Solar mass black holes
from neutron stars and bosonic dark matter

Raghuveer Garani, Dmitry Levkov, Peter Tinyakov

INR RAS & ITMP MSU

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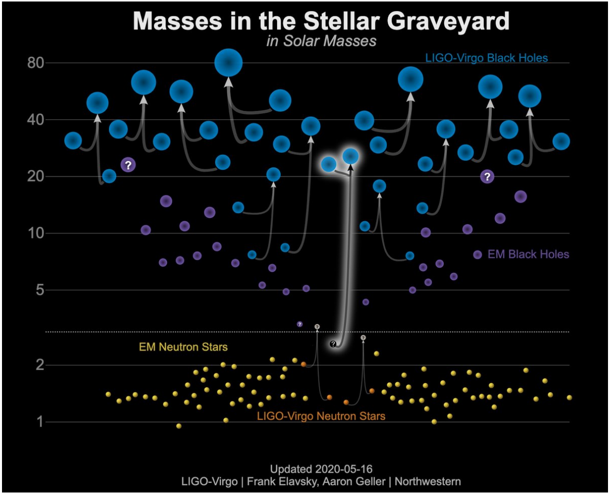
The question

What sort of objects do LIGO & VIRGO register?



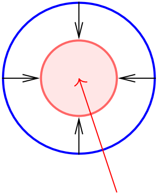
see K.A. Postnov's talk

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

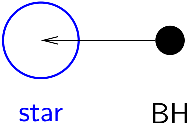
Fermi pressure!

Do black holes with $M_{BH} \approx M_\odot$ exist?

Solar-mass black holes?

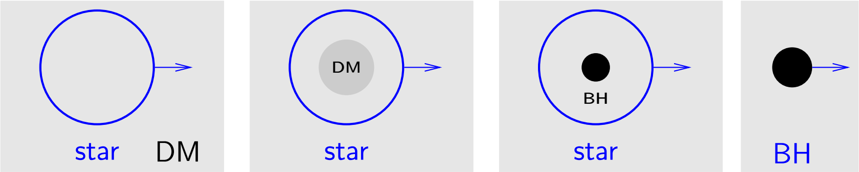
- **Can be primordial**
- **Star + primordial BH**

} — modification of cosmology! (constrains, do not consider)



Goldman, Nussinov '89

- **Can be formed by dark matter inside 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 constraints from existence of neutron stars

- Neutron stars transmute in special models

  $\Rightarrow$ we should search for $M_{BH} \approx M_{\odot}$!

Dark matter capture

- Consider neutron stars — the best DM accumulators!

$M_* \sim 1.5\, M_\odot$ $\quad R_* \sim 10$ км $\quad T_* \sim 10^5$ K

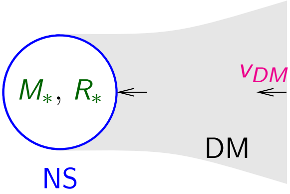
- They move in ambient dark matter

$m \sim$ GeV $\div$ TeV ?

in dwarf galaxy: $\rho_{DM} \sim 100\,\text{GeV}/\text{cm}^3$ $\quad v_{DM} \sim 7\text{km}/\text{s}$

- DM particles bind to the star after collisions with neutrons:

Press, Spergel '85



$$\frac{dM_{DM}}{dt} \sim \underbrace{G\,\frac{\rho_{DM}}{v_{DM}}\,M_* R_*}_{\text{total mass is known}} \times \underbrace{\frac{\sigma_{DM}}{\sigma_{cr}}}_{\text{probability } \boxed{f}}$$

$\sigma_{cr} \sim m_n R_*^2/M_* \sim 10^{-45}$ см^2 $\lesssim$ exp. bounds!

- For $t \sim 10^{10}$ yrs: $M_{DM,\,tot} = \begin{cases} 10^{-14}\, M_\odot \cdot f & \text{in Milky Way} \\ 10^{-10}\, M_\odot \cdot f & \text{in dwarf galaxy} \end{cases}$

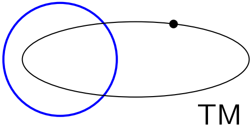
Enough for collapse?

Thermalization

e.g. Garani, Gupta, Raj '21

Gravitationally bound DM $\Rightarrow$ repeating collisions

- $\sigma_{DM} \sim \sigma_{cr}$ — at every pass
- $\sigma_{DM} \gtrsim 10^{-7}\sigma_{cr}$ — in $t \lesssim 10^{10}$ yrs



$\Rightarrow$ **thermalization with neutrons!**

After thermalization: $T_{DM} \sim 10^5$ K

$\rightarrow$ Thermal orbit size [$mU_{NS}(r_{th}) \sim T_{DM}$]

$$r_{th} \sim \sqrt{\frac{T_{DM}}{G\rho_* m}} \sim 20\ \text{cm}\ \left(\frac{m}{100\,\text{GeV}}\right)^{-1/2}$$

thermal sphere!

$\rightarrow$ Consider non-annihilating (asymmetric) DM

$\Rightarrow$ **Dense DM cloud in the center!**

Bose-Einstein condensation inside thermal sphere

Radius is fixed, number of DM particles grows

- Large occulation number $N/(mv_{DM}r_{th})^3 > 1$ if

$$M_{DM} > M_{BEC} = m\,(T_{DM}M_{pl})^3 \rho_*^{-3/2} \sim 10^{-19}\, M_\odot\, \frac{m}{100\,\text{ГэВ}}$$

$\Rightarrow$ Bosonic DM condenses into **classical soliton $\phi(x)$** $\equiv$ **BEC!**

BEC: DM occupies the lowest level

$$\boxed{U_{DM} > U_{NS}} \Rightarrow \text{self-gravitates!}$$

$\Rightarrow$ Fermionic DM is **degenerate**!

Now, supercompact BEC collapses?!

Gravitational collapse

- **Ignore self-interaction**
- **Free bosons:**

$$\underbrace{mv^2 \sim 1/(mR^2)}_{\text{incertainty}} \sim \underbrace{GmM_{DM}/R}_{\text{self-gravity}}$$

BEC

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

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

BEC immediately collapses!

- **Free fermions** — Pauli blocking:

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

Not enough particles!

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

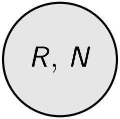
Simplest DM model — complex field $\phi(x)$:

$$L = |\partial_\mu \phi|^2 - V(|\phi|)$$

Conserved U(1) charge $\leftrightarrow$ 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

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

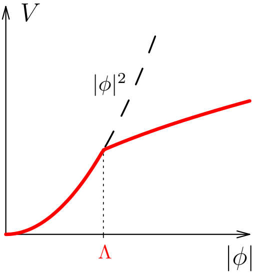
Self-interactions are hidden in $V(\phi)$!

(a) Attraction (Q–ball)

- **Suppose at $|\phi| > \Lambda$**

  $V = m^2 \, |\phi|^\alpha \, \Lambda^{2-\alpha}, \quad \alpha < 2$

- **Important:** $\Lambda \ll M_{pl}$
  - $\to$ Planckian physics is not important
  - $\to$ 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 black hole!

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

(b) Repulsion (Bose star)

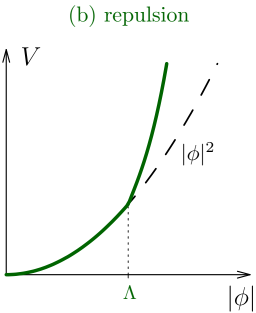
- **Let** $V = m^2|\phi|^2 + m^2|\phi|^\alpha \Lambda^{2-\alpha}, \quad \alpha > 2$
- **Still,** $\Lambda \ll M_{pl}$!
- **Equations**: self-repulsion=grav. attraction

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

- **Black hole:** $R \sim 2GmN$

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

almost fermions $\Rightarrow$ again bad for collapse!



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

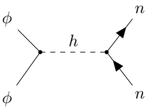
$$\lambda_4 = \left(\frac{2m}{\Lambda}\right)^2 \lesssim \lambda_{4,\,max} = 10^{-12} f^2 \left(\frac{m}{100\ \text{ГэВ}}\right)^4$$ — **super small!**

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

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

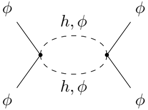
Scattering on neutrons:

$$\sigma_{DM} = \left| \; \text{(diagram)} \; \right|^2 = \frac{y^2 m_n^4}{81\pi m_H^4 m^2}, \qquad f \equiv \frac{\sigma_{DM}}{\sigma_{cr}}$$



But the same interaction generates **effective potential**:

$$V_{\text{eff}} = \text{(diagram)} = |\phi|^4 \underbrace{\frac{y^2}{2\pi^2} \ln \frac{|\phi|}{\Lambda_{ren}}}_{\lambda_{eff}} \leftarrow \boxed{\text{cannot be canceled by fine-tuning!}}$$



Require $\lambda_{eff} < \lambda_{4,\, max} \Rightarrow \boxed{y \gtrsim 400 \text{ и } m \gtrsim PeV}$

The mechanism does not work!

Thus, neutron stars are safe

... unless the DM model 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

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

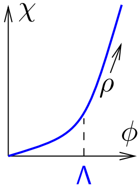
$$V = \lambda|\phi^2 - \Lambda\chi|^2 + m^2|\phi|^2 + \lambda'|\phi|^4/4$$

large term   correction

- **The potential is renormalizable**
- **But special: no terms $|\chi|^4$ and $|\phi\chi|^2$**

- **Valley:** $\boxed{\phi^2 = \Lambda\chi}$ $\leftarrow$ 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

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

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 — small shift of m_ρ^2 !

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

  since $V = V(\Lambda\chi)$, only $|\Lambda\chi|^4$ 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!

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