Phenomenology of wavelike vector dark matter nonminimally coupled to gravity

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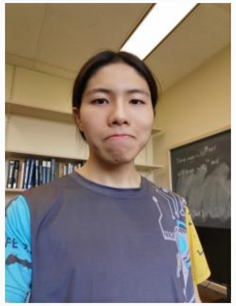
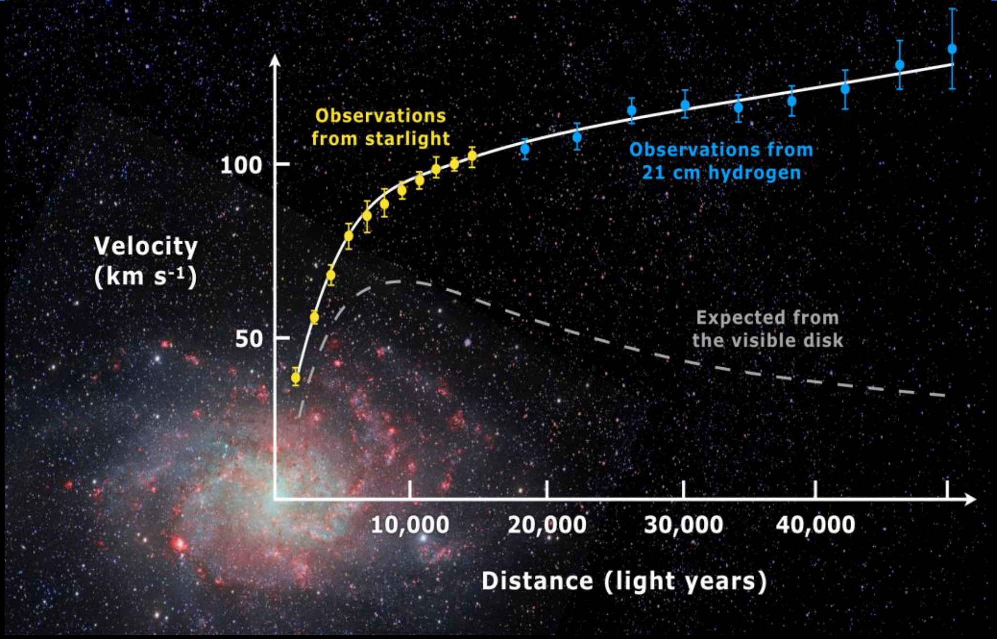


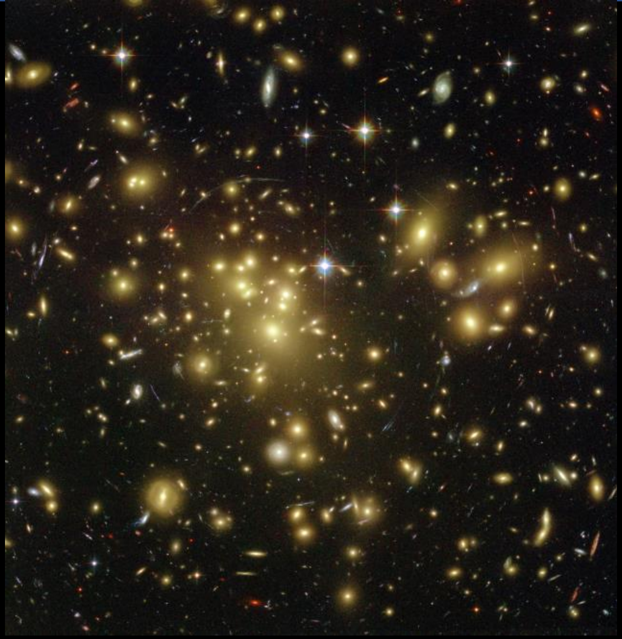
Collaborated with Siyang Ling (PhD student at Rice U).
The paper will be available in arXiv in a few hours.

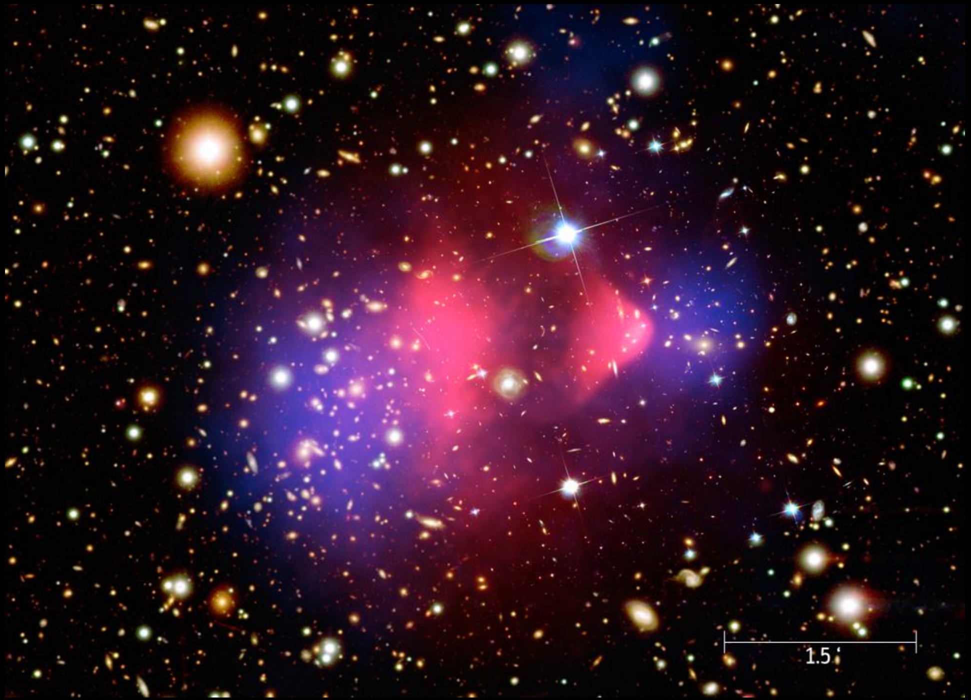
Talk structure

Phenomenology of nonminimally coupled wave VDM

- Wave VDM intro
- Theory: nonrelativistic EFT
  - Wave description
  - Fluid description
- Phenomenology
  - Vector soliton
  - Growth of linear perturbations
  - GW speed

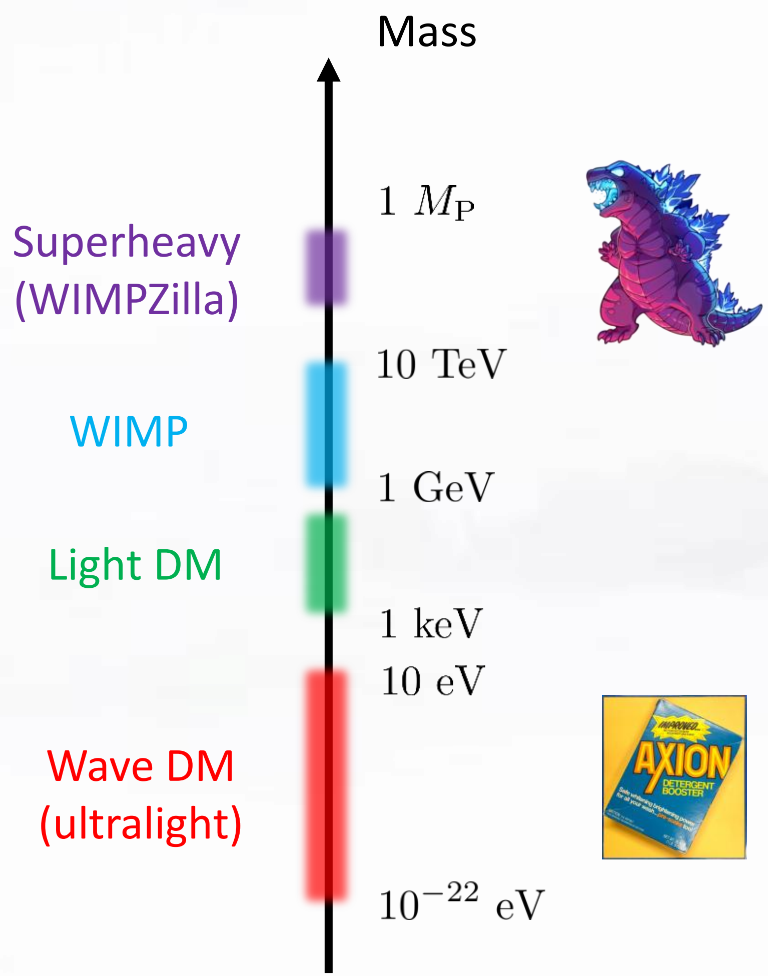


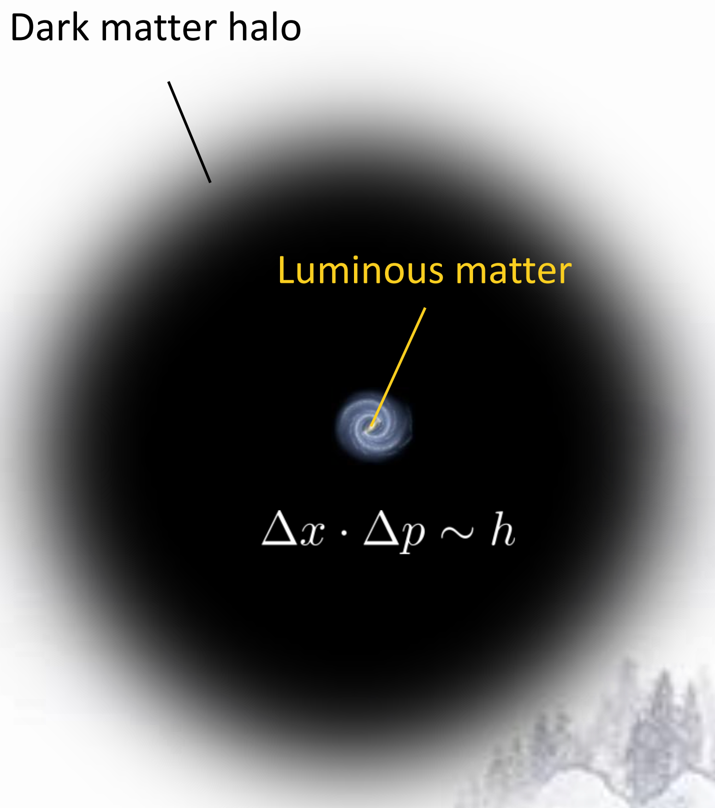




Rotation curves
Low mass-to-light ratios
Bullet cluster
Matter power spectrum
Galaxy cluster's virial velocity
Gravitational lensing
Supernovae type Ia
Cosmic microwave background
Baryon acoustic oscillations
…

DM mass landscape





Wave DM is composed of bosons

Structure is suppressed within de Broglie wavelength

$$\lambda_{\rm dB} = \frac{2\pi}{mv} = 0.48{\rm kpc}\left(\frac{10^{-22}{\rm eV}}{m}\right)\left(\frac{250{\rm km/s}}{v}\right) \lesssim 1\ {\rm kpc}$$

$$m \gtrsim 10^{-22}\ {\rm eV}$$

Number of particles in de Broglie volume $\lambda_{\rm dB}^3$

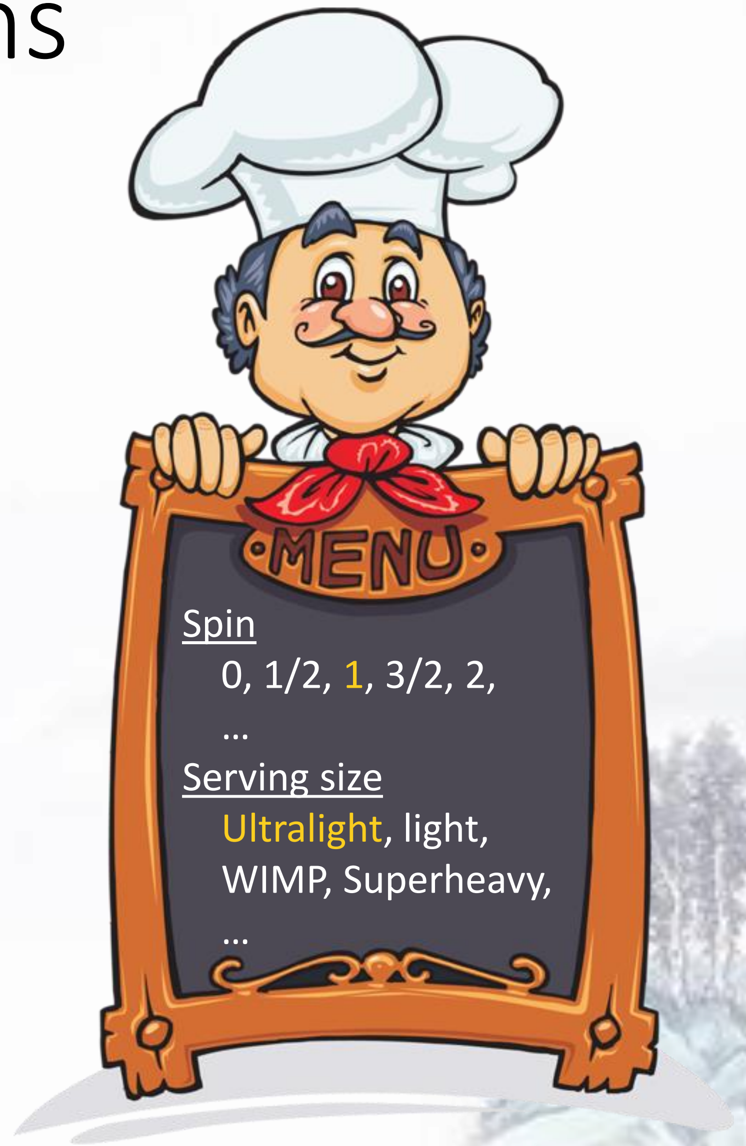
$$N_{\rm dB} \sim \left(\frac{34{\rm eV}}{m}\right)^4 \left(\frac{250{\rm km/s}}{v}\right)^3 \gg 1 \begin{cases} \text{Quantum effects are small} \\ m \ll 30{\rm eV} \end{cases}$$

Wave DM cannot be fermions (Tremaine-Gunn bound)

$$n = \int \frac{d^3p}{(2\pi)^3} f \lesssim \frac{g}{(2\pi)^3}\frac{4\pi}{3}(mv)^3 \sim \frac{\rho_\chi}{m}$$

$$m \gtrsim 20\ {\rm eV}$$

Hui (2021)



VDM production mechanism

Nonminimal coupling
is needed

Kitajima & Nakayama (2023)
Nakayama (2019).

- Misalignment mechanism

-> Fixed polarization in cosmological scales

Graham, et al. (2016);
Kolb & Long (2021).

- Gravitational particle production

-> Natural avoidance of isocurvature constraints

Agrawal, et al. (2020);
Co, et al. (2019);
Bastero-Gil, et al. (2019).

- Scalar-vector oscillation

-> Stealing energy from axions/inflaton

Long & Wang (2019)

- Decay of topological defects

-> Longitudinal modes are preferred at the production,
but the subsequent evolution is complicated

Other motivations for nonminimal couplings:

- Effective theory
- Renormalization of gravity
- Rich phenomenology

For thermal freeze-out and freeze-in, see Barman, et al. (2022).

Theory

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\mathrm{P}}^2}{2} R - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{m^2}{2} X_\mu X^\mu + \frac{\xi_1}{2} R X_\mu X^\mu + \frac{\xi_2}{2} R^{\mu\nu} X_\mu X_\nu \overbrace{+ \cdots}^{\text{Higher-dimension operators, suppressed by powers of } X^2/M_{\mathrm{P}}^2} \right]$$

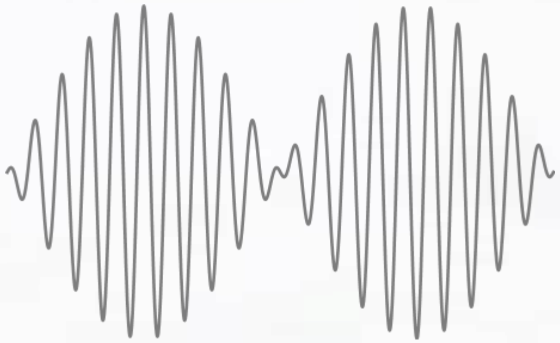
Nonrelativistic EFT

- Wave description: Schroedinger-Poisson-Friedmann (SPF) equations
  Convenient for VDM dynamics, simulations, quantization
- Fluid description: Continuity-Euler-Friedmann equations
  Convenient for structure formation

Nonrelativistic EFT

Vector field equations + Einstein equations

$$X_\mu(t,\boldsymbol{x}) = \frac{1}{\sqrt{2ma}}[e^{-imt}\psi_\mu(t,\boldsymbol{x}) + e^{imt}\psi^*_\mu(t,\boldsymbol{x})]$$



Integrate out fast modes

$$\epsilon_H \sim \frac{H}{m}\ ,\ \epsilon_t \sim \left|\frac{\partial_t}{m}\right|\ ,\ \epsilon_k \sim \left|\frac{\nabla^2}{m^2a^2}\right|\ ,$$
$$\epsilon_\psi \sim \frac{|\psi_i|}{aM_{\rm pl}\sqrt{m}}\ ,\ \epsilon_g \sim \Phi\ ,\ \epsilon_\xi \sim \left|\frac{\xi R}{m^2}\right|\ .$$

Nonrelativistic EFT for slow modes

Wave description

Effective action:

$$S = \int \mathrm{d}^4x \Bigg[M_{\mathrm{P}}^2 a \left(-3\dot{a}^2 + \Phi\nabla^2\Phi - 6a\ddot{a}\Phi\right) + \frac{1}{2}a^2 m \left|\psi_0 - \frac{i}{a^2 m}\nabla\cdot\boldsymbol{\psi}\right|^2 + i\dot{\boldsymbol{\psi}}\cdot\boldsymbol{\psi}^* + \frac{1}{2a^2 m}(\nabla^2\boldsymbol{\psi})\cdot\boldsymbol{\psi}^* - m\Phi|\boldsymbol{\psi}|^2 + \frac{|\boldsymbol{\psi}|^2}{2a^2 m}\left[2\xi_1(\nabla^2\Phi + 3\dot{a}^2 + 3a\ddot{a}) + \xi_2(\nabla^2\Phi + 2\dot{a}^2 + a\ddot{a})\right] \Bigg] \times [1 + \mathcal{O}(\epsilon)]$$

Multicomponent SPF equations:

$$i\partial_t\psi_i = -\frac{\nabla^2}{2ma^2}\psi_i + m\Phi_N\psi_i + 2m\Phi_\xi\psi_i - \frac{(2\xi_1+\xi_2)\nabla^2\Phi_\xi}{2ma^2}\psi_i \ ,$$

Effective self-interactions

$$\frac{\nabla^2}{a^2}\Phi_N = 4\pi G(\rho - \bar{\rho}) \ , \quad \Phi_\xi = -\frac{(2\xi_1+\xi_2)2\pi G}{m^2}\rho \ , \quad \Phi = \Phi_N + \Phi_\xi$$

$$H^2 = \frac{8\pi G}{3}\bar{\rho} \ , \quad \rho = \frac{1}{a^3}m|\boldsymbol{\psi}|^2 \equiv \sum_{i=1}^{3}\rho_i \ ,$$

Energy density for each field component

Fluid description

Madelung transformation

$$\psi_i = \sqrt{\frac{\rho_i a^3}{m}} e^{i\theta} \ , \quad \boldsymbol{v}_i \equiv \frac{1}{ma} \nabla \theta_i$$

Continuity and Euler equations

$$\dot{\rho}_i + 3H\rho_i + \frac{1}{a}\nabla \cdot (\rho_i \boldsymbol{v}_i) = 0 \ ,$$

$$\dot{\boldsymbol{v}}_i + H\boldsymbol{v}_i + \frac{1}{a}(\boldsymbol{v}_i \cdot \nabla)\boldsymbol{v}_i = -\frac{1}{a}\nabla \left(\Phi_N + \Phi_{Q,i} + 2\Phi_\xi - \frac{(2\xi_1 + \xi_2)}{2m^2 a^2} \nabla^2 \Phi_\xi \right)$$

$$\Phi_{Q,i} \equiv -\frac{1}{2a^2 m^2} \frac{\nabla^2 \sqrt{\rho_i}}{\sqrt{\rho_i}}$$

Phenomenology

Phenomenology

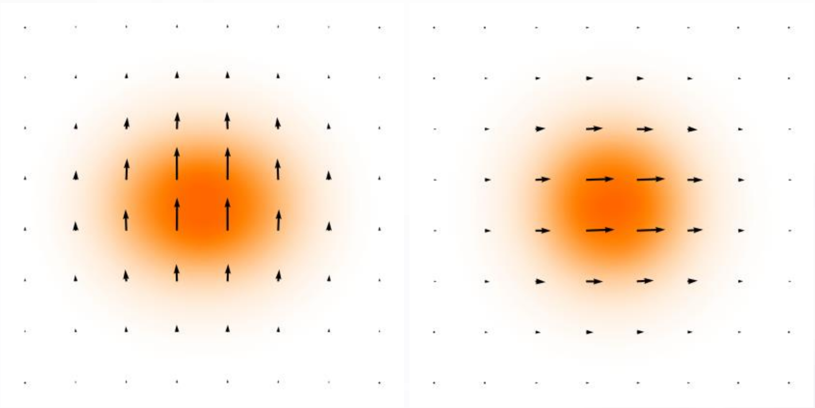
Mass-radius relation of polarized vector solitons
Potential impacts on galaxy density profiles

Growth of linear perturbations
The success of cold DM at large scales should be retained

Correction to the GW speed
Constraints are obtained from GW 170817 & GRB 179817A and lack of gravitational Cherenkov radiation

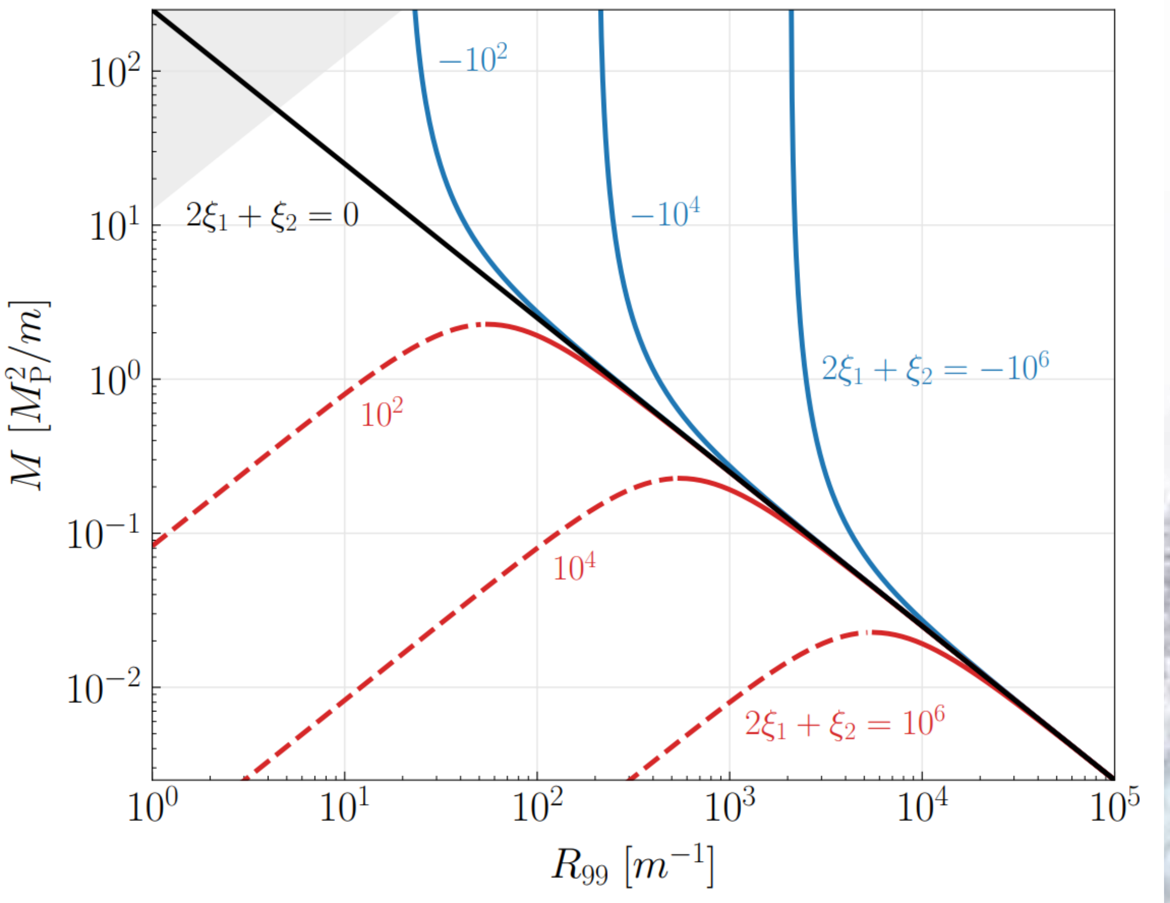
Mass-radius relation of vector solitons

Ground-state vector solitons



$S = 0$ $\qquad$ $S = \hbar N$

$$M = \frac{\beta_1 (mR)^3}{(mR)^4 + \beta_2 (2\xi_1 + \xi_2)(mR)^2 + \beta_3 (2\xi_1 + \xi_2)^2} \frac{M_{\mathrm{P}}^2}{m}$$



Also see:
Jain & Amin (2022)
Zhang, Jain & Amin (2022)

Growth of linear perturbations

$$\delta_i \equiv (\rho_i - \bar{\rho}_i)/\bar{\rho}_i \ , \quad \delta_i \propto \Delta_1 \ , \quad (\partial_t^2 + 2H\partial_t + \Omega^2)\Delta_1 = 0$$

$$\Omega^2 = -4\pi G\bar{\rho}\left[\underbrace{1}_{\text{Cold DM}} - \overbrace{\frac{m^2}{4\pi G\bar{\rho}}\frac{k^4}{4a^4m^4}}^{\text{Wave DM}} + (2\xi_1+\xi_2)\frac{k^2}{a^2m^2} + (2\xi_1+\xi_2)^2\frac{k^4}{4a^4m^4}\right]$$

Cold DM, which is consistent with matter power spectrum observation for $k < k_{\rm obs} \sim 10^3 k_{\rm eq}$

$$\xrightarrow[\text{for } k < k_{\rm obs}]{\text{Require } \Omega^2 \approx -4\pi G} \ |2\xi_1+\xi_2| \ll \frac{a_{\rm eq}^2 m^2}{k_{\rm obs}^2} = 10^{10}\left(\frac{m}{10^{-20}\text{eV}}\right)^2\left(\frac{10^{-28}\text{eV}}{H_{\rm eq}}\right)^2$$

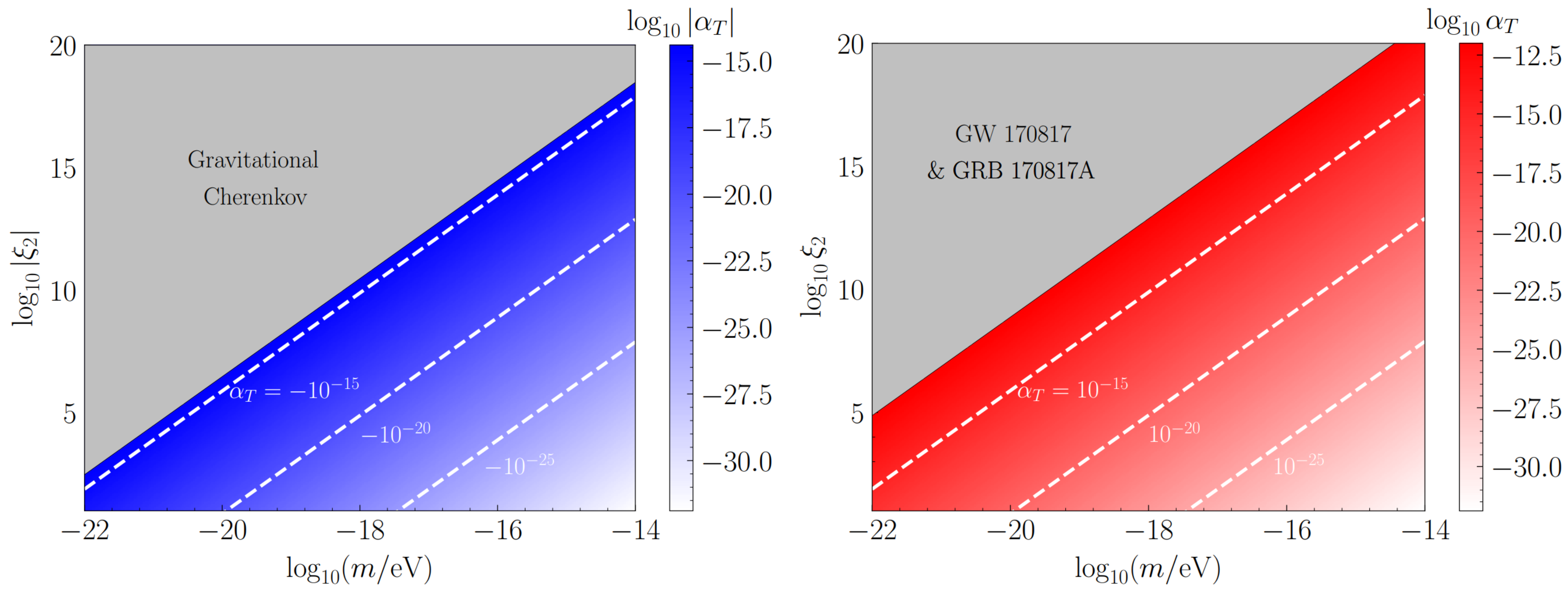
For $\frac{m^2}{4\pi G\bar{\rho}} \ll (2\xi_1+\xi_2)^2$
- -> cold DM at large scales
- -> enhanced small-scale structure than wave DM

For $\frac{m^2}{4\pi G\bar{\rho}} \gg (2\xi_1+\xi_2)^2$ -> wave DM, with Jeans scale $k_J \approx k_{J,0}\left[1 + (2\xi_1+\xi_2)\sqrt{\frac{\pi G\bar{\rho}}{m^2}}\right]$

Constraints on GW speed

Energy density for component in the direction of GWs

$$S^{(2)} = \frac{1}{2}\sum_{\lambda}\int d^4x\, M_*^2\left[\dot{h}_\lambda^2 - c_T^2(\nabla h_\lambda)^2\right] \quad , \quad \alpha_T \equiv c_T^2 - 1 = \frac{\xi_2 \rho_{\hat{n}}}{m^2 M_{\rm P}^2} \simeq \frac{\xi_2 \rho}{3m^2 M_{\rm P}^2}$$



Summary

Phenomenology of nonminimally coupled wave VDM

- Nonrelativistic EFT: wave and fluid description
  Nonminimal couplings induce self-interactions
- Nonminimal couplings can impact small-scale structure
  - Mass-radius relation of vector solitons
    Galactic density profile? Core-halo relation?
  - Small-scale perturbations can be boosted than wave DM
    Matter power spectrum? CMB?
- Nonminimal couplings can affect GW speed
  Potential observation of anisotropy? Parametric enhancement?

Constraint on nonminimal couplings

$$\frac{|\xi_1|}{m^2} \ll 10^{50}\mathrm{eV}^{-2}\ , \quad -3\times 10^{46}\mathrm{eV}^{-2} \lesssim \frac{\xi_2}{m^2} \lesssim 8\times 10^{48}\mathrm{eV}^{-2}$$