SUPRAMASSIVE COMPACT OBJECTS WITH NEUTRON STAR AND DARK MATTER ORIGIN IN THE MASS GAP REGION

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A dark matter compact object that can shed light to the mysteries of our Universe

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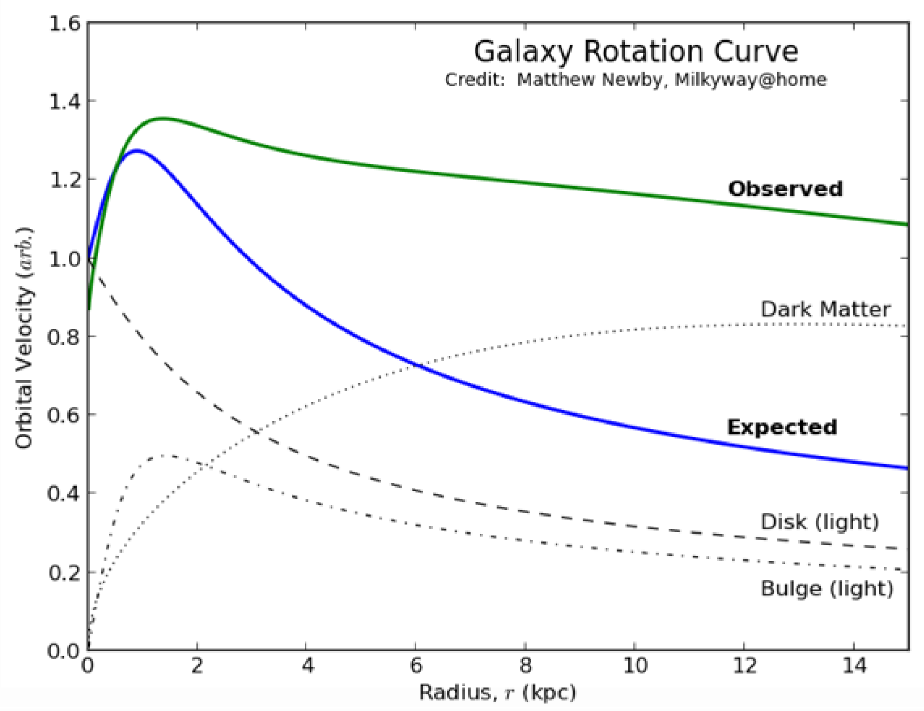
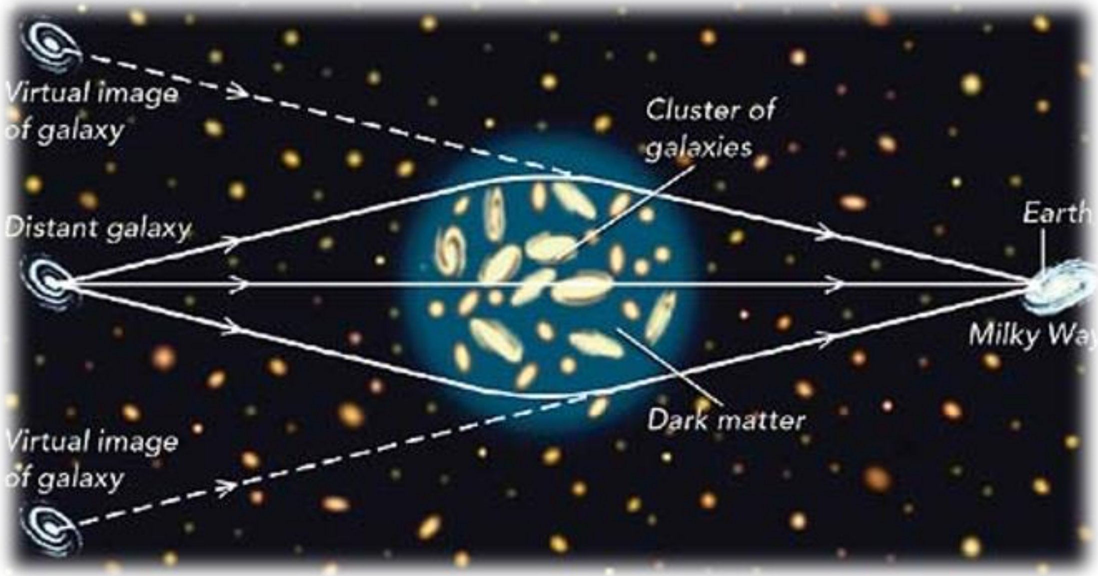
01 Dark Matter

There is matter missing in the universe wherever we look.

We call it *dark matter* since we cannot see it directly through electromagnetic forces (example light), but we can detect their gravitational effects.

Astrophysical observations show us that the visible matter is not sufficient to account for the gravitational forces that hold the cosmic structures (galaxies, clusters of galaxies etc) together, or the way these structures move and behave in the universe.





There are two types of dark matter:

1. Fermionic Dark Matter (Fermions – Pauli Exc. Principle etc)
2. Bosonic Dark Matter (Bosons – Bose Einstein Statistics etc)

These two types of Dark Matter lead to different conclusions, but with a catch!

We need the EOS of the two fluids. We use the APR equation of state for the neutron matter. So that leaves us with the EOS of the two dark matter types:

1. Fermionic EOS:

$$\mathcal{E}_\chi(n_\chi) = m_\chi c^2 n_\chi + \frac{(\hbar c)^2(3\pi^2 n_\chi)^{5/3}}{10\pi^2 m_\chi c^2} \pm \frac{n_\chi^2(\hbar c)^3}{2z^2}, \ (\mathrm{MeV/fm^3})$$

$$P_\chi(n_\chi) = n_\chi \frac{d\mathcal{E}_\chi(n_\chi)}{dn_\chi} - \mathcal{E}_\chi(n_\chi) = n_\chi \mu_\chi - \mathcal{E}_\chi(n_\chi)$$

2. Bosonic EOS:

$$\mathcal{E}_{\mathrm{DM}}(n_\chi) = m_\chi c^2 n_\chi + \frac{u^2}{2}(\hbar c)^3 n_\chi^2,$$

$$P_{\mathrm{DM}}(n_\chi) = \frac{u^2}{2}(\hbar c)^3 n_\chi^2$$

Fermionic dark matter tends to form bigger scale structures due to its nature. Bosonic on the other hand forms smaller formations

But one needs to be cautious, because as the interaction increases, the two cases converge so we cannot find strong differences between the two types.

02 Two Fluid

The simple neutron star is explained with the solution of the Tolman Oppenheimer Volkoff (TOV) equations, the equations that describe a structure that exists in hydrostatic equilibrium.

The way we insert dark matter is the following:

1. We need to define the dark matter particle mass m_x, the interaction between the dark matter particles y (we use repulsive interaction)
2. Instead of the neutron star central pressure that we use as initial condition, we also need the initial central pressure for dark matter and in order to create the M-R diagram, we need some kind of fraction between those two
3. The TOV equation now become 4 instead of 2, one set for each fluid.

TOV equations for simple one-fluid

$$\frac{dM(r)}{dr} = 4\pi\rho(r)r^2$$

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2}\left(1+\frac{P(r)}{\rho(r)c^2}\right)\left(1+\frac{4\pi r^3 P(r)}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2 r}\right)^{-1}$$

$$\exp -2\lambda(r) = 1 - \frac{2GM(r)}{c^2 r}$$

$$\frac{d\Phi(r)}{dr} = \frac{1}{1-2GM(r)/c^2 r}\left(\frac{GM(r)}{c^2 r^2}+\frac{4\pi G r P}{c^4}\right)$$

$$\frac{dP_B}{dr} = -\frac{GM(r)\epsilon_B(r)}{r^2} \times \left(1 + \frac{4\pi r^3 P(r)}{M(r)}\right) \times \left(1 + \frac{P_B(r)}{\epsilon_B(r)}\right)\left(1 - \frac{2GM(r)}{r}\right)^{-1},$$

$$\frac{dP_\chi}{dr} = -\frac{GM(r)\epsilon_\chi(r)}{r^2} \times \left(1 + \frac{4\pi r^3 P(r)}{M(r)}\right) \times \left(1 + \frac{P_\chi(r)}{\epsilon_\chi(r)}\right)\left(1 - \frac{2GM(r)}{r}\right)^{-1},$$

$$\frac{dM_B}{dr} = 4\pi r^2 \epsilon_B(r),$$

$$\frac{dM_D}{dr} = 4\pi r^2 \epsilon_\chi(r),$$

The Two Fluid Model

- We have 4 equations, 2 for each fluid. The *B* notes the baryonic part while *X* notes the dark matter part.
- $P = P_X + P_B$ and $M = M_x + M_B$
- So, initializing the two central pressures, given both Equations of State (EOS) for each fluid we can solve these equations numerically, as we would with the simple one-fluid TOV equations.

03 Stability of these models

$$\left(\frac{\partial N_b}{\partial P_c^{\mathrm{NS}}}\right)_{\mathrm{M=const}} = \left(\frac{\partial N_\chi}{\partial P_c^{\mathrm{NS}}}\right)_{\mathrm{M=con}}$$

$$\left(\frac{\partial N_b}{\partial P_c^{\mathrm{DM}}}\right)_{\mathrm{M=const}} = \left(\frac{\partial N_\chi}{\partial P_c^{\mathrm{DM}}}\right)_{\mathrm{M=c}}$$

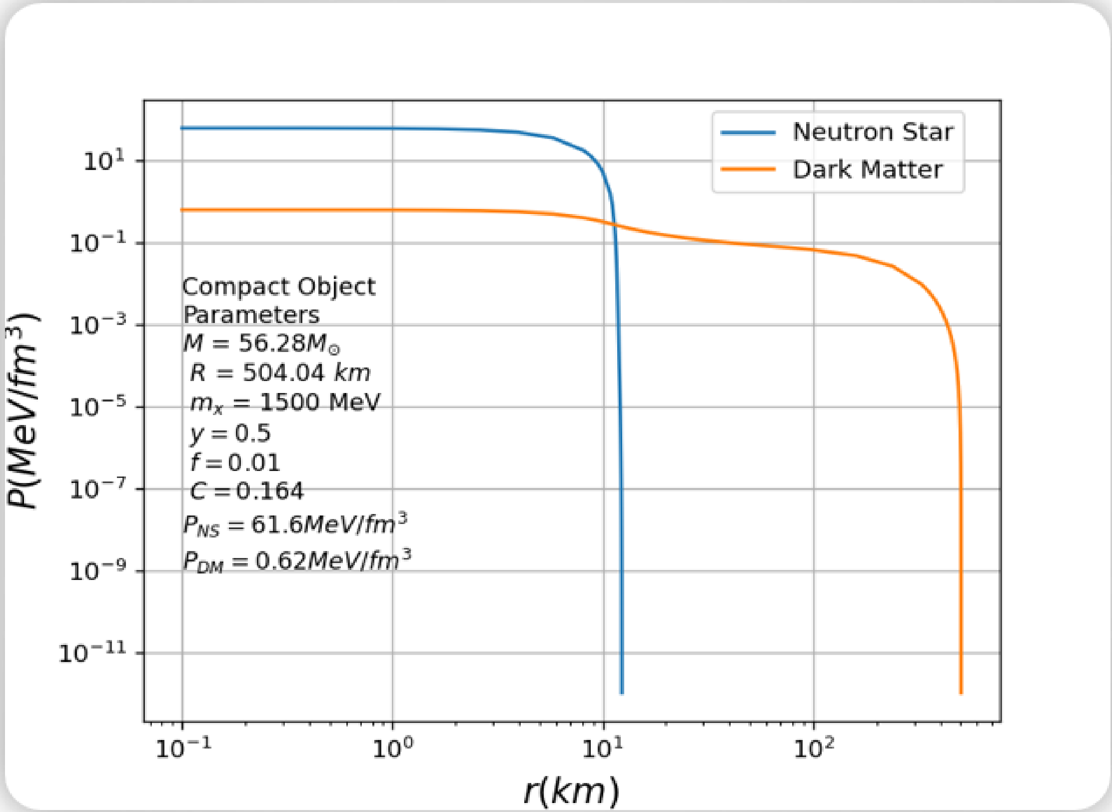
The stability of these models was perhaps the most tricky part of the whole study. The simple one fluid stability here is not correct. We have to study the stability in the two fluid model if we want to be accurate and sure of our findings.

In simple NS configurations, the stability is determined by the M-R diagram. Increasing pressure leads to increasing mass counter clockwise in the diagram. Everything that doesn't follow this rule, is unstable. Thus the curves reach to a maximum where we have the maximum and last stable configuration. Past this (on the left) point in the diagram, everything is unstable.

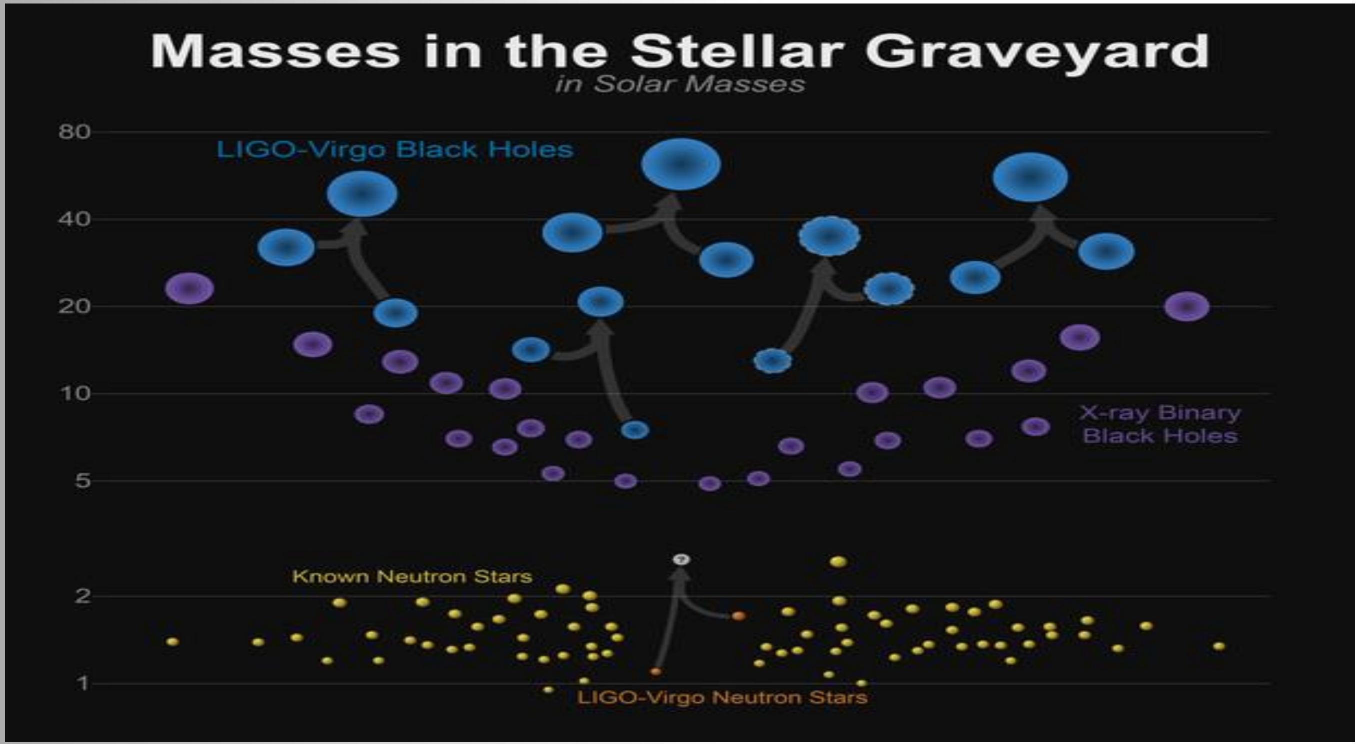
In the Two Fluid, we have to work with the number of baryon and DM particles N_χ and N_b. We can obtain the stability curves for the different EoS and DM parameters by extremizing this number of particles in terms of a fluid pressure for a stable value of total Mass. Simply, it all comes down to solving the above equations and finding the points that fulfill them

1. Initialize dark matter particle mass
2. Initialize the interaction
3. Use a fraction for the dark matter component
4. Derive the M-R diagram
5. Find a desired pure dark star and slowly add neutron matter
6. Keep the total mass constant with the central pressures and check what happens with the N_x and N_b

We end up with formations that expand from tens to hundreds, even thousand km long and from 1 to hundreds of solar masses. Depending on the compactness of the object and the contribution of dm to the total mass we can talk about dm halos or dm compact objects. In literature, people mostly work with dark halos, we chose to work with compact objects



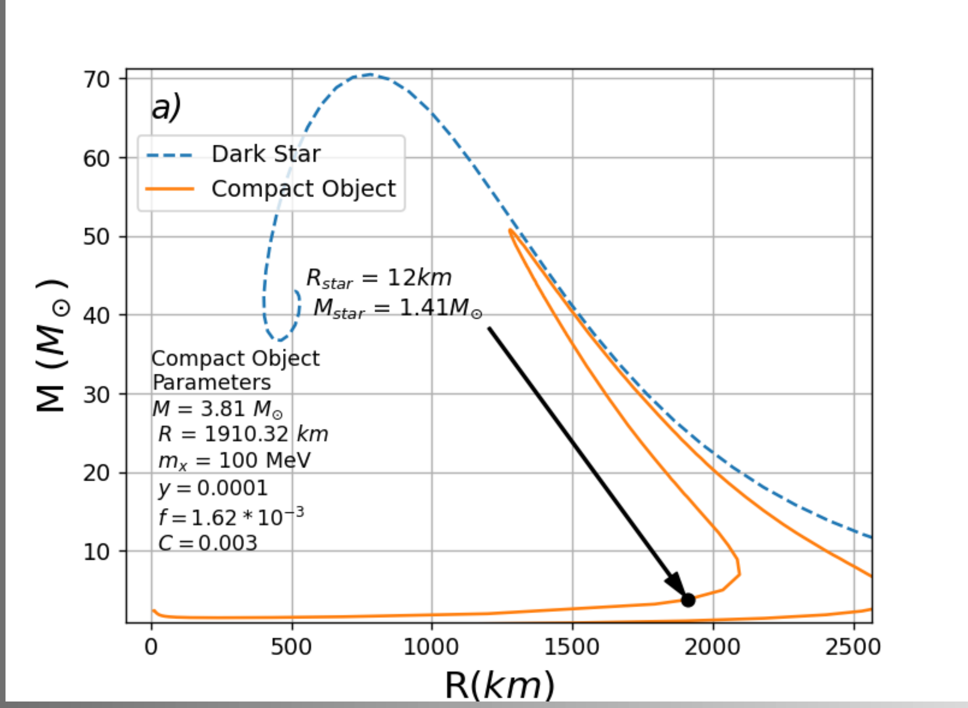
04 Mass Gap

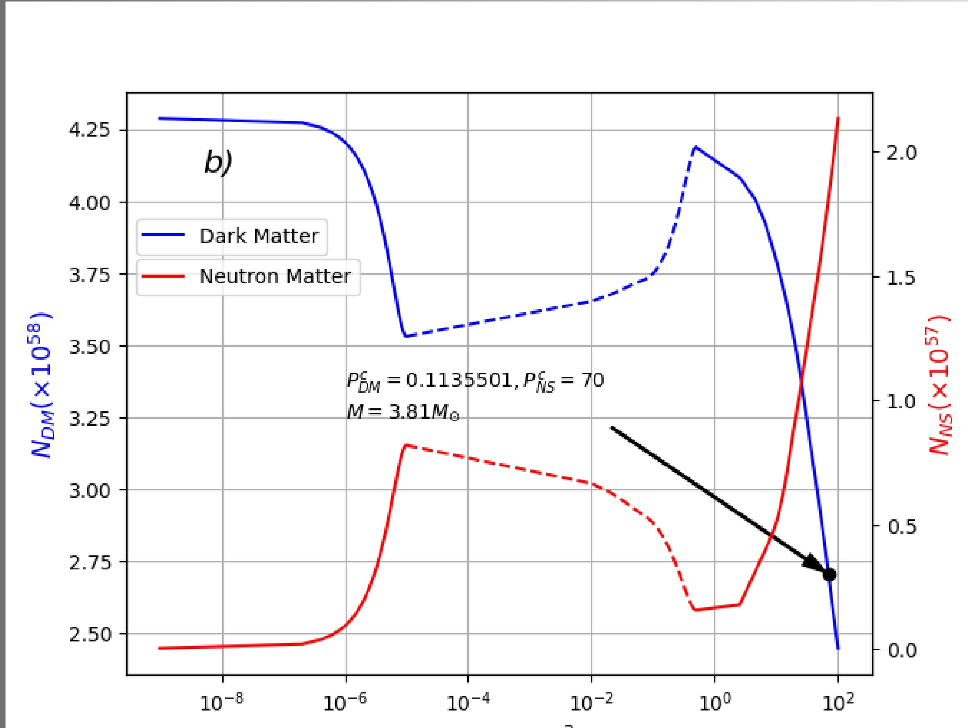


There exists a "gap" in the mass sorting of cosmic compact objects, meaning that the most massive neutron star and the lowest mass black hole are some solar masses apart. The neutron star maximum mass is between 2.2 and 2.5 solar masses (the Sun's mass as a unit of measure). Black holes of less than 5 solar masses rarely have been observed. These limits suggest a “mass gap” between the most massive neutron stars and least massive black holes

Understading the potential that these compact objects have, we went ahead and tested our theory to see if we can in fact receive stable configurations within the mass gap and explain it.

Ordinary looking NS that are the cores of bigger structures can as well cover this gap since the total mass of the object could be around 3-4 solar masses.





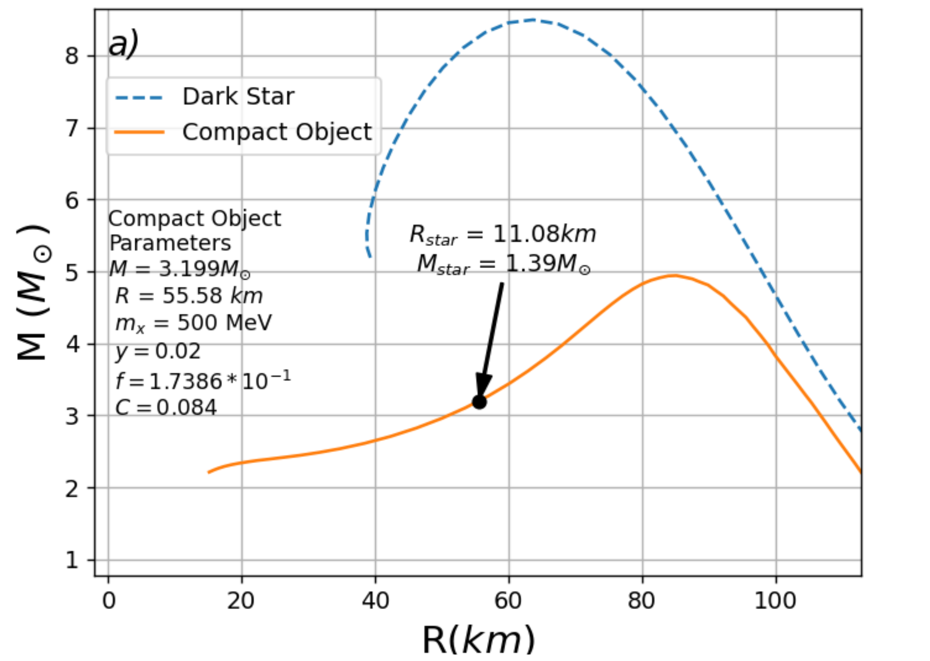
05 Results

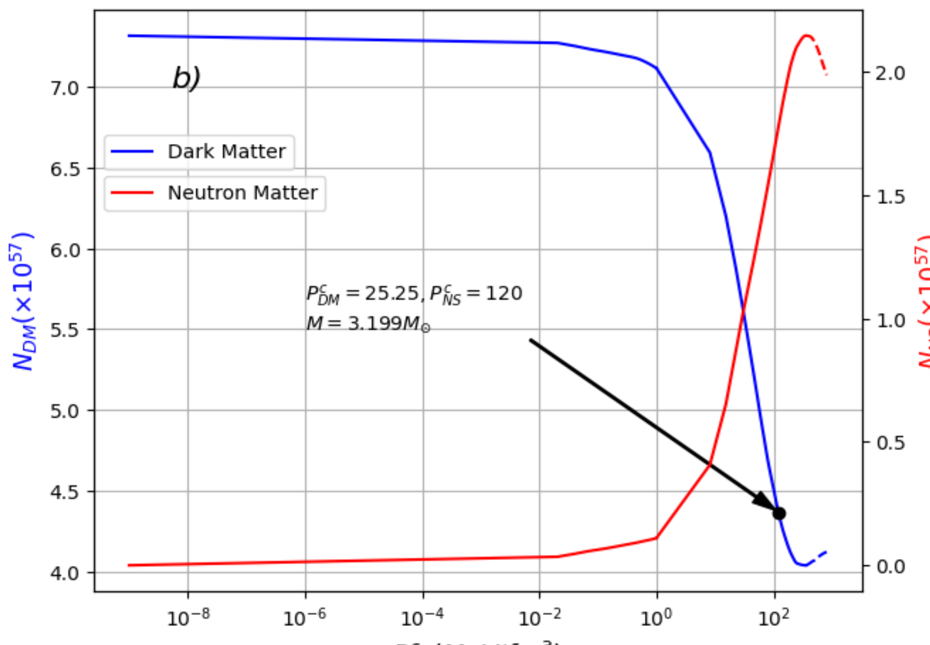
The results show that we can indeed have stable configurations within the gap.

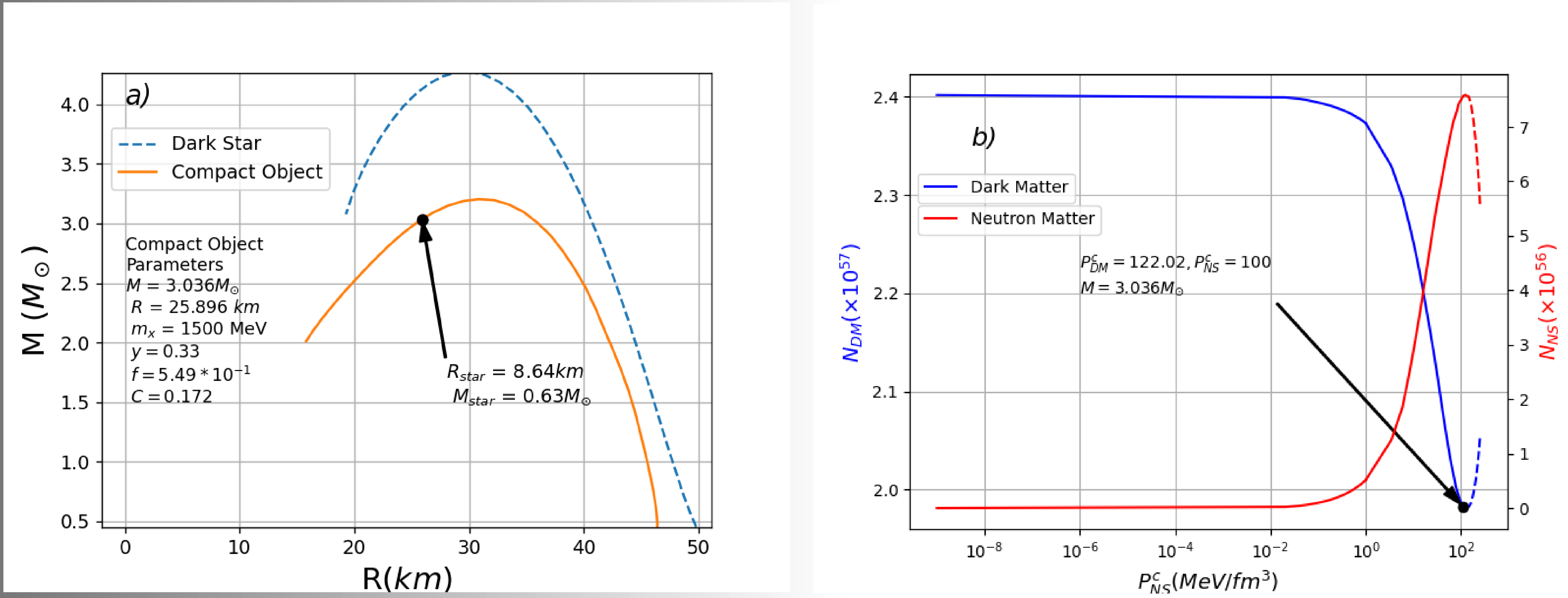
But one needs to be careful on how to obtain these objects and how to interpret these results.

We need a relatively heavy particle and a not so big but in the same time not small interaction in order for these configurations of 3-4 solar masses to exist.

But on the other hand, the more massive the particle gets, the neutron star behaves like it is compressed and gets smaller and less heavy.







This can also be seen from these results. Notice the low mass Neutron Star. This is because the dark particle is heavy and also the interaction is at the same time not great or negligible.

The Star seems to be compressed inside the total object, this is the last stable configuration as you see and it reaches only 0.63 Solar Masses.

We can constrain the dark matter parameters, especially through the gravtiational data we receive, if we such an unusual object.

Concluding remarks and discussion

- Existence of stable configurations of compact objects (NS-DM)
- Not a halo, but a DM component that can be in charge
- Stability needs to be thoroughly examined and not lightly taken
- Gravitational effects is the most prominent way to see these objects
- Neutron star in certain situations can become more compressed
- Gap objects can be found and the gap can be explained
- Great care in the initial parameters of DM, they can cause problems (too small of a NS or stability problems)

Thank you!

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