The parameter space of ultra-light axions

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Based on:

LV, Baum, Redondo, Freese, Wilczek, PLB **777**, 64 (2018)

LV, Phys. Rev. D **96**, 023 (2017)

LV & P. Gondolo, PRL **113**, 011802 (2014)

LV & P. Gondolo, PRD **81**, 063508 (2010)

LV & P. Gondolo, PRD **80**, 035024 (2009)

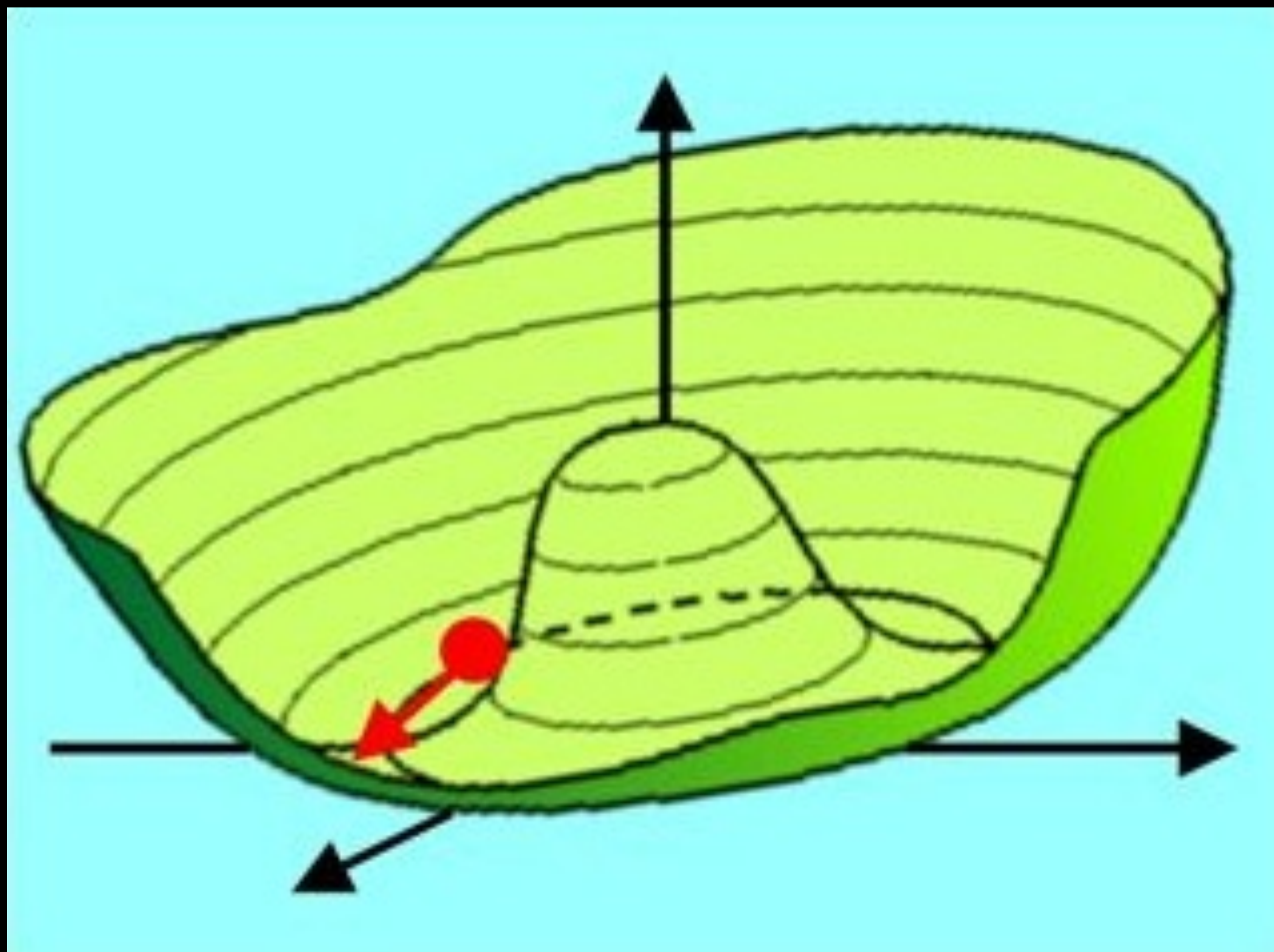
Sources of CP violation in the SM

- Complex phases in the CKM and PMNS matrices
- Violation within the QCD sector through:

$$\mathcal{L}_{\rm strong,CP} = \bar{\theta}\frac{\alpha_s}{2\pi}{\rm Tr}\left({\rm E}^\mu {\rm B}_\mu\right)$$

- A similar term arises from EW with $\theta_{\rm weak} = \arg\left({\rm Det}\, M\right)$
- $\theta = \bar{\theta} + \theta_{\rm weak}$ which is potentially $\mathcal{O}\left(1\right)$
- Strong CP problem (QCD does not violate CP) with $|\theta| \lesssim 10^{-10}$ (measured electric dipole of the neutron)

Axion coherent oscillations



$$\Phi_{\rm PQ} = \rho\, e^{i\theta}$$

$$\langle \rho \rangle \approx f_a$$

~ One parameter theory

$$\theta(t,x) = a(t,x)/f_a$$

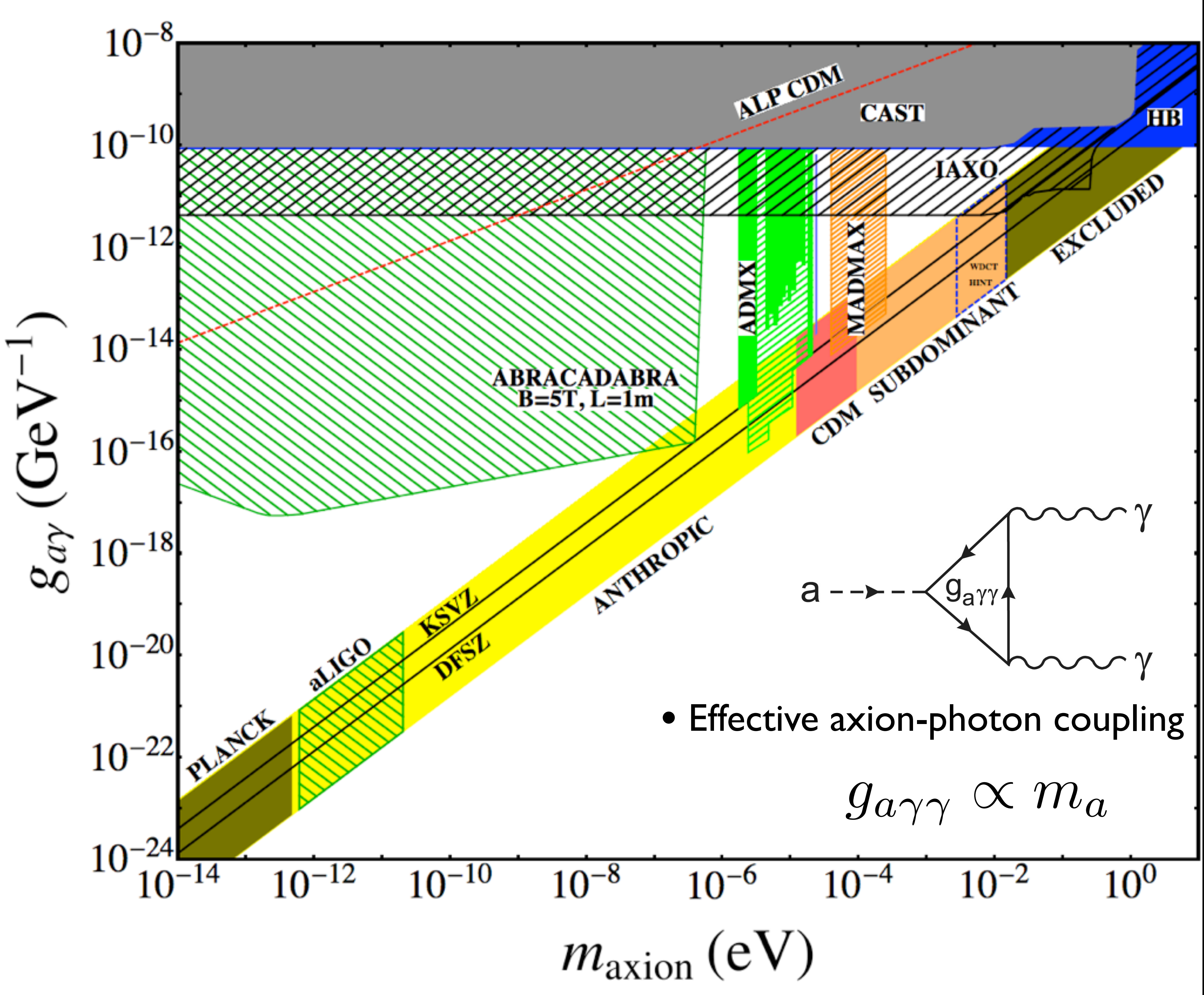
axion mass

$$m_a = 6\,{\rm meV}\,\frac{10^9\,{\rm GeV}}{f_a}$$

$$m_a\, f_a \propto \Lambda_{\rm QCD}^2$$

PQ "Mexican hat" potential, tilted by QCD effects

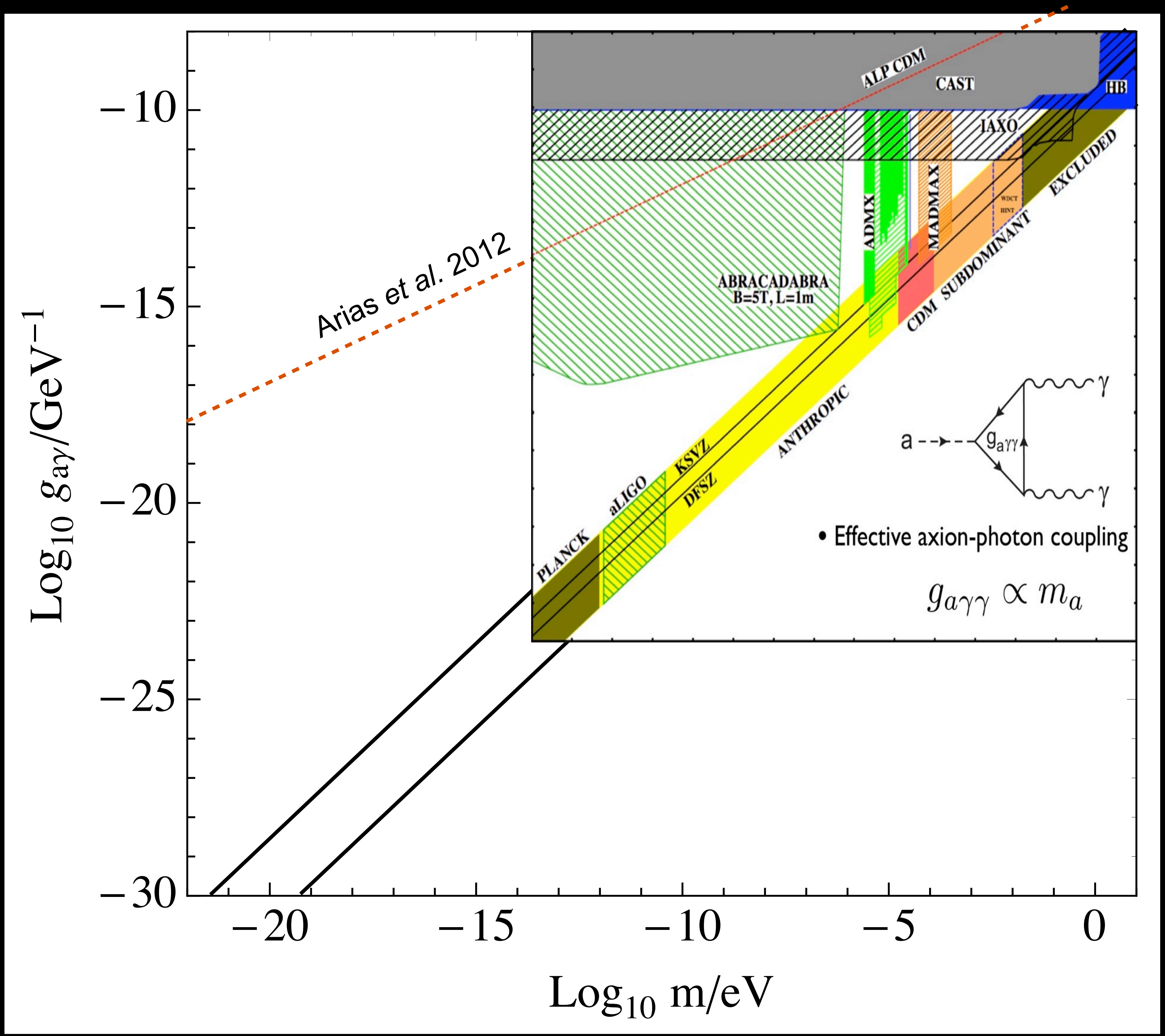
Axion searches



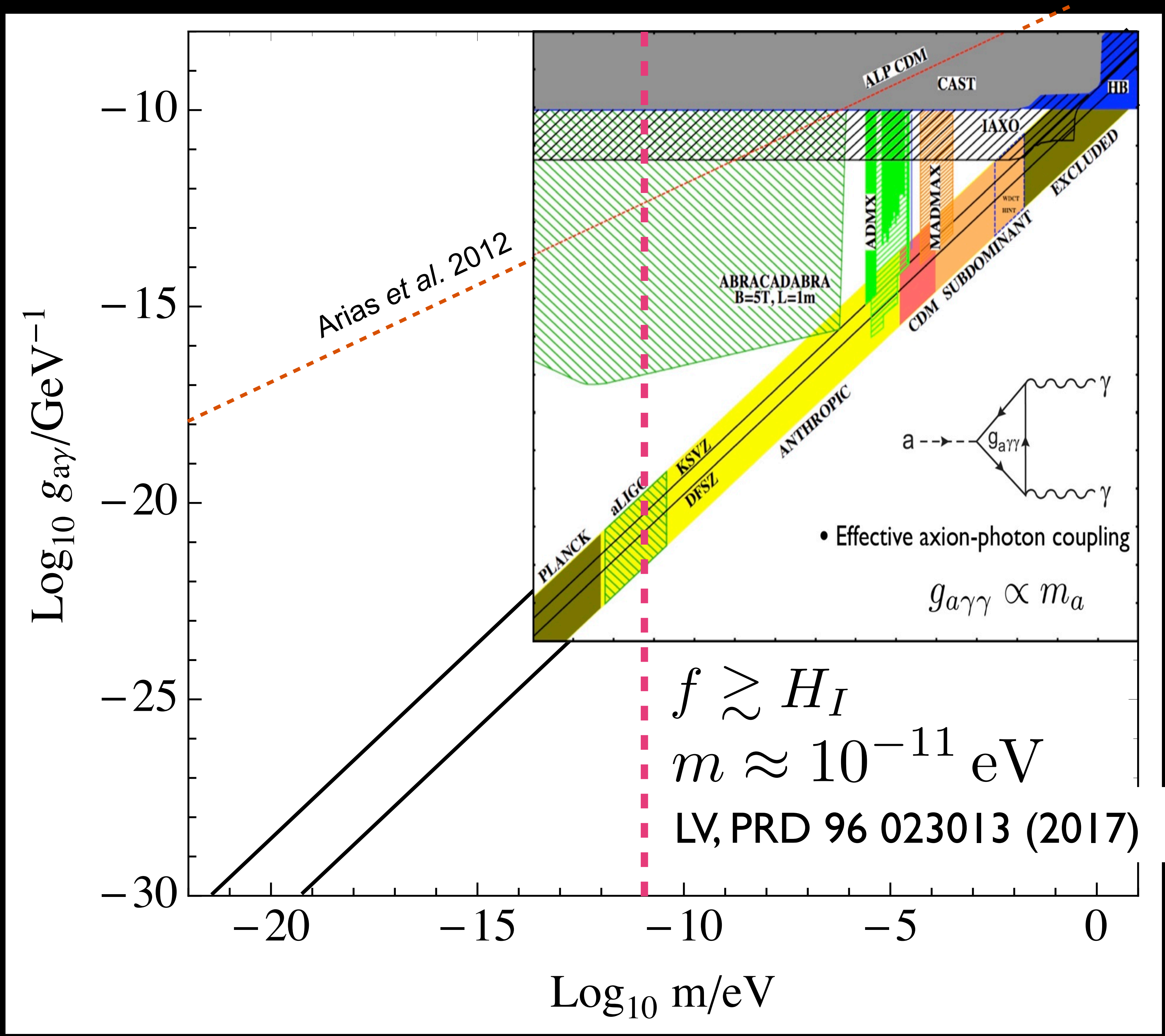
- Effective axion-photon coupling

$$g_{a\gamma\gamma} \propto m_a$$

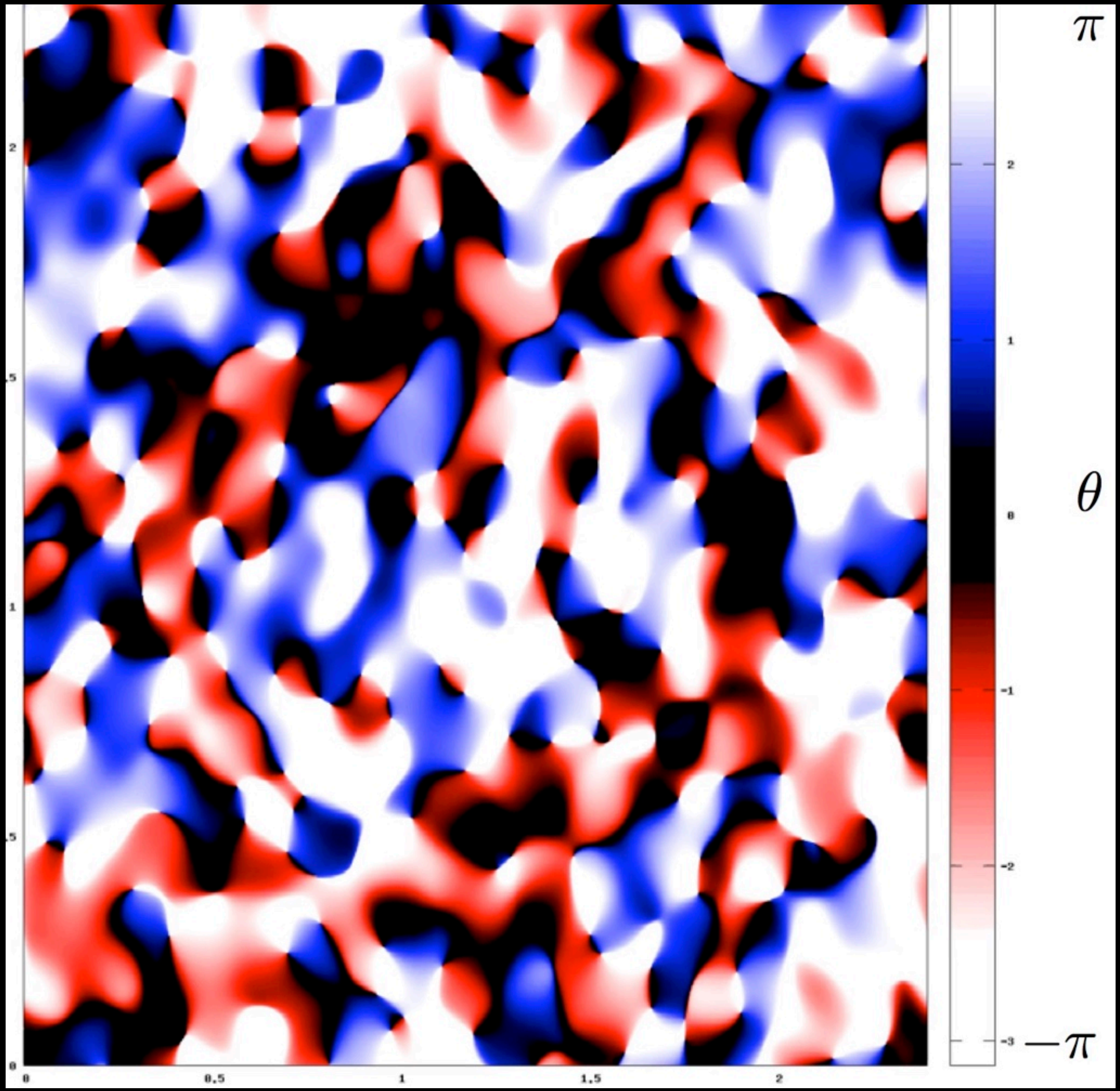
Axion parameter space



Axion parameter space



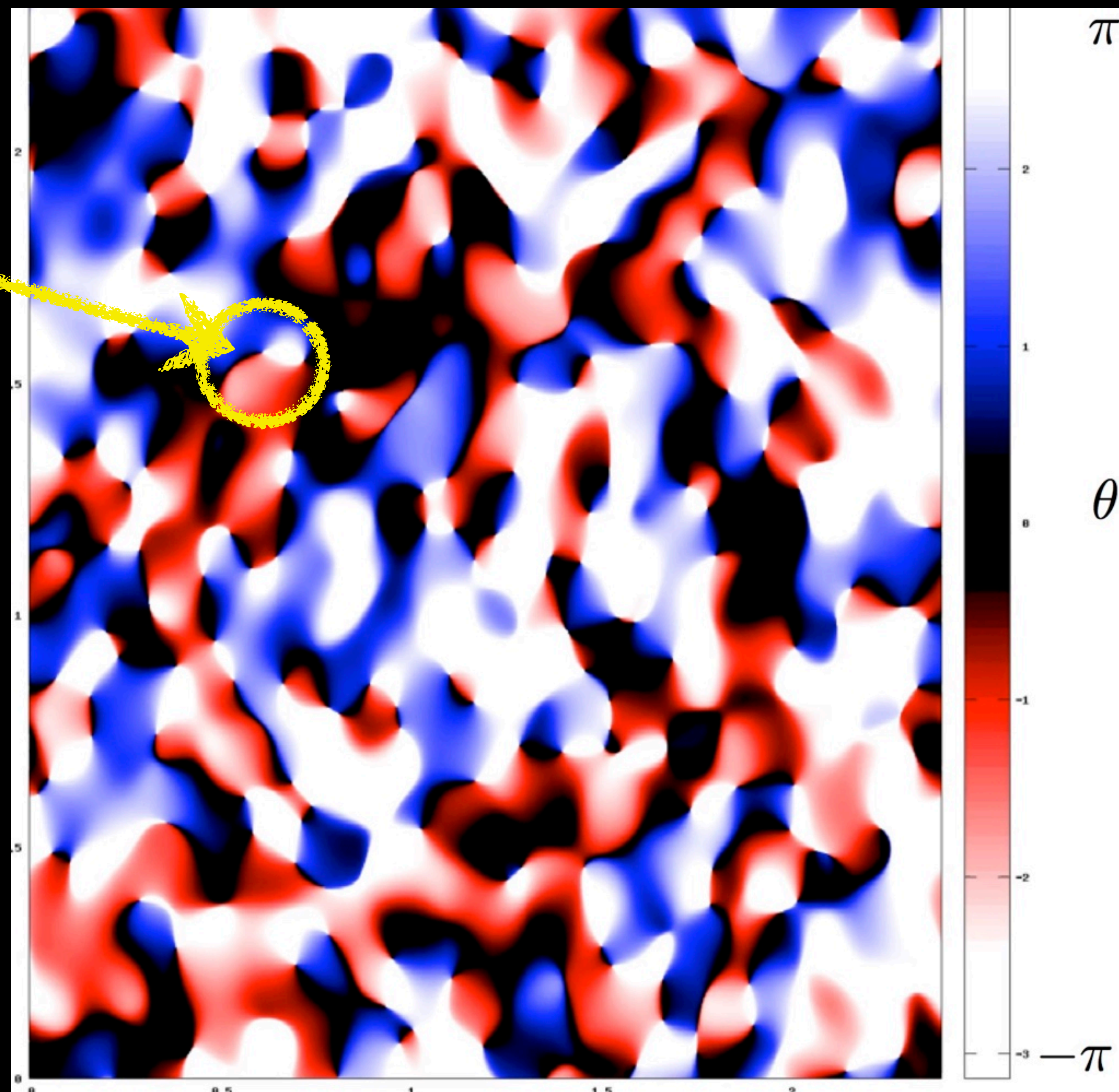
Scenario A: PQ breaks after inflation



Courtesy of J. Redondo

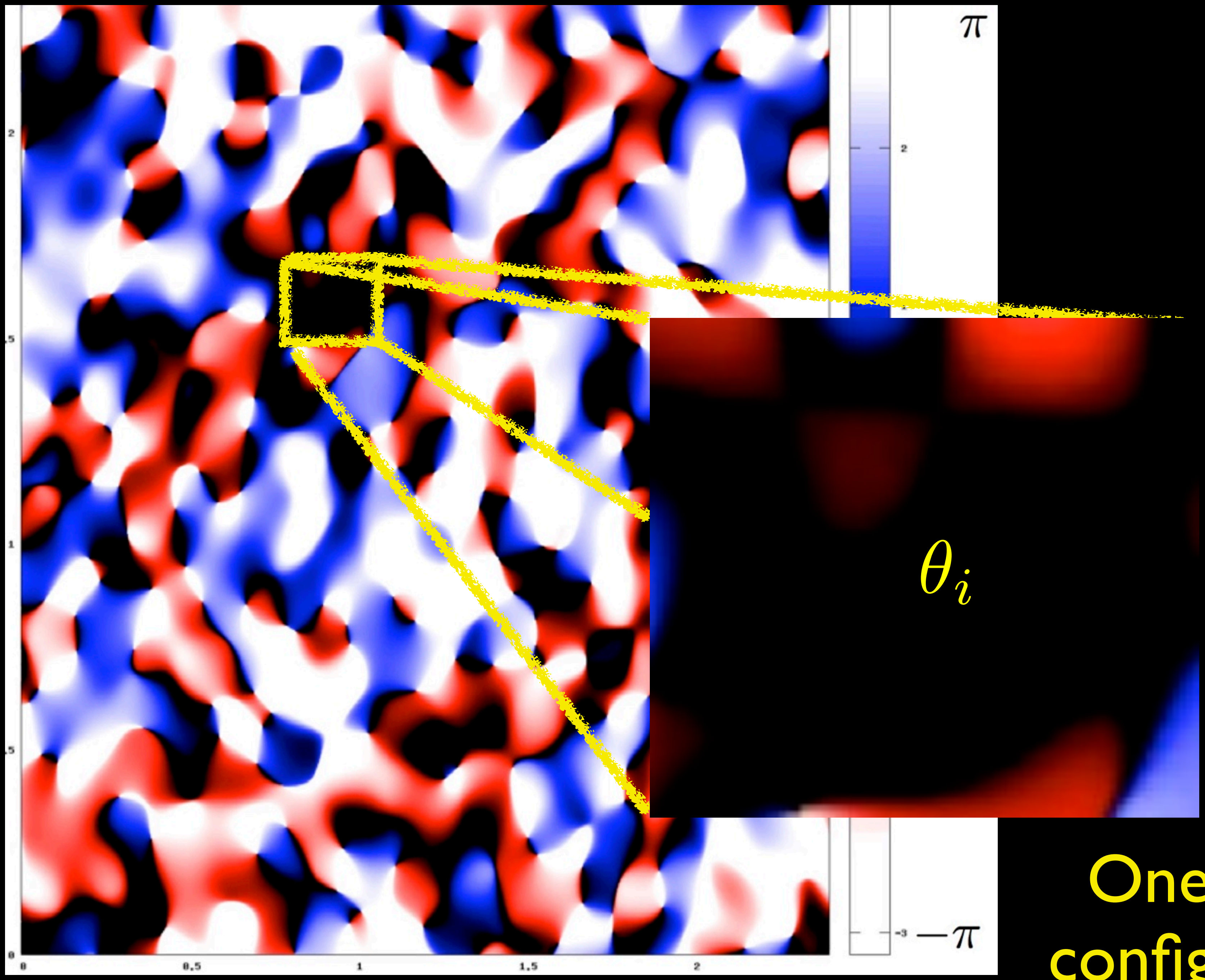
Scenario A: PQ breaks after inflation

Axion strings!



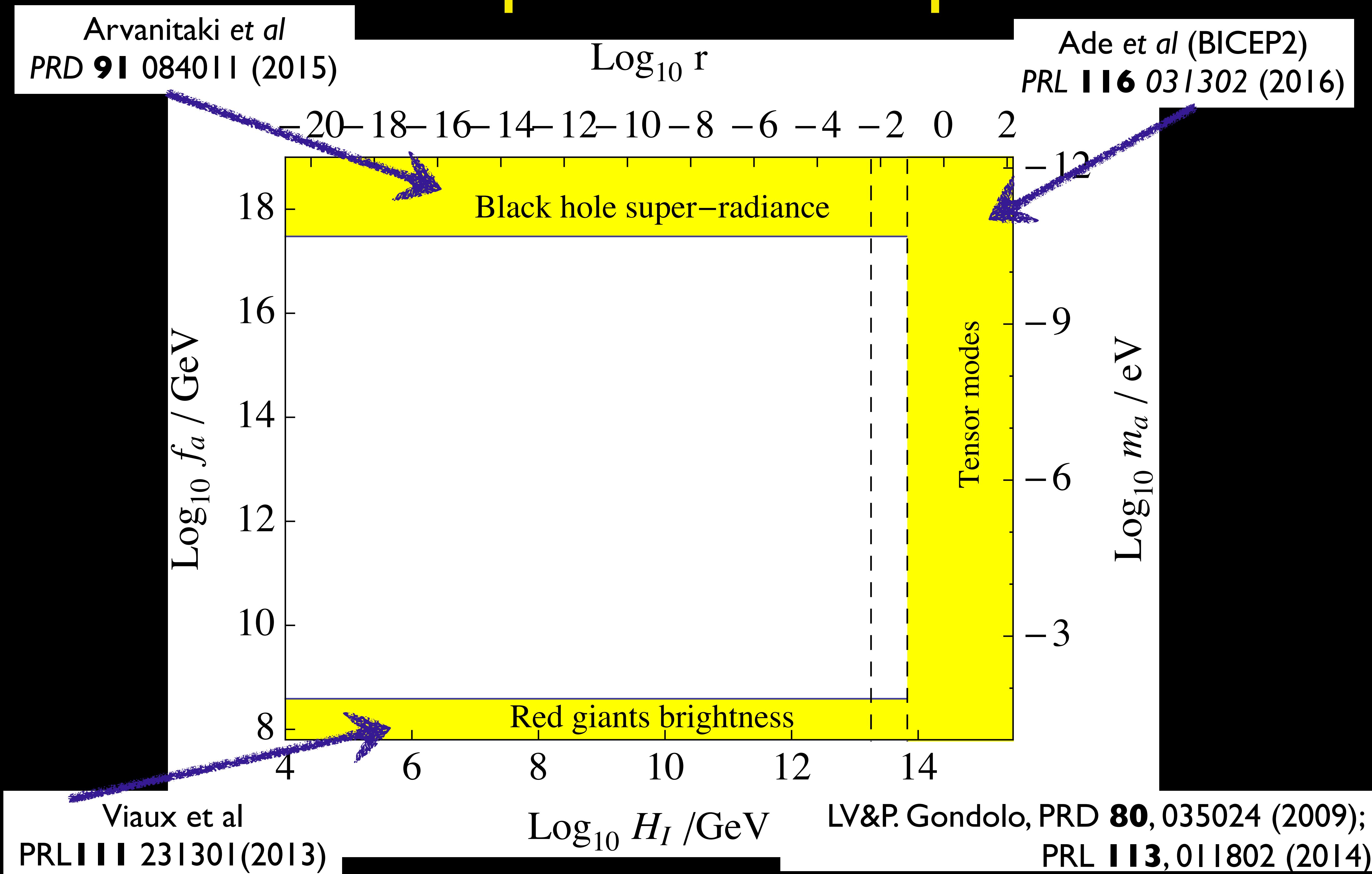
CDM axions also from defects...

Scenario B: PQ breaks during inflation

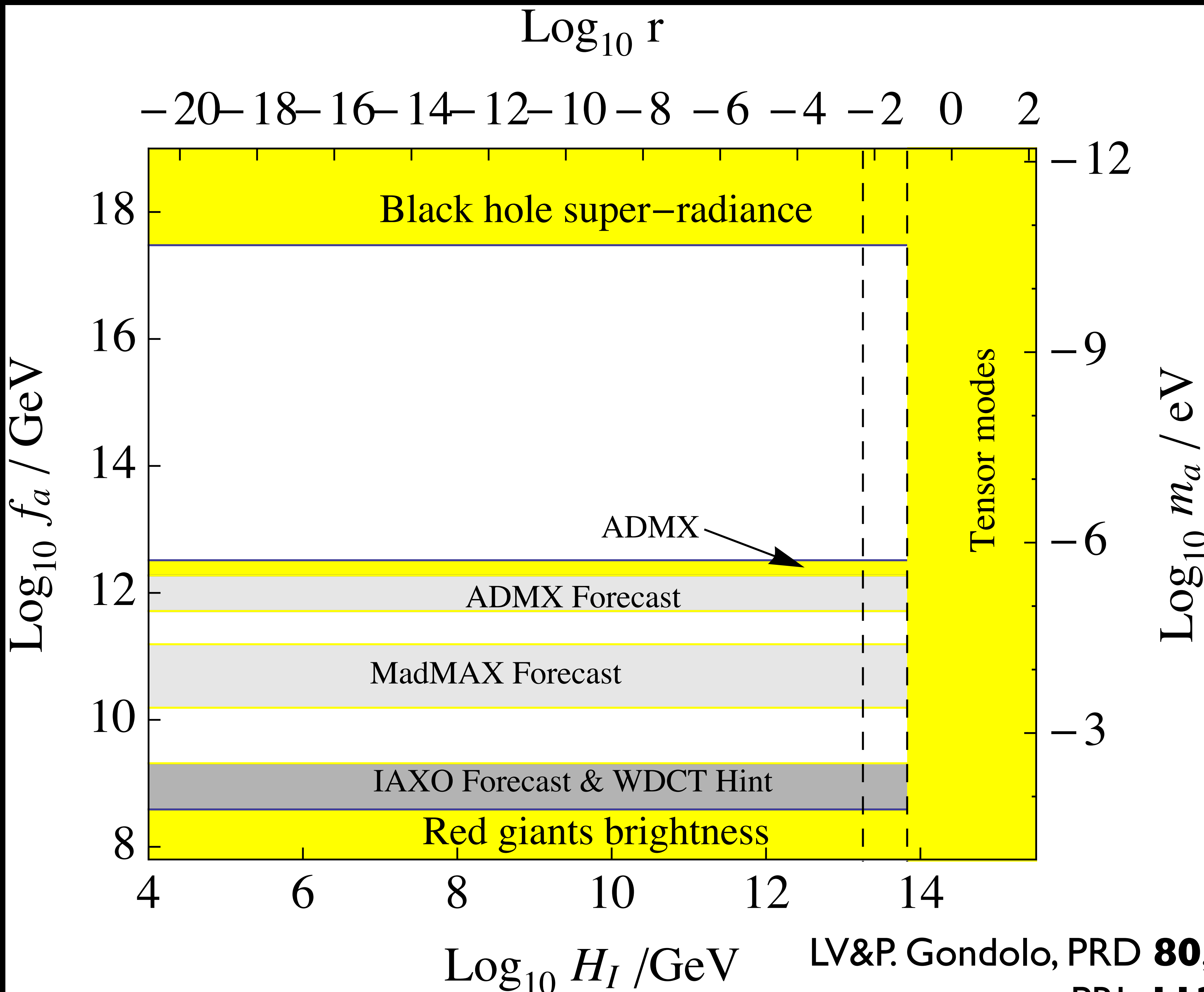


One initial configuration is singled out

Axion parameter space

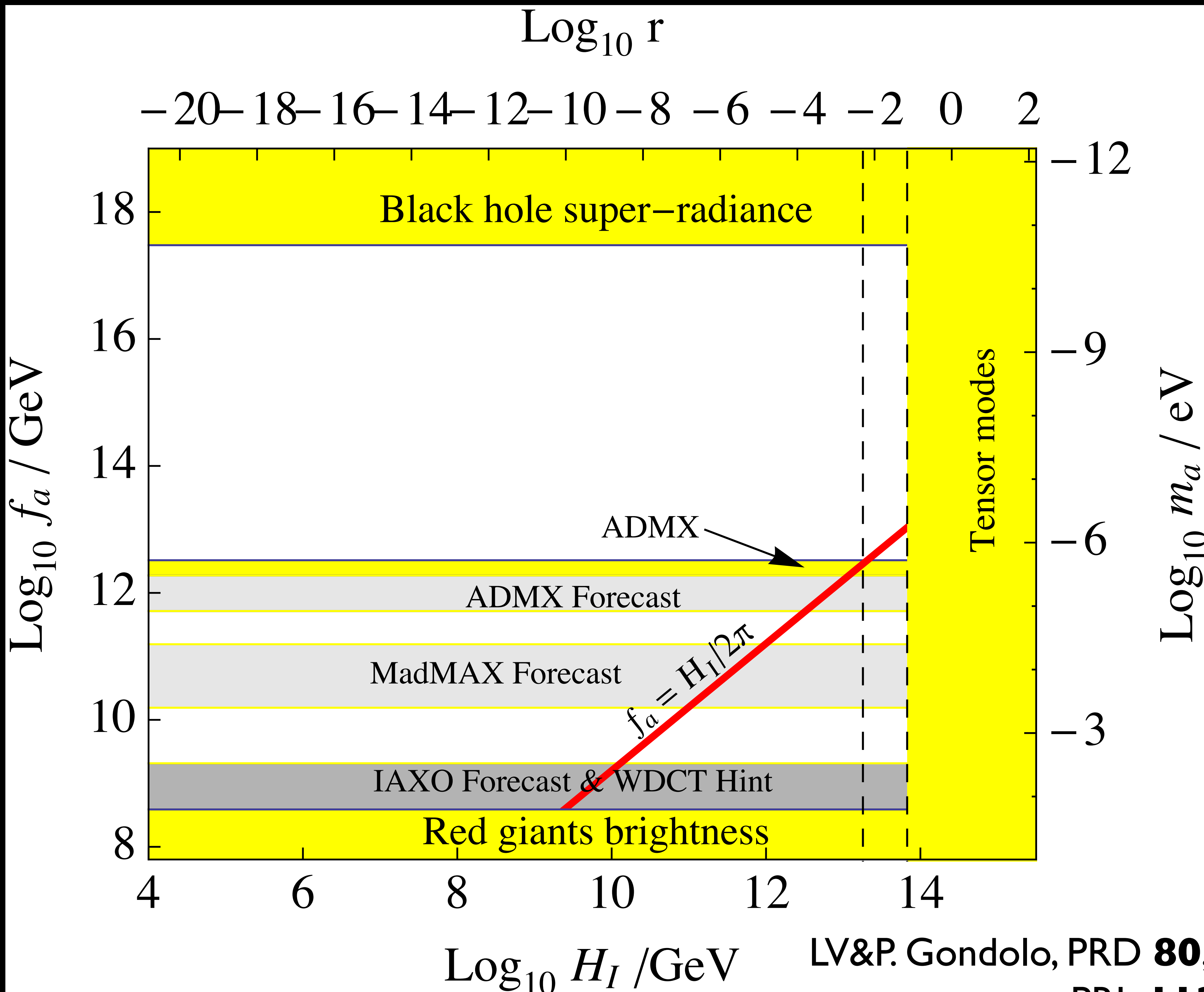


Axion parameter space



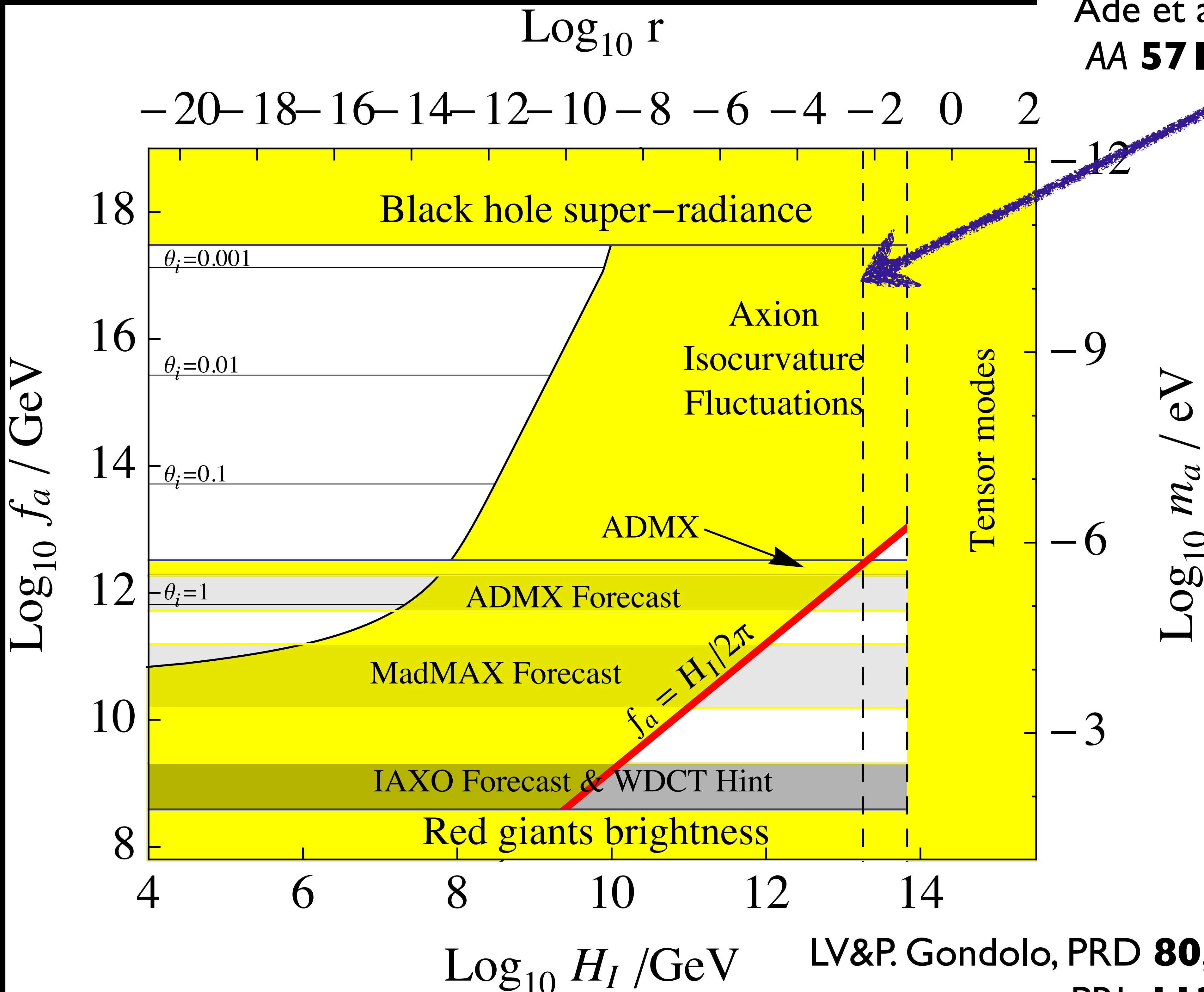
LV&P. Gondolo, PRD **80**, 035024 (2009); PRL **113**, 011802 (2014)

Axion parameter space



LV&P. Gondolo, PRD **80**, 035024 (2009); PRL **113**, 011802 (2014)

Axion parameter space



Ade et al (PLANCK) *AA* **571** *A16* (2014)

LV&P. Gondolo, PRD **80**, 035024 (2009); PRL **113**, 011802 (2014)

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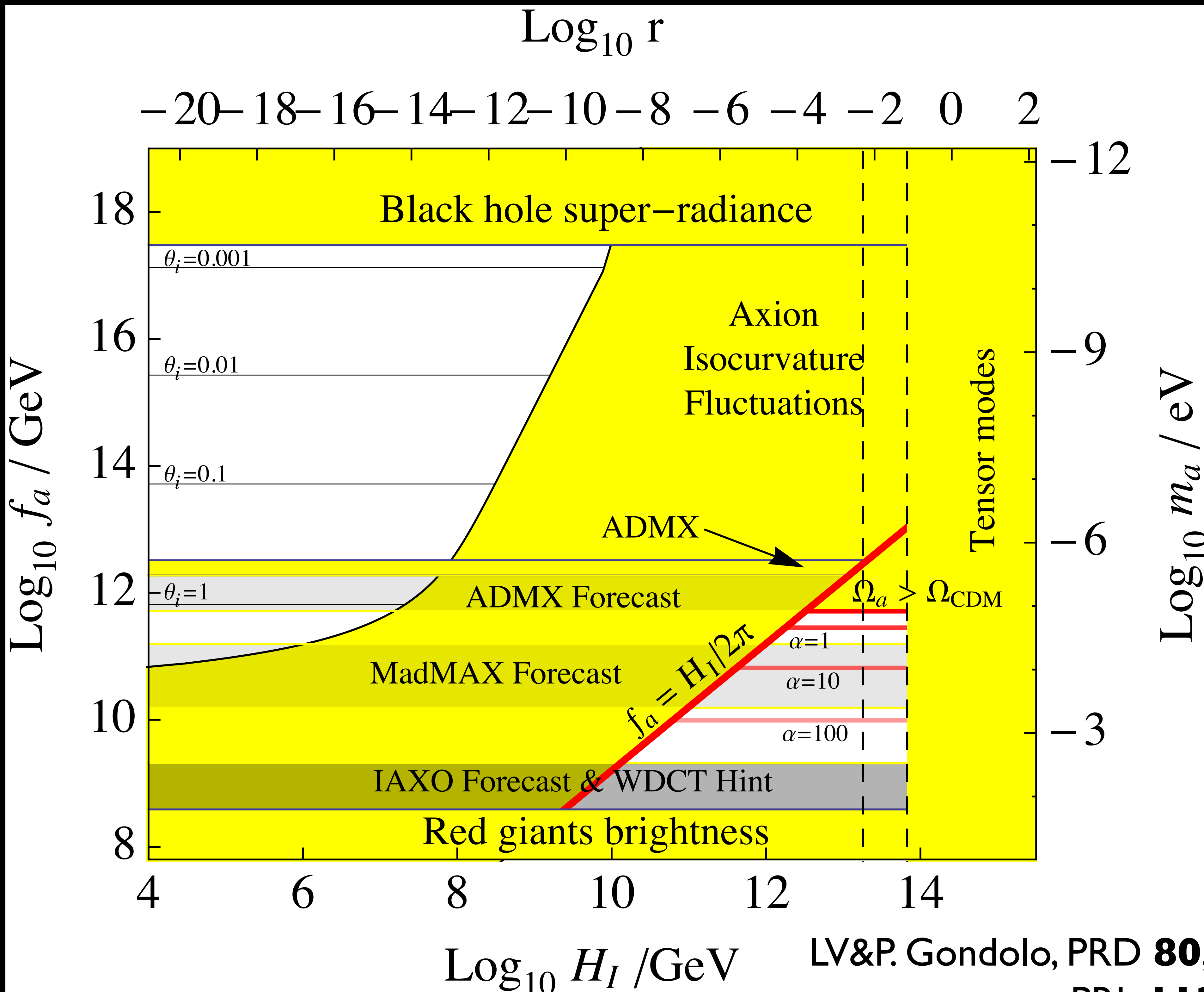


LV&P. Gondolo, PRD **80**, 035024 (2009);
PRL **113**, 011802 (2014)

Ultra-light axions?

- We address the "Missing Satellite" problem, i.e. overabundance of small satellites in numerical simulations compared to observations.

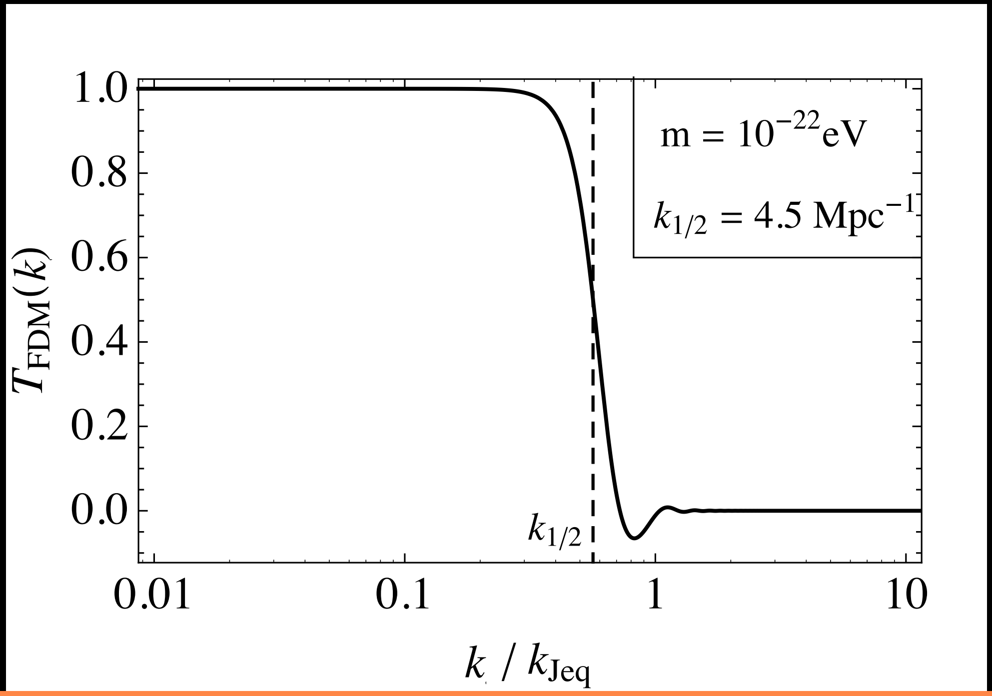
Moore *et al.* (1999); Klypin *et al.* (1999)

- Alleviated by cutoff of $P_{\rm CDM}(k)$ at $k \sim 4.5\, h\, {\rm Mpc}^{-1}$

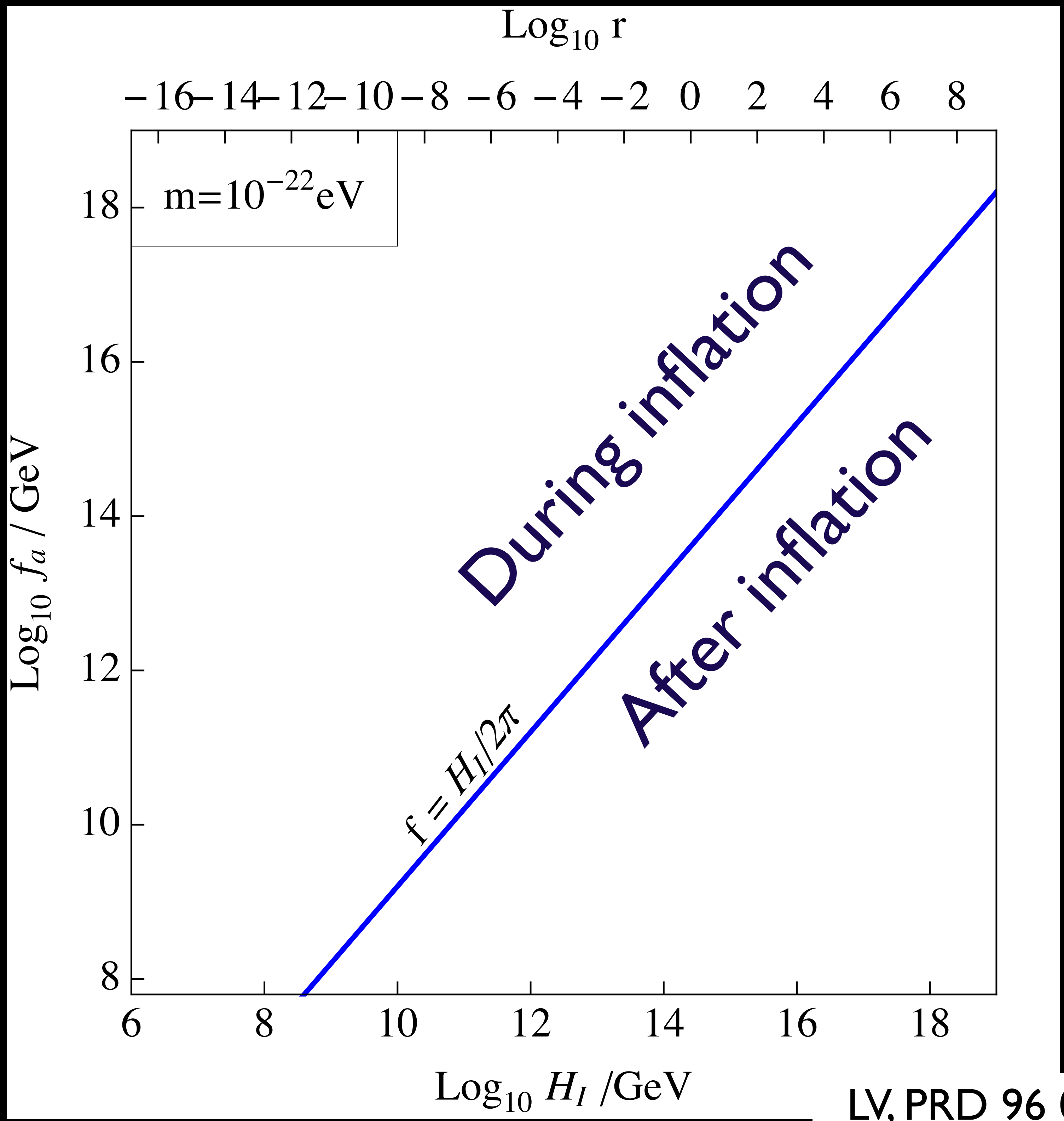
Kamionkowski&Liddle (1999)

- An axion with $m \sim 10^{-22}\,{\rm eV}$ leads to the desired cutoff

Hu, Barkana, Gruzinov, PRL **85** (2000)



Is the Ultra-light Axion viable?



LV, PRD 96 023013 (2017)

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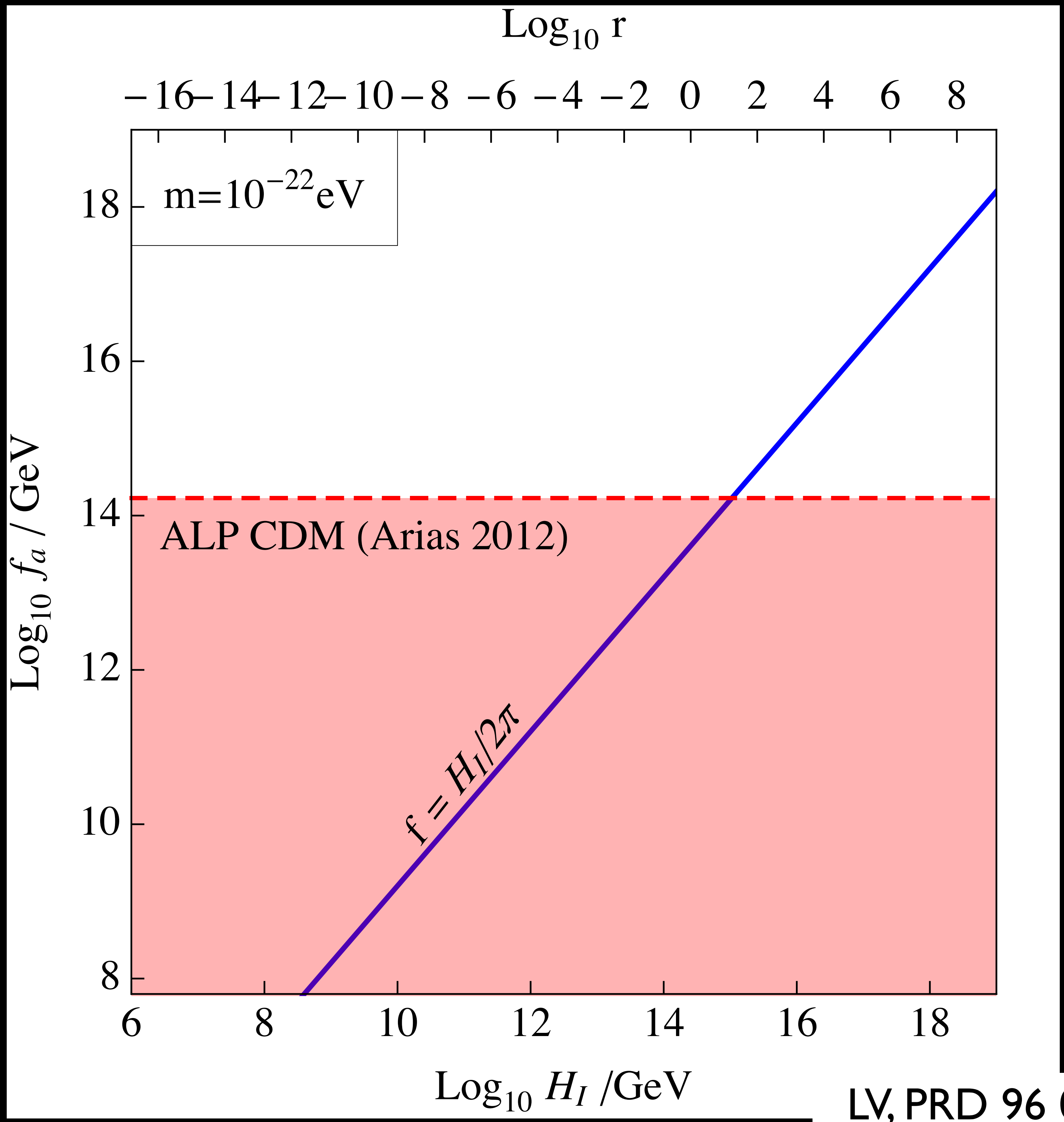

LV, PRD 96 023013 (2017)

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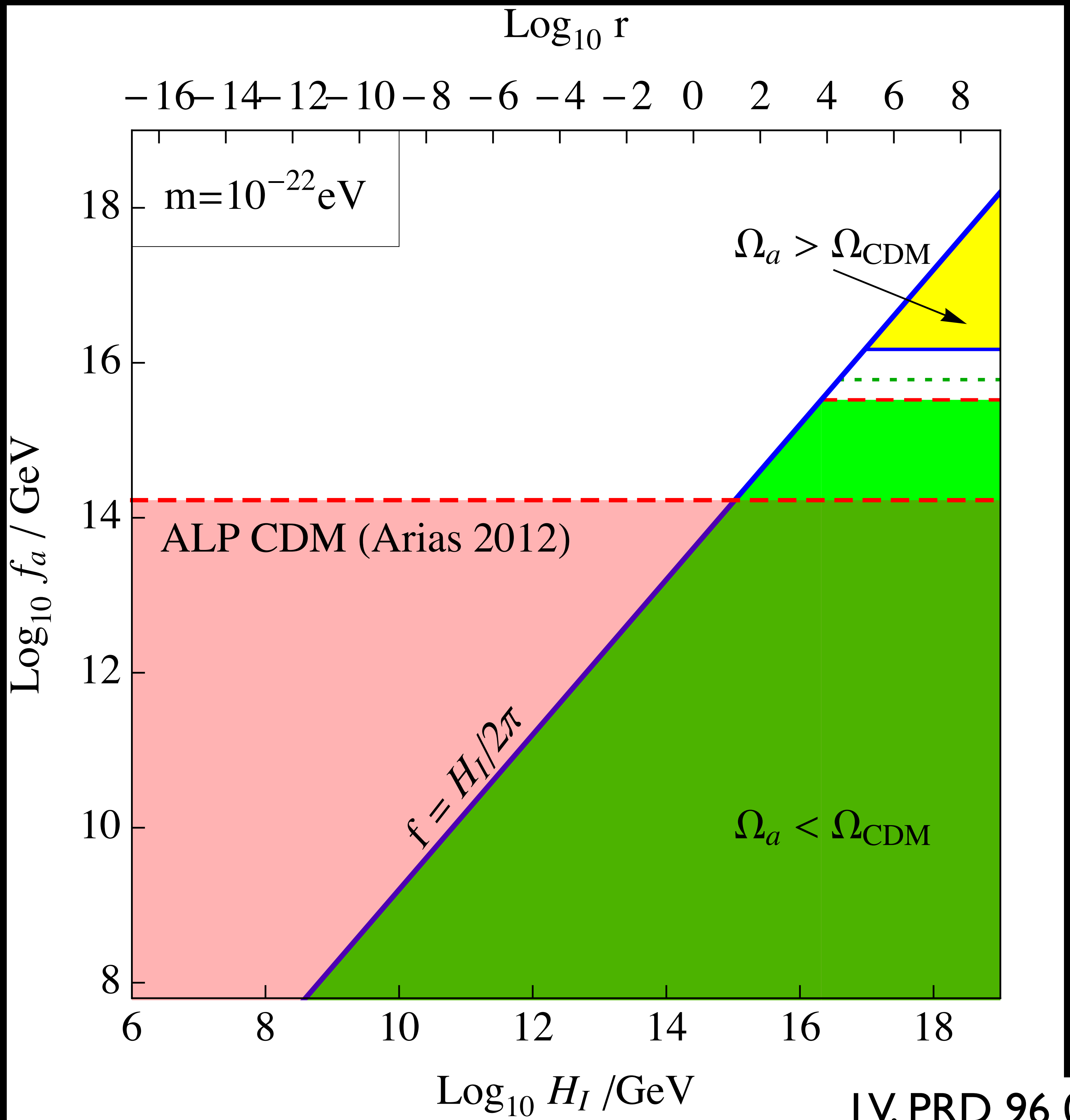


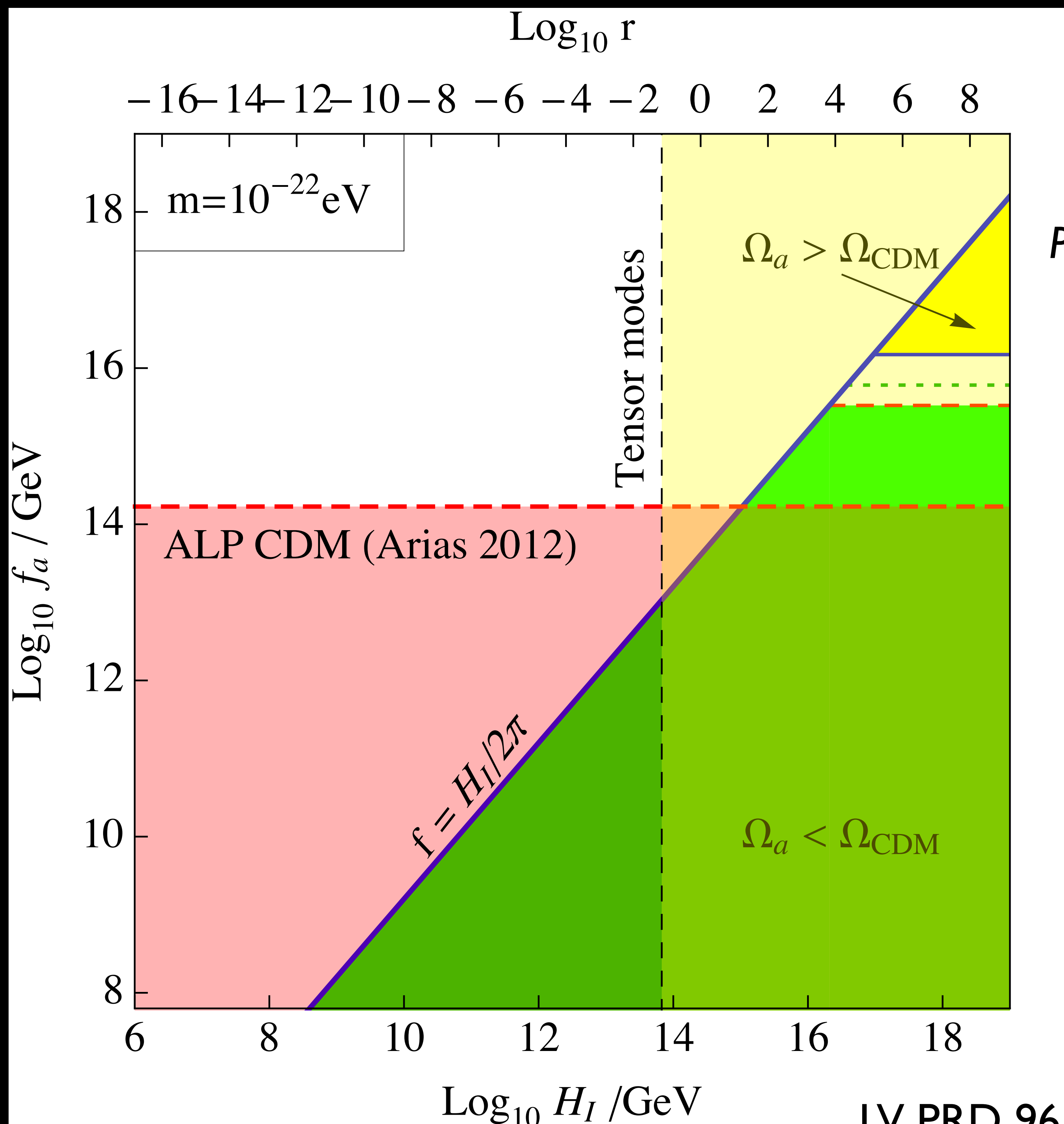
$f \sim$ GUT scale

Hui et al, PRD 95 043541 (2017)

$m(T) \propto T^{-n}$

LV, PRD 96 023013 (2017)

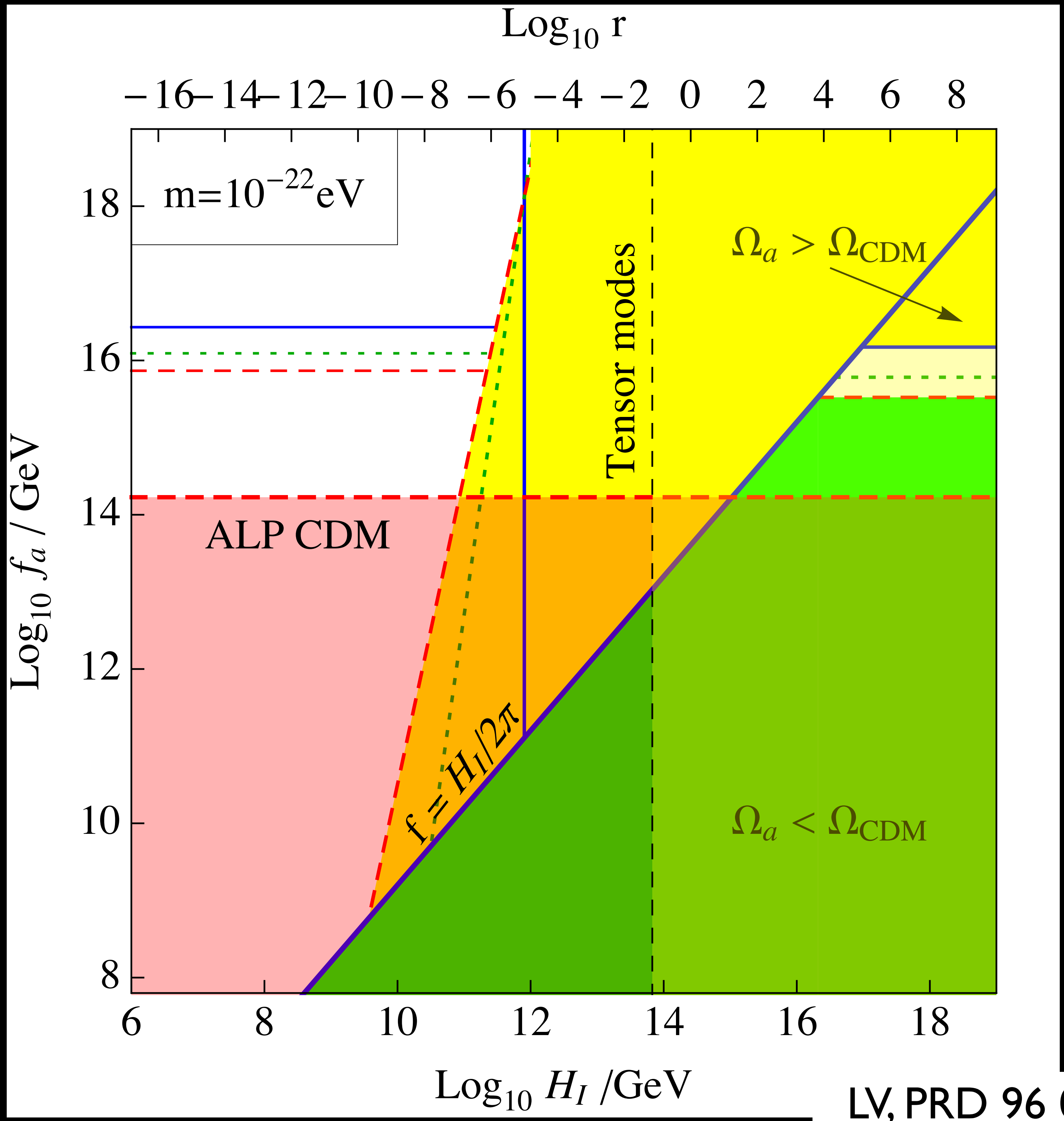
Is the Ultra-light Axion viable?



Ade *et al* (BICEP2)
PRL **116** *031302* (2016)

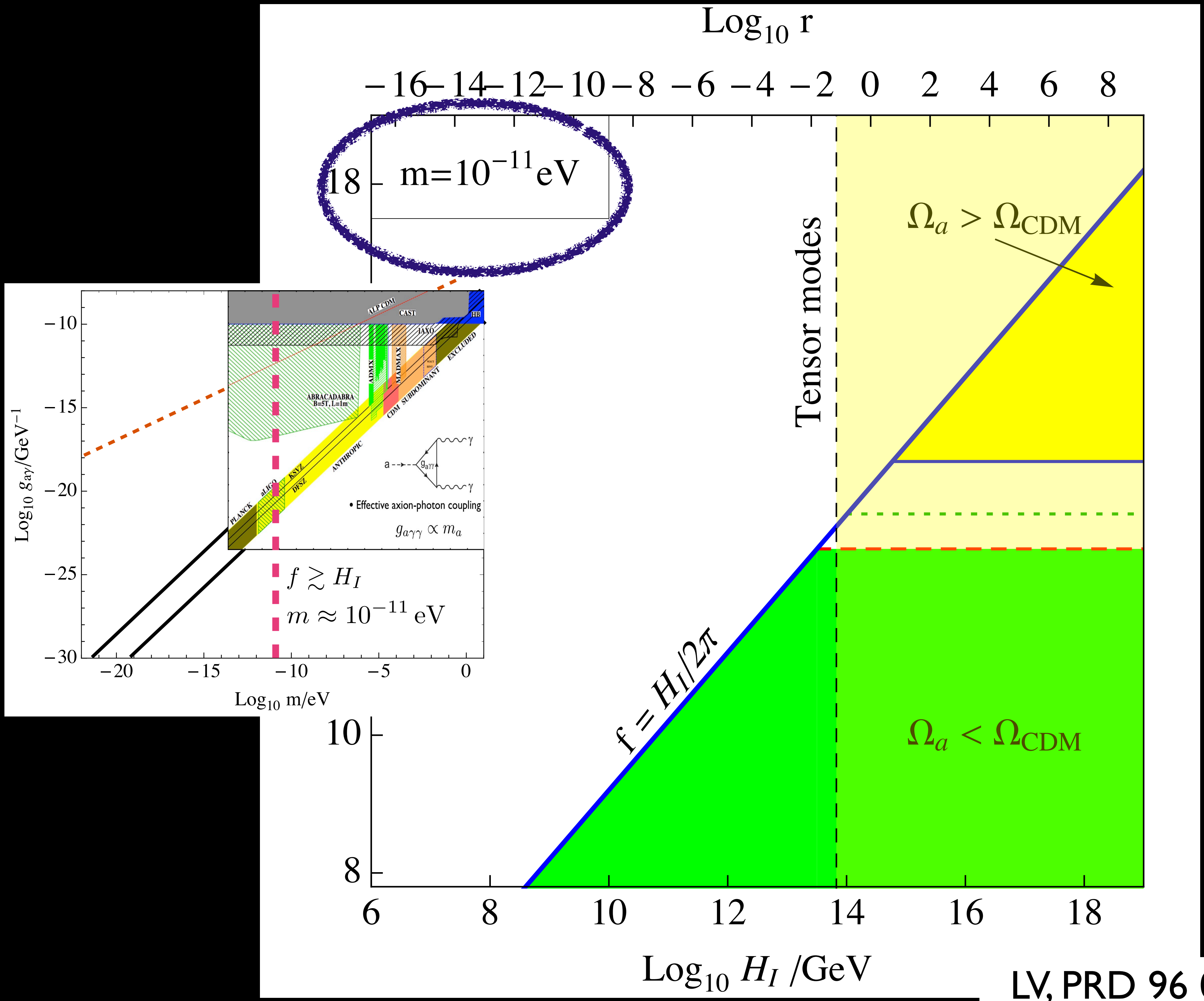
LV, PRD 96 023013 (2017)

Is the Ultra-light Axion viable?



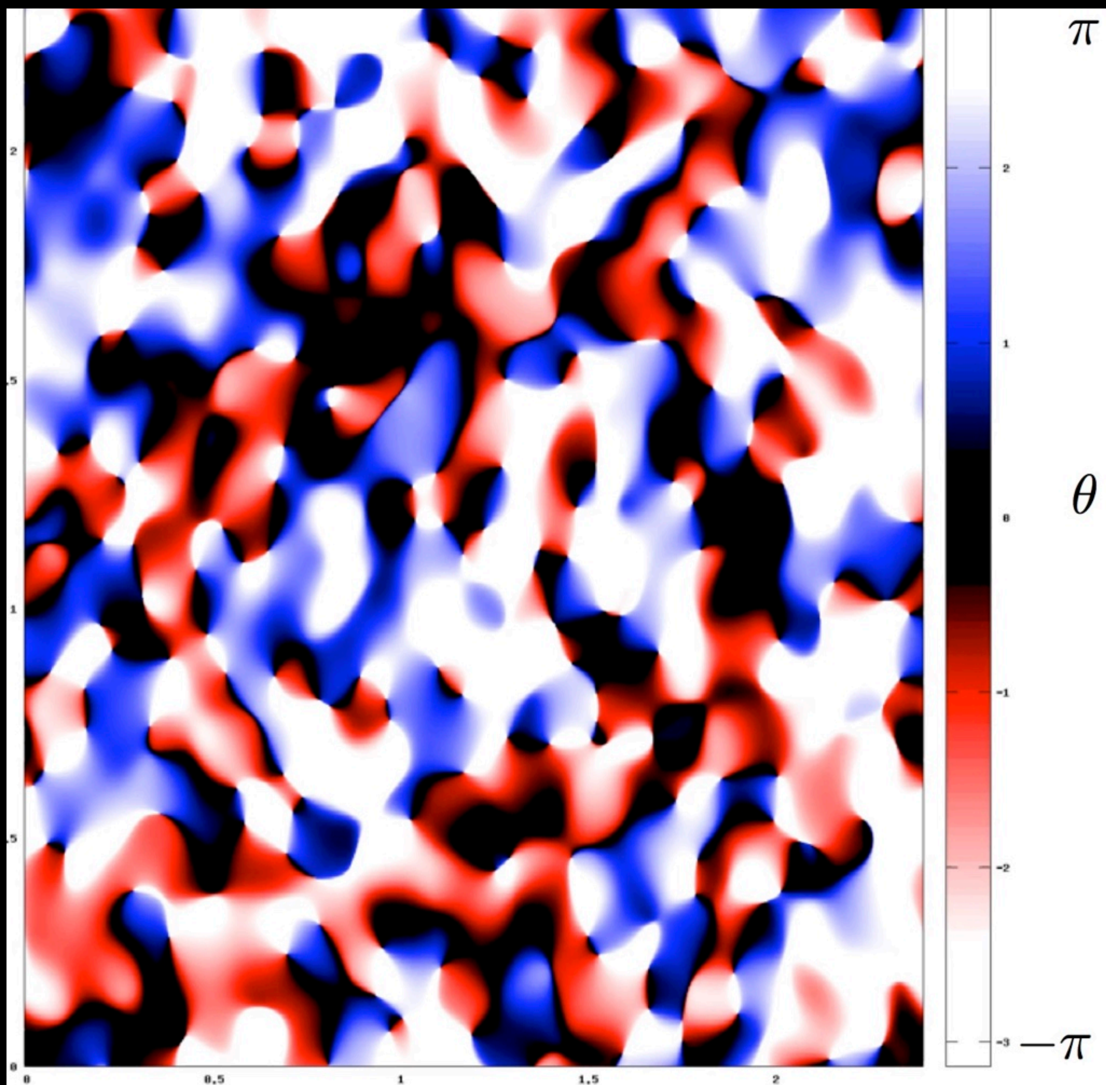
LV, PRD 96 023013 (2017)

ALP parameter space



LV, PRD 96 023013 (2017)

Axion miniclusters



$\mathcal{O}(1)$ overdensities

mass $M = \rho_a \frac{4}{3}\pi\left(\frac{\pi}{H_{\rm osc}}\right)^3$

The radius is fixed by

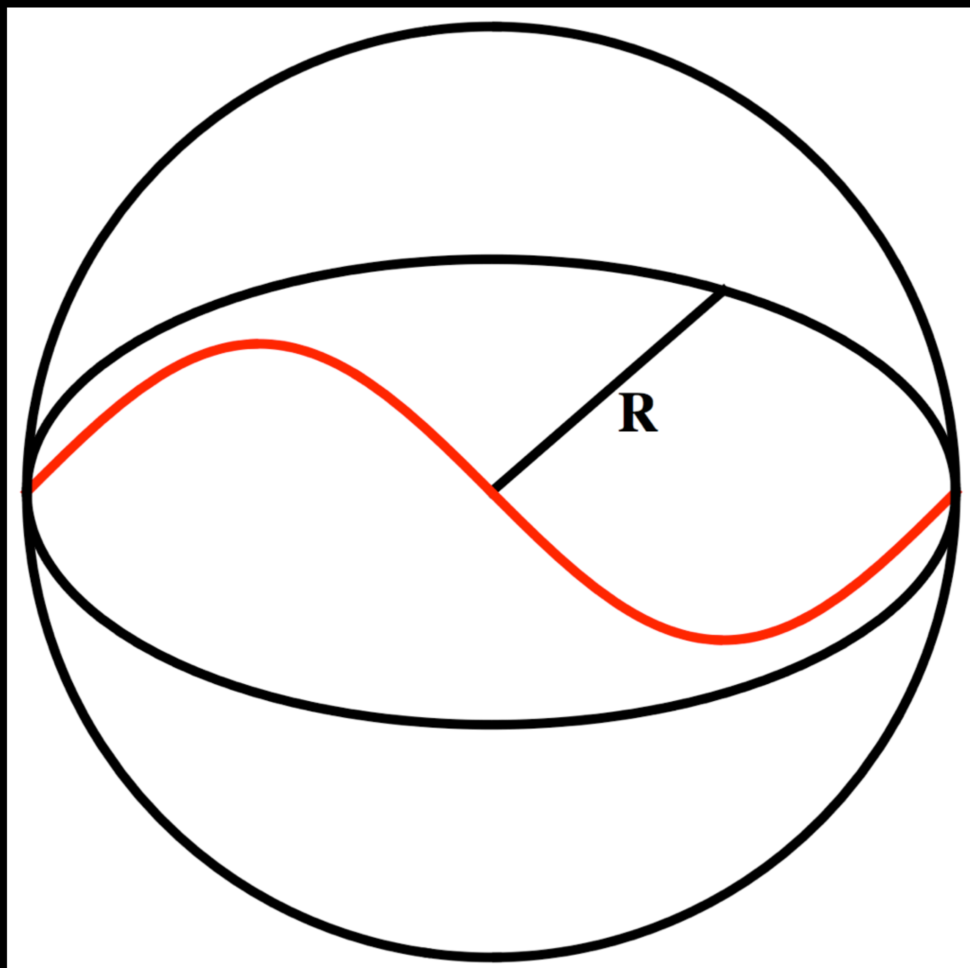
$$\rho_{\rm MC} = 140\delta^3(1+\delta)\rho_a(z_{\rm eq})$$

For an axion mass $m = 100\,\mu{\rm eV}$

$M \approx 10^{-16} M_\odot \quad R \approx 1\,{\rm A.U.}$

One encounter every $\approx {\rm Myr}$

Axion Stars



Made of axions that oscillate in the lowest energy state coherently

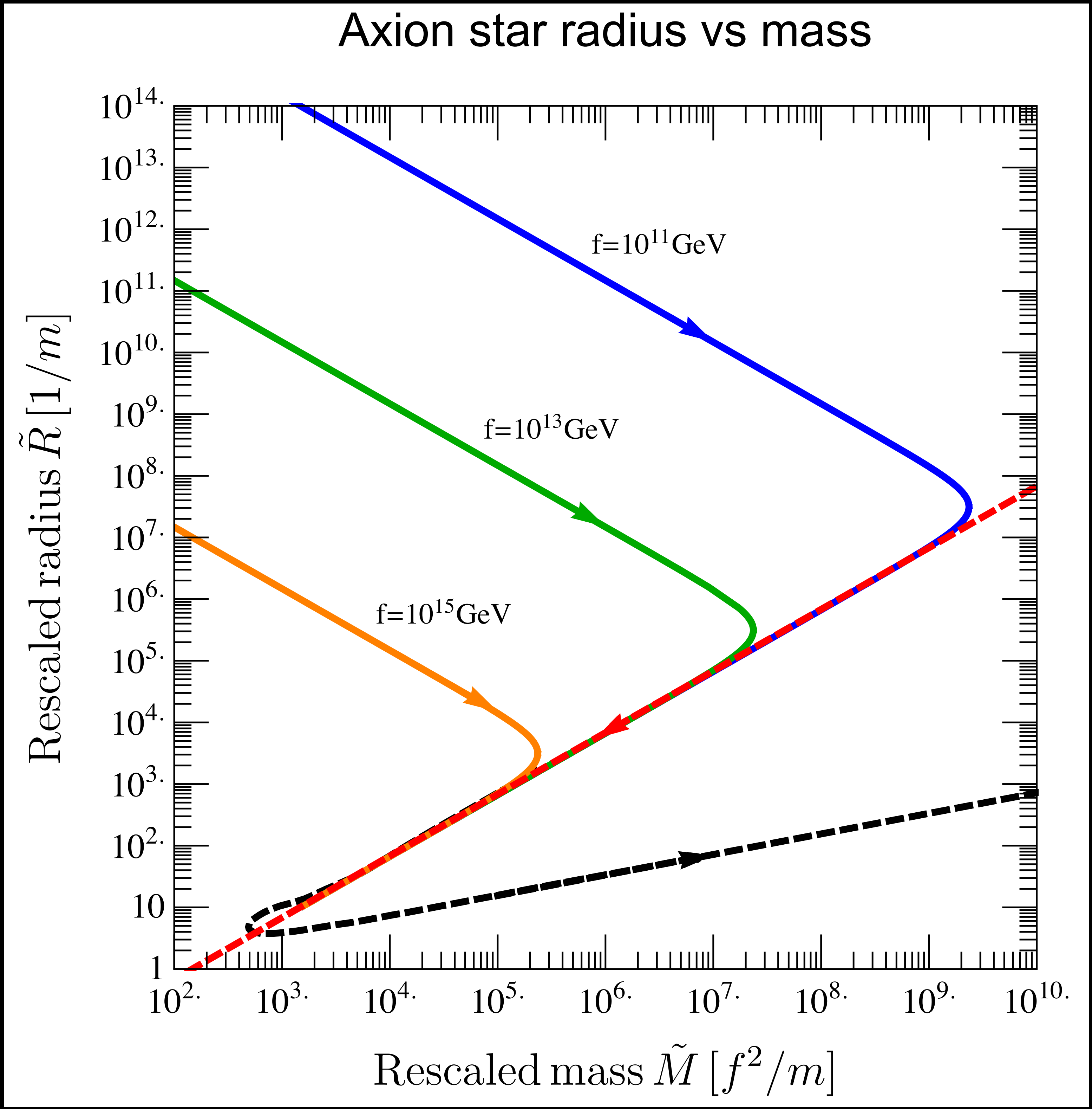
$$v \sim \frac{\hbar}{m\,R}$$

$$M = N\,m$$

$$U \sim -\frac{GM^2}{R} + \frac{M}{2}v^2 + U_{\rm self}$$

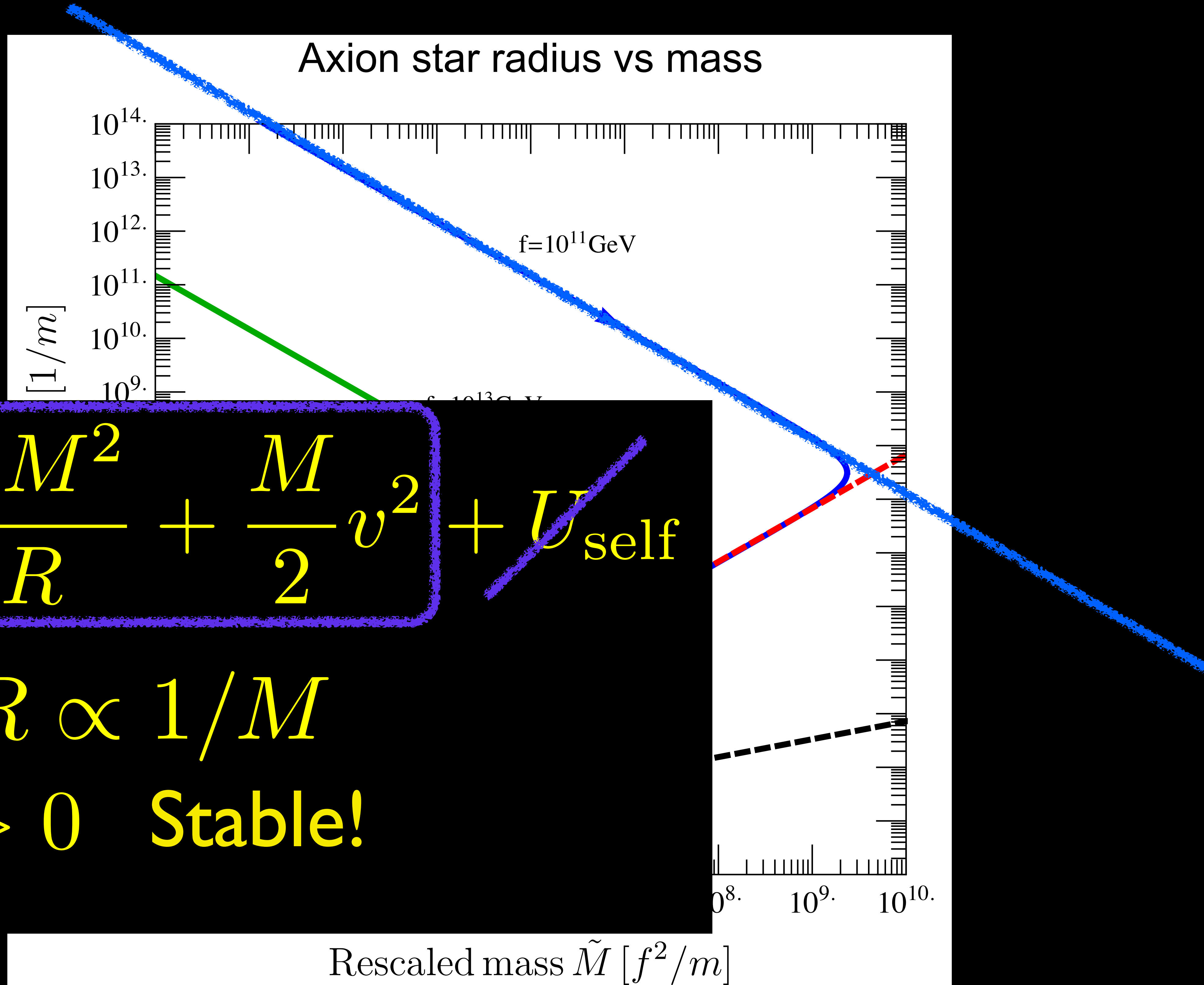
$$\boxed{\nabla U = 0}$$

Axion Stars



Axion star radius vs mass
f=10^11GeV
f=10^13GeV
f=10^15GeV
Rescaled radius $\tilde{R}\,[1/m]$
Rescaled mass $\tilde{M}\,[f^2/m]$

Axion Stars

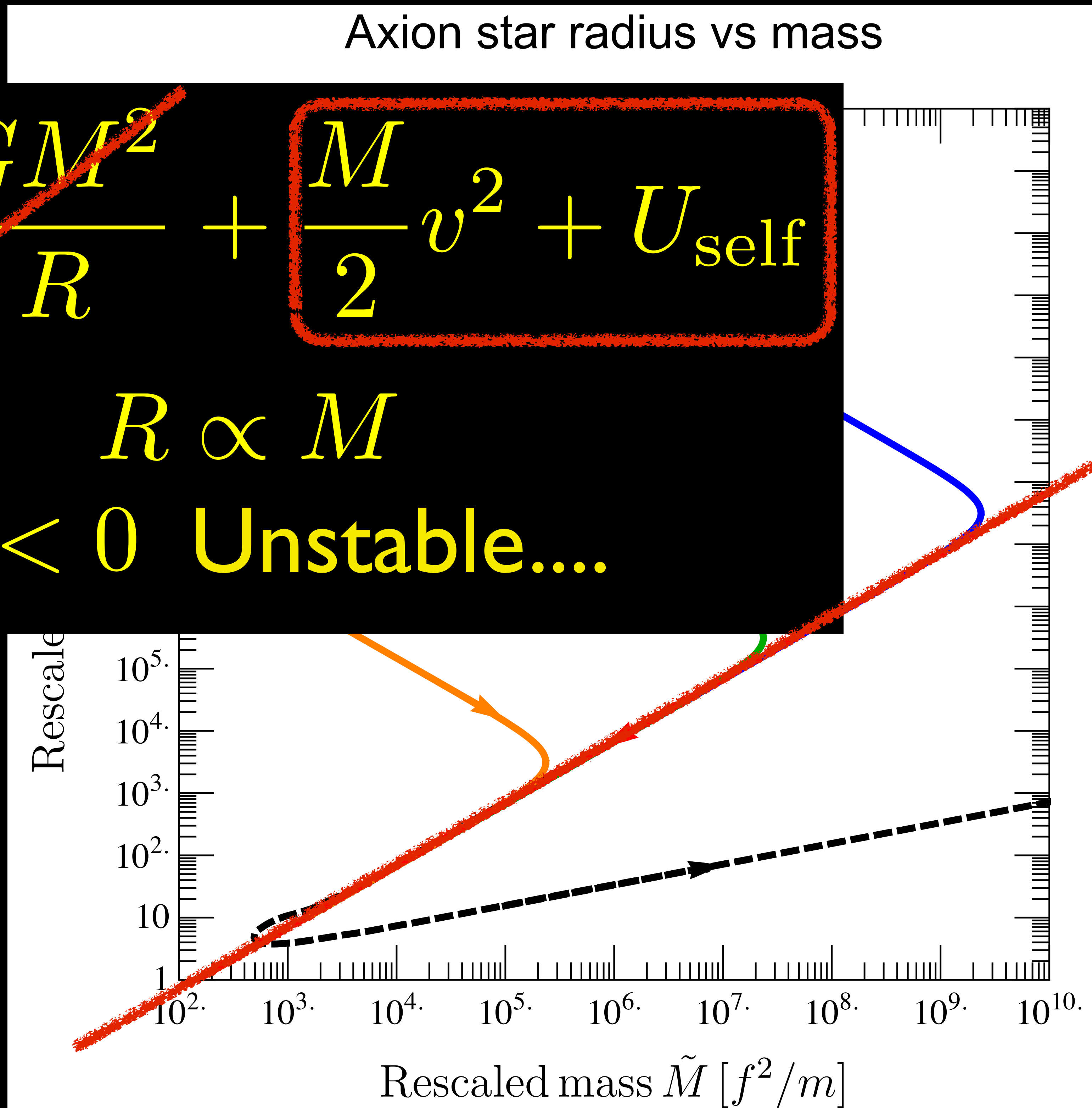


$$U \sim -\frac{GM^2}{R} + \frac{M}{2}v^2 + U_{\rm self}$$

$$R \propto 1/M$$

$\nabla^2 U > 0$ **Stable!**

Axion Stars



$$U \sim -\frac{GM^2}{R} + \frac{M}{2}v^2 + U_{\rm self}$$

$$R \propto M$$

$\nabla^2 U < 0$ Unstable....

Monday, June 11, 18

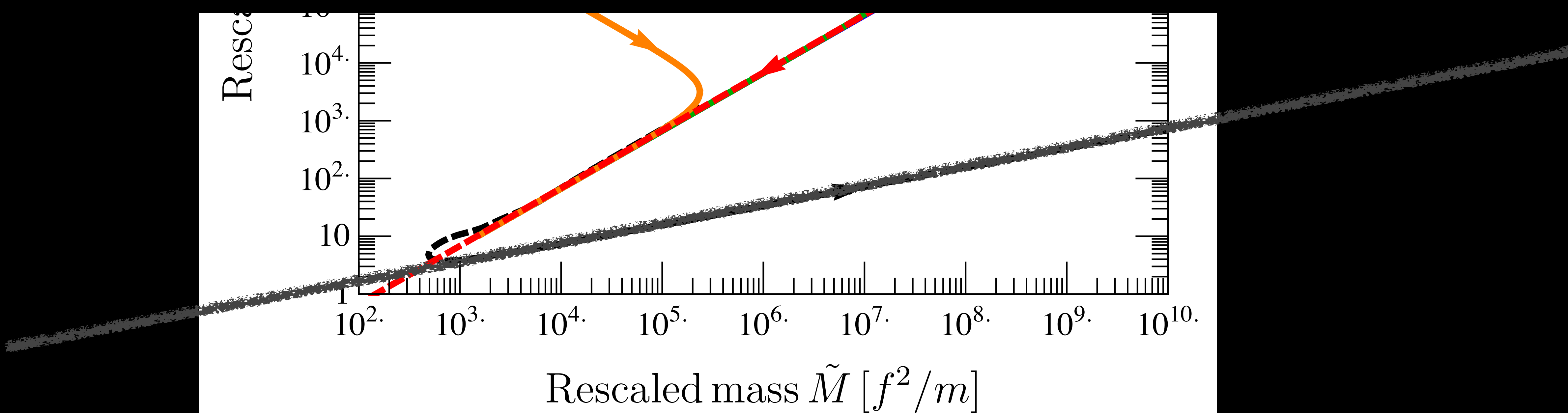
Axion Stars

Axion star radius vs mass

$$U \sim -\frac{GM^2}{R} + \frac{M}{2}v^2 + U_{\rm self}$$

$$\rho \sim M/R^3 \sim {\rm const} \qquad R \propto M^{1/3}$$

$$\tau = \mathcal{O}\left(1000/m\right)$$ **Oscillons**



Conclusions

- Axions are well-motivated, viable CDM candidates;
- Details (coupling, temperature-dependence, defects) require much further efforts. Work in progress...
- The parameter space is being tackled;
- Miniclusters and axion stars are formed, work is needed!
- Ultra-light axions models are difficult to motivate given PLANCK-BICEP2 data