Solar Mass Black Holes and Dark Matter

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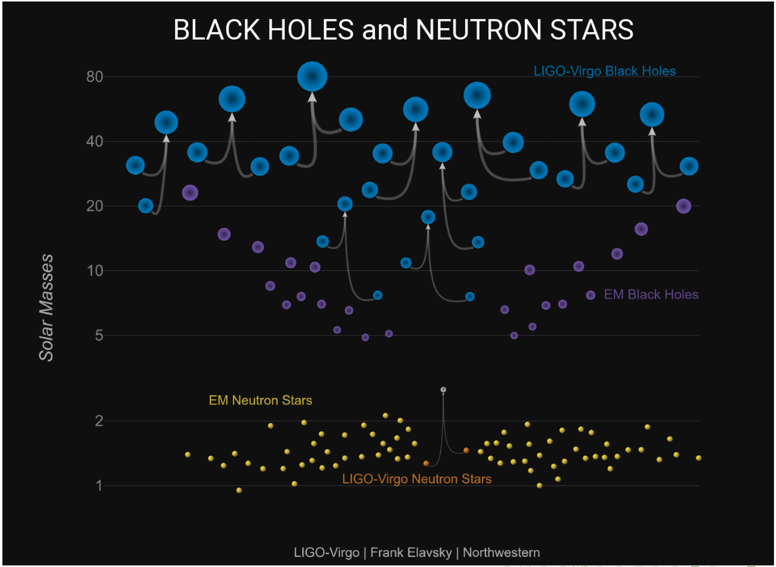
Outline

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 $\sim M_\odot$.

MOTIVATION

LIGO & VIRGO, arXiv:1811.12907



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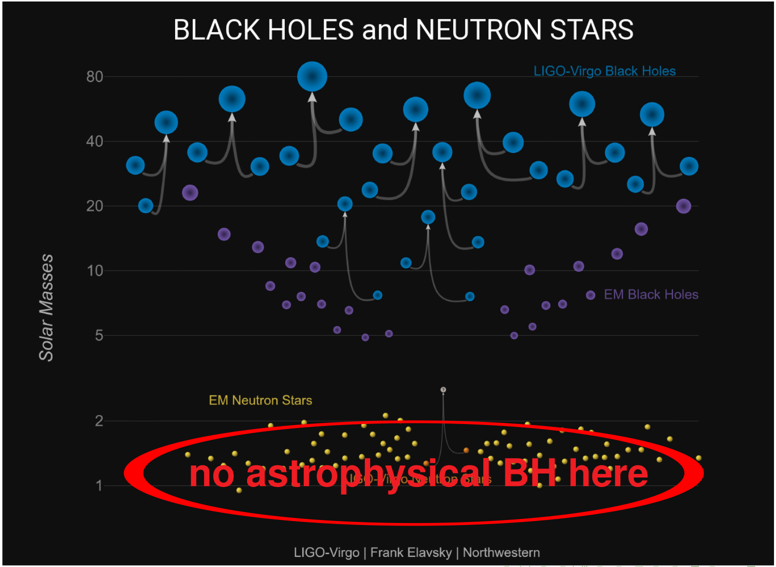

MOTIVATION

- 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 $M_\odot$.
  $\Longrightarrow$ 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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PRIMORDIAL BLACK HOLES

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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:

$$M_{\rm BH} \lesssim M_H \simeq 0.02 \frac{M_{\rm Pl}^3}{T^2}$$

T	MeV	100 MeV	100 GeV	10^8 GeV
M_H	$3 \times 10^4\ M_\odot$ 6×10^{37} g	$3\ M_\odot$ 6×10^{33} g	$3 \times 10^{-6}\ M_\odot$ 6×10^{27} g	$3 \times 10^{-18}\ M_\odot$ 6×10^{15} g

- BH *relative* contribution into energy density grows linearly with the scale factor $a \Longrightarrow$ easy to produce enough or even overproduce.

Plenty of production mechanisms:

- Primordial density perturbations

  Carr, ApJ 201(1975)1

- Soft equation of state at some period of evolution

  Carr, ApJ 201 (1975) 1
  Khlopov, Malomed, Zel'dovich, MNRAS 215 (1985) 575

- Bubble collisions during phase transitions

  Hall, Hsu, PRL64 (1990) 2848
  Jedamzik, PRD55 (1997) 5871
  Jedamzik, Niemeyer, PRD59 (1999) 124014

- Collapse of cosmic strings

  Hawking, Phys.Lett. B231 (1989) 237
  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, PRD71 (2005) 063507

- At preheating

  Green, Malik, PRD64 (2001) 021301

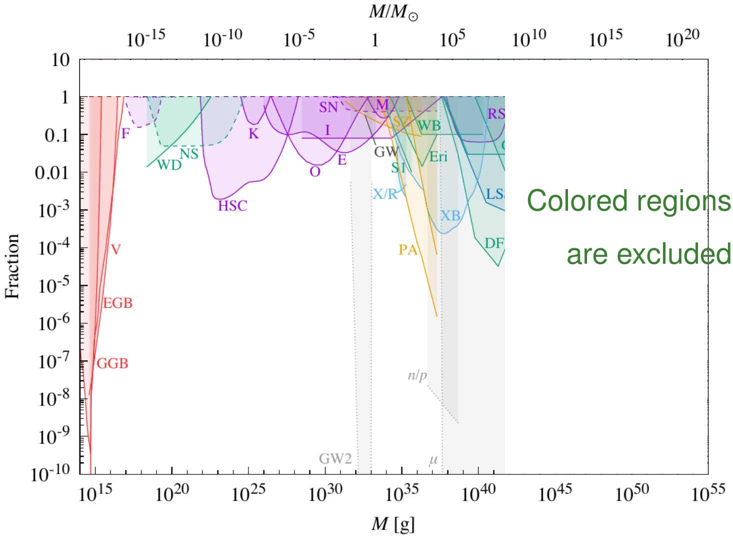
- During inflation

  Garsia-Bellido, Linde, Wands PRD54 (1996) 6040

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 $\sim 20 M_\odot$ 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 $\sim 9 M_\odot$.
- 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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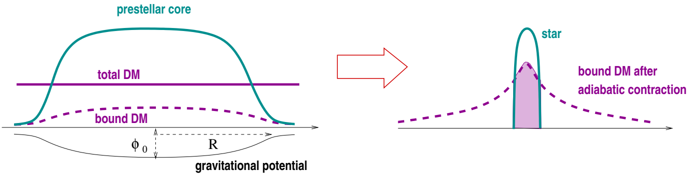

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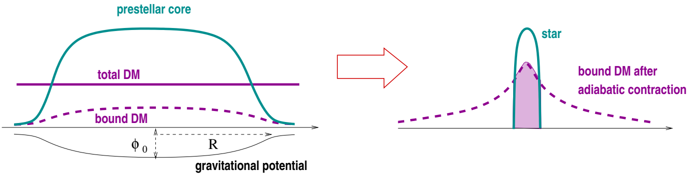
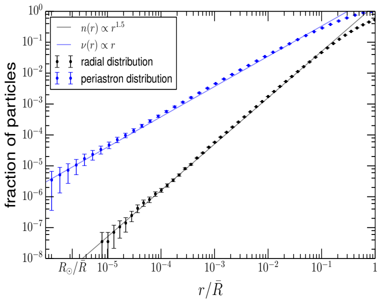


- When the star evolves into a compact remnant (NS or WD), this DM is inherited by the latter.

- 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:

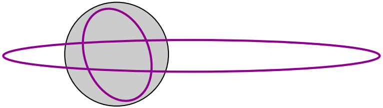


- Number of particles within r,

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

- 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, $\rho_{\rm DM} = 200$ GeV/cm^3 and $v = 7$ km/s, one has

$M_*/M_\odot$	$M_{\rm dm}$	$M_{\rm dm}/M_\odot$
1	9.9×10^{44} GeV	8.8×10^{-13}
5	5.8×10^{46} GeV	5.2×10^{-11}
10	3.6×10^{47} GeV	3.2×10^{-10}
15	9.6×10^{47} GeV	8.6×10^{-10}

- In the MW halo with $\rho_{\rm DM} = 0.3$ GeV/cm^3 and $v = 220$ km/s they should be rescaled by a factor 5×10^{-8} ($\propto \rho_{\rm DM}/v^3$).

CAPTURE DURING LIFETIME

Press, Spergel, Astrophys.J. 296(1985)679

- Start with cross section of the star crossing

$$\pi R_*^2 \left[1 + R_g/(R_* v_\infty^2)\right]$$

- Average with Maxwell distribution

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

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

- Critical cross section $\sigma_{\rm cr} = R_*^2/N$ (= star becomes opaque):

Sun: $5\times 10^{-36}{\rm cm}^2$, WD: $3\times 10^{-40}{\rm cm}^2$, NS: $10^{-45}{\rm cm}^2$

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Numbers

- Assume best case (no suppression), take lifetime 10 Gyr and calculate total DM mass accumulated by NS

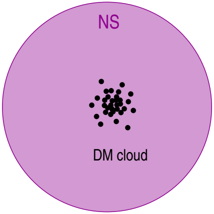
MW	$2.2 \times 10^{44}\mathrm{GeV} = 2 \times 10^{-13} M_\odot$
dwarf galaxies	$1.5 \times 10^{47}\mathrm{GeV} = 1.3 \times 10^{-10} M_\odot$

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

WHAT HAPPENS TO CAPTURED DM?

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

$$r_{\text{th}} = \left(\frac{T_*}{G\rho_* m}\right)^{1/2} \sim 10\ \text{cm}$$



- 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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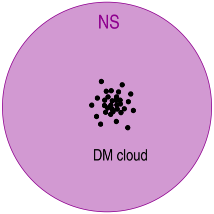

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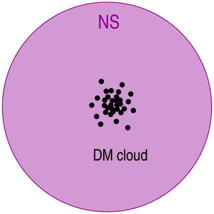

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BOSONIC DM

Kouvaris, PT, PRL 107(2011)091301

- 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

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

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

$$n \gtrsim 5\times 10^{28}{\rm cm}^{-3}\left(\frac{mT_c}{{\rm GeV}\cdot 10^5{\rm K}}\right)^{3/2}$$

BOSONIC DM

- For BEC the self-gravitation condition reads

$$M_{\rm BEC} > 7 \times 10^{-30}\ M_\odot\ (m/{\rm GeV})^{-3/2}$$

$\Longrightarrow$ much easier to satisfy than for the whole cloud

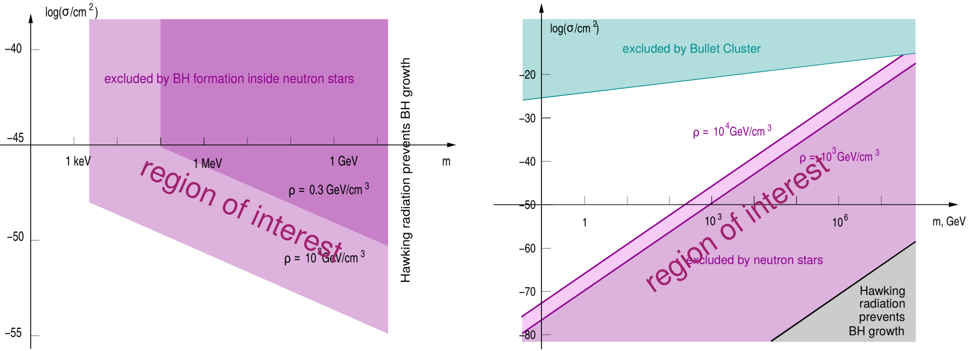
- Once self gravitating, BEC collapses provided the uncertainty principle does not stop the collapse

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

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),

$$N \gtrsim \left(\frac{M_{\rm Pl}}{m}\right)^3 \sim 10^{57} ({\rm GeV}/m)^3$$

- $\Longrightarrow$ Accumulated DM mass must satisfy

$$M \gtrsim m \left(\frac{M_{\rm Pl}}{m}\right)^3 \sim 10^{57}\ {\rm GeV}\ ({\rm GeV}/m)^2$$

- Two ways out:
  - Assume very high masses $m \gtrsim 1000$ 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 $\Longrightarrow$ 2 parameters: coupling α and mediator mass μ

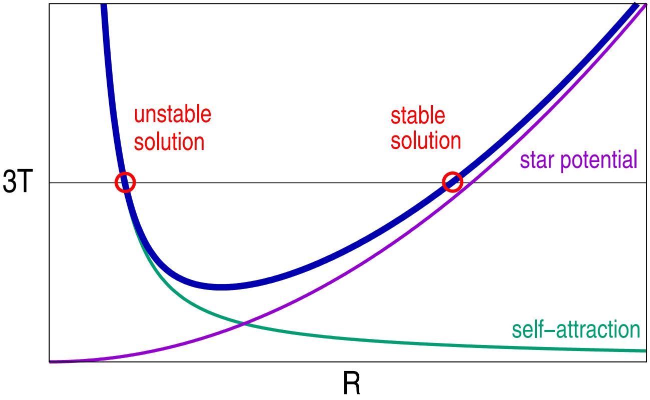
$$V(r) = \alpha e^{-\mu r}/r$$

- 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 $2\langle E_k \rangle = 3T$.

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

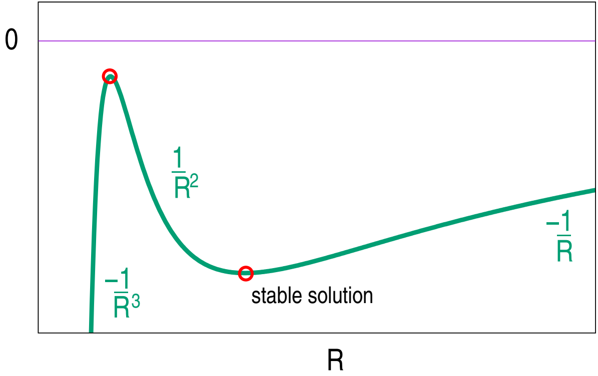


- This critical N is calculated numerically.

- 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 $\partial E/\partial R = 0$. At small N there are two; at some large $N = N_{\rm Ch}$ they merge and disappear.



- Parametrically

$$N_{\rm Ch} = \left(\frac{\mu}{m\sqrt{\alpha}}\right)^3 \left(\frac{M_{\rm Pl}}{m}\right)^3$$

- Note: the parameter $(\mu/m\sqrt{\alpha})$ also controls non-relativistic approximation.
- Examples when this picture works:

#	α	$\frac{\mu}{\rm MeV}$	$\frac{m}{\rm TeV}$	$N_{\rm cr}$	$N_{\rm Ch}$	$\frac{M_{\rm Ch}}{\rm M_\odot}$
1	10^{-3}	10	1	$5 \cdot 10^{35}$	$2 \cdot 10^{37}$	10^{-17}
2	10^{-4}	2	0.2	$2 \cdot 10^{35}$	$7 \cdot 10^{40}$	10^{-14}
3	10^{-4}	1	1	$3 \cdot 10^{33}$	$6 \cdot 10^{35}$	10^{-18}
4	10^{-3}	3	0.2	$2 \cdot 10^{35}$	$7 \cdot 10^{39}$	10^{-15}

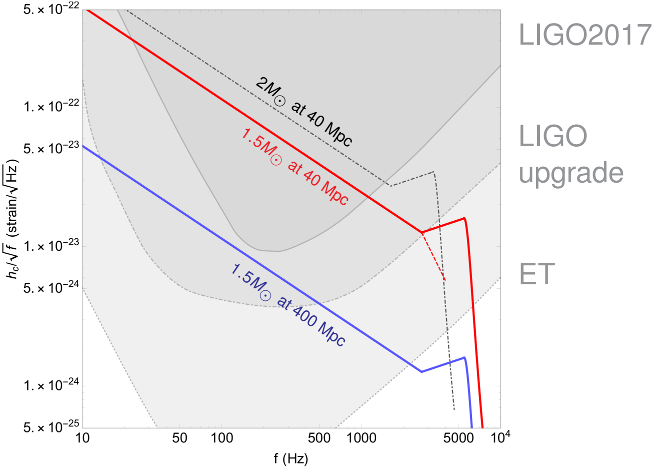
POTENTIAL CAVEAT

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
- $\Longrightarrow$ 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?



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