Solar mass black holes from neutron stars and bosonic dark matter

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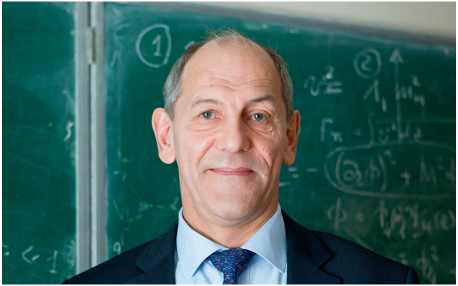
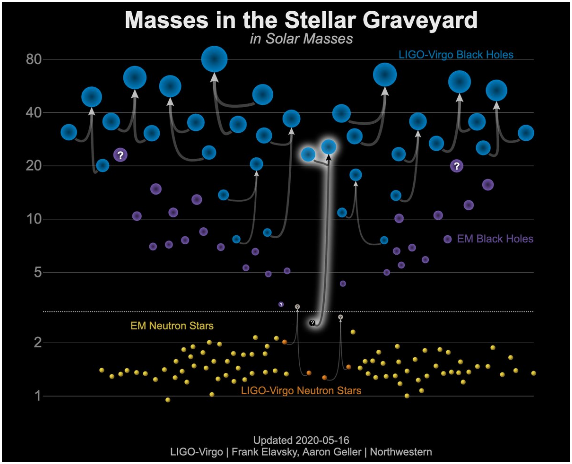


Rubakov Conference '23

R. Garani, DL, P. Tinyakov, arXiv: 2112.09716 [PRD **105** (2022) 063019]

What sort of objects do LIGO & VIRGO register?

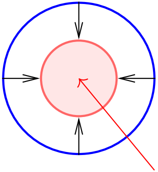


Common knowledge:

- BH: $M_{BH} \gtrsim 2.5\, M_\odot$
- NS: $M_{NS} \lesssim 2.5\, M_\odot$

Rhoades, Ruffini '74

because Supernovae:



neutron core

Fermi pressure!

Can we predict black holes with $M_{BH} \approx M_\odot$?

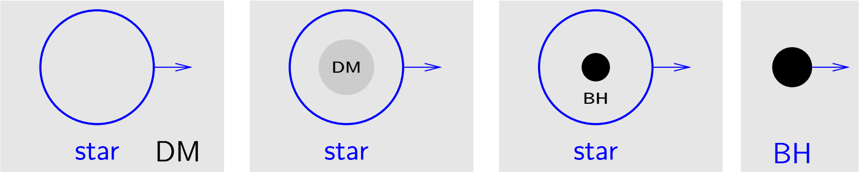
Solar-mass black holes?

- **Can be primordial**
- **Star + primordial BH**

} — modification of cosmology
⇒ constraints, do not consider!

e.g., Goldman, Nussinov '89

- This talk: **form by dark matter inside neutron stars!**



Kouvaris, Tinyakov '11, etc

Only a small fraction of dark matter is captured!

Is it enough for collapse?

Spoiler

- **This mechanism does not work in generic DM models**
  $\Rightarrow$ no generic constraints

- **Neutron stars transmute in special models**
  $\Rightarrow$ we should search for $M_{BH} \approx M_{\odot}$!

Dark matter capture

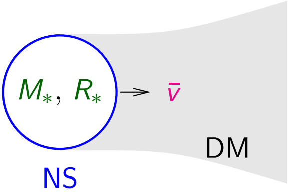
- Neutron stars parameters are known:

$$M_* \sim 1.5\, M_\odot, \quad R_* \sim 10\,\text{km}, \quad T_* \sim 10^5\,\text{K}$$

- They move through dark matter

$$m \sim \text{GeV} \div \text{TeV}, \quad \rho_{DM} \sim 100\, \frac{\text{GeV}}{\text{cm}^3}, \quad \bar{v} \sim 7\, \frac{\text{km}}{\text{s}} \qquad \left(\begin{array}{c}\text{dwarf}\\ \text{galaxy}\end{array}\right)$$

- DM binds to the star after collisions with neutrons *Press, Spergel '85*



$$M_{DM,\,tot} \sim \underbrace{G\, \frac{\rho_{DM}}{\bar{v}}\, M_* R_* t}_{\text{total mass}} \times \underbrace{(\sigma/\sigma_{cr})}_{\text{probability } f}$$

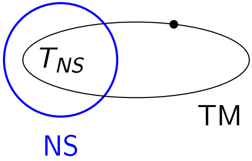
$$\boxed{f \sim 1} \quad \Leftrightarrow \quad \sigma_{cr} \sim 10^{-45}\,\text{см}^2 \lesssim \text{exp. bounds!}$$

- $t \sim 10^{10}$ yrs $\Rightarrow$ $\boxed{M_{DM,\,tot} = 10^{-10}\, M_\odot \times f \quad \text{in dwarf galaxy}}$

Is it enough to form BH?

Thermalization

Gravitationally bound DM: *e.g. Garani, Gupta, Raj '21*



⇒ repeating collisions with neutrons

⇒ **thermalization!** (if $\sigma \gtrsim 10^{-7}\sigma_{cr}$)

⇒ Low temperature: $\omega_{DM} \sim T_{NS} \sim 10^5$ K

⇒ Thermal orbit size: $r_{th} \sim \sqrt{\frac{T_{DM}}{G\rho_* m}} \sim \underbrace{\textbf{20 cm}}_{\text{dense cloud!}} \left(\frac{m}{100\,\text{GeV}}\right)^{-1/2}$

⇒ **Bose-Einstein condensation**!

- radius is fixed, M_{DM} grows
- if $M_{DM} \gtrsim 10^{-19}\, M_\odot$
- for non-annihilating (asymmetric) DM

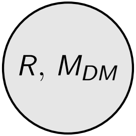
BEC $\equiv$ **classical soliton** $\phi(x)$**!**

⇒ **or degenerate fermionic DM** *Kouvaris, Tinyakov, Tytgat '18*

And now, the collapse begins?

Gravitational collapse

- **Ignore self-interactions**
- **Free bosons:** $\underbrace{mv^2 \sim 1/(mR^2)}_{\text{quantum pressure}} \sim \underbrace{G m M_{DM}/R}_{\text{self-gravity}}$



BEC

Black hole: $R \sim (G M_{DM} m^2)^{-1} < 2 G M_{DM}$

$$\Rightarrow \boxed{M_{DM} > \frac{M_{pl}^2}{m} \sim 10^{-21} M_\odot \, \frac{100\text{ GeV}}{m}} \quad \begin{pmatrix}\text{free}\\ \text{bosons}\end{pmatrix}$$

BEC immediately collapses!

- **Free fermions** — Pauli blocking:

$$\Rightarrow M_{DM} > \frac{M_{pl}^3}{m^2} \sim 10^{-4} M_\odot \left(\frac{100\text{ GeV}}{m}\right)^2 \quad \begin{pmatrix}\text{free}\\ \text{fermions}\end{pmatrix}$$

Not enough particles!

So, the mechanism works for bosonic DM, or not?

We forgot about interactions!

Contradiction:

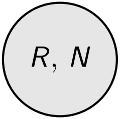
- Even tiny self-interaction prevents collapse
- Interaction $\leftrightarrow$ self-interaction is needed for capture

Simplest DM model — complex field $\phi(x)$: $\boxed{L = |\partial_\mu \phi|^2 - V(|\phi|)}$

U(1) symmetry $\Rightarrow$ particle number

$$N = 2\mathrm{Im}\int d^3\boldsymbol{x}\,\phi\,\partial_0\phi^* \sim \omega\phi_0^2 R^3 \lesssim M_{DM,\,tot}/m$$

(captured)



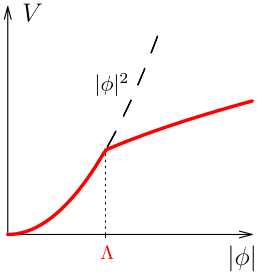
soliton

Stationary solution: Q–ball or Bose star

$$\phi = f(r/\underbrace{R}_{\text{size}})\,\underbrace{\mathrm{e}^{-i\omega t}}_{\text{energy per particle}}$$

$\boxed{\text{Self-interactions — inside } V(\phi)}$

(a) Attraction (Q–ball)



- **Suppose** $\boxed{V = m^2\,|\phi|^\alpha\,\Lambda^{2-\alpha}}$ at $|\phi| > \Lambda$

  $\alpha < 2$

- **Important:** $\Lambda \ll M_{pl}$

  $\rightarrow$ Planckian physics is not important

  $\rightarrow$ gravity is the weakest force!

- **Equations:** self-attraction = kinetic pressure

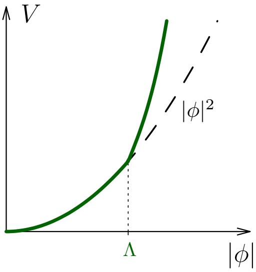
$$\Rightarrow \begin{cases} N \sim (R\Lambda)^2 (Rm)^{\frac{2}{4-\alpha}} & \text{— more compact} \\ \text{BUT: } \omega \sim R^{-1} \ll m & \text{— smaller!} \end{cases}$$

- **Collapse:** $R \sim 2G\omega N \quad \Rightarrow \quad \boxed{mN \sim \frac{M_{pl}^2}{m}\left(\frac{M_{pl}}{\Lambda}\right)^{2-\alpha} \gg \frac{M_{pl}^2}{m}}$

  Harder to form a black hole!

- **Reason:** $\omega \ll m$ — particles inside the Q–ball are almost massless!

(b) Repulsion (Bose star)



- **Let** $\boxed{V = m^2|\phi|^2 + m^2|\phi|^\alpha \Lambda^{2-\alpha}}$ $\alpha > 2$
- **Still,** $\Lambda \ll M_{pl}$!
- **Equations**: self-repulsion=grav. attraction

  Solution: $\omega \approx m$, $N \sim \frac{M_{pl}^3}{m^2\Lambda}\left(\frac{Rm\Lambda}{M_{pl}^2}\right)^{\frac{3\alpha-8}{\alpha-1}}$
- **Black hole:** $R \sim 2GmN$

$$\Rightarrow \boxed{mN \sim \frac{M_{pl}^3}{m^2} \cdot \frac{m}{\Lambda}}$$

almost fermions $\Rightarrow$ again bad for collapse!

- **Take** $\boxed{V_{int} = \lambda_4|\phi|^4/4}$ require $mN < M_{DM,\,tot}$

$$\lambda_4 = \left(\frac{2m}{\Lambda}\right)^2 \lesssim \lambda_{4,\,max} = 10^{-12}\, f^2 \left(\frac{m}{100\ \text{ГэВ}}\right)^4$$ — **super small!**

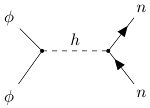
Contradiction to capture: switching off self-interaction?

Add interaction with Higgs: *see also Bell et al. '87*

$$V = \lambda_H \underbrace{\left(H^\dagger H - \frac{v^2}{2} - \frac{y|\phi|^2}{2\lambda_H} \right)^2}_{\text{valley: bracket} = 0} + m^2|\phi|^2 = y|\phi|^2 H^\dagger H + \ldots$$

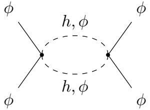
Scattering on neutrons:

$$\sigma = \left| \vphantom{\frac{a}{b}} \right. \text{[diagram]} \left. \vphantom{\frac{a}{b}} \right|^2 = \frac{y^2 m_n^4}{81\pi m_H^4 m^2}\,, \qquad f \equiv \frac{\sigma}{\sigma_{cr}}$$



But the same interaction ⇒ **effective potential**

$$V_{\text{eff}} = \text{[diagram]} = |\phi|^4 \underbrace{\frac{y^2}{2\pi^2} \ln \frac{|\phi|}{\Lambda_{ren}}}_{\lambda_{eff}} \leftarrow$$



cannot be canceled by fine-tuning!

Require $\lambda_{eff} < \lambda_{4,\,max} \Rightarrow$ $y \gtrsim 400$ **and** $m \gtrsim PeV$

The mechanism does not work!

Thus, neutron stars are safe

... unless the DM is very special

1. The potential is almost quadratic, $V \approx m^2|\phi|^2$
2. Both self-attraction and self-repulsion are suppressed
3. Nevertheless, DM interacts with neutrons
4. Loop corrections do not destroy these properties

These requirements contradict to each other!

Model with bended valley

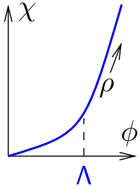
- **Take two fields:** $\begin{cases} \phi \text{ — DM, charge } 1 \\ \chi \text{ — heavy, charge } 2 \end{cases}$

$$V = \lambda|\phi^2 - \Lambda\chi|^2 + m^2|\phi|^2 + \lambda'|\phi|^4/4$$

large term correction

- **The potential is renormalizable**
- **Valley:** $\boxed{\phi^2 = \Lambda\chi}$ ← soliton field is pinned to it
- **Soliton:** $\phi = \phi(\boldsymbol{x})\, \mathrm{e}^{-i\omega t}\ , \quad \chi = \phi^2/\Lambda$
- **Canonically normalized field along valley:**

$$(\partial_\mu\rho)^2 = |\partial_\mu\phi|^2 + |\partial_\mu\chi|^2$$



or $\rho(\phi) = \int\limits_0^\phi d\phi\sqrt{1 + (2\phi/\Lambda)^2} \approx \begin{cases} \phi\ , & \phi < \Lambda \\ \phi^2/\Lambda \equiv \chi\ , & \phi > \Lambda \end{cases}$

Model with bended valley

- **Potential along the valley:** $V(\rho) = V\Big|_{\chi=\phi^2/\Lambda}$
- **Weak fields:** $\boxed{\rho \approx \phi \ll \Lambda}$

$$V(\rho) = m^2\rho^2 + \lambda'\rho^4/4 + \dots$$

Interaction is not dominant:

$$\lambda'/4 = \beta\,(m/\Lambda)^2, \qquad \beta \lesssim 1$$

- **Strong fields**: $\boxed{\Lambda \ll \rho \approx \chi}$

$$V(\rho) = m^2|\phi|^2 + \lambda'|\phi|^4/4 \approx m_\rho^2\rho^2 + \dots\,, \qquad m_\rho = m\sqrt{\beta}$$

free field!

Hence, soliton collapse at

$$\boxed{mN \sim \frac{M_{pl}^2}{m}\cdot\frac{2}{\beta}}$$ ← **almost as for the free particles!**

Quantum corrections

- **The same interaction with Higgs:**

$$V = \lambda_H \left(H^\dagger H - \frac{v^2}{2} - \frac{y|\phi|^2}{2\lambda_H} \right)^2 \Rightarrow \text{the same } \sigma_{DM}!$$

- **Quantum corrections:** $V_{\text{eff}} = \lambda_{eff} |\phi|^4 / 4$

$$\lambda_{\text{eff}} = \frac{1}{\pi^2} \left(4\lambda^2 + 2\lambda\lambda' + \frac{5}{16}\lambda'^2 + \frac{y^2\lambda}{\lambda_H} + \frac{y^2}{2} + \frac{y^3}{2\lambda_H} + \frac{3y^2\lambda'}{8\lambda_H} + \frac{y^4}{8\lambda_H^2} \right) \ln \frac{|\phi|}{\Lambda_{ren}}$$

Harmless at strong fields — just a shift of m_ρ^2 !

- **Surprize:** vertices $|\chi|^4$ and $|\phi\chi|^2$ are not generated!

$V = V(\Lambda\chi) \Rightarrow |\Lambda\chi|^4$ and $|\Lambda\phi\chi|^2$ can be generated nonrenormalizable!

- **Require** $mN < M_{DM,\, tot}$:

$$\Rightarrow y > 10^{-7} \left(\frac{m}{100 \text{ ГэВ}} \right)^{1/2} \beta^{-1/2} \text{ — easy to satisfy!}$$

- **All other bounds are satisfied at** $\lambda' \sim \lambda^2 \sim y^2/\lambda_H \lesssim m^2/\Lambda^2$

Summary

- Self-interactions — both repulsion, and attraction — parametrically increase DM amount needed for collapse.
- Optimal models include long valleys with $V \sim m^2\rho^2/2$ up to $\rho \lesssim M_{pl}$.
- Bending the valley, we:
  1. make the model almost optimal;
  2. preserve interactions needed for capture
- **Neutron stars can transmute into black holes with** $M_{BH} \approx M_{\odot}$!

СПАСИБО ЗА ВНИМАНИЕ!

Acknowledgements: Russian Science Fundation RSF grant 22-12-00215