University of Southern Denmark

Strongly Interacting Dark Matter & Stars

Chris Kouvaris

CP^3 - Origins

Particle Physics & Origin of Mass

ECT*, 3 October 2018

Dark Matter Production Mechanisms

- Thermal Freeze-out (possible signal from Galactic centre and/or Sun)
- Asymmetric Dark Matter
- Freeze-in
- …

Asymmetric Dark Matter

- Asymmetric DM can emerge naturally in theories beyond the SM
- Alternative to thermal production
- Possible link between baryogenesis and DM relic density

TeV WIMP

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{n_{TB}}{n_B}\frac{M_{TB}}{M_p}$$

$$\frac{n_{TB}}{n_B} \sim e^{-M_{TB}/T_*}$$

$$e^{-4}10^3 \simeq 18 \sim 5$$

Light WIMP ~GeV

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{n_{TB}}{n_B}\frac{M_{TB}}{M_p}$$

$$n_{TB} = n_B$$

$$M_{TB} = 5\text{GeV}$$

$$1 \times 5 = 5$$

Nussinov '85, Barr Chivukula Farhi '90, Gudnason CK Sannino '06
Khlopov CK '07, CK '08, Ryttov Sannino '08, Kaplan Luty Zurek '09, Buckley Randall '10
Dutta Kumar '10, Taoso '10, Falkowski Ruderman Volansky '11, Petraki Volkas '13, Zurek '13, …

Asymmetric Composite Dark Matter

Example:

SU(4) ⟶ SO(4)

$$Q = \begin{pmatrix} U_L \\ D_L \\ -i\sigma^2 U_R^* \\ -i\sigma^2 D_R^* \end{pmatrix} \qquad \langle Q_i^\alpha Q_j^\beta \epsilon_{\alpha\beta} E^{ij} \rangle = -2\langle \overline{U}_R U_L + \overline{D}_R D_L \rangle \qquad E = \begin{pmatrix} 0 & \mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}$$

9 Goldstone Bosons

$$\overline{D}_R U_L \ , \qquad \overline{U}_R D_L \ , \qquad \frac{1}{\sqrt{2}}(\overline{U}_R U_L - \overline{D}_R D_L)$$

Eaten by W's and Z

$$U_L U_L \ , \qquad D_L D_L \ , \qquad U_L D_L$$ carrying DM number

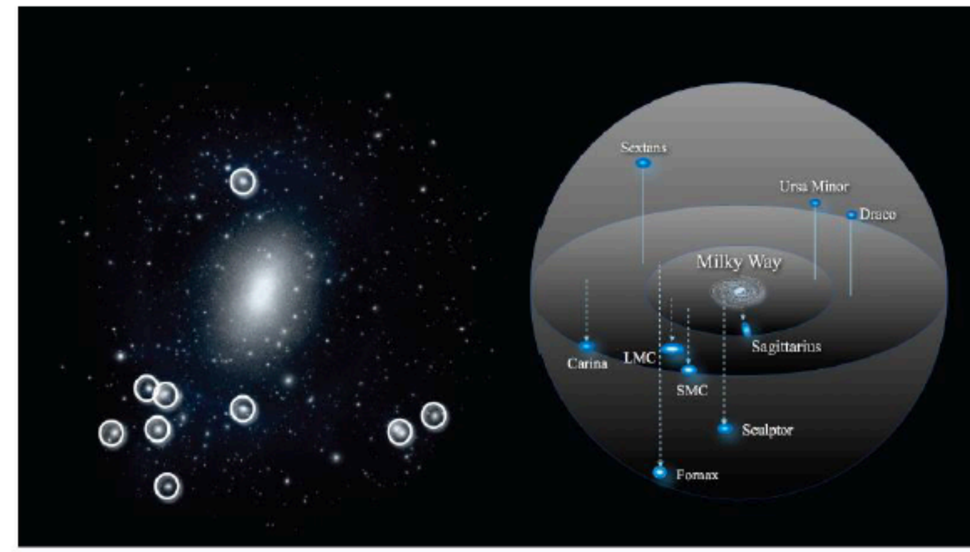
Extra lepton family to cancel Witten global anomaly

Gudnason CK Sannino '06

Why Dark Matter Self-Interactions?

Problems with Collisionless Cold Dark Matter

- Core-cusp profile in dwarf galaxies
- Number of Satellite galaxies
- "Too big to fail"



From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)

Numerical Simulations suggest $0.1\,\mathrm{cm}^2/\mathrm{g} < \sigma/m < 1\,\mathrm{cm}^2/\mathrm{g}$

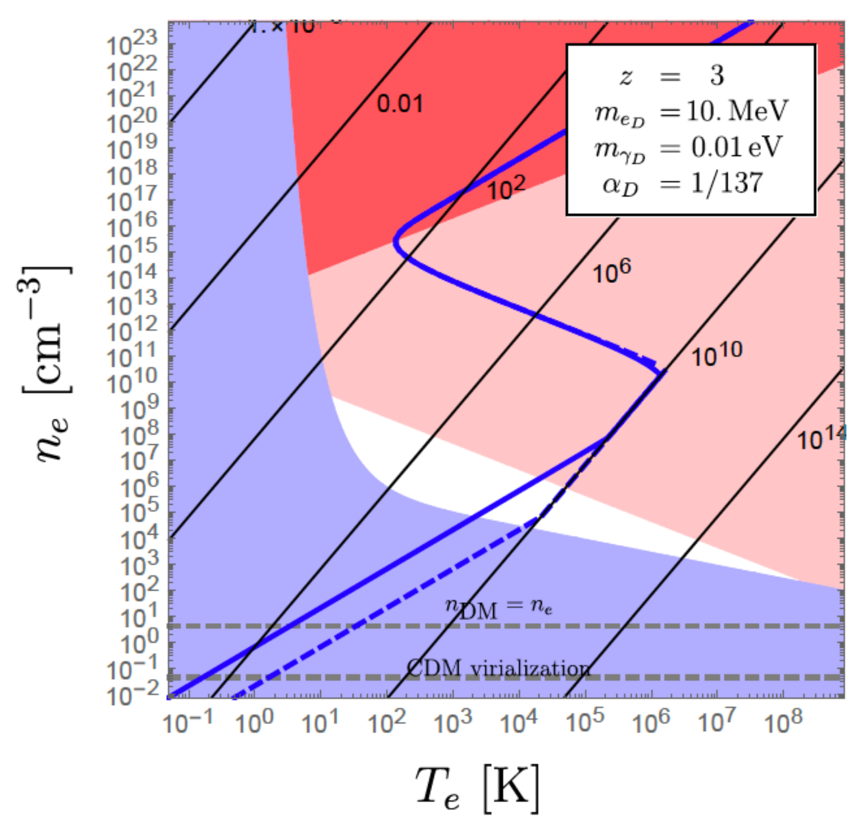
Extra motivation for a small strongly interacting DM component:
Provide seeds for the Supermassive Black hole at the center of galaxy
Pollack Spergel Steinhardt '15

Can Asymmetric Dark Matter Make its own “Compact Stars”?

- Can dark matter have strong self-interactions and lead to gravitational collapse and formation of compact dark objects?

- What are the possible formation mechanisms?

1. Gravothermal collapse
2. Accretion from Supermassive stars
3. Cosmological Perturbations-> Bremsstrahlung Cooling->Asymmetric Dark Stars (Chang, Egana, Essig, CK soon)

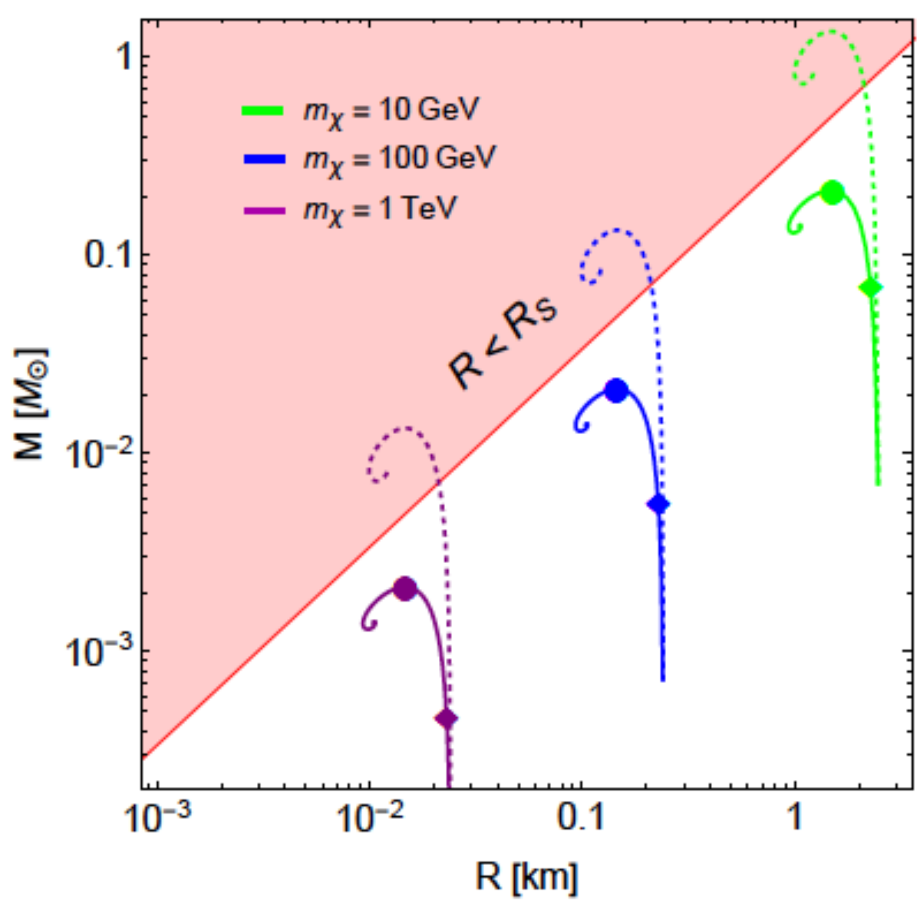


Asymmetric Fermionic Dark Stars

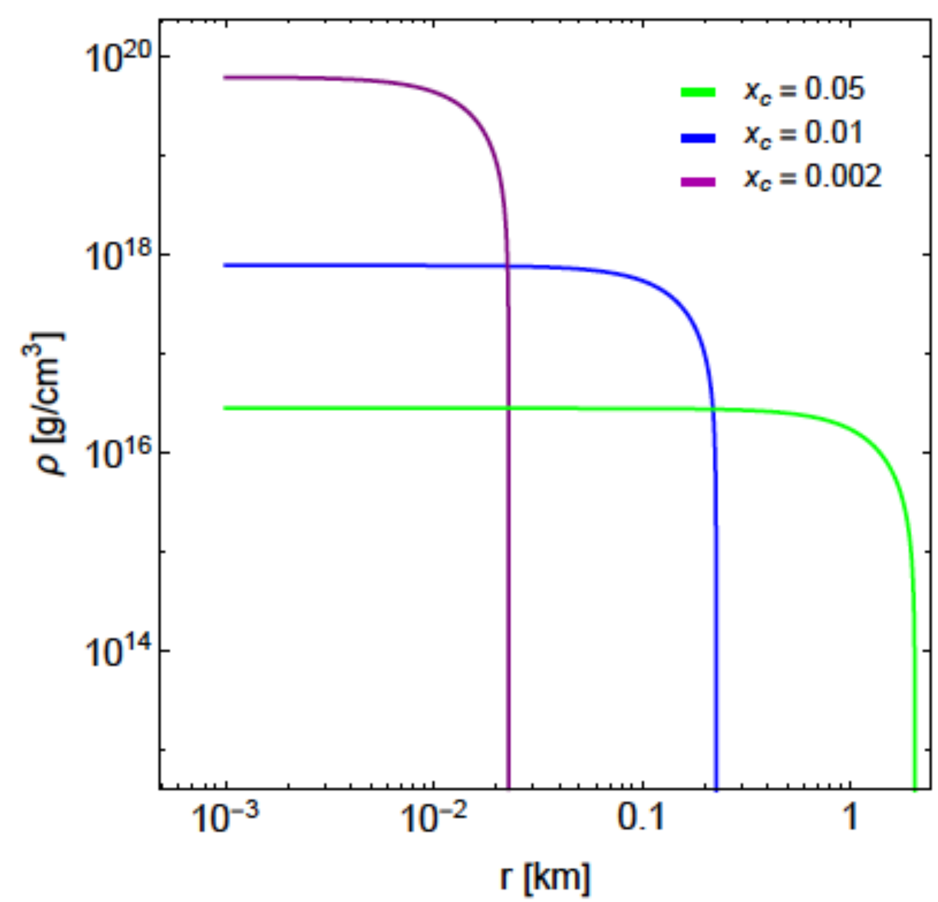
Tolman-Oppenheimer-Volkoff with Yukawa self-interactions

$$P = \frac{g_s}{2} m_\chi^4 \psi(x) \pm \frac{\alpha g_s^2}{18\pi^3} \frac{m_\chi^6}{\mu^2} x^6,$$
$$\rho = \frac{g_s}{2} m_\chi^4 \xi(x) \pm \frac{\alpha g_s^2}{18\pi^3} \frac{m_\chi^6}{\mu^2} x^6.$$

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



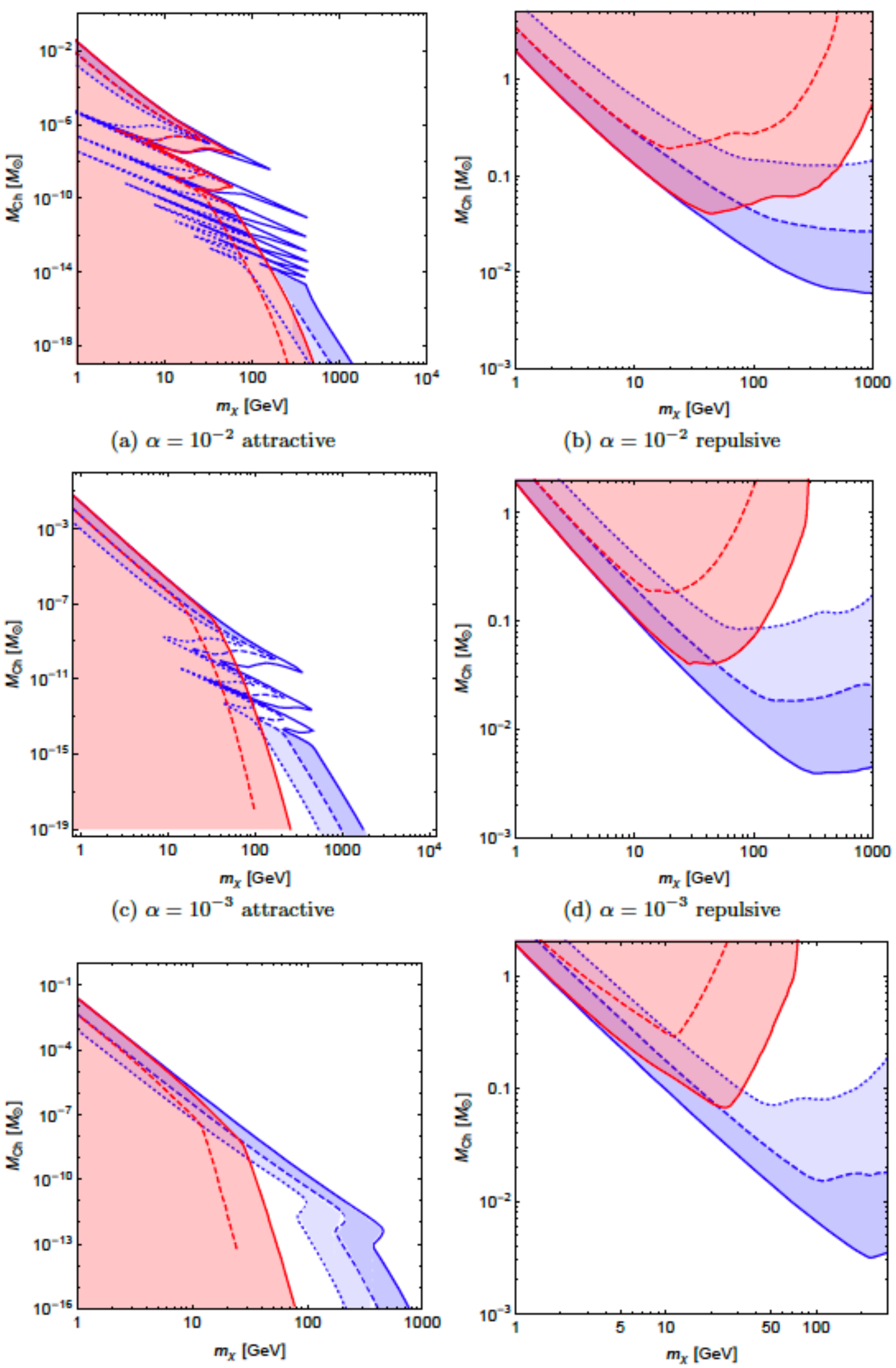
(a) $M(R)$ for repulsive interactions



(b) $\rho(r)$ for repulsive interactions

CK, Nielsen '15

Chandrasekhar Mass Limits for Dark Stars



(a) $\alpha = 10^{-2}$ attractive (b) $\alpha = 10^{-2}$ repulsive

(c) $\alpha = 10^{-3}$ attractive (d) $\alpha = 10^{-3}$ repulsive

(e) $\alpha = 10^{-4}$ attractive (f) $\alpha = 10^{-4}$ repulsive

$$\frac{GNm^2}{r} > k_F = \left(\frac{3\pi^2 N}{V}\right) = \left(\frac{9\pi}{4}\right)^{1/3} \frac{N^{1/3}}{r}$$

$N > M_{pl}^3 / m^3$

Gresham Zurek '18 disagree with the attractive case, finding larger Chandrasekhar mass than the non-interacting case!!! Ignores the BCS theorem.

Asymmetric Bosonic Dark Stars

BEC Bosonic DM with $\lambda\phi^4$

Repulsive Interactions: Solve Einstein equation together with the Klein-Gordon

$$ds^2 = -B(r)dt^2 + A(r)dr^2 + r^2 d\Omega^2$$

$$\frac{A'}{A^2 x} + \frac{1}{x^2}\left(1 - \frac{1}{A}\right) = \left(\frac{\Omega^2}{B} + 1\right)\sigma^2 + \frac{\Lambda}{2}\sigma^4 + \frac{(\sigma')^2}{A}$$

$$\frac{B'}{B^2 x} + \frac{1}{x^2}\left(1 - \frac{1}{A}\right) = \left(\frac{\Omega^2}{B} + 1\right)\sigma^2 - \frac{\Lambda}{2}\sigma^4 + \frac{(\sigma')^2}{A}$$

$$\sigma'' + \left(\frac{2}{x} + \frac{B'}{2B} - \frac{A'}{2A}\right)\sigma' + A\left[\left(\frac{\Omega^2}{B} - 1\right)\sigma - \Lambda\sigma^3\right] = 0,$$

$x = mr$, $\sigma = \sqrt{4\pi G}\Phi$ (Φ the scalar field), $\Omega = \omega/m$ $\quad \Lambda = \lambda M_P^2/(4\pi m^2)$

Attractive Interactions: We can use the nonrelativistic limit solving the the Gross-Pitaevskii with the Poisson

$$E\psi(r) = \left(-\frac{\vec{\nabla}^2}{2m} + V(r) + \frac{4\pi a}{m}|\psi(r)|^2\right)\psi(r) \qquad \vec{\nabla}^2 V(r) = 4\pi G m \rho(r)$$

Eby, CK, Nielsen, Wijewardhana ‘15

Asymmetric Bosonic Dark Stars

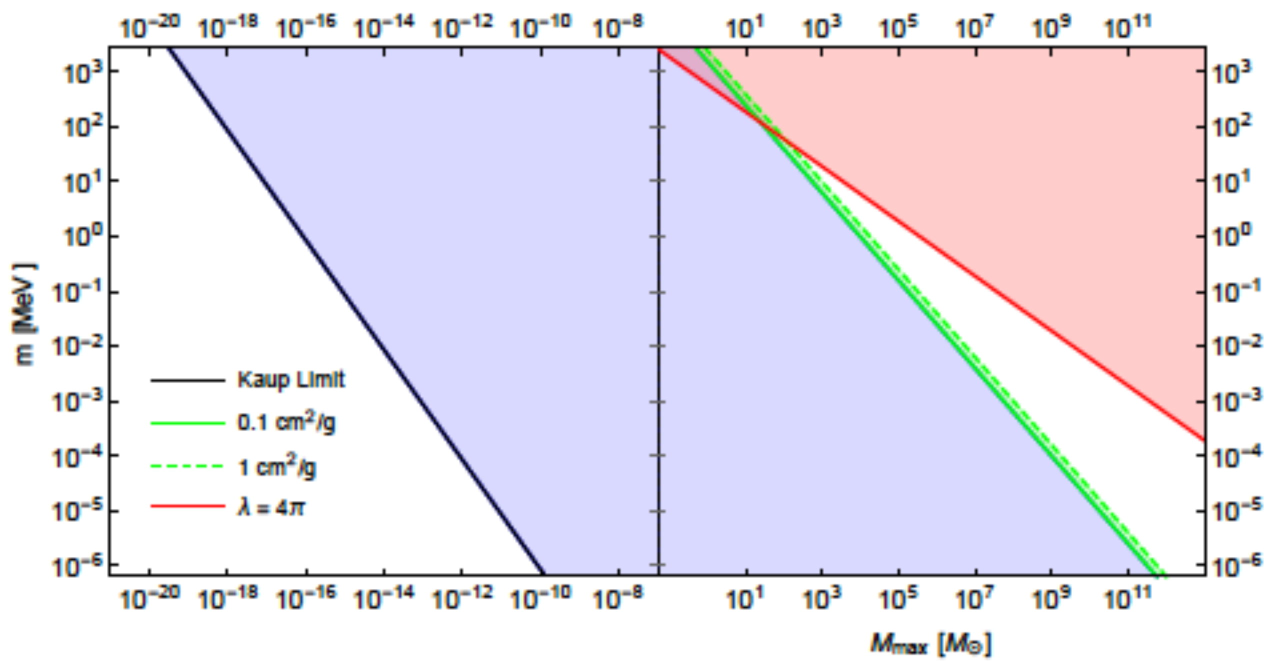
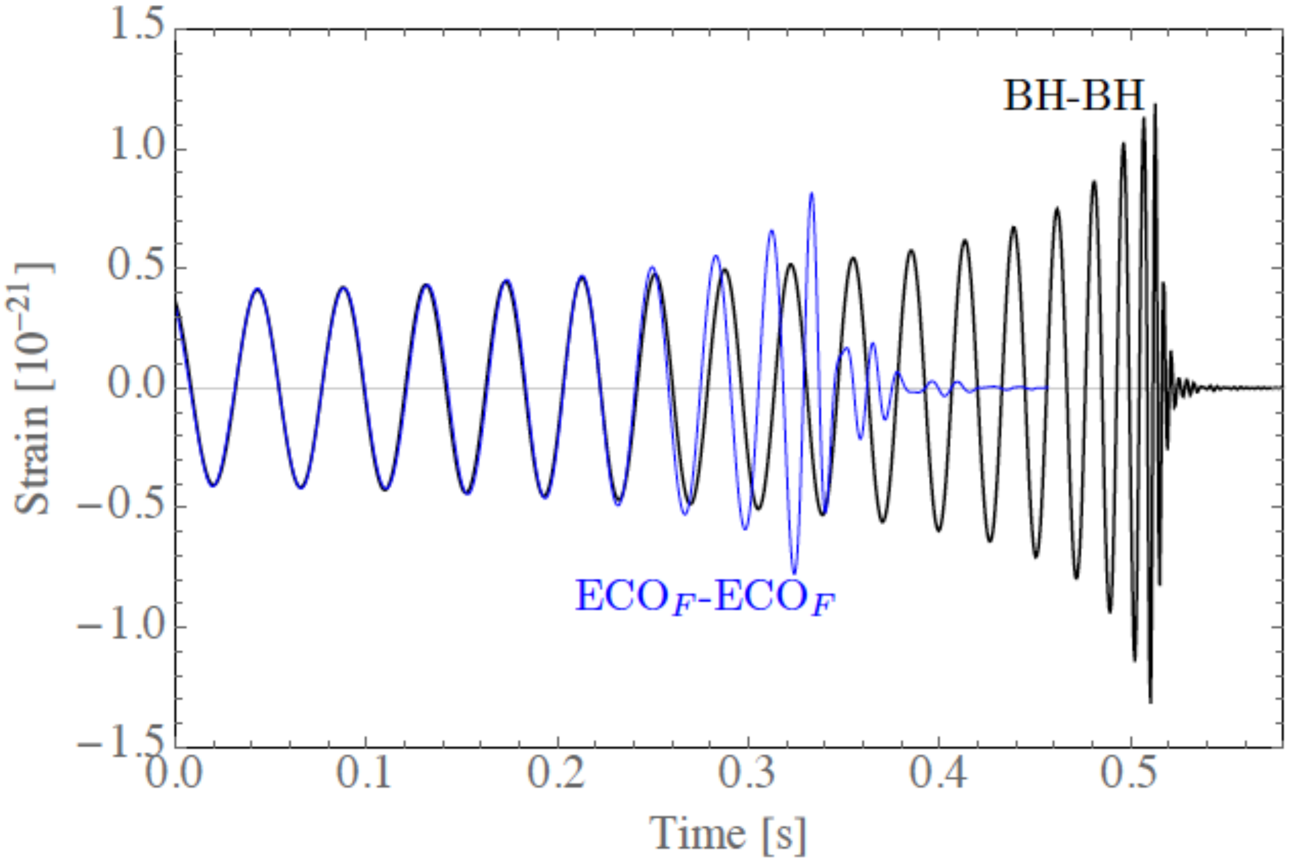


Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass m. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths (smaller than 0.1 cm^2/g) extending down to the Kaup limit which is shown in black. The red shaded region corresponds to $\lambda \gtrsim 4\pi$. Note that the horizontal axis is measured in solar masses $M_\odot$.

Motivated by string theory, Hui, Ostriker, Tremaine, Witten '16

Gravitational Waves from Dark Stars



Giudice, McCullough, Urbano '16

Tidal Deformations of Dark Stars

How stars deform in the presence of an external gravitational field?

$$V = -(1/2)\varepsilon_{ij} x^i x^j$$

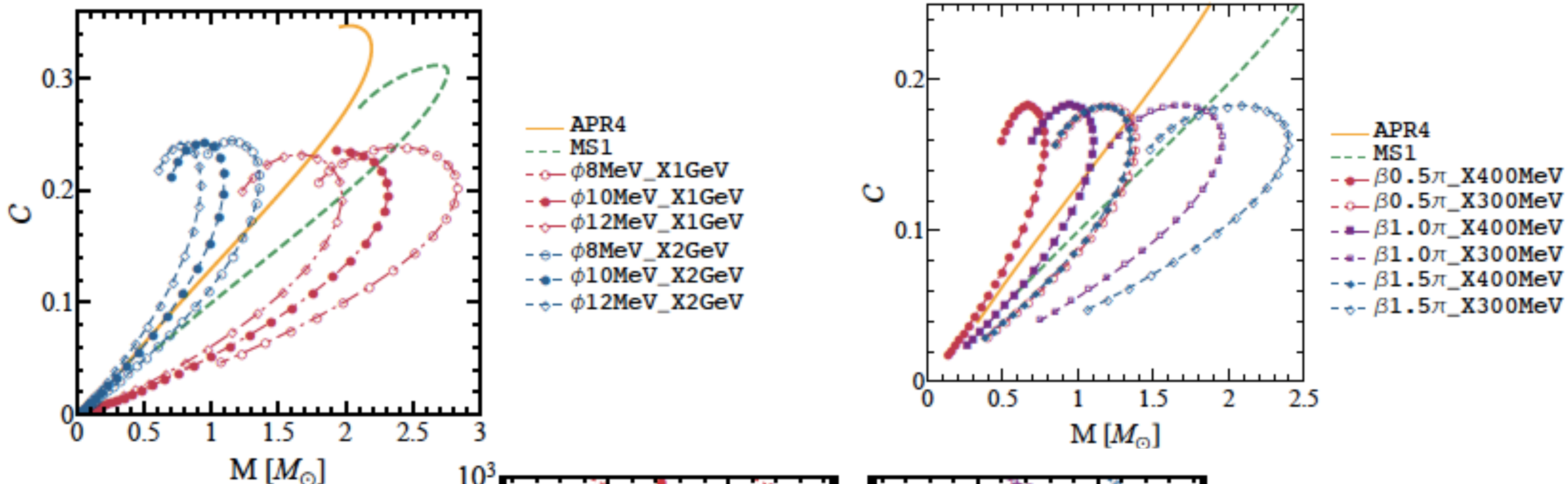
$$Q_{ij} = -\lambda \varepsilon_{ij}$$

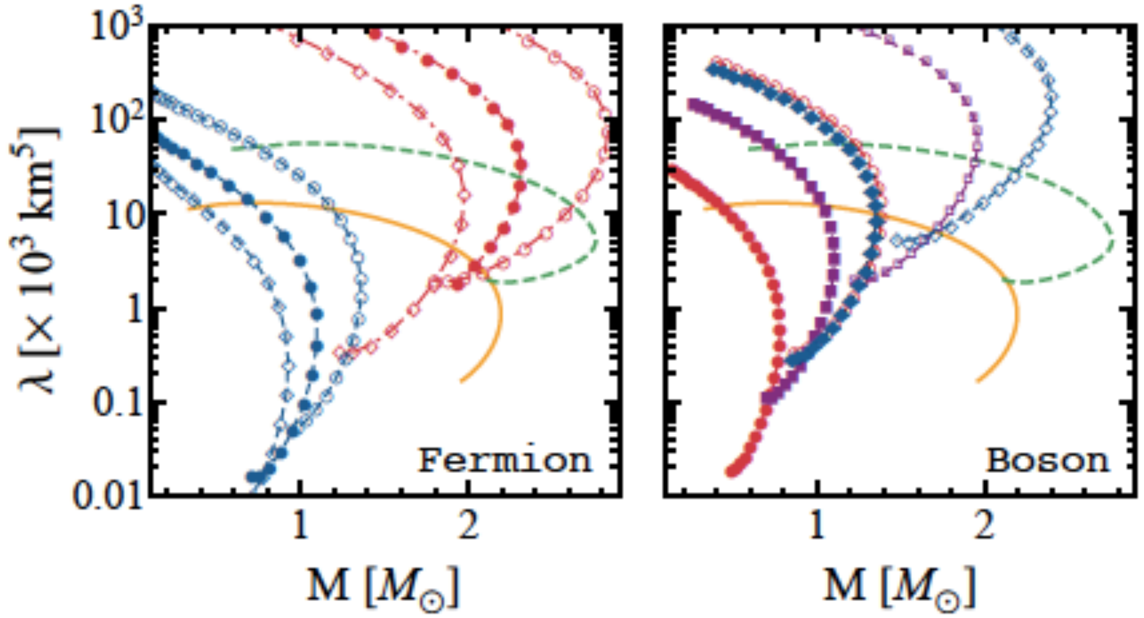
$$\lambda = \frac{2}{3} k_2 R^5$$

Love number

Similarly we can estimate the deformation due to rotation

I-Love-Q for Dark Stars





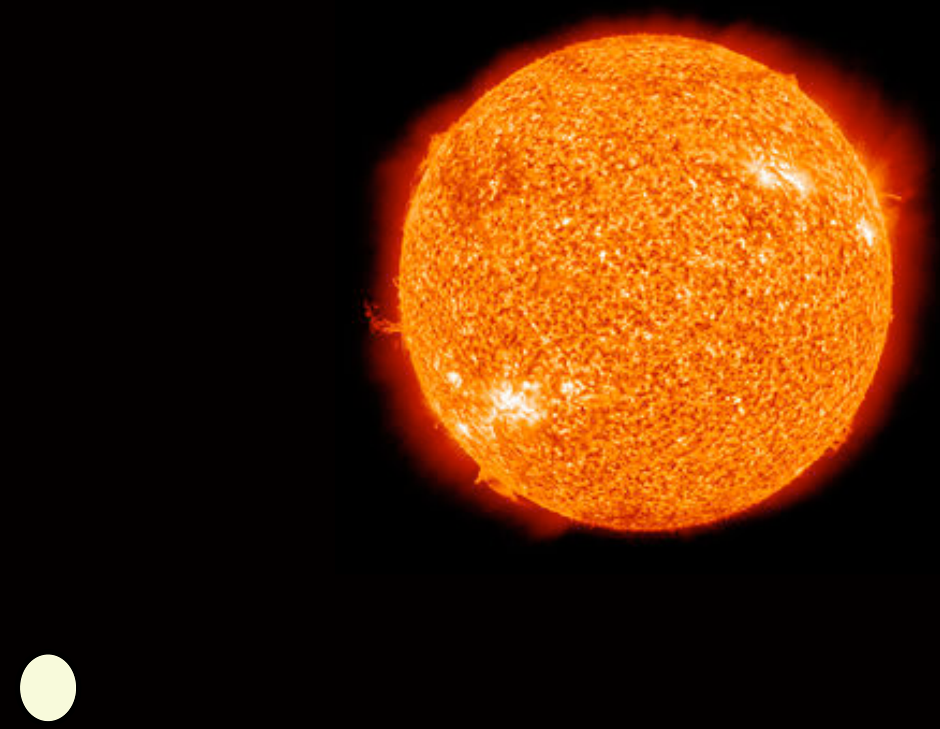
Maselli, Pnigouras,Nielsen, CK, Kokkotas, 17

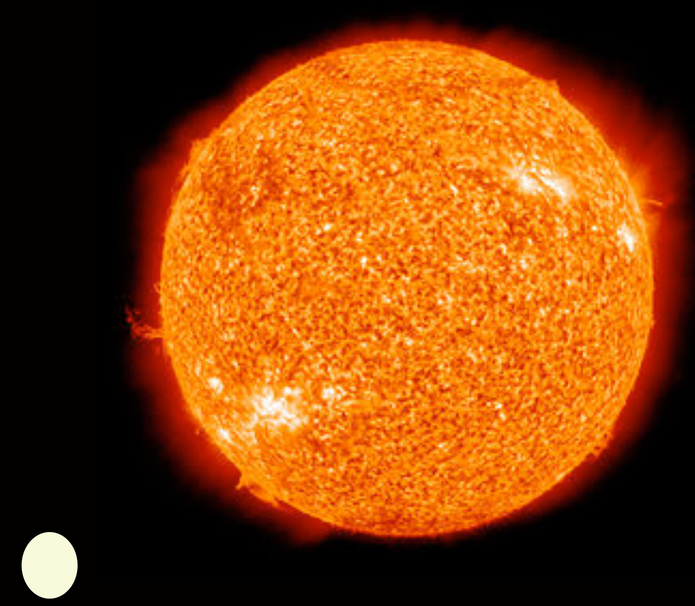
I-Love-Q relations

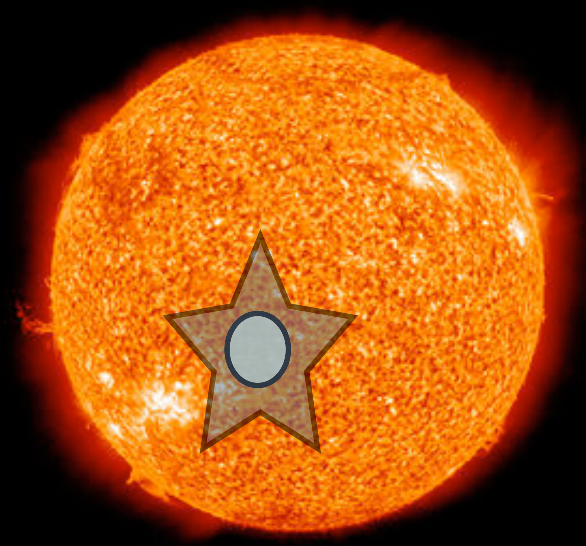
$$\ln y = a + b \ln x + c(\ln x)^2 + d(\ln x)^3 + e(\ln x)^4$$

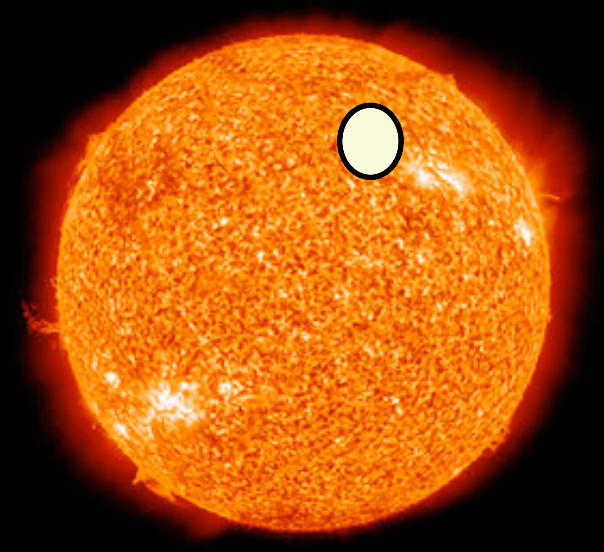
$$\bar{I} = \frac{I}{M^3} \quad , \quad \bar{Q} = -\frac{Q}{M^3\chi^2} \quad , \quad \bar{\lambda} = \frac{\lambda}{M^5}$$

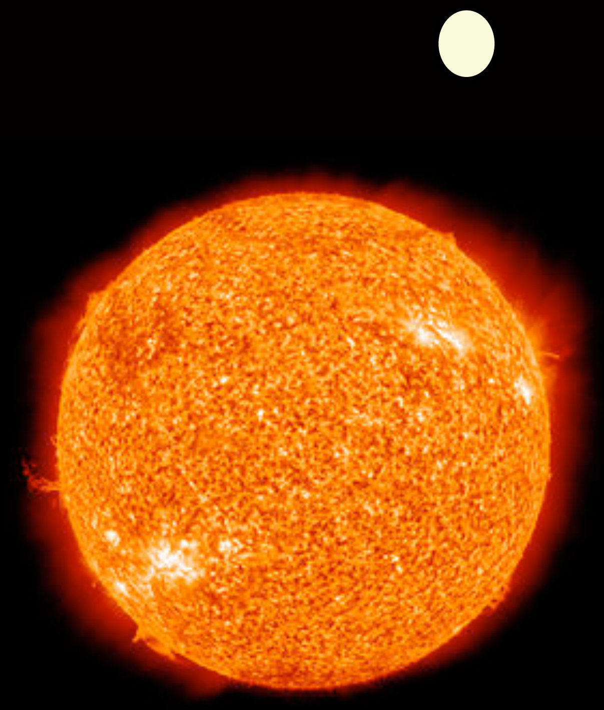
Converting Neutron Stars to Black Holes

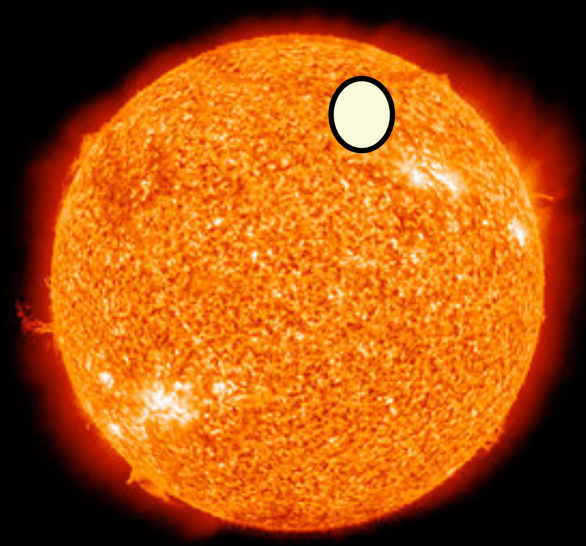


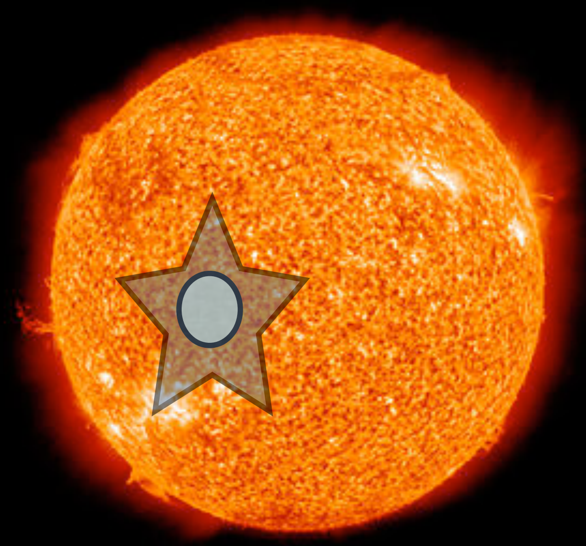


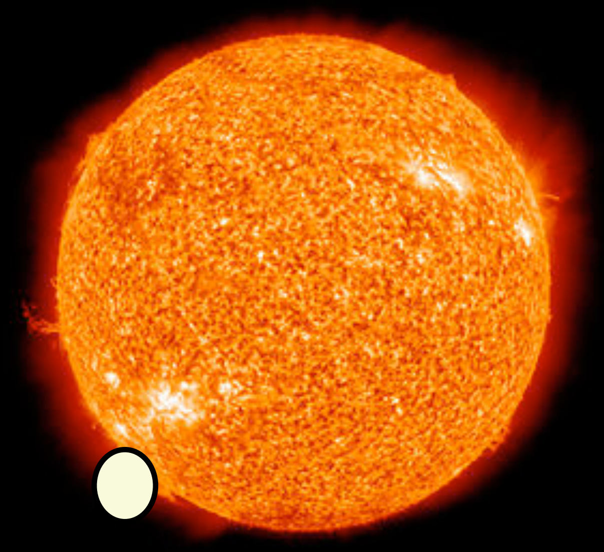


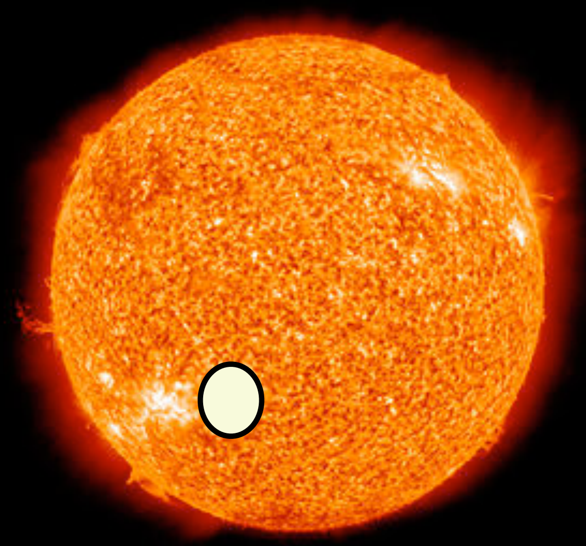


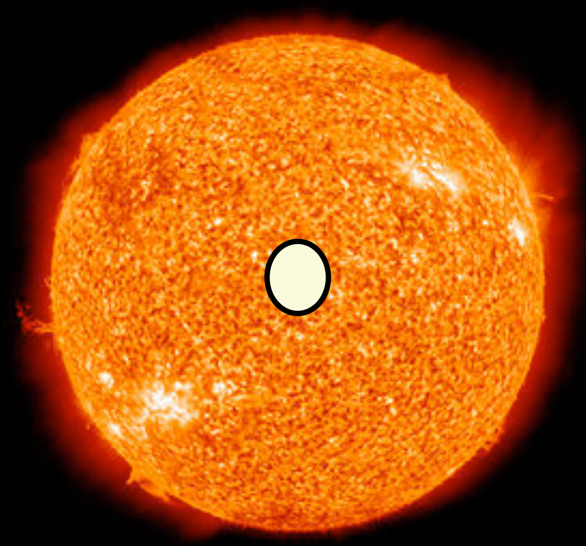


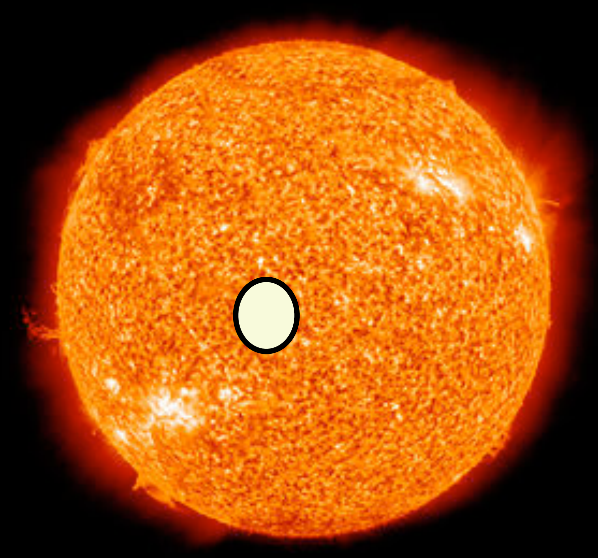


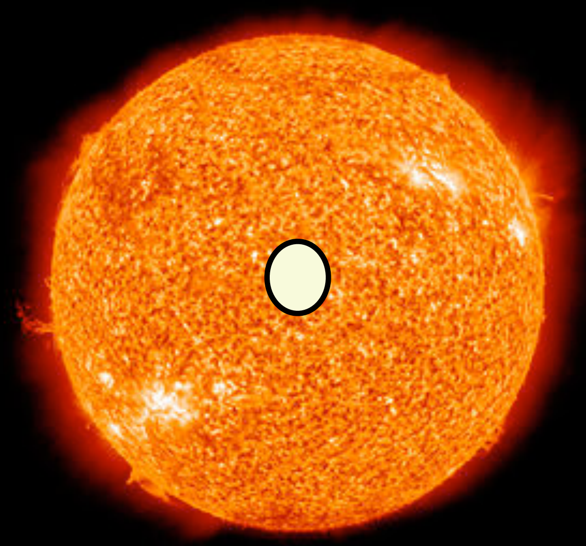


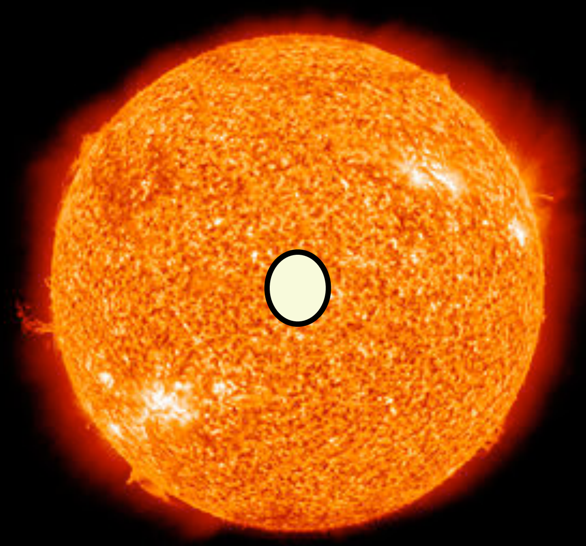


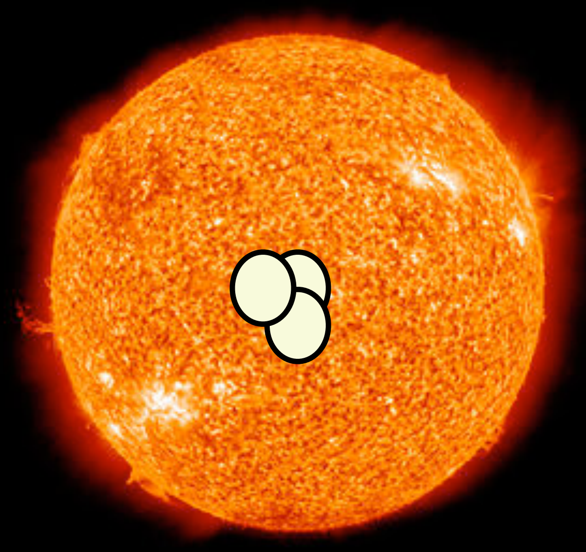


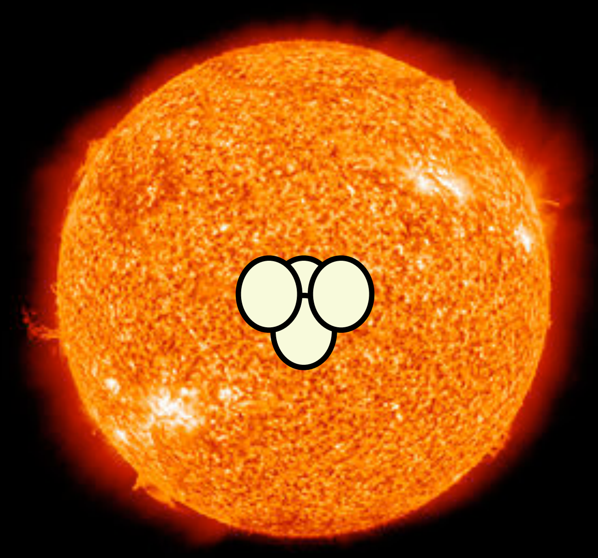


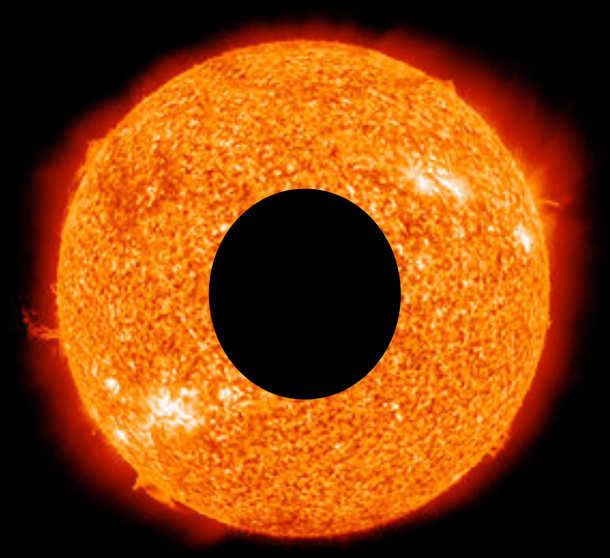


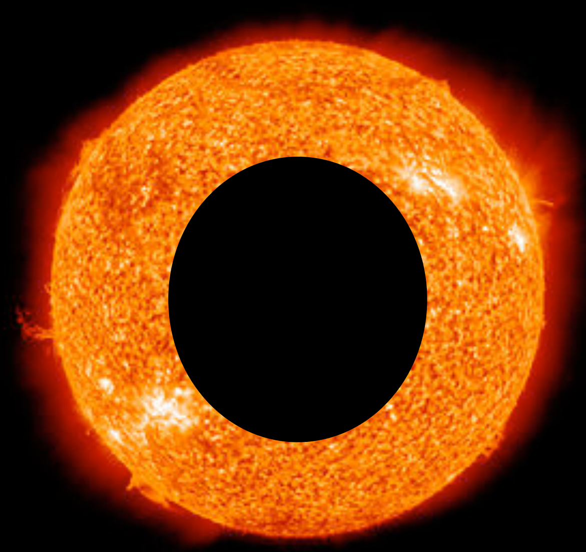


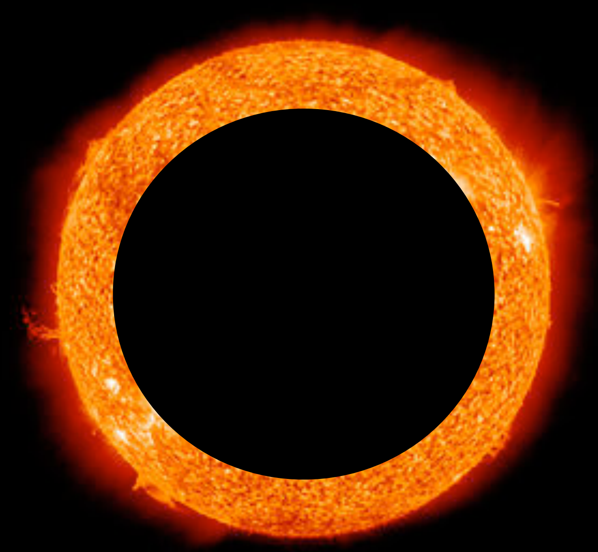












Asymmetric Dark Matter in Neutron Stars

Asymmetric dark matter captured by neutron stars can lead to formation of mini-black holes that eventually destroy the star

Capture

$$M_{\rm acc} = 1.3 \times 10^{43} \left(\frac{\rho_{\rm dm}}{0.3{\rm GeV/cm^3}}\right)\left(\frac{t}{\rm Gyr}\right) f \ {\rm GeV}$$

Press Spergel '85, Gould '86, Nussinov Goldman '89, CK'07

Thermalization

$$t_{\rm th} = 0.2{\rm yr}\left(\frac{m}{\rm TeV}\right)^2\left(\frac{\sigma}{10^{-43}{\rm cm^2}}\right)^{-1}\left(\frac{T}{10^5{\rm K}}\right)^{-1}$$

$$r_{\rm th} = \left(\frac{9kT_c}{8\pi G\rho_c m}\right)^{1/2} = 220{\rm cm}\left(\frac{\rm GeV}{m}\right)^{1/2}\left(\frac{T_c}{10^5 K}\right)^{1/2}$$

Goldman Nussinov'89, CK Tinyakov '10 Bertoni Nelson Reddy '13

BEC formation

$$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3}\frac{2\pi\hbar^2}{mk_B} \approx 3.31\,\frac{\hbar^2 n^{2/3}}{mk_B} \qquad N_{\rm BEC} \simeq 2\times 10^{36}$$

$$r_c = \left(\frac{8\pi}{3}G\rho_c m^2\right)^{-1/4} \simeq 1.6\times 10^{-4}\left(\frac{\rm GeV}{m}\right)^{1/2}{\rm cm}$$

Self-Gravitation

$$M > 8\times 10^{27}\ {\rm GeV}\left(\frac{m}{\rm GeV}\right)^{-3/2}$$

Asymmetric Dark Matter in Neutron Stars

Collapse $$t_{\rm cool} = \tau_{\rm col} \frac{\delta E}{N \delta\epsilon} = \tau_{\rm col} \frac{m \delta E}{M \delta\epsilon} = \frac{4}{3\pi} \frac{p_F}{m_N} \frac{r_0 M_{\rm Pl}^4}{\rho_c \sigma M^2}$$ CK Tinyakov '12

DM-nucleon interactions evacuate the energy from the DM collapsing cloud

Bosons $$\frac{GNm^2}{r} \simeq \frac{\hbar}{r} \longrightarrow M_{crit} = \frac{2M_{\rm Pl}^2}{\pi m}\sqrt{1 + \frac{M_{\rm Pl}^2}{4\sqrt{\pi} m}\sigma^{1/2}}$$

Fermions $$\frac{GNm^2}{r} > k_F = \left(\frac{3\pi^2 N}{V}\right) = \left(\frac{9\pi}{4}\right)^{1/3} \frac{N^{1/3}}{r}$$

Evolution of the Black Hole $$\frac{dM}{dt} = \frac{4\pi \rho_c G^2 M^2}{c_s^3} - \frac{1}{15360\pi G^2 M^2}$$ CK Tinyakov '13

Bondi accretion

Hawking radiation

The effect of Rotation I

The accretion is never perfectly spherical because the neutron star rotates usually with high frequencies.

The conditions for Bondi accretion are valid as long as the angular momentum of an infalling piece of matter is much smaller than the keplerian one in the last stable orbit

The mass of the black hole must be larger than

$$M_{\rm crit} = \frac{1}{12^{3/2}} \left(\frac{3}{4\pi \rho_c} \right)^2 \left(\frac{\omega_0}{G} \right)^3 \frac{1}{\psi^3} \qquad M_{\rm crit} = 2.2 \times 10^{46} P_1^{-3} \ {\rm GeV}$$

CK, Tinyakov '13

viscosity of nuclear matter saves Bondi

$$\frac{\partial}{\partial t} l - \frac{C_0 M^2}{4\pi \rho r^2} \frac{\partial}{\partial r} l = \frac{1}{\rho r^2} \frac{\partial}{\partial r} \left[\rho \nu r^4 \frac{\partial}{\partial r} \left(\frac{1}{r^2} l \right) \right].$$

It subtracts angular momentum at the initial stage where the black hole is still small

in the final stages Bondi accretion is not valid but the star is seconds away from destruction!

Blocking the Hawking Radiation

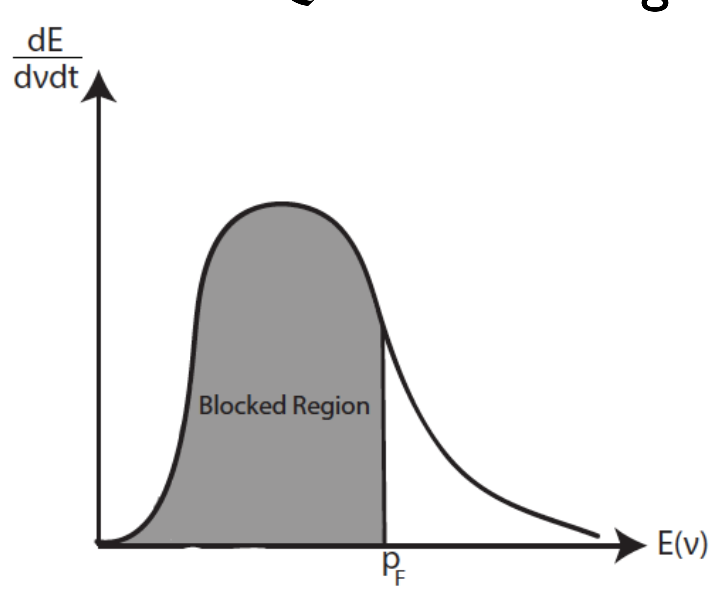
$$T = \frac{1}{8\pi G M_c} = \frac{m}{16} \qquad \frac{dM}{dt} = -(n_f f_f + n_b f_b + n_s f_s + n_2 f_2)\frac{1}{G^2 M^2}$$

Degenerate matter can block potentially the emission of particles

Weak equilibration and electric neutrality $p_F^u = \mu - \frac{m_s^2}{6\mu} \quad p_F^d = \mu + \frac{m_s^2}{12\mu} \quad p_F^s = \mu - \frac{5m_s^2}{12\mu} \quad \mu_e = \frac{m_s^2}{4\mu}$

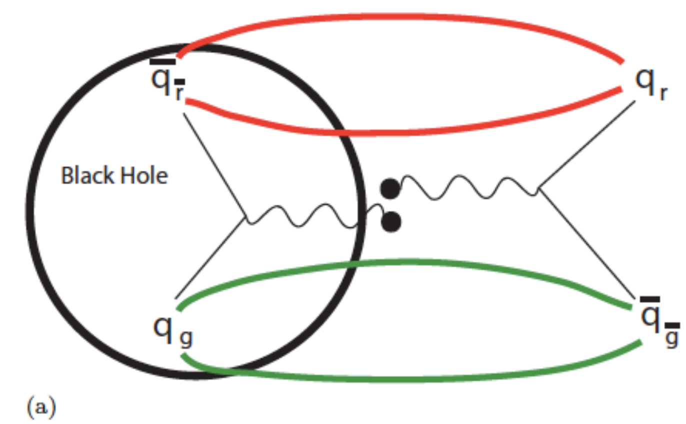
at Bondi radius $\frac{n(r)}{n_\infty} \simeq \frac{\lambda_s}{\sqrt{2}}\left(\frac{GM}{c_s^2 r}\right)^{3/2}$

Quark Blocking

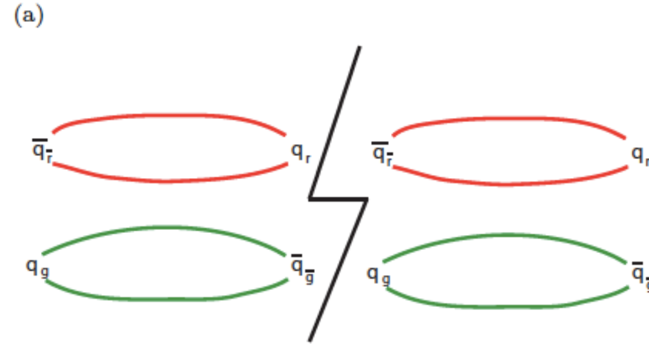


Autzen CK '14

Gluon Blocking



$$\frac{dN}{dt} = 10^{-2}\frac{1}{GM}$$



$$\Delta t = 100GM = \frac{200}{\pi m} >> \lambda_d = \frac{2\pi}{0.37m}$$

The effect of Rotation II

A maximally spinning black hole will stop the accretion

$$a = J/GM^2$$

$$\frac{1}{a}\frac{da}{dt} = \frac{1}{J}\omega_0 r_s^2 \frac{dM}{dt} - \frac{g(a)}{G^2 M^3} - \frac{2}{M}\frac{dM}{dt}$$

$$a_{\max} = 2 \times 10^{-23} T_5^4 / P_1^{10}$$

After formation the black hole spins down, then it spins up and at the last stages it spins down again

Temperature Considerations

Radiation from in falling matter can in principle impede further accretion in two ways:

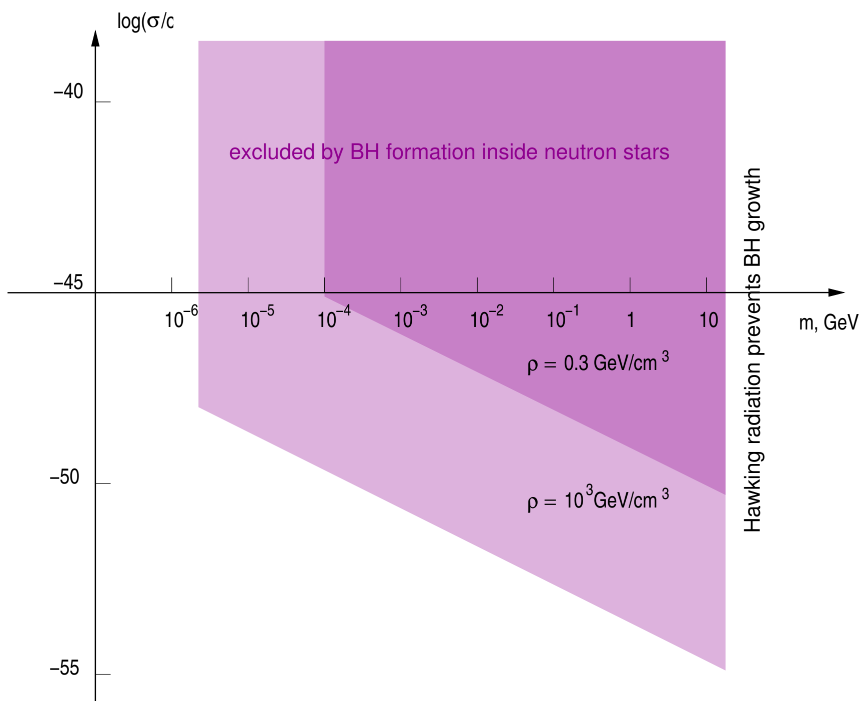
Reduce viscosity

Increase radiation pressure

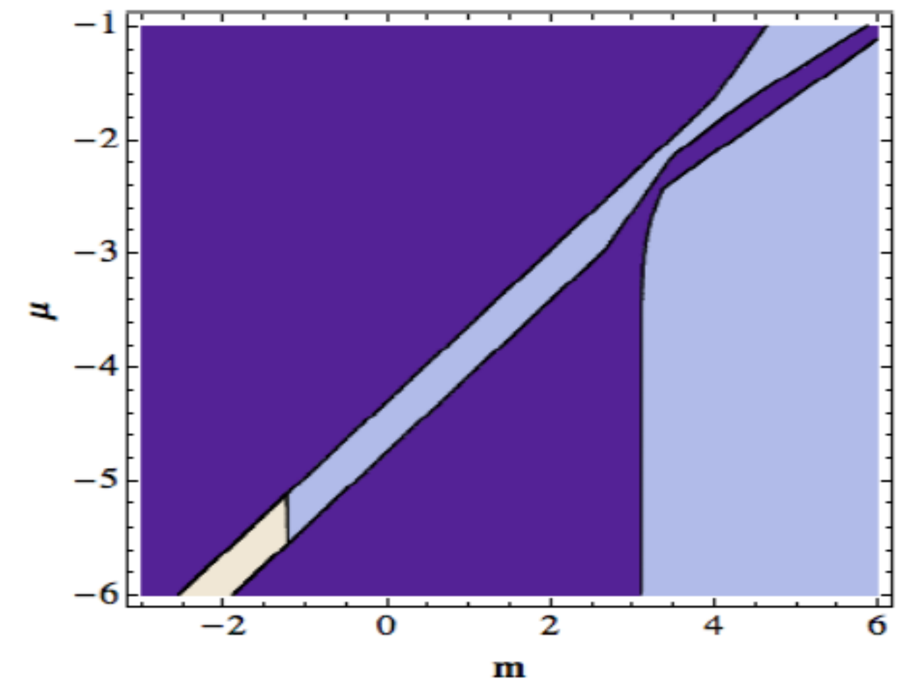
e-e Bremsstrahlung close to the horizon is the dominant radiation mechanism

$$\epsilon = \frac{L_{ee}}{dM/dt} \simeq 5 \times 10^{-12} T_5 \left(\frac{M}{M_0}\right) \qquad \delta T = \frac{L_{ee}}{4\pi k r} \simeq 458 \left(\frac{M}{M_0}\right)^2 \left(\frac{r_B}{r}\right) \mathrm{K}$$

Destroying Stars



CK, Tinyakov Phys.Rev. Lett. '11
McDermott, Yu, Zurek '11



CK Phys.Rev. Lett. '12

$$\alpha\phi\bar{\psi}\psi \quad V(r) = -\alpha \exp[-\mu r]/r$$

Attractive Yukawa $\alpha = 10^{-5}$

Compositeness scale

$$\Lambda_{crit} = m^{1/3} M_{\rm Pl}^{2/3} \left(1 + \frac{\lambda m_{pl}^2}{32\pi m^2}\right)^{-1/3}$$

Solar Mass Non-Priomordial Black Holes

-Assume DM attractive Yukawa self-interactions within the range that solve the problems of CCDM.

#	α	μ	m	$N_{\rm cr}$	$N_{\rm Ch}$	$M_{\rm Ch}$
1	10^{-4}	1 MeV	1 TeV	$3 \cdot 10^{33}$	$6 \cdot 10^{35}$	$5 \cdot 10^{-19} M_\odot$
2	10^{-3}	10 MeV	1 TeV	$5 \cdot 10^{35}$	$2 \cdot 10^{37}$	$2 \cdot 10^{-17} M_\odot$
3	10^{-3}	1 MeV	200 GeV	$1.3 \cdot 10^{34}$	$3 \cdot 10^{38}$	$5 \cdot 10^{-17} M_\odot$
4	10^{-4}	1 MeV	200 GeV	$3.7 \cdot 10^{34}$	$8 \cdot 10^{39}$	$2 \cdot 10^{-15} M_\odot$

-Assume NS binary distribution follows that of galactic baryonic matter, e.g., bulge and double disk

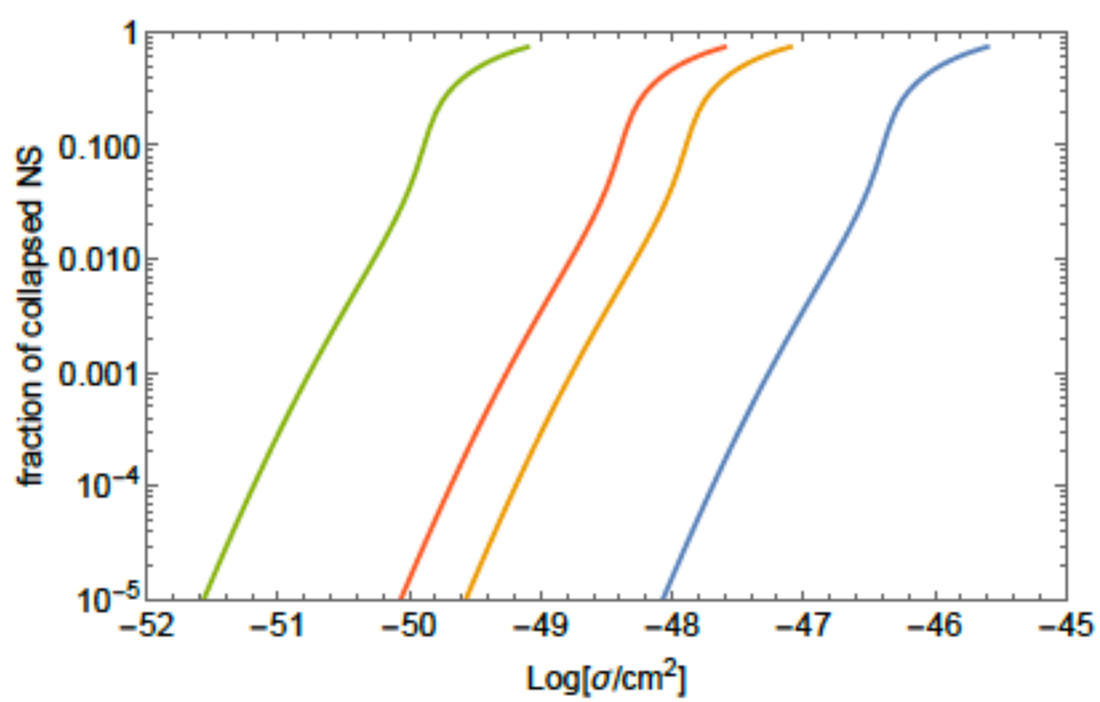


FIG. 1. Fraction of NS collapsed to BH in our Galaxy as a function of the DM-nucleon cross section for benchmark models 1–4 from left to right.

CK, Tinyakov, Tytgat '18

Constraints from young pulsars close to the galactic centre and old NS close to the Earth.

Solar Mass Non-Priomordial Black Holes

Detectors	BNS range (Mpc)	BNS detections (per year)
LIGO/Virgo	105/80	$4 - 80$ (2020+)
KAGRA	100	$11 - 180$ (2024+)
ET	$\sim 5 \cdot 10^3$ $(z \approx 2)$	$\mathcal{O}(10^3 - 10^7)$

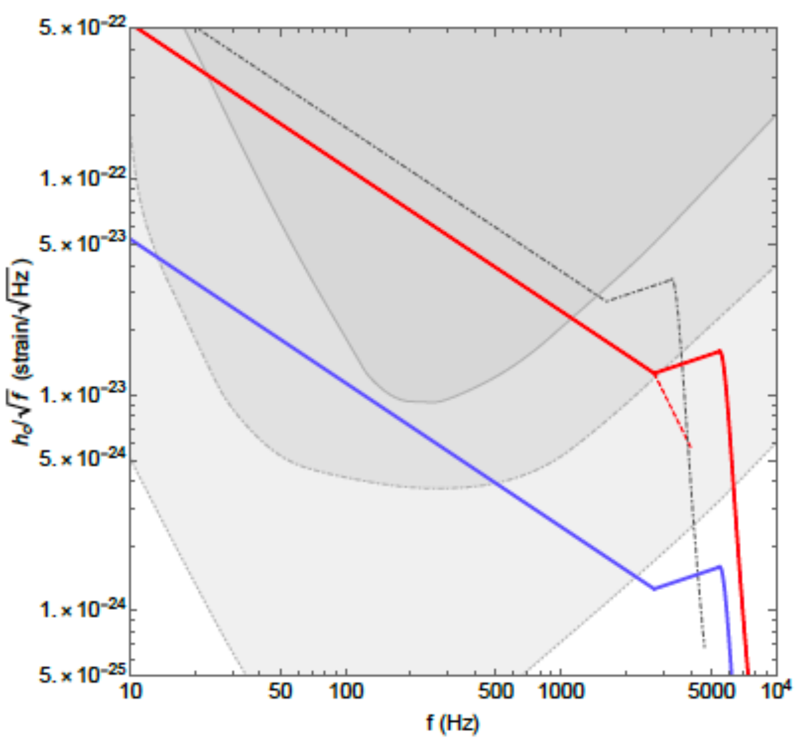


FIG. 2. Spectrum of GW from a $(1.5 + 1.5)M_\odot$ BBH at 40 Mpc (red solid). The spectrum of a corresponding BNS is schematically depicted by the break (red dashed). Also shown are a $(1.5+1.5)M_\odot$ BBH at 400 Mpc (blue solid) and a $(2+2)M_\odot$ BBH at 40 Mpc (grey dot-dashed). The sensitivity curves are for to LIGO2017 (black solid), LIGO design (black dot-dashed) and ET design (black dotted).

CK, Tinyakov, Tytgat '18

-Severe constraints on Asymmetric (Composite) Dark Matter Models orthogonal to direct detection and bullet cluster.

Conclusions

Asymmetric Dark Matter

- Alternative to thermally produced dark matter
- Possible link between baryogengesis and dark matter relic abundance
- Easily embedded to BSM physics

Dark Matter Self-Interactions & Asymmetric Dark Matter

- Solve problems of CCDM
- Asymmetric DM can create compact objects of tens/hundreds of solar masses
- Distinguishable from BH-BH or NS-NS binaries

Collapsing Neutron Stars

- Set strict constraints based on the existence of old nearby NS
- Non-primordial solar mass BH
- Setting new constraints on the absence of signal