UNIVERSITY OF SOUTHERN DENMARK

Gravitational Waves from Dark Matter

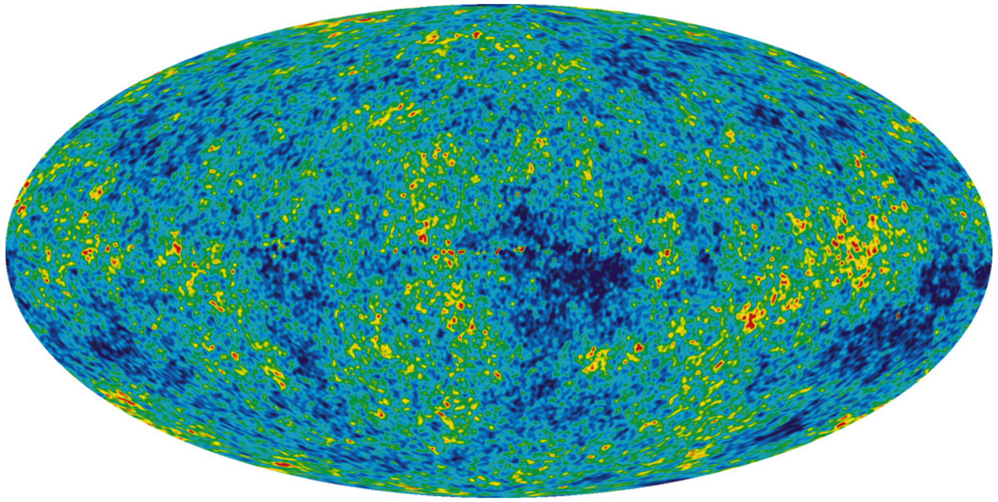
Chris Kouvaris

CP^3 - Origins

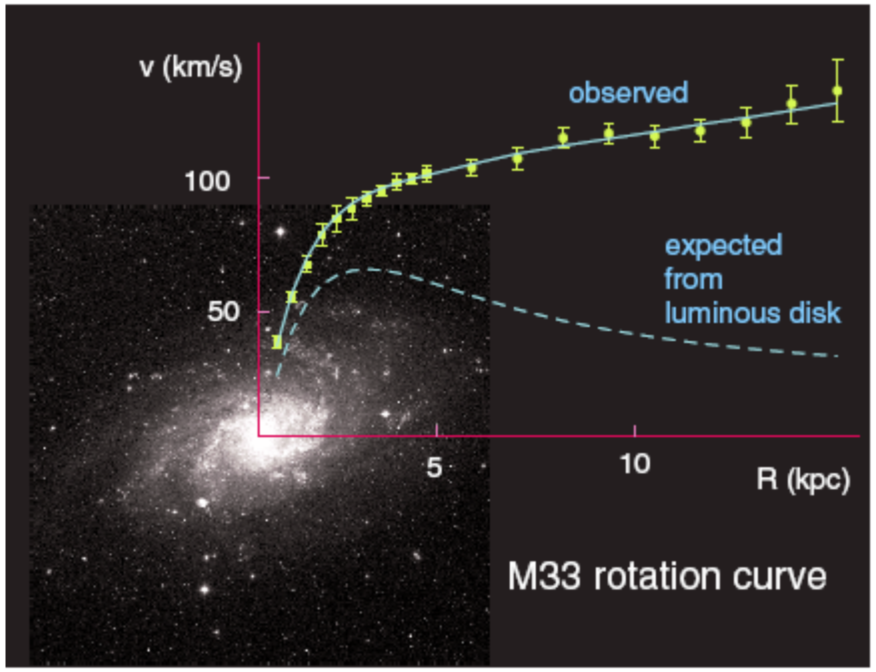
Particle Physics & Origin of Mass

NTUA, Athens, 26 March 2018

Dark Matter

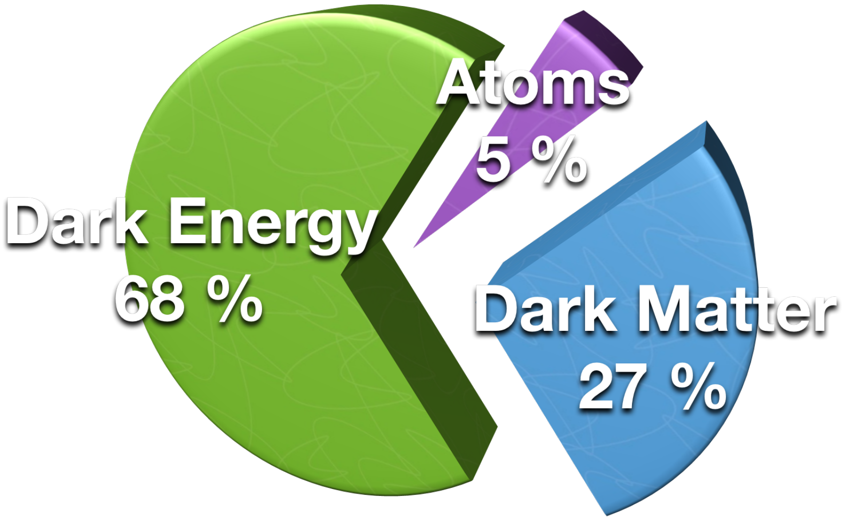


Microwave Background Radiation



M33 rotation curve

Bullet Cluster



Dark Matter candidates

- Axions & ALPs
- Sterile Neutrinos
- WIMPs
- Dark Atoms
- Mirror Dark Matter
- WIMPzillas
- MACHOs
- Primordial Black Holes
- ???

Outline

- Asymmetric Dark Matter
- Why Dark Matter Self-Interactions?
- Asymmetric Dark Stars and GW production
- Dark Matter inducing Neutron Star Collapse to Black Hole producing non-primordial solar mass black hole binaries

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 Dark Matter

Example:

SU(4) ⟶ SO(4)

$$Q = \begin{pmatrix} U_L \\ D_L \\ -i\sigma^2 U_R^* \\ -i\sigma^2 D_R^* \end{pmatrix}$$

$$\langle Q_i^\alpha Q_j^\beta \epsilon_{\alpha\beta} E^{ij} \rangle = -2\langle \overline{U}_R U_L + \overline{D}_R D_L \rangle$$

$$E = \begin{pmatrix} 0 & \mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}$$

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

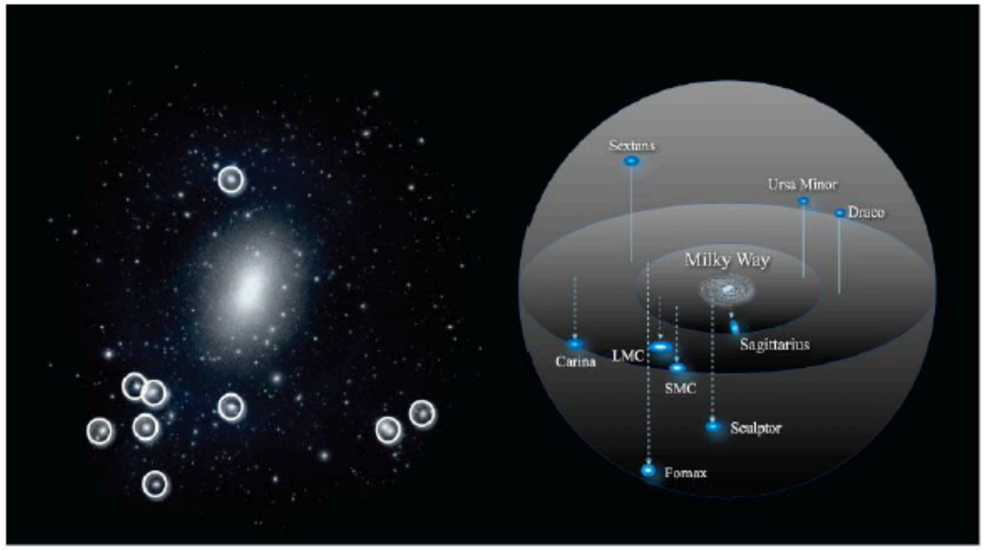
Extra lepton family to cancel Witten global anomaly

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”



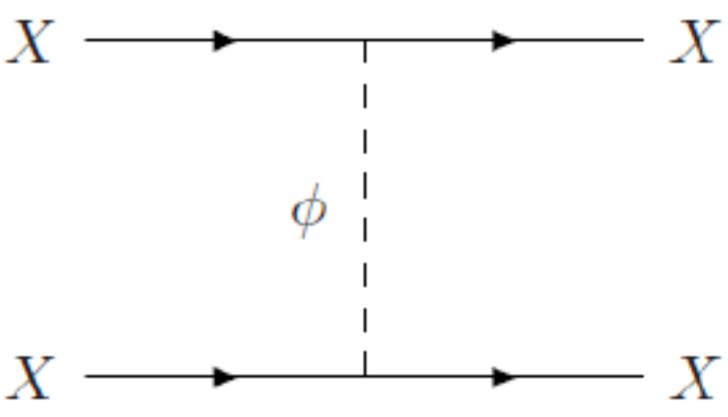
From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)

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

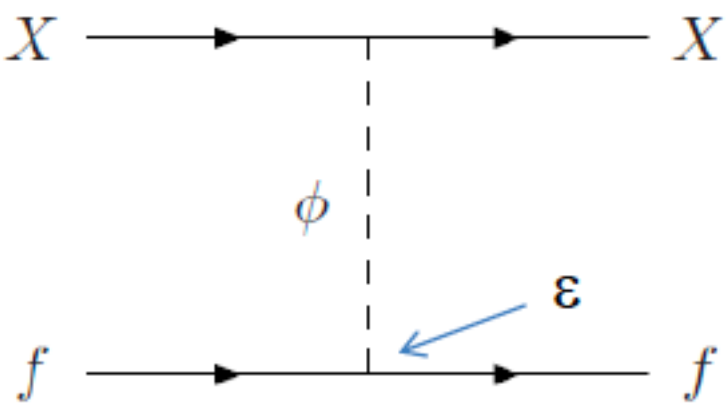
Extra motivation:
Provide seeds for the Supermassive Black hole at the center of galaxy
Pollack Spergel Steinhardt ‘15

Self-Interacting Dark Matter

$$\mathscr{L}_{\text{int}} = \begin{cases} g_\chi \bar{\chi} \gamma^\mu \chi \phi_\mu & \text{vector mediator} \\ g_\chi \bar{\chi} \chi \phi & \text{scalar mediator} \end{cases} \qquad \alpha_X = g_X^2/(4\pi)$$



DM self-interactions



Direct detection

Problem:

- DM self-interactions must be sufficiently strong to solve the CCDM issues without destroying the ellipticity of galaxies or violate constraints from the bullet cluster. This means specific region of DM mass, mediator mass and coupling.
- The product of coupling α_X and kinetic mixing ε cannot be large because it is constrained by direct detection.
- ε cannot be small because BBN constrains the lifetime of ϕ.

BBN constrain the lifetime of ϕ

$$\tau_\phi \approx 3 \text{ seconds} \times \left(\frac{\varepsilon_\gamma}{10^{-10}}\right)^{-2} \left(\frac{m_\phi}{10 \text{ MeV}}\right)^{-1}$$

$$\text{BR}(\phi \to e^+e^-) \approx 1$$

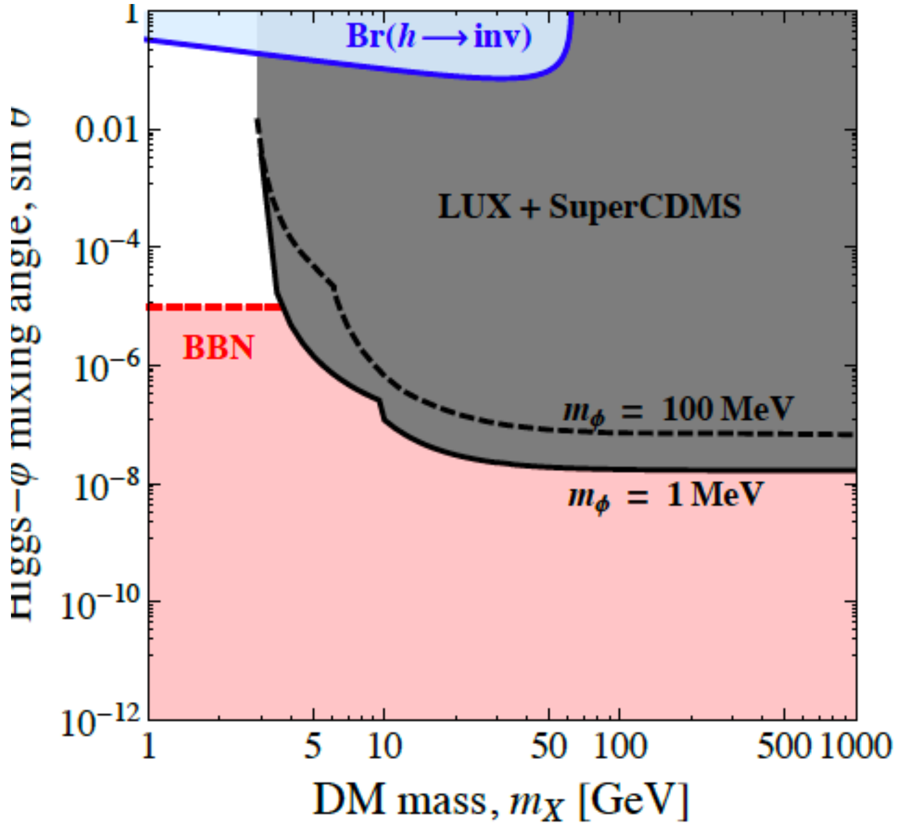
How can this tension be resolved?

$$\begin{aligned}\mathcal{L}_{\rm DM} &= \frac{1}{2}|\partial_\mu S|^2 + \overline{X} i\gamma^\mu \partial_\mu X + y_X S\overline{X}X - V(S,\Sigma),\\ V(S,\Sigma) &= m^2|\Sigma|^2 + \frac{1}{2}m_S^2 S^2 + \lambda|\Sigma|^4 + \frac{1}{4}\lambda_S S^4\\ &+ \frac{\lambda_{S\Sigma}}{2}|\Sigma|^2 S^2 + \frac{\mu_3}{3}S^3 + \mu_1|\Sigma|^2 S.\end{aligned}$$

$$\begin{aligned}\sigma^0 &= \cos\theta\ h + \sin\theta\ \phi,\\ s &= \cos\theta\ \phi - \sin\theta\ h,\end{aligned}$$

$$\sin\theta \simeq \frac{v_{\rm EW}\mu_1}{m_h^2} + \lambda_{S\Sigma}\frac{v_{\rm EW}w}{m_h^2}$$

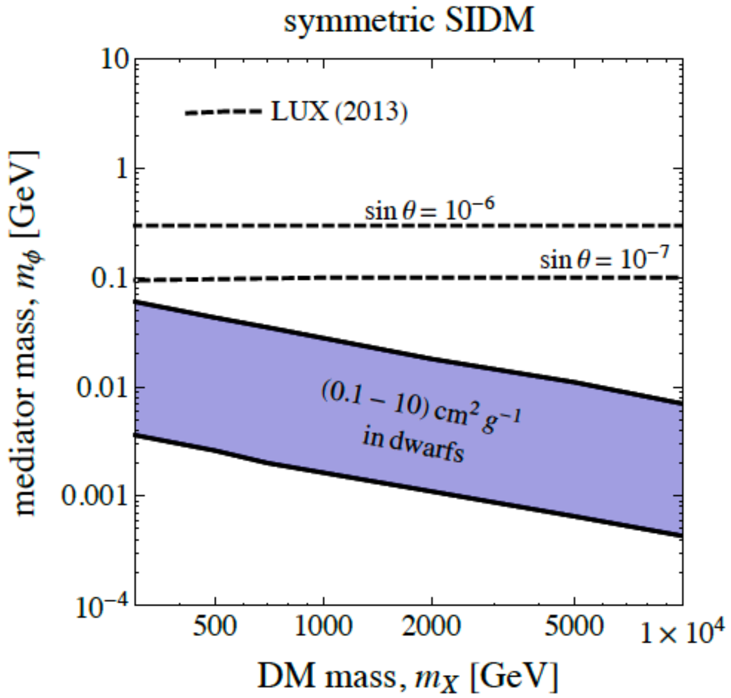
Effective Higgs portal $\mathcal{L} \supset y_X \phi \overline{X}X + a\phi|H|^2 + b\phi^2|H|^2$



Possible solution: Couple mediator ϕ to sterile or active neutrinos and make it decay before BBN

$$\phi\,(LH)^2\,/\Lambda^2$$

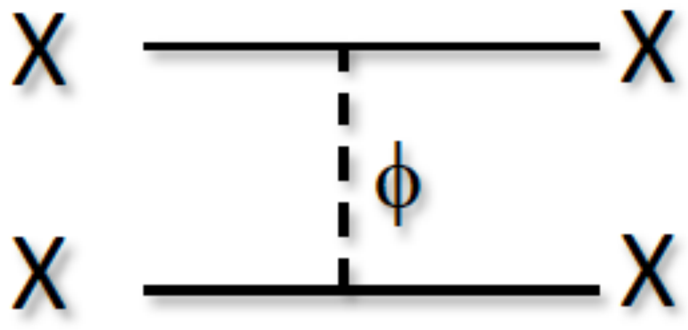
$$\Lambda \lesssim 2\times 10^{11}\ {\rm GeV}\sqrt{\frac{m_\phi}{100\ {\rm MeV}}}$$



CK, Shoemaker, Tuominen '14

Light Mediators

Light Mediators lead to an increased cross section due to Sommerfeld Enhancement



self-interaction

Perturbative $\alpha_X m_X / m_\phi \ll 1$ $\sigma_T^{\rm Born} = \frac{8\pi\alpha_X^2}{m_X^2 v^4}\left(\log\left(1 + m_X^2 v^2/m_\phi^2\right) - \frac{m_X^2 v^2}{m_\phi^2 + m_X^2 v^2}\right)$

Non-perturbative $\alpha_X m_X / m_\phi \gg 1$

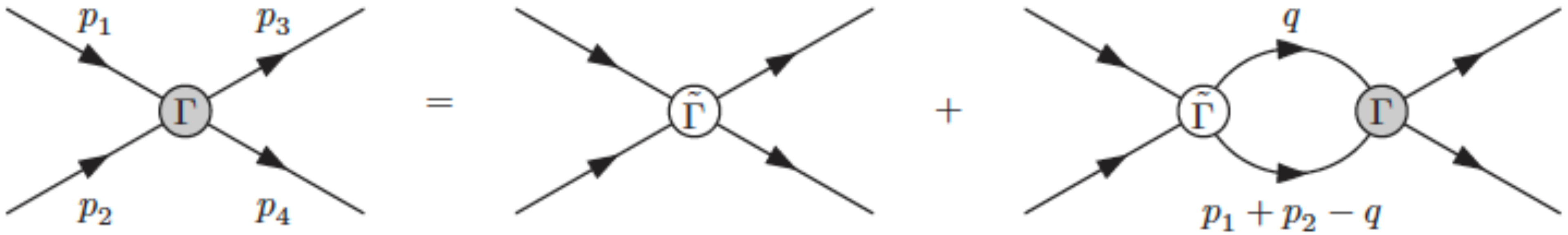
Classical Limit $m_X v / m_\phi \gg 1$ The problem is identical to plasma physics

$V(r) = \pm\frac{\alpha_X}{r}e^{-m_\phi r}$ m_ϕ is equivalent to Debye screening mass in plasma

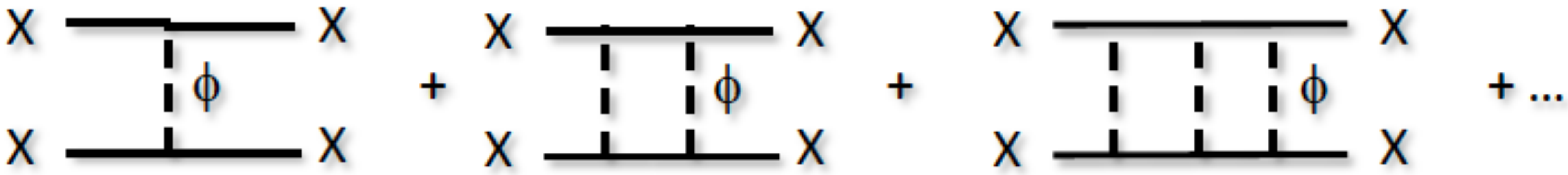
$$\sigma_T^{\rm clas} = \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 \ln\left(1 + \beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2 / \left(1 + 1.5\beta^{1.65}\right) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \beta \gtrsim 10^3 \end{cases} \qquad \beta \equiv 2\alpha_X m_\phi/(m_X v^2)$$

Light Mediators

Resonant Limit $m_X v/m_\phi \lesssim 1$ Bethe-Salpeter equation



$$i\Gamma(p_1,p_2;p_3,p_4) \;=\; i\tilde{\Gamma}(p_1,p_2;p_3,p_4) + \int \frac{d^4q}{(2\pi)^4}\,\tilde{\Gamma}\;G(q)\;G(p_1+p_2-q)\;\Gamma$$

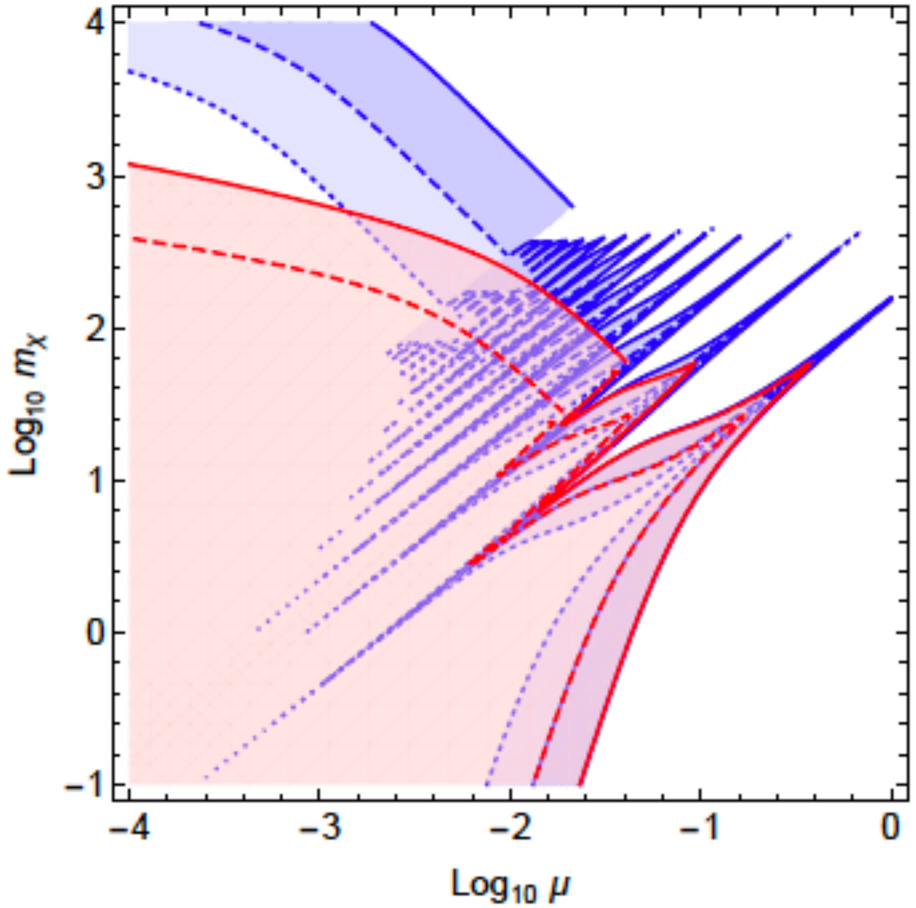


Non-relativistic limit equivalent to Schrodinger equation

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dR_\ell}{dr}\right) + \left(k^2 - \frac{\ell(\ell+1)}{r^2} - 2\mu V(r)\right)R_\ell = 0$$

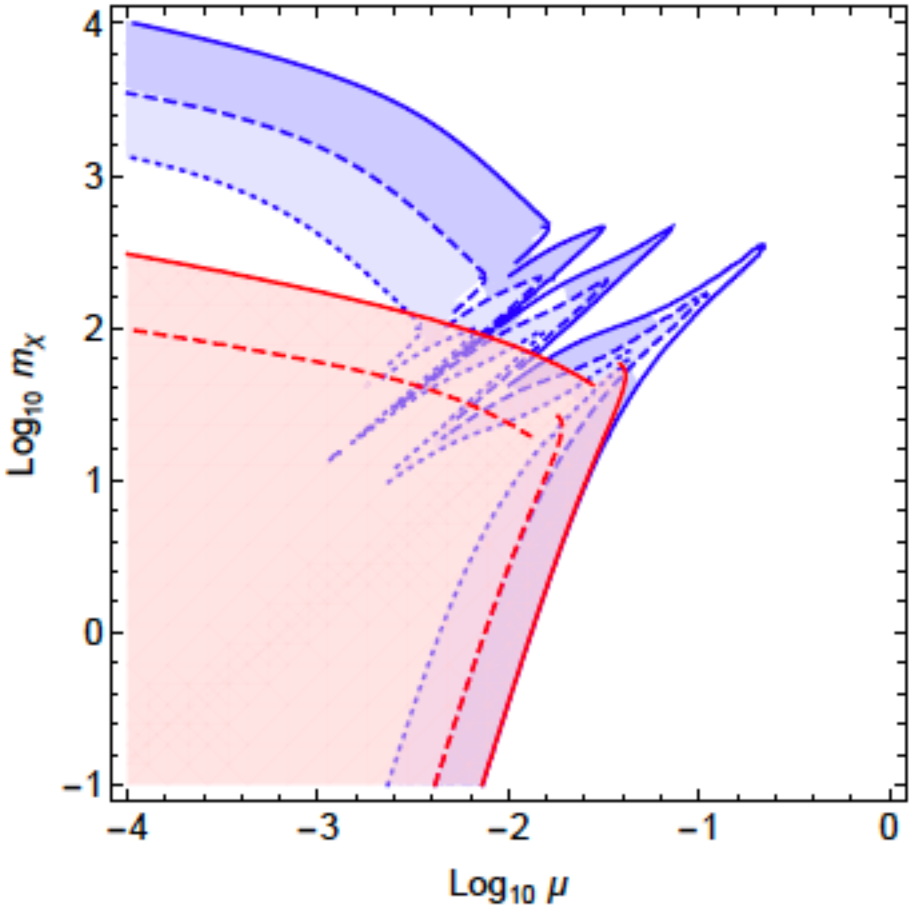
$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2}\left|\sum_{\ell=0}^{\infty}(2\ell+1)e^{i\delta_\ell}P_\ell(\cos\theta)\sin\delta_\ell\right|^2$$

Light Mediators



$\alpha = 10^{-2}$ attractive

CK, Nielsen '15



$\alpha = 10^{-3}$ attractive

Can Dark Matter Make its own "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. Dark photon radiation (with D. Egana and R. Essig)
3. Cosmological perturbations
4. Accretion from Supermassive stars

- Detection prospects with LIGO or lensing?

- Vibration modes of "dark stars"

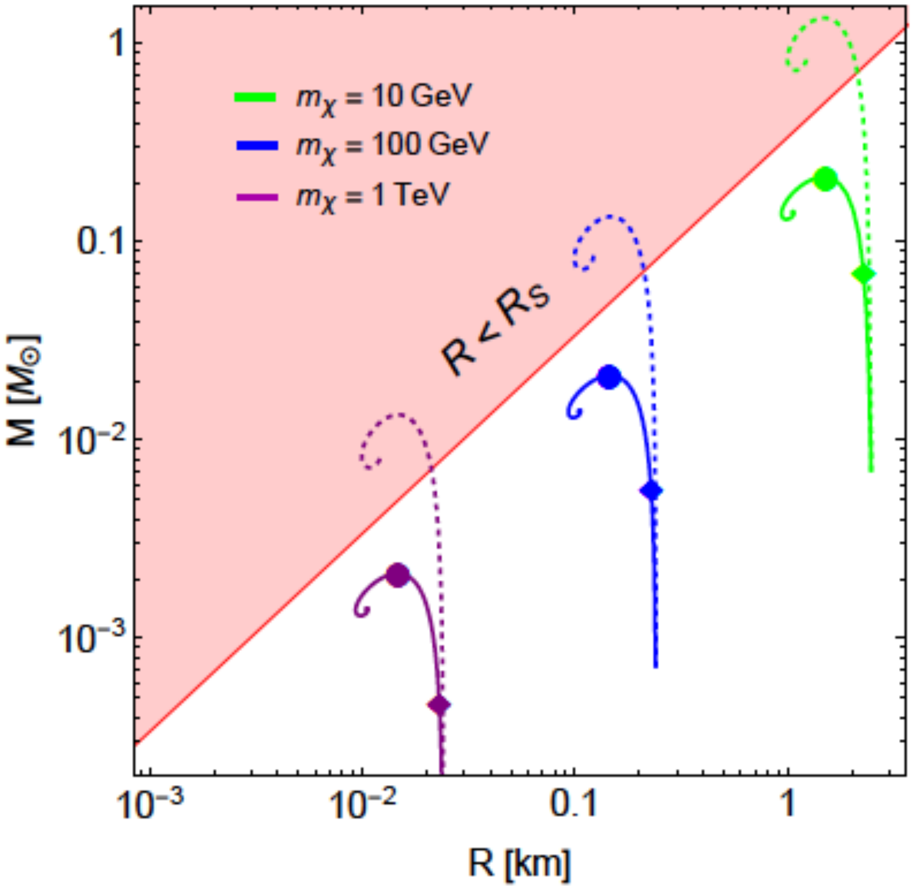
Asymmetric Fermionic Dark Stars

Tolman-Oppenheimer-Volkoff with Yukawa self-interactions

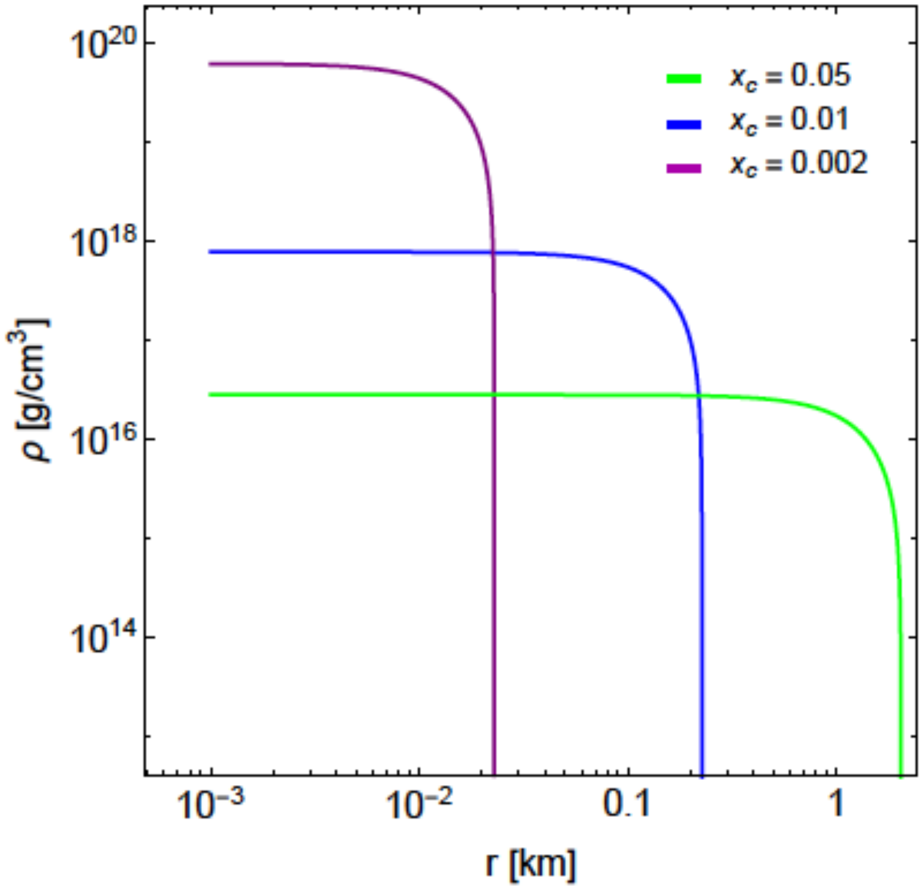
$$P = \frac{g_s}{2} m_\chi^4 \psi(x) \pm \frac{\alpha g_s^2}{18\pi^3} \frac{m_\chi^6}{\mu^2} x^6,$$

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

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



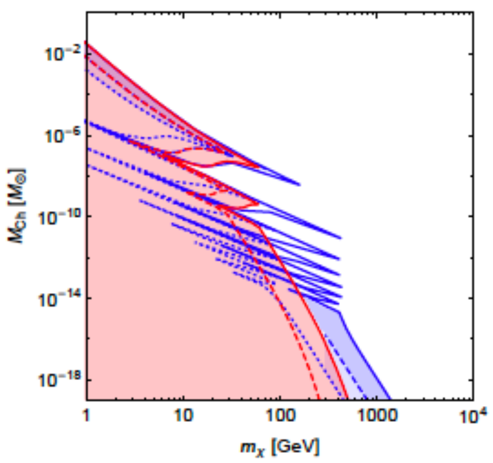
(a) $M(R)$ for repulsive interactions



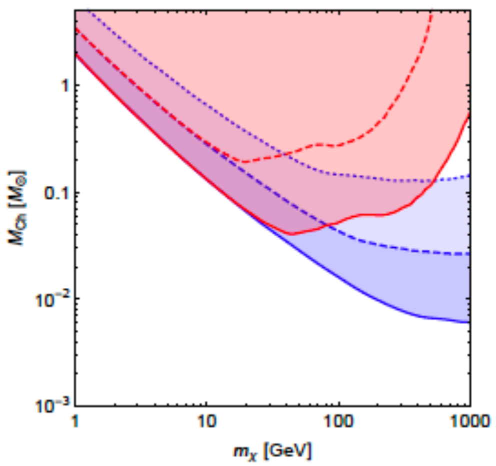
(b) $\rho(r)$ for repulsive interactions

CK, Nielsen '15

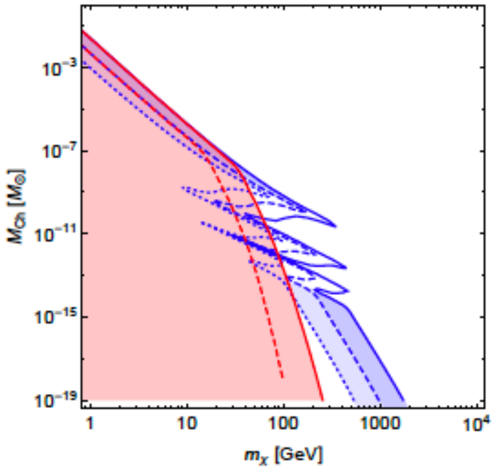
Chandrasekhar Mass Limits for Dark Stars



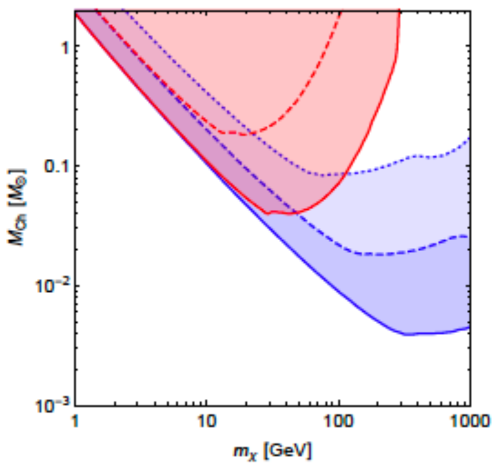
(a) $\alpha = 10^{-2}$ attractive



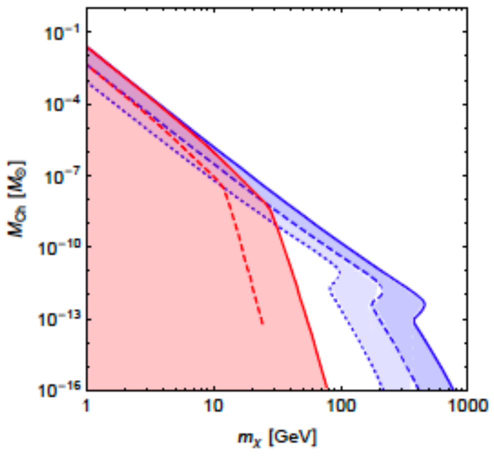
(b) $\alpha = 10^{-2}$ repulsive



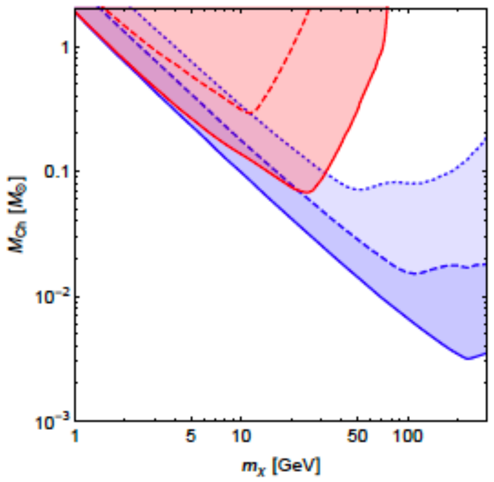
(c) $\alpha = 10^{-3}$ attractive



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



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



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

Asymmetric Bosonic Dark Stars

BEC Bosonic DM with λϕ ^{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), $\Omega = \omega/m$ $\quad \Lambda = \lambda M_{\rm P}^2/(4\pi m^2)$

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

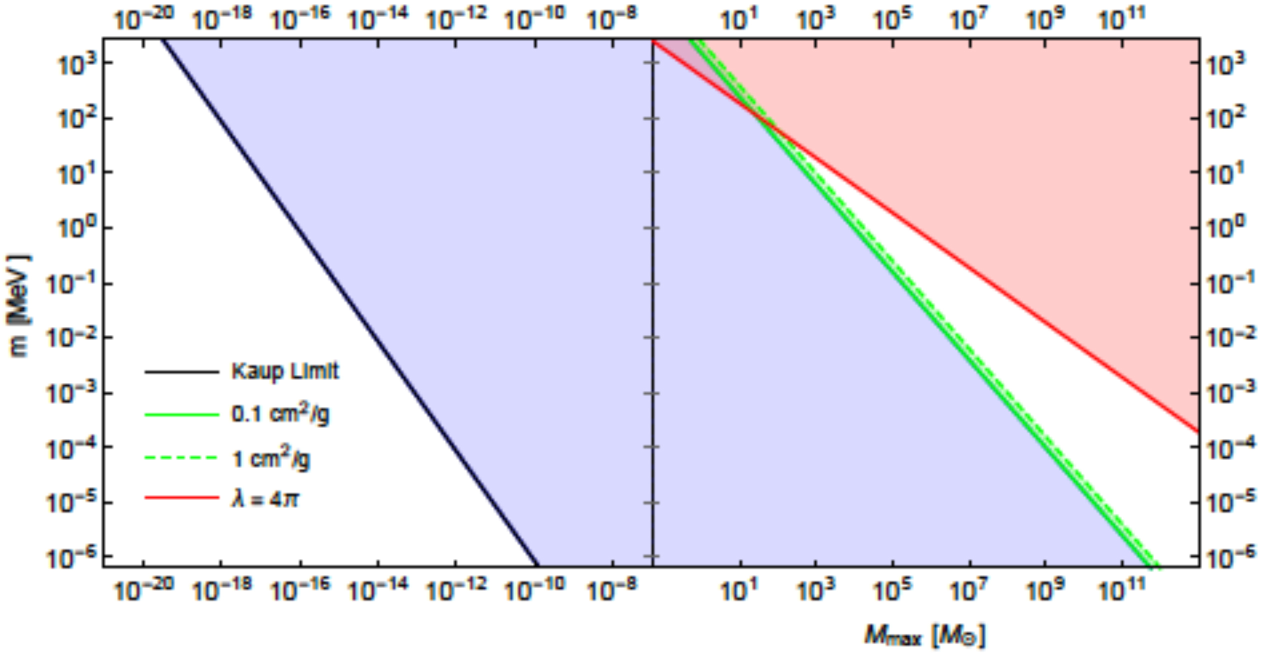
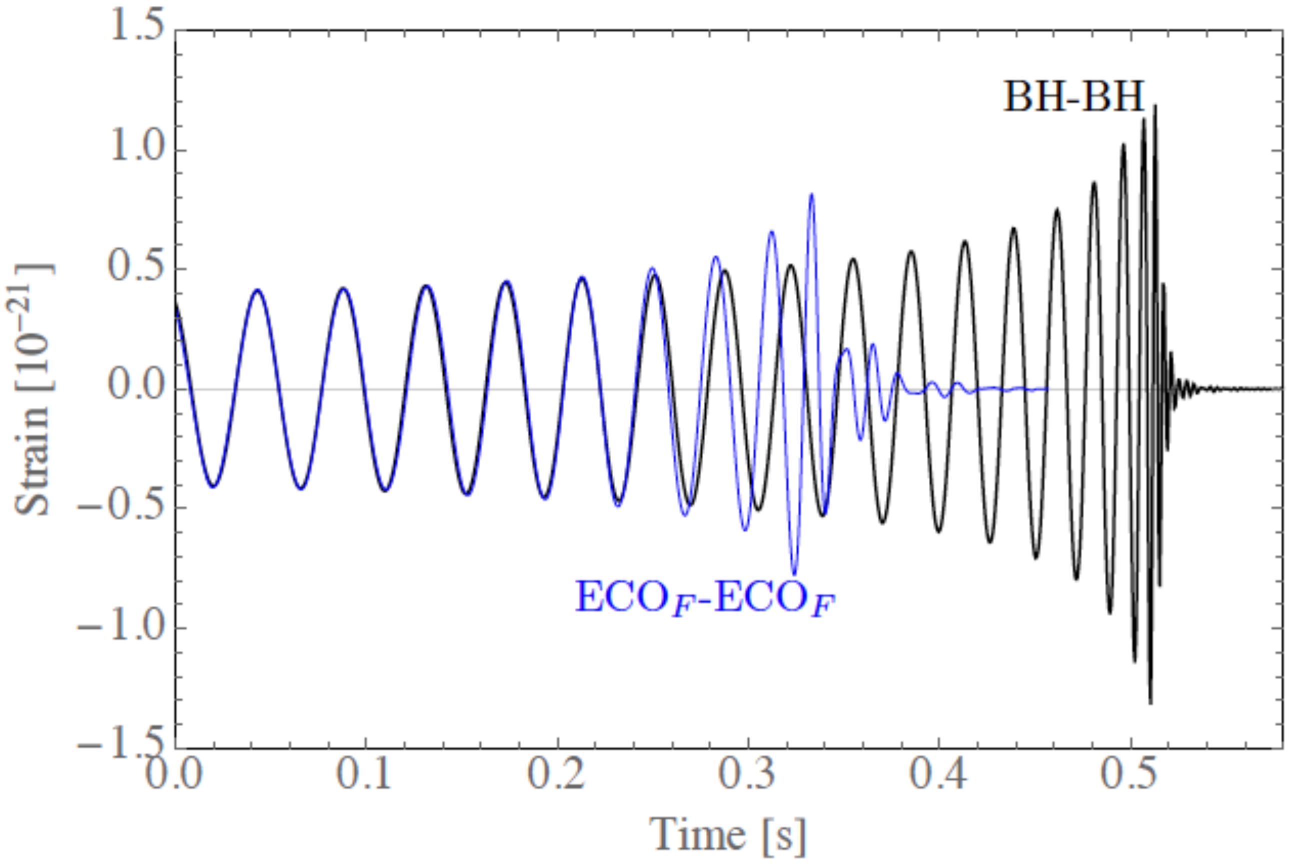


Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass m. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths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

Observation

- Gravitational Waves: DS+DS->DS or BH with K.Kokkotas (Univ. of Tubingen)
  DS+NS-> DS*
  DS+BH->BH
  Spinning DS

Tidal Deformations of Dark Stars

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

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

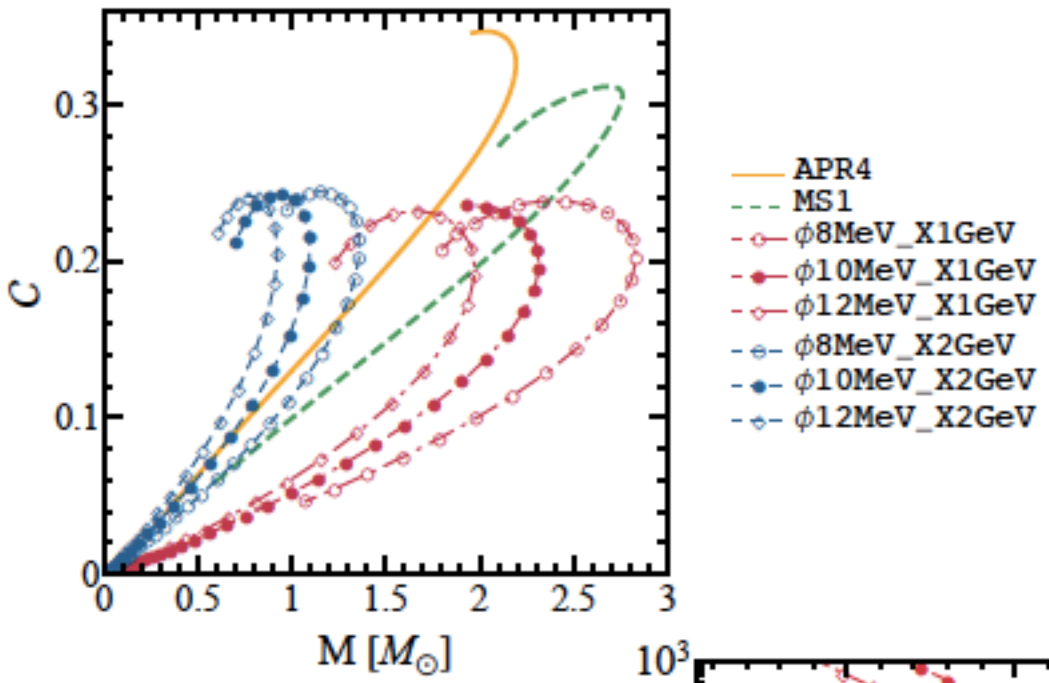
$$Q_{ij}=-\lambda\varepsilon_{ij}$$

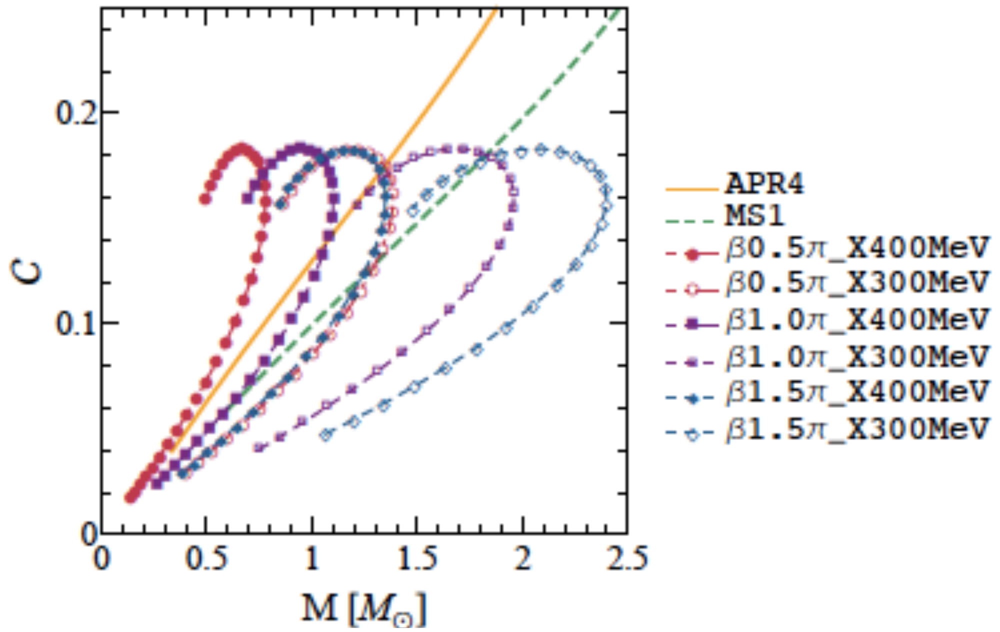
$$\lambda=\frac{2}{3}k_2R^5$$

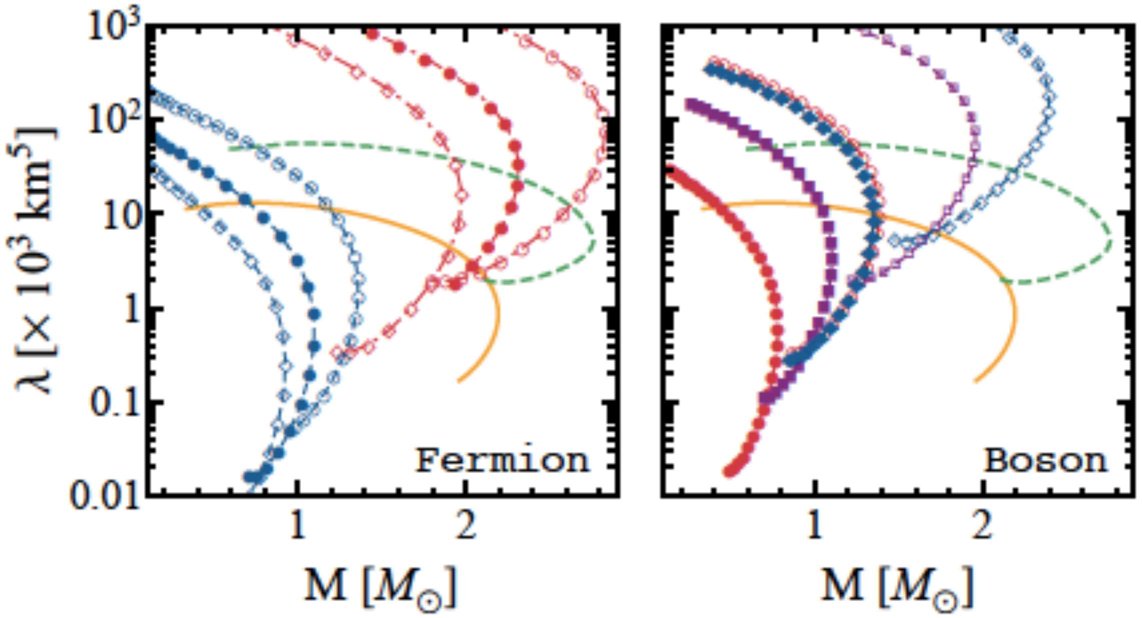
Love number

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

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

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

Asymmetric Dark Stars

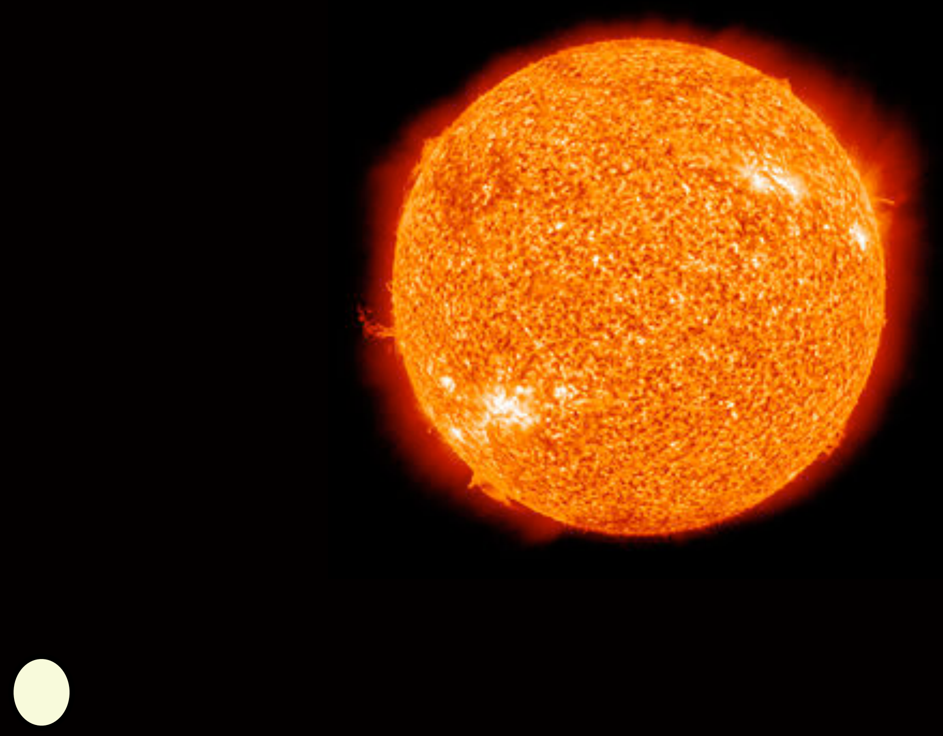
Electromagnetic Signals:

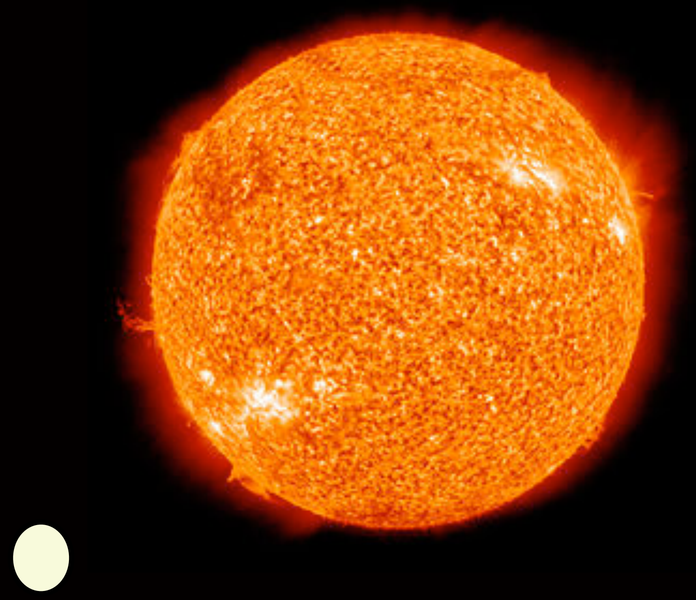
- X-rays from accretion of interstellar gas
- Unique Spectrum because photons come from the bulk of the star and not the surface

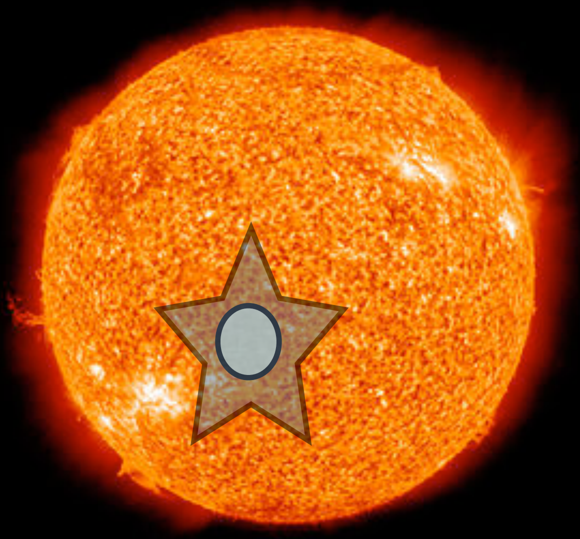
New Dark Matter Constraints:

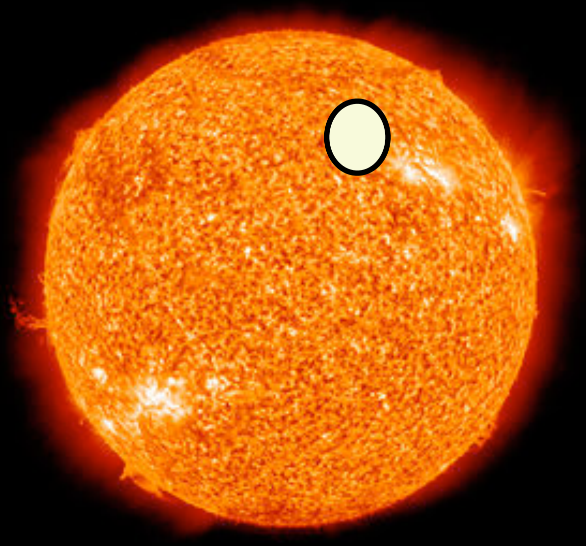
- Lighter dark matter forms heavier stars, thus better constrained by GW
- Constraints of dark matter self-interactions

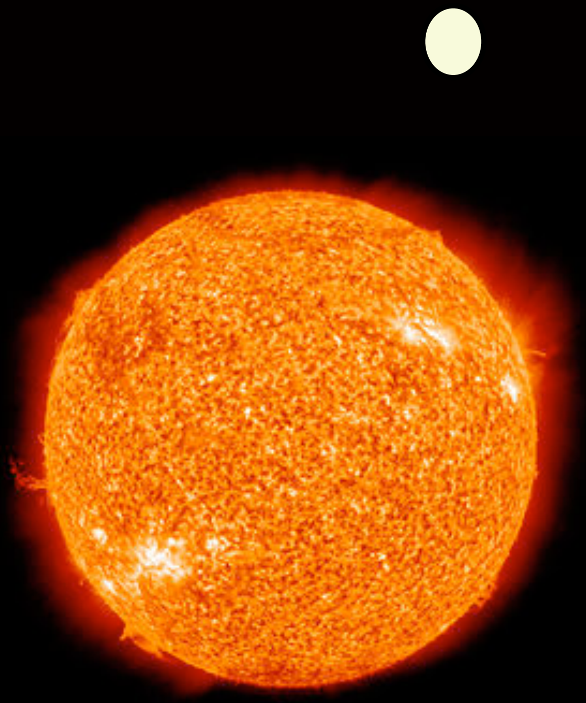
Converting Neutron Stars to Black Holes

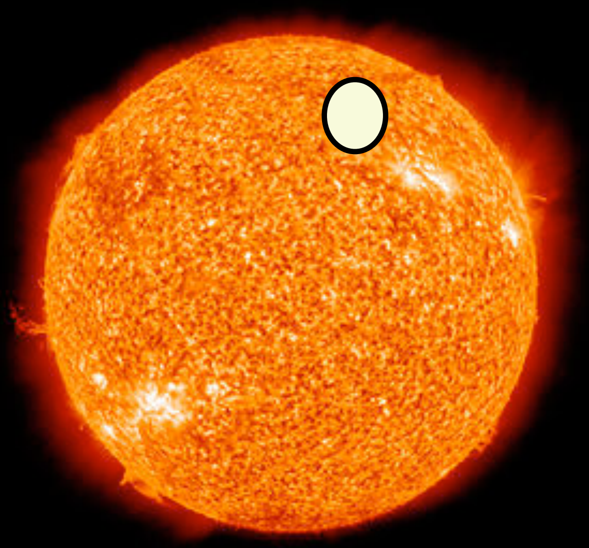


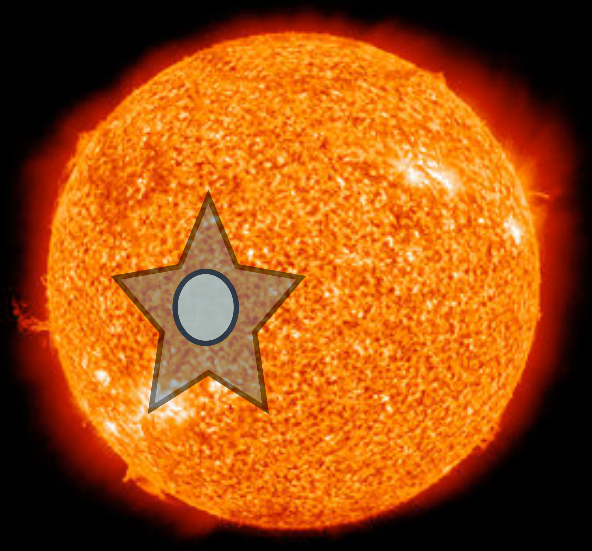


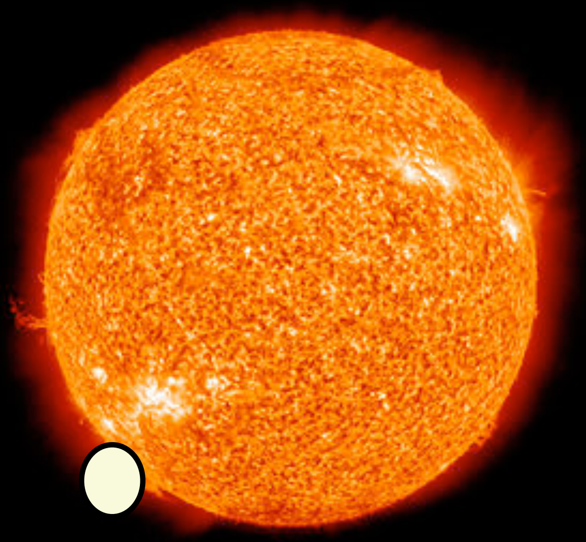


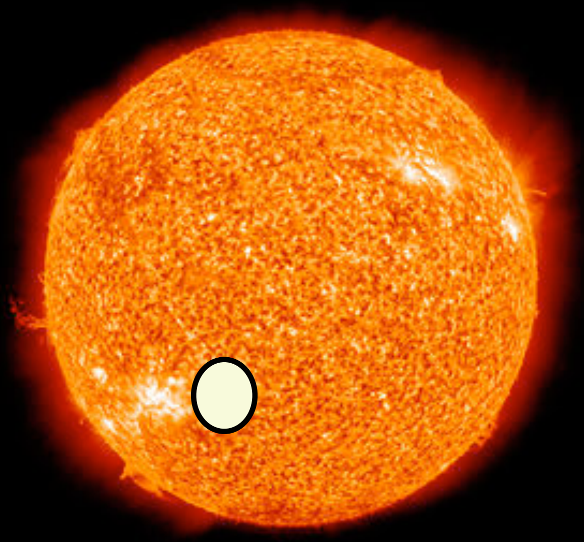


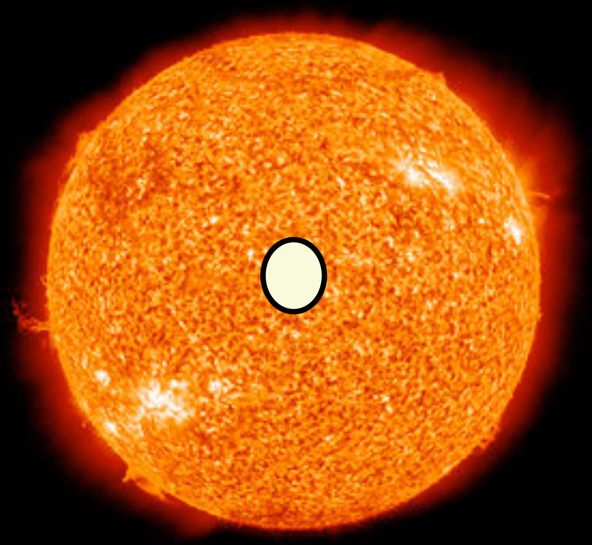


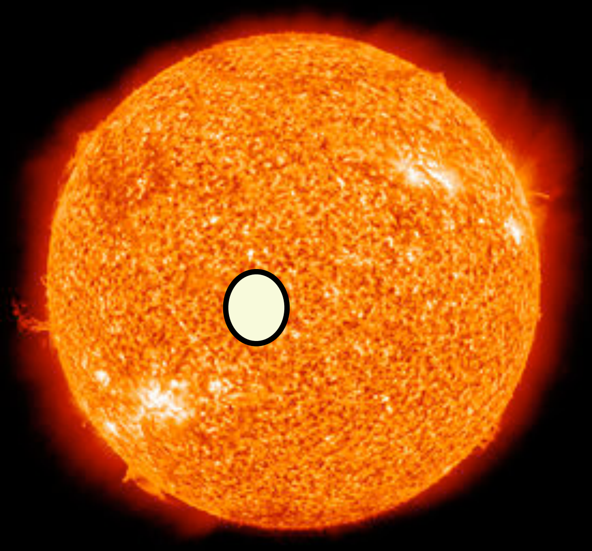


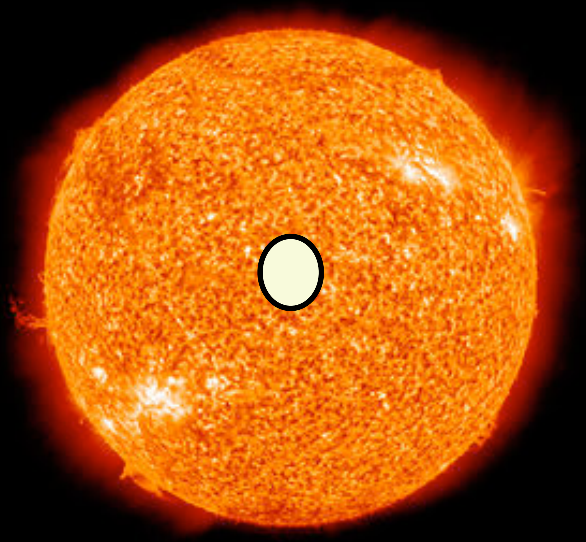


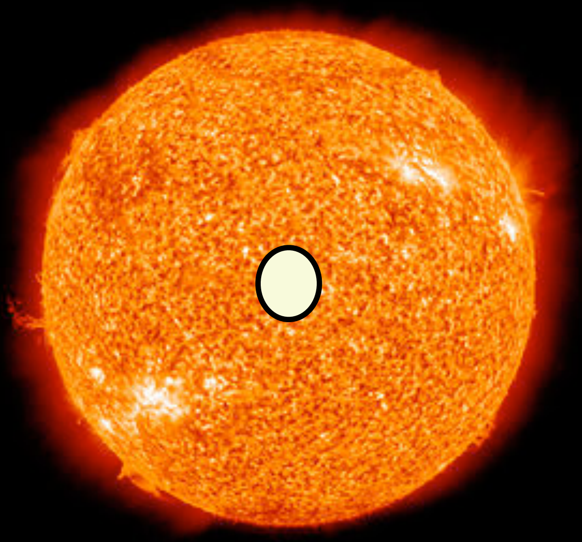


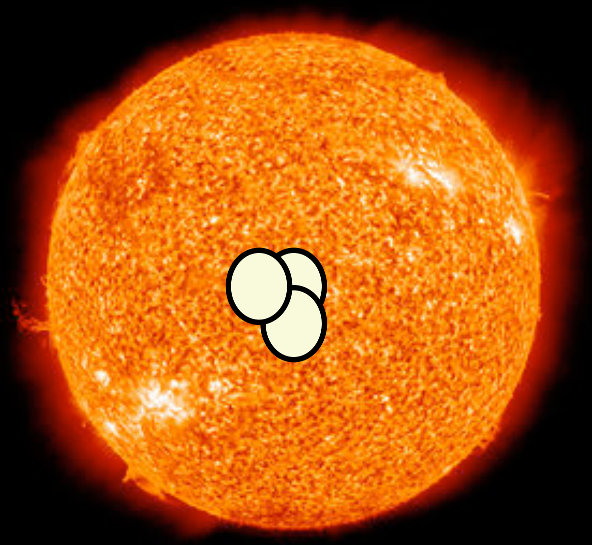


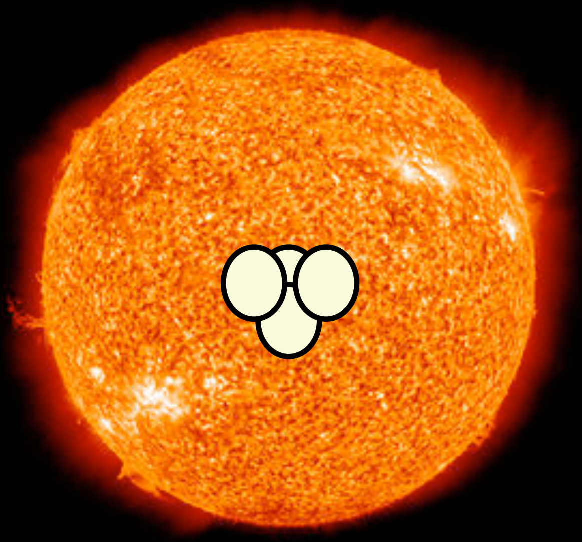


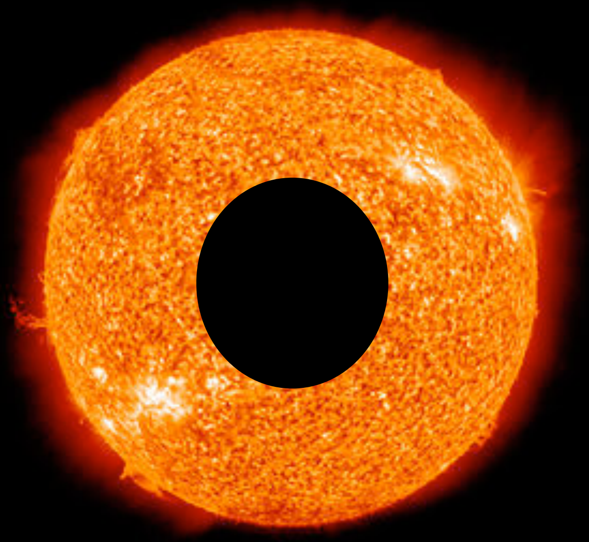


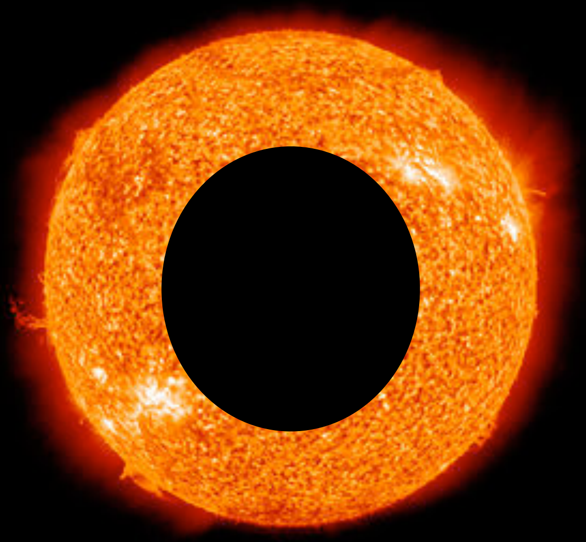


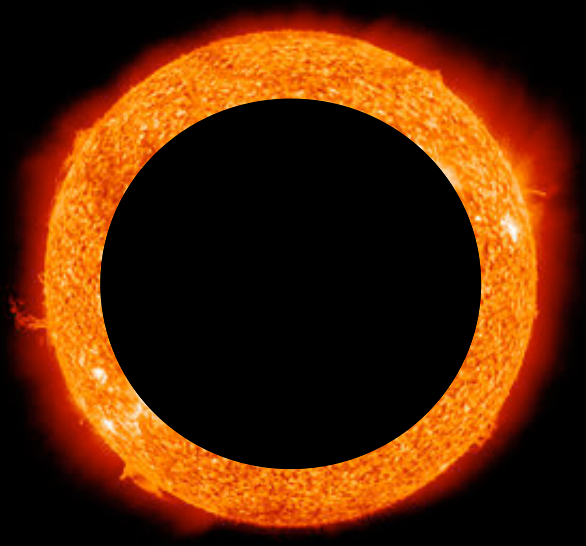












Asymmetric Dark Matter in Neutron Stars

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

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

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

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

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

$$M_{\rm crit} = \frac{1}{12^{3/2}}\left(\frac{3}{4\pi\rho_c}\right)^2\left(\frac{\omega_0}{G}\right)^3\frac{1}{\psi^3} \qquad M_{\rm crit} = 2.2\times10^{46}P_1^{-3}\ {\rm GeV}$$

CK, Tinyakov '13

viscosity of nuclear matter saves Bondi

$$\frac{\partial}{\partial t}l - \frac{C_0M^2}{4\pi\rho r^2}\frac{\partial}{\partial r}l = \frac{1}{\rho r^2}\frac{\partial}{\partial r}\left[\rho\nu r^4\frac{\partial}{\partial r}\left(\frac{1}{r^2}l\right)\right].$$

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

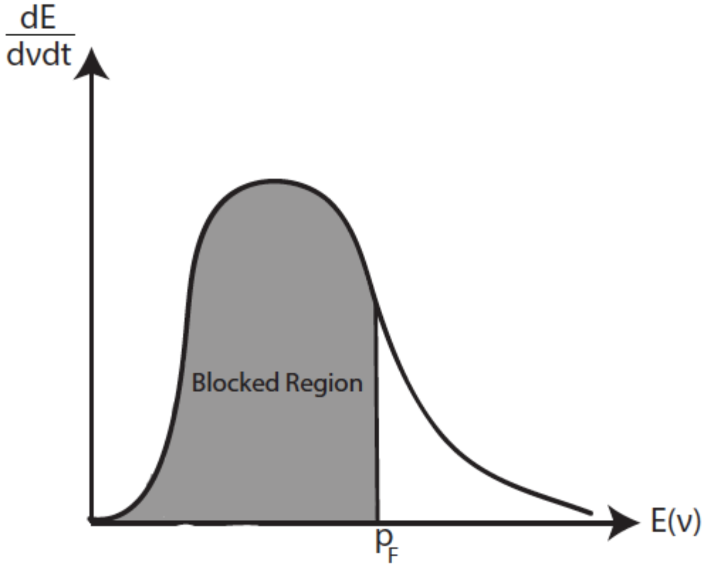
$$T = \frac{1}{8\pi G M_c} = \frac{m}{16} \qquad \frac{dM}{dt} = -(n_f f_f + n_b f_b + n_s f_s + n_2 f_2)\frac{1}{G^2 M^2}$$

Degenerate matter can block potentially the emission of particles

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

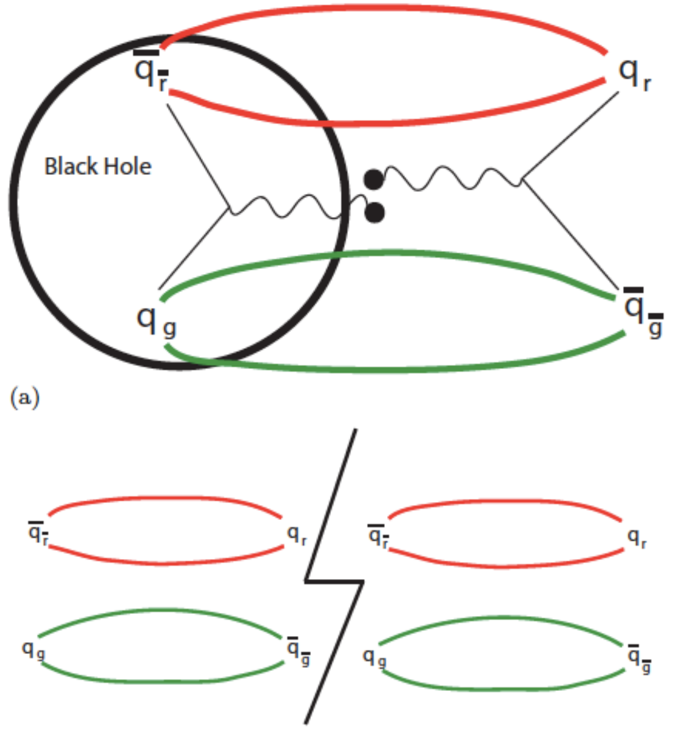
at Bondi radius $\frac{n(r)}{n_\infty} \simeq \frac{\lambda_s}{\sqrt{2}}\left(\frac{GM}{c_s^2 r}\right)^{3/2}$

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

$$a = J/GM^2$$

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

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

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:

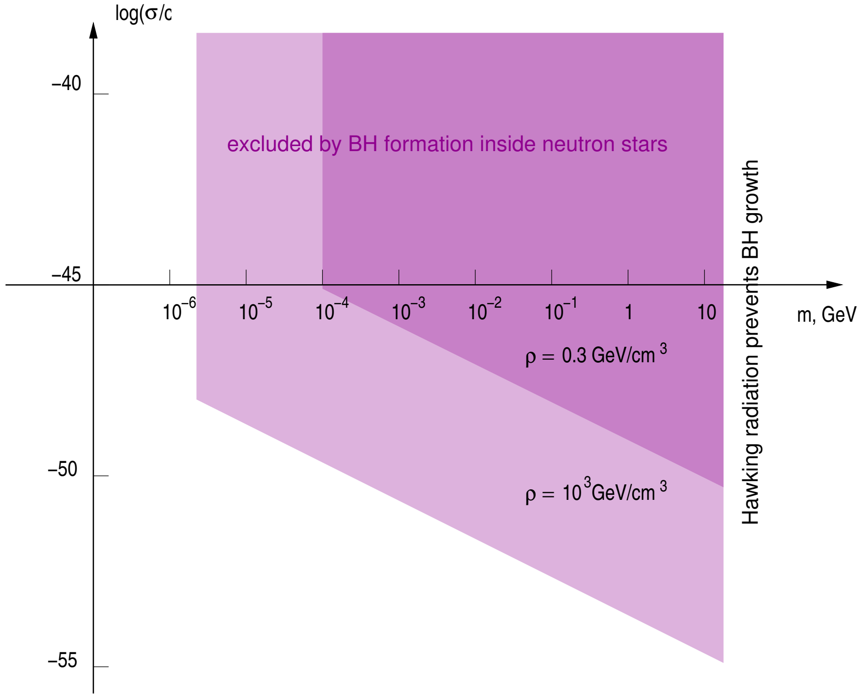
Reduce viscosity

Increase radiation pressure

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

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

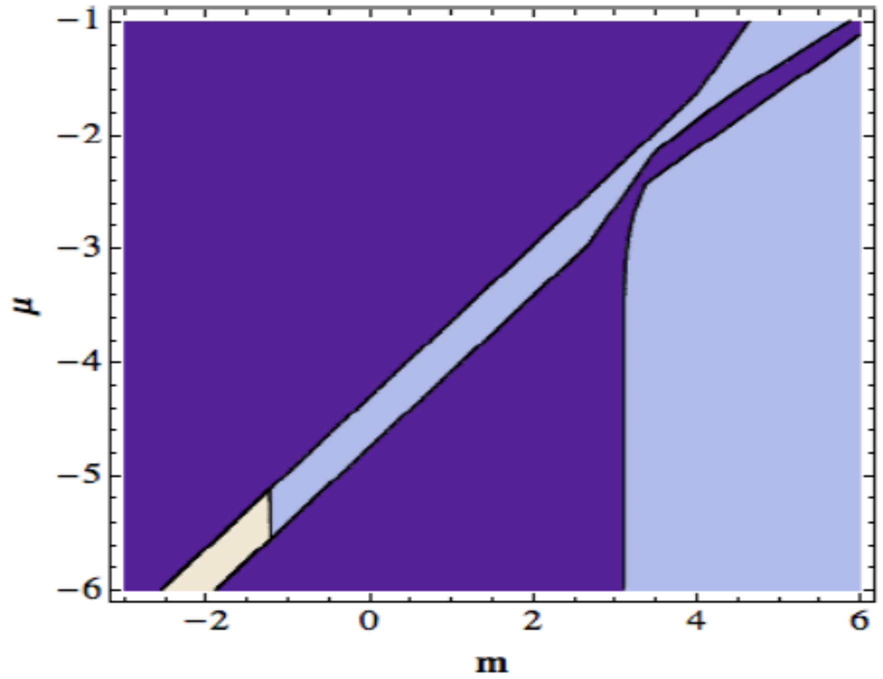
Destroying Stars



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

Compositeness scale

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



CK Phys.Rev. Lett. '12

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

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

Setting New Constraints on Dark Matter Self-Interactions

Dark Matter self-interactions can be constrained severely because they could cause collapse of neutron stars that will lead to an increase in the expected rate of binaries seen in LIGO

Solar mass black holes are not necessarily primordial. They can be an indication of asymmetric self-interacting dark matter

New constraints can be also imposed because fast rotating compact objects can lead to supernovae type of explosions when the collapse is triggered by asymmetric dark matter

Solar Mass Non-Priomordial Black Holes

Yukawa Self-Interactions $E_{\rm yu} = -\sum_j \alpha \frac{e^{-\mu r_{ij}}}{r_{ij}}$ $E_{\rm yu} = -\frac{3N\alpha}{\mu^2 r_{\rm th}^3} e^{-\frac{\mu r_{\rm th}}{N^{1/3}}} \left(1 + \frac{\mu r_{\rm th}}{N^{1/3}}\right)$

Virial Theorem

$$2\langle E_k\rangle = \frac{8}{3}\pi G\rho_c m r^2 + \frac{GNm^2}{r} + 9\alpha\mu\frac{e^{-x}}{x}\left(\frac{1}{x^2} + \frac{1}{x} + \frac{1}{3}\right)$$

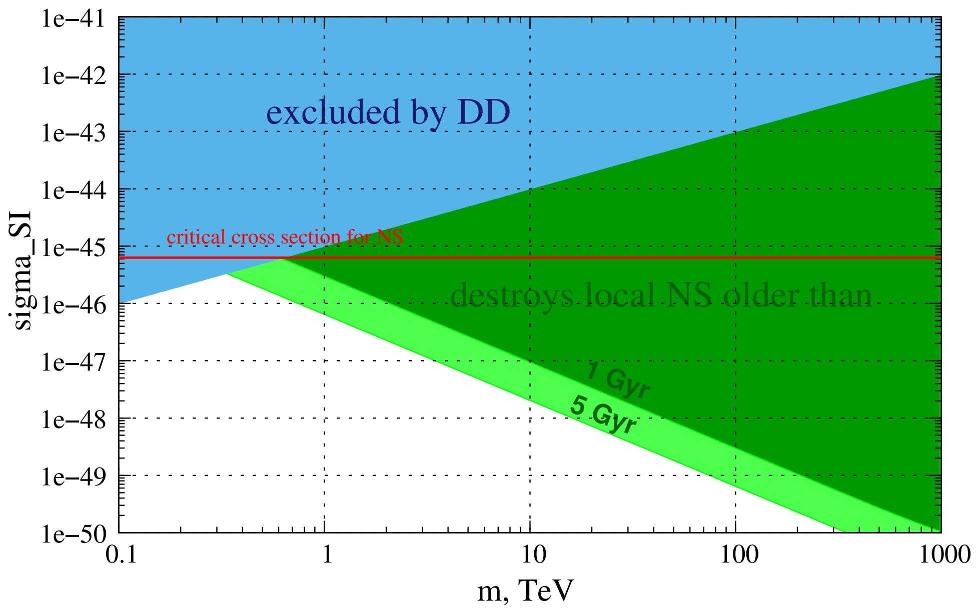
$$x = \mu r/N^{1/3}$$

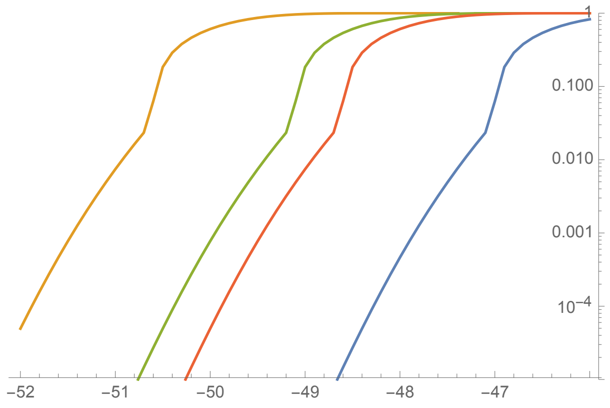
Collapse starts when 2nd and 3rd term comparable to 1st

We take a Burkert profile and a bulge plus a double disk model for the NS-NS binary distribution

compatible with constraints from old nearby NS as well as pulsars close to the galactic center.

aLIGO/Virgo 0.4-400 events/year
Einstein Telescope 10^3-10^7





CK, Tinyakov, Tytgat… soon

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