# C01 Ultimate Theory

**Non-supersymmetric AdS and the Swampland**

Hirosi Ooguri[a,b] and Cumrun Vafa[c]

**Spacetime Equals Entanglement**

Yasunori Nomura,[1,2,3] Nico Salzetta,[1,2] Fabio Sanches,[1,2] and Sean J. Weinberg[1,2]

**Quantum radiation produced by the entanglement of quantum fields**

Satoshi Iso,[1] Naritaka Oshita,[2,3] Rumi Tatsukawa,[4] Kazuhiro Yamamoto,[4] and Sen Zhang[5]

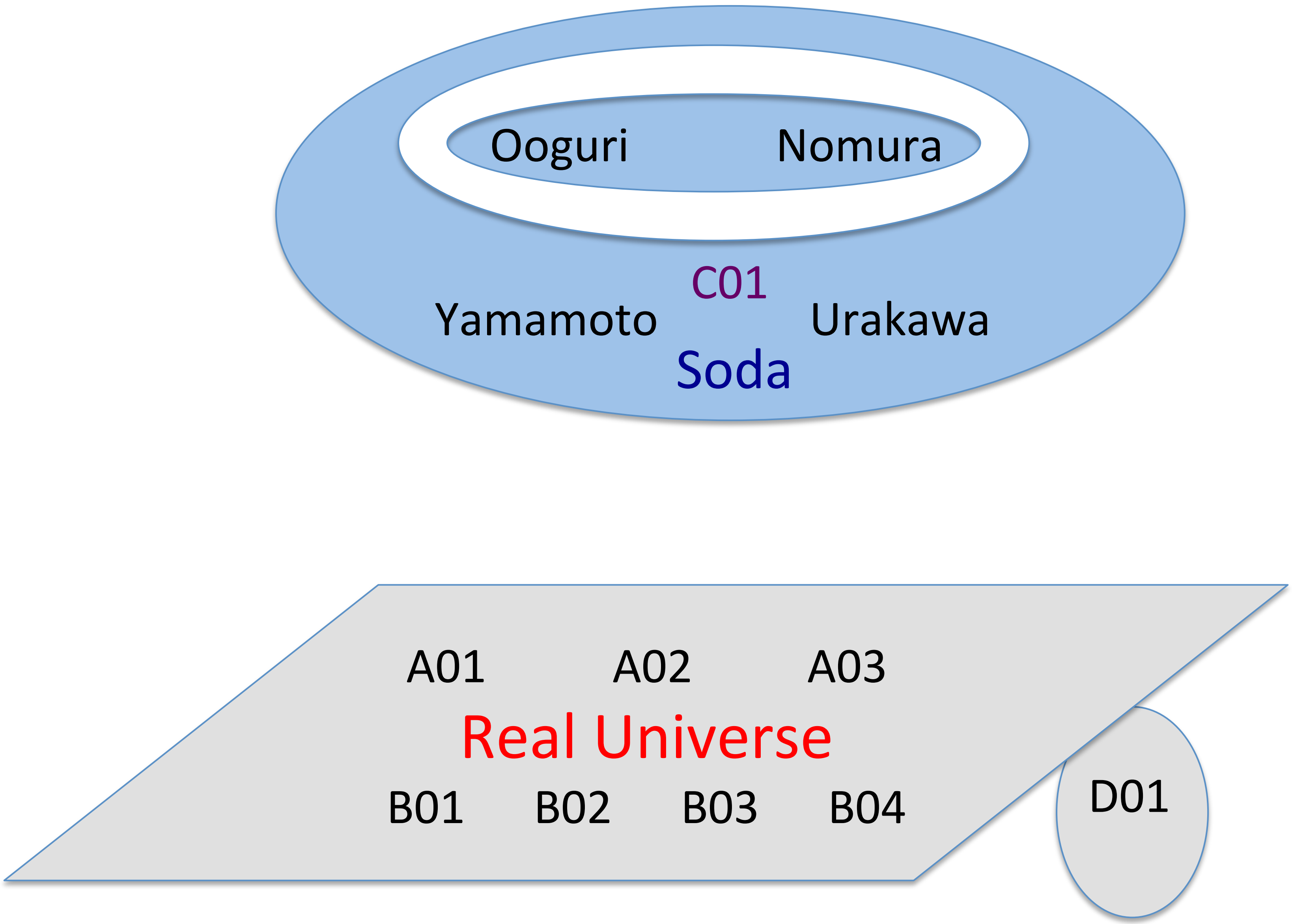
**Quantum discord in de Sitter space**

Sugumi Kanno[∗♭], Jonathan P. Shock[♮†] and Jiro Soda[‡]

**Consistency relations and conservation of $\zeta$ in holographic inflation**

Jaume Garriga[a,b], Yuko Urakawa[c]

# Where are we?



Ooguri
Nomura
C01
Yamamoto
Urakawa
Soda
A01
A02
A03
Real Universe
B01
B02
B03
B04
D01

# Key words of my talk

Detecting ultralight axion dark matter wind

String theory = C01 A02, B03

with pulsar timing arrays and laser interferometers

D01

signal enhancement in modified gravity

A02, B01

explaining dark energy

A03

新学術領域「加速宇宙」シンポジウム、KEK、2017.3.9

# *Ultralight axion dark matter in accelerating universe*

*Jiro Soda*

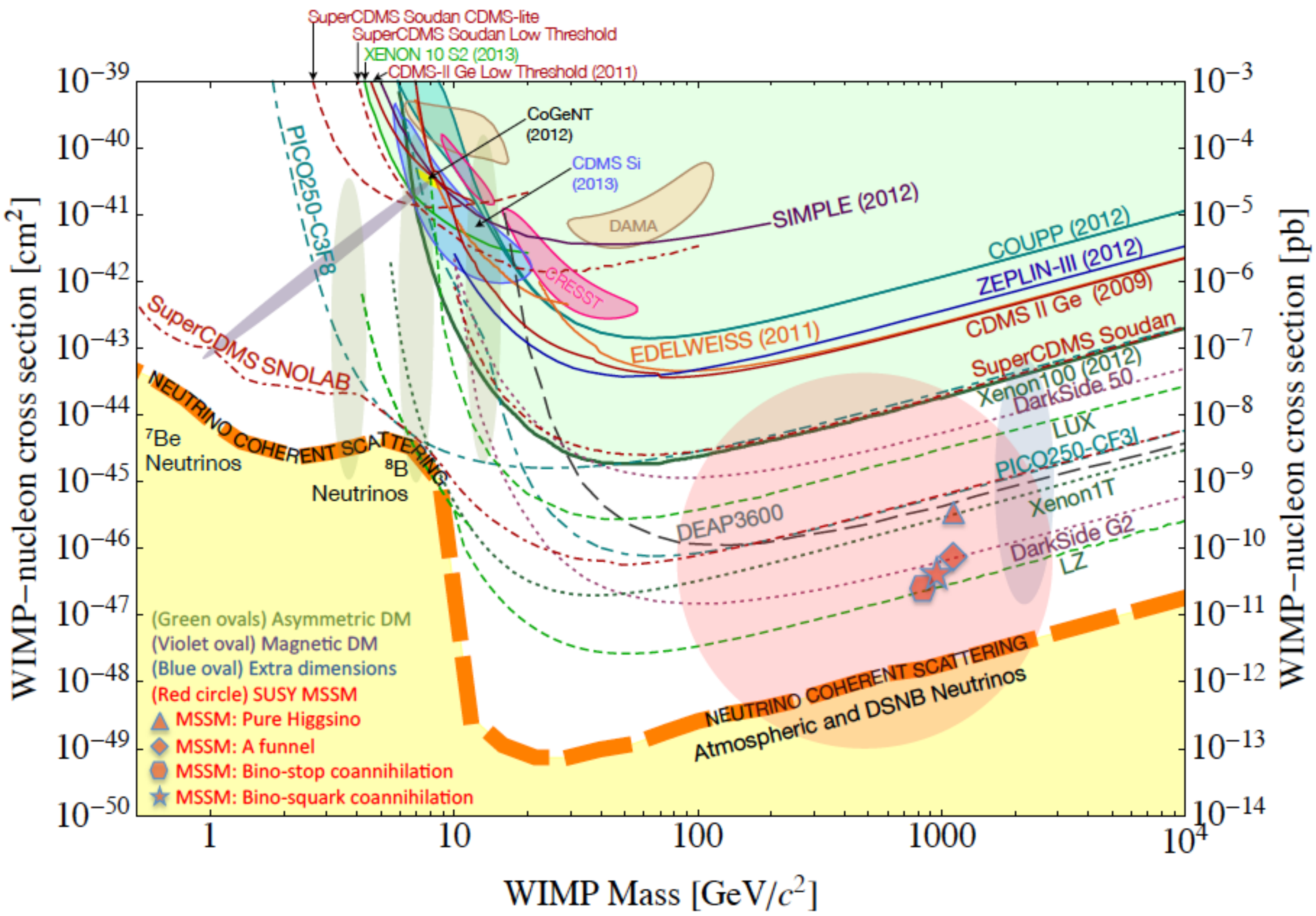
*Kobe University*

A. Aoki, J.S., Phys.Rev.D93 (2016) 083503

A. Aoki, J.S., arXiv:1608.05933

A. Aoki, J.S., in preparation

# WIMP?



SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
$^7$Be Neutrinos
$^8$B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm$^2$]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/$c^2$]
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$10^{-40}$
$10^{-41}$
$10^{-42}$
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1000
$10^4$

# *Axion dark matter?*

No evidence of supersymmetry has been found at the LHC.
Hence, there is no reason to stick to neutralinos.

Moreover, the standard ΛCDM Model has several problems, such as the cusp problem.

An ultralight scalar field (axion) dark matter erases the cusp on small scales because of the effective quantum pressure. In fact, de Broglie wavelength of dark matter is given by

$$\lambda_{dB} = \frac{2\pi}{k} = \frac{2\pi}{mv} \approx 3.8\mathrm{kpc}\left(\frac{10^{-3}}{v}\right)\left(\frac{10^{-23}\mathrm{eV}}{m}\right)$$

It is worth investigating the ultralight axion dark matter seriously.

M.R.Baldeschi et al. 1983
M.Membrado et al. 1989
S.J.Sin 1994
J.W.Lee, I.G.Koh 1996
W.Hu et al. 2000
For complete references see J.W.Lee 2016

# *Axion in string theory*

QCD axion

Reslove the Strong CP problem

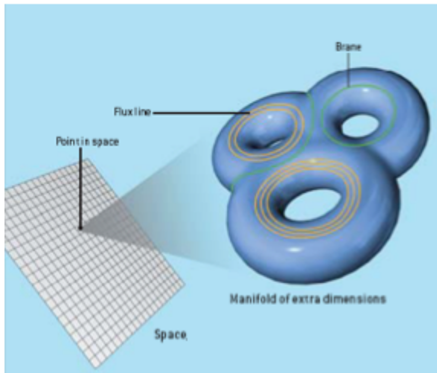
$$m_a \approx 6\times 10^{-6}\,\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$$

$f_a$ : decay constant

string axions

Model independent axion $\qquad H = dB = *d\theta$

Model dependent axion $\qquad a_i = \int_{C_{p_i}} F_p$




$$m_a \approx \frac{\mu^2}{f_a} e^{-\#\,\mathrm{moduli}/2}$$

Mass distribution is logarithmically flat

# Contents

# *Axion oscillation*

# Ultralight Axion

The model
$$S=\frac{1}{2}\int d^4x\sqrt{-g}\,R-\int d^4x\sqrt{-g}\left[\frac{1}{2}\nabla^\mu\phi\nabla_\mu\phi+\frac{1}{2}m^2\phi^2\right]$$

Occupation number
$$\frac{N}{\Delta x^3\Delta p^3}\approx\frac{n}{k^3}=\frac{\rho_{DM}}{m\,k^3}\approx 10^{90}\left(\frac{\rho_{DM}}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{10^{-23}\mathrm{eV}}{m}\right)^4$$

Since the occupation number is so high, classical field description is quite good.

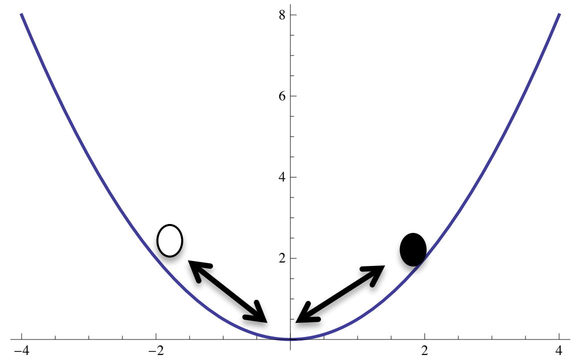
Since the typical velocity of the dark matter $\quad v\approx 10^{-3}$

We have a monochromatic frequency
$$E\approx m+\frac{1}{2}mv^2\approx m$$

# Axion oscillation

The axion is an coherently oscillating scalar field

$$\phi = A(\mathbf{x})\cos\left(mt + \alpha(\mathbf{x})\right)$$




The energy density becomes

$$\rho_{DM} = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2 \approx \frac{1}{2}m^2A^2$$

Indeed, oscillating part of the energy density $\left(\nabla\phi\right)^2 \approx k^2\phi^2$ is small

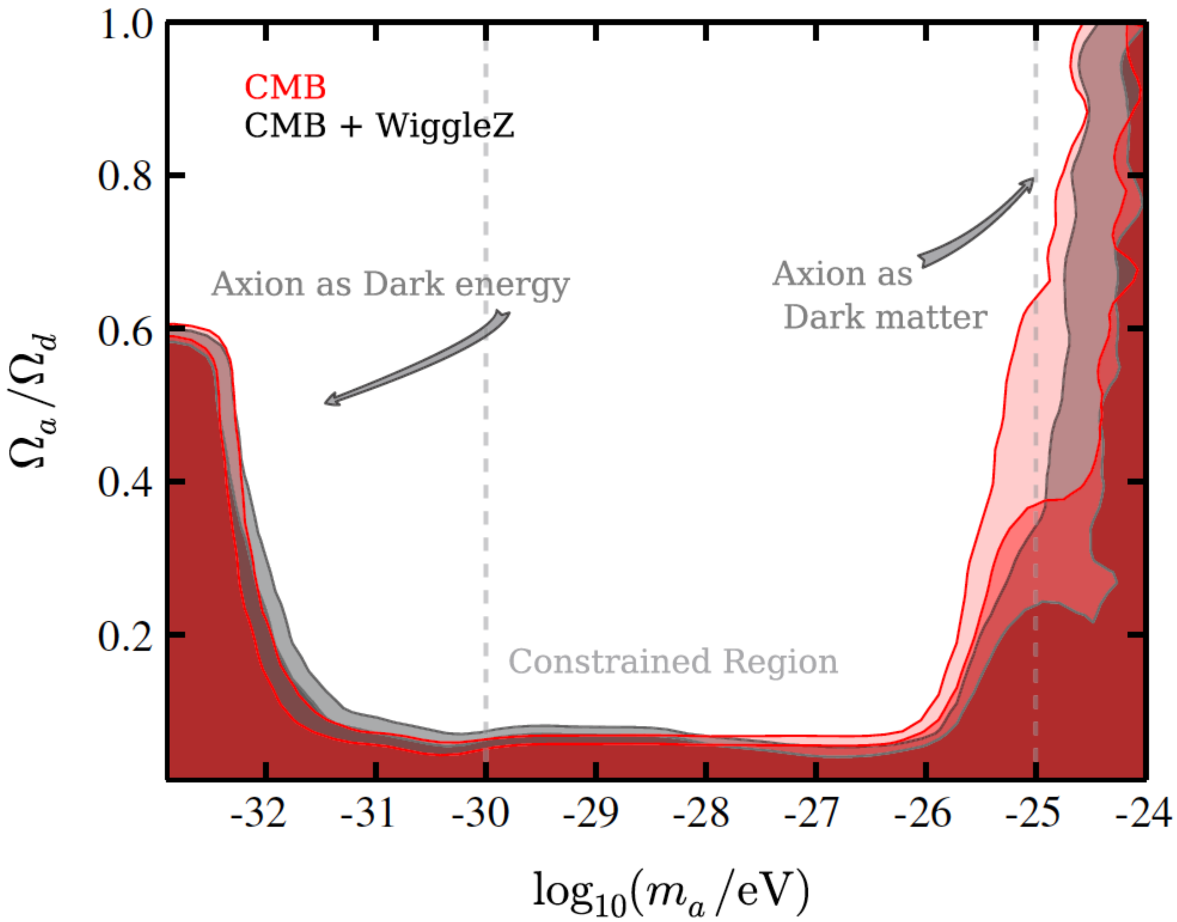
$$\rho_{DM}^{osc} \approx \frac{k^2}{m^2}\rho_{DM} \approx v^2\rho_{DM} \approx 10^{-6}\rho_{DM}$$

The pressure is given by

$$p_{DM} = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2 \approx -\frac{1}{2}m^2A^2\cos\left(2mt + 2\alpha(\mathbf{x})\right)$$

The average value of the pressure over the oscillation period is zero.
Hence, the axion can be regarded as the dust matter on cosmological scales.

# Cosmological Axion



# Time dependent gravitational potential

On the galactic scales, the background spacetime can be regarded as the Minkowski spacetime.

The perturbed metric in the conformal Newtonian gauge takes the form

$$ds^2 = -\left(1+2\Psi\right)dt^2 + \left(1-2\Phi\right)\delta_{ij}dx^i dx^j$$

The spatial component of Einstein equation reads

$$R = -6\ddot{\Phi} + 2\nabla^2\left(2\Phi - \Psi\right) = -T = \rho_{DM}\left[1+3\cos\left(2mt+2\alpha(\mathbf{x})\right)\right]$$

Since the time independent part obeys $\Phi_0 = \Psi_0 \approx -\dfrac{\rho_{DM}}{2k^2}$

We obtain $-6\delta\ddot{\Phi} = 3\rho_{DM}\cos\left(2mt+2\alpha(\mathbf{x})\right)$

$$\delta\Phi = \frac{\rho_{DM}}{8m^2}\cos\left(2mt+2\alpha(\mathbf{x})\right) \ll \Phi_0$$

# *Probing Axion DM with Pulsar Timing Arrays*

# Effect on the pulsar timing

Khmelnitsky & Rubakov 2014

The timing residual is given by the frequency shift $\Delta t = -\int_0^t \frac{\Omega(t') - \Omega_0}{\Omega_0} dt'$

Since the distance is typically larger than the Compton length $D \geq 100\mathrm{pc} \gg \mathrm{m}^{-1}$

we obtain the pulsar timing residual

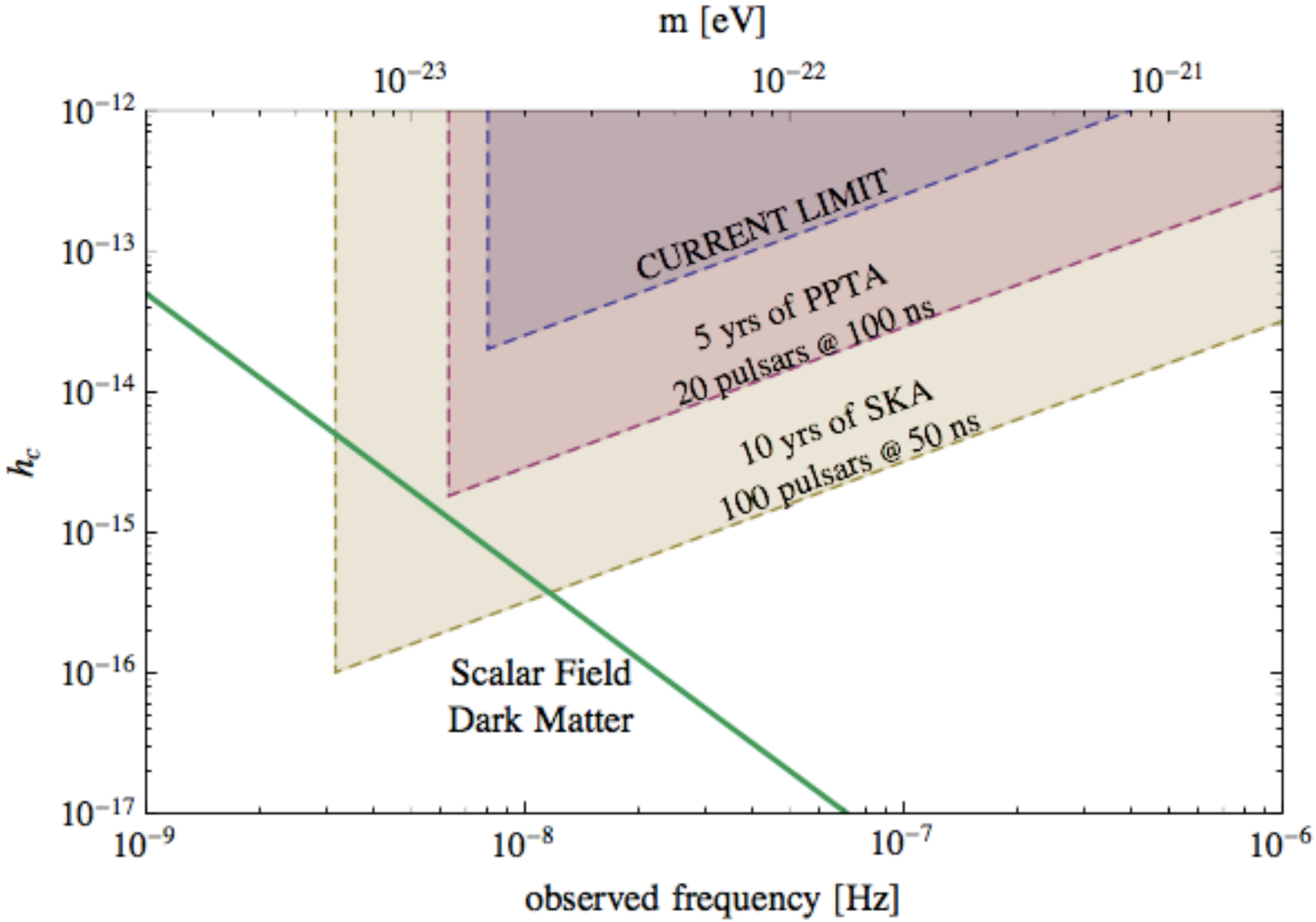
$$\Delta t = \frac{\rho_{DM}}{8m^3} \sin\left(mD + \alpha(\mathbf{x}) - \alpha(\mathbf{x}_p)\right) \cos\left(2mt + \alpha(\mathbf{x}) + \alpha(\mathbf{x}_p) - mD\right)$$

This can be compared with the timing residual due to GWs .
Correspondence is given by

$$h_c = 2\sqrt{3}\left|\delta\Phi\right| = 2\times 10^{-15}\left(\frac{\rho_{DM}}{0.3\mathrm{GeV}/\mathrm{cm}^3}\right)\left(\frac{10^{-23}\mathrm{eV}}{m}\right)^2 \qquad f = \frac{\omega}{2\pi} = 5\times 10^{-9}\mathrm{Hz}\left(\frac{m}{10^{-23}\mathrm{eV}}\right)$$

# Detectability of axion oscillation with the pulsar timing

Khmelnitsky & Rubakov 2014



# *Probing Axion DM with interferometers*

# Detecting axion wind

Axion oscillation

$$T_{\mu\nu} = \begin{pmatrix} \rho & 0 \\ 0 & -\rho\cos\omega t\,\delta_{ij} \end{pmatrix}$$

Actually, interferometer is moving with the velocity v.
Laser interferometer feels the wind of axion!

Boosted energy momentum tensor

$$t' = \gamma\left(t + \vec{v}\cdot\vec{x}\right)$$

$$\vec{x}' = \vec{x} + \frac{\gamma-1}{v^2}\left(\vec{v}\cdot\vec{x}\right)\vec{v} + \gamma\vec{v}\,t$$

$$T_{00} = \rho\gamma^2\left[1 - v^2\cos\omega t'\right]$$

$$T_{0i} = \rho\gamma^2 v_i\left[1 - \cos\omega t'\right]$$

$$T_{ij} = -\rho\cos\omega t'\delta_{ij} + \rho\gamma^2 v_i v_j\left[1 - \cos\omega t'\right]$$

This boosted oscillation produces oscillating potentials.

$$\delta g_{\mu\nu} = \begin{pmatrix} -1-2\Psi & 0 \\ 0 & (1-2\Phi)\delta_{ij} \end{pmatrix} + \delta\tilde{g}_{\mu\nu}$$

$$\delta\Phi\left(t,\vec{x}\right) = \frac{\rho}{8m^2}\cos\omega\gamma\left(t + \vec{v}\cdot\vec{x}\right)$$

$$\delta\Psi\left(t,\vec{x}\right) = -\frac{\rho}{8m^2}\cos\omega\gamma\left(t + \vec{v}\cdot\vec{x}\right)$$

# Laser interferometer Signal

Aoki & Soda 2016

In the synchronous gauge, we have

$$\delta g_{\mu\nu} = \begin{pmatrix} -1 & 0 \\ 0 & (1-2\delta\Phi)\delta_{ij} + 2\delta B_{,ij} \end{pmatrix} \qquad \delta B_{,ij} = \frac{\rho}{8m^2} v_i v_j \cos\omega\gamma\left(t + \vec{v}\cdot\vec{x}\right)$$

The signal detected by the interferometer should be

$$s = D_{ij} h_{ij} \qquad D_{ij} = \frac{1}{2}\left(m_i m_j - n_i n_j\right)$$

Namely, we obtain

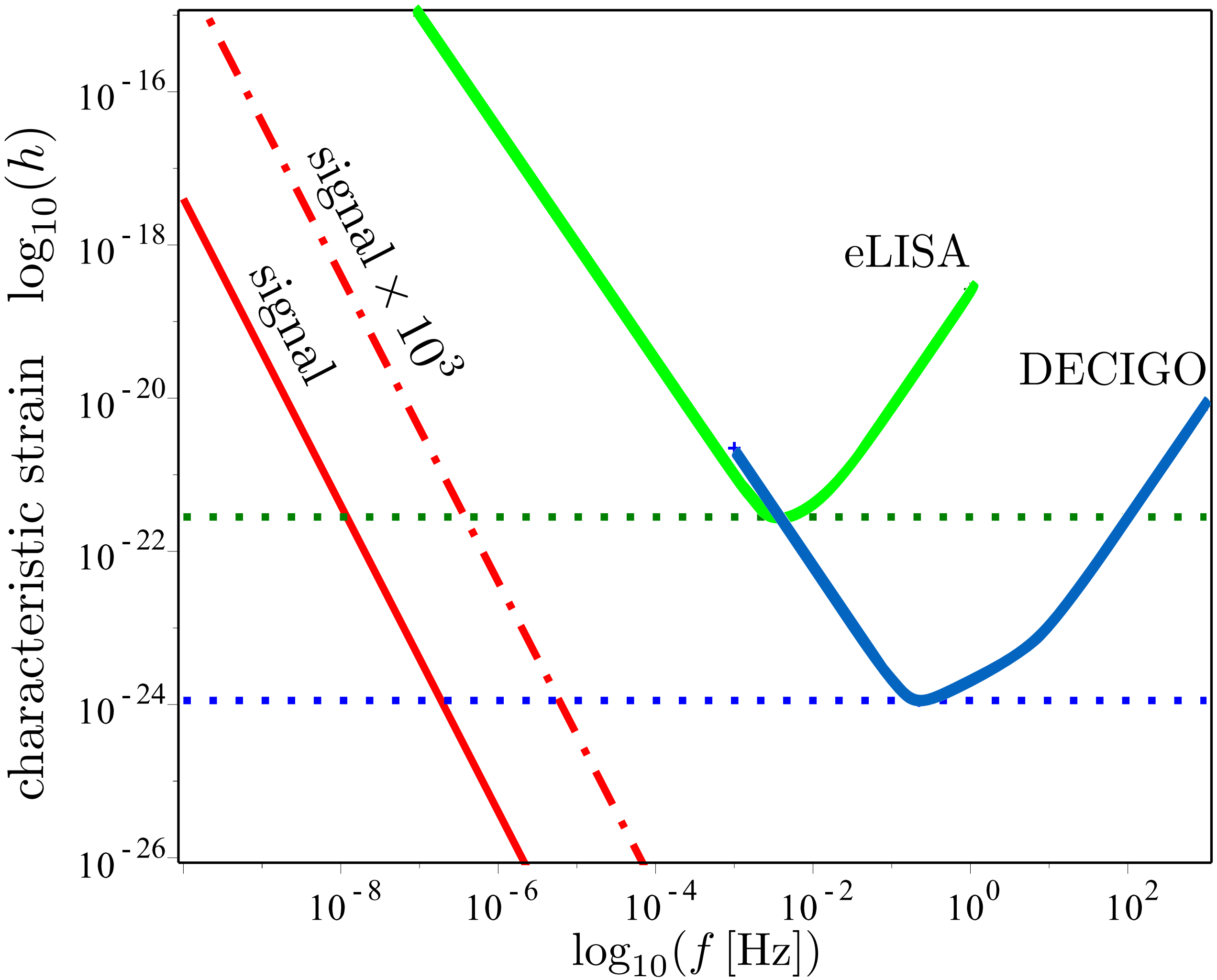
$$s(t) = \left[\left(\vec{v}\cdot\vec{m}\right)^2 - \left(\vec{v}\cdot\vec{n}\right)^2\right]\frac{\rho v^2}{8m^2}\cos\omega\gamma t$$

The amplitude can be estimated as

$$\frac{\rho v^2}{8m^2} = 1.6\times 10^{-21}\left(\frac{v}{10^{-3}}\right)^2\left(\frac{10^{-23}\mathrm{eV}}{m}\right)^2$$

This is quite small signal.
However, if the resonance occurs, we have a chance to detect the oscillation.

# *Detectability of axion oscillation with laser interferometer*



# Axion Oscillation in Accelerating Universe

# Dark energy and f(R) theory

f(R) dark energy model $S=\frac{1}{2}\int d^4x\sqrt{-g}\left[R+f(R)\right]+S_m$

We assume the deviation from Einstein is small $f(R)\ll R$ $f_R \equiv f'(R)\ll 1$

The equations of motion becomes

$$G_{\mu\nu}-\frac{1}{2}g_{\mu\nu}f+\left(R_{\mu\nu}+g_{\mu\nu}\nabla^{\alpha}\nabla_{\alpha}-\nabla_{\mu}\nabla_{\nu}\right)f_R=T_{\mu\nu}$$

Since the spatial derivative is small compared to the time derivative $\nabla^{\alpha}\nabla_{\alpha}f_R \approx -\ddot{f}_R$

$$3\ddot{f}_R+R=-T \quad \Rightarrow \quad 3f''(R)\ddot{R}+3f'''(R)\dot{R}^2+R=-T$$

Note that we can read off the mass scale $M^2=\frac{1}{3f''\left(R_0\right)}$

# *Axion oscillation in f(R) theory*

Aoki & Soda 2016

A simple solvable model is

$$f(R)=\frac{R^2}{6M^2}$$

The field equation reads

$$\frac{1}{M^2}\ddot{R}+R=\rho_{DM}\left[1+3\cos 2mt\right]$$

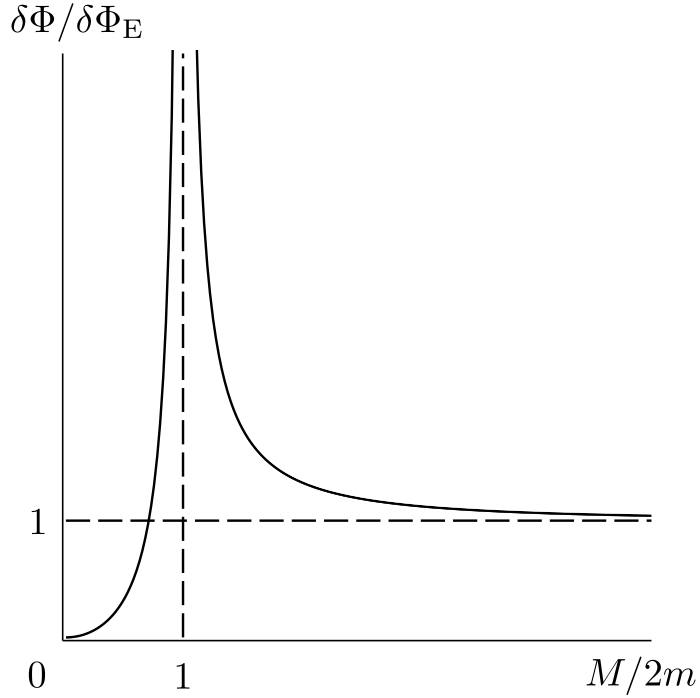
If we ignore homogeneous solutions, we get

$$R=\rho_{DM}+\frac{3\rho_{DM}}{1-\left(2m/M\right)^2}\cos 2mt$$

Since we know $R=-6\ddot{\Phi}+2\nabla^2\left(2\Phi-\Psi\right)$

Time dependent part can be solved as

$$\frac{\delta\Phi}{\delta\Phi_E}=\frac{1}{1-\left(2m/M\right)^2}$$



# *Hu - Sawicki model*

For $R \geq R_c$ a viable model so called Hu-Sawicki model is given by

$$f(R) = -\mu R_c \left[ 1 - \frac{R_c^{2n}}{R^{2n}} \right]$$

$$R_0 = \rho_{DM}$$

$$M^2 = \frac{1}{3f''(R_0)} = \frac{R_c}{6n(2n+1)\mu} \left( \frac{8\pi G \rho_{DM}}{R_c} \right)^{2n+2}$$

Assuming , $R_c \approx \frac{2\Lambda}{\mu}$ $n = 1$ we get an interesting number

$$M \approx 1.5\mu \times 10^{-23}\,\mathrm{eV}$$

Thus, we have a chance to observe
the oscillation of the gravitational potential in the pulsar timing residual data.

# *Summary*

- We have shown that coherent oscillation of axion dark matter can be detected with pulsar timing arrays or space laser interferometers.

- Remarkably, it is sensitive to the dark energy models.

  The signal could be enhanced significantly.

- We need construct micro-Herz laser interferometer.