Title: Particle Phenomenology in the Era of Gravitational Wave Astronomy

Date: Oct 09, 2018 01:00 PM

URL: http://pirsa.org/18100076

Abstract: <p>After the detection of black hole and neutron star binary mergers at LIGO/Virgo, gravitational wave becomes a new observational channel that we didn't have access to years ago.</p>

<p>It is an interesting question to ask what kind of new particle physics this channel can probe.</p>

<p>To answer this question, one needs to fill the gap between the scales of the astrophysical processes and the fundamental structures.</p>

<p>In this talk, I will demonstrate a few ways of extracting particle physics information directly from binary merger events of neutron stars and boson stars, and using this information to constrain well motivated dark sectors, including dark gauge boson and axion like particles.</p>

<p>An outline of future directions will also be discussed.</p>

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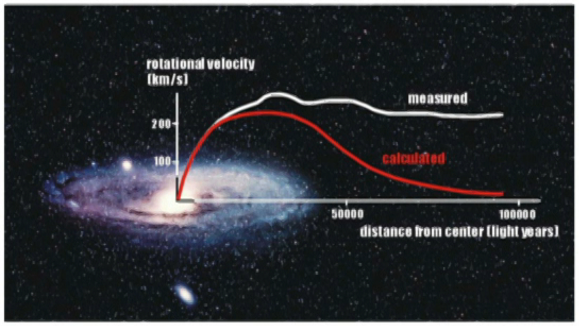
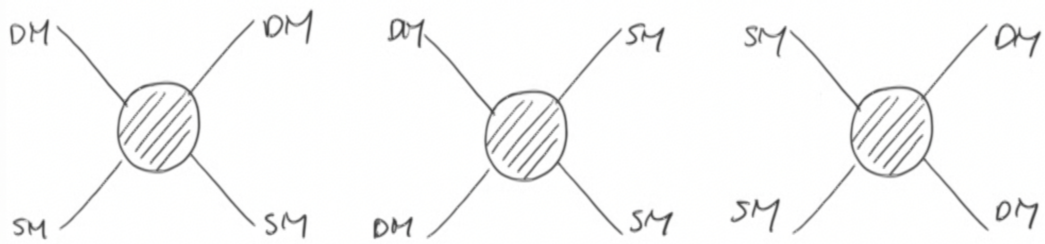


- Dark matter (most likely) exists, and we are actively searching DM-SM coupling.
- How about the complementary: extract information of the dark sector without assuming



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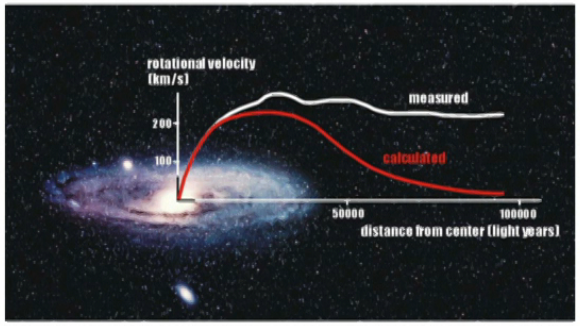

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- Benefits:
  - Remain agnostic about the production mechanism, *i.e.* beyond thermal DM

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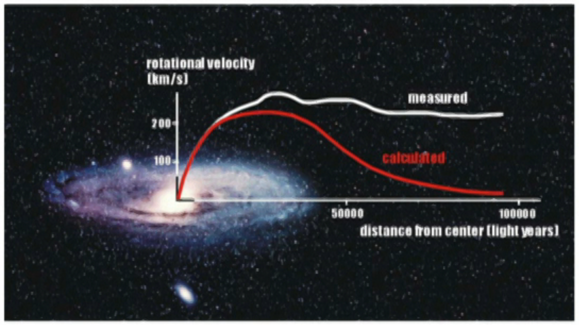

- Dark matter (most likely) exists, and we are actively searching DM-SM coupling.
- How about the complementary: extract information of the dark sector
- Benefits:
    - Remain agnostic about the production mechanism, *i.e.* beyond thermal DM
    - Extract information on structure of dark sector independent of the form and size of $\chi\chi\bar{f}f$ (break degeneracy)

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Portal	Particles	Operators(s)
"Vector"	Dark photons	$\epsilon B_{\mu\nu} F'^{\mu\nu}, \; F'_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{\phi}{f} F\tilde{F}, \frac{\phi}{f} G\tilde{G}, \frac{\partial_\mu \phi}{f} \overline{\psi}\gamma^\mu \gamma^5 \psi, \; V(\phi/f)$
"Higgs"	Dark scalars	$(\mu\phi + \lambda_2 \phi^2) H^\dagger H, \, \lambda\phi^4$
"Neutrino"	Fermionic DM	$y_N \overline{L} H N, \, y_{12} \overline{N}_2 H N_1, \; g' \overline{N} \gamma^\mu N A'_\mu$

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DM + dark photon

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$$\mathcal{L} = i\overline{\chi}\gamma^\mu\partial_\mu\chi - g'\overline{\chi}\gamma^\mu A'_\mu\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + ..$$

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DM + dark photon

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- Assumption: Asymmetric dark matter self-interacting through dark photon.
- To what extent can it affect NS mergers if NS contains aDM?

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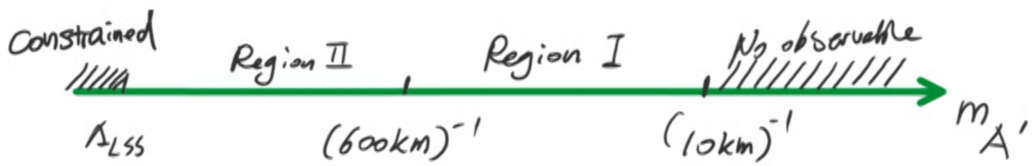

Region I:

- The interaction can be described by Yukawa potential $\propto \exp(-m_{A'}\, r)/r$.
- $P = -\dot{E}$

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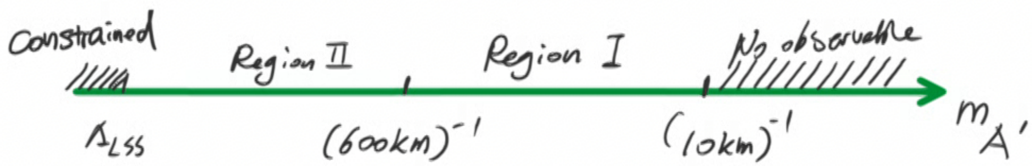

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- $P = -\dot{E}$
- $\exp(-m_{A'}\ r)/r \sim 0$ (r large)
  $\sim 1/r$ (r small)


Constrained
Region II
Region I
Region I:
The interaction can be described by Yukawa potential
P = −Ė
exp(−m_A' r)/r ∼ 0
∼ 1/r
(r large)
(r small)

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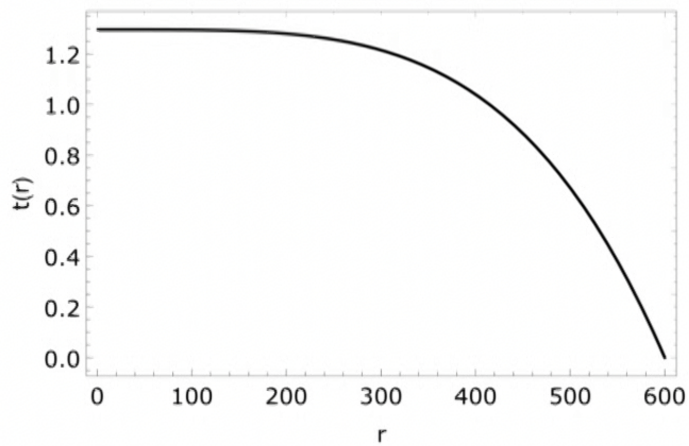
$$t = \frac{5c^5}{256 G^3 m^2 \mu}\left(r_0^4 - r^4\right)$$



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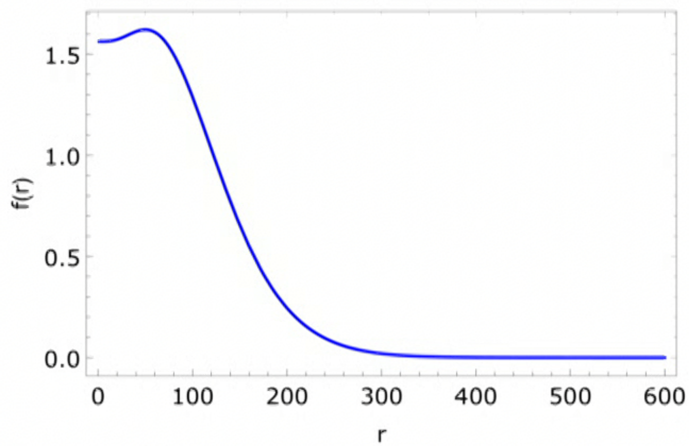
$$t = \frac{5c^5}{256 G^3 m^2 \mu}\left((r_0^4 - r^4) + \tilde{\alpha}'(f(r_0) - f(r))\right)$$



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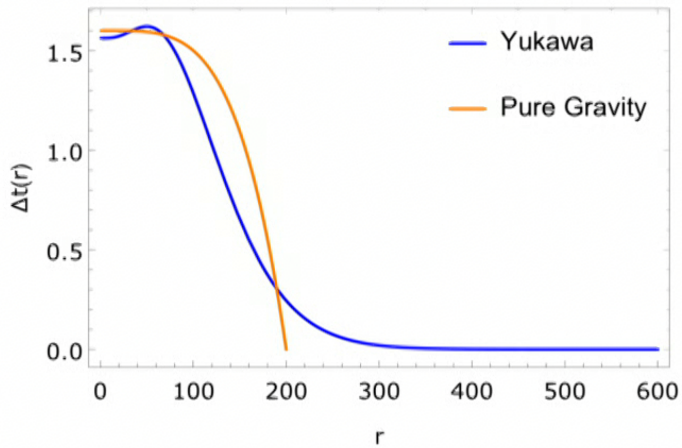

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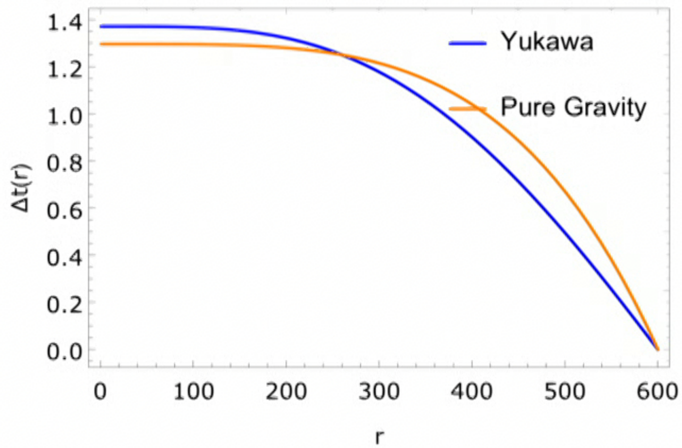

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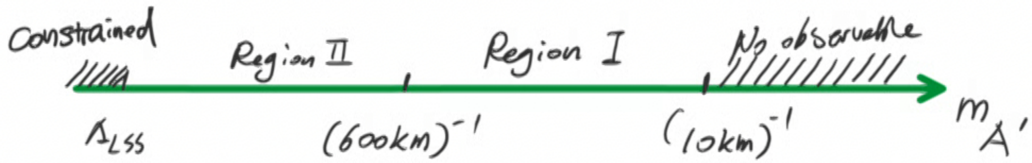

Region I:

- $P = -\dot{E}_{Gravity} + \Delta \dot{E}_Y \, \Theta(r - r_c)$

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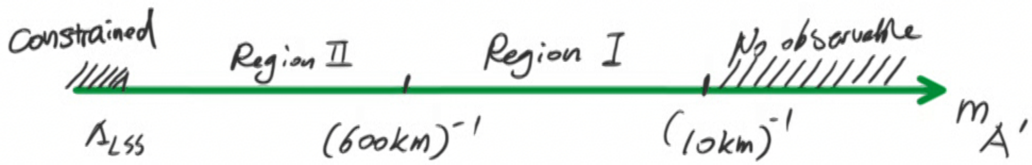

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Region II:

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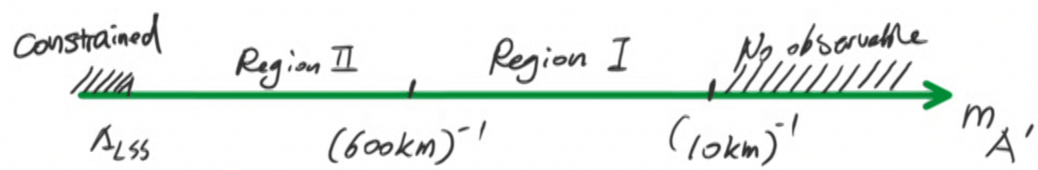

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- Potential correction cannot be distinguished from gravity $\sim 1/r$.

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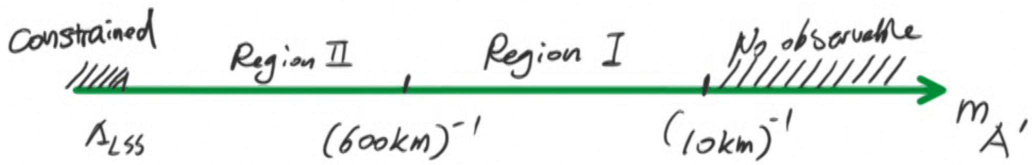

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- $P + \Delta P_D = -\dot{E}_{Gravity}$
- Light mediators have dipole momentum ($\sim r^2$), while $P_{GW} \sim r^4$.

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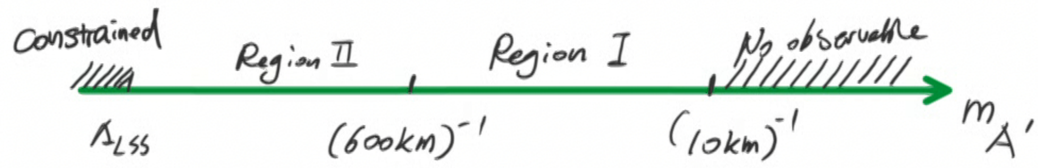

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$$\omega(t) = \left(\frac{3}{8X(t_c - t)}\right)^{3/8} - \frac{Y}{10X}\left(\frac{3}{8X(t_c - t)}\right)^{1/8}$$

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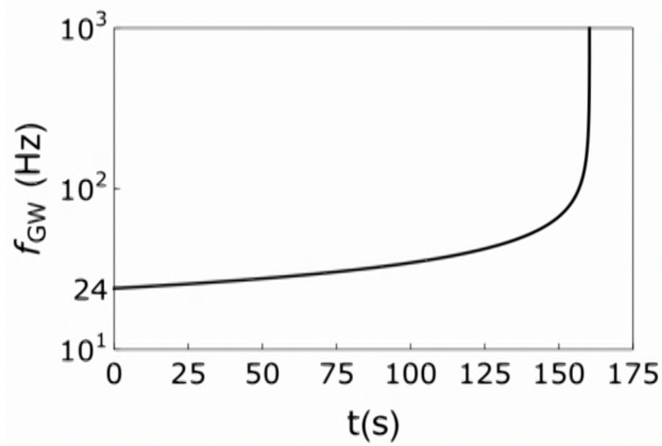

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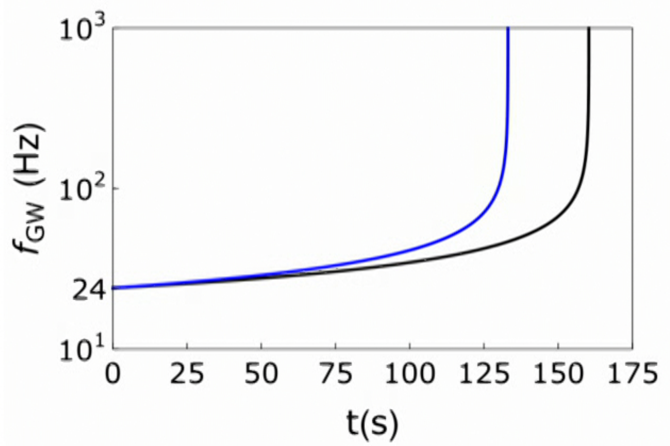

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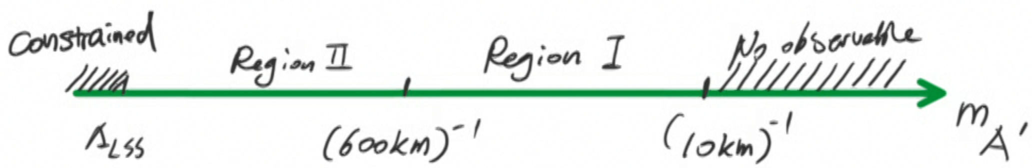

Region I + Region II, NS merger is sensitive to vector force mediator

$$m_{A'} \lesssim (10 \text{ km})^{-1} \approx 10^{-11} \text{ eV}$$

Constrains the amount of DM confined in NS.

$$\tilde{\alpha}' \equiv \frac{g' q_1 q_2}{G_N M_1 M_2} = \frac{g'}{G_N} \left(\frac{f}{m_\chi} \right)^2$$

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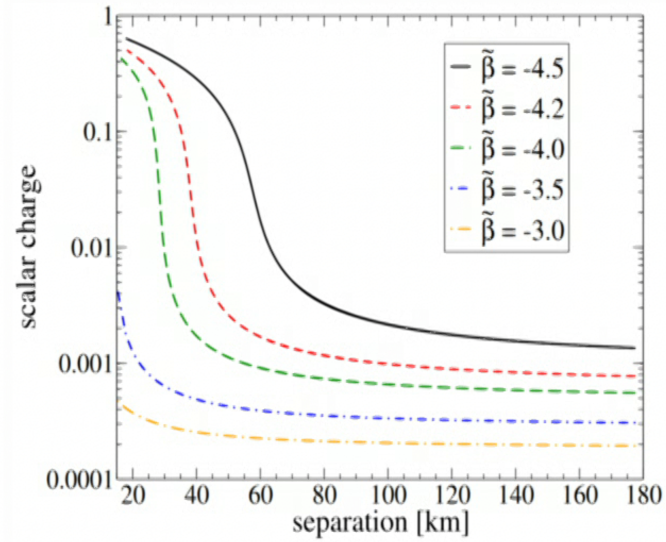
aDM v.s. Scalar-Tensor Theory



Palenzuela, Barausse, Ponce, Lehner (1310.4481)
Sagunski, Zhang, Johnson, Lehner, Sakellariadou, Liebling, Palenzuela, Neilson (1709.06634)

- Very similar signal, but different origins and parameter space
- Different dynamical process: scalarization vs finite range
- Different source of charge: $T^{\mu\nu}$ vs aDM $U(1)'$ in NS
- Different parameter region motivated by DM accumulation etc.
- Different force behavior: attractive vs repulsive $\tilde{\alpha}' > 0$

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DM + dark photon

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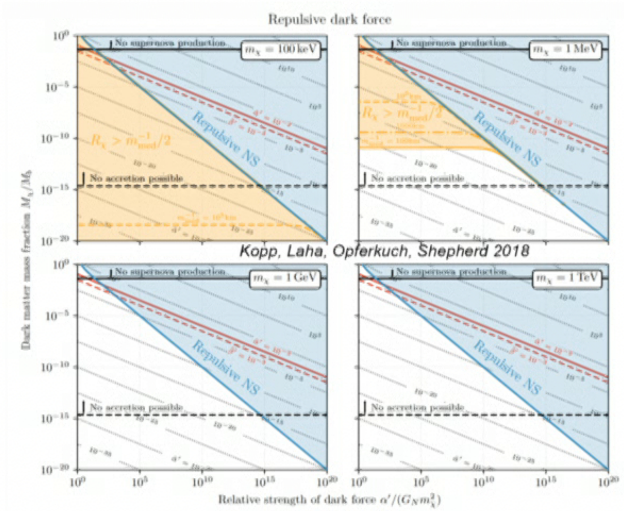
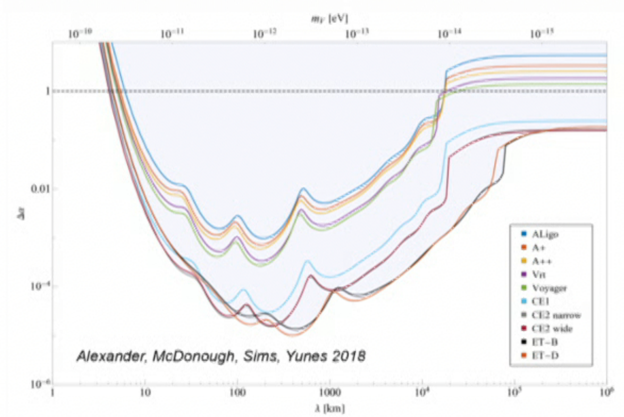
A simple estimate gives $|\alpha'| \lesssim 1/3$ constraint can be put by LIGO/Virgo.





For more detailed follow-ups, c.f. Kopp, Laha, Opferkuch, Shepherd 2018; Alexander, McDonough, Sims, Yunes 2018

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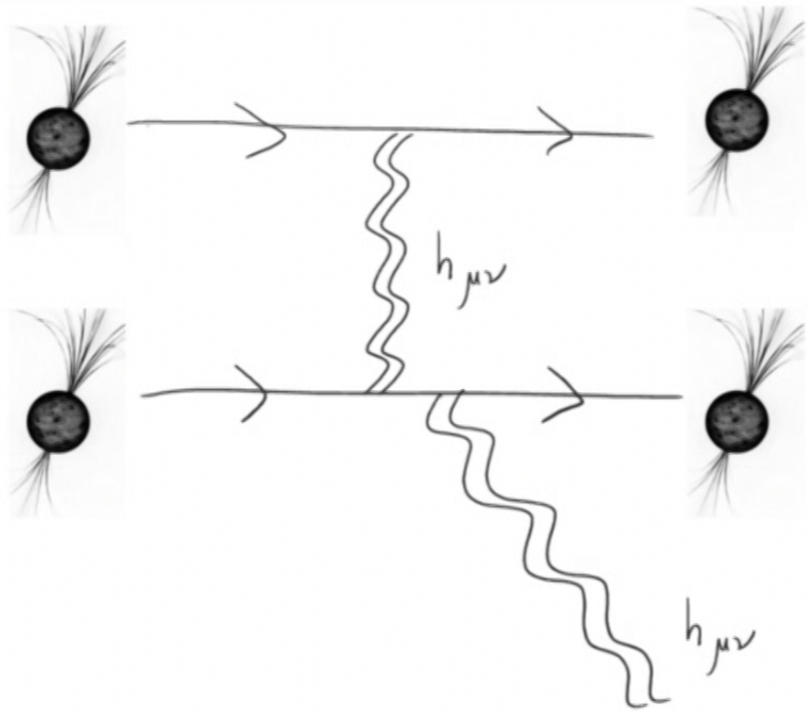

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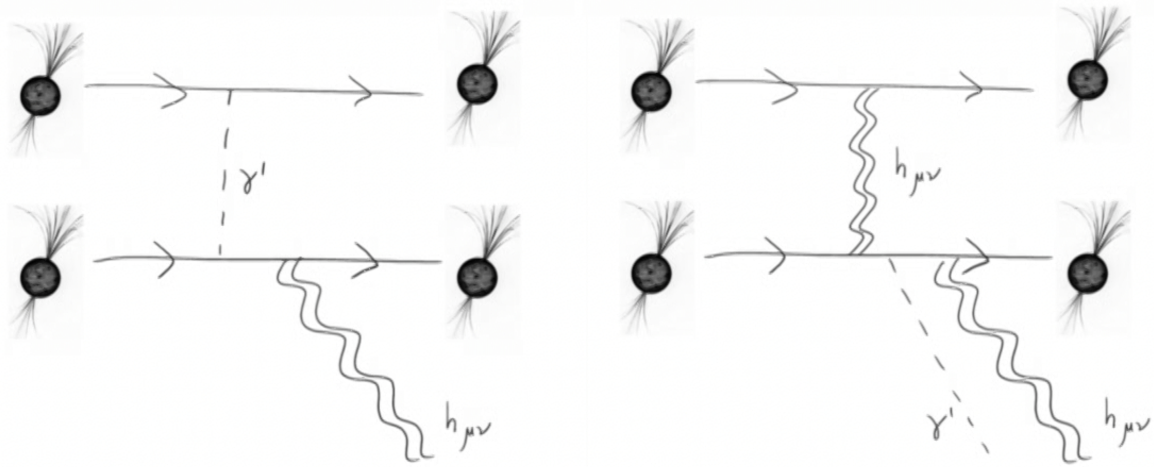

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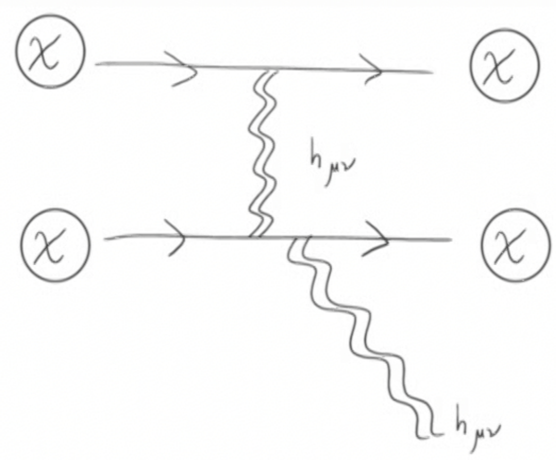
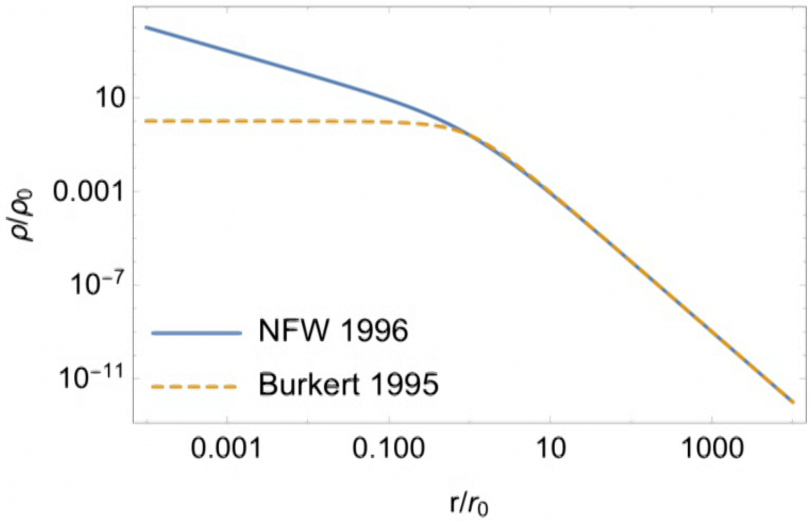


Galactic Scale Dark Matter Puzzles

- Core-cusp problem



$$\rho_{DM}(r) = \frac{\rho_0}{r/r_0(1+r/r_0)^2}$$

$$\rho_{DM}(r) = \frac{\rho_0 r^3}{(r+r_0)(r^2+r_0^2)}$$

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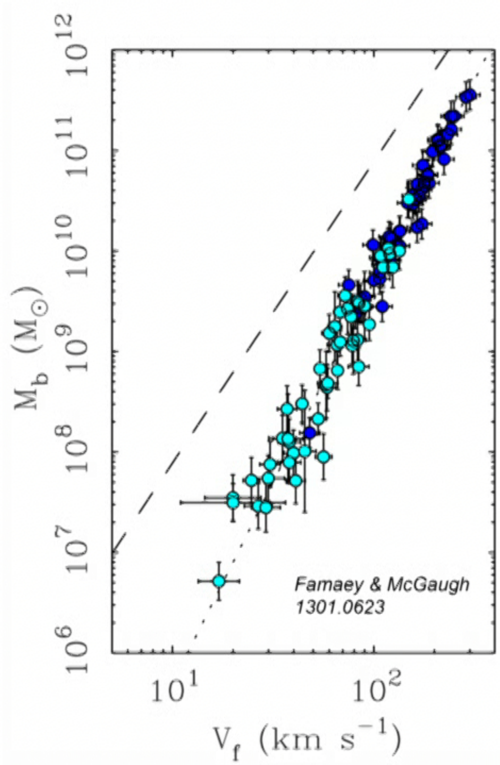
Galactic Scale Dark Matter Puzzles

- Core-cusp problem
- Baryonic Tully-Fisher relation



- CDM: $M_b \propto v_f^3$ (Mo, Mao, White 1998)
- Observation: $M_b \propto v_f^4$

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Beyond Thermal Dark Matter

- These evidence reflect our limited understanding of dark matter dynamics at galactic and sub-galactic scales.
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Beyond Thermal Dark Matter

- These evidence reflect our limited understanding of dark matter dynamics at galactic and sub-galactic scales.
- It is worth looking beyond thermally produced DM.
- A class of models with interesting (sub-)galactic phenomenology can be effectively described as

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \lambda\phi^4$$

- Light scalar BEC to address baryonic Tully-Fisher relation Bray & Goetz 2014 (1409.7347)
- Light scalar BEC to address core/cusp problem Harko 2011 (1105.2996)
- "Superfluid dark matter" Berezhiani & Khoury 2015

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$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m^2\phi^2 - \frac{\lambda_3}{3!}\frac{m^2}{f}\phi^3 - \frac{\lambda_4}{4!}\frac{m^2}{f^2}\phi^4$$

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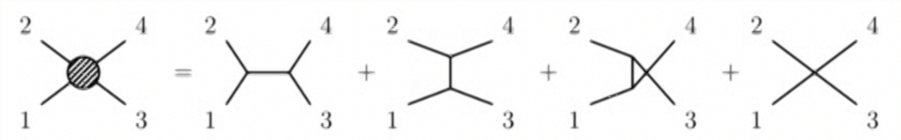

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$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m^2 \phi^2 - \frac{\lambda_{eff}}{4!} \frac{m^2}{f^2} \phi^4$$

- Bose-Einstein condensate to form clumps of macroscopic size $\sim \frac{M_{Pl}^2}{m}$

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- Bose-Einstein condensate to form clumps of macroscopic size $\sim \frac{M_{Pl}^2}{m}$

Macroscopic scale	Microscopic mechanism	Compactness $\frac{G_N M}{R}$
White dwarf	Pauli exclusion principle (degeneracy pressure of e^-)	$\sim \mathcal{O}(10^{-4})$
Neutron star	Pauli exclusion principle (degeneracy pressure n)	~ 0.2
Boson star	Heisenberg's uncertainty principle (kinetic energy of scalars)	?

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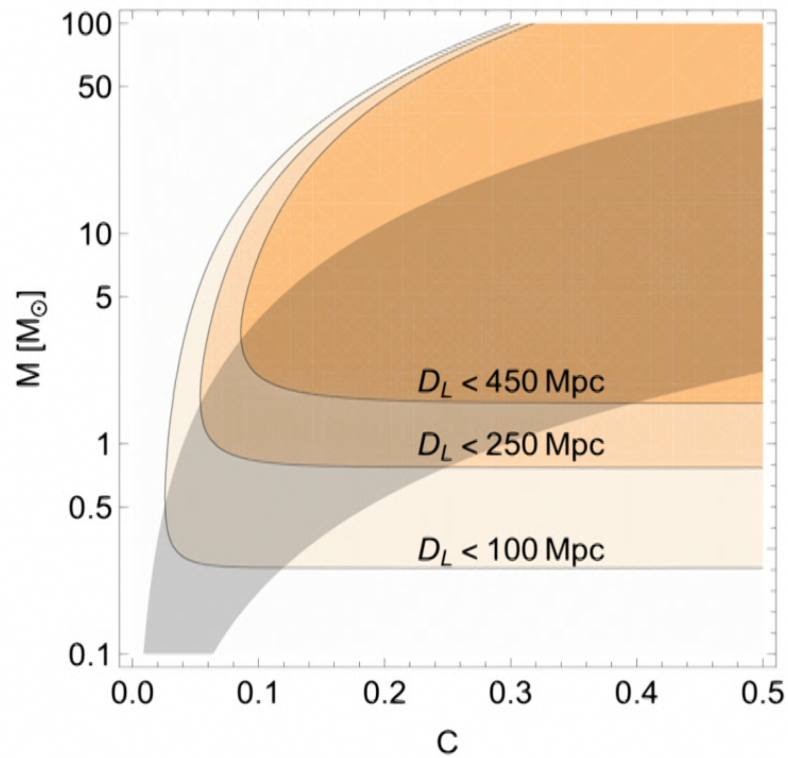
LIGO/Virgo's Resolution of Compact Binaries



Boson Star

- Stable solution:
  Colpi, Shapiro, Wasserman 1986
  Tkachev 1986
  Gleiser 1988
  Schunck and Mielke 2008
  Eby, Suranyi, Wijewardhana 2015
  Fan 2016
  Visinelli, Baum, Redondo, Freese, Wilczek 2017;
  Chavanis 2018
  Schiappacasse, Hertzberg 2018

- Gravitational wave:
  Croon, Gleiser, Mohapatra, CS 2018
  Helfer, Lim, Garcia, Amin 2018
  Widdicombe, Helfer, Marsh, Lim 2018
  Bezares, Palenzuela 2018;

- Reviews:
  Schunck and Mielke 2008
  Giudice, McCullough, Urbano 2016...

Boson Star – Non-relativistic Limit

- In the NR limit, the system can be described by Schrödinger-Newton equation

$$i\dot{\psi} = -\frac{1}{2m}\nabla^2\psi - G_N m^2\psi \int d^3\mathbf{x}' \frac{\psi^*(\mathbf{x}')\psi(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|},$$

$$H = \underbrace{H_{kin}}_{|\nabla\psi|^2 \propto N} + \underbrace{H_{grav}}_{|\psi(x)|^2|\psi(x')|^2 \propto -N^2}$$

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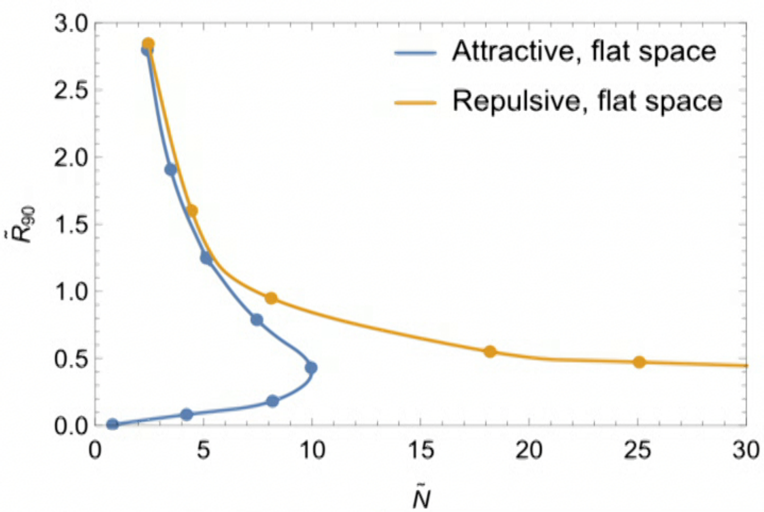
$$H = \underbrace{H_{kin}}_{N} + \underbrace{H_{grav}}_{-N^2} + \underbrace{H_{int}}_{\psi^4 \propto \pm N^2}$$



- Attractive interaction: wave function is collapsed by gravity + attractive interaction ∼ dilute boson star
- Repulsive interaction: wave function is stabilized by self-interaction ∼ dense boson star

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Boson Star – Numerical GR

$$\mathcal{L} = -\frac{1}{2} g^{\mu\nu} \nabla_\mu \phi^* \nabla_\nu \phi - \frac{1}{2} m^2 |\phi|^2 - \frac{\lambda}{4!} \left(\frac{m^2}{f^2} \right) |\phi|^4,$$

$$g_{\mu\nu} = \begin{bmatrix} -B(r) & & & \\ & A(r) & & \\ & & r^2 & \\ & & & r^2 \sin^2\theta \end{bmatrix} \qquad G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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$$g_{\mu\nu} = \begin{bmatrix} -B(r) & & & \\ & A(r) & & \\ & & r^2 & \\ & & & r^2 \sin^2\theta \end{bmatrix} \qquad G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\left(\frac{\tilde{\mu}^2}{B} + 1 \right) \tilde{\Phi}^2 + \frac{1}{A} \tilde{\Phi}'^2 + \frac{1}{2} \tilde{\lambda} \tilde{\Phi}^4 - \frac{A'}{\tilde{r} A^2} + \frac{1}{\tilde{r}^2 A} - \frac{1}{\tilde{r}^2} = 0,$$

$$\left(\frac{\tilde{\mu}^2}{B} - 1 \right) \tilde{\Phi}^2 + \frac{1}{A} \tilde{\Phi}'^2 - \frac{1}{2} \tilde{\lambda} \tilde{\Phi}^4 - \frac{B'}{\tilde{r} A B} - \frac{1}{\tilde{r}^2 A} + \frac{1}{\tilde{r}^2} = 0,$$

$$\frac{1}{A} \tilde{\Phi}'' + \left(\frac{\tilde{\mu}^2}{B} - 1 \right) \tilde{\Phi} + \tilde{\Phi}' \left(\frac{B'}{2AB} - \frac{A'}{2A^2} + \frac{2}{A \tilde{r}} \right) - \tilde{\lambda} \tilde{\Phi}^3 = 0,$$

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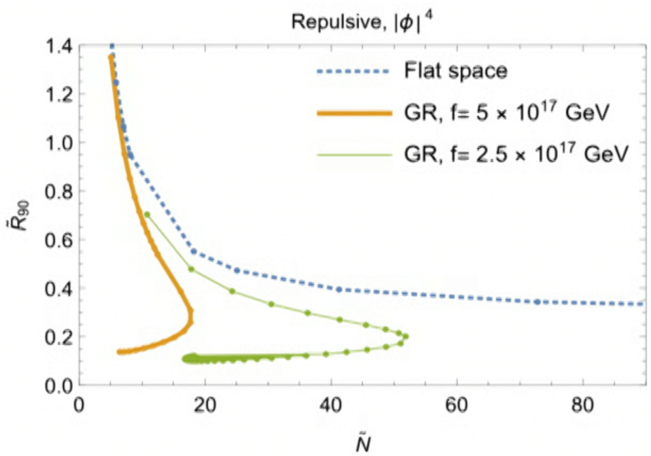
Boson Star – Numerical GR

$$\left(\frac{\tilde{\mu}^2}{B}+1\right)\tilde{\Phi}^2+\frac{1}{A}\tilde{\Phi}'^2+\frac{1}{2}\tilde{\lambda}\tilde{\Phi}^4-\frac{A'}{\tilde{r}A^2}+\frac{1}{\tilde{r}^2A}-\frac{1}{\tilde{r}^2}=0,$$

$$\left(\frac{\tilde{\mu}^2}{B}-1\right)\tilde{\Phi}^2+\frac{1}{A}\tilde{\Phi}'^2-\frac{1}{2}\tilde{\lambda}\tilde{\Phi}^4-\frac{B'}{\tilde{r}AB}-\frac{1}{\tilde{r}^2A}+\frac{1}{\tilde{r}^2}=0,$$

$$\frac{1}{A}\tilde{\Phi}''+\left(\frac{\tilde{\mu}^2}{B}-1\right)\tilde{\Phi}+\tilde{\Phi}'\left(\frac{B'}{2AB}-\frac{A'}{2A^2}+\frac{2}{A\tilde{r}}\right)-\tilde{\lambda}\tilde{\Phi}^3=0,$$



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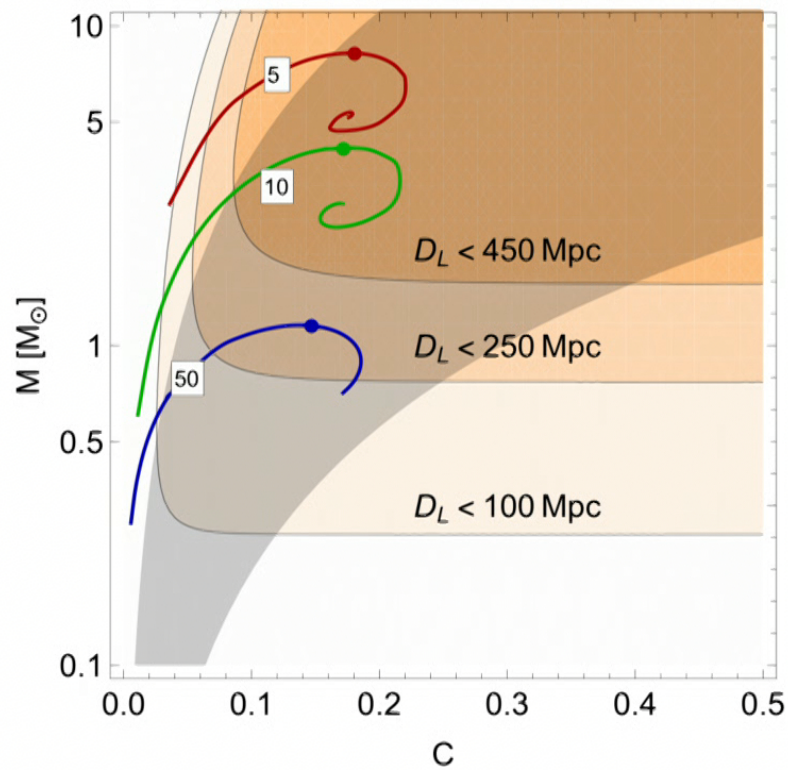
Boson Star – Numerical GR

In the context of binary mergers,



From top to bottom, $f = 5 \times 10^{16}$ GeV, $f = 10^{17}$ GeV, $f = 5 \times 10^{17}$ GeV.

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Boson Star – Numerical GR

$$\left(\frac{\tilde{\mu}^2}{B}+1\right)\tilde{\Phi}^2+\frac{1}{A}\tilde{\Phi}'^2+\frac{1}{2}\tilde{\lambda}\tilde{\Phi}^4-\frac{A'}{\tilde{r}A^2}+\frac{1}{\tilde{r}^2A}-\frac{1}{\tilde{r}^2}=0,$$

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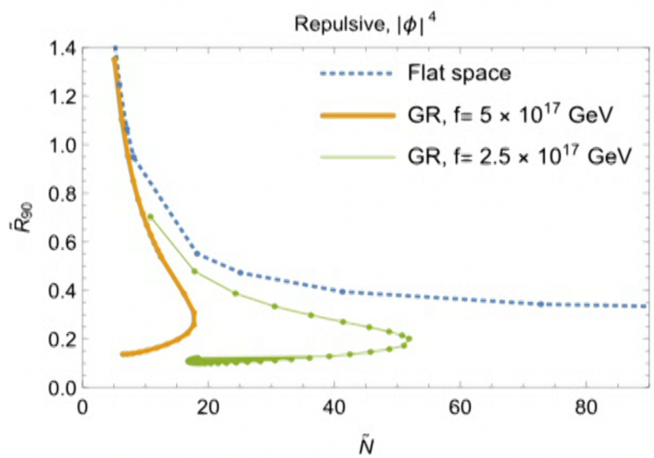

- Obs1: Turning point appears in Einstein-Klein-Gordon system even for repulsive self-interaction.
- Obs2: It is not captured in Schrödinger-Newton, or Klein-Gordon in flat spacetime.
- Obs3: Comparing the wave function in SN, KG, EKG shows small difference.
- Conjecture: It is caused by the spacetime curvature effect, instead of the momentum suppressed correction

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Boson Star – Numerical GR

$$\left(\frac{\tilde{\mu}^2}{B}+1\right)\tilde{\Phi}^2+\frac{1}{A}\tilde{\Phi}'^2+\frac{1}{2}\tilde{\lambda}\tilde{\Phi}^4-\frac{A'}{\tilde{r}A^2}+\frac{1}{\tilde{r}^2 A}-\frac{1}{\tilde{r}^2}=0,$$

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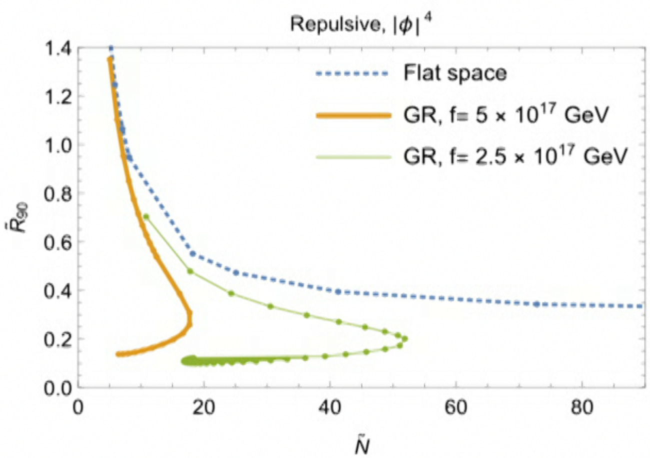

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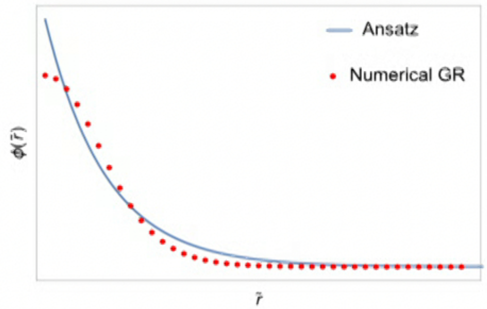
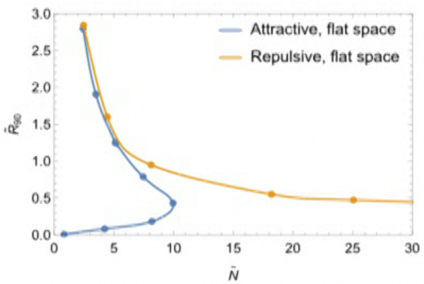
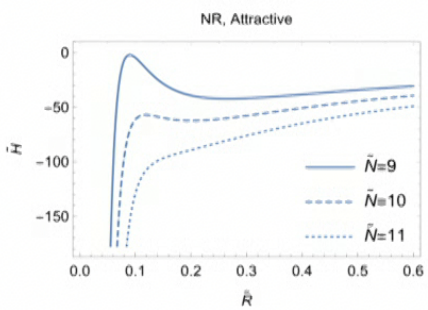
Boson Star – Understanding the Turning Point

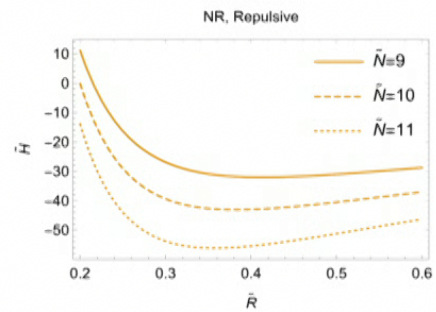
Exponential ansatz: $\psi(r) = \sqrt{\frac{N}{\pi R^3}} e^{-r/R}$ approximates the wave function well except for the center. Plug in the Schrödinger-Newton system.



$$H_{NR} = \frac{N}{2mR^2} \mp \frac{N^2}{128\pi f^2 R^3} - \frac{5 G_N m^2 N^2}{16R}$$







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Boson Star – Understanding the Turning Point

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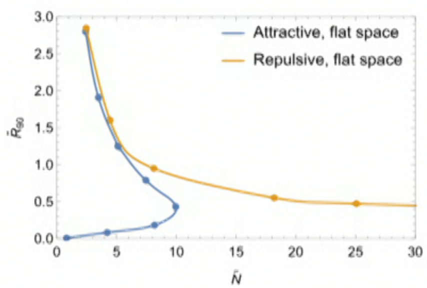

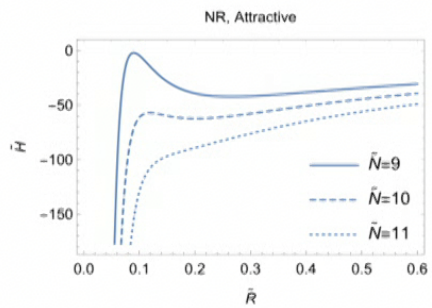

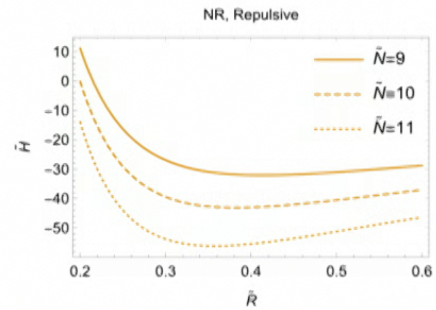

Lessons learned:

- Both gravity and self-int $\propto N^2$, gravity long range ($\sim 1/R$), self-int wins at small scale ($\sim 1/R^3$).
- To have a turning point, we need to flip the sign of H_{NR} at small R,
- which requires $-1/R^3$ or higher order.
- The contribution is curvature related.

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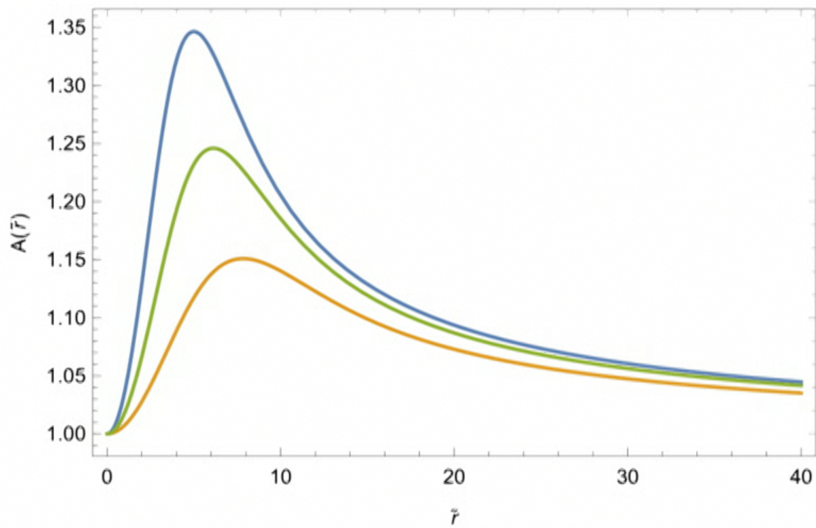
Boson Star – Understanding the Turning Point

- To have a turning point, we need to flip the sign of $H(R)$ at small R,
- which requires $-1/R^3$ or higher order.
- The contribution is curvature related.

$$T_0^0 = \frac{\mu^2}{2B}\Phi^2 + \frac{1}{2}m^2\Phi^2 + \frac{1}{2A}(\partial_r\Phi)^2 + \frac{\lambda}{4!}\left(\frac{m^2}{f^2}\right)\Phi^4.$$



Let's check whether the contribution of A is $\sim -1/R^3$.

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Boson Star – Understanding the Turning Point

Keep the exponential ansatz for the scalar wave function, but also account for the back reaction of the spacetime:

$$ds^2 = -(1 + 2V(r))dt^2 + (1 - 2V(r))dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2,$$

$$\Phi(r) = \sqrt{\frac{N}{\pi m R^3}}\, e^{-r/R}, \qquad V(r) = -\frac{G_N M(r)}{r}.$$

Integrate the energy density

$$H = \int_0^\infty dr\, 4\pi r^4\ T^0_0$$


the Turning Point

Boson Star – Understanding the Turning Point

Keep the exponential ansatz for the scalar wave function, but also account for the back reaction of the spacetime:

$$ds^2 = -(1 + 2V(r))dt^2 + (1 - 2V(r))dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2,$$

$$\Phi(r) = \sqrt{\frac{N}{\pi m R^3}}\, e^{-r/R}, \qquad V(r) = -\frac{G_N M(r)}{r}.$$

We recover all the NR limit

$$H = H_{mass} + H_{kin} + H_{grav} + H_{int} + \Delta H$$

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Boson Star – Understanding the Turning Point

Keep the exponential ansatz for the scalar wave function, but also account for the back reaction of the spacetime:

$$ds^2 = -(1+2V(r))dt^2 + (1-2V(r))dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2,$$

$$\Phi(r) = \sqrt{\frac{N}{\pi m R^3}}\, e^{-r/R}, \qquad V(r) = -\frac{G_N M(r)}{r}.$$

We recover all the NR limit , with an extra term:

$$H = \underbrace{mN}_{H_{mass}} + \underbrace{\frac{N}{2mR^2}}_{H_{kin}} \underbrace{- \frac{5G_N m^2 N^2}{16R}}_{H_{grav}} + \underbrace{\left(\frac{1}{128\pi f^2}\right)\frac{N^2}{R^3}}_{H_{int}} \underbrace{- \left(\frac{5G_N}{16}\right)\frac{N^2}{R^3}}_{H_{curv}}$$

In the limit of small self-interaction, we recover $C_{max} \sim 0.18$.

Boson Star – Scalar Dark Matter

What we have learned:

- Boson star from Bose-Einstein condensate can be compact if the self-interaction is repulsive;
- The limit of it's maximal mass comes from the curvature effect. It "damps" the kinetic energy.
- On small scale, it is similar to the self-interaction N^2/R^3, more effective than Newtonian gravity N^2/R.
- This effect gets important when the boson star is compact $\sim$ relevant for LIGO/Virgo.

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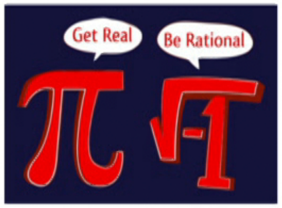
Boson Star – toward more realistic models

Portal	Particles	Operators(s)
"Vector"	Dark photons	$\epsilon B_{\mu\nu} F'^{\mu\nu}, \;\; F'_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{\phi}{f} F\tilde{F}, \frac{\phi}{f} G\tilde{G}, \frac{\partial_\mu \phi}{f} \overline{\psi}\gamma^\mu\gamma^5\psi, \;\; V(\phi/f)$
"Higgs"	Dark scalars	$(\mu\phi + \lambda_2\phi^2) H^\dagger H, \; \lambda\phi^4$
"Neutrino"	Sterile neutrinos	$y_N \overline{L} H N, \; y_{12} \overline{N}_2 H N_1, \;\; g' \overline{N} \gamma^\mu N A'_\mu$

- Light scalars are very dangerous in EFT...
- ...unless it is a pseudo Nambu-Goldstone boson with an approximate shift symmetry



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Boson Star – toward more realistic models

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) \underbrace{-\frac{1}{2}m^2\phi^2 - \frac{\lambda_{eff}}{4!}\frac{m^2}{f^2}\phi^4 + \cdots}_{V(\phi)},$$

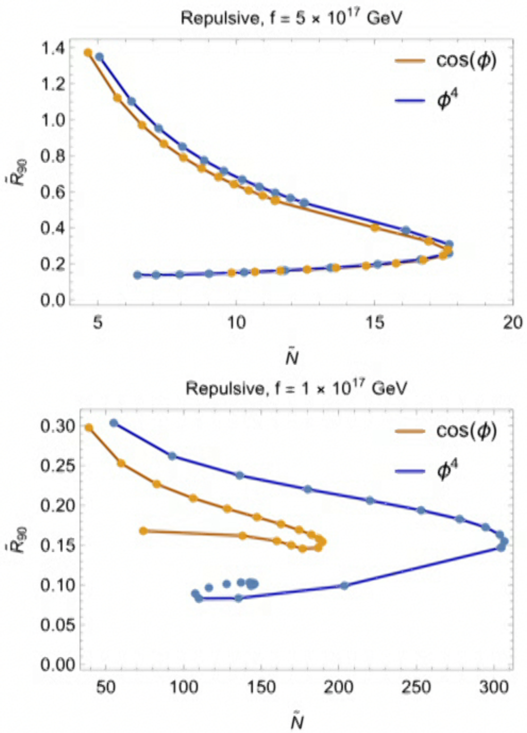
- It is known that QCD axions are attractive. That leads to small compactness, even if it is stable. $\Lambda(1-\cos(\phi/f)) = m^2\phi^2 - \lambda\phi^4 + \ldots$. Also hard to have galactic scale correlation length. (Sikivie et al.)
- $5D$ gauged U(1) with 5th dimension compactified on a circle. (Fan 2016)

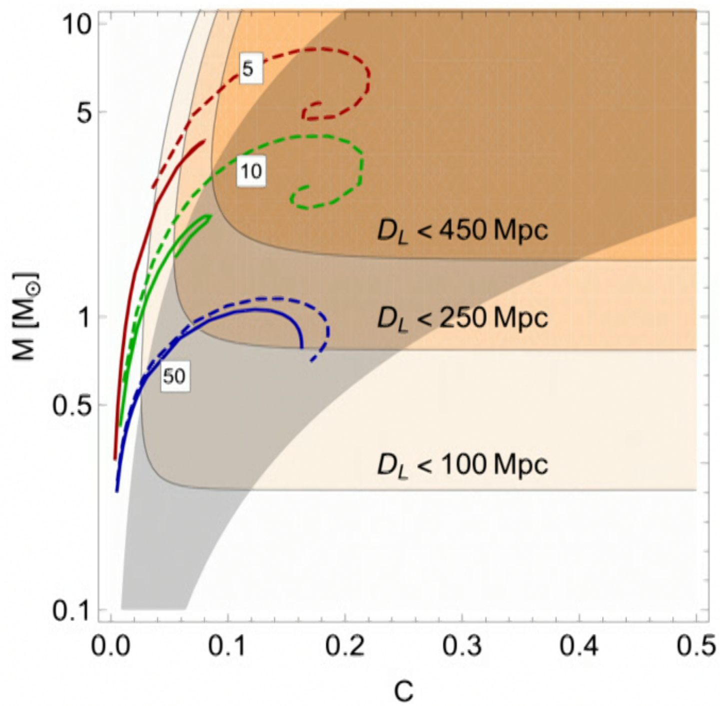
$$V(\phi) \supset -\Lambda^4\left(\sum_{i=1}^{n_B}\cos\left(\frac{q_{Bi}\phi}{f}\right) - \sum_{i=1}^{n_F}\cos\left(\frac{q_{Fi}\phi}{f}\right)\right),$$

$$m^2 \propto \sum q_{Bi}^2 - \sum q_{Fi}^2, \qquad \lambda_4 \propto \sum q_{Bi}^4 - \sum q_{Fi}^4, \qquad \lambda_6 \propto \sum q_{Bi}^6 - \sum q_{Fi}^6, \ldots$$

Boson Star – toward more realistic models

The subleading terms can be significant:





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Summary

We can infer the structures of dark sector without relying on the coupling with the Standard Model.

- Gravitational wave opens a new window to dark sector, because of
  - universality of gravity
  - relevant scales for light particles
  - gravitational 'charge': monopole (no shielding), quadrupole ($f \sim t^{-3/8}$), etc.
- In light of light dark sector
  - fermionic dark matter + dark photon in neutron stars $\Rightarrow$ modification of the merger process.
  - scalar dark matter condensate to boson stars $\Rightarrow$ the maximal mass limited by the spacetime metric
  - axion like particles condensate to compact boson stars $\Rightarrow$ nonlinearity of the full potential changes mass profile
- Outlook
  - mapping LIGO/Virgo sensitivity band to the fundamental parameter space;
  - extended dark sector, e.g. non-minimal coupling to curvature, shielded dark charge, etc.
  - coherent dark matter wave, time oscillation signal.