Vortex Stability in Ultralight Scalar Solitons

Anthony Mirasola

Nathan Musoke, Noah Glennon, Mark Neyrinck, Chanda Prescod-Weinstein

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Solitons in SFDM

- SFDM models follow Gross-Pitaevskii-Poisson Equations

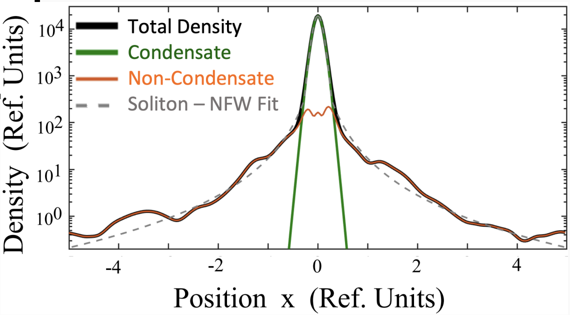
GPP Equations

$$i\frac{\partial\psi}{\partial t} = \frac{-\hbar^2}{2m}\nabla^2\psi + \frac{\lambda}{2m^2}|\psi|^2\psi + m\Phi\psi$$

$$\nabla^2\Phi(\mathbf{r}) = 4\pi G\rho(\mathbf{r}) = 4\pi|\psi|^2$$

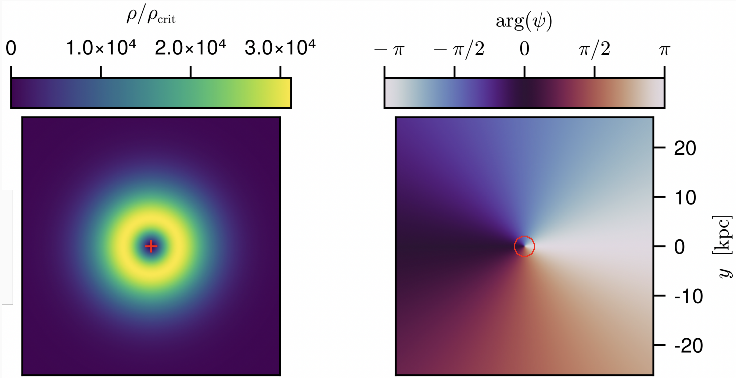
- Ground state solutions are solitons
- Low T equilibrium state condenses into soltion + excited “NFW skirt”

Figure from N.P. Proukakis et al. arXiv:2303.02049 [astro-ph.CO] (2023)



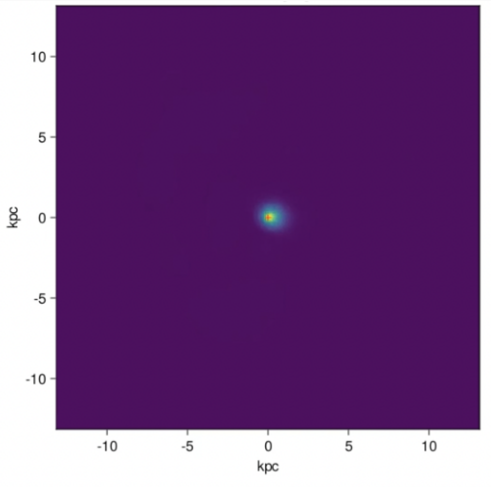
Rotation in Scalar Fields

- Scalar fields have irrotational velocity: $\mathbf{v} = \frac{\hbar}{m}\nabla \arg \psi$
- Rotating superfluid must develop a vortex where density $\to 0$
- Maximum angular momentum carried by a vortex is $L = N\ell\hbar$



Decay of Vortex-Solitons

- Vortices in center of SFDM solitons have been shown to be unstable
- Vortex-soliton breaks into two pieces, one of which is tidally disrupted by the other
- Decay happens faster than free-fall time



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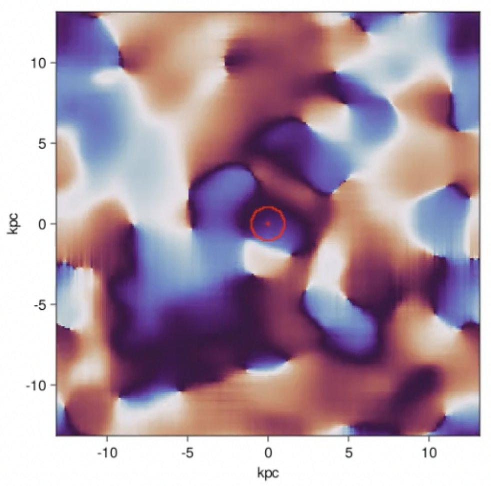


Suppressing the decay channel

- Central vortex is not the lowest-energy state with same angular momentum
- If potential from baryonic/other matter dominates SFDM self-gravity, GPP become linear equations

GPP Equations

$$i\frac{\partial\psi}{\partial t} = \frac{-\hbar^2}{2m}\nabla^2\psi + \frac{\lambda}{2m^2}|\psi|^2\psi + m(\Phi_{sol} + \Phi_{bg})\psi$$

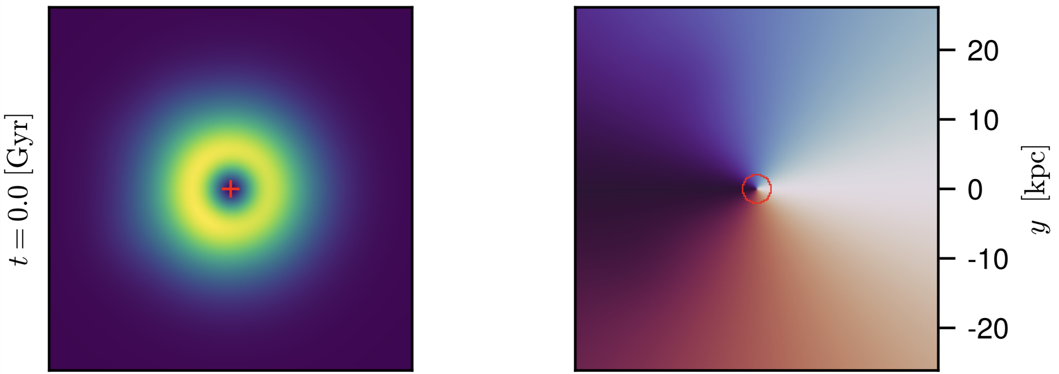
$$\nabla^2\Phi_{sol}(\mathbf{r}) = 4\pi G\rho(\mathbf{r}) = 4\pi|\psi|^2$$

- $\ell = 1$ configuration is a Hydrogen wave-function
- Eigenstate is stable against perturbations

How strong of a background potential needed to stabilize the vortex?

Stabilized Vortex-Solitons

- $M_{bg} = 3.5 \times 10^7 M_\odot$, $M_{sol} = \sqrt{2} M_{bg}$
- Initial vortex-soliton perturbed by random Gaussian overdensities
- Vortex persists as long as we run simulation



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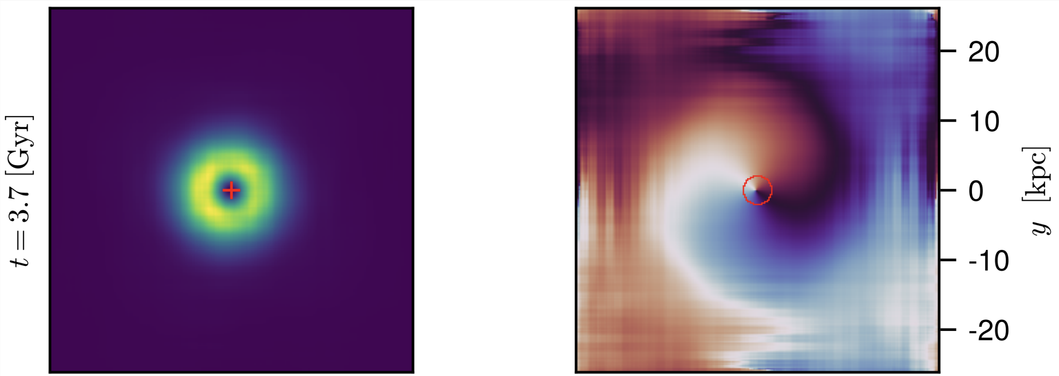

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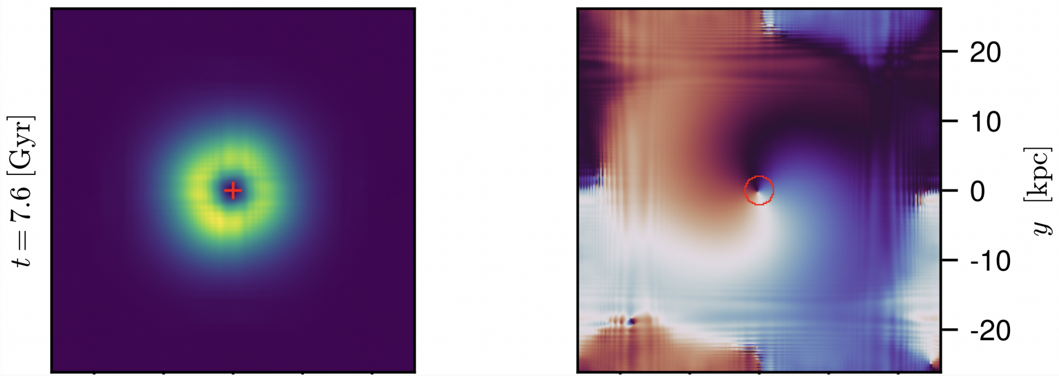
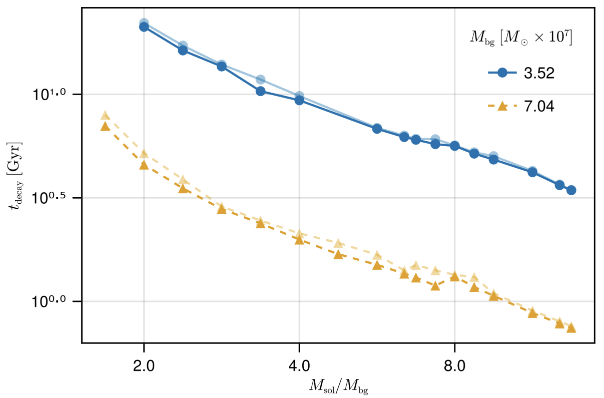


Decay Time vs. Soliton Mass

- Decay time is inversely proportional to M_{sol}/M_{bg} ratio
- Most DM halos do not have black holes heavy enough to support vortex-solitons
- $M_{black\ hole} \propto M_{halo}^{1.55\pm0.05}$, while $M_{sol} \propto M_{halo}^{1/3}$
- So only expect vortices in most massive halos with "ultramassive" black holes



Conclusions

- Future directions include multi-axion models:
  - Core-halo relation changes
  - One species can act as “background potential” for another
- Self-consistent simulations including SFDM and baryons are needed
- Effects of vortices on dynamical heating and other observational signatures are not understood

- Thank You!

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