Les Houches lectures: wave dark matter

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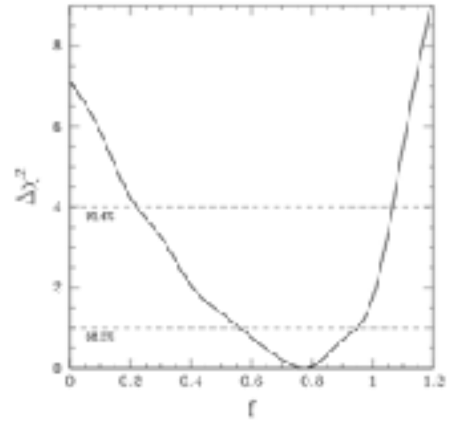
Review article 2101.11735 (+ references therein)

Acknowledgements:
Bovy, Bryan, Dalal, Joyce, Kabat, Landry, Li,
Ostriker, Santoni, Tremaine, Witten, Wong, Yavetz

Rich evidence for dark matter - from its gravitational effects

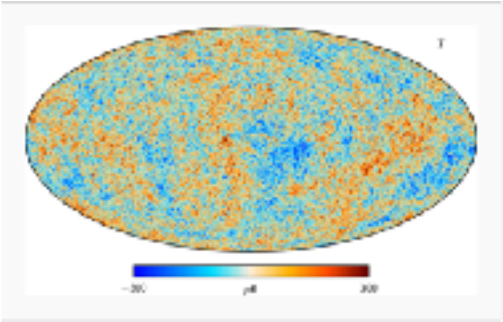
- Dynamical measurements.

- Gravitational lensing measurements.

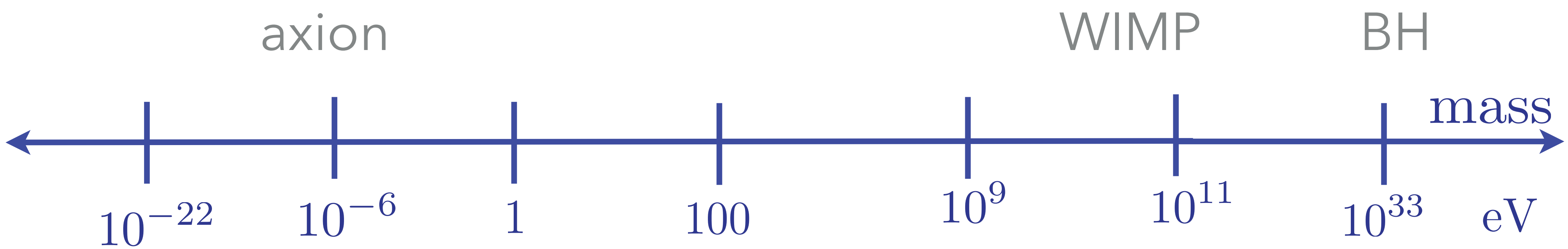


Hoekstra, Yee, Gladders

- Growth of perturbations.



We have rich evidence for the existence of DM, but remain ignorant about its basic properties e.g. mass:



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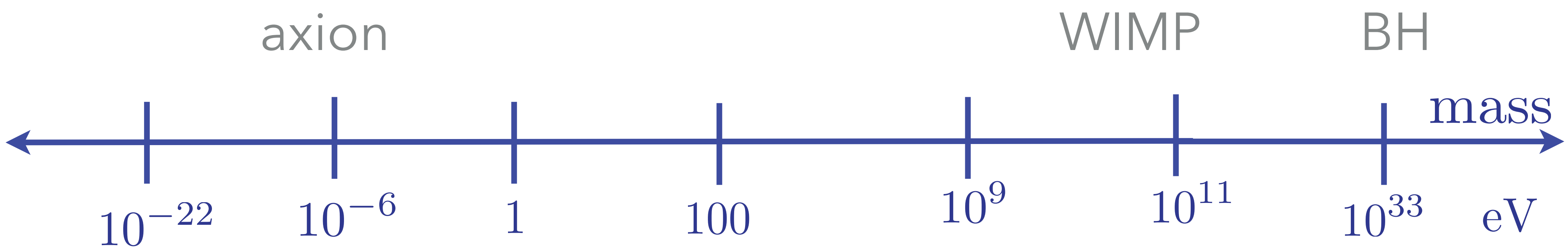

What we do know: mass density in solar neighborhood is $0.3\ \mathrm{GeV/cm^3}$

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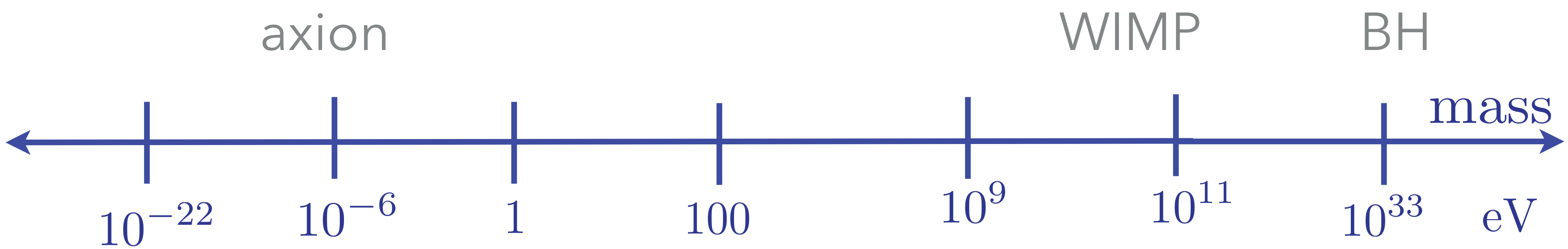

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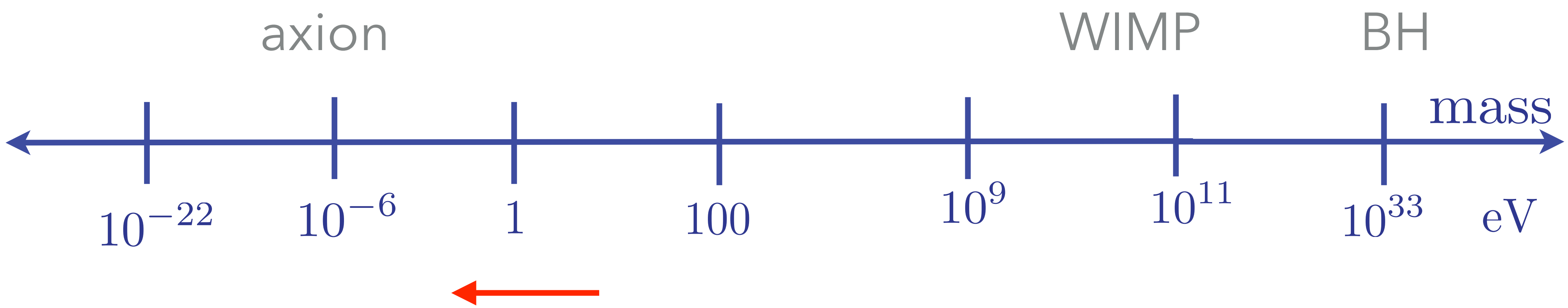

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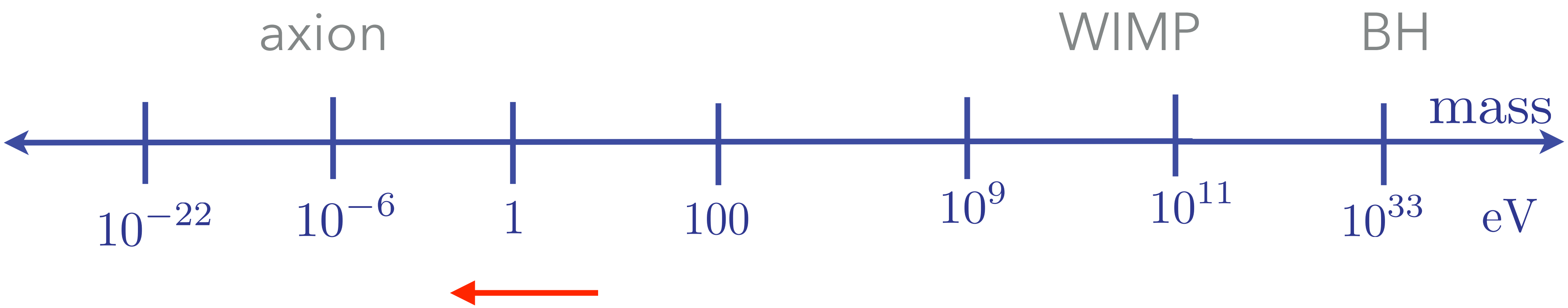
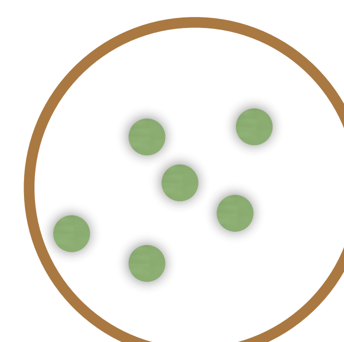


What we do know: mass density in solar neighborhood is $0.3\ \mathrm{GeV/cm^3}$

Question: at what mass is the interparticle separation < de Broglie wavelength?
(1/mv)

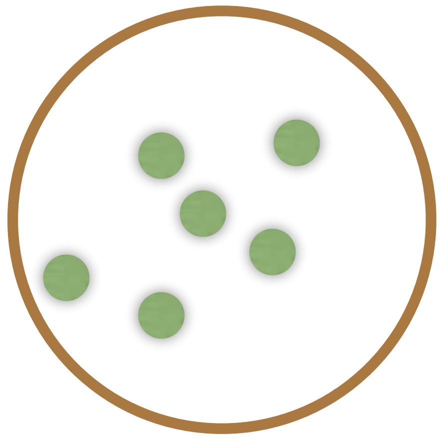
wave regime $\qquad m < 30\,\mathrm{eV}$

$$
\begin{aligned}
1/mv \sim\ & 10^{-3}\,\mathrm{cm} \quad \text{for} \quad m = 10\,\mathrm{eV} \\
& 10^{4}\,\mathrm{cm} \quad \text{for} \quad m = 10^{-6}\,\mathrm{eV} \\
& 100\,\mathrm{pc} \quad \text{for} \quad m = 10^{-22}\,\mathrm{eV}
\end{aligned}
$$



bosonic

Let's discuss:



Particle physics motivations

Wave dynamics and phenomenology

Astrophysical implications (ultra-light DM)

Experimental implications (light DM)

$$
\begin{aligned}
1/mv \sim 10^{-3}\,\mathrm{cm} \quad &\text{for} \quad m = 10\,\mathrm{eV} \\
10^{4}\,\mathrm{cm} \quad &\text{for} \quad m = 10^{-6}\,\mathrm{eV} \\
100\,\mathrm{pc} \quad &\text{for} \quad m = 10^{-22}\,\mathrm{eV}
\end{aligned}
$$

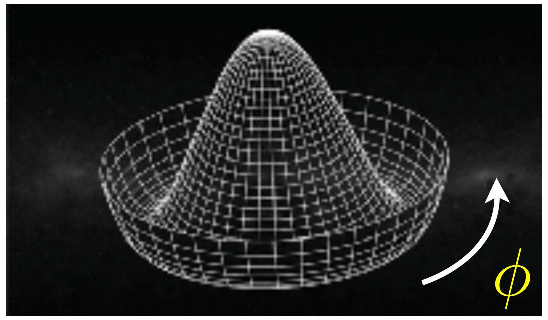
QCD axion

Fuzzy DM (Hu, Barkana, Gruzinov)

Particle physics motivations

- A natural candidate for a light (scalar) particle is a pseudo-Nambu-Goldstone boson.

  A well known example is the QCD axion (Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov, Zhitnitsky; Dine, Fischler, Srednicki; Preskill, Wise, Wilczek; Abbott, Sikivie).



  There are also many axion-like-particles in string theory (Svrcek, Witten; Arvanitaki et al.)

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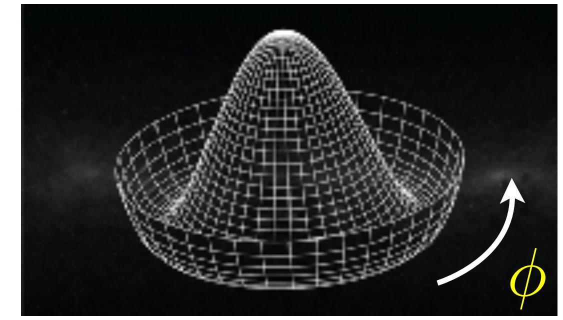

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Footnote on ultra -light version

mass m $\leftarrow$ $10^{-22}\,\mathrm{eV}$ $\rightarrow$

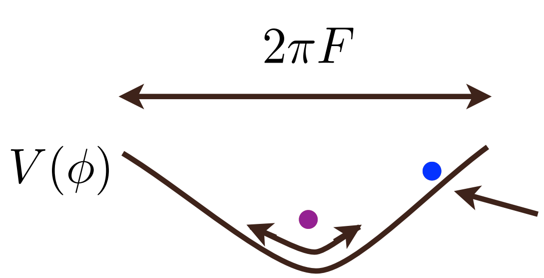
Fuzzy dark matter (FDM)
Hu, Barkana, Gruzinov
Amendola, Barbieri

- Consider an angular field (a pseudo Nambu-Goldstone) of periodicity $2\pi F$ i.e. an axion-like field with a potential from non-perturbative effects (not QCD axion).

$$\mathcal{L} \sim -\frac{1}{2}(\partial\phi)^2 - \Lambda^4(1 - \cos[\phi/F]) \qquad m \sim \Lambda^2/F$$

(candidates: Arvanitaki et al. Svrcek, Witten)

- Relic abundance matches dark matter abundance (mis-alignment mechanism).



$\phi \sim F$ at early times until $H \sim m$

$$\Omega_{\rm matter} \sim 0.1 \left(\frac{F}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

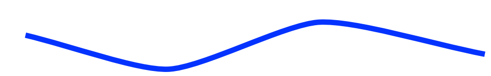
(Preskill, Wise, Wilczek; Abbot, Sikivie; Dine, Fischler, with constant m)

Dynamics of wave dark matter:

- Ignoring self-interactions $\longrightarrow$ $-\Box\phi + m^2\phi = 0$

$$\phi = \frac{1}{\sqrt{2m}}\left[\psi e^{-imt} + \psi^* e^{imt}\right]$$

Non-relativistic limit $\longrightarrow$ $i\dot{\psi} = \left[-\frac{\nabla^2}{2m} + m\Phi_{\rm grav.}\right]\psi$



- An alternative viewpoint: ψ as a (classical) fluid. $\psi = \sqrt{\rho/m}\, e^{i\theta}$ i.e. $\rho = m\,|\psi|^2$

mass conservation $\dot{\rho} + \nabla \cdot \rho v = 0$ where $v = \frac{1}{m}\nabla\theta$

Euler equation $\dot{v} + v \cdot \nabla v = -\nabla\Phi_{\rm grav.} + \frac{1}{2m^2}\nabla\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$

superfluid
(see also Berezhiani, Khoury; Fan; Alexander, Cormack)

- $+$ Poisson eq. : $\nabla^2\Phi_{\rm grav.} = 4\pi G\rho = 4\pi G m|\psi|^2$

21–4The meaning of the wave function

When Schrödinger first discovered his equation he discovered the conservation law of Eq. (21.8) as a consequence of his equation. But he imagined incorrectly that P was the electric charge density of the electron and that $\boldsymbol{J}$ was the electric current density, so he thought that the electrons interacted with the electromagnetic field through these charges and currents. When he solved his equations for the hydrogen atom and calculated ψ, he wasn't calculating the probability of anything—there were no amplitudes at that time—the interpretation was completely different. The atomic nucleus was stationary but there were currents moving around; the charges P and currents $\boldsymbol{J}$ would generate electromagnetic fields and the thing would radiate light. He soon found on doing a number of problems that it didn't work out quite right. It was at this point that Born made an essential contribution to our ideas regarding quantum mechanics. It was Born who correctly (as far as we know) interpreted the ψ of the Schrödinger equation in terms of a probability amplitude—that very difficult idea that the square of the amplitude is not the charge density but is only the probability per unit volume of finding an electron there, and that when you do find the electron some place the entire charge is there. That whole idea is due to Born.

The wave function $\psi(\boldsymbol{r})$ for an electron in an atom does not, then, describe a smeared-out electron with a smooth charge density. The electron is either here, or there, or somewhere else, but wherever it is, it is a point charge. On the other hand, think of a situation in which there are an enormous number of particles in exactly the same state, a very large number of them with exactly the same wave function. Then what? One of them is here and one of them is there, and the probability of finding any one of them at a given place is proportional to $\psi\psi^*$. But since there are so many particles, if I look in any volume $dx\,dy\,dz$ I will generally find a number close to $\psi\psi^*\,dx\,dy\,dz$. So in a situation in which ψ is the wave function for each of an enormous number of particles which are all in the same state, $\psi\psi^*$ *can* be interpreted as the density of particles. If, under these circumstances, each particle carries the same charge q, we can, in fact, go further and interpret $\psi^*\psi$ as the density of *electricity*. Normally, $\psi\psi^*$ is given the dimensions of a probability density, then ψ should be multiplied by q to give the dimensions of a charge density. For our present purposes we can put this constant factor into ψ, and take $\psi\psi^*$ itself as the electric charge density. With this understanding, $\boldsymbol{J}$ (the current of probability I have calculated) becomes directly the electric current density.

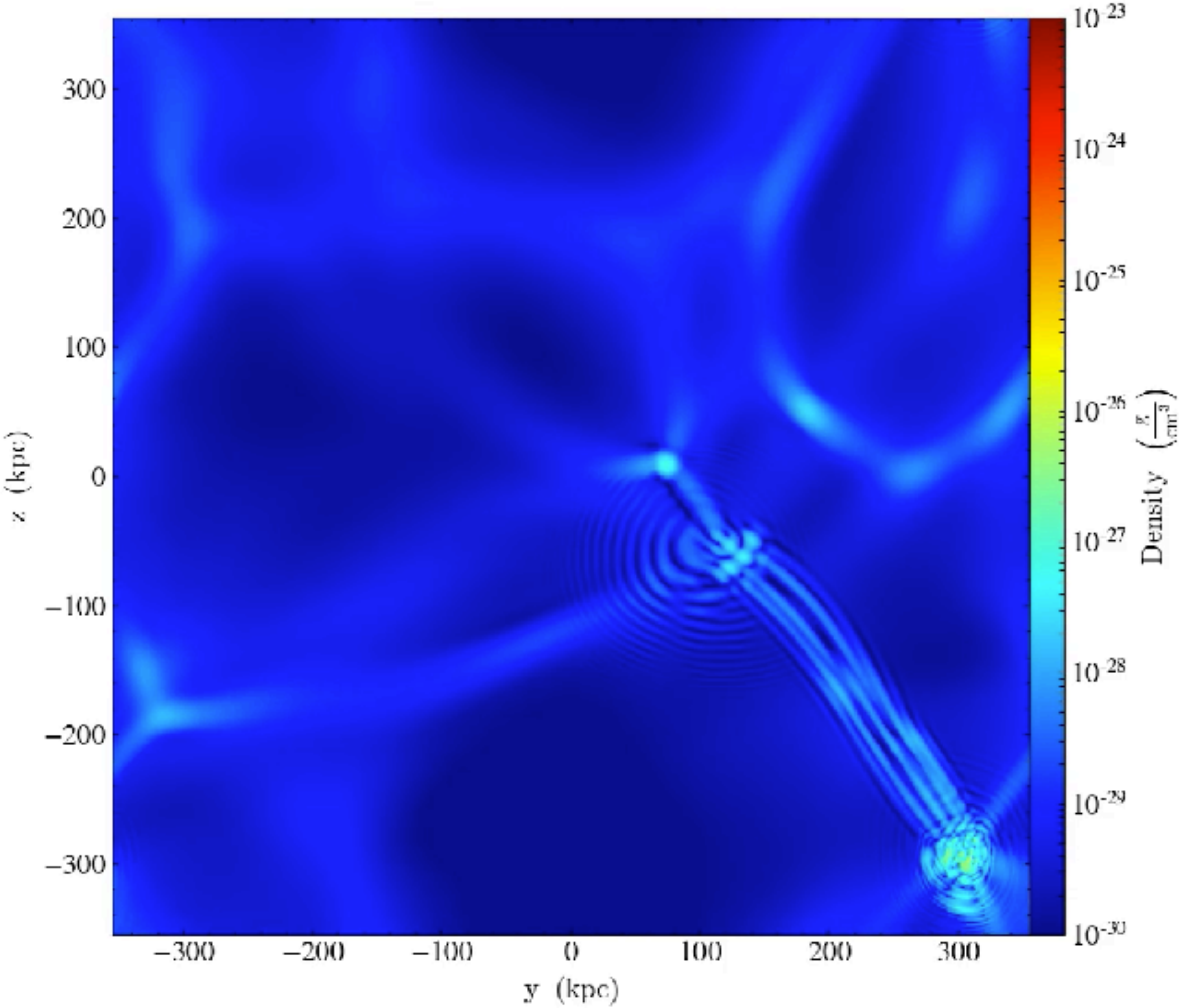
Long history of scalar field as dark matter:

Baldeschi, Ruffini, Gelmini; Turner; Press, Ryden, Spergel; Sin; Hu, Barkana, Gruzinov; Peebles; Goodman; Lesgourgues, Arbey, Salati; Amendola, Barbieri; Chavanis; Suarez, Matos; Matos, Guzman…

Dark matter as superfluid:

Rindler-Daller, Shapiro; Berezhiani, Khoury; Fan; Alexander, Cormack; Alexander, Gleyzer, McDonough, Toomey; Ferreira, Franzmann, Khoury, Brandenberger…

Wave effects in a cosmological simulation

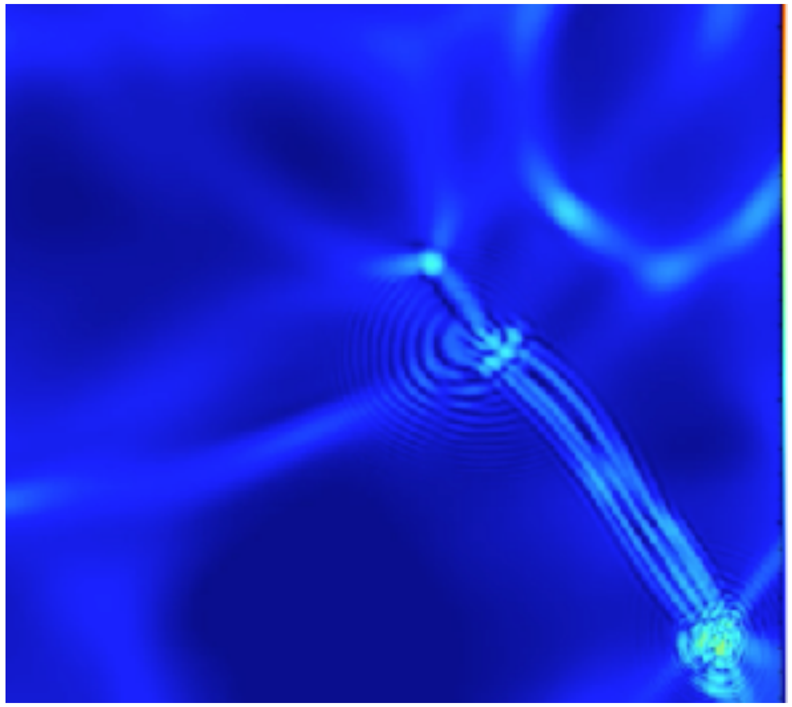


Li, LH, Bryan

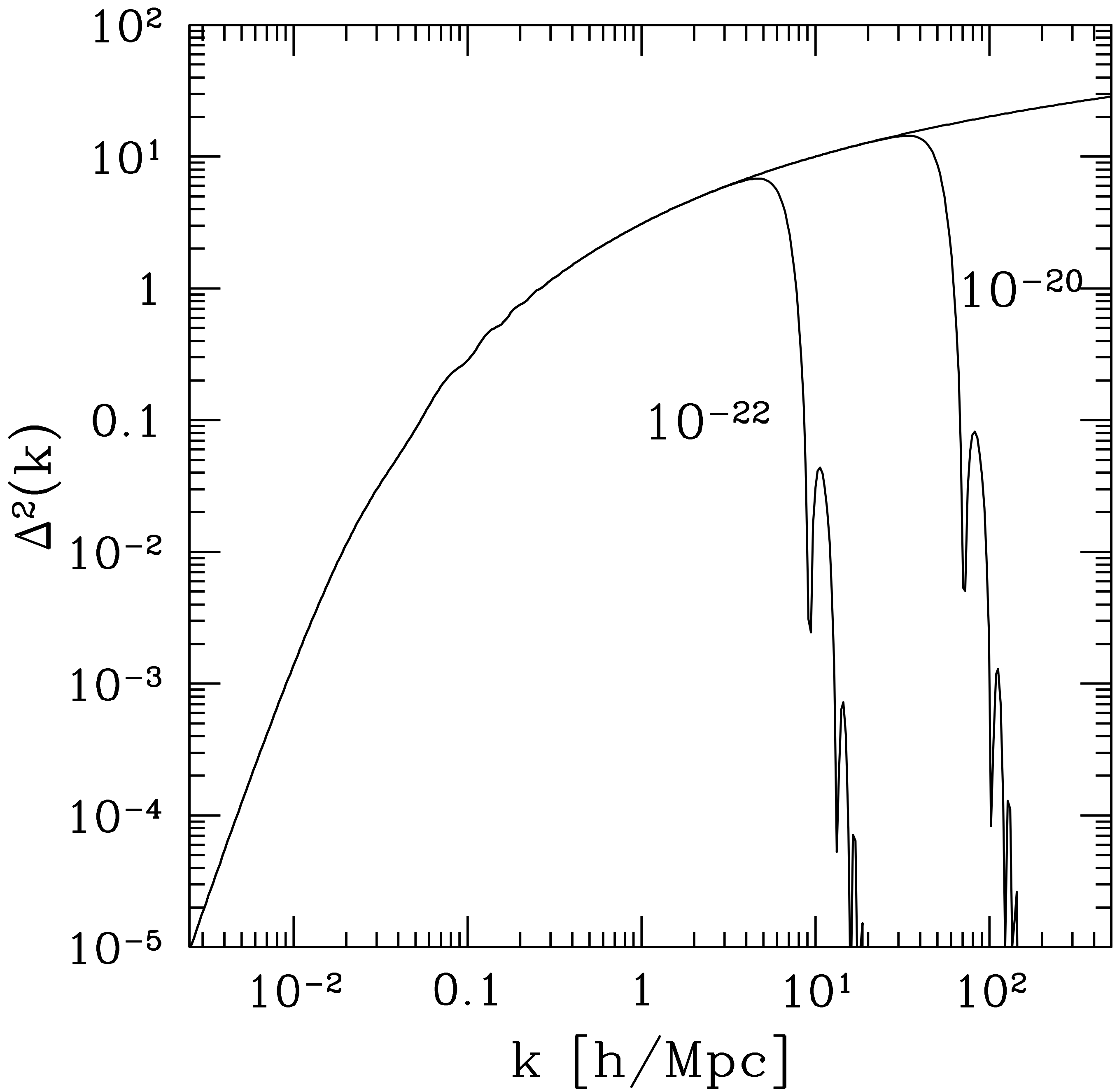
See Schive, Chiueh, Broadhurst; Veltmaat, Niemeyer; Schwabe, Niemeyer, Engels; Mocz et al.; Nori, Baldi; Kendall, Easther

Wave effects from light/ultra-light DM:

- Lyman-alpha forest
- solitonic halo core
- interference substructure
- vortices (and walls)
- dynamical friction
- evaporation of sub-halos by tunneling
- direct detection
- detection by pulsar timing array
- gravitational lensing
- scattering of tidal streams
- soliton oscillations
- black hole hair



$$\textit{linear} \text{ power spectrum } \Delta^2 \equiv 4\pi k^3 P(k)/(2\pi)^3$$



Linear perturbation theory for wave dark matter predicts suppressed power at high k.

Lyman-alpha forest constraint

Irsic, Viel, Haehnelt, Bolton, Becker 2017

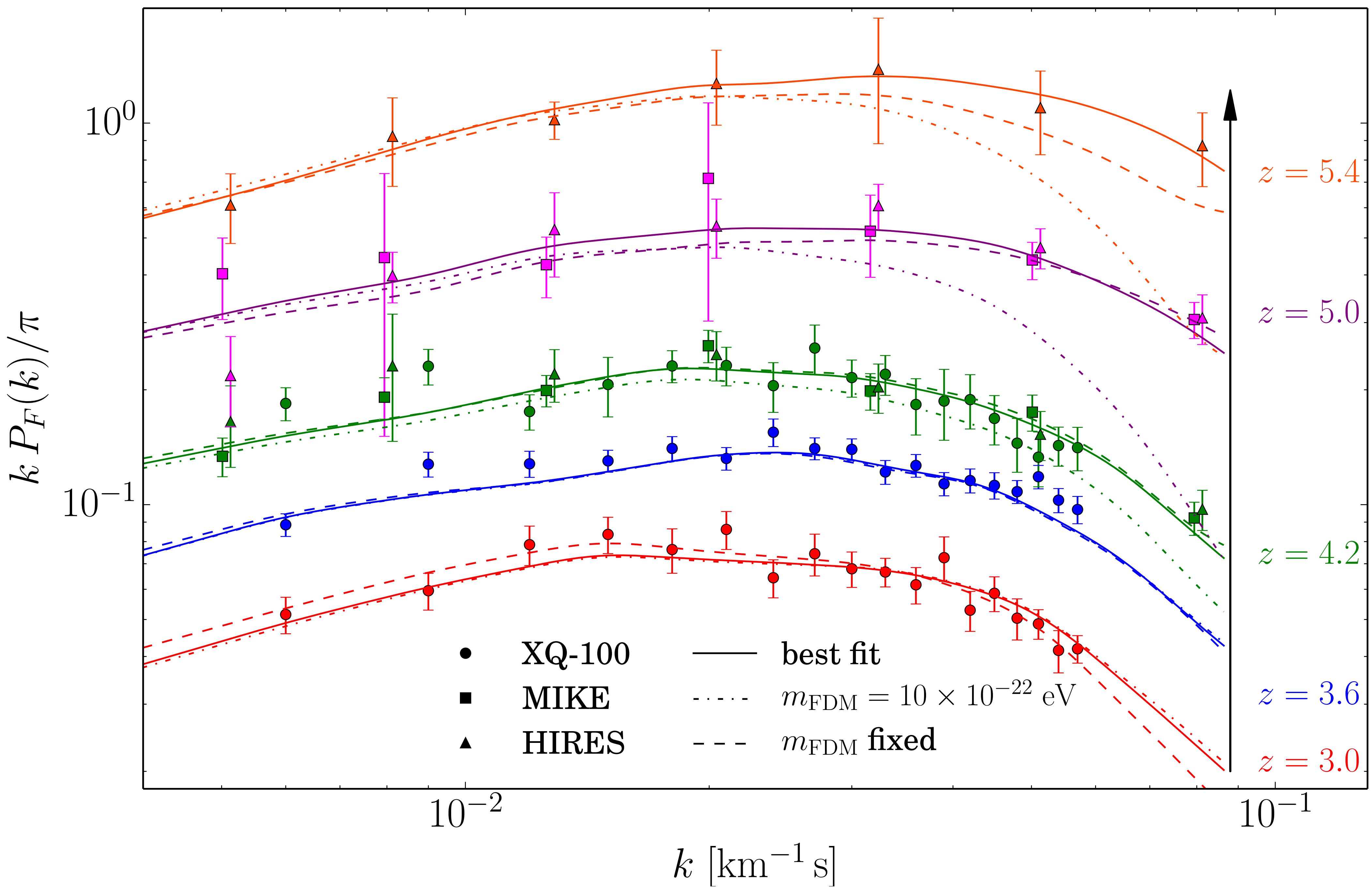


Figure thanks to Vid Irsic and Matteo Viel

Importance of ionizing background and reionization history fluctuations?

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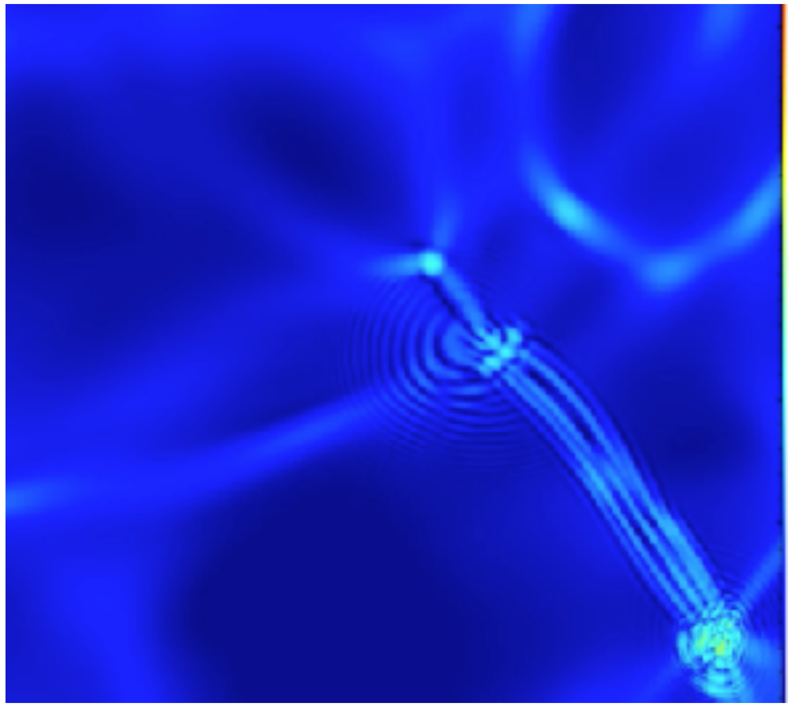


Useful estimates

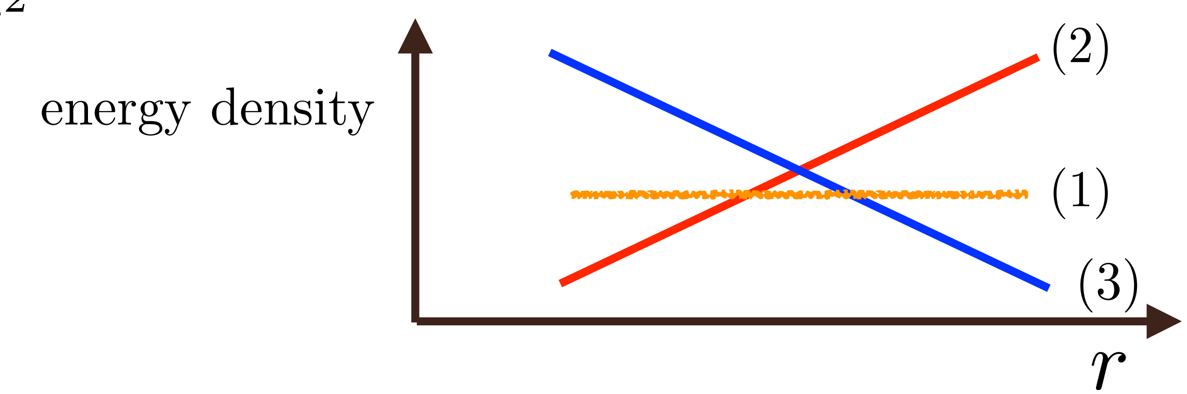
recall $\rho \sim m^2\phi^2$

(1) self interaction $= \lambda\phi^4 \sim \left(\frac{m}{F}\right)^2 \phi^4 \sim \left(\frac{m}{F}\right)^2 \left(\frac{\rho}{m^2}\right)^2$

(2) gravity $= \rho\,\Phi_{\text{grav.}} \sim \rho\left(\frac{G\rho r^3}{r}\right) \sim G\rho^2 r^2$

(3) gradient energy $= \frac{\phi^2}{r^2} \sim \frac{\rho}{m^2 r^2}$

(related to quantum pressure)



- Self-interaction unimportant for much, but not all, of the parameter space. (see footnote 10 in review/lecture notes)

- de Broglie scale as the transition scale between (2) and (3):

$$\text{compare } \Phi_{\text{grav.}} \sim v^2 \text{ vs. } \frac{1}{m^2 r^2} \longrightarrow r \sim \frac{1}{m\,v}$$

- solitons as objects where (2) and (3) balance: (eqs. 22 - 24 in review/lecture notes)

$$\frac{GM_{\text{soliton}}}{r_{\text{soliton}}} \sim \frac{1}{m^2 r^2_{\text{soliton}}} \longrightarrow r_{\text{soliton}} \sim \frac{1}{m^2 G M_{\text{soliton}}} \sim \frac{M^2_{\text{pl.}}}{m^2 M_{\text{soliton}}}$$

Solitons tend to condense at centers of halos.

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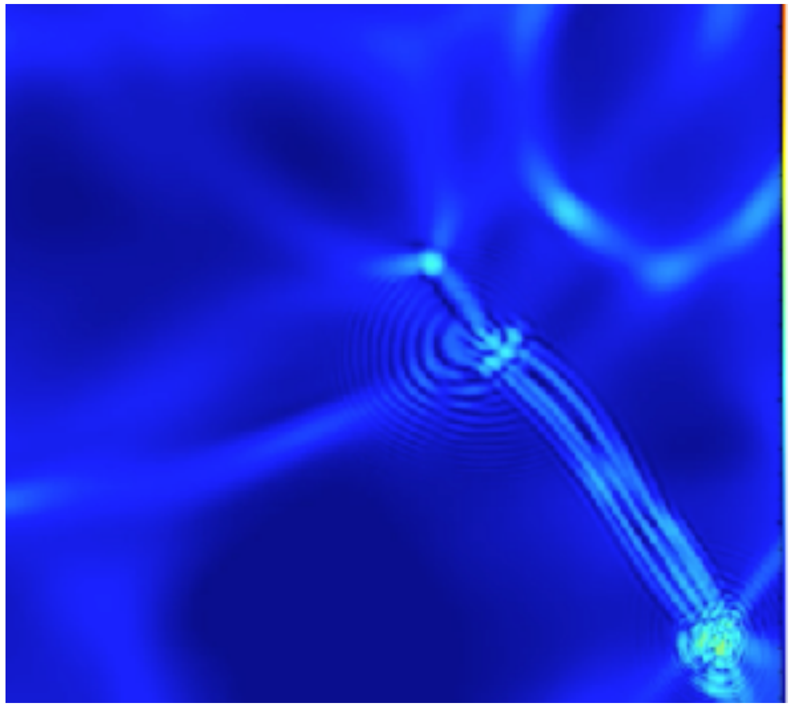

Interference substructures - general considerations

$$\psi(t,x) = \sum_k A_k \, e^{iB_k} e^{ik\cdot x - i\omega_k t}$$

- B_k is a randomly distributed phase (for a virialized halo), leading to a Gaussian random ψ .

- $A_k \sim e^{-k^2/k_0^2}$ is a simple example, describing a thermal distribution of momenta . k_0 is the characteristic momentum scale (momentum dispersion). The characteristic length scale associated with it is $1/k_0 \sim 1/(mv)$ i.e. the de Broglie scale.

- $\omega_k = k^2/(2m)$ tells us the characteristic frequency is $k_0^2/(2m)$ i.e. the characteristic time scale is $m/k_0^2 \sim 1/(mv^2)$ i.e. de Broglie time.

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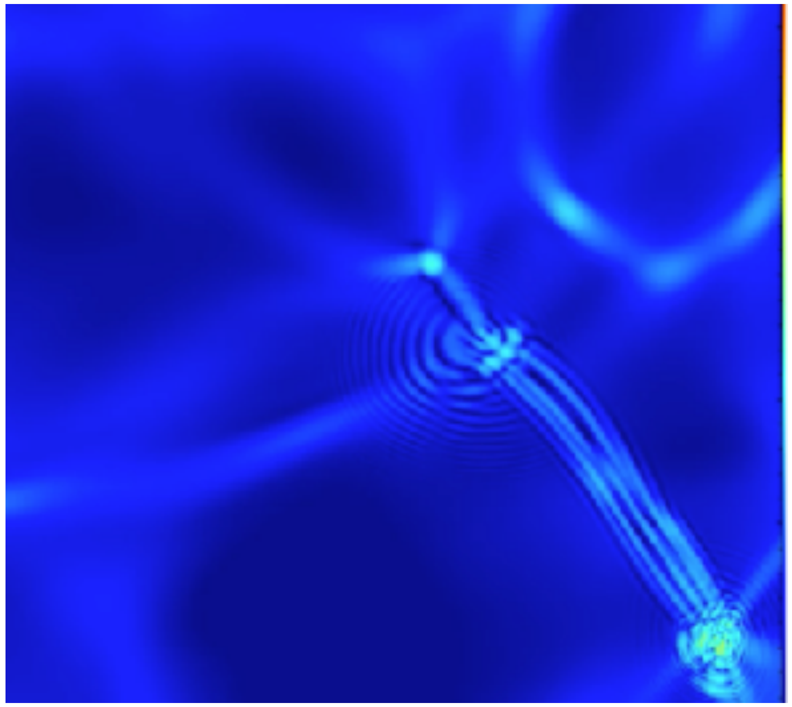


Vortices

- Consider again fluid formulation: $\psi = \sqrt{\rho/m}\, e^{i\theta}$

$$\dot{\rho} + \nabla \cdot \rho v = 0 \quad \text{where} \quad v = \frac{1}{m}\nabla\theta$$

$$\dot{v} + v \cdot \nabla v = -\nabla\Phi_{\text{grav.}} + \frac{1}{2m^2}\nabla\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

- Naively, vorticity cannot exist, because the velocity field is a gradient flow. In addition, one might think Kelvin's theorem should hold i.e. no vorticity is generated if there's no vorticity to begin with.

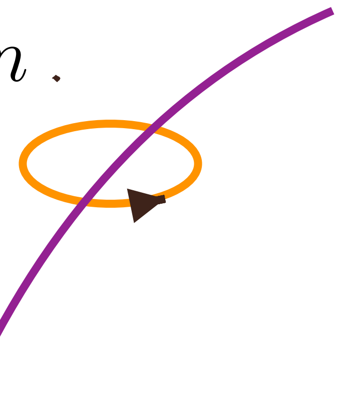
- The loophole: where $\rho = 0$. Note: such complete destructive interference can only occur in the late universe when O(1) fluctuations are present. No vortices in the early universe.

- The phenomenon of vortices is well understood in condensed matter physics.

Structure of a vortex

- Generically, in 3D, the set of points where both the real & the imaginary parts of the wavefunction vanish fall on a line i.e. a line/string defect.

- The phase of the wavefunction must wraps around the line by $2\pi n$.
  Thus, a vortex: $\oint \vec{v} \cdot d\vec{\ell} = 2\pi n/m$

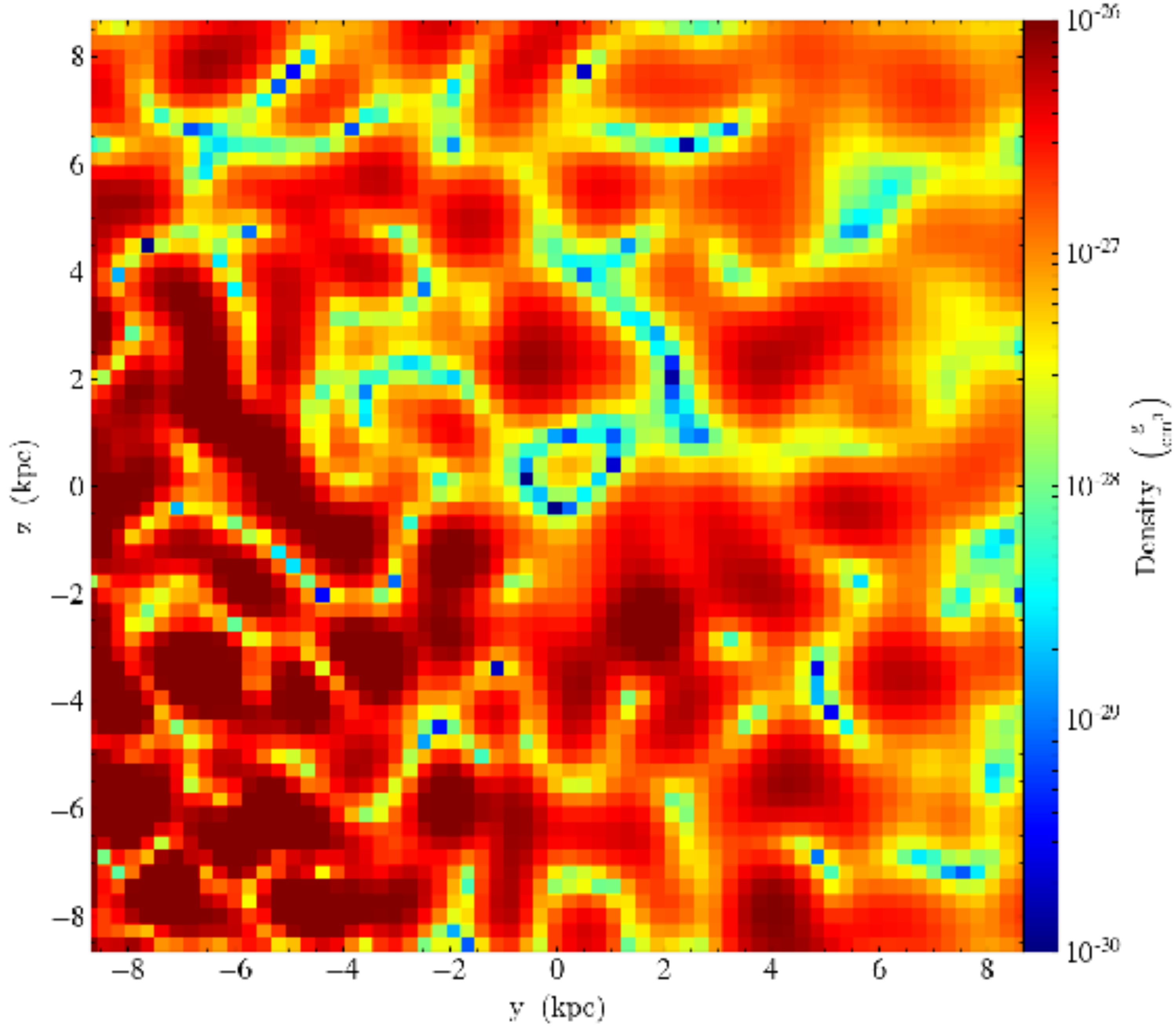


- Taylor expansion reveals further details (case of $n = 1$):

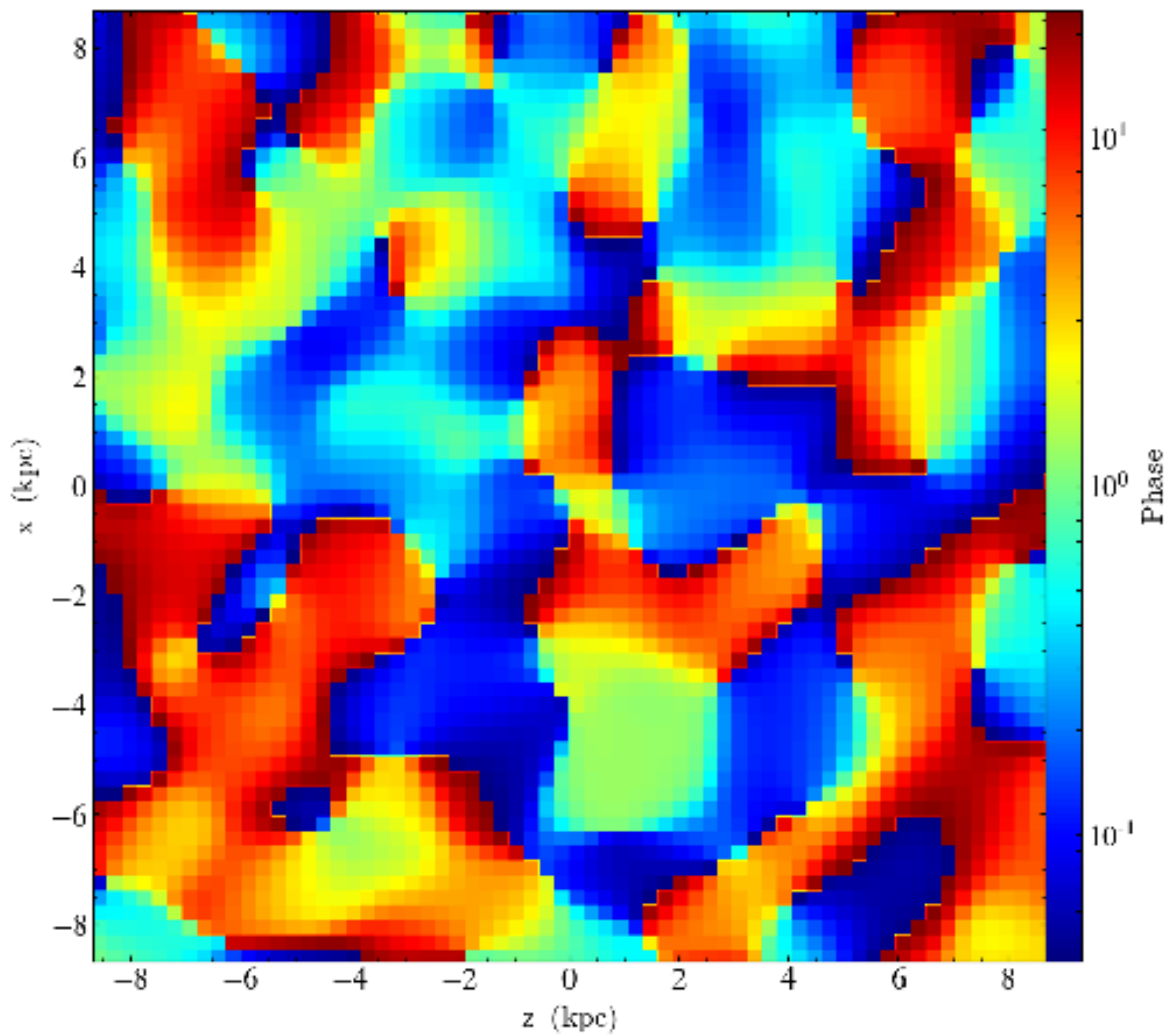
$$\psi(\vec{x}) \sim \cancel{\psi(0)} + \vec{x} \cdot \vec{\partial}\psi\big|_0 + \ldots \qquad \rho \sim r^2 \qquad (\text{also } v \sim 1/r)$$

- Vortex generally takes the form of a loop i.e. vortex ring.

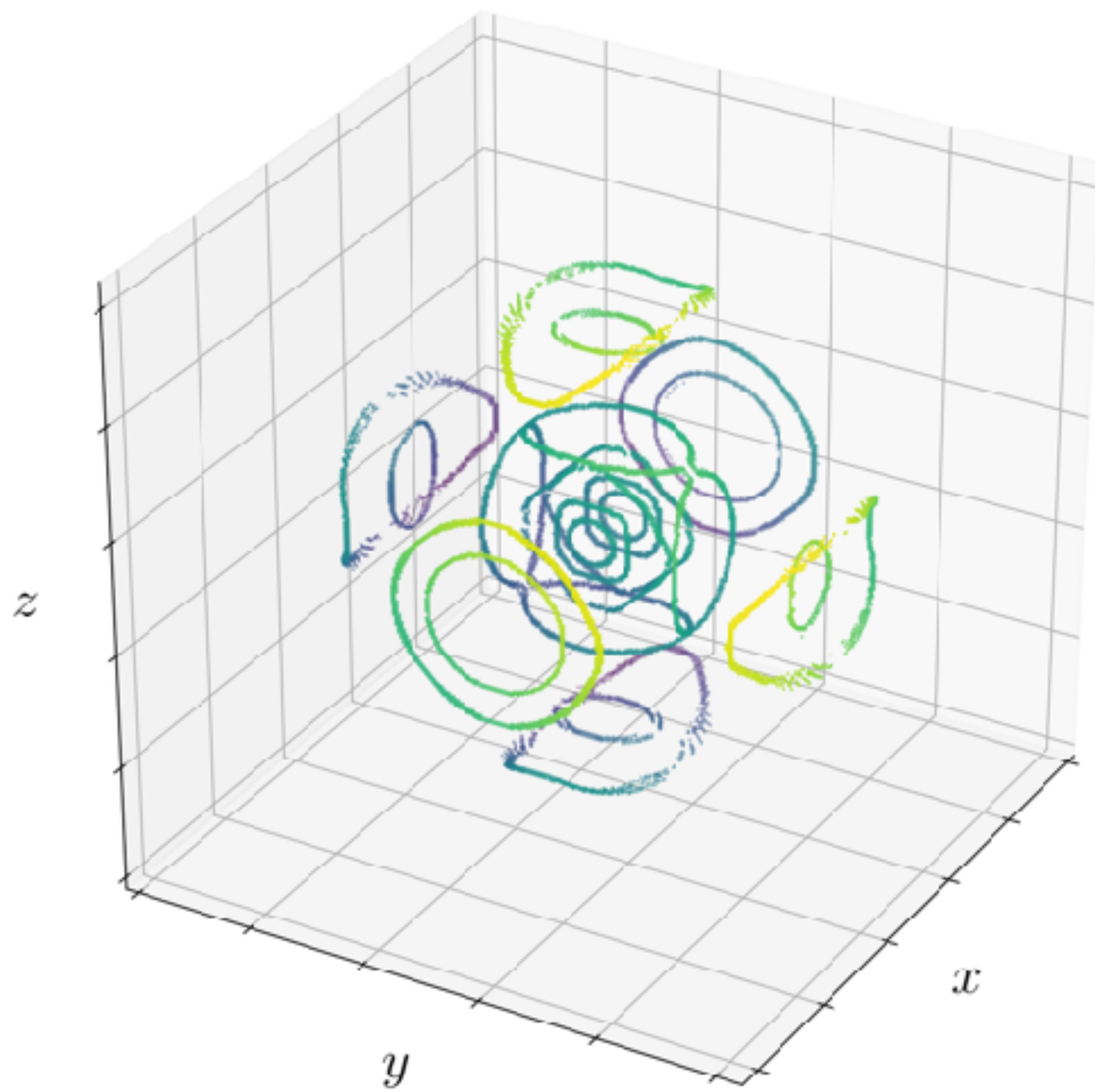
Note: this is not the usual axion string.



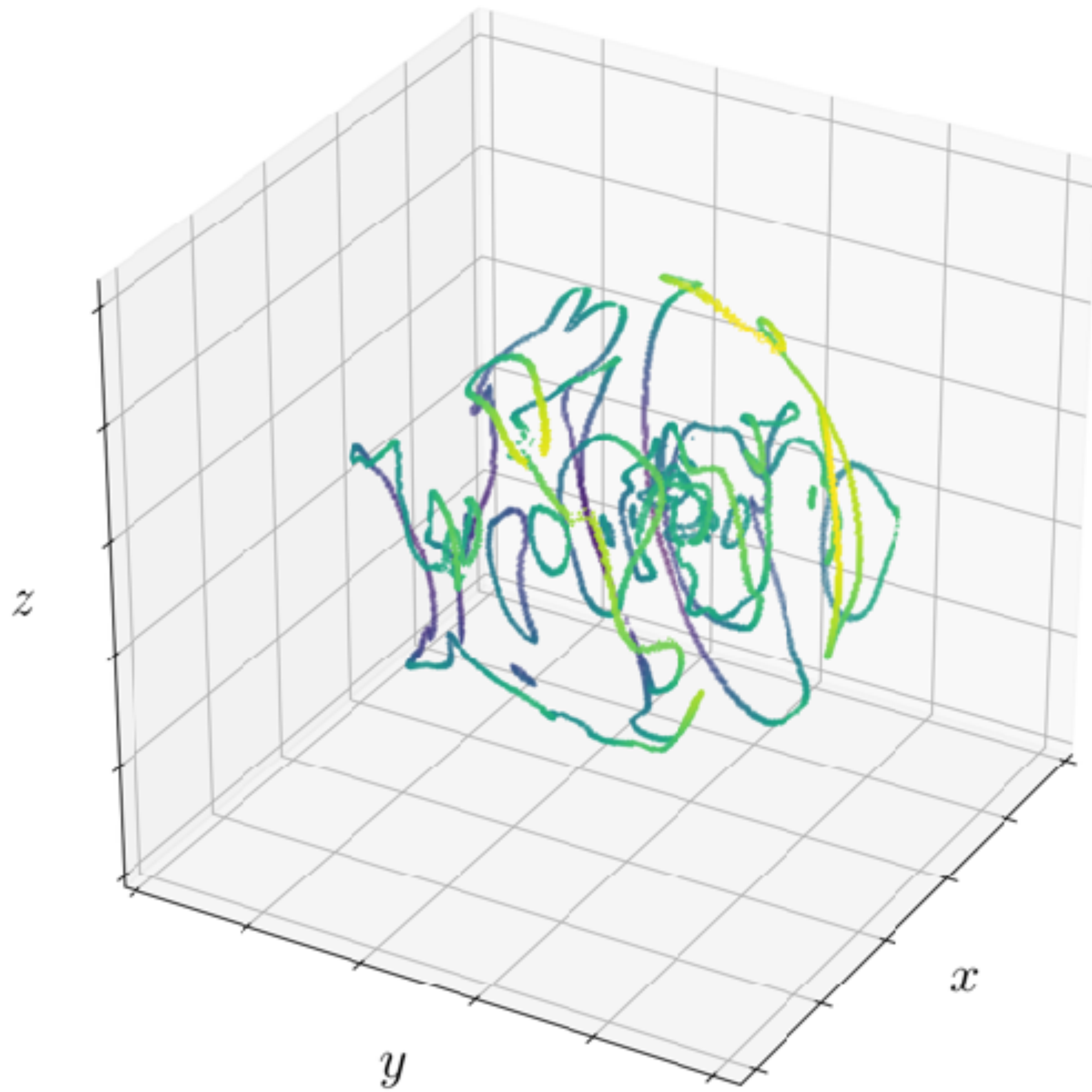
z (kpc)
y (kpc)
Density

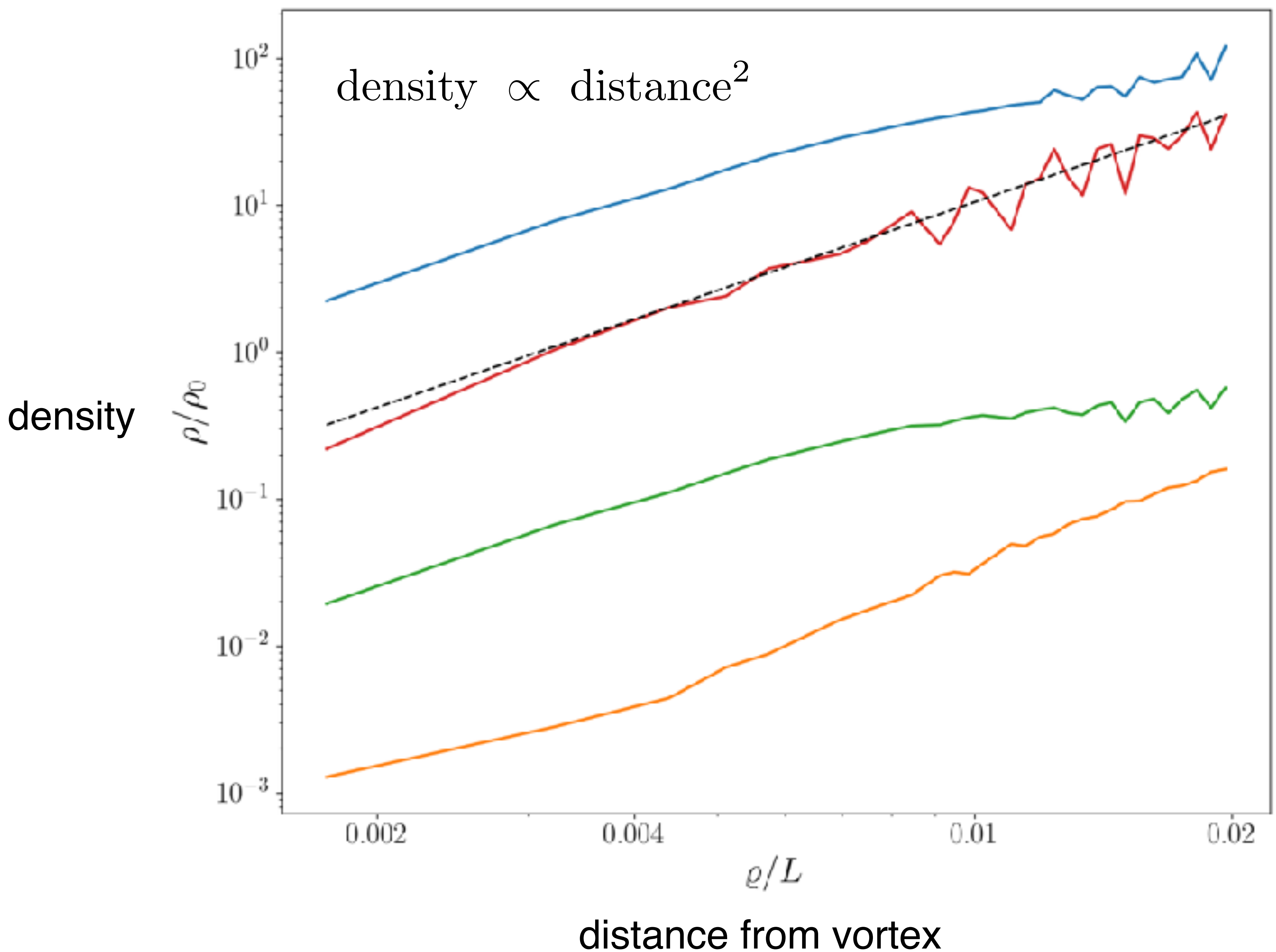


x (kpc)
z (kpc)
Phase

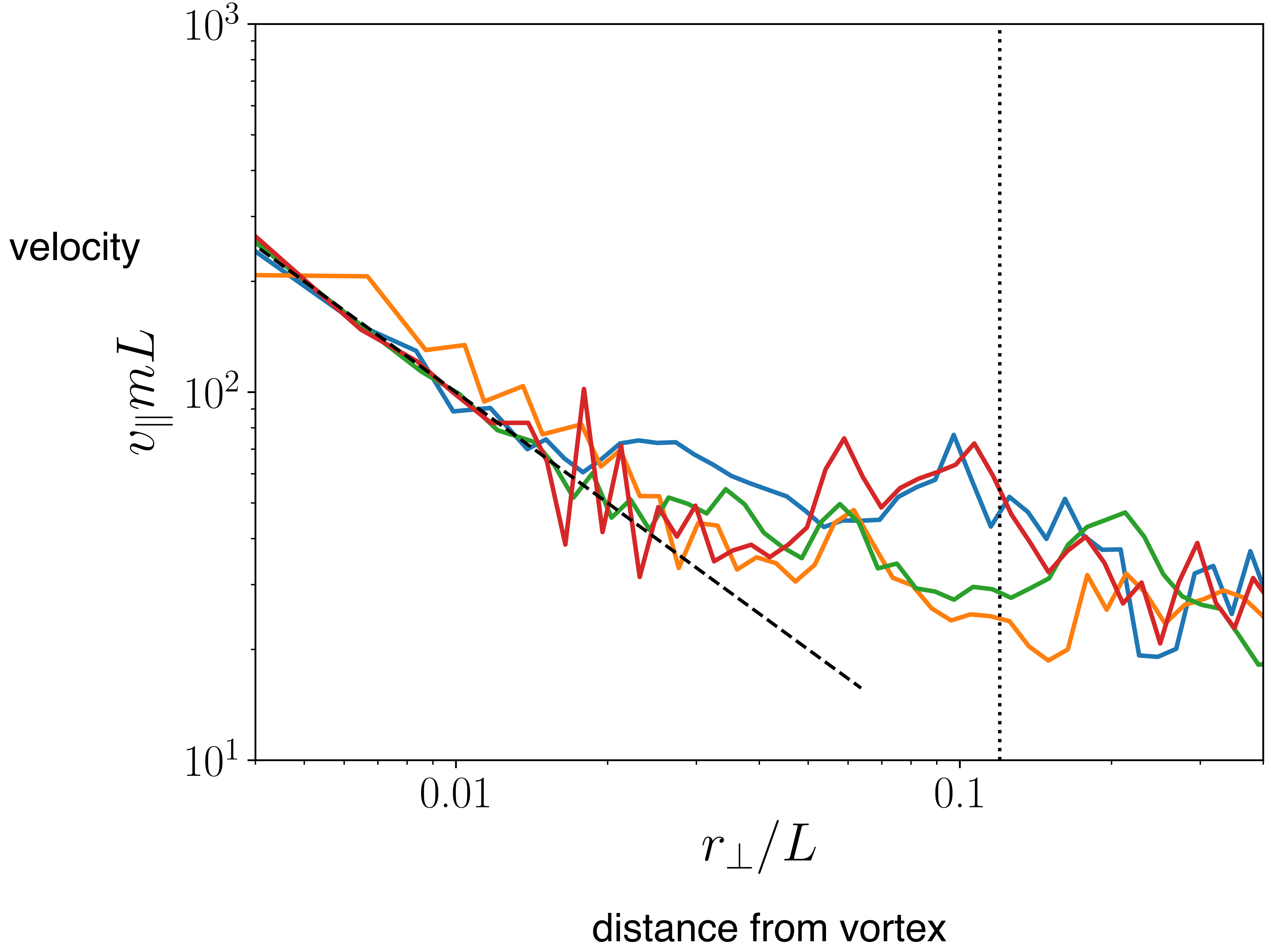


z
y
x


z
y
x

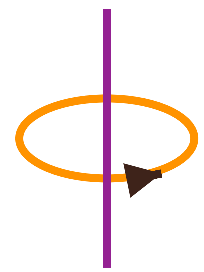


density $\propto$ distance^2
density
ρ/ρ_0
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0.002
0.004
0.01
0.02
ϱ/L
distance from vortex

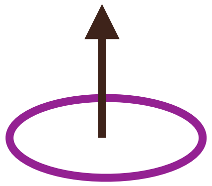

velocity
10^3
10^2
10^1
$v_\parallel m L$
0.01
0.1
$r_\perp / L$
distance from vortex

Simple solutions of the free equation: $\quad i\,\partial_t \psi = -\frac{\nabla^2}{2m}\psi$

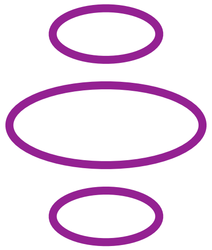
$$\psi = x + iy$$



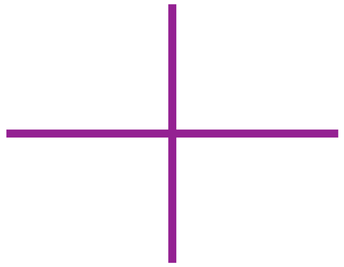
$$\psi = x^2 + y^2 - R^2 + 2i(-Rz + t/m)$$

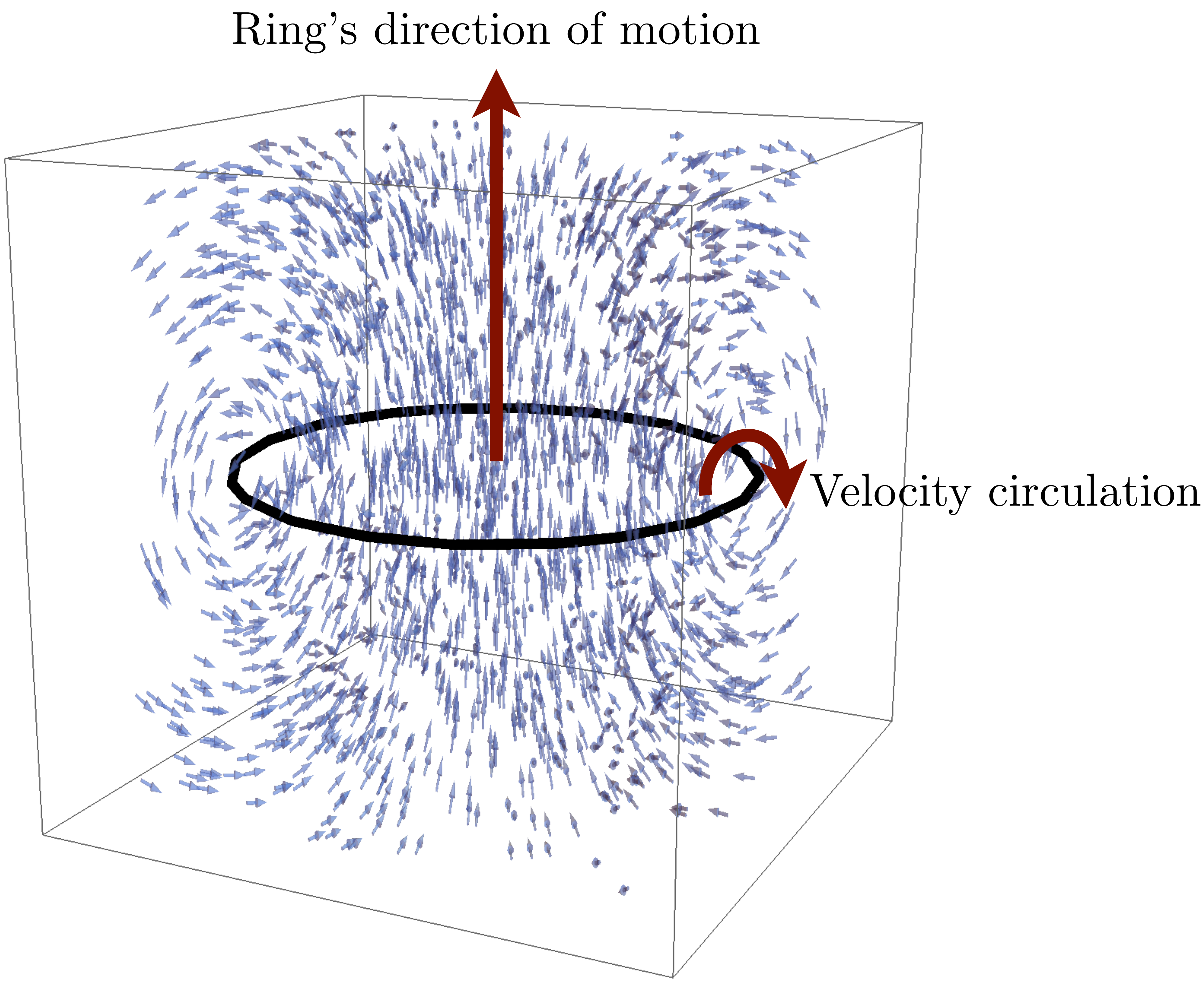


$$\psi = x^2 + y^2 + z^2 - R^2 + i(-2Rz + 3t/m)$$

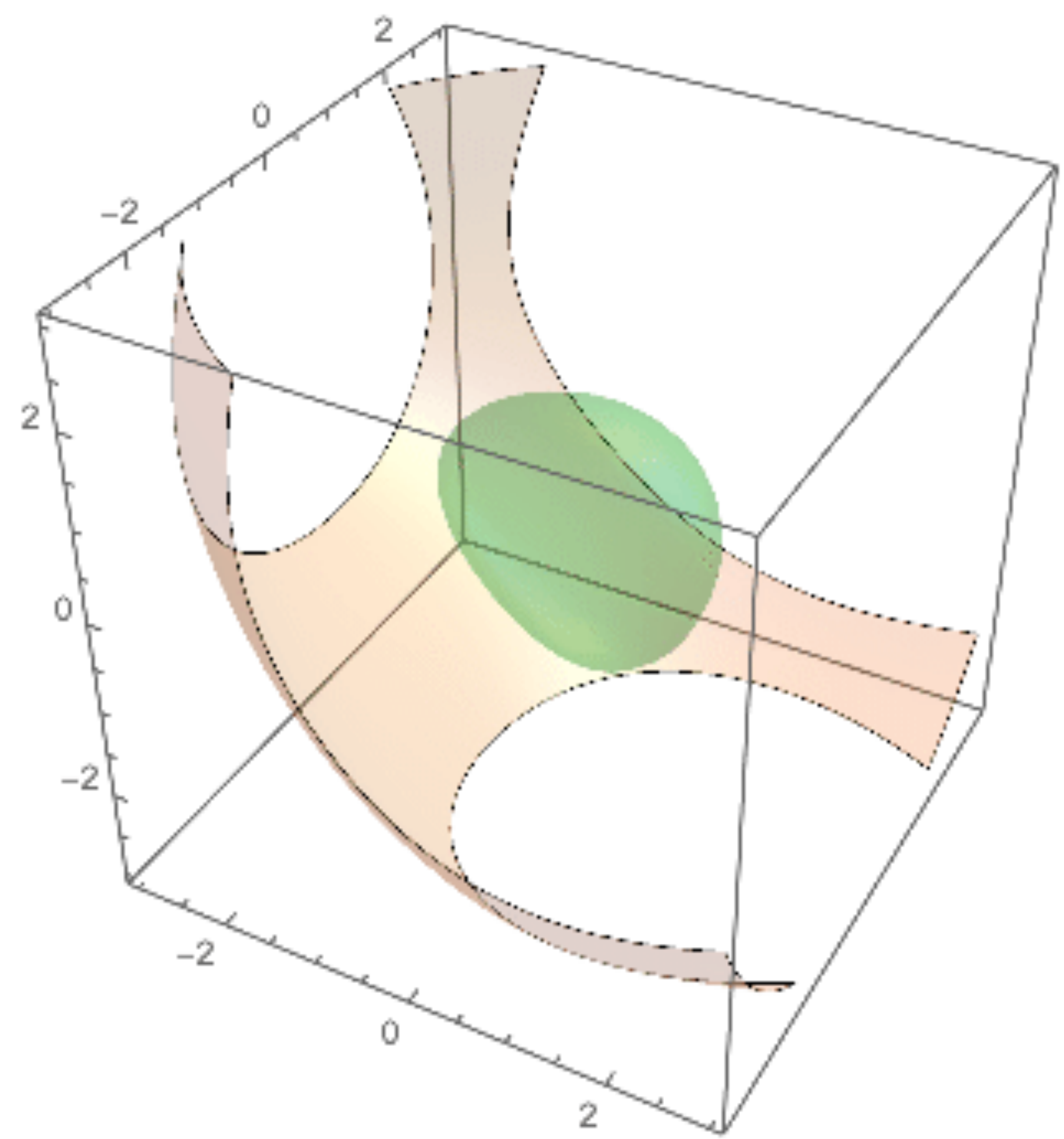


$$\psi = (x + iy)(y + iz) - t/m$$

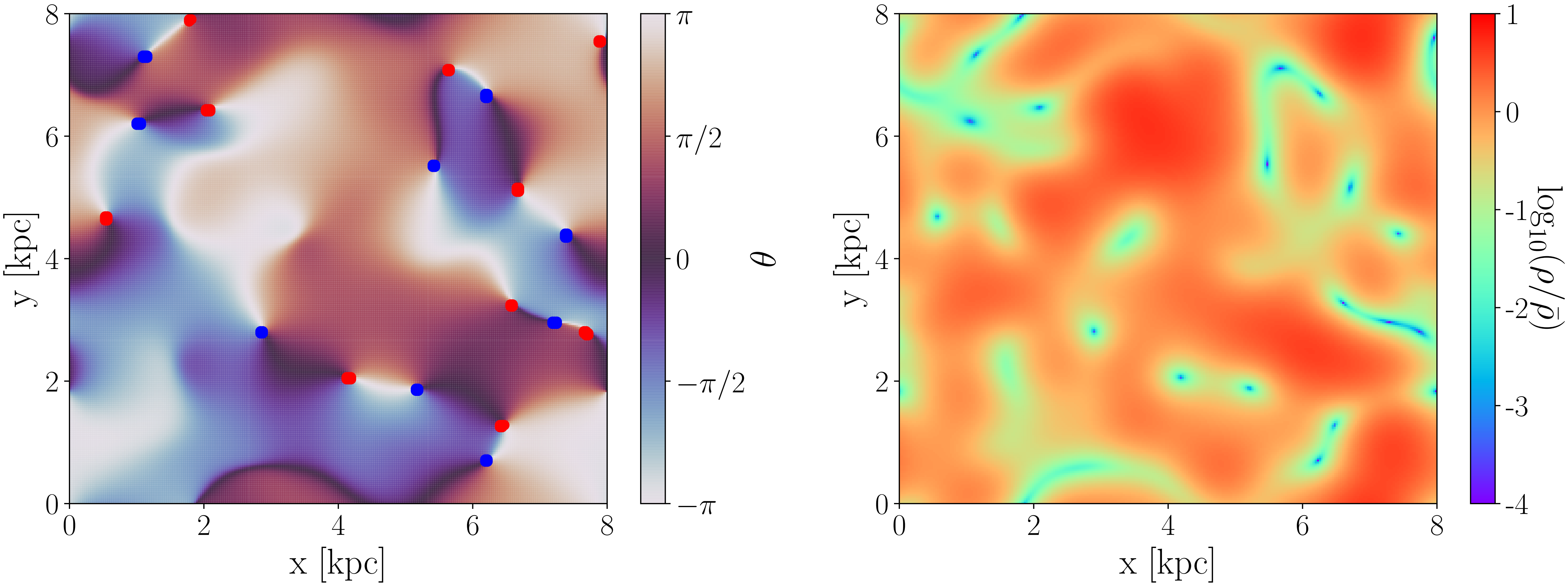




Ring's direction of motion
Velocity circulation



2
0
−2
2
0
−2
−2
0
2



A 2D example built from a superposition of waves with random phases

Vortices appear and disappear in pairs.

Additional comments:

- Should defects be rare? No - roughly one vortex ring per de Broglie volume. Can compute this analytically for a model halo composing of a superposition of waves with random phases: essentially looking for zero-crossing. Note: this holds even if the halo has no net angular momentum.
- Smaller rings move faster: $v \sim \frac{1}{mR}$. Curved segments also move faster.
- Vortices (and interference substructures) are transient phenomena. Coherent time scale is de Broglie time $1/mv^2$ (million years for ultra-light). Vortices can't arbitrarily appear or disappear - Kelvin's theorem.
- Angular momentum eigenstates have vortices, though angular momentum does not require vortices (e.g. can always add s-wave with large amplitude).
- See condensed matter literature.

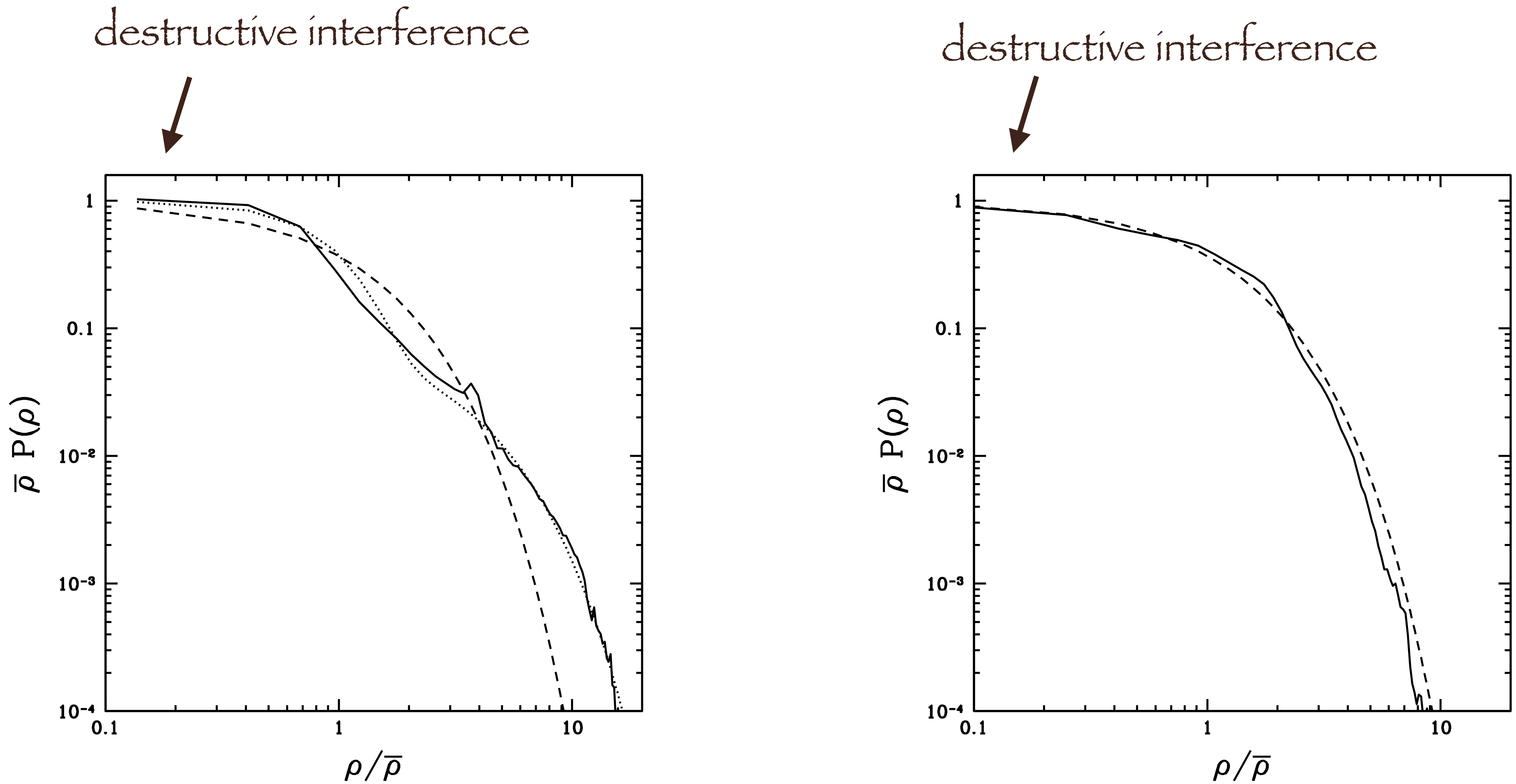
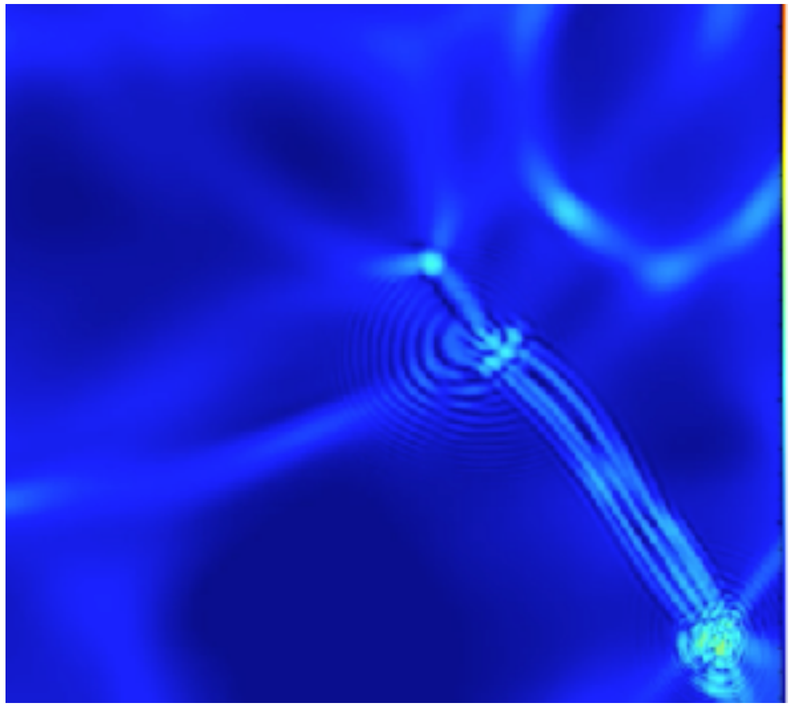


Figure 5: The one-point probability distribution of density: $P(\rho)d\rho$ gives the probability that the density ρ takes the values within the interval $d\rho$. The solid lines are measured from numerical wave simulations of two halos that form from mergers of smaller seed halos and gravitational collapse. The left panel is from a simulation where the initial seed halos are distributed uniformly, and the right panel is from a simulation where the initial seed halos are distributed randomly. The dashed line in each panel shows the analytic prediction from the random phase halo model: $\bar{\rho}P(\rho) = e^{-\rho/\bar{\rho}}$. The dotted line on the left panel is $\bar{\rho}P(\rho) = 0.9\, e^{-1.06(\rho/\bar{\rho})^2} + 0.1\, e^{-0.42(\rho/\bar{\rho})}$. See [72] for details.

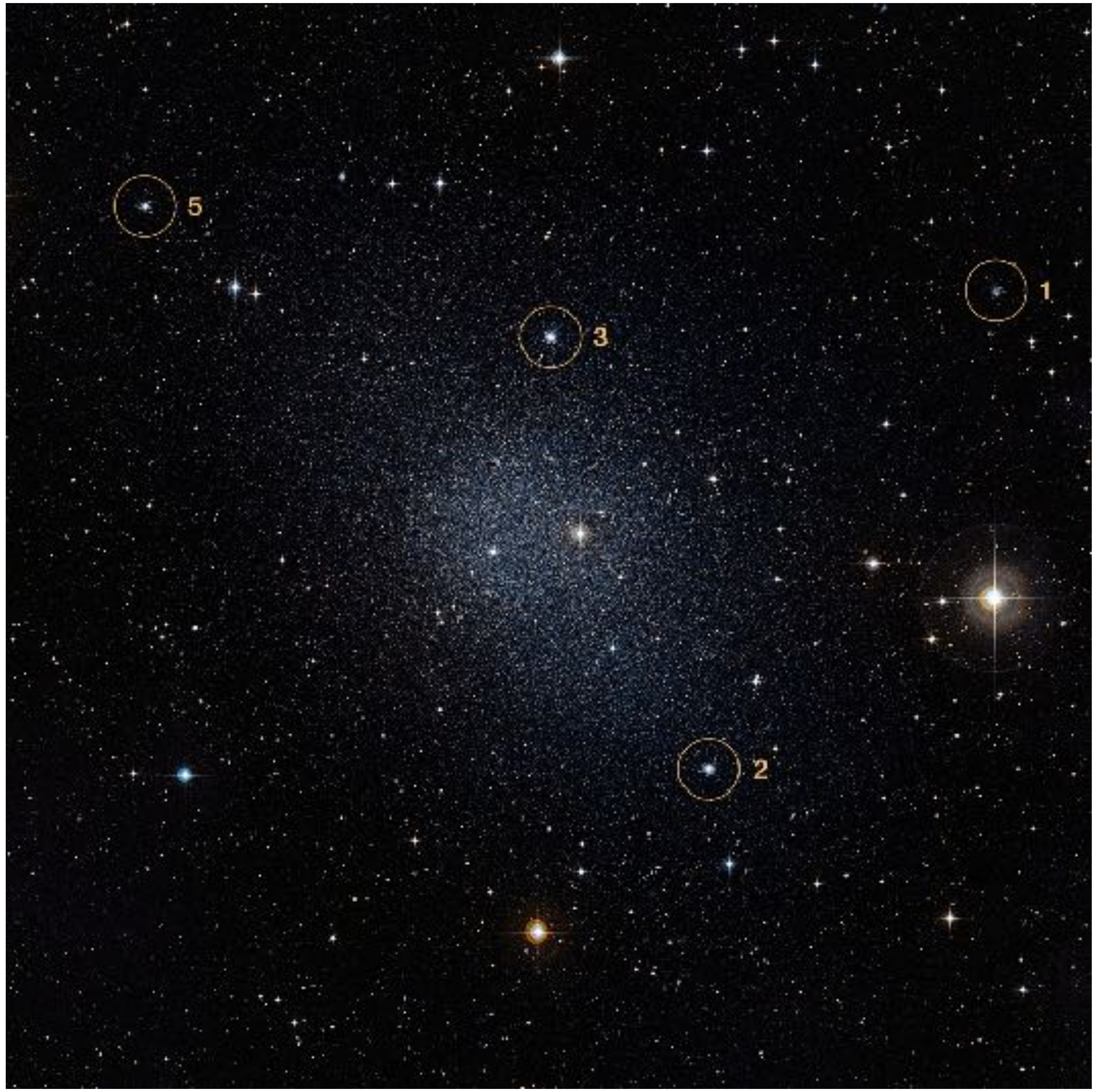
Wave effects from light/ultra-light DM:

- Lyman-alpha forest ✓
- solitonic halo core ✓
- interference substructure ✓
- vortices (and walls) ✓
- dynamical friction
- evaporation of sub-halos by tunneling
- direct detection
- detection by pulsar timing array
- gravitational lensing
- scattering of tidal streams
- soliton oscillations
- black hole hair



Fornax galaxy and its globular clusters

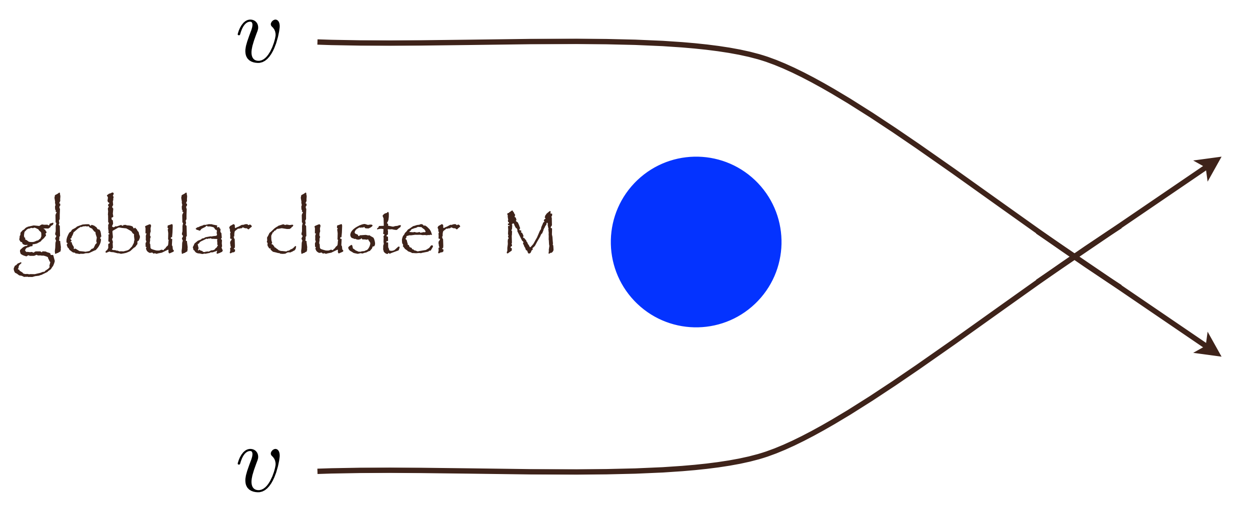
ESO/Digitized Sky Survey 2



Dynamical friction issue: Tremaine 1976

Dynamical friction

- Chandrasekhar's classic calculation:



- Quantum stress smooths out density wake, lowering friction.
  (see also Lora et al.)

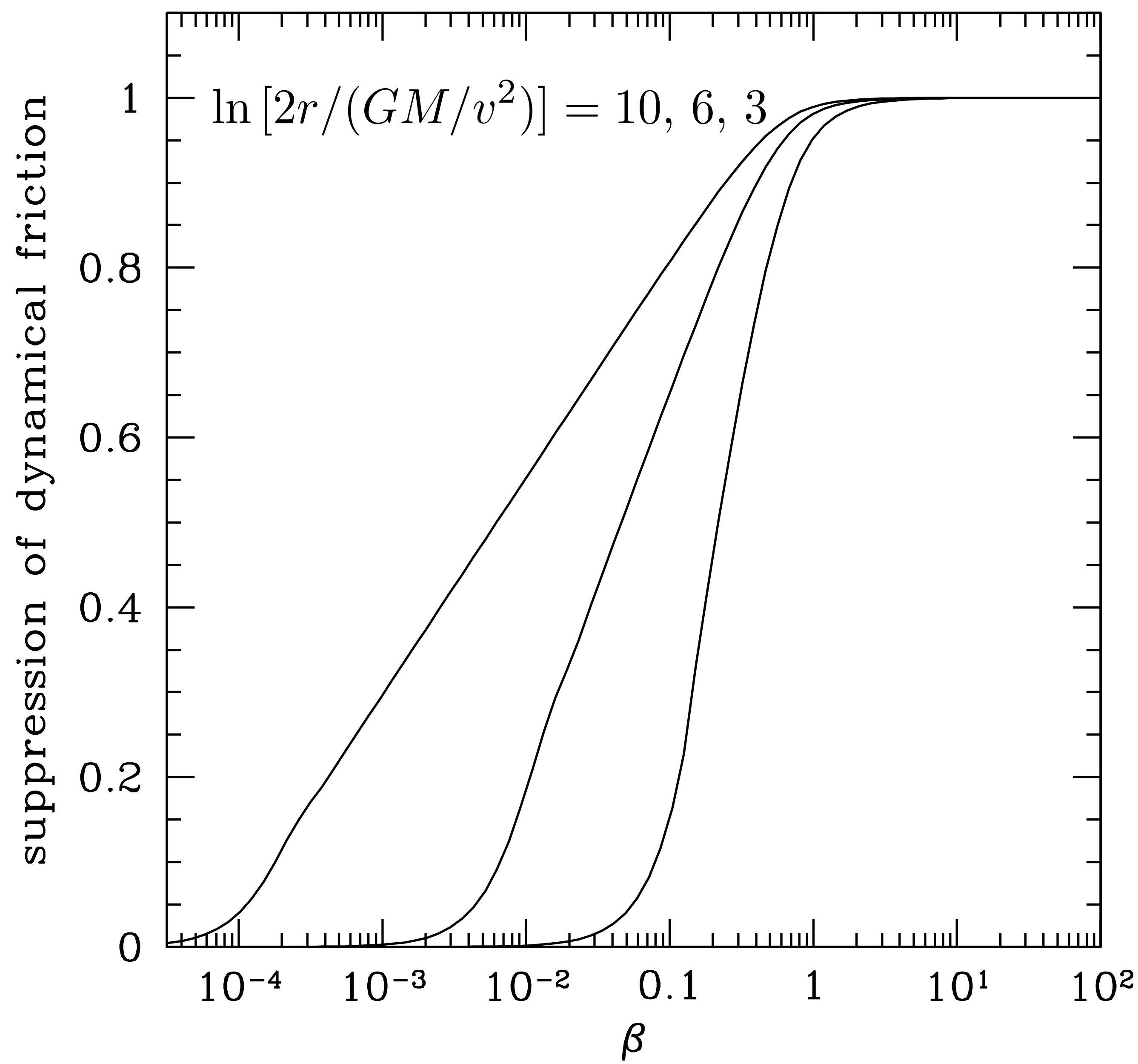
- Use known solution for the Coulomb scattering problem:

  $\psi \propto F\,[\,i\beta, 1, ikr(1 - \cos\theta)\,]$ where F is the confluent hypergeometric func.

  $\beta \equiv (GM/v^2)/k^{-1}$ with $k^{-1} = (mv)^{-1} =$ de Broglie wavelength

  Small β means quantum stress is important.

- Key - integrate momentum flux to compute friction: $\oint dS_j\, T_{ij}$



$$\beta \equiv (GM/v^2)/k^{-1}$$
$$= 0.0023 \left(\frac{M}{10^5 M_\odot}\right)\left(\frac{10\,\mathrm{km/s}}{v}\right)\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)$$

Conclusion:

Given the density profile of a galaxy (which can be experimentally determined), standard CDM has a definite prediction for the dynamical friction, which can be checked against observations.

Fuzzy DM of m $\sim 10^{-22} - 10^{-21}\,\mathrm{eV}$ can lower dynamical friction by an order of magnitude.

Would be useful to study other systems: Lotz et al. 2001

Wave effects from light/ultra-light DM:

- Lyman-alpha forest ✓
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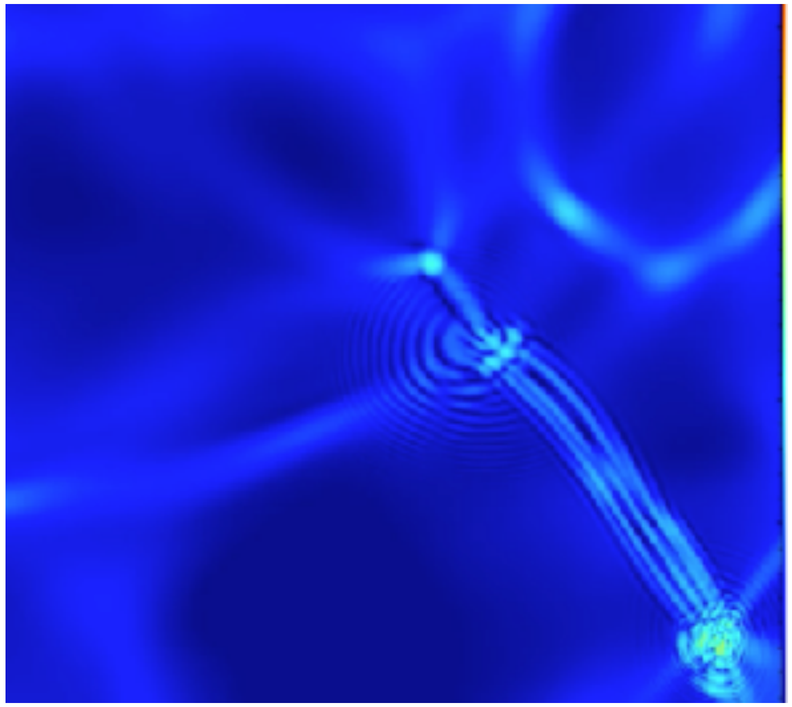
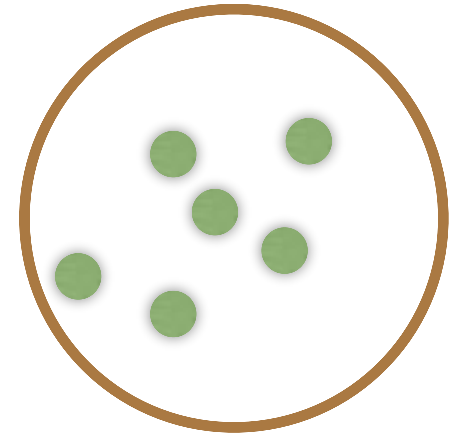


Let's discuss:



Particle physics motivations

Wave dynamics and phenomenology

Astrophysical implications (ultra-light DM)

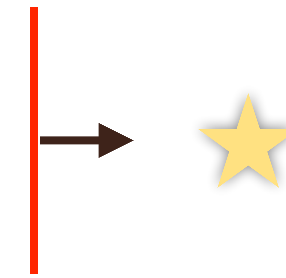
Experimental implications (light DM)

$$
\begin{aligned}
1/mv \sim 10^{-3}\,\mathrm{cm} &\quad \text{for} \quad m = 10\,\mathrm{eV} \\
10^{4}\,\mathrm{cm} &\quad \text{for} \quad m = 10^{-6}\,\mathrm{eV} \\
100\,\mathrm{pc} &\quad \text{for} \quad m = 10^{-22}\,\mathrm{eV}
\end{aligned}
$$

QCD axion

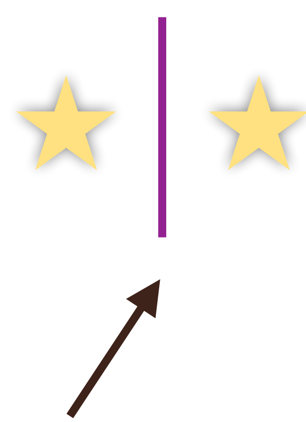
Fuzzy DM (Hu, Barkana, Gruzinov)

Observational signatures (for ultralight DM):

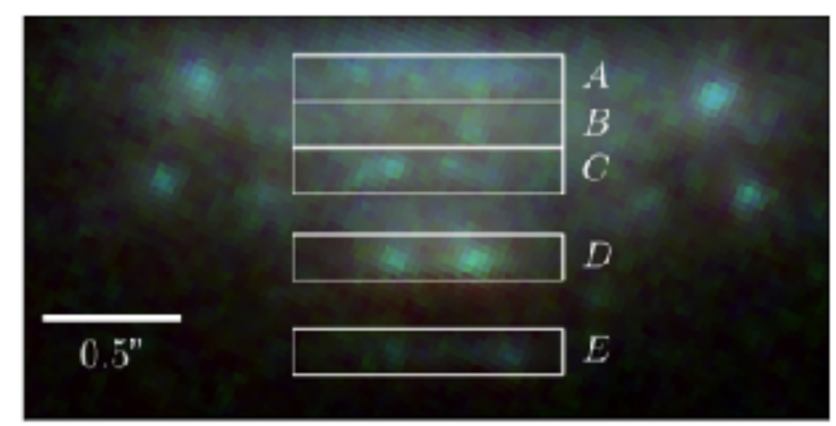


- Gravitational lensing by a vortex can lead to 10^{-4} arcsec displacement of distant sources in 10^5 years. (Mishra-Sharma, Van Tilburg, Weiner)

- In lensing events with extreme magnification (> 100), interference substructure can lead to fluctuations at the 10 percent level.



critical line



Dai et al.: strongly lensed arc

(See also: Dalal, Kochanek; Alexander et al.; Chan et al.; Broadhurst et al.)

- Heating, scattering of tidal streams. (Amorisco, Loeb; Dalal, Bovy, LH, Li)

Substructures scatter tidal streams

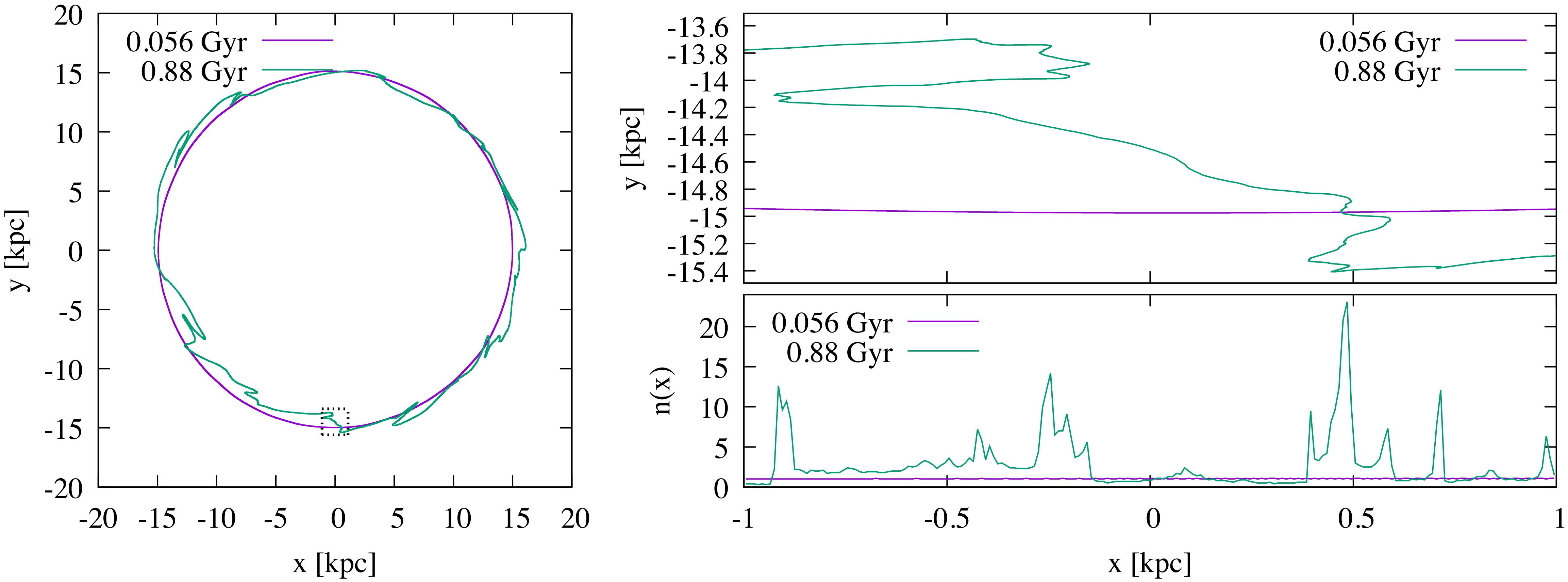


FIG. 5. Examples of fold caustics. (Left) The two curves show streams evolved in a simulation with $\lambda = 2.4\,\mathrm{kpc}$. Over time, the stream folds on itself, producing density variations on scales much smaller than λ. (Right) The upper panel zooms in on the region enclosed by the dotted black square in the left panel. The bottom panel shows the binned 1D number density of particles; note the large spikes in density at fold locations in the upper panel, reflecting the universal $n \propto x^{-1/2}$ divergence at fold caustics in 1D.

Dalal, Bovy, LH, Li

Experimental implications (light DM e.g. QCD axion):

$$\mathcal{L} \sim \frac{\phi}{f} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\partial_\mu \phi}{f} \bar{\Psi}\gamma^5\gamma^\mu\Psi$$

Reviews: Sikivie 2003

Graham et al. 2015, Marsh 2016

- Coupling to EM

ADMX (cavity) - photon from axion in magnetic field ϕ^2

ABRACADABRA - magnetic flux from axion in magnetic field $\dot{\phi}$

ADBC - rotation of polarization of photon propagating in axion $\Delta\phi$

- Coupling to spin $\hat{H} \sim \vec{\nabla}\phi \cdot \hat{\sigma}$

CASPEr - spin precession like in NMR $\vec{\nabla}\phi$

Eot-Wash - torsional spin pendulum $\vec{\nabla}\phi$

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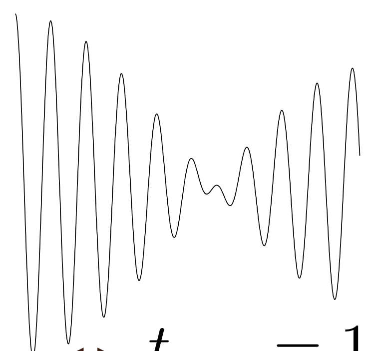
-

$$\phi \sim \psi e^{-imt} + \psi^* e^{imt}$$

slow fast



$t_{\text{osc.}} = 1/m \sim 10^{-9}\ \text{s}$

$t_{\text{coherent}} = 1/(m\, v^2) \sim 10^{-3}\ \text{s}$

Derevianko; Foster, Rodd, Safdi; Centers et al.

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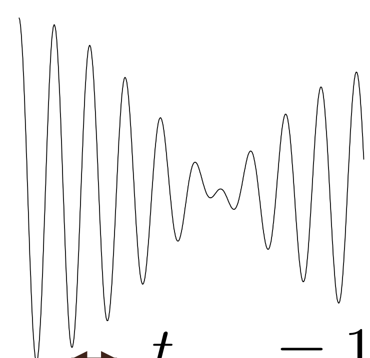
- $$\phi \sim \underbrace{\psi}_{\text{slow}} \underbrace{e^{-imt}}_{\text{fast}} + \psi^* e^{imt}$$



$t_{\rm osc.} = 1/m \sim 10^{-9}\,{\rm s}$

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Derevianko; Foster, Rodd, Safdi; Centers et al.

- Measure correlation functions e.g.

$\langle \phi(t)^2\phi(t')^2\rangle - \langle\phi^2\rangle^2 \sim [|t-t'|/t_{\rm coherent}]^{-3} + {\rm osc.}$ (or even space-time correlations).

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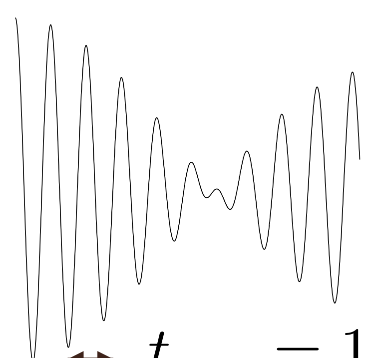
slow fast



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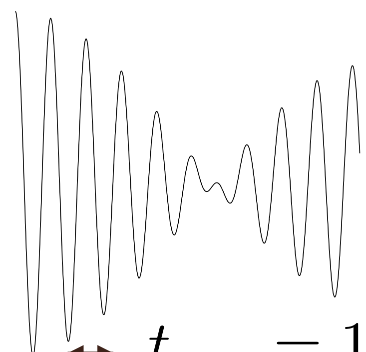

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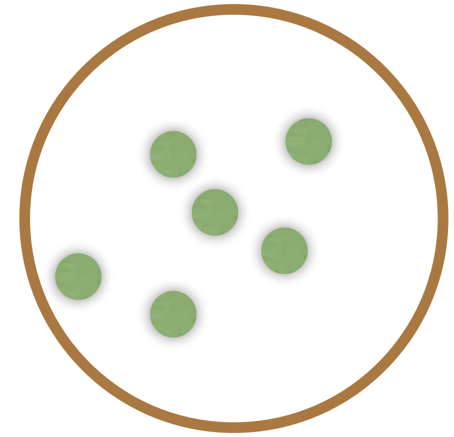
- At vortices $\quad \phi = 0 \quad$ but $\quad \vec{\nabla}\phi \neq 0$.

- Phase of oscillation might be interesting: $\quad \phi \sim |\psi|\cos(mt-\theta)$.

Let's discuss:



Particle physics motivations $\checkmark$

Wave dynamics and phenomenology $\checkmark$

Astrophysical implications (ultra-light DM) $\checkmark$

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Fuzzy DM (Hu, Barkana, Gruzinov)