PRESENTATION

What's a theorist doing?

- explanation & prediction -

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@ICRR Young Researchers' Workshop

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Plan of Talk

1. Overview
2. Example research
3. Baryogenesis
4. Dark Matter models
5. Summary

Theory group covers

- BSM (e.g. GUT)
- WIMP
- Axion
- Dark photon
- Oscillon/Q-ball
- inflation
- CMB
- Primordial BH
- (RH/sterile) Neutrino
- Baryogenesis

etc…

What are you doing?

Plan of Talk

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Example

PRESENTATION

1. Modeling
2. computing
3. explaining
4. predicting

Generation of Primordial Black Holes and Gravitational Waves from Dilaton-Gauge Field Dynamics

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Abstract. We study the observational signatures from particle production of a $U(1)$ gauge field kinetically coupled to an inflaton. Regarding the form of gauge kinetic function, we consider the possibility that it becomes stabilized at a certain time, which makes the growing power of the gauge field evolve non-monotonically with a sharp transition. Remarkably, the copious production of the gauge field occurs on super-horizon scales at the late stage of inflation and perturbations are enhanced on the intermediate scales during inflation. We find that it can predict a bumpy shape of the curvature power spectrum which leads to the generation of primordial black holes as a dark matter after inflation. We also estimate two types of tensor modes sourced by the gauge field: the primordial gravitational waves generated during inflation and the induced gravitational waves provided by the enhanced curvature perturbation after inflation. We show that both of them are potentially testable with the future space-based gravitational wave interferometers.

Keywords: inflation, primordial black holes, primordial gravitational waves

ArXiv ePrint: 1912.XXXXX

1. **Modeling**
2. computing
3. explaining
4. predicting

Write down a Lagrangian

$$\mathcal{L} = \frac{M_{\rm Pl}^2}{2} R - \frac{1}{2}(\partial_\mu \varphi)^2 - V(\varphi) - \frac{1}{4} I^2(\varphi) F_{\mu\nu} F^{\mu\nu},$$

An inflation model
with the inflaton and
(dark) electromagnetic fields

Analytic calc.

1. Modeling
2. computing
3. explaining
4. predicting

$$A_i(t,\boldsymbol{x}) = \int \frac{d\boldsymbol{k}}{(2\pi)^3}\left(\hat{A}^X_{\boldsymbol{k}}(t)e^X_i(\hat{\boldsymbol{k}}) + i\hat{A}^Y_{\boldsymbol{k}}(t)e^Y_i(\hat{\boldsymbol{k}})\right)e^{i\boldsymbol{k}\cdot\boldsymbol{x}} ,$$

$$\hat{A}^\lambda_{\boldsymbol{k}}(t) = A^\lambda_k(t)a^\lambda_{\boldsymbol{k}} + A^{\lambda *}_k(t)a^{\lambda\dagger}_{-\boldsymbol{k}} , \qquad \left[a^\lambda_{\boldsymbol{k}},\ a^{\lambda'\dagger}_{-\boldsymbol{k}'}\right] = (2\pi)^3\delta^{\lambda\lambda'}\delta(\boldsymbol{k}+\boldsymbol{k}')$$

$$E_k = \frac{\bar{I}\dot{A}_k}{a} \to \begin{cases} -ie^{i\frac{n}{2}\pi}\frac{4H^2\Gamma(n+\frac{1}{2})}{\sqrt{2\pi k^3}}\left(\frac{x}{2}\right)^{2-n} & (n\geq 2) \\ 0 & (0<n<2) \end{cases}$$

$$B_k = \frac{k\bar{I}A_k}{a^2} \to \begin{cases} -ie^{i\frac{n}{2}\pi}\frac{4H^2\Gamma(n-\frac{1}{2})}{\sqrt{2\pi k^3}}\left(\frac{x}{2}\right)^{3-n} & (n\geq 3) \\ 0 & (0<n<3) \end{cases}$$

$$n(\varphi) = -\frac{\dot{\varphi}}{HM_{\rm Pl}}\frac{B_1c_1\exp\left(c_1\frac{\varphi}{M_{\rm Pl}}\right)}{B_1\exp\left(c_1\frac{\varphi}{M_{\rm Pl}}\right)+B_2} \simeq \frac{1}{M_{\rm Pl}\gamma N}\frac{B_1c_1\left(2M_{\rm Pl}^2\gamma^2N\right)^{\frac{c_1}{\gamma M_{\rm Pl}}}}{B_1\left(2M_{\rm Pl}^2\gamma^2N\right)^{\frac{c_1}{\gamma M_{\rm Pl}}}+B_2} .$$

$$\left[\partial_x^2 + 1 - \frac{2-\bar{V}_{\varphi\varphi}/H^2}{x^2}\right](a\delta\hat{\varphi}_{\boldsymbol{k}}) \simeq a^3\frac{2}{k^2}\frac{\bar{I}_\varphi}{\bar{I}}\delta\hat{\rho}_{E,\boldsymbol{k}} ,$$

$$\delta\hat{\rho}_{E,\boldsymbol{k}} = \int\frac{d\boldsymbol{p}}{(2\pi)^3}\frac{1}{2}\left(\hat{E}^X_{\boldsymbol{p}}e^X_i(\hat{\boldsymbol{p}}) + i\hat{E}^Y_{\boldsymbol{p}}e^Y_i(\hat{\boldsymbol{p}})\right)\left(\hat{E}^X_{\boldsymbol{k}-\boldsymbol{p}}e^X_i(\widehat{\boldsymbol{k}-\boldsymbol{p}}) + i\hat{E}^Y_{\boldsymbol{k}-\boldsymbol{p}}e^Y_i(\widehat{\boldsymbol{k}-\boldsymbol{p}})\right)$$

$$\mathcal{P}_{\delta\varphi,s}(k)|_{\tau\to 0} \simeq \frac{2\pi^2\mathcal{F}^2}{9M_{\rm Pl}^2\epsilon_H}\left(\frac{H}{2\pi}\right)^4\int\frac{dp^*}{(2\pi)^3}\frac{\cos^2(\theta_{\hat{p}}+\theta_{\widehat{k-p}})+1}{p^{*3}|\boldsymbol{k}-\boldsymbol{p}|^{*3}}X^2_{\rm peak}(p)X^2_{\rm peak}(|\boldsymbol{k}-\boldsymbol{p}|)$$

$$M(k) \equiv \tilde{\gamma}\rho\frac{4\pi H^{-3}}{3}\bigg|_{k=aH} \simeq 10^{20}{\rm g}\left(\frac{\tilde{\gamma}}{0.2}\right)\left(\frac{g_*}{106.75}\right)^{-\frac{1}{6}}\left(\frac{k}{7\times 10^{12}{\rm Mpc}^{-1}}\right)^{-2}$$

$$P_\delta(\bar{\delta}_R){\rm d}\bar{\delta}_R = \frac{1}{\sqrt{2\pi\sigma_g^2(\bar{\delta}_R+\sigma_g^2)}}\exp\left(-\frac{\bar{\delta}_R+\sigma_g^2}{2\sigma_g^2}\right)$$

$$h_{ij}(t,\boldsymbol{x}) = \int\frac{d\boldsymbol{k}}{(2\pi)^3}\hat{h}_{ij}(\boldsymbol{k},t)e^{i\boldsymbol{k}\cdot\boldsymbol{x}} = \int\frac{d\boldsymbol{k}}{}\left[e^+_{ij}(\hat{\boldsymbol{k}})\hat{h}^+_{\boldsymbol{k}}(t) + e^\times_{ij}(\hat{\boldsymbol{k}})\hat{h}^\times_{\boldsymbol{k}}(t)\right]e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$

$$\mathcal{P}^{++}_{h,s}(k)|_{\tau\to 0} \simeq \frac{2}{\pi^2}\frac{\mathcal{G}^2H^4}{9M_{\rm Pl}^4}\int\frac{dp^*}{(2\pi)^3}\left[\cos^2\theta_{\hat{p}}\cos^2\theta_{\widehat{k-p}} \ldots\right.$$

$$\mathcal{P}^{\times\times}_{h,s}(k)|_{\tau\to 0} \simeq \frac{2}{\pi^2}\frac{\mathcal{G}^2H^4}{9M_{\rm Pl}^4}\int\frac{dp^*}{(2\pi)^3}\left[\cos^2\theta_{\hat{p}} + \cos^2\theta \ldots\right.$$

Example

PRESENTATION

Primordial BH as DM

1. Modeling
2. computing
3. explaining
4. predicting

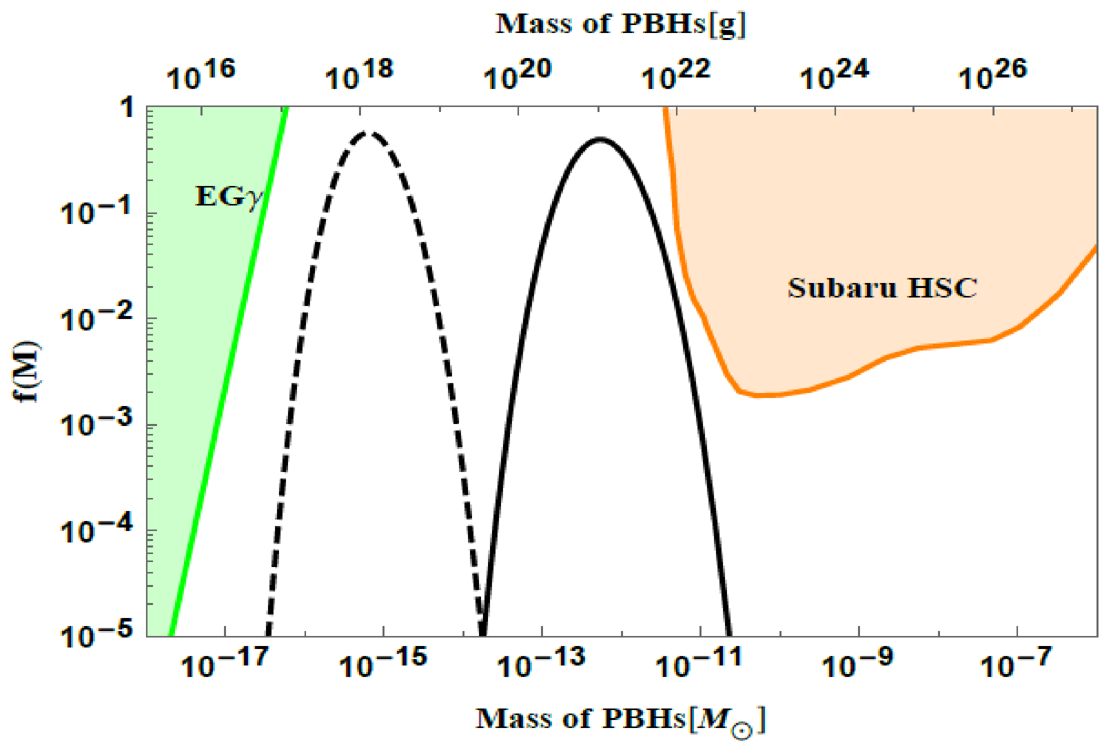

Figure 4. Plot of mass spectrum of PBHs in our model with $\{B_2/B_1 \simeq 8.8 \times 10^{25},\ c_1 \simeq 23\}$ (solid line) and $\{B_2/B_1 \simeq 2.6 \times 10^{15},\ c_1 \simeq 17\}$ (dashed line) for the case of top-hat window function. The green region around $M < \mathcal{O}(10^{17})$g is excluded by the extragalactic gamma ray [92] and the orange region $\mathcal{O}(10^{22})\text{g} < M$ is excluded by the Subaru/HSC [93].

Example

PRESENTATION

Primordial GWs

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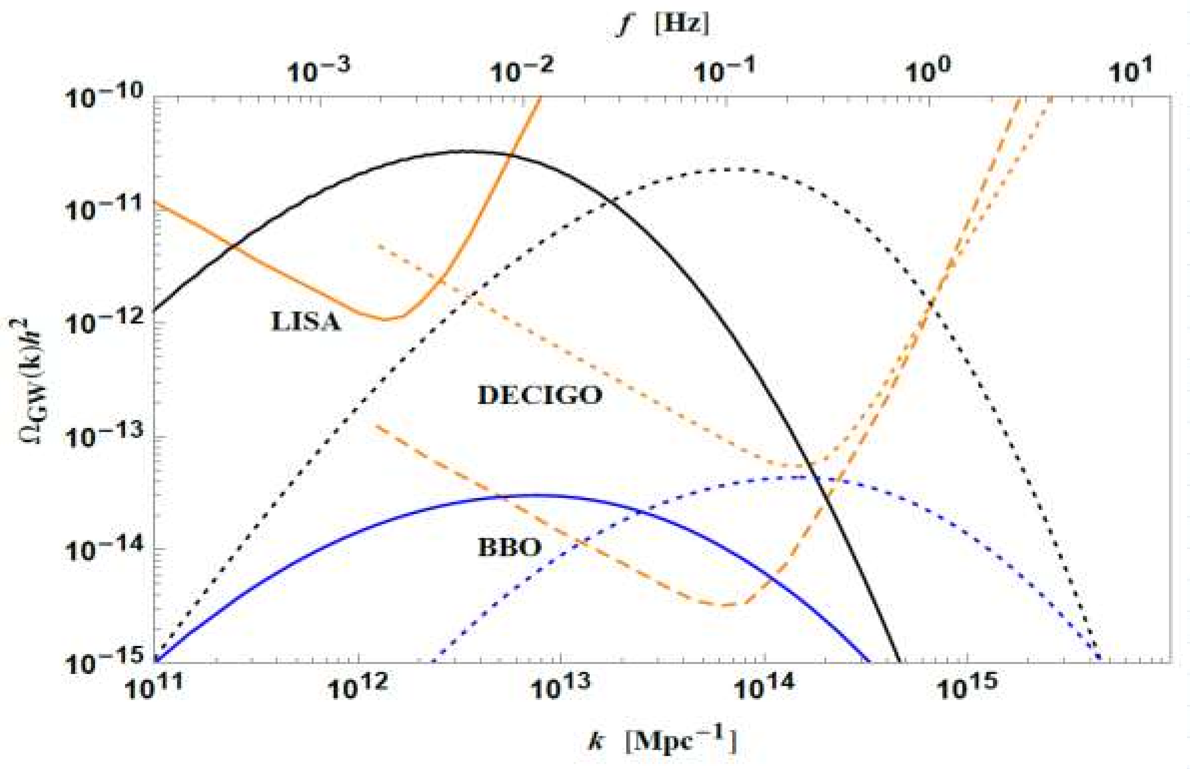

PGWs produced in this model will be tested by future GW interferometers.

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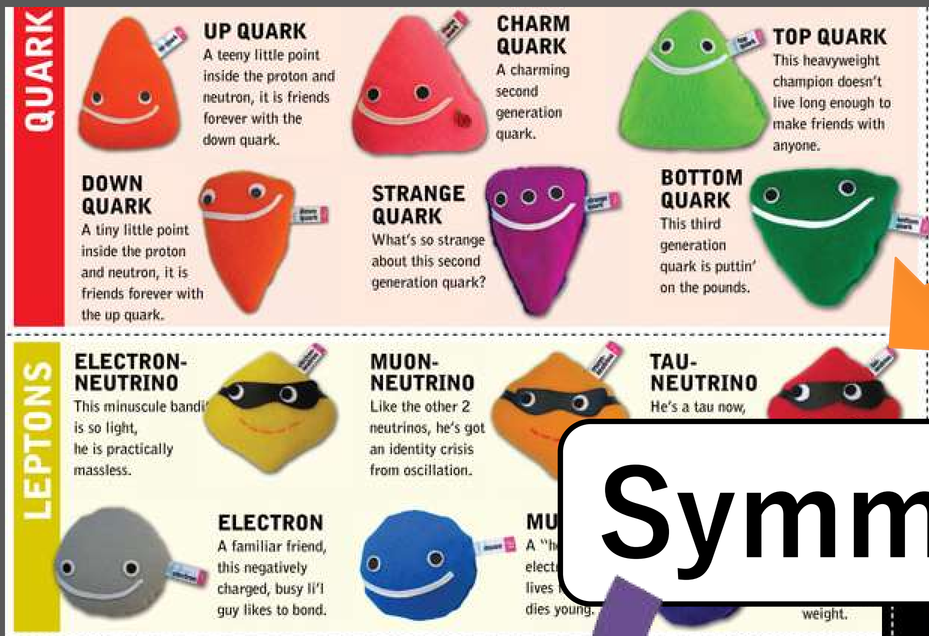
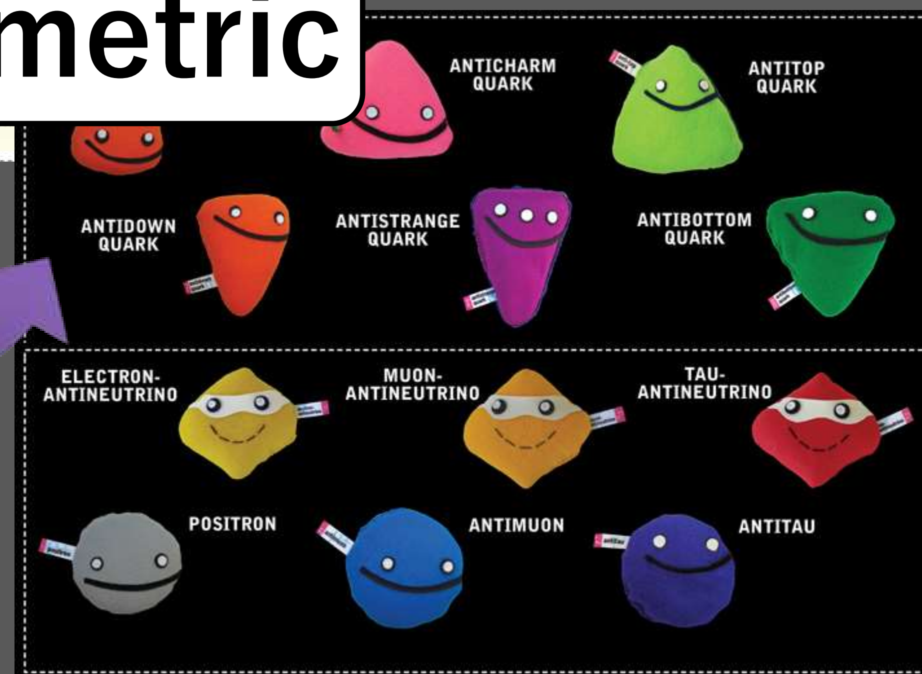
What's Baryogenesis?



Particles

Symmetric



Anti-particles

What's Baryogenesis?

$$n_b = n_{\bar{b}}$$

What's Baryogenesis?

$$\frac{n_b - n_{\bar{b}}}{s} \approx 10^{-10}$$

Baryogenesis

- Observation : $\frac{n_b - n_{\bar{b}}}{s} \approx 10^{-10}$

Baryogensis

A mechanism generates
the baryon asymmetry
In the primordial Universe

Baryogensis models

- **Leptogenesis**
  with right-handed neutrino

- じ**baryogenesis** (じば=MF)
  with helical magnetic field

Baryogensis models

- **Leptogenesis**
  with right-handed neutrino

- じ**baryogenesis** (じば=MF)
  with helical magnetic field

Physics of right-handed neutrinos

Right-handed neutrinos can explain phenomena beyond the Standard Model (SM).

$$\mathscr{L} = \mathscr{L}_{SM} + i\bar{\nu}_{RI}\gamma^{\mu}\partial_{\mu}\nu_{RI} - F_{\alpha I}\bar{L}_{\alpha}\tilde{\Phi}\nu_{RI} - \frac{[M_M]_I}{2}\bar{\nu}^c_{RI}\nu_{RI} + h.c.$$

1. Seesaw mechanism
   ⟶ Neutrino oscillations

2. Leptogenesis
   ⟶ Baryon Asymmetry of the Universe (BAU)

3. Dark Matter (DM)
   ⟶ Sterile neutrino

Neutrino Minimal Standard Model (νMSM)

[Asaka, Shaposhnikov ('05)] [Asaka, Blanchet, Shaposhnikov ('05

Right-handed neutrinos with masses below the electroweak scale, ~ 100 GeV, can explain phenomena beyond the Standard Model (SM) and be probed experimentally.

$$\mathscr{L} = \mathscr{L}_{SM} + i\bar{\nu}_{RI}\gamma^{\mu}\partial_{\mu}\nu_{RI} - F_{\alpha I}\bar{L}_{\alpha}\tilde{\Phi}\nu_{RI} - \frac{[M_M]_I}{2}\bar{\nu}^c_{RI}\nu_{RI} + h.c.$$

1. Seesaw mechanism
   → Neutrino oscillations
2. Leptogenesis
   → Baryon Asymmetry of the Universe (BAU)

Heavy Neutral Leptons (HNLs) with $M = \mathcal{O}(1\text{-}10)$ GeV

Search for long-lived particles

N_2 N_3

3. Dark Matter (DM)
   → Sterile neutrino

with $M = \mathcal{O}(10)$ keV

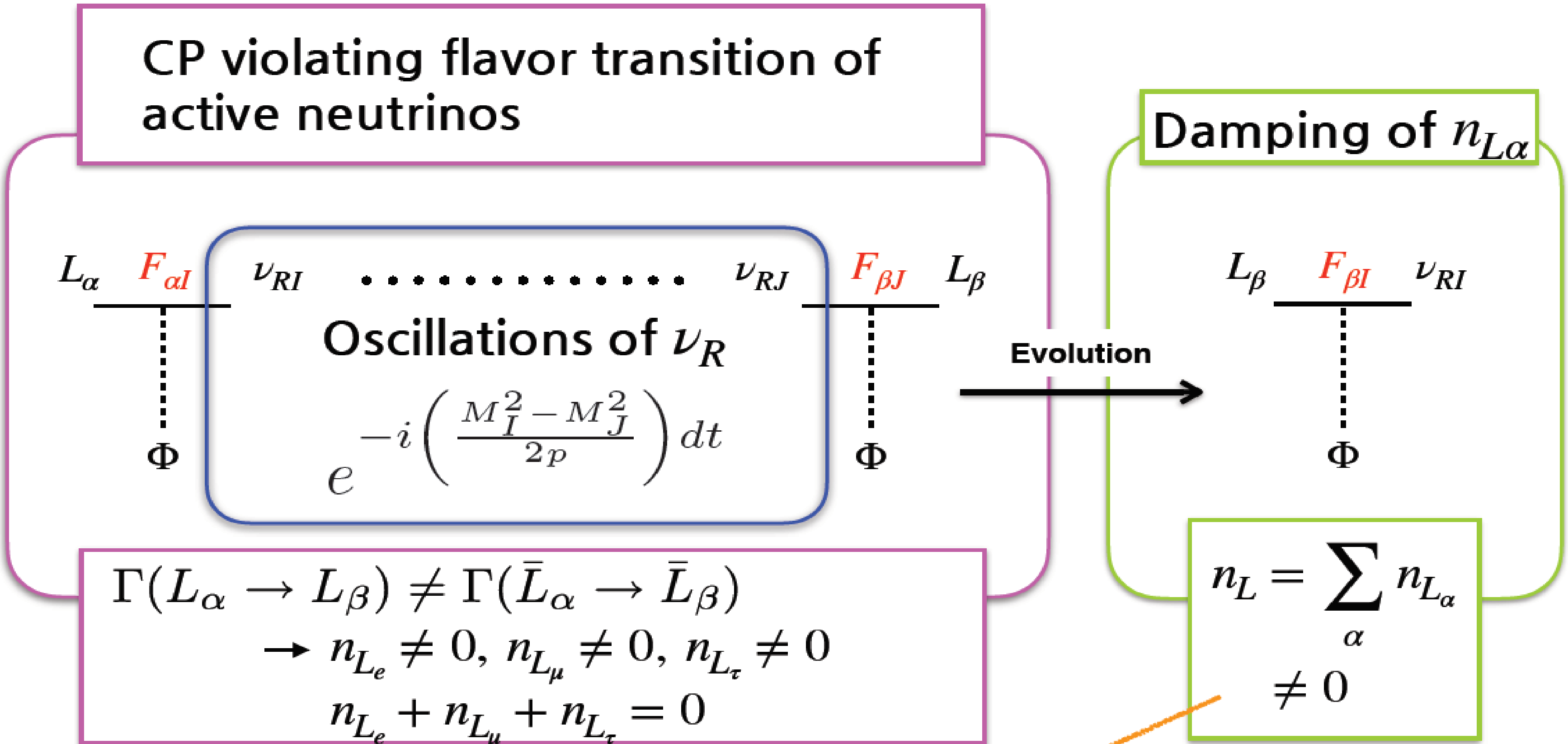
X-ray obsearvations

N_1

Baryogenesis via RHν oscillation [4]

[Akhmedov, Rubakov, Smirnov ('98)] [Asaka, Shaposhnikov ('05)]

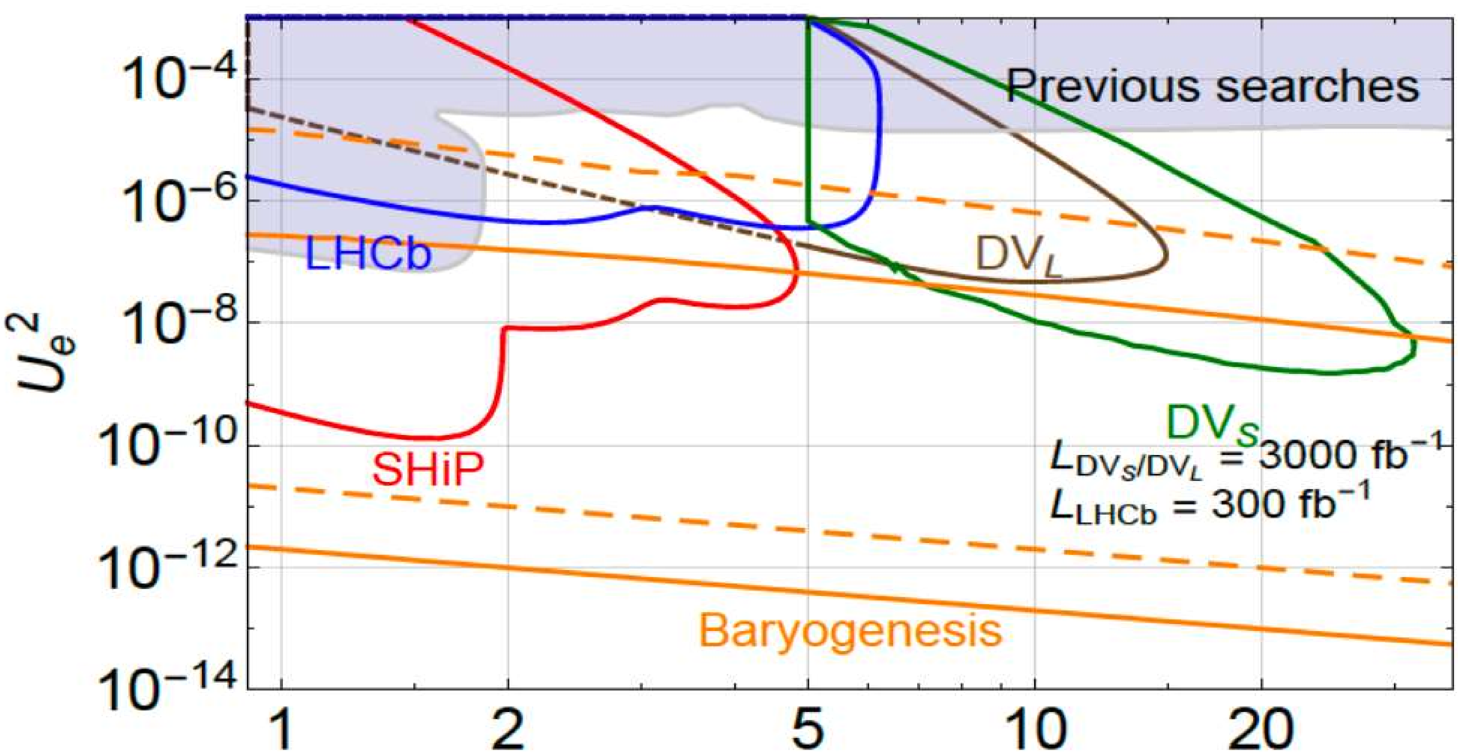
Net lepton asymmetry is produced in evolution with flavor difference in Yukawa couplings.



$$n_B(T_{\rm SF}) = -\frac{28}{79} n_L(T_{\rm SF}) \text{ at } T_{\rm SF} \simeq 130\,\mathrm{GeV}$$

Summary plots

DV searches at LHC and SHiP complete each other.



[Boiarska, Bondarenko, Boyarsky, SE, Ovchynnikov, Ruchayskiy, Timiryasov ('19)]

Baryogensis models

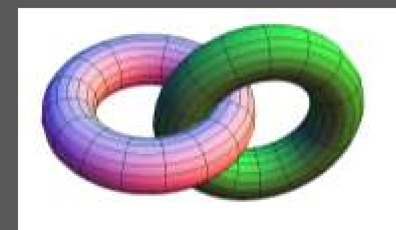
- **Leptogenesis**
  with right-handed neutrino

- じ**baryogenesis** (じば=MF)
  with helical magnetic field

Magnetic Helicity

$$\nabla_\mu J_B^\mu = \nabla_\mu J_L^\mu \simeq Y_{\mu\nu}\tilde{Y}^{\mu\nu} + W_{\mu\nu}\tilde{W}^{\mu\nu} + G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\frac{1}{V}\int d^3x\, F_{\mu\nu}\tilde{F}^{\mu\nu} = 2\dot{h}/a^3$$



Source term is time derivative of magnetic helicity

$$\boldsymbol{h} \equiv \frac{1}{V}\int d^3x\, \boldsymbol{A}\cdot\boldsymbol{B} = \int \frac{d^3k}{(2\pi)^3}\, k\left[\left|A_k^{(R)}\right|^2 - \left|A_k^{(L)}\right|^2\right]$$

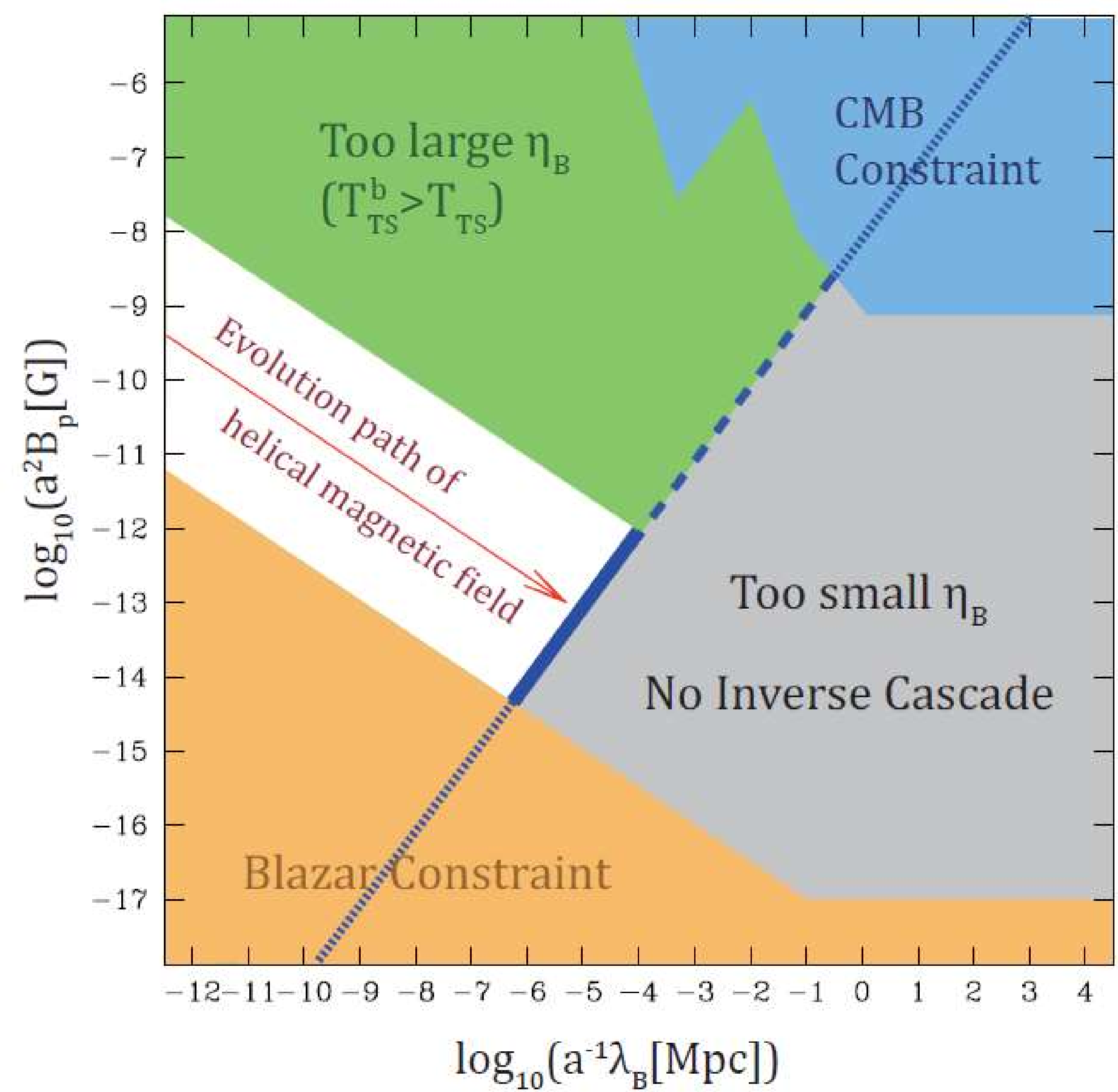
Helicity is difference between 2 polarization (CS number)

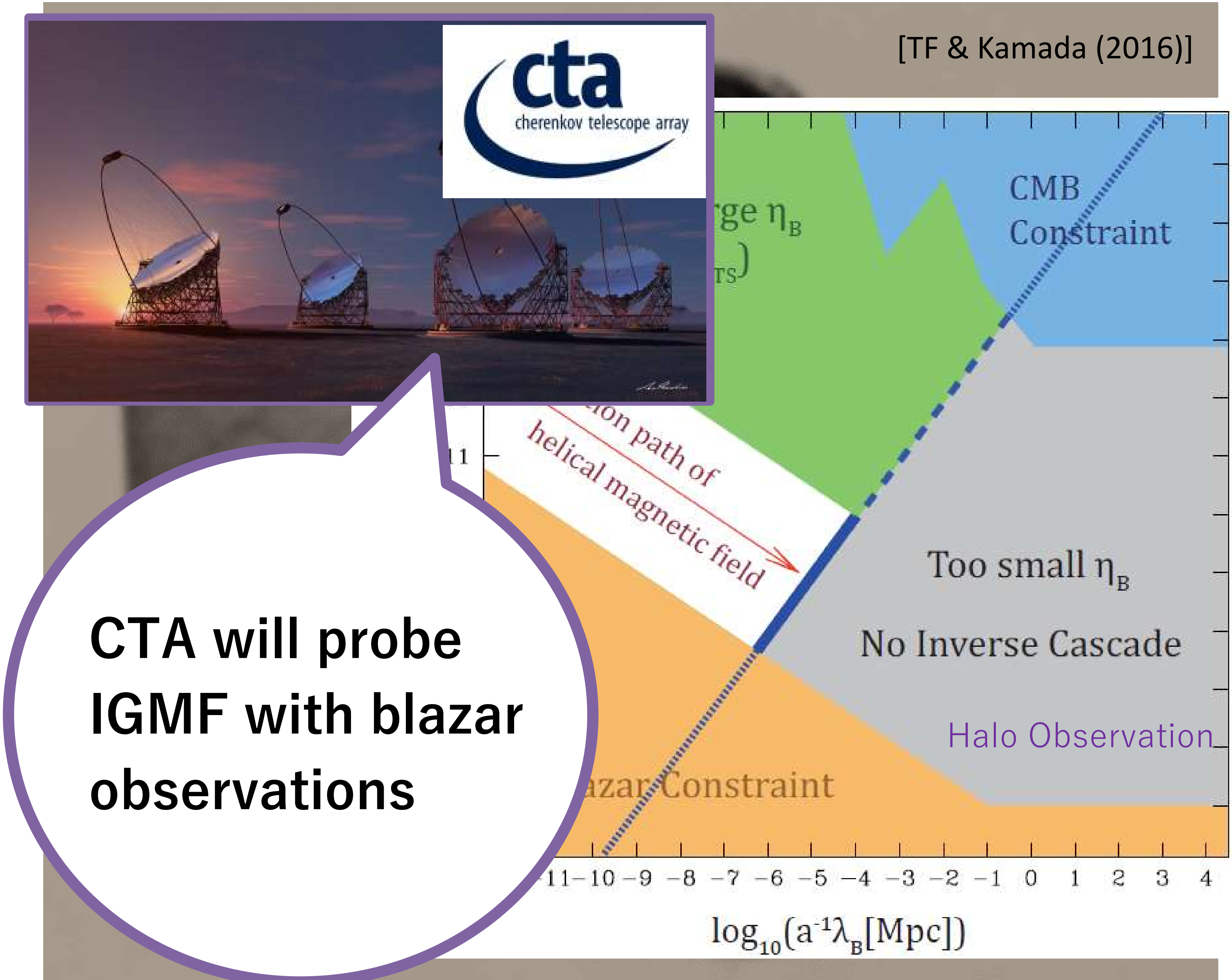
$$A_i(\eta, \boldsymbol{x}) = \sum_{\lambda=1}^{2}\int \frac{\mathrm{d}^3k}{(2\pi)^3} e^{i\boldsymbol{k}\cdot\boldsymbol{x}} e_i^{(\lambda)}(\hat{\boldsymbol{k}})\left[a_{\boldsymbol{k}}^{(\lambda)}\mathcal{A}_k^{(\lambda)}(\eta) + a_{-\boldsymbol{k}}^{\dagger(\lambda)}\mathcal{A}_k^{(\lambda)*}(\eta)\right]$$

$$k_i e_i^{(\pm)}(\boldsymbol{k}) = 0, \quad \varepsilon_{ijl}k_j e_l^{(\pm)}(\boldsymbol{k}) = \mp i k e_i^{(\pm)}(\boldsymbol{k}),$$

Results

[TF & Kamada (2016)]




[TF & Kamada (2016)]
cta
cherenkov telescope array
CMB
Constraint
rge η_B
TS)
ion path of
helical magnetic field
Too small η_B
No Inverse Cascade
Halo Observation
azar Constraint
11
−11 −10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4
$\log_{10}(a^{-1}\lambda_B[\mathrm{Mpc}])$
CTA will probe IGMF with blazar observations

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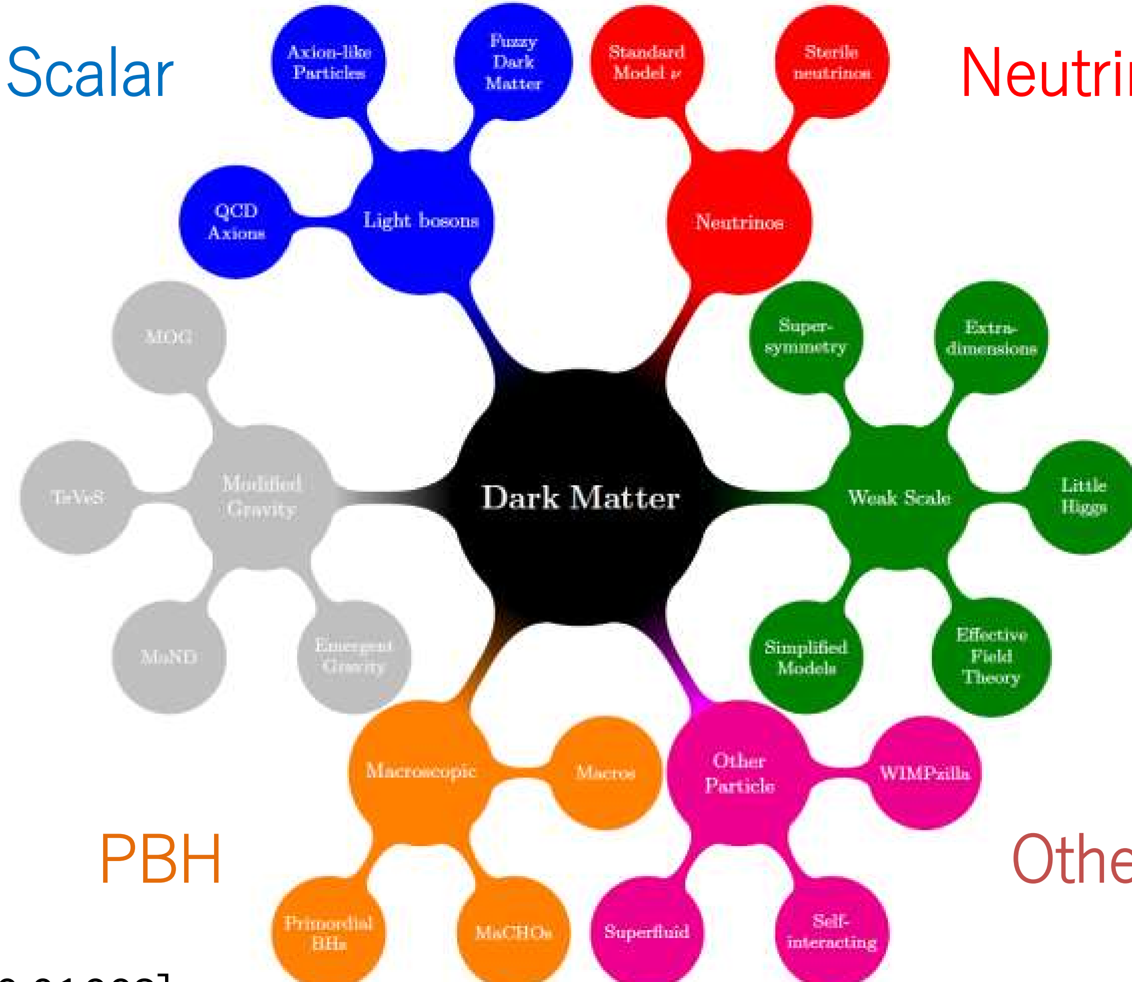
DM candidates

Scalar

Neutrino



M-Gravity

WIMP

PBH

Other

Berton&Tait[1810.01668]

DM candidates

Sterile Neutrino

Berton&Tait[1810.01668]

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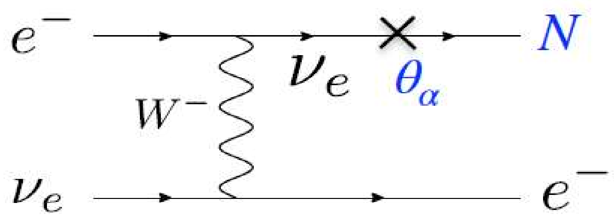
N_1

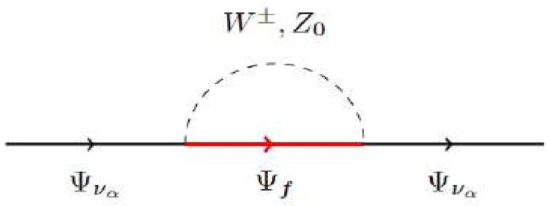
Problem on sterile neutrino DM

Thermal production



$$\Gamma_N \sim \theta_M^2(T)\,\Gamma_\nu \approx 7\pi G_F^2 T^4 E_\nu$$

$$\theta_M^2(T) \simeq \frac{\theta^2}{\left(1 + \frac{2p}{M_1^2} b(p,T)\right) + \theta^2}$$



(a) bubble diagram

$$b(p,T) = \frac{16 G_F^2}{\pi \alpha_W} p (2 + \cos^2\theta_W) \frac{7\pi^2 T^4}{360}$$

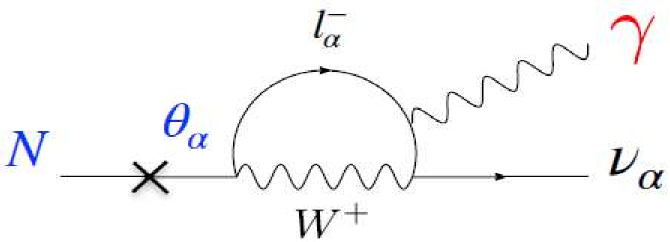
Solving Boltzmann eq., we find

$$f_N \approx 1.8 \times 10^{-2} \left(\frac{\theta^2}{10^{-8}}\right)\left(\frac{M}{\mathrm{keV}}\right) f_\nu \longrightarrow \Omega_N h^2 \approx 0.12 \left(\frac{\theta^2}{1.4 \times 10^{-8}}\right)\left(\frac{M}{\mathrm{keV}}\right)^2$$

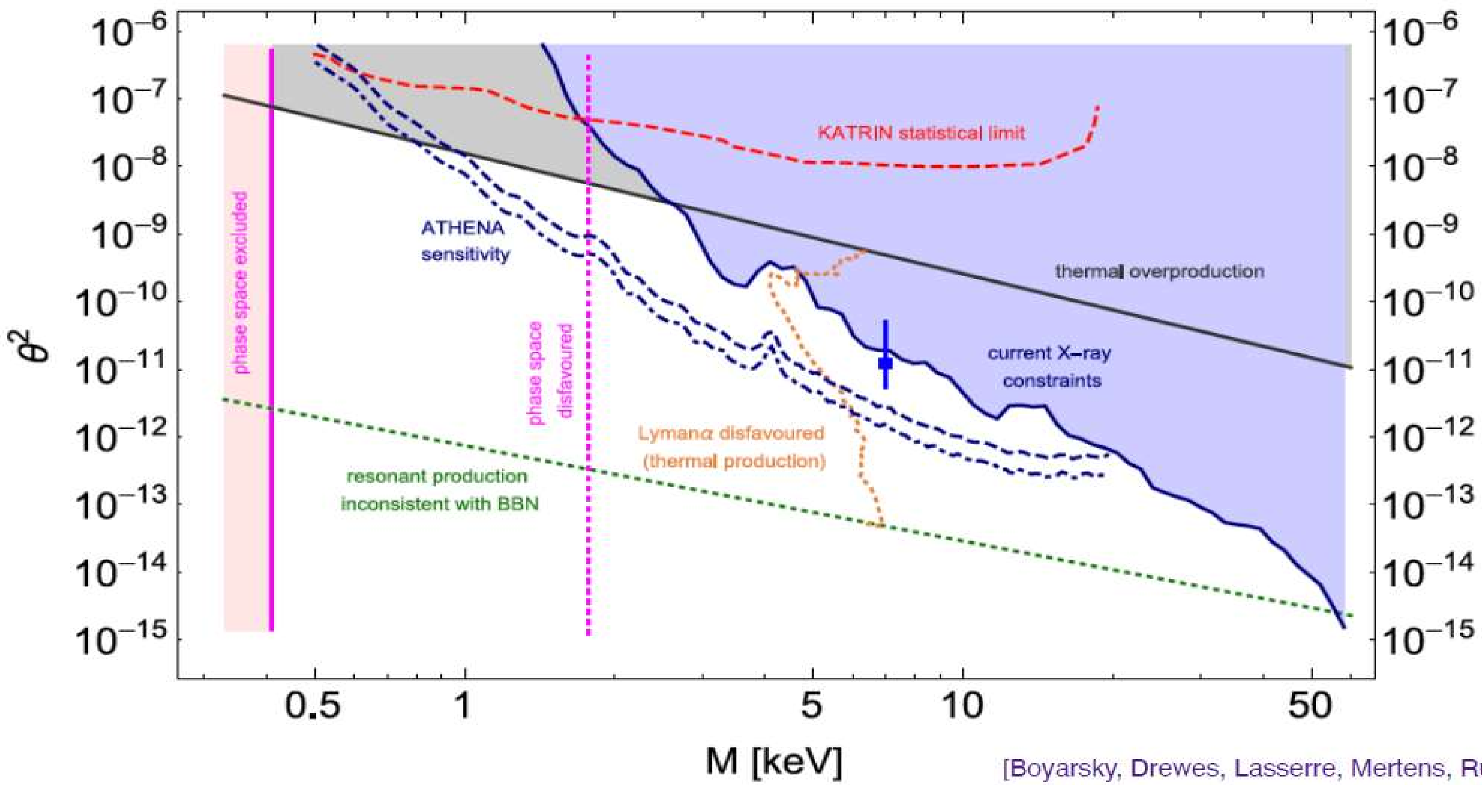
$(\Omega_{DM} h^2 = 0.12)$

Search for sterile neutrino DM

X線観測



$$\Gamma_{N\to\gamma\nu} = \frac{9\,\alpha\,G_F^2}{256\pi^4}\theta^2 M^5$$
$$= 5.5\times 10^{-22}\theta^2\left[\frac{M}{1\,\mathrm{keV}}\right]^5\ \mathrm{s}^{-1}$$



[Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy ('18)]

DM candidates

Axion DM

Berton&Tait[1810.01668]

Example

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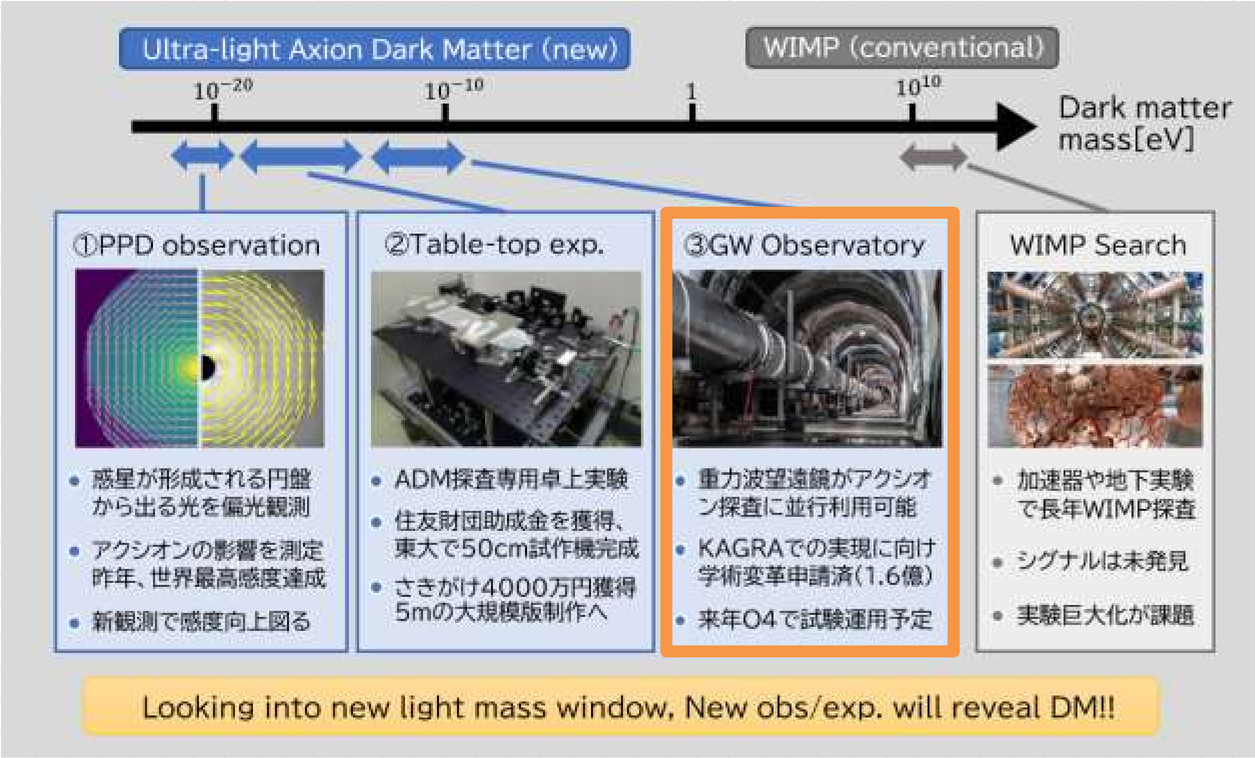
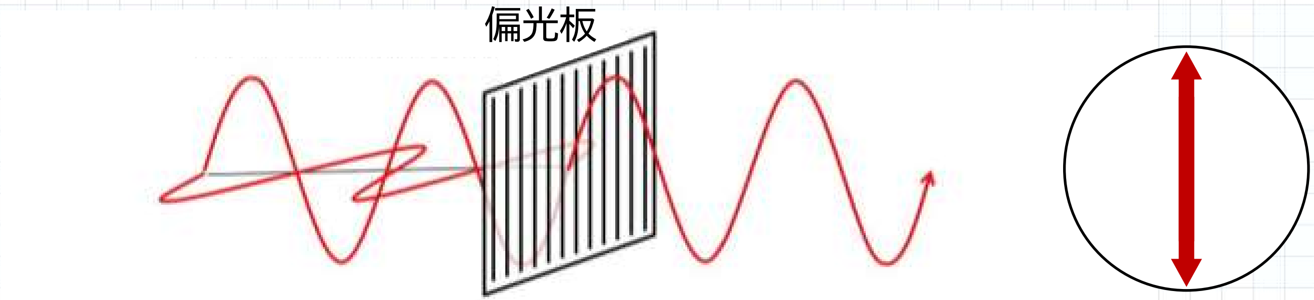
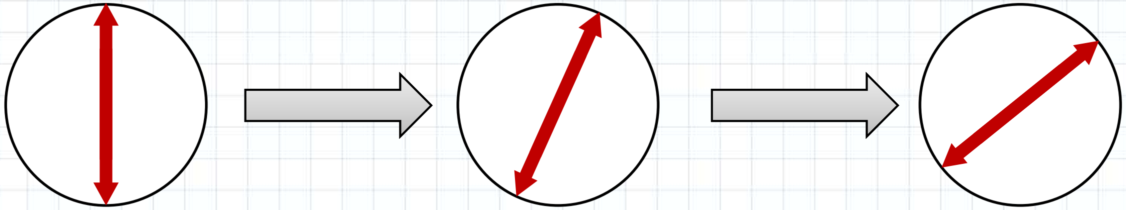


Axion birefringence

Photon has two (linear) polarizations



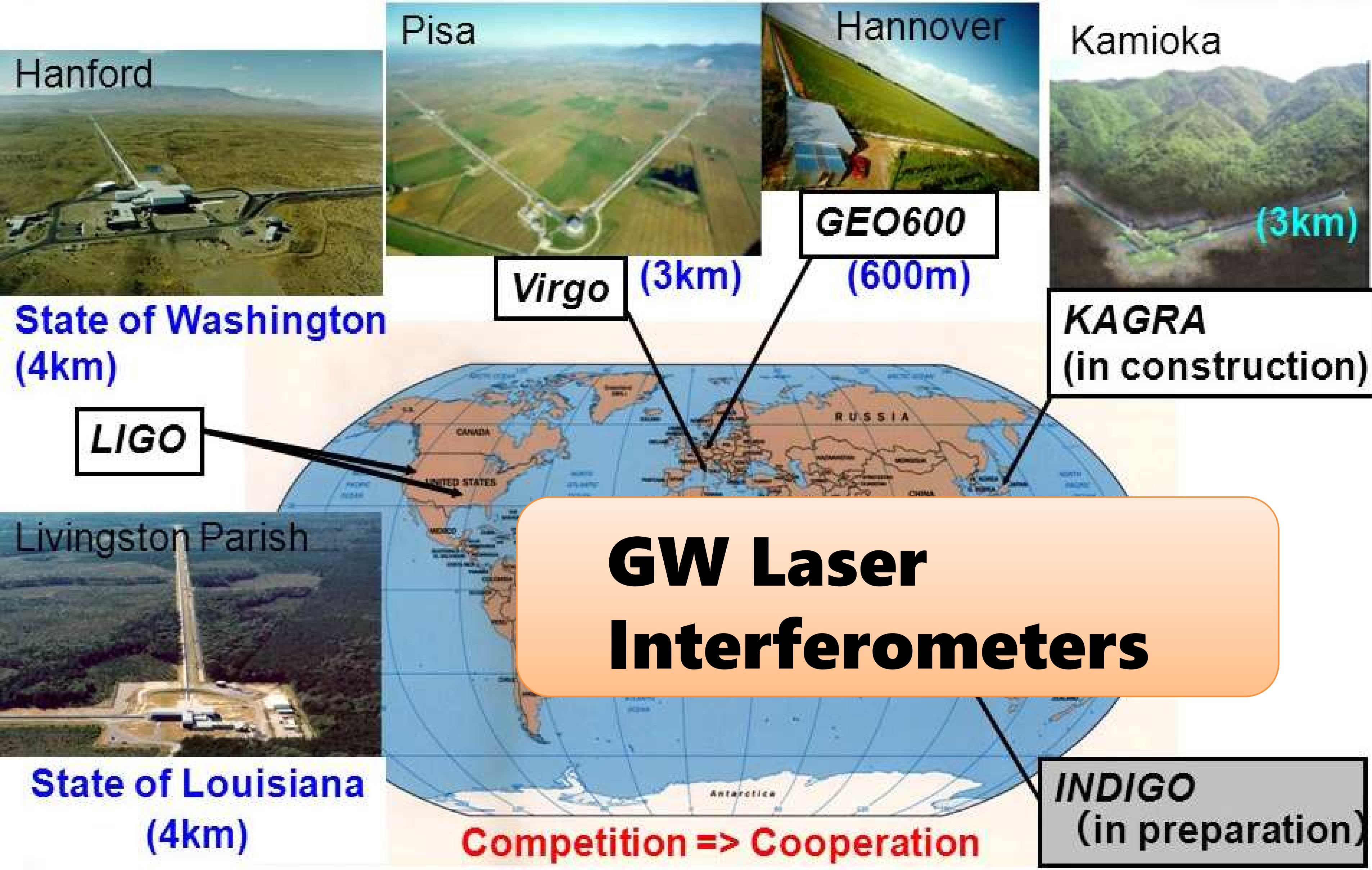
Pol. angle of a γ flying thru ADM rotates



Pointed out in 1992. Not yet used.

[Harari & Sikivie, Phys. Lett. B 289, 67 (1992)]

New experiment



New experiment

[DeRocco &Hook (2018),
Obata, TF, Michimura(2018)]

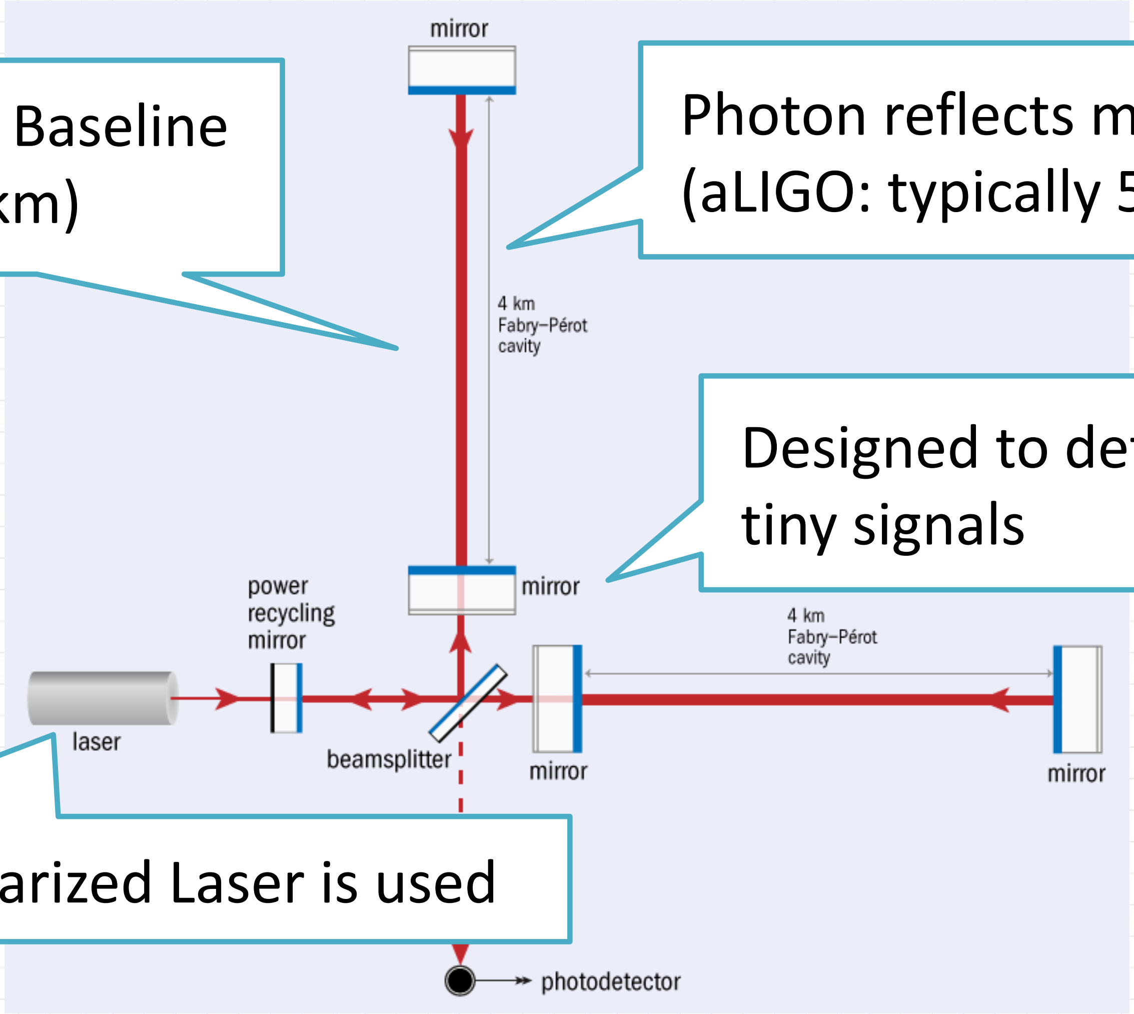
GW interferometer is

Very Long Baseline
(aLIGO: 4km)

Photon reflects many times
(aLIGO: typically 500 times)

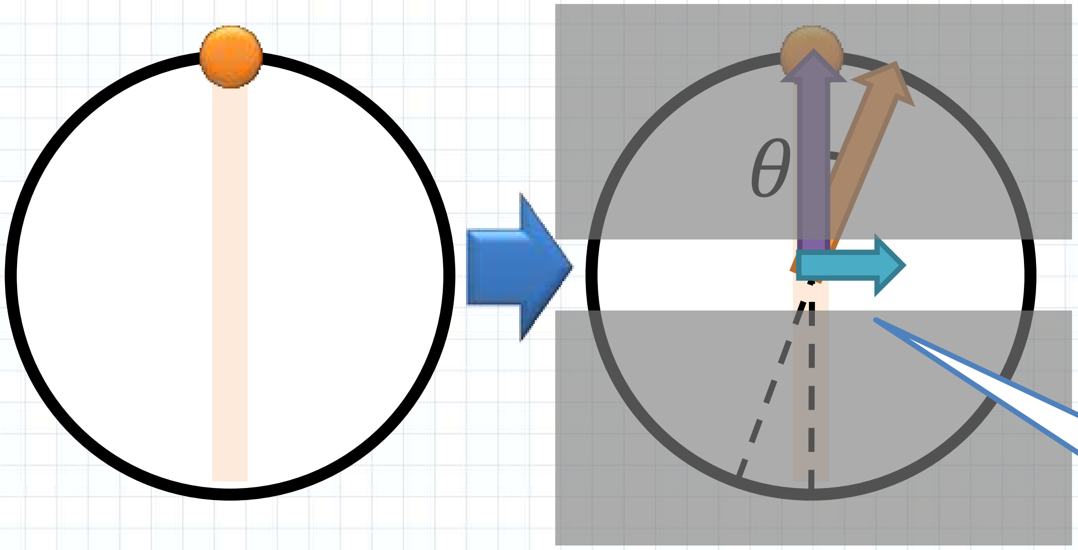
Designed to detect
tiny signals

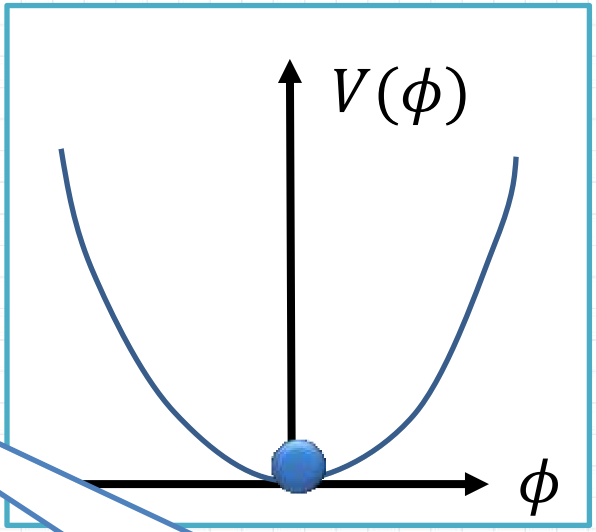
Linear Polarized Laser is used



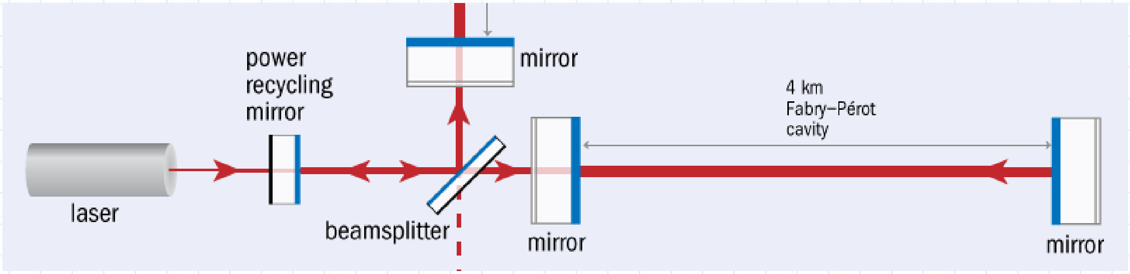
New Observation

- Measure the other polarization component (horizontal) by filtering the original pol. component (vertical)





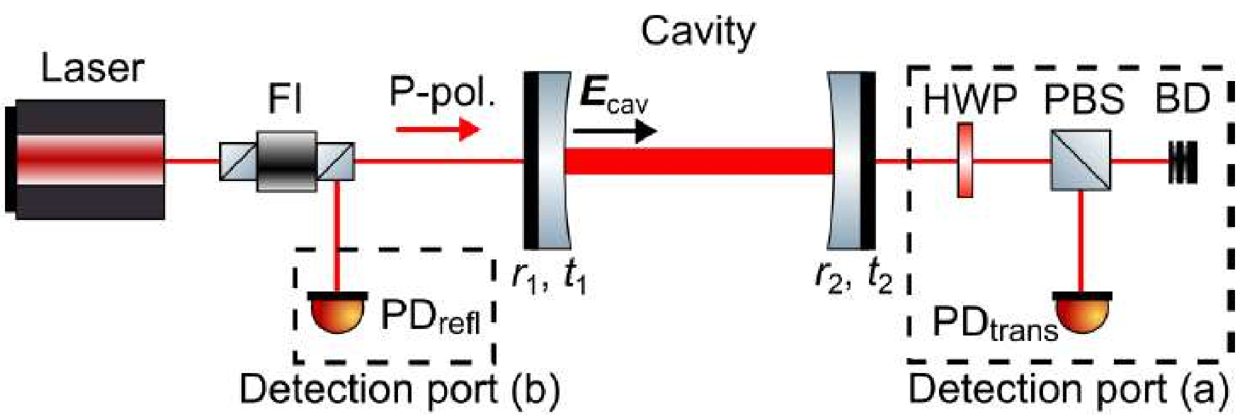
Only if $\theta \neq 0$ by ADM, we detect signal



 [Nagano, TF, Michimura, Obata, PRL(2019)]

Coexist with GW observation

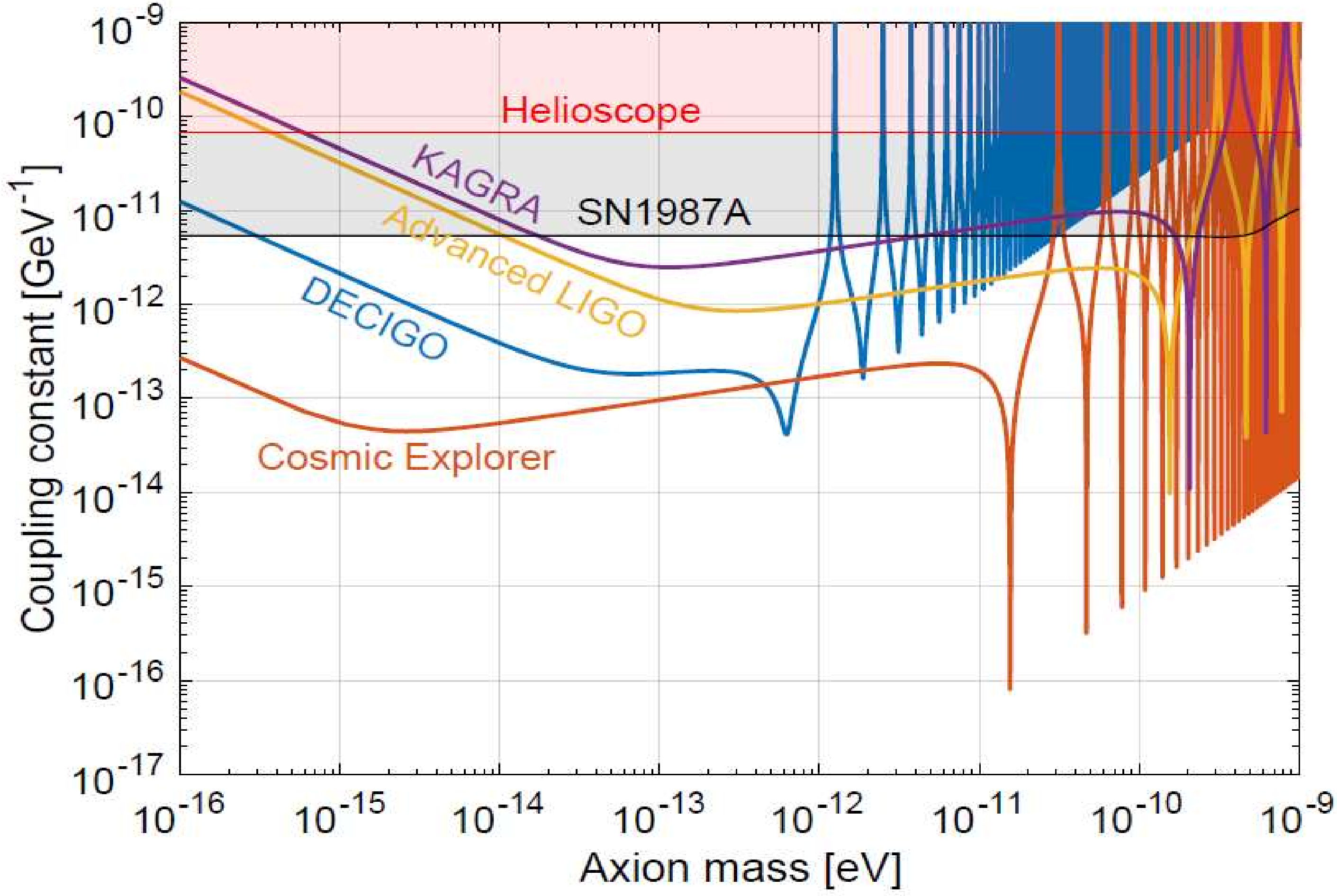
- Tiny signal compensated by long operation time



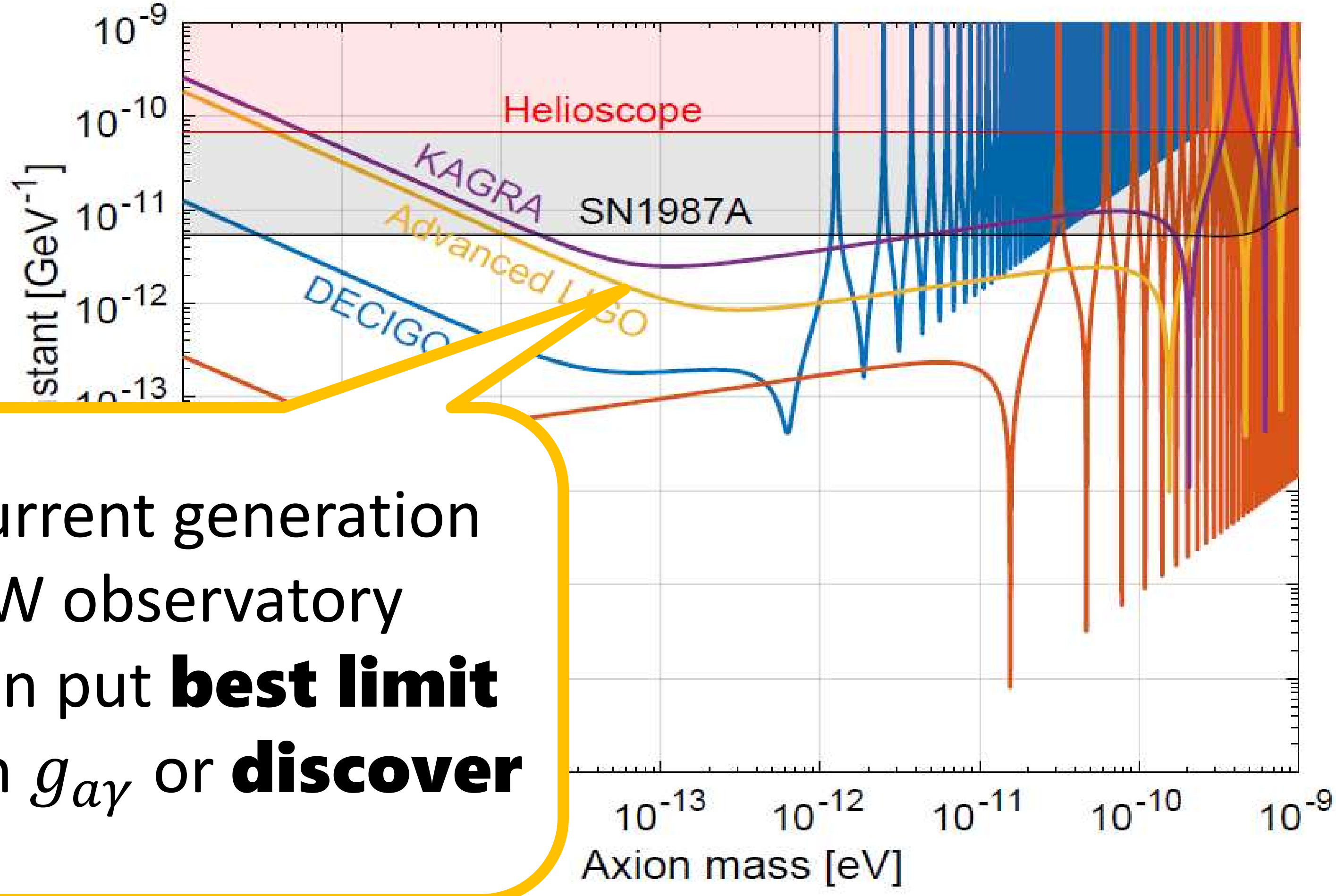
Additional instruments at the tail enable interferometers to probe ADM during the GW observation run **without loosing any sensitivity to GWs** ⟹ **Long Run!**

New Experiment

Sensitivity Curve for 1 year run



Sensitivity Curve for 1 year run



Current generation GW observatory can put **best limit** on $g_{a\gamma}$ or **discover**

New experiment

State of Washington
(4km)

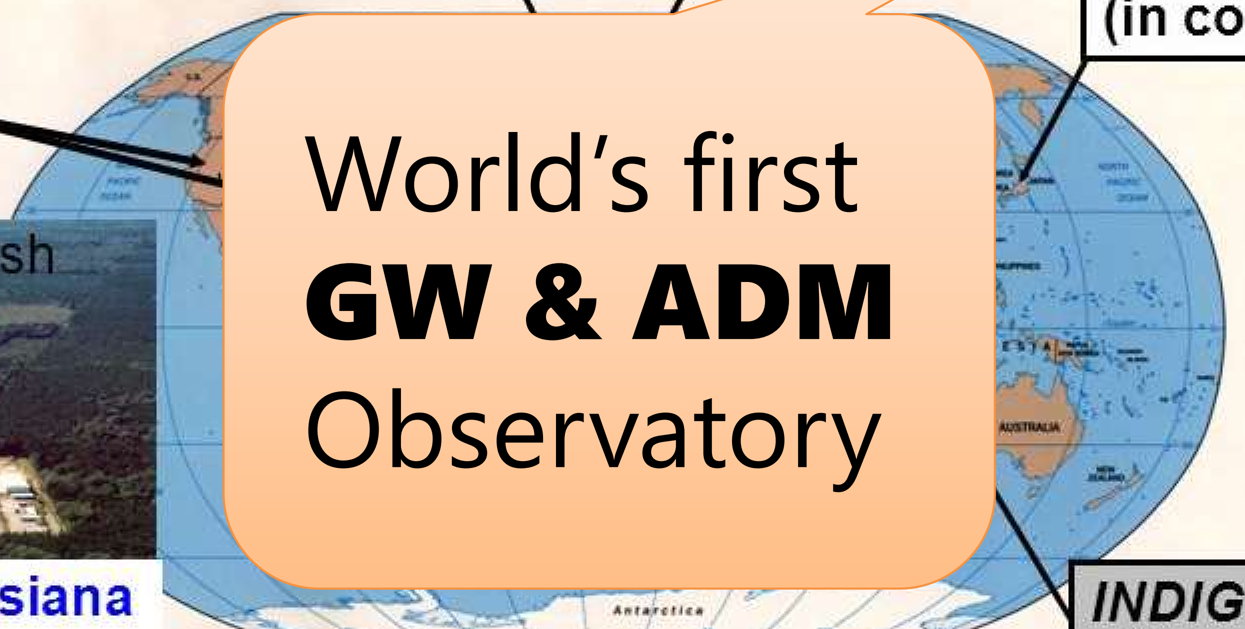
Virgo (3km)

GEO600
(600m)

KAGRA
(in construction)

LIGO

State of Louisiana
(4km)



World's first
GW & ADM
Observatory

INDIGO
(in preparation)

Competition => Cooperation

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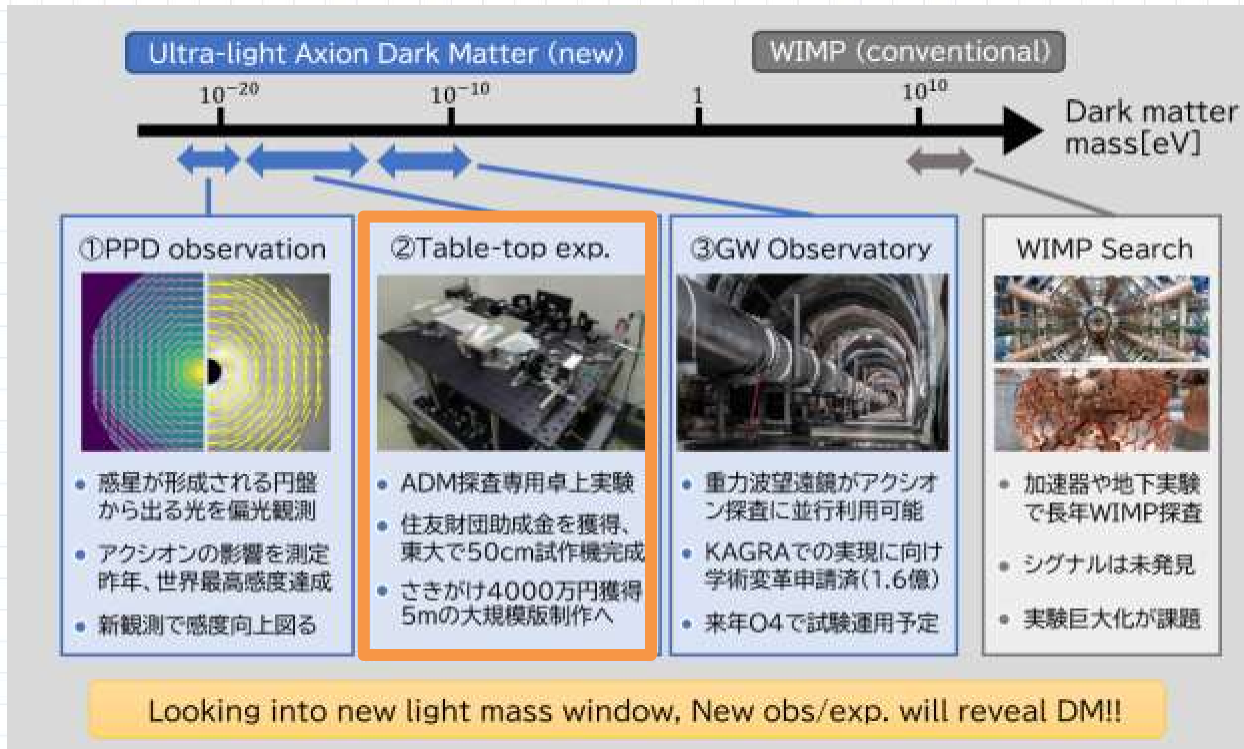
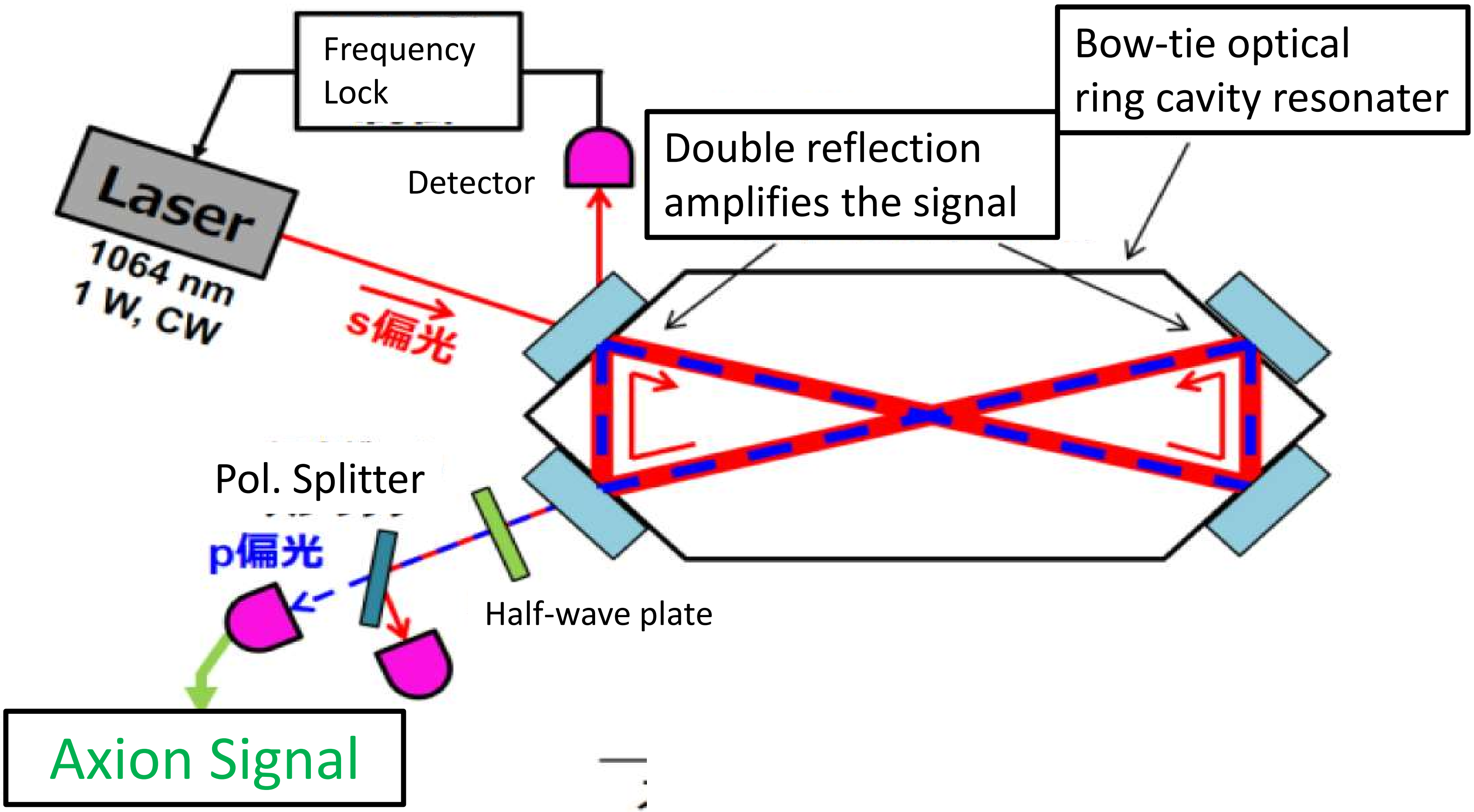


New experiment : DANCE

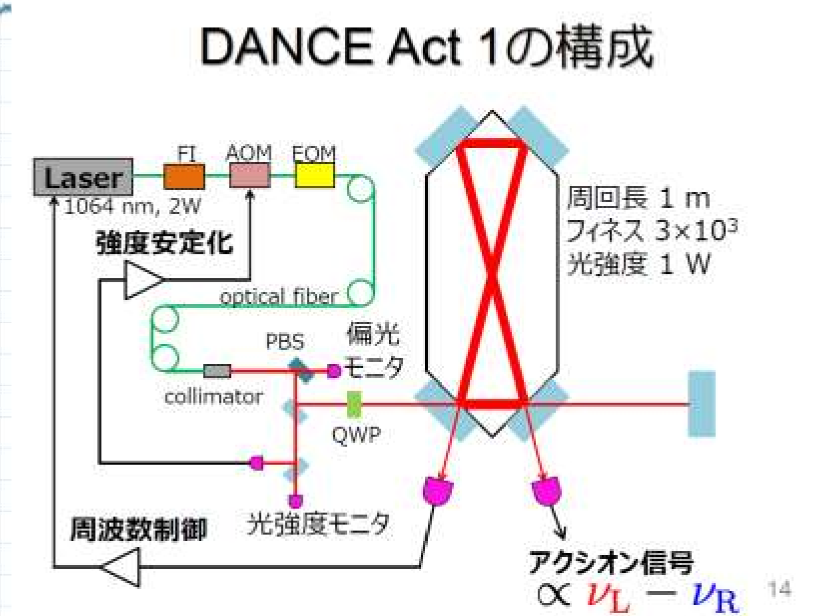
Dark matter Axion search with riNg Cavity Experiment

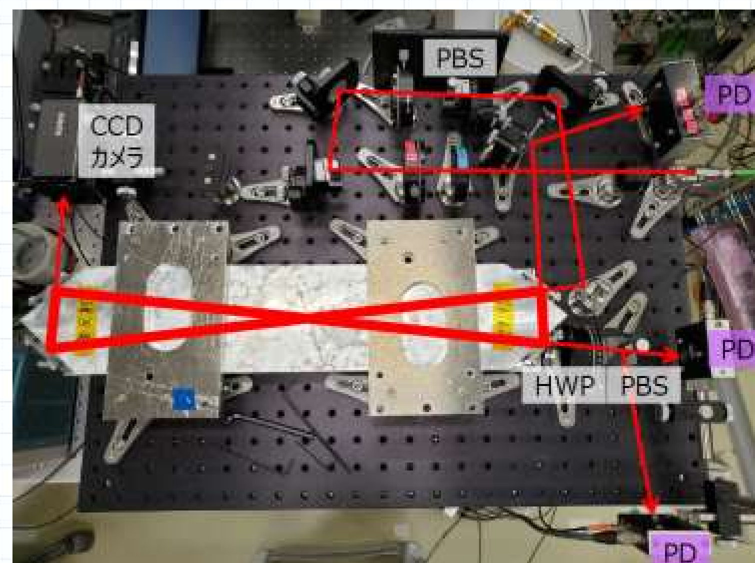
[Obata, TF, Michimura(2018)]
[Liu+(2018), ADBC experiment]



DANCE Act.1 has started!

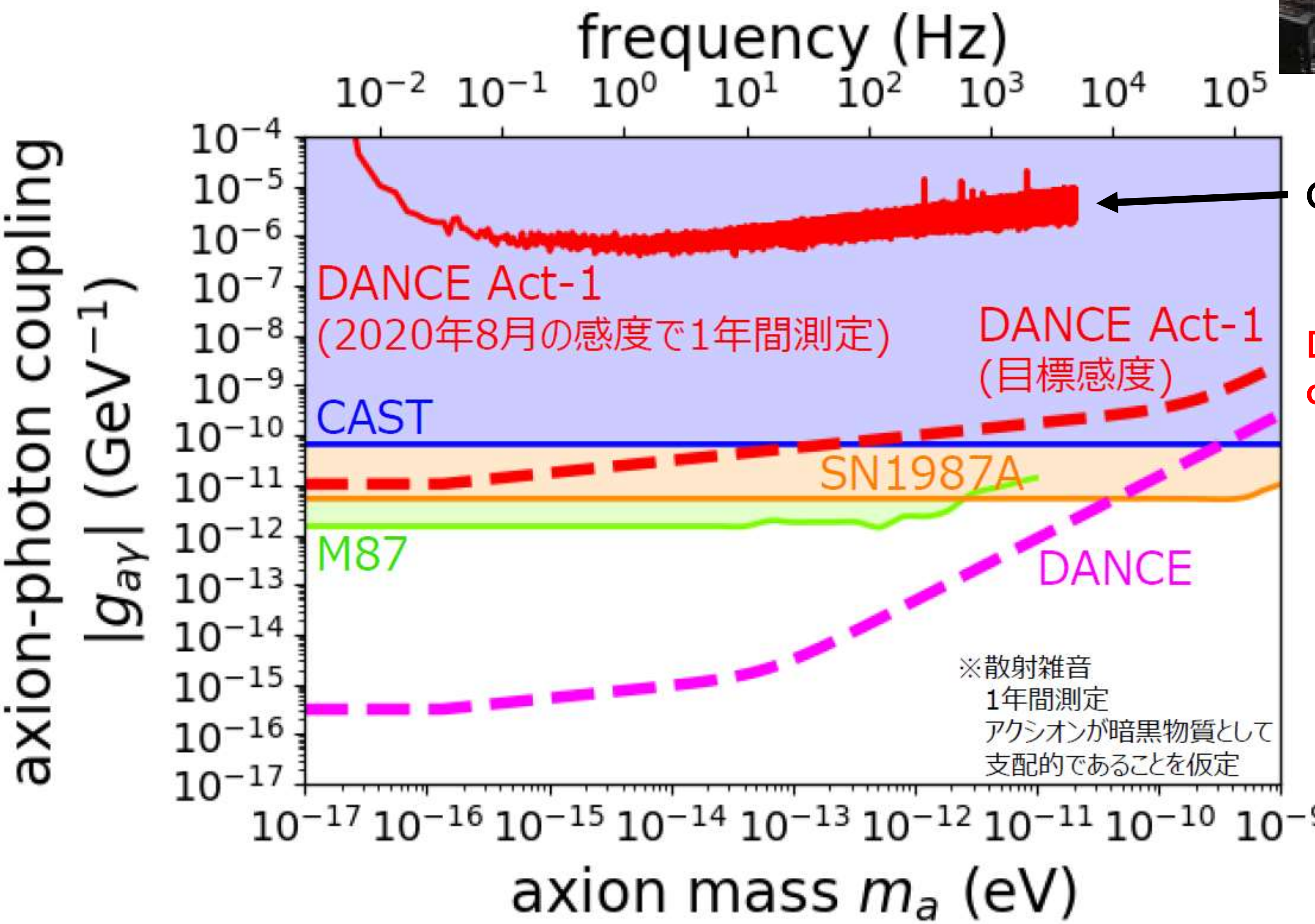
- We got a grant (35kUSD/yr) last year and started with a 50cm-size prototype.
- We finished constructing prototype experiment (Act.1) in U. Tokyo. (Ando lab.)
- The first test result was obtained 3 month ago





Current Status of DANCE Act-1

- **The first test result**

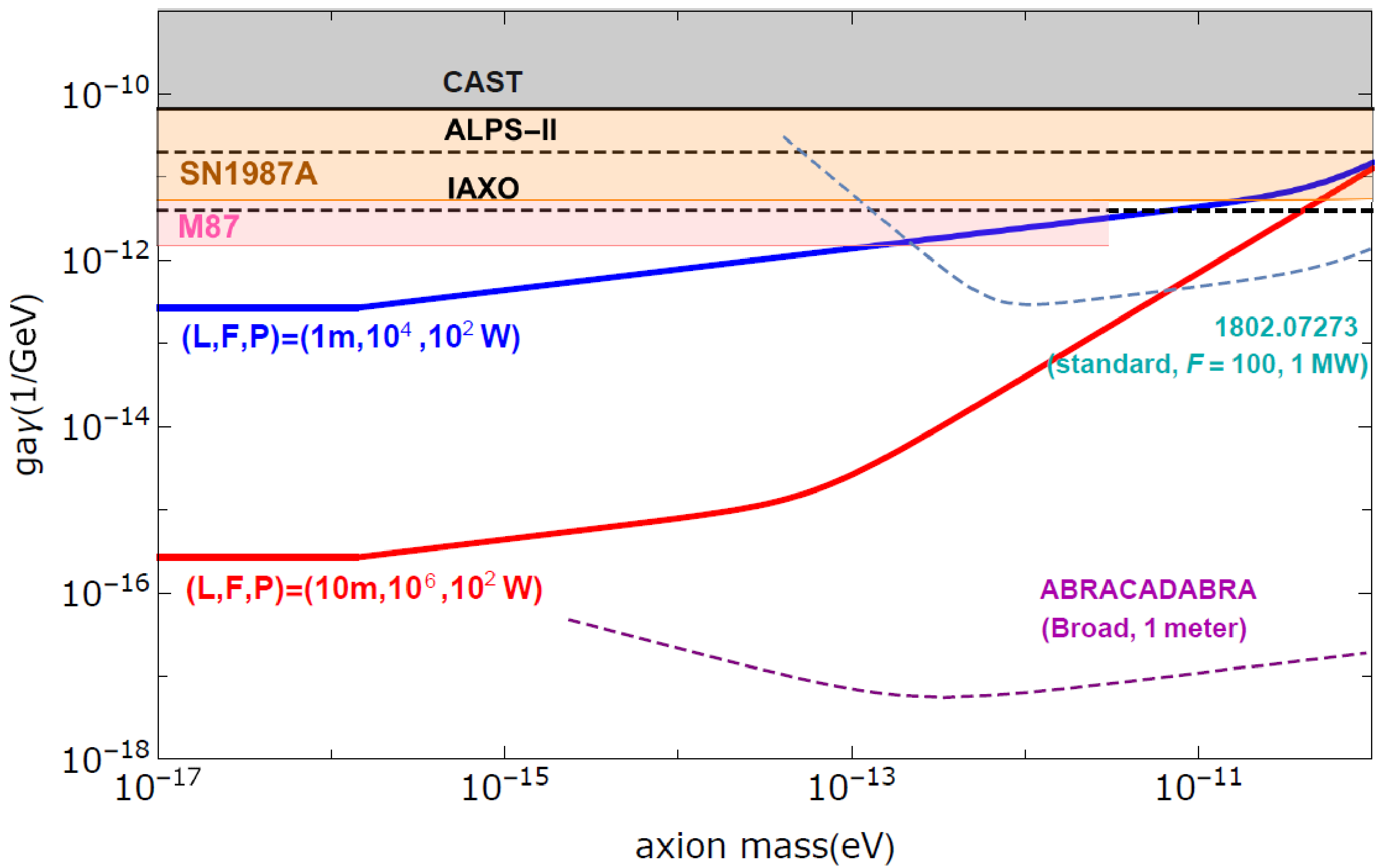


Current sensitivity

Design sensitivity of the prototype

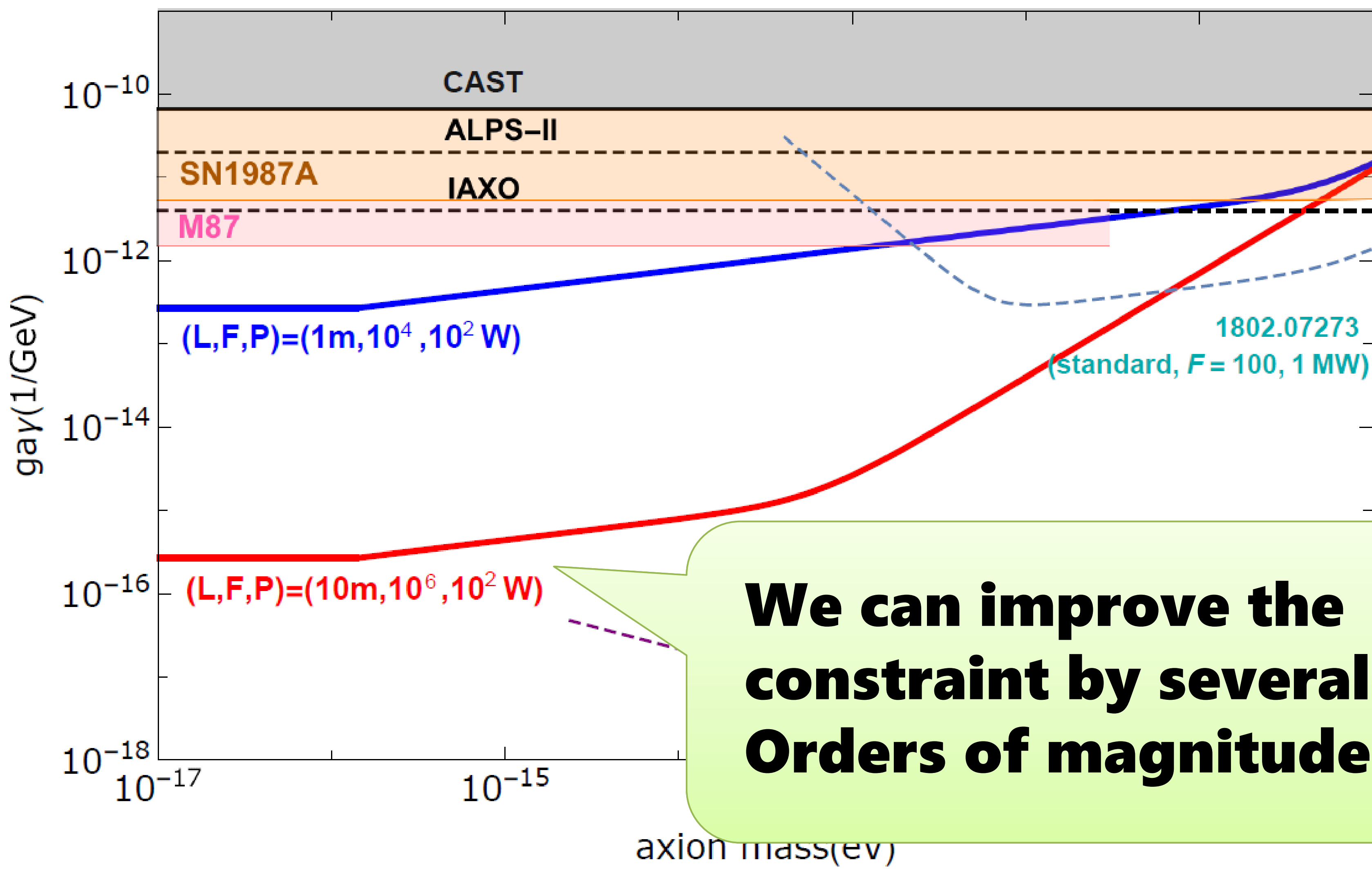
New experiment : DANCE

[Obata, TF, Michimura(2018)]



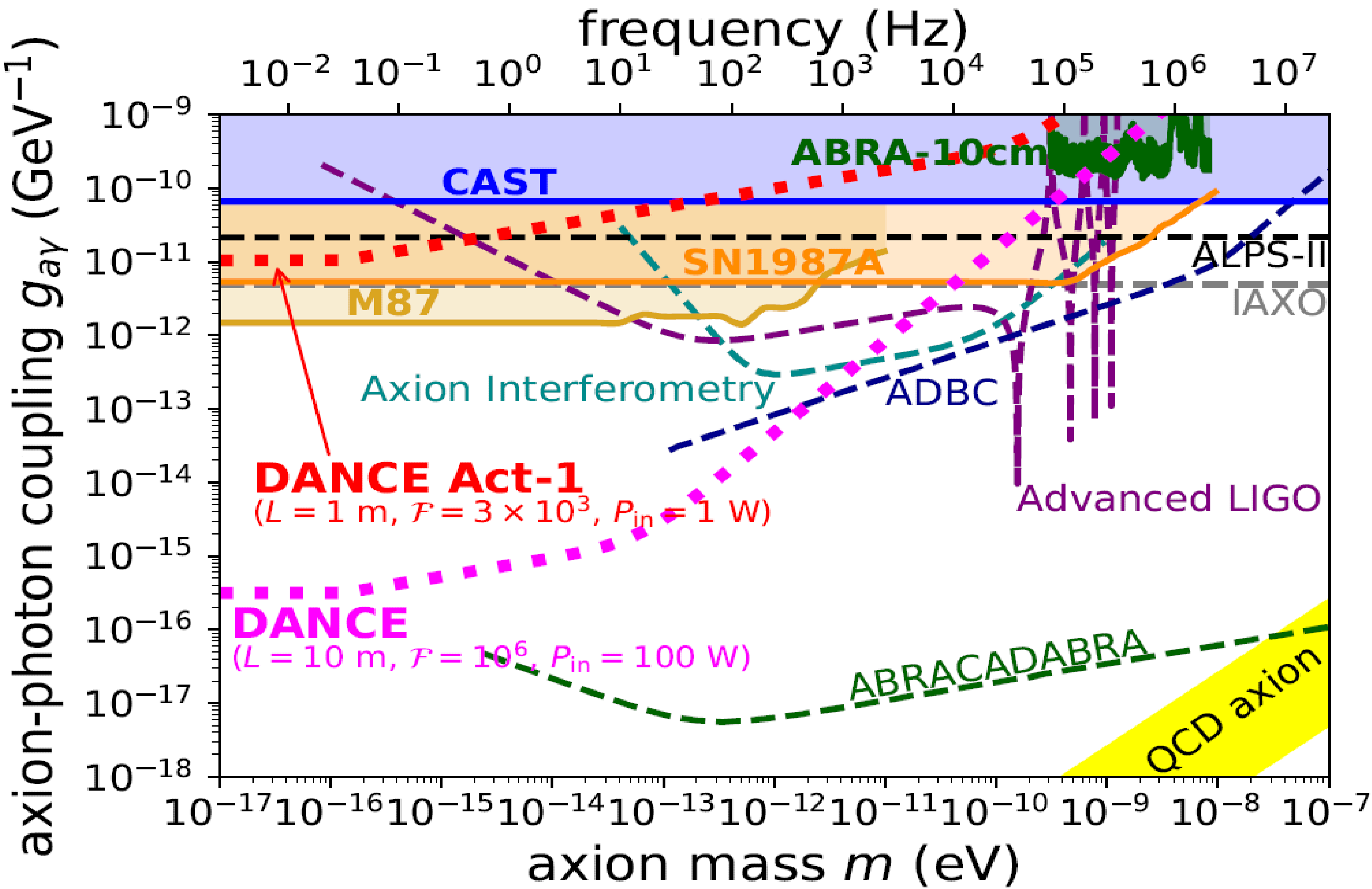
New experiment : DANCE

[Obata, TF, Michimura(2018)]



We can improve the constraint by several Orders of magnitude!

Recent Proposals for ADM Search



Plan of Talk

1. Introduction
2. Optical Ring Cavity
3. Protoplanetary Disk
4. GW Interferometer
5. Summary

Summary

- ICRR theory group covers many topics in HEP/Cosmo
- A typical theory work consists of
  (i) model (ii) compute (iii) explain (iv) predict
- Baryogenesis: how to produce matter> anti-matter
  Leptogenesis – RH neutrino, see-saw, collider
  じbaryogenesis – helical MF, Inter-galactic MF, CTA
- Dark matter: what is it!?
  sterile ν – thermal production and more, X-ray observation
  Axion – birefringence, proposed exp.: KAGRA&table-top