Polarized solitons in higher-spin dark matter

Mudit Jain

Based on

PRD 105 (2022) 5, 056019   MJ and M. Amin

PRD 105 (2022) 9, 096037   H.Y. Zhang, MJ, and M. Amin

arXiv:2203.11935 (to appear in JCAP)   M. Amin, MJ, R. Karur, and P. Mocz
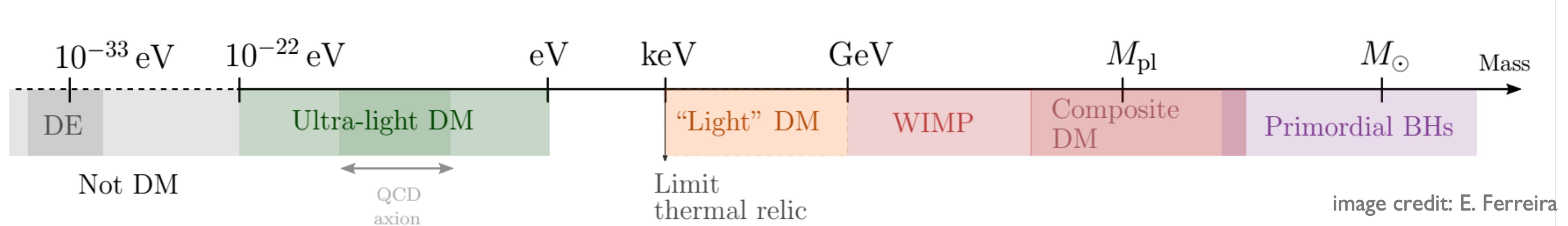
arXiv:2205.03418 (submitted to PRD)   MJ
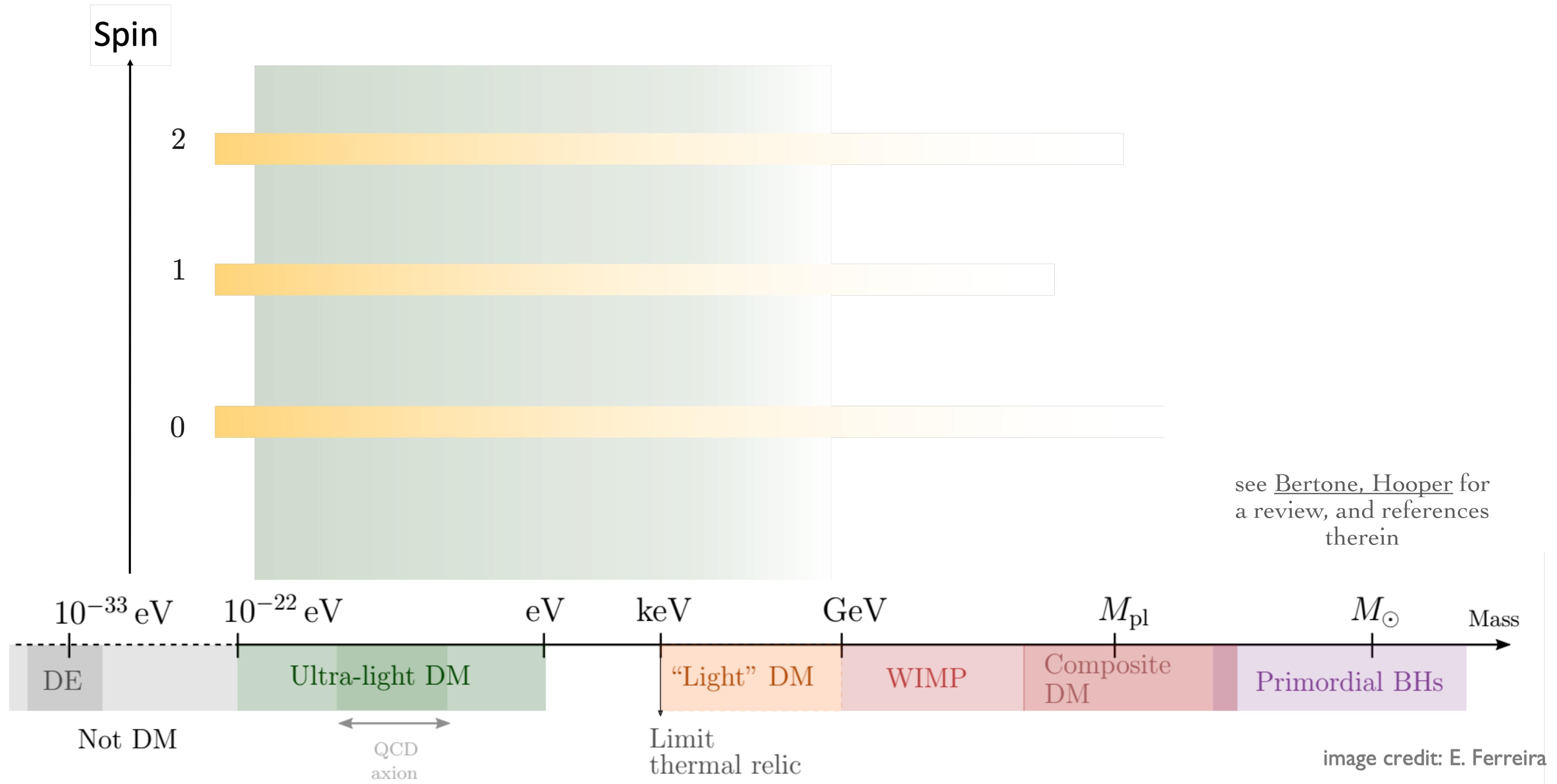
- More work in progress. Stay tuned

dark matter mass ?

10^{-33} eV 10^{-22} eV   eV   keV   GeV M_{pl} $M_{\odot}$ Mass

DE   Ultra-light DM   "Light" DM   WIMP   Composite DM   Primordial BHs

Not DM

QCD axion

Limit thermal relic

image credit: E. Ferreira

dark matter mass ?   spin ?   self-interactions ?   huge dark sector ?

see Bertone, Hooper for a review, and references therein

image credit: E. Ferreira

dark matter mass ?   spin ?   self-interactions ?   huge dark sector ?

Spin

$N \gg 1$

2 — large occupation numbers

1 — Classical fields/wave dynamics

— microscopic to astrophysical scales $\lambda_c \sim 10\,\mathrm{nm}\,(10\,\mathrm{eV}/m) \sim 10^5\,R_\odot\,(10^{-21}\,\mathrm{eV}/m)$

0

see <u>Bertone, Hooper</u> for
a review, and references
therein

| $10^{-33}\,\mathrm{eV}$ | $10^{-22}\,\mathrm{eV}$ | | eV | keV | GeV | M_{pl} | $M_\odot$ | Mass |

DE   Ultra-light DM   "Light" DM   WIMP   Composite DM   Primordial BHs

Not DM

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Limit
thermal relic

image credit: E. Ferreira

(non-topological) soliton

long lived, coherent states of a field, formed due to a balance between nonlinearities and/or dispersion
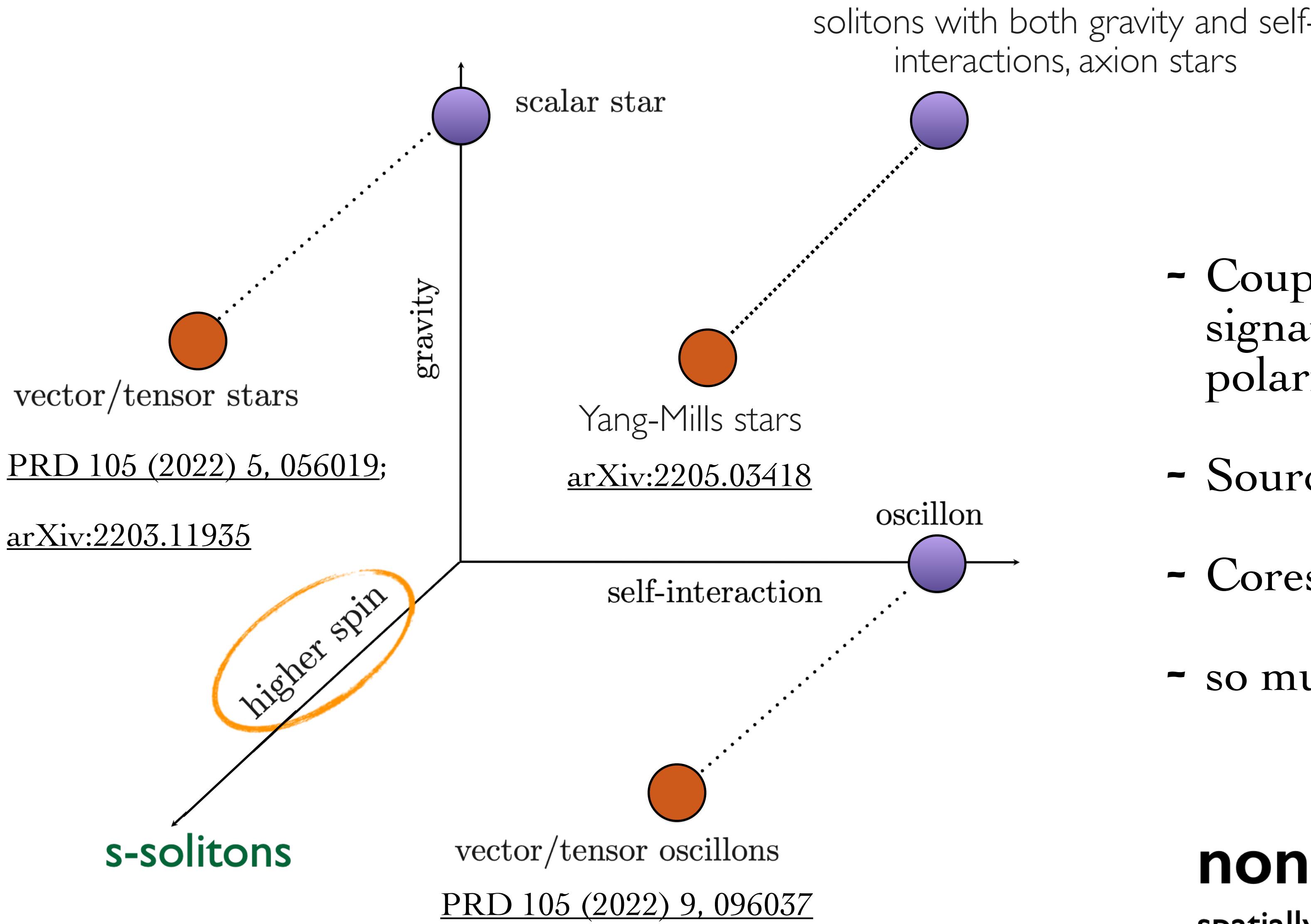
- discovered in nonlinear waves in water in canals (John Scott Russell, 1834)
- optics, hydrodynamics, BECs, high energy physics, and cosmology

Executive Summary

huge (macroscopic) intrinsic spin!

solitons with both gravity and self-interactions, axion stars

scalar star

gravity

vector/tensor stars

PRD 105 (2022) 5, 056019;

arXiv:2203.11935

Yang-Mills stars

arXiv:2205.03418

oscillon

higher spin

self-interaction

s-solitons

vector/tensor oscillons

PRD 105 (2022) 9, 096037
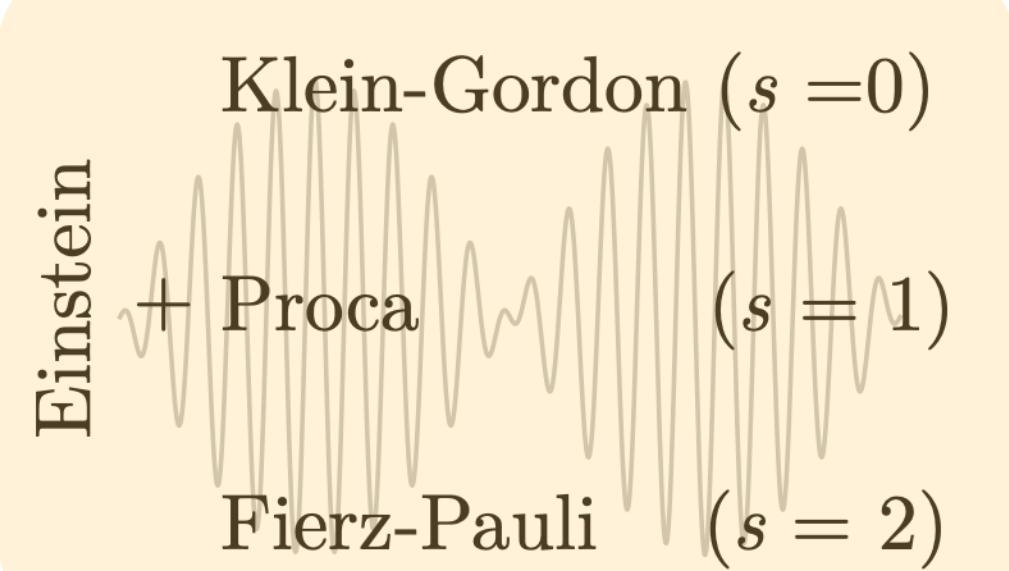
- Couplings with the Standard Model, signatures due to intrinsic spin polarization;

- Source gravitational waves?

- Cores of galaxies

- so much more
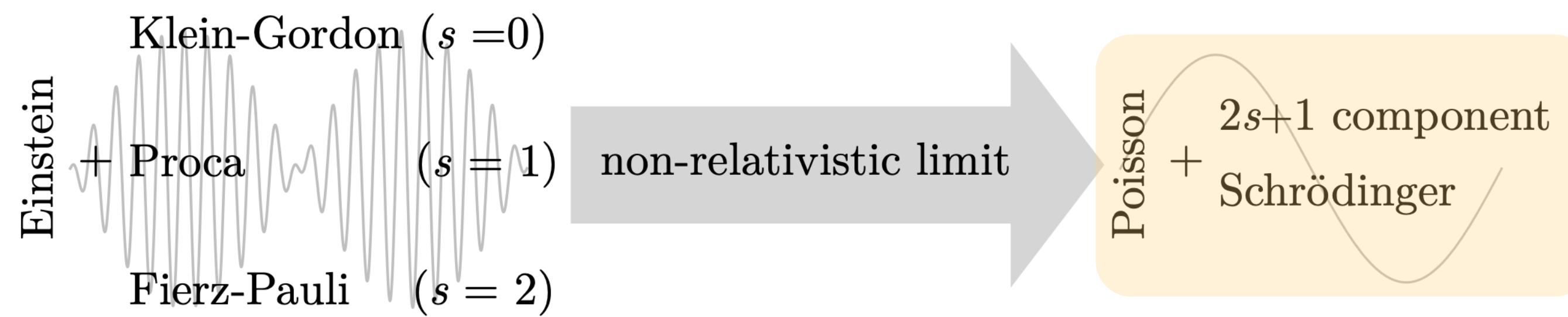
non-topological solitons

spatially localized, coherently oscillating, long-lived

spin-s field as dark matter

Einstein

Klein-Gordon $(s = 0)$

$+$ Proca $(s = 1)$

Fierz-Pauli $(s = 2)$

non-relativistic limit = multicomponent Schrödinger-Poisson

spin-s fields as dark matter

Einstein

Klein-Gordon $(s = 0)$

$+$ Proca $(s = 1)$

Fierz-Pauli $(s = 2)$

non-relativistic limit →

Poisson $+$ $2s{+}1$ component Schrödinger

spin multiplicity $\lambda =$

$\boldsymbol{S}_{\text{tot}}/\hbar = \lambda N \hat{z}$

extremally polarized solitons
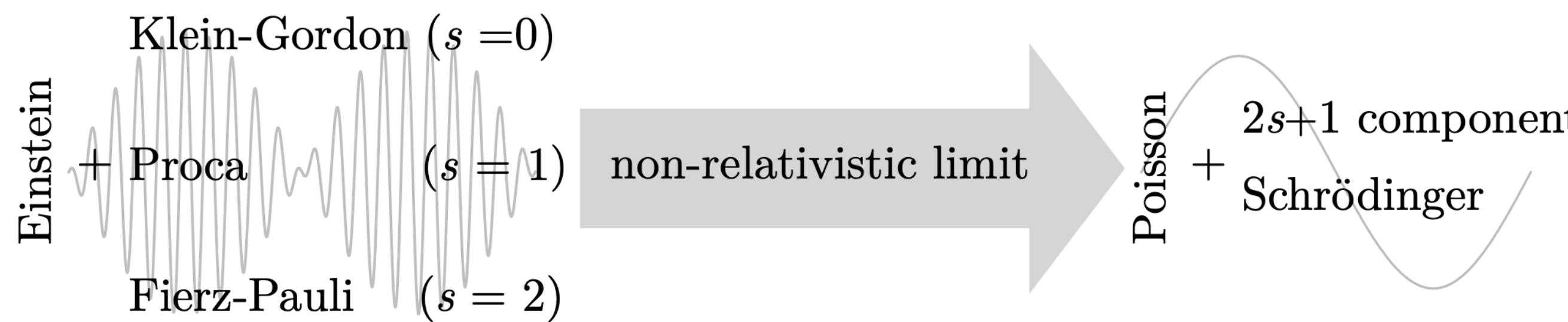
(focus on lowest energy states, no orbital angular momentum)

PRD 105 (2022) 5, 056019

$$i\frac{\partial}{\partial t}\boldsymbol{\Psi} = -\frac{1}{2m}\nabla^2\boldsymbol{\Psi} + m\,\Phi\,\boldsymbol{\Psi}$$

$$\nabla^2\Phi = \frac{m}{2m_{\text{pl}}^2}\,\text{Tr}[\boldsymbol{\Psi}^\dagger\boldsymbol{\Psi}].$$
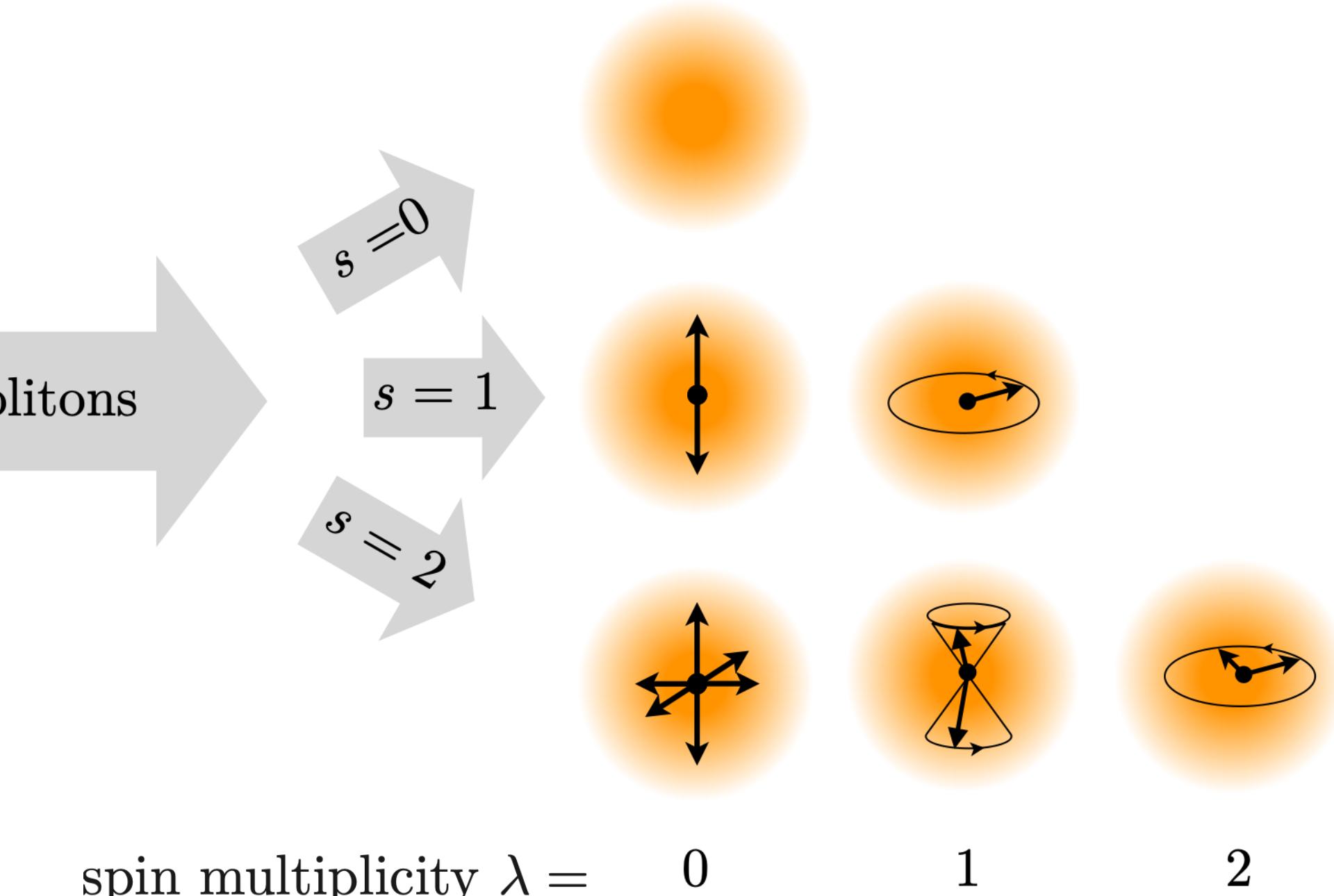
extension to FRW: $\partial_t \to \partial_t + 3H/2, \nabla \to \nabla/a$

spin-s fields as dark matter

Klein-Gordon ($s = 0$)

Einstein + Proca ($s = 1$)

Fierz-Pauli ($s = 2$)

non-relativistic limit

Poisson + 2s+1 component Schrödinger

s+1 solitons

$s = 0$

$s = 1$

$s = 2$

Macroscopic/Astrophysical intrinsic spin

Degenerate; can form infinitely many partially polarized solitons

spin multiplicity $\lambda =$ 0   1   2

scale separation
- phenomenology/numerical simulations

macroscopic spin $\boldsymbol{S}_{\text{tot}}/\hbar = \lambda N\hat{z}$

N = # of particles in soliton

- also see Salesian et al, Adshead et al, Aoki et al.

extremally polarized solitons

(focus on lowest energy states, no orbital angular momentum)
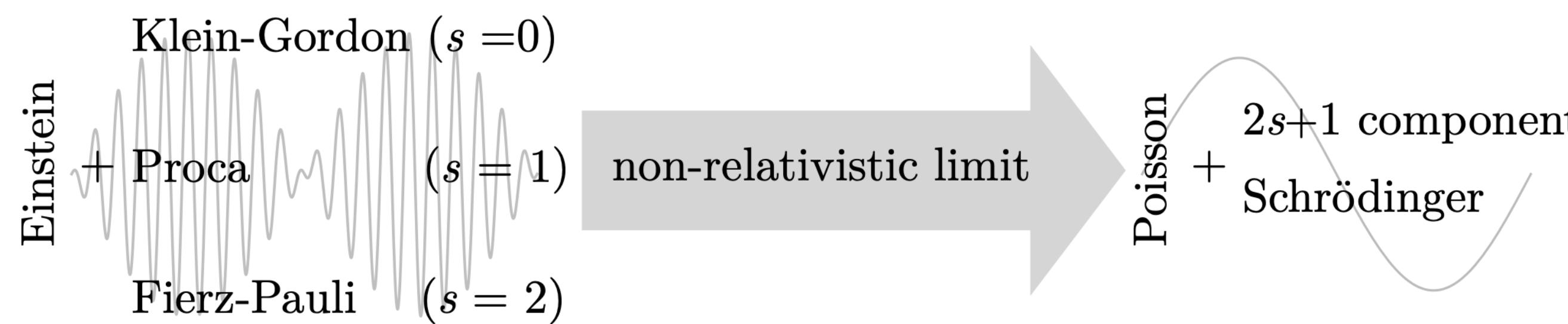
$$i\frac{\partial}{\partial t}\boldsymbol{\Psi} = -\frac{1}{2m}\nabla^2\boldsymbol{\Psi} + m\,\Phi\,\boldsymbol{\Psi} \boxed{+ \partial_{\boldsymbol{\Psi}^\dagger}V_{\text{self}}}$$

$$\nabla^2\Phi = \frac{m}{2m_{\text{pl}}^2}\,\text{Tr}[\boldsymbol{\Psi}^\dagger\boldsymbol{\Psi}].$$
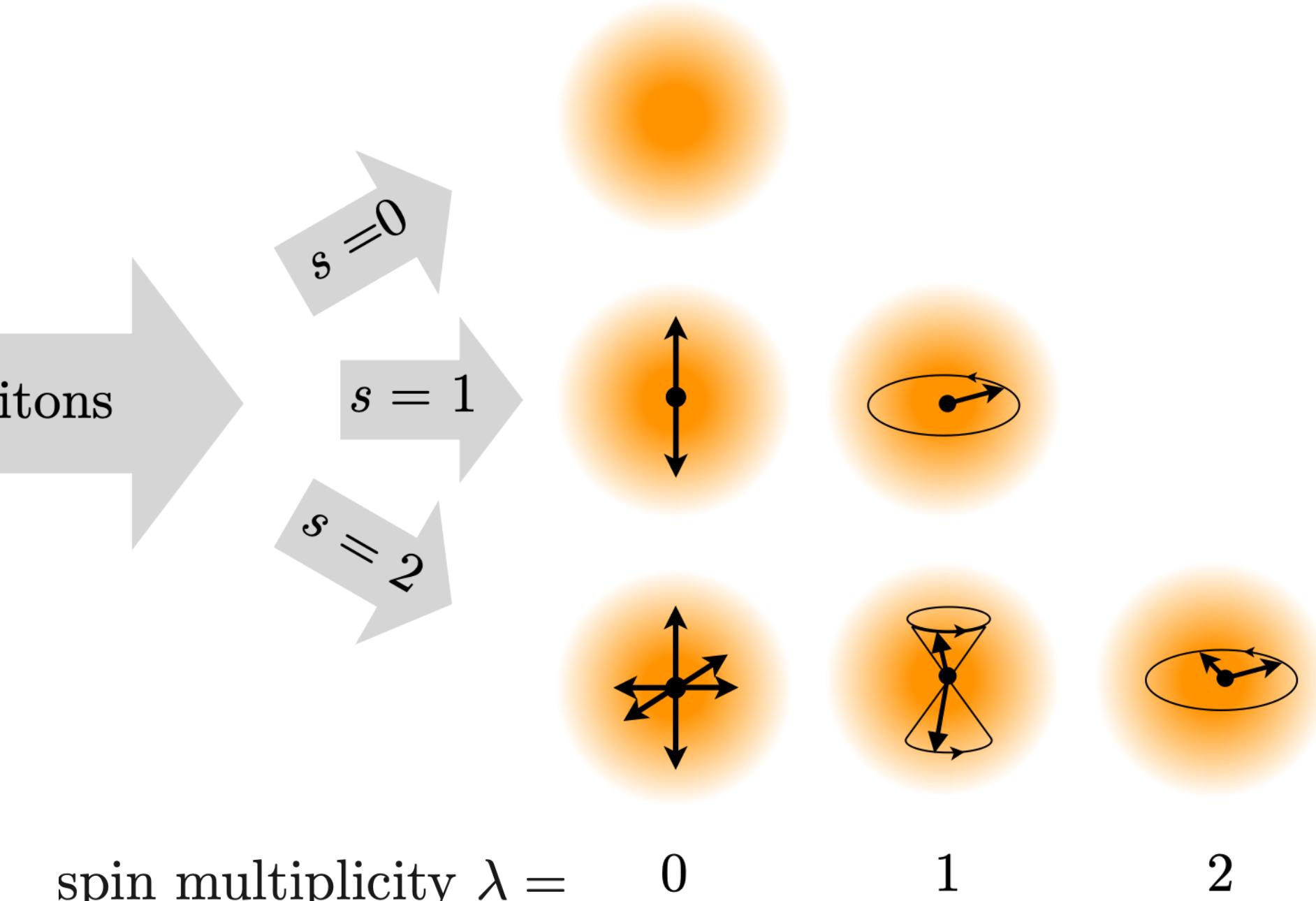
extension to FRW: $\partial_t \to \partial_t + 3H/2, \nabla \to \nabla/a$

spin-s fields as dark matter

Einstein

Klein-Gordon ($s = 0$)

$+$ Proca ($s = 1$)

Fierz-Pauli ($s = 2$)

non-relativistic limit

Poisson

$+$ 2s+1 component

Schrödinger

s+1 solitons

$s = 0$

$s = 1$

$s = 2$

Macroscopic/Astrophysical intrinsic spin

~~Degenerate; can form infinitely many partially polarized solitons~~

spin multiplicity $\lambda = $ 0   1   2

scale separation
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macroscopic spin $\boldsymbol{S}_{\text{tot}}/\hbar = \lambda N\hat{z}$

N = # of particles in soliton

– Chavanis, Schiappacasse et al, Hertzberg et al, Croon et al,…

$r_{s,95} \times (m^2/g m_{\mathrm{pl}})$

$M_s \times (g/m_{\mathrm{pl}})$

Gravity ~ gradient pressure

attractive self interactions ~ gradient pressure

Attractive self interactions

$*_{g \to \sqrt{2}\,g\,m/M_\varphi}$
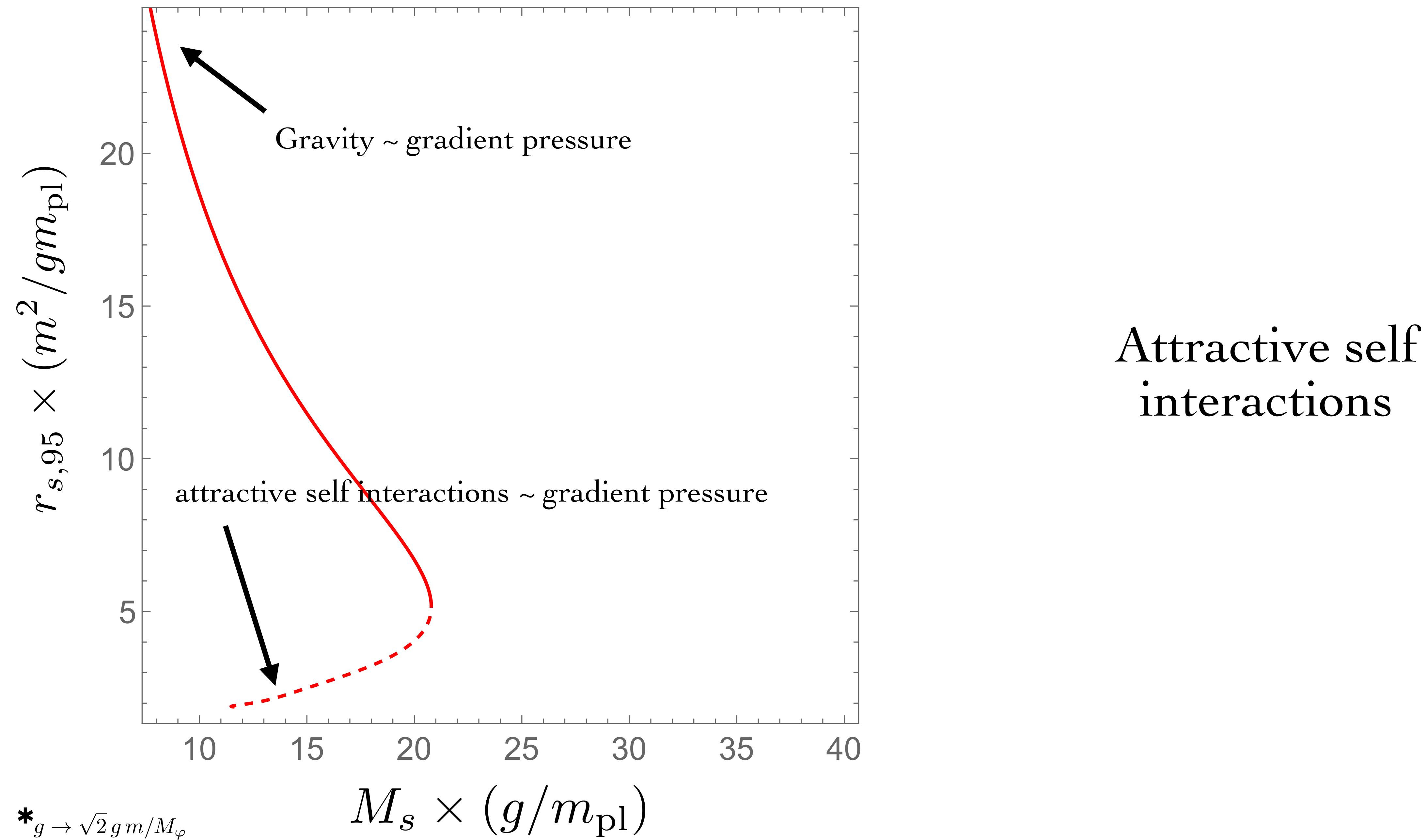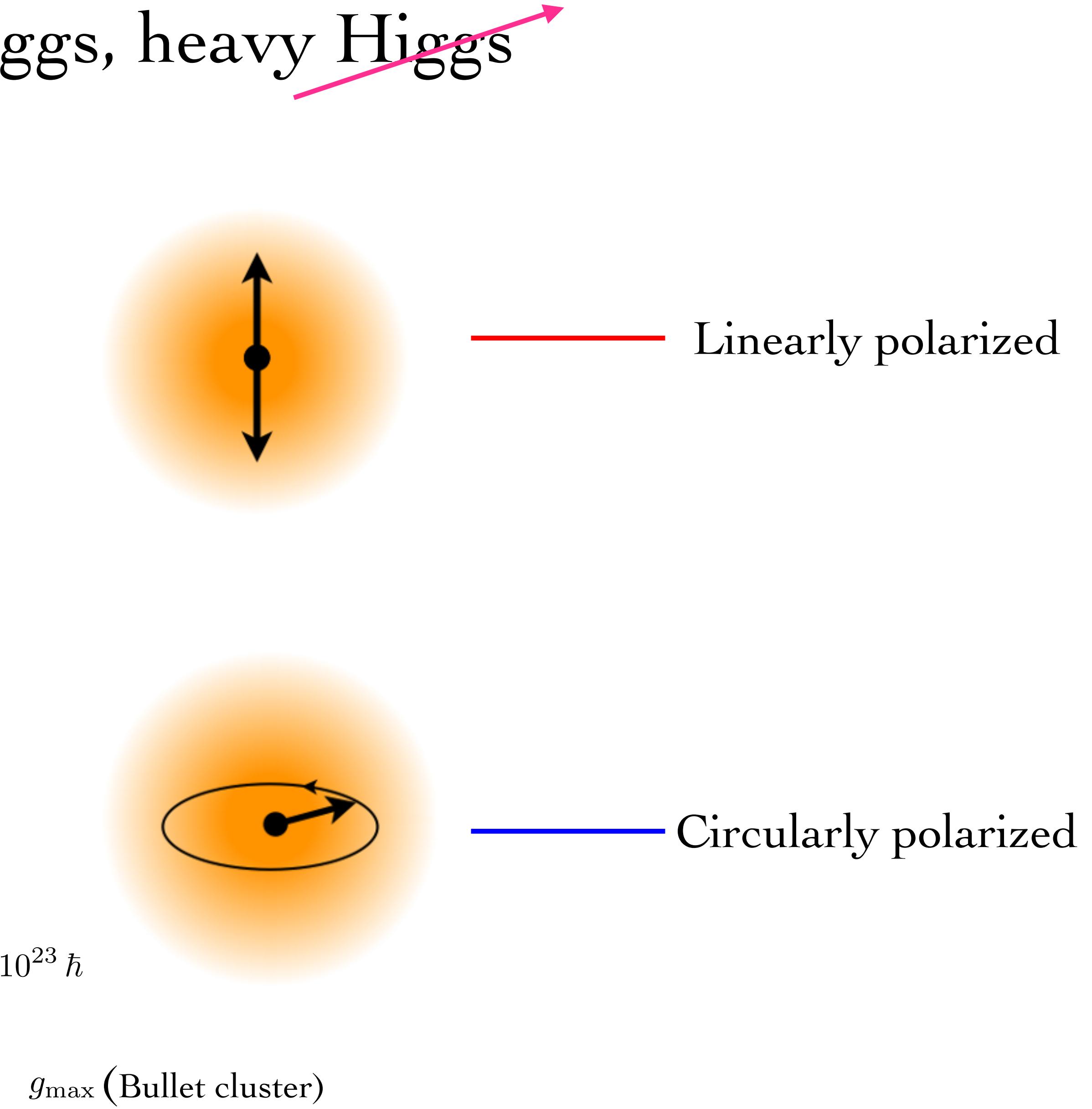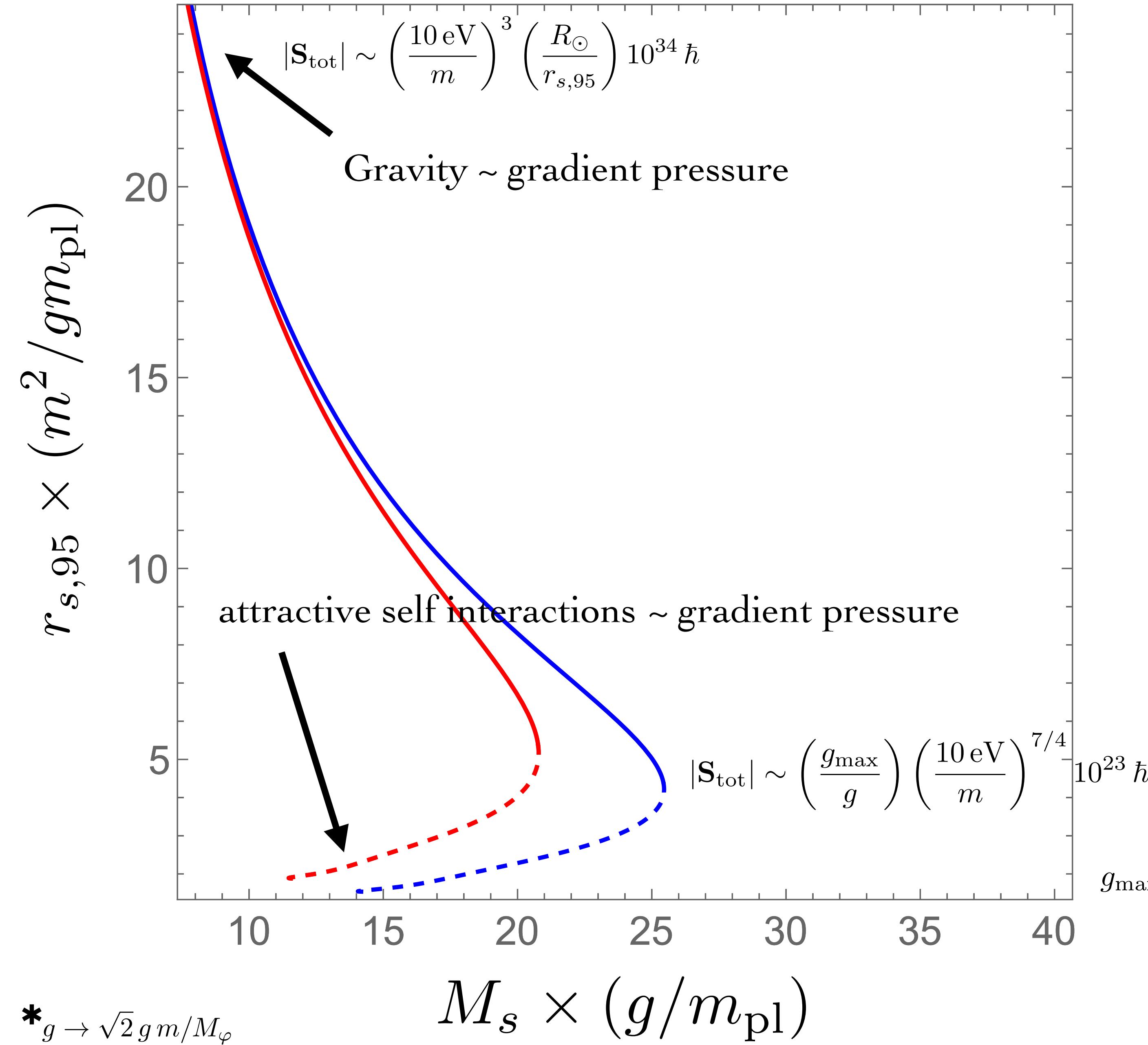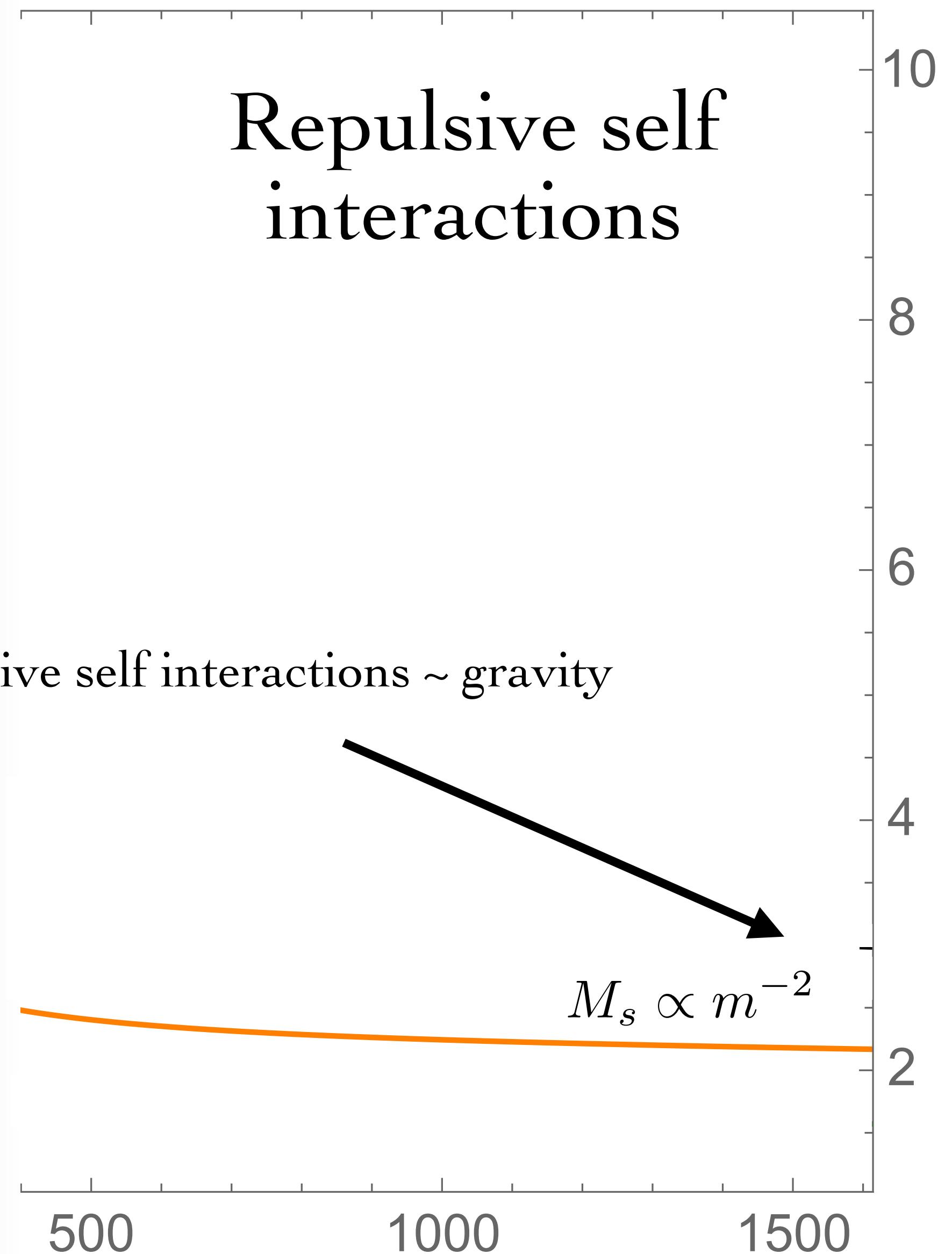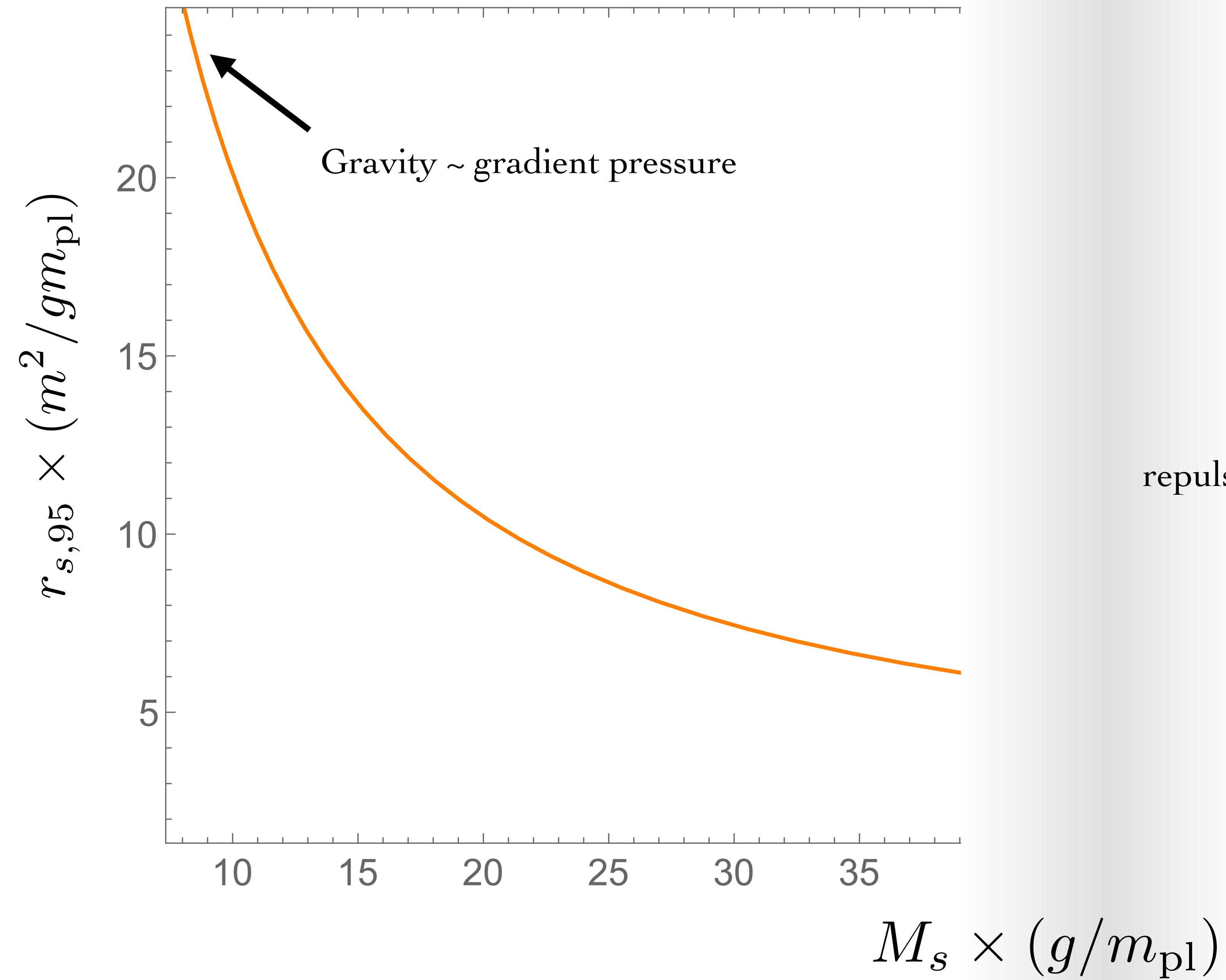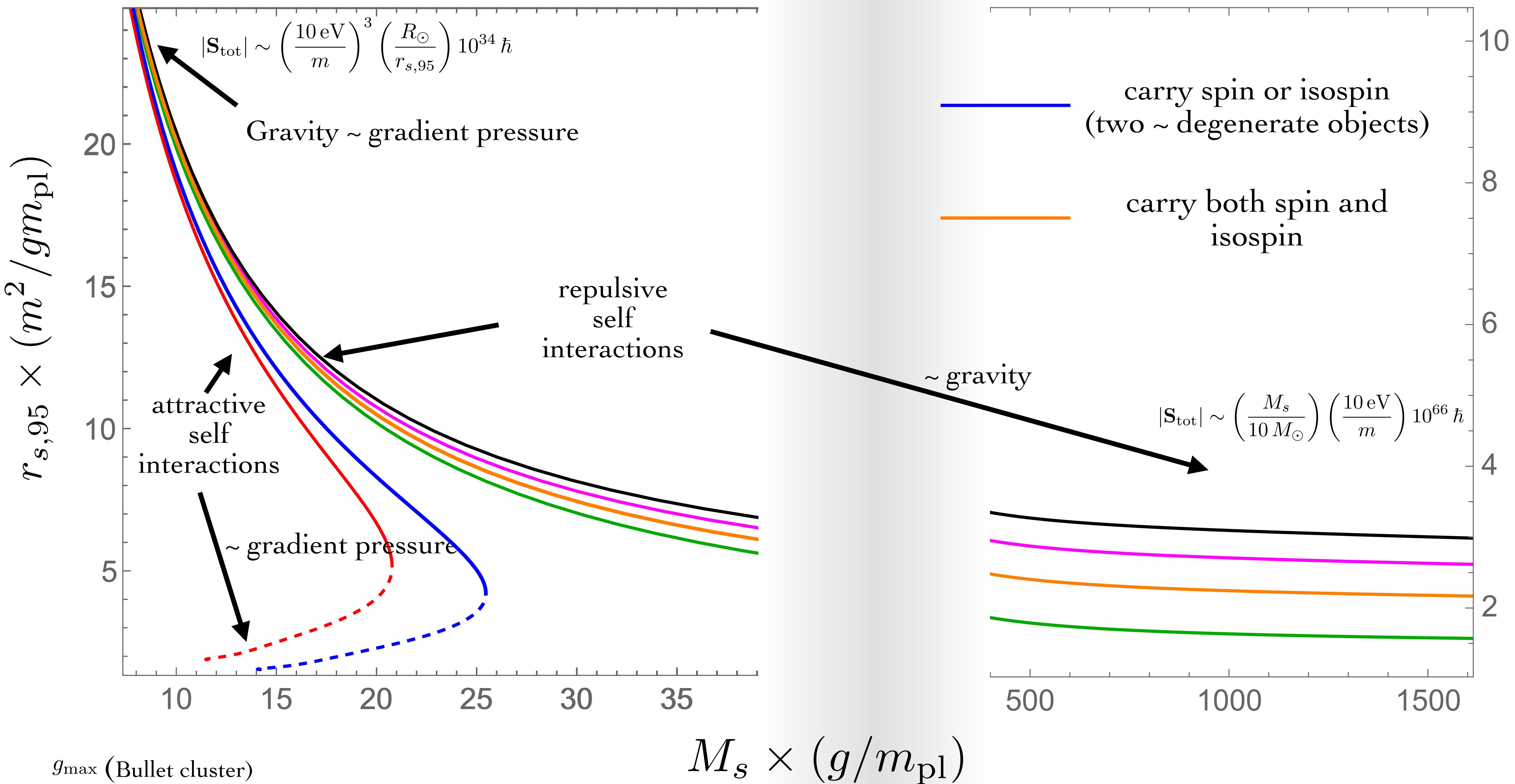
arXiv:2205.03418 U(1) Abelian Higgs, heavy Higgs

$$|\mathbf{S}_{\text{tot}}| \sim \left(\frac{10\,\text{eV}}{m}\right)^3 \left(\frac{R_\odot}{r_{s,95}}\right) 10^{34}\,\hbar$$

Gravity ~ gradient pressure

attractive self interactions ~ gradient pressure

$$|\mathbf{S}_{\text{tot}}| \sim \left(\frac{g_{\text{max}}}{g}\right) \left(\frac{10\,\text{eV}}{m}\right)^{7/4} 10^{23}\,\hbar$$

g_{max} (Bullet cluster)

Linearly polarized

Circularly polarized

$r_{s,95} \times (m^2/g\,m_{\text{pl}})$

$M_s \times (g/m_{\text{pl}})$

$*_{g \to \sqrt{2}\,g\,m/M_\varphi}$

see 2111.08700 for vector Oscillons (w/o gravity)

– Chavanis, Schiappacasse et al, Hertzberg et al, Croon et al,…

Gravity ~ gradient pressure

Repulsive self interactions

repulsive self interactions ~ gravity

$M_s \propto m^{-2}$

$r_{s,95} \times (m^2/g m_{\rm pl})$

$M_s \times (g/m_{\rm pl})$

arXiv:2205.03418
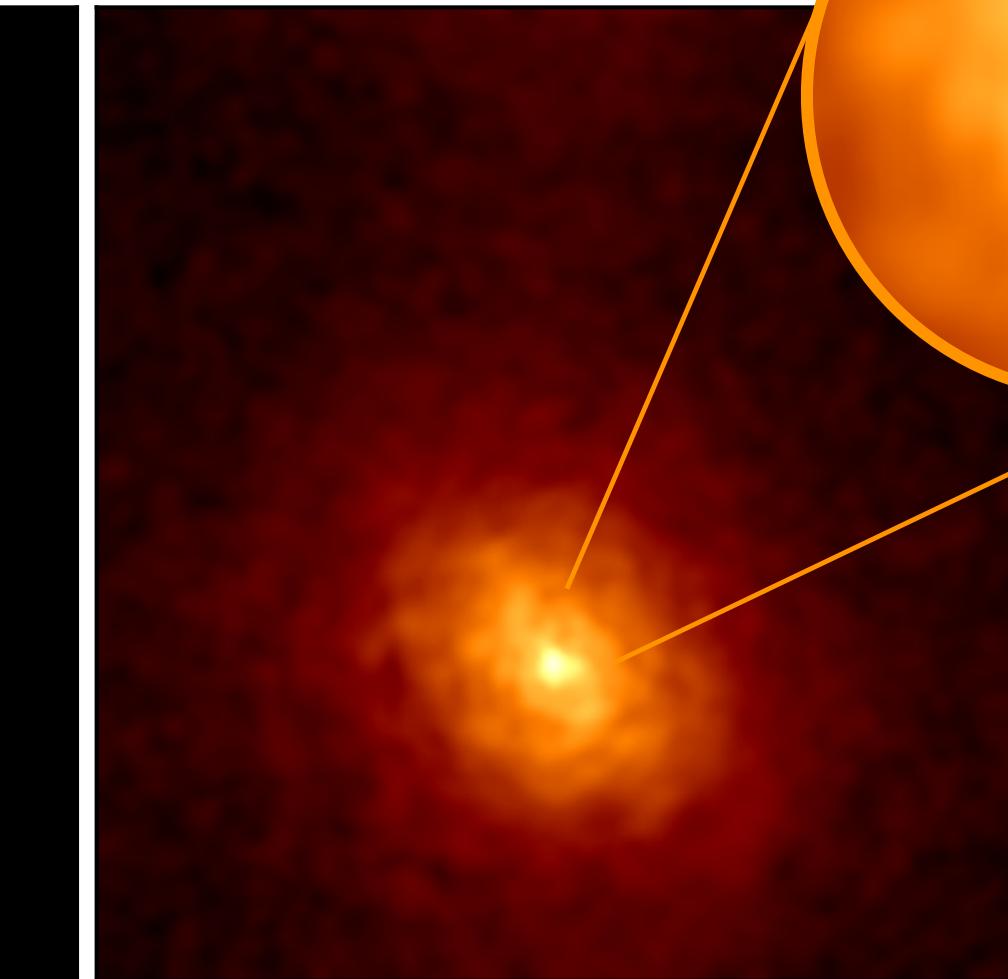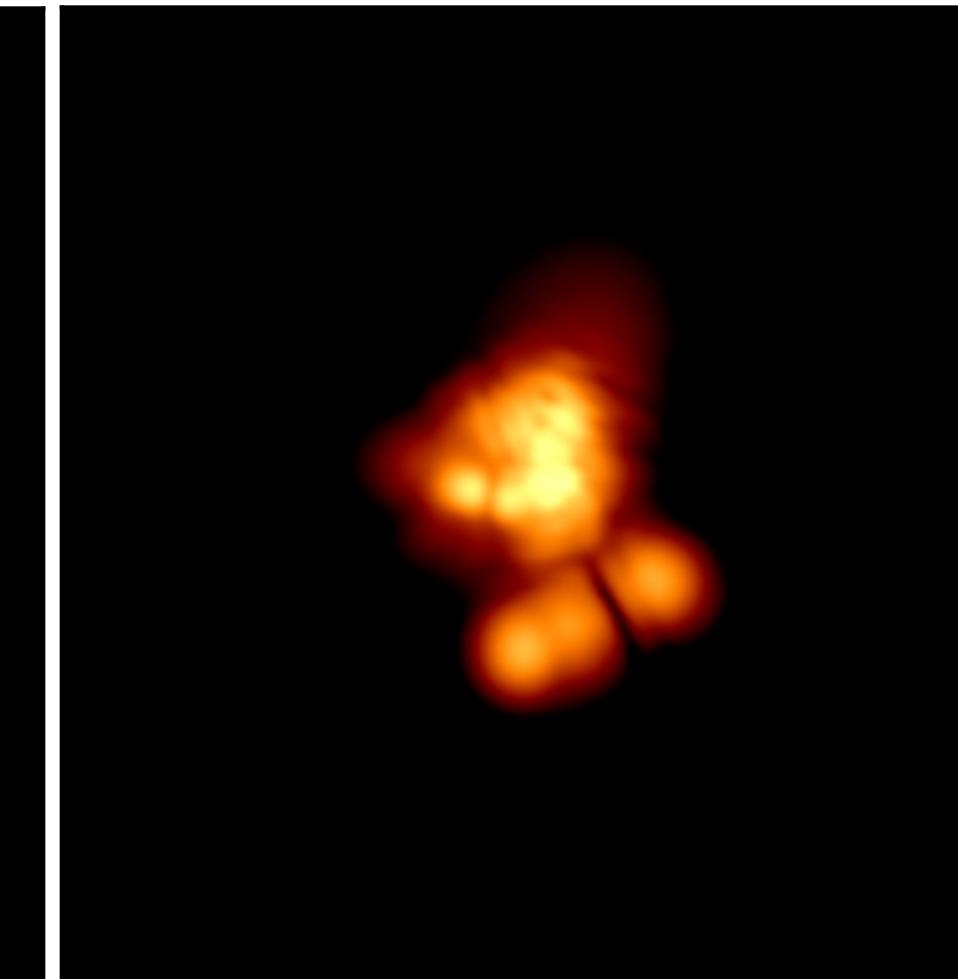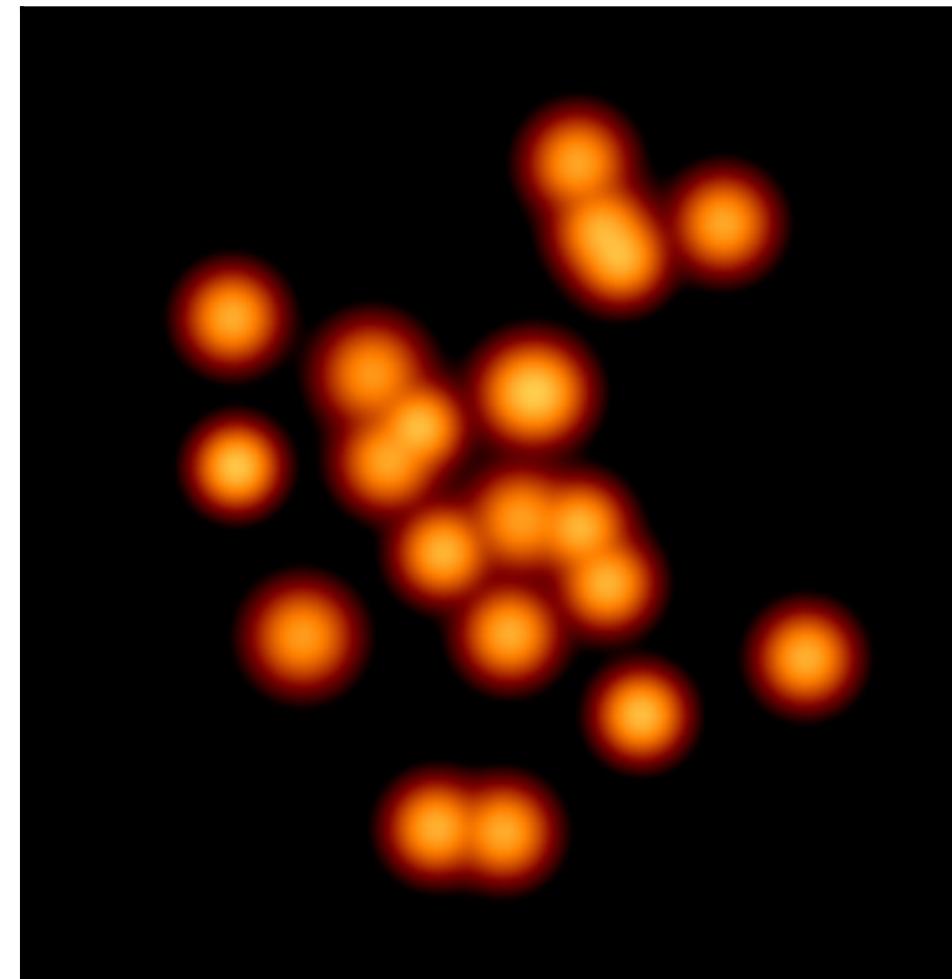
Higgsed SU(2) Yang-Mills, heavy Higgs

$|\mathbf{S}_{\text{tot}}| \sim \left(\frac{10\,\text{eV}}{m}\right)^3 \left(\frac{R_\odot}{r_{s,95}}\right) 10^{34}\,\hbar$

Gravity ~ gradient pressure

attractive self interactions

~ gradient pressure

repulsive self interactions

~ gravity

$|\mathbf{S}_{\text{tot}}| \sim \left(\frac{M_s}{10\,M_\odot}\right)\left(\frac{10\,\text{eV}}{m}\right) 10^{66}\,\hbar$

carry spin or isospin
(two ~ degenerate objects)

carry both spin and isospin

$r_{s,95} \times (m^2/g\,m_{\text{pl}})$

$M_s \times (g/m_{\text{pl}})$

g_{max} (Bullet cluster)

Phenomenology
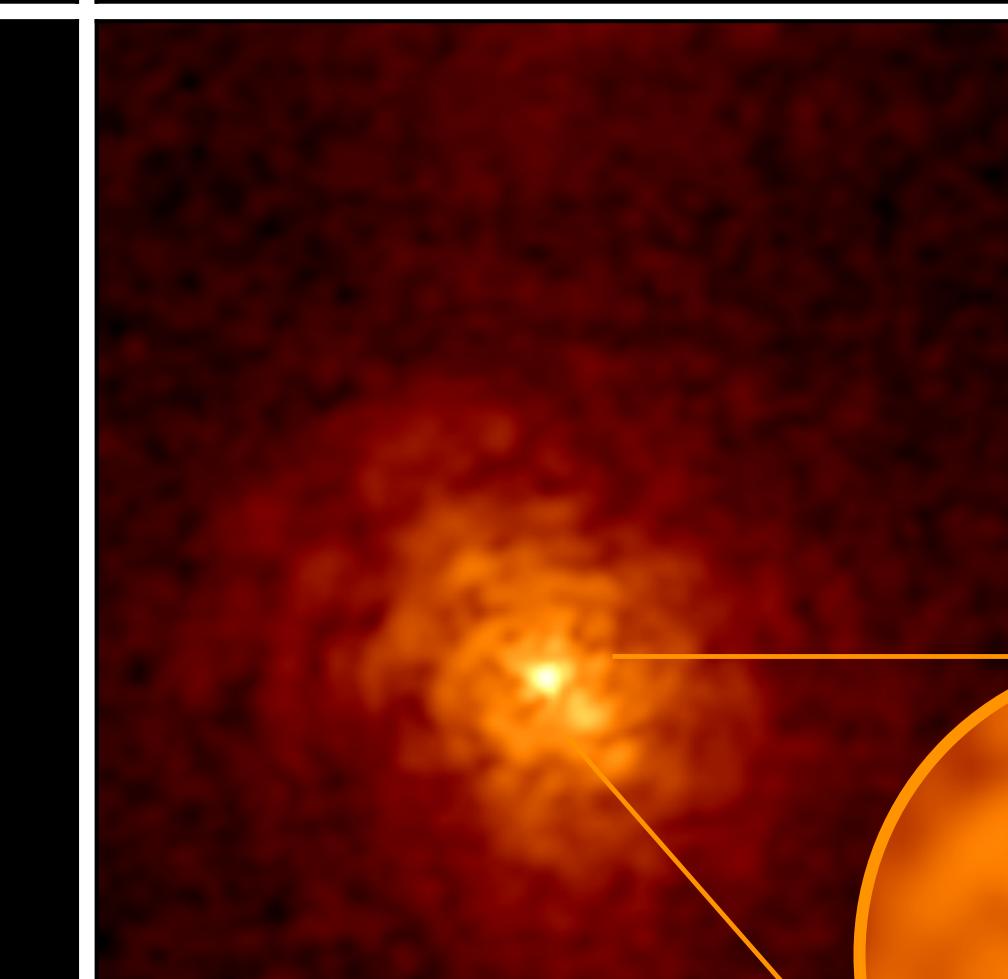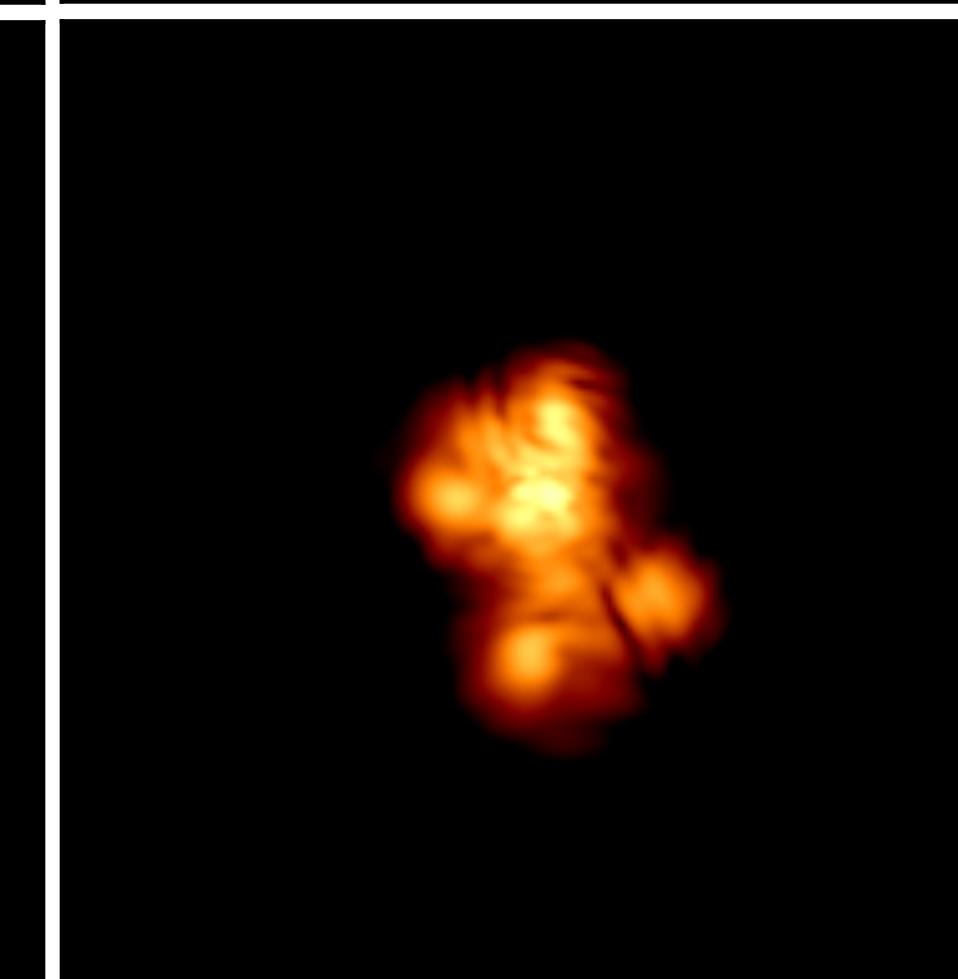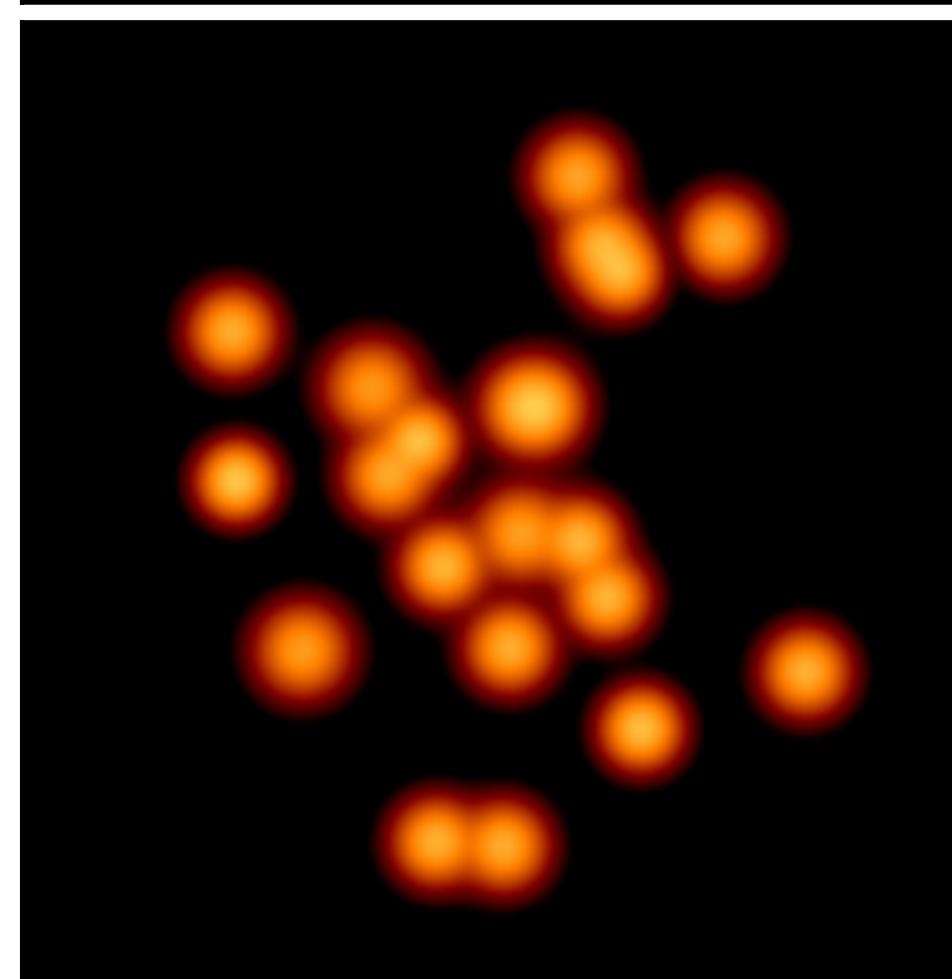
2203.11935 Gravity ~ gradient pressure (no/negligible self interactions)

- less interference in VDM

- less dense granules in VDM

- VDM Halo cores can have huge spin

0 0.34 1.36

$t/t_{\text{dyn}} \longrightarrow$

- also see Gorghetto et al
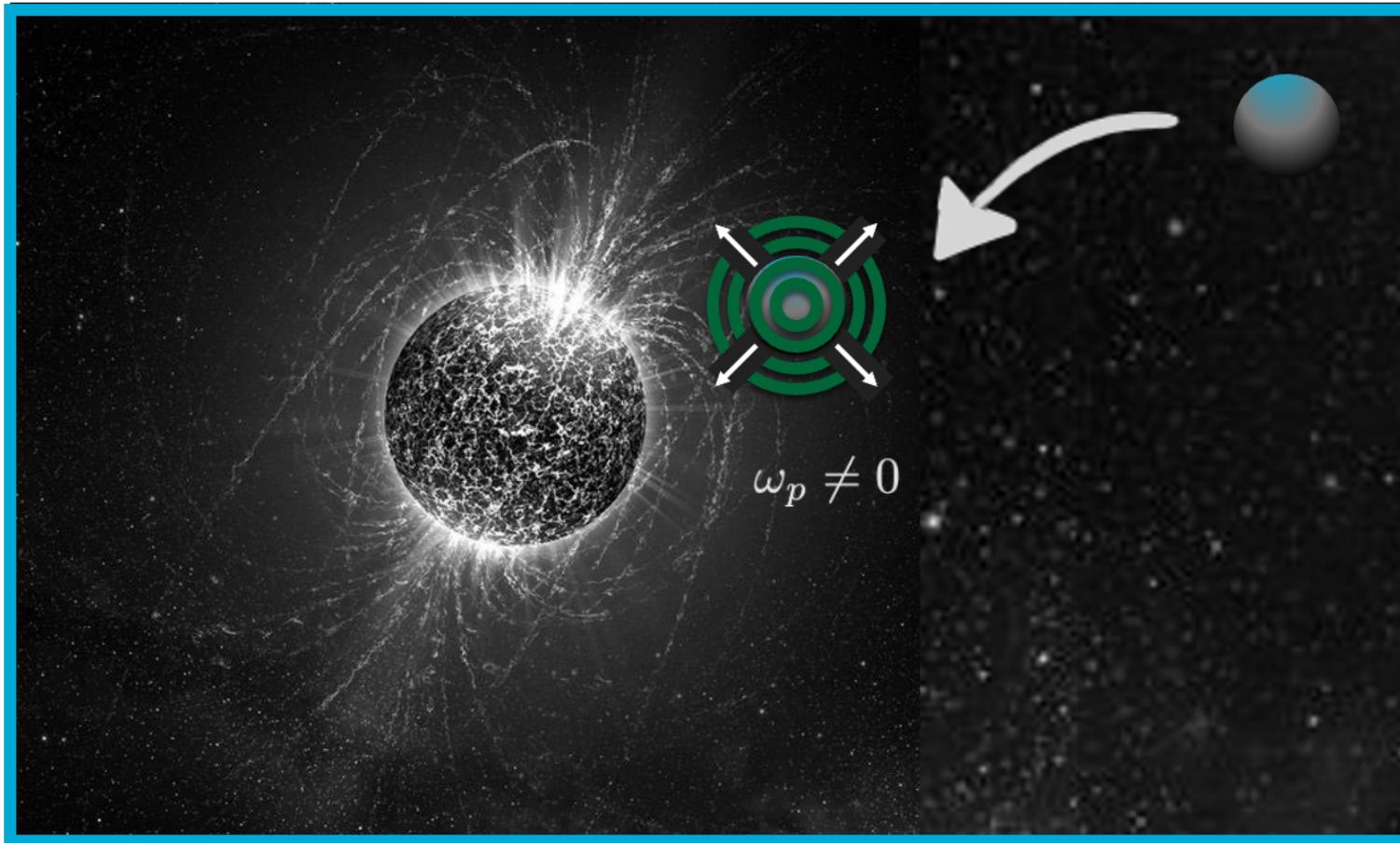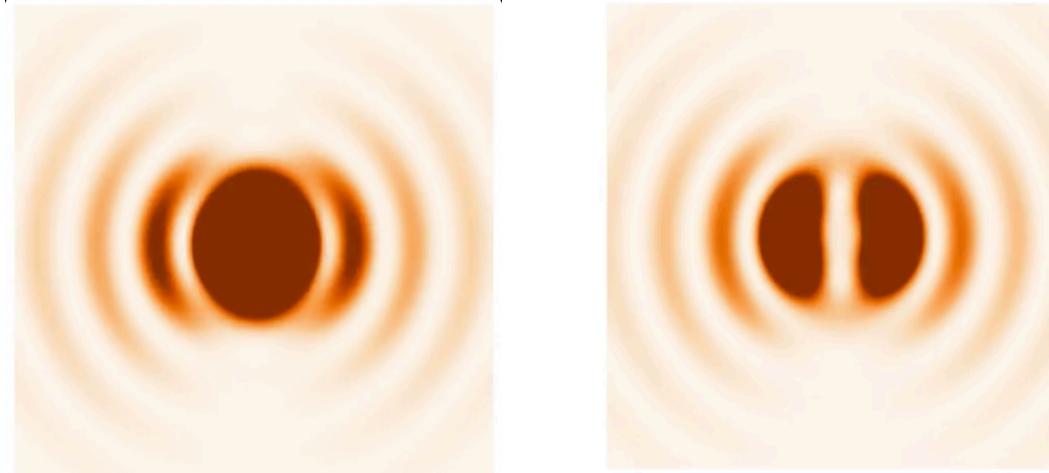
SM coupling and radiation
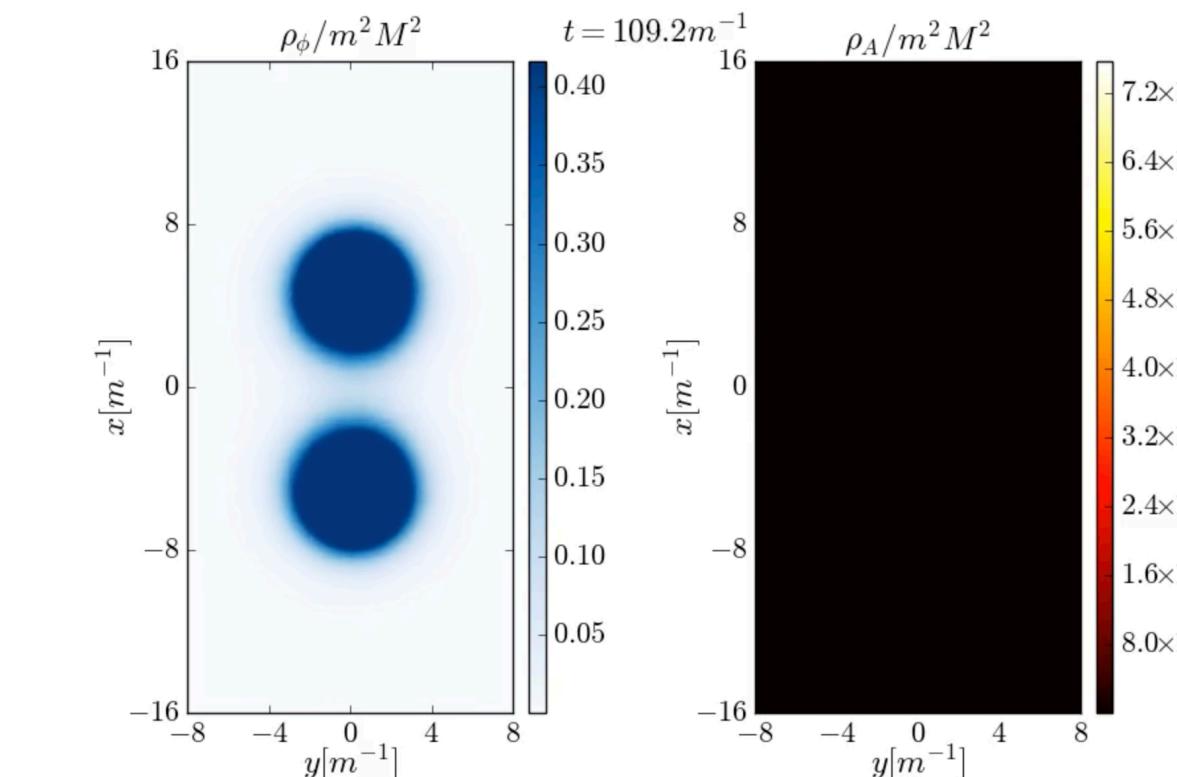
$$\mathcal{L}_{int} \sim g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

"Searching for axions at Magnetic White Dwarfs"

– Dessert et al

– Amin et al

– Amin et al
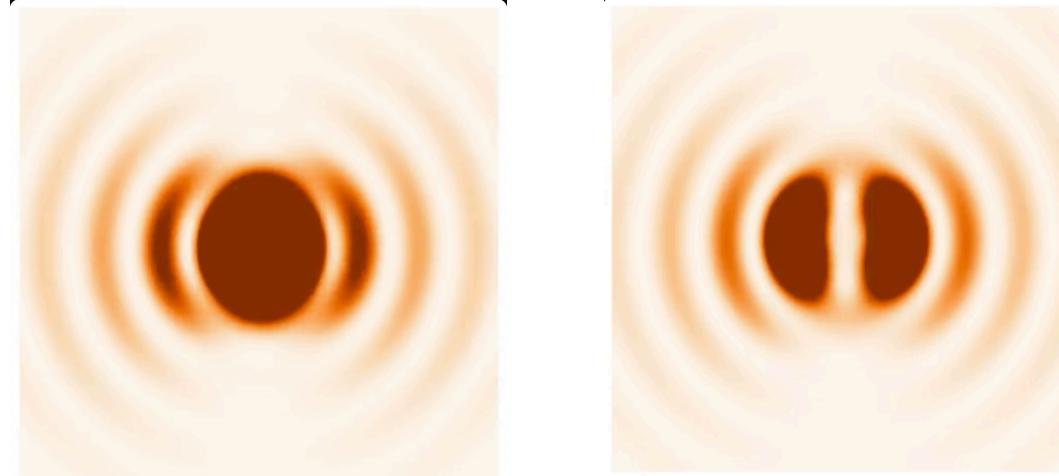
SM coupling and radiation

$$\mathcal{L}_{int} \sim \begin{cases} g^2_{W\gamma} W_\mu W^\mu \, F_{\alpha\beta} \tilde{F}^{\alpha\beta} & \text{spin}-1 \\ g^2_{H\gamma}(H_{\mu\nu}H^{\mu\nu} - H^2) \, F_{\alpha\beta} \tilde{F}^{\alpha\beta} & \text{spin}-2 \end{cases}$$

$$\sim g^2_{\mathcal{F}\gamma} \operatorname{Tr}[\boldsymbol{\mathcal{F}}\boldsymbol{\mathcal{F}}] \, F_{\alpha\beta}\tilde{F}^{\alpha\beta} \qquad \text{NR limit}$$

$$\mathcal{L}_{int} \sim g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{int} \sim \lambda_{\varphi h} H^\dagger H \Phi^\dagger \Phi$$

"Searching for axions at Magnetic White Dwarfs"

– Dessert et al

$\omega_p \neq 0$
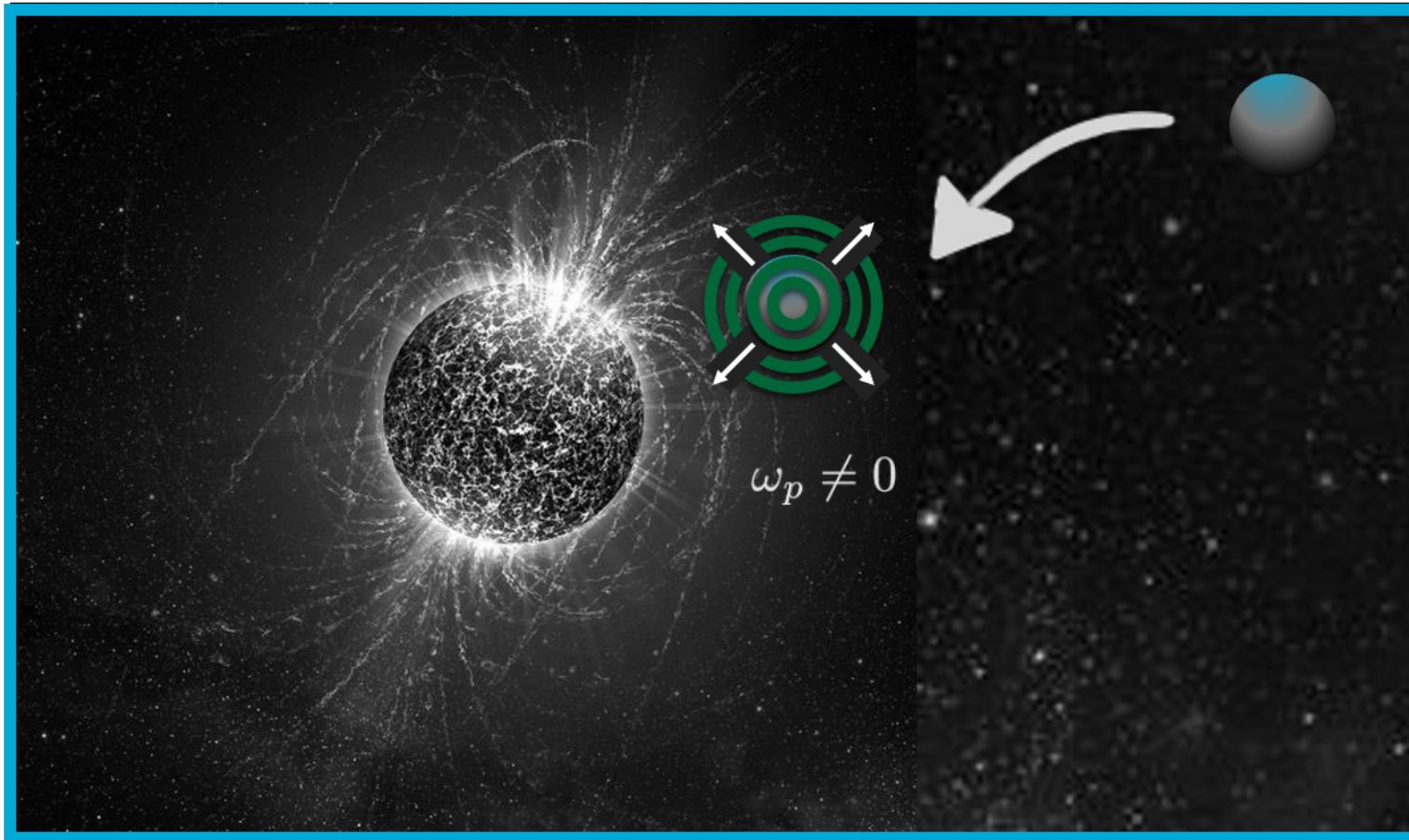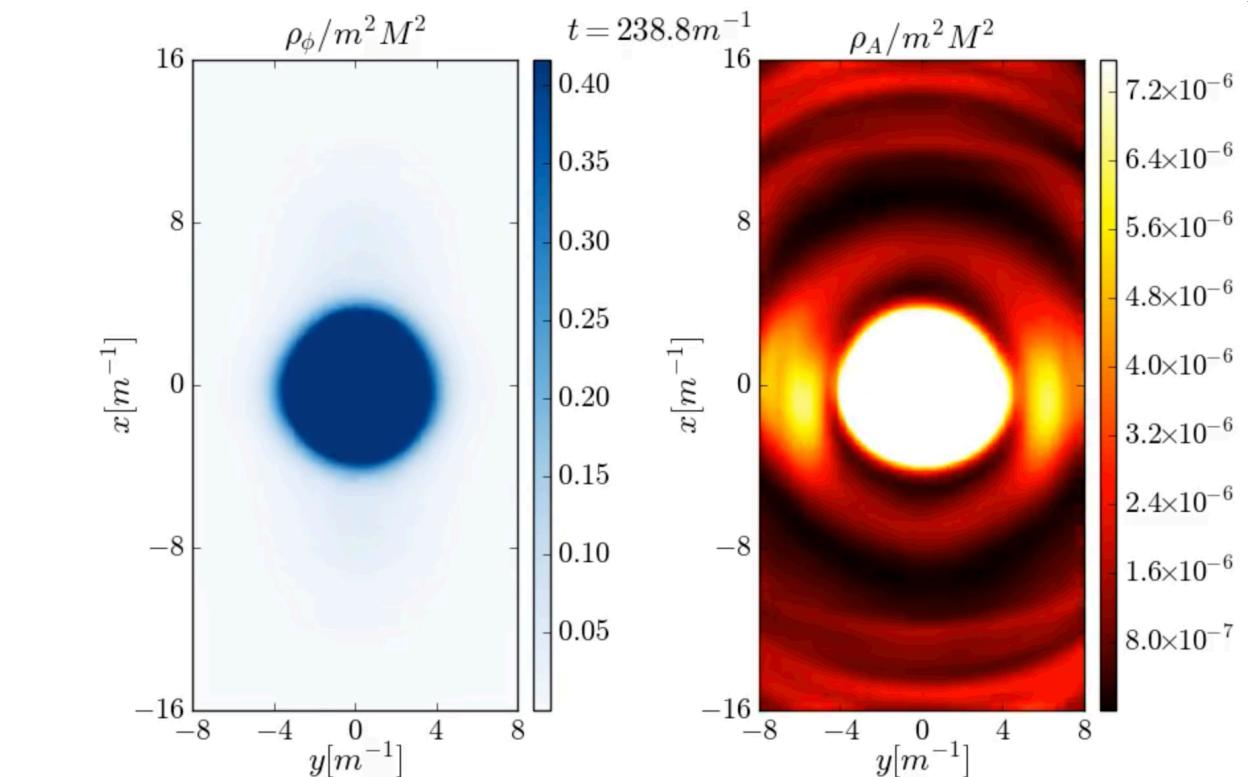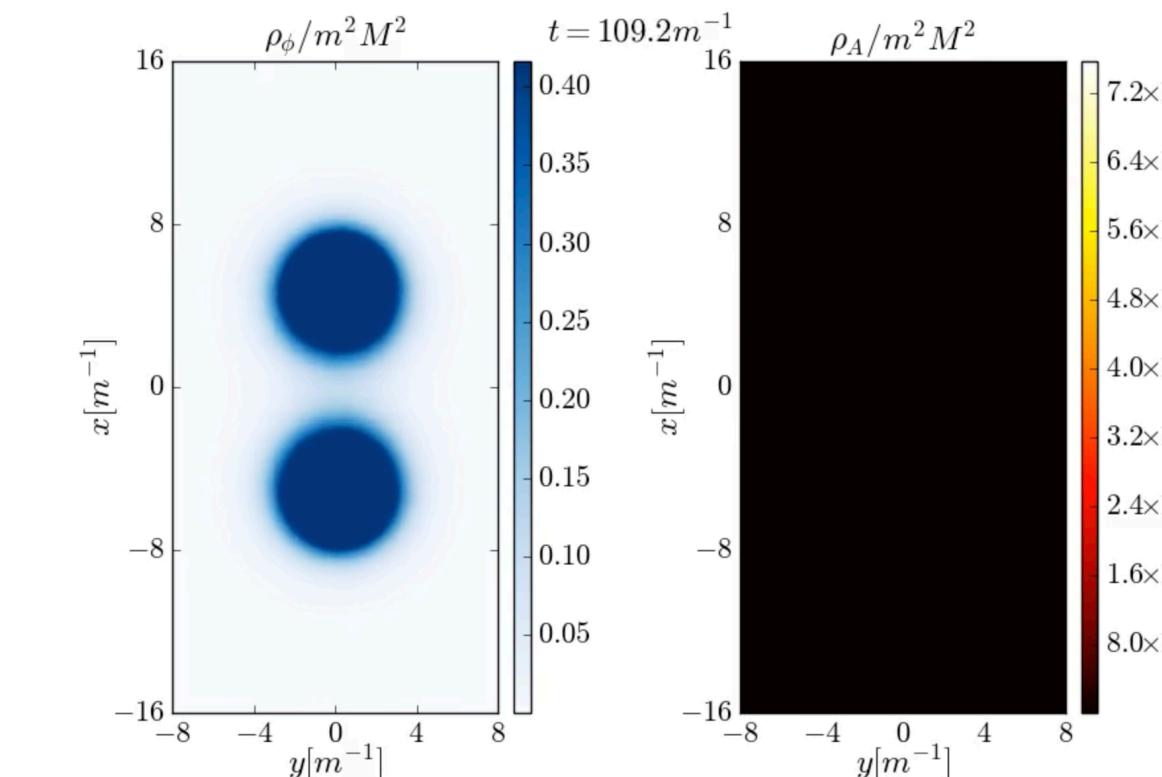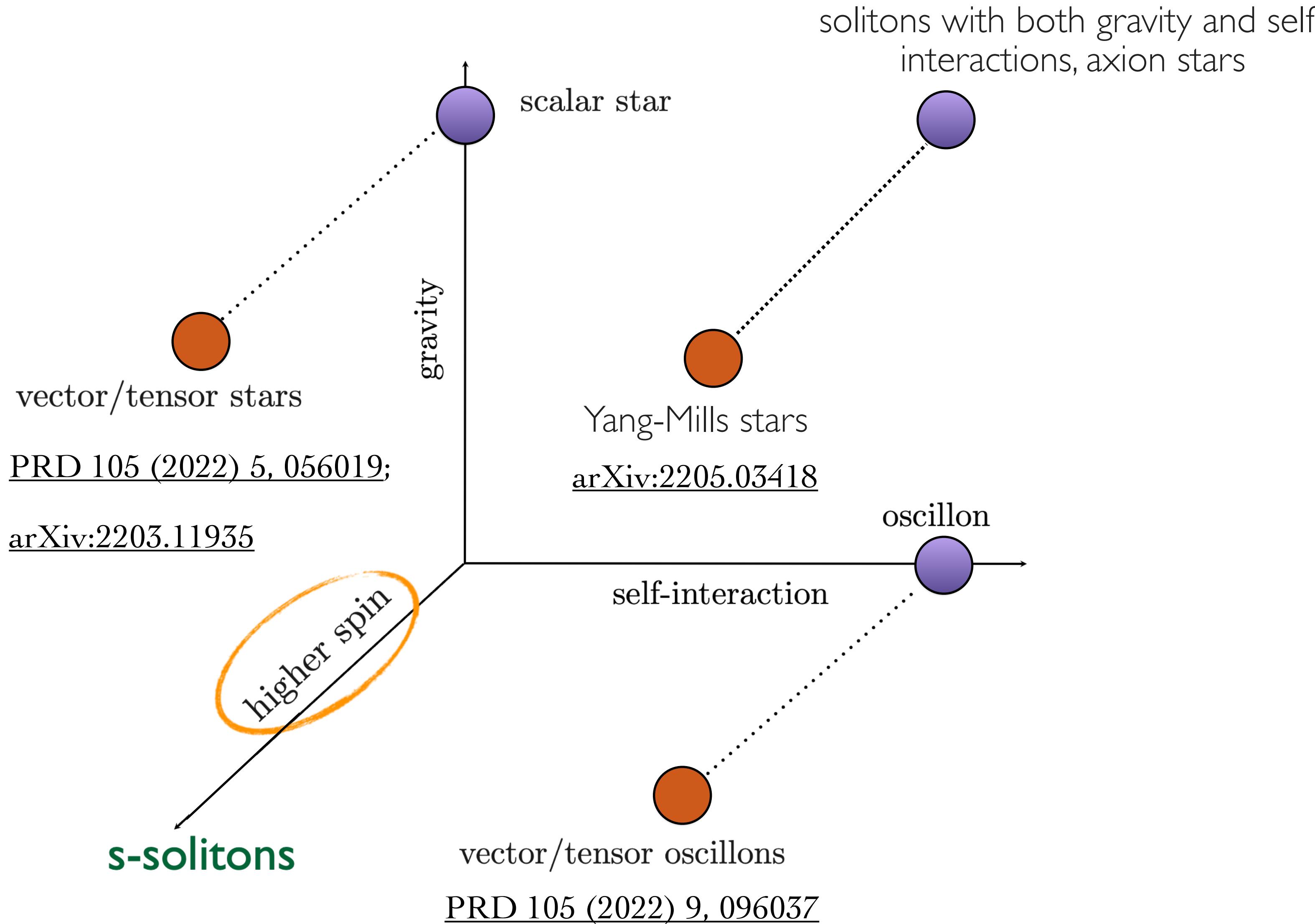
– Amin et al

– Amin et al

non-topological solitons

spatially localized, coherently oscillating, long-lived

solitons with both gravity and self-interactions, axion stars

scalar star

gravity

vector/tensor stars

PRD 105 (2022) 5, 056019;

arXiv:2203.11935

Yang-Mills stars

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oscillon

self-interaction

higher spin

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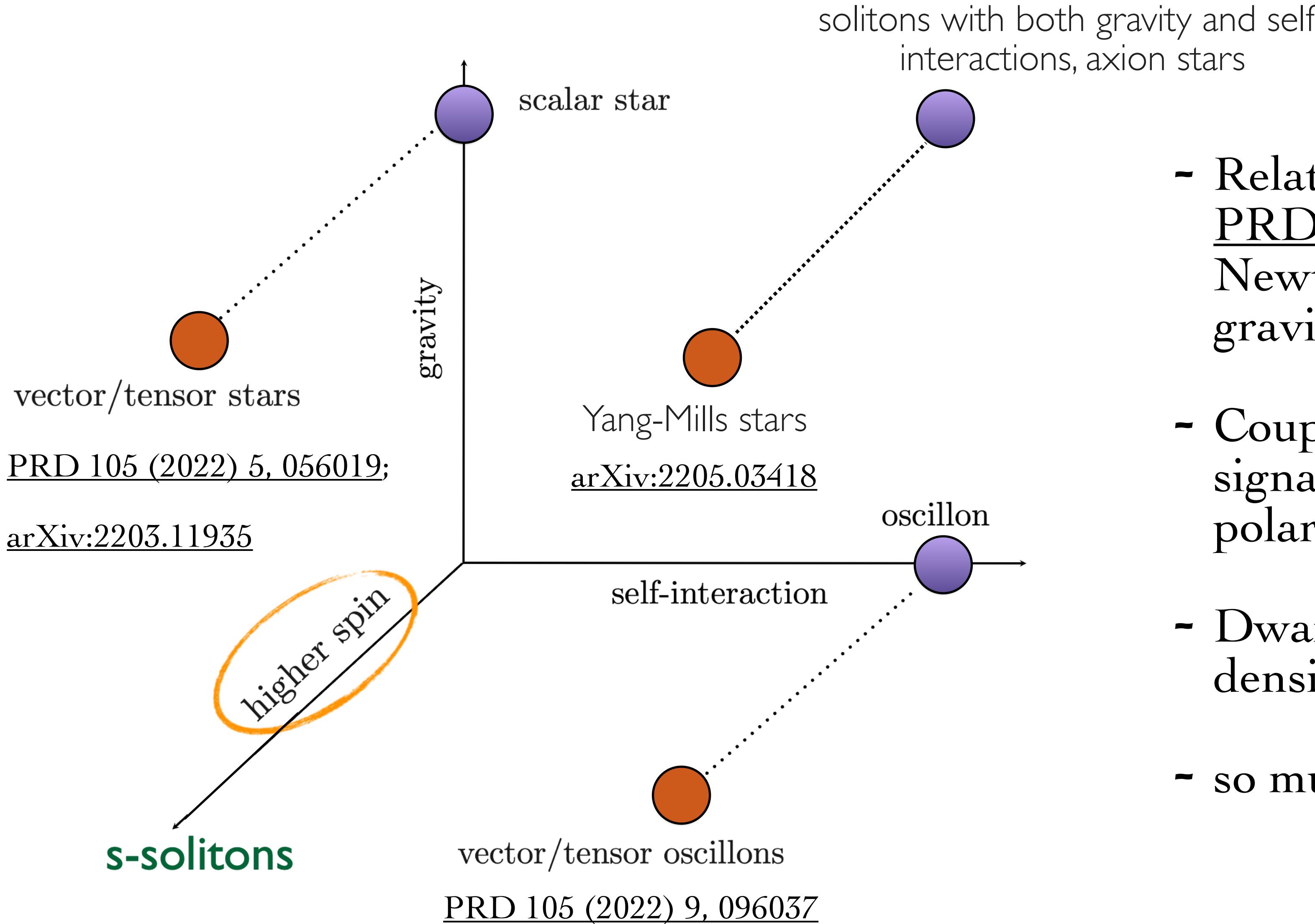
Summary

huge (macroscopic) intrinsic spin!

non-topological solitons

spatially localized, coherently oscillating, long-lived

Many phenomenological implications

solitons with both gravity and self-interactions, axion stars

scalar star

gravity

vector/tensor stars

PRD 105 (2022) 5, 056019;

arXiv:2203.11935

Yang-Mills stars

arXiv:2205.03418

self-interaction

oscillon

higher spin

s-solitons

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PRD 105 (2022) 9, 096037

- Relativistic corrections (also see PRD 105 (2022) 9, 096037); Post Newtonian corrections ⟷ sourcing gravitational waves

- Couplings with the Standard Model, signatures due to intrinsic spin polarization;

- Dwarf galaxies core radius vs density relationship

- so much more

Thanks!