The price of tuning
Unique probes of tuned axions

Anson Hook
Stanford

AH, Junwu Huang : 1708.08464

Tuning

- Usually Tuning is a bad thing
  - Naturalness has guided particle physics thinking for a very long time
- What if we're wrong?
  - Is this a bad thing?
- No!
- Interesting signatures can result from tuning

Axion solution

$$\mathcal{L} \supset \frac{g^2}{32\pi^2}(\theta - \frac{a}{f_a})G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a$$

- One parameter solution (KSVZ axion)
- Also a dark matter candidate
- String theory motivation for not just one axion, but many many axions

Axion solution

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Axion dynamically sets
the neutron EDM to 0

$$V = -m_\pi^2 f_\pi^2 |\cos\left(\frac{a}{2f_a}\right)|$$

Axion parameter space

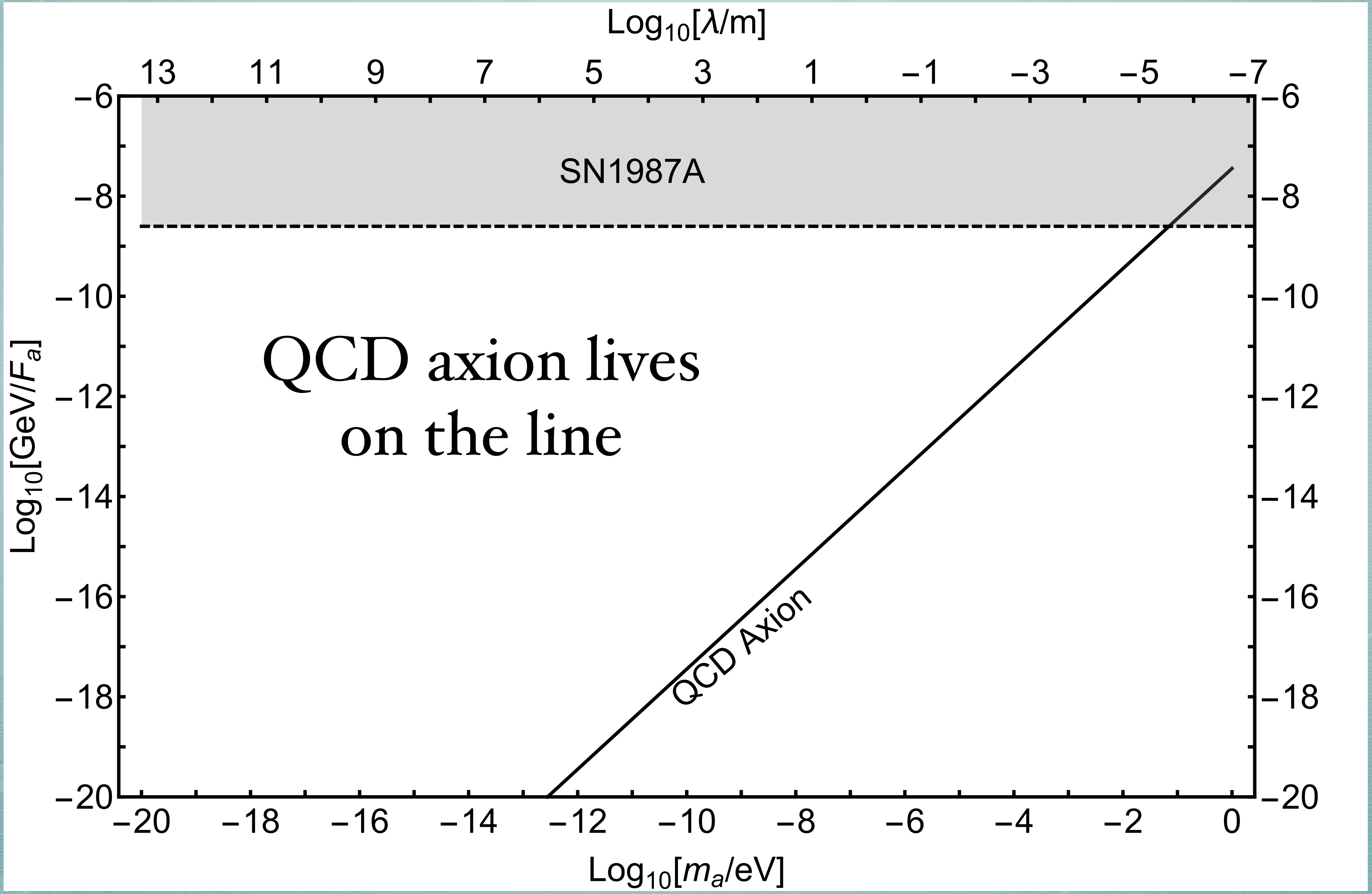
- Instead of

$$V = -m_\pi^2 f_\pi^2 |\cos\left(\frac{a}{2f_a}\right)|$$

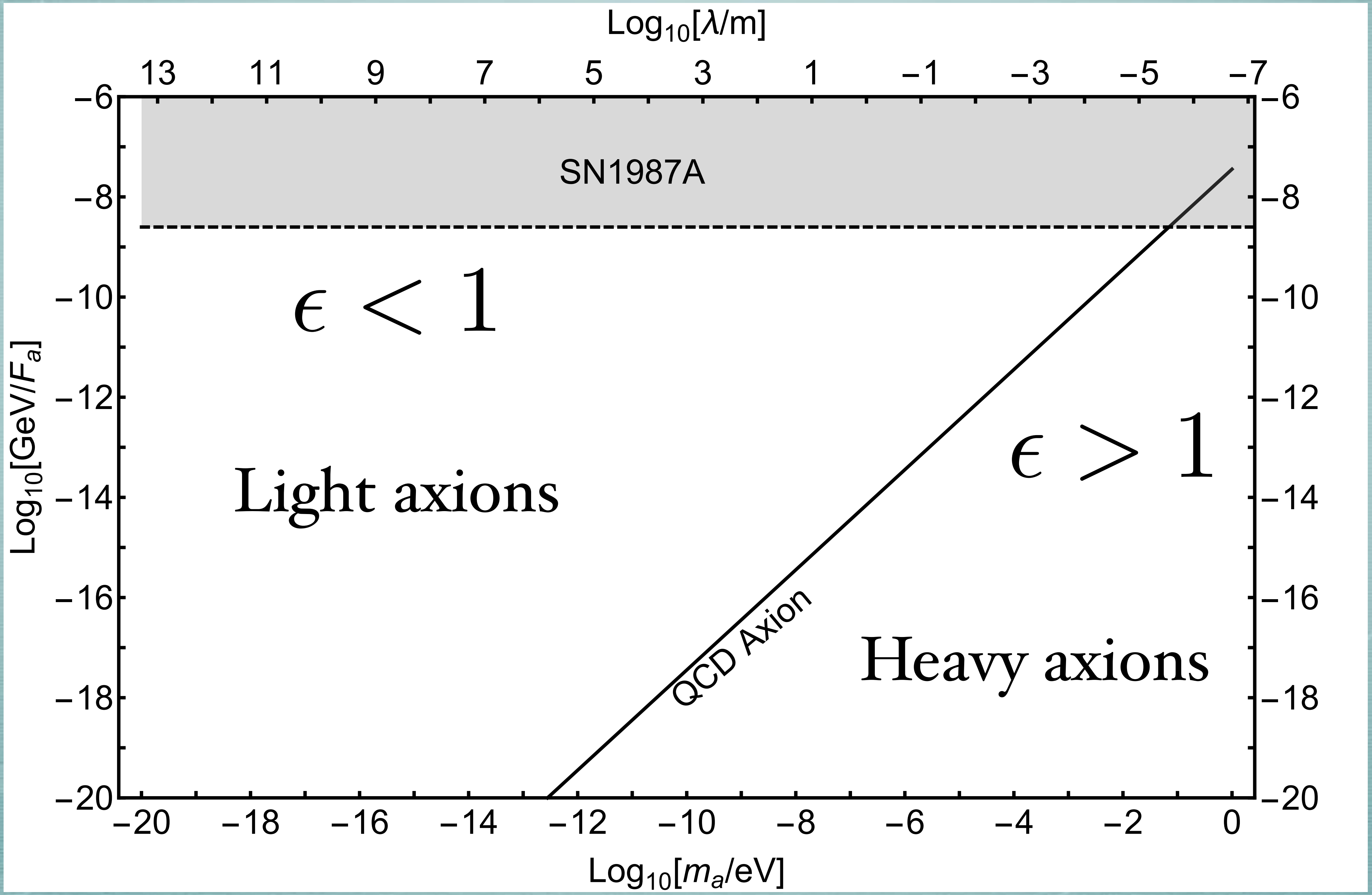
- We have

$$V = -\epsilon m_\pi^2 f_\pi^2 |\cos\left(\frac{a}{2f_a}\right)|$$

Axion parameter space



Axion parameter space



Tuning

$$\mathcal{L} \supset y\phi\overline{\psi}\psi$$

- The biggest different between tuned particles and non-tuned particles is sensitivity to finite density corrections

$$m_\phi \sim y\Lambda \qquad\qquad m_\phi \sim yT$$

- If tuned, thermal mass can be larger than bare mass

Neutron Stars + axions

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- Large finite density objects
- How does the axion behave around and in large density objects?

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- Large finite density objects
- How does the axion behave around and in large density objects?
- At high density, QCD deconfines so finite density makes the QCD contribution to the axion potential go away

Neutron Stars + axions

- Axion potential depends on quark condensate

$$m_u(\langle\overline{u}u\rangle_{n_N} - \langle\overline{u}u\rangle_0) = -m_u(\langle\frac{\partial H}{\partial m_u}\rangle_{n_N} - \langle\frac{\partial H}{\partial m_u}\rangle_0)$$

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$$H = E = m_n n_N$$

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$$= -m_u \langle \frac{\partial E}{\partial m_u}\rangle = \sum_{N=n,p} n_N \sigma_N^u$$

$$H = E = m_n n_N \qquad \sigma_N^u \equiv m_u \frac{\partial m_N}{\partial m_u}$$

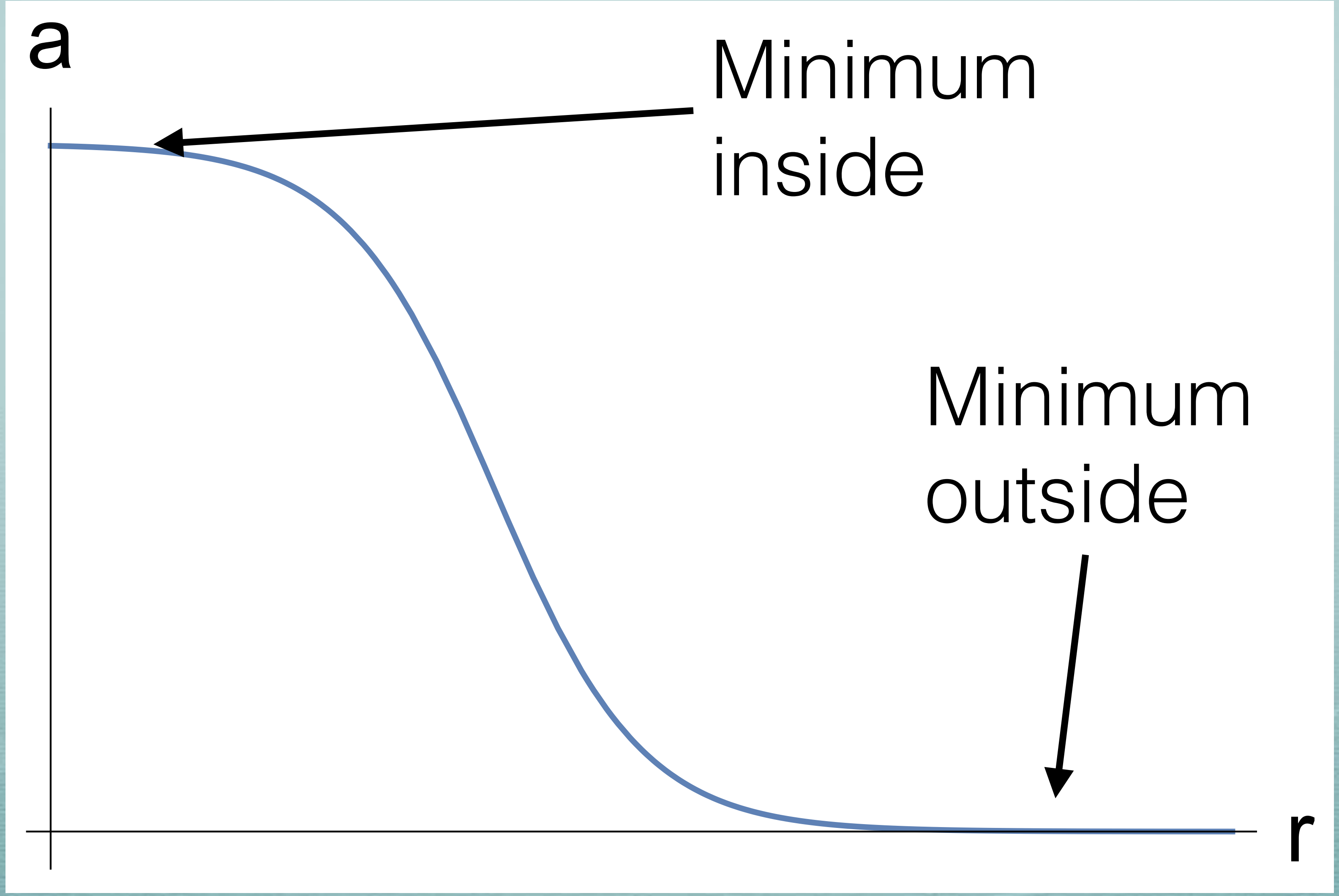
Neutron Stars + axions

$$V = -m_\pi^2 f_\pi^2 (\epsilon - \frac{\sigma_N n_N}{m_\pi^2 f_\pi^2}) |\cos\left(\frac{a}{2f_a}\right)| + \mathcal{O}(\left(\frac{\sigma_N n_N}{m_\pi^2 f_\pi^2}\right)^2)$$

- If object is dense enough, sign of the potential flips when perturbation theory still valid!
    - Part of the reason why we needed a slightly tuned axion
- Neutron stars can source the axion!

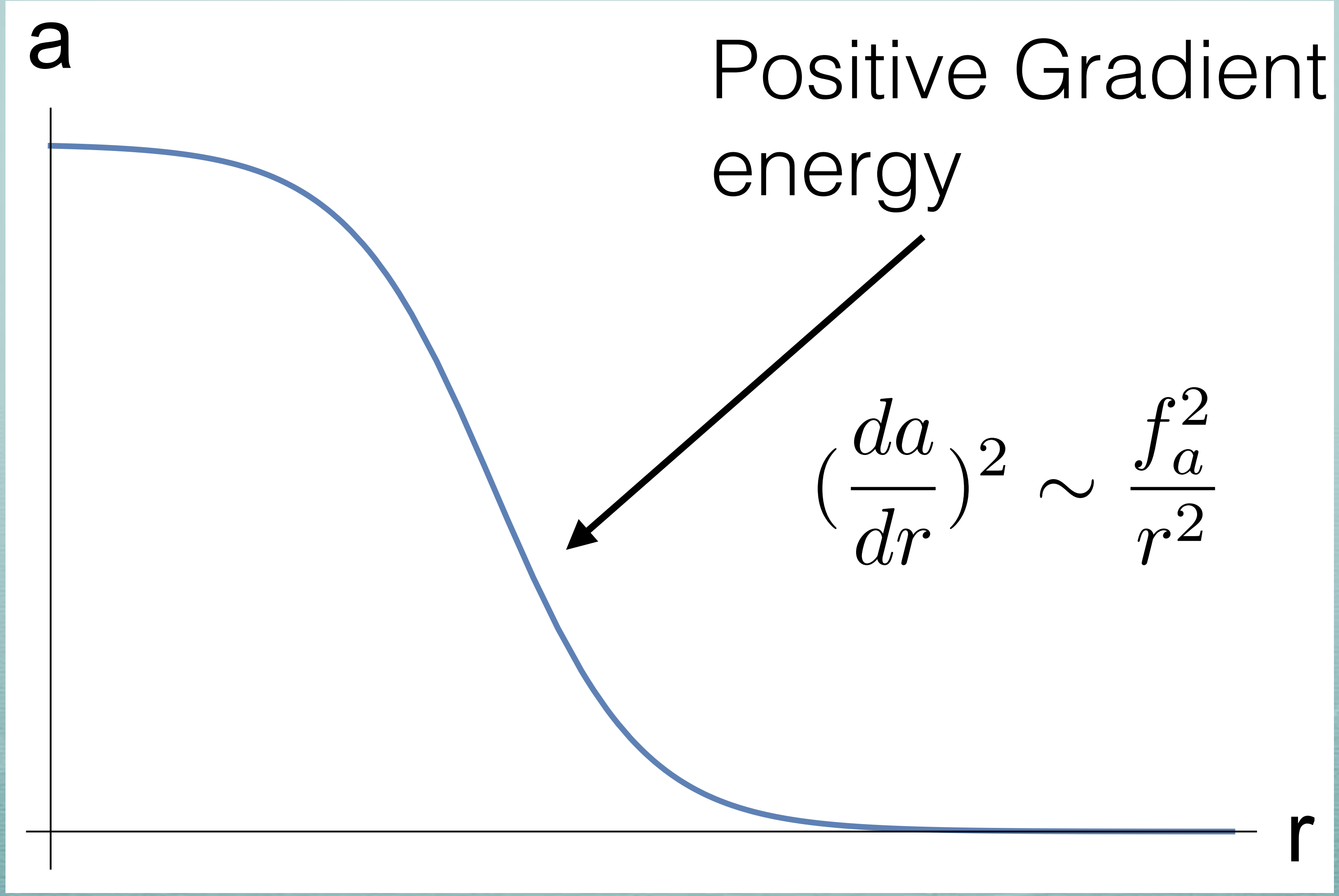
Neutron Stars as axion sources

- When does this happen?



Neutron Stars as axion sources

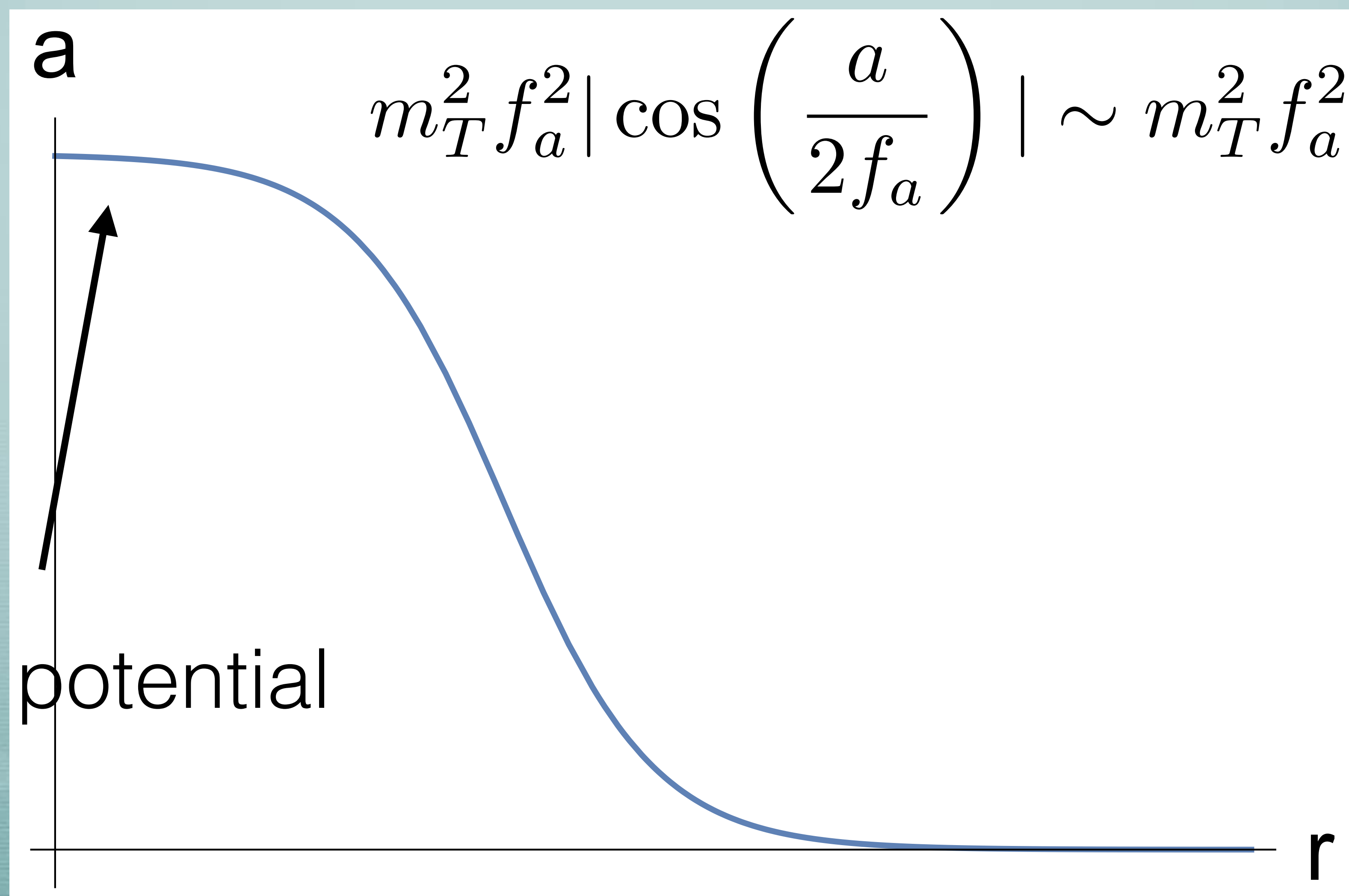
- Energy!



Neutron Stars as axion sources

- Energy!

$$m_T = m_\pi f_\pi \frac{\sqrt{\frac{\sigma_N n_N}{m_\pi^2 f_\pi^2} - \epsilon}}{2 f_a}$$



Gain in potential energy

Neutron Stars as axion sources

$$\Delta E \sim \text{Volume} \times \left(\frac{f_a^2}{r^2} - m_T^2 f_a^2 \right) < 0$$

- Critical radius at which neutron stars start to source the axion

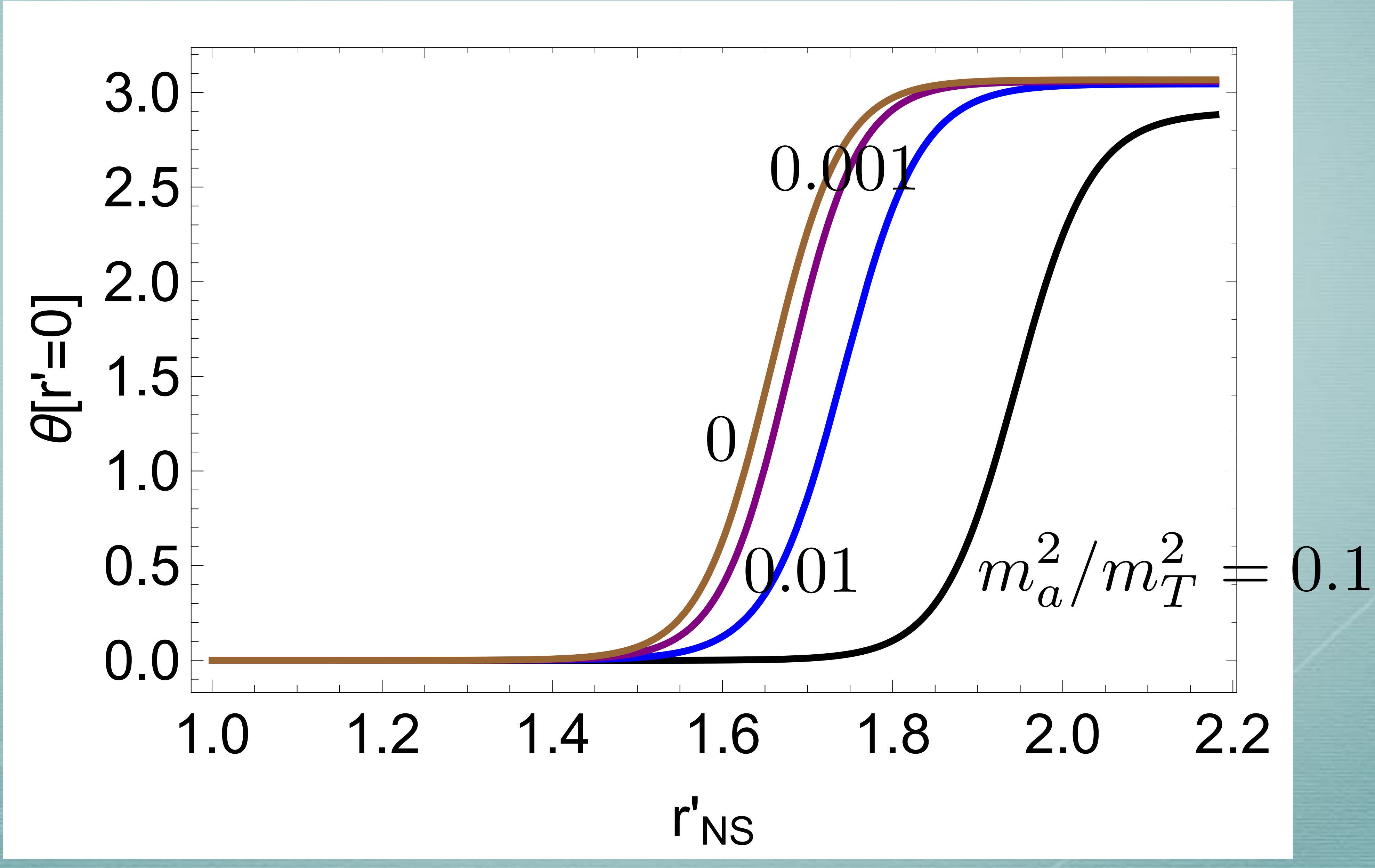
$$r_{\text{crit}} \gtrsim \frac{1}{m_T}$$

Neutron Stars as axion sources

$$r_{\text{crit}} \gtrsim \frac{1}{m_T}$$

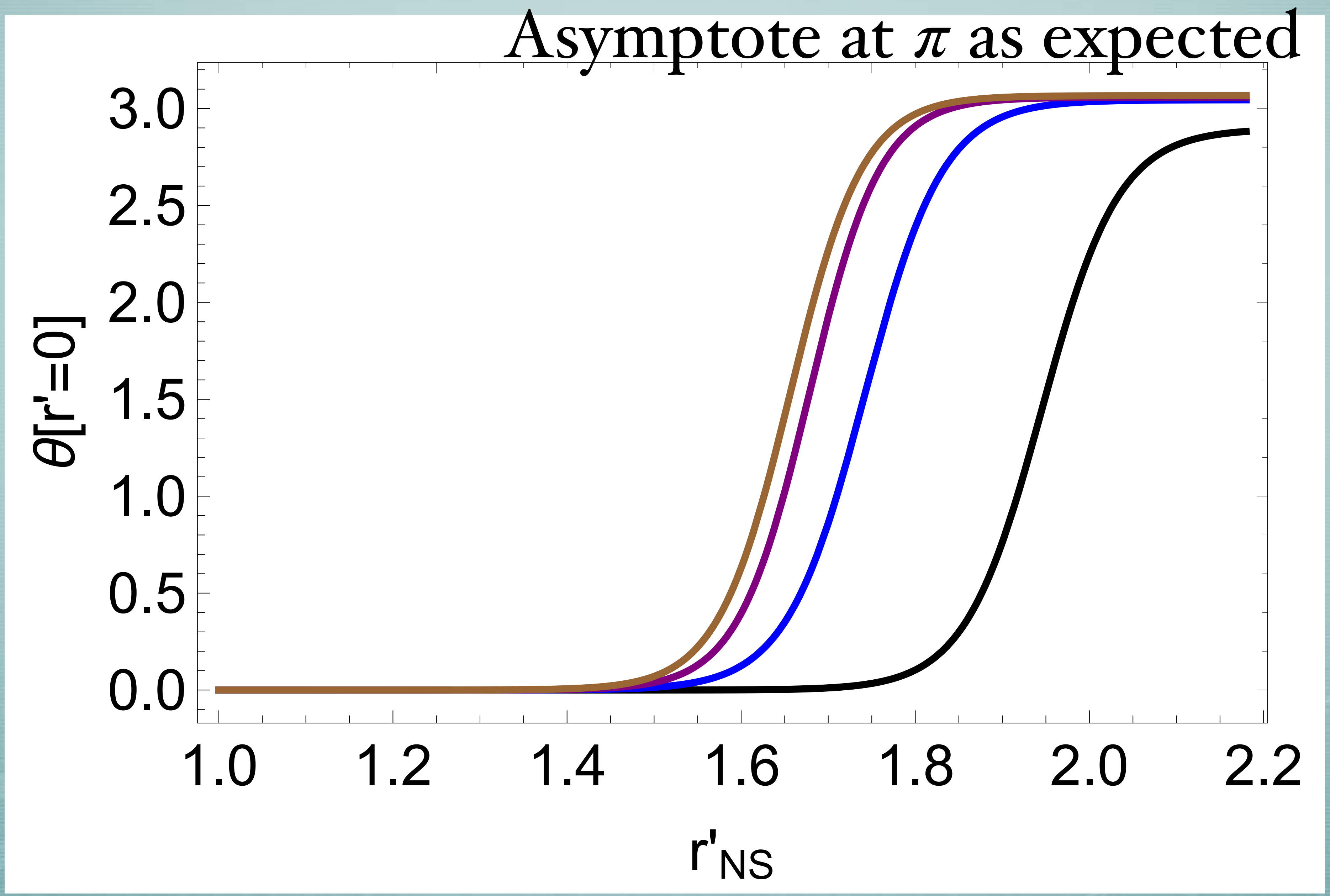
- Both neutron stars and nuclei are nuclear densities
- Only neutron stars large enough to source the axion
- Nuclei too small!
    - Fifth force constraints do not apply

Neutron Stars as axion sources



$r' = r\,m_T$

Neutron Stars as axion sources



$$r' = r\, m_T$$

Axionic Force

- What happens when two objects that source the axion get close to each other? (Hint : the electron sources the electromagnetic field)

Axionic Force

- What happens when two objects that source the axion get close to each other? (Hint : the electron sources the electromagnetic field)
- There is a force!
- The axion mediates a force between neutron stars!

Axionic Force

$$a = q\frac{e^{-m_a r}}{4\pi r}$$

- Because the axion has a field value about π inside of the neutron star

$$q \sim 4\pi^2 f_a r_{NS}$$

- At long distances, easy to show that the force is a standard Yukawa force

$$V = -q_1 q_2 e^{-m_a D}/4\pi D$$

Axionic Force

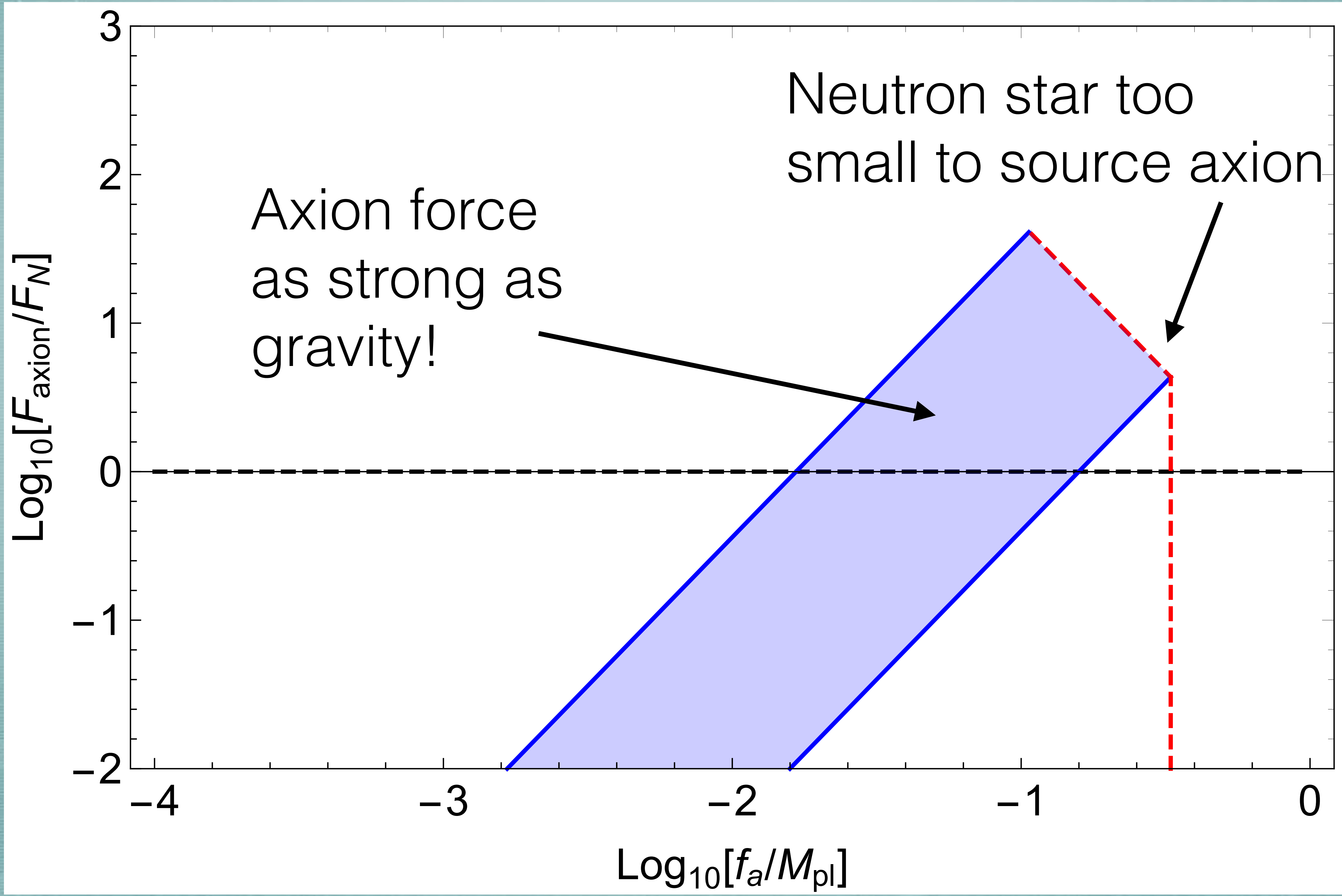
$$V = -q_1 q_2 e^{-m_a D}/4\pi D$$

- Attractive or Repulsive interaction

$$V = -m_\pi^2 f_\pi^2 (\epsilon - \frac{\sigma_N n_N}{m_\pi^2 f_\pi^2}) |\cos\left(\frac{a}{2f_a}\right)| + \mathcal{O}(\left(\frac{\sigma_N n_N}{m_\pi^2 f_\pi^2}\right)^2)$$

- Due to symmetry, for every solution (charge) there is a negative solution

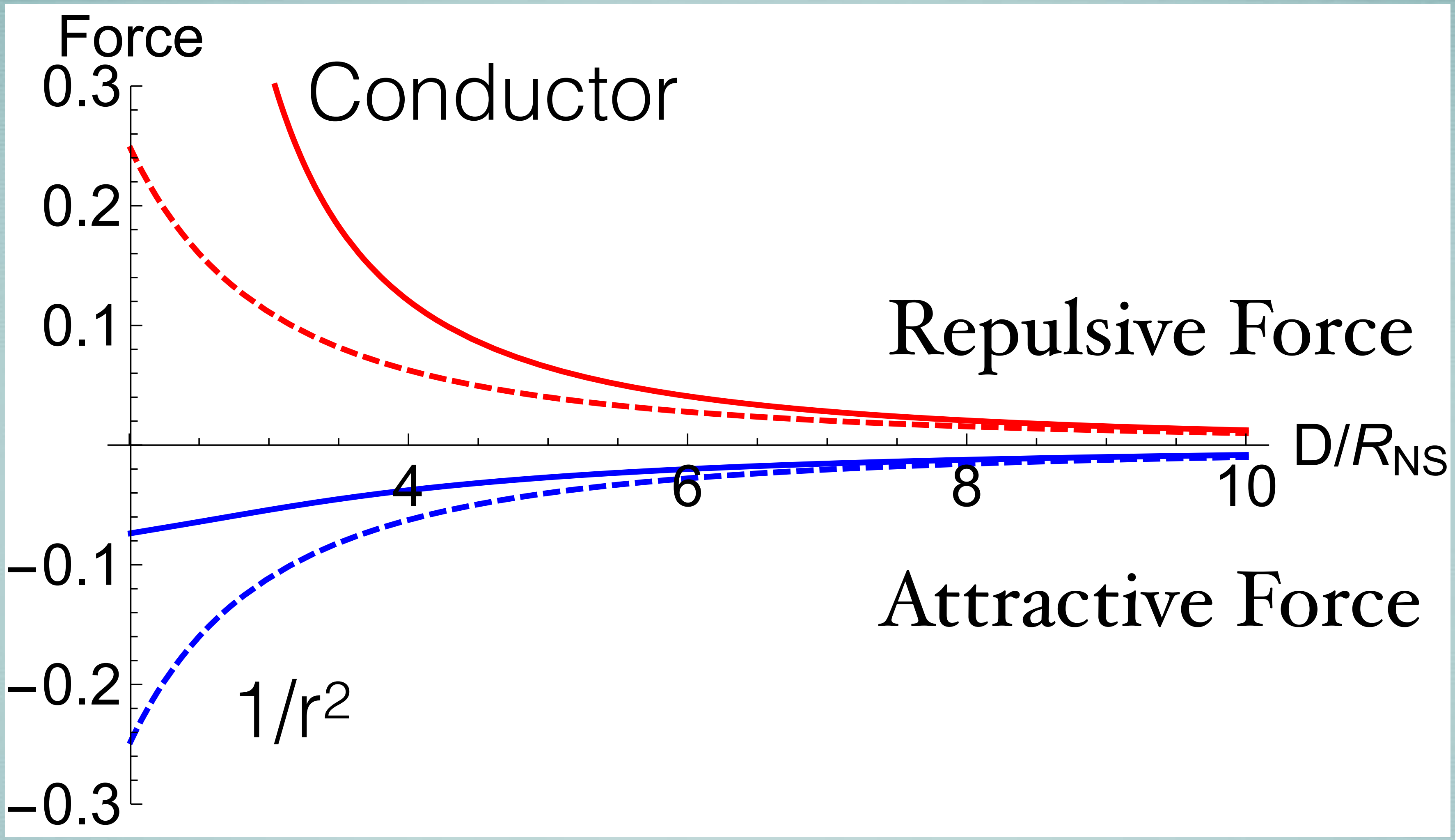
Axionic Force



Axionic Force

- Axion force is actually a boundary condition problem
  - In the limit where the tachyonic mass is infinite
- The axion is stuck to a particular value at the surface of the neutron star
- This is just like a conductor!
- The force between neutron stars can be calculated just like in E+M with a method of images

Axionic Force



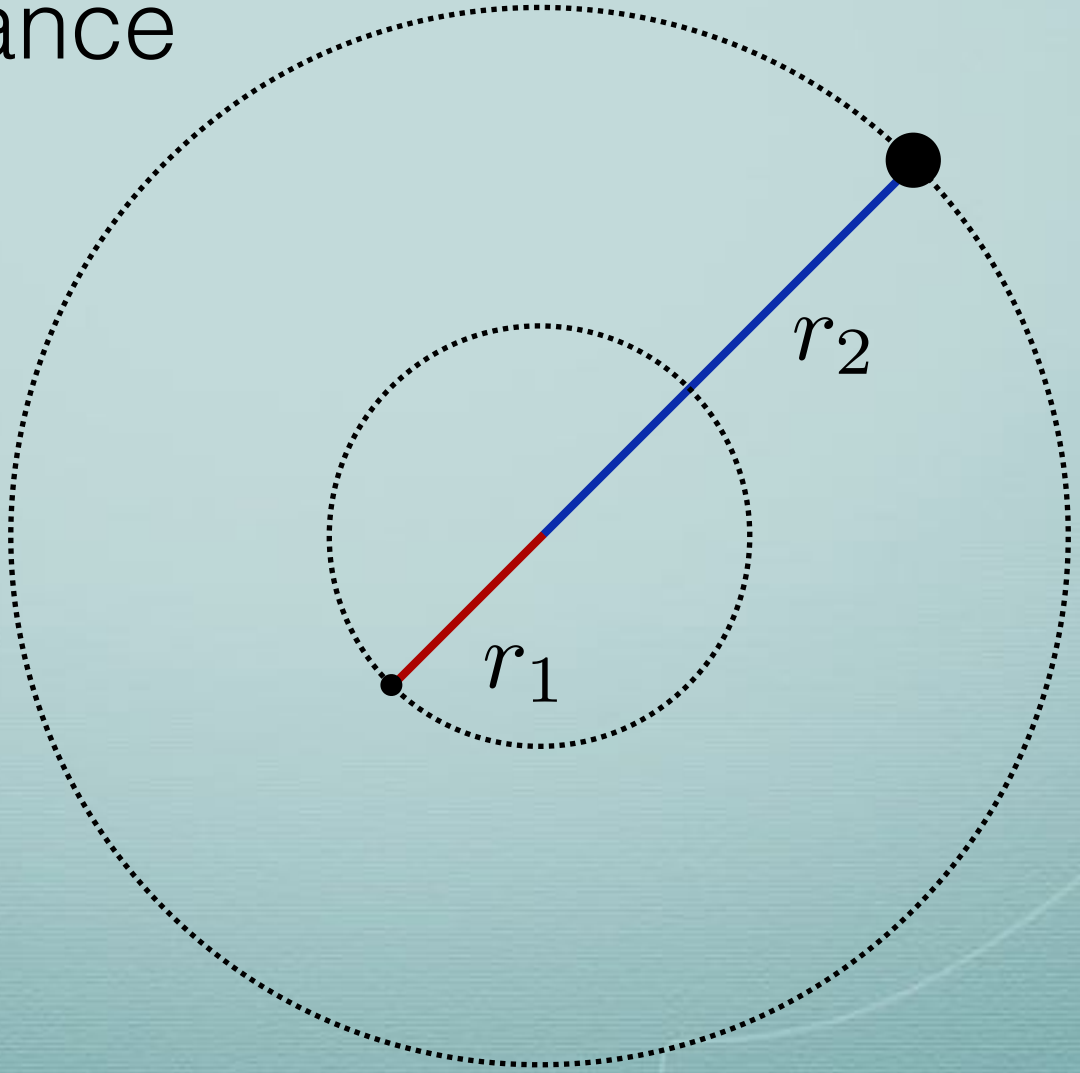
- Not a standard $1/r^2$ force at short distances
- Attractive force weaker
- Repulsive force stronger

LIGO implications

- LIGO has seen merging neutron stars
- What sort of implications will this have for neutron stars inspirals?
    - Mergers will need numerical simulations
- New force
    - At $r \sim 1/m$, the new force kicks in and increases or decreases the frequency
- New radiation
    - When frequency $\sim m$, new scalar Larmor radiation

Inspiral

- Inspiral can be calculated in a simple analytic way
- Assume instantaneously circular orbit with time dependent distance



Inspiral

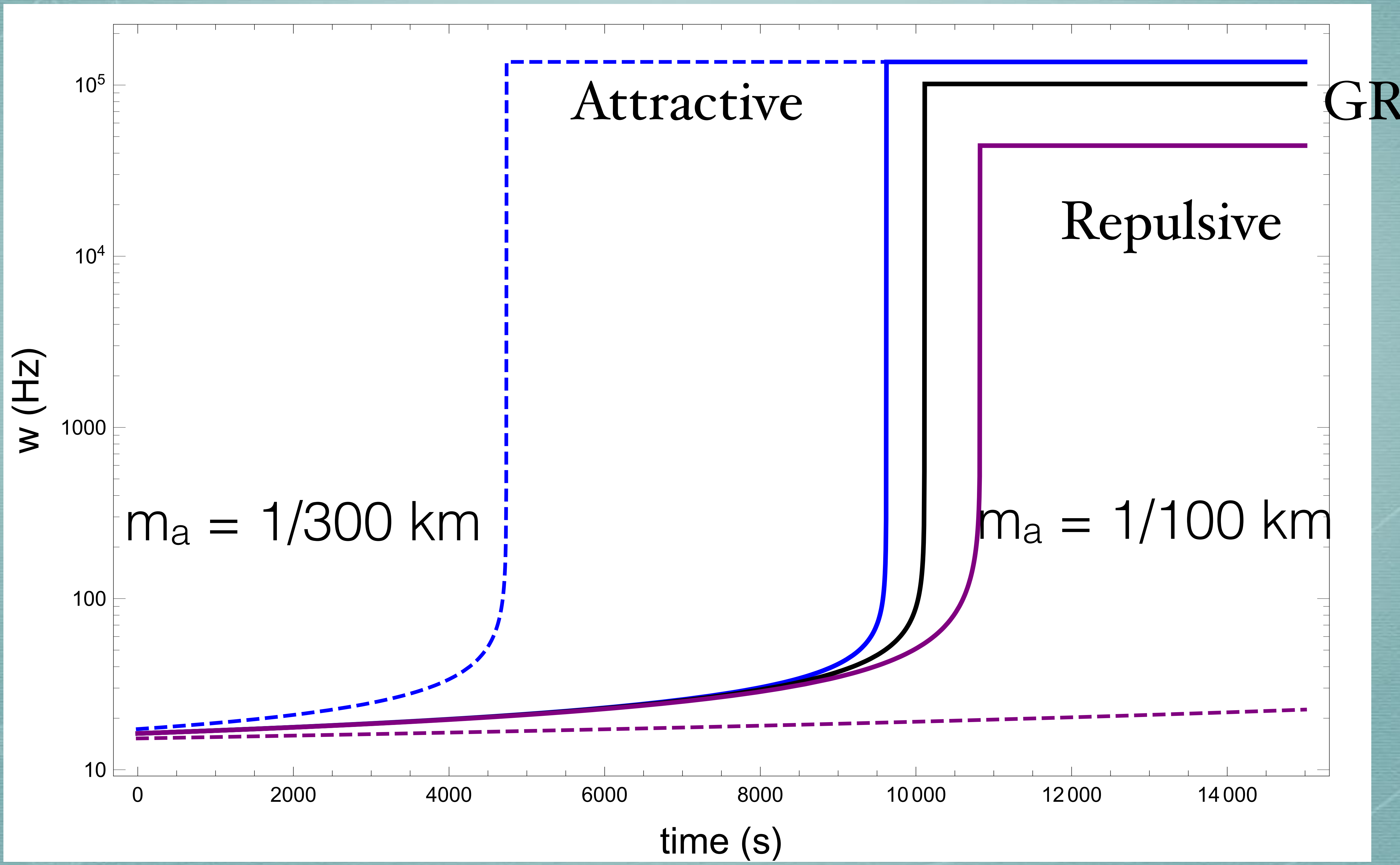
- Power emitted comes from gravitational quadrople radiation and scalar dipole radiation

$$\frac{dE}{dt} = -\frac{32}{5}G\mu^2 D^4\omega^6 - \frac{1}{4}\frac{\omega^4 p^2}{6\pi}(1 - \frac{m_a^2}{\omega^2})^{3/2}\Theta(\omega^2 - m_a^2)$$

$$p = q_1 r_1 - q_2 r_2$$

- Can calculate everything we want about the early inspiral phase from here

Inspiral - 80% gravity



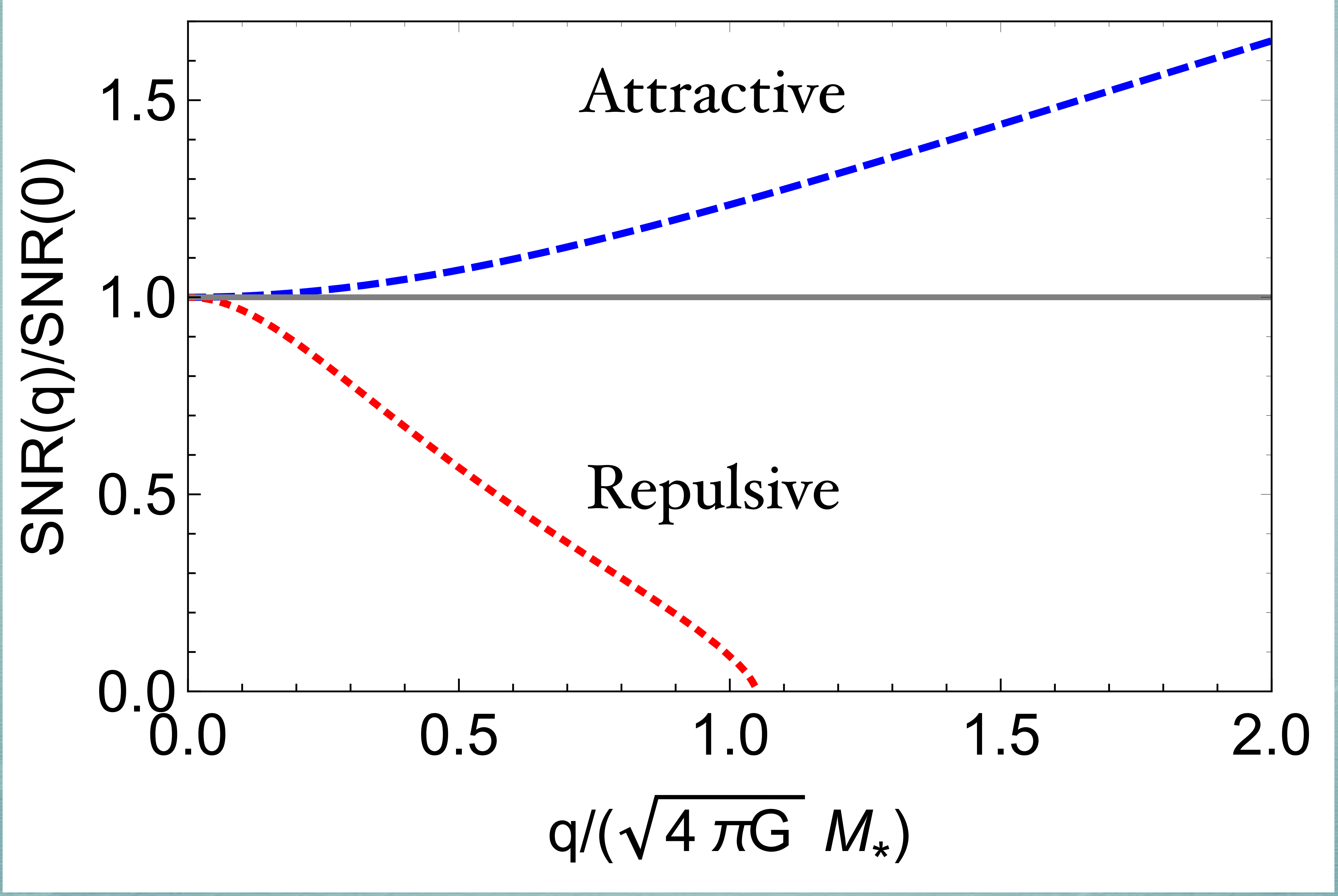
Inspiral

- Two major effects
- Quality factor
  - Increases : Repulsive Interactions
  - Decreases : Attractive Interactions
- Amplitude
  - Decreases : Repulsive Interactions
  - Decreases : Attractive Interactions

$$Q \sim \frac{w^2}{\dot{w}}$$

$$h_+(t) = \frac{4G\mu\omega^2 D^2}{r}\frac{1+\cos\theta_i}{2}\cos 2\omega t, \qquad h_\times(t) = \frac{4G\mu\omega^2 D^2}{r}\cos\theta_i \sin 2\omega t$$

Inspiral - Optimal Filter



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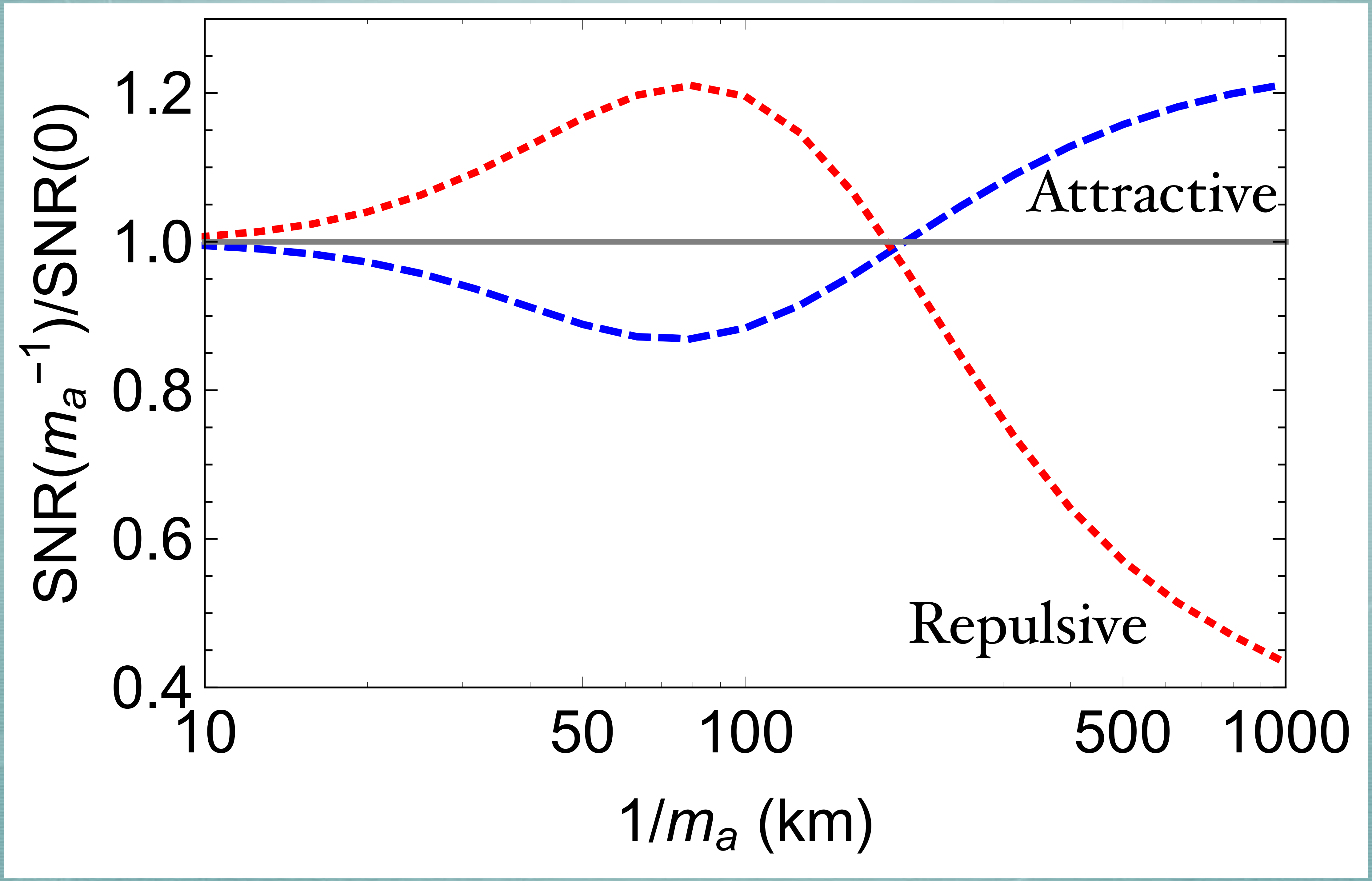
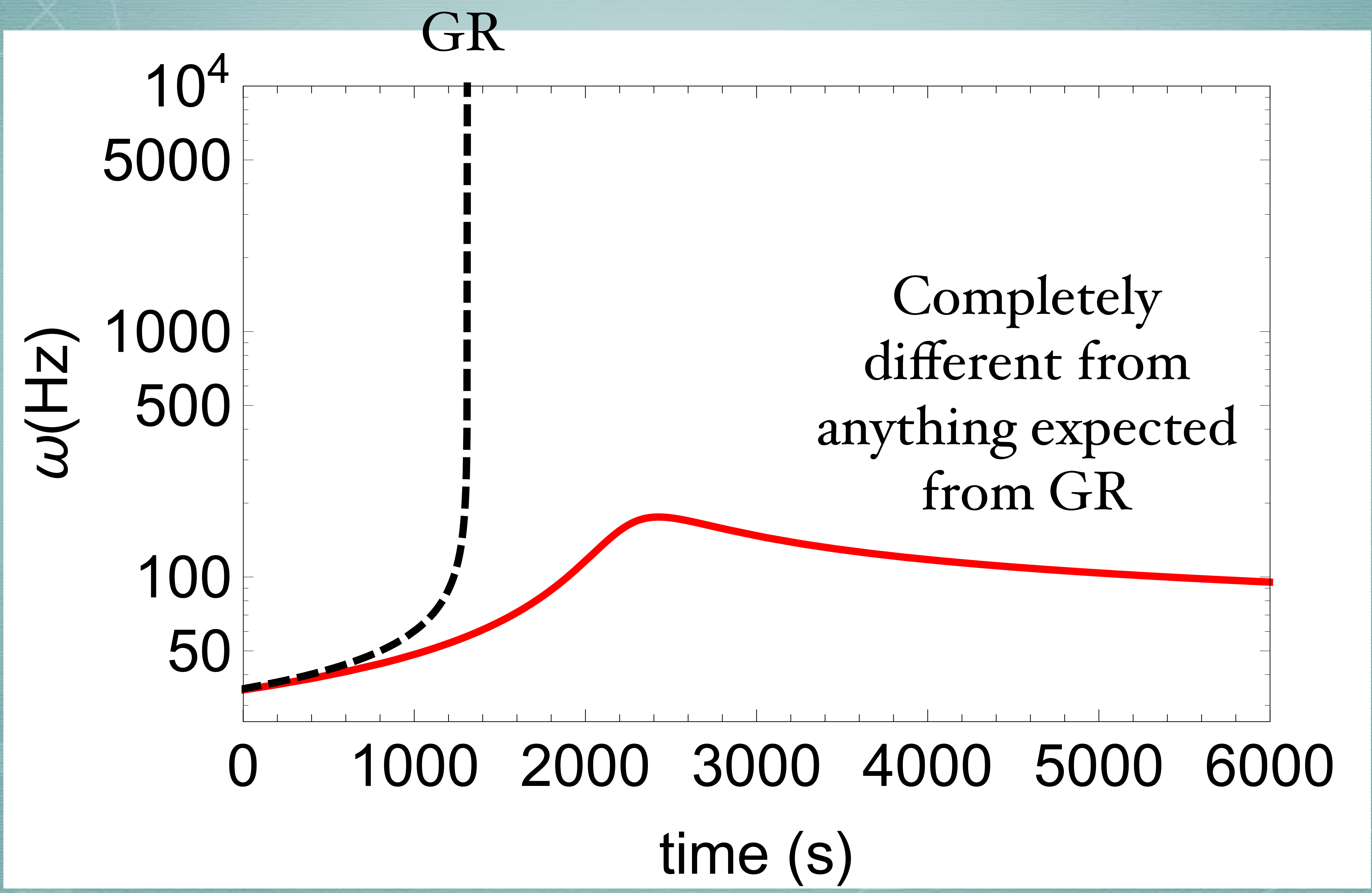


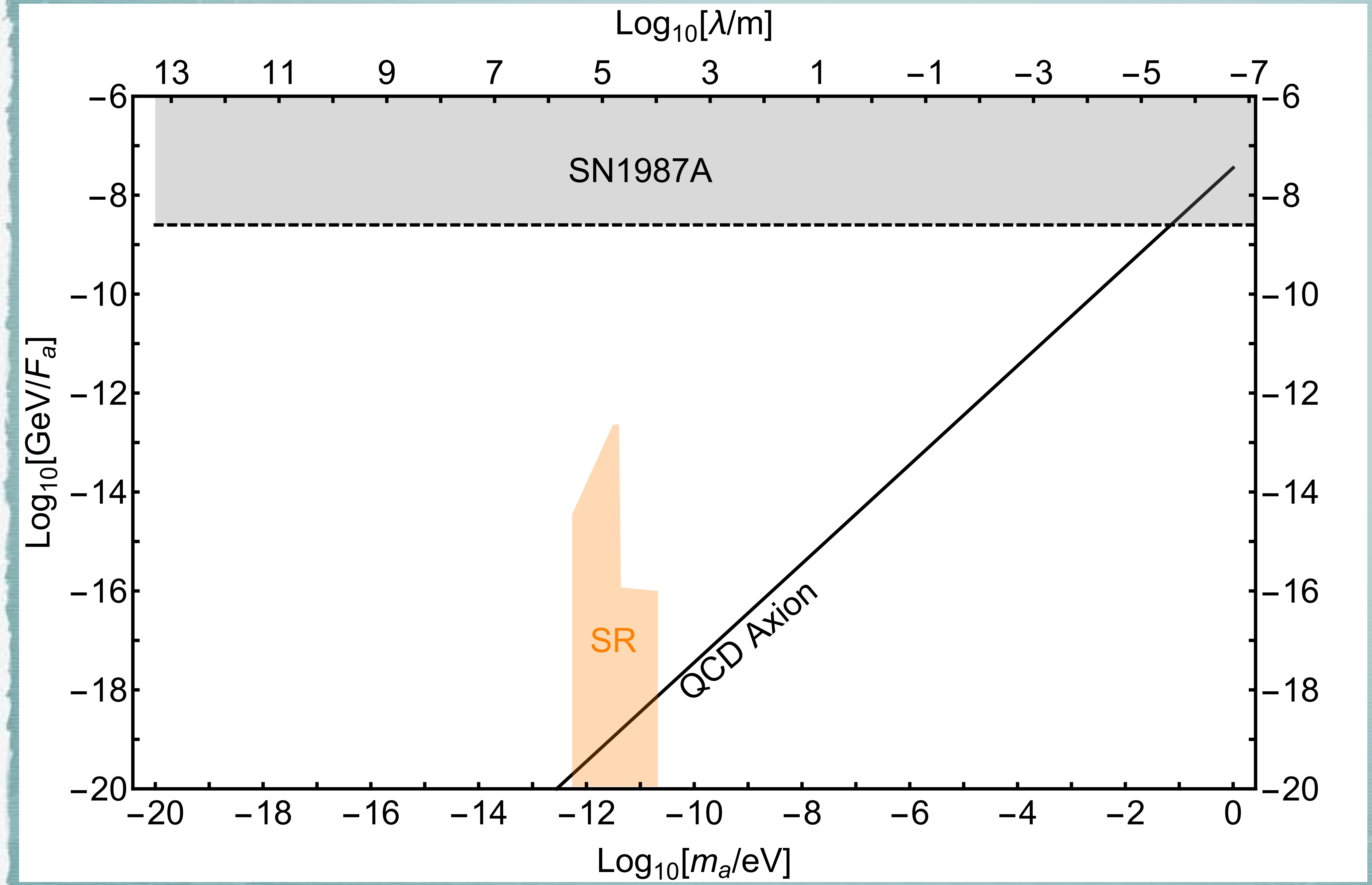
Inspiral - 110% gravity



Constraints

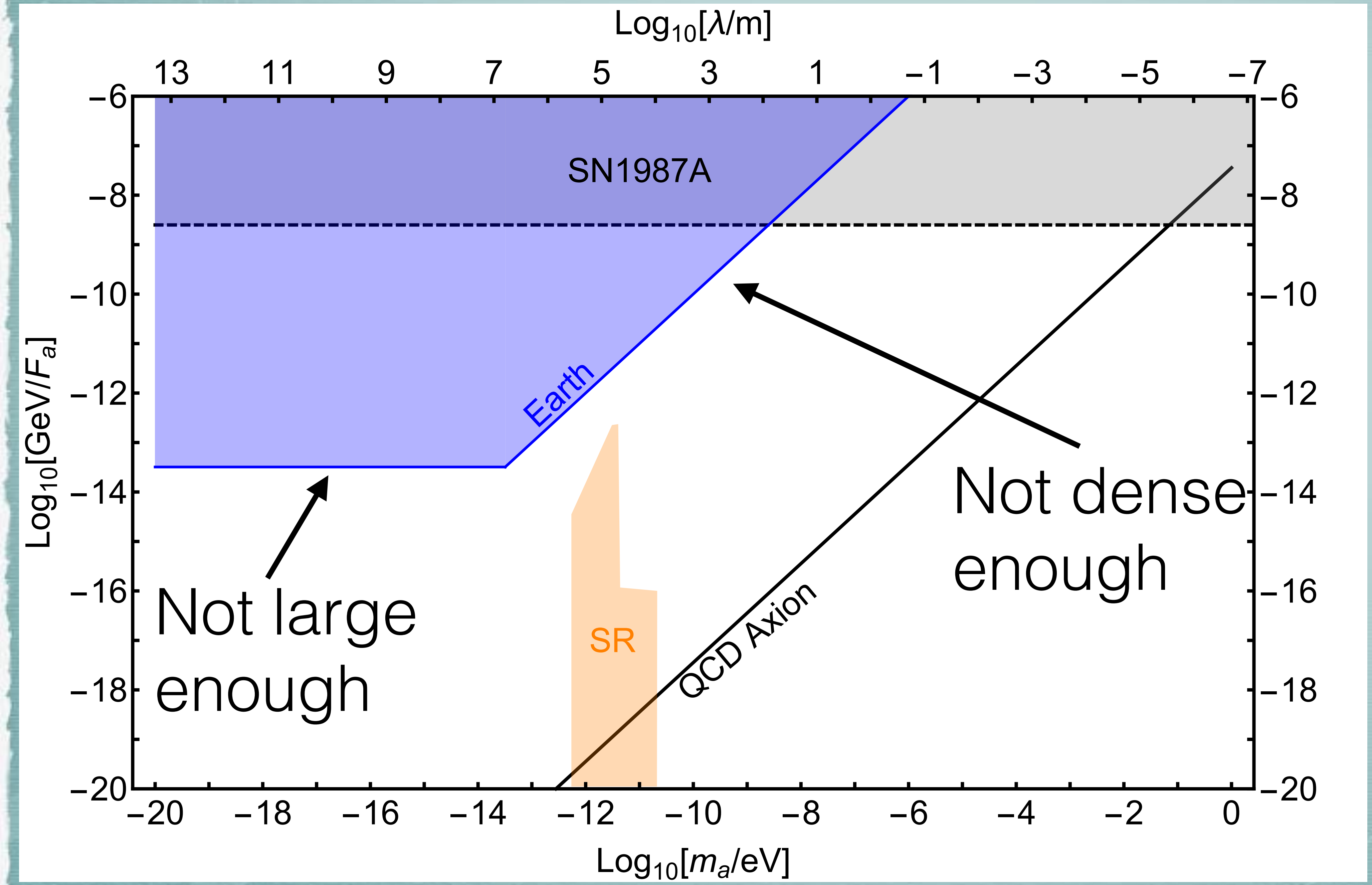
- As mentioned before objects can source the axion which leads to new constraints as theta angle is around π for these objects

Constraints



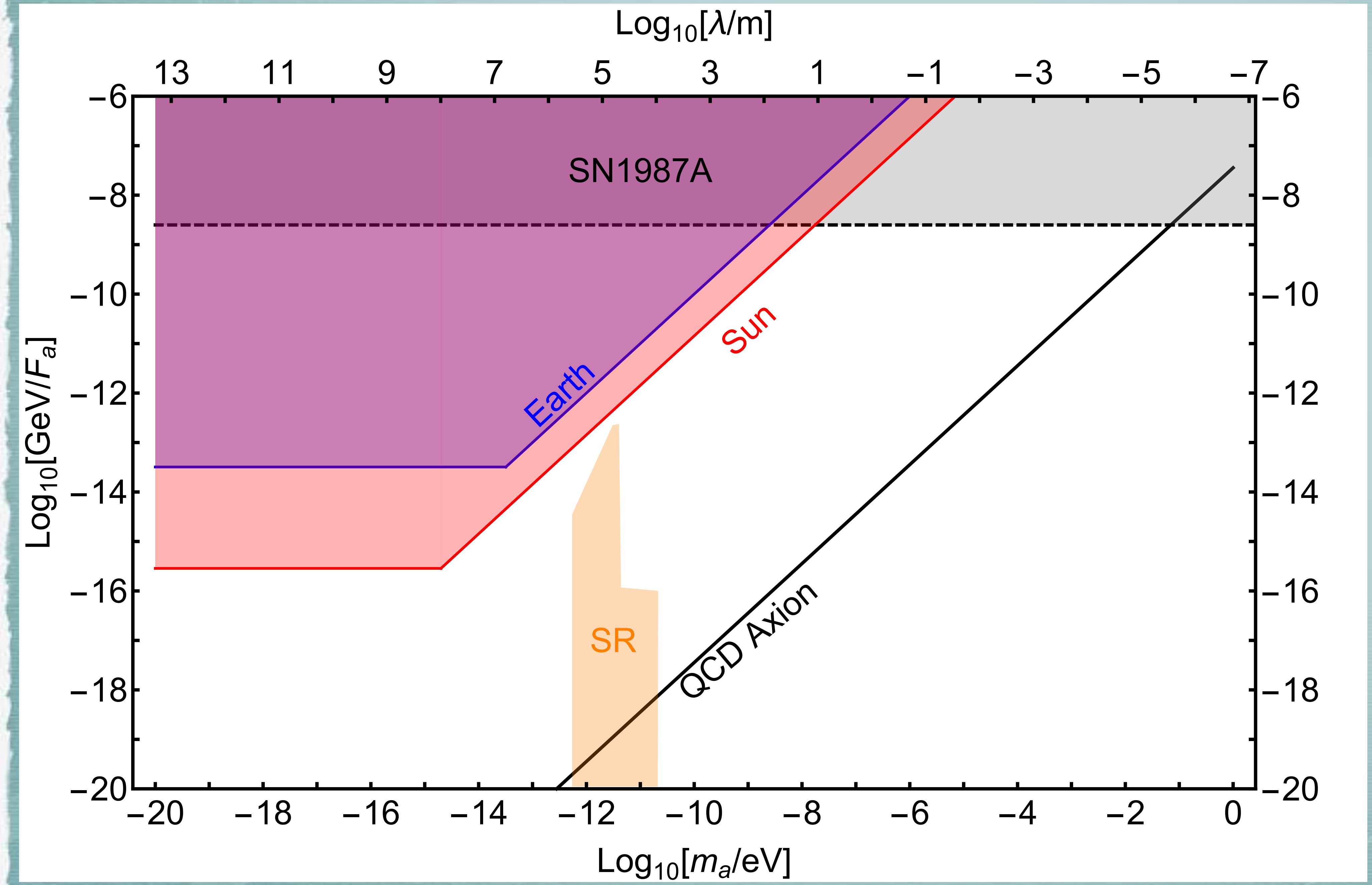
Super Radiance spin downs highly spinning black holes

Constraints



Theta on Earth measured to be very small

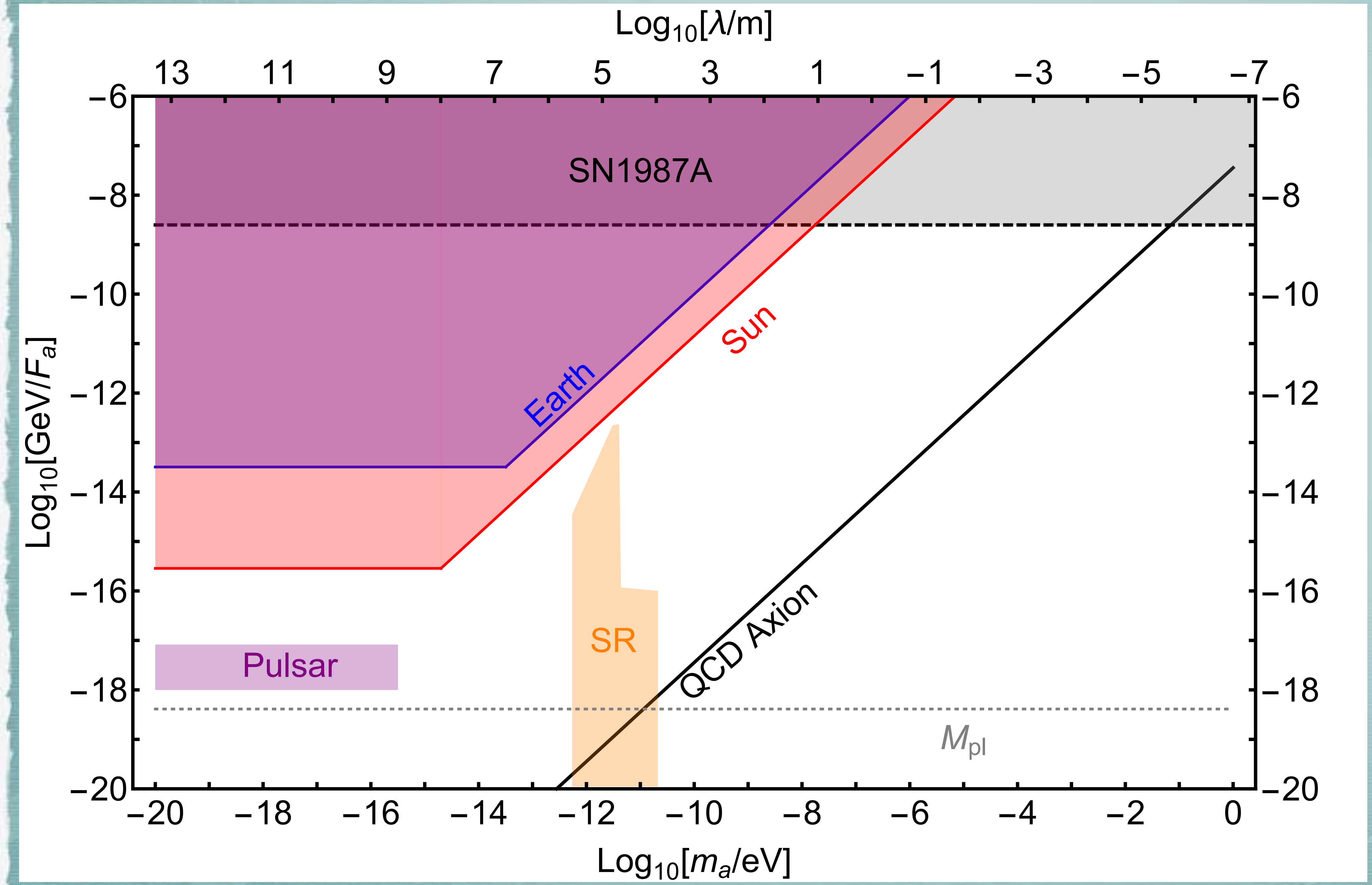
Constraints



Be^7-Li^7 862 keV neutrino line measured

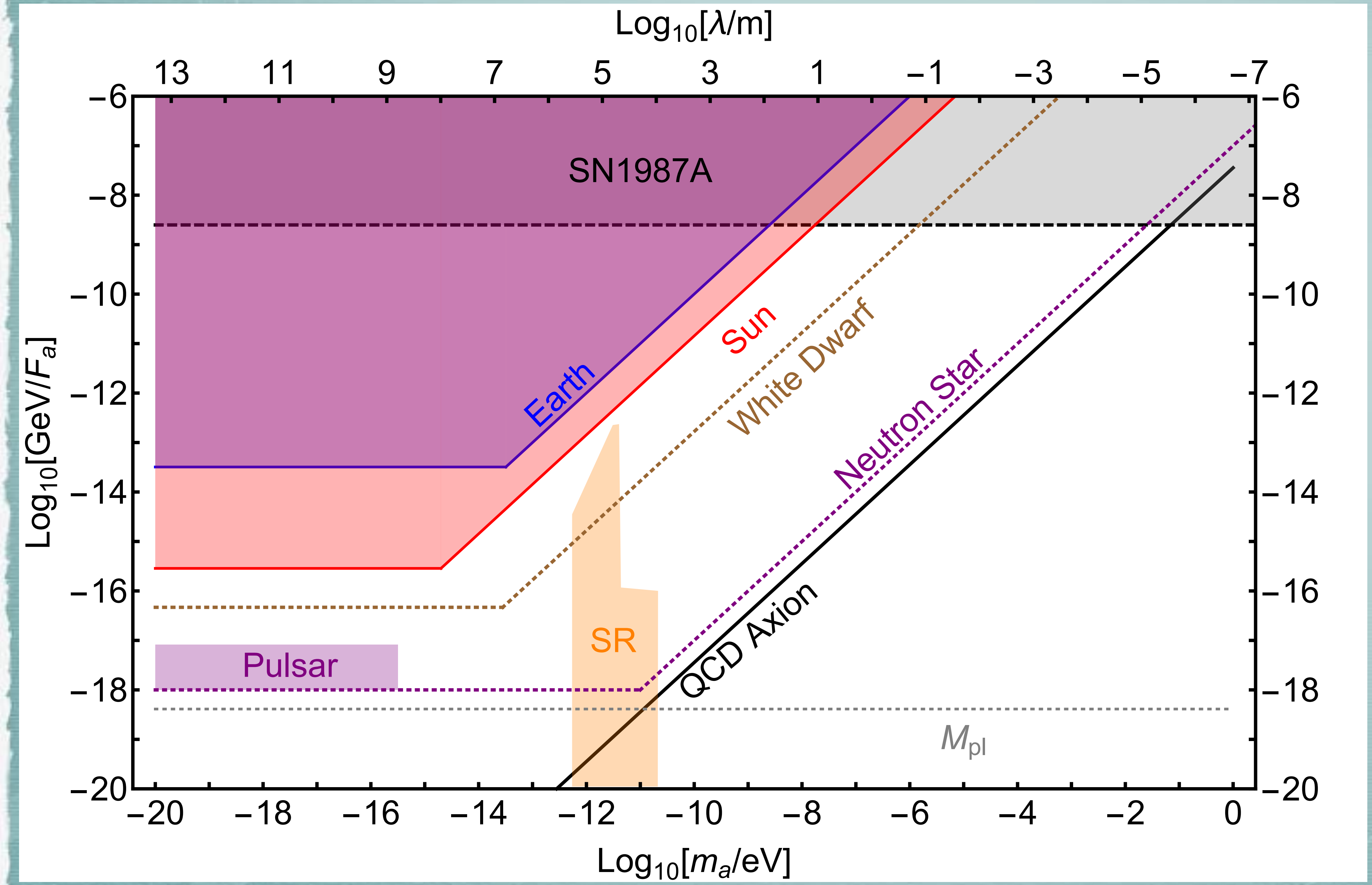
m_p-m_n changed by 10 MeV

Constraints



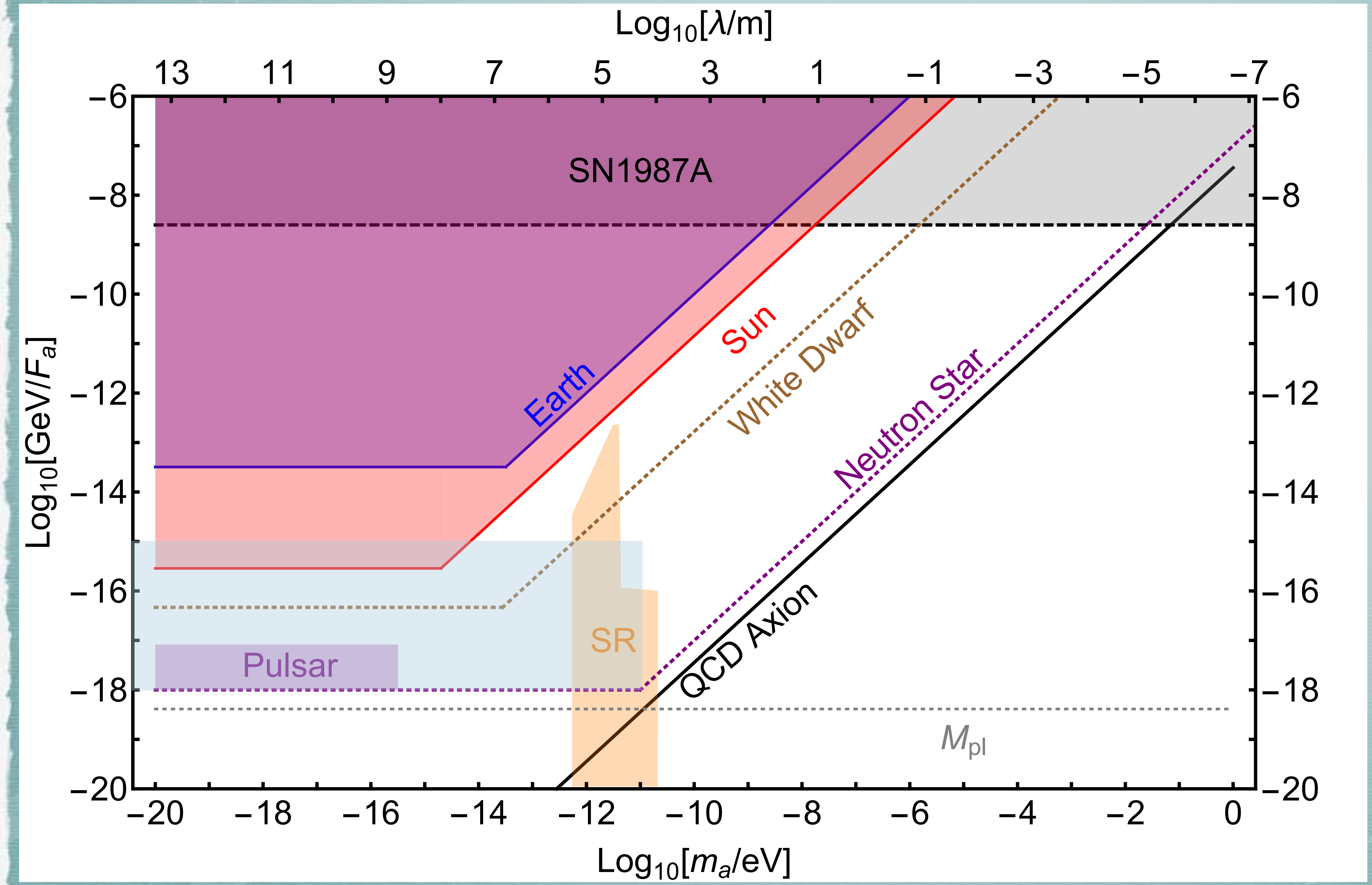
Hulse-Taylor and other binaries feel only GR at O(1)

Constraints



If we understood white dwarf/ neutron star nuclear emission lines at theta = π

Constraints



Very dependent on equation of state and masses but in principle can exclude

Conclusion

- Tuning is not always bad
- Tuned axions can
  - Mediate forces stronger than gravity between neutron stars while evading 5th force experiments
  - Attractive or repulsive of force
  - Distance scale of force is naturally 10-100 km
  - Not necessarily a $1/r^2$ force

Conclusion

- To Do : Numerical Simulations!
  - To see that force is not $1/r^2$, neutron stars need to be very close
  - Interactions between neutron stars will change boundary condition
  - To see effect on late inspiral/merger
  - Effect of equation of state
  - What happens for a non tuned axion
  - …