Exploring string axiverse in GW cosmology

a la Misao :-)

Yuko Urakawa (Nagoya university, IAR)

J.Soda & Y.U.(1710.00305)

N. Kitajima, J.Soda,& Y.U.(in progress)

w/ Naoya Kitajima (Nagoya U.), Jiro Soda (Koba U.)

Axions (or ALPs) from string theory

Superstring theory in compact 6D

↓

4D low energy EFT + Axions + Moduli ….

Wide mass ranges ⟶ Probe of exDim

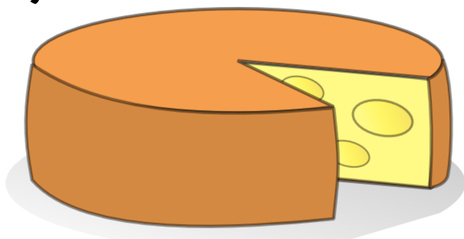
↓

Inflaton, DM candidate (Fuzzy DM)

Wu et al.(00), …

ex. Large Volume Scenario *Conlon et al. (05)*

Predicts light mass axions



Scalar potential of axion

continuous shift sym. → (NP effects, e.g. instanton effects) → $\phi \to \phi + 2\pi n/f$

$\phi \to \phi + c$

$n \in \mathbf{Z}$

$V(\phi) \sim \Lambda^4 \cos\phi/f$

Are you sure with $\cos\phi/f$?

- ~~Dilute instanton gas approximation~~

for $\phi/f << 1$ $\qquad V(\phi) \propto \phi^2$

for $\phi/f \geqq 1$ $\qquad \cos\phi/f$? $\qquad$ *Witten(79, 80)*

SU(N) in large N on $R \times T^3$ $\qquad f_{\text{eff}} \propto N$ → Plateau structure

Dubovski et al. (11), Yamazaki & Yonekura(17), ⋯

Scalar potential of axion

continuous shift sym.

$\phi \to \phi + c$

NP effects
e.g. instanton effects

$\phi \to \phi + 2\pi n/f$

$n \in \boldsymbol{Z}$

$V(\phi) \sim \Lambda^4 \cos\phi/f$

Potential can be more flatten than $\cos\phi/f$

i) ~~Dilute instanton gas approximation~~

$$V(\phi) = M^4 \left[1 - \frac{1}{(1+(\phi/F)^2)^p}\right]$$

Yamazaki & Yonekura(17), Nomura, Watari, & Yamazaki (17)

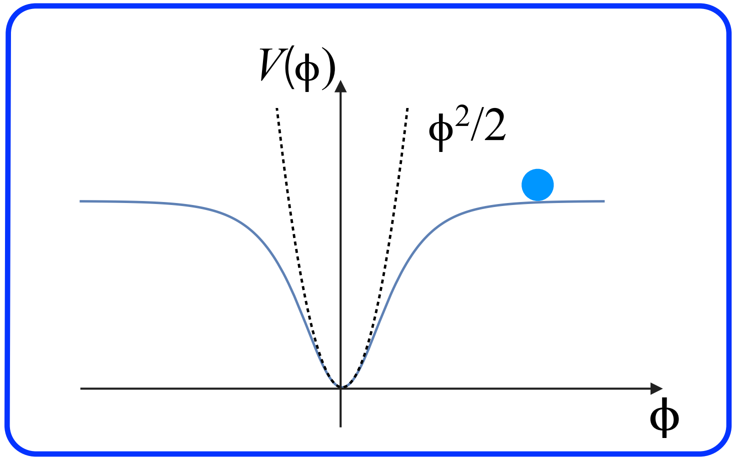
ii) Non-min. coupling w/gravity, Non-canonical kinetic term

→ α attractor model *Kallosh & Linde + (13, 14,···)*

iii) Superposition of multiple cosine terms

e.g., alignment mechanism *Kim, Nilles, & Peloso (04)*

Plateau phenomenology : ϕ = inflaton



i) Reconcile the tension w/ PLANCK observation

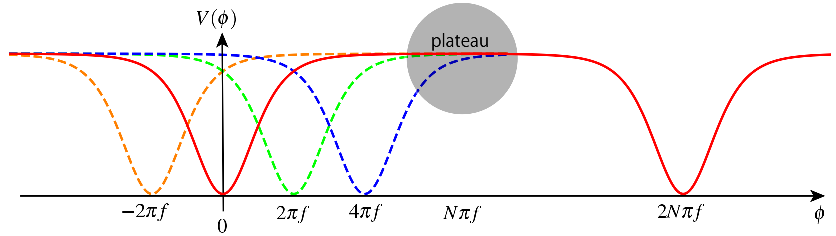
$V(\phi) \propto \phi^2$ → plateau structure

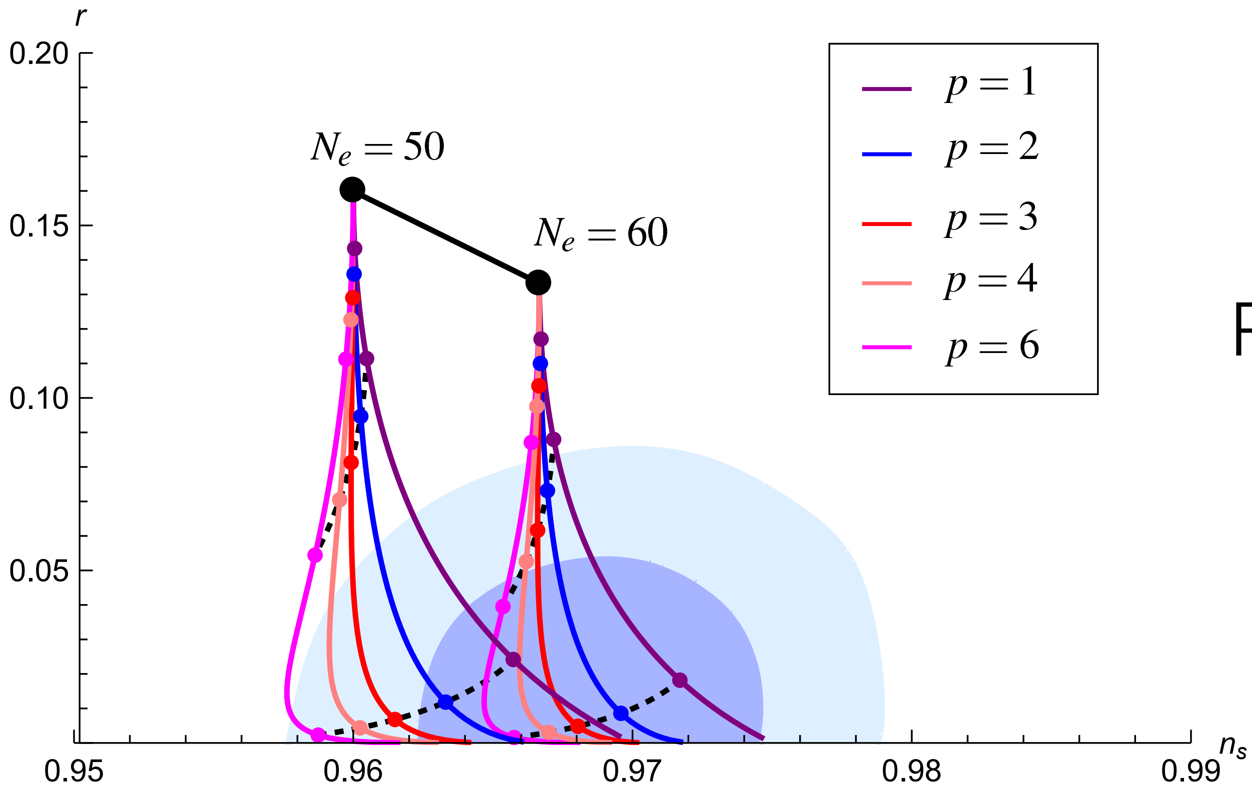
Recall Renata's talk

Pure natural inflation

Nomura, Watari, & Yamazaki (17),
Nomura & Yamazaki (17)

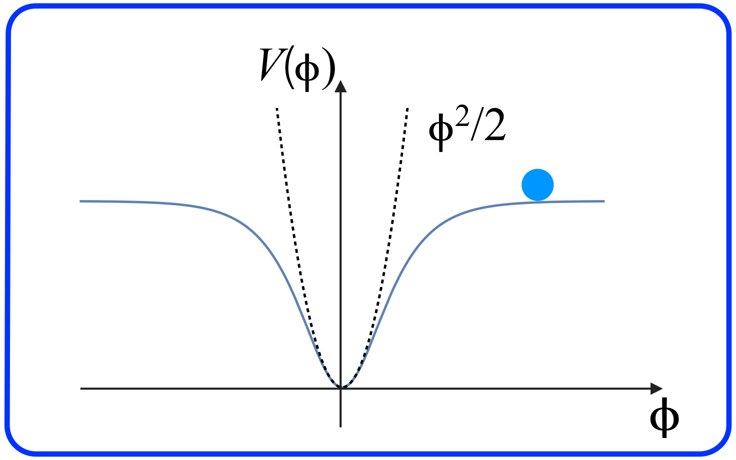
$$V(\phi) = M^4 \left[1 - \frac{1}{(1 + (\phi/F)^2)^p}\right]$$





Consistent w/
Planck, BICEP/KECK

Plateau phenomenology : ϕ inflaton



i) Reconcile the tension w/ PLANCK observation

$V(\phi) \propto \phi^2$ → plateau structure

Recall Renata's talk

ii) Drastic reheating process

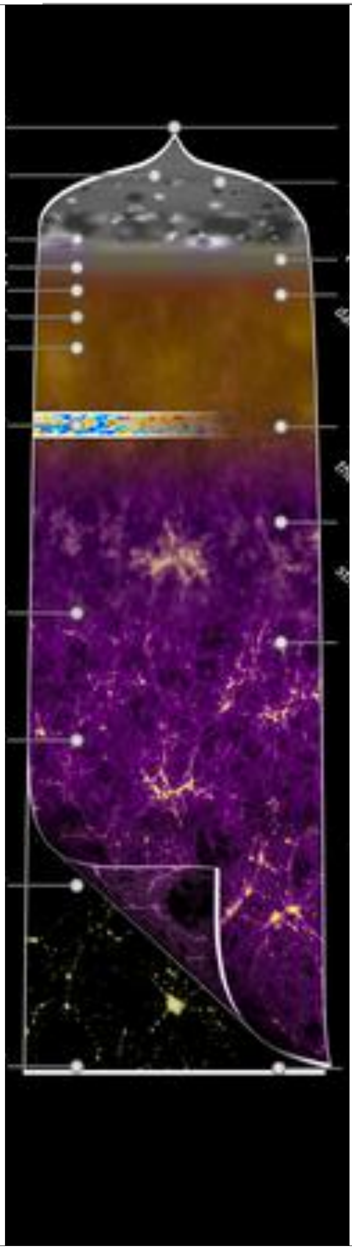
- GW emission

Antusch +(17), Kawasaki+(17), ⋯

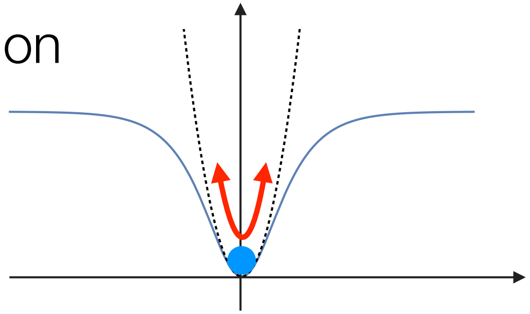
- Oscillon/I-ball formation

Gleiser(94), Kasuya+(03), Amin + (10, 12, 17), ⋯.

Plateau phenomenology: Post inflation



← Onset of oscillation



H/m << 1

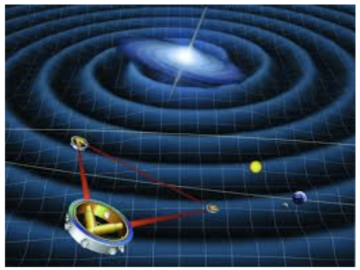
$\phi(t)$ $\longrightarrow$ $\delta\phi(t, x)$

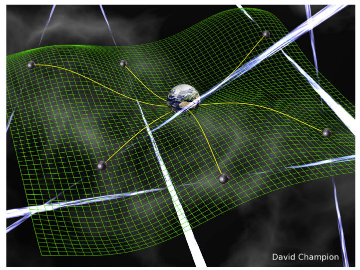
inst. turbulence

(b)GW

axion

~~bio~~-marker

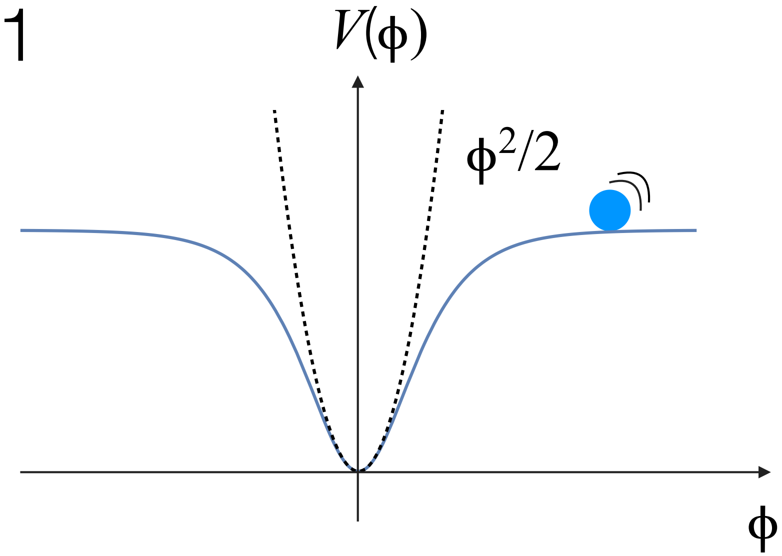




Outline of the story

Soda & Y.U.(17)
Kitajima, Soda & Y.U.(in prep.)

1. Axion slowly rolls down $H/m >> 1$



Outline of the story

Soda & Y.U.(17)
Kitajima, Soda & Y.U.(in prep.)

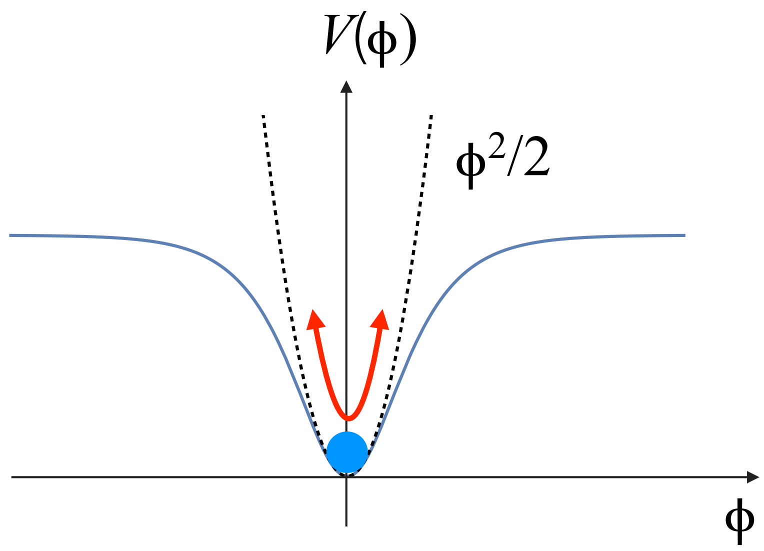
1. Axion slowly rolls in plateau

2. Onset of oscillation $H_{osc}/m < 1$

Especially w/plateau

(or $\cos\phi/f$ w/fine tuned IC)

$H_{osc}/m << 1$



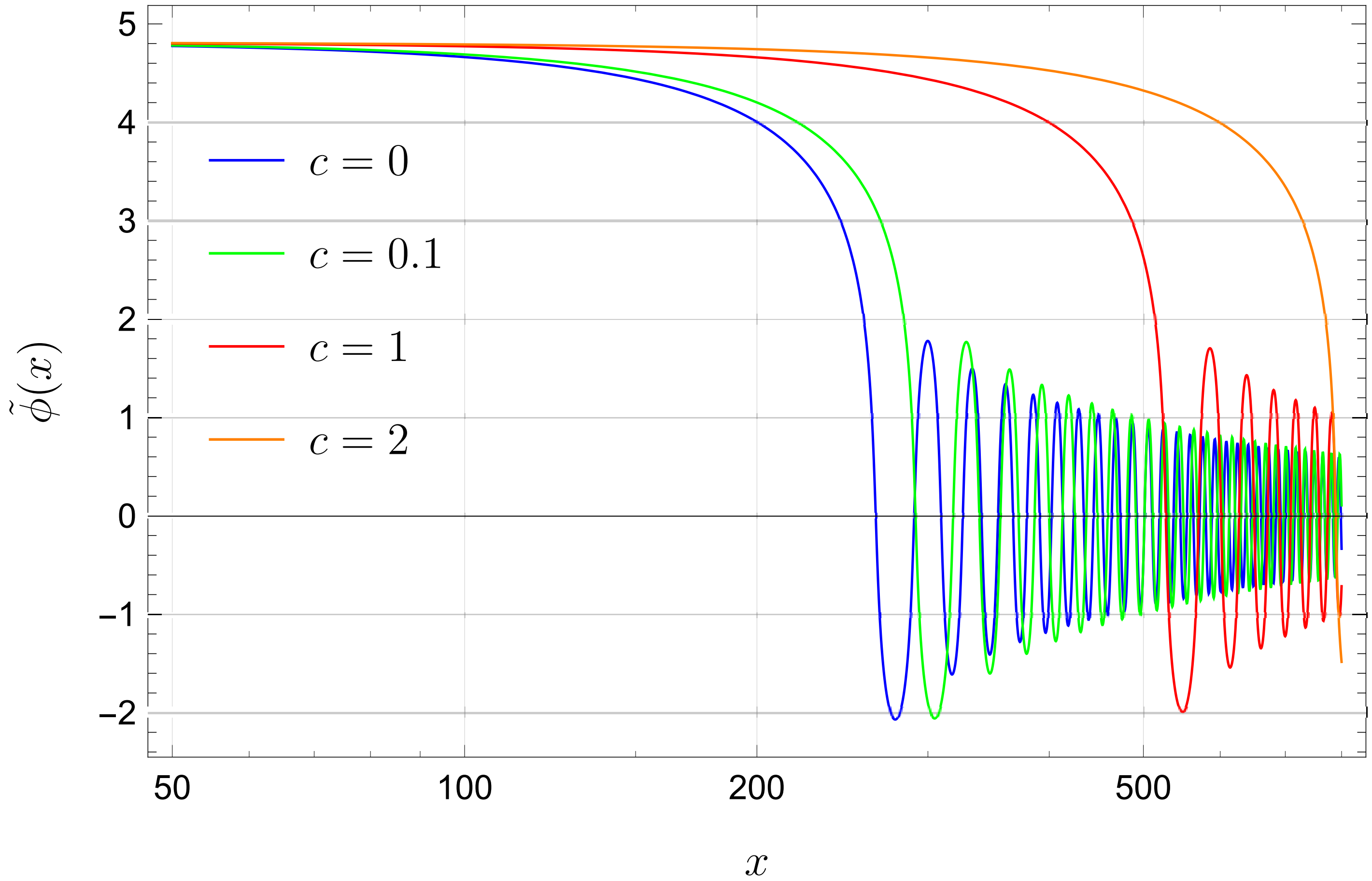
α-attractor

$$V(\phi) = \frac{(m_a f)^2}{2} \frac{(\tanh\frac{\phi}{f})^2}{1 + c(\tanh\frac{\phi}{f})^2}$$

Background evolution

RD

Soda & Y.U.(17)



$x = m/H$

Onset of oscillation is not $m \sim H$, but delayed!

Outline of the story

Soda & Y.U.(17)
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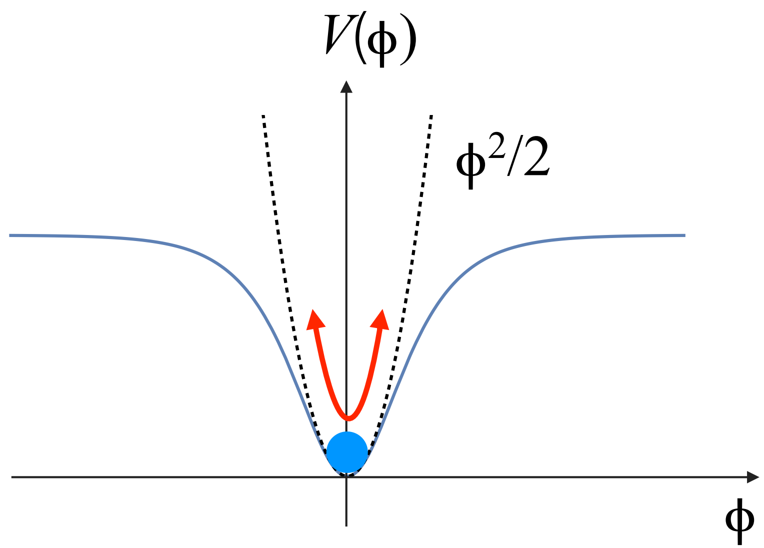
1. Axion slowly rolls in plateau

2. Onset of oscillation $H_{osc}/m < 1$

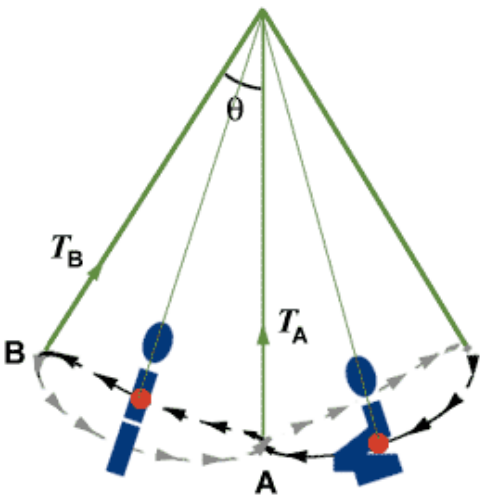
3. Exponential growth due to PR



if $H_{osc}/m << 1$

No disturbance due to cosmic exp.

Parametric resonance



Repeat: Up & Down in a half of osc. period

→ Periodic ext. force

→ Enhancing the amplitude

"Parametric resonance instability"

<u>Mathieu equation</u>

$$\frac{d^2}{dx^2}\tilde{\varphi} + (A - 2q\cos 2x)\tilde{\varphi} = 0$$

resonance band $A \sim n^2$

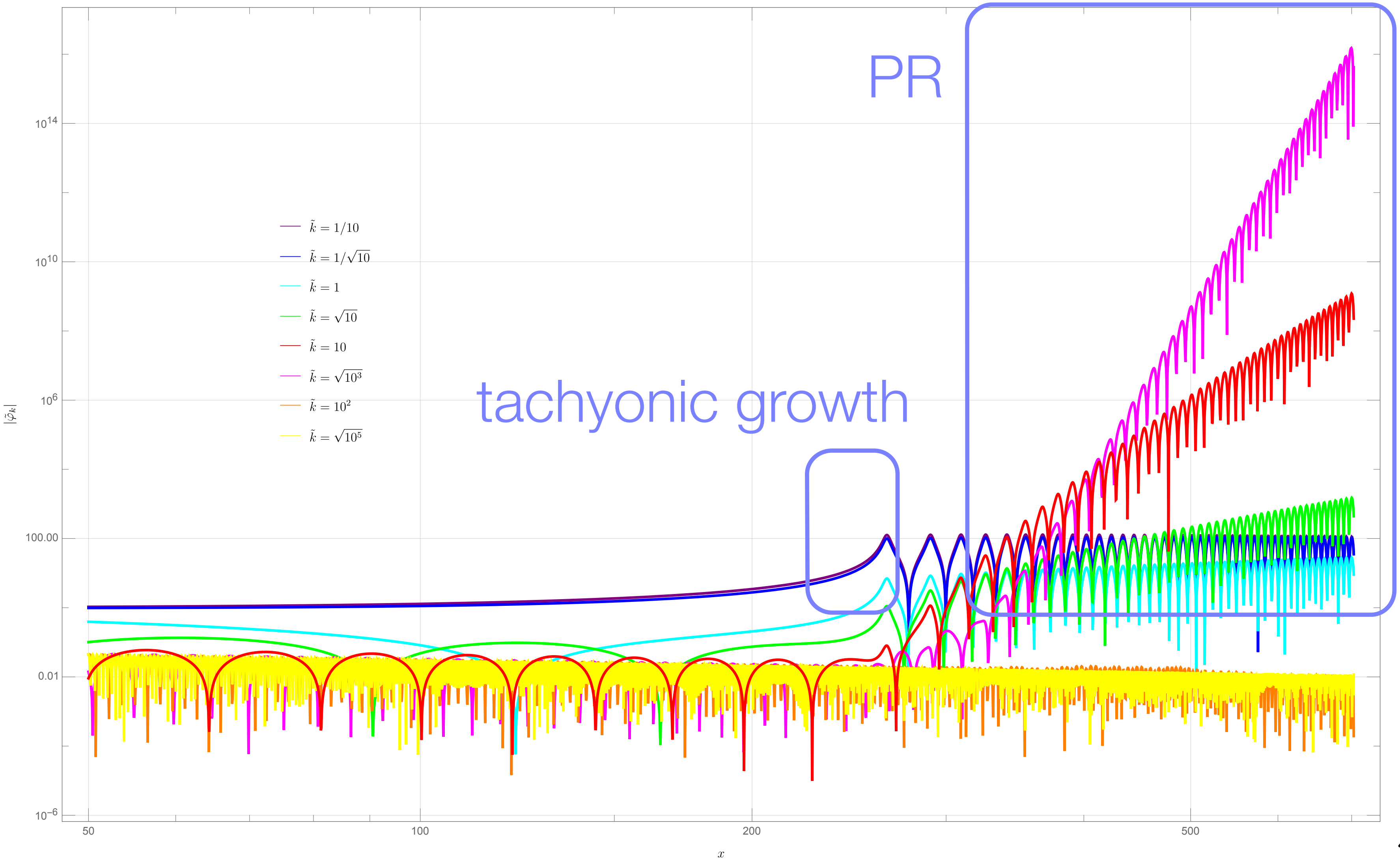
ex. First band $\tilde{\varphi} \propto e^{\gamma x}$ $\gamma \simeq q/2$

Energy transfer $\phi(t) \longrightarrow \delta\phi(t, x)$

Linear perturbation

Soda & Y.U.(17)

PR in $k_r/(a_{osc}\, m) \sim O(1)$, $k_r/(a_{osc}\, H) >> 1$

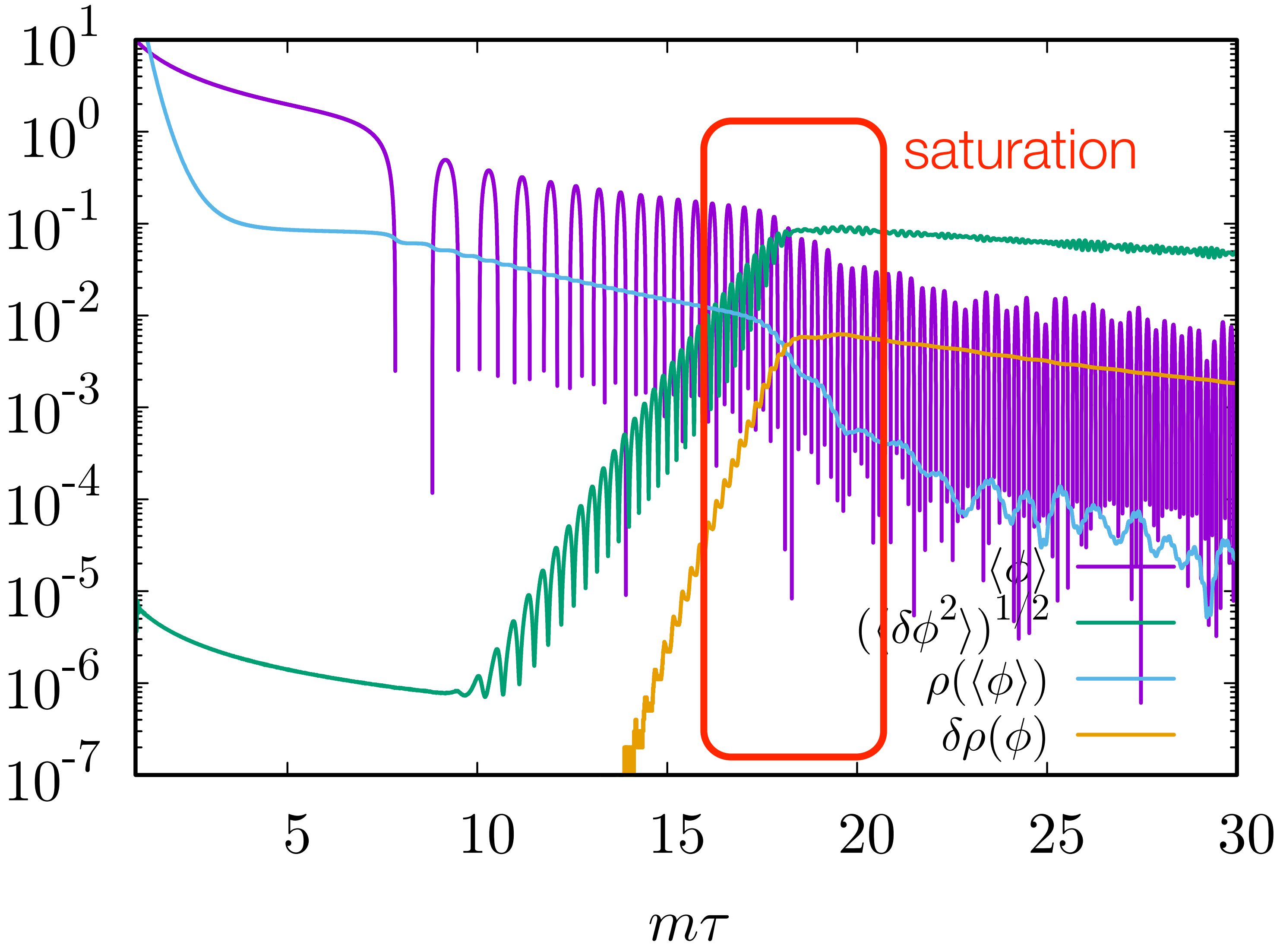


$\tilde{k} = k/(a_i m)$

Energy transfer

Kitajima, Soda & Y.U.(in prep.)

Lattice simulation $N_{grid}=(128)^3$



Outline of the story

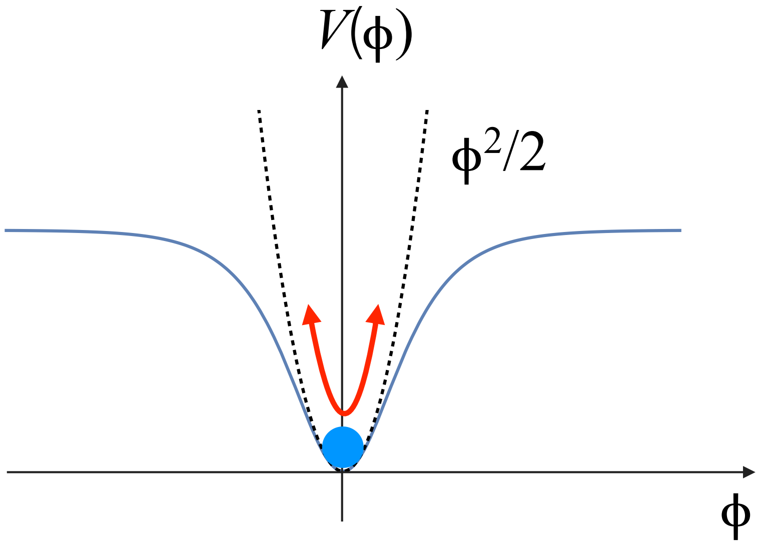
1. Axion slowly rolls in plateau

2. Onset of oscillation $H_{osc}/m < 1$

3. Exponential growth due to PR

if $H_{osc}/m < 1$

Energy transfer $\phi(t) \longrightarrow \delta\phi(t, x)$



4. Rescattering → PR becomes inefficient *eg. Kofman, Linde, Starobinsky*

$$\frac{\delta\phi}{\phi}, \frac{\delta\rho}{\rho} \sim O(1)$$

Outline of the story

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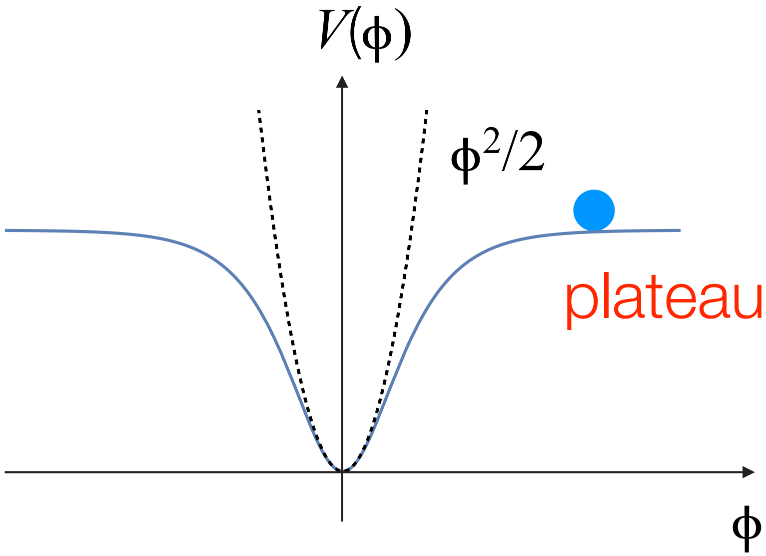


if $H_{osc}/m < 1$ No disturbance due to cosmic exp.

4. Rescattering → PR becomes inefficient *eg. Kofman, Linde, Starobinsky*

5. Turbulence turbulence → GW emission

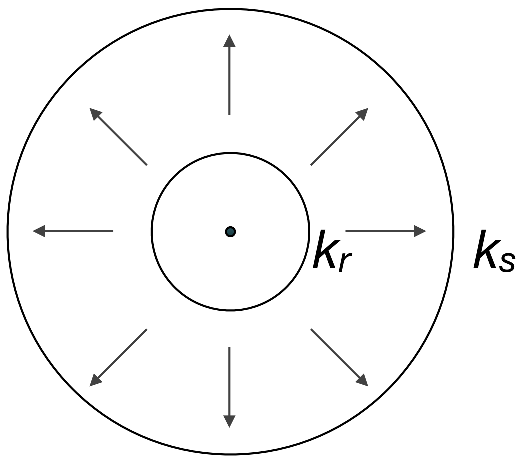
Micha & Tkachev (02,04)

see also Caprini & Durrer(06)

Kolmogorov turbulence

stationary turbulence: source k_r (IR) → sink k_r (UV)

in k-space

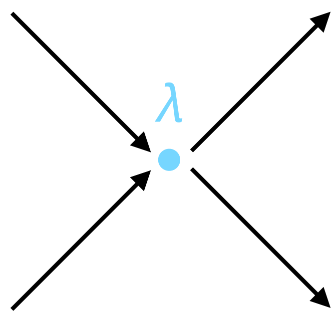


kinetic theory $dn_k/dt = I_k[n]$

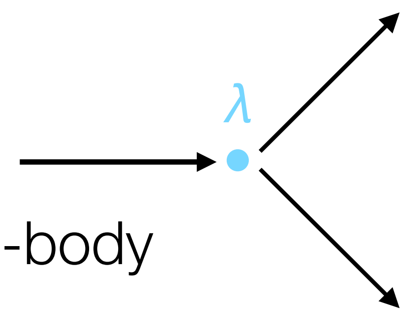
Collision integral

take $\lambda\phi^4$ theory, now w/ $\phi(t)$

4-body



3-body



assump: const. flux in k for massless ϕ

Micha & Tkachev (02,04)

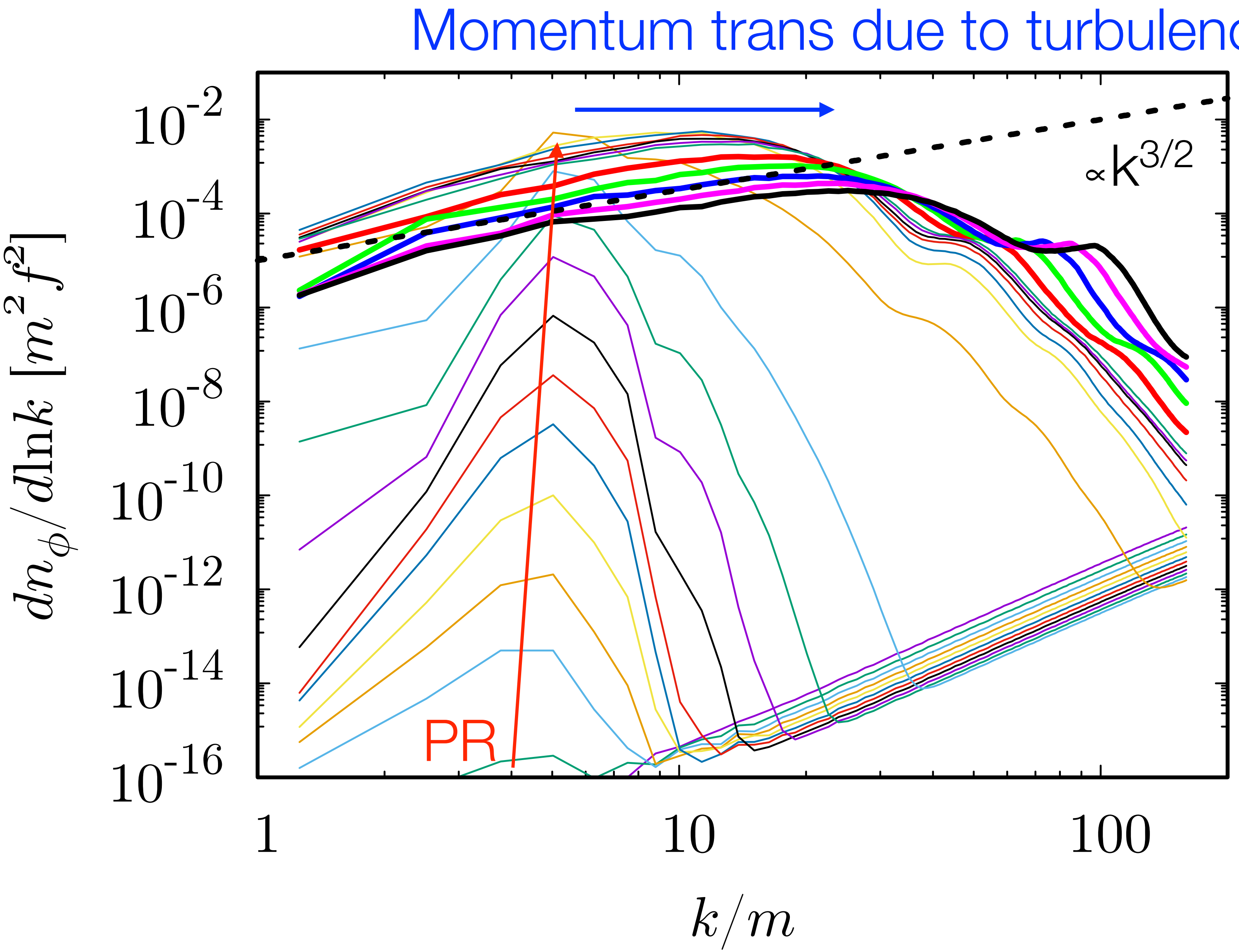
$$dn/d\ln k = k^3 n(k) \propto k^{3-s}$$

$s=5/3$ for 4-body

$s=3/2$ for 3-body

Lattice simulation

Kitajima, Soda, Y.U. (in preparation)



3-body scattering

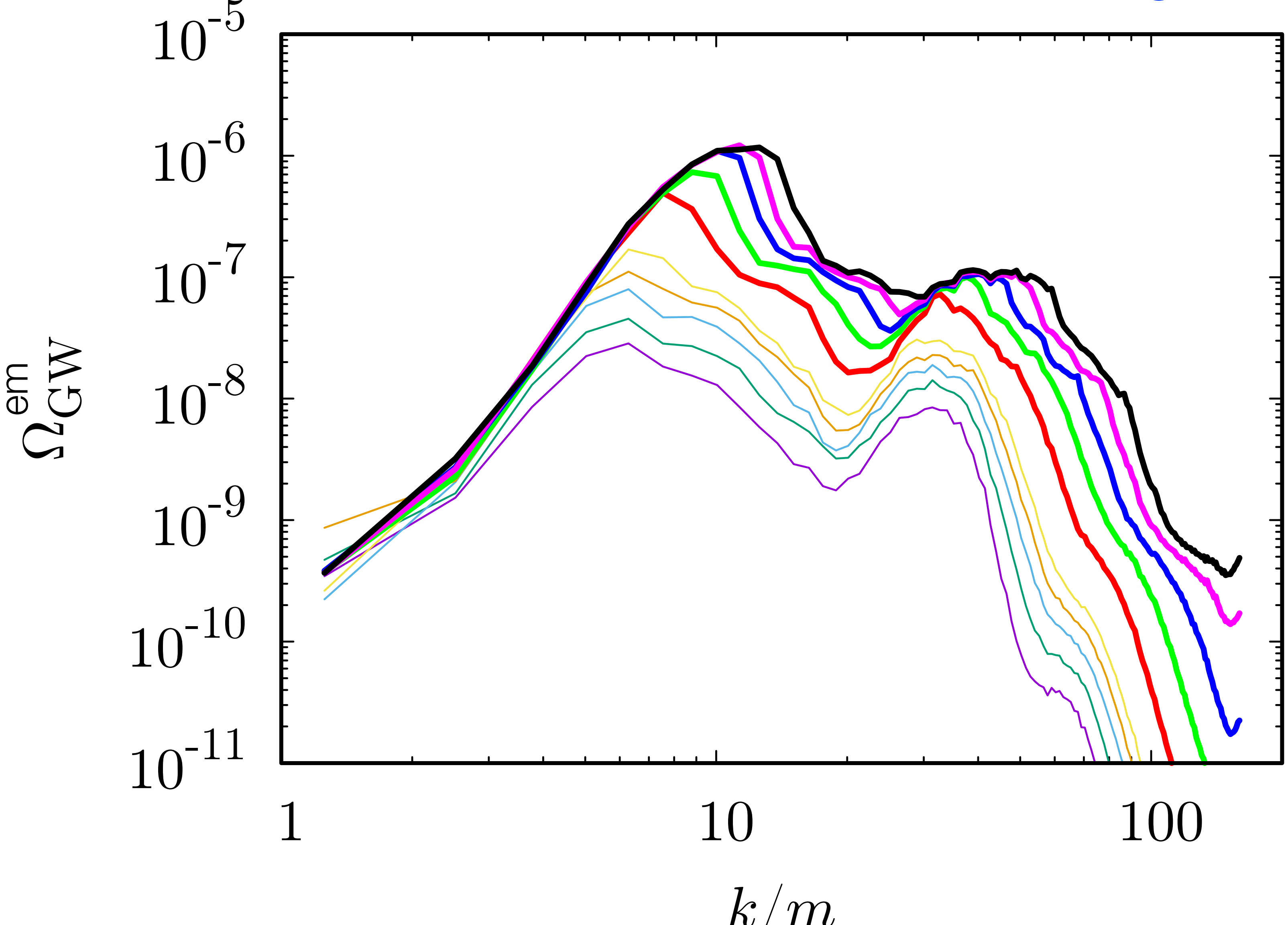
$\phi(t) \neq 0$

$N_{grid}=(256)^3$

GW spectrum

Kitajima, Soda, Y.U. (in preparation)

momentum transfer converges earlier for GW

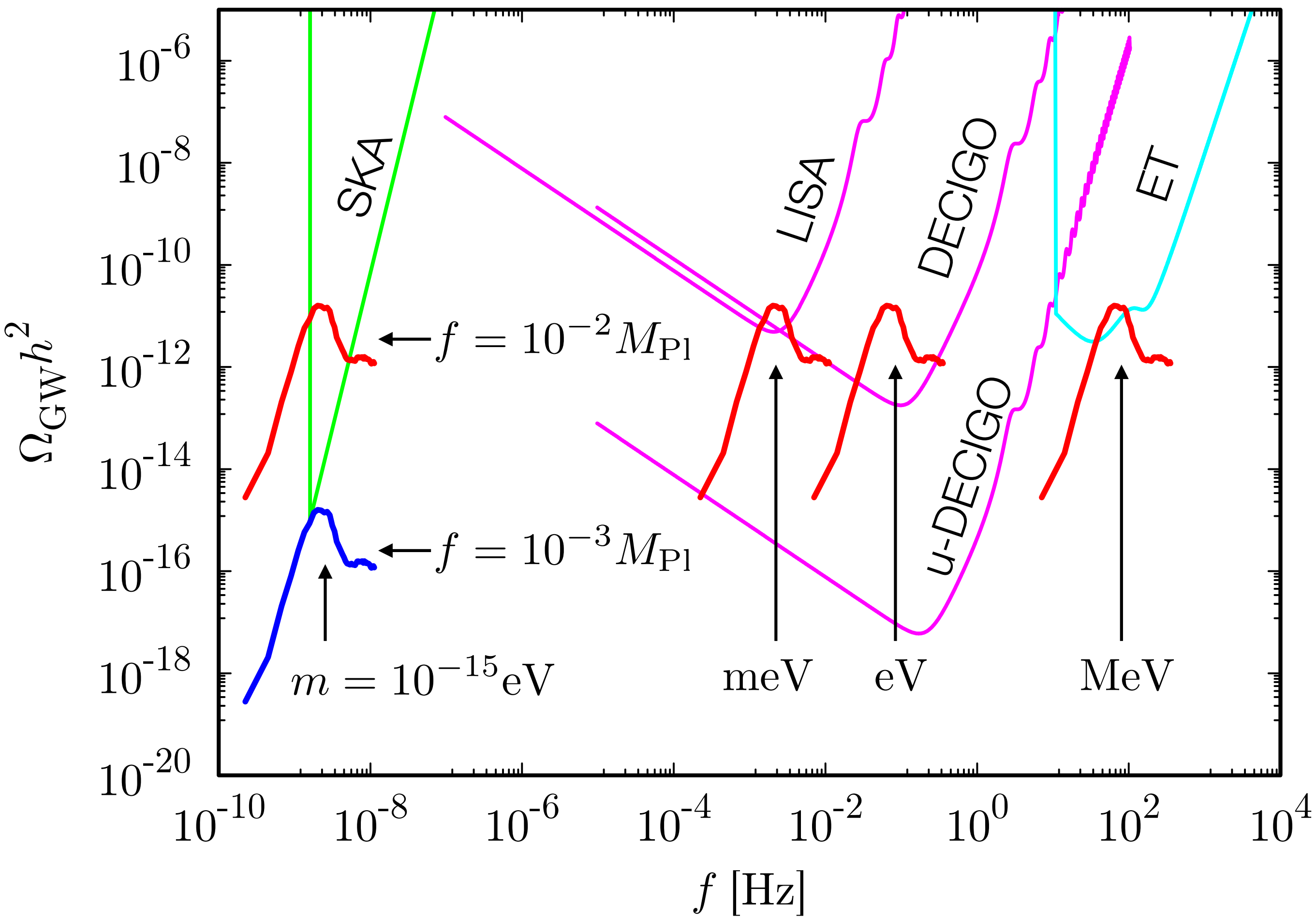


$f \sim 0.01 M_{pl}$

$\times \Omega_r$ at present

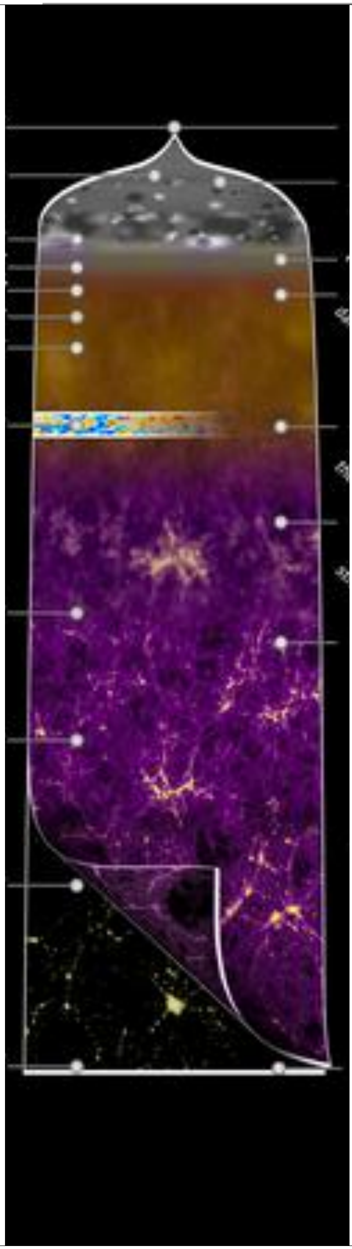
New window of string axiverse

Kitajima, Soda, Y.U. (in preparation)



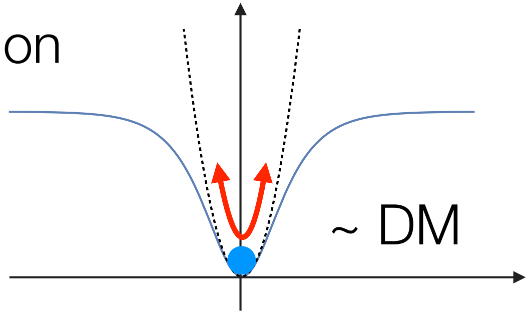
Axions from string theory $\boldsymbol{f}\sim 10^{15}\text{-}10^{16}$ GeV e.g.,Svrcek & Witten (06)

Plateau phenomenology: ϕ = DM



← Onset of oscillation

← Equal time



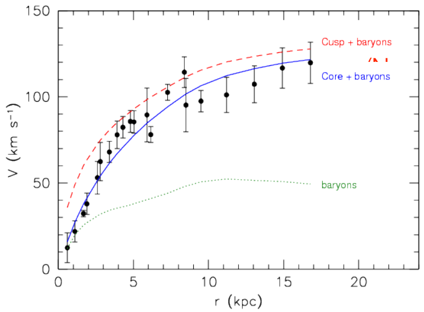
H/m << 1

$\phi(t)$ ⟶ $\delta\phi(t, x)$

inst. turbulence

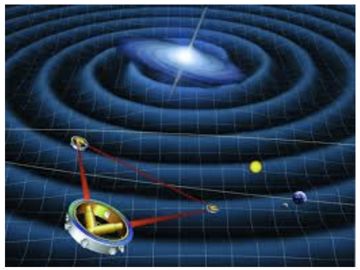
(b)GW

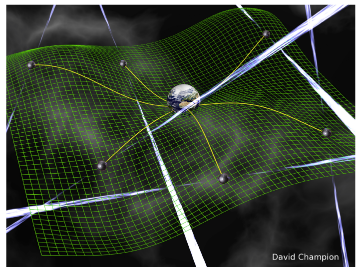
if $\Omega_c \sim \Omega_{axion}$



implications to small scales issues?

axion ~~bio~~-marker





GWs from axion DM

preliminary

Kitajima, Soda, Y.U. (in preparation)

Lattice sim. $\Omega_{GW} \sim 10^{-10} \times (f/0.01M_p)^4$

Abundance of axion

freq. of GW f_0 ⟶ mass m

+

abundance of axion ⟶ decay const. f

Crude Order estimation

using $\varphi(t, x) \sim f\,(a_{osc}/a)^{3/2}$

$\beta_\phi = \Omega_\phi/\Omega_c \leqq 1$

$$\Omega_{GW} \simeq 3.41 \times 10^{-16} \Delta^2 \left(\frac{\mathrm{nHz}}{f_0}\right)^2 \left(\frac{\kappa}{10}\right)^4 \beta_\phi^2$$

Δ : Sym. suppression (< 1)

$\kappa = k_{peak}/m$

e.g., α - attractor $\Delta^2 \sim 0.2$, $\kappa = 12$

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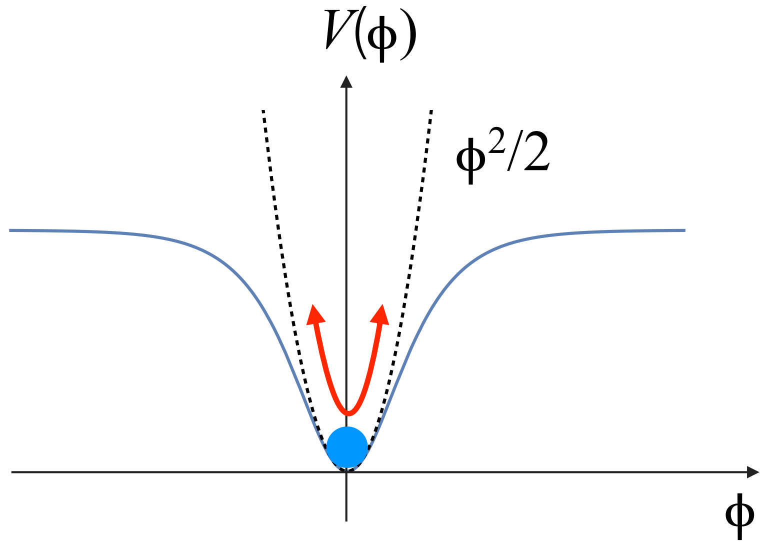


2. Onset of oscillation $H_{osc}/m < 1$

3. Exponential growth due to PR

if $H_{osc}/m < 1$

No disturbance due to cosmic exp.

4. Rescattering → PR becomes inefficient *eg. Kofman, Linde, Starobinsky*

5. Momentum transfer due to turbulence → GW emission

Micha & Tkachev (02,04)

6. GW&ϕ decoupled, Oscillon/I-ball formation

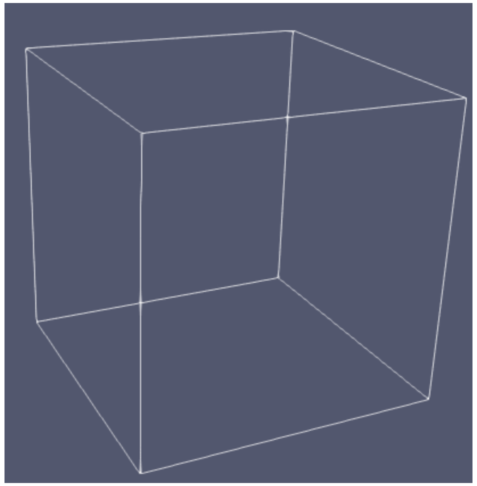
Gleiser(94), Kasuya+(03),Amin + (10, 12, 17),⋯.

Oscillon formation

Preliminary

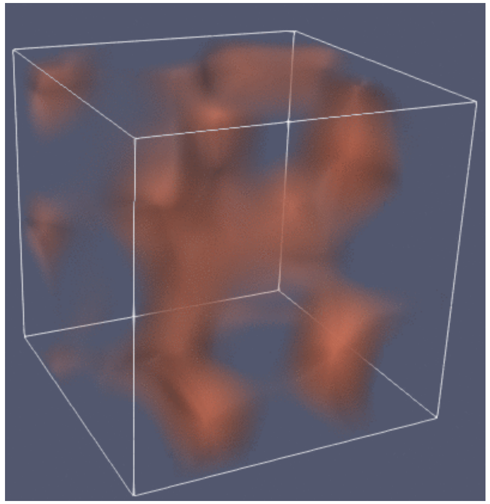
Kitajima, Soda, Y.U. (in preparation)

$a \sim a_0$



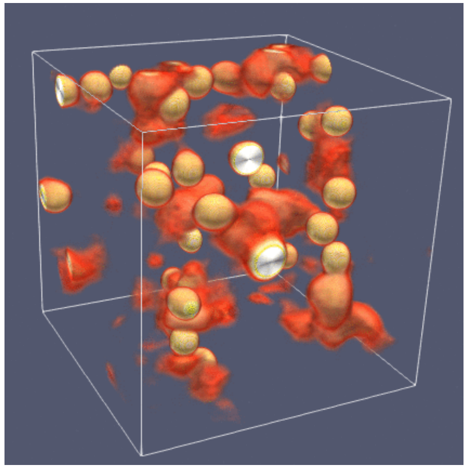
$a \sim 20\, a_0$

rescattering



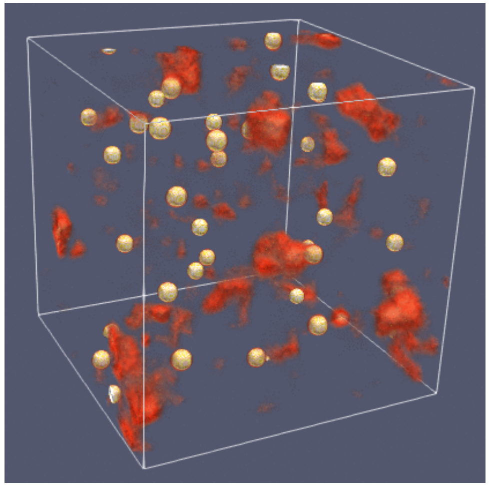
$a \sim 35 a_0$

turbulence



$a \sim 90\, a_0$

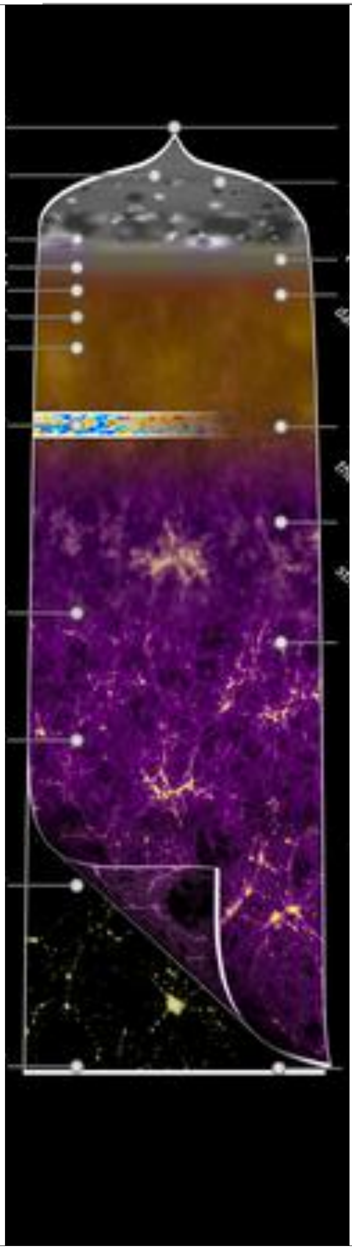
oscillon



$N_{grid}=(128)^3$

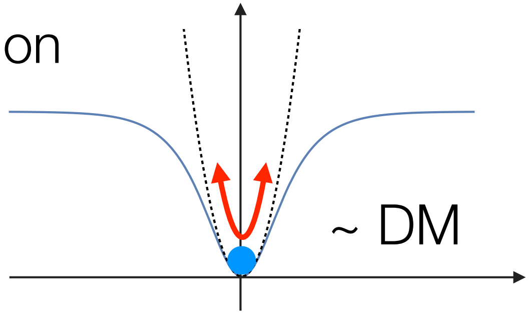
$$c = 5,\ \ \phi_i/f = 10,\ \ \rho/\langle\rho\rangle > 2\ \ \text{(red)},\ \ 10\ \ \text{(yellow)}$$

Plateau phenomenology: ϕ = DM



← Onset of oscillation

← Equal time



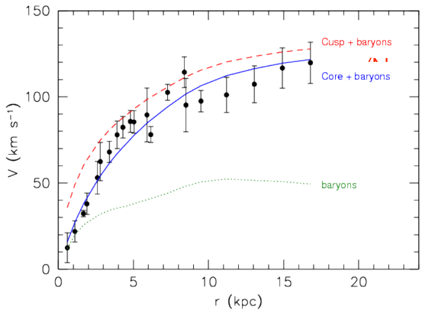
$H/m << 1$

$\phi(t) \longrightarrow \delta\phi(t, x)$

inst. turbulence

(b)GW

if $\Omega_c \sim \Omega_{axion}$



implications to small scales issues?

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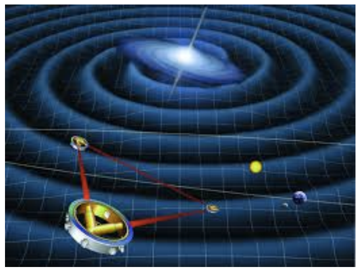
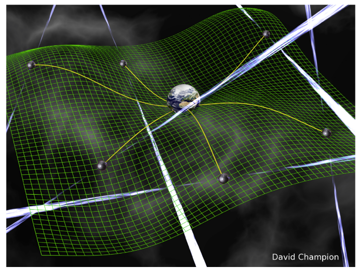




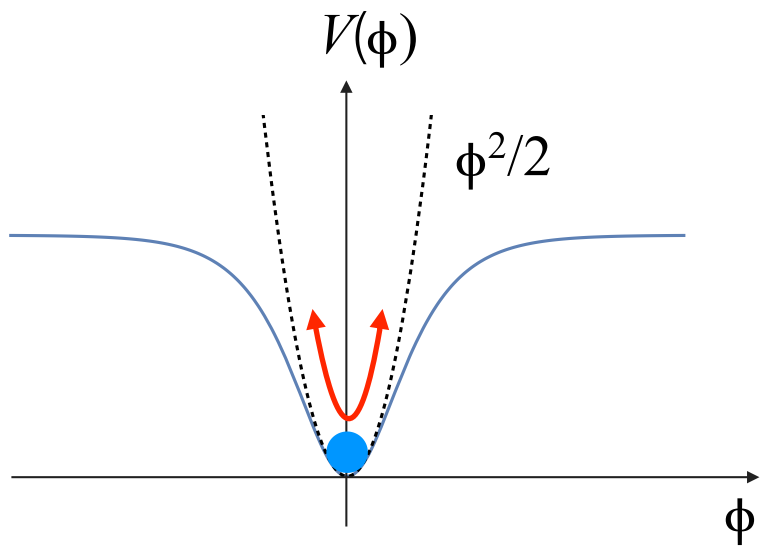
Outline of the story

1. Axion slowly rolls in plateau

2. Onset of oscillation $H_{osc}/m < 1$

3. Exponential growth due to PR

if not $H_{osc}/m << 1$



4. PR finished due to red-shift

Yet, for DM= axion, imprints on structure formation

Resonance peak in spectrum

Future issues: More on ϕ=DM

Alternative solution to small scale issues of ΛCDM??

ULA w/ $m \sim 10^{-22} eV$

→ Emergent pressure smooths at $k > k_J$

k_J : Jeans scale

→ Tension with small scale observations? Recall Takeshi's talk

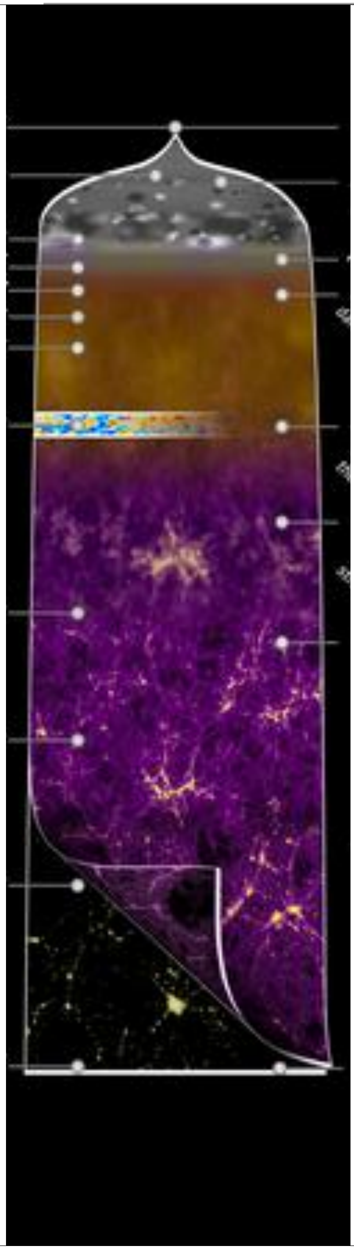
Irsic et al. (17), Kim et al. (17), ⋯ for $\lambda = 0$

Non-negligible impact of self-interaction

Zhang&Chiueh(17), Schieve&Chiueh(17), Desjacques + (17)

Resonance scale $k_r > k_J \propto a^{1/4}$ Evade tension?

Summary



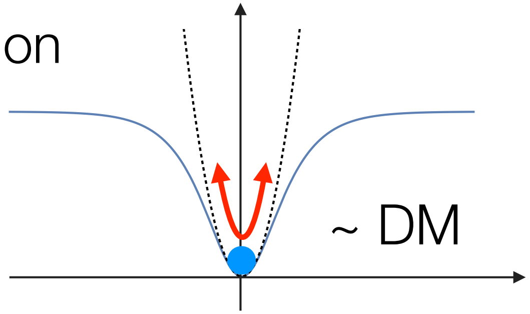
Onset of oscillation

Equal time

$\phi(t)$ → $\delta\phi(t, x)$

inst.

turbulence

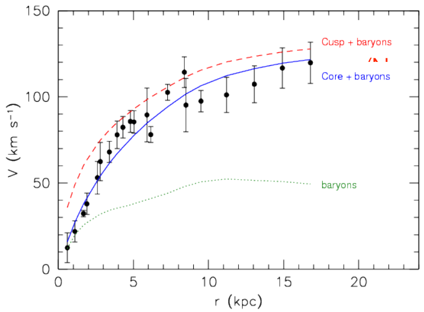


~ DM

H/m << 1

(b)GW

if $\Omega_c \sim \Omega_{axion}$



implications to small scales issues?

axion

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