Axions in cosmology and astrophysics

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Based on:

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

LV, PRD **96**, 023 (2017)

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

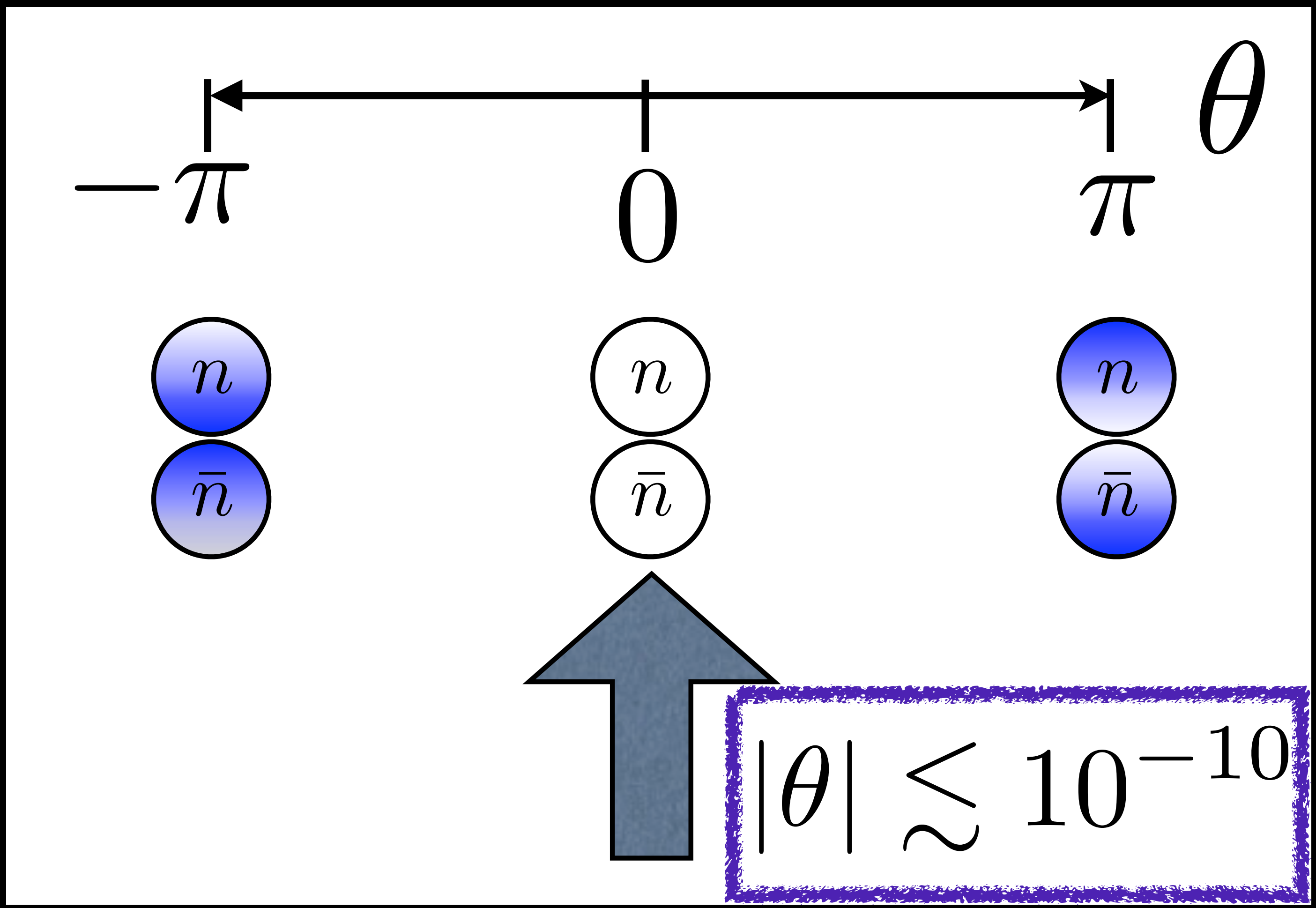
LV & P. Gondolo, PRD **81**, 063508 (2010)

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

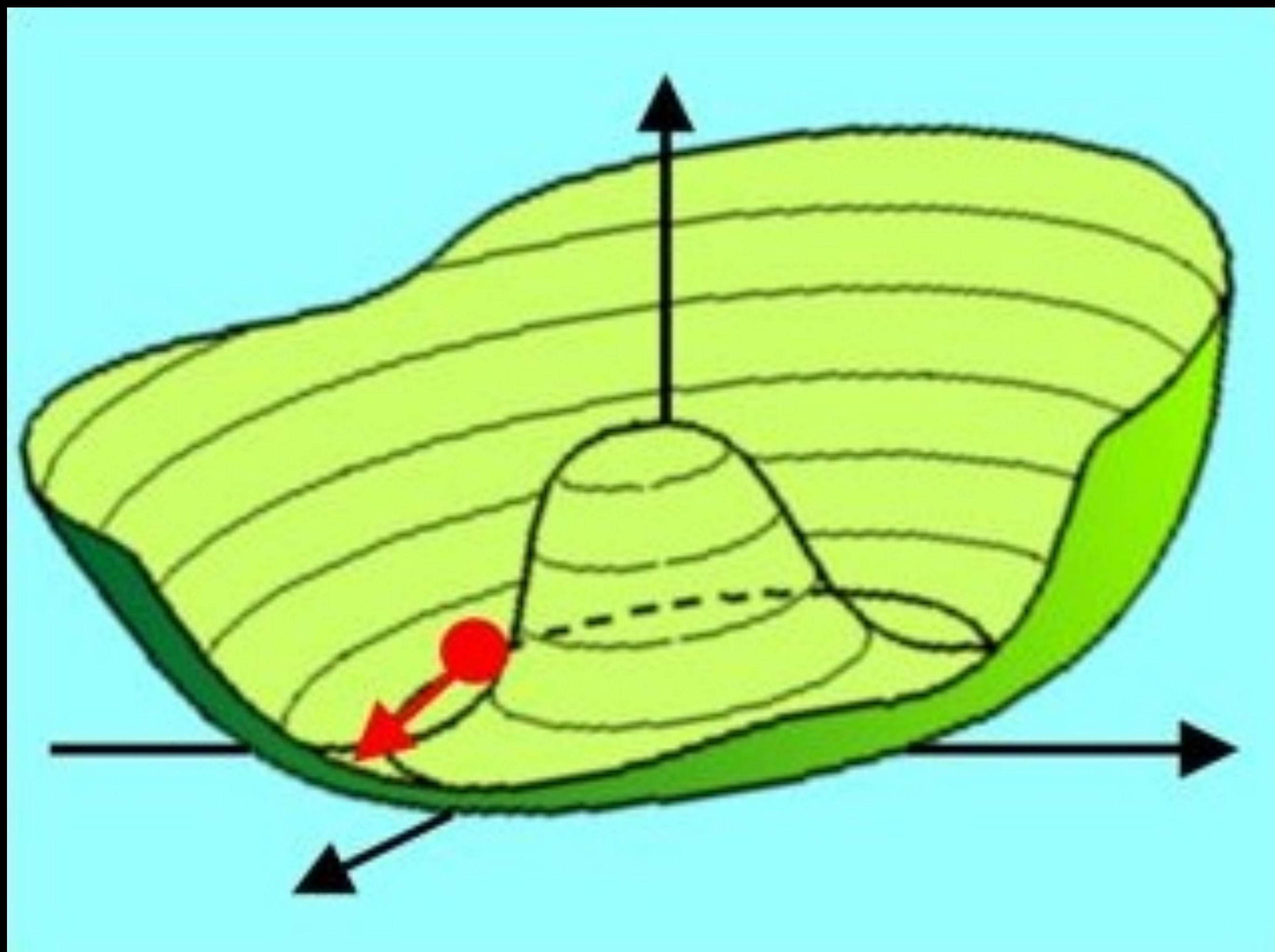
Sources of CP violation in the SM

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

θ controls matter-antimatter differences in QCD



Axion coherent oscillations



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

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

~ One parameter theory

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

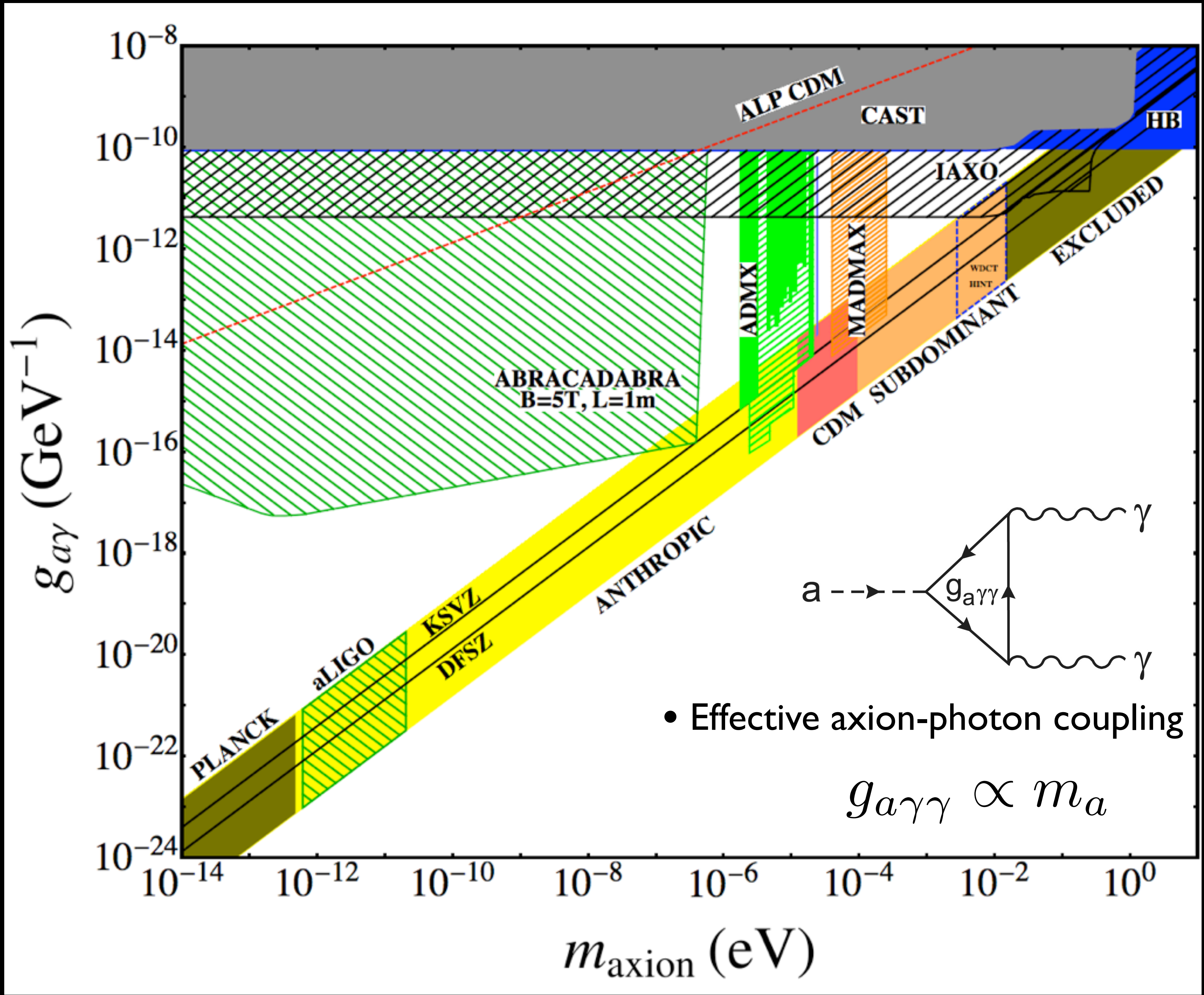
axion mass

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

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

PQ "Mexican hat" potential, tilted by QCD effects

Axion searches



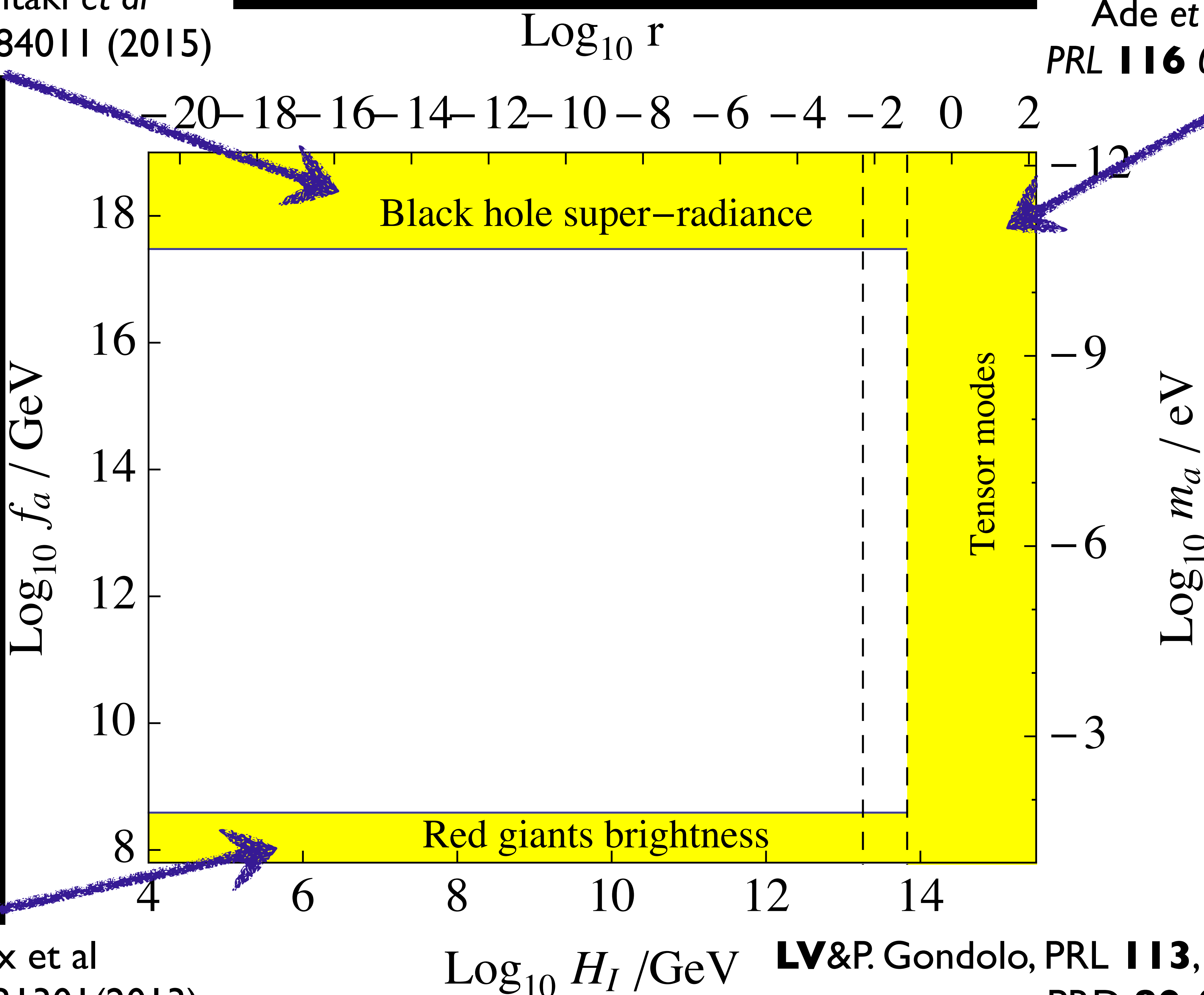
- Effective axion-photon coupling

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

Axion parameter space

Arvanitaki *et al*
PRD **91** 084011 (2015)

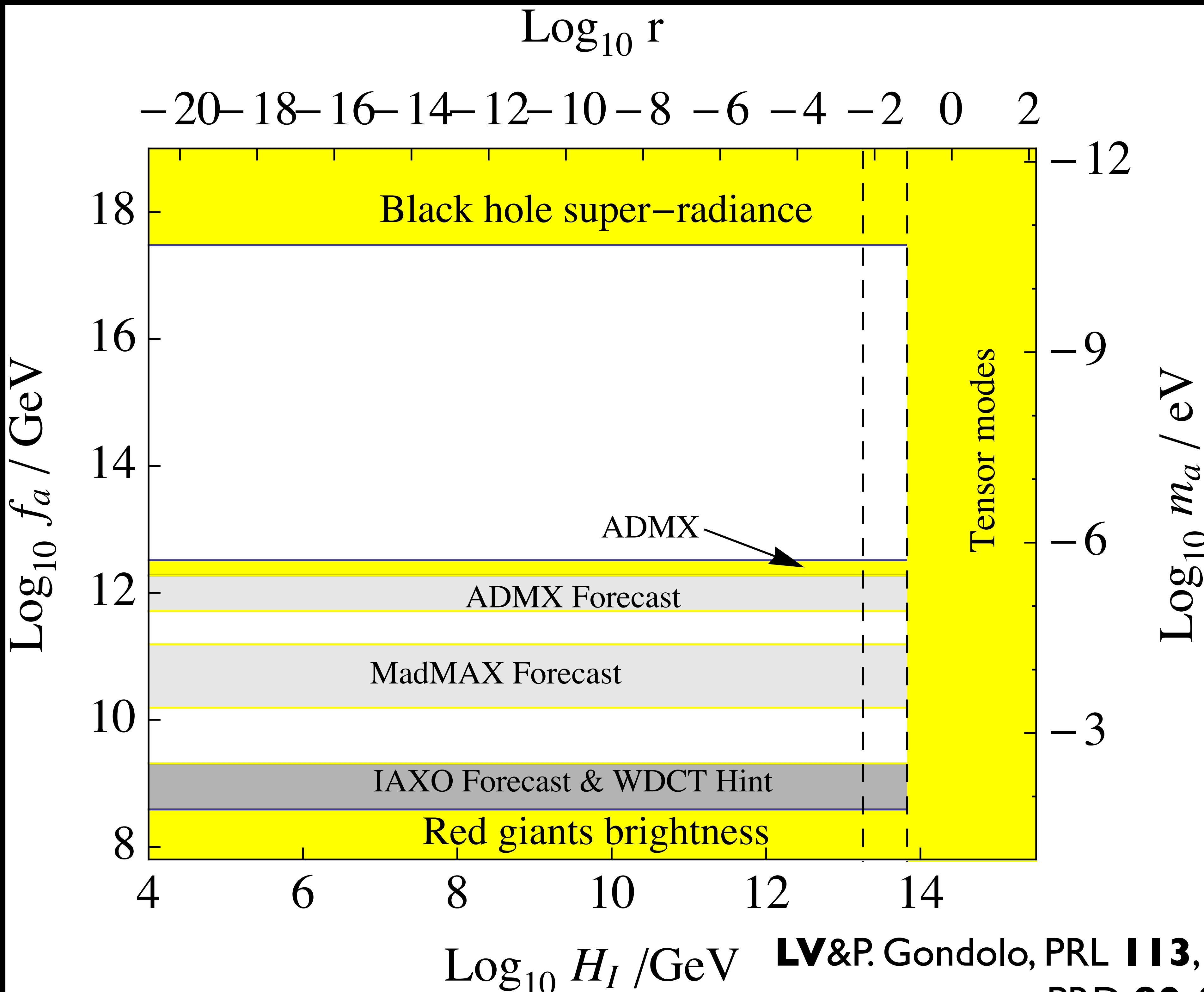
Ade *et al* (BICEP2)
PRL **116** *031302* (2016)



Viaux et al
PRL**111** 231301(2013)

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

Axion parameter space



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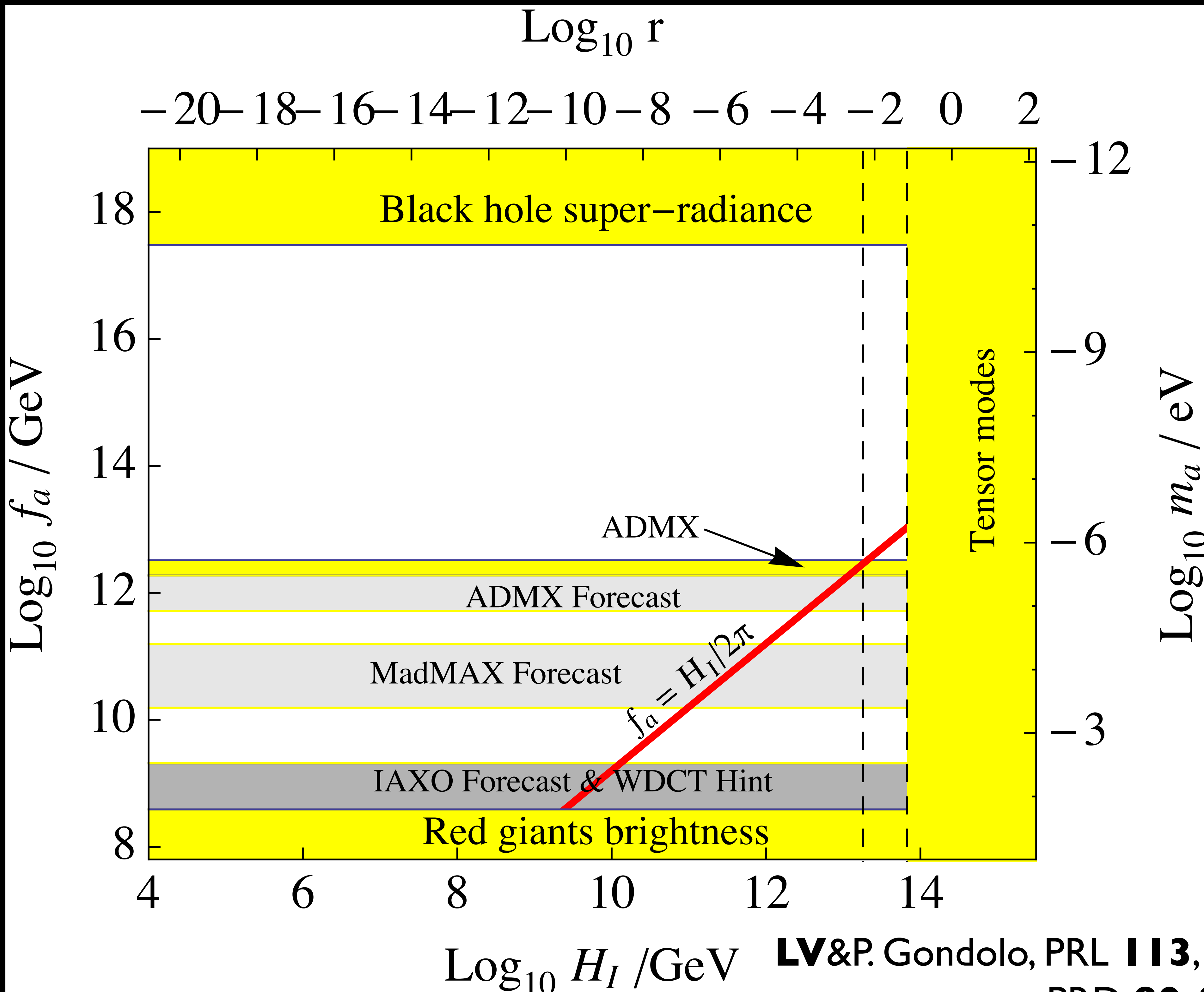
Axion parameter space



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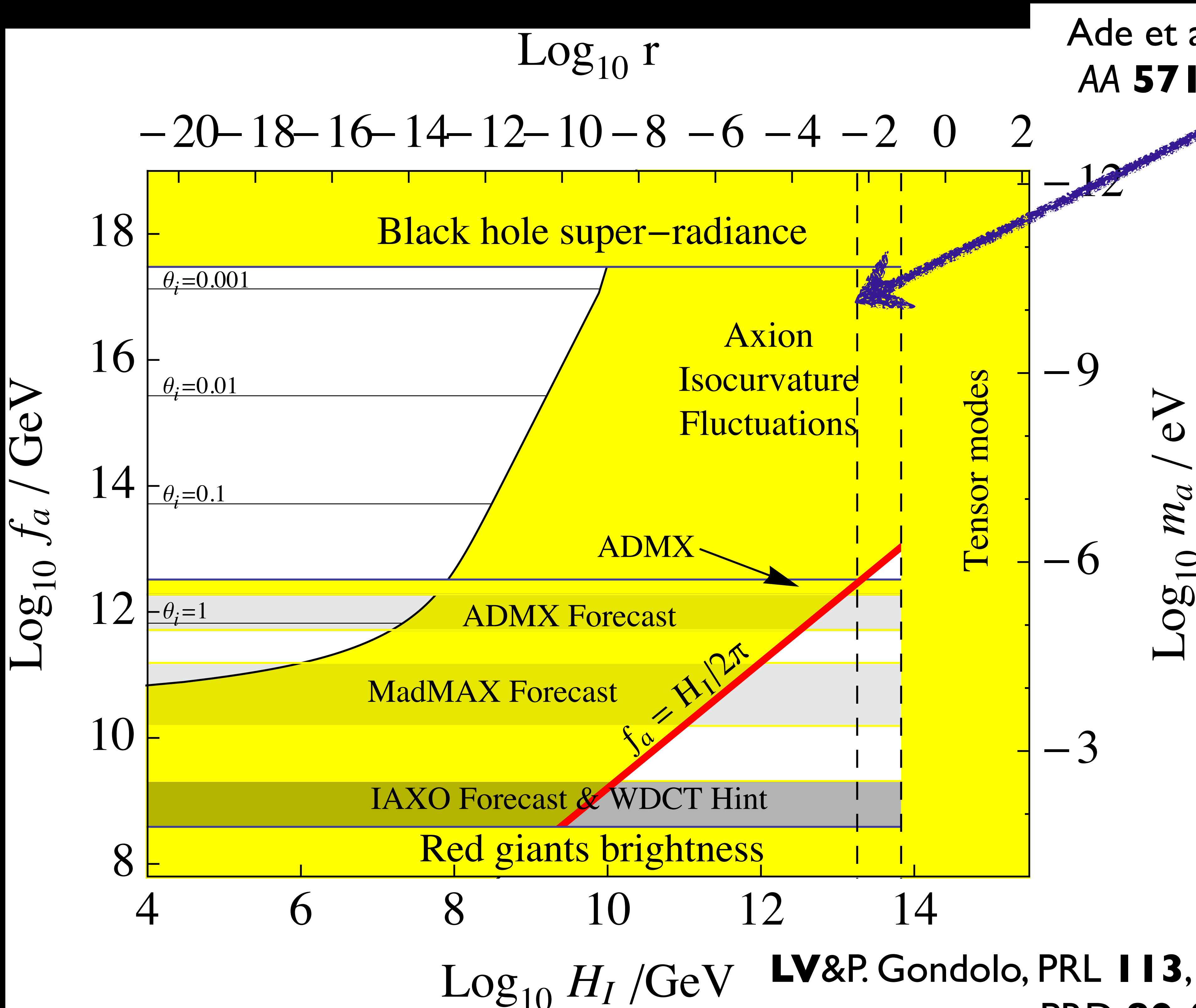
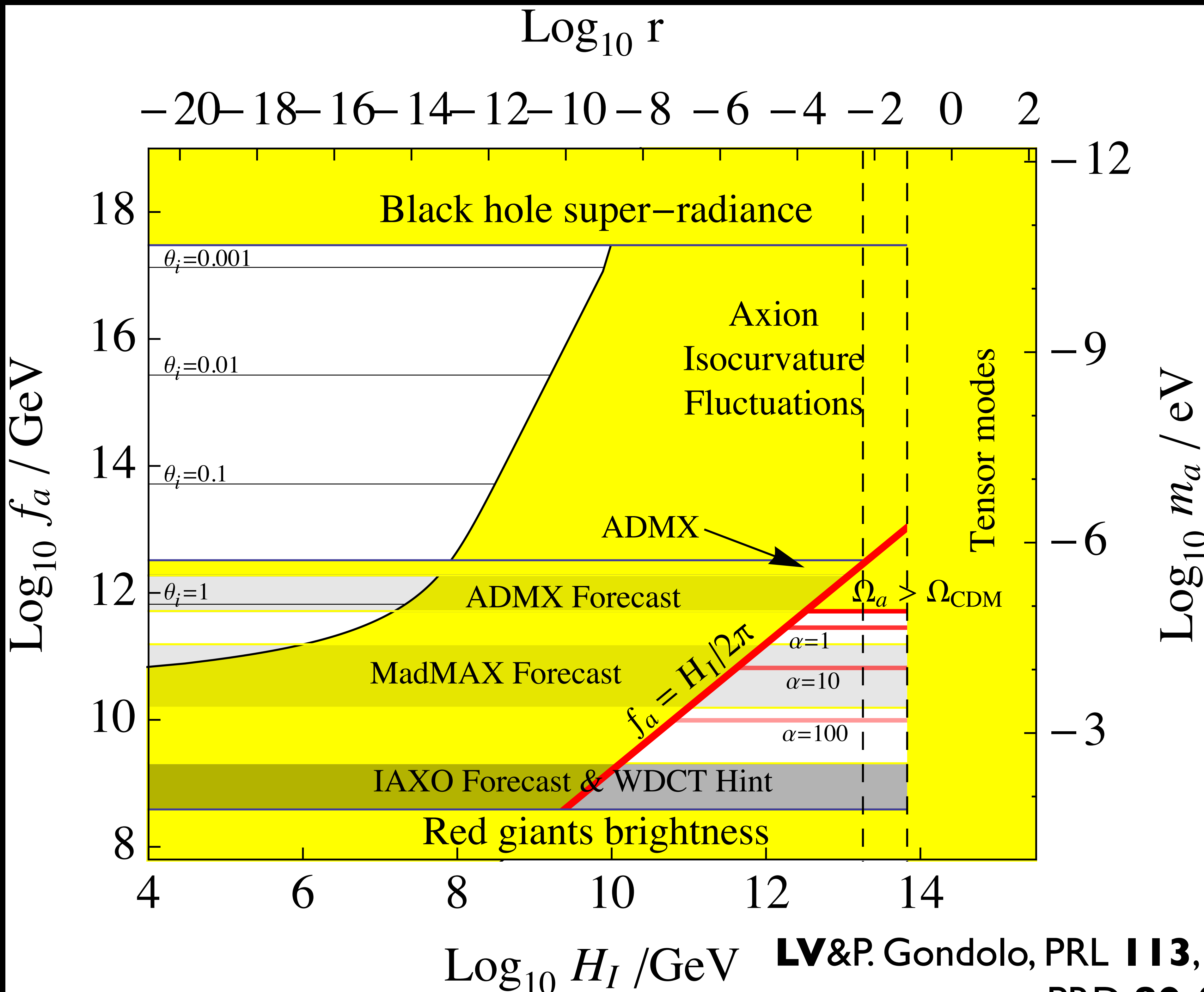


Ade et al (PLANCK) *AA* **571** *A16* (2014)

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

Axion parameter space



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

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)

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

Kamionkowski&Liddle (1999)

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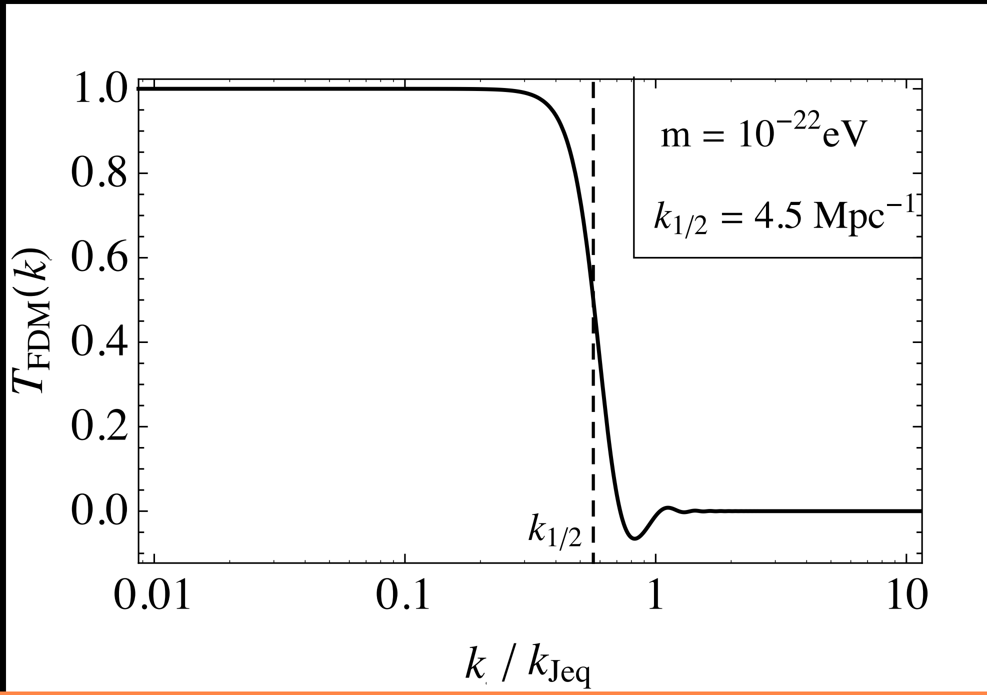
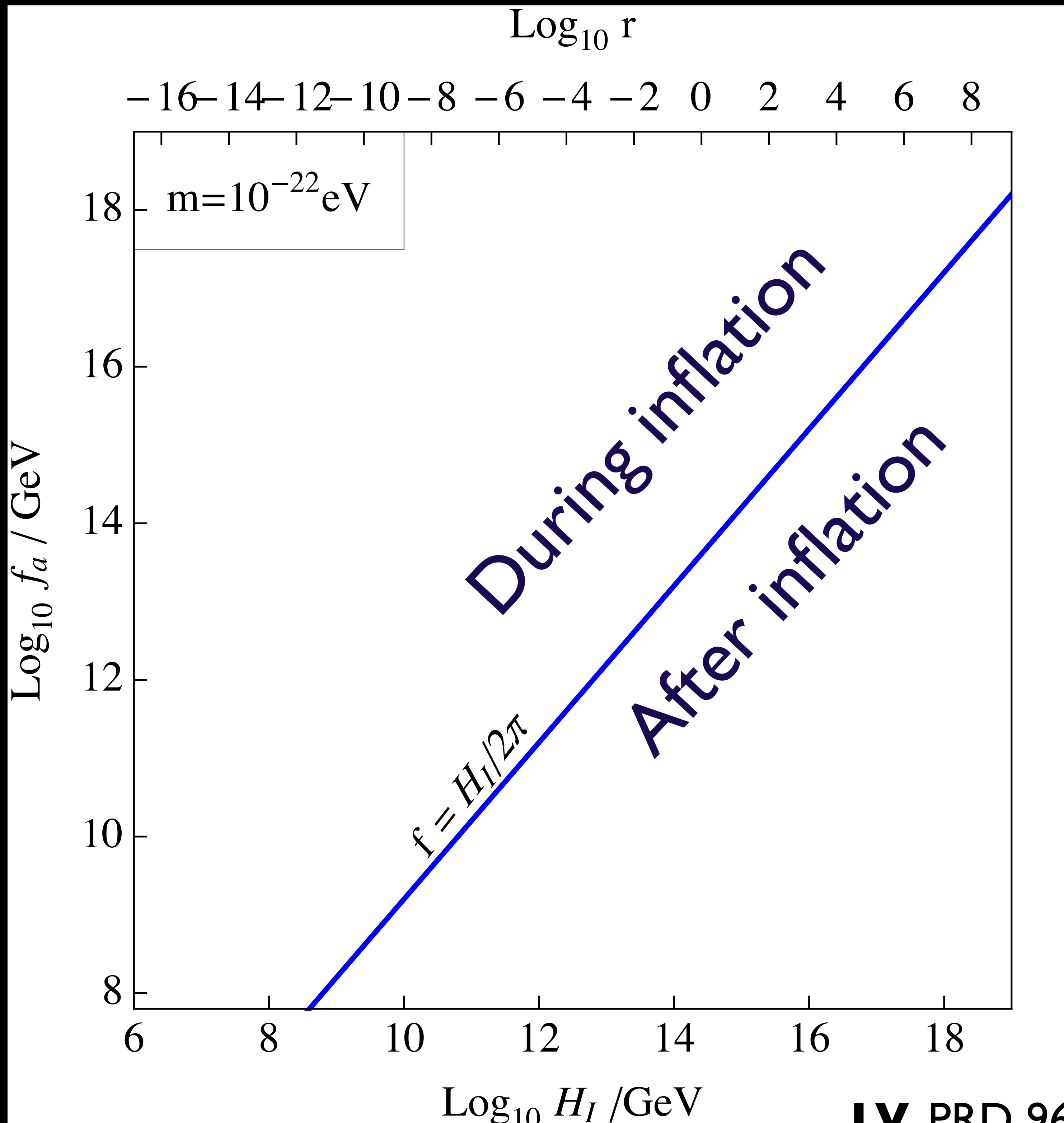
Kamionkowski&Liddle (1999)

- 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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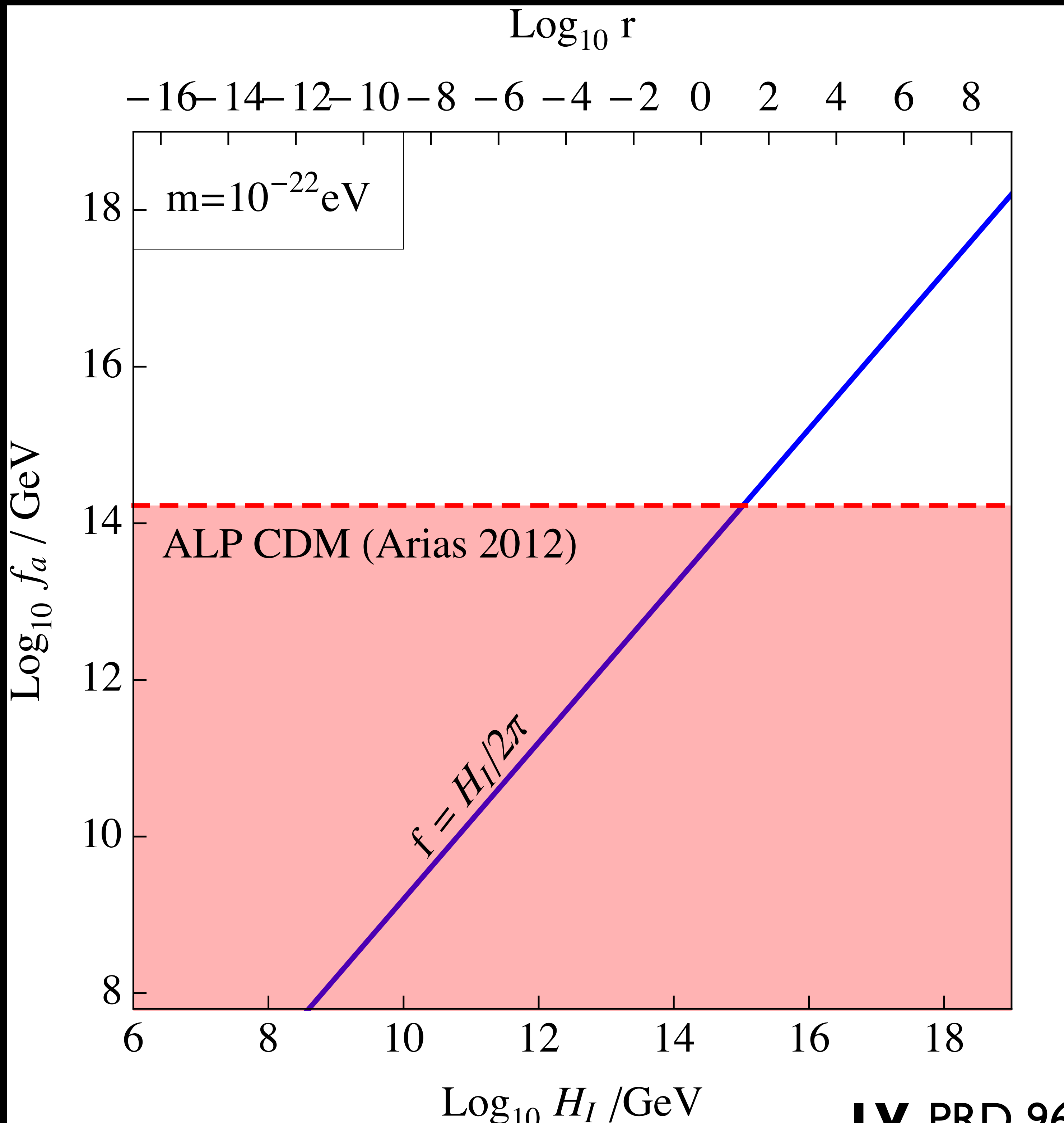

LV, PRD 96 023013 (2017)

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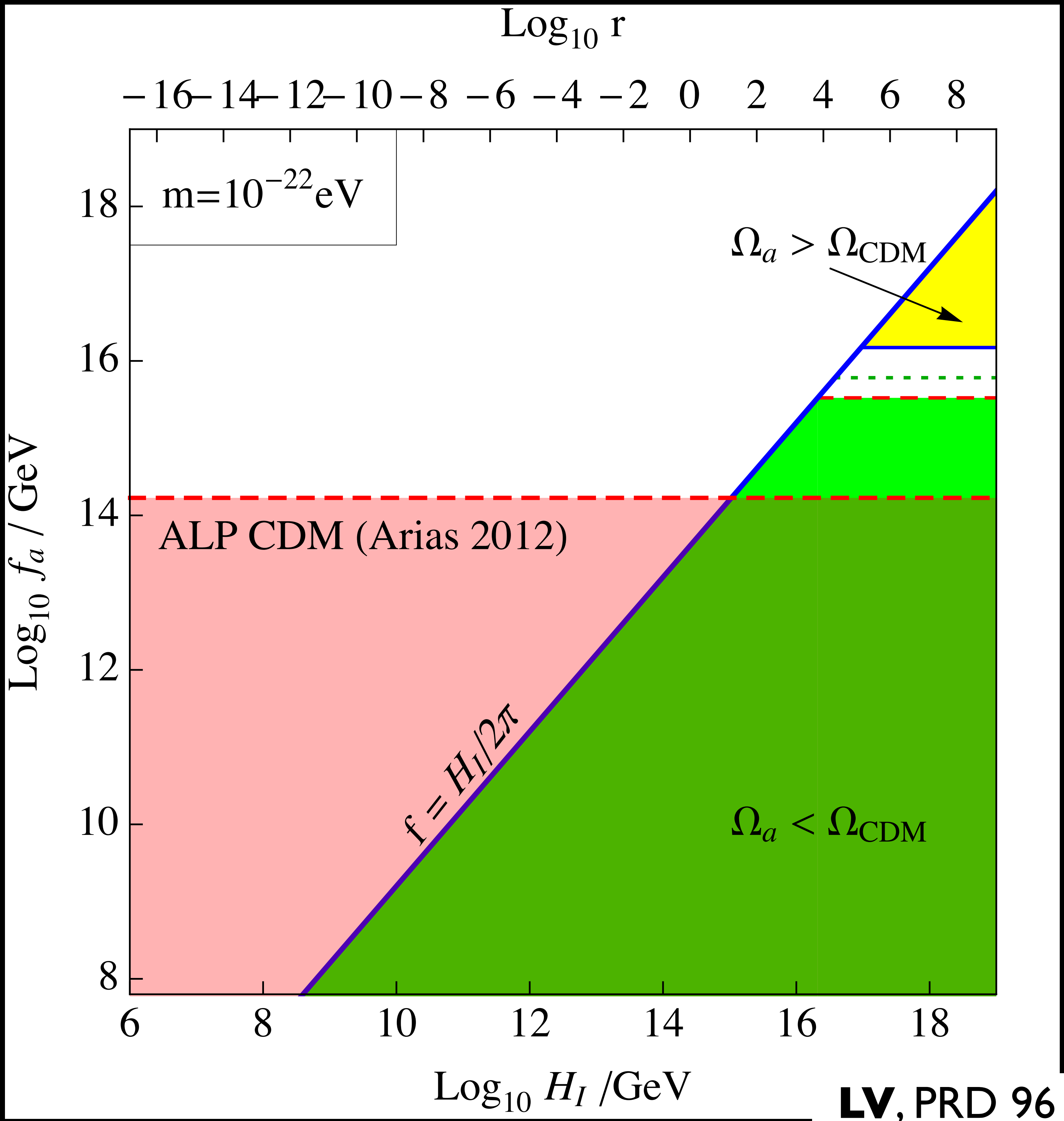

$f \sim$ GUT scale

Hui et al, PRD 95 043541 (2017)

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

LV, PRD 96 023013 (2017)

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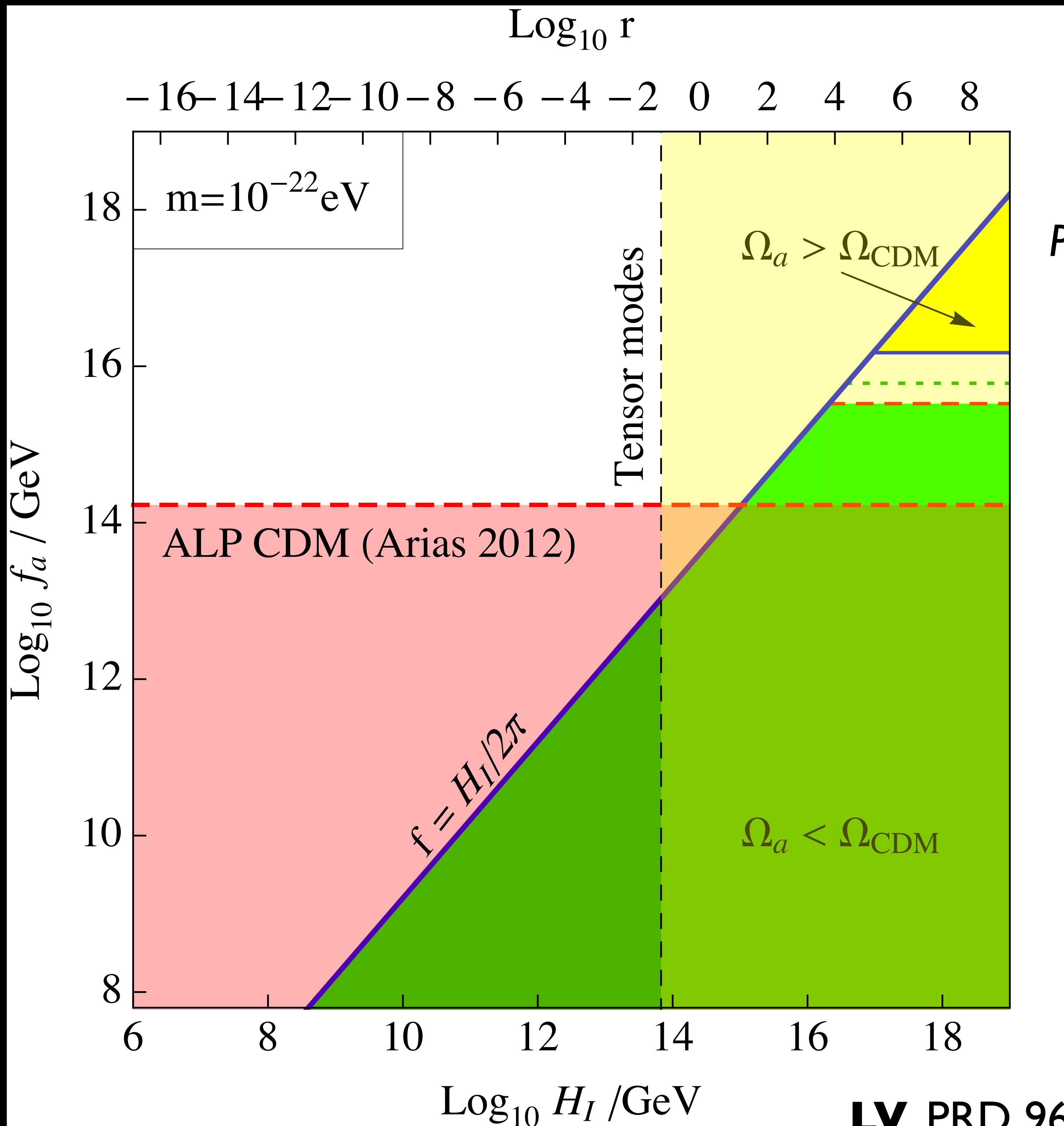

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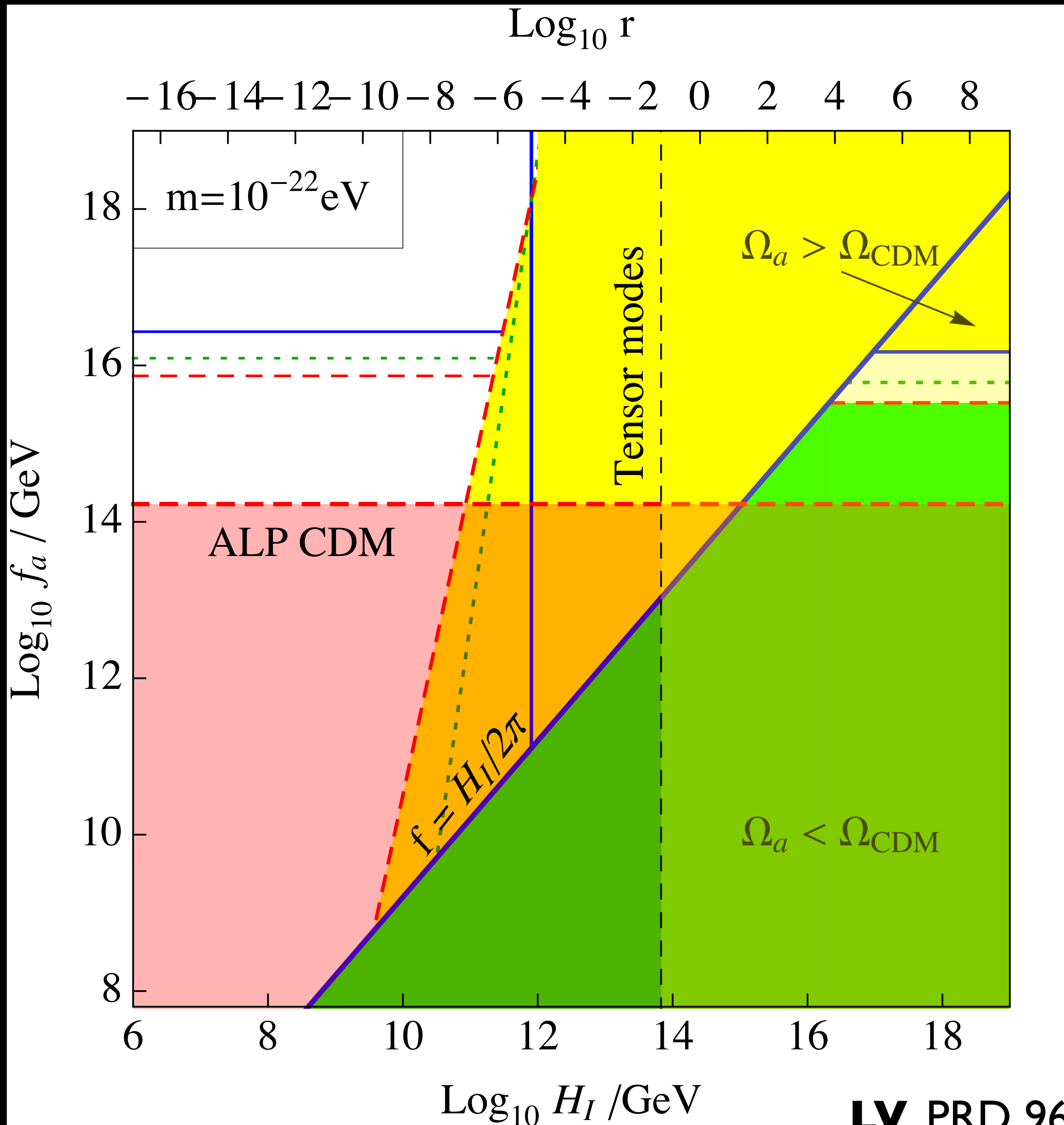
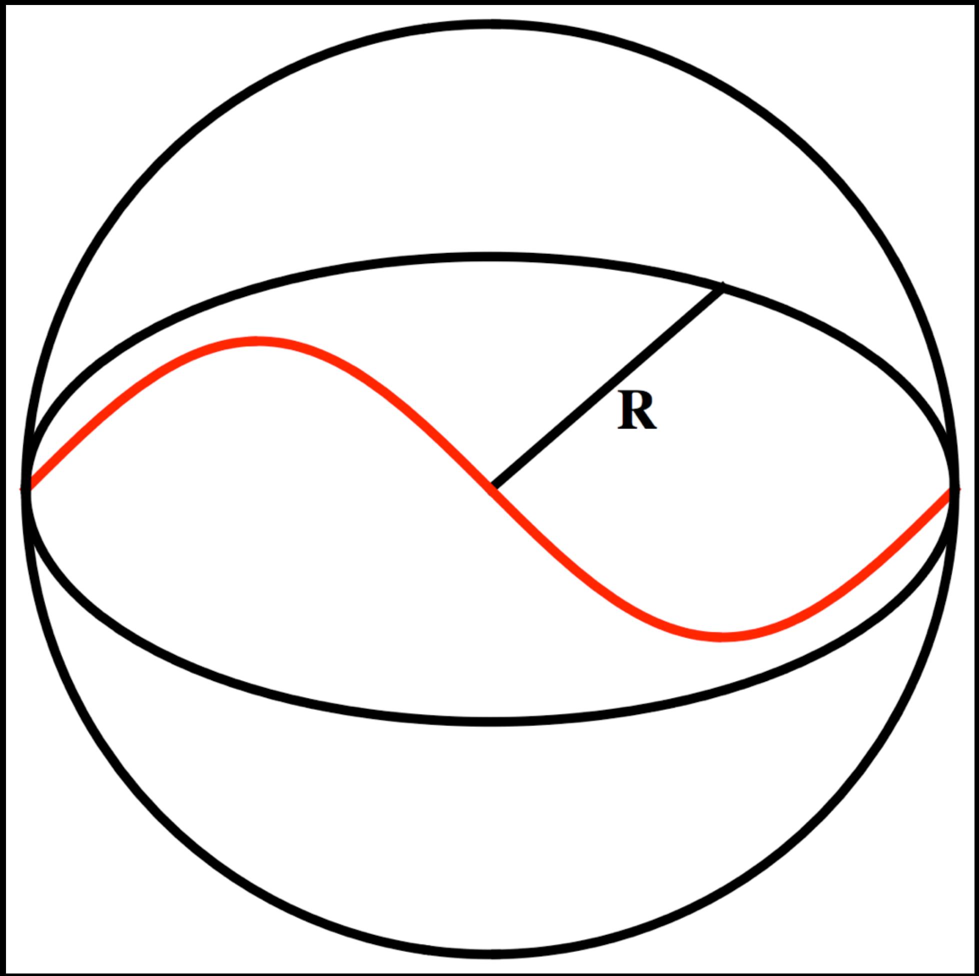


LV, PRD 96 023013 (2017)

Axion Stars



Axions that oscillate in the lowest energy state coherently

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

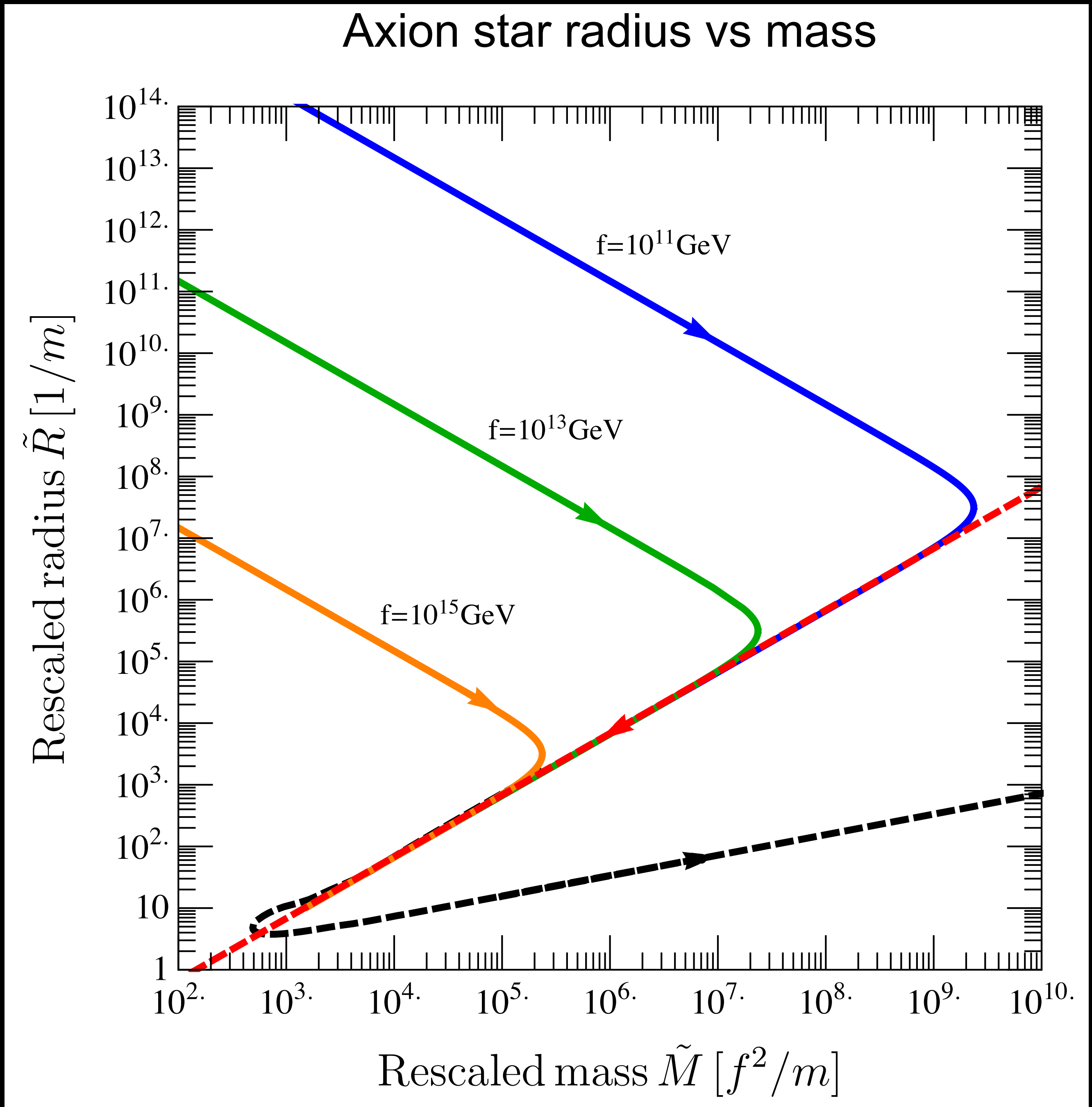
$$M = N\,m$$

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

Schiappacasse and Hertzberg, JCAP **1801**, 037 (2018)

See talk by E. Schiappacasse!

Axion Stars

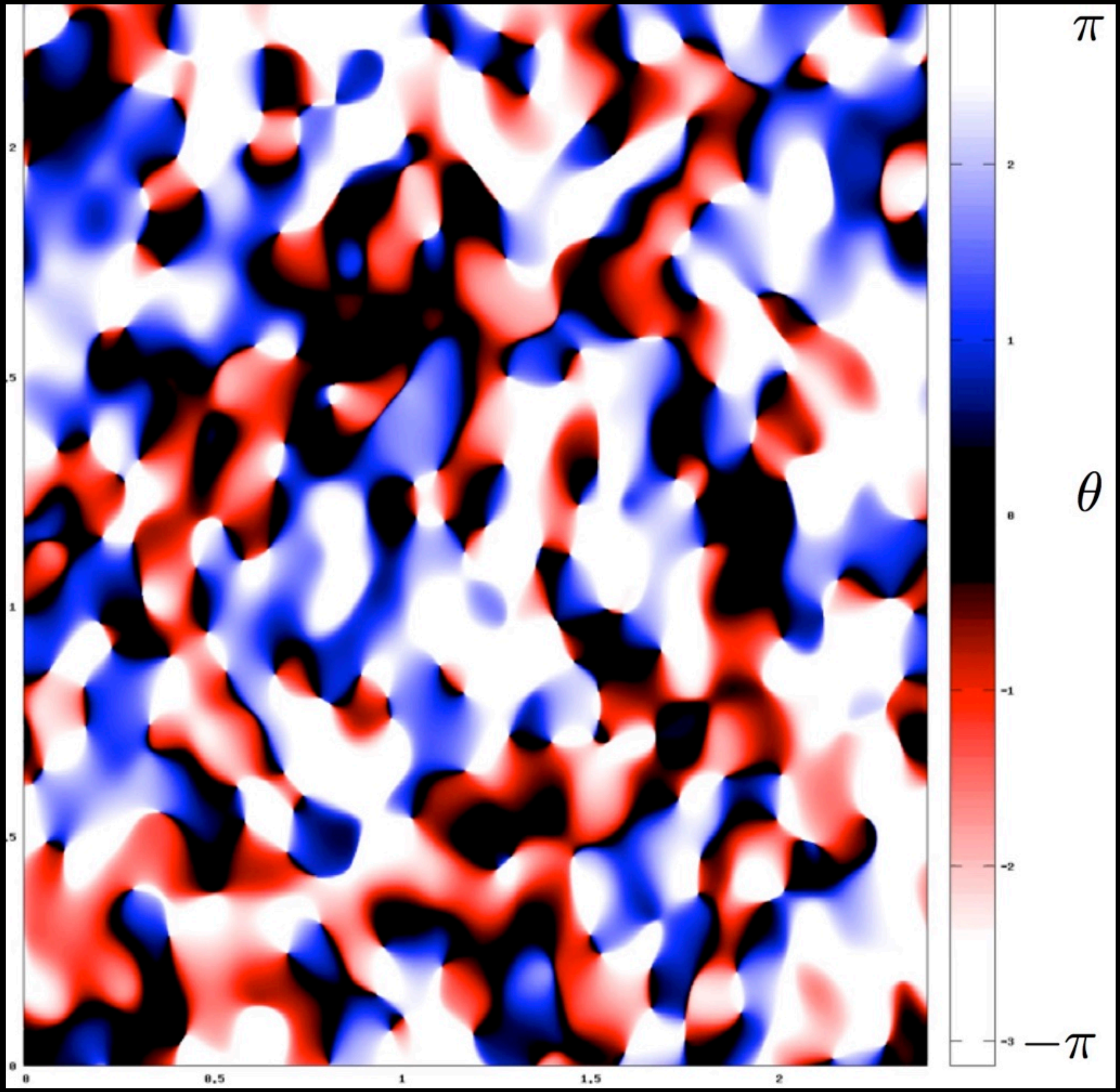


LV, Baum, Redondo, Freese, Wilczek, PLB **777**, 64 (2018)

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

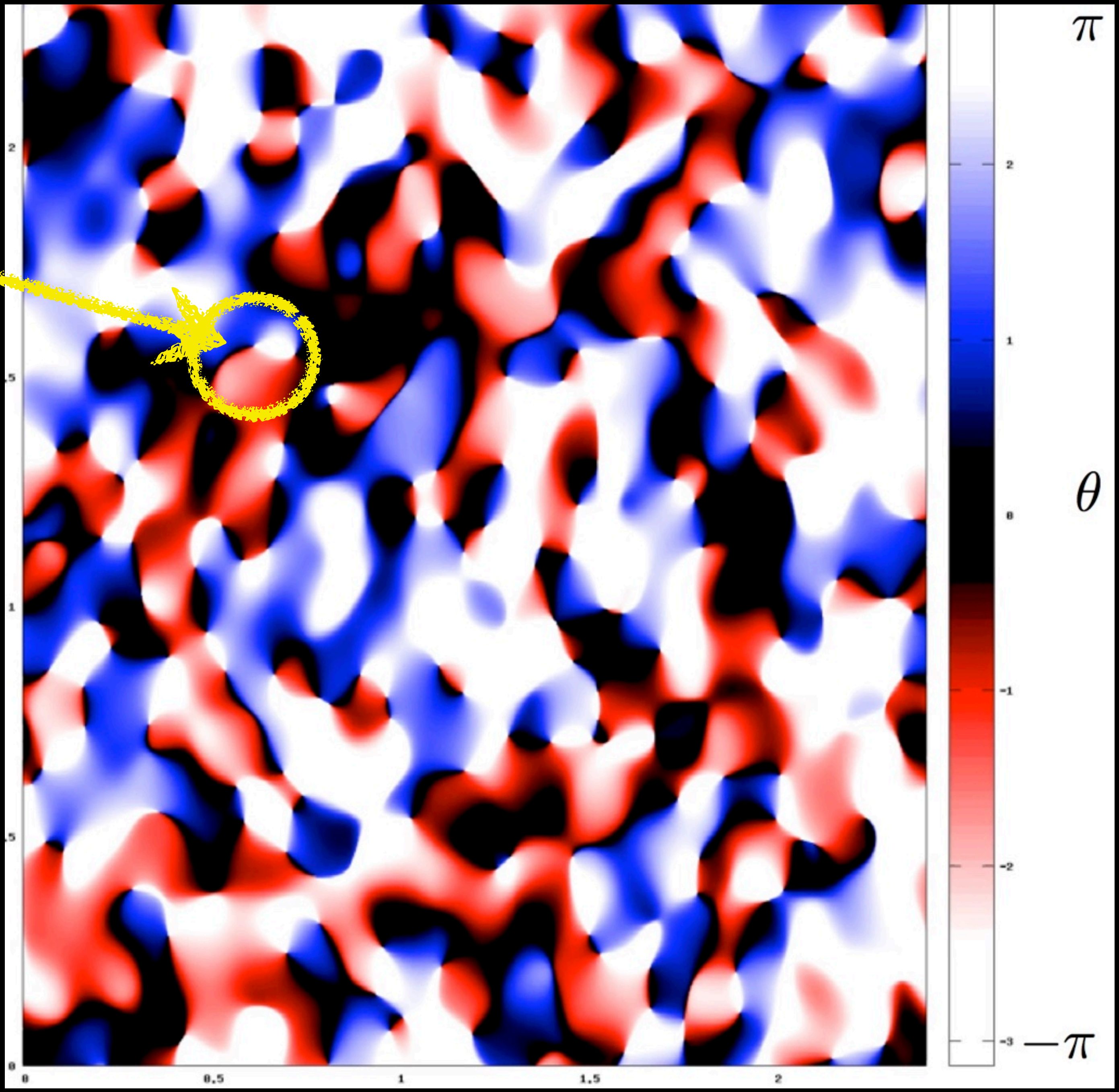
Scenario A: PQ breaks after inflation



Courtesy of J. Redondo

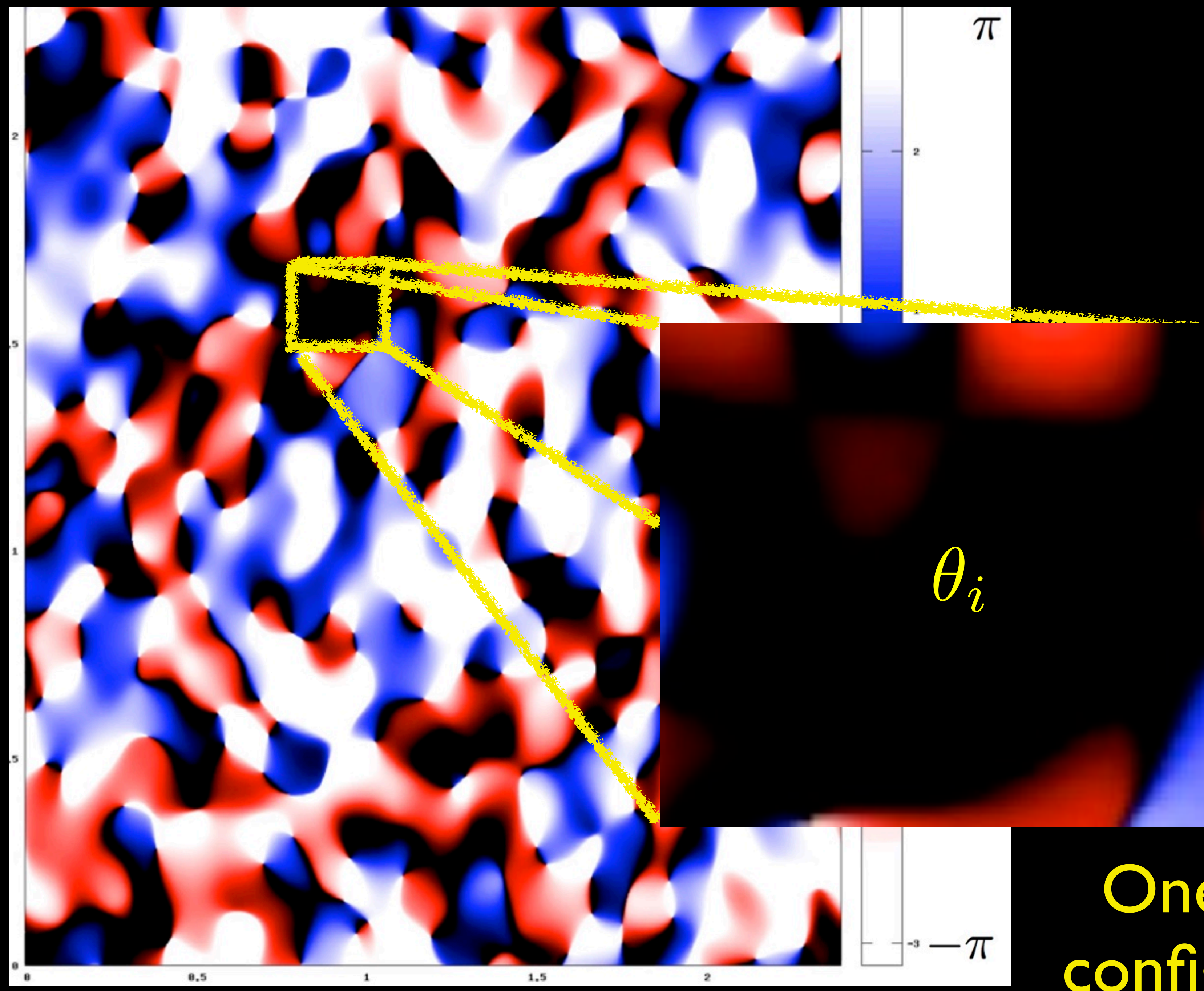
Scenario A: PQ breaks after inflation

Axion strings!



CDM axions also from defects...

Scenario B: PQ breaks during inflation



One initial configuration is singled out