University of Southern Denmark

Asymmetric Dark Stars and Their Signs in the Sky

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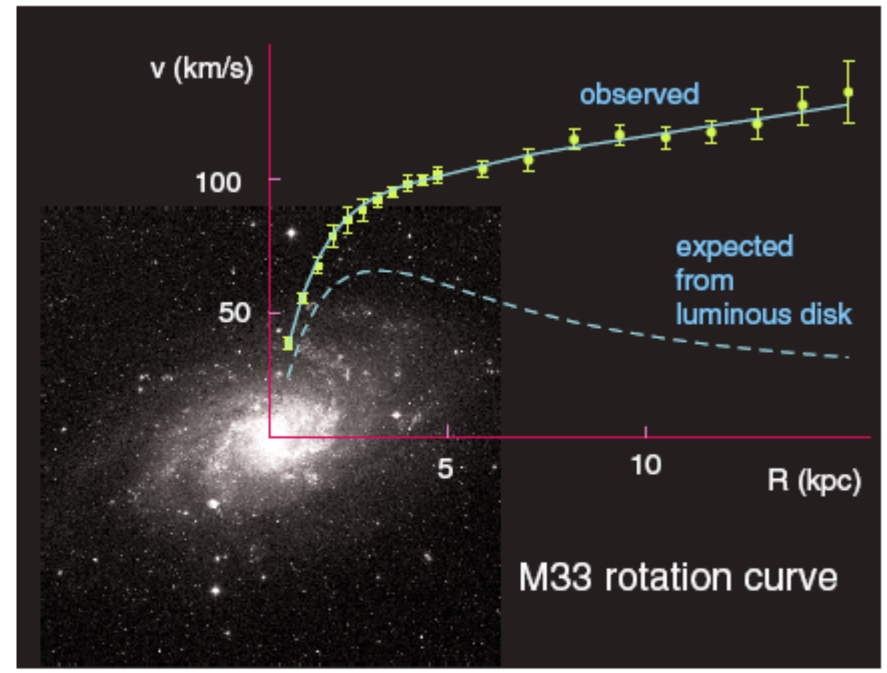
CP^3 - Origins

Particle Physics & Origin of Mass

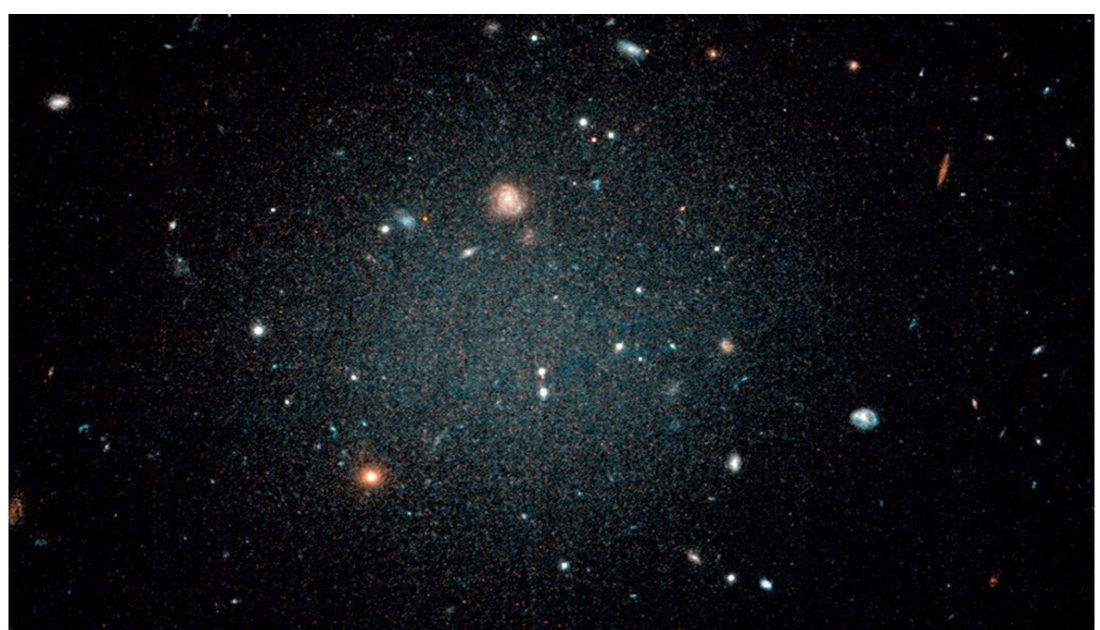
HKUST, Hong Kong, 10 Jan. 2020

The Missing Mass of the Universe

bullet cluster

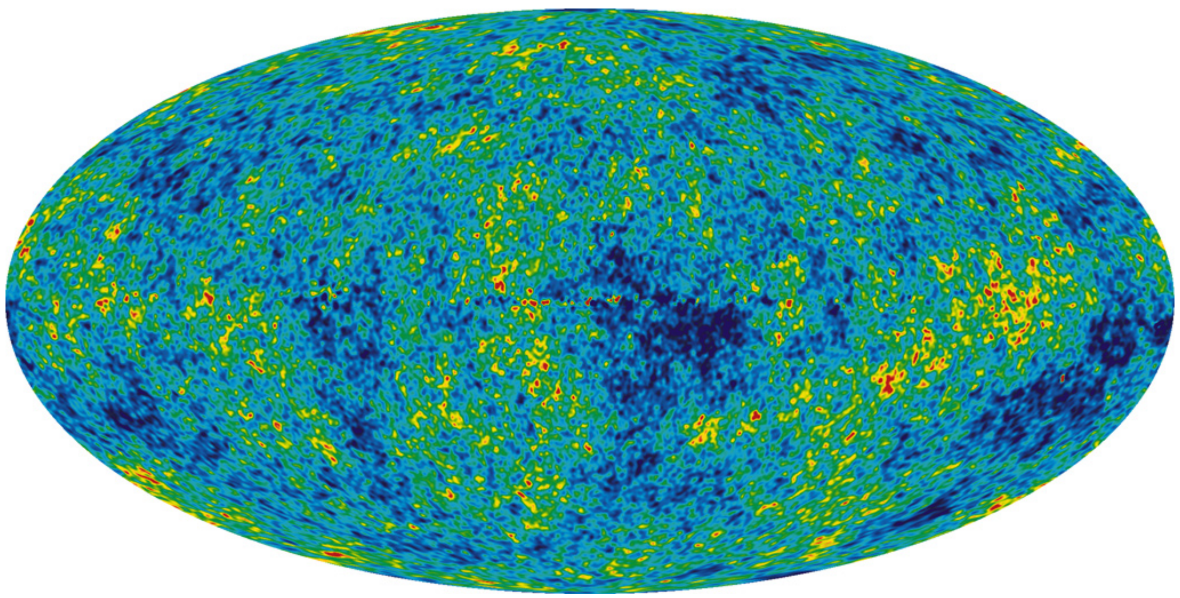


Rotation curves of galaxies

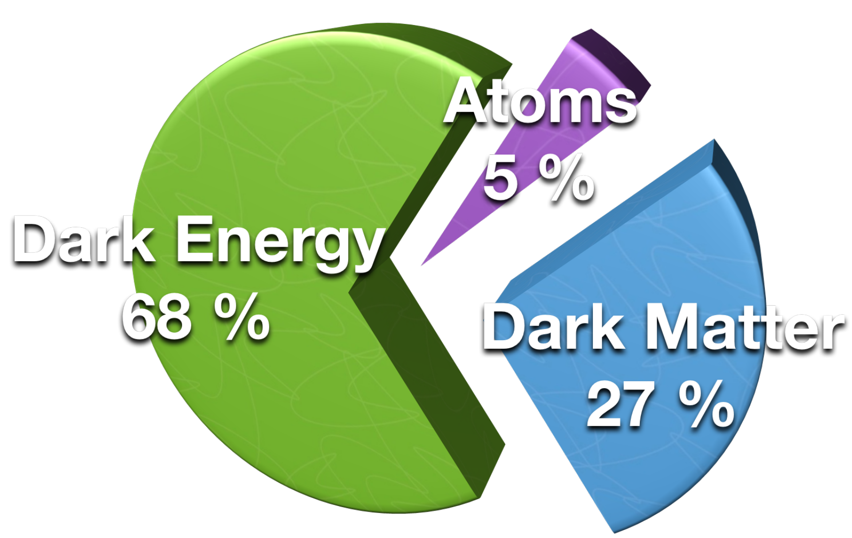


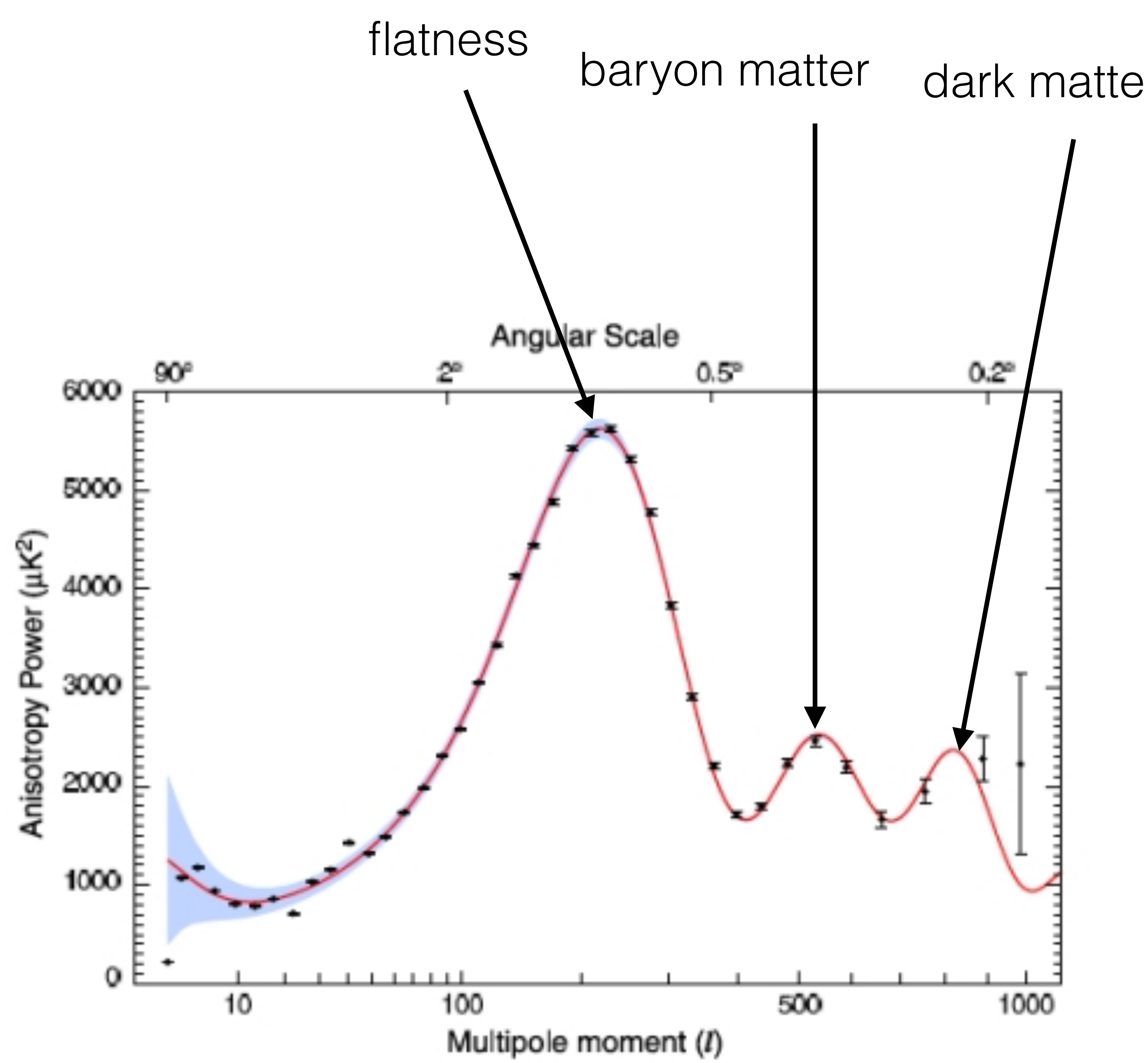
NGC1052-DF2

Dark Matter



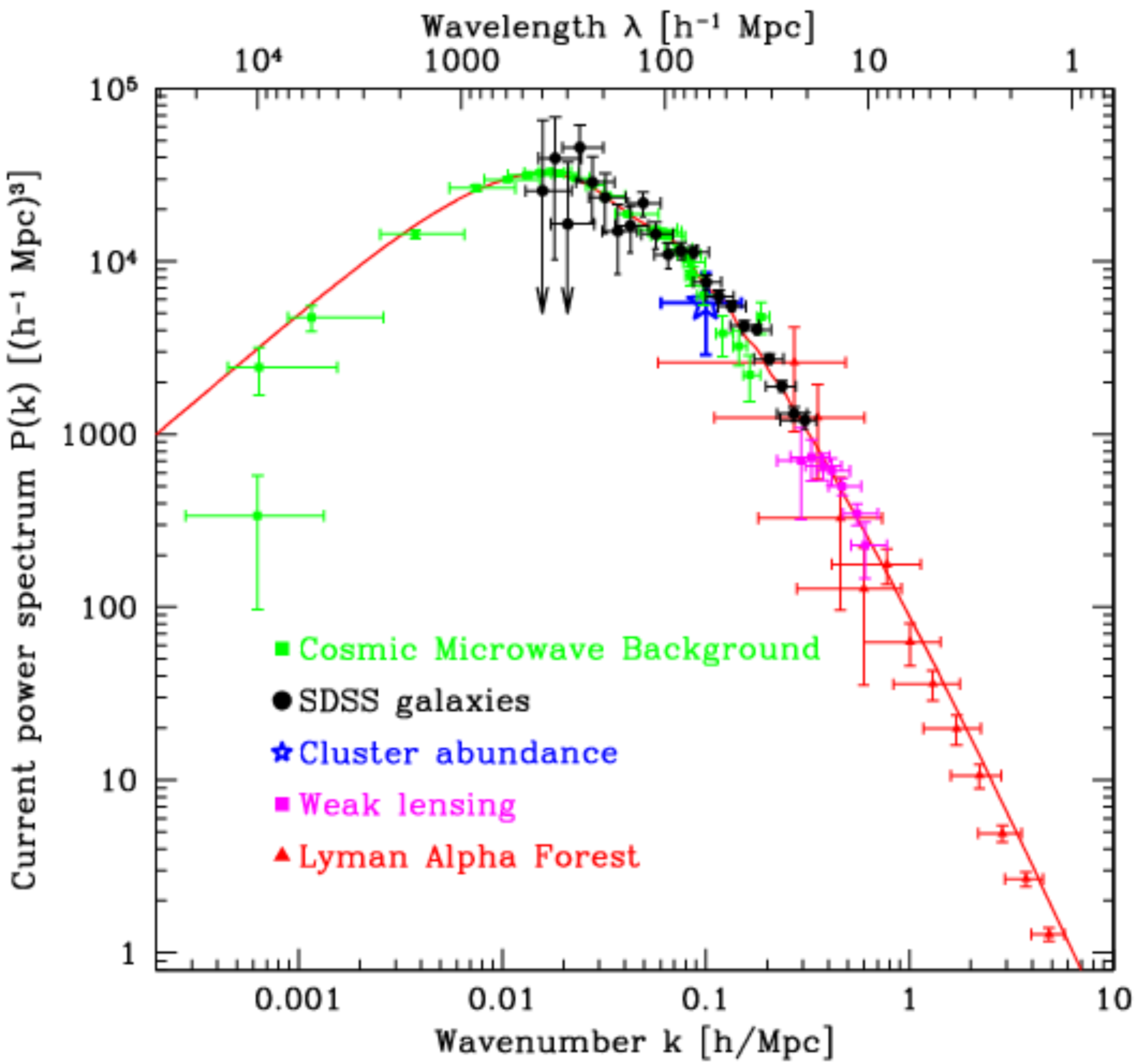
Microwave Background Radiation





Why Dark Matter Self-Interactions?

CCDM very consistent with Large Scale Structure

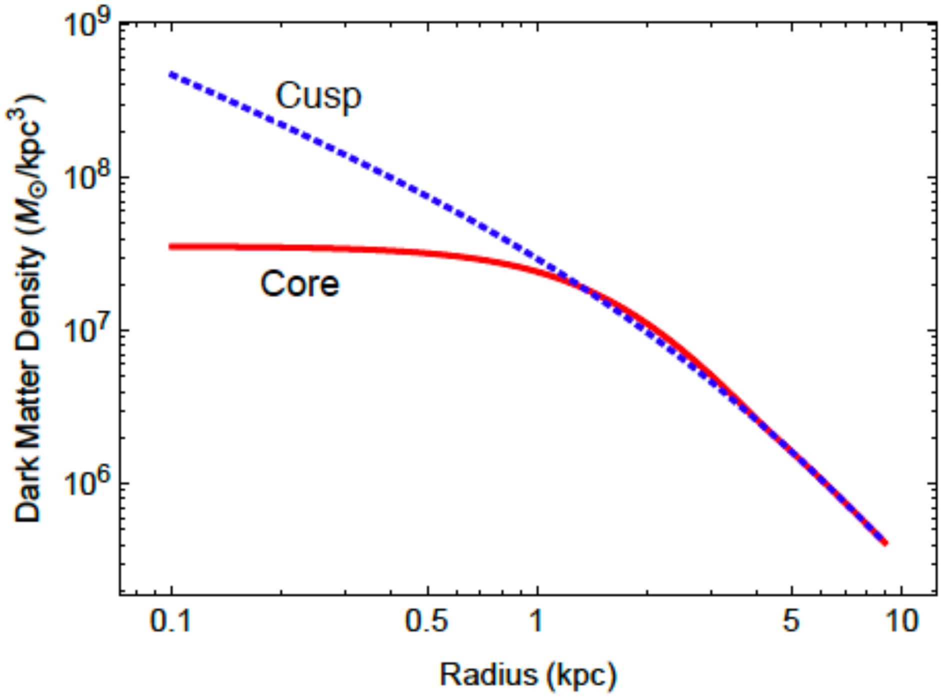


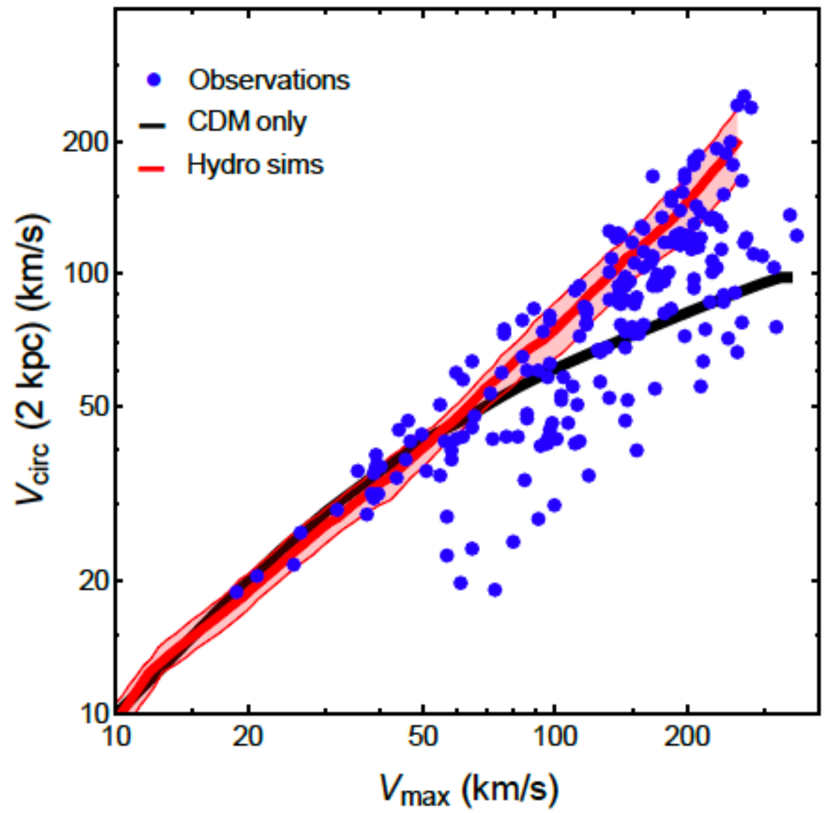
Why Dark Matter Self-Interactions?

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

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

$$n_{TB} = n_B$$

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

$$1 \times 5 = 5$$

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?

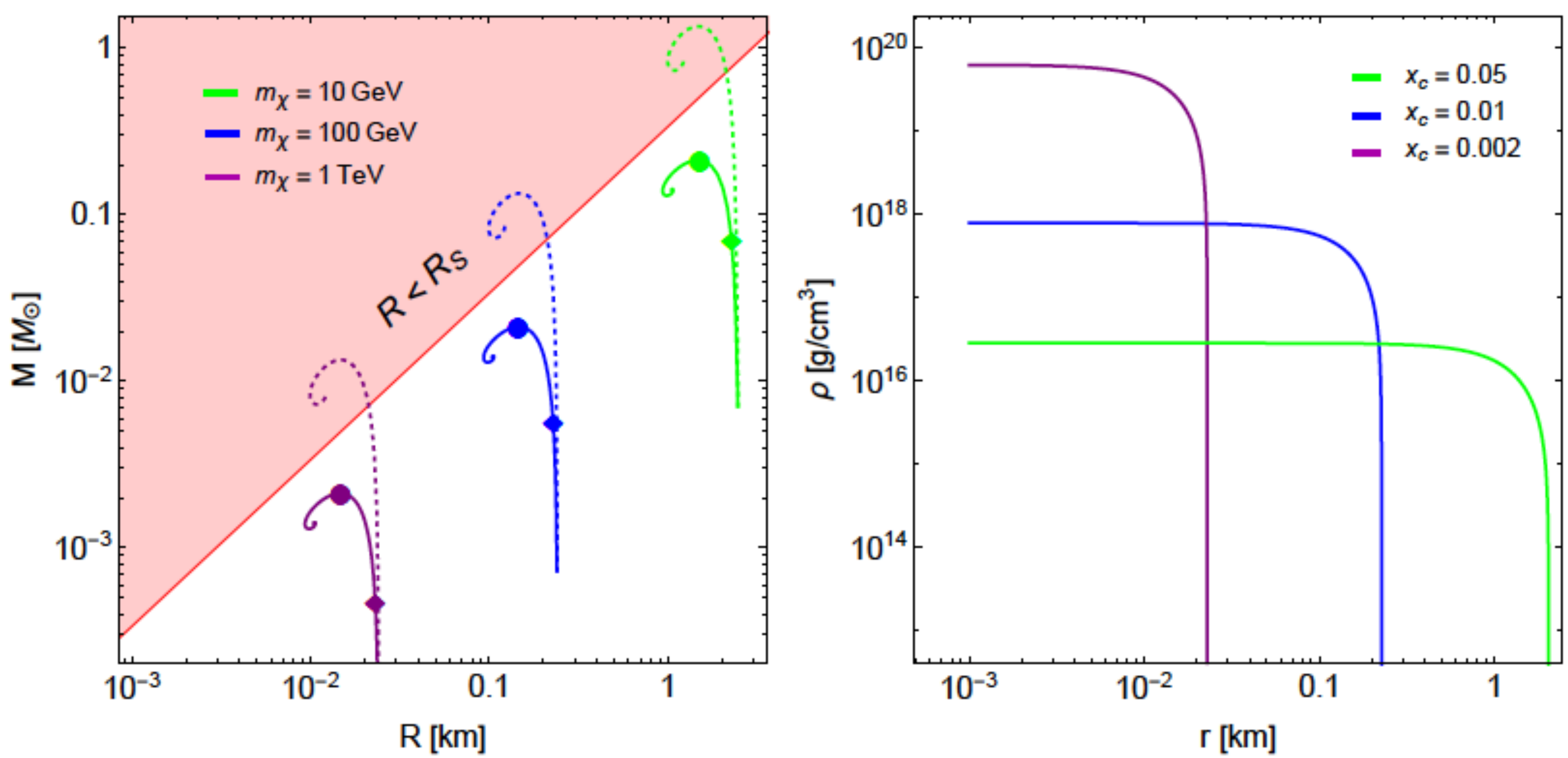
Asymmetric Fermionic Dark Stars

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

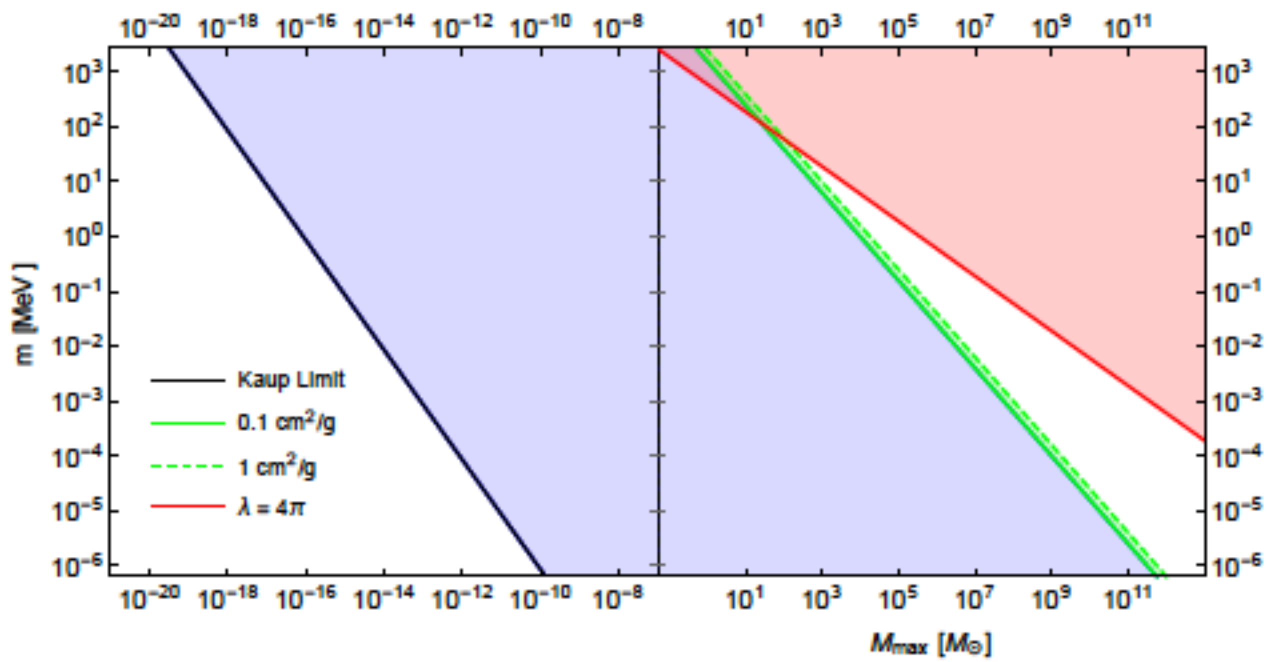
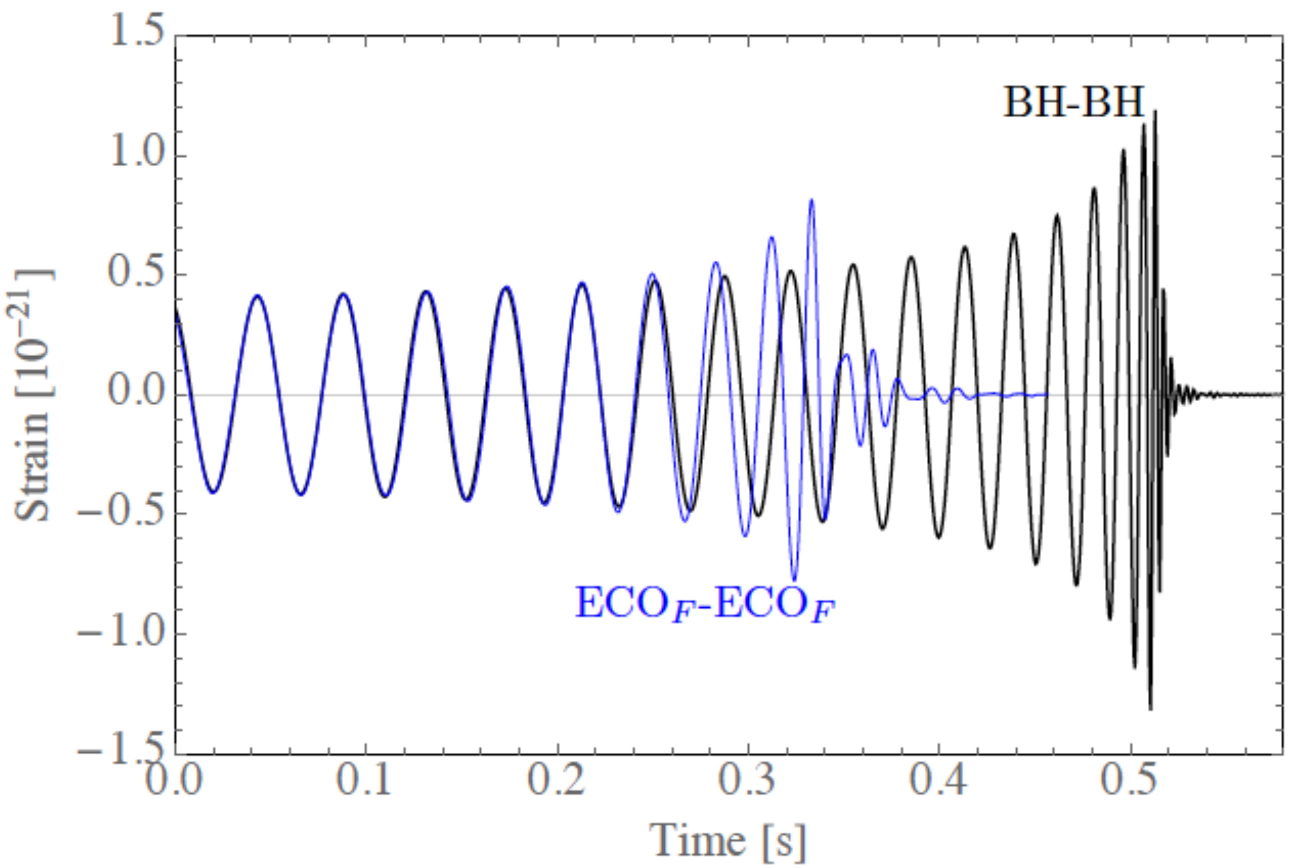


Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass m. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths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

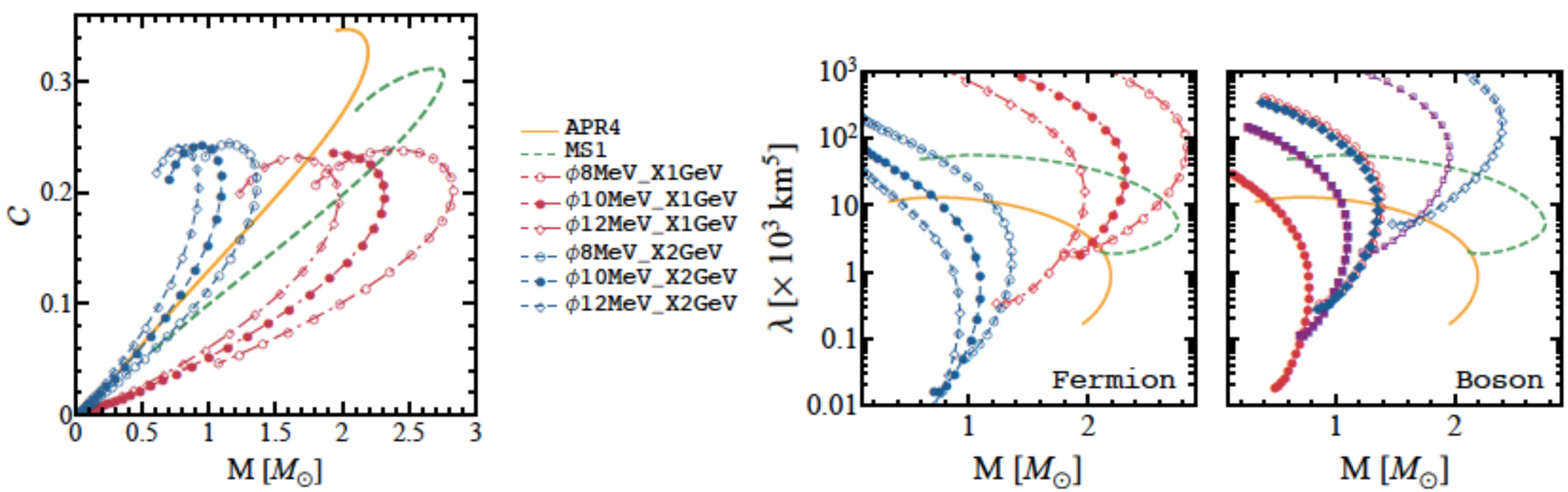
How stars deform in the presence of an external gravitational field?

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

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

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

Love number



Maselli, Pnigouras,Nielsen,
CK, Kokkotas, 17

The Bright Side of Dark Stars

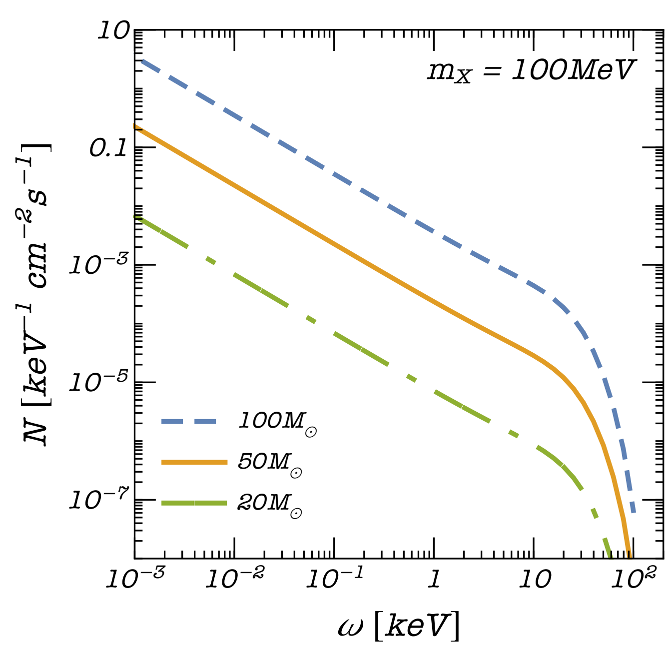
Dark Stars could shine via dark Bremsstrahlung if there is e.g. kinetic mixing between the dark and ordinary photon

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

In vacuum DM should not couple to photon because the mixing term can disappear by reshifting the photon. However the photon acquires a Debye mass ~kgμ/π

and this induces an effective $\varepsilon = \kappa^3 g^2 \mu^2/(\pi^2 m^2)$

- 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



Maselli, CK, Kokkotas ‘19

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.

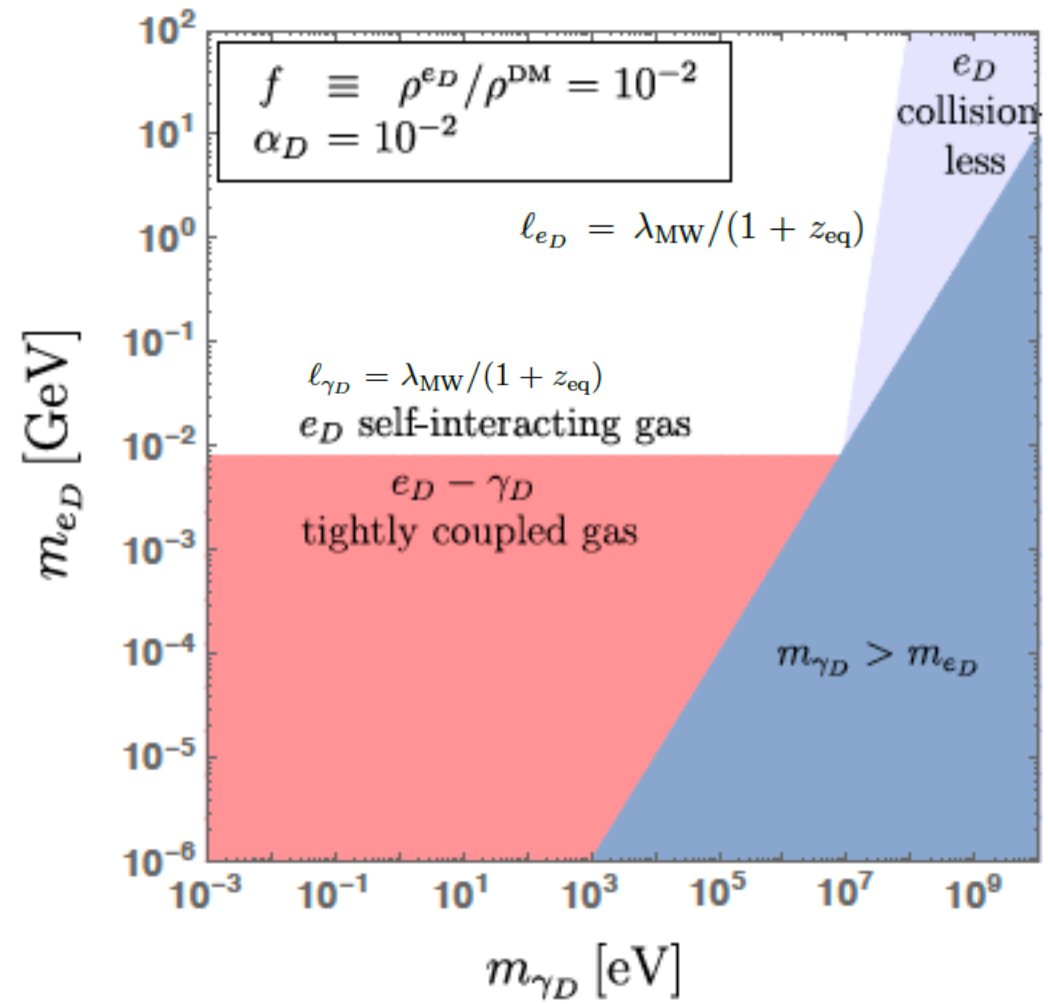
$\ell_{\gamma_D} \gg \lambda_P \gg \ell_{e_D}$ self-interacting e_D gas. e_D and γ_D decoupled

$\lambda_P \gg \ell_{\gamma_D} \gg \ell_{e_D}$ 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



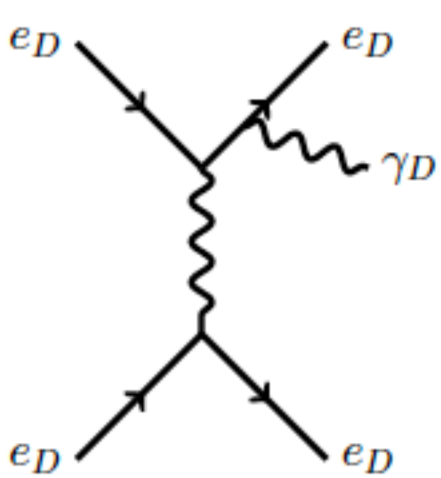
Perturbations grow as long as

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

Chang, Egana-Ugrinovic, Rouven, CK '18

Formation of Asymmetric Dark Stars

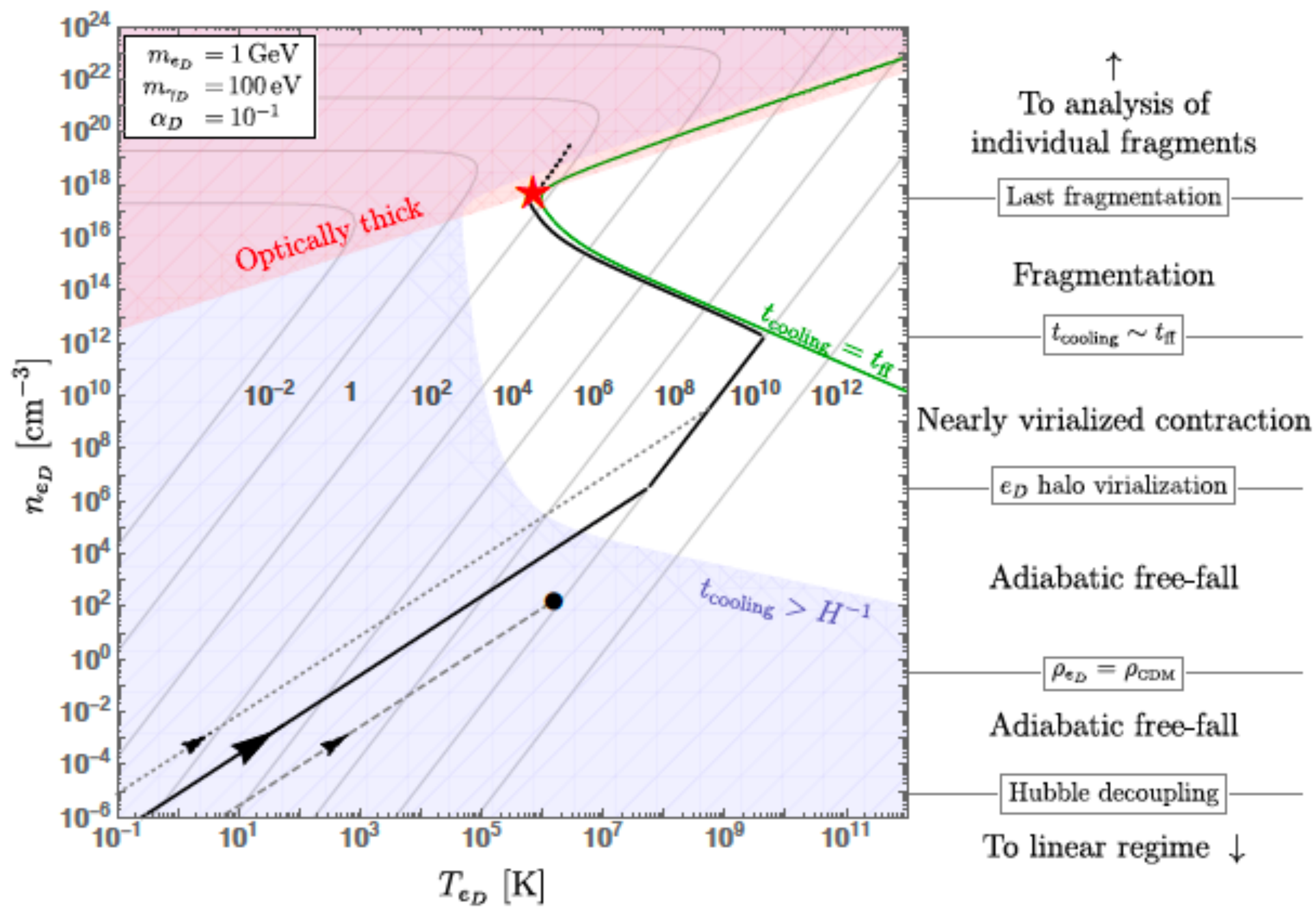
Collapse can proceed via dark photon Bremsstrahlung Cooling



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

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

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



Chang, Egana-Ugrinovic
CK, Essig, 18

Formation of Asymmetric Dark Stars

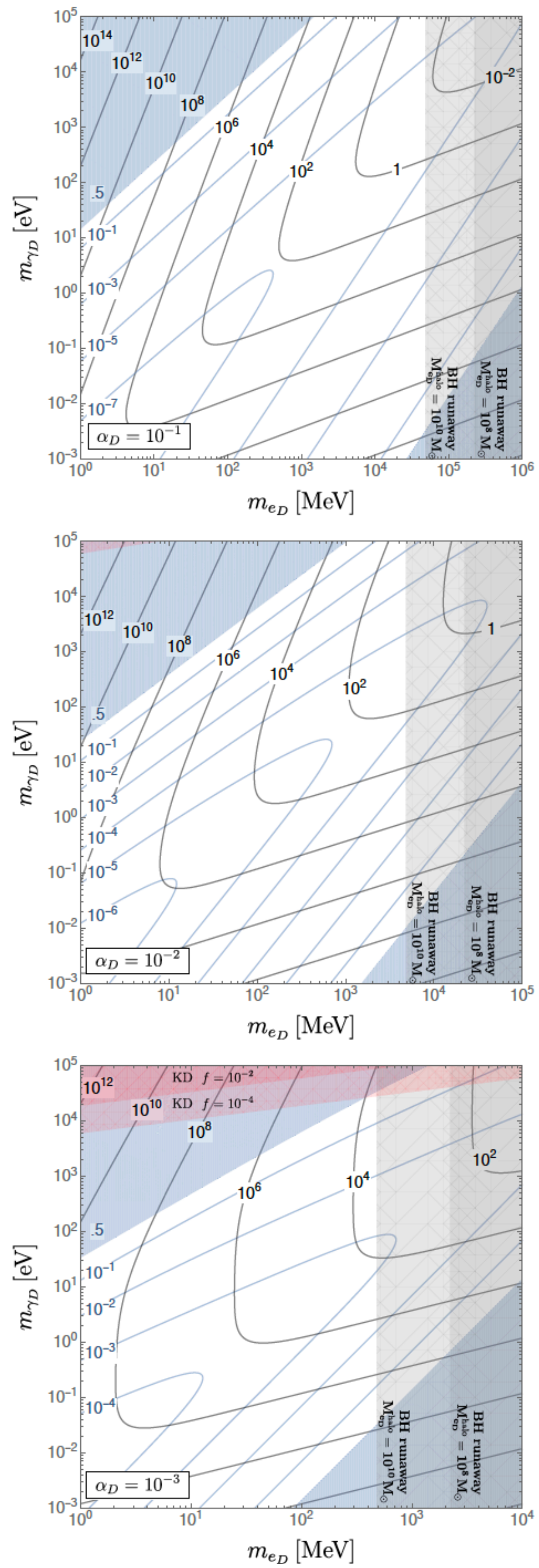


Figure 7: *Black contours:* mass of the dark electron exotic compact objects formed via fragmentation of a dark electron halo, in units of solar mass, as a function of the dark electron and dark photon masses. The dark fine-structure constant has been set to $\alpha_D = 10^{-1}$ (top), $\alpha_D = 10^{-2}$ (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.

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
- They could also produce photons