Inflation Ends, What's Next?

Mustafa A. Amin (RICE University)

background image: depositphotos.com

after inflation: a GAP in our cosmic history

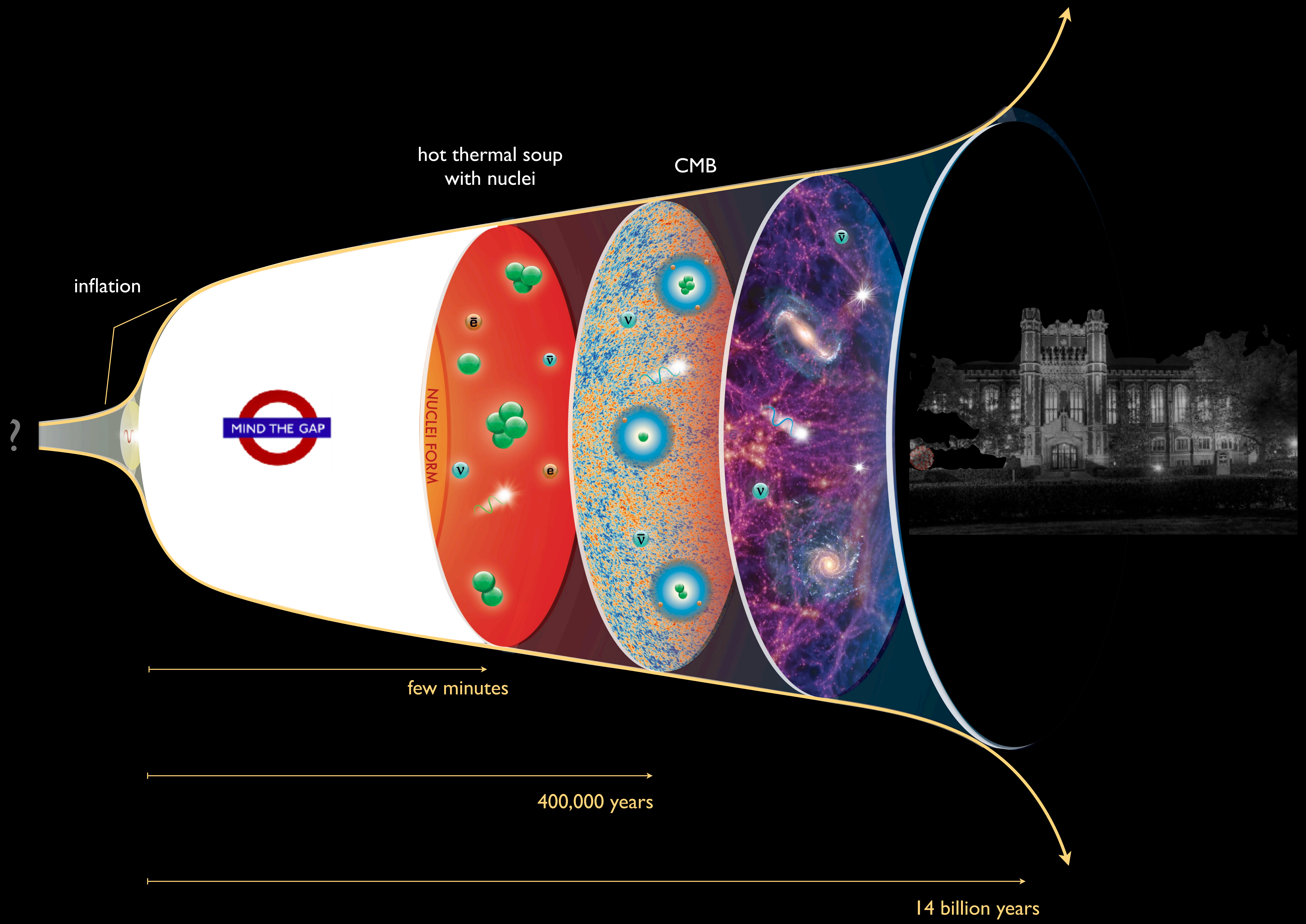
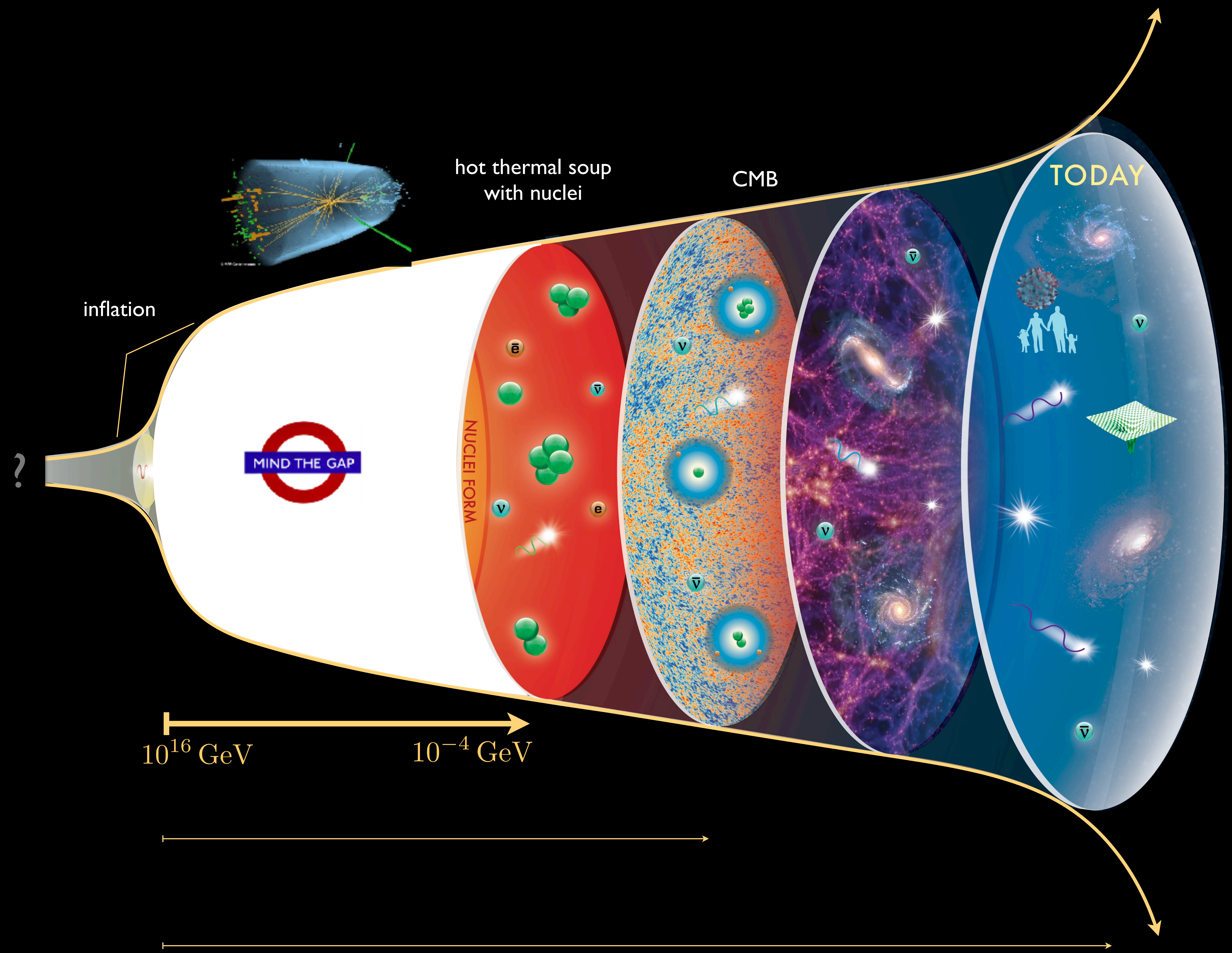


*image is my modification of the one produced by the PDG, 2014

after inflation: a huge energy GAP in our cosmic history



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after inflation: GAP — connects physics of inflation to the Standard Model

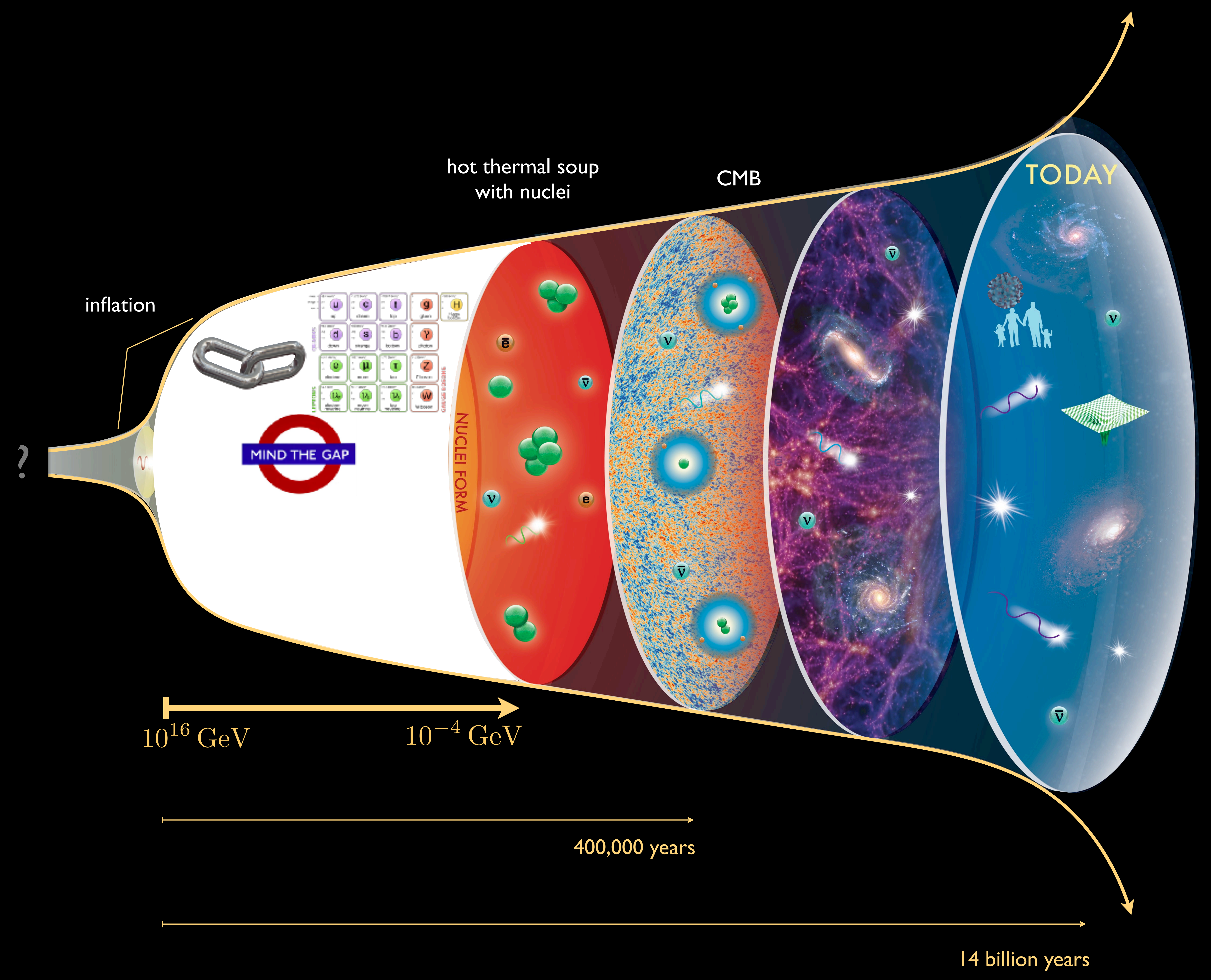


*image is my modification of the one produced by the PDG, 2014

after inflation: GAP — consequences ?

Observationally challenging because:
early times and small length scales (no inflationary "amplifier"), thermalization etc. But there is hope !

focus on: “soon” after the end of inflation, simple models with “universal” dynamics

For reviews: see MA et. al (2014), Lozanov (2019), Allahverdi et. al (2020)

2104.10128 1907.04402 2006.16182

[with apologies for works which I will be unable to cite/highlight]

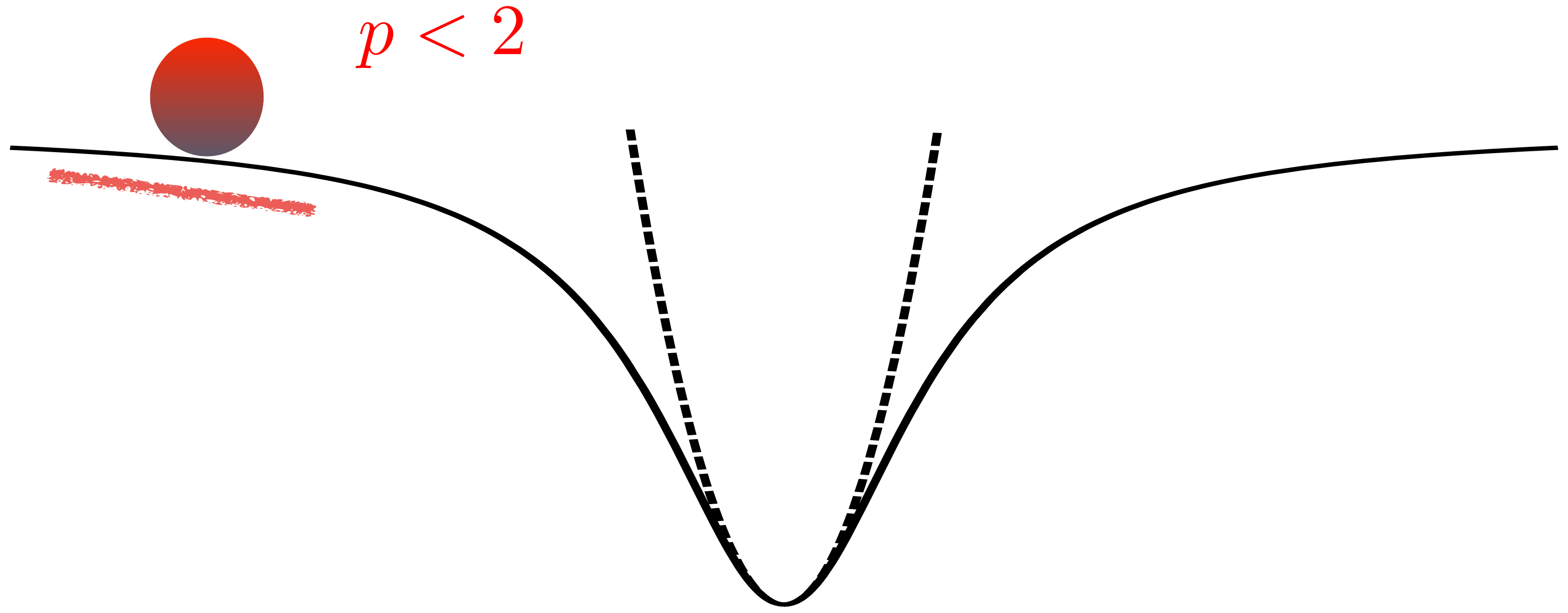
what we “know” about inflation (simplest case - scalar field driven inflation)

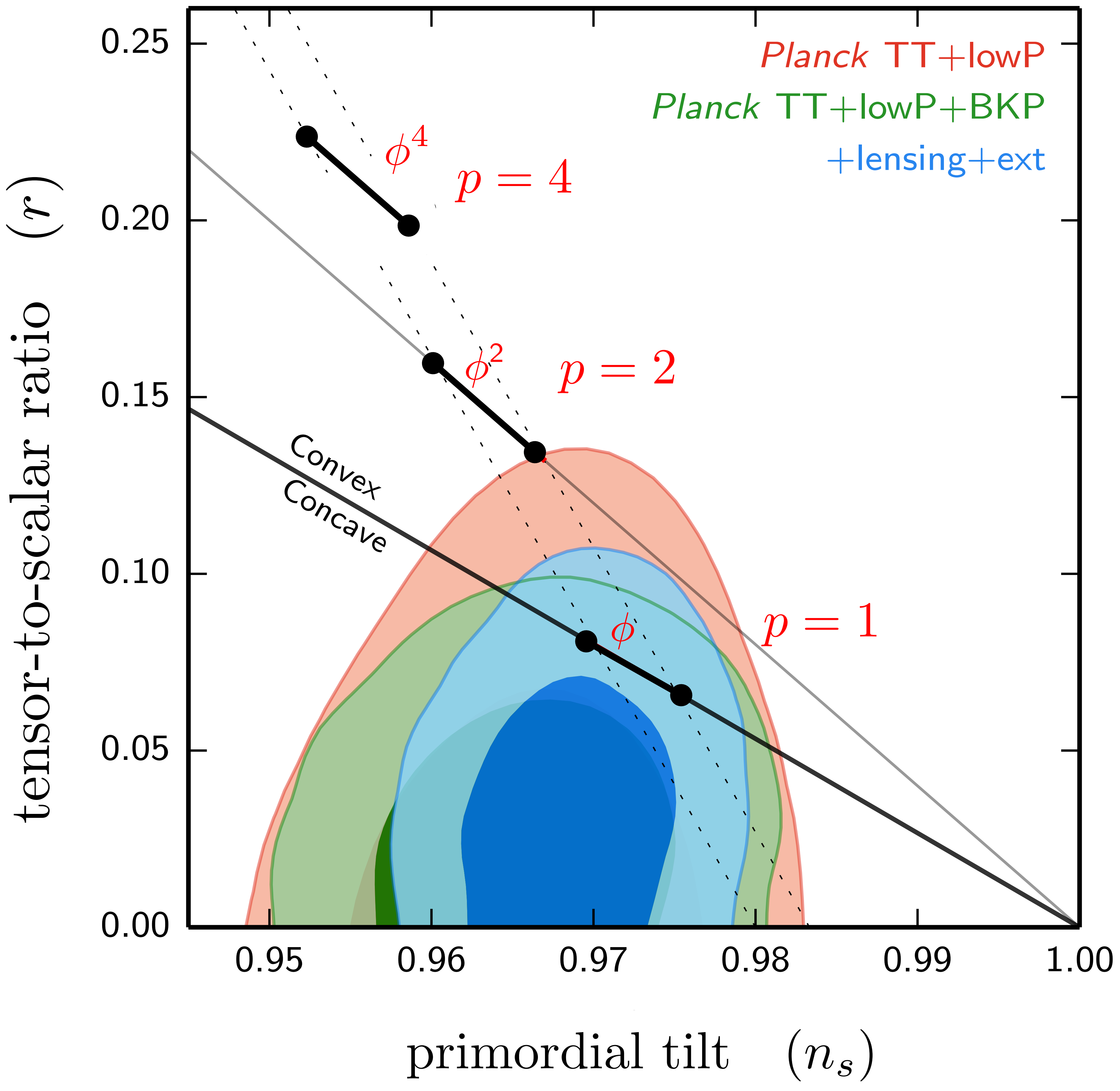
— flattened potentials

$$S = \int d^4x \sqrt{-g} \left[\frac{m_{\rm pl}^2}{2} R - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right]$$

$$V(\phi) \propto \phi^p$$

$p < 2$



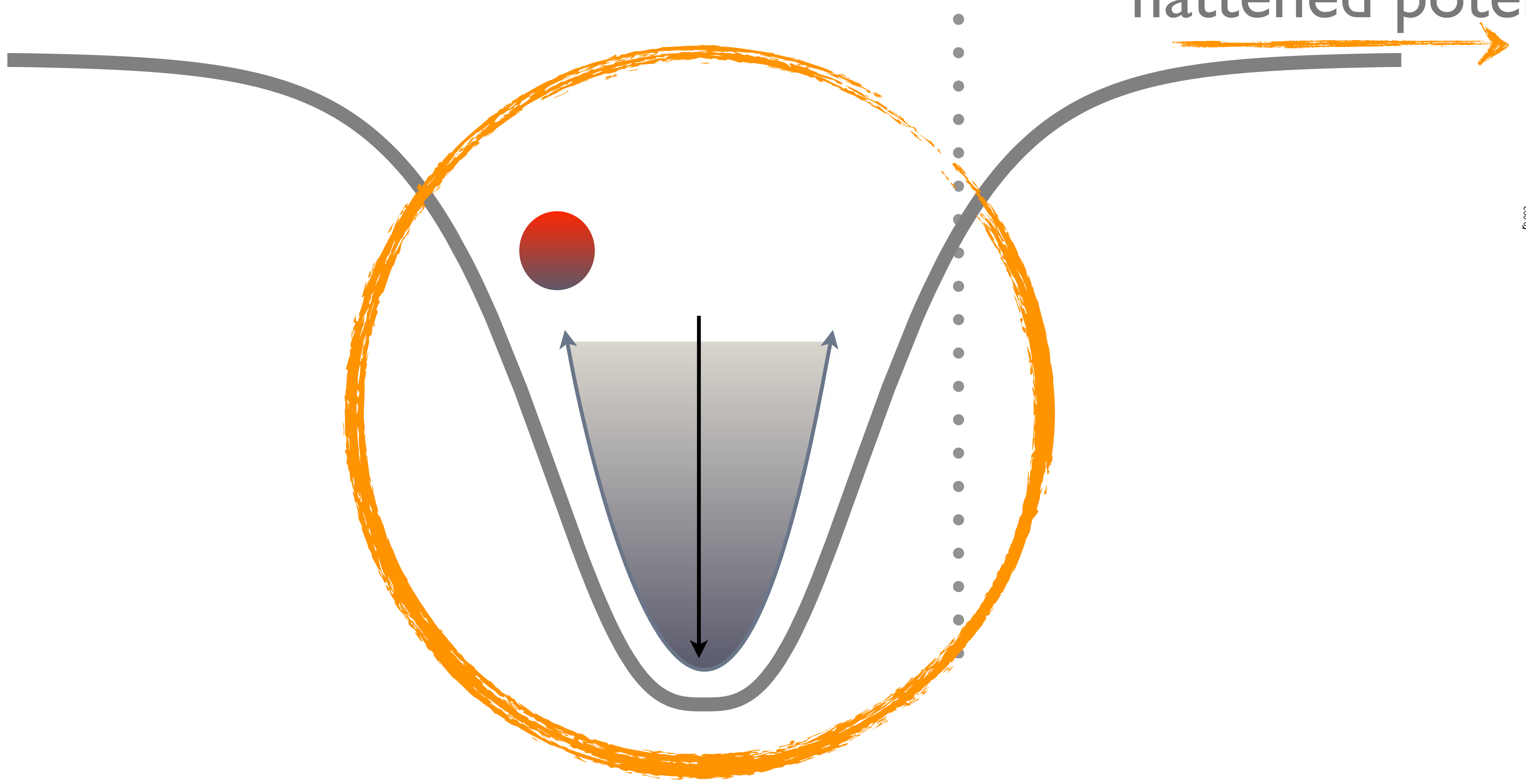


for example:
Starobinsky(1979/80), Nanopolous et. al (1983), Silverstein & Westhpal (2008), Kallosh & Linde (2013), McAllister et. al (2014) … also see C.Vafa’s talk.

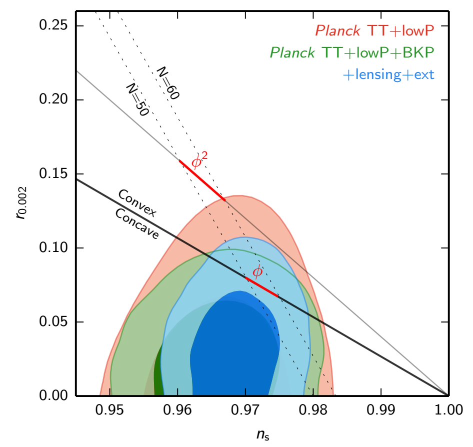
end of inflation ?

- shape of the potential (self couplings)
- couplings to other fields

$\chi\ ,\psi\ A_\mu$

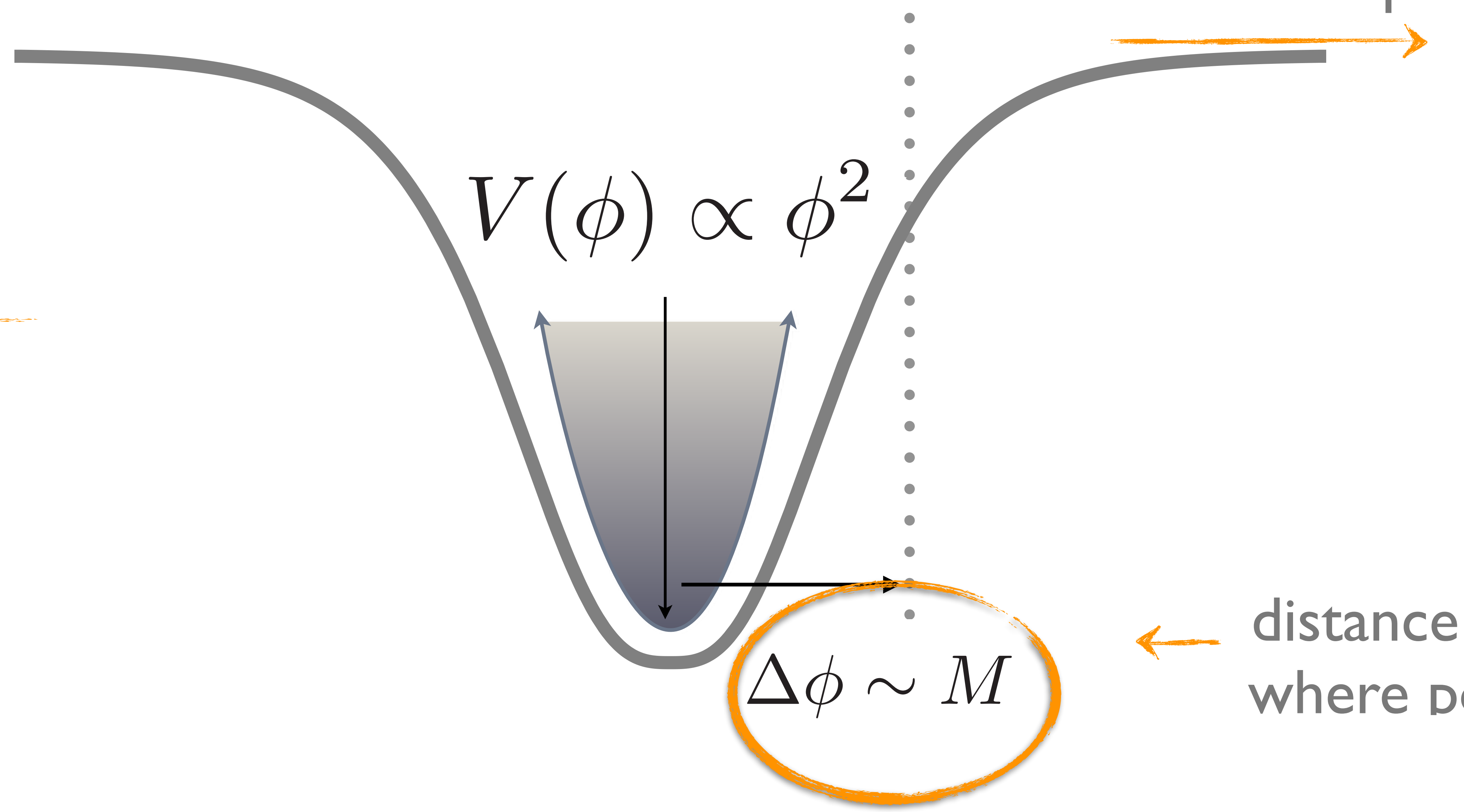


flattened potential $\phi^{p<2}$



end of inflation (simplest)

- shape of the potential (self couplings)
- couplings to other fields  $\chi\ ,\psi\ A_\mu$



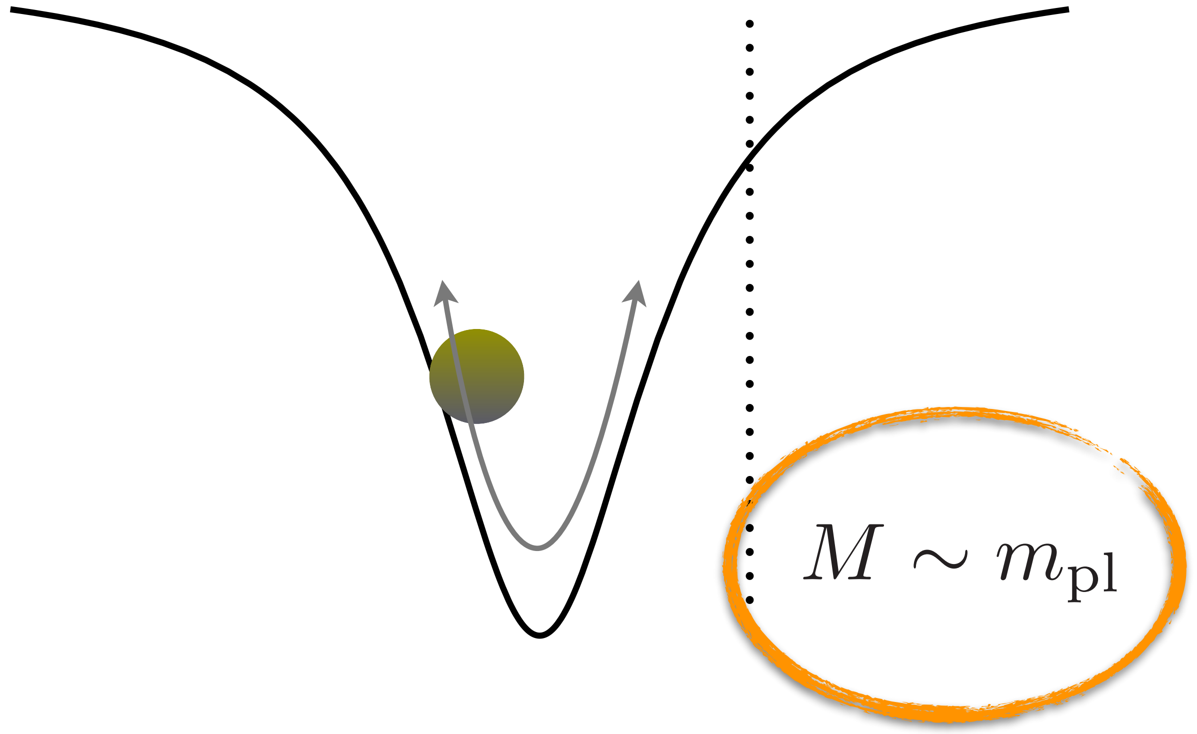
flattened potential $\phi^{p<2}$

distance from minimum where potential flattens

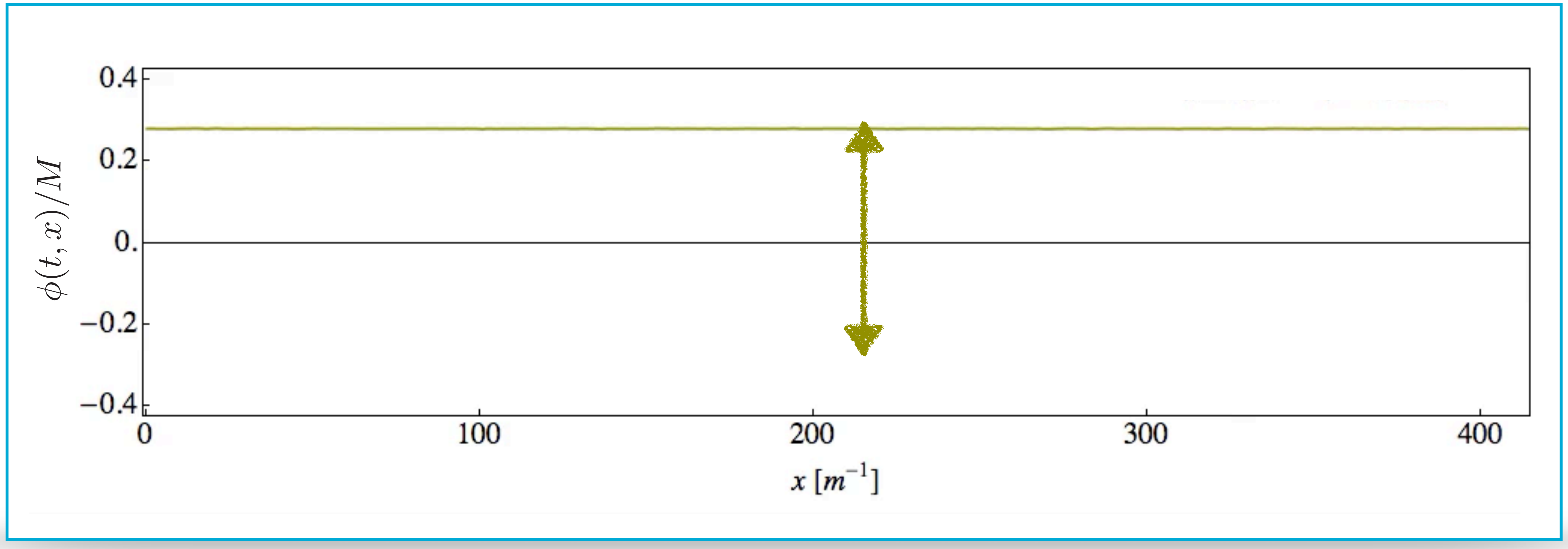
*there will still be gravitational particle production of other fields, see for example Kolb & Long (2021) and earlier papers

oscillating “free” scalar field: matter-dominated expansion +“slow” gravitational instability

- expansion ✓
- self-interactions ✗
- gravitational int. ✓



$$\Box\phi \approx m^2\phi$$



$w \to 0$

oscillating "free" scalar field: matter-dominated expansion +"slow" gravitational instability

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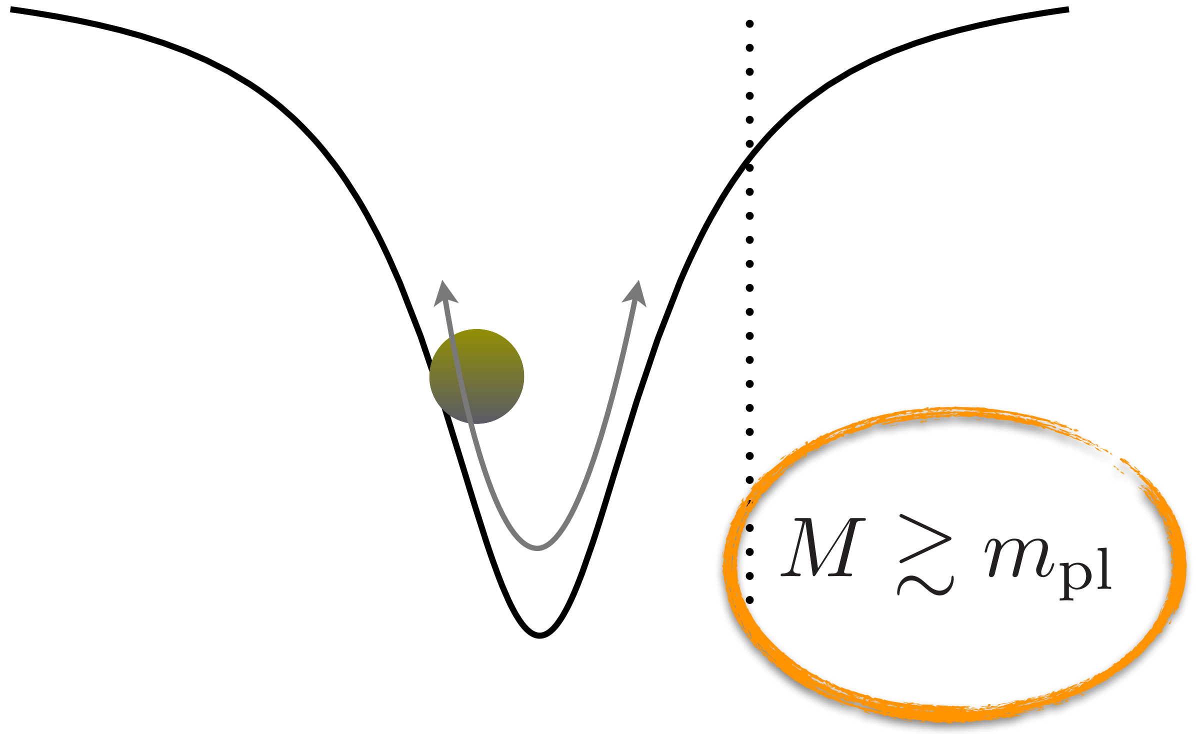

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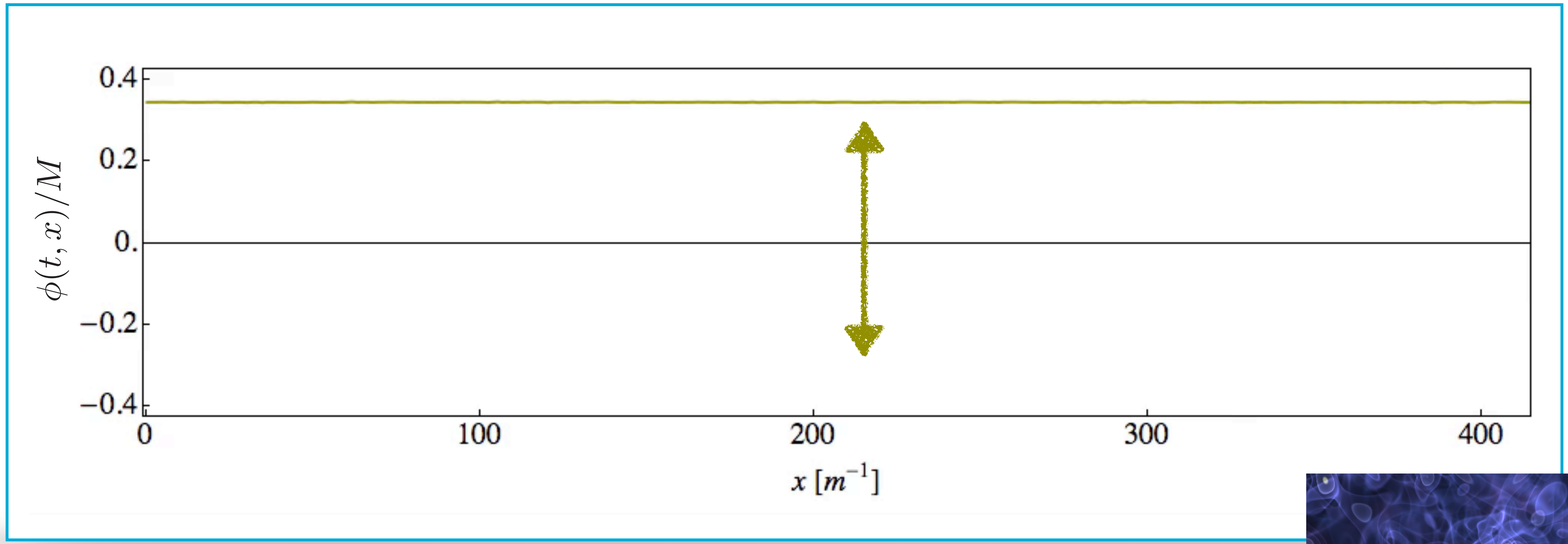
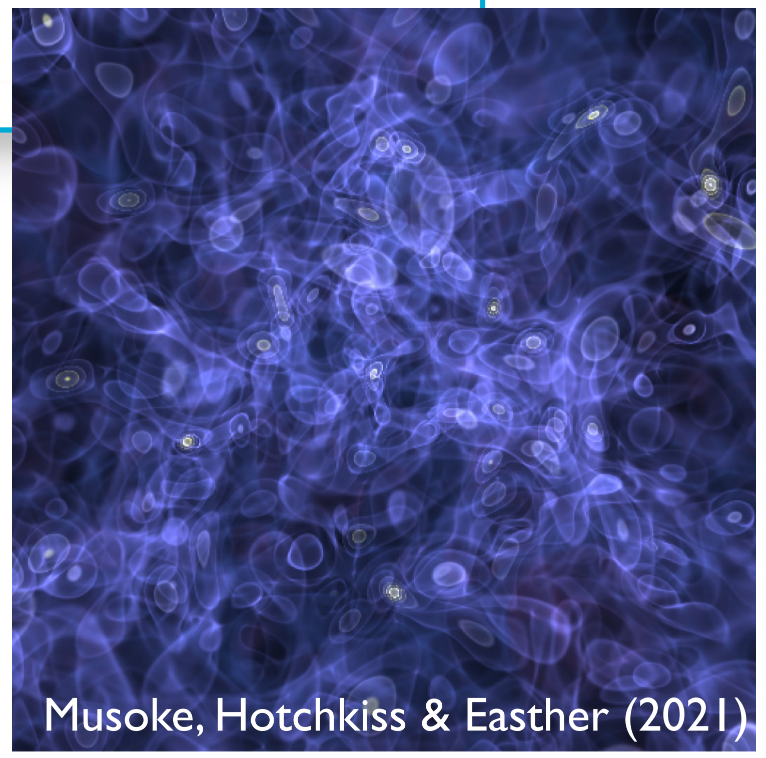


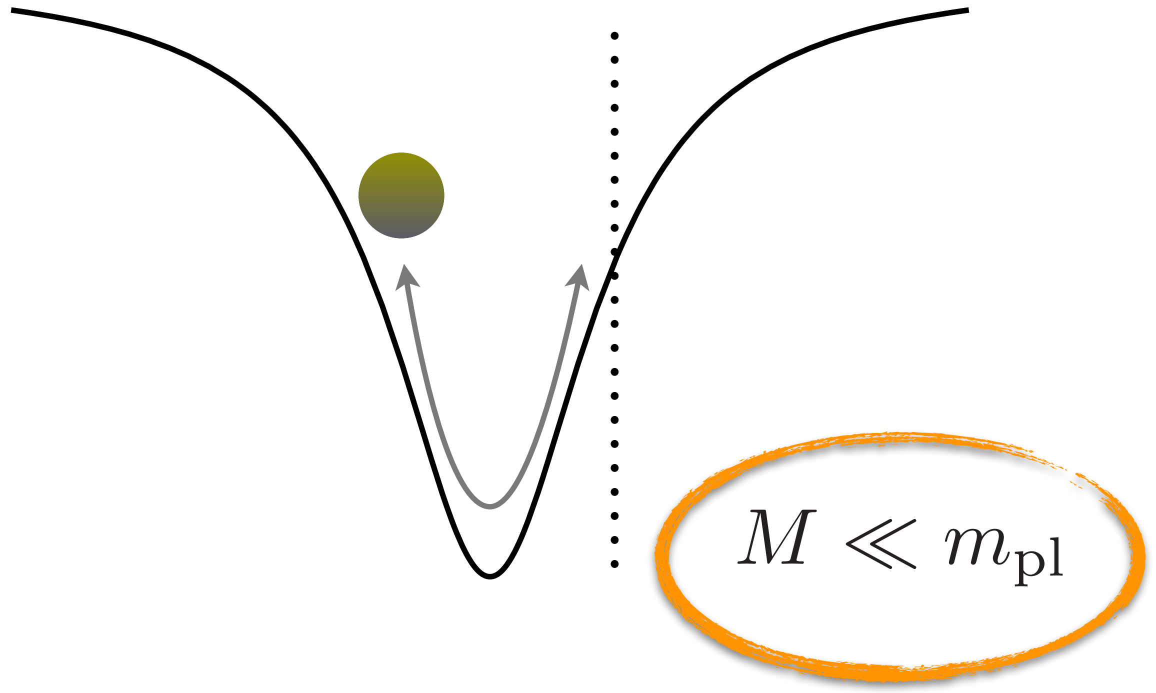


*similar to a matter dominated universe, also see Adrienne Erikcek's talk

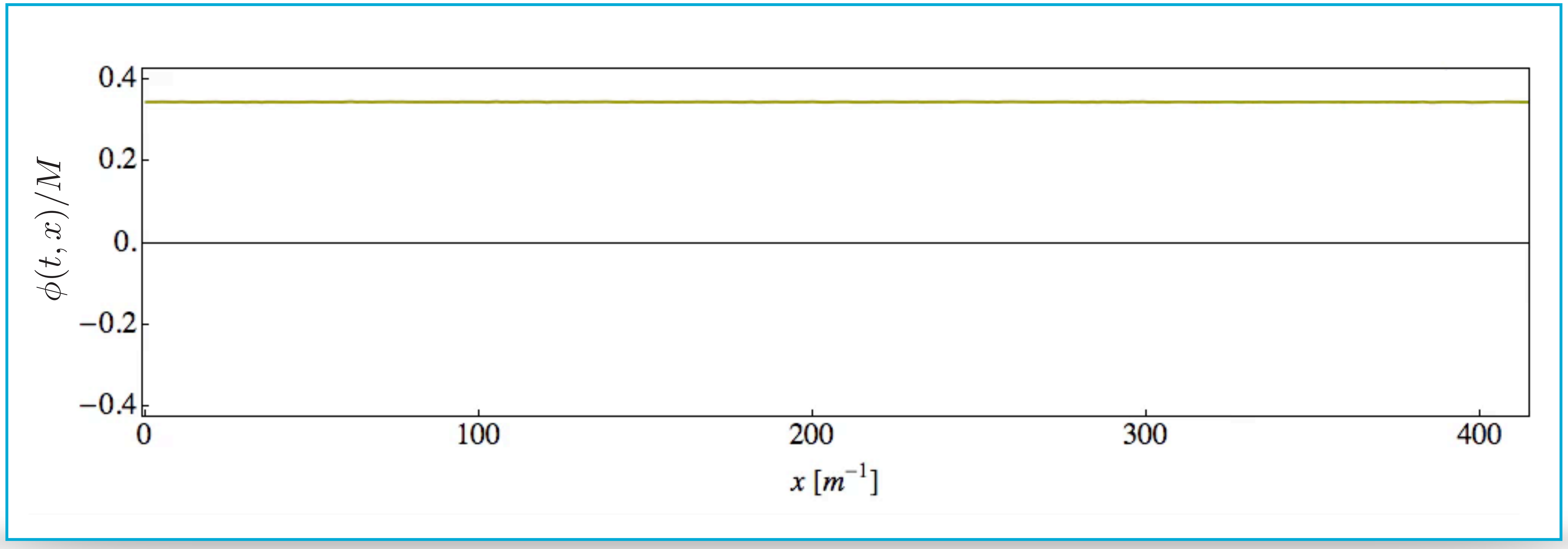
*also see N. Musoke's talk

oscillating scalar field: self-interaction driven fast instability & "oscillon" formation

expansion ✓
self-interactions ✓
gravitational int. ✗



$$\Box\phi = V'(\phi)$$



MA (2010) 1006.3075

*without oscillons, but relevant for instabilities, see related (much) earlier work: Khlopov, Malomed & Zeldovich (1985)

oscillating scalar field: self-interaction driven fast instability & "oscillon" formation

expansion ✓

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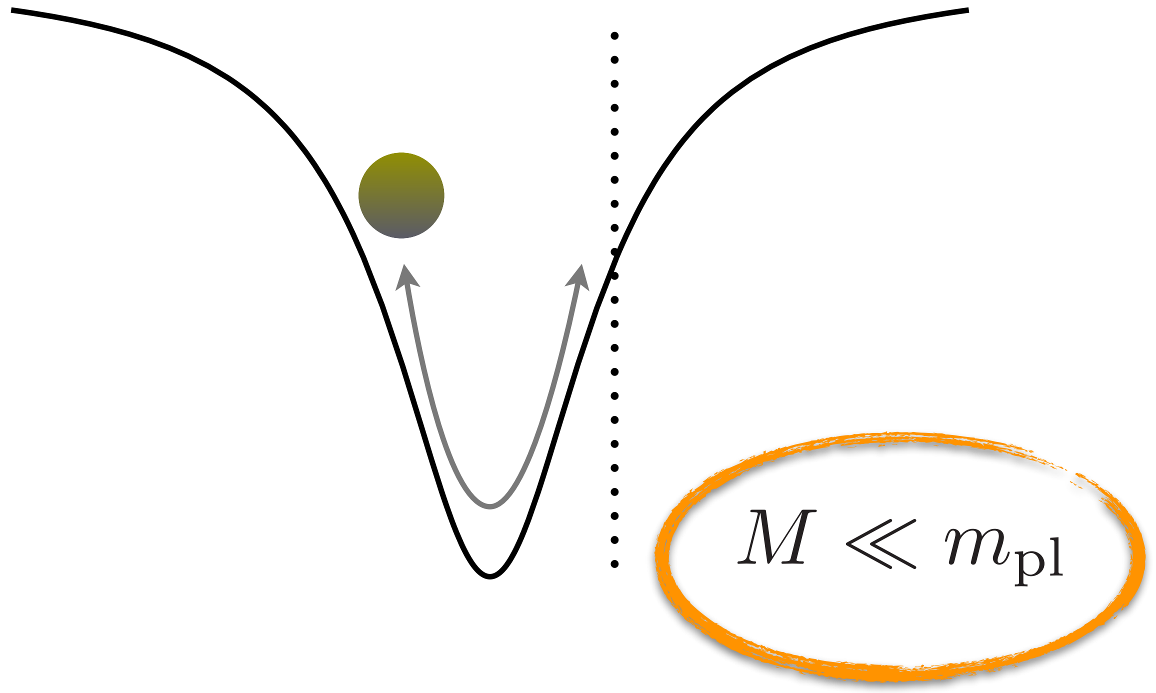
gravitational int. ✗



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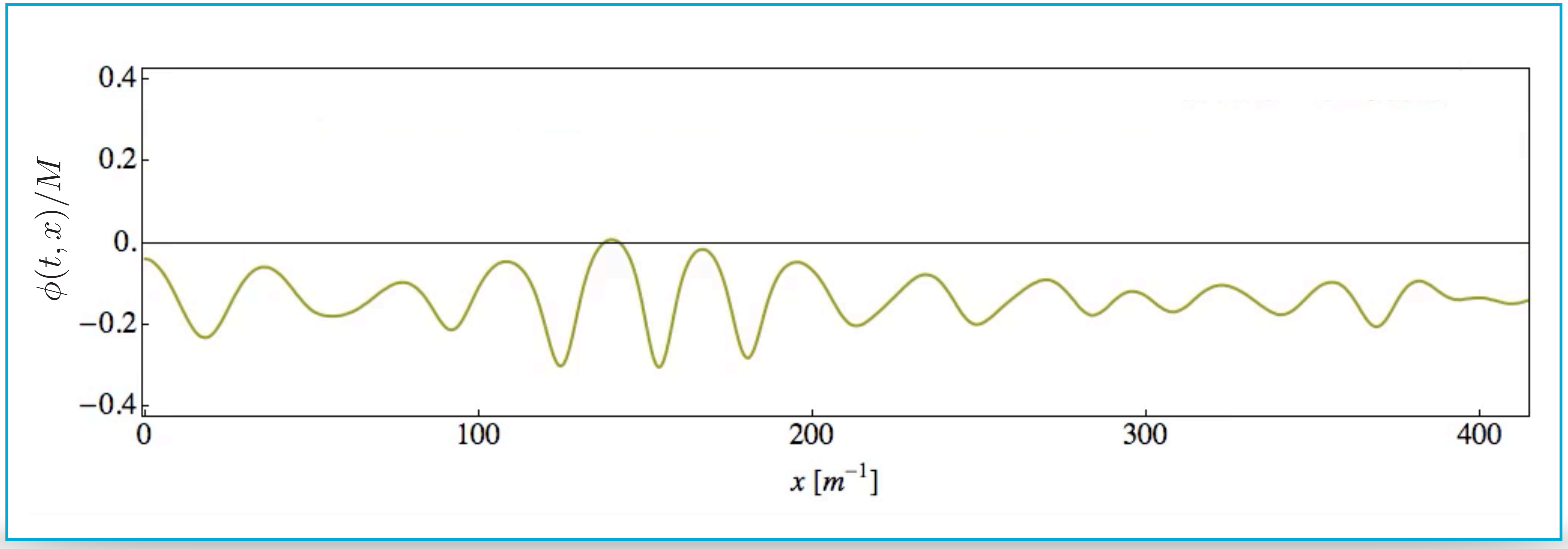

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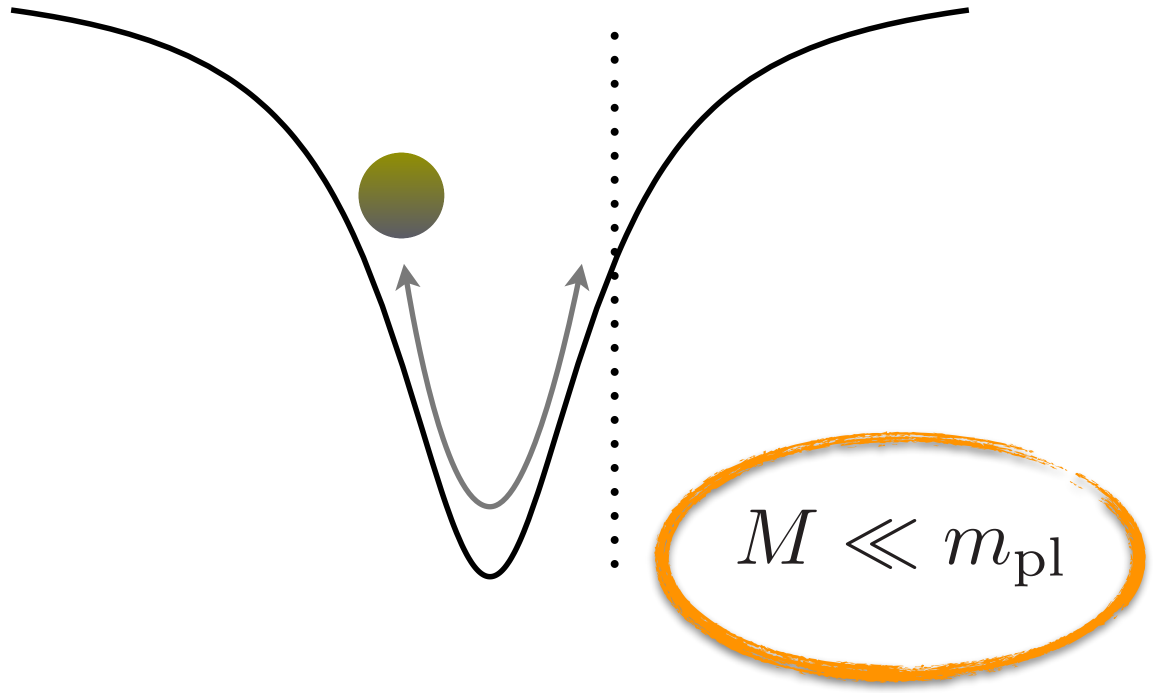

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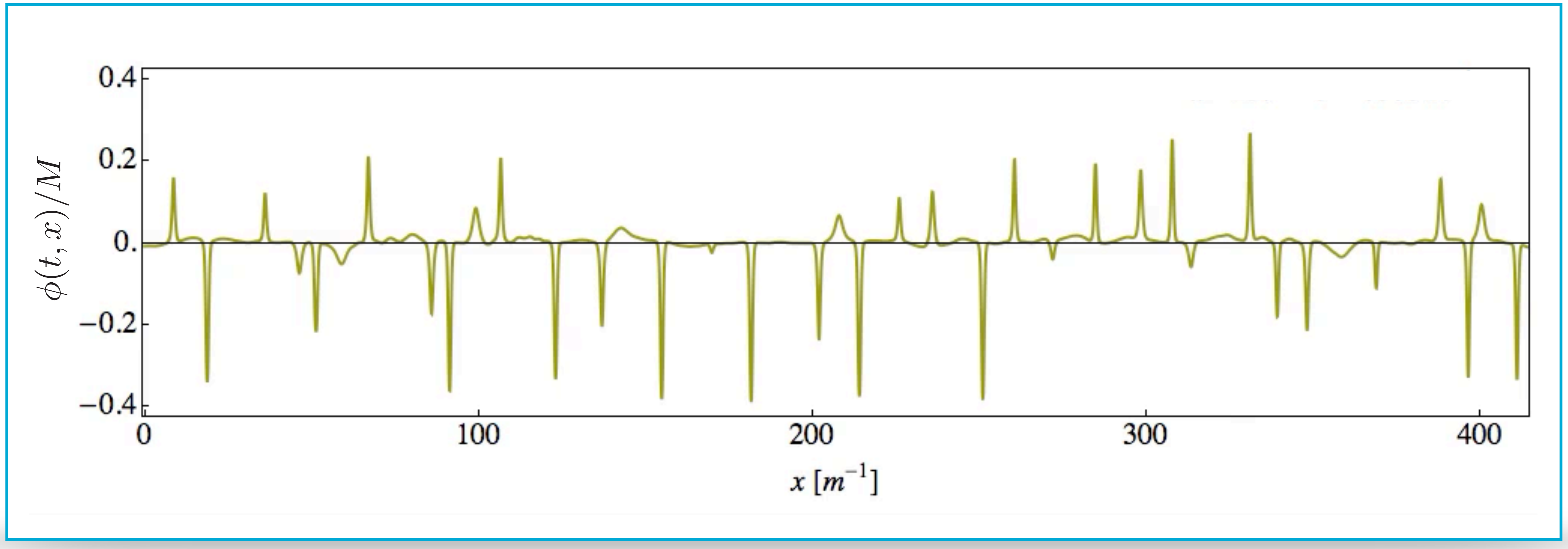

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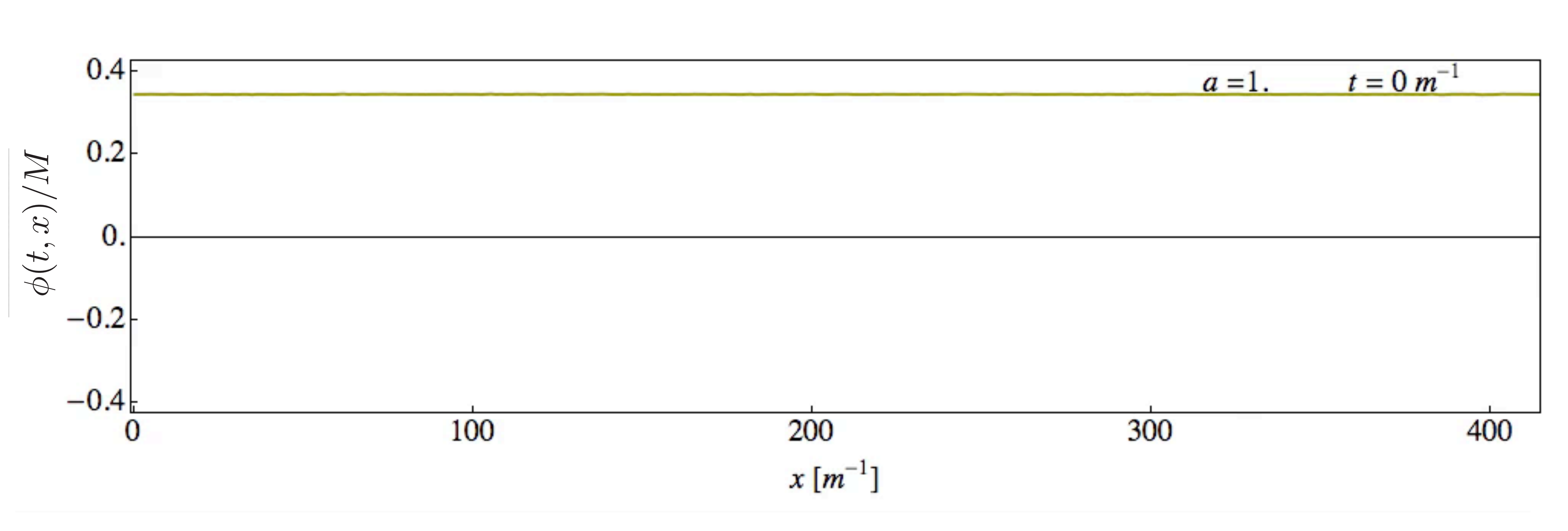
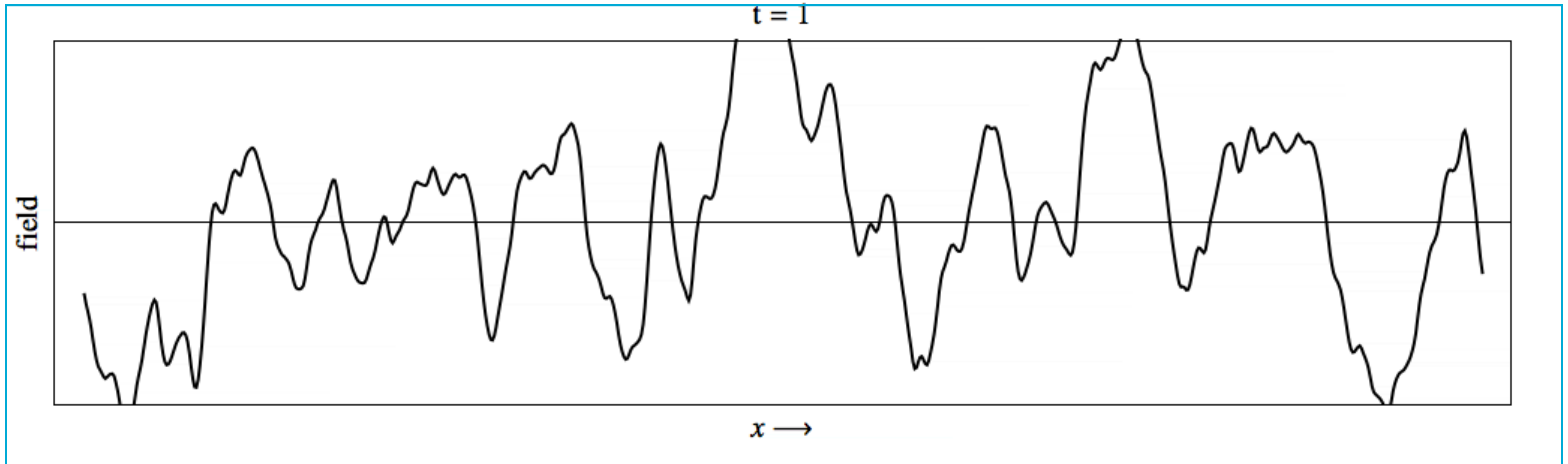
insensitivity to initial conditions



MA (2010)

instability growth rate/Hubble > 1

based on Farhi et. al (2008)



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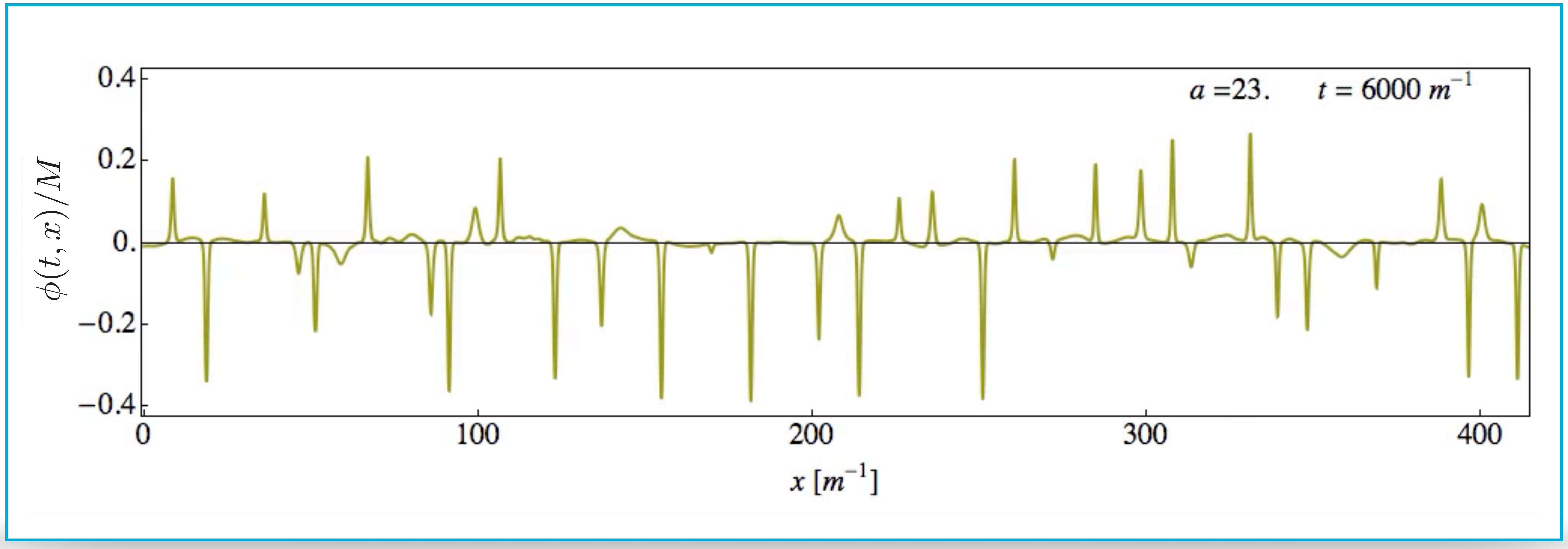

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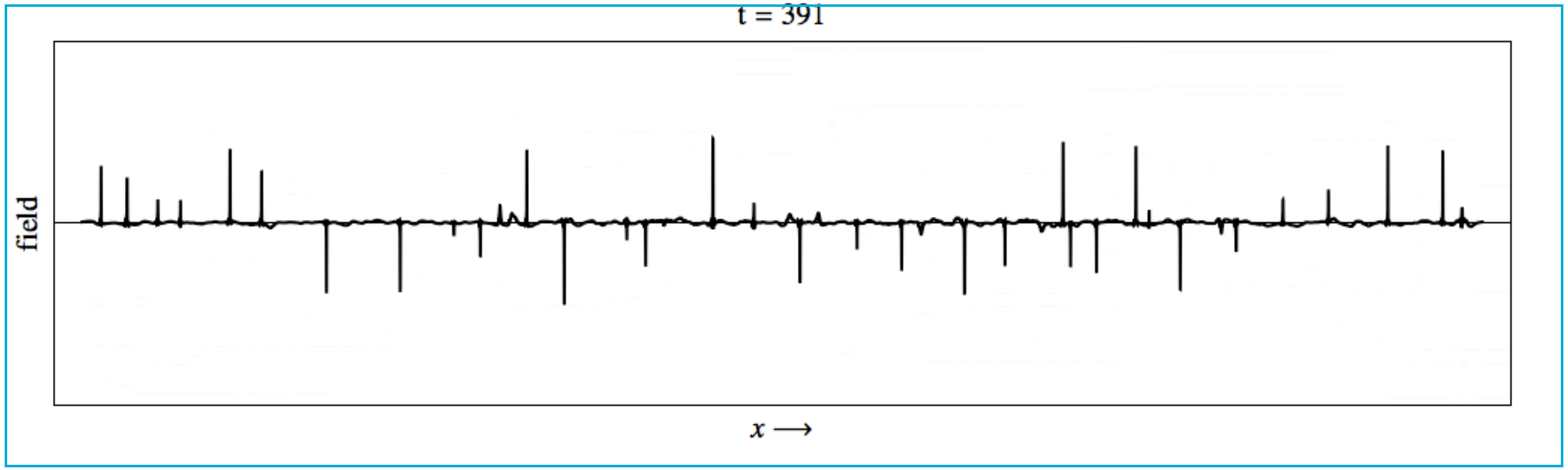
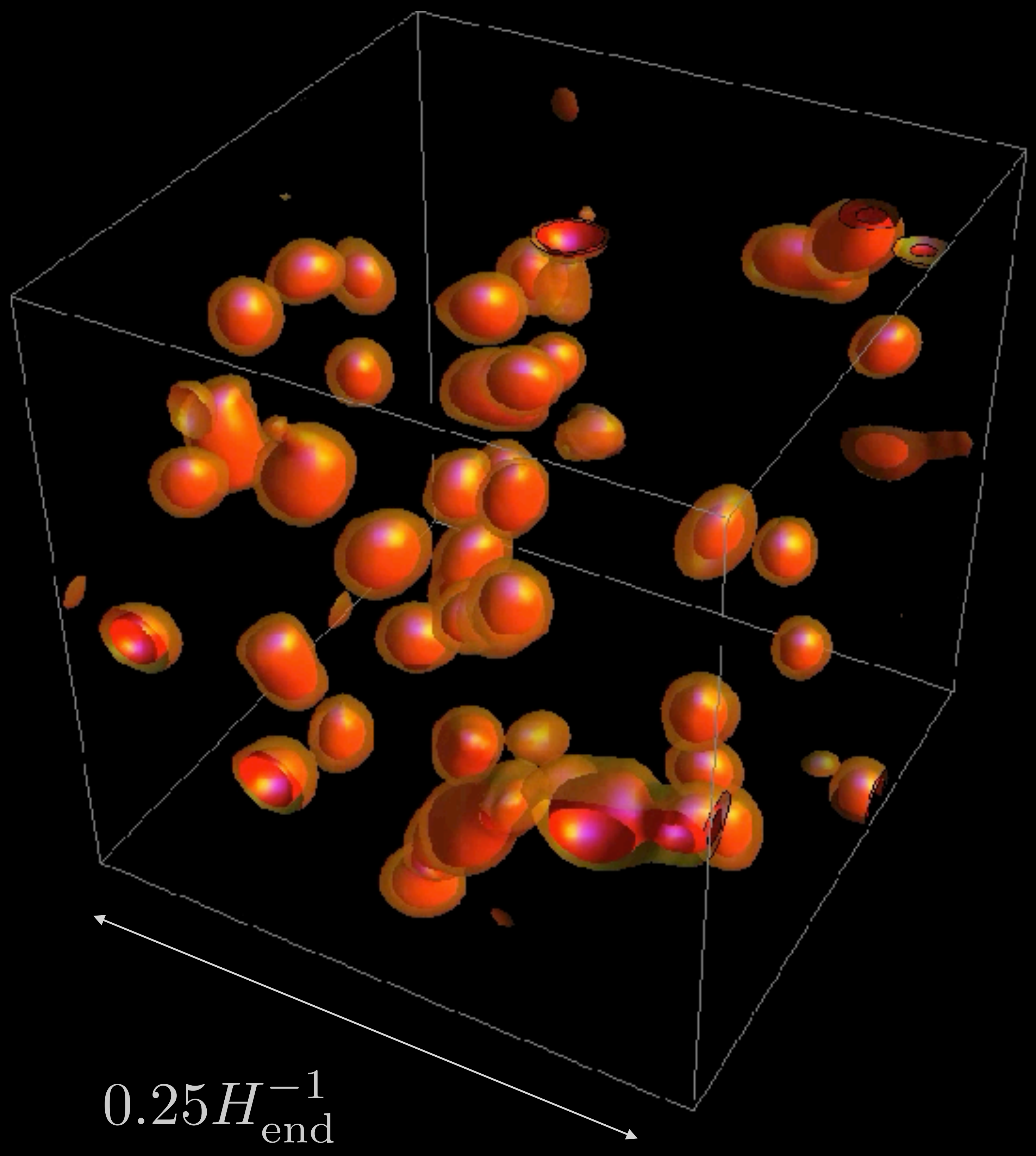


oscillating scalar field: self-interaction driven fast instability & "oscillon" formation

expansion

self-interactions ✓

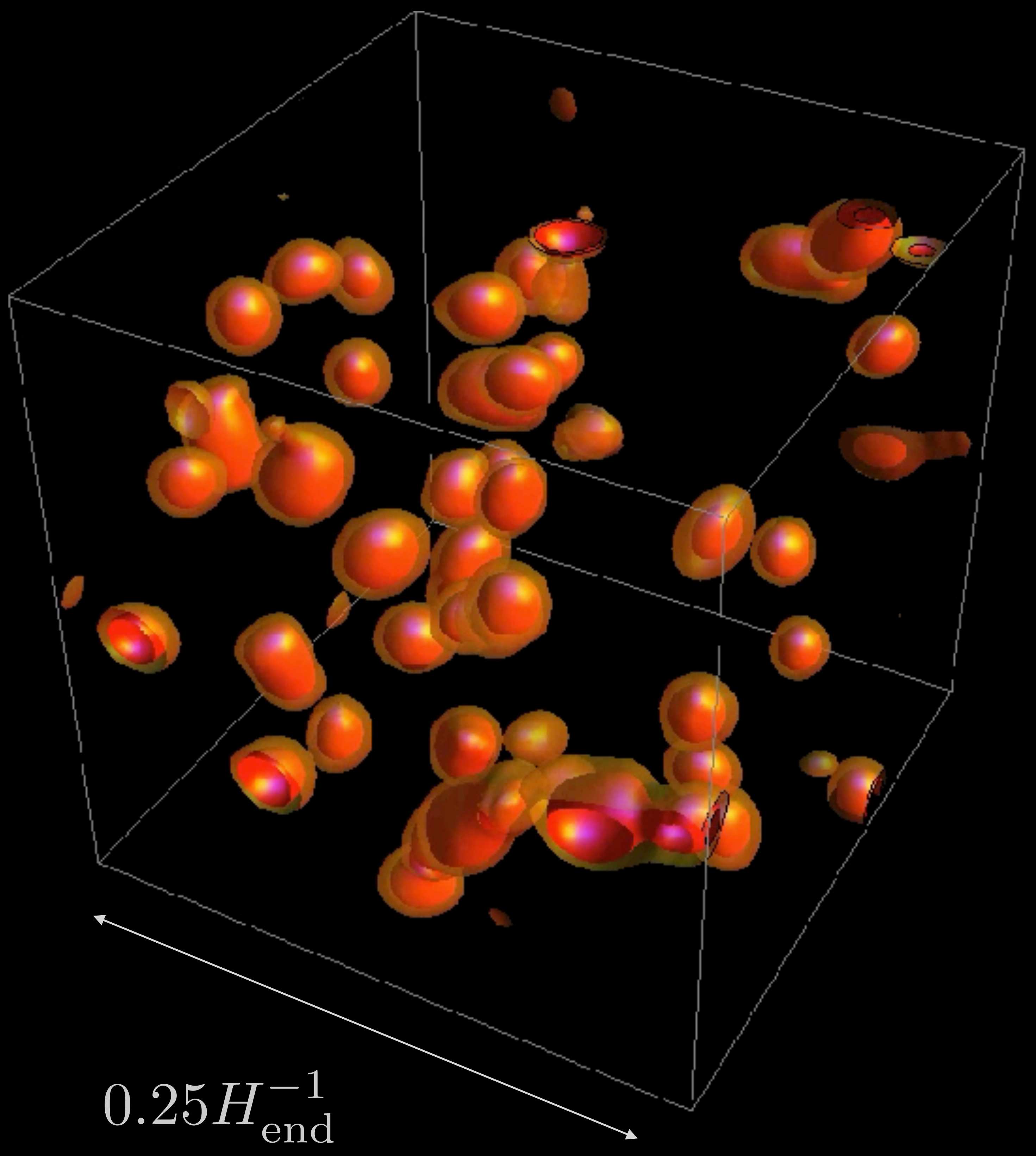
gravitational int. ✗



MA, Easther, Finkel, Flauger & Hertzberg (2011) 1106.3335

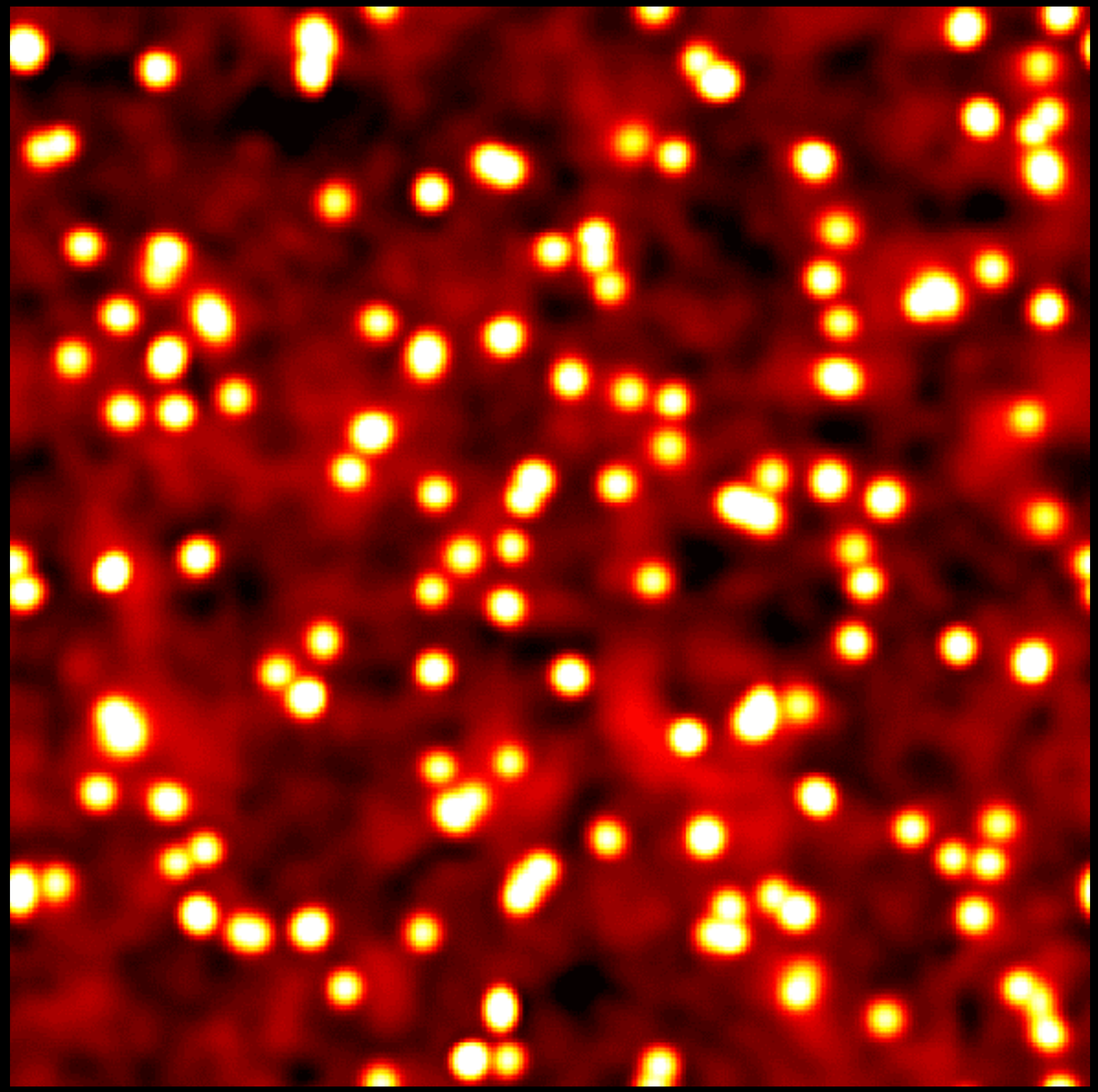
self-interaction driven fast instability & “oscillon” formation + gravitational clustering

expansion ✓
self-interactions ✓
gravitational int. ✗



MA, Easther, Finkel, Flauger & Hertzberg (2011) 1106.3335

expansion ✓
self-interactions ✓
gravitational int. ✓



MA & Mocz (2019) 1902.07261

* non-relativistic, Schrodinger-Poisson

relativistic to non-relativistic effective theory

Klein-Gordon-Einstein

integrate out 'fast' modes

Nonrelativistic EFT for 'slow' modes

= Schrödinger-Poisson + corrections

Salehian, Zhang, MA, Kaiser, Namjoo, (2021)

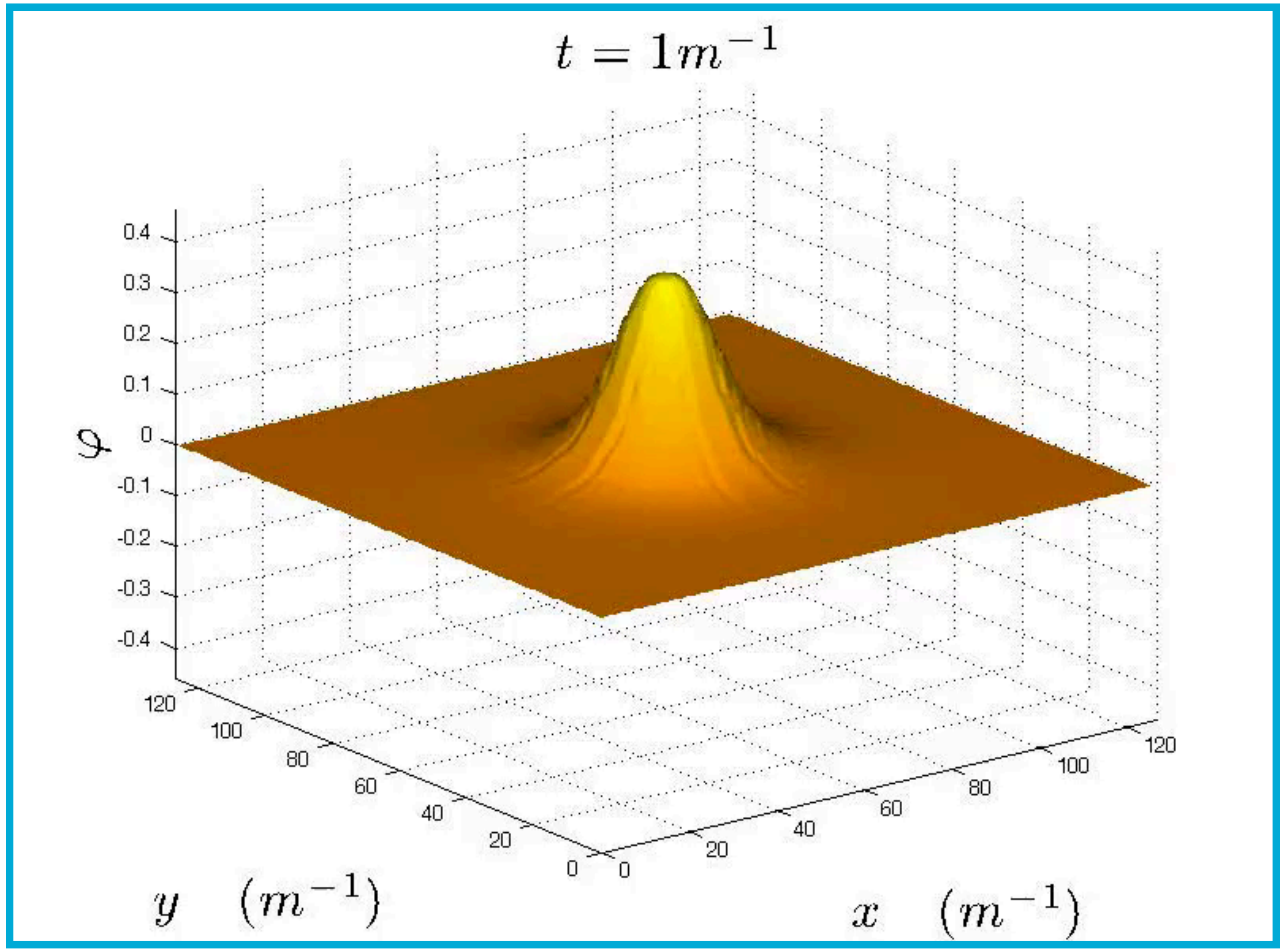
2104.10128

solitons : oscillons

spatially localized

coherently oscillating

exceptionally long-lived



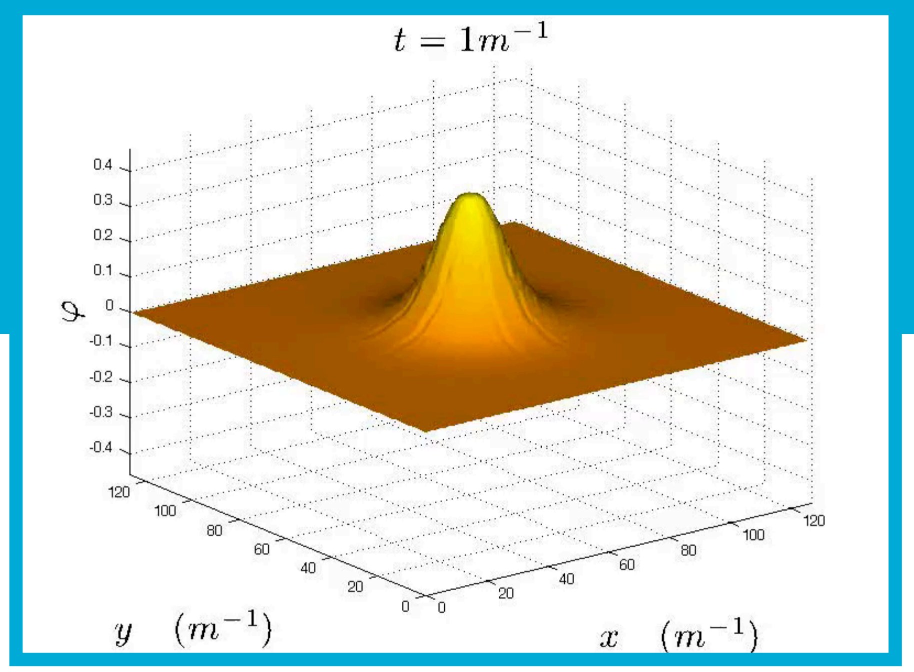
For example:

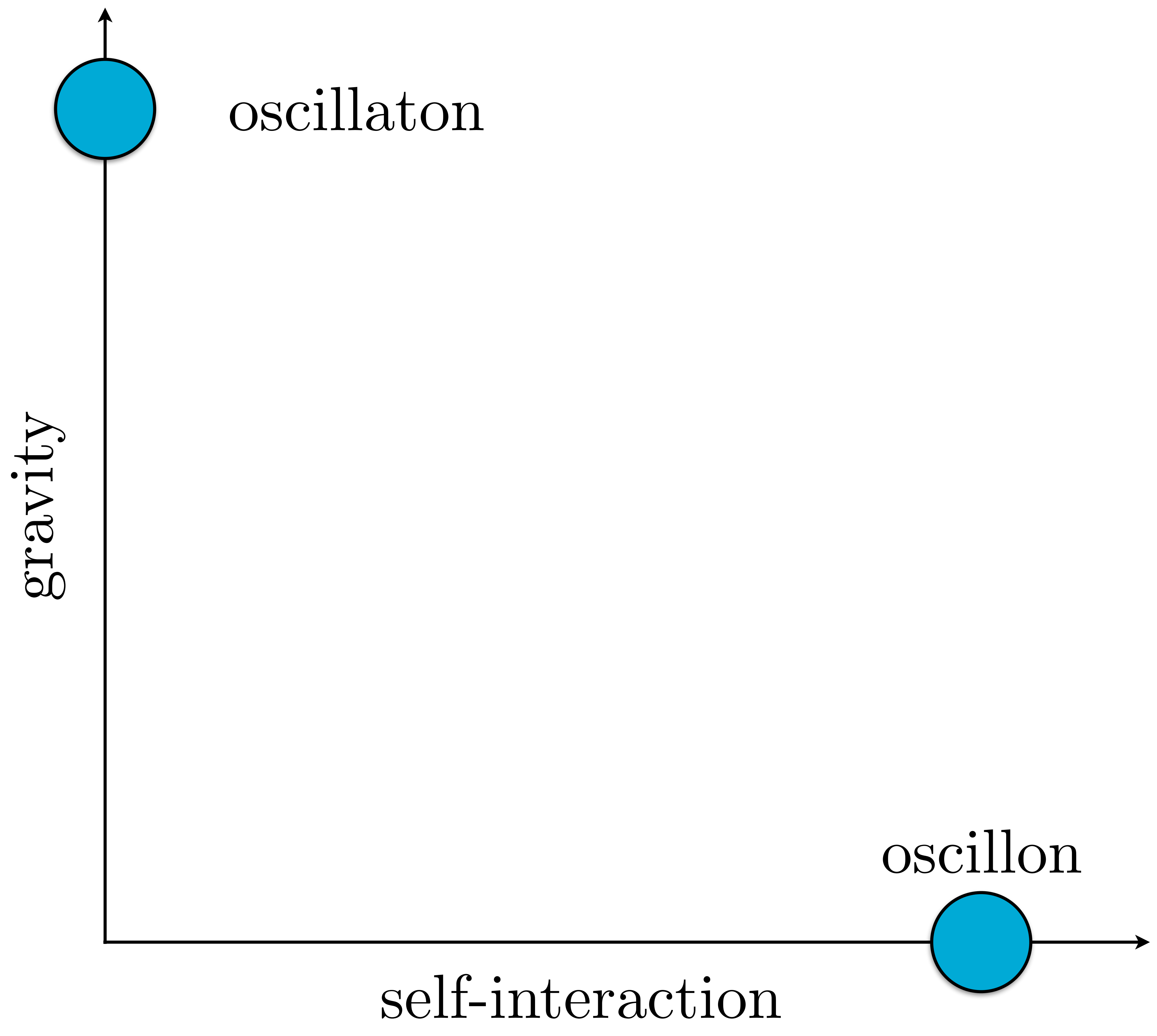
Bogolubsky & Makhankov (1976)
Gleiser (1994)
Copeland et al. (1995)
MA & Shirokoff (2010)
Hertzberg (2011)
MA (2013)
Mukaida et. al (2016)
Zhang, MA, et. al (2020)

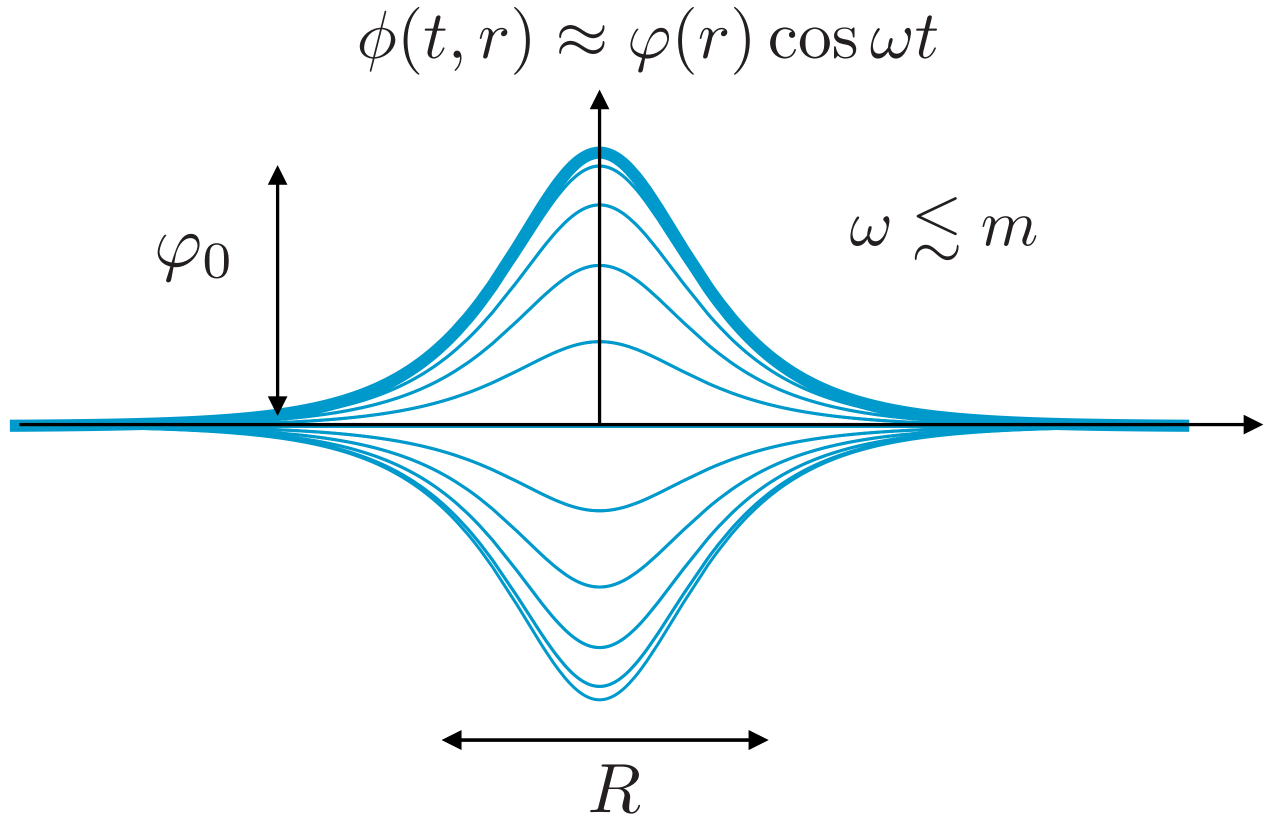
*see talk by David Cyncynates on lifetimes in the parallel session also

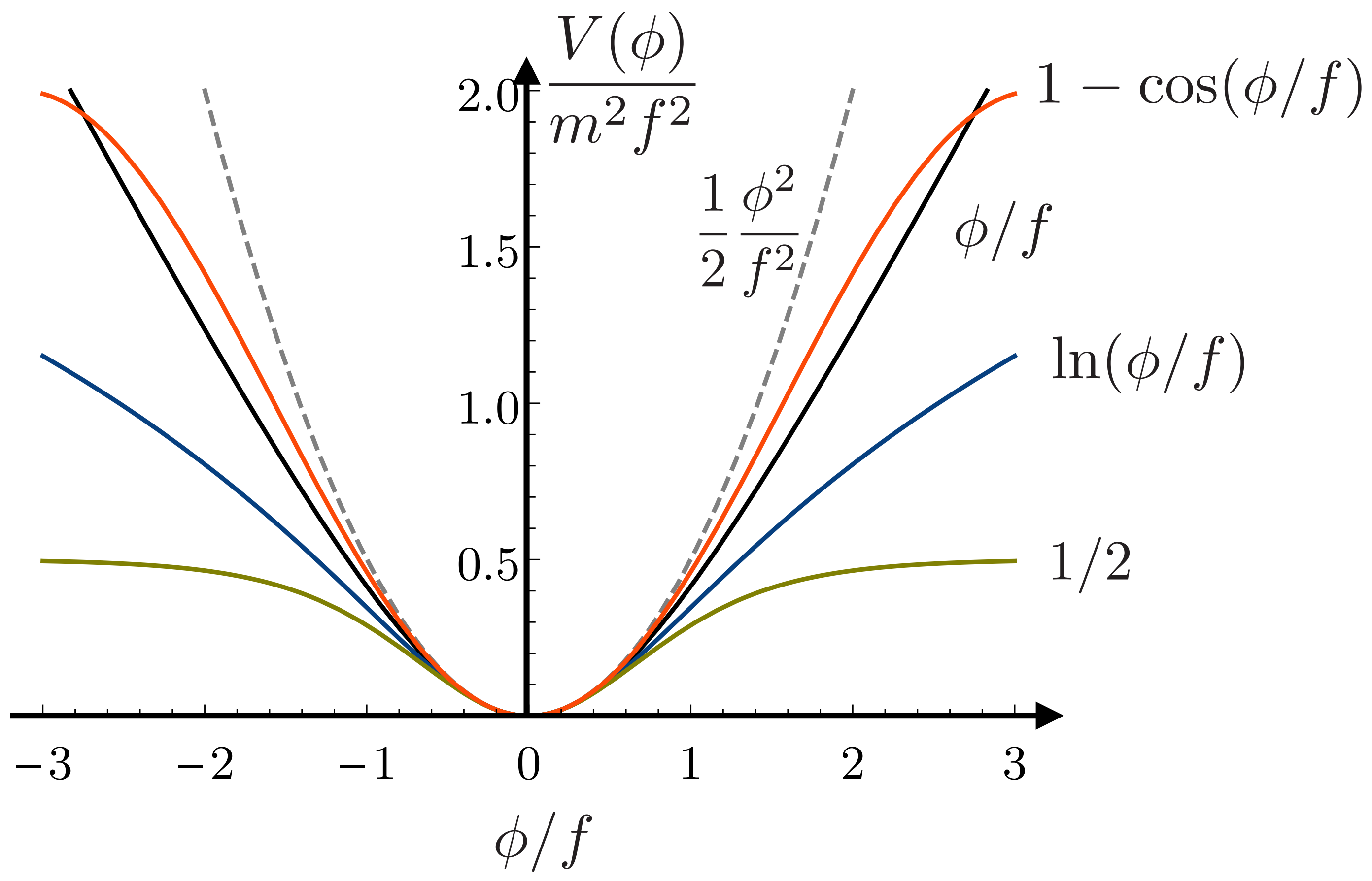
solitons : oscillons, scalar-stars …

spatially localized, coherently oscillating, long-lived



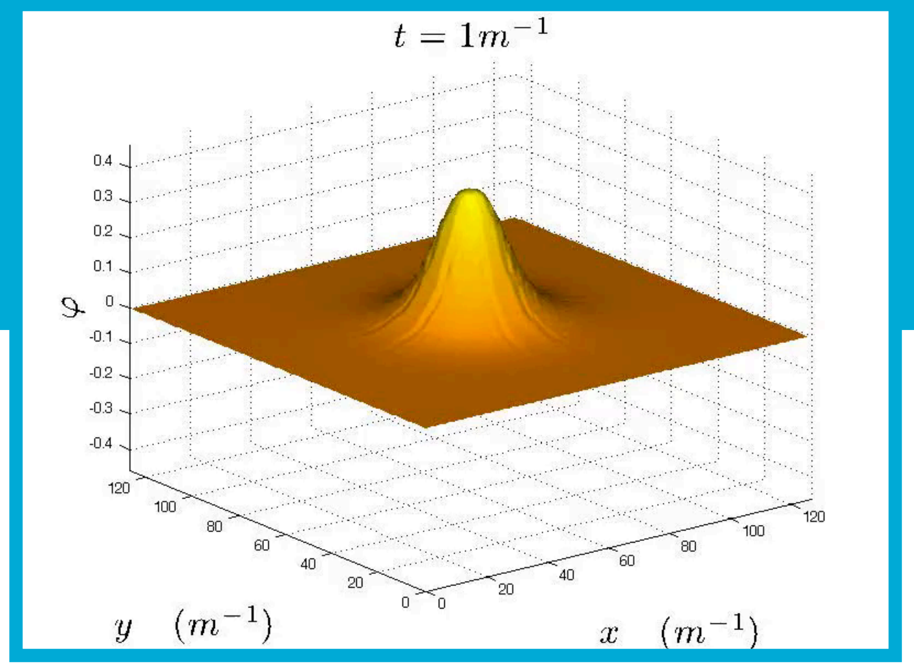


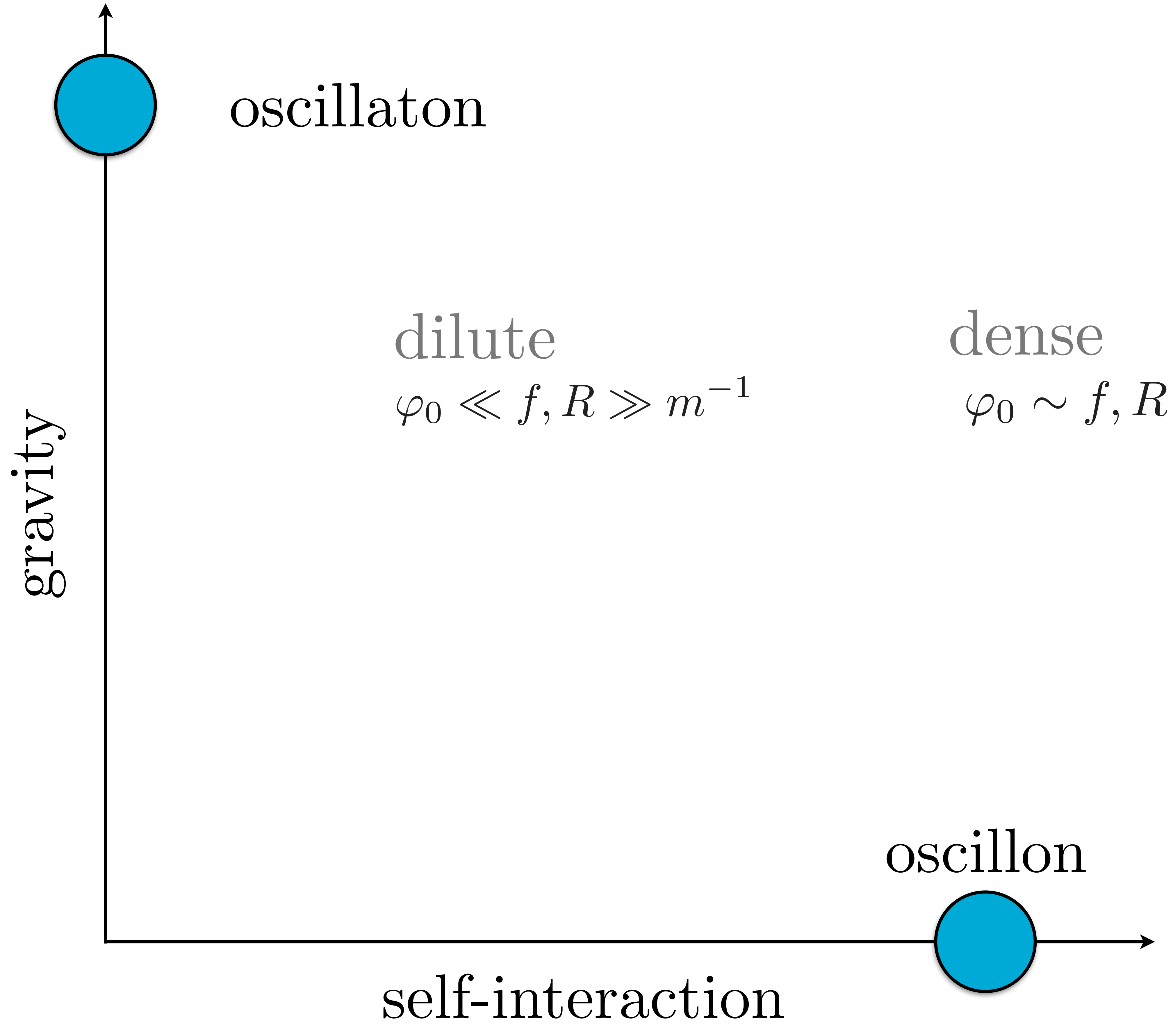


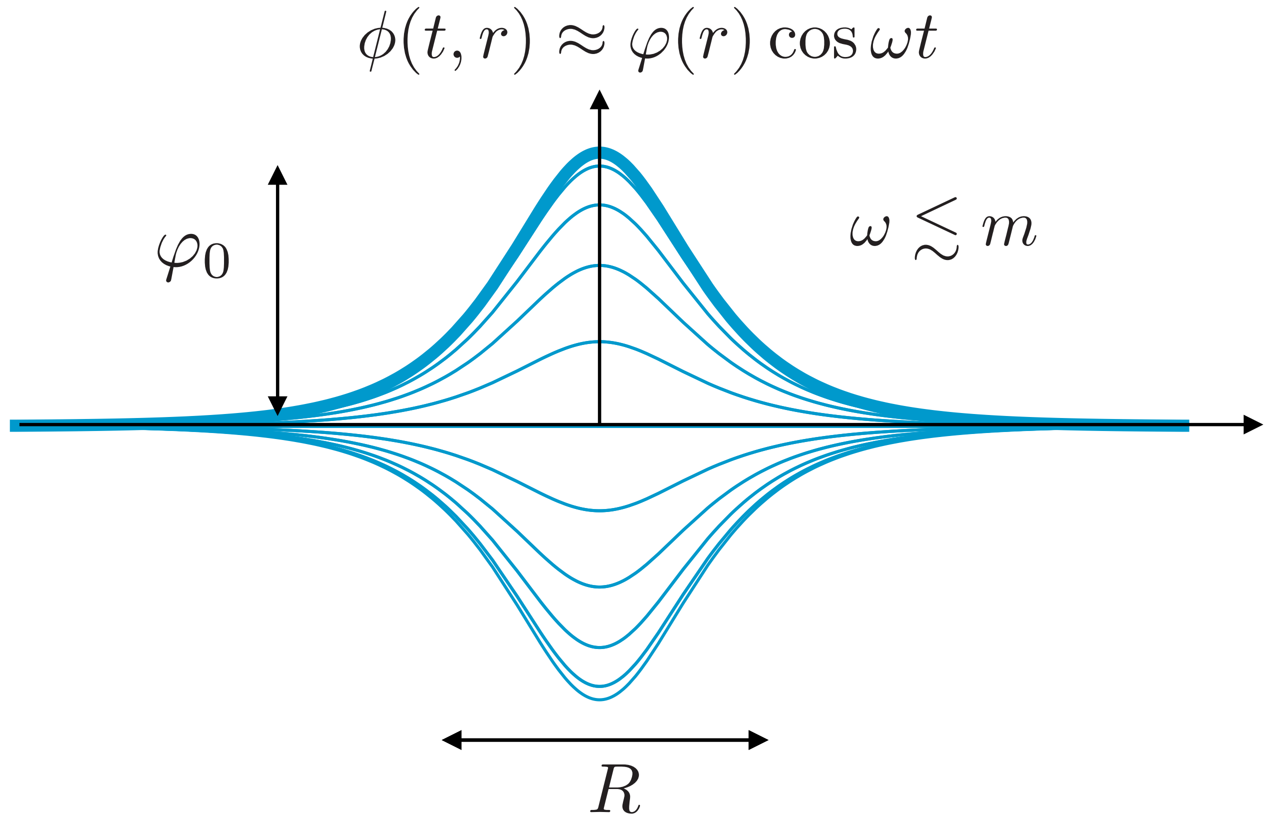


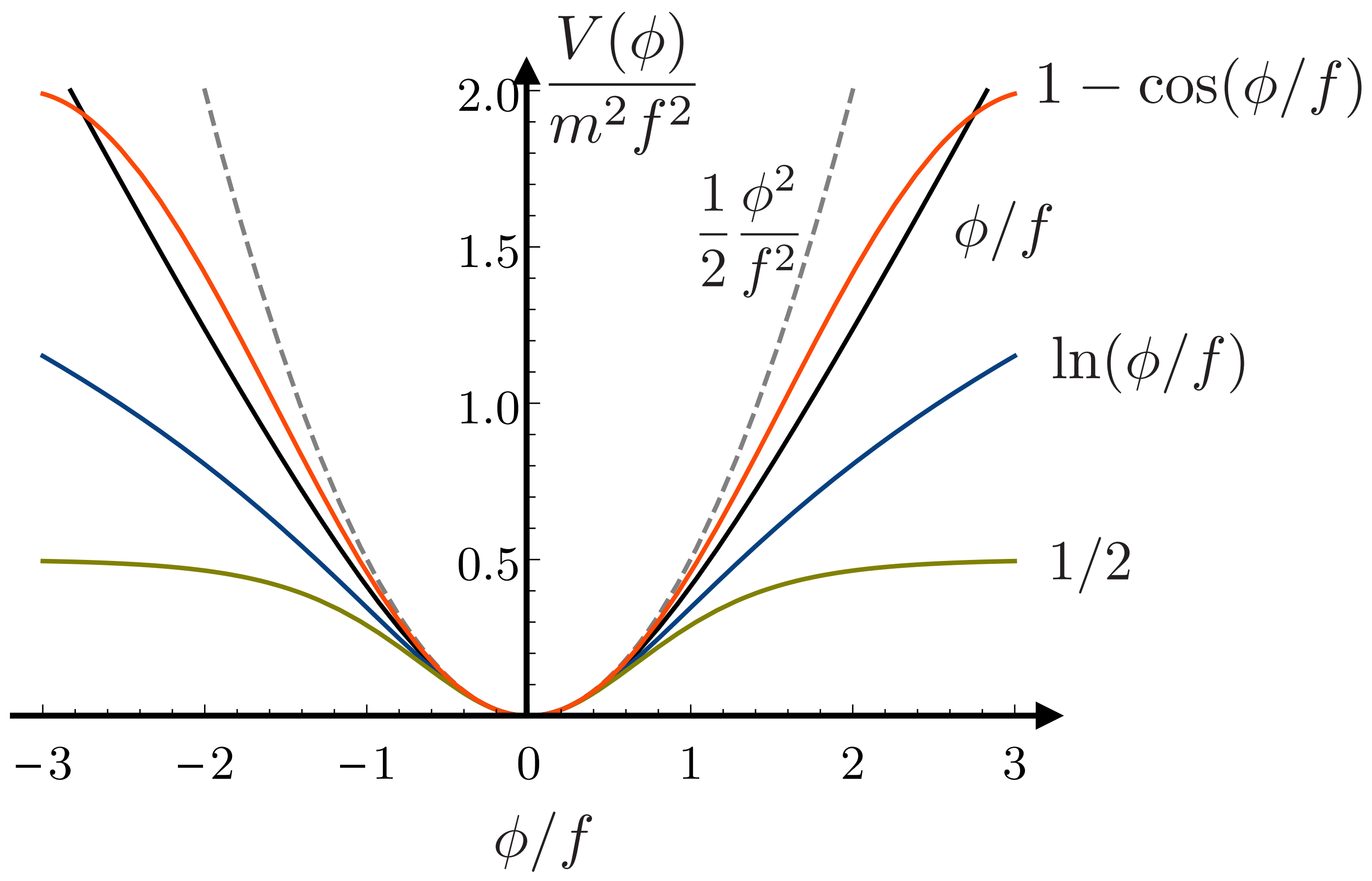
solitons : oscillons, scalar stars …

spatially localized, coherently oscillating, long-lived







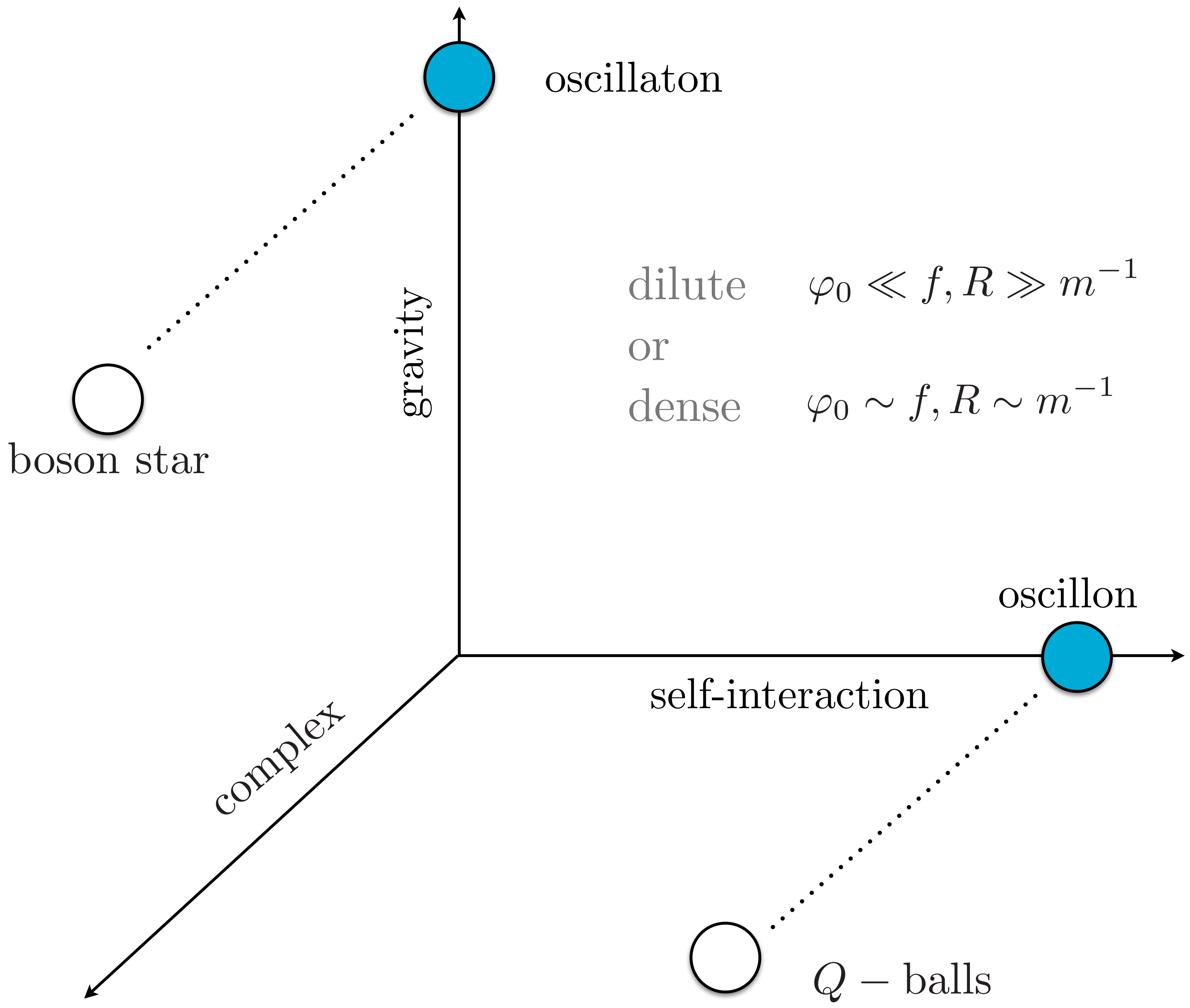


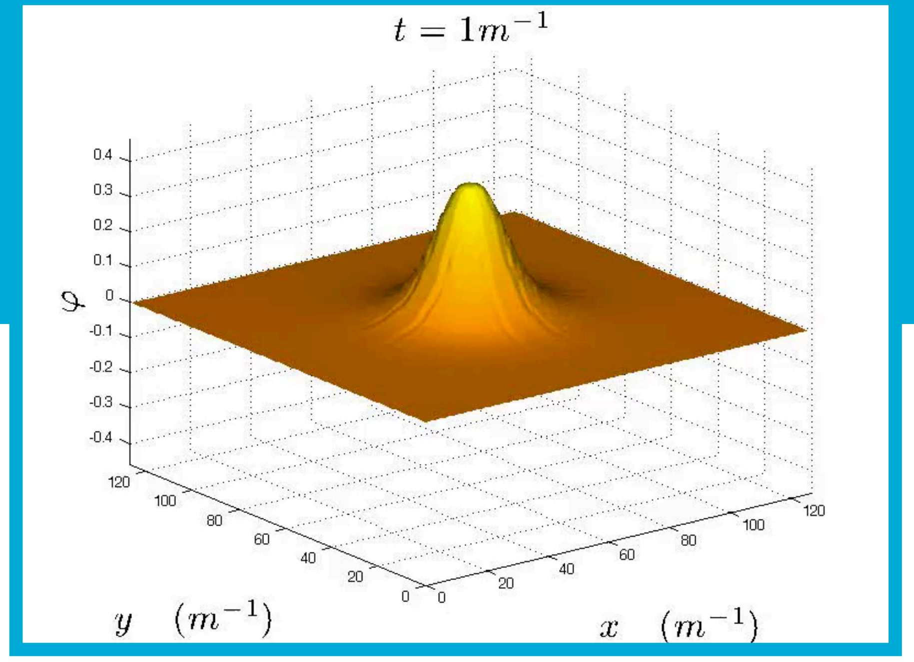
*lifetimes can be much, much larger than the Hubble time scale at the end of inflation

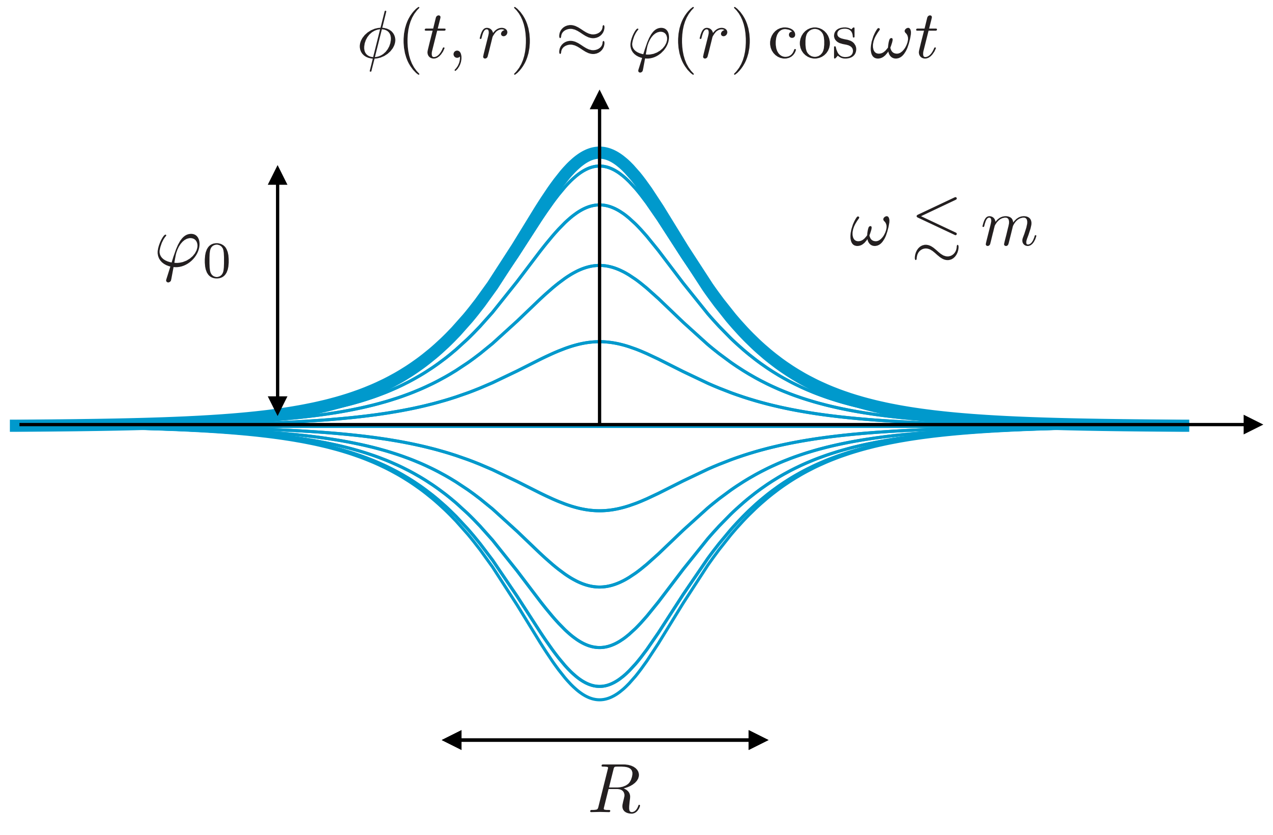
*for regime with strong field gravity regime, see also Muia et. al & Nazari et. al (2019,20)

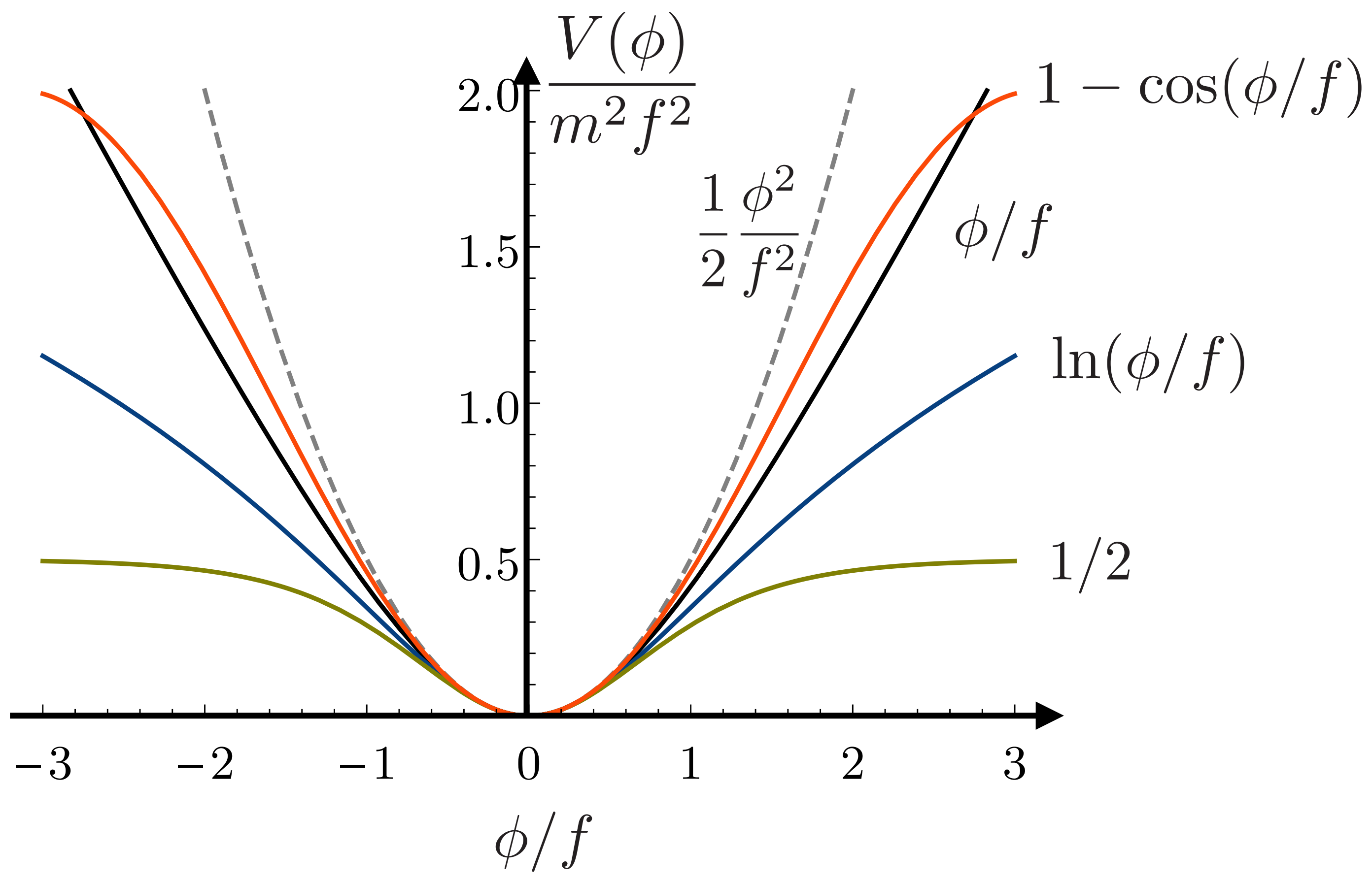
solitons : oscillons, scalar/boson stars, Q-balls

spatially localized, coherently oscillating, long-lived









- see entire parallel session “ BSM with Compact Objects”

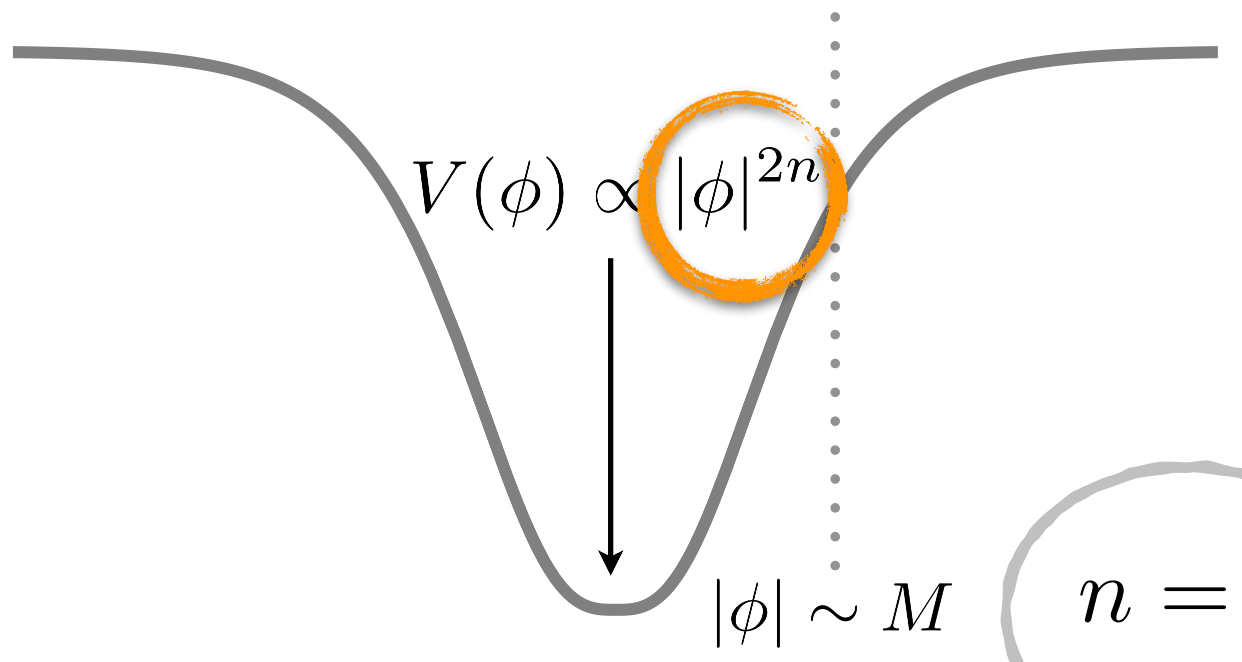
dynamics in quadratic power law minima + wings

Homogeneous oscillations

$$w = \frac{n-1}{n+1}$$

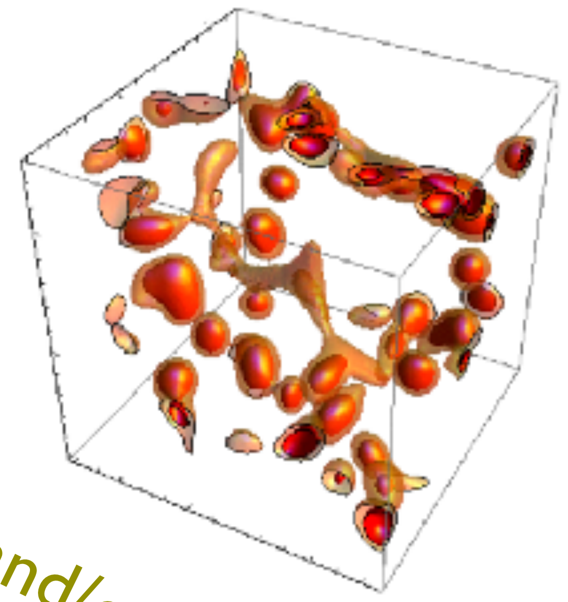
Turner (1983)

inflaton potential



$n = 1$

field fragments into solitons and/or just gravitationally clusters



eq. of state

$w \to 0$

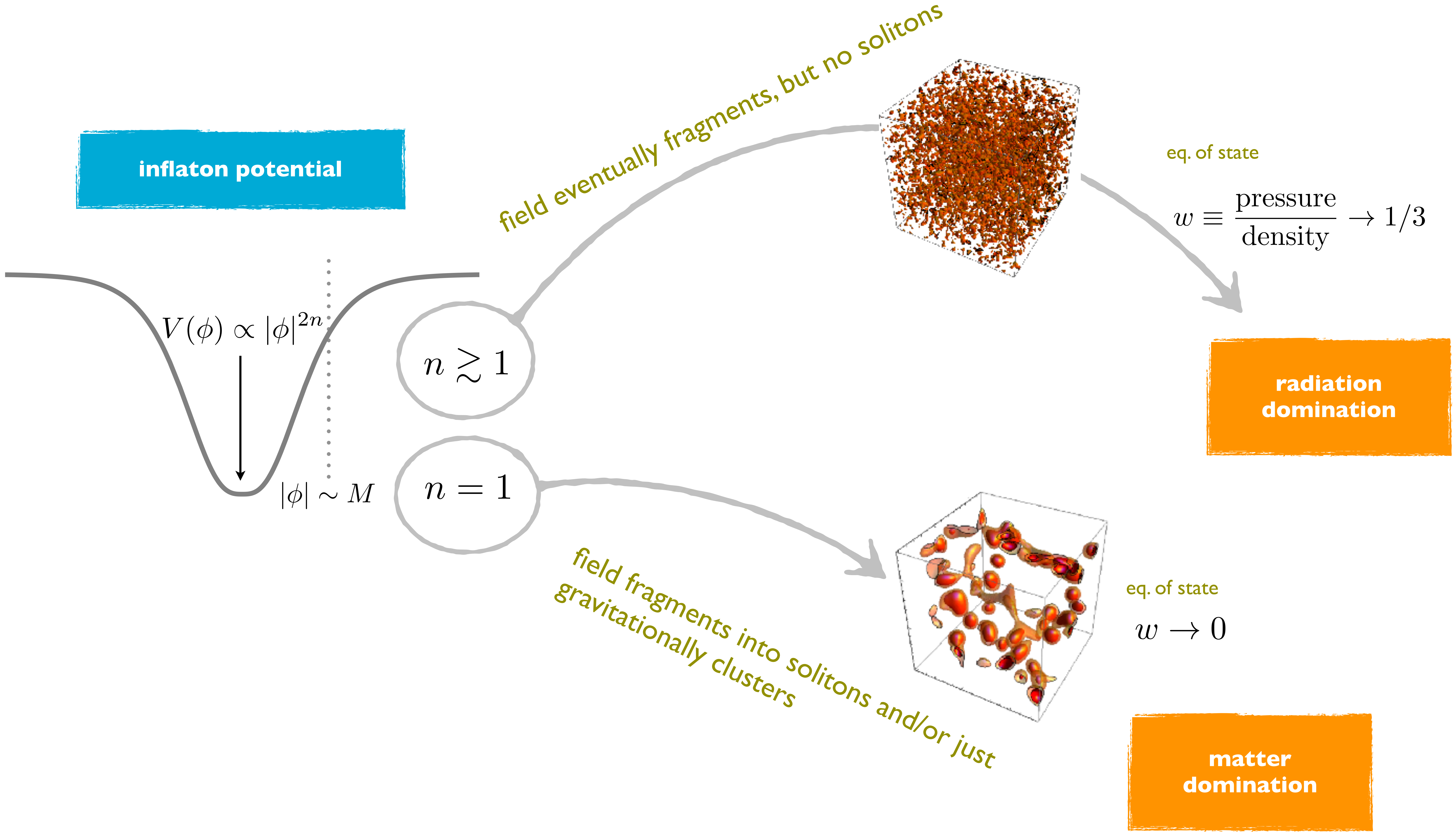
matter domination

dynamics in different power law minima + wings

Homogeneous oscillations

$$w = \frac{n-1}{n+1}$$

Turner (1983)



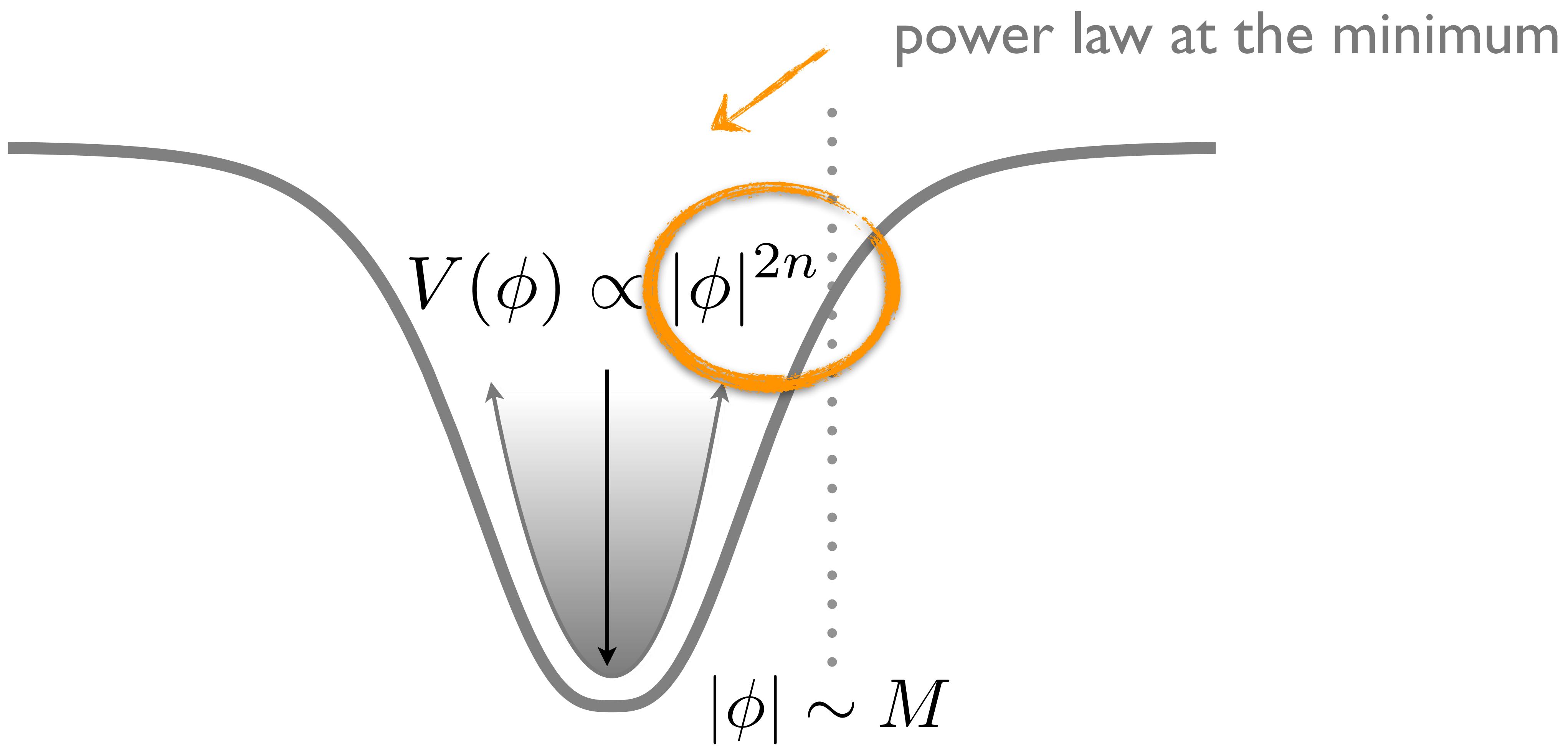
Lozanov & MA (2016/17) 1608.01213, 1710.06851

equation of state from oscillating fields

the *spatially averaged* equation-of-state of fields

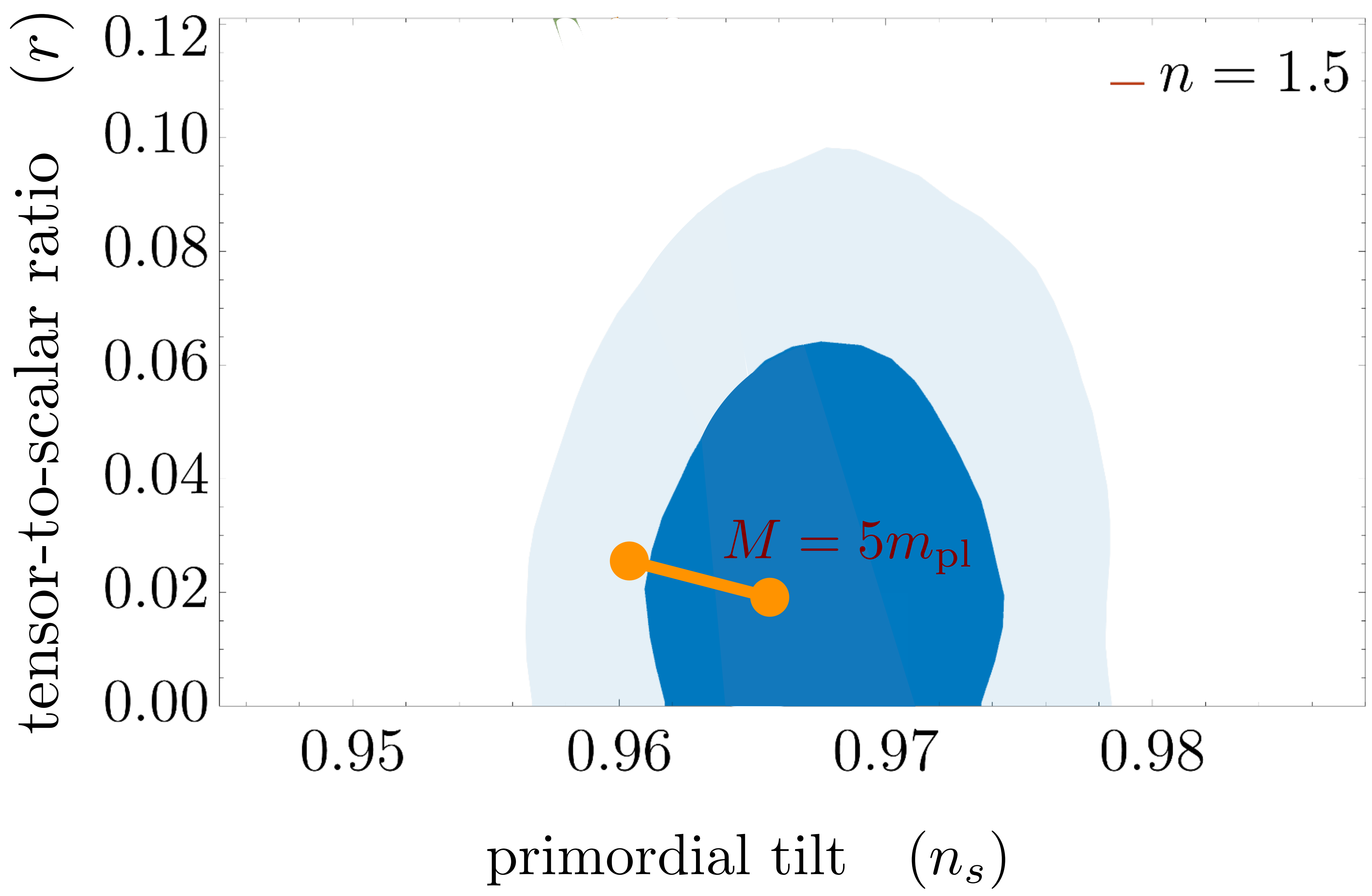
- $(n = 1)$ quadratic minima $w = 0$
- $(n > 1)$ non-quadratic minima $w = 1/3$ (after sufficient time)

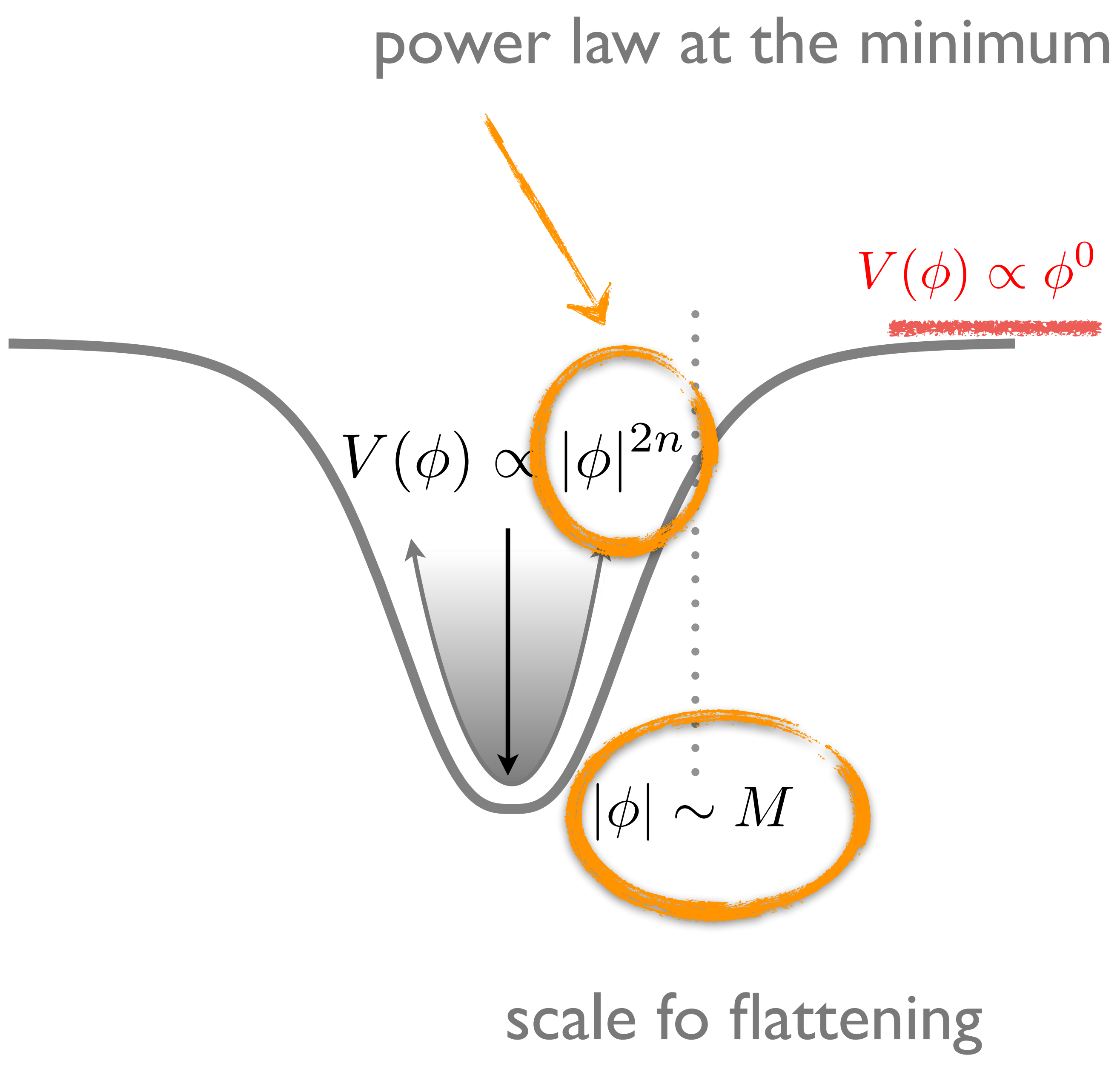
why? $\mu_k/H \propto \phi^{-1}$



Lozanov & MA (2016/17)

eq. of state & CMB observables





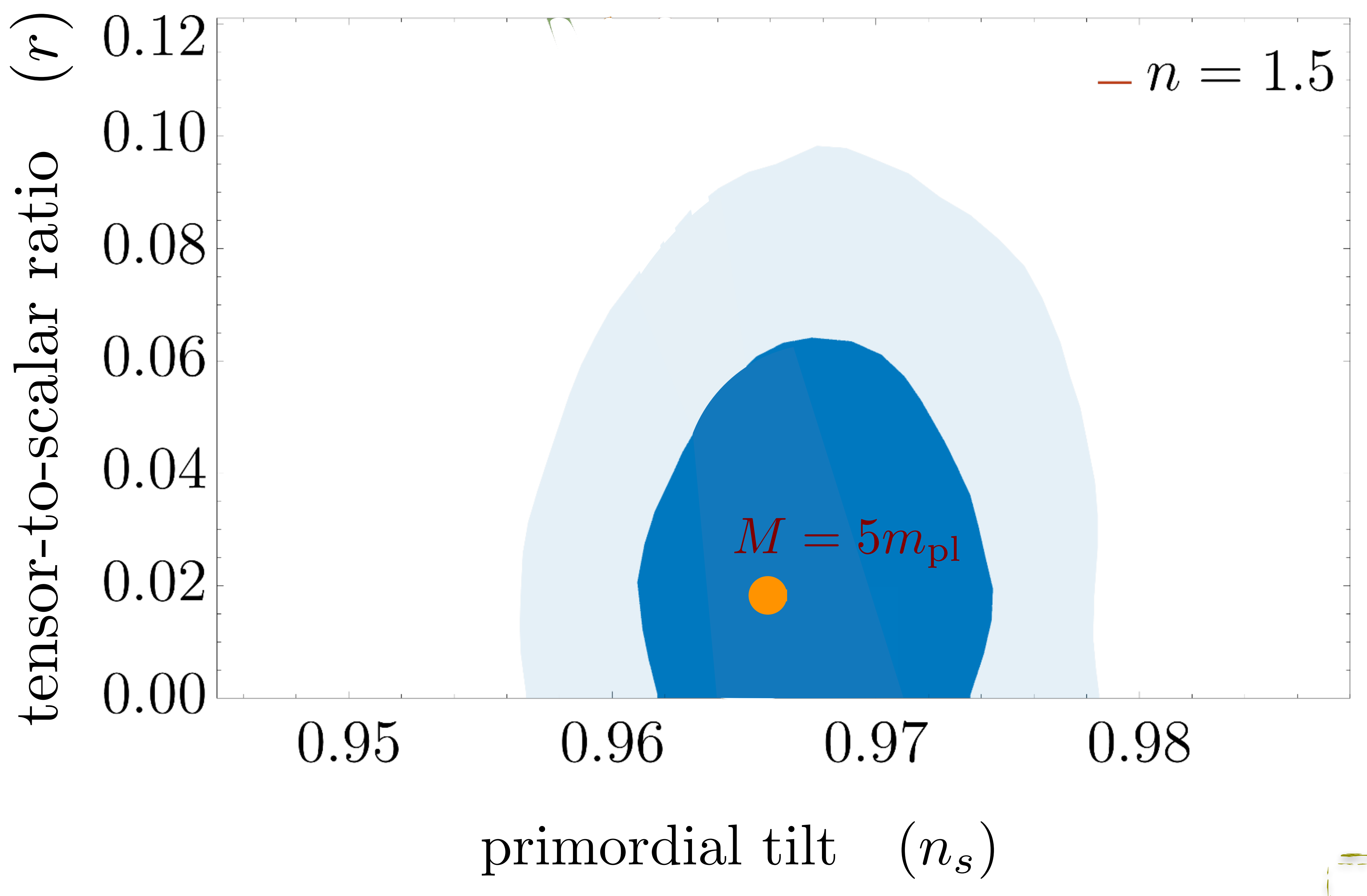
* non-quadratic minimum

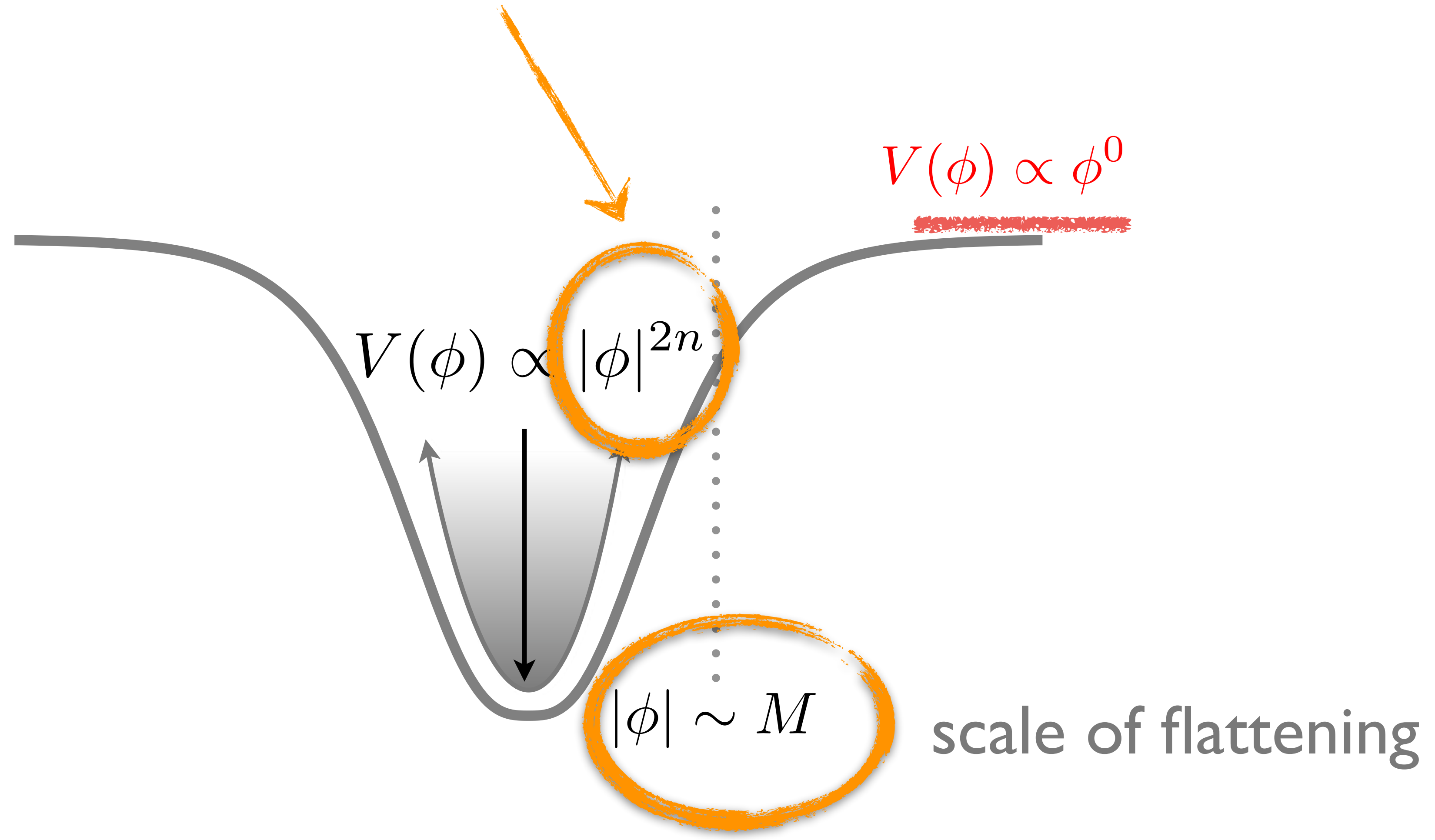
$n \neq 1$

* no oscillons here

also see: Kamionkowski & Munoz (2014), Cook et. al (2015) and others

upper bound on duration to radiation domination





Lozanov & MA (2017)

$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\dfrac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

$n \neq 1$

* non-quadratic minimum

* addition of other light fields, see Antusch, Figueroa, Marschall, Torrenti (2020)

couplings to other fields

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\right.$$

$$-\frac{1}{2}(\partial\chi)^2 - m_\chi^2\chi^2 + g_{\phi\chi}\phi\chi^2 + \ldots$$

$$\left. -\bar{\psi}(i\gamma\cdot\partial - m)\psi - g_{\phi\psi}\phi\bar{\psi}\psi + \ldots \right]$$

* lots of fun to be had with perturbative and non-perturbative dynamics

coupling to "photons"

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\right.$$

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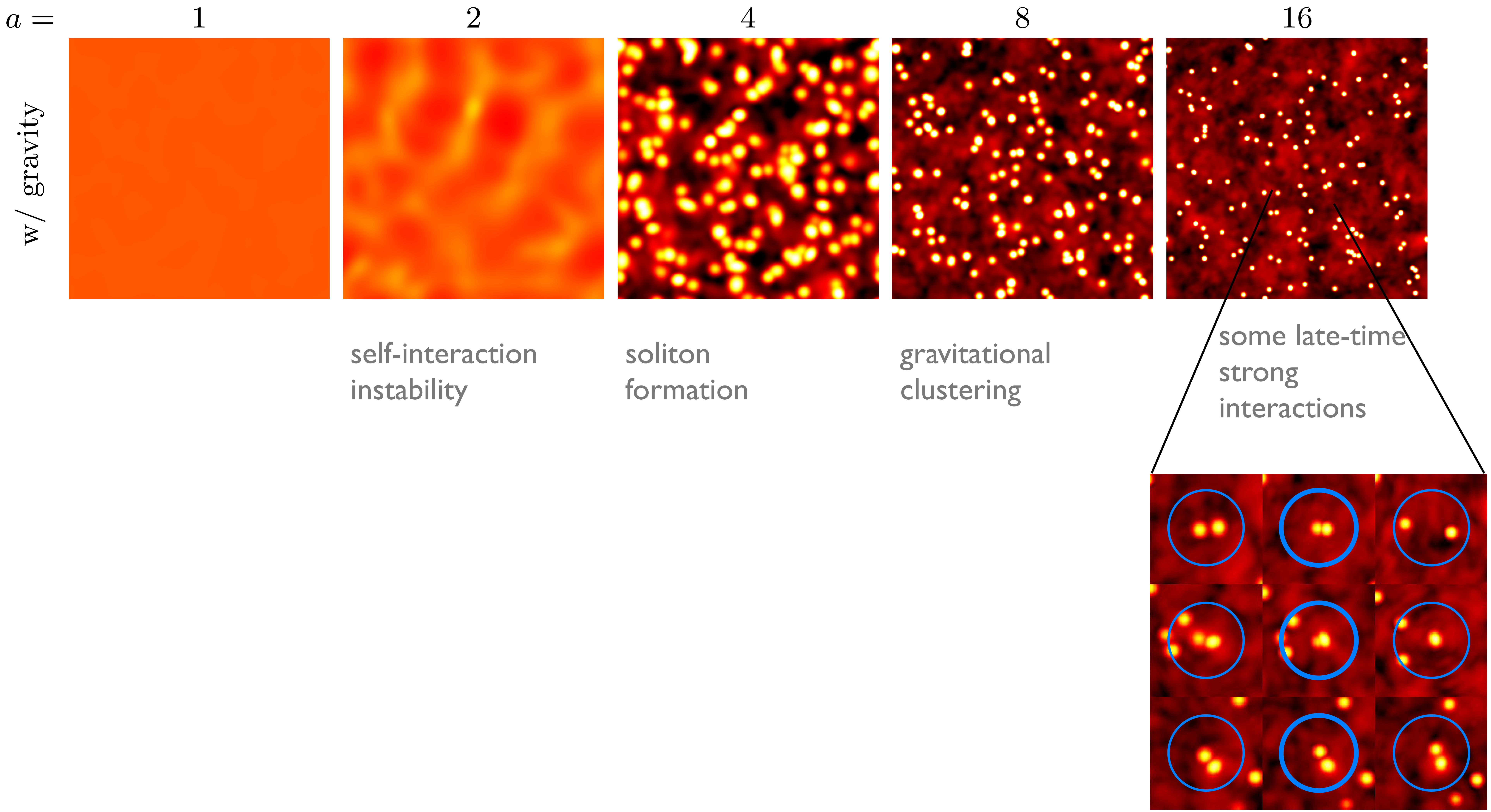
$$\left.-\bar{\psi}(i\gamma\cdot\partial - m)\psi - g_{\phi\psi}\phi\bar{\psi}\psi + \ldots\right]$$

an application: “photons” from oscillons



MA & Mocz (2019)

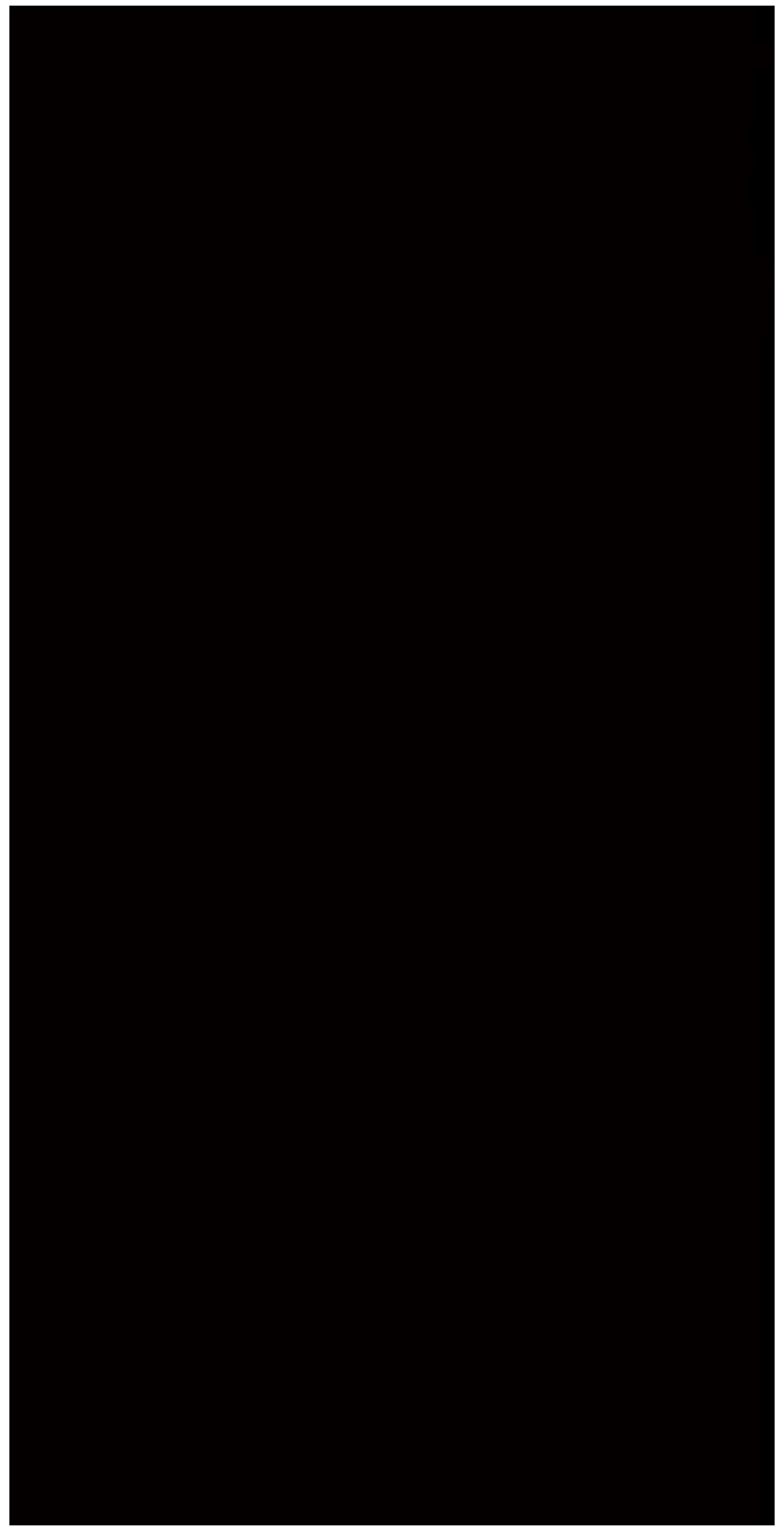
*this scenario be modified because the coupling to photons is very strong Adshead et. al (2016) and later papers.

photons from oscillons

MA & Mou (2020)

2009.11337

- no emission before merger
- explosive after merger
- a threshold & resonant effect



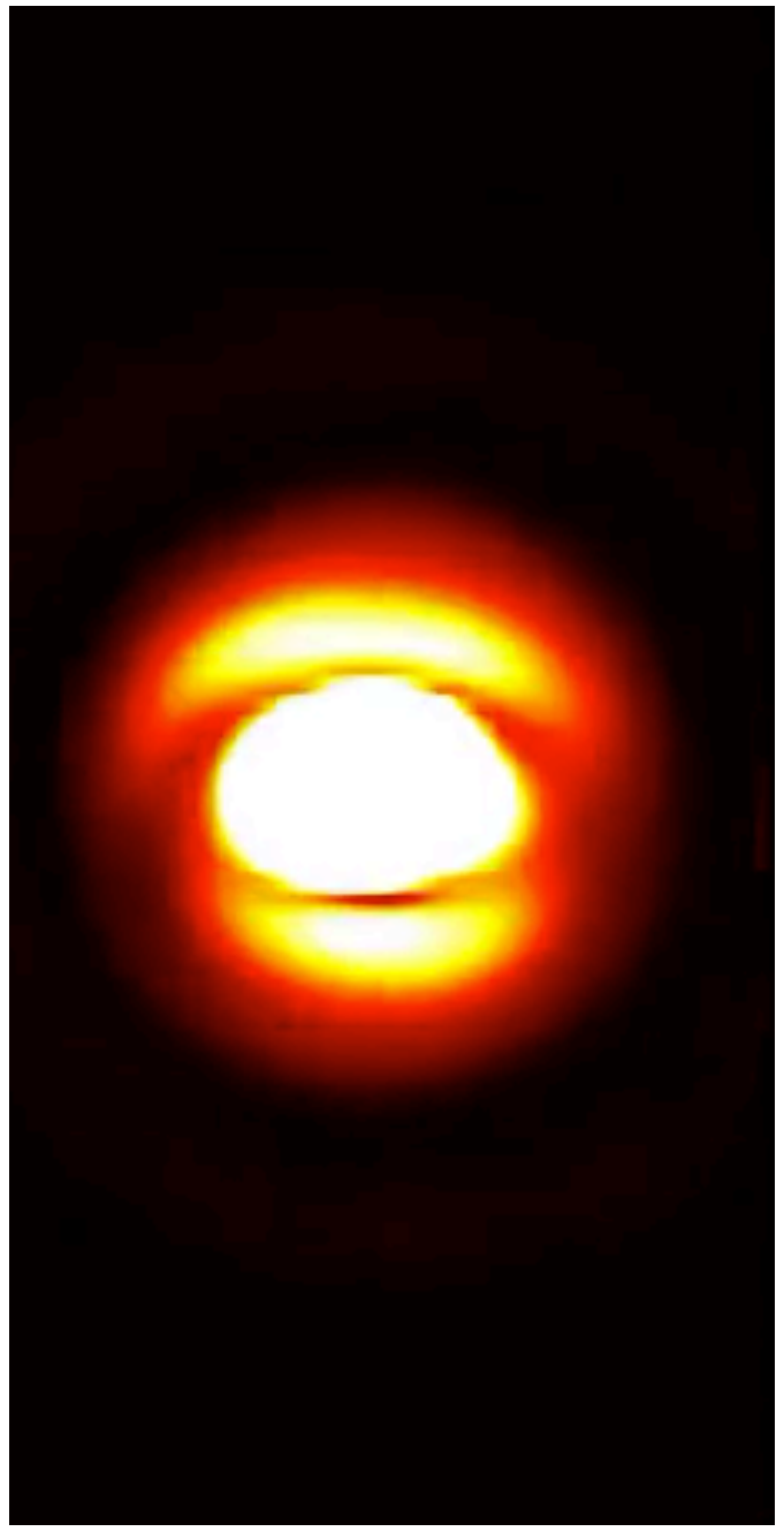
*might not be easy to achieve because the amplitude is highest at the end of inflation, so most photons produced then before (if) soliton formation. Also, likely not enough for reheating

* but other mechanisms to produce the solitons might work, also applications in the late universe

photons from oscillons

MA & Mou (2020)

2009.11337



- no emission before merger
- explosive after merger
- a threshold & resonant effect

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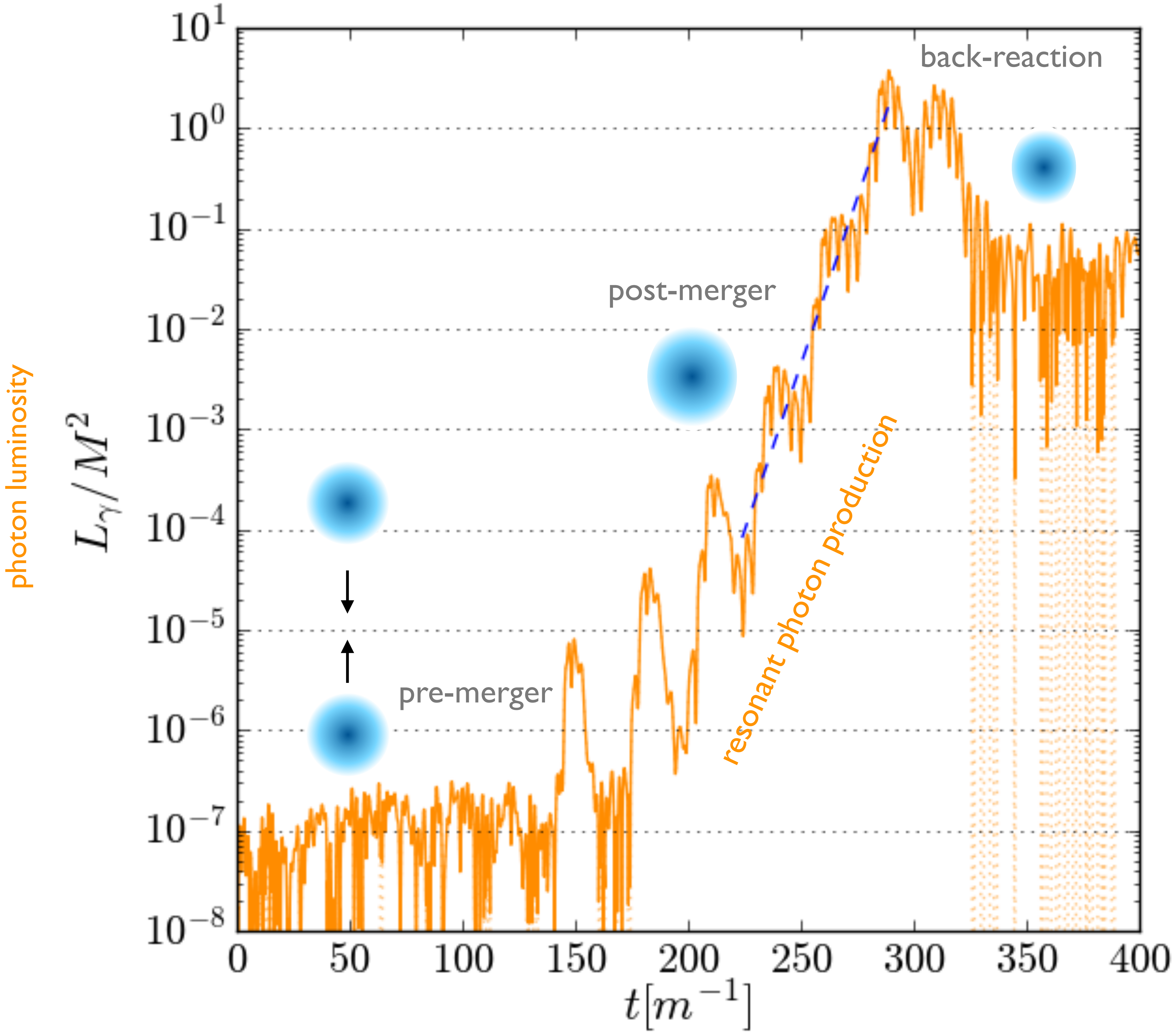
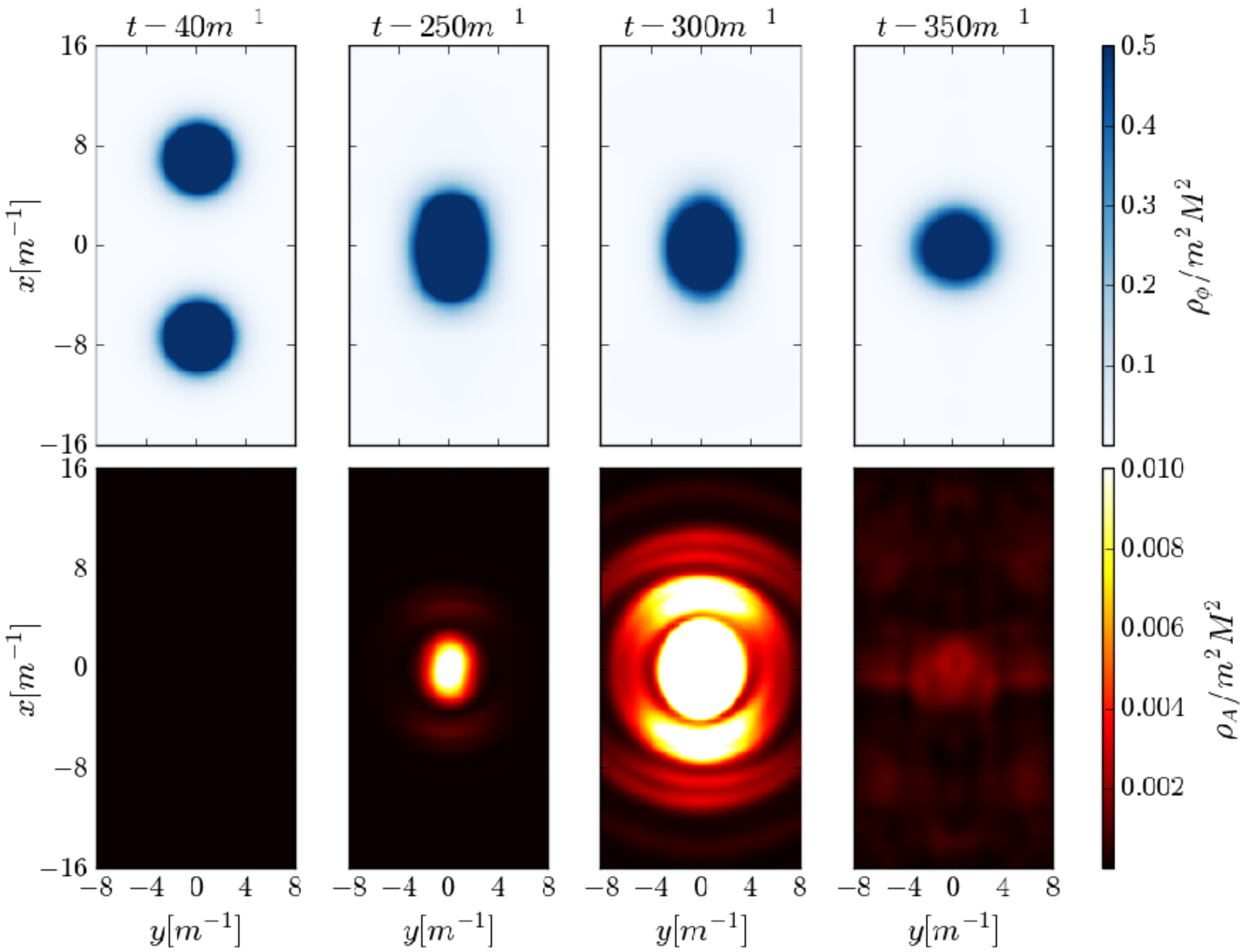
explosive, self-regulating photon production from mergers



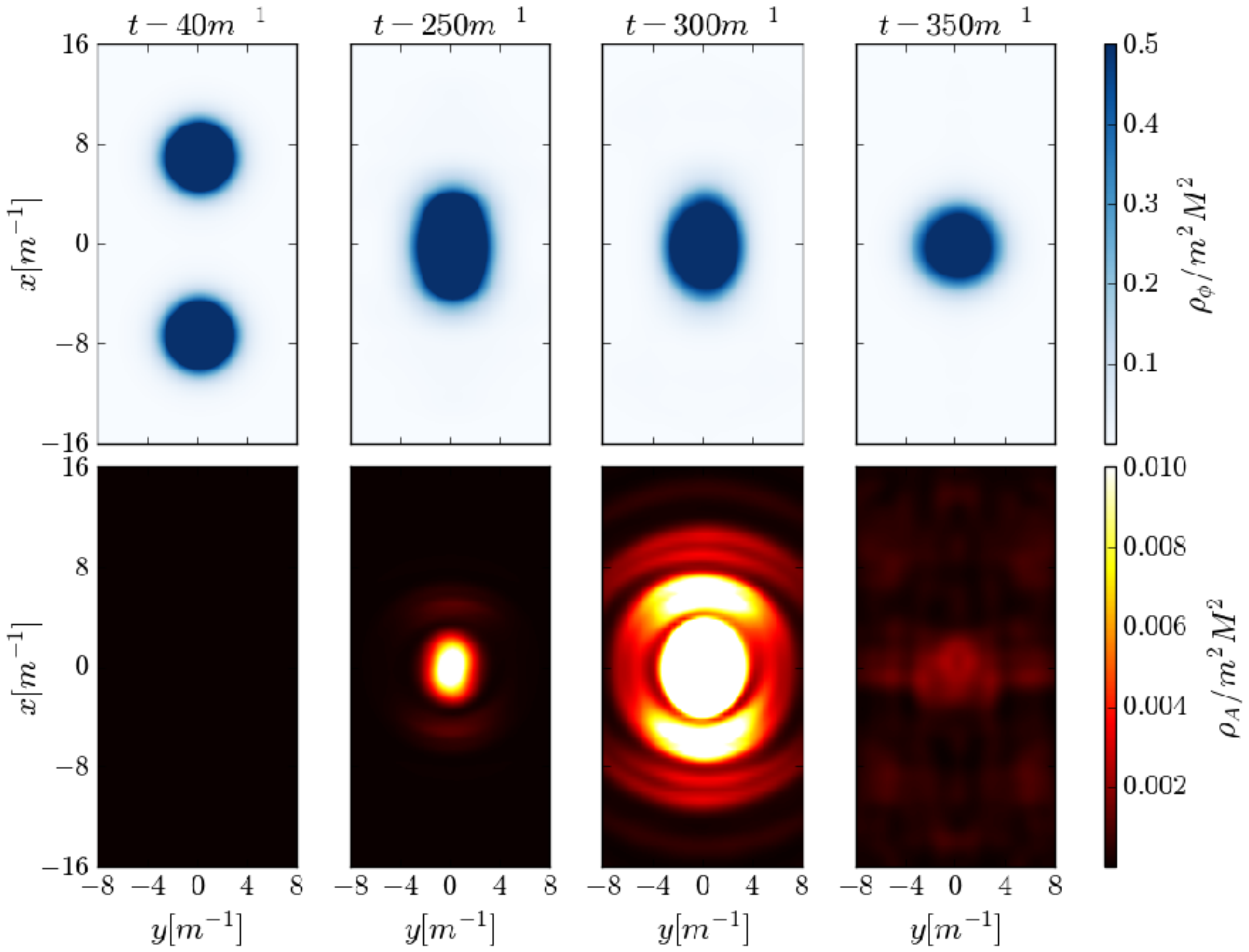


*after backreaction shuts of resonance, the luminosity falls to small values — at late times the apparent moderate value it due to a periodic box

explosive photon production from soliton mergers

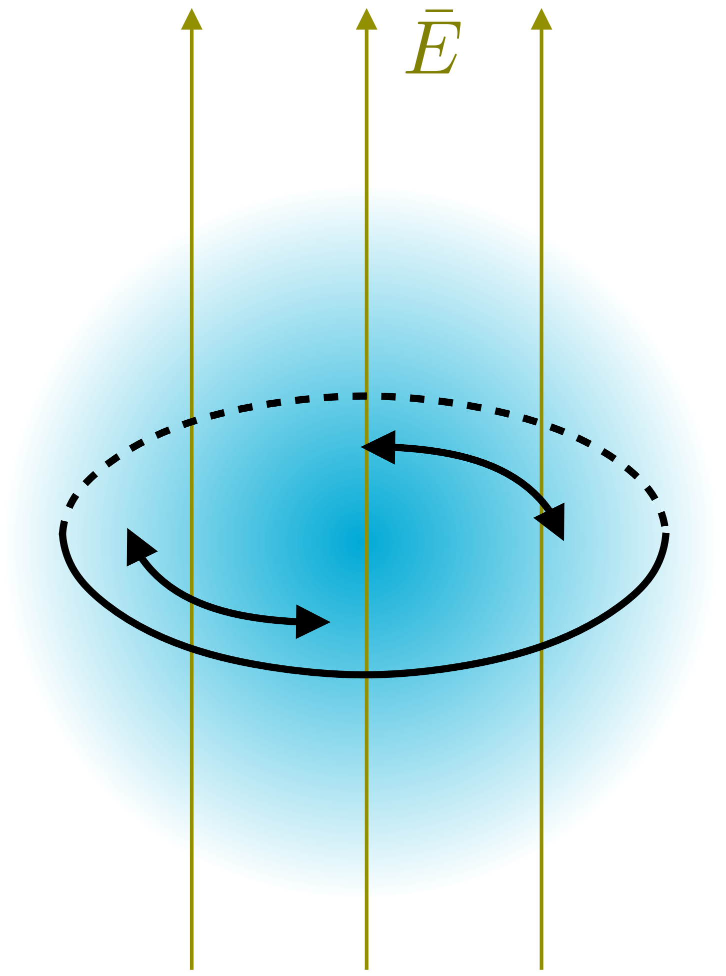
~30% of total energy goes into axion waves

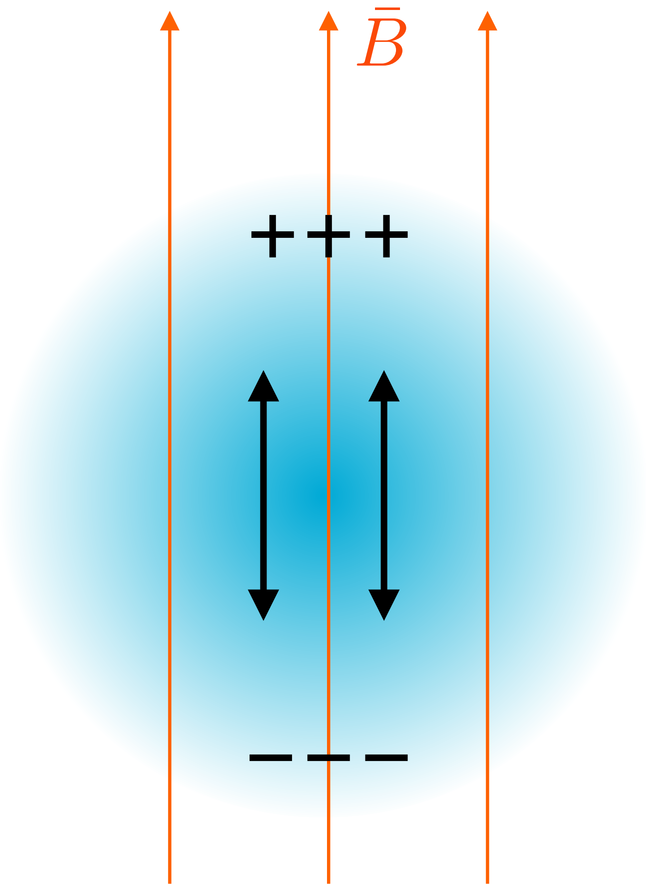
~20% of remaining goes into EM radiation

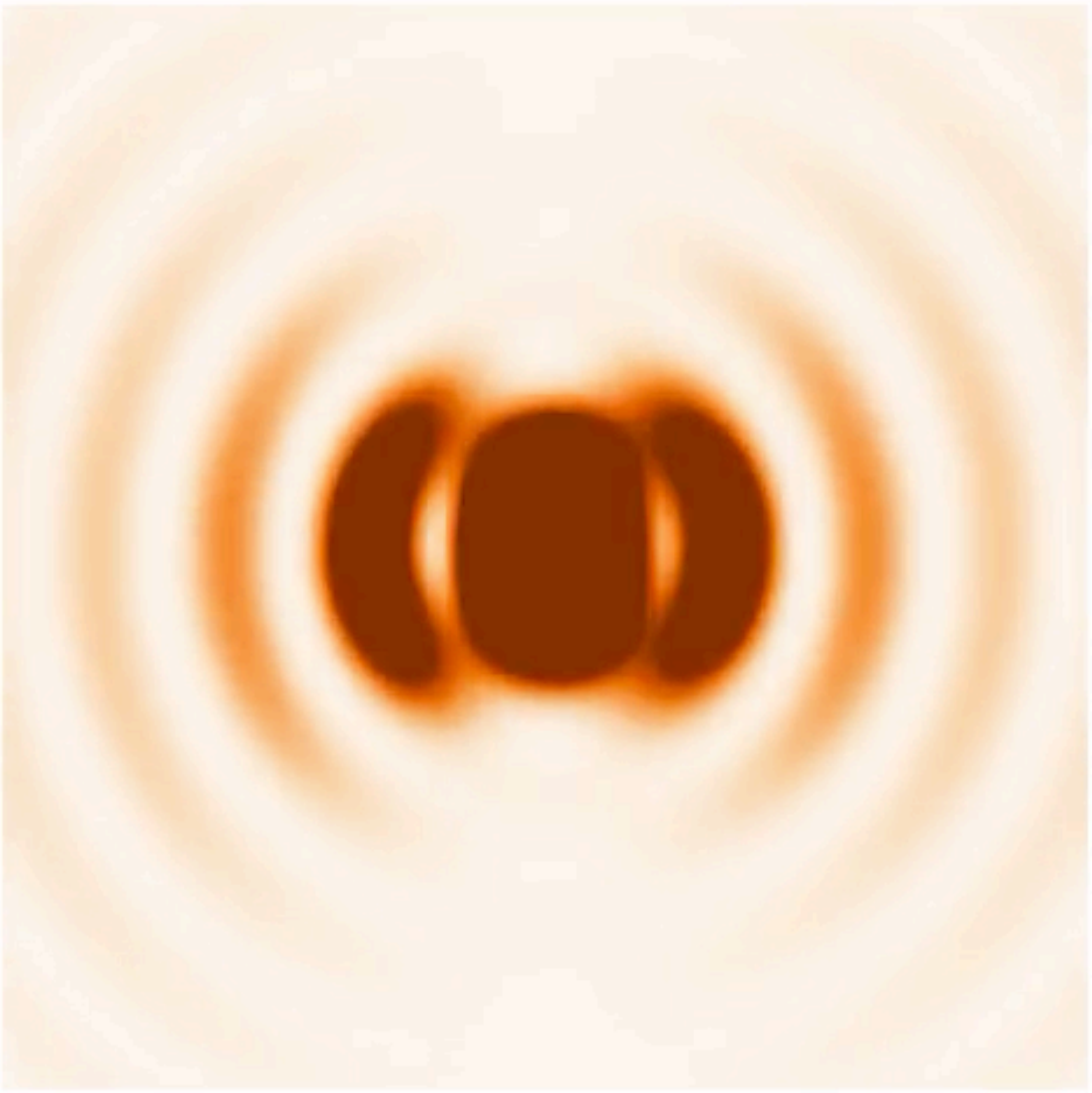


* for an exploration of gravitational wave production from mergers, see Helfer, Garcia et. al (2018)

“photons” from oscillons: in external fields





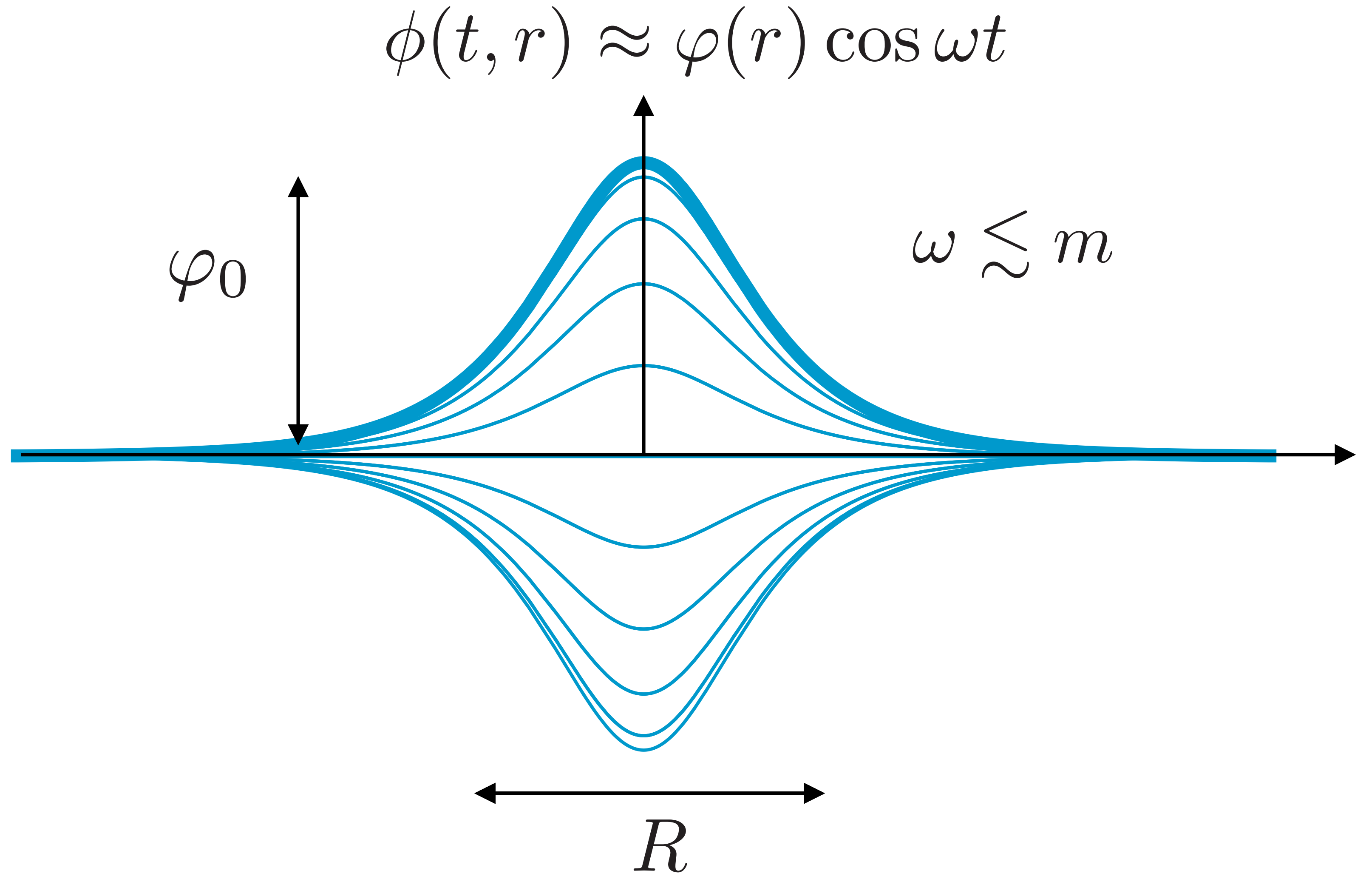


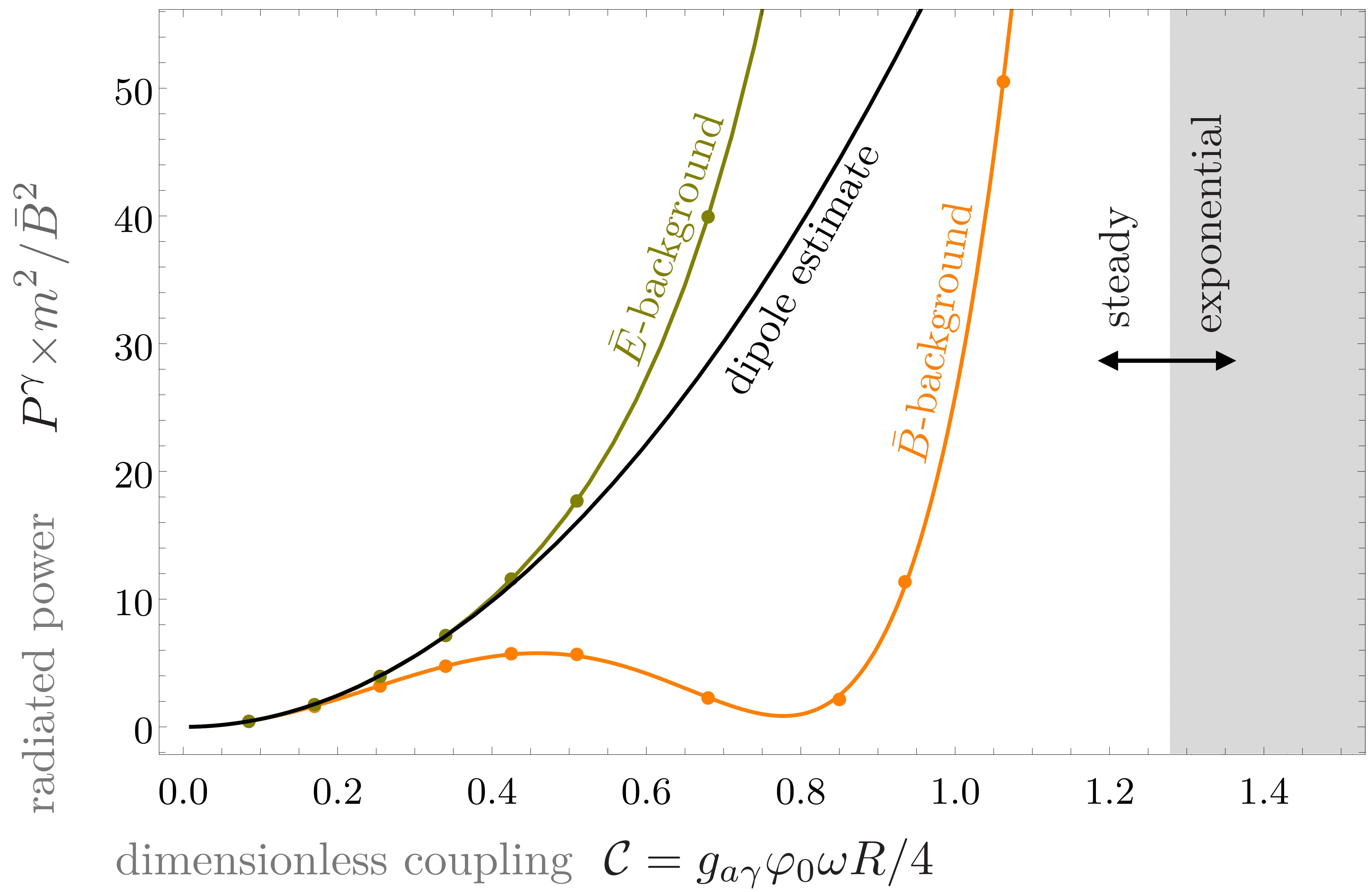
MA, Long, Mou & Saffin (2021)
2103.12082

explosive vs. steady radiation

scalar stars/oscillons/solitons can radiate energy in electromagnetic fields $g_{a\gamma}\phi\mathbf{E}\cdot\mathbf{B}$

radiated power depends on axion-photon coupling and characteristics of soliton configuration





MA, Long, Mou & Saffin (2021)

coupling to massive "photons"

$$S = \int d^4x \sqrt{-g} \left[\frac{m_{\rm pl}^2}{2} R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{g_{\phi\gamma}}{4} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{2} m_\gamma^2 A^2 + V_{\rm nl}(A^2) \right.$$

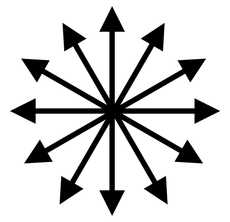
$$-\frac{1}{2}(\partial\chi)^2 + m_\chi^2 \chi^2 + g_{\phi\chi}\phi\chi^2 + \ldots$$

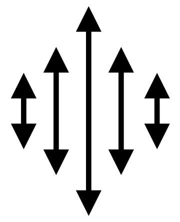
$$\left. -\bar{\psi}(i\gamma\cdot\partial - m)\psi - g_{\phi\psi}\phi\bar{\psi}\psi + \ldots \right]$$

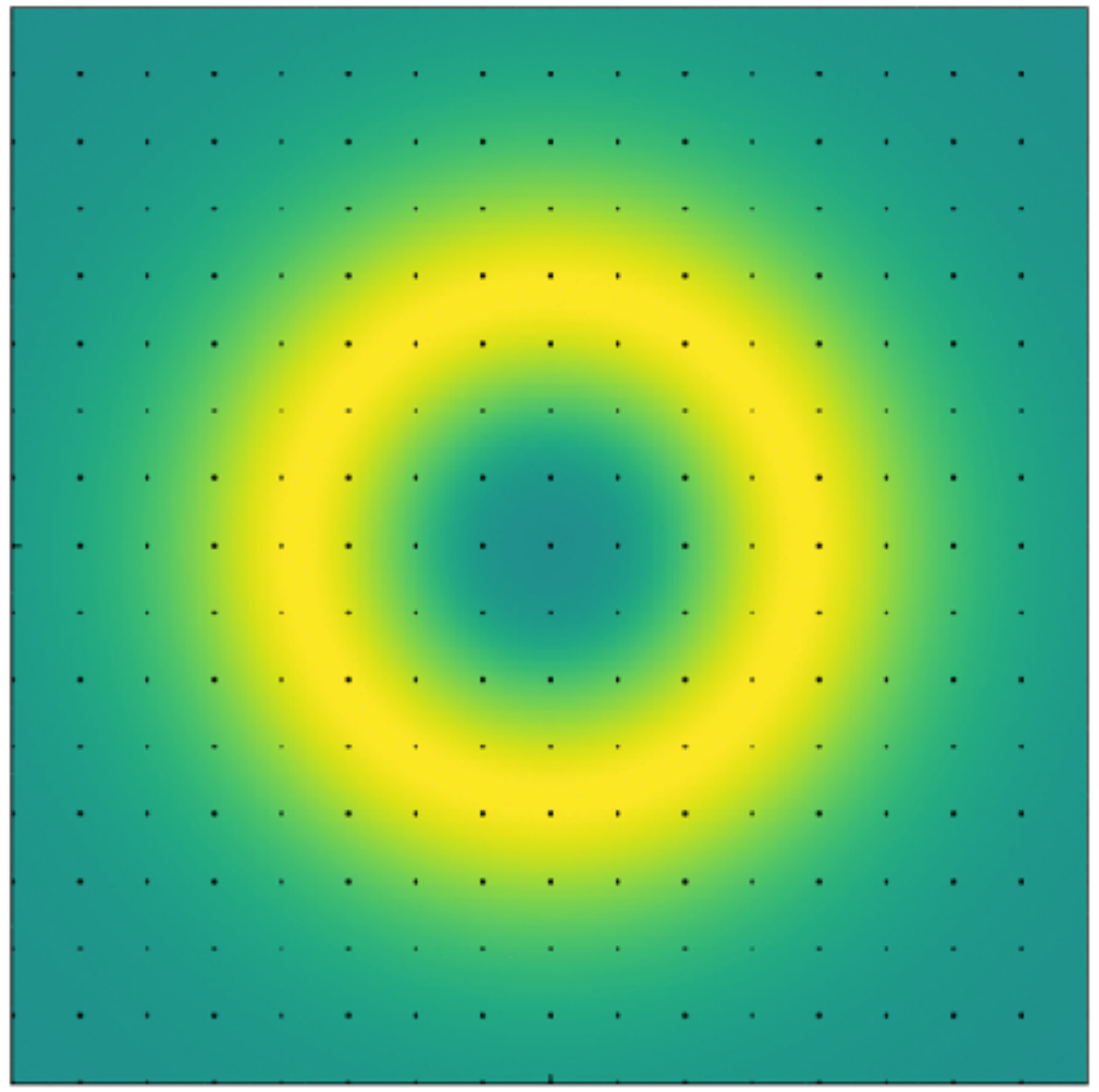
* production could be via "misalignment" of inflaton, for example: Co et. al (2018), Agrawal et. al (2018) in context of dark matter

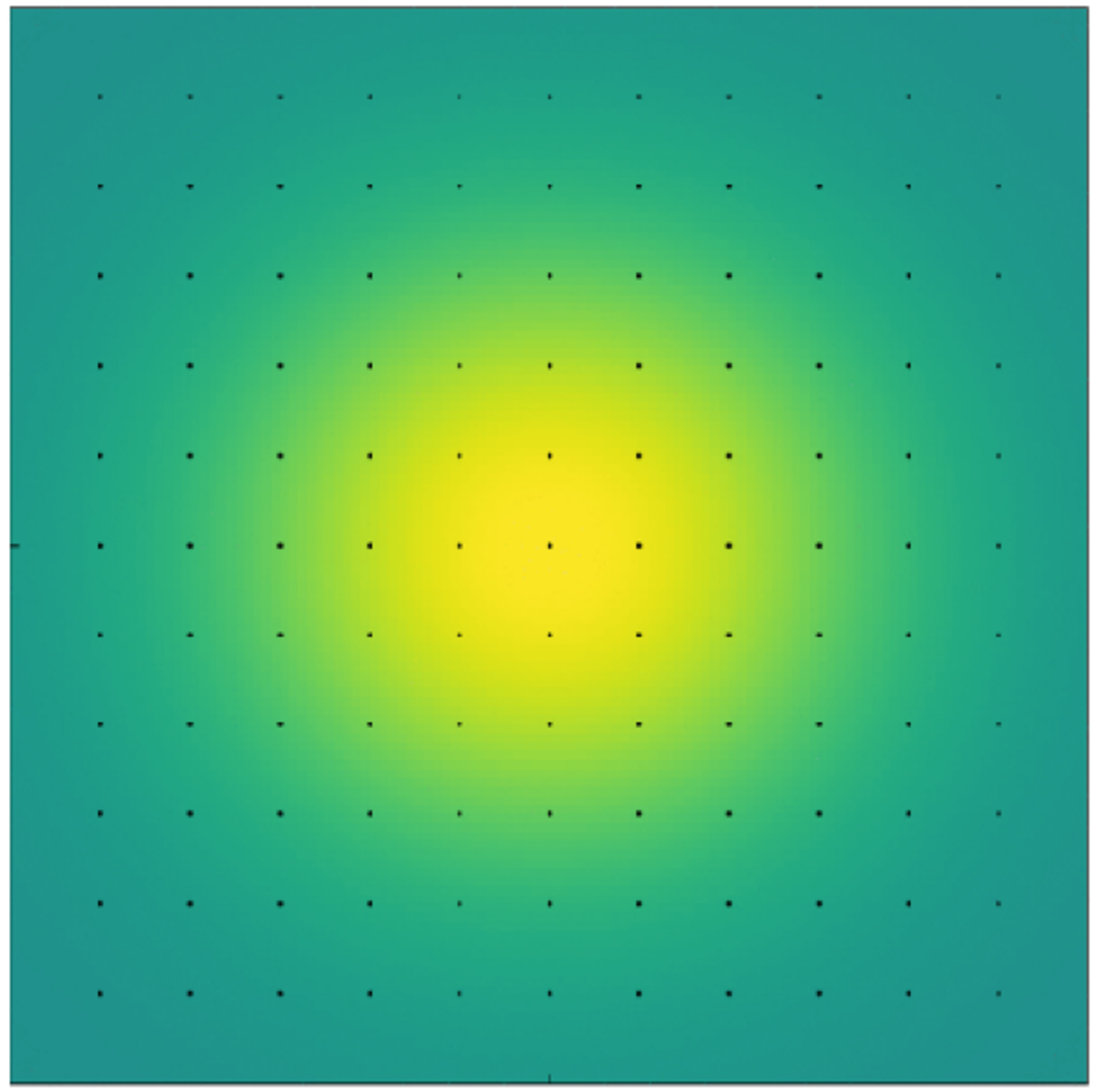
Vector oscillons

$$S = \int d^4x \sqrt{-g} \left[\frac{m_{\rm pl}^2}{2} R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4} \phi F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2} m_\gamma^2 A^2 + V_{\rm nl}(A^2) \right]$$

hedgehog oscillon 

directional oscillon (easier to form) 



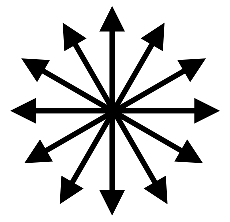


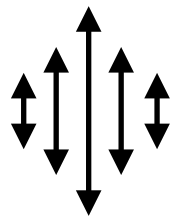
Zhang & MA (coming out < month)

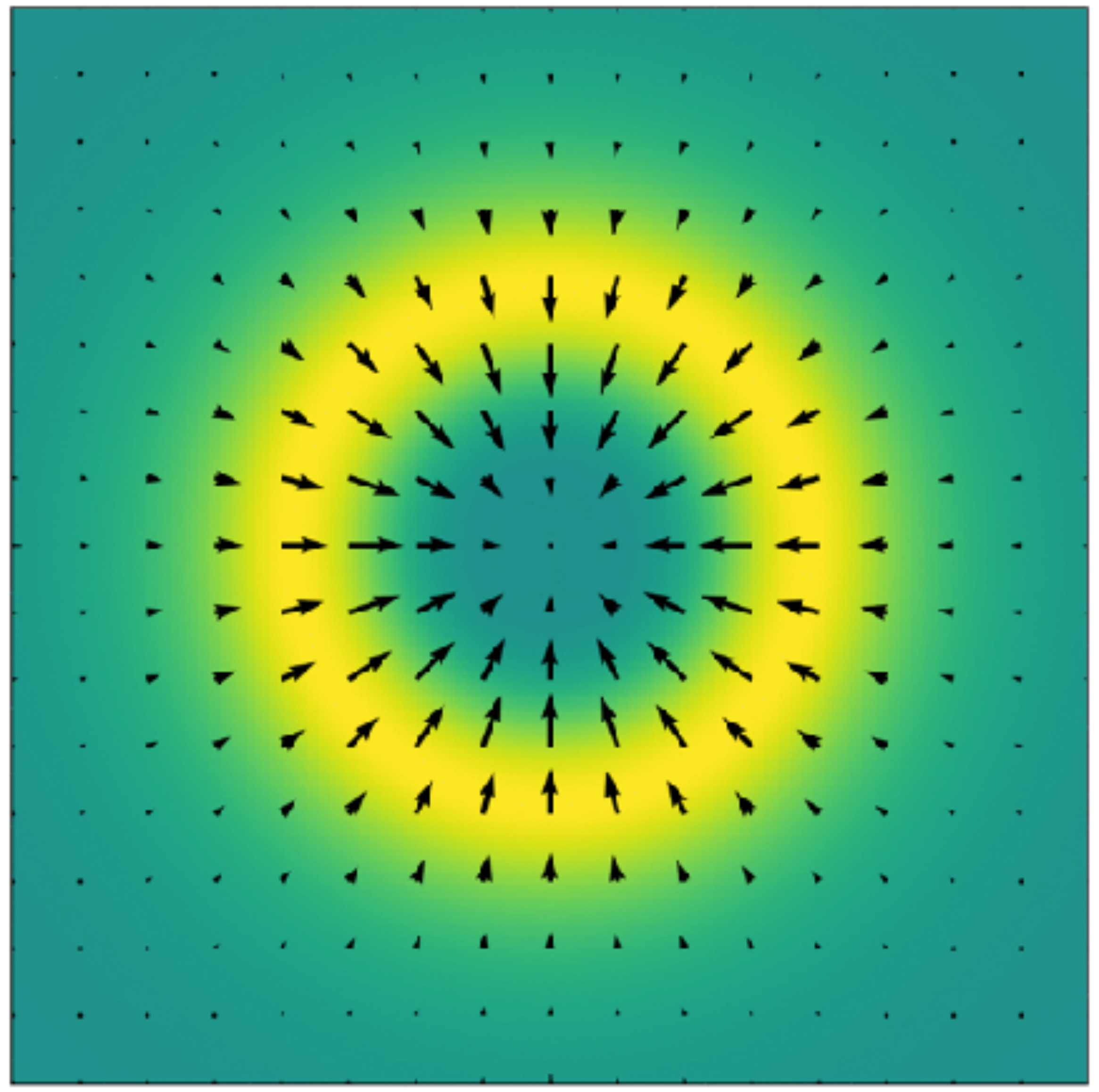
* for dilute ones supported by gravity, see Adshead and Lozanov (2021), for analogs in complex vector fields for the hedgehog case, see Loginov (2015)

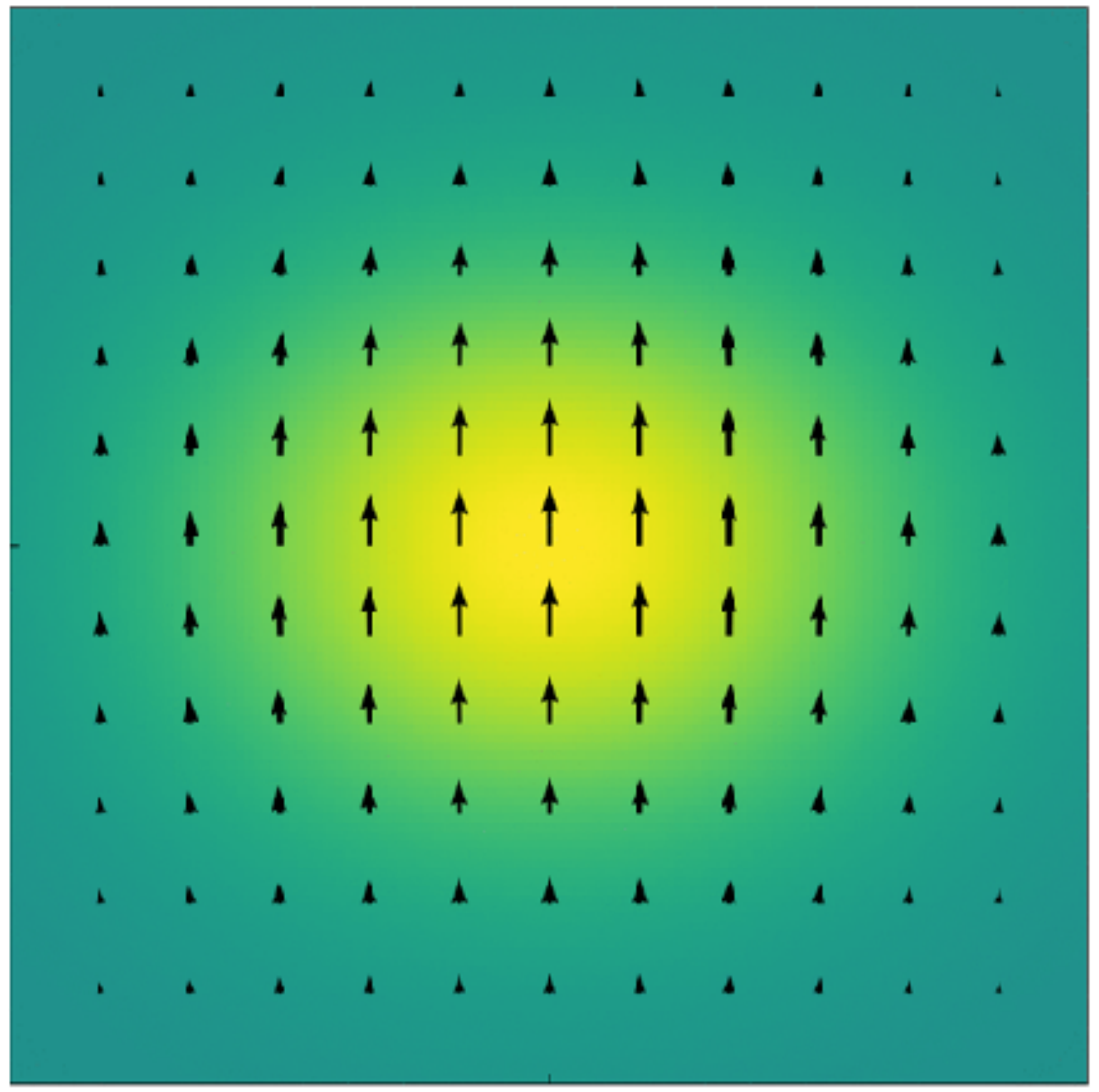
Vector oscillons

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}m_\gamma^2 A^2 + V_{\rm nl}(A^2)\right]$$

hedgehog oscillon 

directional oscillon (easier to form) 





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Vector oscillons

WORK IN PROGRESS

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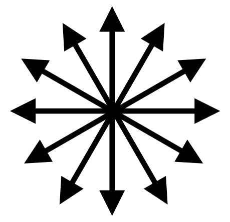
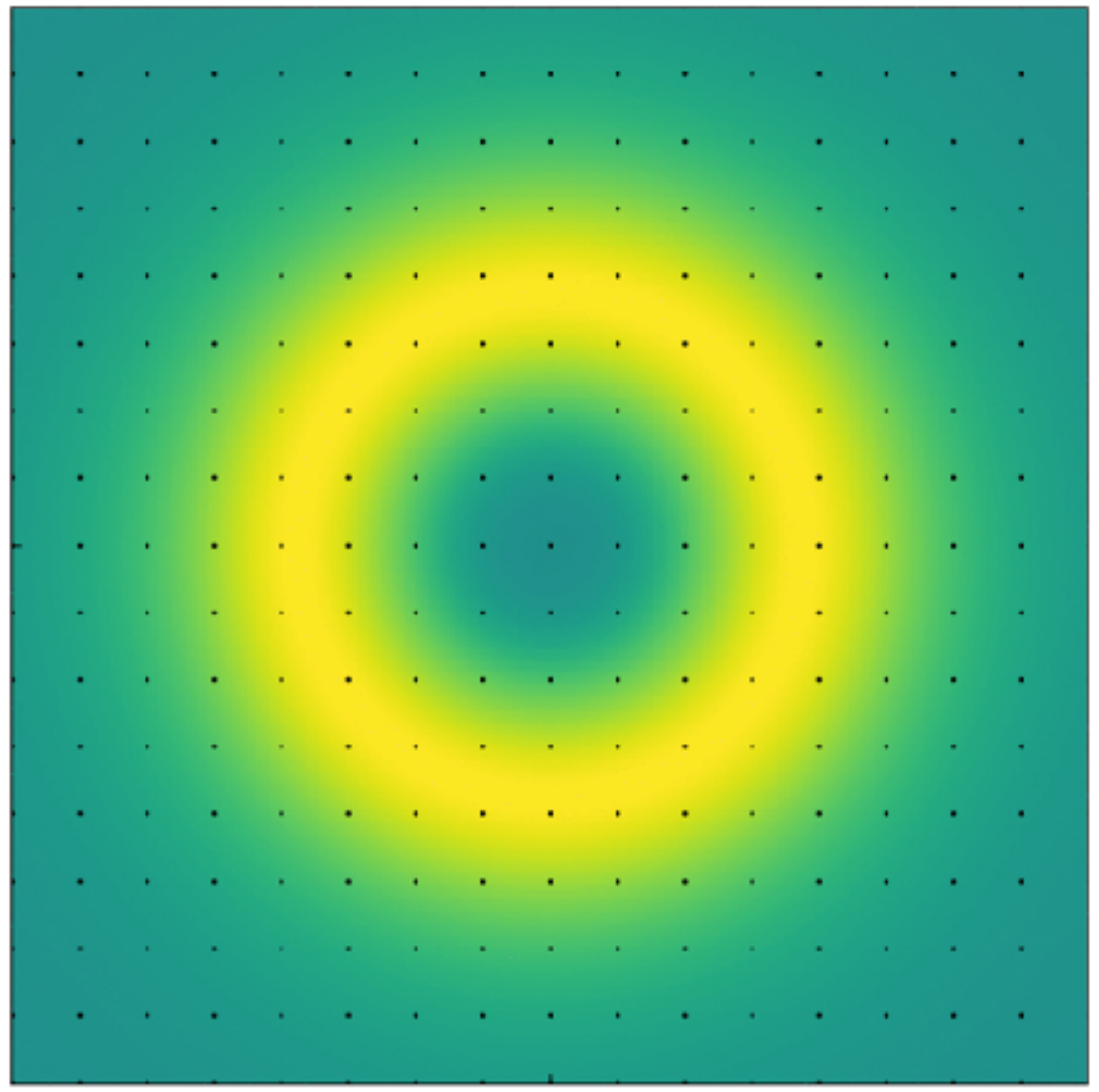
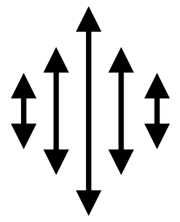
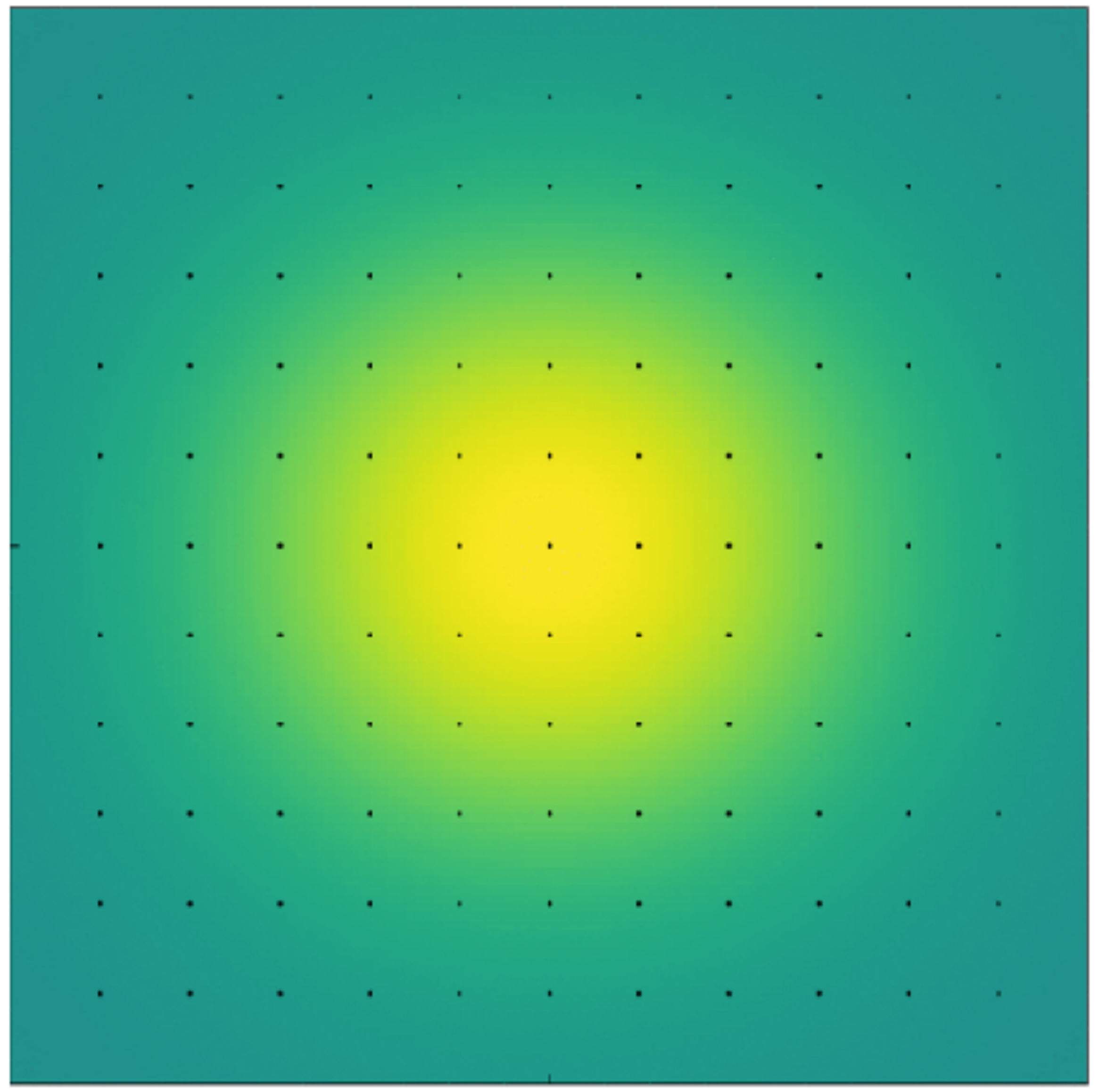
hedgehog oscillon 



directional oscillon (easier to form) 



Zhang & MA (coming out < month)

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Vector oscillons

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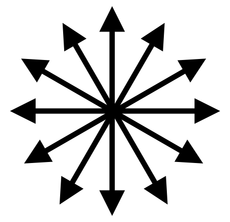
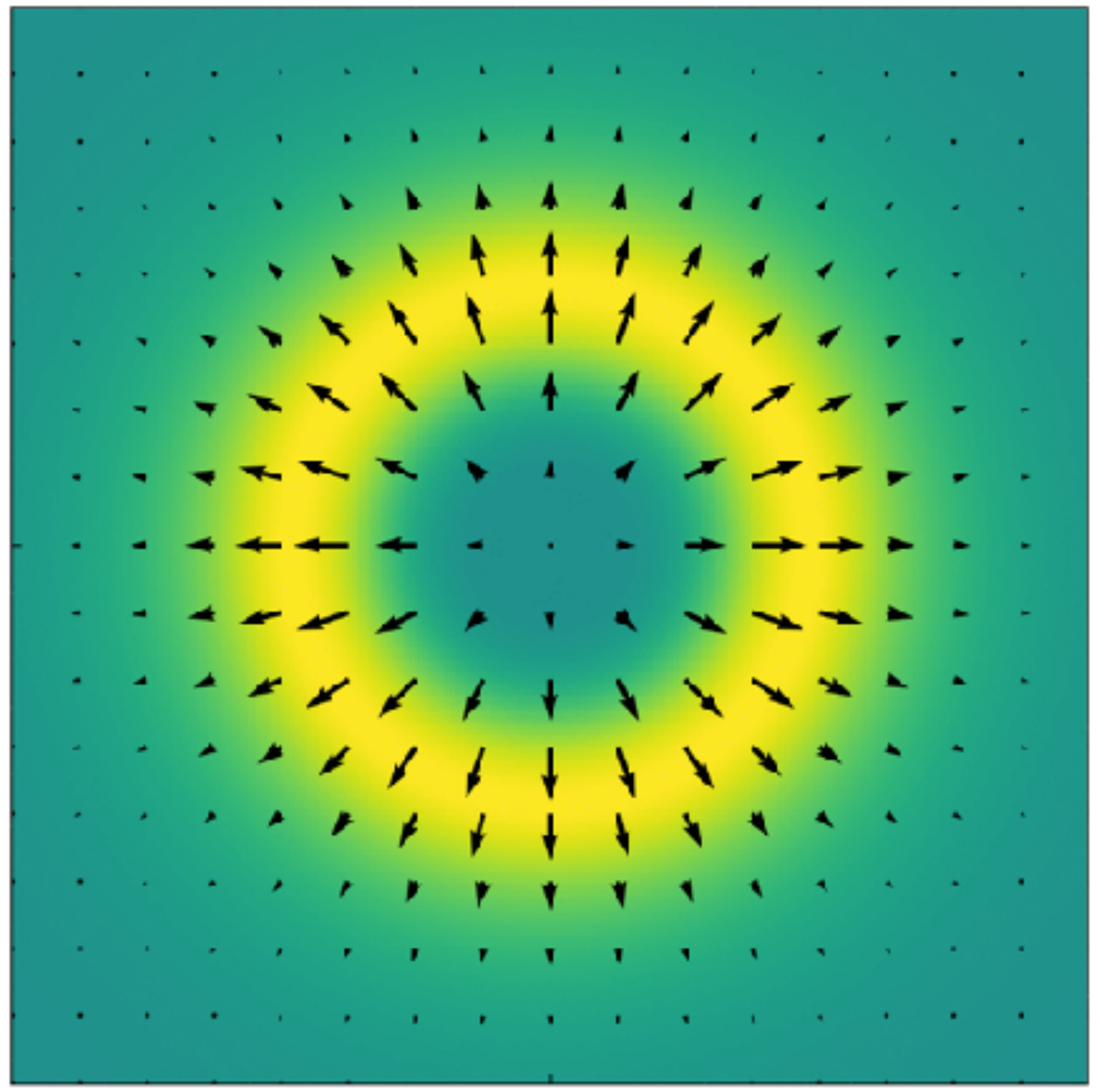
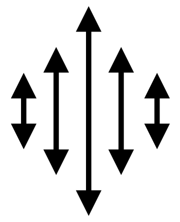
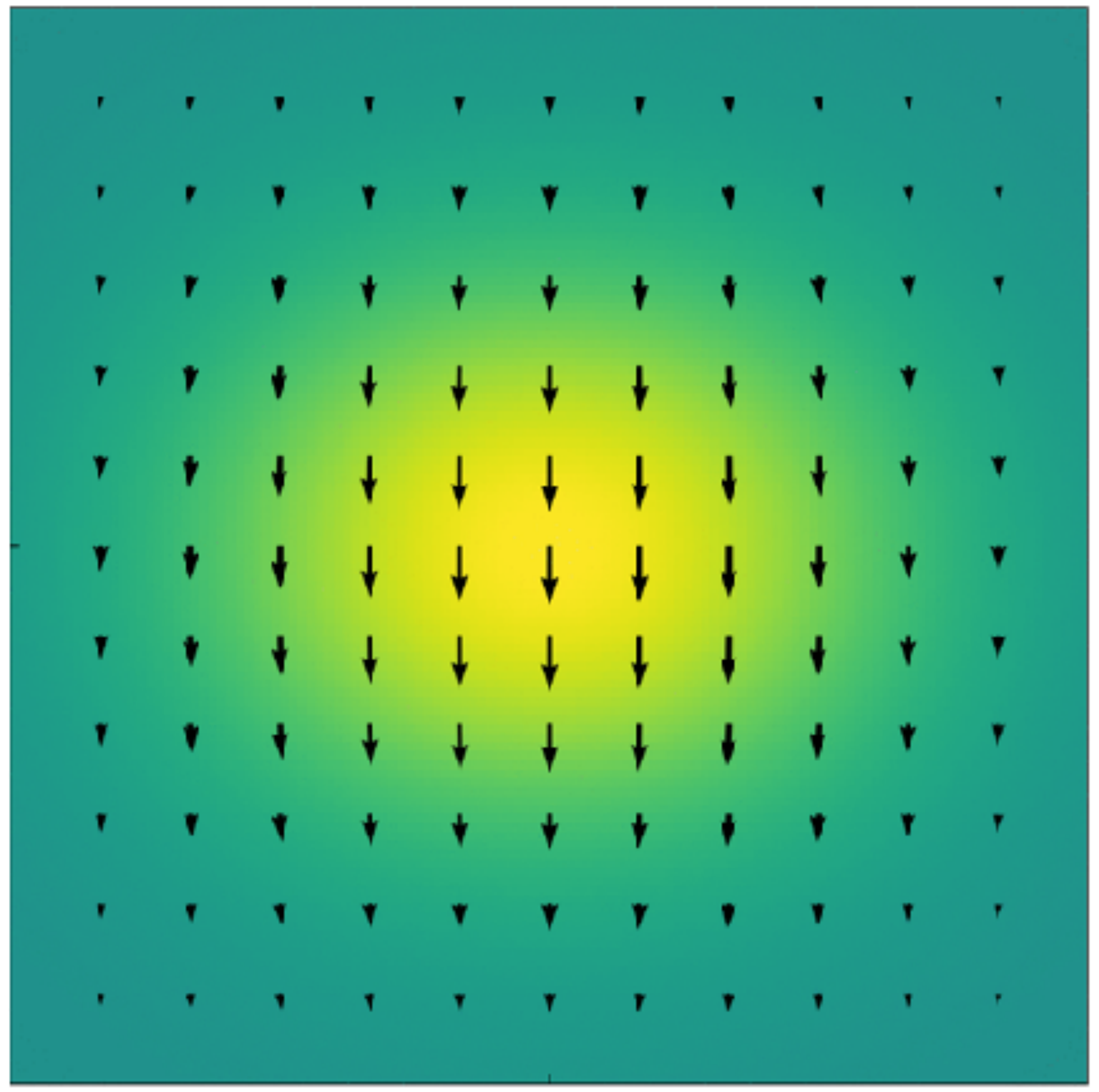
hedgehog oscillon 



directional oscillon (easier to form) 



Zhang & MA (coming out < month)

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lots more to explore!

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}m_\gamma^2 A^2 + V_{\rm nl}(A^2)\right.$$

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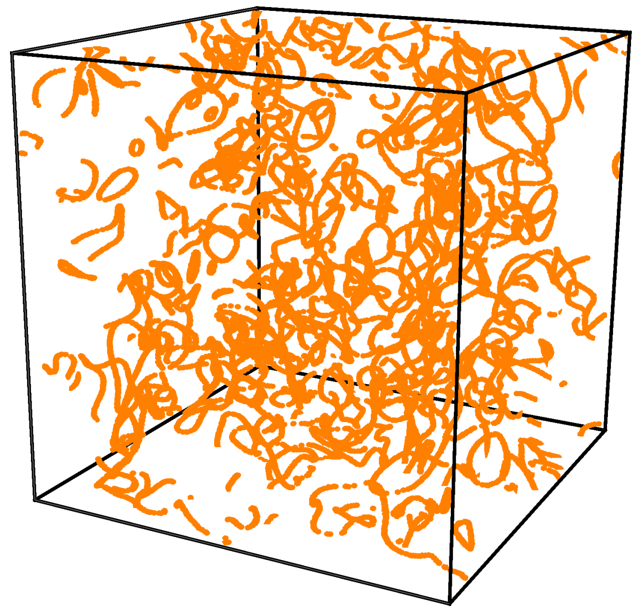
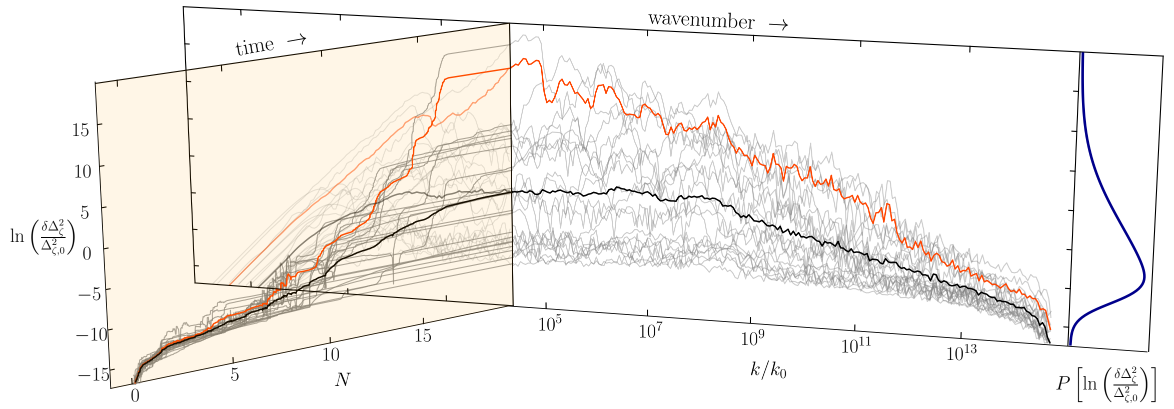


* Abelian Higgs / GFiRe (Lozanov & MA 2019)
  1603.05663, 1911.06827

* thermal vs. non-thermal effects, see for example Garcia & MA 2018
  1806.01865

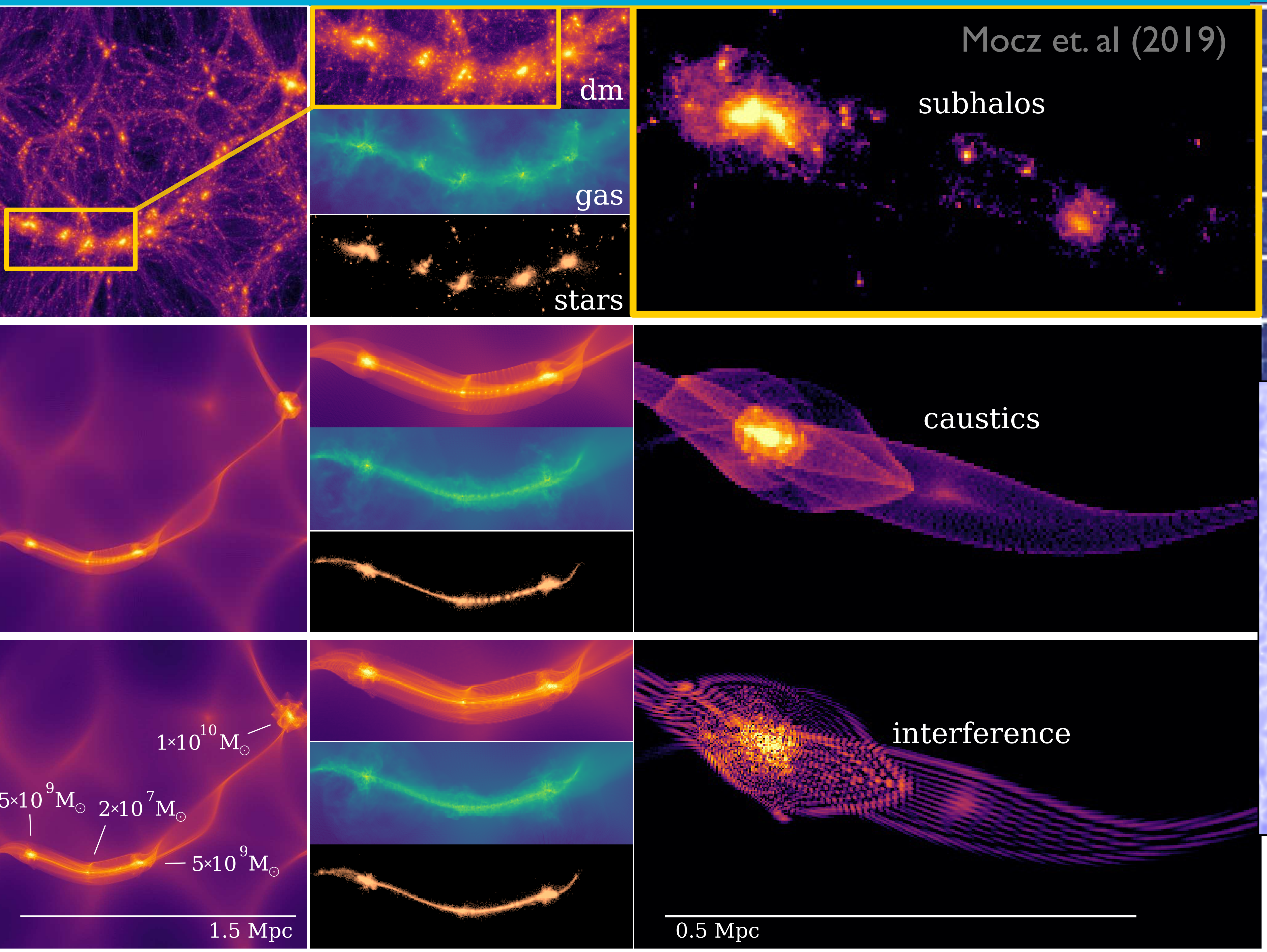


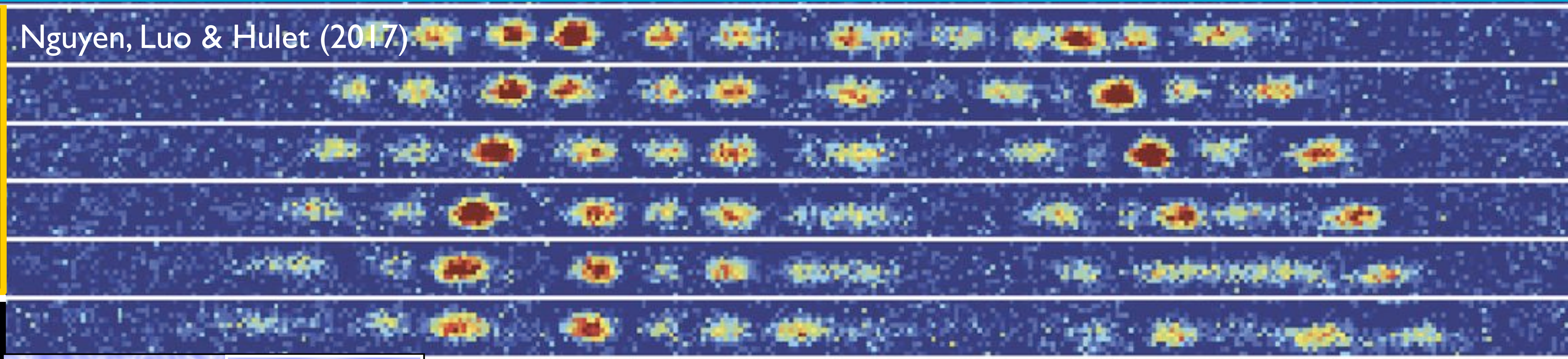
* towards model independent characterization: *Wires to Cosmology* (MA, Baumann, Carlsten, Garcia, Green, Wen +)
  2001.09158, 1512.02637

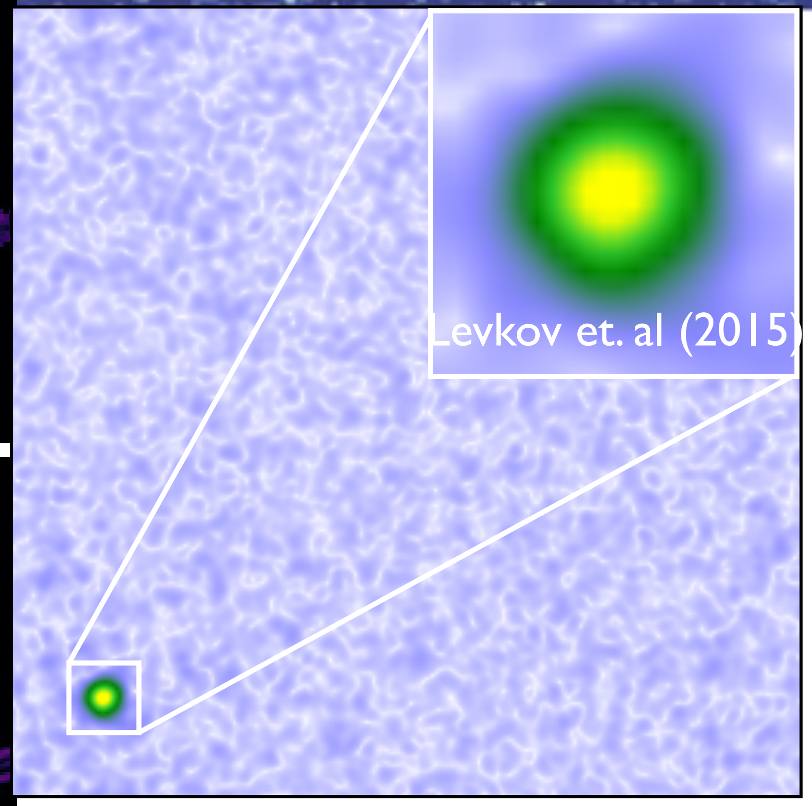
(also earlier paper on random potentials, for example McAllister et. al 2012, and recent multifield reheating, Martin & Pinol 2021)

* lots more to explore: see talk by Qianshu Lu on "Spillway Preheating" (Fan, Lozanov and Lu 2021 2101.11008)

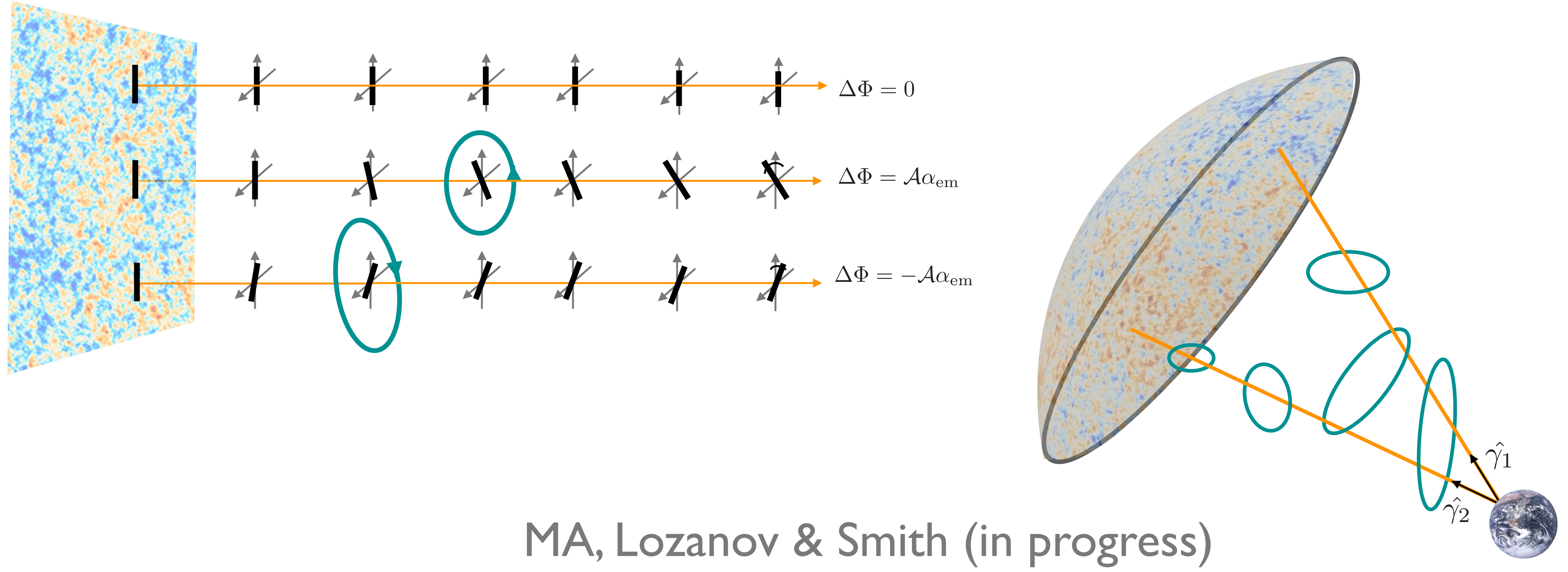
related phenomenology for moduli, axions, early dark energy etc. and BECs



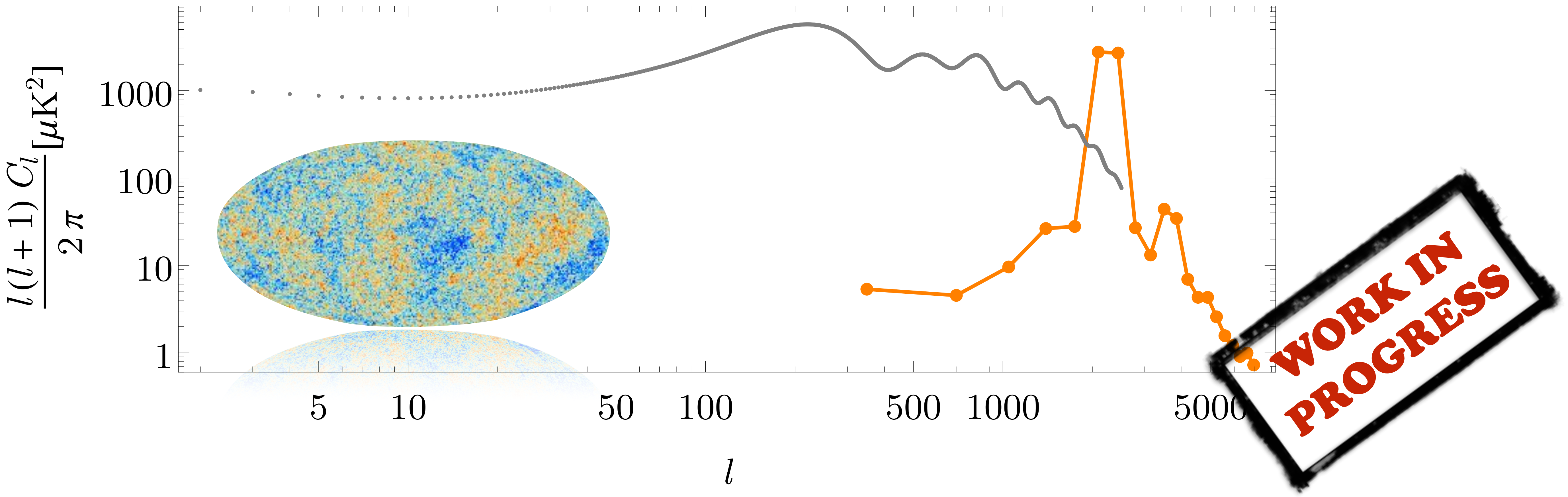


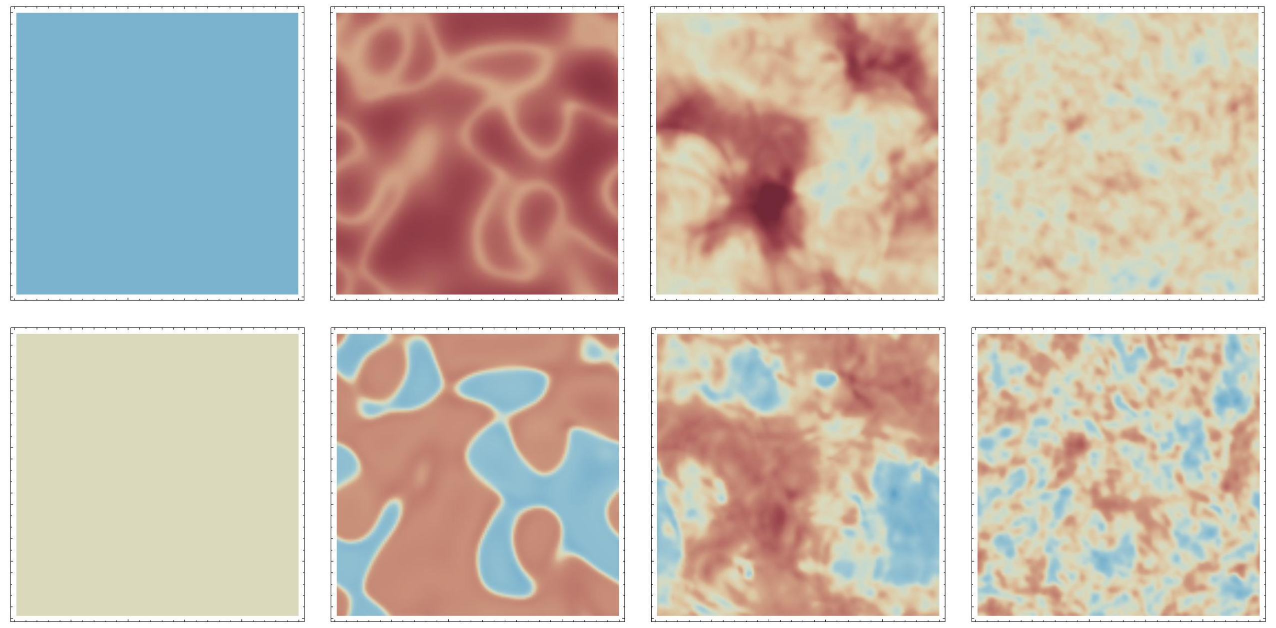


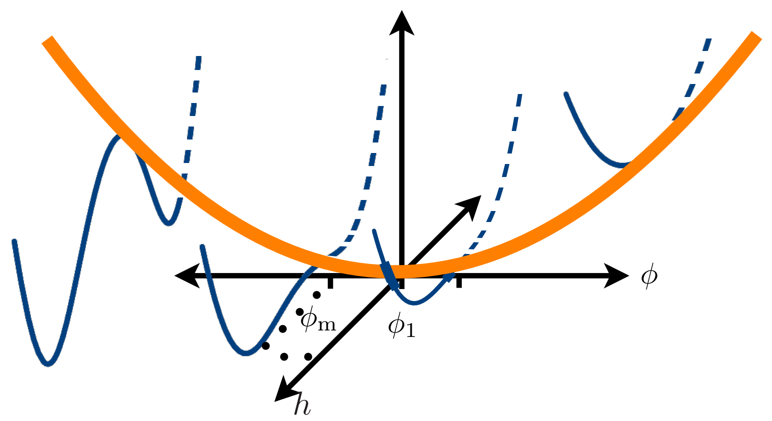
Long, Jain & MA (2021) 2103.10962



MA, Lozanov & Smith (in progress)







MA, Fan, Lozanov, Reece (2018)

For a general moduli review, see Kane Watson and Sinha (2015)

after inflation: a GAP in our cosmic history