Black Holes and Dark Matter

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Outline

1. Motivation
2. BH as DM
3. BH from DM
4. Summary

MOTIVATION

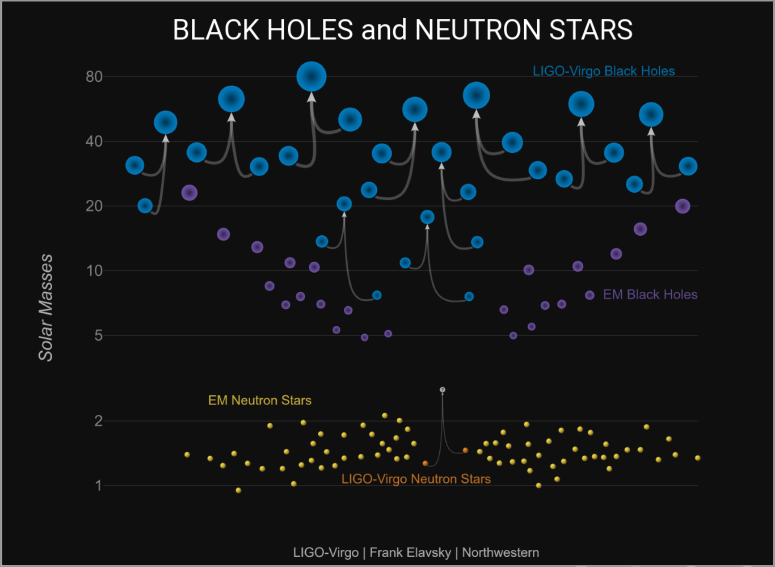
- GR works extremely well at intermediate scales and in classical regime
- Outside of this "zone of comfort" things are not so clear:
  - no satisfactory quantum extension is known
  - the extreme non-linear solutions — black holes (BH) — are conceptually not well understood
  - at large scales (at and beyond galactic size) there are inconsistencies with observations that require to assume the existence of (otherwise undetected) dark matter (DM); at the same scales the dark energy appears whose nature is unknown

MOTIVATION

- The first two of these problems are known to be related: Hawking radiation by BH and information paradox is certainly a quantum phenomenon
- I will argue that BH may also be related to DM, and in more than one way
- One more reason to focus on BH is recent breakthroughs in their observations:
  - LIGO & VIRGO detection of GW from BH mergers
  - EHT observations of the BH in M87

GW detectors progress very fast; the number of detected mergers grows quickly.

LIGO & VIRGO, arXiv:1811.12907



First image of the BH in the center of M87 by EHT

EHT, Astrophys.J. 875 (2019) L1-L6

CAN BLACK HOLES BE DARK MATTER?

PRIMORDIAL BLACK HOLES

Hawking, MNRAS 152 (1971) 75

- BH may be produced in the early Universe in collapse of large matter fluctuations.
- 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.

Plethora 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

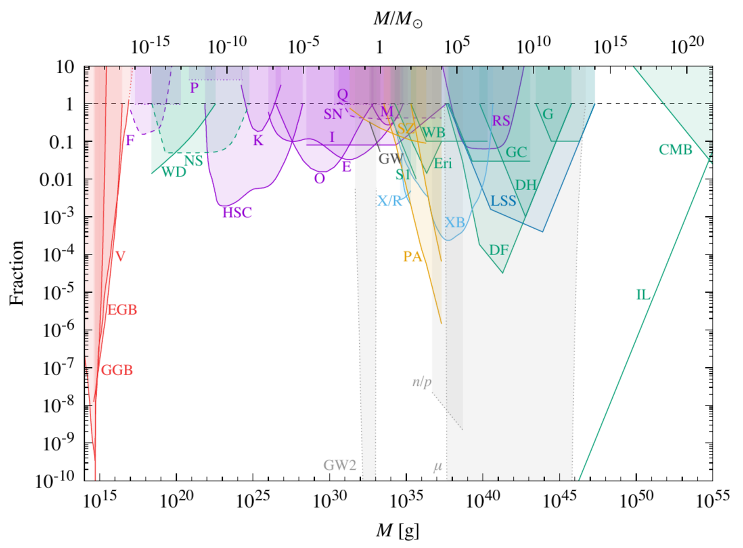
- During inflation

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

Experimental constraints

MANY constraints from various arguments:

Carr, talk at "Dark side of BH", 2019



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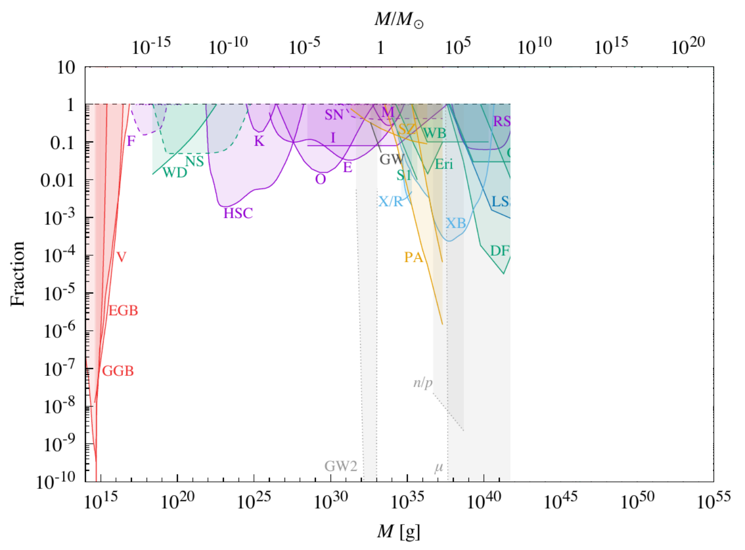

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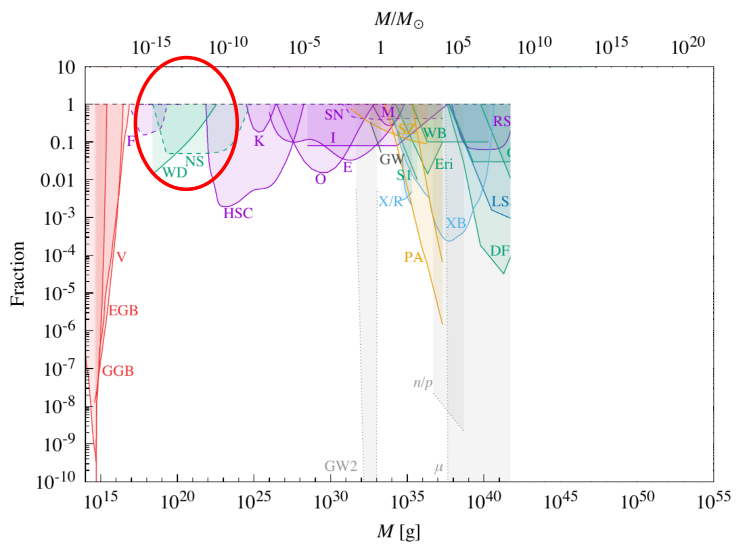

Constraints from capture of PBH by NS

- In this mass range PBH abundance may be constrained from their capture by neutron stars (NS)

  Capela, Pshirkov, PT, PRD 87 (2013) 023507

  Capela, Pshirkov, PT, PRD 87 (2013) 123524

  Capela, Pshirkov, PT, PRD 90 (2014) 083507

- If a PBH is captured by the NS it accretes the matter and destroys the NS in a short time. Thus, a mere existence of NS puts constraints on the PBH abundance: it has to be such that the probability of capture by NS is $\ll 1$.
- Clearly, capture rate F as a function of local PBH density and velocity dispersion is a key quantity.
- There are two capture mechanisms: during lifetime and at star formation

CAPTURE DURING LIFETIME

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

- Take cross section of the star crossing

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

- Average with Maxwell distribution

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

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

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

Sun: $5\times10^{-36}\mathrm{cm}^2$, WD: $3\times10^{-40}\mathrm{cm}^2$, NS: $10^{-45}\mathrm{cm}^2$

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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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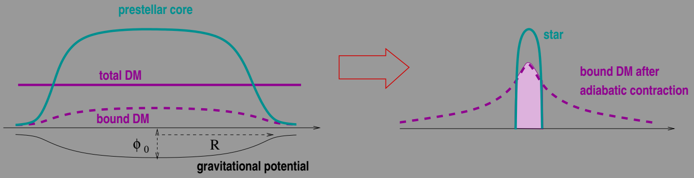

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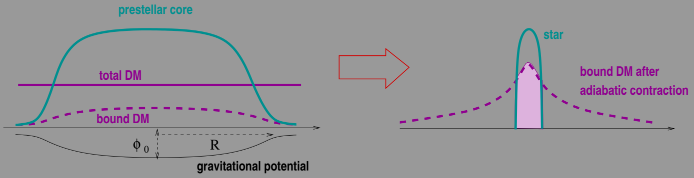

- When the star evolves into a compact remnant (NS or WD), this DM is inherited by the latter.

- The density of bound DM, assuming Maxwellian parent distribution with $\bar{v}$:

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

- DM after the adiabatic contraction:

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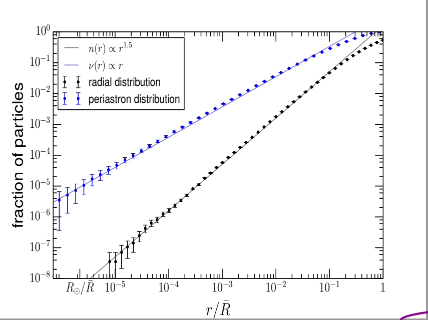
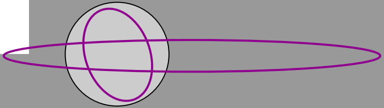


- Number of particles within r,

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

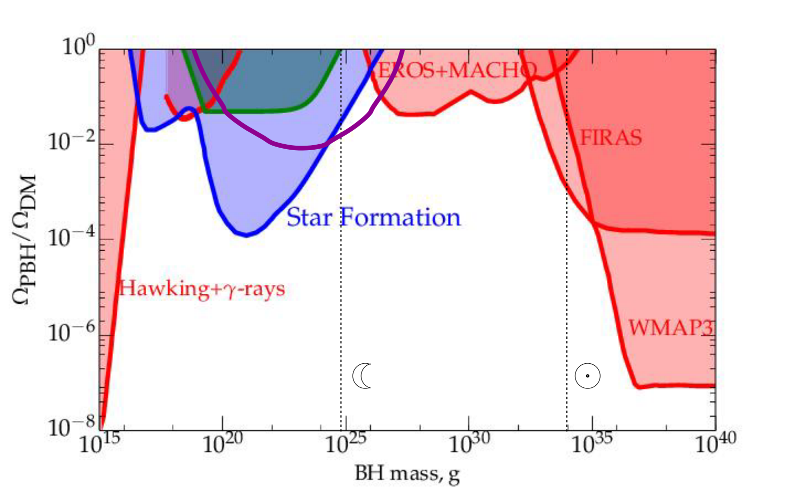
- Number of particles with periastron $< r$,

$$\nu(r) \propto r$$



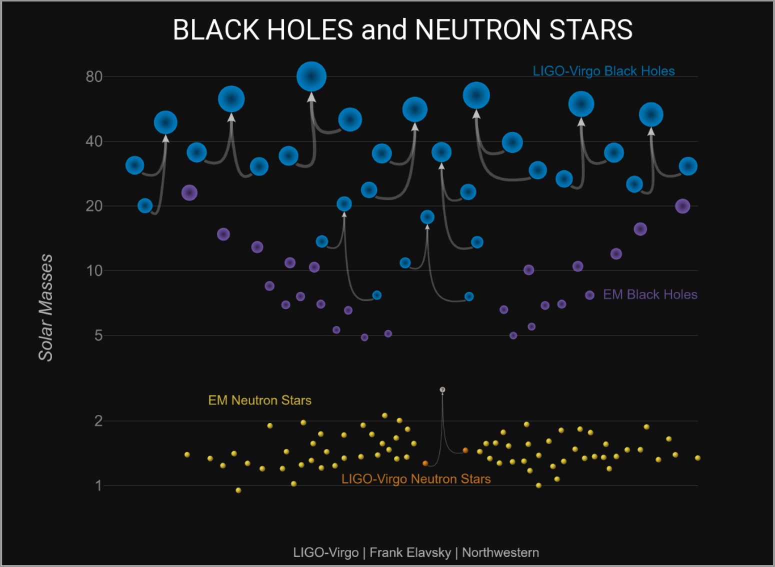
RESULTING CONSTRAINTS

Assuming $\rho_D = 10^4$ GeV/cm^3 and $v = 7$km/s



LIGHT BH FROM NS AND DM

Are there BH with mass $\lesssim 2M_\odot$?



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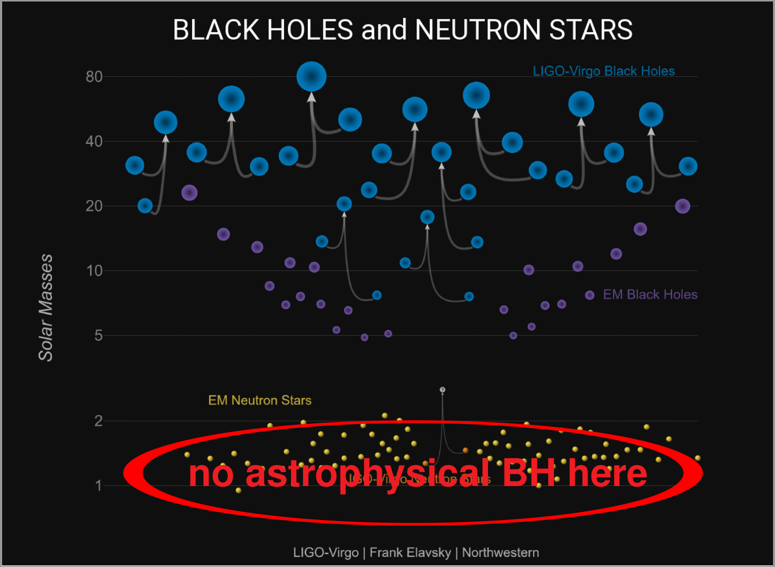


BASIC PICTURE

- 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 reasonable time
- This can only work for non-annihilating (e.g. asymmetric) DM

What happens to captured DM?

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

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

- 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:

$$M > 2 \times 10^{43} \text{ GeV} \, (m/100 \text{ GeV})^{-3/2} \qquad \text{for NS}$$

BOSONIC DM

Kouvaris, PT, PRL 107(2011)091301

- In case of bosons the DM forms Bose-Einstein condensate which is much more compact and may self-gravitate at smaller total accumulated mass
- 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 BEC the self-gravitation condition reads

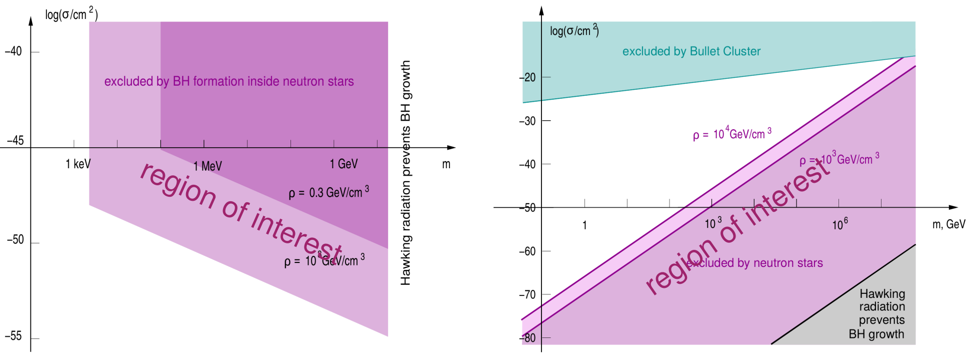
$$M_{\rm BEC} > 8\times 10^{27}\ {\rm GeV}\ (m/{\rm GeV})^{-3/2}$$

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

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

BOSONIC DM

- 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 $\Longrightarrow$ two parameters: coupling α and mediator mass μ
- The modified Chandrasekhar condition is

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

- Examples when this picture works:

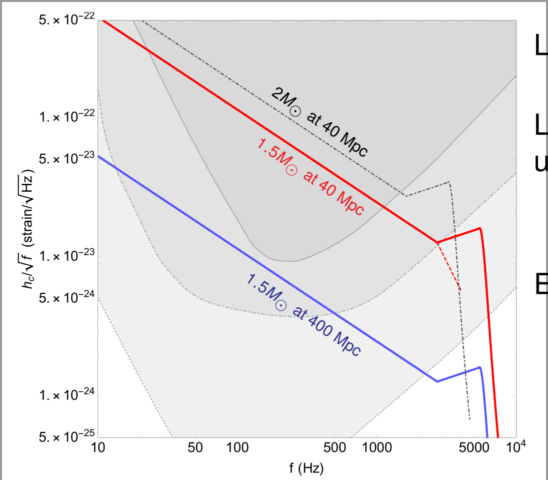
α	$\frac{\mu}{\rm MeV}$	$\frac{m}{\rm TeV}$	$N_{\rm cr}$	$N_{\rm Ch}$	$\frac{M_{\rm Ch}}{\rm M_\odot}$
10^{-3}	10	1	$5 \cdot 10^{35}$	$2 \cdot 10^{37}$	10^{-17}
10^{-4}	2	0.2	$2 \cdot 10^{35}$	$7 \cdot 10^{40}$	10^{-14}
10^{-4}	1	1	$3 \cdot 10^{33}$	$6 \cdot 10^{35}$	10^{-18}
10^{-3}	3	0.2	$2 \cdot 10^{35}$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

- Potential caveat: there may be another stable state on the way to Schwarzchild radius

Gresham, Zurek, arXiv:1809.08254

DETECTION PROSPECTS

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



LIGO2017

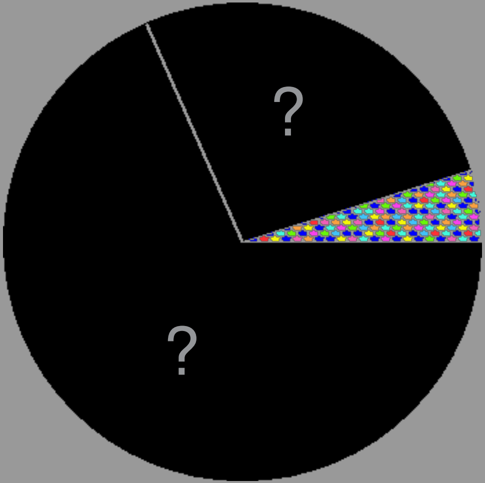
LIGO upgrade

ET

Summary

Both scenarios can be tested by observing NS in DM-rich environment with small velocity dispersion, such as dwarf galaxies

- There are things that we know, but there is a lot more that we don't know!



BACKUP

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

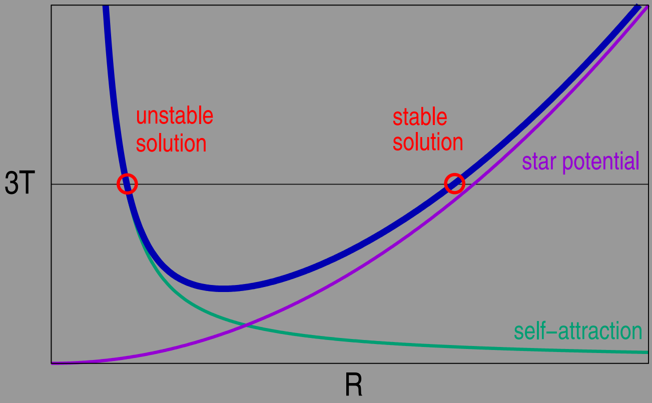
$$V(r) = \alpha e^{-\mu r}/r$$

- 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

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

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

- At small N the solution for R always exists, but at some critical value N_{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 $N = N_{\mathrm{Ch}}$ they merge and disappear.