UNIVERSIDAD
DE SANTIAGO
DE CHILE

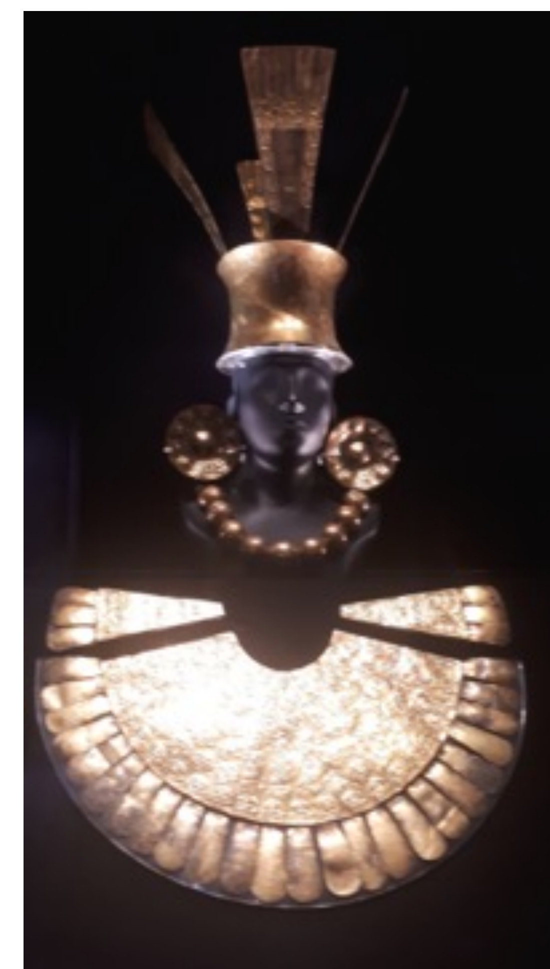
Dark matter production of scalar and vector type

Paola Arias Reyes

Universidad de Santiago de Chile

XII Latin American Symposium on High Energy Physics

29th November, 2018. Lima, Perú



- Evidence for dark matter from gravitational interaction, for instance rotation curves from galaxies, gravitational lensing…etc.

- Recently a galaxy with no dark matter was found. **Hint for a particle?**

- If so, should be cold (dust-like), non baryonic and ***if*** coupled to any SM particle by nuclear, weak or electromagnetic should be a very feeble coupling.

- Main candidates are LSP (WIMP dark matter), and the QCD axion. More generically WISPs.

The tale of axions and hidden photons as Cold Dark Matter (CDM)

axion led the way, as a solution of the absence of CP violation in the strong sector

$$\mathcal{L} \subset -\frac{\alpha_s}{8\pi}\frac{\phi}{f_\phi} G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{\phi}{f_\phi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

spin-0
very light and
weakly coupled

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Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

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THE NOT-SO-HARMLESS AXION

Michael DINE
The Institute for Advanced Study, Princeton, NJ 08540, USA

and

Willy FISCHLER
Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA

Abstract: *Cosmological aspects of a very weakly interacting axion are discussed…. Demanding that axions do not dominate the present energy density of the universe is shown to give an upper bound on the axion decay constant of at most 10^{12} GeV.*

Hidden sector photons

TWO U(1)'S AND ϵ CHARGE SHIFTS

Bob HOLDOM

Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

Received 24 October 1985

If new particles are gauged by a new U(1) then their electromagnetic charges may be shifted by a calculable amount.

Hidden sector photons

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$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + \frac{m_{\gamma'}^2}{2}X_\mu X^\mu$$

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Kinetic mixing parameter, generated at loop level via heavy messenger exchange, predicted to be very small

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very light, hidden Higgs or Stueckelberg mechanism

To sum up:

axion-like particles are spin-0 bosons, that couple effectively to 2-photons vía

$$g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Hidden photons are spin-1 gauge bosons, that kinetically mix with photons.

$$\chi F_{\mu\nu}X^{\mu\nu}$$

both can be very light $m \lesssim eV$

Non-thermal production mechanisms

Light scalars or zero modes of light vector bosons can be produced non-thermally during the early universe.
WISP dark matter

$$L_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2$$

$$L_A = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_A A_\mu A^\mu + \frac{1}{12}RA^\mu A_\mu$$

Arias et al, JCAP 2012

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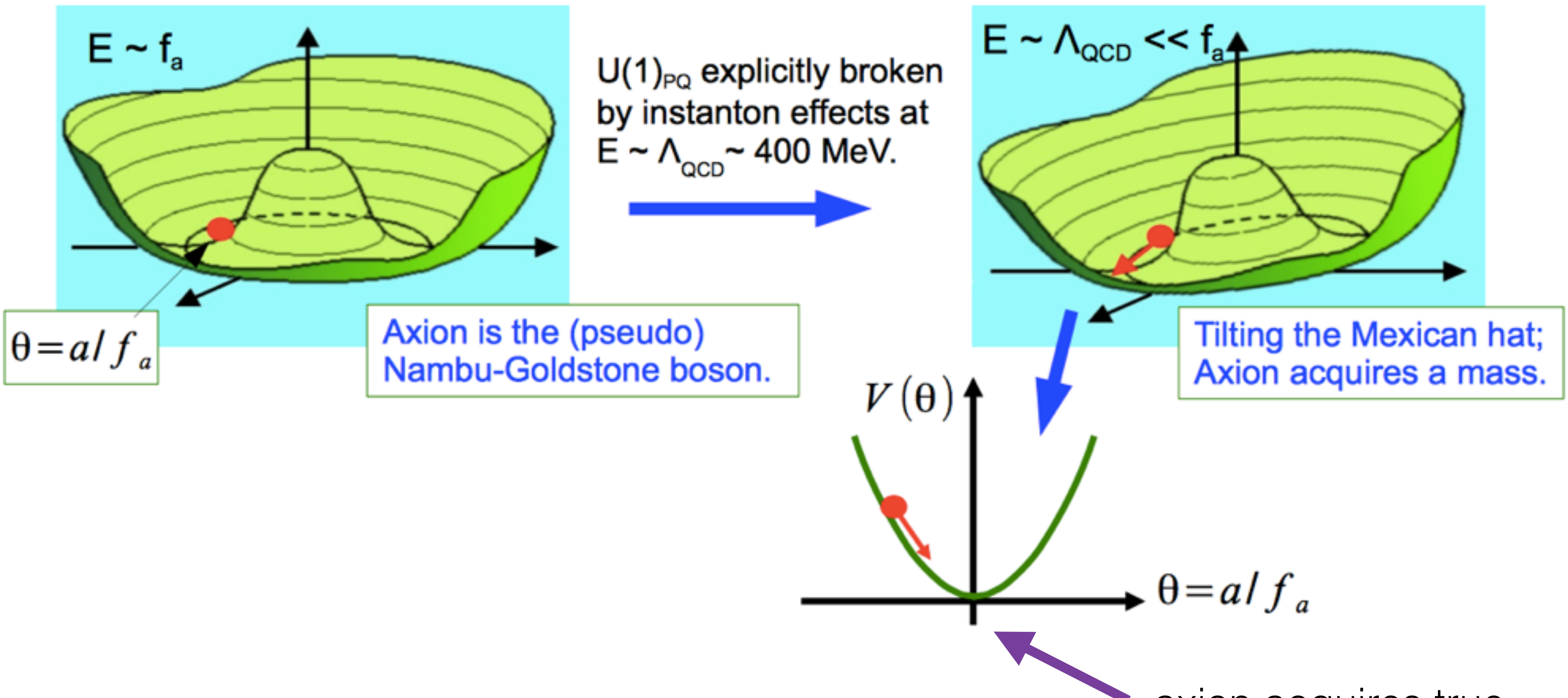
In a FRW universe: $\ddot{\phi} + 3H\dot{\phi} + m^2(T)\phi = 0$

$3H \gg m$ a is frozen

$3H \sim m$ the field "feels" its mass
starts to oscillate, coherently

Fig. from Y. Wong 2011



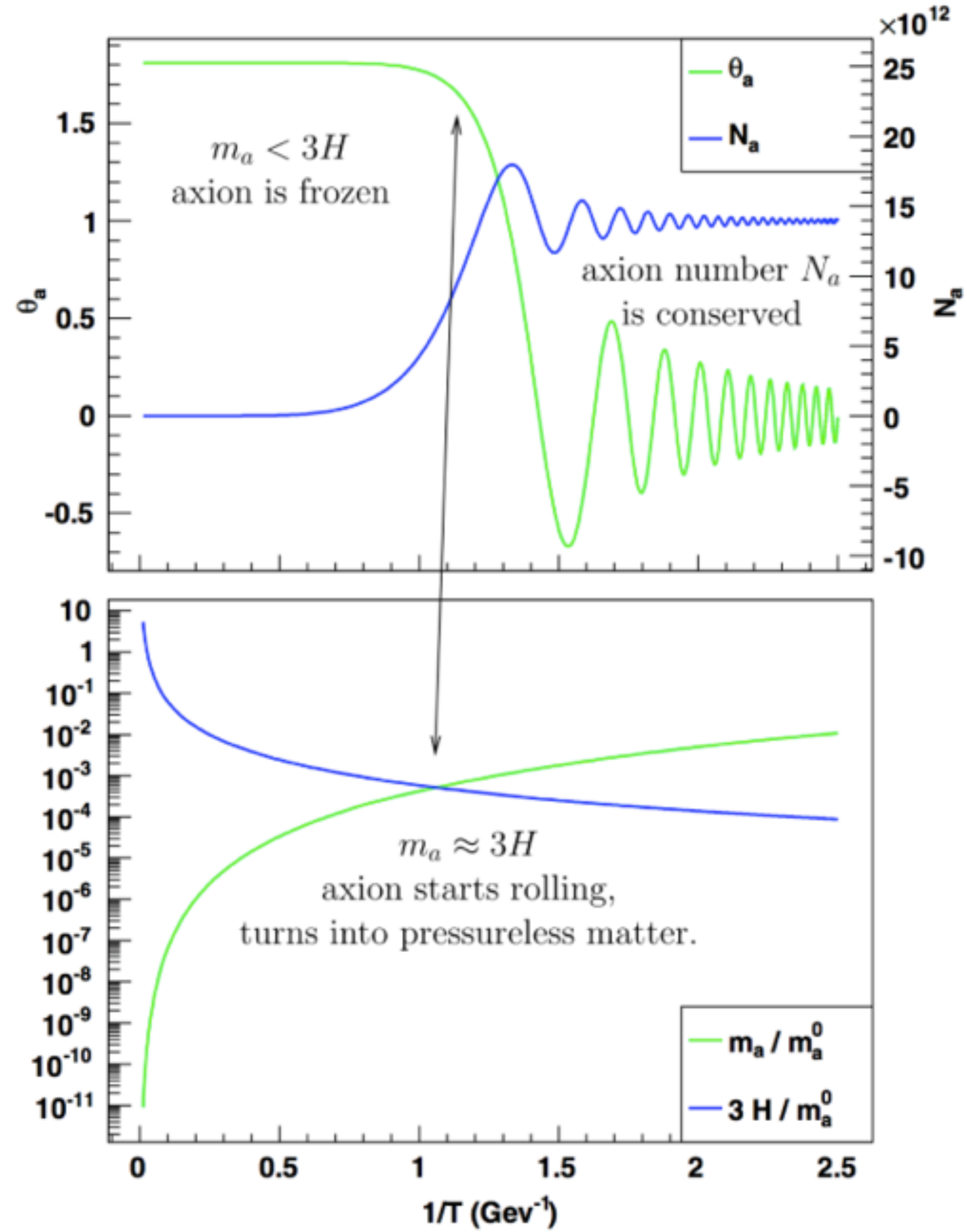
$$\langle a \rangle = 0$$

axion acquires true expectation vale that solves strong CP

$$\ddot{\phi} + 3H\dot{\phi} + m^2(T)\phi = 0$$

zero momentum condensate

Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = CDM



Wantz, Shellard 2009

For vector U(1)s there is another interesting non-thermal production mechanism

Graham et al PRD 2015

Vector dark matter from inflationary perturbations

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Vector dark matter from inflationary perturbations

$$S = \int \sqrt{|g|} d^3x dt \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} m^2 A_\mu A^\mu \right)$$

massive abelian vector field present at inflation

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Transverse mode is almost conformally invariant. Longitudinal mode on the other hand

$$S_L = \int \frac{a^3 d^3k dt}{(2\pi)^3} \frac{1}{2a^3} \left(\frac{a^2 m^2}{k^2 + a^2 m^2} |\partial_t A_L|^2 - m^2 |A_L|^2 \right)$$

For $k \gg ma$ $\Rightarrow$ $\pi(\vec{k},t) = \frac{m}{k} A_L(\vec{k},t)$

For $k \gg ma$ $\Longrightarrow$ $\pi(\vec{k},t) = \frac{m}{k} A_L(\vec{k},t)$

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behaves as
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$$\phi(\vec{k}, t) = \frac{m}{\sqrt{k^2 + a^2 m^2}} A_L(\vec{k}, t)$$

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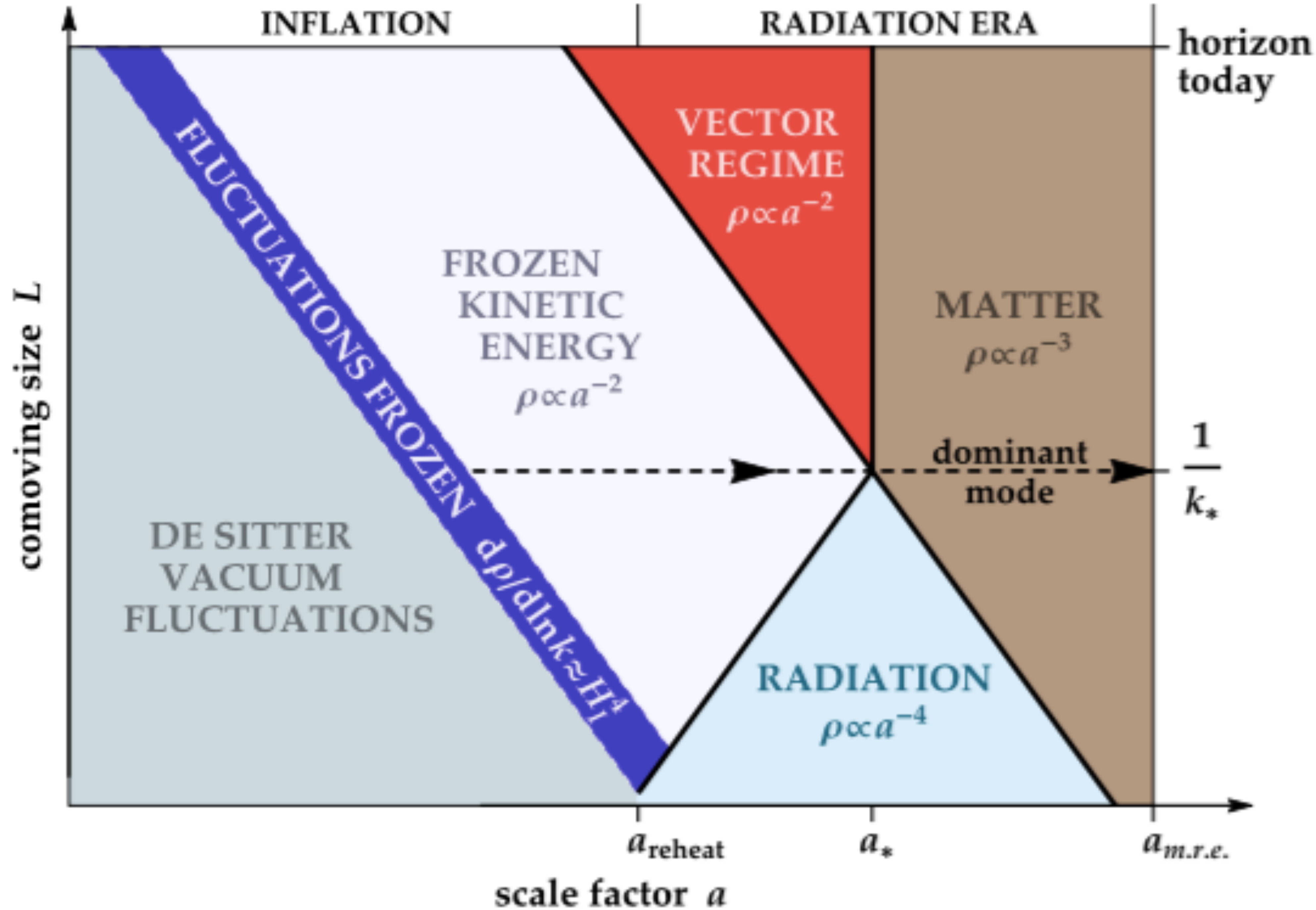
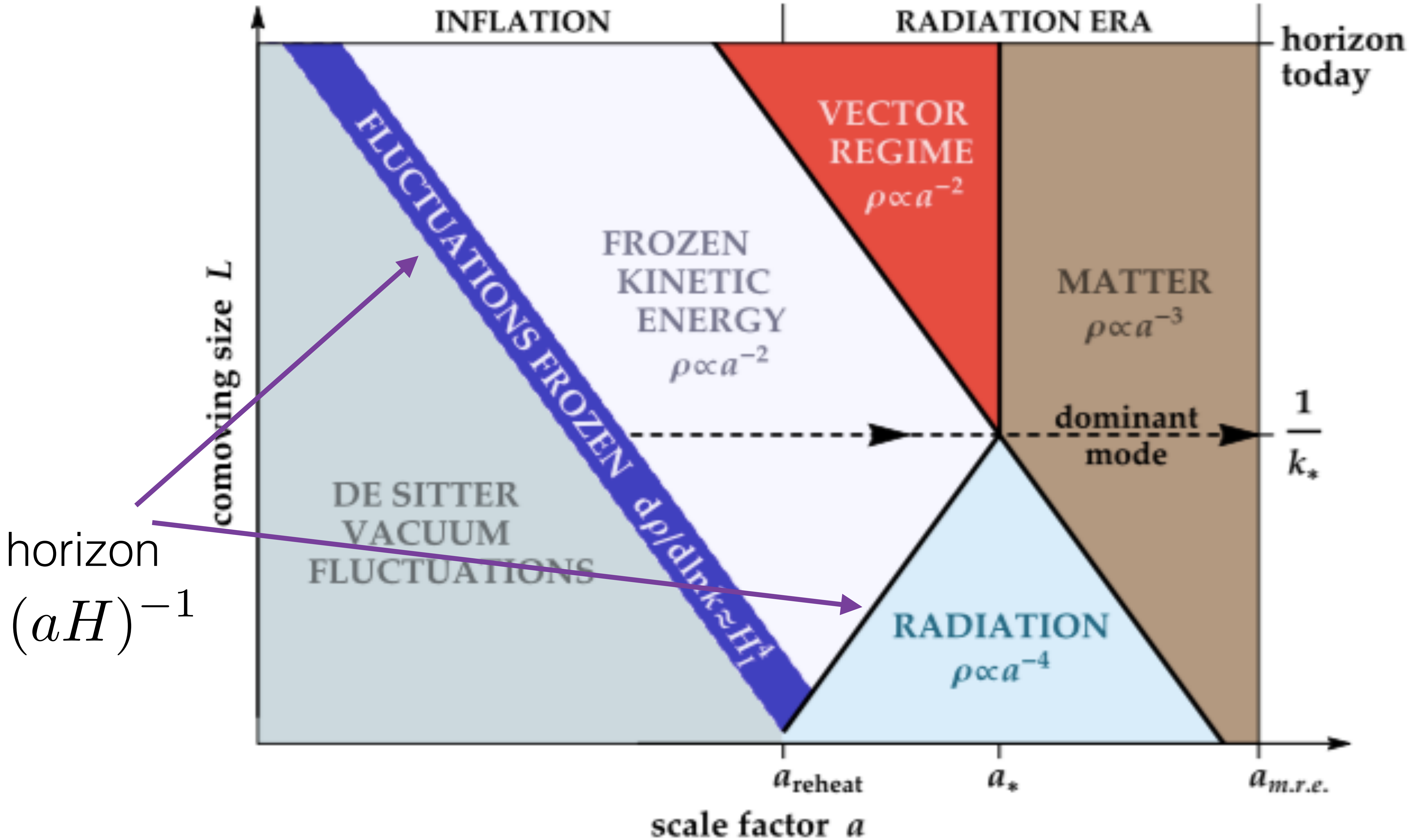


INFLATION
RADIATION ERA
horizon today
VECTOR REGIME
$\rho \propto a^{-2}$
FROZEN KINETIC ENERGY
$\rho \propto a^{-2}$
MATTER
$\rho \propto a^{-3}$
FLUCTUATIONS FROZEN
$d\rho/d\ln k \approx H_I^4$
dominant mode
$\frac{1}{k_*}$
DE SITTER VACUUM FLUCTUATIONS
RADIATION
$\rho \propto a^{-4}$
comoving size L
$a_{\rm reheat}$
a_*
$a_{m.r.e.}$
scale factor a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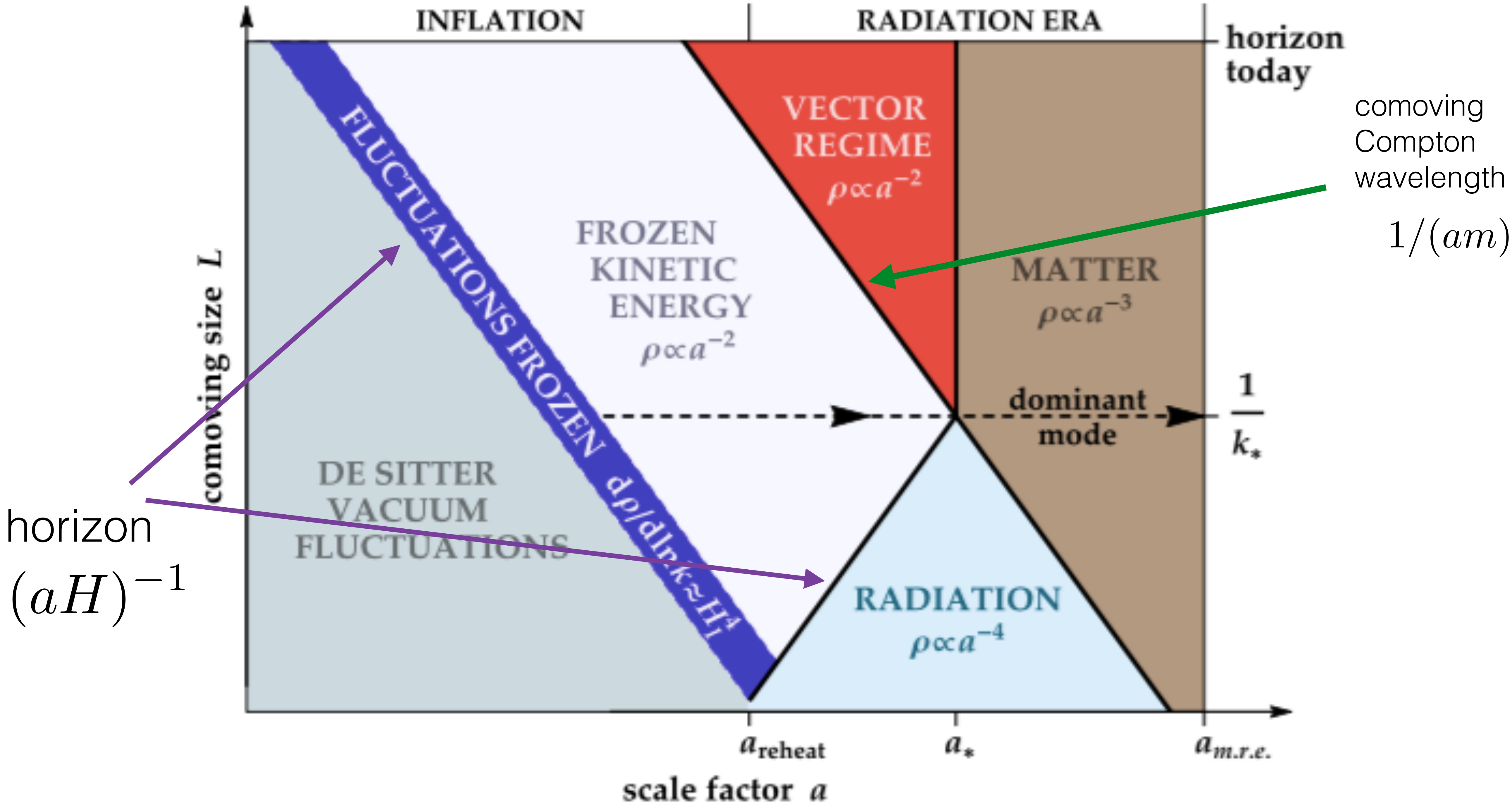
DE SITTER VACUUM FLUCTUATIONS
RADIATION ρ∝a^−4
comoving size L
scale factor a
a_reheat
a_*
a_m.r.e.
horizon
(aH)^−1



INFLATION
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comoving Compton wavelength
$1/(am)$
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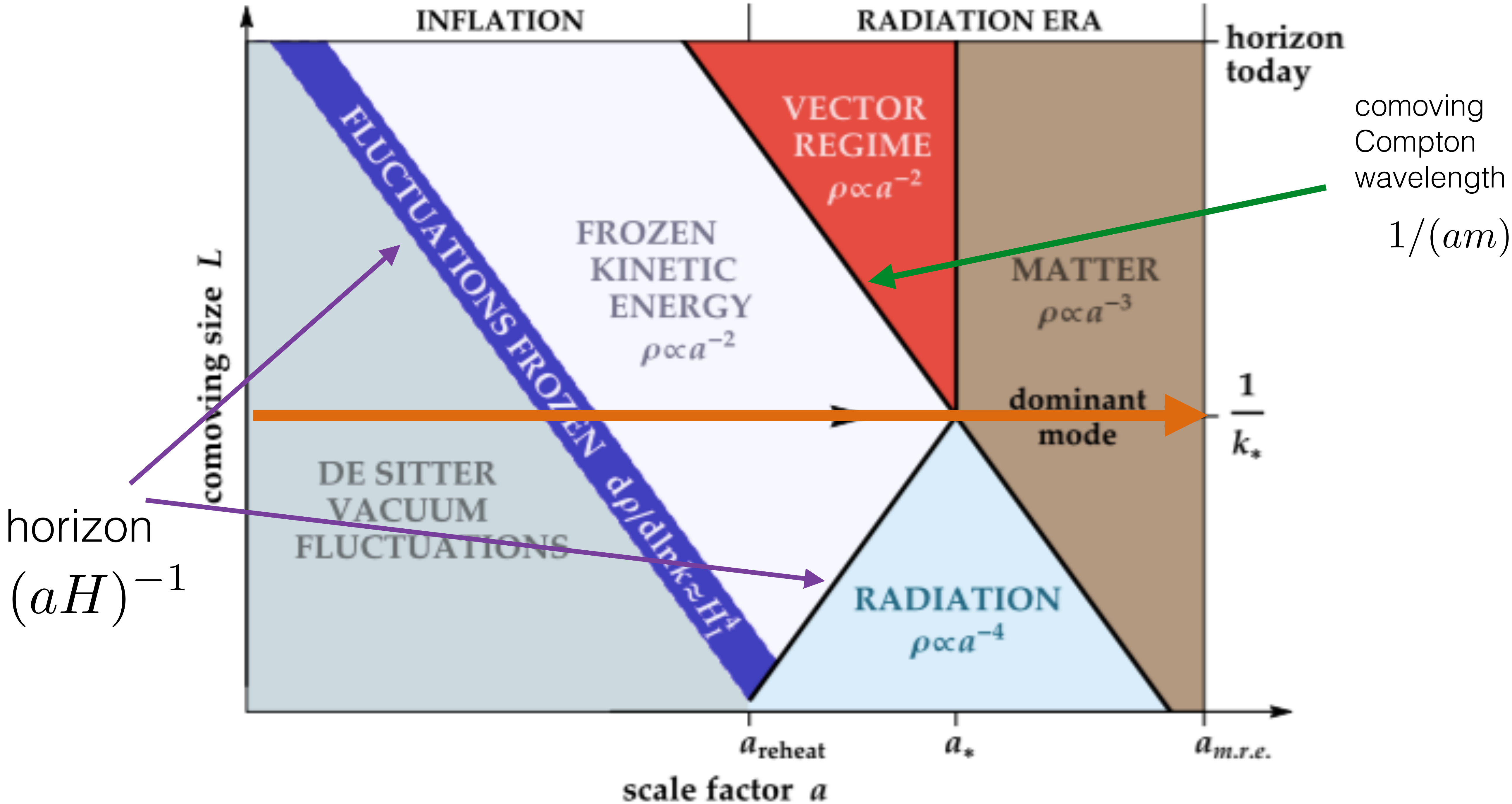

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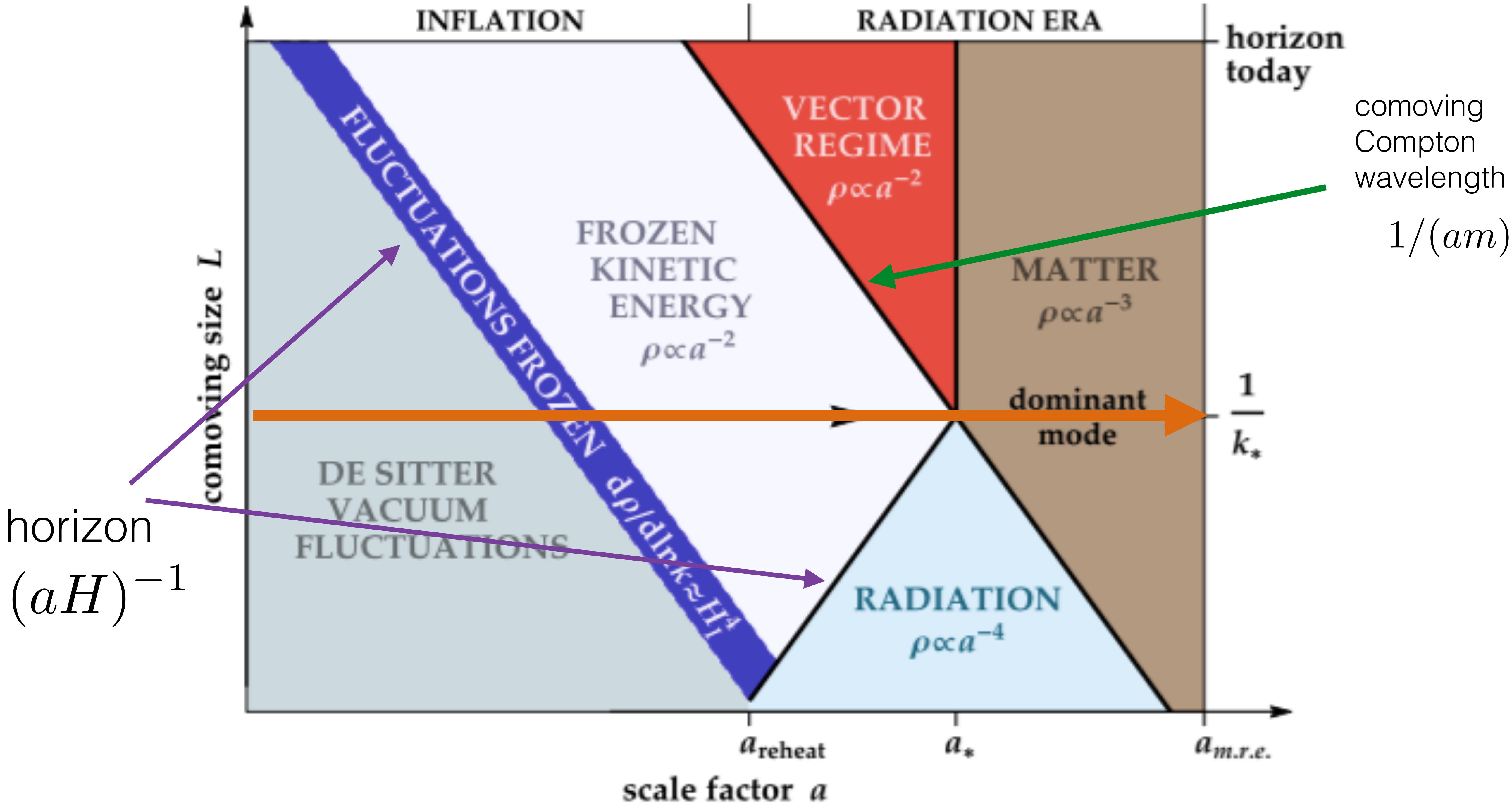
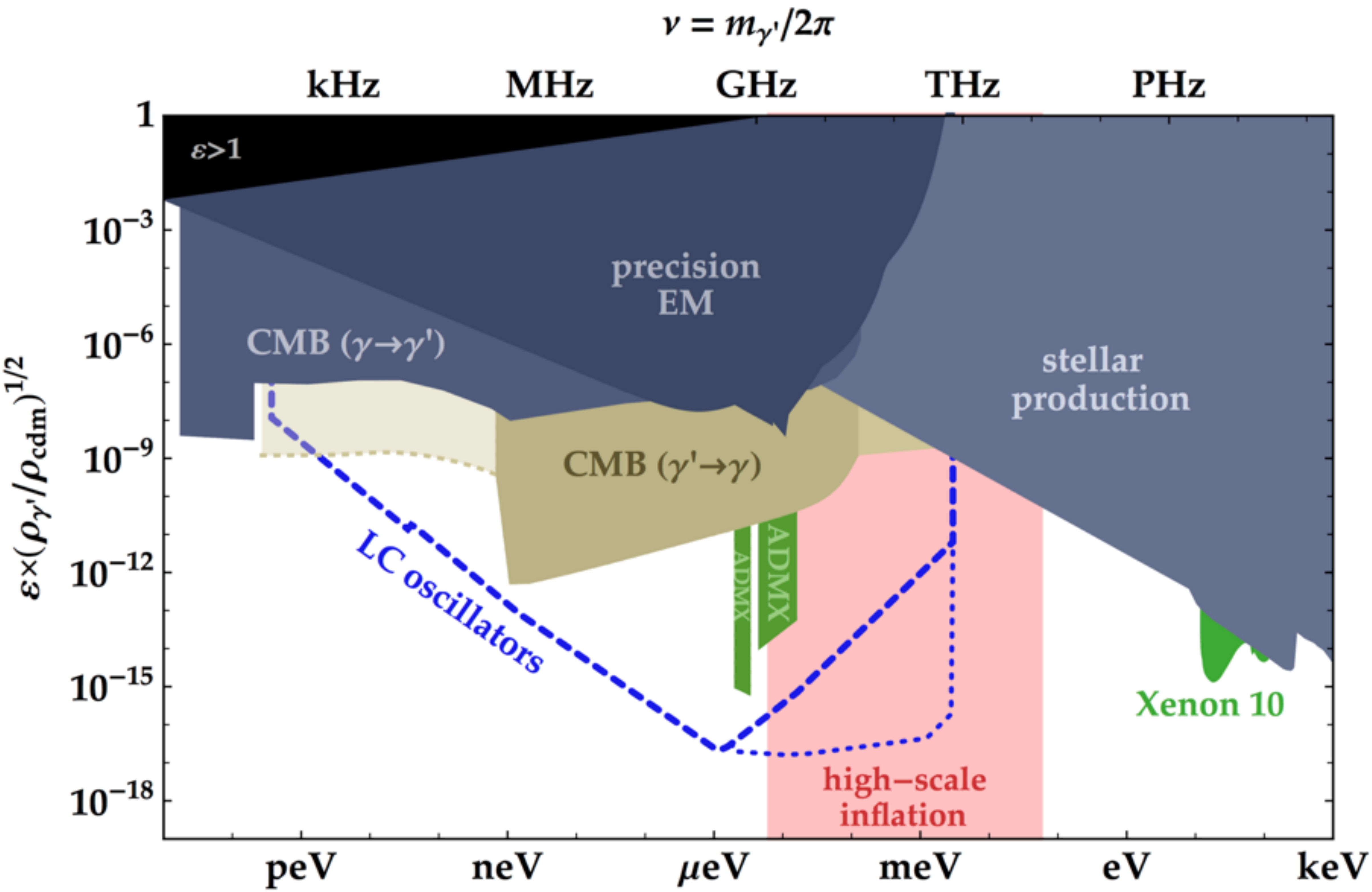
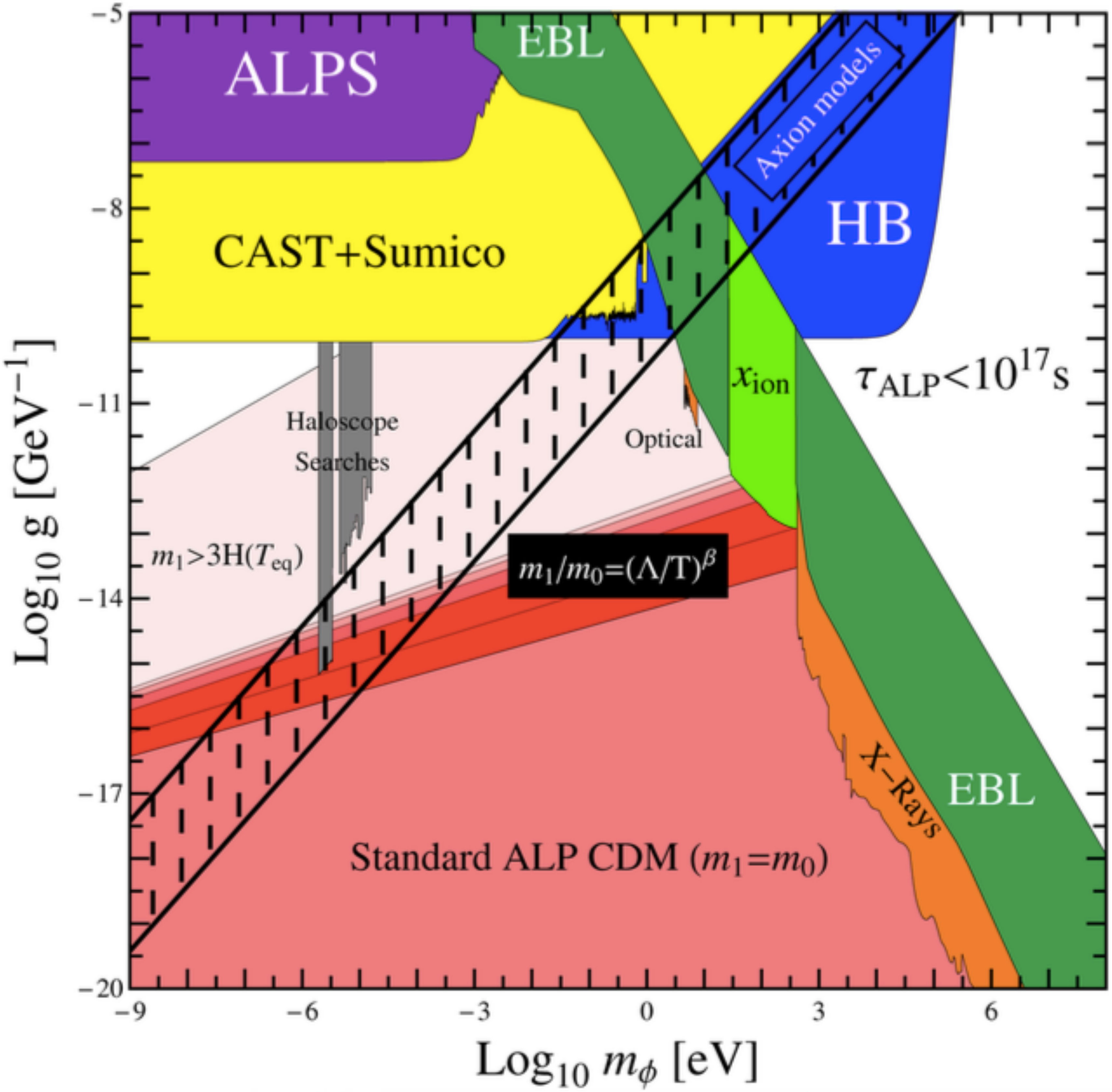


Dominant contribution from $H(a_*) = m \qquad k^* = ma_*$

$$\frac{\Omega_A}{\Omega_{CDM}} = \sqrt{\frac{m}{6\times 10^{-6}\,\text{eV}}}\left(\frac{H_I}{10^{14}\,\text{GeV}}\right)^2$$



ν = m_γ'/2π
kHz
MHz
GHz
THz
PHz
ε>1
precision
EM
CMB (γ→γ')
stellar
production
CMB (γ'→γ)
ADMX
ADMX
LC oscillators
Xenon 10
high−scale
inflation
ε×(ρ_γ'/ρ_cdm)^1/2
1
10^−3
10^−6
10^−9
10^−12
10^−15
10^−18
peV
neV
μeV
meV
eV
keV



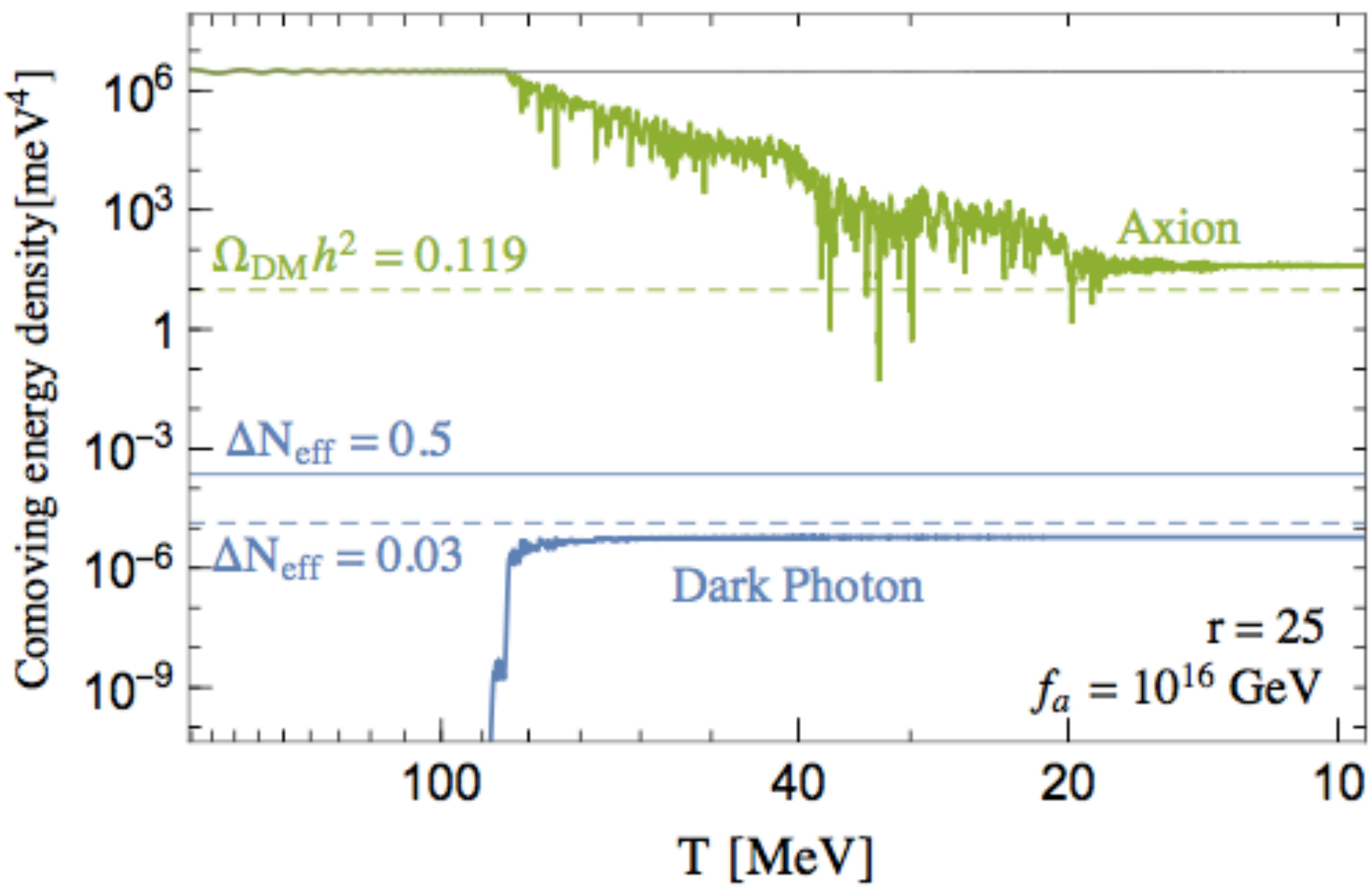
Arias et al JCAP 2012

Coupling of axions to HP can be quite useful

Mixing of ALPs-HPs and photons can give rise to resonances in the probability of oscillation even in vacuum

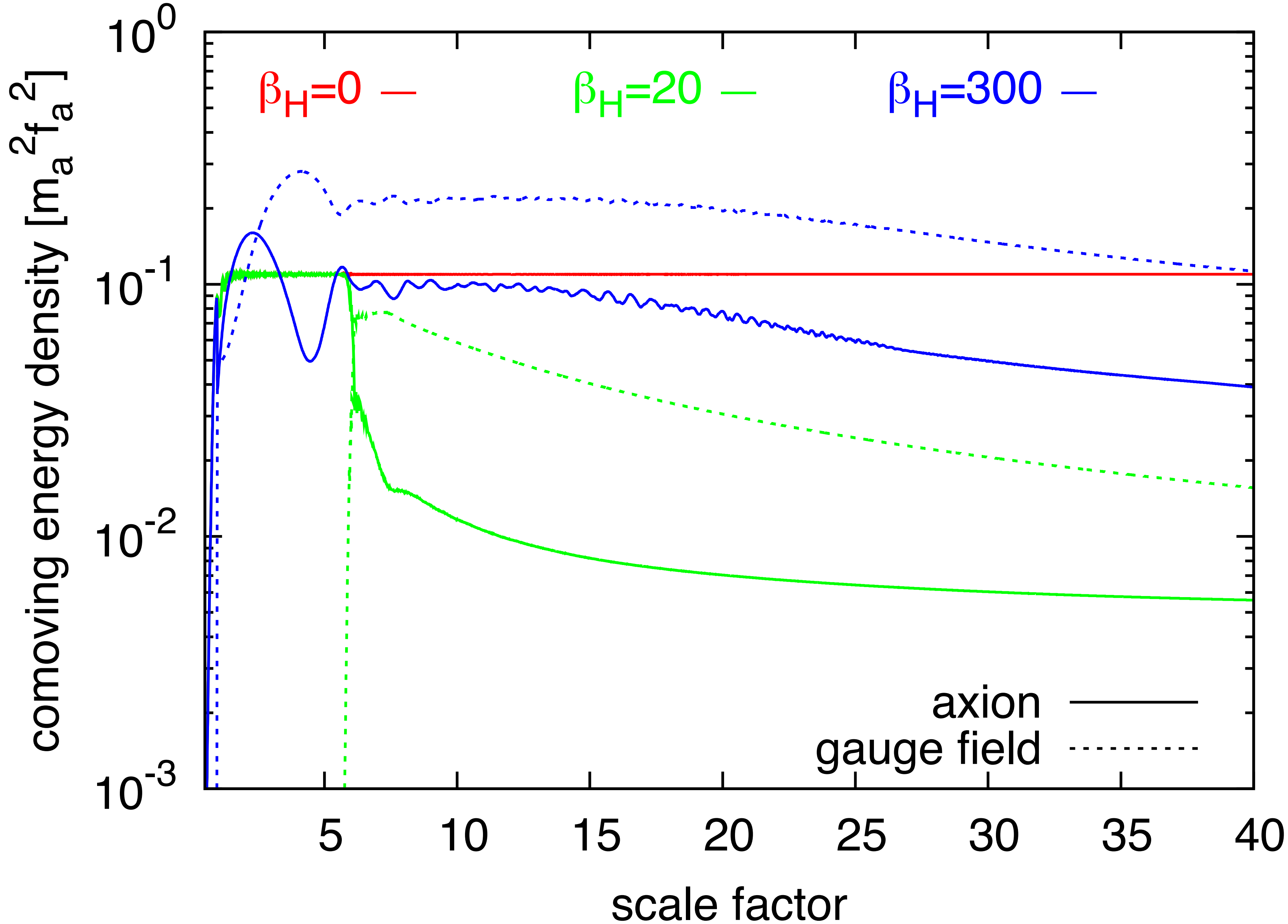
Alvarez, PA, Maldonado EPJC, 2018

Cosmology:



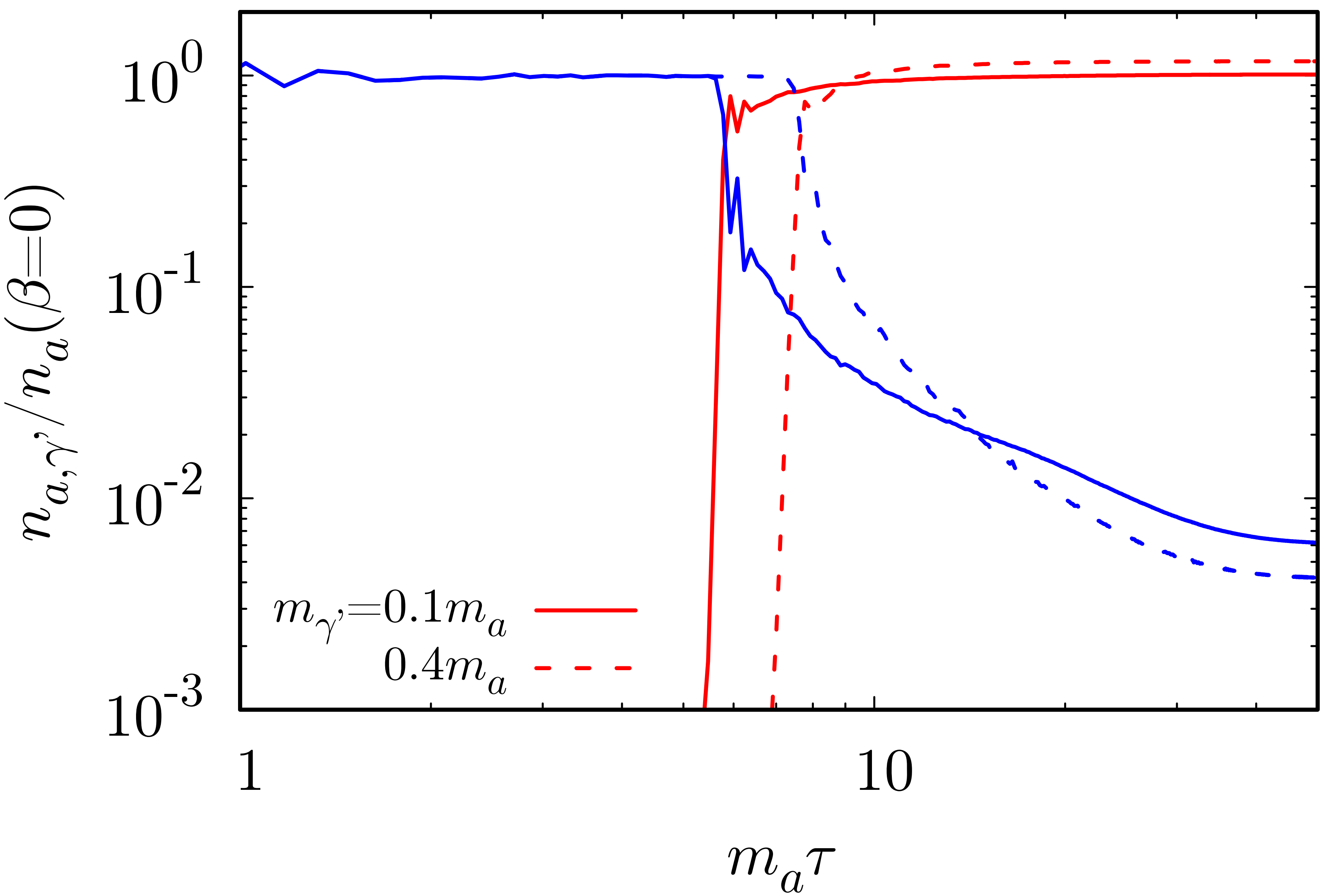
Coupling of QCD axion to massless HP opens up the axion window

Agrawal et al.
JHEP 1803 (2018) 049



also found in Kitajima et al, PLB 781, 2018

Massive HP+ALP it is more exciting!



HP dark matter from axion energy transfer

$$m_{\gamma'}/m_a \sim 10^{-3} - 1$$

Agrawal, Kitajima, Reece, Sekiguchi, Takahashi, arXiv:1810.07188

Outlook

- Many extensions of the standard model predict scalars and vectors weakly coupled to the visible sector
- Mechanisms to produce them non-thermally in the early universe are quite natural
- Many experiments worldwide that exploit the coupling to photons and matter
- Nowadays has become very popular to consider a scenario where both scalars and vectors are present in the early universe, interesting DM scenario.

Thank you!

And thanks to FONDECYT project 1161150 :)