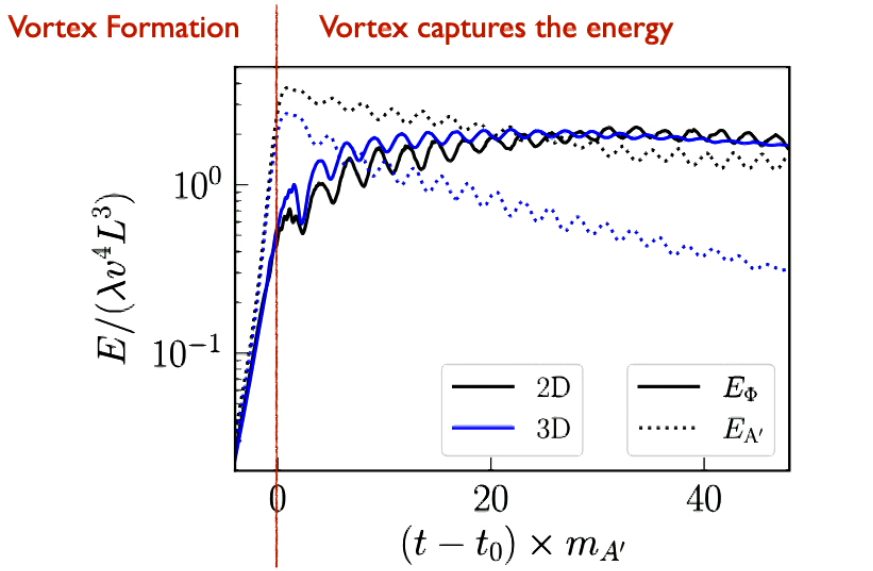
$$\vec{E} = \frac{d\vec{A}}{dt} = \vec{v} \cdot \nabla \vec{A}$$

$$\frac{d\vec{d}}{dl} = \frac{\vec{v}}{g_D}$$

Dark photon dark matter?

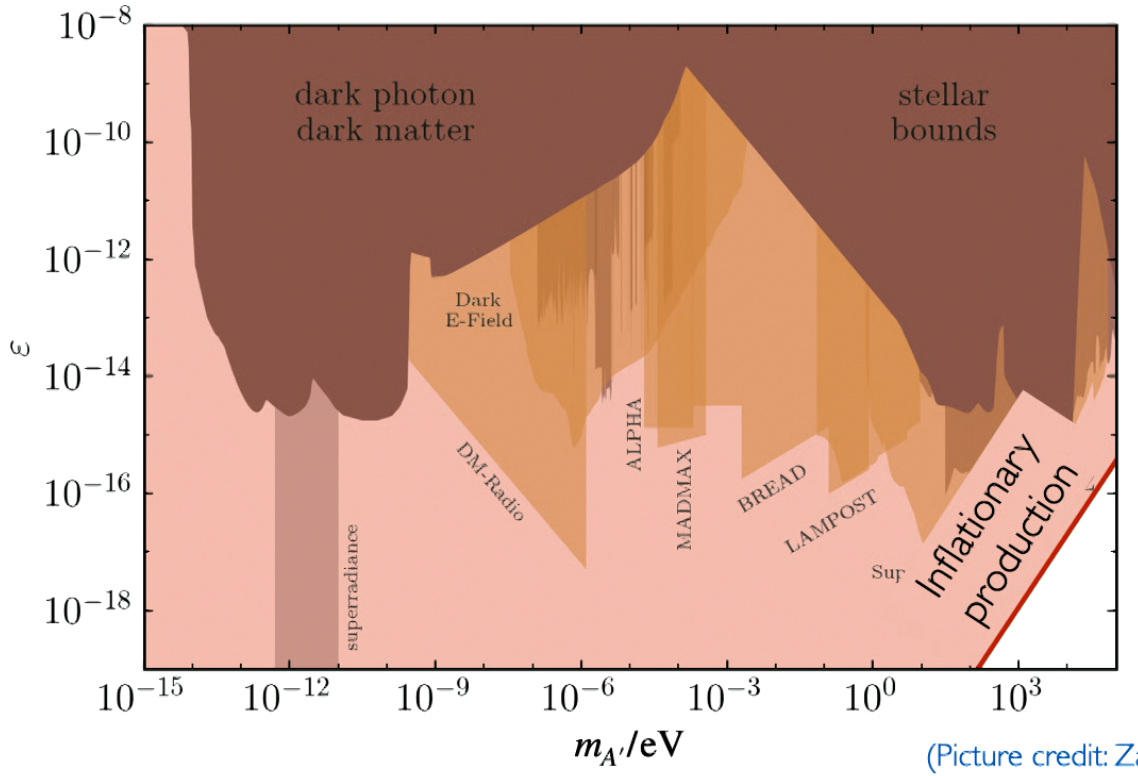


Vortex forms once the critical field is reached



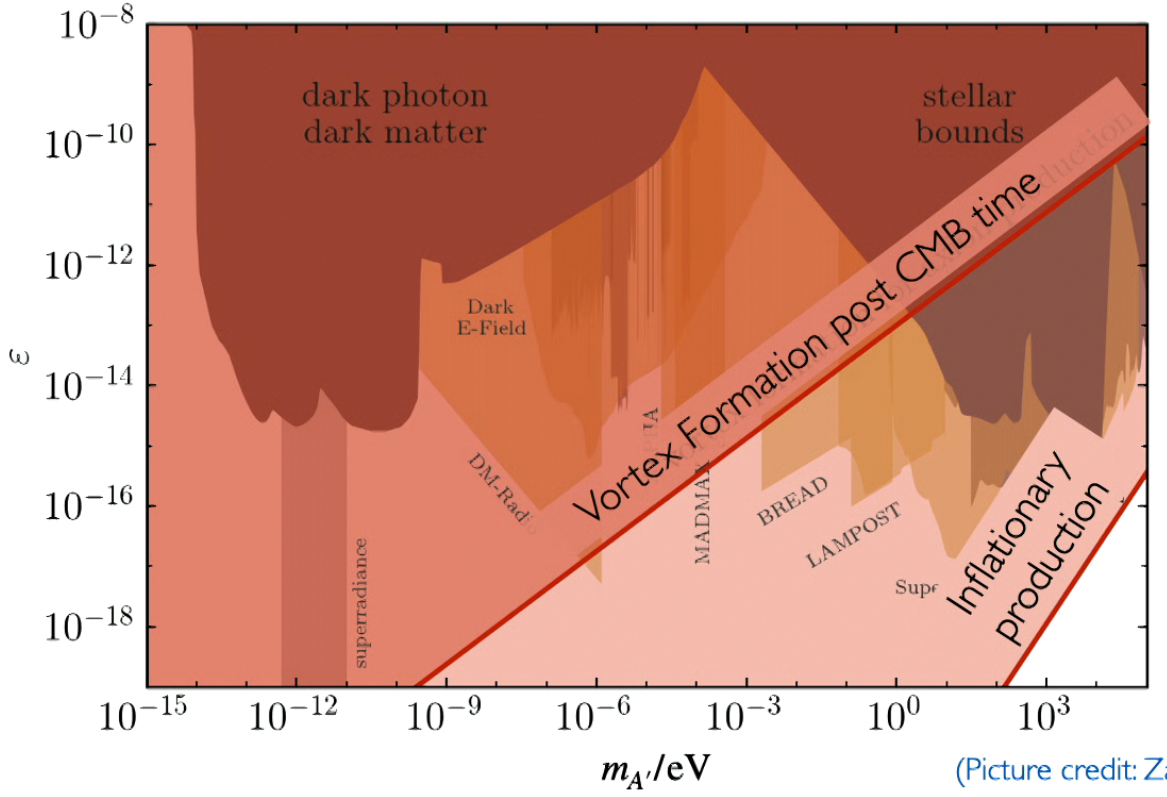
The energy density in the dark photon **depletes**

Vortex Formation when:



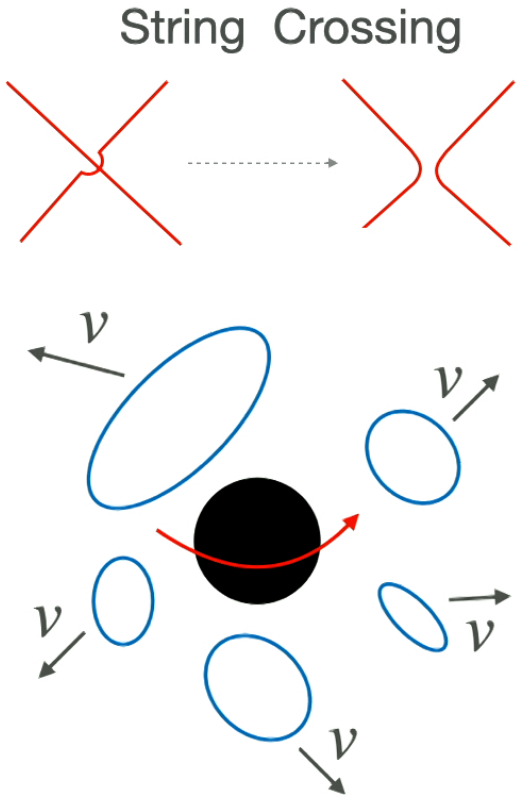
(Picture credit: Zach Weiner)

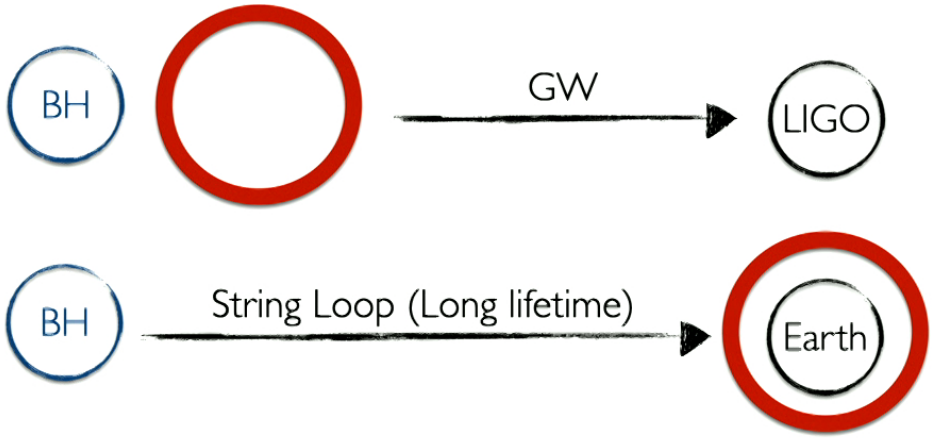
Vortex Formation when:



(Picture credit: Zach Weiner)

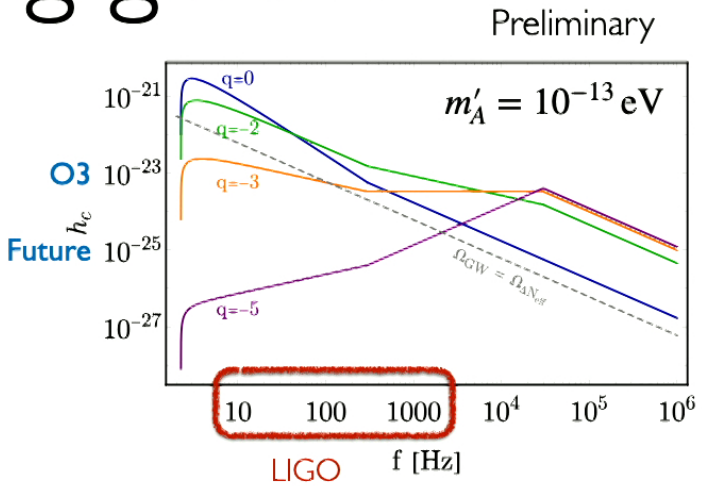
Fate of the vortices





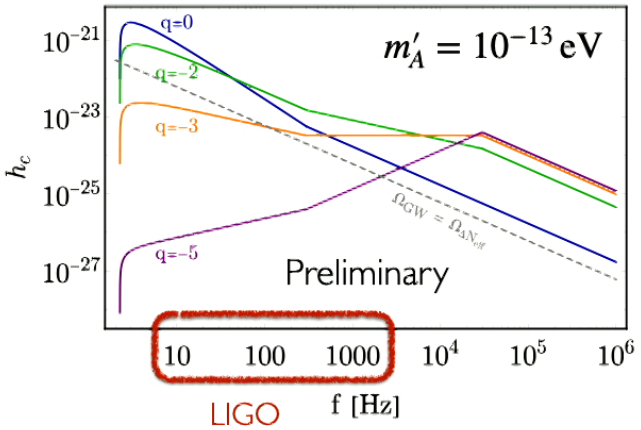
GW & String glitches

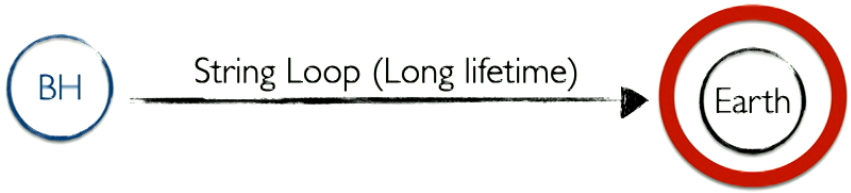
Preliminary results with Ristow, Brzeminski and Hook



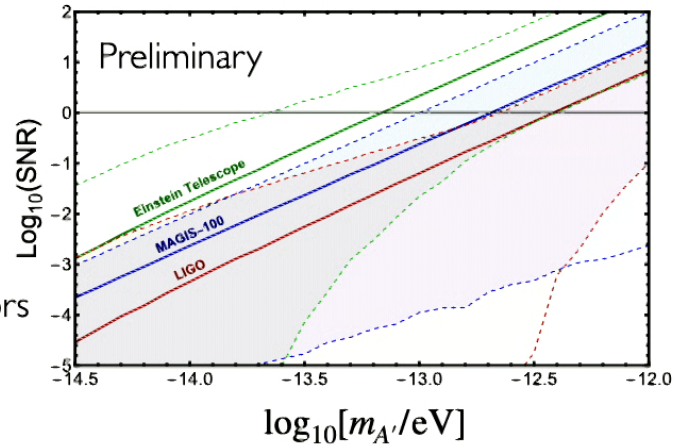
GW & String glitches

Preliminary results with Ristow, Brzeminski and Hook

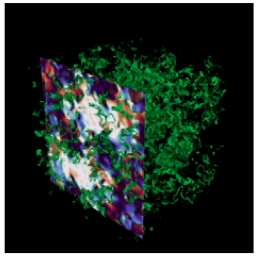




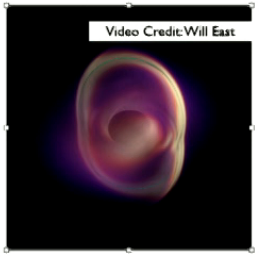
Accelerometers: Gravitational wave detectors

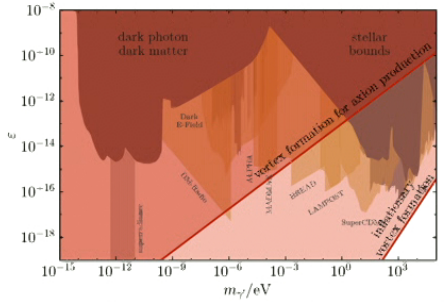


Systems:

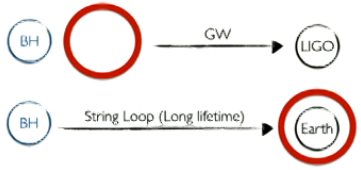


String Bosenova



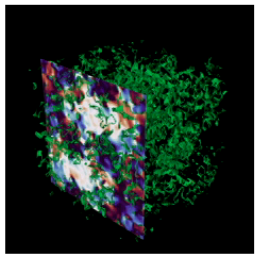


Dark photon dark matter?

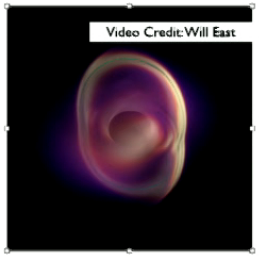


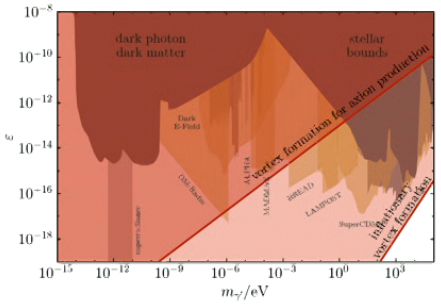
Direct detection & GW

Systems:

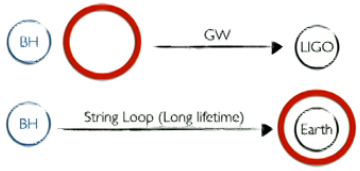


String Bosenova

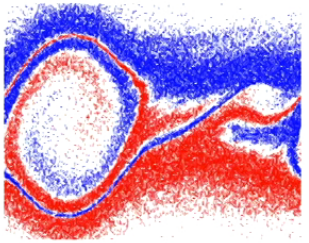




Dark photon dark matter?

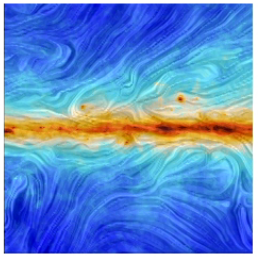


Direct detection & GW



Two stream instability
and freeze-in

Mardon (Talk) & Lasenby 2020



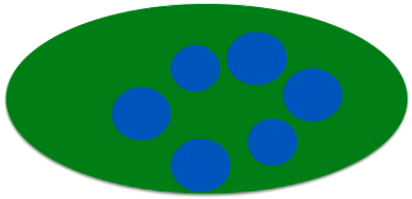
Photon mass?

Adelberger, Dvali, Gruzinov, 2003

Conclusions

- Light bosonic dark matter/dark sector
- Novel collective dynamics affect
  - How to search?
  - Where to search?

Patchy dark screening



Dark photon vortices