Particle physics panel

- DM and light scalars - LH
- Superradiance - Richard Brito
- Superradiance & open questions - Robert Lasenby

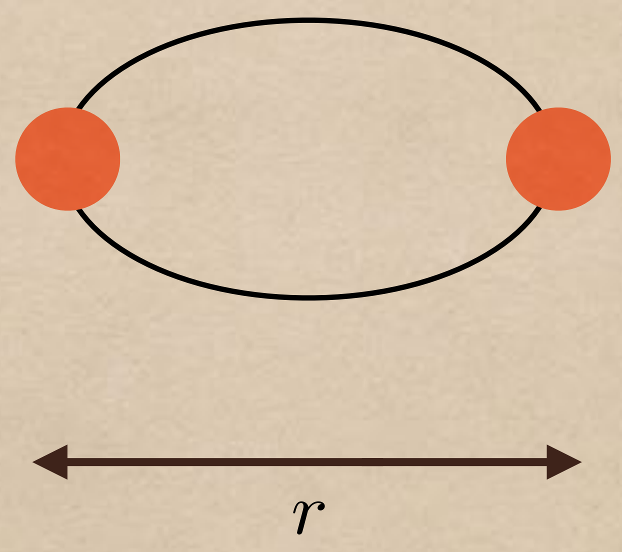
Dark matter, light scalars and GW/GR

Lam Hui

Columbia University

How much dark matter is there?

$$M \sim 10^{-30} M_\odot \left(\frac{\rho}{10^3\,\mathrm{GeV/cm^3}} \right) \left(\frac{r}{10^3\,\mathrm{km}} \right)^3$$



Light scalars (or bosons) have interesting collective effects, which can greatly enhance their density.

Examples:

1. Superradiance, where the light scalar needs not be dark matter.

2. Dark matter is a light scalar.

Work done with Jerry Ostriker, Scott Tremaine, Edward Witten
and with Greg Bryan, Xinyu Li

Light axion dark matter

mass $m \sim 10^{-22\pm1}$ eV

Fuzzy dark matter
Hu, Barkana, Gruzinov

- A natural candidate for such a light particle is a pseudo Nambu-Goldstone boson.

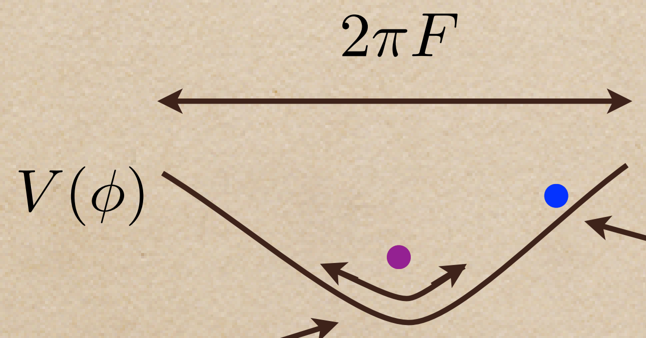
- Concrete realization: an angular field of periodicity $2\pi F$ i.e. an axion-like field with a potential from non-perturbative effects (not QCD axion).

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

$$m \sim \Lambda^2/F$$

- Relic abundance:

(standard story - see Kolb & Turner; review by Marsh)



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

$\rho_\phi \sim m^2 F^2 \quad , \quad \rho_{\mathrm{rad.}} \sim H^2 M_{\mathrm{pl}}^2 \sim m^2 M_{\mathrm{pl}}^2 \sim T^4$

subsq. oscill. : $\rho_\phi \propto a^{-3}$
self – interaction can be ignored

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

(low scale inflation)

Dynamics of a free massive scalar

$$m^{-1} \sim 0.06\,\mathrm{pc}$$
$$(mv)^{-1} \sim 2\ \mathrm{kpc}\ (10\,\mathrm{km\,s^{-1}}/v)$$

- Ignoring self-interaction:

$$-\Box\phi + m^2\phi = 0$$

- Non-relativistic limit:

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

$$|\ddot{\psi}| \ll m|\dot{\psi}| \longrightarrow i\dot{\psi} = \left[-\frac{\nabla^2}{2m} + m\Phi_{\mathrm{grav.}}\right]\psi$$

- High occupancy implies ψ should be thought of as a classical scalar. See simulations by Hsi-Yu Schive, Tzihong Chiueh & Tom Broadhurst, Mocz et al., Veltmaat & Niemeyer.

- An alternative viewpoint: ψ as a (classical) fluid.

$$\rho = m\,|\psi|^2 \quad \text{i.e.} \quad \psi = \sqrt{\rho/m}\,e^{i\theta}$$

Recall conservation of probability: current $\propto i(\psi\nabla\psi^* - \psi^*\nabla\psi)$

Reinterpreted as conservation of mass:

$$\dot{\rho} + \nabla\cdot\rho v = 0 \quad \text{where} \quad v = \frac{1}{m}\nabla\theta \qquad \text{i.e. a superfluid.}$$

Fluid formulation (Madelung)

- Euler equation:

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

"quantum pressure"

- More precisely, an unusual form of stress:

$$T_{ij} = \rho v_i v_j + \frac{1}{2m^2} \left[\partial_i \sqrt{\rho}\, \partial_j \sqrt{\rho} - \sqrt{\rho}\, \partial_i \partial_j \sqrt{\rho} \right]$$

- Can be implemented in standard hydrodynamics codes (Mocz & Succi).

- For linear perturbations (on cosmological bgd.):

Jeans scale $\sim 0.1\,{\rm Mpc}$

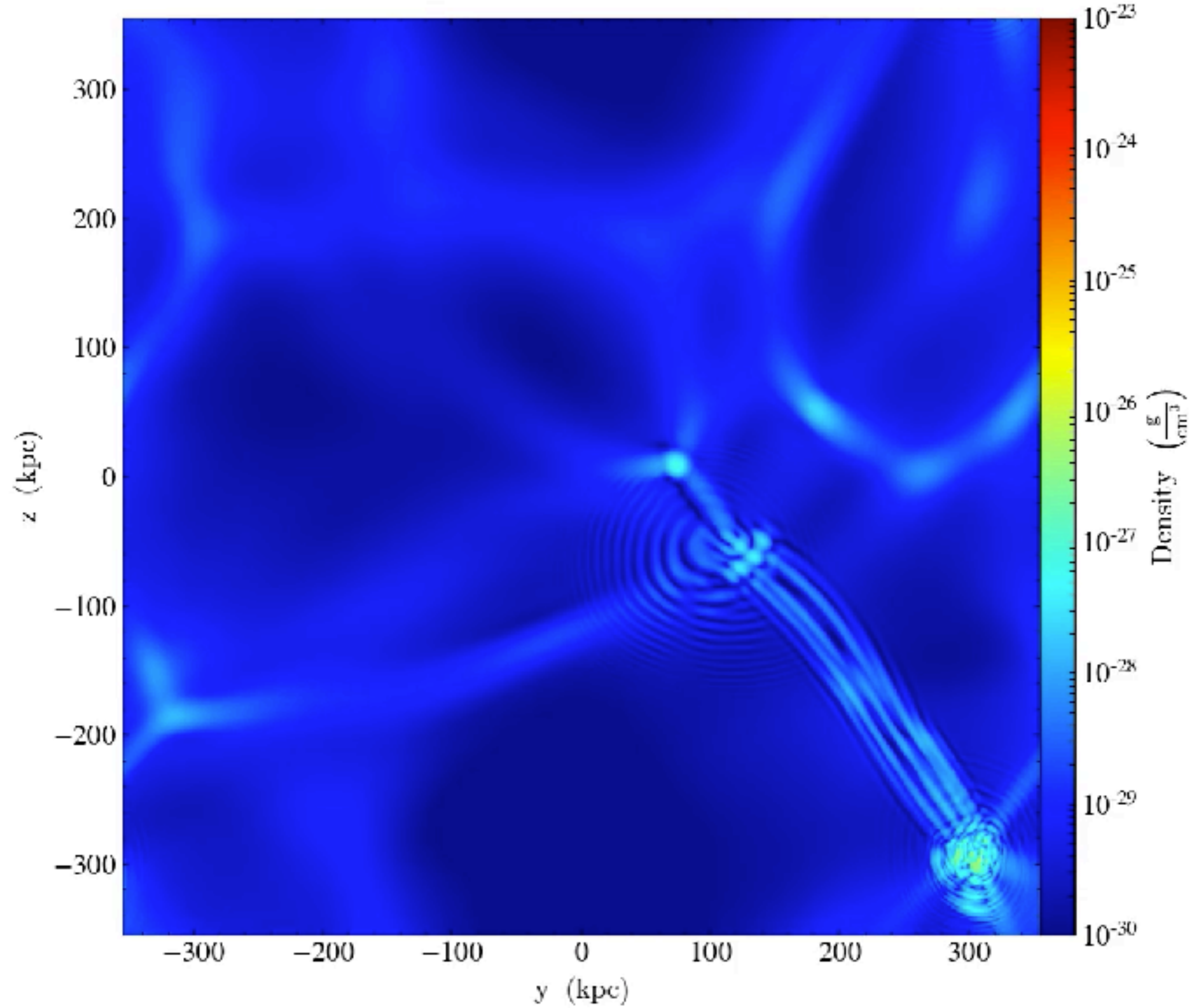
Perturbations suppressed on small scales - could help avoid small scale problems of standard CDM (Hu, Barkana, Gruzinov: Fuzzy DM ; Amendola, Barbieri).

Typical focus: density profile (cusp versus core), number of satellite galaxies.

Issue: baryonic effects complicate the interpretation of the data.

Possible diagnostics of FDM vs conventional CDM:

- dynamical friction
- evaporation of sub-halos by tunneling
- interference
- tidal streams and gravitational lensing
- heating of stars
- Lyman-alpha forest
- direct detection
- detection by pulsar timing array
- vortices
- compact solitons



300
200
100
0
−100
−200
−300
z (kpc)
−300
−200
−100
0
100
200
300
y (kpc)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
Density $\left(\frac{g}{cm^3}\right)$

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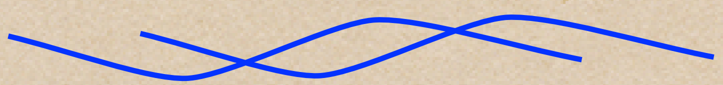
- interference 
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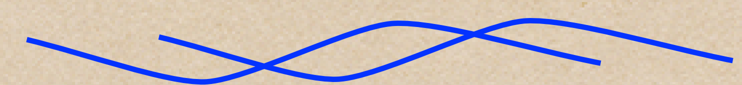

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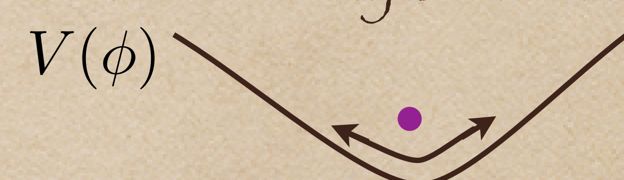
Khmelnitsky & Rubakov



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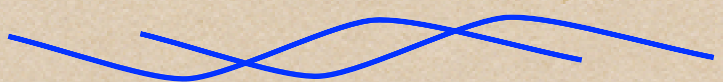

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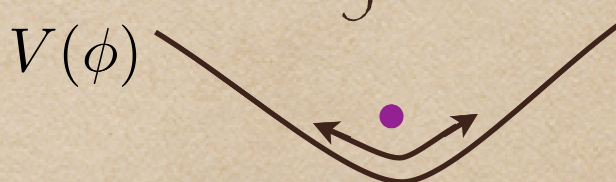
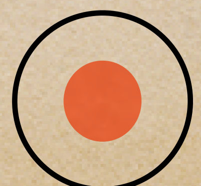


Schive et al.

$$\frac{r_S}{r} \sim \left(\frac{F}{M_{\mathrm{p}}}\right)^2$$



$$M_{\mathrm{soliton}} \sim 10^9 M_\odot \text{ in Virgo}$$

$$M_{\mathrm{max}} \sim 10^{10} M_\odot \left(\frac{F}{10^{17}\,\mathrm{GeV}}\right)$$

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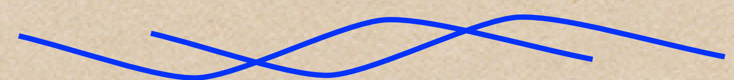
- dynamical friction

effect on event rates?

- evaporation of sub-halos by tunneling
- interference



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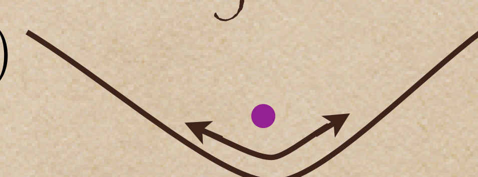
Khmelnitsky & Rubakov

$V(\phi)$



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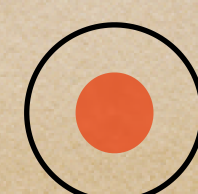

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Scalar as BH hair - EFT for black hole perturbations

1. Time-dependent scalar for inflation
   —> r-dependent scalar for black hole.

2. Slow-roll expansion for inflationary perturbations
   —> "light-ring" expansion for quasi-normal modes around black hole.

Work done with Gabriele Franciolini, Riccardo Penco, Luca Santoni & Enrico Trincherini.

Related to large literature on parametrizing deviation from GR.

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