Solar Mass Black Holes and Dark Matter

P. Tinyakov (ULB)

June 3, 2019, ICRR
Outline

1 Motivation

2 Primordial black holes

3 BH from compact stars and DM
   Bosonic DM
   Fermionic DM

4 Summary
MOTIVATION

• GW detectors progress very fast; the number of detected merger events grows quickly.
• These observations will soon map out the mass spectrum of stellar-size BH with good accuracy, including the low-mass region $\sim M_\odot$. 
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LIGO & VIRGO, arXiv:1811.12907
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**MOTIVATION**

**BLACK HOLES and NEUTRON STARS**

LIGO-Virgo Black Holes

EM Black Holes

**EM Neutron Stars**

**no astrophysical BH here**
• The low mass ($\sim M_\odot$) region is of a particular interest, because stellar evolution predicts NO black holes with masses below or about $2 M_\odot$.
  $\implies$ Searching for such light BH is a zero-background search for new physics.

• What could be the origin of light BH with masses $\lesssim M_\odot$?
  (I) Such BH may be primordial
  (II) They can also be formed from compact stars – neutron stars (NS) and white dwarfs – with the help of DM
  [the main focus of this talk]
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  [the main focus of this talk]
PRIMORDIAL BLACK HOLES
PRIMORDIAL BLACK HOLES

Hawking, MNRAS 152 (1971) 75

- BH may be produced in the early Universe in collapse of large matter overdensities.
- For causality, their mass is limited by the total mass within horizon at the time of production:

\[ M_{\text{BH}} \lesssim M_H \sim 0.02 \frac{M_{\text{Pl}}^3}{T^2} \]

<table>
<thead>
<tr>
<th>( M_H )</th>
<th>3 ( \times 10^4 ) ( M_\odot )</th>
<th>3 ( M_\odot )</th>
<th>3 ( \times 10^{-6} ) ( M_\odot )</th>
<th>3 ( \times 10^{-18} ) ( M_\odot )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_\odot )</td>
<td>( 6 \times 10^{37} ) g</td>
<td>( 6 \times 10^{33} ) g</td>
<td>( 6 \times 10^{27} ) g</td>
<td>( 6 \times 10^{15} ) g</td>
</tr>
<tr>
<td>( 100 ) MeV</td>
<td>100 GeV</td>
<td>( 10^8 ) GeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- BH relative contribution into energy density grows linearly with the scale factor \( a \rightarrow \) easy to produce enough or even overproduce.
Plenty of production mechanisms:

- Primordial density perturbations
  

- Soft equation of state at some period of evolution
  

- Bubble collisions during phase transitions
  
  Hall, Hsu, PRL 64 (1990) 2848
  Jedamzik, PRD 55 (1997) 5871
  Jedamzik, Niemeyer, PRD 59 (1999) 124014

- Collapse of cosmic strings
  
  Polnarev, Zembowicz, PRD 61 (1991) 1106

- Collapse of closed domain walls
  
  Rubin, Khlopov, Sakharov, Grav.Cosmol. 6 (2001)
  Dokuchaev, Eroshenko, Rubin, Grav.Cosmol. 11 (2005) 99

- At reheating

  Suyama et al, PRD 71 (2005) 063507

- At preheating

  Green, Malik, PRD 64 (2001) 021301

- During inflation

Experimental constraints

Numerous constraints from various arguments:

Carr, talk at “Dark side of BH”, 2019

Colored regions are excluded
BH FROM COMPACT STARS AND DM
BASIC PICTURE

- Stars do not collapse into BH if lighter than $\sim 20M_\odot$ because the collapse is halted by the Fermi pressure of electrons and nucleons. Instead, they form neutron stars (NS) or white dwarfs if lighter that $\sim 9M_\odot$.
- However, stars may accumulate DM and concentrate it enough to make a small seed BH inside the star that would then grow by accretion and convert the star into a $O(M_\odot)$ BH.
- This can only work for compact stars, for two reasons:
  - They concentrate DM much better
  - They are dense enough to be eaten up in a short time
- This can only work for non-annihilating (e.g. asymmetric) DM
DM IN COMPACT STARS

How does DM get into stars? Basically, two ways:

- Acquired at the formation of the progenitor
- Captured during the evolution of the progenitor and lifetime of the compact star
Capture at star formation

Capela, Pshirkov, PT, PRD87.023507, PRD90.083507

• The stars are formed in the collapse of baryonic matter in giant molecular clouds. These clouds have some DM density gravitationally bound to them.

• Collapsing baryons gravitationally drag the DM along by adiabatic contraction, so some DM ends up inside the star.

• When the star evolves into a compact remnant (NS or WD), this DM is inherited by the latter.
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- The density of bound DM, assuming Maxwellian parent distribution with $\bar{v}$:

$$\rho_{\text{bound}} \sim \bar{\rho}_{DM} \left( \frac{\phi_0}{\bar{v}^2} \right)^{3/2} = \text{const} \cdot \frac{\bar{\rho}_{DM}}{\bar{v}^3}$$

- DM after the adiabatic contraction:

- Number of particles within $r$,

$$n(r) \propto r^{3/2}$$

- Number of particles with periastron $< r$,

$$\nu(r) \propto r$$
• How much gets captured? Depends on the progenitor mass and ambient DM density and velocity. For numbers typical of dwarf galaxies, $\rho_{DM} = 200 \text{ GeV/cm}^3$ and $v = 7 \text{ km/s}$, one has

<table>
<thead>
<tr>
<th>$M_*/M_\odot$</th>
<th>$M_{dm}$</th>
<th>$M_{dm}/M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$9.9 \times 10^{44} \text{ GeV}$</td>
<td>$8.8 \times 10^{-13}$</td>
</tr>
<tr>
<td>5</td>
<td>$5.8 \times 10^{46} \text{ GeV}$</td>
<td>$5.2 \times 10^{-11}$</td>
</tr>
<tr>
<td>10</td>
<td>$3.6 \times 10^{47} \text{ GeV}$</td>
<td>$3.2 \times 10^{-10}$</td>
</tr>
<tr>
<td>15</td>
<td>$9.6 \times 10^{47} \text{ GeV}$</td>
<td>$8.6 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

• In the MW halo with $\rho_{DM} = 0.3 \text{ GeV/cm}^3$ and $v = 220 \text{ km/s}$ they should be rescaled by a factor $5 \times 10^{-8} \propto \rho_{DM}/v^3$. 
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CAPTURE DURING LIFETIME


- Start with cross section of the star crossing

\[ \pi R_\ast^2 \left[ 1 + \frac{R_g}{(R_\ast v_\infty^2)} \right] \]

- Average with Maxwell distribution

\[ F = \sqrt{6\pi} \frac{\rho_{DM}}{v_\infty m} \frac{R_g R_\ast}{1 - \frac{R_g}{R_\ast}} \left[ 1 - \exp\left( -\frac{3E_{\text{loss}}}{mv_\infty^2} \right) \right] \left( \frac{\sigma}{\sigma_{cr}} \right) \]

\[ = \sqrt{6\pi} \frac{\rho_{DM}}{v_\infty m} \frac{R_g R_\ast}{m} \times \text{(possible suppression)} \]

- Critical cross section \( \sigma_{cr} = \frac{R_\ast^2}{N} (= \text{star becomes opaque}) \):

Sun: \( 5 \times 10^{-36} \text{cm}^2 \), WD: \( 3 \times 10^{-40} \text{cm}^2 \), NS: \( 10^{-45} \text{cm}^2 \)
CAPTURE DURING LIFETIME


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Sun: \( 5 \times 10^{-36} \text{cm}^2 \), WD: \( 3 \times 10^{-40} \text{cm}^2 \), NS: \( 10^{-45} \text{cm}^2 \)
• Assume best case (no suppression), take lifetime 10 Gyr and calculate total DM mass accumulated by NS

\[
\begin{array}{l|l}
\text{MW} & 2.2 \times 10^{44}\text{GeV} = 2 \times 10^{-13} M_\odot \\
\text{dwarf galaxies} & 1.5 \times 10^{47}\text{GeV} = 1.3 \times 10^{-10} M_\odot \\
\end{array}
\]

• Note: DM-to-nucleon cross section is strongly constrained by direct detection, so for Sun and WD there is typically strong suppression as compared to these numbers.
WHAT HAPPENS TO CAPTURED DM?

- Once gravitationally bound, DM thermalizes and settles in a cloud of the size

\[ r_{th} = \left( \frac{T^*_s}{G \rho^*_m} \right)^{1/2} \sim 10 \text{ cm} \]

- When (and if) DM mass density exceeds that of the star it decouples from the star potential and start shrinking under its own gravity.

- This self-gravitation condition reads:

\[ M > 2 \times 10^{-14} M_\odot (m/100 \text{ GeV})^{-3/2} \]
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• This self-gravitation condition reads:

\[ M > 2 \times 10^{-14} \, M_\odot \, (m/100 \, \text{GeV})^{-3/2} \]
• In case of bosons this constraint should be reconsidered because bosons may form Bose-Einstein condensate which is much more compact and may self-gravitate at smaller total accumulated mass.

• For a NS, the size of BEC state is

\[ r_{\text{BEC}} = \left( G \rho_* m^2 \right)^{-1/4} \sim 2 \times 10^{-4} \text{ cm (GeV}/m^{1/2} \]

• For a given temperature, there is a critical density of particles above which BEC is formed:

\[ n \gtrsim 5 \times 10^{28} \text{ cm}^{-3} \left( \frac{m T_c}{\text{GeV} \cdot 10^5 \text{K}} \right)^{3/2} \]
**BOSONIC DM**

- For BEC the self-gravitation condition reads

\[ M_{\text{BEC}} > 7 \times 10^{-30} \, M_\odot \, (m/\text{GeV})^{-3/2} \]

\( \implies \) much easier to satisfy than for the whole cloud

- Once self gravitating, BEC collapses provided the uncertainty principle does not stop the collapse

\[ N_{\text{BEC}} \gtrsim \left( \frac{M_{\text{Pl}}}{m} \right)^2 \sim 10^{38} \left( \frac{m}{\text{GeV}} \right)^{-2} \]

Note: this condition is more restrictive than self-gravitation of BEC.
**BOSONIC DM**

- Thus one gets constraints on bosonic DM together with parameter range where **some NS can be converted into light BH**:
**FERMIONIC DM**

*Kouvaris, PT, Tytgat, PRL 121(2018)221102*

- For fermions *Pauli principle* prevents collapse unless the number of particles is big enough (Chandrasekhar limit),
  \[ N \gtrsim \left( \frac{M_{\text{Pl}}}{m} \right)^3 \sim 10^{57} (\text{GeV}/m)^3 \]

- Accumulated DM mass must satisfy
  \[ M \gtrsim m \left( \frac{M_{\text{Pl}}}{m} \right)^3 \sim 10^{57} \text{ GeV } (\text{GeV}/m)^2 \]

- Two ways out:
  - Assume very high masses \( m \gtrsim 1000 \text{ TeV} \) — not very attractive
  - Add attractive self-interactions — obviously, more attractive
ATTRACTIVE FERMIONIC DM

- Self-interactions modify both the self-gravitation and Chandrasekhar conditions

- Assume scalar exchange $\Rightarrow$ 2 parameters: coupling $\alpha$ and mediator mass $\mu$

$$V(r) = \alpha e^{-\mu r} / r$$

- Self-gravitation condition: assume uniform sphere of radius $r$ and use the virial theorem. In the limit when the range of the potential $1/\mu$ is larger than interparticle distance $r_0$ but smaller than the size of DM sphere $R$ this gives

$$2\langle E_k \rangle = G\rho_* mR^2 + \frac{GNm^2}{R} + \frac{N\alpha e^{-\mu r_0}}{\mu^2 R^3} (3 + 3\mu r_0 + \mu^2 r_0^2)$$

- In thermal equilibrium $2\langle E_k \rangle = 3T$. 

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At small $N$ the solution for $R$ always exists, but at some critical value $N_{cr}$ it disappears.

This critical $N$ is calculated numerically.
• Chandrasekhar limit: consider $E(R)$

$$E(R) = \frac{N^{2/3}}{mR^2} - \frac{GNm^2}{R} - \frac{N\alpha}{\mu^2 R^3}$$

and look for extrema $\frac{\partial E}{\partial R} = 0$. At small $N$ there are two; at some large $N = N_{Ch}$ they merge and disappear.
- Parametrically

\[ N_{\text{Ch}} = \left( \frac{\mu}{m \sqrt{\alpha}} \right)^3 \left( \frac{M_{\text{Pl}}}{m} \right)^3 \]

- Note: the parameter \( \frac{\mu}{m \sqrt{\alpha}} \) also controls non-relativistic approximation.

- Examples when this picture works:

<table>
<thead>
<tr>
<th>#</th>
<th>( \alpha )</th>
<th>( \mu ) MeV</th>
<th>( m ) TeV</th>
<th>( N_{\text{cr}} )</th>
<th>( N_{\text{Ch}} )</th>
<th>( \frac{M_{\text{Ch}}}{M_{\odot}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 10^{-3} )</td>
<td>10</td>
<td>1</td>
<td>( 5 \cdot 10^{35} )</td>
<td>( 2 \cdot 10^{37} )</td>
<td>( 10^{-17} )</td>
</tr>
<tr>
<td>2</td>
<td>( 10^{-4} )</td>
<td>2</td>
<td>0.2</td>
<td>( 2 \cdot 10^{35} )</td>
<td>( 7 \cdot 10^{40} )</td>
<td>( 10^{-14} )</td>
</tr>
<tr>
<td>3</td>
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<td>1</td>
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<td>( 7 \cdot 10^{39} )</td>
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</tr>
</tbody>
</table>
POTENTIAL CAVEAT

Gresham, Zurek, arXiv:1809.08254

- When the DM cloud collapses under gravity and self-interaction, the non-relativistic approximation breaks
- For relativistic fermions, the source of scalar field $\bar{\psi}\psi$ is no longer equal to the number of fermions $\psi^\dagger\psi$, so the self-attraction may be dumped
- $\implies$ there might exist another stable phase before the Schwarzschild radius is reached
- However, the situation is far from clear as in this regime many condensates may develop. The question is under study.
DETECTION PROSPECTS

- Can light BH mergers be detected and distinguished from NS mergers?

LIGO2017
LIGO upgrade
ET
Summary

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• But it would not necessarily mean that these BH are primordial. Instead, it may point towards existence of a particular type of DM.
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