UNIVERSITY OF SOUTHERN DENMARK

# Asymmetric Dark Stars


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CP$^3$ - Origins

Particle Physics & Origin of Mass


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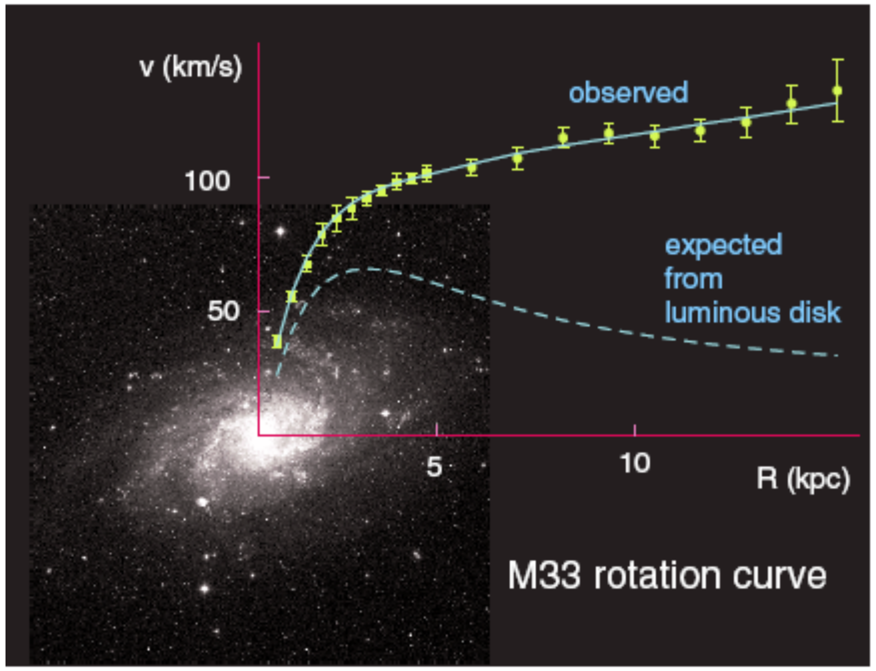
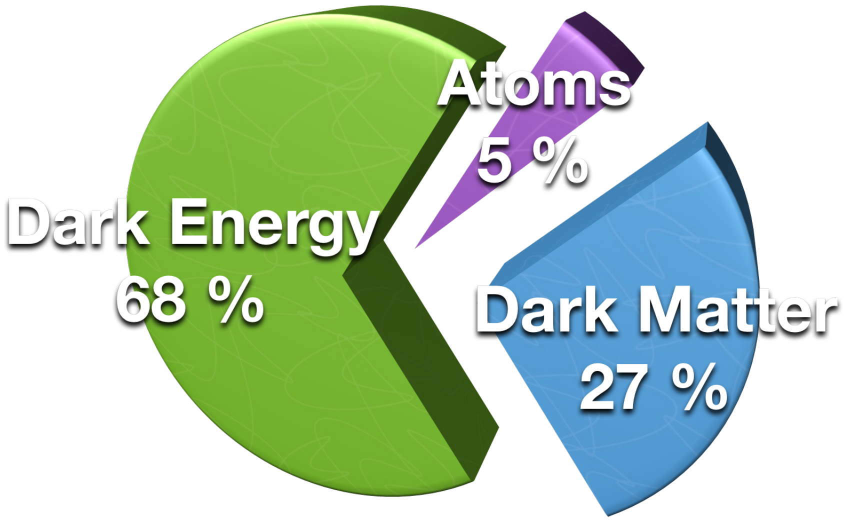
# Dark Matter




Microwave Background Radiation

Rotiational Curves

Bullet Cluster



# Dark Matter is <u>NOT</u>

- Baryons!!!
- MACHOs ruled out by microlensing observations $10^{-7}$–$30\,M_{\odot}$
- Neutrinos

Light neutrinos: are problematic in small scale structure
m>500 eV (Tremaine-Gunn) otherwise neutrinos violate Pauli blocking in dwarf galaxies. But for m>500 eV gives too much dark matter
Heavy Neutrinos: m> 2 GeV (Lee-Weinberg)
excluded by direct dark matter search experiments unless the mass is huge

- ChaMPs (Charged Massive Particles)
- SIMPs (Strongly Interacting Massive Particles)

ruled out by anomalous hydrogen isotope searches in ocean water*

# Dark Matter could be

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

# 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

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

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 Matter in Neutron Stars

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

Press Spergel '85, Gould '86,
Nussinov Goldman '89,
CK'07,
CK Tinyakov '10

Capture

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

BEC formation

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

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

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

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

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

Can rotation slow down the accretion to the point that invalidate the constraints?

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 can help!

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

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!

# The effect of Rotation II

A maximally spinning black hole will stop the accretion

$$a = J/GM^2$$

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

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

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

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

# Blocking the Hawking Radiation

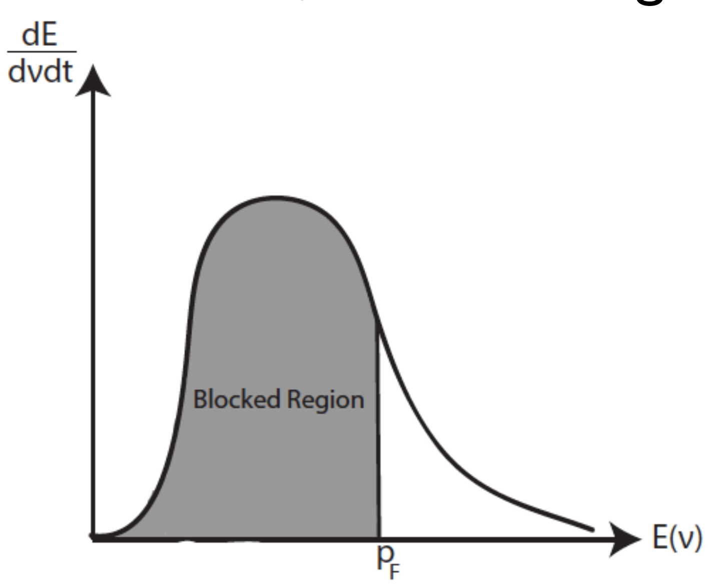
$$T = \frac{1}{8\pi G M_c} = \frac{m}{16} \qquad \frac{dM}{dt} = -(n_f f_f + n_b f_b + n_s f_s + n_2 f_2)\frac{1}{G^2 M^2}$$

Degenerate matter can block potentially the emission of particles

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

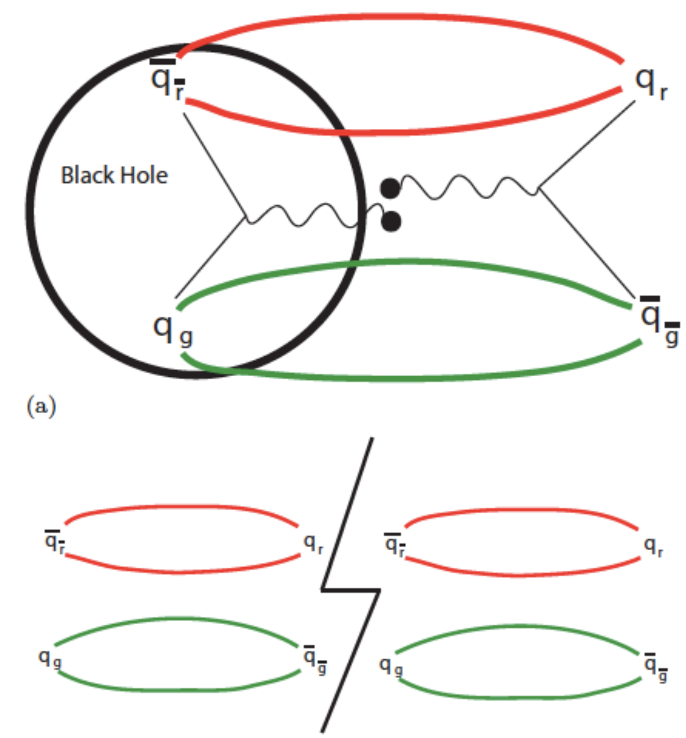
at Bondi radius $\frac{n(r)}{n_\infty} \simeq \frac{\lambda_s}{\sqrt{2}}\left(\frac{GM}{c_s^2 r}\right)^{3/2}$

## Quark Blocking




Autzen CK '14

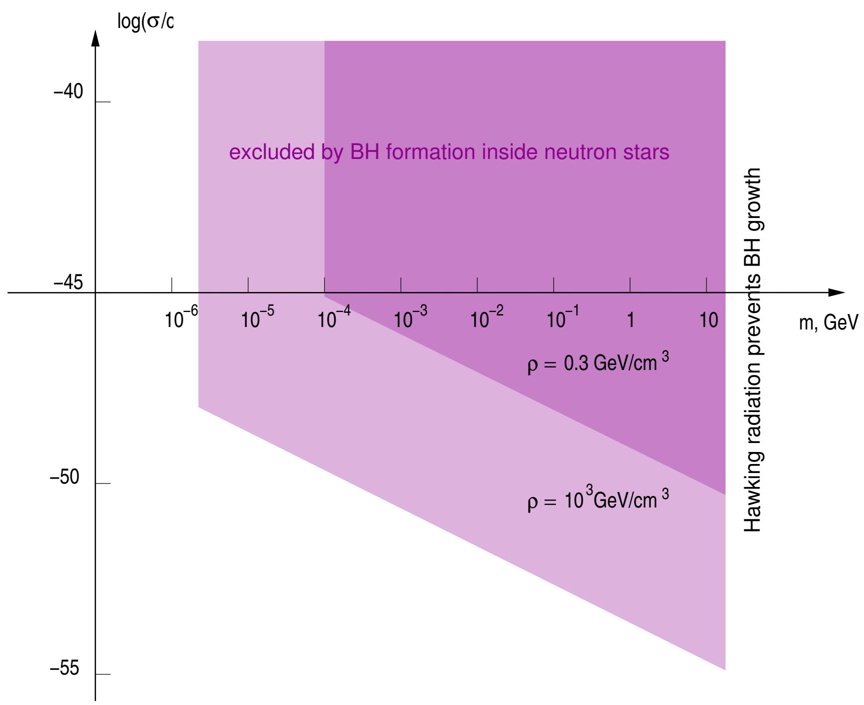
## Gluon Blocking




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

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

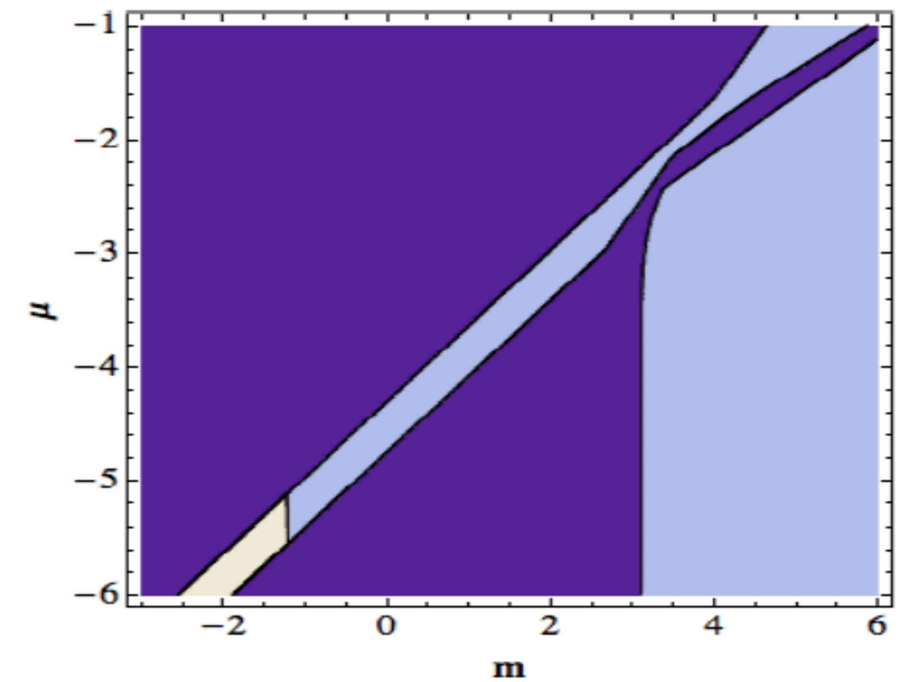
# Destroying Stars




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 $\alpha = 10^{-5}$

# Bosonic Asymmetric Dark Matter

For m>10 TeV, self-gravitation takes place before BEC formation

Could this lead to the collapse of the whole WIMP sphere into a single black hole?

The answer is no!

The WIMP sphere has to go through a BEC formation

Small black holes form one after the other

$$t_{\rm cool} \simeq 1.5 \times 10^3 {\rm s} \times \left(\frac{m}{10{\rm TeV}}\right)^{5/3} \left(\frac{T}{10^5 {\rm K}}\right)^{-3} \left(\frac{\sigma}{10^{-43}\,{\rm cm}^2}\right)^{-1} > \tau = 5 \times 10^3 {\rm s} \left(\frac{10{\rm TeV}}{m}\right)^3$$

# 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"

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

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

# Asymmetric Dark Stars

***Asymmetric fermionic dark matter with Yukawa self-interactions***

$$V_{ij} = \pm \alpha \frac{e^{-\mu r_{ij}}}{r_{ij}}$$

Equation of state

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

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

$$x = p_F / m_\chi$$

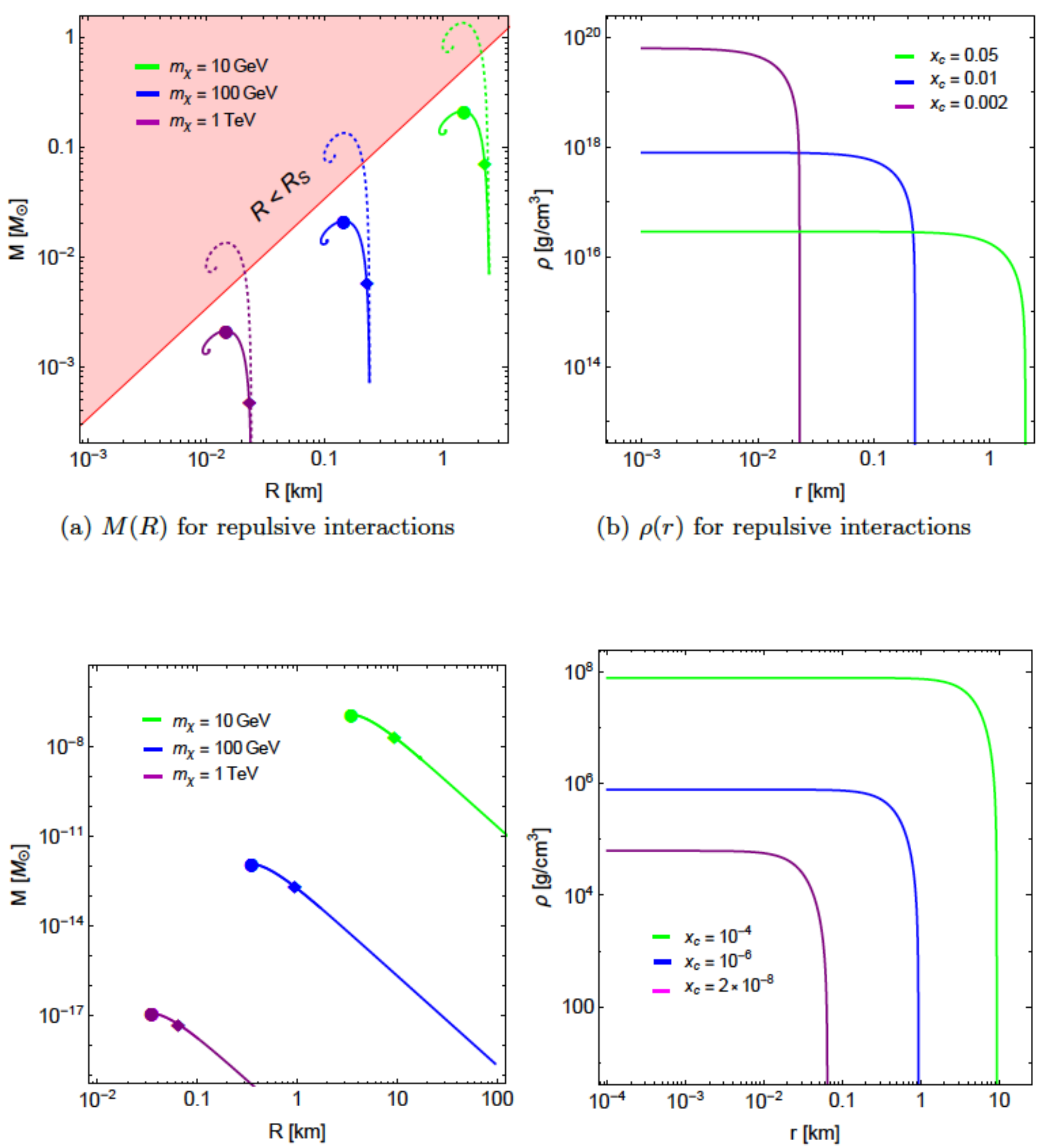
it can be approximated by polytropic $P = K\rho^\gamma + \beta\rho^2$

Tolman-Oppenheimer-Volkoff

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

# Asymmetric Fermionic Dark Stars

***Dark star profiles***



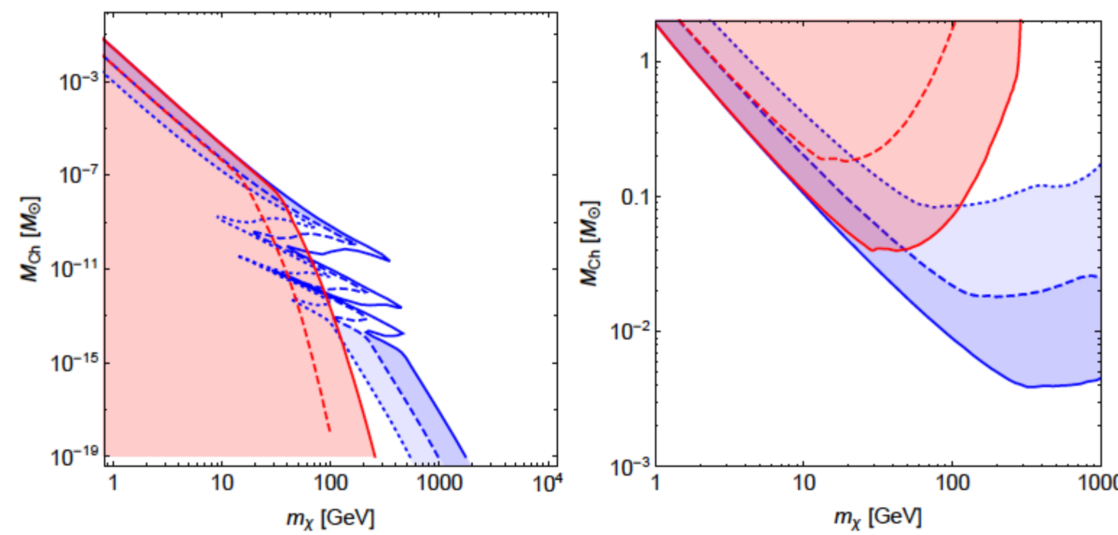

(a) $M(R)$ for repulsive interactions

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

(e) $M(R)$ for attractive interactions

(f) $\rho(r)$ for attractive interactions

***Chandrasekhar Mass***




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

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

CK, Nielsen ‘15

# Asymmetric Bosonic Dark Stars

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

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

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

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

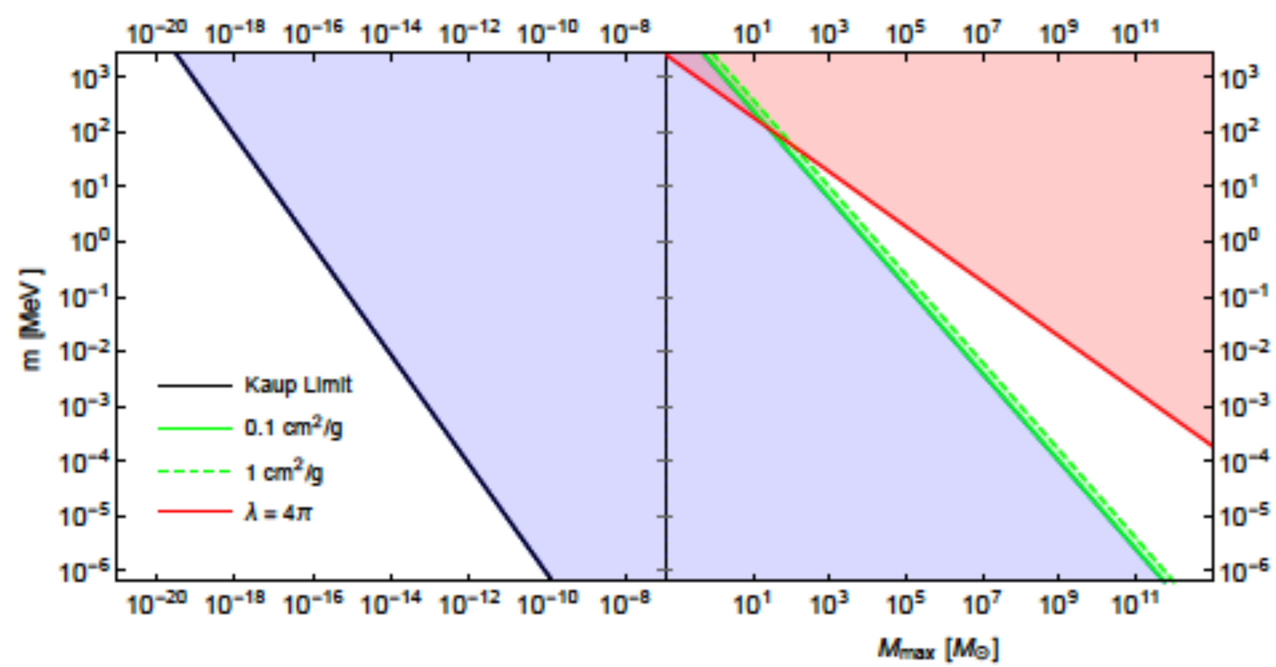
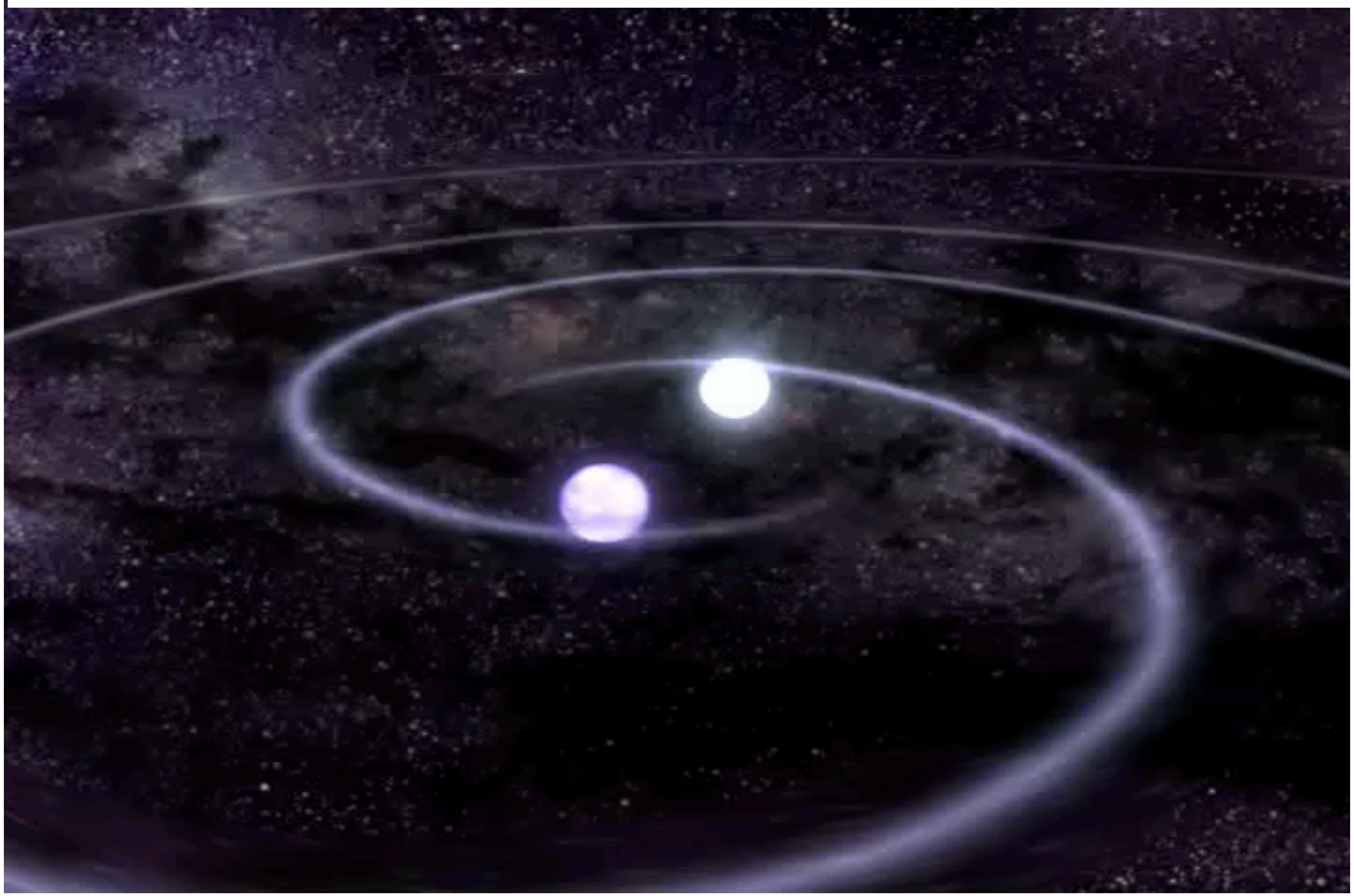


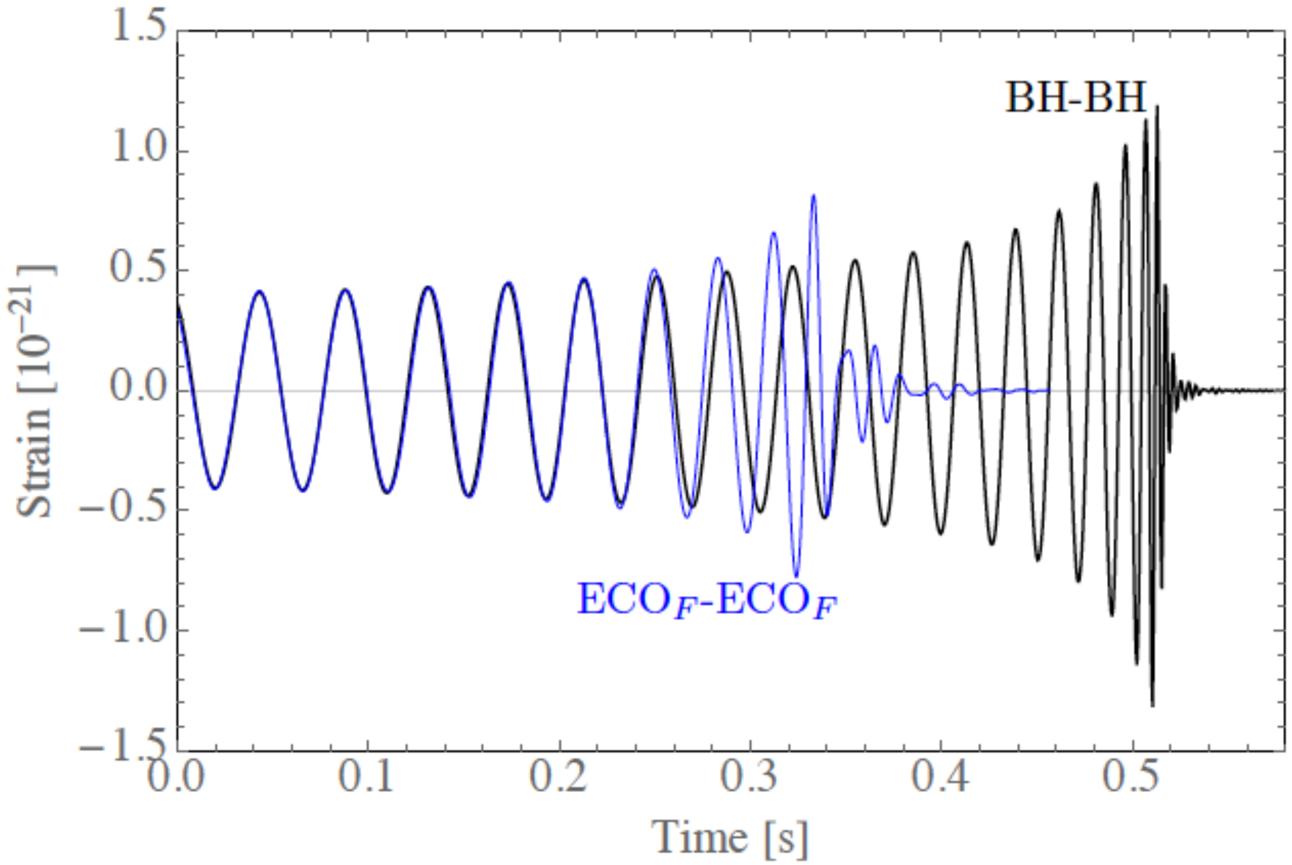

Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass $m$. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths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

Eby, CK, Nielsen, Wijewardhana '15

# Gravitational Waves of Dark Stars



# “Odd Neutron Stars & Weird Black Holes”




Giudice, McCullough, Urbano ‘16

**Observation**

- Gravitational Waves: DS+DS->DS or BH (Solving numerically Einstein’s equations) with K.Kokkotas (Univ. of Tubingen)

  DS+NS-> DS*

  DS+BH->BH

  Spinning DS
- Gravitational Lensing

# Tidal Deformations of Dark Stars

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

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

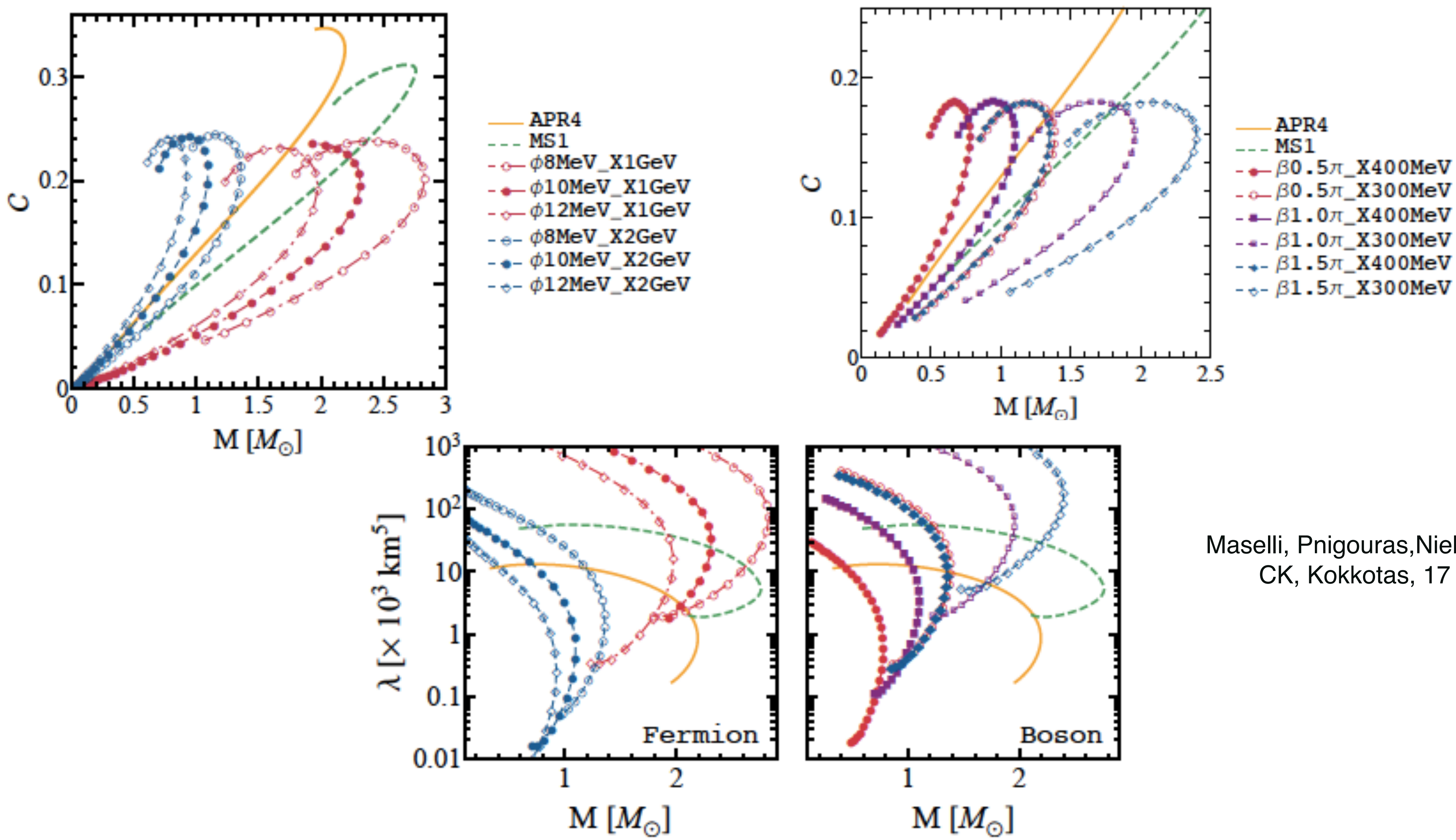
$$Q_{ij}=-\lambda\varepsilon_{ij}$$

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

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

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

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

# Conclusions

Asymmetric Dark Matter accumulated onto neutron stars could turn them to solar mass black holes

- New Dark Matter Constraints

Asymmetric Dark Matter with self-interactions could potentially form its own compact stars.

- It Solves the problems of the CDM paradigm.
- small dark matter masses correspond to large compact objects that can be tested with LIGO.
- alternative constraints to direct detection experiments that lose sensitivity at low masses.
- Manifests itself as atypical neutron stars or black holes.