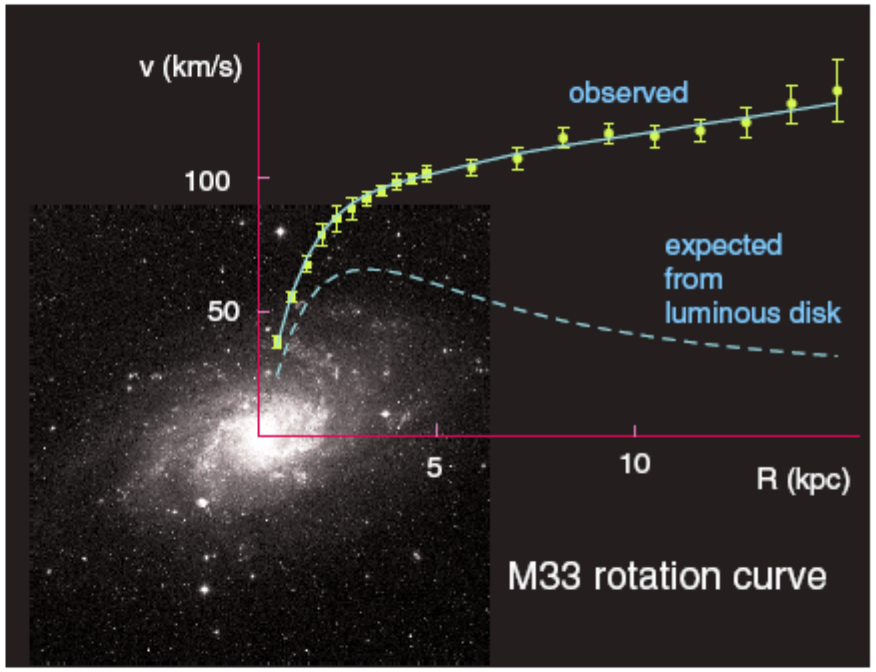
Dark Stars

Chris Kouvaris

Dark Matter & Stars, Lisbon 4/5/2023

The Missing Mass of the Universe

Coma cluster



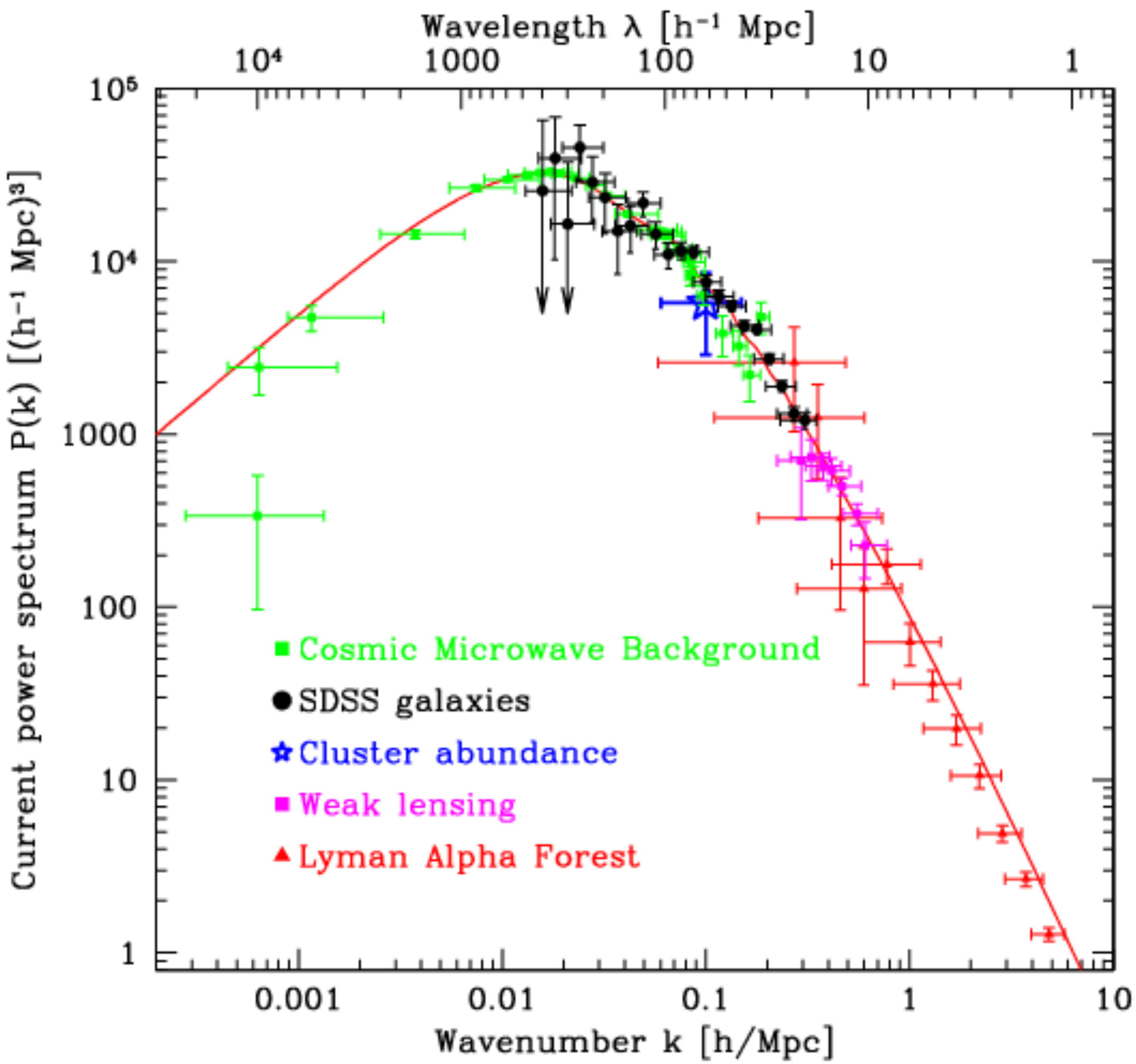
Rotation curves of Andromeda are not falling according to Newton's law!

Bullet Cluster

Galaxy NGC 1052-DF2,
no dark matter!!!

Why Dark Matter Self-Interactions?

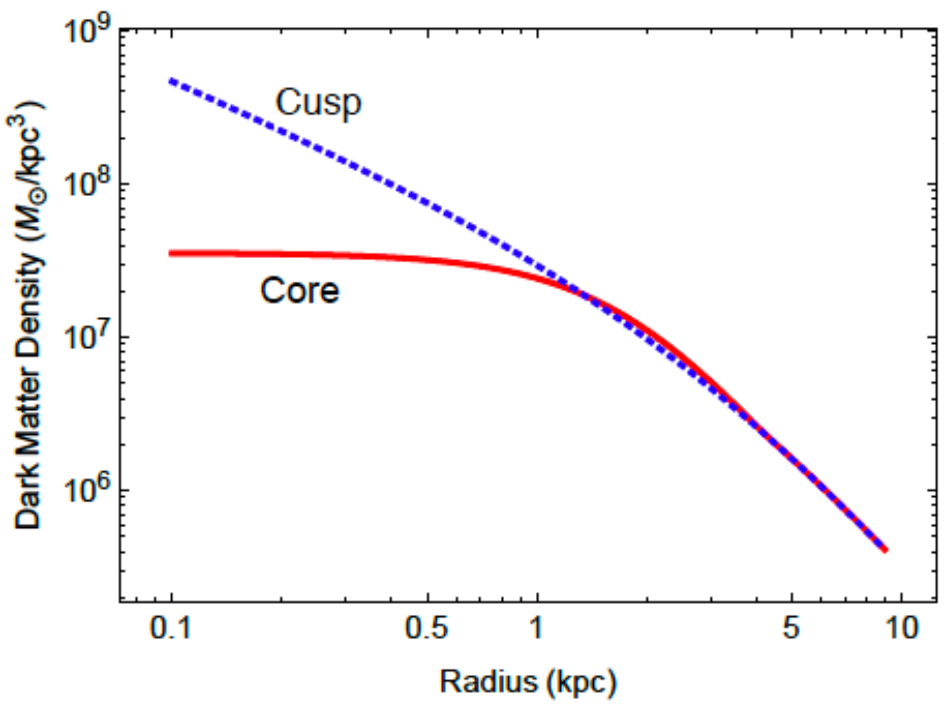
CCDM very consistent with Large Scale Structure

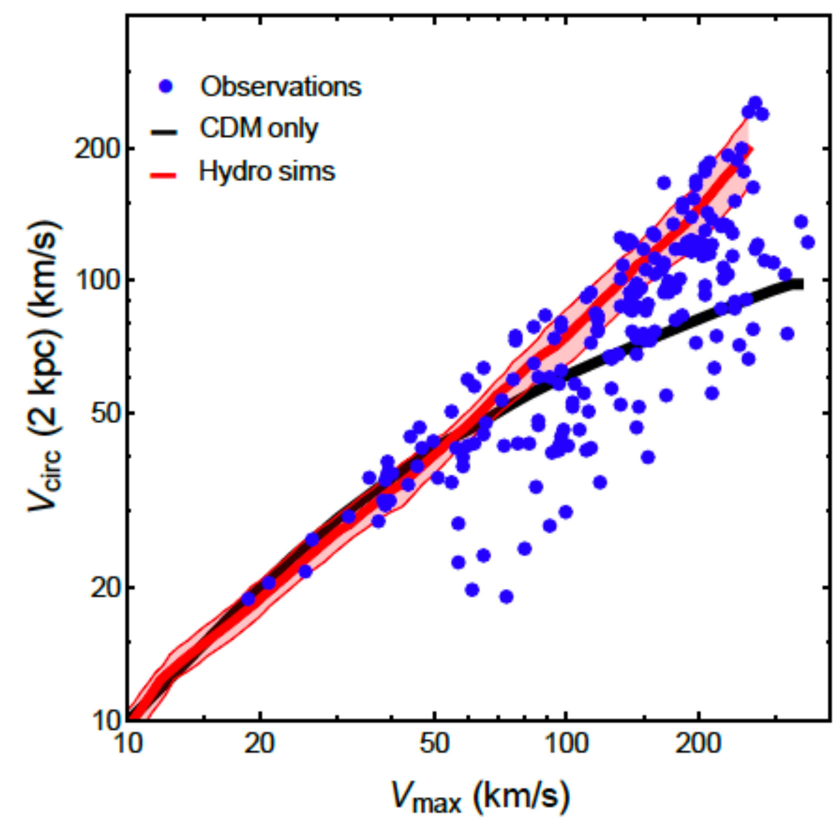


Why Dark Matter Self-Interactions?

However CCDM seems problematic in small scales

Problems with Collisionless Cold Dark Matter
- Core-cusp profile in dwarf galaxies
- Diversity Problem
- “Too big to fail”





$$R_{\rm scat} = \sigma v_{\rm rel}\rho_{\rm dm}/m \approx 0.1\ {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1\ {\rm M}_\odot/{\rm pc}^3}\right)\left(\frac{v_{\rm rel}}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m}{1\ {\rm cm}^2/{\rm g}}\right)$$

$$\sigma/m \sim 1\ {\rm cm}^2/{\rm g} \approx 2\times 10^{-24}\ {\rm cm}^2/{\rm GeV}$$

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

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

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

$$n_{TB} = n_B$$

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

$$1 \times 5 = 5$$

Asymmetric Dark Stars

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

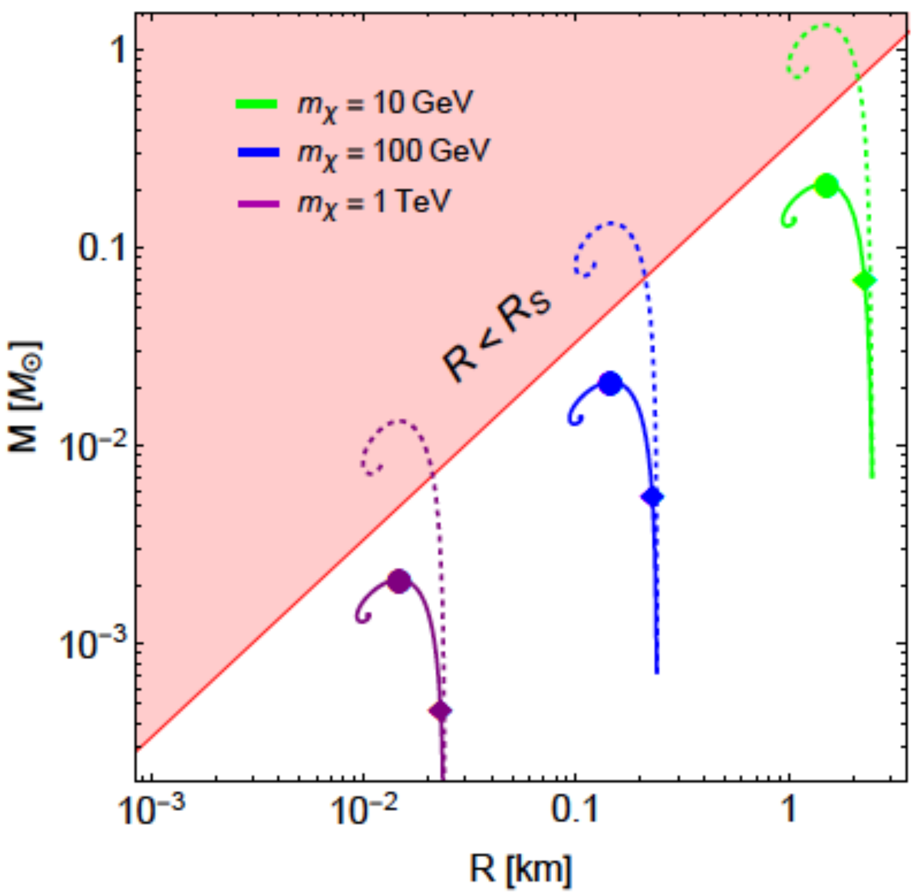
- How do they look like?
- Can we detect them and distinguish them from NS or BH?
- What is the formation mechanism?

Asymmetric Dark Stars

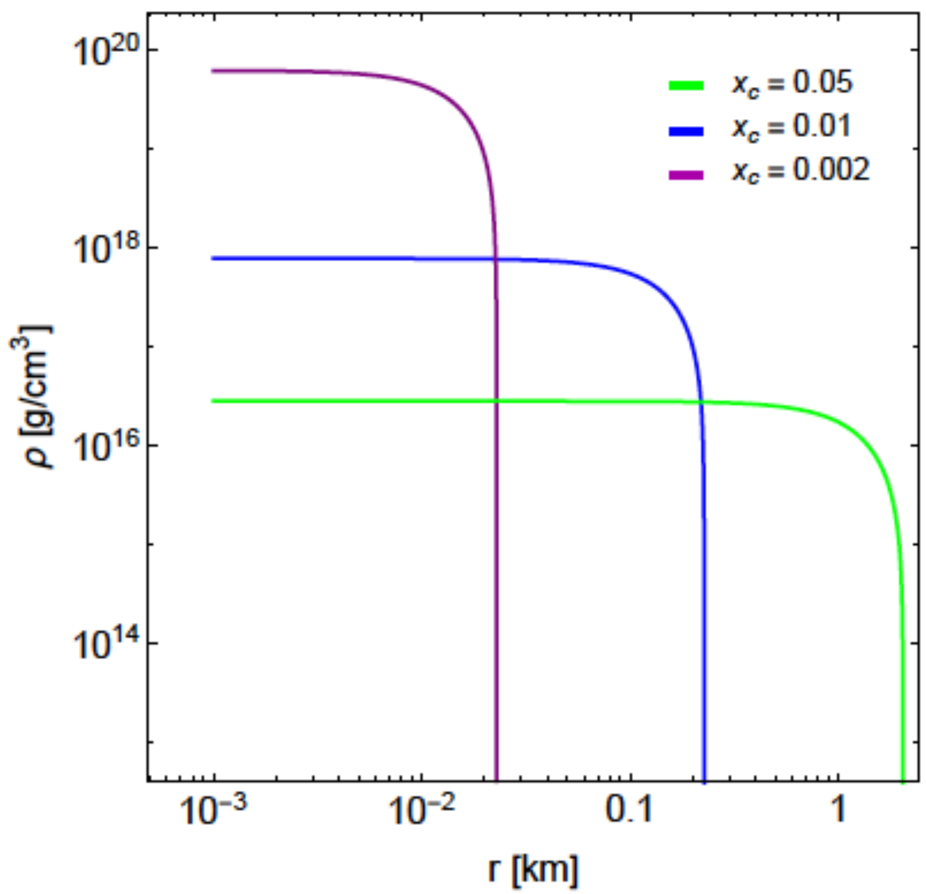
Tolman-Oppenheimer-Volkoff with Yukawa self-interactions

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

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



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

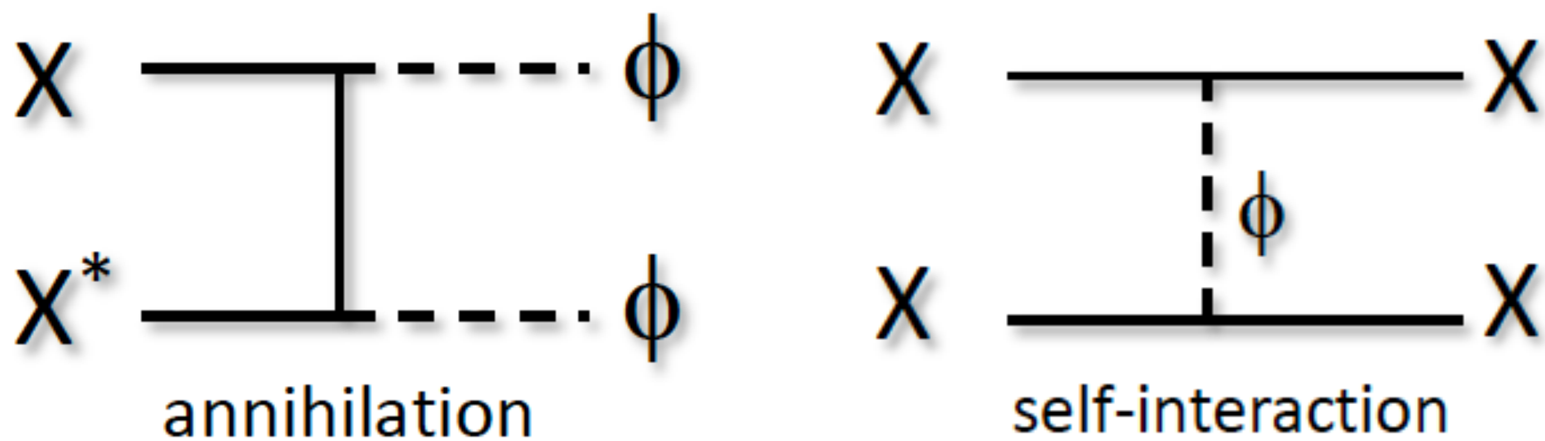


(b) $\rho(r)$ for repulsive interactions

CK, Nielsen '15

Light Mediators

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



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 $\alpha_X m_X / m_\phi \gg 1$

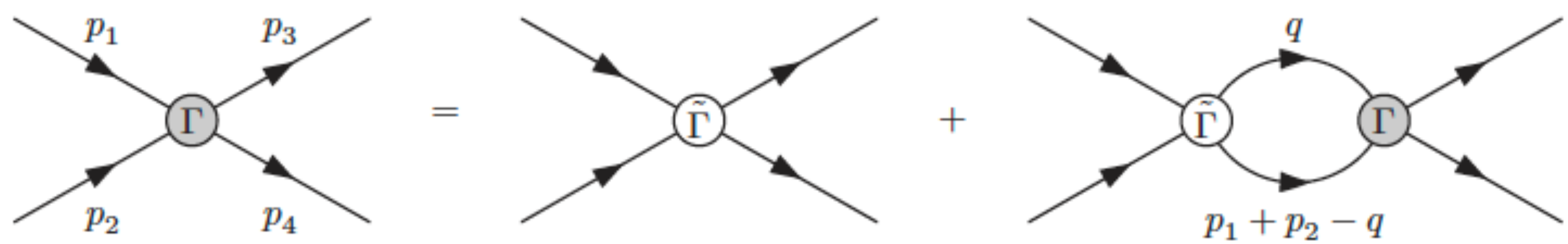
Classical Limit $m_X v / m_\phi \gg 1$ The problem is identical to plasma physics

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

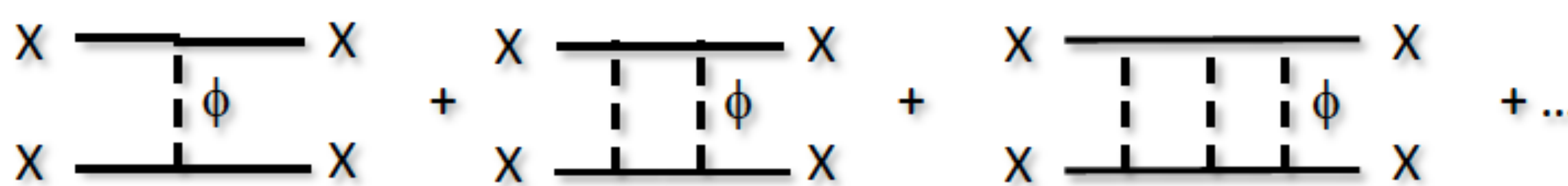
$$\sigma_T^{\rm clas} = \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 \ln\left(1+\beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2 / \left(1 + 1.5\beta^{1.65}\right) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2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

Light Mediators

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



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

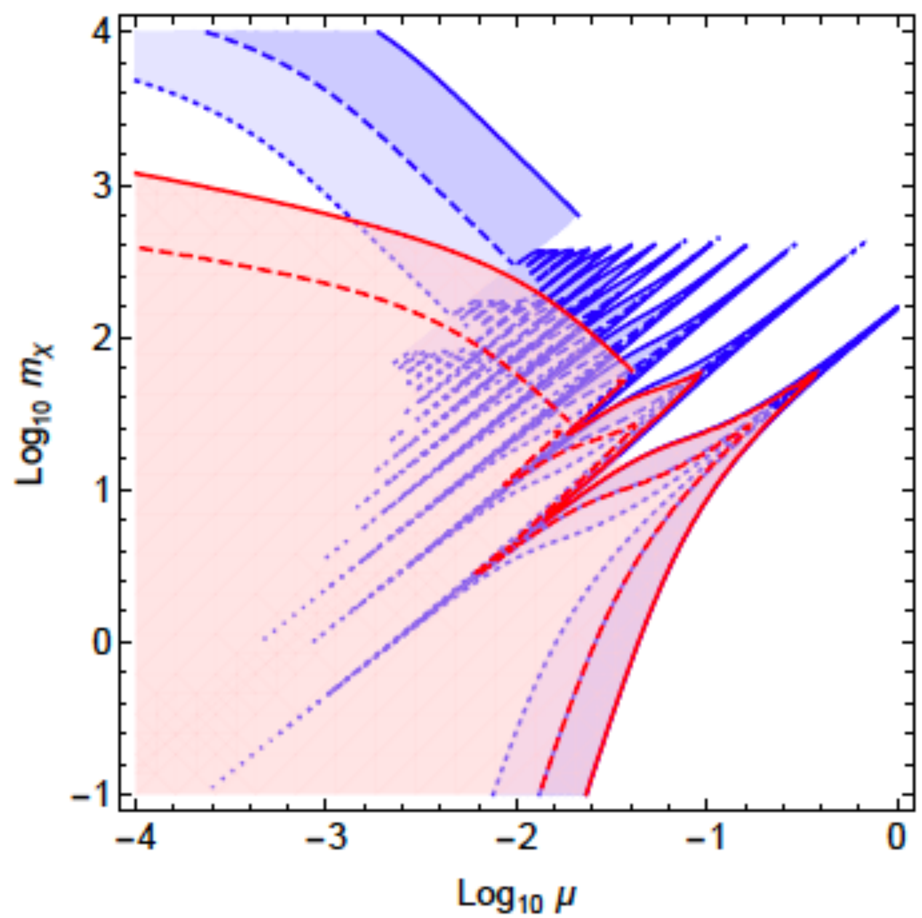


Non-relativistic limit equivalent to Schrodinger equation

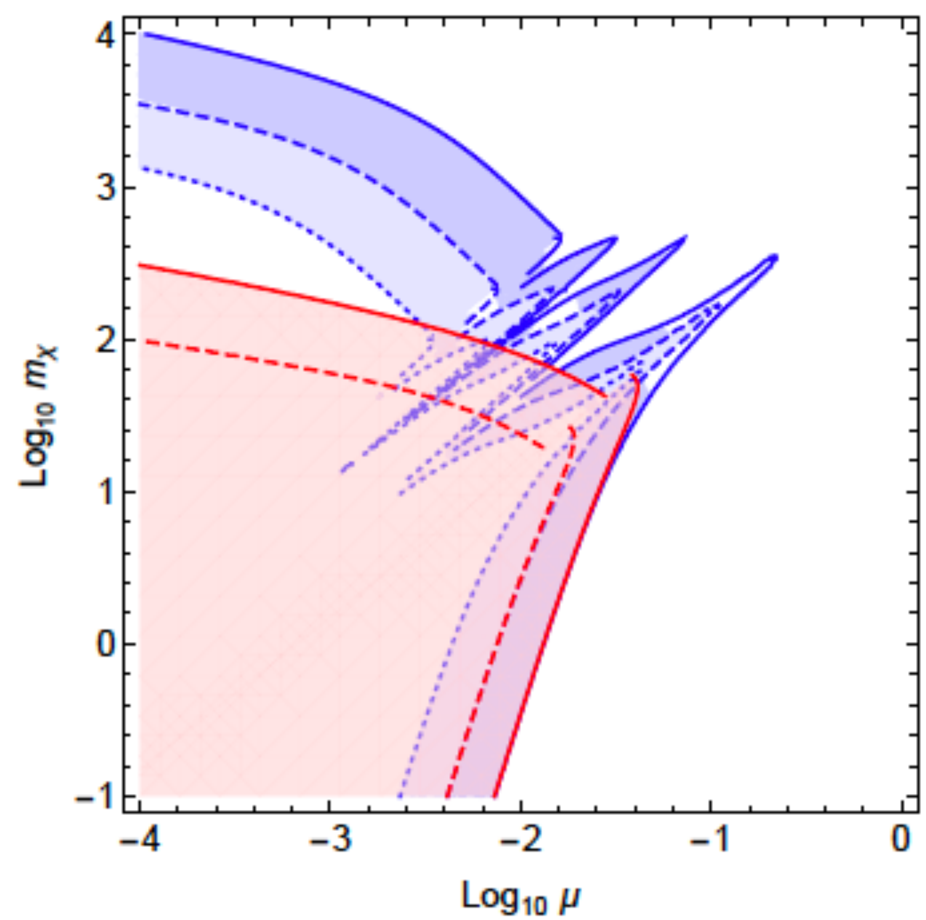
$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dR_\ell}{dr}\right) + \left(k^2 - \frac{\ell(\ell+1)}{r^2} - 2\mu V(r)\right)R_\ell = 0$$

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

Light Mediators



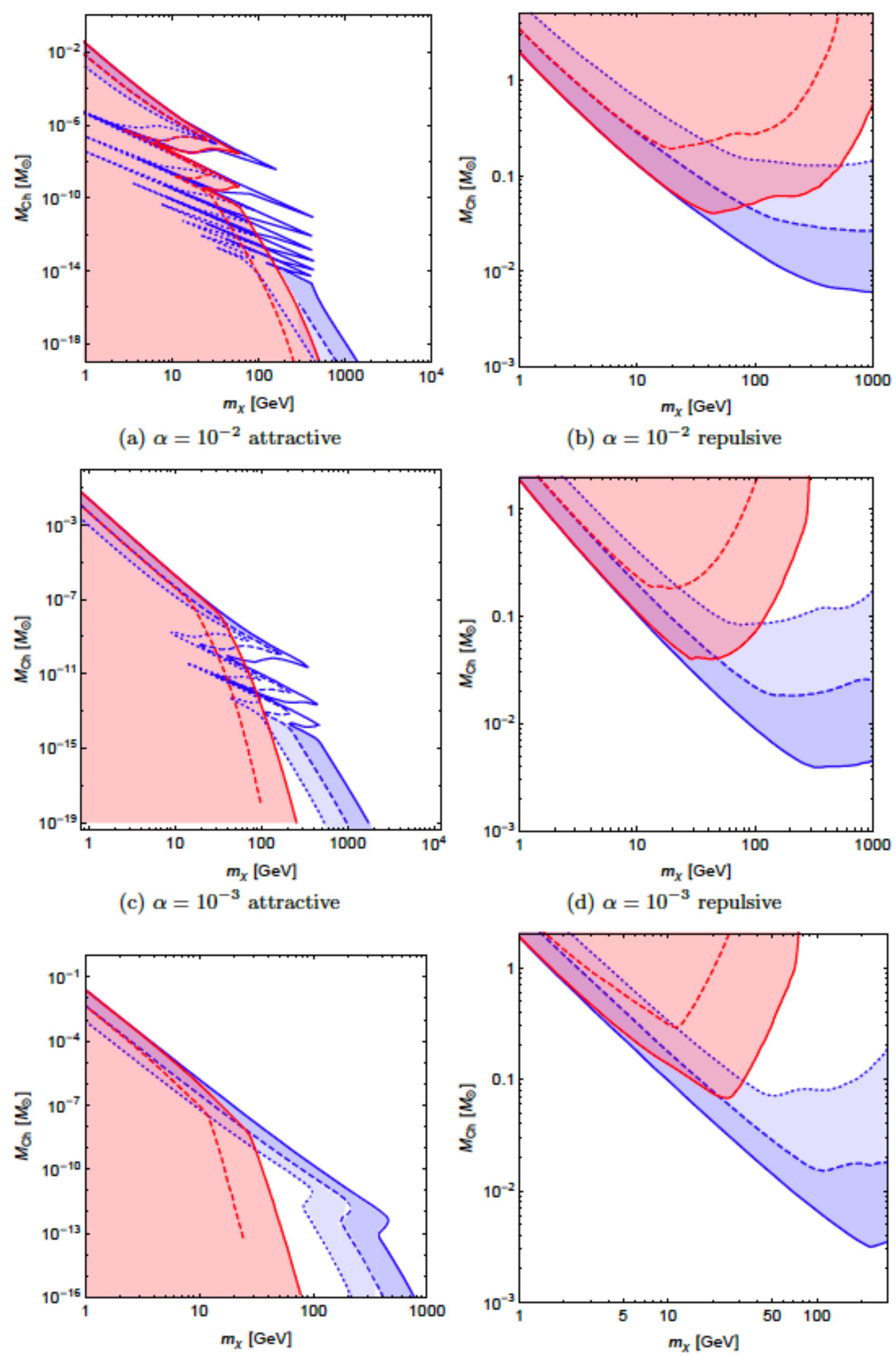
$\alpha = 10^{-2}$ attractive



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

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 $\lambda\phi^4$

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

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

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

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

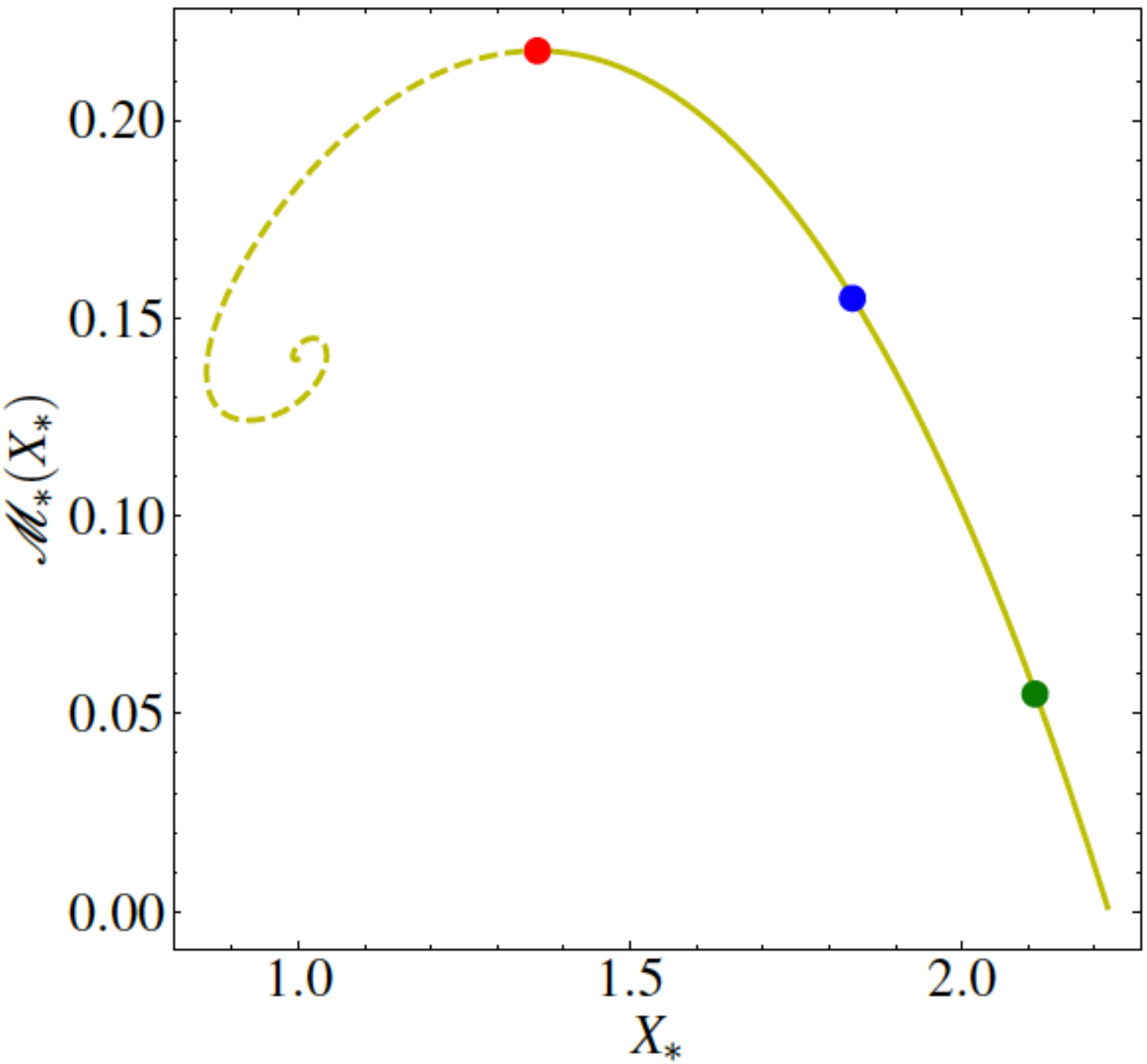
$$\sigma'' + \left(\frac{2}{x} + \frac{B'}{2B} - \frac{A'}{2A}\right)\sigma' + A\left[\left(\frac{\Omega^2}{B} - 1\right)\sigma - \Lambda\sigma^3\right] = 0,$$

$x = mr$, $\sigma = \sqrt{4\pi G}\Phi$ (Φ the scalar field), $\Omega = \omega/m$ $\quad \Lambda = \lambda M_P^2/(4\pi m^2)$ Colpi Shapiro Wasserman ‘86

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

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

Asymmetric Bosonic Dark Stars



Eby Nielsen CK Wijewardhana '16

Asymmetric Bosonic Dark Stars

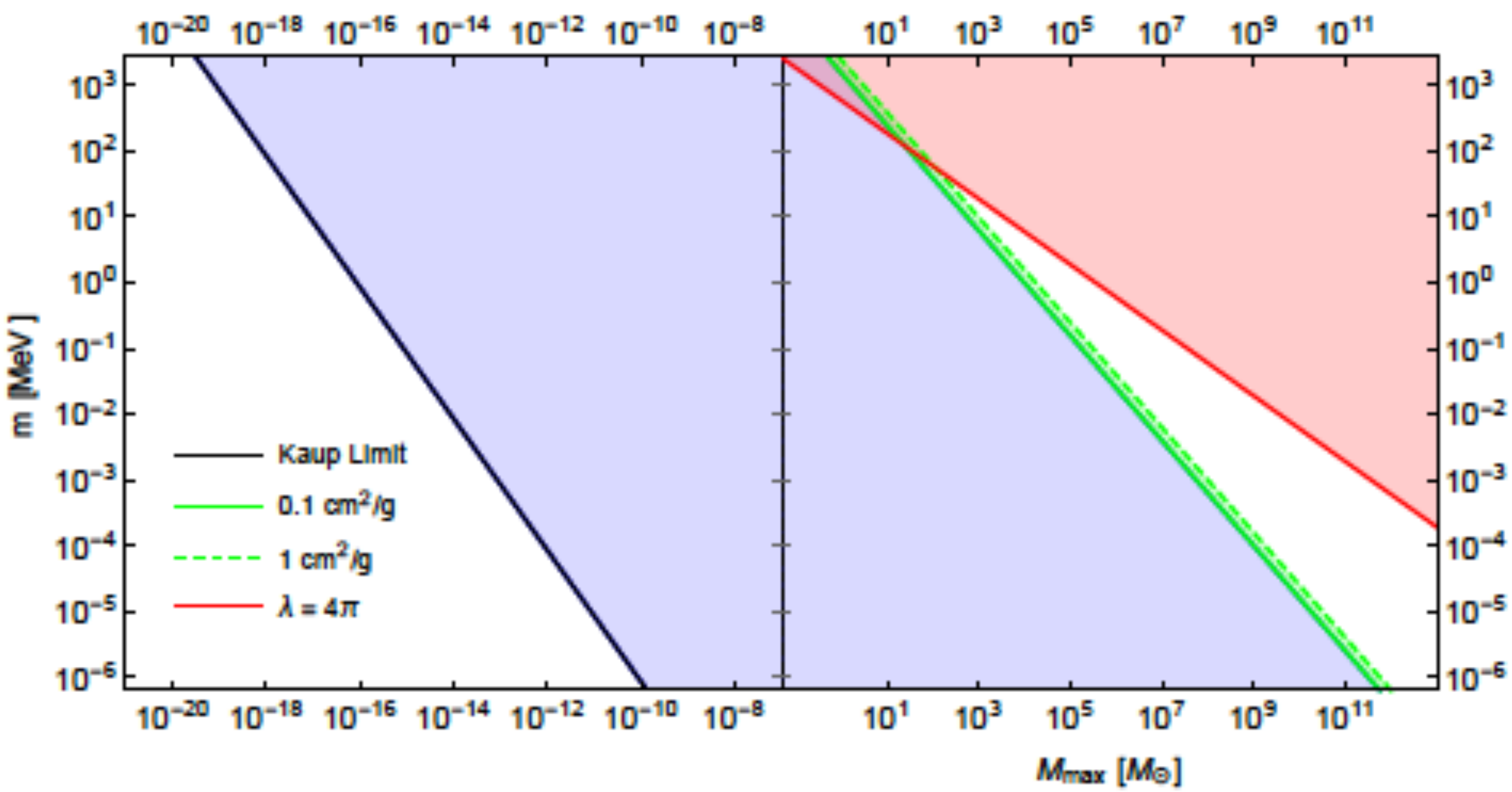
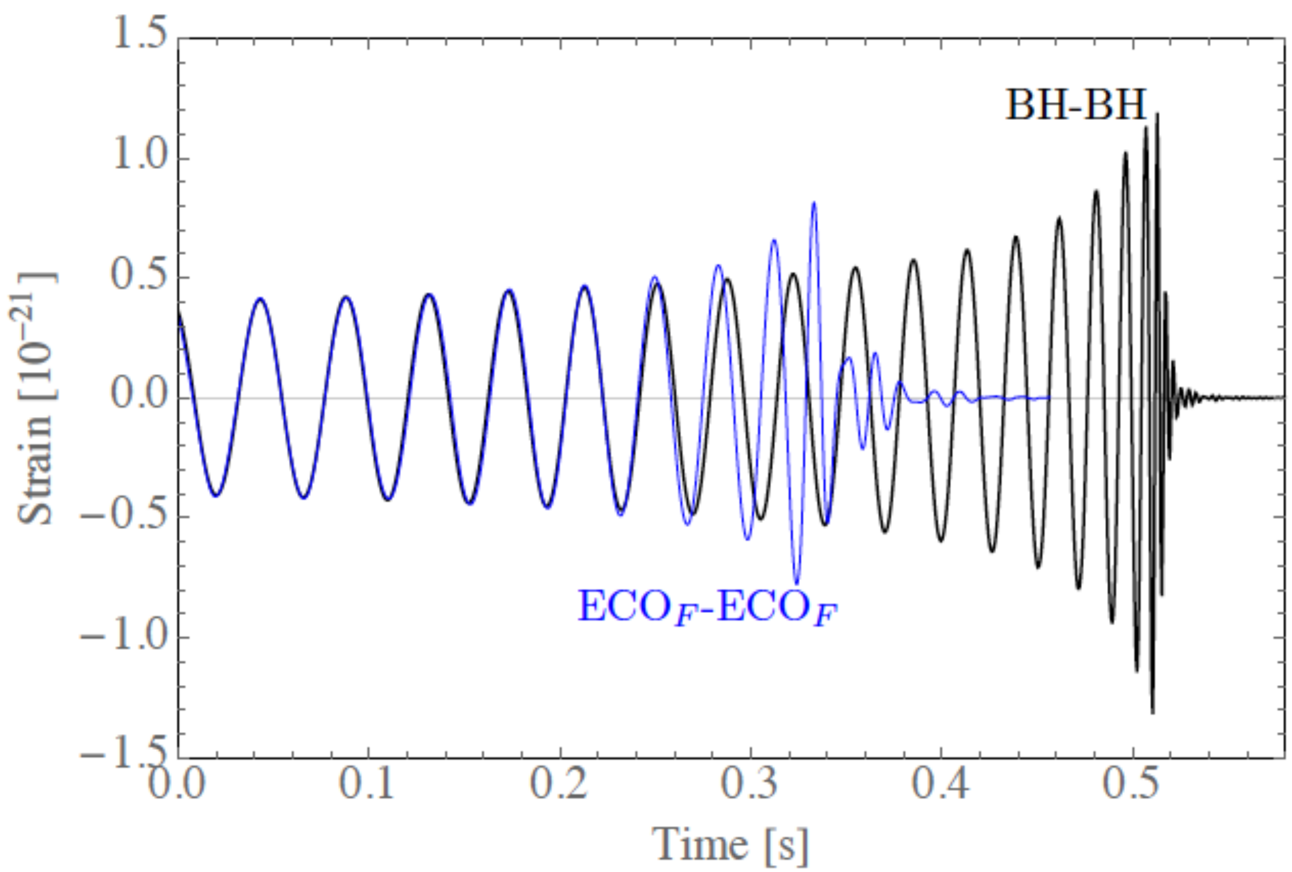


Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass m. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths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



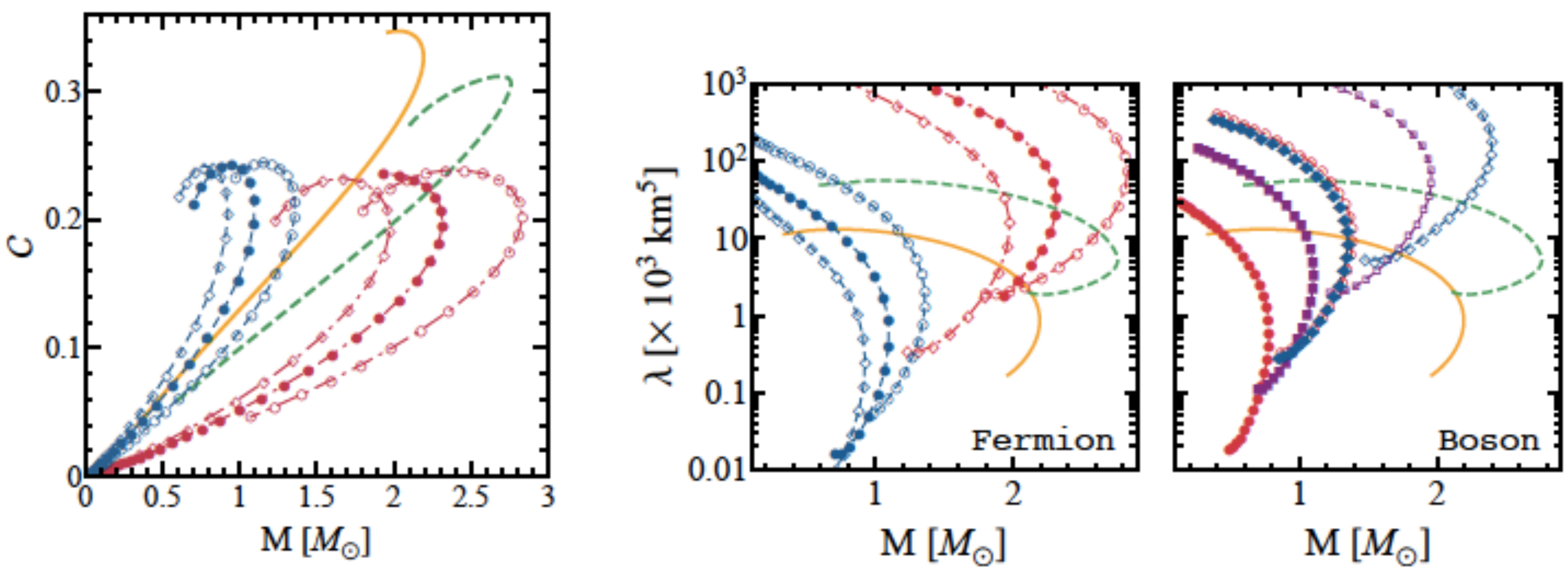
Giudice, McCullough,
Urbano ‘16

Tidal Deformations of Dark Stars

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

$V=-(1/2)\varepsilon_{ij}x^i x^j$ $\quad Q_{ij}=-\lambda\varepsilon_{ij}$ $\quad \lambda=\frac{2}{3}k_2 R^5$

Love number

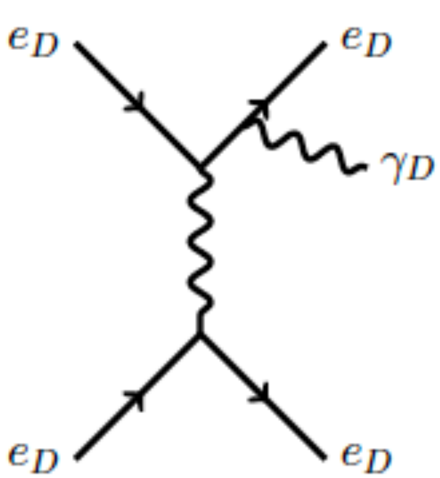


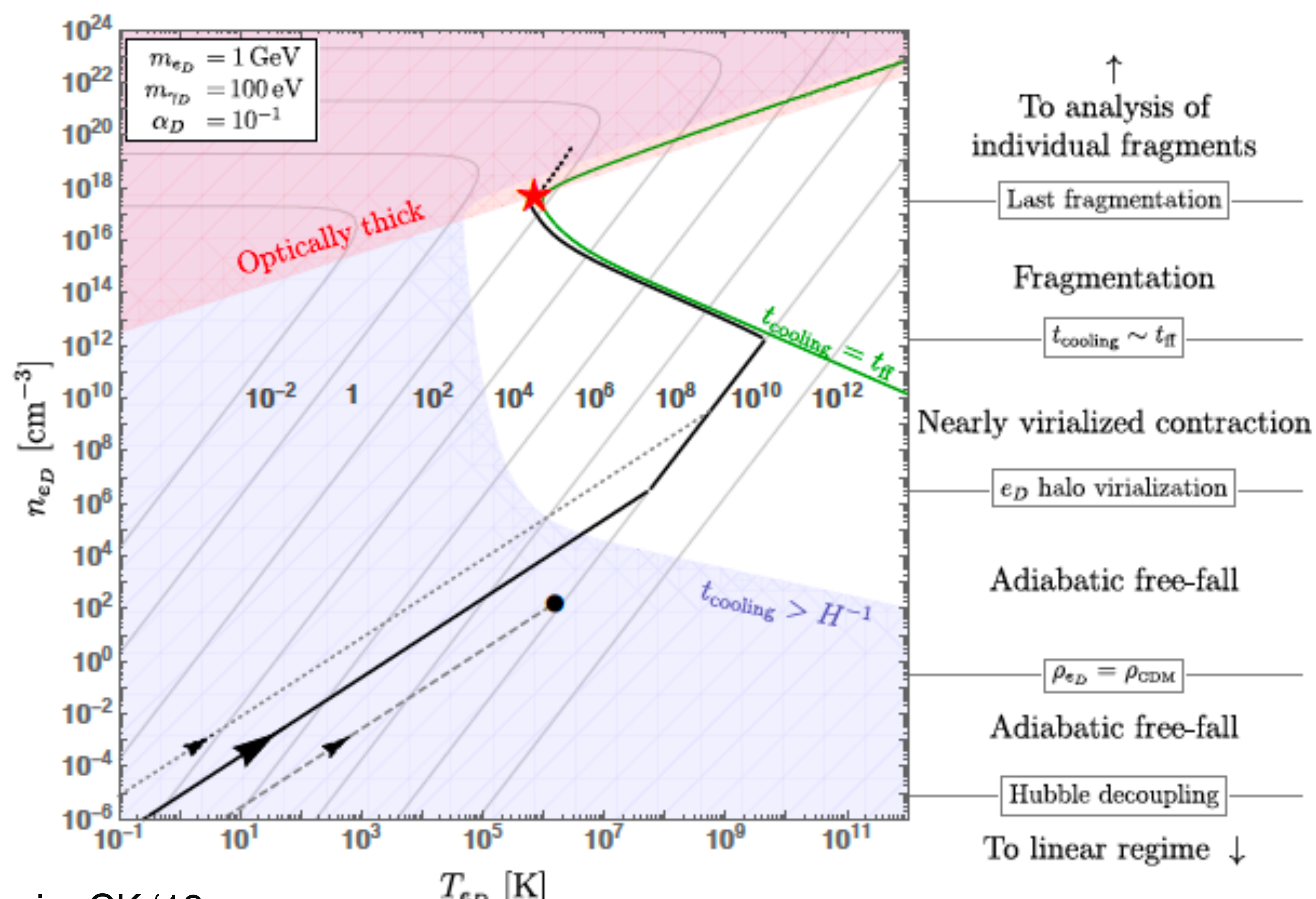
Maselli, Pnigouras,Nielsen,
CK, Kokkotas, 17

Formation of Asymmetric Dark Stars

Collapse can proceed via dark photon Bremsstrahlung Cooling

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





Chang, Egana-Ugrinovic, Essig, CK '19

Relativistic Proton Capture rate

Dark stars can accrete protons and electrons

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

$$\frac{dt}{d\sigma} = \frac{1}{B(r)}, \quad \vartheta = \frac{\pi}{2}, \quad r^2 \frac{d\varphi}{d\sigma} = J = \text{const.}$$

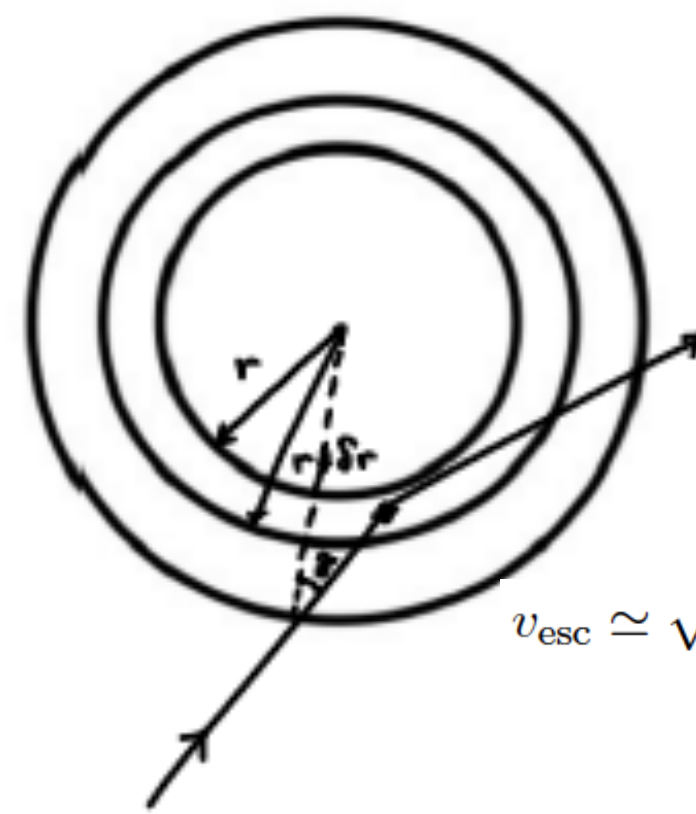
$$A(r)\left(\frac{dr}{d\sigma}\right)^2 + \frac{J^2}{r^2} - \frac{1}{B(r)} = -E = \text{const.}$$

$$J_{\max} = \sqrt{\frac{1 - B(r)}{B(r)} + u^2}$$

$$dF = n f(u) u \cos\theta \frac{1}{2} d\cos\theta du$$

$$dF_{\text{tot}} = \pi n \frac{f(u)}{u} du dJ^2$$

$$dC = dF_{\text{tot}} \frac{dl}{l_{\text{mfp}}}$$



$$v_{\text{esc}} \simeq \sqrt{1 - B(r)}$$

$$C = \frac{n\sigma}{m} \int_0^\infty 4\pi \frac{f(u)}{u} du \int_0^{r_*} \frac{1 - B(r)}{B(r)} r^2 \rho(r) dr$$

Betancourt, Brenner, Ibarra, CK '22

$$C = n_0 \left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2} 4\pi^2 (2GMR) \frac{1}{1 - 2GM/R} \frac{1}{3} \bar{v}^2$$

Goldman Nussinov '89, CK '07

Dark Star Outbursts

after capture there is a thermalisation stage where protons settle in a thermal radius

$$r_{\rm th} \approx \sqrt{\frac{15 k_B T}{4\pi G \rho_{\rm core} m_{\rm p}}}$$

Thermal Evolution of star

$$\frac{dT}{dt} = -\frac{L_\gamma + L_{\gamma'}}{C_{\rm v}}$$

BEC critical temperature

$$T_{\rm c} = \frac{2\pi}{m k_{\rm B}} \left(\frac{n}{\xi(\frac{3}{2})} \right)^{2/3}$$

Heat Capacity

$$C_{\rm v} = \frac{15}{4} k_{\rm B} N \frac{\xi(\frac{5}{2})}{\xi(\frac{3}{2})} \left(\frac{T}{T_{\rm c}} \right)^{\frac{3}{2}}$$

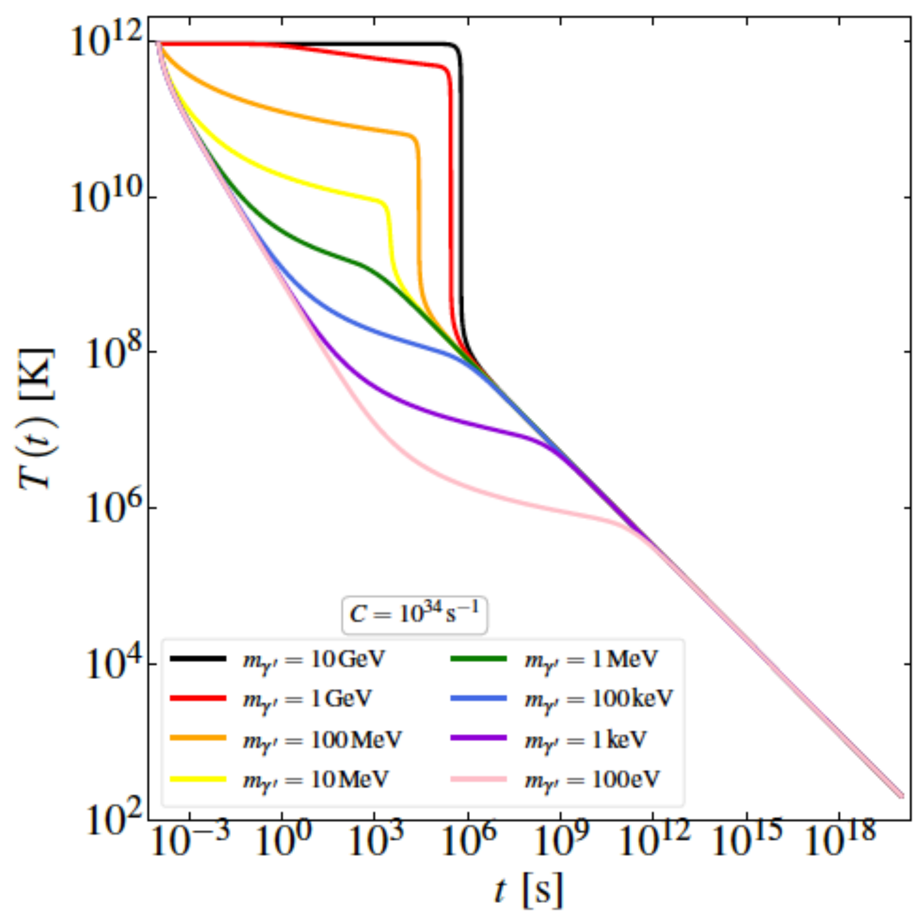
$$L_\gamma = (4\pi r_{\rm th}^2) \int_0^\infty I(\nu) d\nu \qquad I(\nu) = \frac{2h}{c^2} \frac{\nu^3}{{\rm e}^{\frac{h\nu}{k_B T}} - 1} \left(1 - {\rm e}^{-\tau(\nu)} \right)$$

$$\tau(\nu) \equiv r_{\rm th} \alpha_\nu \qquad \alpha_\nu = \frac{4}{3} \left(\frac{2\pi}{3} \right)^{\frac{1}{2}} g_{\bar{f}f} \frac{e^6}{h m_e^2 c^2} n_e n_p \left(\frac{m_e c^2}{k_B T} \right)^{1/2} \frac{1 - {\rm e}^{-\frac{h\nu}{k_B T}}}{\nu^3}$$

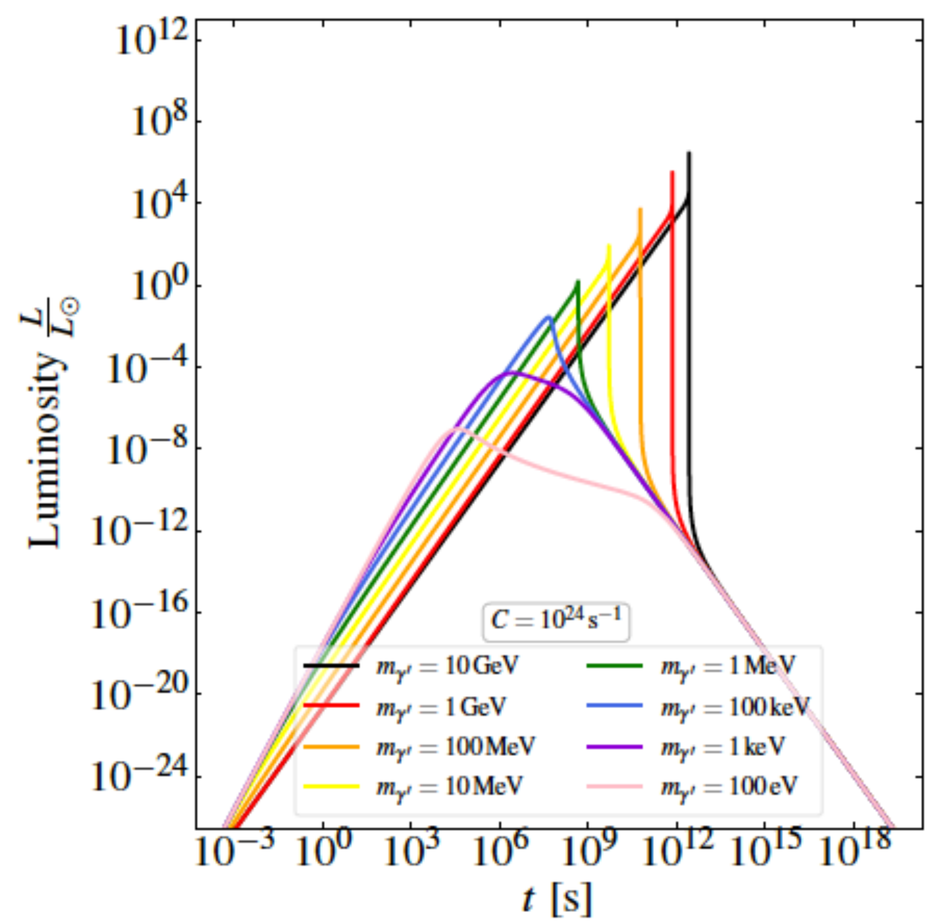
with $\tau \ll 1$ (optically thin limit)-> Bremsstrahlung
when $\tau \gg 1$ blackbody radiation

Dark Star Outbursts

Temperature



Luminosity



Outbursts can last from days to months

At first the photon luminosity scales as $n_p^2 T^2 \sim t^2/T$

As temperature reduces, the luminosity and the energy loss increase dramatically until the thermal radius becomes opaque for the photons.

At this point the spectrum becomes the blackbody one with luminosity~ T^5

there is one extra power of T due to the thermal radius dependence on T.

Observing Dark Stars

Nearby dark stars will present themselves as γ-ray point sources during the outburst.

Dark stars at larger distances could contribute in principle to the diffuse γ-ray background

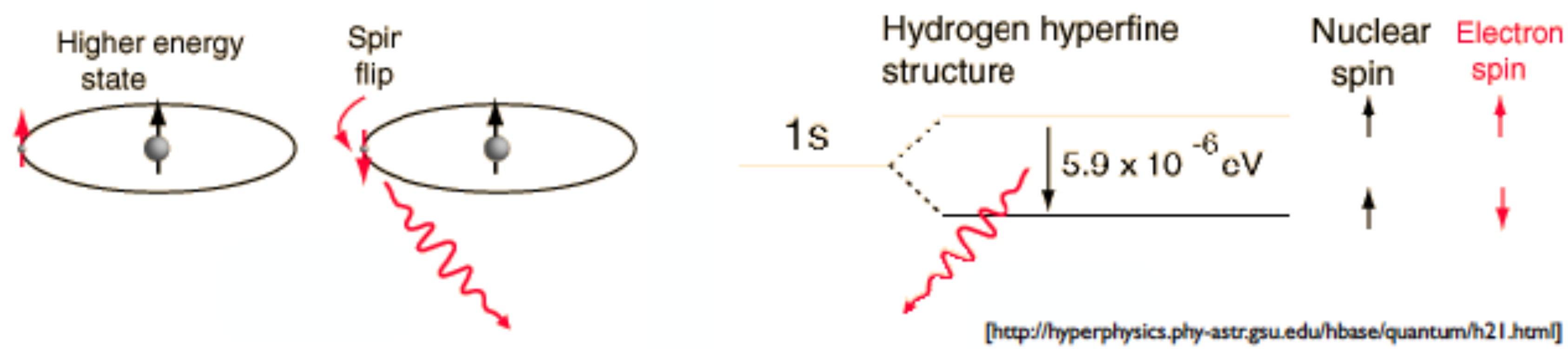
The number density of dark stars in outburst depends strongly on the dark star formation scenario (e.g. a uniform distribution vs a delta function in time)

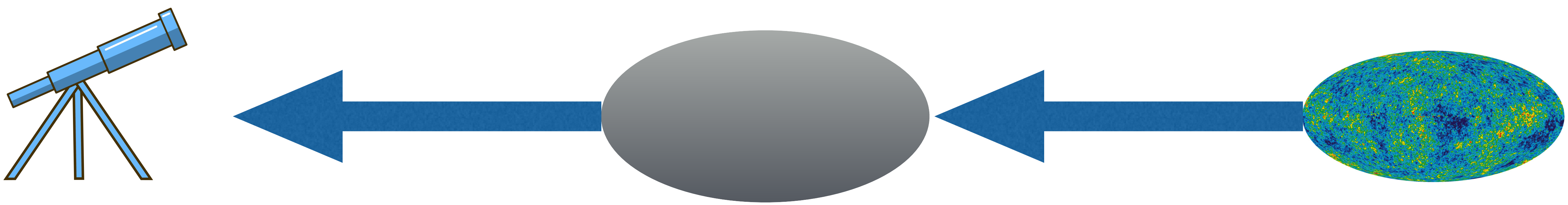
What if dark matter particles annihilate (or decay) to SM particles within the dark star?

The γ-ray spectrum will probe the density profile of dark matter and not the square of that as It is expected for usual dark matter annihilation.

Due to the potential compactness of the dark stars, one could probe dark matter annihilation cross sections at the Planck scale!

Can Dark Stars affect the 21cm Line?

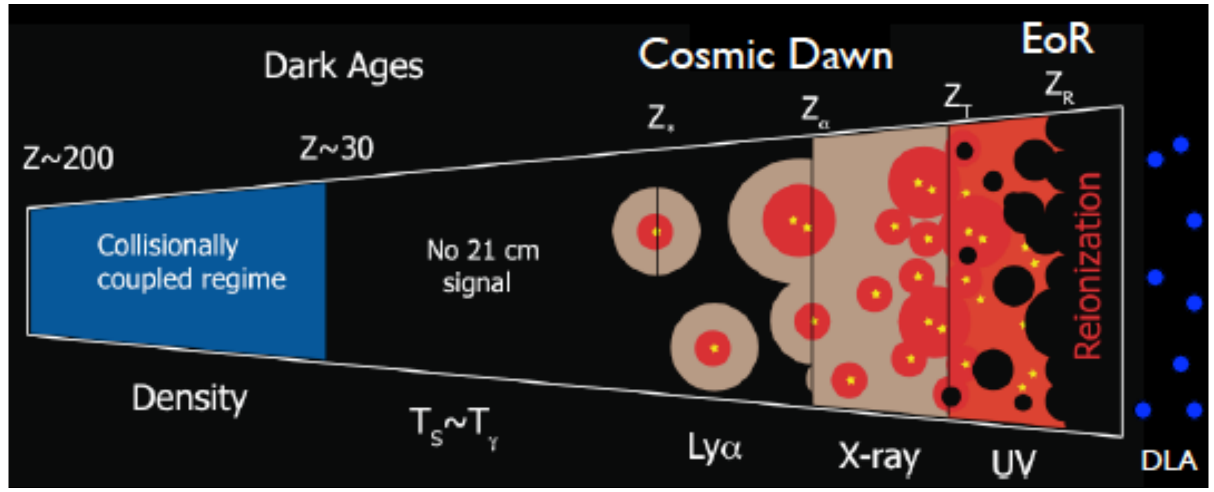


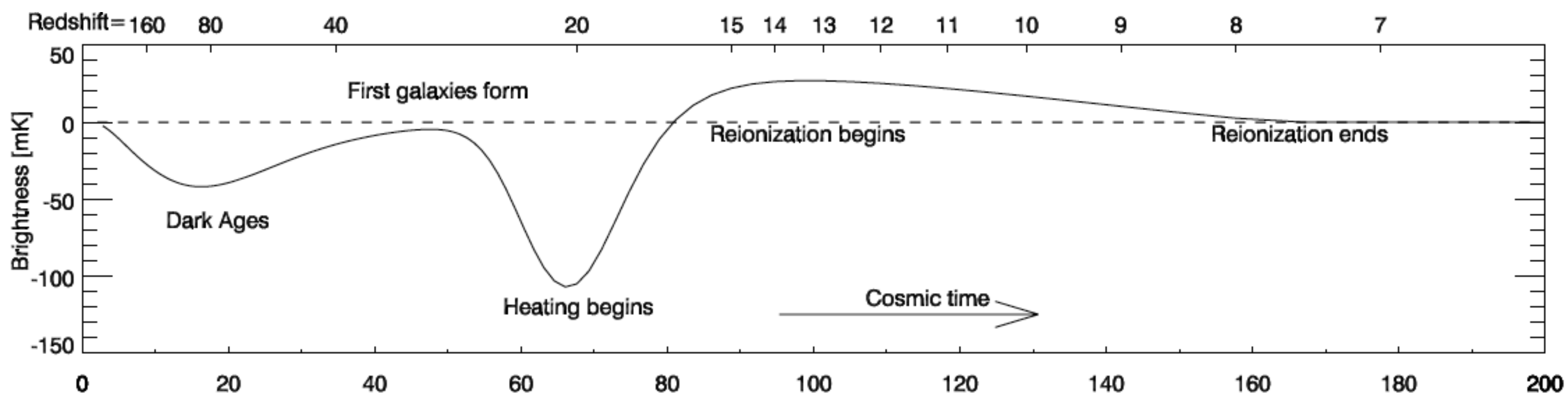


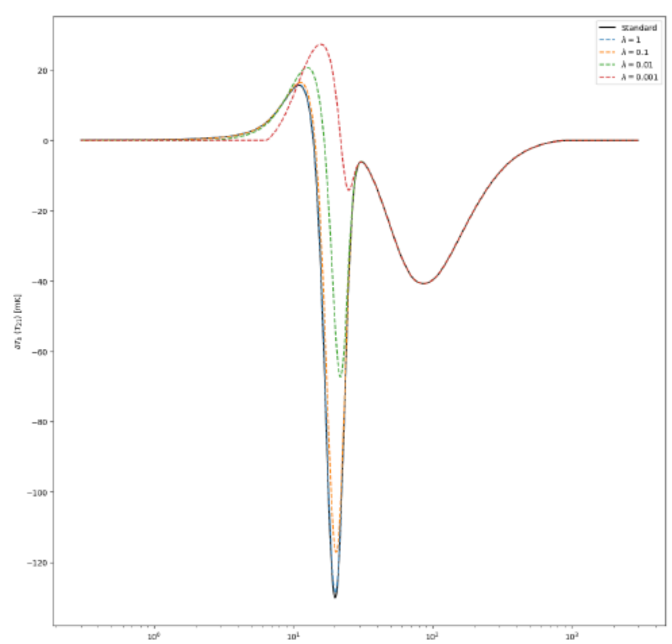
$$\delta T_b = \frac{T_S - T_R}{1+z}(1 - \mathrm{e}^{-\tau_\nu}) \approx 27 x_{\rm HI}\,(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2}\left(\frac{T_S - T_R}{T_S}\right)\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]\,\mathrm{mK}$$

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

Can Dark Stars affect the 21cm Line?







Betancourt Ibarra CK in prep

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.

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

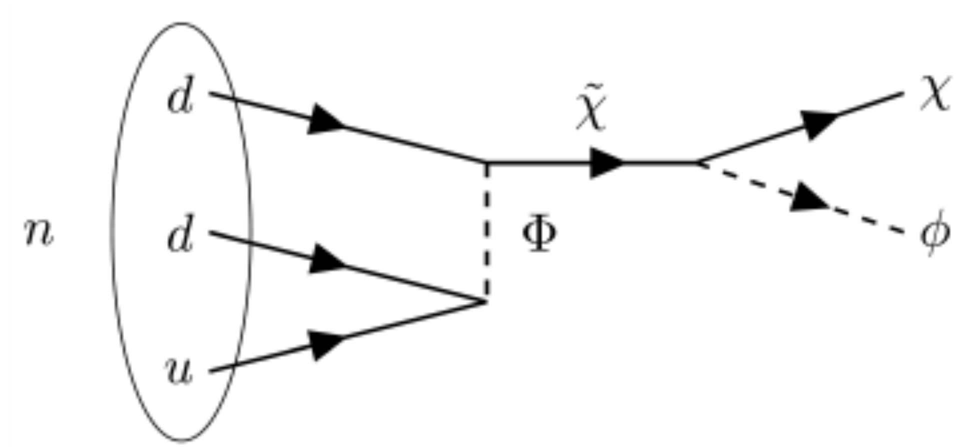
Avoid proton decays $p \to n^* + e^+ + \nu_e$ $\qquad m_p - m_e < M_f < m_n$

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

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



Fornal Grinstein '18

The Higgs portal induces neutron-DM interactions

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

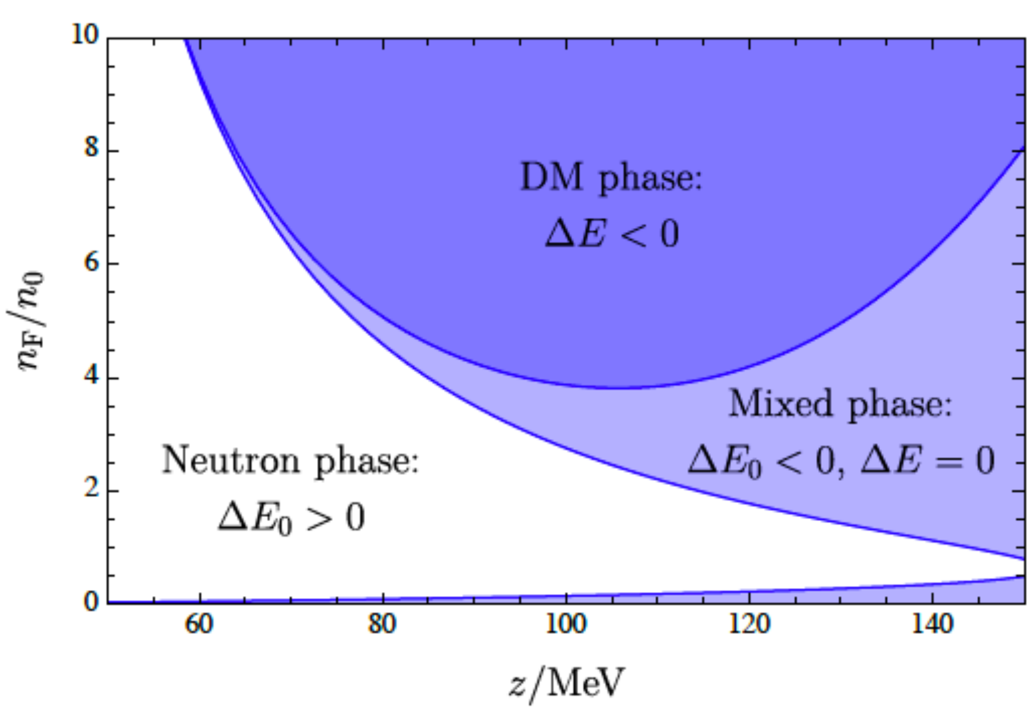
Baryon-DM Interactions via the Higgs Portal

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

Asymmetric Dark Matter in Neutron Stars

Press Spergel '85, Gould '86,
Nussinov Goldman '89,
CK'07
Goldman Nussinov'89,
CK Tinyakov '10, '11, CK'11
Bertoni Nelson Reddy '13
Bramante Fukushima, Kumar, '13
Baryakhtar, Bramante Li, Linden Raj
CK Tinyakov Tytgat '18

Capture

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

Thermalization

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

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

Self-Attraction

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

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

Collapse

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

Growth of Black Hole

$$\frac{dM}{dt} = \frac{4\pi\rho_c G^2 M^2}{c_s^3} - \frac{1}{15360\pi G^2 M^2}$$

The effect of Rotation

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 innermost 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

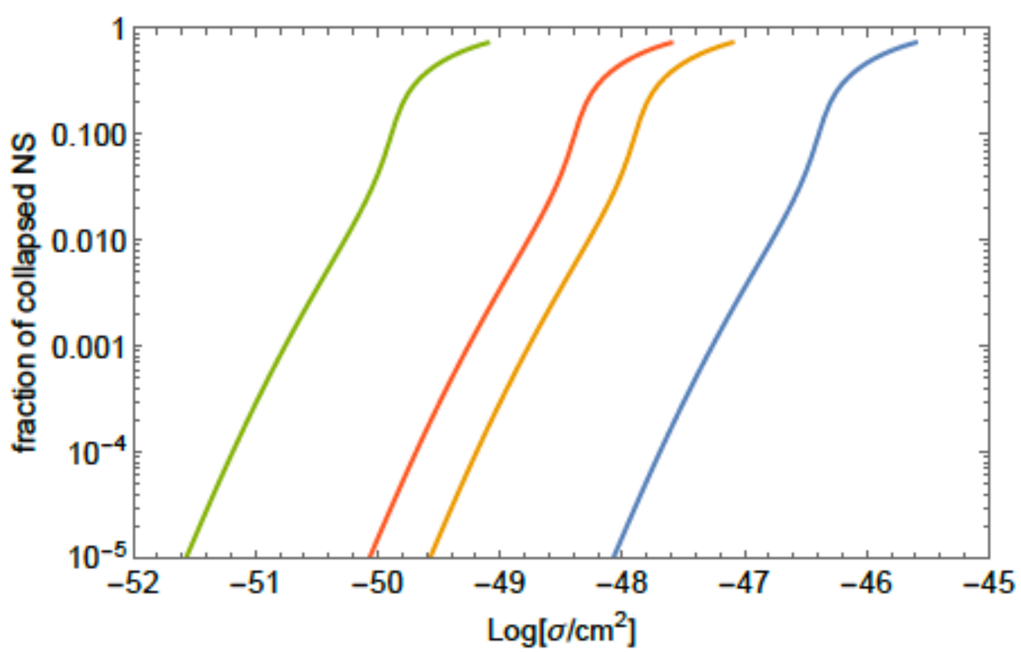
$$\frac{\partial}{\partial t} l - \frac{C_0 M^2}{4\pi \rho r^2} \frac{\partial}{\partial r} l = \frac{1}{\rho r^2} \frac{\partial}{\partial r} \left[\rho \nu r^4 \frac{\partial}{\partial r} \left(\frac{1}{r^2} l \right) \right].$$

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!

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 PRL '18

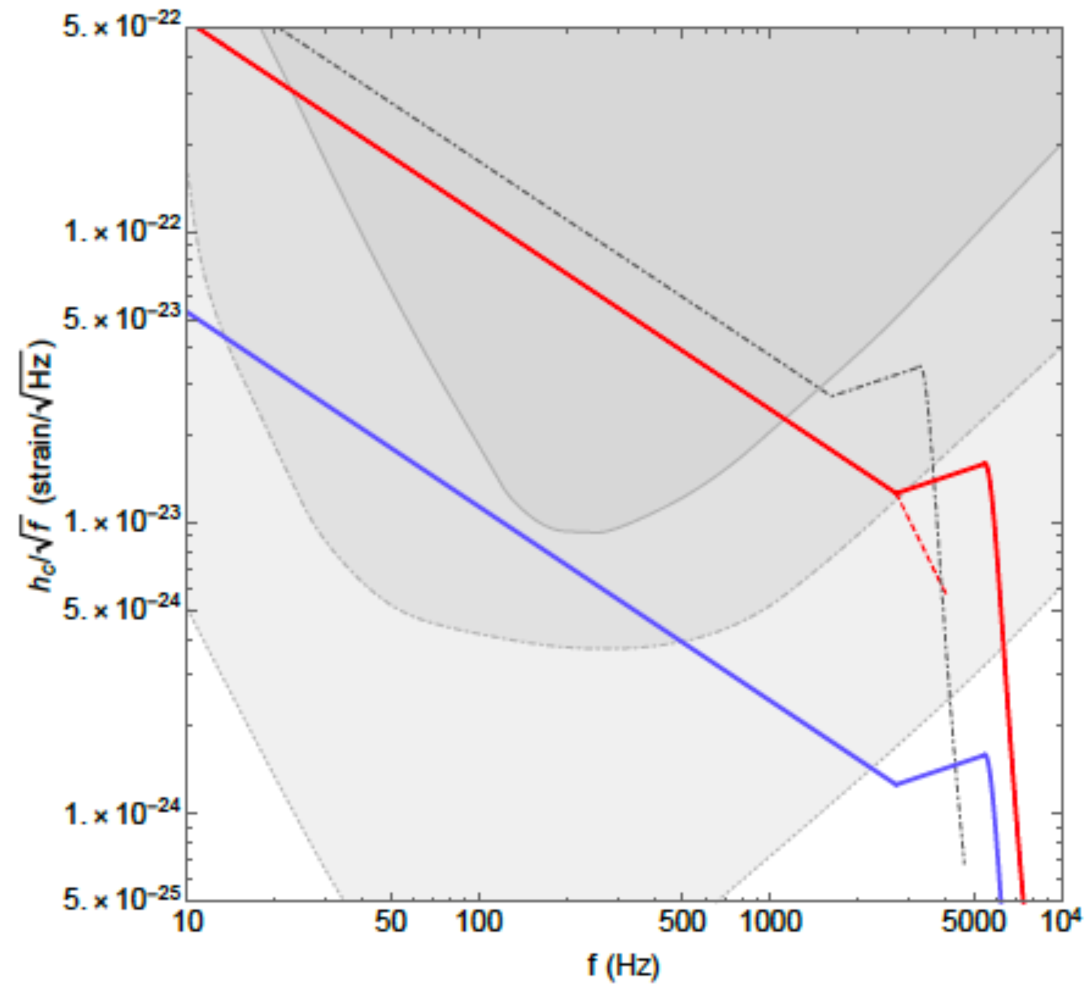


FIG. 2. Spectrum of GW from a $(1.5 + 1.5)M_\odot$ BBH at 40 Mpc (red solid). The spectrum of a corresponding BNS is schematically depicted by the break (red dashed). Also shown are a $(1.5+1.5)M_\odot$ BBH at 400 Mpc (blue solid) and a $(2+2)M_\odot$ BBH at 40 Mpc (grey dot-dashed). The sensitivity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

Conclusions

Asymmetric Dark Stars

- Formation scenarios involving dark photons
- They can be distinguished from neutron stars and black holes
- Luminosity outbursts
- Changes in the 21cm line spectrum

Anomalous decay of Neutron

- Repulsive interactions between neutrons and dark matter can stabilise neutron stars

Converting neutron stars to black holes

- Black holes lighter than ~3 solar masses might not necessarily be of primordial origin.
- Testable at future interferometers