

Periodic string & GW bursts

Junwu Huang
July, 2025 @ IHEP



Michael Fedderke, **Junwu Huang**, and Nils Siemonsen, 2503.03116

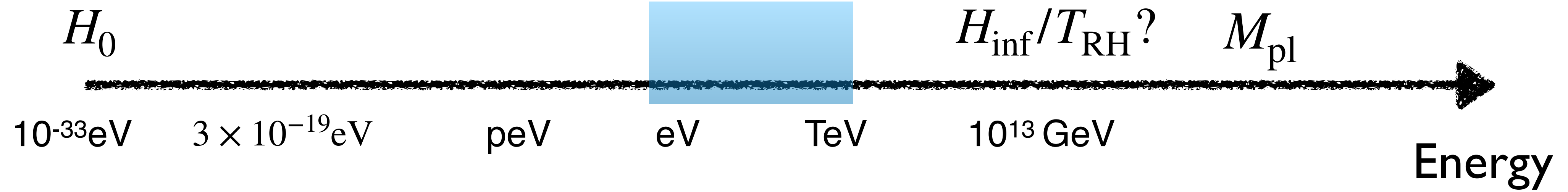
Outline

- A review of (Extremely weakly interacting) Light Bosons
- (Brief) String formation in Gauged $U(1)$ theories [Will East, Junwu Huang, 2206.12432](#)
- (Detailed) Periodic string formation in Global $U(1)$ theories [Michael Fedderke, Junwu Huang, and Nils Siemonsen, 2503.03116](#)
- Phenomenological implications

Light Bosons

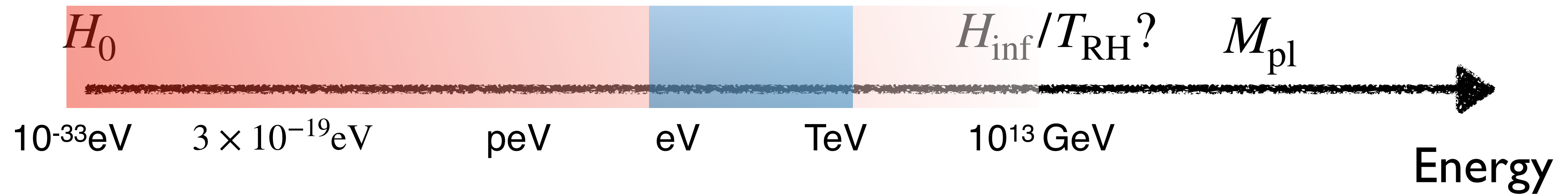
Light Bosons

Standard Model



Light Bosons

Standard Model



Light Bosons as dark matter



- Experimentally motivation
 - Dark Matter candidate Produced purely gravitationally!
- Theoretical motivation
 - Strong CP problem

Peccei and Quinn, PRL 38, 1440, 1977

Weinberg, PRL 40, 223, 1978

Wilczek, PRL 40, 279, 1978

- String Axiverse

Svrcek, Witten (2006),

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell (2009)

Light Bosons



- Light bosons as weakly interacting classical wave:



At finite density, as particles get lighter, wavelength increases, and inter-particle spacing gets smaller



When is it not weakly interacting?

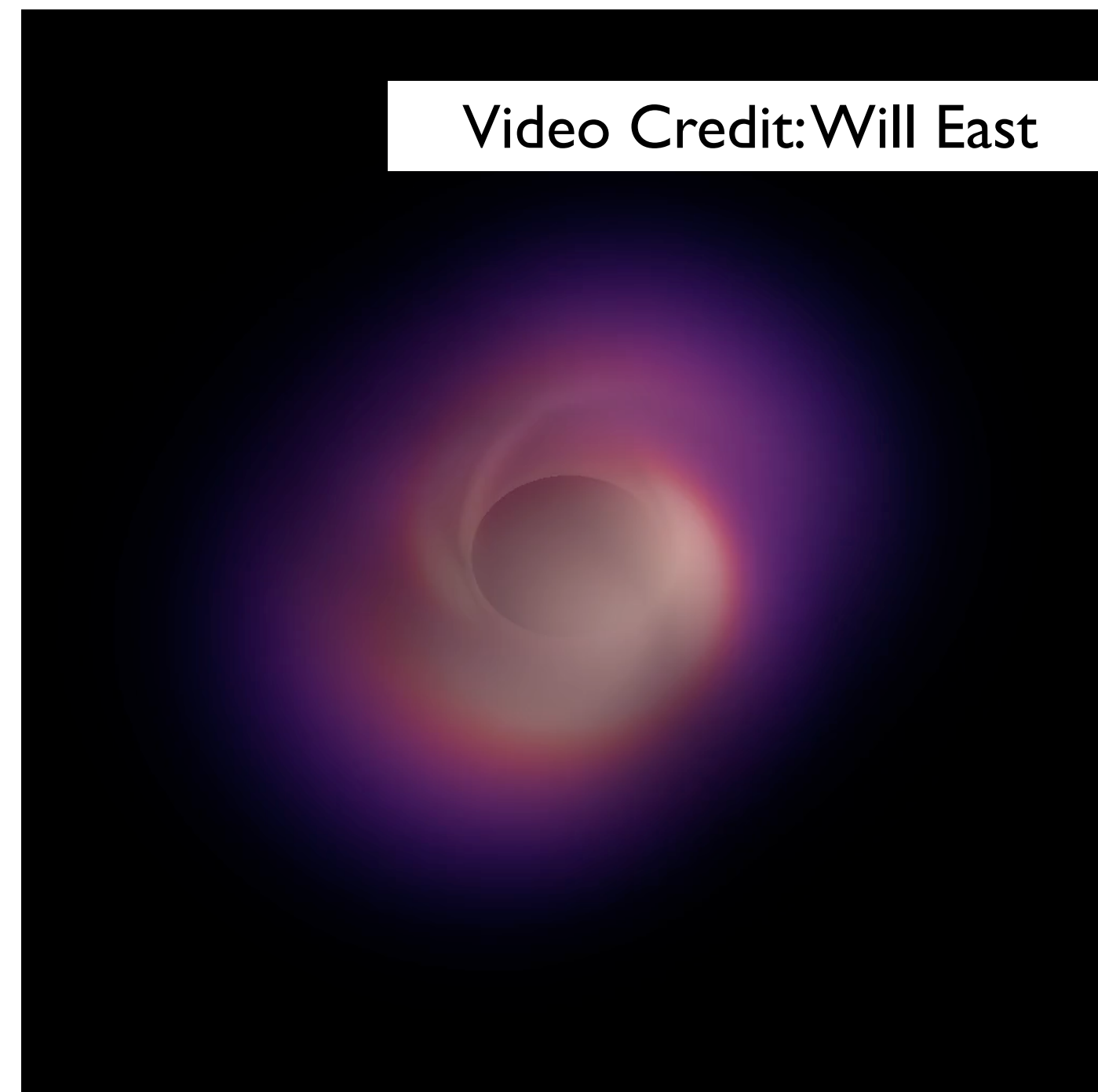
~~Weakly interacting Classical Wave~~

Critical density

New dynamics & phenomenon

Dark photon example

Will East, Junwu Huang, 2206.12432



Dark photon in the Stuckelberg limit

$$\mathcal{S} = \int d^4x \left[\frac{1}{2} \left| D'_\mu \Phi \right|^2 - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\lambda}{4} \left(|\Phi|^2 - v^2 \right)^2 \right]$$

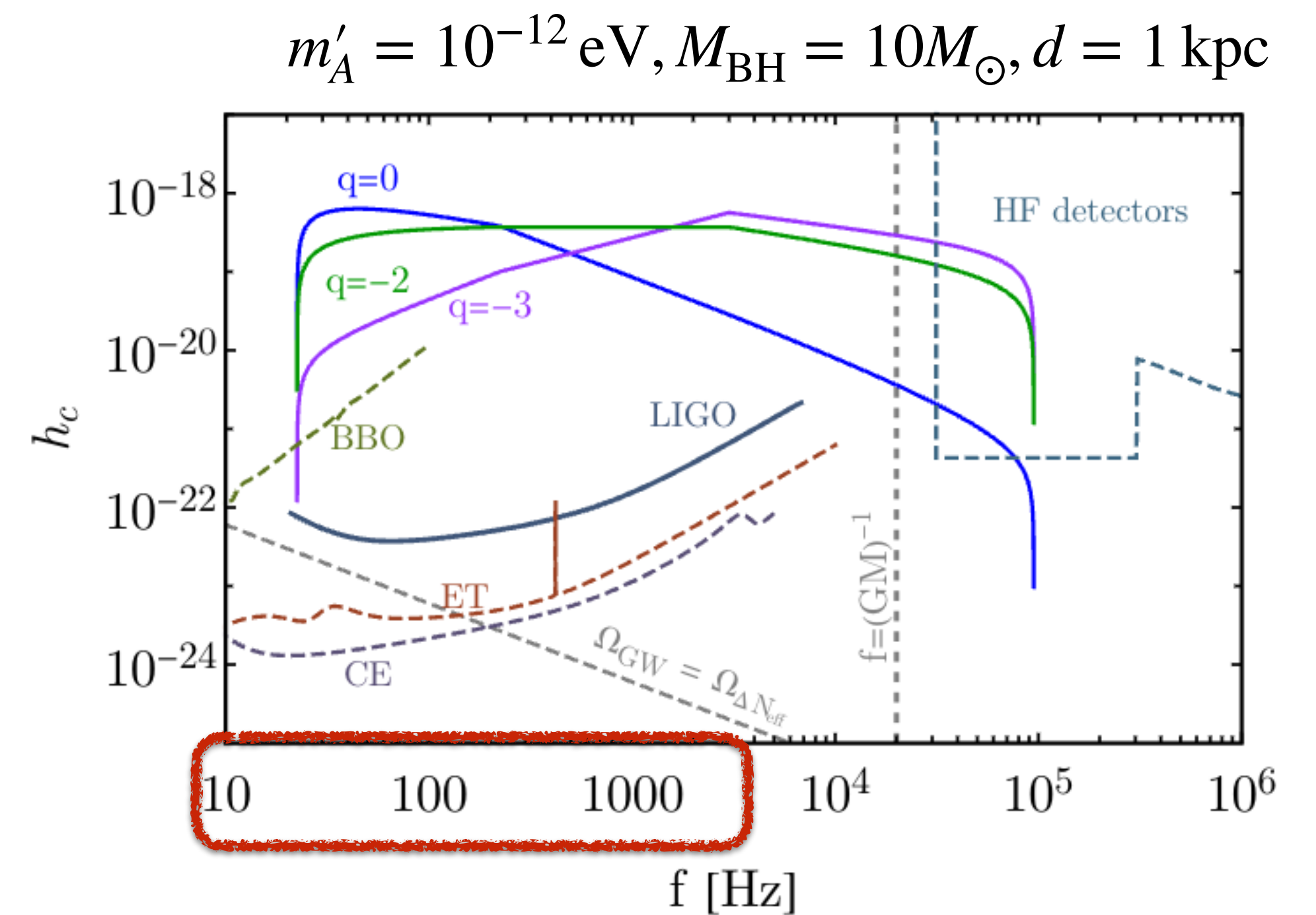
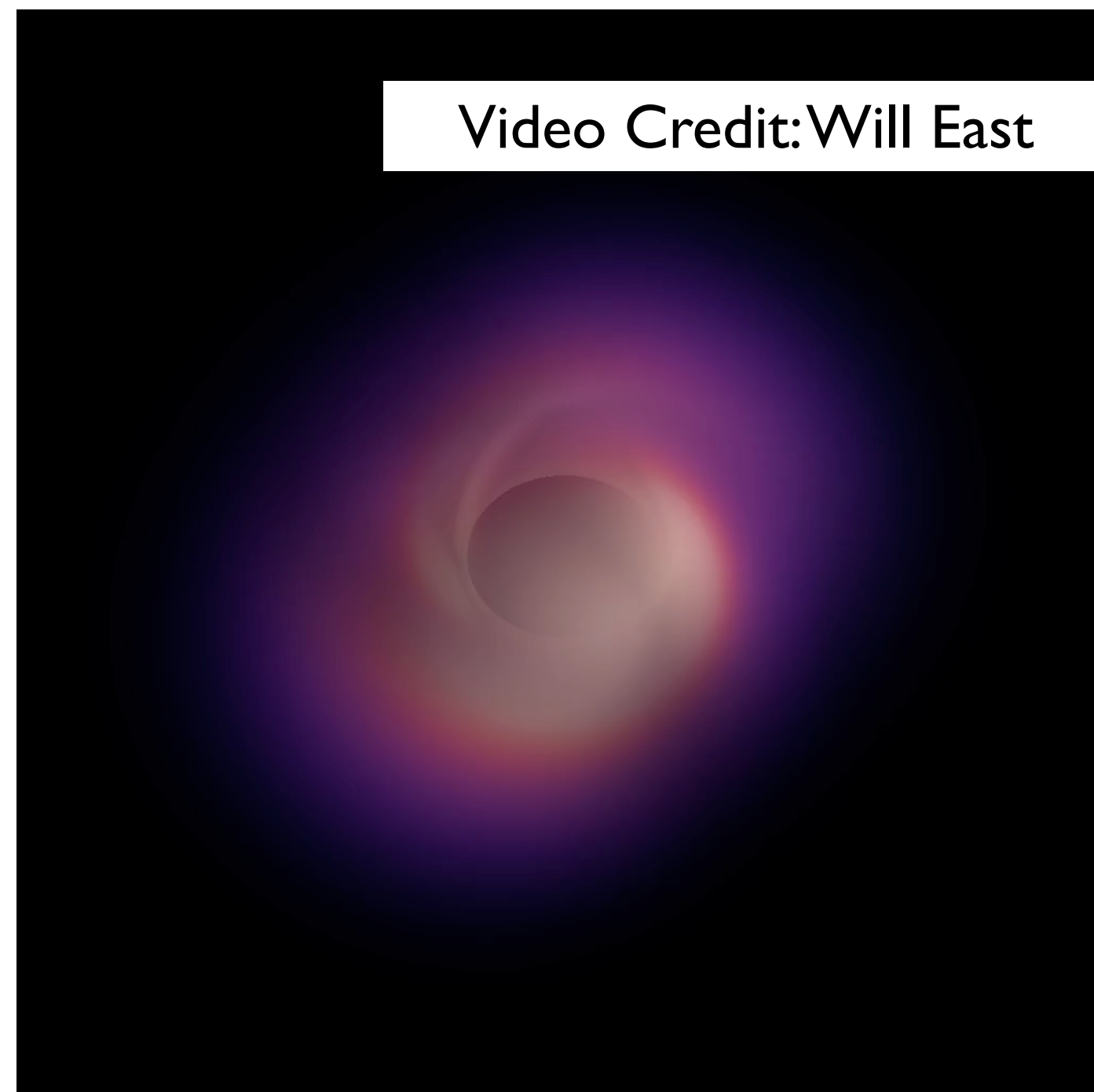
$$m_\Phi^2 / m_{A'}^2 = \lambda / g_D^2 \rightarrow \infty \quad \text{Heavy higgs, light dark photon}$$

As dark photon density (Electromagnetic field) increases, gauged strings form, which subsequently absorbs energy in the background field.

Dark photon example

Will East, Junwu Huang, 2206.12432

Dawid Brzemiński, Anson Hook, Junwu Huang, Clayton Ristow, 2407.18991



Global $U(1)$

Global U(1)

- Action with a U(1) global symmetry

$$\mathcal{S} = \int d^4x \left[\frac{1}{2} \left| \partial_\mu \Phi \right|^2 - \frac{\lambda}{4} \left(\left| \Phi \right|^2 - v^2 \right)^2 \right],$$

$$\Phi(\vec{x}, t) \equiv \rho(\vec{x}, t) e^{i\theta(\vec{x}, t)}$$

- Conserved current:

$$j^\mu \equiv \frac{i}{2} \left[\Phi \partial^\mu \Phi^* - \Phi^* \partial^\mu \Phi \right] = \rho^2 \partial^\mu \theta$$

Global U(1)

- Action with a U(1) global symmetry

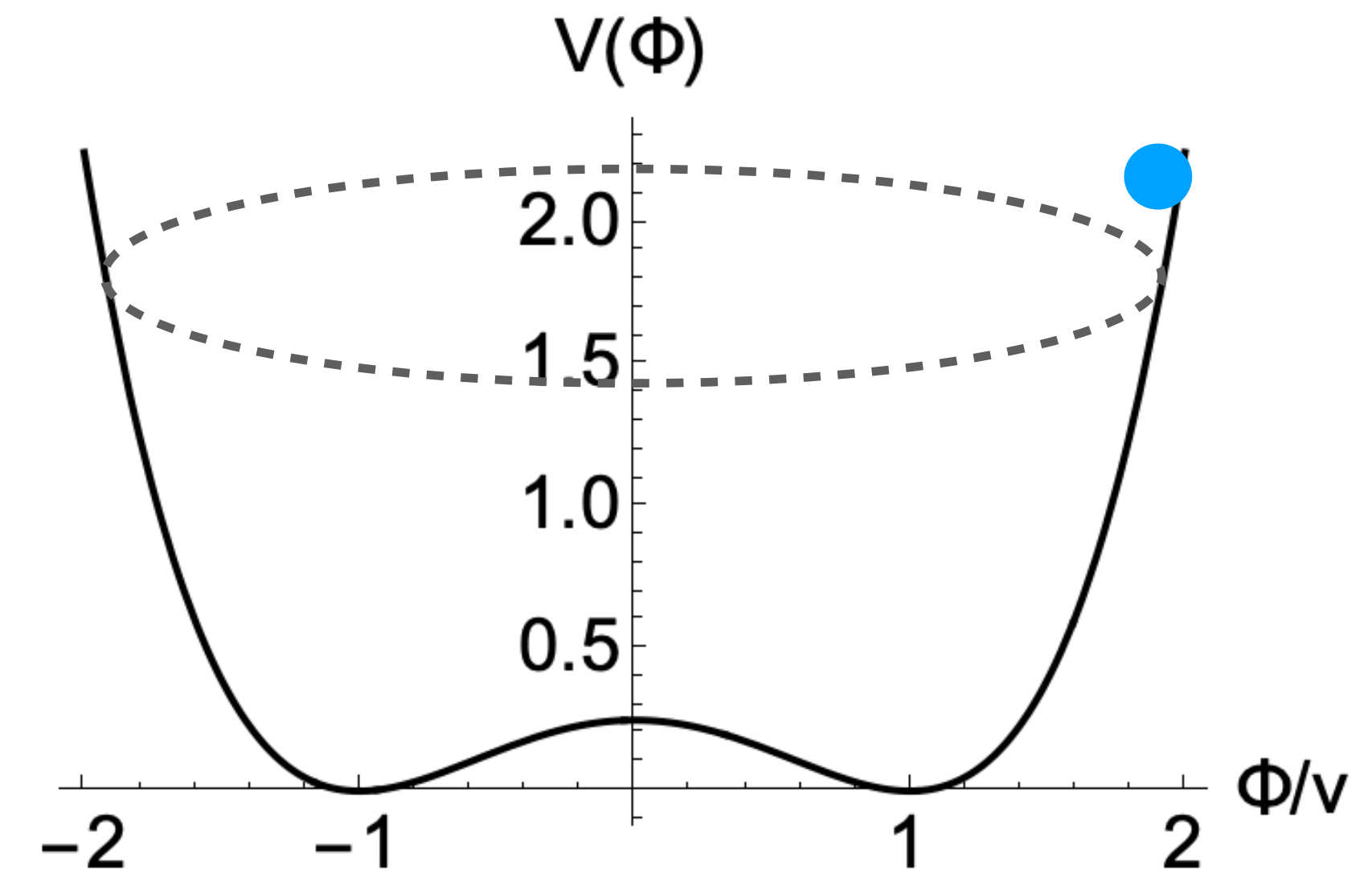
$$\mathcal{S} = \int d^4x \left[\frac{1}{2} |\partial_\mu \Phi|^2 - \frac{\lambda}{4} (|\Phi|^2 - v^2)^2 \right],$$

$$\Phi(\vec{x}, t) \equiv \rho(\vec{x}, t) e^{i\theta(\vec{x}, t)}$$

- Conserved current:

$$j^\mu \equiv \frac{i}{2} [\Phi \partial^\mu \Phi^* - \Phi^* \partial^\mu \Phi] = \rho^2 \partial^\mu \theta$$

Consider the field dynamics in an expanding universe



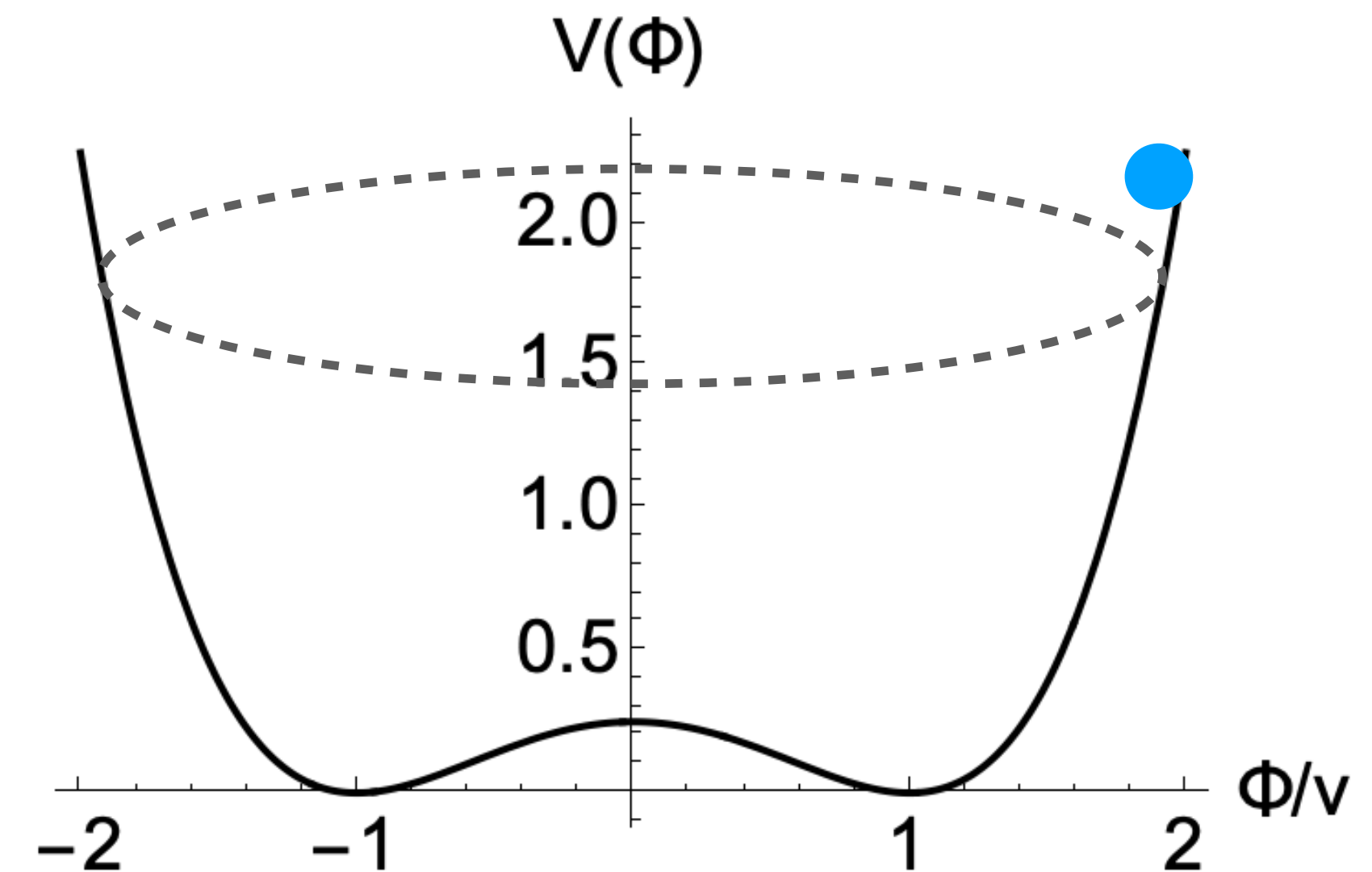
Tkachev, Khlebnikov, Kofman, Linde, hep-ph/9805209
Co, Hall, Harigaya 1711.10486 and more

Why you should care?

- Small initial charge density
 - Reheating after inflation

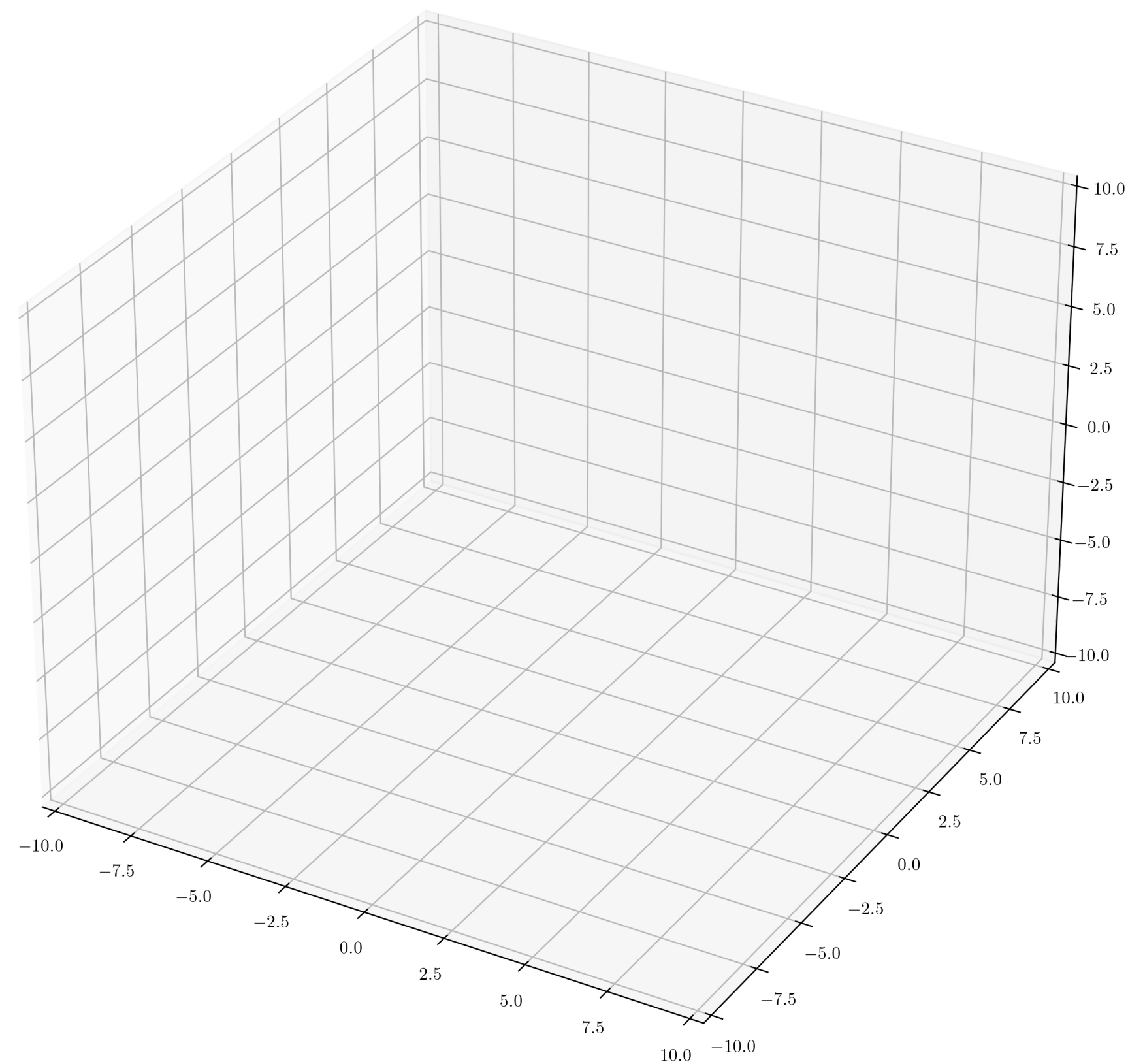
[Tkachev, Khlebnikov, Kofman, Linde, hep-ph/9805209](#)

- A unique GW signal
- Large initial charge density
 - Setting up Kination?
 - Baryogenesis (Affleck Dine)
 - Axion production [Co, Hall, Harigaya 1711.10486 and more](#)
 - Higgs inflation and reheating



Periodic String Burst

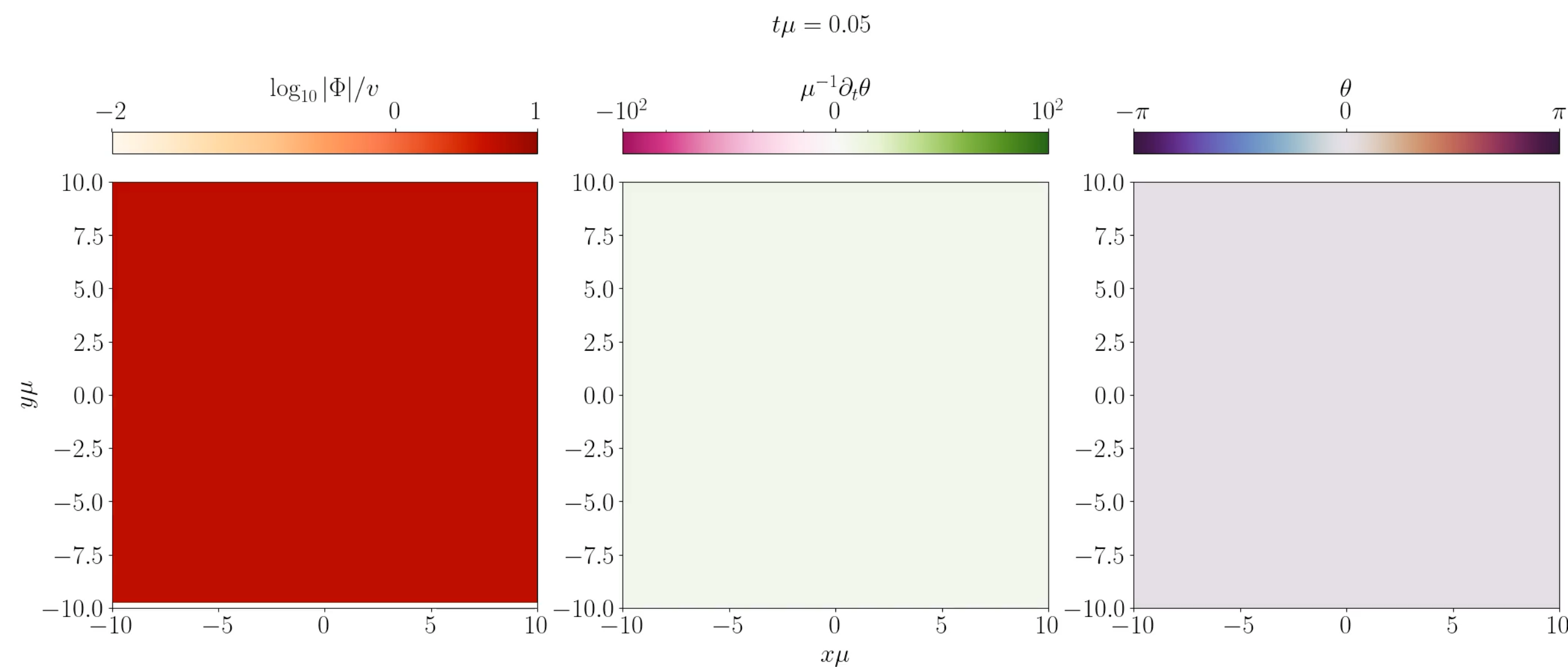
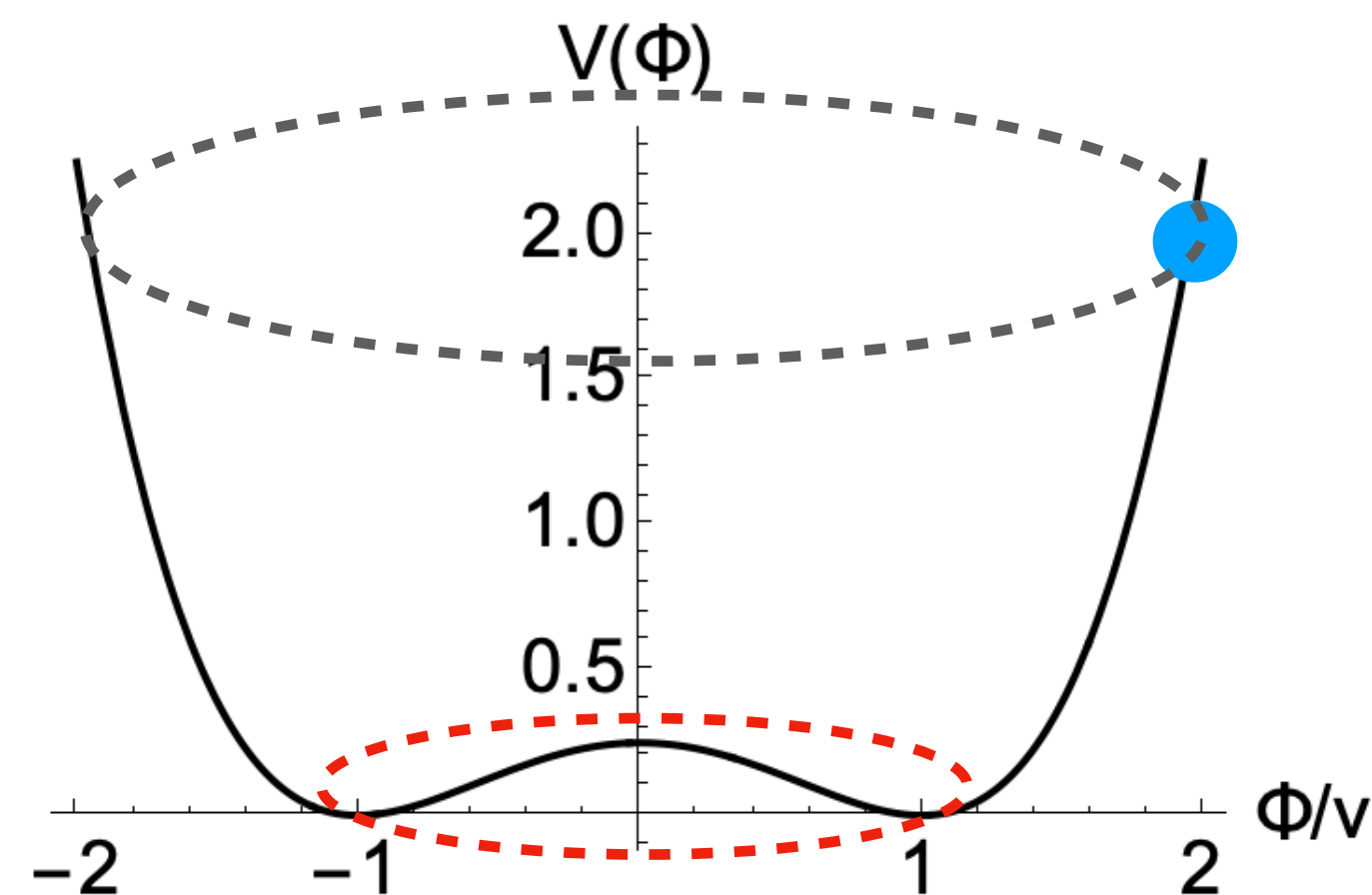
Video Credit: Nils Siemonsen



~~Cosmic Evolution~~

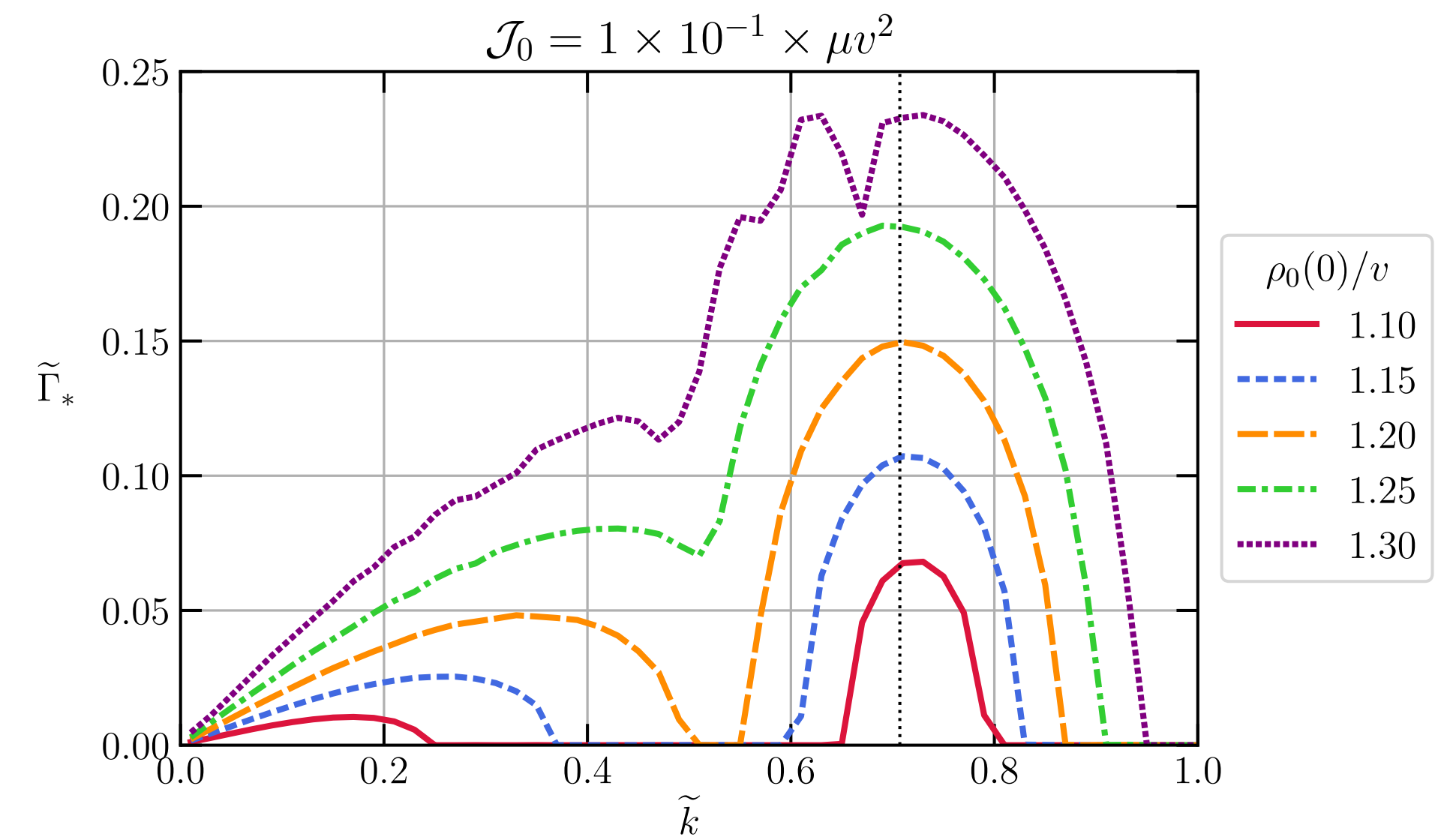
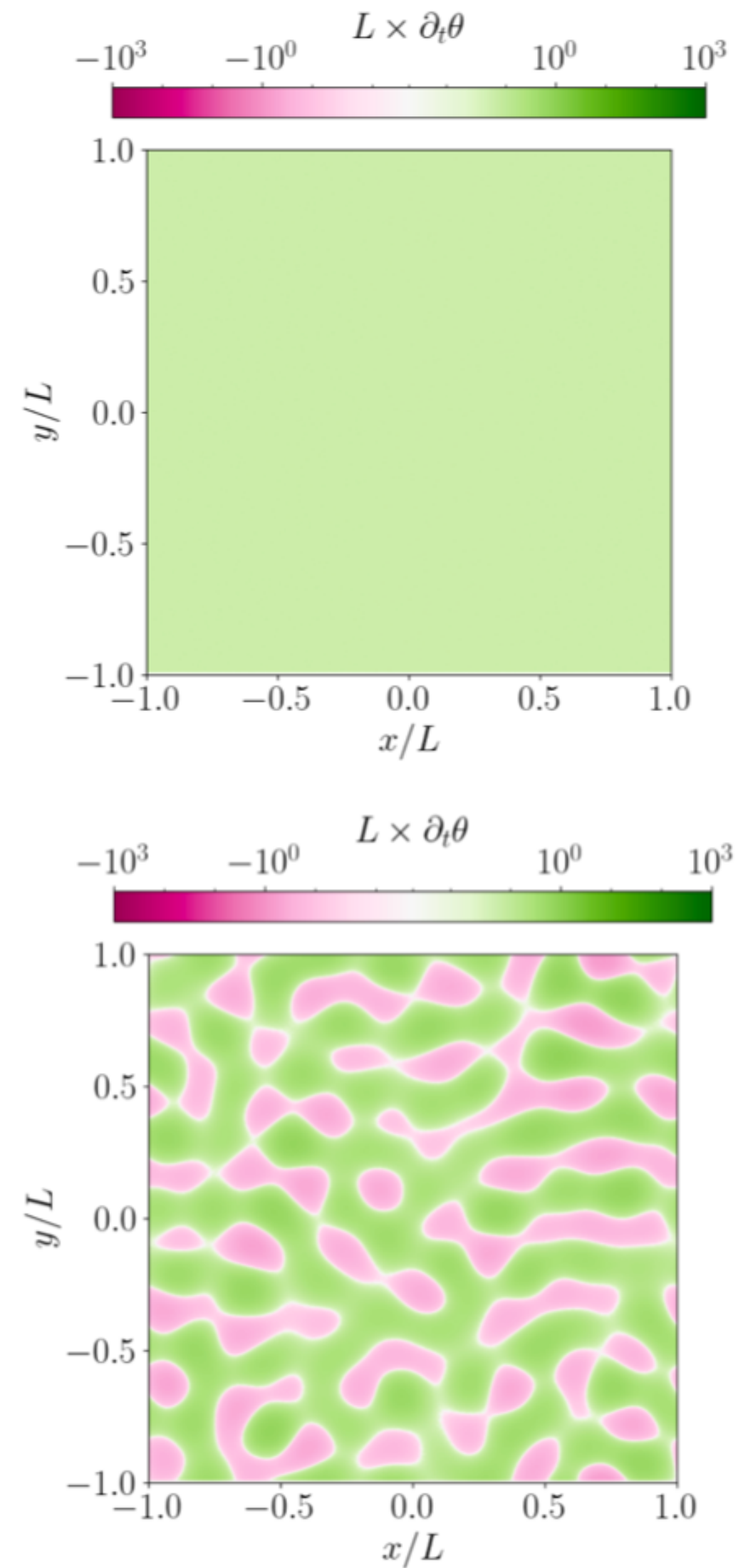
$$J^0 \ll \lambda^{1/2} v^3 = \mu v^2, H = 0$$

Video Credit: Nils Siemonsen



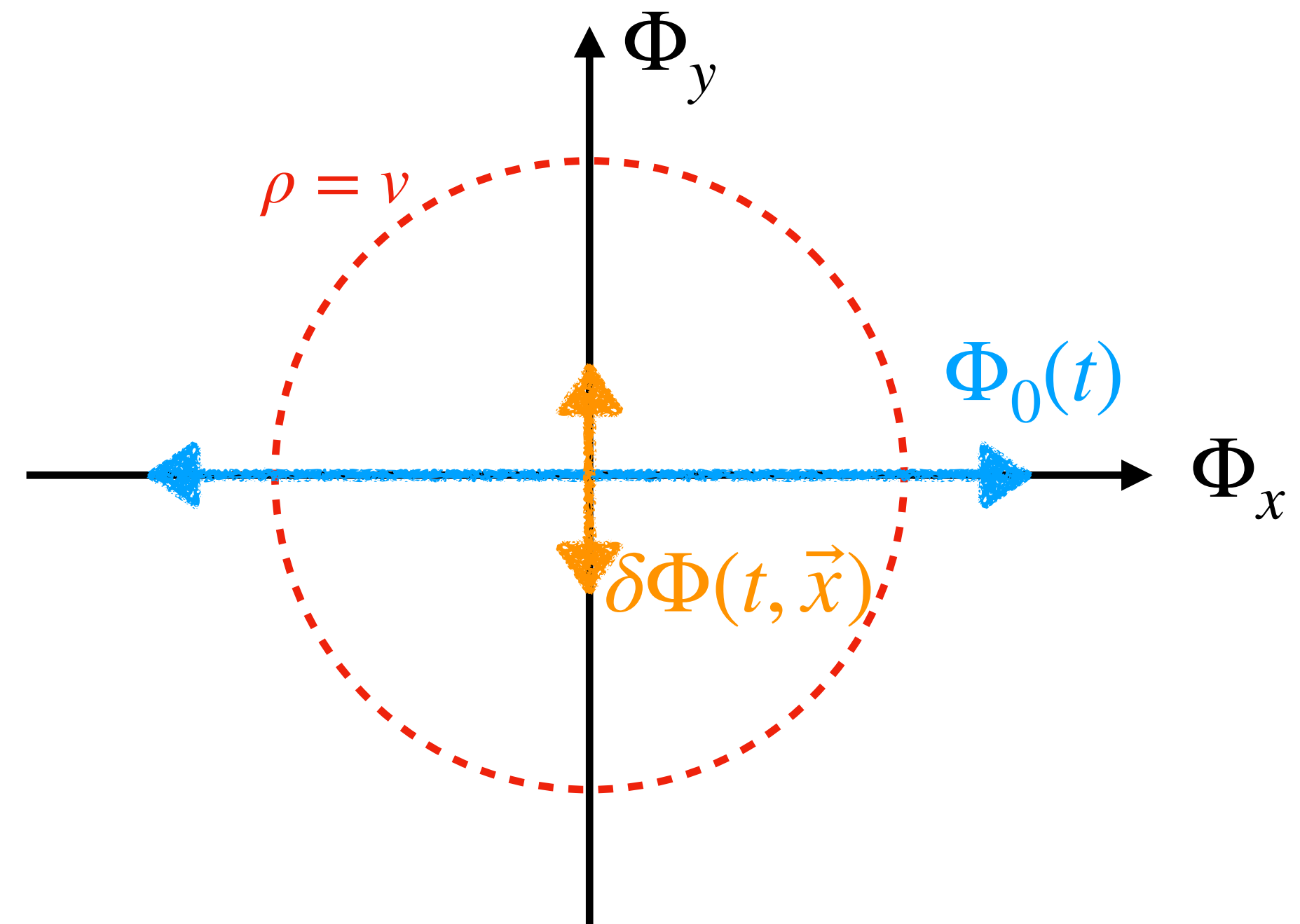
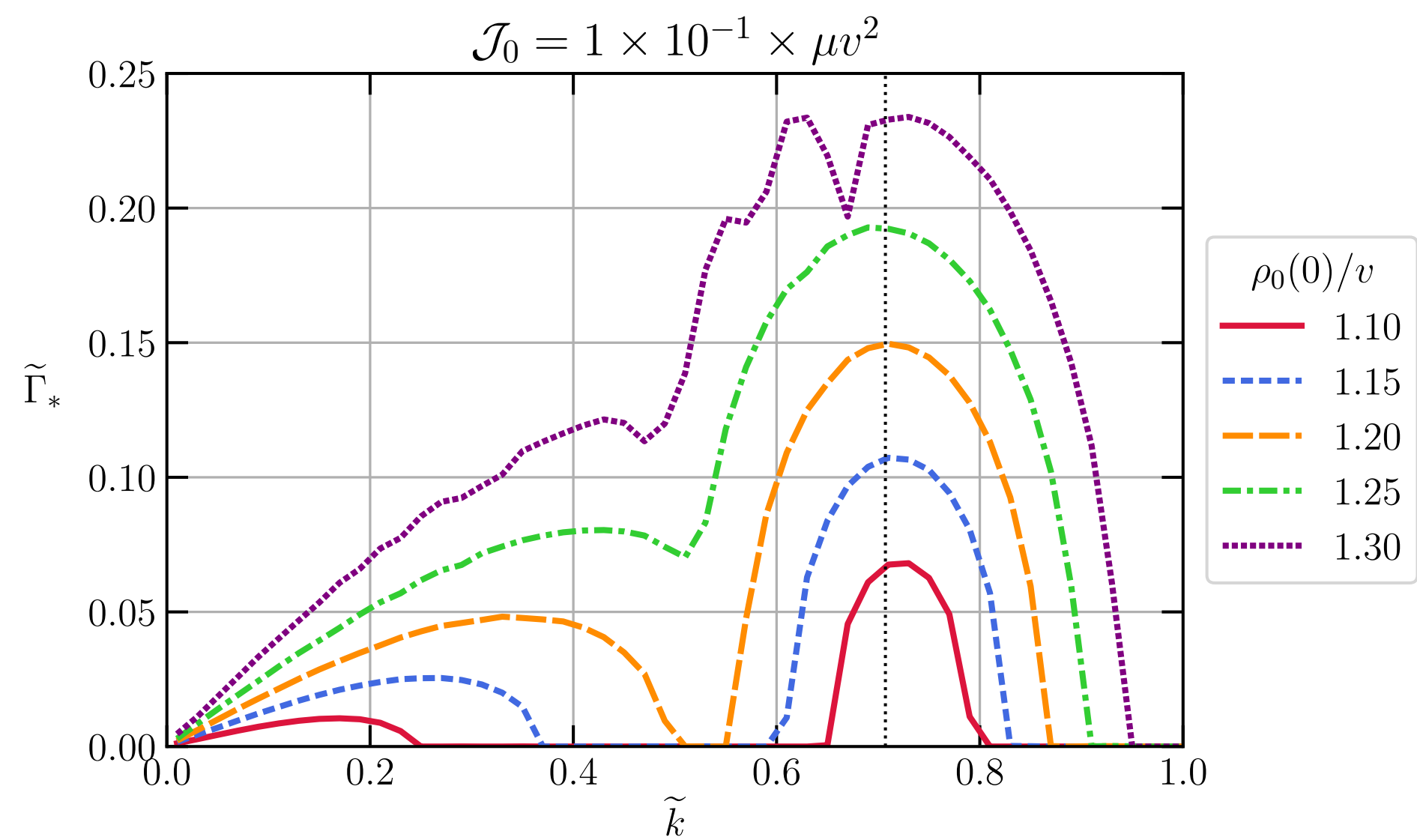
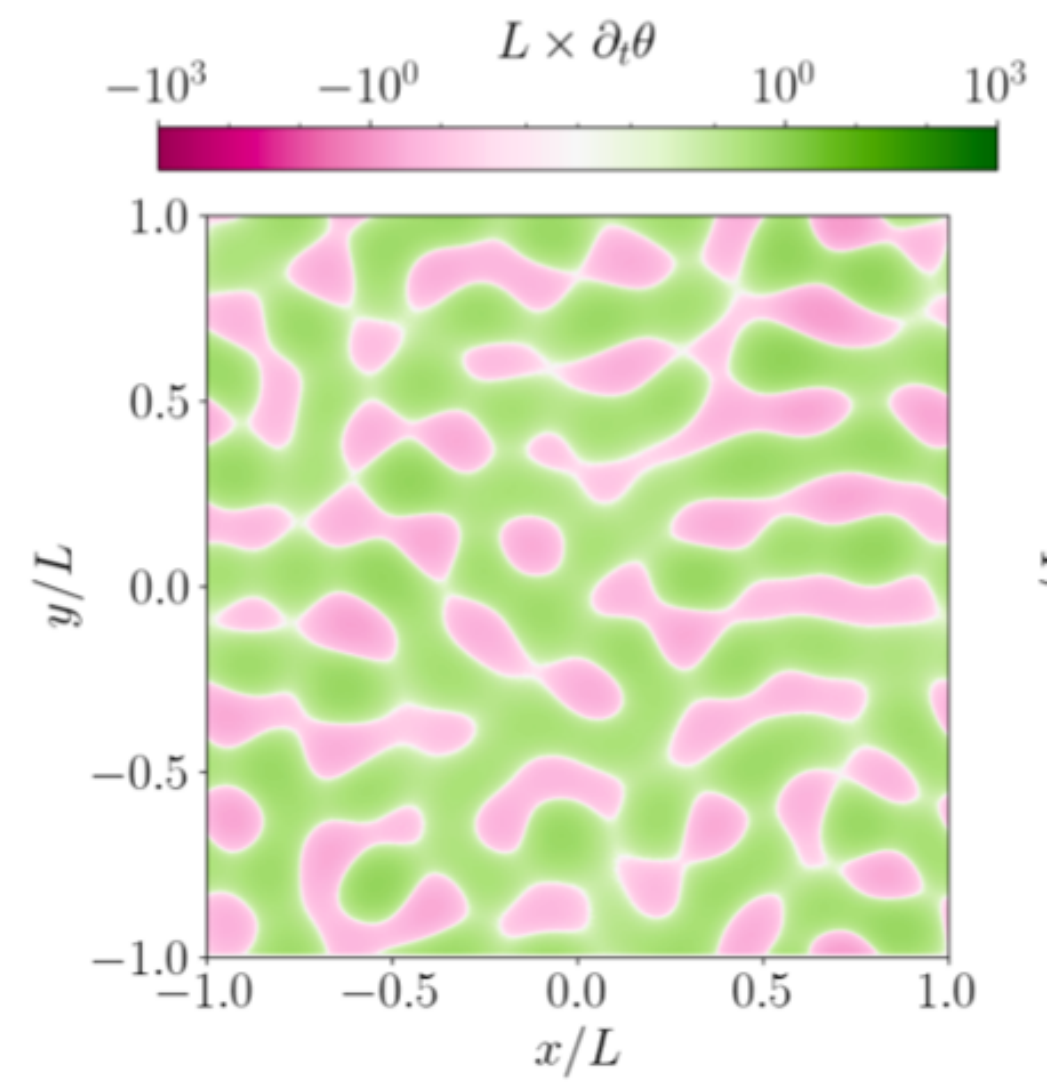
We numerically solve the system in 2D (shown here) and 3D (to come) with an initially displaced radial mode

Parametric Resonance

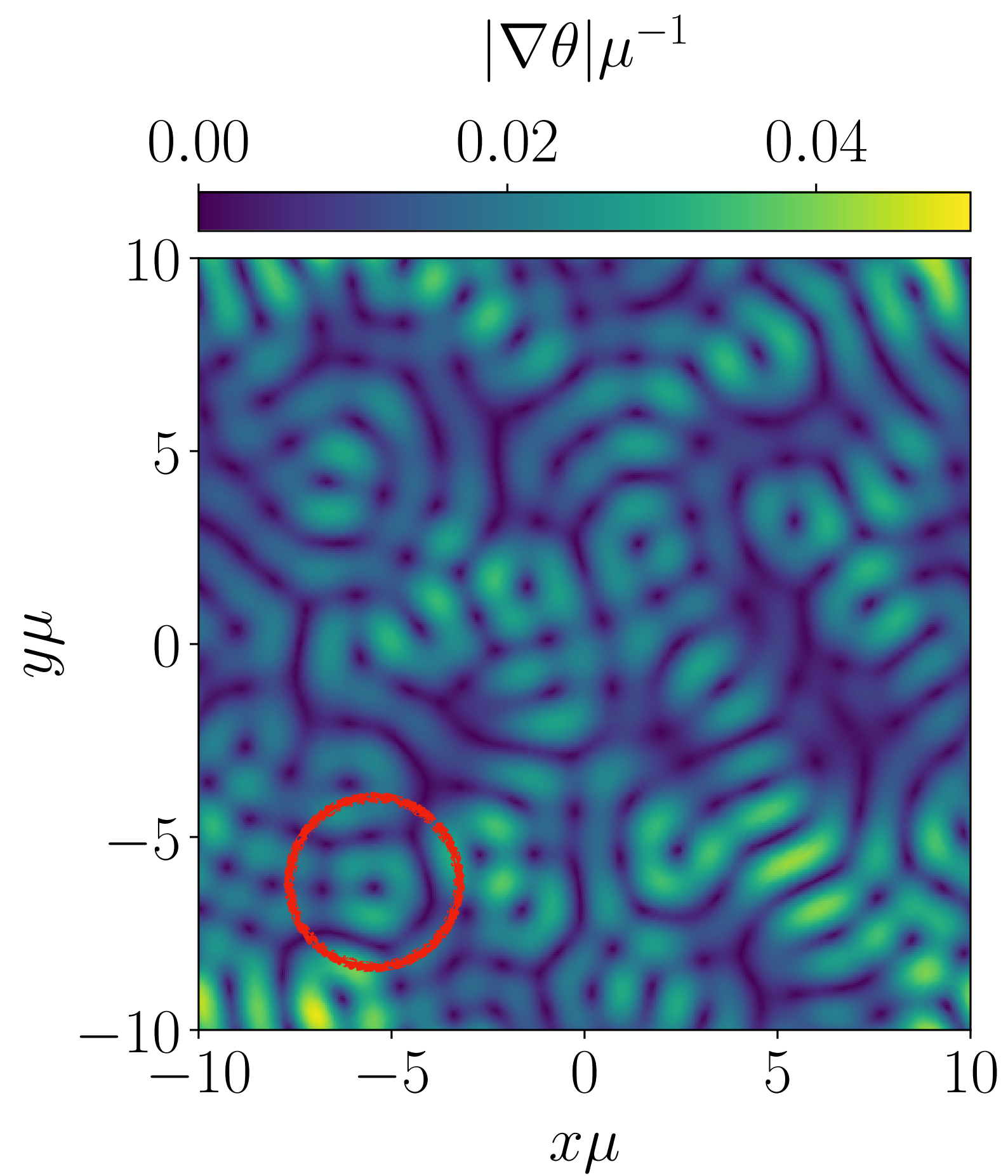
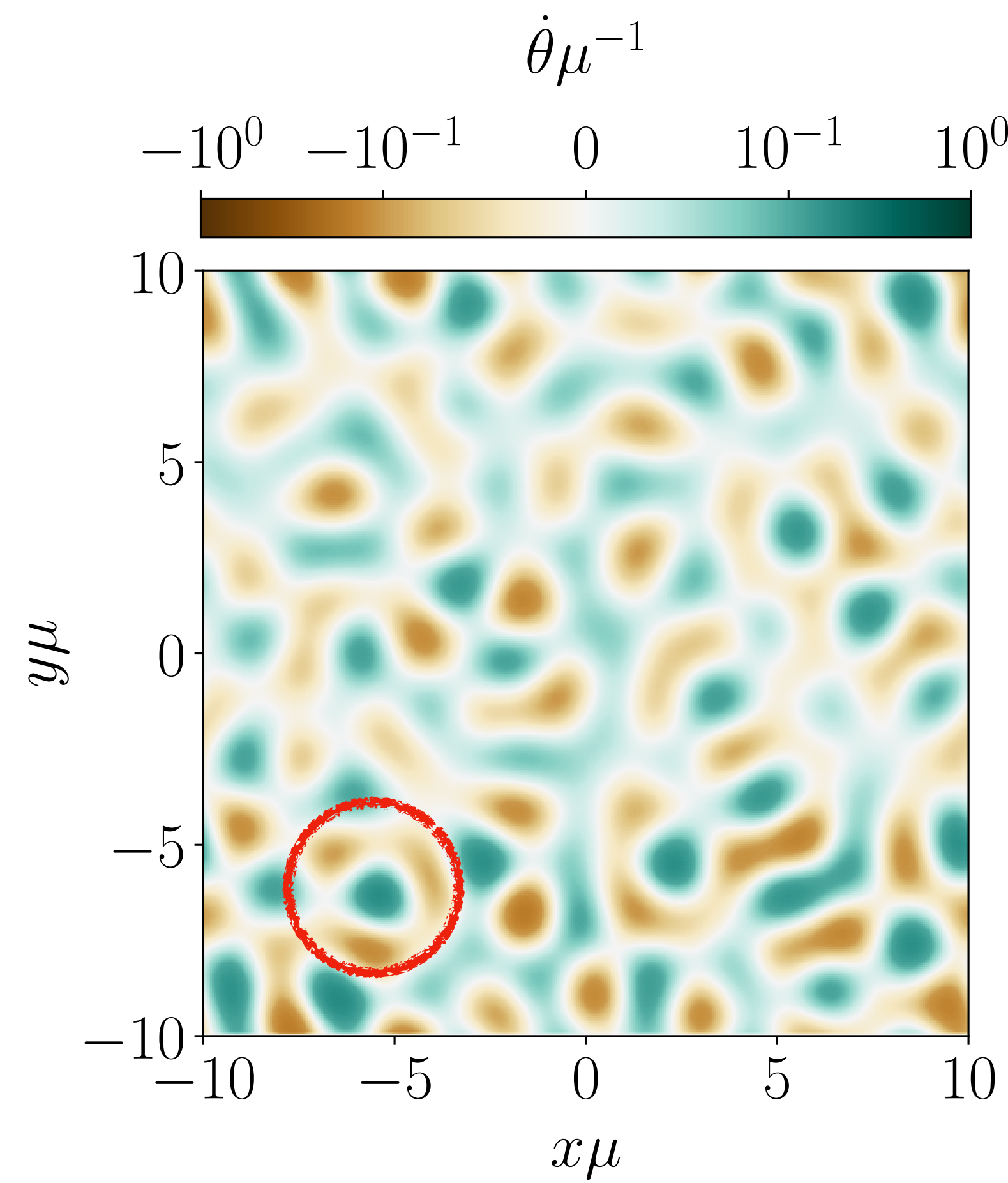


Tkachev, Khlebnikov, Kofman, Linde, hep-ph/9805209
Co, Hall, Harigaya 1711.10486 and more

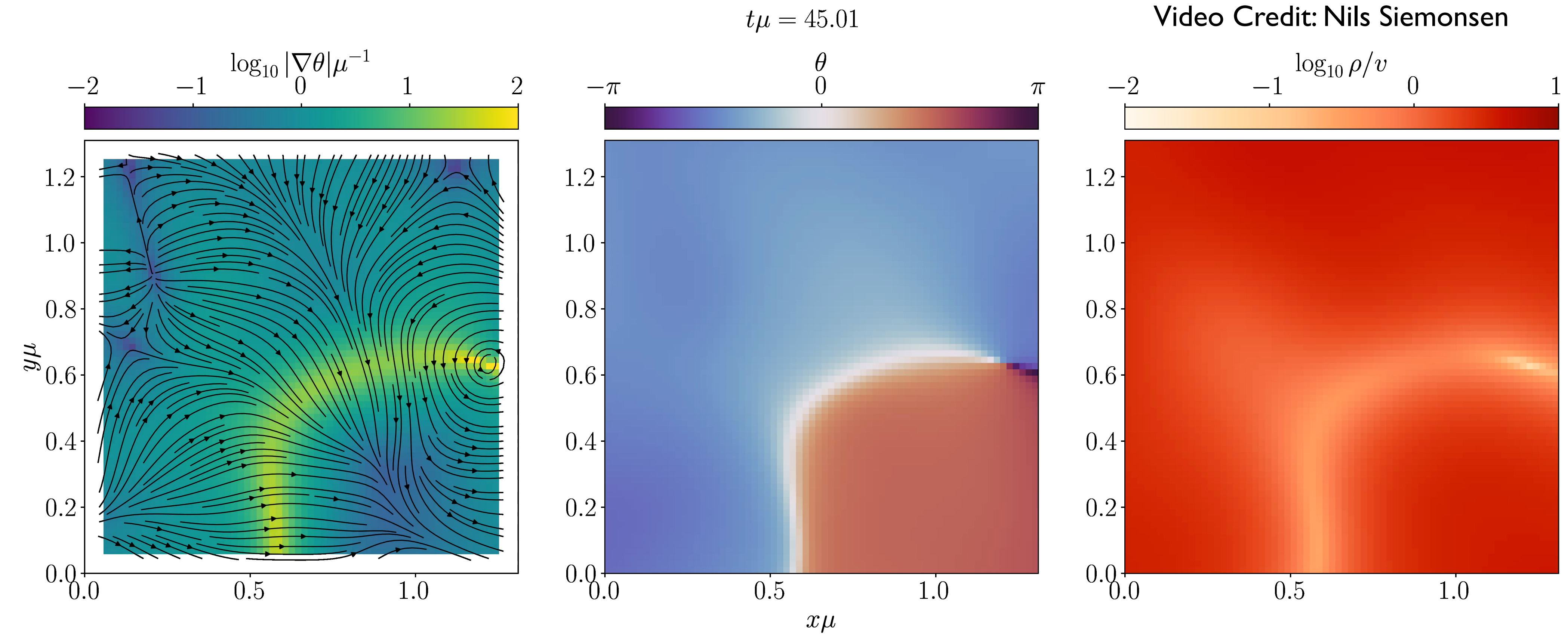
Parametric Resonance



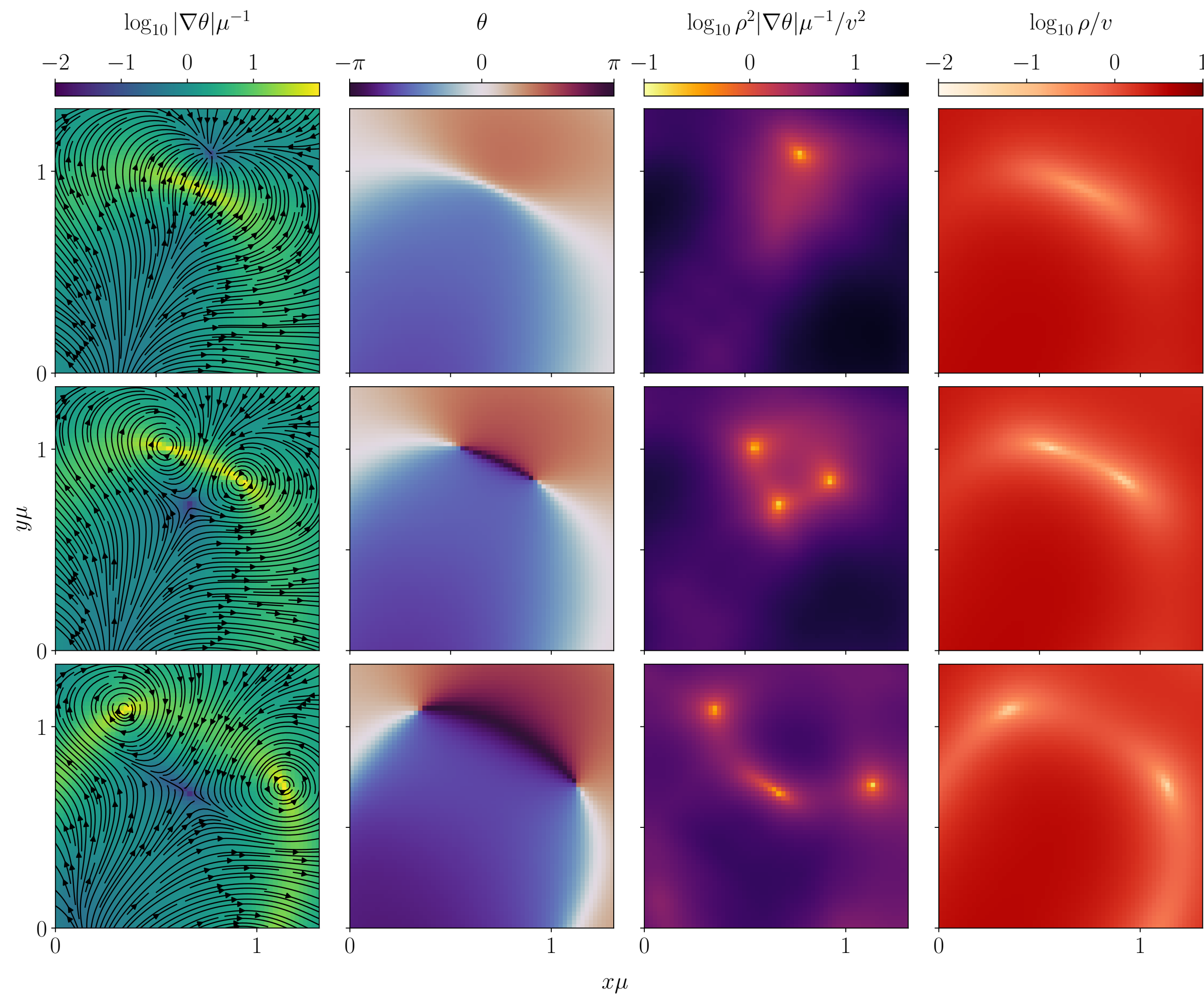
Counter rotation



Vortex formation



Vortex formation

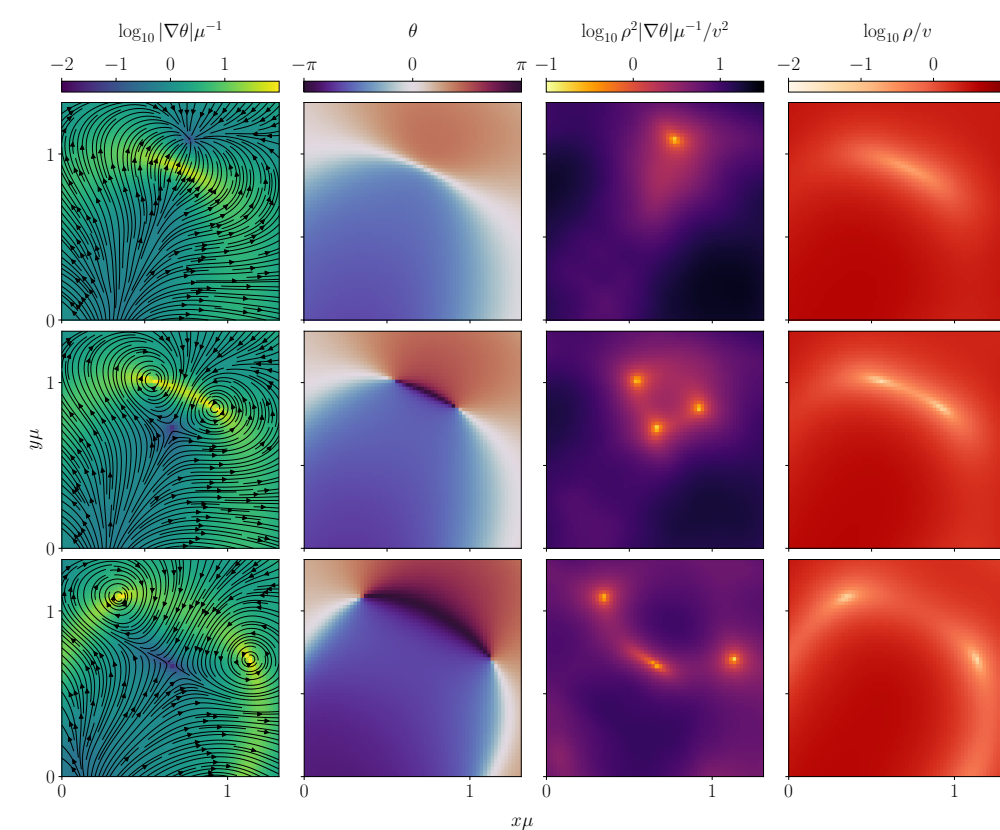
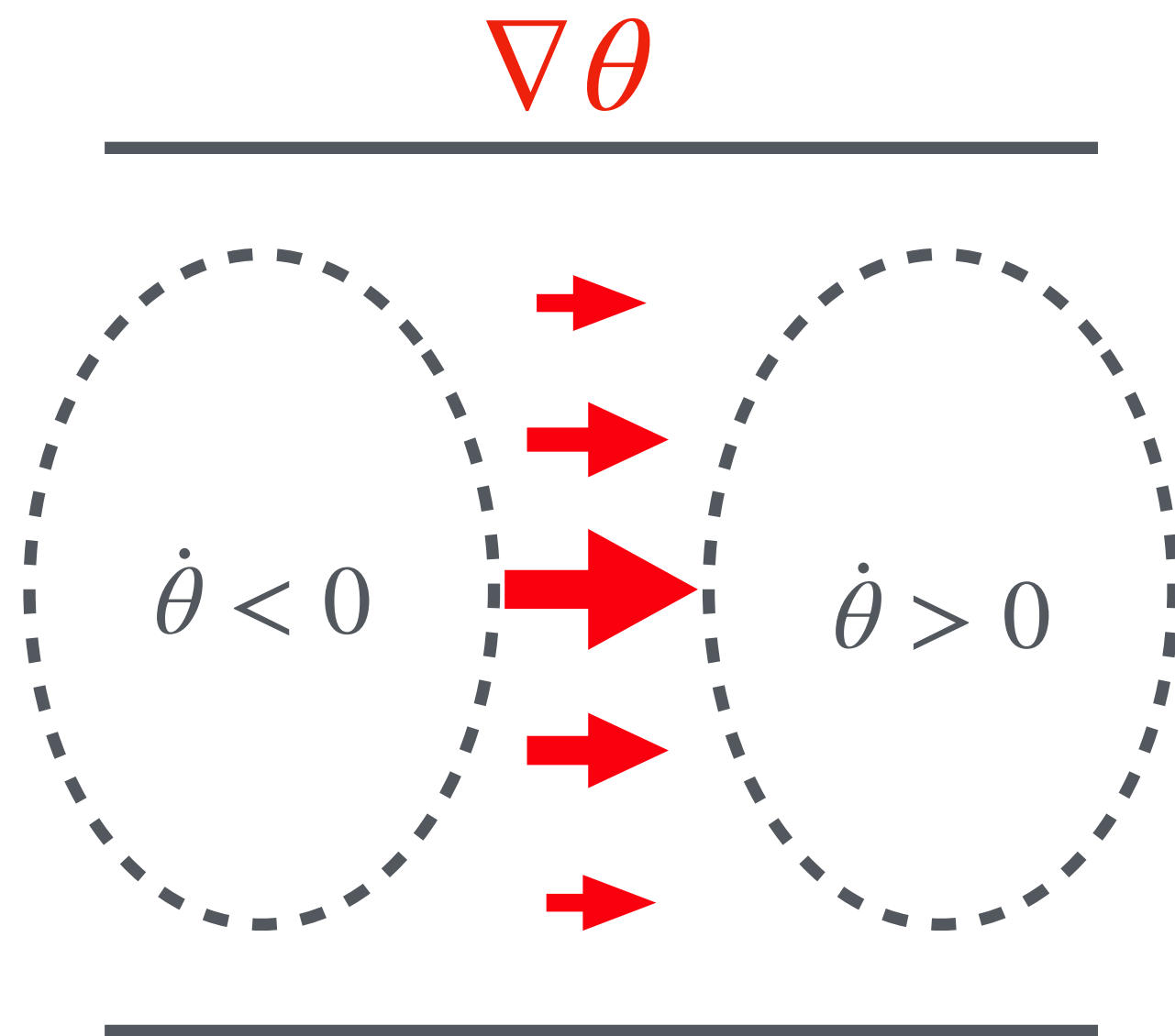


Counter rotating region form
(Zoom in view of the domain boundary)

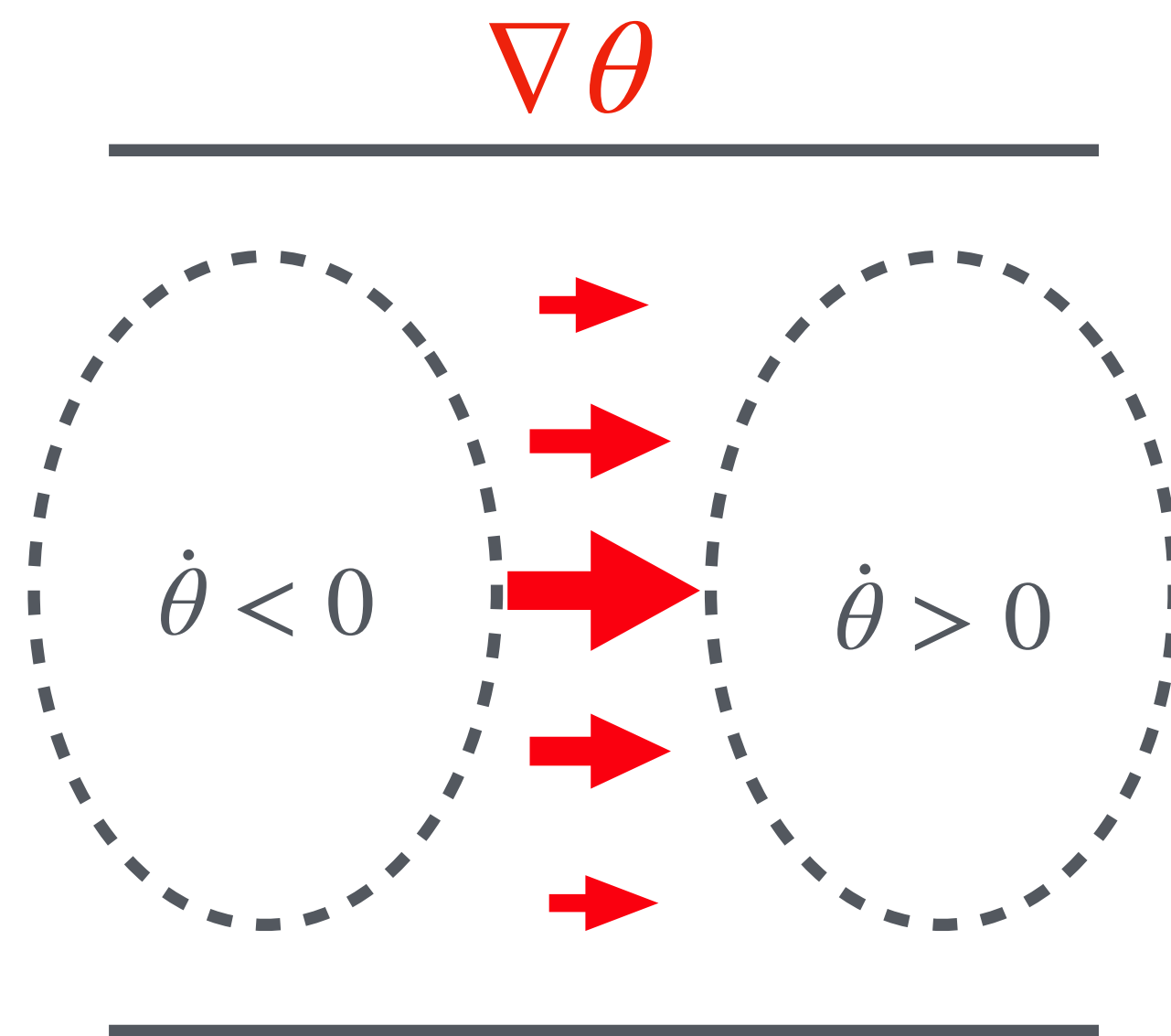
Vortex form

Vortex move apart confined
along the domain boundary

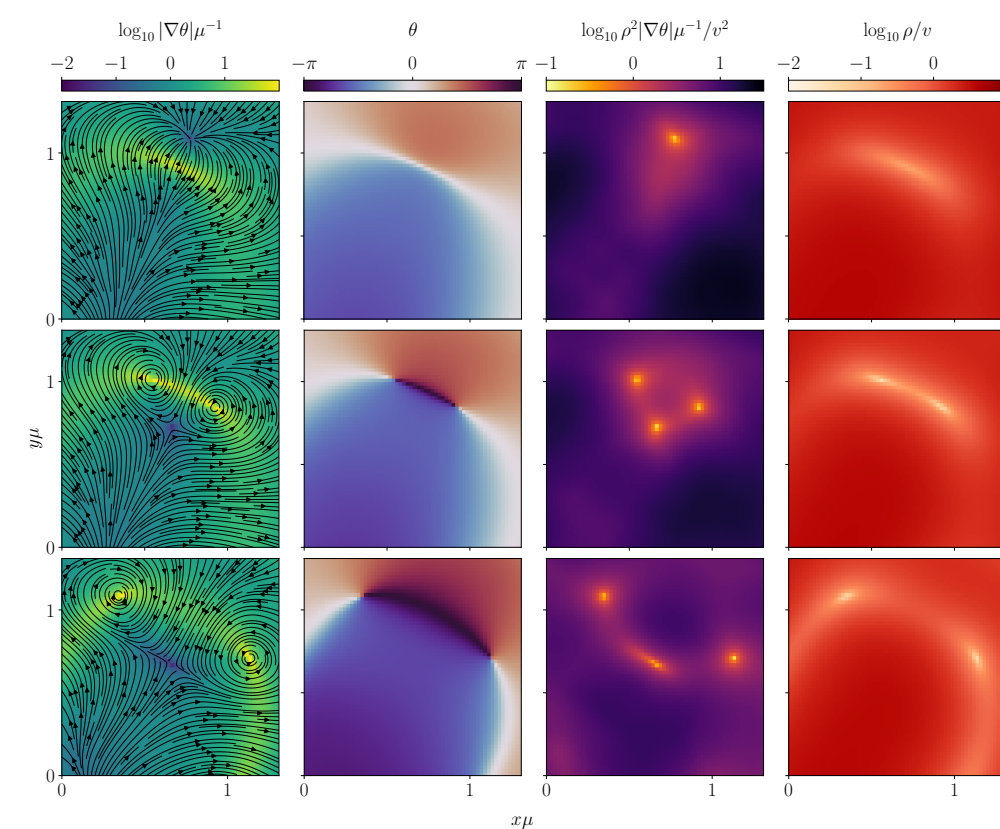
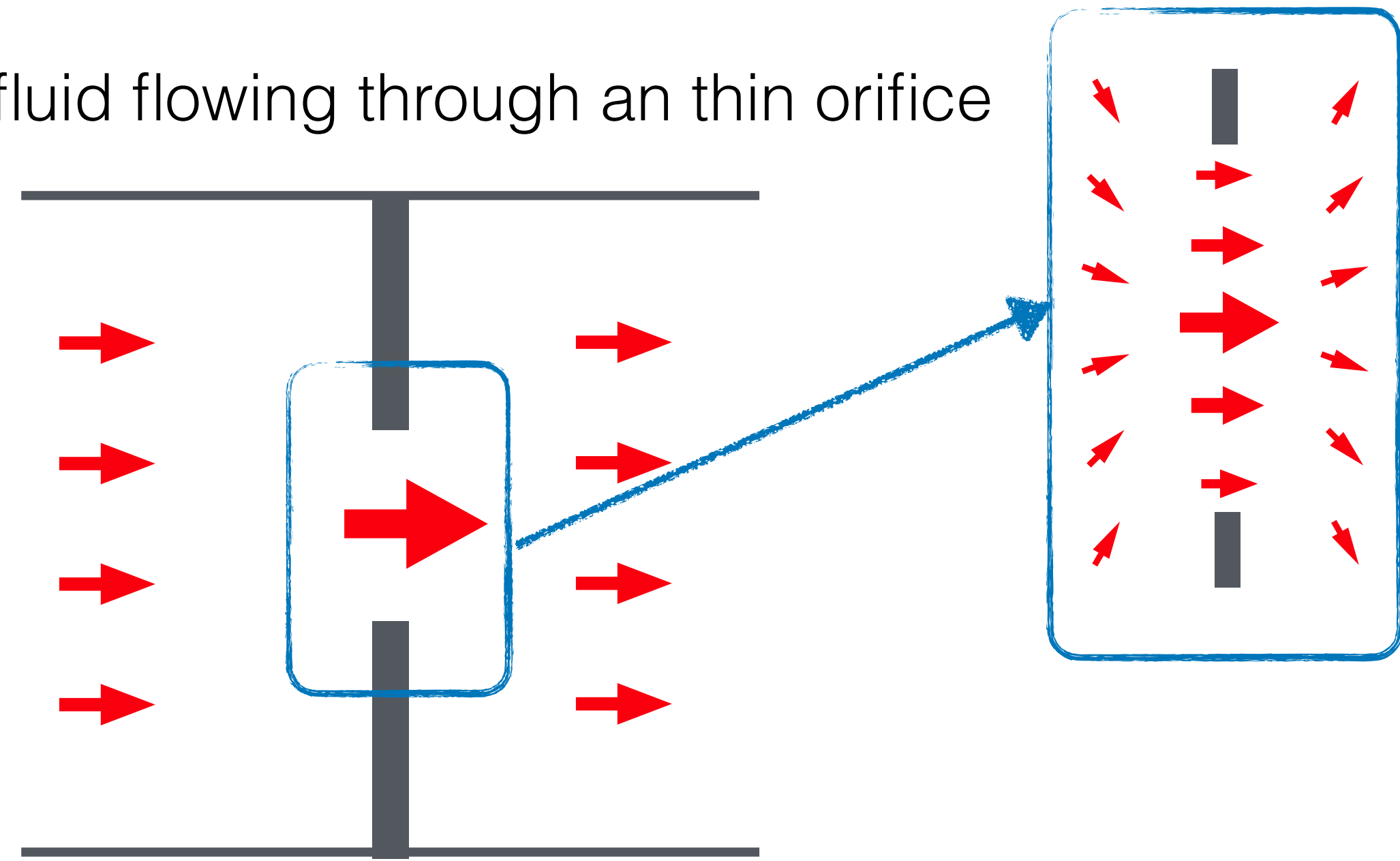
Vortex formation condition



Vortex formation condition

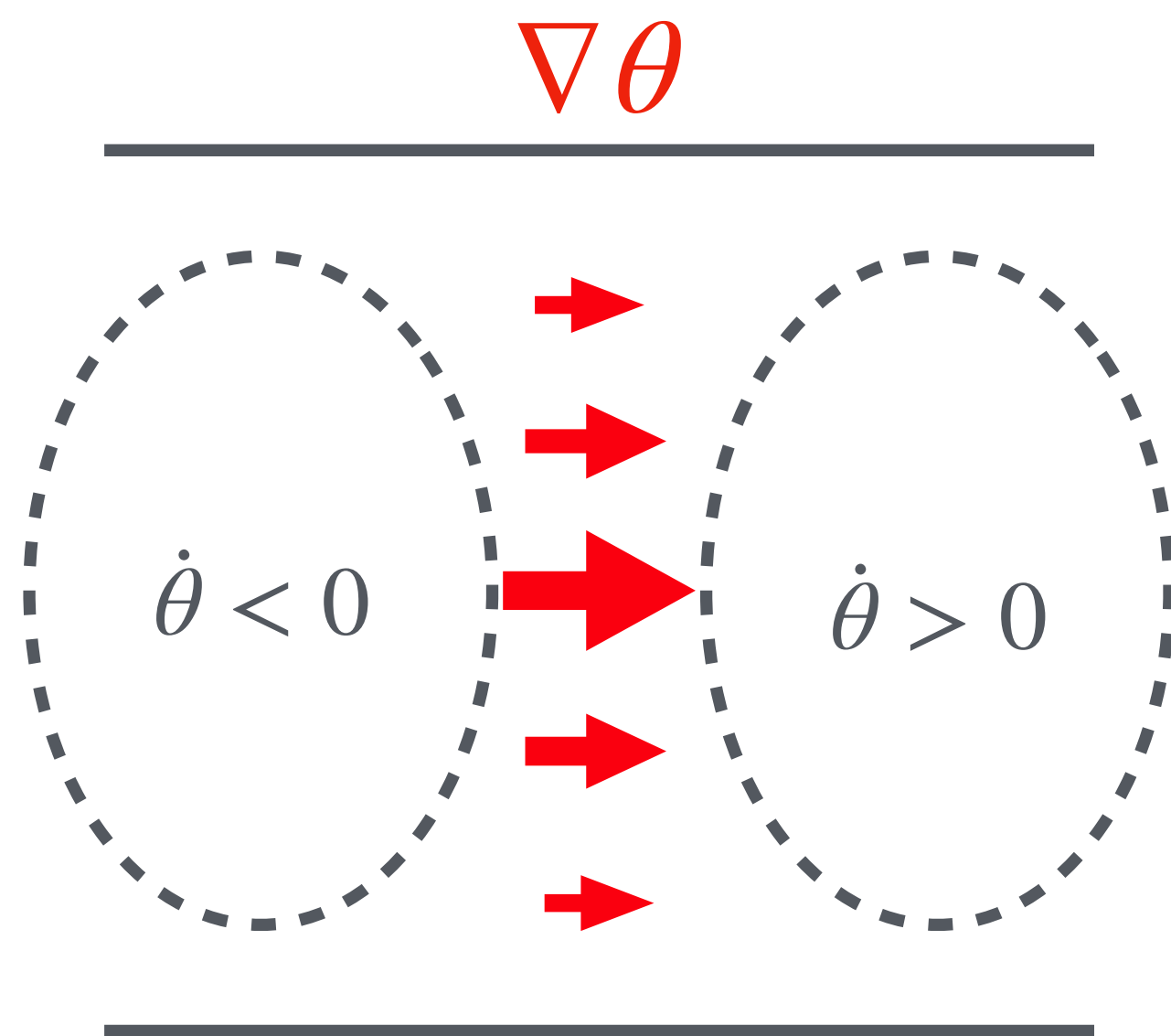


Superfluid flowing through an thin orifice

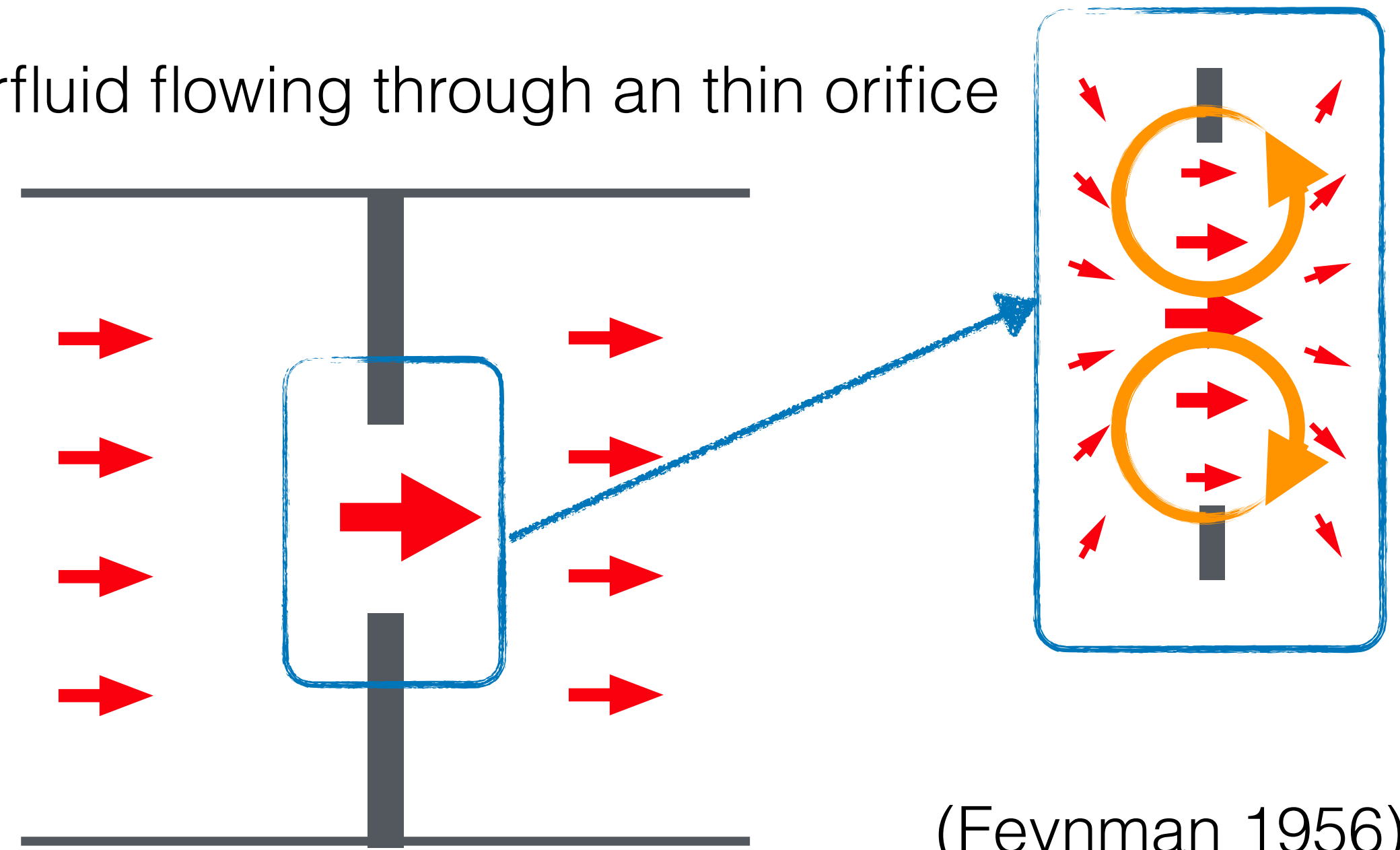


Useful analogy: Superfluid

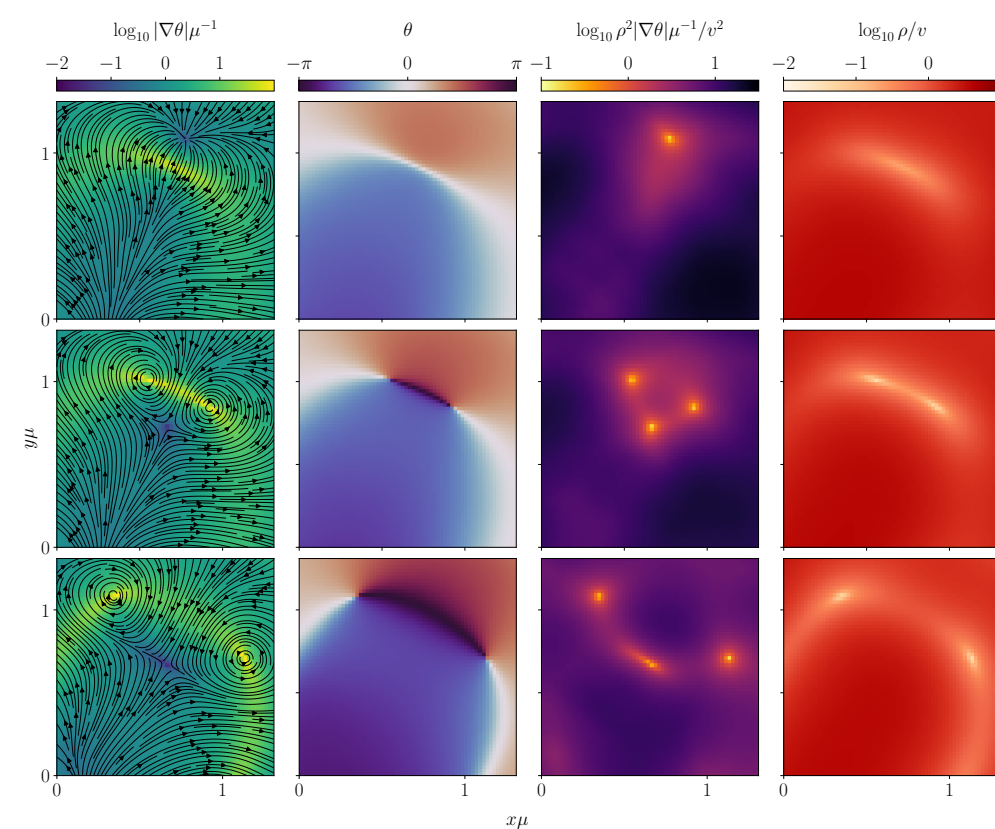
Vortex formation condition



Superfluid flowing through an thin orifice

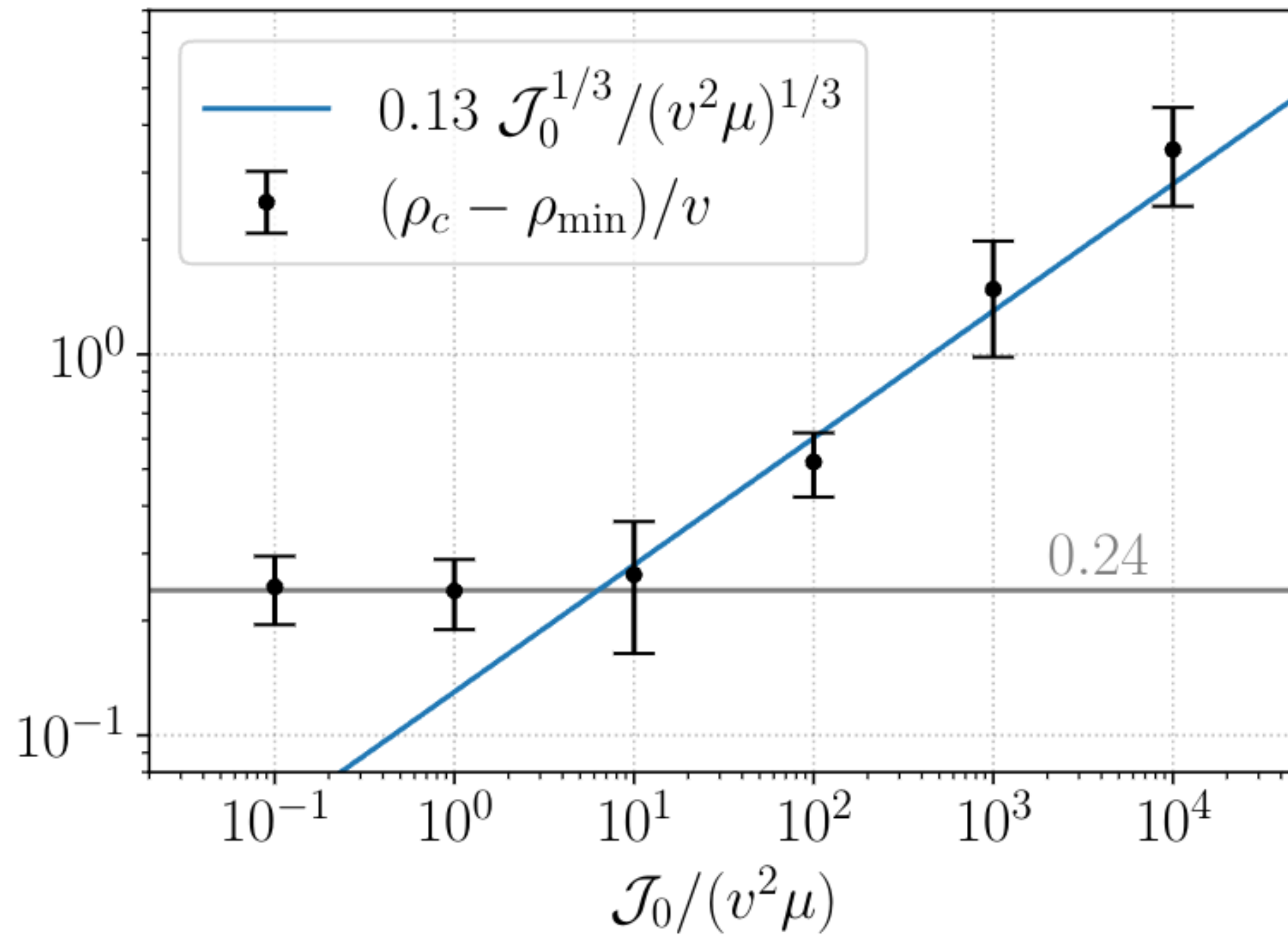


(Feynman 1956)



$$\text{Critical velocity : } v_{\text{Feynman}} = \frac{2}{m_* a} \rightarrow \nabla\theta = 1/a$$

Vortex formation condition (Global)



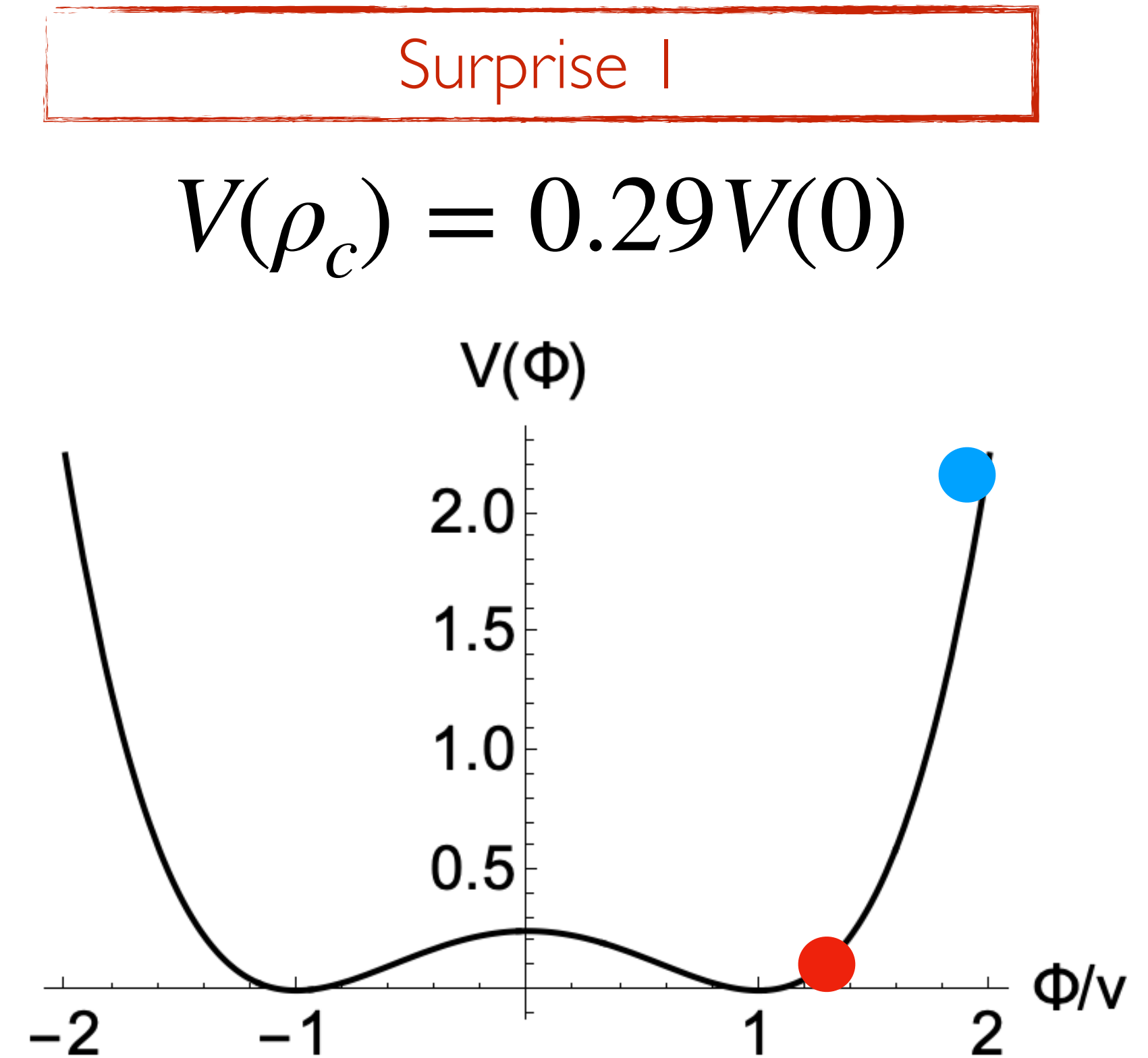
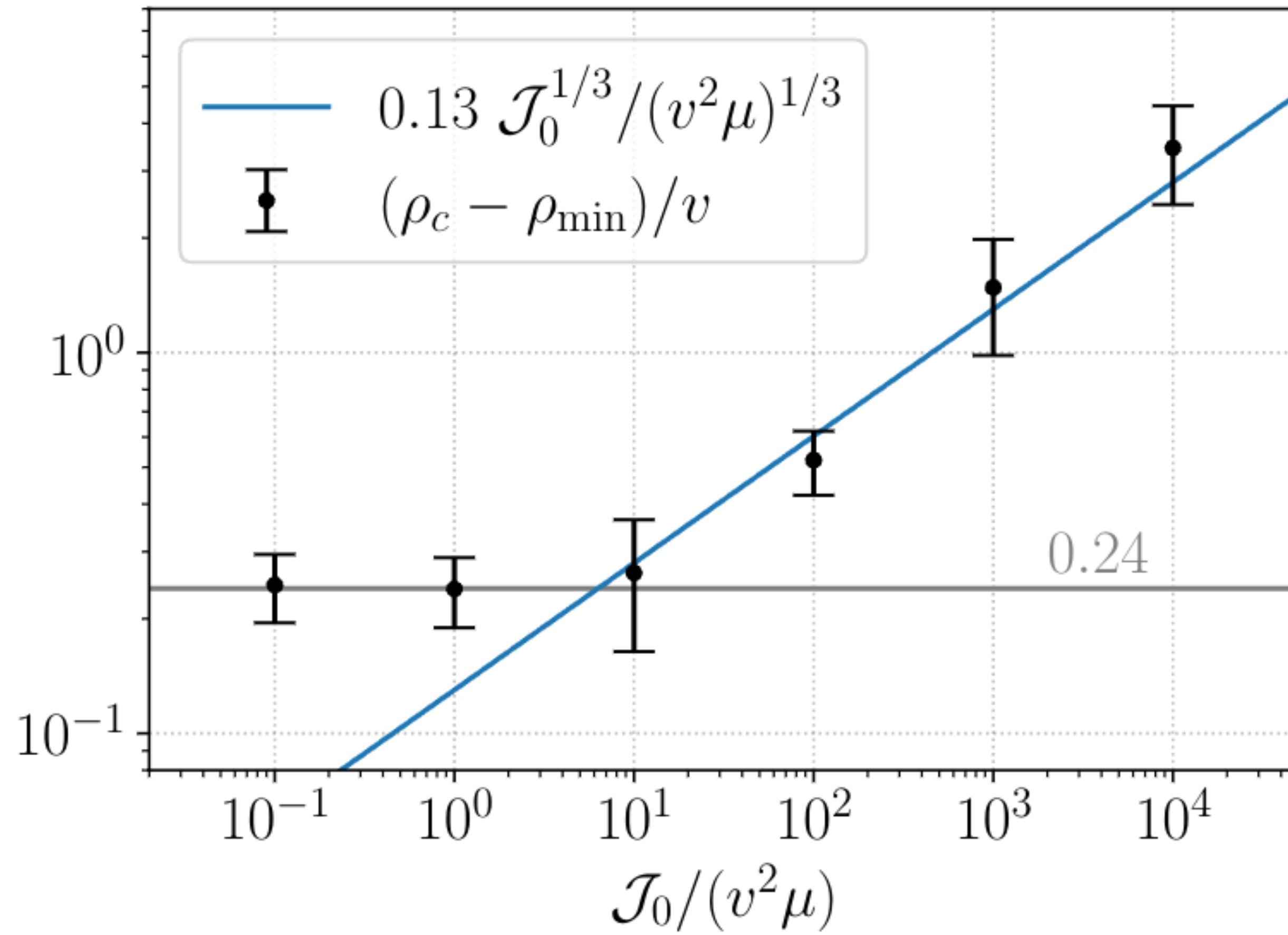
Surprise I

Small initial rotation:

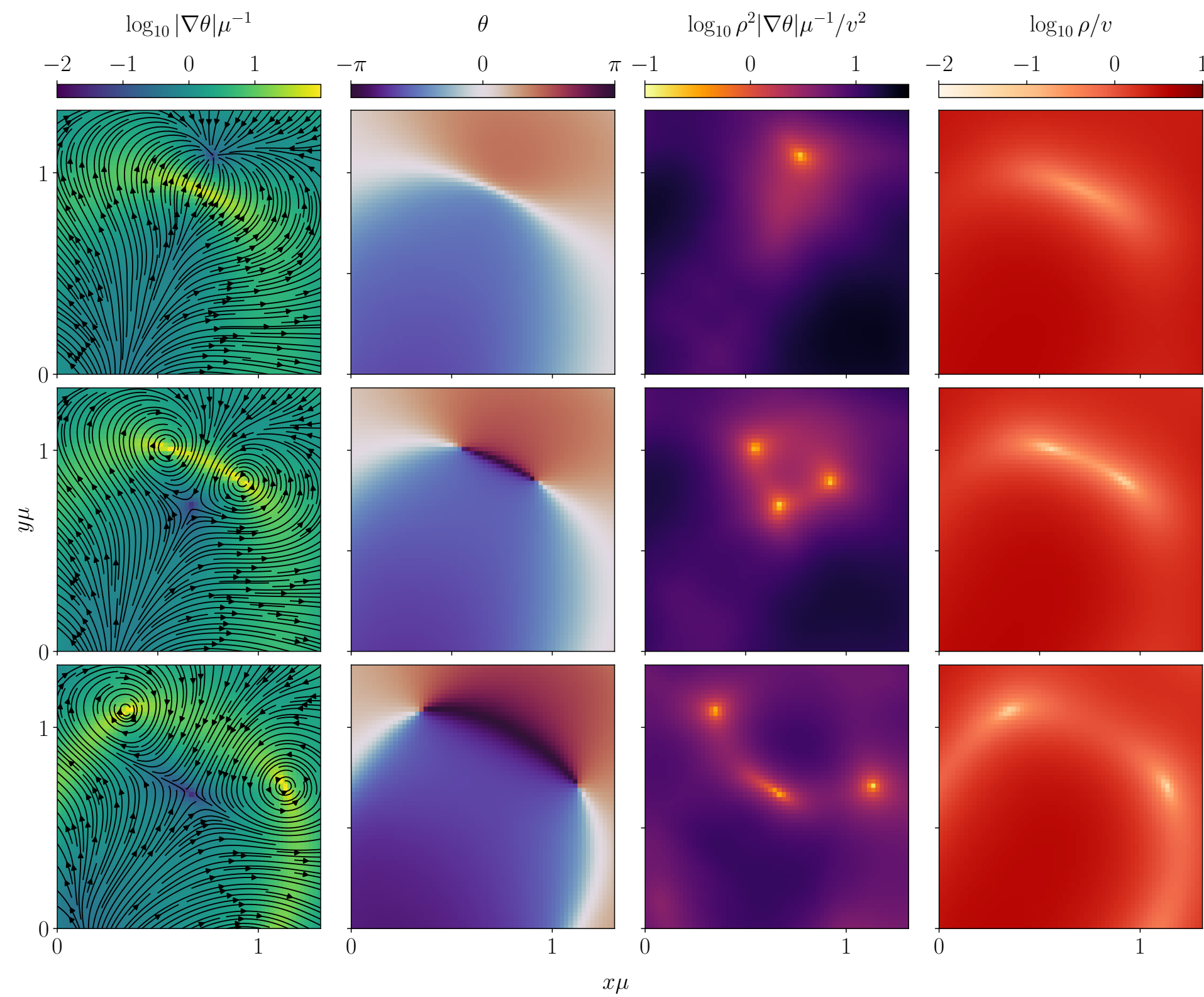
$$\rho_c = 1.24v$$

$$V(\rho_c) = 0.29V(0)$$

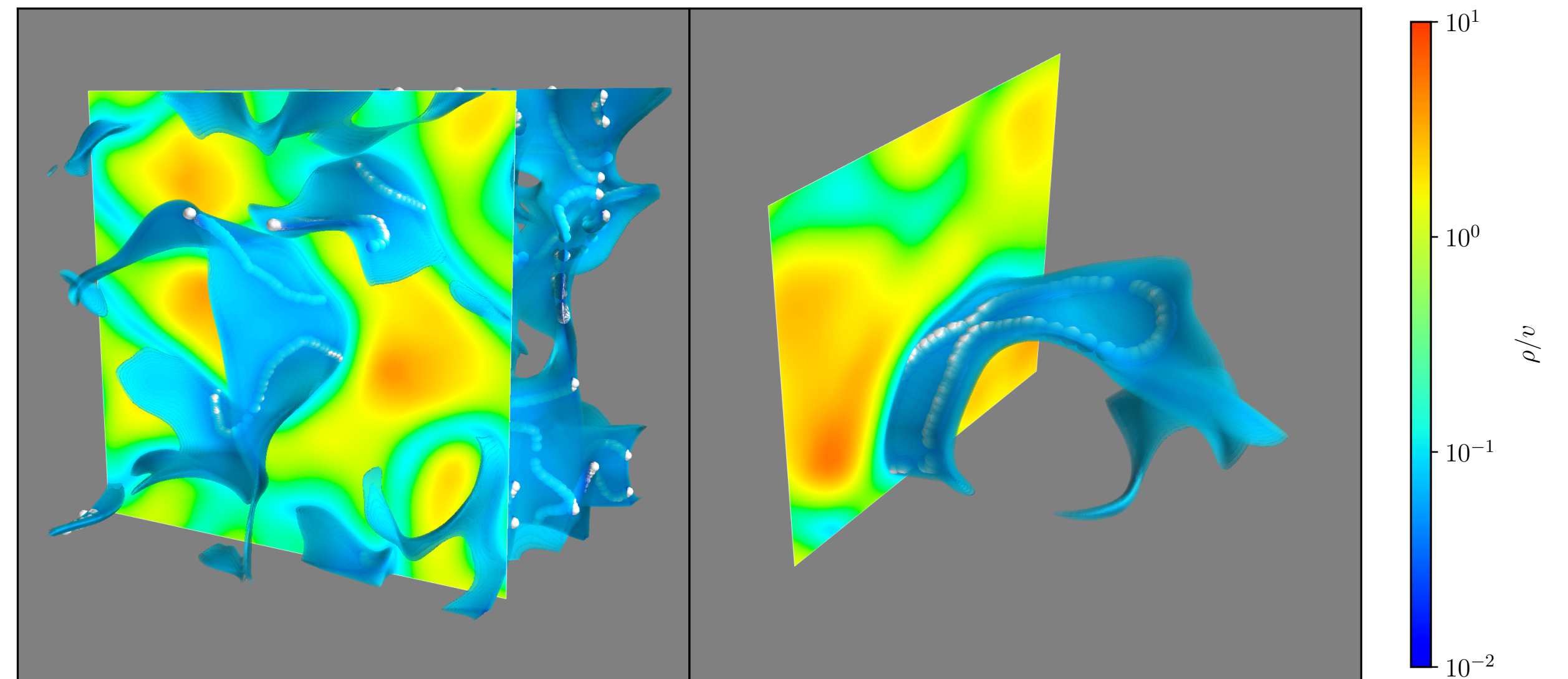
Vortex formation condition (Global)



Vortex confinement



Surprise 2



Vortices/Strings are confined to domain boundaries in both 2D/3D simulations

Vortex movement and confinement

Anderson 1966, Ao Thouless 1993, Haldane Wu 1985

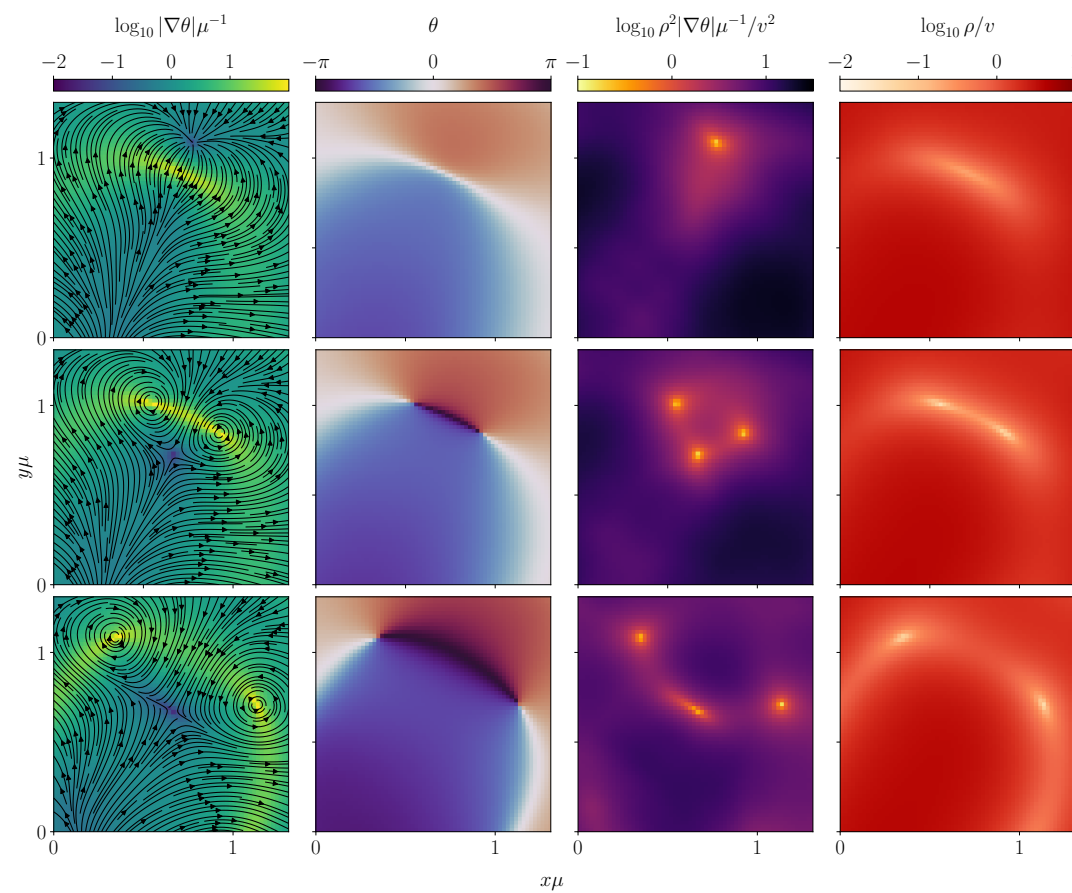
Some analogies: Superfluid

Superfluid: Magnus Force

$$\vec{F}_i = n_s K_i \hat{z} \times (\vec{v}_V - \vec{v}_s) \quad \vec{v}_s \sim \nabla \theta(x)$$

Confinement: Particle Vortex Duality

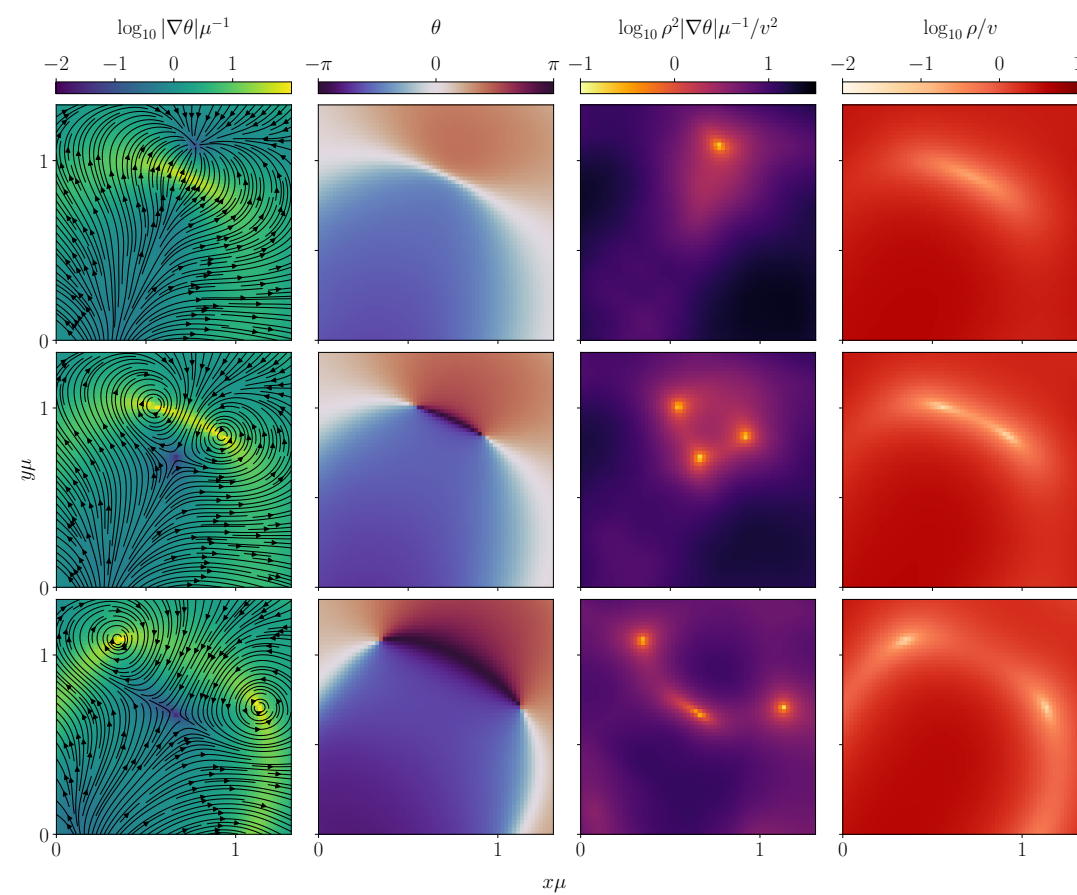
$$\frac{1}{2\pi} \epsilon_{\mu\nu\rho} F^{\mu\nu} = \partial_\rho \theta \quad \longrightarrow \quad \begin{aligned} E^i &\sim \partial^j \theta \\ B^i &\sim \dot{\theta} \end{aligned}$$



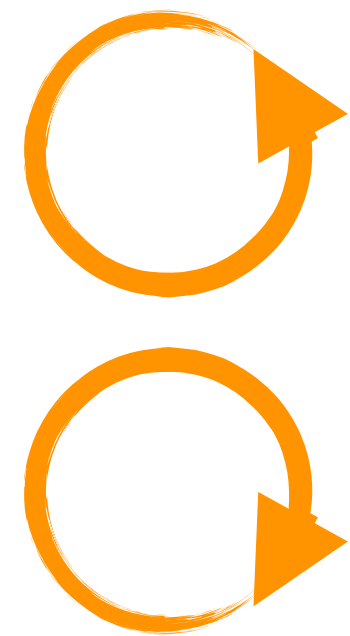
Vortex movement and confinement

Anderson 1966, Ao Thouless 1993, Haldane Wu 1985

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Confinement: Particle Vortex Duality



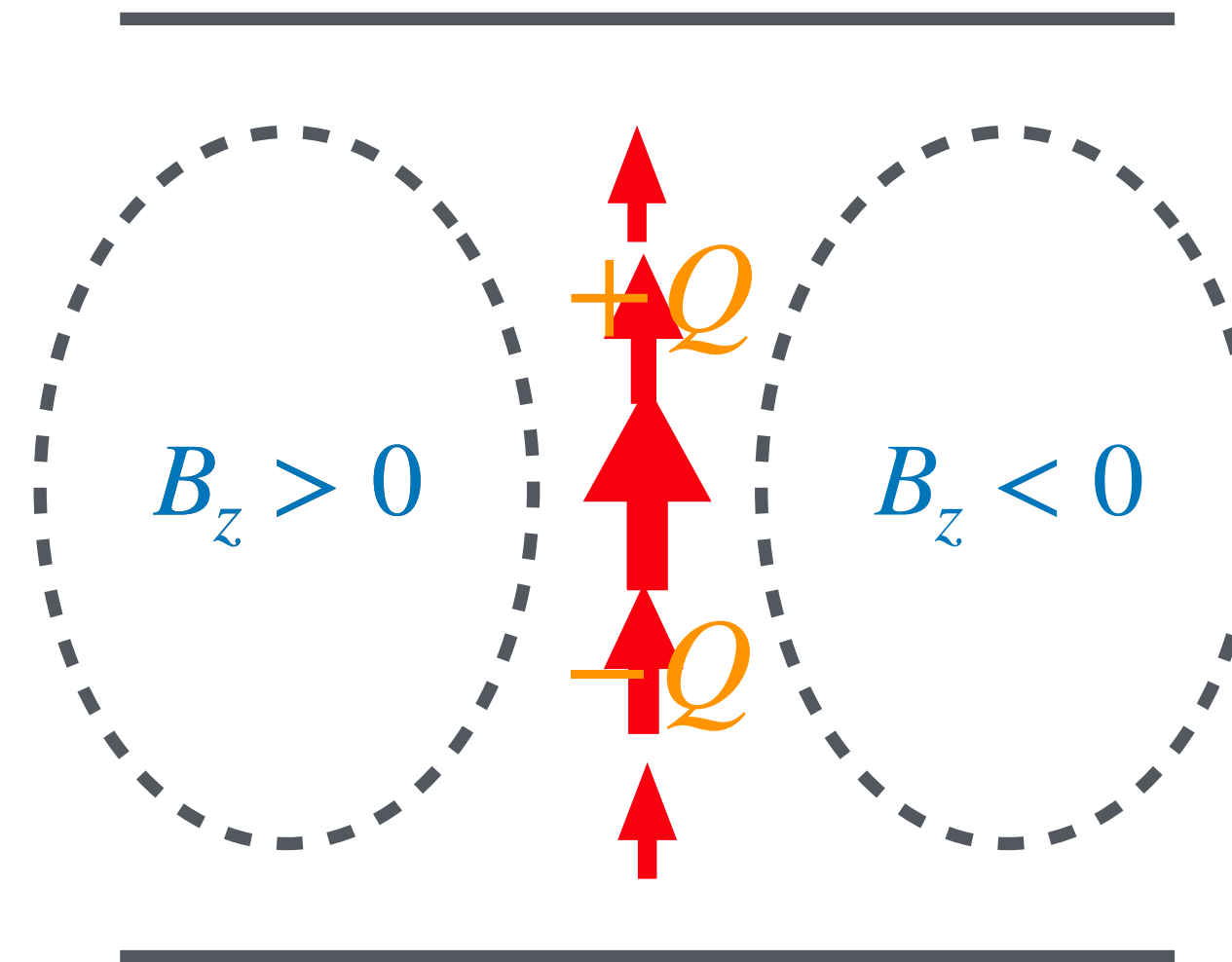
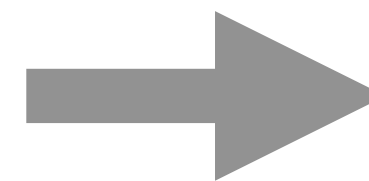
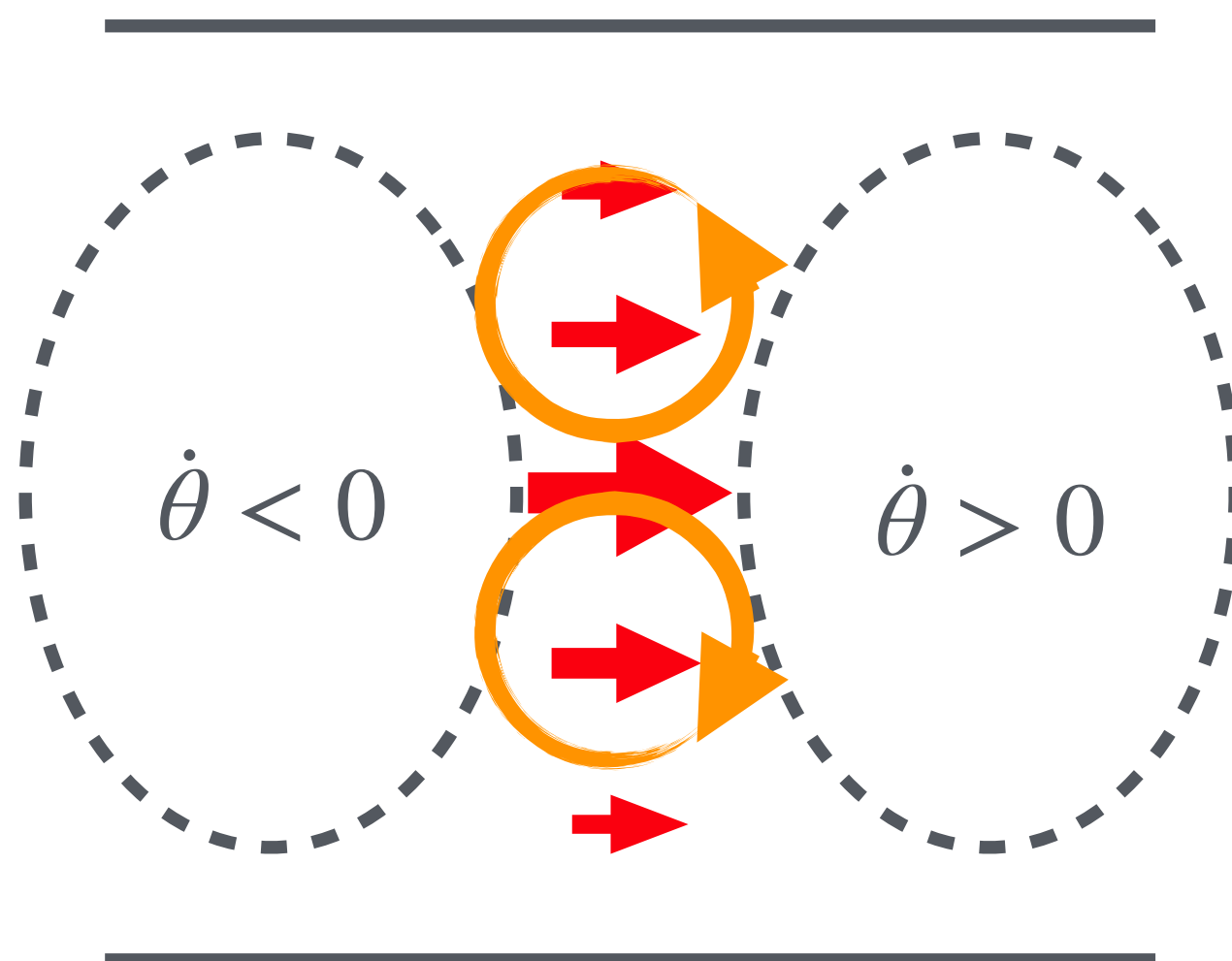
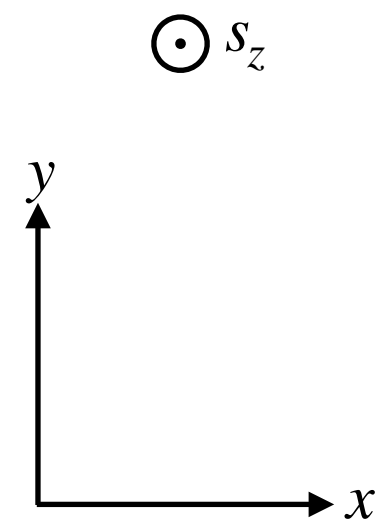
$+Q$

$-Q$

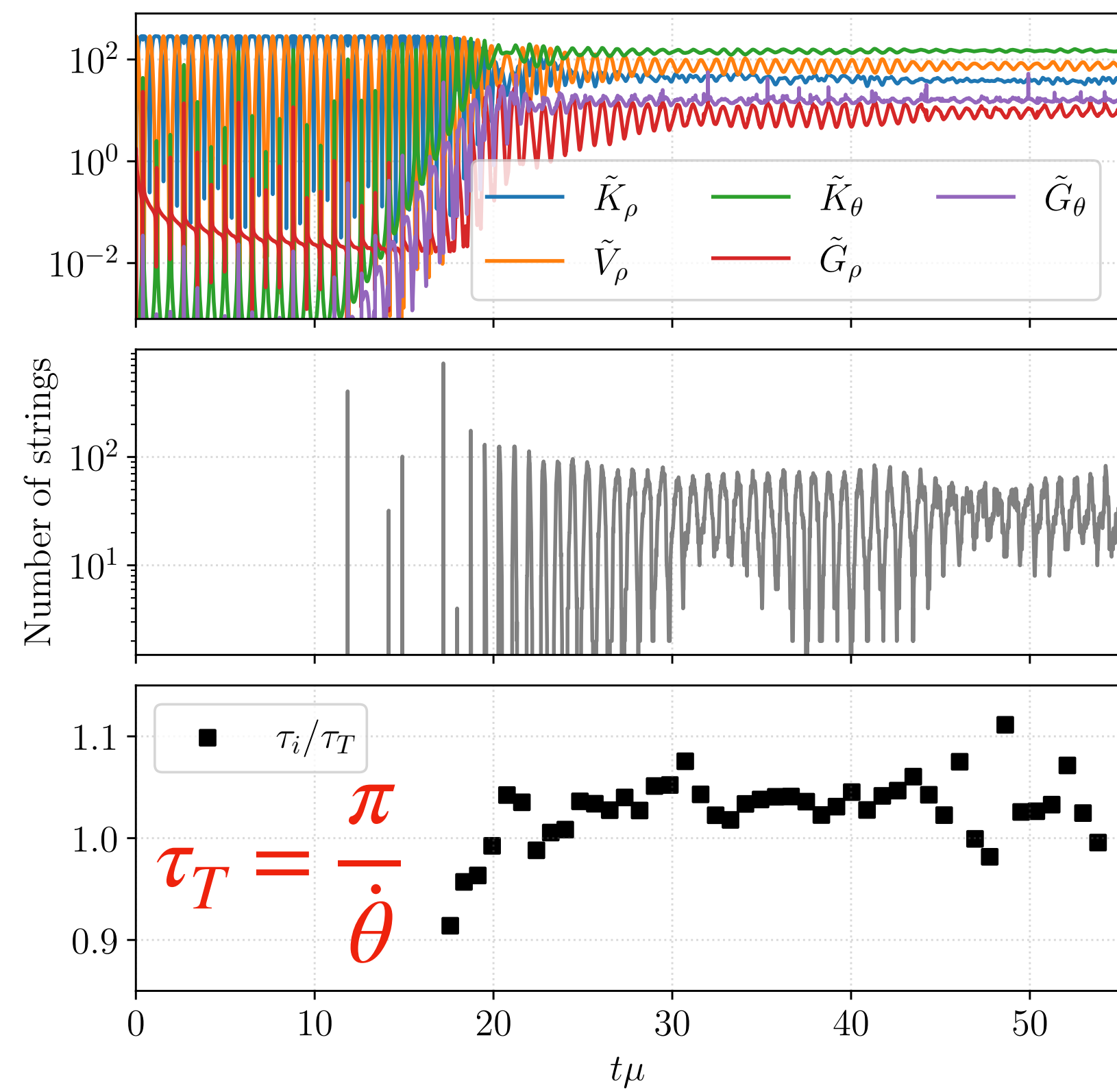
$$\partial_\rho \theta = \frac{1}{2\pi} \epsilon_{\mu\nu\rho} F^{\mu\nu}$$

$$\partial^j \theta \sim E^i$$

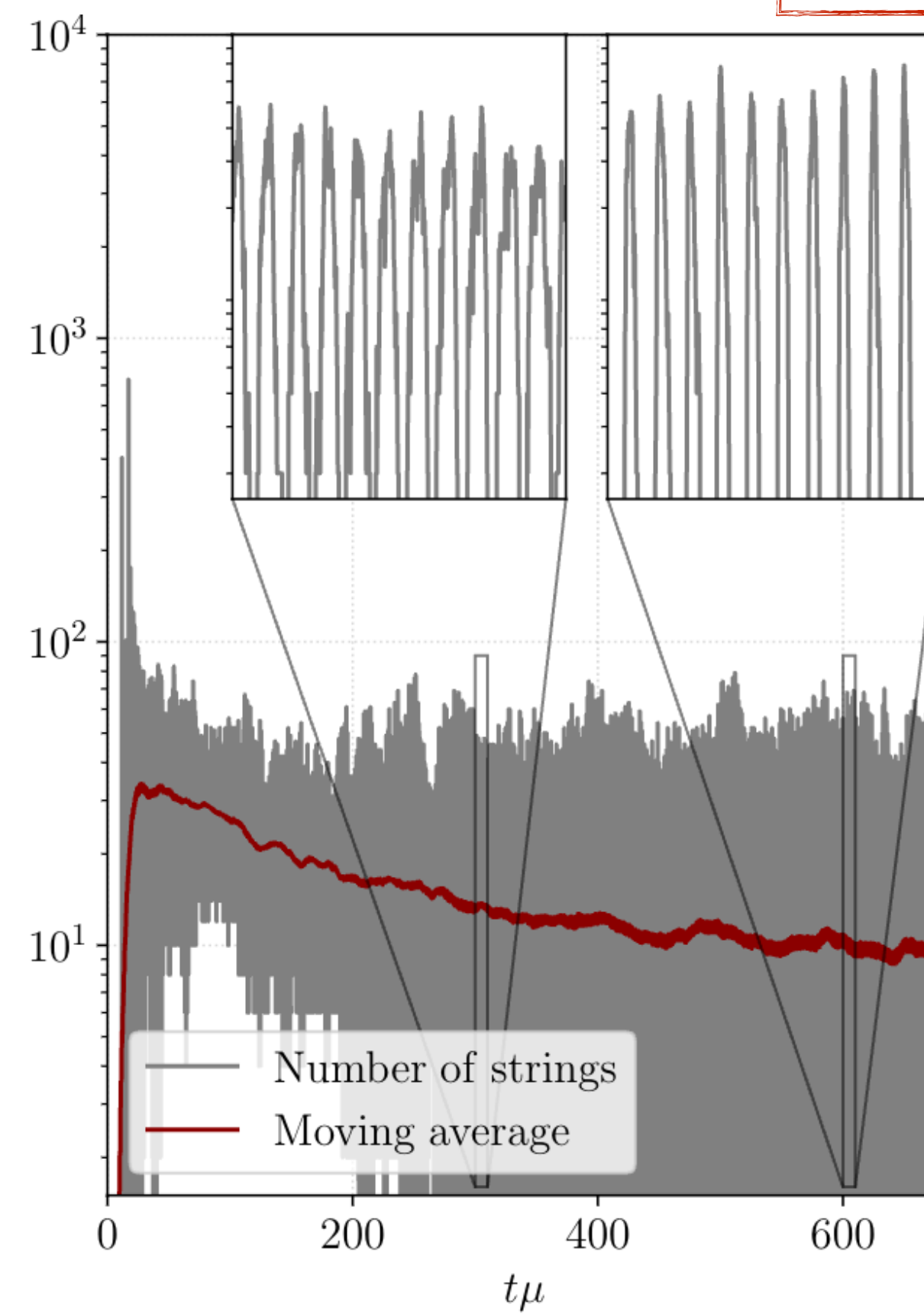
$$\dot{\theta} \sim B^i$$



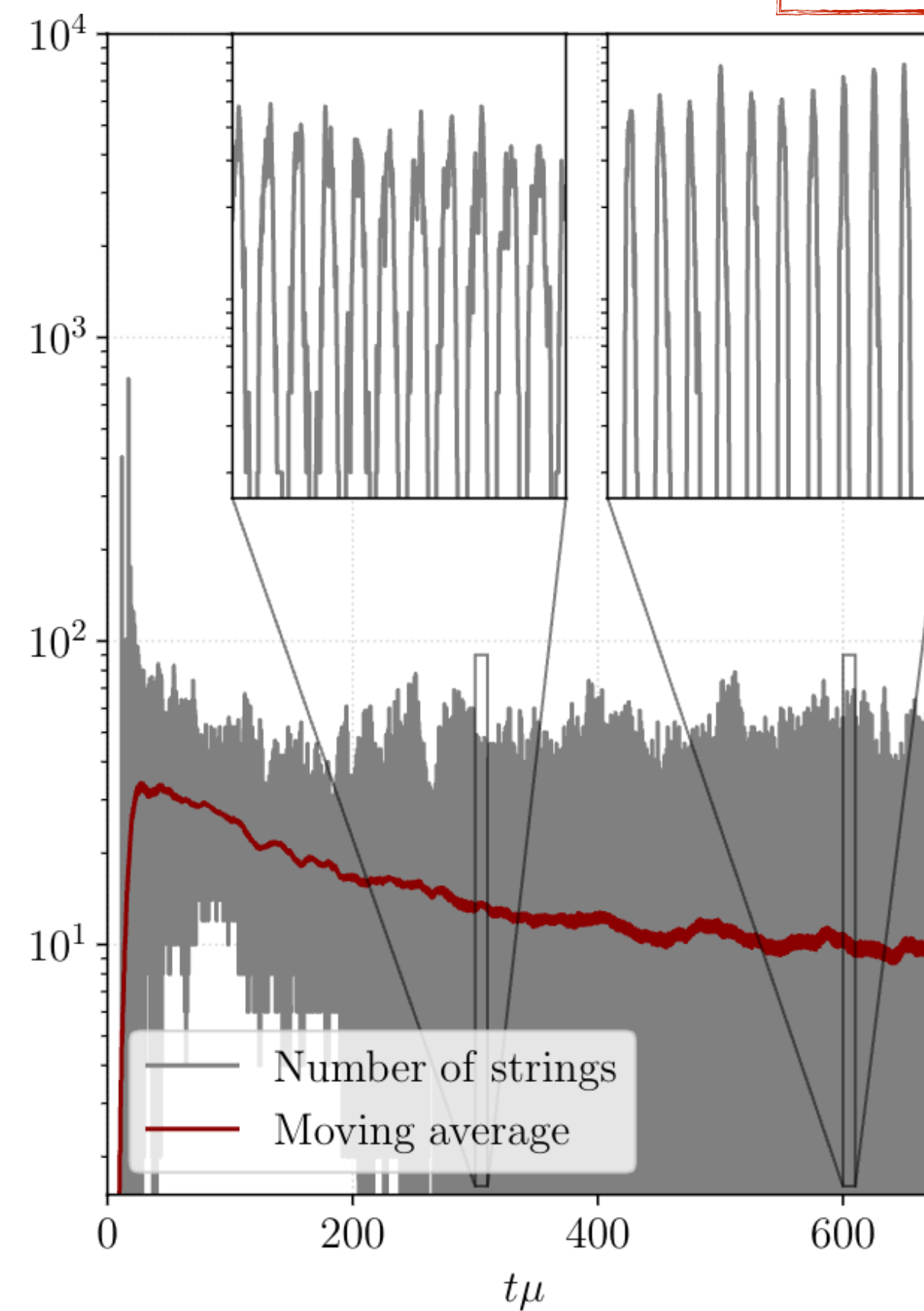
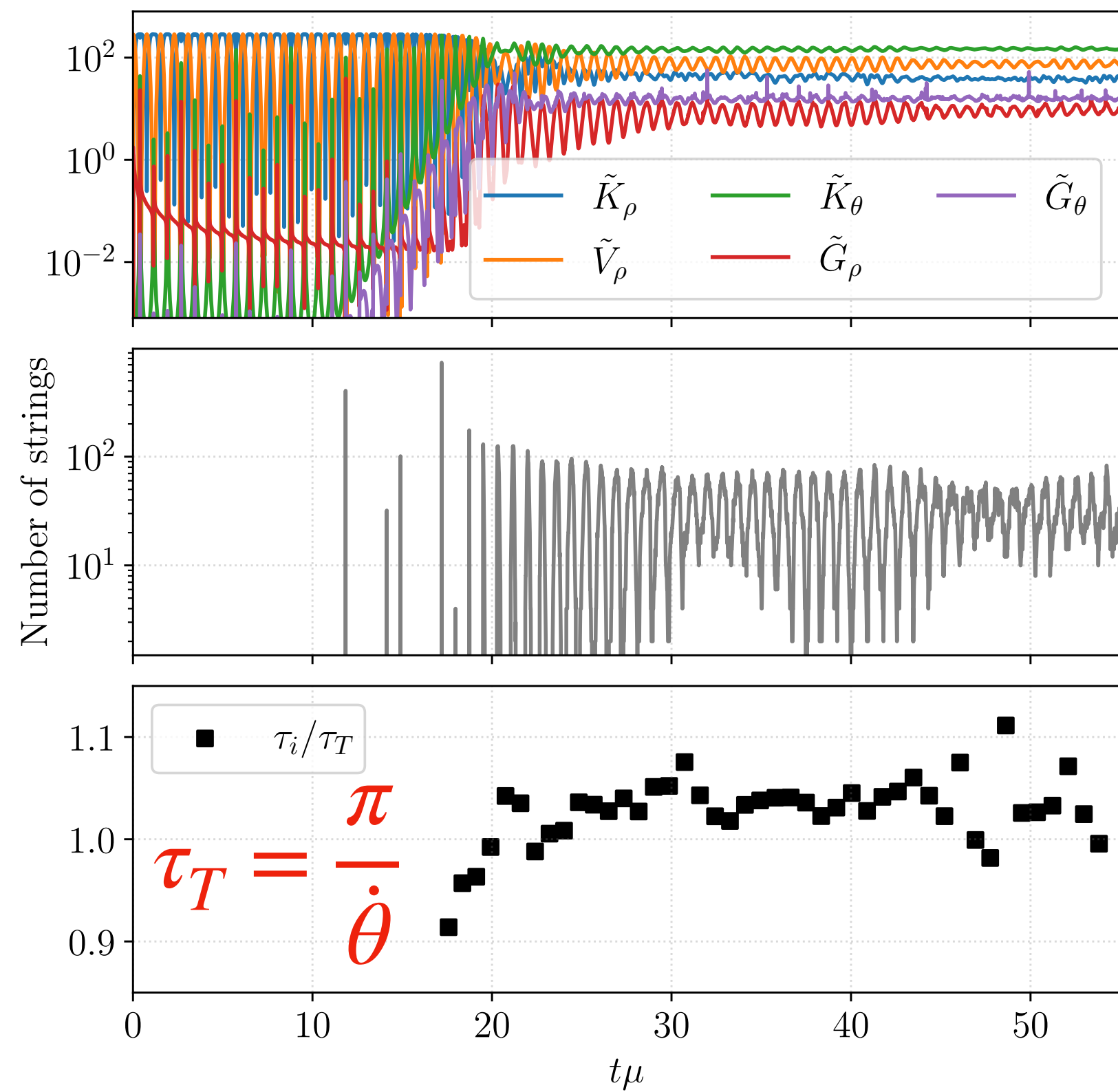
Periodic string formation (2D)



Surprise 3



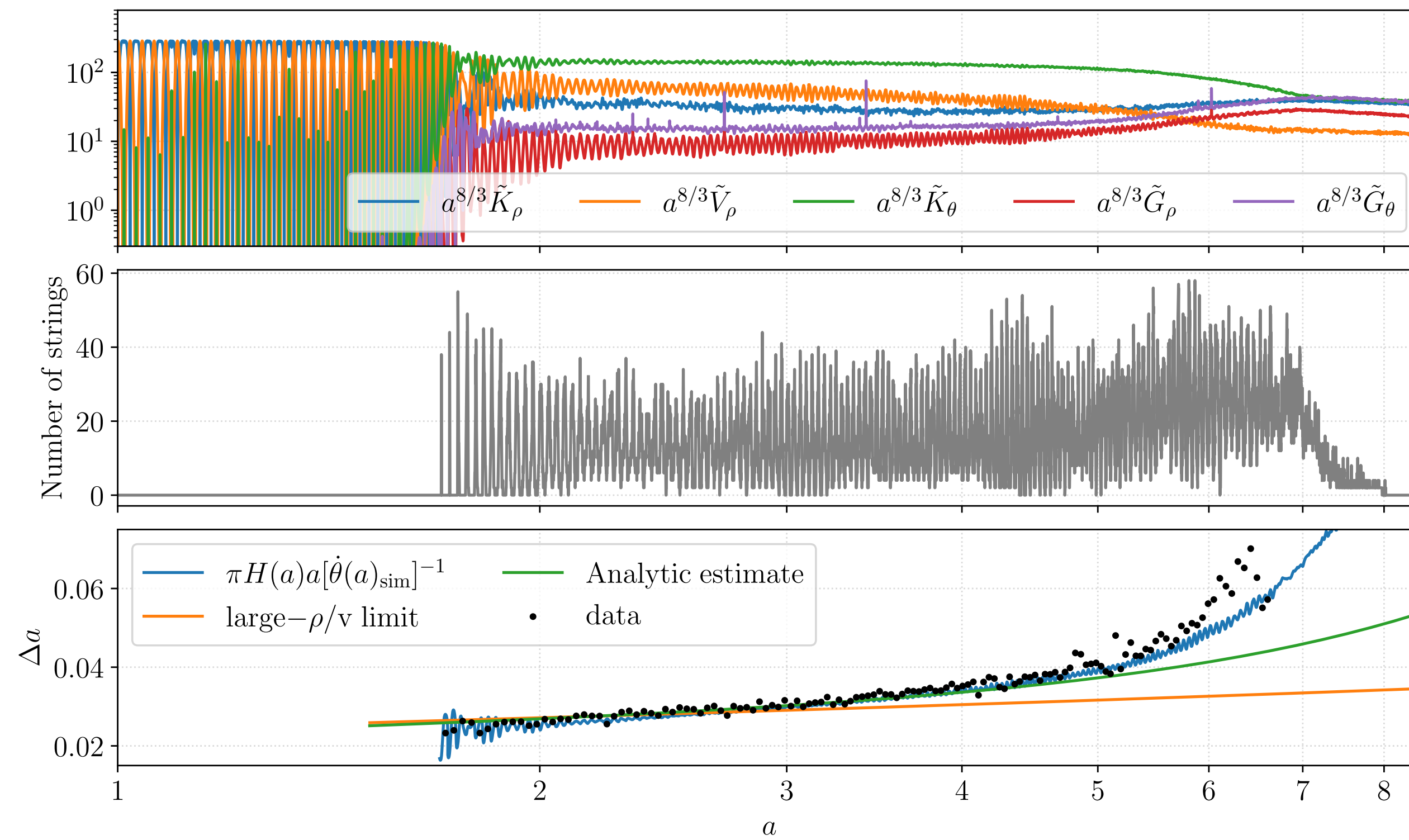
Periodic string formation (2D)



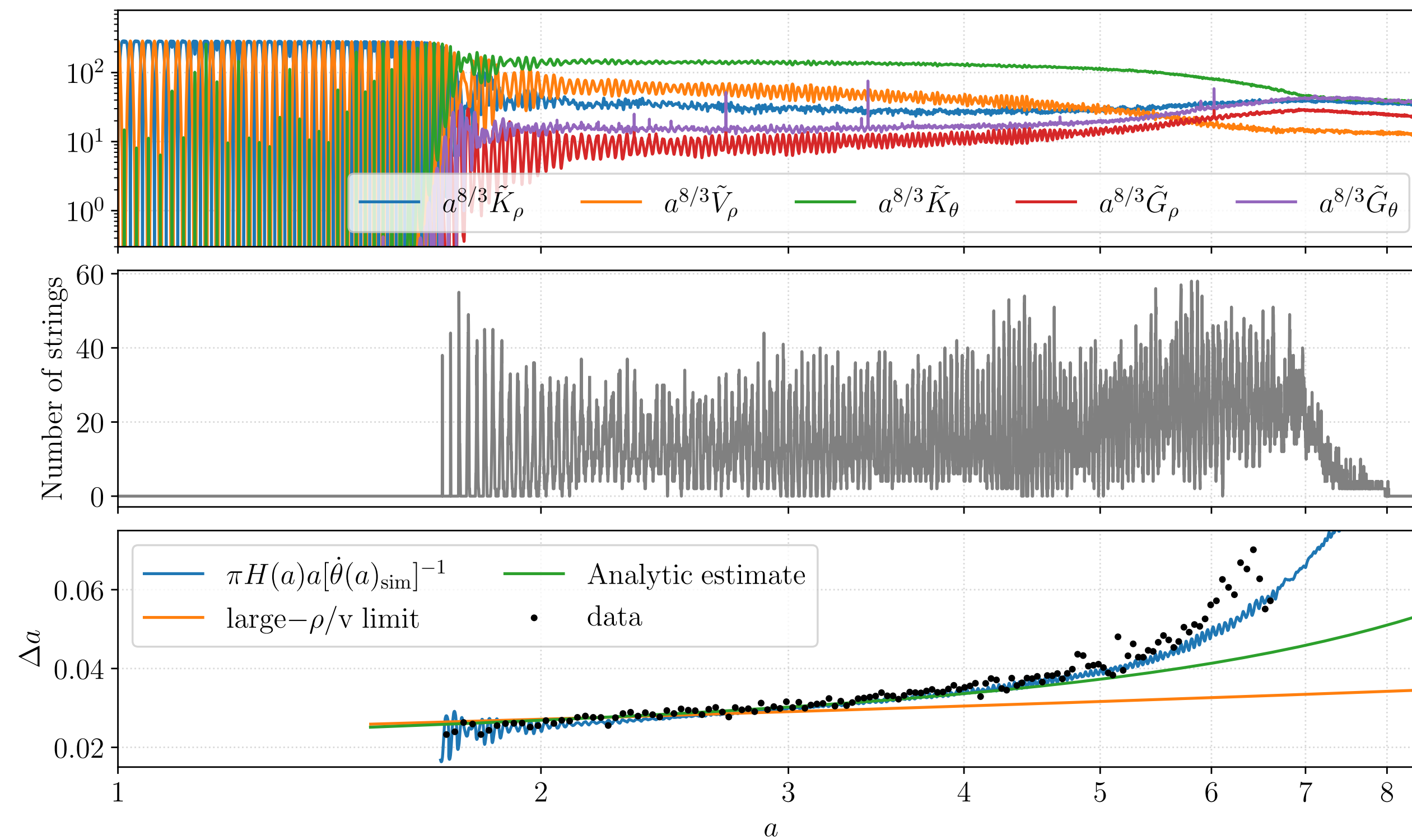
Surprise 3

Take home
Strings periodically form and annihilate for a long time. These annihilations produce scalar and gravitational wave periodically

Expanding universe

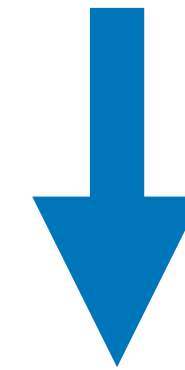


Expanding universe



In the large ρ/v limit:

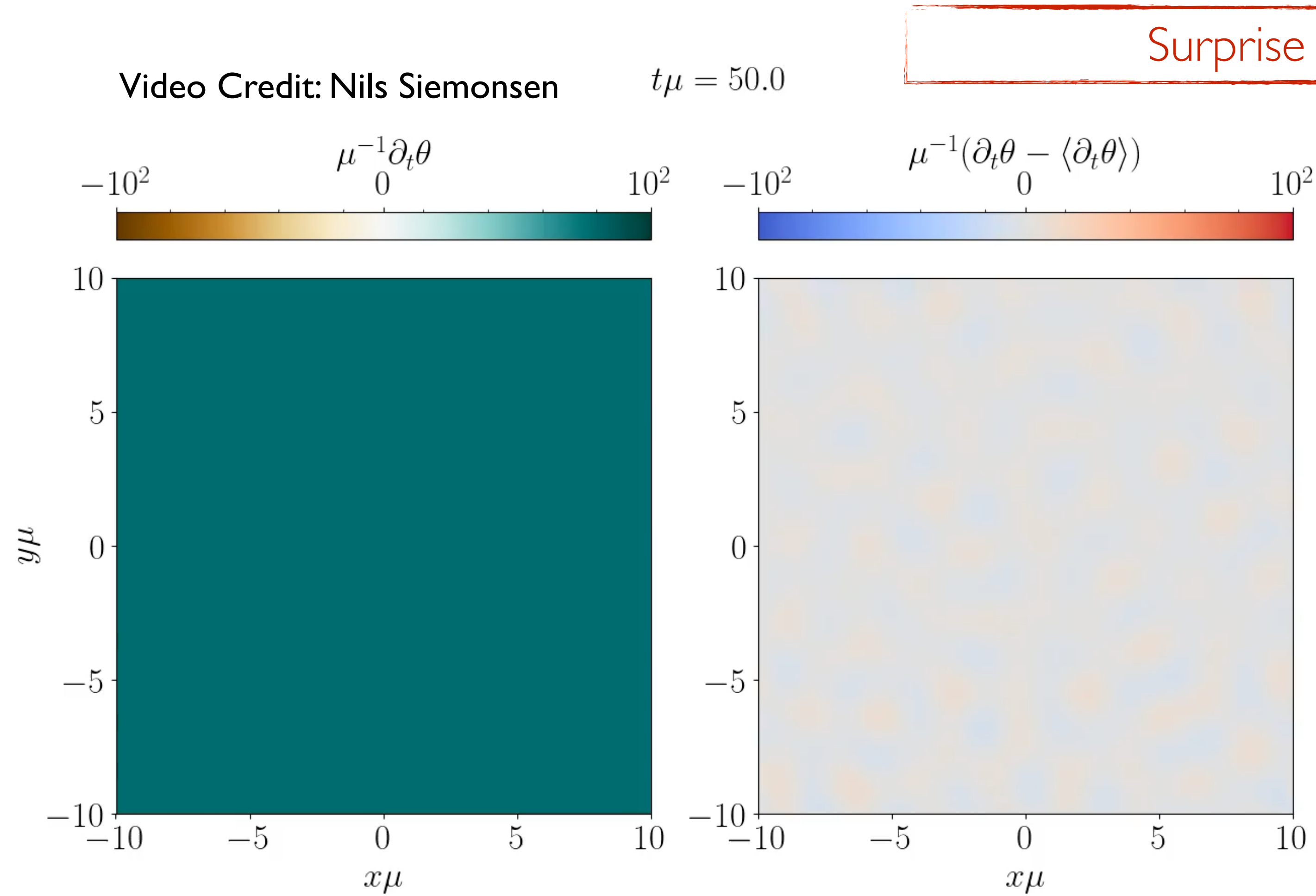
$$\left(\frac{a_i}{a_1}\right)^{D/6+1/2} = 1 + (i-1) \frac{D+3}{6} \frac{\pi H(a_1)}{|\dot{\theta}(a_1)|}.$$



$$\frac{f_{i+1}^\Omega}{f_1^\Omega} = 1 + i \frac{\pi H(a_1)}{|\dot{\theta}(a_1)|}$$

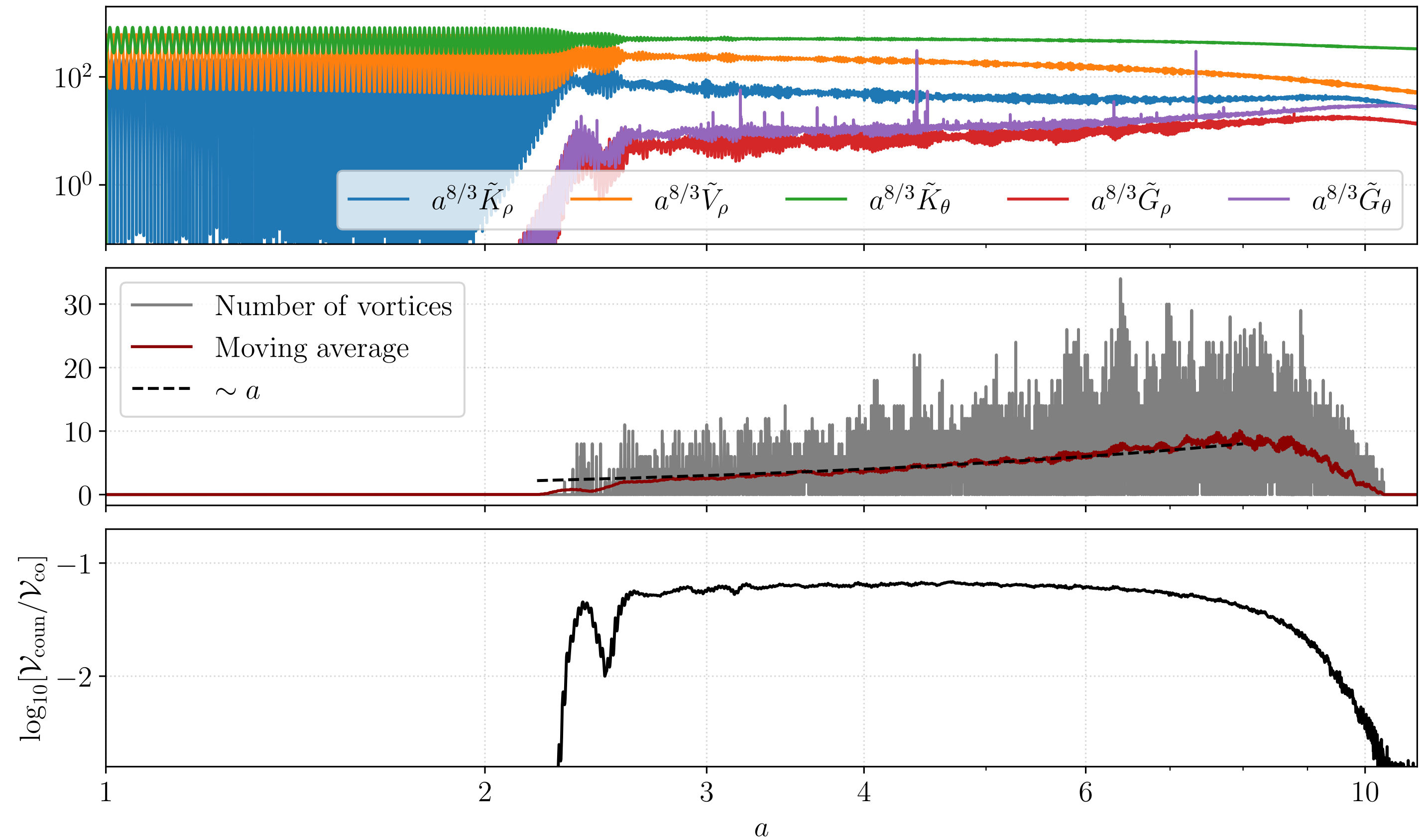
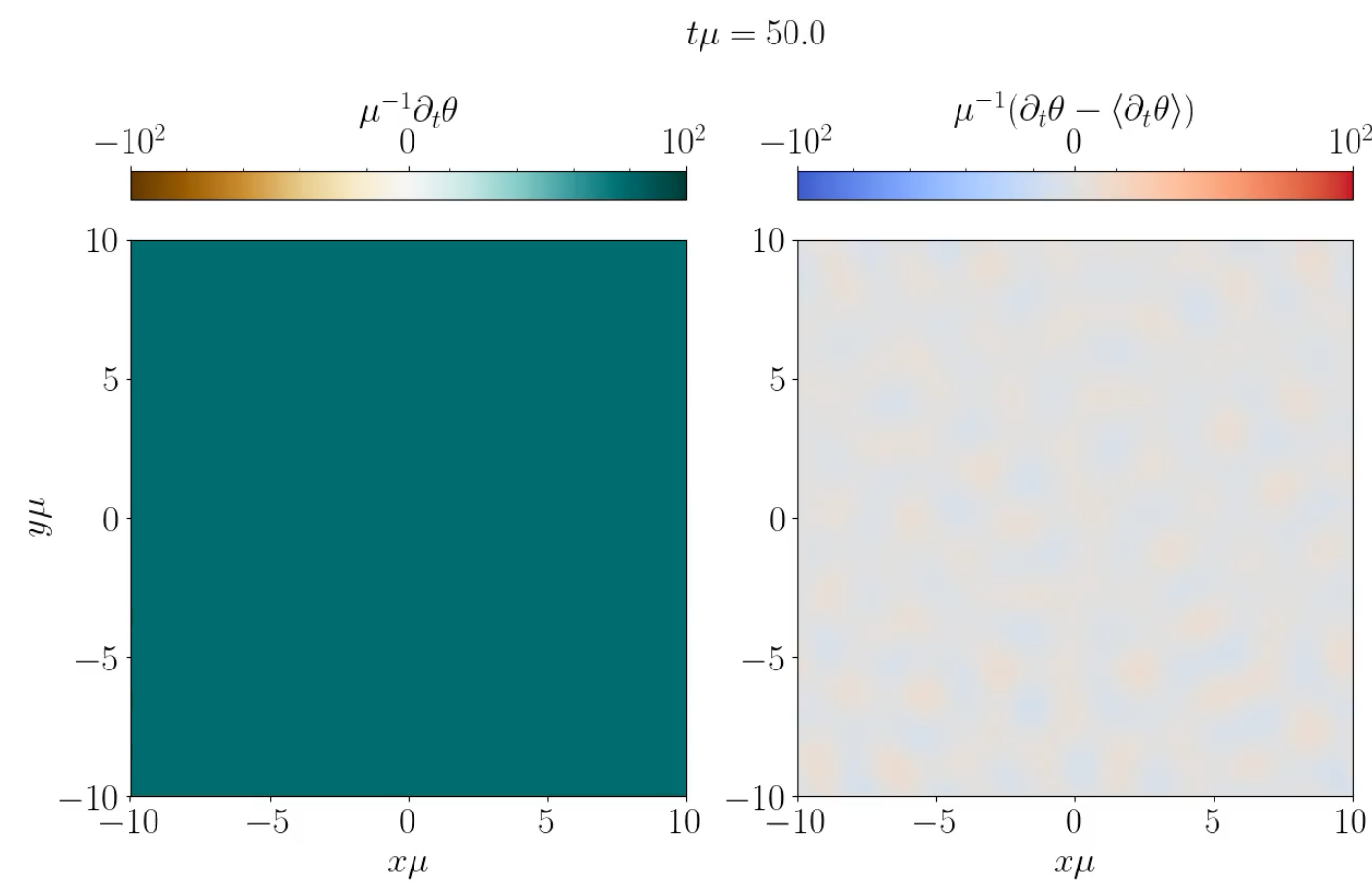
Can we search for this gravitational wave frequency comb?

What if I launch it with a rotation?



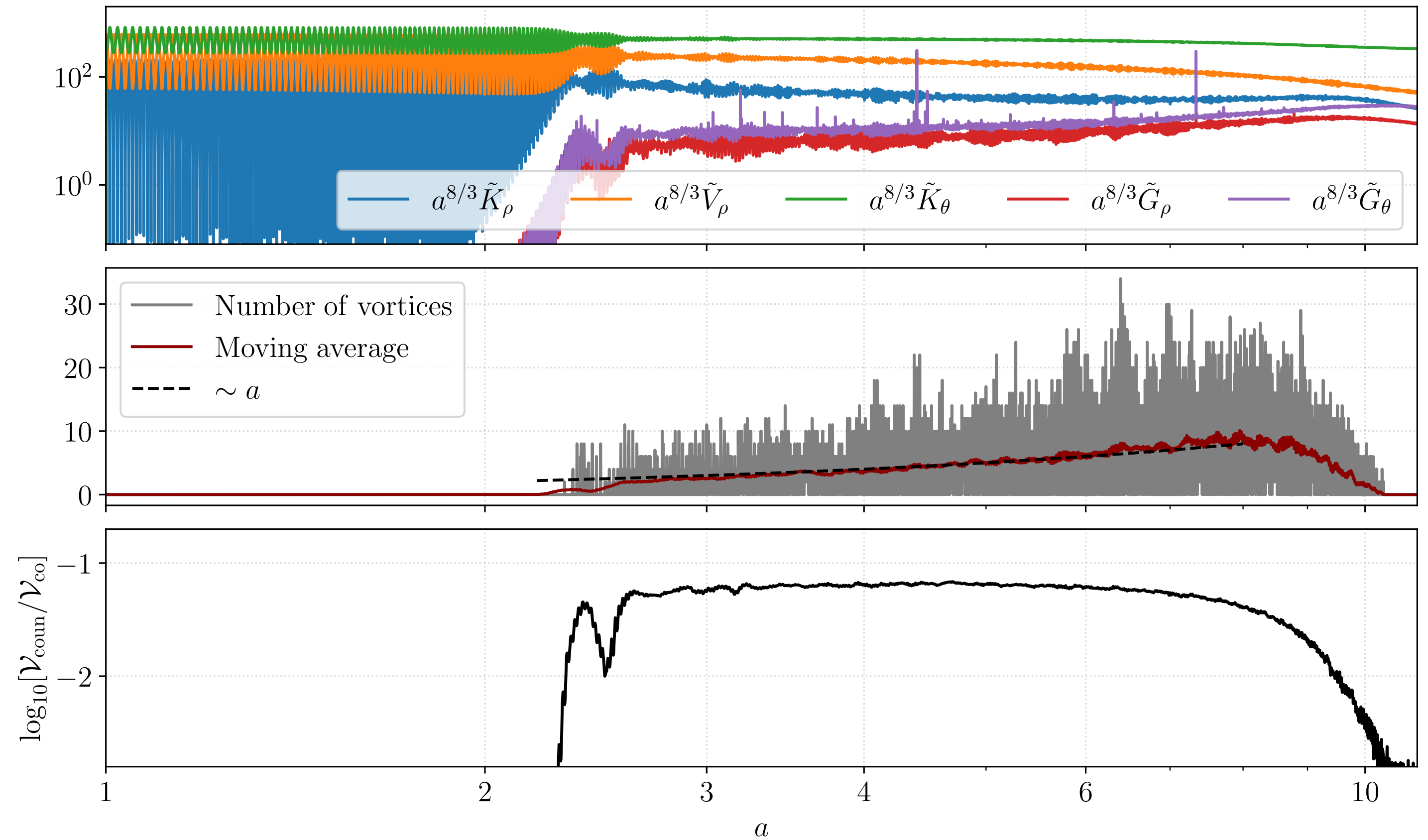
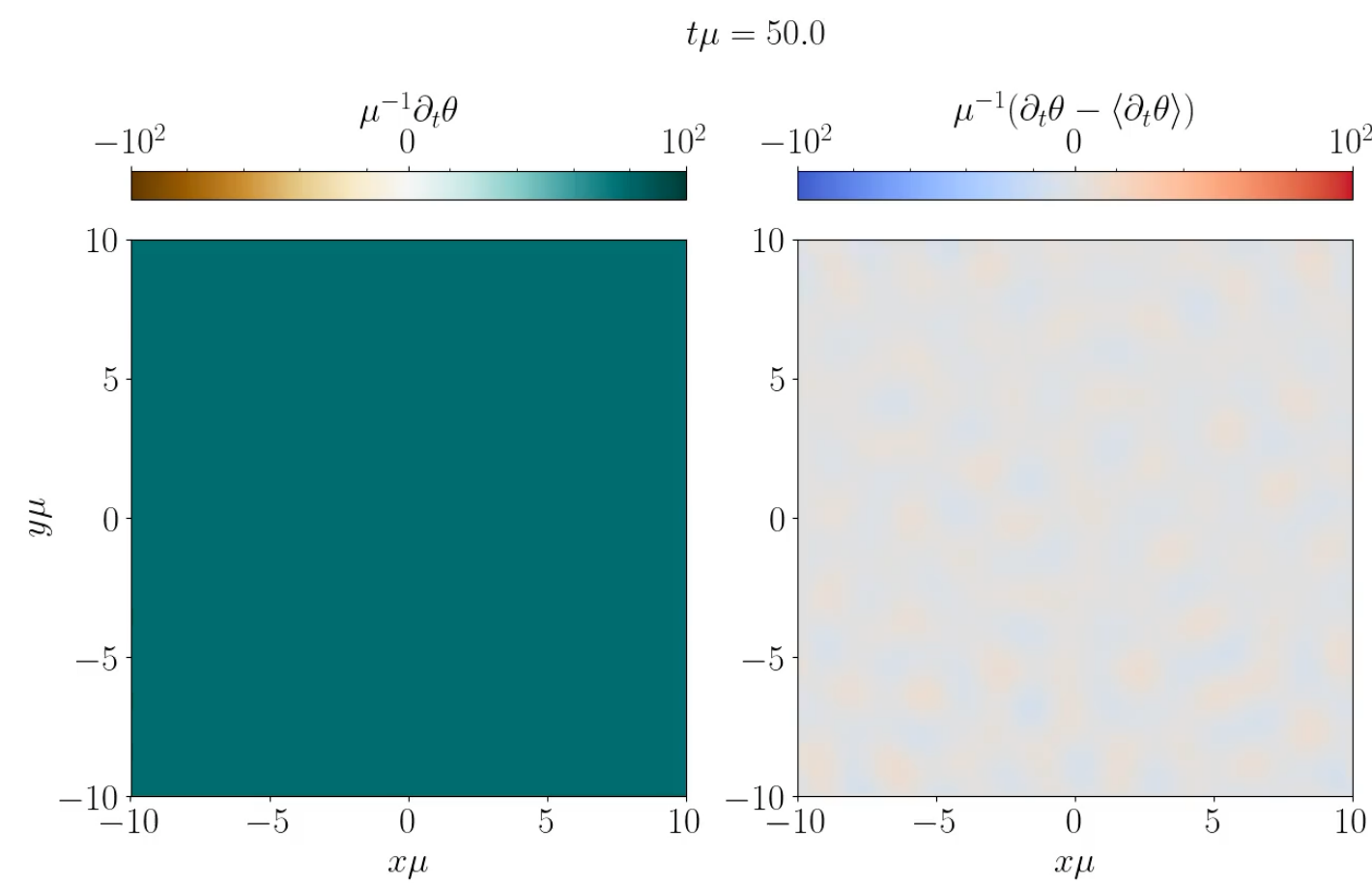
What if I launch it with a rotation?

Video Credit: Nils Siemonsen



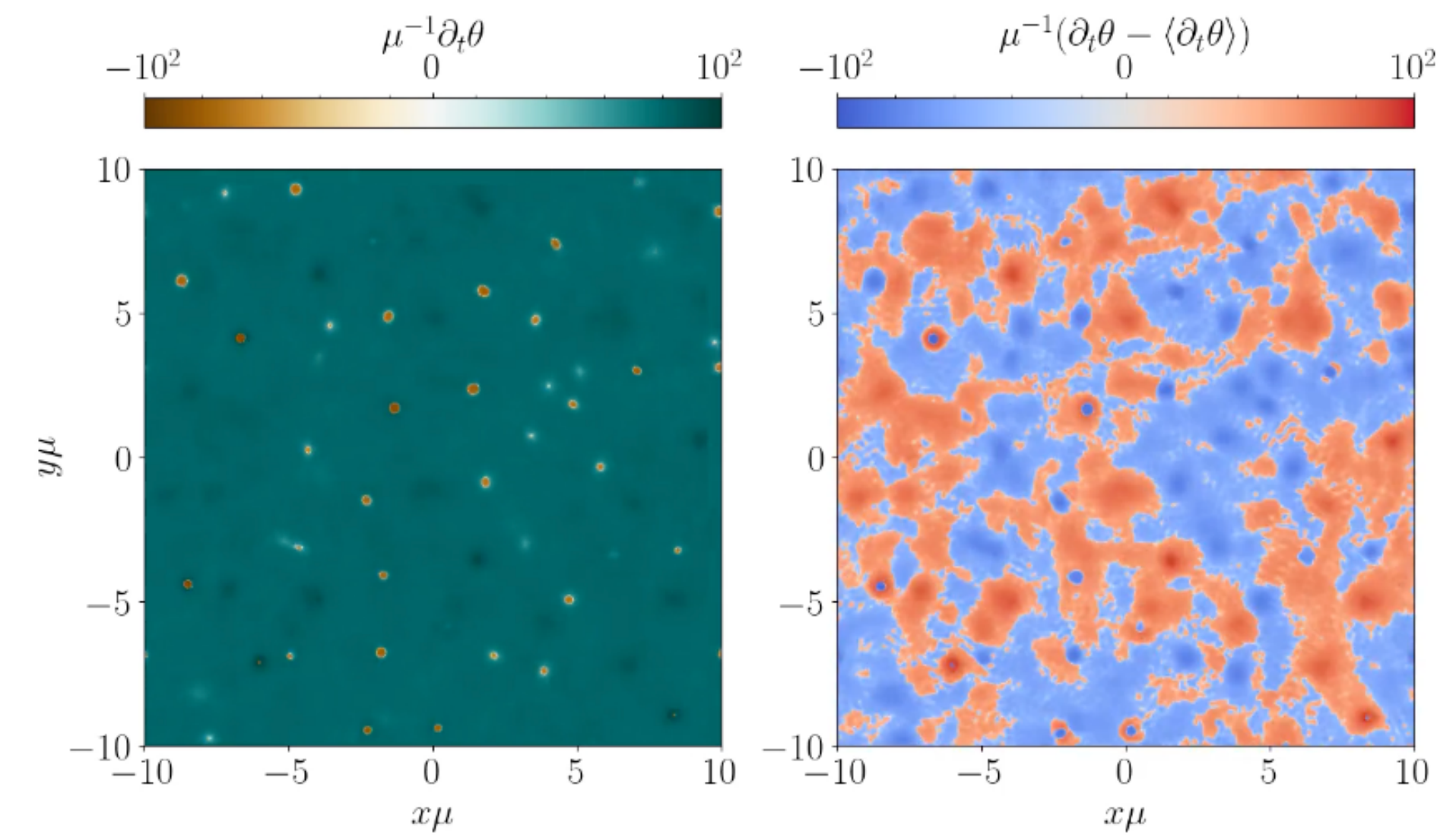
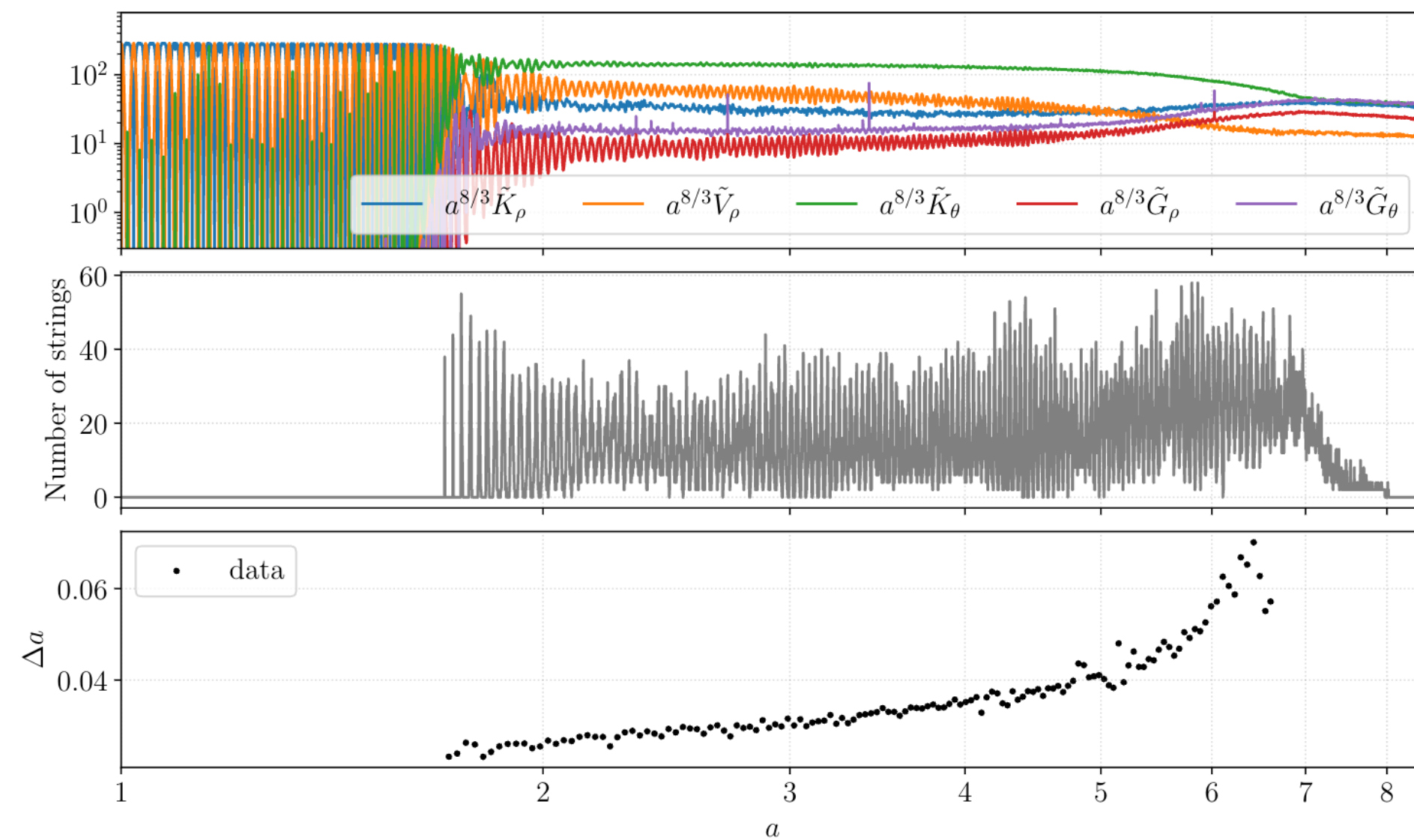
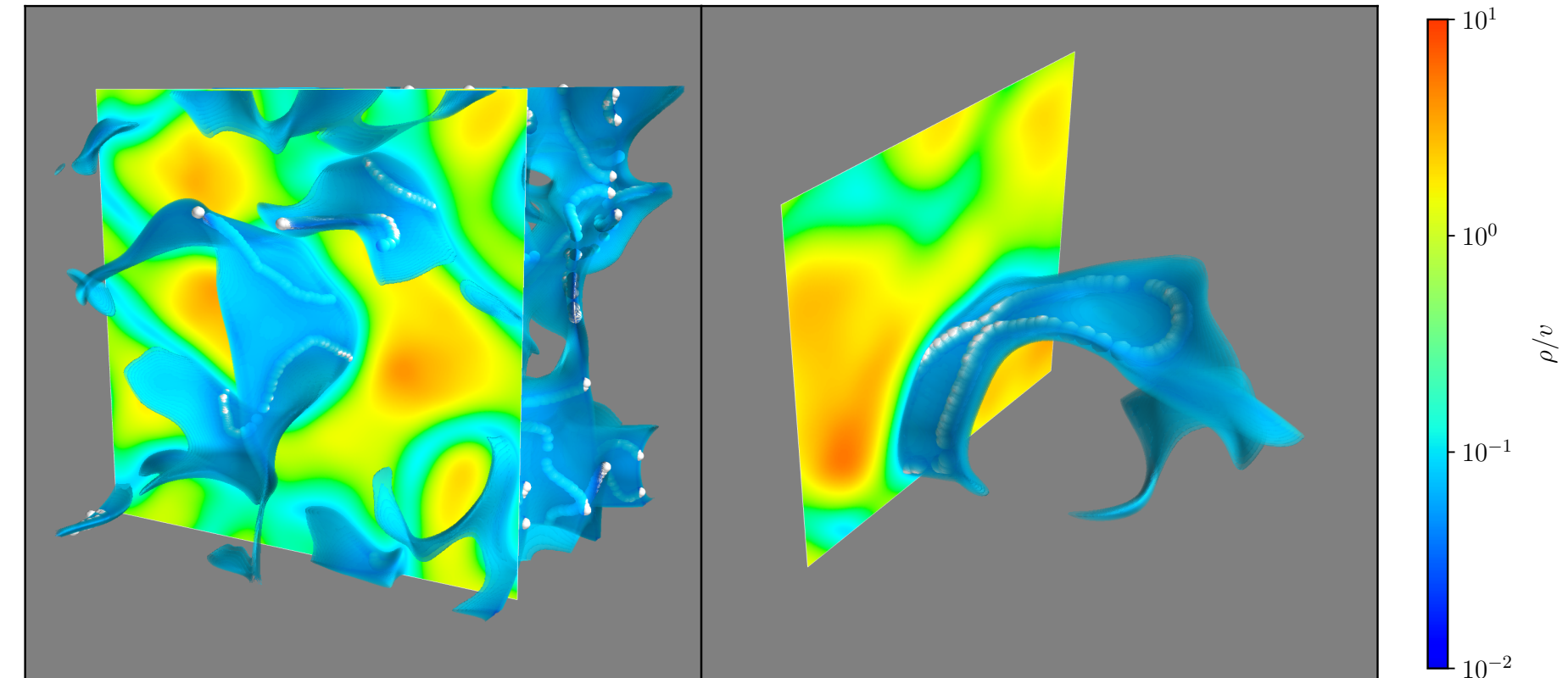
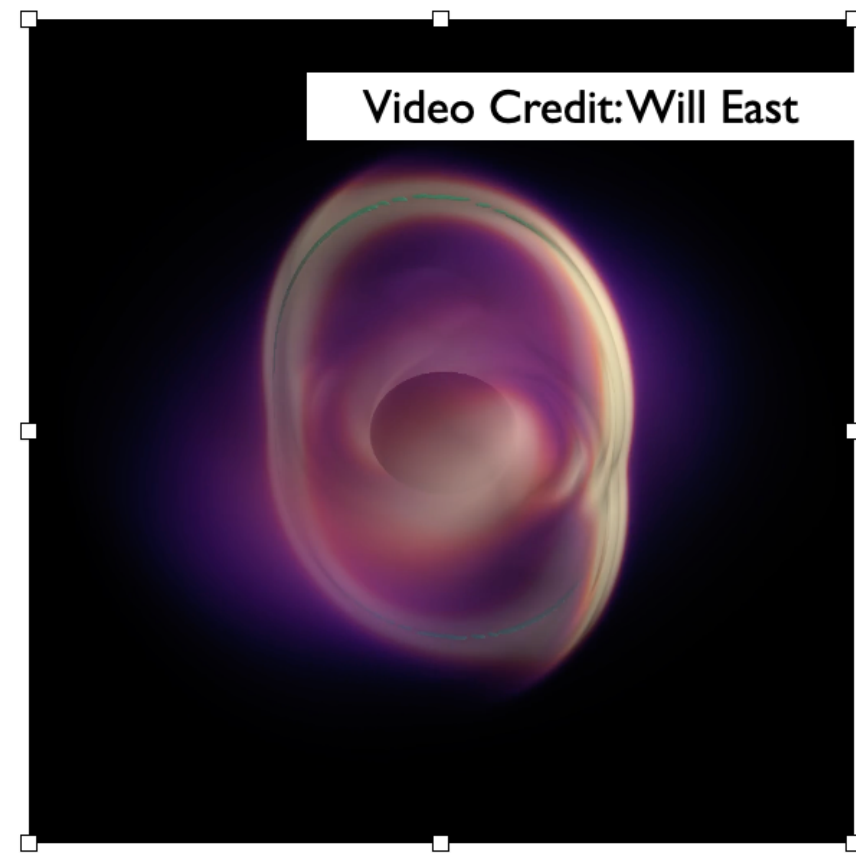
What is I launch it with a rotation?

Video Credit: Nils Siemonsen



Kination, Axion kinetic Misalignment & variants, Affleck Dine?

Conclusion



Take home
Don't trust k-space ($k=0$) analysis of non-linear systems.
If one digs deep, it is actually kind of interesting.

