Title: Spin-2 dark matter from anisotropic Universe in bigravity

Speakers: Yusuke Manita

Series: Cosmology & Gravitation

Date: January 30, 2023 - 12:00 PM

URL: https://pirsa.org/23010118

Abstract: Abstract: TBD

Zoom Link: https://pitp.zoom.us/j/91979071868?pwd=Z0VWSFhJTEJFWkZRbzBtcWdtV0Ezdz09

Spin-2 dark matter from anisotropic Universe

Yusuke Manita (Kyoto University)

Based on 2211.15873

Collaborators:Katsuki Aoki(YITP), Tomohiro Fujita(WIAS), and Shinji Mukohyama(YITP)

Overview

"Spin-2 dark matter"

Observation

Testing by GW detectors.

implication!

Theory

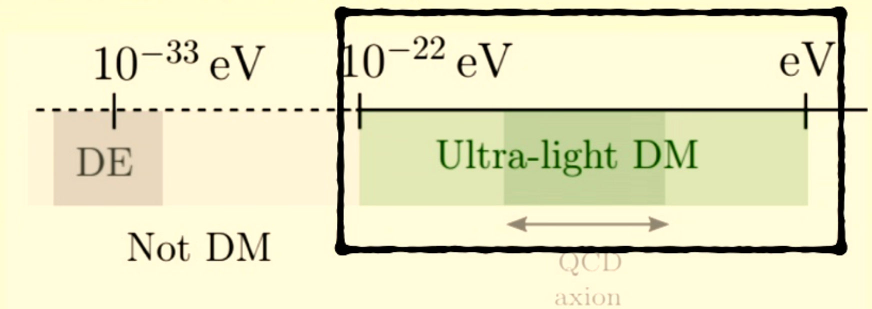
✓Spin-2 DM is regarded as a massive graviton.

✓DM production from the anisotropic Universe.

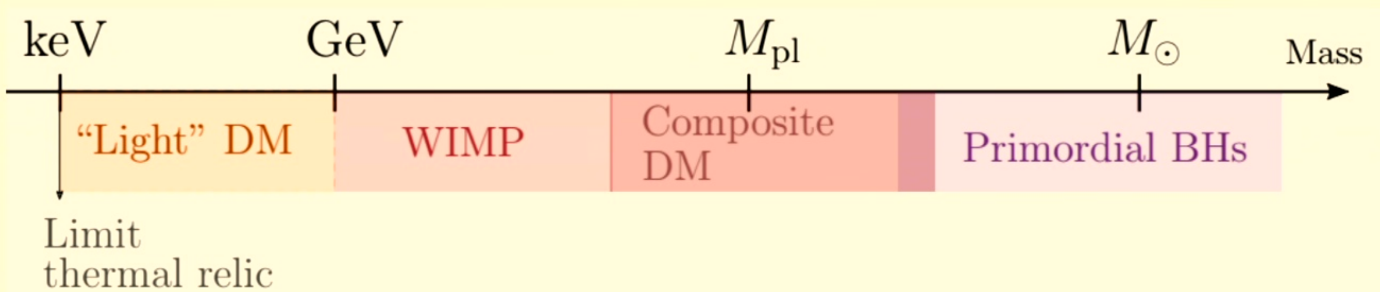
Yusuke Manita (KyotoU), "Spin-2 dark matter from anisotropic Universe in bigravity"

Ultra-light DM

[Ferreira, 2020]

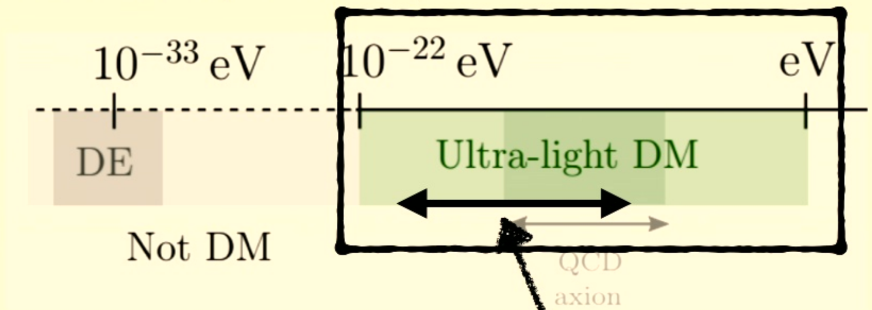


- Light
- Boson
- Classical wave



Ultra-light DM

[Ferreira, 2020]



- Light
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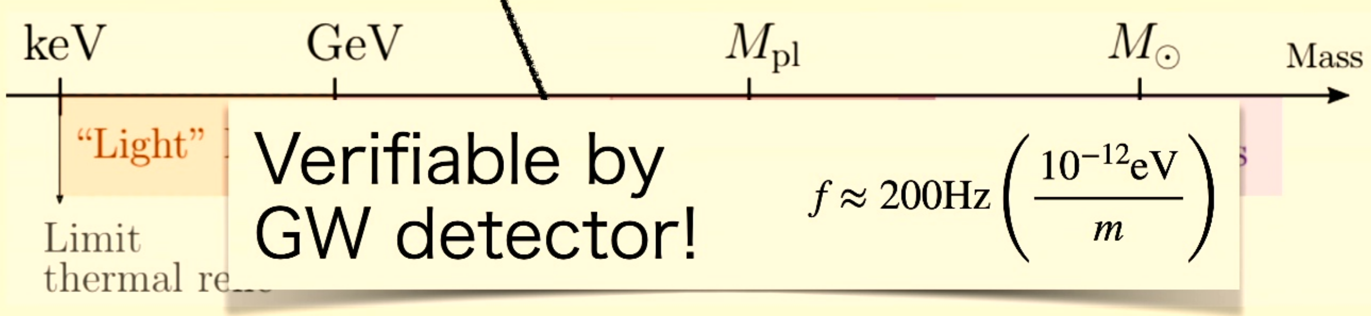

Verifiable by GW detector!

$$f \approx 200\text{Hz}\left(\frac{10^{-12}\text{eV}}{m}\right)$$

Ultraligh spin-2 DM can be tested by GW detector!

Spin-2 dark matter

- **Spin-2 DM** is a tensor dark matter originating from **bigravity**.

  Maeda, Volkov (2013), Aoki, Mukohyama (2017), Babichev et al. (2017)

- Spin-2 DM is regarded as a massive graviton.

$$\mathscr{L}_{\mathrm{int}} \sim \frac{1}{M_G} \varphi_{\mu\nu} T^{\mu\nu}$$

→ Ultralight Spin-2 DM can be searched by the **GW detector**!

Armaleo, Nacir, Urban, (2021); YM, Aoki, Fujita, Mukohyama, in prep.

Production mechanism

Today's topic

- Production from

  phase transition of anisotropy

  YM, Aoki, Fujita, Mukohyama, 2211.15873

- Anisotropic perturbation of the massive graviton can be regarded as a spin-2 DM.

  ✓Anisotropy behaves as a dust fluid [Maeda, Volkov, 2013].

  ✓Structure formation [Aoki, Maeda, 2017].

Bigravity

- Bigravity is a gravity theory with two metrics $\{g_{\mu\nu}, f_{\mu\nu}\}$.

- It is a theory of massive graviton which couples to the massless graviton.
  → **Bigravity describes spin-2 particles in a gravitational field.**

$$S = \underbrace{\frac{1}{2\kappa_g^2}\int d^4x\sqrt{-g}R^{(g)}}_{\text{Einstein-Hilbert term}} + \underbrace{\frac{1}{2\kappa_f^2}\int d^4x\sqrt{-f}R^{(f)}}_{\text{Einstein-Hilbert term}} + \underbrace{\frac{m^2}{\kappa^2}\int d^4x\mathscr{L}_{\rm int}[g_{\mu\nu}, f_{\mu\nu}]}_{\text{Interaction term}}$$

HRBG [Hassan, Rosen, 2012],

MTBG [De Felice, Larrouturou, Mukohyama, Oliosi, 2020]

Hassan-Rosen bigravity

[Hassan, Rosen, 2012]

- Nonlinear ghost-free bigravity obtained by extending the dRGT theory. Lorentz invariant bigravity.

$$\mathcal{L}_{\rm int} = \sqrt{-g}\sum_{n=0}^{4} b_n e_n(\mathcal{K}) = \sqrt{-f}\sum_{n=0}^{4} b_{4-n} e_n(\tilde{\mathcal{K}}),$$

where

$$\mathcal{K}^{\mu}{}_{\alpha}\mathcal{K}^{\alpha}{}_{\nu} = g^{\mu\alpha} f_{\alpha\nu}, \qquad \tilde{\mathcal{K}}^{\mu}{}_{\alpha}\tilde{\mathcal{K}}^{\alpha}{}_{\nu} = f^{\mu\alpha} g_{\alpha\nu}$$

$$e_n(\mathcal{K}) = -\,\delta^{\mu_1\cdots\mu_n}_{\nu_1\cdots\nu_n}\,\mathcal{K}^{\mu_1}{}_{\nu_1}\cdots\mathcal{K}^{\mu_n}{}_{\nu_n}$$

- DOF is 2(massless± 2)+5(massive$\pm 2, \pm 1, 0$)=7.

Minimal theory of bigravity

[De Felice, Larrouturou, Mukohyama, Oliosi, 2020]

- Ghost-free bigravity obtained by extending the minimal theory of massive gravity. Lorentz violating bigravity.
- By choosing constraint well, the physical degrees of freedom are reduced to 2+2. → tensor mode only.
- **Background equations in the homogeneous universe are the same as HRBG.**
- **There is no scalar mode, so there is no Yukawa force or Higuchi ghosting.**

Background equation

Friedmann equation

$$H_g^2 = \sigma_g^2 + \frac{{m_g}^2}{3}\left[b_0 + b_1\left(e^{-2\beta} + 2e^{\beta}\right)\xi + b_2\left(2e^{-\beta} + e^{2\beta}\right)\xi^2 + b_3\xi^3\right],$$

→ Cosmic expansion is sourced by anisotropy. $\sigma_g = \dot{\beta}_g, \beta = \beta_g - \beta_f$

Equations of anisotropies

$$\frac{1}{a_g^3}\frac{d}{dt}\left(a_g^3\sigma_g\right) + \kappa_g^2\frac{\partial U}{\partial \beta} = 0, \quad \frac{1}{a_g^3}\frac{d}{dt}\left(a_f^3\sigma_f\right) - \kappa_f^2\frac{\partial U}{\partial \beta} = 0$$

→ The anisotropies behave as two fluids.

Constraint equation

The background eq. are nonlinear ODE.
→ First, let's look at the fixed point!

Anisotropic fixed point

[Condition of fixed point]

$$\dot{H}_g = \dot{H}_f = \dot{\beta}_g = \dot{\beta}_f = \dot{\xi} = 0 \quad \rightarrow \text{stationary solution}$$

[result]

Isotropic fixed point $\beta = 0$	Anisotropic fixed point $\beta \neq 0$ (NEW)
$(H_g - H_f\xi)(b_1 + 2b_2\xi + b_3\xi^2) = 0$	$c_4 e^{12\beta} + c_3 e^{9\beta} + c_2 e^{6\beta} + c_1 e^{3\beta} + c_0 = 0$
• Normal branch	$\xi =$ (**Function of** β)
• Self-accelerating branch	$H_g, H_f =$ (**Function of** β **and** ξ)
Strauss+, 2012, De Felice+, 2020, etc.	

Local stability

Linearizing around each fixed point,

$$H_g \to H_{g0} + \epsilon H_{g1}\,, \quad \beta \to \beta_0 + \epsilon\beta_1\,, \cdots$$

- Equation of the massive anisotropy

$$\Rightarrow \quad \ddot{\beta}_1 + 3H_{g0}\dot{\beta}_1 + M^2\beta_1 = 0\,.$$

M is determined for each fixed point.

Anisotropic fixed point

[Condition of fixed point]

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Stability condition: $M^2 > 0$

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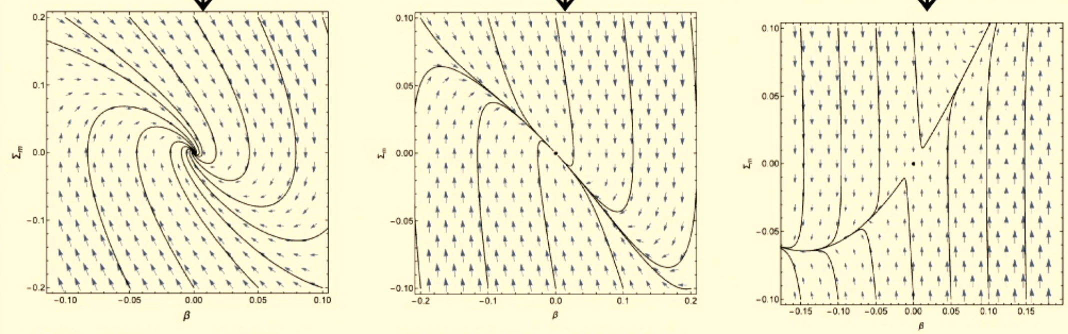
	stable spiral (damped-oscillation)	stable node (over-damping)	saddle point (unstable)
M^2	$+$	$+$	$-$
$9H_{g0}^2 - 4M^2$	$-$	$+$	$+$

Isotropic
fixed point

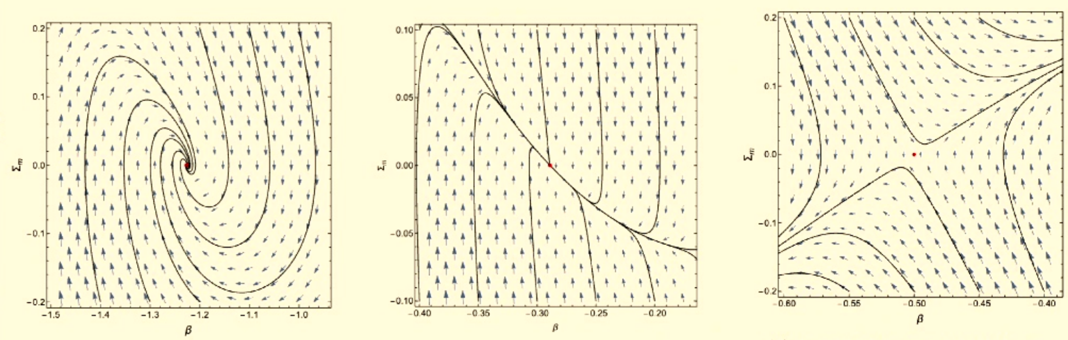


(a) $b_0 = 9.32, b_1 = -0.0162, b_2 = -0.0479, b_3 = 0.0122, b_4 = 0.00549, \alpha = 1.$

(b) $b_0 = 6.61, b_1 = -0.0542, b_2 = -0.00258, b_3 = 0.00320, b_4 = 0.00357, \alpha = 1.$

(c) $b_0 = 50, b_1 = 1, b_2 = 8.15, b_3 = -12.0, b_4 = 26.6, \alpha = 1.$

Anisotropic
fixed point



(d) $b_0 = -6.8, b_1 = 4, b_2 = -1.9, b_3 = 0.95, b_4 = -1, \alpha = 1.$

(e) $b_0 = 50, b_1 = 1, b_2 = 8.15, b_3 = -12.0, b_4 = 26.6, \alpha = 1.$

(f) $b_0 = 9.32, b_1 = -0.0162, b_2 = -0.0479, b_3 = 0.0122, b_4 = 0.00549, \alpha = 1.$

Yu:

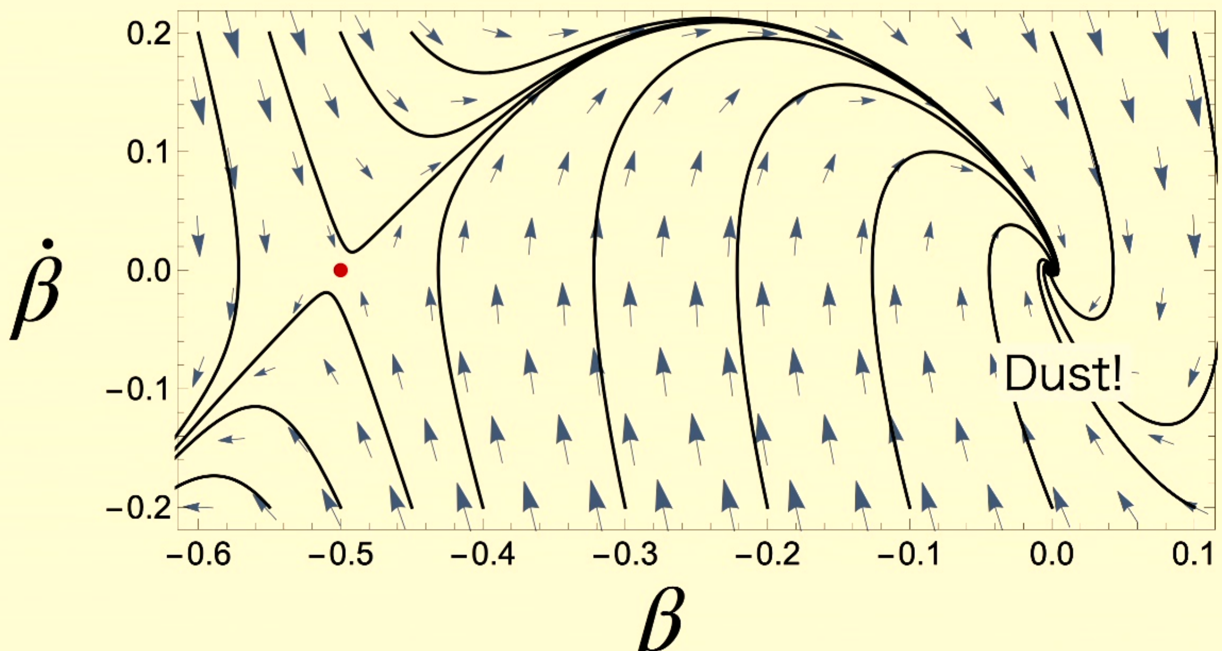
Global behavior

Anisotropic fixed point

saddle(unstable)

Isotropic fixed point

stable-spiral (damped-oscillation)



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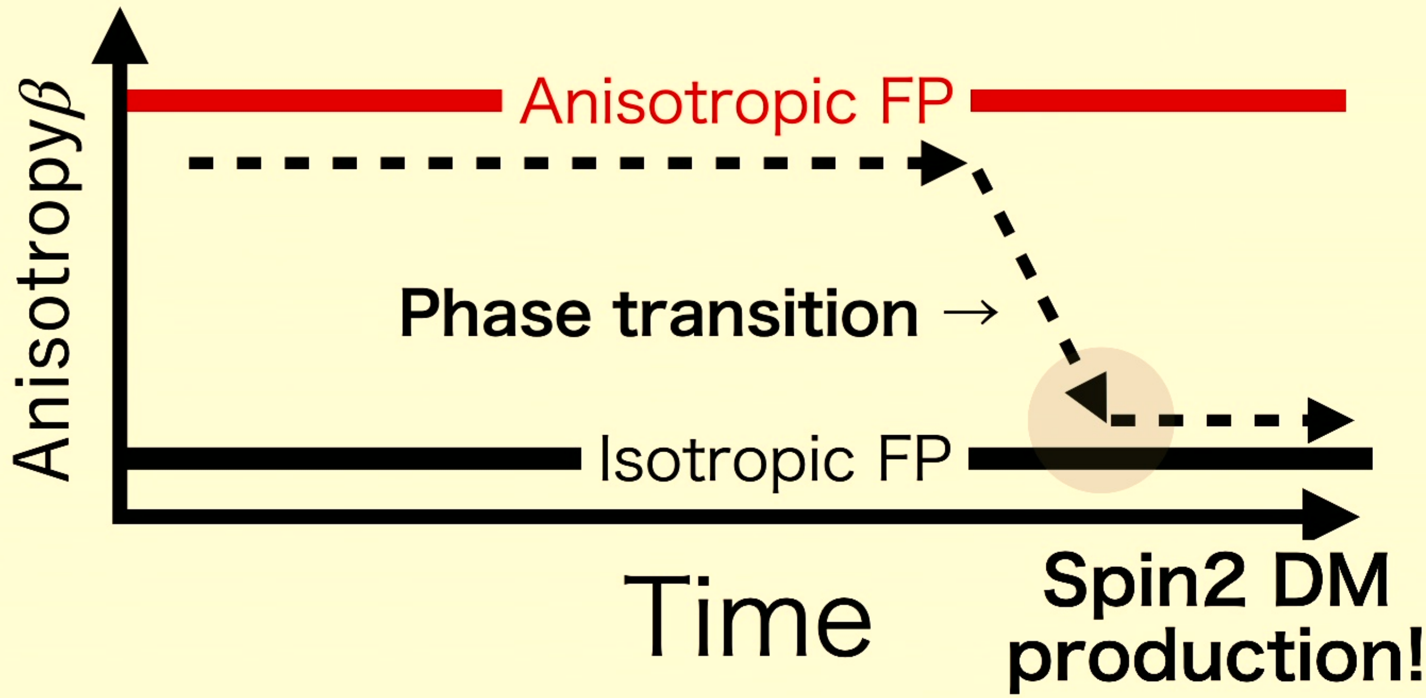
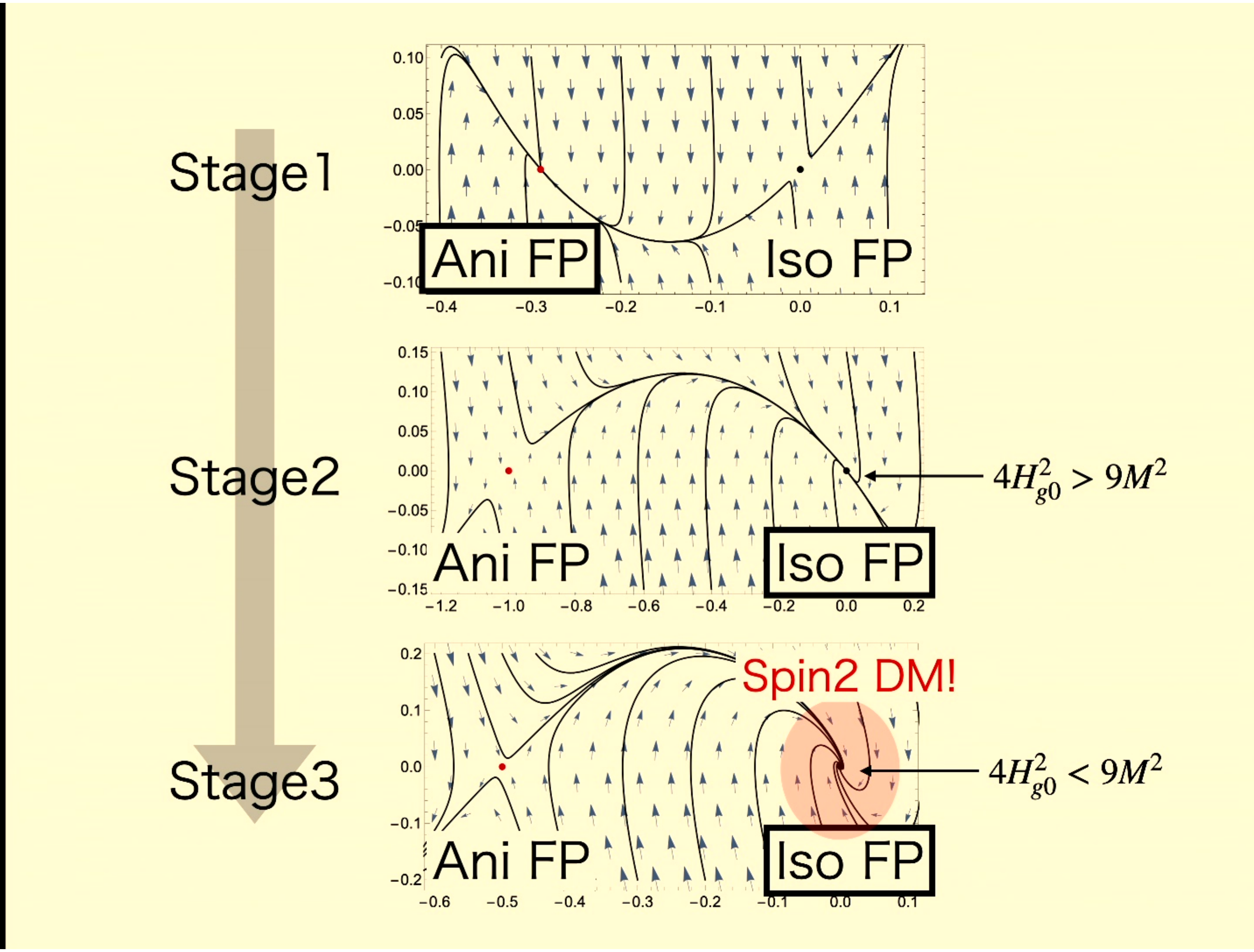
Spin-2 dark matter production

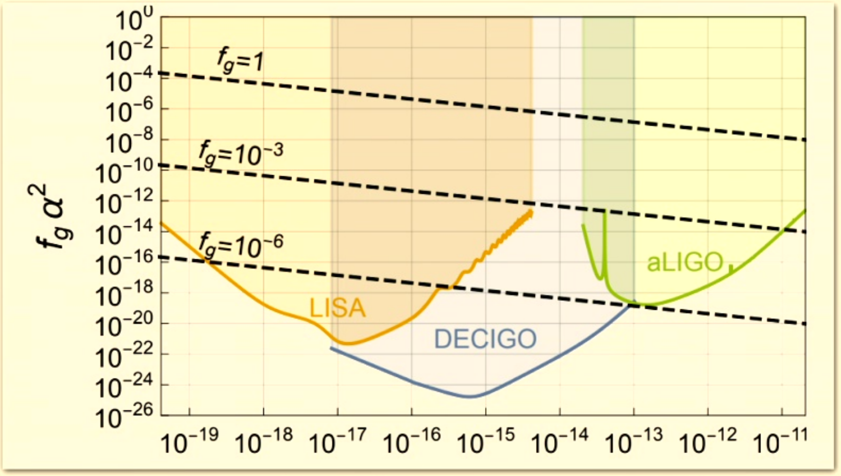
DM from anisotropic Universe

The **external fields** (inflaton, radiation) occurs a phase transition from Isotropic to anisotropic FP.




Stage1
Stage2
Stage3
Ani FP
Iso FP
Ani FP
Iso FP
$4H_{g0}^2 > 9M^2$
Spin2 DM!
Ani FP
Iso FP
$4H_{g0}^2 < 9M^2$

Estimate of DM abundance



Spin-2 DM mass[eV]

- Order estimate.
  The exact abundance cannot be determined without solving for the time evolution of the outer field.
- [asumption]
  Phase transition occurs at radiation dominant.
  $\beta(a_{\rm tr}) = \mathcal{O}(1)$。

$$f_g \equiv \frac{\Omega_{\rm spin-2}}{\Omega_{\rm DM}} \sim \alpha^2 \Omega_{r,0}^{3/4} \left(\frac{m}{H_0}\right)^{1/2}$$

$\alpha := \frac{\kappa_g}{\kappa_f}$ is a coupling constant.

DM from anisotropic Universe

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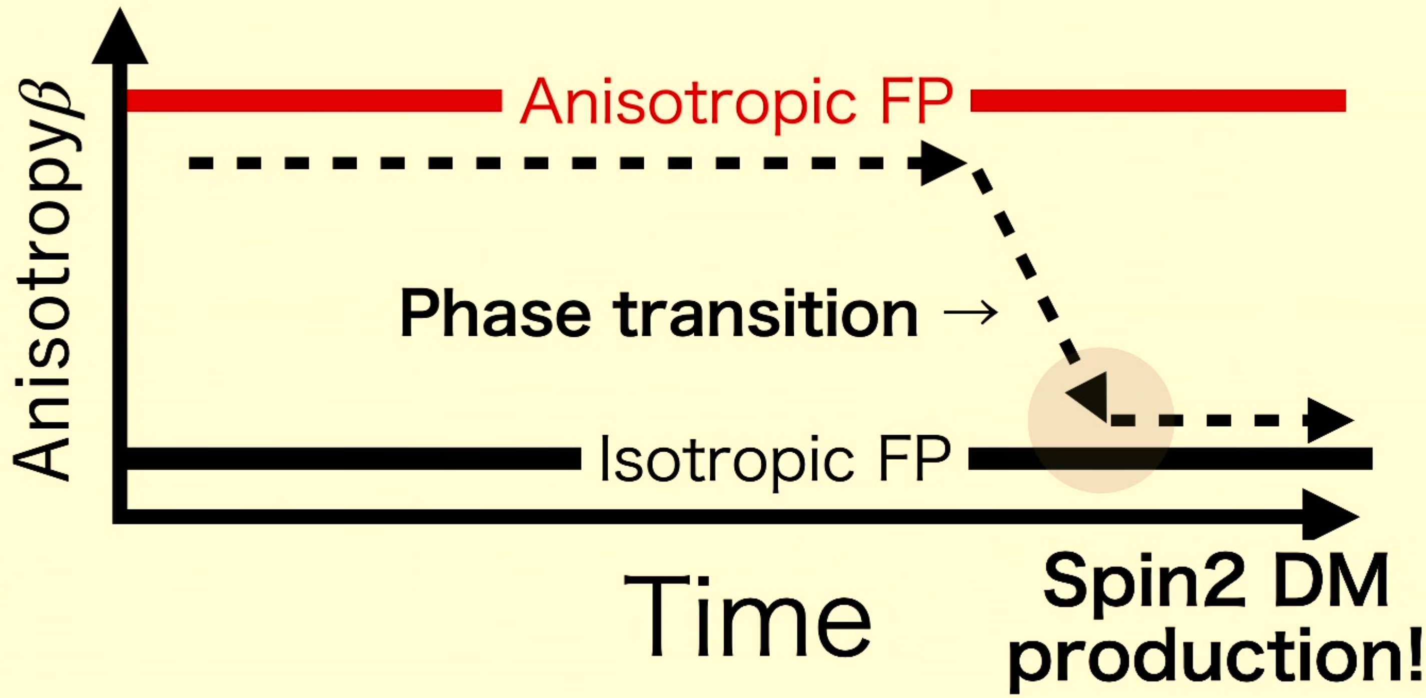

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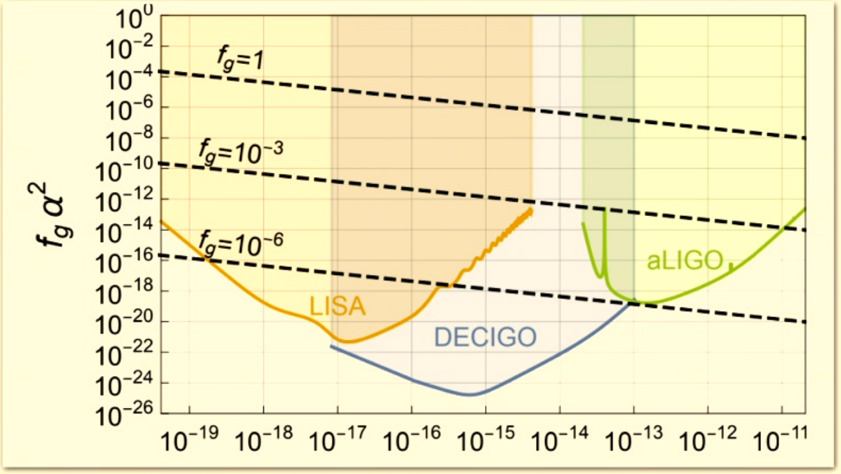

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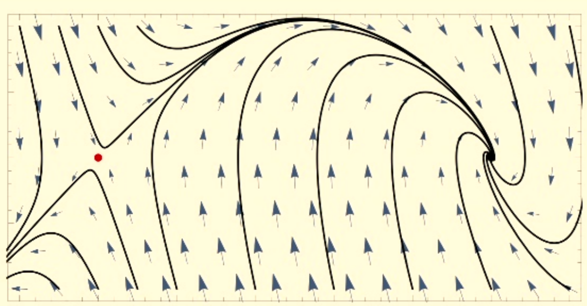
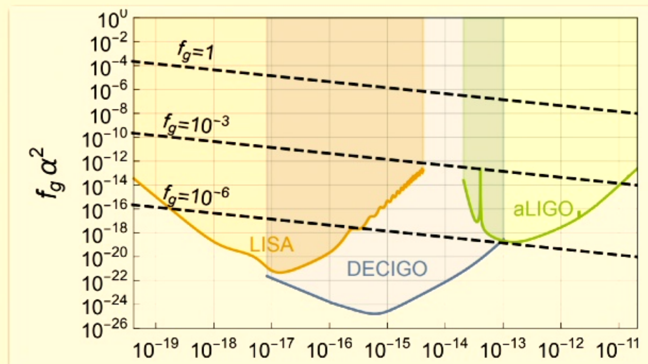
Summary

- The spin-2 DM can be produced by the phase transition of the anisotropic Universe!

- It can be tested by GW detector!





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