University of Southern Denmark

Dark Stars, Dark Matter and Black Holes

Chris Kouvaris

CP^3 - Origins

Particle Physics & Origin of Mass

Solvay Inst. Brussels, 5 April 2019

Why Dark Matter Self-Interactions?

Problems with Collisionless Cold Dark Matter

- Core-cusp profile in dwarf galaxies
- Diversity Problem
- "Too big to fail"

See Hai-Bo Yu's talk

Extra motivation:
Provide seeds for the Supermassive Black hole at the center of galaxy
Pollack Spergel Steinhardt '15

Numerical Simulations suggest $0.1 cm^2/g < \sigma/m < 1 cm^2/g$

An Alternative to WIMPs: 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

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

$$n_{TB} = n_B$$

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

$$1 \times 5 = 5$$

Asymmetric Dark Stars

Can asymmetric dark matter with self-interactions form its own compact objects?

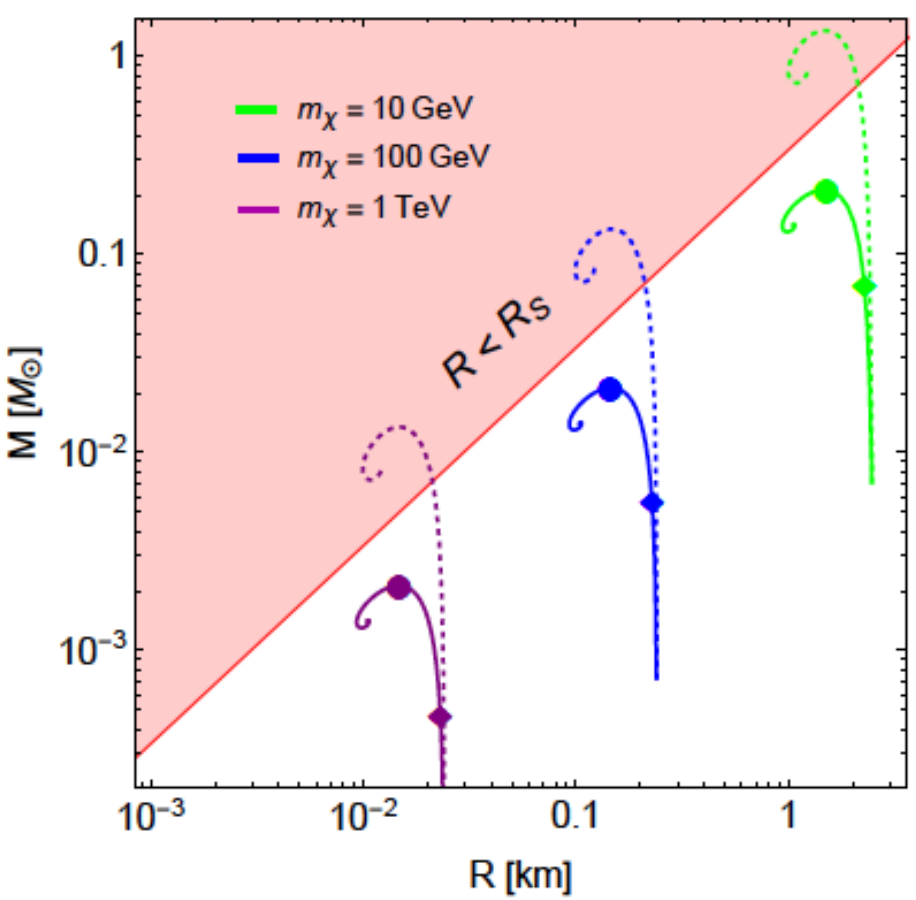
- How do they look like?
- Can we detect them and distinguish them from NS or BH?
- What is the formation mechanism?

Asymmetric Fermionic Dark Stars

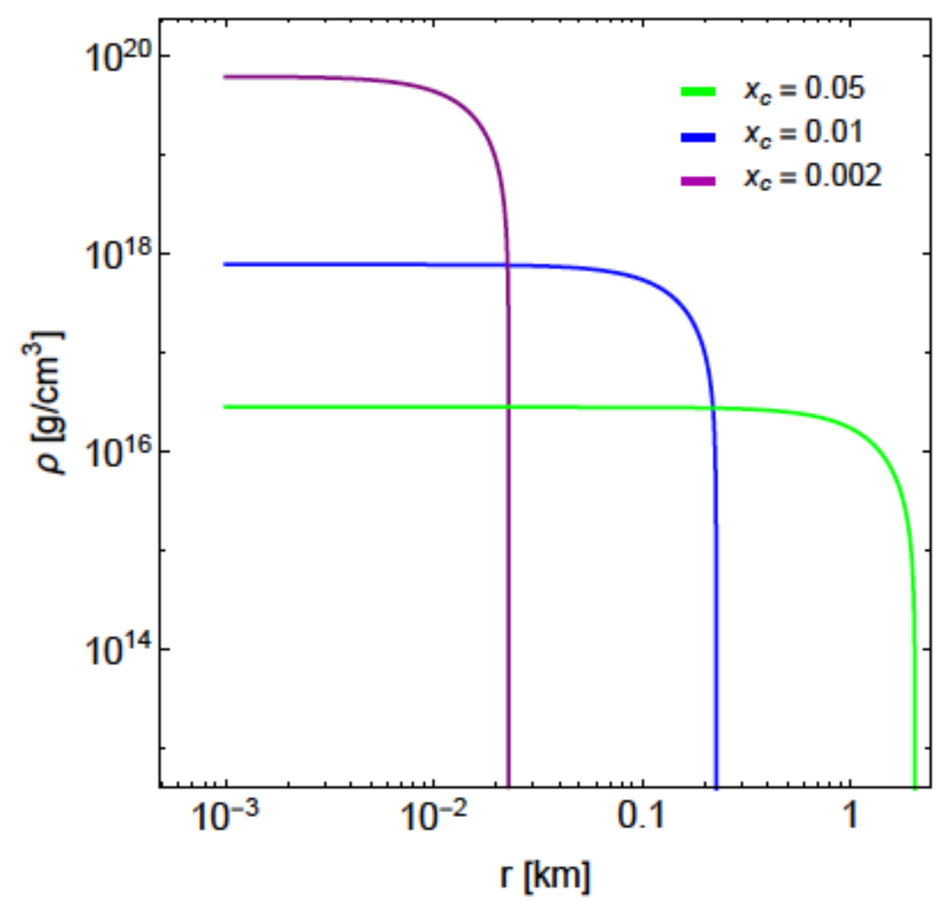
Tolman-Oppenheimer-Volkoff with Yukawa self-interactions

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

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



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



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

CK, Nielsen '15

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

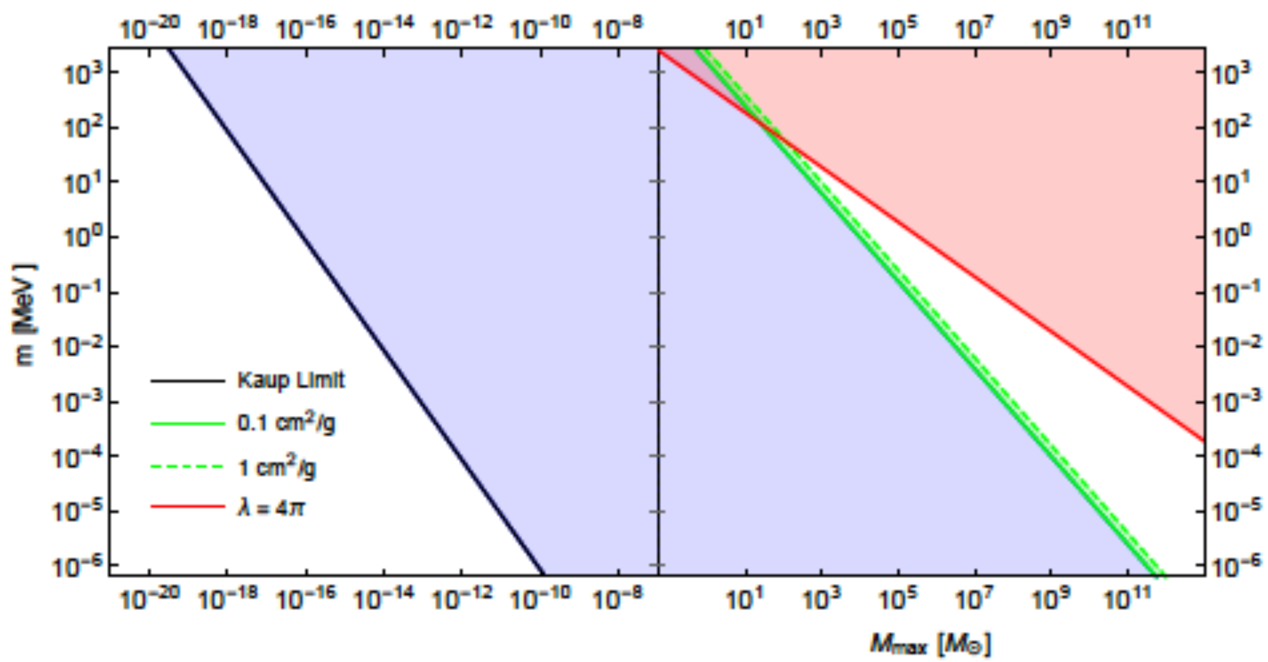
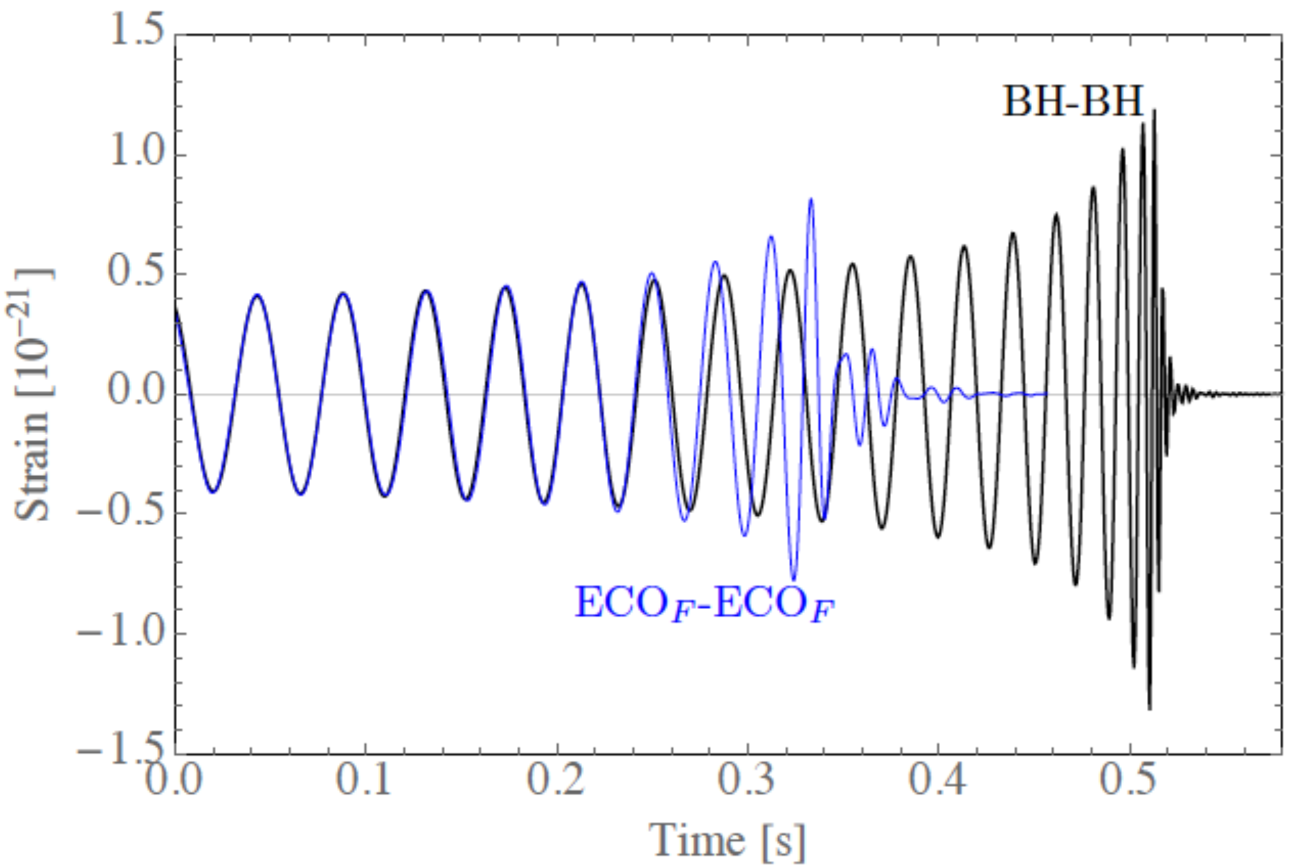


Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass m. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths (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 $M_\odot$.

Gravitational Waves from Dark Stars



Giudice, McCullough, Urbano ‘16

Observation

- Gravitational Waves:
- DS+DS->DS or BH
- DS+NS-> DS*
- DS+BH->BH
- Spinning DS

Tidal Deformations of Dark Stars

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

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

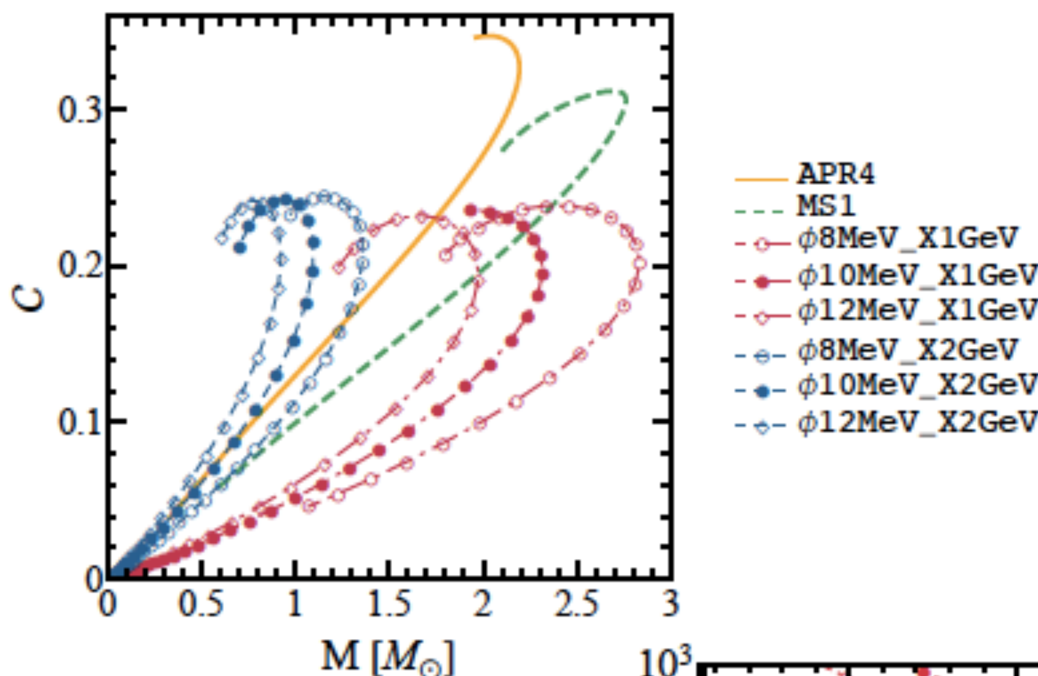
$$Q_{ij}=-\lambda\varepsilon_{ij}$$

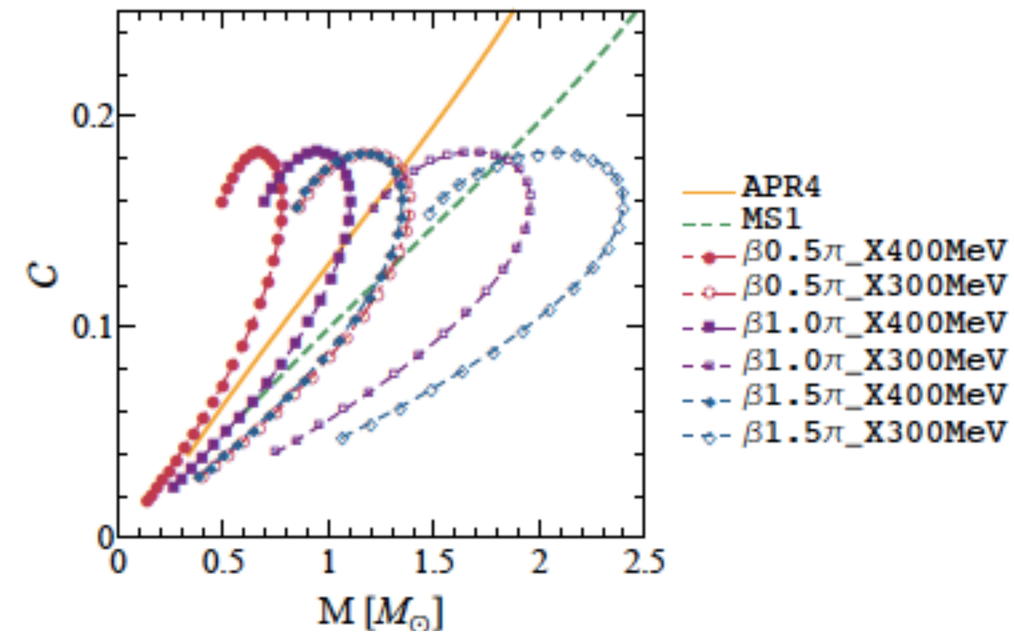
$$\lambda=\frac{2}{3}k_2R^5$$

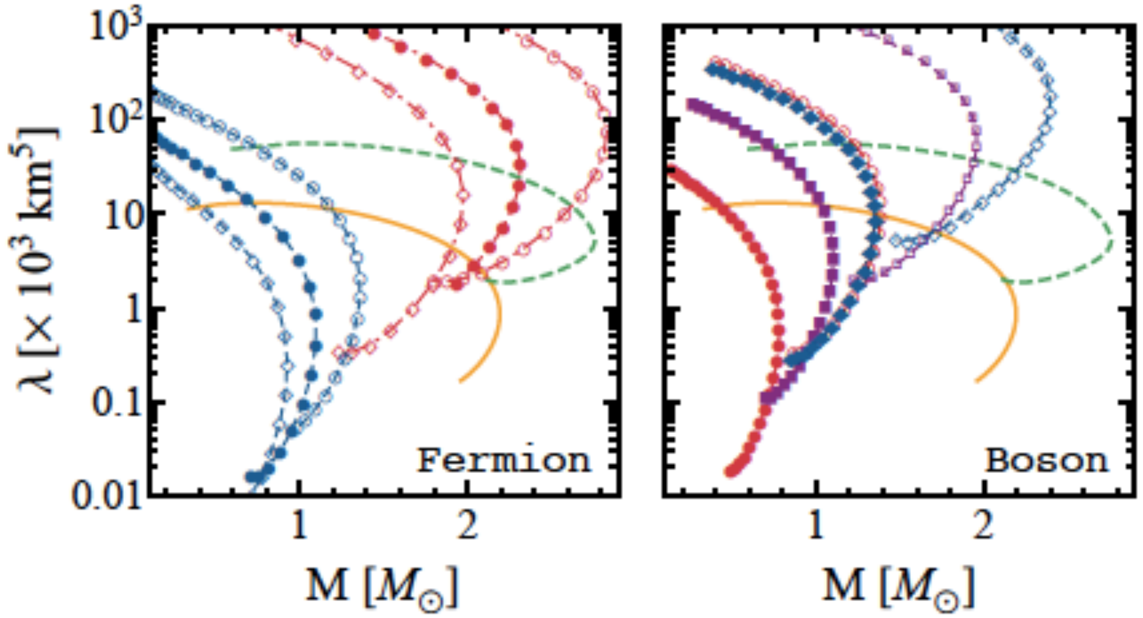
Love number

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

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

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

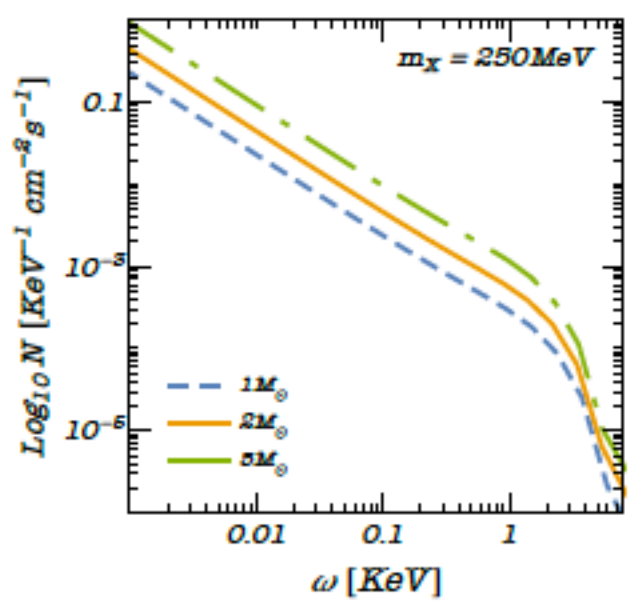
The Bright Side of Dark Stars

Dark Stars could shine via dark Bremsstrahlung if there is e.g. kinetic mixing between the dark and ordinary photon

- The luminosity might not be small compared to neutron stars because it is a volume vs surface effect.
- The morphology of the spectrum is different from that of a blackbody radiation due to the dependence of the gravitational redshift on the depth of photon production

$$\mathscr{L}_D = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m_\phi^2 A'_\mu A'^\mu + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

$$\frac{d^2E}{dSdt_\infty} = \frac{32}{3\pi^5}\frac{T^4}{d^2}\frac{m_X^2}{m_\phi^4}\alpha_X^3\epsilon^2\int_0^\infty AI_2 dz \int_0^R \sqrt{g_{00}g_{rr}}\frac{p_F^3 r^2}{e^\tau}dr \qquad \tau(r) = \int_r^R \sqrt{g_{rr}}n_X(y)\sigma_c dy$$



Maselli,
CK, Kokkotas… soon

How Asymmetric Dark Stars form?

A small fraction of asymmetric SIMP DM interacting via dark photons

$$\mathcal{L} \supset i\,\bar{\Psi}_{e_D}\gamma^\mu D_\mu \Psi_{e_D} - m_{e_D}\bar{\Psi}_{e_D}\Psi_{e_D} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + m_{\gamma_D}^2 A_\mu A^\mu$$

- Dark Fine Structure Constant should be sufficiently large to deplete antiparticles
- Relic dark photons should neither overclose the Universe nor violate BBN constraints of Neff

$$\ell_{e_D} = 1/(\sigma_M n_{e_D}) \quad , \quad \ell_{\gamma_D}^C = 1/(\sigma_C n_{e_D})$$

$\ell_{\gamma_D} \gg \ell_{e_D} \gg \lambda_P$ collisionless dark electron regime.

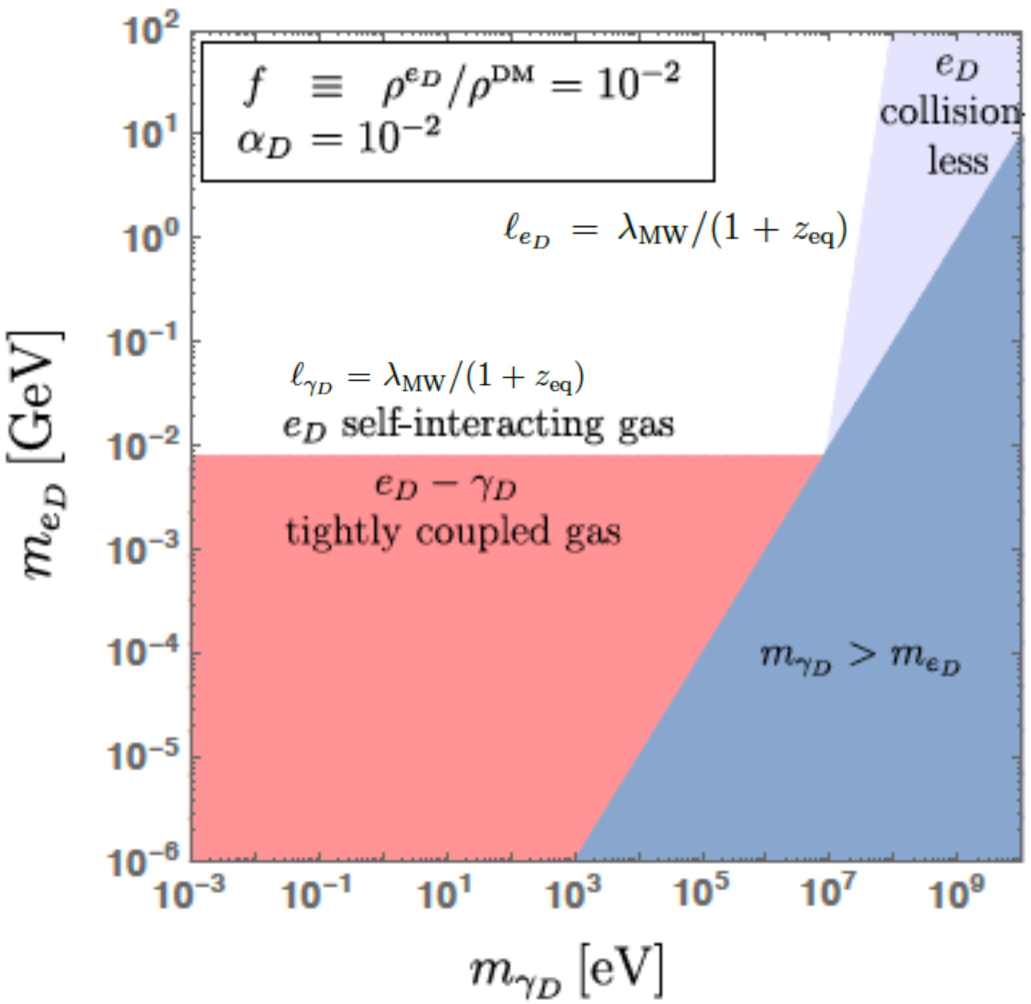
$\ell_{\gamma_D} \gg \lambda_P \gg \ell_{e_D}$ self-interacting e_D gas. e_D and γ_D decoupled

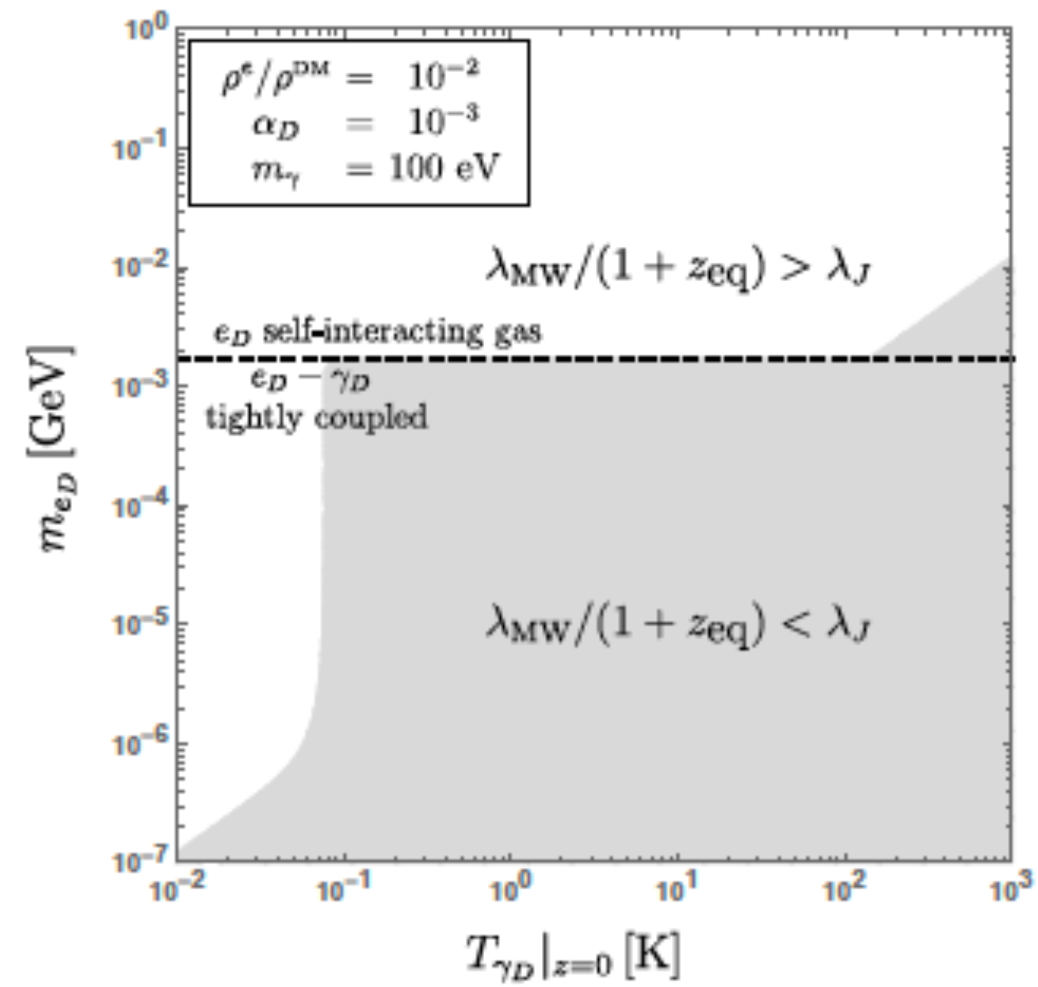
$\lambda_P \gg \ell_{\gamma_D} \gg \ell_{e_D}$ tightly coupled $e_D - \gamma_D$ gas.

$$P_{e_D} = n_{e_D}T_{e_D} + \frac{2\pi\alpha_D n_{e_D}^2}{m_{\gamma_D}^2} \qquad c_s^{e_D} = \sqrt{\frac{T_{e_D}}{m_{e_D}} + \frac{4\pi\alpha_D n_{e_D}}{m_{e_D}m_{\gamma_D}^2}}$$

$$c_s^{e_D\gamma_D} = \left[\frac{(c_s^{\gamma_D})^2 + R_{e\gamma}\,(c_s^{e_D})^2}{1+R_{e\gamma}}\right]^{1/2} \qquad R_{e\gamma} = \xi\frac{\rho_0^{e_D}}{\rho_0^{\gamma_D}}$$

Formation of Asymmetric Dark Stars



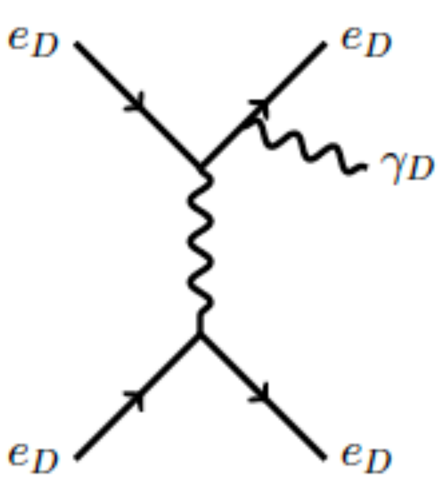


Perturbations grow as long as $$\lambda > \lambda_J = c_s \left(\frac{\pi}{\rho_0(z) G} \right)^{1/2}$$

Chang, Egana-Ugrinovic, Rouven, CK ‘18

Formation of Asymmetric Dark Stars

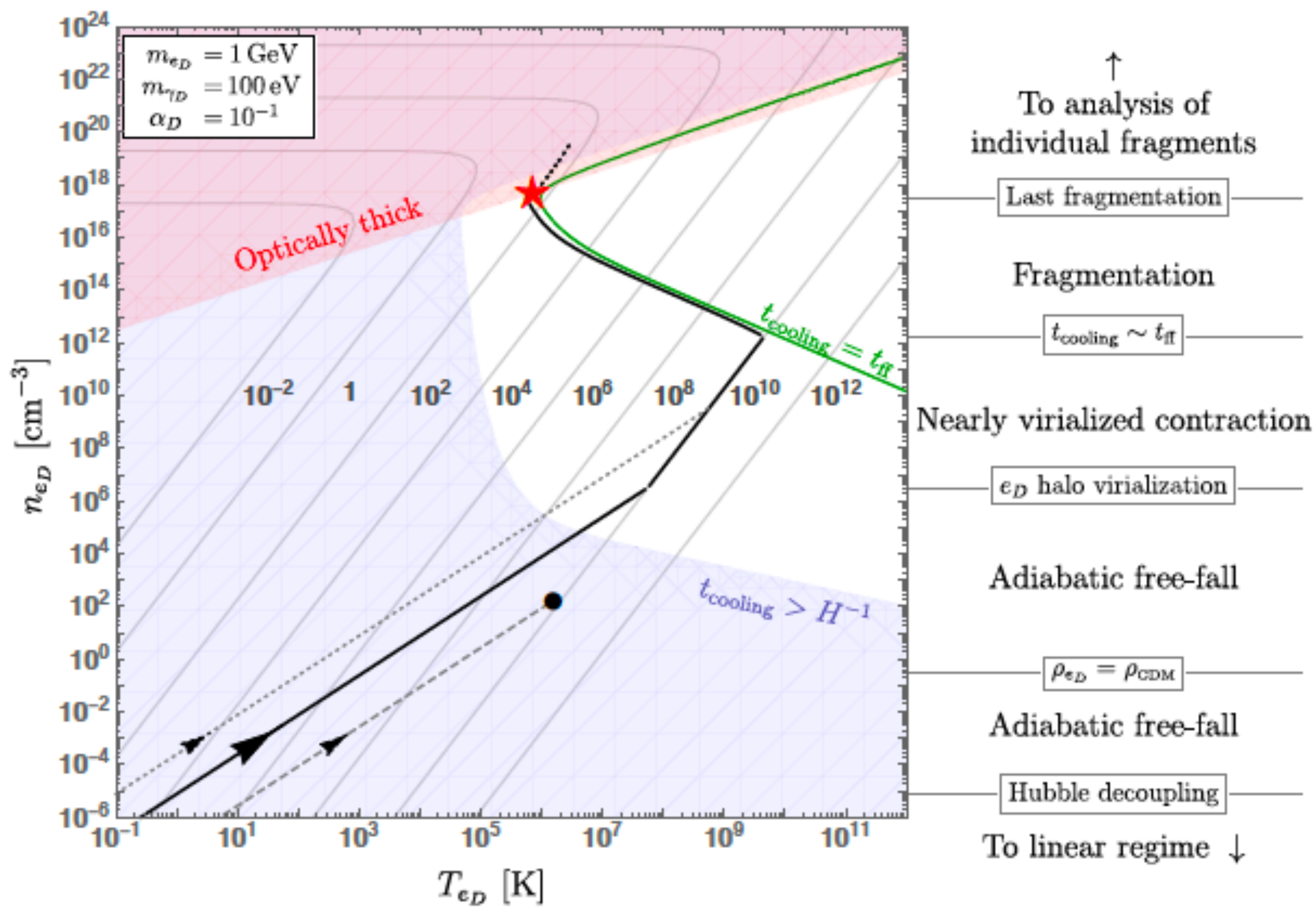
Collapse can proceed via dark photon Bremsstrahlung Cooling



$$\frac{3}{2m_{e_D}}\frac{dT_{e_D}}{dt} = -\frac{P_{e_D}}{M}\frac{dV}{dt} - \Lambda \qquad \frac{3}{2m_{e_D}}\frac{dT_{e_D}}{dt} = \frac{P_{e_D}}{\rho_{e_D}^2}\frac{d\rho_{e_D}}{dt} - \Lambda$$

$$t_{\text{cooling}} \equiv \frac{3T_{e_D}}{m}\frac{1}{\Lambda}$$

$$t_{\text{collapse}} \equiv \left(\frac{d\log\rho_{e_D}}{dt}\right)^{-1}$$



Formation of Asymmetric Dark Stars

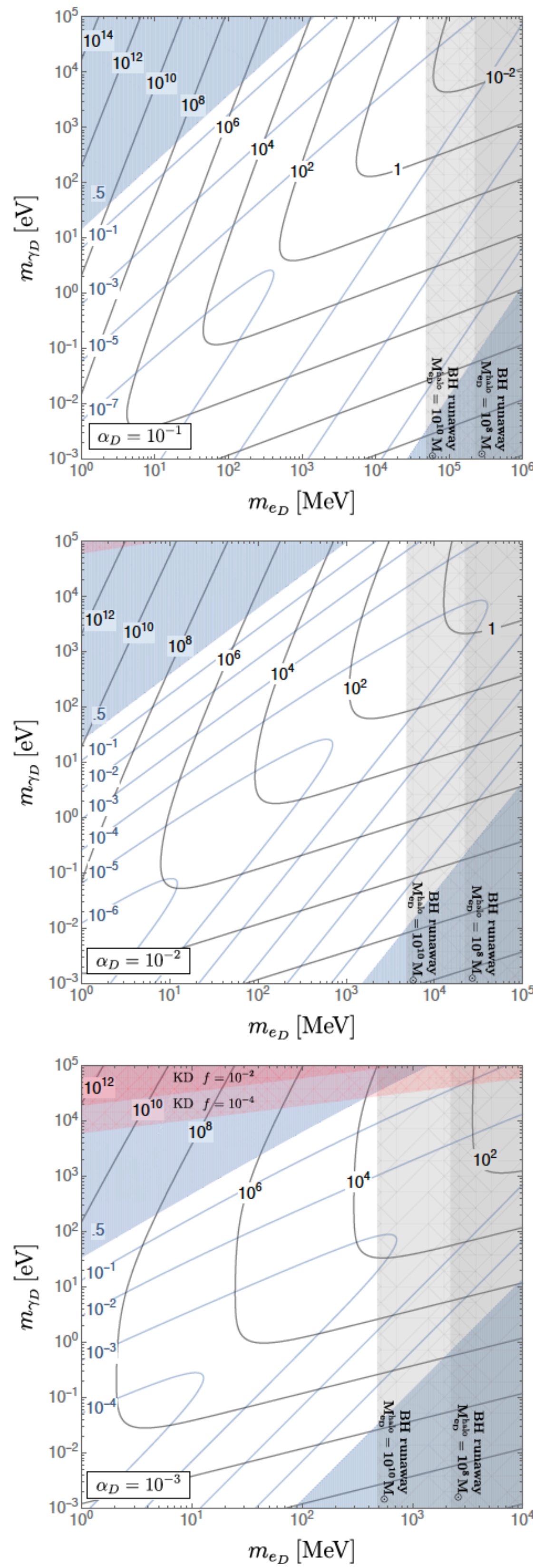


Figure 7: *Black contours:* mass of the dark electron exotic compact objects formed via fragmentation of a dark electron halo, in units of solar mass, as a function of the dark electron and dark photon masses. The dark fine-structure constant has been set to $\alpha_D = 10^{-1}$ (top), $\alpha_D = 10^{-2}$ (middle) and $\alpha_D = 10^{-3}$ (bottom). *Blue contours:* compactness of the above objects. *Shaded blue:* regions where the dark electron exotic compact objects are black holes (compactness $C_{\rm BH} = 1/2$). *Shaded gray and red:* regions where no fragmentation occurs. In gray, no fragmentation occurs since the whole dark electron halo runs away into a black hole before it can fragment. We plot these regions for two choices of dark electron halo mass. In red, we show the regions where dark electrons are kinetically decoupled (KD) during linear growth of perturbations (c.f. Eq. (15)), so instead of forming a compact dark electron halo which fragments, dark electrons settle in an NFW-like halo typical of CDM. We show these regions for two choices of the dark electron to dark matter ratio.

Neutron Decay Anomaly and Neutron Star Stability

There is a 4σ discrepancy between bottle and beam experimental measurements of the decay width of neutron.

$$\tau_{\rm bottle} = 879.6 \pm 0.6 \text{ s} \qquad \tau_{\rm beam} = 888.0 \pm 2.0 \text{ s}$$

This could be explained if neutron could partially decay to a DM particle Fornal Grinstein '18.

$$\tau_n^{\rm beam} = \frac{\tau_n}{\text{Br}(n \to p + \text{anything})}$$

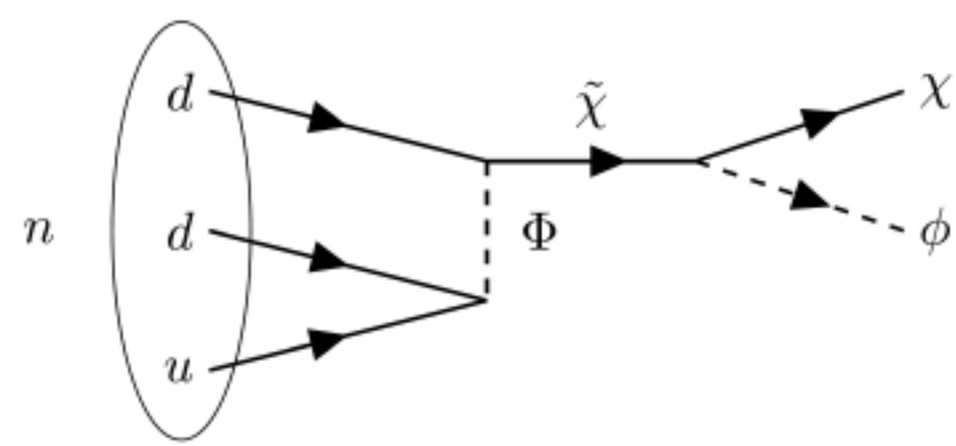
Avoid proton decays $p \to n^* + e^+ + \nu_e$ $m_p - m_e < M_f < m_n$

However such a scenario leads to significant conversion of neutrons to DM, softening the NS EoS making NS unable to reach 2 Msun. Baym Beck Geltenbort Shelton '18, Cline Cornell '18

Adding repulsive DM self-interactions is barely consistent with 2 Msun NS. Cline Cornell '18, Grinstein Nielsen CK '18.

Baryon-DM Interactions via the Higgs Portal

$$\mathcal{L} = \lambda_q \,\epsilon^{ijk}\, \overline{u^c_{L}}_i \, d_{Rj} \Phi_k + \lambda_\chi \Phi^{*i} \bar{\tilde{\chi}}\, d_{Ri} + \lambda_\phi \,\bar{\tilde{\chi}}\, \chi\, \phi \; + \mu H^\dagger H \phi + g_\chi \bar{\chi} \chi\, \phi + \text{h.c.}$$



The Higgs portal induces neutron-DM interactions

$$g_n = \frac{\mu \sigma_{\pi n}}{m_h^2} \qquad \sigma_{\pi n} \;=\; \sum_q \langle n | m_q \bar{q} q | n \rangle \approx 370 \text{ MeV}$$

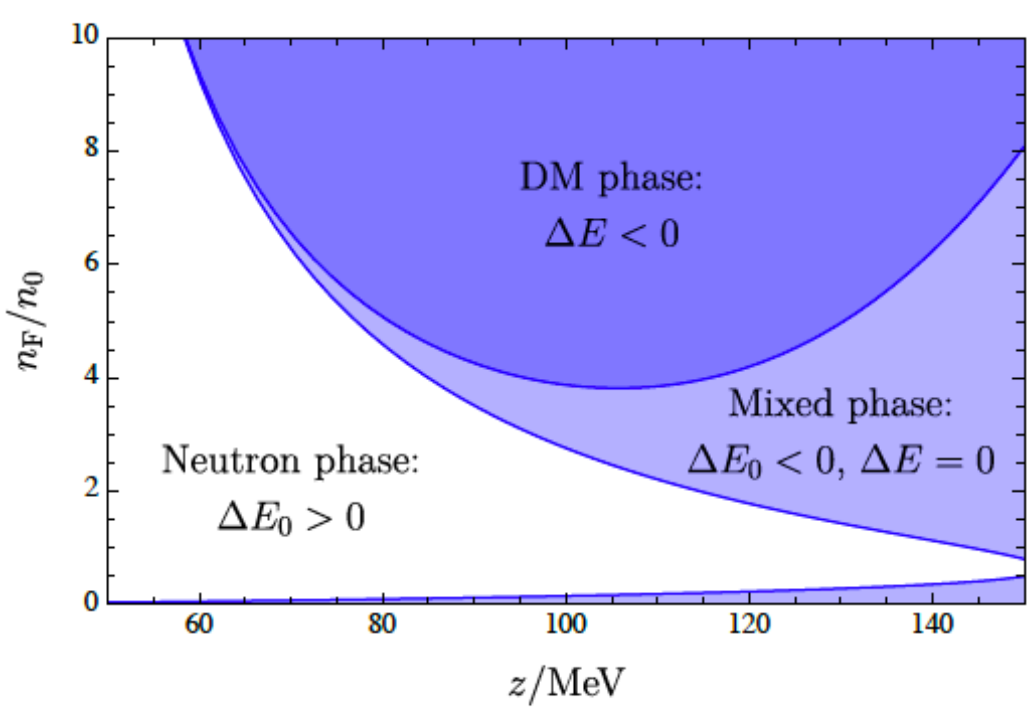
Baryon-DM Interactions via the Higgs Portal

Energy density

$$\varepsilon(n_n, n_\chi) = \varepsilon_{\rm nuc}(n_n) + \varepsilon_\chi(n_\chi) + \frac{n_\chi n_n}{2z^2}$$

chemical equilibrium

$$\Delta E \equiv \frac{\partial \varepsilon(n_{\rm F} - n_\chi, n_\chi)}{\partial n_\chi} = \mu_\chi(n_\chi) - \mu_{\rm nuc}(n_n) + \frac{n_{\rm F} - 2n_\chi}{2z^2} \qquad z \equiv m_\phi / \sqrt{|g_\chi g_n|}$$



$g_\chi \lesssim 4 \times 10^{-4}$ DM Self-Interactions constraints

$g_n \sim -10^{-14}$ Constraints from rapid cooling of stars

$m_\phi \sim 0.1$ eV

Grinstein Nielsen CK '18

Converting Neutron Stars to Black Holes

Astrophysical black holes produced as the end result of stellar evolution are expected to have masses above $3M_{sun}$. Therefore in case of a $\sim M_{sun}$ black hole discovery, one would naively expect that it is of primordial origin.

This does not have to be the case. Asymmetric DM could implode inside NS converting them to black holes of $<3M_{sun}$. This can set constraints on DM self-interactions since they dictate how easily asymmetric DM can collapse.

Asymmetric Dark Matter in Neutron Stars

Capture

$$N_{\rm acc} = \sqrt{6\pi}\,\frac{\rho_{\rm dm}}{mv}\,\frac{RR_g}{1-R_g/R}\,f\,t$$

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

Thermalization

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

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

$$r_{\rm th} = \left(\frac{15T}{8\pi G\rho_c m}\right)^{1/2} \simeq 8\,{\rm cm}\left(\frac{\rm TeV}{m}\right)^{1/2}$$

Self-Attraction

$$2\langle E_k\rangle = \frac{8\pi}{5}G\rho_c m r^2 + \frac{3GNm^2}{5r} + \frac{3N\alpha e^{-\mu r_0}}{2\mu^2 r^3}\left(3+3\mu r_0+\mu^2 r_0^2\right)$$

$$r_0 = n_0^{-1/3} = r(4\pi/3N)^{1/3}$$

CK Tinyakov Tytgat '18

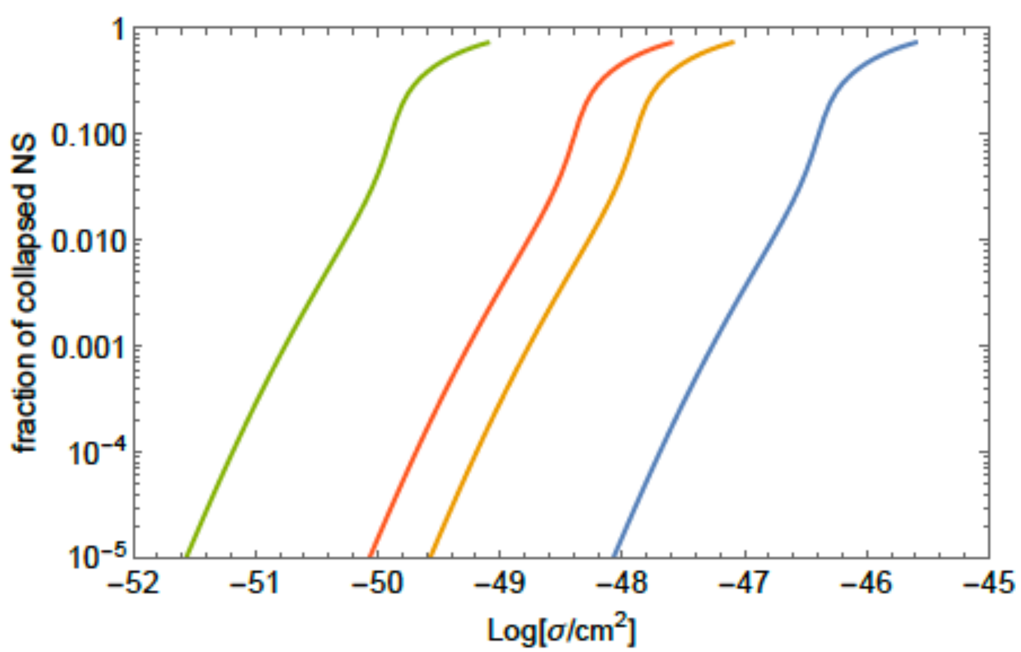
Collapse

$$N_{\rm Ch} = 0.3\left(\frac{\mu}{m\sqrt{\alpha}}\right)^3\left(\frac{M_{\rm Pl}}{m}\right)^3$$

CK Nielsen '15

Setting New Constraints on Dark Matter Self-Interactions

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



CK Tinyakov Tytgat '18

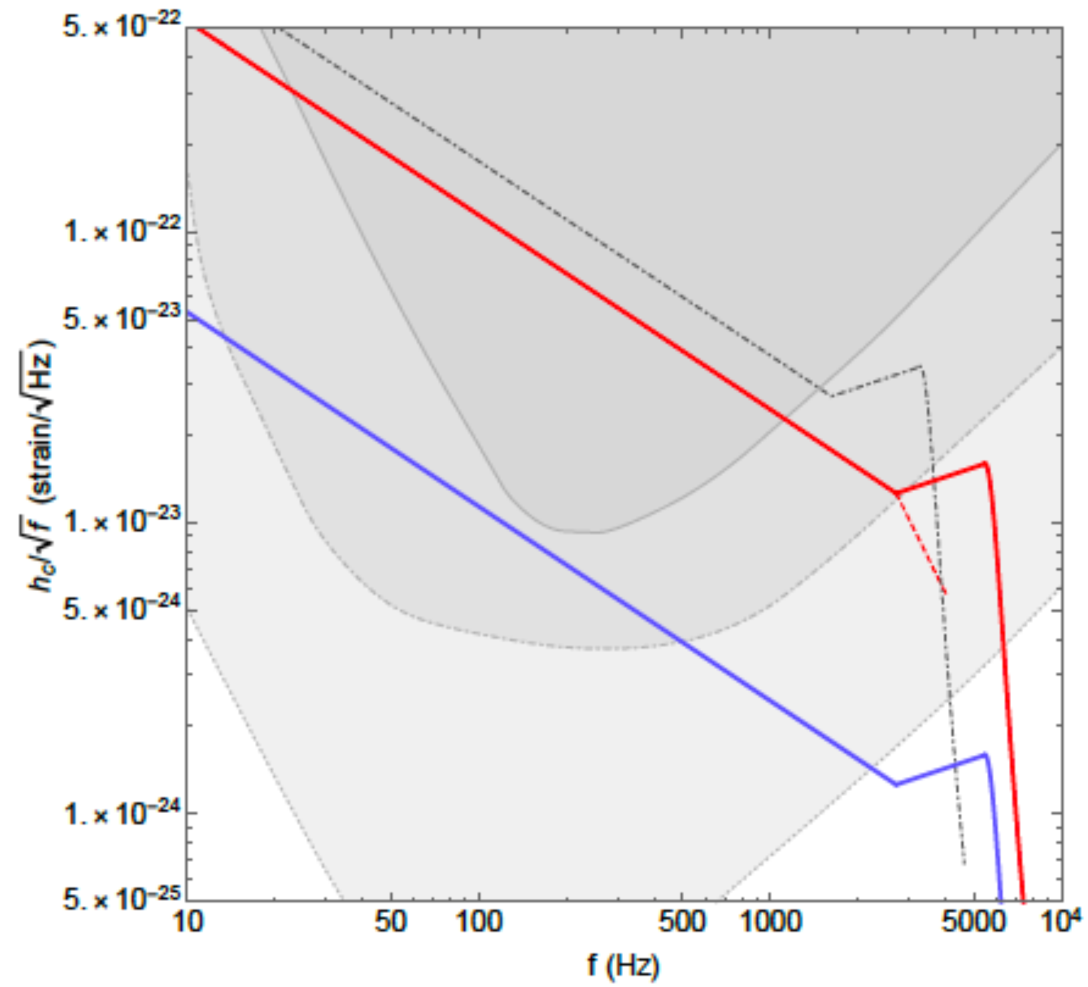


FIG. 2. Spectrum of GW from a $(1.5+1.5)M_\odot$ BBH at 40 Mpc (red solid). The spectrum of a corresponding BNS is schematically depicted by the break (red dashed). Also shown are a $(1.5+1.5)M_\odot$ BBH at 400 Mpc (blue solid) and a $(2+2)M_\odot$ BBH at 40 Mpc (grey dot-dashed). The sensitivity curves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

Conclusions

Dark Matter Self-Interactions

- important to solve CCDM problems

Asymmetric Dark Stars

- can be probed by gravitational waves
- New Dark Stars distinguishable from NS and BH binaries

Neutron Decay Anomaly

- if this persists, deviation from SM
- strong constraints from NS

Dark Matter Collapse inside NS

- create astrophysical black holes with $M<3M_{sun}$
- new constraints on asymmetric DM and DM self-interactions