University of Southern Denmark

The possibility of Compact Dark Stars

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CP3 - Origins

Particle Physics & Origin of Mass

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Dark Matter & Compact Objects

Dark Matter forming Compact Stars

Dark Matter forming Black Holes

Dark Matter changing properties of Compact Stars

Constraining Dark Matter with Compact Stars

WIMP annihilation and Cooling of Stars

WIMP annihilation as a heating mechanism for
•neutron stars (CK '07, CK Tinyakov '10, Lavallaz Fairbairn '10)
•white dwarfs (Bertone Fairbairn '07, McCullough '10)

WIMP collapse to a Black Hole

WIMPs can be trapped inside stars and later collapse forming a black hole that destroys the star
(Goldman Nussinov '89, CK Tinyakov '10, '11, '13 McDermott Yu Zurek '11, CK'11, '12
Guver Erkoca Reno Sarcevic '12, Fan Yang Chang '12, Bell Melatos Petraki '13, Bramante Fukushima Kumar Stopnitzky '13,
Bramante Linden '14, Autzen CK '14)

Pulsar slowing down

WIMPs can slow down the rotation of a pulsar (Perez-Garcia, CK '14)

Triggering Supernovae Ia

WIMPs can trigger the collapse in masses lower than the Chandrasekhar limit (Bramante '15)

Triggering Neutron Star explosions

WIMPs can trigger the explosion of neutron stars with stranglets (Silk Perez-Garcia '11, '12)

Primordial black hole capture by neutron stars

Capela, Pshirkov, Tinyakov '12, Loeb, Pani, 14

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

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

$$n_{TB} = n_B$$

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

$$1 \times 5 = 5$$

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

Open Questions

- Can dark matter have strong self-interactions and lead to gravitational collapse and formation of compact dark objects?

- What are the possible formation mechanisms?

A. Gravothermal collapse?
B. Dark photon radiation?
C. Cosmological perturbations?
D. Accretion from Supermassive stars?

- Detection prospects with LIGO or lensing?

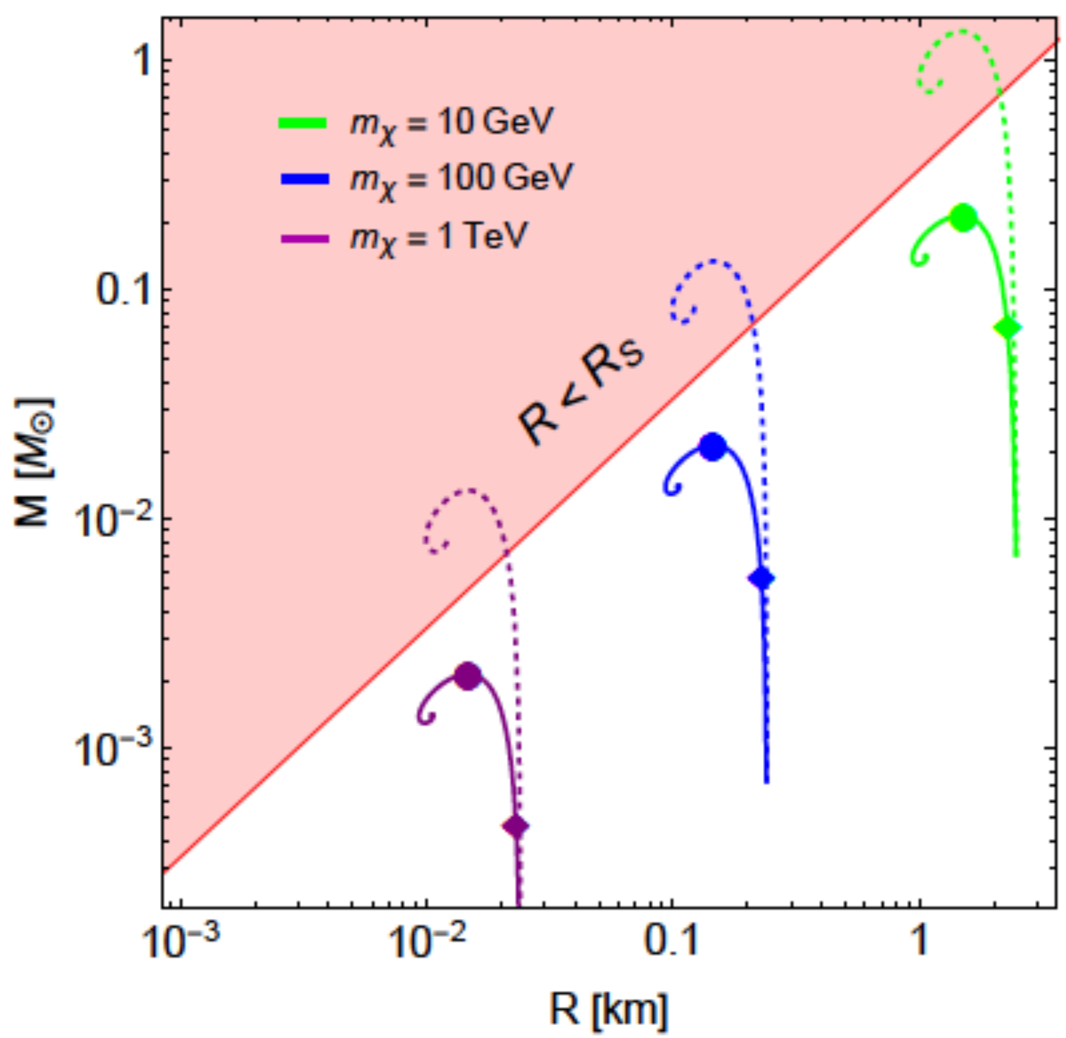
- Vibration modes of “dark stars”

Note: These compact asymmetric dark stars are different from dark stars formed by annihilating dark matter
Freese, Gondolo, Spolyar 2008

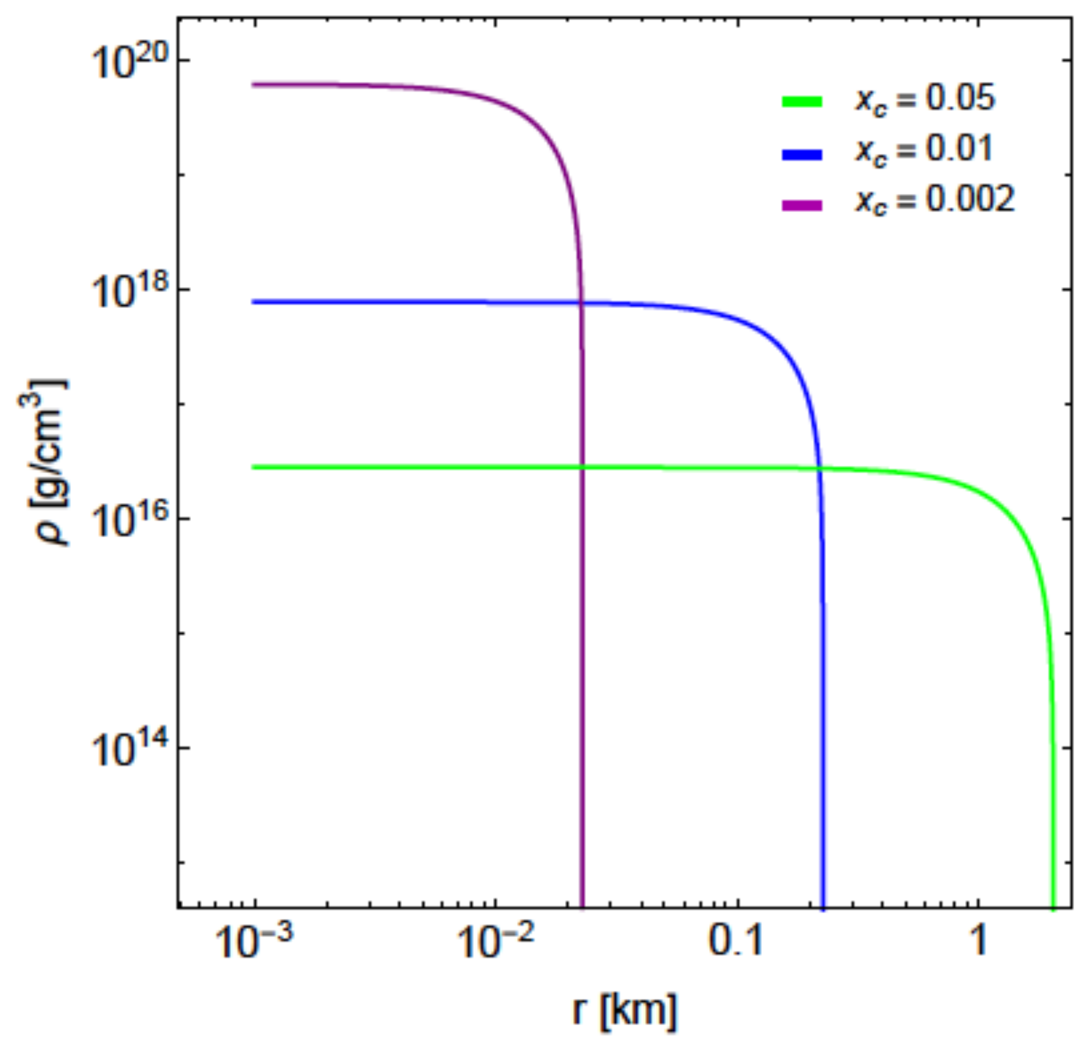
Asymmetric Fermionic Dark Stars

Tolman-Oppenheimer-Volkoff with Yukawa self-interactions

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



(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

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

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

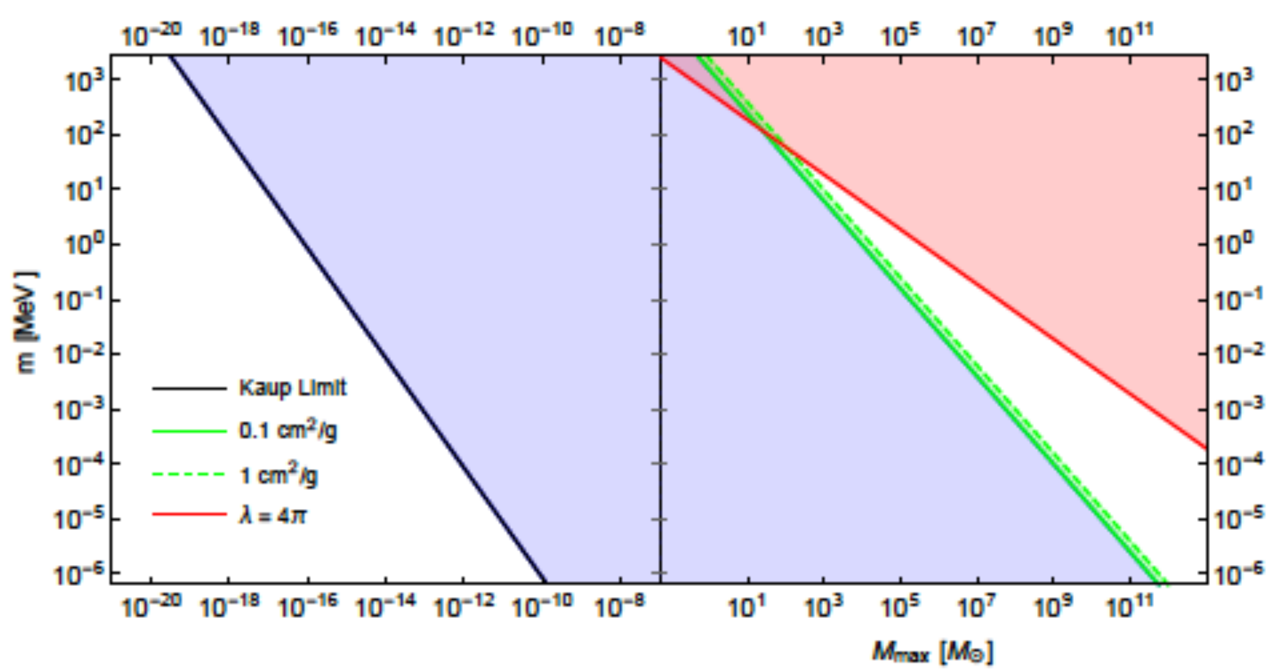
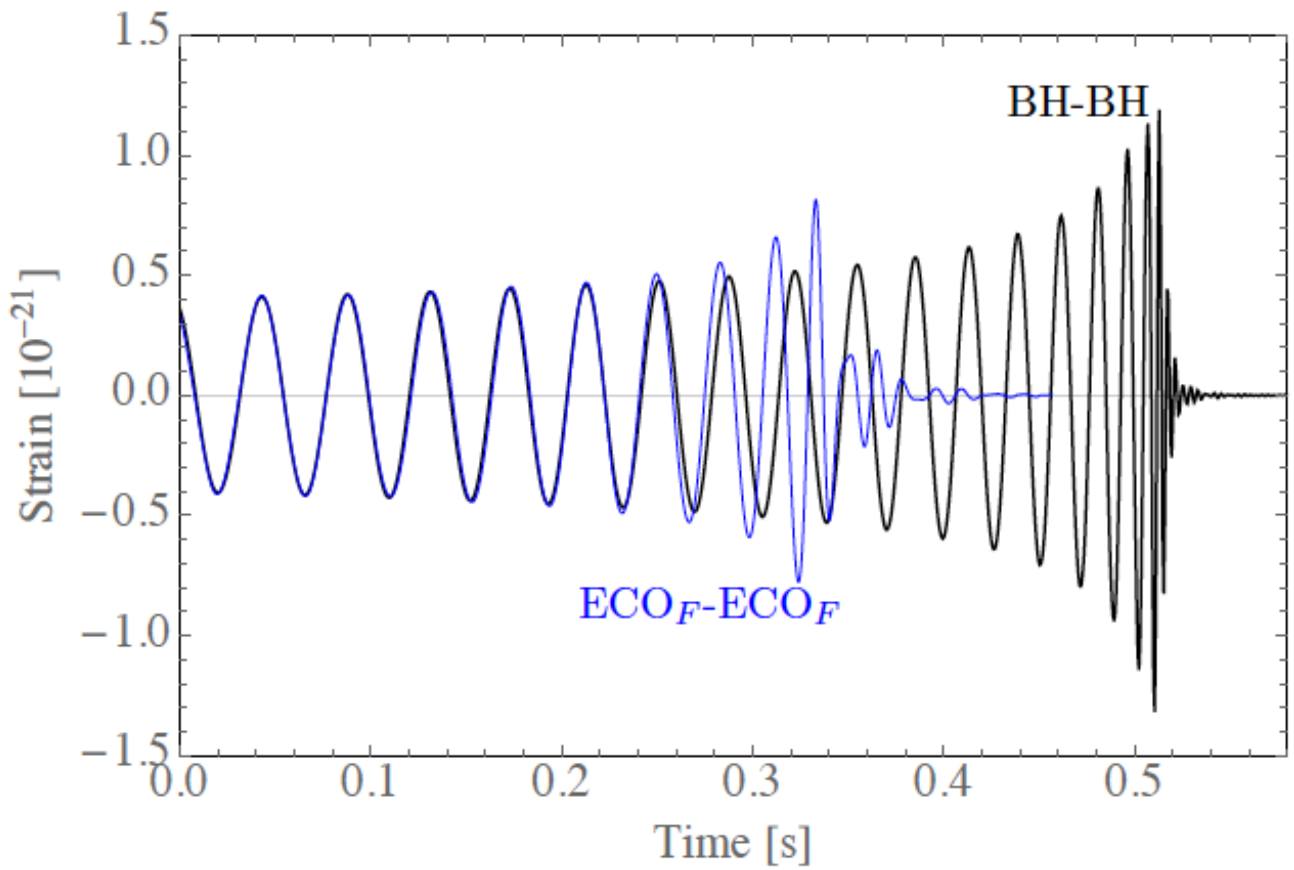


Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass m. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths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



Giudice, McCullough,
Urbano '16

Tidal Deformations of Dark Stars

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

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

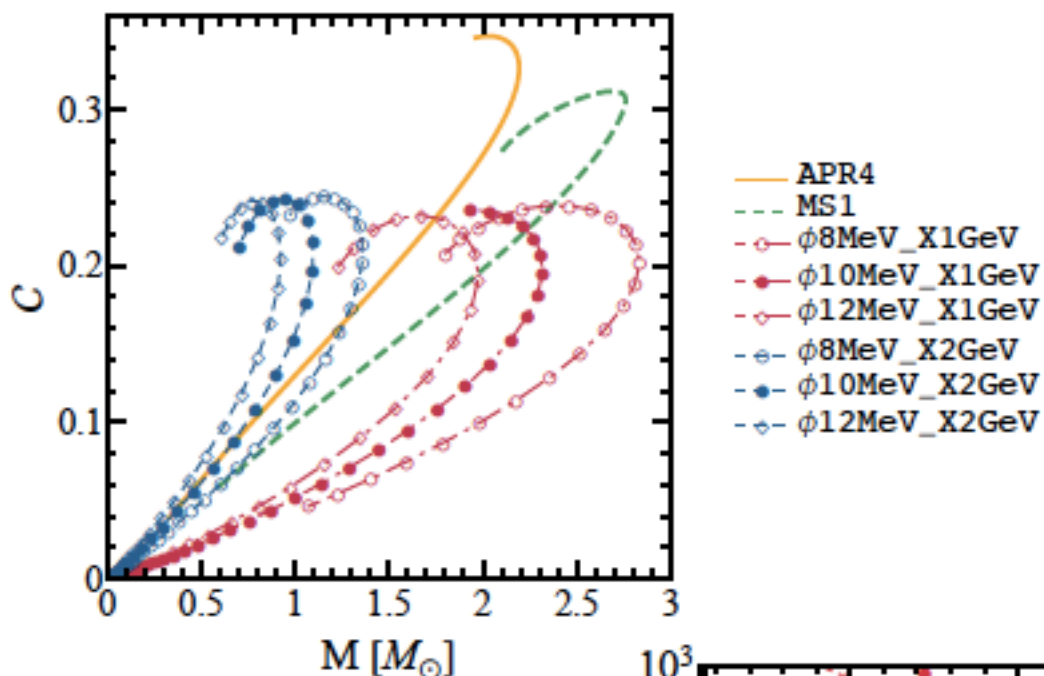
$$Q_{ij}=-\lambda\varepsilon_{ij}$$

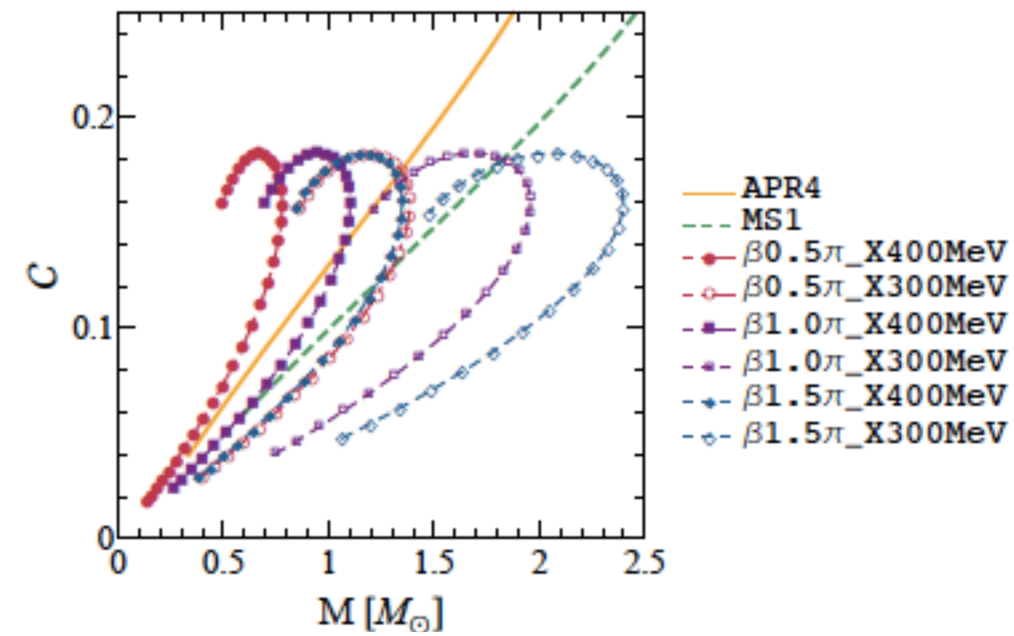
$$\lambda=\frac{2}{3}k_2R^5$$

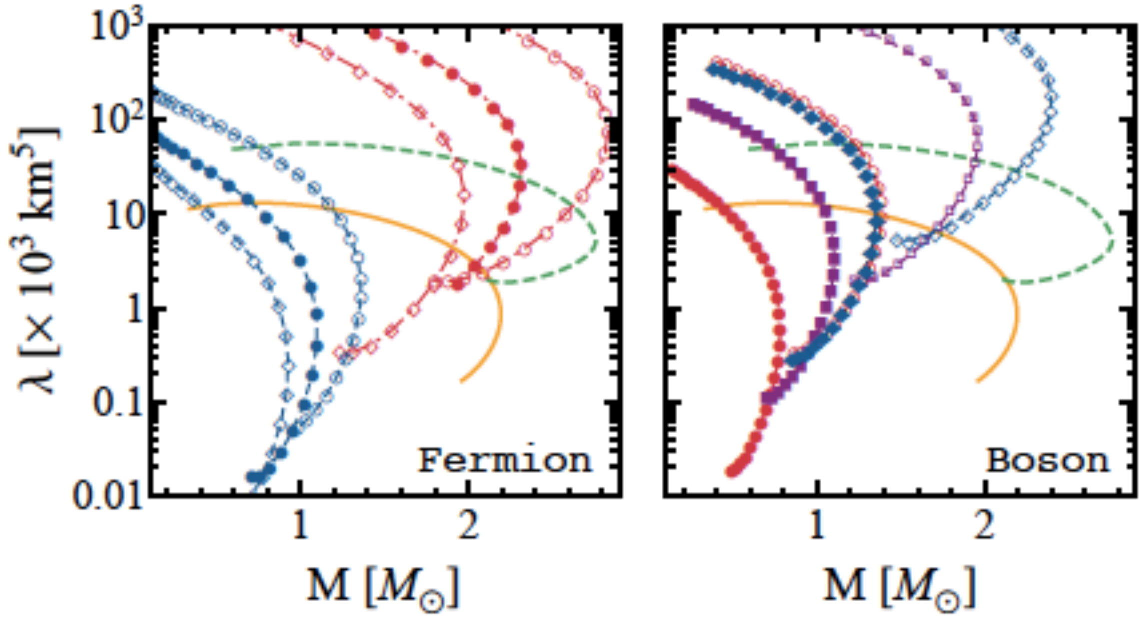
Love number

Similalry we can estimate the deformation due to rotation

I-Love-Q for Dark Stars







Maselli, Pnigouras,Nielsen, CK, Kokkotas, 17

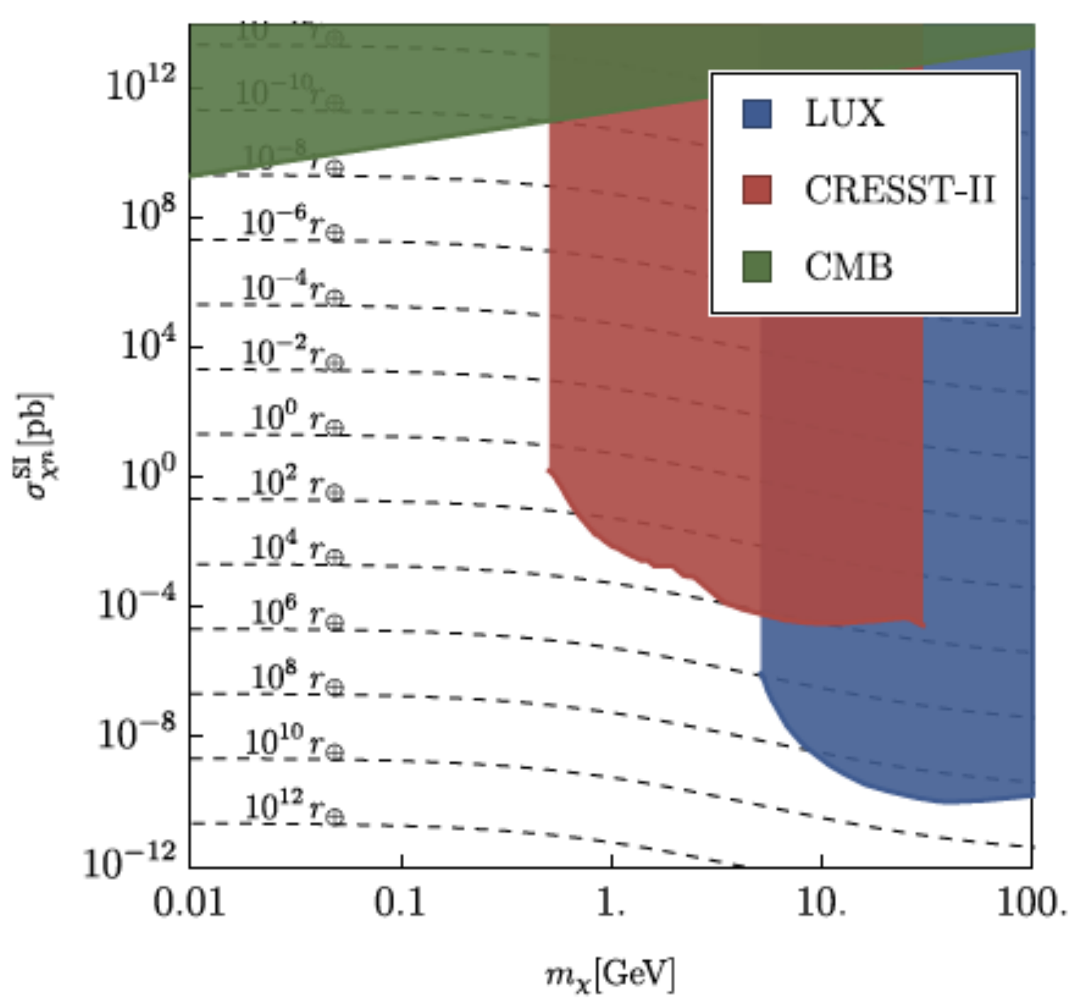
I-Love-Q relations

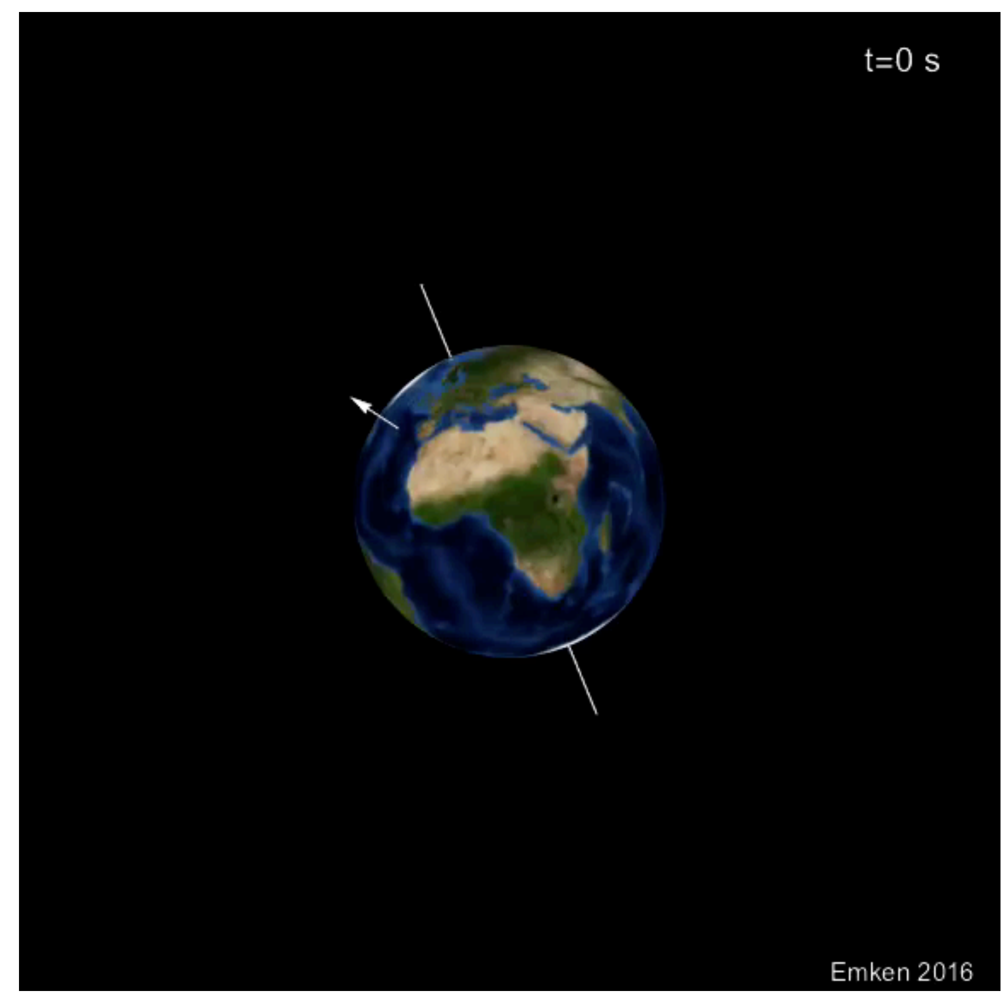
$$\ln y = a + b \ln x + c(\ln x)^2 + d(\ln x)^3 + e(\ln x)^4$$

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

DAMASCUS: Dark Matter Simulation Code for Underground Scatterings

- fully parallelized code
- Precise Recoil Spectrum
- Test self-consistency of experiments
- Probe Currently Elusive Dark Matter

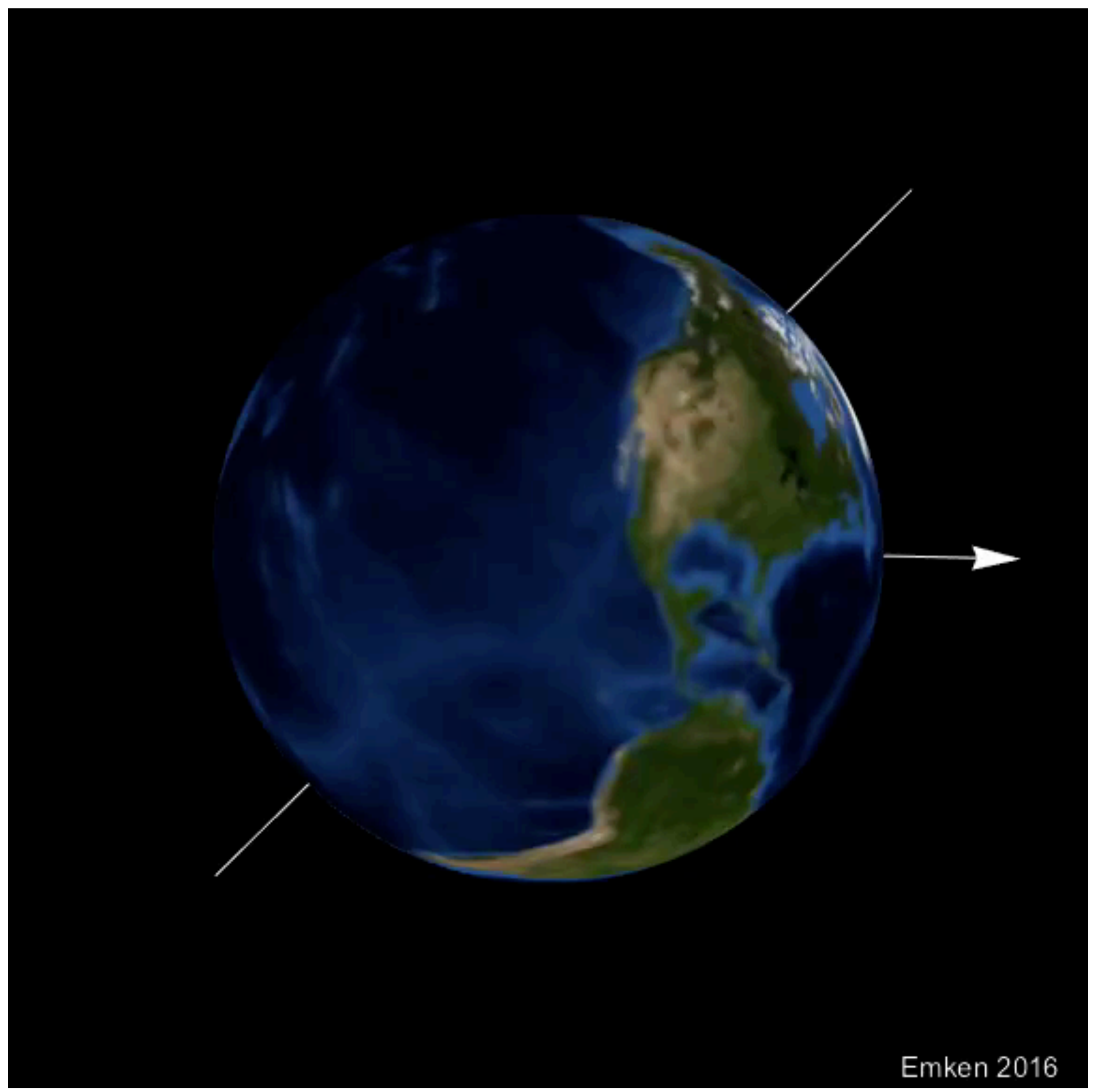




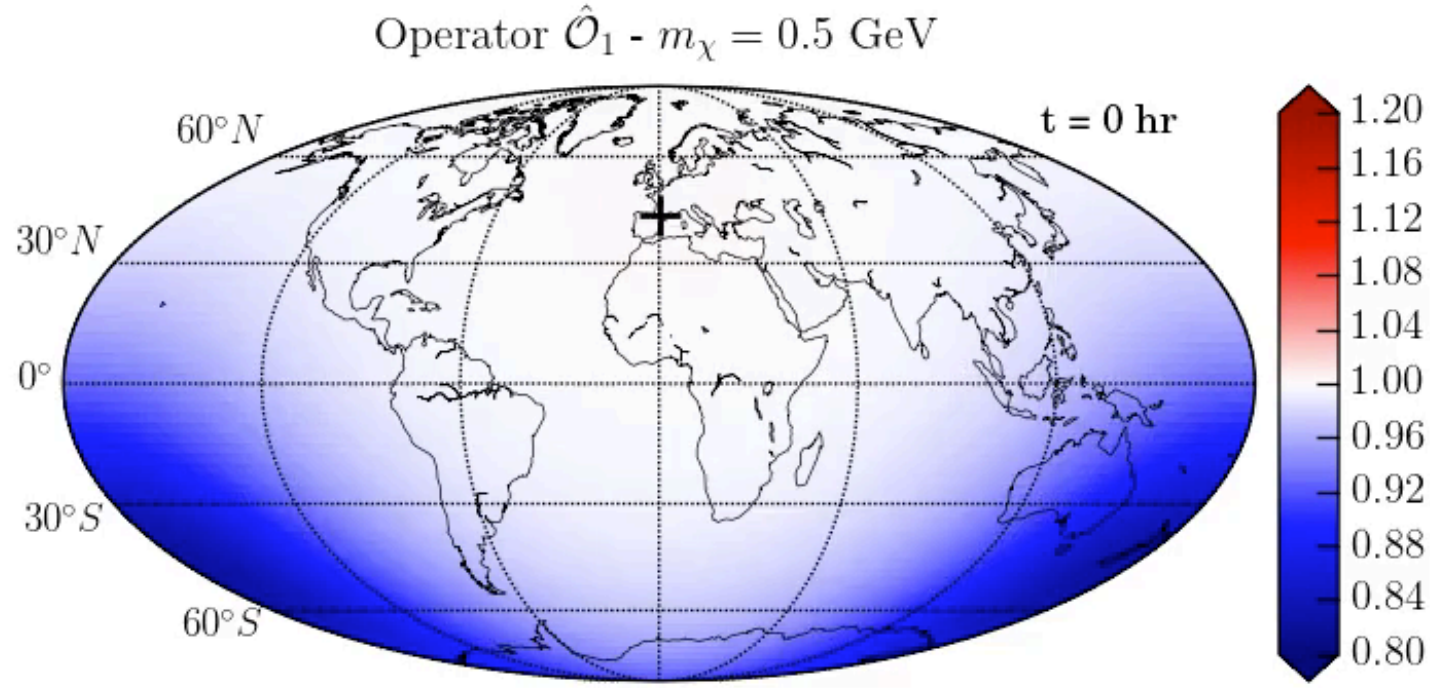
Daily Modulation in the Dark Matter Signal

The dark matter signal in underground detectors has three types of diurnal modulation:

- Shadowing effect
- Gravitational focusing
- Rotational velocity of the Earth

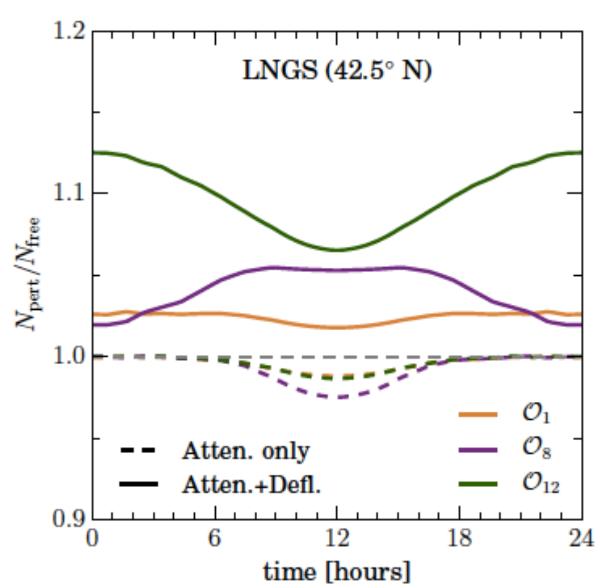


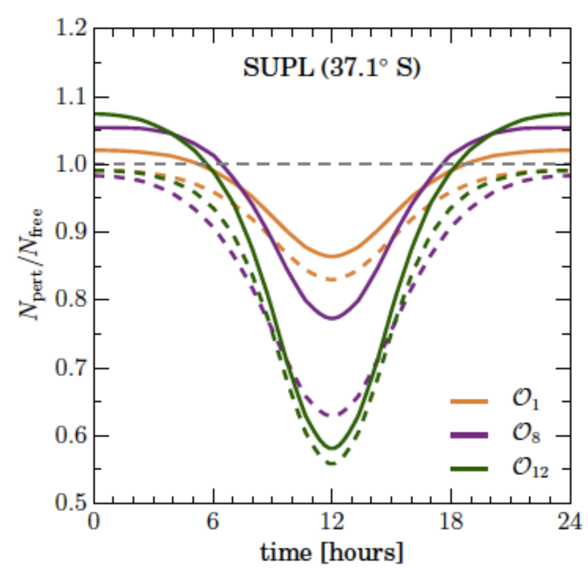
The Shadow of the Earth



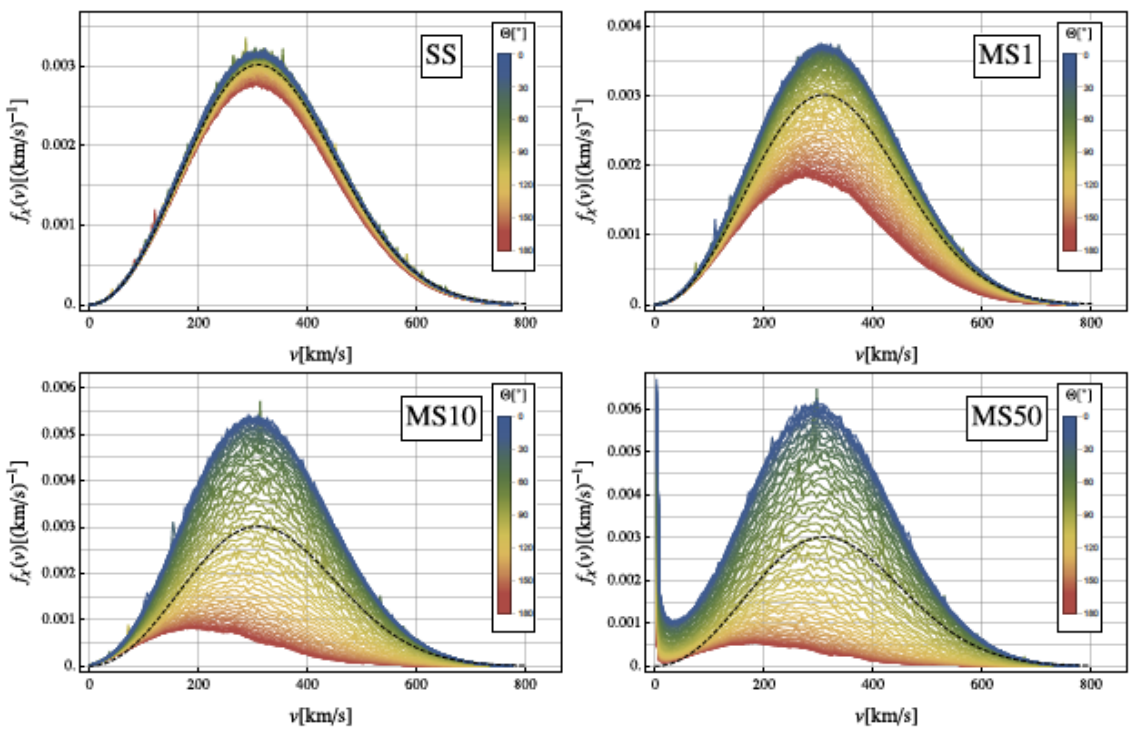
Relative rate enhancement due to Earth-scattering *(attenuation only)*

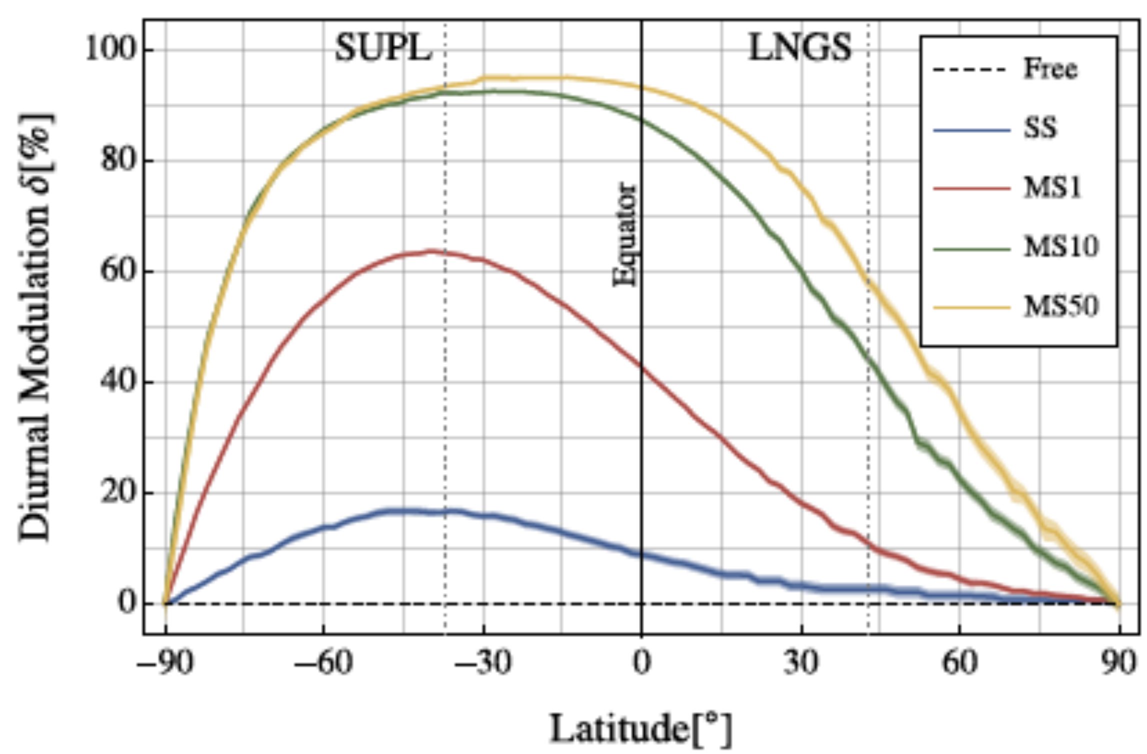
(Kavanagh, CK, Catena '17)





DAMASCUS running on high cross section





Emken, CK '17

Conclusions

Looking for compact dark stars with LIGO

- Different mass range than direct detection
- Distinguishable from black holes and neutron stars mergers
- Identify dark matter self-interactions

Probing Light Dark Matter using the daily modulation DM signals from

- Phase space not covered by current detectors
- self-consistency of diect detection experiments
- DAMASCUS: Publicly available code