Title: Lumps and bumps in the early universe

Date: Nov 09, 2010 02:00 PM

URL: http://pirsa.org/10110050

Abstract: I will discuss the emergence of large, localized, pseudo-stable configurations (oscillons) from inflaton fragmentation at the end of inflation. Remarkably, the emergent oscillons take up >50 per cent of the energy density of the inflaton. First, I will give an overview of oscillons, provide some analytic solutions and discuss their stability. Then, I will discuss the conditions necessary for their emergence and provide estimates for their cosmological number density. I will show results from detailed 3+1-dimensional numerical simulations and compare them to the analytic estimates. Finally, I discuss possible observational consequences of oscillons in the early universe.

LUMPS AND BUMPS IN THE EARLY UNIVERSE

1) 1002.3380 PHYS. REV. D, (WITH D. SHIROKOFF)
2) 1006.3075 ACCEPTED PHYS REV D. (MA)
3) 1009.2505 ACCEPTED JCAP (MA, EASTHER AND FINKEL)

MUSTAFA AMIN (MIT)

SUPPORTED BY A PAPPALARDO FELLOWSHIP

9.11.2010

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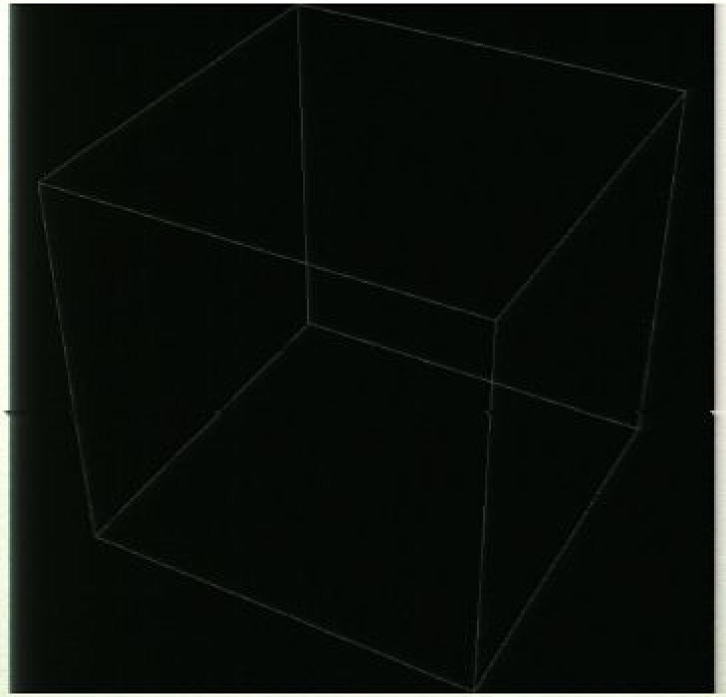

- inflaton fragmentation into pseudo-solitons: **oscillons**
- populating the universe after inflation : **reheating**

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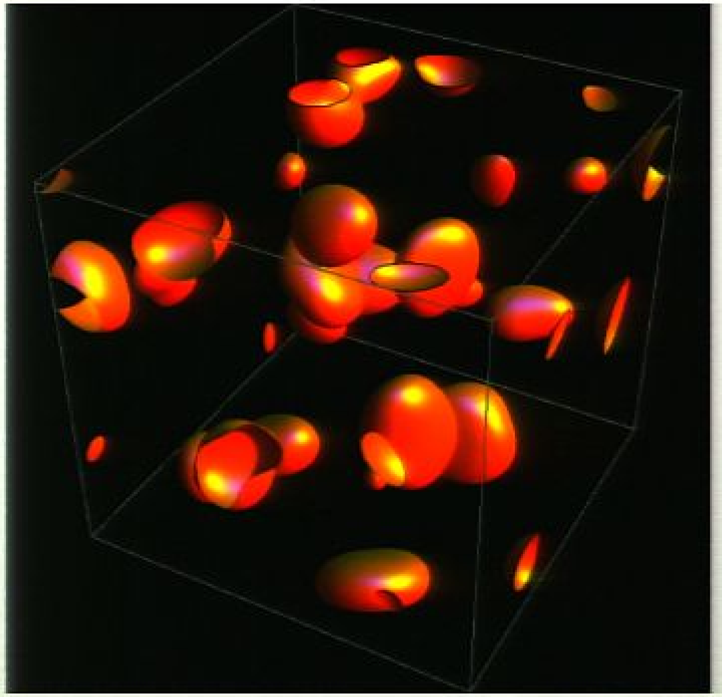

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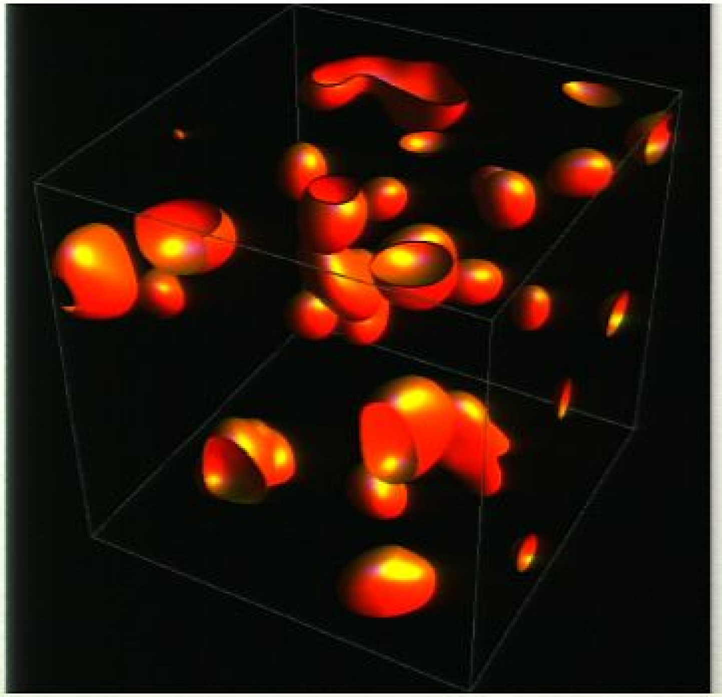

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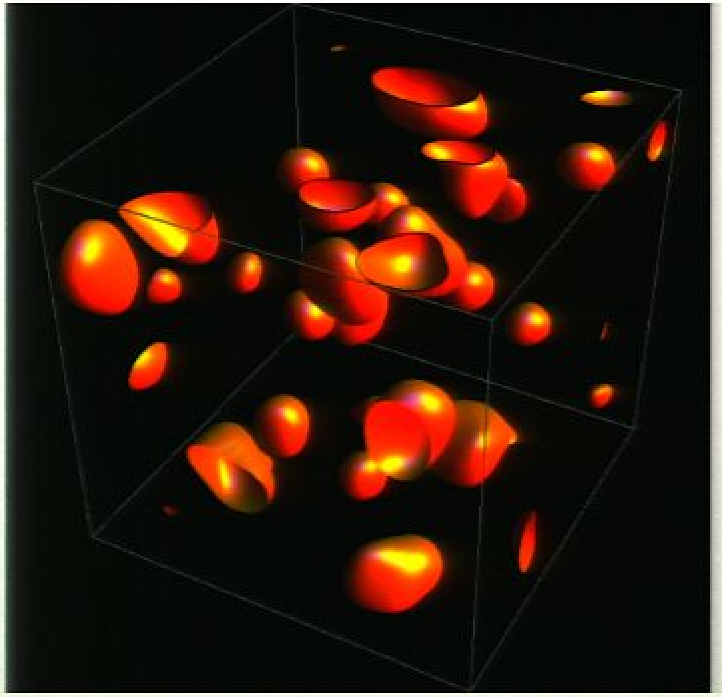

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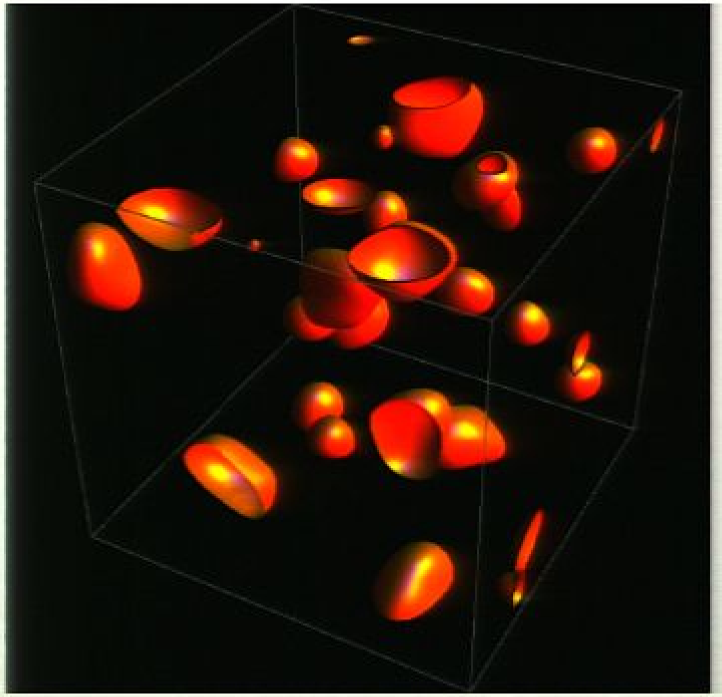

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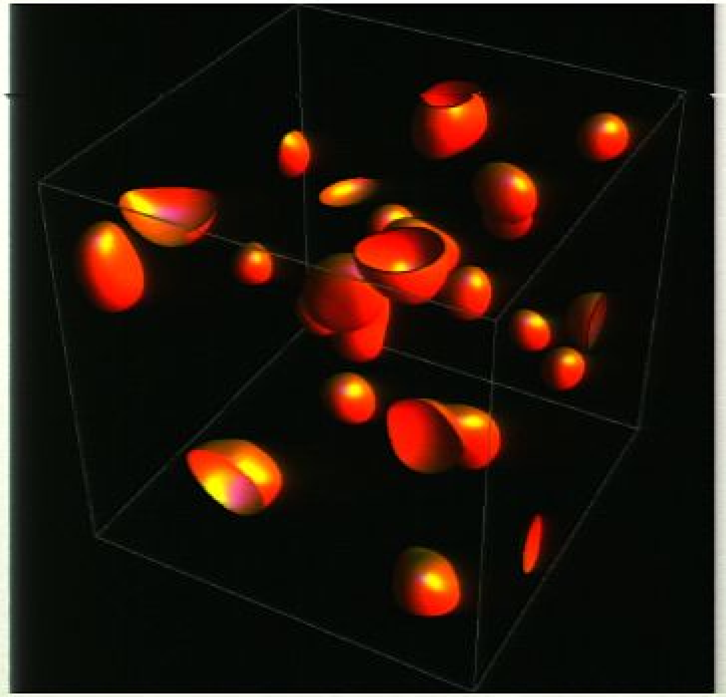

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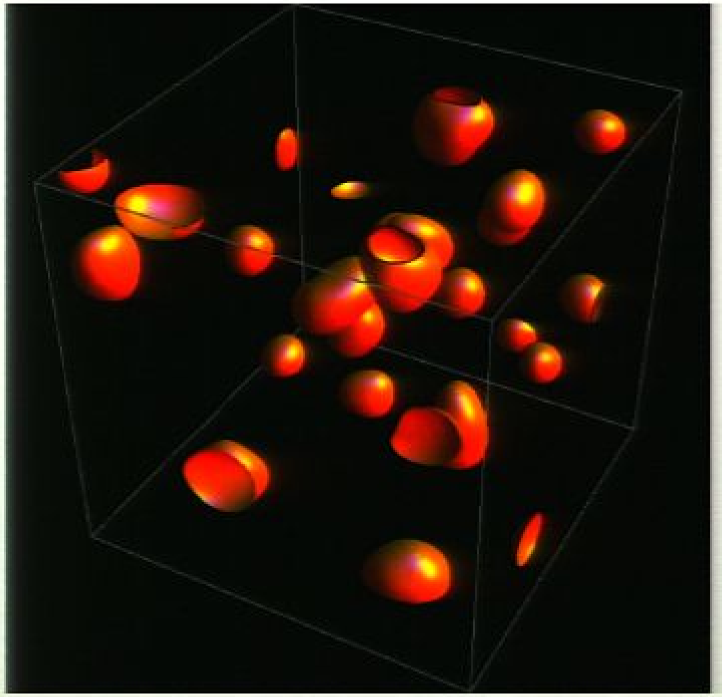

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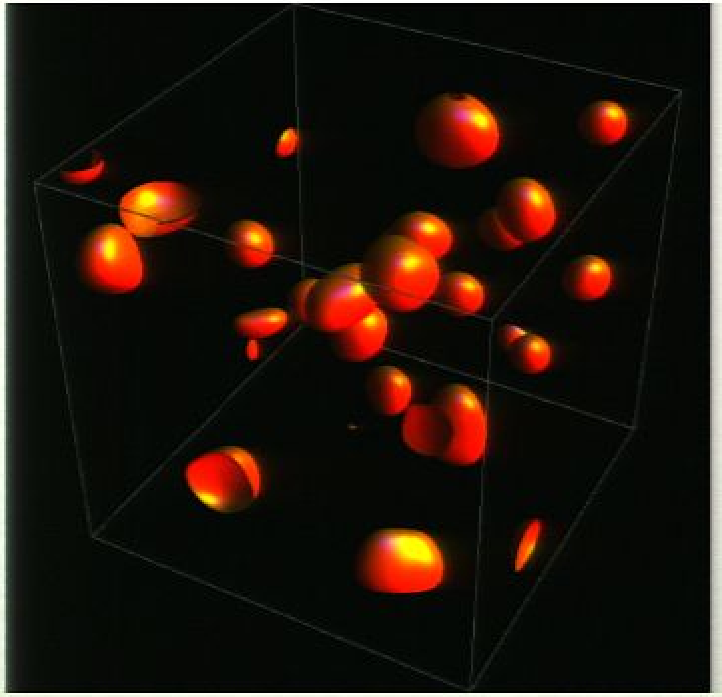

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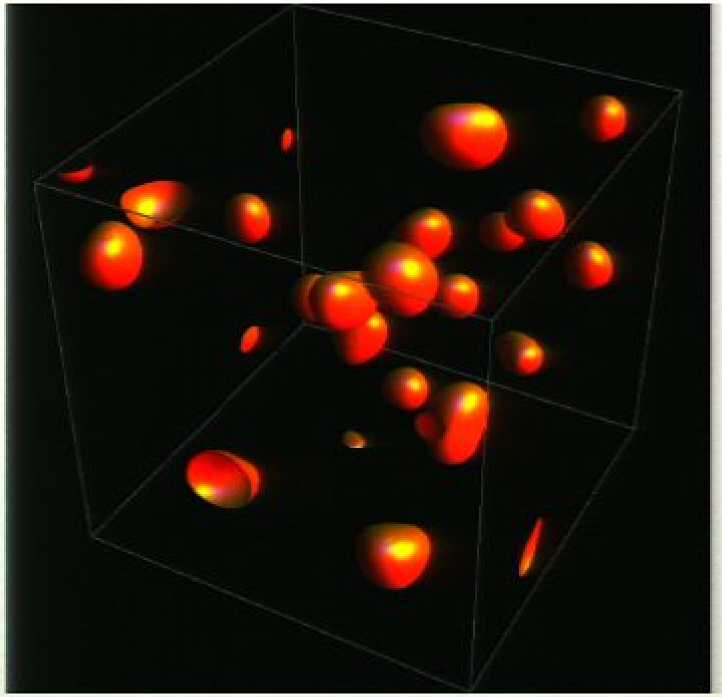

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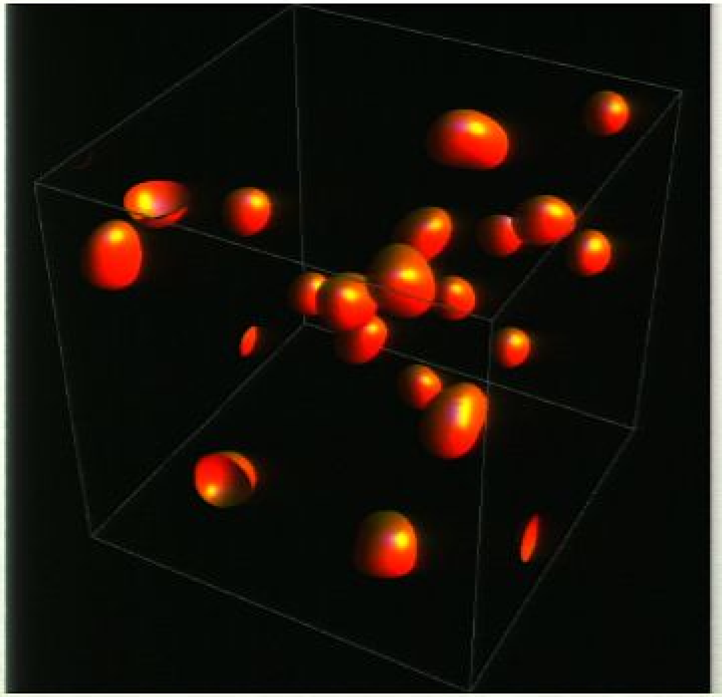

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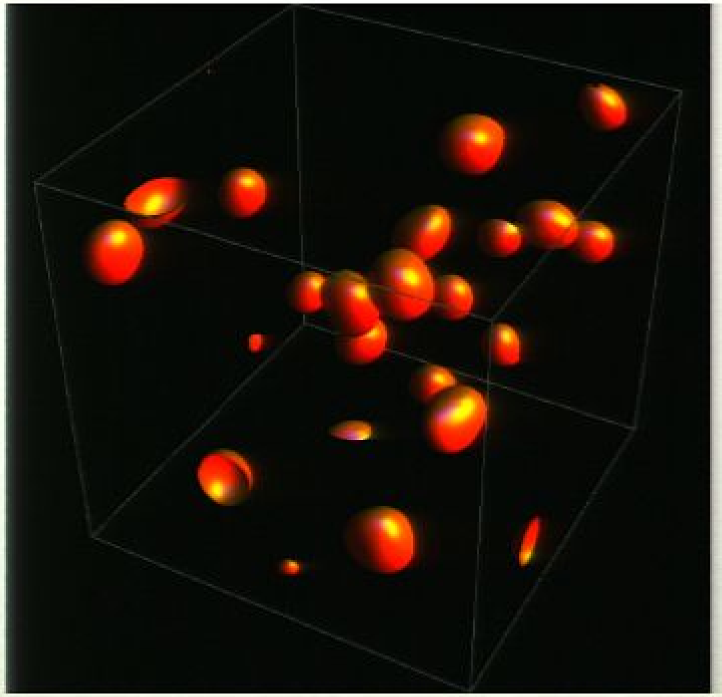

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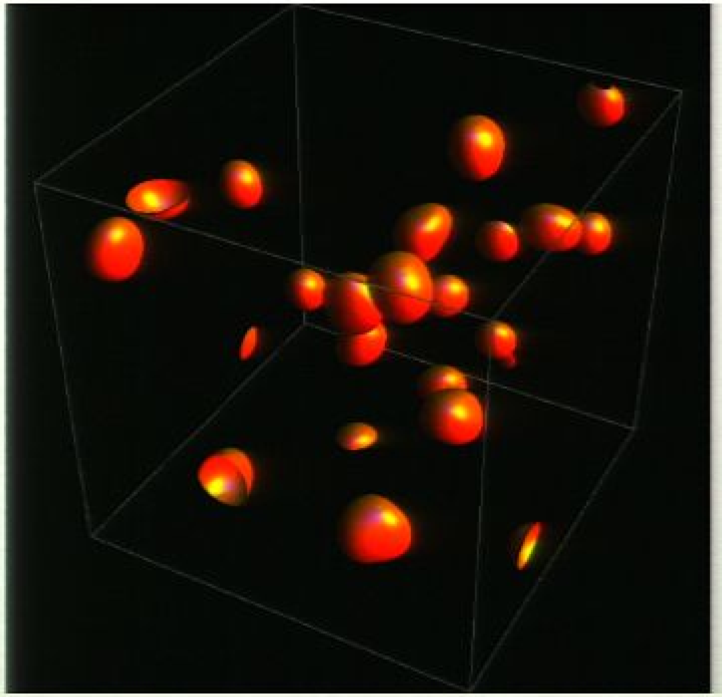

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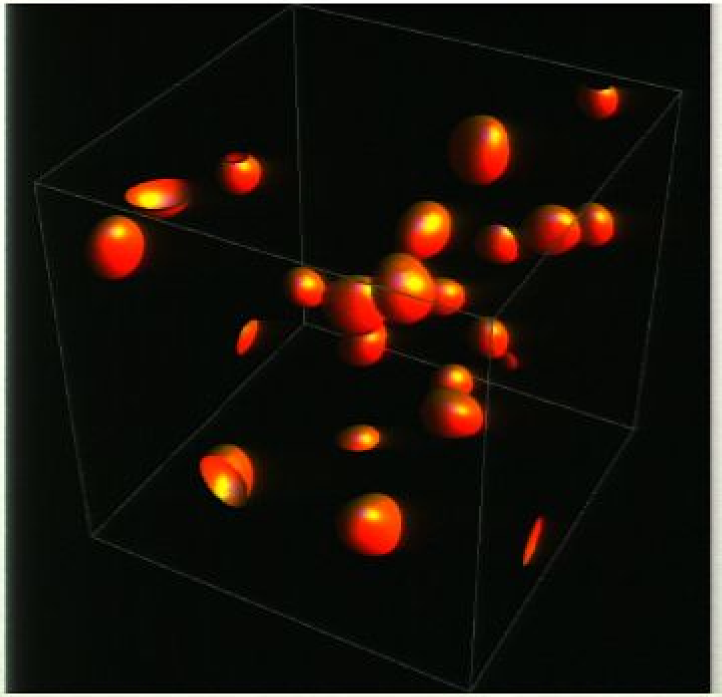

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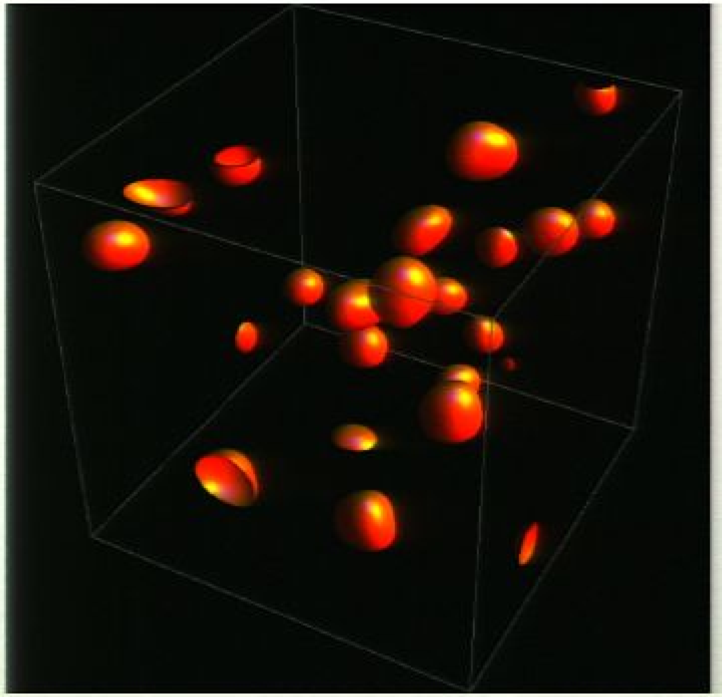

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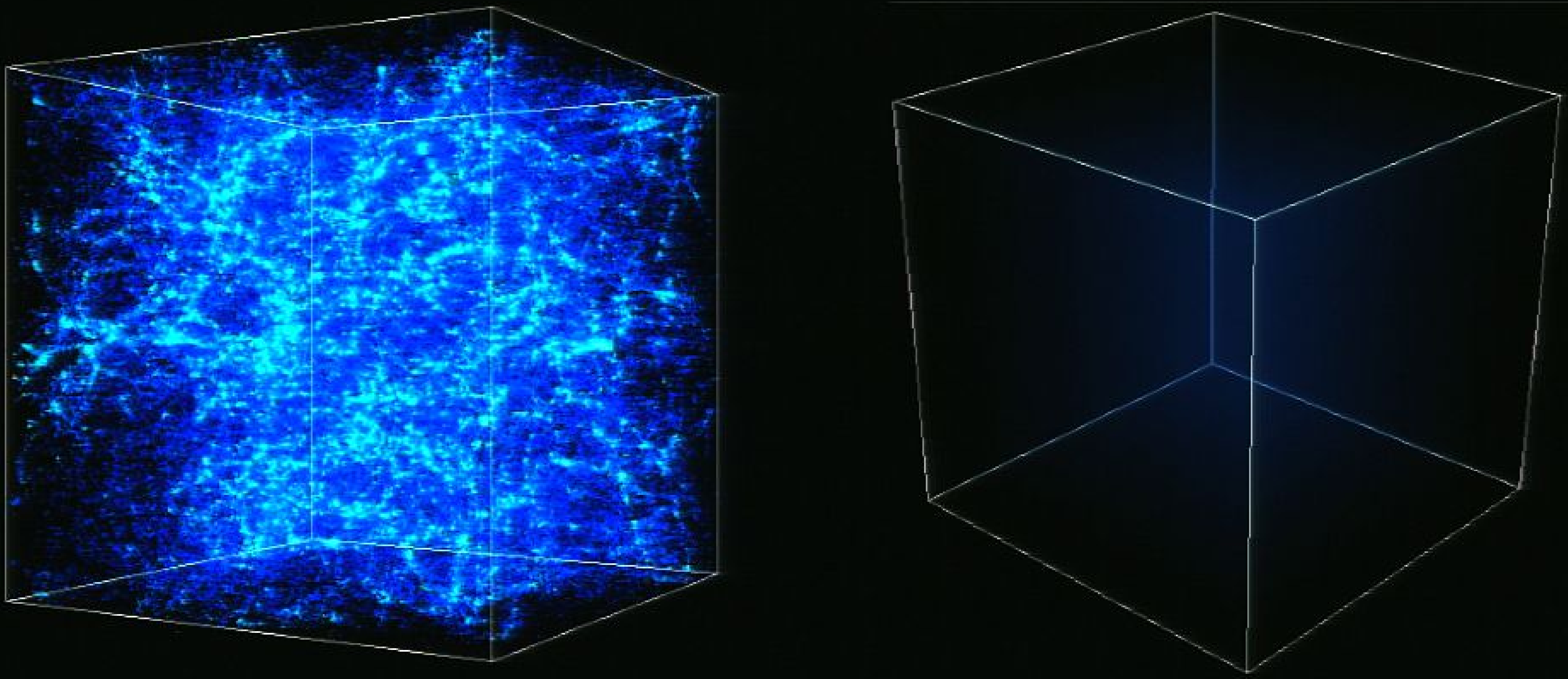
Structure formation

$$z < 100$$



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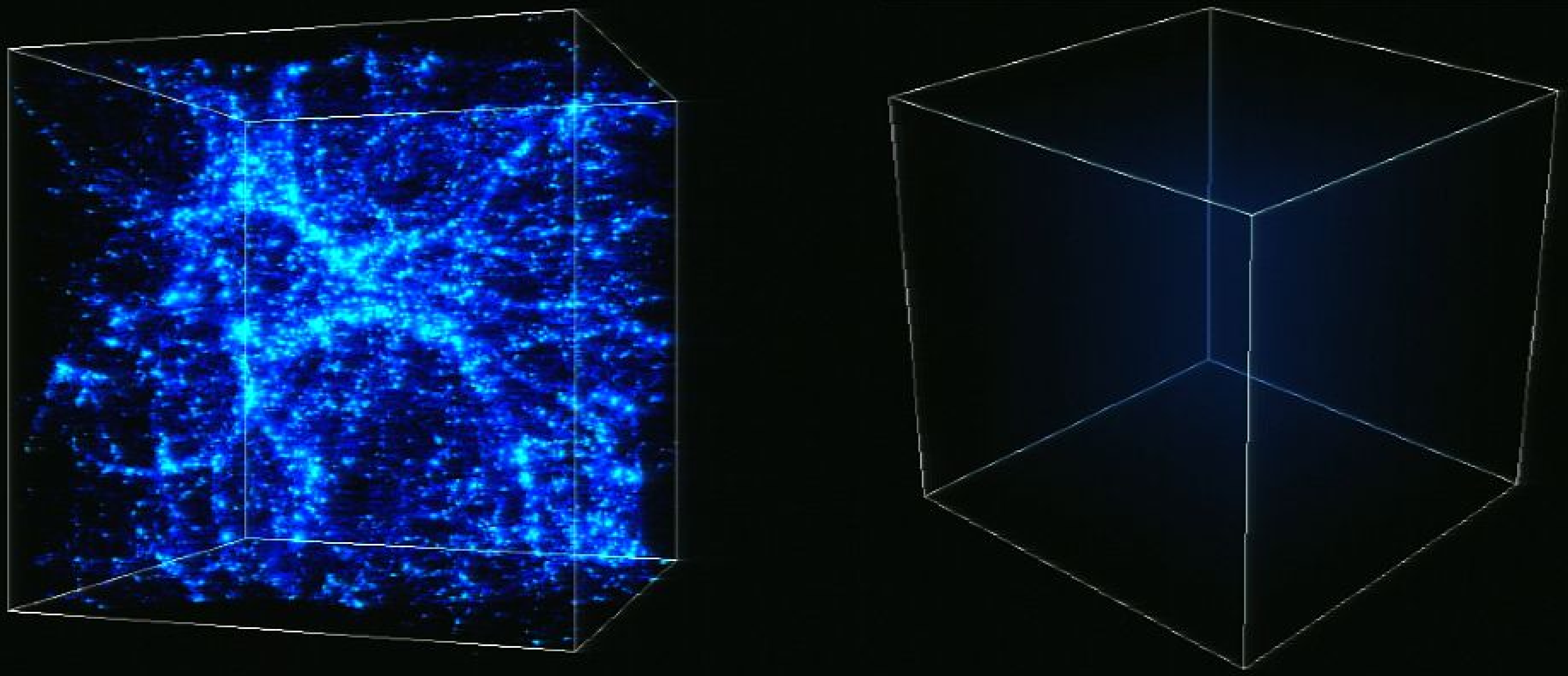

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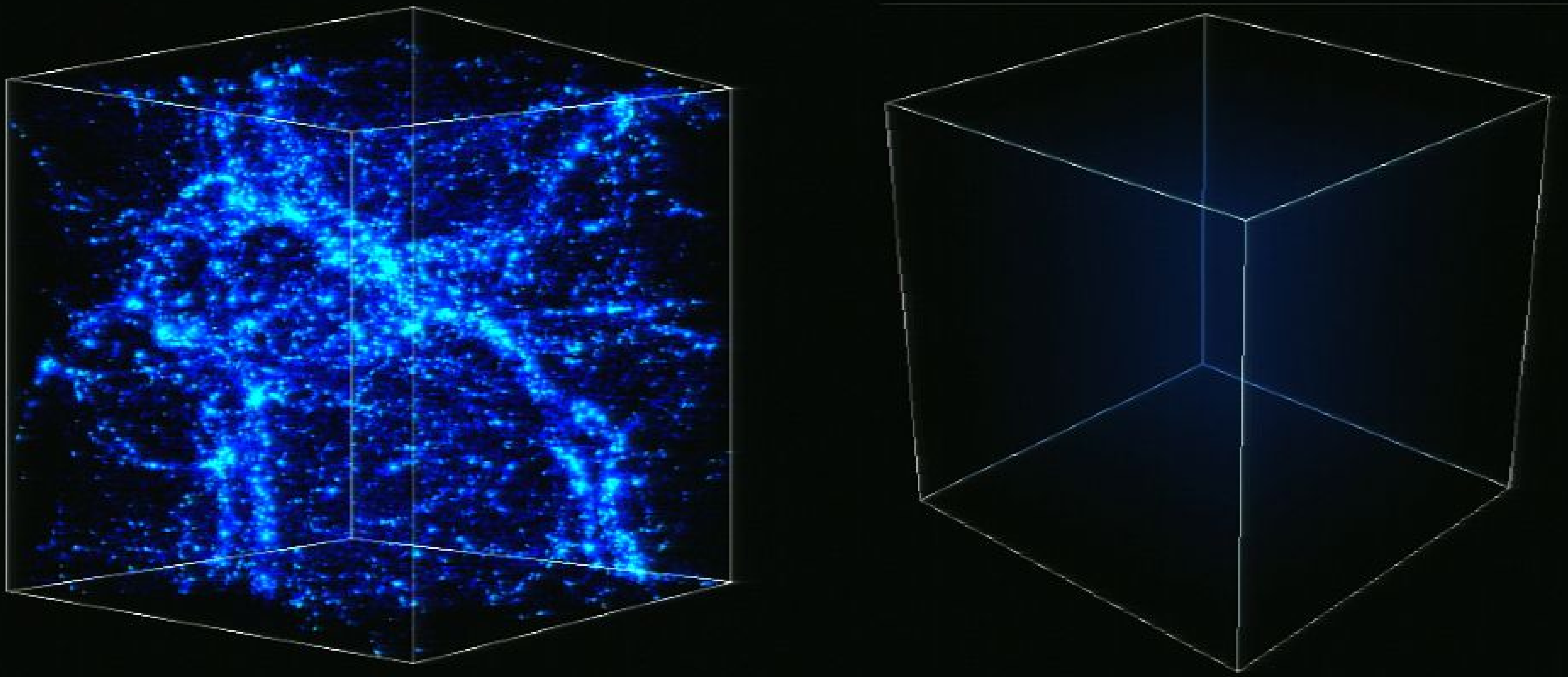

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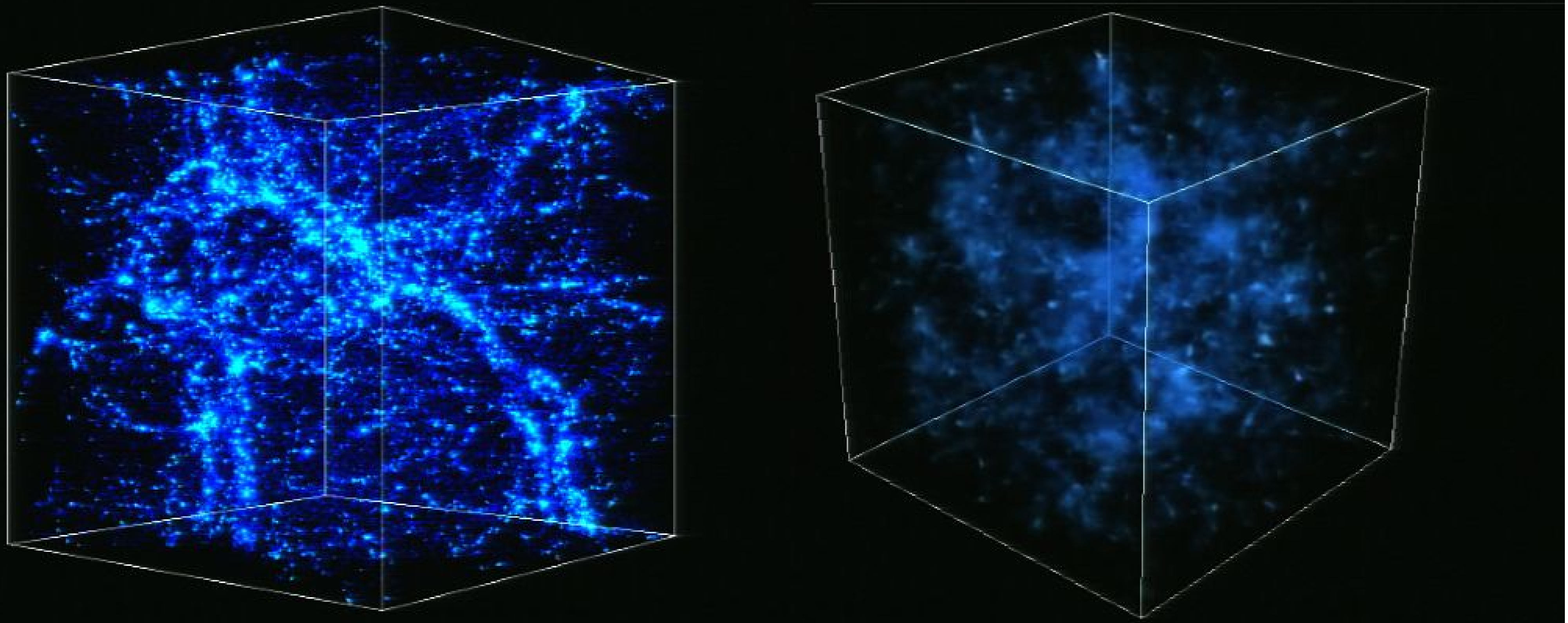

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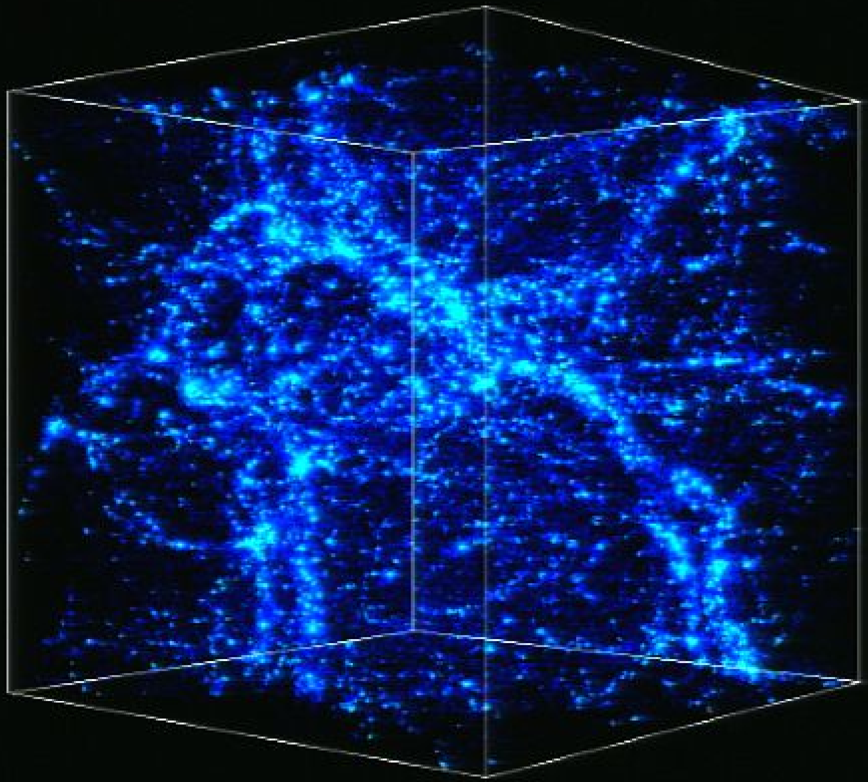
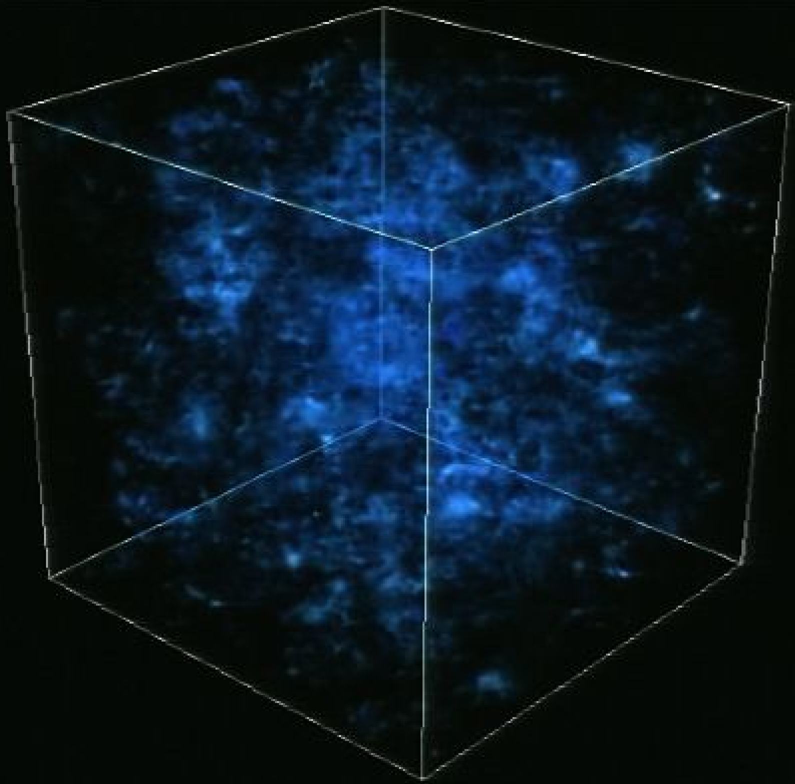
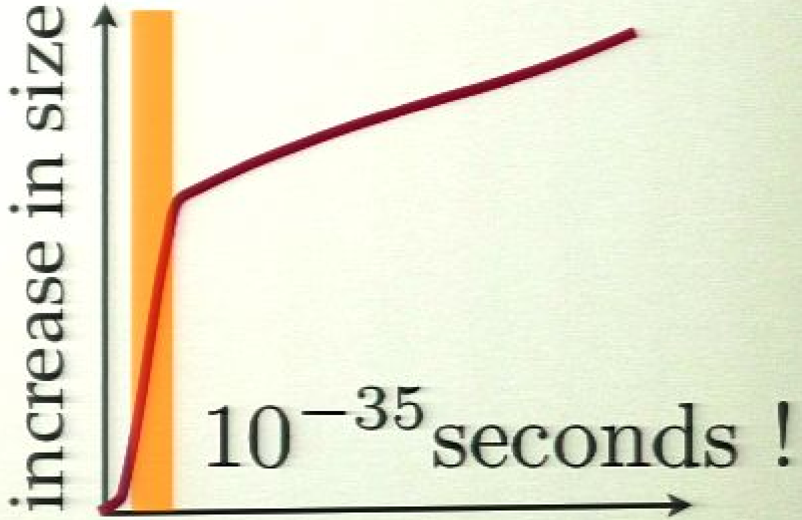




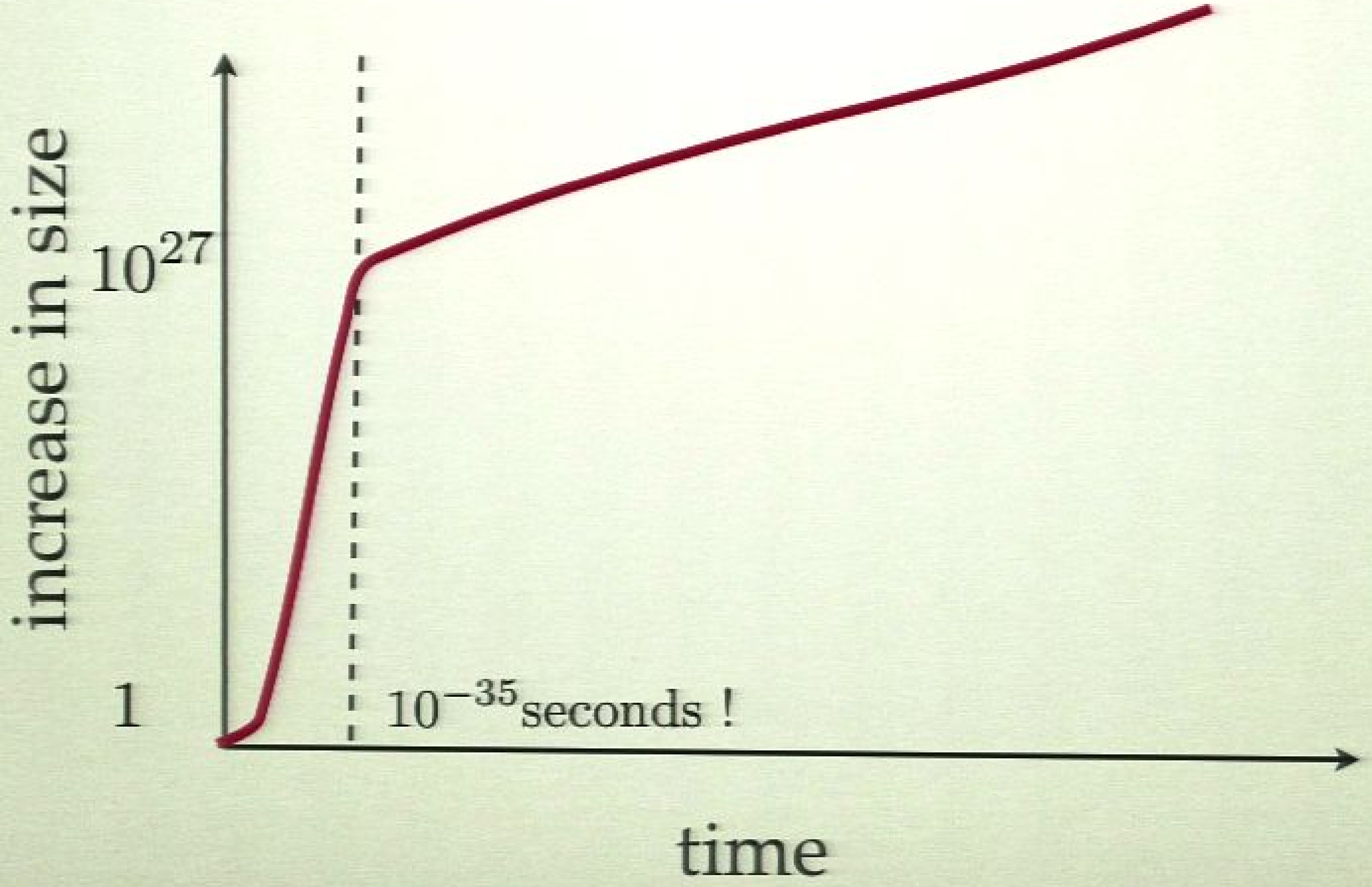
SYNOPSIS

- inflation and its end
- fragmentation → localized clumps !
- clumps ?
- generic emergence ?
- number densities and energy fraction ?
- consequences

INFLATION



POPULATING THE UNIVERSE



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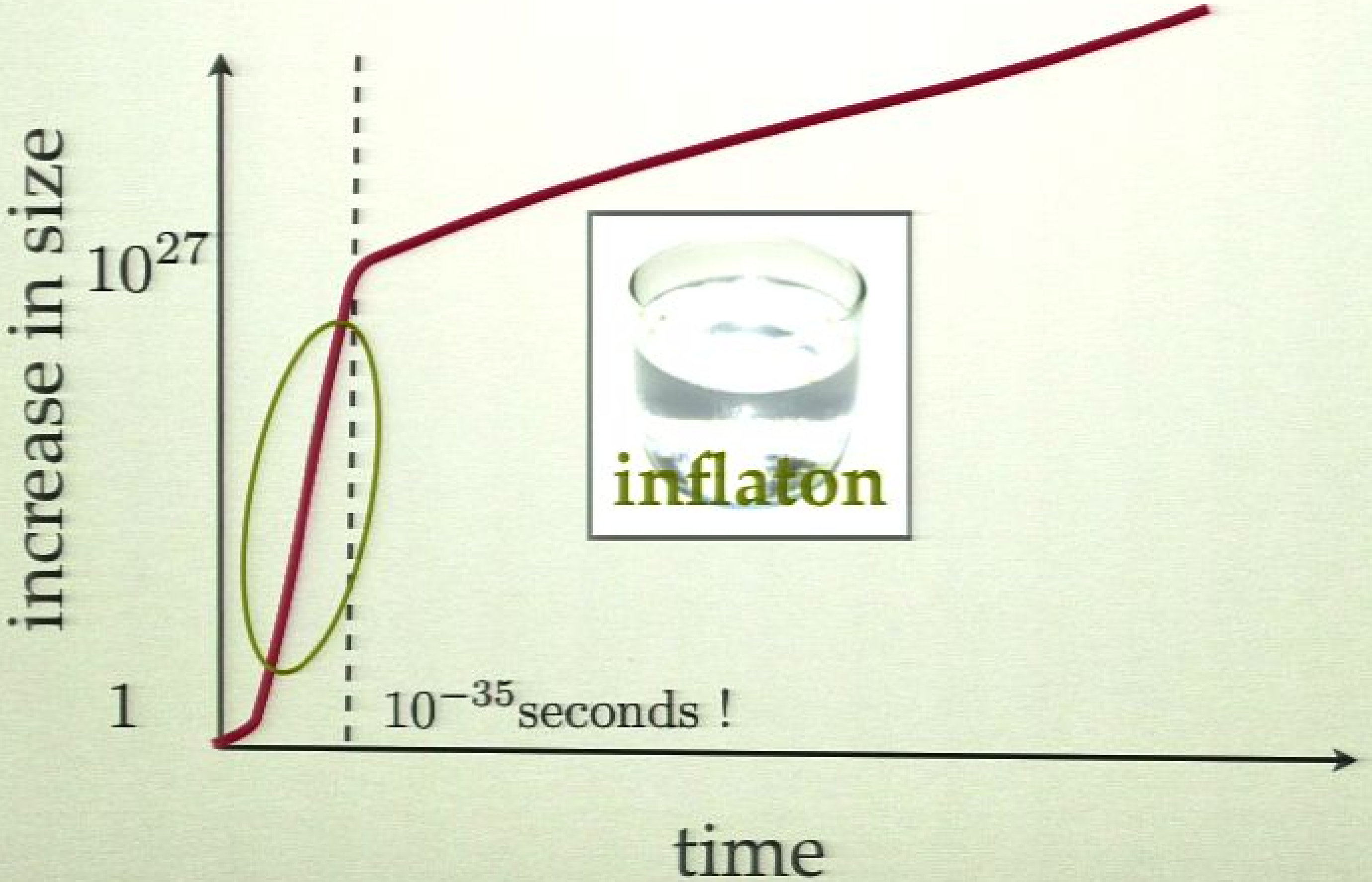

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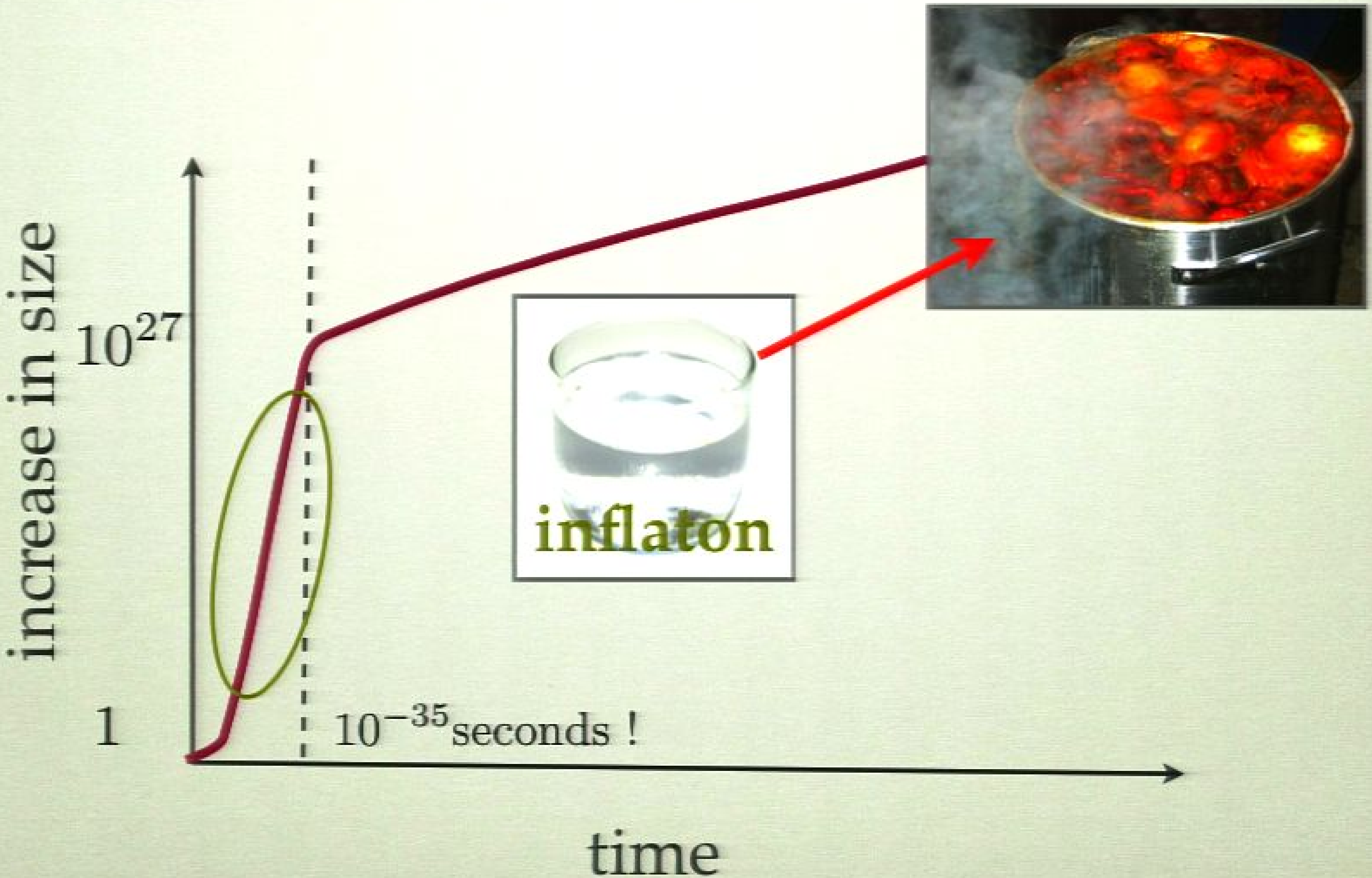

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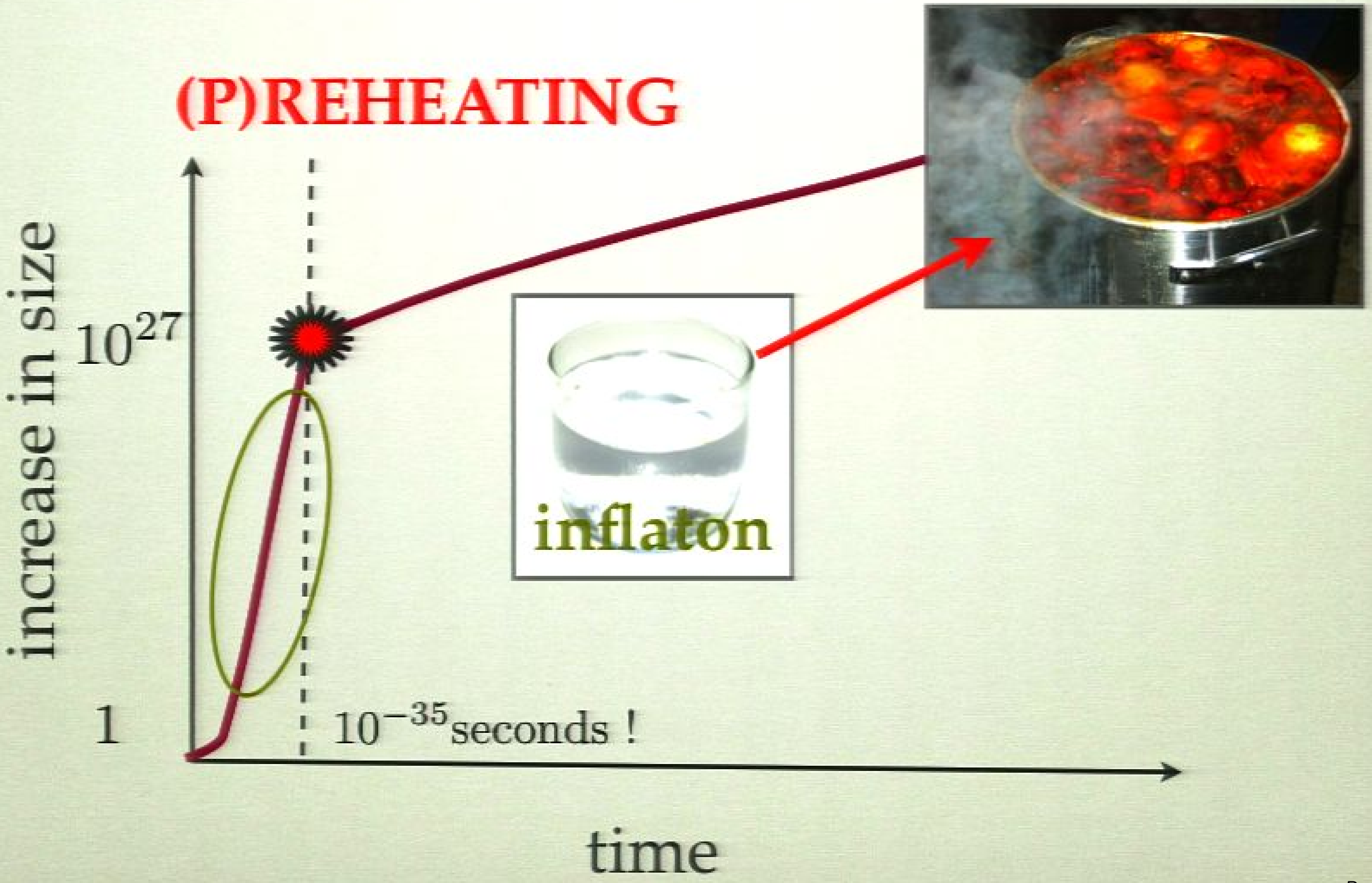

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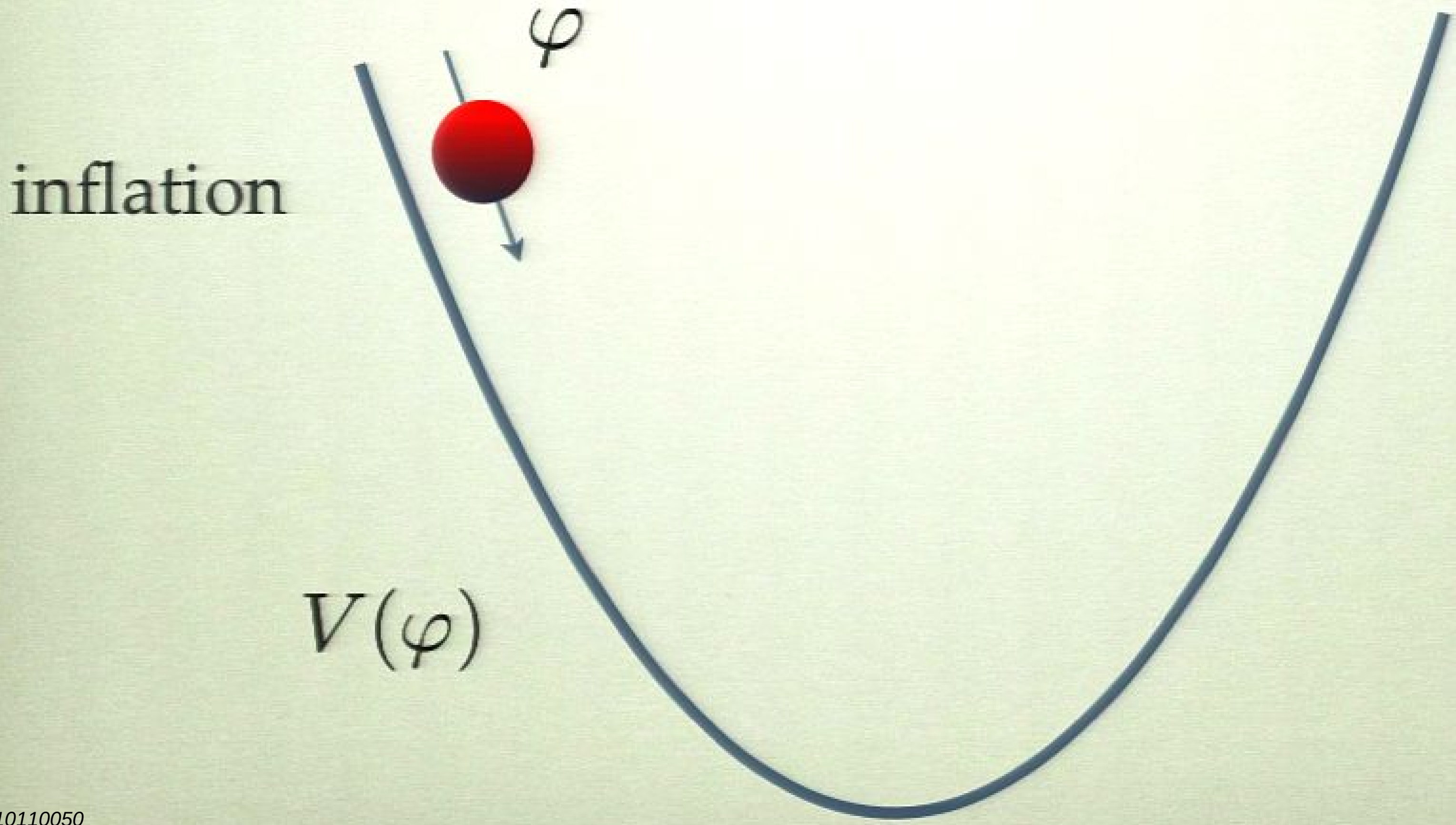

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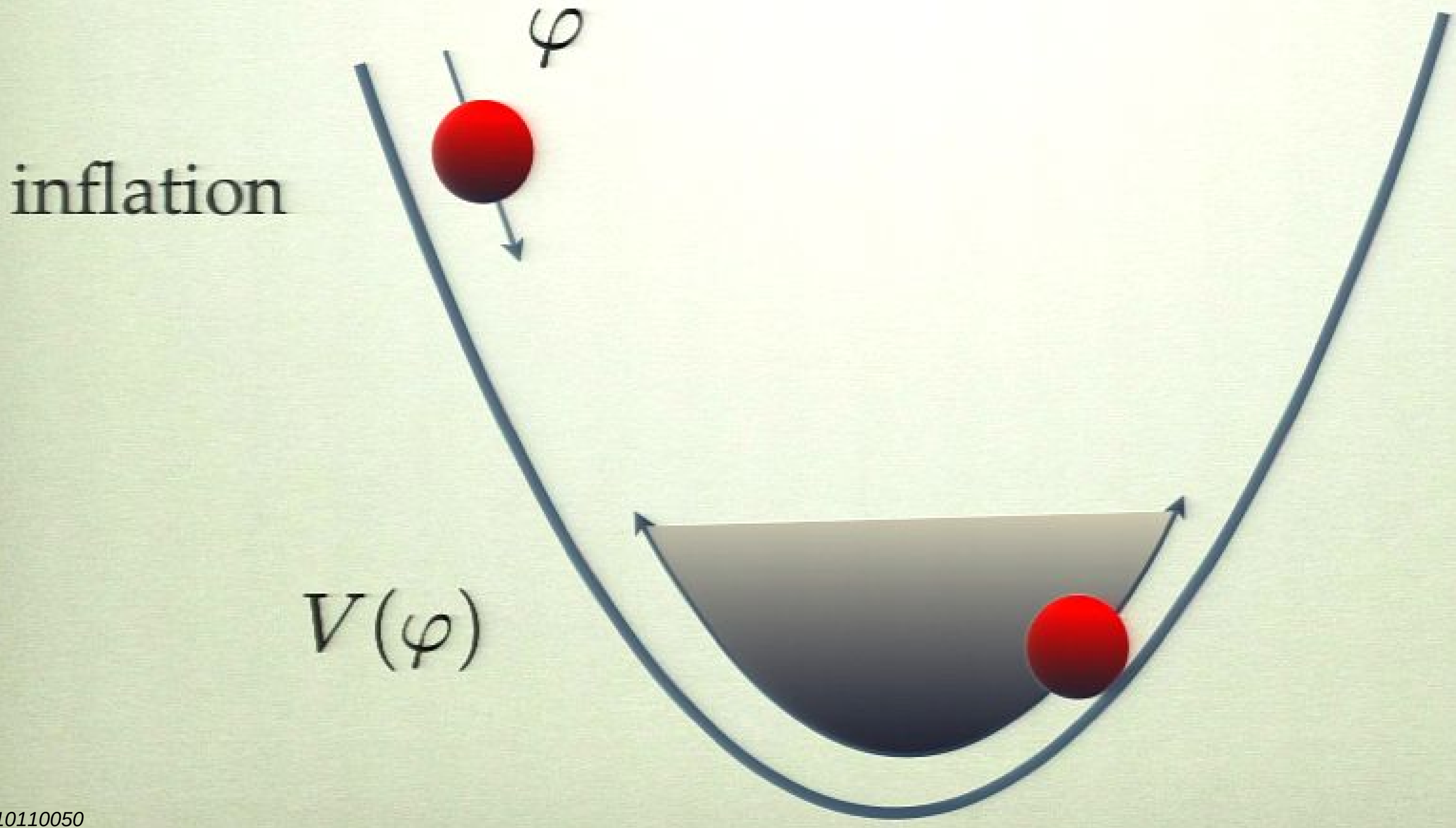

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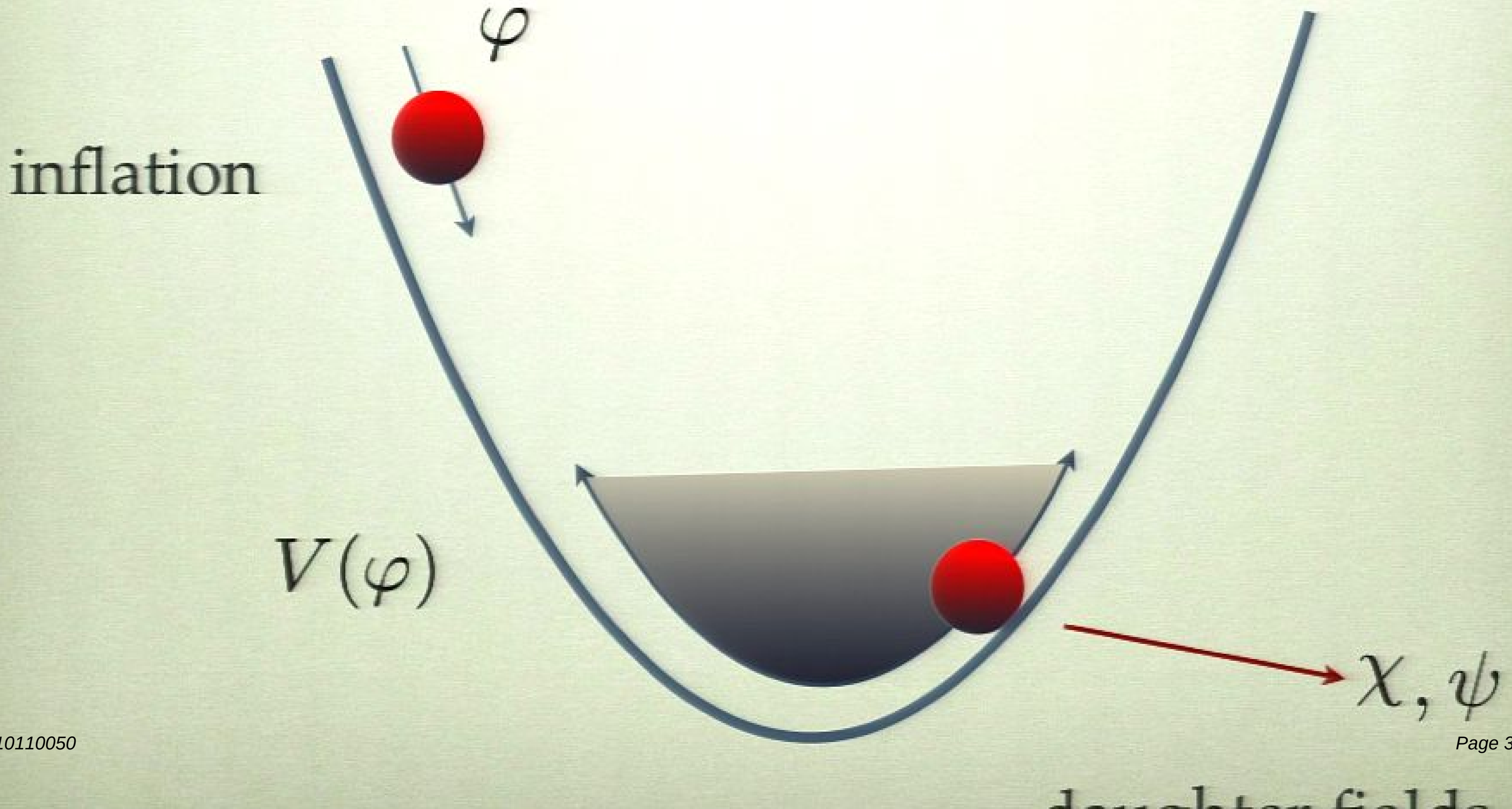
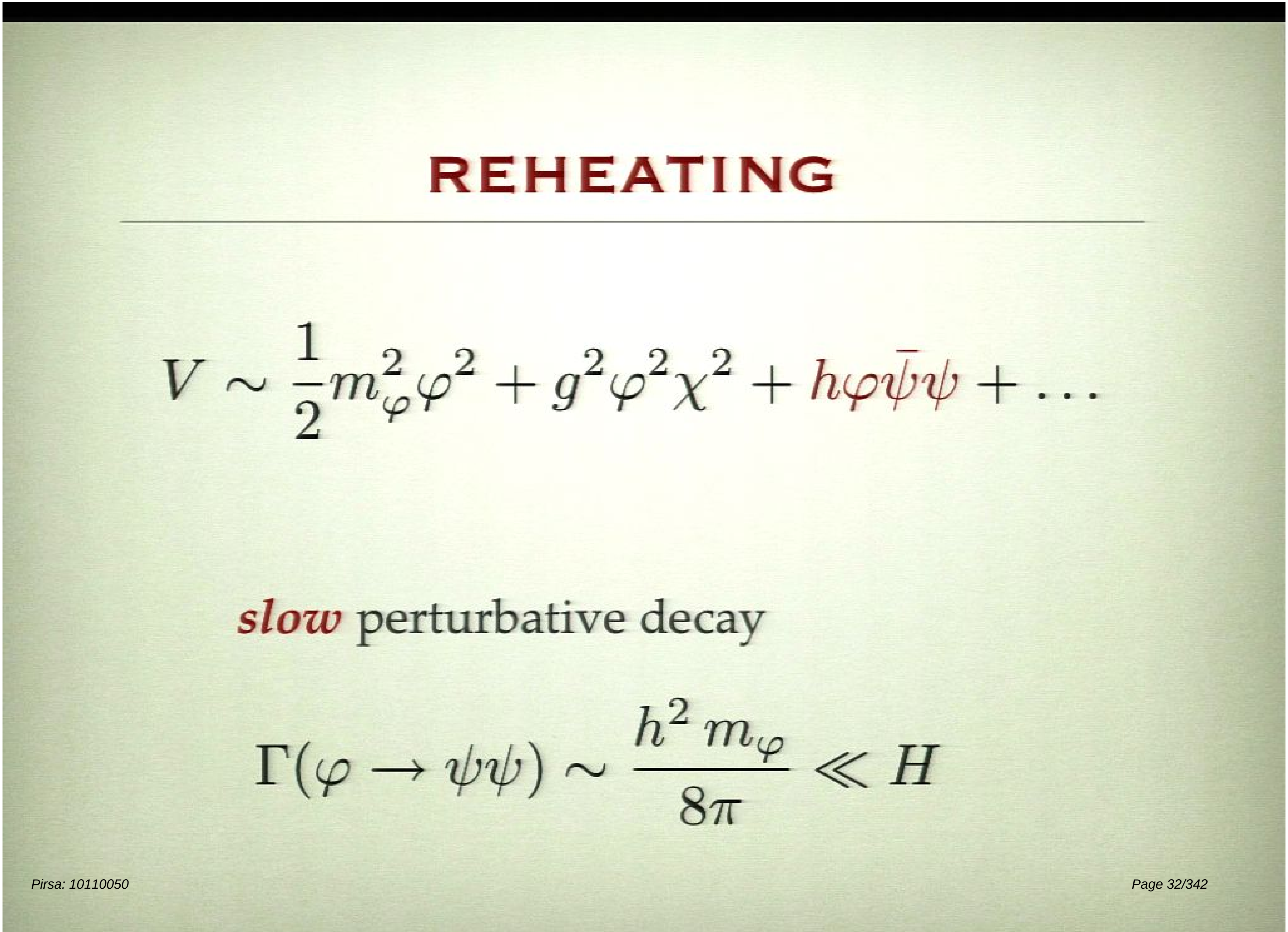




REHEATING

$$V \sim \frac{1}{2} m_\varphi^2 \varphi^2 + g^2 \varphi^2 \chi^2 + h\varphi\bar{\psi}\psi + \ldots$$

slow perturbative decay

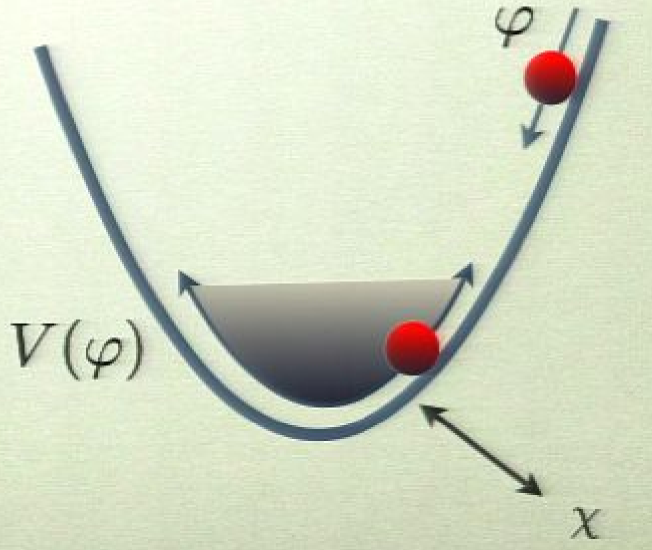
$$\Gamma(\varphi \to \psi\psi) \sim \frac{h^2\, m_\varphi}{8\pi} \ll H$$

PREHEATING

$$V \sim \frac{1}{2}m_\varphi^2\varphi^2 + g^2\varphi^2\chi^2 + h\varphi\bar{\psi}\psi + \ldots$$

explosive particle production

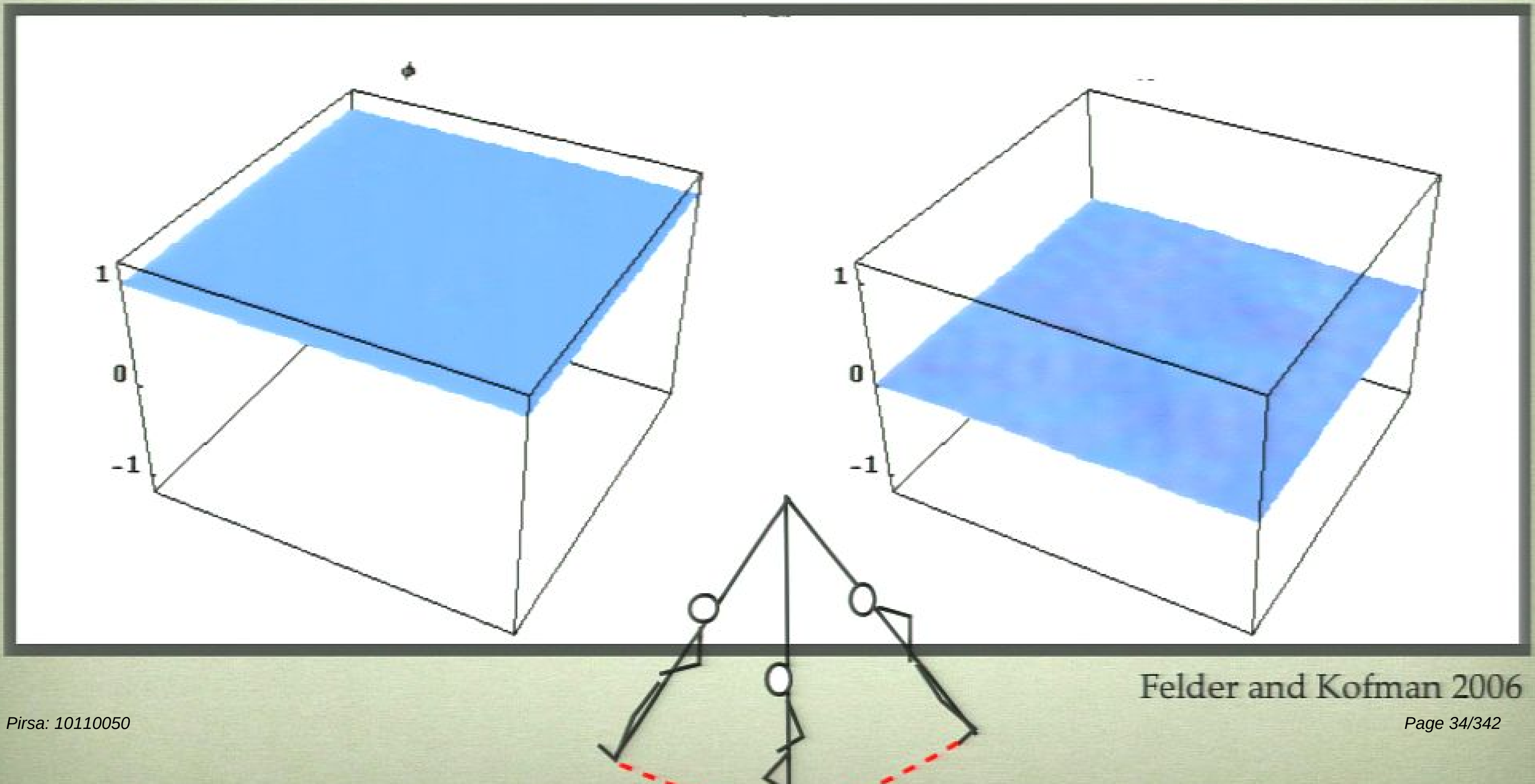
$$\Box\chi = V_{,\chi} = g^2\varphi^2\chi$$



similarly for $\chi = \delta\varphi$

PREHEATING

inflaton daughter fields



Felder and Kofman 2006

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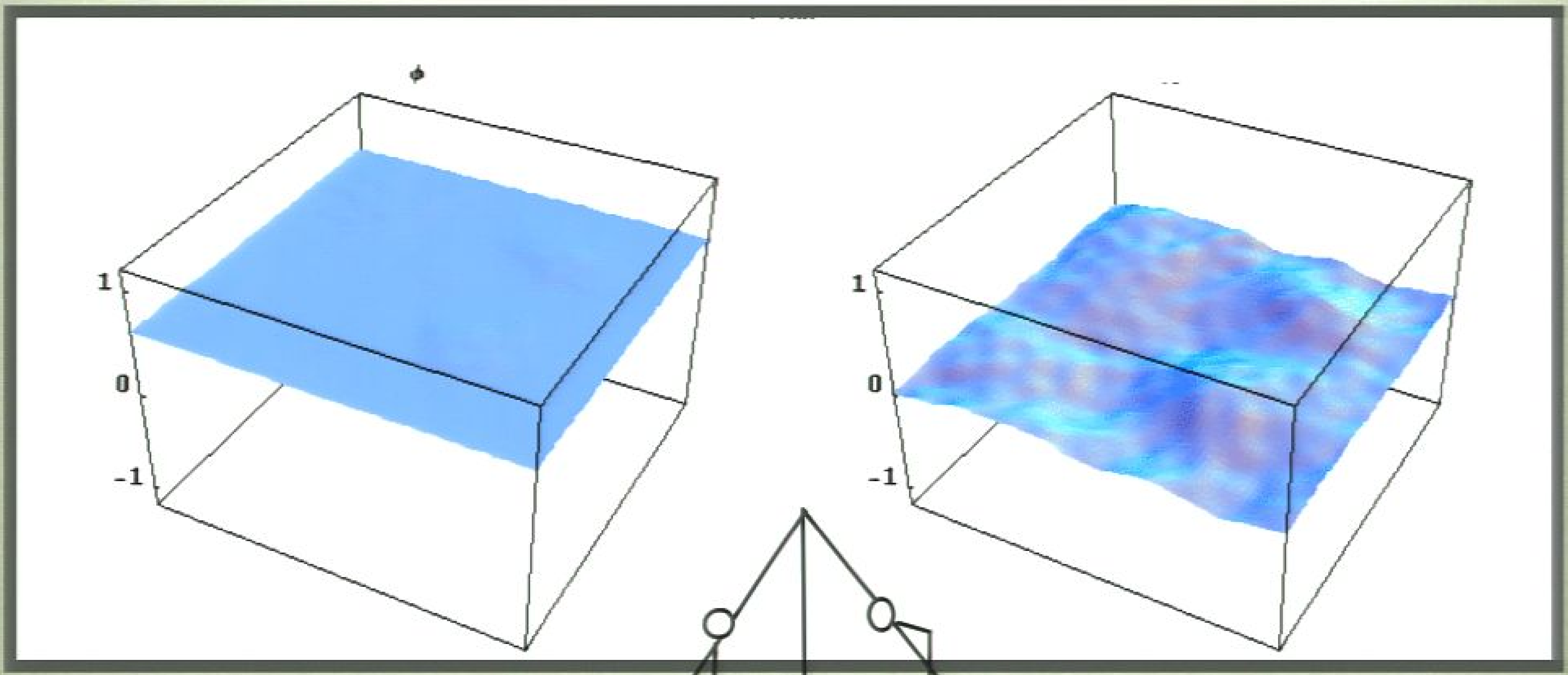

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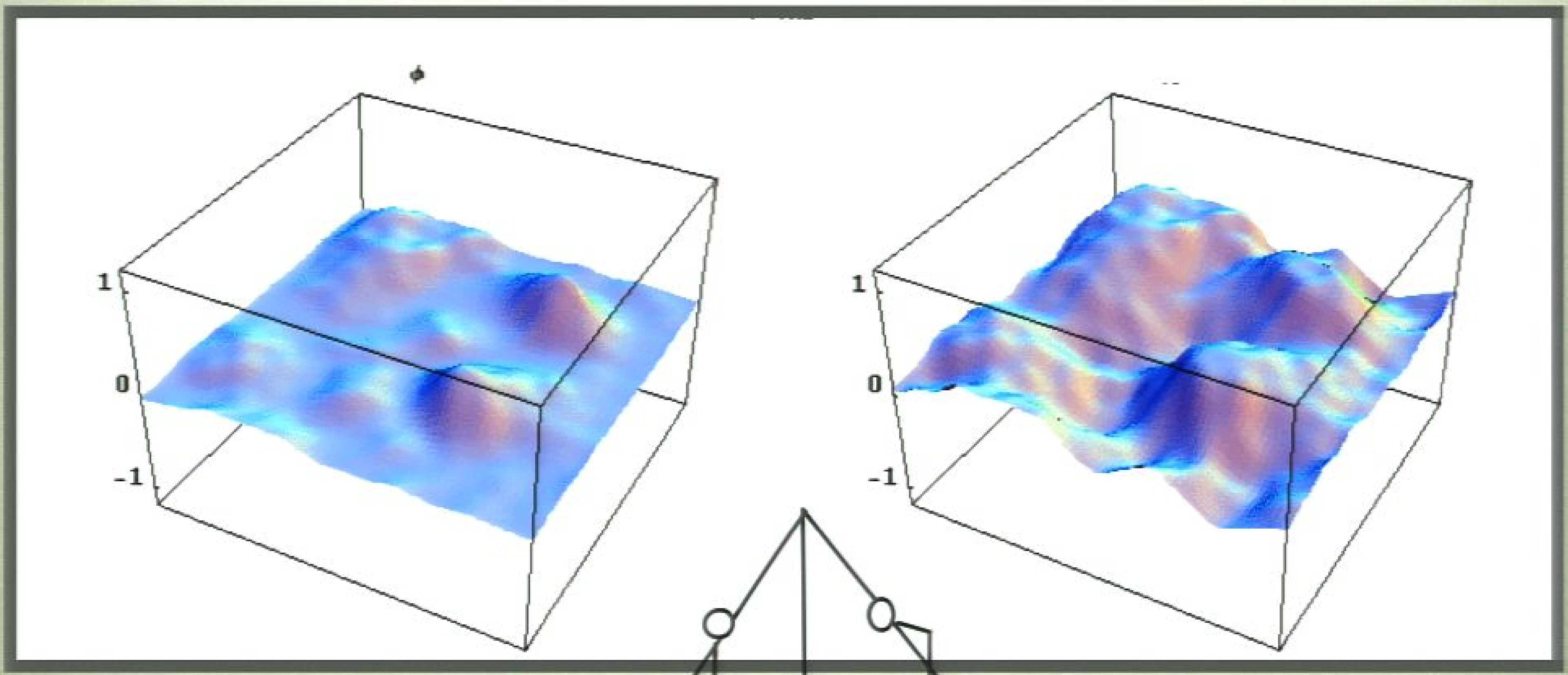

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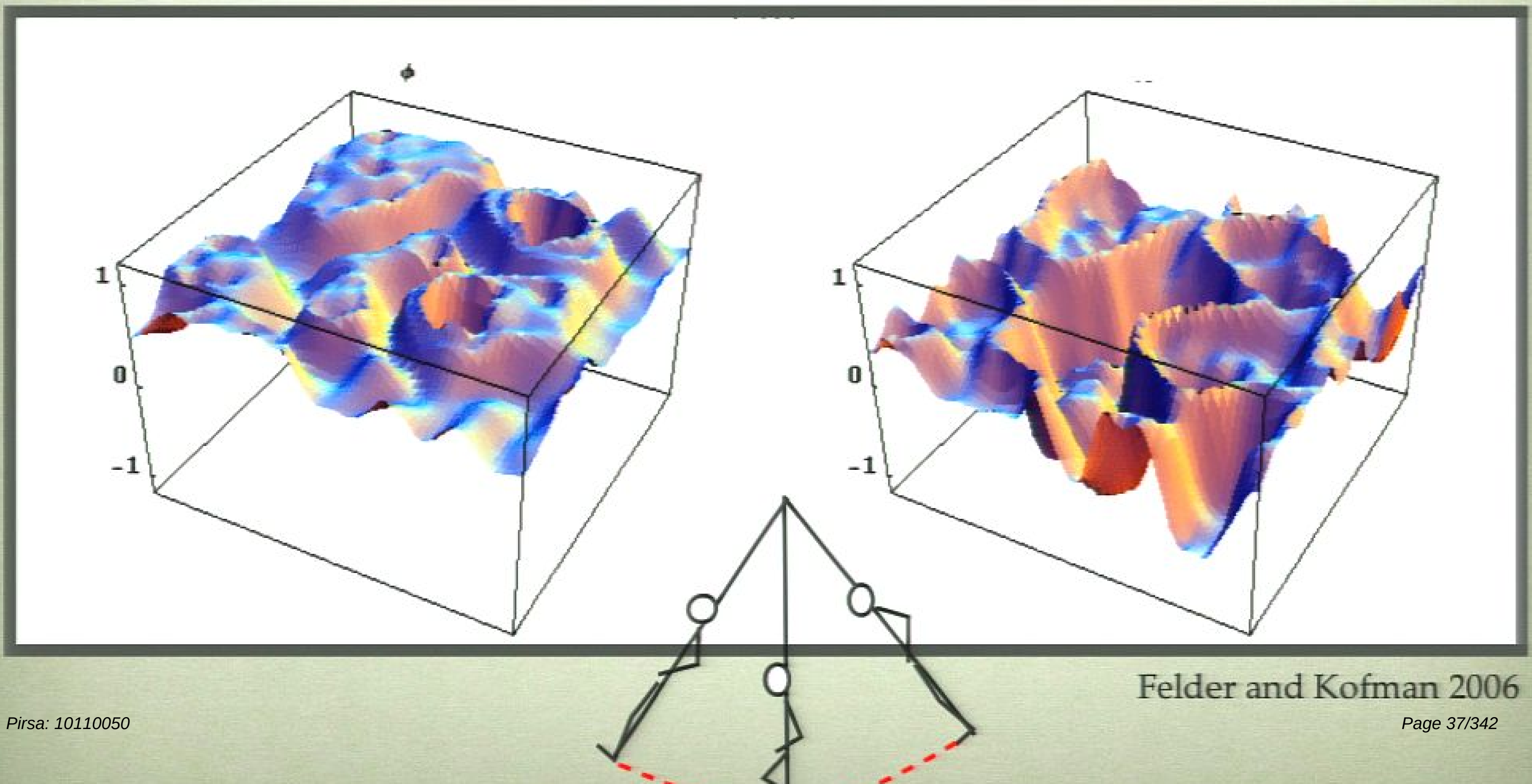

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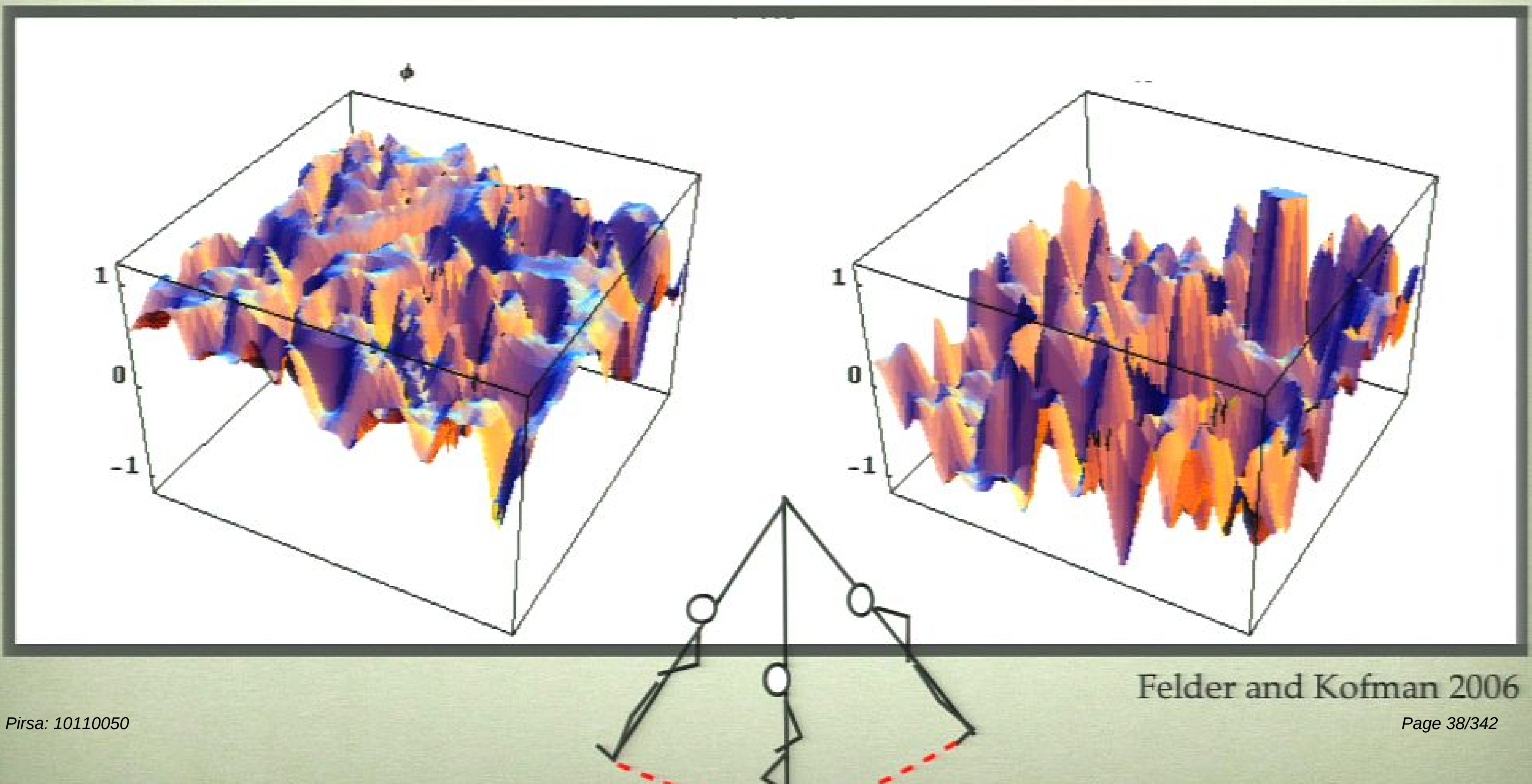

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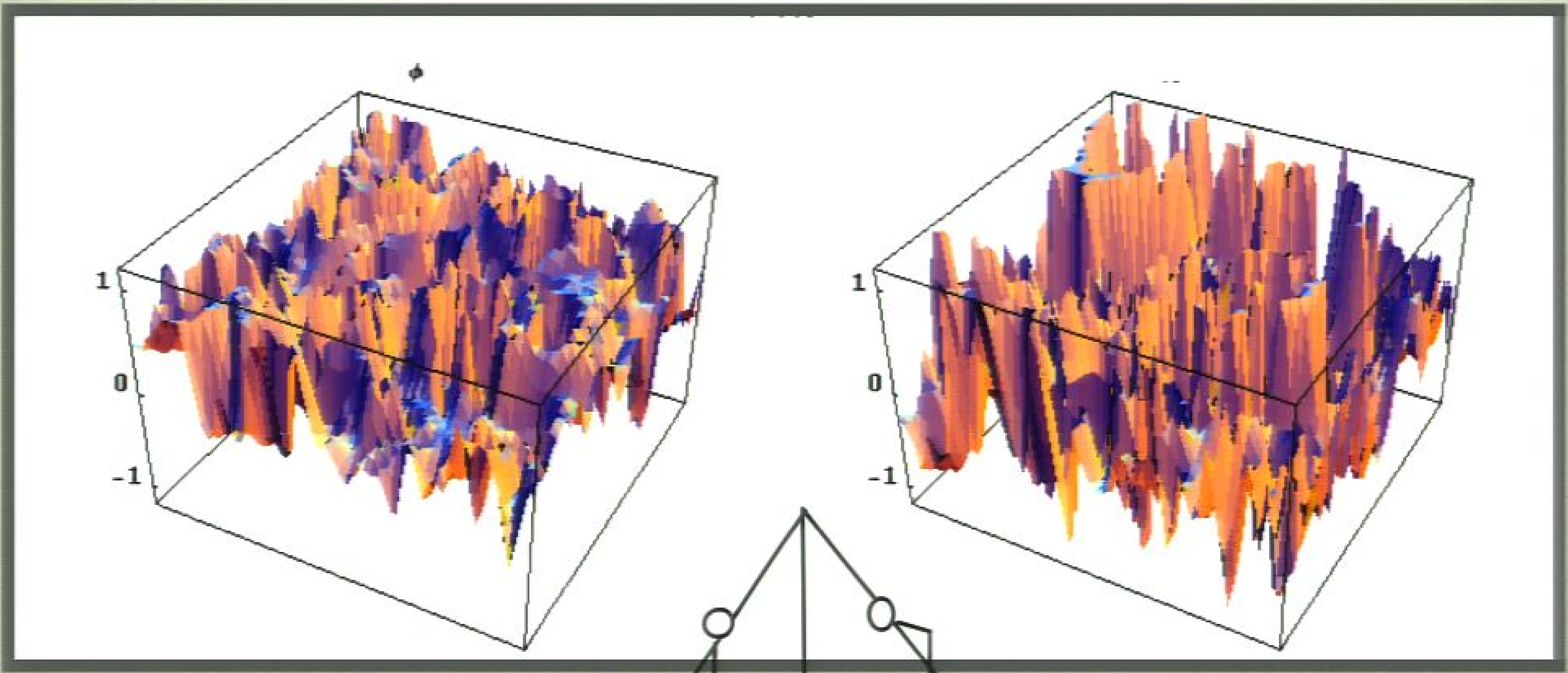

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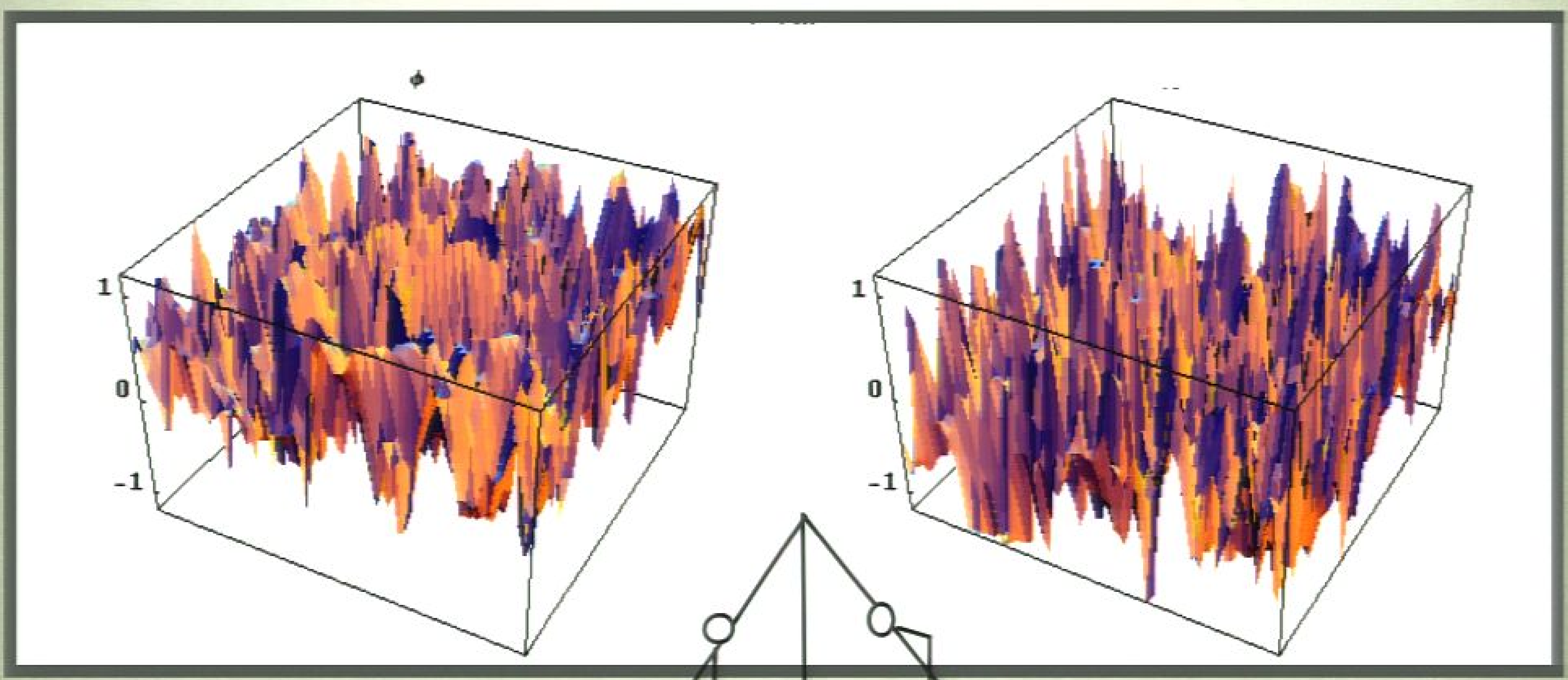

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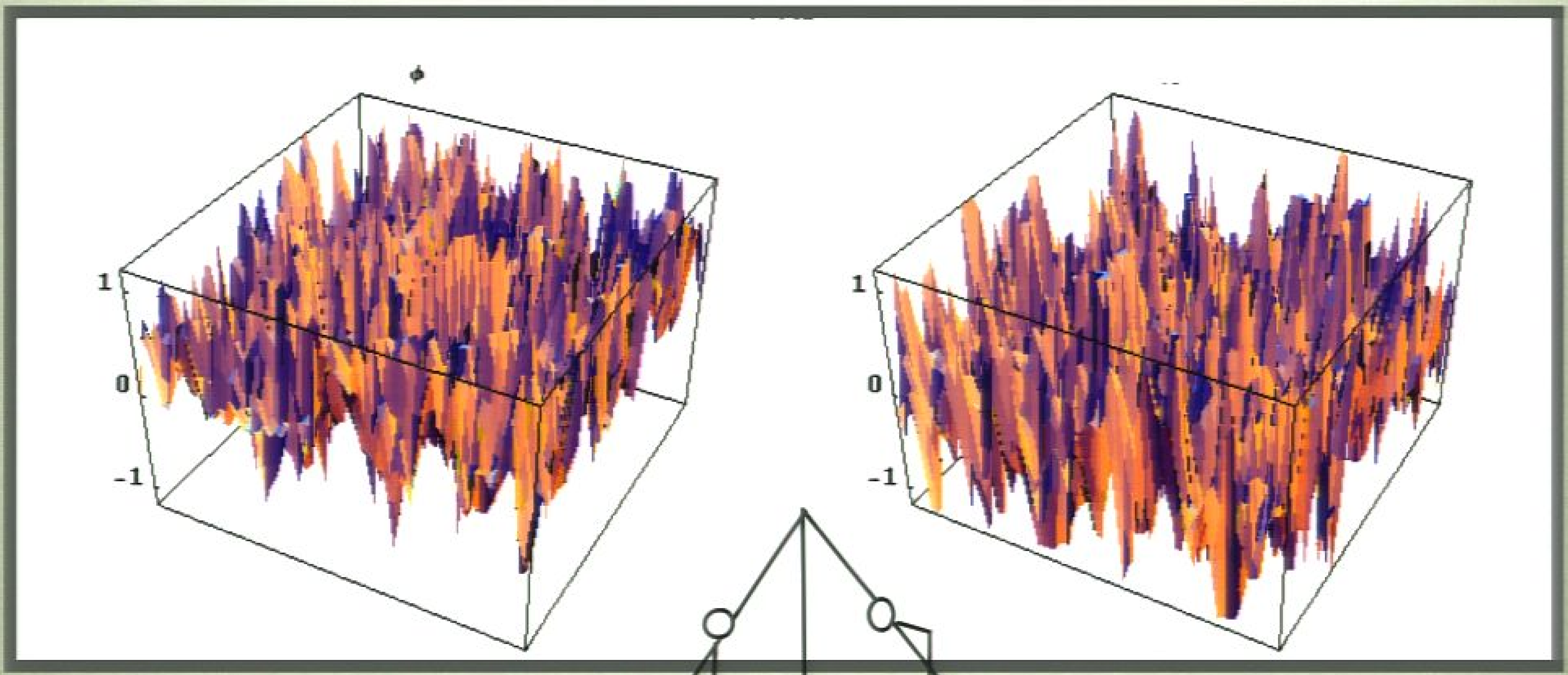
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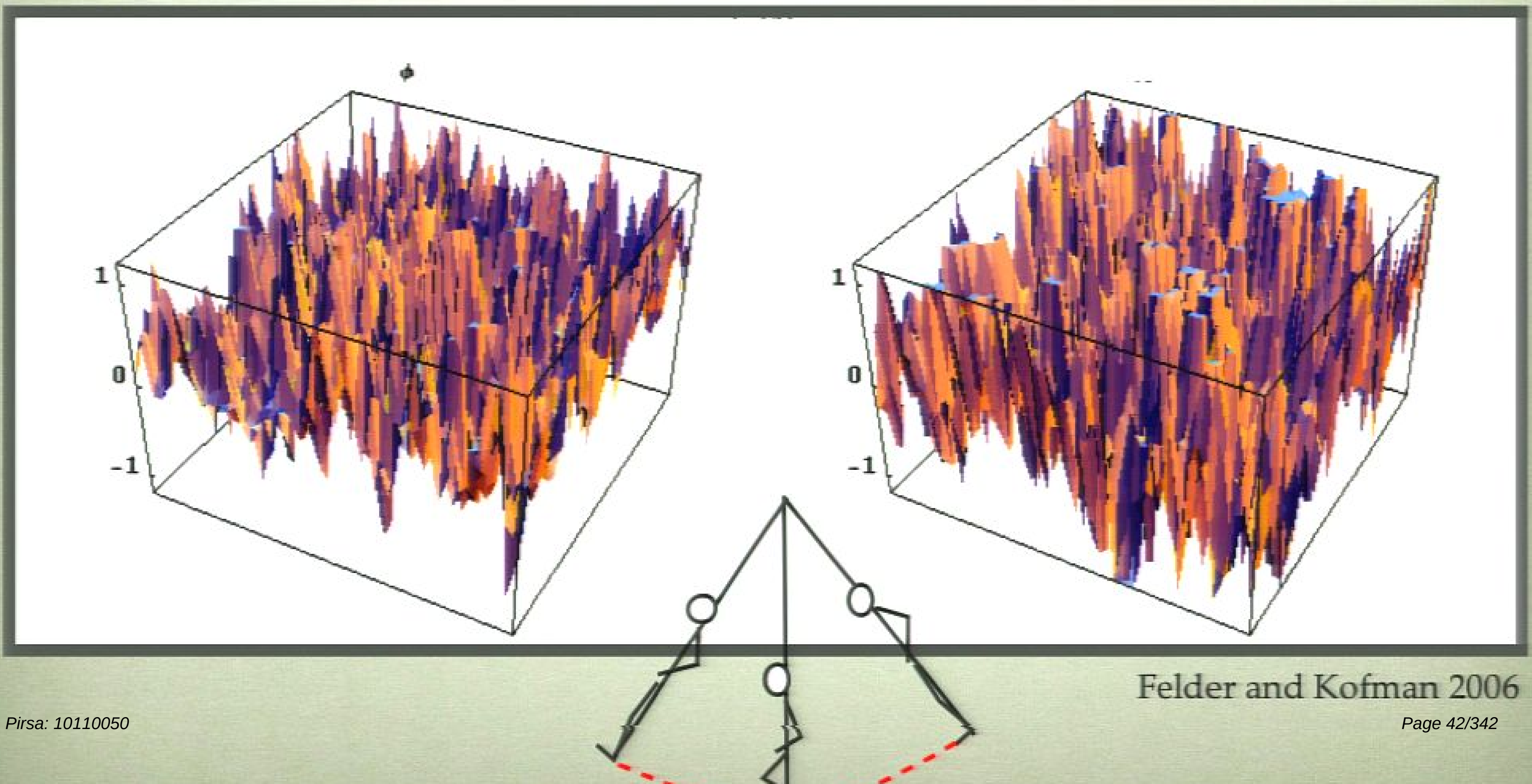
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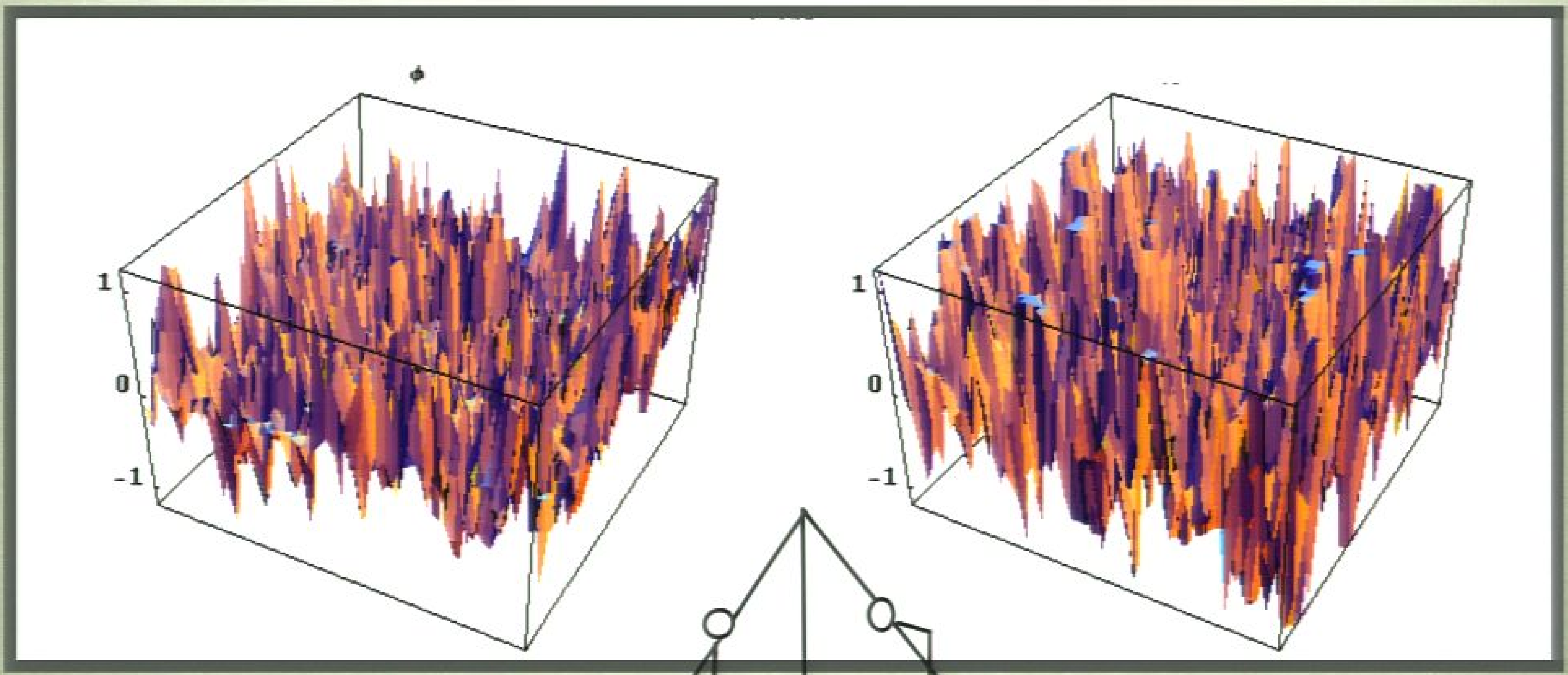

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Felder and Kofman 2006

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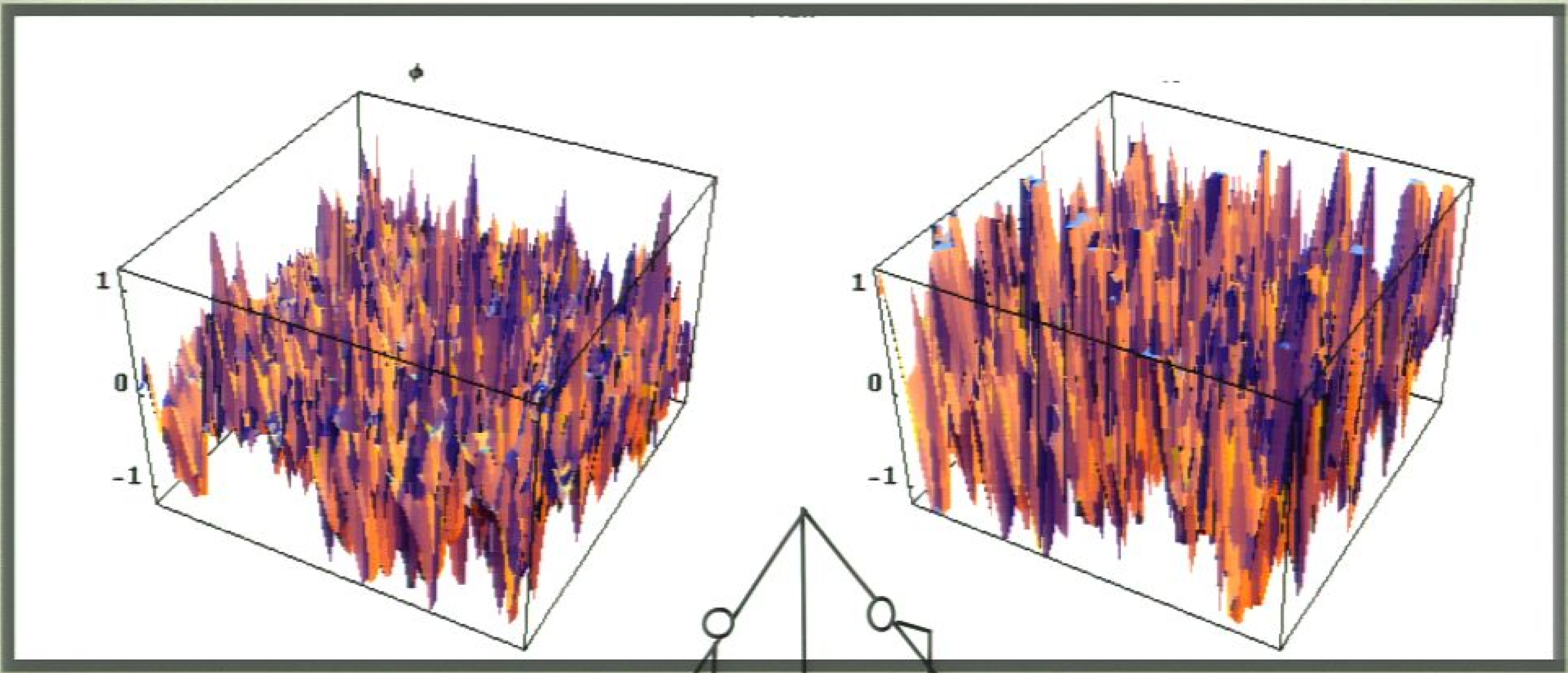

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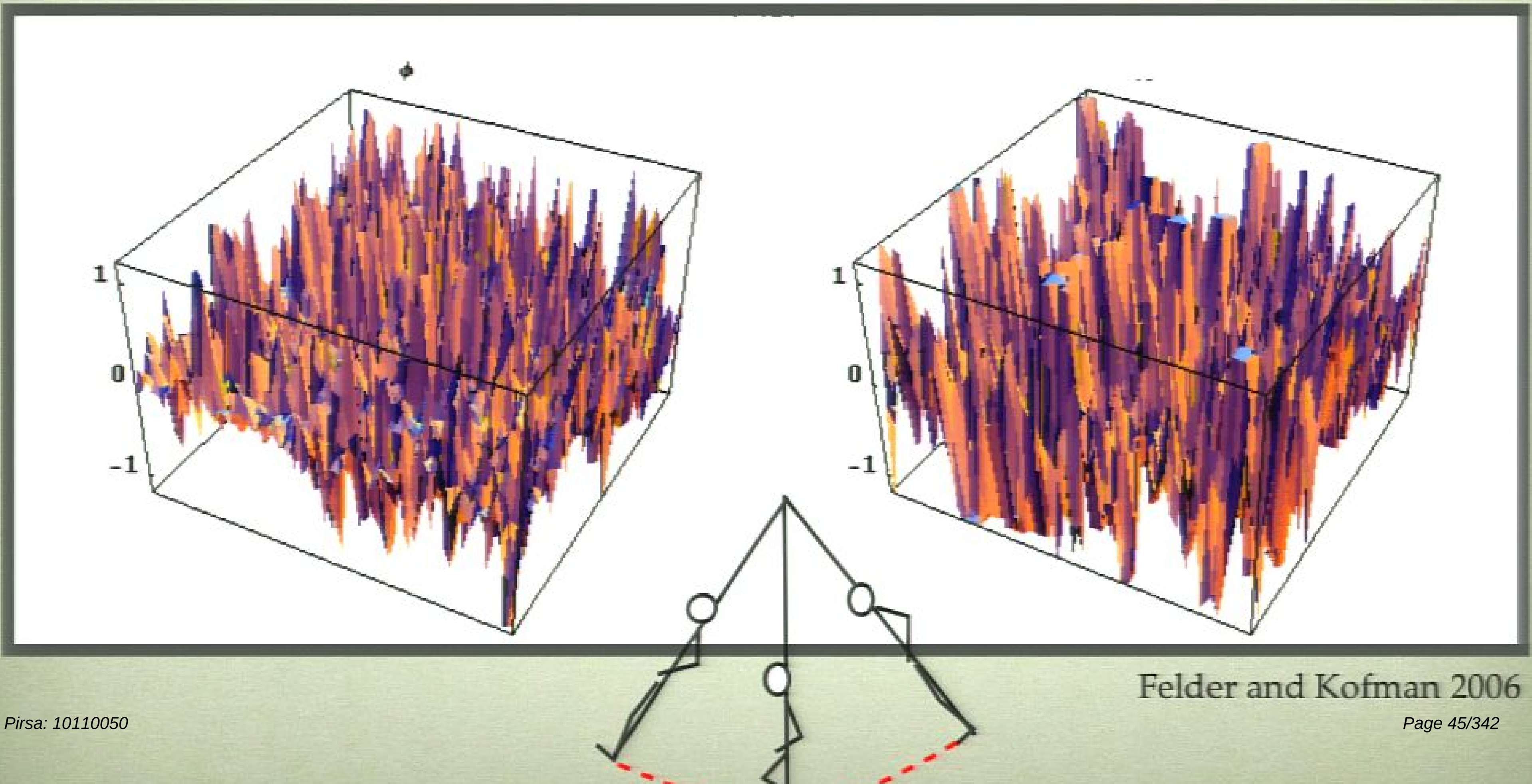

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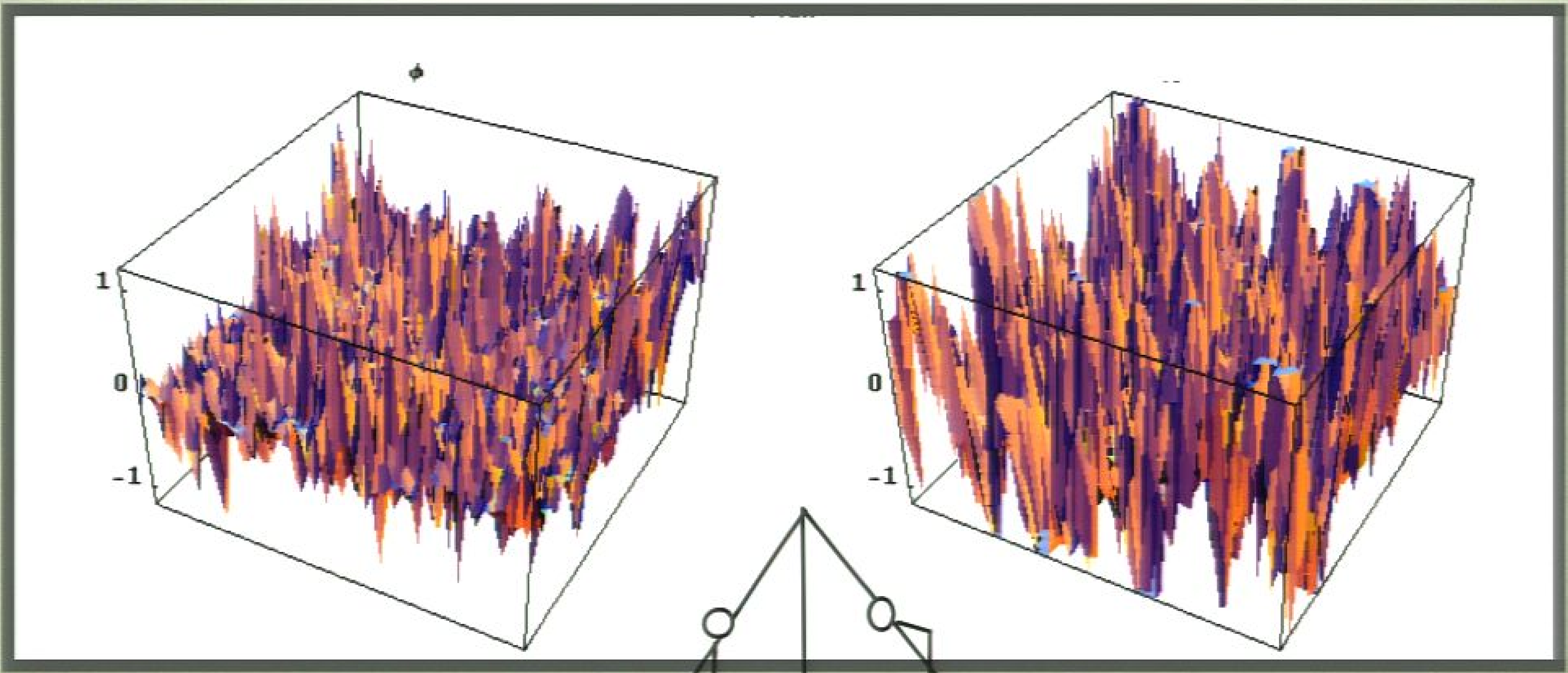

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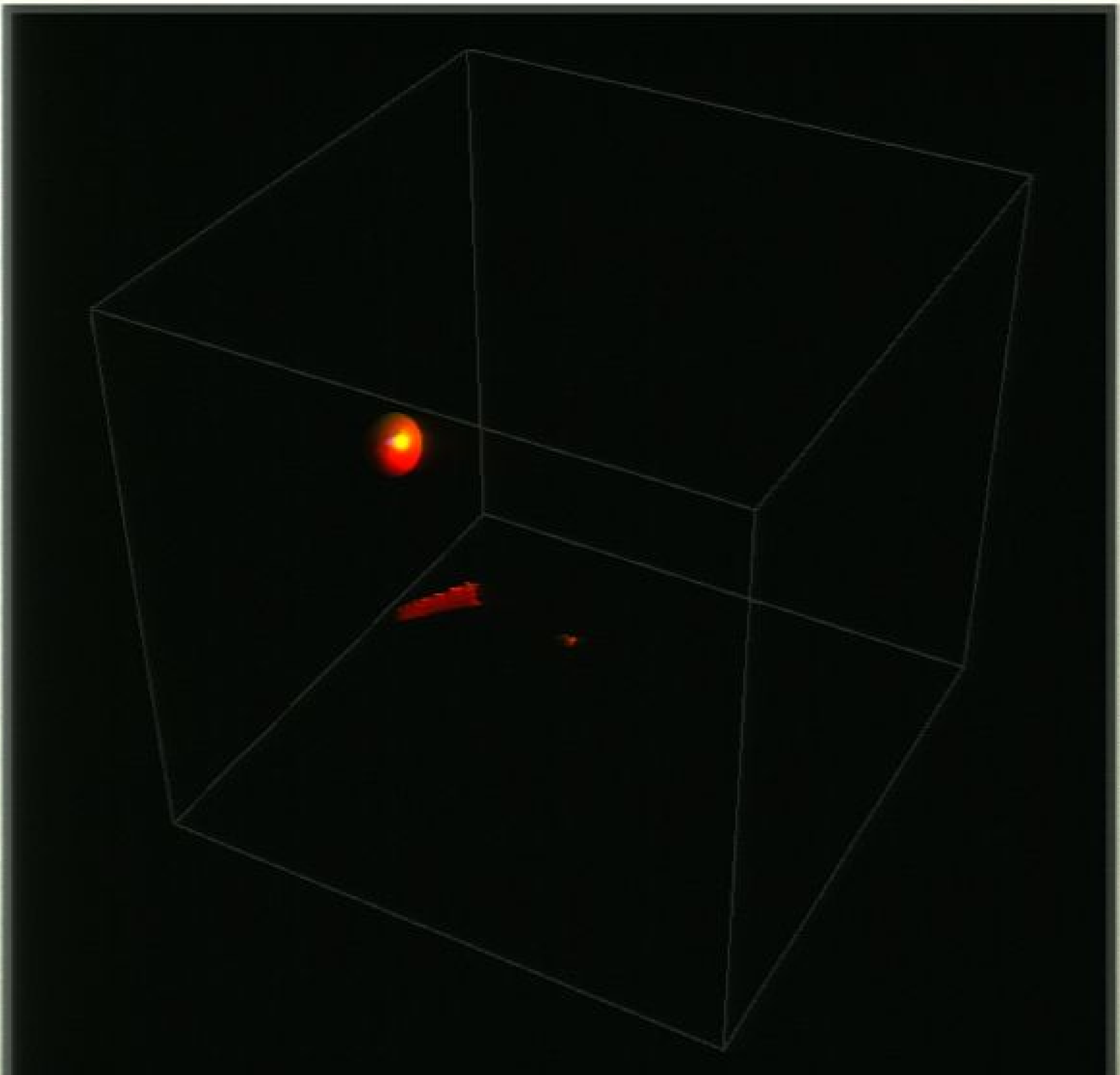
FRAGMENTATION: TURBULENT MESS ...



4 Hubble radii at the end of inflation
(a few meters today)

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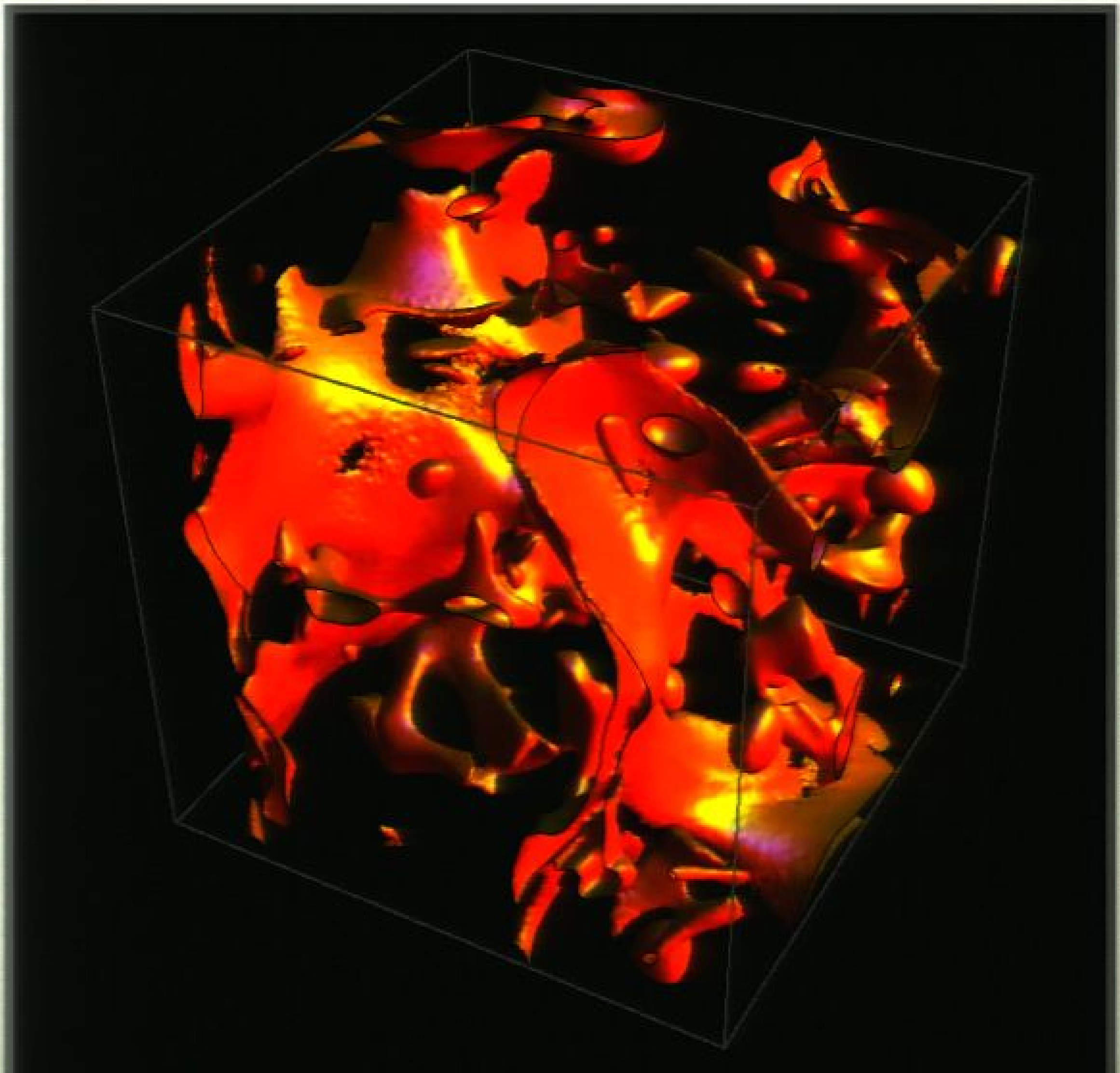

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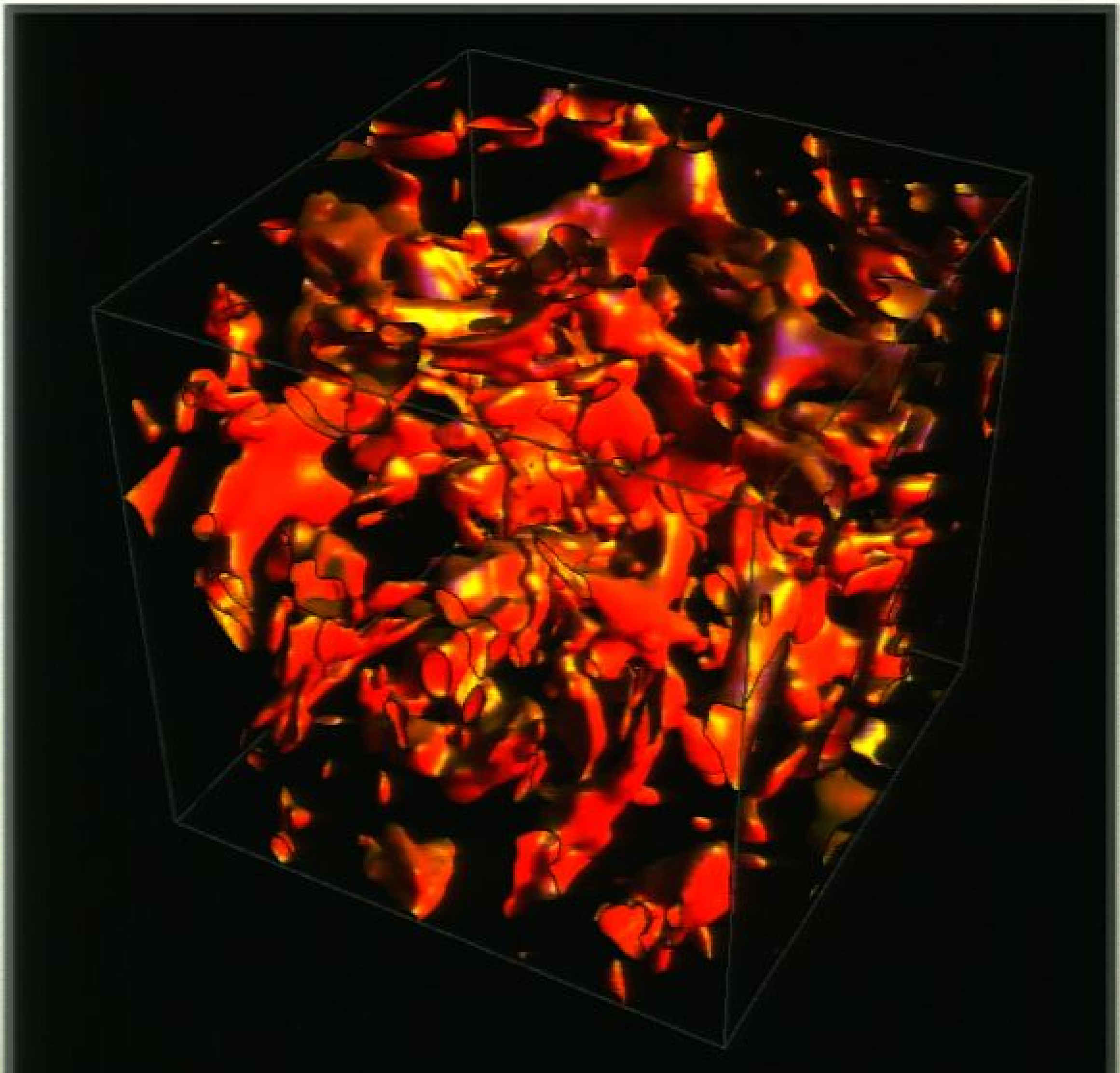

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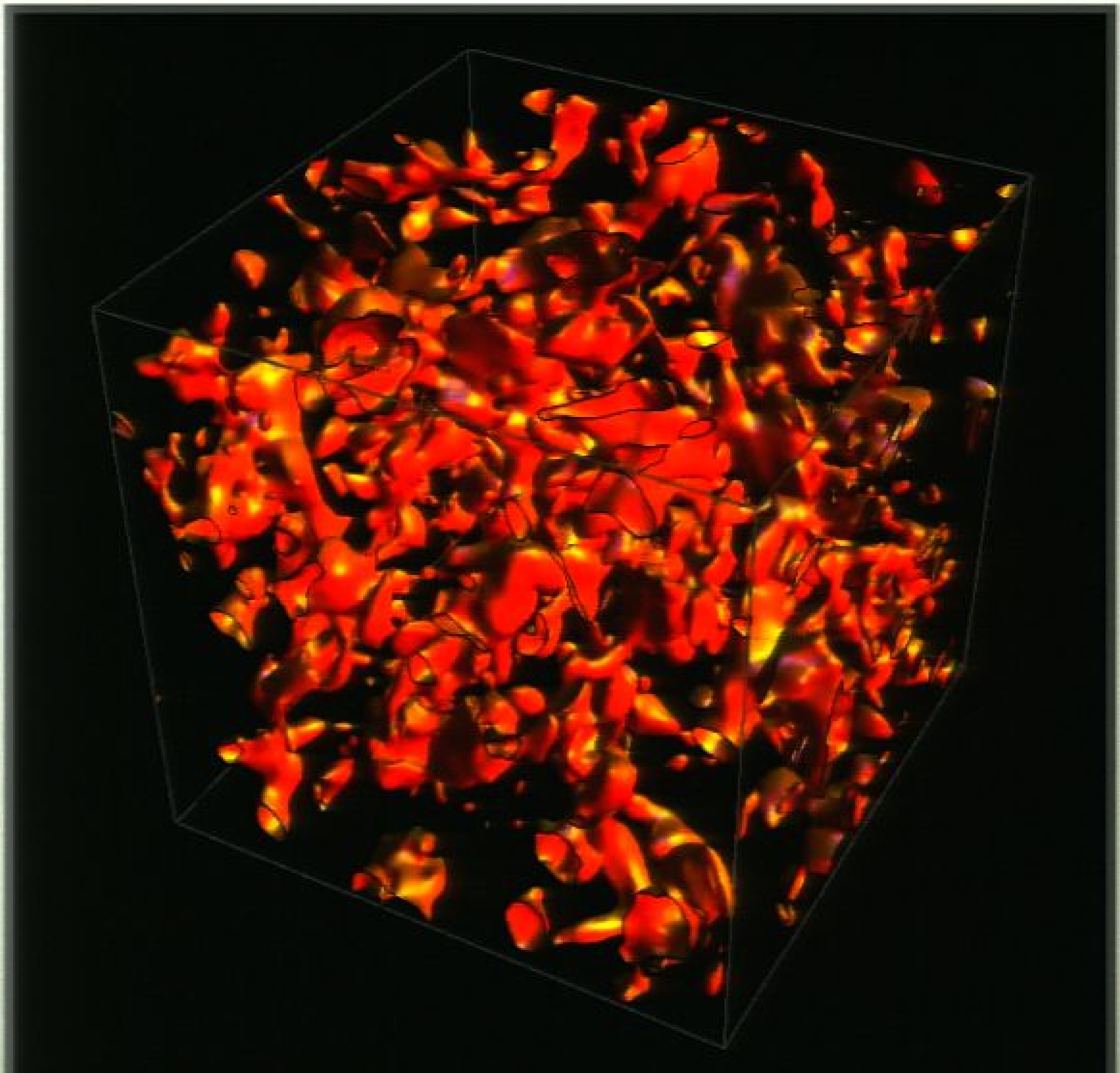

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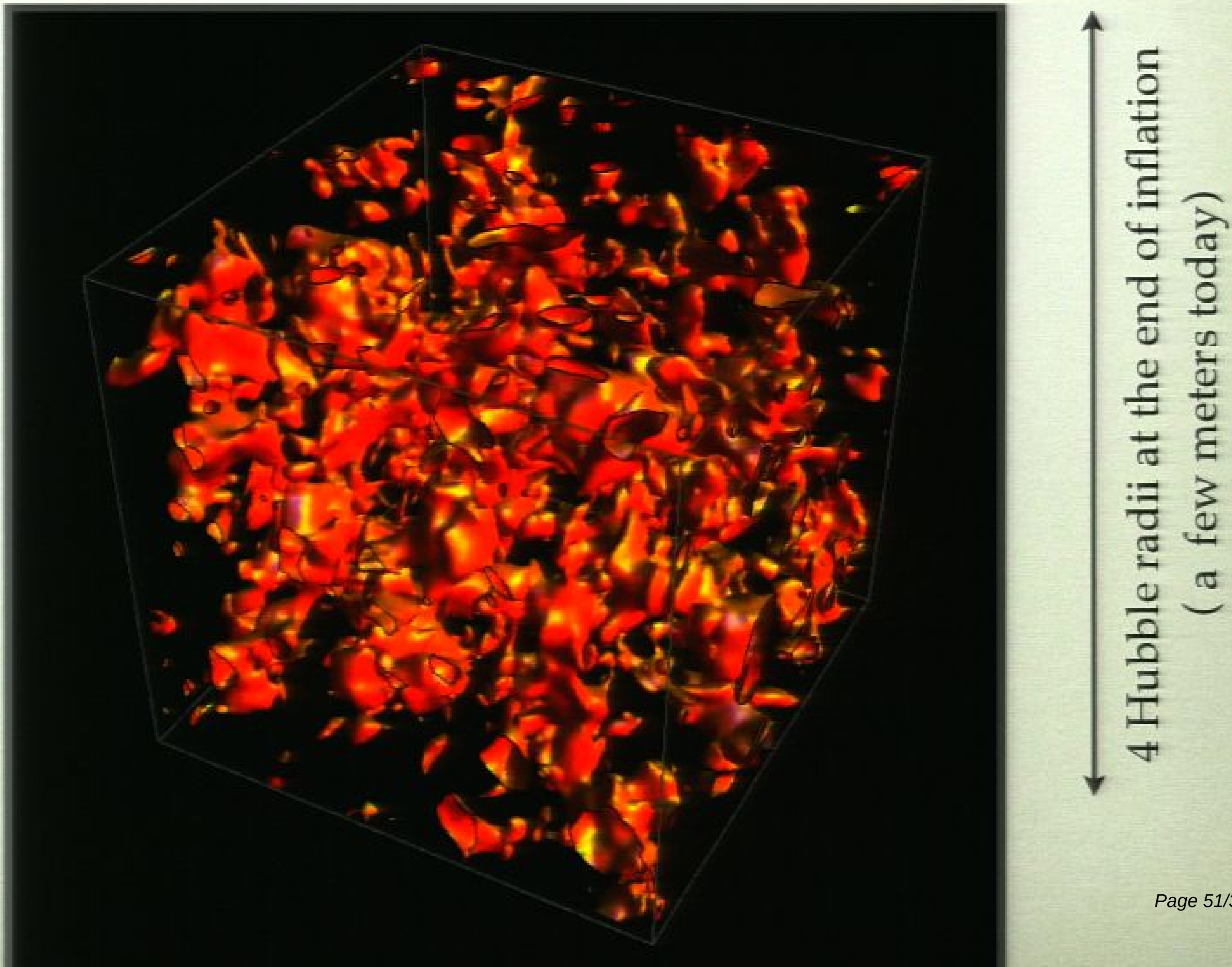

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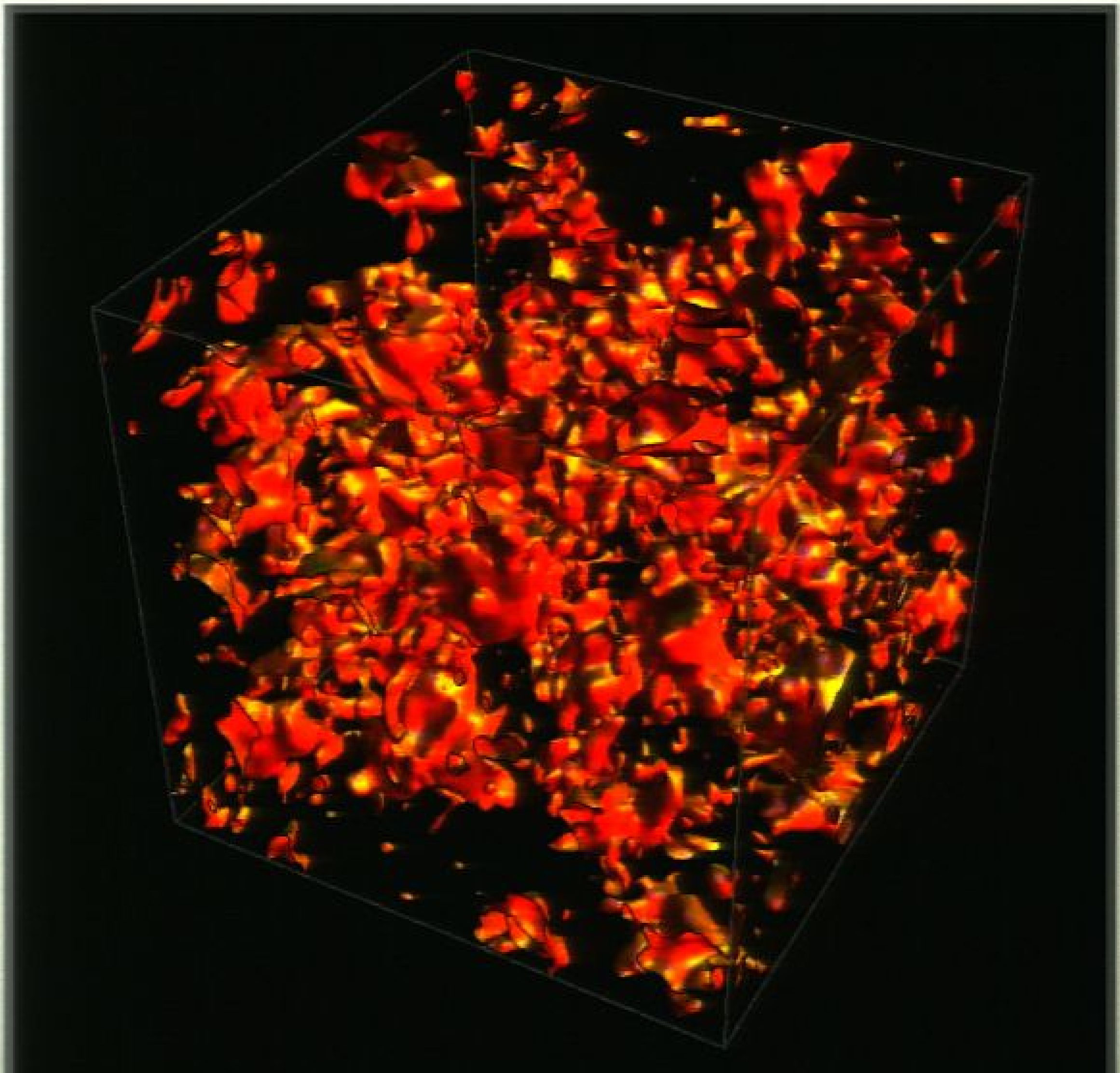

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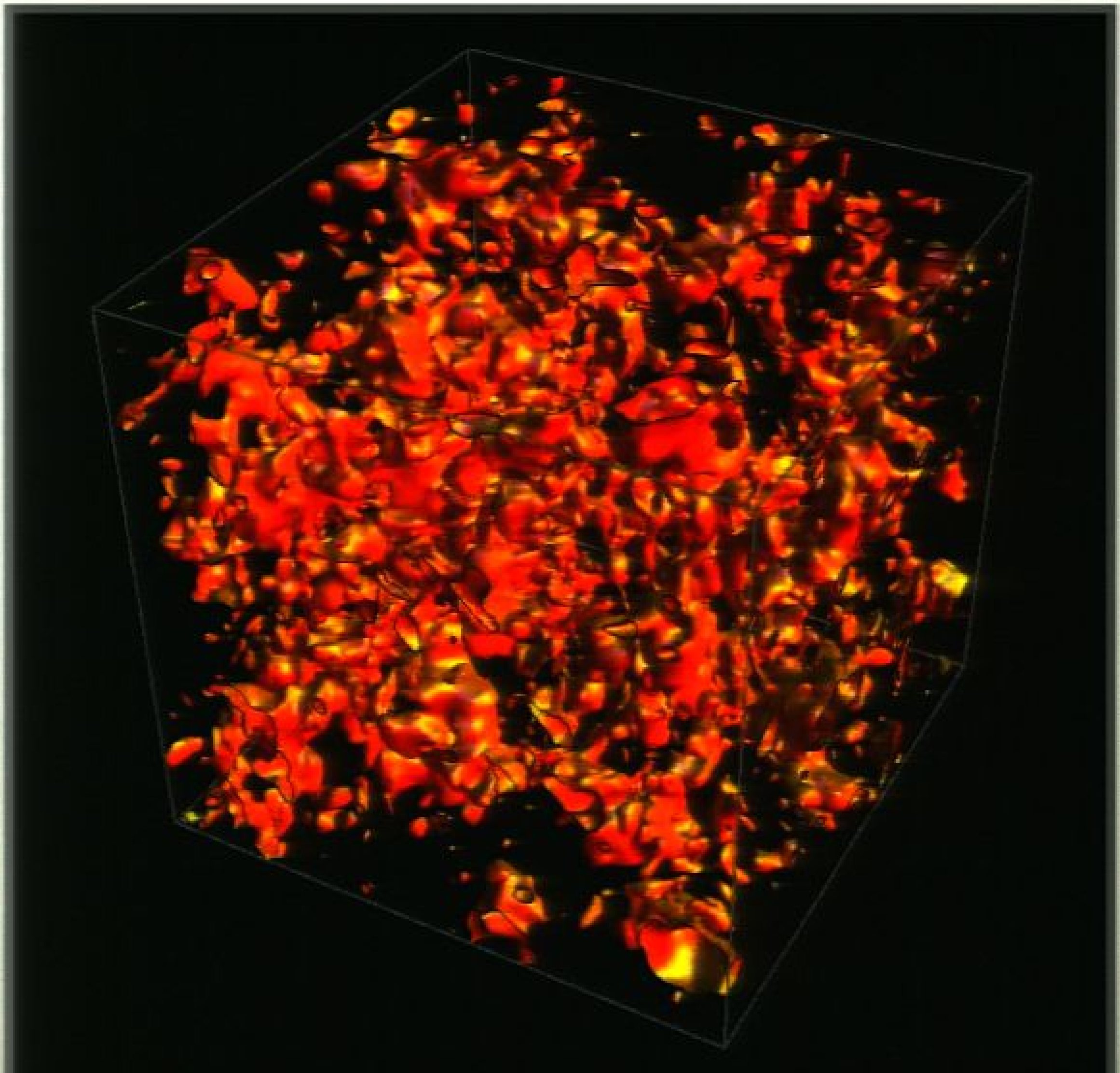

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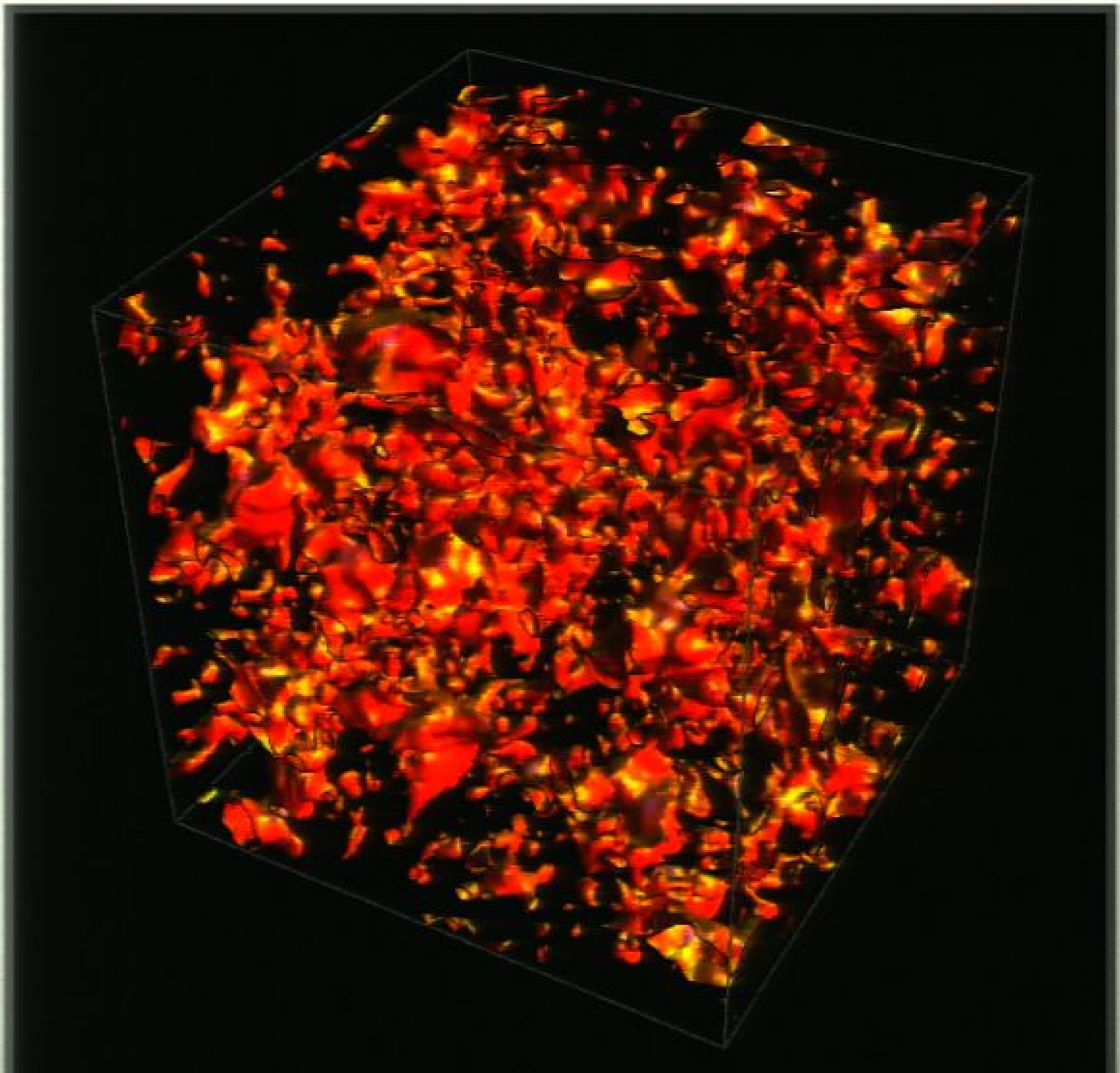

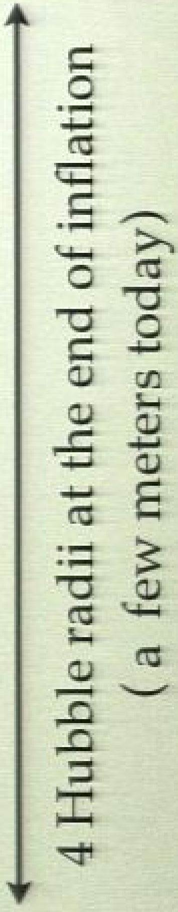

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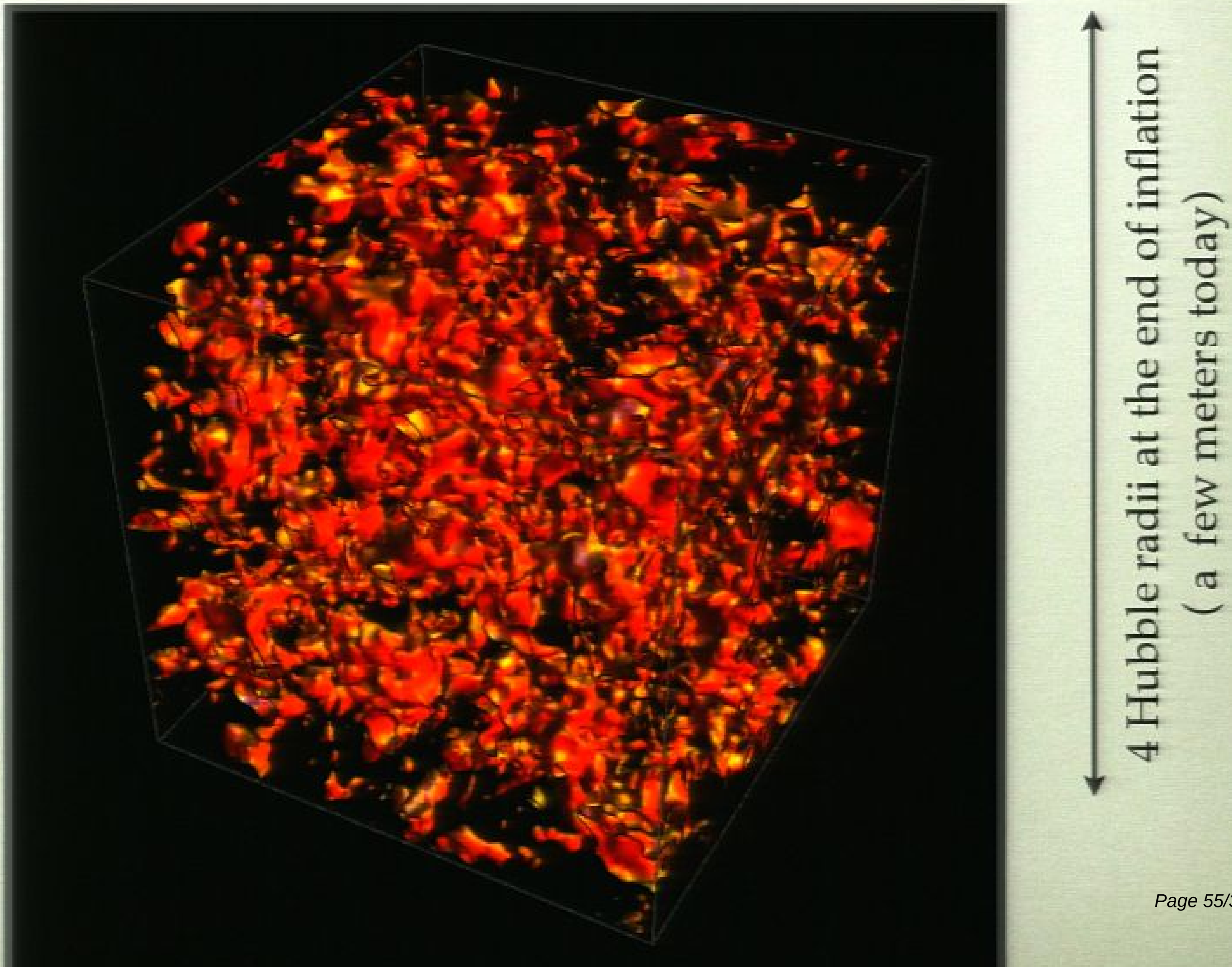

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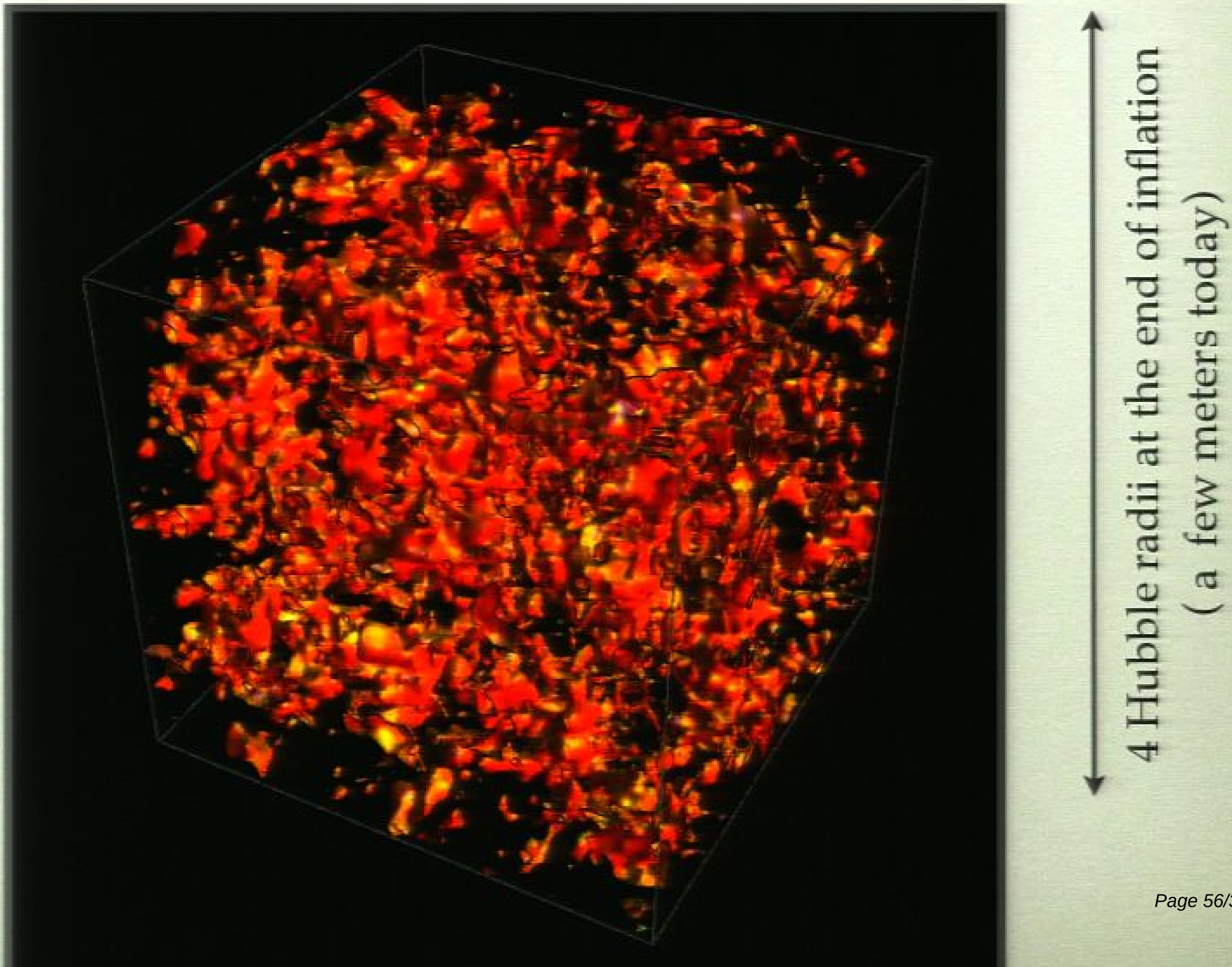
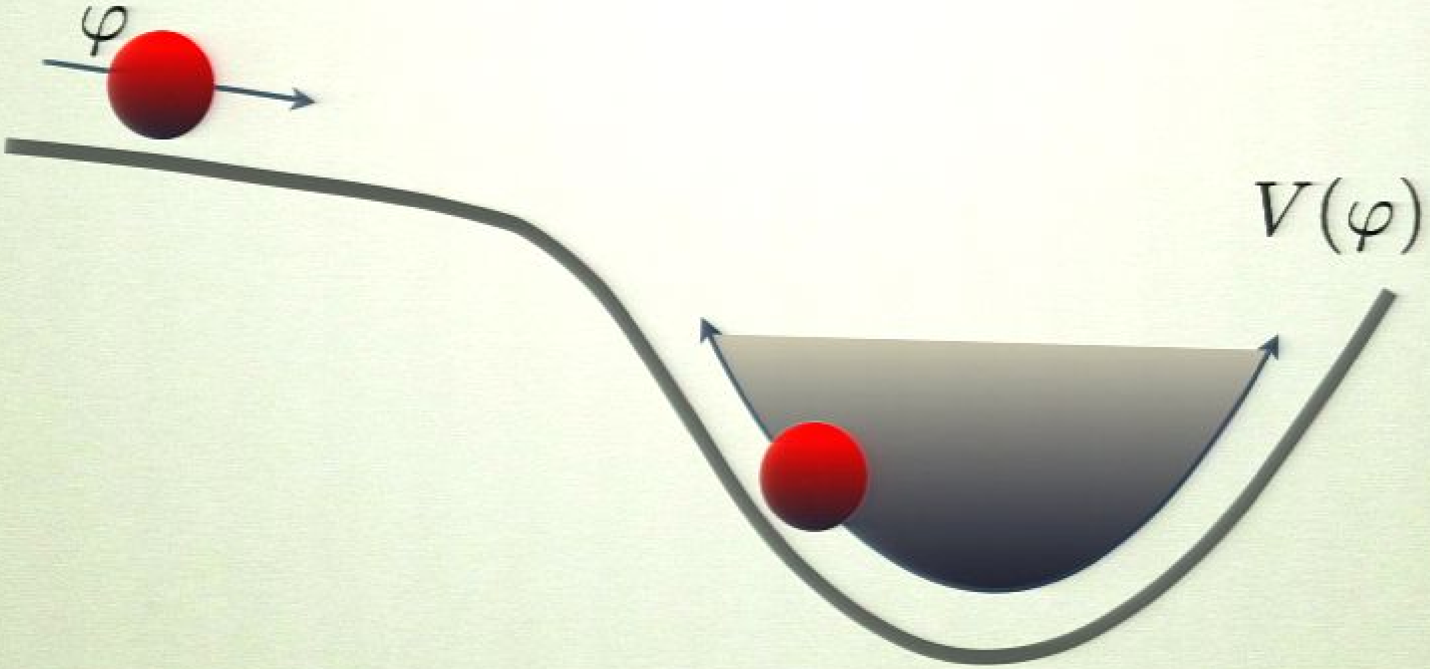
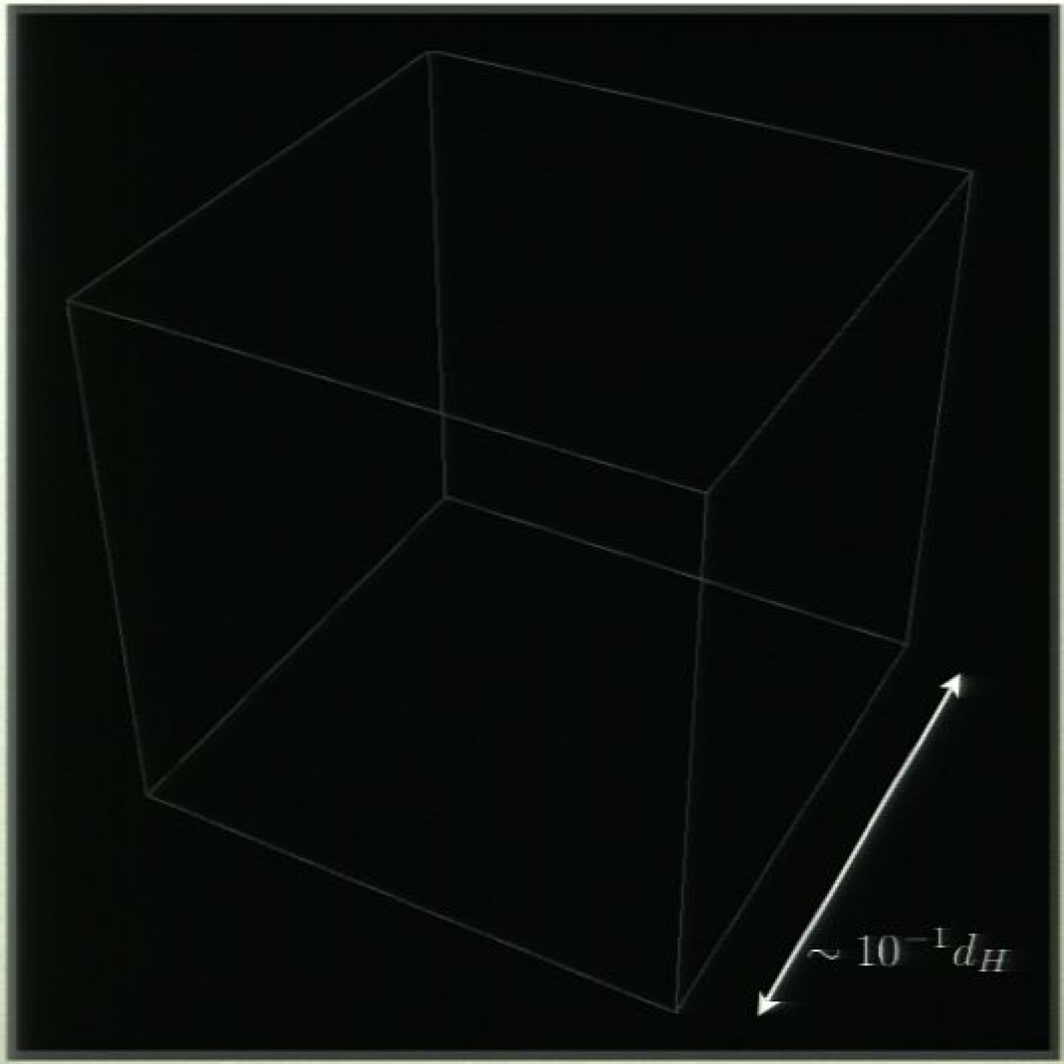


BUT ...



$$V \sim \frac{1}{2}m^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + \frac{g^2}{6m^2}\varphi^6 + \ldots + h\varphi\bar{\psi}\psi$$

PSEUDO STABLE LUMPS



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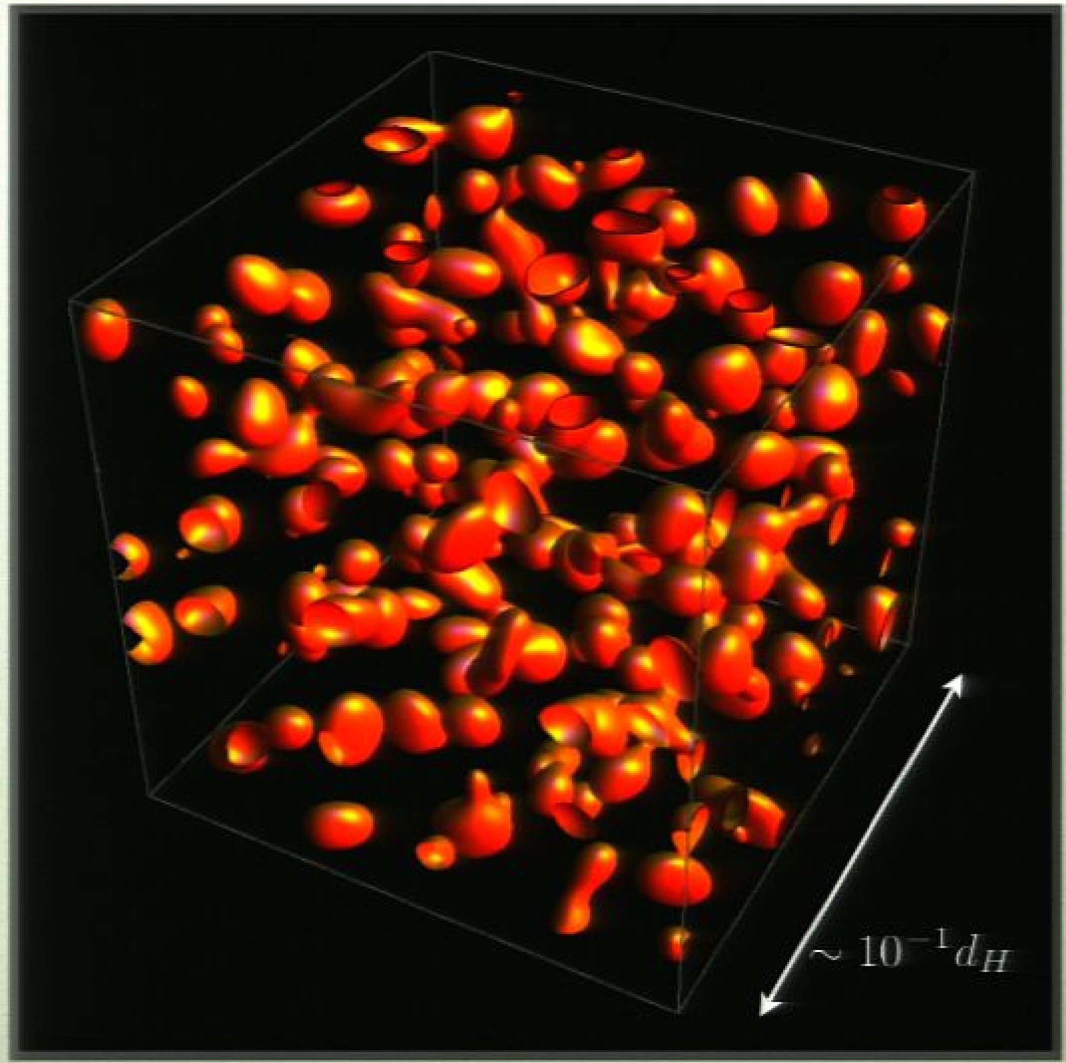
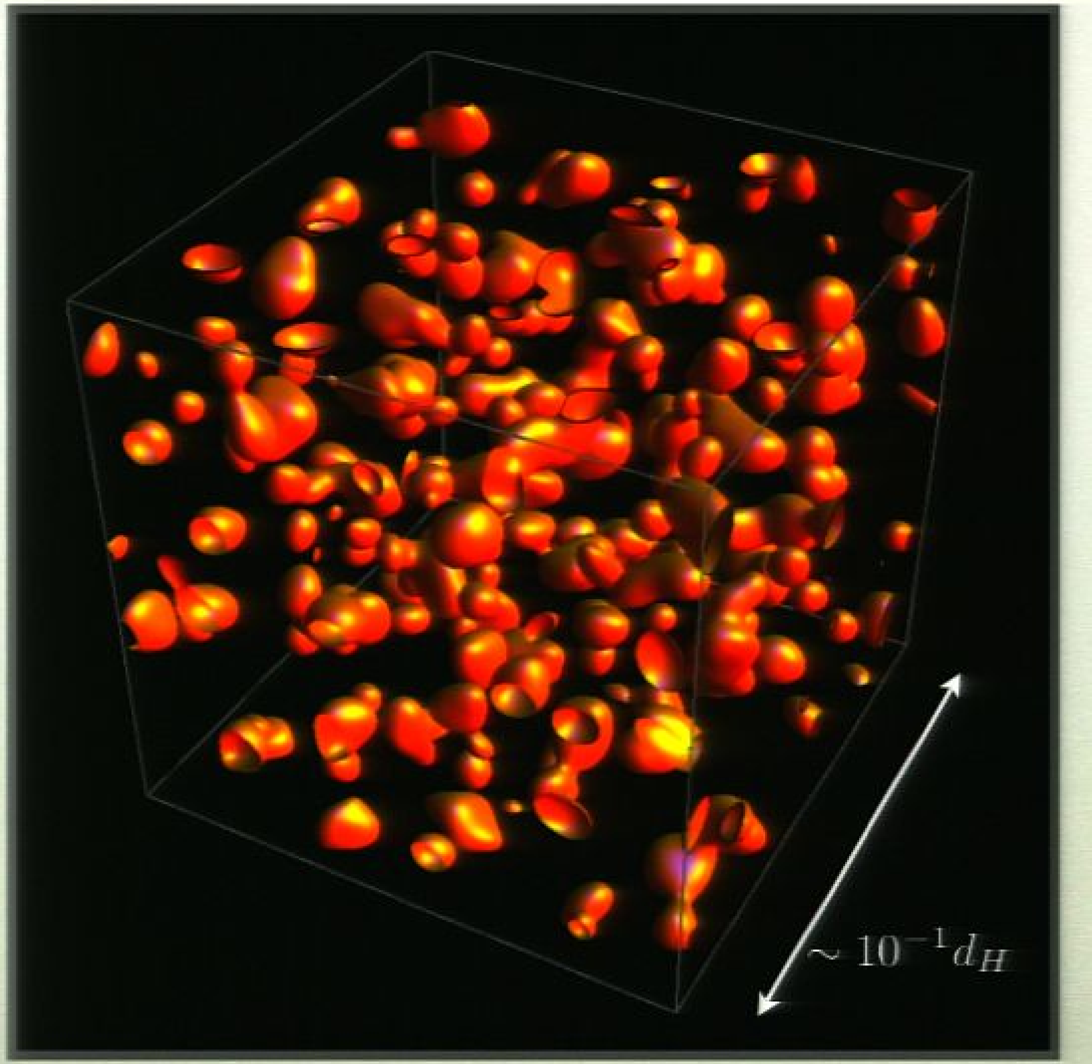


PSEUDO STABLE LUMPS



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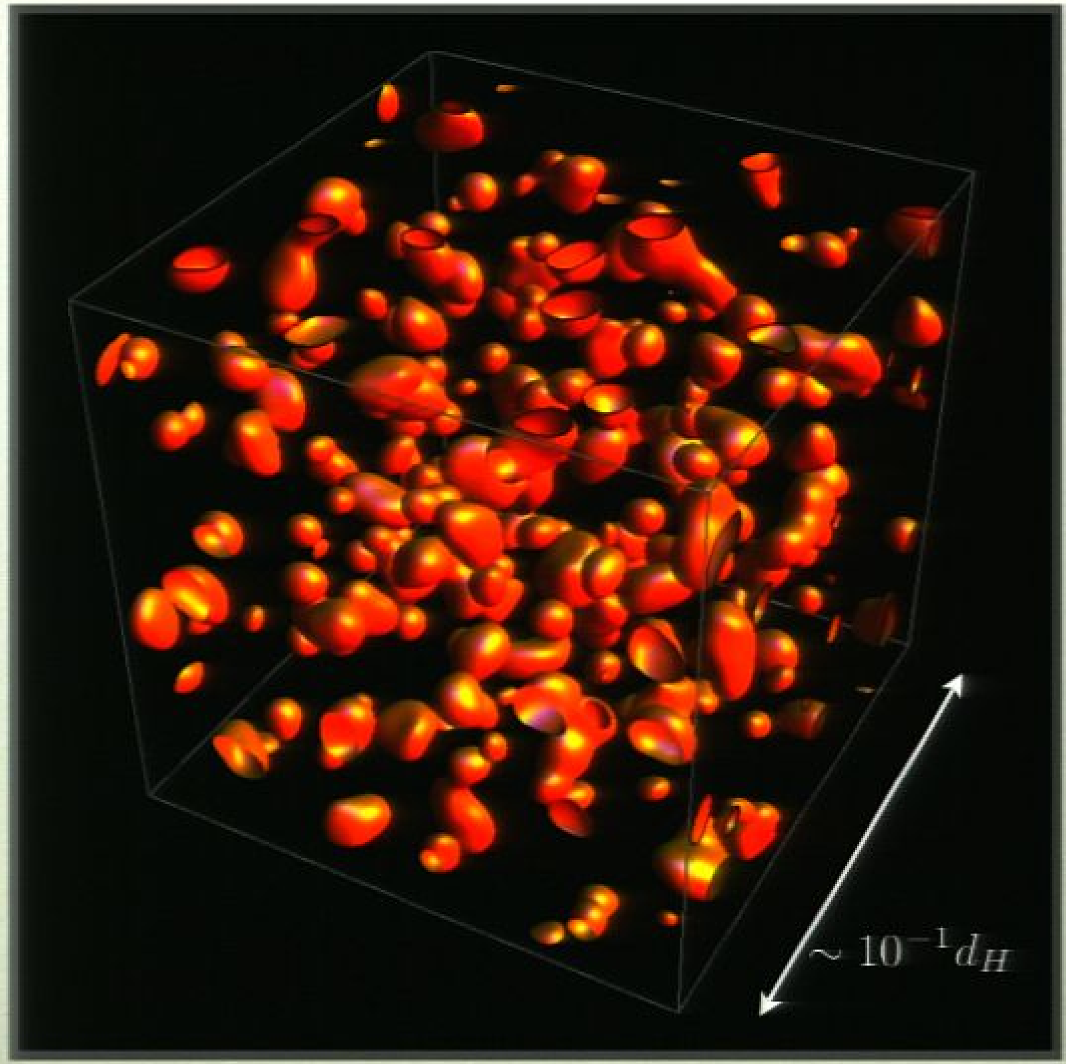

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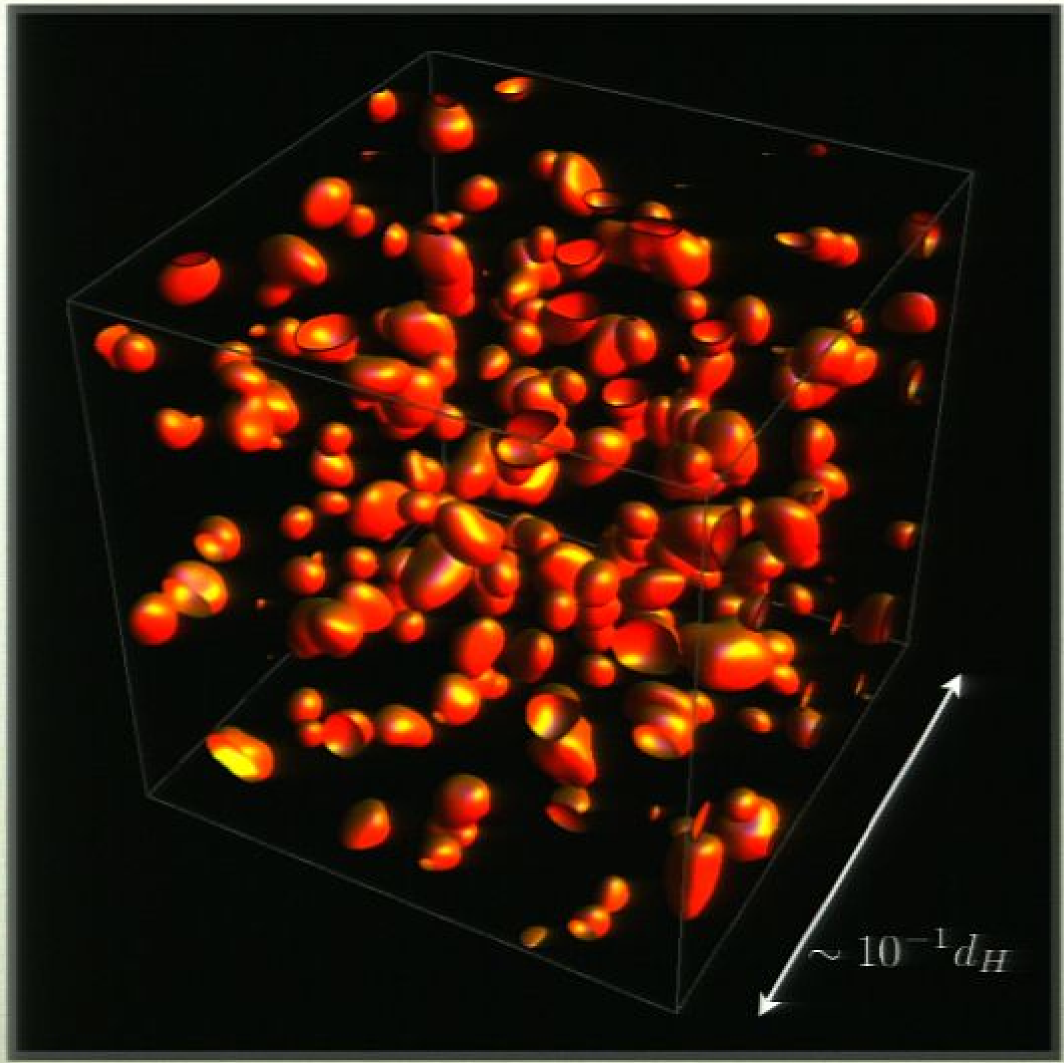

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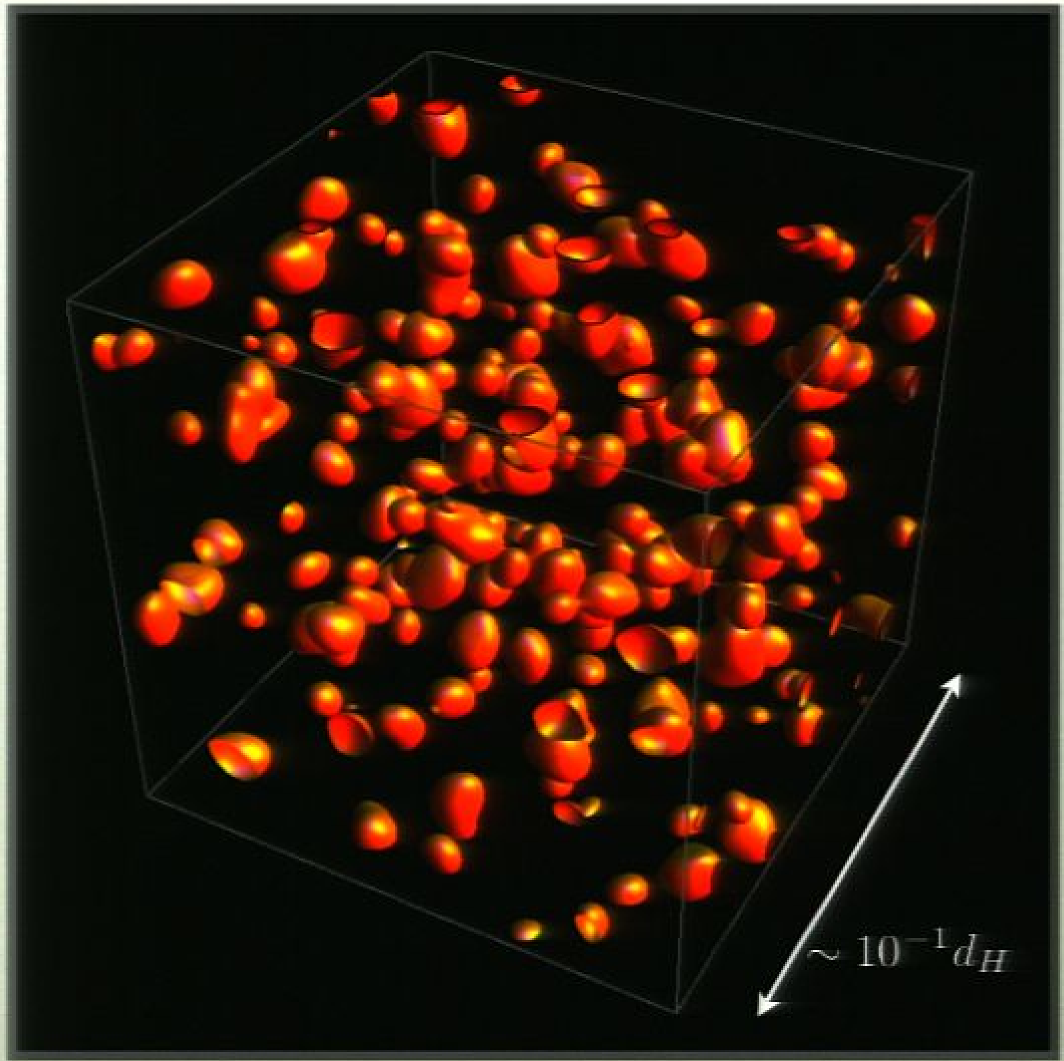

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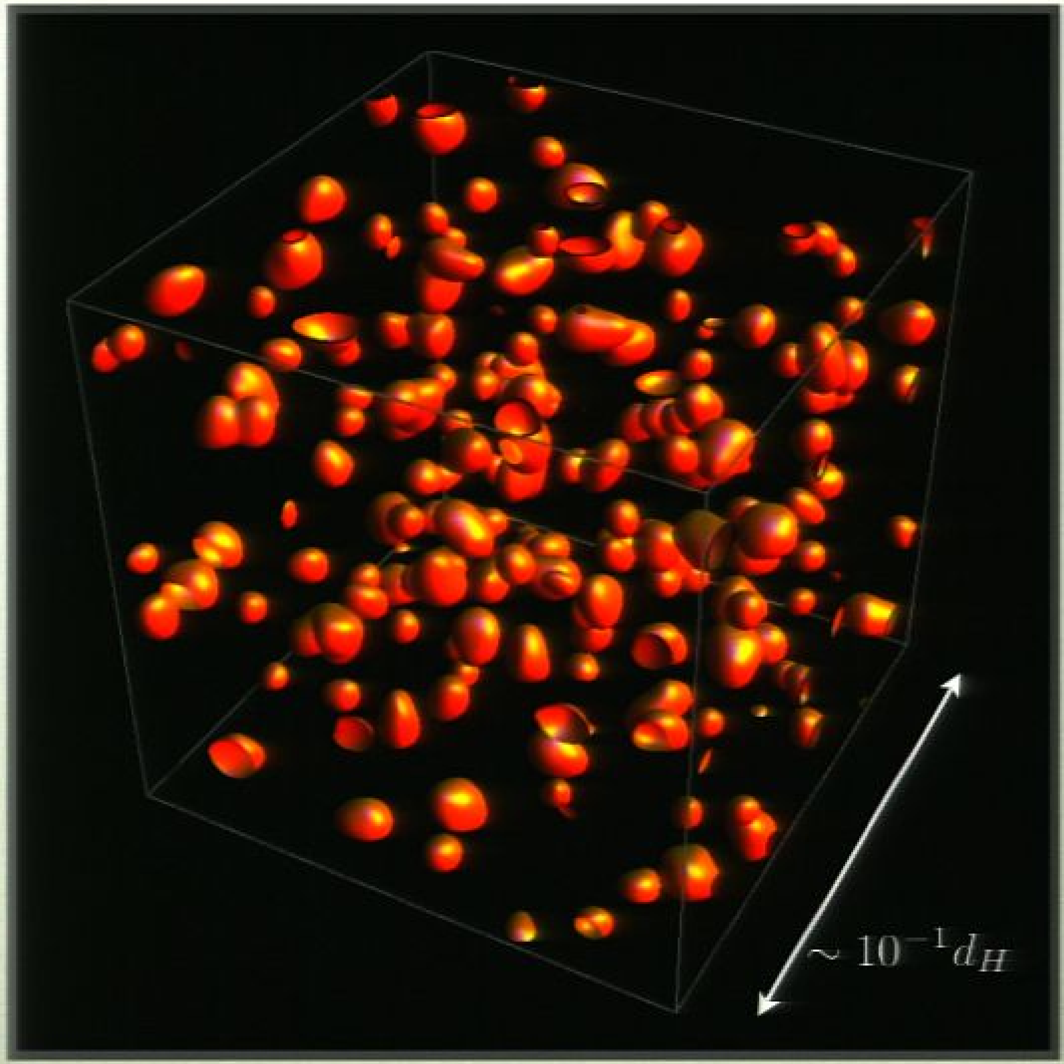

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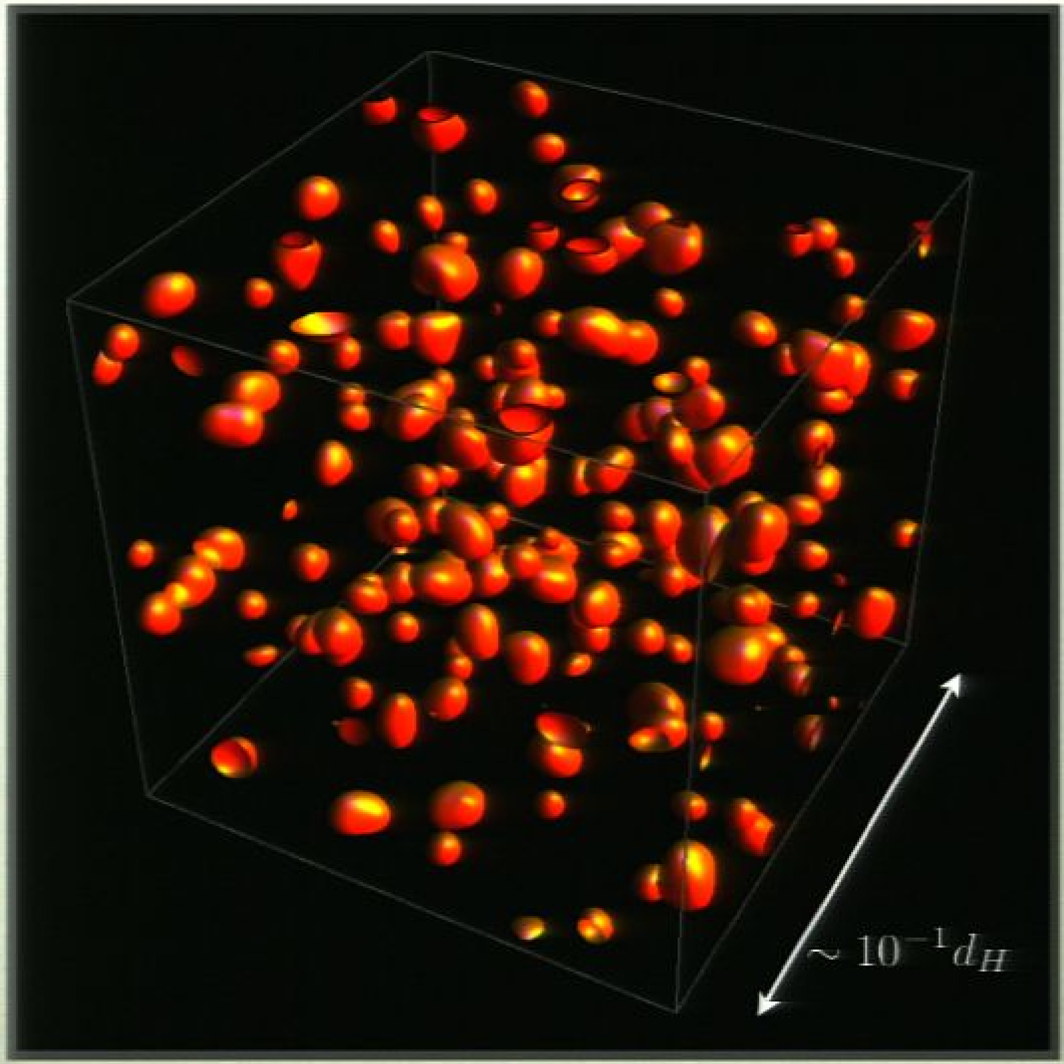

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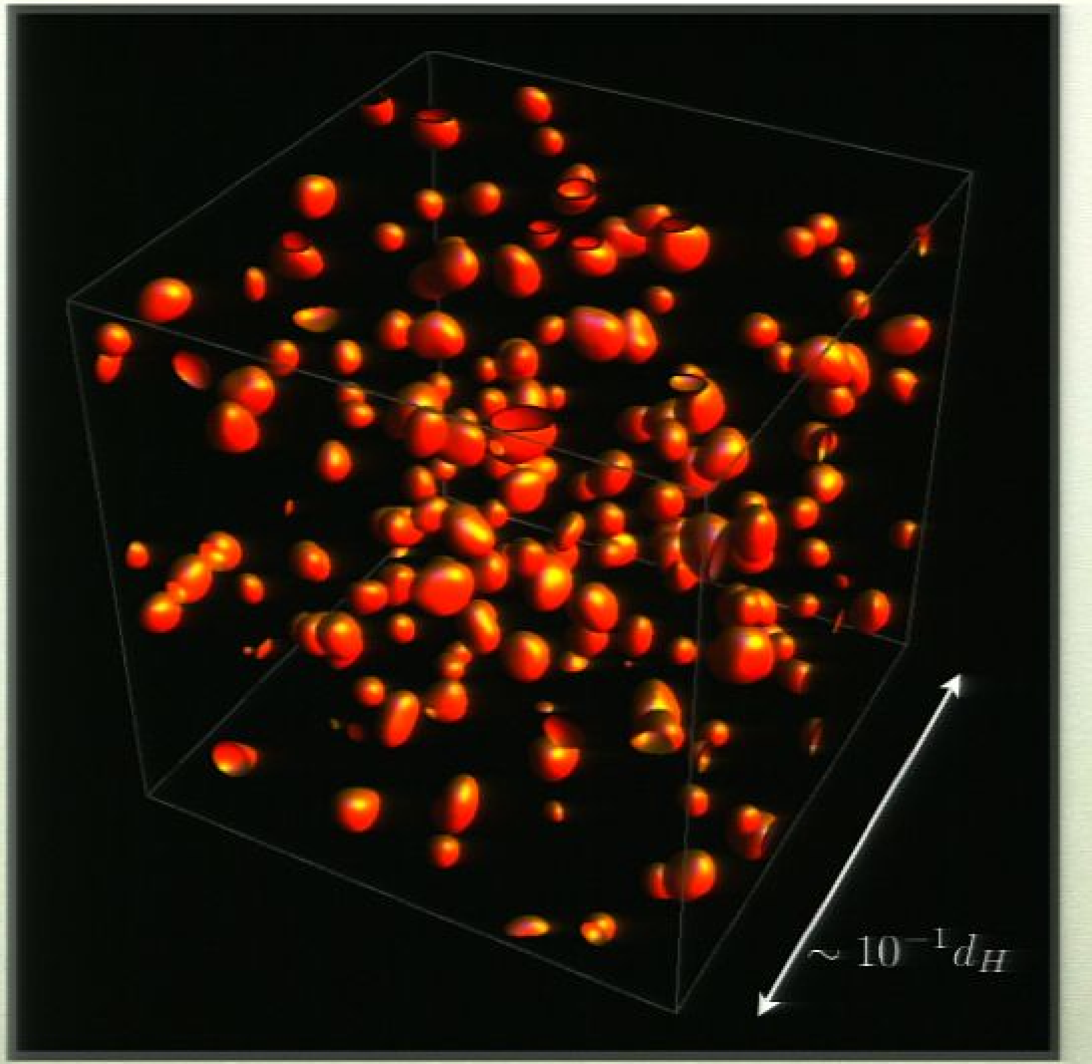

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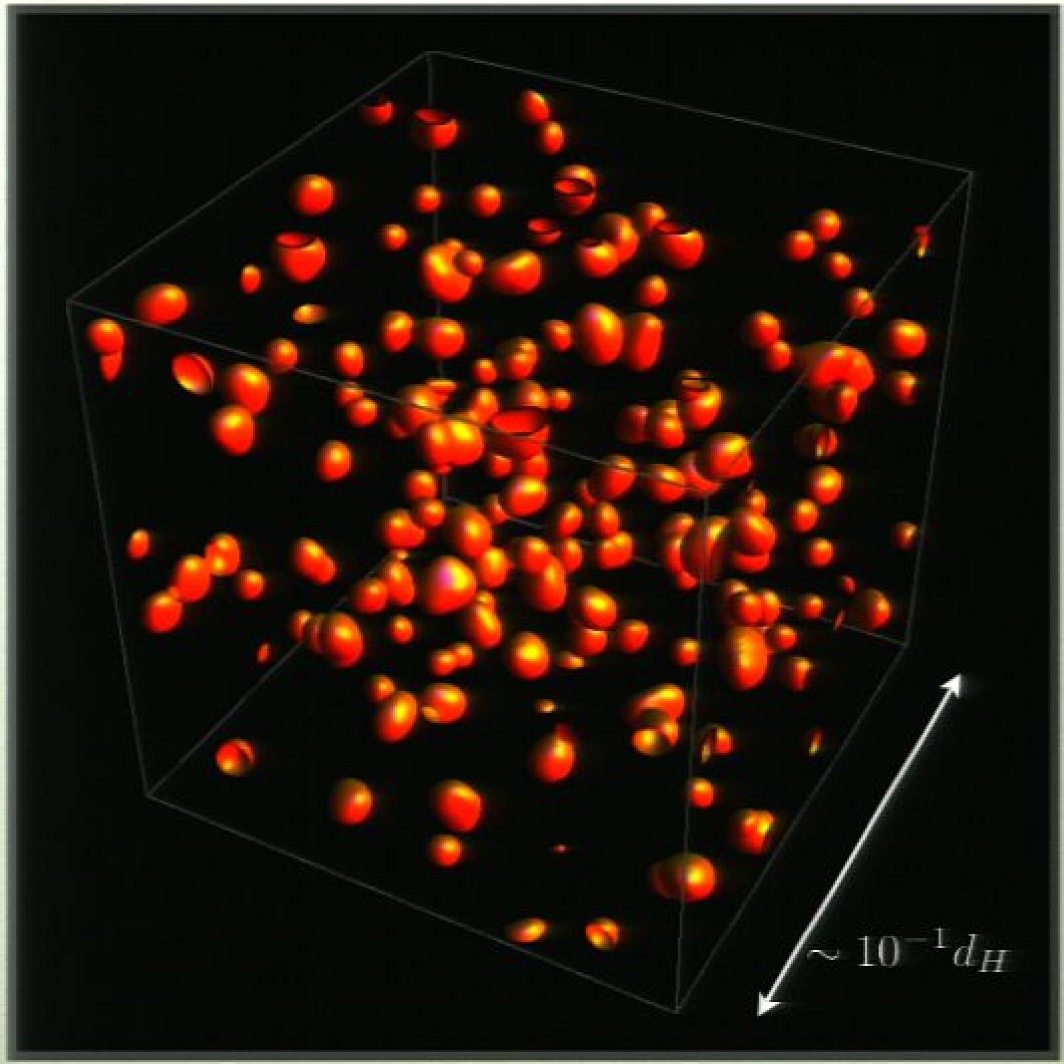

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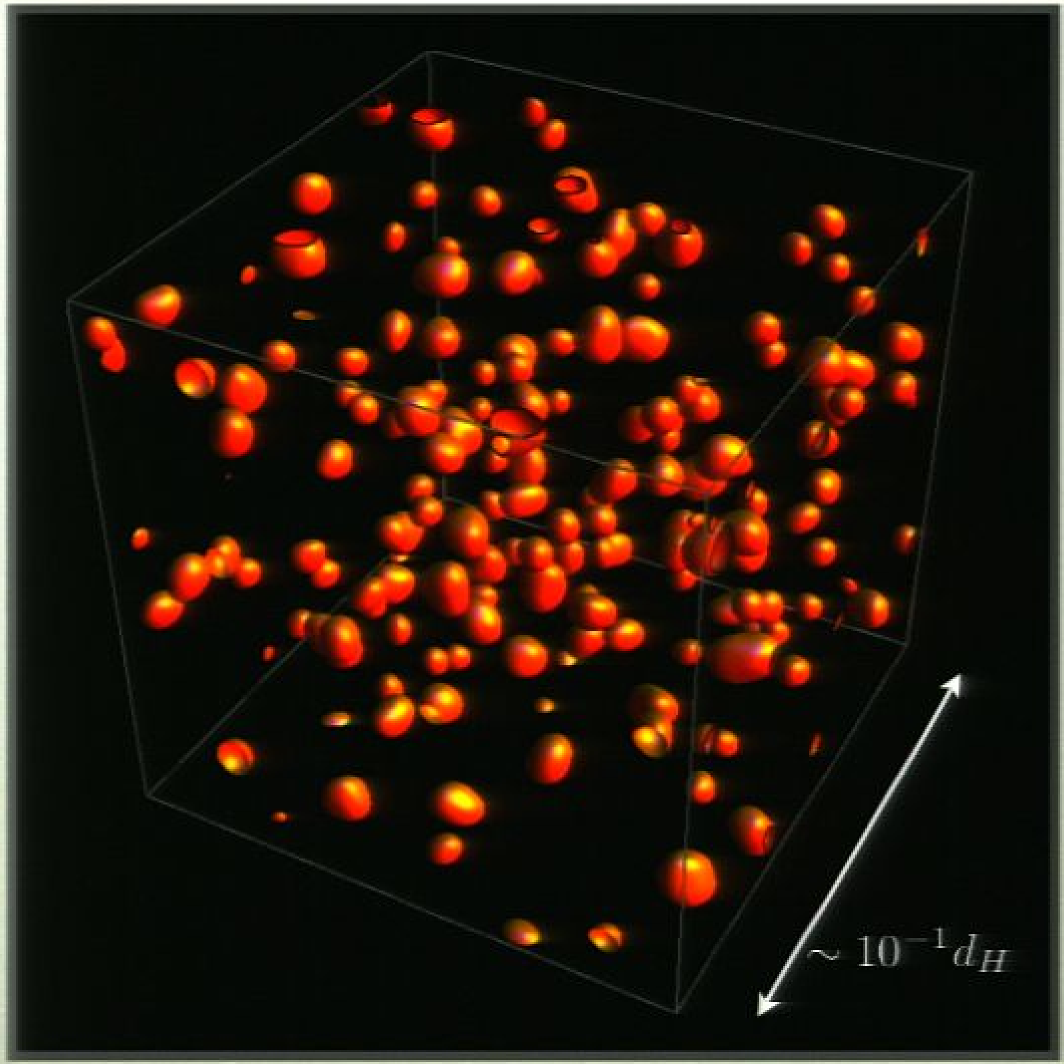

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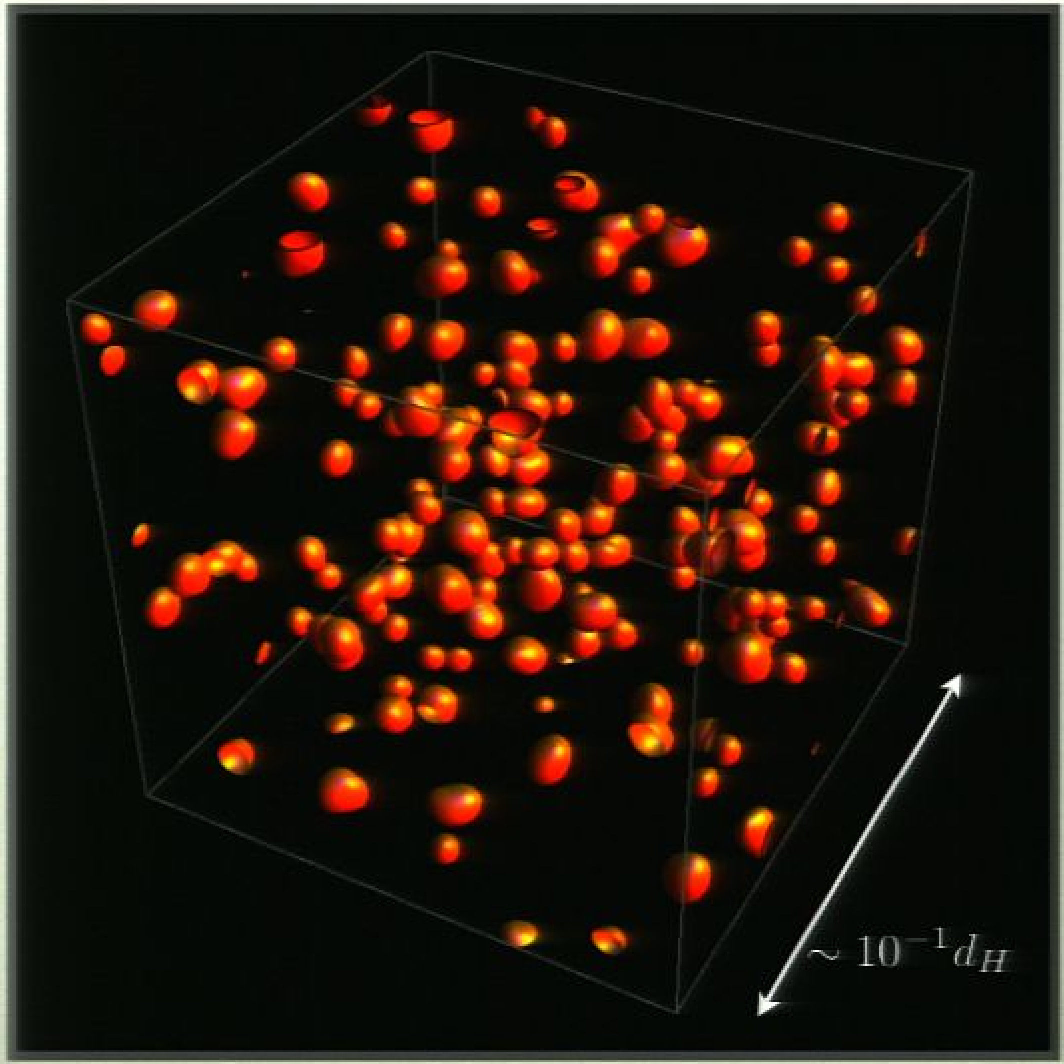

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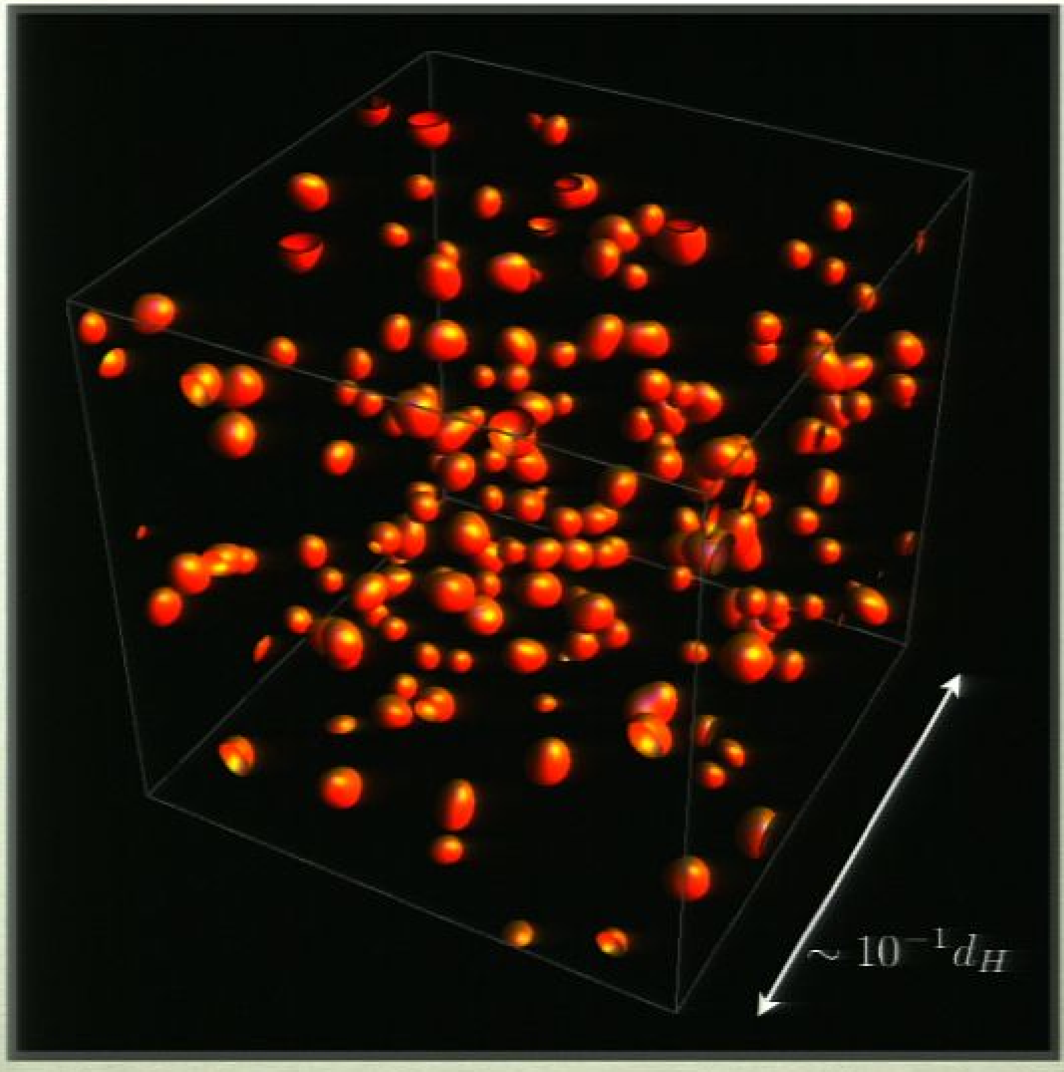

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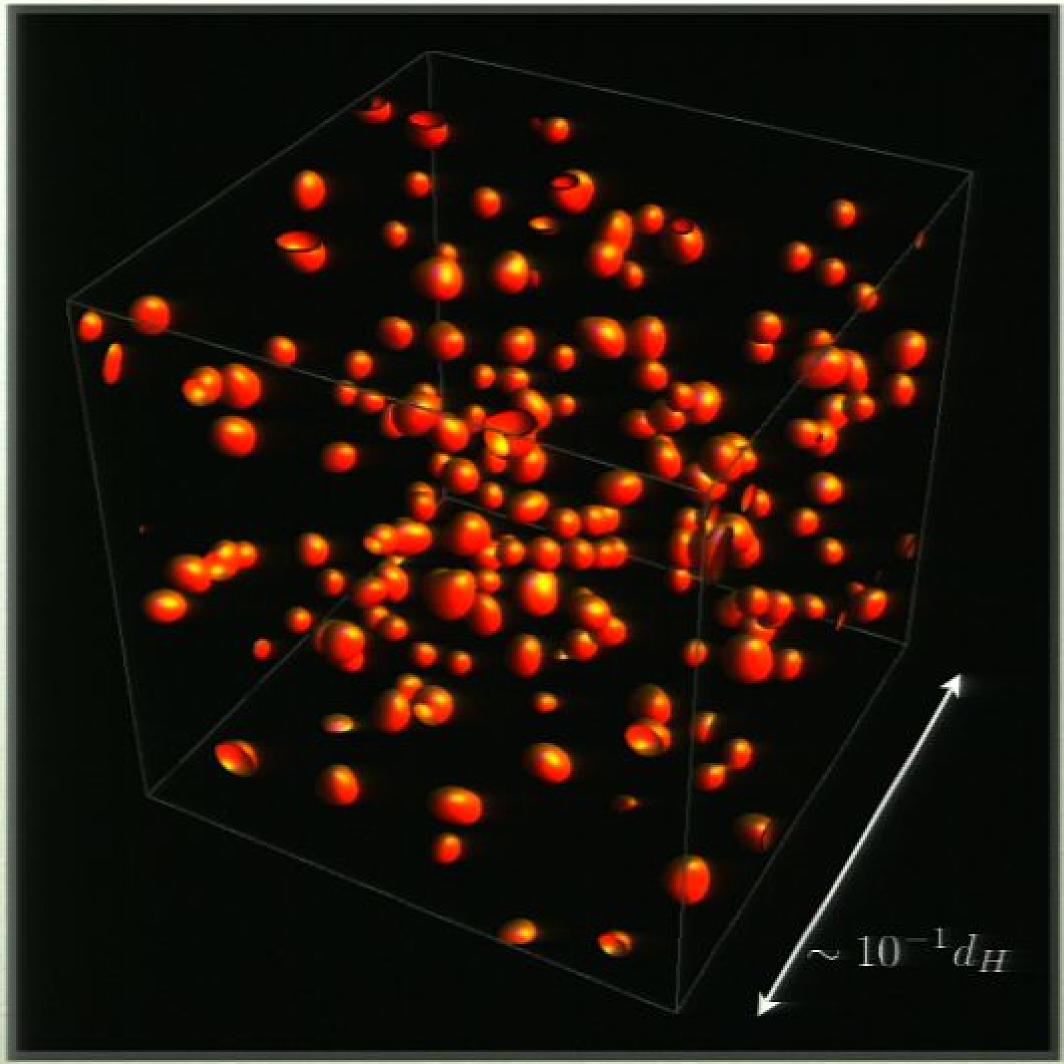
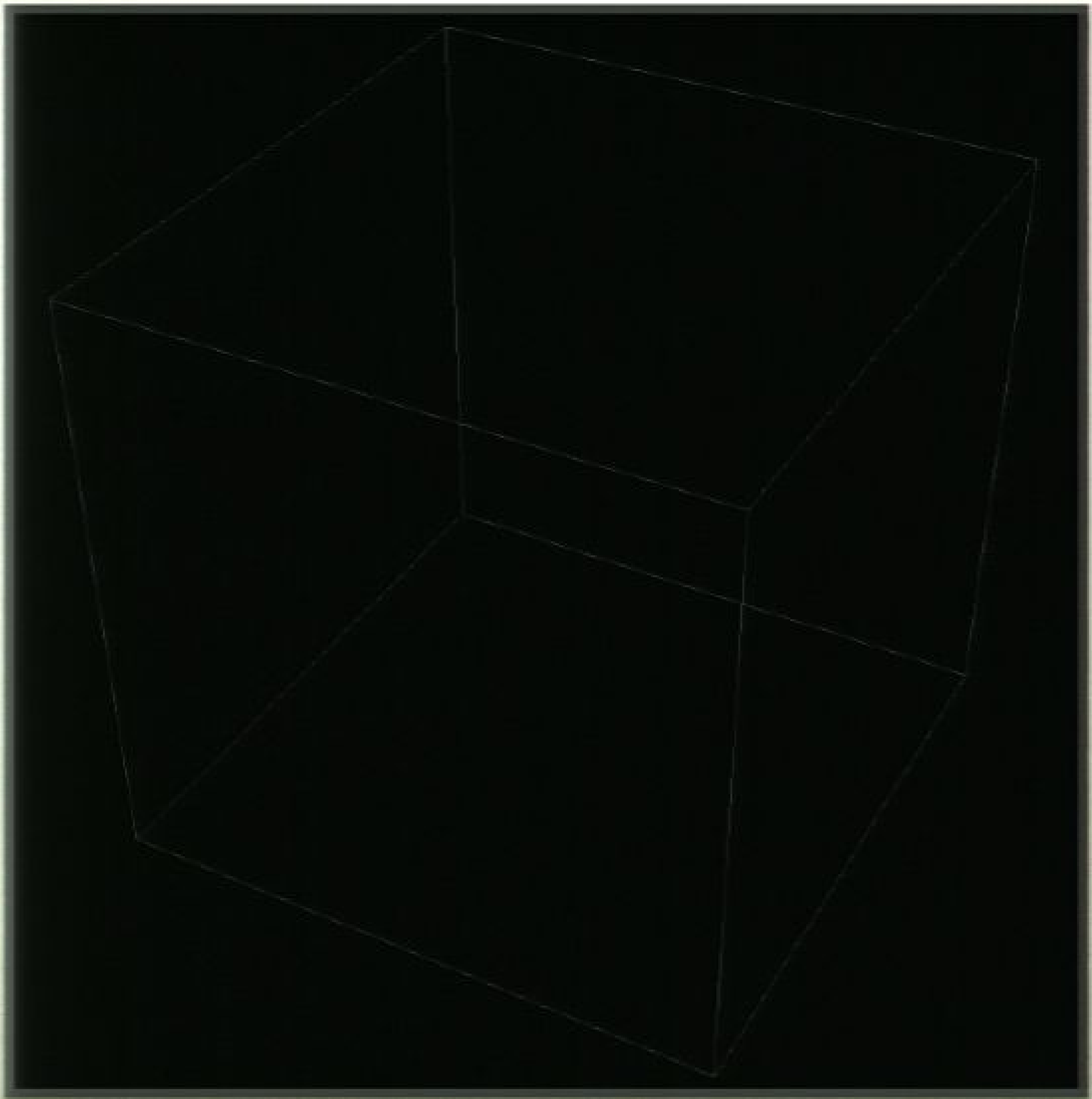


CLOSER LOOK



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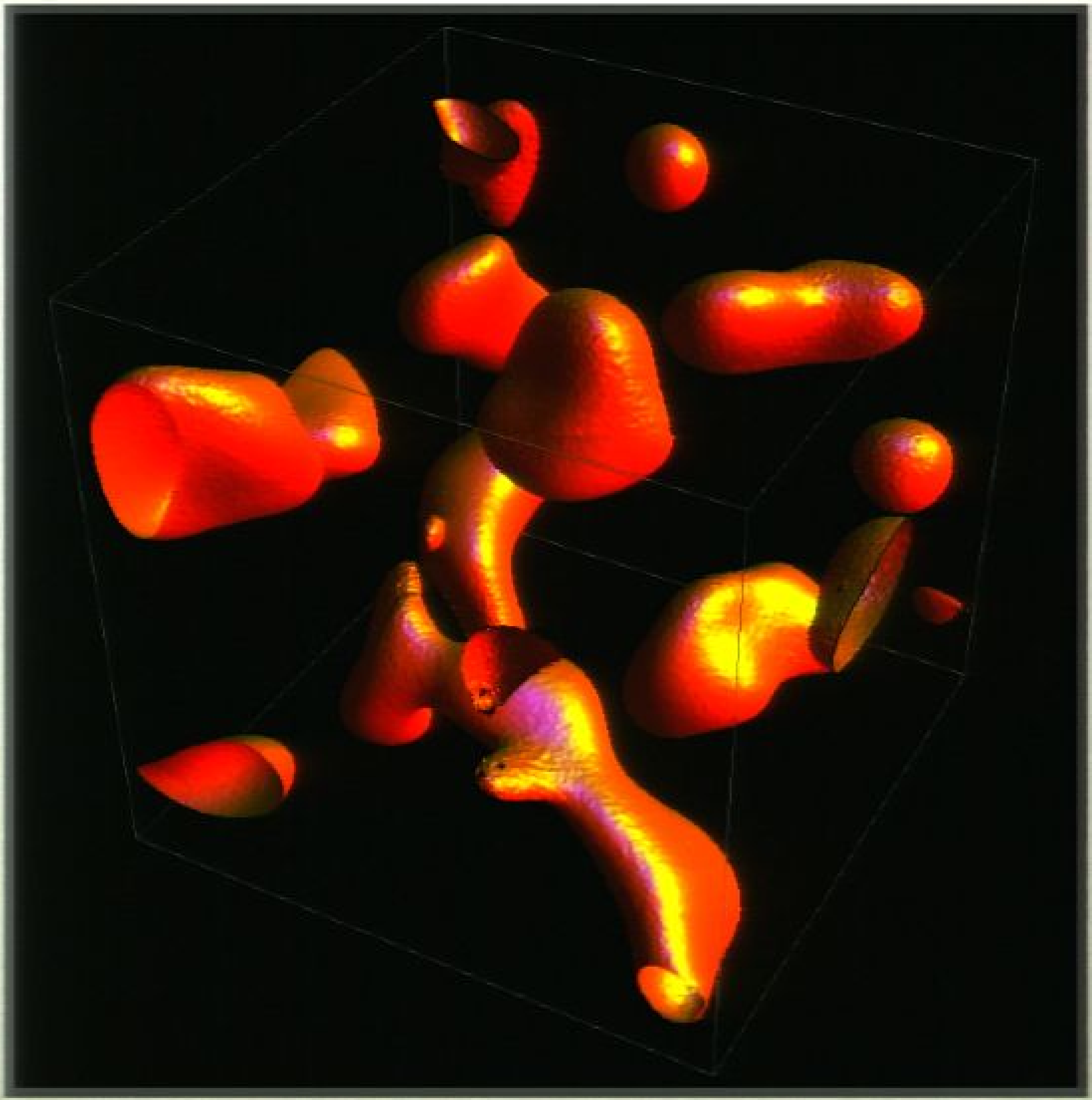

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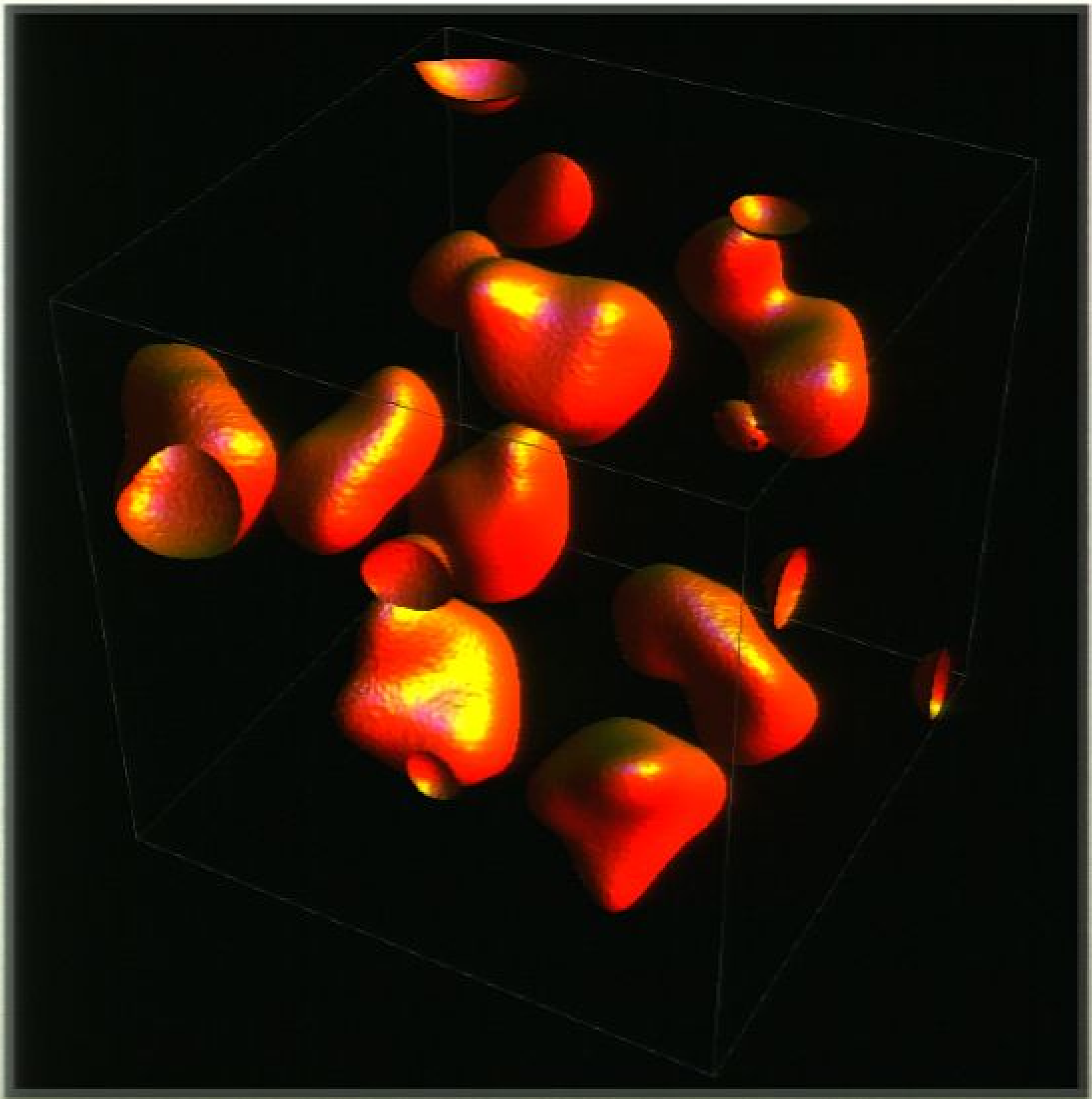

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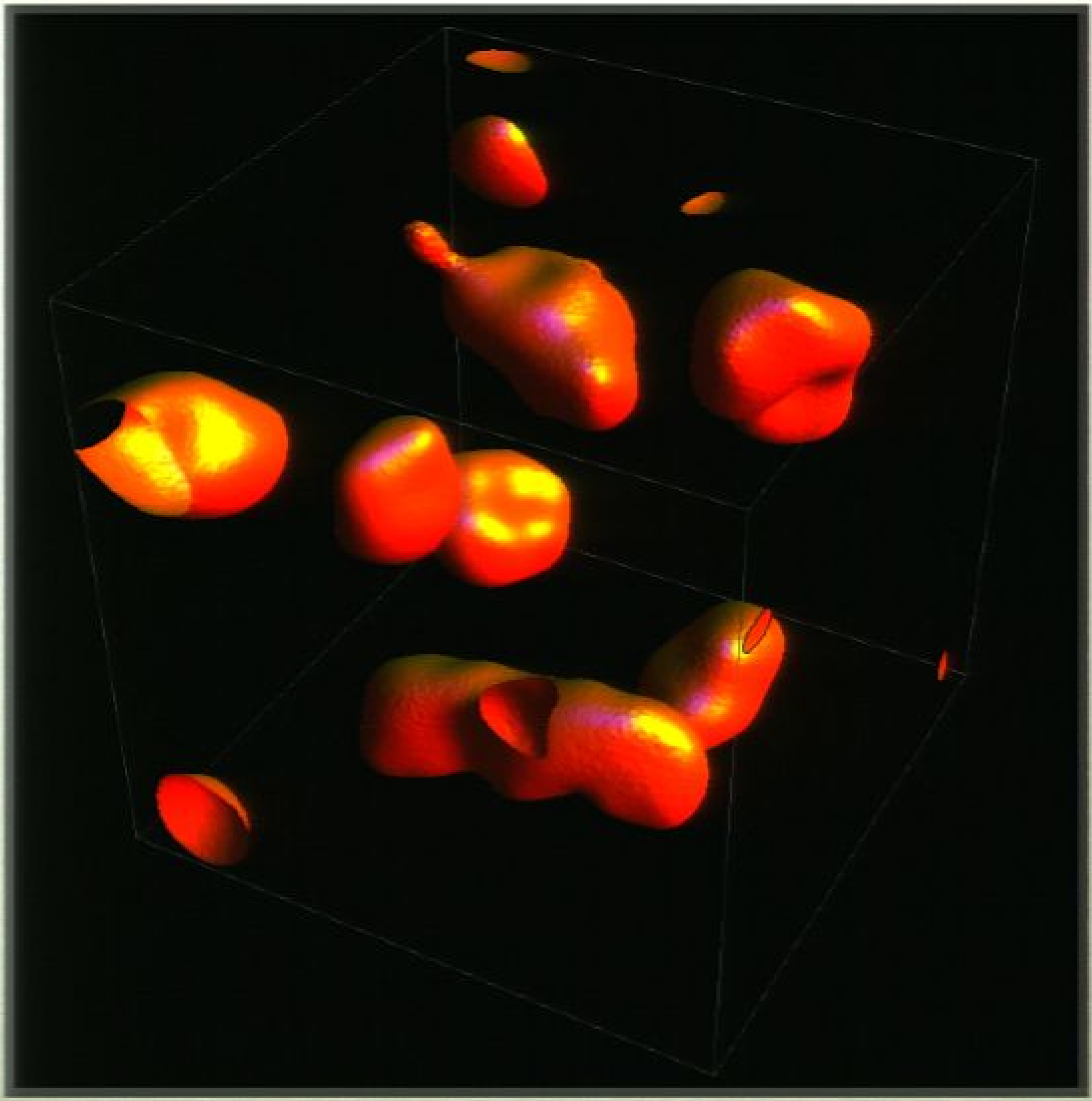
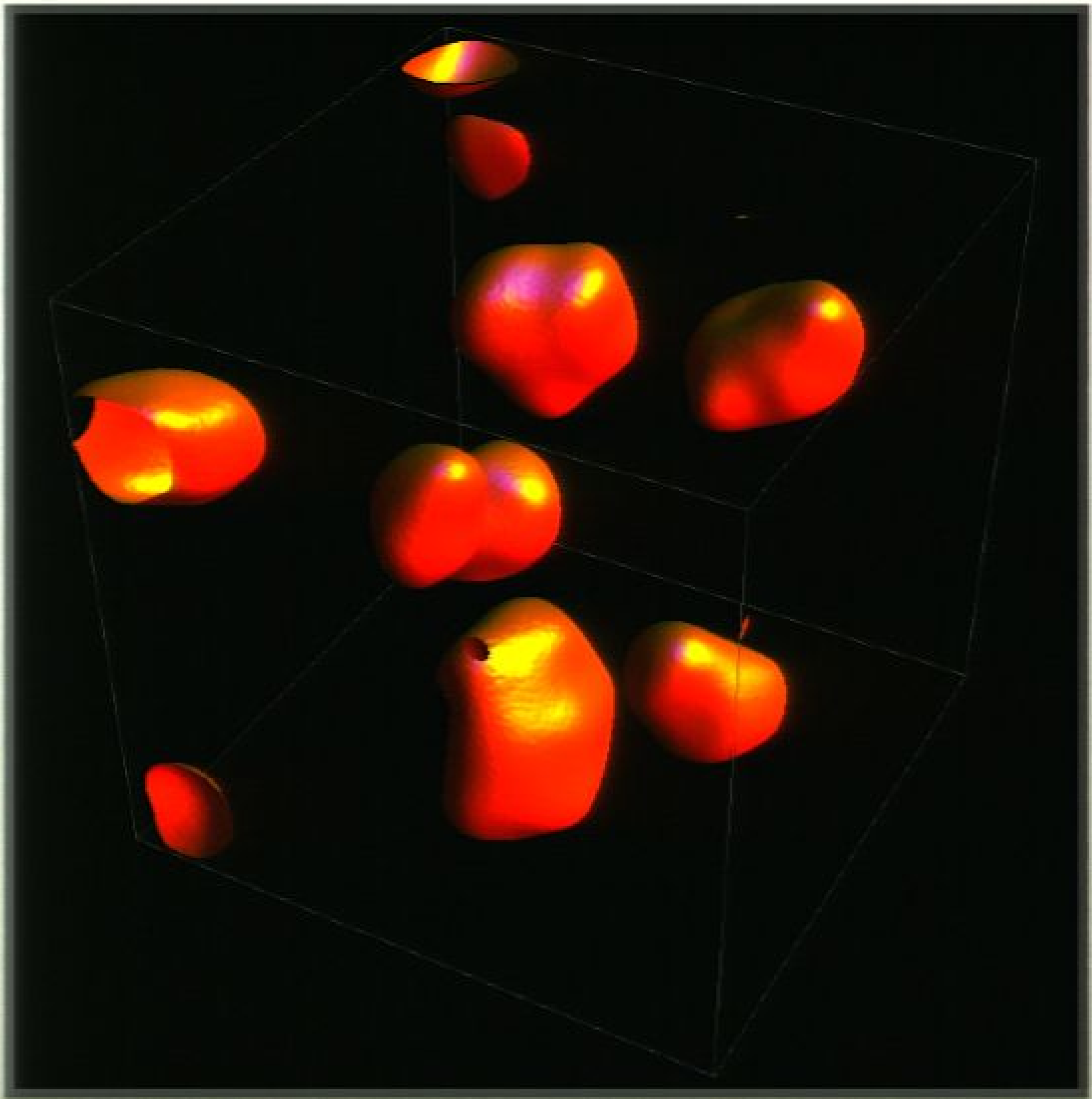


CLOSER LOOK



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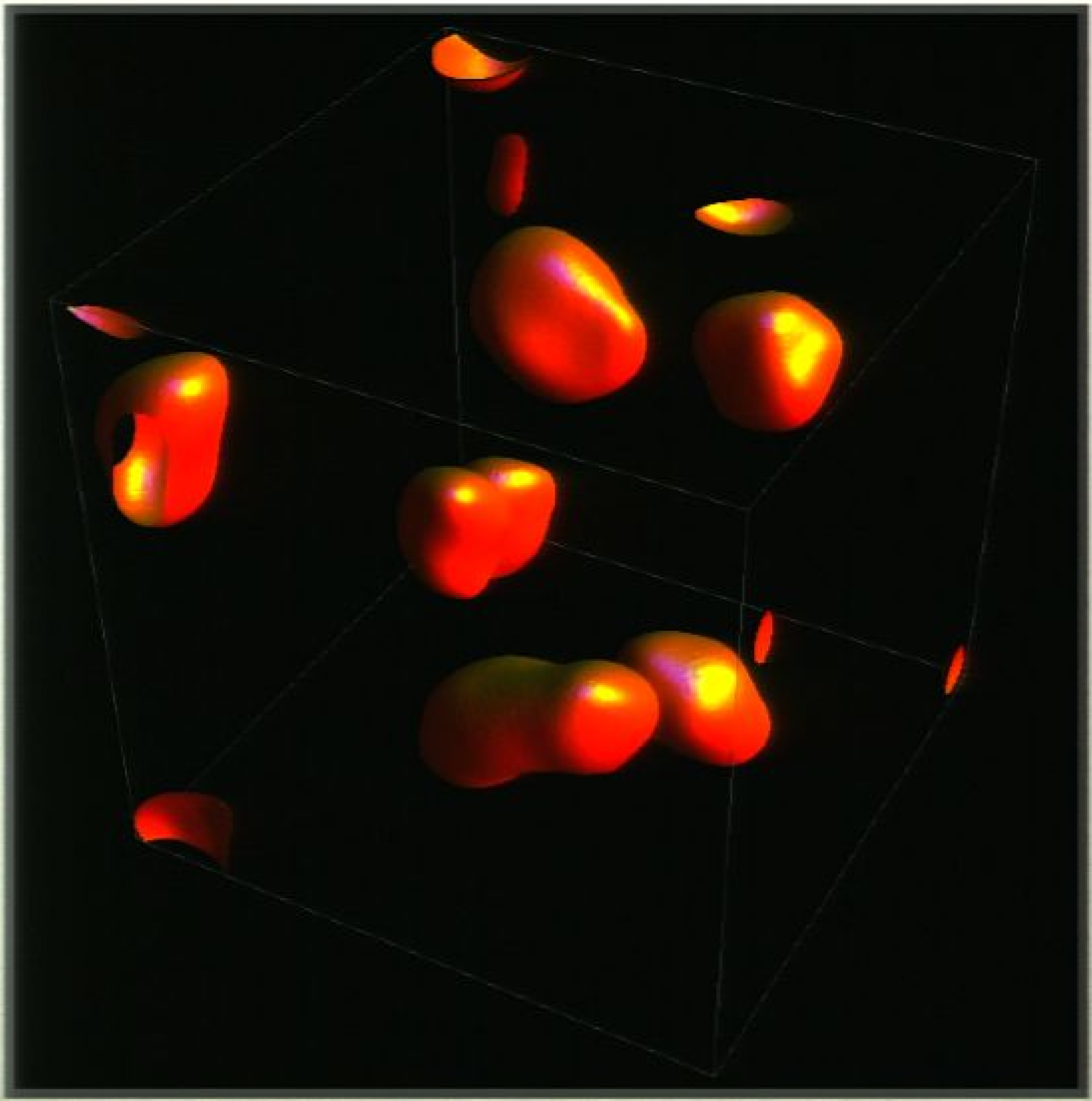
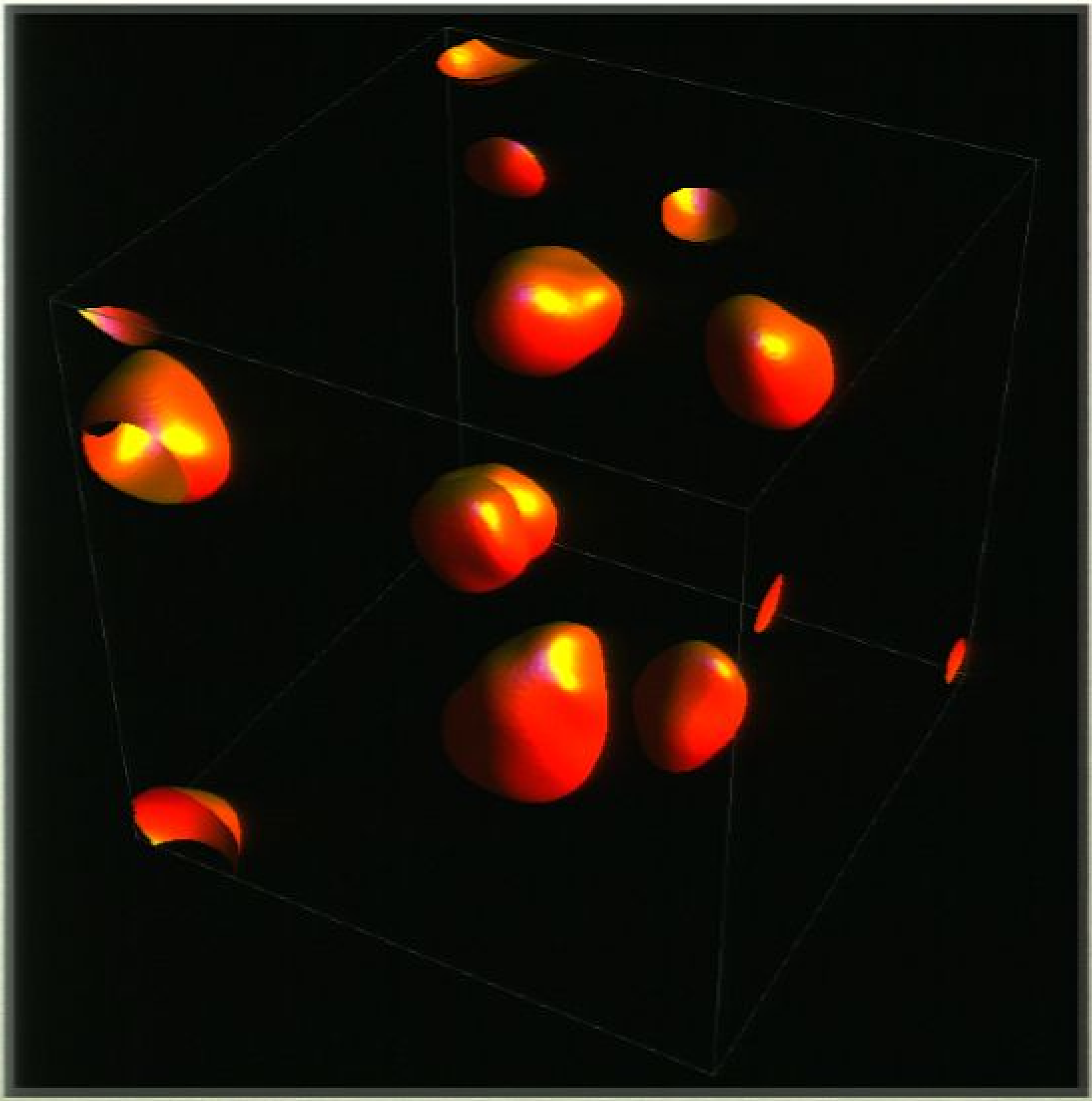
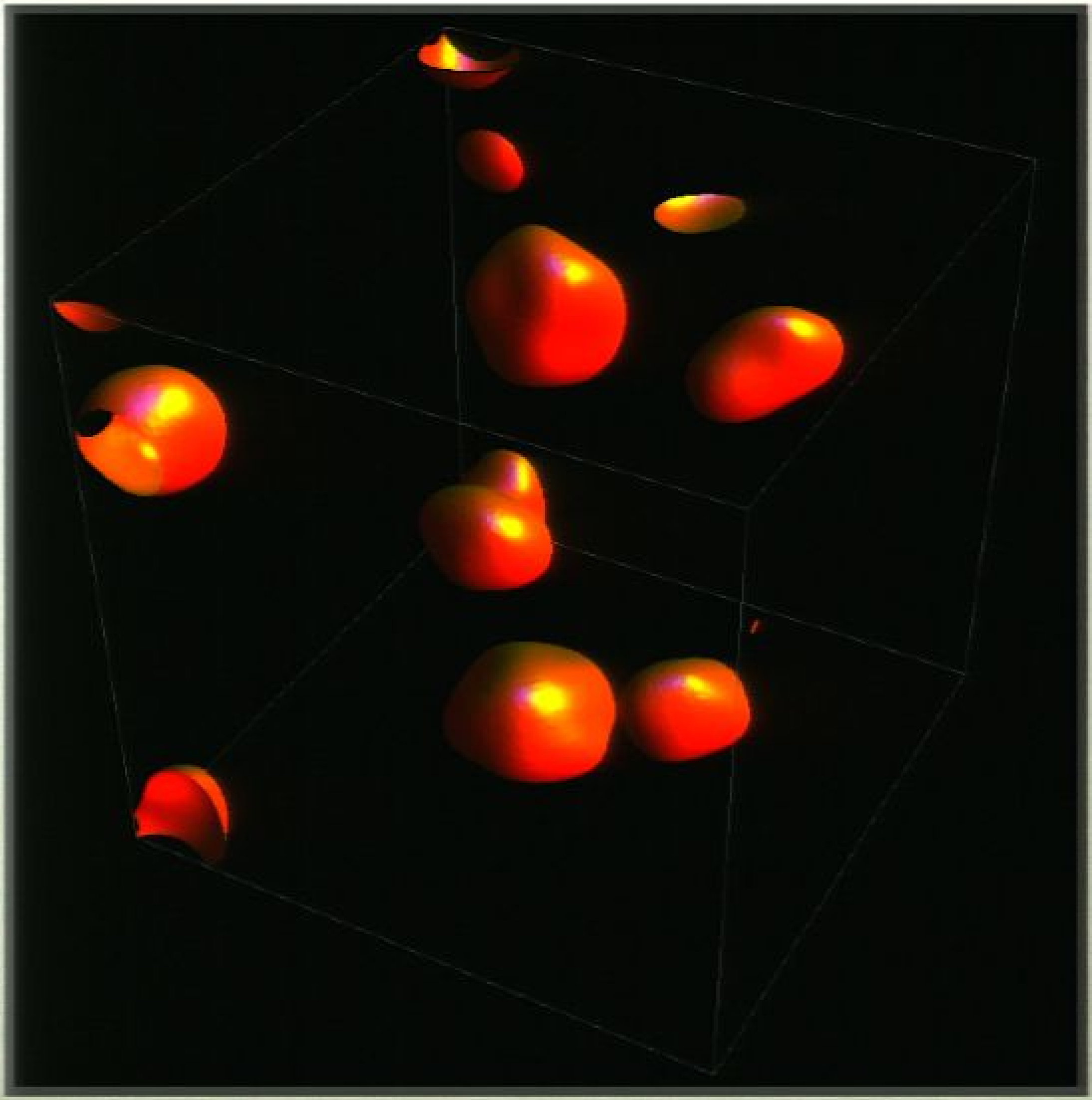


CLOSER LOOK



CLOSER LOOK



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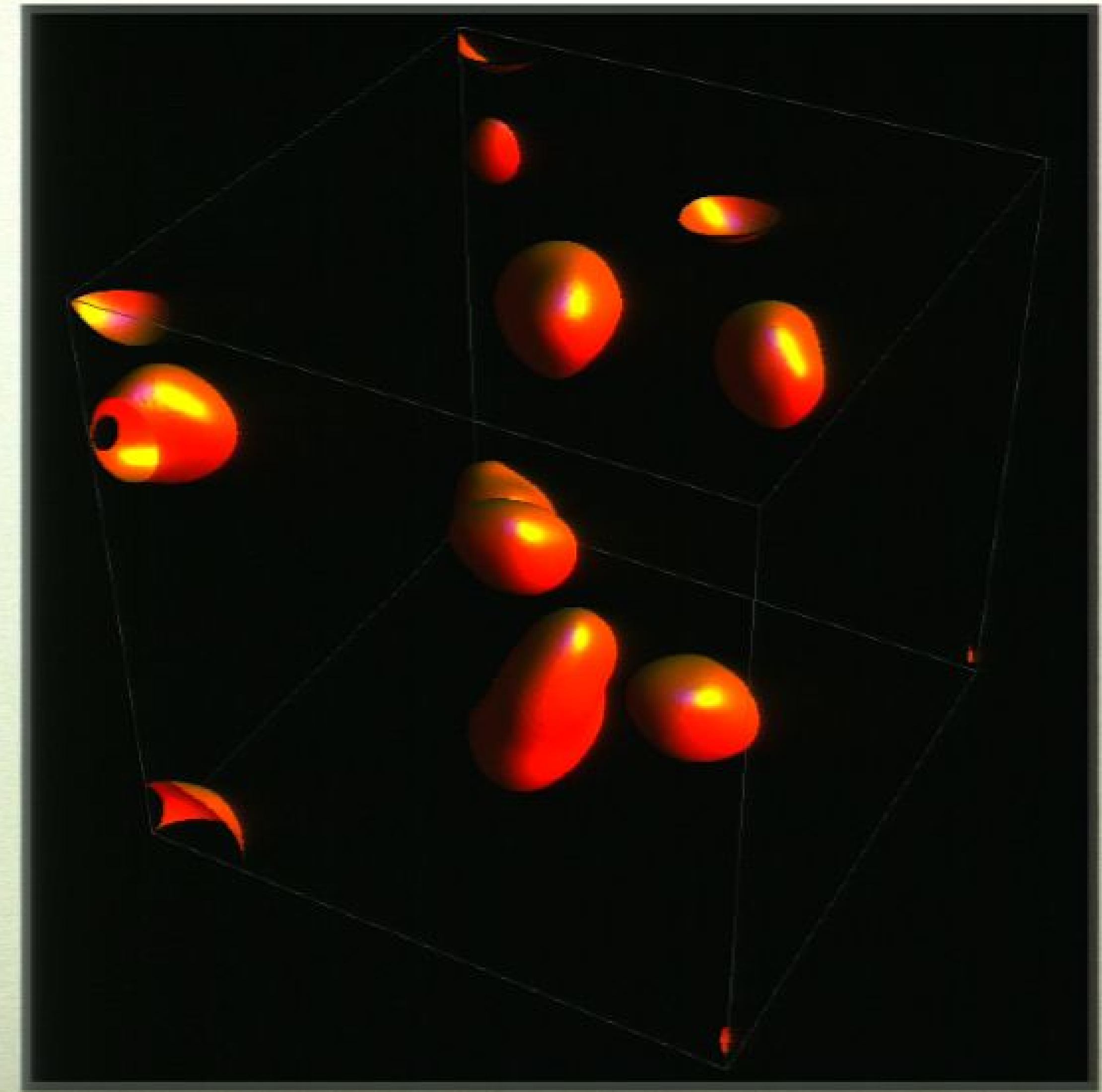

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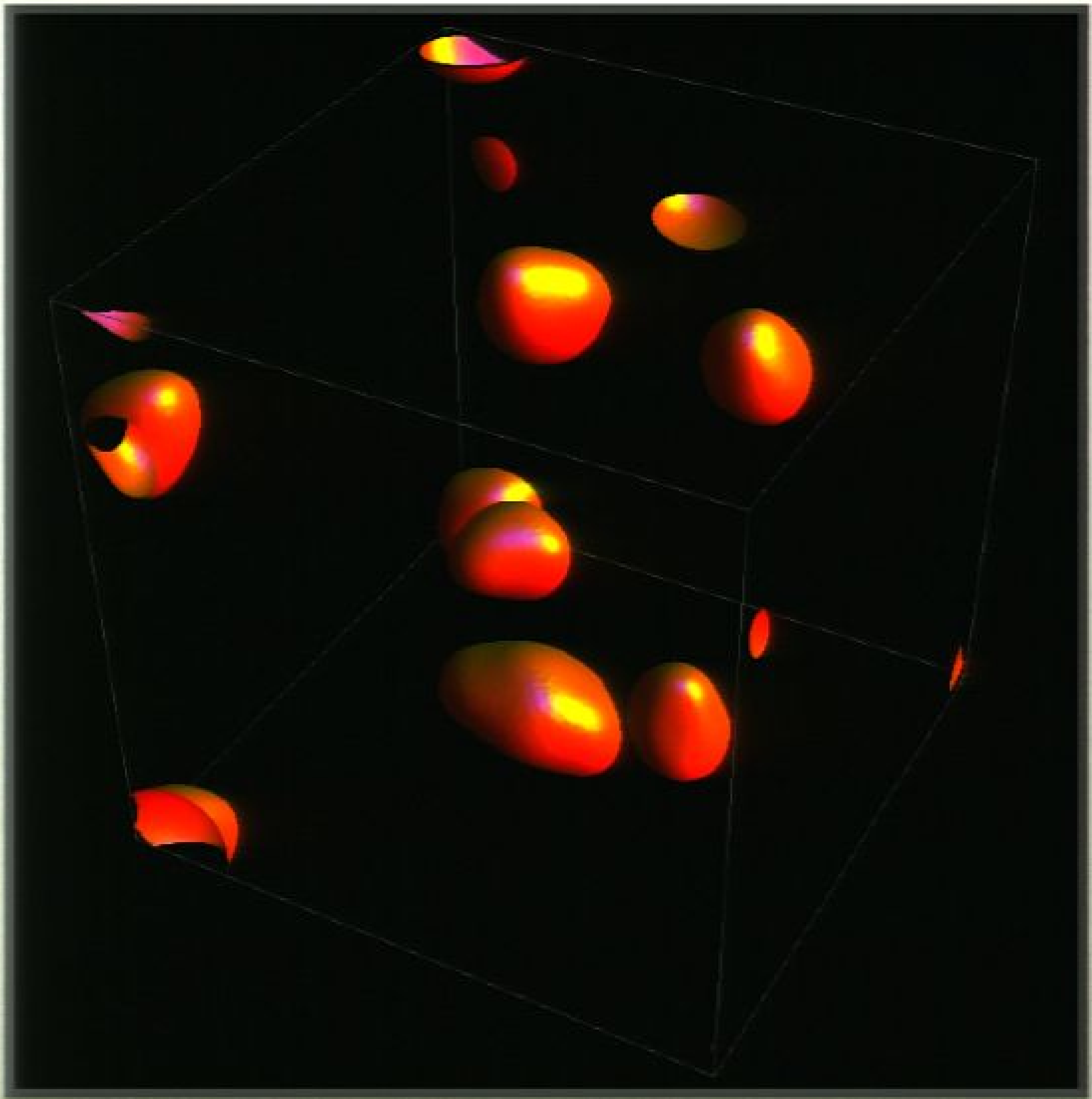

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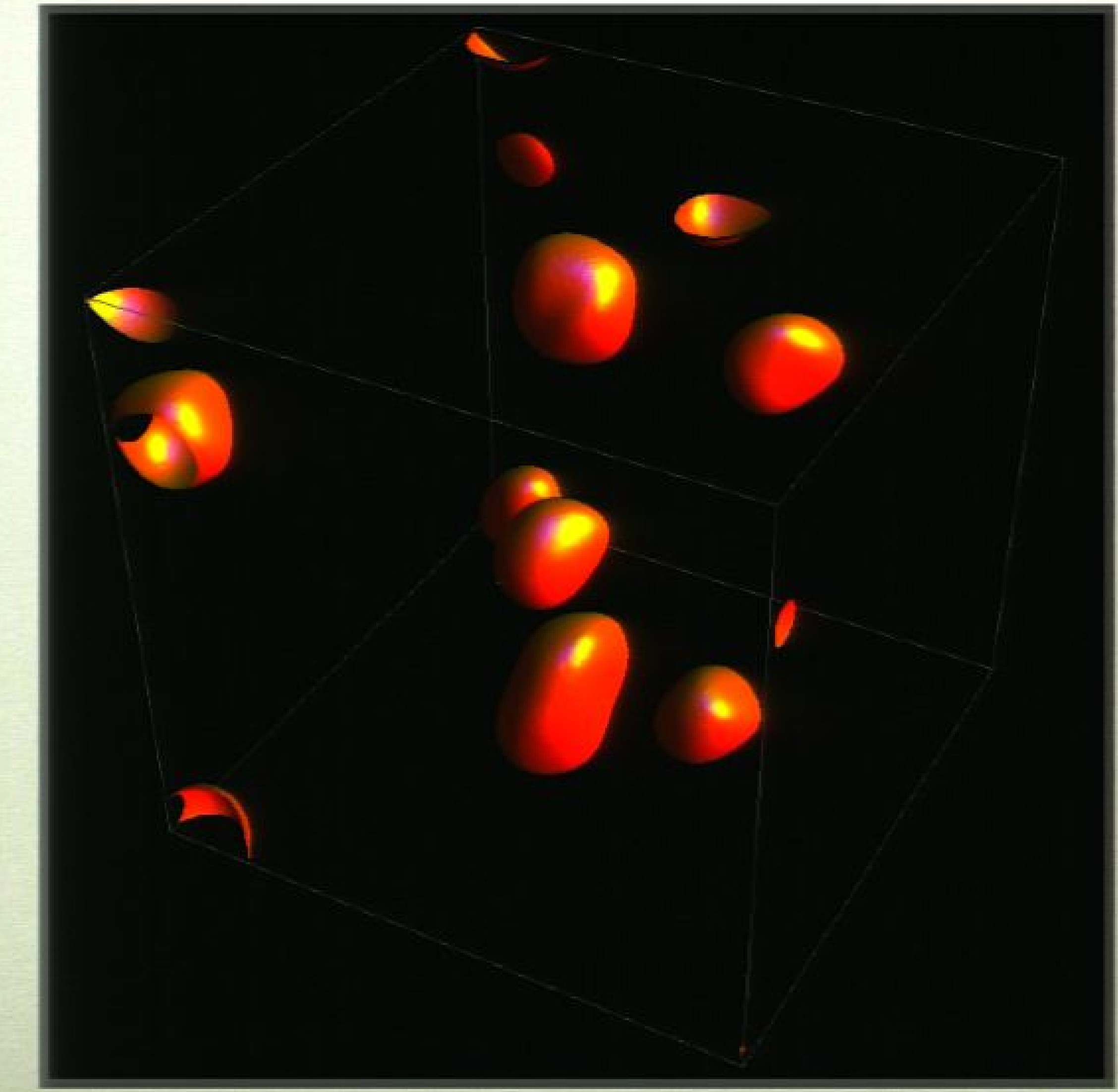

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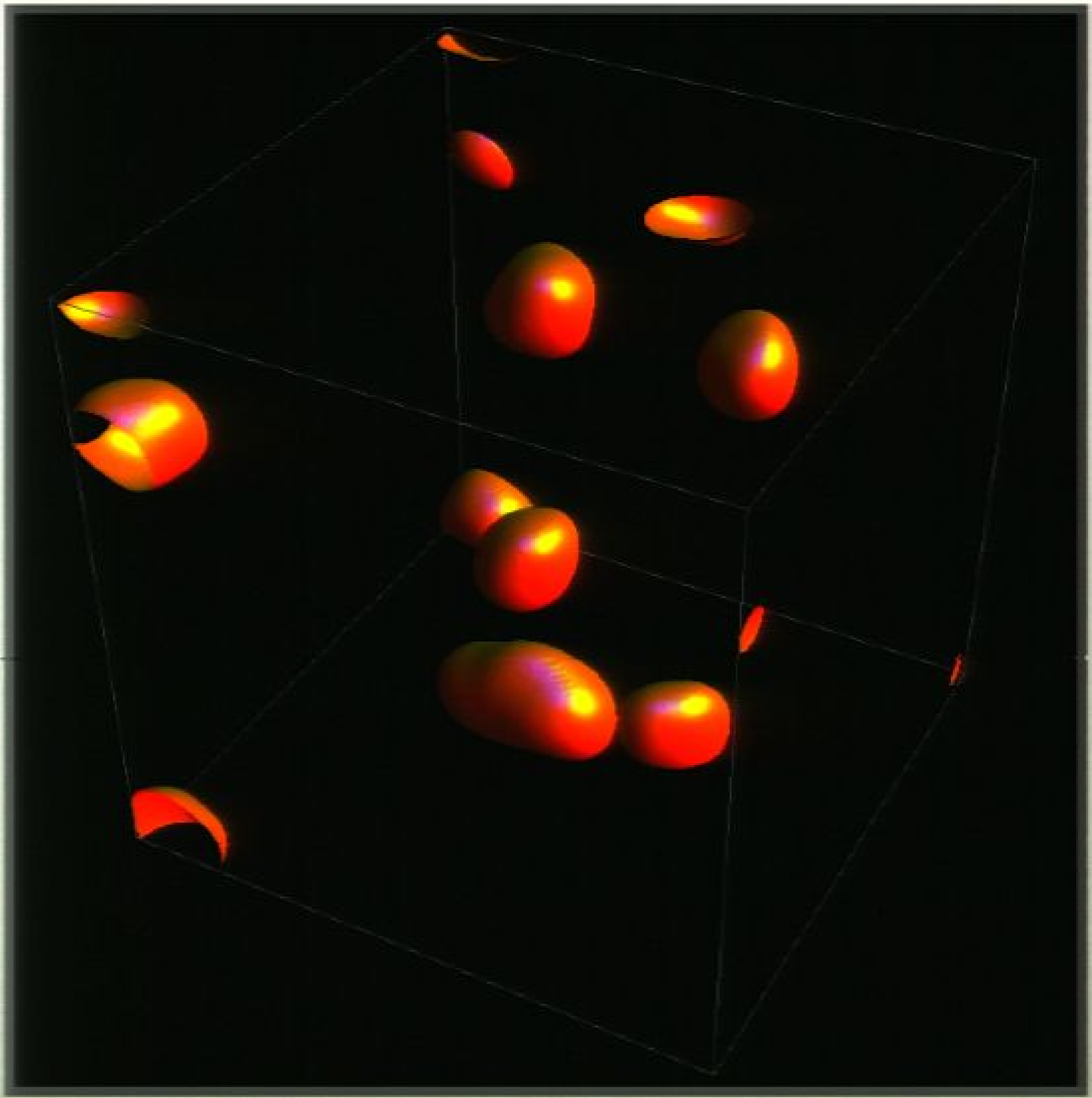

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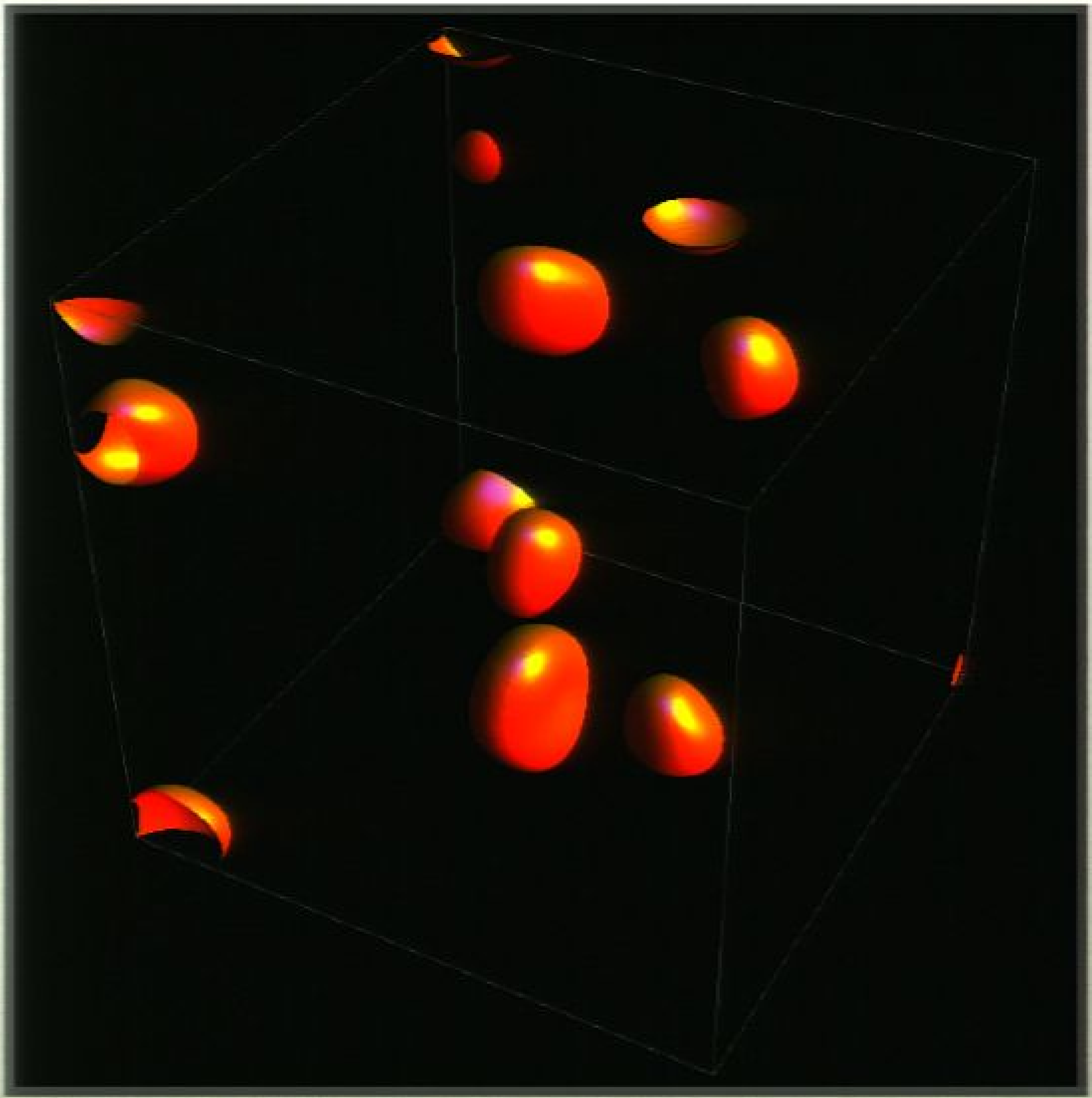

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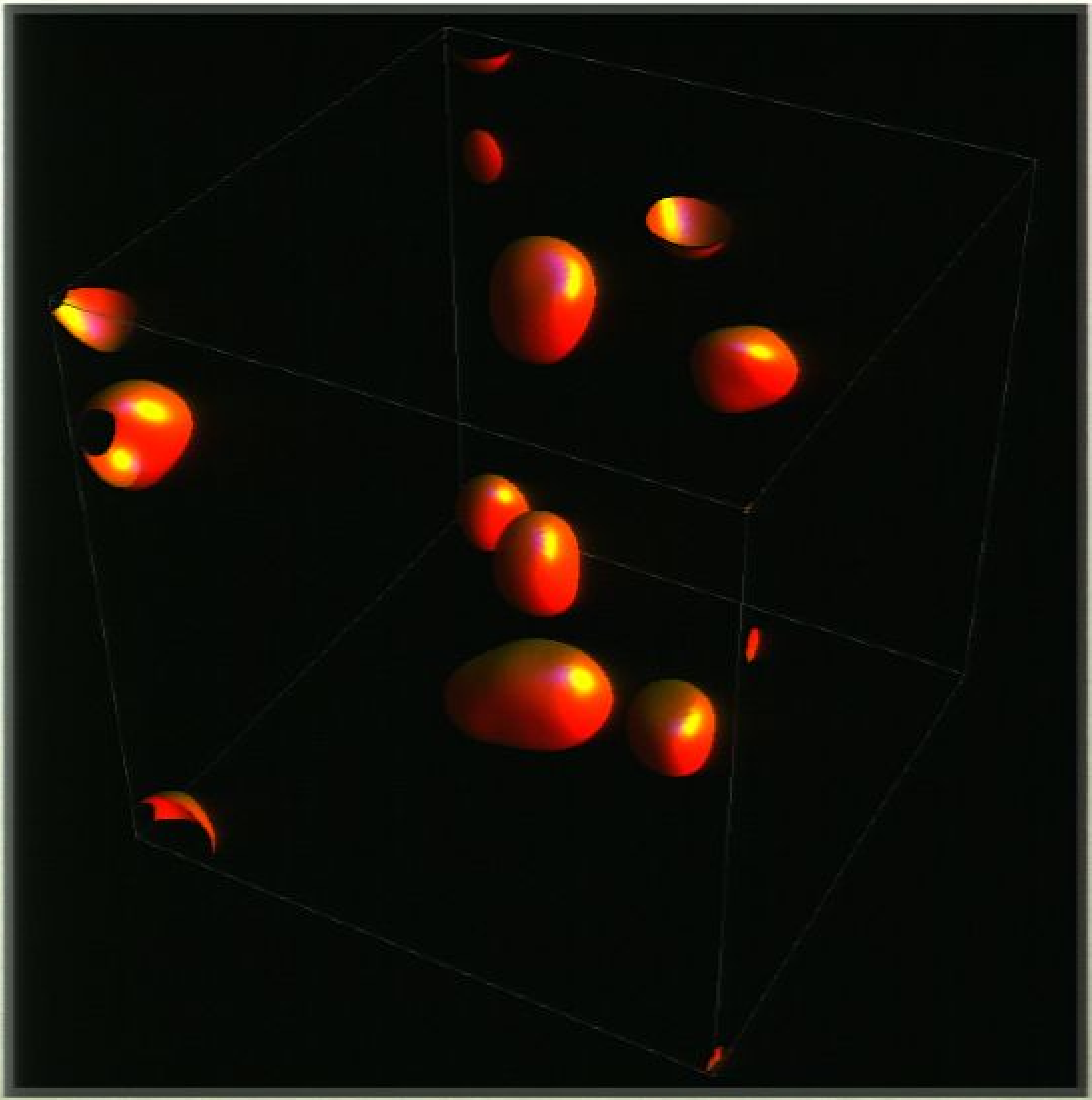

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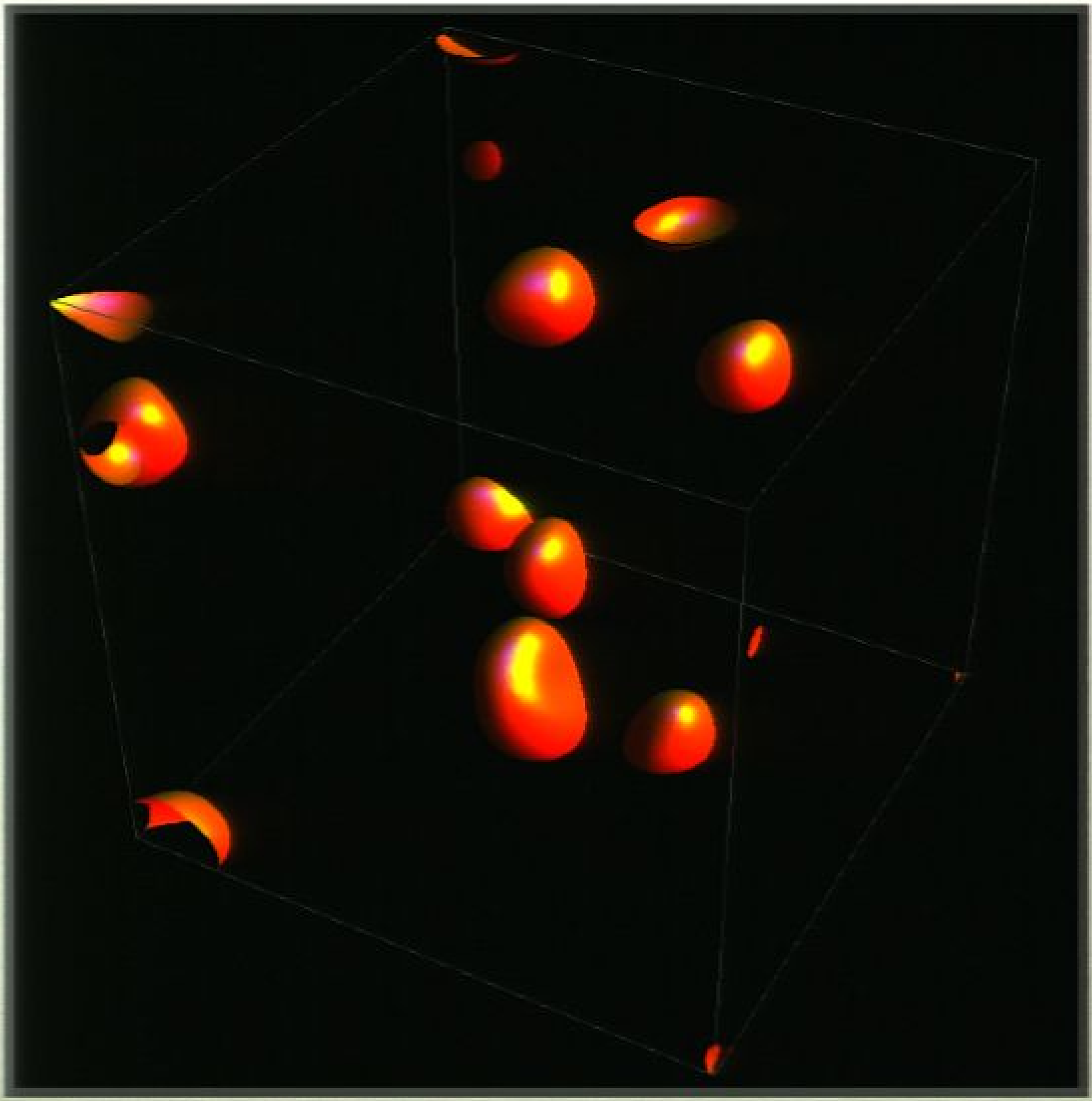

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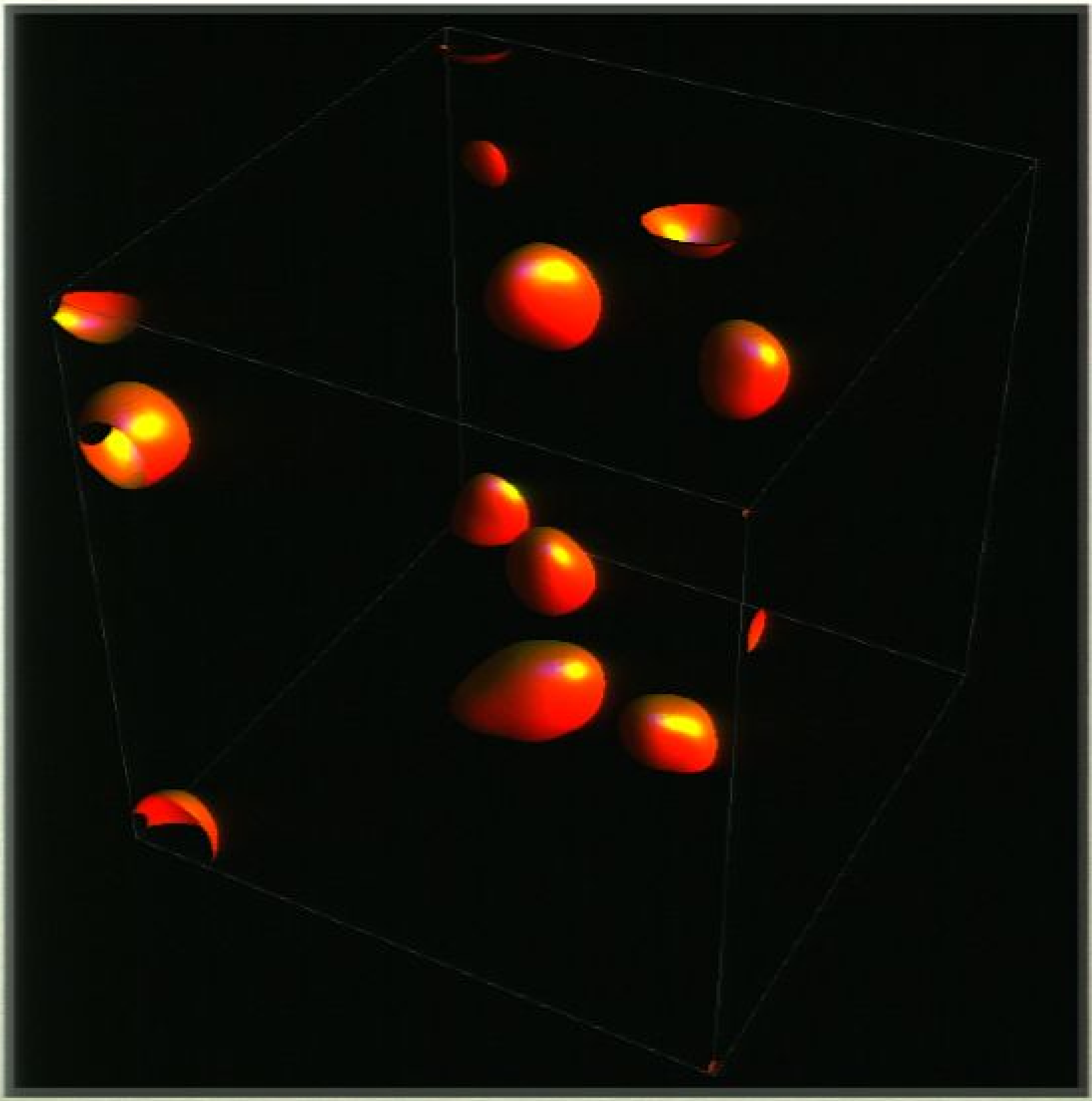
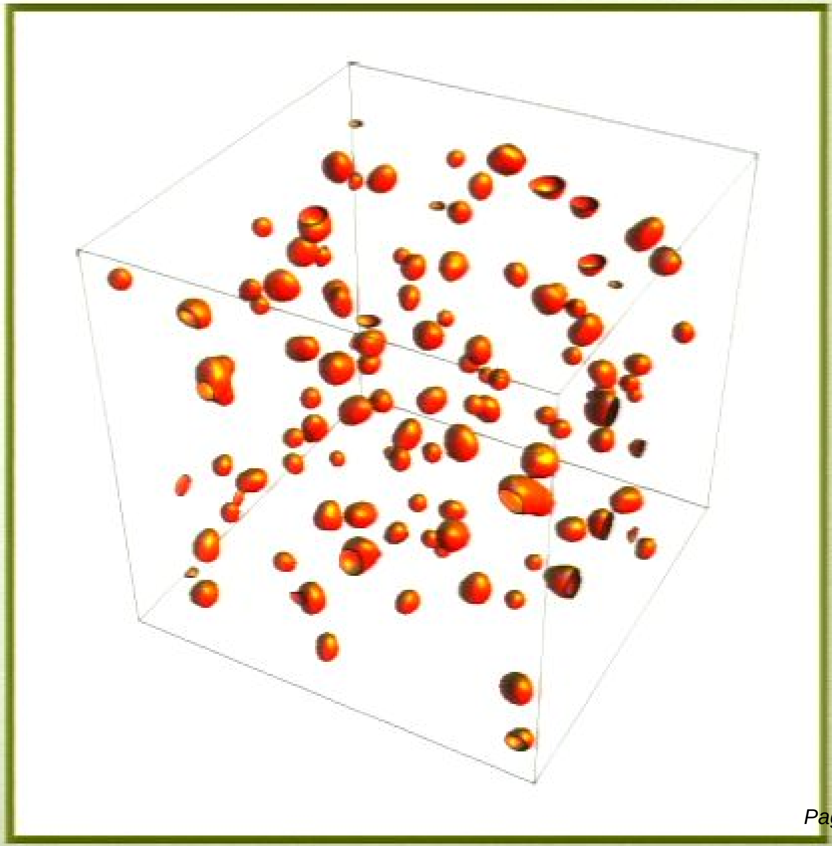


LUMPS?



- consequences ?
- what are they ?

3+1

CONSEQUENCES IF ...

3+1

CONSEQUENCES IF ...

- last for many Hubble times (at that time)

3+1

CONSEQUENCES IF ...

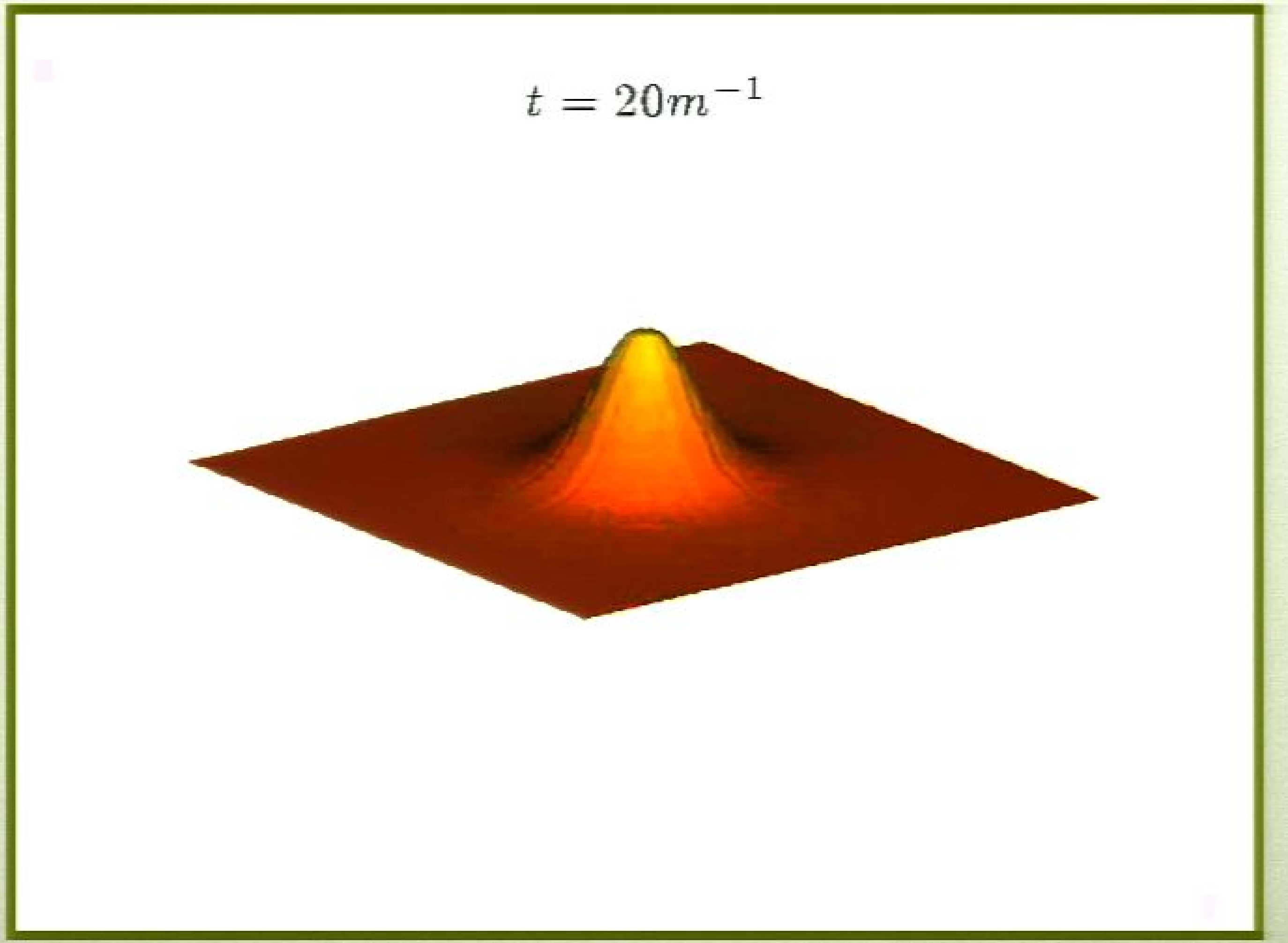
- last for many Hubble times (at that time)
- dominate the energy density

PLAN

- **individual blobs**: *MA & Shirokoff 2010*
  - solution & stability
- **post inflationary cosmological emergence**:
  - analytics and 1+1 d simulations MA (2010)
- **lattice simulations**
  - 3+1 d simulations MA, Easther and Finkel *(2010)*

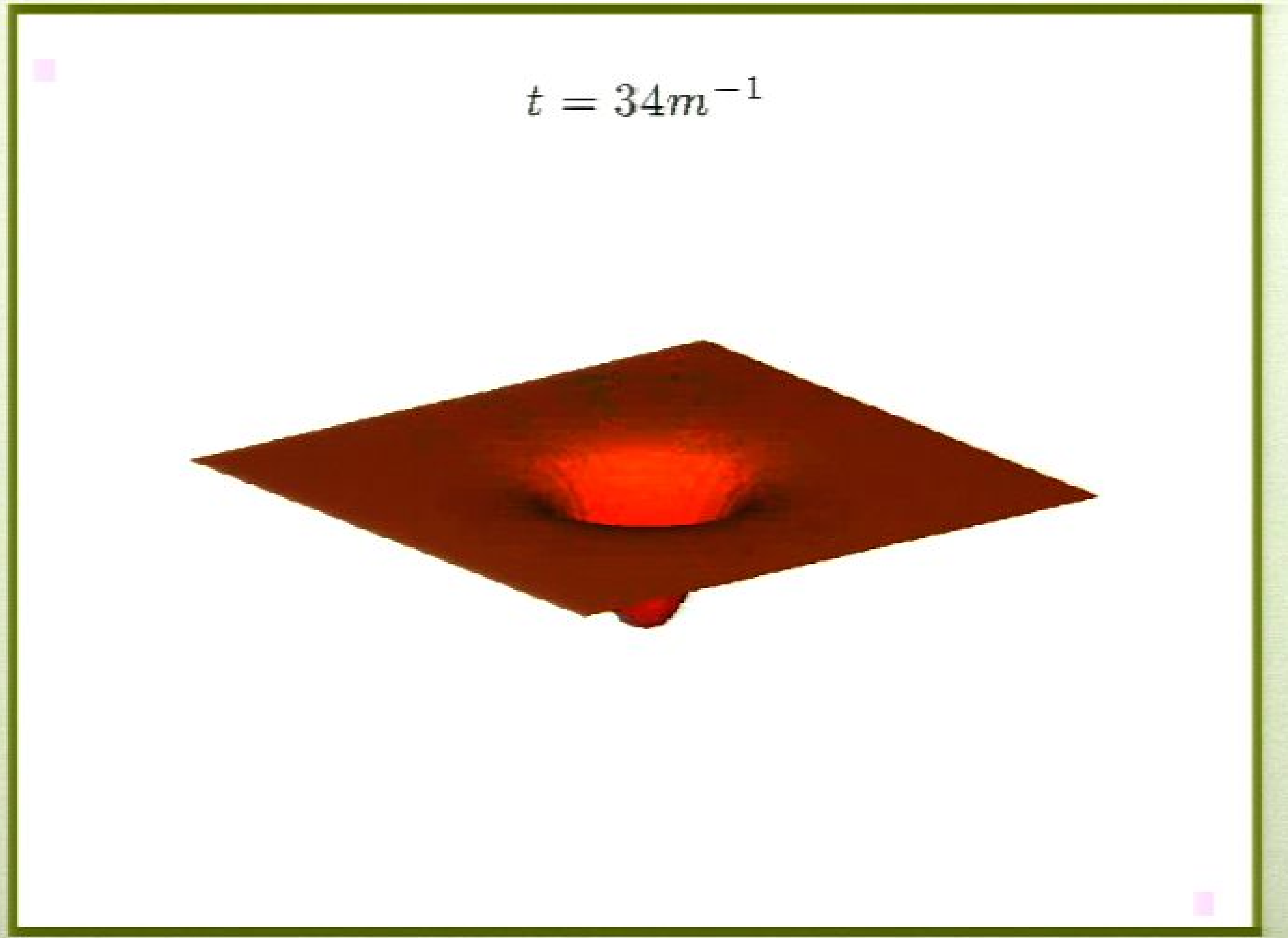
INDIVIDUAL OSCILLONS

MASSIVE FREE FIELD

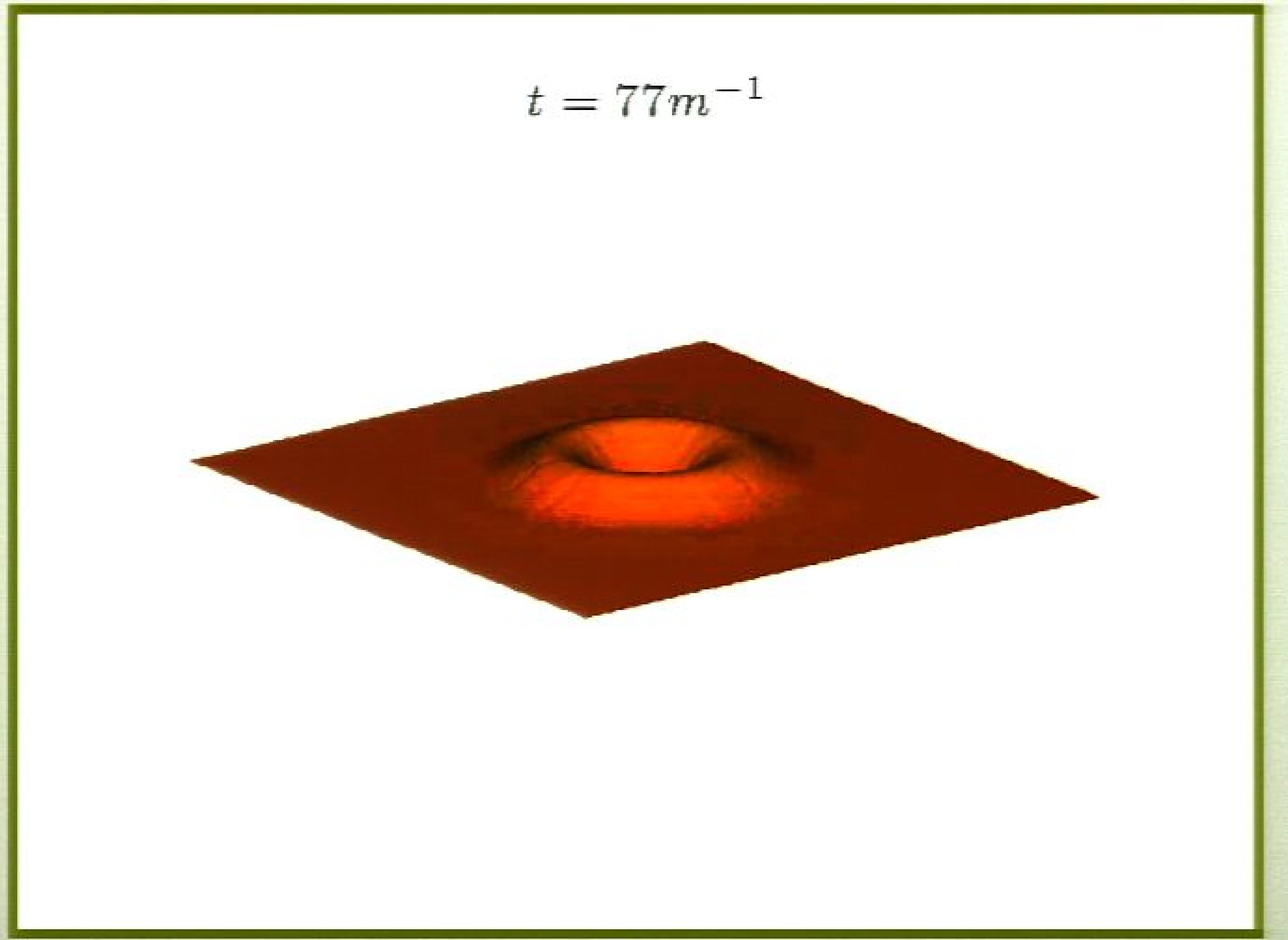


$t = 20m^{-1}$

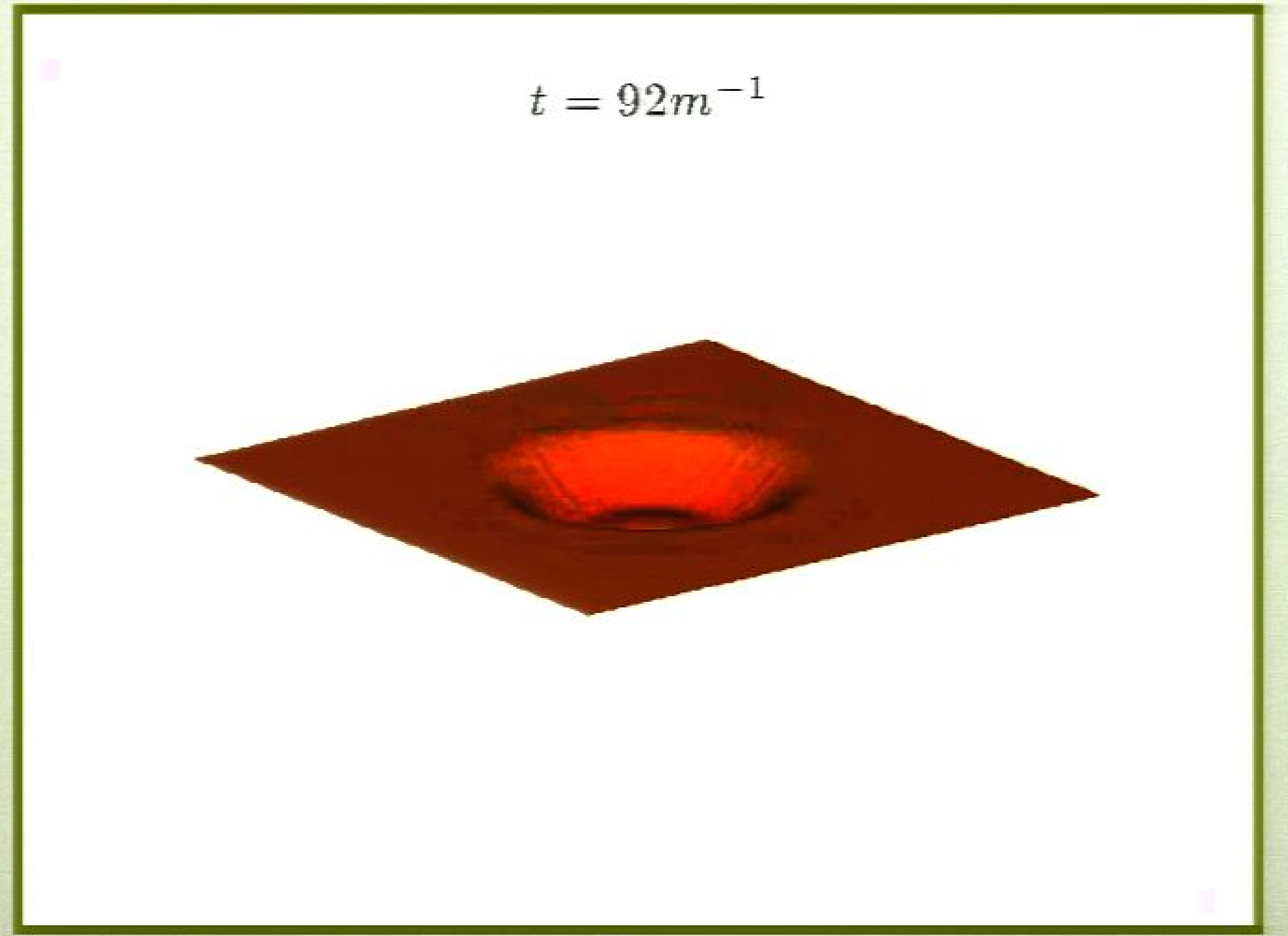
MASSIVE FREE FIELD



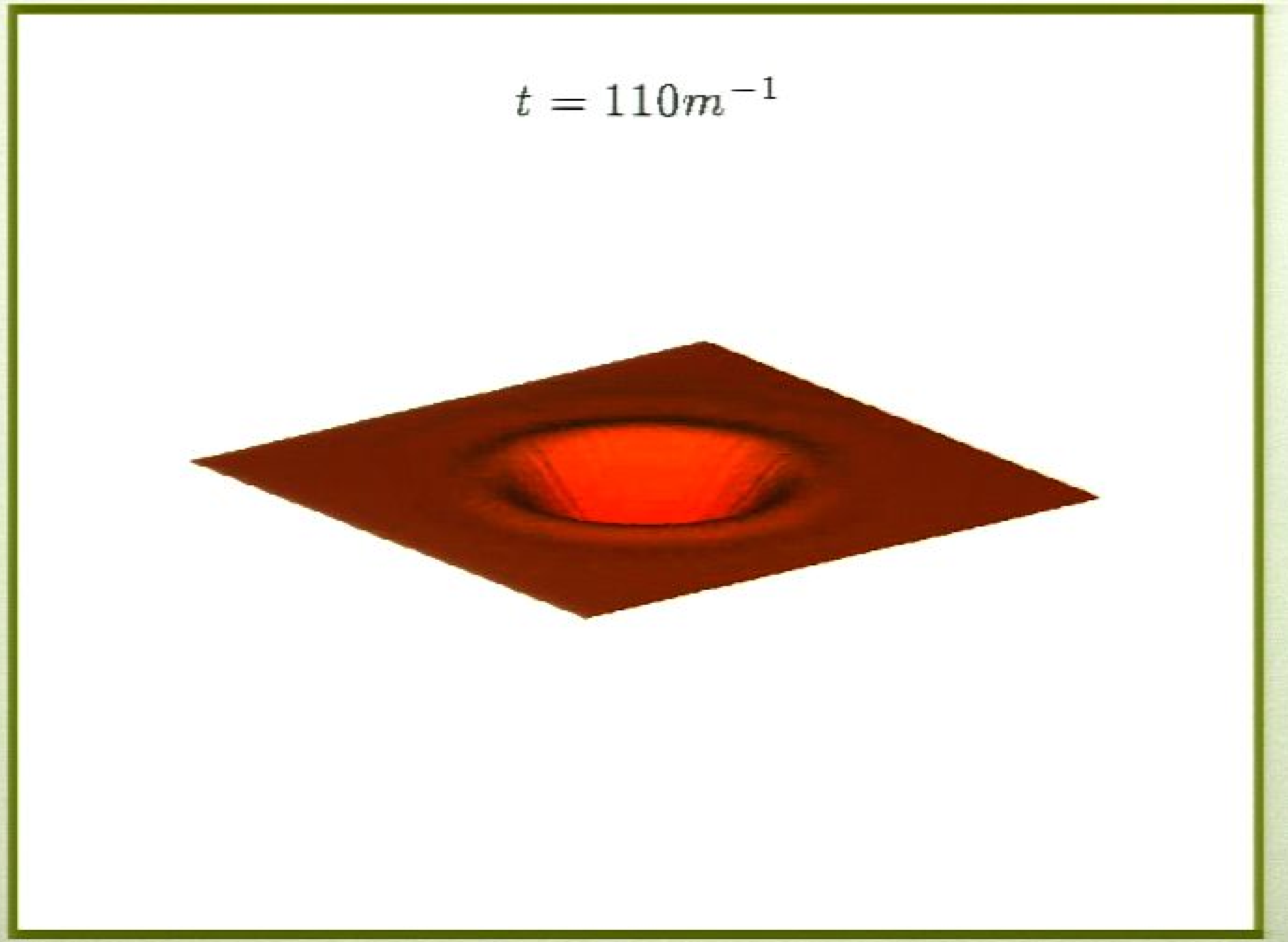
MASSIVE FREE FIELD



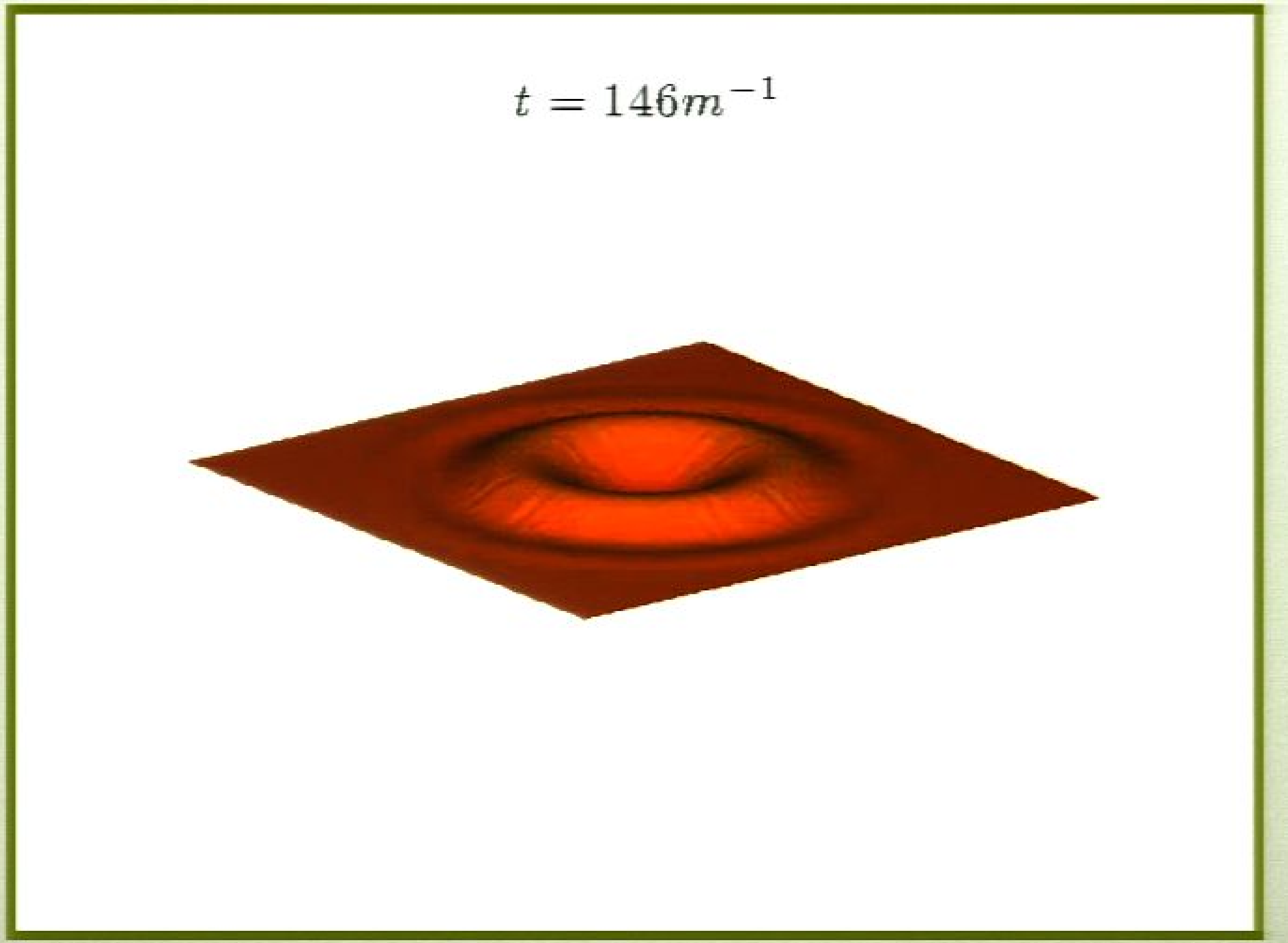
MASSIVE FREE FIELD



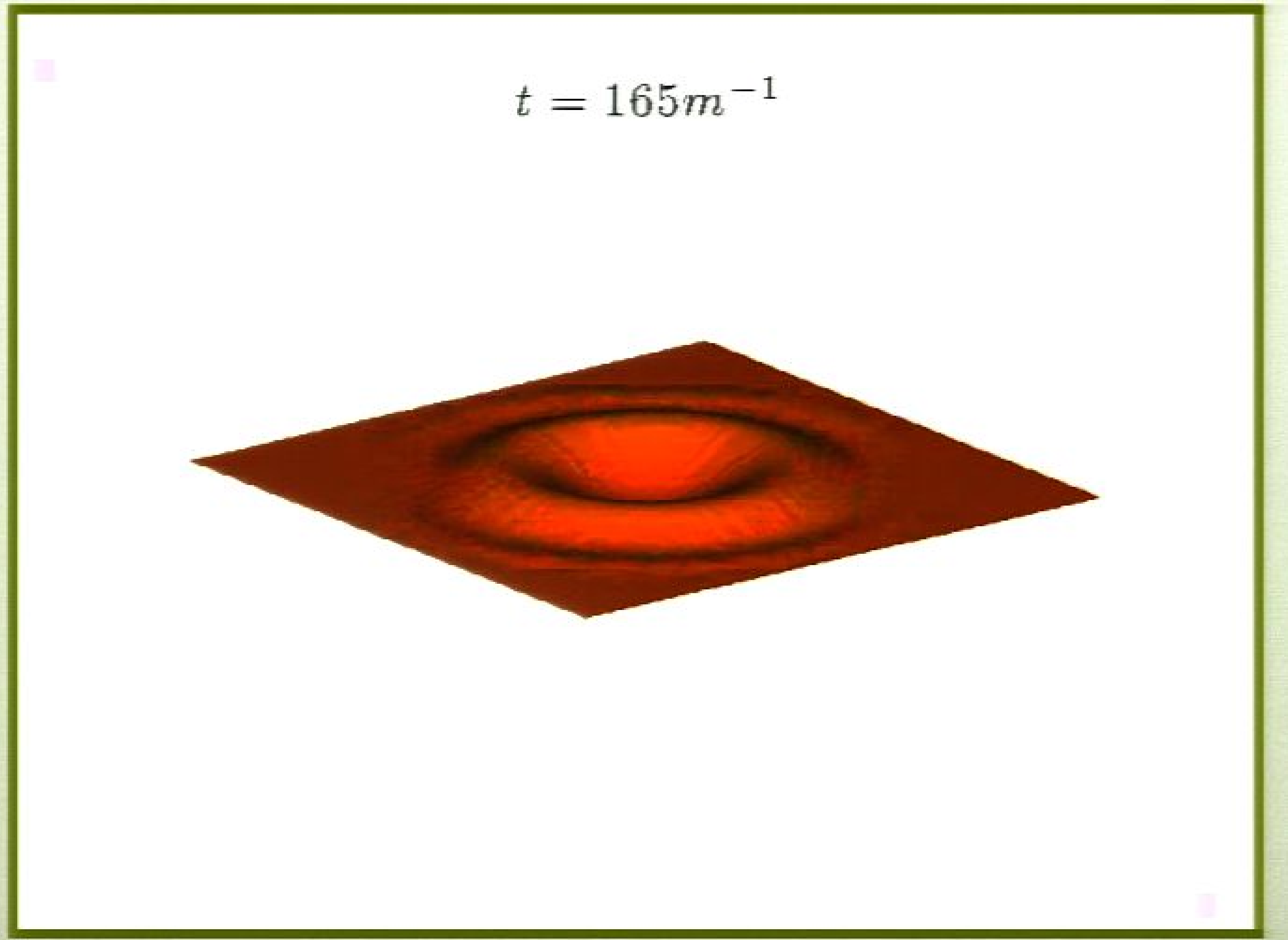
MASSIVE FREE FIELD



MASSIVE FREE FIELD



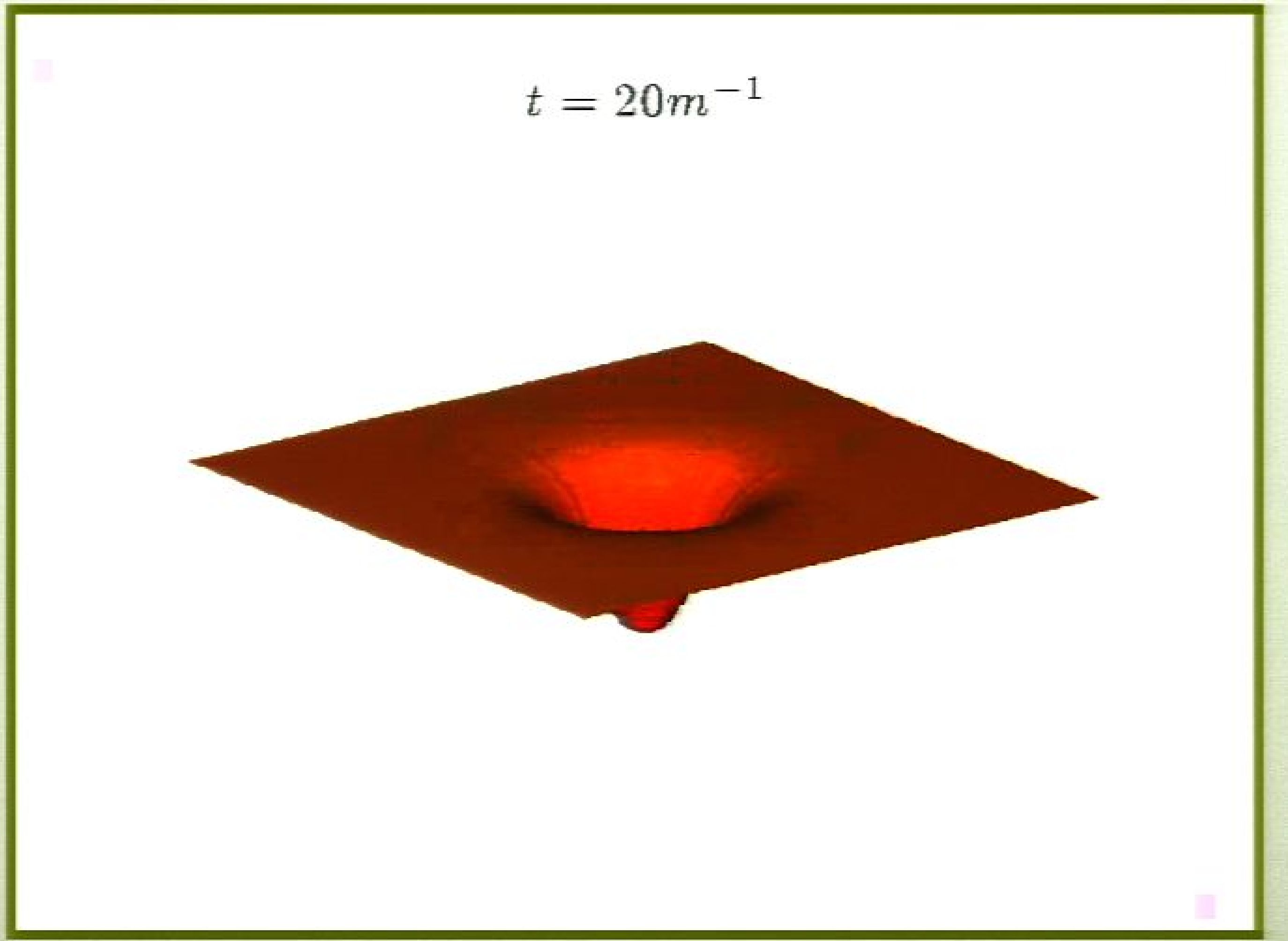
MASSIVE FREE FIELD



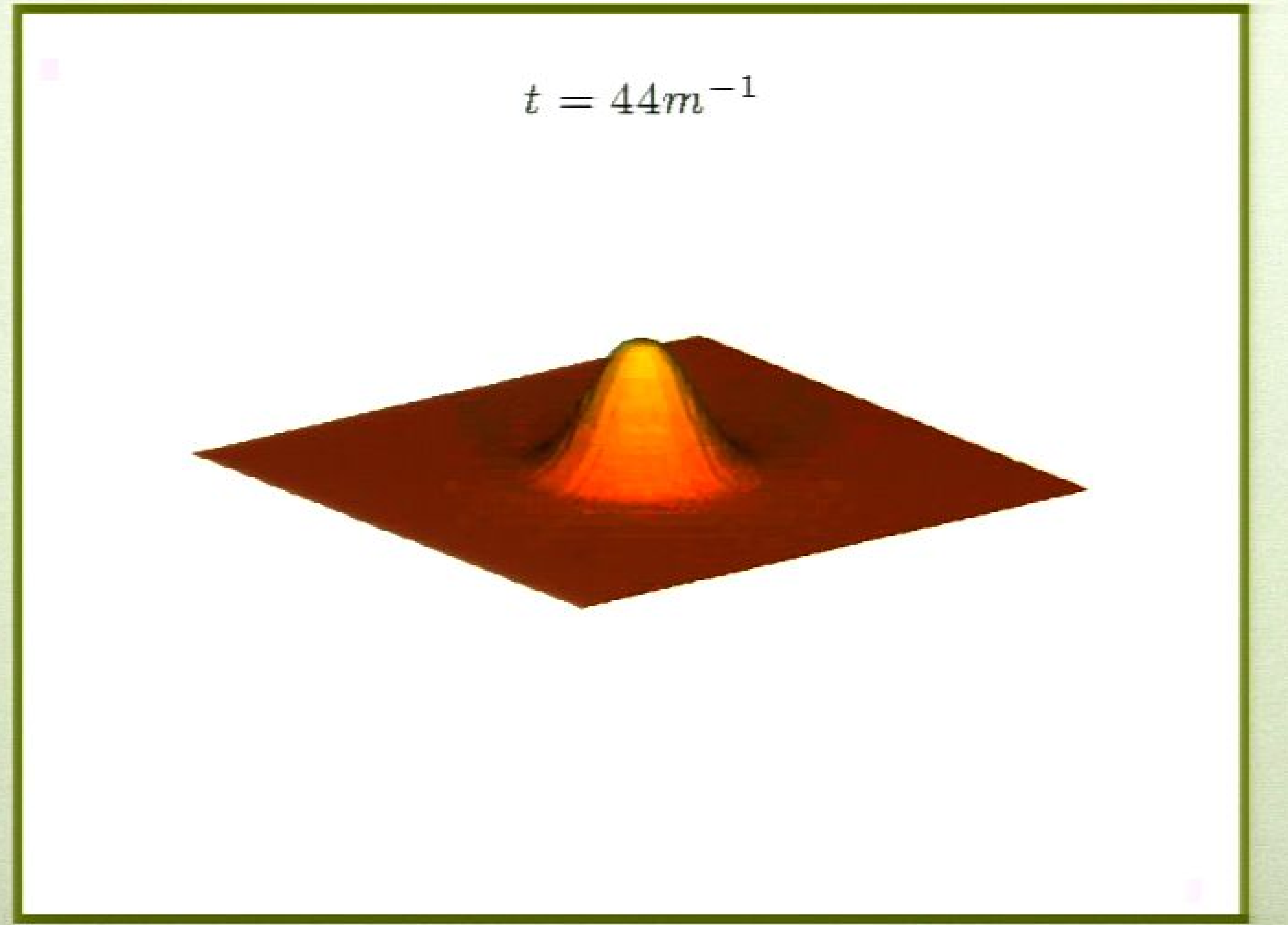
$t = 165m^{-1}$

INDIVIDUAL OSCILLONS

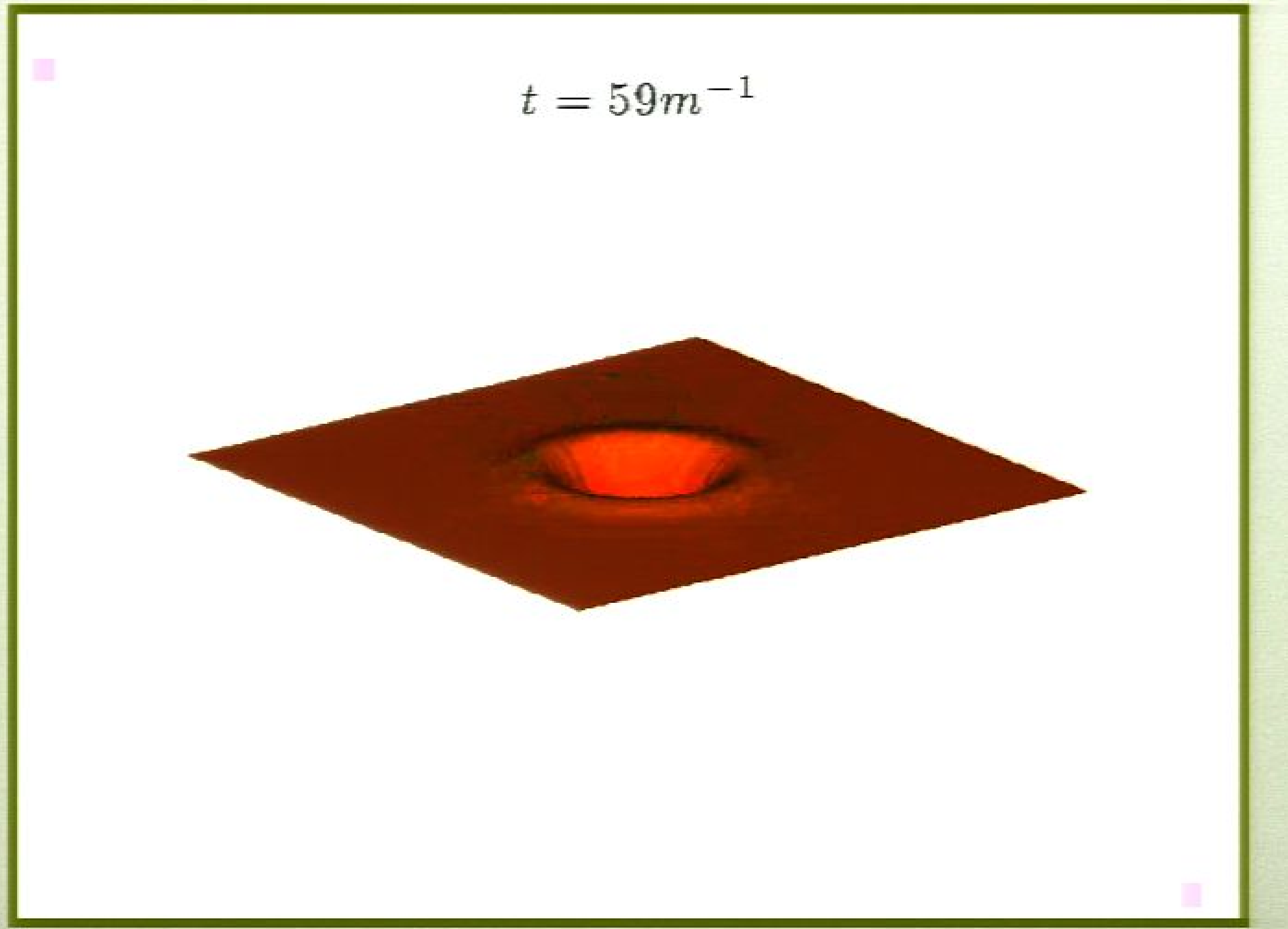
MASSIVE FREE FIELD



MASSIVE FREE FIELD


$t = 44m^{-1}$

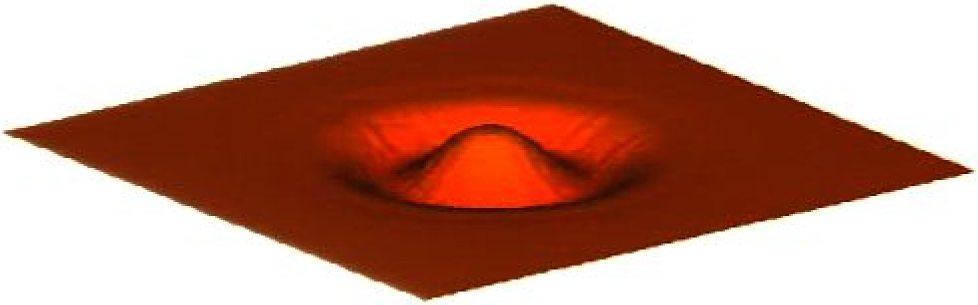
MASSIVE FREE FIELD



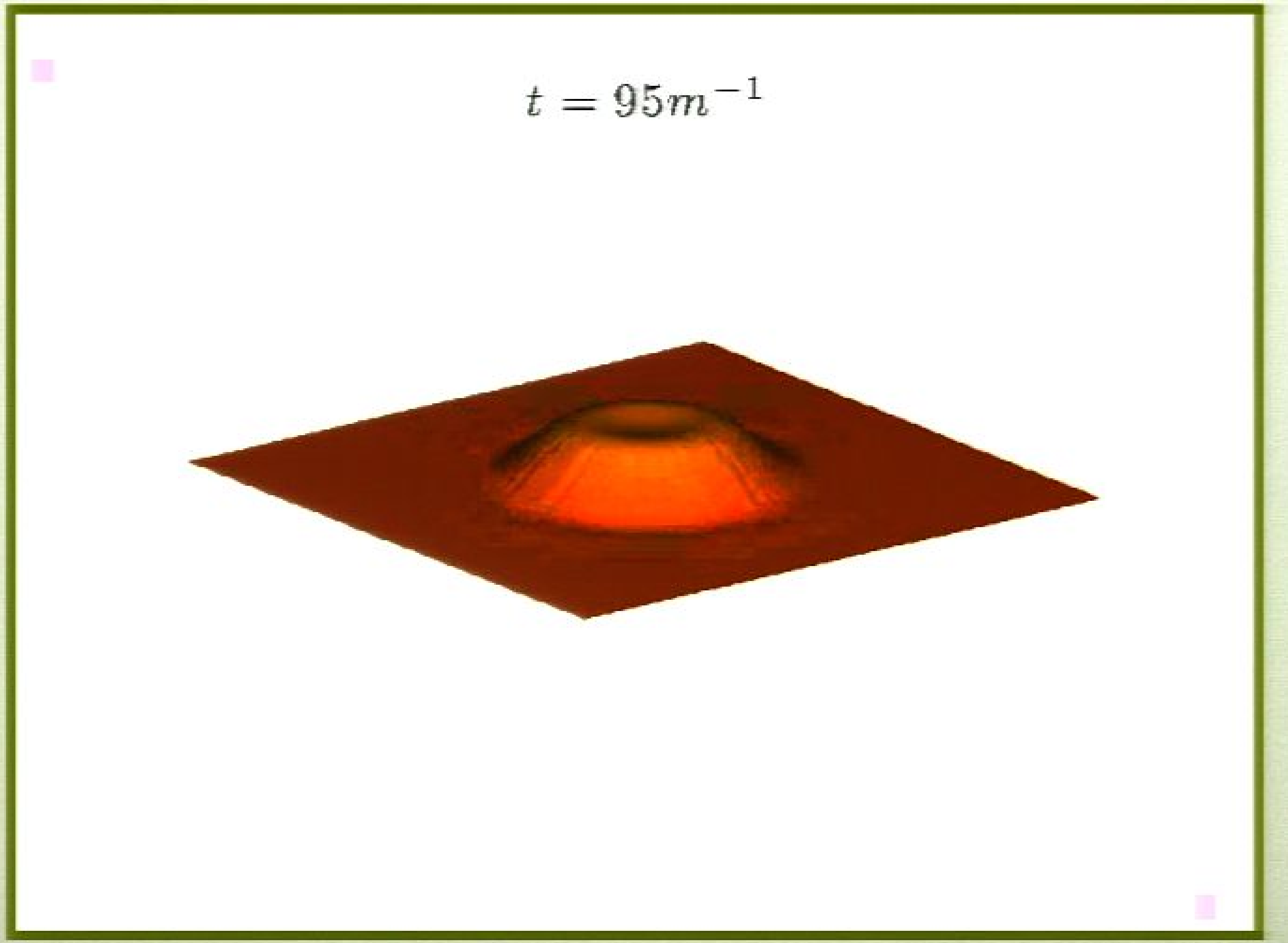
$t = 59m^{-1}$

MASSIVE FREE FIELD

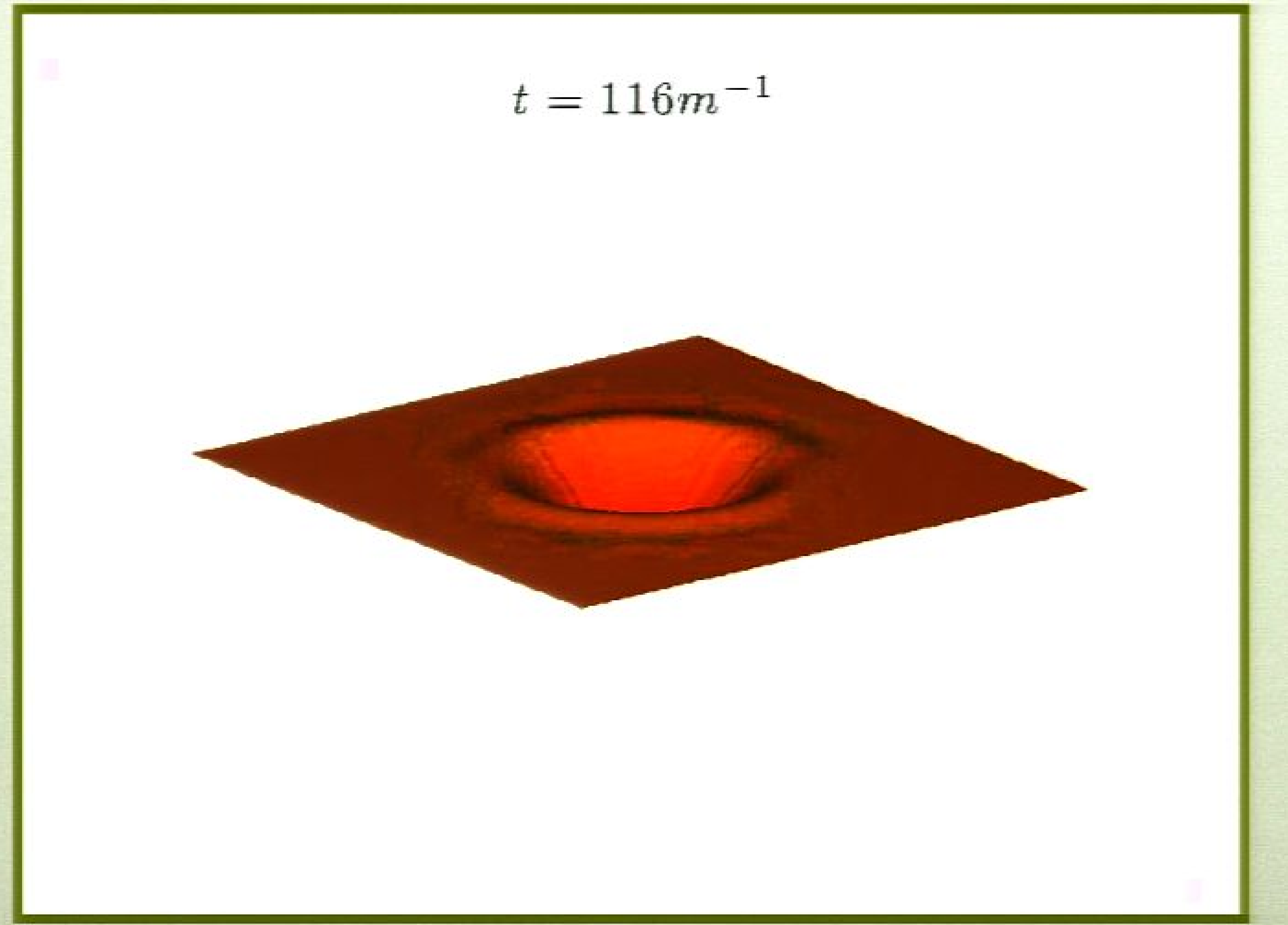
$t = 74m^{-1}$



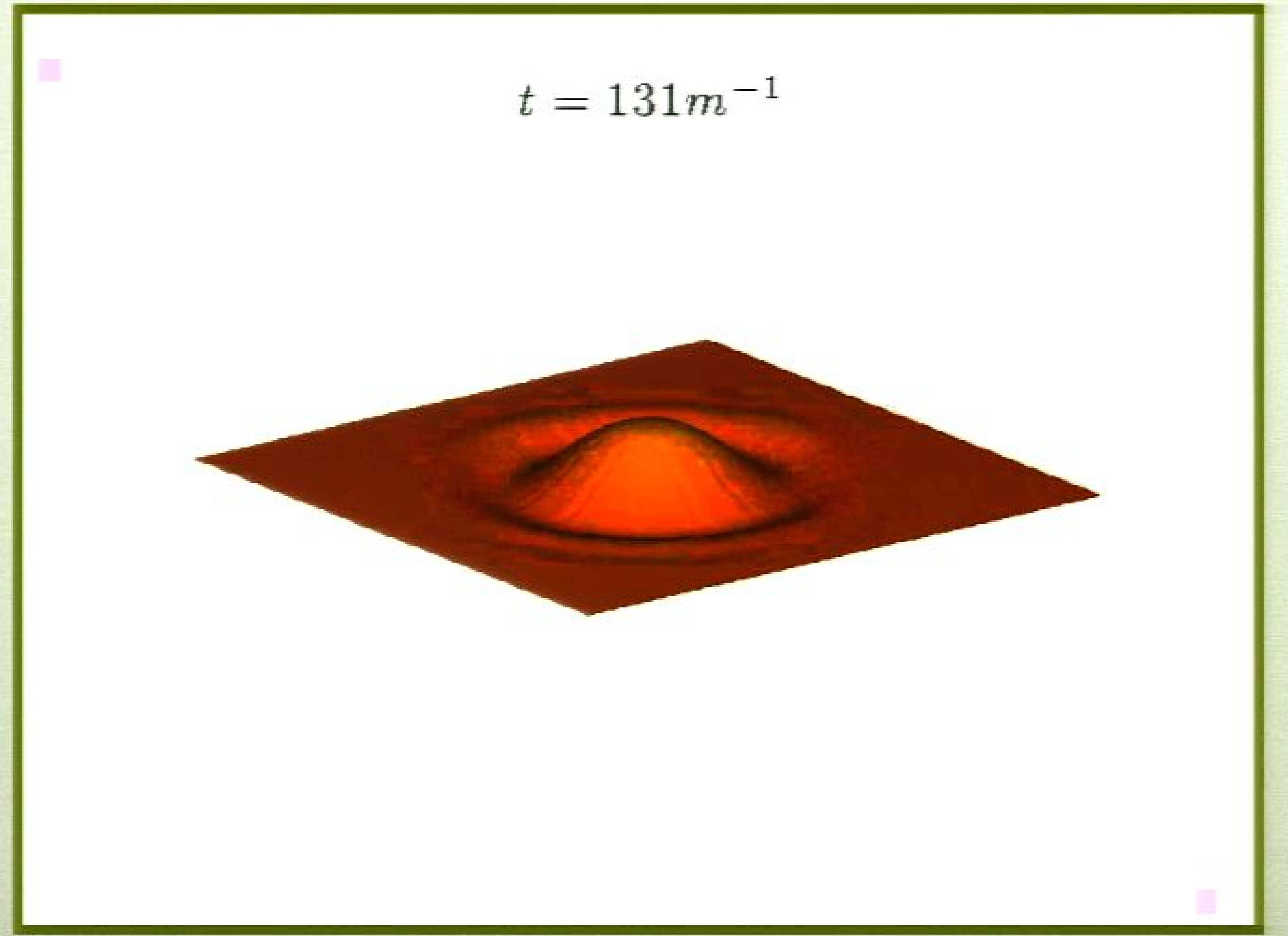
MASSIVE FREE FIELD



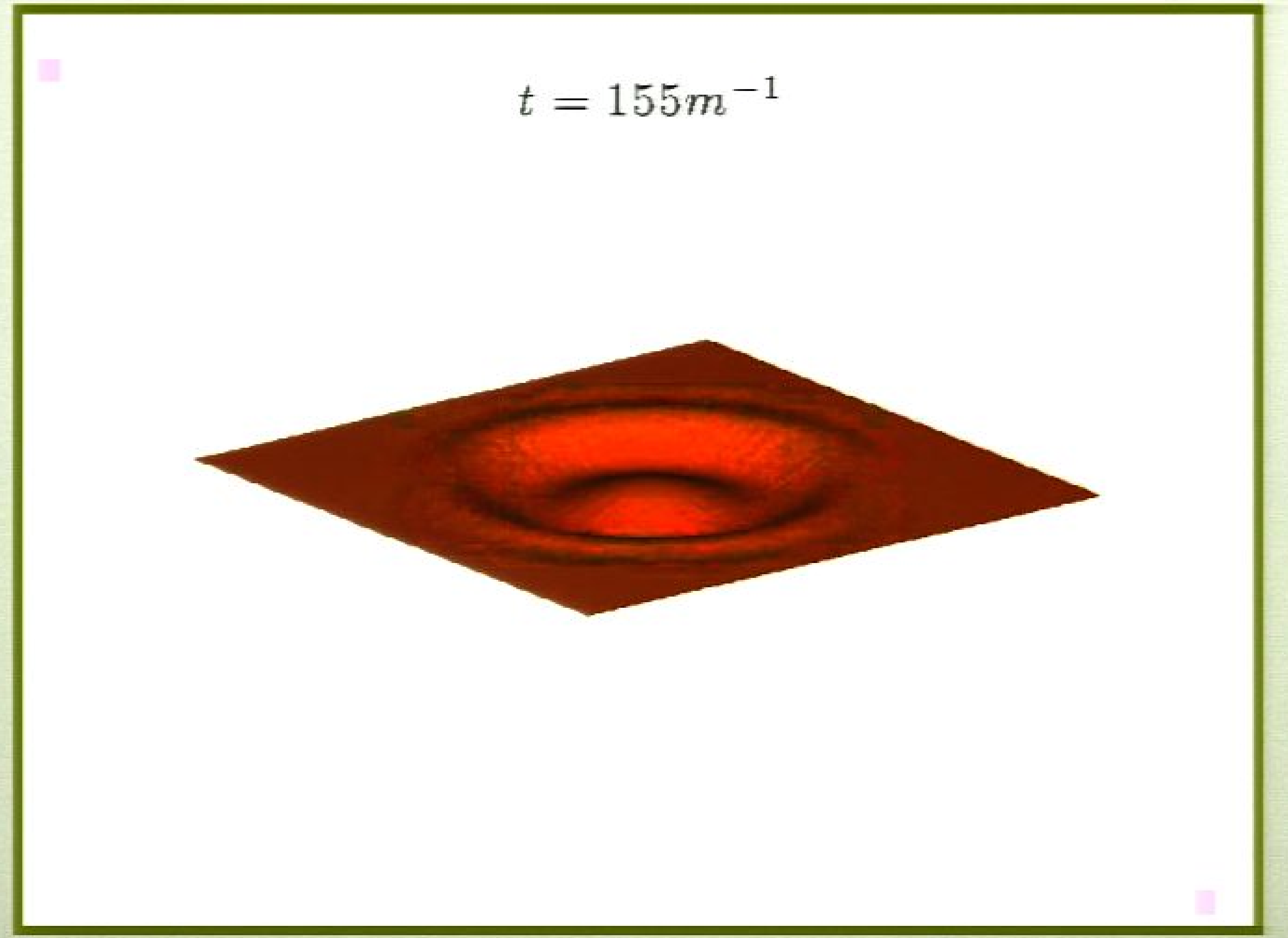
MASSIVE FREE FIELD



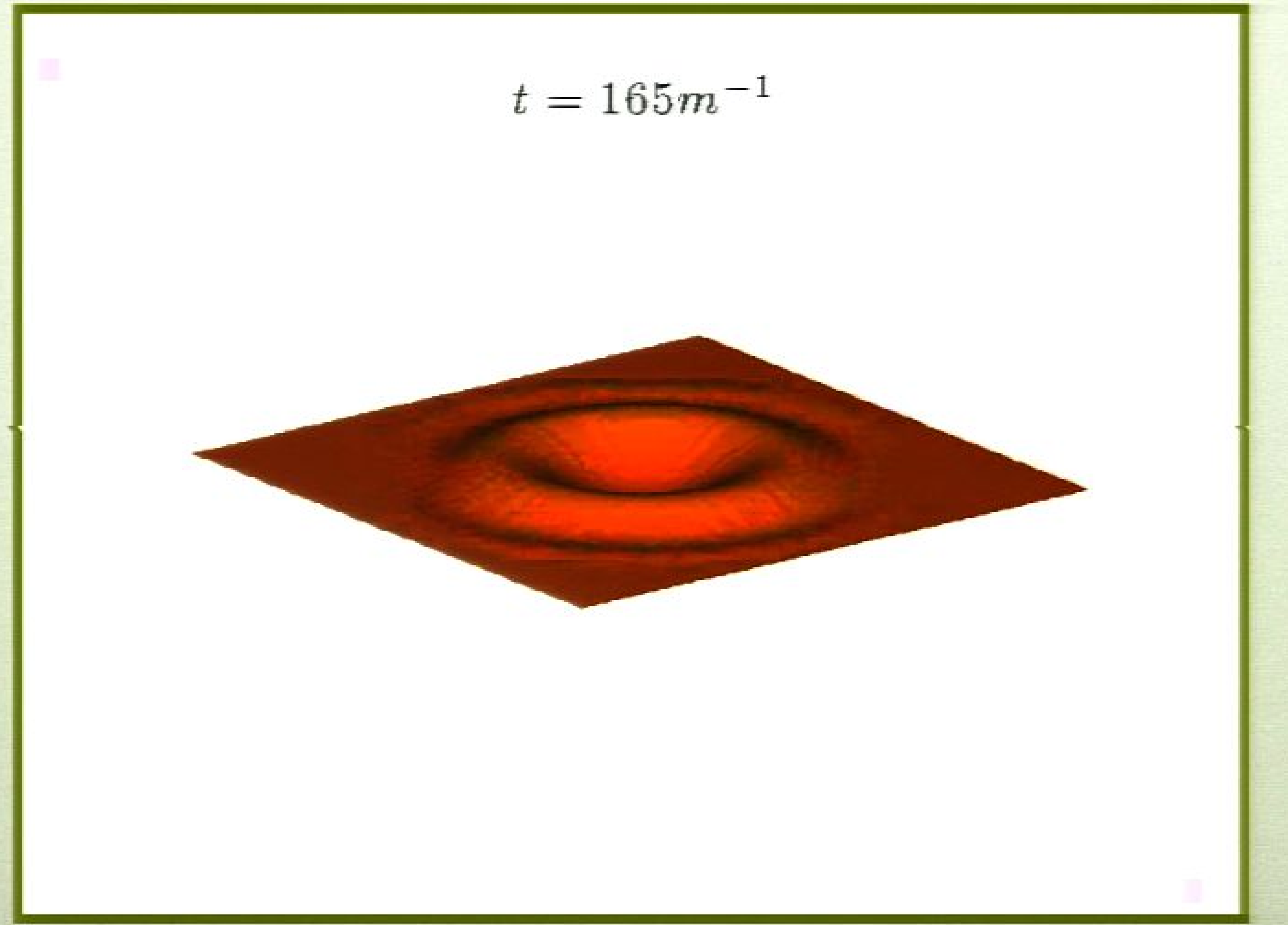
MASSIVE FREE FIELD



MASSIVE FREE FIELD



MASSIVE FREE FIELD

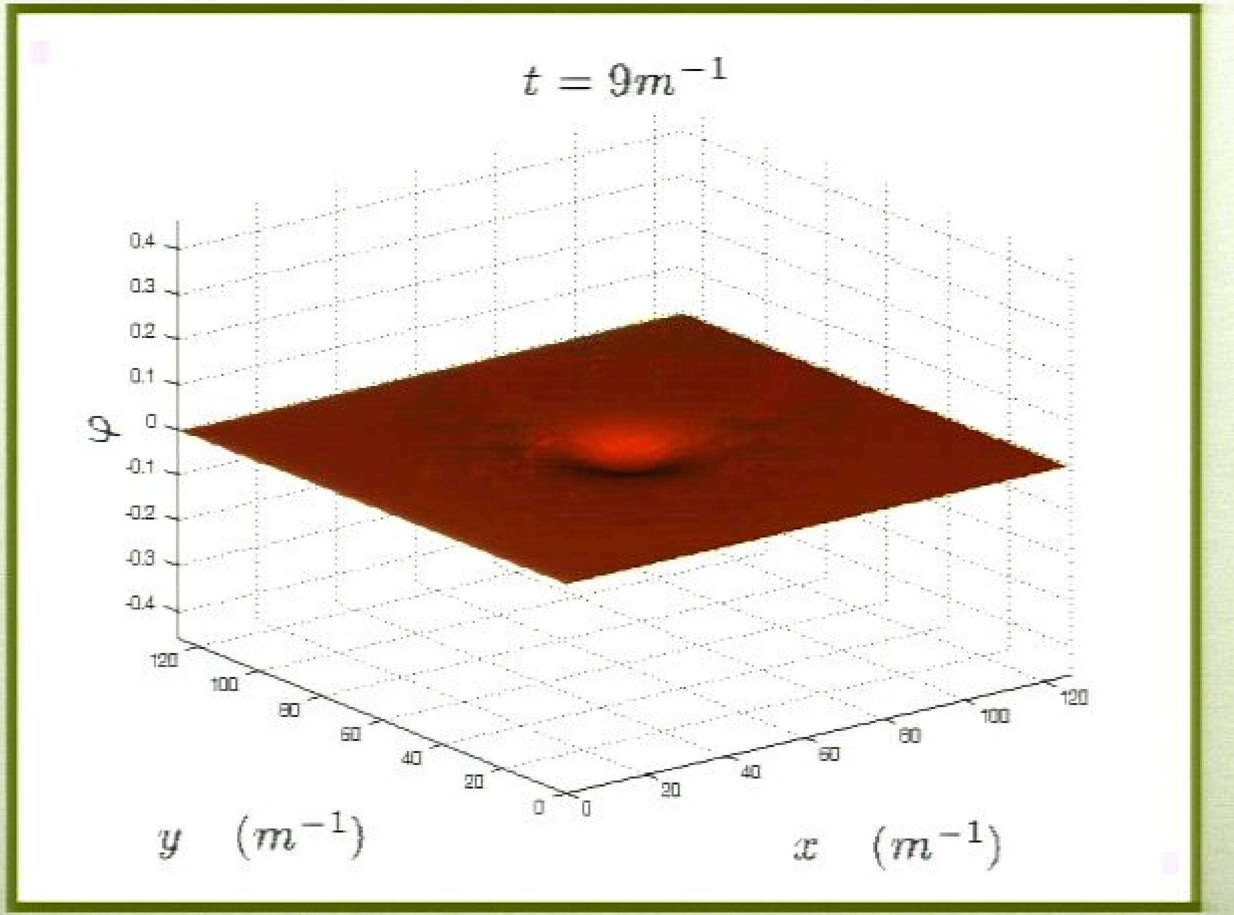


$t = 165m^{-1}$

OSCILLONS

(BREATHERS IN CONDENSED MATTER)

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



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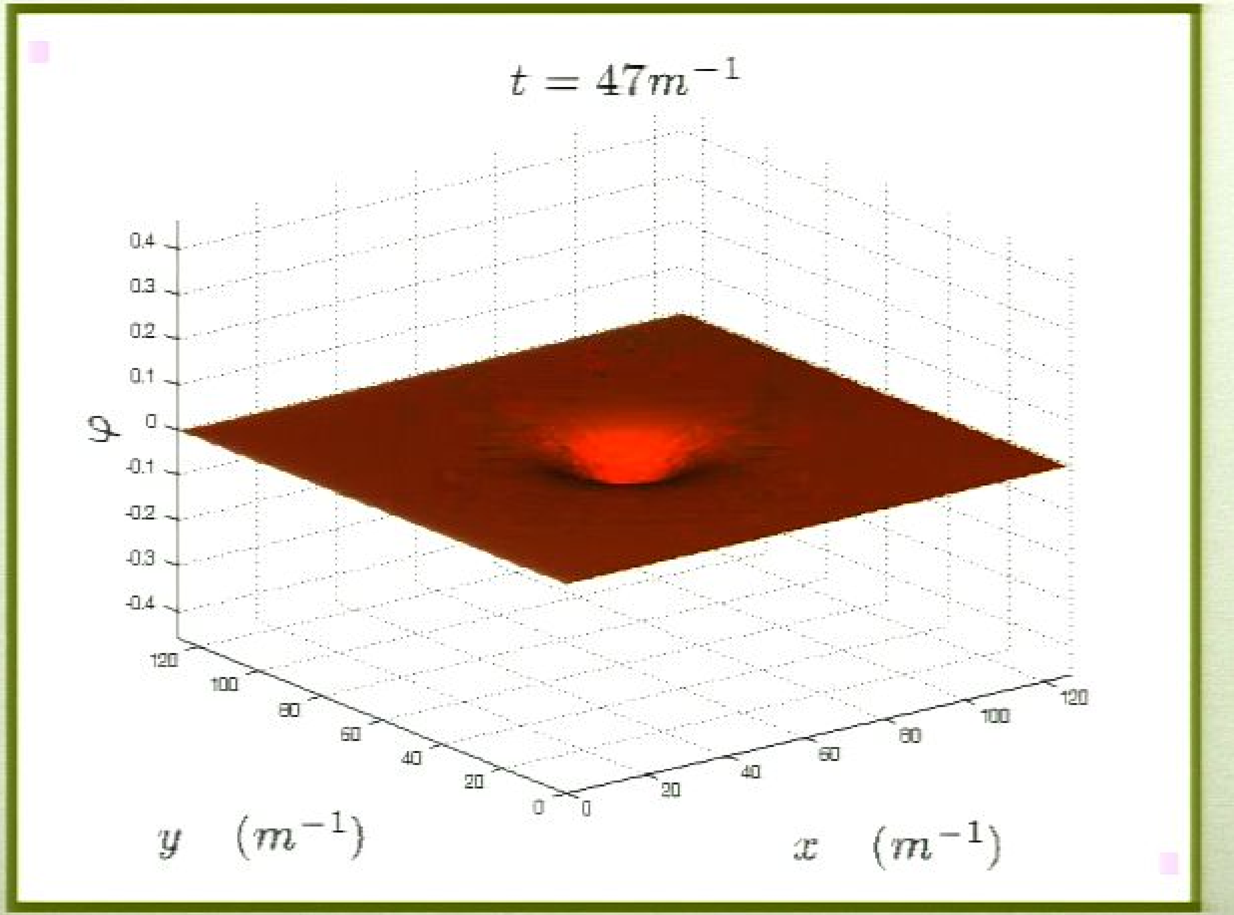

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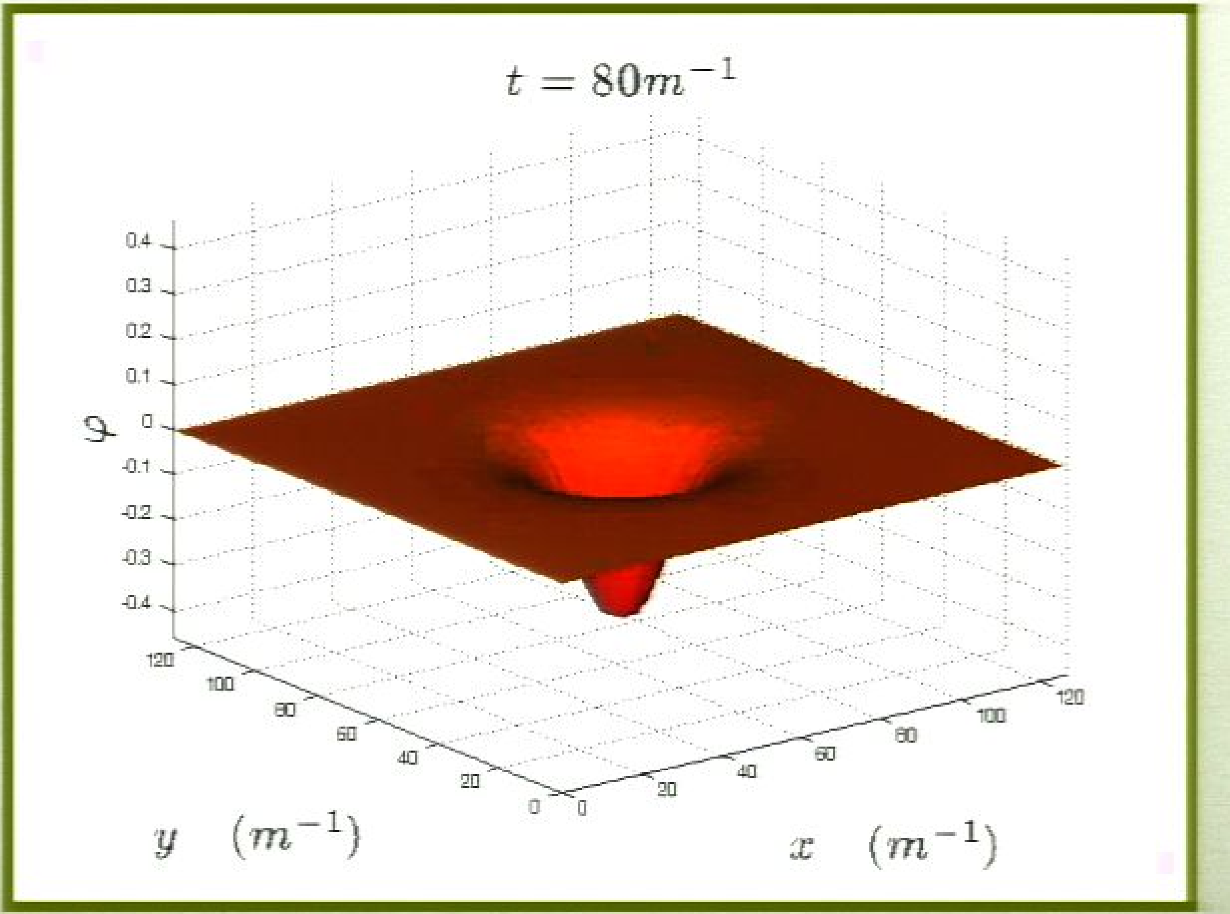

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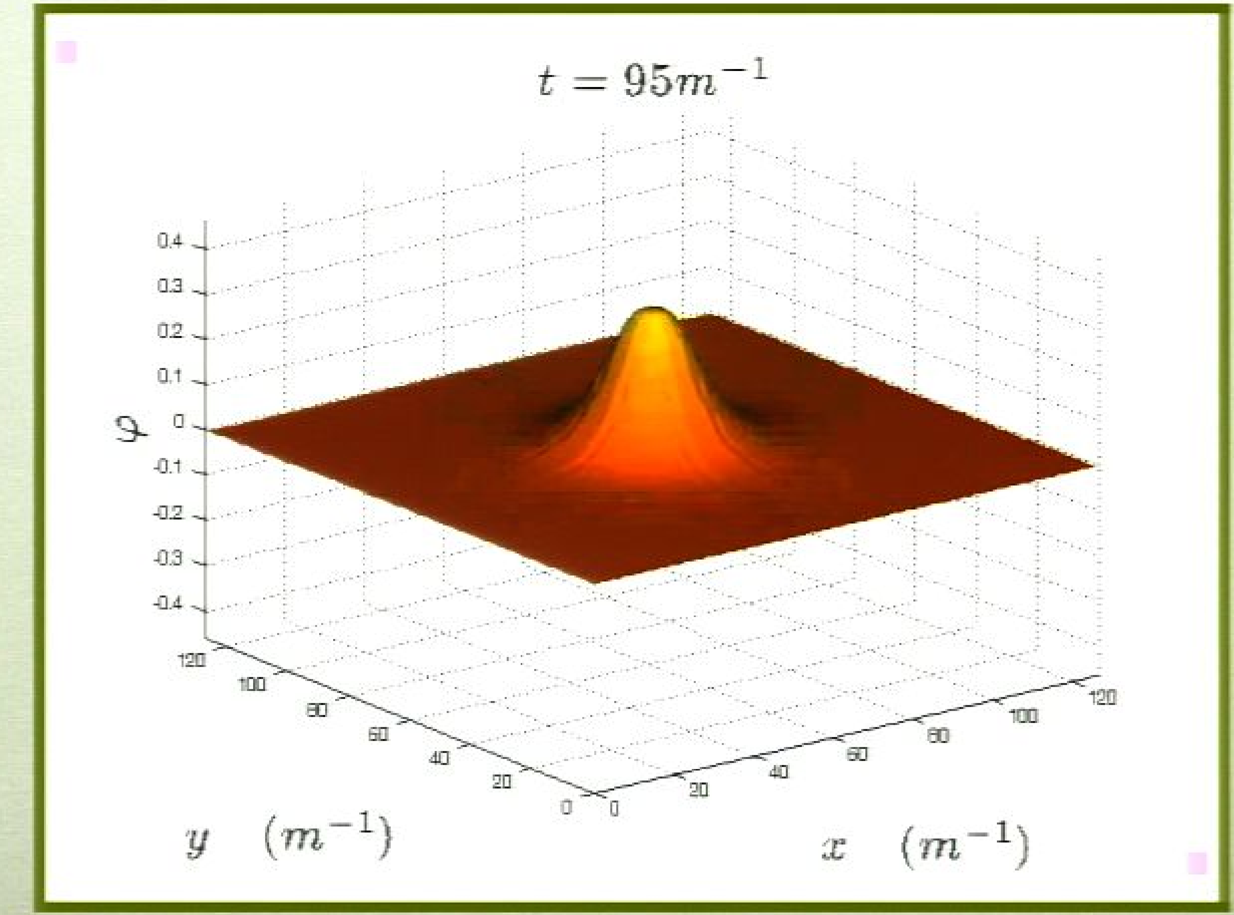

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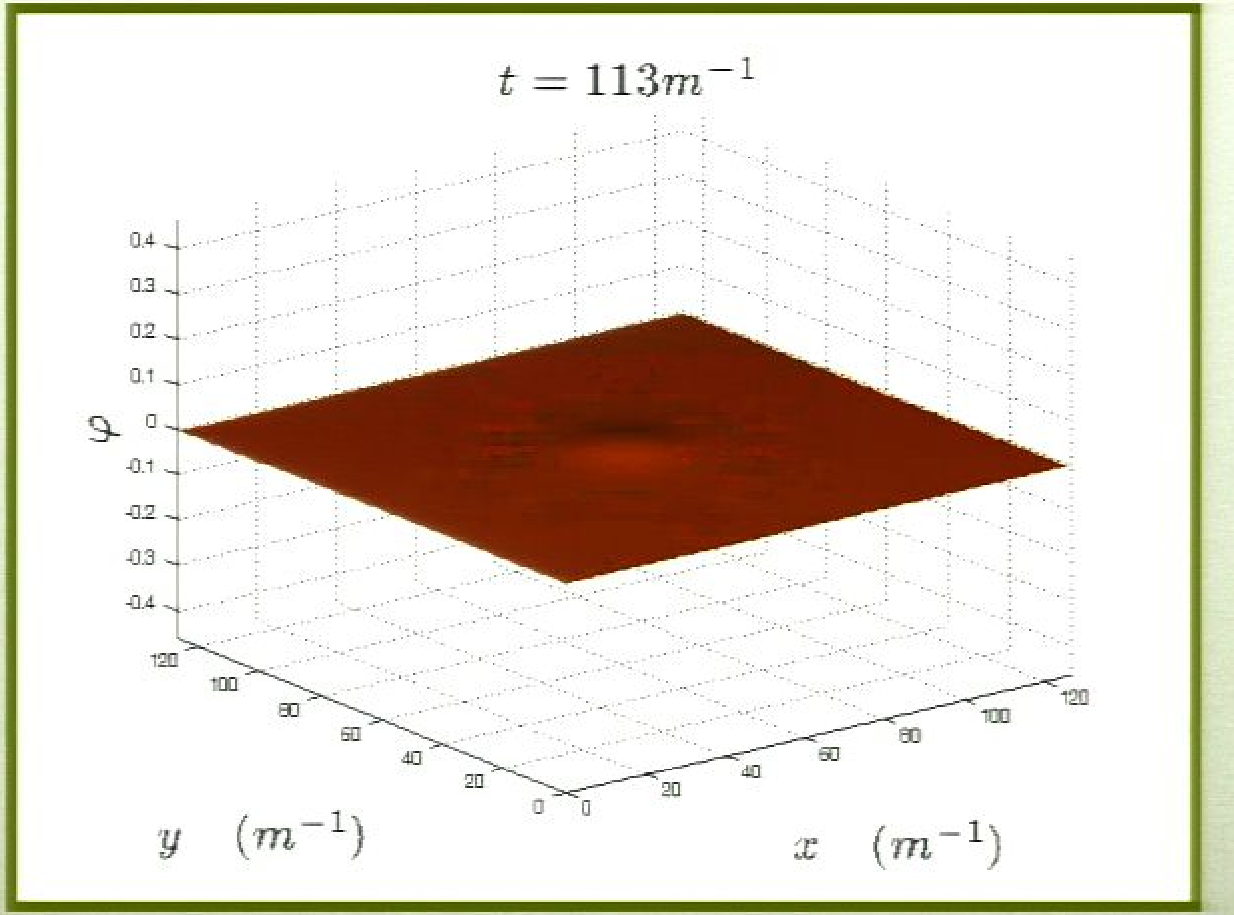

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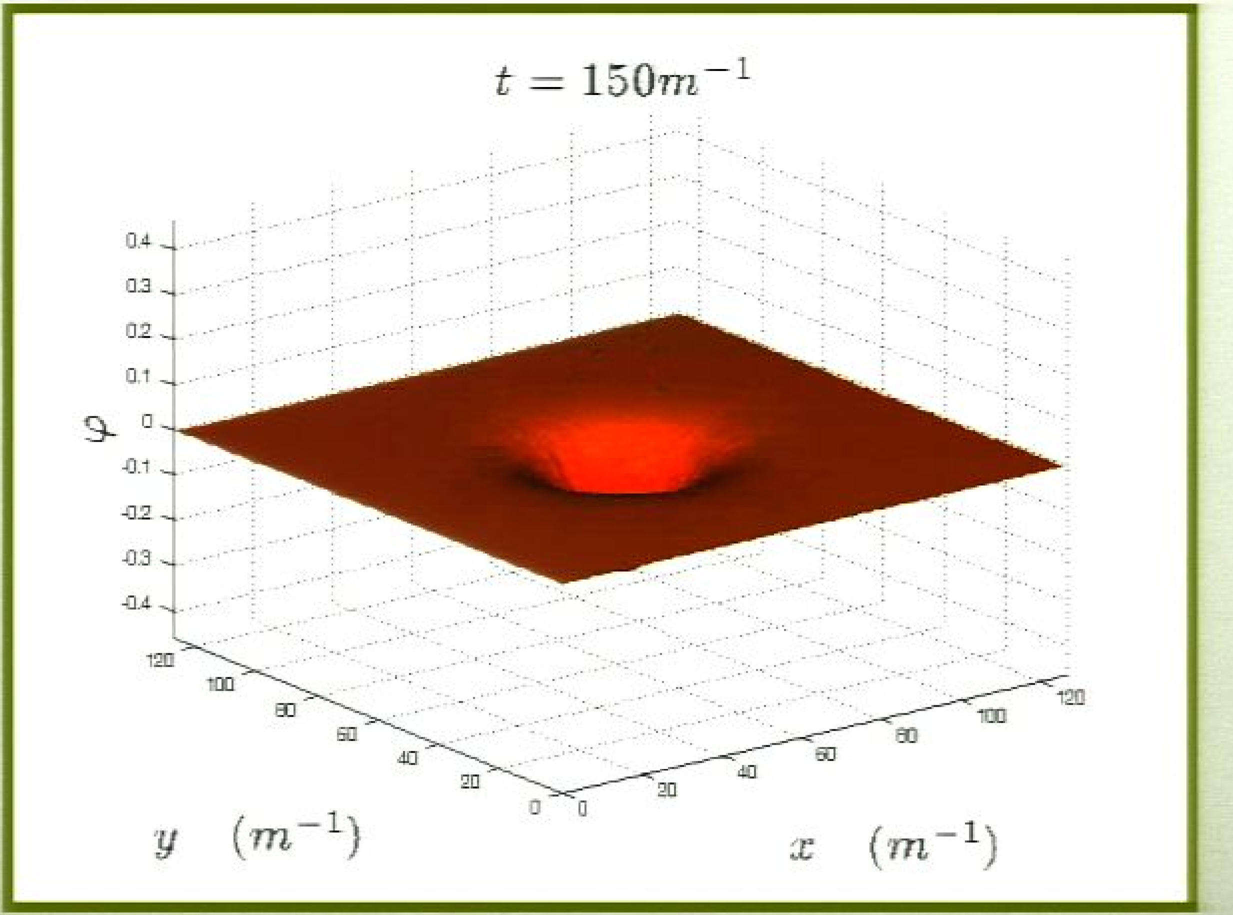

OSCILLONS

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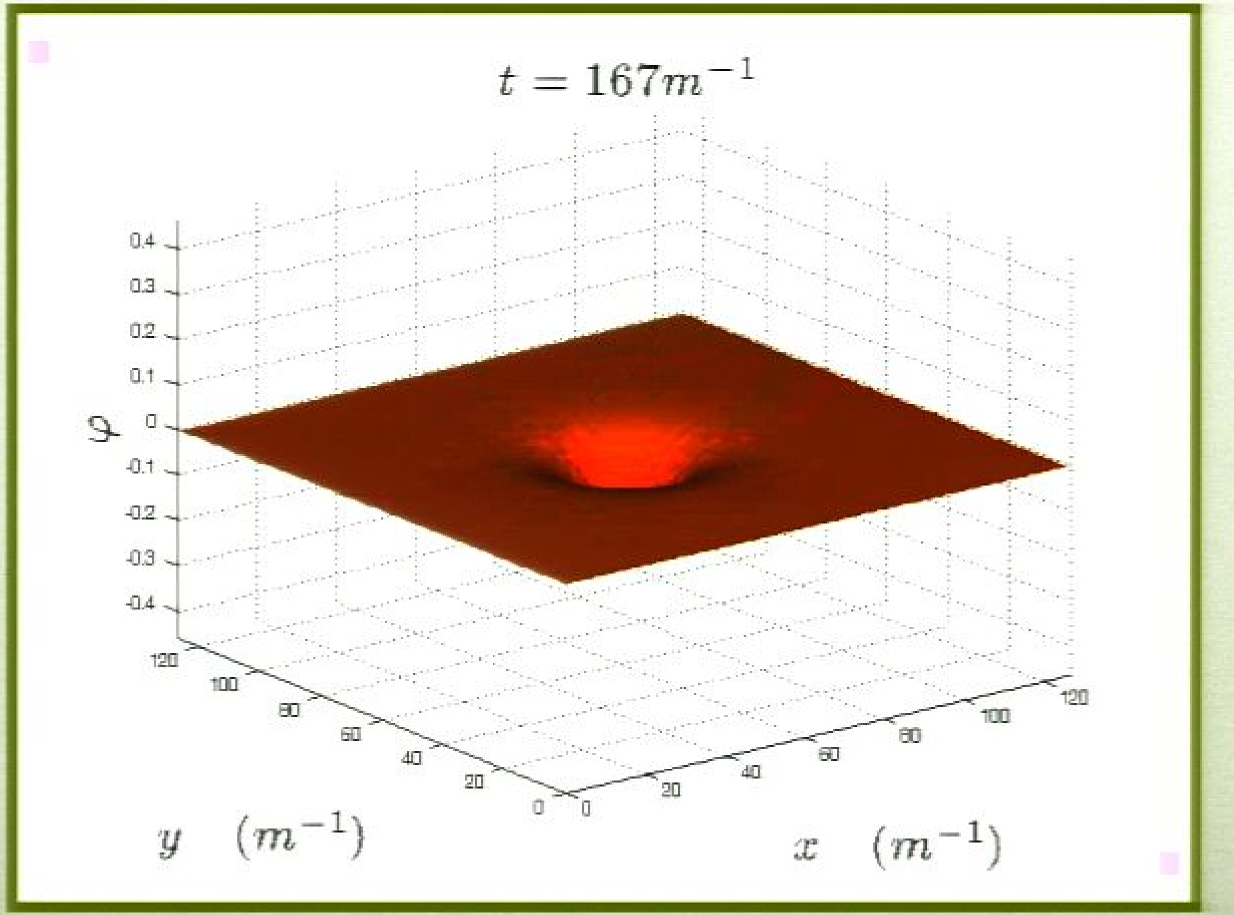

OSCILLONS

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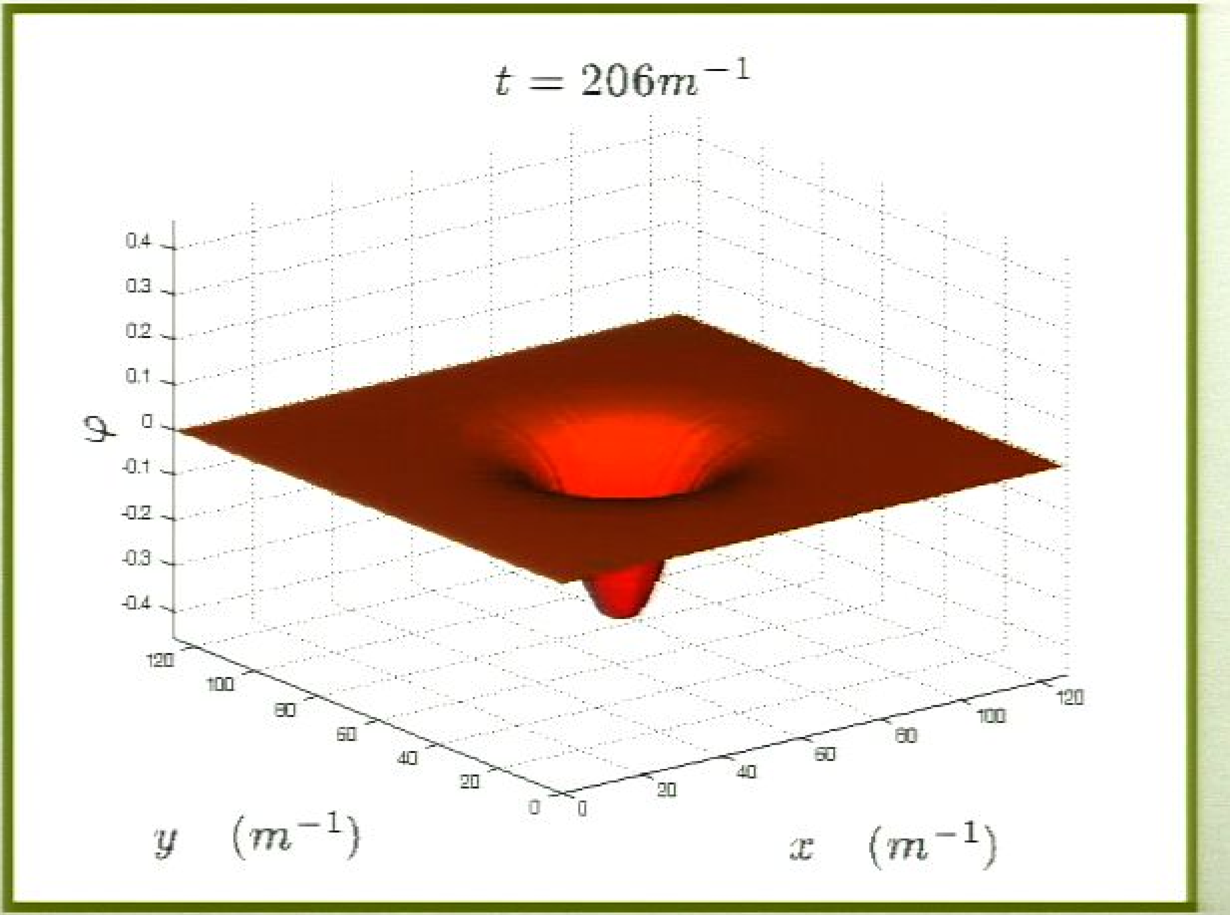

OSCILLONS

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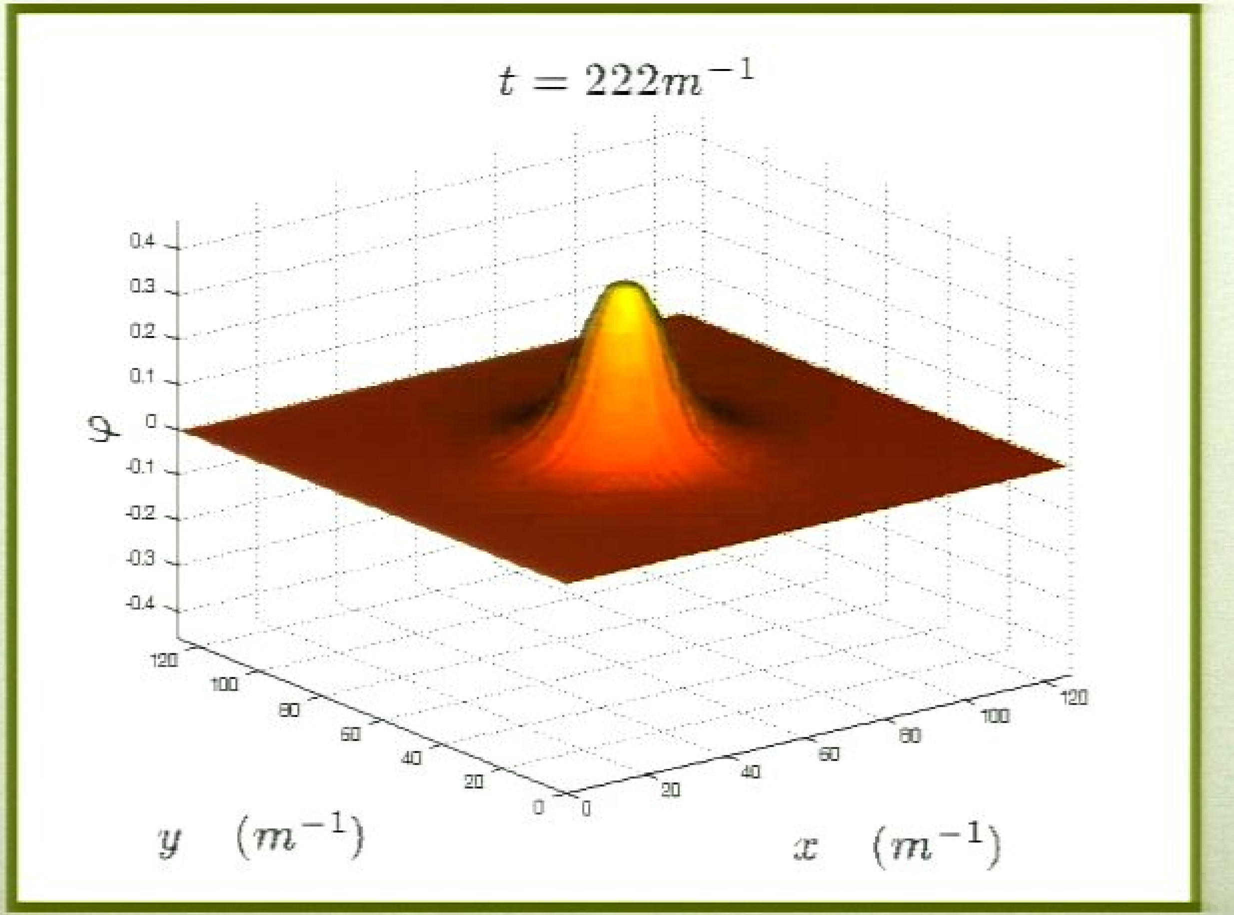

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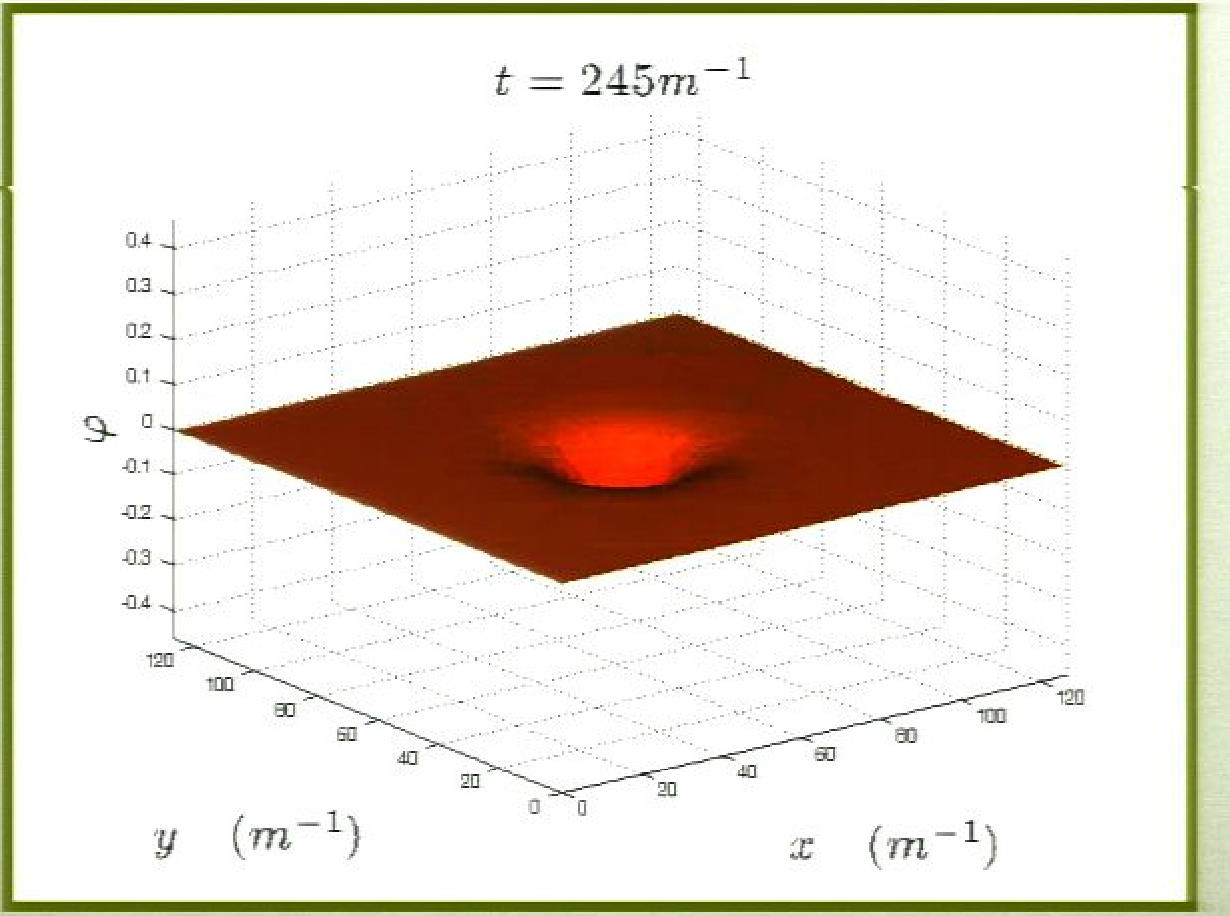

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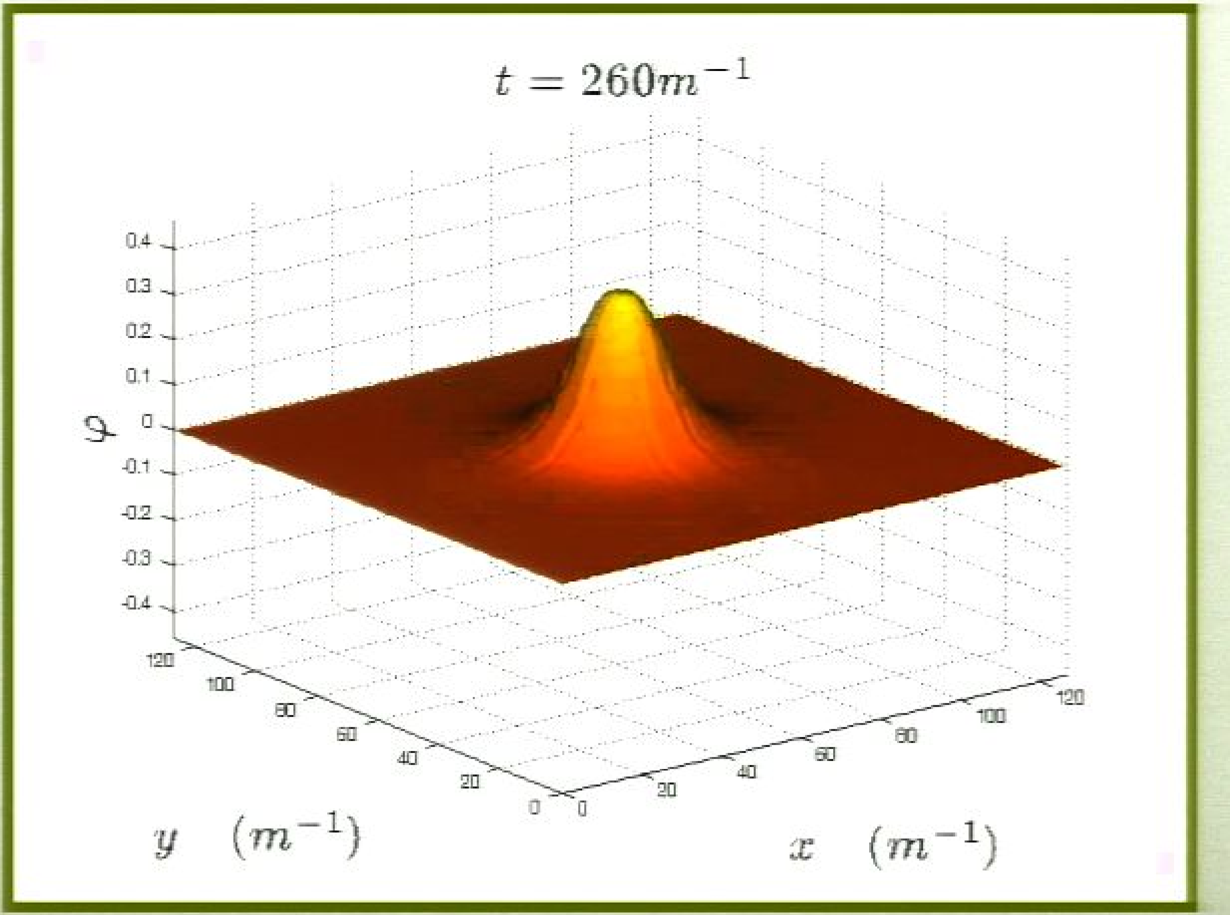

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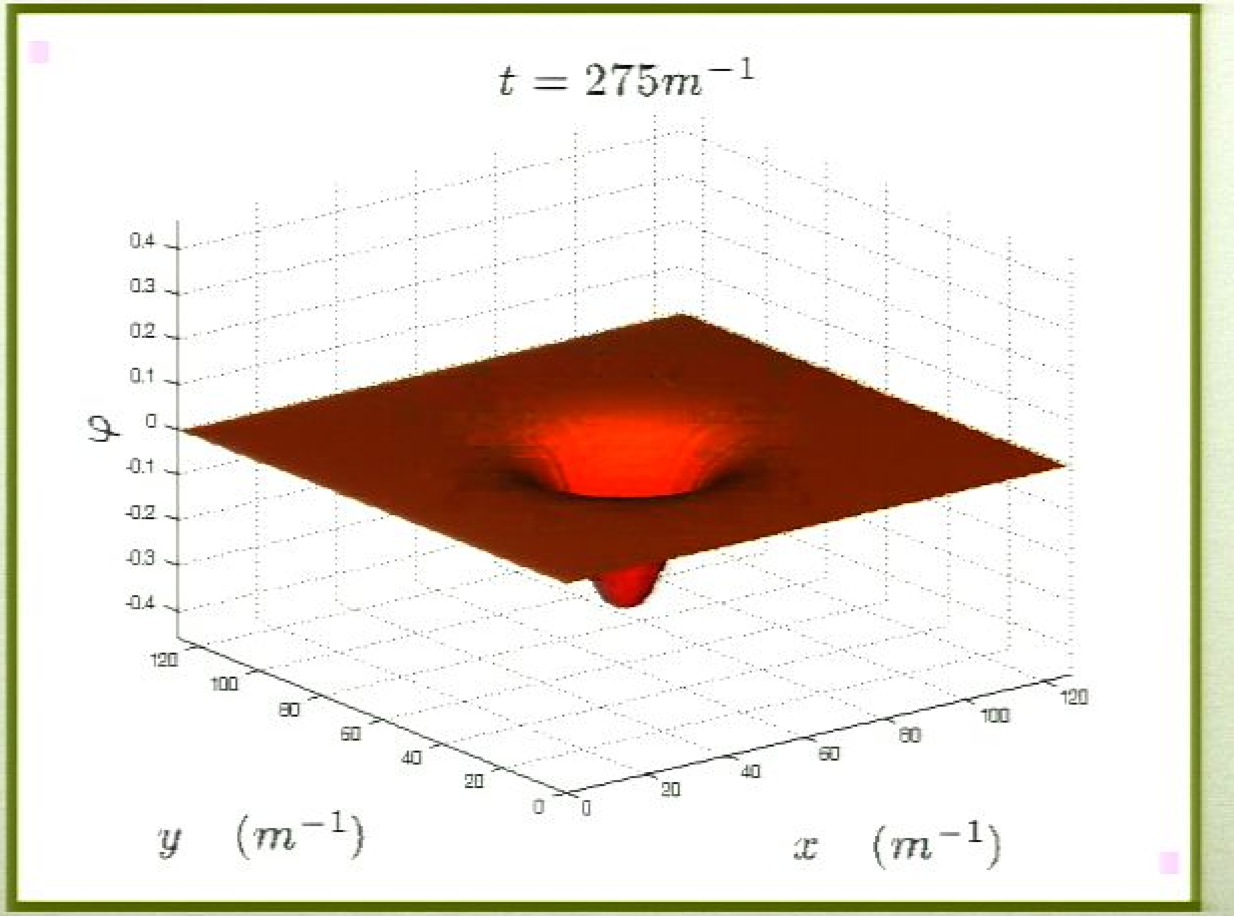

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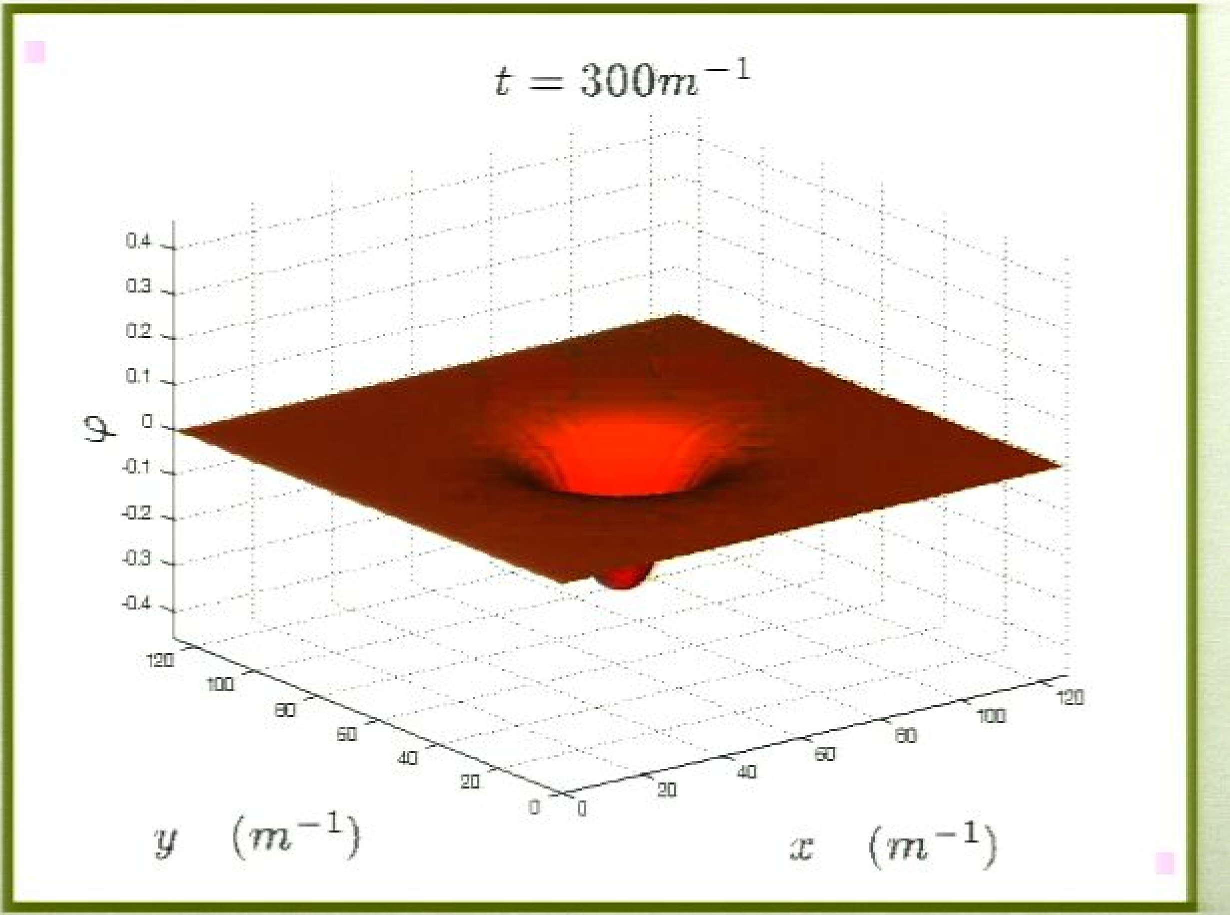

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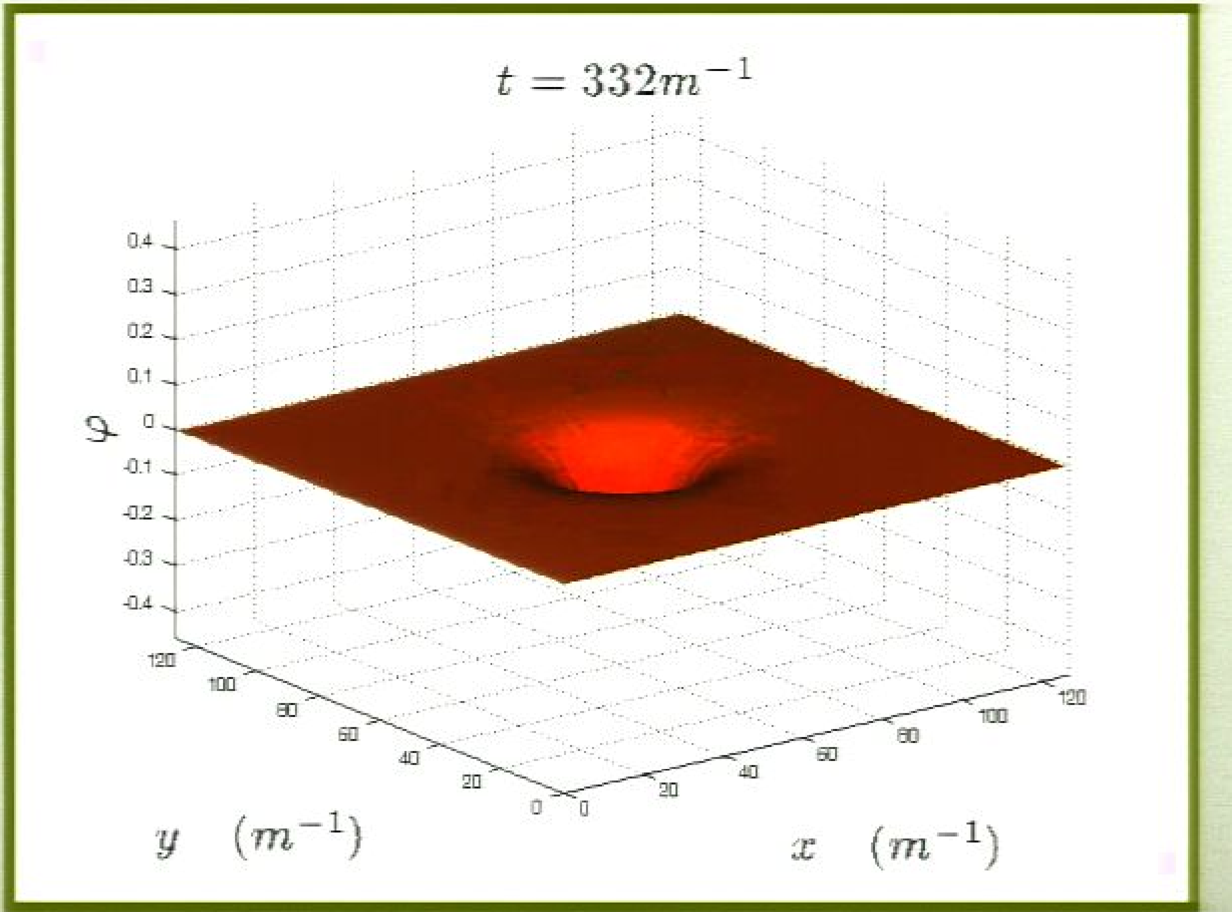

OSCILLONS

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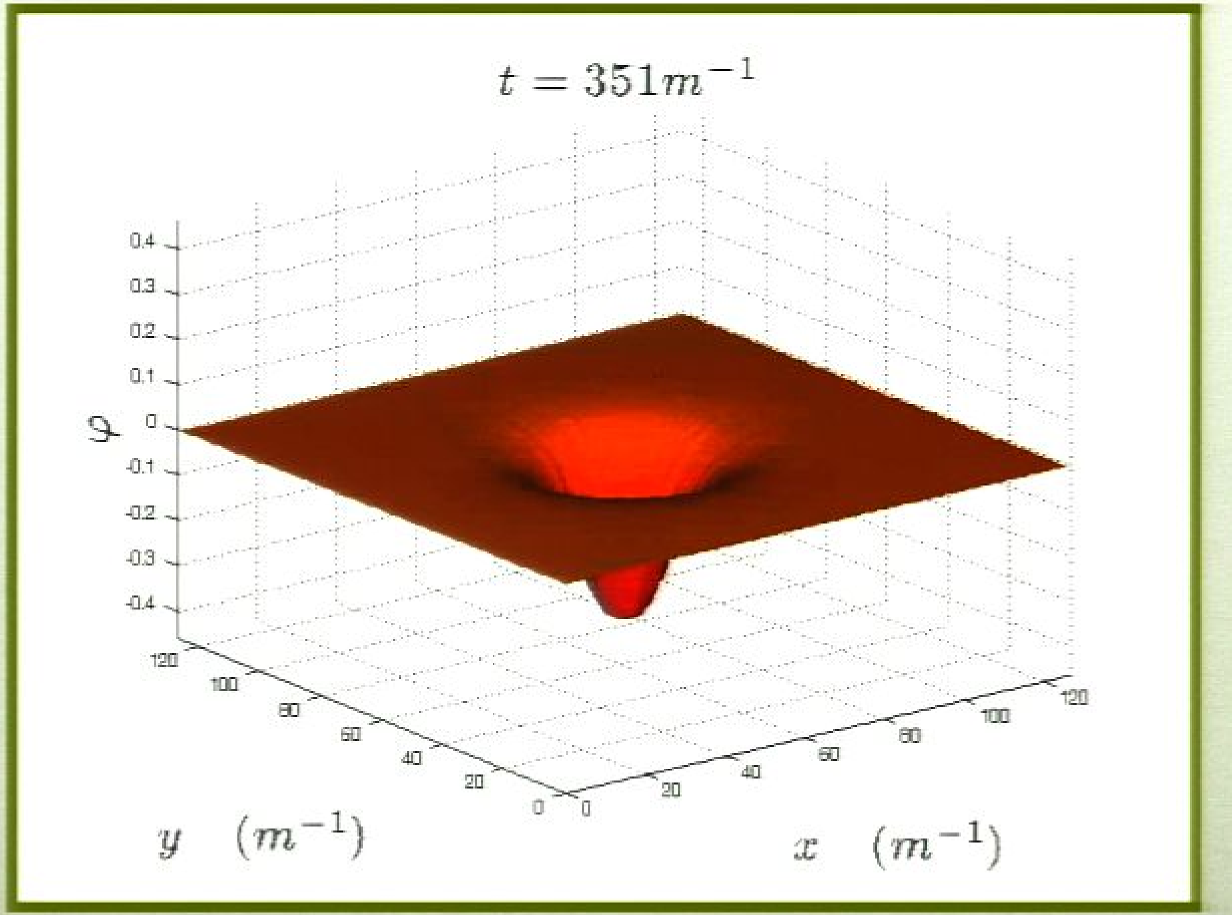

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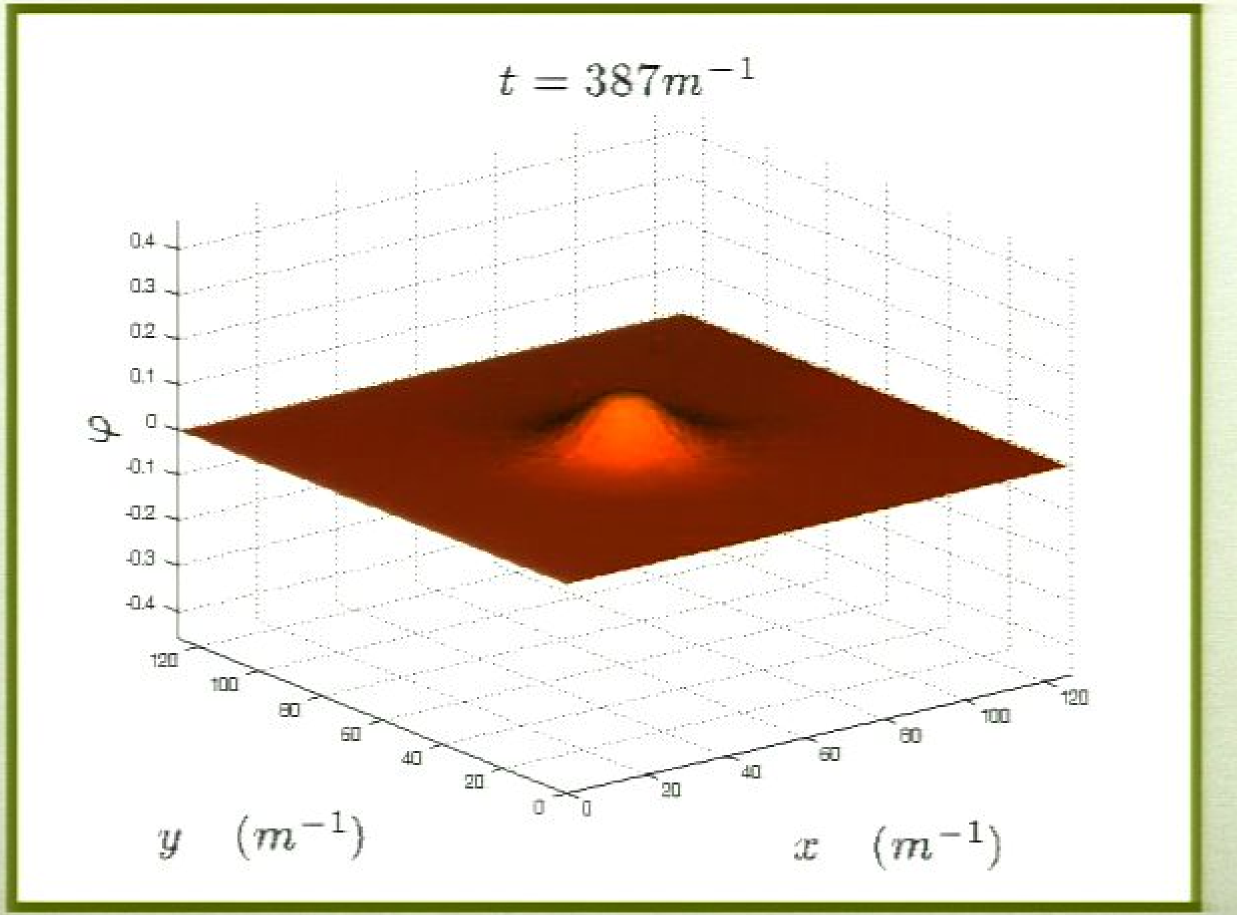

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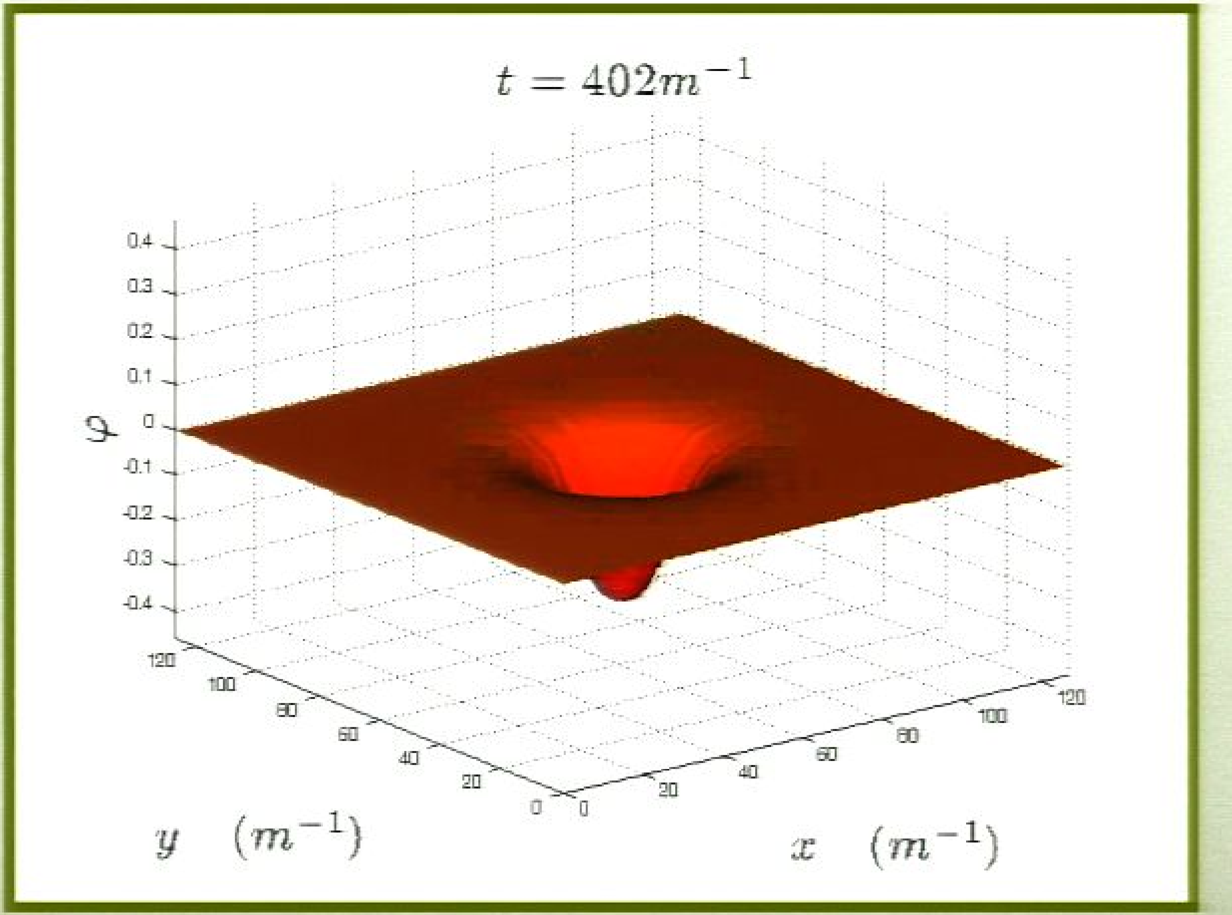

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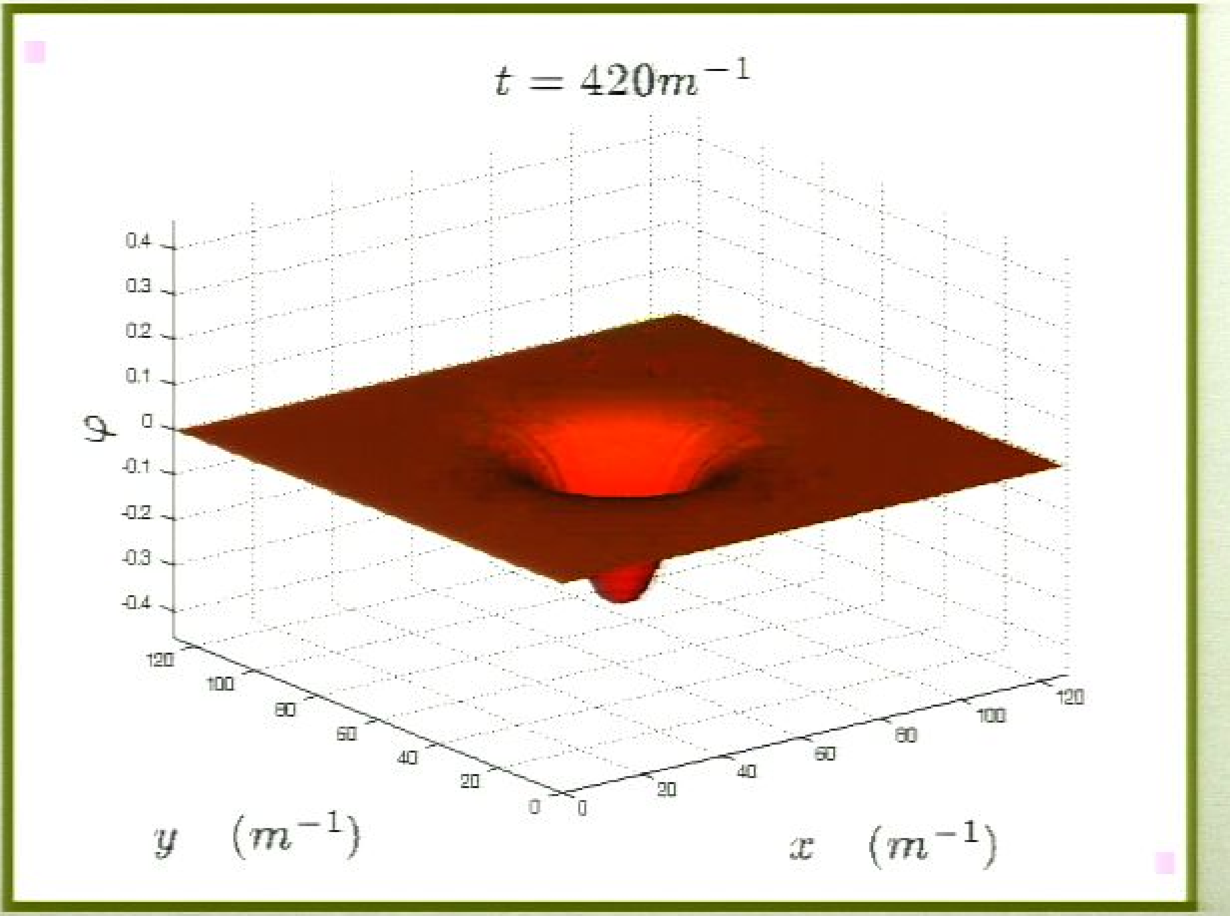

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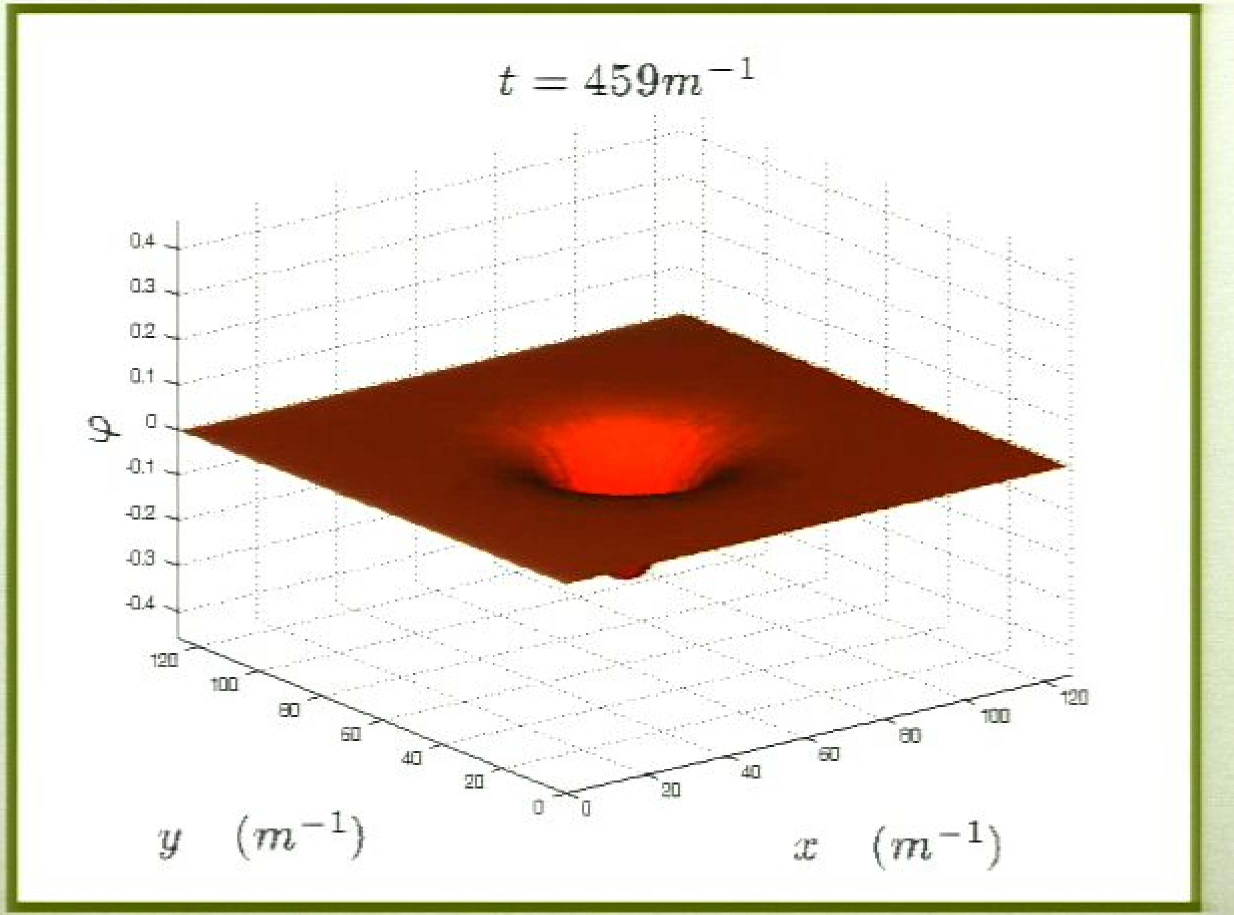

OSCILLONS

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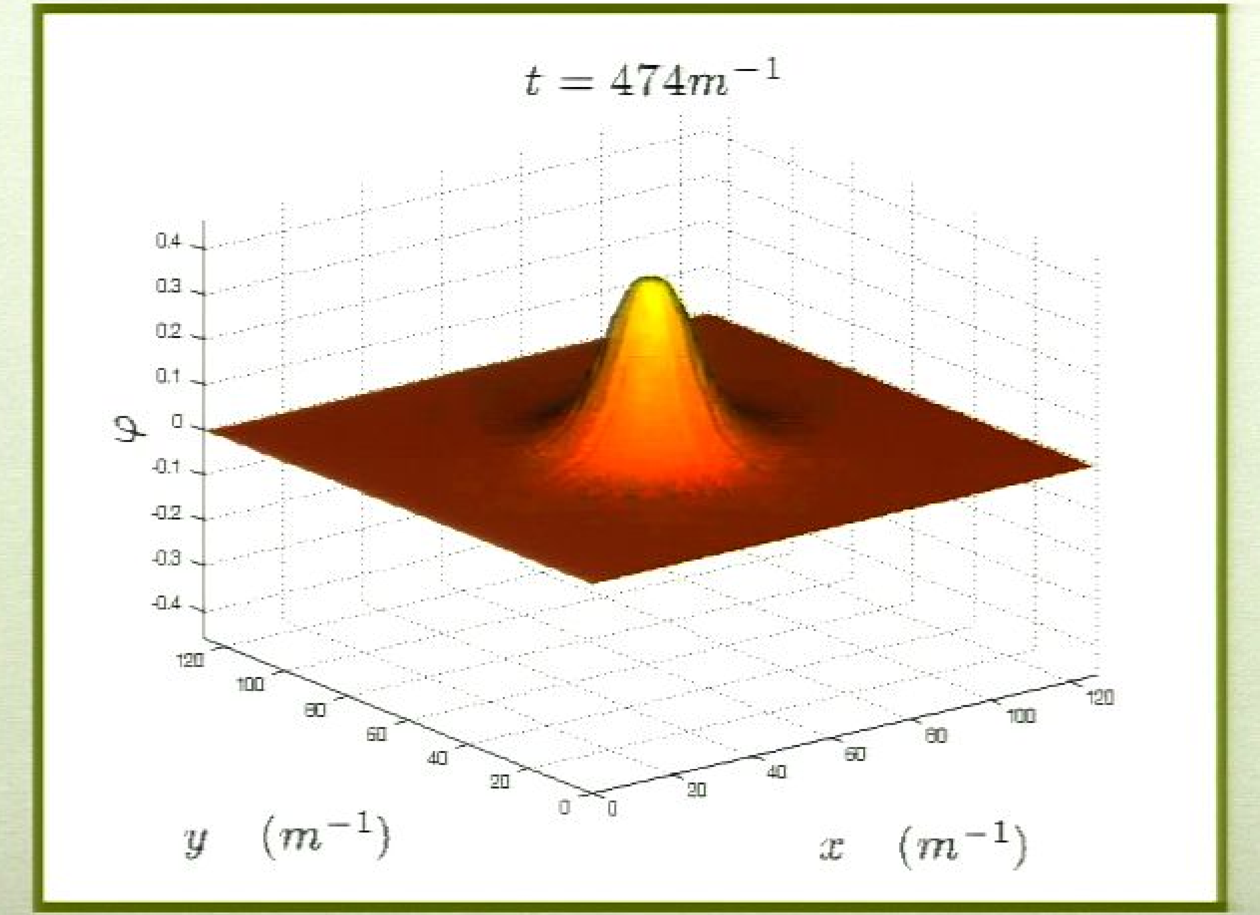

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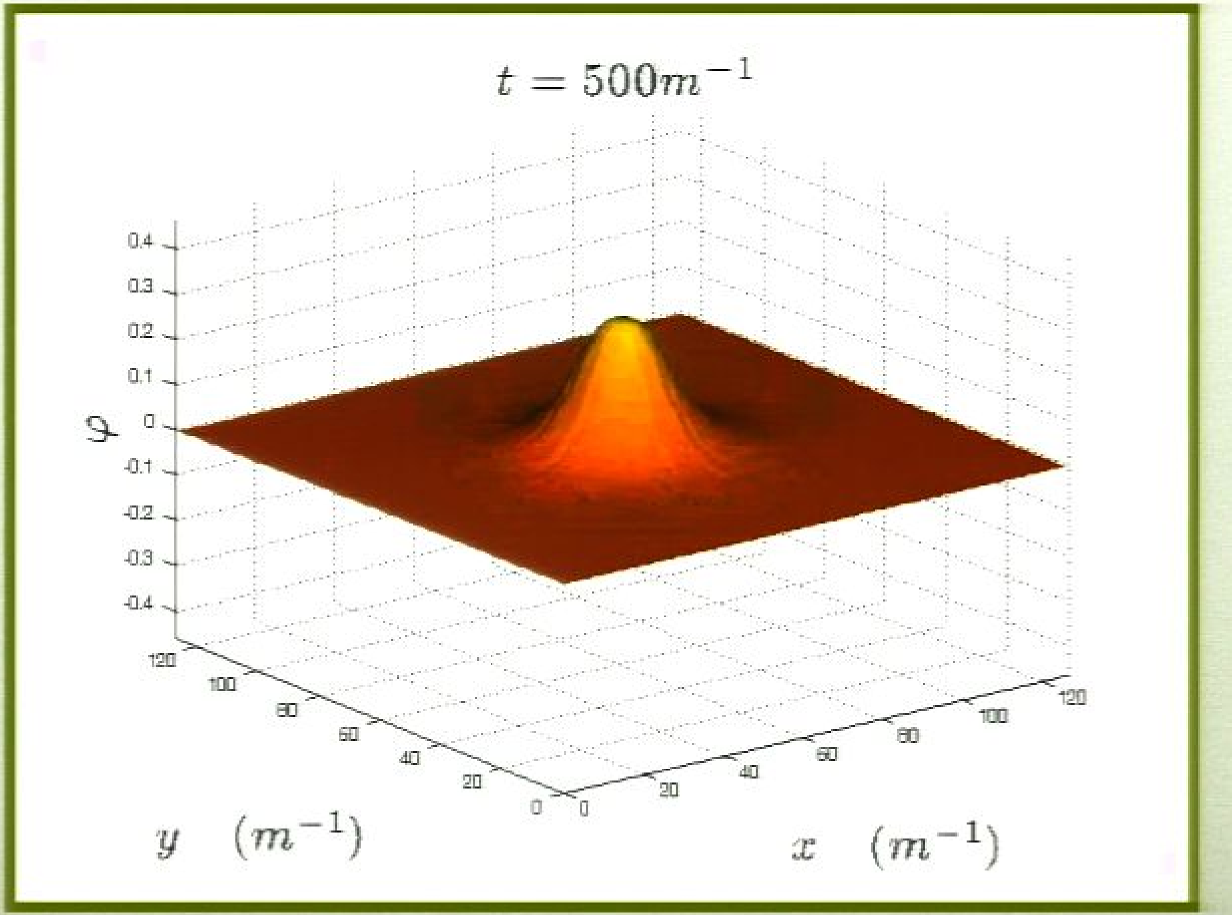

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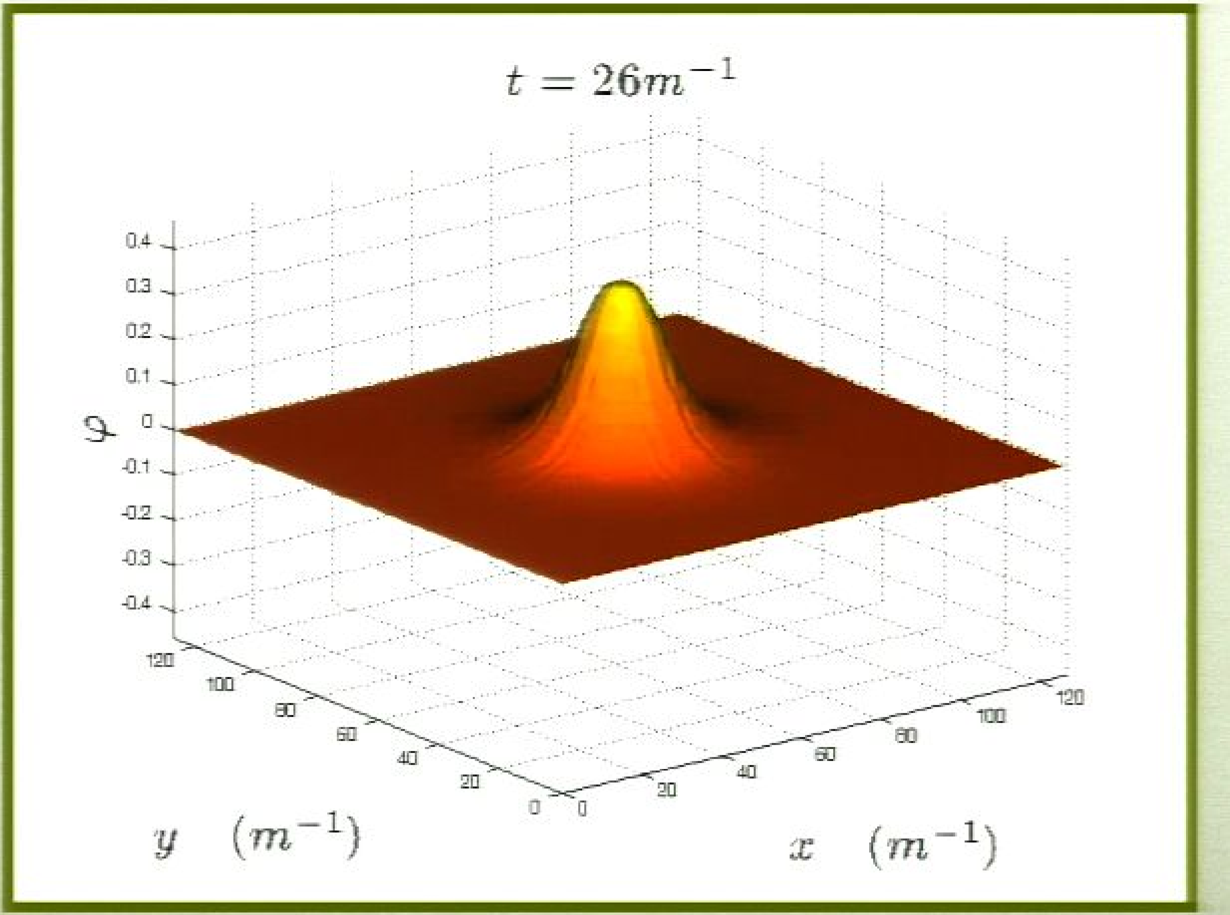

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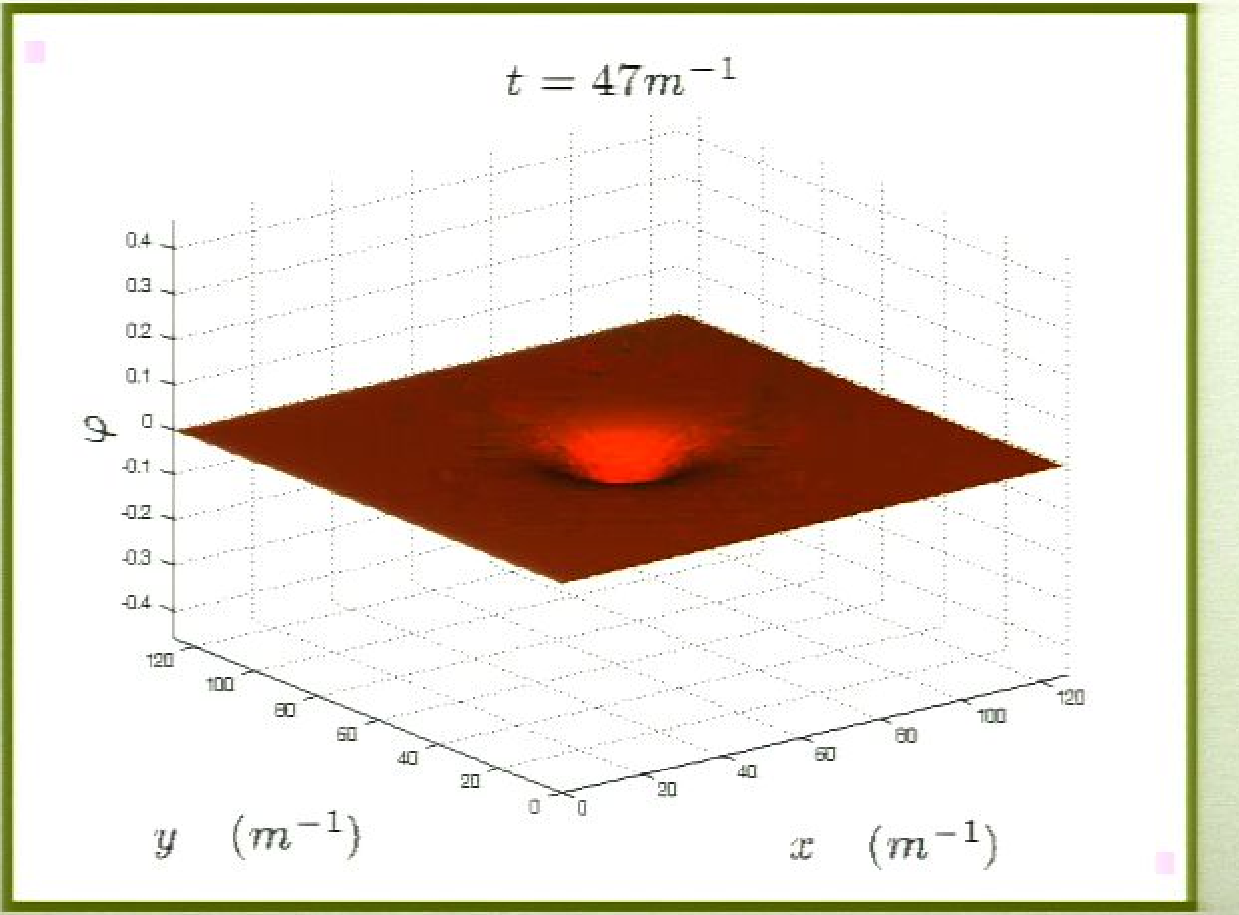

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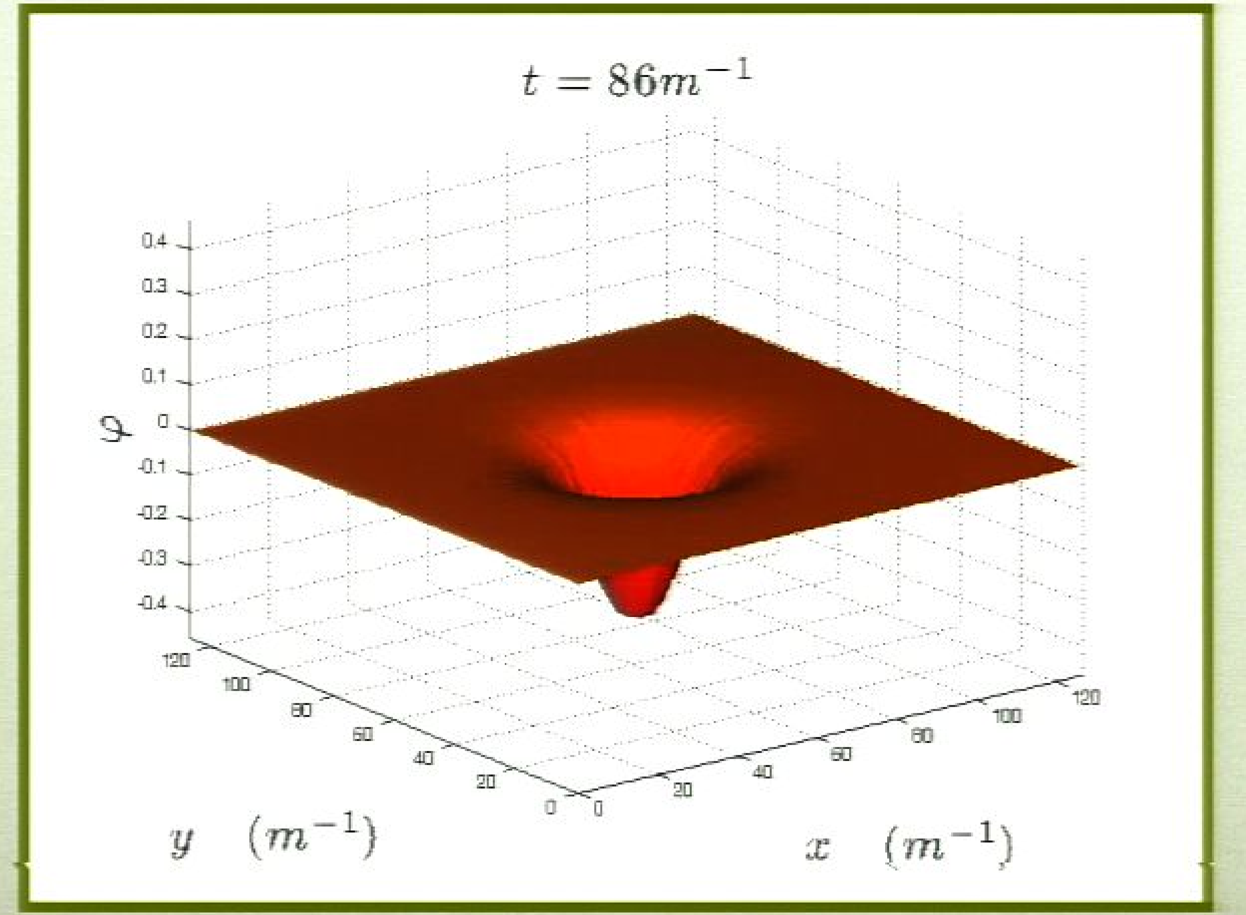

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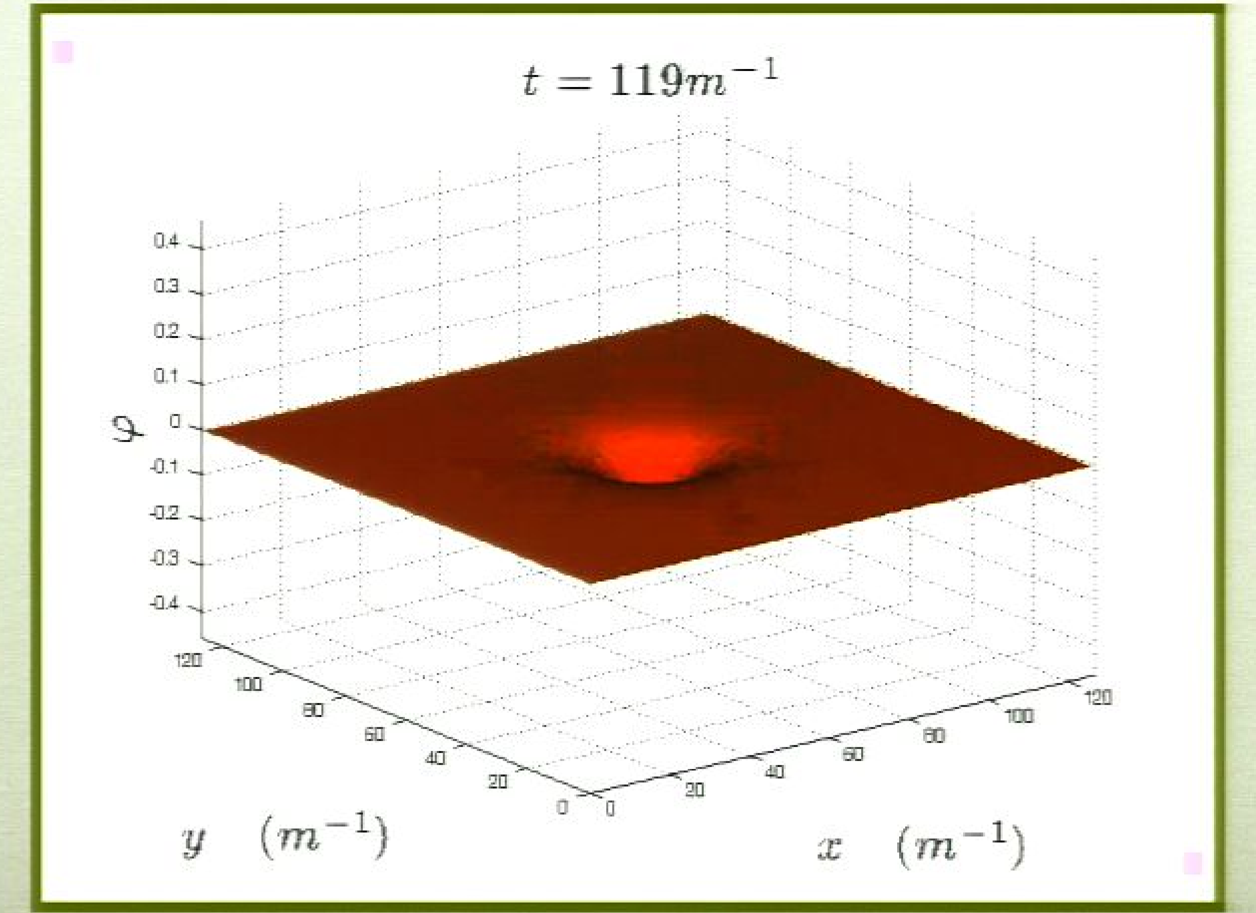

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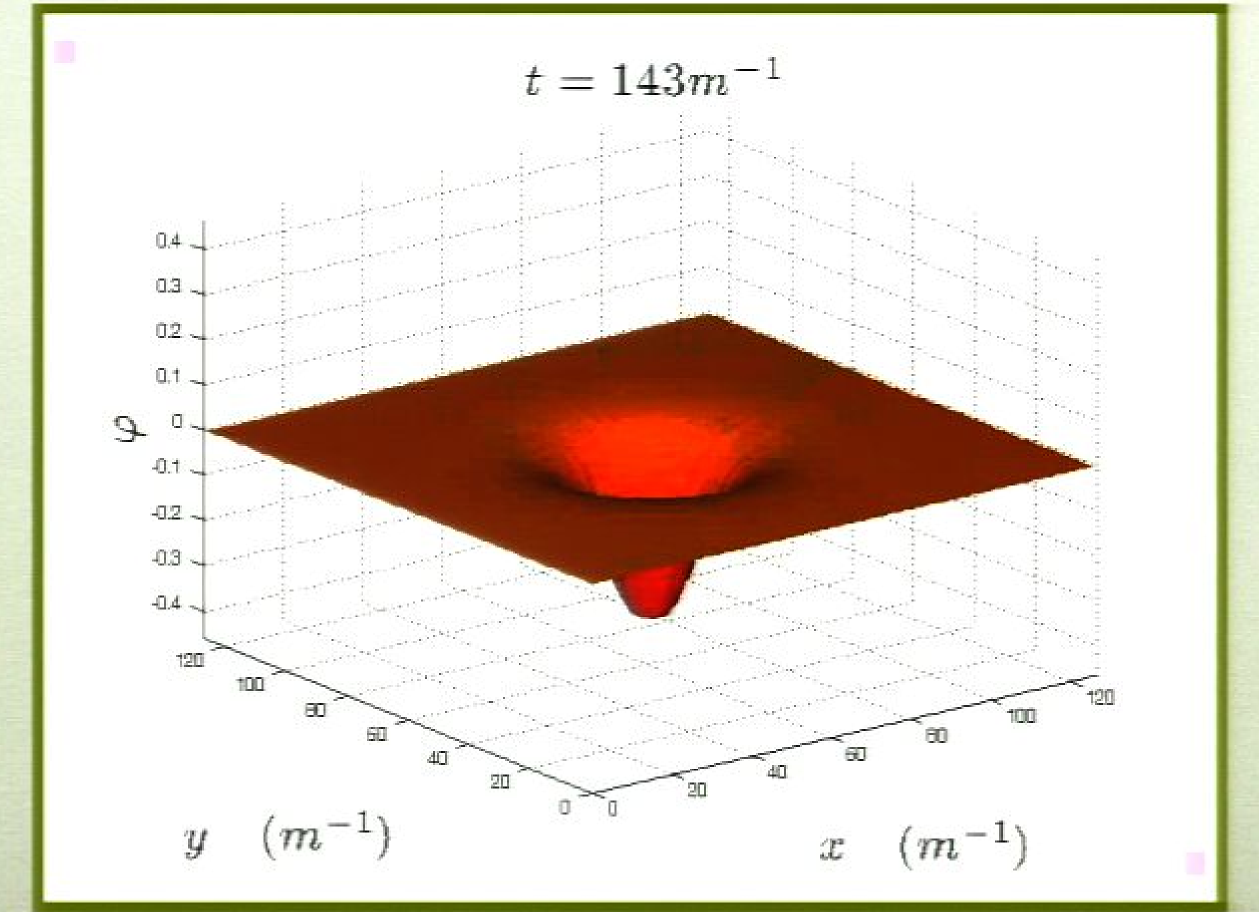

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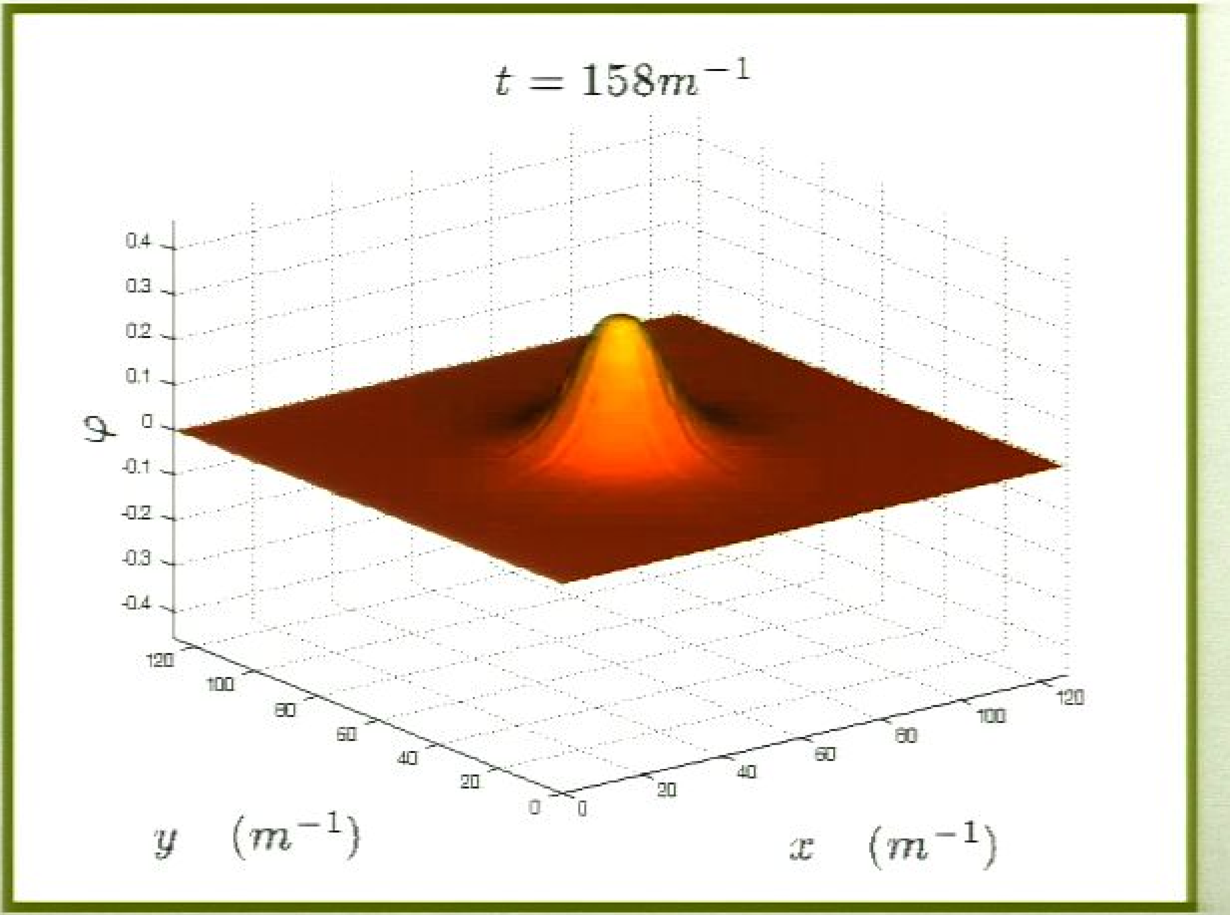

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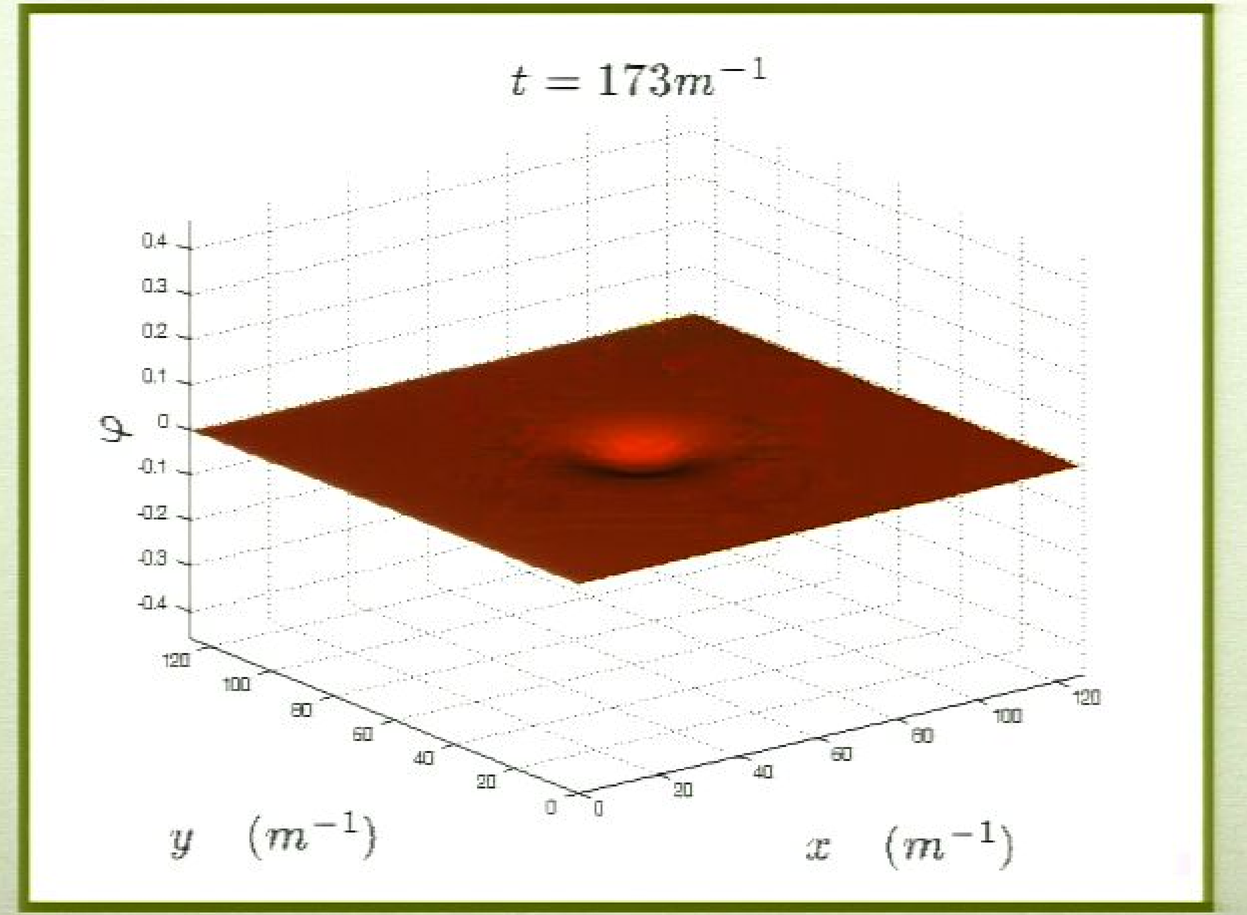

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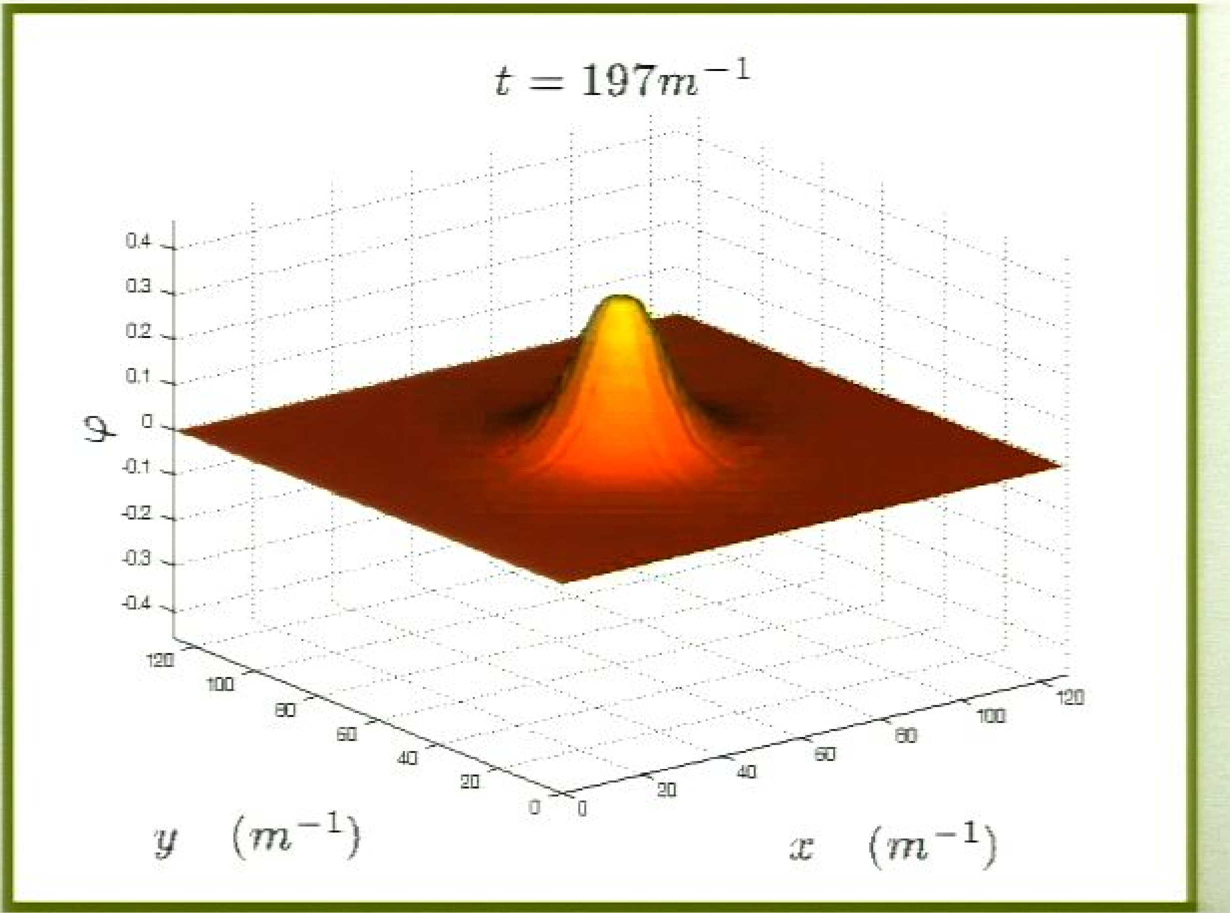

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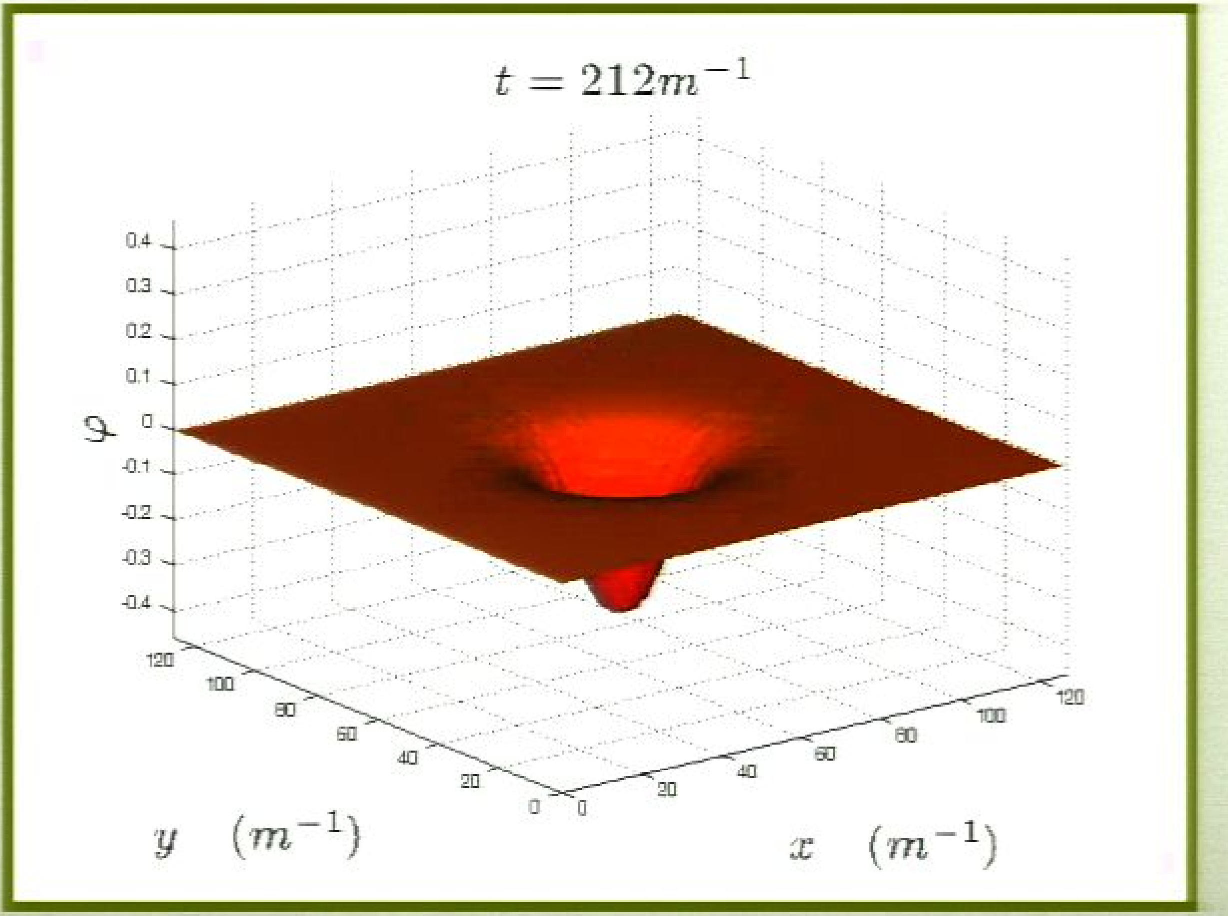

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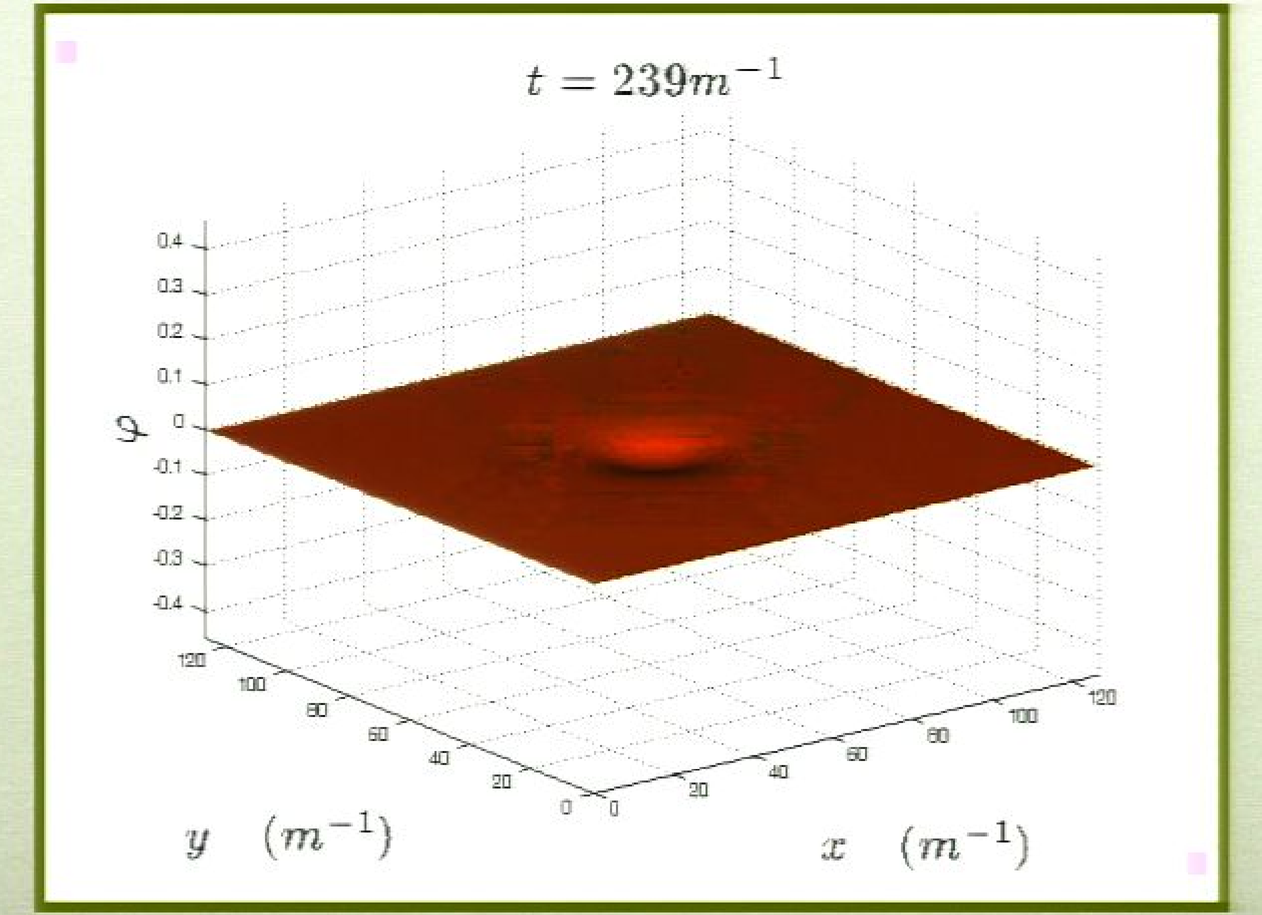

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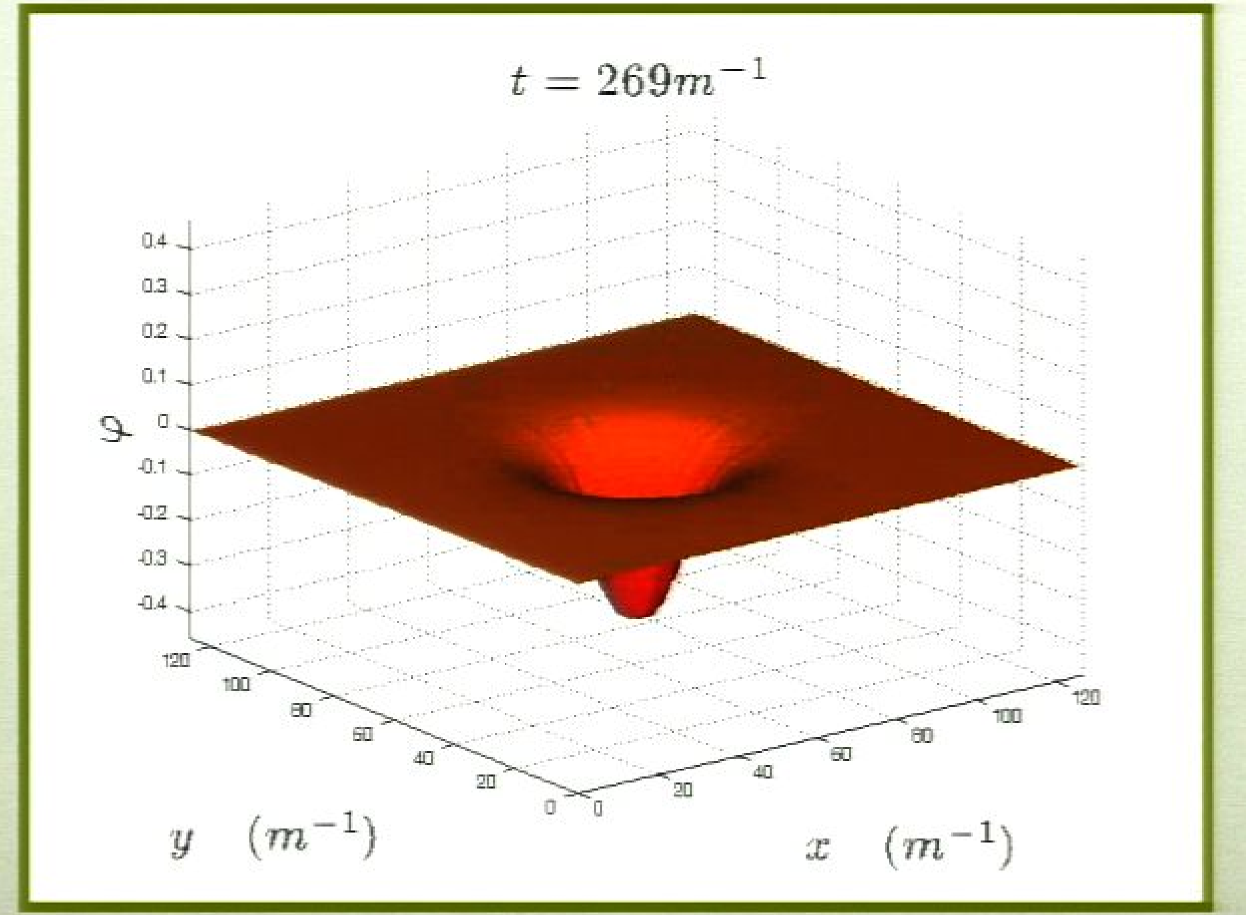

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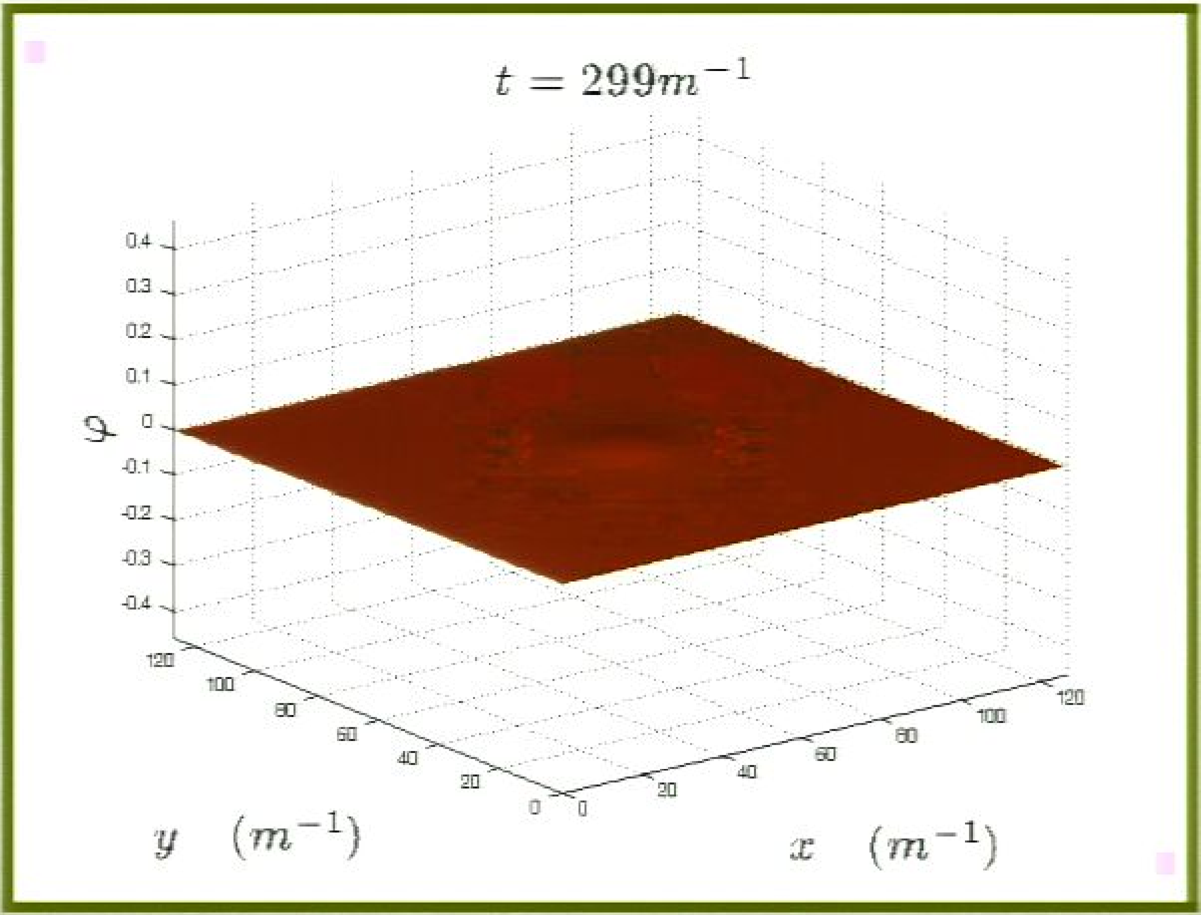

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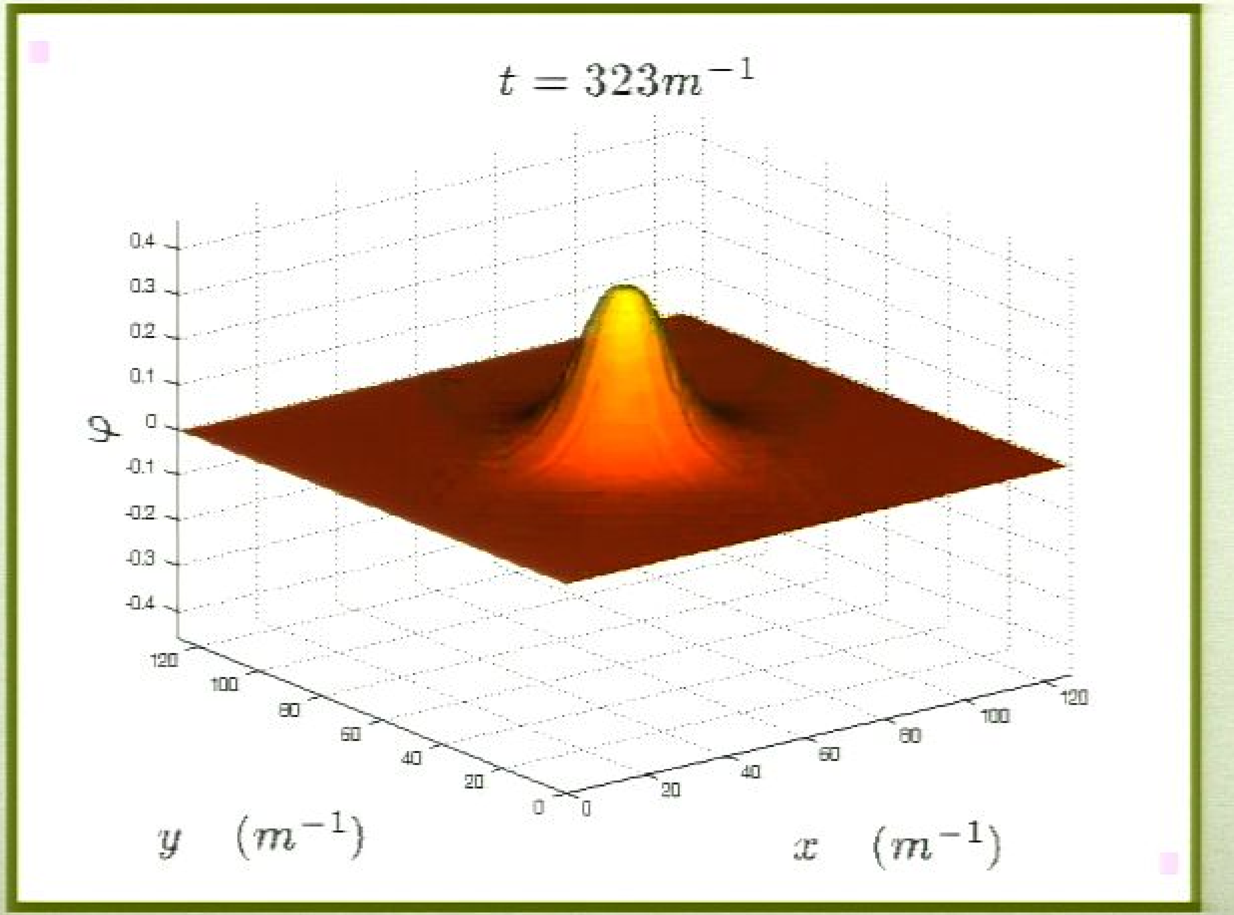

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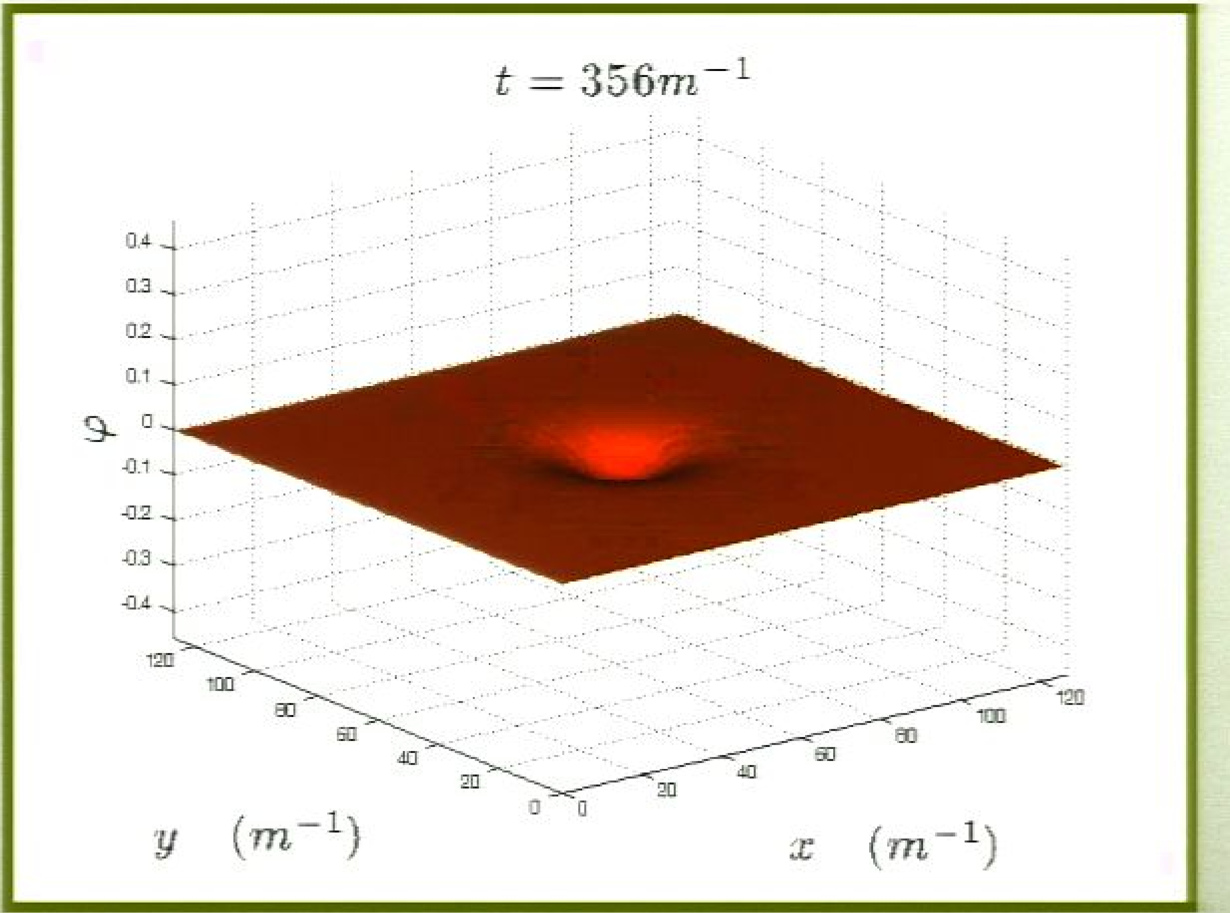

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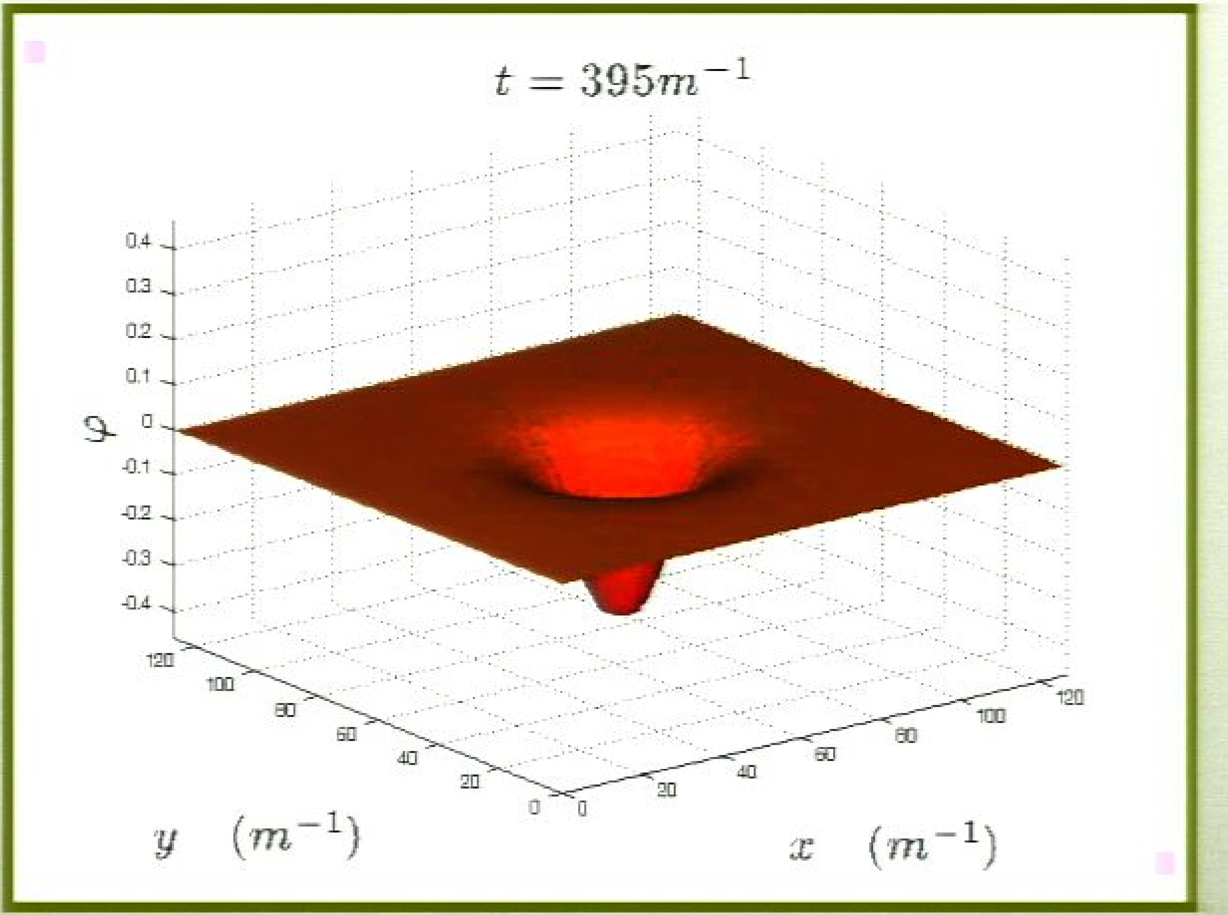

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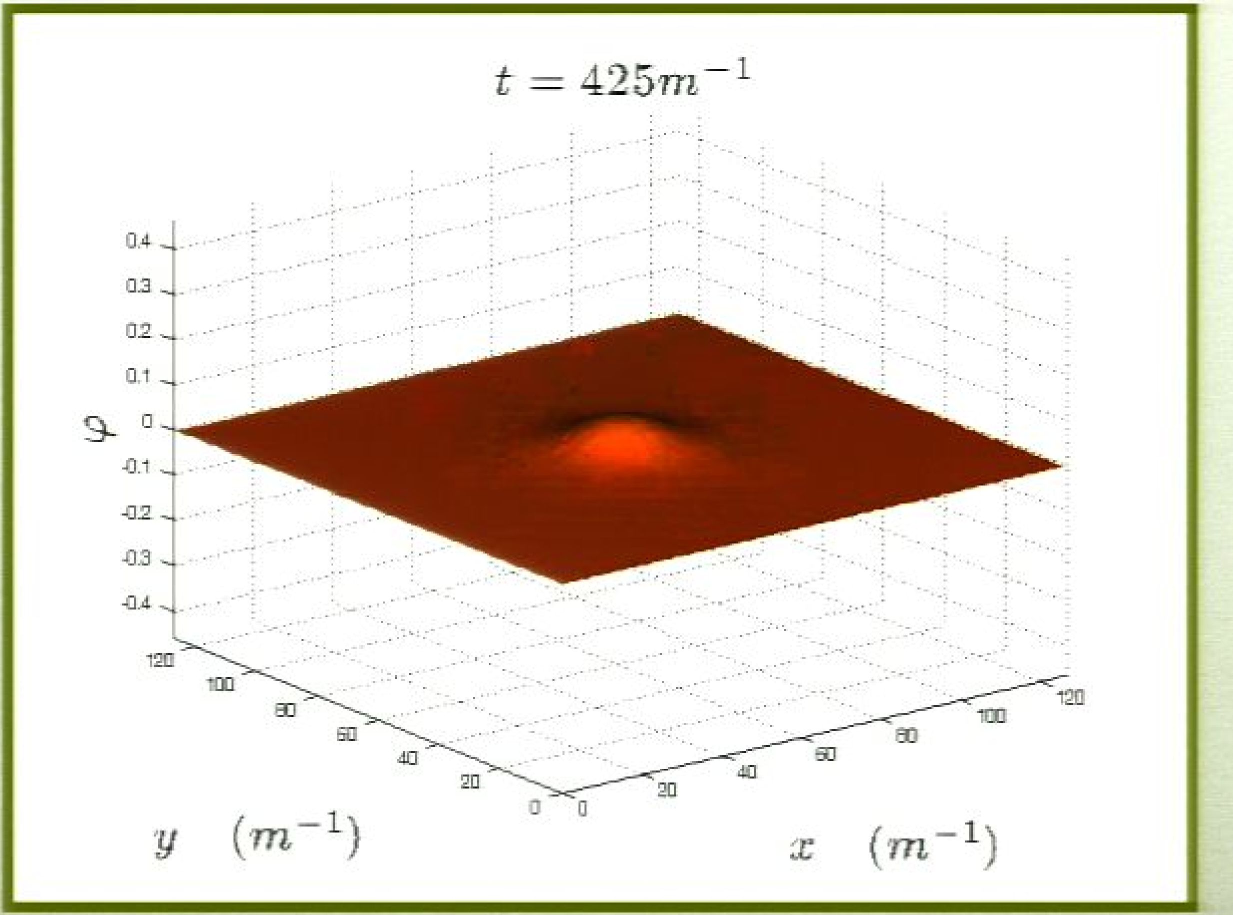

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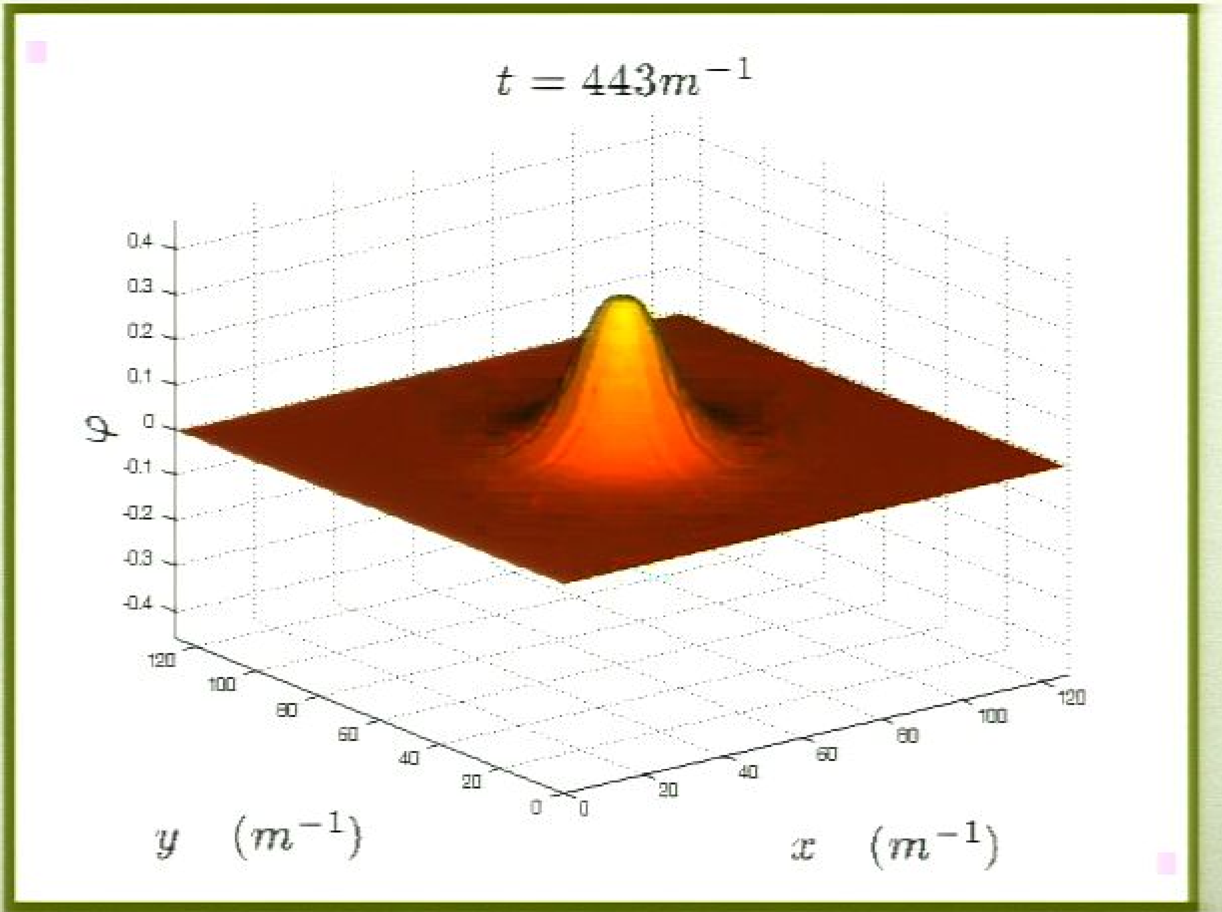

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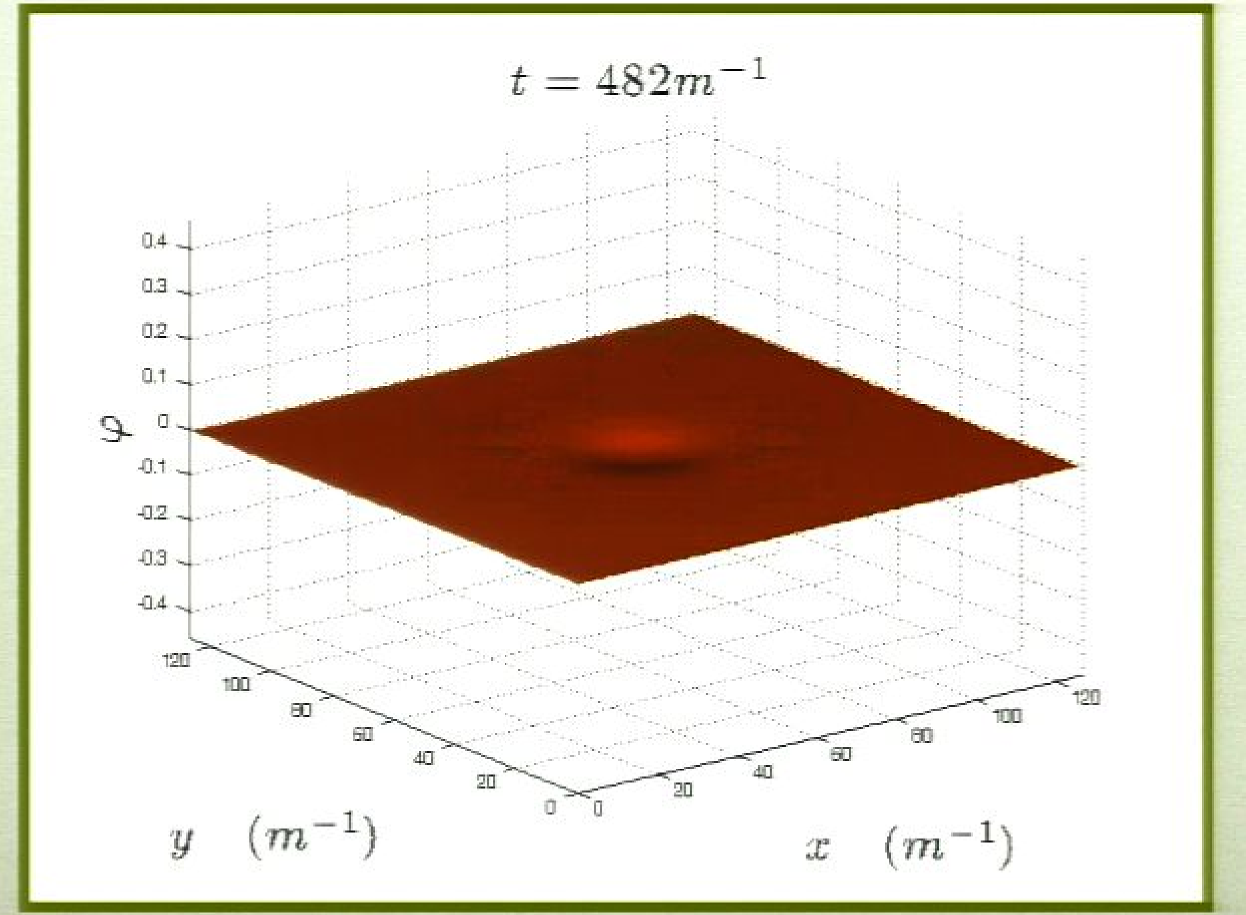

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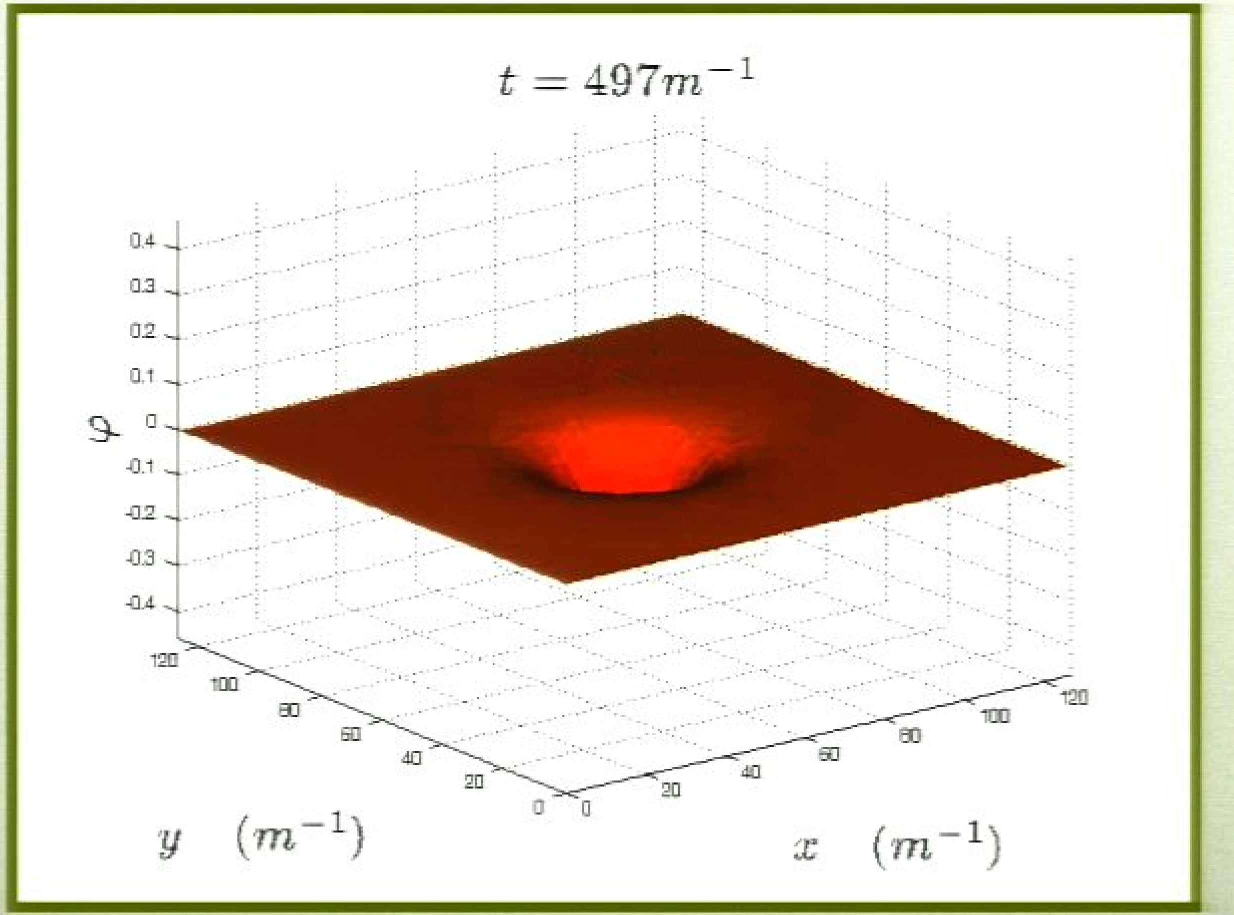

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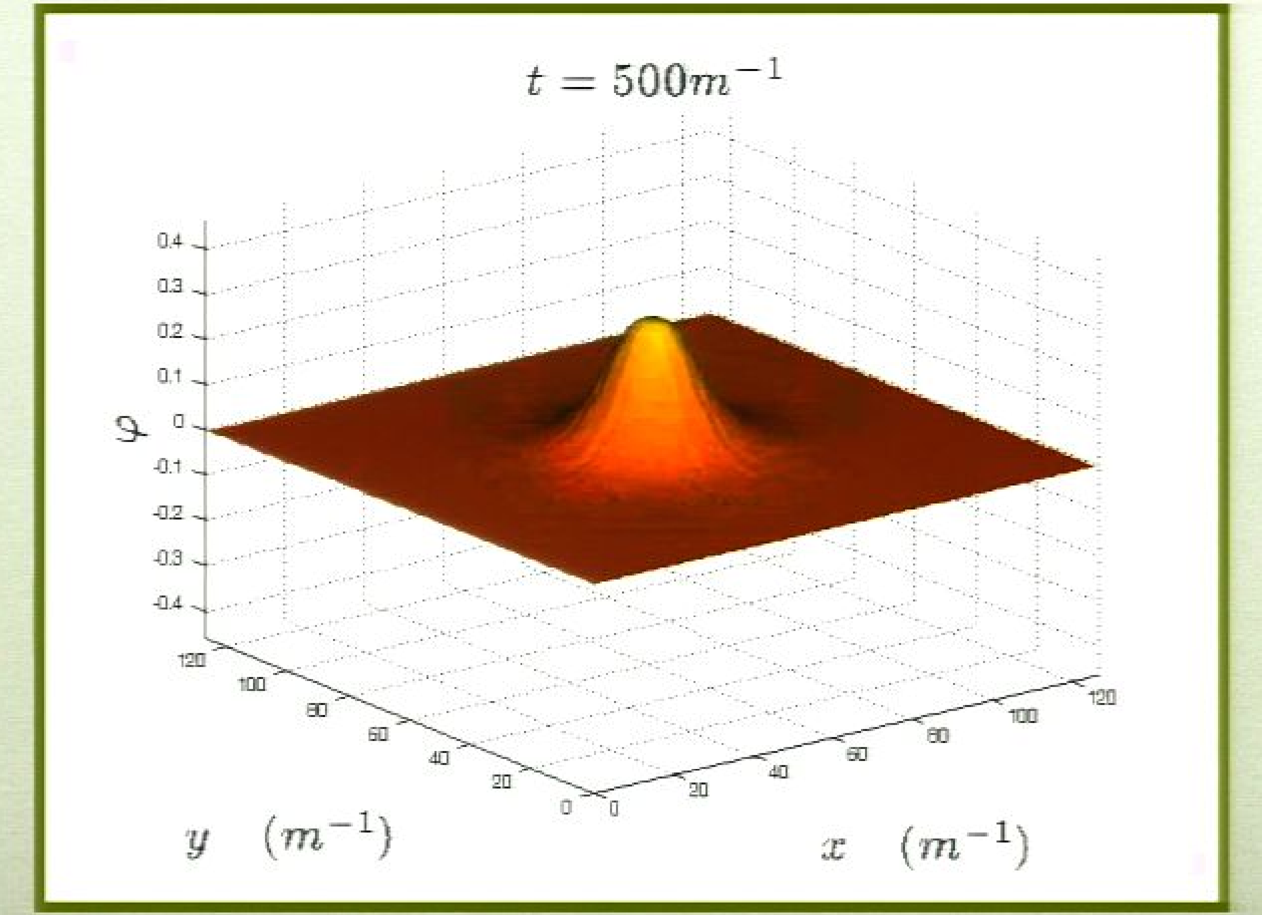
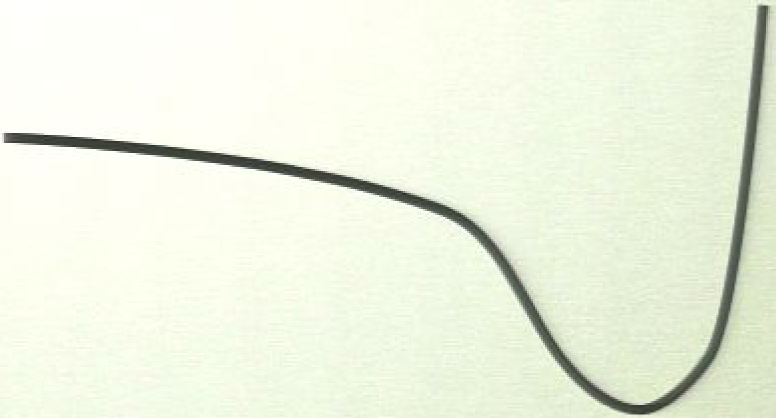


NECESSARY CONDITION

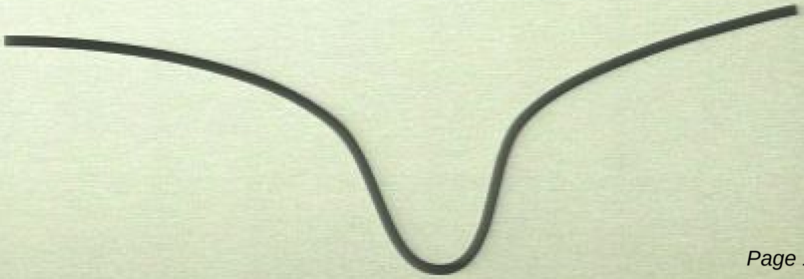
Examples:

$$V(\varphi) - \frac{1}{2}m^2\varphi^2 < 0$$

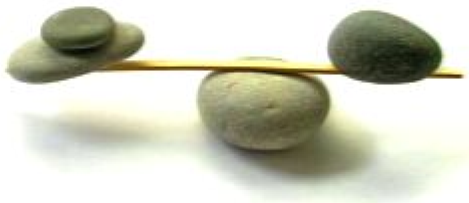
for some range of φ



symmetry breaking



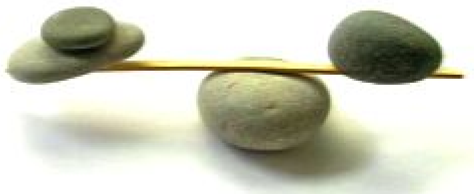
axion monodromy



WHY ?

$$\partial_t^2\varphi - \partial_x^2\varphi + V'(\varphi) = 0$$

localized periodic solution: $\varphi(t,x) \sim \Phi(x)\cos\omega t$



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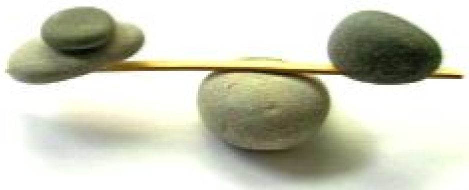

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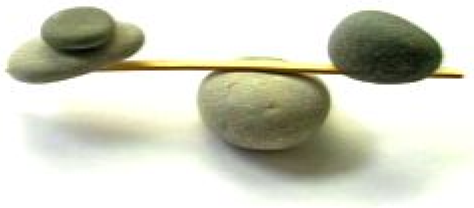
$$\left[(m^2-\omega^2)\varphi\right] + \left[-\partial_x^2\varphi\right] + \left[V'(\varphi) - m^2\varphi\right] \sim 0$$

frequency curvature non-linearity



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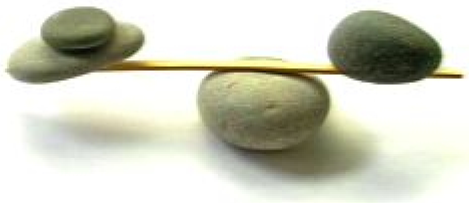
+ve +ve



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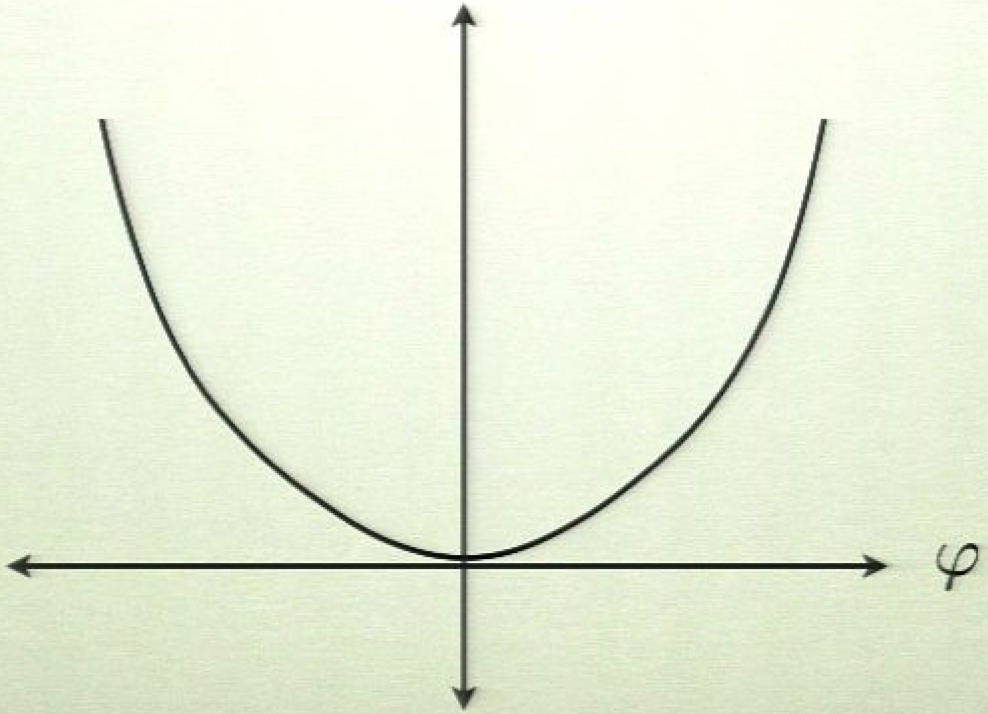
frequency	curvature	non-linearity
+ve	+ve	

Need, at least somewhere $V'(\varphi) - m^2\varphi < 0$

EXAMPLE

$$V(\varphi) = \frac{1}{2}m^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + \frac{g^2}{6m^2}\varphi^6 \qquad \lambda^2 \ll g^2$$



quasi-stable, approximately single frequency solutions exist in the model.

HOW TO SOLVE -2

$$\phi = \left(\frac{\lambda}{g}\right)\phi_1 + \left(\frac{\lambda}{g}\right)^2 \phi_2 + \dots$$ asymptotic expansion

$$\partial_\tau^2\phi_1 + \phi_1 = 0 \quad \Rightarrow \quad \phi_1 = \Phi_\alpha(\varrho)\cos\tau$$ oscillatory soln

$$\partial_\tau^2\phi_3 + \phi_3 = \alpha^2\partial_\tau^2\phi_1 + \partial_\varrho^2\phi_1 + \frac{2}{\varrho}\partial_\varrho\phi_1 + \phi_1^3 - \phi_1^5$$

kill resonance

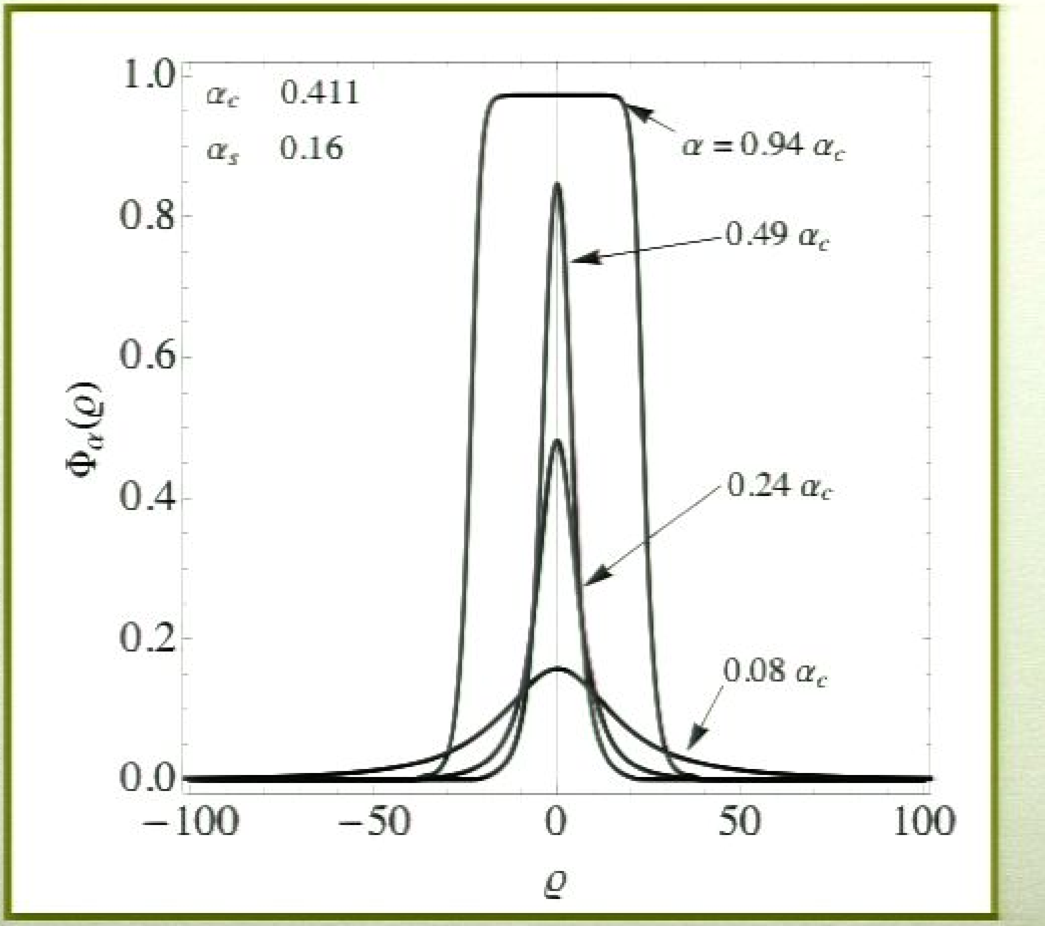
$$\Rightarrow \quad \partial_\tau^2\phi_3 + \phi_3 = \left[-\alpha^2\Phi + \partial_\varrho^2\Phi + \frac{2}{\varrho}\partial_\varrho\Phi + \frac{3}{4}\Phi^3 - \frac{5}{8}\Phi^5\right]\cos\tau,$$

$$+ \left[\frac{1}{4}\Phi^3 - \frac{5}{16}\Phi^5\right]\cos 3\tau - \frac{1}{16}\Phi^5\cos 5\tau.$$

$$\Rightarrow \quad \partial_\varrho^2\Phi_\alpha + \frac{2}{\varrho}\partial_\varrho\Phi_\alpha - \alpha^2\Phi_\alpha + \frac{3}{4}\Phi_\alpha^3 - \frac{5}{8}\Phi_\alpha^5 = 0$$ profile equation

PROFILES

$$\partial_\varrho^2\Phi_\alpha + \frac{2}{\varrho}\partial_\varrho\Phi_\alpha - \alpha^2\Phi_\alpha + \frac{3}{4}\Phi_\alpha^3 - \frac{5}{8}\Phi_\alpha^5 = 0$$



field amplitude

HOW TO SOLVE -1

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

$$\partial_t^2\varphi - \partial_r^2\varphi - \frac{2}{r}\partial_r\varphi + m^2\varphi - \lambda\varphi^3 + \frac{g^2}{m^2}\varphi^5 = 0$$

$$\phi = \frac{\sqrt{\lambda}}{m}\varphi$$

$$\varrho = (\lambda/g)mr$$

$$\tau = \omega t$$

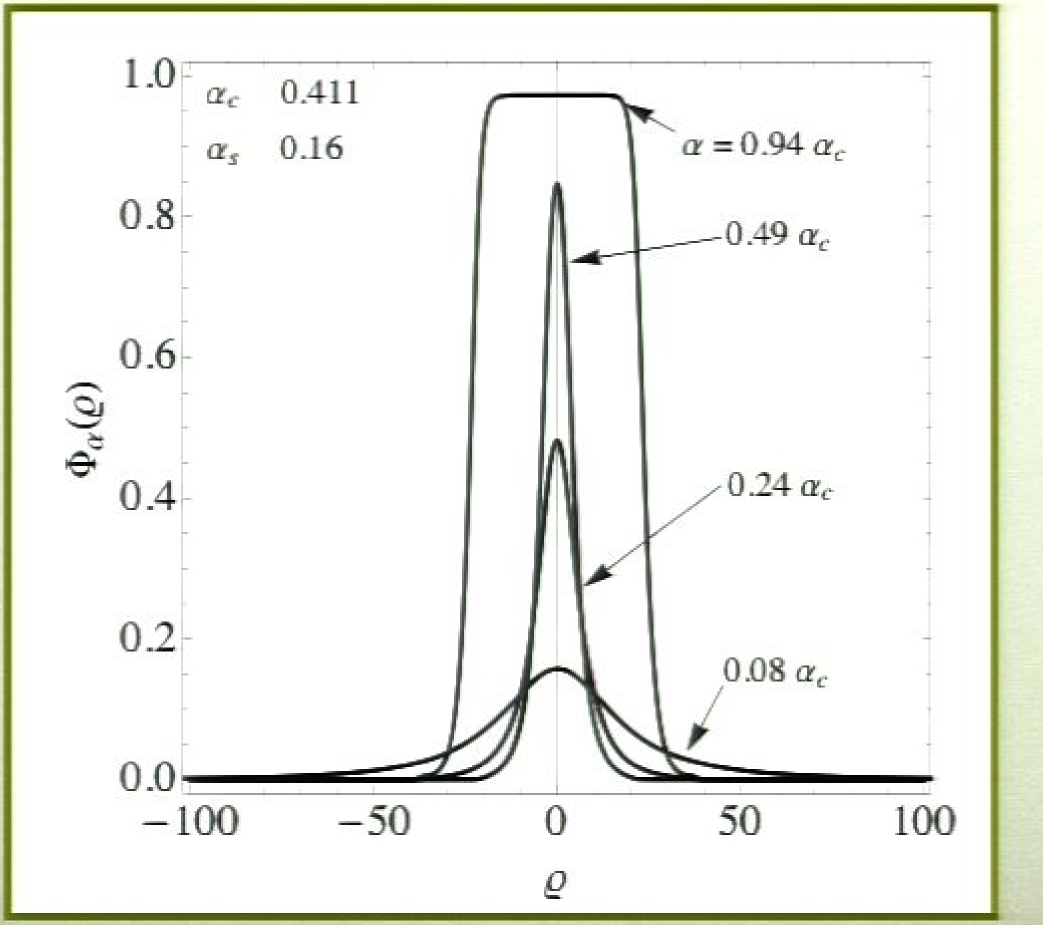
$$\omega^2 = m^2\left[1 - (\lambda/g)^2\alpha^2\right]$$

$$\partial_\tau^2\phi + \phi + \frac{\lambda}{g}\left[-\alpha^2\partial_\tau^2\phi - \partial_\varrho^2\phi - \frac{2}{\varrho}\partial_\varrho\phi - \phi^3 + \phi^5\right] = \mathcal{O}[(\lambda/g)^3]$$

PROFILES

$$\partial_\varrho^2\Phi_\alpha + \frac{2}{\varrho}\partial_\varrho\Phi_\alpha - \alpha^2\Phi_\alpha + \frac{3}{4}\Phi_\alpha^3 - \frac{5}{8}\Phi_\alpha^5 = 0$$

field amplitude



HOW TO SOLVE

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

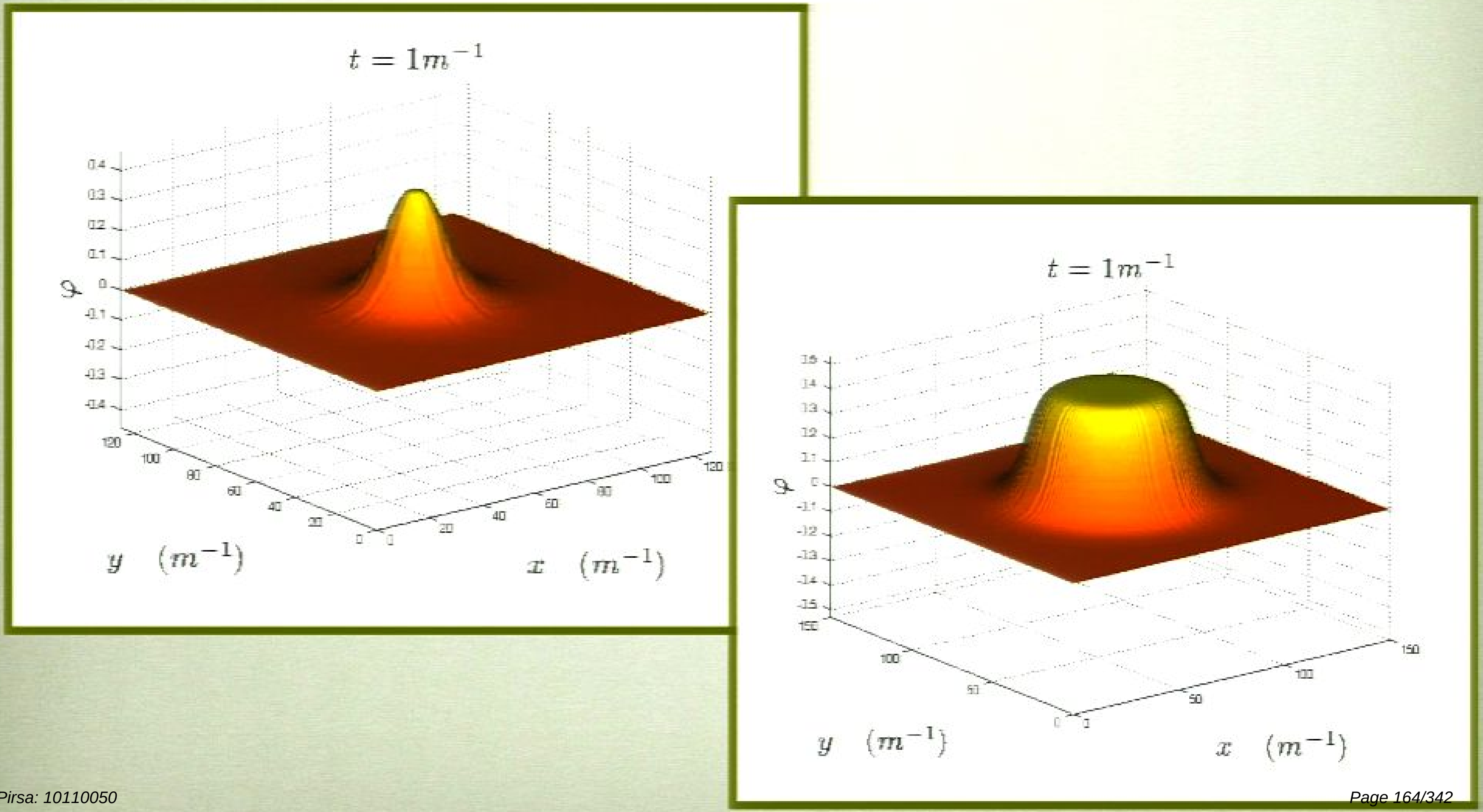
$$\varrho = (\lambda/g)mr$$

$$\omega^2 = m^2\left[1-(\lambda/g)^2\alpha^2\right]$$

$$\varphi(t,r) \approx \frac{m}{\sqrt{\lambda}}\left[\left(\frac{\lambda}{g}\right)\Phi_\alpha(\varrho)\cos\omega t + \mathcal{O}[(\lambda/g)^3]\right]$$

3+1

SOLUTIONS



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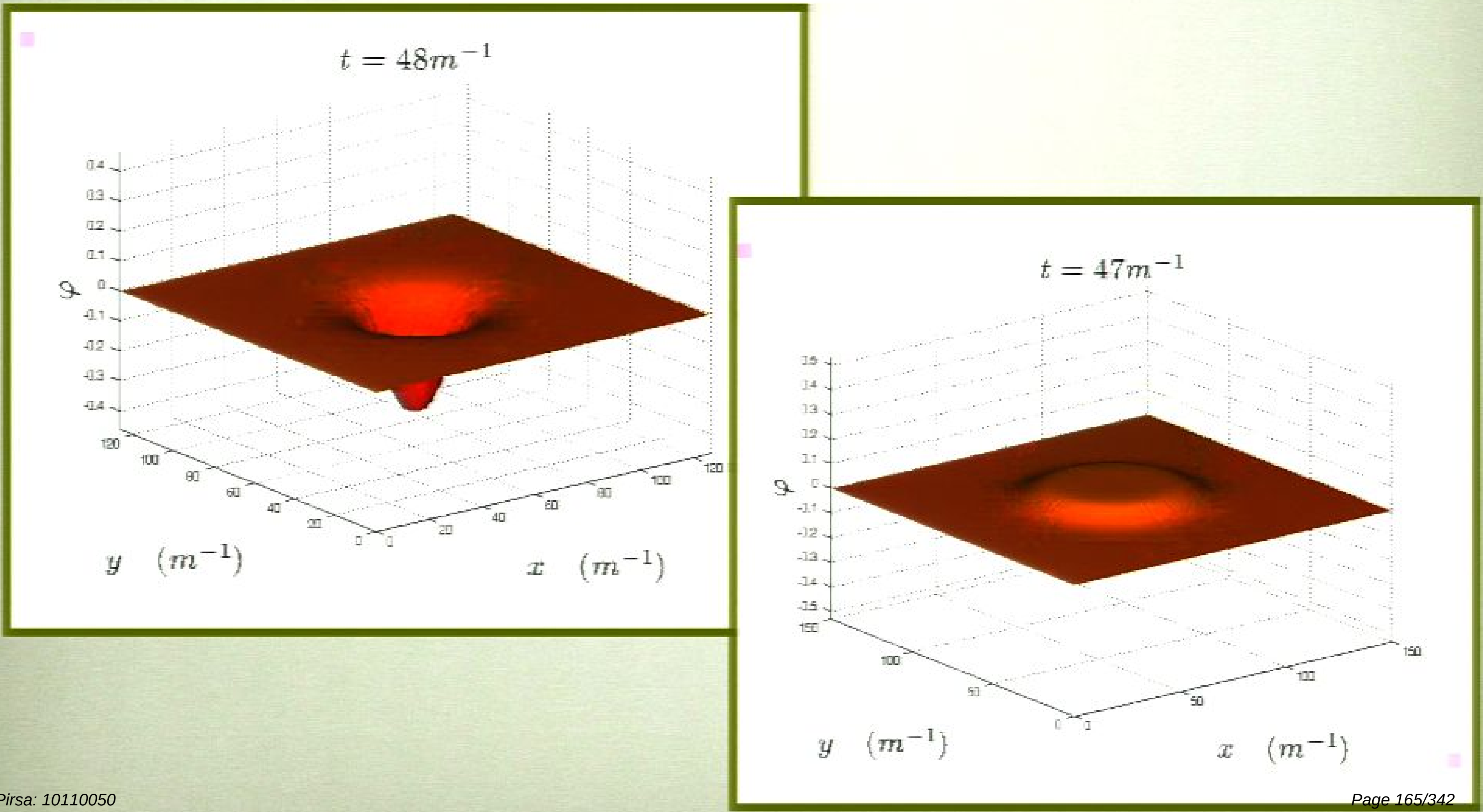

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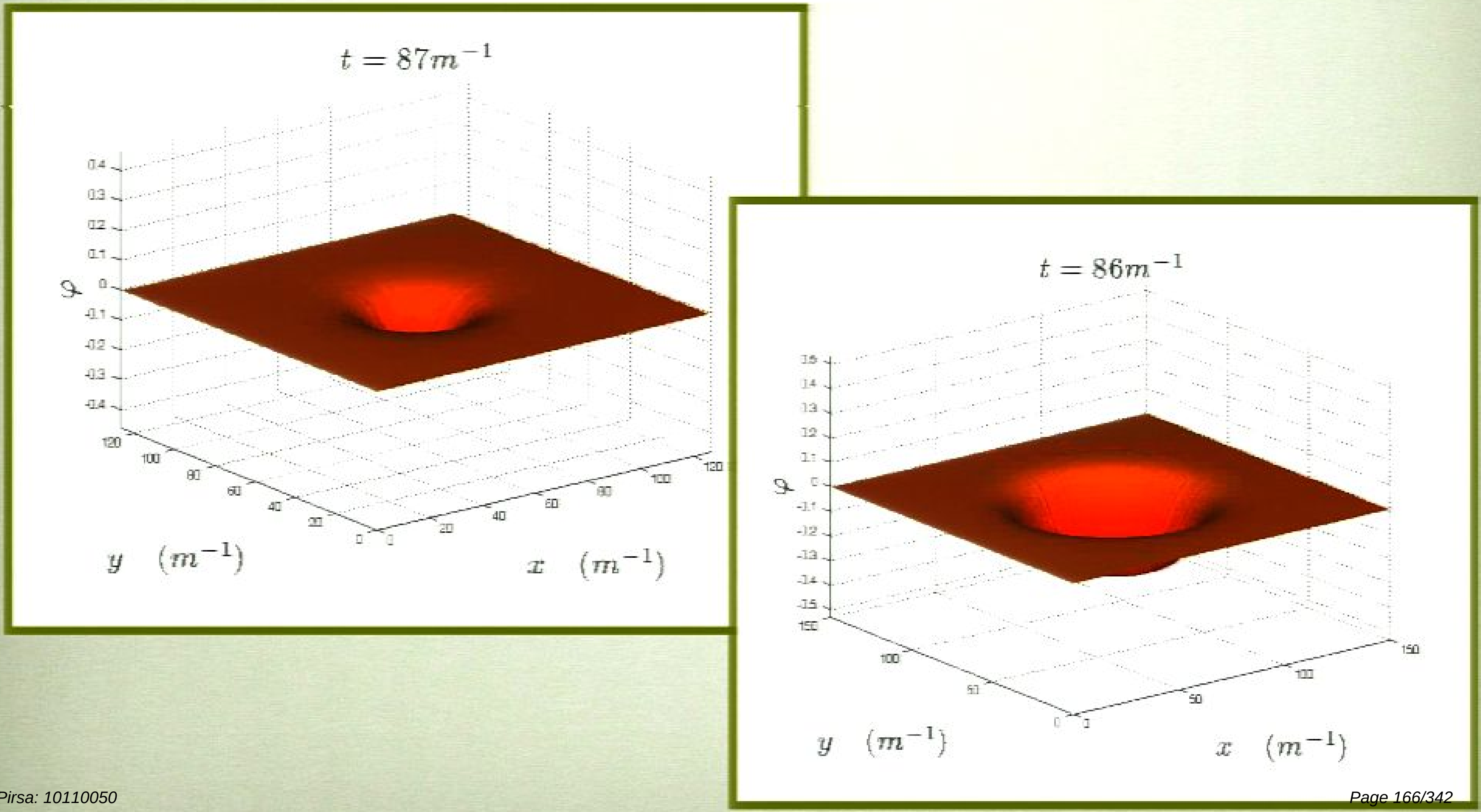

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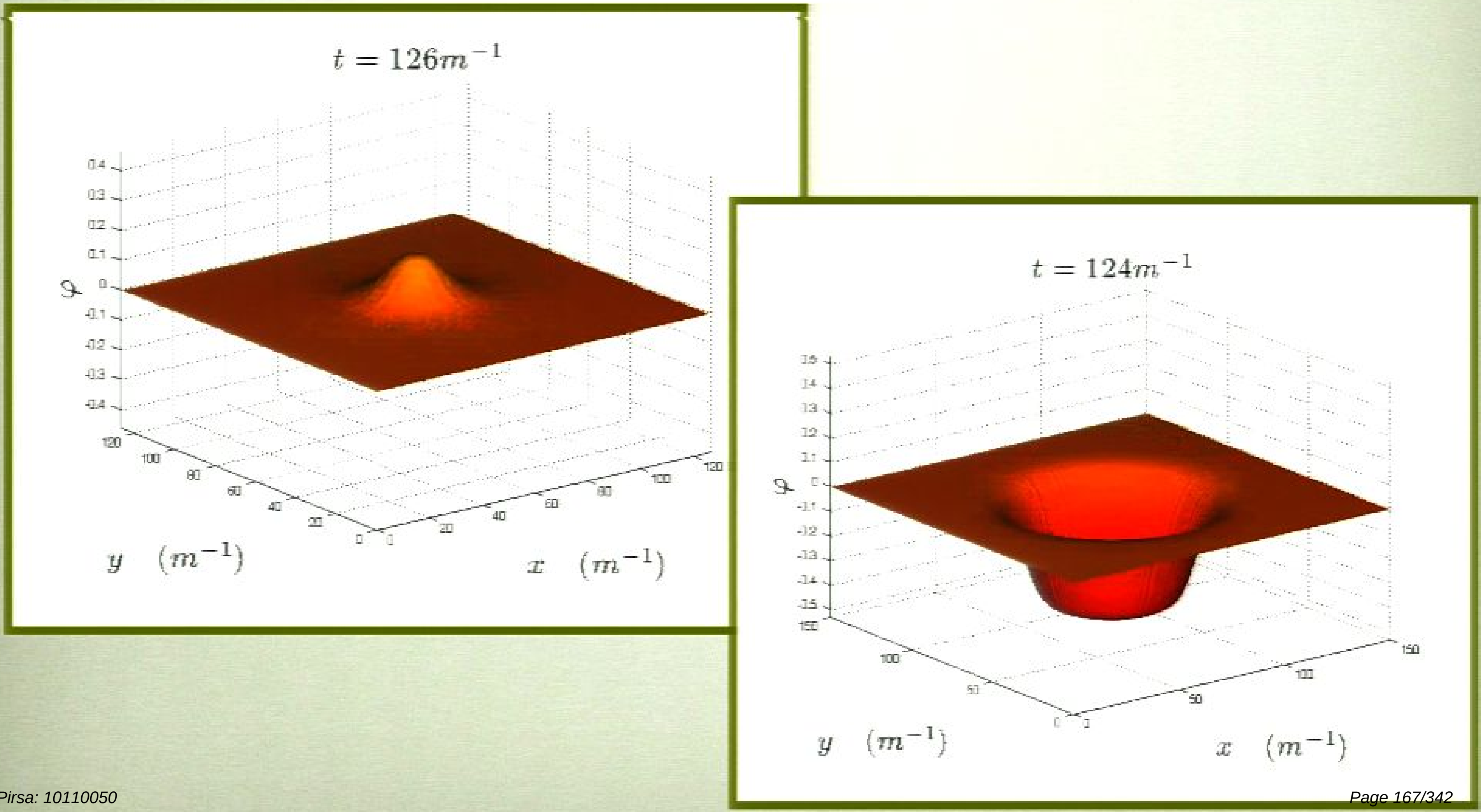

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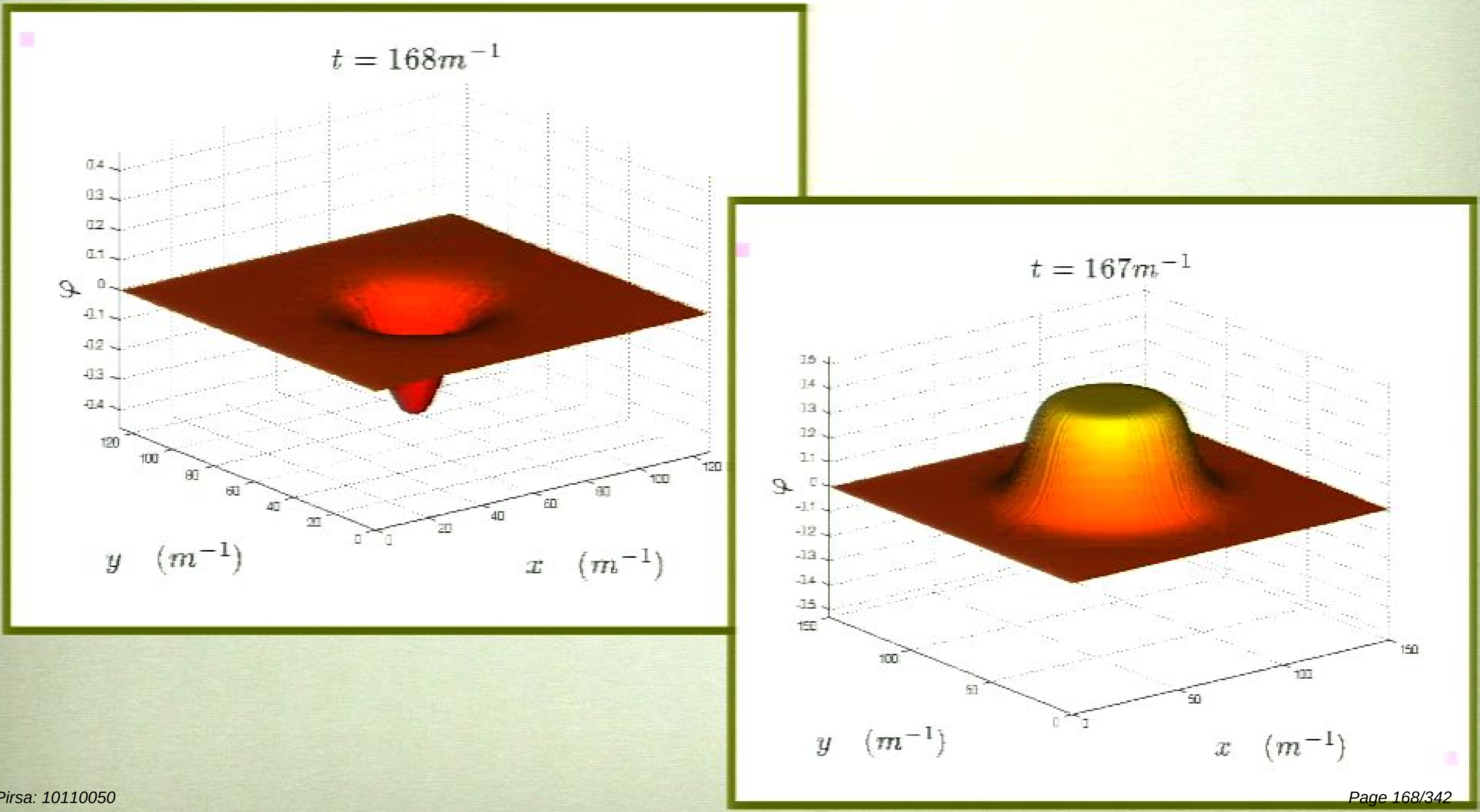

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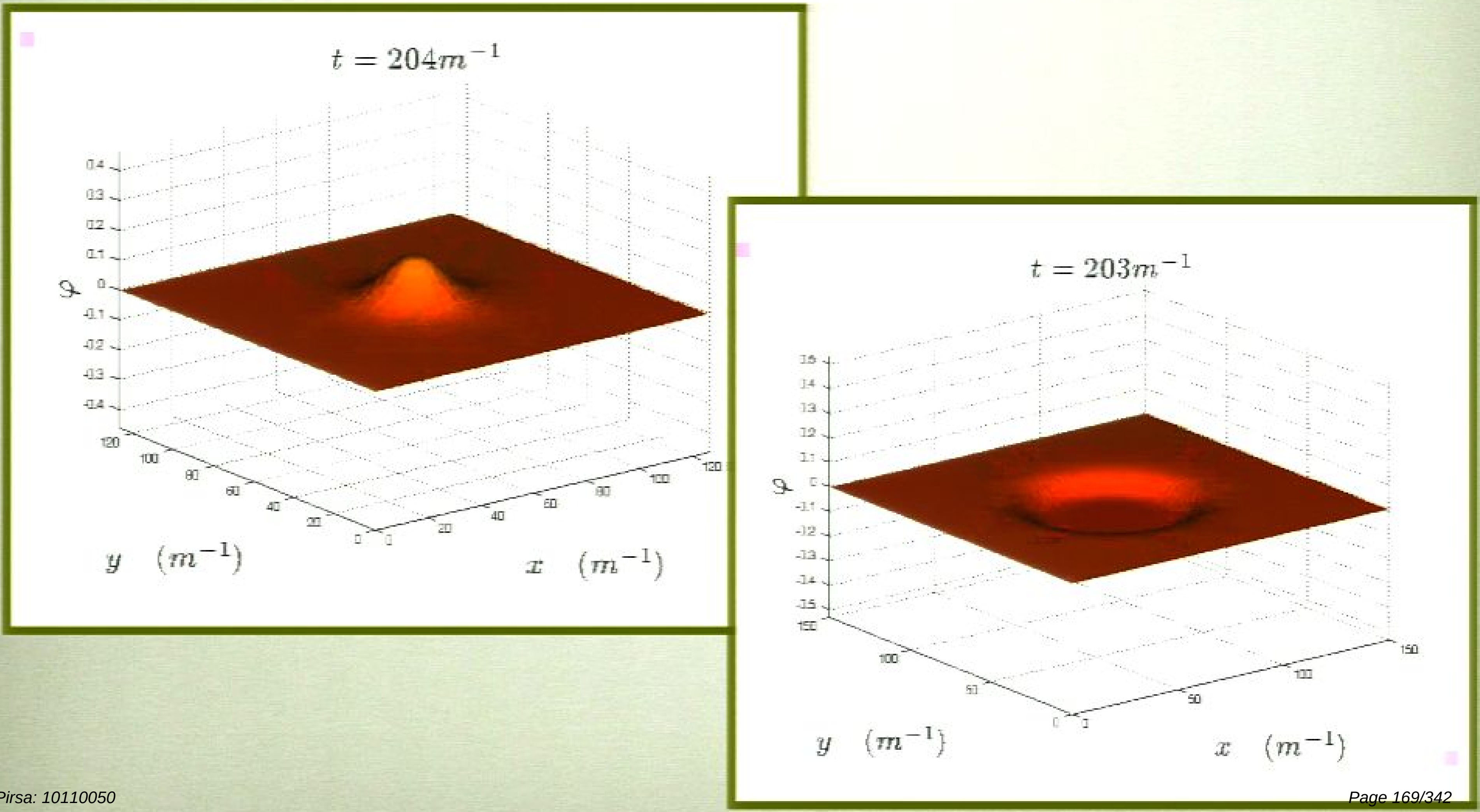

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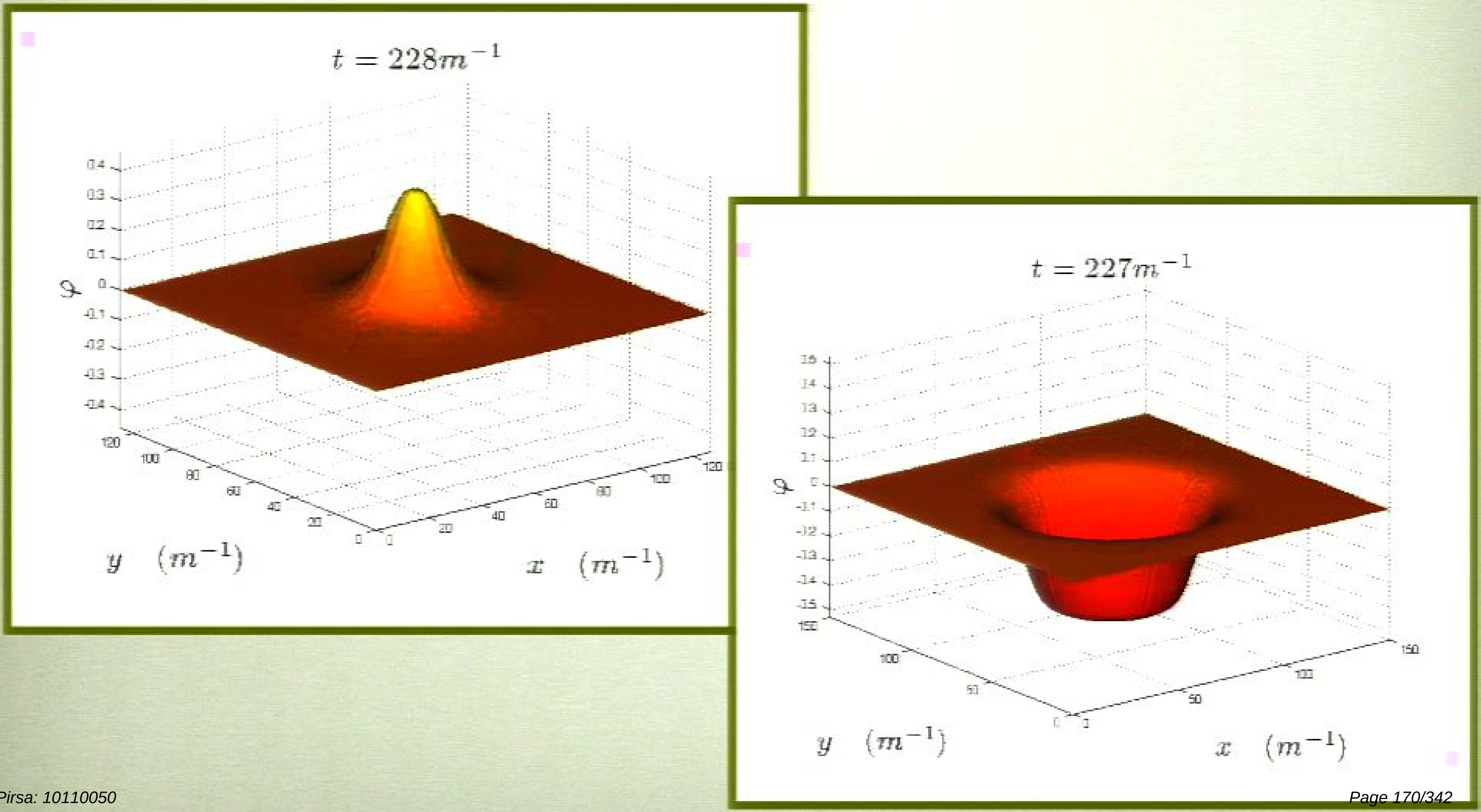

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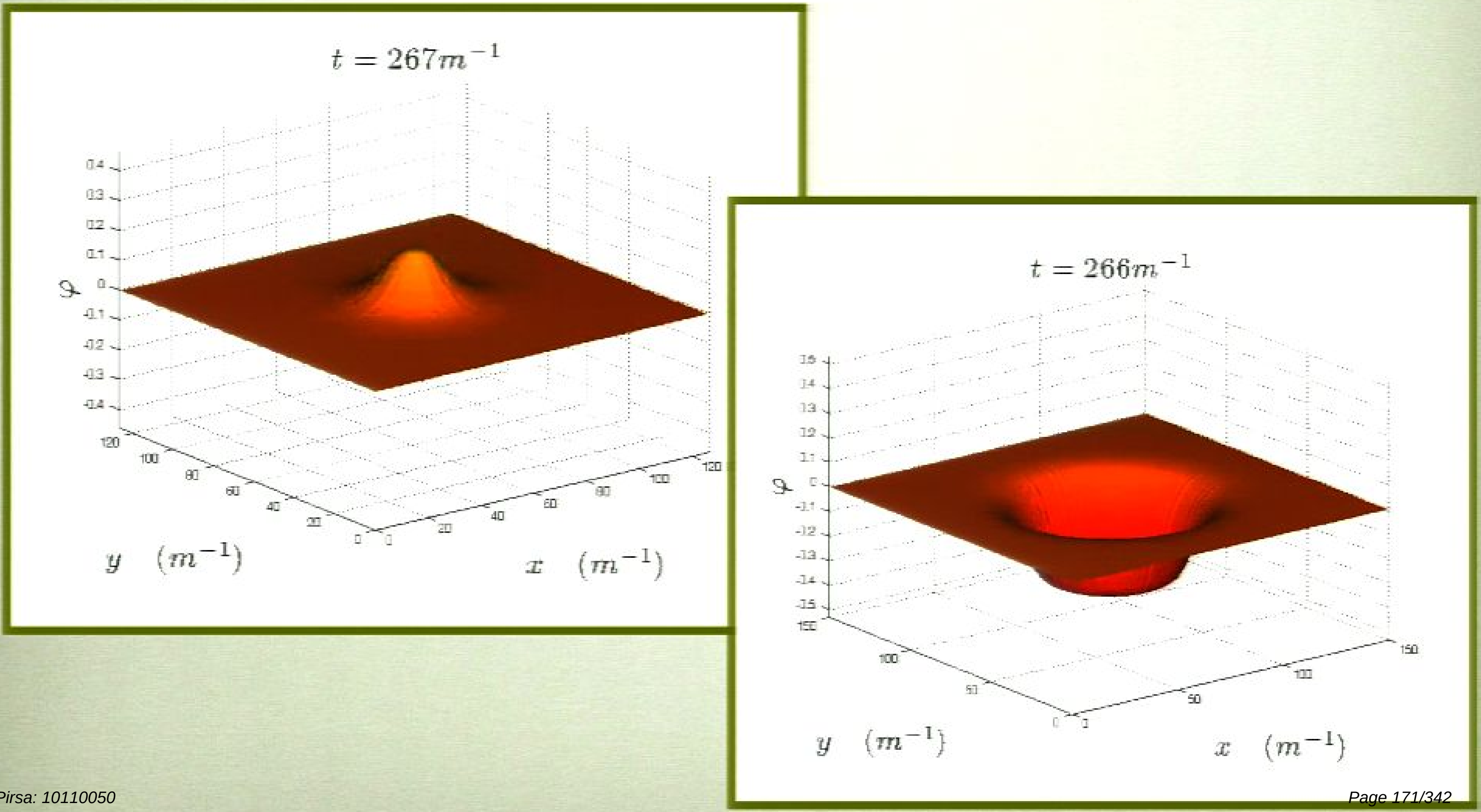

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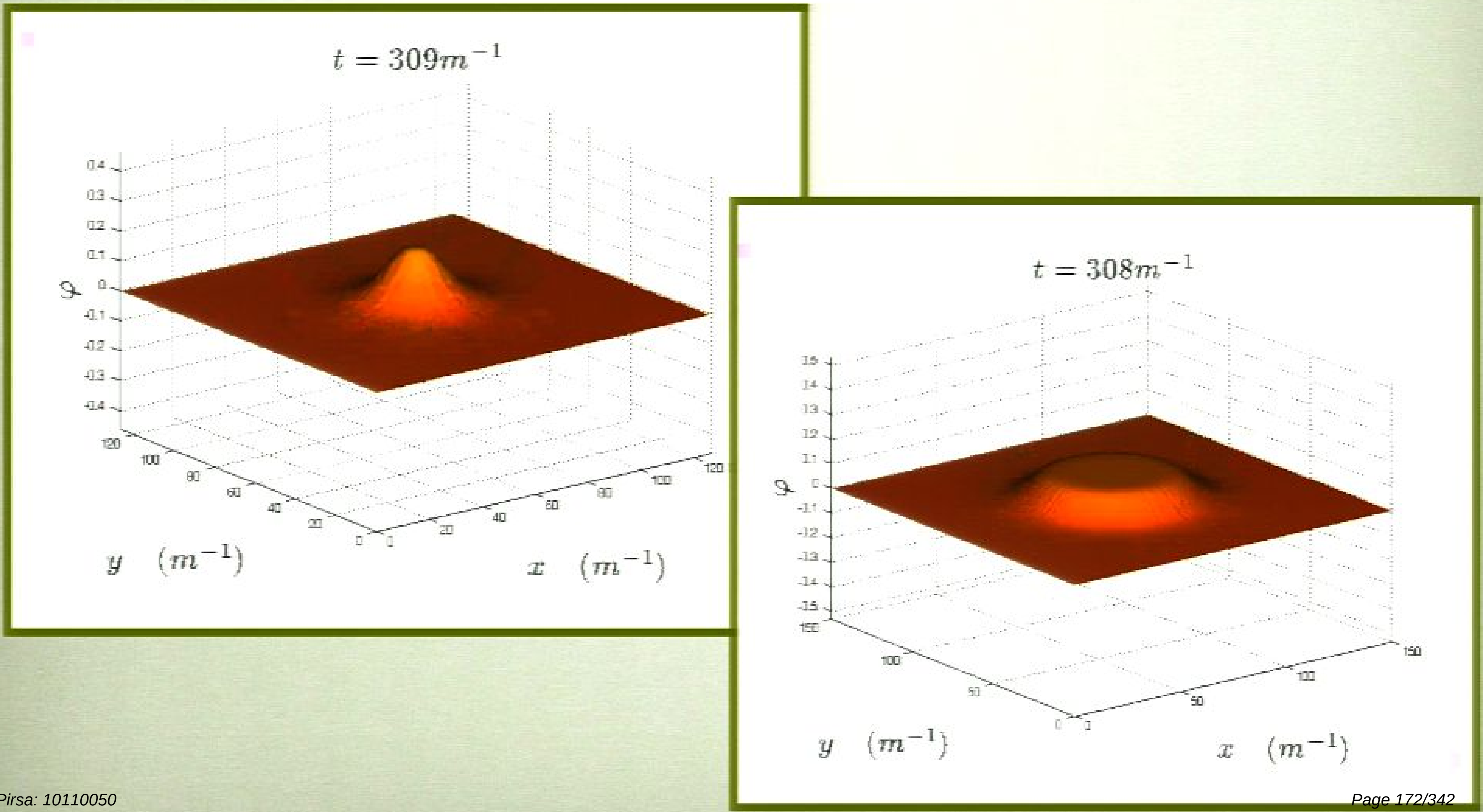

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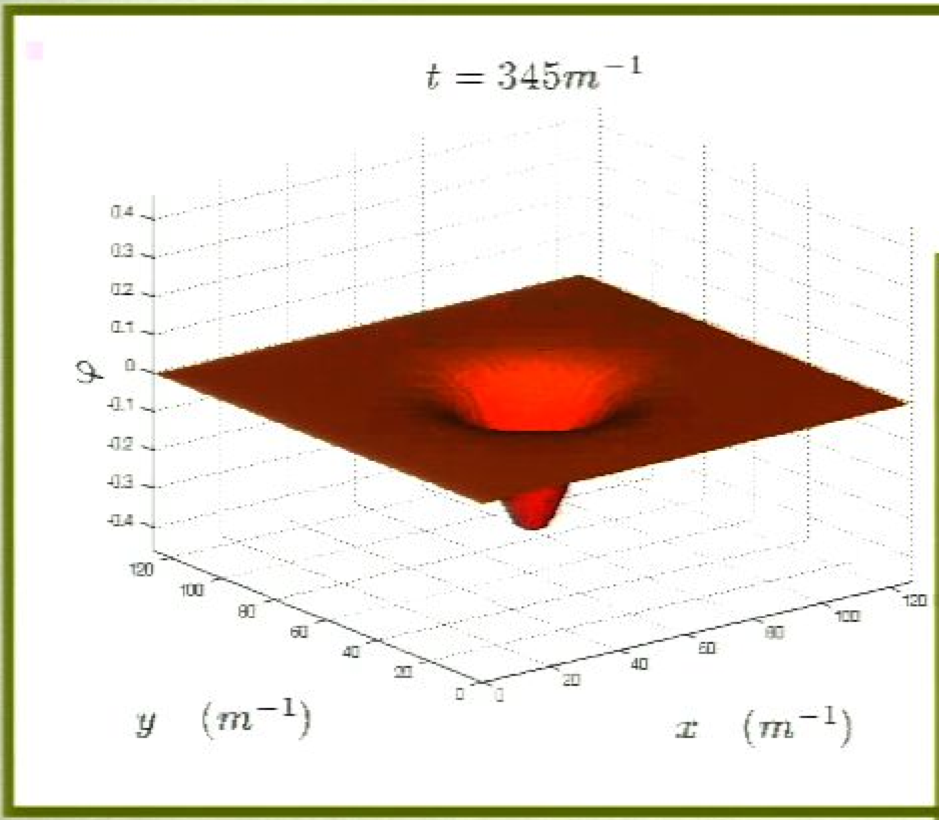

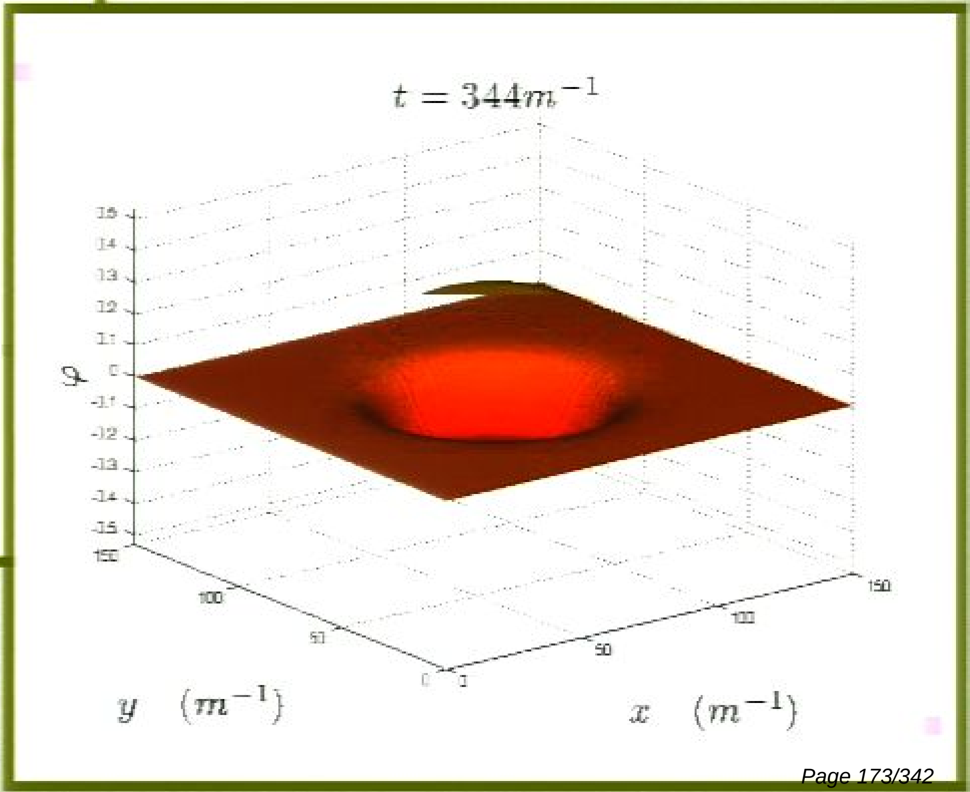

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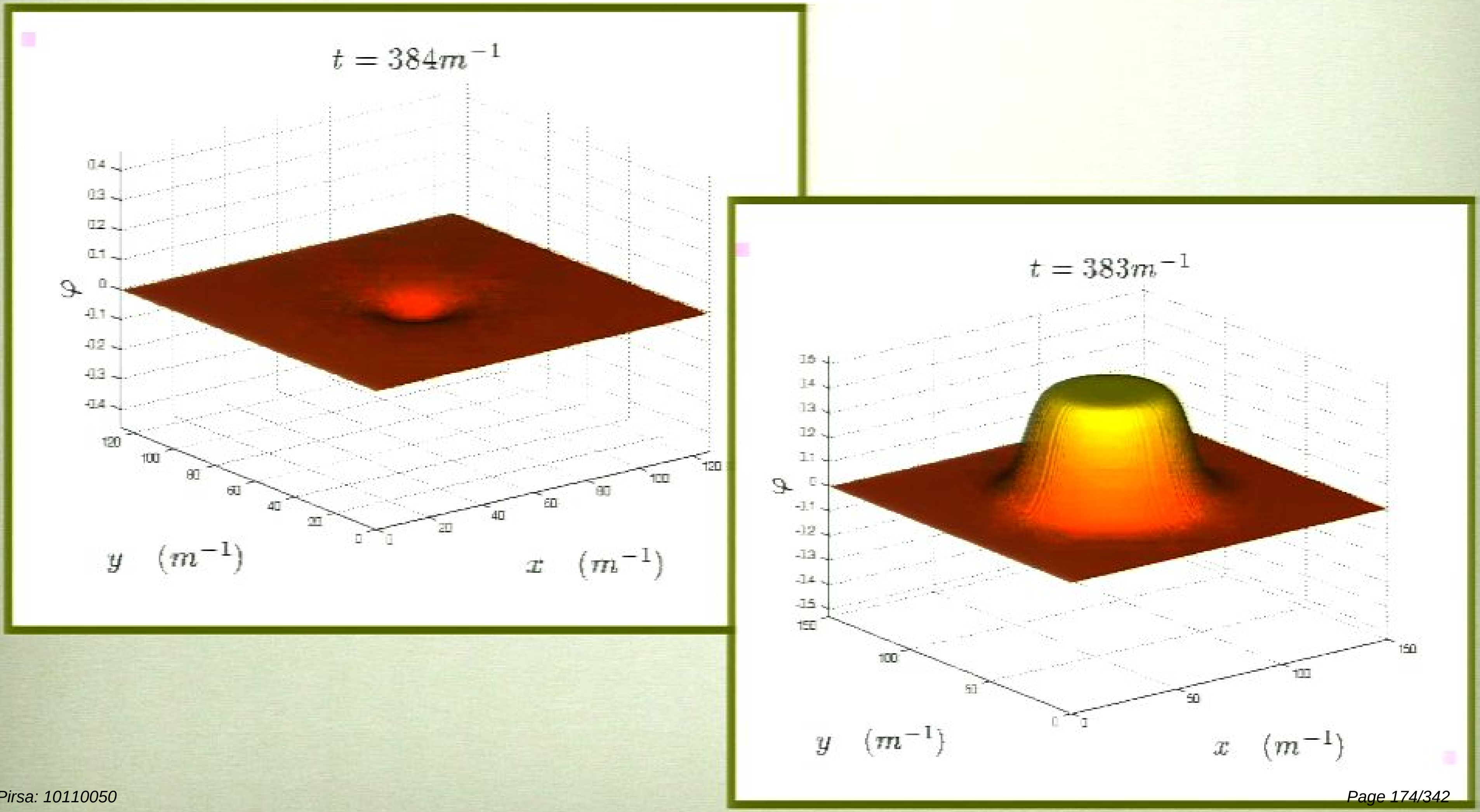

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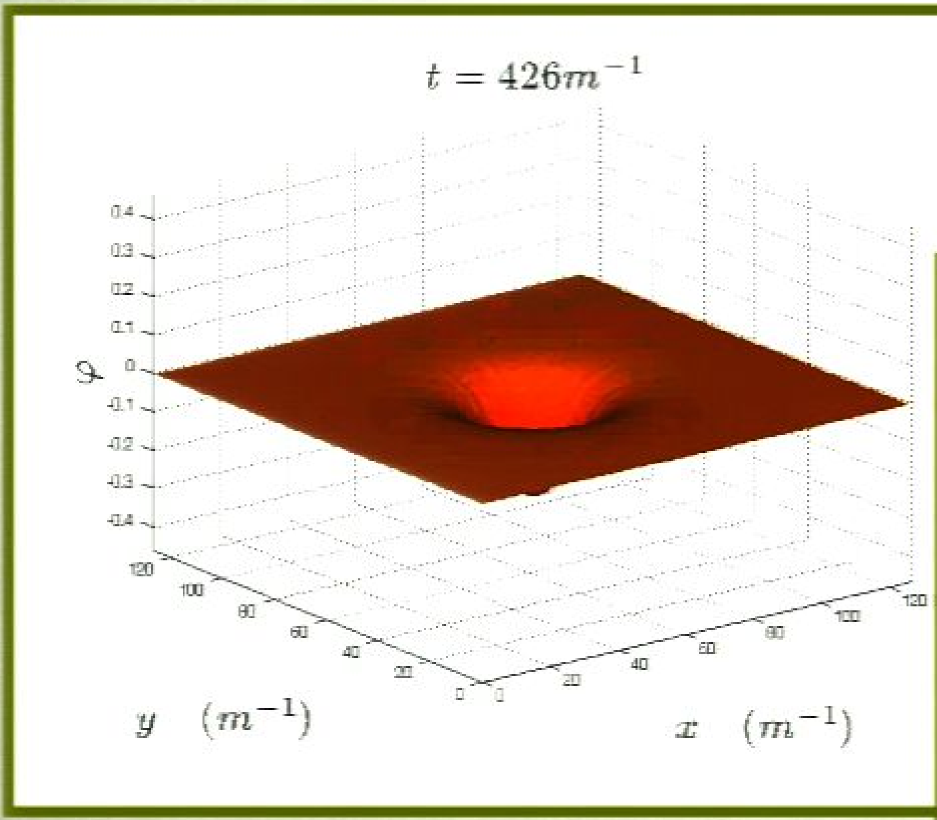
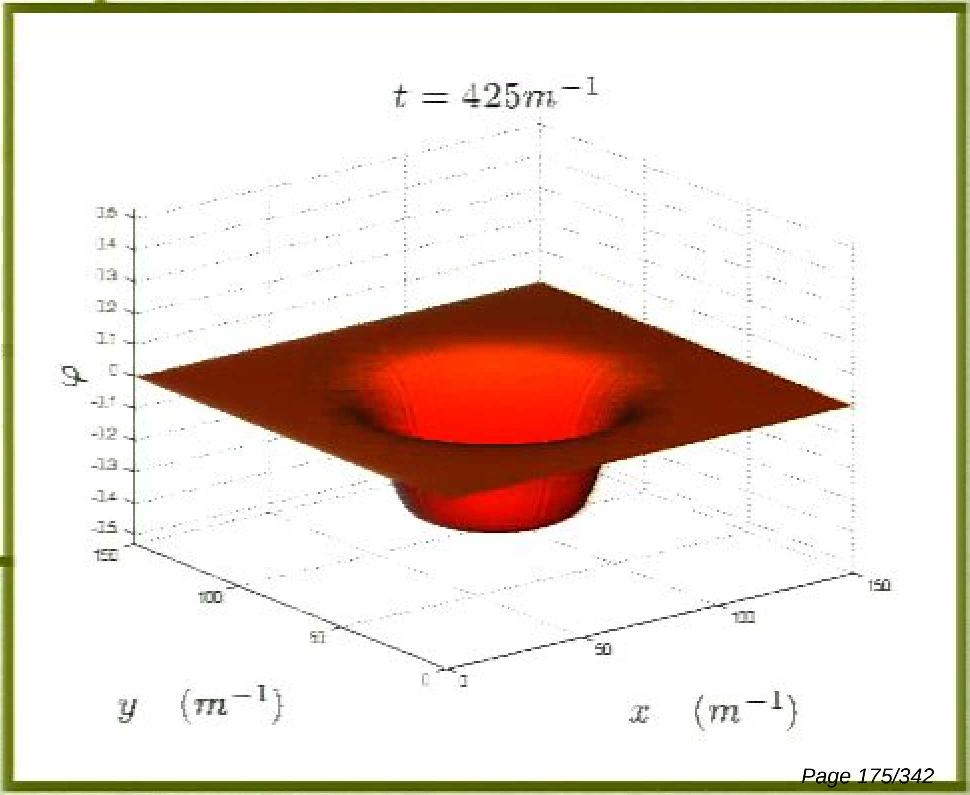

$t = 426 m^{-1}$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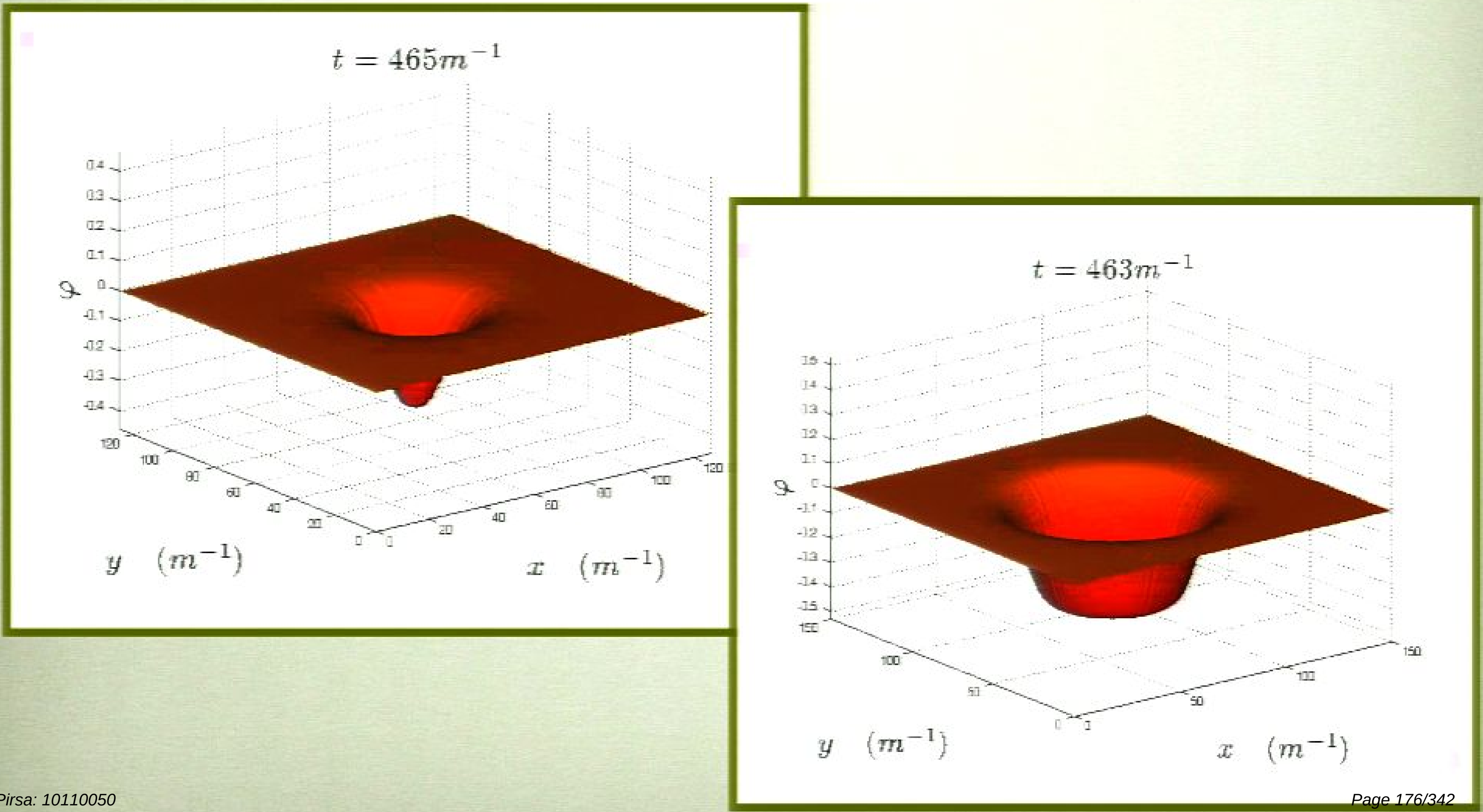

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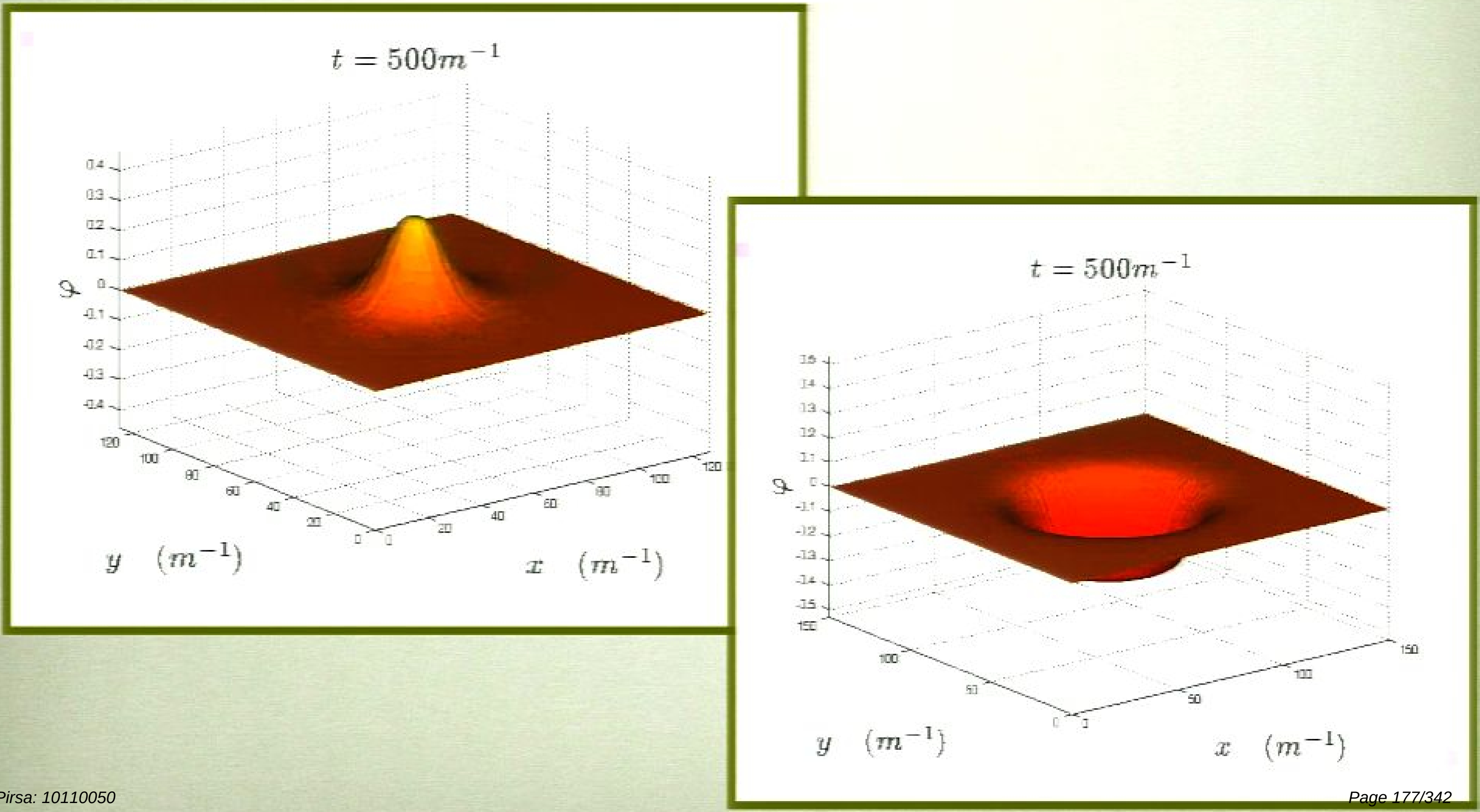
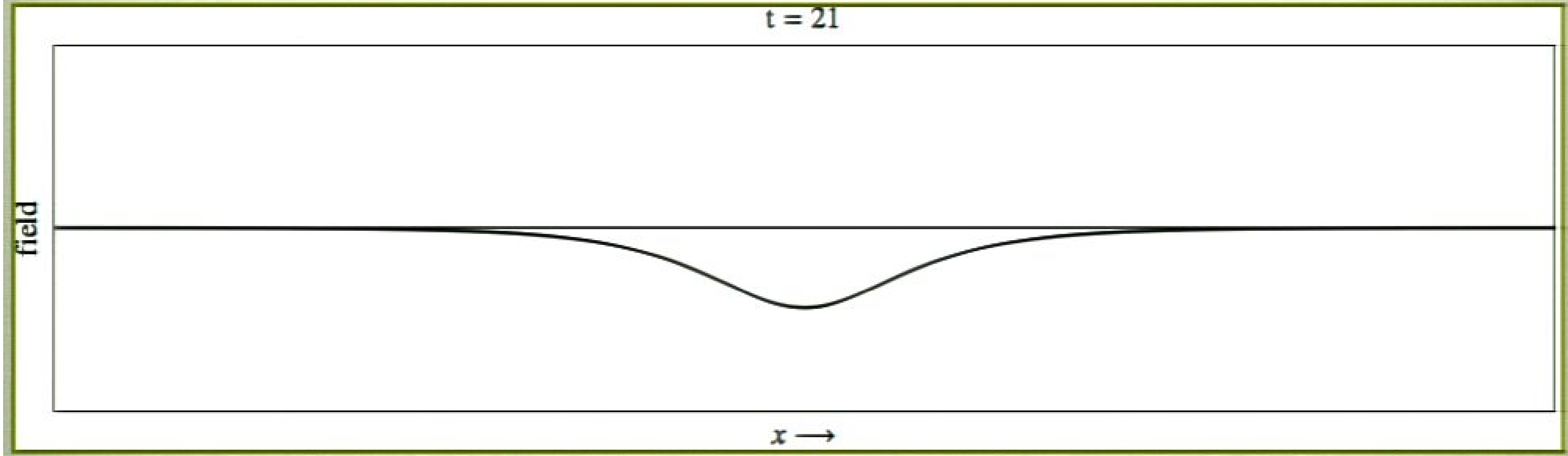


WHAT ABOUT STABILITY ?



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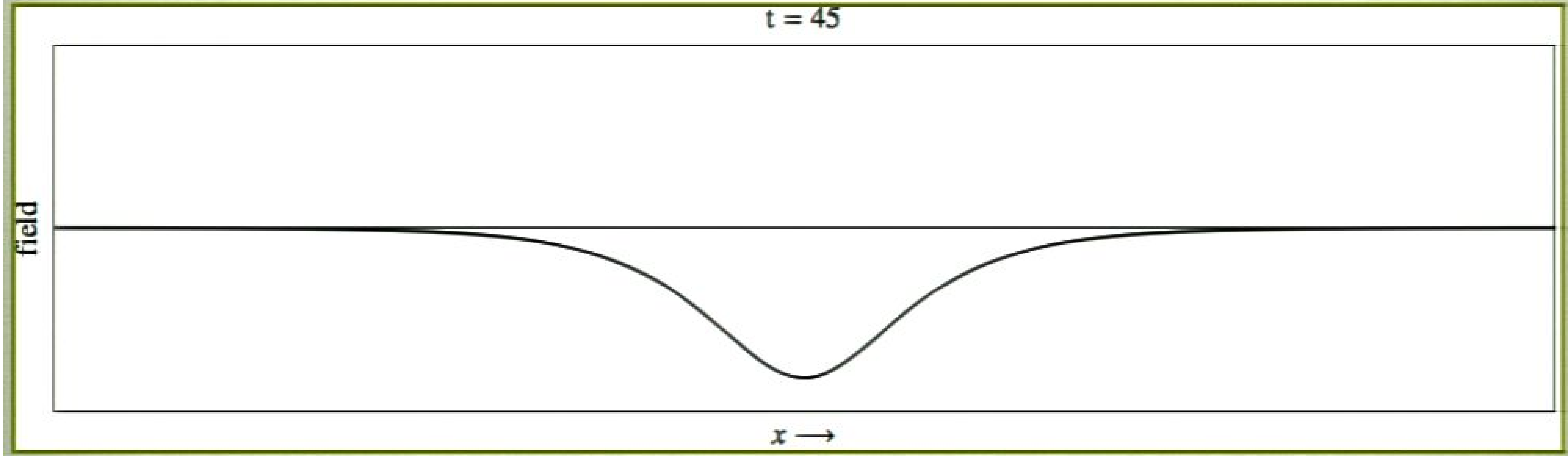
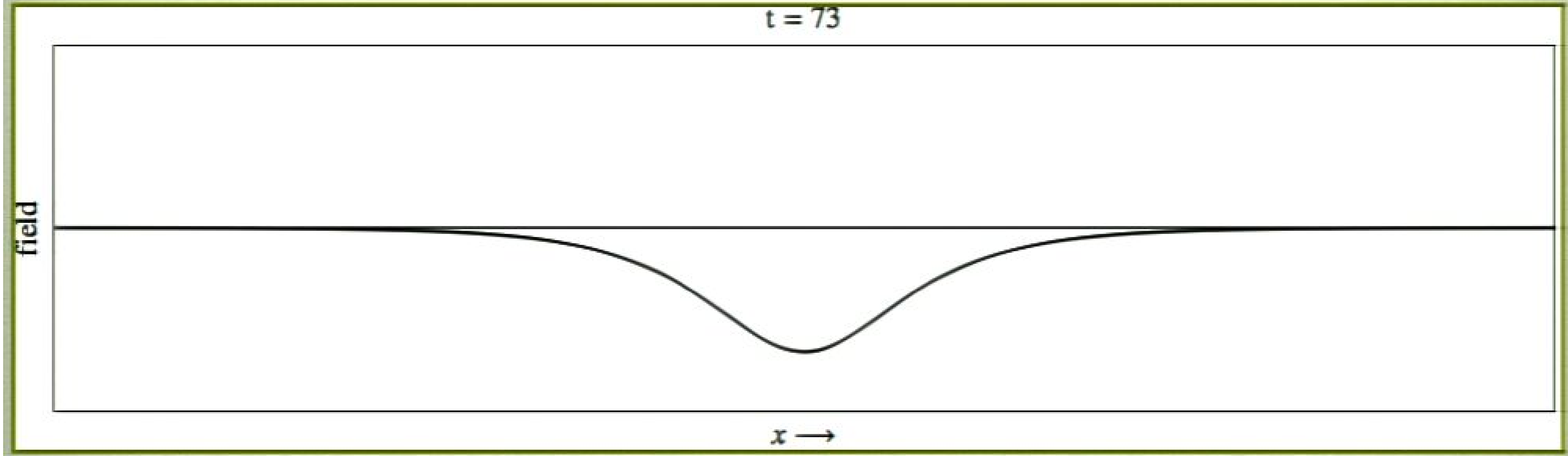


WHAT ABOUT STABILITY ?



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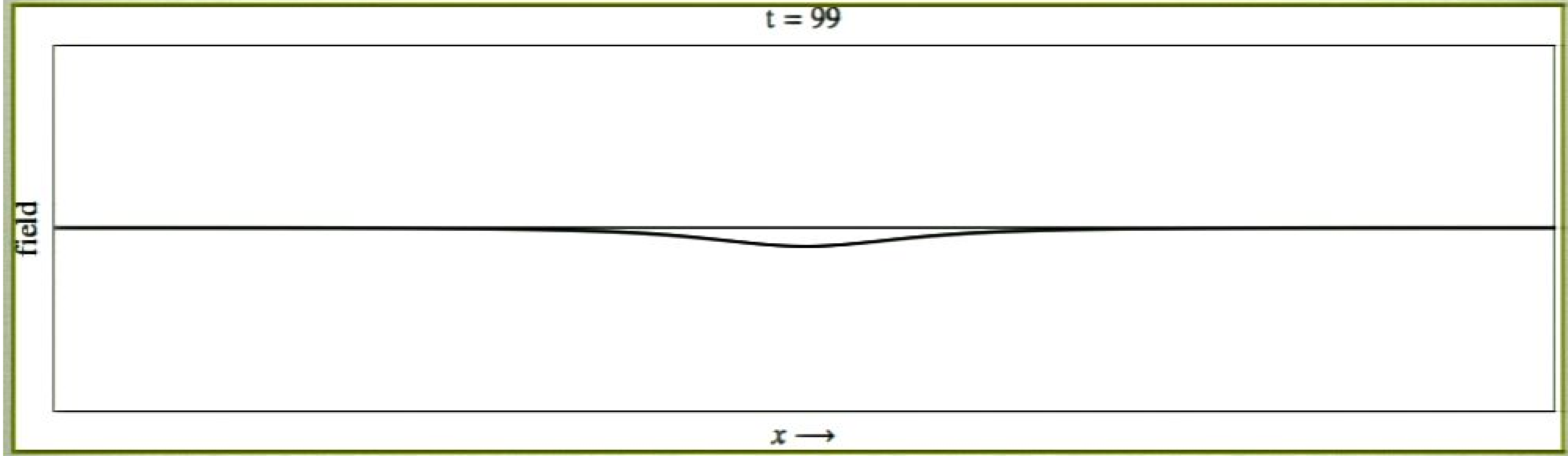

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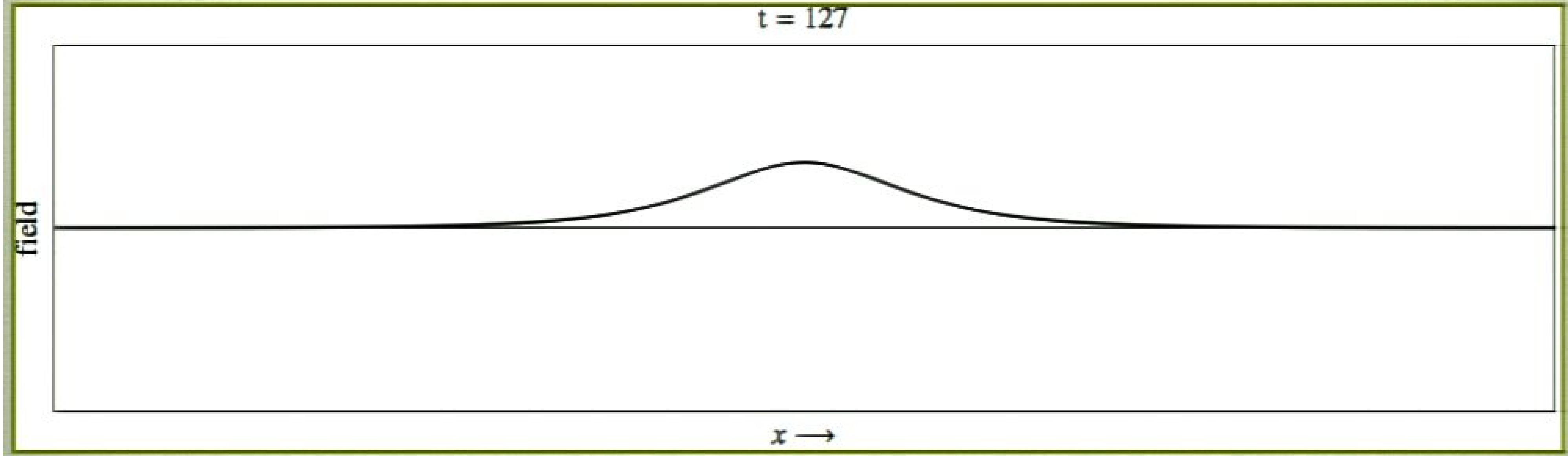

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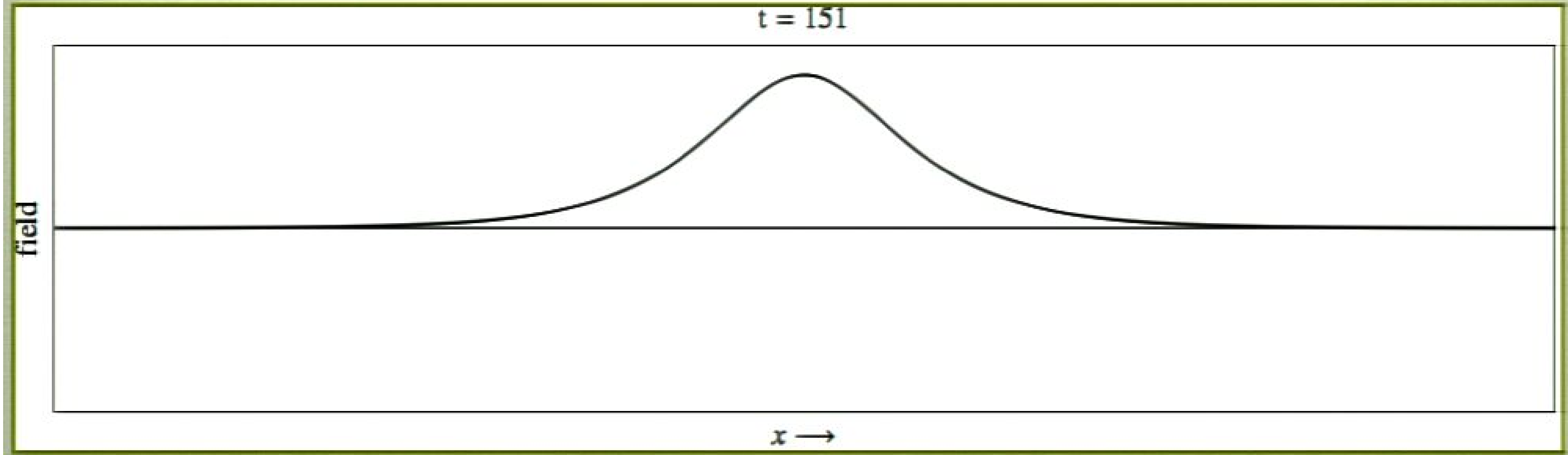

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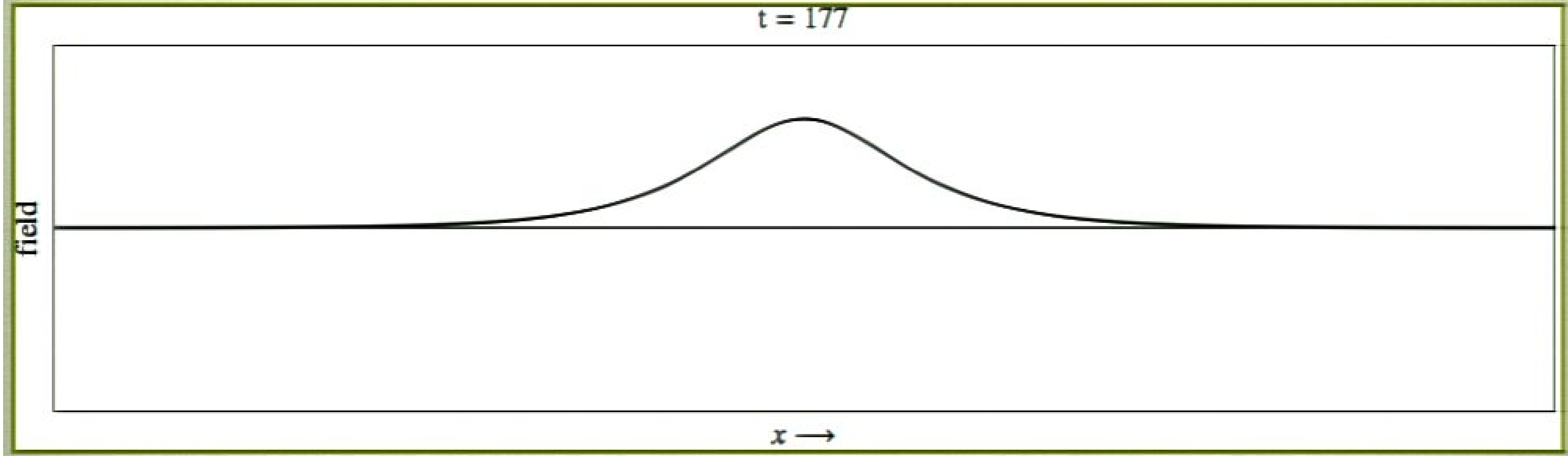

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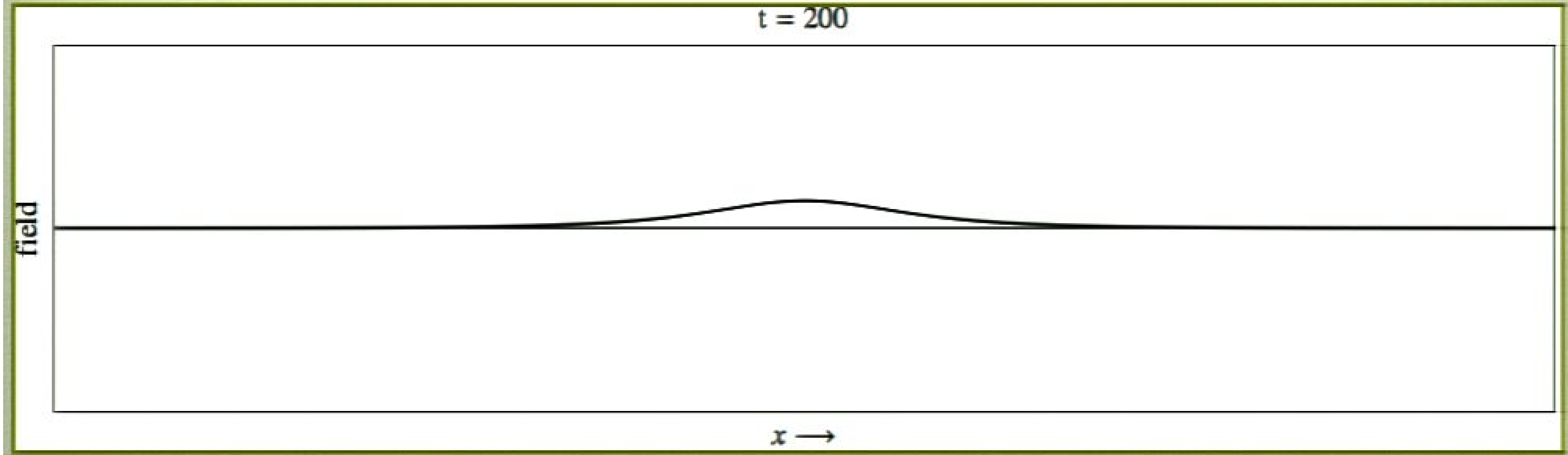
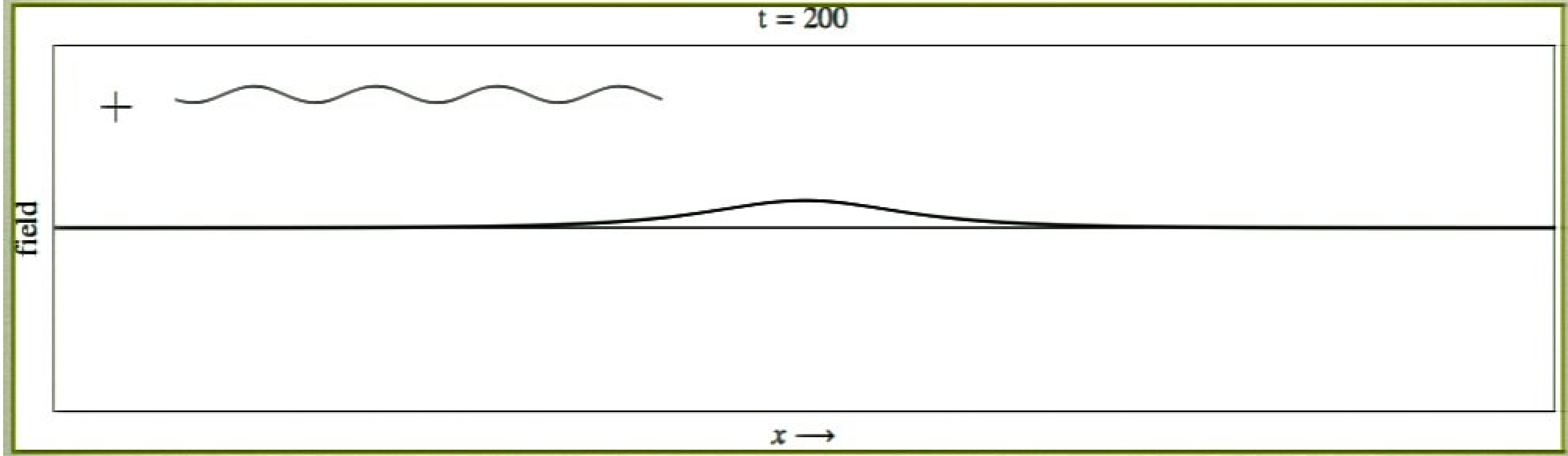


WHAT ABOUT STABILITY ?

perturbations



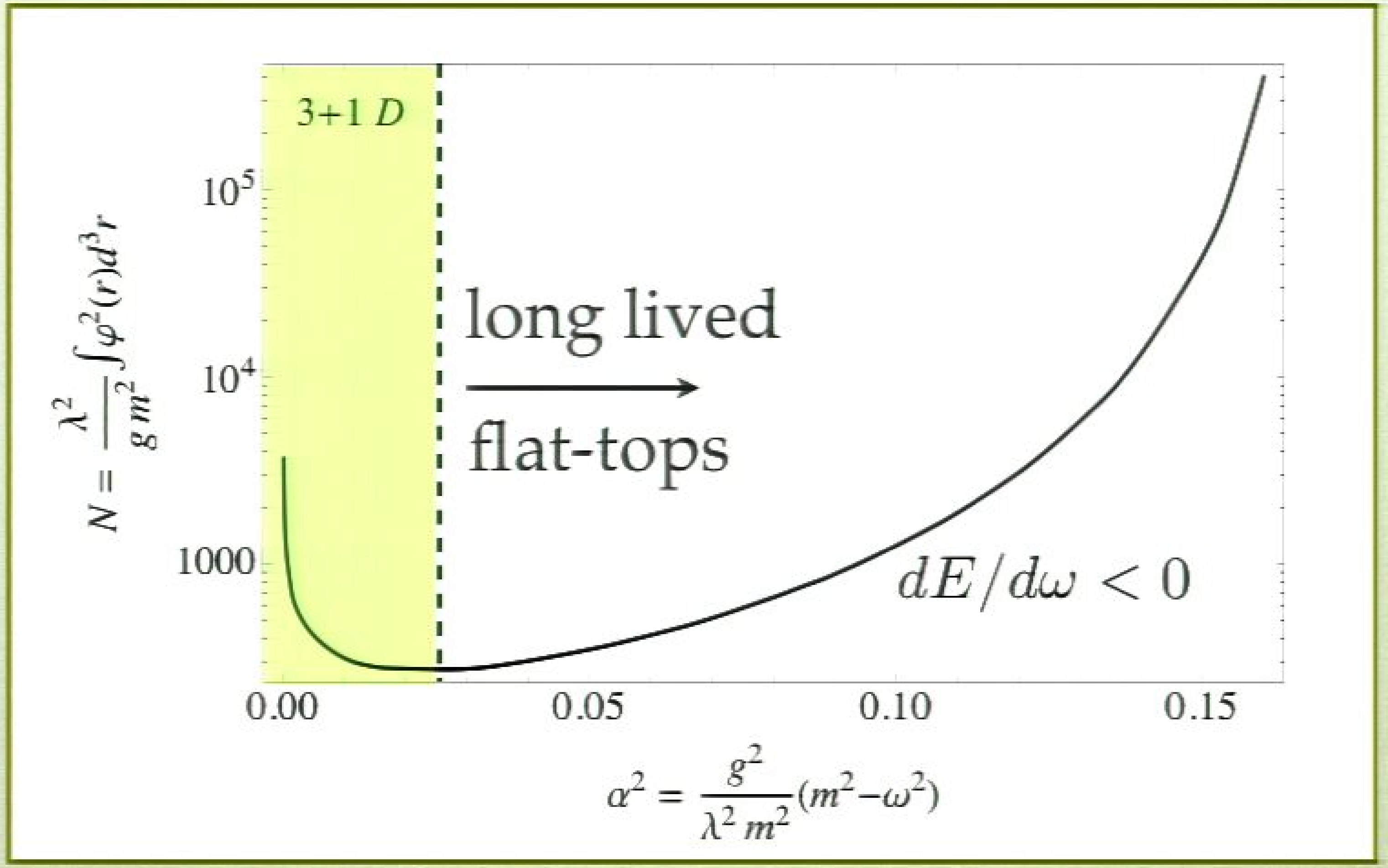
LINEAR STABILITY ANALYSIS

- *collapse* instability ? wavelength $\sim$ width

- *Floquet* instability ? wavelength $\ll$ width

COLLAPSE INSTABILITY ?

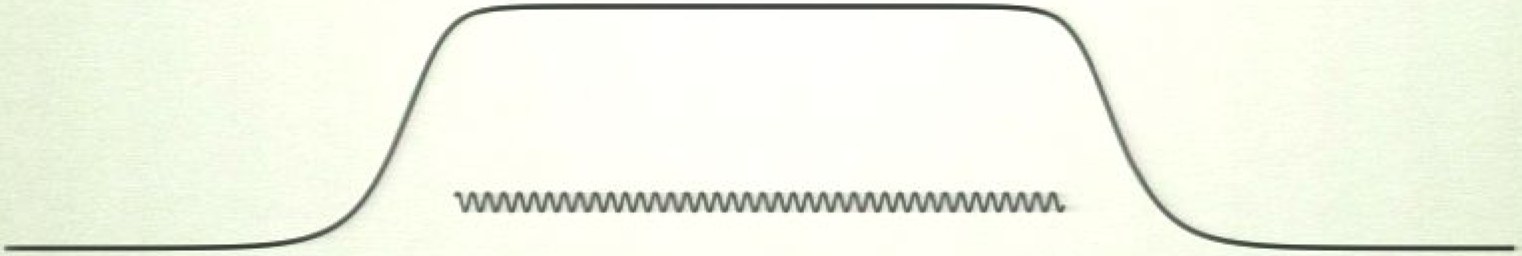
~ energy



~ frequency shift

MA & D.Shirokoff (2010)

FLOQUET INSTABILITY ?



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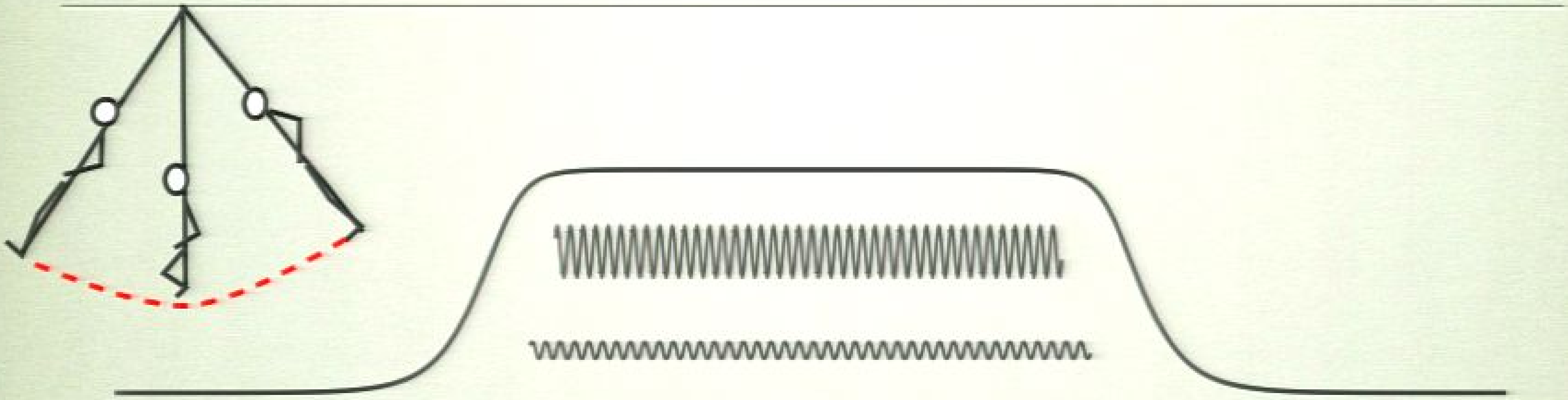

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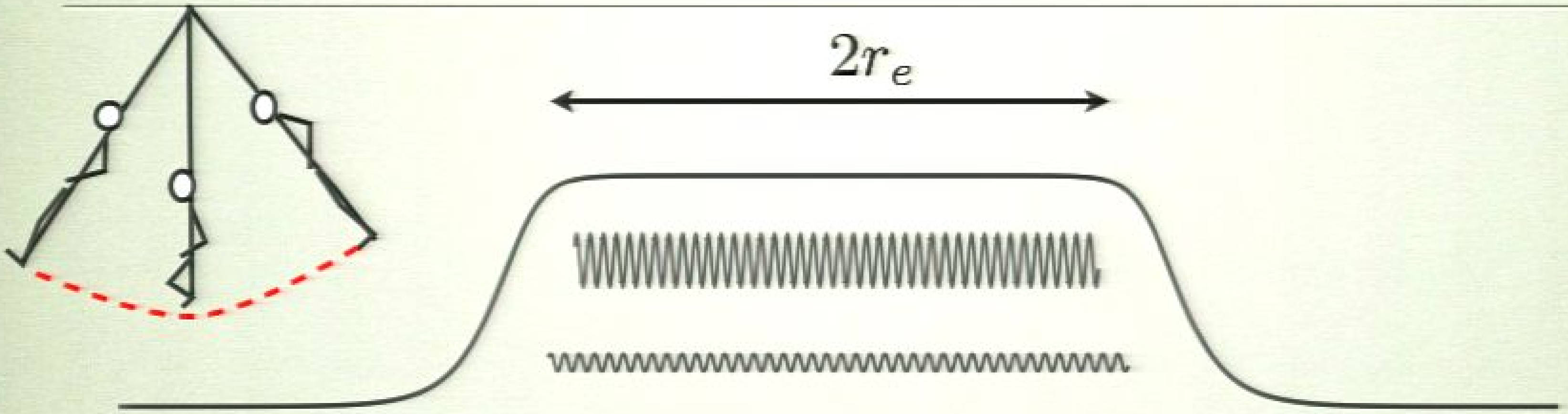
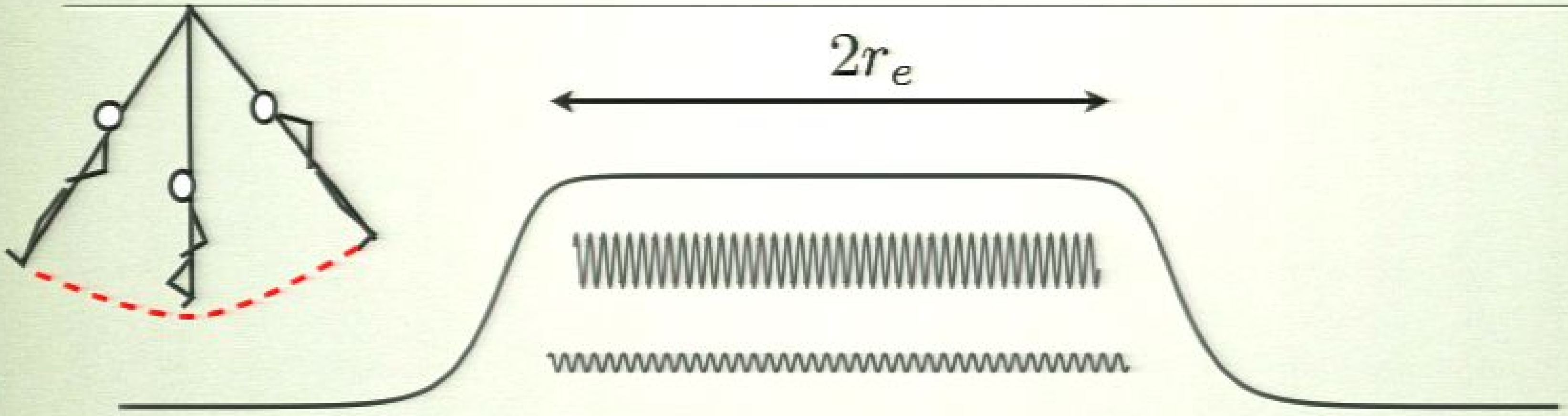


$$\mu_{max} \sim \begin{cases} (\lambda/g)^2\, m, & \text{if } (\lambda/g)^2 m > 1/2r_e \\ 0 \end{cases}$$

FLOQUET INSTABILITY ?

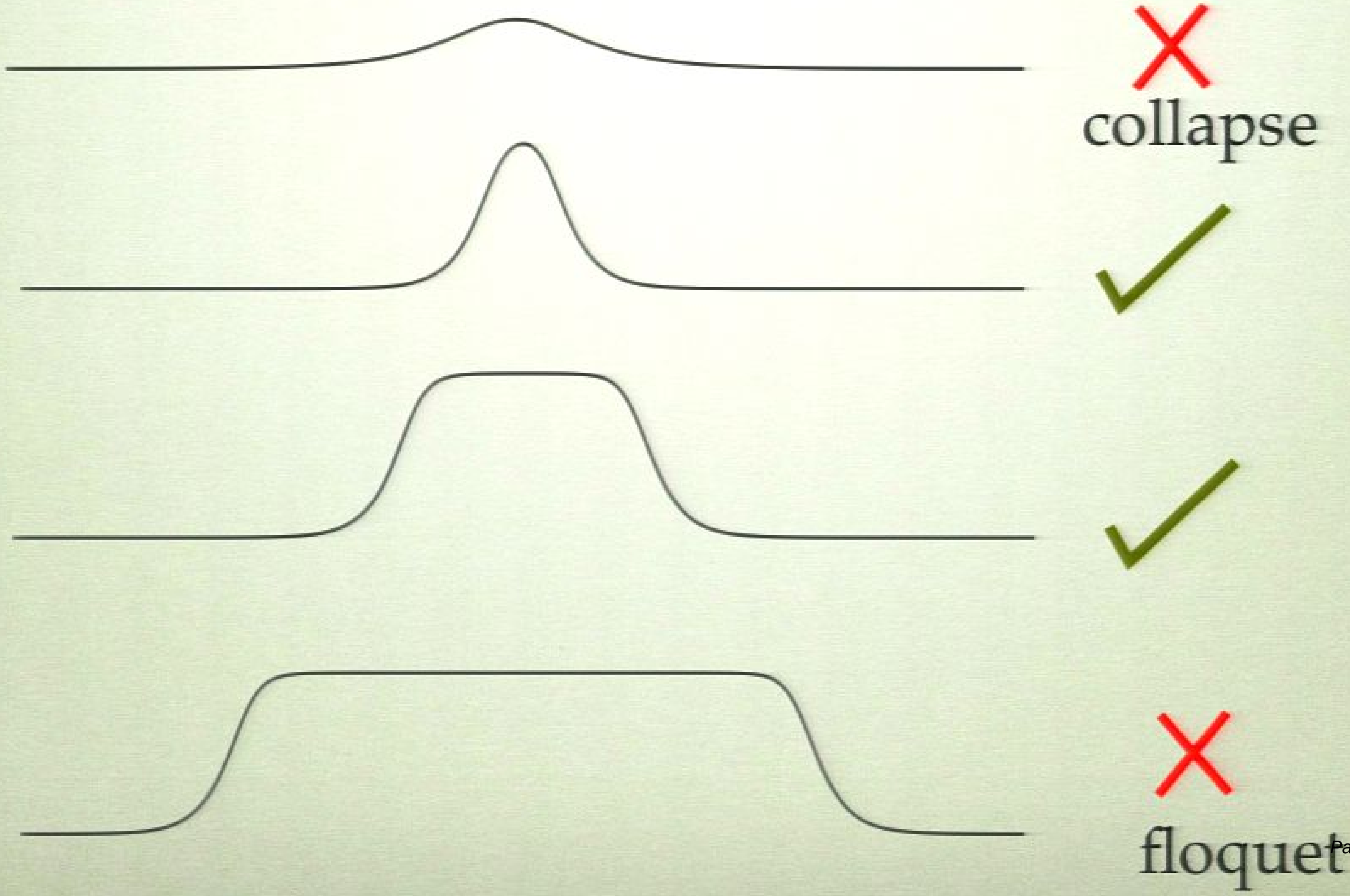


$$\mu_{max} \sim \begin{cases} (\lambda/g)^2\, m, & \text{if } (\lambda/g)^2 m > 1/2r_e \\ 0 \end{cases}$$

narrow band instability

Hertzberg (2010)

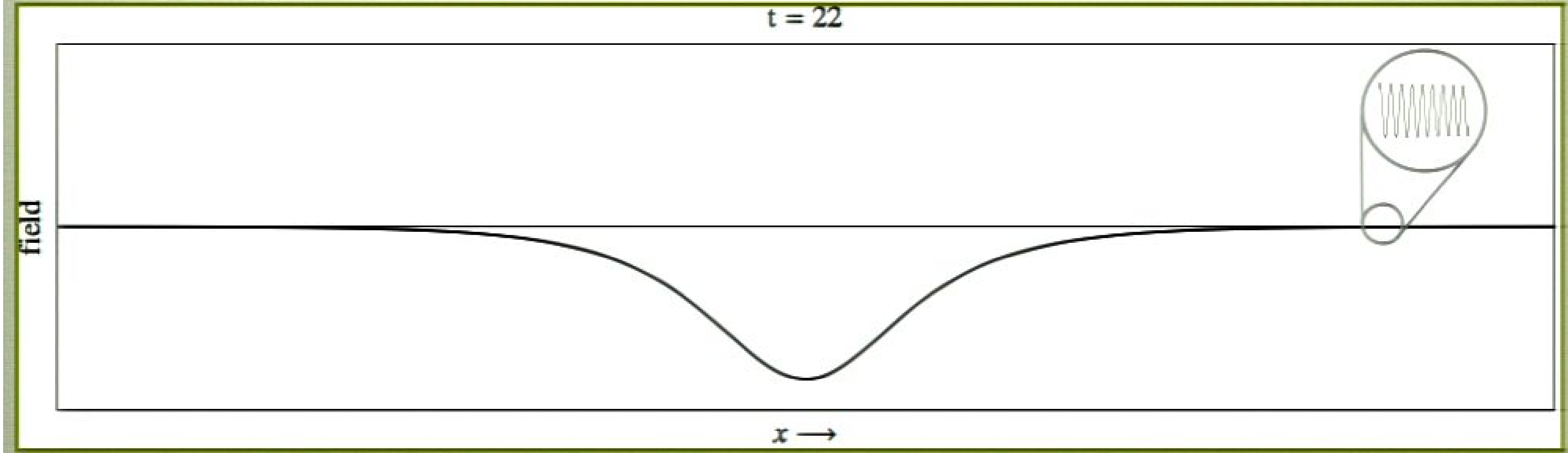
LINEAR STABILITY



OUTGOING RADIATION

- classical : *Kruskal and Segur* (1987)

radiative tail



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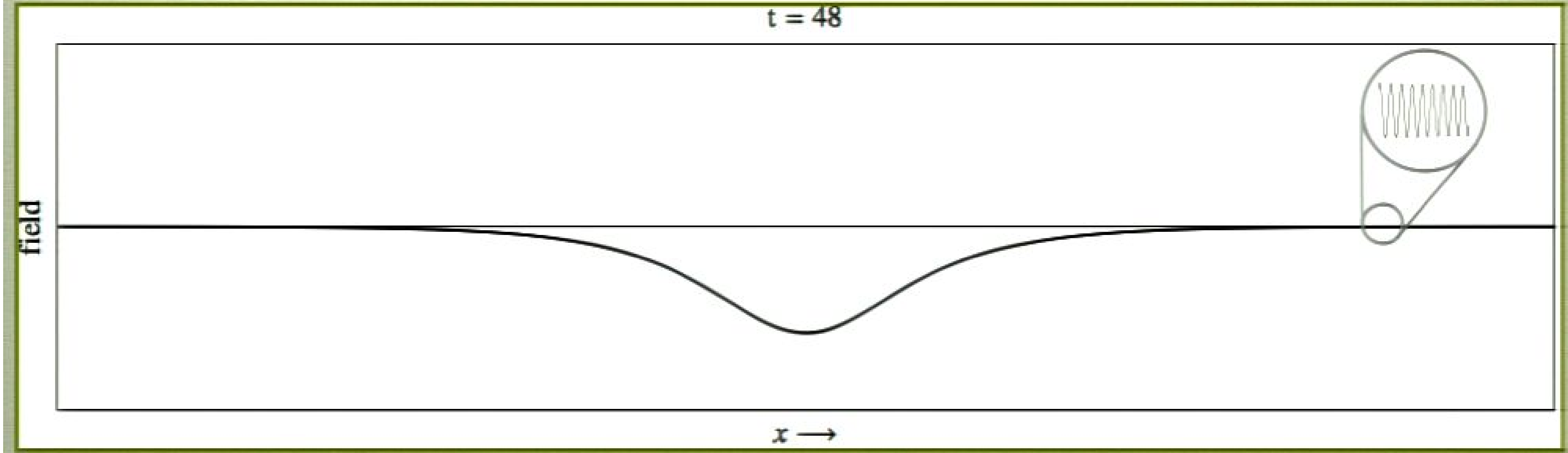

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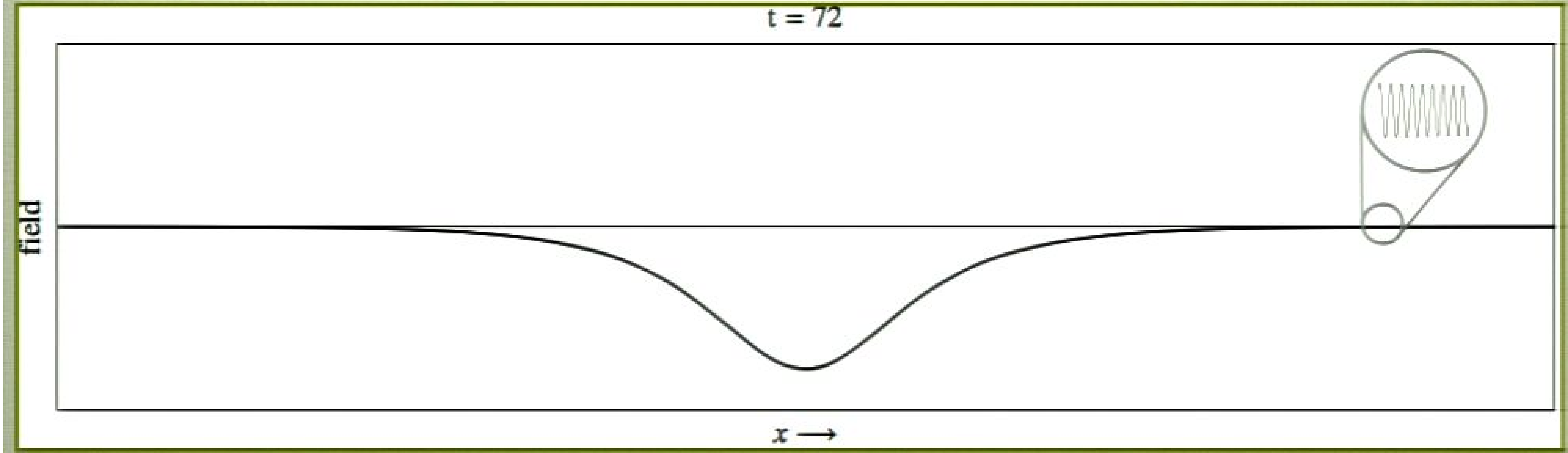

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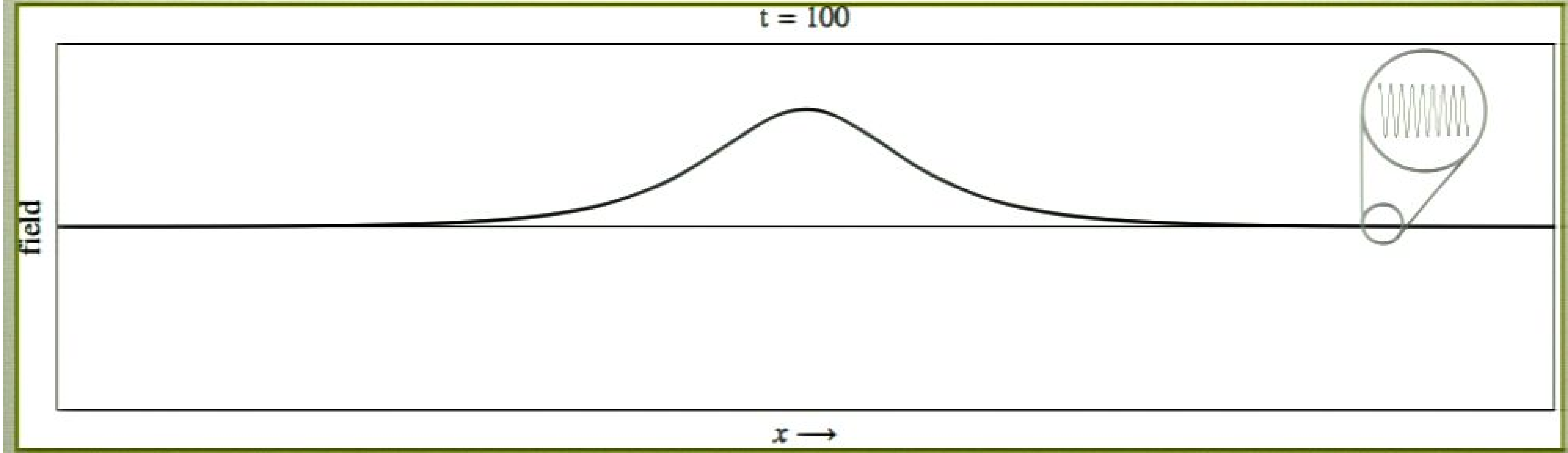

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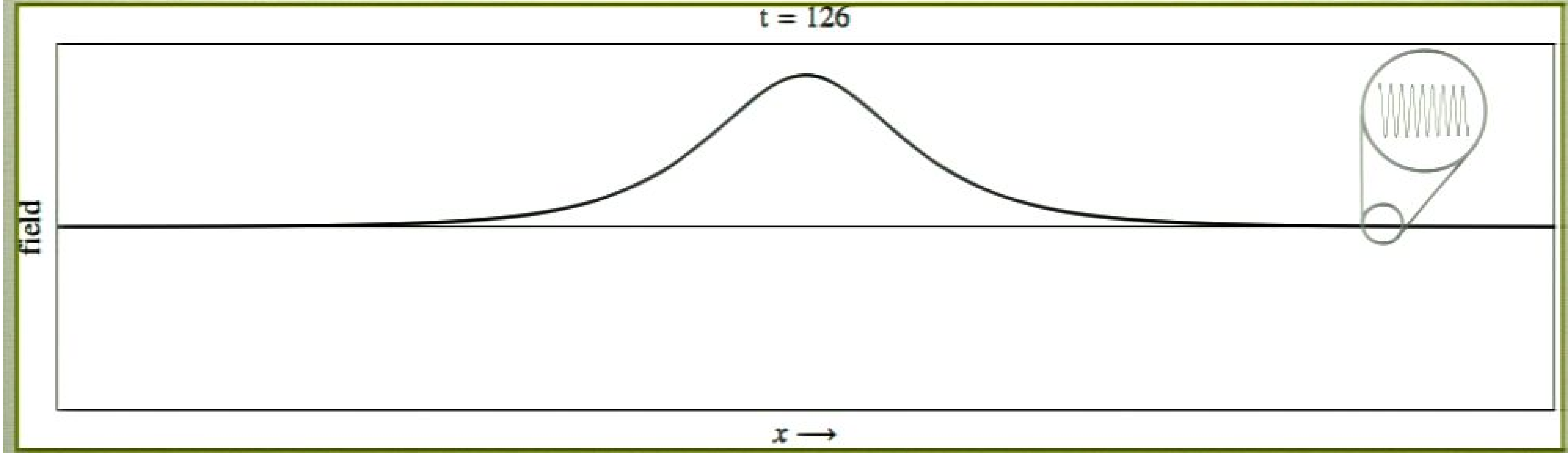

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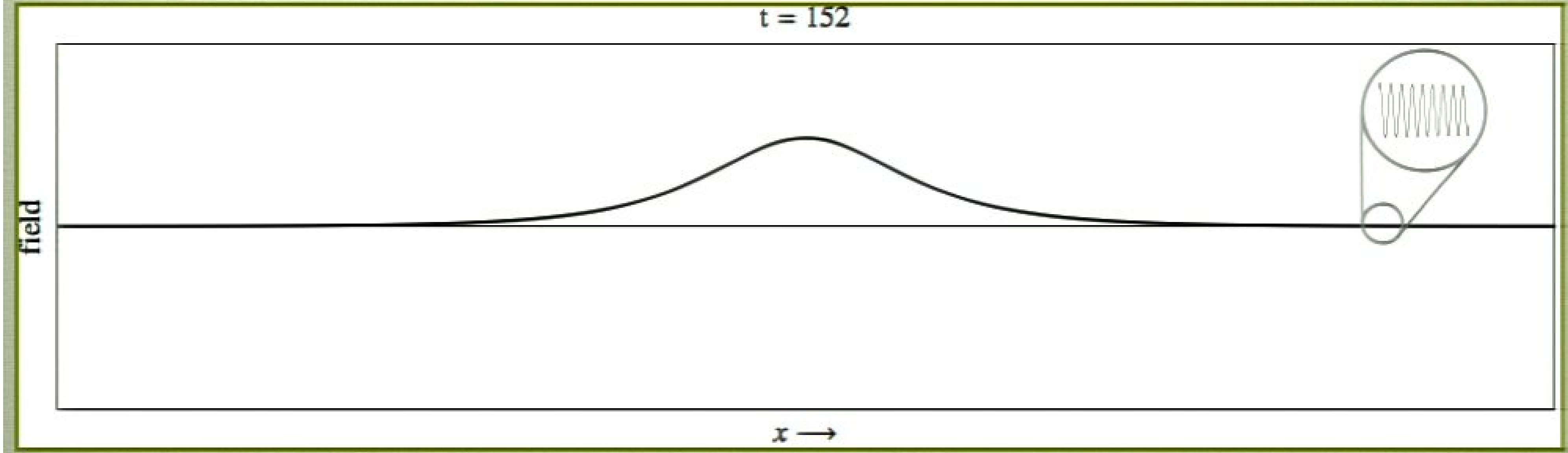


DECAY RATES

$$\Gamma_{\text{classical}} \sim m\,\frac{\lambda}{g}e^{-b\frac{g}{\lambda}}$$

$$\Gamma_{\text{quantum}} \sim m\,\frac{\lambda^3}{g^2}$$

Kruskel & Segur(1987) , Hertzberg (2010)

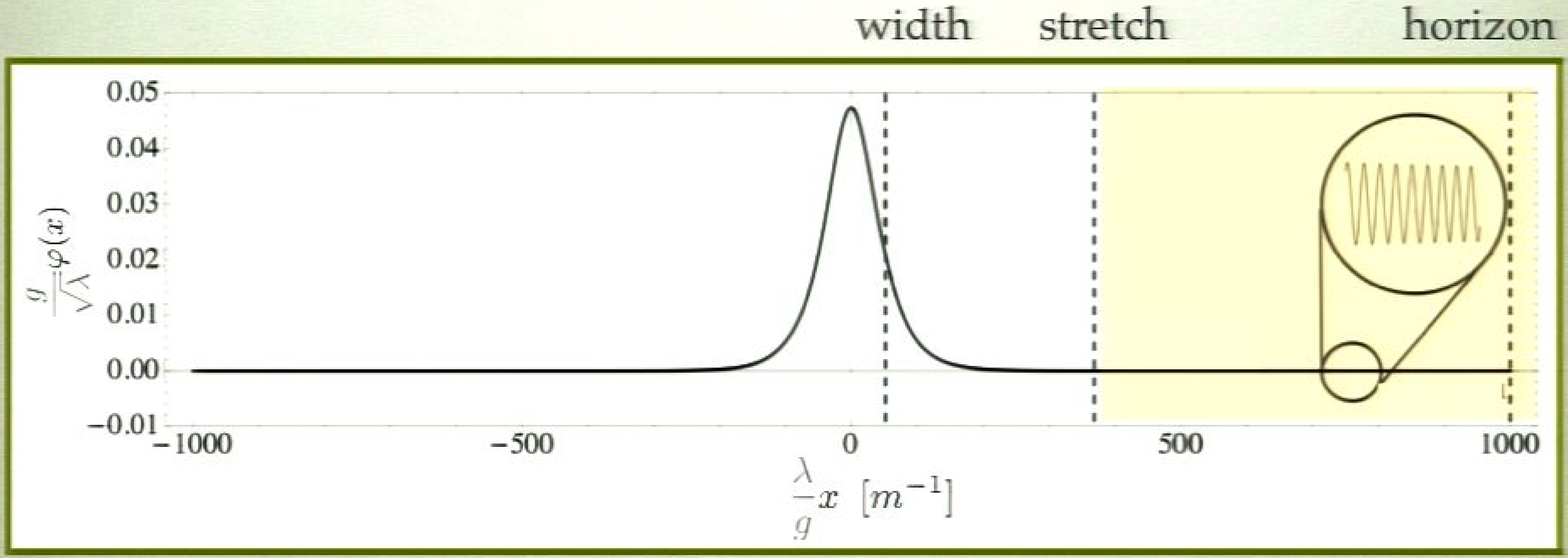
EXPANDING BACKGROUND

$$\partial_t^2\varphi - \nabla^2\varphi + 3H\partial_t\varphi + m^2\varphi - \lambda\varphi^3 + \frac{g^2}{m^2}\varphi^5 = 0$$

- *stretching* instability ?
- *radiative* tail

INCLUDING EXPANSION

- loss of energy $\Gamma_{\mathrm{H}} \sim m\, e^{-mH^{-1}(\alpha\lambda/g)^2}$



Farhi et. al (2007)

LONG LIVED IF ...

$$\Gamma \sim \Gamma(expansion) + \Gamma(radiation)$$

$$\Gamma \ll H \ll m$$

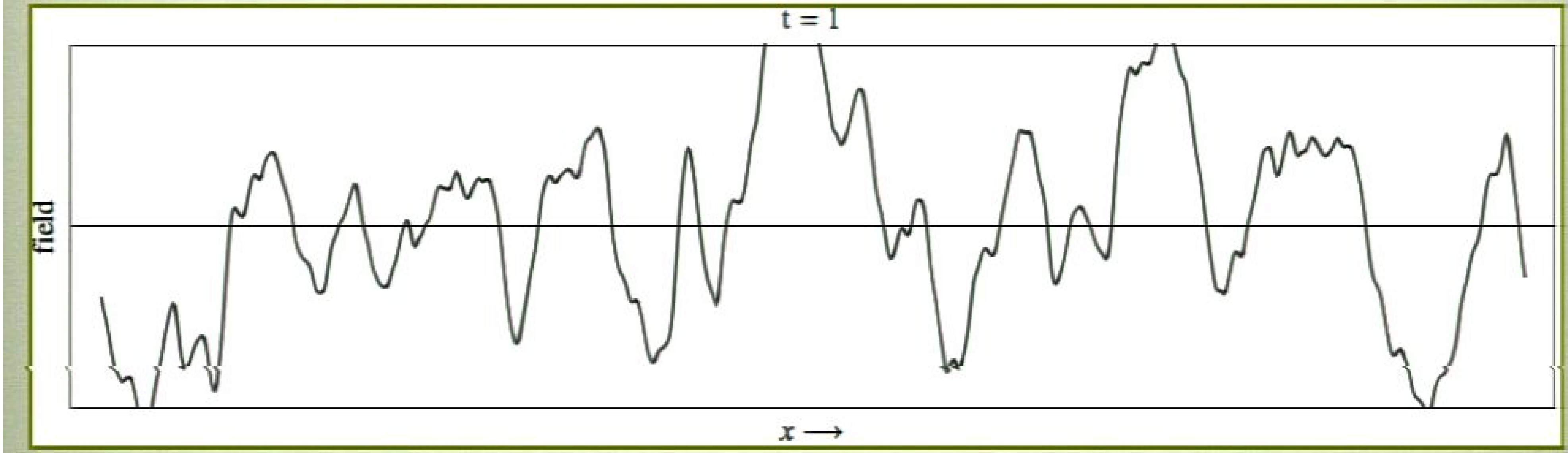
possible for inflaton (and axions)

SO FAR ...

- **individual blobs**: *MA & Shirokoff 2010*
  - 3+1 expanding universe
- **cosmological emergence**:
  - conditions for emergence ?
  - number density ? *MA* (2010)

COSMOLOGICAL EMERGENCE

GENERIC EMERGENCE



$> 80\%$ energy density in oscillons !

Farhi, Graham, Guth, ***Iqbal****, Rosales, Stamatopoulos* 2008

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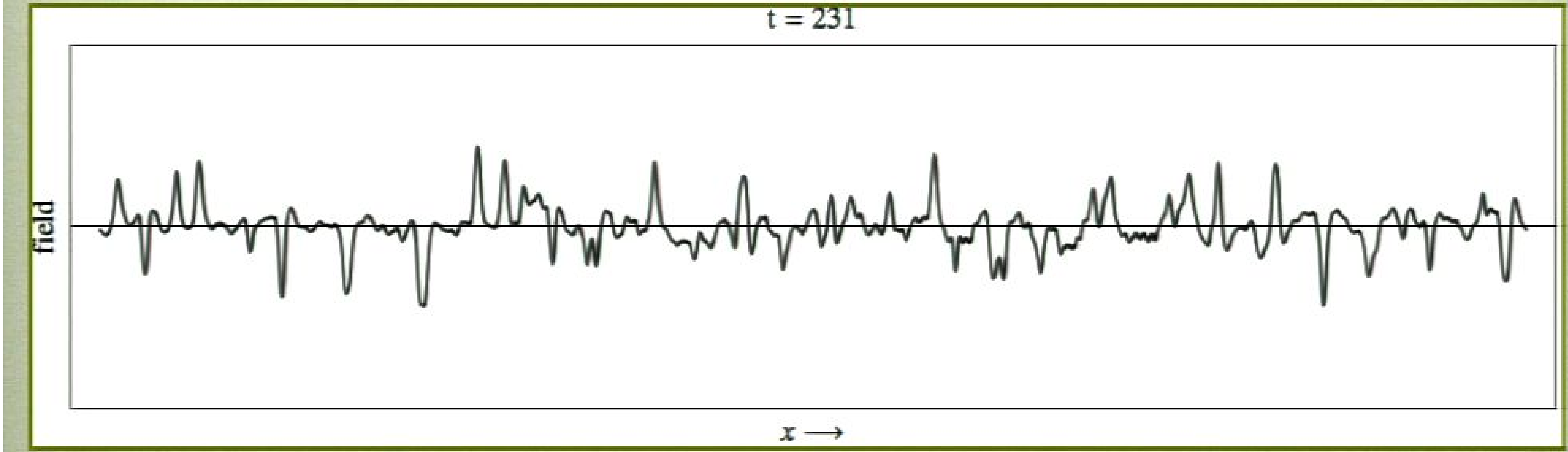

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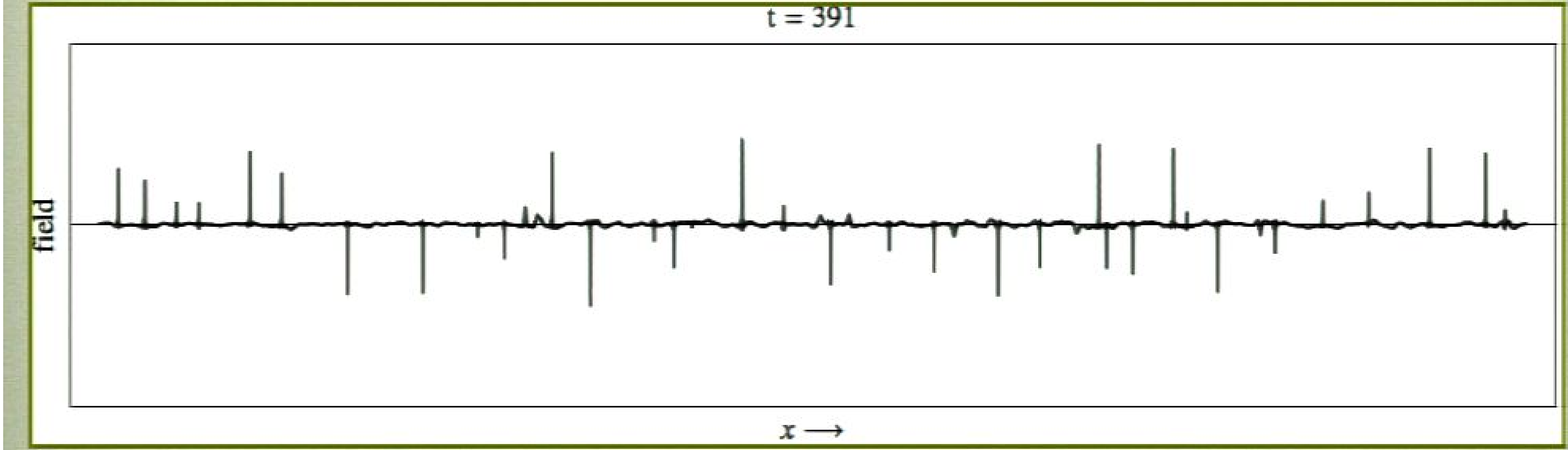

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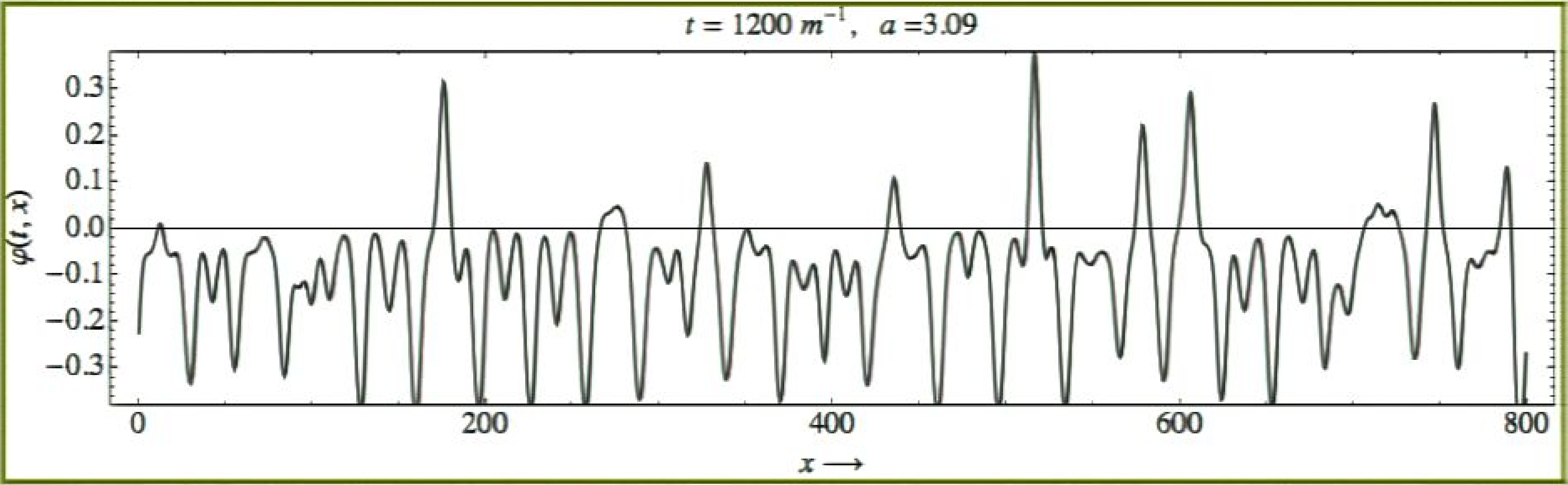
NEED LARGE FLUCTUATIONS

- start with tiny "quantum" fluctuations

- amplify them via resonance

1+1

POST-INFLATIONARY EMERGENCE



1+1

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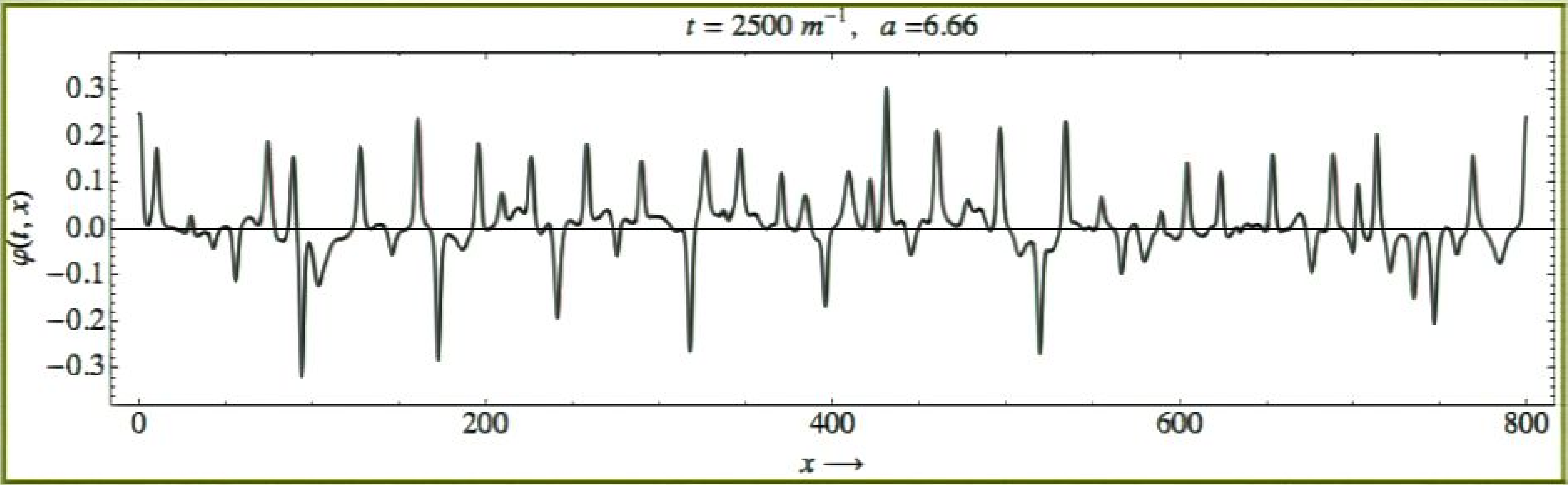

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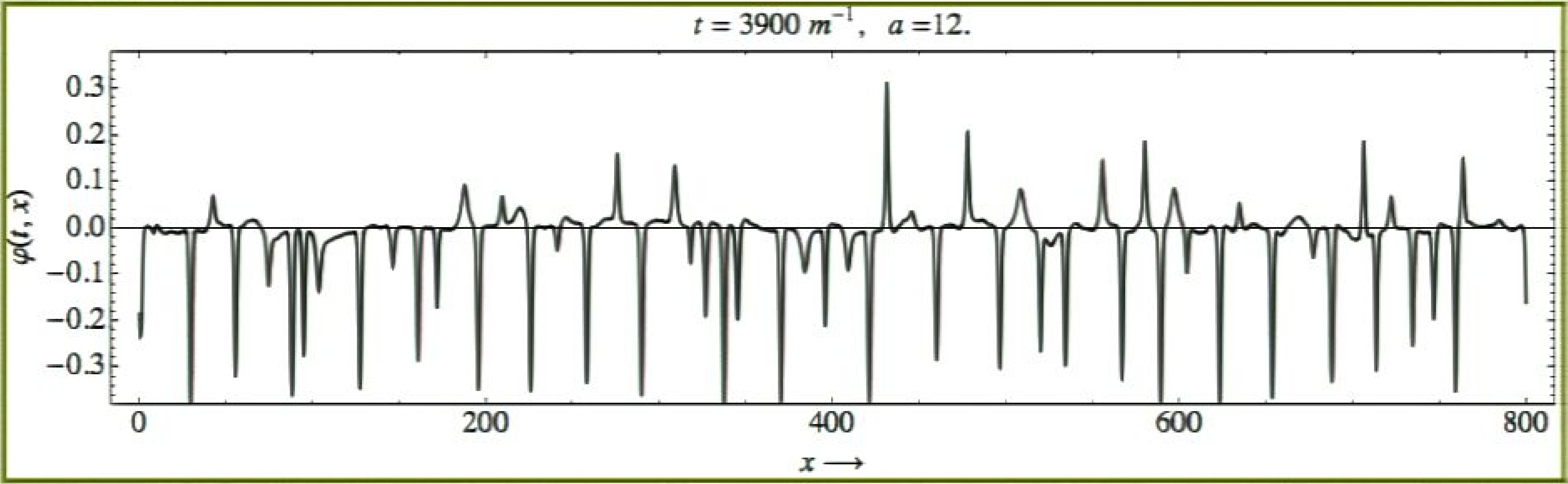

1+1

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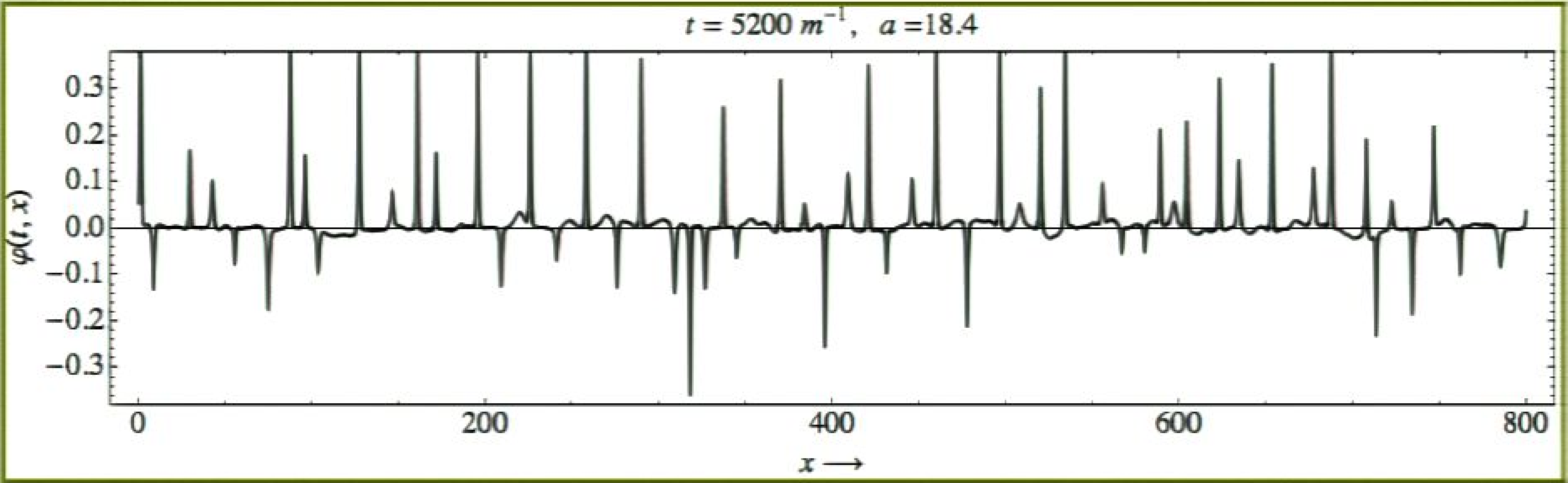

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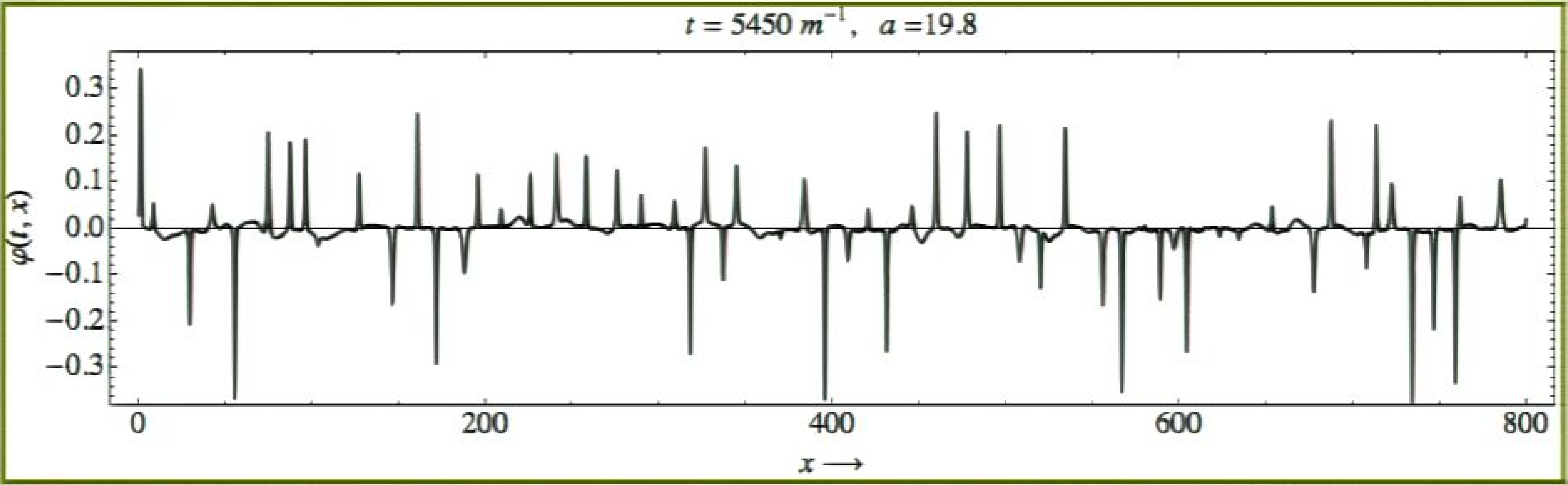

AMPLIFICATION IF ...

- growth rate μ_k
- expansion rate H

$$\boxed{\mu_k \gg H}$$

$$\frac{\mu_k(a)}{H} \approx \underbrace{\left[\left(\frac{m_{pl}}{m}\right)\frac{\lambda^{3/2}}{g}\right]}_{\beta} f(k,a) \gg 1$$

MA (2010)

1+1

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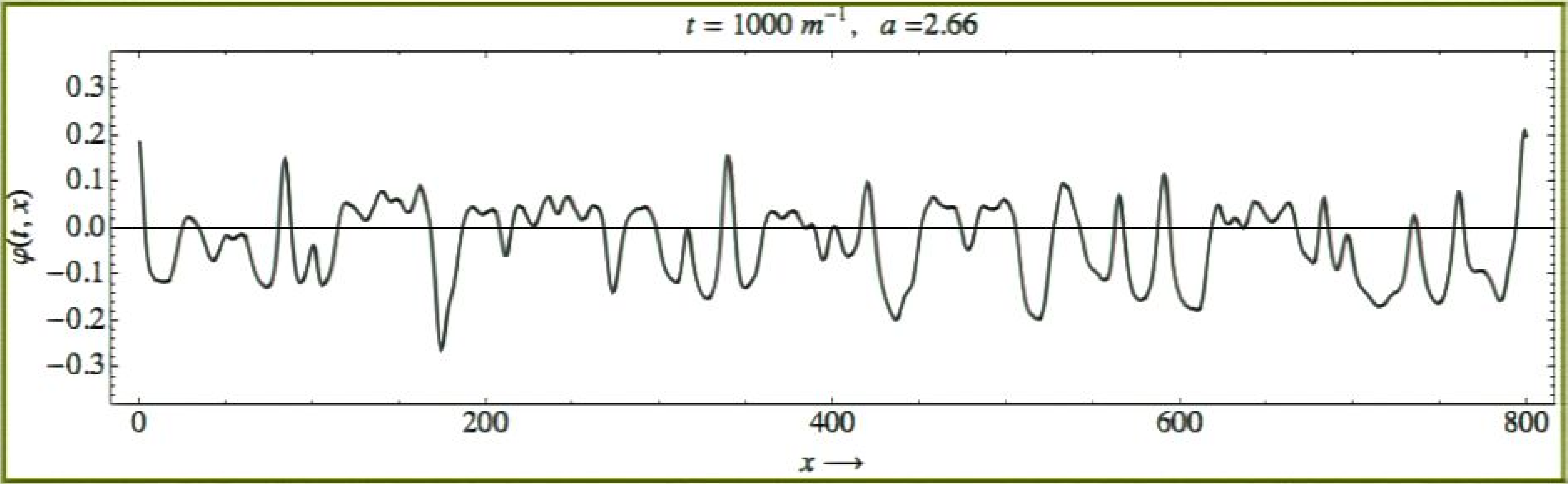

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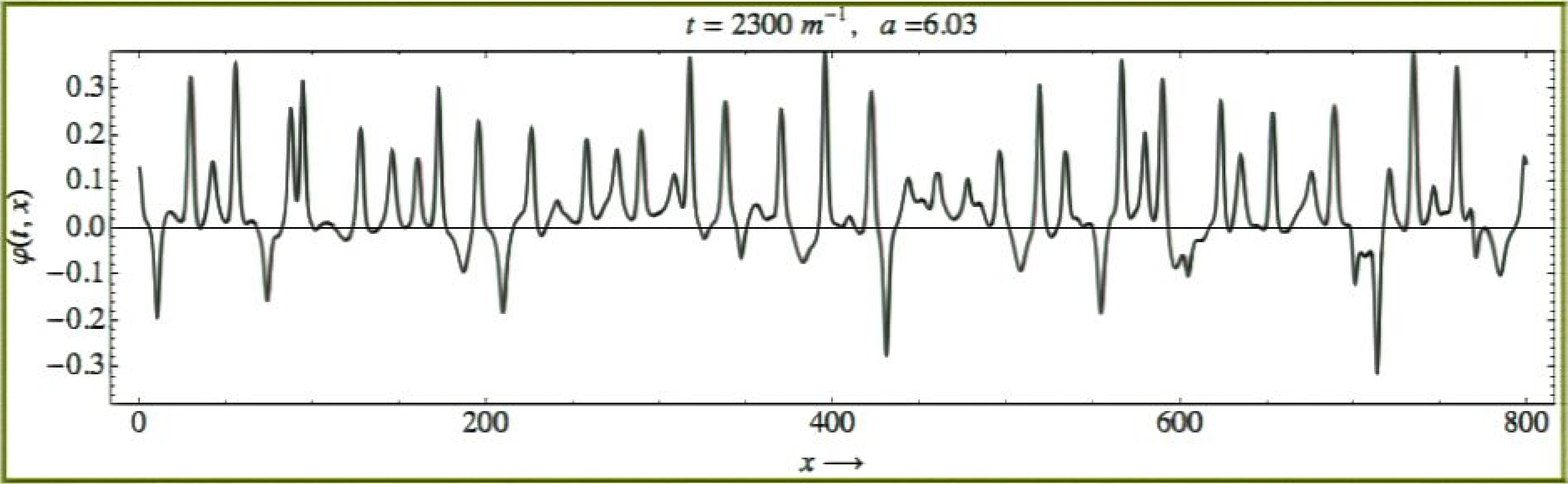

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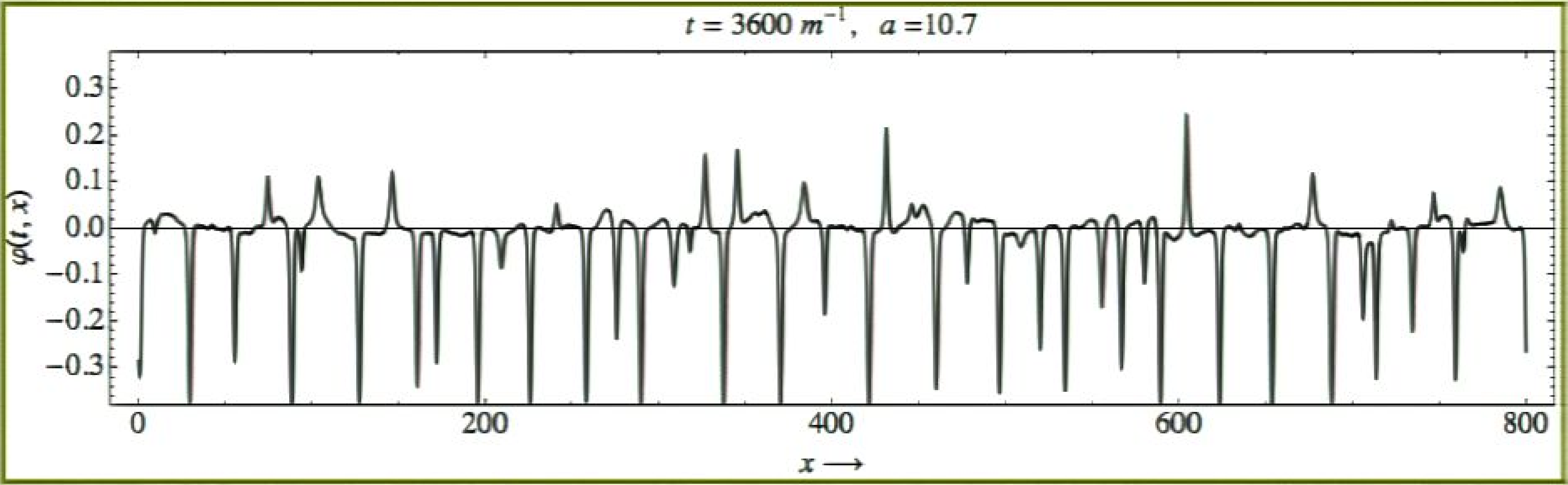

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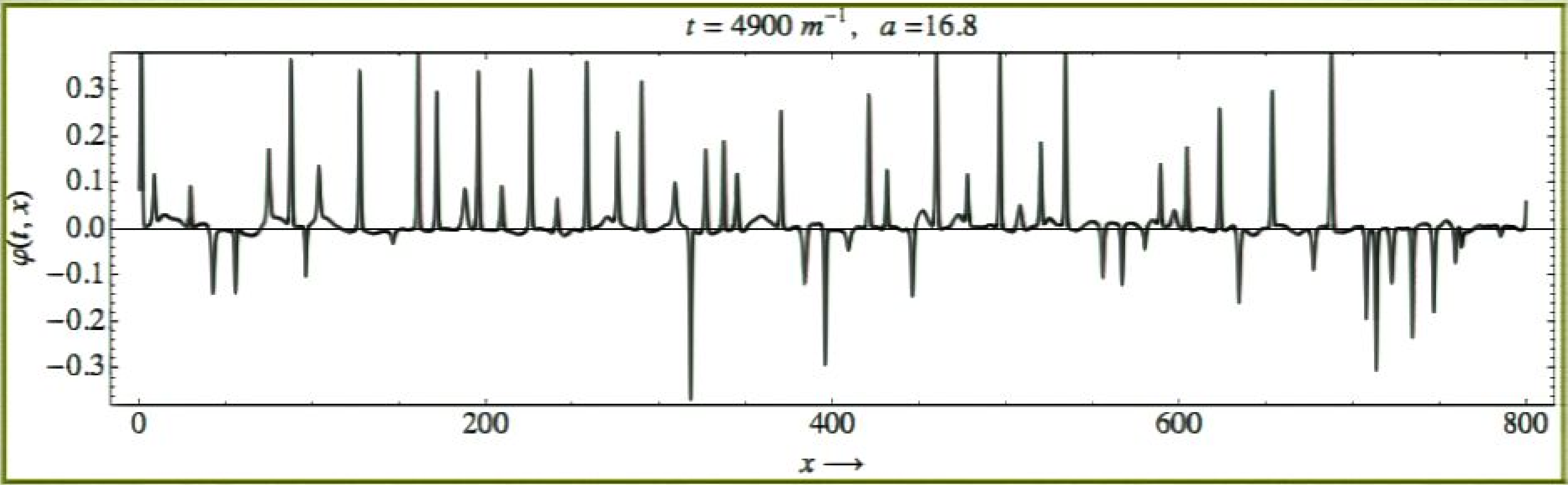

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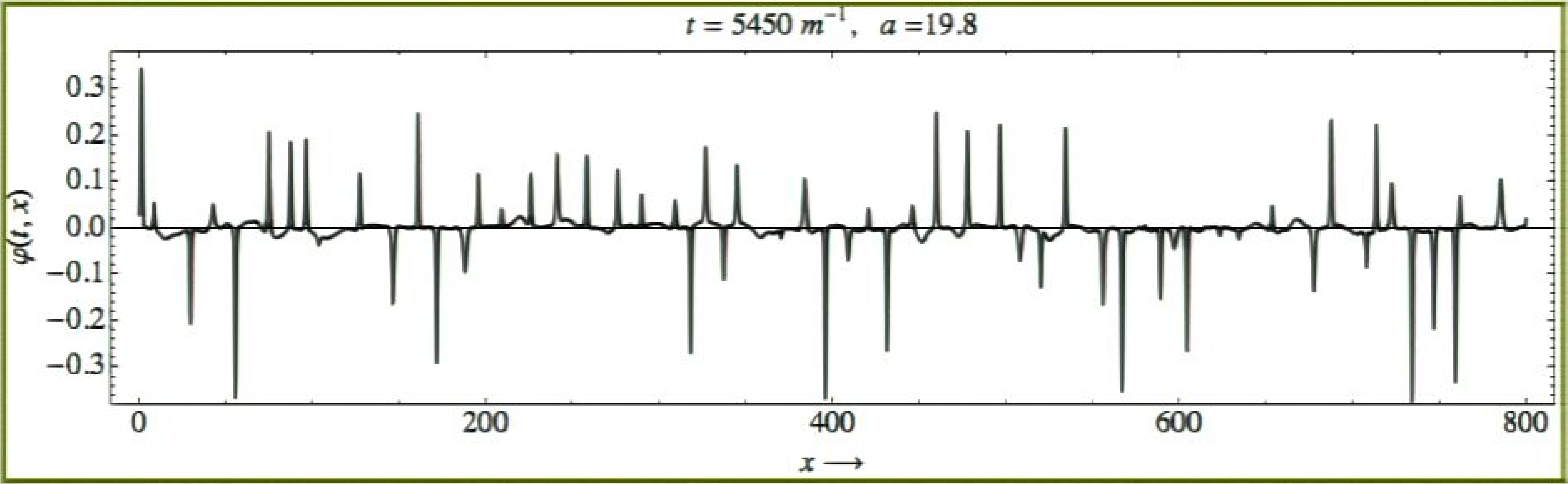

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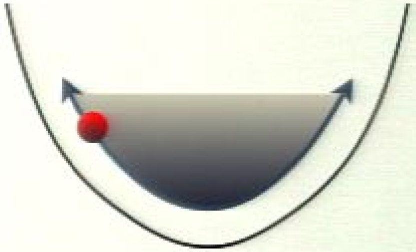
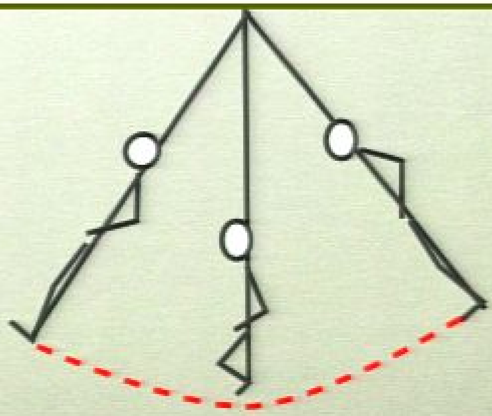
MA (2010)

LINEARIZED FLUCTUATIONS

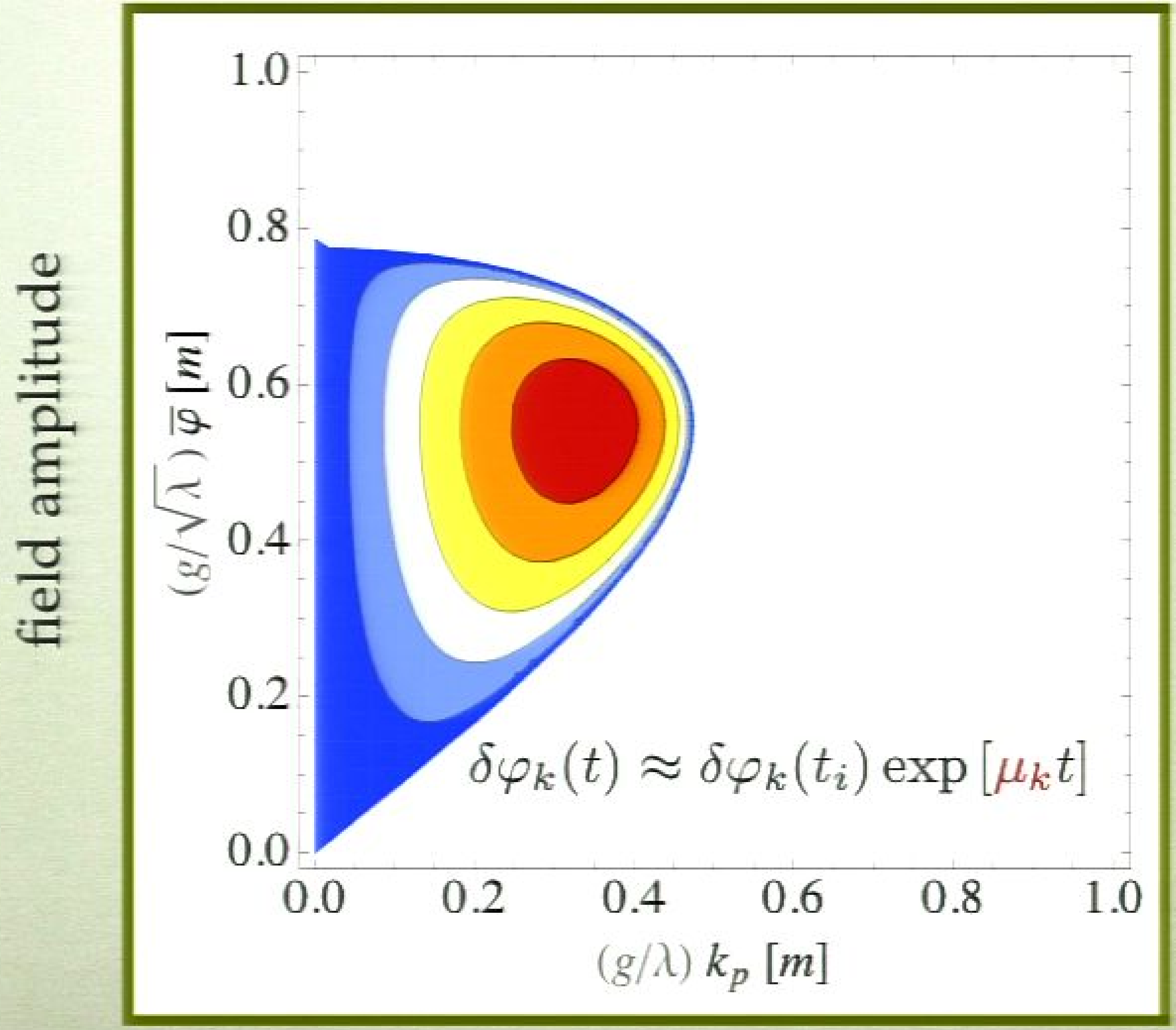
$$V(\varphi) = \frac{1}{2}m^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + \frac{g^2}{6m^2}\varphi^6$$



$$\boxed{\partial_t^2 \delta\varphi_k + 3H\partial_t\delta\varphi_k + \left(\frac{k^2}{a^2} + V''(\bar{\varphi})\right)\delta\varphi_k = 0}$$



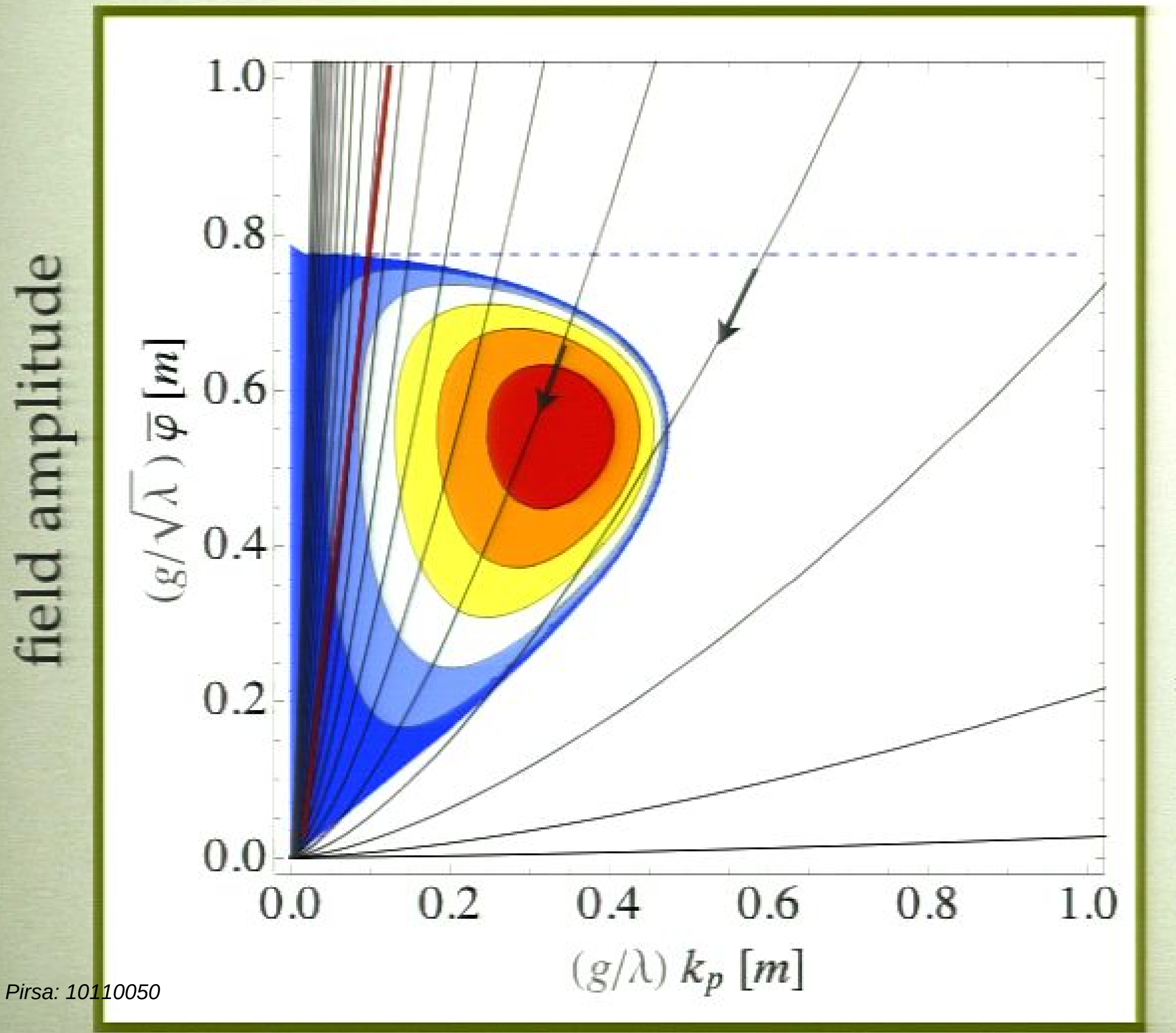
FLOQUET GROWTH: FLAT SPACE



$$\delta\varphi_k(t) \approx \delta\varphi_k(t_i)\exp\left[\mu_k t\right]$$

MA (2010)

FLOQUET ANALYSIS: EXPANDING UNIVERSE



$$\delta\varphi_k \approx \frac{\delta\varphi_k(t_i)}{a^{3/2}(t)} \exp\left[\int dt\, \mu_k(t)\right]$$

$$= \frac{\delta\varphi_k(a_i)}{a^{3/2}} \exp\left[\int d\ln a\, \frac{\mu_k(a)}{H(a)}\right]$$

LINEAR THEORY BREAKS DOWN

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- end of *quasi-exponential* growth

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- fragmentation

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- rapid mode-mode coupling

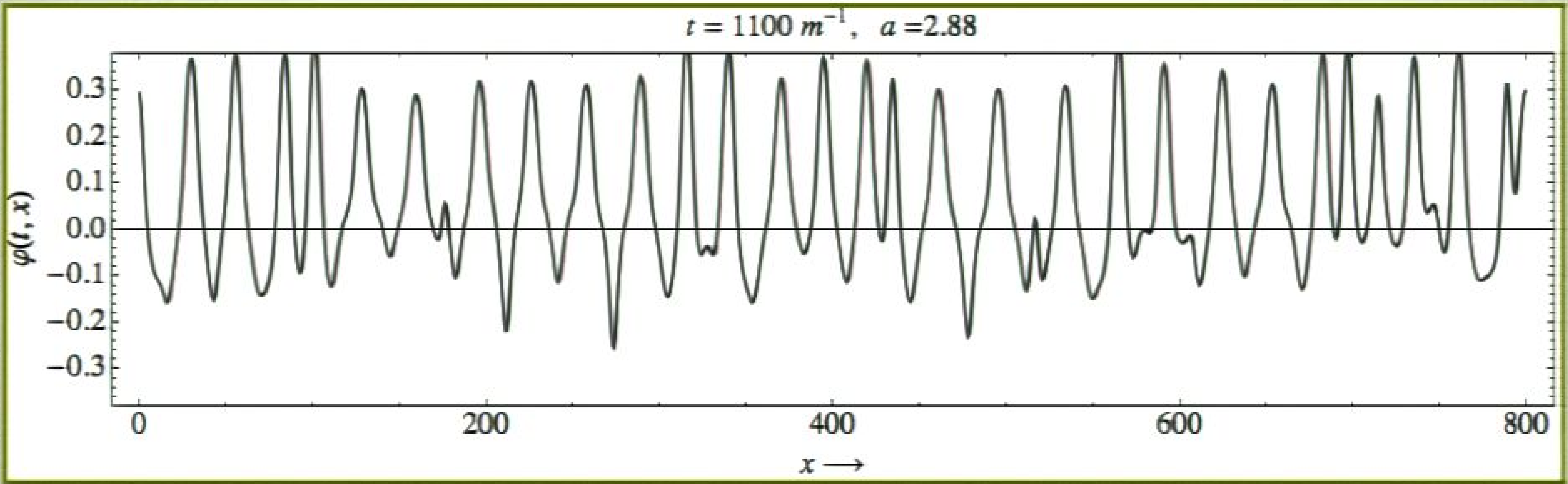
LINEAR THEORY BREAKS DOWN

- end of *quasi-exponential* growth
- fragmentation
- rapid mode-mode coupling
- oscillon formation

PREDICTING THE NUMBER DENSITY

ONE IMPORTANT SCALE

$$k_{nl}$$



MA (2010)

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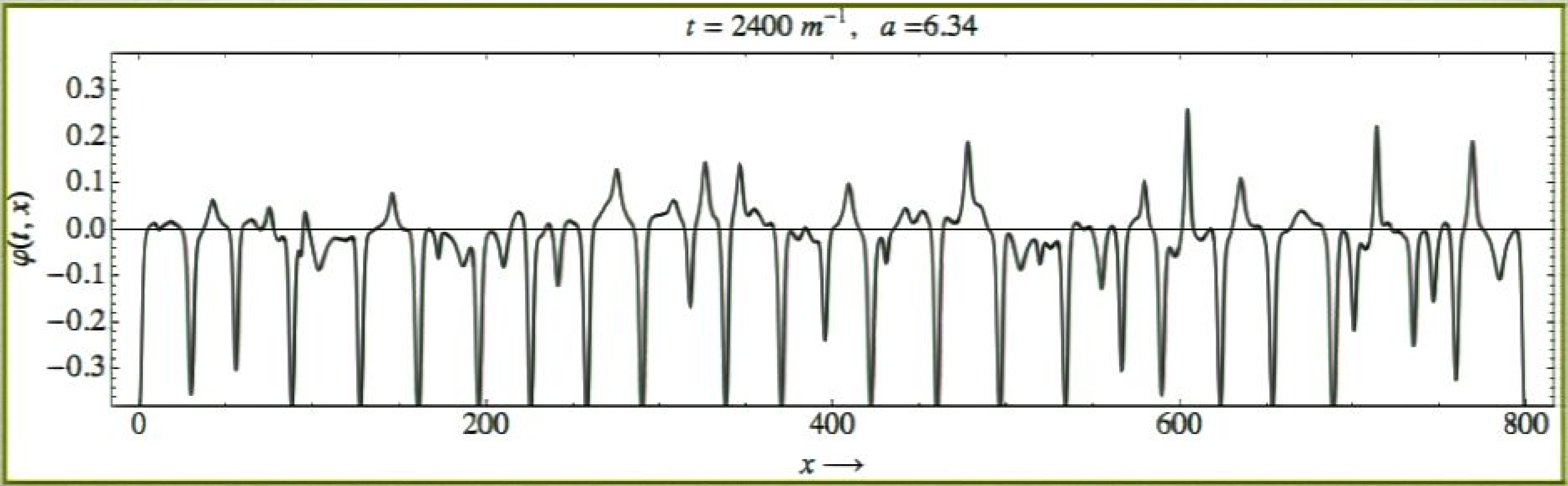

MA (2010)

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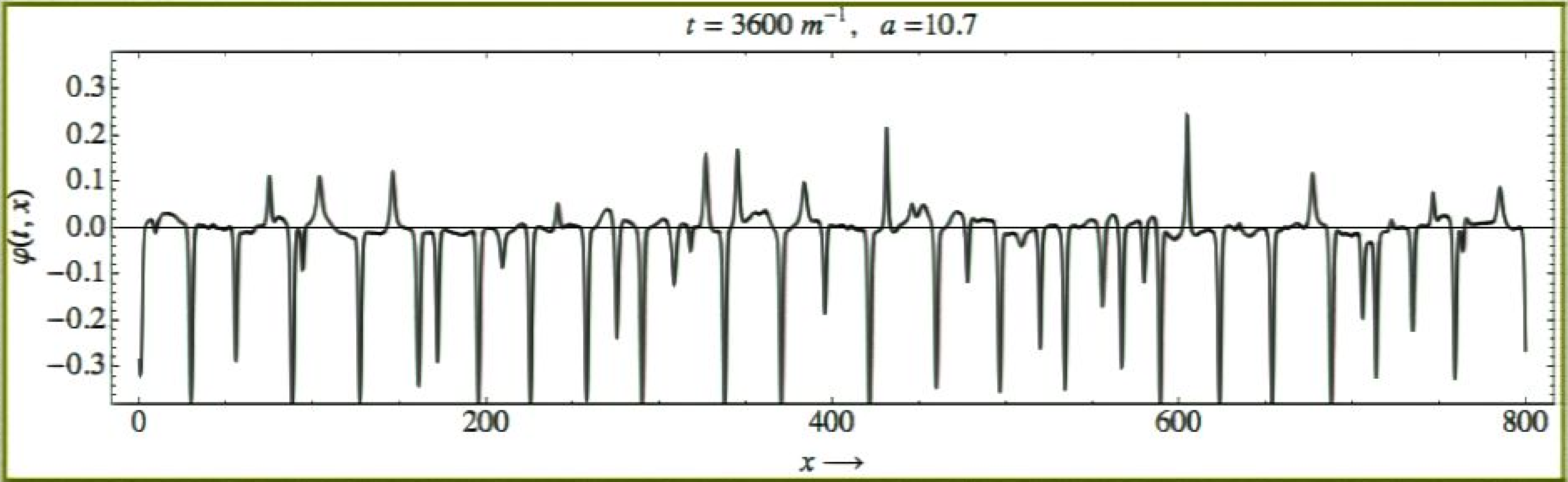

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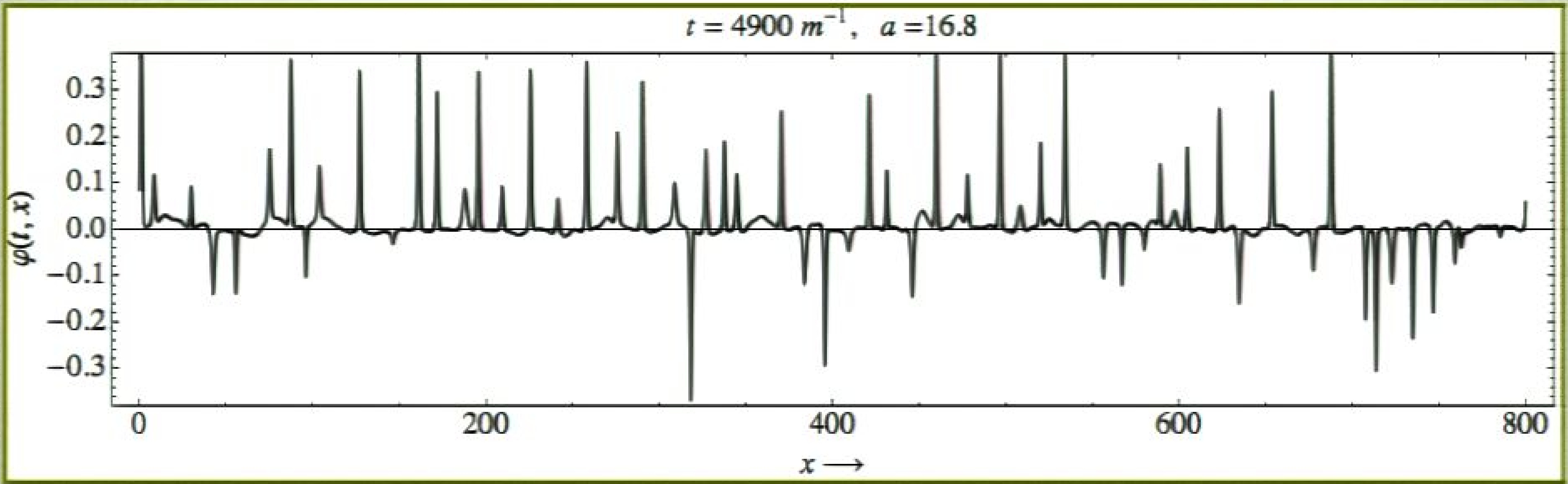

MA (2010)

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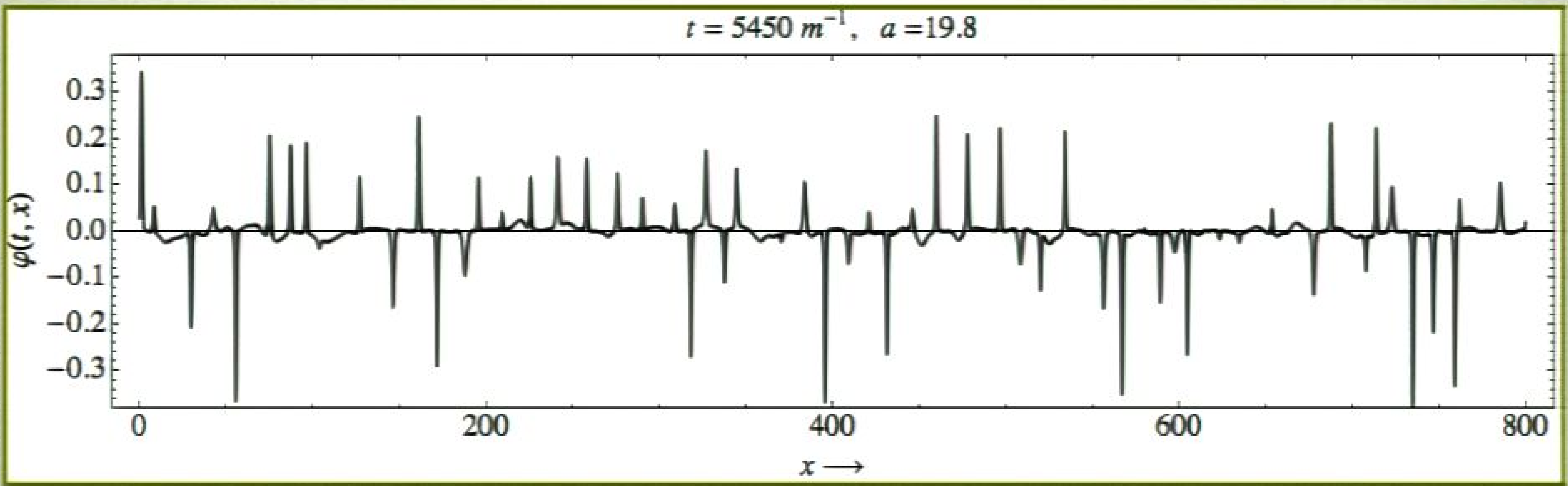
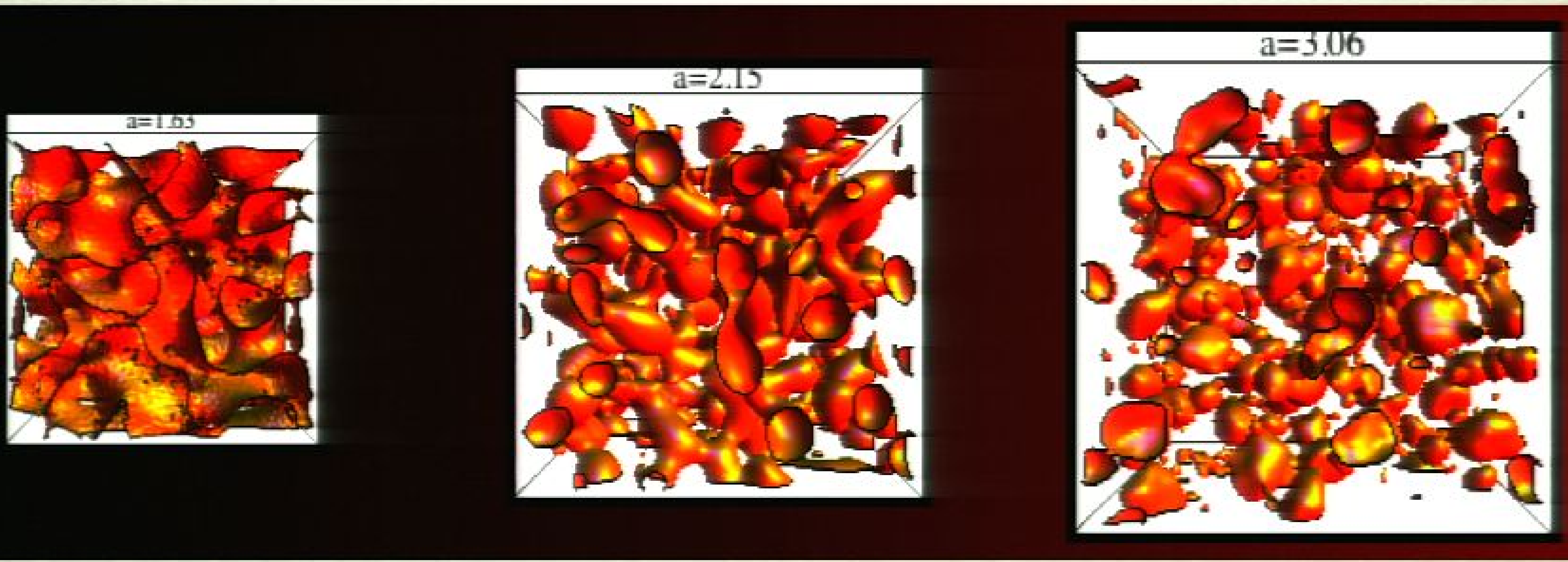


MA (2010)

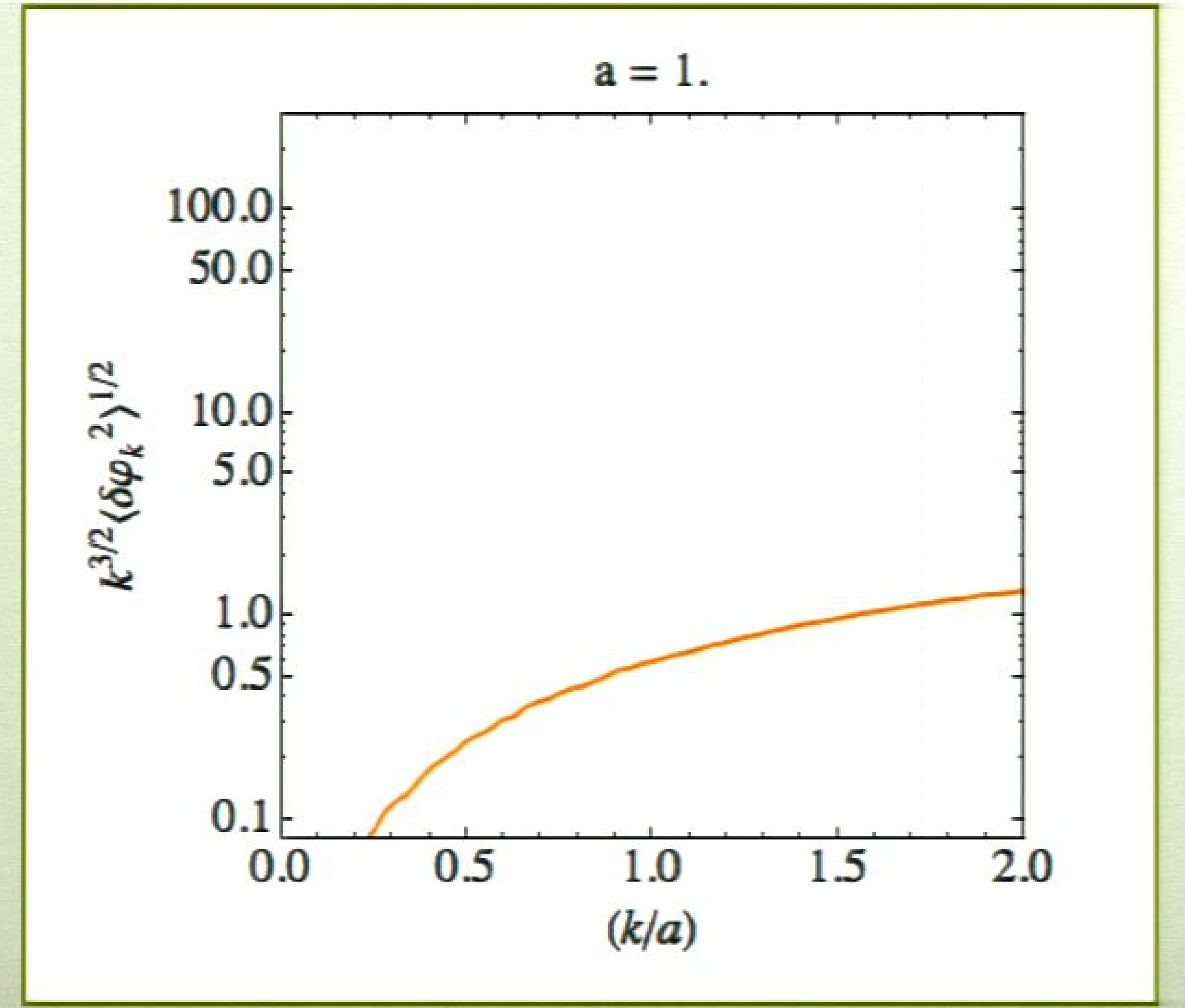
HOW MANY PEAKS ?

$$k_{nl}$$



MA (2010)

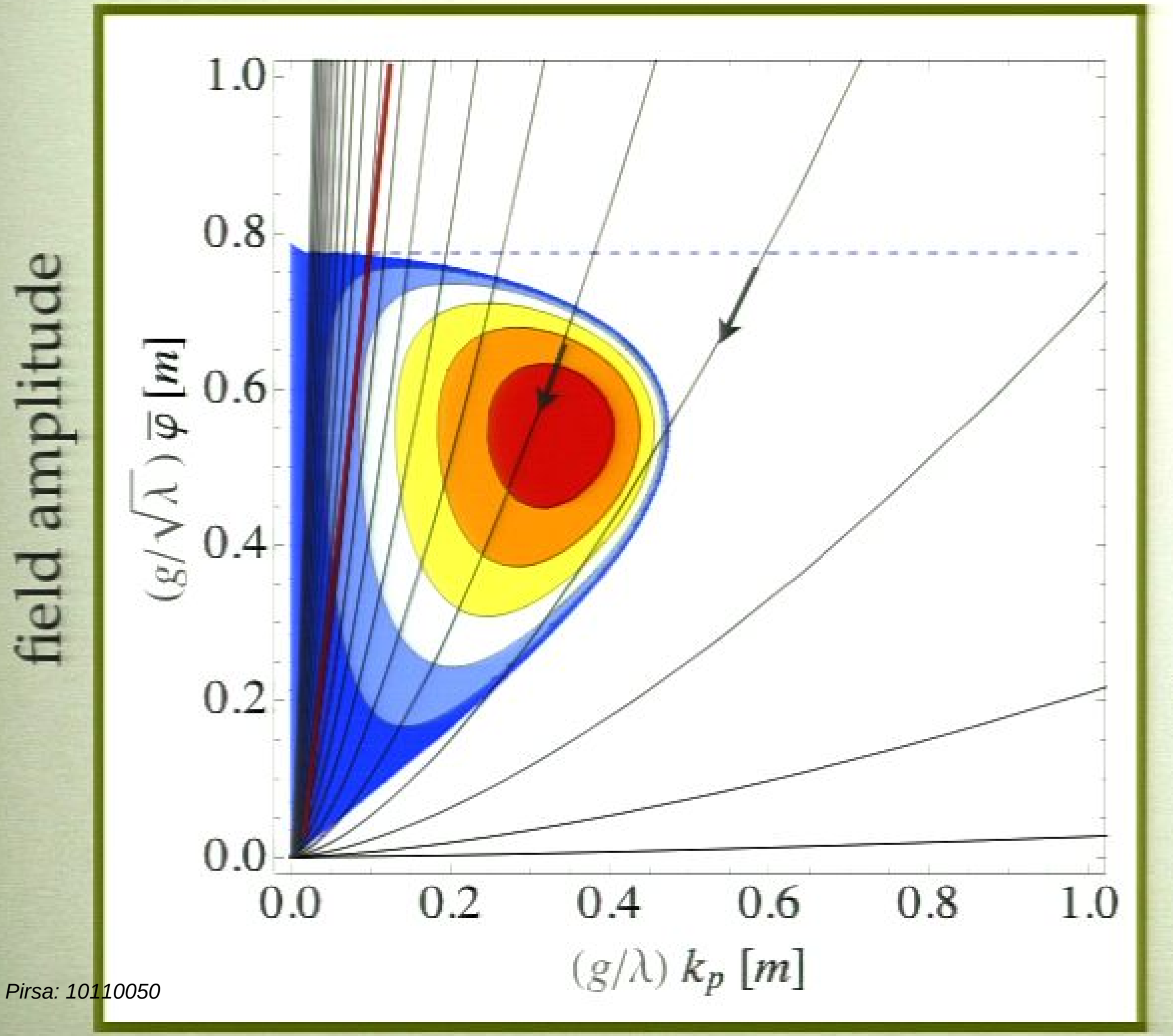
POWER SPECTRUM



NEED LARGE FLUCTUATIONS

- start with tiny "quantum" fluctuations
- amplify them via resonance

FLOQUET ANALYSIS: EXPANDING UNIVERSE



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LINEAR THEORY BREAKS DOWN

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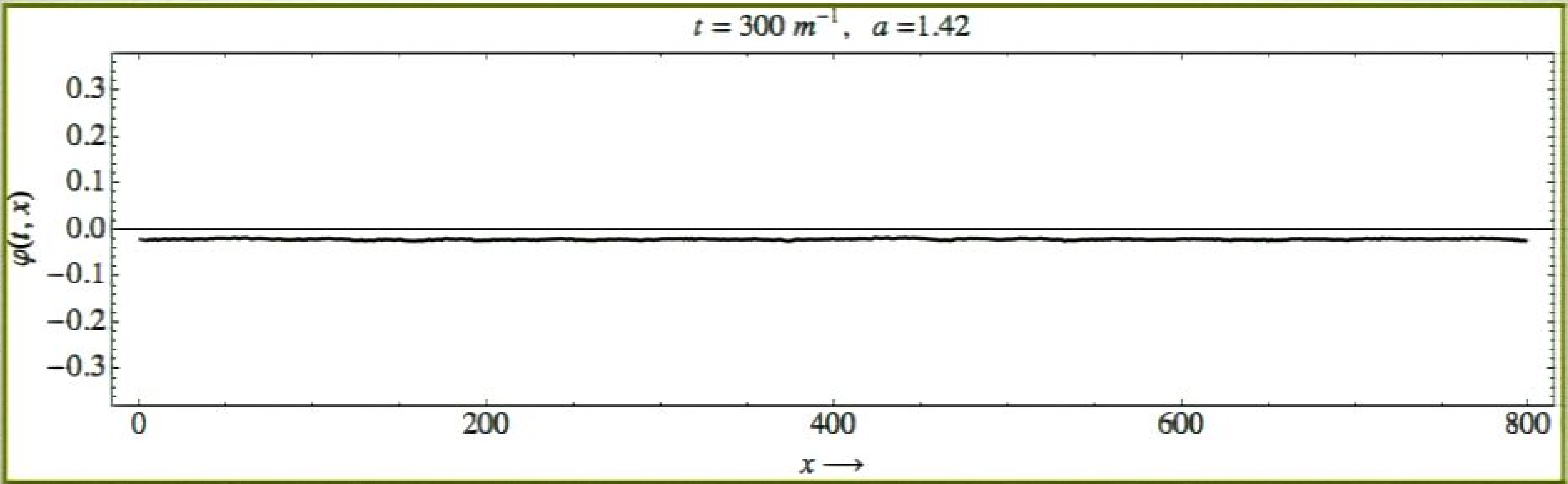

MA (2010)

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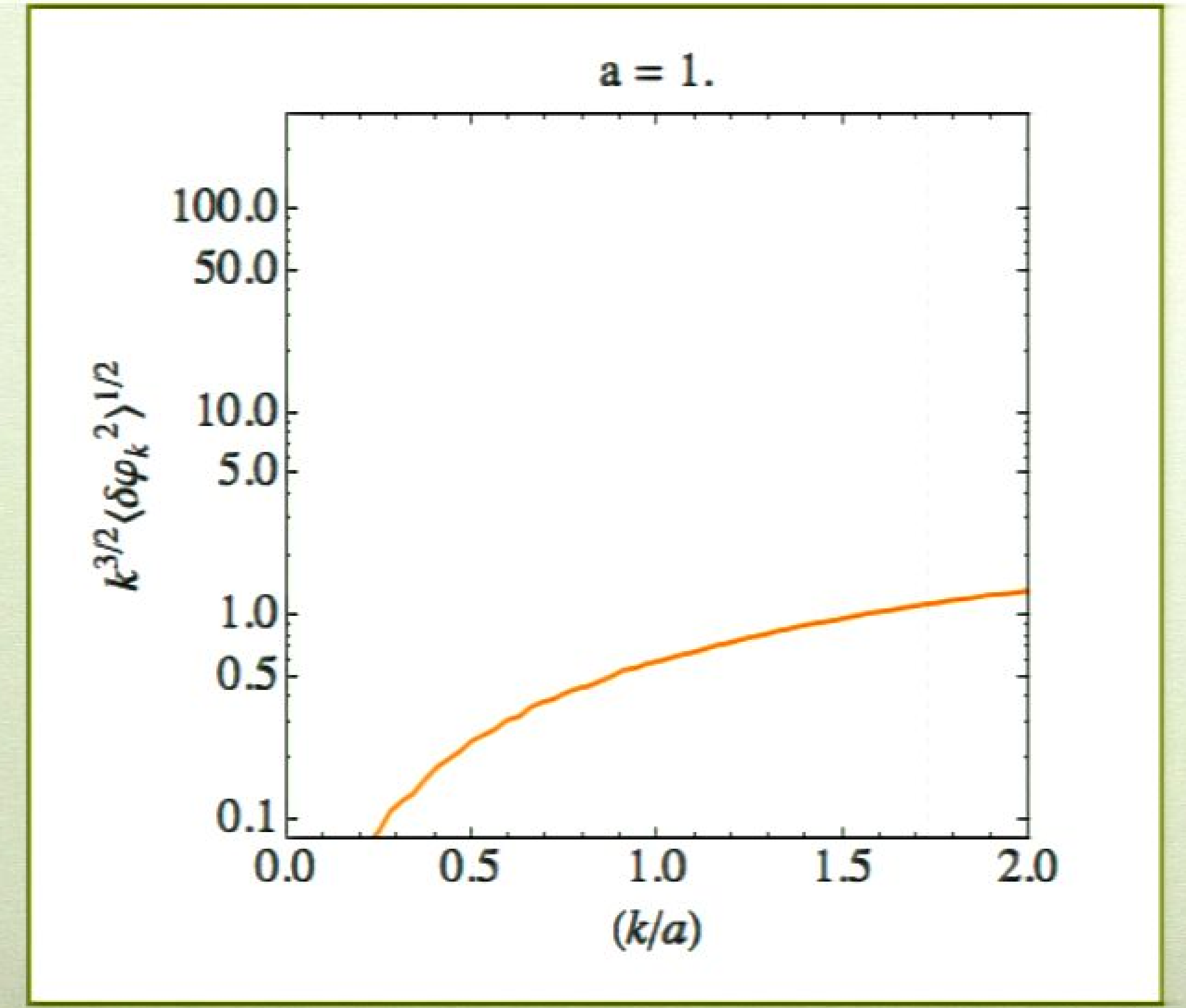

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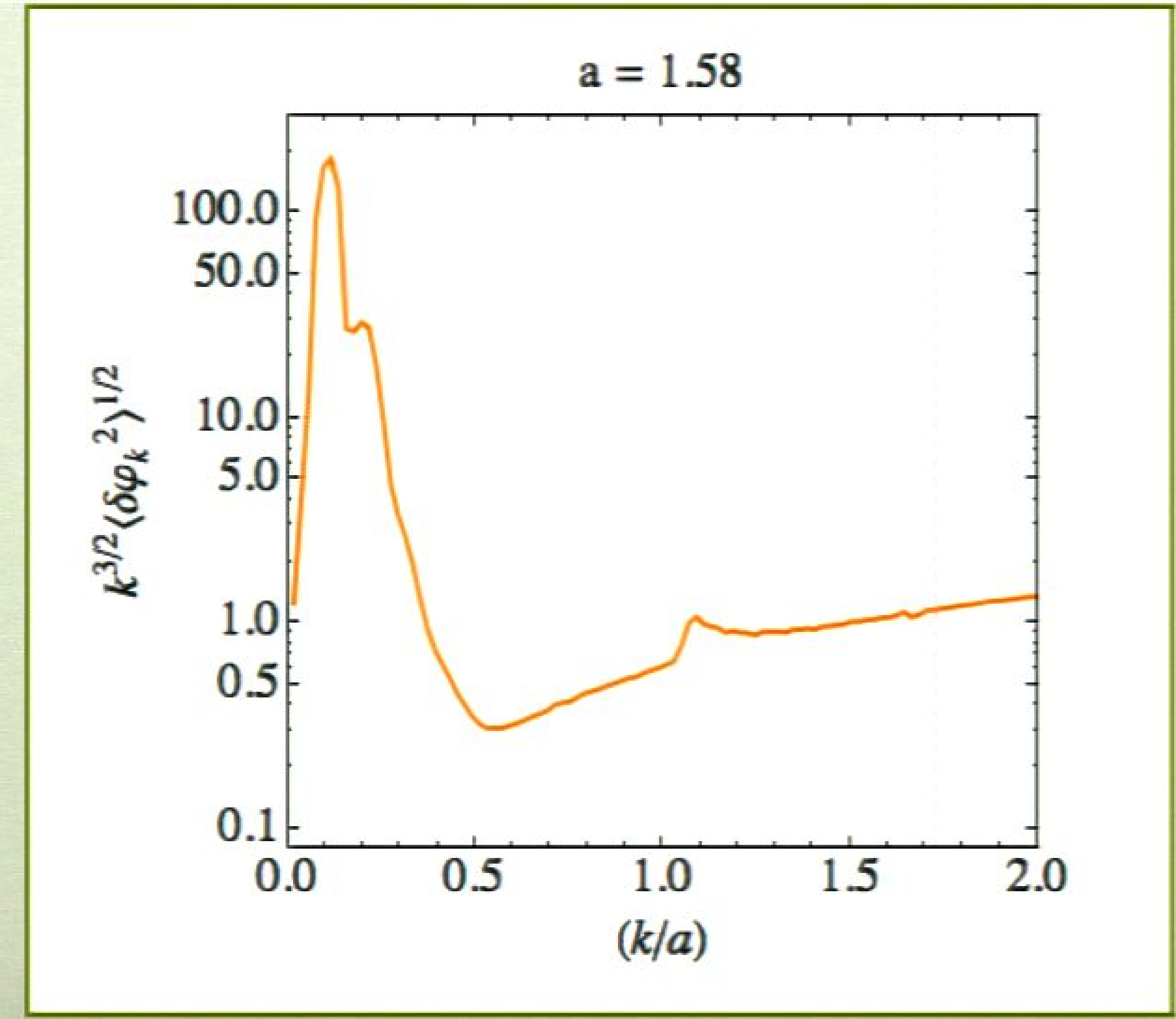


NUMBER DENSITY

$$n_{osc}a^3 \sim \left(\frac{k_{nl}}{2\pi}\right)^3$$

$$\approx \beta^{-3/5}\left(\frac{\lambda}{g}\frac{m}{2\pi}\right)^3$$

MA (2010)

$$\frac{\mu_k}{H} \sim \beta \equiv \left[\left(\frac{m_{pl}}{m}\right)\frac{\lambda^{3/2}}{g}\right]$$

NUMERICAL SIMULATIONS

NUMERICAL SIMULATIONS

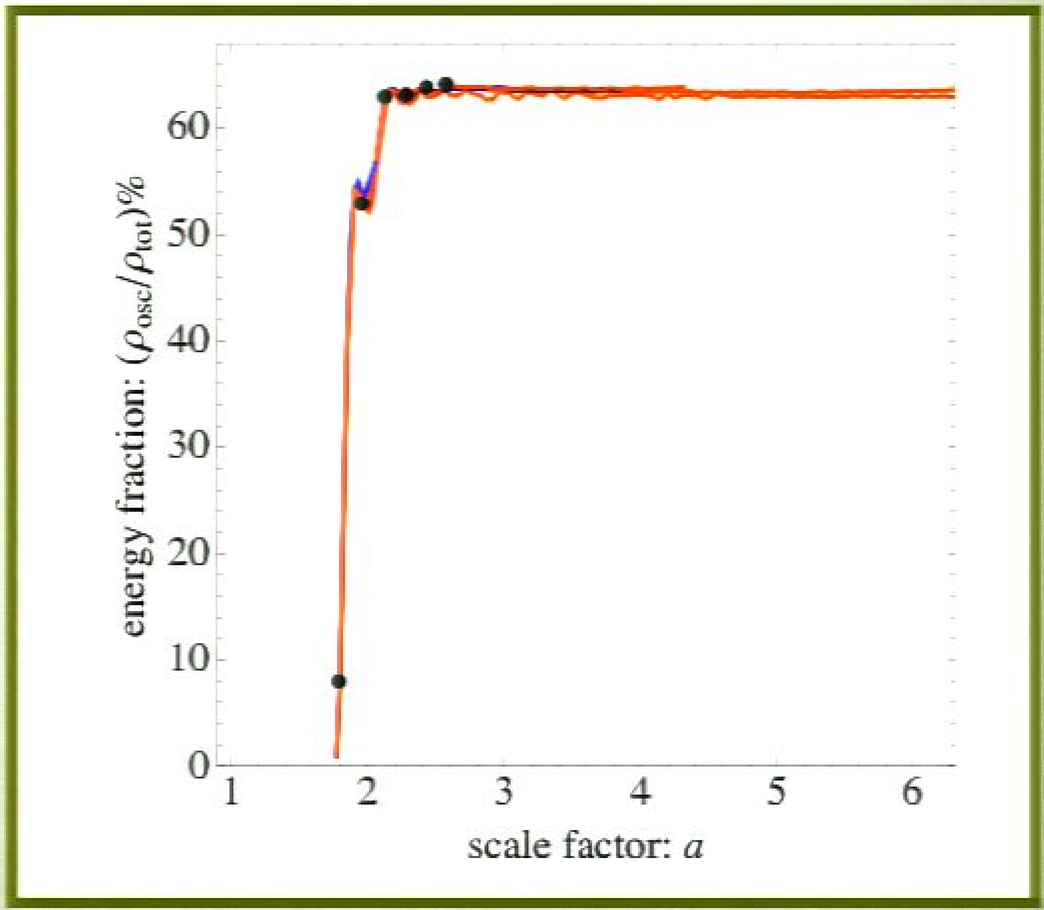
- verify individual characteristics
- confirm predictions for number densities and determine energy fraction
- more realistic inflationary potentials where analytics are difficult (eg. monodromy models)

SIMULATION CODES

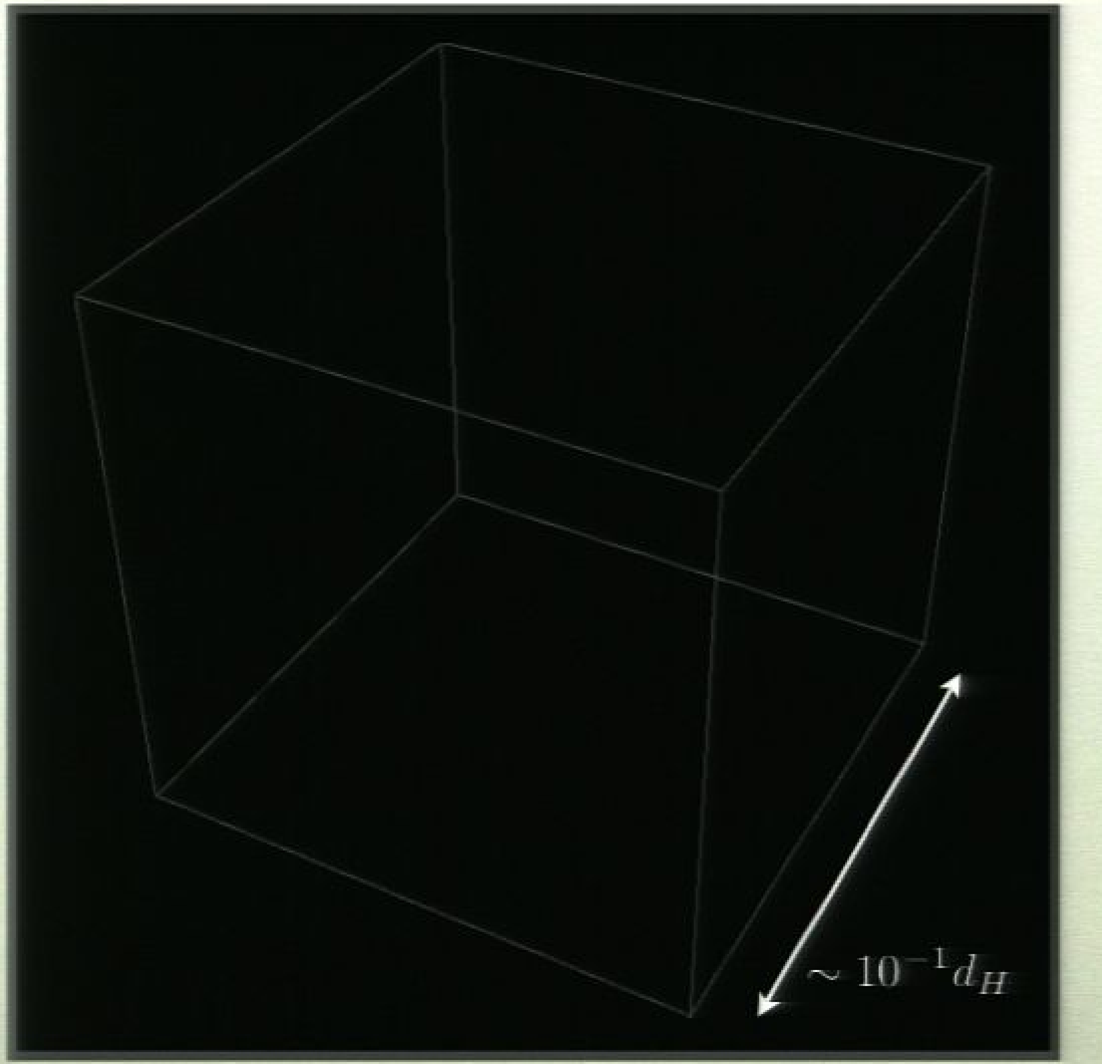
- used modified versions of
  - **PSpectRe** (*Pseudo-Spectral* by Easther, Finkel & Roth 2008)
  - **Defrost** (*Finite Difference* by Frolov 2007)

ROBUSTNESS OF NUMERICS

- black points: defrost (N = 1024, L = 400)
- orange curves PSpectRe (N = 256, L = 200, 400, 600)
- blue curve PSpectRe (N = 384, L = 400)



OSCILLONS?



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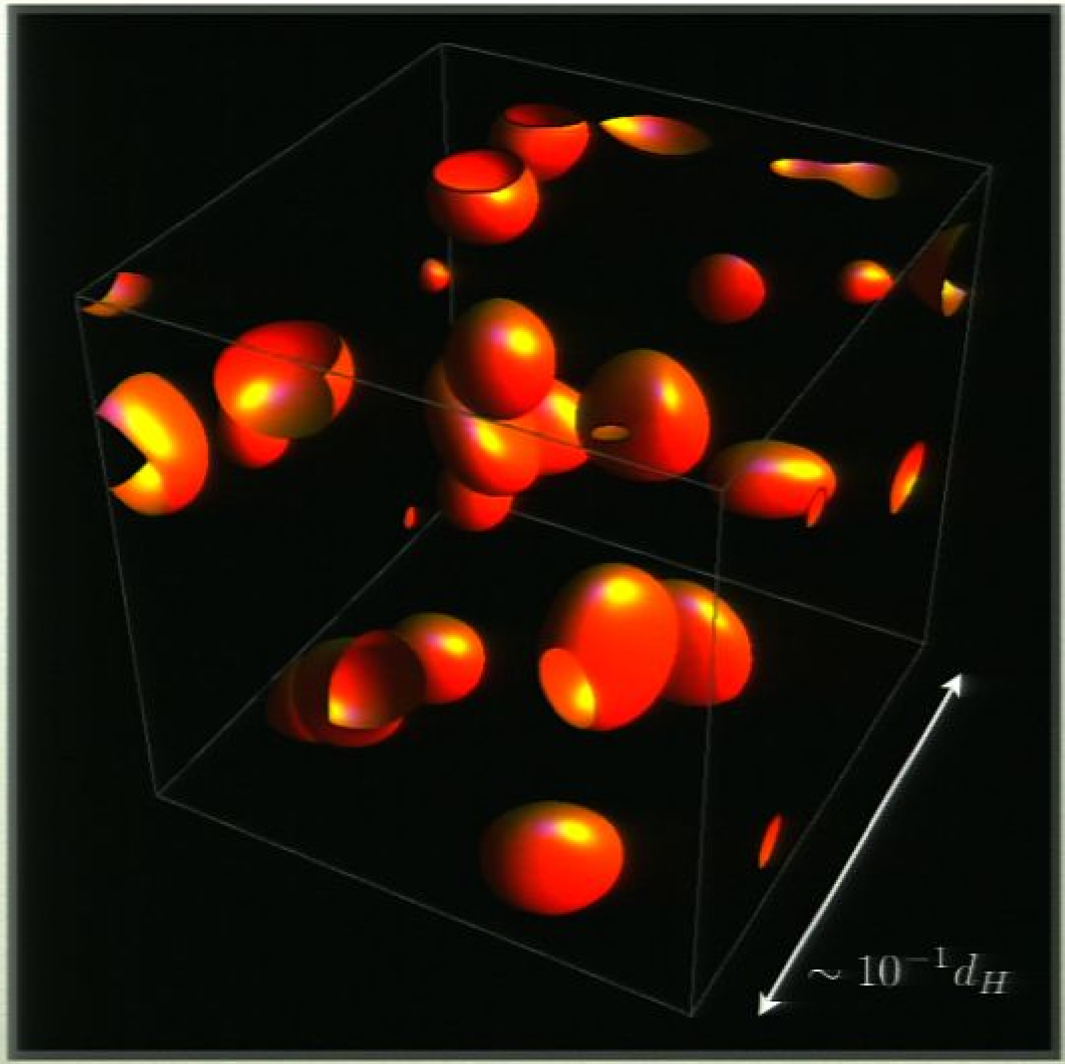

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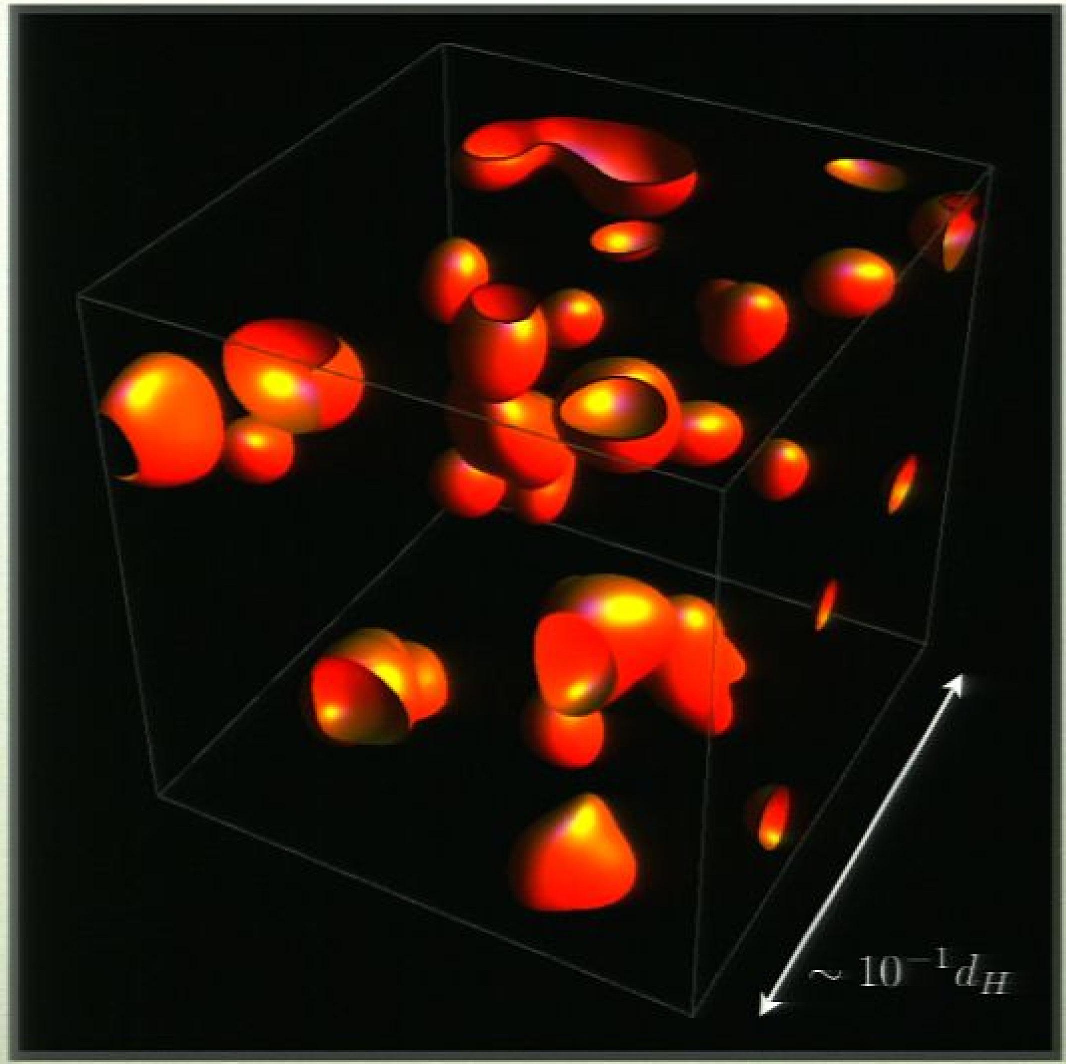

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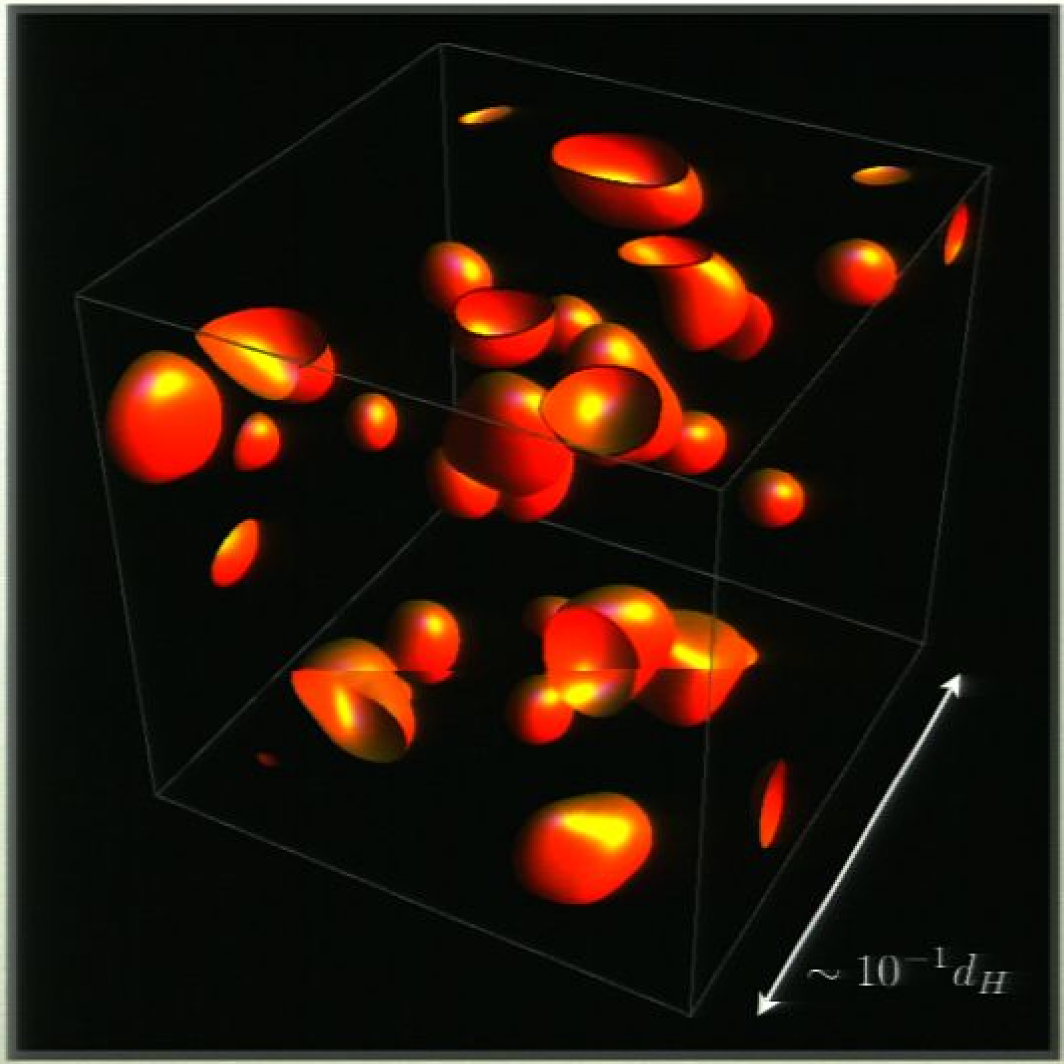
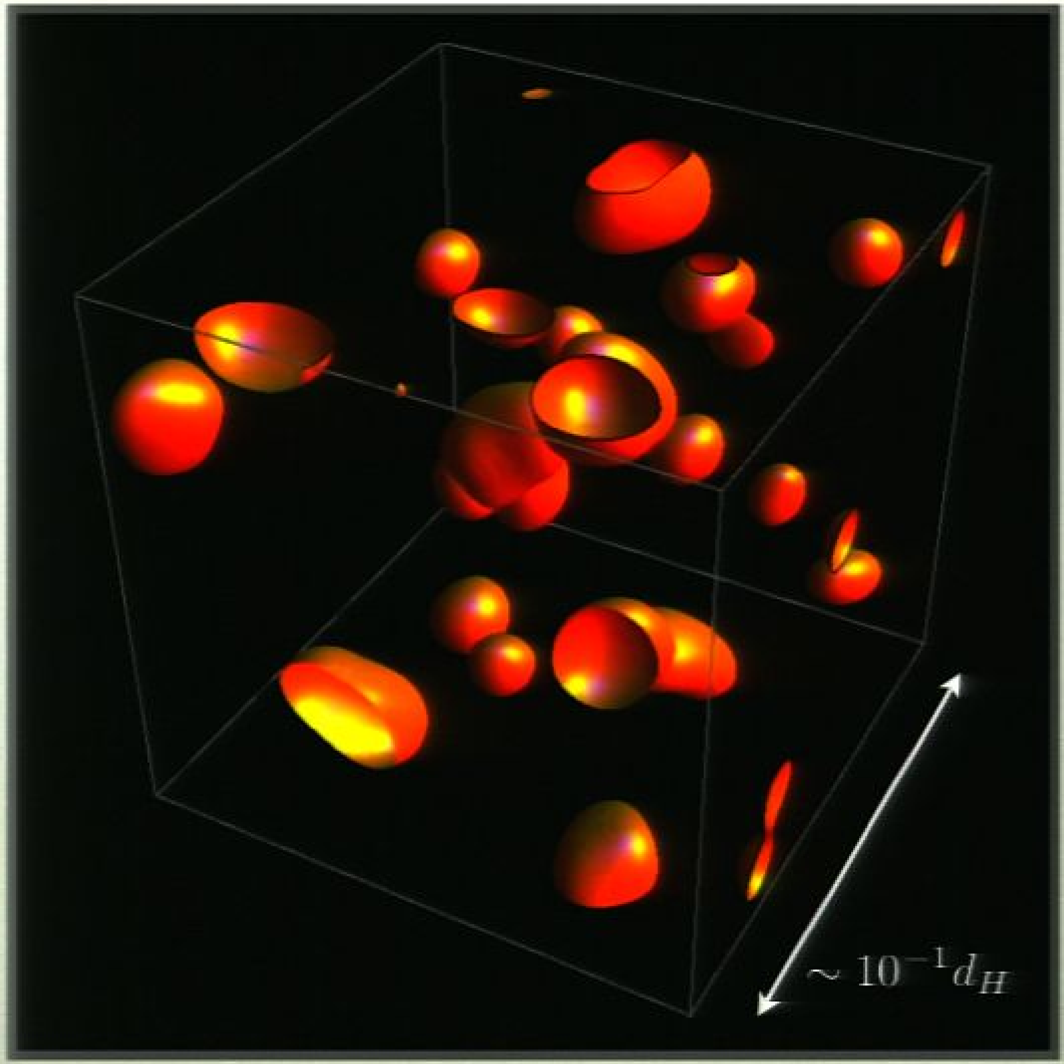


OSCILLONS?



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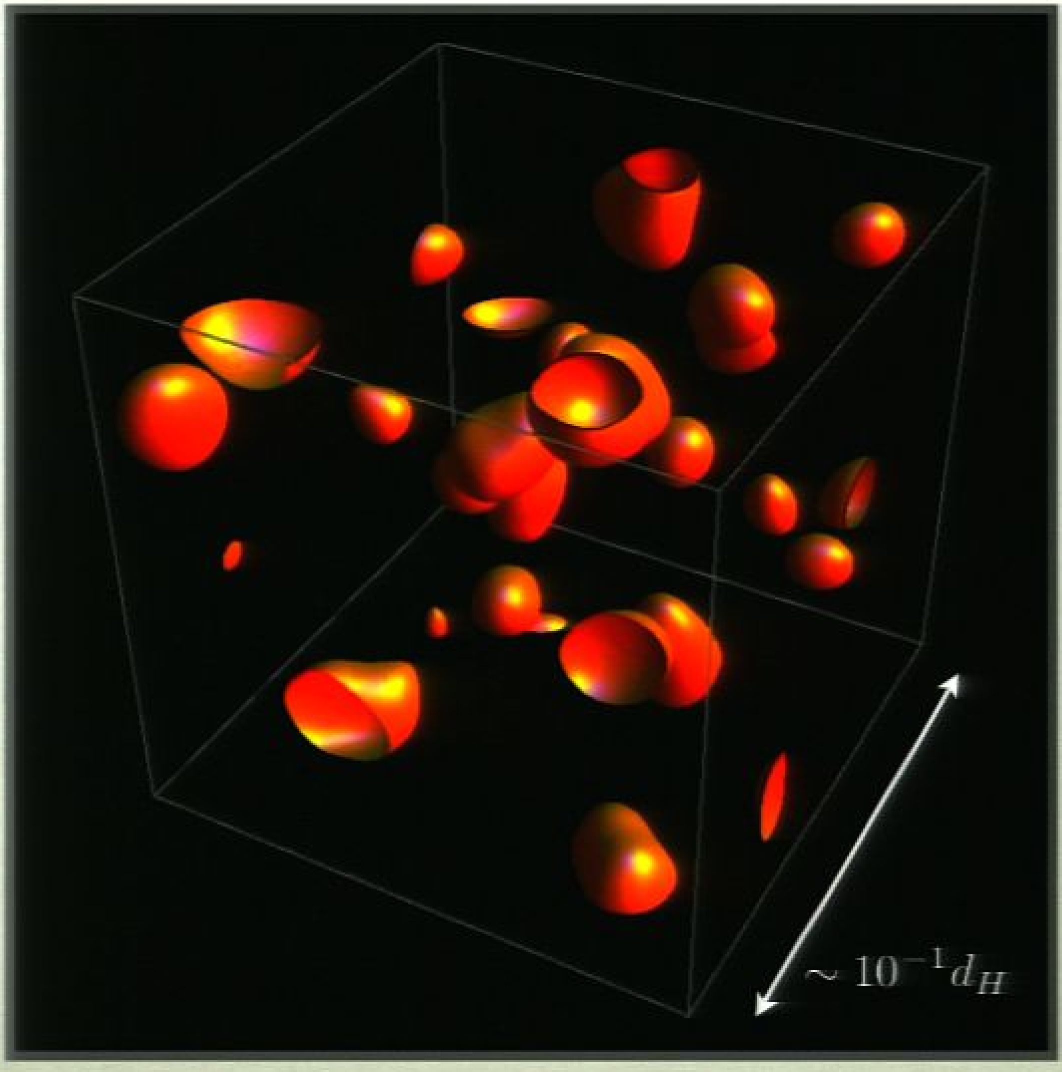

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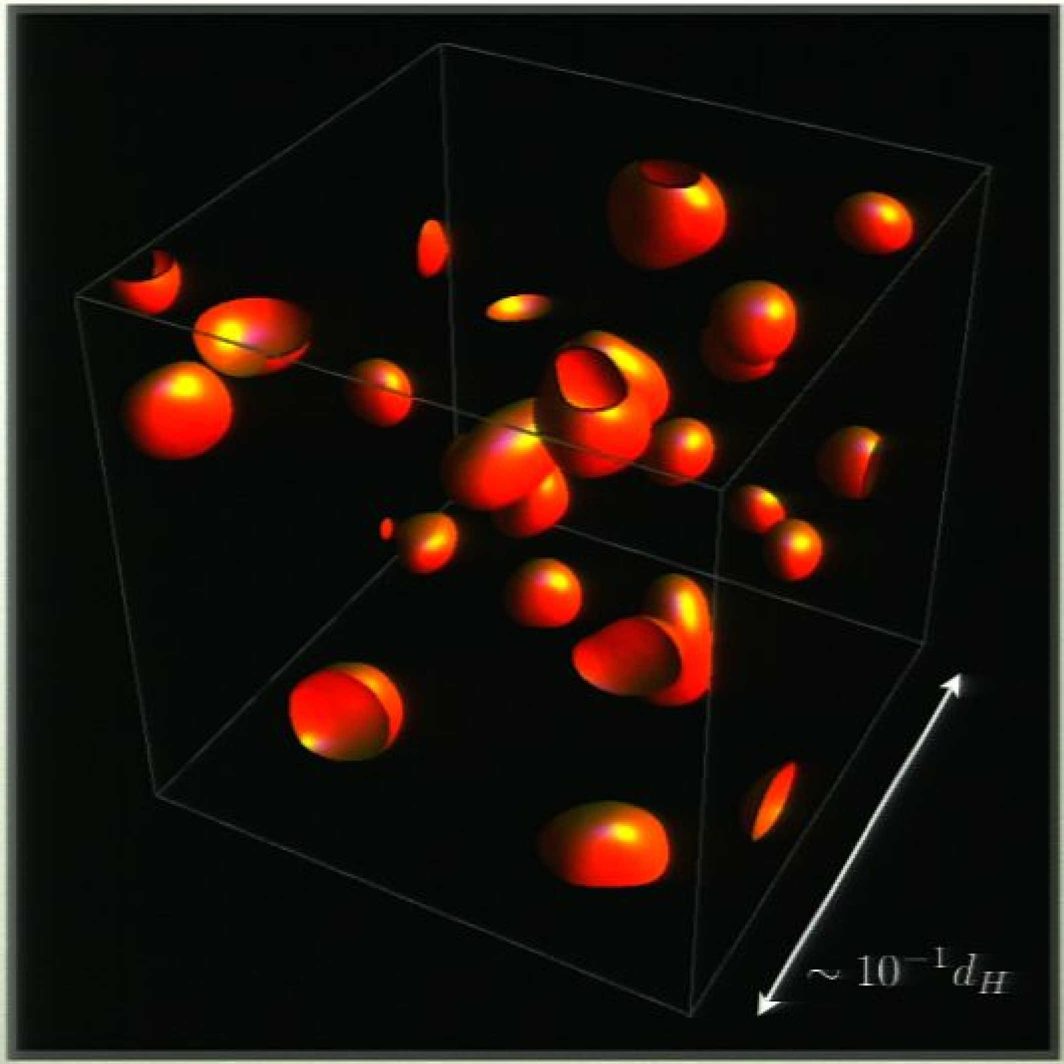

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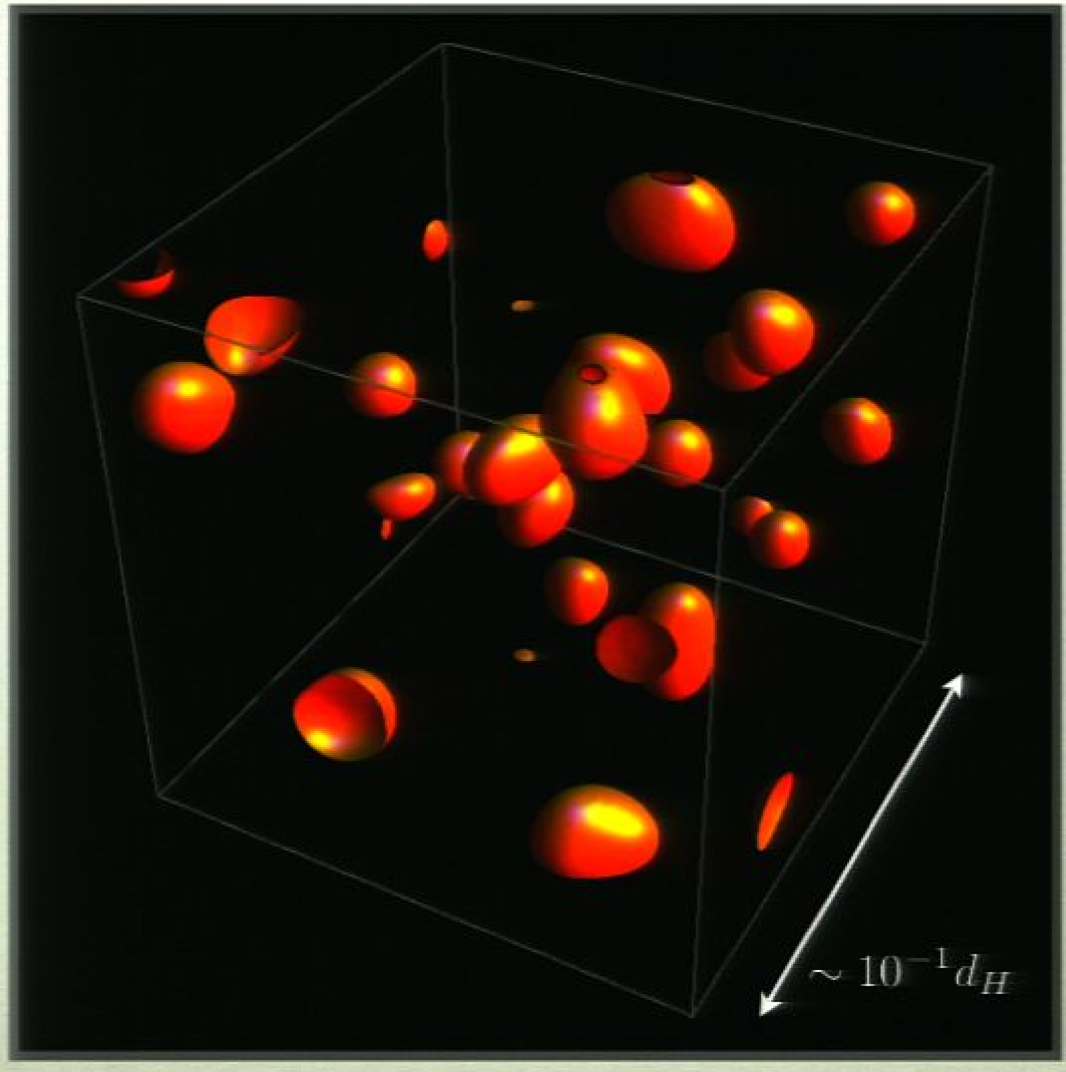

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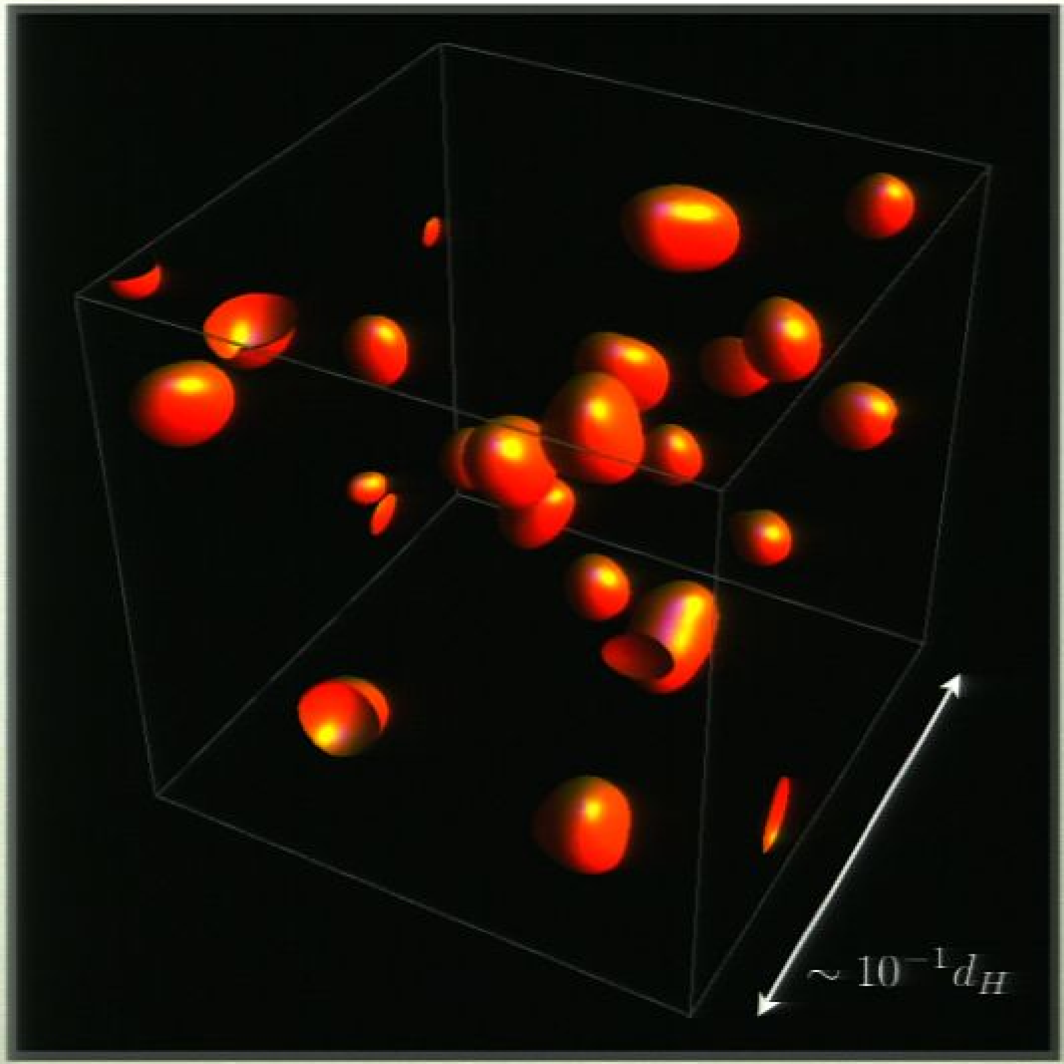

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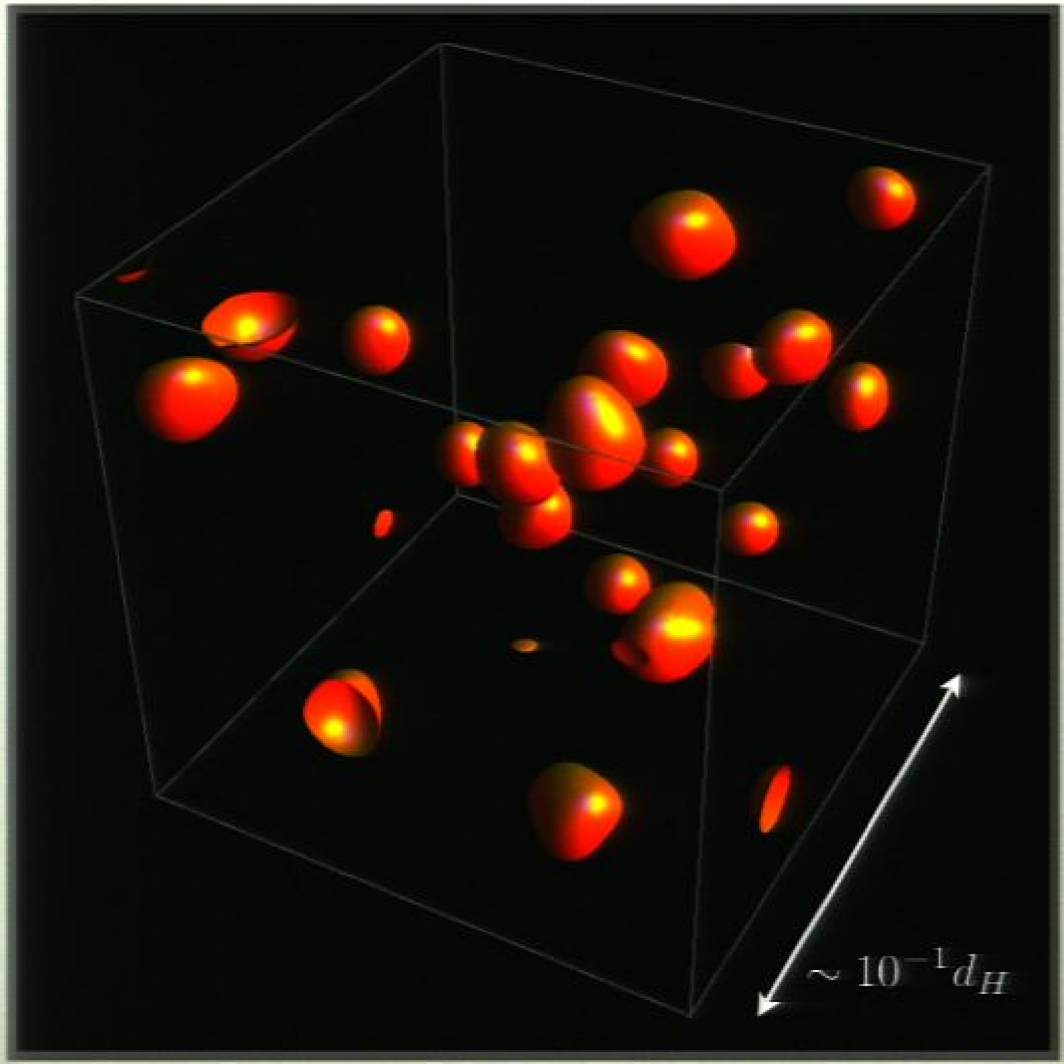

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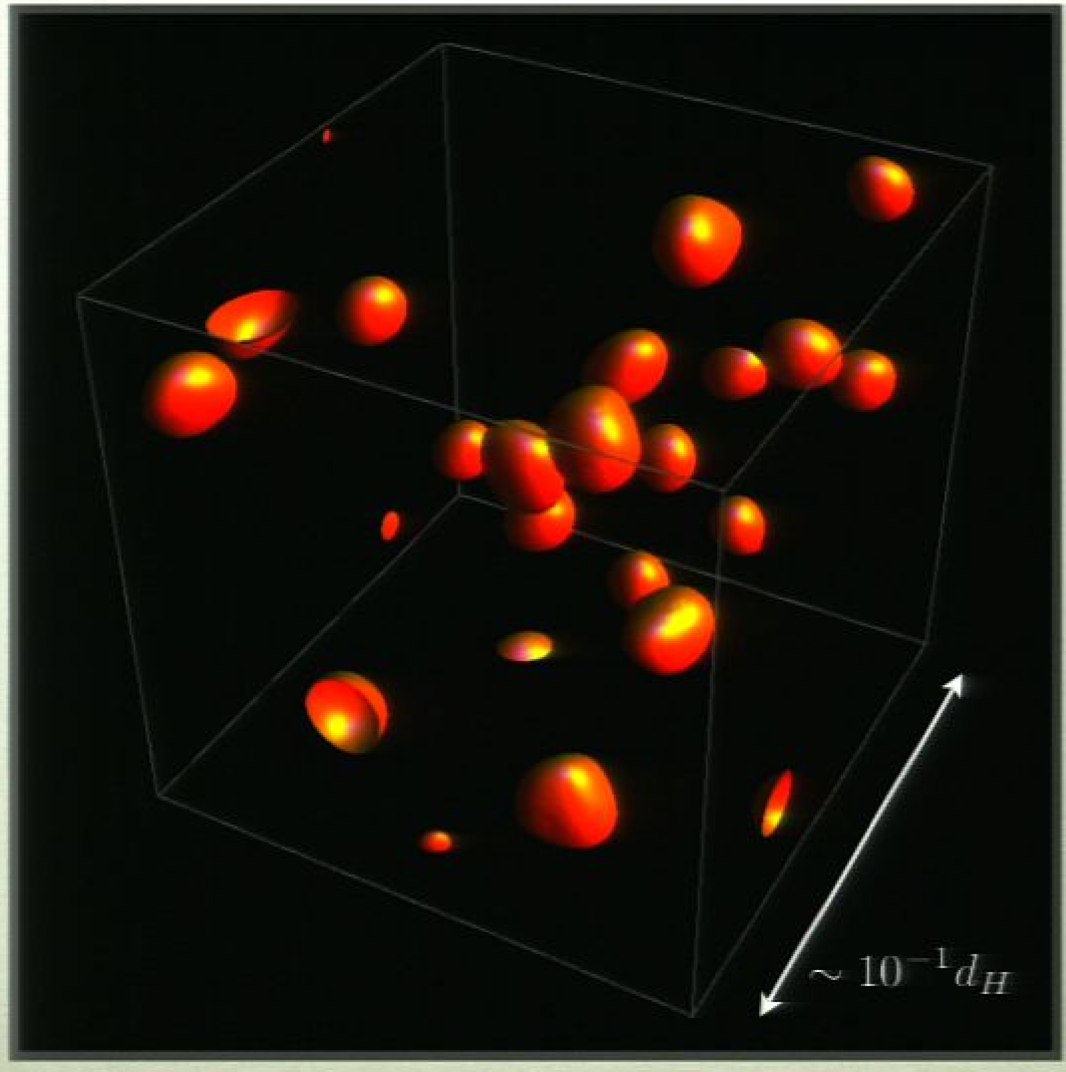

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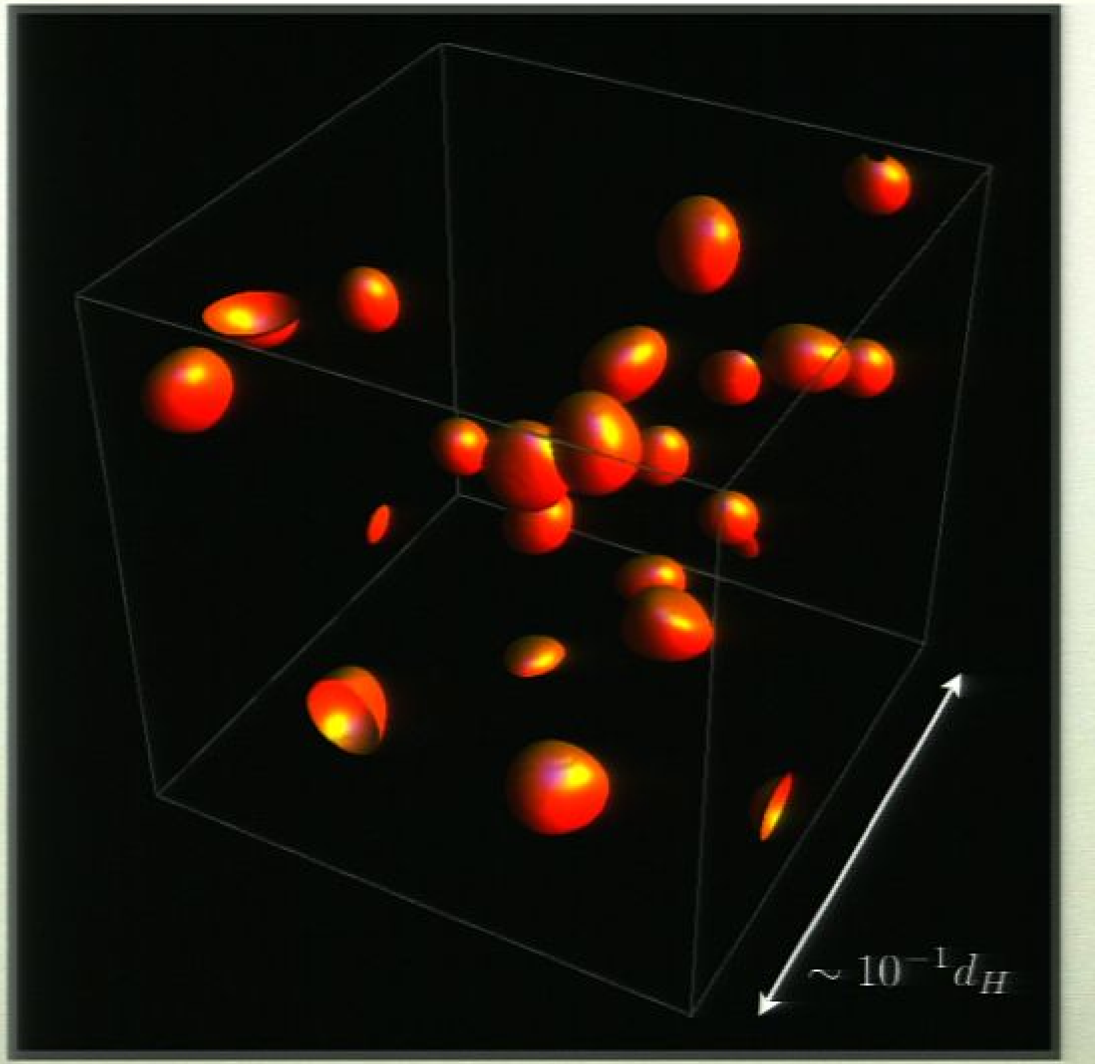

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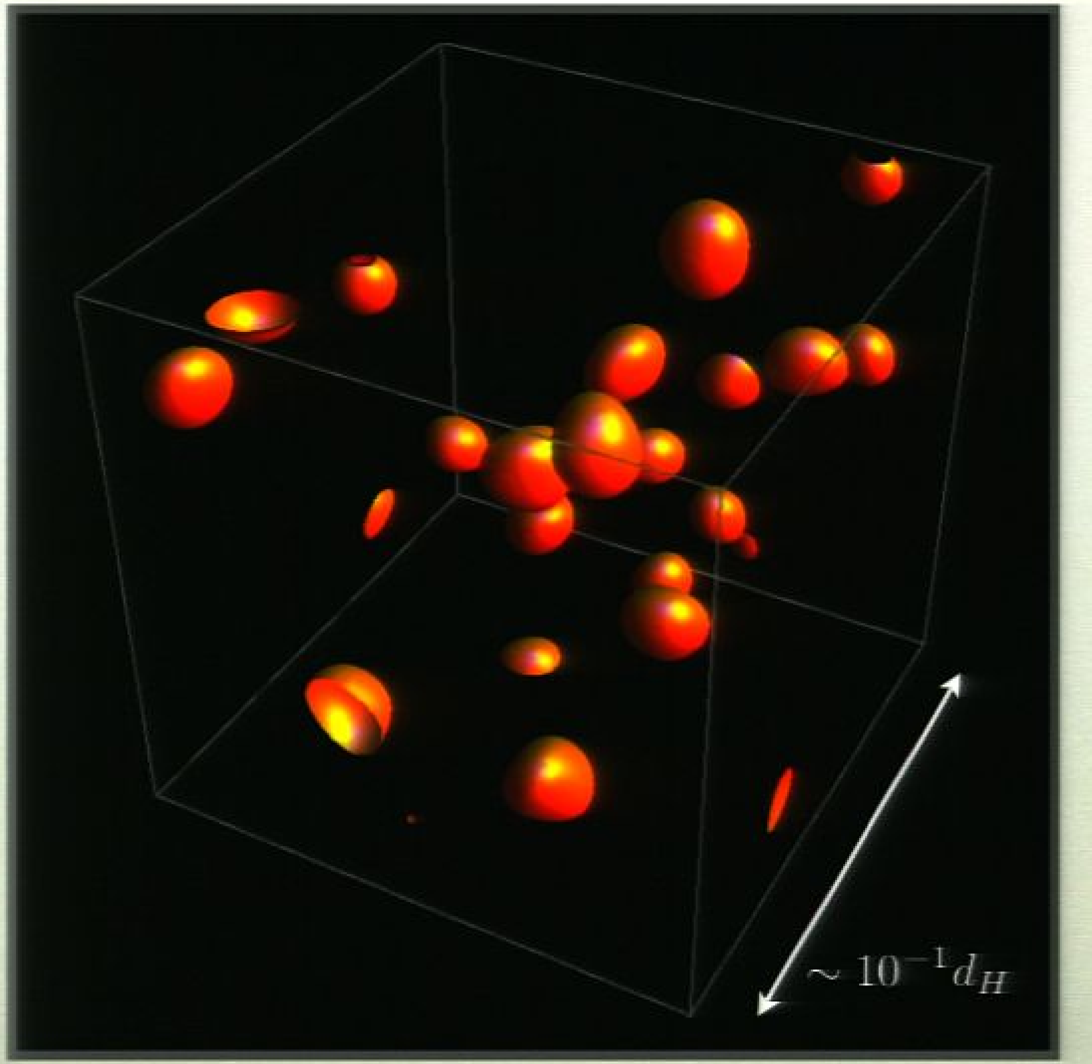

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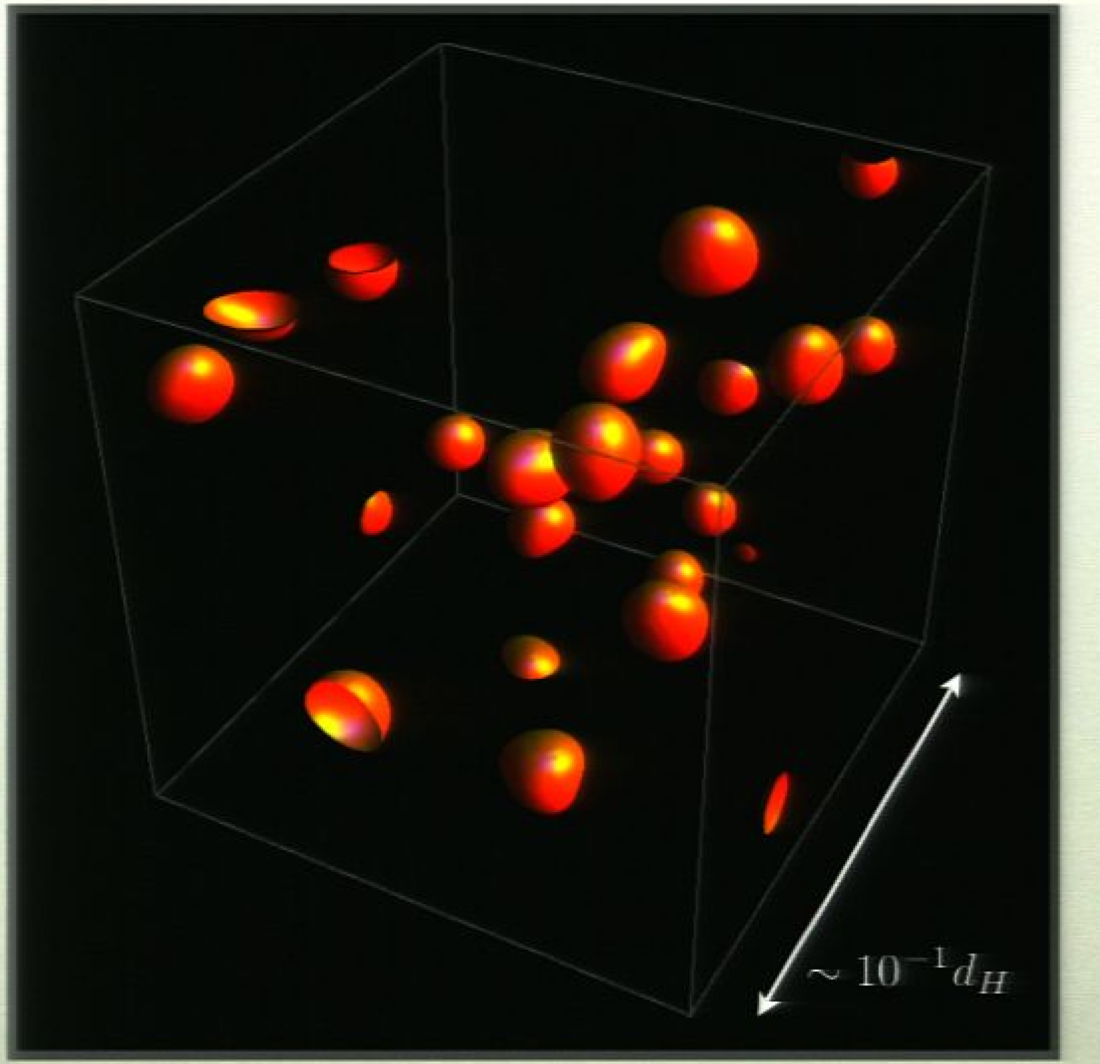

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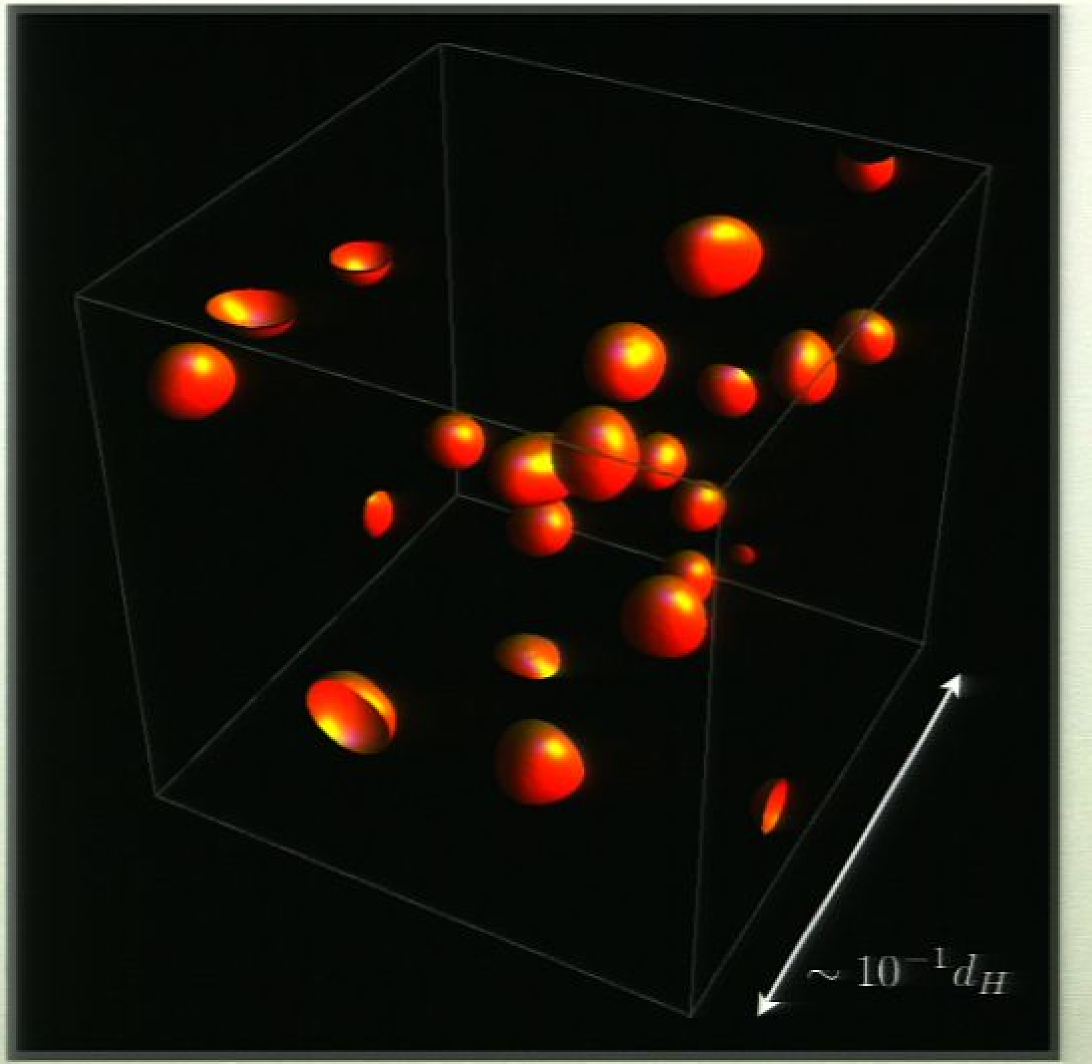

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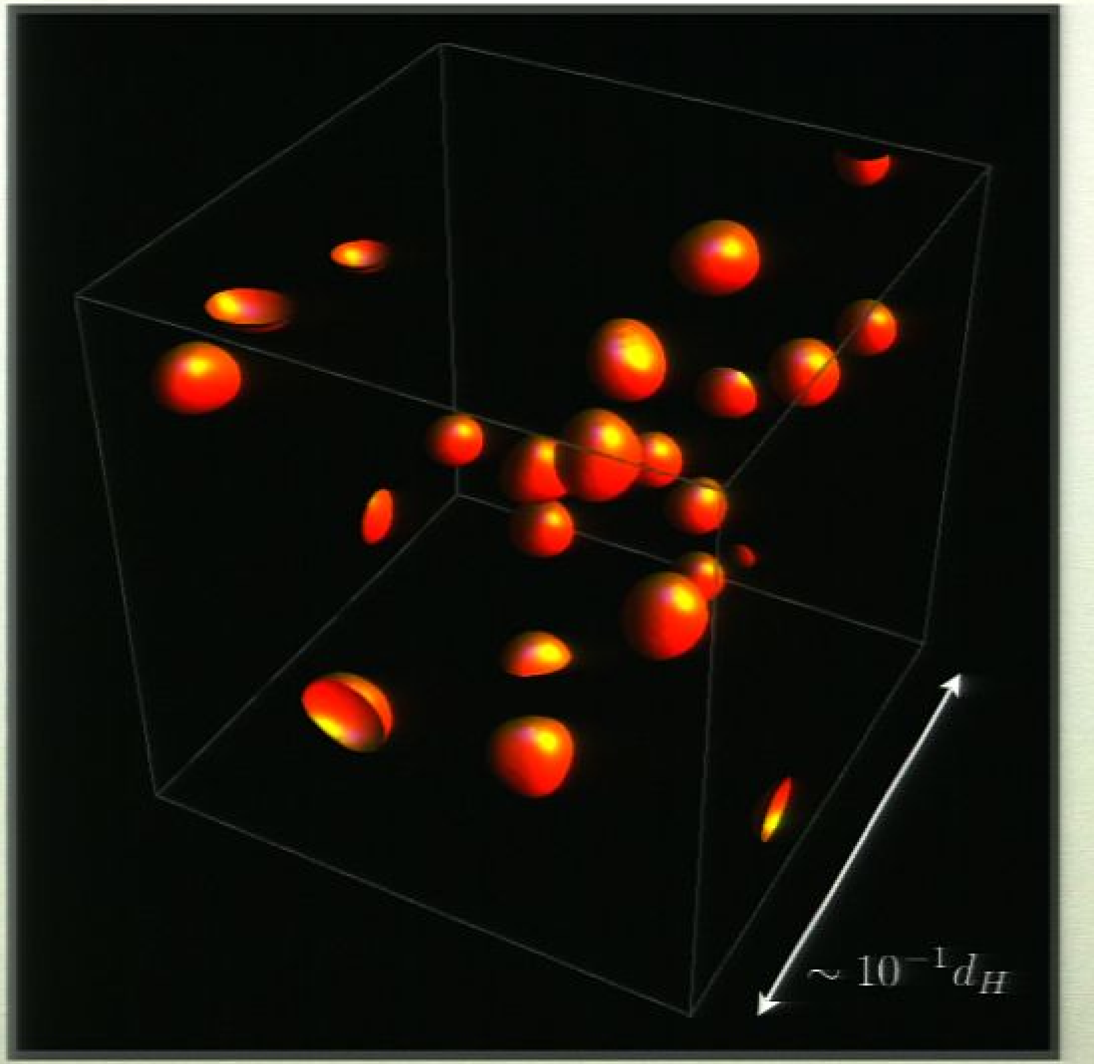

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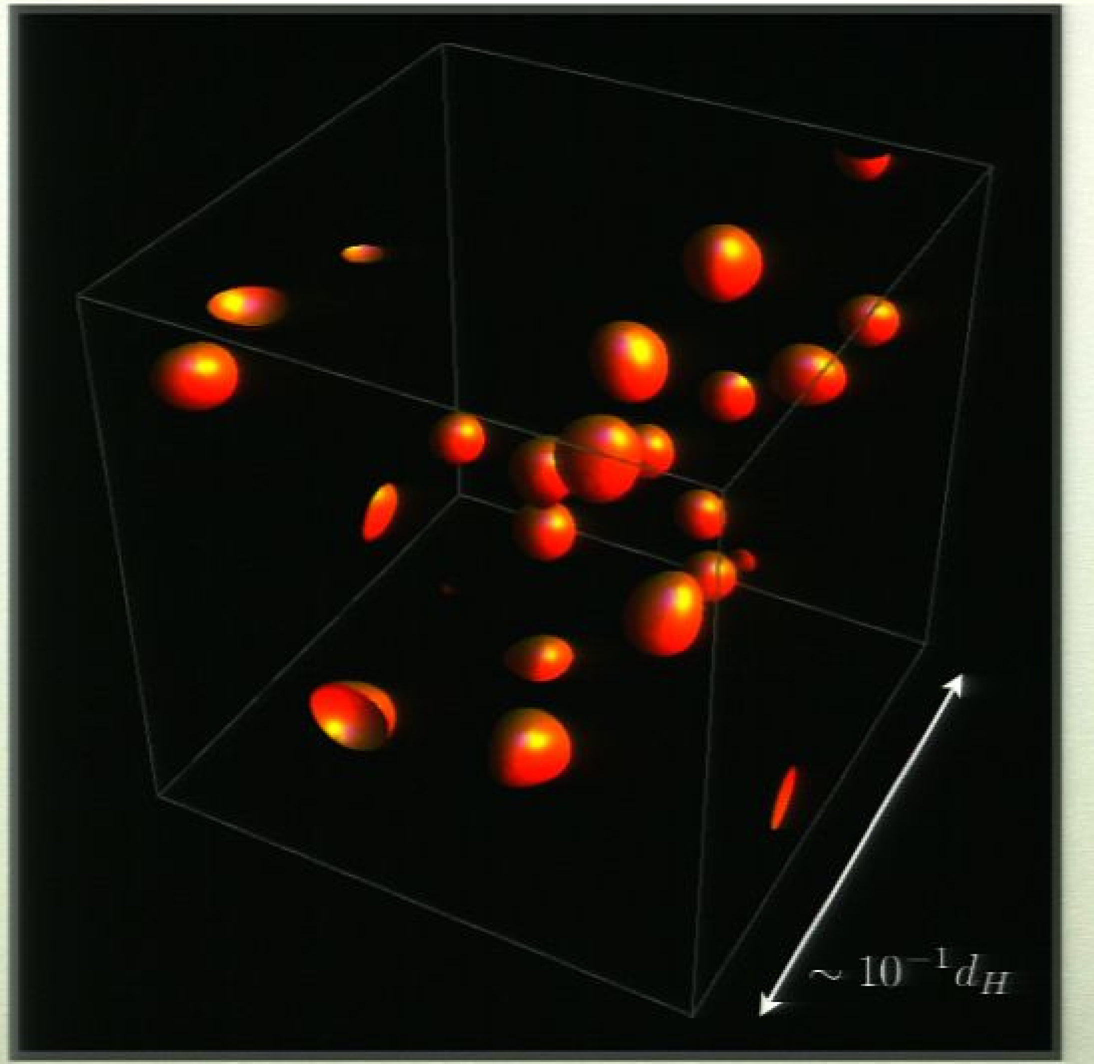

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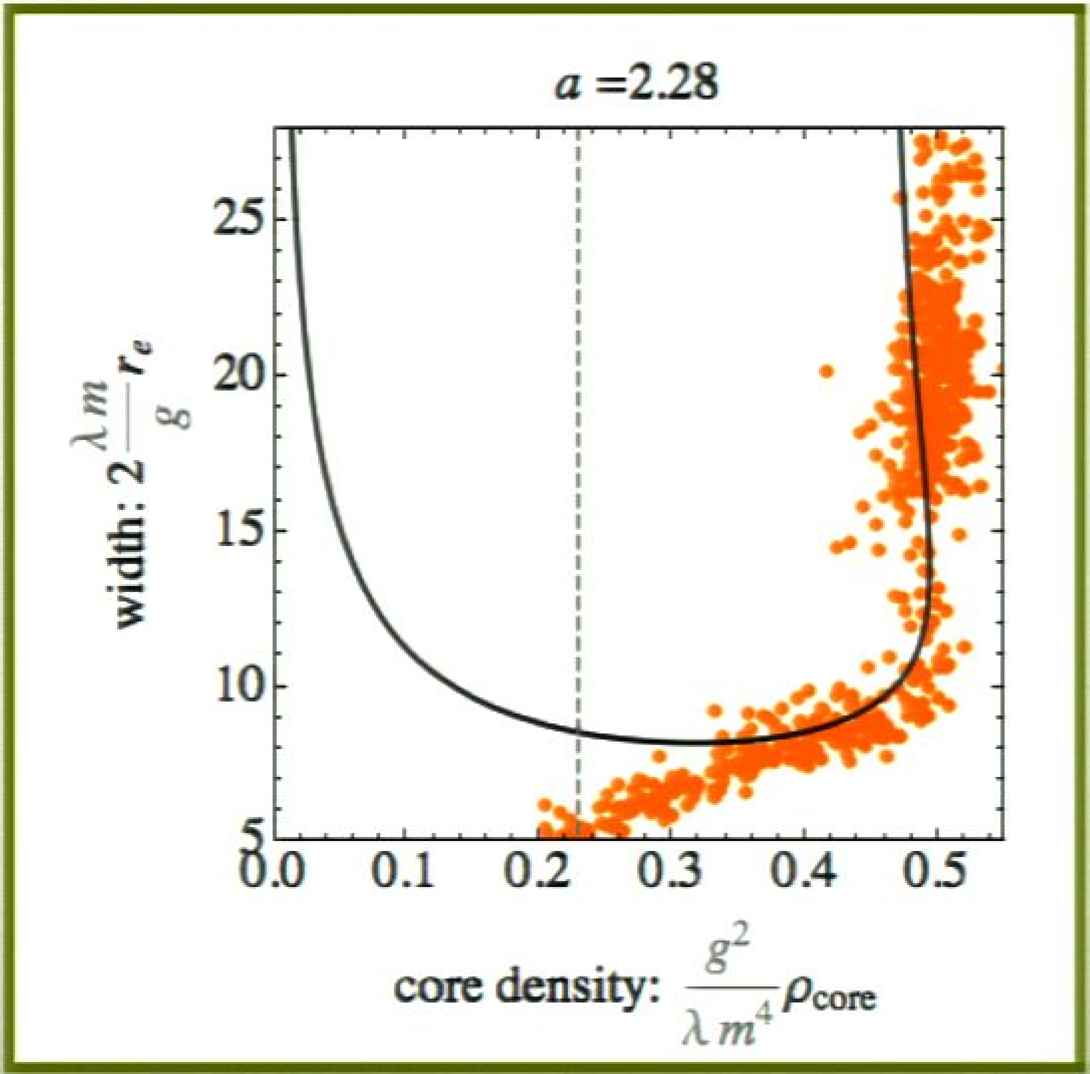

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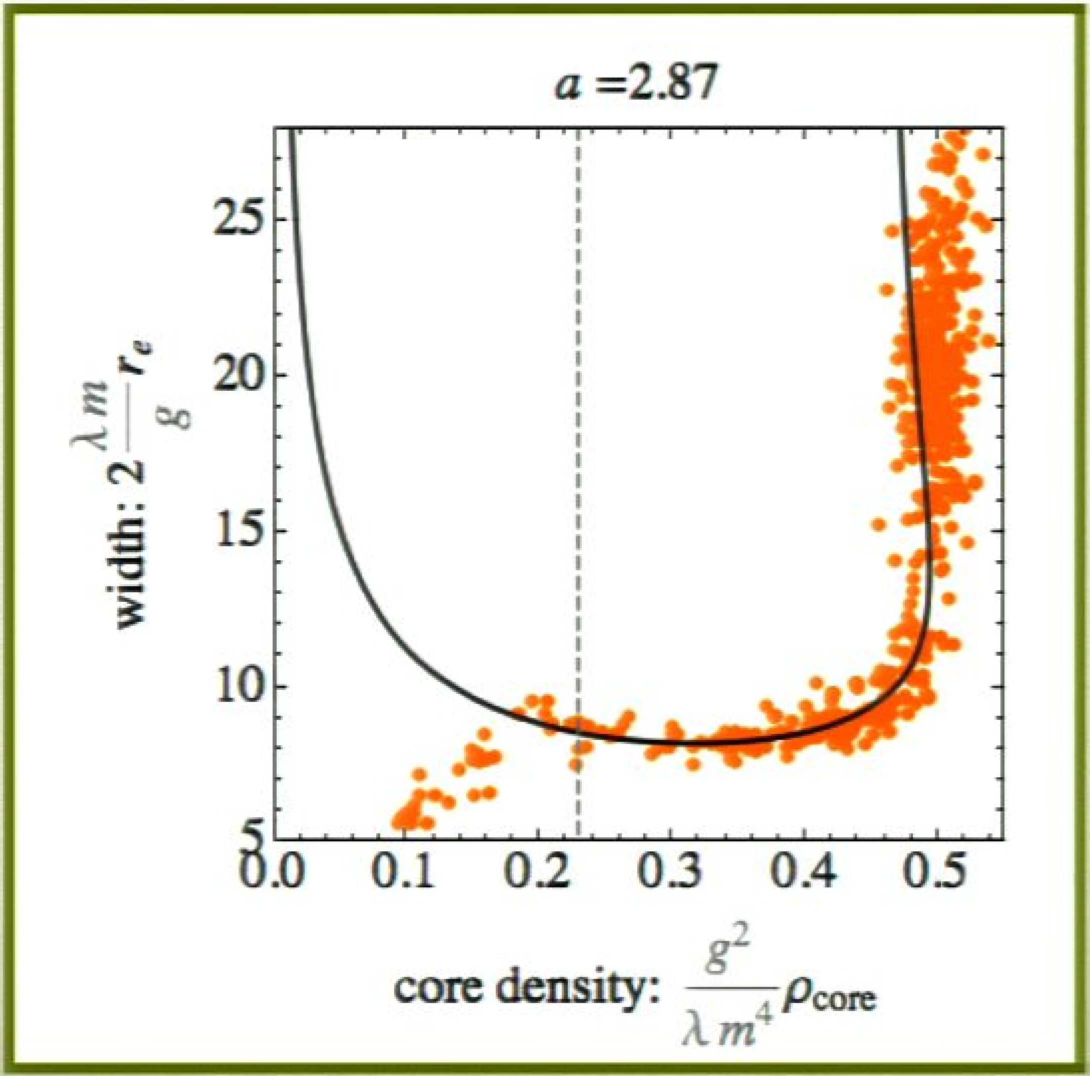

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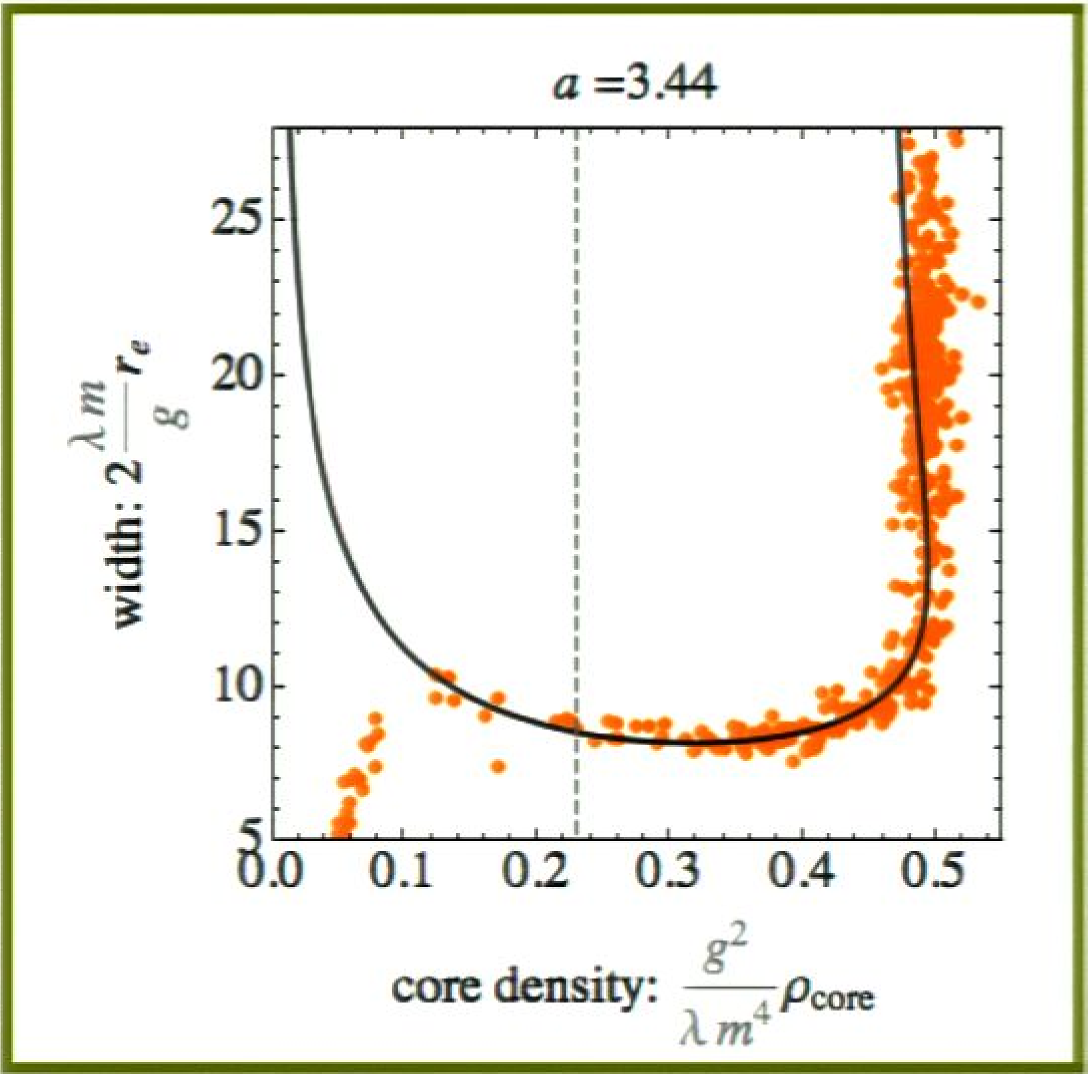

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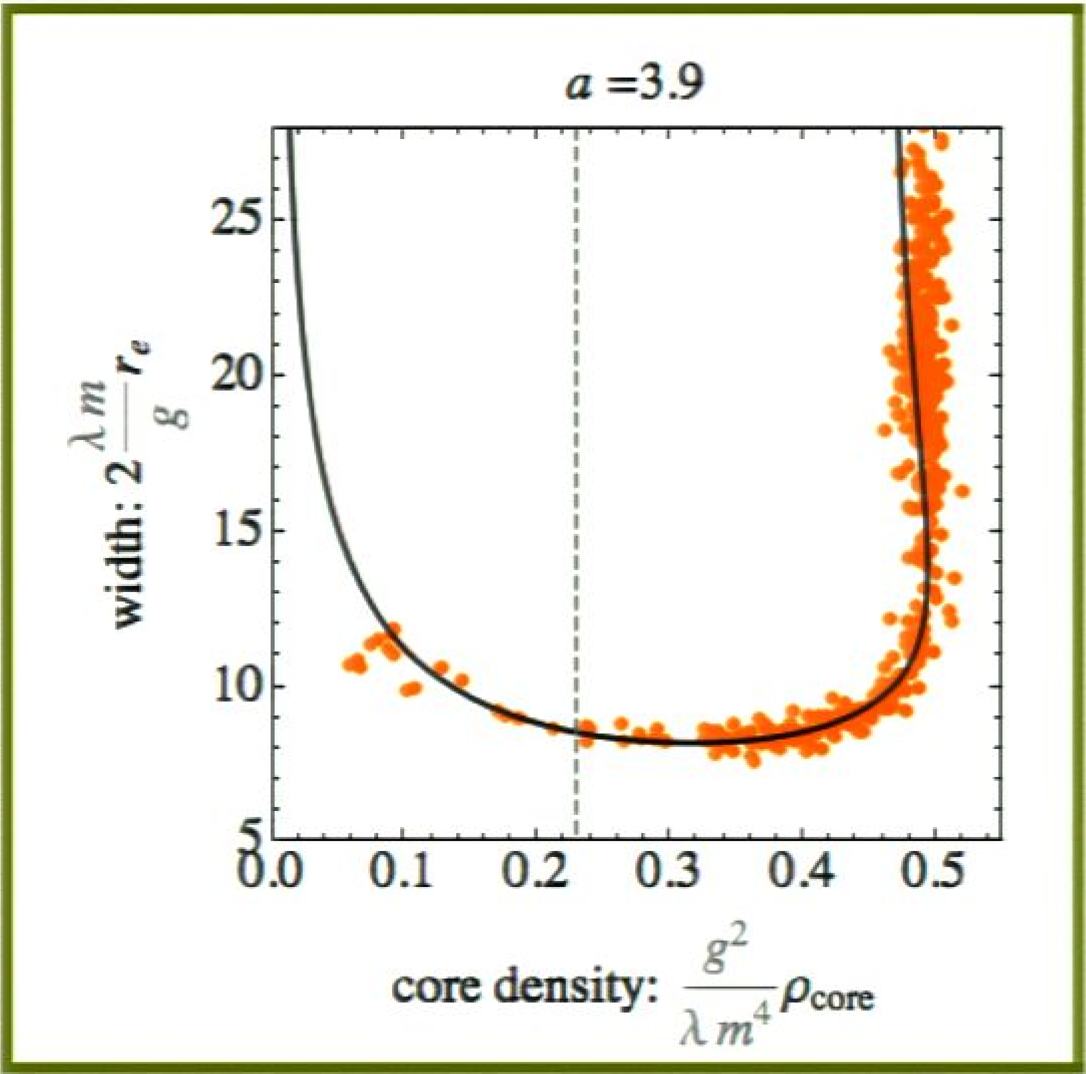

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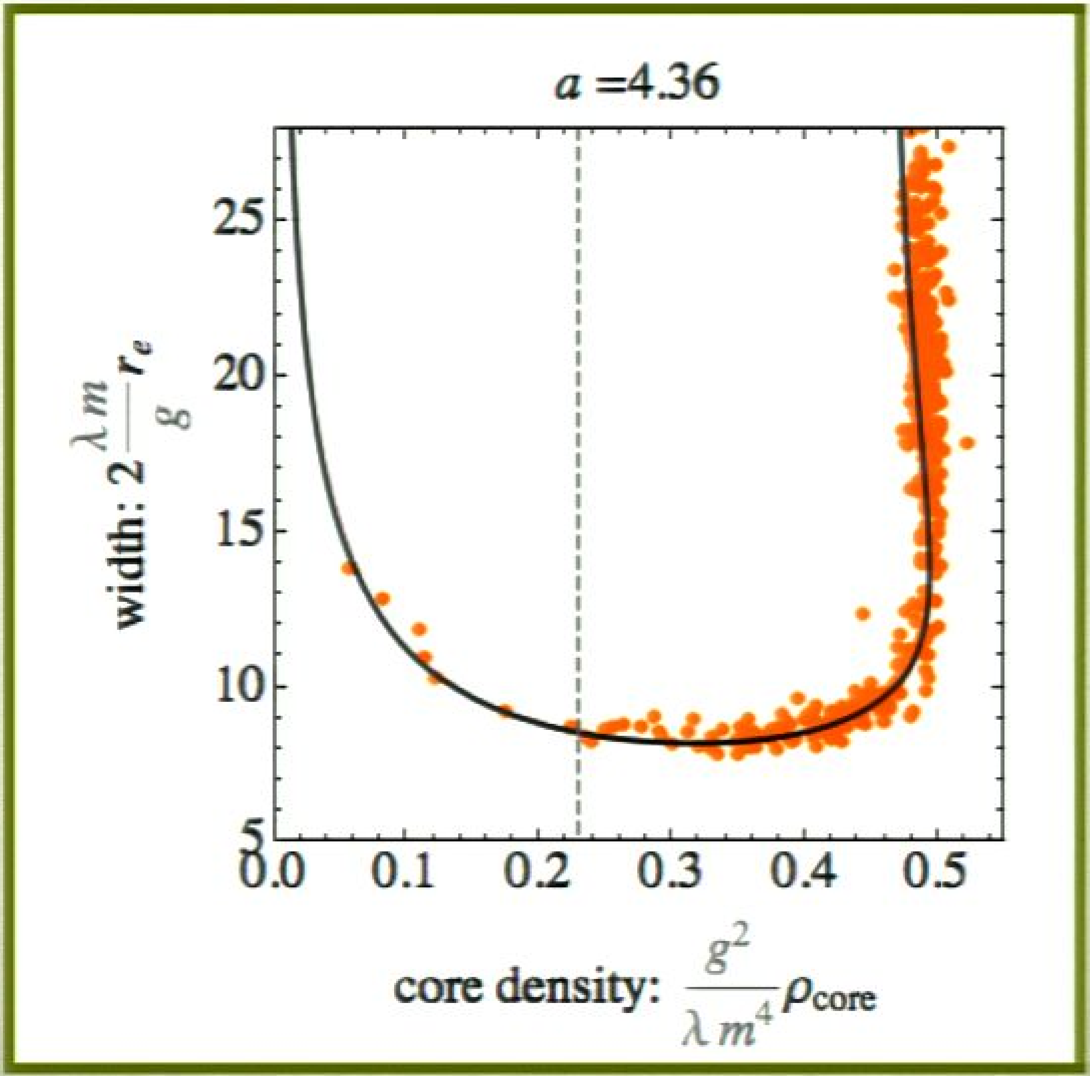

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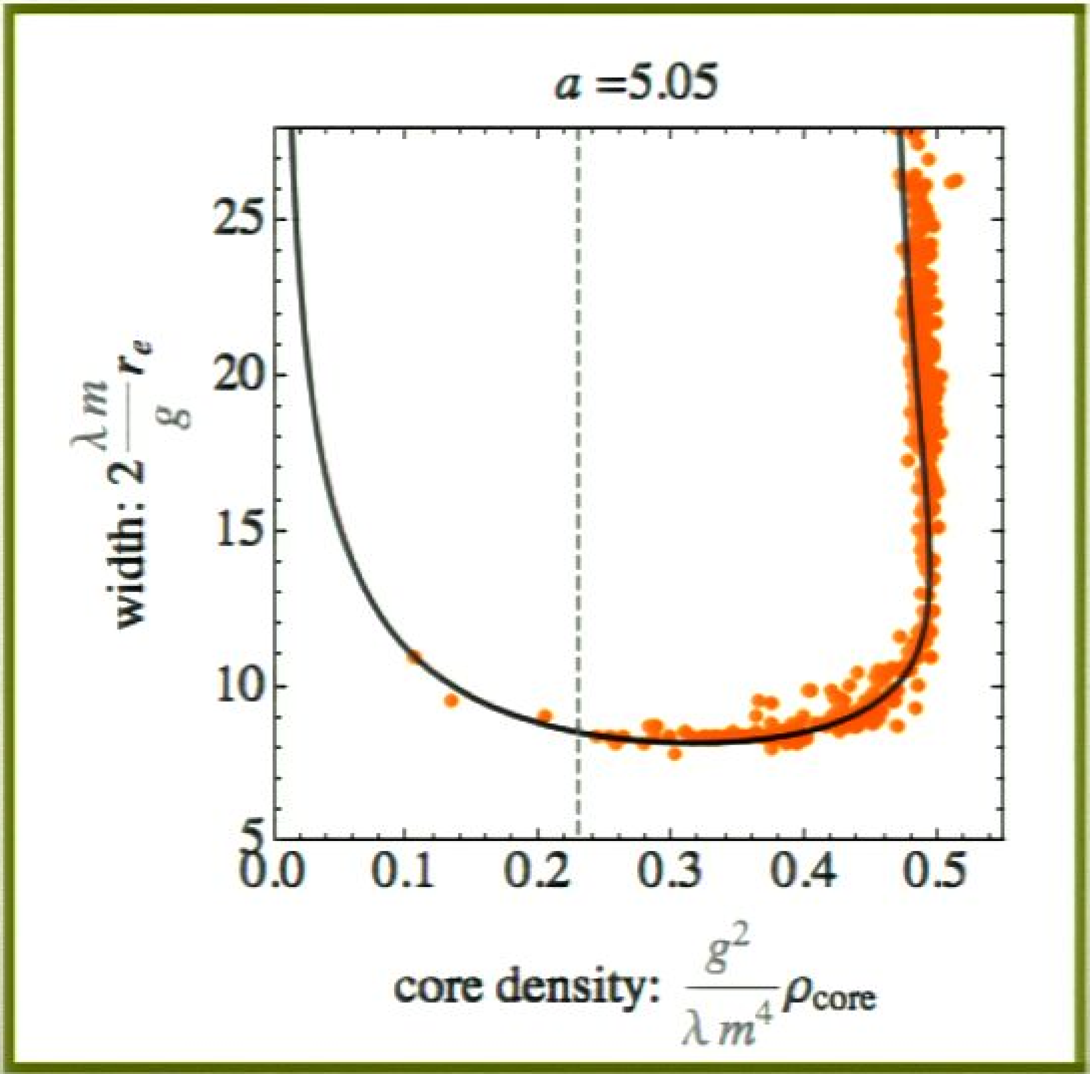

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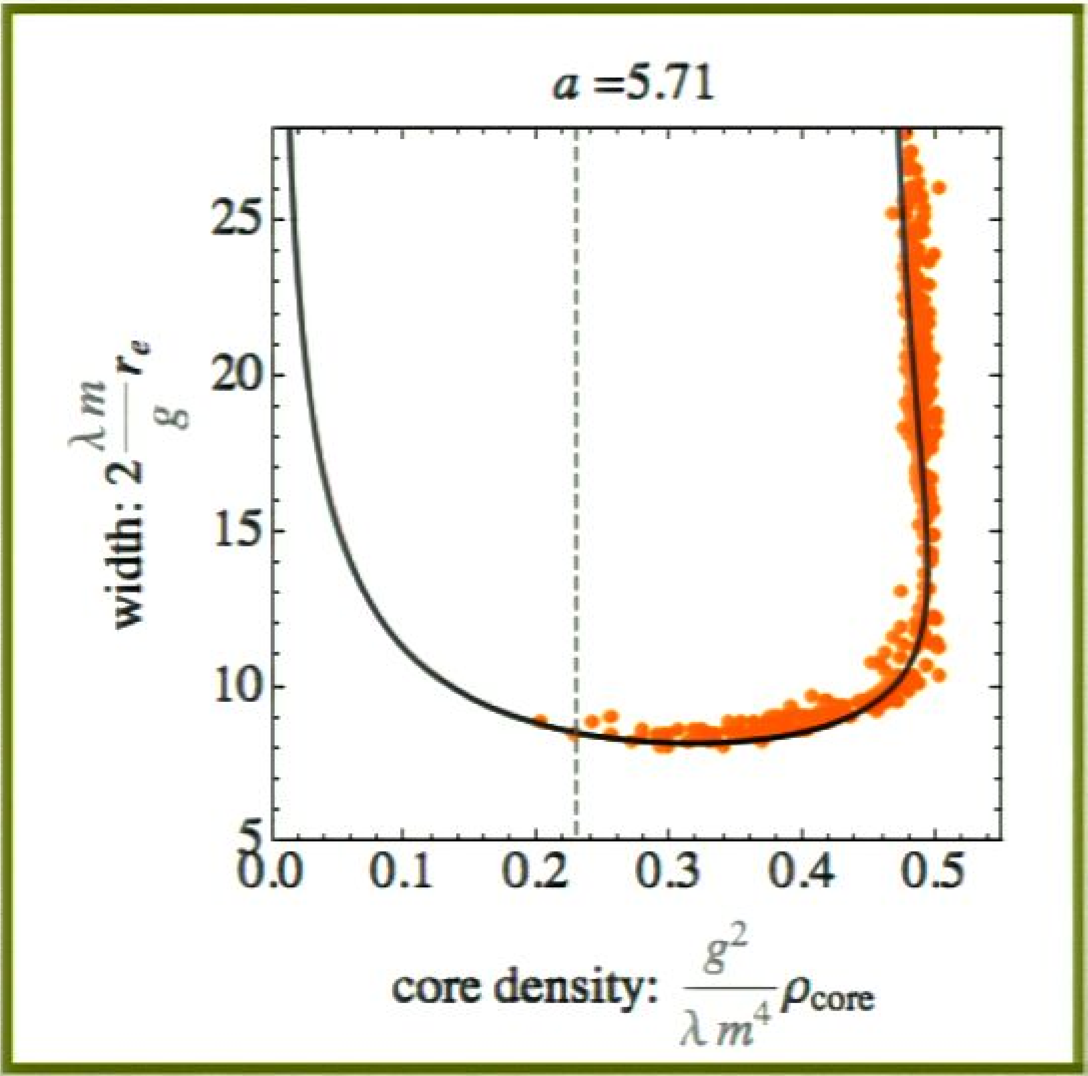

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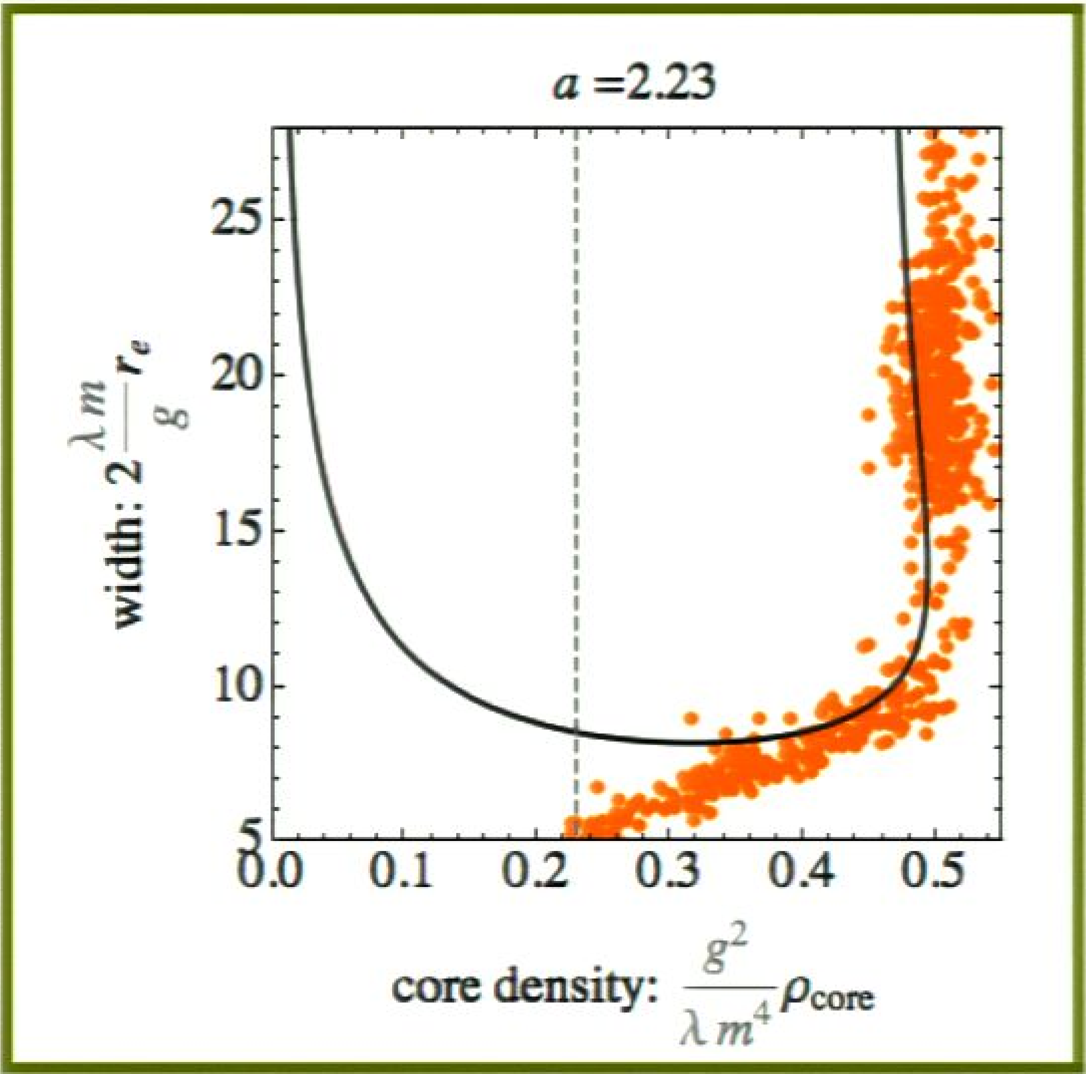

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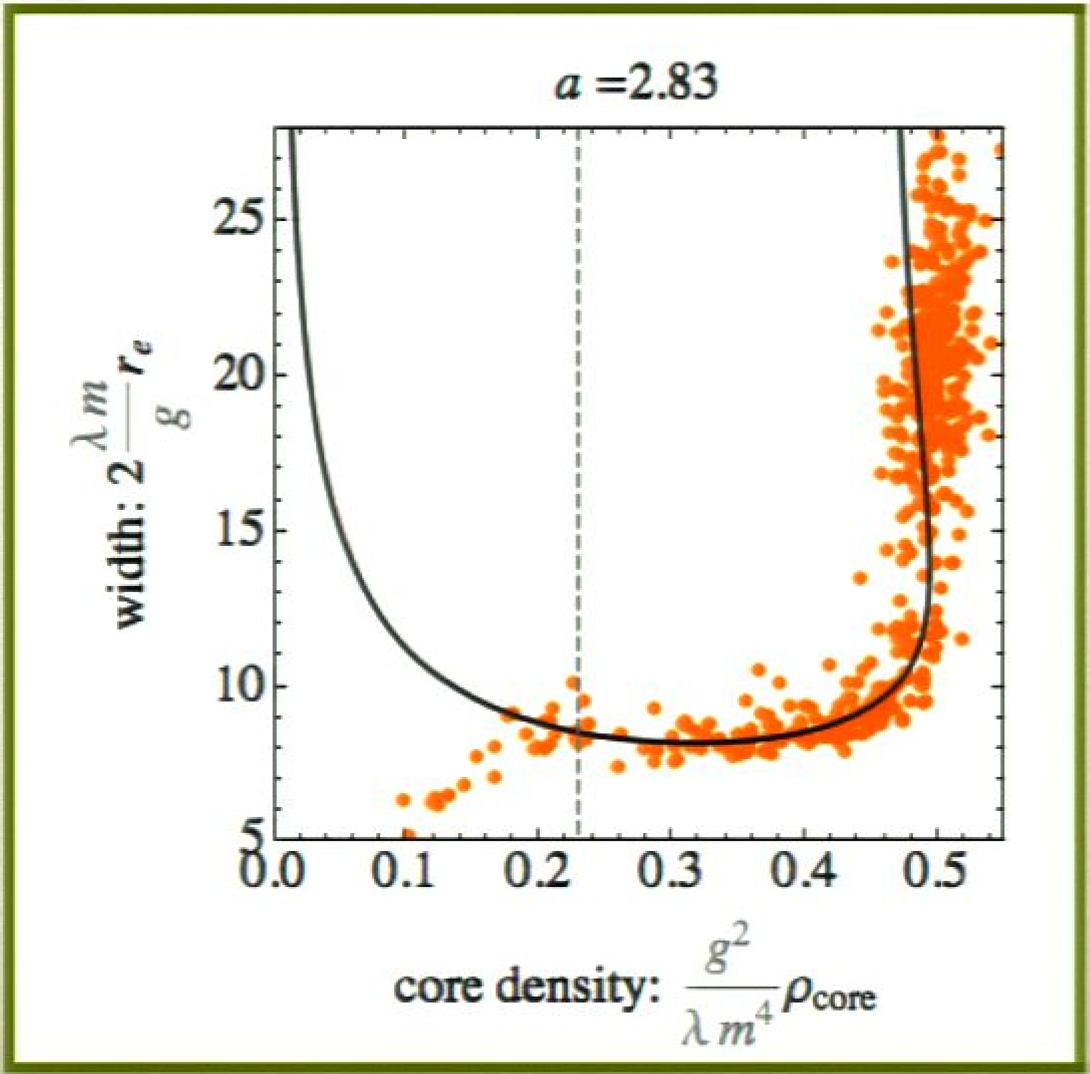

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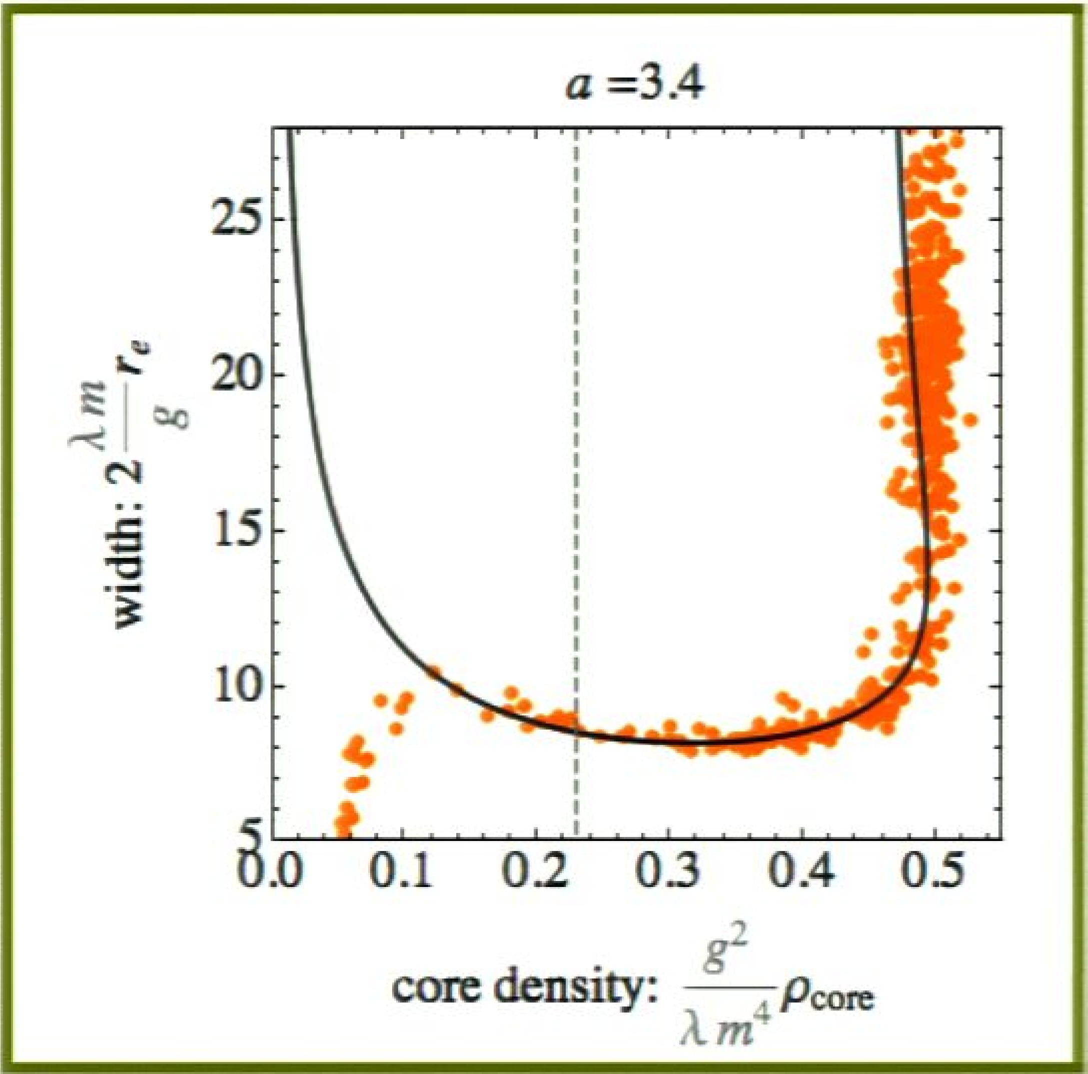

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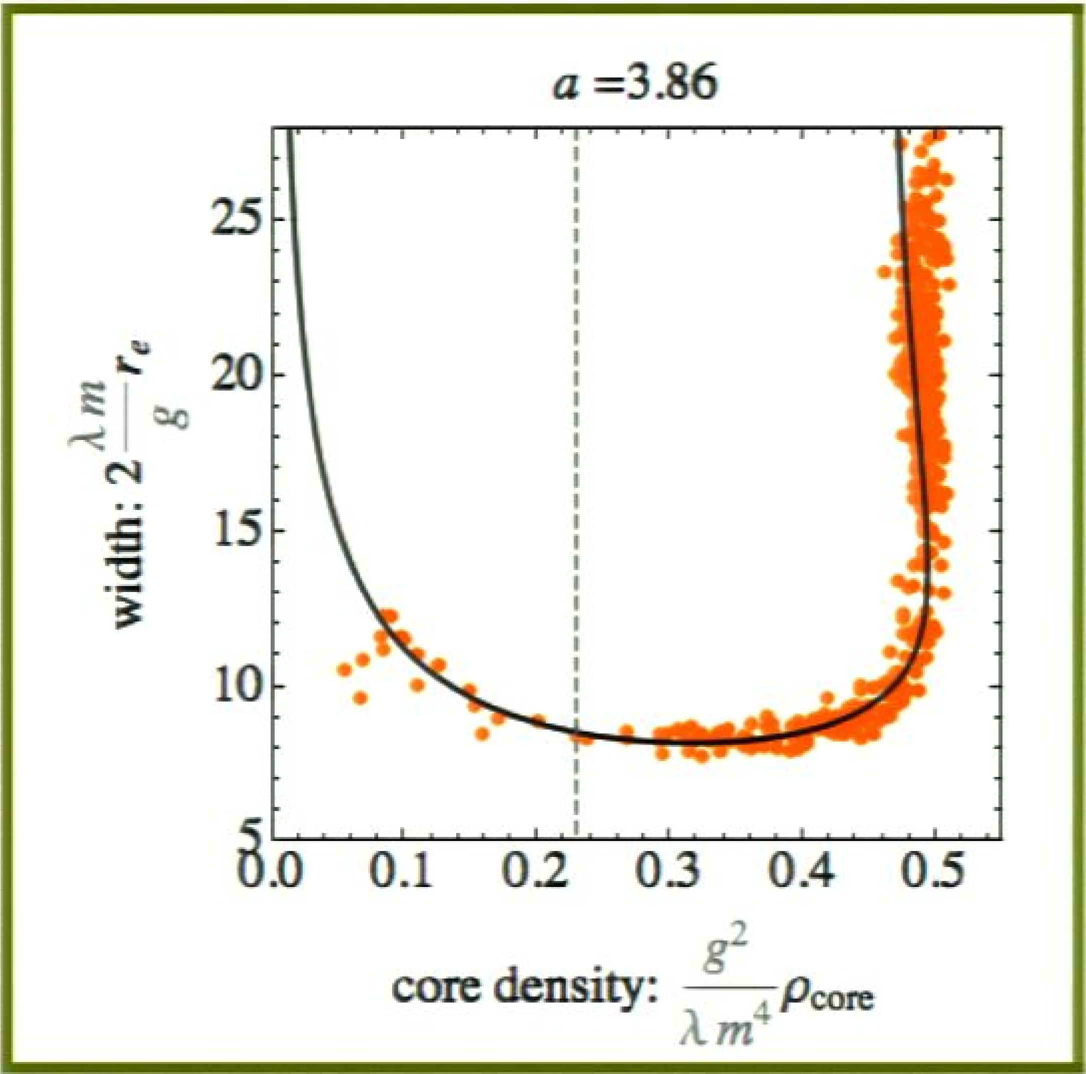

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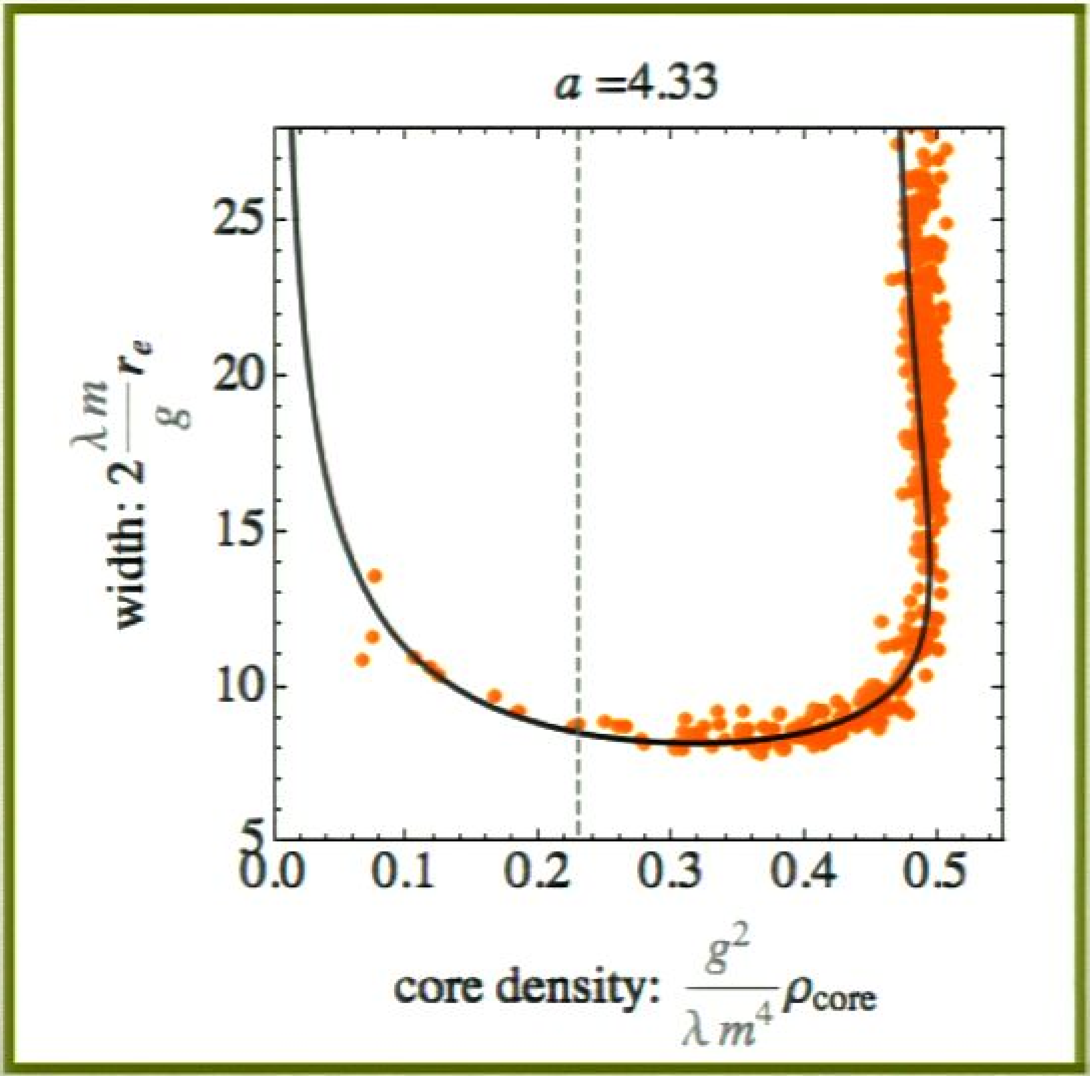

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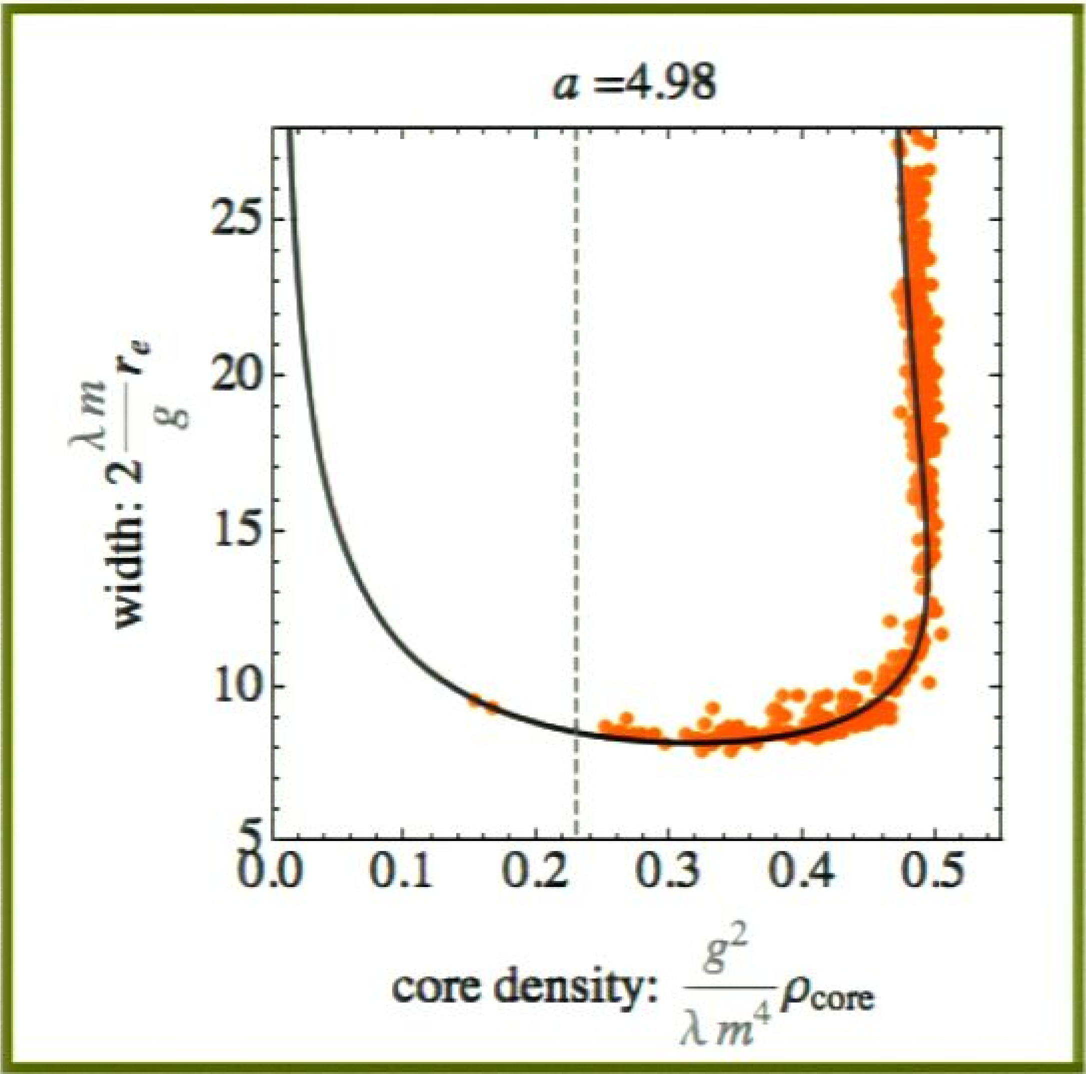

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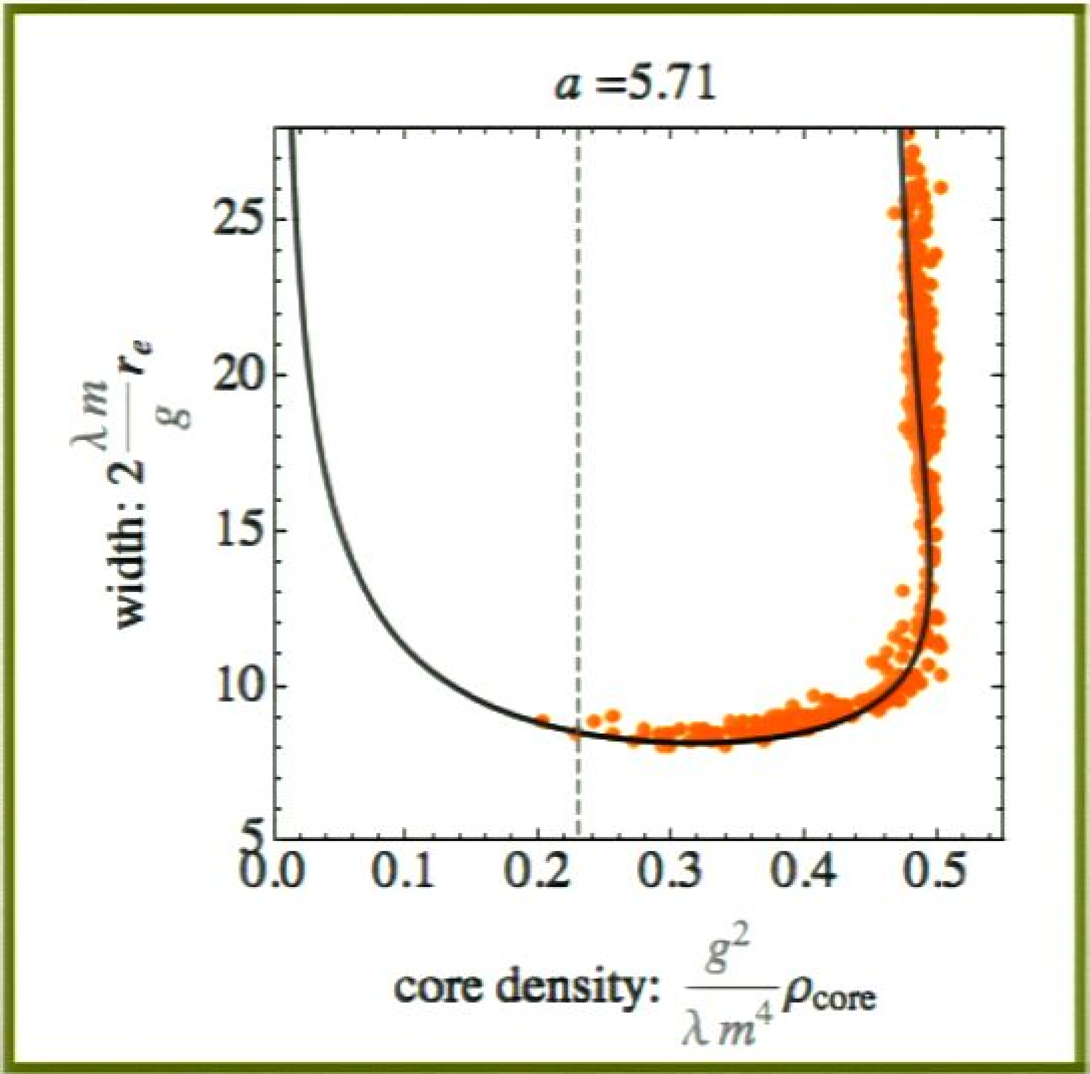
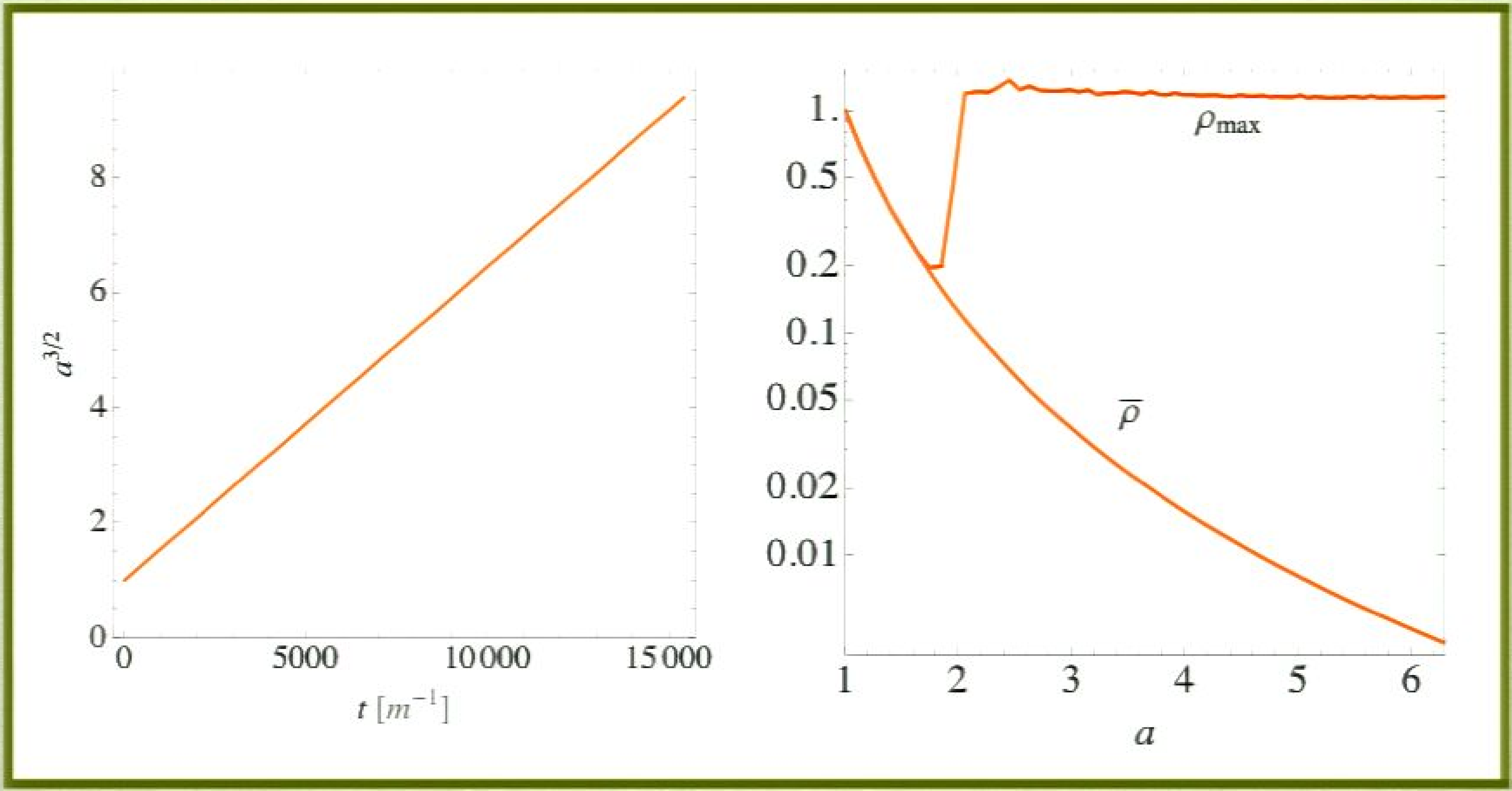
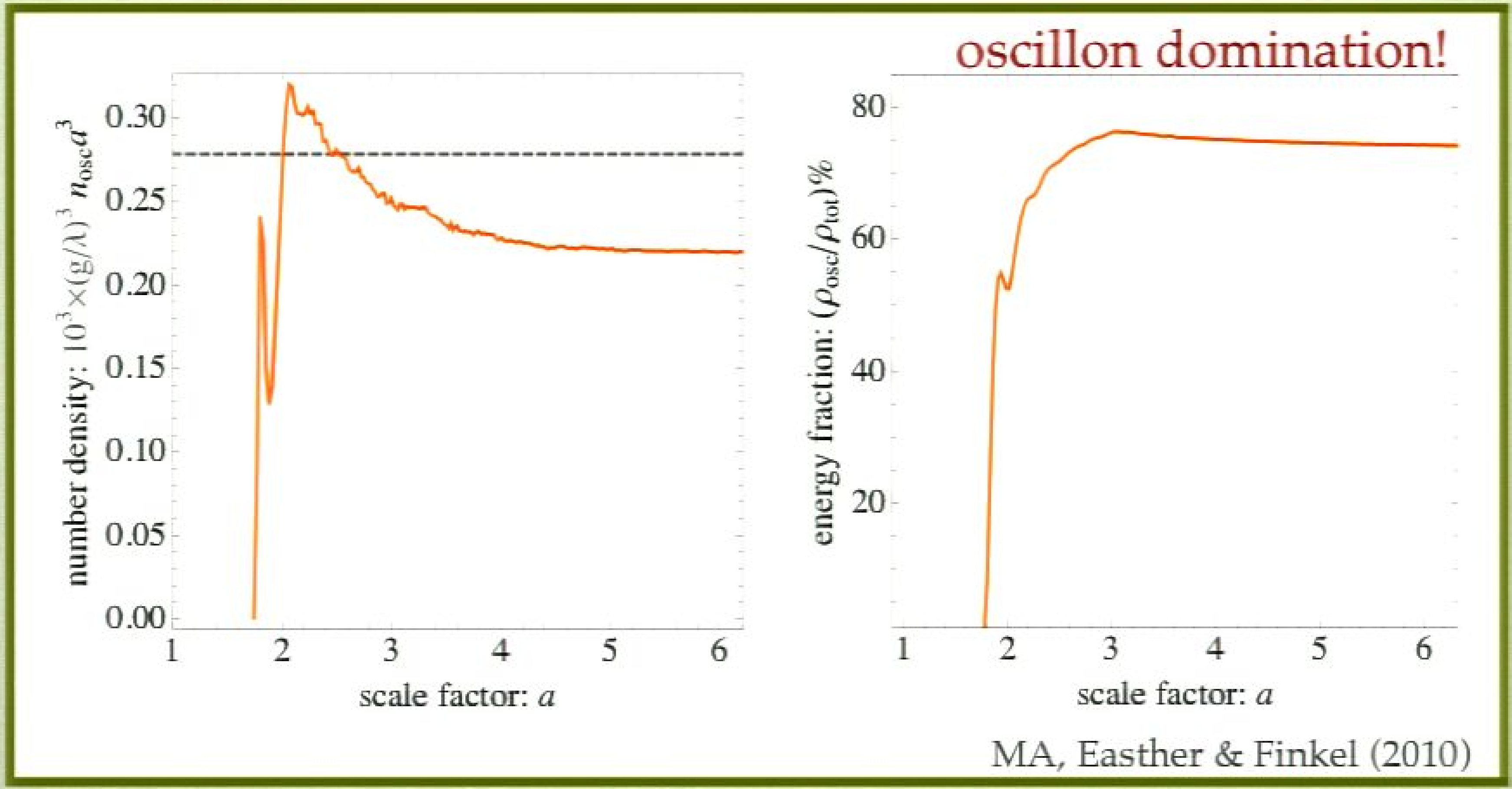


EXPANSION HISTORY



NUMBER DENSITY AND ENERGY FRACTION EVOLUTION

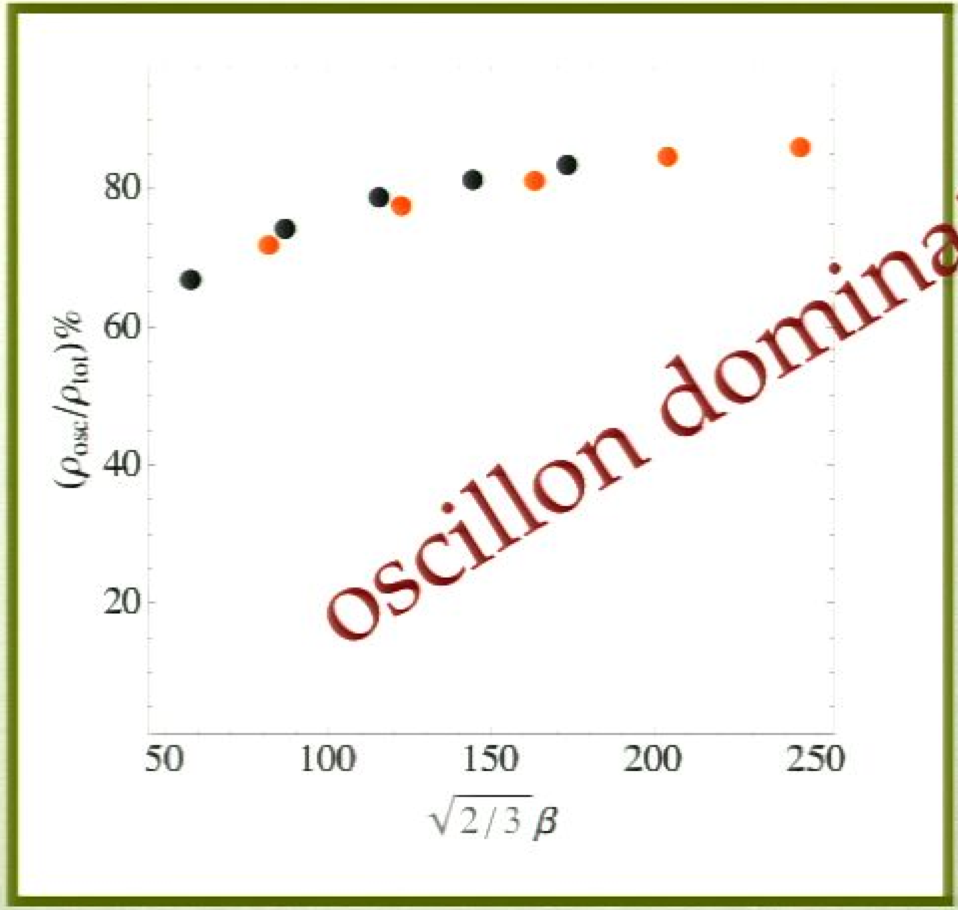


MA, Easther & Finkel (2010)

previous best: Gleiser et. al ~ 3%

ENERGY FRACTION

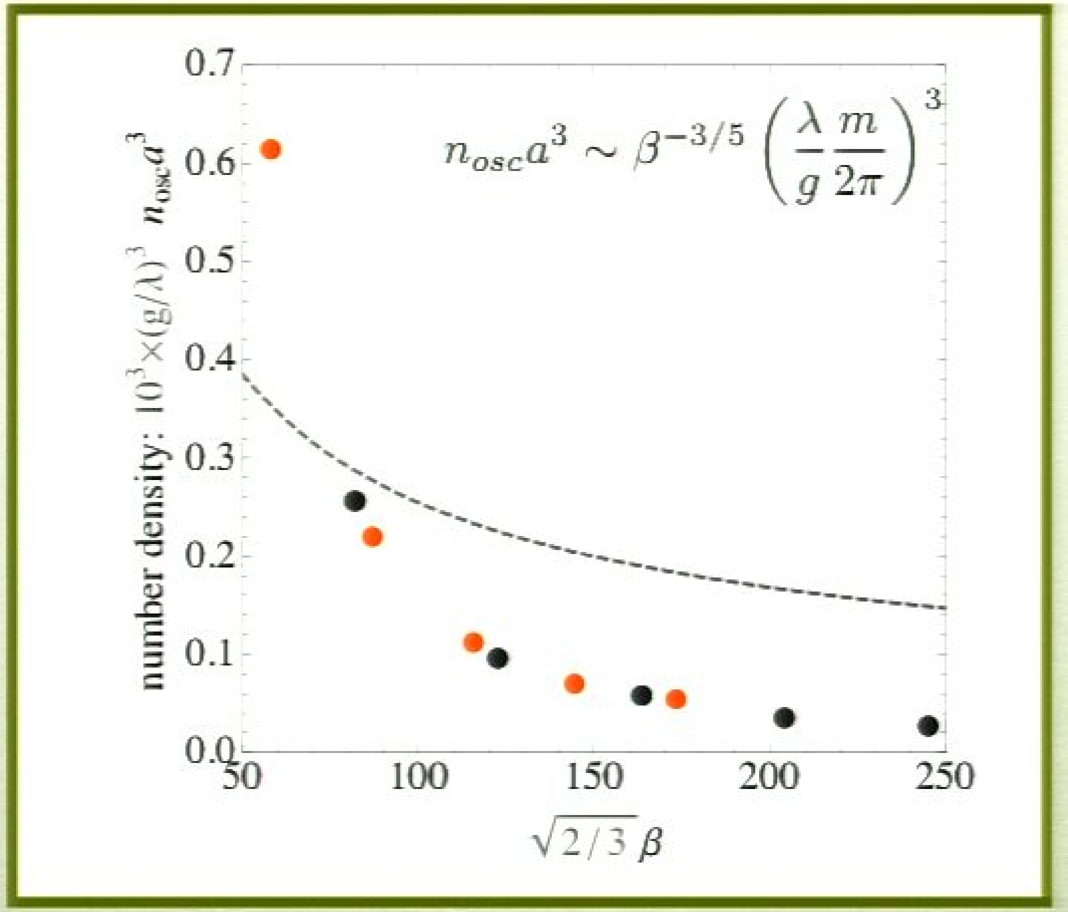
energy fraction in oscillons



oscillon domination!

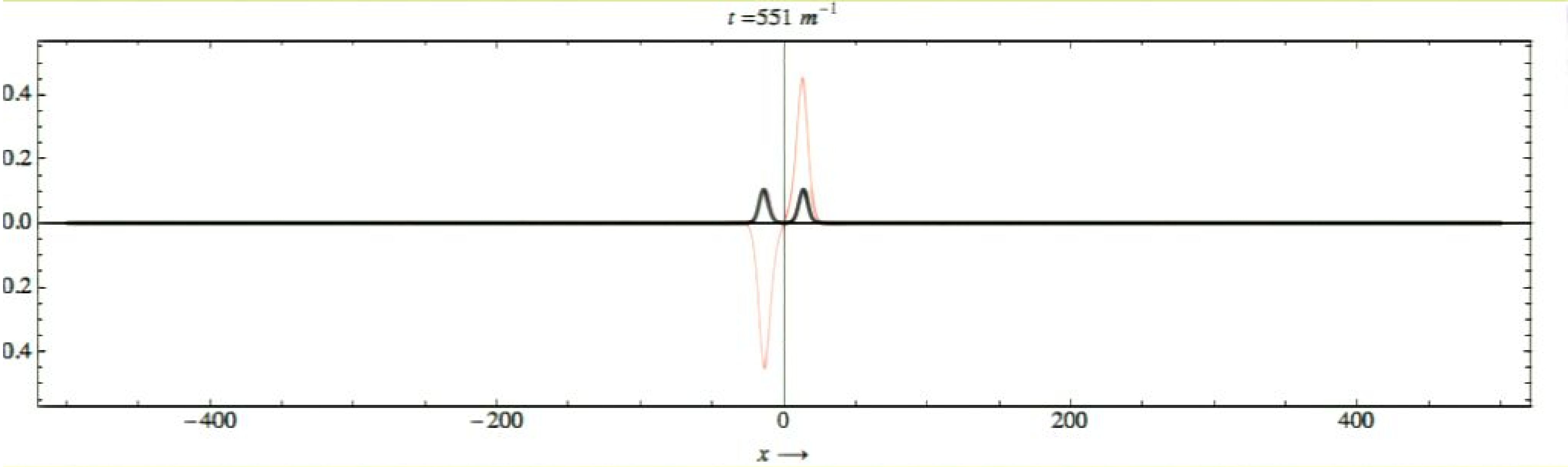
$$\frac{\mu_k}{H} \sim \beta \equiv \left[\left(\frac{m_{pl}}{m} \right) \frac{\lambda^{3/2}}{\;} \right]$$

NUMBER DENSITY



$\frac{\mu_k}{} \sim \beta = \left[\left(\frac{m_{pl}}{}\right)\frac{\lambda^{3/2}}{}\right]$

COLLISIONS



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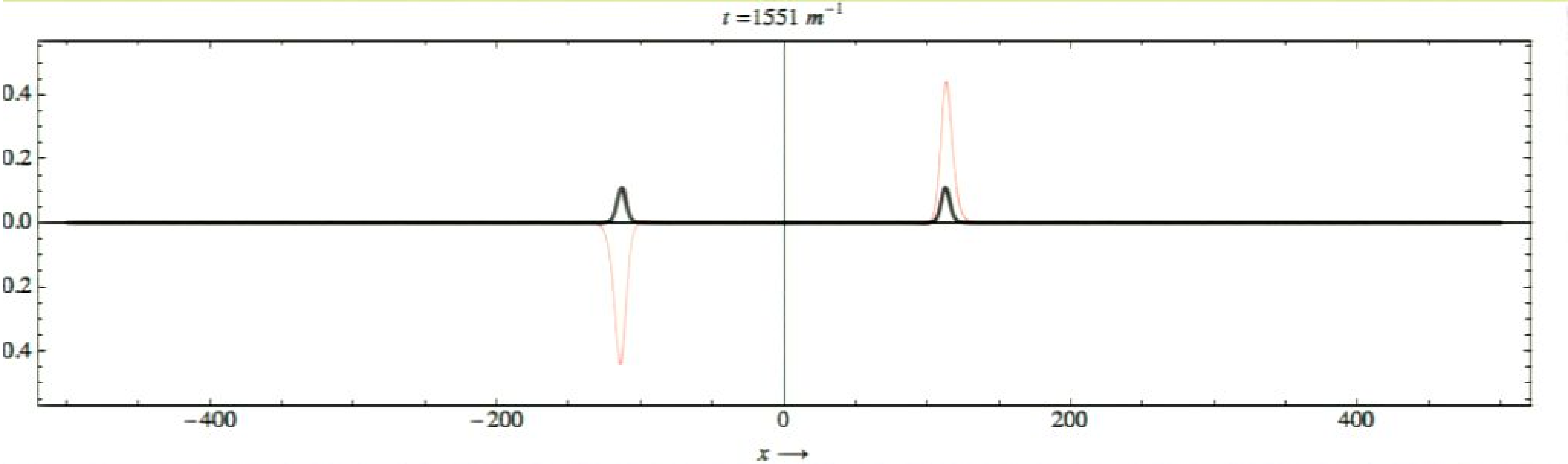

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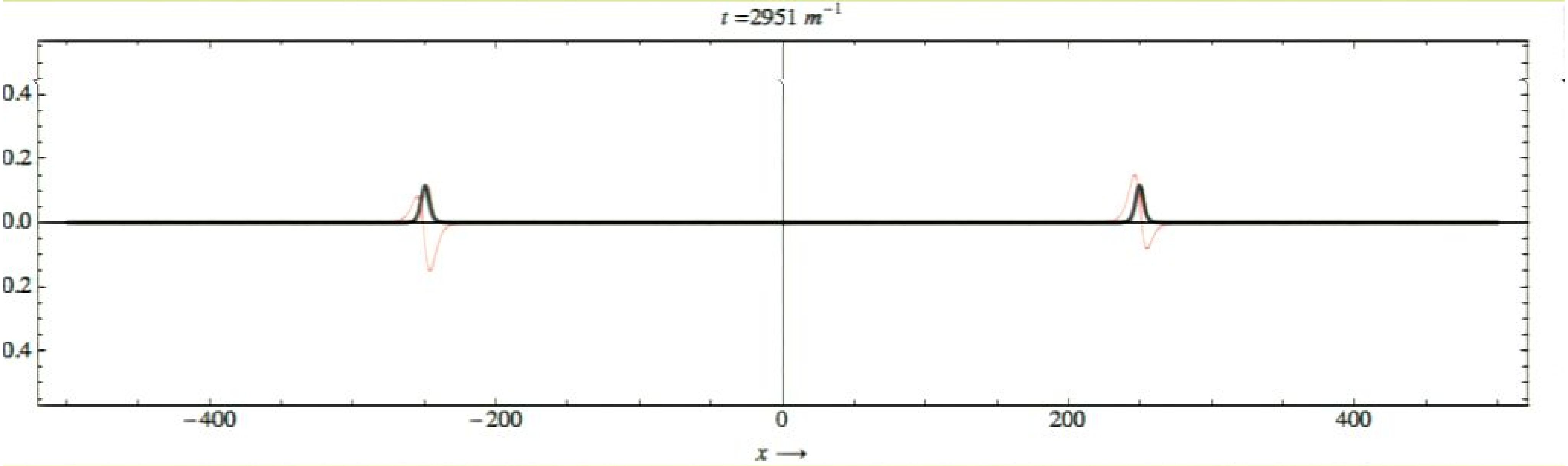

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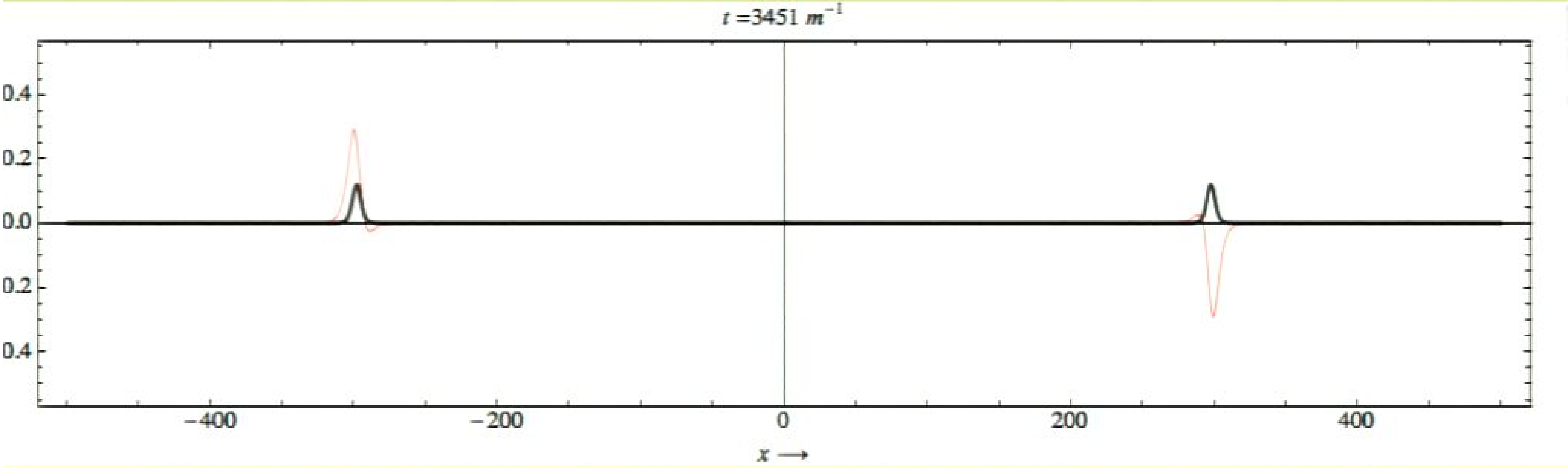

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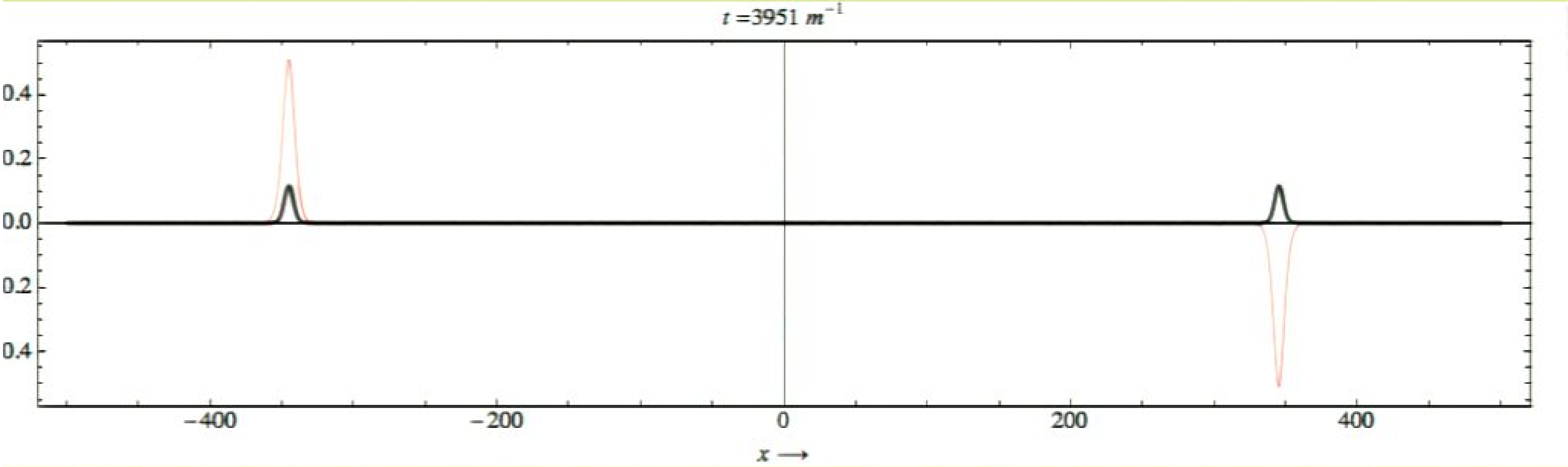

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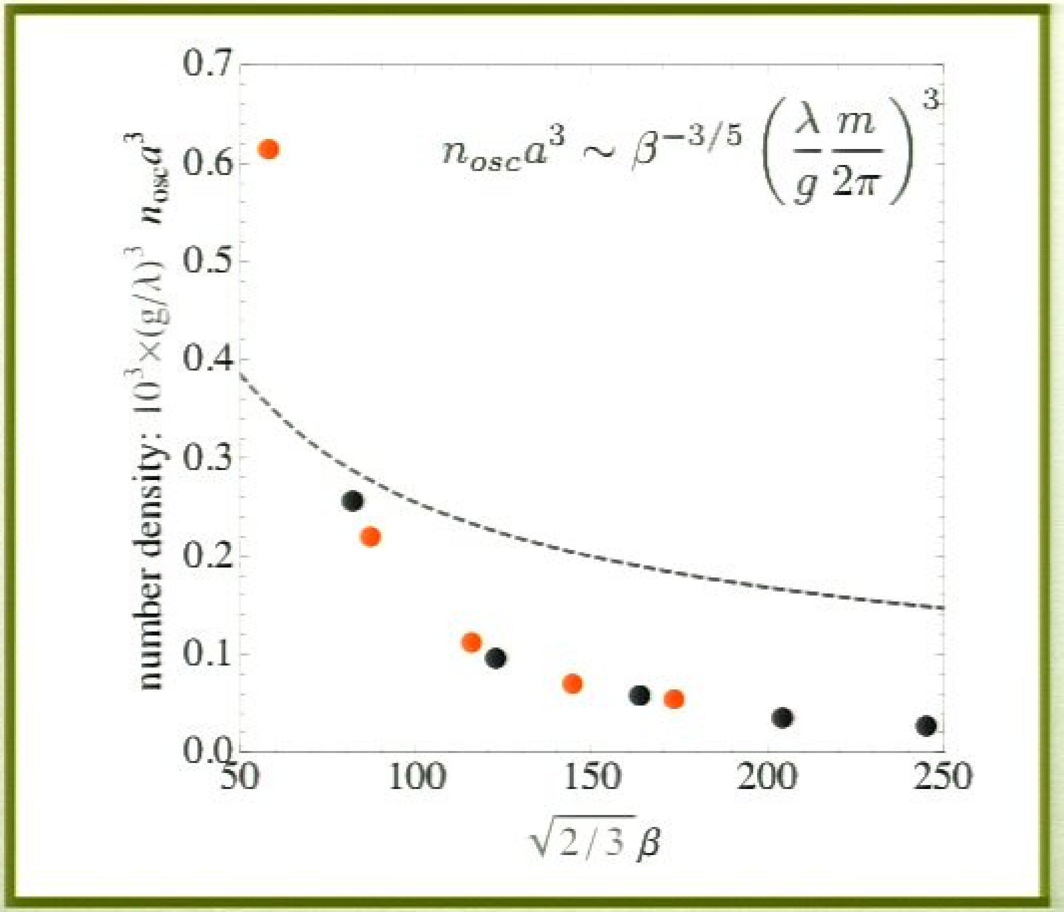
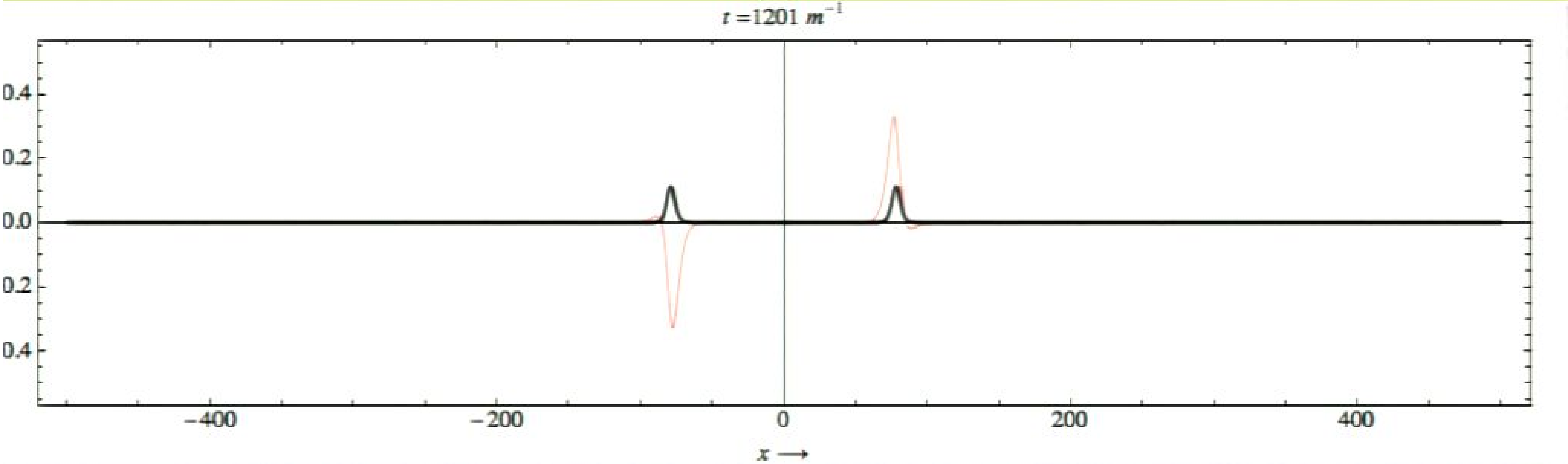


$\mu_k \sim \beta = \Big[\Big(m_{pl} \Big) \lambda^{3/2}$

COLLISIONS



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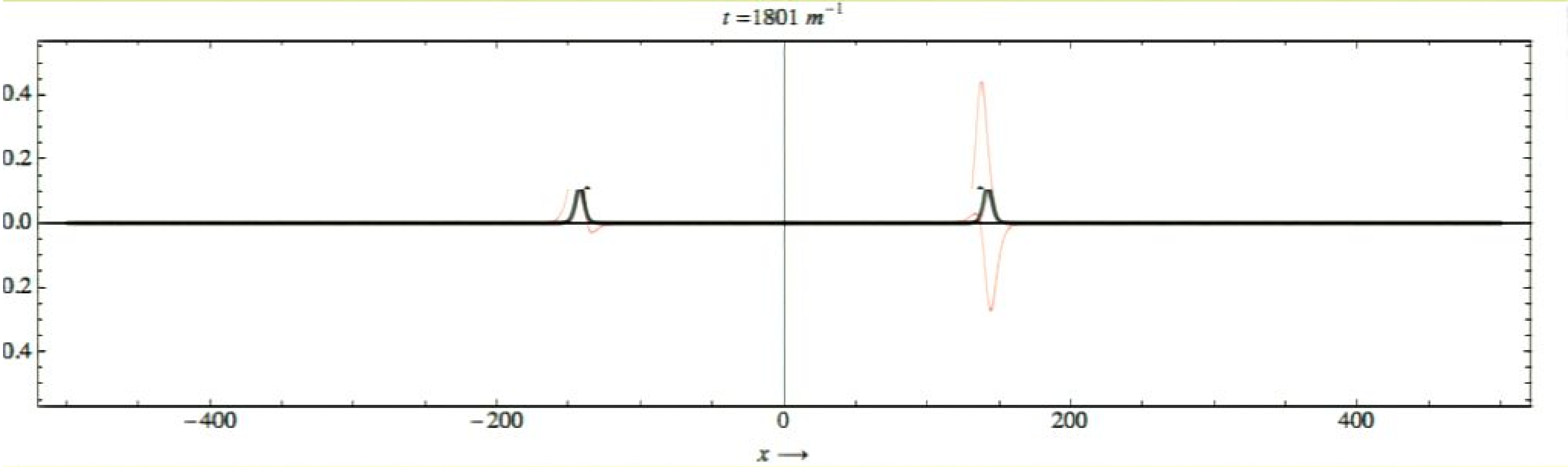

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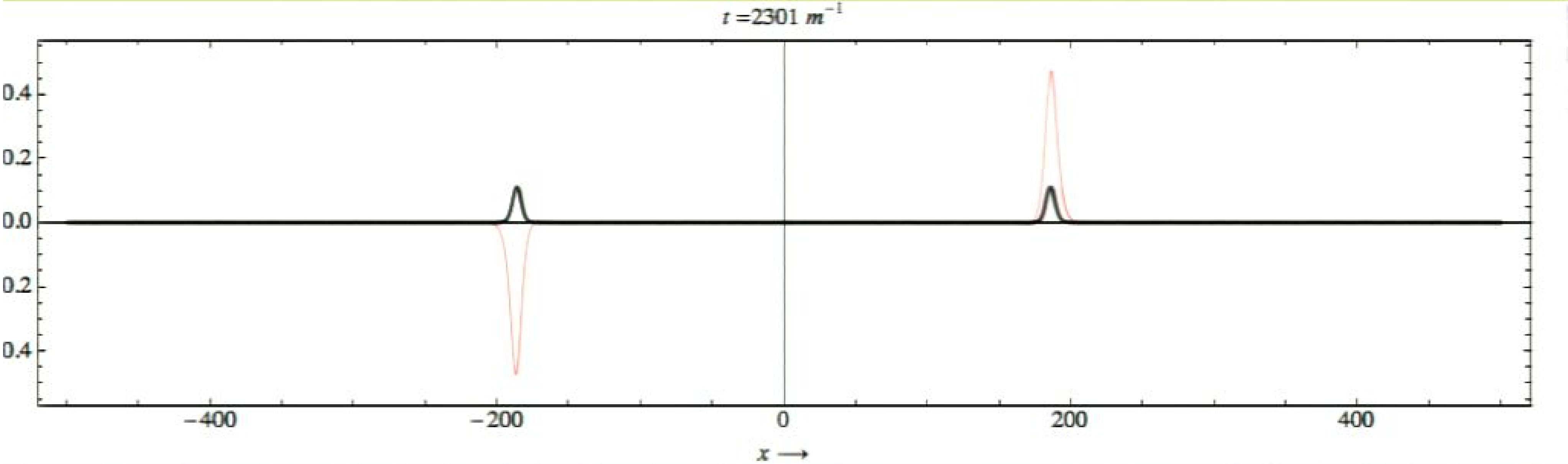

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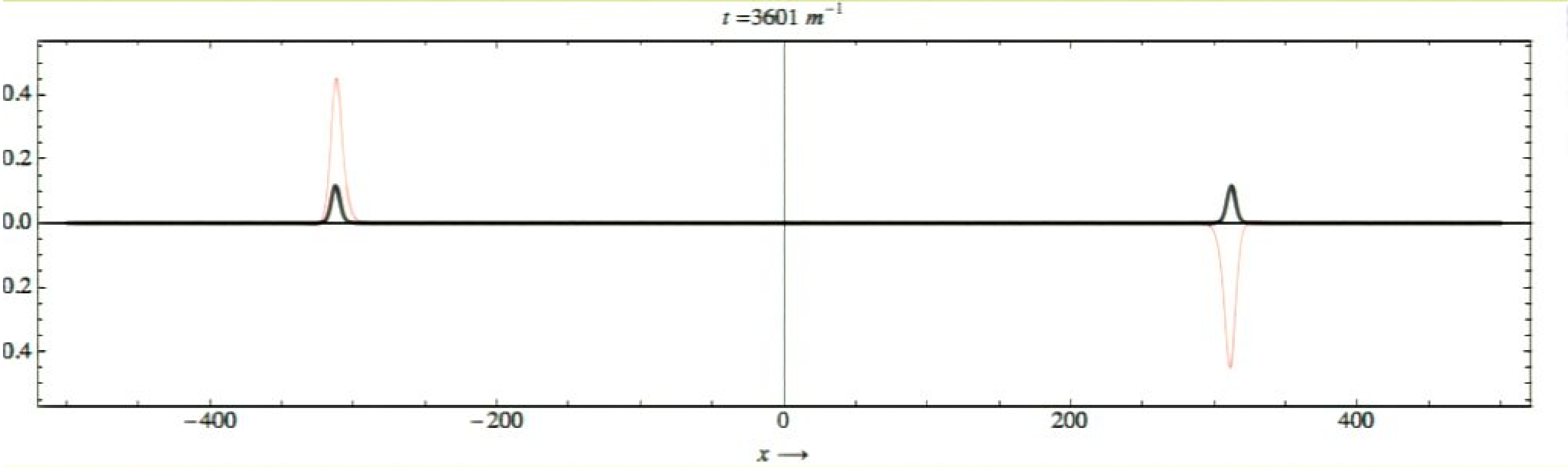

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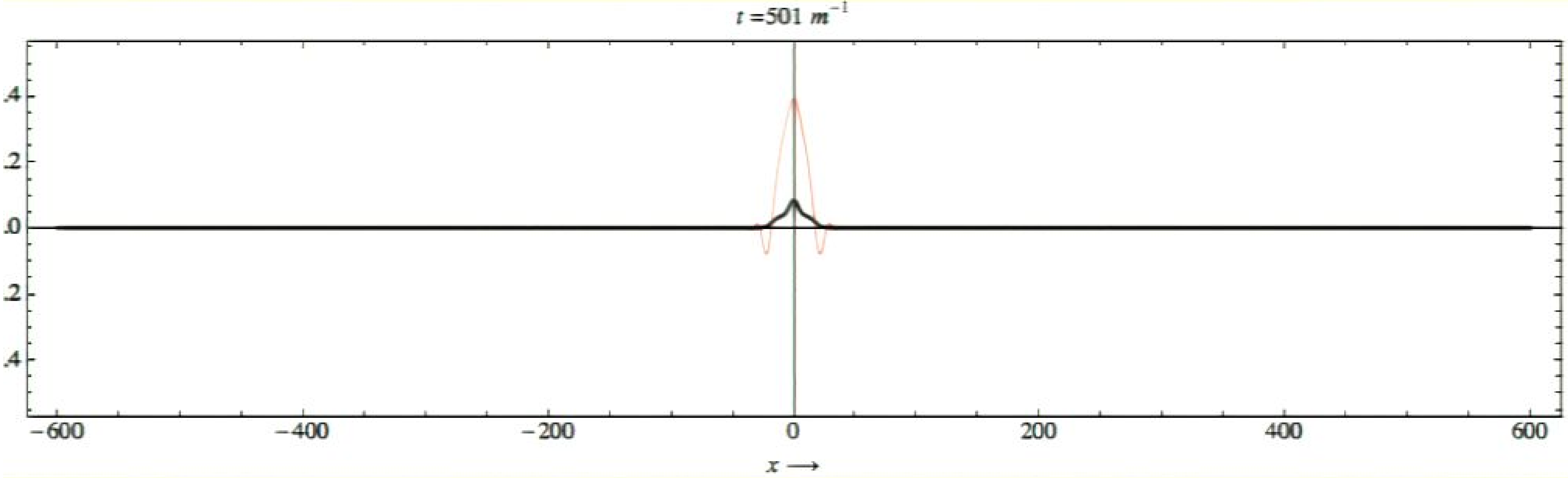

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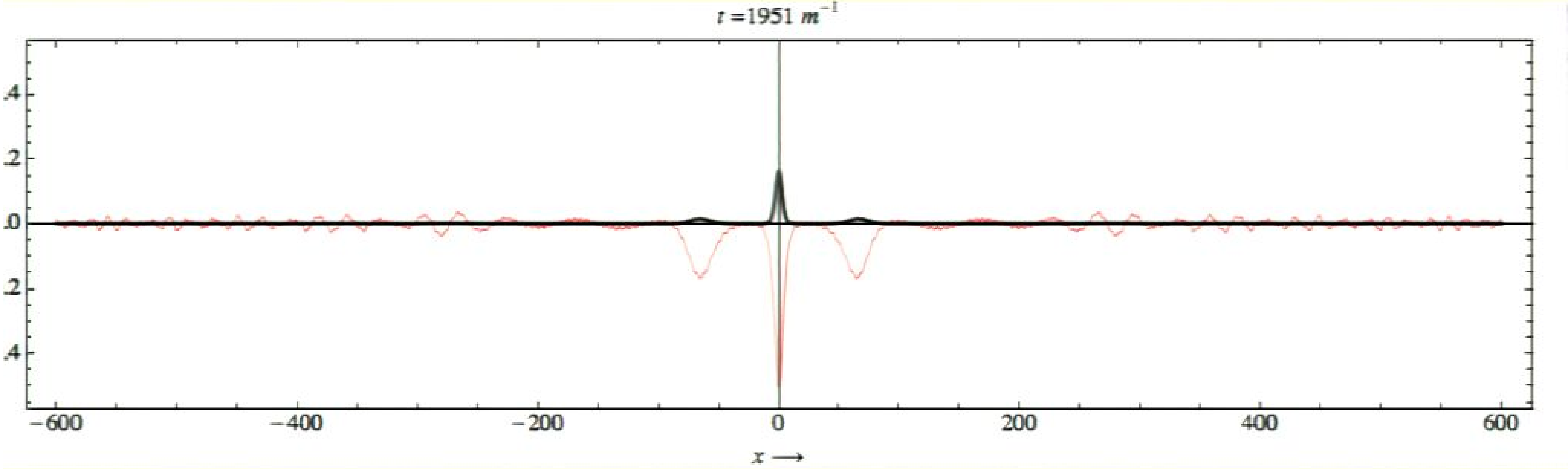

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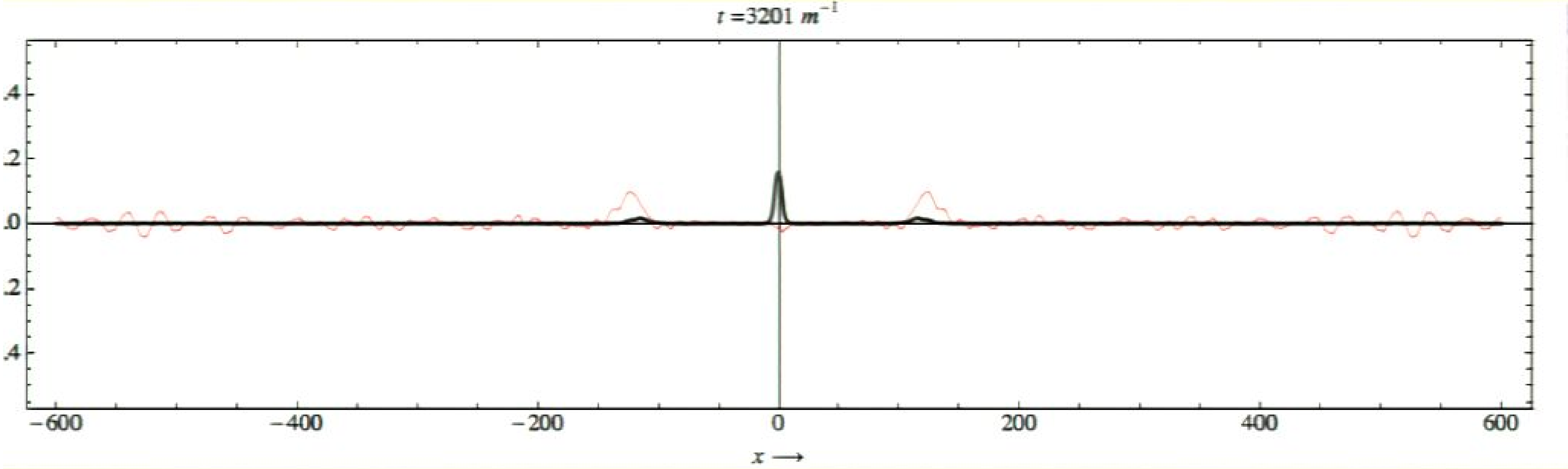

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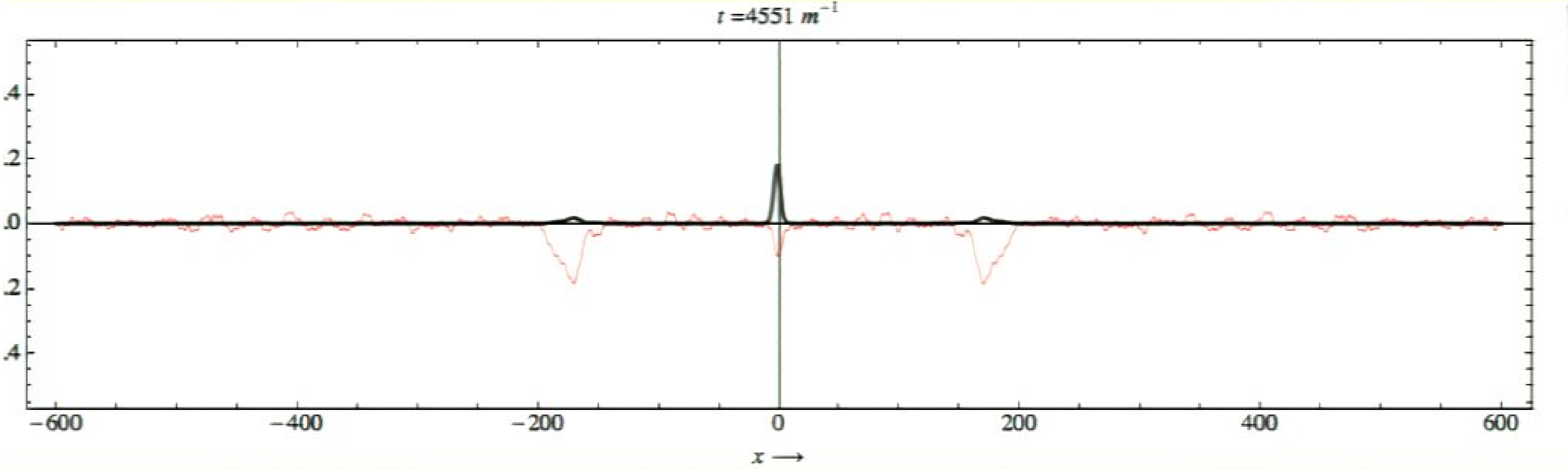

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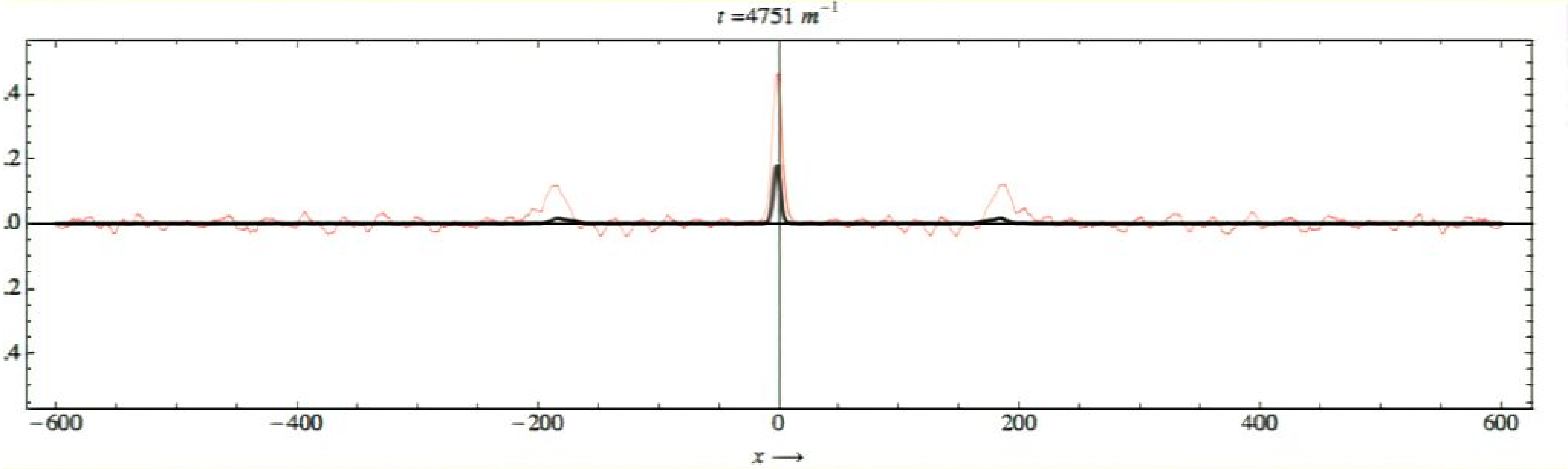
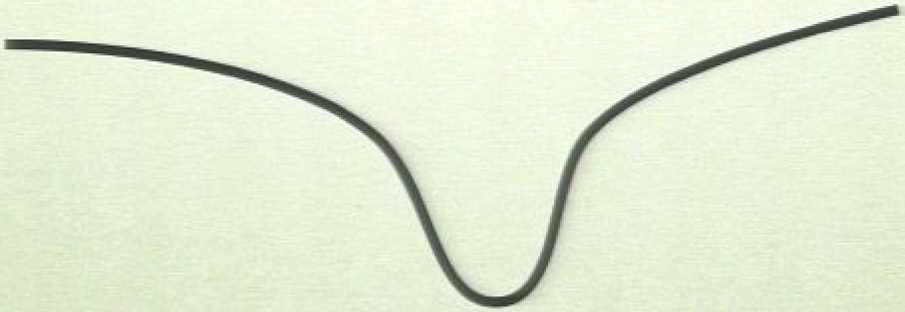


REALISTIC EXAMPLES

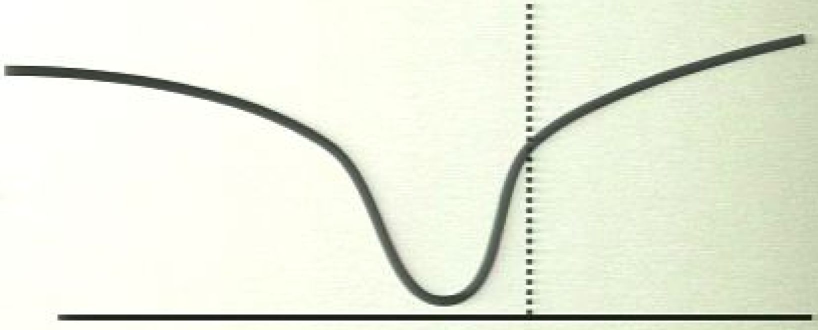
- satisfy relevant WMAP constraints
- examples: axion monodromy (Silverstein & Weshtpal), supergravity (Kallosh & Linde)



MA, Easther, Finkel , Flauger & Hertzberg (in prep)

WMAP CONSTRAINTS

$$\boxed{V(\varphi) = m^2 M^2 \left(\sqrt{1 + \left(\frac{\varphi}{M}\right)^2} - 1 \right)}.$$



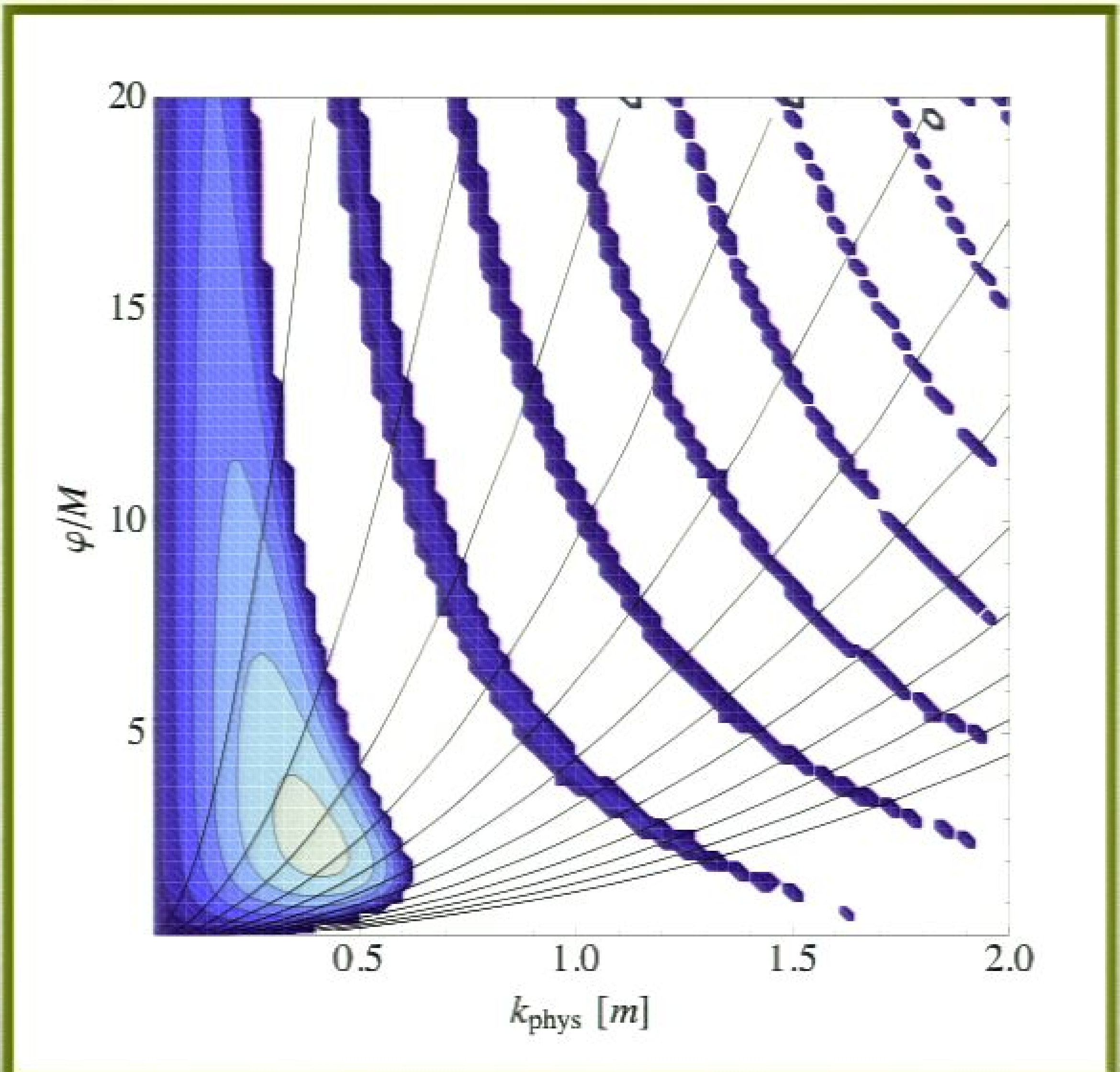
$\varphi \sim M$

$$\Delta^2_{\mathcal{R}} = (2.445 \pm 0.096) \times 10^{-9}$$

$$k = 0.002\,\mathrm{Mpc}^{-1}$$

$$m^2 M \approx 2.2 \times 10^{-10} m_{pl}^3. \qquad \varphi \gg M$$

MONODROMY



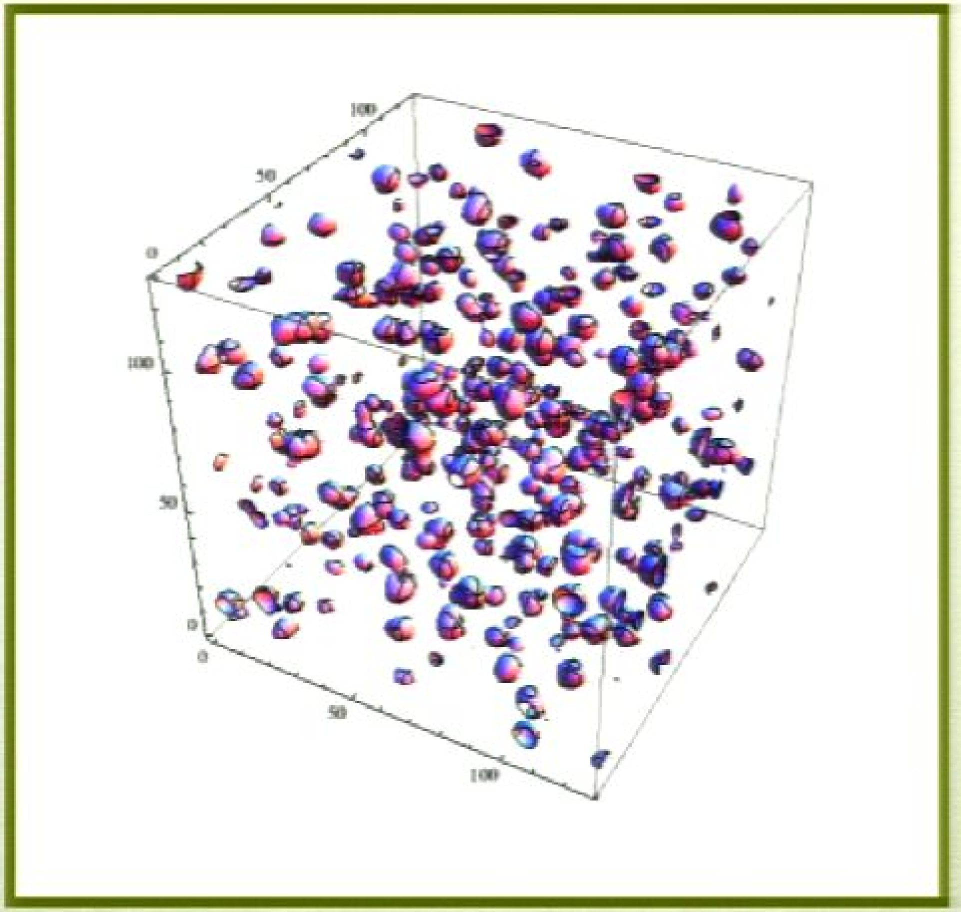
EMERGENCE CONSTRAINT

$$V(\varphi) = \frac{1}{2}m^2\varphi^2 - \frac{1}{4}\lambda\varphi^4 + \frac{1}{6}\frac{g^2}{m^2}\varphi^6 - \ldots$$

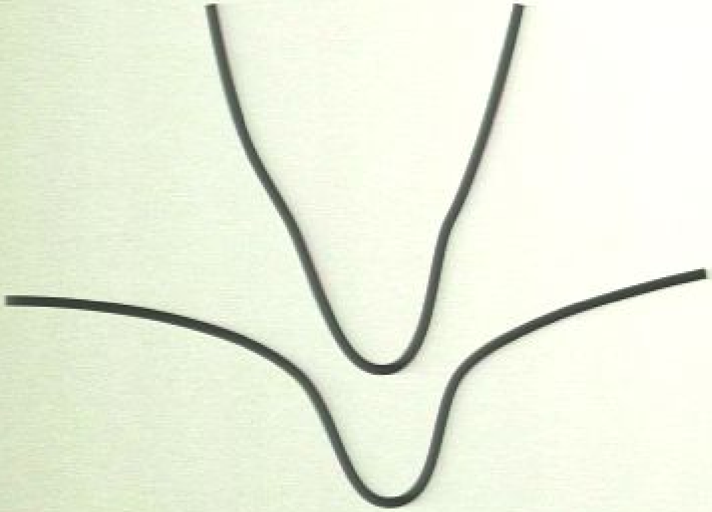
$$\lambda = \frac{1}{2}\frac{m^2}{M^2}, \; g = \sqrt{\frac{3}{2}}\lambda \ldots$$

$$\boxed{\mu_k \gg H} \qquad M \approx 10^{-2} m_{pl}$$

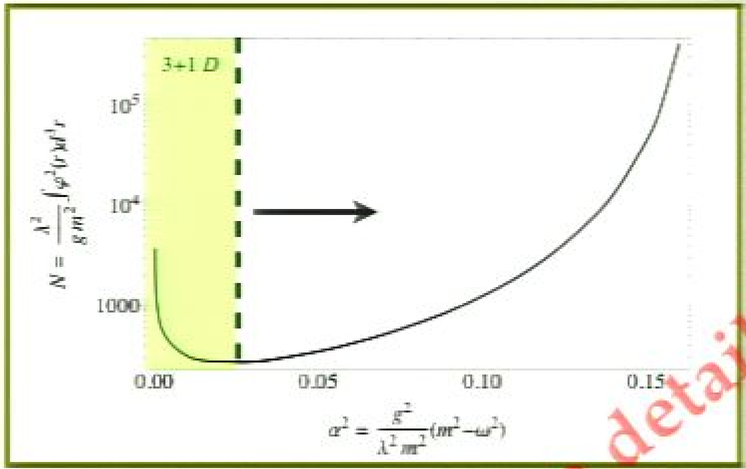
MONODROMY OSCILLONS!



A HEURISTIC GUIDE ...



necessary



stability

$$\boxed{\mu_k \gg H}$$

emergence

$$\boxed{\Gamma \ll H \ll m}$$

cosmologically relevant

needs to be checked in detail

3+1

WHAT TO DO WITH THEM?

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- gravitational effects:

3+1

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  - early universe structure formation

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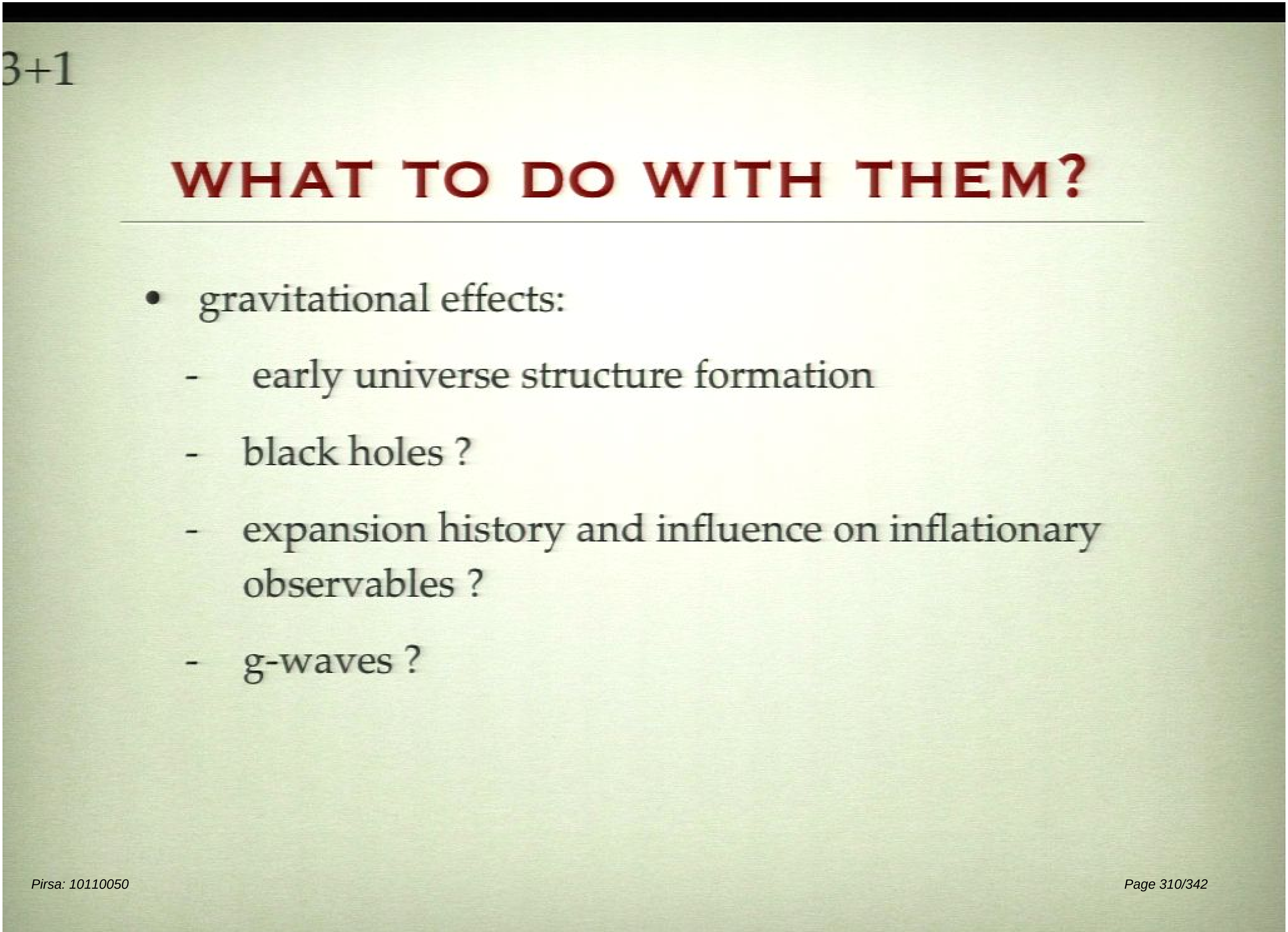

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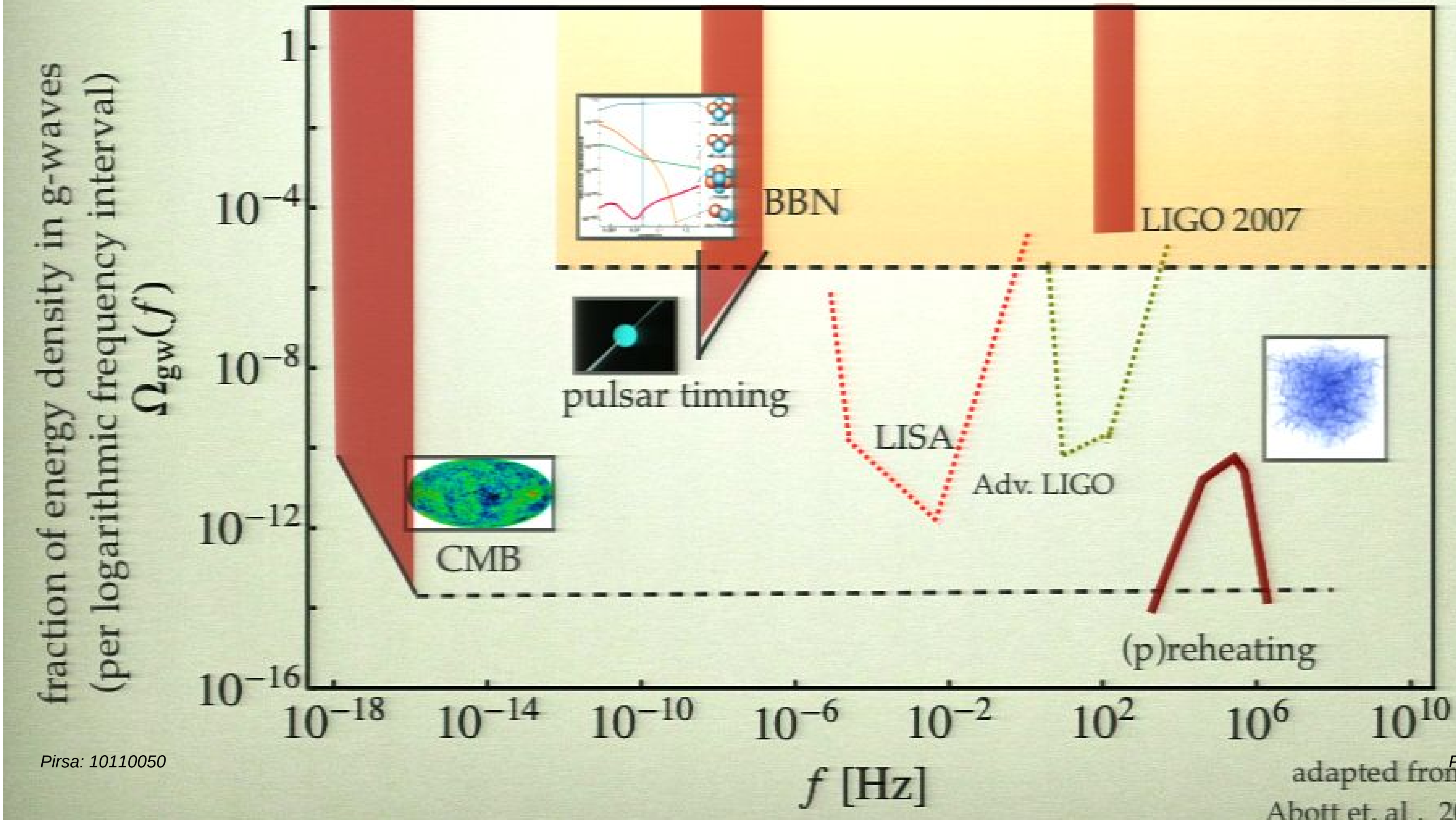
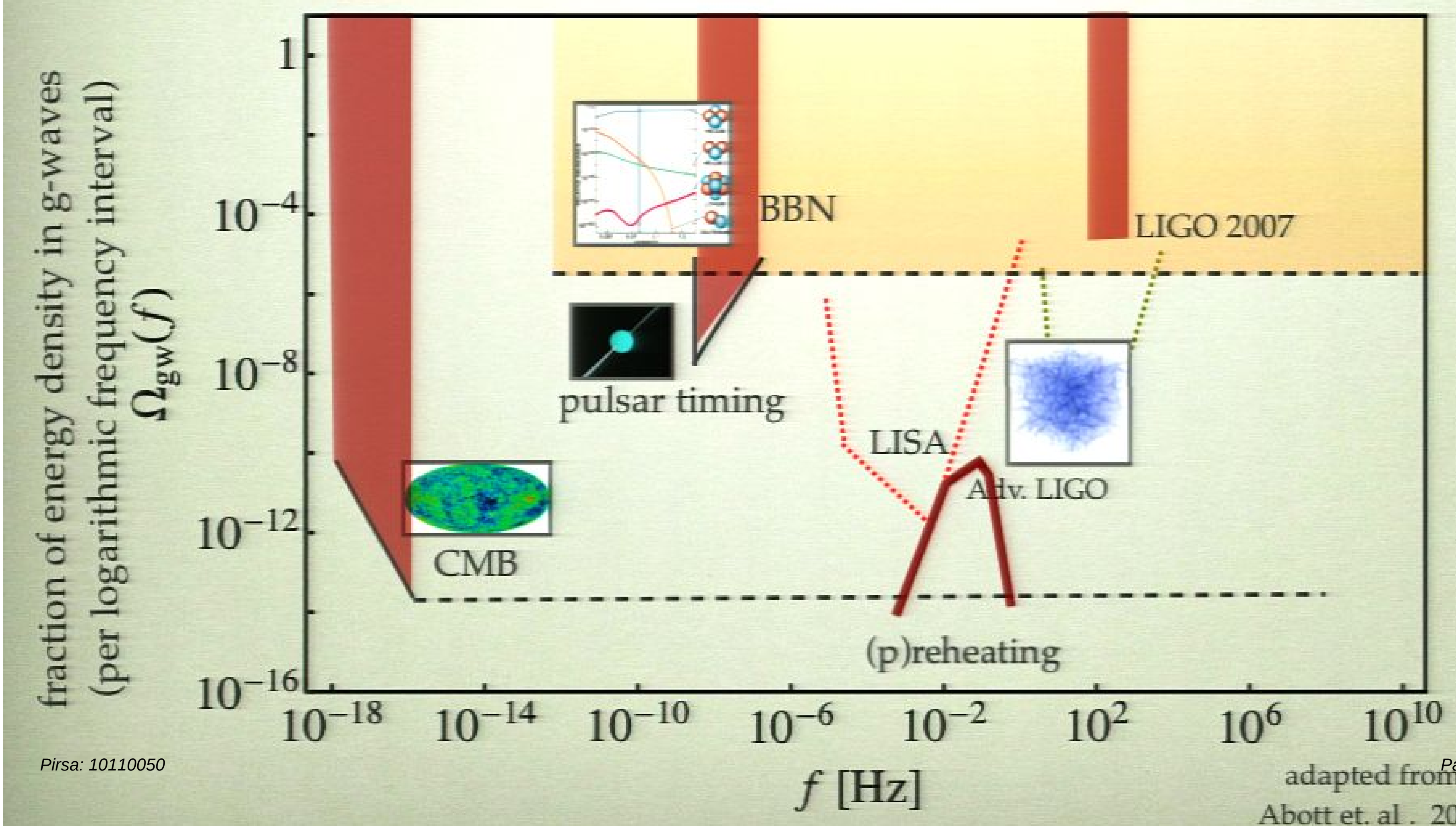
- thermalization, enhanced decay rates
- SU(2) oscillons *(Graham &Farhi 2007)*

GRAVITATIONAL WAVES



adapted from
Abott et. al . 2007

GRAVITATIONAL WAVES



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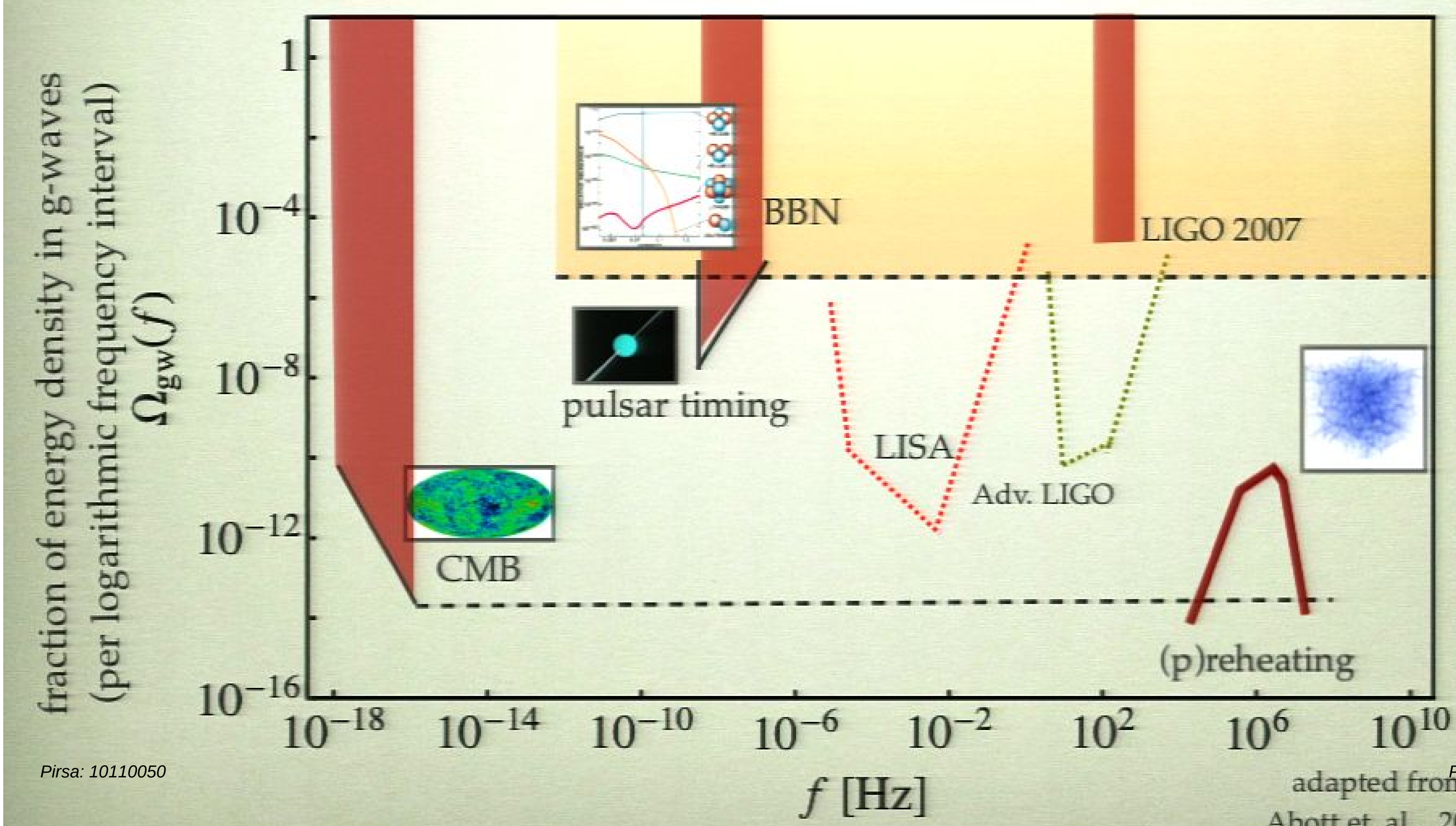
GRAVITATIONAL WAVES



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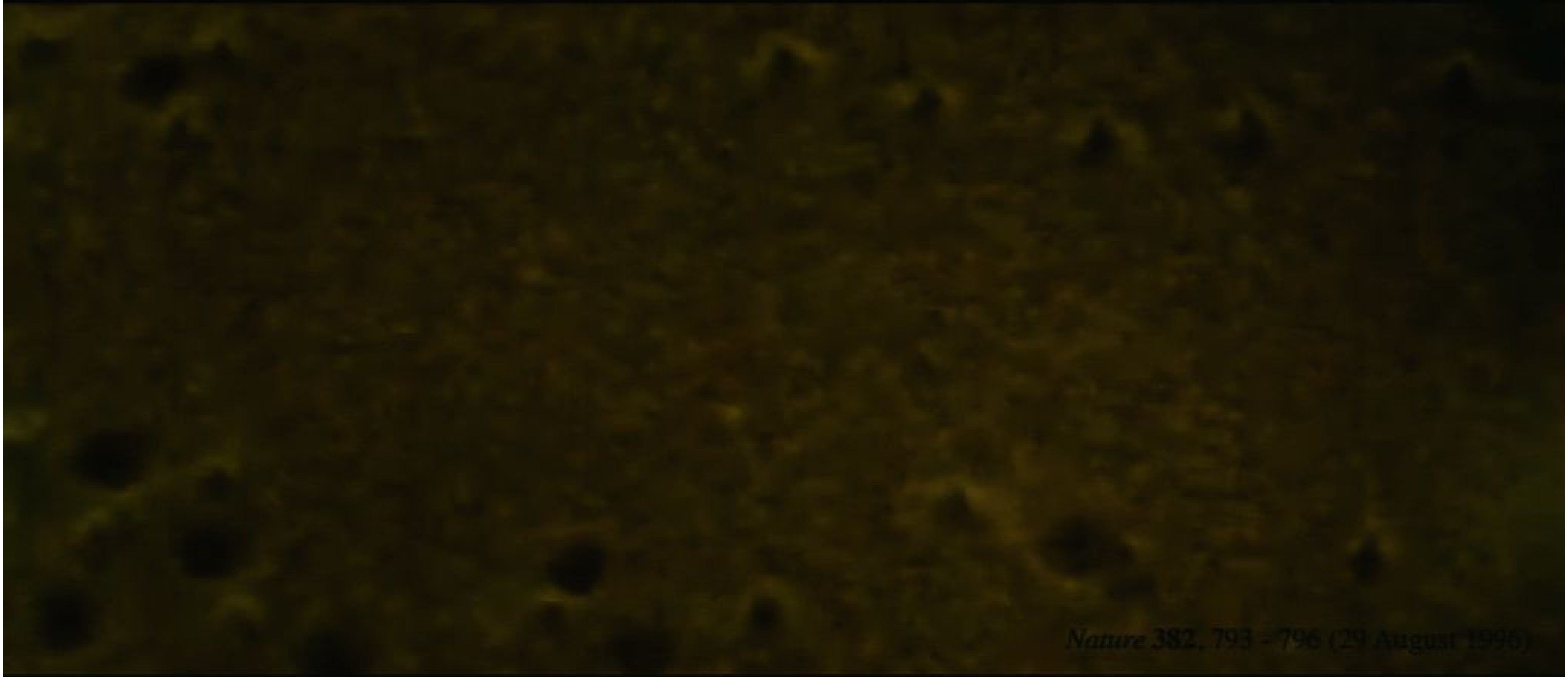
- *existence, emergence and stability conditions*
- possible implications: enhanced g-waves, structure formation, blackholes, CMB observables ?

ACKNOWLEDGEMENTS

- **Alan Guth**, Eddie Farhi, Ruben Rosales, Evangelos Sfakianakis, Mark Mezei, David Shirokoff & Antony Speranza (MIT)
- Richard Easther & Hal Finkel (Yale)
- Mark Hertzberg (Stanford)

Nature **382**, 793 - 796 (29 August 1996)



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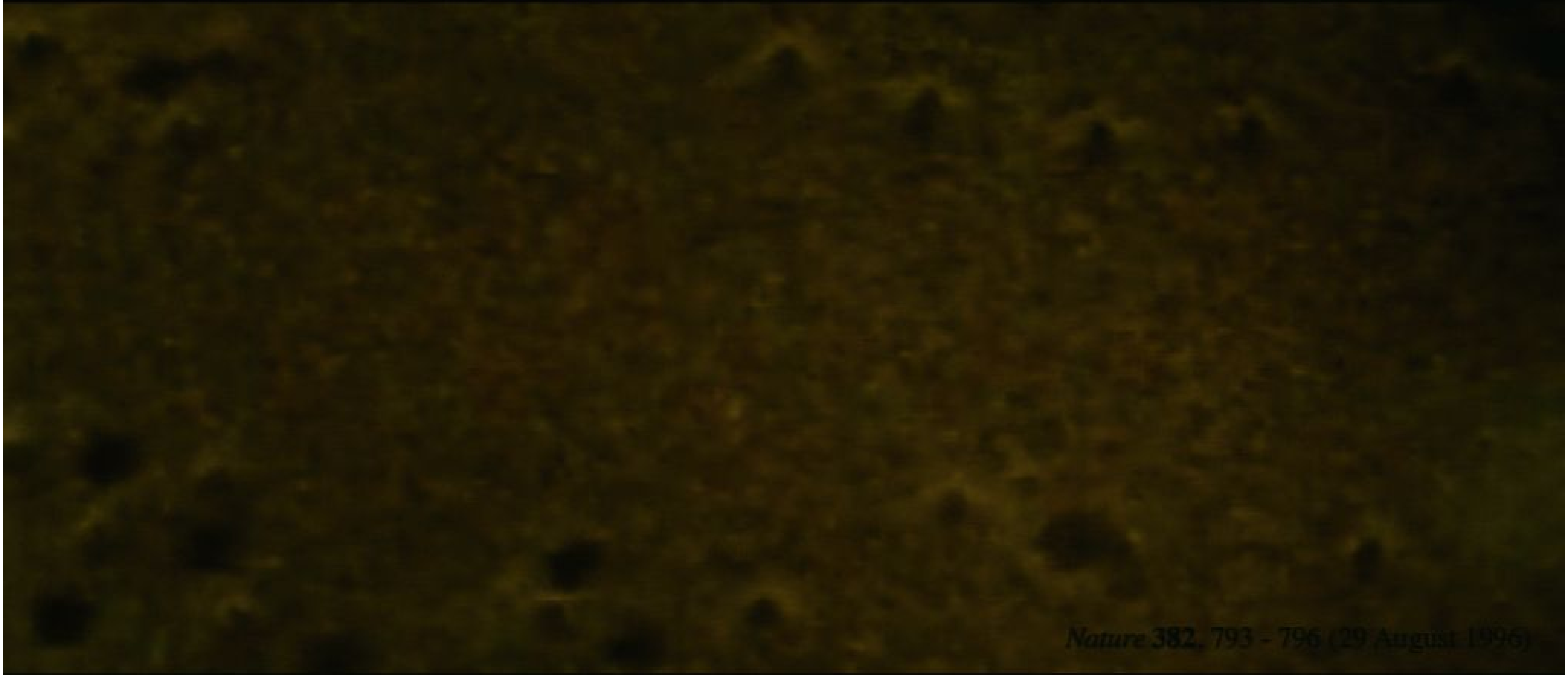

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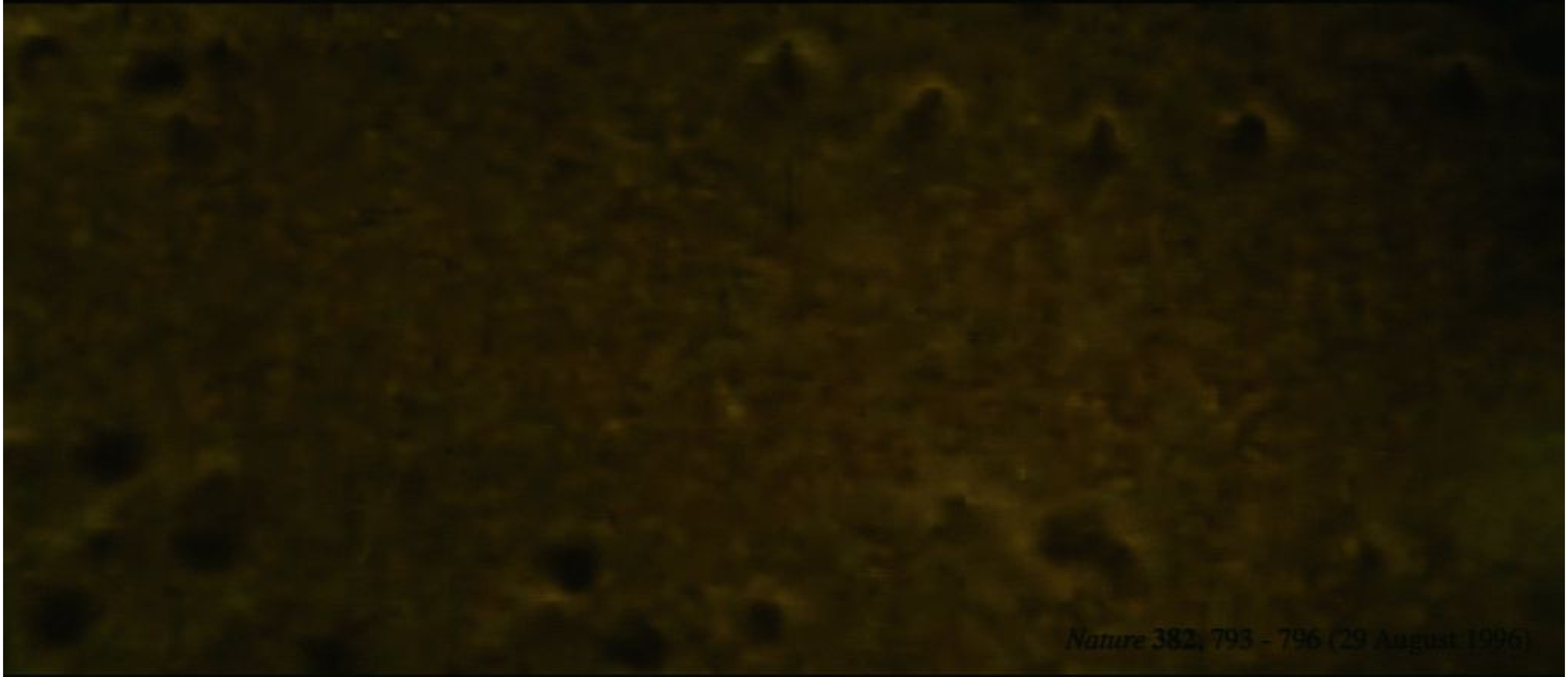

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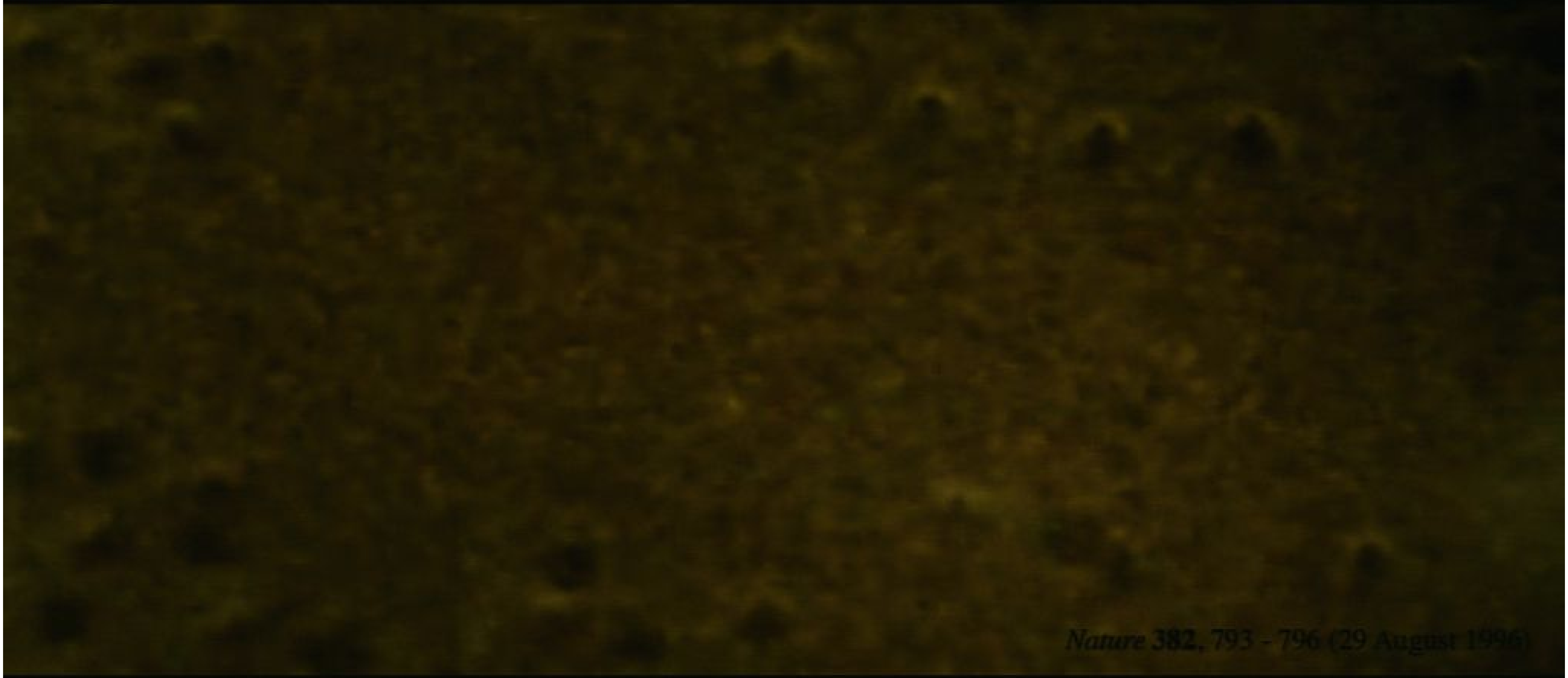

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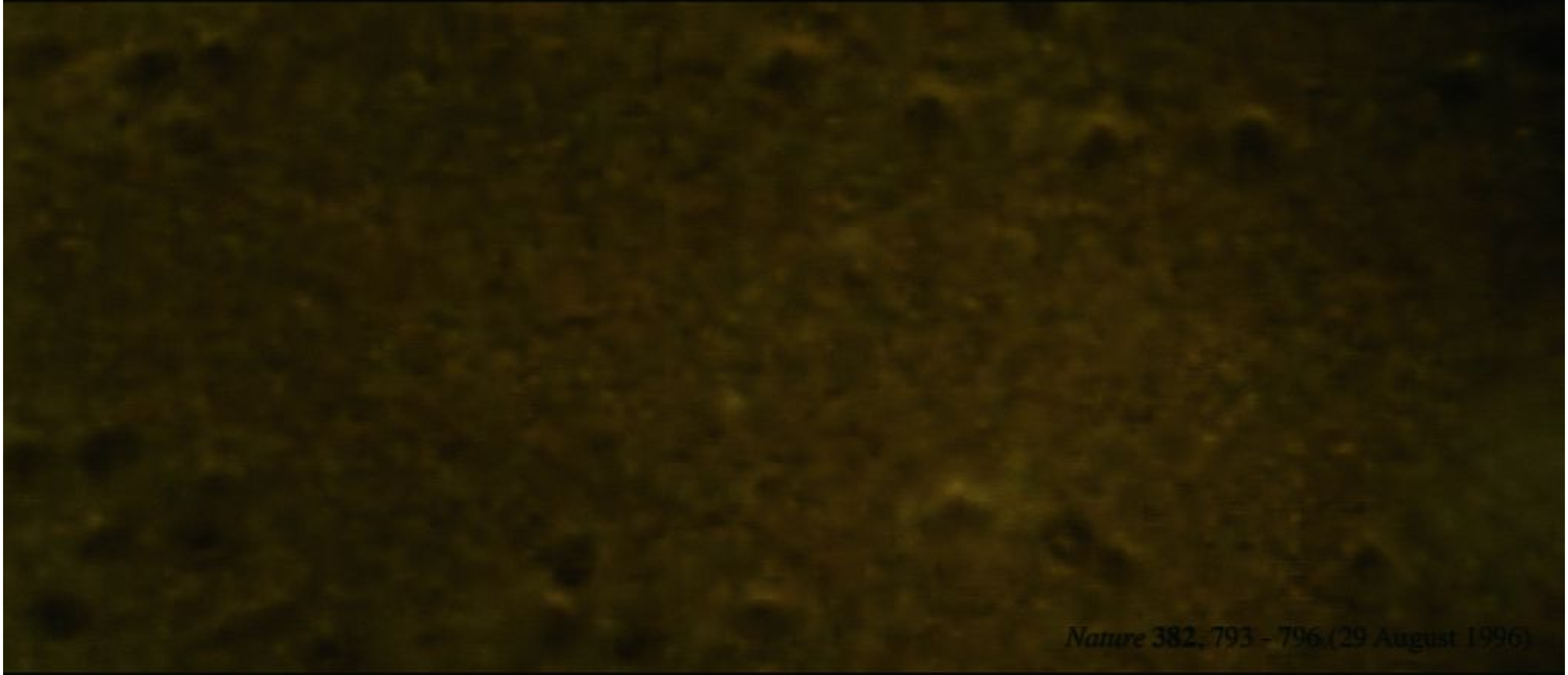

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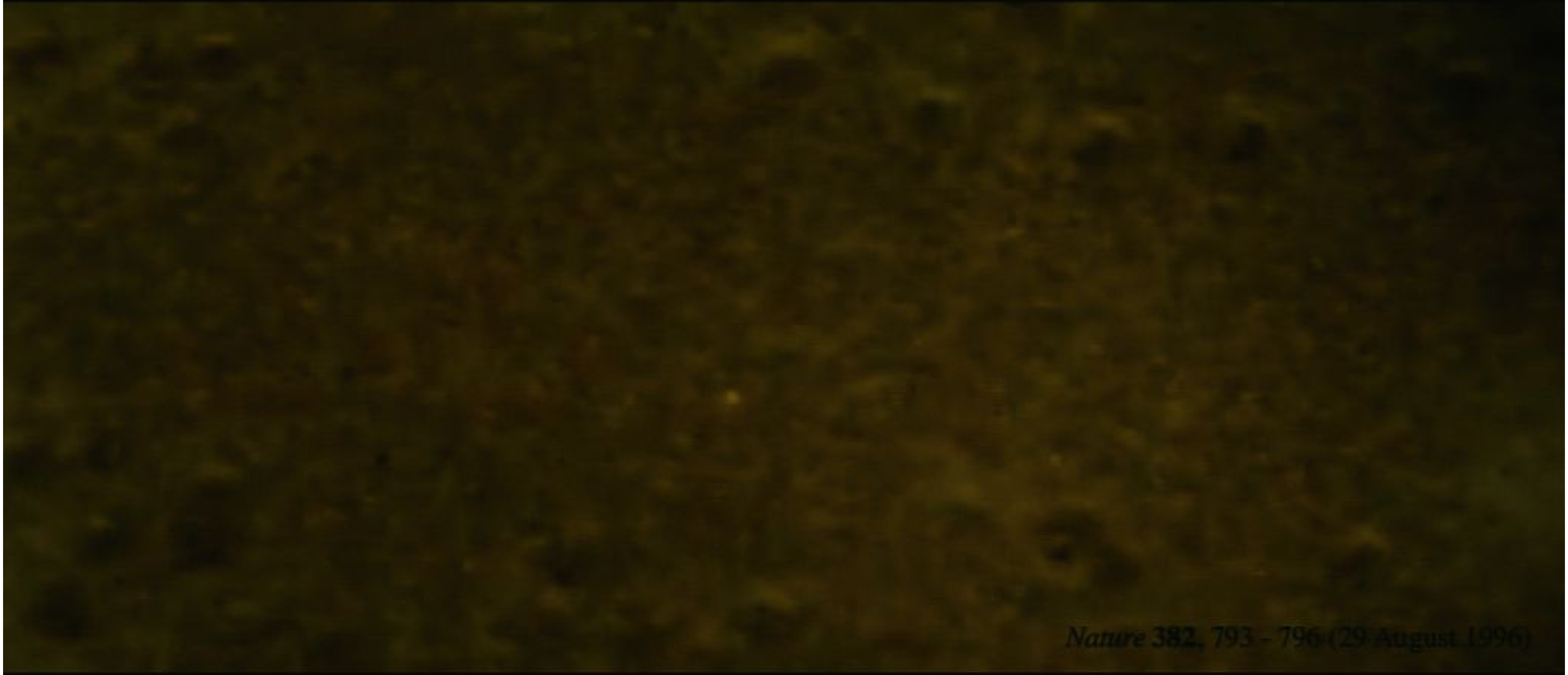

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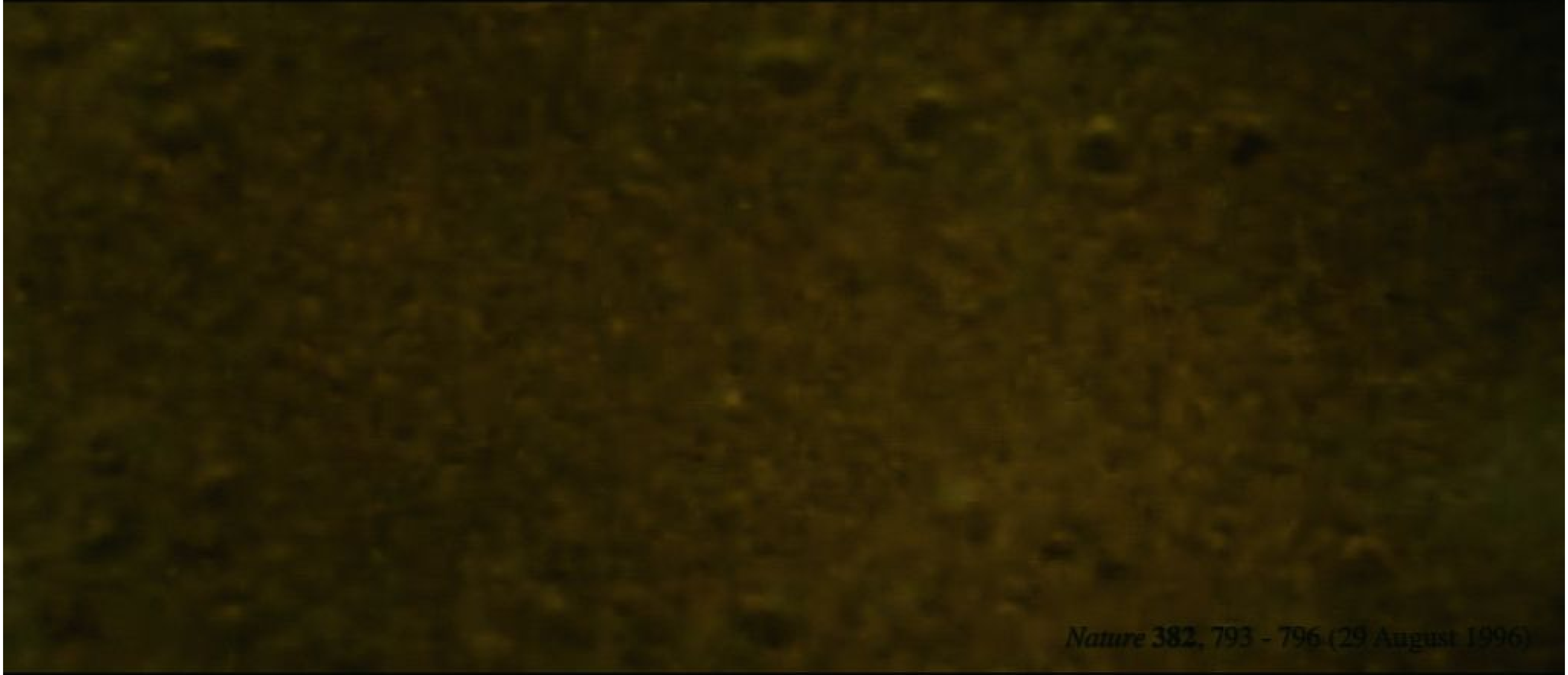

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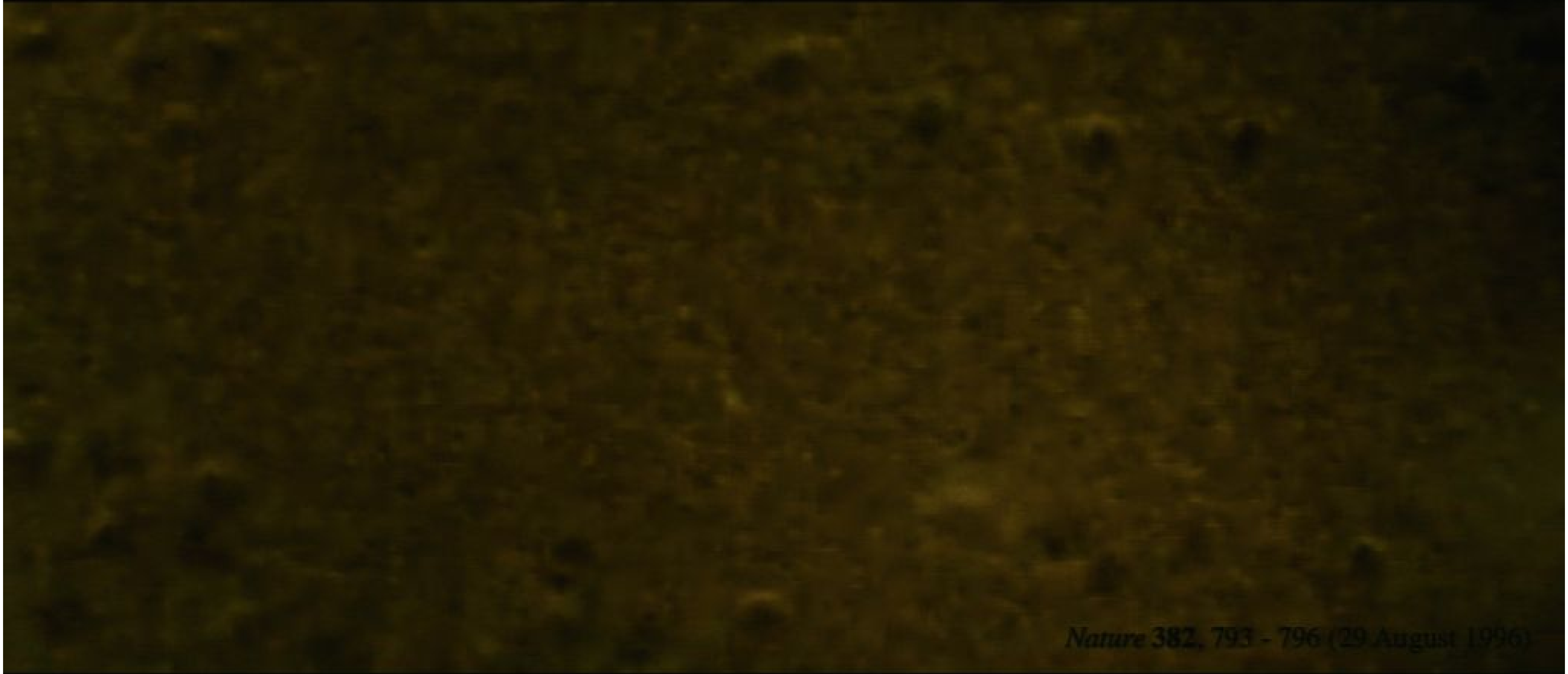

Nature **382**, 793 - 796 (29 August 1996)

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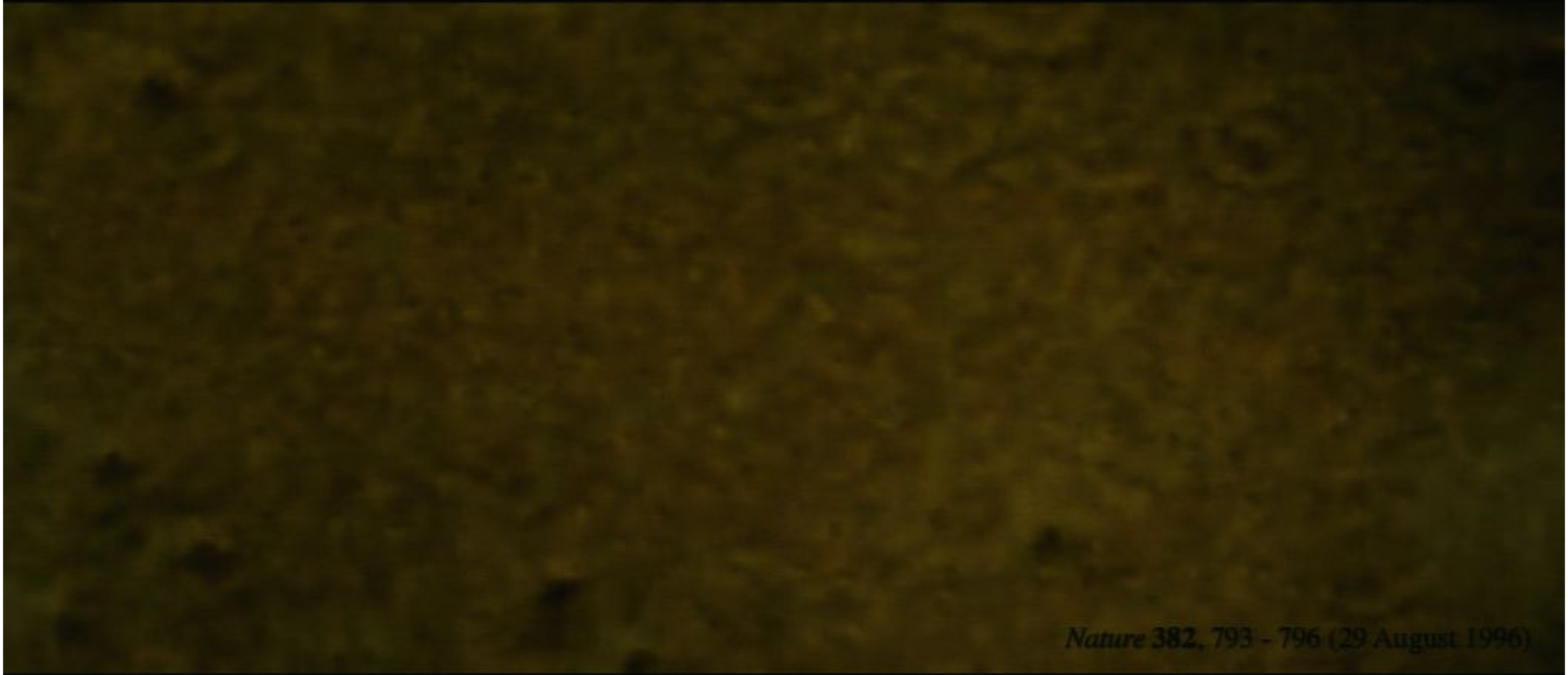

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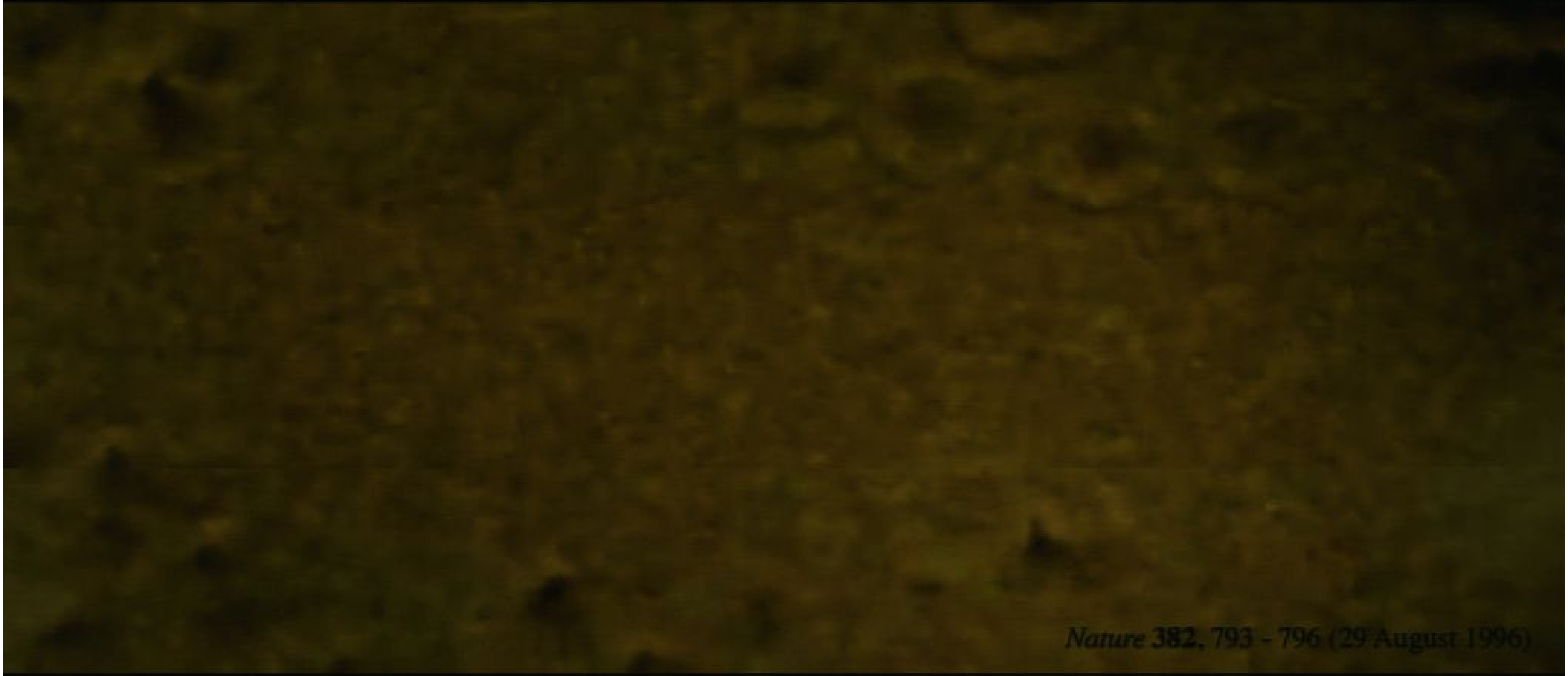

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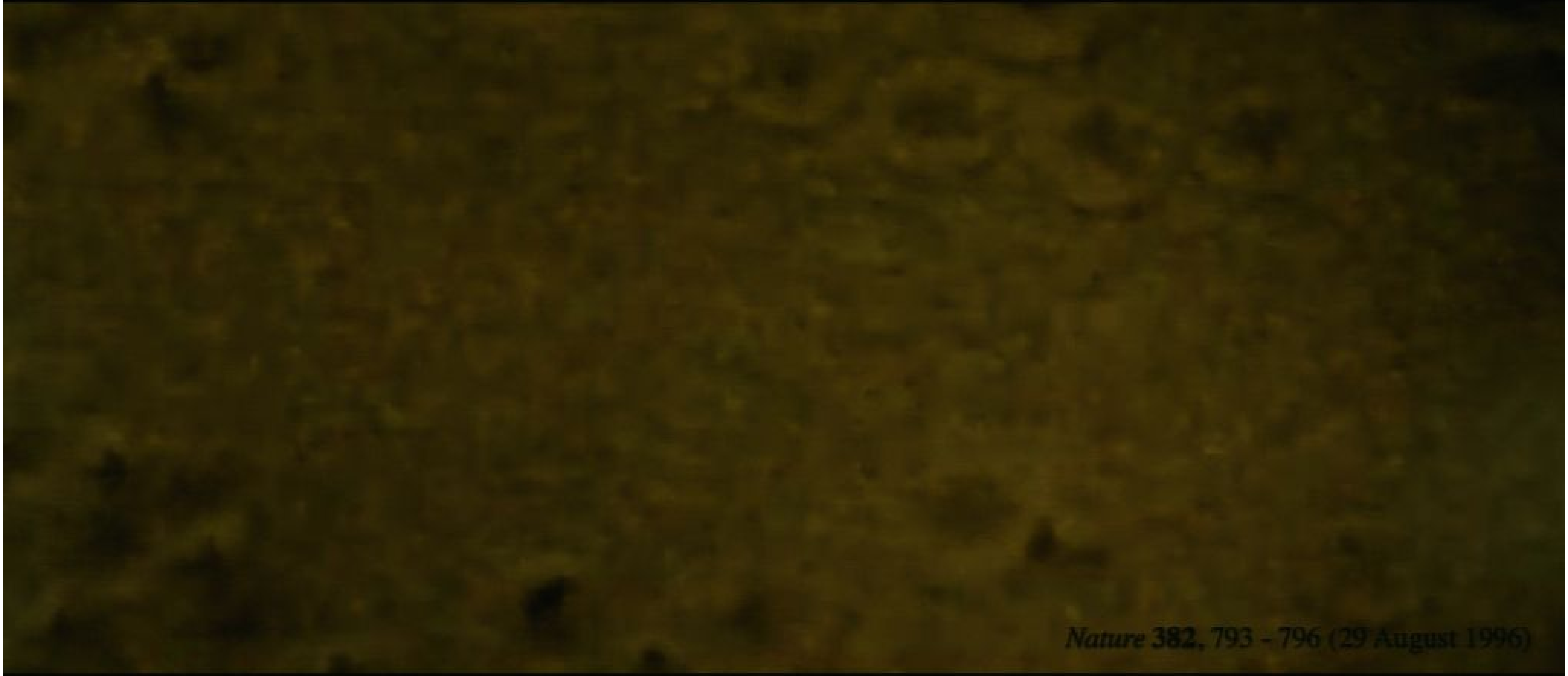

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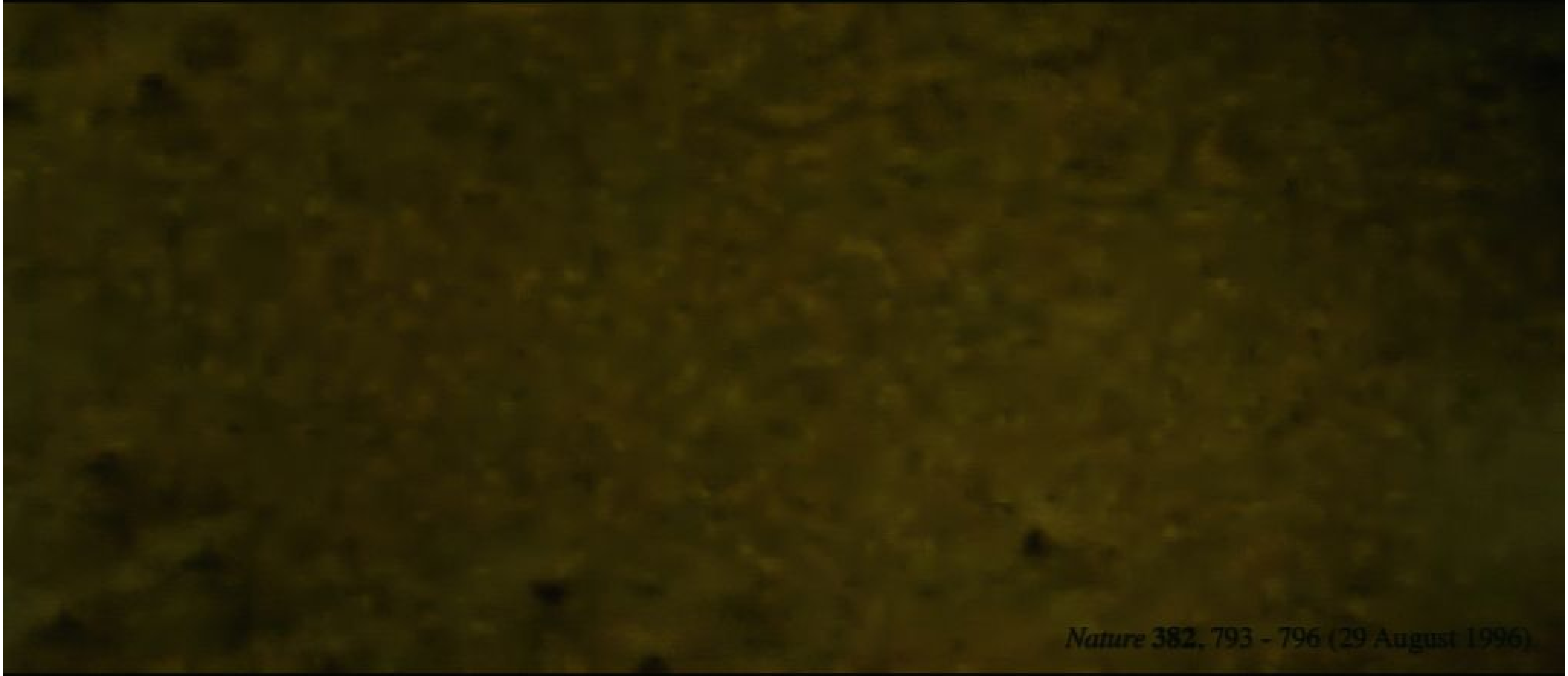

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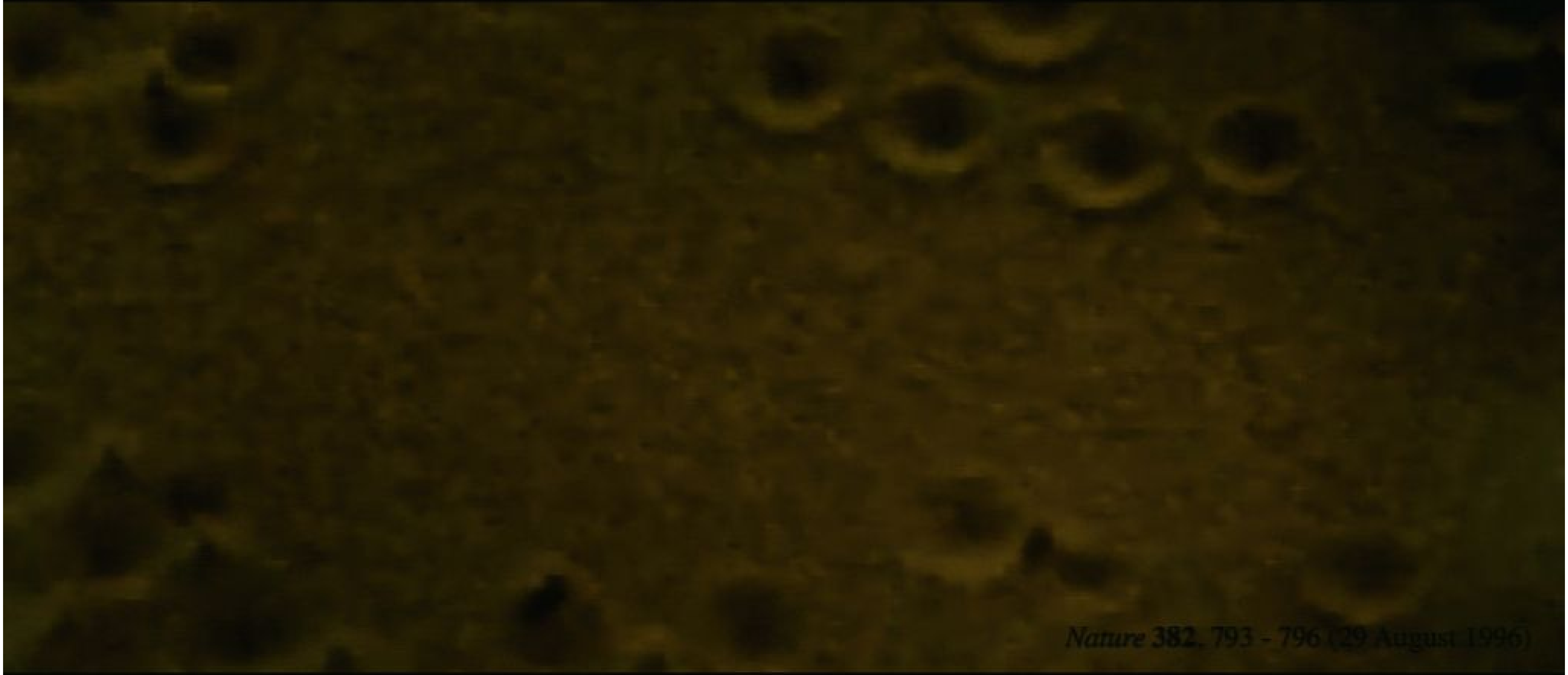

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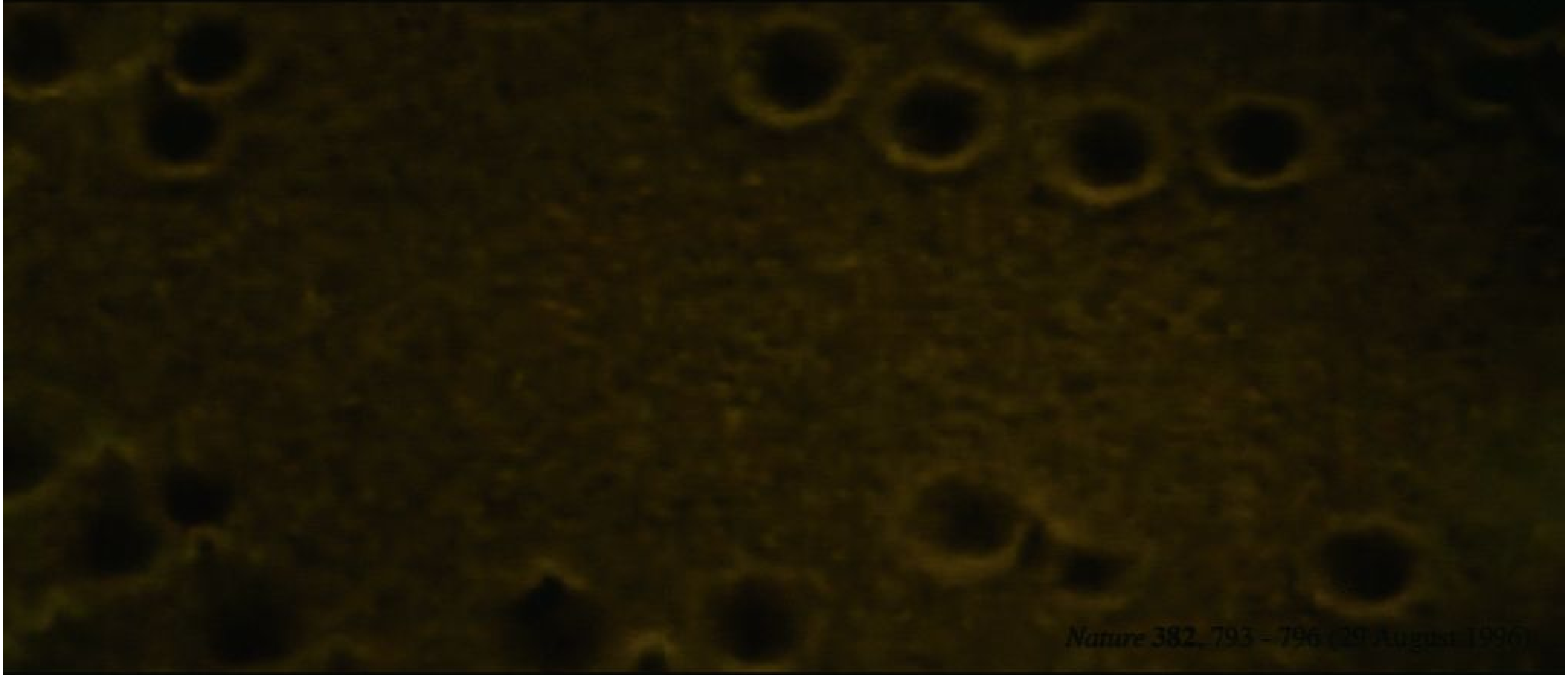

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