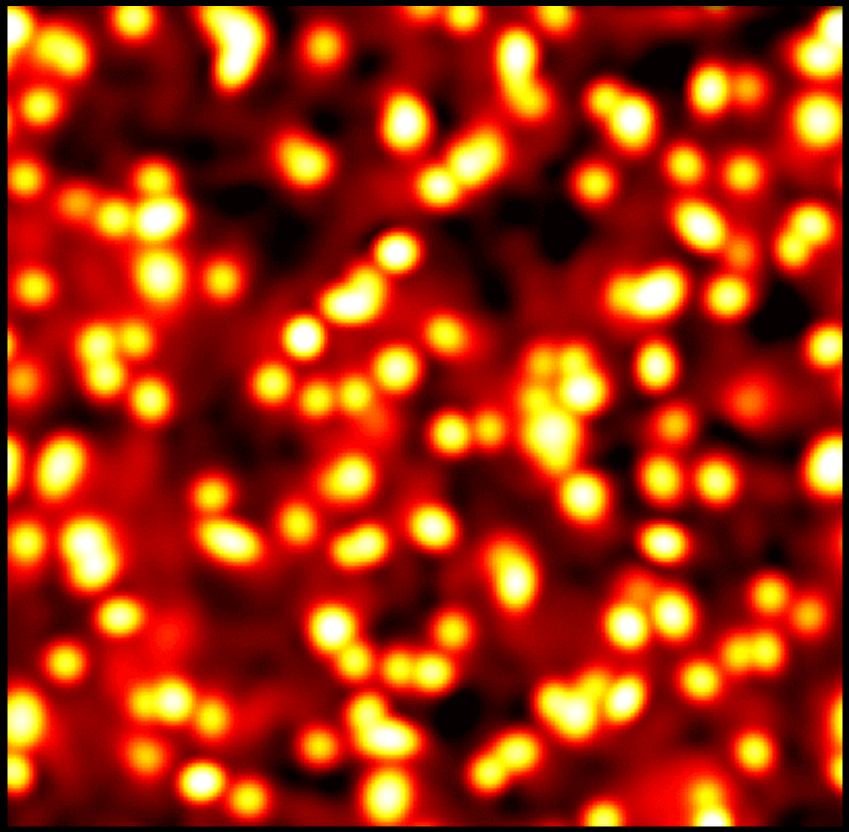
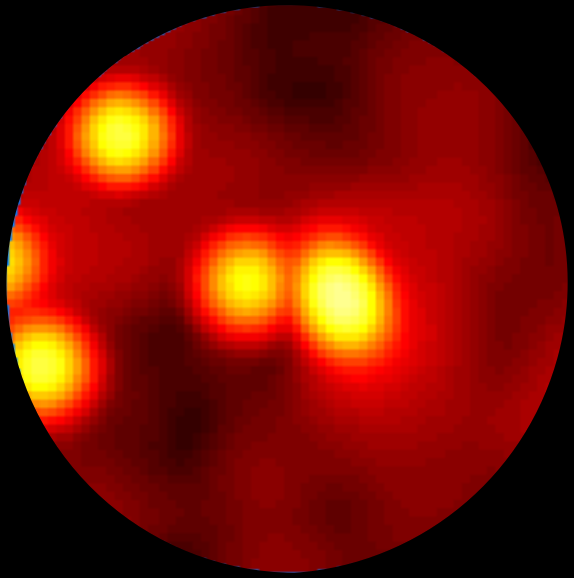
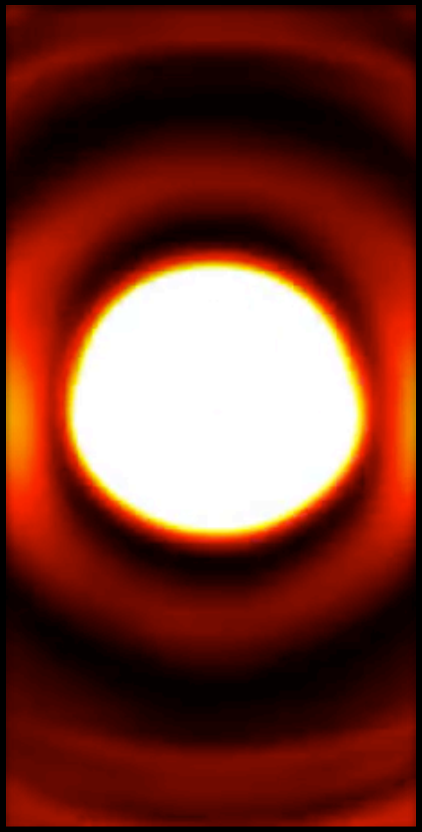
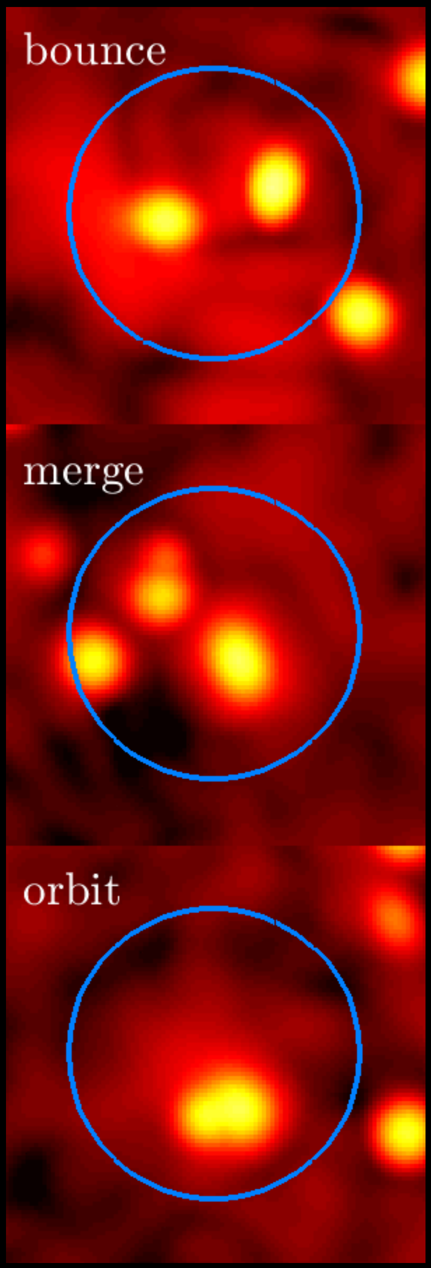
Smashing Solitons of Cosmology

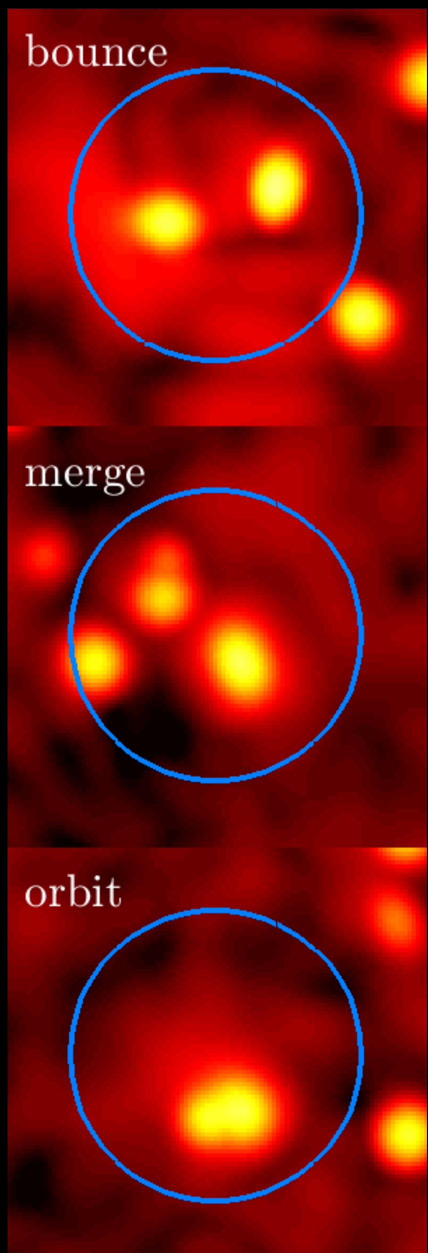






Mustafa A. Amin


bounce
merge
orbit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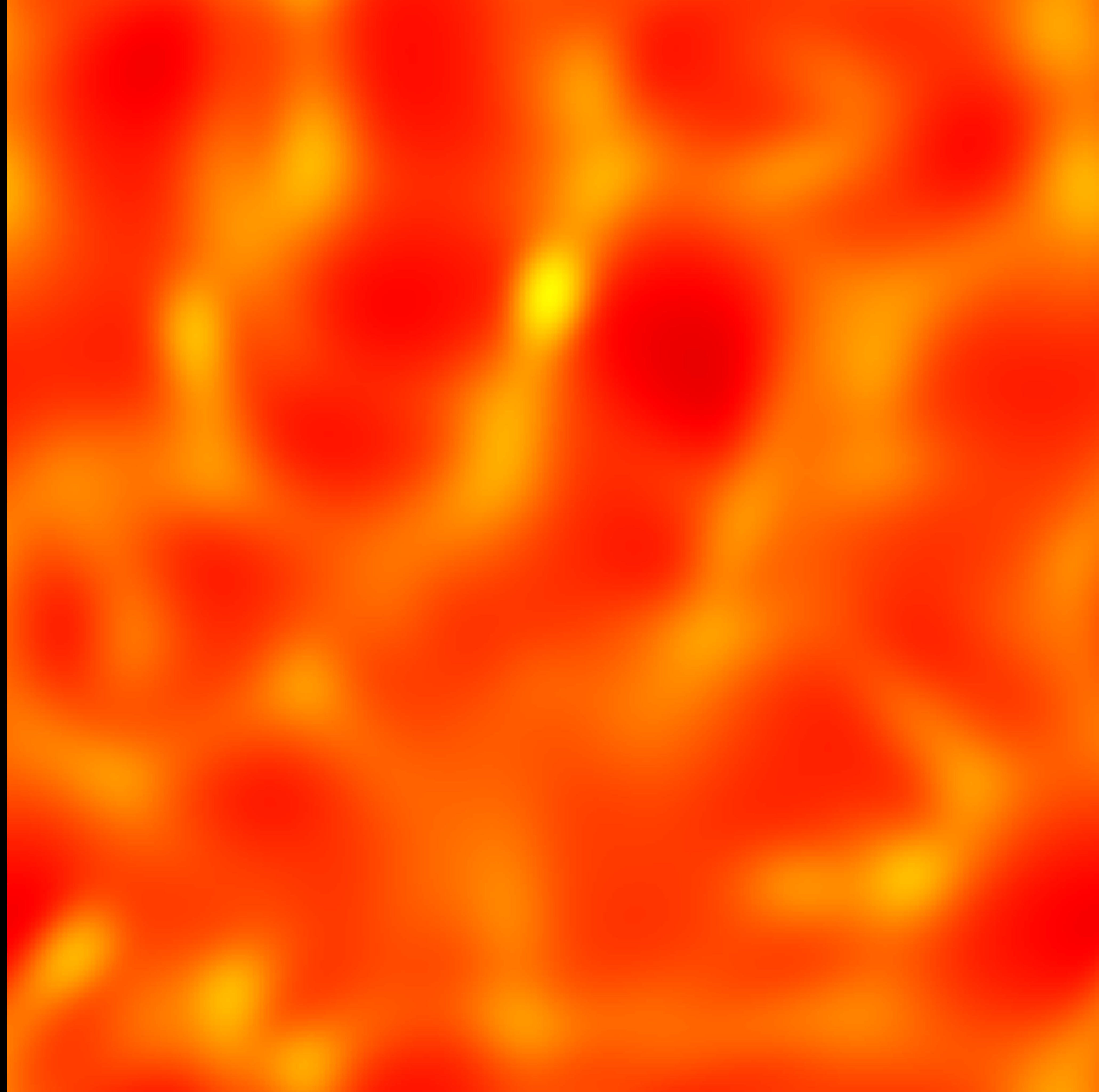
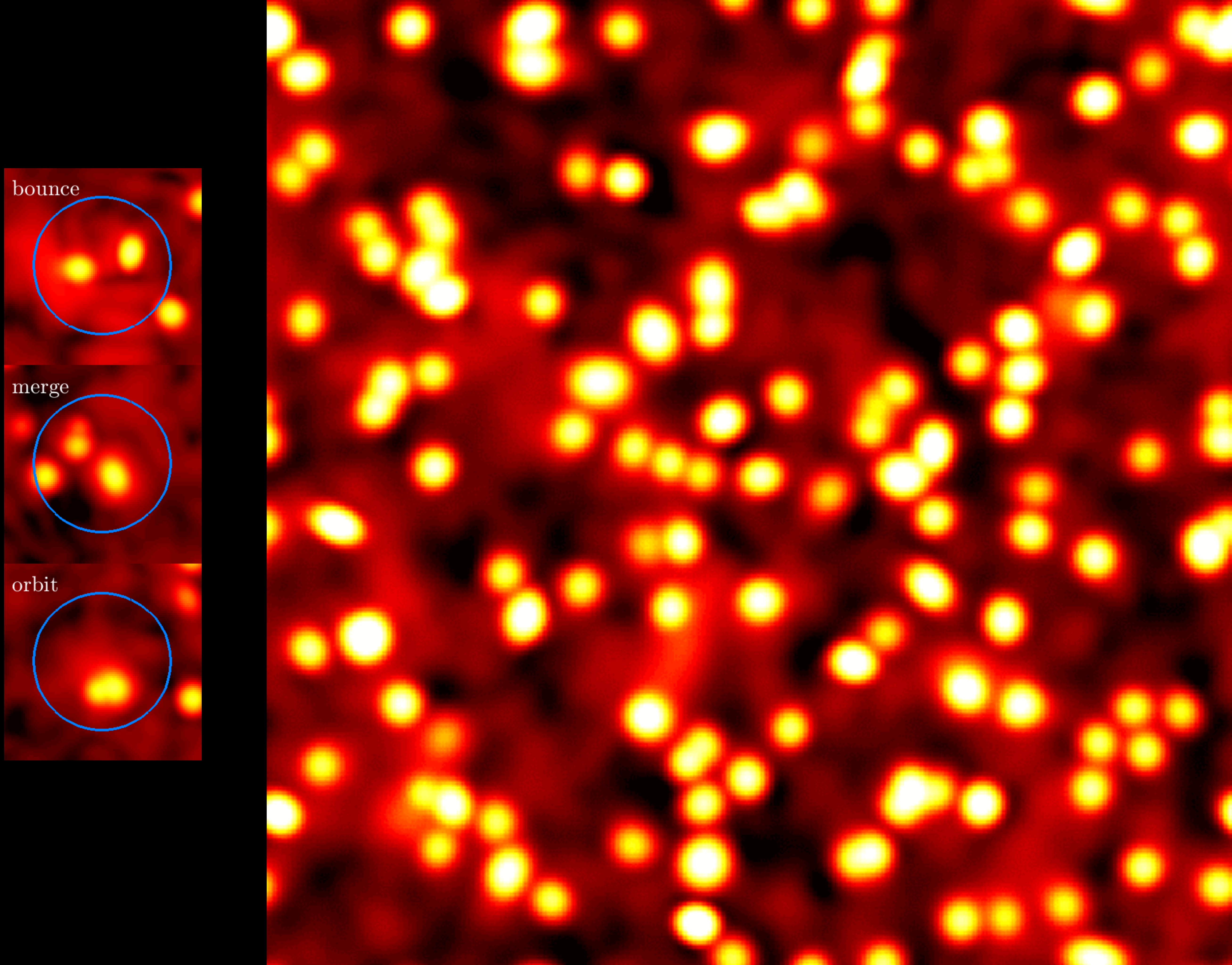



bounce
merge
orbit

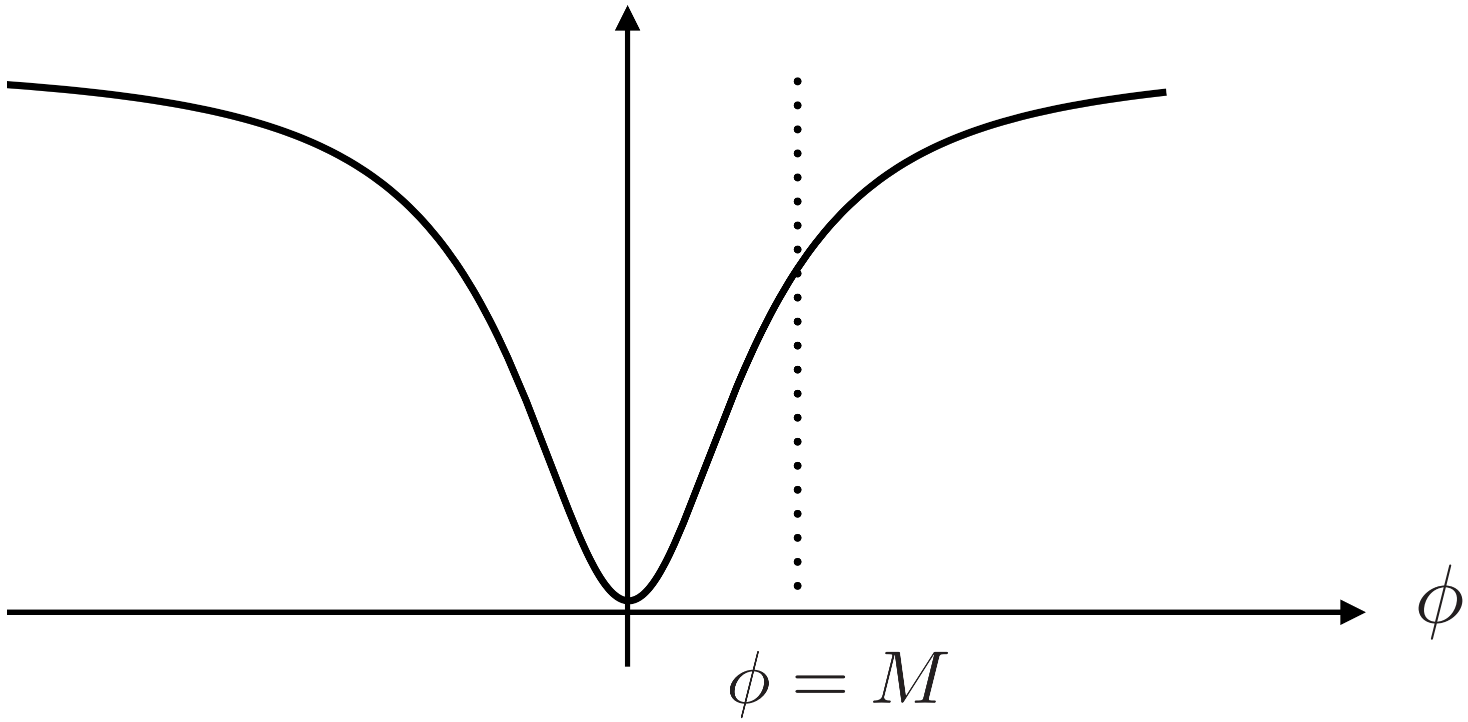
plan for the talk

- **WHAT** was it that you saw ?
- **WHY** is it relevant for cosmology ?
- **IMPLICATIONS** ?

cosmological scalar fields
self-interaction + gravity

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

$$V(\phi) = \frac{1}{2} m^2 \phi^2 + V_{\rm nl}(\phi)$$



*opening up means of the potential there is an attractive interaction in addition to gravity

why study such systems ?

- relevant for end of inflation because observations favor such "opened up" potentials for inflation

- relevant for axions/axion-like fields (dark matter)

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

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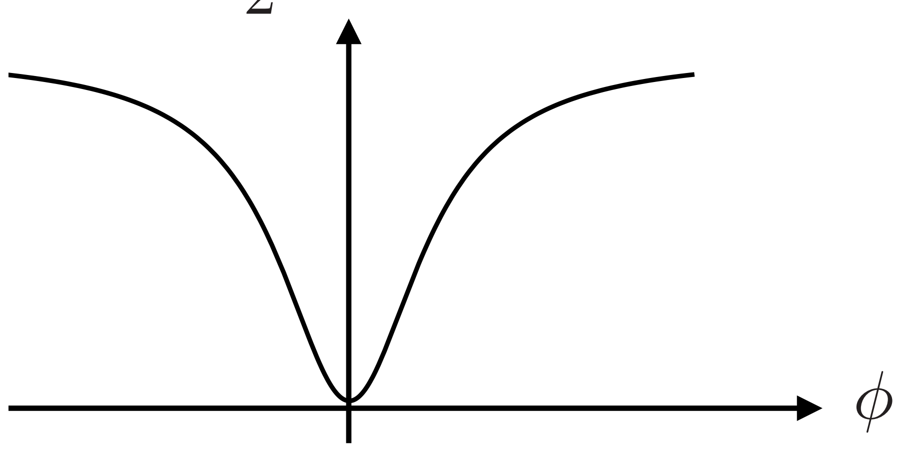


observational implications

incomplete list!

- eq. of state & energy transfer after inflation ?
- stochastic gravitational wave-generation ?
- primordial black hole (PBH) formation ?

after inflation

- distinguishability from "usual" dark matter ?
- additional early/late early structure formation
- compact objects
  - eg. sources of gravitational waves ?
- source of signature in light

dark matter

plan for the talk

- ✓ motivation
- → understanding the dynamics: soliton formation & interactions
- implications

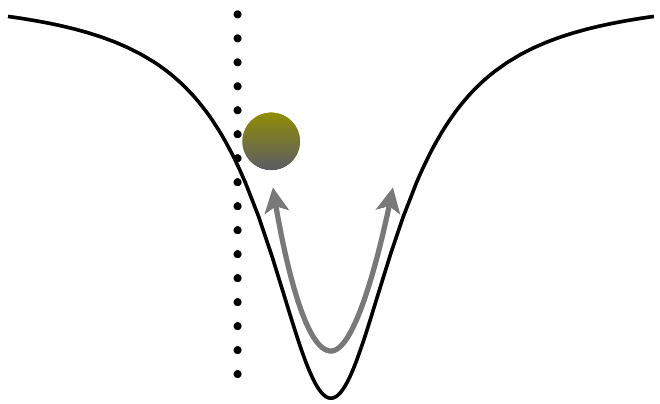
instability — formation of solitons
(non-topological "solitons" in real scalar fields)

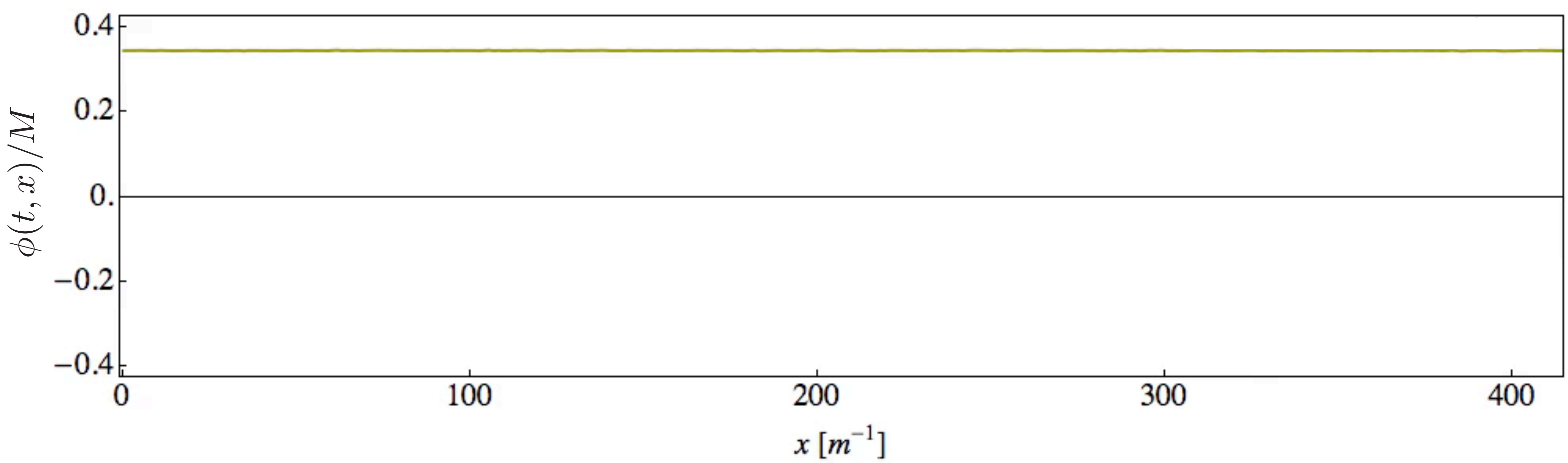
expansion ✓

self-interactions ✓

gravitational int. ✗

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





MA (2010)
1006.3075

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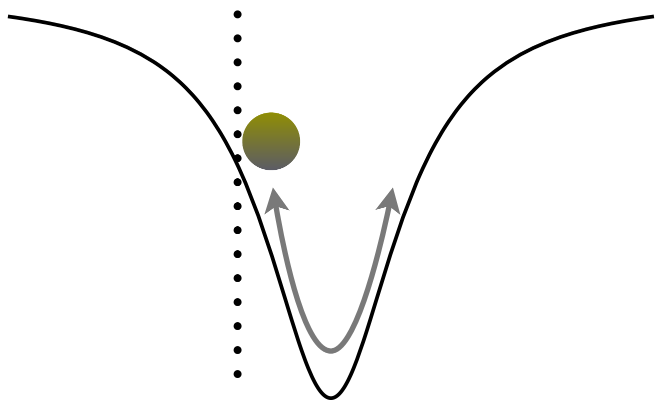

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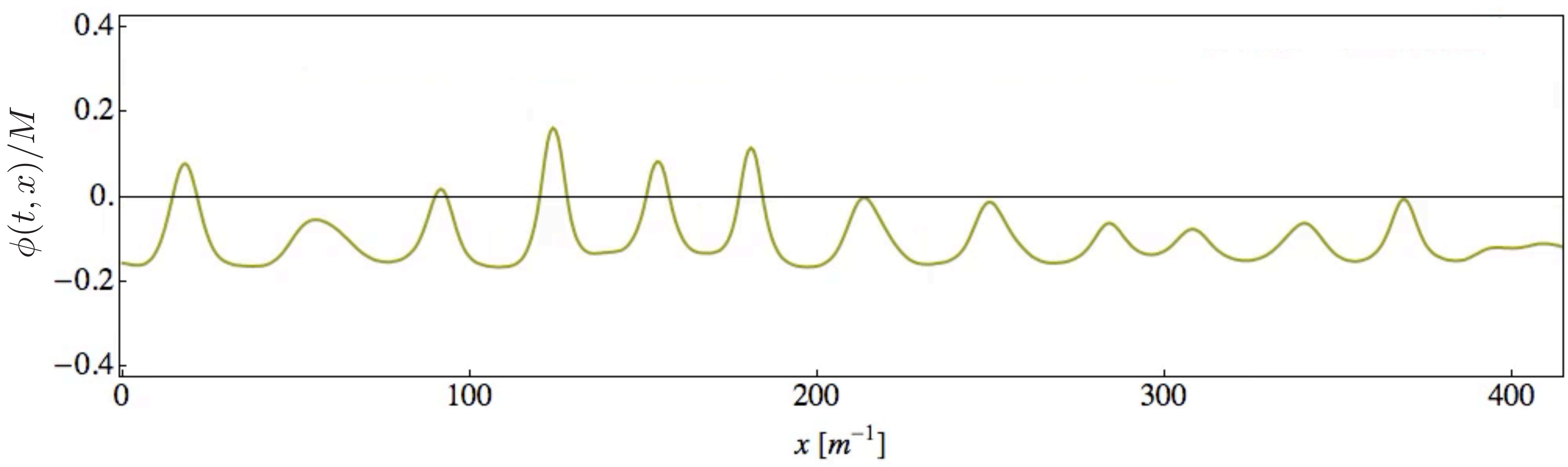

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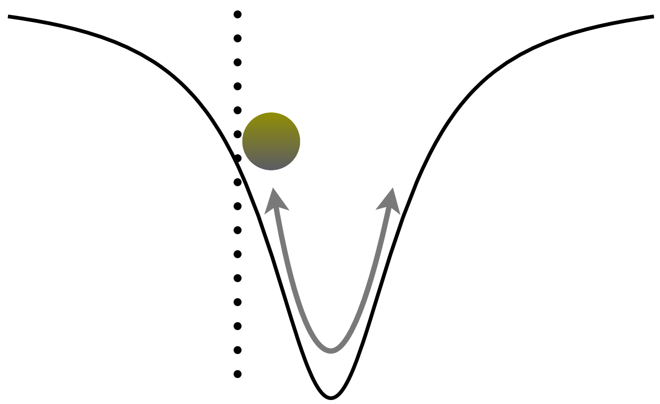

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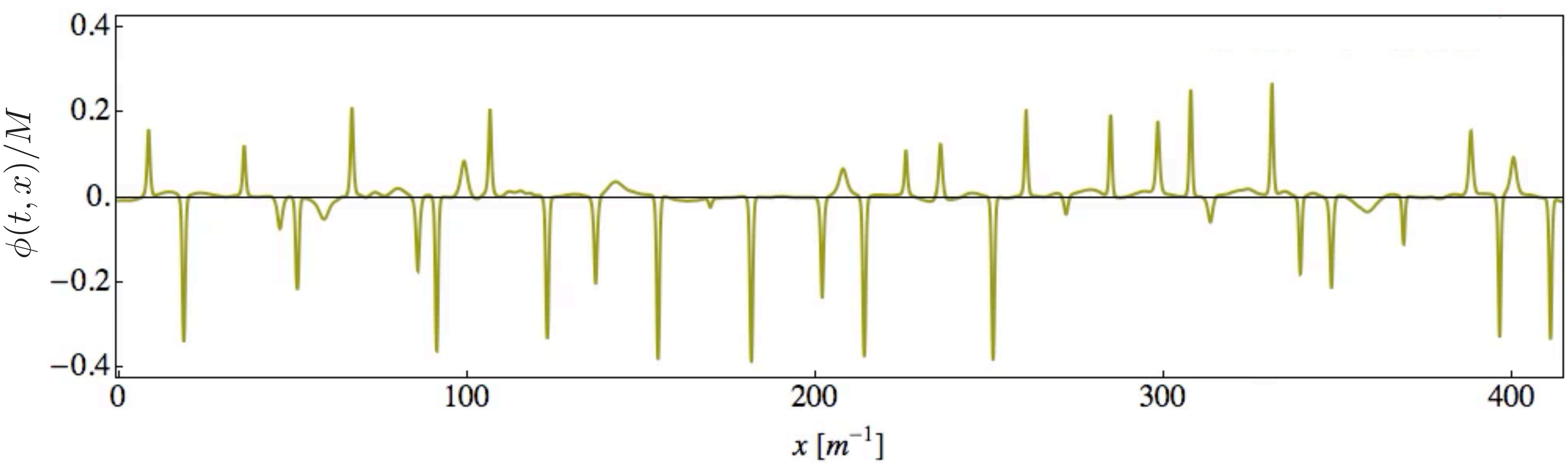
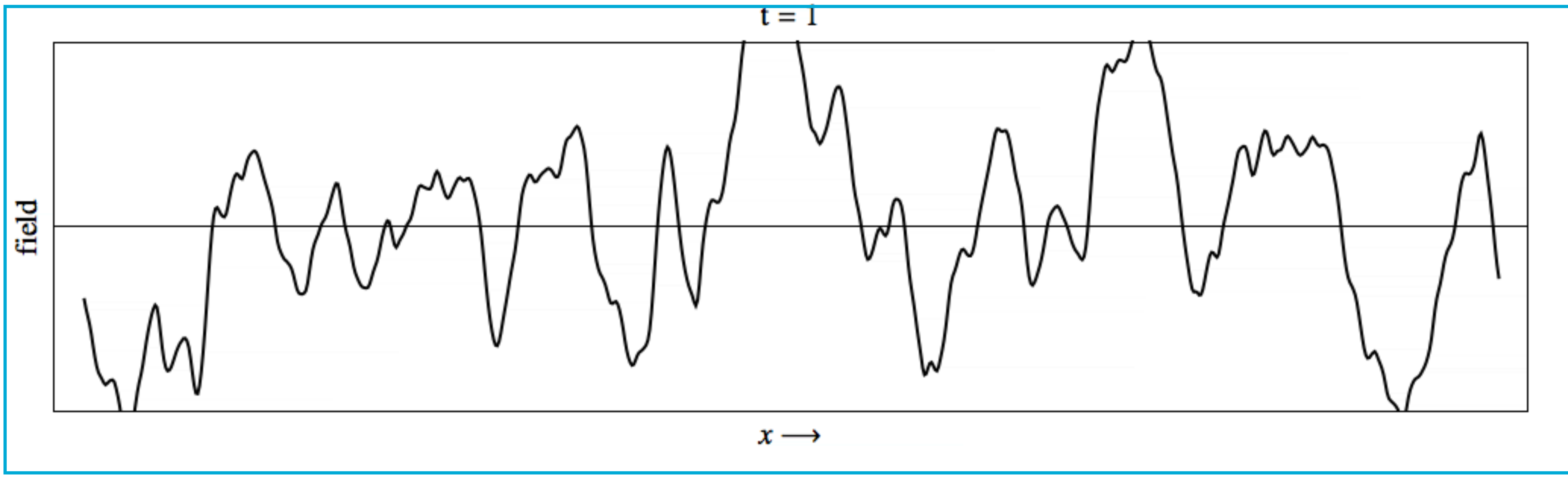


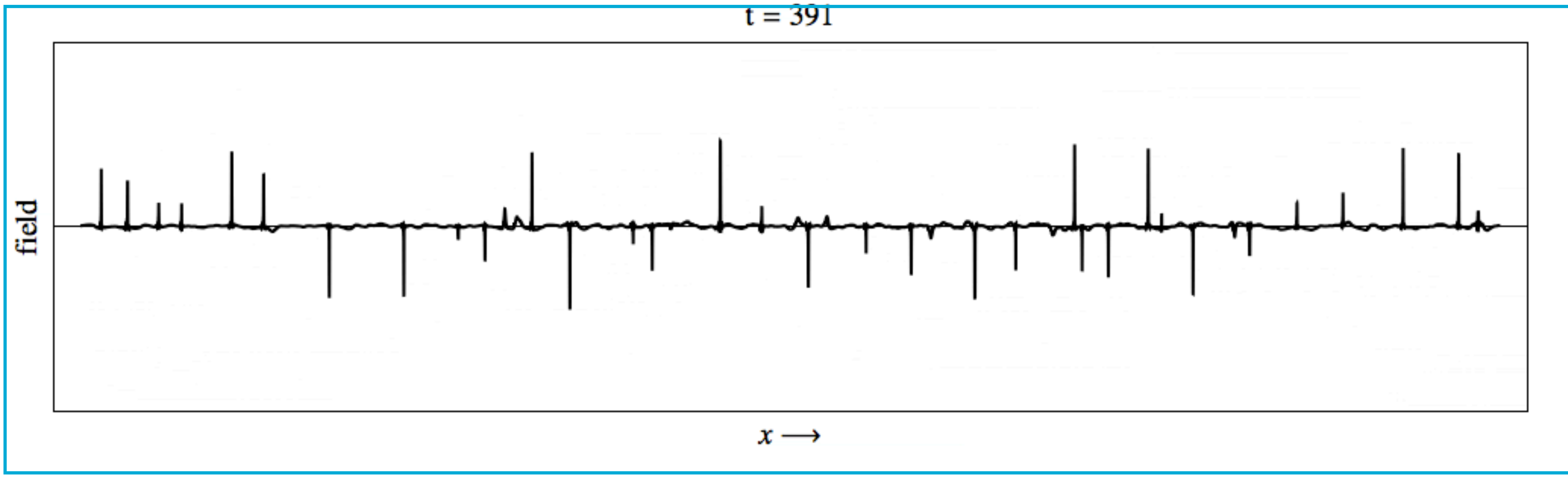
MA (2010)
1006.3075

insensitive to initial conditions



simulation of "quasi-thermal" example in Farhi, Guth, Iqbal, Graham 2008

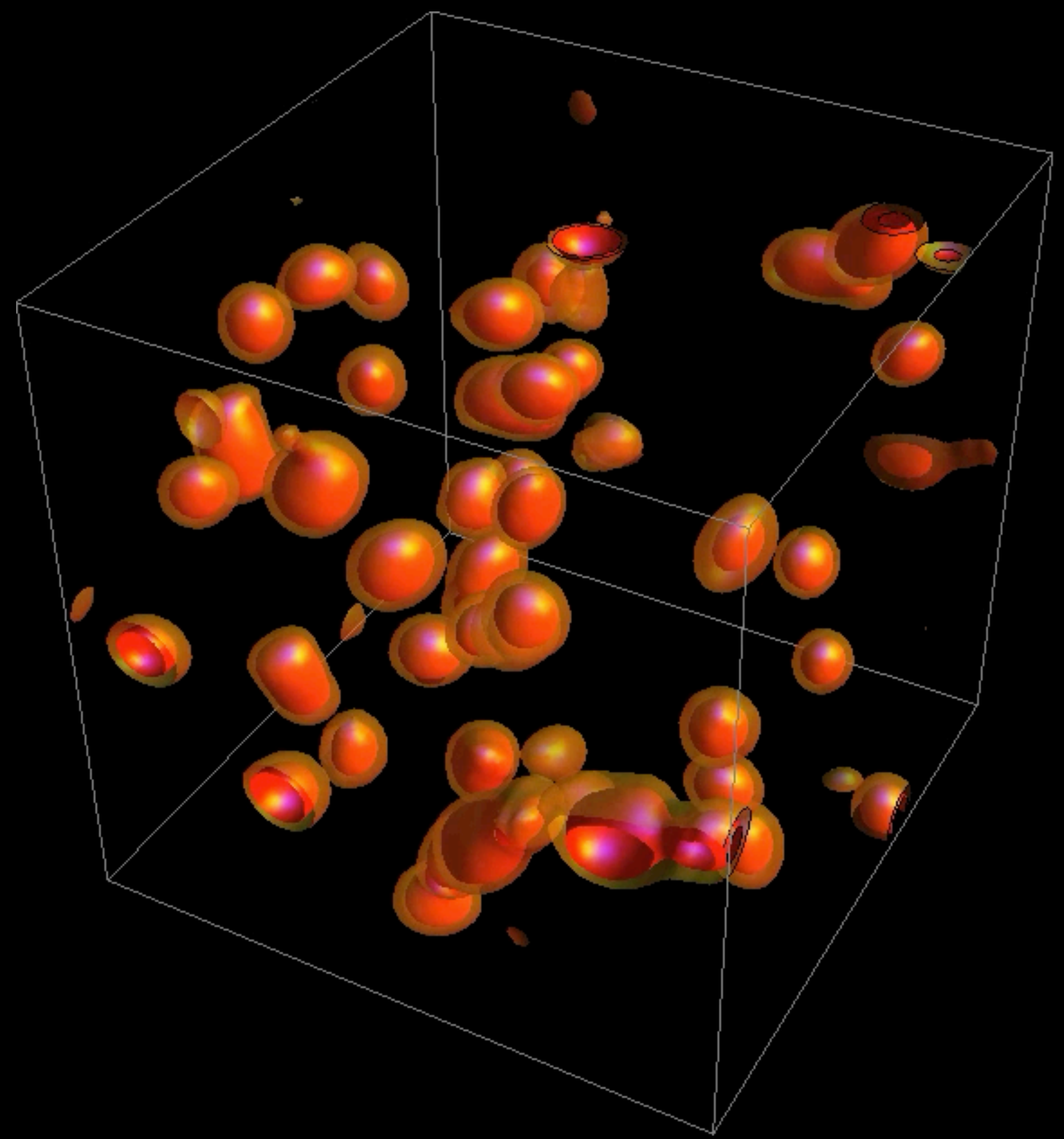
insensitive to initial conditions



simulation of "quasi-thermal" example in Farhi, Guth, Iqbal, Graham 2008

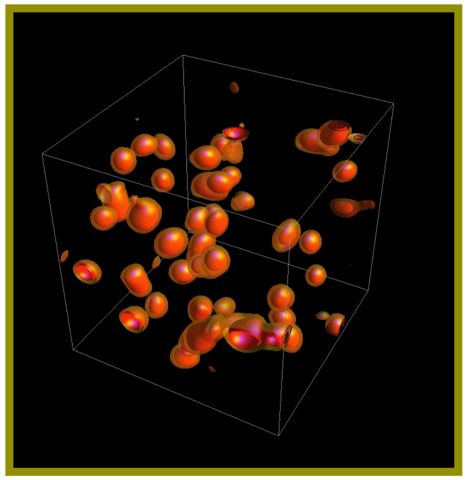
soliton formation in 3D

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



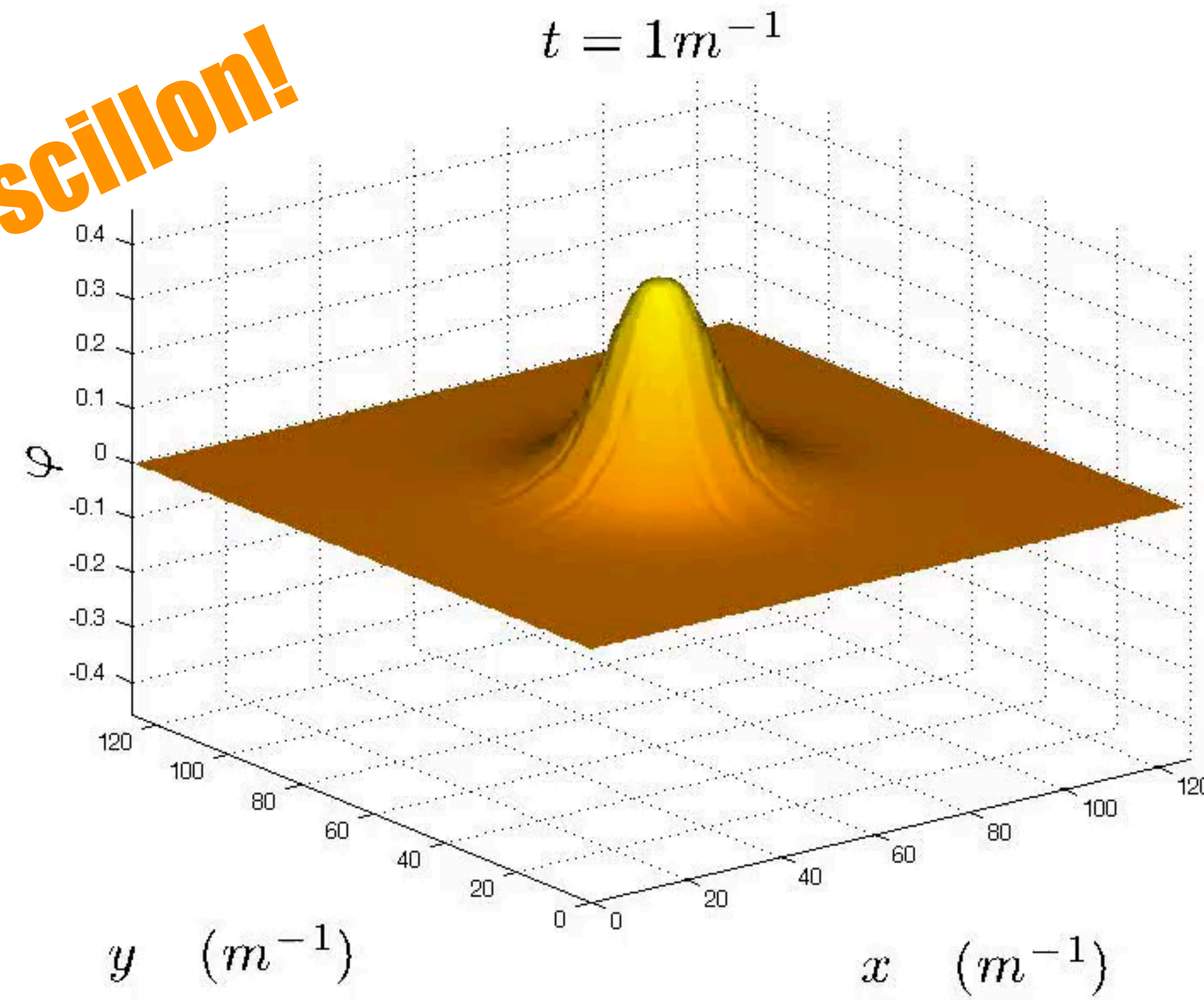
MA, Easther, Finkel, Flauger & Hertzberg (2011)
1106.3335

solitons ?



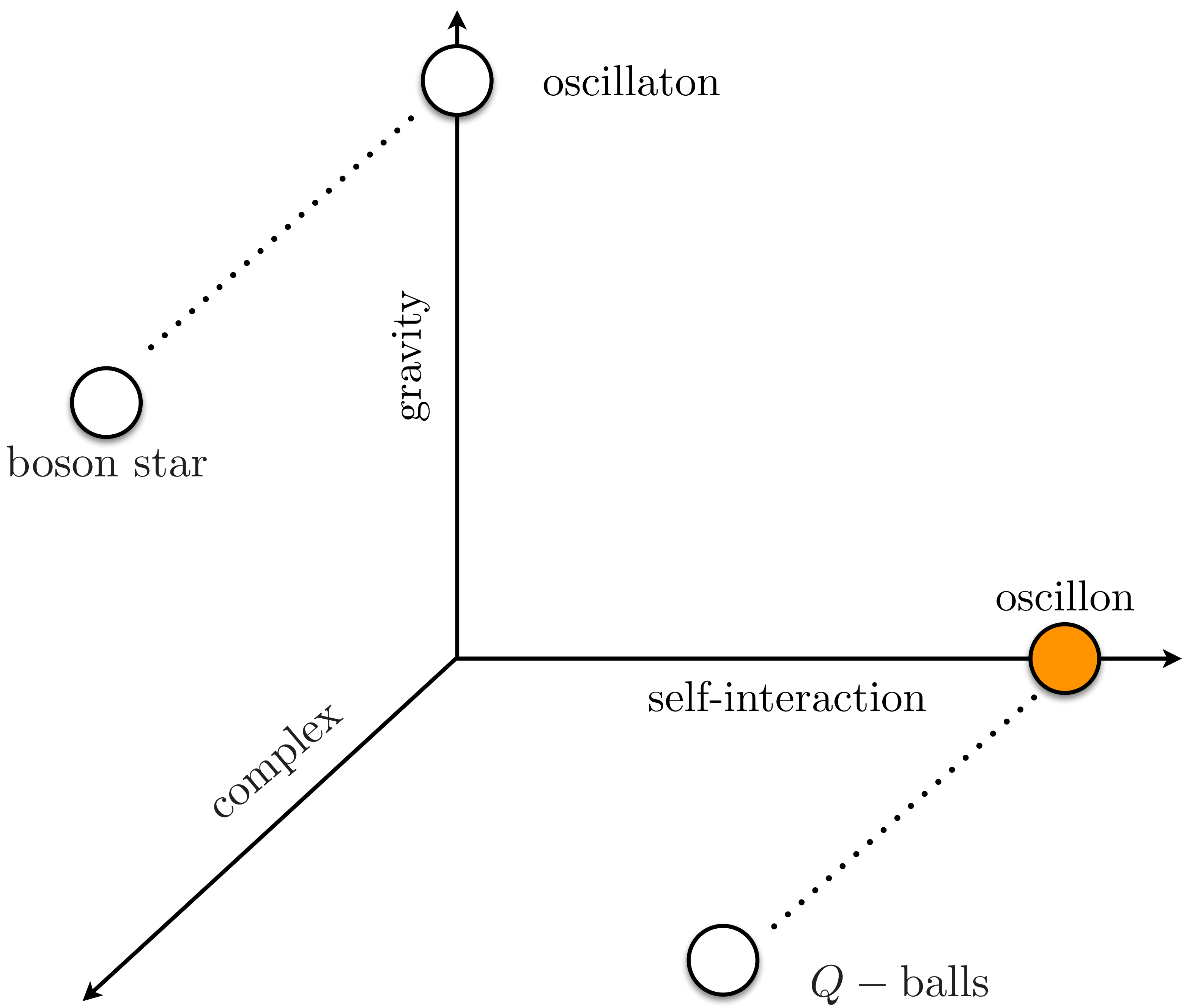
(1) oscillatory (2) spatially localized (3) **very long lived**

oscillon!



For example:
Bogolubsky & Makhankov (1976)
Segur & Kruskal (1987)
Gleiser (1994)
Copeland et al. (1995)
MA & Shirokoff (2010)
Hertzberg (2011)
MA (2013)
Mukaida et. al (2016)
Salmi & Hindmarsh (2014)
Zhang, MA, et. al (2020)

family of scalar field solitons

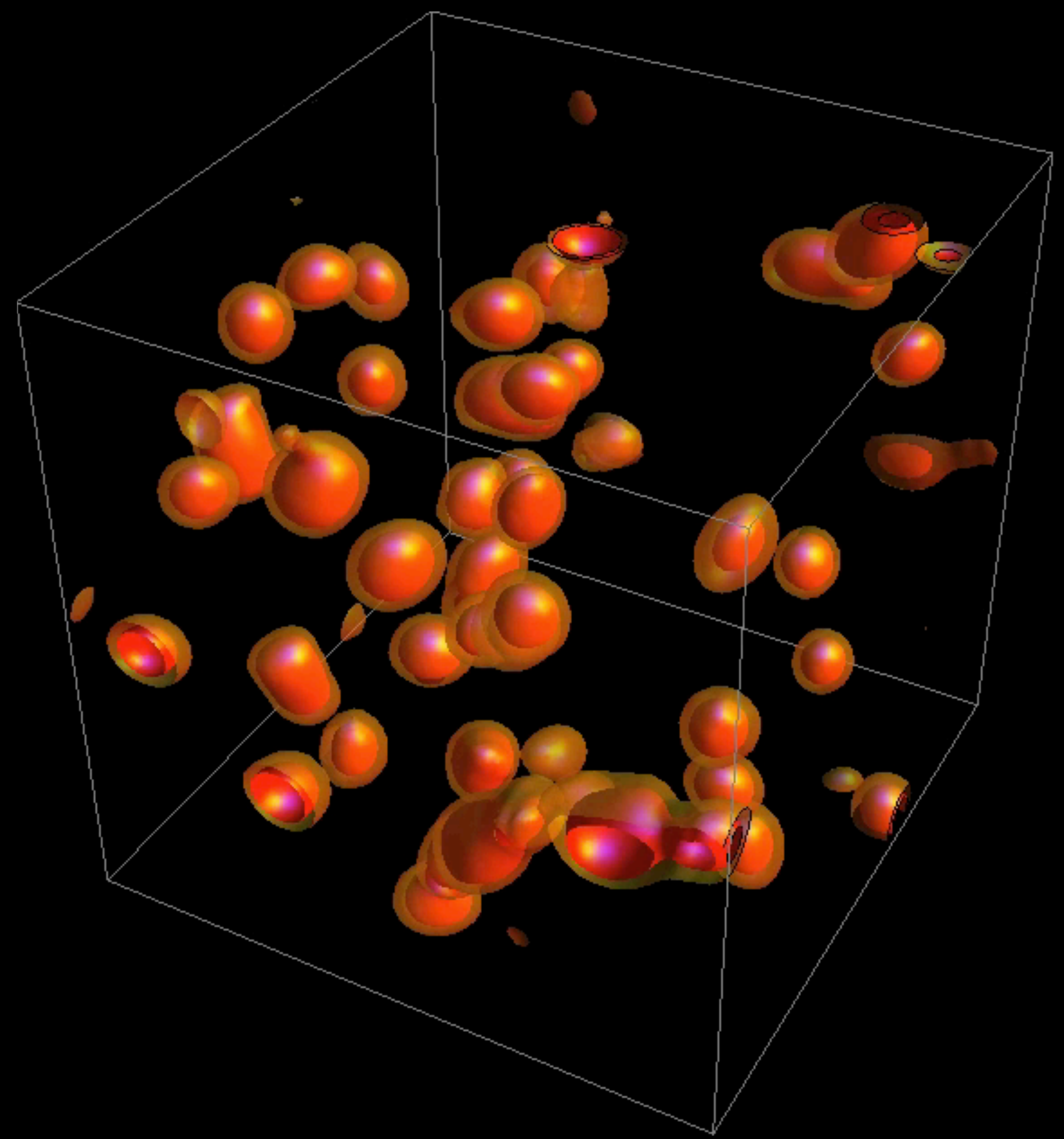


long term dynamics ?

expansion ✓

self-interactions ✓

gravitational int. ✗



assuming coupling to other fields is sufficiently weak expansion ✓

self-interactions ✓

gravitational interactions

include gravity ?

- gravitational clustering takes time …
- long time makes it difficult to resolve very fast oscillatory time scale

self-interactions

+ gravity*

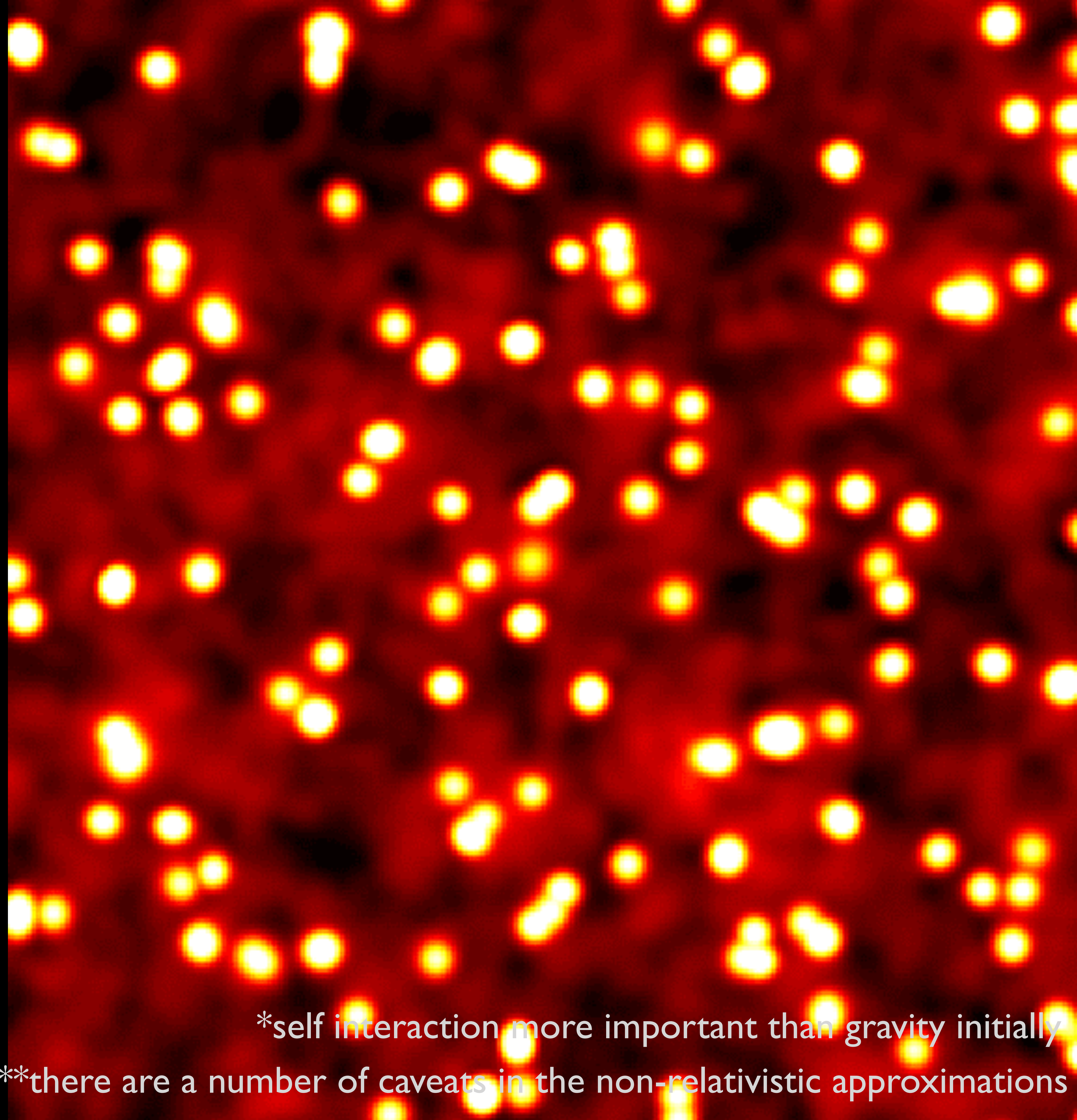
(Schrodinger-Poisson)

expansion

self-interactions

gravitational int.

relativistic?



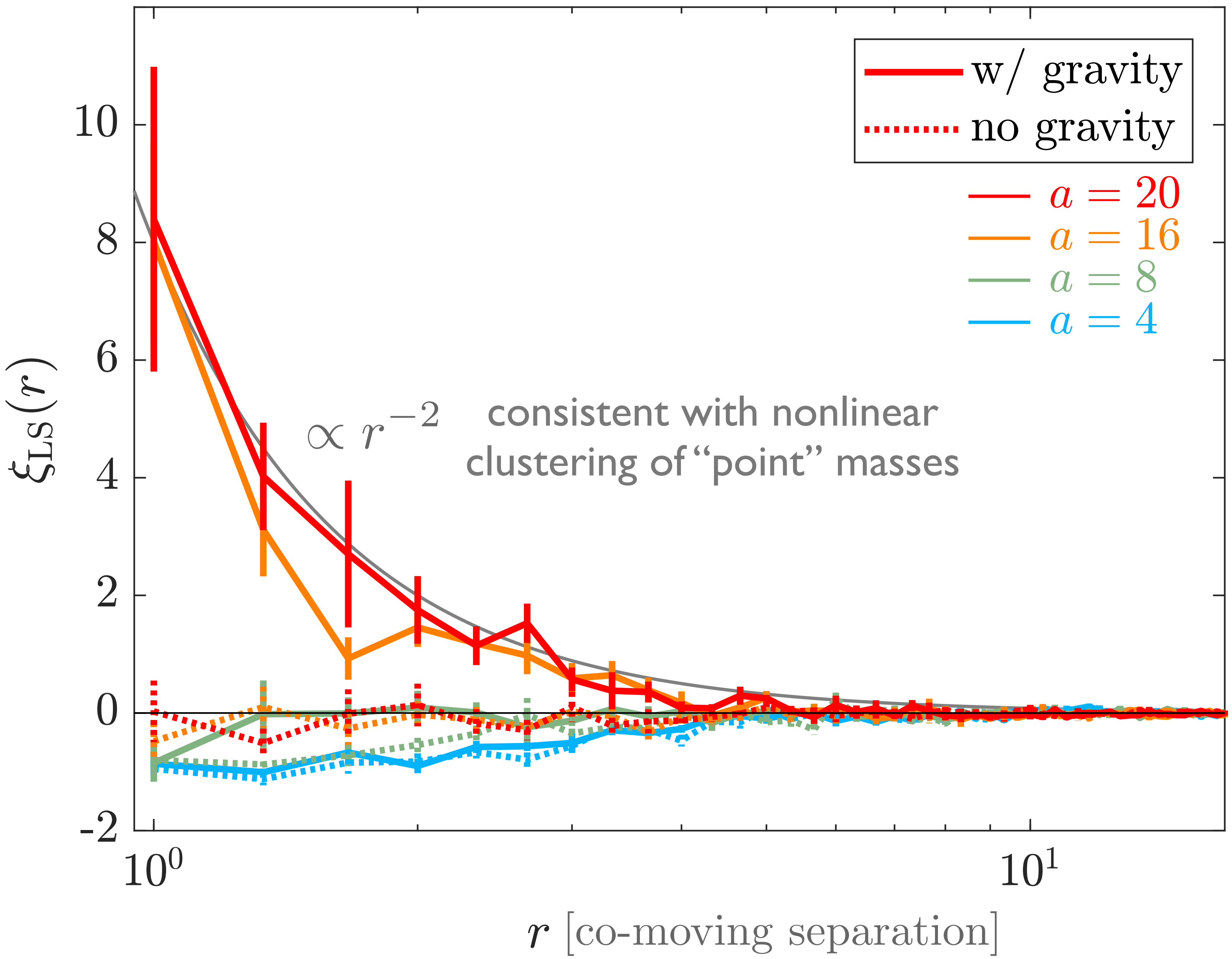
*self interaction more important than gravity initially

**there are a number of caveats in the non-relativistic approximations

MA & Mocz (2019)

1902.07261

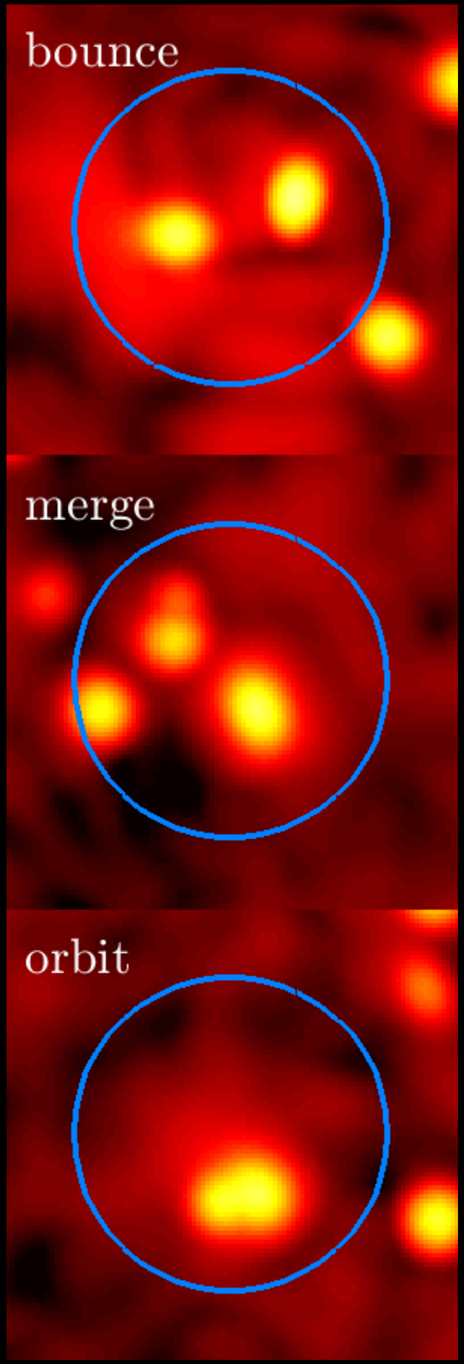
gravitational clustering of solitons

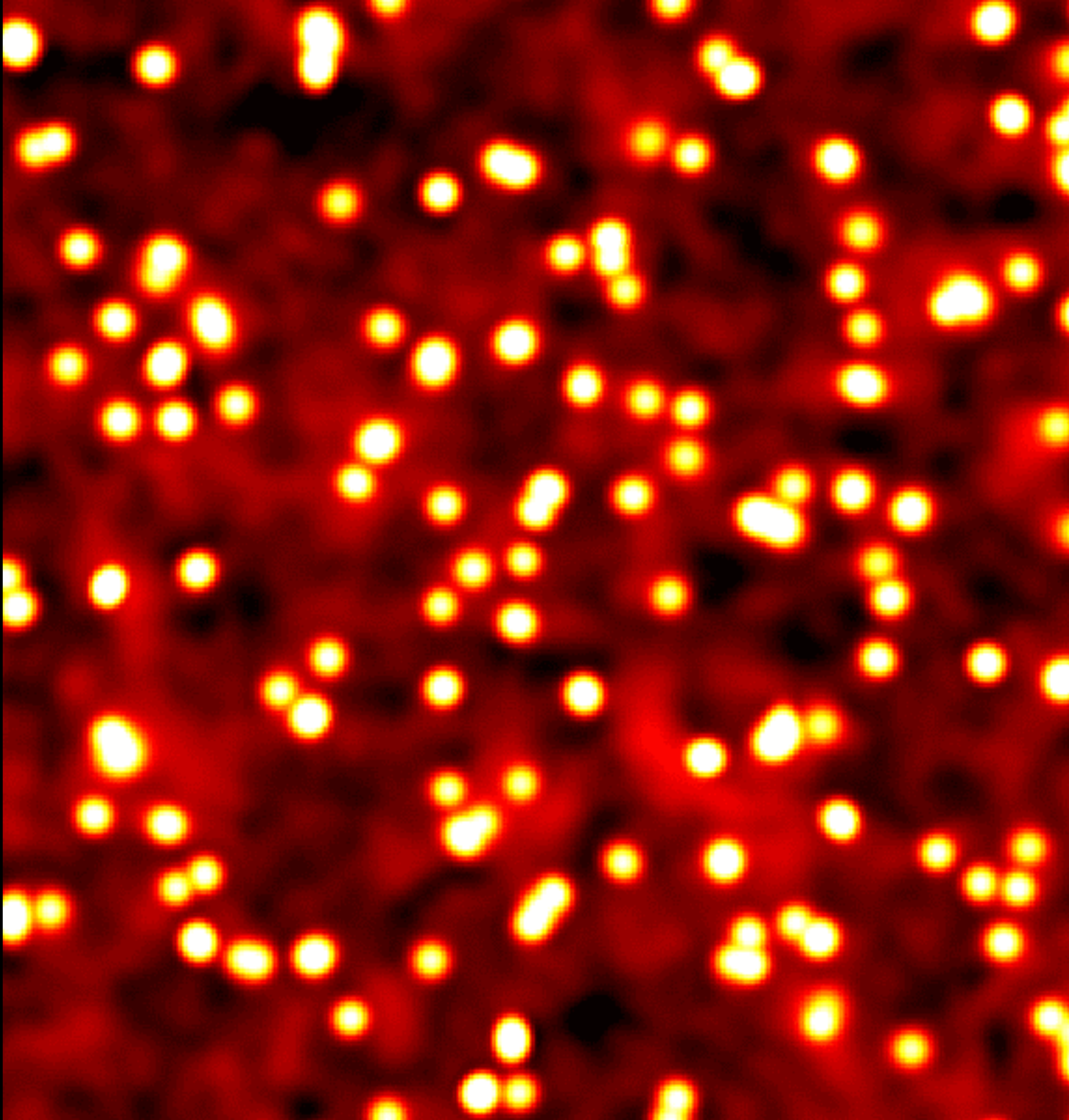


self-interactions

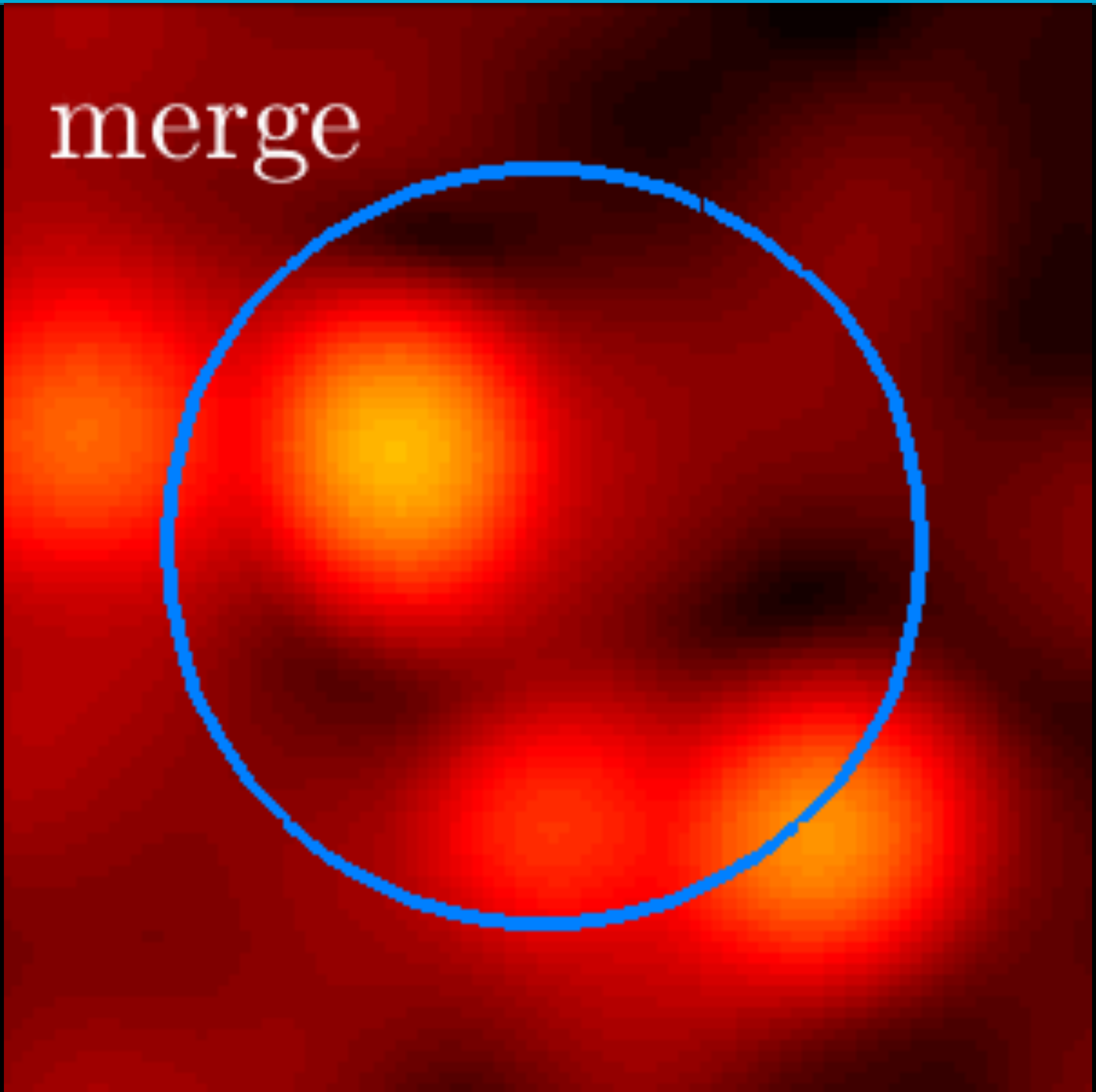
+ gravity*

(Schrodinger-Poisson)





strong interactions: mergers



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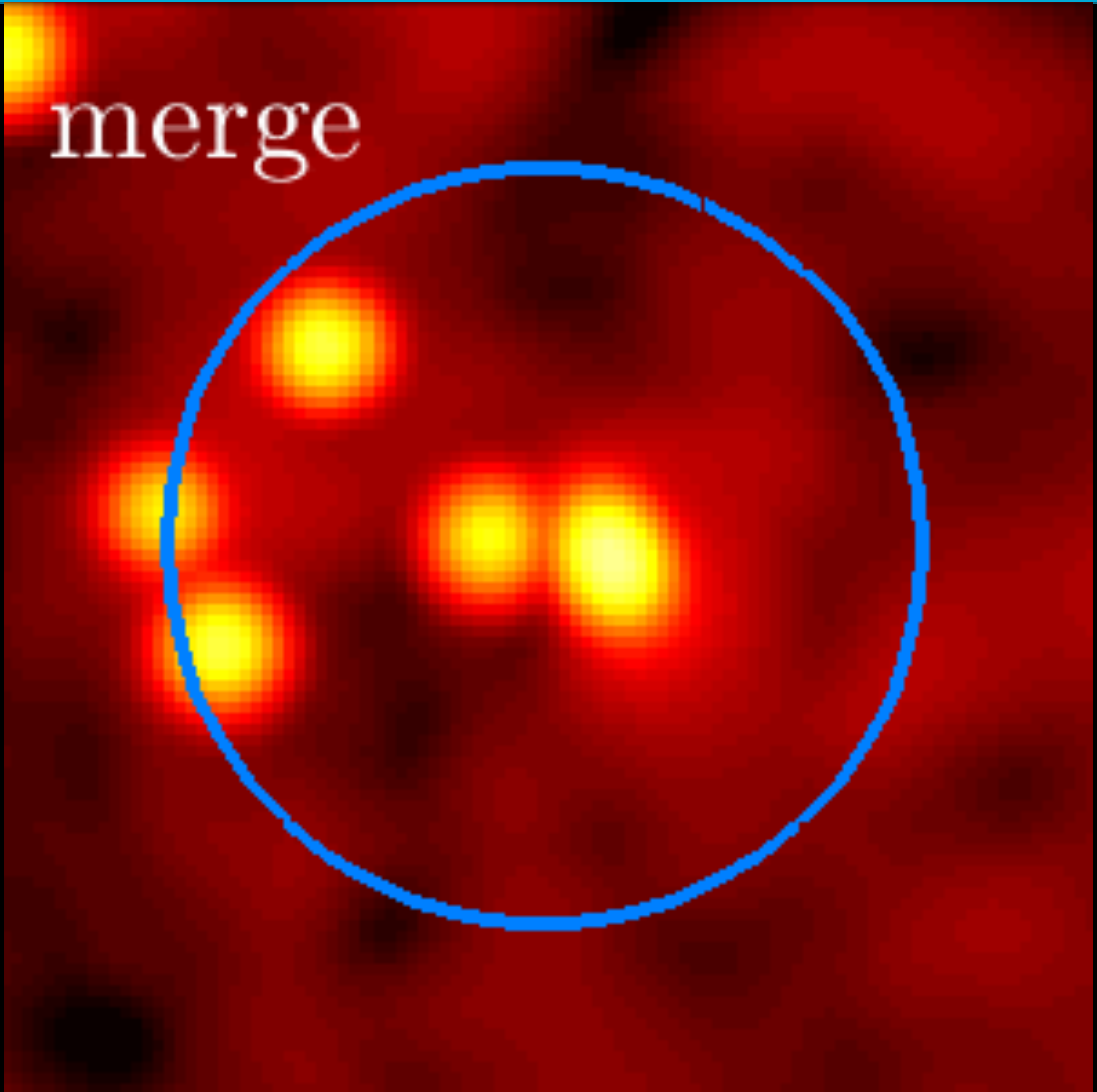

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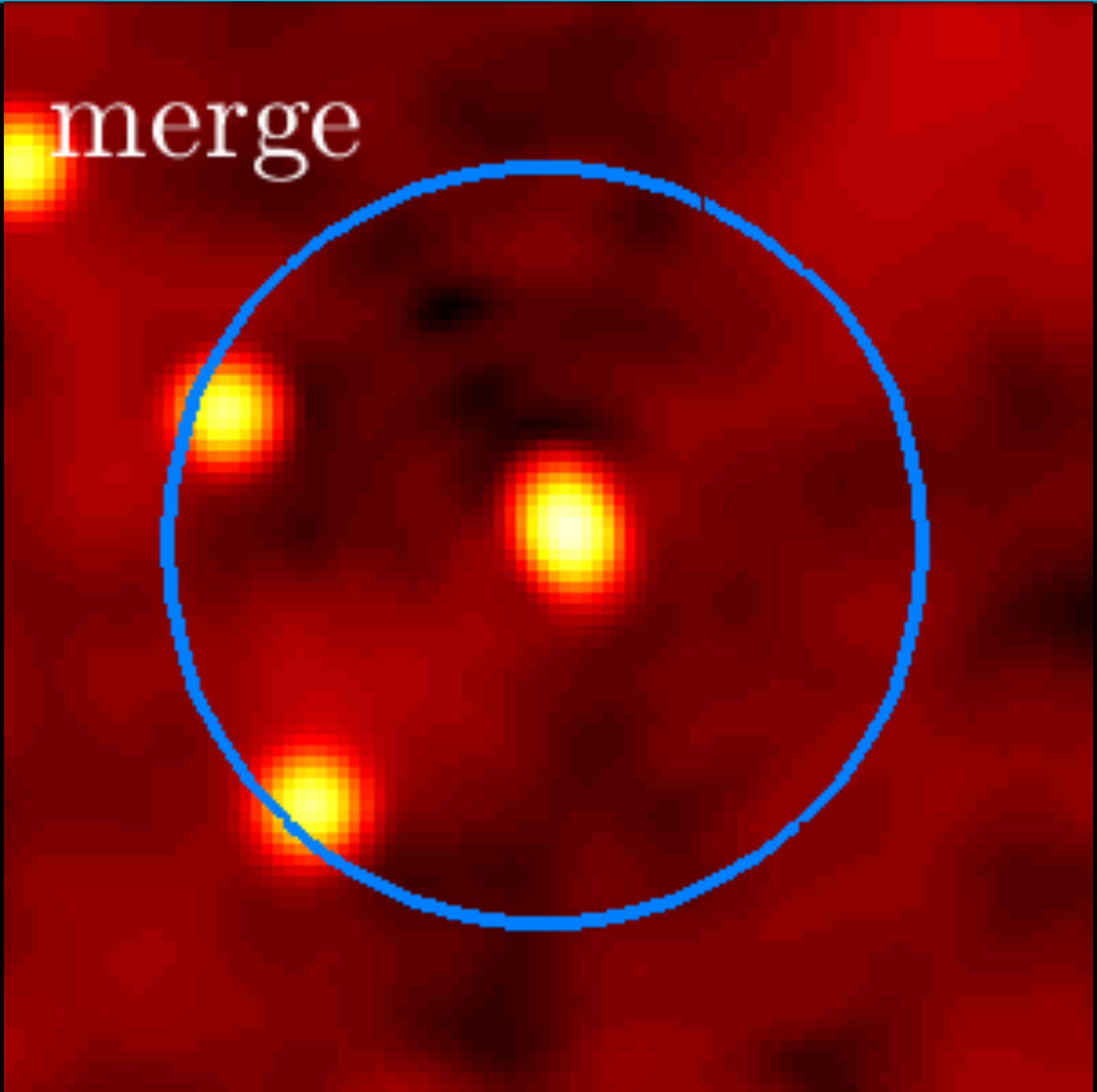
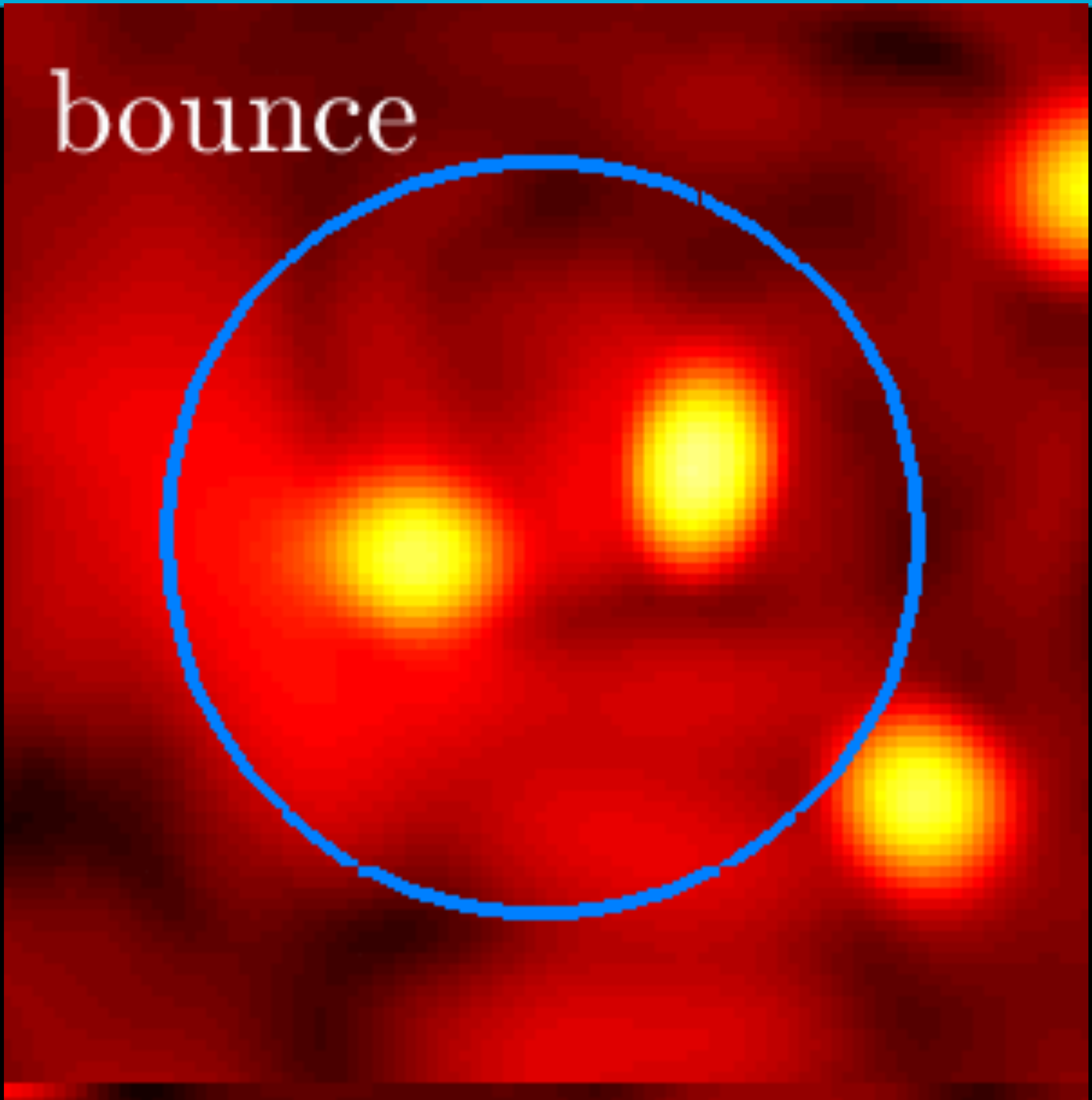


strong interactions: bounce



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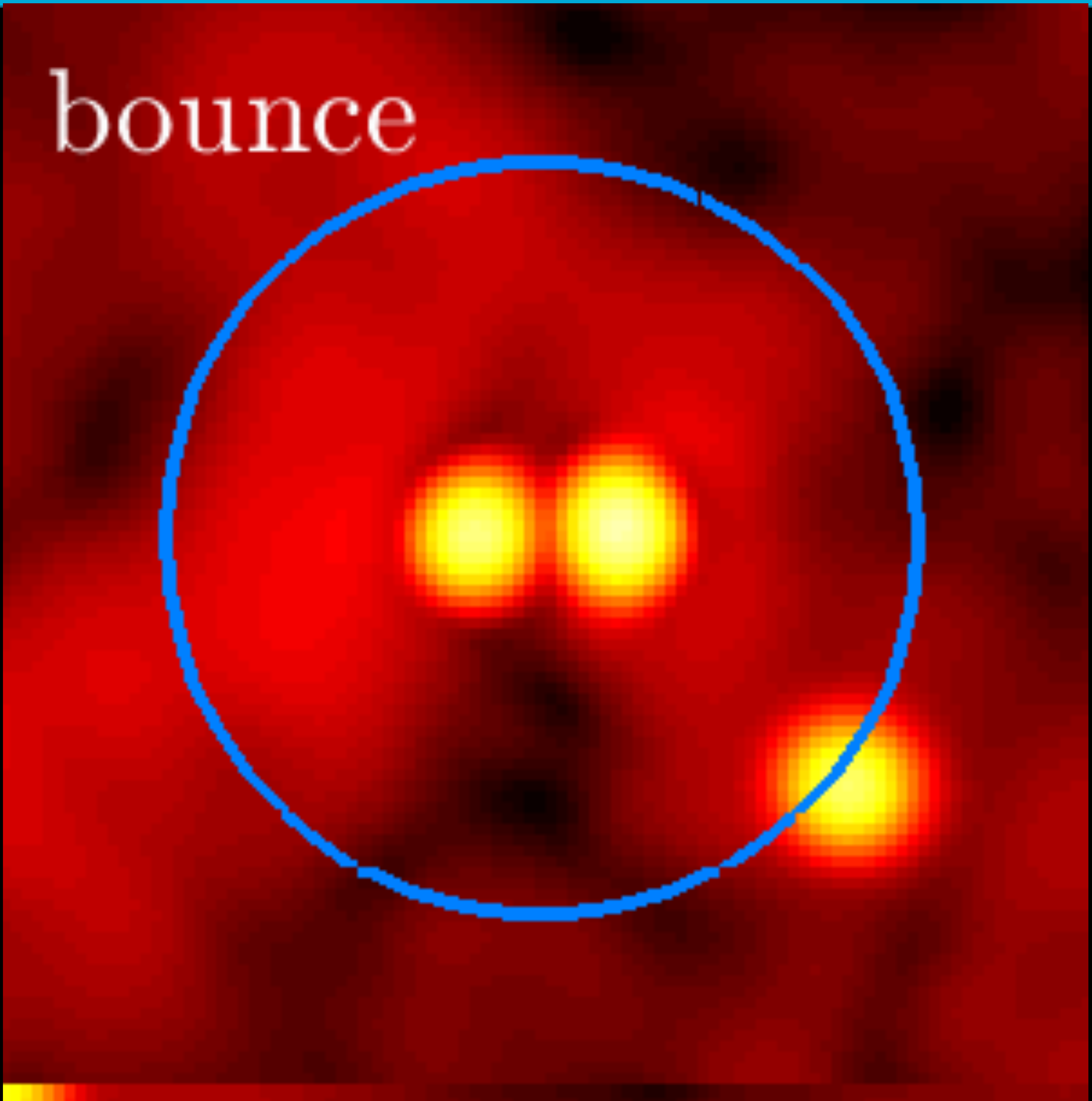

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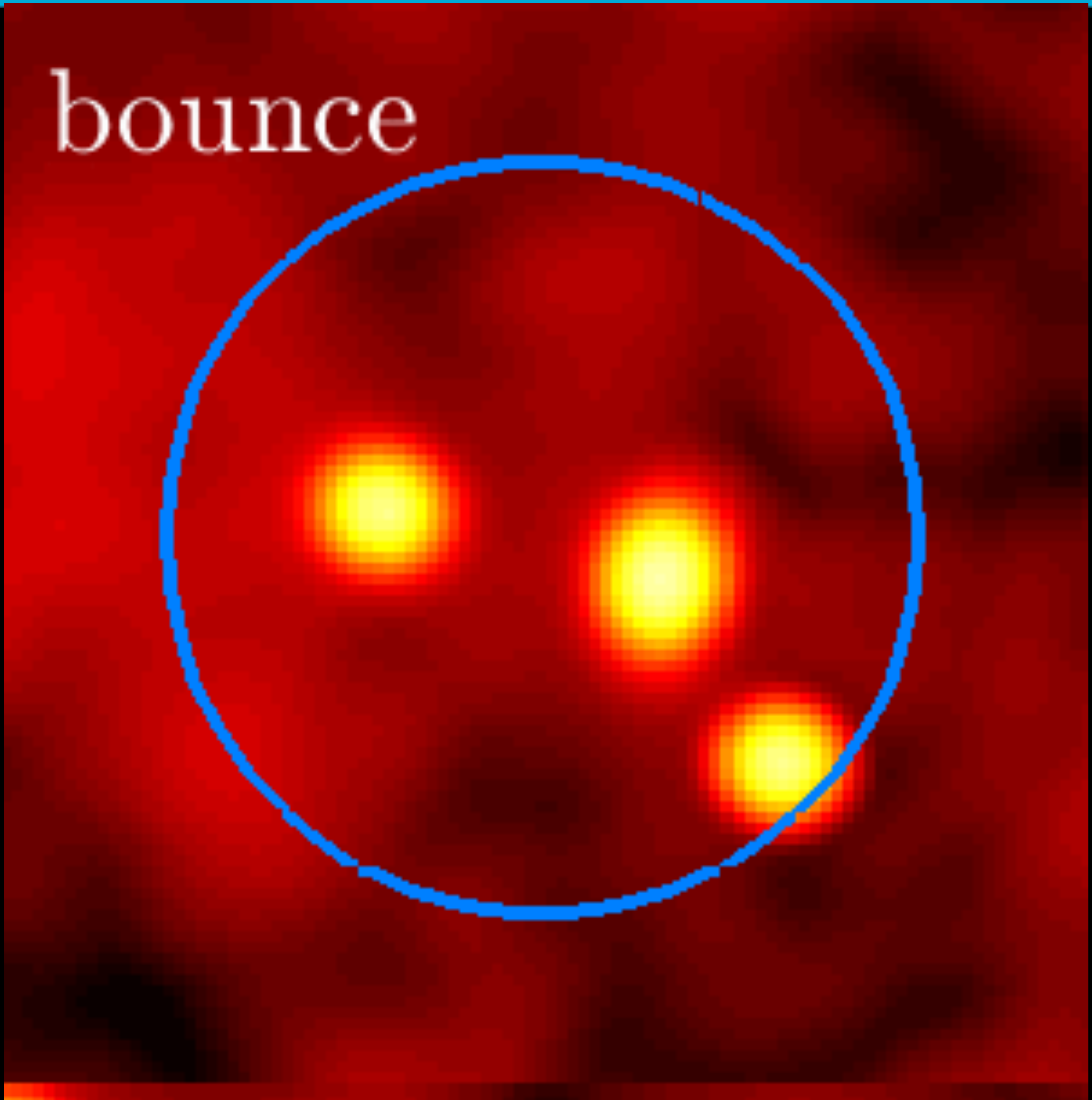
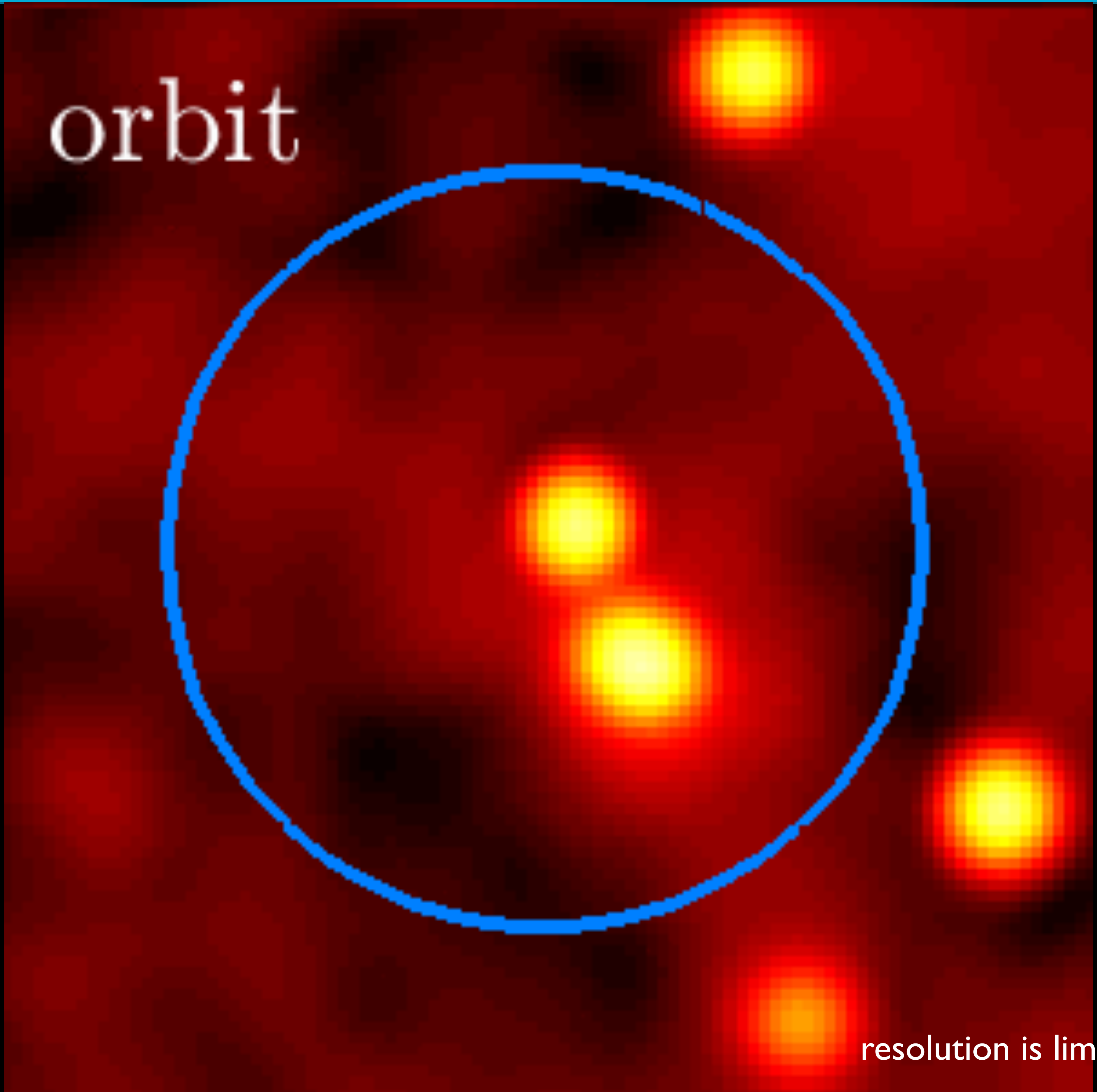
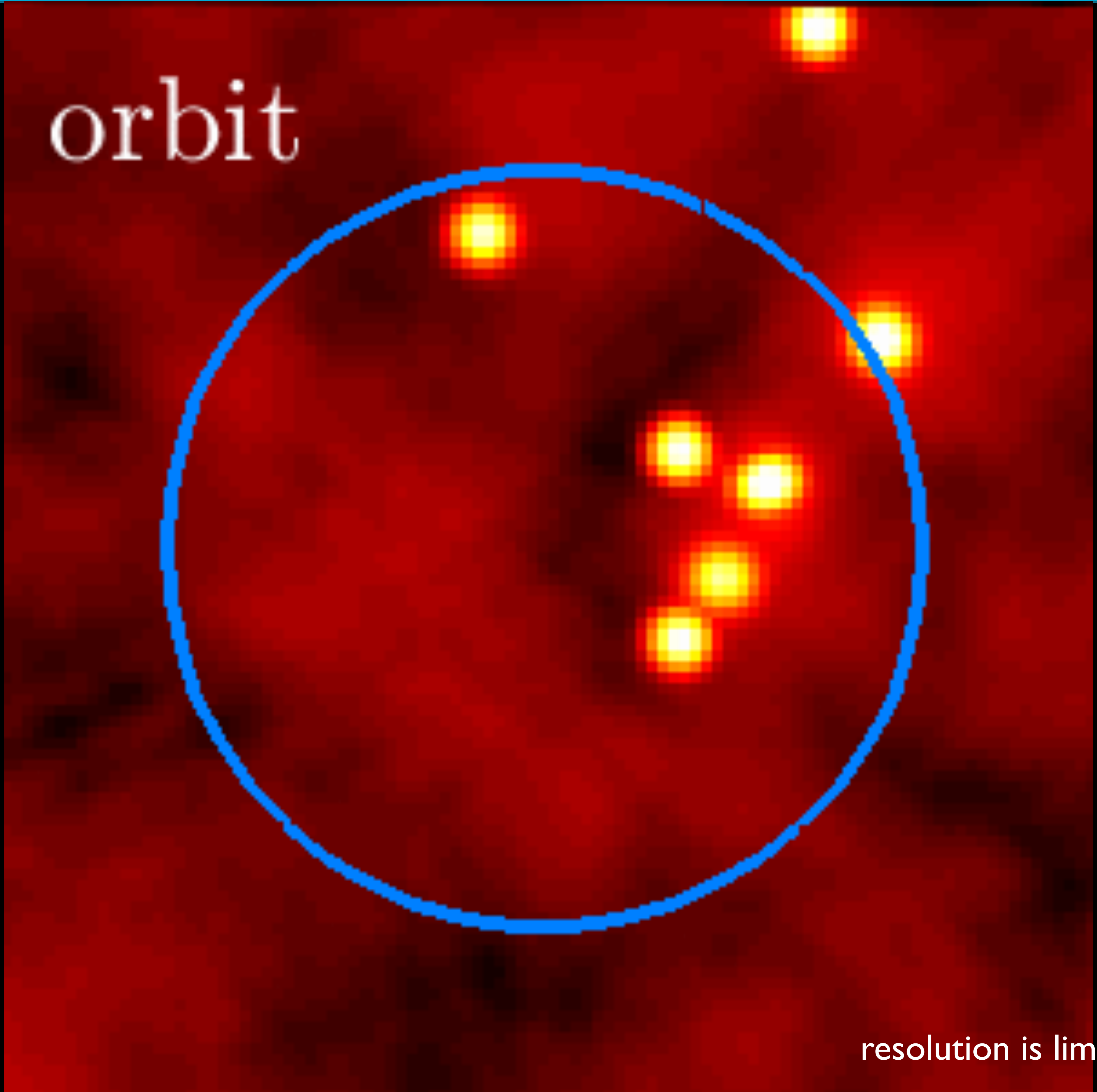


strong interactions: orbit



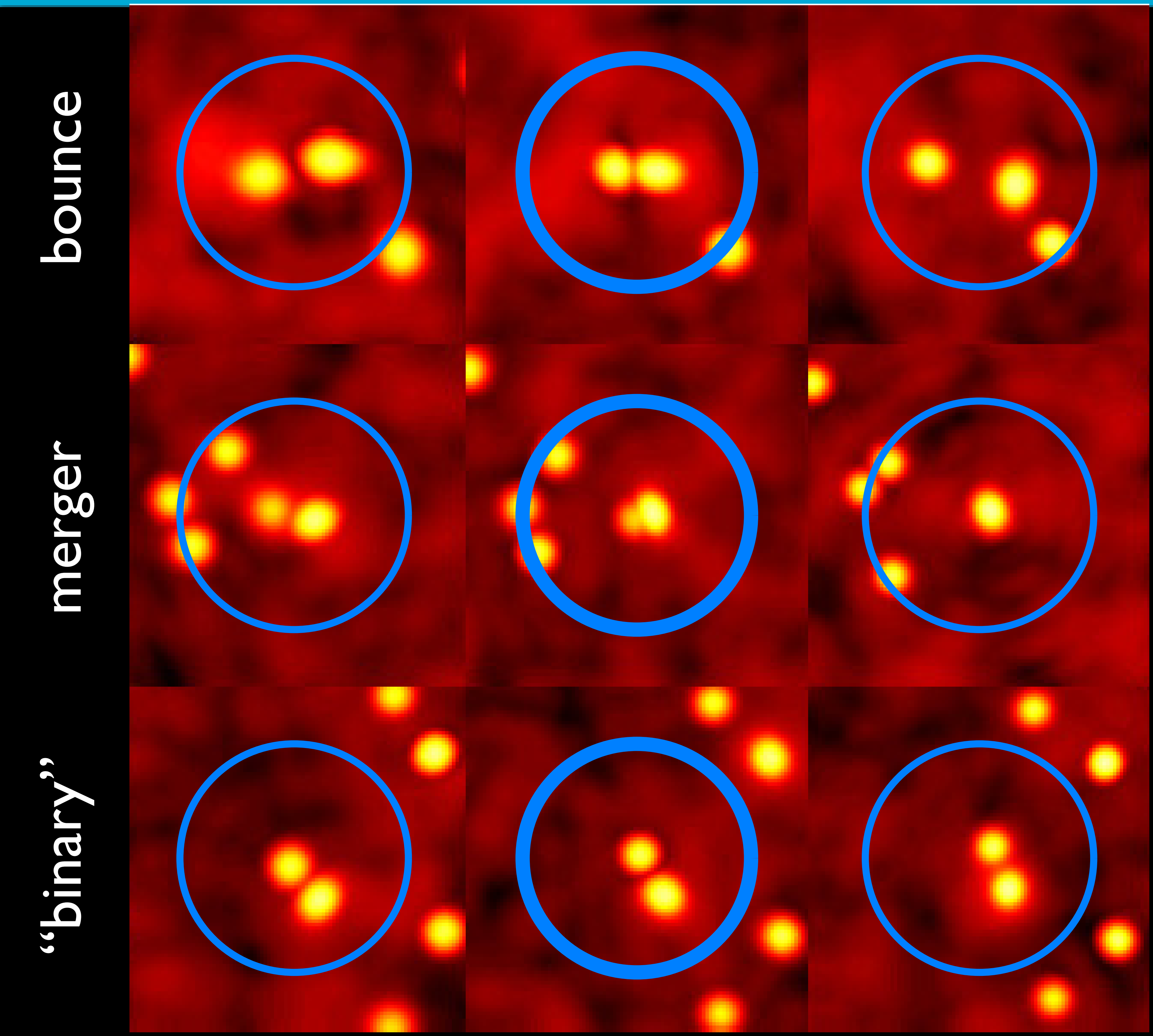
resolution is limited at late very times

strong interactions: orbit



resolution is limited at late very times

phase dependent interactions



$\phi \propto \Re[\psi]$

$\psi_a(t, \mathbf{x}) = \Psi_a(\mathbf{x}) e^{-i\nu_a t + \theta_a}$

$|\theta_1 - \theta_2| \simeq \pi$

$|\theta_1 - \theta_2| \simeq 0$

EFT of non-topological solitons
— MA & Iqbal (in progress)

+ undergrads
Anamitra Paul and Rohith Karur

observational implications

- gravitational
- non-gravitational (typically more fields needed)

observational implications

incomplete list!

- eq. of state & energy transfer after inflation ?
- stochastic gravitational wave-generation ?
- primordial black hole (PBH) formation ?

early universe

- distinguishability from “usual” dark matter ?
- additional early/late early structure formation
- sources of gravitational waves ?
- source of signature in light

late universe

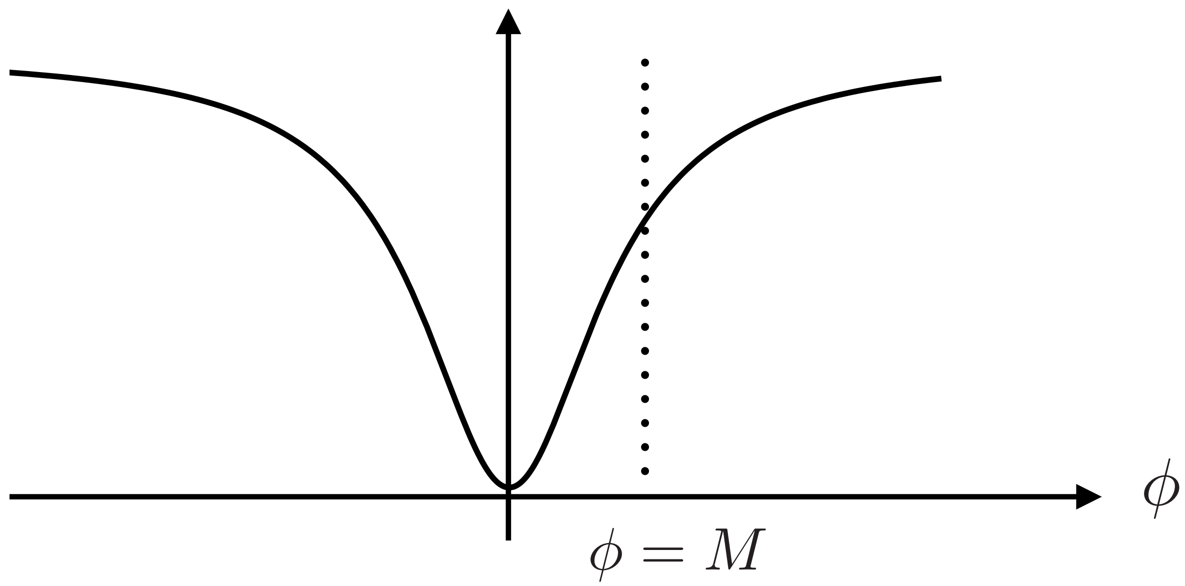
relevant scales

size of soliton $R_{\rm osc} \sim 10\, m^{-1}$

$$R_{\rm osc} \sim 10^{-10} \left(\frac{10^{-2}\,{\rm GeV}}{m}\right) {\rm cm}$$

$$R_{\rm osc} \sim \left(\frac{10^{-14}\,{\rm eV}}{m}\right) R_\odot$$

$$V(\phi) = \frac{1}{2} m^2 \phi^2 + V_{\rm nl}(\phi)$$



mass of soliton $M_{\rm osc} \sim 100 \frac{M^2}{m}$

$$M_{\rm osc} \sim 10 \left(\frac{M}{10^{12}\,{\rm GeV}}\right)^2 \left(\frac{10^{-2}{\rm GeV}}{m}\right) {\rm kg}$$

$$M_{\rm osc} \sim \left(\frac{M}{10^{16}\,{\rm GeV}}\right)^2 \left(\frac{10^{-14}{\rm eV}}{m}\right) M_\odot$$

*numbers are different when held together by gravity instead of self interactions

exploring soliton collisions with full numerical GR

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

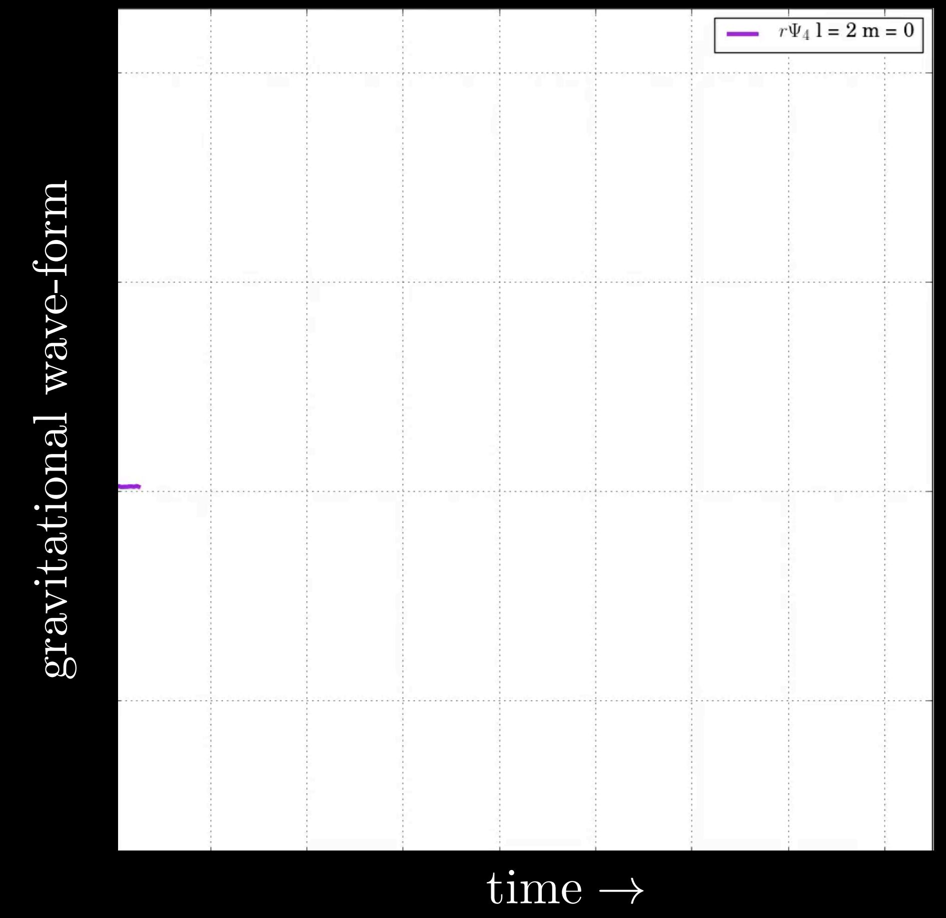
$$V(\phi) = \frac{1}{2}m^2\phi^2 + \cancel{V_{\rm nl}(\phi)}$$

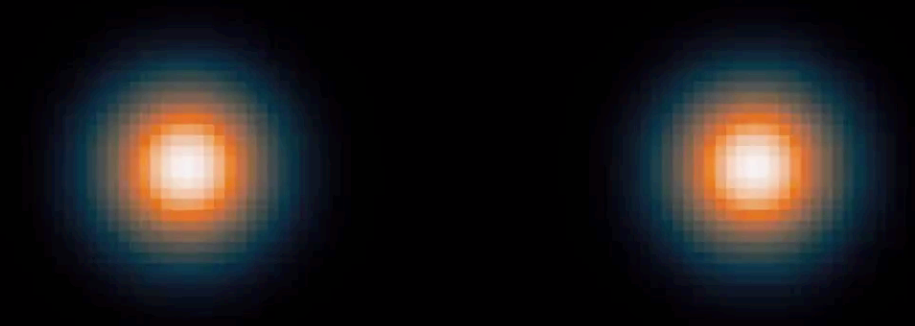
ignore self-interactions

interested in gravitational wave emission from ultra-compact solitons

Helfer, Lim, Garcia & MA (2018)

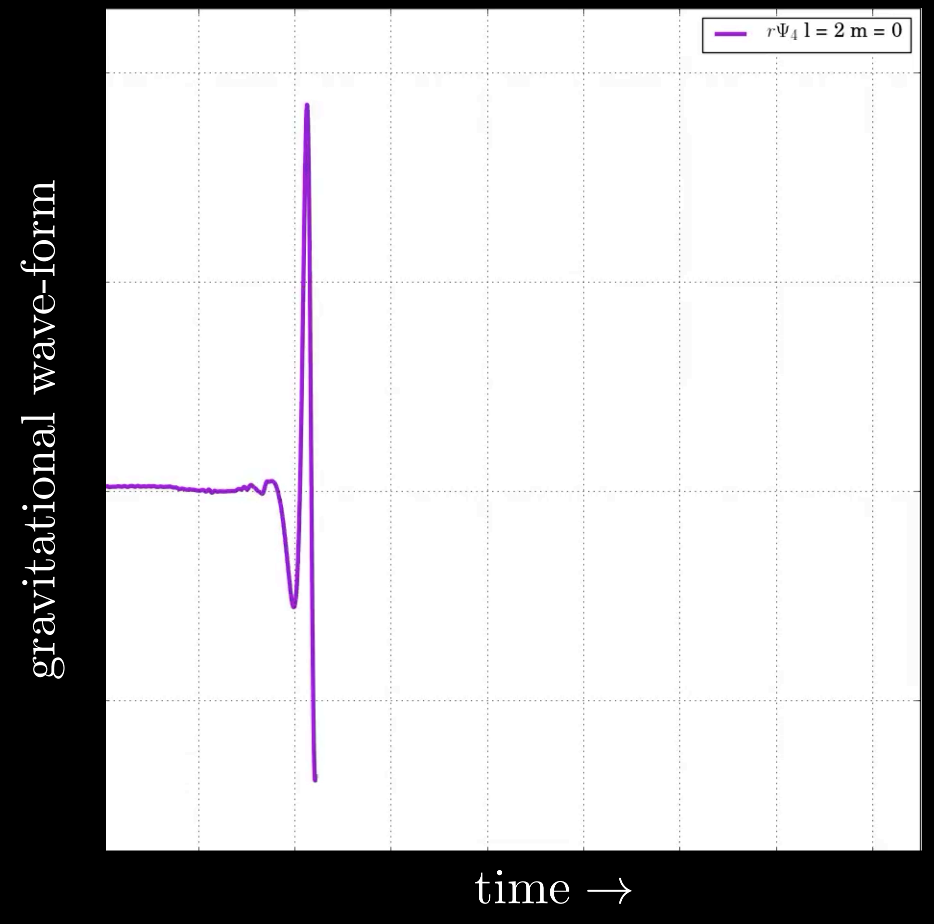
sub-critical collisions (no black hole formation)





using GRChombo

sub-critical collisions (no black hole formation)



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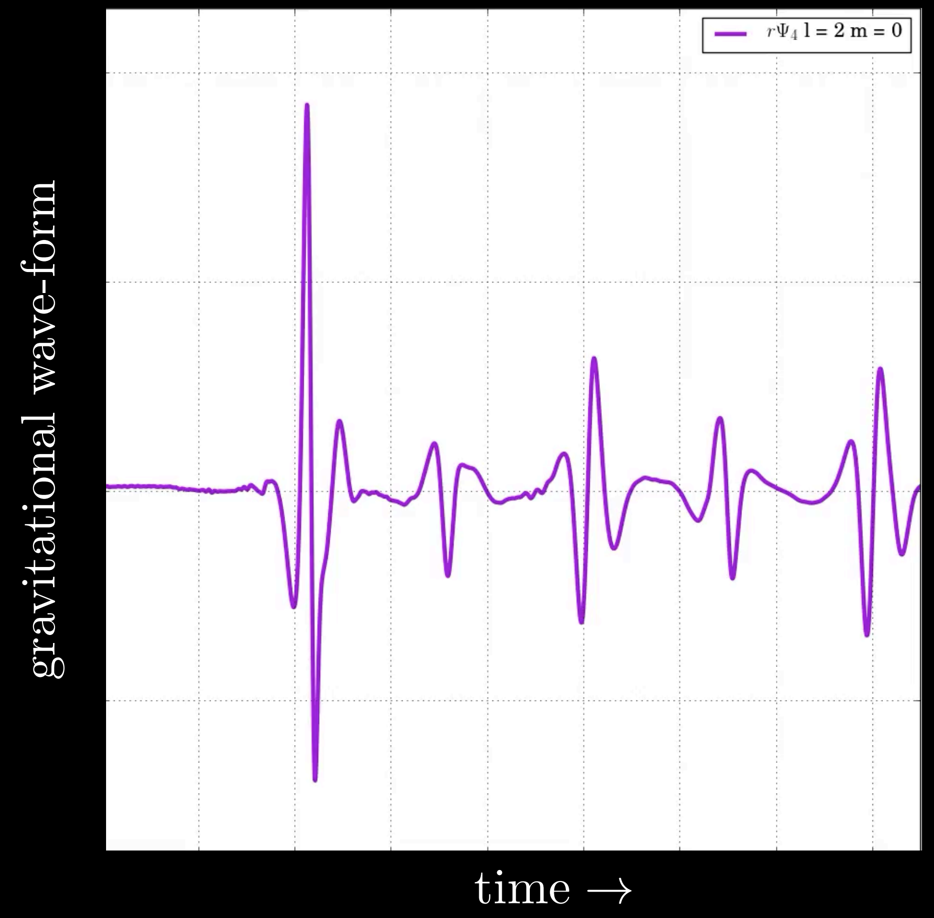
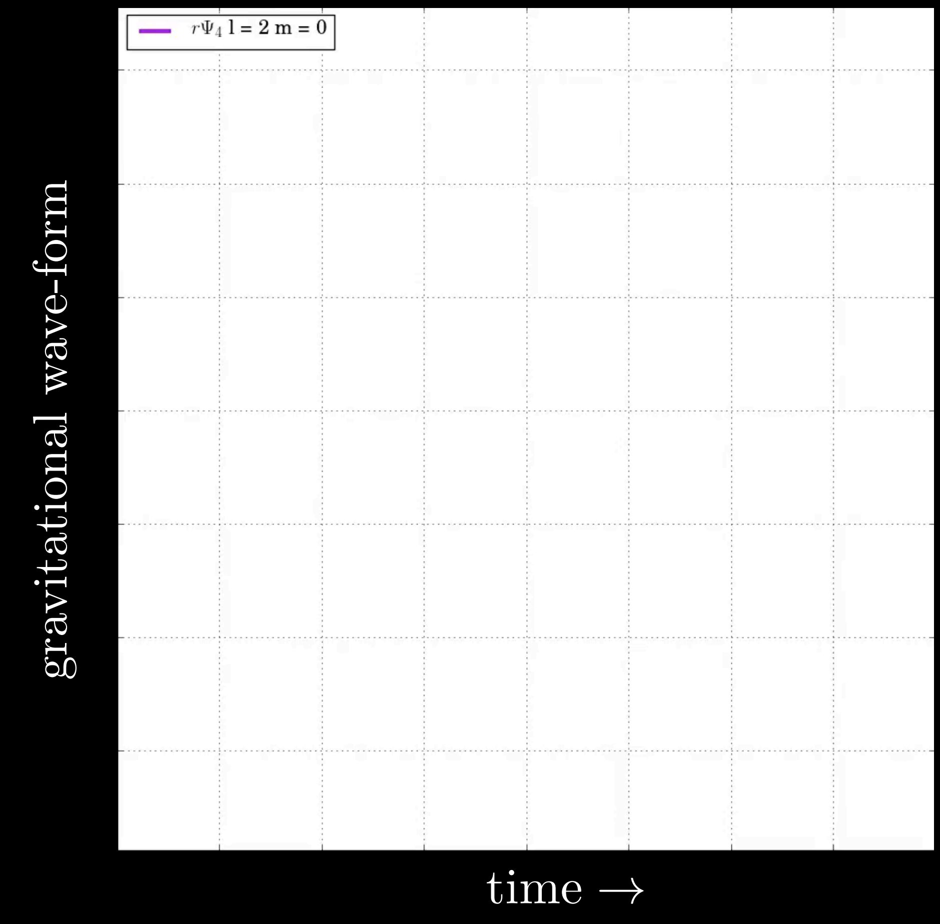
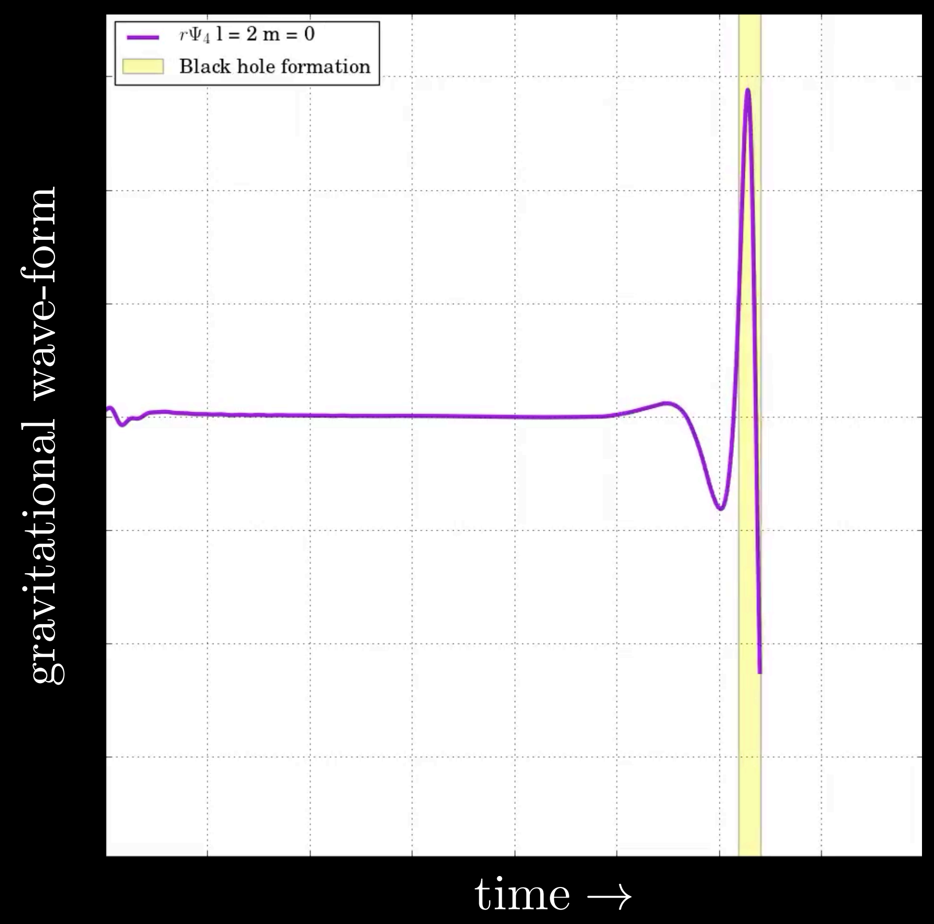


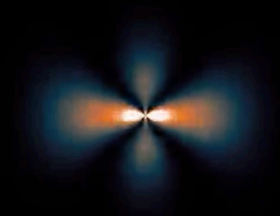
using GRChombo

critical collisions (black-hole formation after collision)



critical collisions
(black-hole formation after collision)





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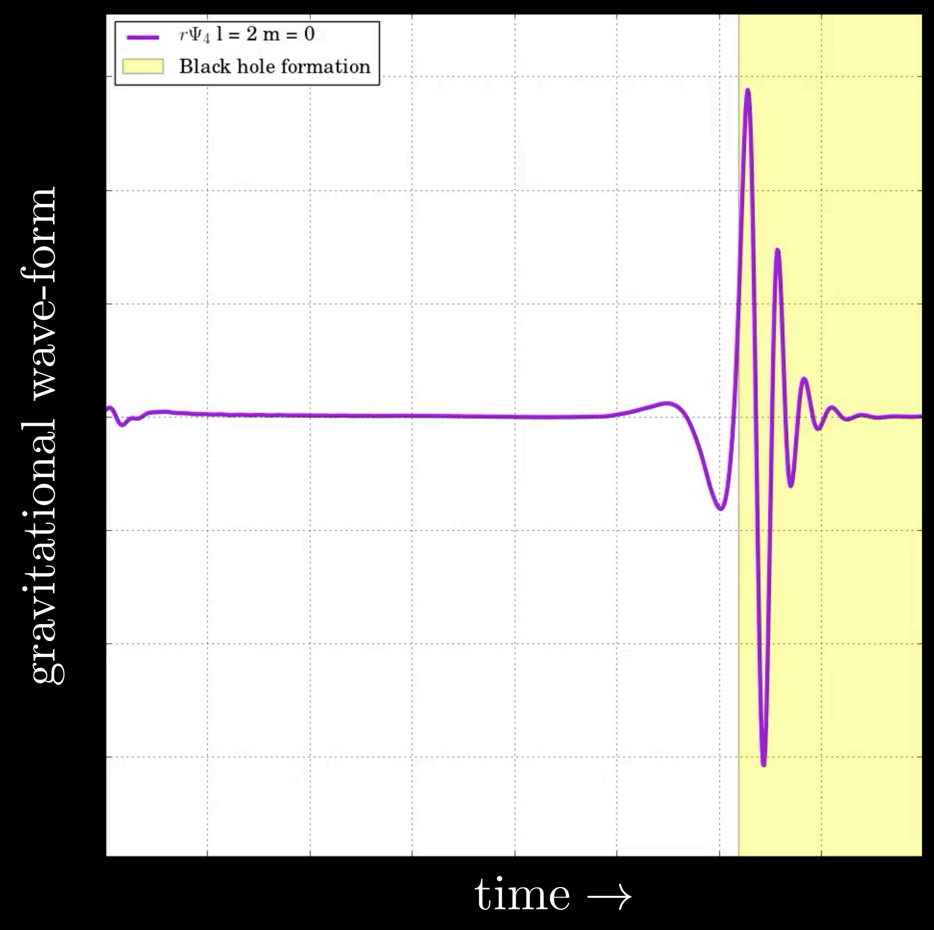
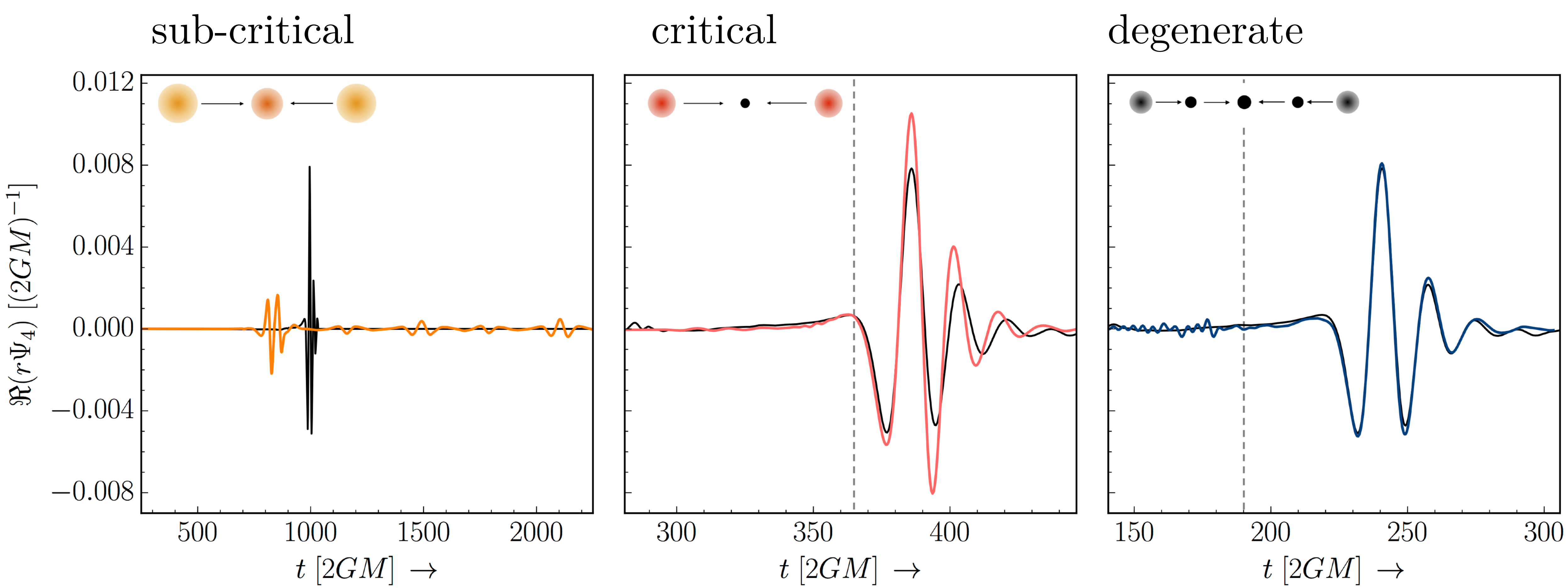


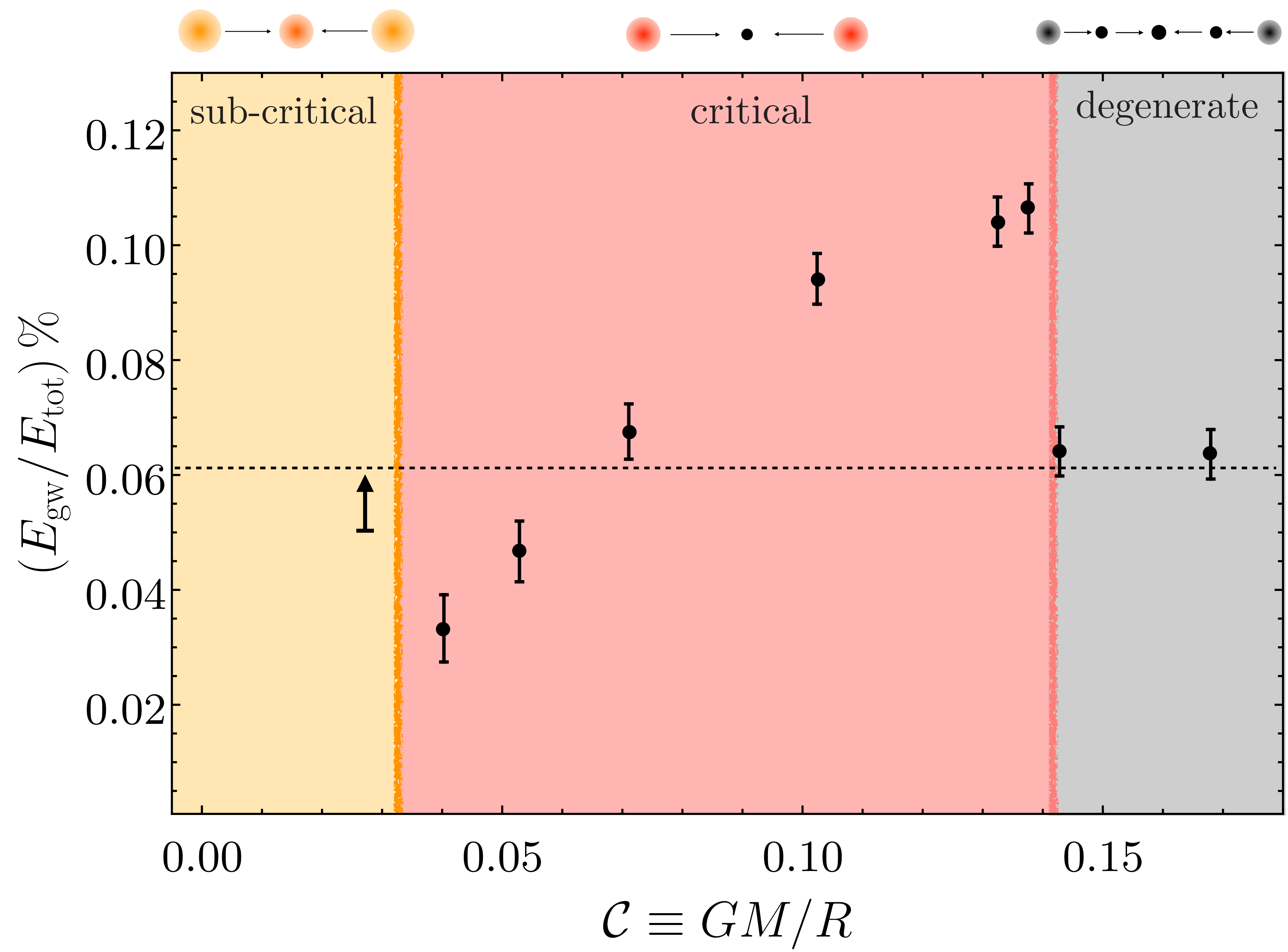
implications

gravitational waves from ultra-compact soliton collisions



black = corresponding mass black hole g-wave signal implications

more energy in g-waves than corresponding mass BHs



important caveats/questions

- how likely are these ultra-compact solitons to form and collide ?
- head-on collisions: inspirals might change the answers
- distinguishability?

electromagnetic bursts from oscillon mergers?

WORK IN PROGRESS

$$S = \int d^4x \left[-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \right]$$

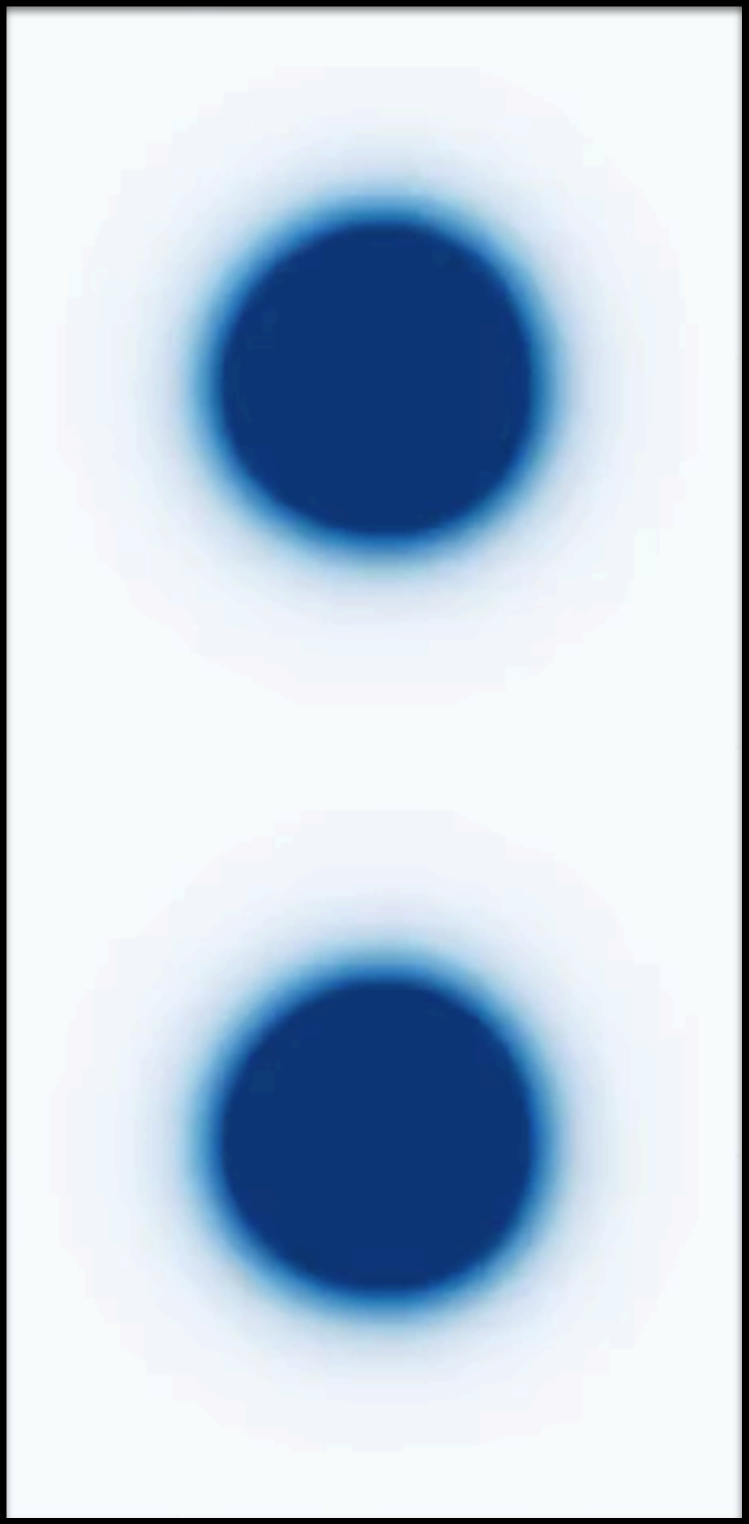
$$V(\phi) = \frac{1}{2}m^2\phi^2 + V_{\rm nl}(\phi)$$

interested in electromagnetic wave emission from merger of oscillons [we ignore gravity]

* for the idea in a non-relativistic, non-interacting context with analytic estimates
* see Tkachev (2014, for FRBs), Hertzberg & Schiappacasse (2018), Hertzberg et. al (2020)

electromagnetic bursts from mergers

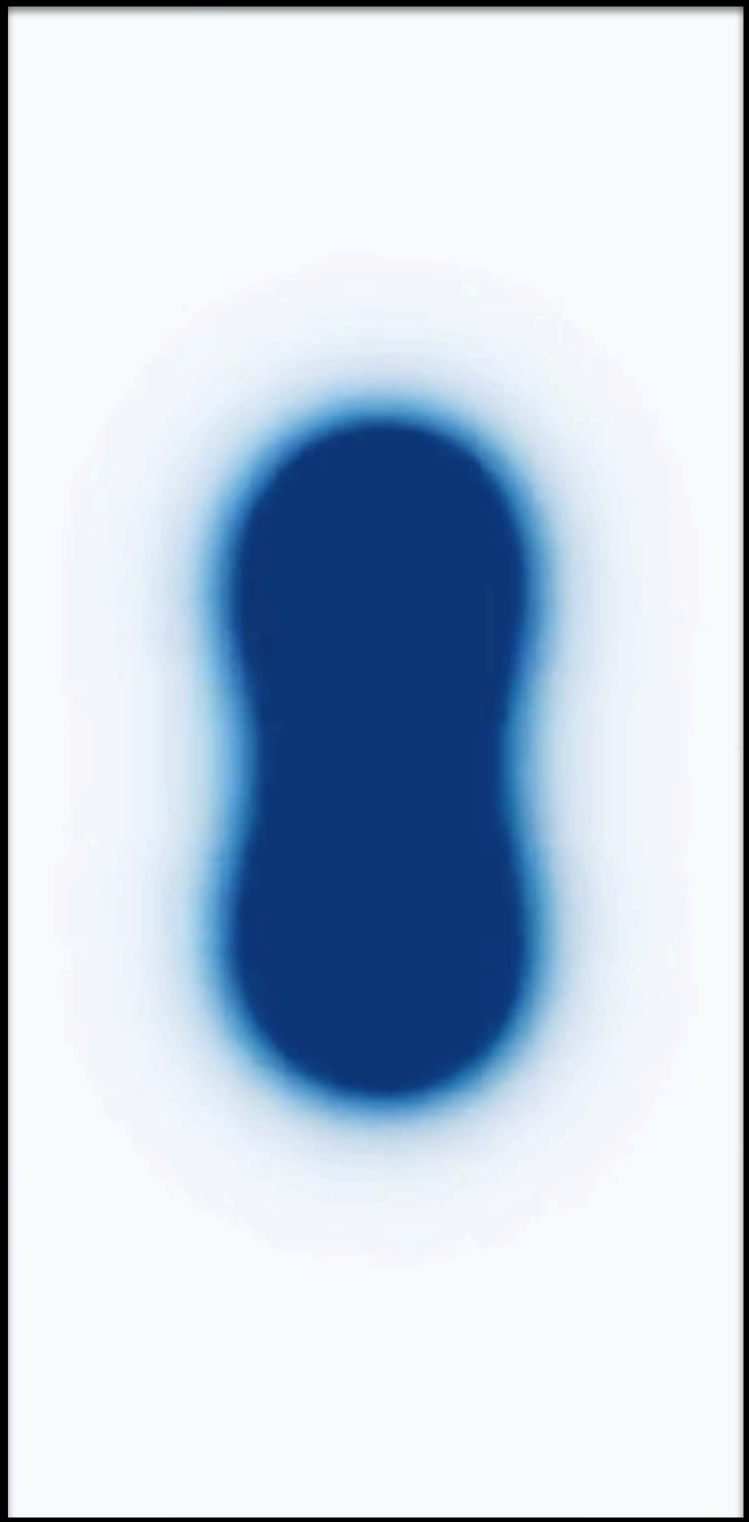
WORK IN PROGRESS



MA & Mou (in progress)

electromagnetic bursts from mergers

WORK IN PROGRESS



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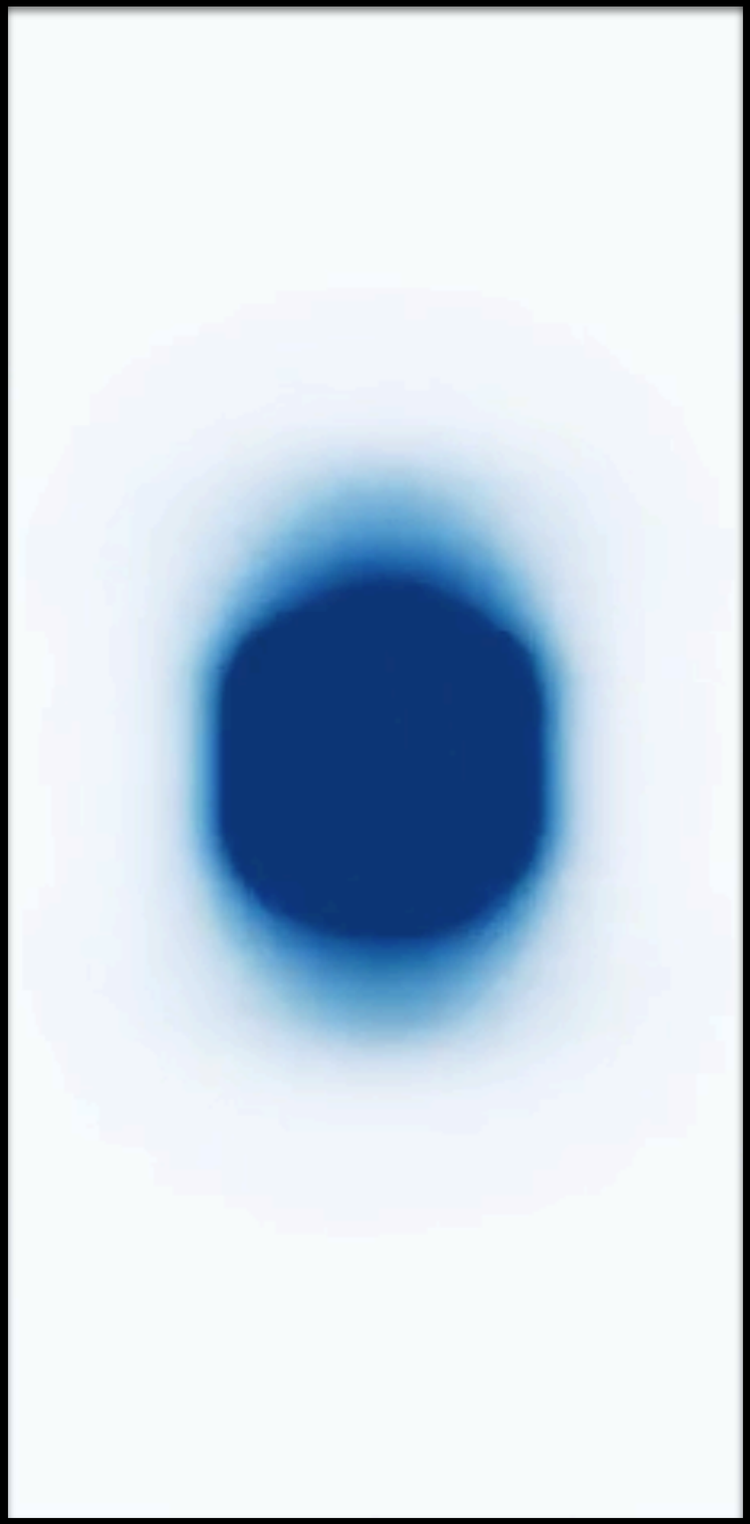
WORK IN PROGRESS



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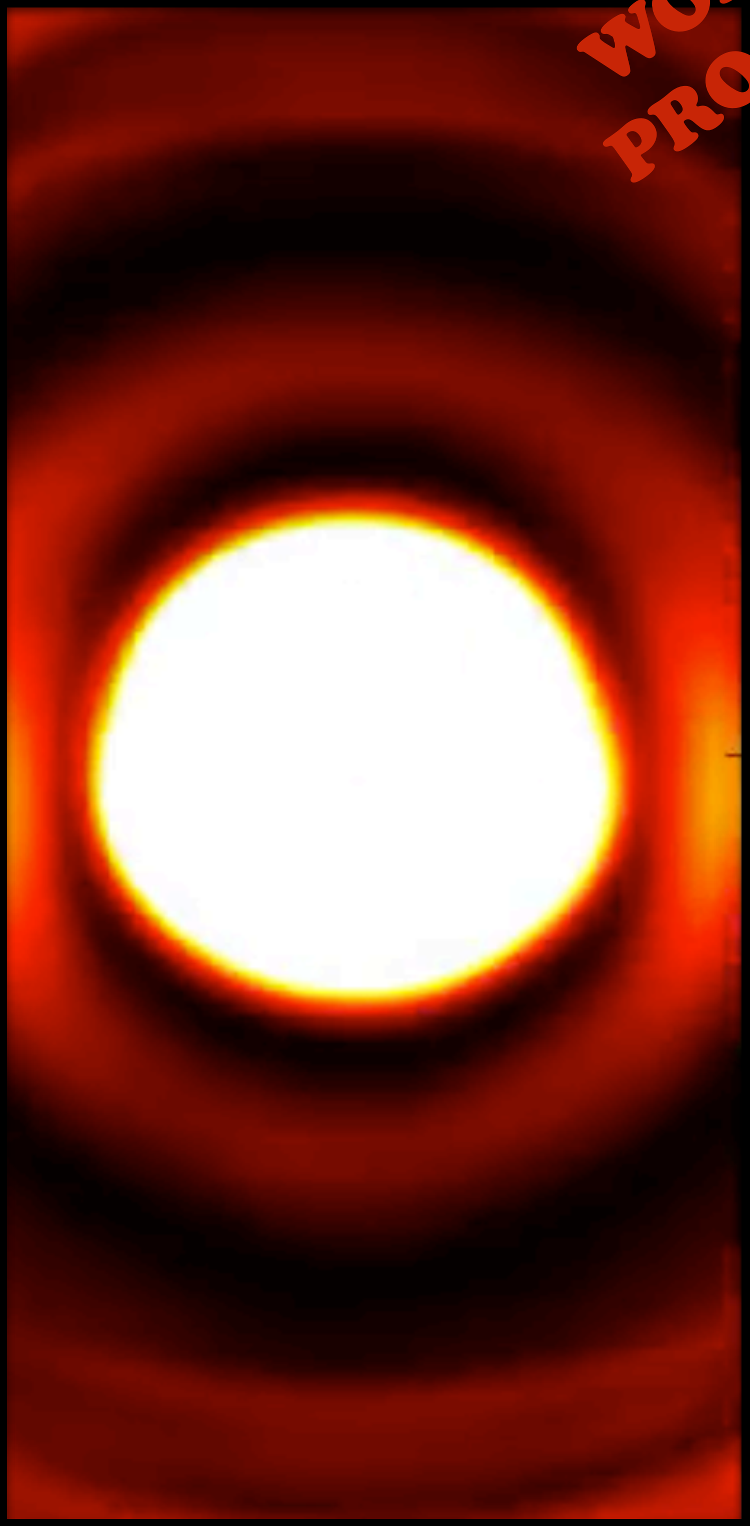

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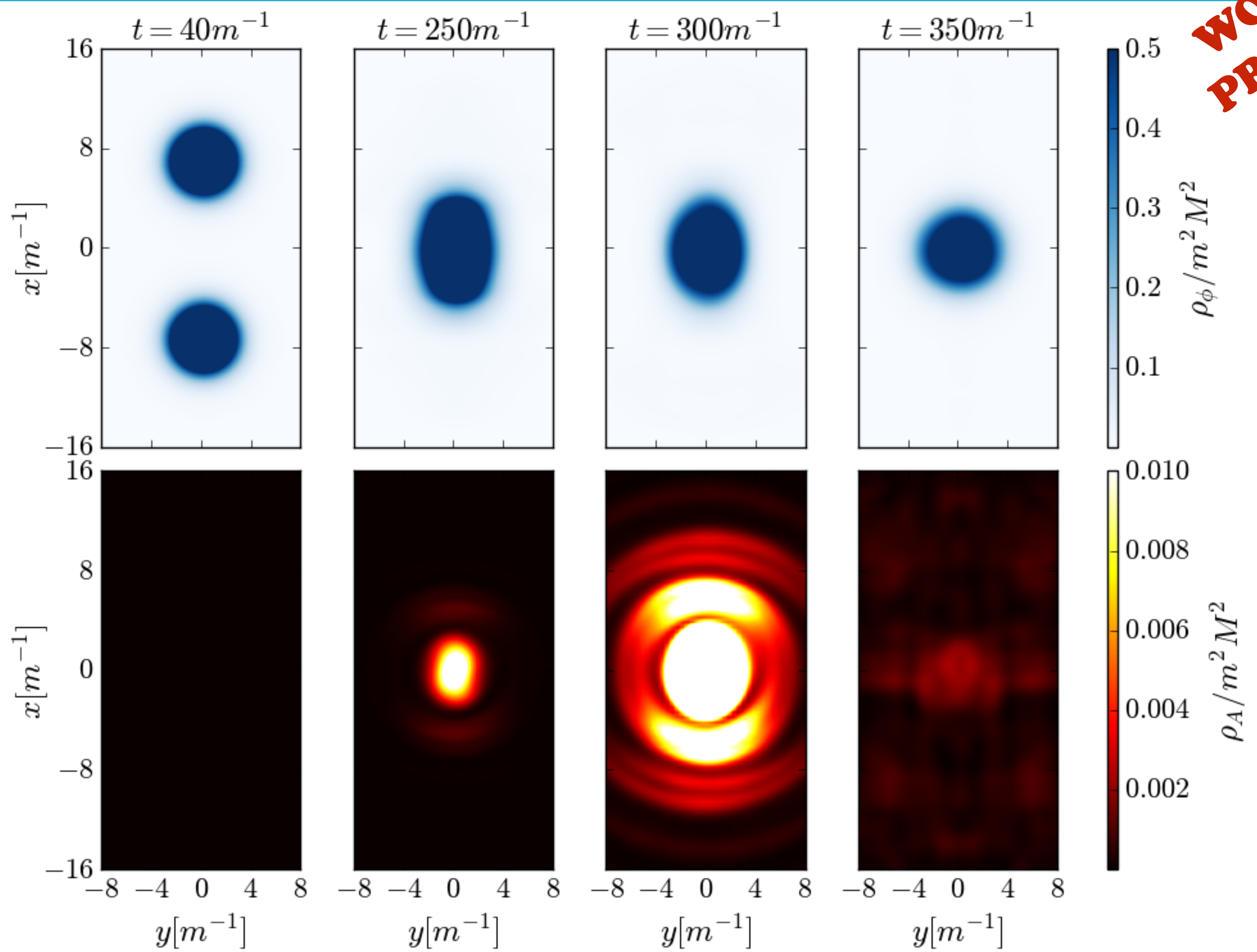
WORK IN PROGRESS



important elements

WORK IN PROGRESS

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

*assumption about axion-photon coupling $g_{a\gamma} \sim 1/M$

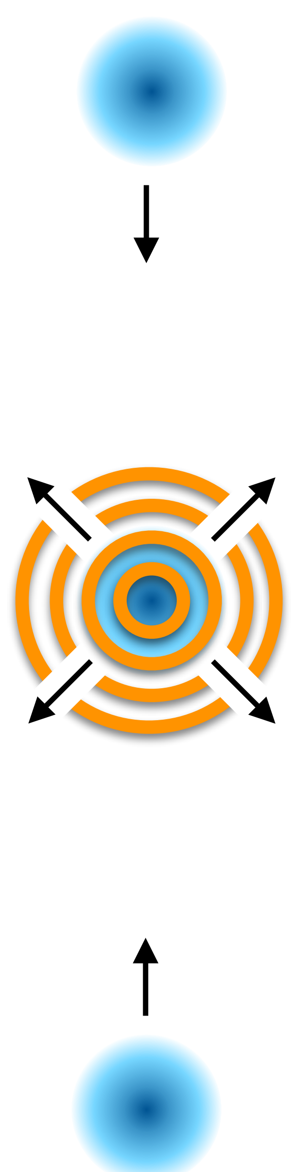
some numbers

WORK IN PROGRESS

energy emitted ?

$$E_\gamma \sim 0.1 \times M_{\rm osc} c^2$$

$$\sim 10^{36} \left(\frac{M}{10^{12}\,\mathrm{GeV}}\right)^2 \left(\frac{10^{-2}\mathrm{eV}}{m}\right) \mathrm{GeV}$$



frequency ?

$$\omega_\gamma \sim m$$

$$\sim 10^4 \left(\frac{m}{10^{-2}\mathrm{eV}}\right) \mathrm{GHz}$$

*choice of numbers is partly related to making these axions dark matter

caveats

WORK IN PROGRESS

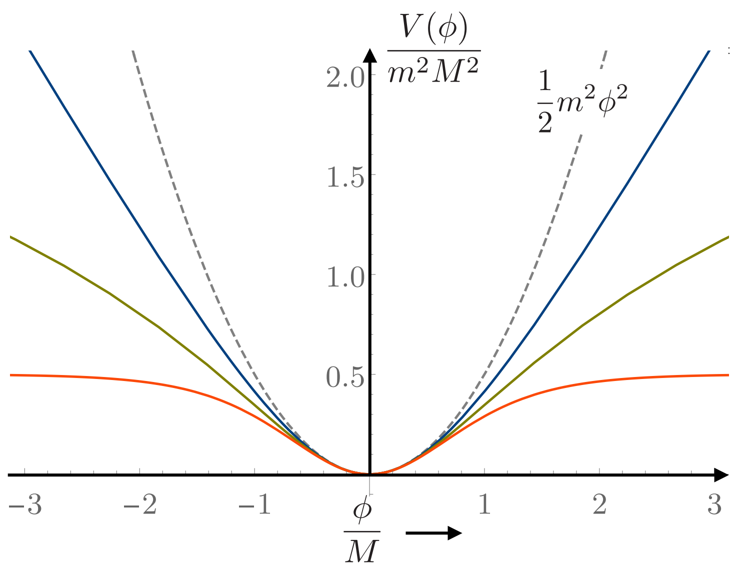
$$\Gamma \sim \mathcal{O}(1) \left(\frac{f_{\rm osc}}{10^{-2}}\right)^2 \left(\frac{10^{12}\,\mathrm{GeV}}{M}\right)^4 \left[1 + 10^{-6}\left(\frac{M}{10^{12}\,\mathrm{GeV}}\right)^2\right] \frac{\text{collisions}}{\text{galaxy year}}\,.$$

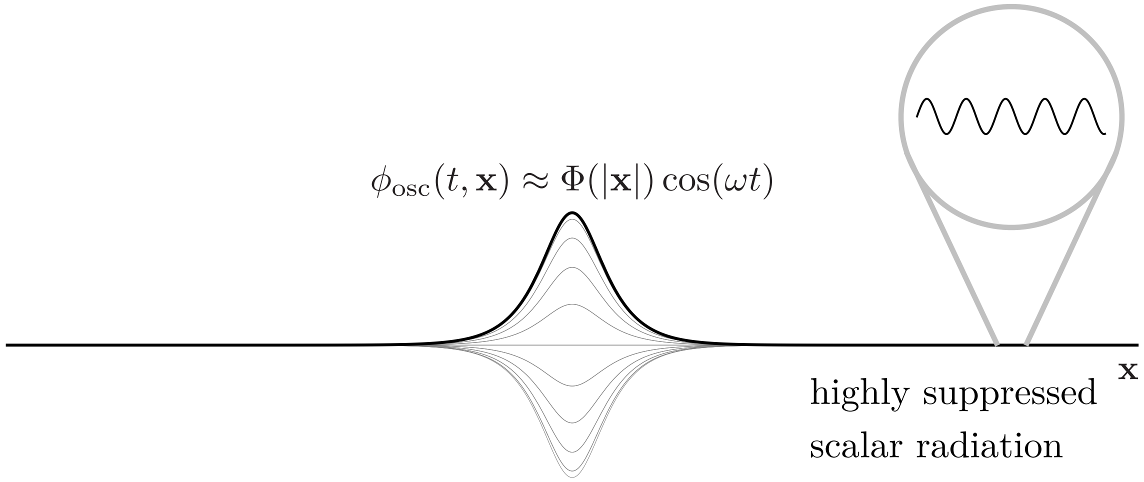
- merger rates? (collision rate > one/per yr/galaxy!)
- detailed history of formation, abundance/ distribution in a galaxy?
- off-axis, in-spirals, different phases etc.
- lifetimes of solitons with strong self-interactions
- axion-photon coupling? $g_{a\gamma} \sim M^{-1}$

Classical Decay Rates of Oscillons

Hong-Yi Zhang, Mustafa A. Amin, Edmund J. Copeland, Paul M. Saffin, Kaloian D. Lozanov

arXiv: 2004.01202

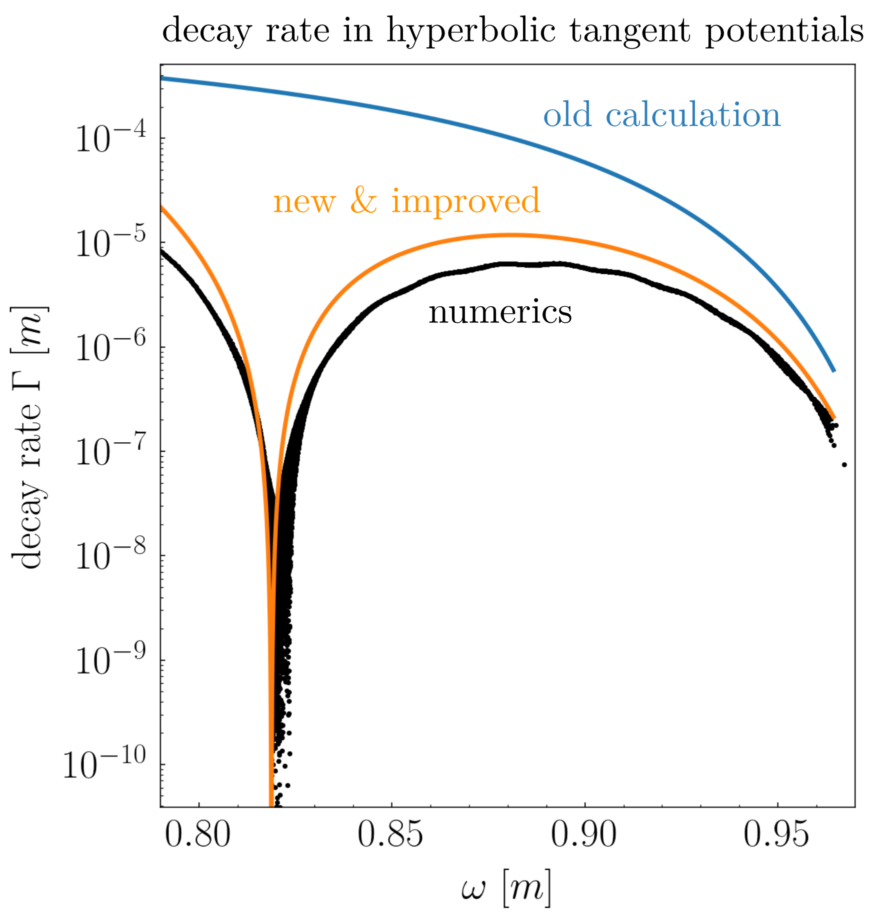




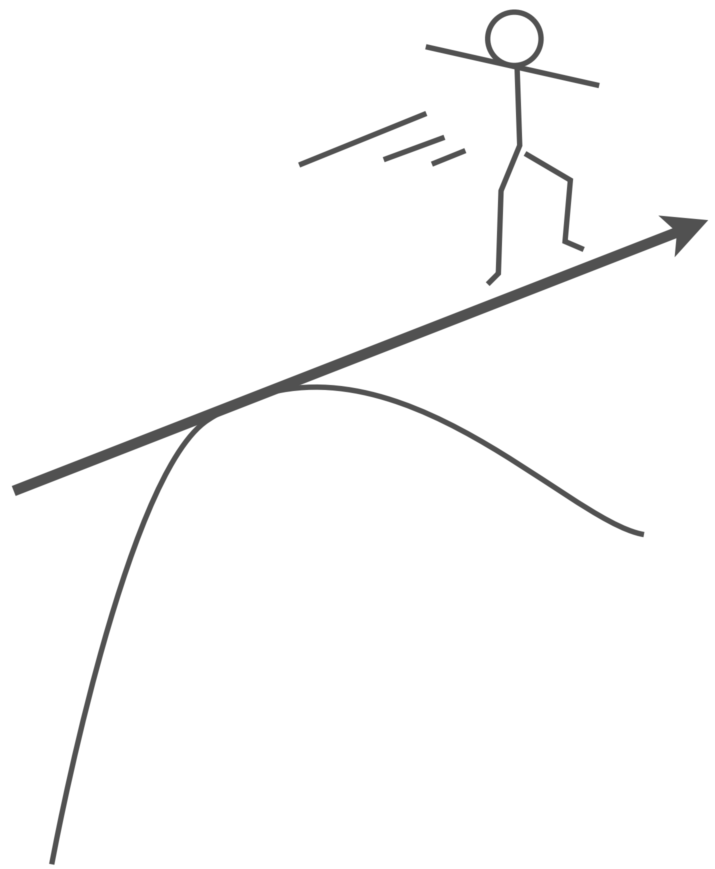
- decay rates for **large amplitude oscillons**

key improvement:
systematically including a spacetime-dependent effective mass term in the radiation calculation.

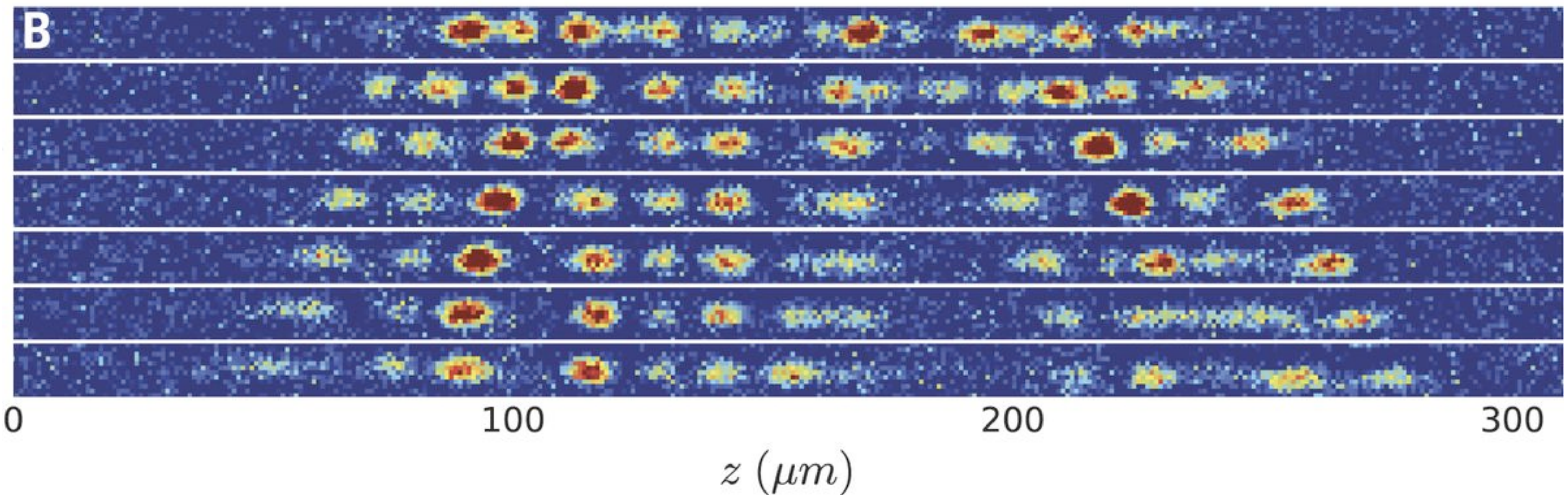
Capable of capturing **non-trivial features** at large amplitudes



tangential digression



related solitons in BECs



Nguyen, Luo & Hulet (2017)

nonlinear Klein Gordon — nonlinear Schrodinger eq.

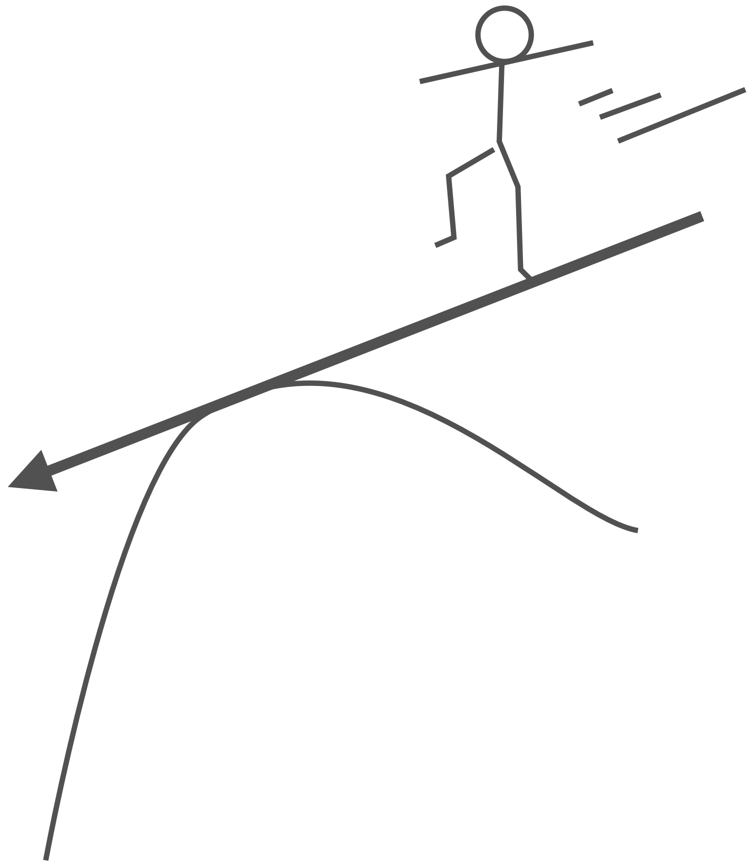
$$\partial_t^2\phi - c^2\nabla^2\phi + \partial_\phi V(\phi) = 0$$

$$\partial_t^2\varphi - c_\mathrm{s}^2\nabla^2\varphi + \partial_\varphi \mathcal{V}(\varphi) = 0 \qquad \longleftrightarrow \qquad i\partial_t\psi = \left[-\frac{1}{2m}\nabla^2 + U'(|\psi|^2)\right]\psi$$

relative phase between different condensates

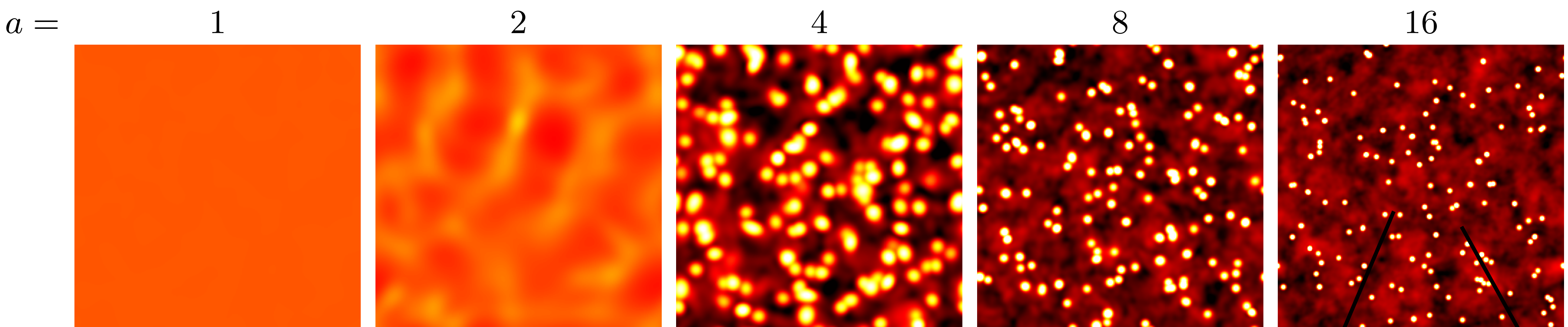
non-relativistic

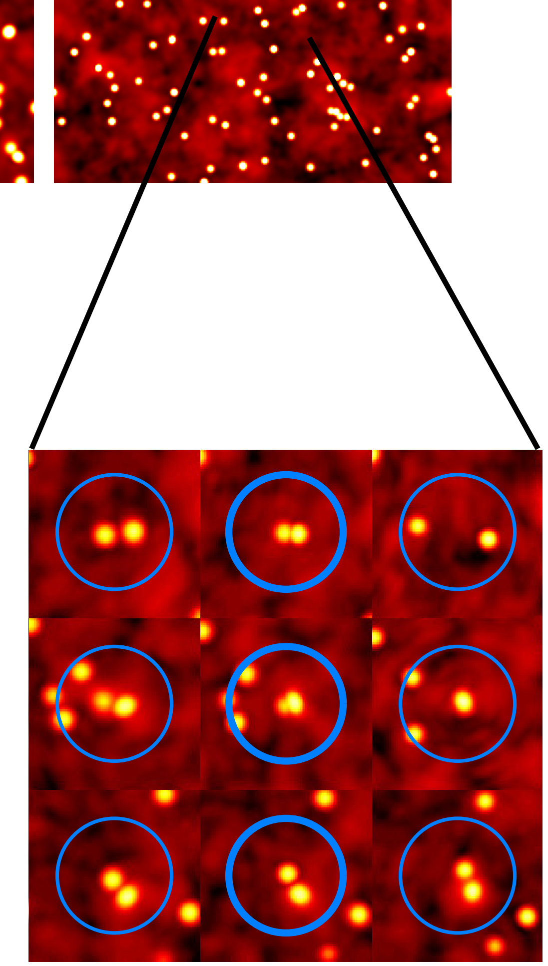
end tangential digression



summary

	self-interaction instability	soliton formation	gravitational clustering	some late-time strong interactions

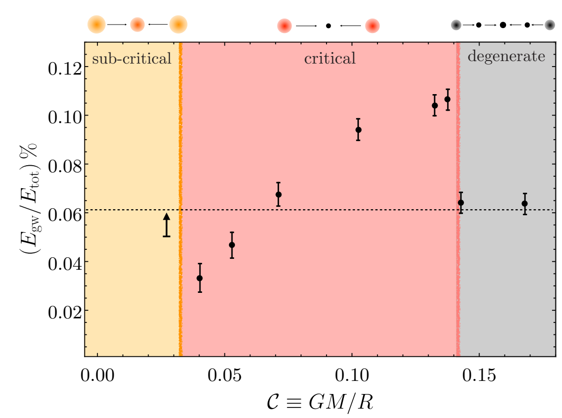


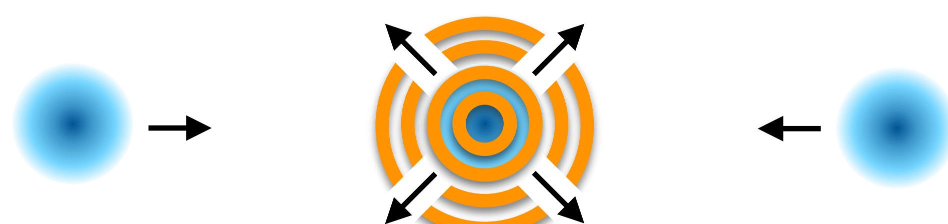


time

implications:

- gravitational waves
- small scale clustering
- EM Bursts ?





thanks !

thanks!