(Runaway) Gravitational Production of Dark Photons

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Main Takeaways

arXiv:2403.15536, PRL
arXiv:2405.19390, JHEP

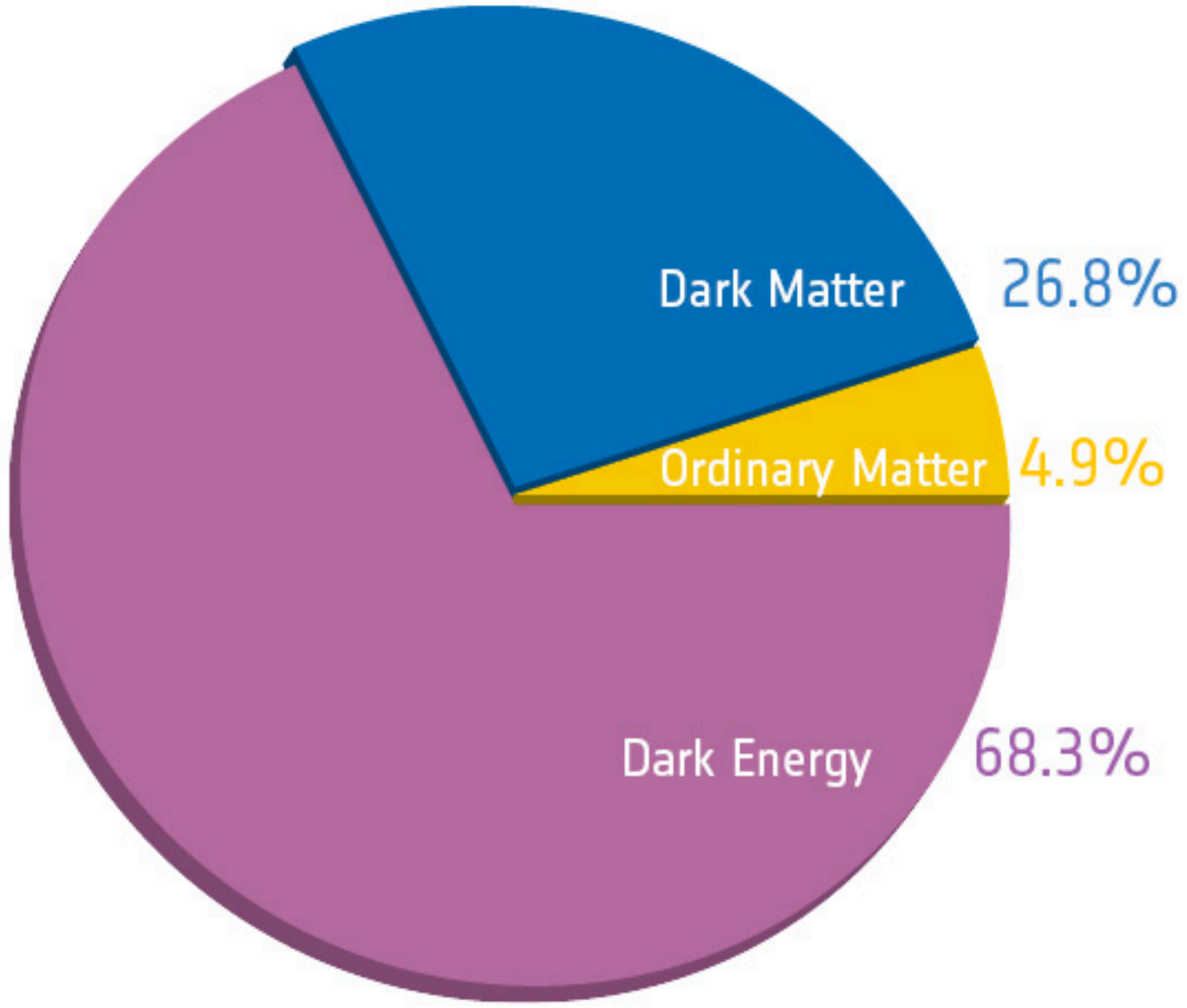
With Rocky Kolb, Evan McDonough, Christian Capanelli

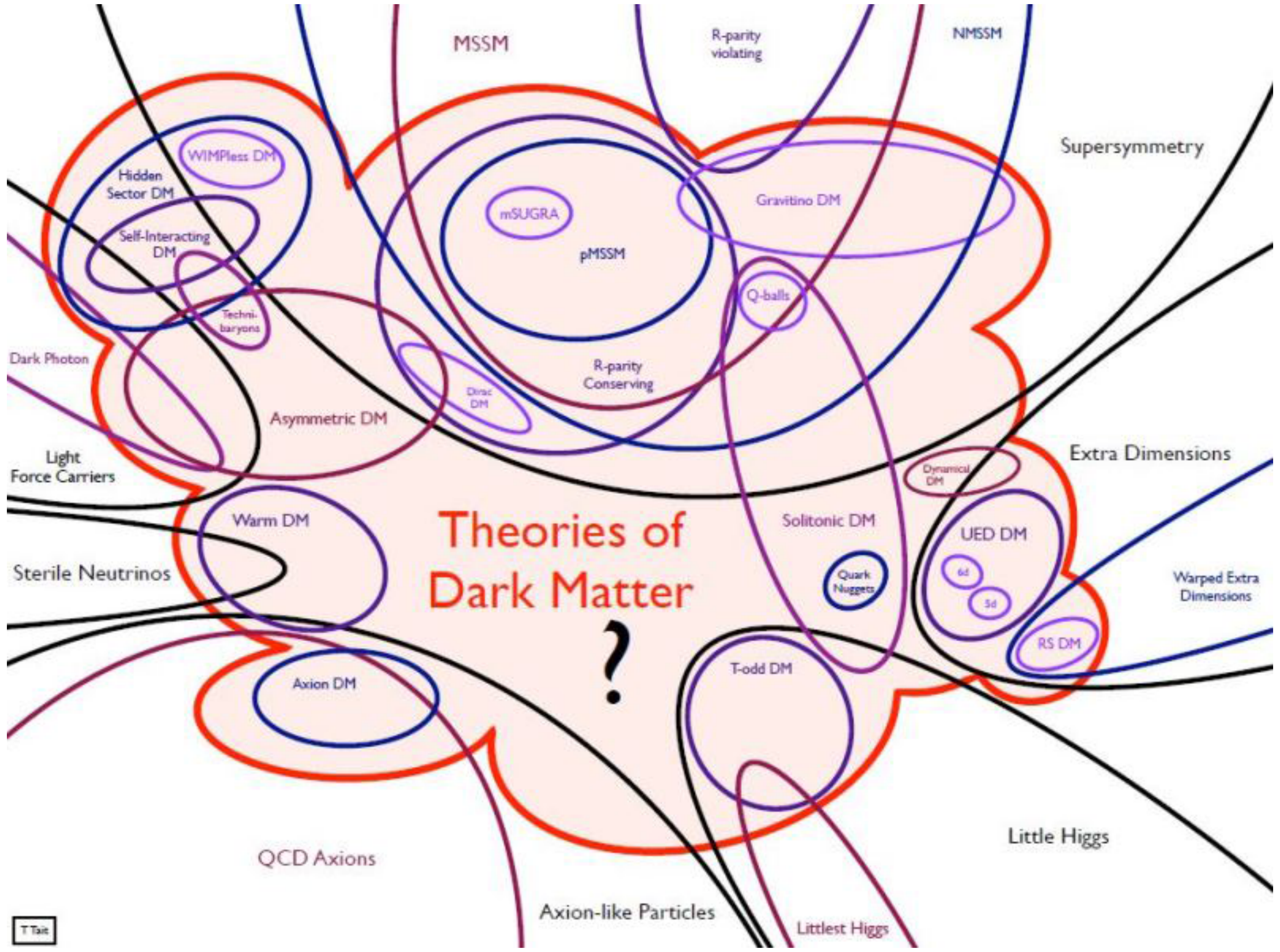
1. Gravitational particle production can produce dark photon dark matter.

2. Adding nonminimal couplings to gravity can lead to ghost and runaway instabilities.

3. There is a stable region of parameter space which avoids both these problems and can lead to production of the correct dark matter relic abundance.

Dark Matter





T. Tait/University of California, Irvine

Ultralight axions:
10^{-22} eV

WIMPs:
GeV - TeV

Black holes:
$10^4 M_\circ \sim 10^{60}$ GeV

Cosmological Gravitational Particle Production

- Expansion of universe → particle production

(e.g. Schrodinger, 1939; Parker 1965; Kuzmin & Tkachev, 1998; Chung, Kolb & Riotto, 1998)

- Two sets of operators at early and late times

$$(\hat{a}, \hat{a}^\dagger)^{\text{early}} \neq (\hat{a}, \hat{a}^\dagger)^{\text{late}}$$
$$\hat{a}^e |0^e\rangle = 0 |0^e\rangle$$
$$\hat{a}^l |0^e\rangle \neq 0 |0^e\rangle$$

- Corresponds to particle creation

$$\langle N \rangle = \int \frac{d^3k}{(2\pi)^3} \langle 0^e | \hat{a}^{\dagger l} \hat{a}^l | 0^e \rangle$$

Cosmological Gravitational Particle Production

- Early, late time operators related via

$$\hat{a}^{l}_{\mathrm{k}} = \alpha^*_{-\mathrm{k}} \hat{a}^{e}_{\mathrm{k}} - \beta_{-\mathrm{k}} \hat{a}^{\dagger e}_{-\mathrm{k}}$$
$$\hat{a}^{\dagger l}_{\mathrm{k}} = \alpha_{-\mathrm{k}} \hat{a}^{\dagger e}_{-\mathrm{k}} - \beta^*_{-\mathrm{k}} \hat{a}^{e}_{\mathrm{k}}$$

- β in terms of mode functions, χ_k

$$|\beta_k|^2 = \lim_{\eta \to \infty} \left[\frac{\omega_k}{2} |\chi_k|^2 + \frac{1}{2\omega_k} |\partial_\eta \chi_k|^2 - \frac{1}{2} \right]$$

- Particle number from β

$$n_k = \frac{k^3}{2\pi^2} |\beta_k|^2 \quad \to \quad na^3 = \int \frac{dk}{k} n_k$$

Dark Photons

$$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu$$

- Massive spin-1 field (Proca)

Portal to dark sector

- Kinetic mixing with SM photon, $\mathscr{L} \supset \epsilon F^{\text{dark}}_{\mu\nu} F^{\mu\nu\text{SM}}$
- Observable consequences: e.g. Caputo+ 2020, Berlin+ 2022, East & Huang 2023, Cyncynates & Weiner 2023, Arsenadze+ 2024

Dark Matter

- Can be produced via GPP: Graham+ 2015, Ema, Nakayama, & Tang 2019, Ahmed, Grzadkowski, & Socha 2020; Kolb & Long 2020
- Also via e.g. freeze-in (Postma & Redondo 2008), misalignment (Nelson & Scholtz 2011)

Dark Photons with Nonminimal Couplings to Gravity

$$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu - \frac{1}{2}\xi_1 R A_\mu A^\mu - \frac{1}{2}\xi_2 R_{\mu\nu} A^\mu A^\nu$$

- We add two dimension-four operators which obey the symmetries of the theory
- $\xi_1 = \xi_2 = 0 \rightarrow$ minimal coupling
- $\xi_1, \xi_2 \neq 0 \rightarrow$ expected from loop corrections, self interactions, etc.

Dark Photons with Nonminimal Couplings to Gravity

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Two Questions:

1. How does the addition of $\xi_1, \xi_2 \neq 0$ impact dark photon production via GPP?
   (See also Ozsoy & Tasinato, 2023, Cembranos et al., 2023)

2. What are the allowable values of ξ_1, ξ_2 to
   A. Avoid instabilities?
   B. Produce the correct relic abundance of DM?

Dark Photons with Nonminimal Couplings to Gravity

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Addition of $\xi_1, \xi_2 \neq 0$ leads to time dependent effective masses

Dark Photons with Nonminimal Couplings to Gravity

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Addition of $\xi_1, \xi_2 \neq 0$ leads to time dependent effective masses

$$m_t^2 = m^2 - \xi_1 R - \frac{1}{2}\xi_2 R - 3\xi_2 H^2$$

$$m_x^2 = m^2 - \xi_1 R - \frac{1}{6}\xi_2 R + \xi_2 H^2$$

Dark Photons with Nonminimal Couplings to Gravity

Decompose the field

$$S^L = \int d\eta \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \left[\frac{1}{2} \frac{a^2 m_t^2}{k^2 + a^2 m_t^2} \left| \partial_\eta A_{\boldsymbol{k}}^L \right|^2 - \frac{1}{2} a^2 m_x^2 \left| A_{\boldsymbol{k}}^L \right|^2 \right]$$

Canonically normalize

$$A_{\boldsymbol{k}}^L(\eta) = \kappa(\eta) \chi_{\boldsymbol{k}}^L(\eta) \qquad \kappa^2(\eta) = \frac{k^2 + a^2 m_t^2}{a^2 m_t^2}$$

$$S^L = \int d\eta \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \left(\frac{1}{2} \left| \partial_\eta \chi \right|^2 - \frac{1}{2} \omega_L^2 |\chi|^2 \right)$$

Dark Photons with Nonminimal Couplings to Gravity

Longitudinal mode equation

$$S^L = \int d\eta \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \left(\frac{1}{2} \left| \partial_\eta \chi \right|^2 - \frac{1}{2} \omega_L^2 |\chi|^2 \right)$$

ω_L^2 hiding a lot of complexity

$$\omega_L^2 = k^2 \frac{m_x^2}{m_t^2} + a^2 m_x^2 + \frac{3k^2 a^4 m_t^2 H^2}{(k^2 + a^2 m_t^2)^2} + \frac{k^2 a^2 R}{6(k^2 + a^2 m_t^2)}$$

$$+ \frac{Hak^2 m_t^{2\prime}}{m_t^2} \frac{(-k^2 + 2a^2 m_t^2)}{(k^2 + a^2 m_t^2)^2} + \frac{k^2 (m_t^{2\prime})^2}{4(m_t^2)^2} \frac{(k^2 + 4a^2 m_t^2)}{(k^2 + a^2 m_t^2)^2} - \frac{k^2 m_t^{2\prime\prime}}{2m_t^2 (k^2 + a^2 m_t^2)}$$

Instabilities of the Theory: Ghosts

Ghost: wrong sign kinetic term

To avoid ghosts: $\kappa^2 > 0$

$$\kappa^2(\eta) = \frac{k^2 + a^2 m_t^2}{a^2 m_t^2} > 0$$

$$\Downarrow$$

$$m_t^2 > 0$$

$$\Downarrow$$

$$m^2 - \xi_1 R - \frac{1}{2}\xi_2 R - 3\xi_2 H^2 > 0$$

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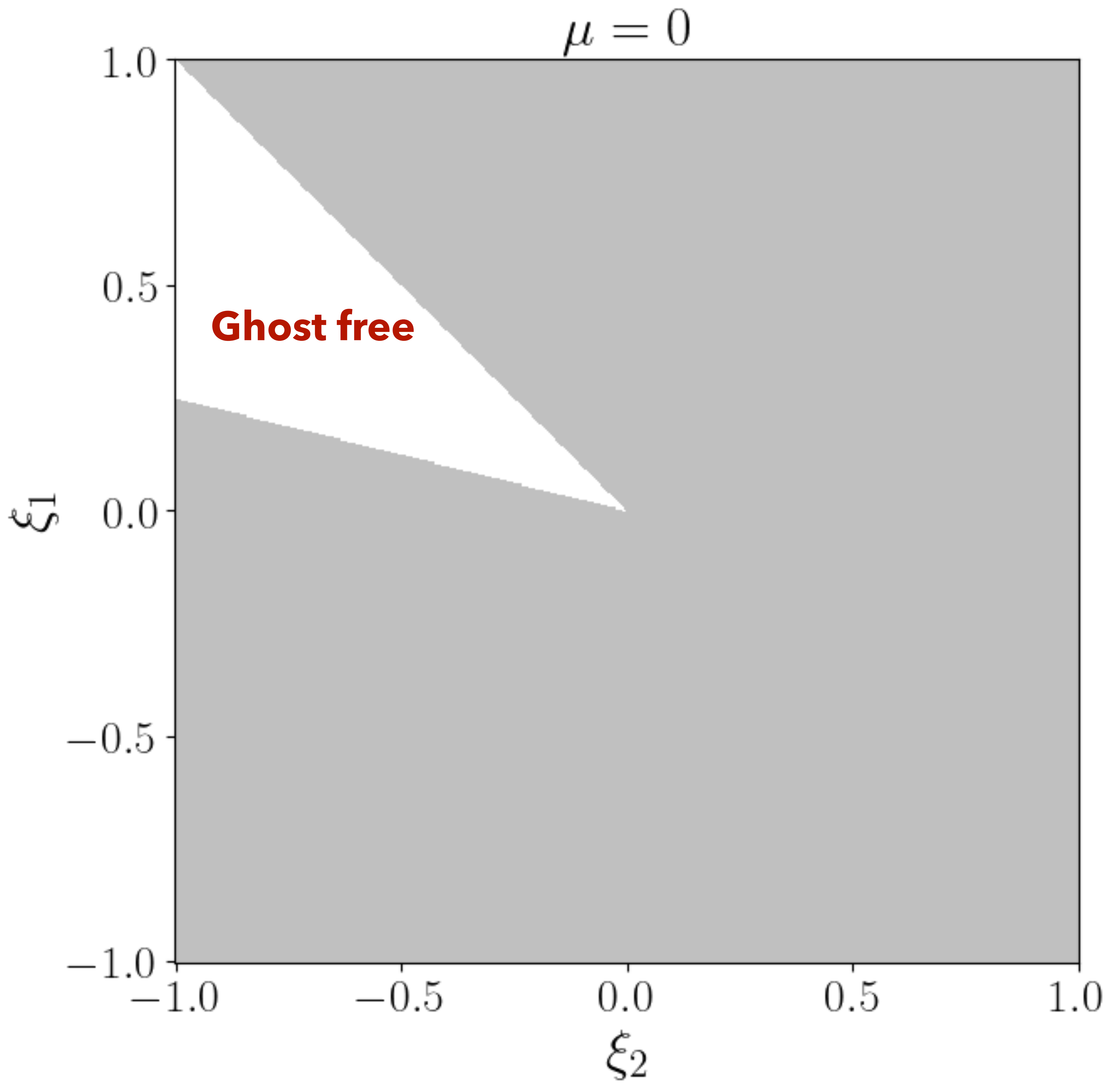

$$\mu = m/H_e$$

Instabilities of the Theory: Runaway

Tachyon: wrong sign mass term

$$\omega_L^2 = k^2 \frac{m_x^2}{m_t^2} + a^2 m_x^2 + f(a, k, \xi_1, \xi_2, R, H)$$

$\omega^2 < 0$ not necessarily a problem

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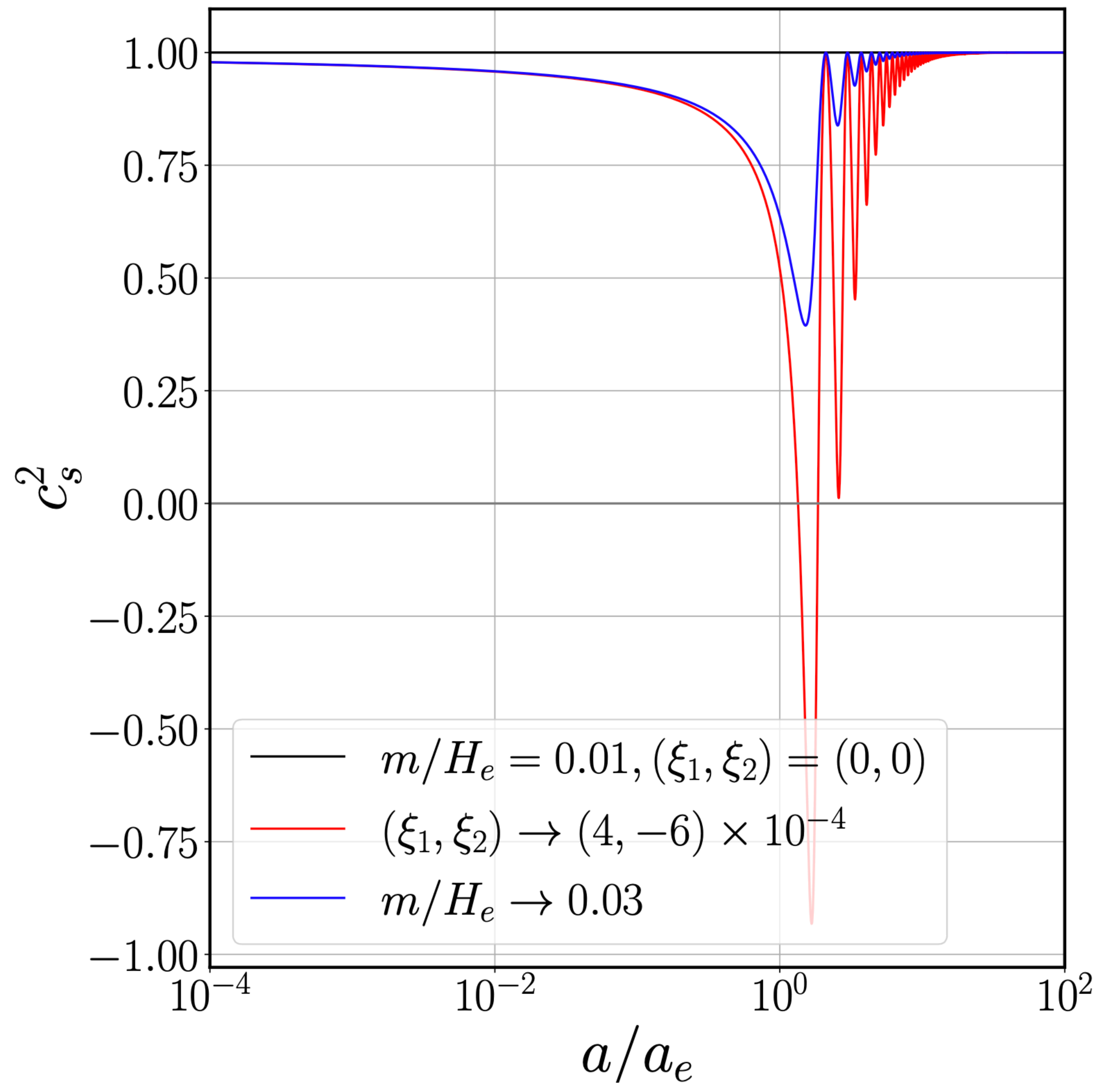
But ω^2 also has modified sound speed, c_s

$$c_s^2 = \frac{m_x^2}{m_t^2}$$



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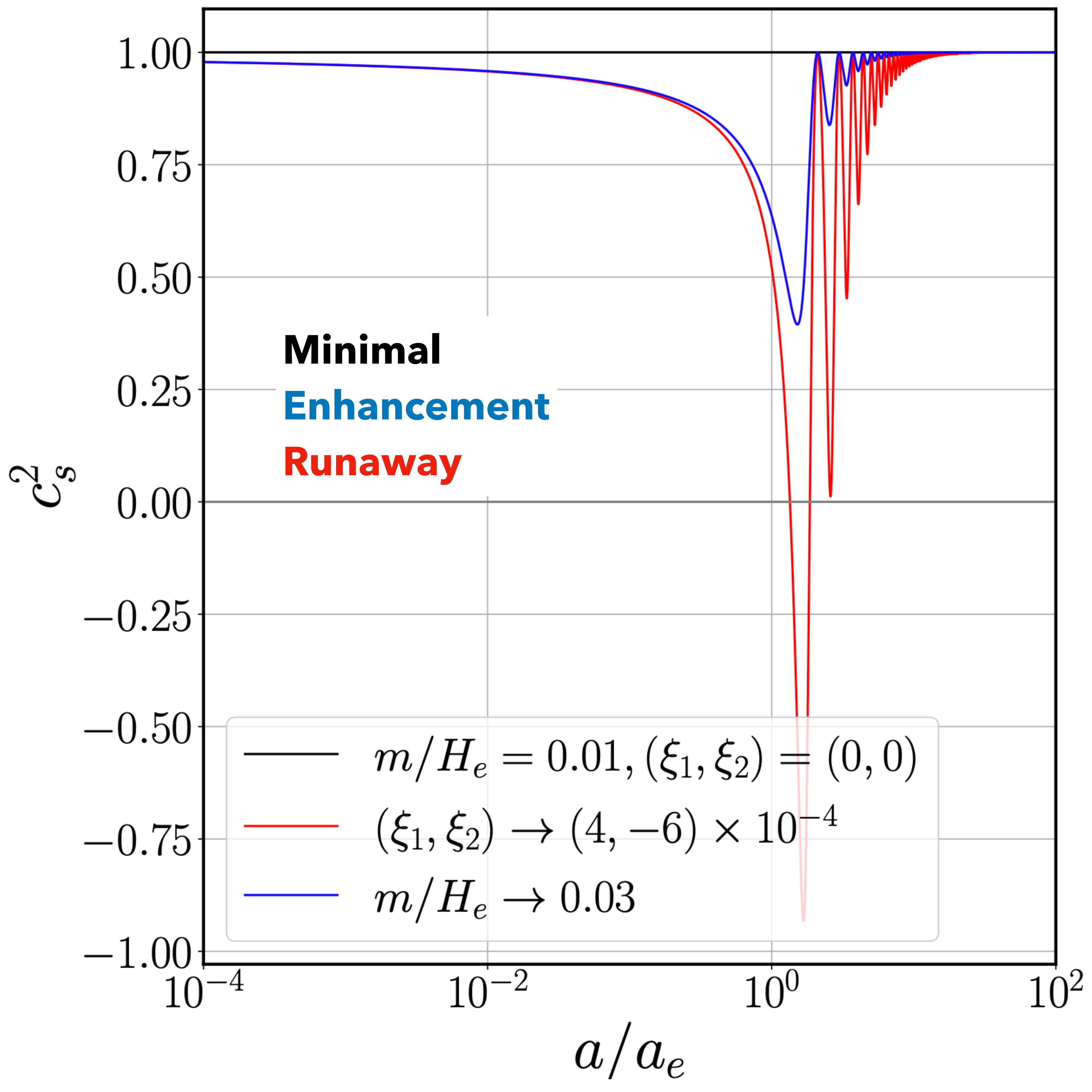
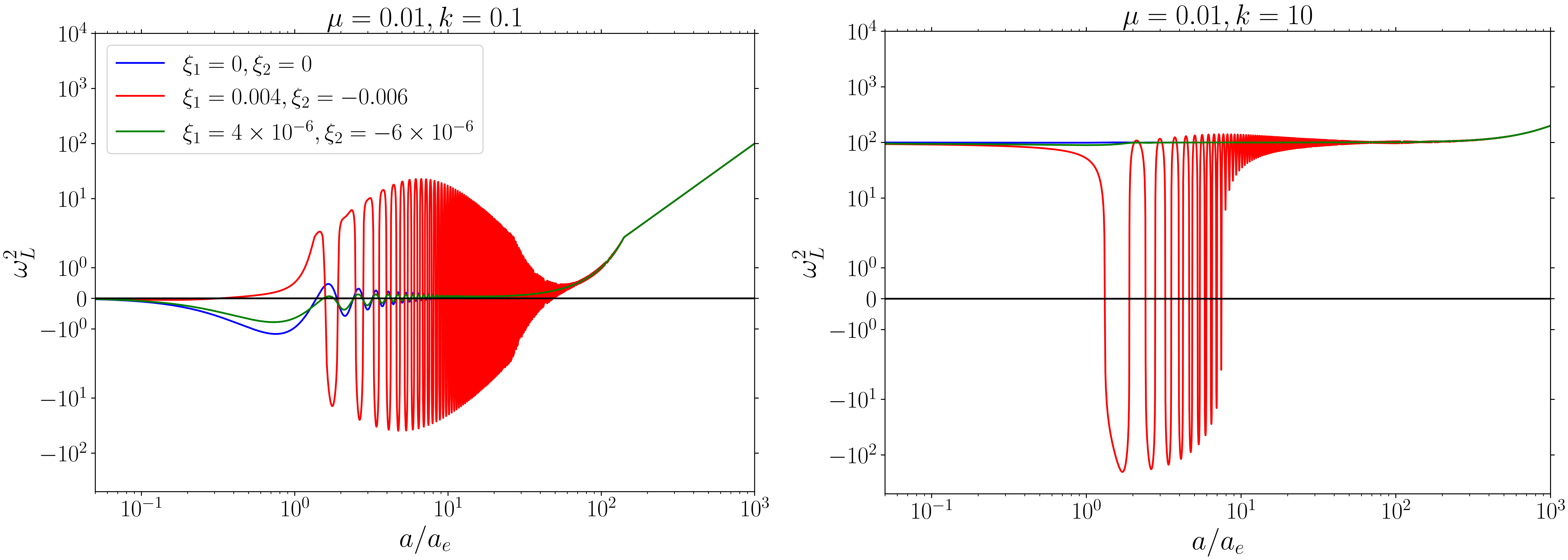
But ω^2 also has modified sound speed, c_s

$$c_s^2 = \frac{m_x^2}{m_t^2}$$

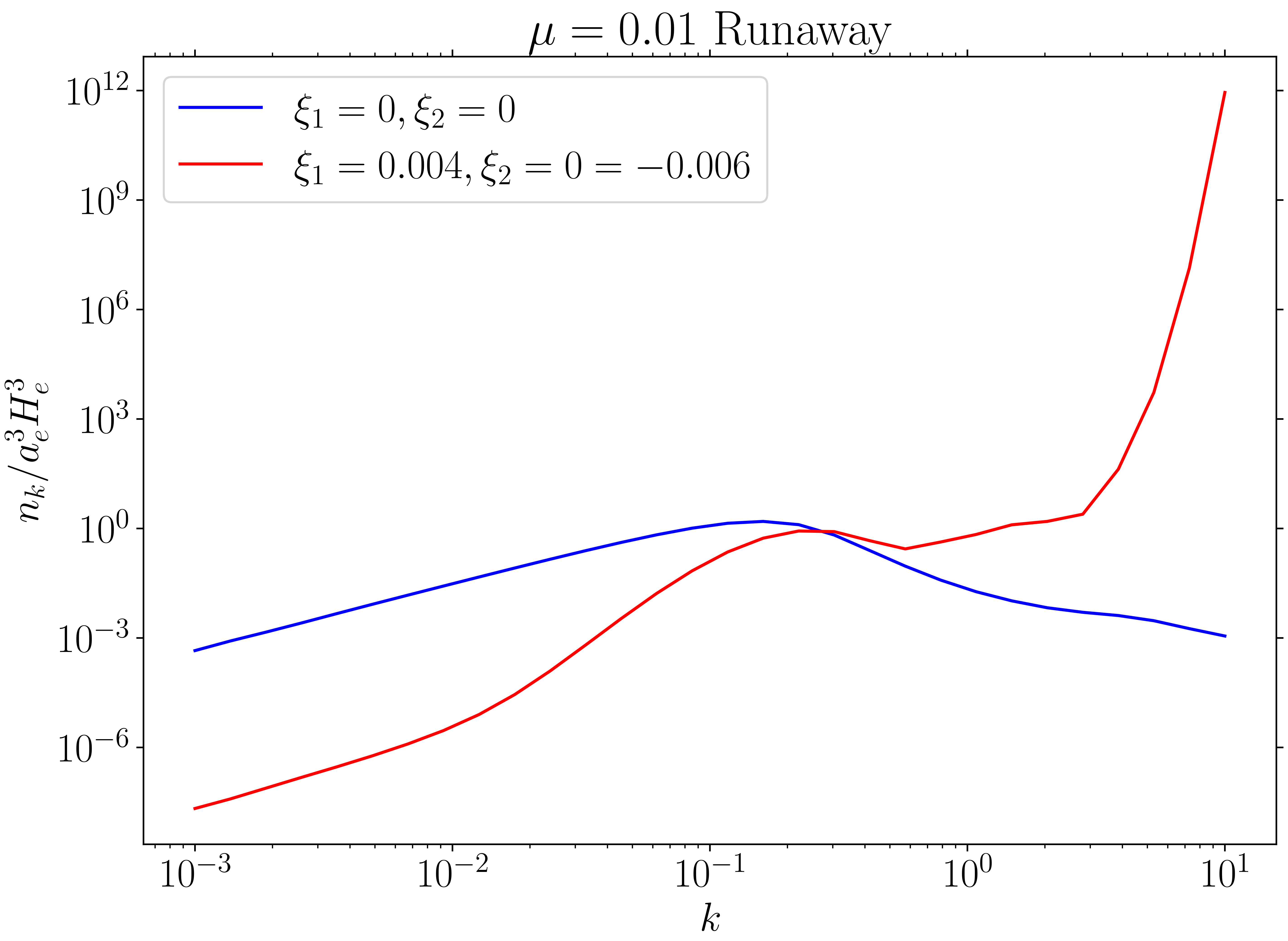
$c_s^2 < 0$ leads to runaway production.



Instabilities of the Theory: Runaway



Instabilities of the Theory: Runaway



Instabilities of the Theory: Runaway

To avoid runaway: $c_s^2 = \frac{m_x^2}{m_t^2} > 0$

↓

$$m_x^2 > 0$$

↓

$$m^2 - \xi_1 R - \frac{1}{6}\xi_2 R + \xi_2 H^2 > 0$$

Instabilities of the Theory: Runaway

To avoid runaway: $c_s^2 = \dfrac{m_x^2}{m_t^2} > 0$

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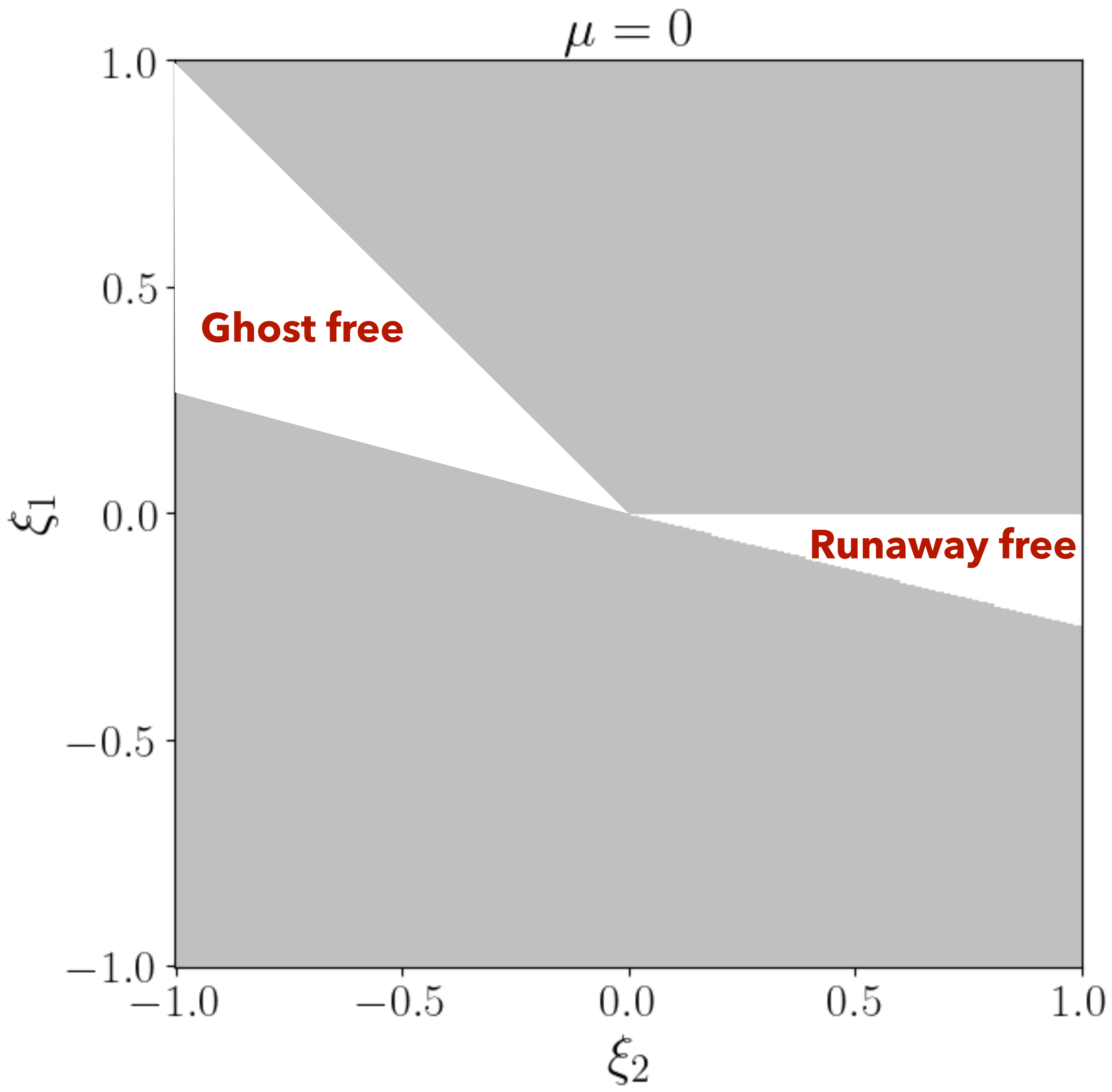
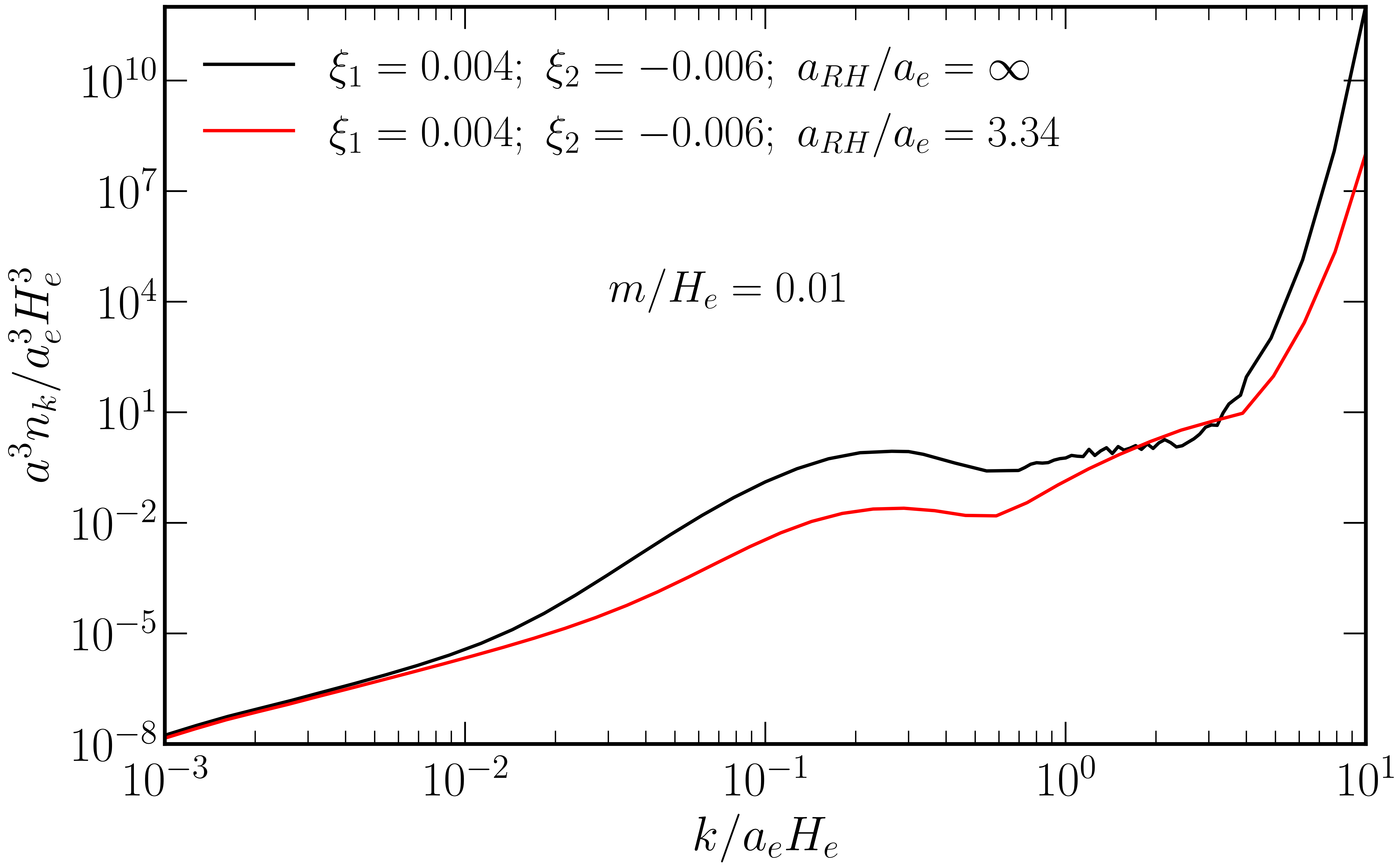


In the $m \to 0$ limit, there is no overlap for ghost-free and non-runaway regions.

Potential Solutions for the Runaway?

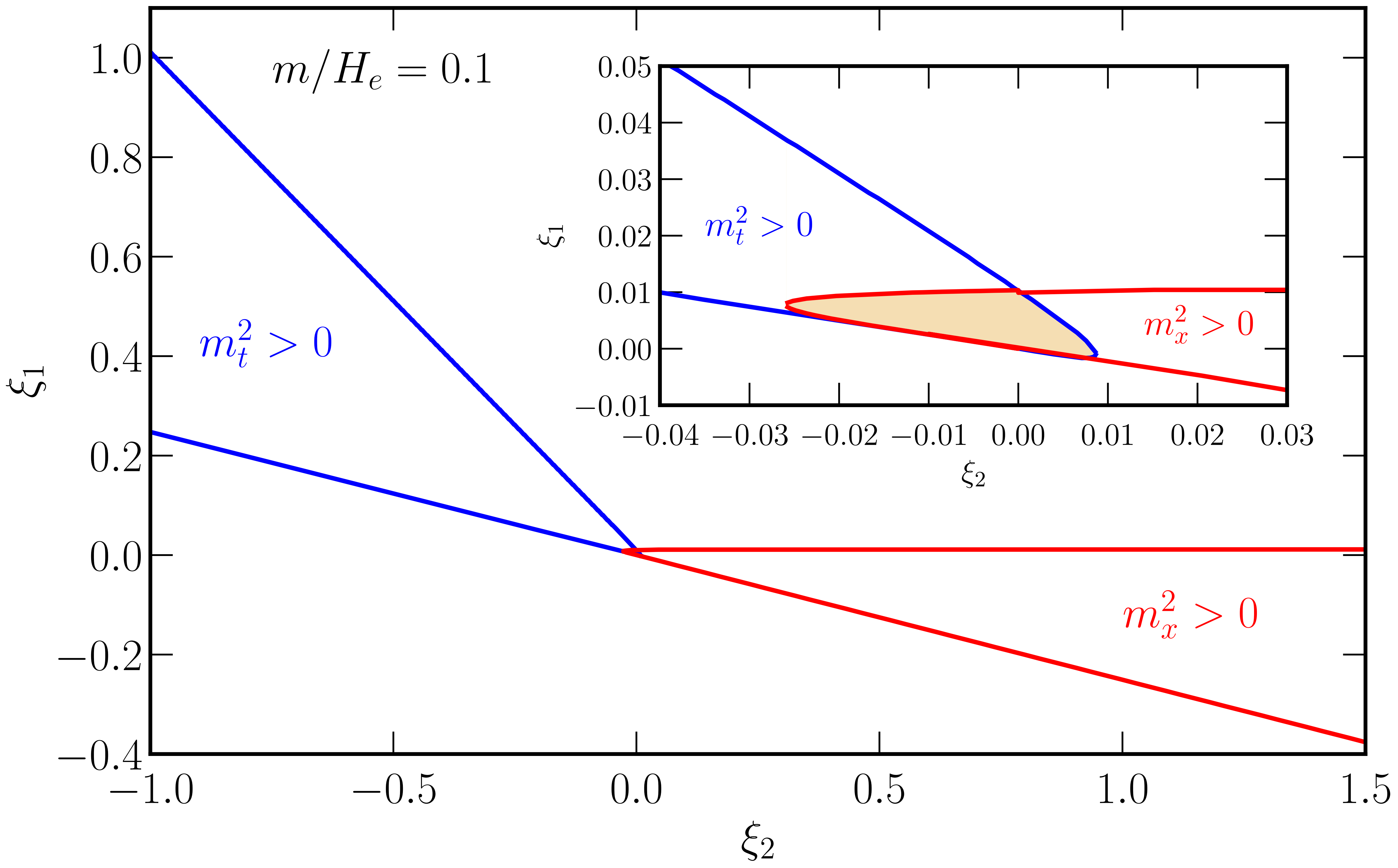
- Impose a cutoff?
  - For cutoff to really solve the problem, would need $\Lambda \lesssim H_e$
- UV completion?
  - In e.g., Abelian Higgs model, we still expect to generate nonminimal couplings
- Disformal gravity? (Hell 2024)
  - Removes coupling to $R_{\mu\nu}$ at tree level
- What about early reheating?

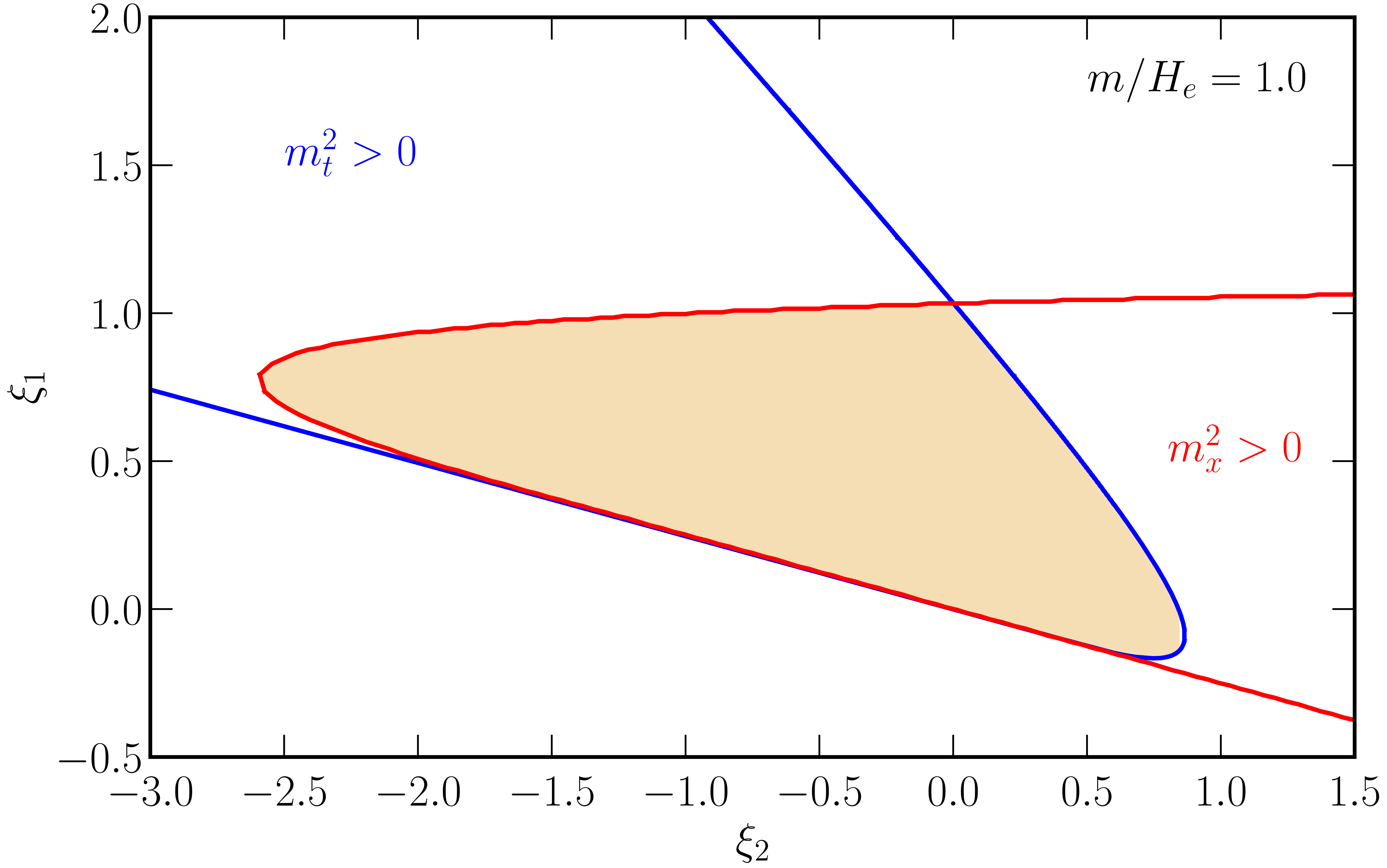
Aside: Runaway in Early Reheating



Stable Region

For m > 0, there exists a small region to avoid ghosts & runaway

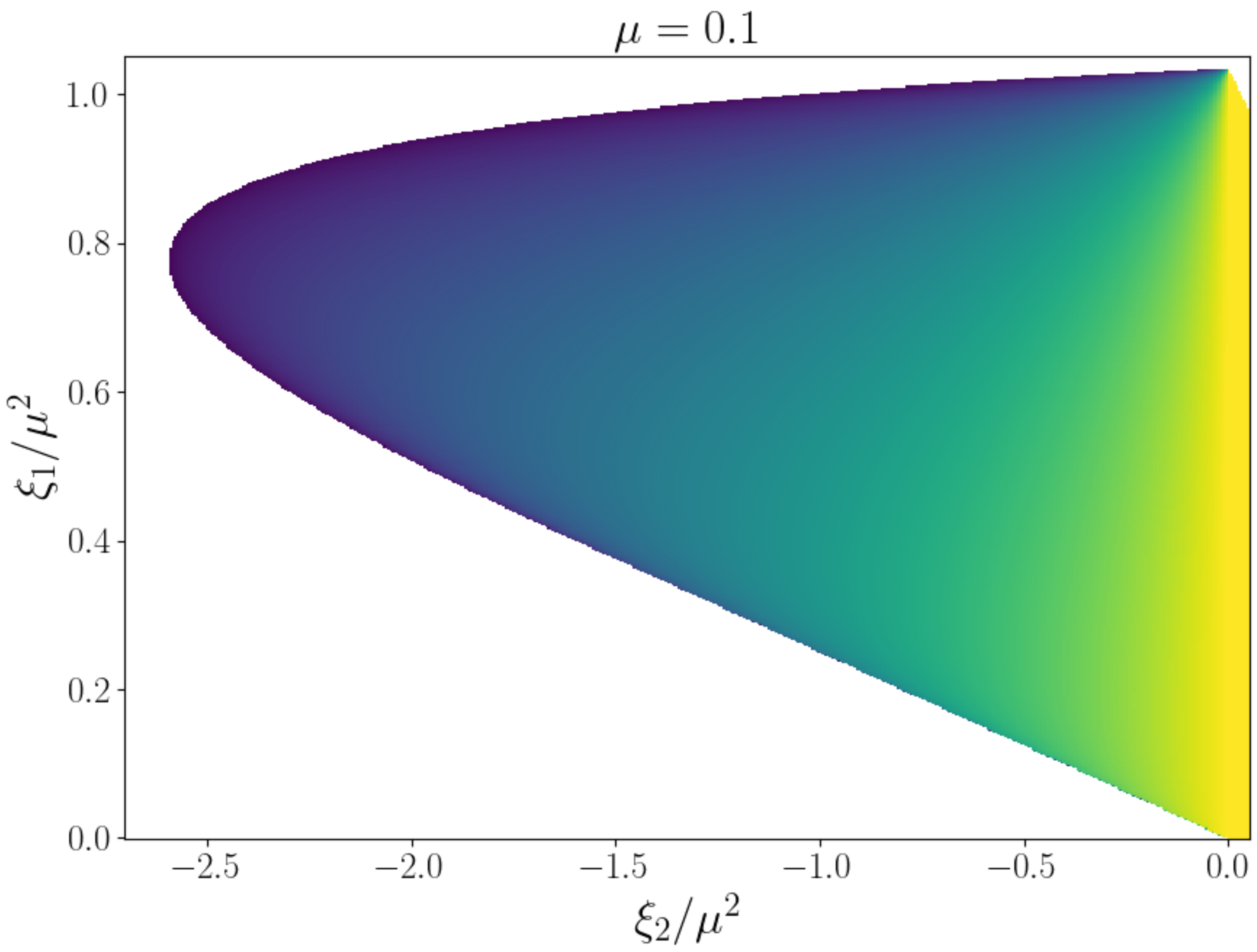




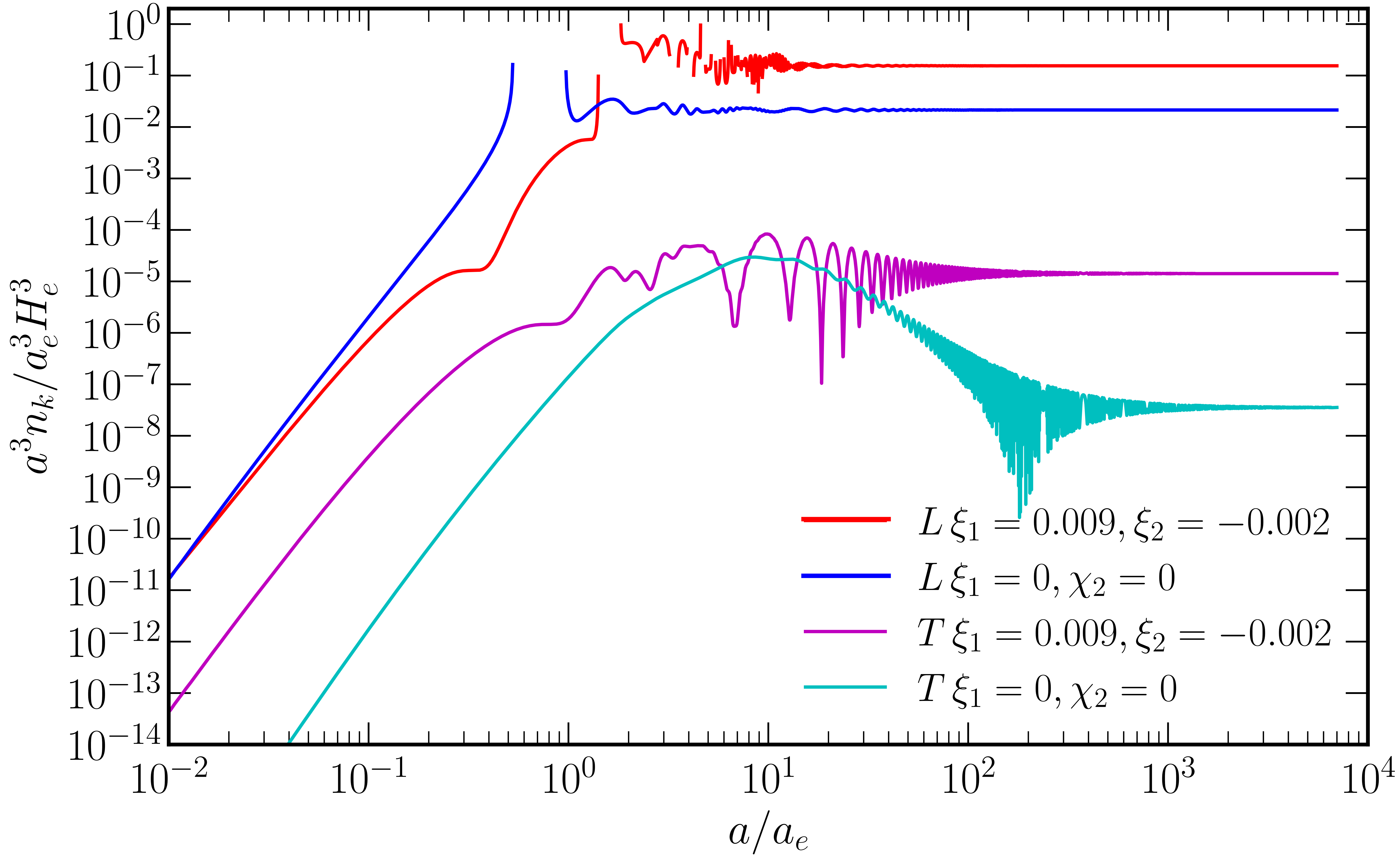
Stable Region

We now restrict ourselves to the 'stable region'

1. Ghost-free: $m_t^2 > 0$
2. Runaway-free: $m_x^2 > 0$
3. Subluminal propagation: $|c_s^2| < 1$

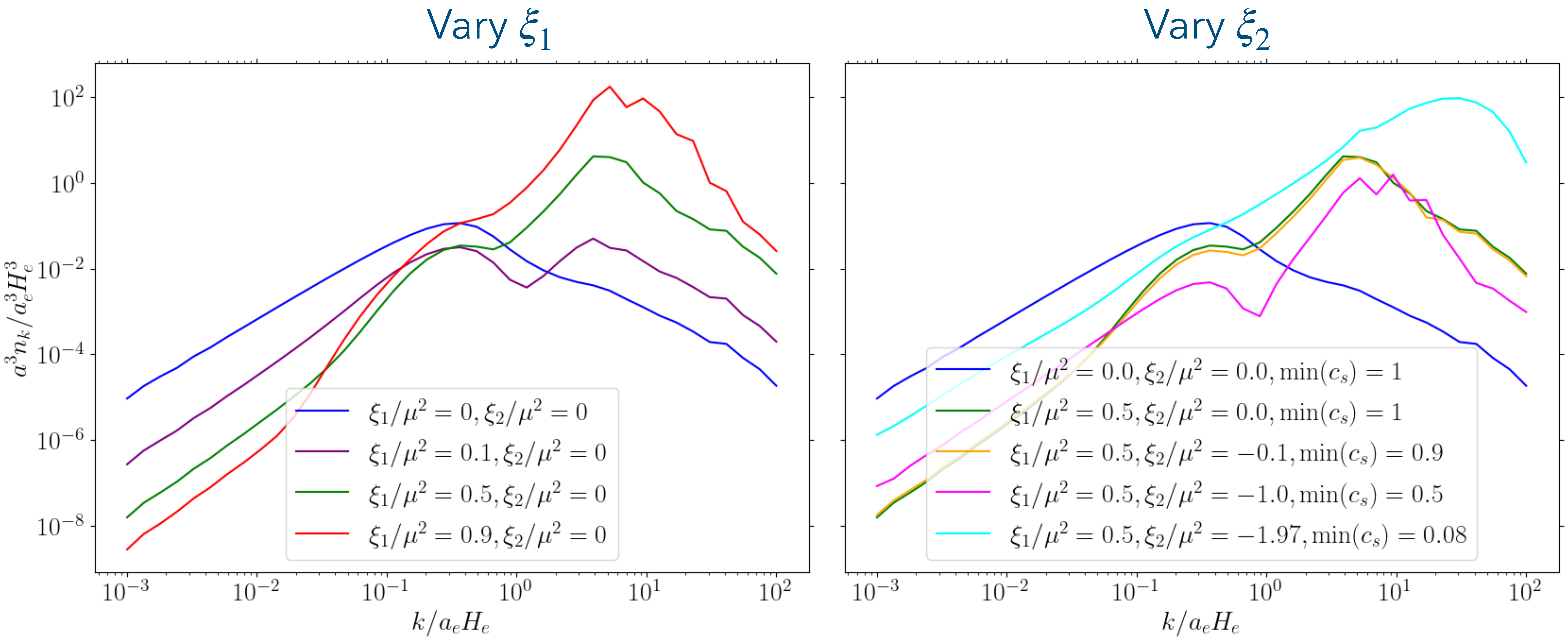


GPP in the Stable Region



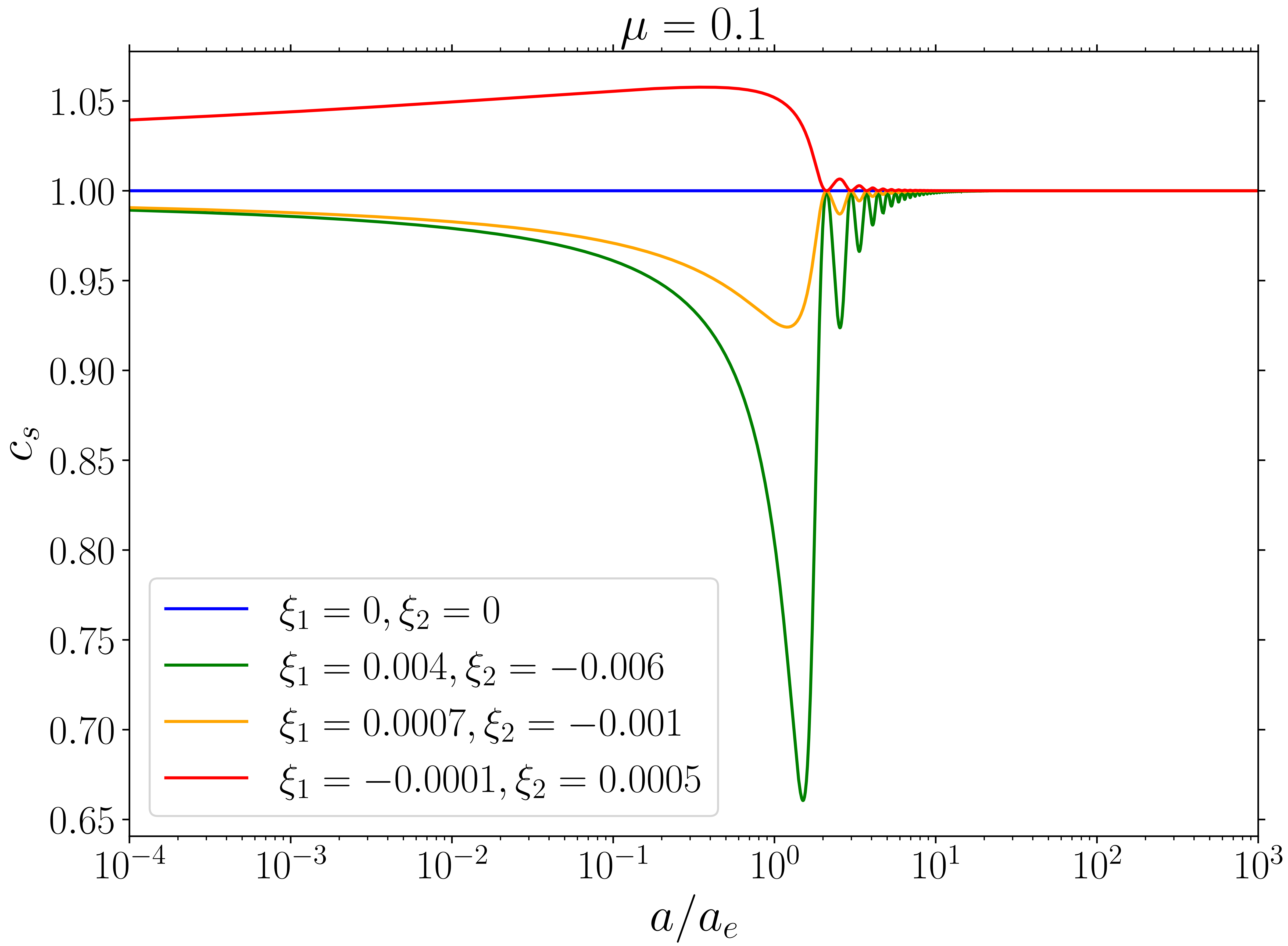
Transverse modes enhanced with $\xi_{1,2} \neq 0$ but still subdominant

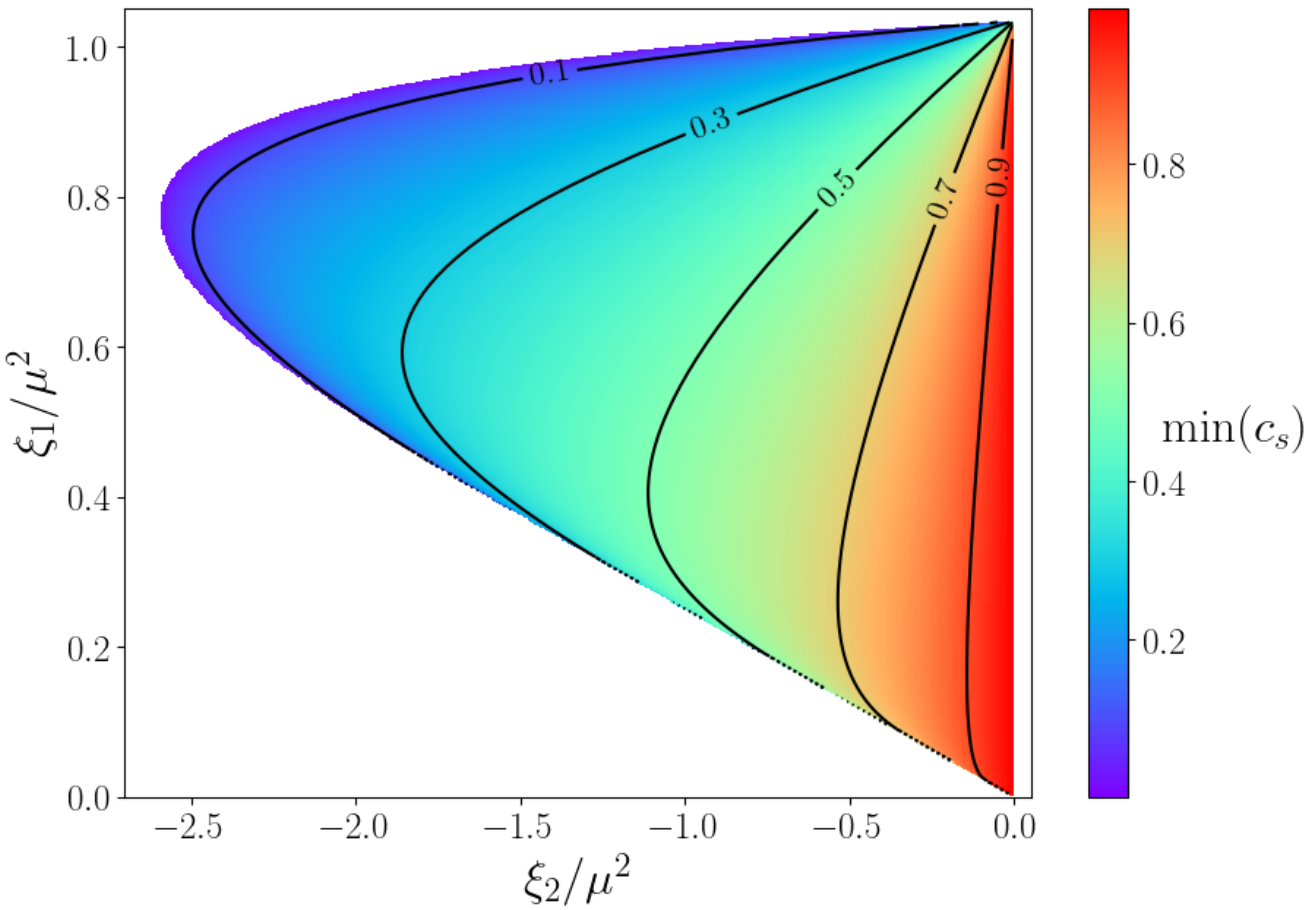
GPP in the Stable Region



GPP in the Stable Region

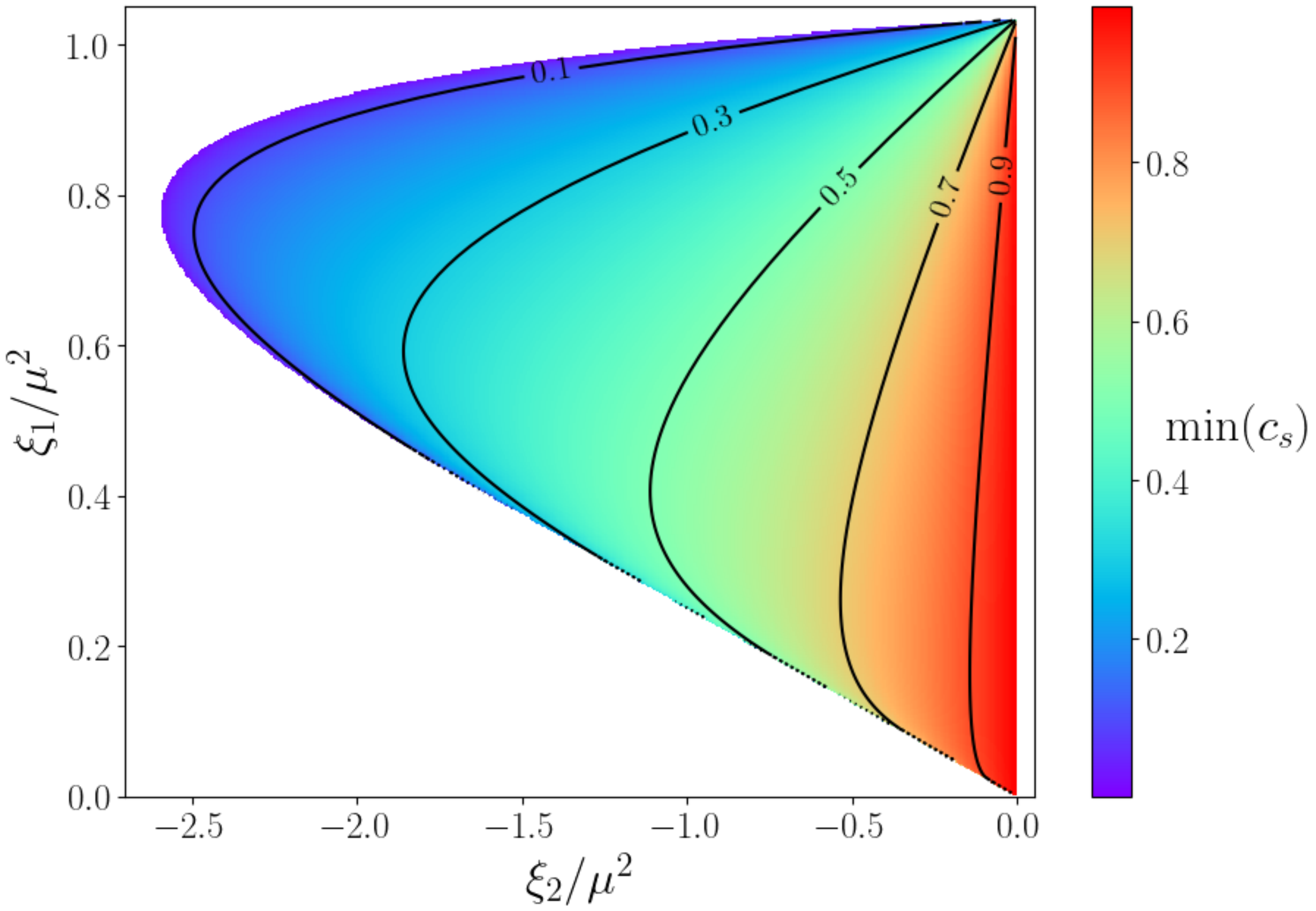
Main effect: variation in c_s

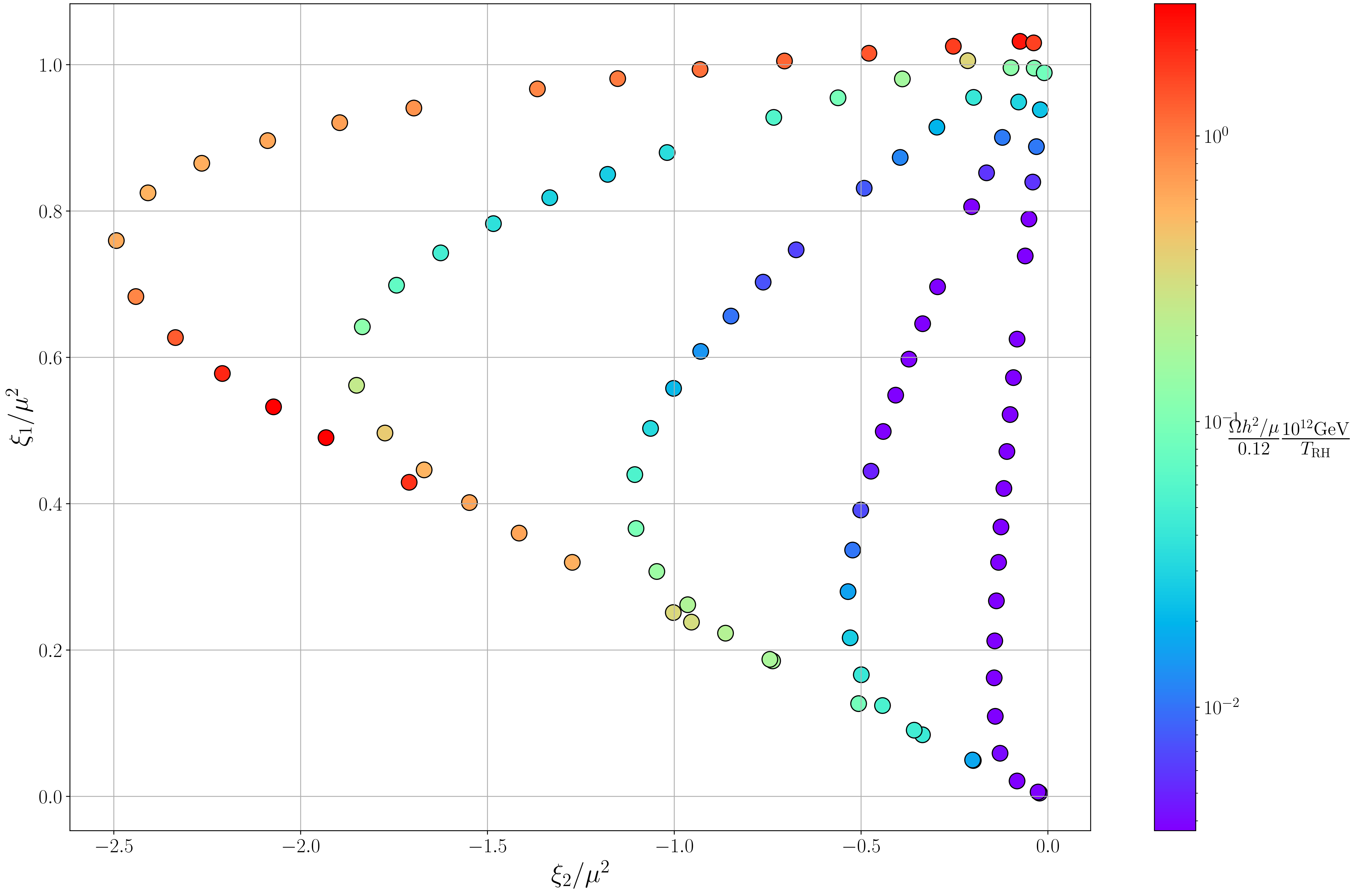




Relic Density

$$\frac{\Omega h^2}{0.12} = \frac{m_\chi}{H_e}\left(\frac{H_e}{10^{12}\text{GeV}}\right)^2\left(\frac{T_{\text{RH}}}{10^9\text{GeV}}\right)\frac{na^3}{10^{-5}}$$





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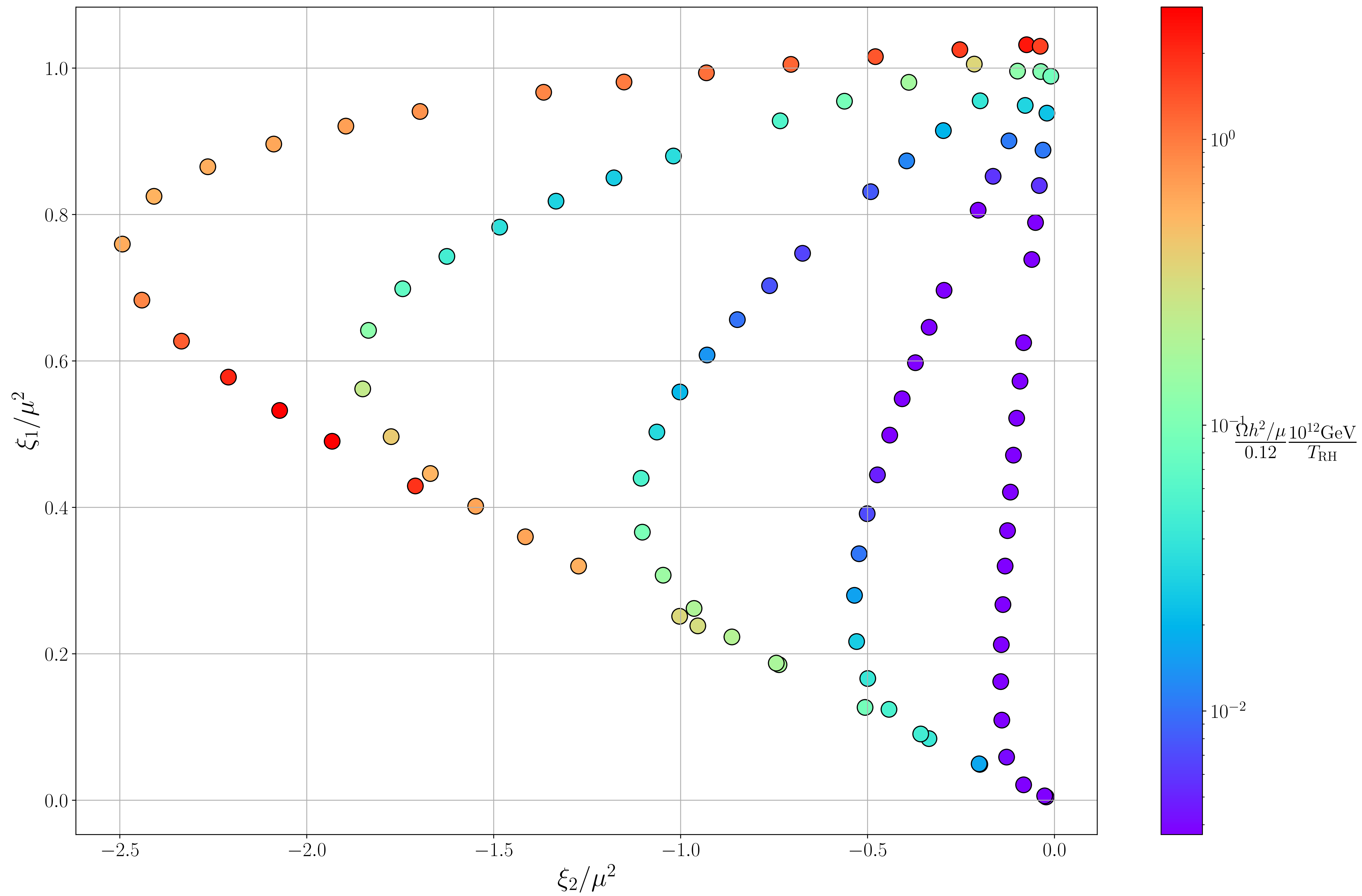
- Can obtain $\Omega h^2/0.12 = \mathcal{O}(1)$ by changing H_e, T_{RH}
- Largest increase of particle production towards edge of stable region
- Allows for lower particle masses for a wider range of parameters than minimal theory



Summary & Conclusions

- Adding nonminimal couplings to gravity can lead to ghost and runaway instabilities for gravitational production of massive spin-1 fields.
- In the ghost-free, non-runaway stable region of parameter space for the couplings, we can obtain the correct relic density of dark matter.
- Addition of nonminimal couplings in the stable region allows for a wider viable parameter space than in the minimal theory.

Thank you!

Extra Slides

Cosmological Gravitational Particle Production

- Many ways to calculate GPP

  We use numerical methods, but also a variety of analytic strategies can be employed, see e.g. LJ, Kolb, Thyme 2024.

- DM production for a wide range of masses & spins - Generic!

  (e.g. Chung, Kolb & Riotto, 1998+; Graham, Mardon & Rajendran 2015; Ema, Nakayama, & Tang 2019; Kolb & Long, 2020; Ahmed, Grzadkowski, & Socha 2020; Alexander, LJ & McDonough, 2020; Kolb, Long, & McDonough 2021; Kolb, Ling, Long & Rosen, 2022; Capanelli, LJ, Kolb, McDonough, 2023….)

See Kolb & Long 2023 for a nice review.

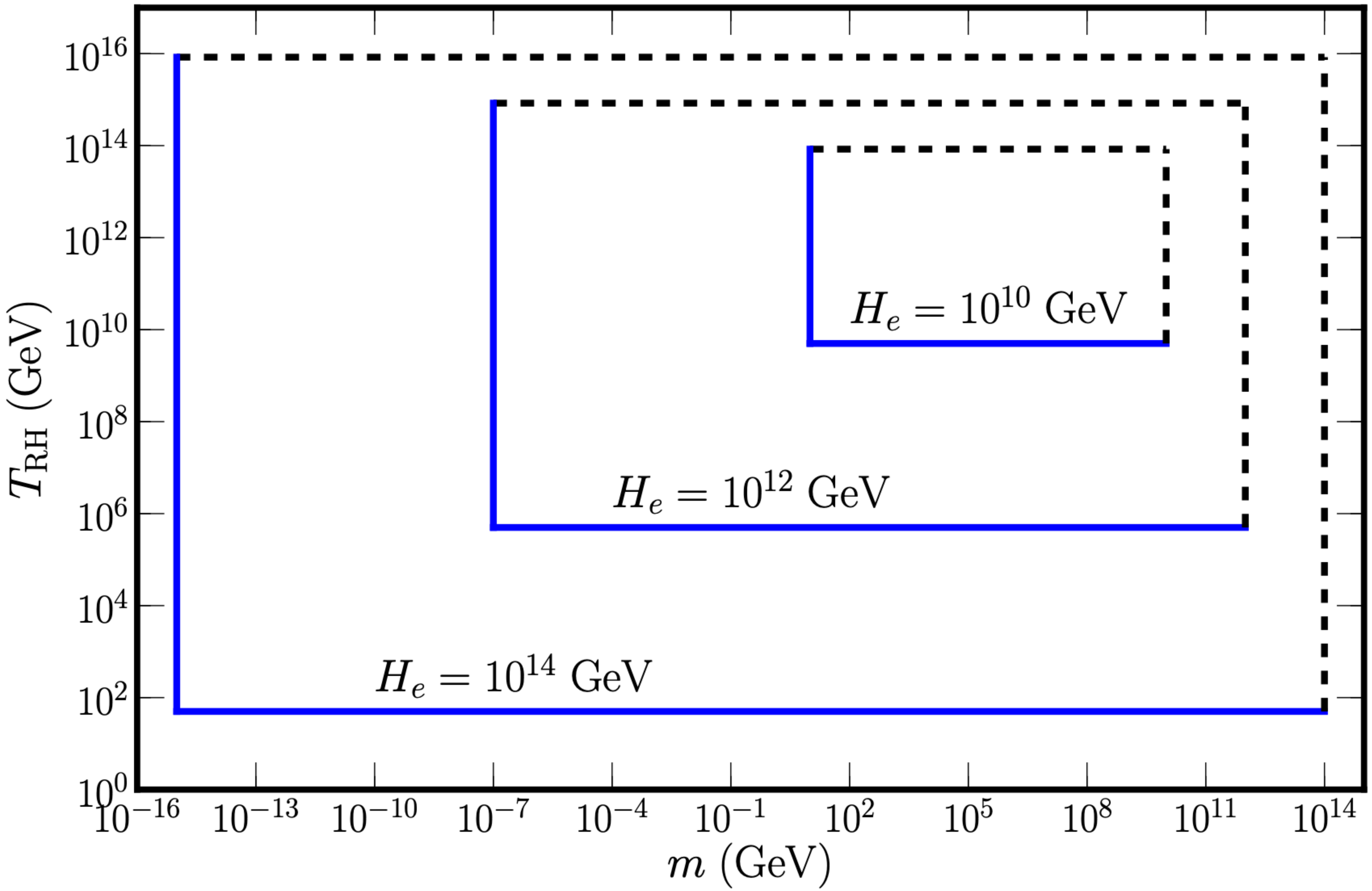
Dark Photons with Nonminimal Couplings to Gravity

Transverse mode equation

$$S^T = = \sum_{b=1,2} \int d\eta \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \left(\frac{1}{2} \left| \partial_\eta A_{\boldsymbol{k}}^{T_b} \right|^2 - \frac{1}{2}\omega_T^2 \left| A_{\boldsymbol{k}}^{T_b} \right|^2 \right)$$

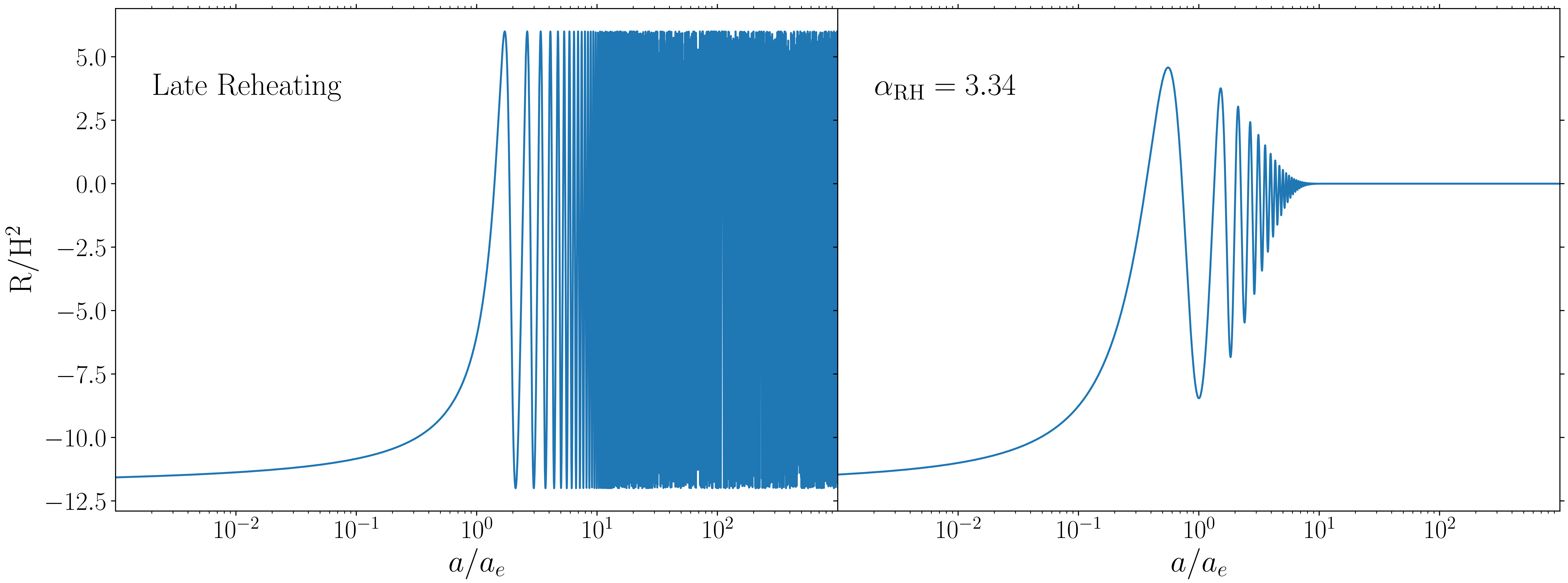
$$\omega_T^2(\eta) = k^2 + a^2 m_x^2$$

Mass Range (Minimal)

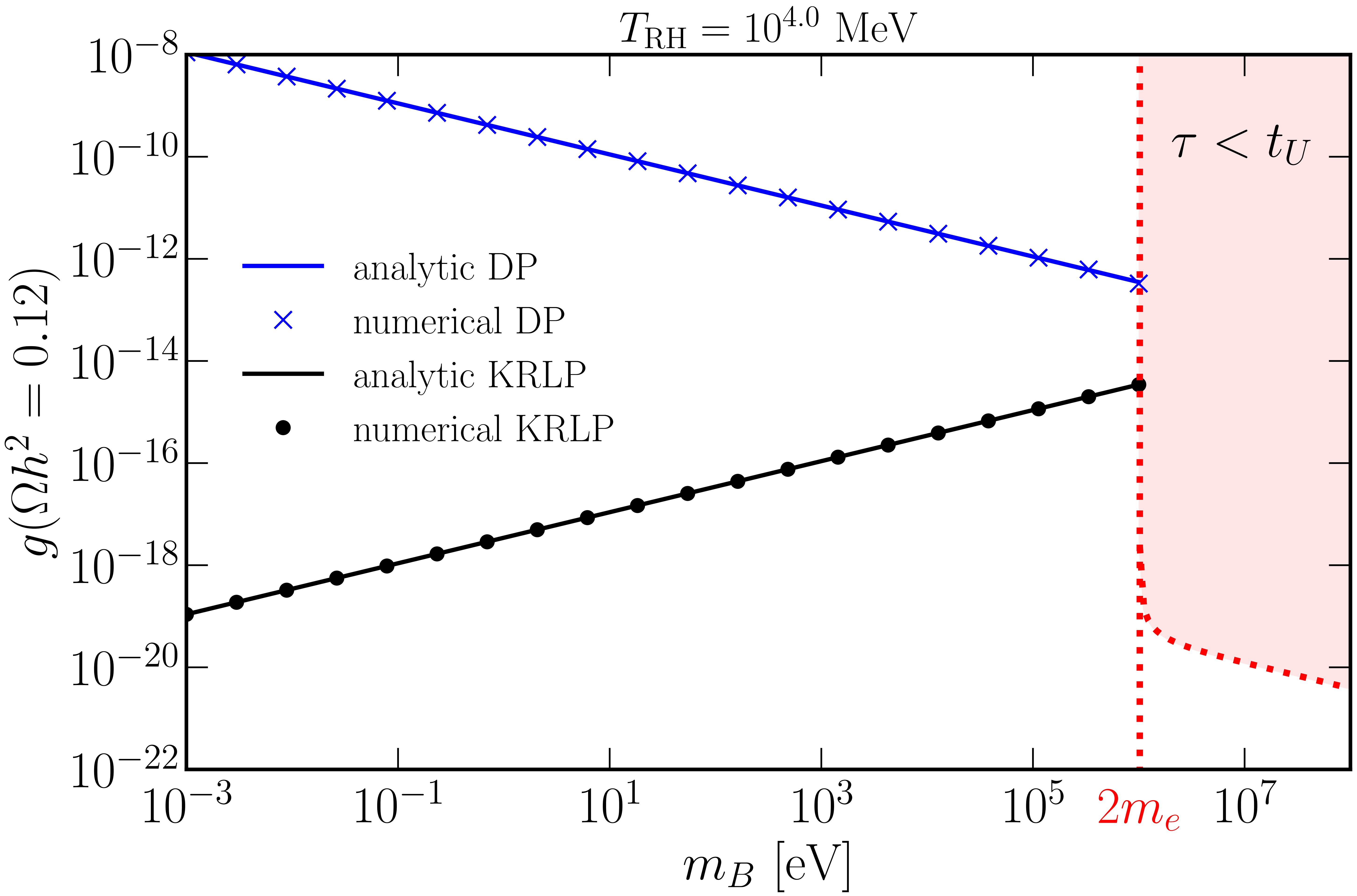


Kolb & Long, 2020

Aside: Runaway in Early Reheating



Freeze-In of KRLPs



KRLP

$$\mathscr{L}_{int} = gB_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$$

- Independent of m_f
- Scales like $\sim T_{RH}^{1/2}$

Dark Photon (Redondo & Postma, 2008)

$$\mathscr{L}_{int} = gA_{\mu}\bar{\psi}\gamma^{\mu}\psi$$

- Scales like $\sim m_f^{1/2}$
- Independent of T_{RH}

Early Reheating Equations

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) + \Gamma_\varphi \dot{\varphi} = 0$$

$$\dot{\rho}_\varphi + 3H\rho_\varphi + \Gamma_\varphi \rho_\varphi = 0$$

$$\dot{\rho}_R + 3H\rho_R - \Gamma_\varphi \rho_\varphi = 0$$

Γ_φ : Decay width

Abelian Higgs

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 + \mu^2|\phi|^2 - \lambda|\phi|^4$$

Can generate couplings:

$$\mathscr{L}_1 = \frac{\xi_1}{(gv)^2} R D_\mu \phi D^\mu \phi^*$$

$$\mathscr{L}_2 = \frac{\xi_2}{(gv)^2} R D_\mu \phi D_\nu \phi^* R^{\mu\nu}$$

CGPP of KRLPs

Add non minimal couplings?

$$S = \frac{1}{12}\int d^4x\sqrt{-g}\left(H_{\mu\nu\rho}H^{\mu\nu\rho} - 3m^2 B_{\mu\nu}B^{\mu\nu} - \xi_1 R B^{\mu\nu}B_{\mu\nu} - \xi_2 R^{\mu\nu\rho\sigma}B_{\mu\nu}B_{\rho\sigma}\right)$$

Dualize

↓

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu - \frac{1}{2}\xi_1 R A_\mu A^\mu - \frac{1}{2}\xi_2 R^{\mu\nu}A_\mu A_\nu\right)$$

GPP of nonminimally coupled KRLPs identical to Proca!

Dualities

Massless KR

"Kalb-Ramond axion"

(Svrcek & Witten, 2006)

$$d\theta = \star\, dB$$

$$S = \int d^4x H_{\mu\nu\rho} H^{\mu\nu\rho}$$

↓

$$S = \int d^4x \partial_\mu \theta \partial^\mu \theta$$

= axion

Massive KR

Dual to a *pseudovector*

(e.g. Smailagic & Spalluci, 2001; Hell, 2022)

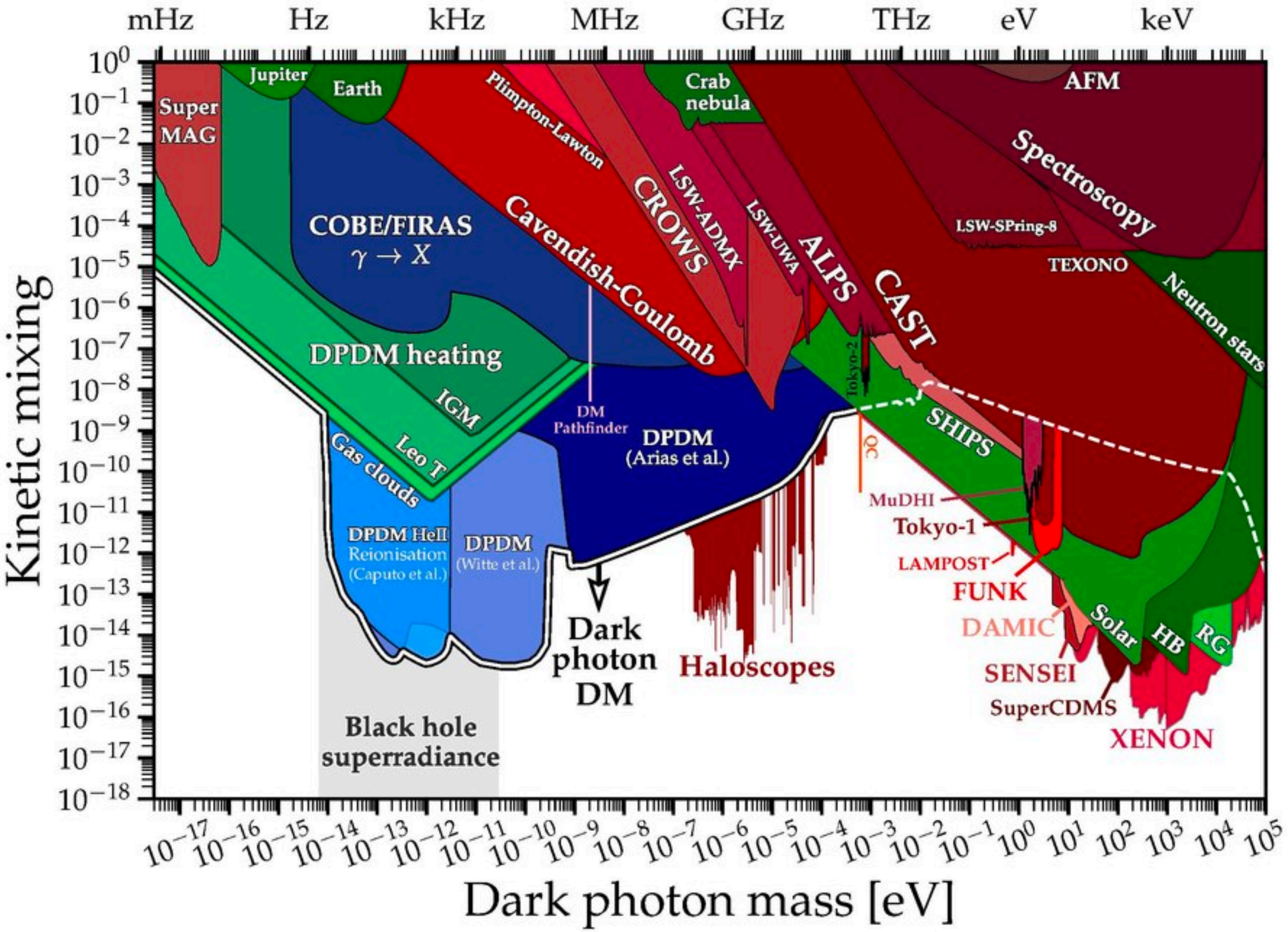
$$B_{ij} = \epsilon_{ijk} B^k$$

$$S = \int d^4x \left(H_{\mu\nu\rho} H^{\mu\nu\rho} - m^2 B_{\mu\nu} B^{\mu\nu} \right)$$

↓

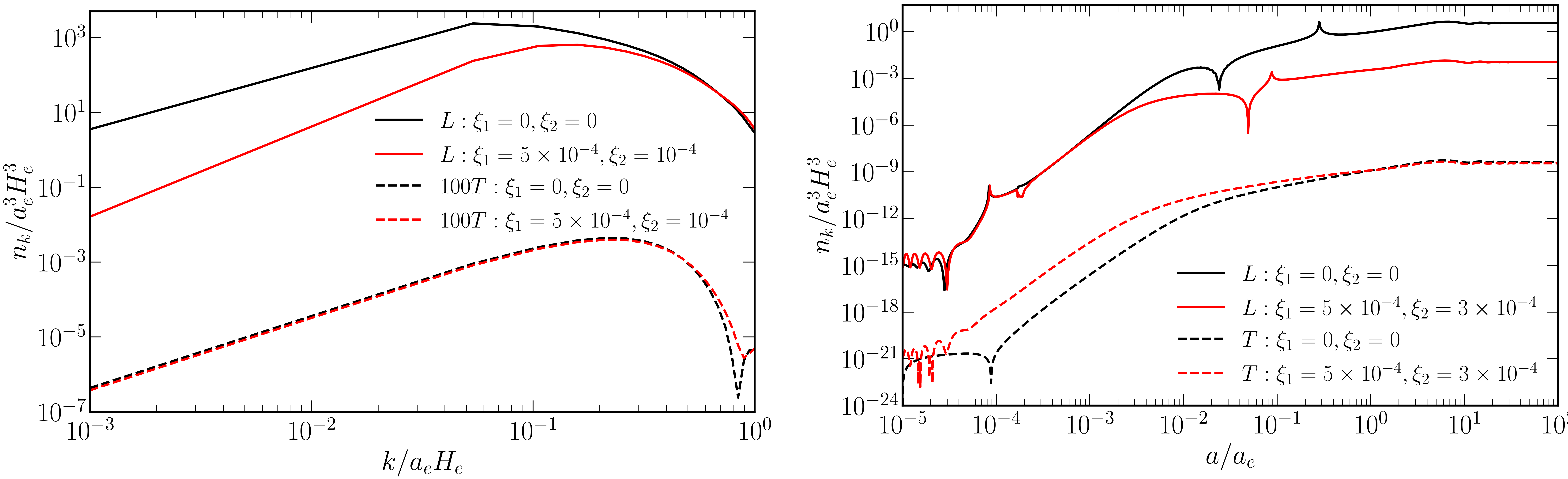
$$S = \int d^4x \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu \right)$$

≠ Proca


mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
Super MAG
Jupiter
Earth
Plimpton-Lawton
Crab nebula
AFM
Spectroscopy
COBE/FIRAS
γ → X
Cavendish-Coulomb
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
LSW-SPring-8
TEXONO
Neutron stars
DPDM heating
IGM
Leo T
Gas clouds
DM Pathfinder
DPDM (Arias et al.)
Tokyo-2
QC
SHIPS
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
XENON
Solar
HB
RG
DPDM HeII Reionisation (Caputo et al.)
DPDM (Witte et al.)
Dark photon DM
Haloscopes
Black hole superradiance

Cosmological Gravitational Particle Production

Compare: minimal and non-minimal coupling



Full parameter space in progress

Capanelli, LJ, Kolb, McDonough, 2023

Interactions built from symmetry properties

- KRLP is an antisymmetric matrix
- $B_{\mu\nu}$ a pseudovector (parity even)
- $H_{\mu\nu\rho}$ parity odd
- $\star B$ parity even

Dark photon-like portal

$$\mathscr{L}_{int} = gB_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$$

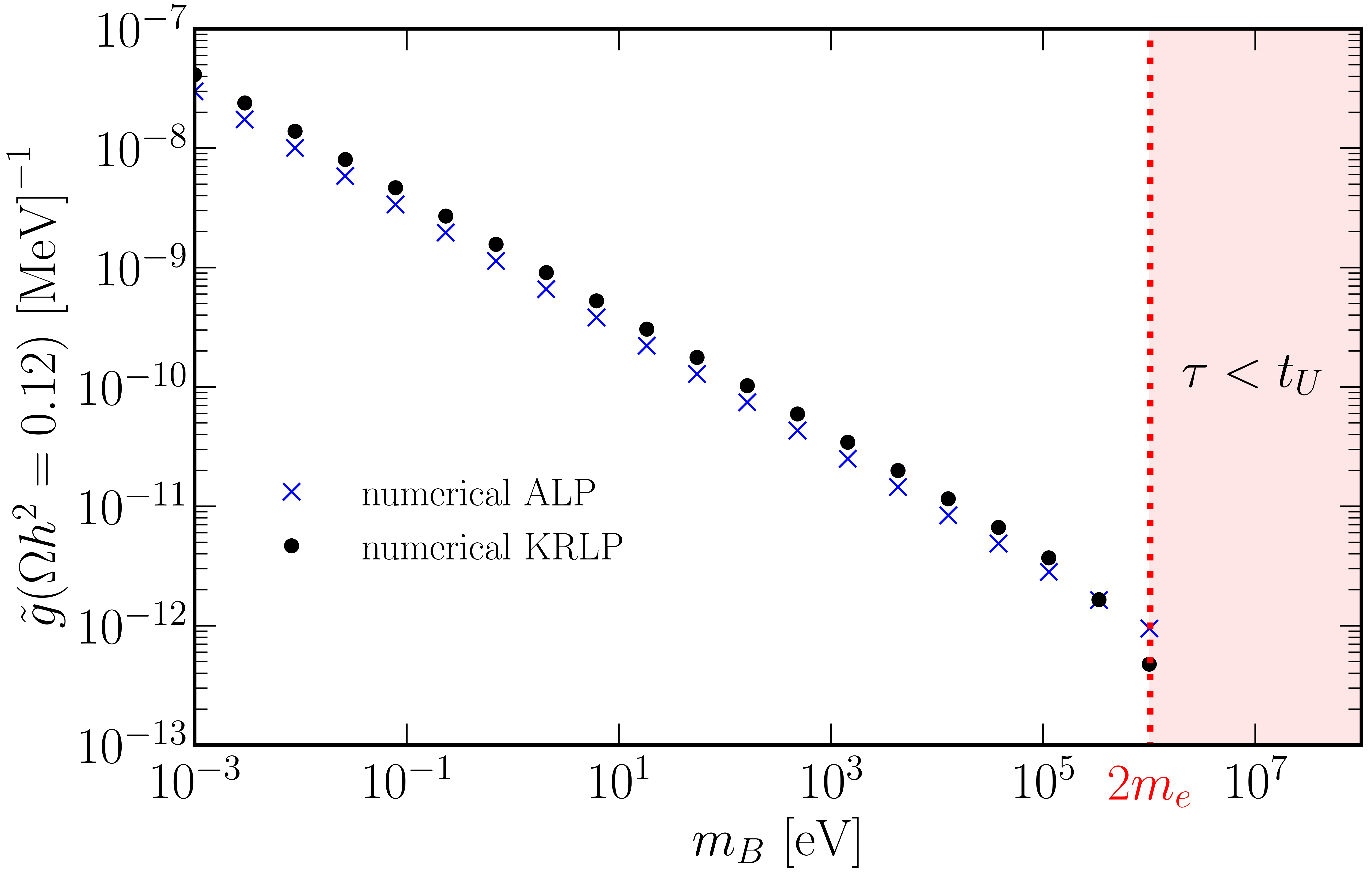
$$\sigma^{\mu\nu} = [\gamma^\mu, \gamma^\nu]$$

Axion-like portal

$$\mathscr{L}_{int} = \tilde{g}\tilde{H}_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$$

$$\tilde{H} = \star H$$

Freeze-in: Axion-like Portal



KRLP

$$\mathscr{L}_{int} = \tilde{g}\tilde{H}_\mu \bar{\psi}\gamma^\mu\gamma^5\psi$$

Axion (Langhoff et al., 2022)

$$\mathscr{L}_{int} = \tilde{g}\partial_\mu\theta\bar{\psi}\gamma^\mu\gamma^5\psi$$

- Scales like $\sim m_f^{1/2}$
- Independent of T_{RH}

C. Capanelli, LJ, E. Kolb, E. McDonough

Kalb-Ramond-Like-Particles (KRLPs)

Kalb-Ramond-Like-Particles   Kalb & Ramond, 1974

$$S = \int d^4x \left(H_{\mu\nu\rho} H^{\mu\nu\rho} - m^2 B_{\mu\nu} B^{\mu\nu} \right)$$

$$H = dB$$

- Antisymmetric, *massive* two-form field, $B_{\mu\nu}$
- EFT-inspired, $B_{\mu\nu}$-like objects appear in many areas of physics
- $(1,0) \oplus (0,1)$ representation of the Lorentz group

GPP of KRLPs

Duality: Massive KR → massive pseudovector

(See Hell 2022 for caveats)

$$S = \frac{1}{12}\int d^4x\sqrt{-g}\left(H_{\mu\nu\rho}H^{\mu\nu\rho} - 3m^2 B_{\mu\nu}B^{\mu\nu}\right)$$

↓ $B_{ij} = \epsilon_{ijk}A^k$

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

GPP of minimally coupled KRLPs identical to Proca

Add non minimal couplings?

Proca

$$\xi_1 R A_\mu A^\mu$$

$$\xi_2 R^{\mu\nu} A_\mu A_\nu$$

↓

$$m_t^2 = m^2 - \xi_1 R - \frac{1}{2}\xi_2 R - 3\xi_2 H^2$$

$$m_x^2 = m^2 - \xi_1 R - \frac{1}{6}\xi_2 R + \xi_2 H^2$$

Add non minimal couplings?

Proca

$$\xi_1 R A_\mu A^\mu$$

$$\xi_2 R^{\mu\nu} A_\mu A_\nu$$

↓

$$m_t^2 = m^2 - \xi_1 R - \frac{1}{2}\xi_2 R - 3\xi_2 H^2$$

$$m_x^2 = m^2 - \xi_1 R - \frac{1}{6}\xi_2 R + \xi_2 H^2$$

KRLP

$$\xi_3 R B^{\mu\nu} B_{\mu\nu}$$

$$\xi_4 R^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma}$$

↓

$$m_t^2 = m^2 - \frac{2}{3}\xi_3 R - \frac{2}{9}\xi_4 R - \frac{4}{3}\xi_4 H^2$$

$$m_x^2 = m^2 - \frac{2}{3}\xi_3 R - \frac{2}{27}\xi_4 R + \frac{4}{3}\xi_4 H^2$$

GPP of KRLPs

Add non minimal couplings?

Redefine: $\xi_3 \to \frac{3}{2}\xi_1$, $\xi_4 \to \frac{9}{4}\xi_2$ ⟶ Effective masses are the same (on FRW)

We get GPP of non minimally coupled KRLPs from non minimally coupled spin-1!

Future Directions

- Experimental prospects: dark photon and axion experiments (Belle-II, DarkLight)

- Couplings to cosmic strings

 (e.g. Vilenkin & Vachaspati, 1987)

- Cosmological collider signaturess

(e.g. Chen & Wang, 2010; Arkani-Hamed & Maldecena, 2015; Lee et al., 2016)

- Terrestrial collider signatures

- Primordial gravitational waves

- & much more!