Axions and Axion-Like Particles as the CDM

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Stockholm University & NORDITA

Based on:

LV *et al.*, astro-ph/1710.08910, submitted to PLB

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)

Timeline of the axion theory

- Strong CP problem (QCD does not violate CP)

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

with $\bar{\theta} < 10^{-9}$ (measured electric dipole of the neutron)

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Wilczek, PRL **40** 279 (1978); Weinberg, PRL **40** 223 (1978)

Axions "cleanse" the PQ problem

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Kim, PRL **43** 103 (1979); Shifman *et al*, Nuc Phys. B **166** 493 (1980)
Dine *et al*, Phys. Lett. B **104** 199 (1981); Zhitnitsky, SJNP B **31** (1980)

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- 1981-1983 Axion as the CDM

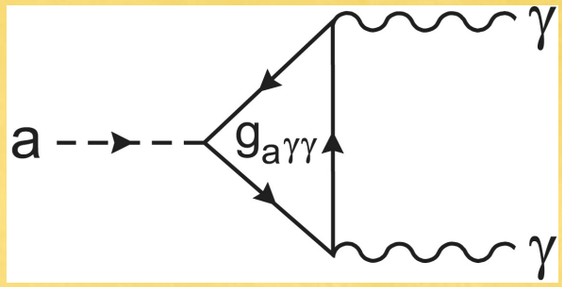
Dine *et al*, PLB **104** 199 (1981); Preskill *et al*, PLB **120** 127 (1983)

Axion physics primer

Motivations

QCD is CP-conserved by PQ symmetry

- Effective axion-photon coupling
- $g_{a\gamma\gamma} \propto m_a$
- $m_a f_a \propto \Lambda^2_{\rm QCD}$

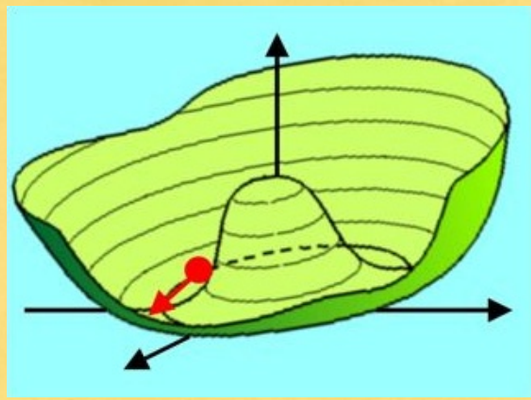


Axion cosmology

Axions are non-thermal relics

Non-relativistic, so **CDM candidates**

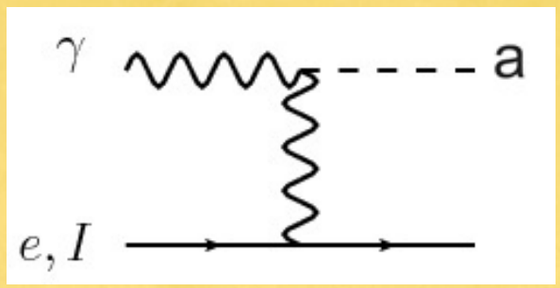
Axion mass $\sim 10 \mu eV$ (but see later....)



Solar & Stellar axions

"Primakoff" effect, look for axions emitted

CAST, Barth *et al,* JCAP **1305** 010 (2013)
IAXO, Armengaud *et al,* arXiv:1401.3233



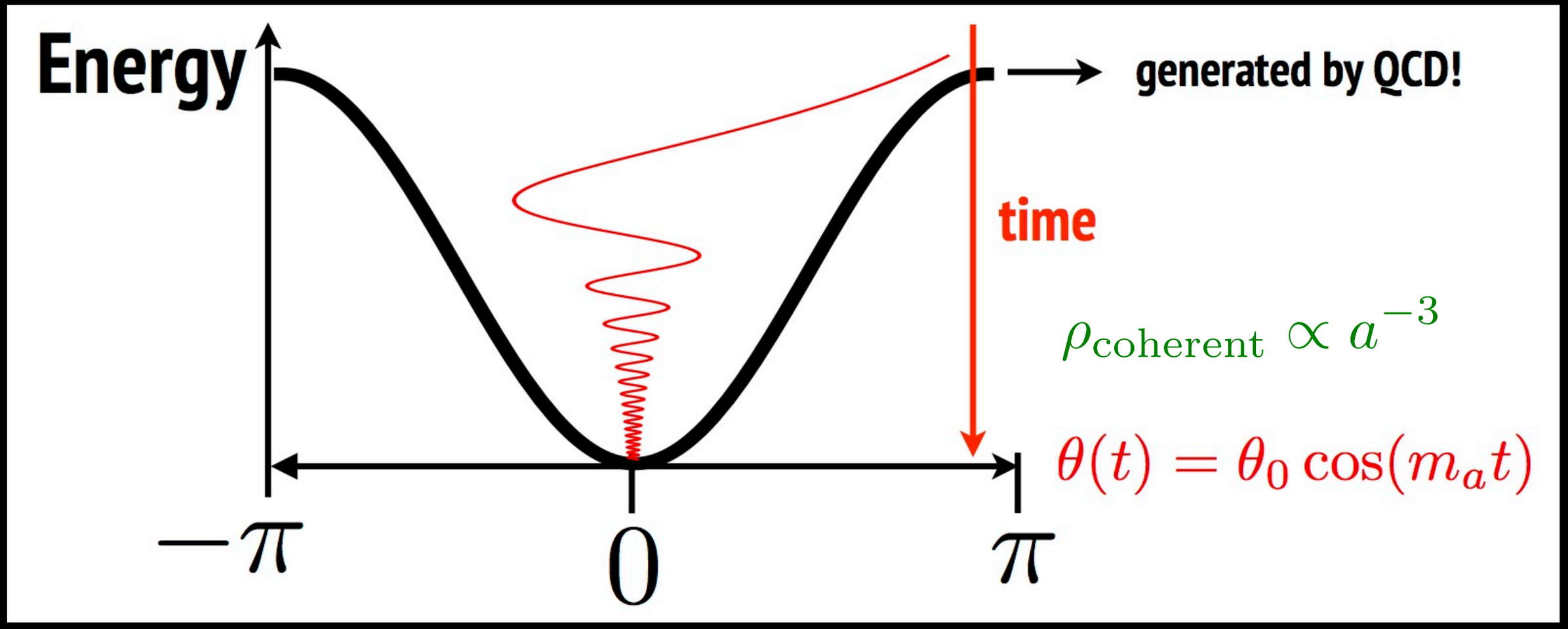
Cavity and other lab searches

* Axion-photon convert in strong **B** field
Sikivie, PRL **51** 1415 (1983), best for $m_a \lesssim 10\,\mu\mathrm{eV}$
ADMX, Asztalos *et al,* PRL **104** 041301 (2010)
ADMXHF, Brubaker *et al,* PRL **118** 061302(2017)
CULTASK, Chung, PoS CORFU2015 **047** (2016)

* CASPER NMR: Budker, PRX **4** 021030 (2014)

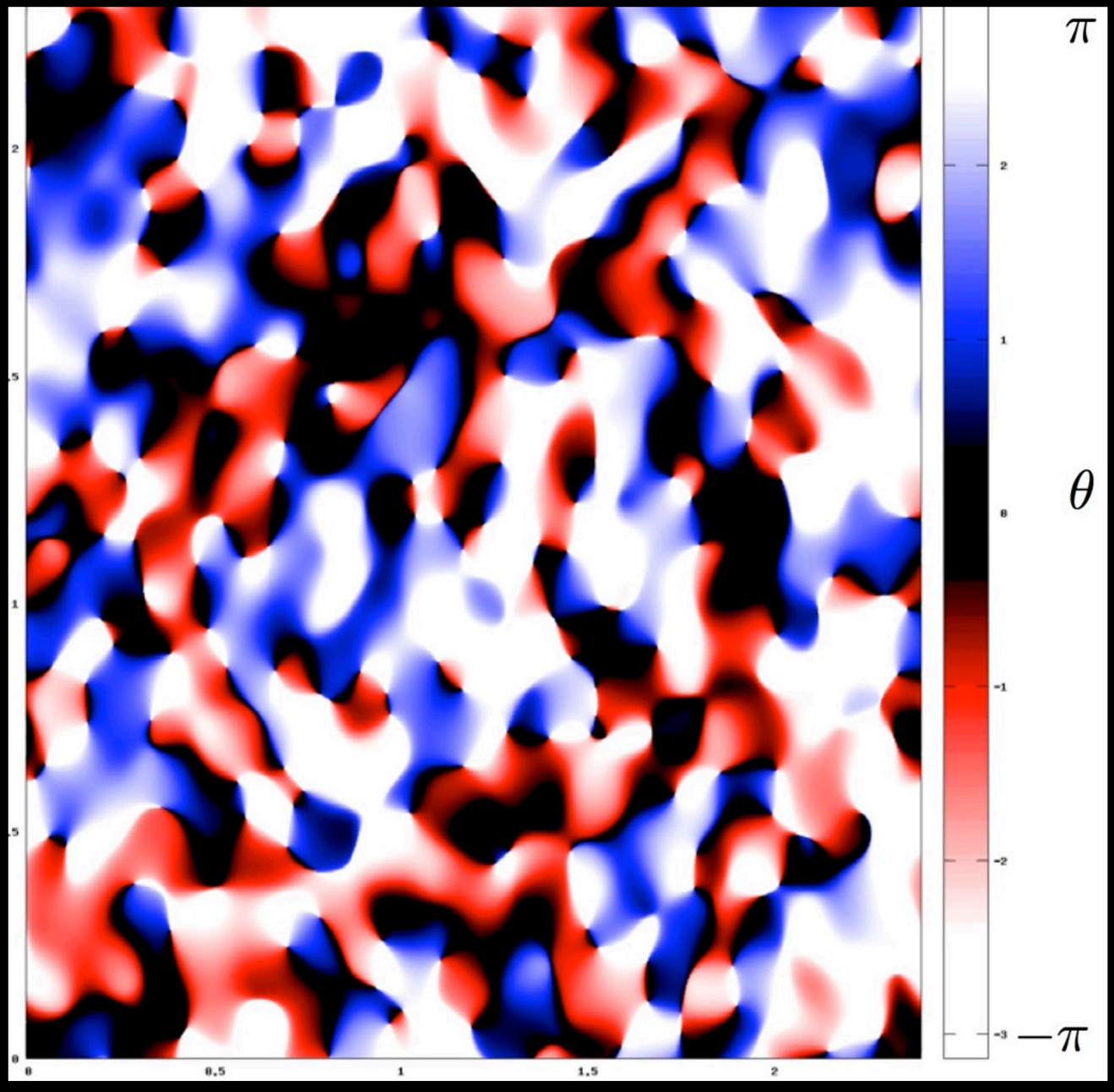
* MadMAX Haloscope, PRL **118**, 091801(2017)

Axion coherent oscillations



Courtesy of J. Redondo

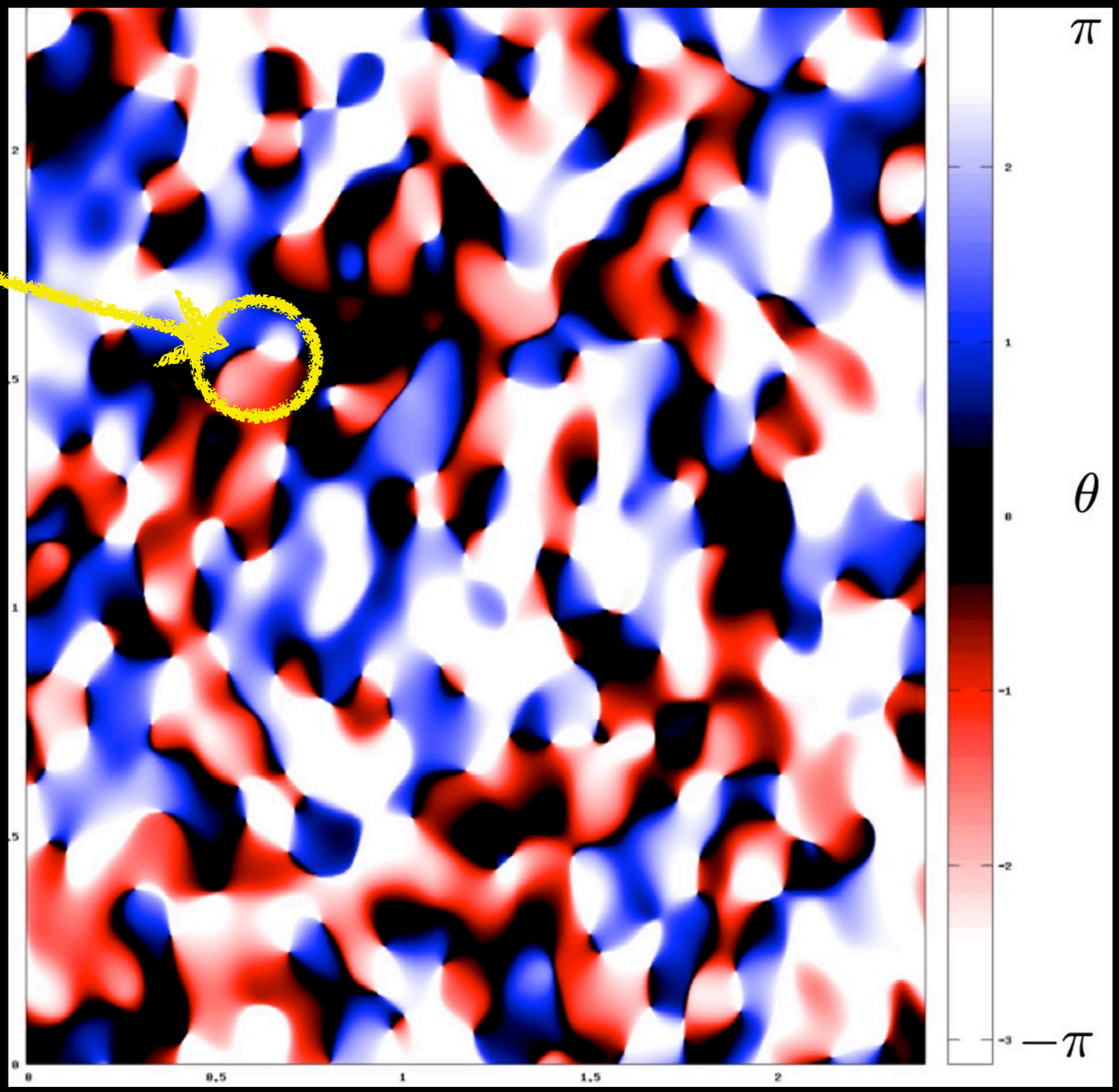
Scenario A: PQ breaks after inflation



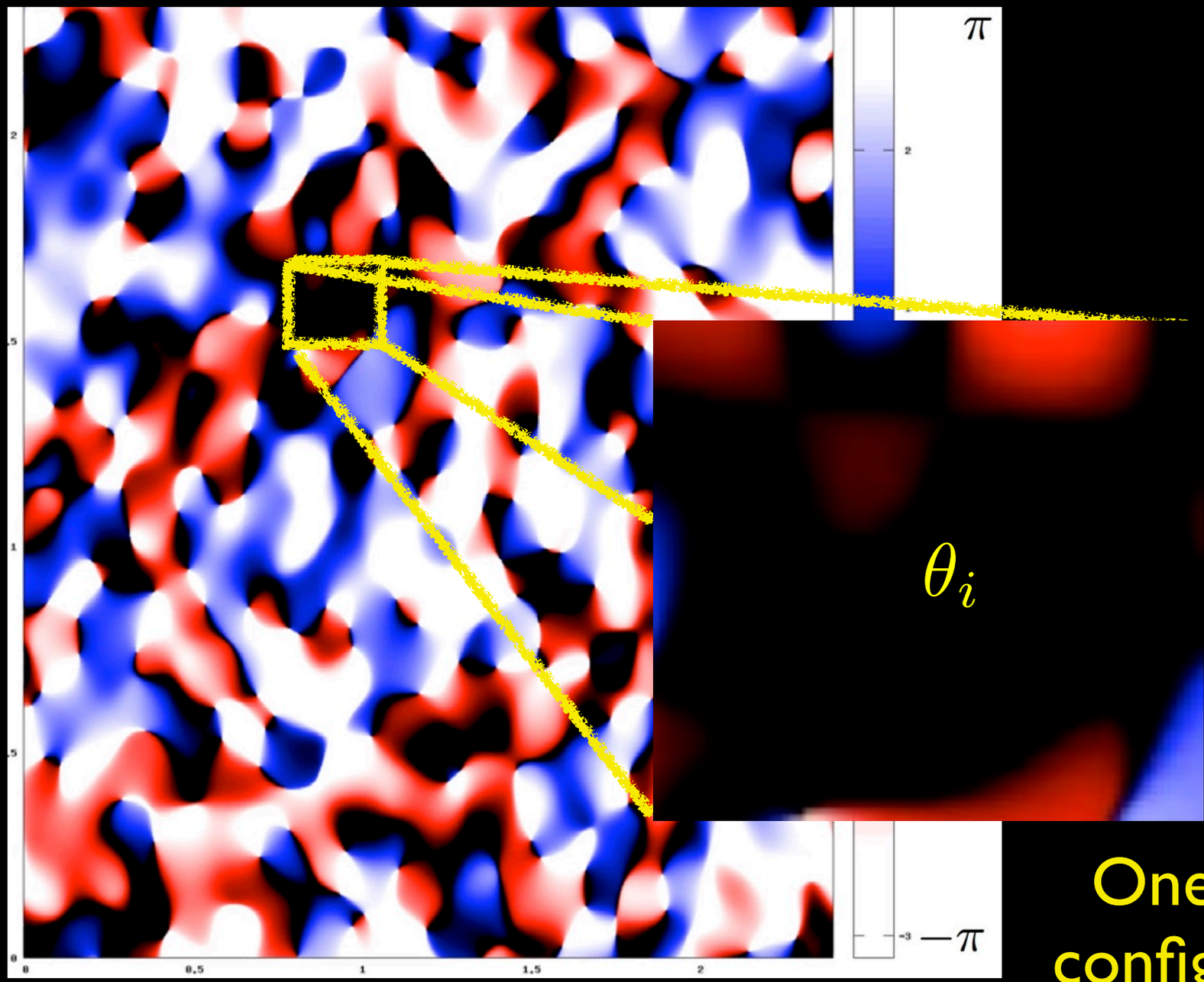
Scenario A: PQ breaks after inflation

Axion strings!

CDM axions also from defects...



Scenario B: PQ breaks during inflation

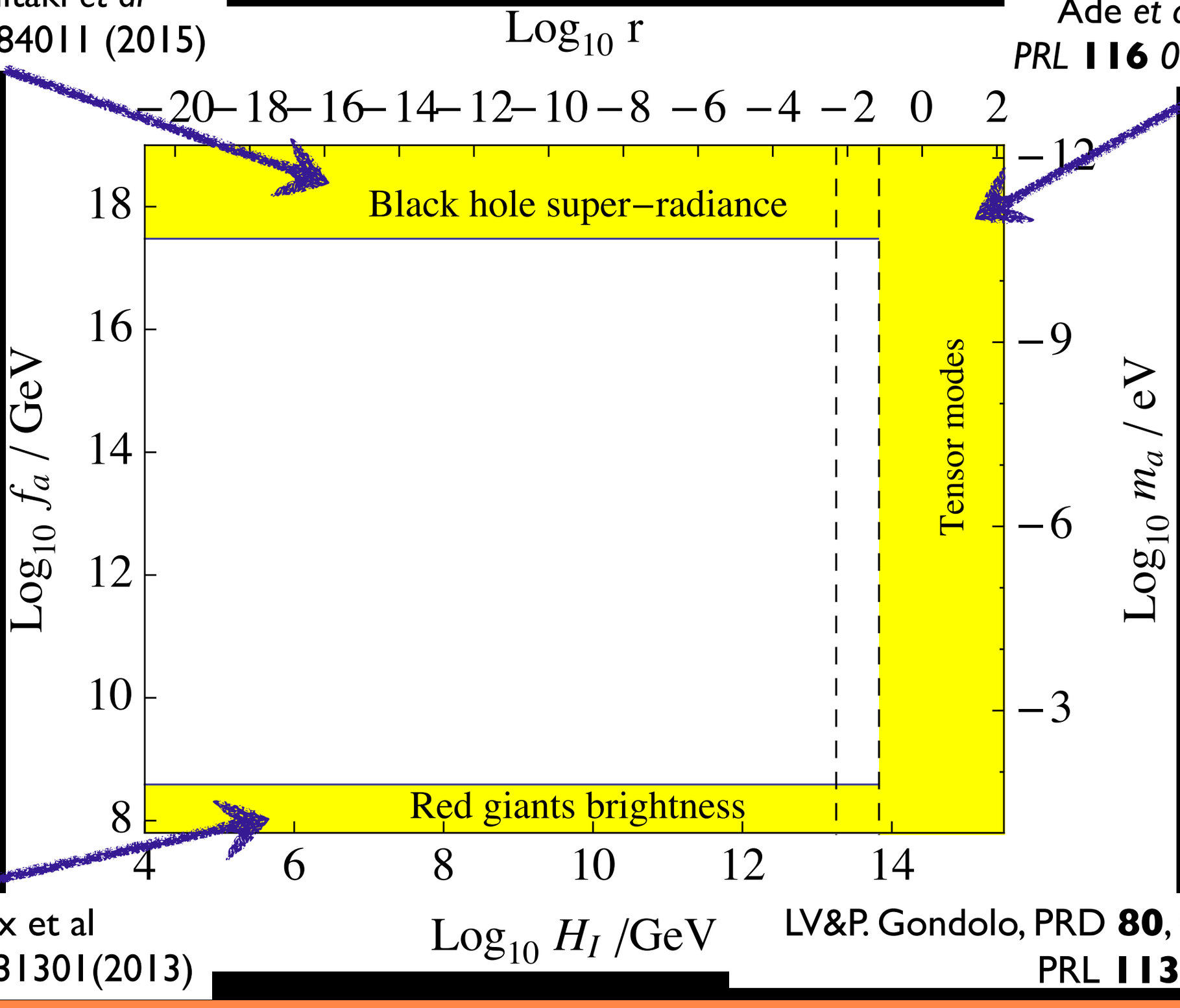


One initial configuration is singled out

Axion parameter space

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, PRD **80**, 035024 (2009);
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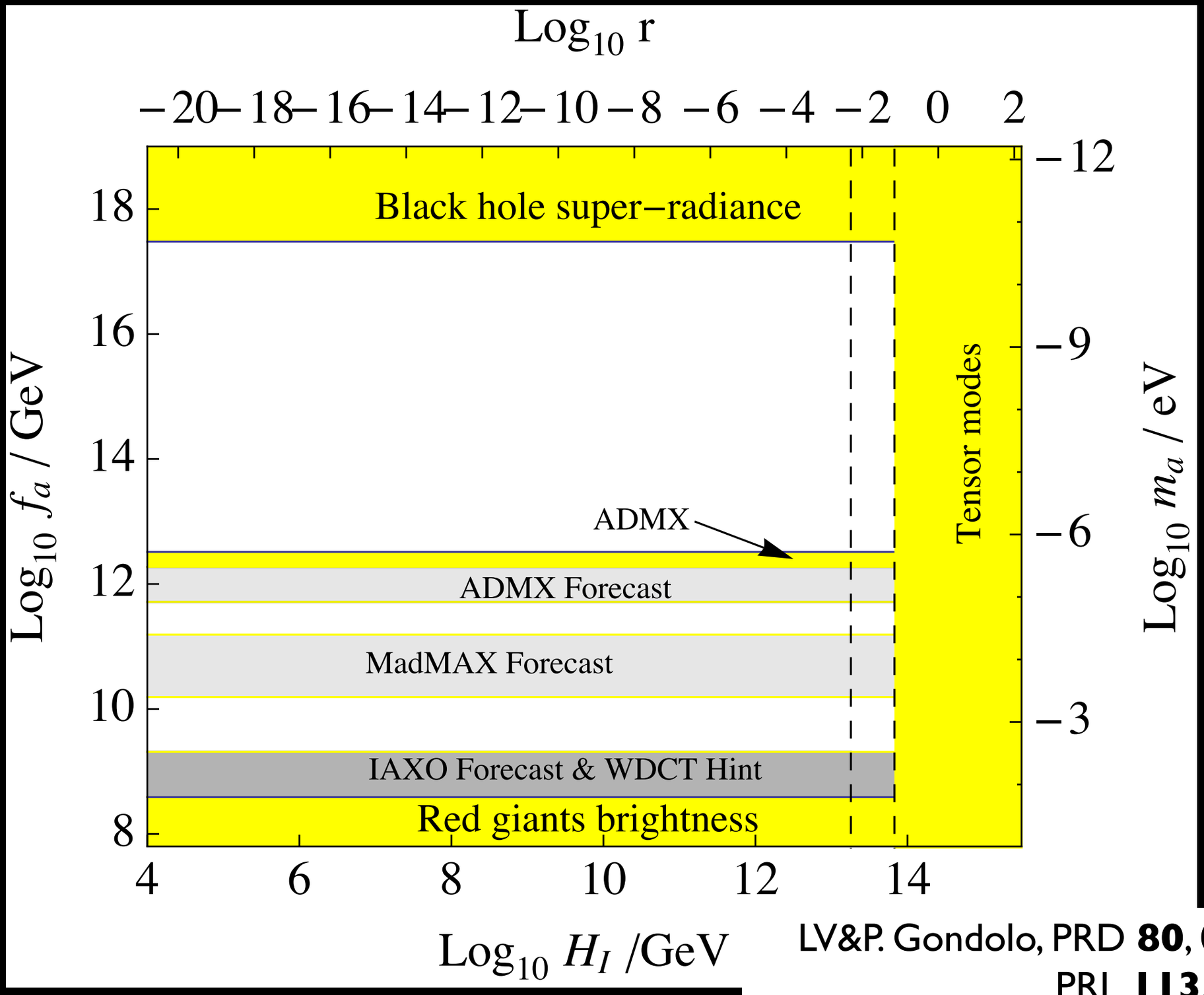

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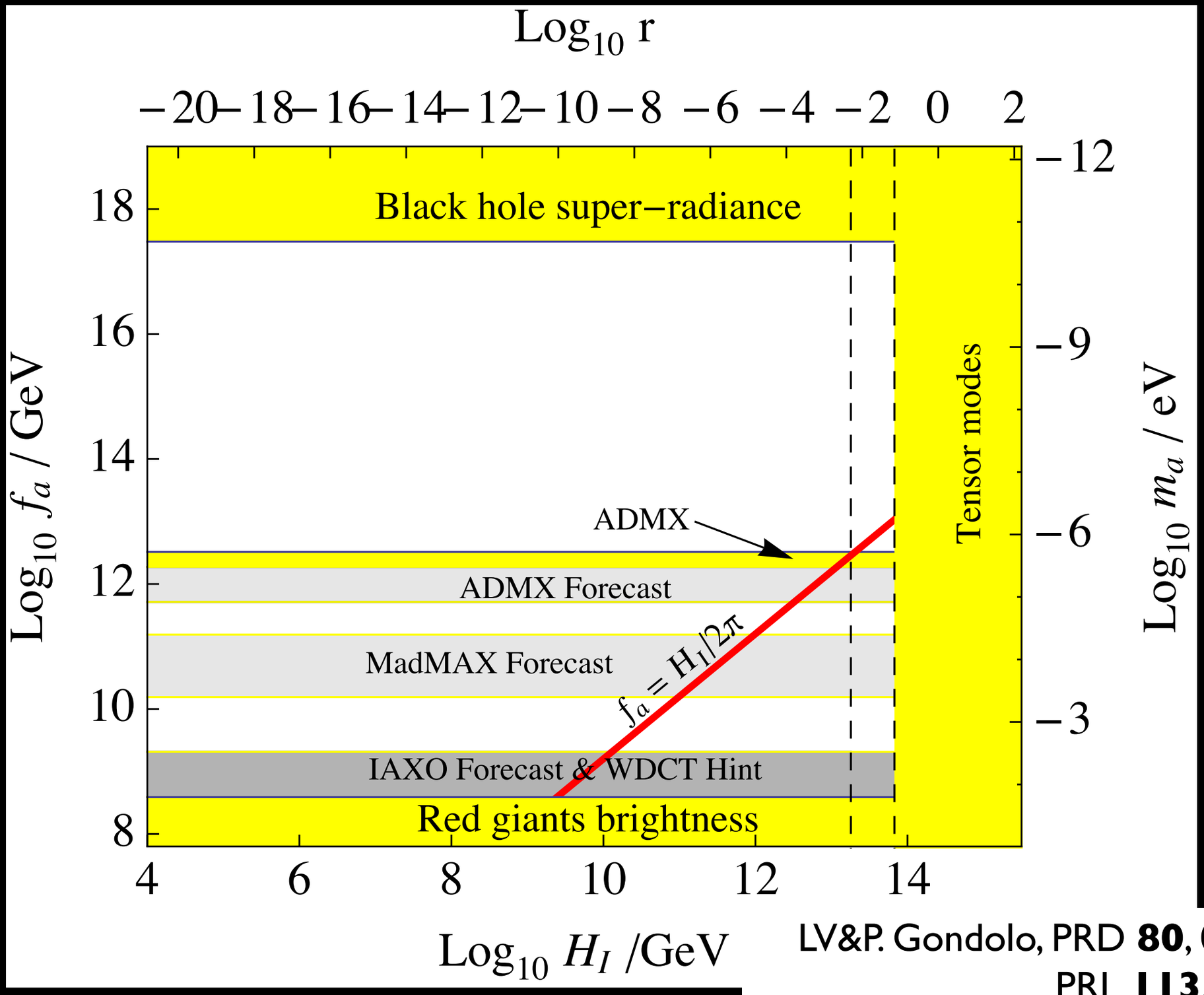

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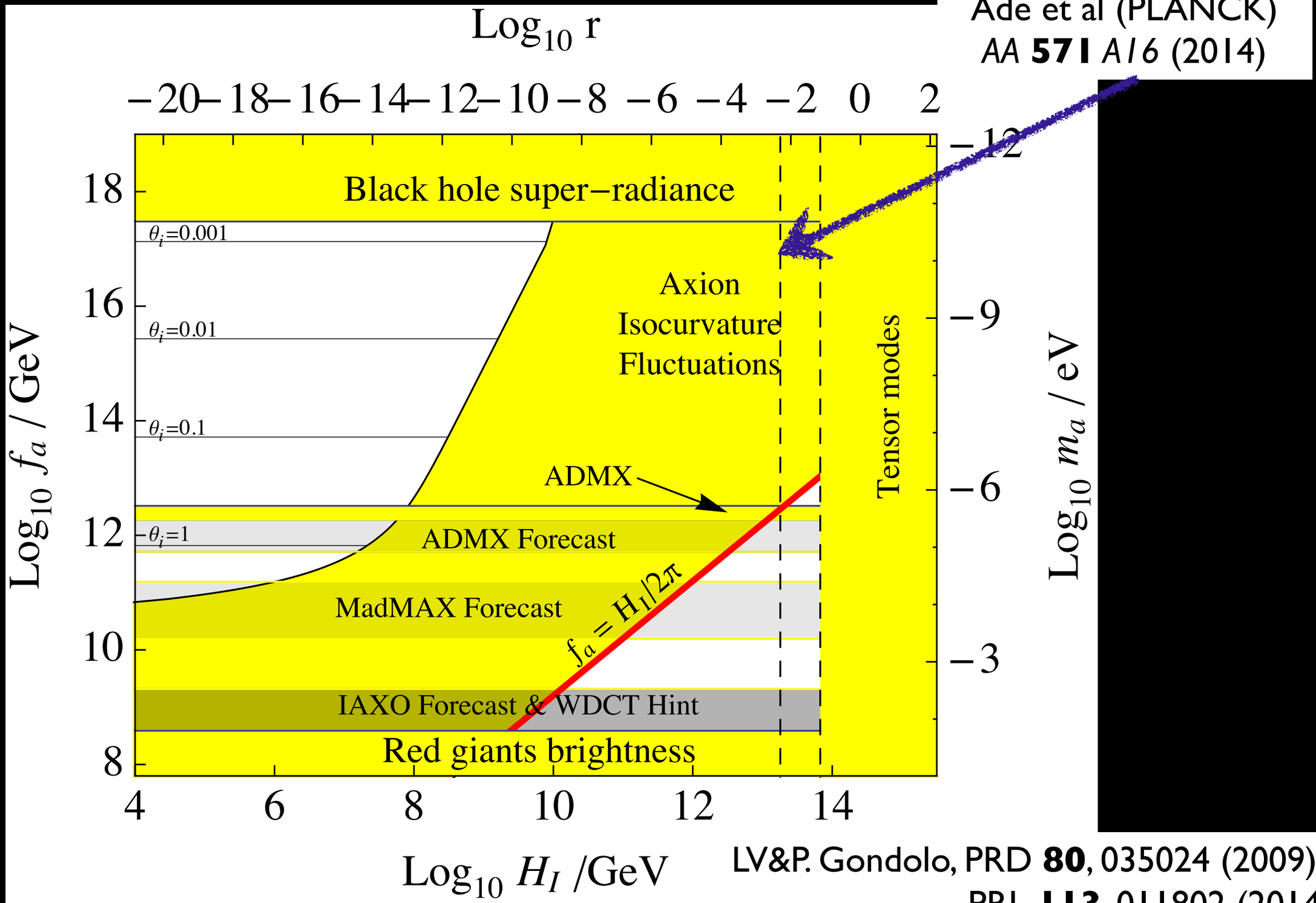

Ade et al (PLANCK)
AA **571** *A16* (2014)

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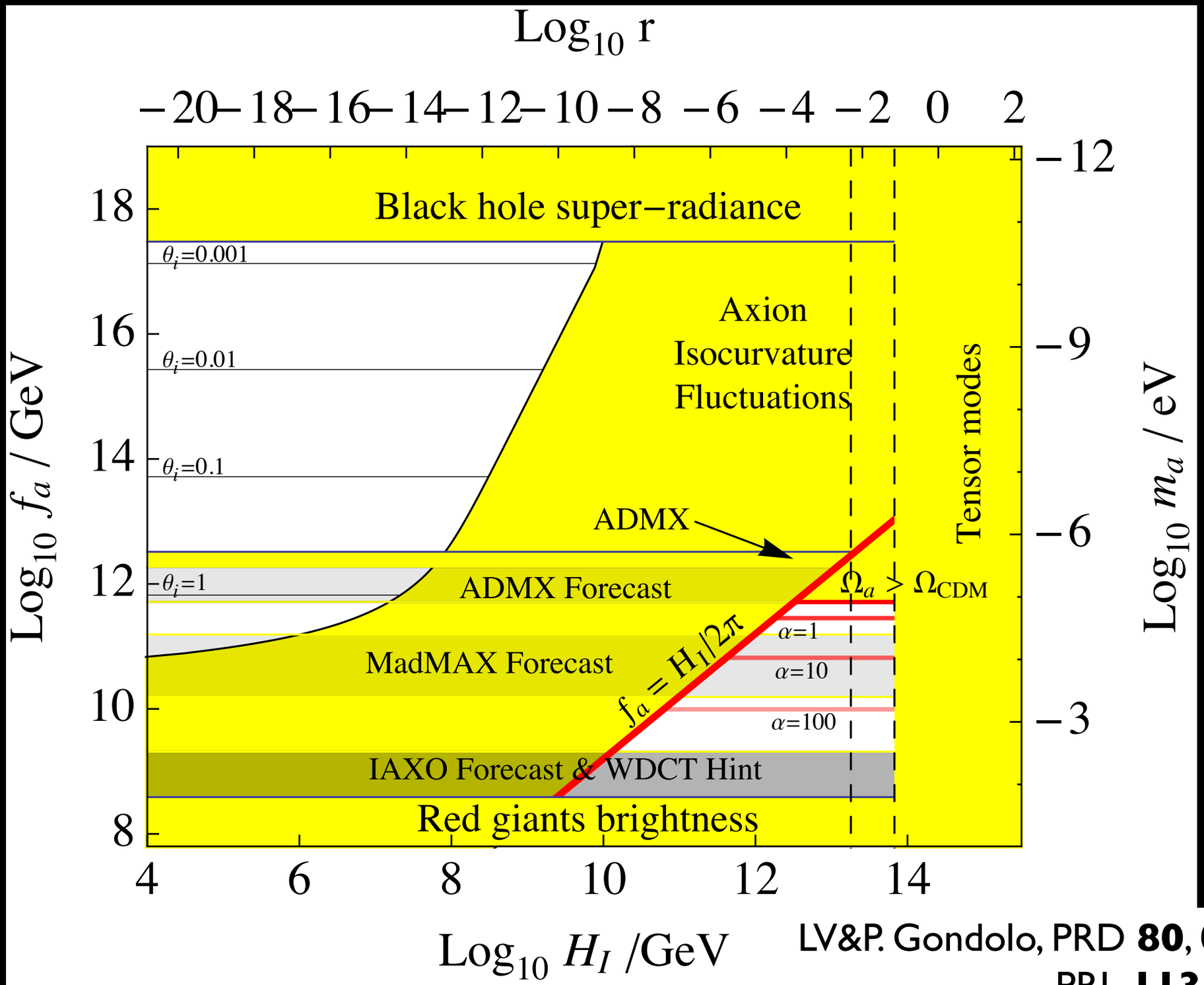

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Ultra-light axions?

- 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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Kamionkowski&Liddle (1999)

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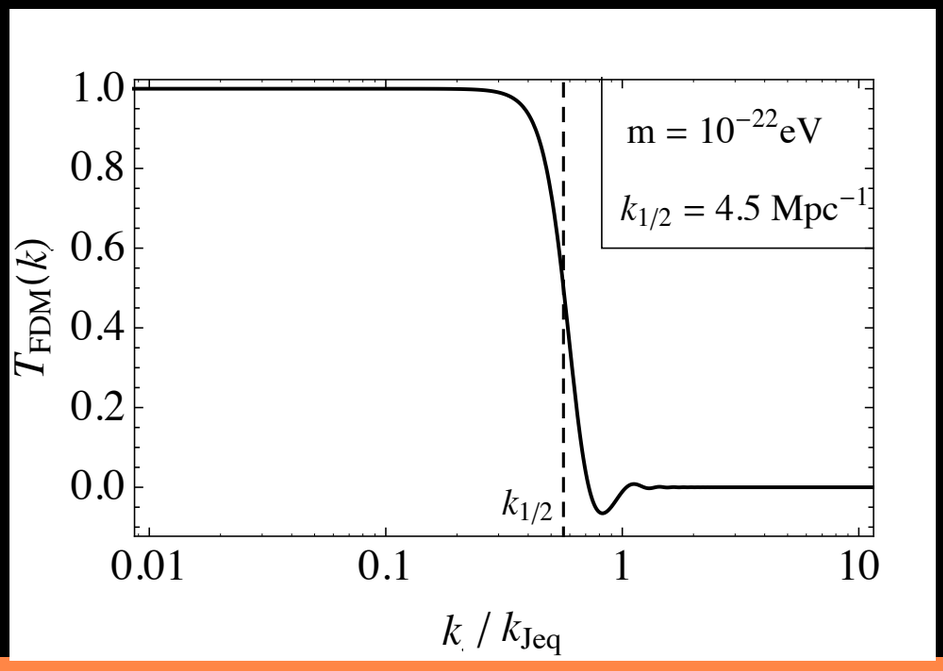
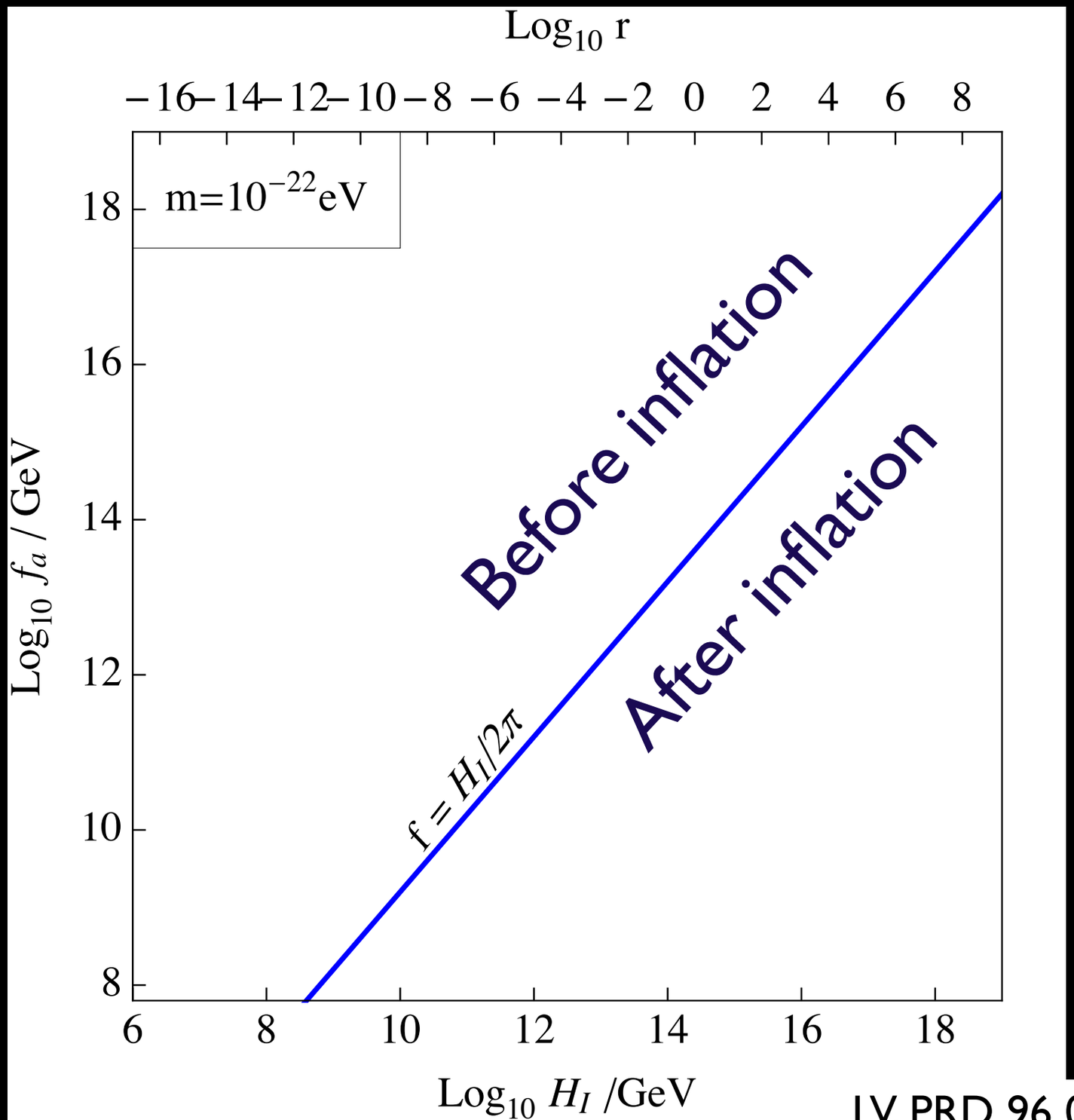
Kamionkowski&Liddle (1999)

- 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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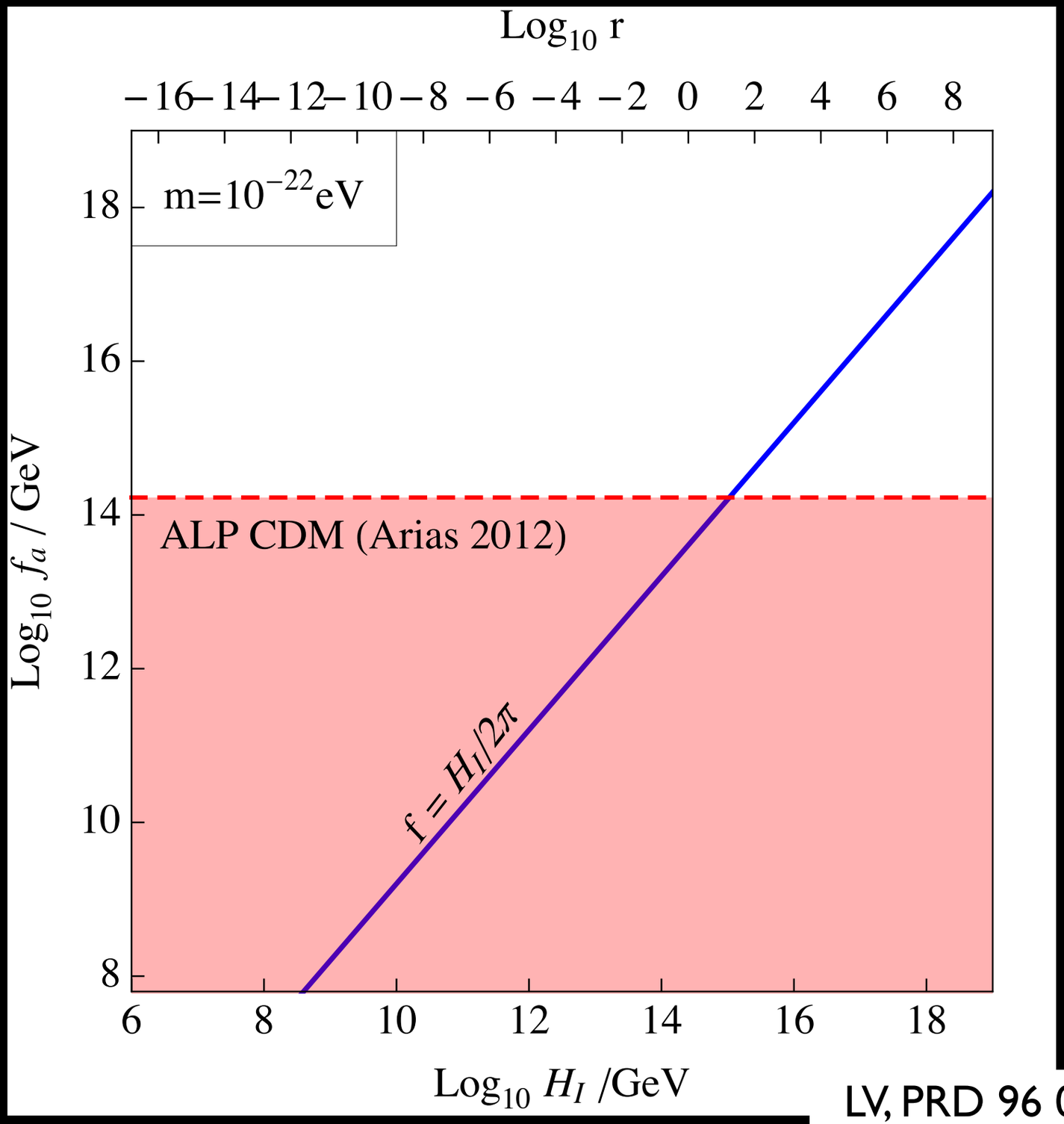

LV, PRD 96 023013 (2017)

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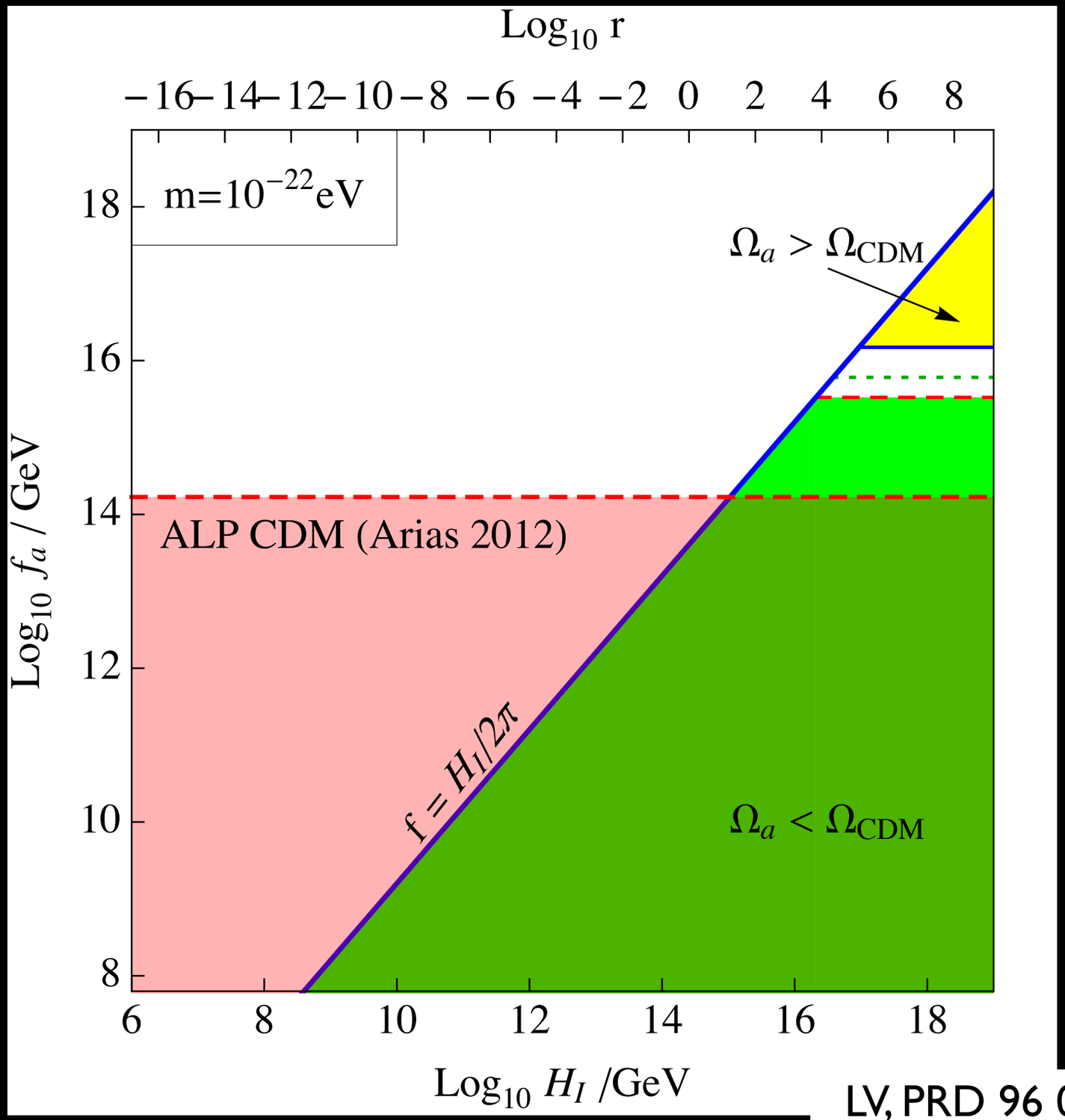

$f \sim$ GUT scale

Hui et al, PRD 95 043541 (2017)

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

LV, PRD 96 023013 (2017)

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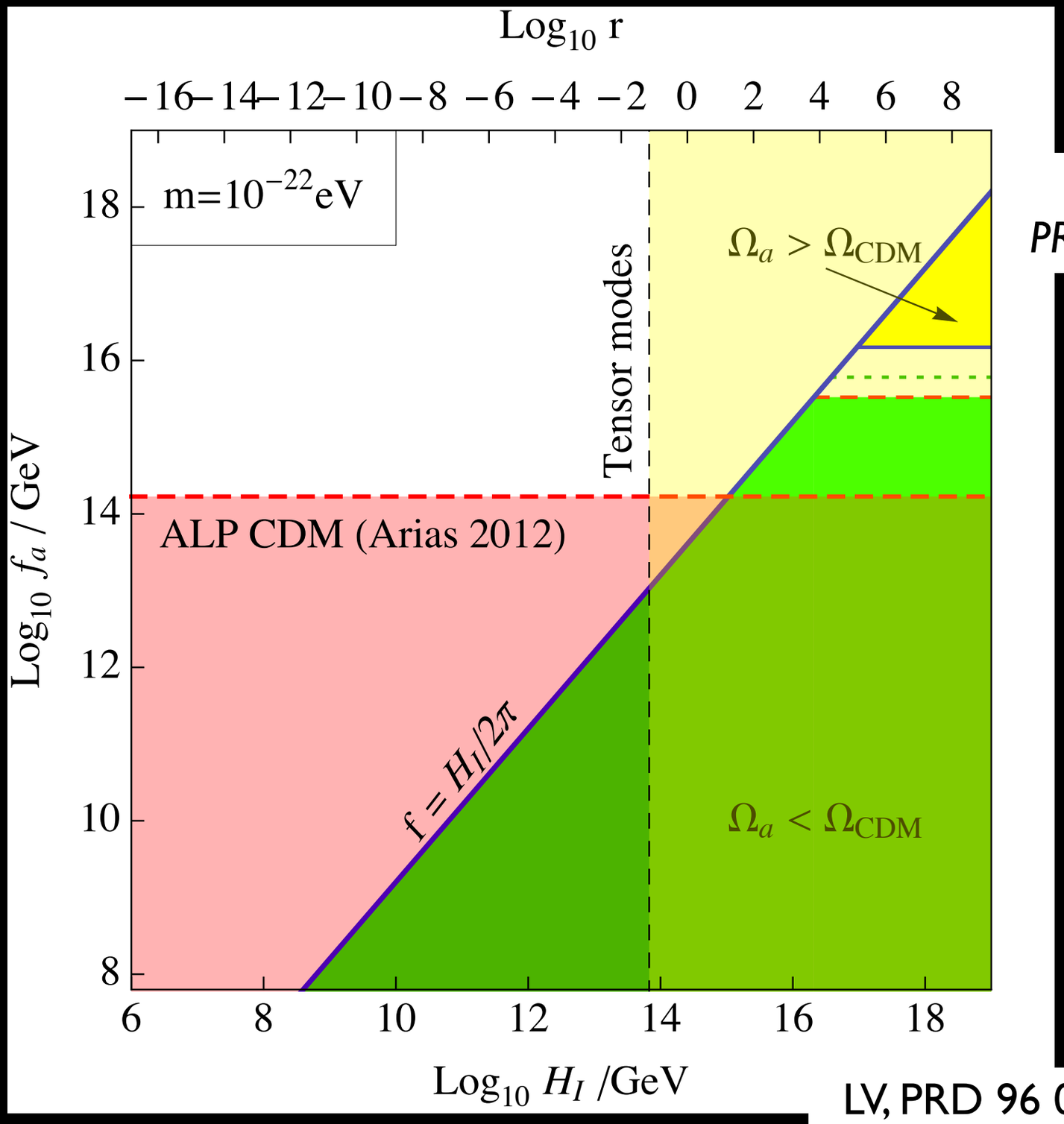

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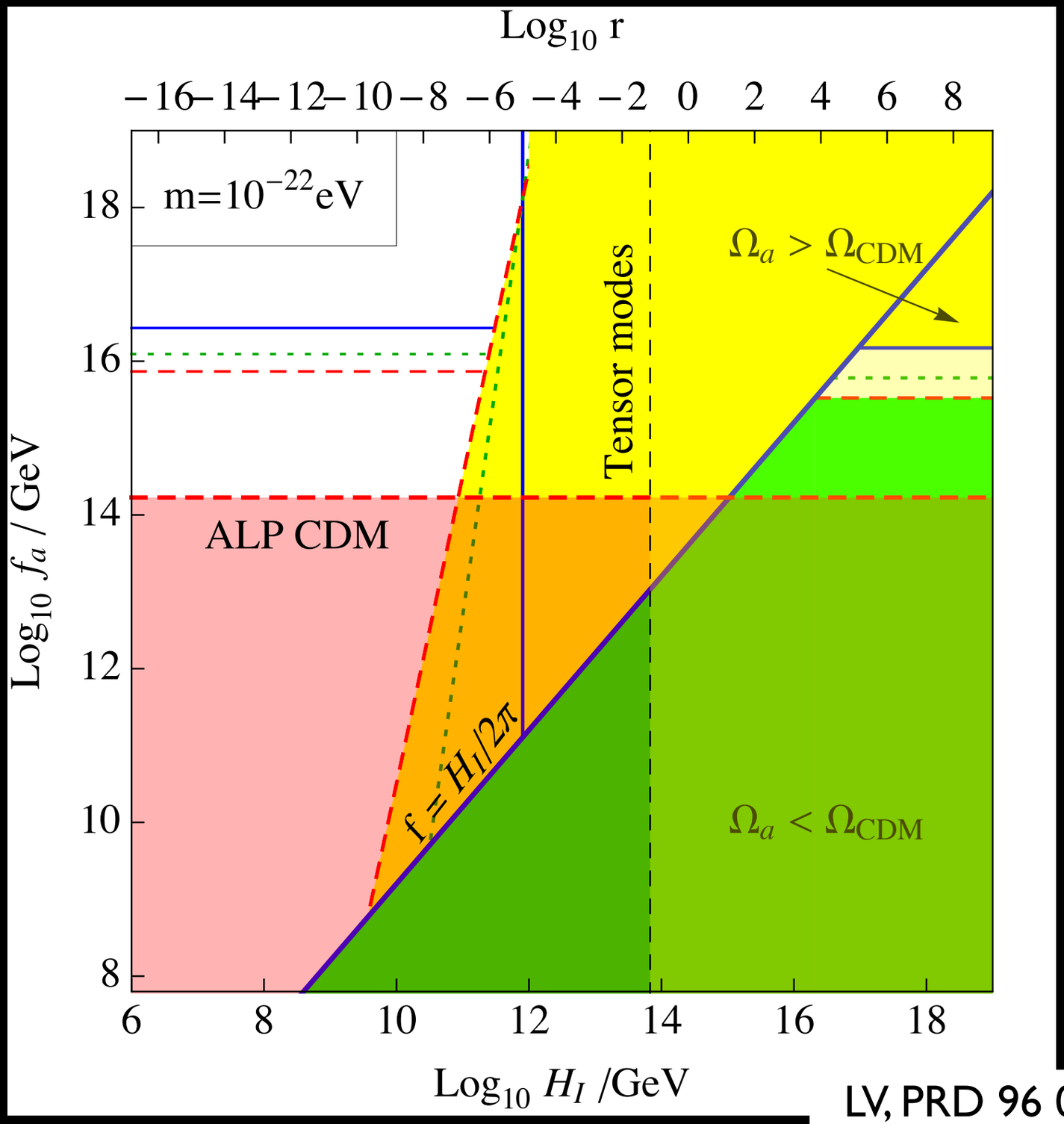

LV, PRD 96 023013 (2017)

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;

- Ultra-light axions models are difficult to motivate given PLANCK-BICEP2 data