Cosmological search of axion dark matter

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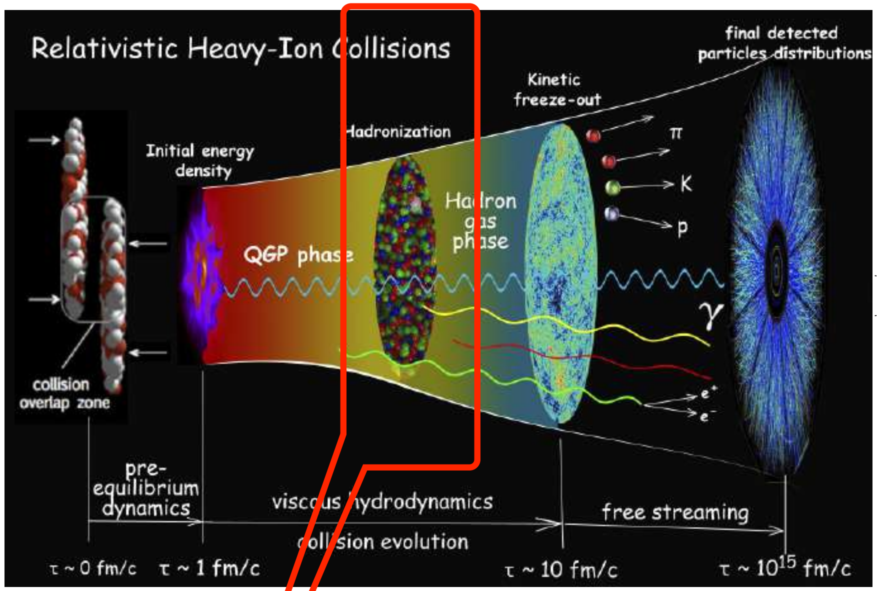
w/ Hayato Fukunaga, Kazuhiro Kogai (Nagoya U.), Naoya Kitajima (Tohoku U.)

Can we learn little bang from big bang?

Little bang

Heinz (13)

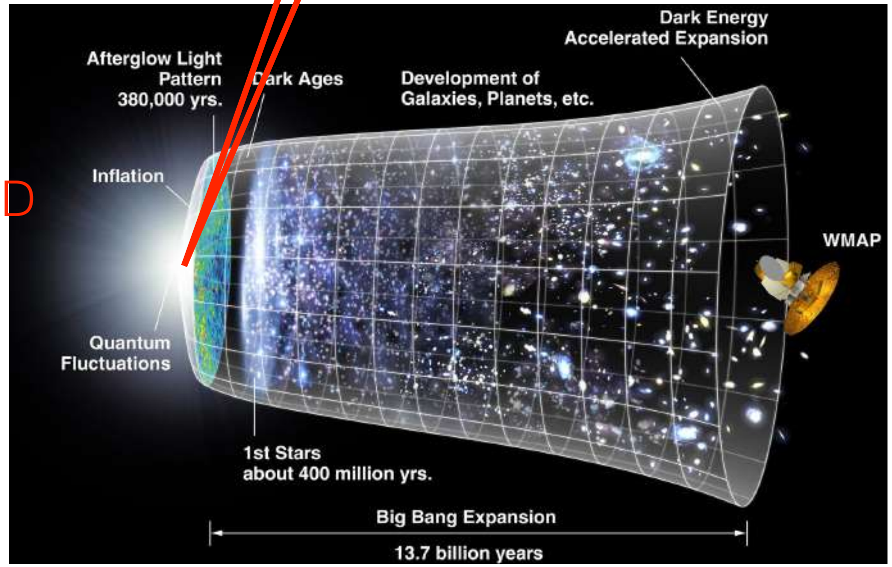


J-PARC

LHC/RHIC

T~ Λ_{QCD}

Big bang

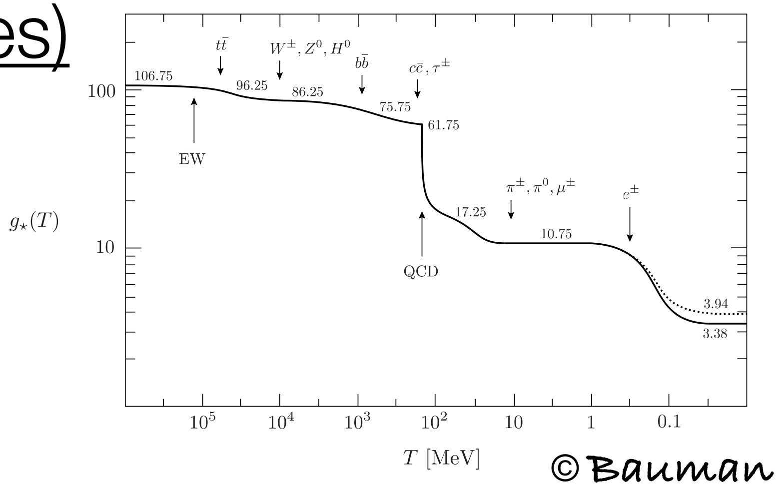


Learning QCD from cosmology

Through radiation (= relativistic species)

- Equation of state
- # of relativistic species

$$\rho_r = \sum_i \rho_i = \frac{\pi^2}{30} g_\star(T) T^4$$



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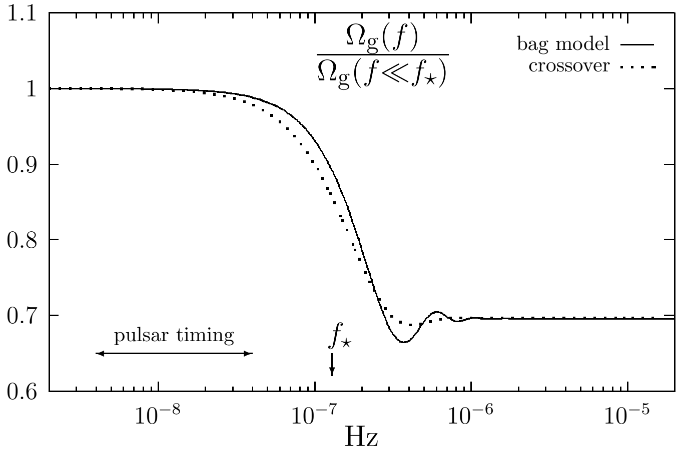
- Expansion history of Universe
- Drop of Ω_{gw} at f ~ 10^{-7}Hz
- PBH abundance w/$M_\odot$

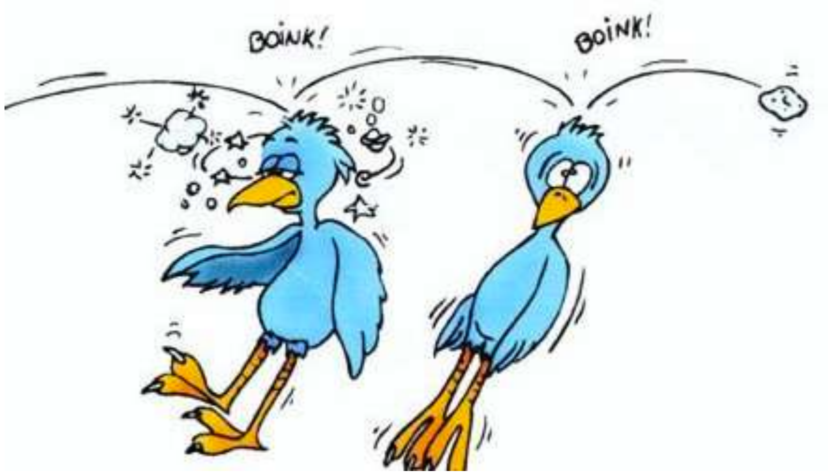


Schwarz (98)

Through dark matter ?

if 1st order PT : Production of GWs, Magnetic fields …

Axion dark matter



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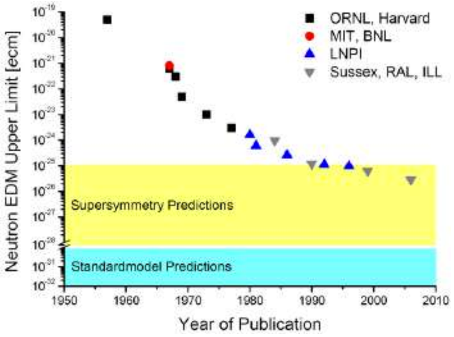

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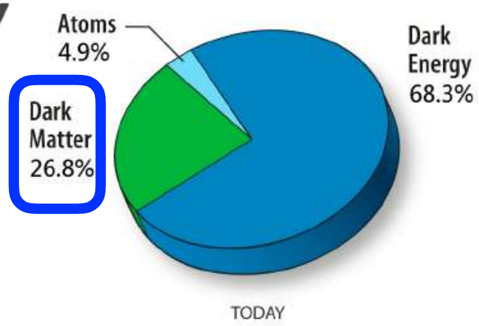

Axion as dark matter

- T ~ f   Symmetry breaking

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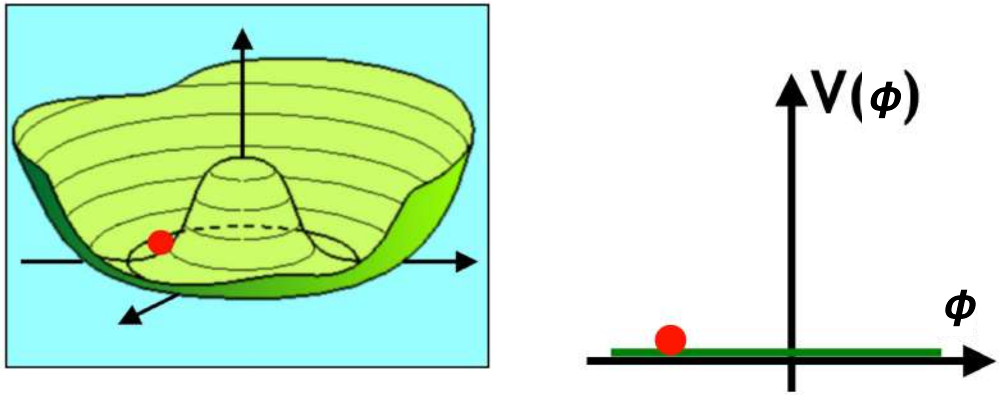


azimuthal symmetry
axion is massless

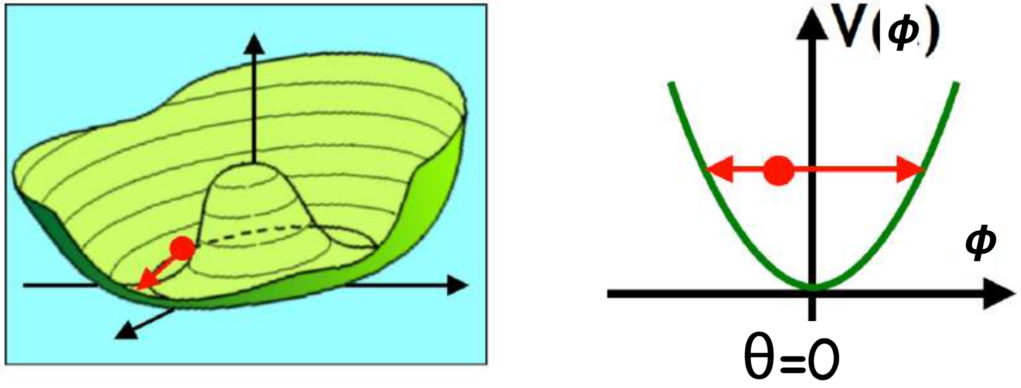
- T ~ 0.1 GeV

Axion acquires potential through the non-perturbative effect of QCD matters.

→ dark matter

No number changing process

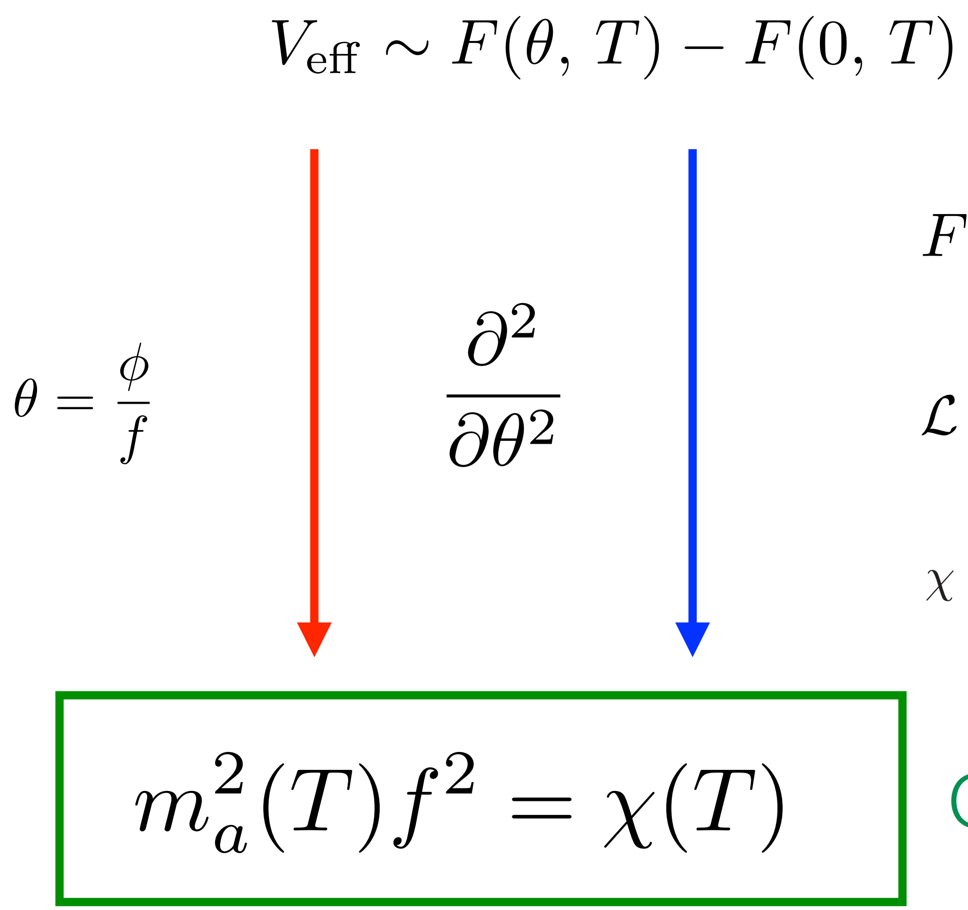
$\rho_a \sim m_a n_a \propto 1/(\text{Volume})$



Topological susceptibility

Effective field theory treatment

Free energy : F(θ, T) = -ln Z/$\mathcal{V}$



$$V_{\text{eff}} \sim F(\theta, T) - F(0, T)$$

$$\theta = \frac{\phi}{f}$$

$$\frac{\partial^2}{\partial\theta^2}$$

$$\boxed{m_a^2(T) f^2 = \chi(T)}$$

$$F(\theta, T) - F(0, T) \underset{|\theta|<<1}{\sim} \frac{1}{2}\chi(T)\theta^2$$

$$\mathcal{L} \ni \theta q(x) \qquad q(x) \equiv \frac{\alpha_s}{8\pi^2}\theta F_{\mu\nu a}F^{\mu\nu a}$$

$$\chi = \int d^4x \langle q(x) q(0)\rangle_{\theta=0}$$

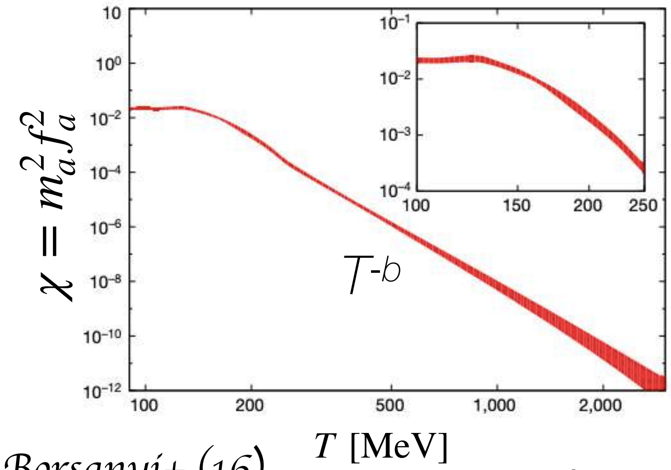
QCD meets cosmology

$$T \propto 1/a$$

Temperature dep. axion potential from QCD dynamics

$$V(\theta, T) = \frac{\chi(T)}{\chi(T=0)} V_0(\theta)$$

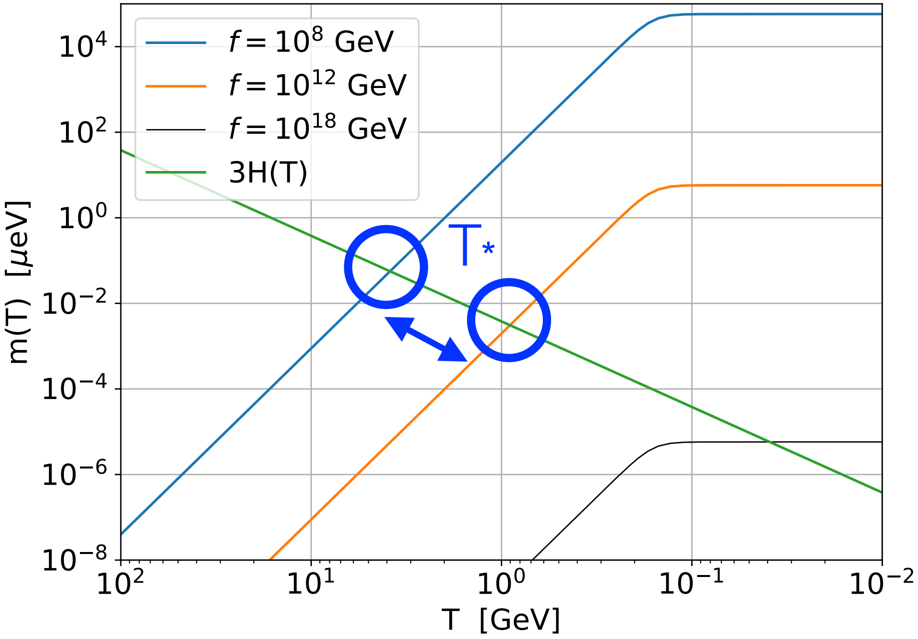
Axion abundance



Borsanyi+ (16)

$b \sim 8.2$

Axion starts oscillation $3H(T_*) \sim m(T_*)$



Pheno.constraints $10^8\mathrm{GeV} < f < 10^{12}\mathrm{GeV}$

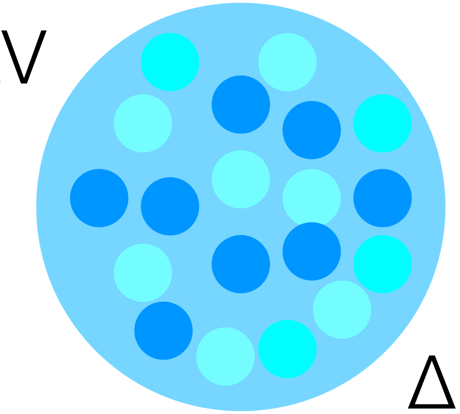
$$T_* \simeq 1.0\,\mathrm{GeV}\left(\frac{10^{12}\,\mathrm{GeV}}{f}\right)^{0.16}$$

(Misalignment) Axion abundance $\Omega_a h^2 \sim 0.1\left(\frac{f}{10^{12}\mathrm{GeV}}\right)^{1.16}\theta_i^2$

2 axion scenarios

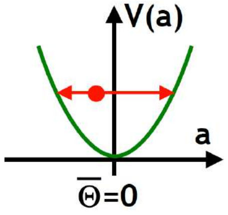
i) PQ symmetry was broken during inflation $f \geqq H_{inf}$

VEV



$\Delta\theta << 1$

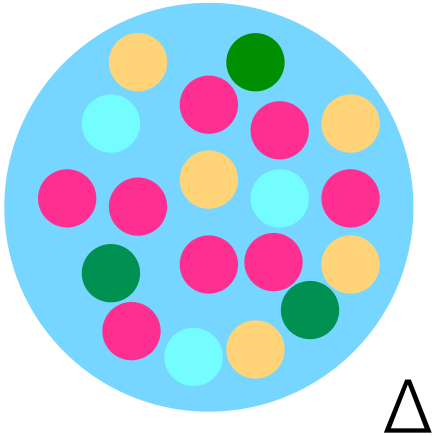
$$\xrightarrow{T \sim \Lambda_{QCD}}$$



$$\frac{\delta\rho_a}{\bar{\rho}_a} \ll 1$$

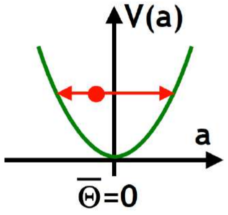
ii) PQ symmetry got broken after inflation $f < H_{inf}$

VEV



$\Delta\theta \sim O(1)$

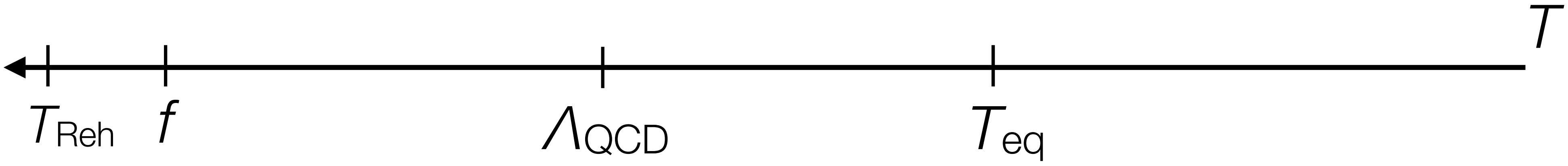
$$\xrightarrow{T \sim \Lambda_{QCD}}$$

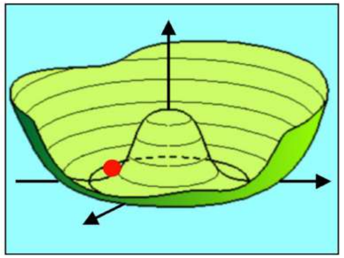


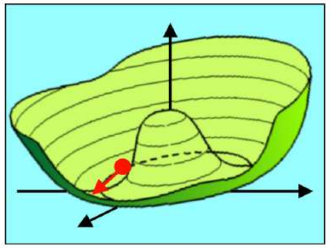
$$\frac{\delta\rho_a}{\bar{\rho}_a} \sim O(1)$$

Kolb&Tkacev(93, 94)

AMC formation in post-inflationary scenario

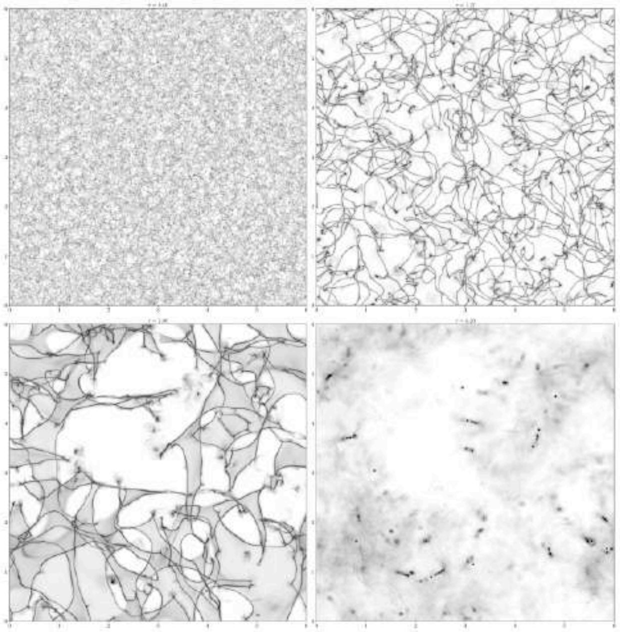






Gravitational collapse

Virialization *Kolb&Tkacev(93, 94)*



Vaquero, Redondo, Stadler (18)

See also Fluery&Moore(15),...

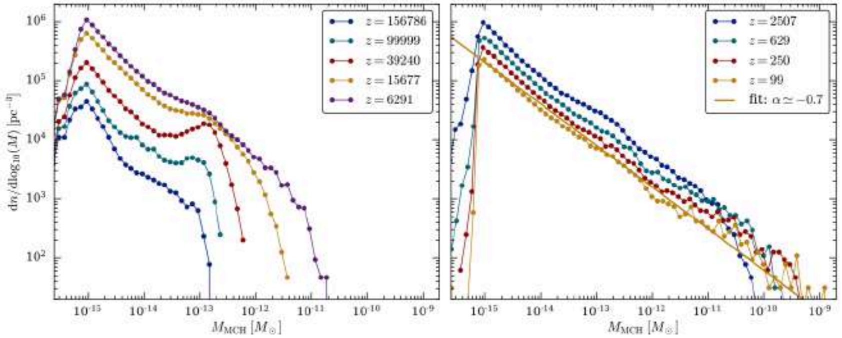


FIG. 2. MC-HMF at different redshifts z separated into times before (left) and after matter-radiation equality (right). The slope of the MC-HMF at $z_f = 99$ is $\alpha \simeq -0.7$.

Eggmeier et al(19)

See also Kavanagh et al. (20), Xaio et al.(21)

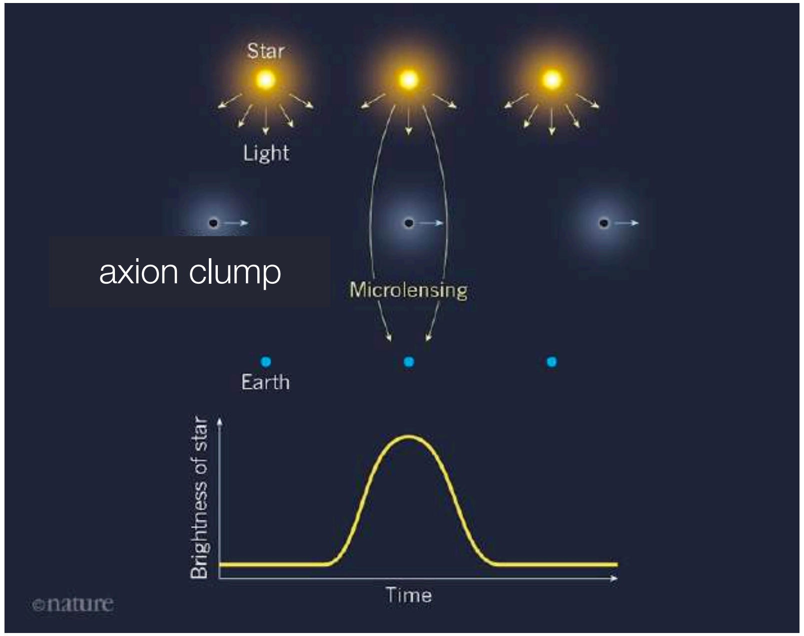
Axion minicluster (AMC) search

- Microlensing
- Pulsar Timing array

…. and so on

typical velocity
of DM

$v \sim 10^{-3}c$



Kolb&Tkacev(95),
Fairbairn et al. (17),
Dai&Miralda-Escude(19)

Is AMC the smoking gun of post-inflation scenario?

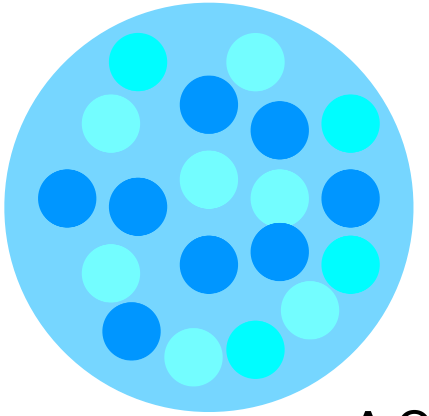
If yes, a detection of AMC gives the upper bound on f.

$f < H_{\mathrm{inf}}/2\pi < 10^{13}$ GeV (PLANCK/BICEP/Keck)

Is that true?

Fukunaga, Kitajima & Y.U.(20), Kitajima, Kogai, Y.U. (in prep.)

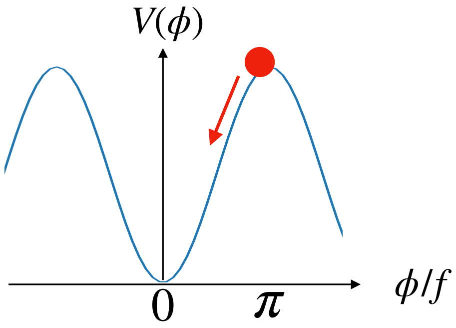
PQ symmetry broken during inflation $f \gtrsim H_{\rm inf}$



$\Delta\theta << 1$

T ~ $\Lambda_{\rm QCD}$ ⟶

$$\frac{\delta\rho_a}{\bar{\rho}_a} \sim O(1)\ ?$$



$$V(\phi) = m(T)^2 f^2 (1 - \cos(\phi/f))$$

1) Interaction btwn QCD matters and axion

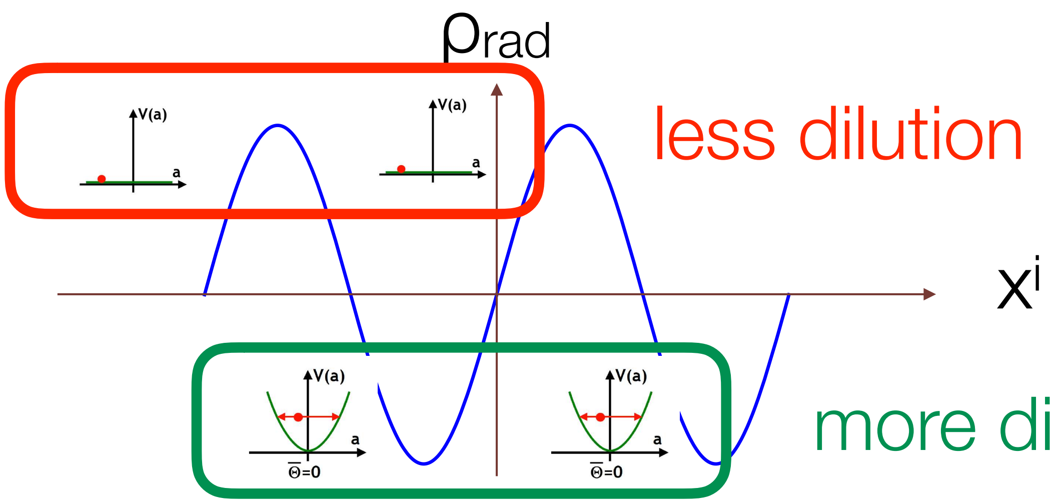
- ✔- Direct int. NEW!!
- \- Indirect int. via gravity (clustering) *Arvanitaki et al. (19)*

2) Self interaction $\lambda\phi^4$ (λ<0) attractive force for $\phi/f \sim \pi$

Direct interaction w/QCD matters (~ radiation)

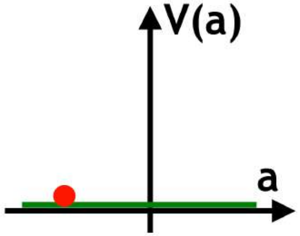
Inhomogeneous Universe

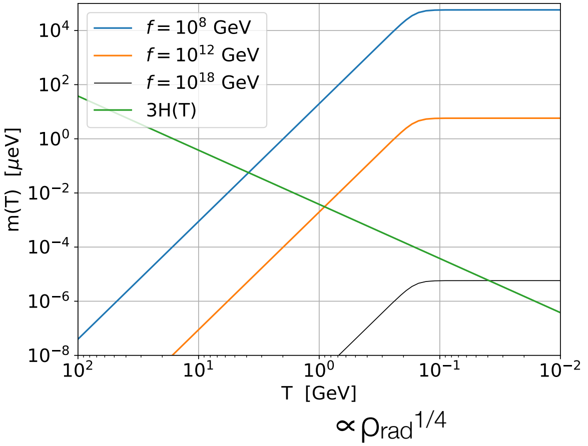
Kitajima, Kogai, Y.U. (in prep.)

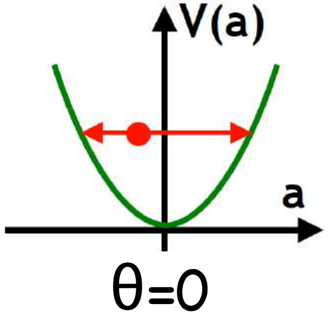


less dilution → high density axion

more dilution → low density axion



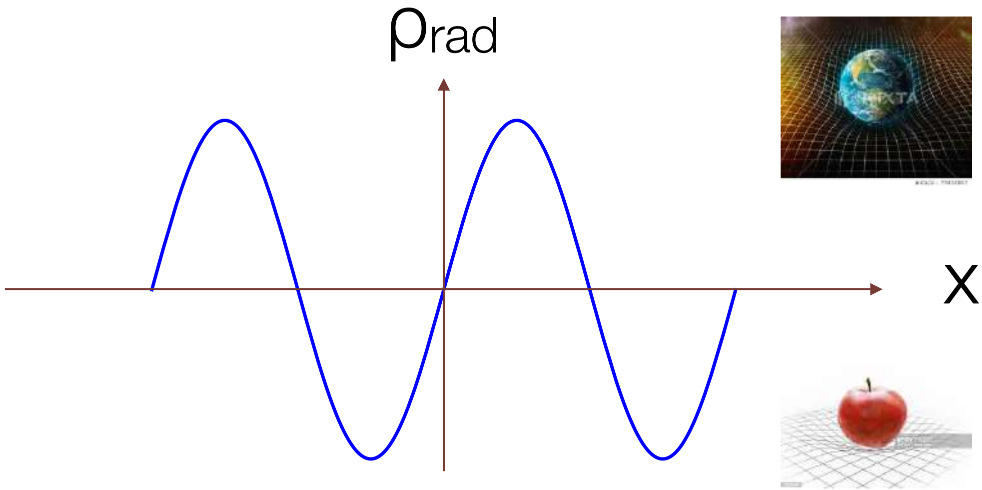




Indirect interaction w/QCD matters (~ radiation)

Inhomogeneous Universe

Kitajima, Kogai, Y.U. (in prep.)



Through eq. ….

$$\nabla_\mu T^\mu{}_{\nu(\rm axion)} = -\nabla_\mu T^\mu{}_{\nu(\rm rad)}$$

$\uparrow$ indirect

$\uparrow$ direct

Linear perturbation

Kitajima, Kogai, Y.U. (in prep.)

$\delta\phi$: Inhomogeneity of axion

Φ: Gravitational potential

at longitudinal gauge

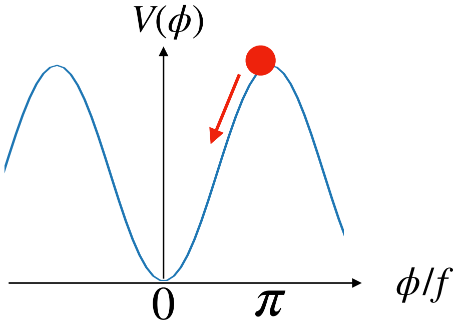
Equations

$$\partial_t^2\delta\phi + 3H\partial_t\delta\phi + \left(\frac{k}{a}\right)^2\delta\phi + \underset{\text{incl. self-int.}}{\underline{V_{\phi\phi}\delta\phi}} + \underset{\text{indirect int.}}{\underline{4\dot{\phi}\partial_t\Phi - 2V_\phi\Phi}} + \underset{\text{direct int.}}{\underline{V_{\phi\rho_r}\delta\rho_r}} = 0$$

$$\triangle\Phi \sim 4\pi G\delta\rho$$ + GR corrections

IC

$$\Delta \equiv \pi - \phi_i/f$$ (+ slow-roll initial velocity)



For Δ<<1, the self-interaction was initially important.

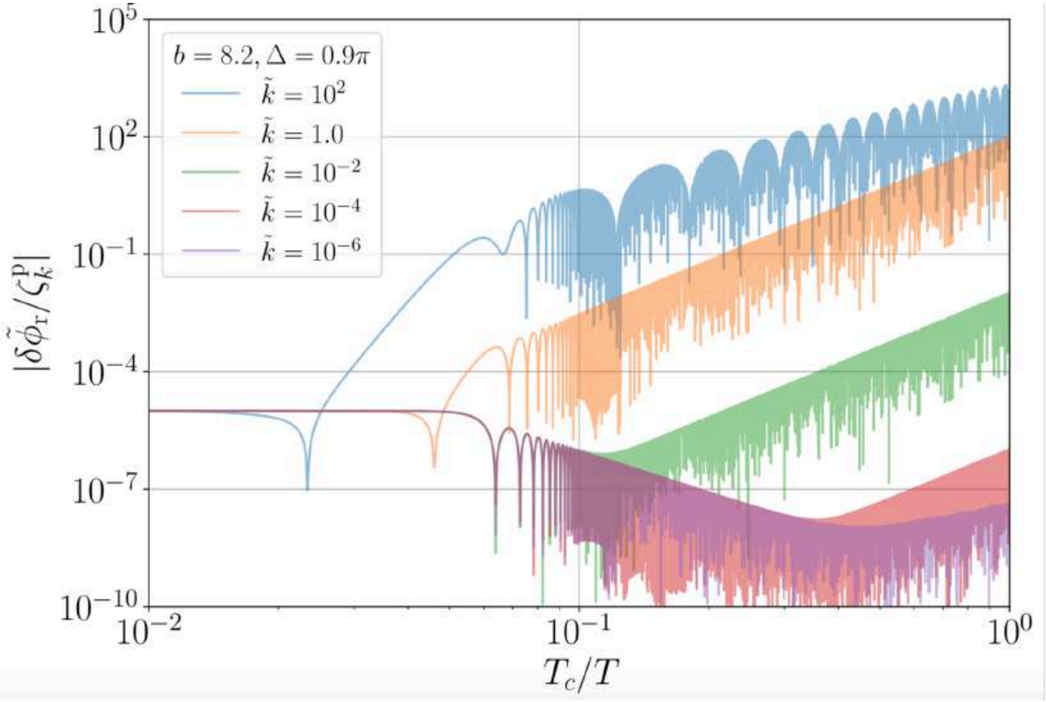
Linear perturbation: Δ=O(1)

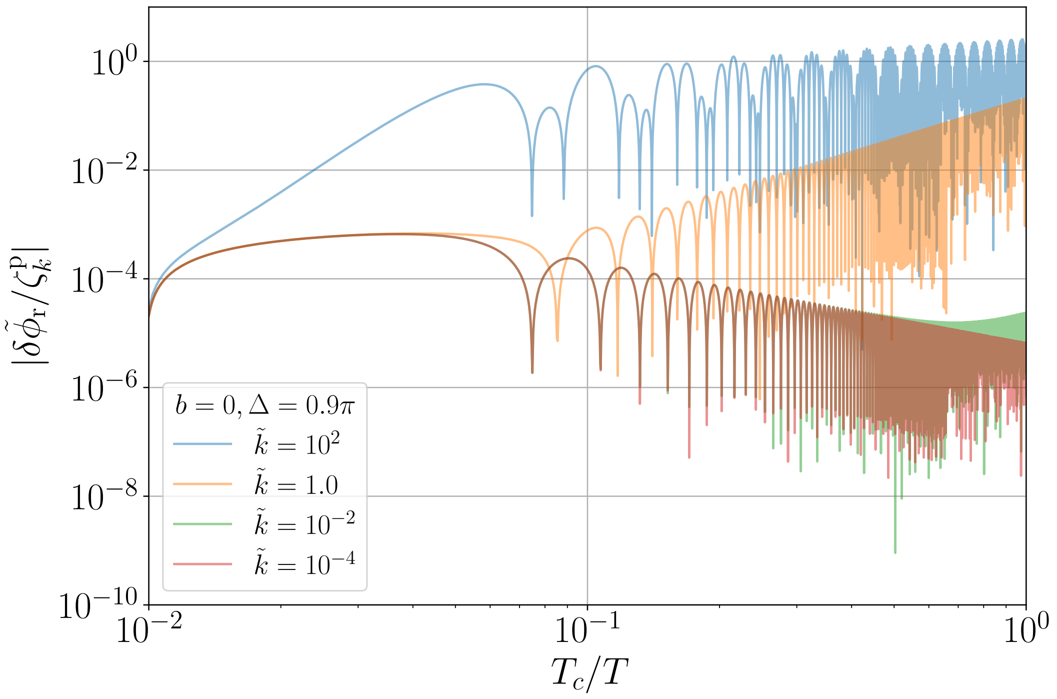
Kitajima, Kogai, Y.U. (in prep.)

$$\partial_t^2\delta\phi + 3H\partial_t\delta\phi + \left(\frac{k}{a}\right)^2\delta\phi + \underbrace{V_{\phi\phi}\delta\phi}_{\text{no self-int.}} + \underbrace{4\dot{\phi}\partial_t\Phi - 2V_\phi\Phi}_{\text{indirect int.}} + \underbrace{V_{\phi\rho}\delta\rho_{\mathrm{r}}}_{\text{direct int.}} = 0$$

(axion) $V_{\phi\rho_r} \neq 0\,, \qquad V_{\phi\phi} \sim m^2$

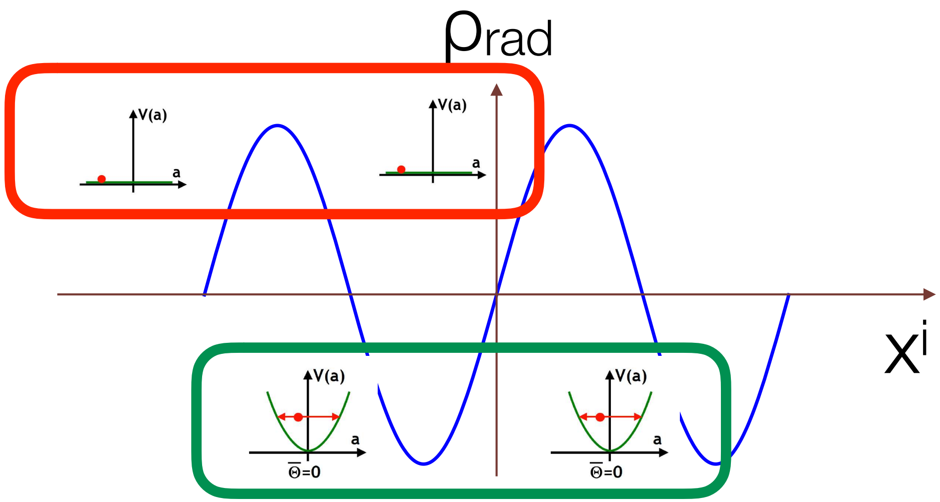
(ALP like) $V_{\phi\rho_r} = 0\,, \qquad V_{\phi\phi} \sim m^2$





ζ^{p}~Primordial amplitude (of radiation)

Significance of direct interaction



Kitajima, Kogai, Y.U. (in prep.)

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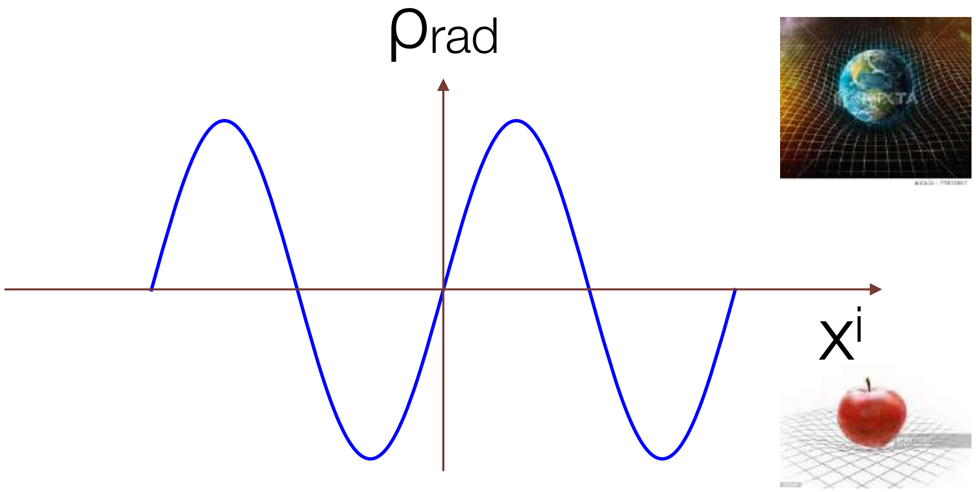


Arvanitaki et al. (19)

$\delta\rho_{\rm rad}/\rho_{\rm rad}$ ~ const. oscillation

Φ ~ decaying oscillation

$$\triangle\Phi \sim 4\pi G\delta\rho \sim 4\pi G\delta\rho_{\rm rad}$$

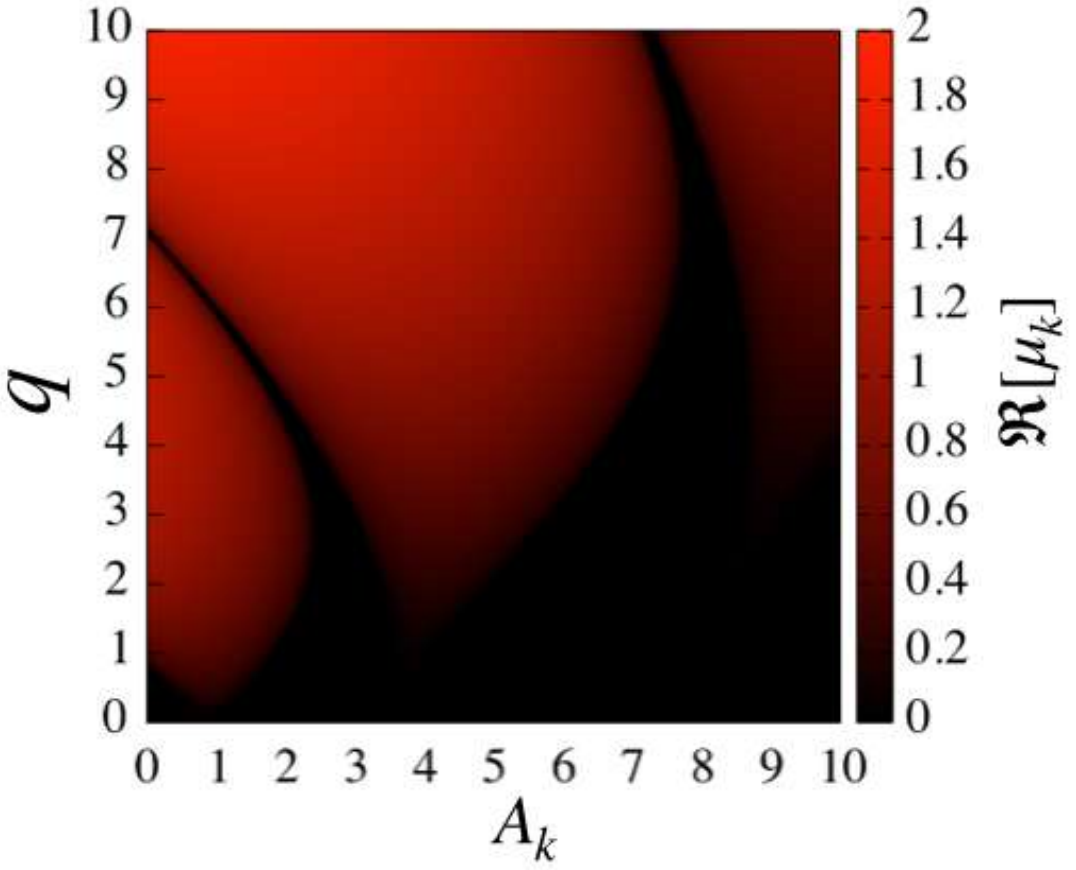
$$\Phi \sim (\delta\rho_{\rm rad}/\rho_{\rm rad}) \times (aH/k)^2 \propto (\delta\rho_{\rm rad}/\rho_{\rm rad}) \times a^{-2}$$

(in subhorizon)

Impact of self-interaction

Floquet theorem (1883)

axion in coherent oscillation → resonant growth $\delta\phi \propto e^{\mu_k m t}$



strong

interaction

weak

IR

wave number

UV

Parametric Resonance in cosmology

Cosmic expansion makes Bose enhancement inefficient.

$q(t) \propto \phi_{\mathrm{bg}}^{\#}(t) \propto \rho_{\mathrm{bg}}^{\#\#}(t)$ (#, ## > 0) $\qquad A_k(t) \sim \left(\frac{k}{a(t)m}\right)^2$

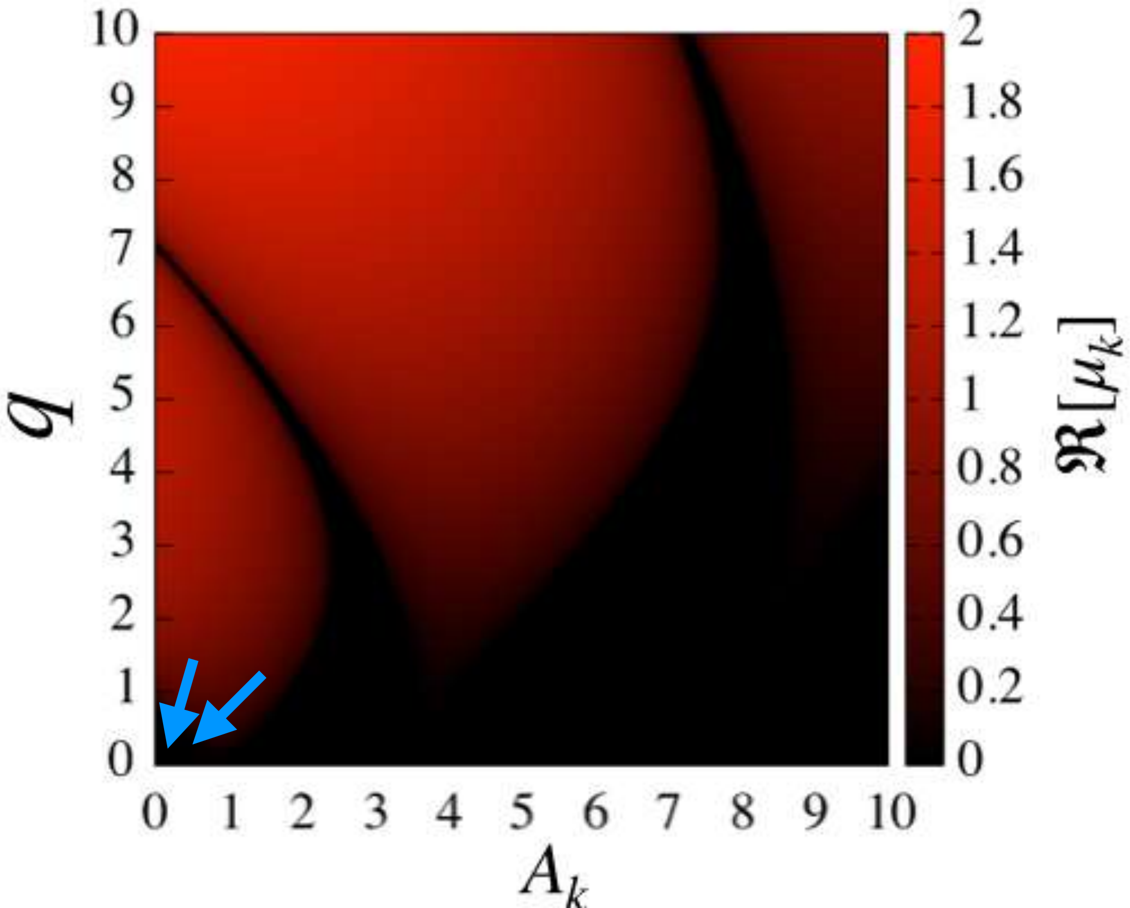
Time scale of ↙

= 1/H_{osc}

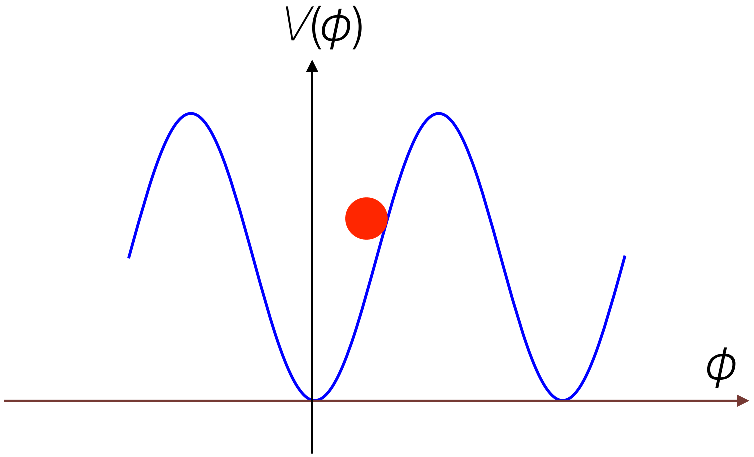
Time scale of exp.growth

= Period of oscillation

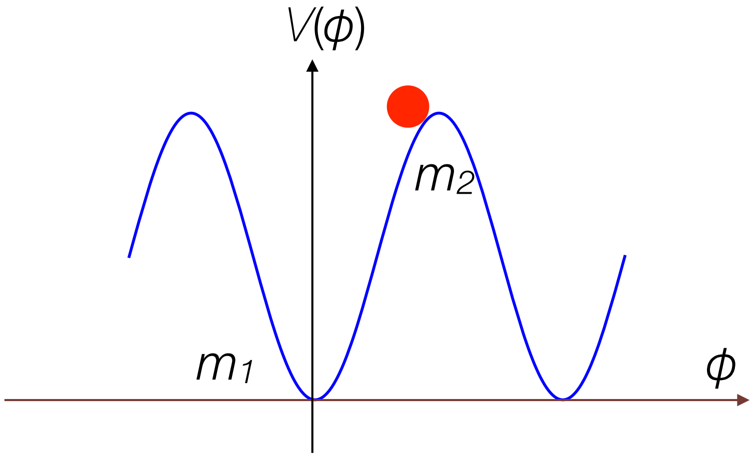
$\mathcal{T} = 2\pi/m$



Parametric Resonance in cosmology



$V(\phi) \sim m^2\phi^2$



$m_1 >> m_2$

(also due to temp. dep.of m)

Onset of oscillation

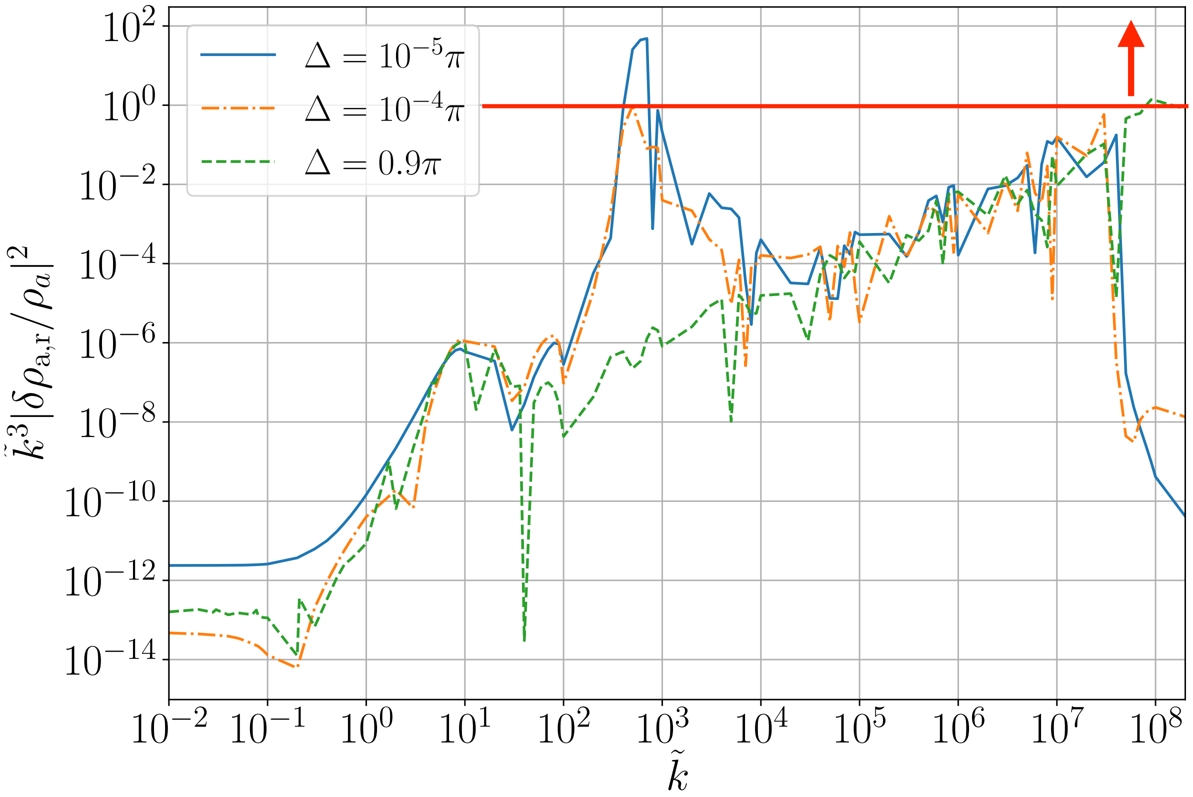
$H_{\mathrm{osi}} \sim m$

$\mathcal{T} \sim 1/m \sim 1/H_{\mathrm{osi}}$

$H_{\mathrm{osi}} \sim m_2$

$\mathcal{T} \sim 1/m_1 << 1/H_{\mathrm{osi}} \sim 1/m_2$

Power spectrum of axion density perturbation



break down of perturbation

$\tilde{k} \equiv k/(a_c H_c)$

$\mathcal{P}_\zeta = 2.1\times10^{-9}$

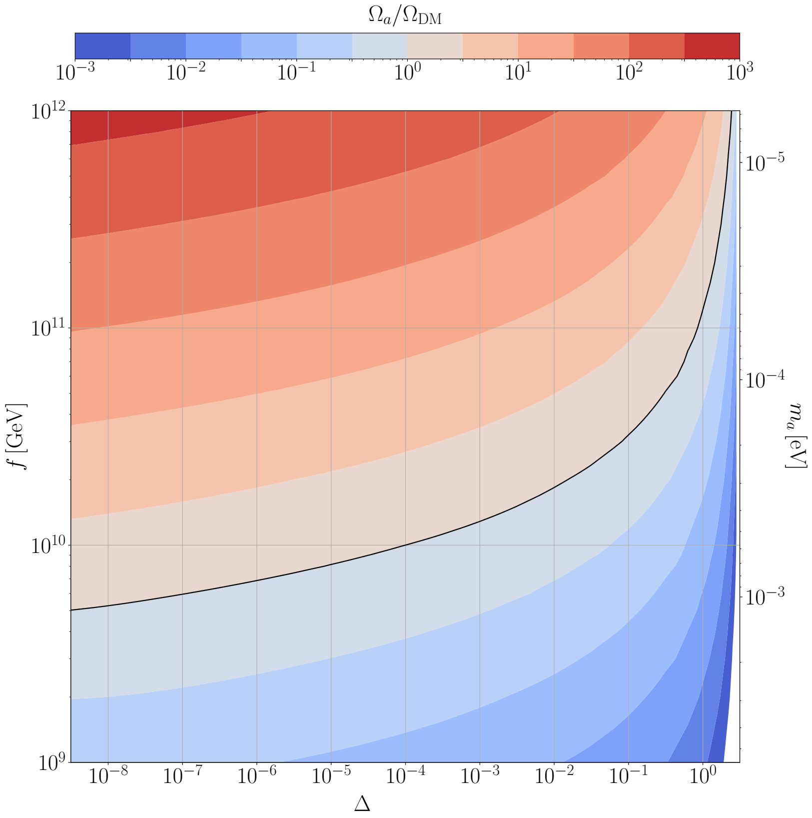
Kitajima, Kogai, Y.U. (in prep.)

- Radiation sources $\delta\rho_a$ only in sub horizon scales
- Resonance peak for fine-tuned IC, $\Delta \ll 1$

Axion abundance

For Δ<<1, Ω_a is enhanced due to the delayed oscillation.

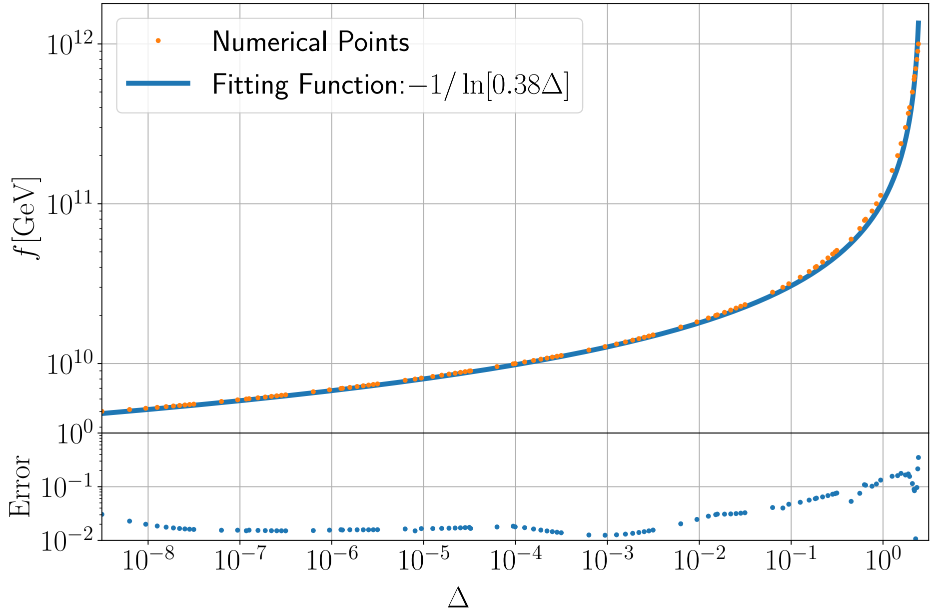
Turner(86), Lyth(92),⋯



Oscillation starts earlier as ↘

(black line: $\Omega_a=\Omega_c$)

For $\Omega_a=\Omega_c$, i.e., DM=axion



fitting $$\left(\frac{f(\Delta)}{10^{11}[\mathrm{GeV}]}\right) = -\frac{1}{[\log(0.38\Delta)]}$$

Kitajima, Kogai, Y.U. (in prep.)

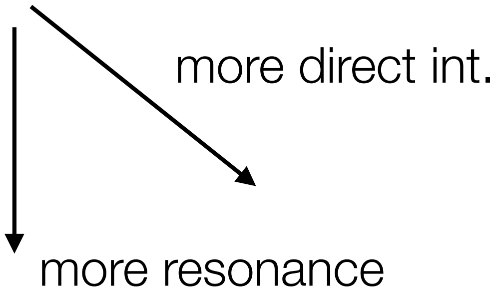
$$\Delta \equiv \pi - \phi_i/f$$

AMC formation

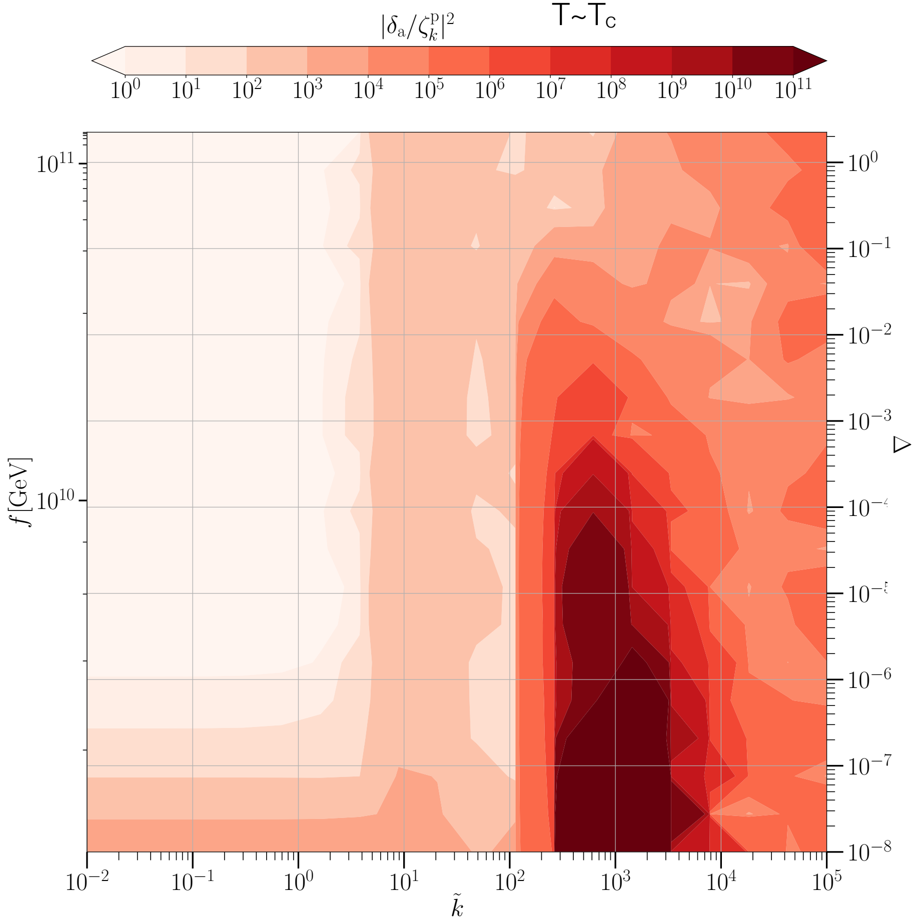
Kitajima, Kogai, Y.U. (in prep.)

Enhancement at T=T$_c$

x $\mathcal{P}_\zeta$ → ~ $<(\delta\rho_a/\rho_a)^2>$


more direct int.

more resonance



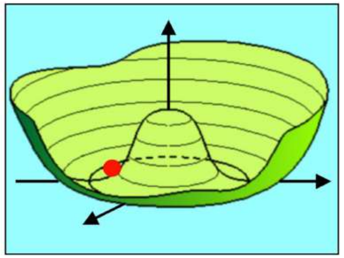
$\delta\rho_a/\rho_a$ reaches O(1) at T=Tc,

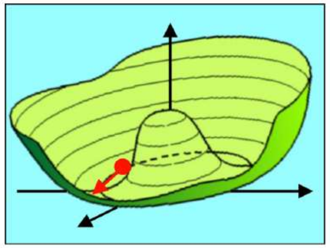
1) $\mathcal{P}_\zeta > 10^{-3}$ at $k \sim a_c H_c$

2) For $\mathcal{P}_\zeta \sim 10^{-9}$, fine-tuned IC w/$\Delta < 10^{-3}$

Future issues

AMC formation in pre-inflation scenario?





Gravitational collapse

Virialization

Lattice sim. in progress

N body sim., peak theory,….

1) $\mathcal{P}_\zeta > 10^{-3}$

if $\mathcal{P}_\zeta > 10^{-2}$

$O(M_\odot)$ PBH

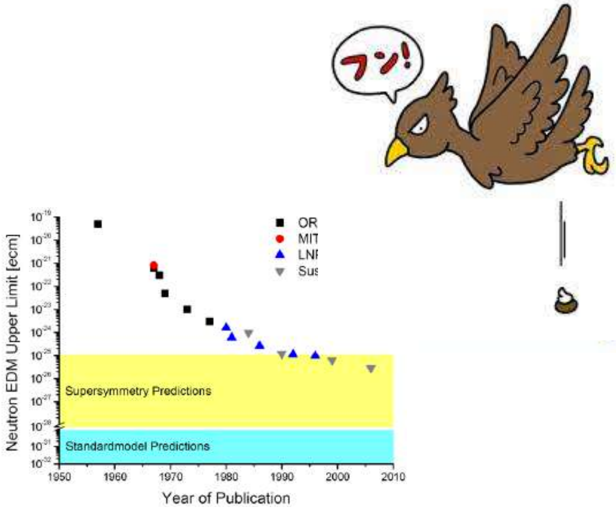
2) Fine-tuned IC

* More realistic input from QCD physics

If time permits….

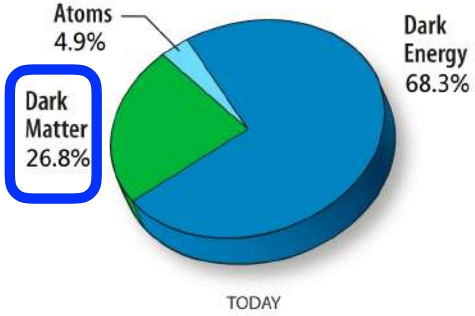
ALP dark matter

✗



like particle

✓



nHz GW signature from ALP dark matter

w/Kitajima (Tohoku), Soda (Kobe)

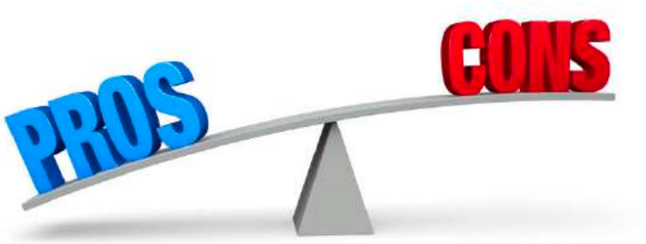
Phys. Rev. Lett. 126. (2021) 12, 121301
Kitajima, Soda, Y.U.

partly based on JCAP 10 (2018) 014
EPJC 78 (2018) 9, 779

ALP dark matter w/GUT scale f

axion w/ $f \sim 10^{15\text{-}16}$GeV $(H_{\rm inf} < f)$

anthropic window

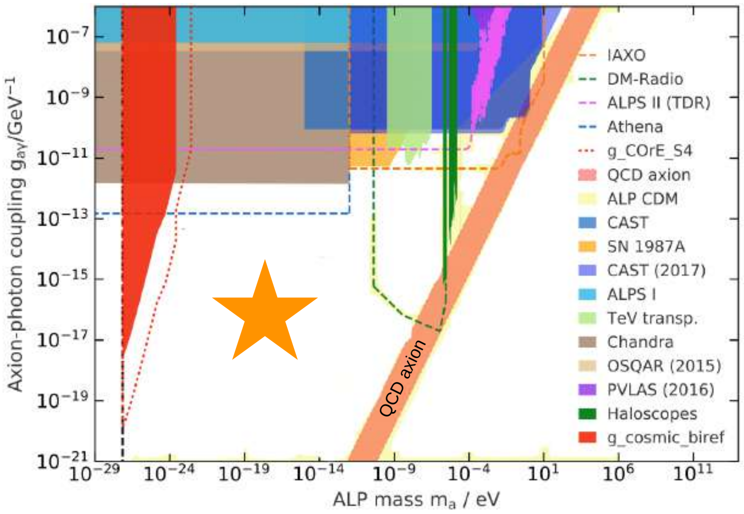


Model building

Svrcek & Witten (06)

Weakly coupled $\propto 1/f$

Sigl & Trivedi (18)



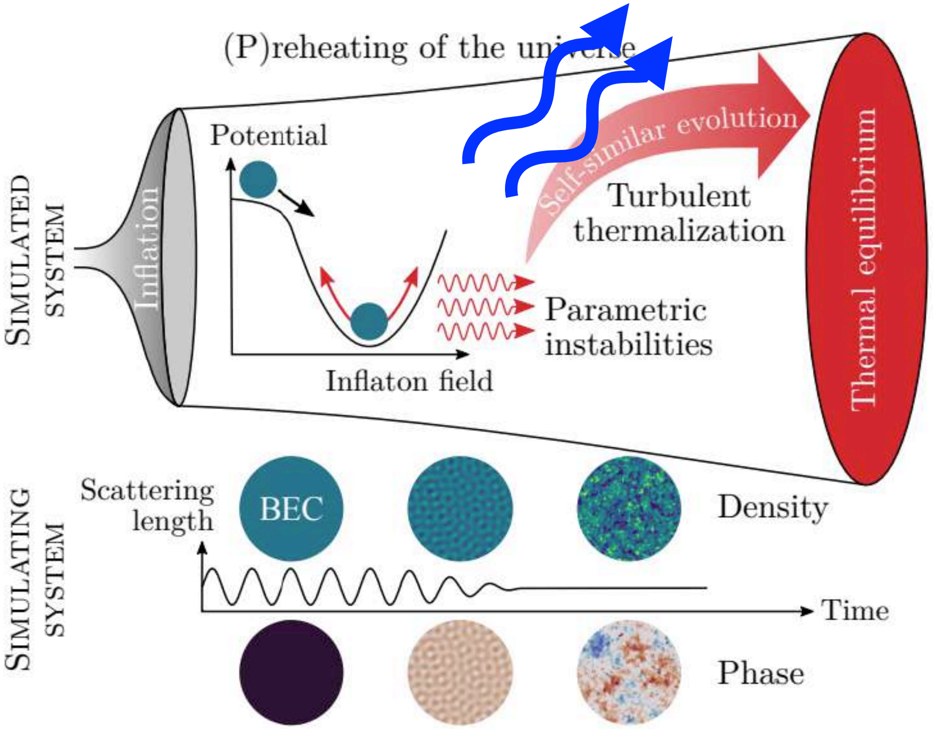
non-thermal production $\Omega_a h^2 \sim 2.8 \left(\frac{g_{*\rm osc}}{10}\right)^{-1/4}\left(\frac{m}{10^{-14}{\rm eV}}\right)^{1/2}\left(\frac{f\theta_i}{10^{16}{\rm GeV}}\right)^2$

Recall reheating

Transition from inflation to thermalized Universe

Traschen, Brandenberger (90), Kofman, Linde, Starobinsky (97)
Khlebnikov, Tkachev (96), ...

Gravitational Waves (GWs)



Typically very high frequency

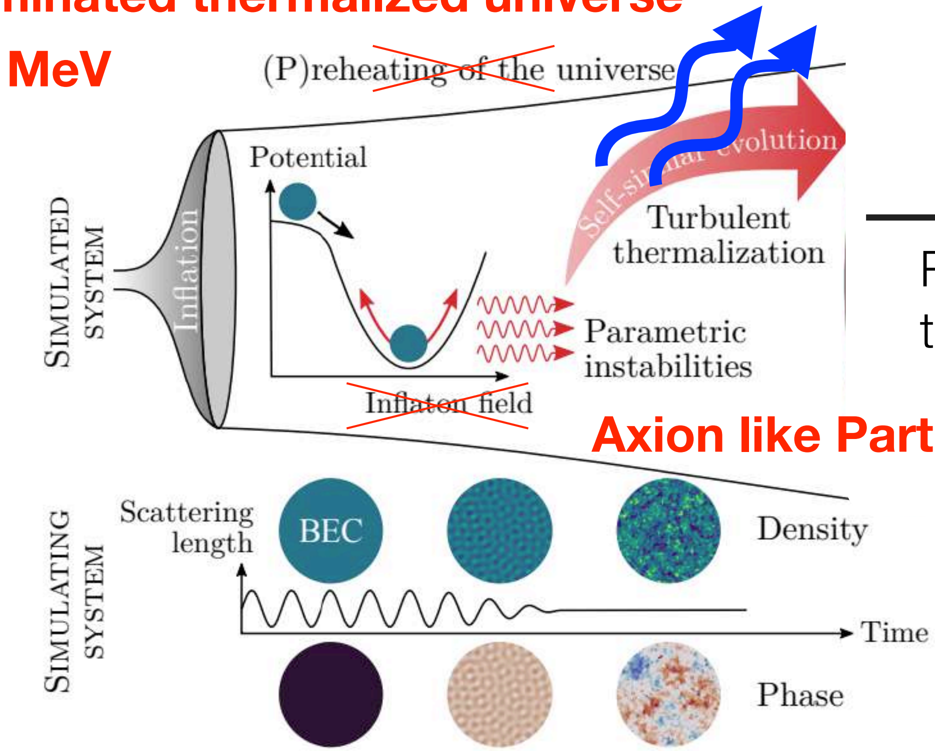
Drawing from Chatrchyan et al. (20)

Bottom-line story

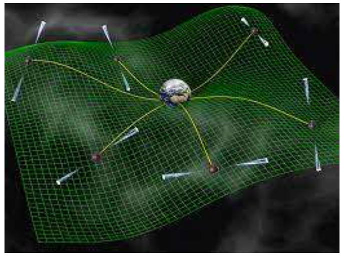
Detectable GWs via pulsar observations

Radiation dominated thermalized universe

e.g. T = MeV



Axion like Particle (ALP) dark matter



Relic ALP becomes DM, dominating the Universe around T~eV

Drawing from Chatrchyan et al. (20)

nHz GW from pulsar timing array (PTA)

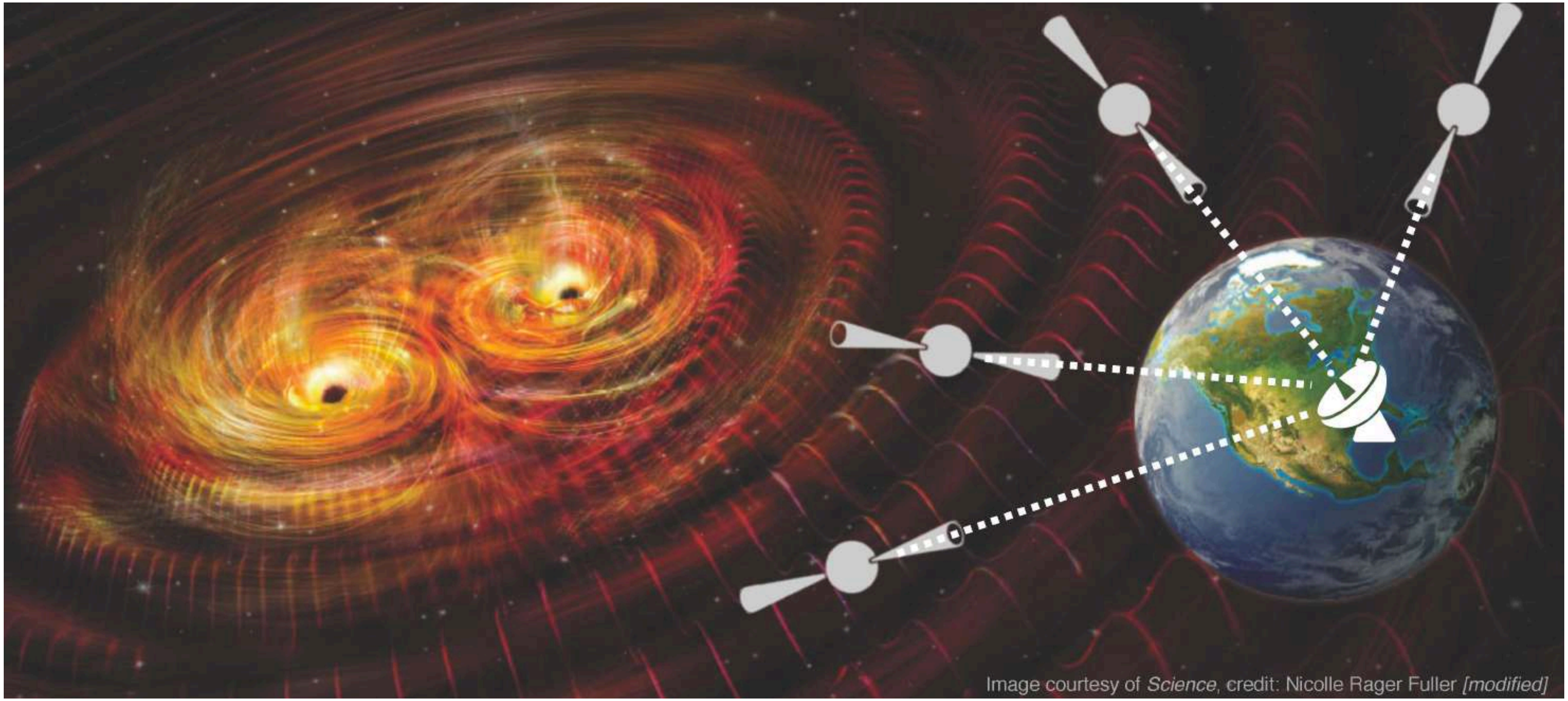
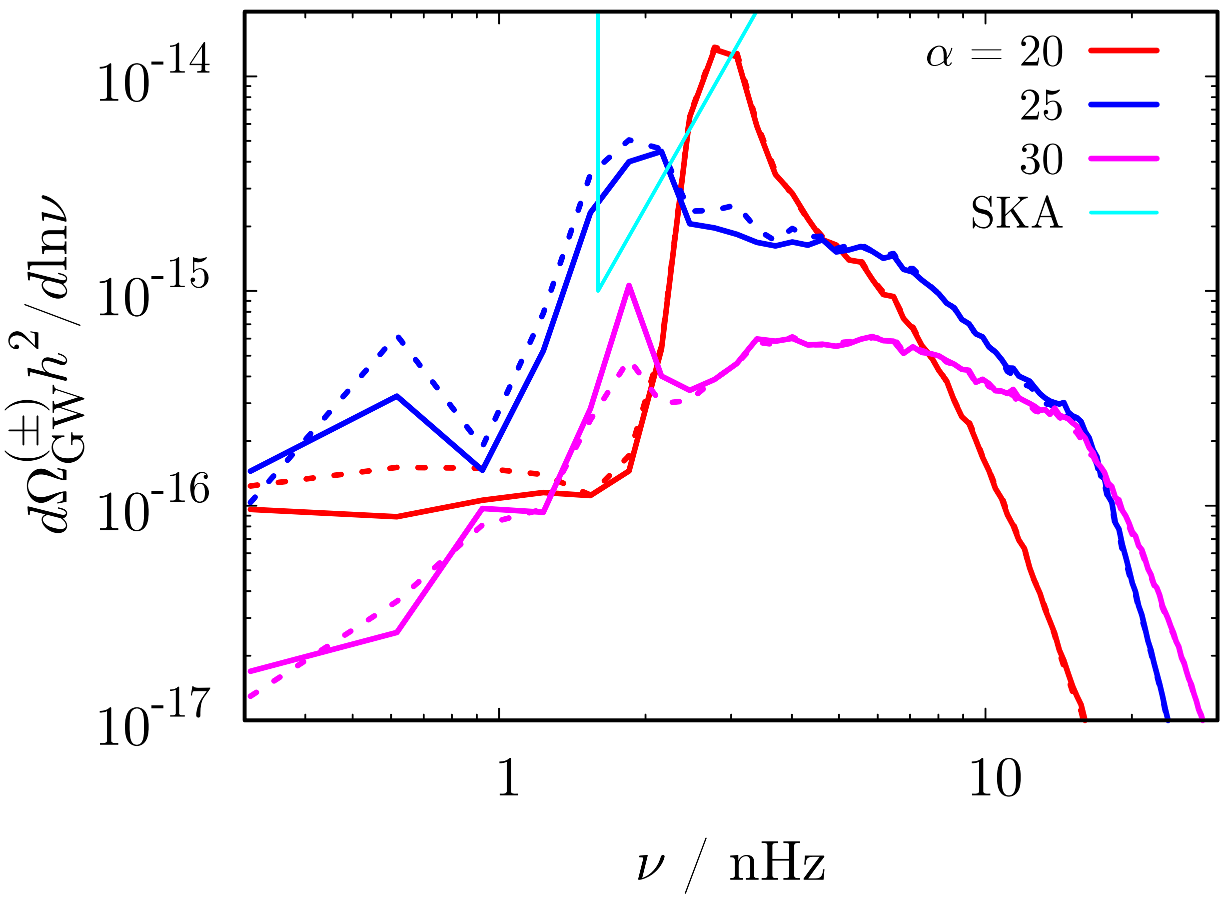


Image courtesy of *Science*, credit: Nicolle Rager Fuller *[modified]*

Time residual of periodic emissions from pulsars
(rapidly rotating NSs)

nHz GW signature from ALP dark matter

Kitajima, Soda & Y.U. (20)

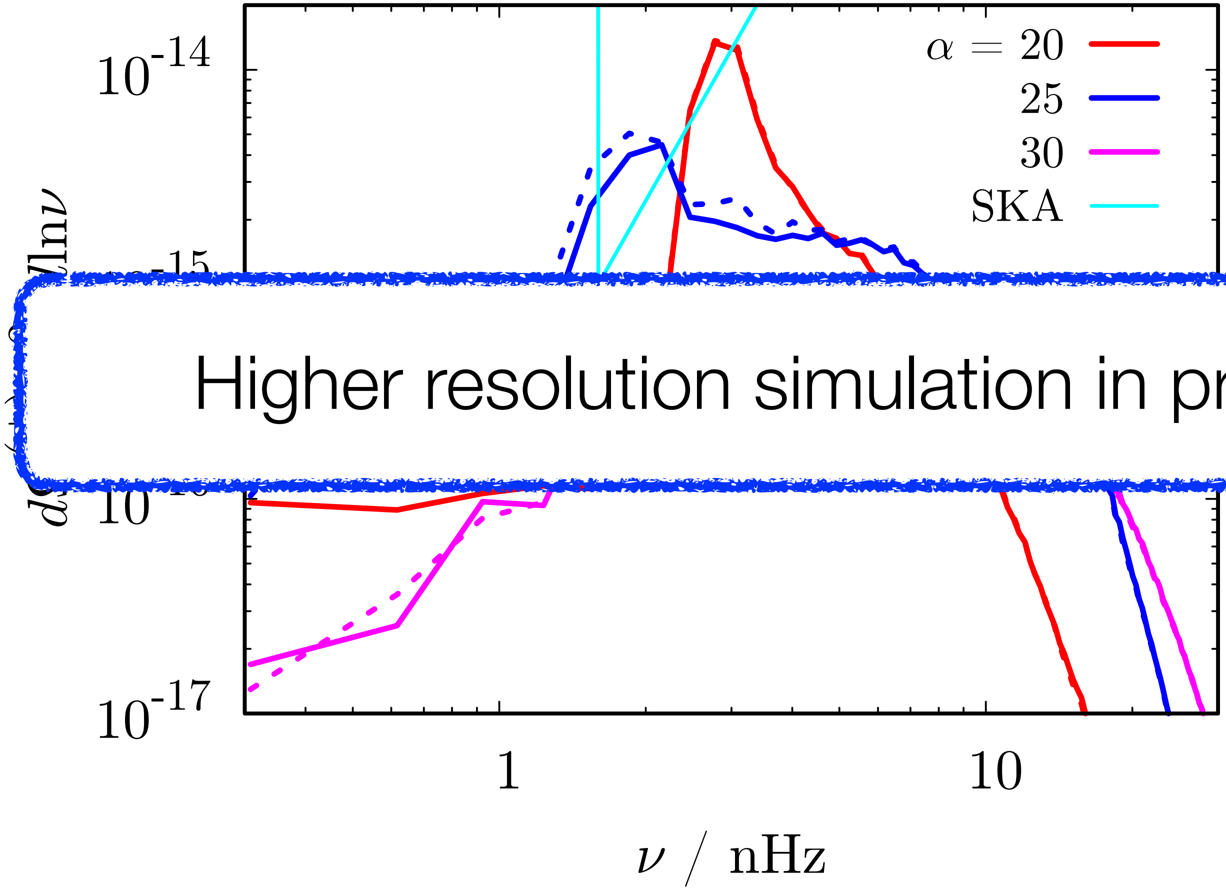


$f = 10^{16}$ GeV, $m = 2 \times 10^{-14}$ eV, $\theta_i = 2$,

since $\alpha\frac{\phi}{f}F\tilde{F}$, GWs are circularly polarized!

nHz GW signature from ALP dark matter

Kitajima, Soda & Y.U. (20)



Higher resolution simulation in progress

$f = 10^{16}$ GeV, $m = 2 \times 10^{-14}$ eV, $\theta_i = 2$,

since $\alpha\frac{\phi}{f}F\tilde{F}$, GWs are circularly polarized!

ALP dark matter w/GUT scale *f*

axion w/ $f \sim 10^{15\text{-}16}$GeV

Weakly coupled w/SM

$\propto 1/f$

Model building *Svrcek & Witten (06)*

PTA window *Kitajima, Soda, YU (20)*