Dark Stars

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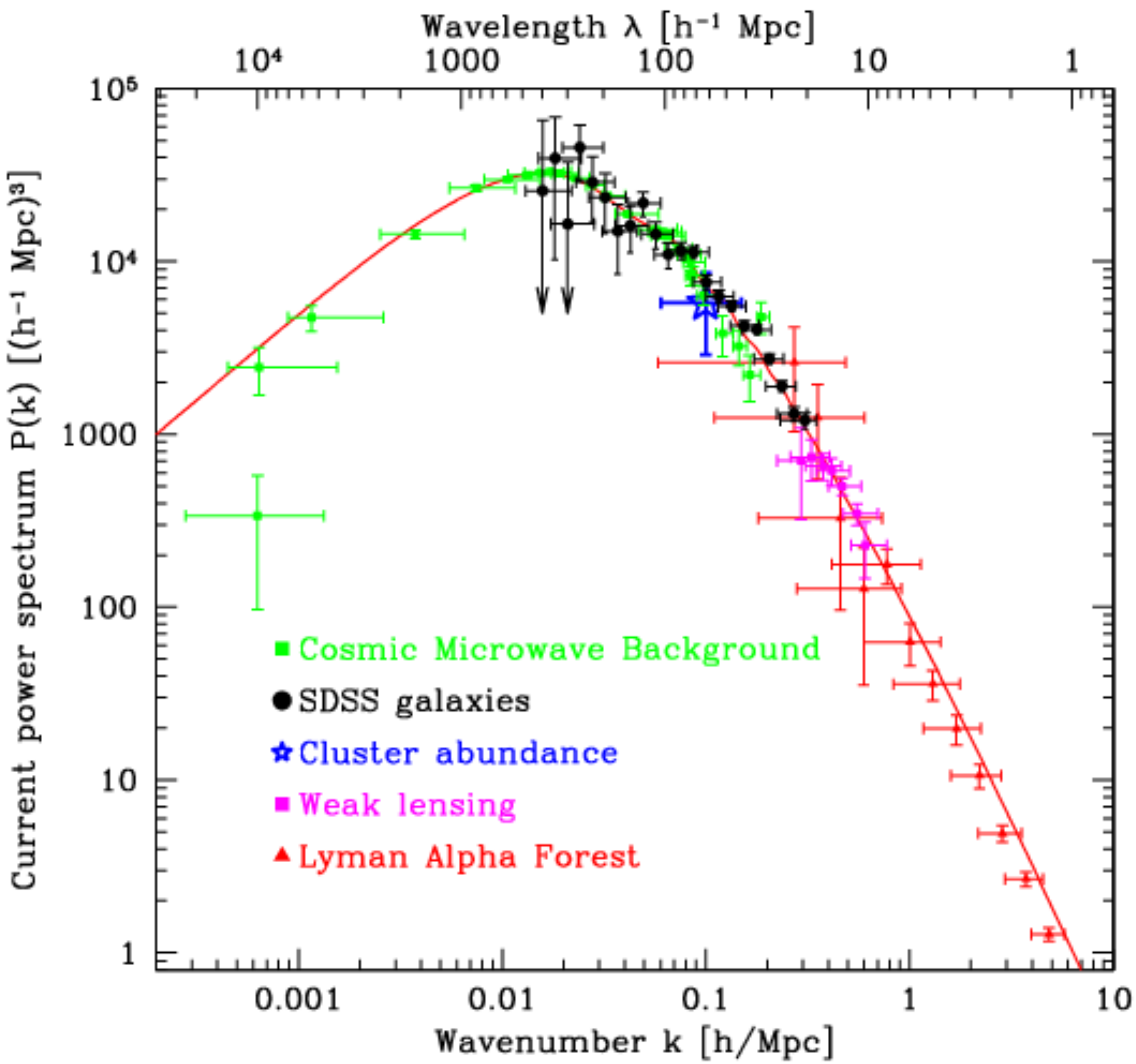
Identification of Dark Matter 2024, L' Aquila 9/7/2024

Why Dark Matter Self-Interactions?

CCDM very consistent with Large Scale Structure

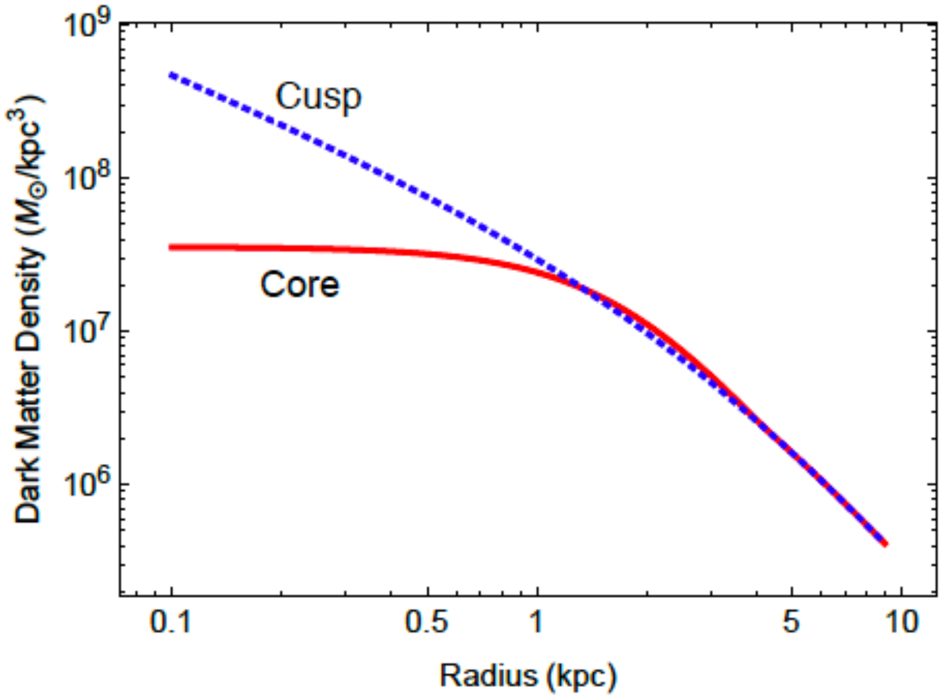


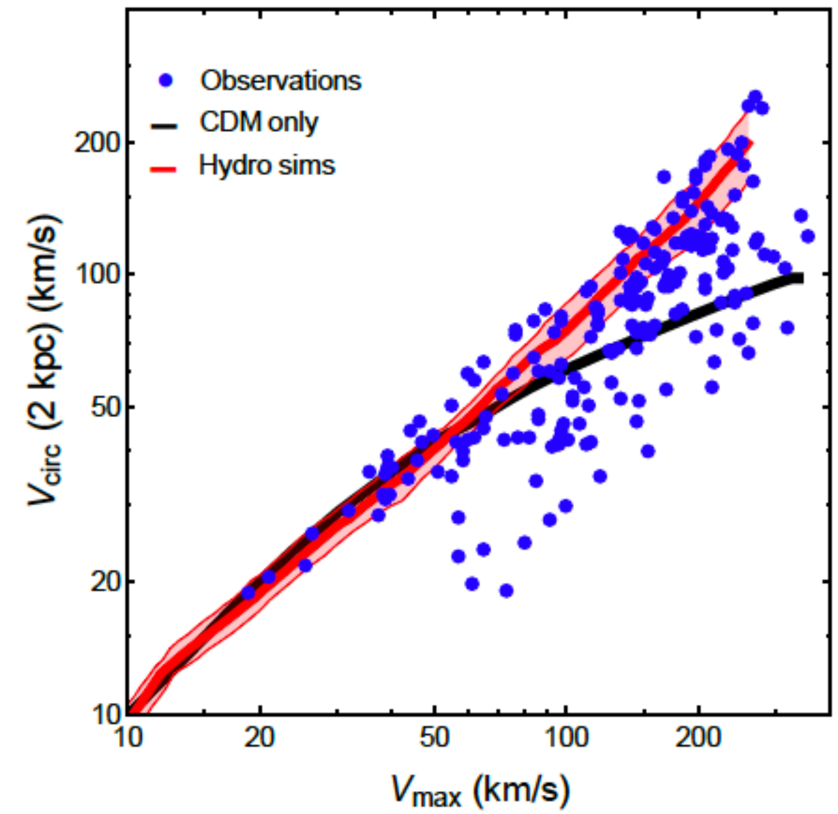
Why Dark Matter Self-Interactions?

However CCDM seems problematic in small scales

See Hai-Bo Yu's talk

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





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

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

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

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

$$n_{TB} = n_B$$

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

$$1 \times 5 = 5$$

Nussinov '85

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 are different from dark stars made of symmetric annihilating DM Spolyar Freese Gondolo '07
These are stars powered by DM annihilation instead of fusion and they can alter/impede population III star formation.

Asymmetric Dark Stars

Fermions

$$\frac{N}{V} = \frac{g}{(2\pi\hbar)^3}\int_0^{p_F} 4\pi p^2 dp = \frac{p_F^3}{3\pi^2}$$

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

$$E = E_{\rm kin} + V \sim p_F - G\frac{Mm}{r} = \left(\frac{9\pi}{4}\right)^{1/3}\frac{N^{1/3}}{r} - G\frac{Nm^2}{r} \leq 0 \Rightarrow M_{\rm crit} \sim \frac{M_{\rm Pl}^3}{m^2} \sim M_\odot\left(\frac{\rm GeV}{m}\right)^2$$

Bosons

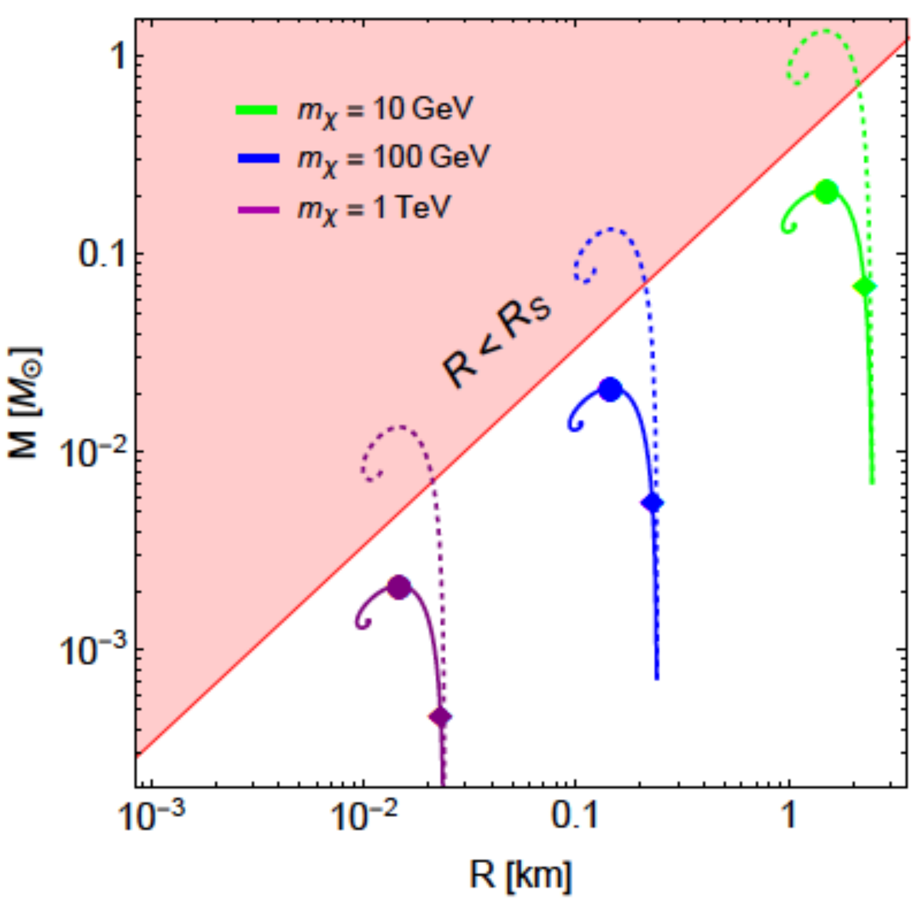
$$E = E_{\rm kin} + V \sim p - G\frac{Mm}{r} = \frac{\hbar}{r} - G\frac{Nm^2}{r} \leq 0 \Rightarrow M_{\rm crit} \sim \frac{M_{\rm Pl}^2}{m} \sim 10^{-19}M_\odot\left(\frac{\rm GeV}{m}\right)$$

Asymmetric Dark Stars

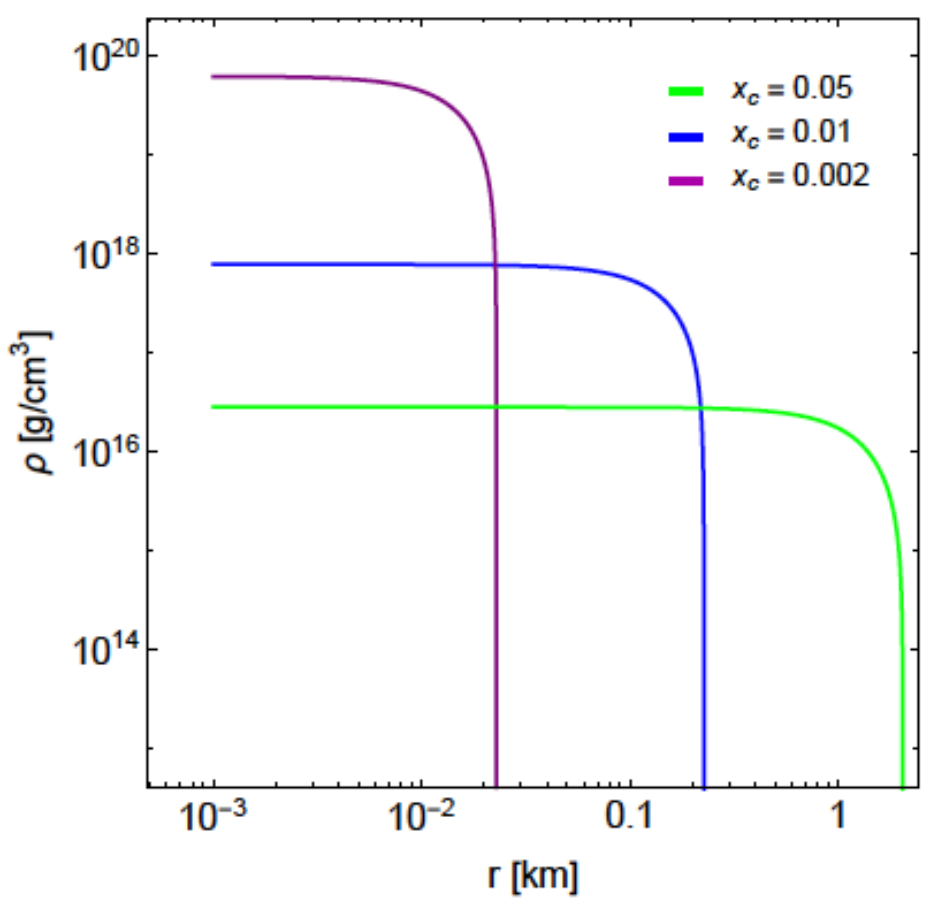
Tolman-Oppenheimer-Volkoff with Yukawa self-interactions

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

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



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



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

CK, Nielsen ‘15

Asymmetric Bosonic Dark Stars

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

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

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

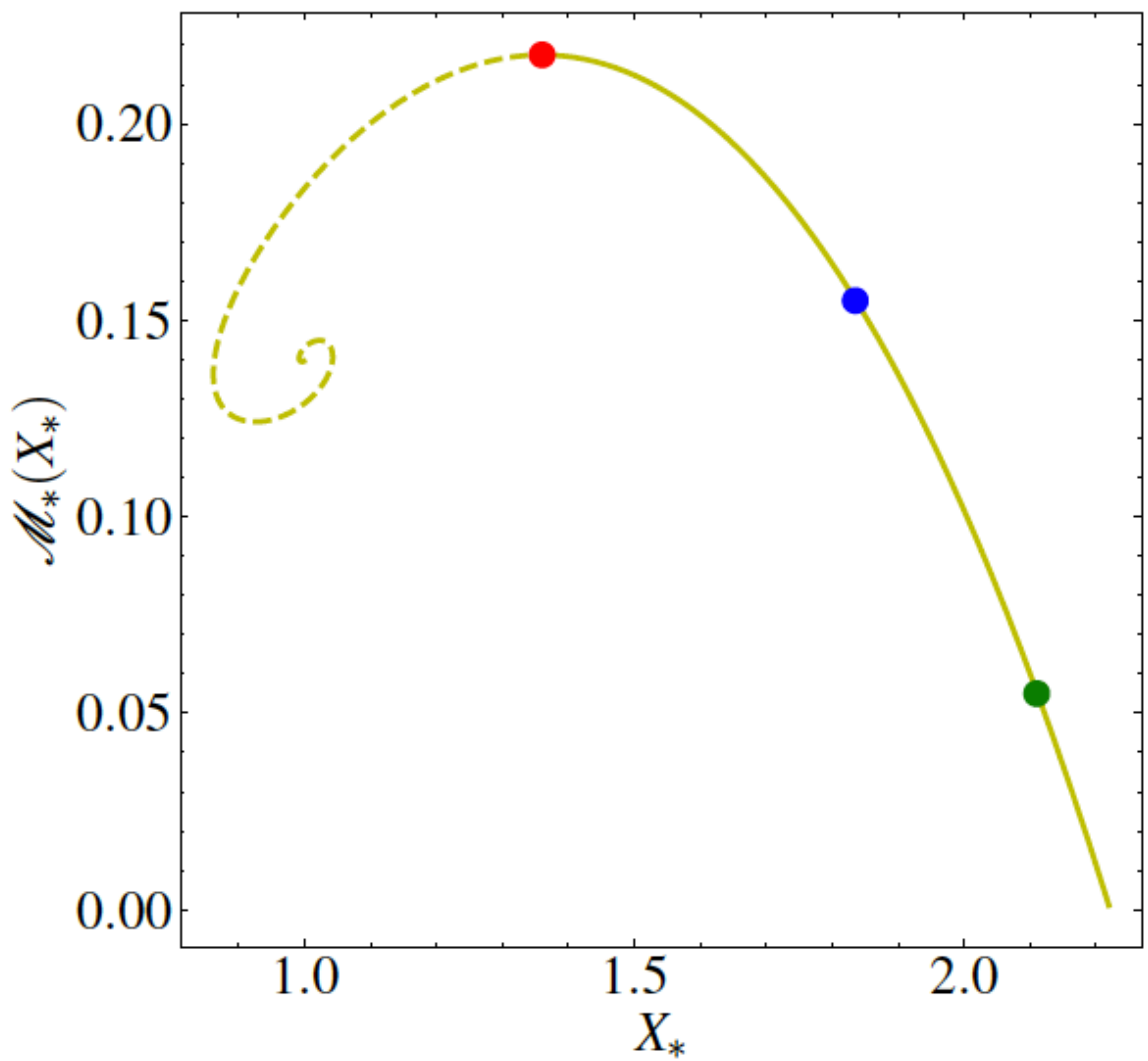
$$\frac{A'}{A^2 x} + \frac{1}{x^2}\left(1 - \frac{1}{A}\right) = \left(\frac{\Omega^2}{B} + 1\right)\sigma^2 + \frac{\Lambda}{2}\sigma^4 + \frac{(\sigma')^2}{A}$$
$$\frac{B'}{B^2 x} + \frac{1}{x^2}\left(1 - \frac{1}{A}\right) = \left(\frac{\Omega^2}{B} + 1\right)\sigma^2 - \frac{\Lambda}{2}\sigma^4 + \frac{(\sigma')^2}{A}$$
$$\sigma'' + \left(\frac{2}{x} + \frac{B'}{2B} - \frac{A'}{2A}\right)\sigma' + A\left[\left(\frac{\Omega^2}{B} - 1\right)\sigma - \Lambda\sigma^3\right] = 0,$$

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



Asymmetric Bosonic Dark Stars

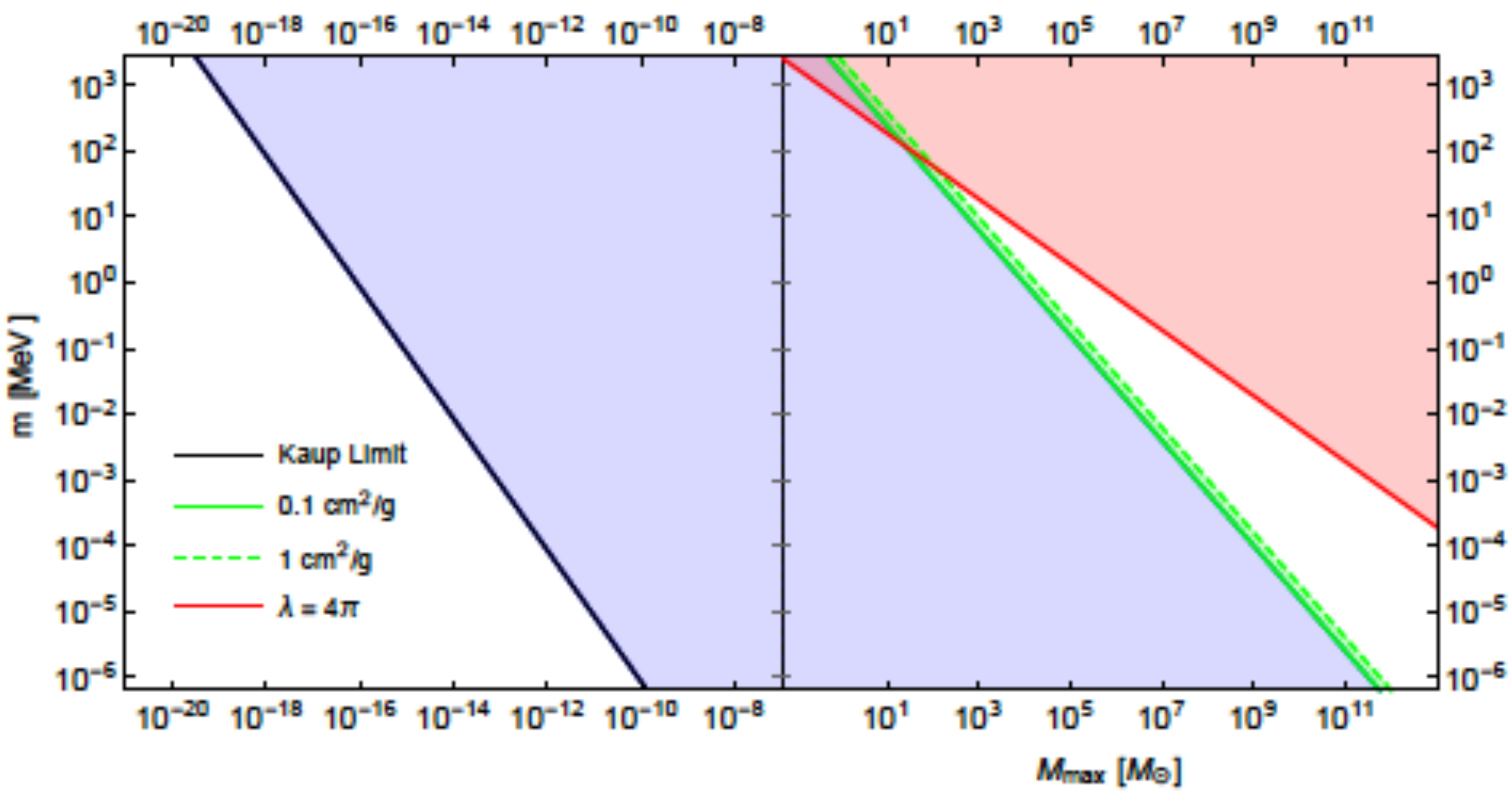
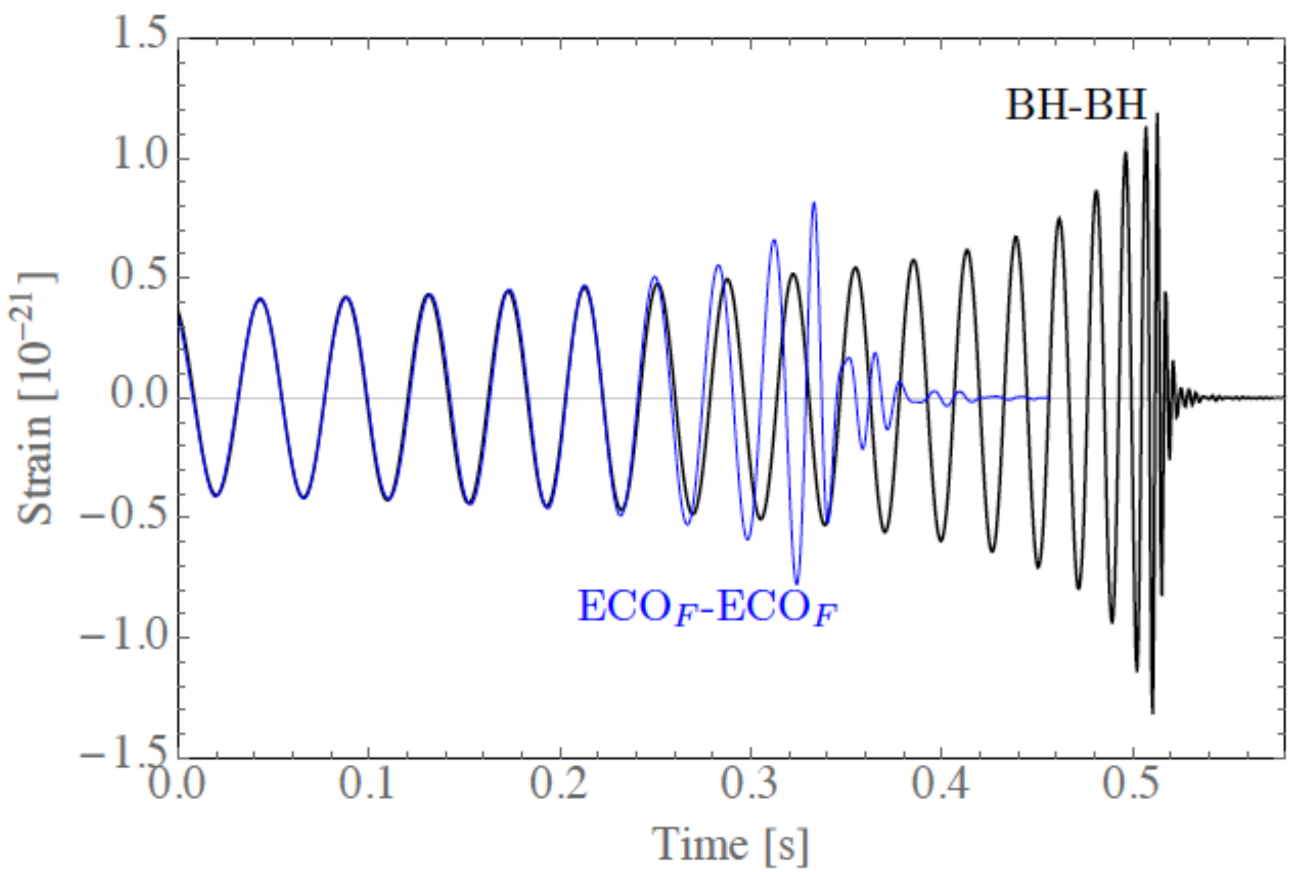


Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass m. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths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



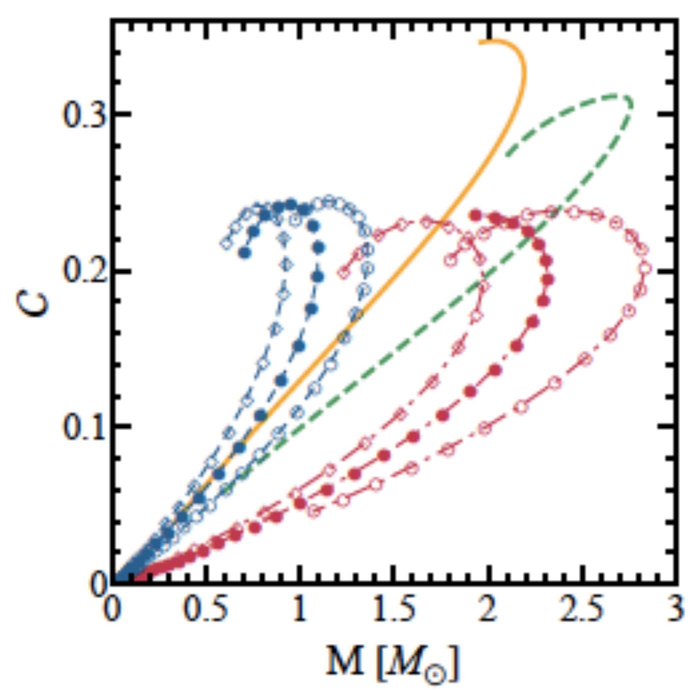
Giudice, McCullough,
Urbano '16

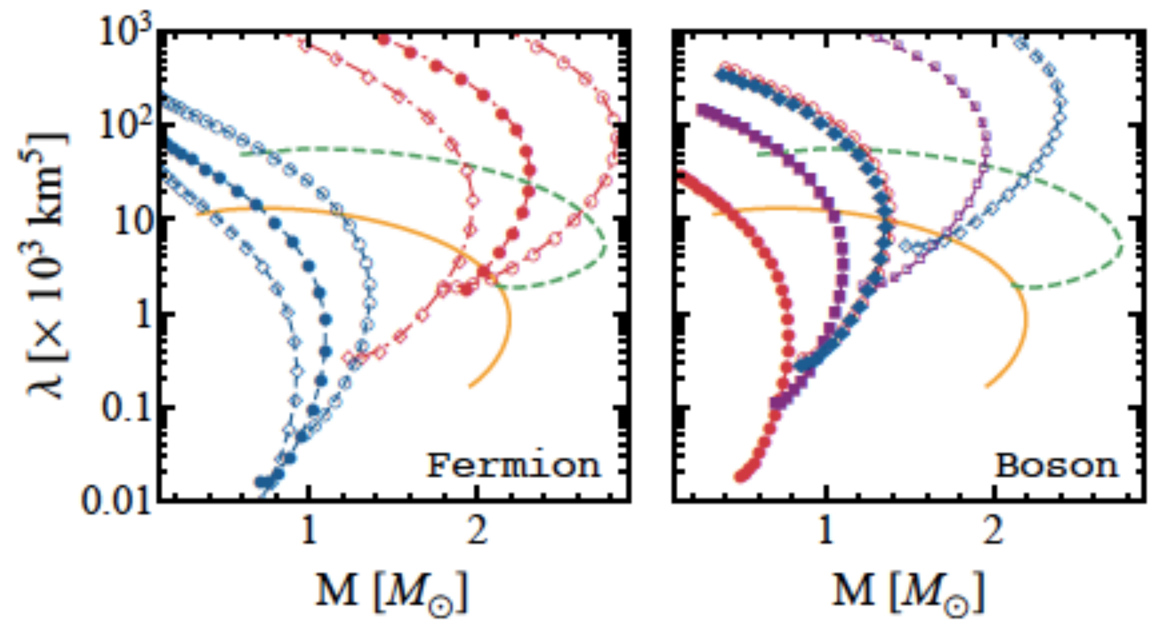
Tidal Deformations of Dark Stars

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

$V=-(1/2)\varepsilon_{ij}x^i x^j$ $\quad Q_{ij}=-\lambda\varepsilon_{ij}$ $\quad \lambda=\frac{2}{3}k_2R^5$

Love number



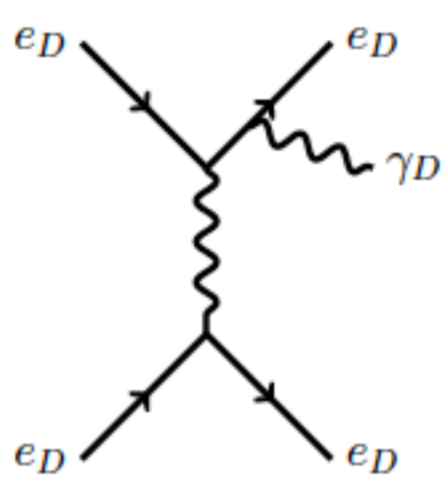


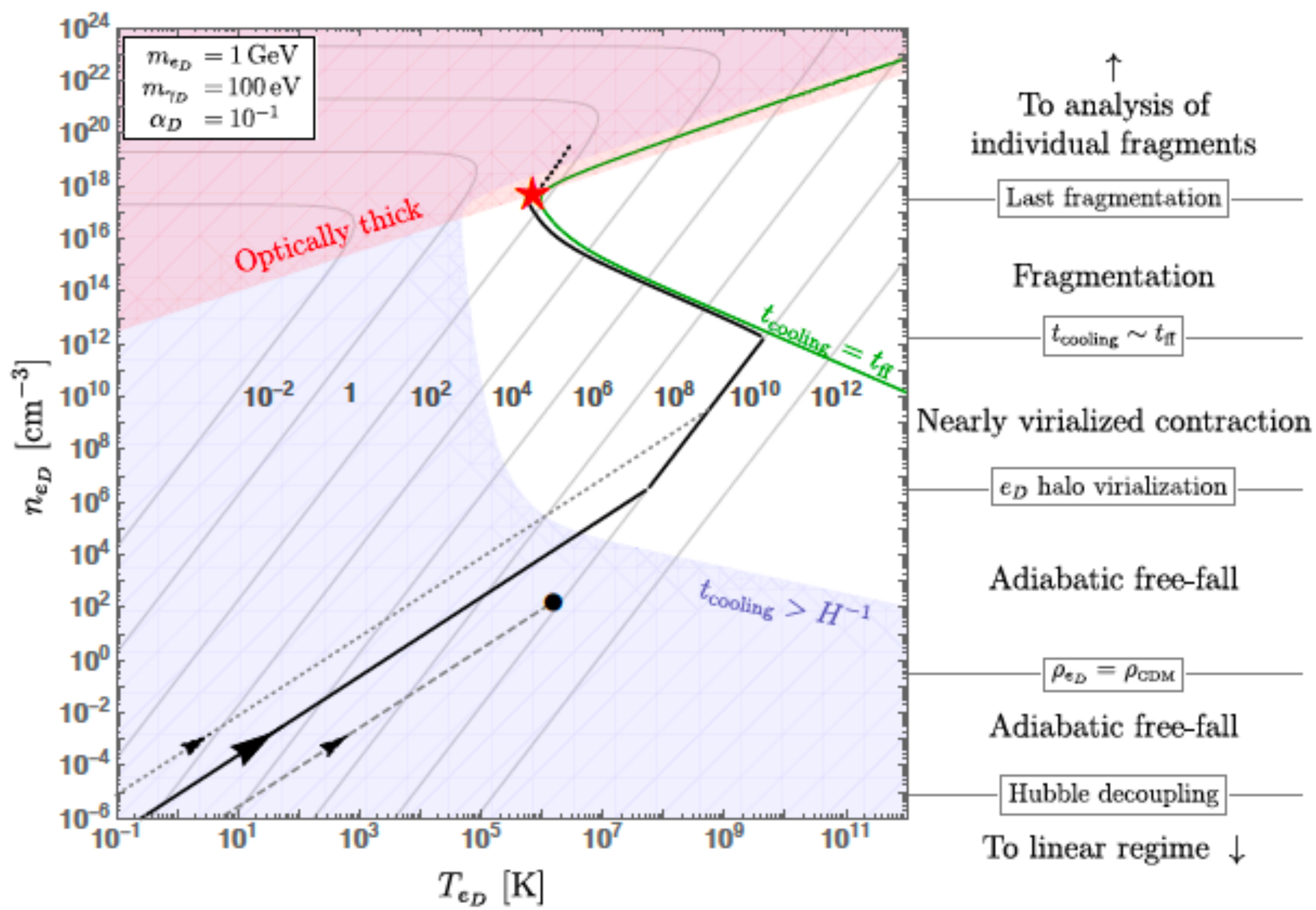
Maselli, Pnigouras Nielsen CK, Kokkotas '17, Karkevandi Shakeri Sagun Ivanytskyi '21

Formation of Asymmetric Dark Stars

Collapse can proceed via dark photon Bremsstrahlung Cooling

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

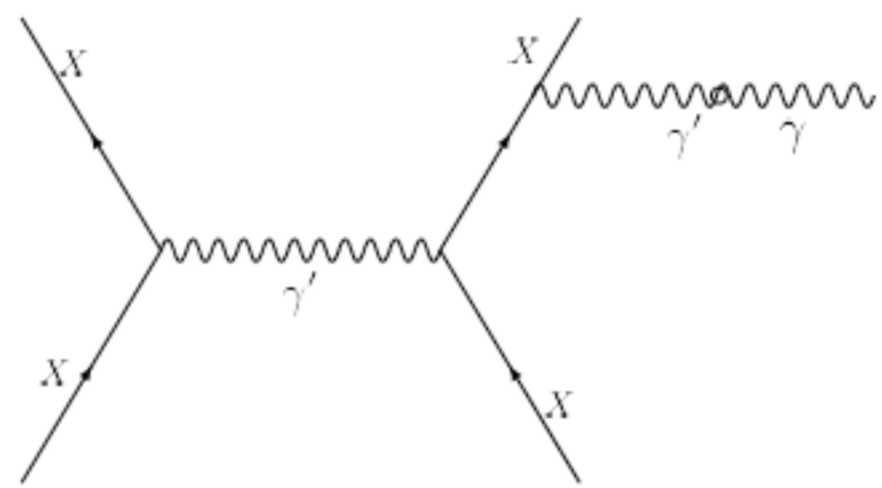




Latif Lupi Schleicher D'Amico Panci Bovino '18, Egana-Ugrinovic, Essig, CK '19

Can Dark Stars Shine?

$$\mathcal{L} = \bar{X}\gamma^{\mu} D_{\mu} X - m_{\mathrm{X}} \bar{X} X - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_{\mu} A'^{\mu} + \frac{1}{2} m_D^2 A_{\mu} A^{\mu} + \frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu} + \ldots$$



It is essential that photons gets a mass:

- Accreted protons and electrons induce a Debye mass
- Higgs-like scalar that couples to photons
- Dark Matter is degenerate and photons get a Debye mass

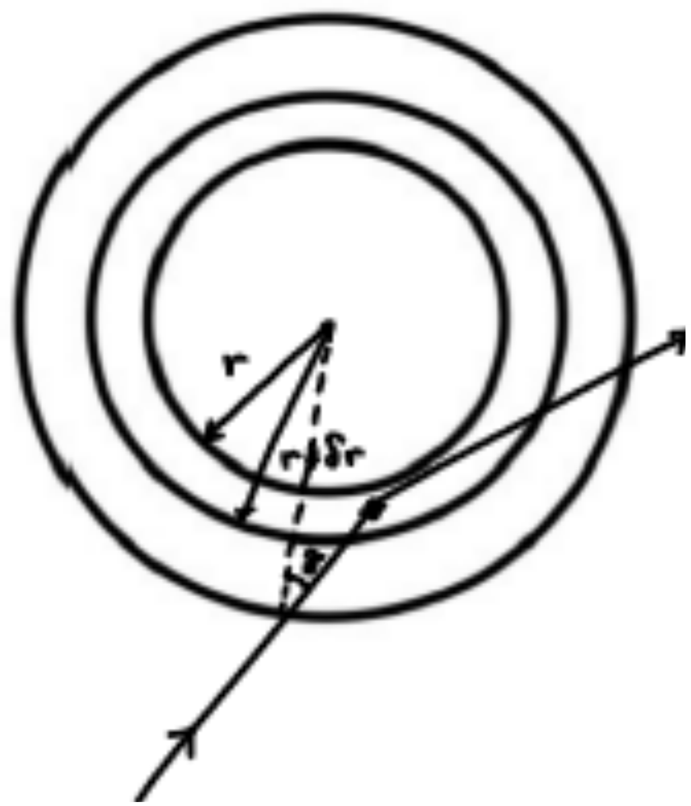
Maselli CK Kokkotas '19, Garani Tytgat Vandecasteele '22

Alternatively 2-to-2 scattering between dark photons -> photons

Relativistic Proton Capture rate

Dark stars can accrete protons and electrons

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



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

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

Bell Busoni Robles ‘19, 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

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

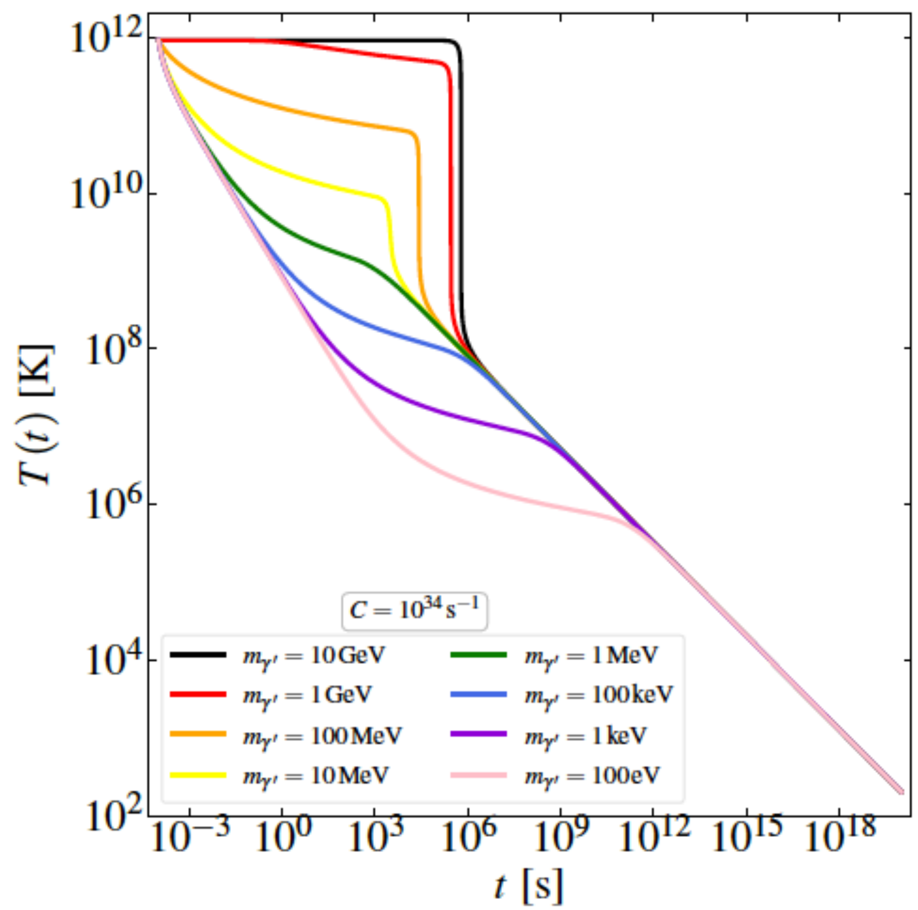
Thermal Evolution of star $$\frac{dT}{dt} = -\frac{L_\gamma + L_{\gamma'}}{C_{\rm v}}$$

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

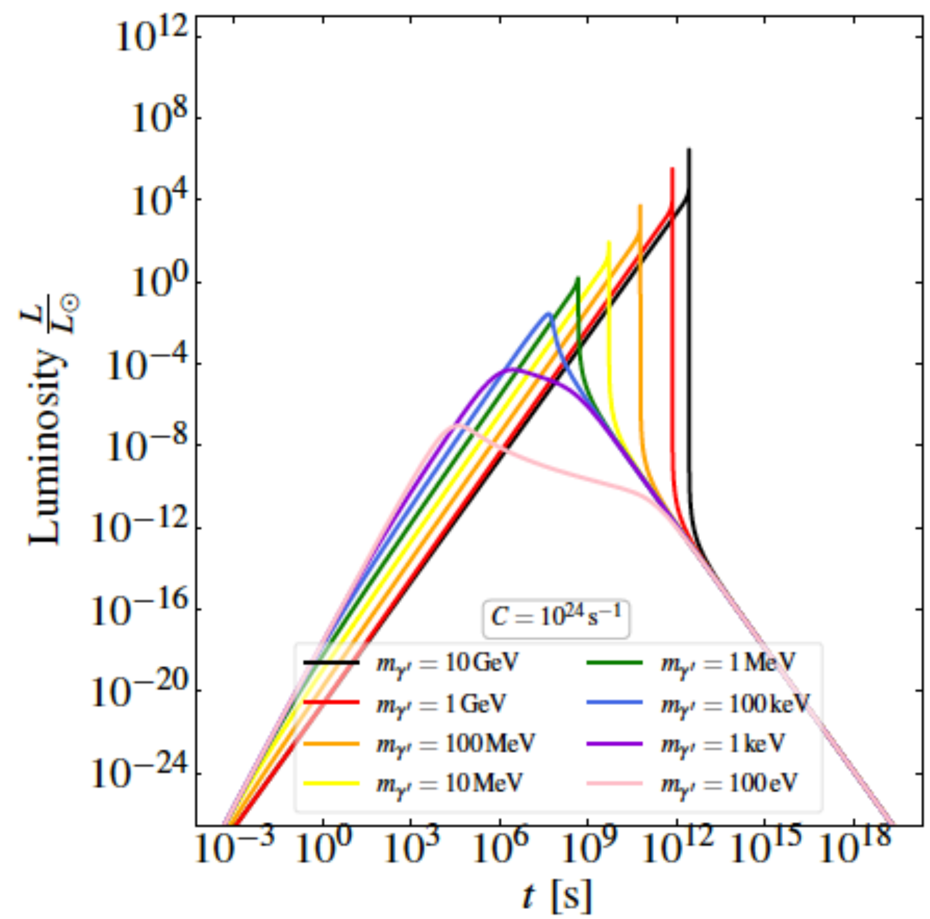
with τ<<1 (optically thin limit)-> Bremsstrahlung
when τ>>1 blackbody radiation

Dark Star Outbursts

Temperature



Luminosity



Betancourt, Brenner, Ibarra, CK ’22

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 $\sim T^5$

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!

Dark Matter Admixed Neutron Stars

Dark matter can collapse together with baryonic matter and for some sort of a hybrid star.
It can be studied as a two-fluid system solving a coupled system of TOV equations. Leung Chu Lin '11

There can also be a form of chemical equilibrium between DM and neutrons e.g in neutron decay
Fornal Grinstein '18, Ellis Hutsi Kannike, Marzola, Raidal, Vaskonen '18

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

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

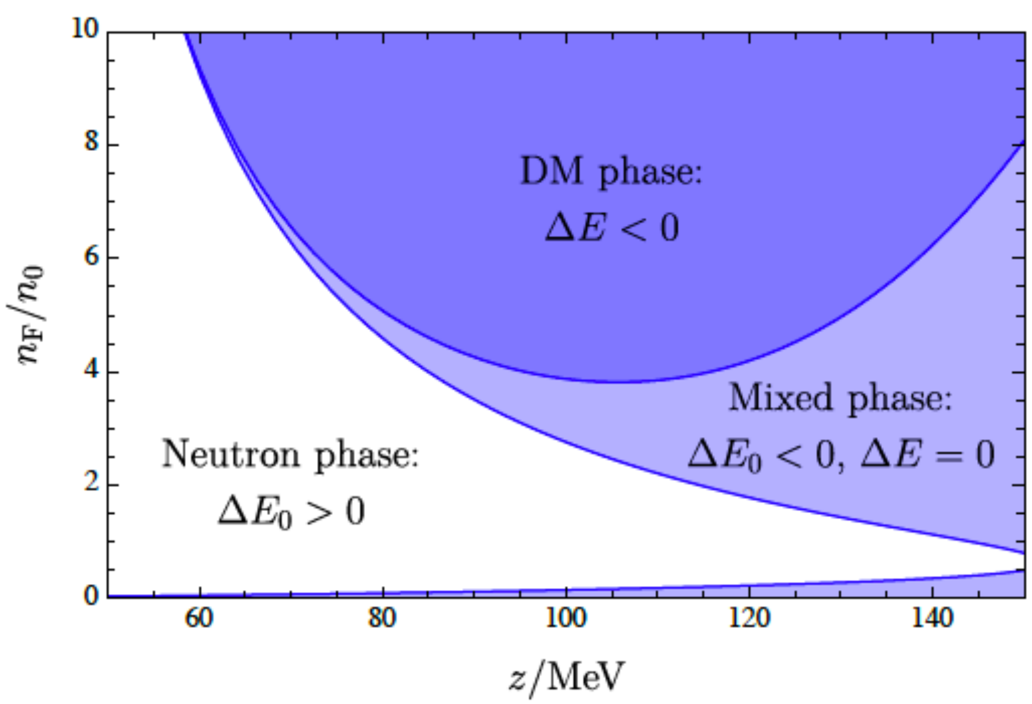
Baryon-DM Interactions in Chemical Equilibrium inside Neutron Stars

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

$m_\phi \sim 0.1\ \rm eV$

Grinstein Nielsen CK '18

Conclusions

Small Scale Issues for CDM

- DM Self-Interactions can alleviate the issues
- If there is an efficient way of evacuating energy, DM can collapse

Asymmetric Dark Stars

- Formation scenarios involving dark photons
- They can be distinguished from neutron stars and black holes in merger events
- Mixing photons and dark photons can lead to emission of ordinary photons
- Luminosity outbursts

Admixed Stars

- DM can form hybrid stars with baryonic matter. The EoS is expected to be softer and the objects should have smaller maximum mass compared to neutron stars
- They can have different luminosities, and GW production signal.