Axions and Axion-Like Particles as the CDM

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Based on:

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

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

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

LV, accepted in PRD (2017)

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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Peccei & Quinn, PRL **38** 1440 (1977)

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

Axions "cleanse" the CP problem

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Kim, PRL **43** 103 (1979); Shifman *et al*, Nuc Phys. B **166** 493 (1980)
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- 1981-1983 Axion as the CDM

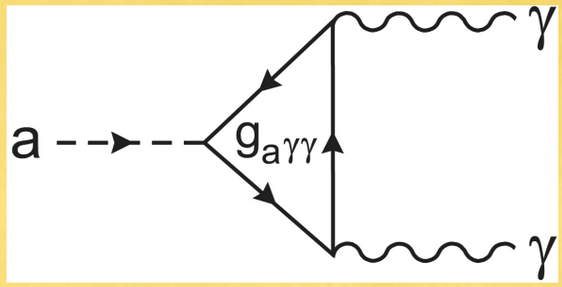
Dine *et al*, PLB **104** 199 (1981); Preskill *et al*, PLB **120** 127 (1983)

Axion physics primer

Motivations

QCD is CP-conserved by PQ symmetry

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

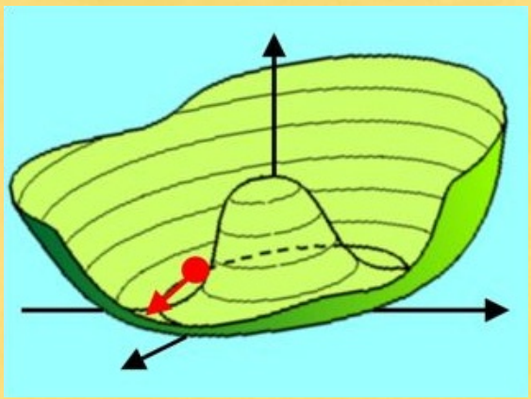


Axion cosmology

Axions are non-thermal relics

Non-relativistic, so **CDM candidates**

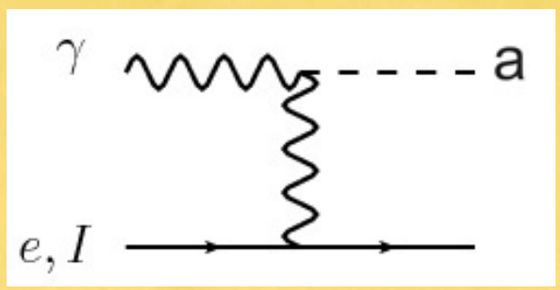
Axion mass $\sim 10 \mu eV$ (but see later....)



Solar & Stellar axions

"Primakoff" effect, look for axions emitted

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



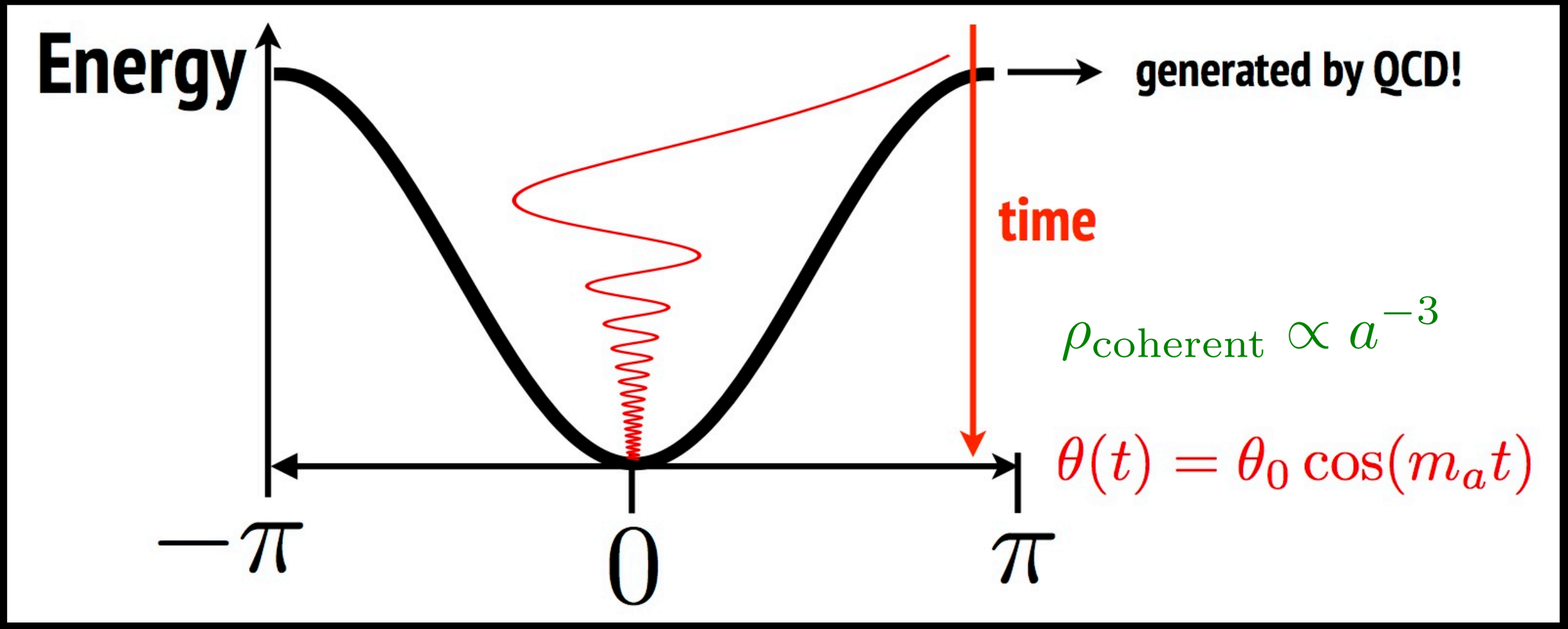
Cavity and other lab searches

* 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)

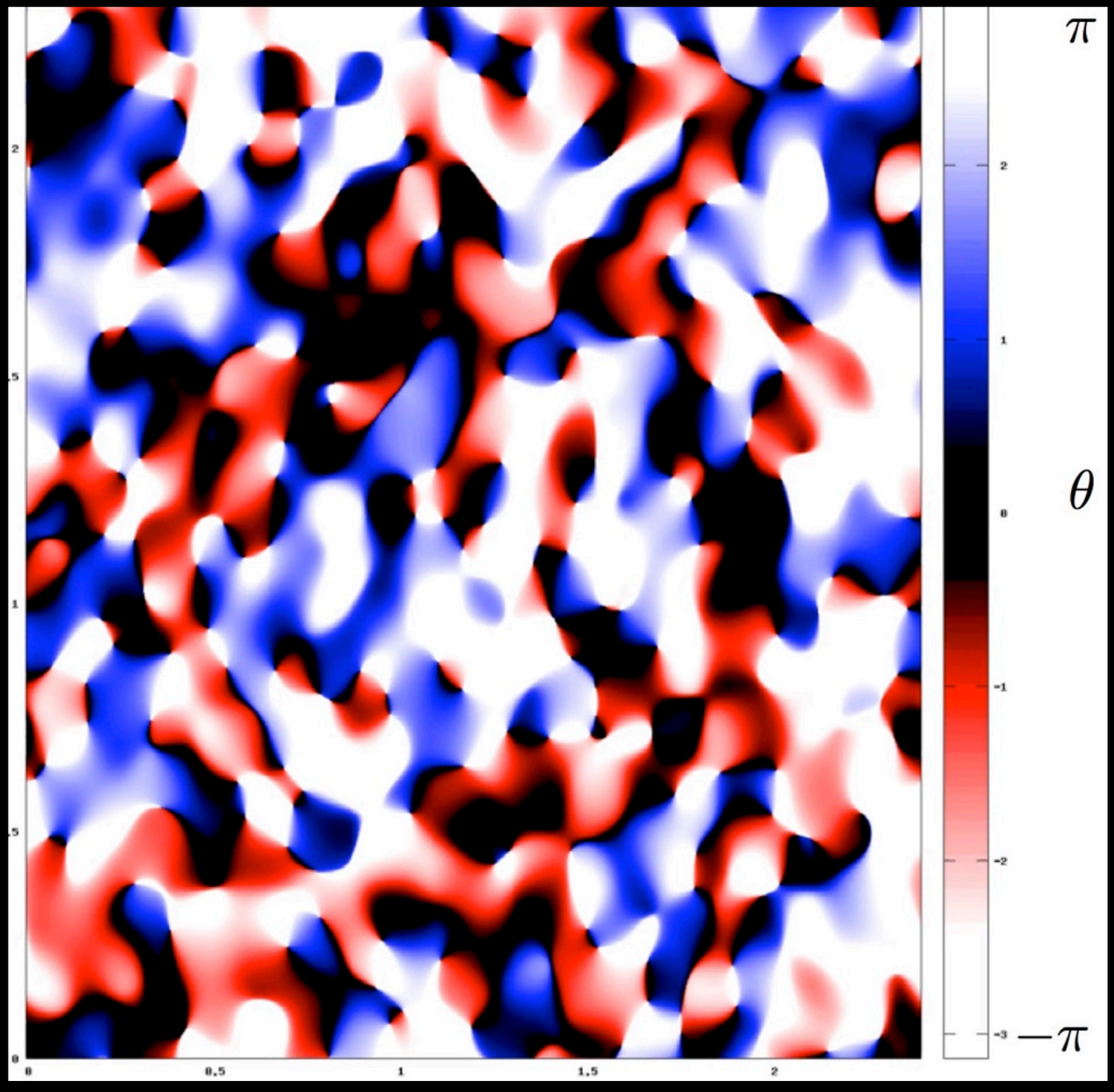
* MadMAX Haloscope, PRL **118**, 091801(2017)

Axion coherent oscillations



Courtesy of J. Redondo

Scenario A: PQ breaks after inflation



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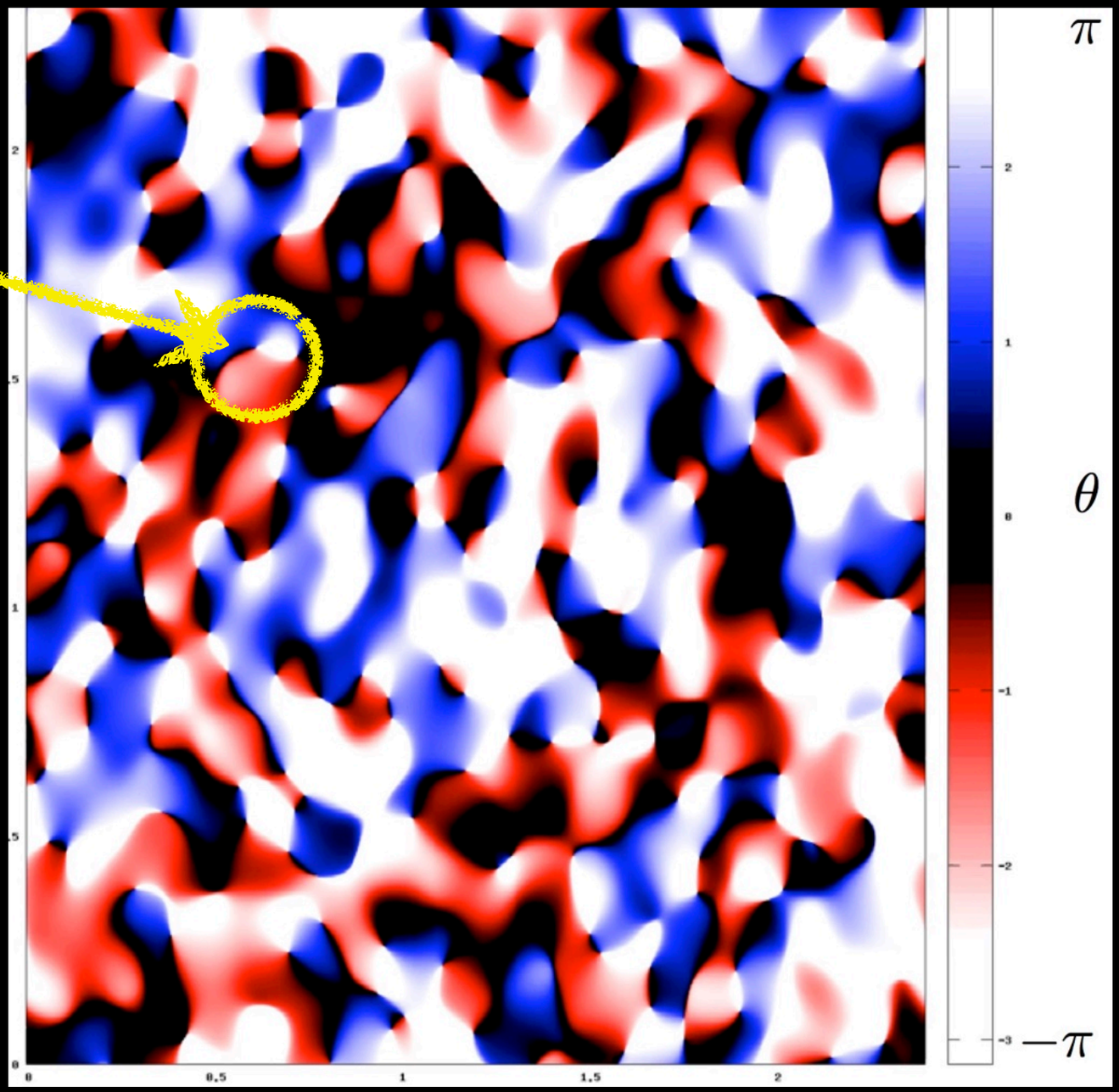
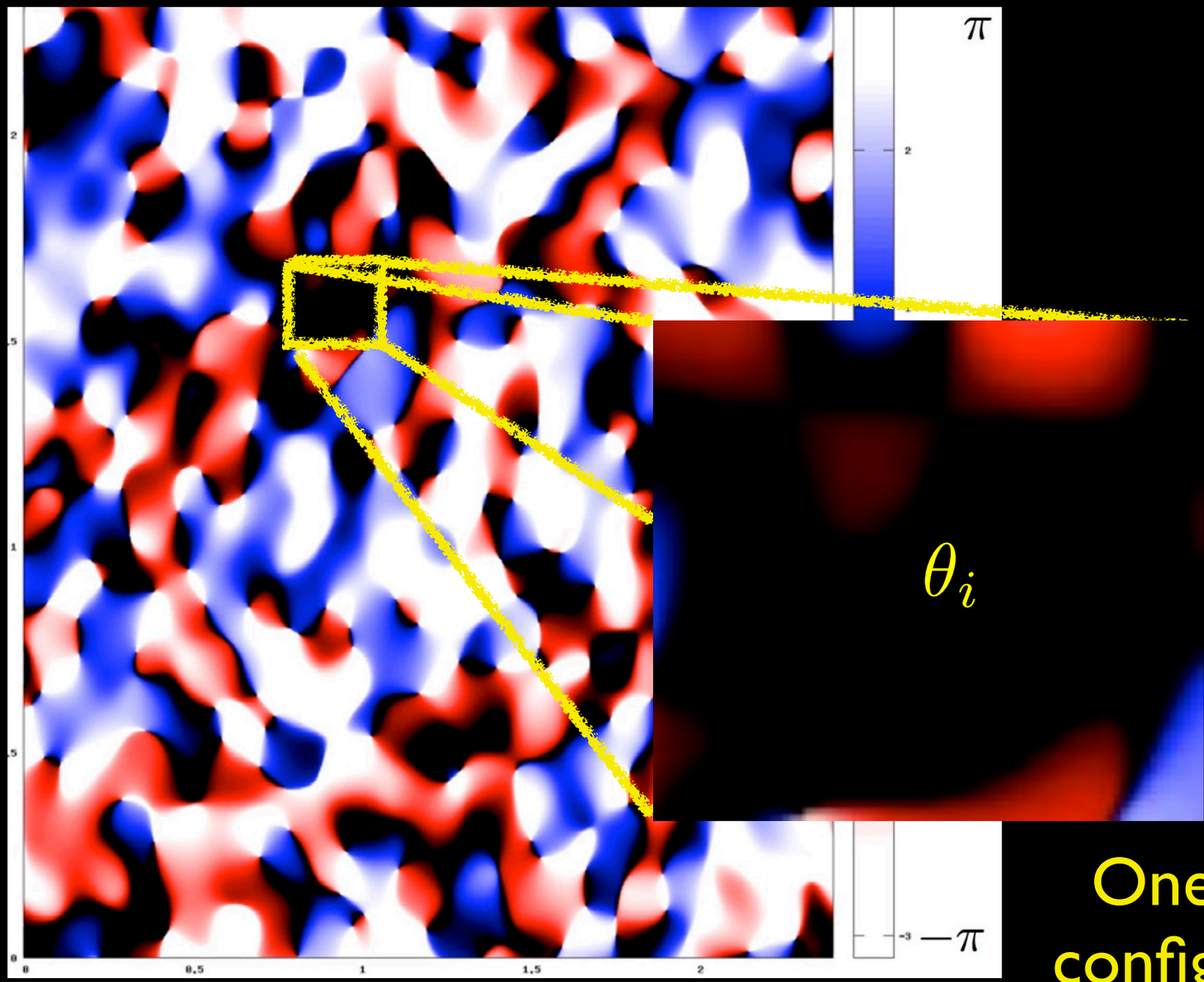
Axion strings!

CDM axions also from defects...



Scenario B: PQ breaks during inflation

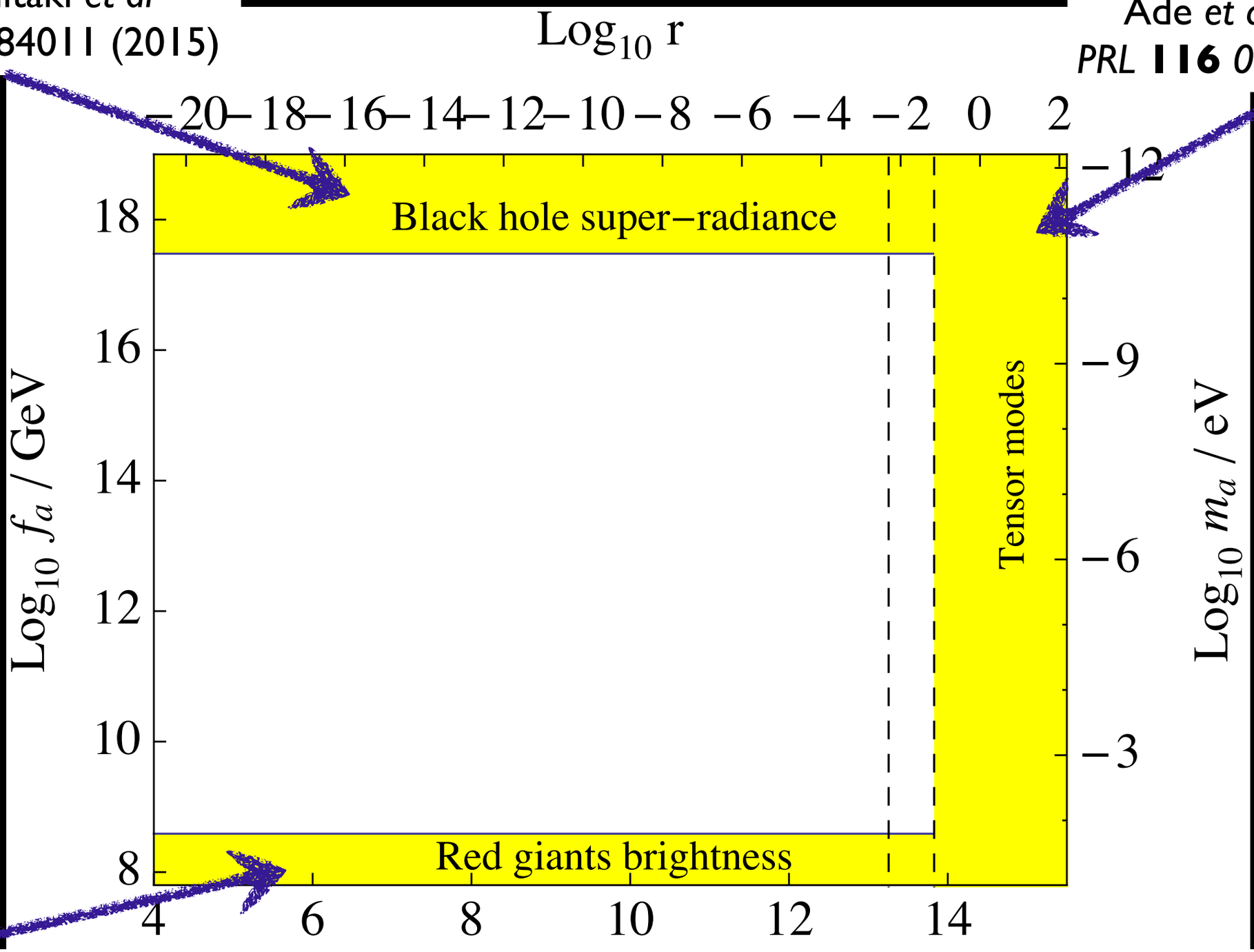


One initial configuration is singled out

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);
PRL **113**, 011802 (2014)

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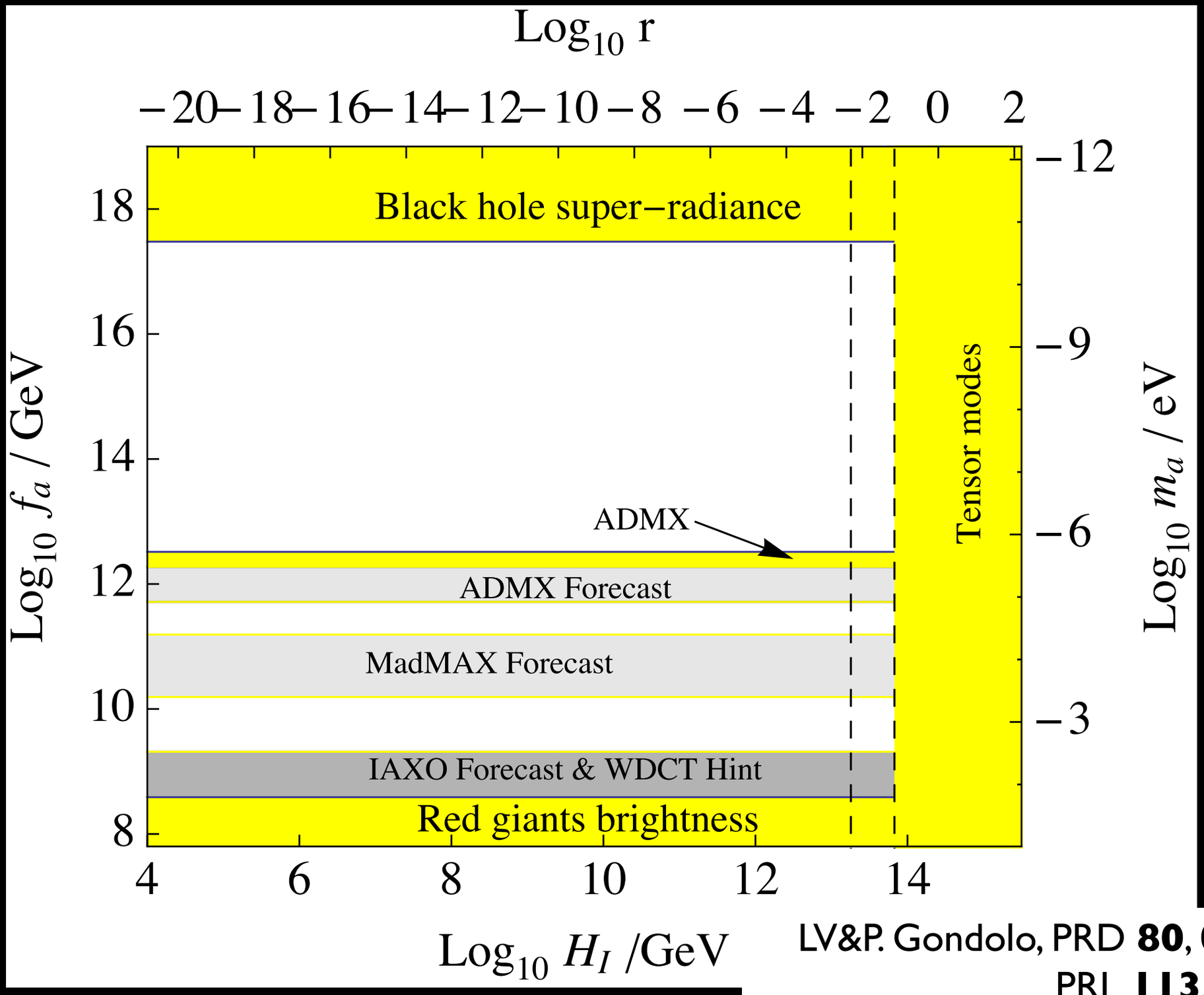

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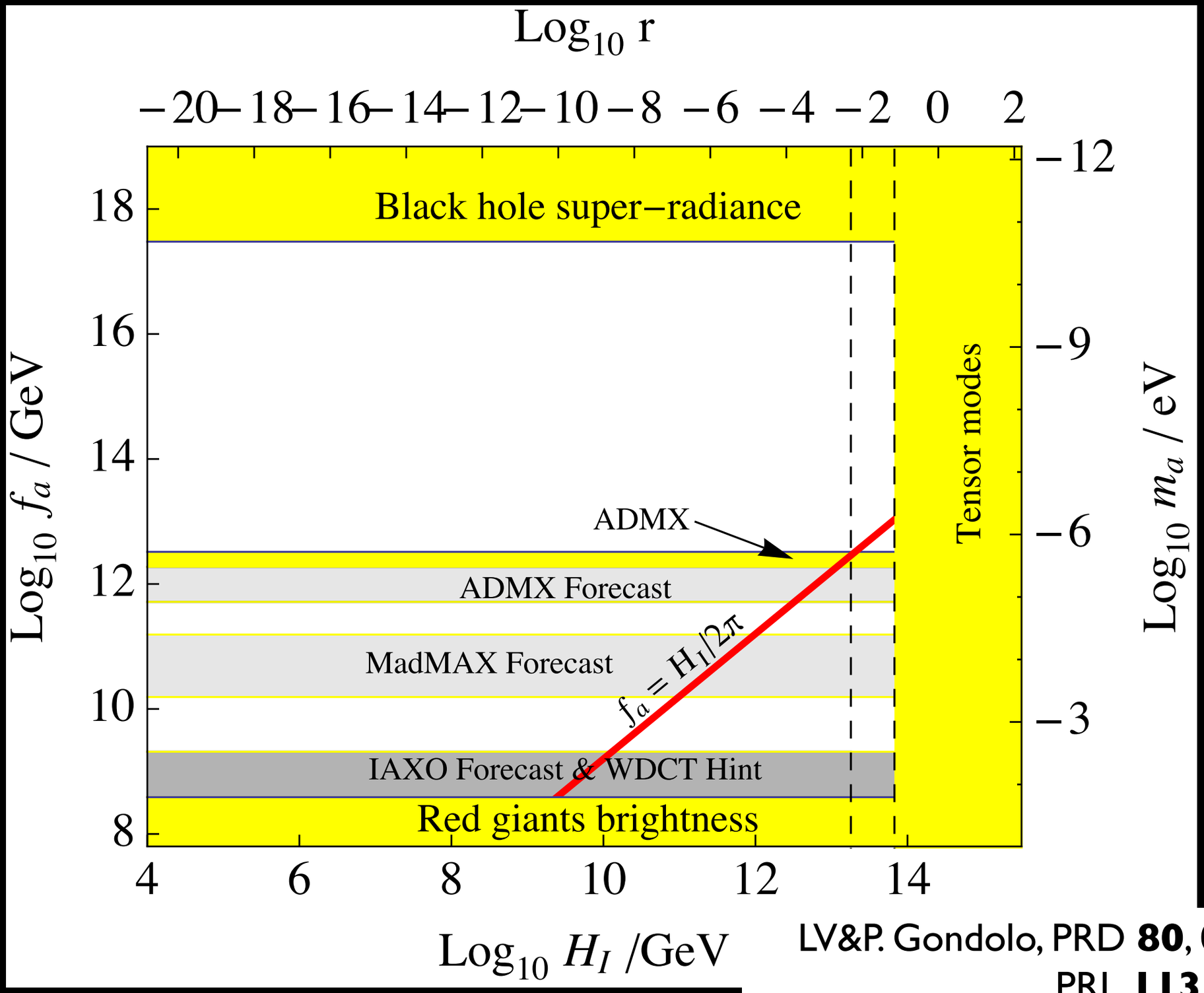

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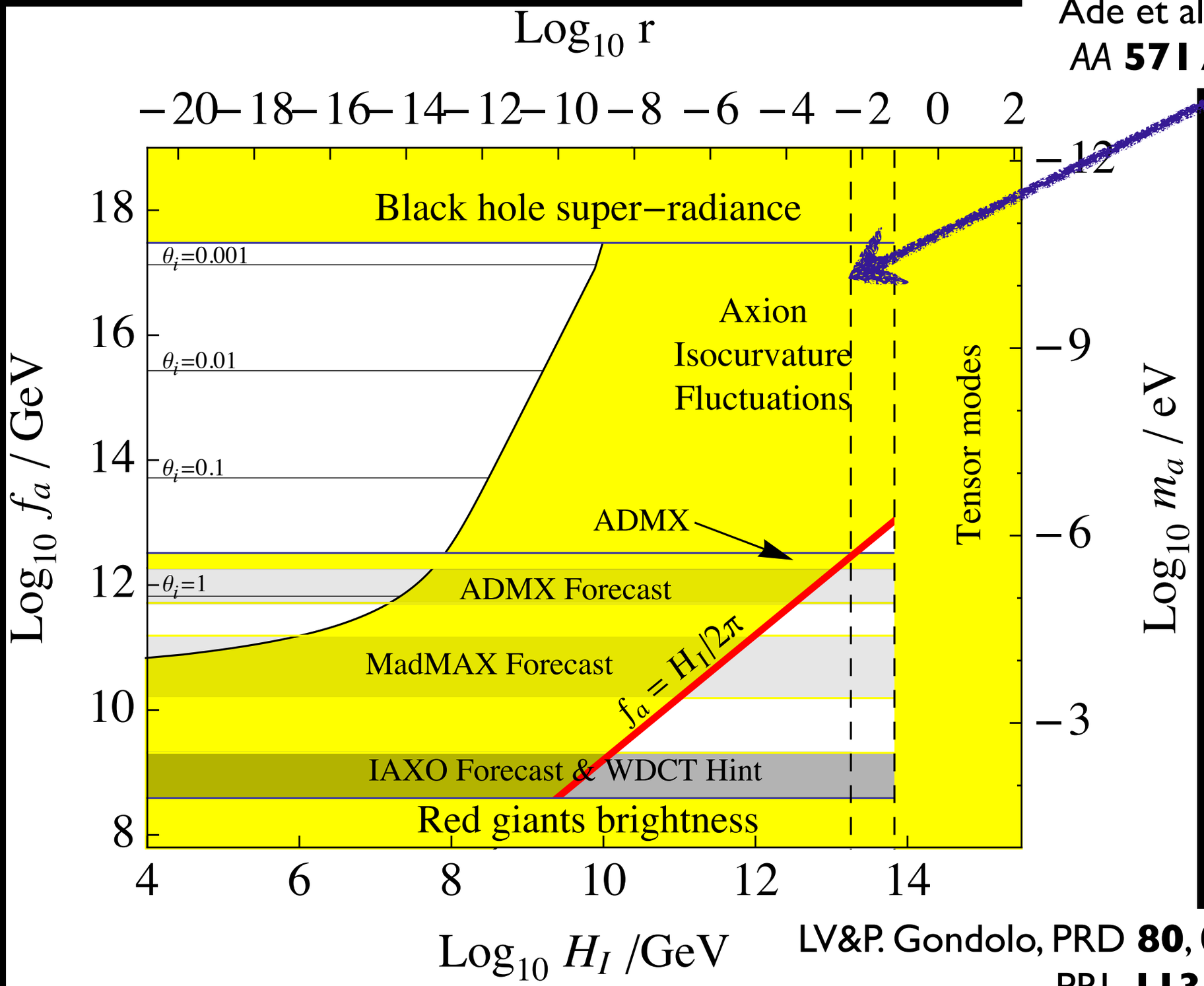
PRL **113**, 011802 (2014)

Axion parameter space

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



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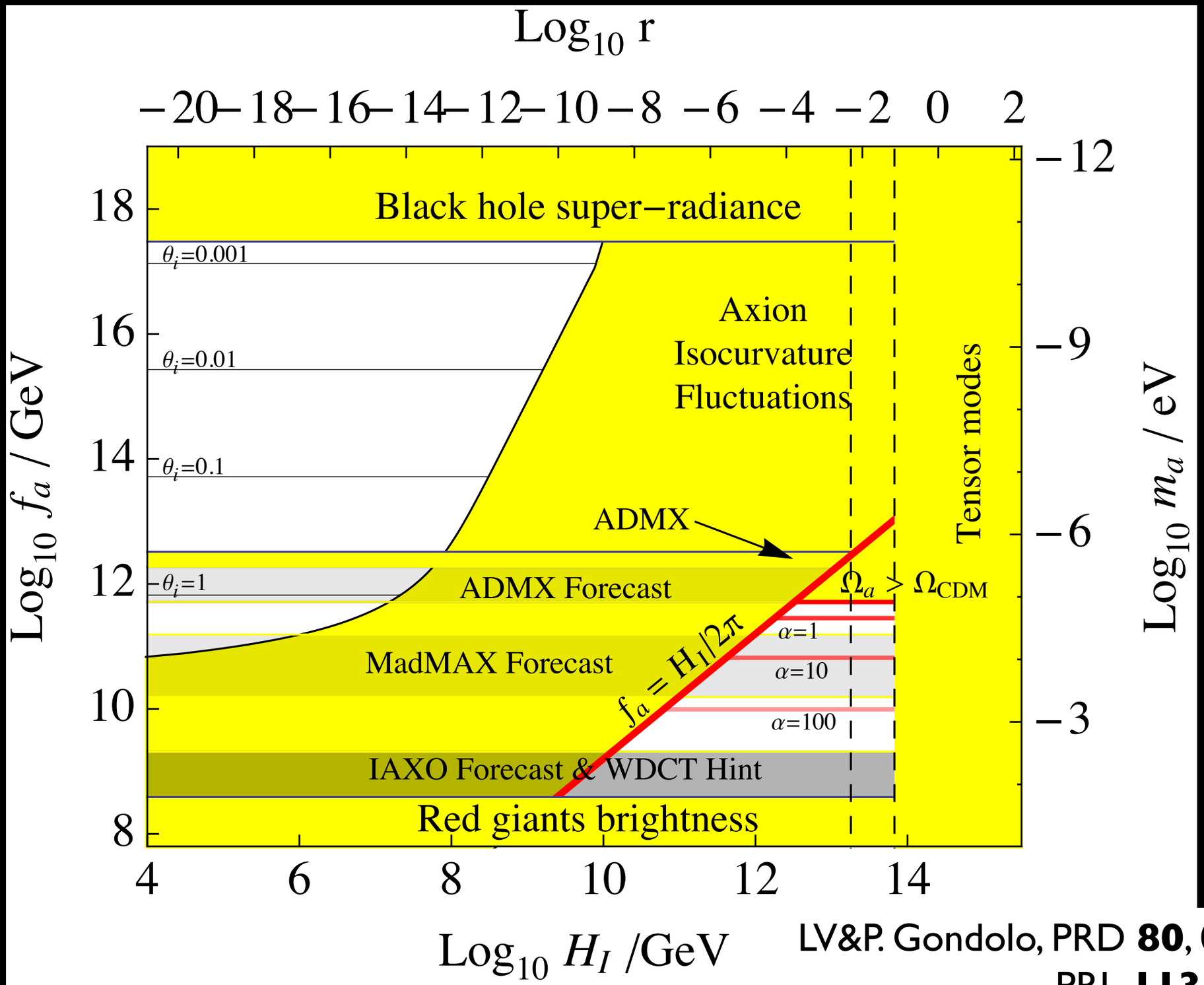

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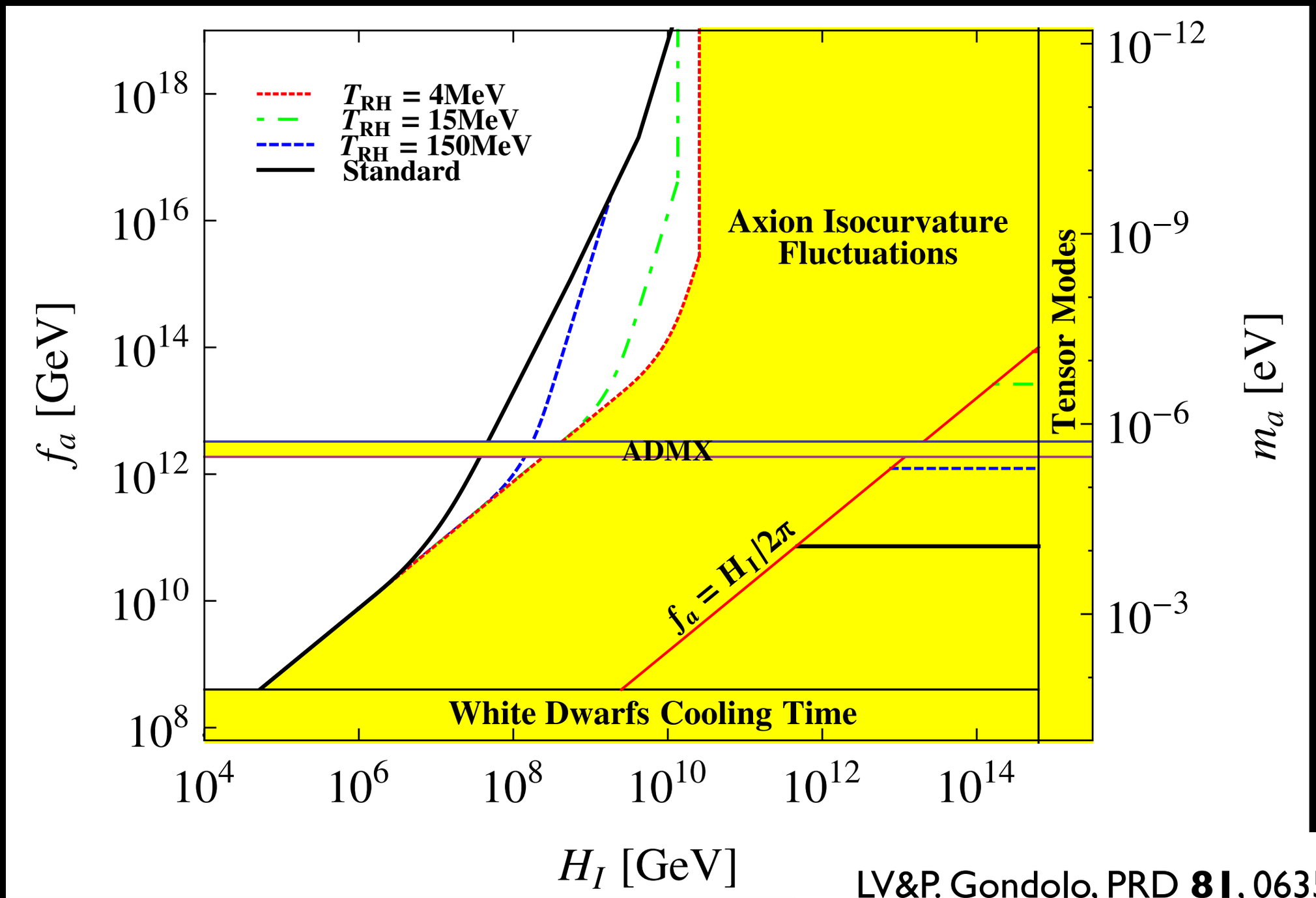
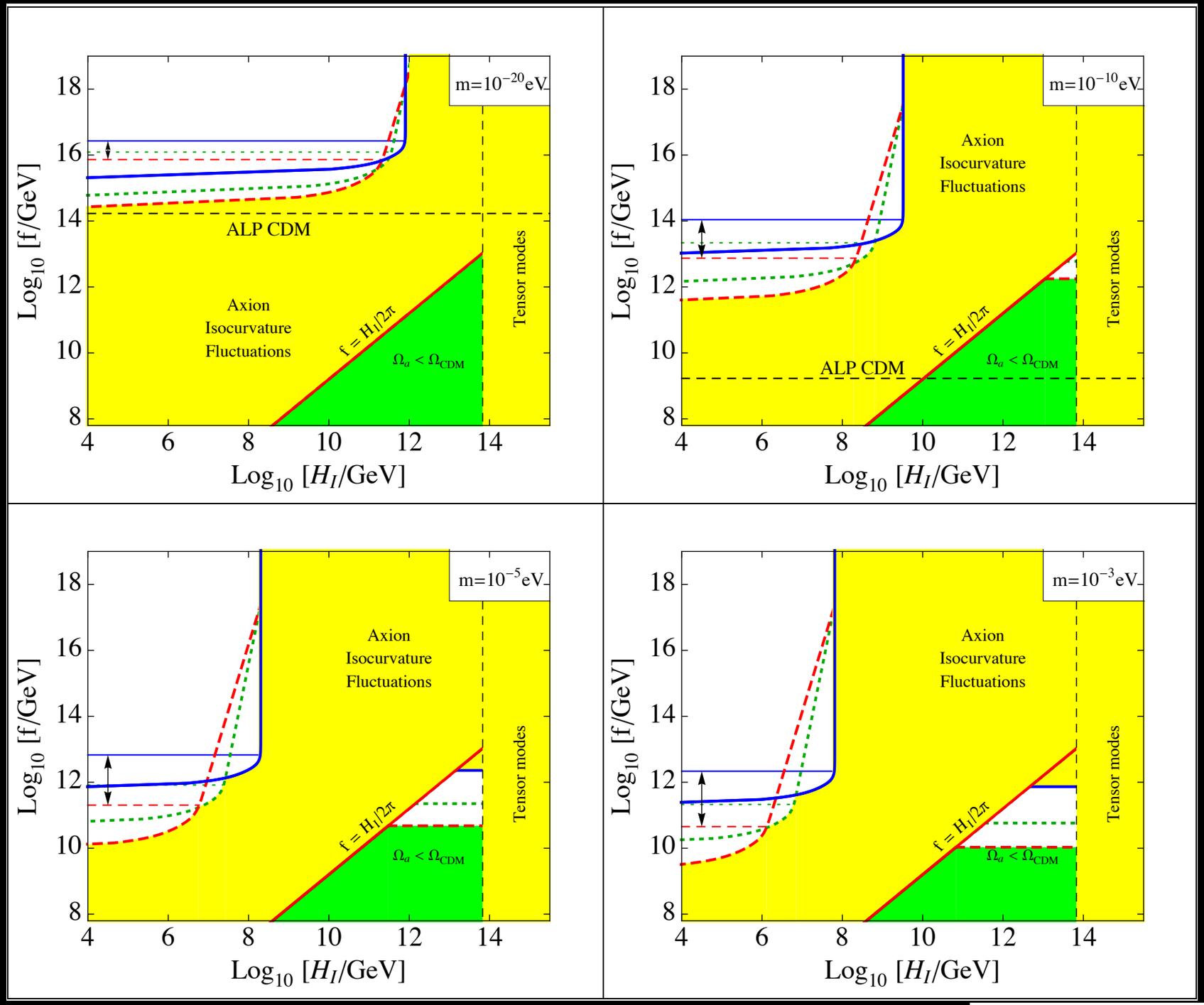
More: non-standard cosmologies



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

More: ALPs and ultra-light axions



LV, accepted in PRD (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;
- Stuctures and clumps (miniclusters, axion stars) might play an important role in the direct detection;
- ALPs might also play a role, coupling to the QCD axion