Oscillons and Dark Matter

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IFAE Barcelona

Talk based on: J.Ollé, O. Pujolàs, FR; **1906.06352**

25
1991-2016
Institut de Física d'Altes Energies

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University of Sussex, 08/07/2019

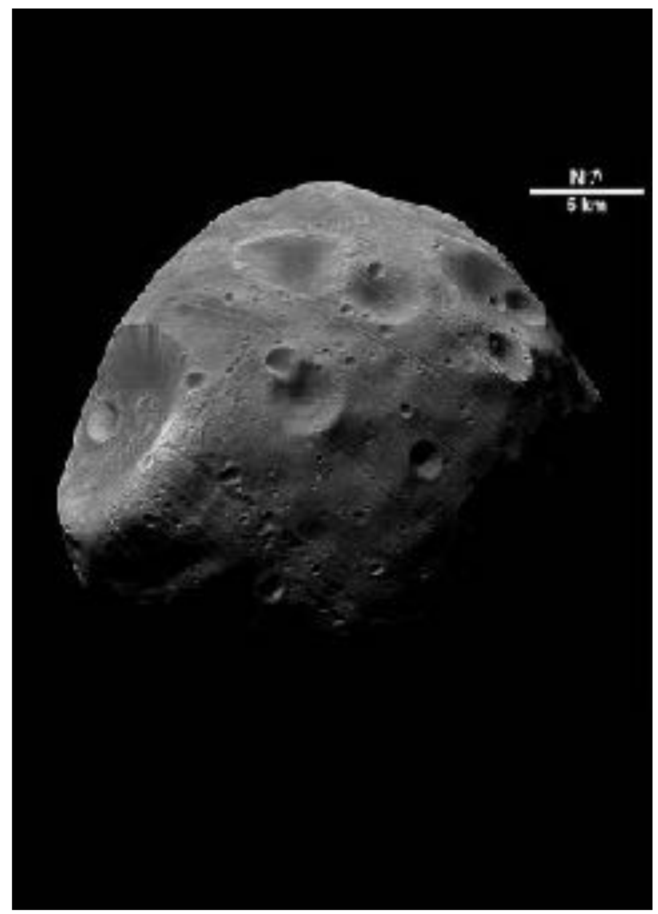
Outline

- Utra-Light scalar Dark Matter (ULDM)
- Attractive self-interactions
- Oscillon biography
- Observational legacy

What we see

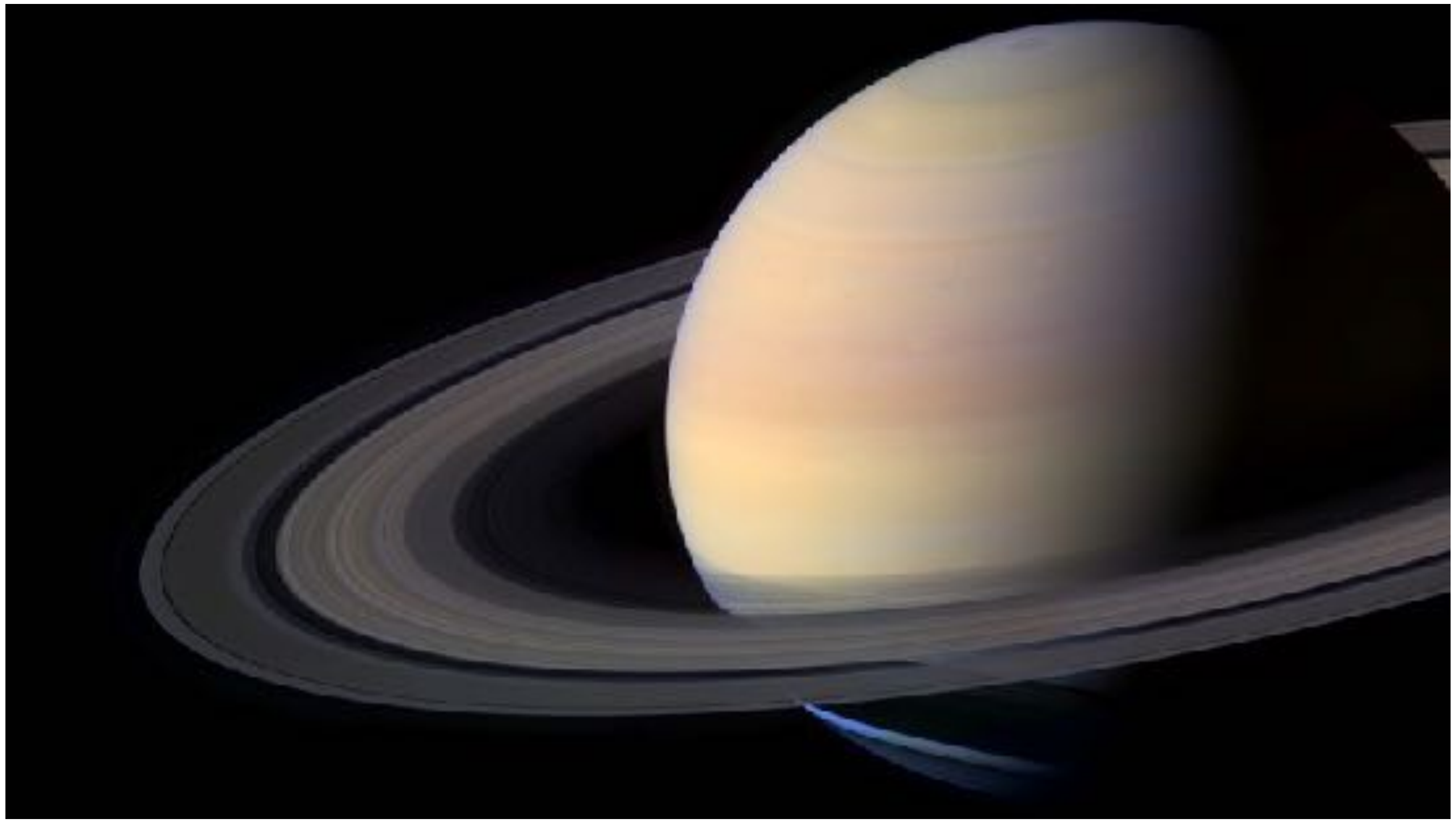
Visible structures in the Universe arise as **gravitational** bound states

What we see



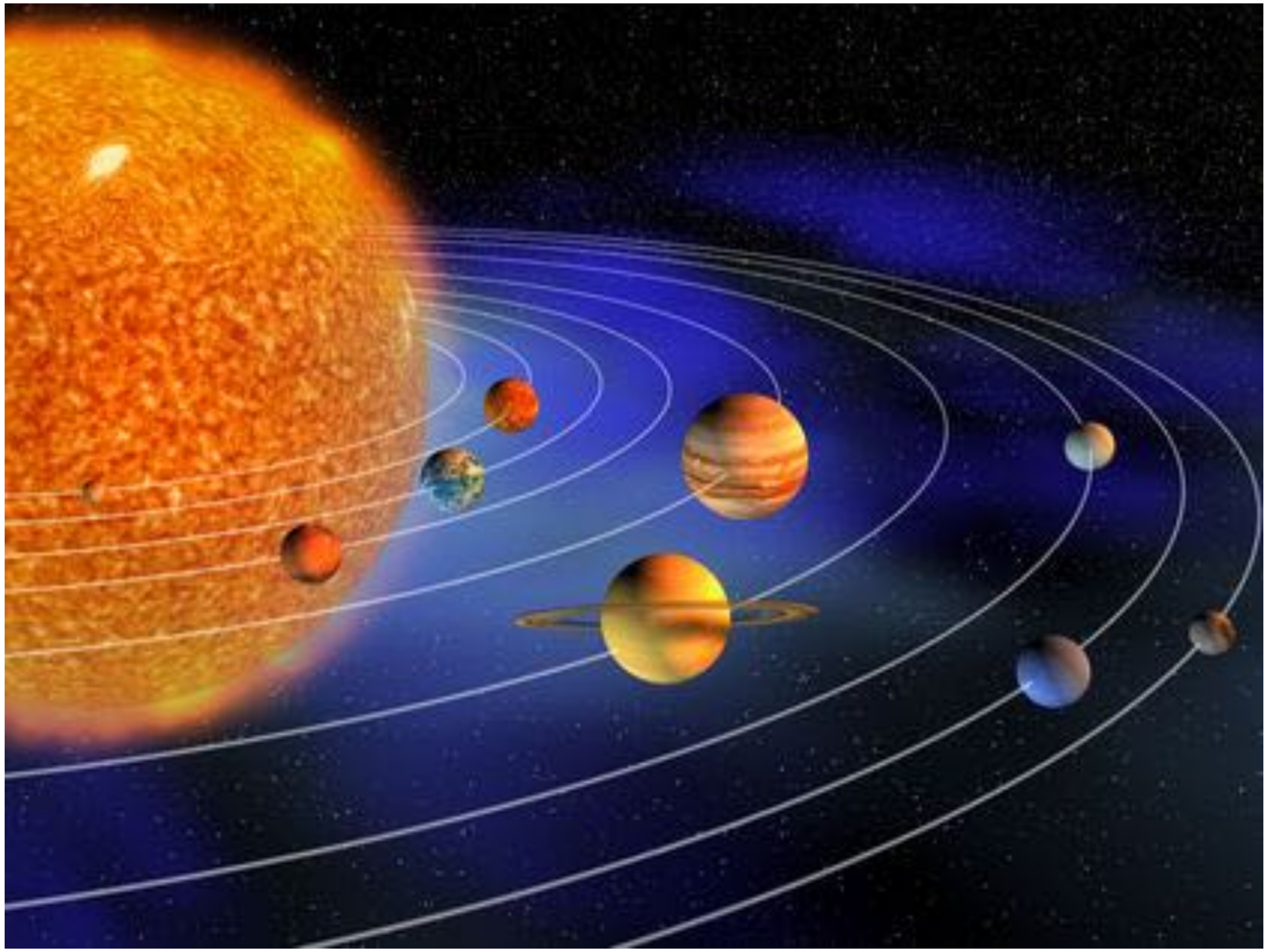
r~10 - 100 km

What we see



$r \sim 10^3$ - 10^4 km

What we see



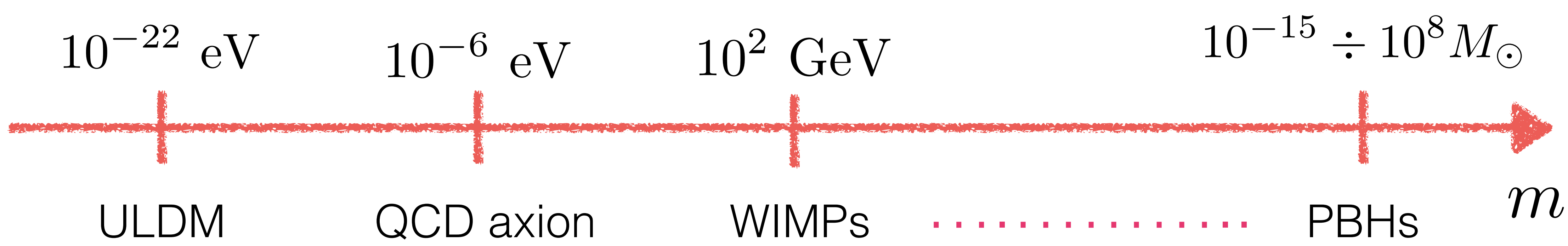
$r \sim 10^{10}$ km $\sim 10^{-3}$ pc

What we see

$r \sim 10^2$ pc -10 kpc

What we do not see/know

- What is the typical length/mass scale of Dark Matter (DM)?



- Does DM form **bound states**?

- Does DM experience **dark forces** (i.e. not gravity)?

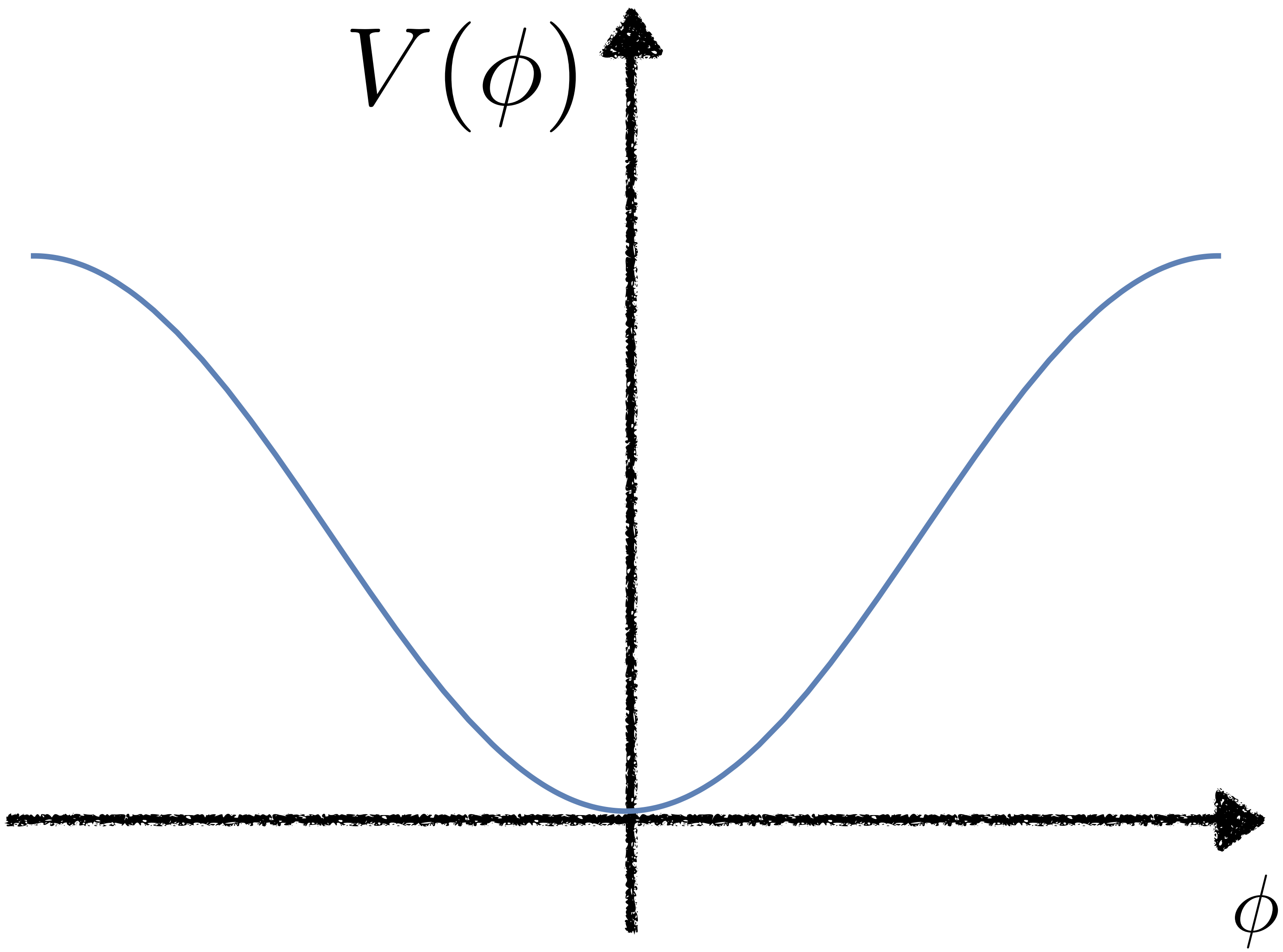
Small (scale) troubles

- Cold Dark Matter (CDM) paradigm works very well on **cosmological** scales (CMB, LSS, Lyman-$\boldsymbol{\alpha}$).

- On **sub-galactic** scales, N-body CDM simulations produce **cusps**, whereas observations show smooth **cores**.

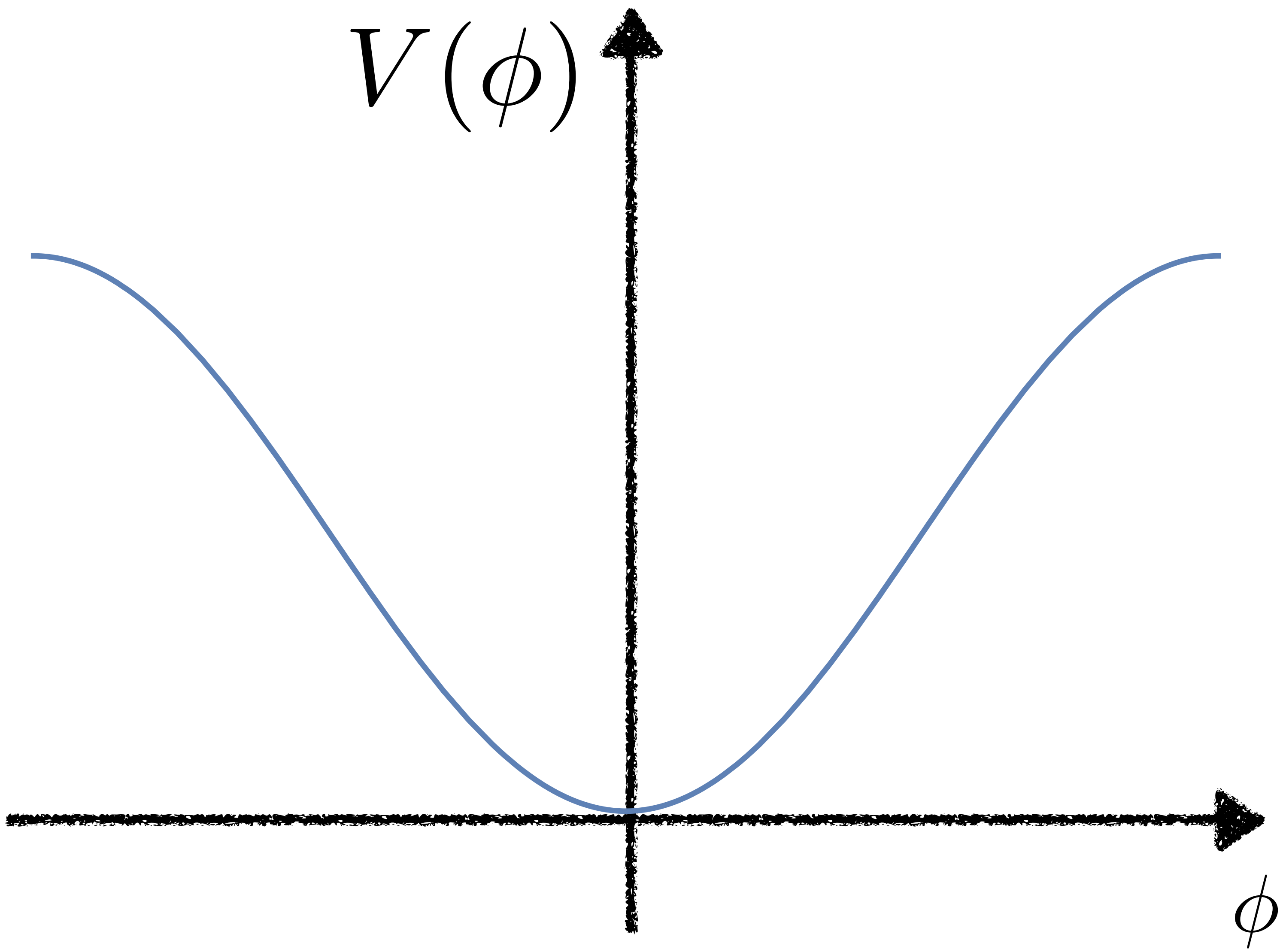
- Maybe simple pressureless CDM is not the whole story.

(Pseudo)Scalar Dark Matter



(Pseudo)Scalar Dark Matter

Motivation: simplicity/
strong CP/string
axiverse



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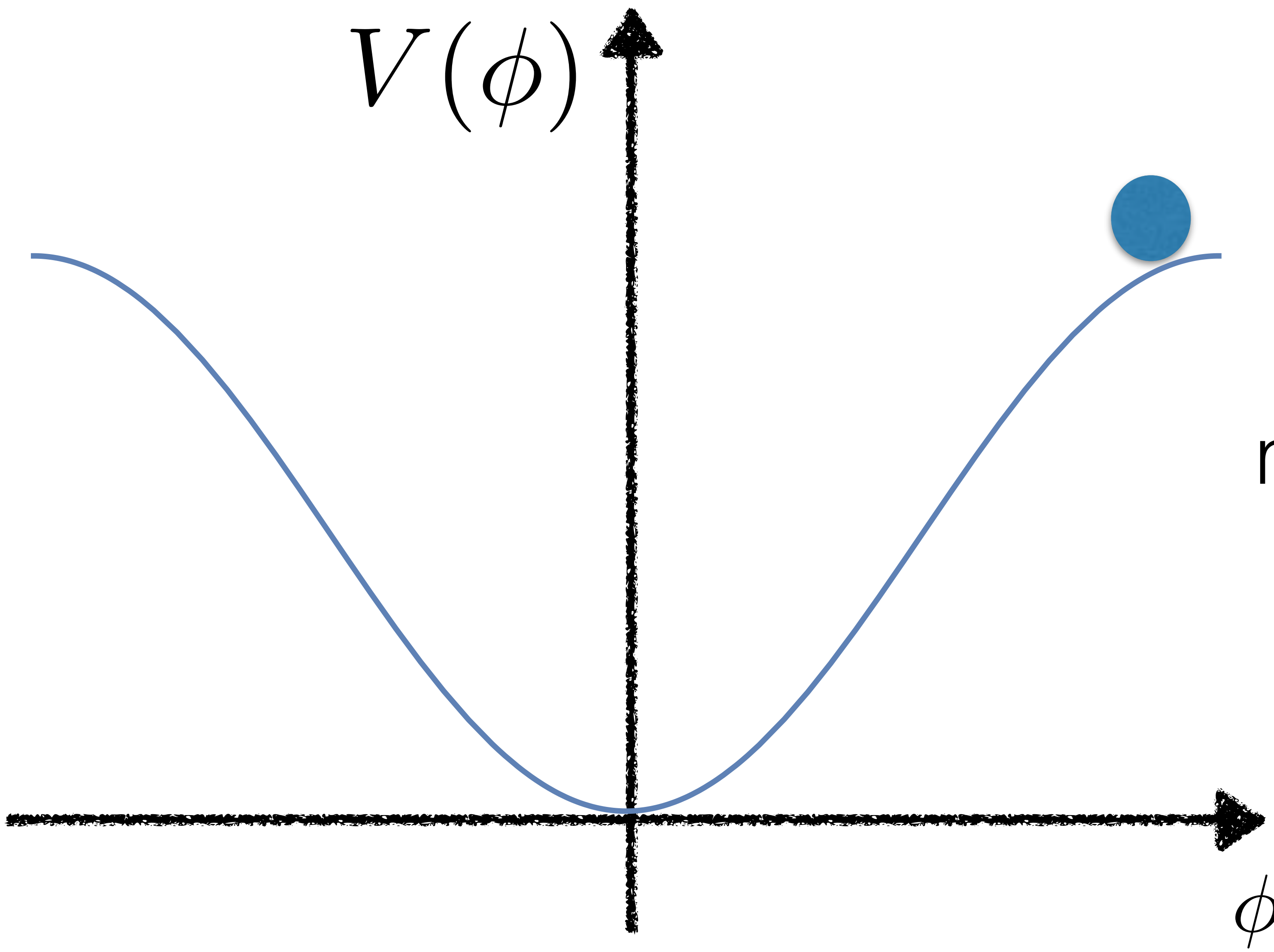
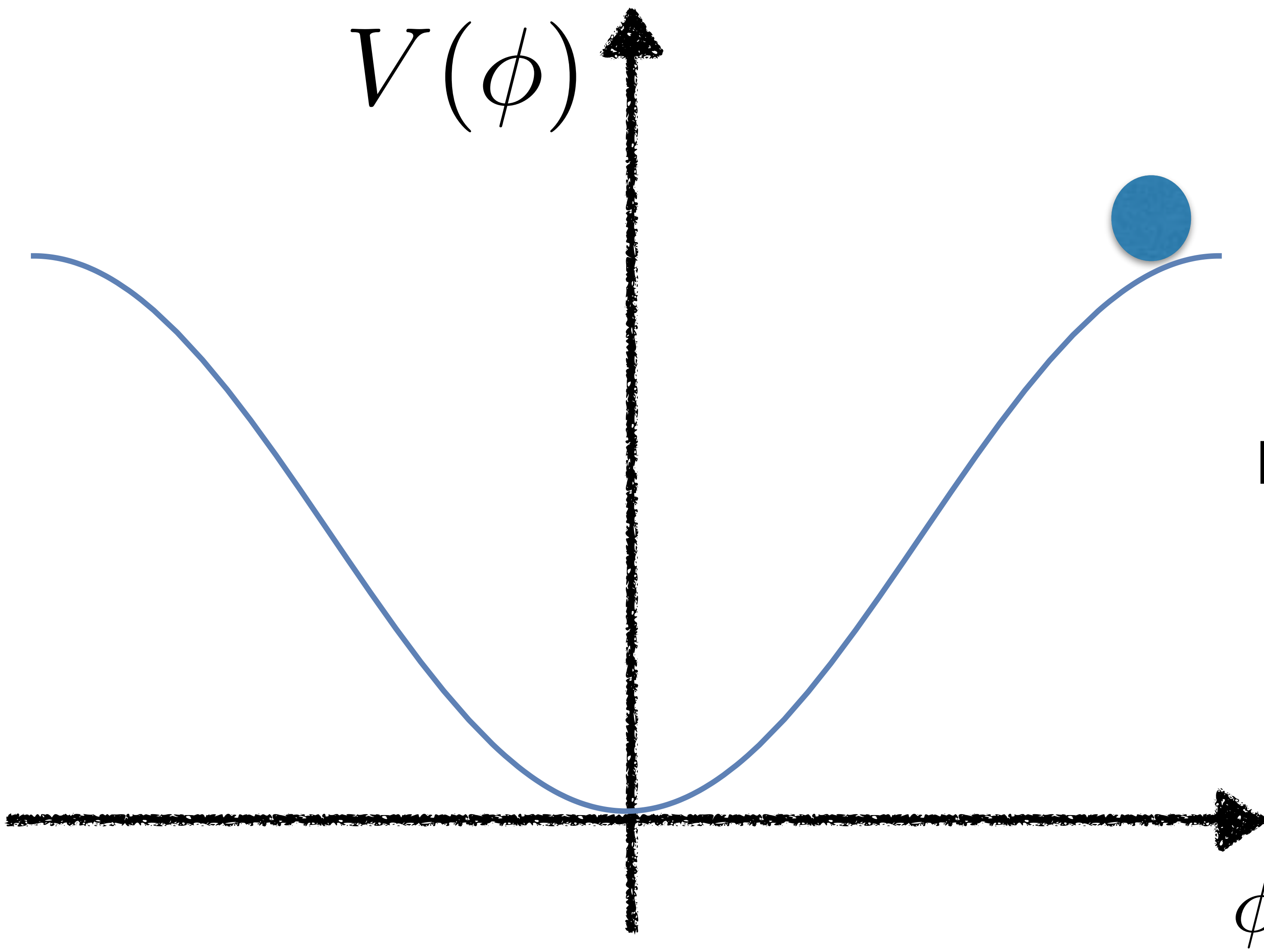


Initially
misaligned
$\phi_0 \sim F$

(Pseudo)Scalar Dark Matter

Motivation: simplicity/ strong CP/string axiverse

Oscillations start once $H(T) \simeq m$



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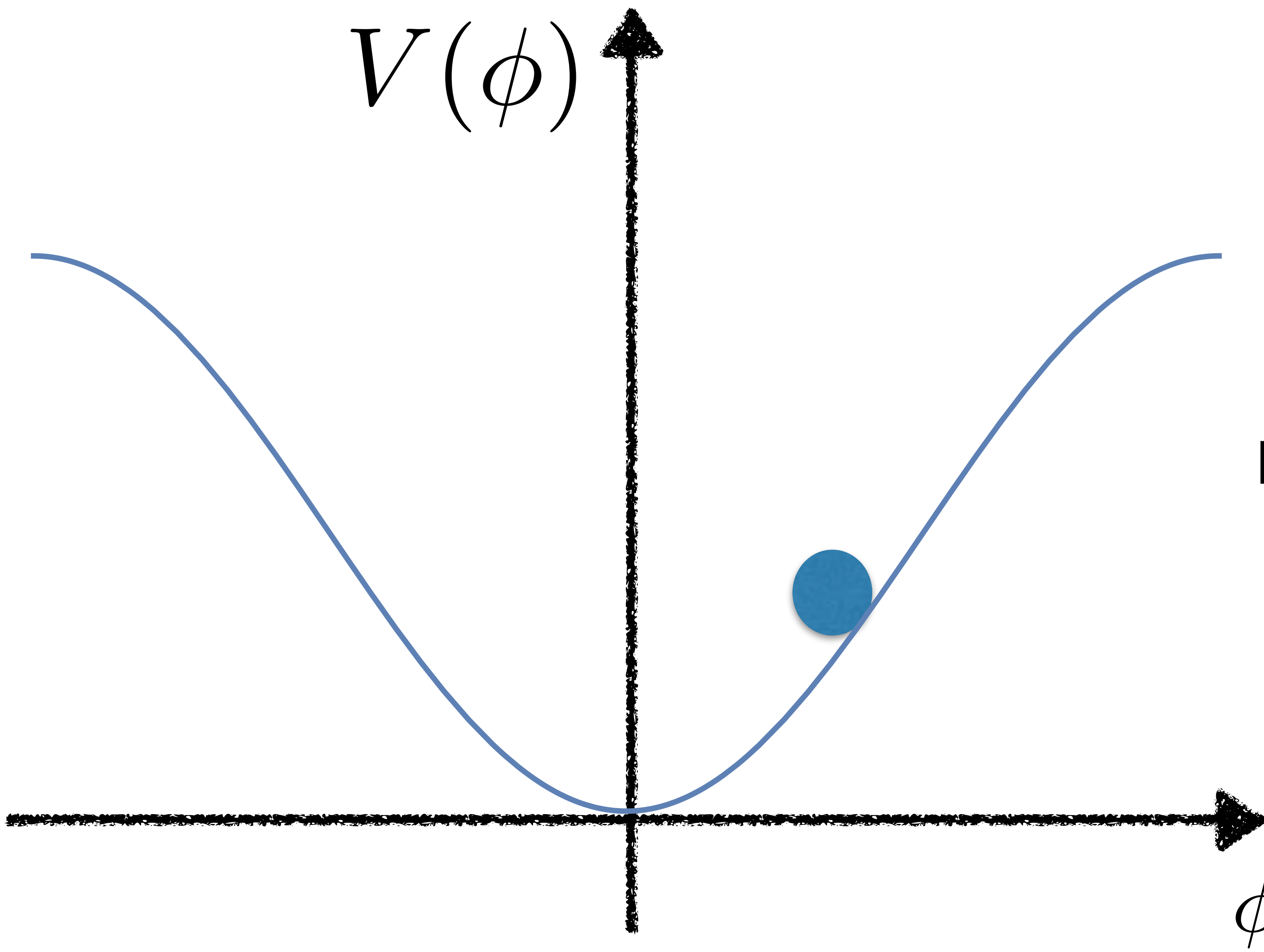

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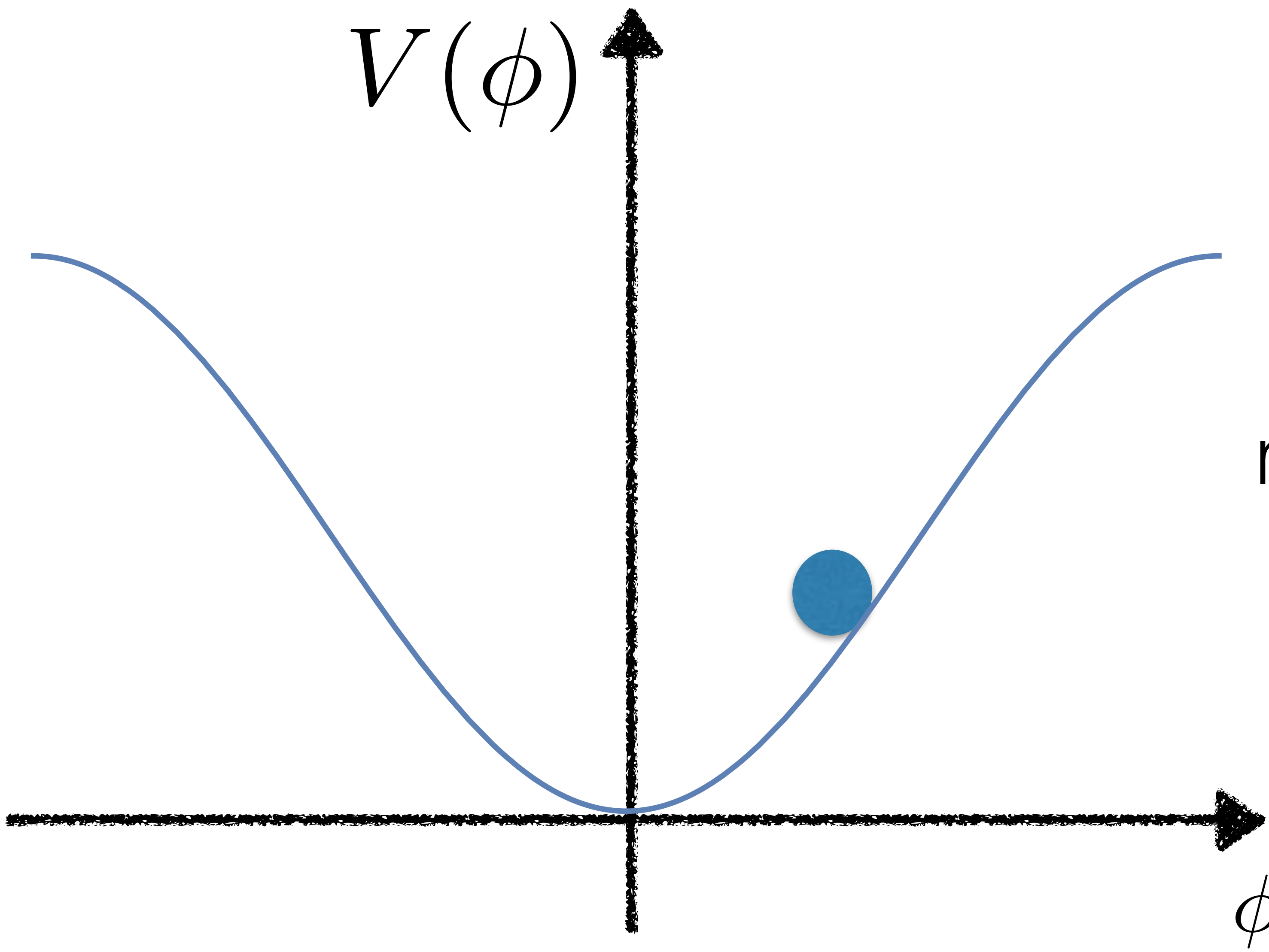


Initially
misaligned
$\phi_0 \sim F$

$\longrightarrow \rho_\phi \sim a^{-3}$

Ultra-Light scalar Dark Matter (ULDM)

- Particle de Broglie wavelength

$$\lambda_{dB} \approx 190 \text{ pc} \left(\frac{100 \text{ km/s}}{v} \right) \left(\frac{10^{-22} \text{ eV}}{m} \right)$$

- Galactic-core size for

$$m \sim 10^{-21} \text{ eV} \div 10^{-22} \text{ eV}$$

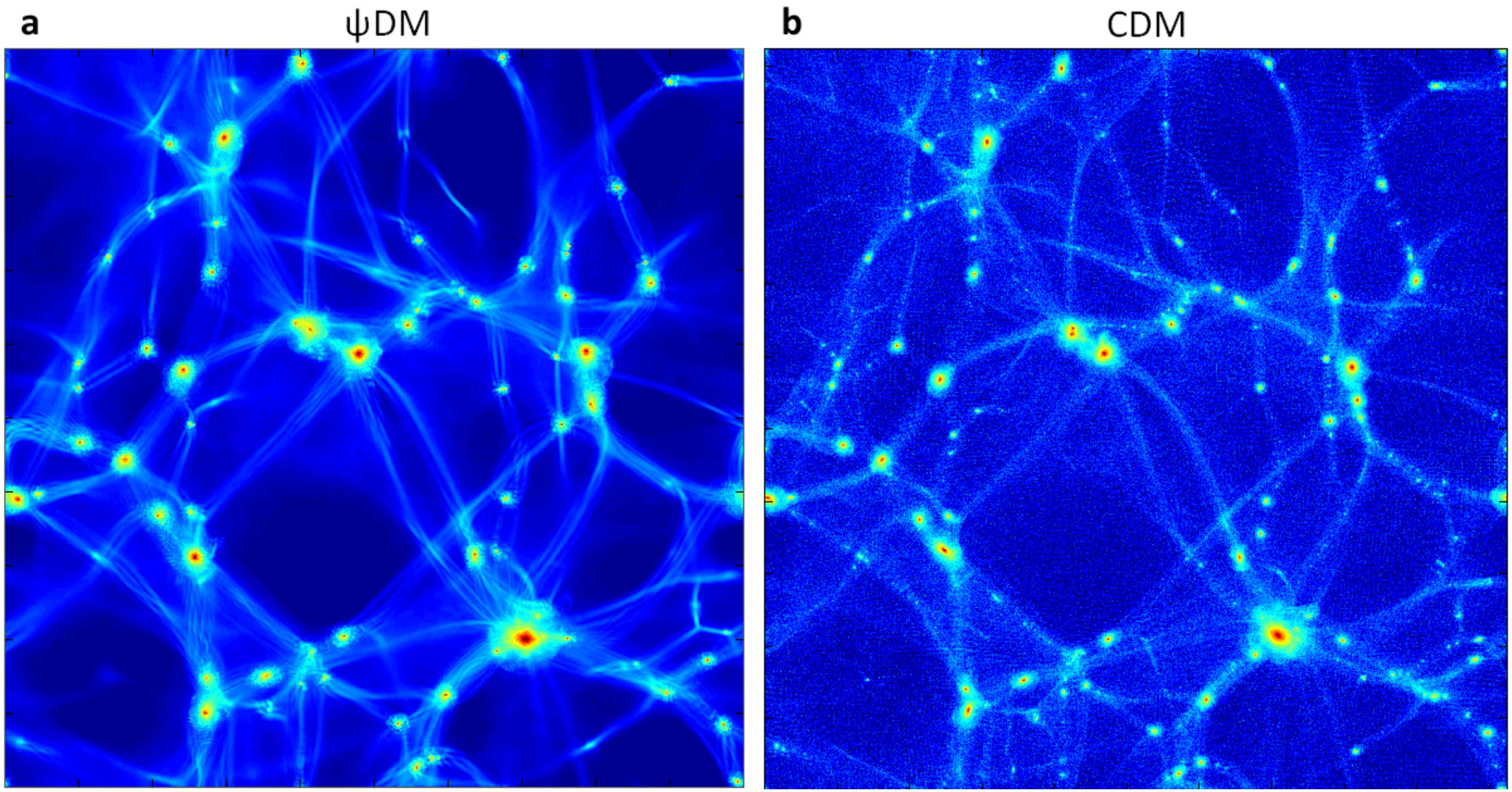
Fuzzy Dark Matter! Hu, Barkana, Gruzinov ’00/…/

Hui, Ostriker, Tremaine Witten ‘16

Pros of ULDM

Pros of ULDM

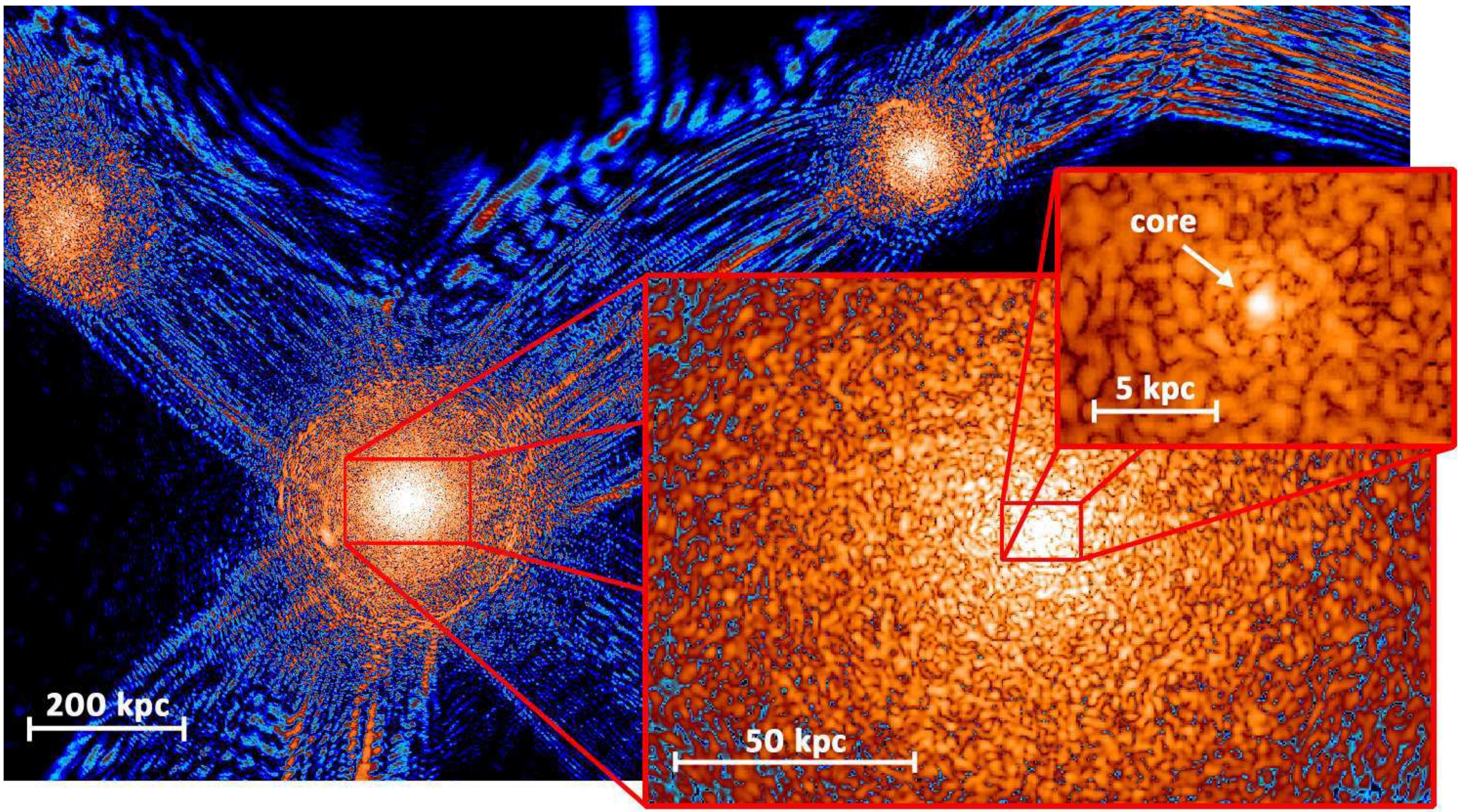
Schive, Chiueh, Broadhurst '14



Indistinguishable from CDM on cosmological scales

Pros of ULDM

Schive, Chiueh, Broadhurst '14



Develops cores on sub galactic scales!

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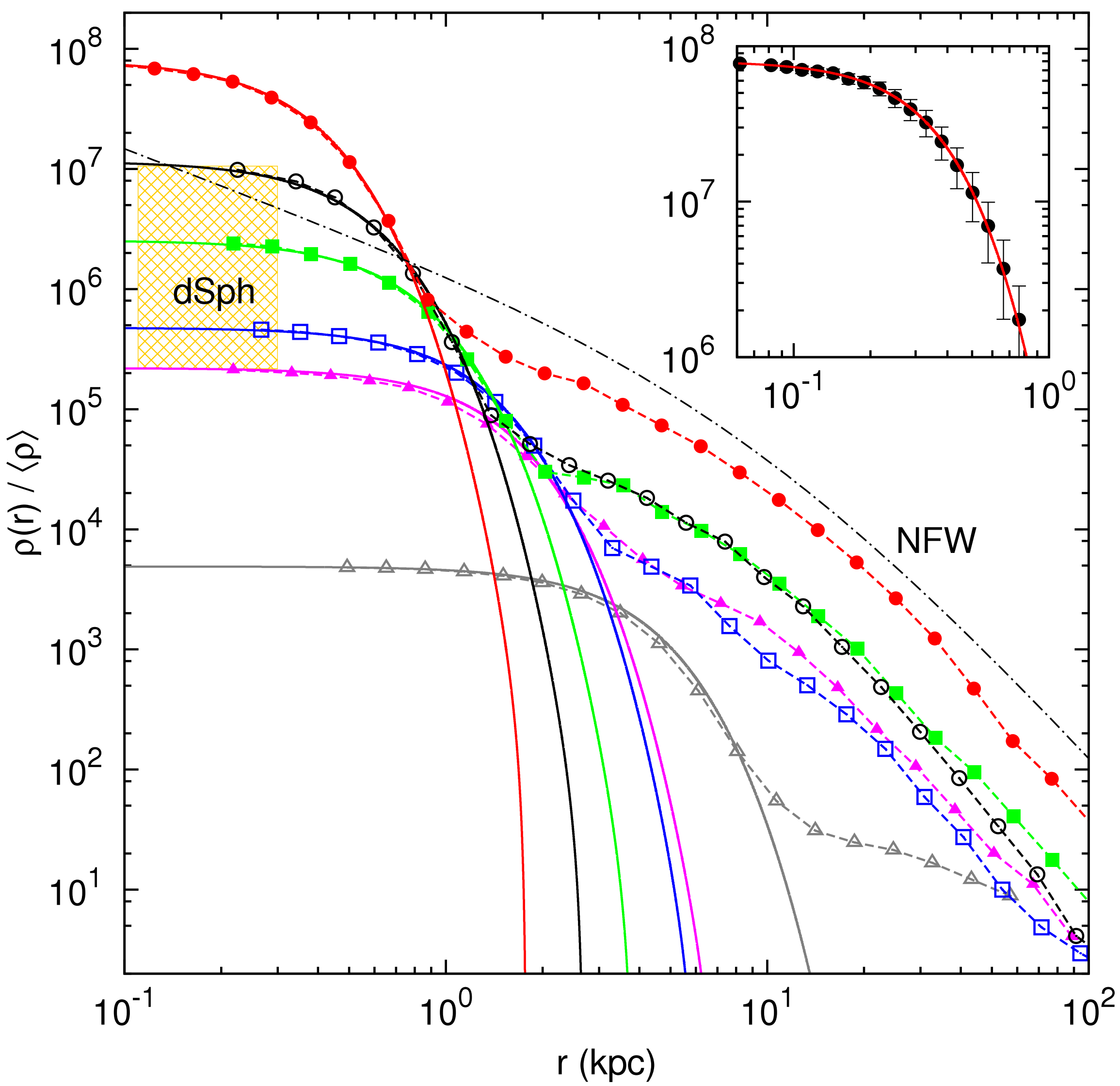

Develops cores on sub galactic scales!

Understanding the core

- **Non-relativistic** regime

$$\phi(x,t) = \frac{1}{\sqrt{2m}} e^{-imt}\psi(x,t) + \text{c.c.}$$

- Solve **Schrödinger-Poisson** equation

$$i\partial_t \psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi$$
$$\nabla^2\Phi = 4\pi G|\psi|^2$$

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Wave pressure

Gravity

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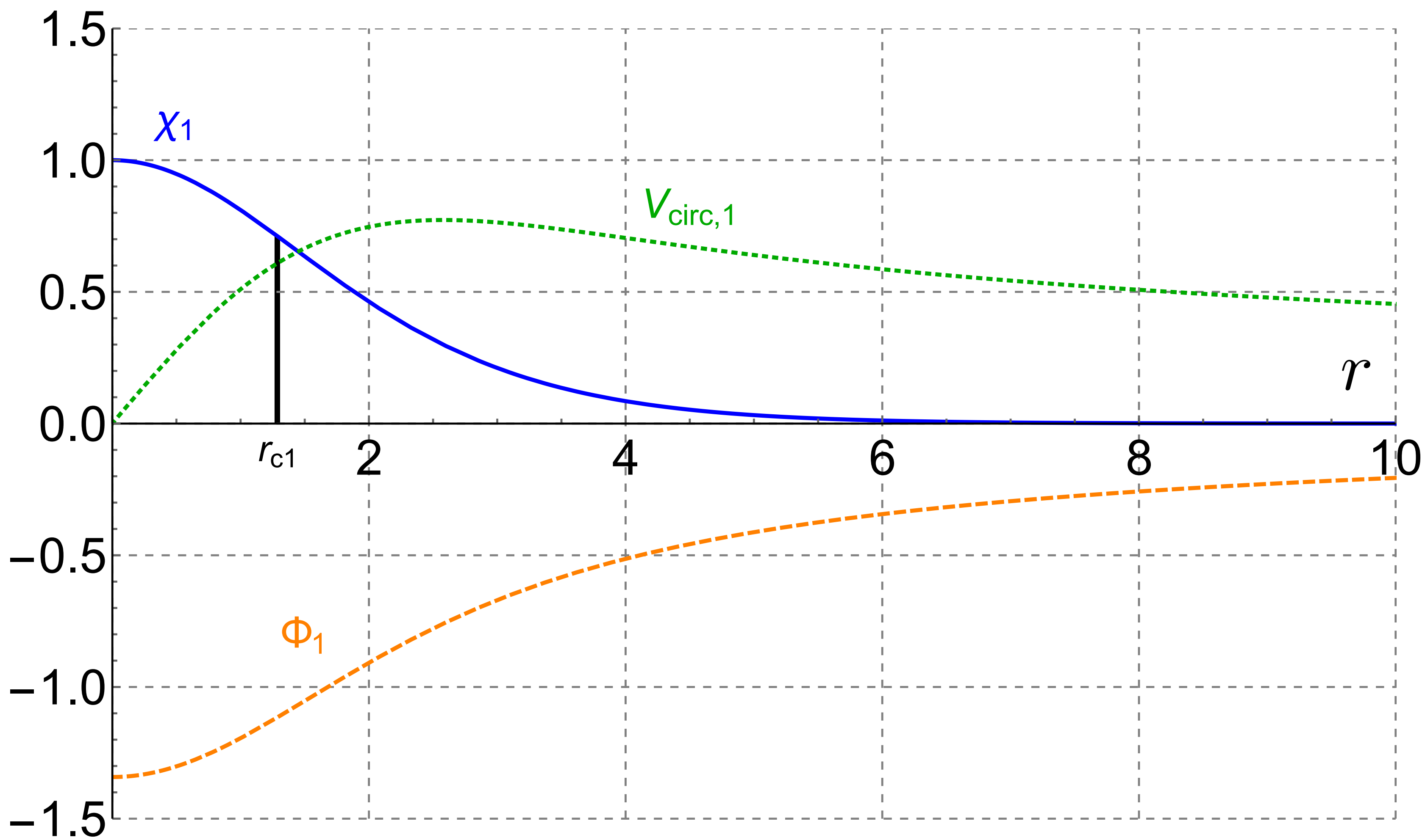
Wave pressure

Gravity

Solitonic Cores

Bar, Blas, Blum, Sibiryakov ‘ 18

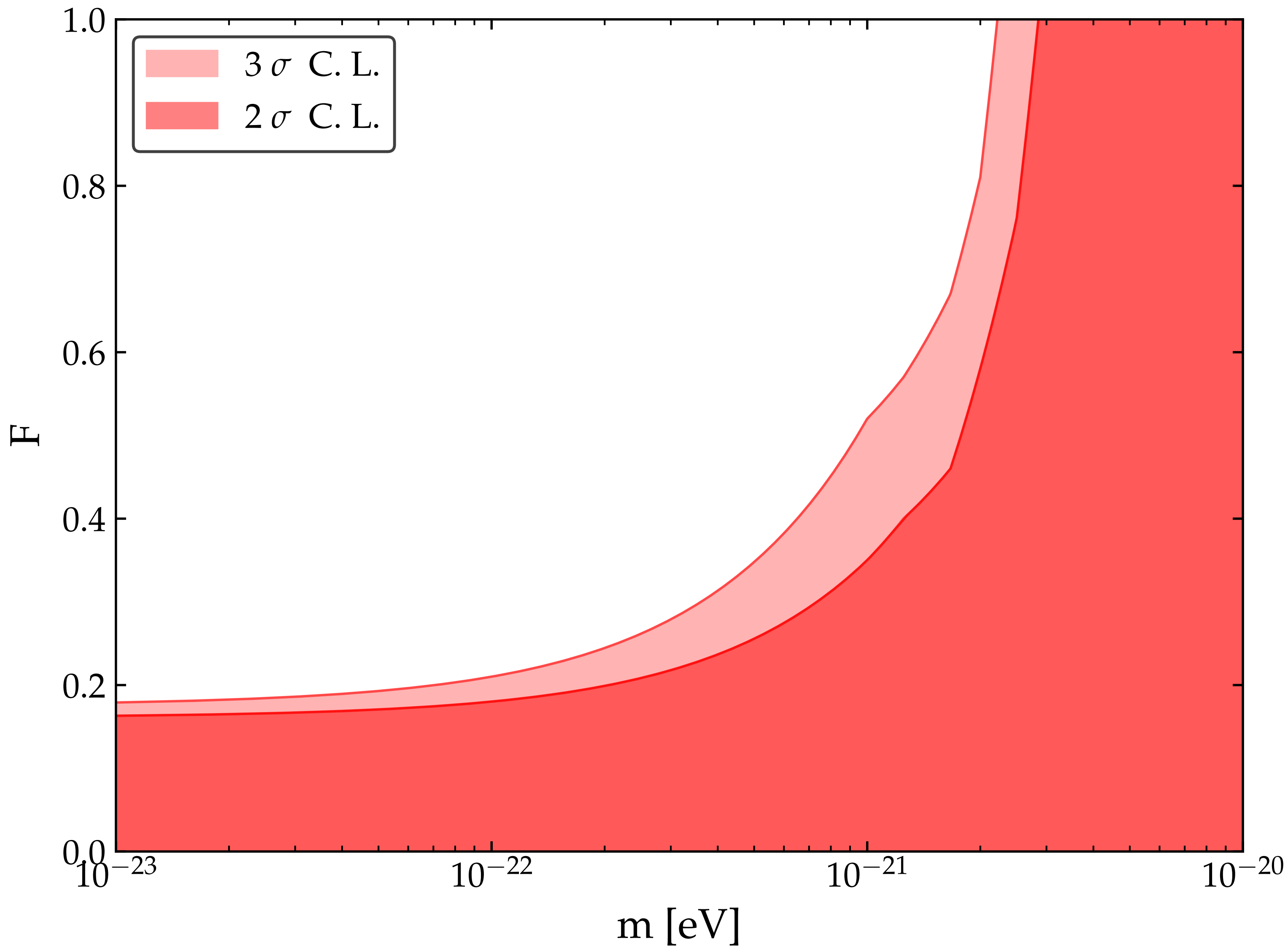


$$\psi(x,t) = \left(\frac{mM_P}{\sqrt{4\pi}}\right) e^{-i\gamma m t}\chi(x)$$

$$|\gamma| \ll 1$$

Cons of ULDM

Iršič et al./Armengaud et al./Kobayashi et al. `17



from Kobayashi, Murgia, De Simone, Iršič, Viel `17

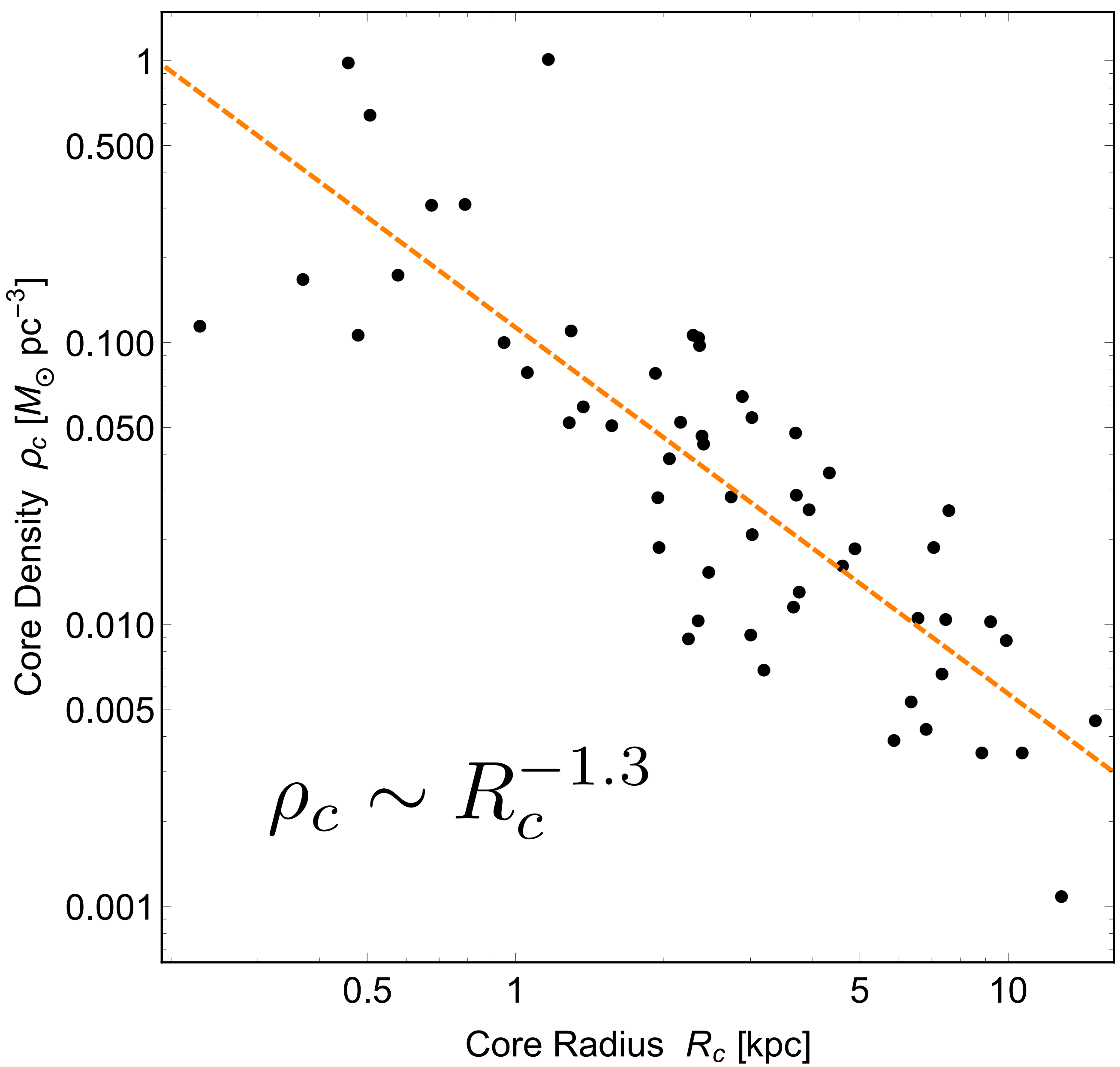
Lyman-α forest

Matter power spectrum is suppressed on small scales for

$$m \lesssim 10^{-21}\ \mathrm{eV}$$

Cons of ULDM

Deng, Hertzberg, Namjoo, Masoumi `18



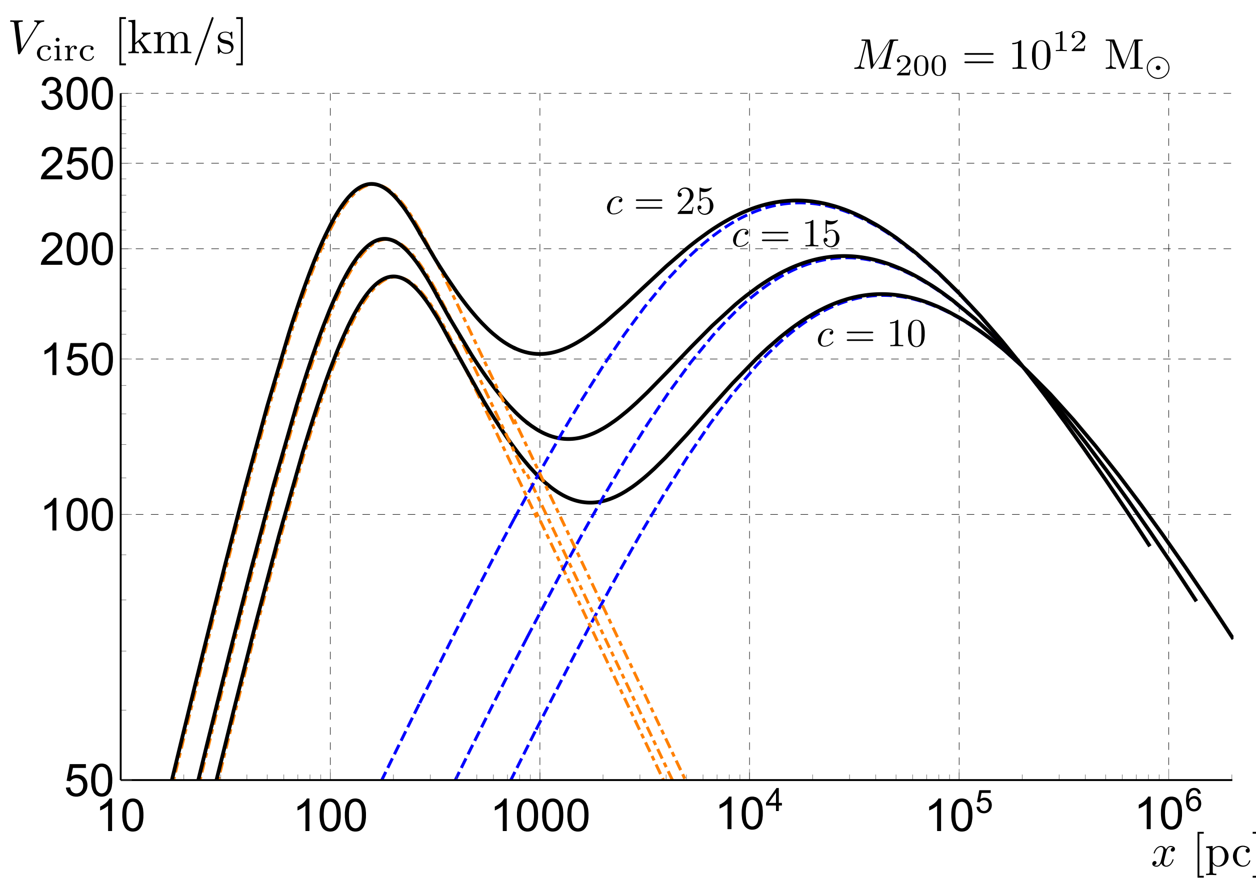
For ULDM solitons

$$\rho_c \sim R_c^{-4}$$

Cons of ULDM

Cons of ULDM

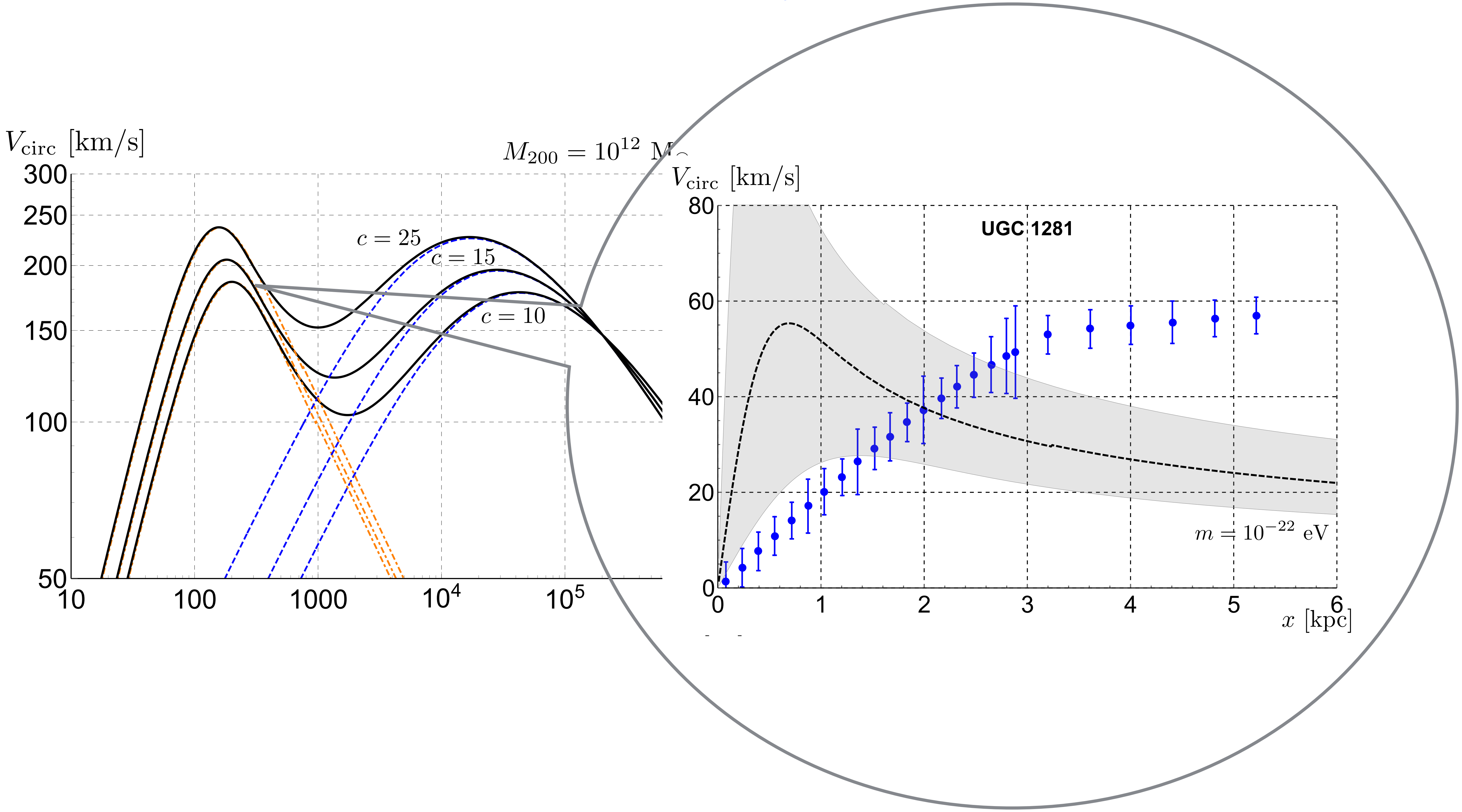
Bar, Blas, Blum, Sibiryakov ' 18



Soliton + host halo rotation curve

Cons of ULDM

Bar, Blas, Blum, Sibiryakov ' 18



Inner velocity is overestimated for $m \lesssim 10^{-21}$ eV

However

- Constraints are derived assuming **homogeneous** field with **cosine potential** at matter-radiation (MR) equality.

- Soliton solution obtained neglecting early **attractive self interactions.** see Hertzberg, Schiappacasse '18 for late effects of self interactions

- ULDM with $m \gtrsim 10^{-21}\ \mathrm{eV}$ maybe do not solve core vs cusp, but still very interesting!

In this talk

Implications of self interactions in axion potentials

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Implications of self interactions in axion potentials

↓

DM **bound states/inhomogeneities** at MR equality!

lot of activity since
Kolb, Tkachev '93/'94/…

Implications of attractive self-interactions

Inhomogeneity from axion potentials

- Standard axion potential from gauge (and gravitational?) instantons:

$$V(\phi) \sim \Lambda^4 \left[1 - \cos\left(\frac{\phi}{F}\right)\right]$$

- If PQ symmetry **broken after inflation**, axion is inhomogeneous from the very beginning due to **topological defects** (strings and domain walls).

- Initial overdensities lead to ***miniclusters***.

Kolb, Tkachev ’93/’94/…

Axions with large F

- **Ultra-Light Axions** (ULAs) usually come with

$$F \gtrsim 10^{14}\ \mathrm{GeV} \gtrsim H_{\mathrm{inflation}}$$

- Field very likely homogenised by **inflation**!

$$\phi(x,t) = \phi(t) + \delta\phi(t,x) \qquad \text{with} \qquad \delta\phi \ll \phi$$

- However, self-interactions can lead to growth of inhomogeneities!

Hertzberg, Schiappacasse '17 / Fukunaga, Kitajima, Urakawa '19

Parametric Resonance

- Motion of field is periodic. Perturbations obey

$$\delta\ddot{\phi}_k(t) + 3H\delta\dot{\phi}_k(t) + \left(\frac{k^2}{a^2} + V''(\phi)\right)\delta\phi_k(t) = 0$$

Parametric Resonance

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- V'' is also periodic → **Floquet** theory

$$\delta\phi_k(t) \sim e^{\mu_k t} f(t)$$

Instability when $\Re\left(\mu_k\right) > 0$

Parametric Resonance

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- V'' is also periodic **Floquet** theory

$$\delta\phi_k(t) \sim e^{\mu_k t} f(t)$$

Instability when $\Re\left(\mu_k\right) > 0$

Requires V'' > 0, i.e. attractive self-interactions!

Axion potentials

- Parametric Resonance occurs **if potential is flatter than quadratic** in some region.

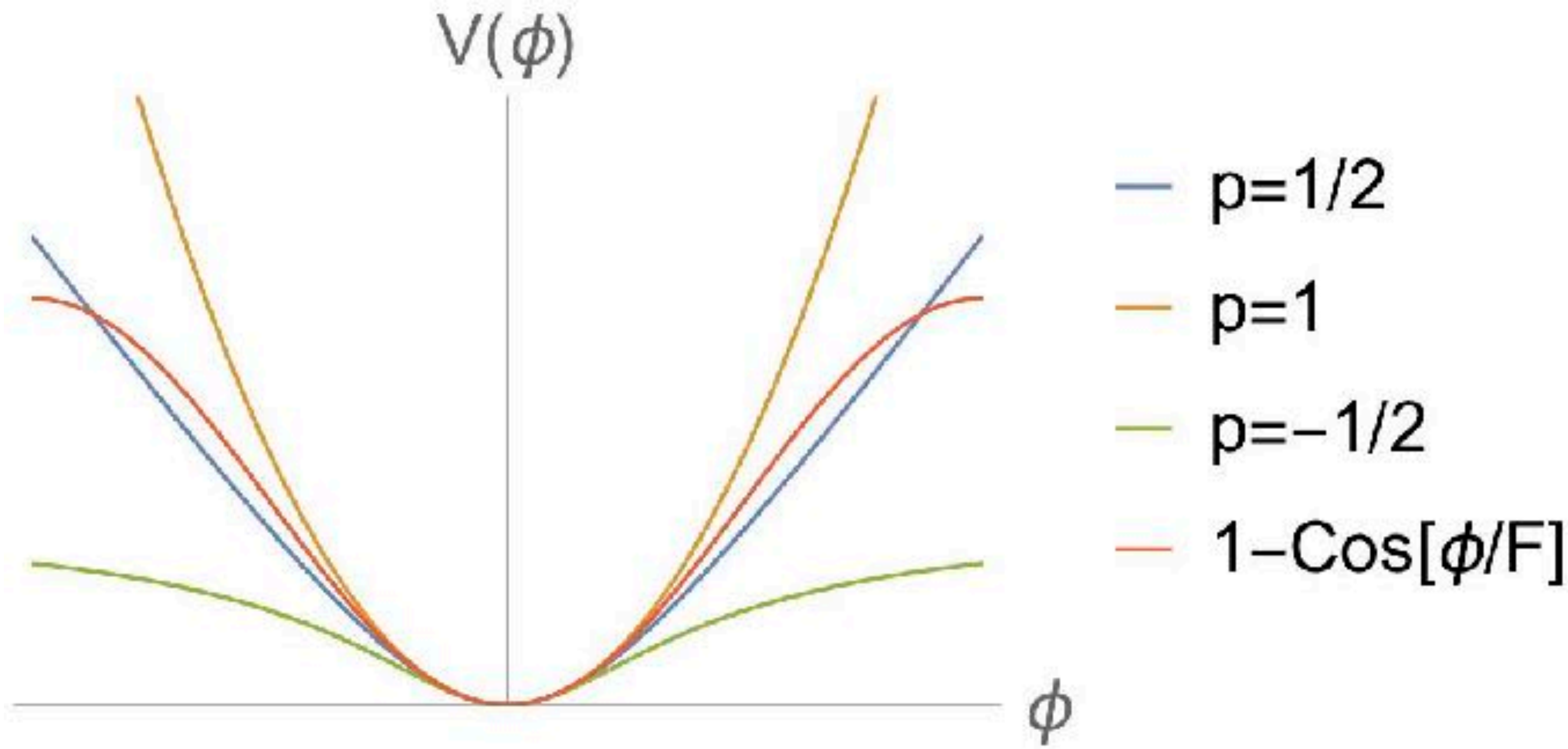
- However, not efficient for cosine potential…

Hertzberg, Schiappacasse '17 / Fukunaga, Kitajima, Urakawa '19

- Well motivated possibility from UV point of view: breaking of shift symmetry/multi-branched potential:

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

Axion potentials



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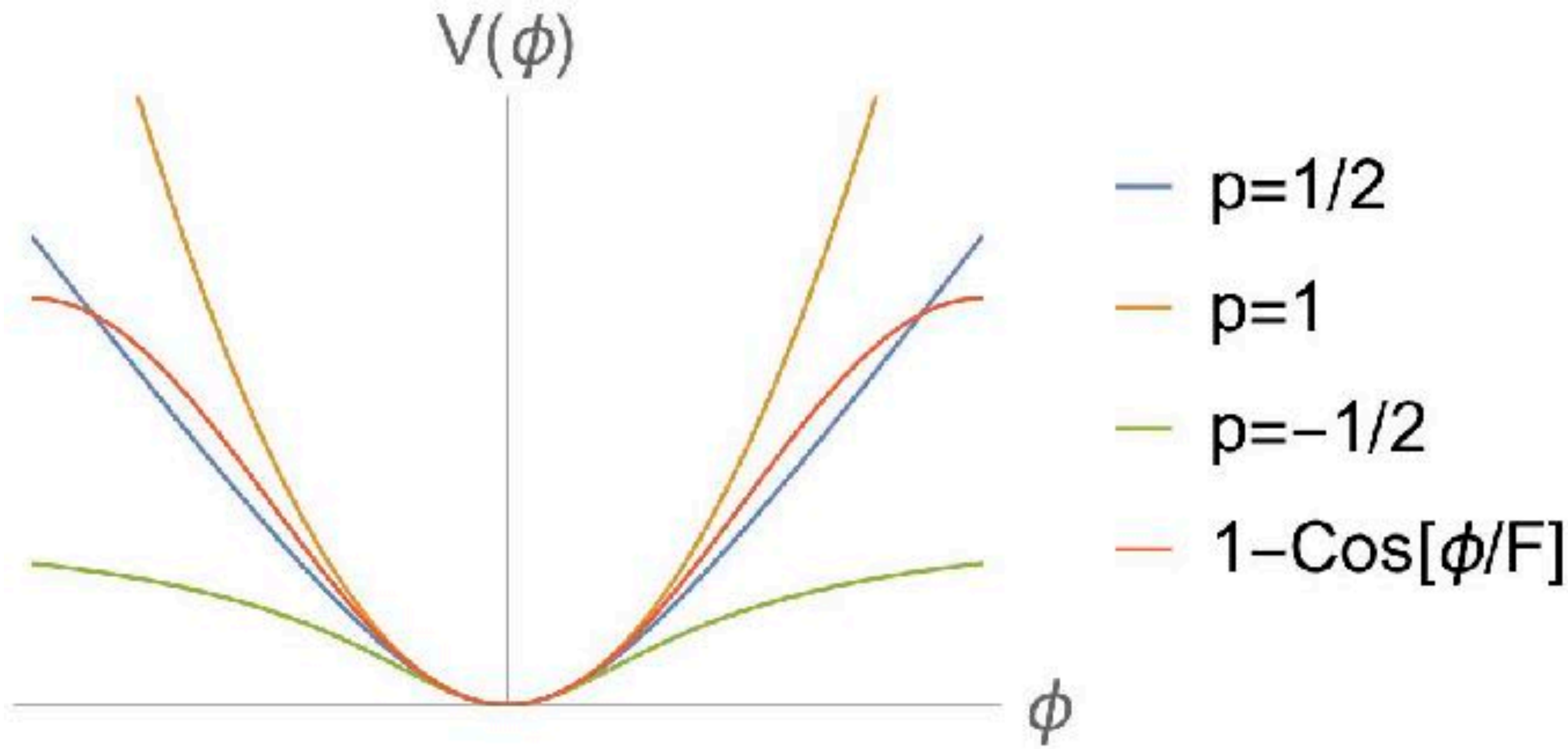
Axion potentials



$$0 \leq p < 1$$

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

Axion monodromy

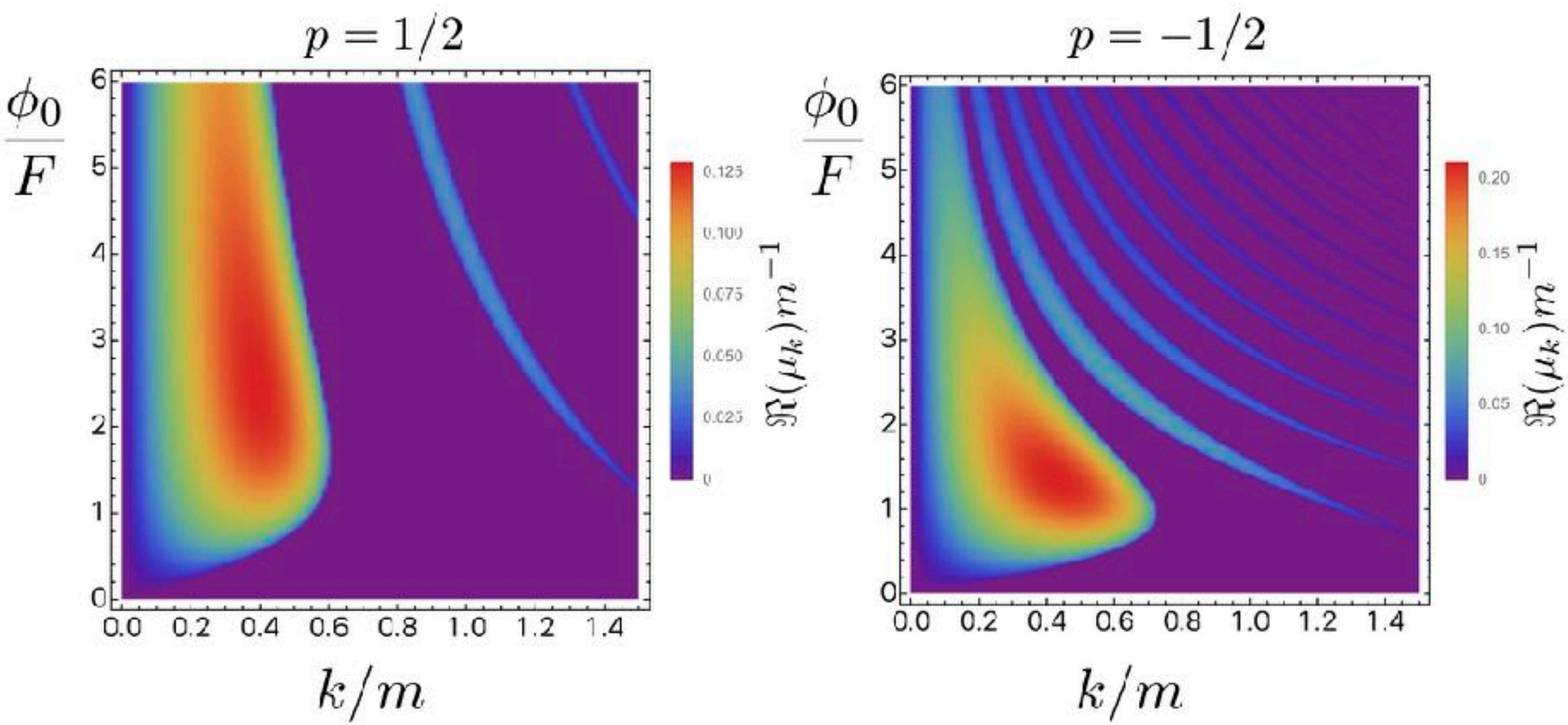
Silverstein, Westphal '08/+McAllister '08/…/+Dong, Horn '10

$p < 0$ **Plateau**

for inflation Kallosh, Linde '13/…/Nomura, Qatari, Yamazaki '17/…, for DM Kitajima, Soda, Urakawa '18

Self-resonance in axion potentials

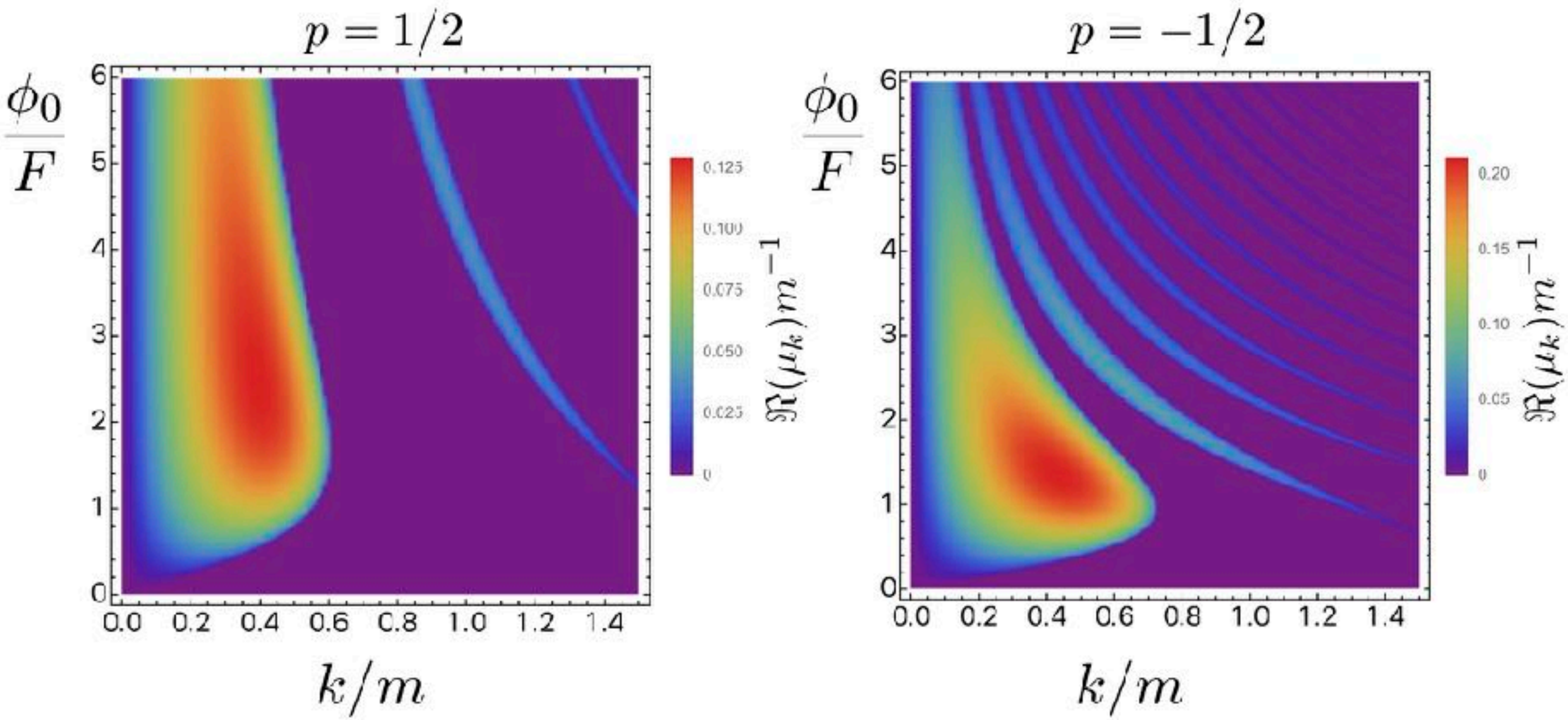
see also Amin, Easther, Finkel, Flauger, Hertzberg '11/… in reheating context



Initial misalignment can be larger than F

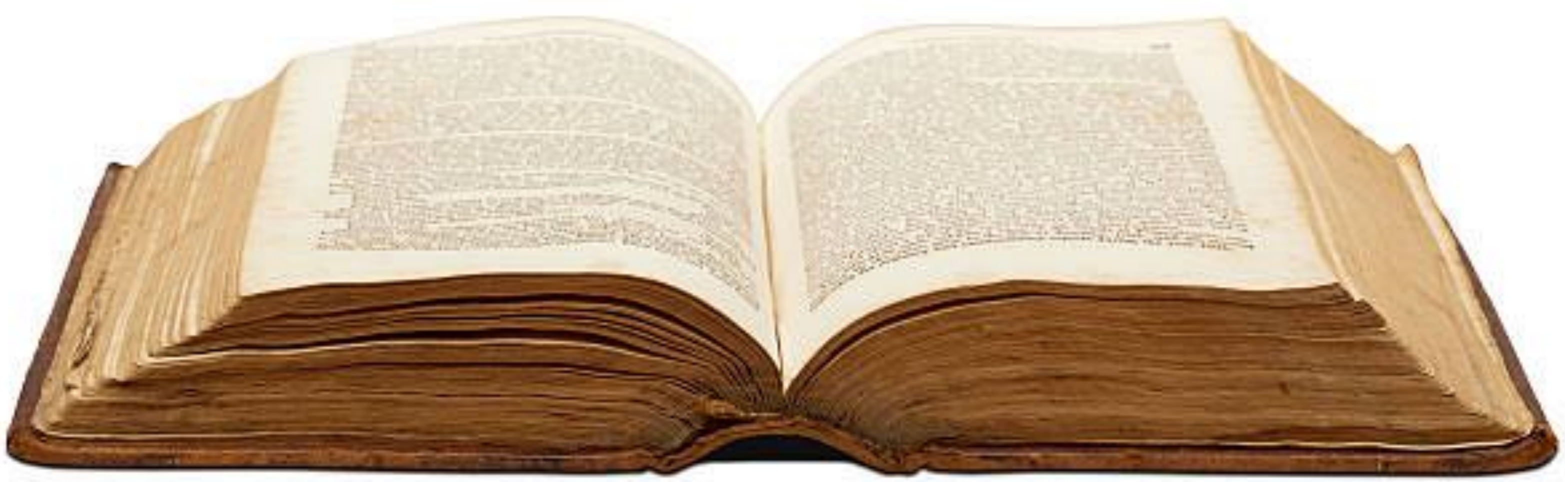
Self-resonance in axion potentials

see also Amin, Easther, Finkel, Flauger, Hertzberg '11/… in reheating context

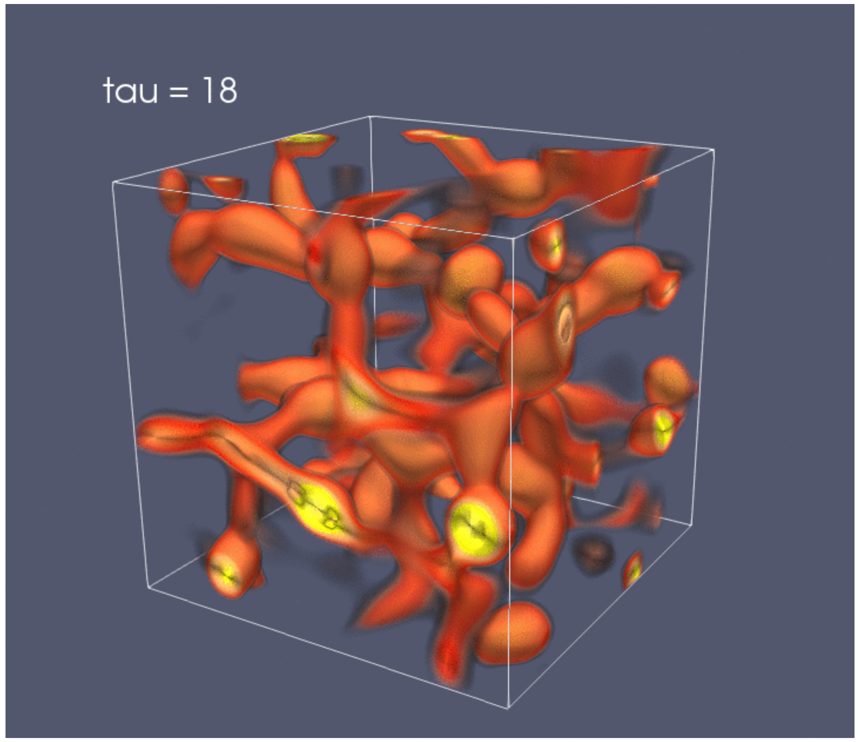


Hubble friction changes resonant k, but effect still there.

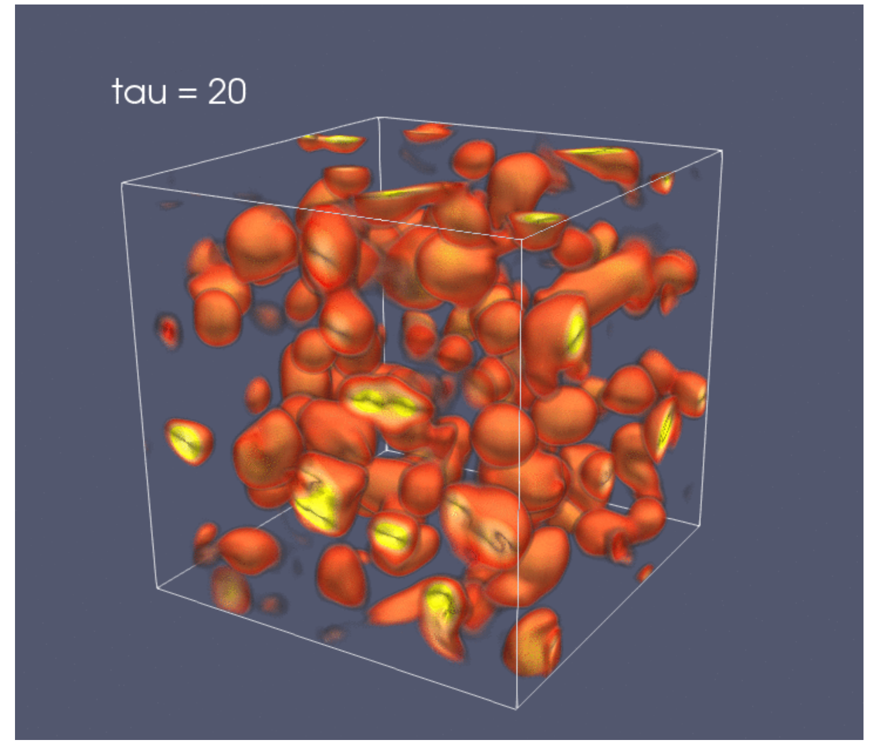
Oscillon Biography



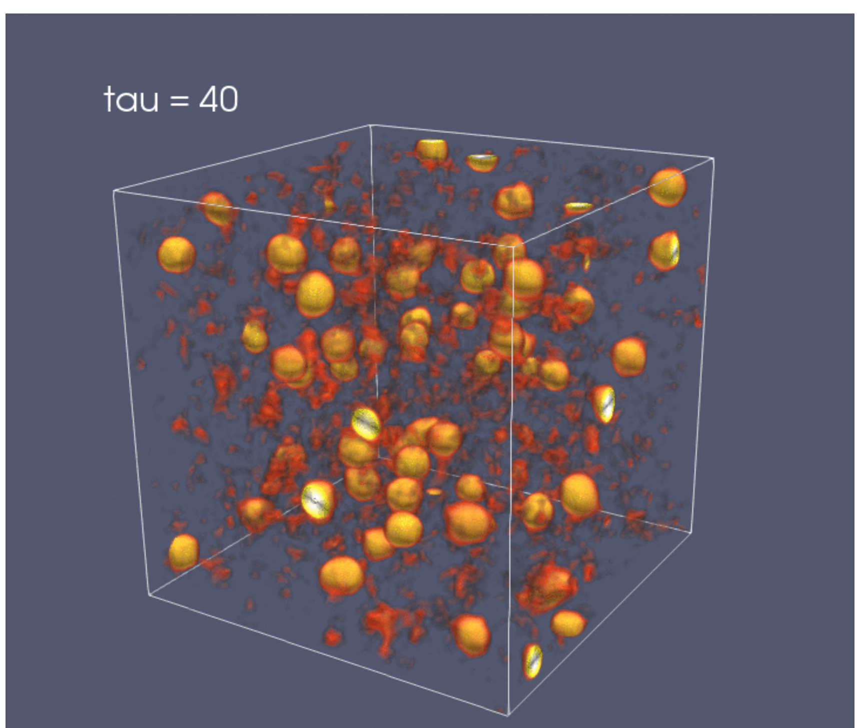
Chapter I: Birth



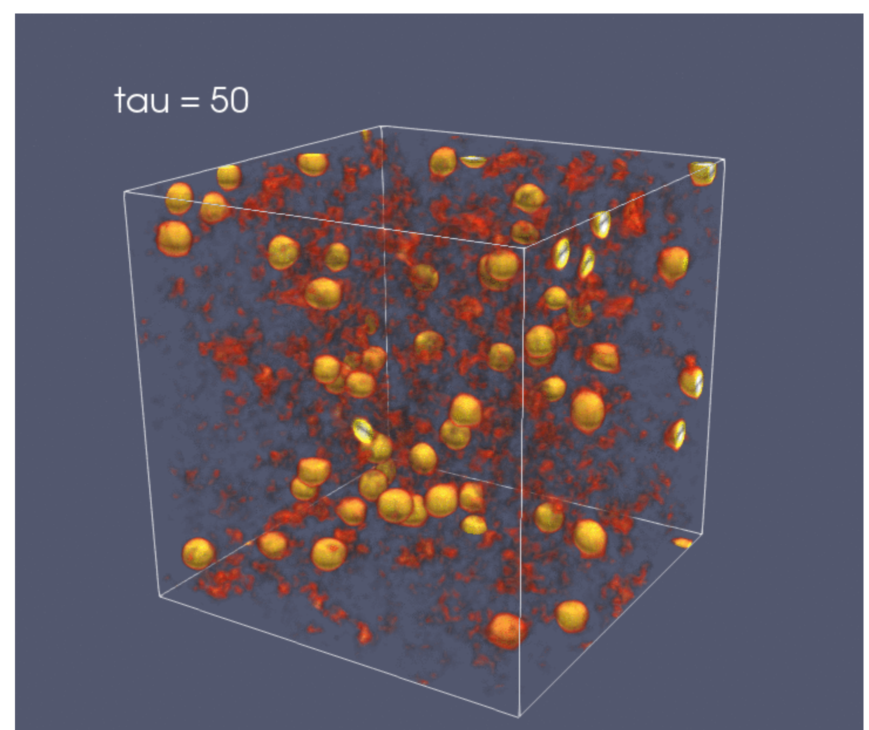
(a) $m\tau = 18$



(b) $m\tau = 20$



(c) $m\tau = 40$



(d) $m\tau = 50$

from Kitajima, Soda, Urakawa ‘18

Oscillon birth

- Parametric resonance leaves behind **localized, approx spherically symmetric** overdensities. Profile well fitted by

$$\delta\phi \sim \frac{A}{\cosh(r/\sigma)}$$

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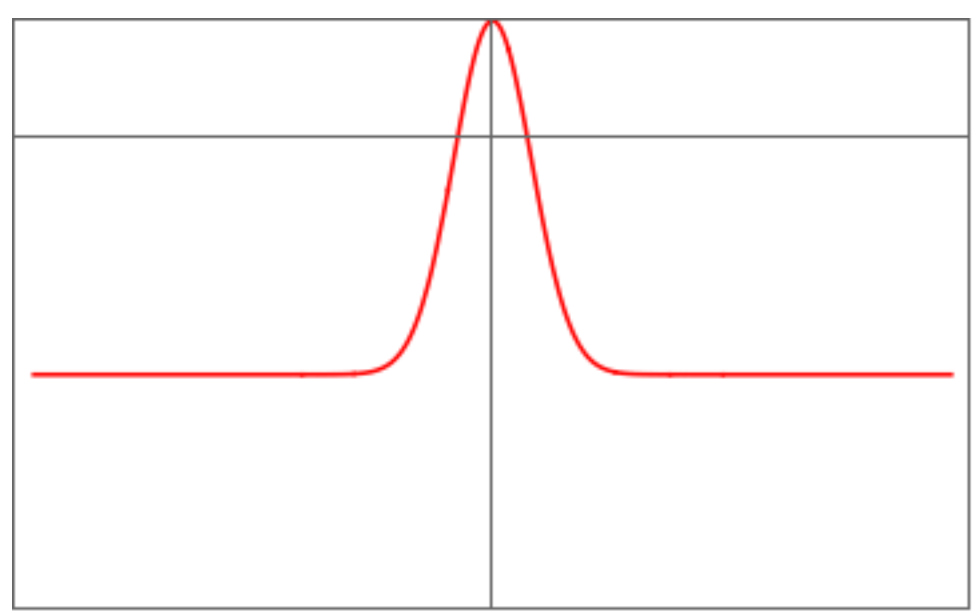


- Configurations keep oscillating in time!

Oscillons

Bogolyubosky, Makhanov ´76/
Gleiser '93/Copeland, Gleiser,
Muller ´95/…/ Hindmarsh et al

Oscillons are **attractor** solution of Klein-Gordon equation in flat spacetime with nonlinear potential (similar to breather of sine-gordon in 1+1).

$$\ddot{\phi}(t,r) - \partial_r^2\phi(t,r) - \frac{2}{r}\partial_r\phi(t,r) + V'(\phi(t,r)) = 0$$

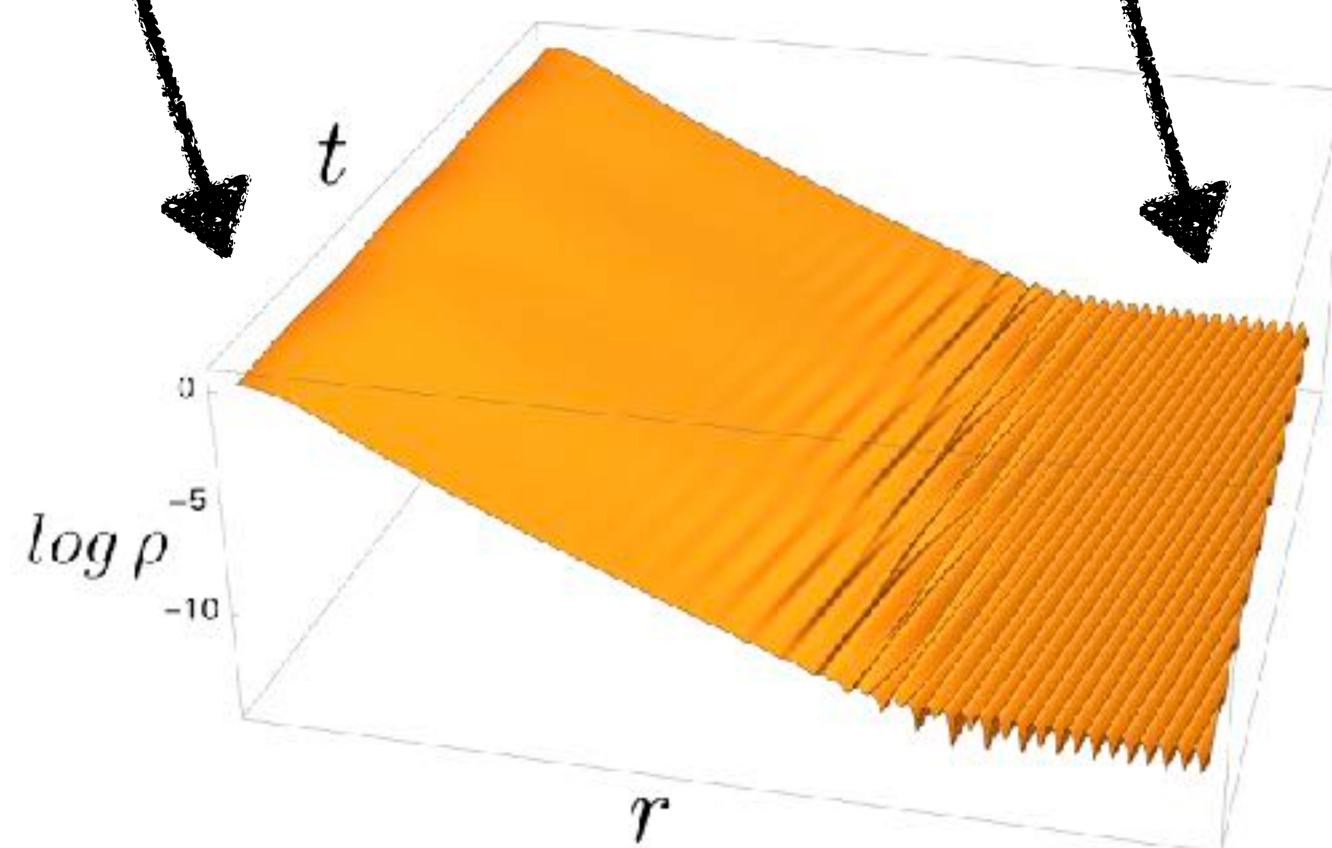
Oscillons

Bogolyubosky, Makhanov ´76/ Gleiser ’93/Copeland, Gleiser, Muller ´95/…/Hindmarsh

Localized oscillating **bound state**

+

radiated scalar waves.



Oscillons

Bogolyubosky, Makhanov ´76/ Gleiser ’93/Copeland, Gleiser, Muller ´95/…/Hindmarsh

Localized oscillating **bound state**

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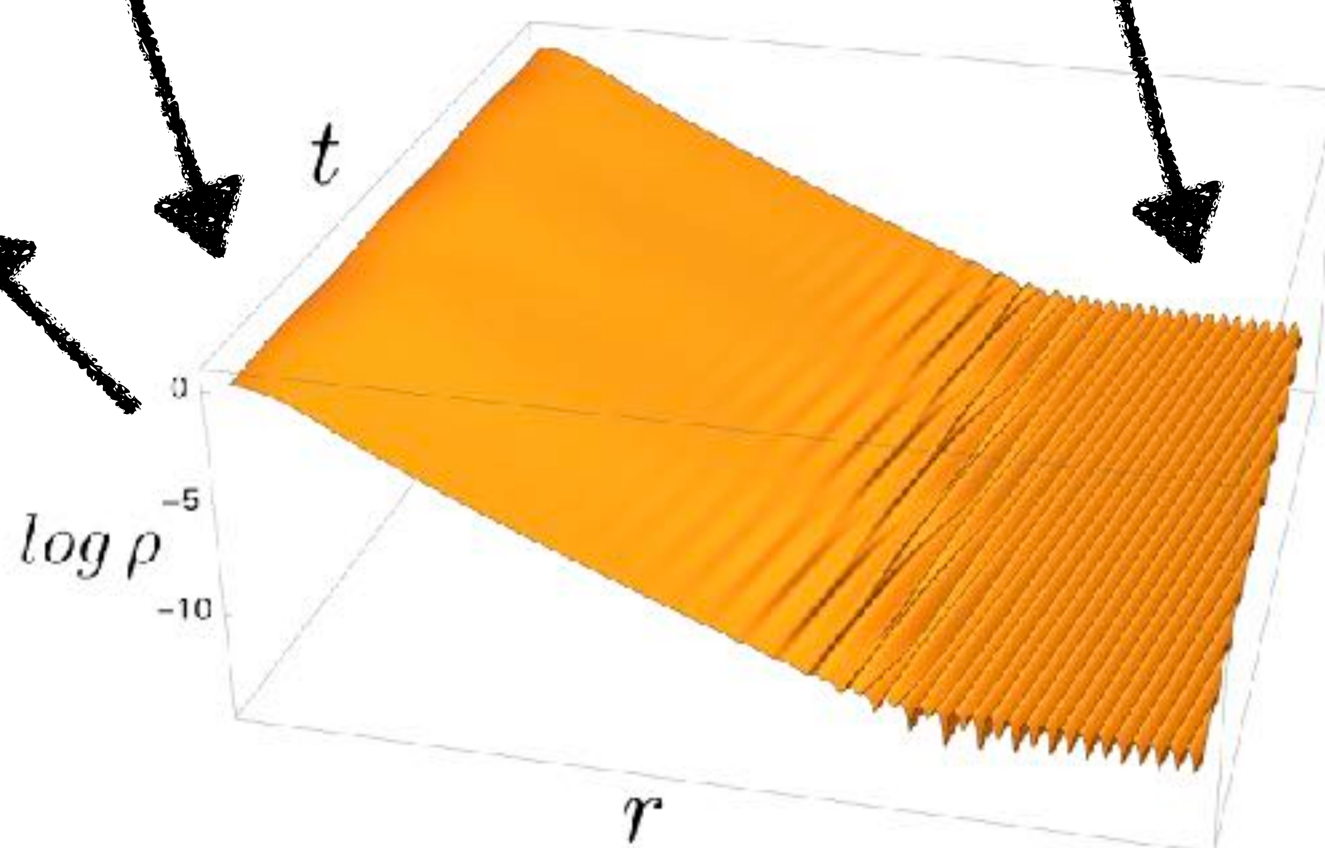
radiated scalar waves.

Radiated energy is very small!

Very large lifetime!



Oscillons are kept together purely by attractive **self-interactions**, **gravity** not involved.

see Ikeda, Yoo, Cardoso '17 for gravity effects

Well-known in **inflationary** models, in connection with late reheating.

Amin, Easther, Finkel, Flauger, Hertzberg '11/…/ Lozanov, Amin '19

Sometimes referred to as **axitons** for QCD axion DM, but in this case they decay soon and/or form very late.

Kolb, Tkachev '93/…/ Visinelli et al. '18

Oscillon ID

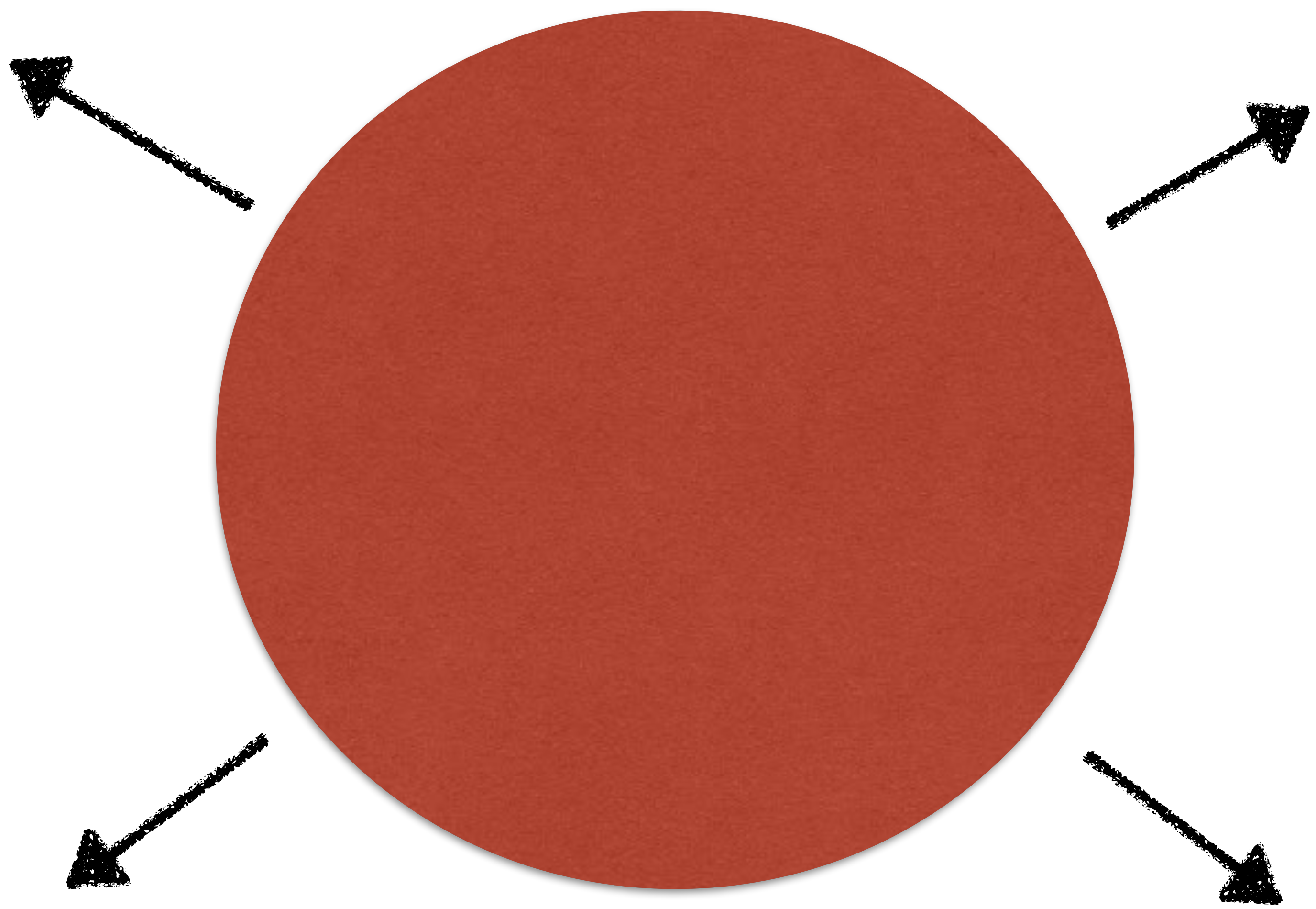
Core amplitude

$$\phi_c \sim F$$

Radius

$$R_{\rm osc} \sim m^{-1}$$

$$1 \ \mathrm{km} \div 10^2 \ \mathrm{pc}$$



Mass

$$M_{\rm osc} \sim V \ R_{\rm osc}^3 \sim \frac{F^2}{m}$$

$$10^{-12} M_\odot \div 10^8 M_\odot$$

Frequency

$$\omega_{\rm osc} \lesssim m$$

Oscillon ID

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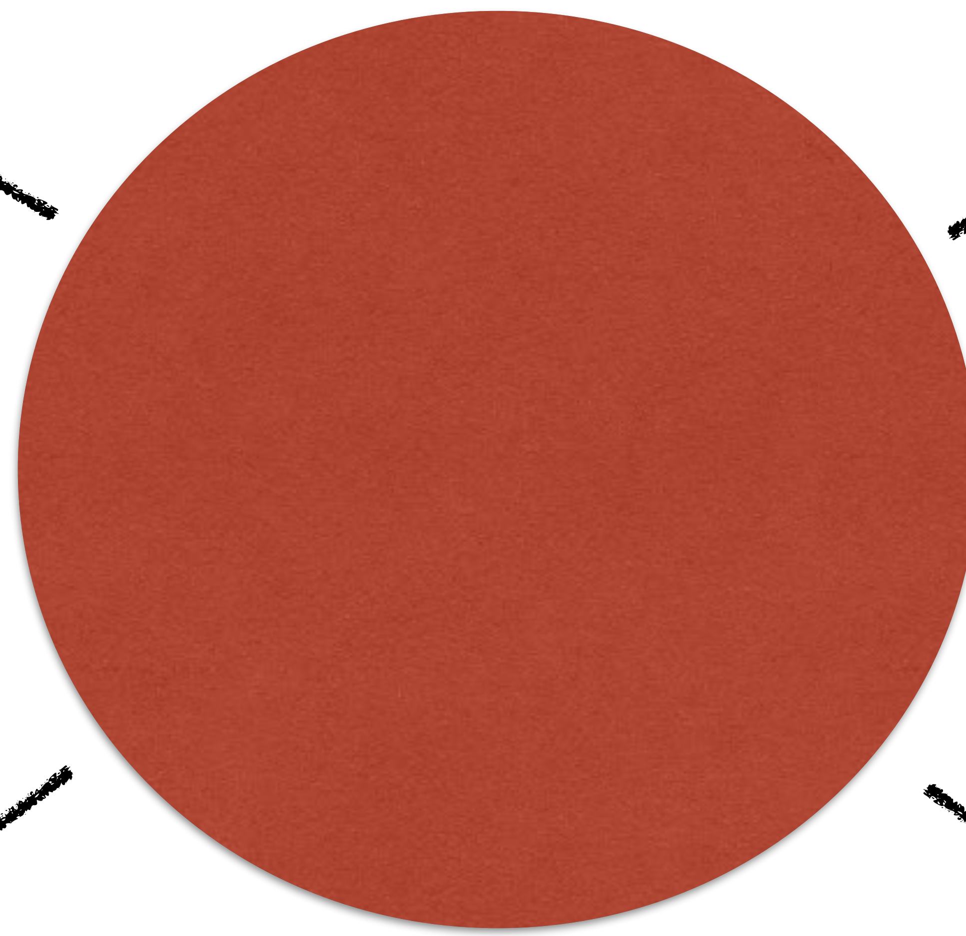

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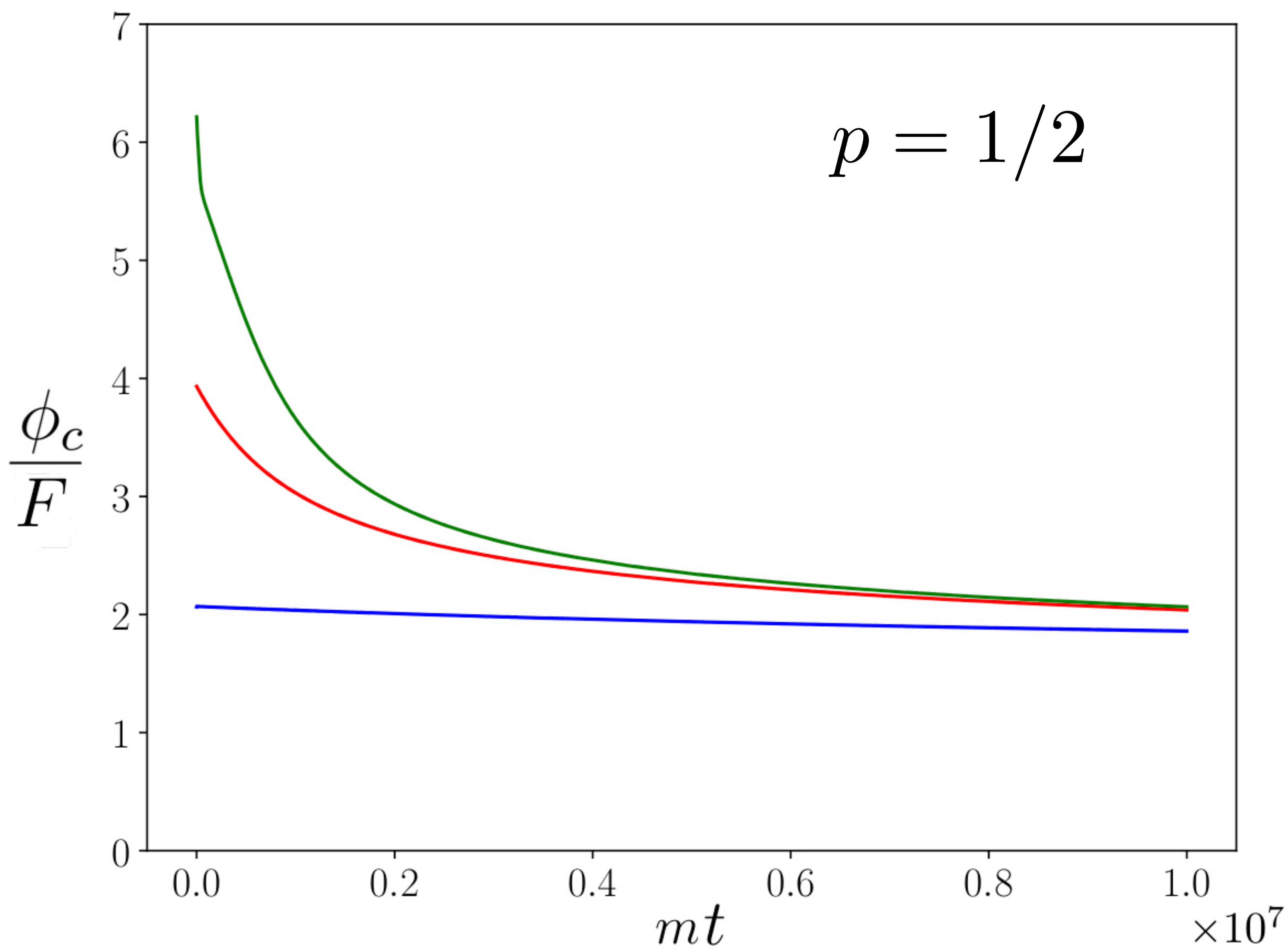
Frequency

$$\omega_{\rm osc} \lesssim m$$

Chapter II: Lifetime

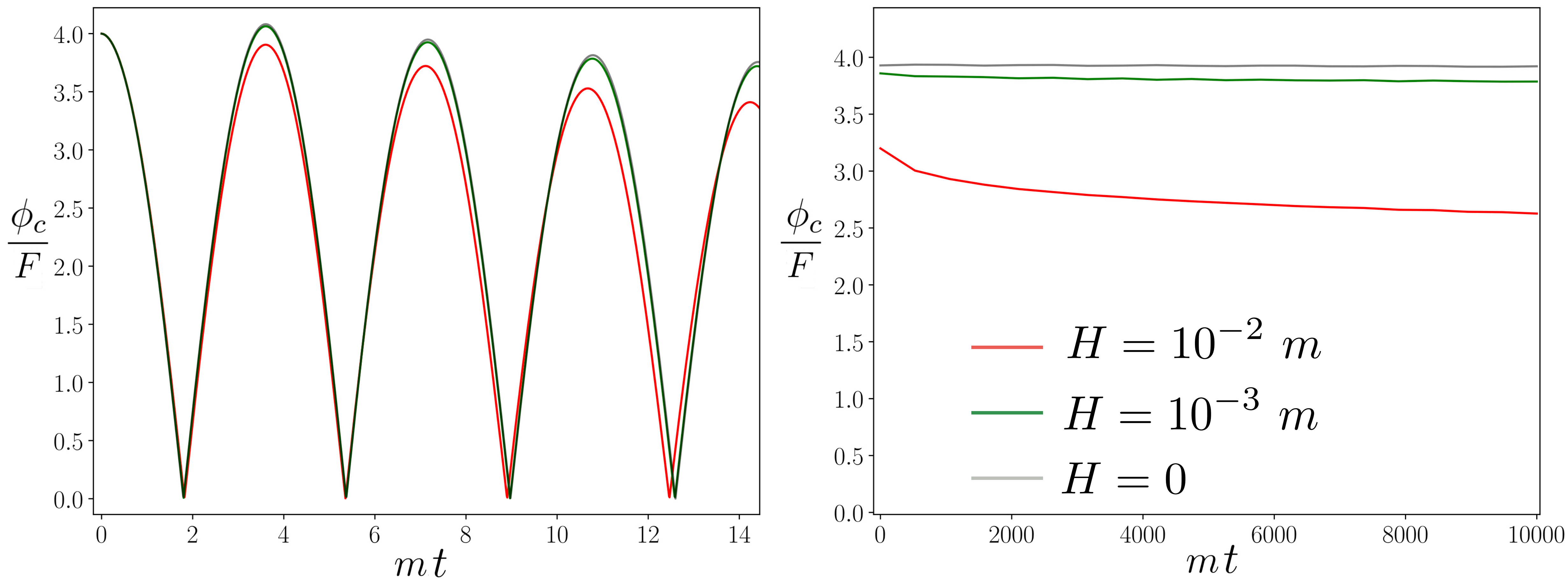
- Long-lived oscillon is attractor, initial conditions not particularly relevant to estimate lifetime.



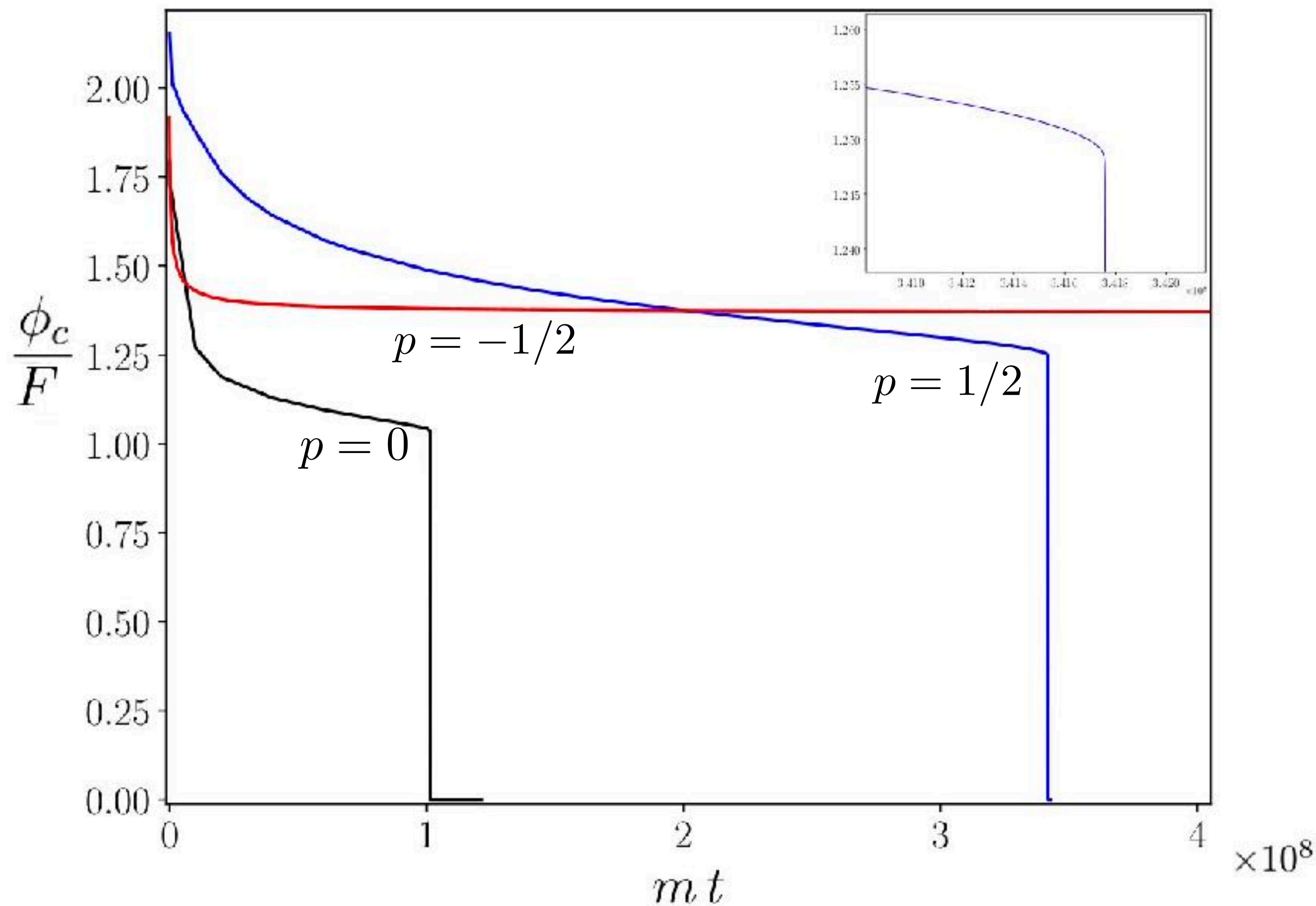
see Salmi, Hindmarsh '12 for previous estimates

Oscillon lifetime

- Oscillon radius is much smaller than Hubble radius at formation, object is essentially **decoupled** from Hubble flow and behaves as DM.



Oscillon lifetime



Oscillon lifetime

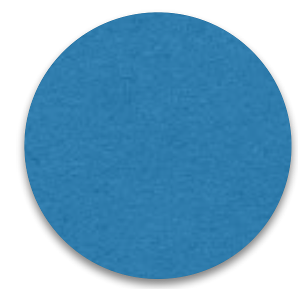
$0 \leq p < 1$	$p < 0$
$\tau \sim 10^8\ m^{-1}$	$\tau \gg 10^8\ m^{-1}$ No decay observed yet!

For small m, oscillon survive until MR equality!

Chapter III: death

- Decay occurs via burst of scalar waves with

$$k \sim R_{\rm osc}^{-1} \lesssim m$$



- Potential warm contribution to DM.

- However, overdensity will generically be trapped by its own **gravitational** potential, leading to mini clusters and/or gravitational solitons.

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Chapter IV: Legacy

or

Observational Impact

Oscillon independence

- **Before** parametric resonance, will-be DM is made only of parent homogeneous (pseudo)scalar field.

- **After** parametric resonance

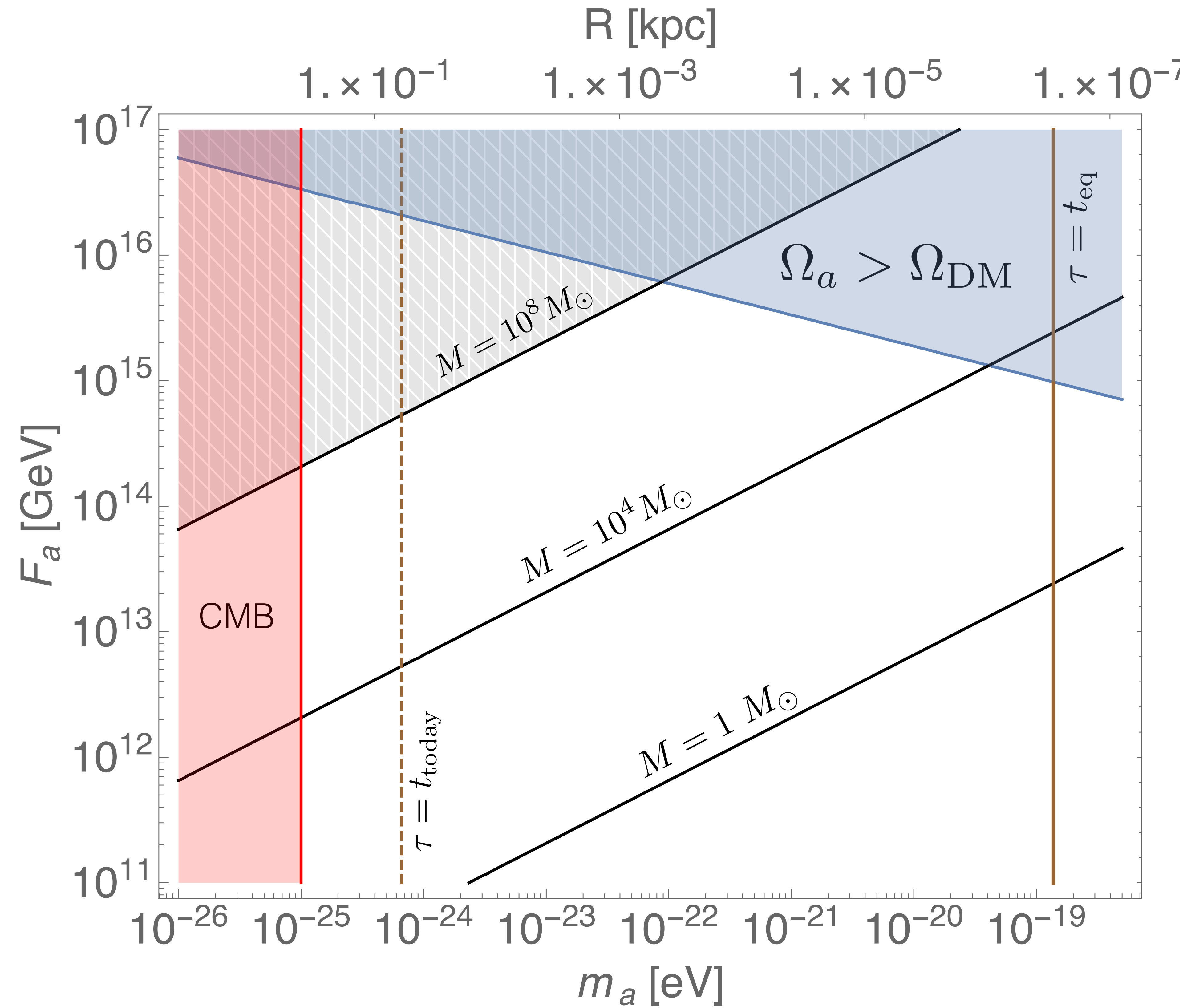
Light scalar quanta/waves from misalignment $+$ Heavy oscillons

$\longrightarrow$ Usually $\rho_{\rm oscillon} \gtrsim 0.5\ \rho_{\rm DM}$

Observational impact depends on **epoch** at which oscillon decays.

Determined by the lifetime τ , which depends on **p** and **m**.

$p = 1/2$


R [kpc]
1. × 10^-1
1. × 10^-3
1. × 10^-5
1. × 10^-7
F_a [GeV]
10^17
10^16
10^15
10^14
10^13
10^12
10^11
m_a [eV]
10^-26
10^-25
10^-24
10^-23
10^-22
10^-21
10^-20
10^-19
CMB
Ω_a > Ω_DM
τ = t_eq
τ = t_today
M = 10^8 M_⊙
M = 10^4 M_⊙
M = 1 M_⊙

Decay after MR equality

- If decay occurs after MR equality, **gravity** comes into play. Difficult to understand further evolution (numerical simulations?)

- **Single oscillon**: does gravity increase stability?

- **Overdensities of oscillons**: they grow and lead to interactions, e.g. mergers, disruptions.

- **Oscillon leftovers**: gravitational soliton waiting for them at

$$R_{\rm sol} \sim \left(\frac{M_p}{F}\right)^2 R_{\rm osc}$$

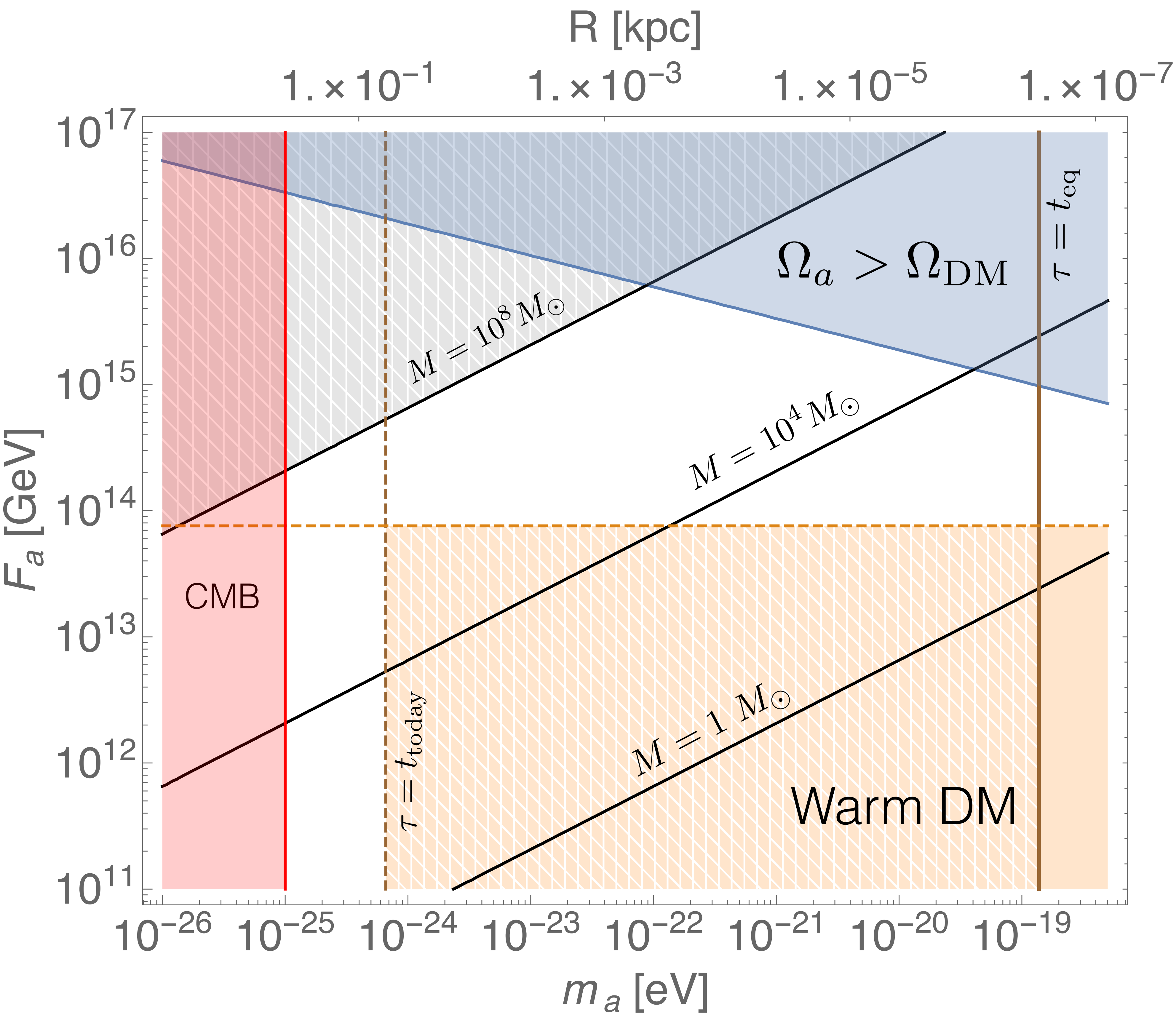
Constraints from warm DM?

Not straightforward due to gravity.

Conservative constraint

$$R_{\rm sol} \lesssim H^{-1}(\tau)$$

Constraints from warm DM?

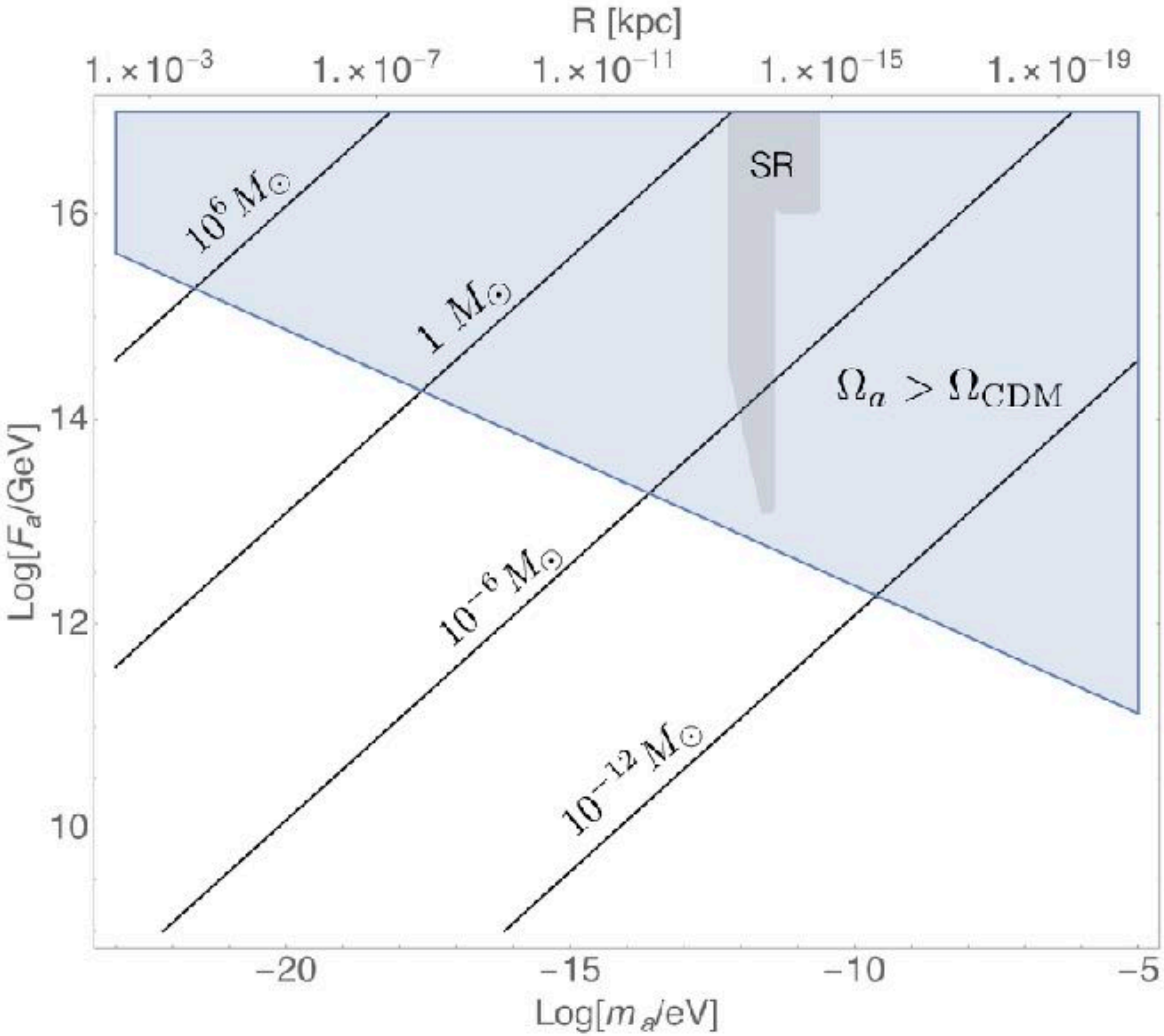


$p = 1/2$

Immortal oscillons?

- Can gravity extend lifetime (independently of p)?
- Potentials with p<0: currently only a lower bound ~ $10^9\ m^{-1}$ on lifetime.
- Simple fits suggest that lifetime is much larger!

Immortal oscillons?



DM constraints and oscillon masses for

$$p = -1/2$$

Summary

- **Attractive self-interactions** in the DM sector can lead to bound states/structures.

- Relevant e.g. for ULDM, with/without connection to **cusp vs core** problem.

- **Self-interactions** can lead to fragmentation of originally homogeneous field.

Summary

- Parametric resonance leads to formation of **long-lived oscillating** bound states (oscillons) in certain well motivated potentials.
- For small masses and/or $p<0$, oscillons survive until and beyond MR equality!
- Need to take them into account as **initial conditions** for numerical simulations/analytical studies of ULDM.

Open questions

- Fate of decaying oscillons after MR equality?
    - Effects of **gravity** on oscillons?

      Amin, Mocz ‘19
    - **Oscillon-to-soliton** transition?
    - **Black hole** formation? Cotner, Kusenko, Takhistov ‘18
- p<0, how to estimate **lifetime**?
- **Signatures** of oscillons/solitons today? Khmelnitsky, Rubakov ’13/De Martino et al. ´17

Thank you!

Gravitational soliton solution

Fundamental solution

$$M_1 \approx 2.8 \cdot 10^{12} \left(\frac{10^{-22}\ \mathrm{eV}}{m} \right) M_\odot$$

$$R_1 \approx 0.08 \left(\frac{10^{-22}\ \mathrm{eV}}{m} \right)\ \mathrm{pc}$$

One-parameter family of solutions

$$M_\lambda = \lambda M_1$$

$$R_\lambda = \lambda^{-1} R_1$$

$$\lambda \ll 1$$

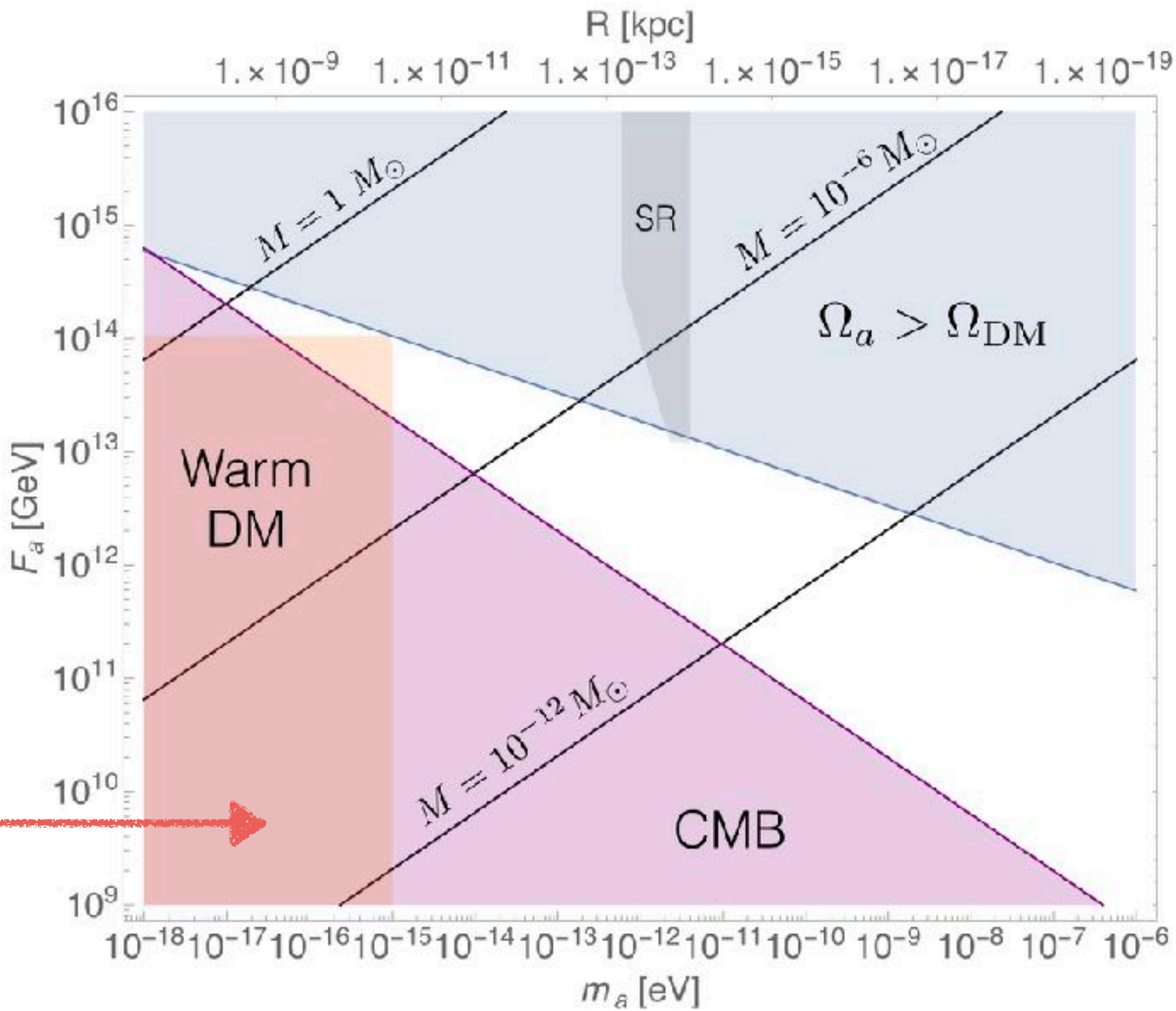
$$M_\lambda = M_{\mathrm{osc}} \sim \frac{F^2}{m}$$

$$R_\lambda \sim \left(\frac{M_p}{F} \right)^2 R_{\mathrm{osc}}$$

Matching to oscillon

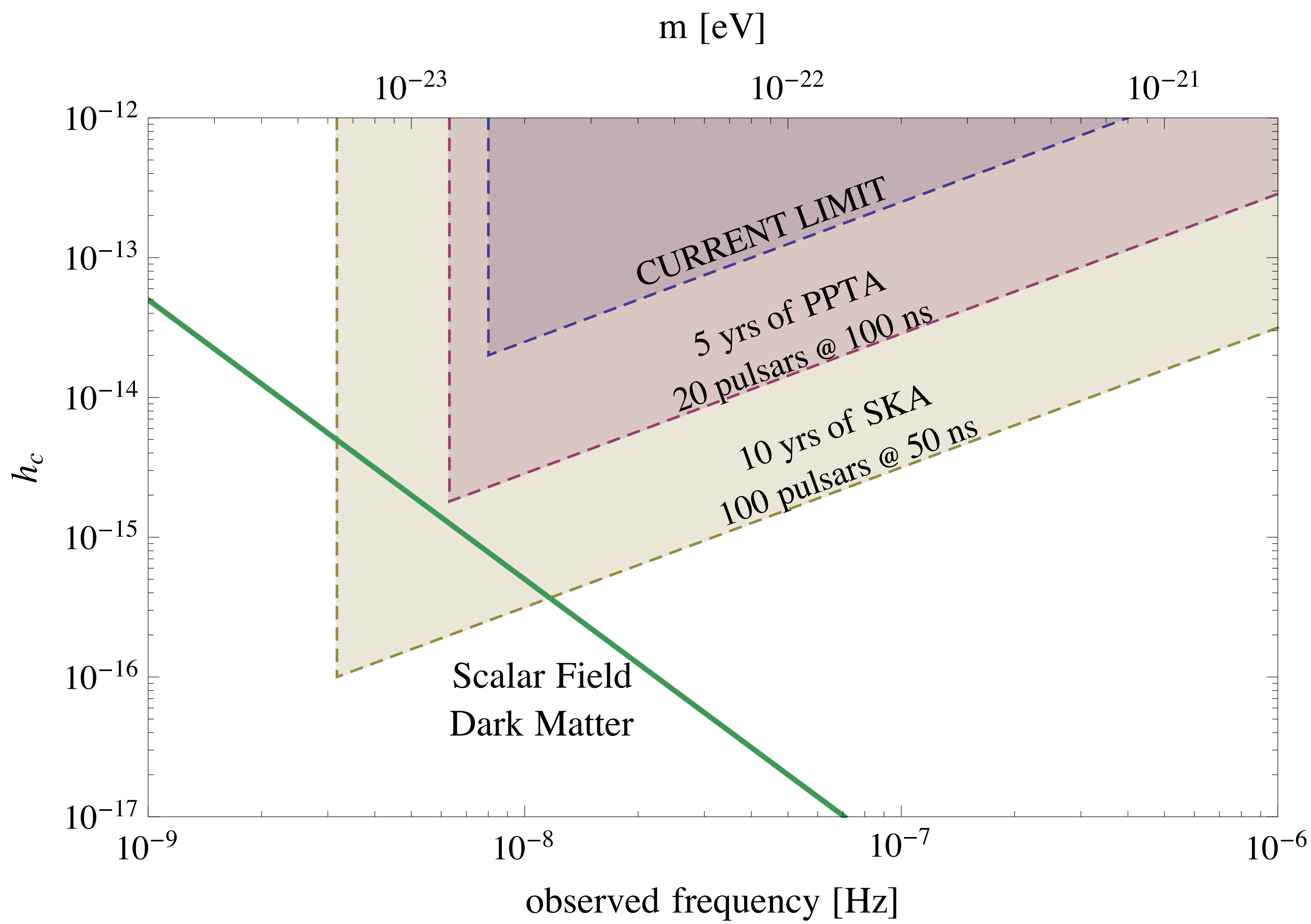
Decay before MR equality

$p = 1/2$



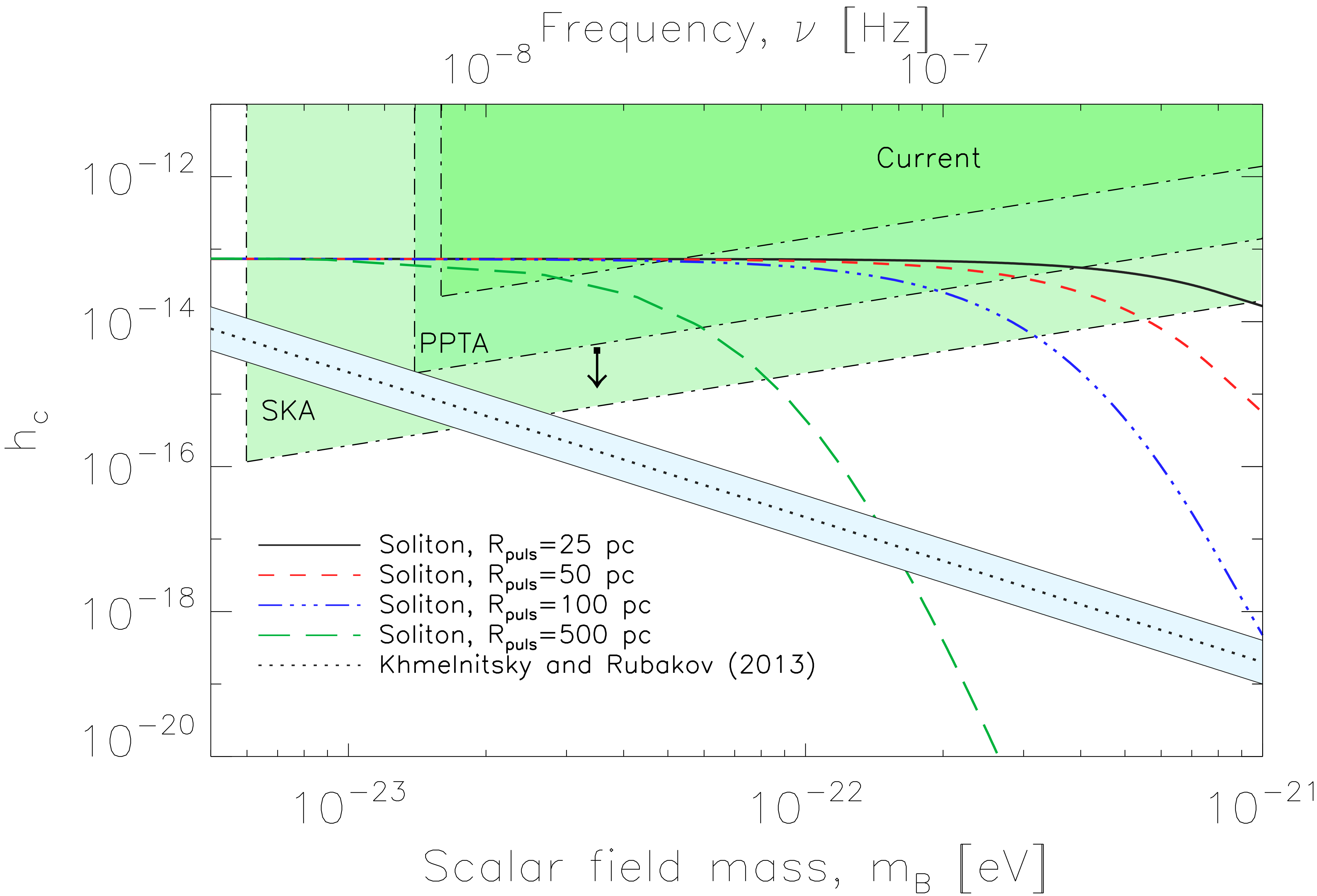
$R_{\rm sol} \lesssim 10^{-3} H_{\rm eq}$

Signature of ULDM from PTAs



Khmelnitsky, Rubakov '13

Signature of ULDM from PTAs



De Martino, Broadhurst, Tye, Chiueh, Schive, Lazkoz ‘17

Solitonic core enhances the signal

What about oscillons?